
Astrophysical MHD turbulence:

From the Big Bang to the modern Universe
& from stars to the cosmic web



Nordita Program • Stockholm • 25/05/2026

Jennifer Schober

Argelander Institute for Astronomy

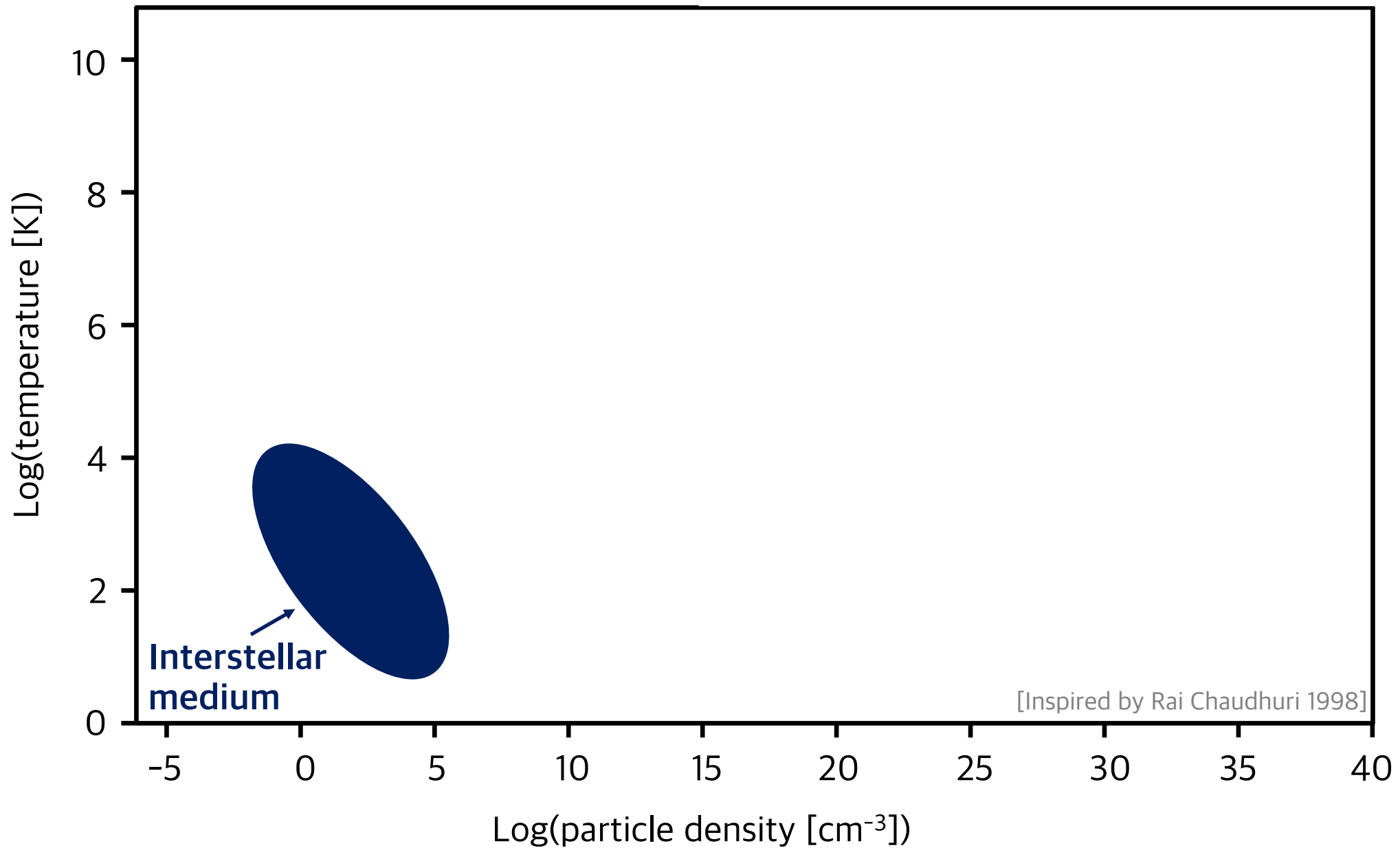




Tarantula Nebula © ESO, M.-R. CIONI/VISTA MAGELLANIC CLOUD SURVEY, CAMBRIDGE ASTRONOMICAL SURVEY UNIT, NASA/SOFIA

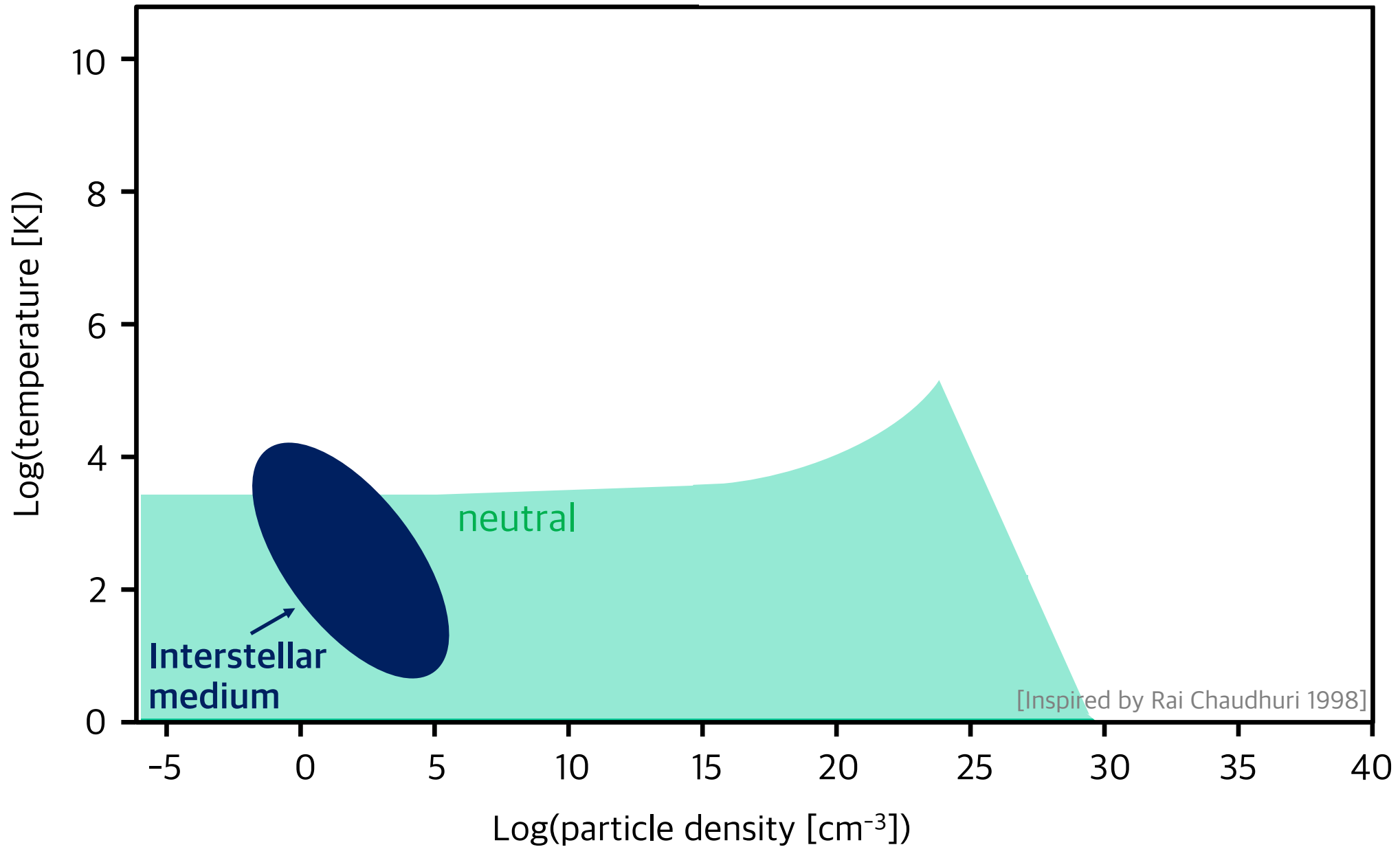
Plasma Universe: overview

Nordita program
25/05/2026



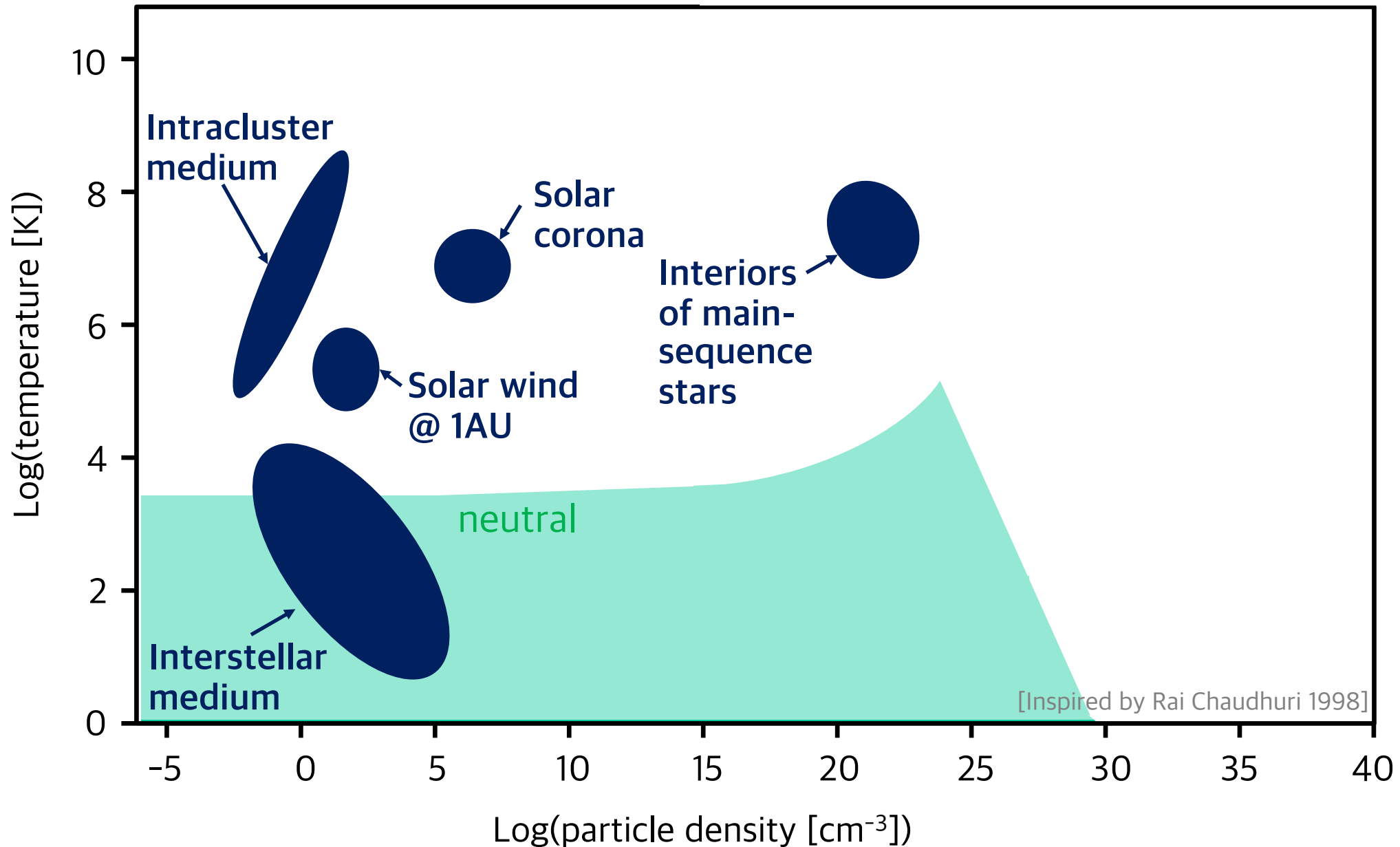
Plasma Universe: overview

Nordita program
25/05/2026



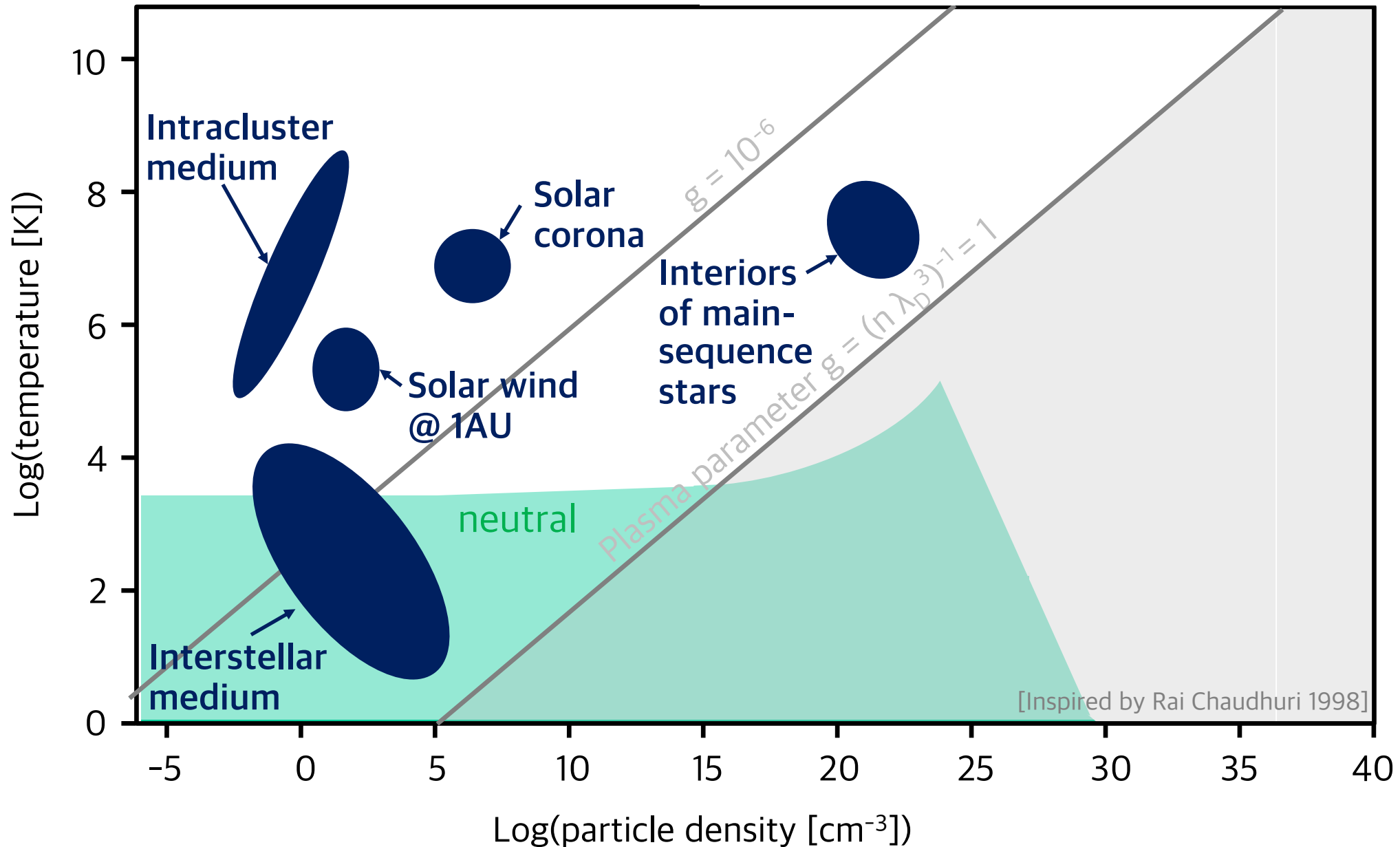
Plasma Universe: overview

Nordita program
25/05/2026



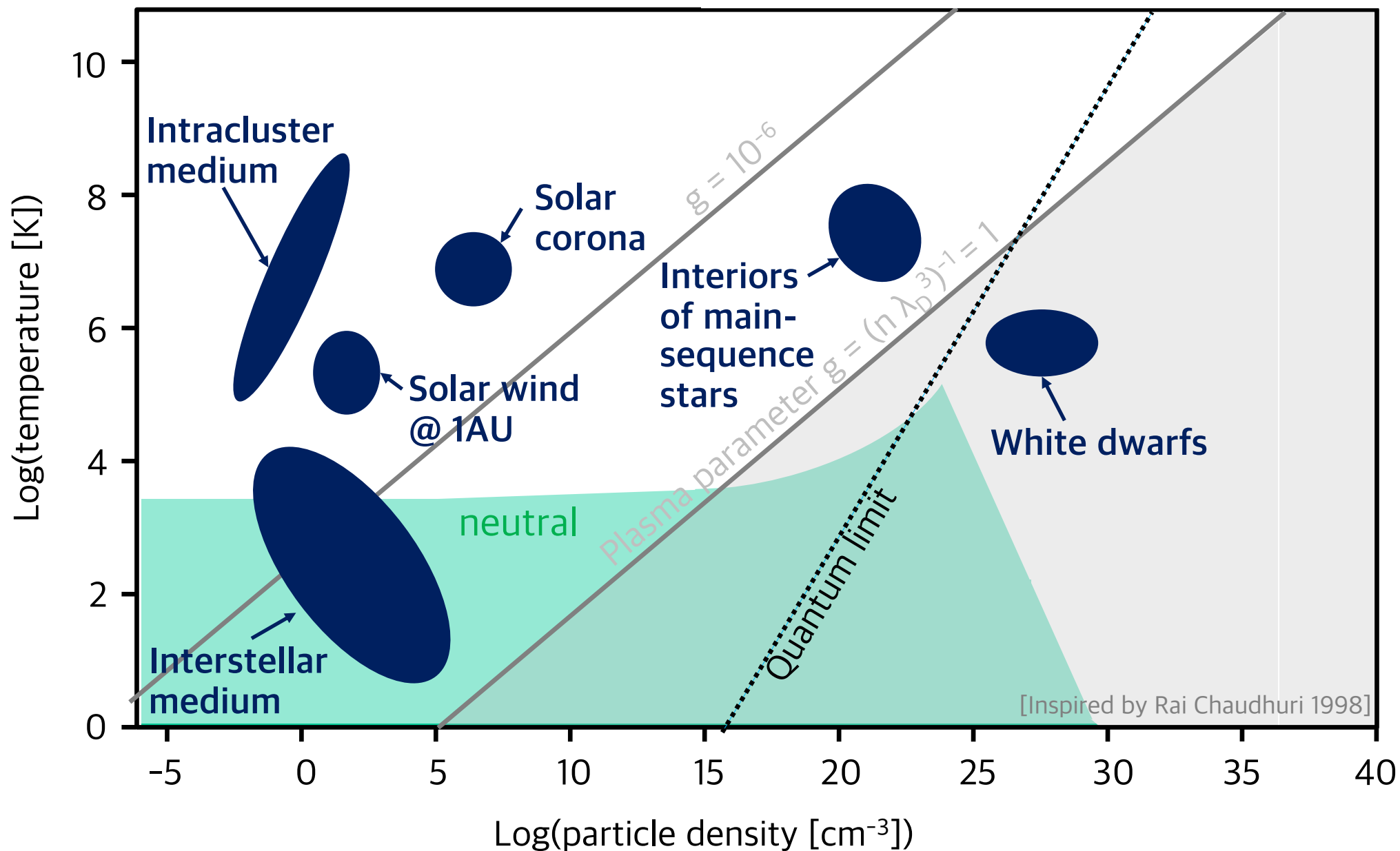
Plasma Universe: overview

Nordita program
25/05/2026



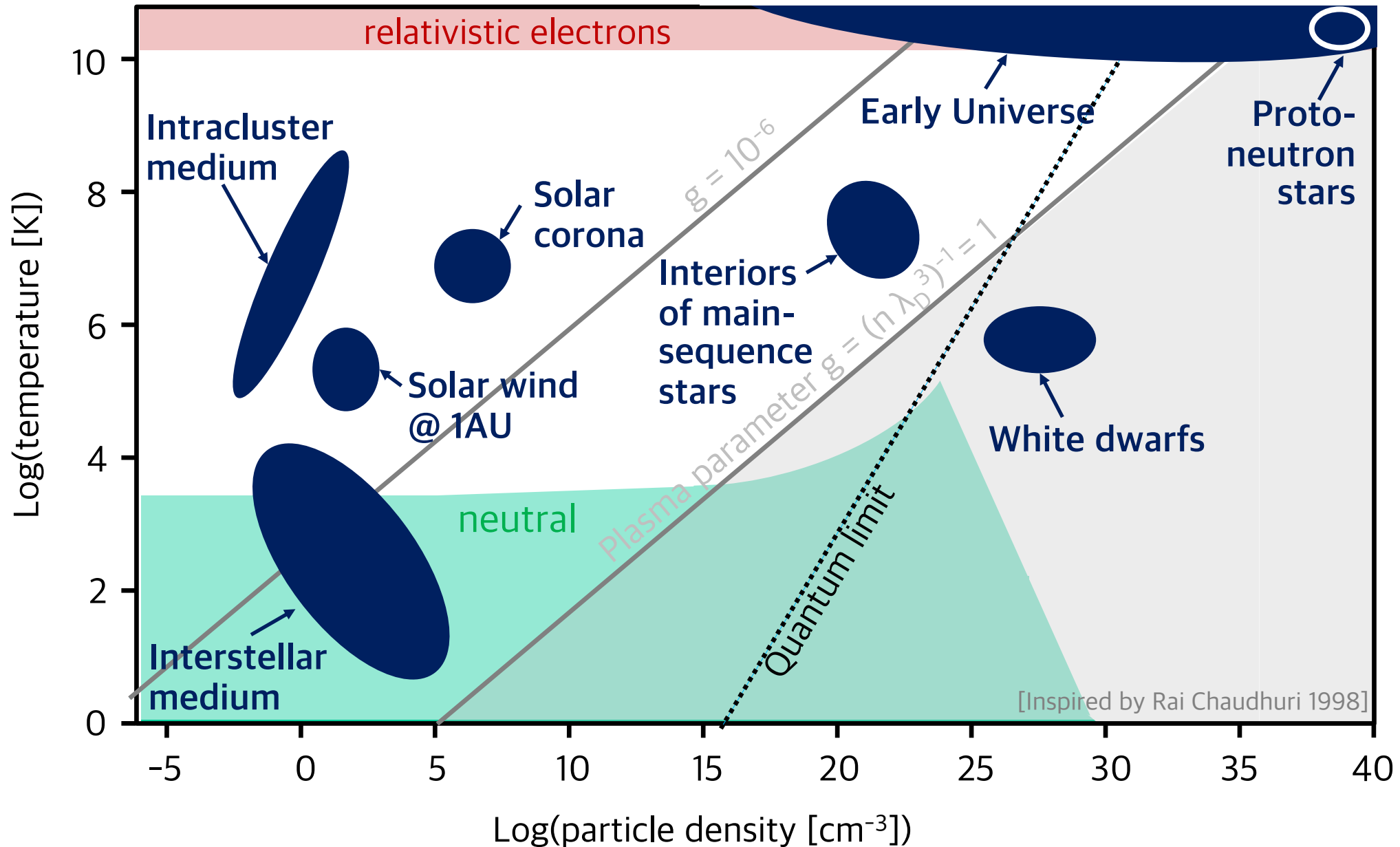
Plasma Universe: overview

Nordita program
25/05/2026



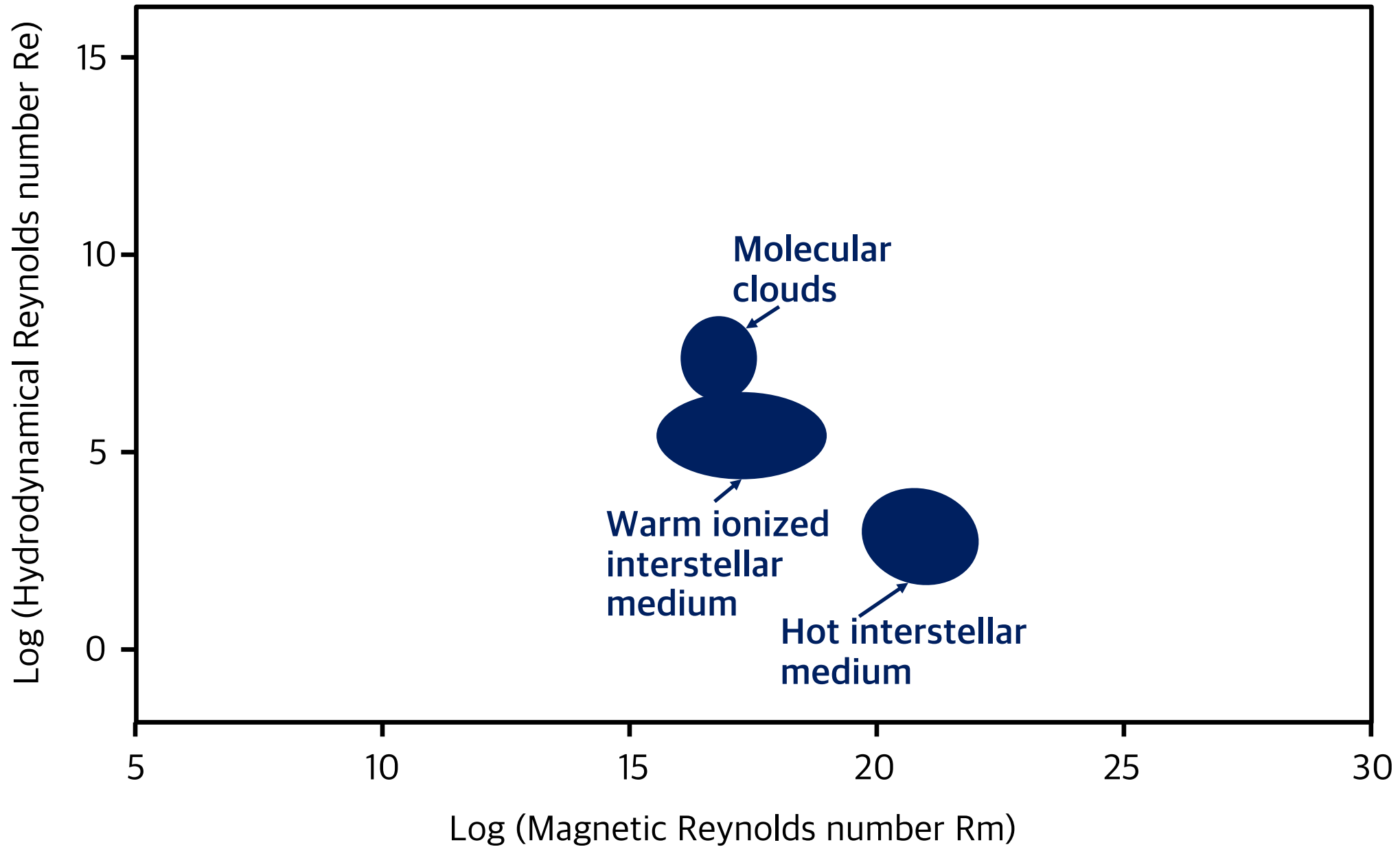
Plasma Universe: overview

Nordita program
25/05/2026



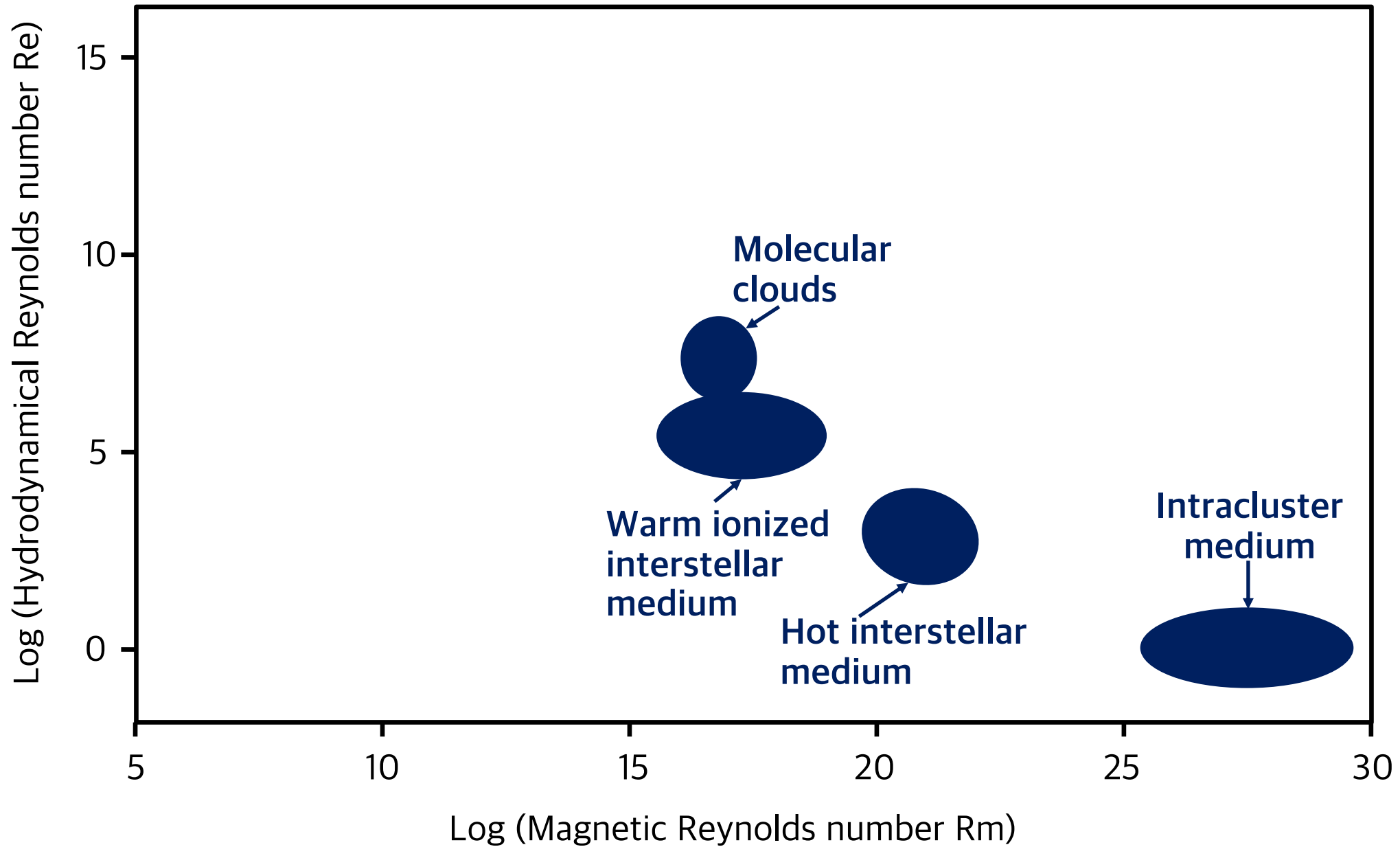
Plasma Universe: turbulence

Nordita program
25/05/2026



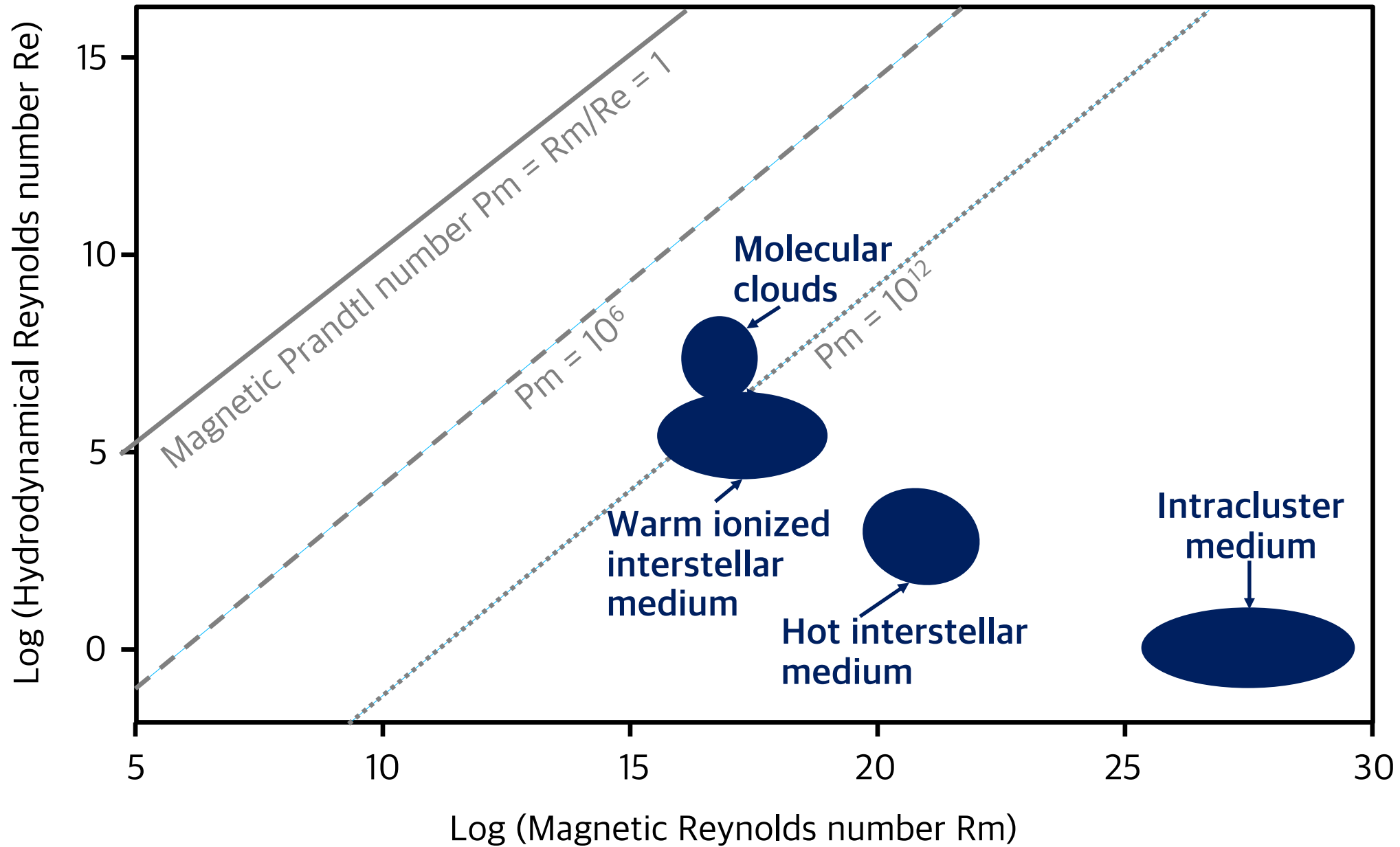
Plasma Universe: turbulence

Nordita program
25/05/2026



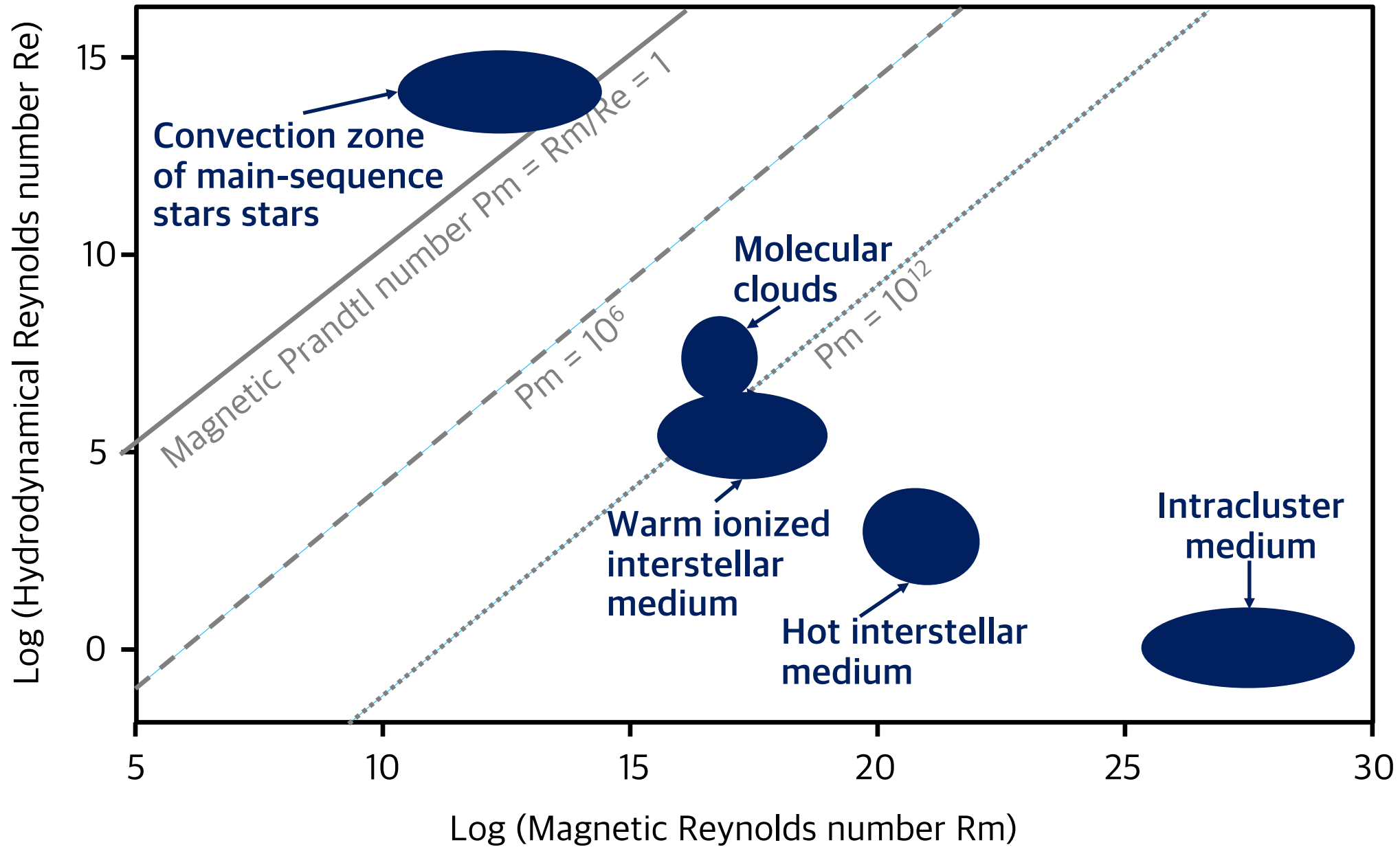
Plasma Universe: turbulence

Nordita program
25/05/2026



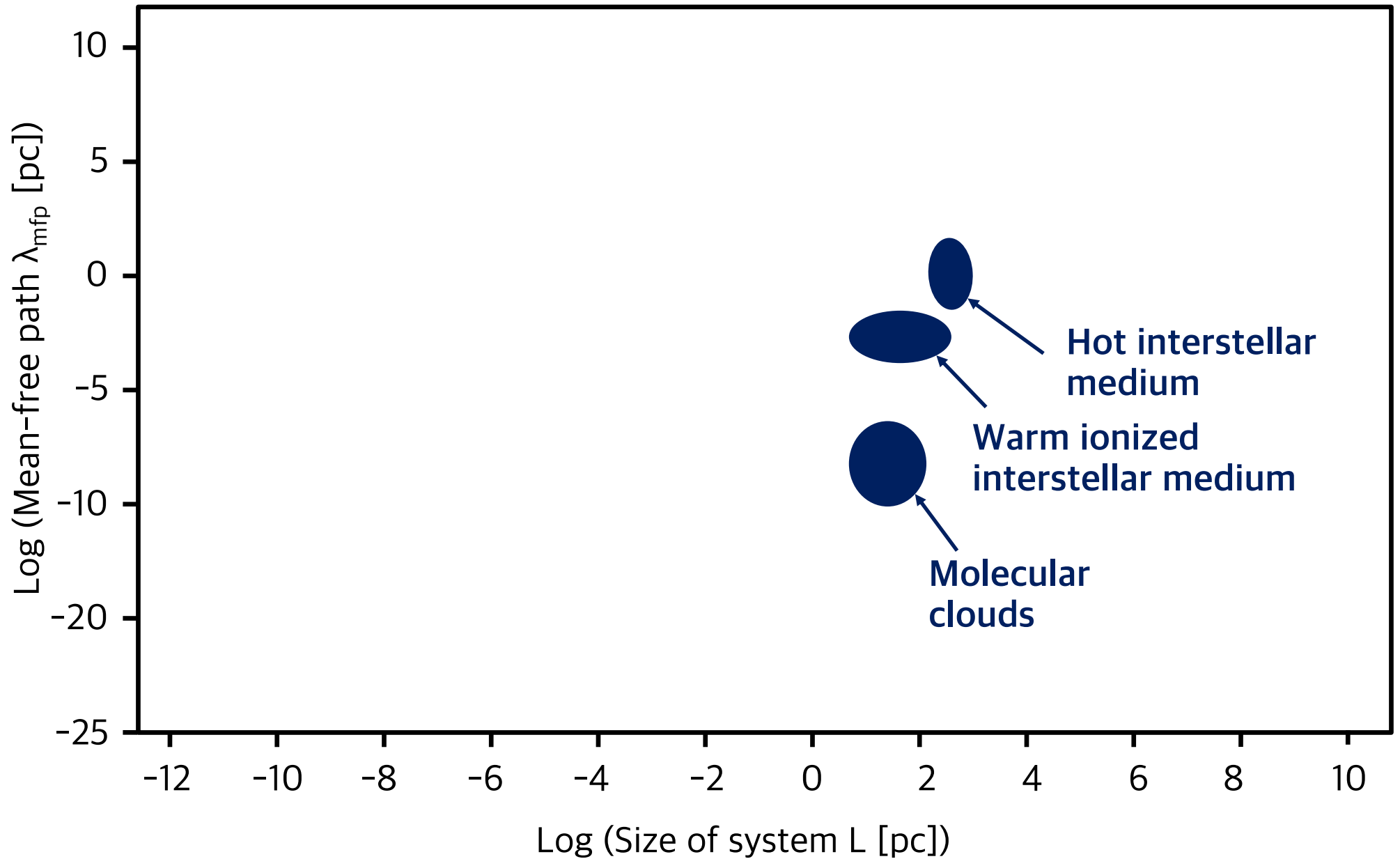
Plasma Universe: turbulence

Nordita program
25/05/2026



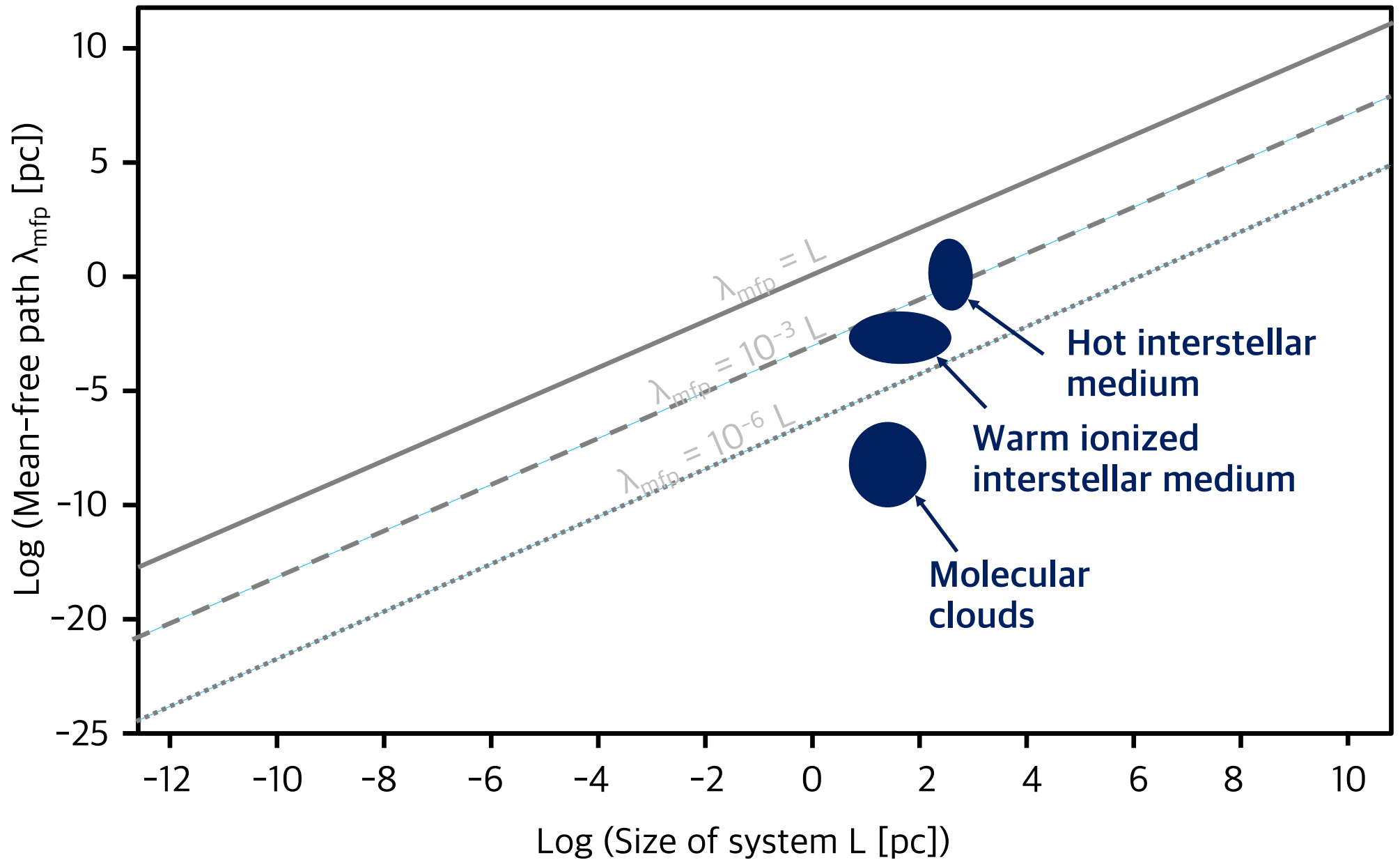
Plasma Universe: collisionality

Nordita program
25/05/2026



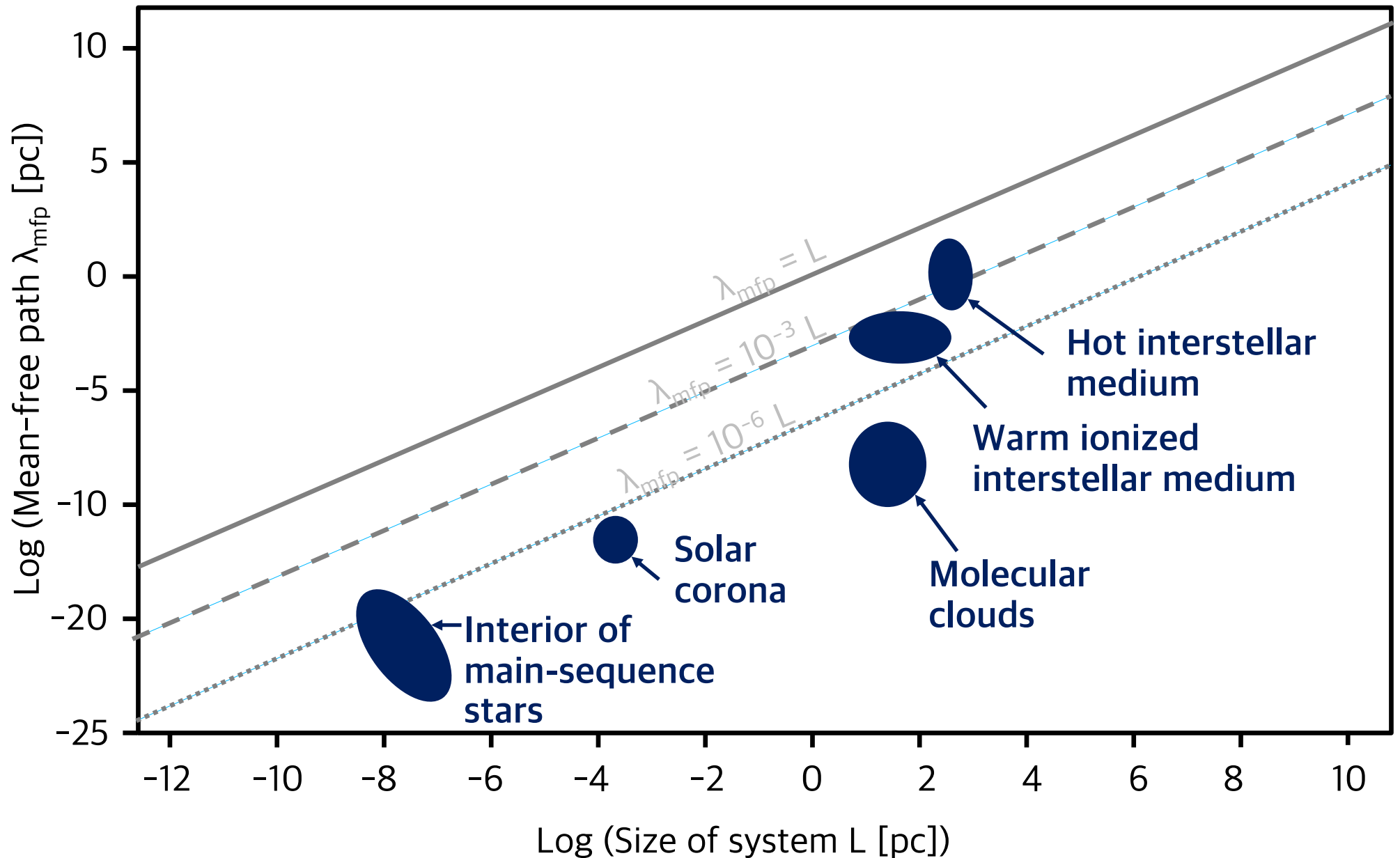
Plasma Universe: collisionality

Nordita program
25/05/2026



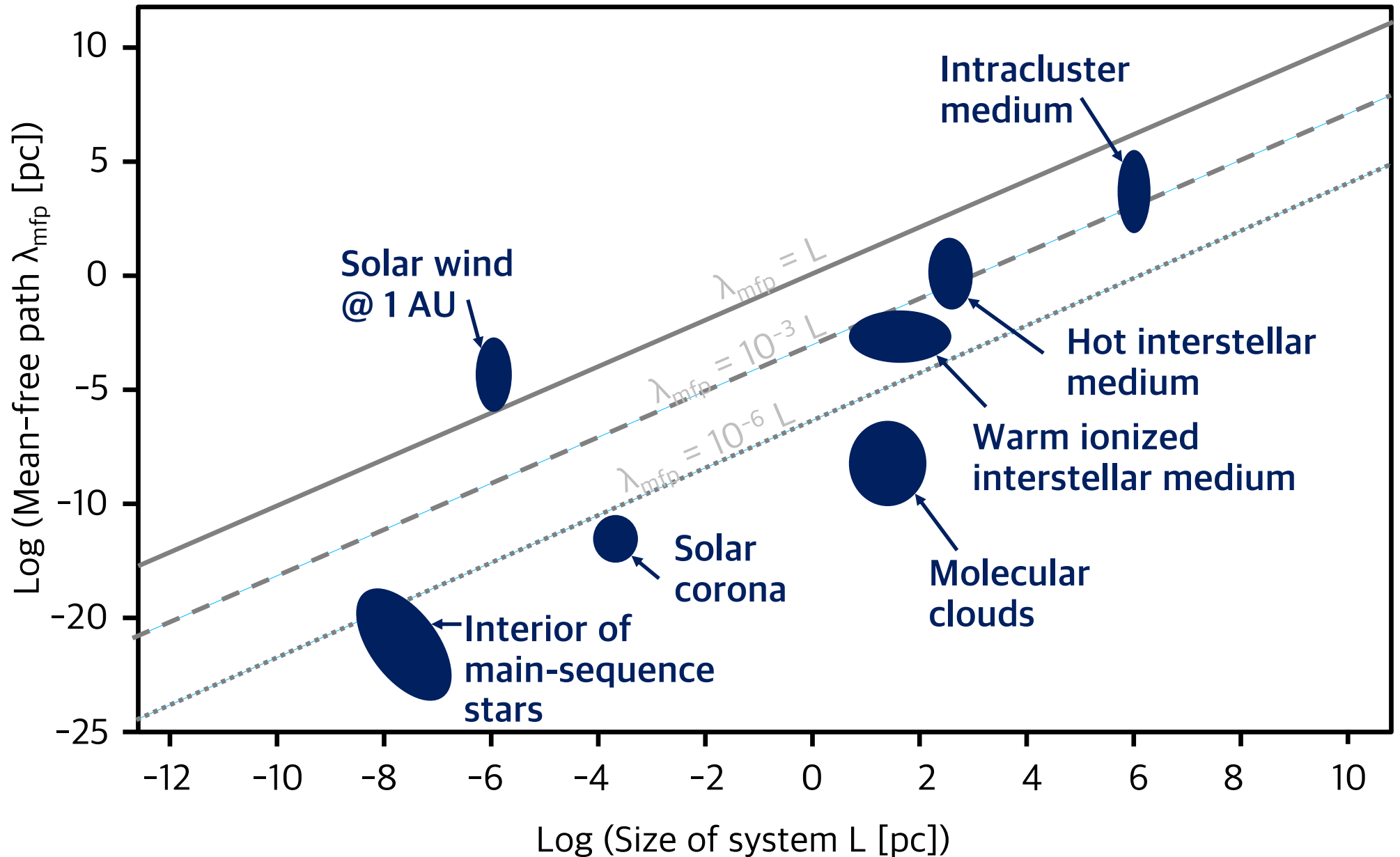
Plasma Universe: collisionality

Nordita program
25/05/2026



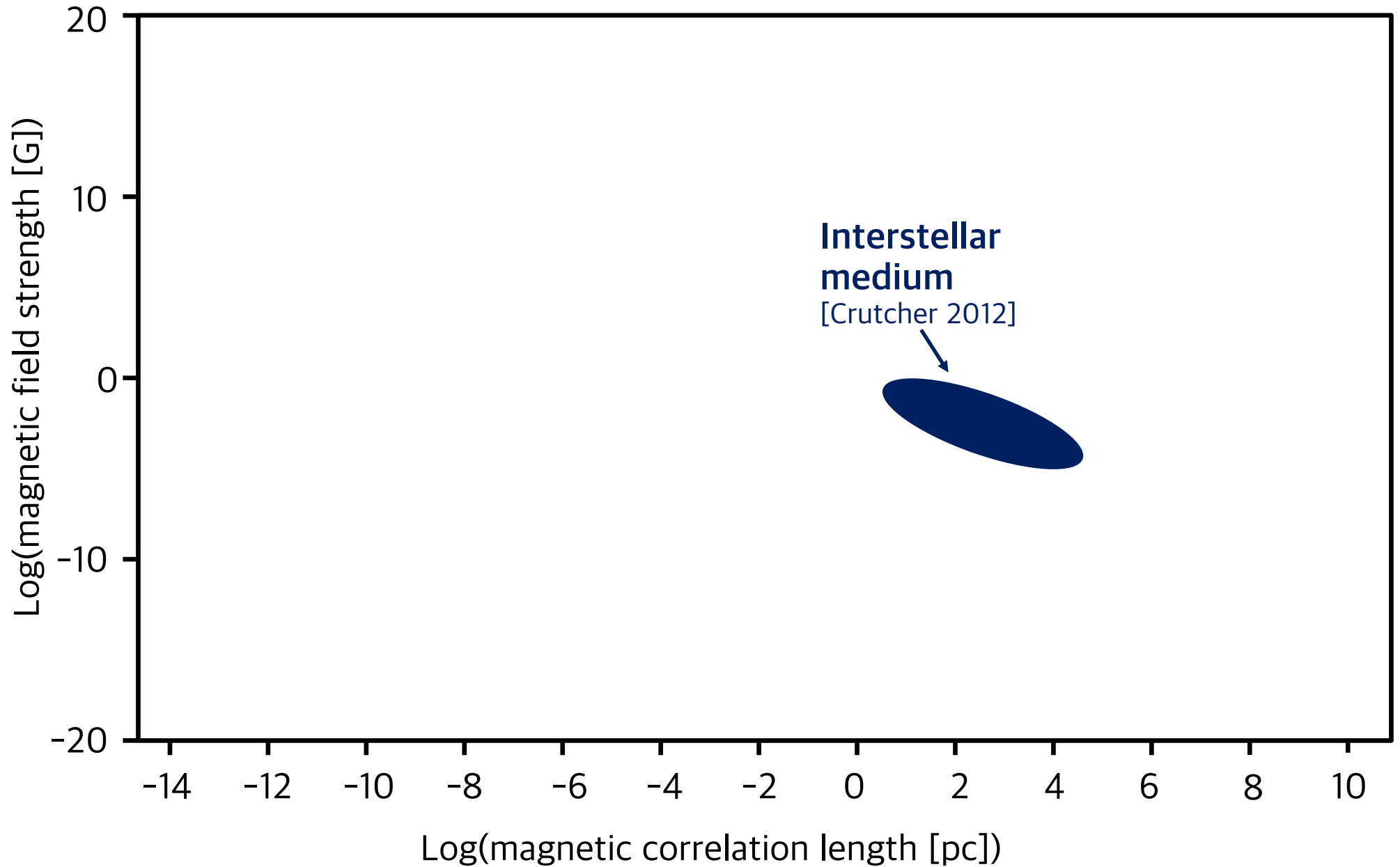
Plasma Universe: collisionality

Nordita program
25/05/2026



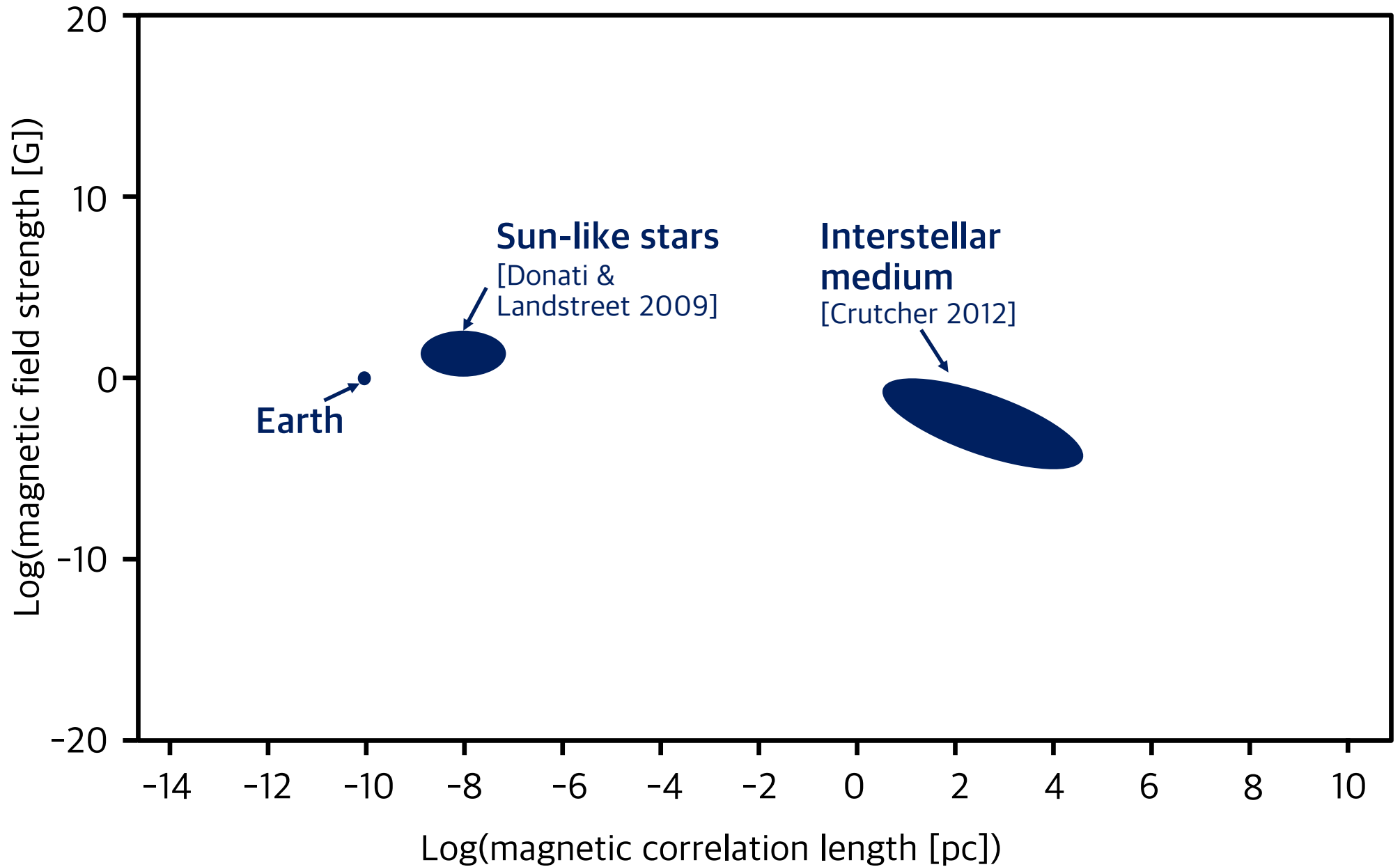
Plasma Universe: magnetic fields

Nordita program
25/05/2026



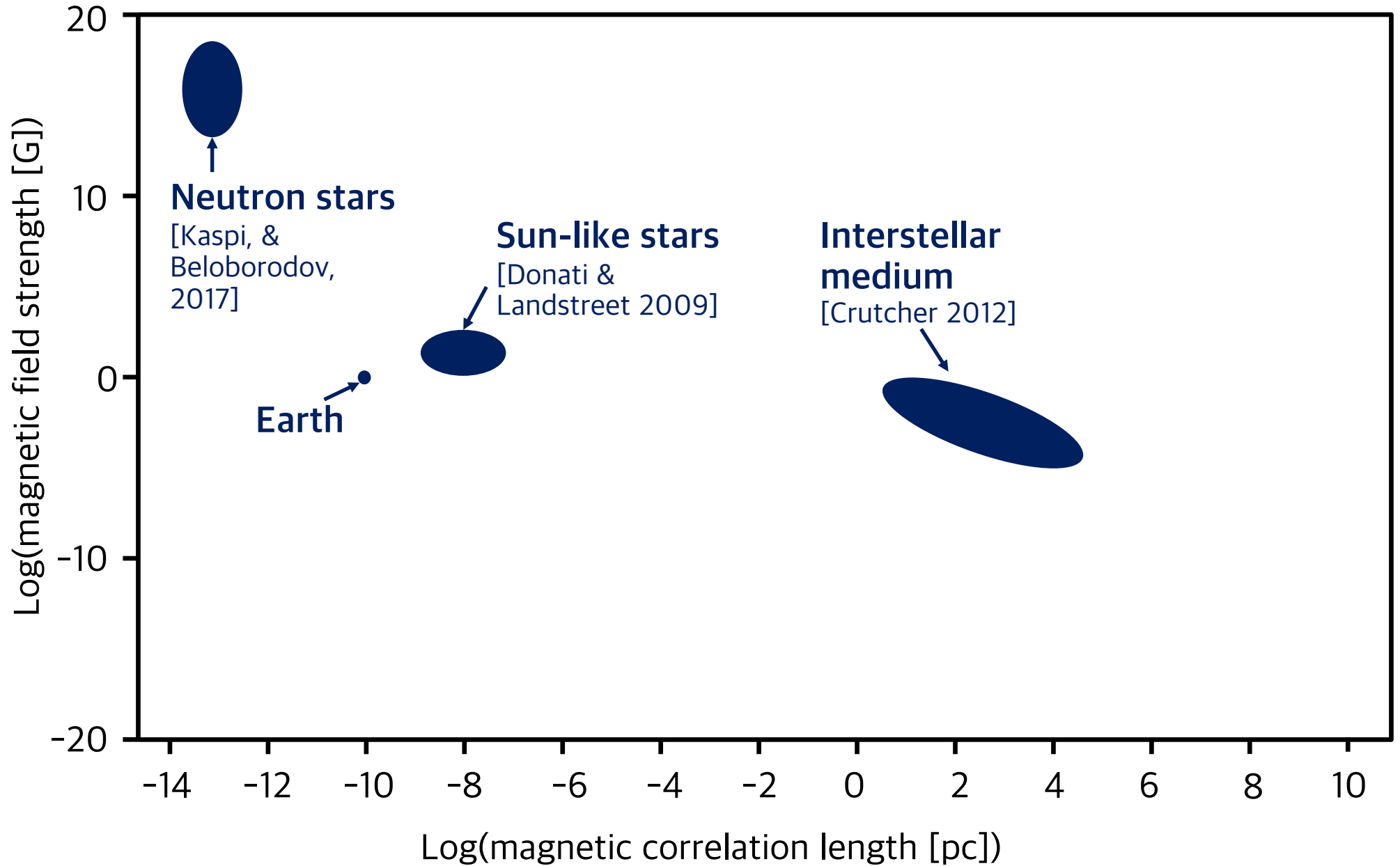
Plasma Universe: magnetic fields

Nordita program
25/05/2026



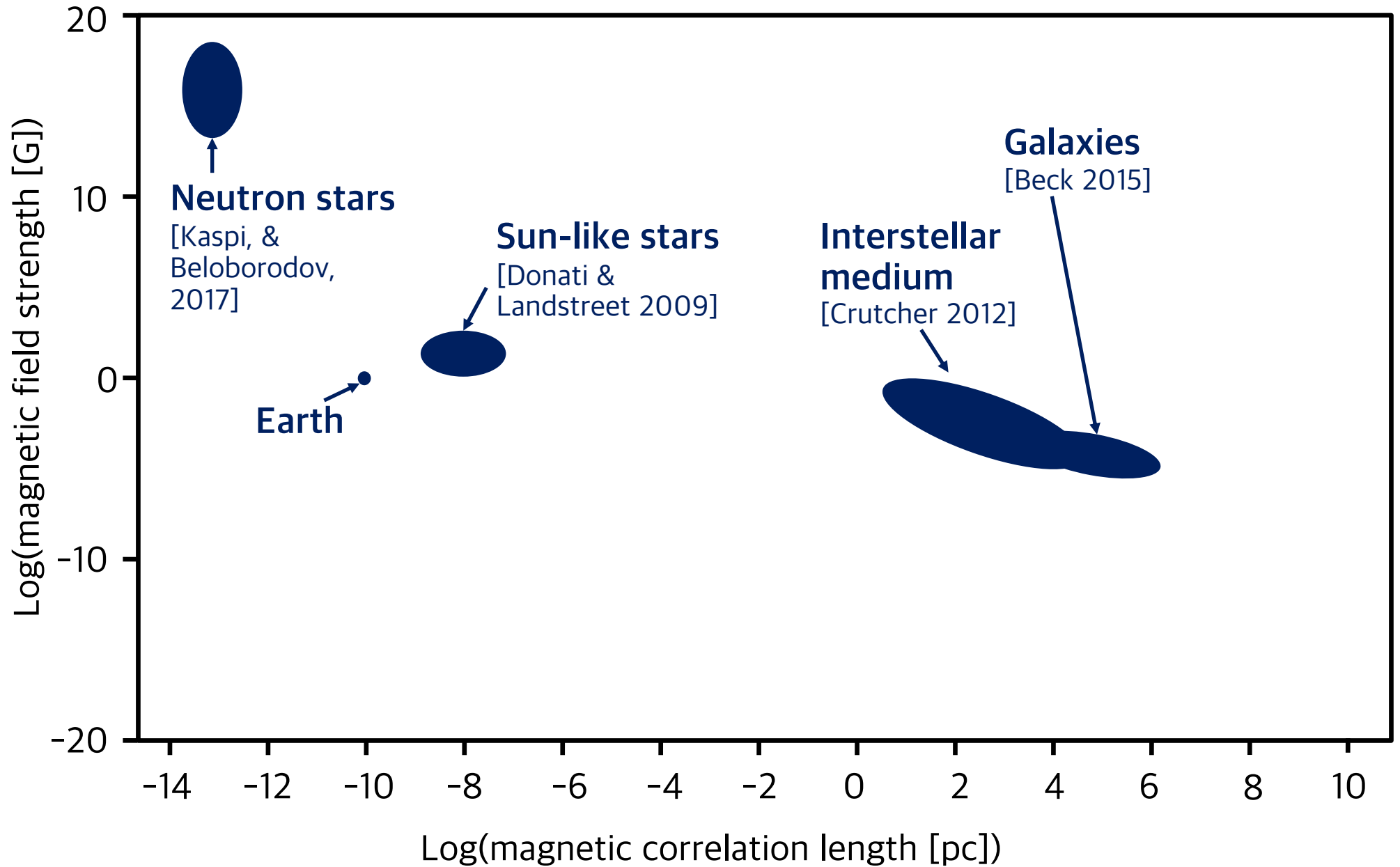
Plasma Universe: magnetic fields

Nordita program
25/05/2026



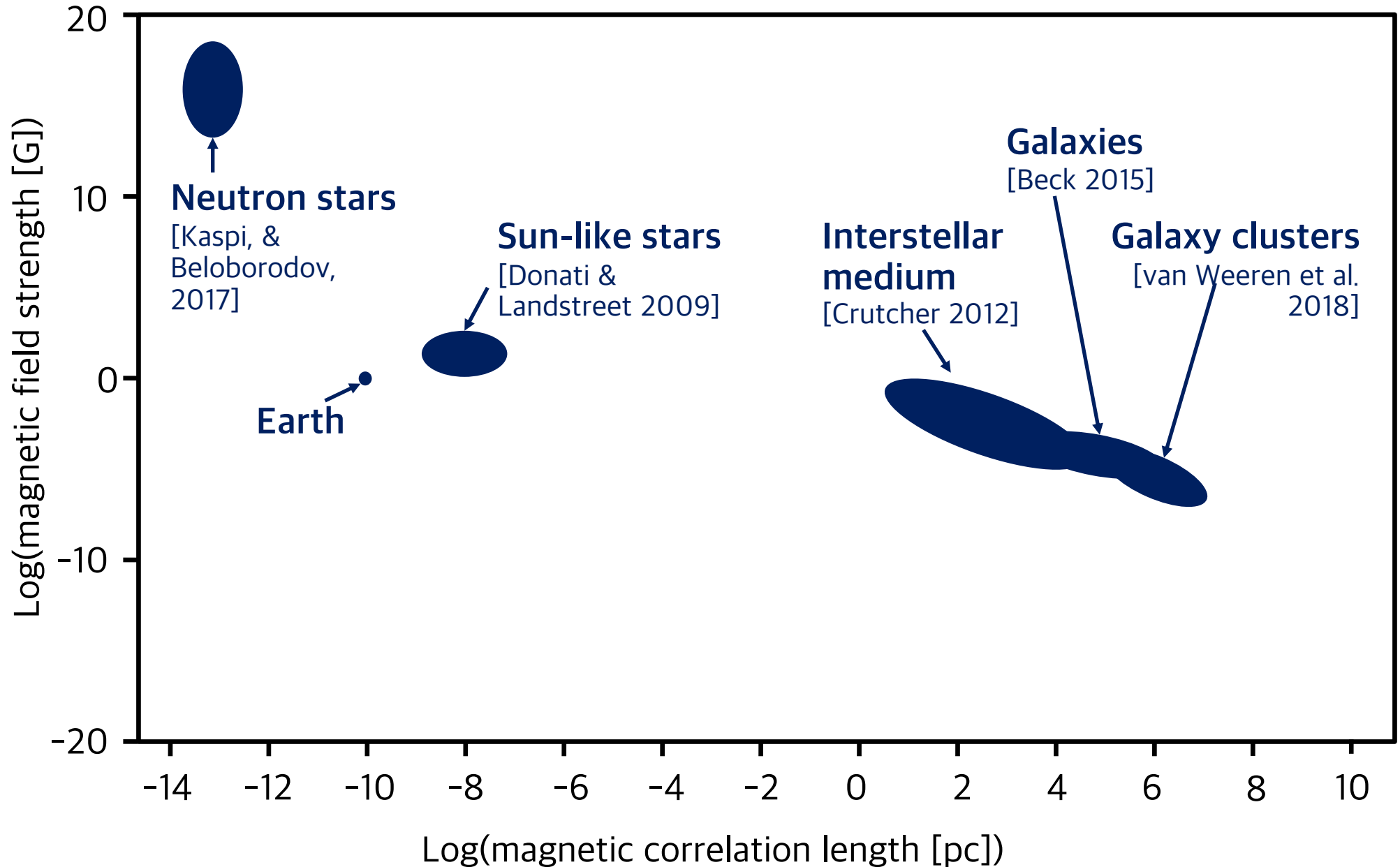
Plasma Universe: magnetic fields

Nordita program
25/05/2026



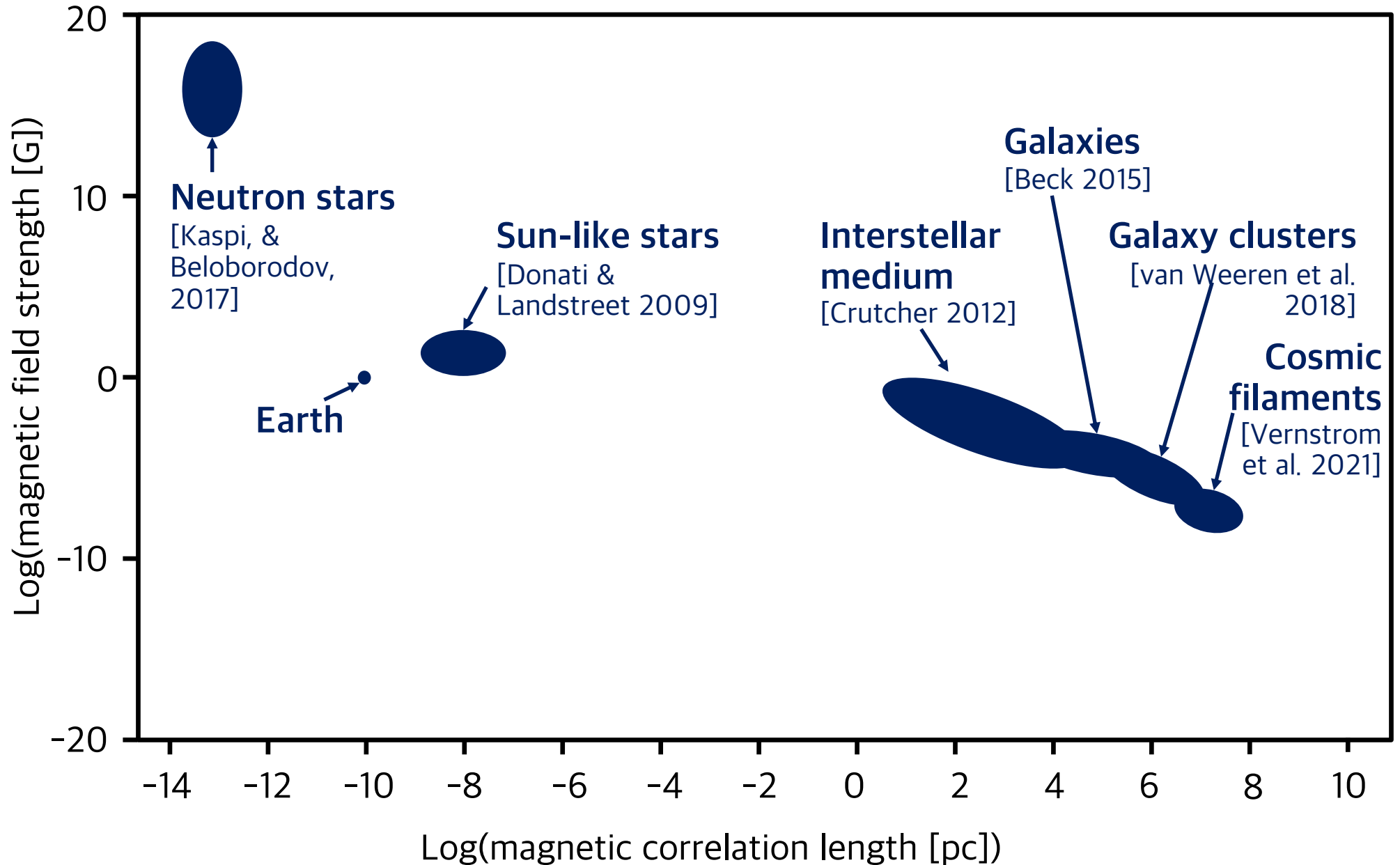
Plasma Universe: magnetic fields

Nordita program
25/05/2026



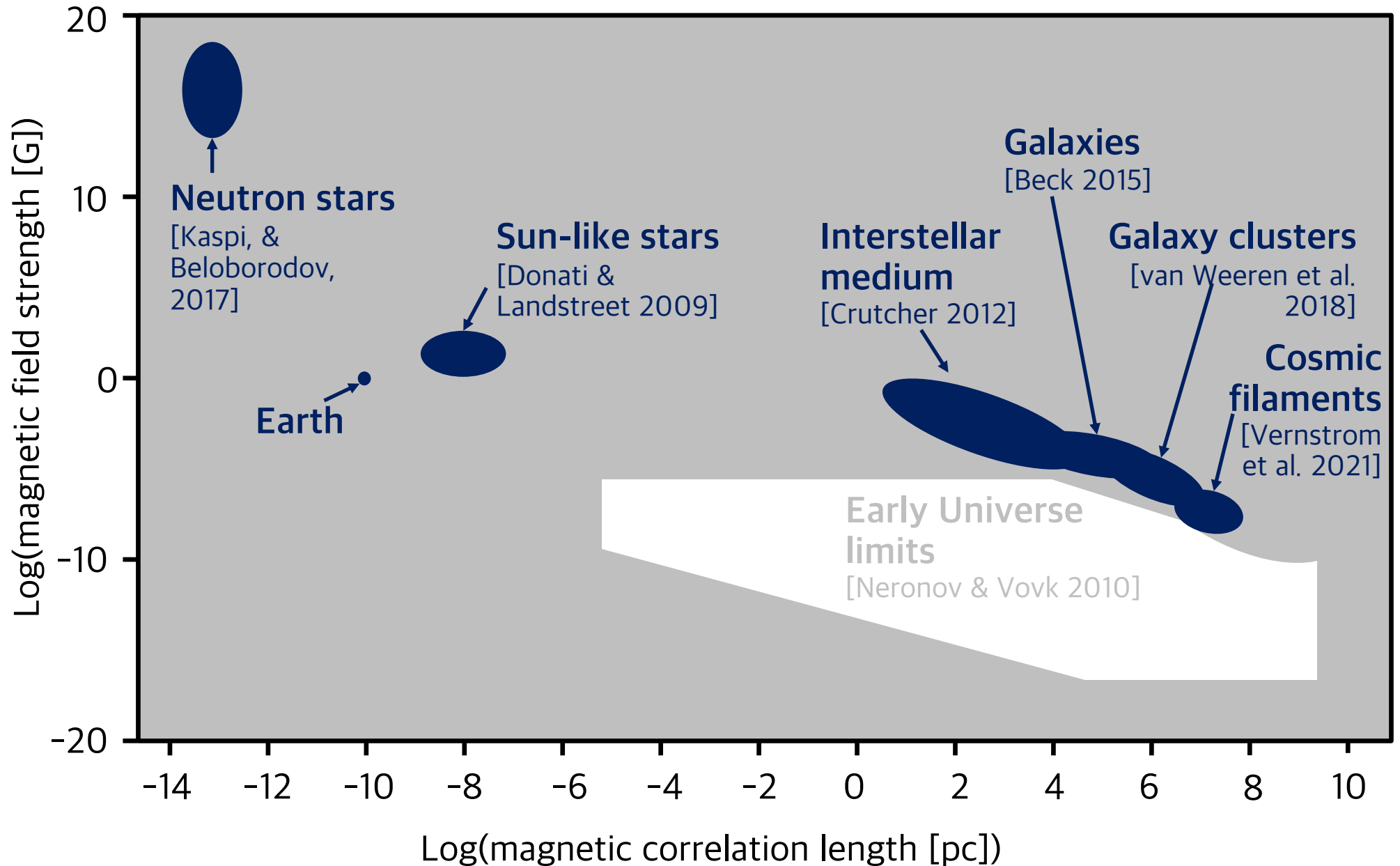
Plasma Universe: magnetic fields

Nordita program
25/05/2026



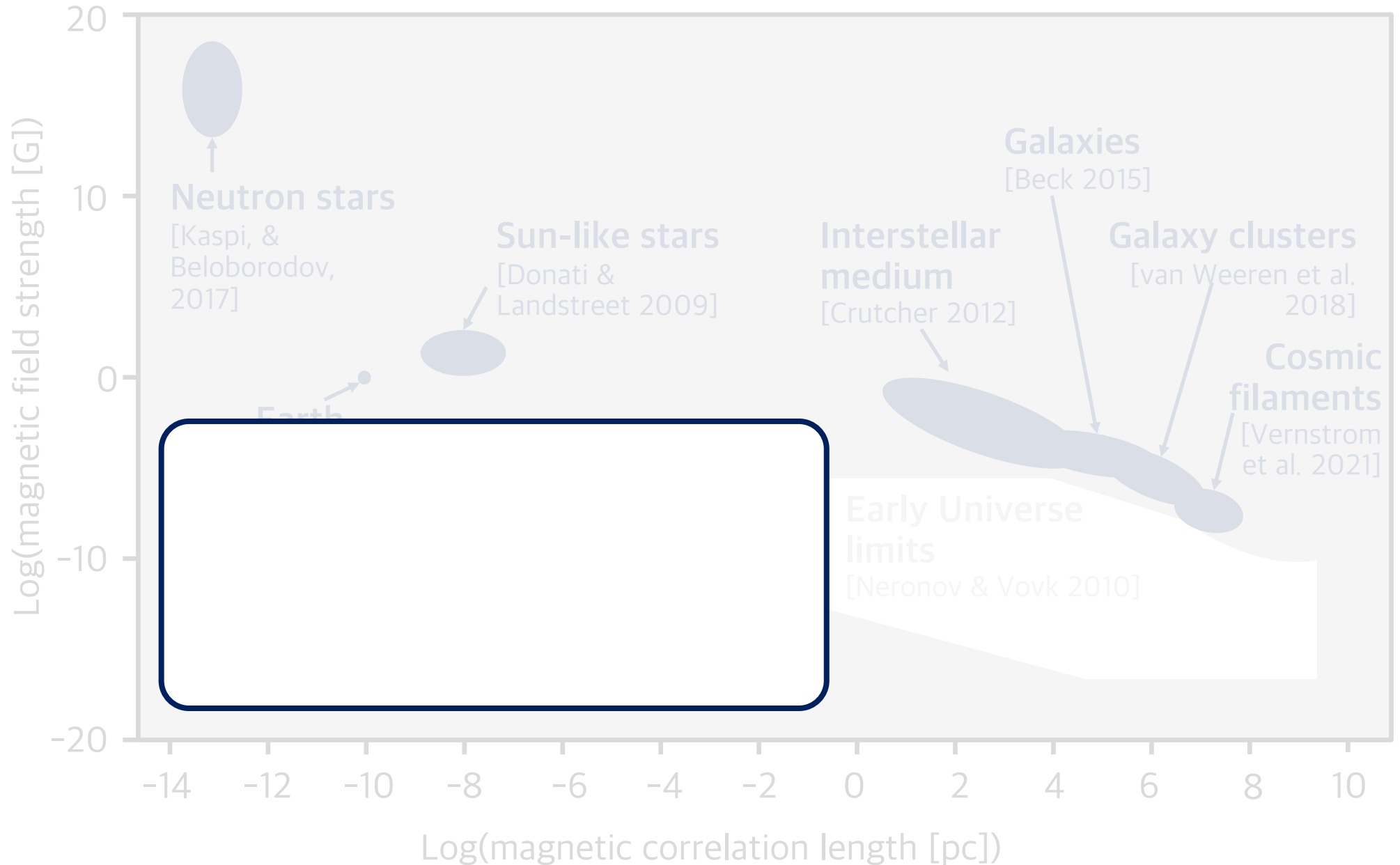
Plasma Universe: magnetic fields

Nordita program
25/05/2026



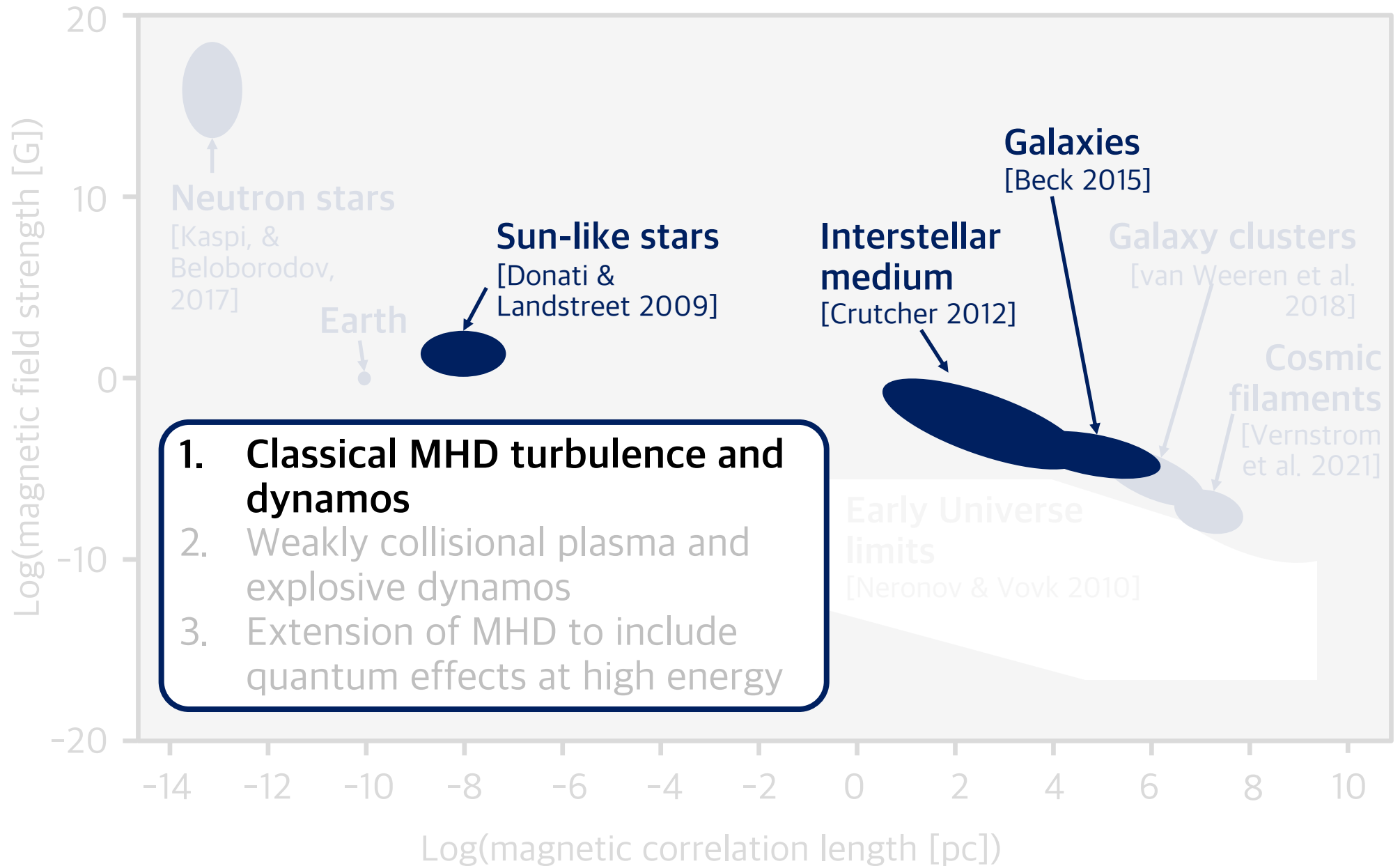
Overview of this talk

Nordita program
25/05/2026



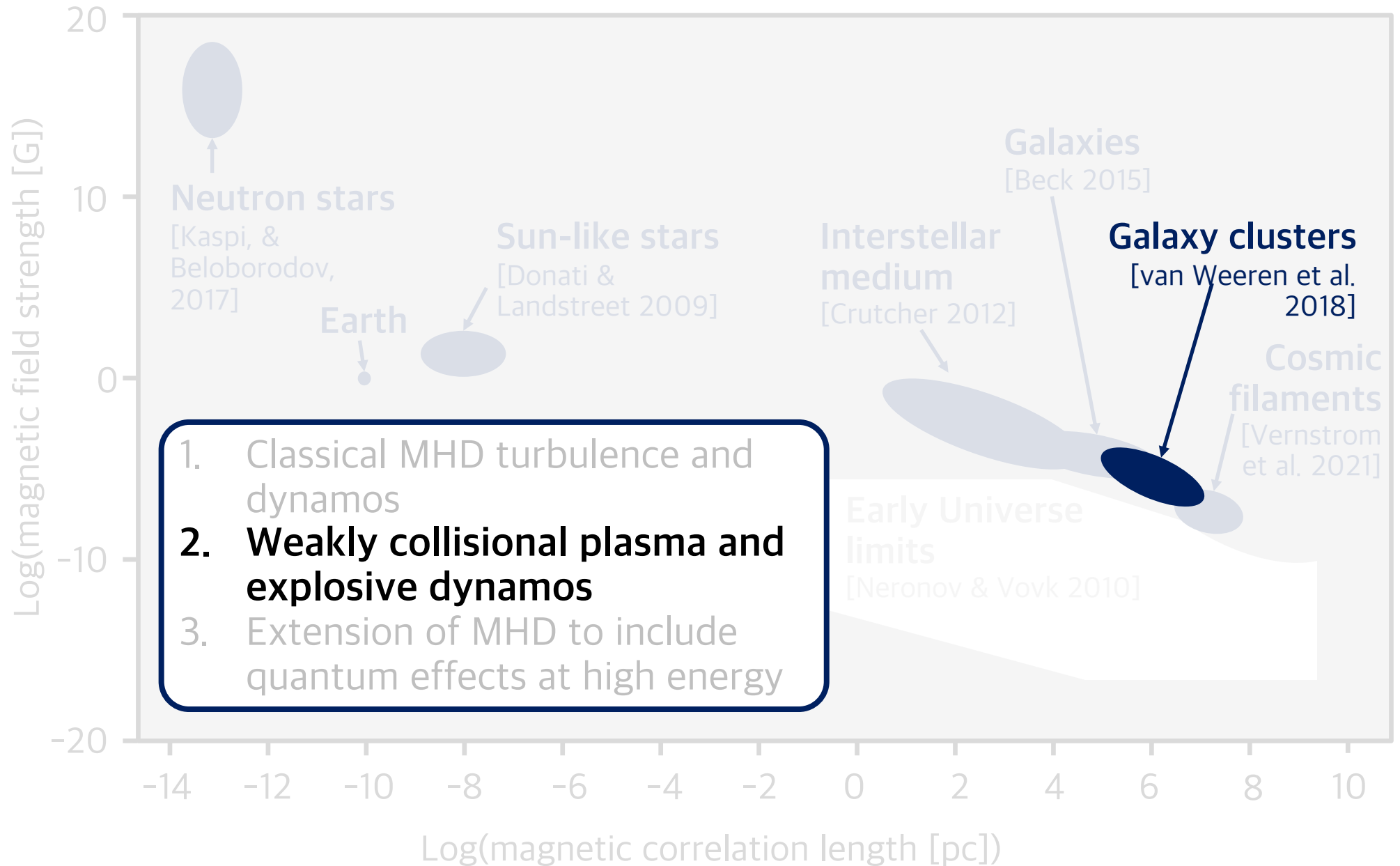
Overview of this talk

Nordita program
25/05/2026



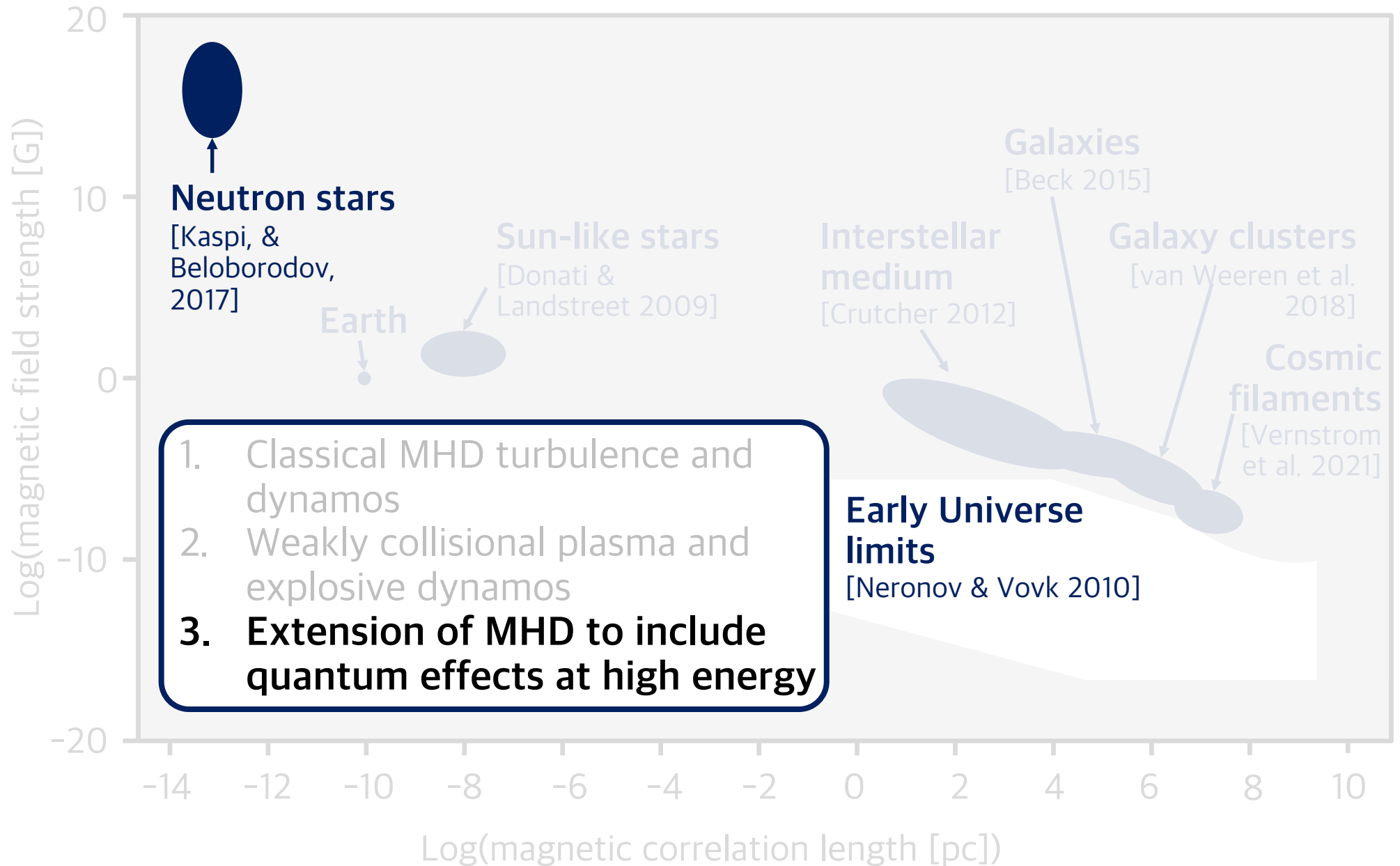
Overview of this talk

Nordita program
25/05/2026



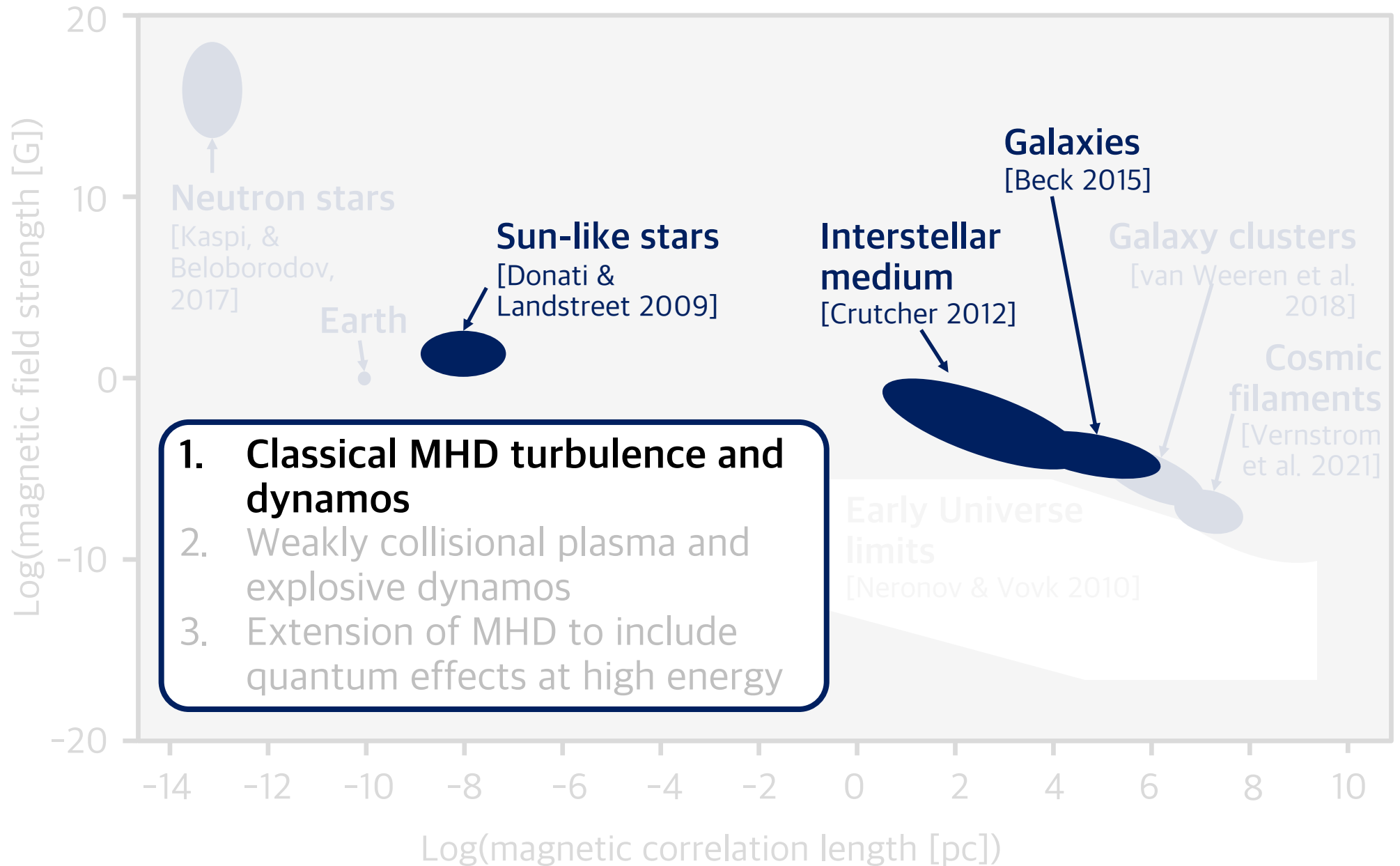
Overview of this talk

Nordita program
25/05/2026



Overview of this talk

Nordita program
25/05/2026



Brief history of the Universe

Nordita program
25/05/2026

Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

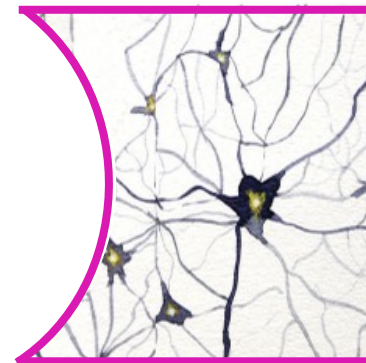
↗️ 5×10^{10} ly

Brief history of the Universe

Nordita program
25/05/2026

Modern Universe:

Large-scale cosmic web,
galaxy clusters, galaxies,
stars, ...

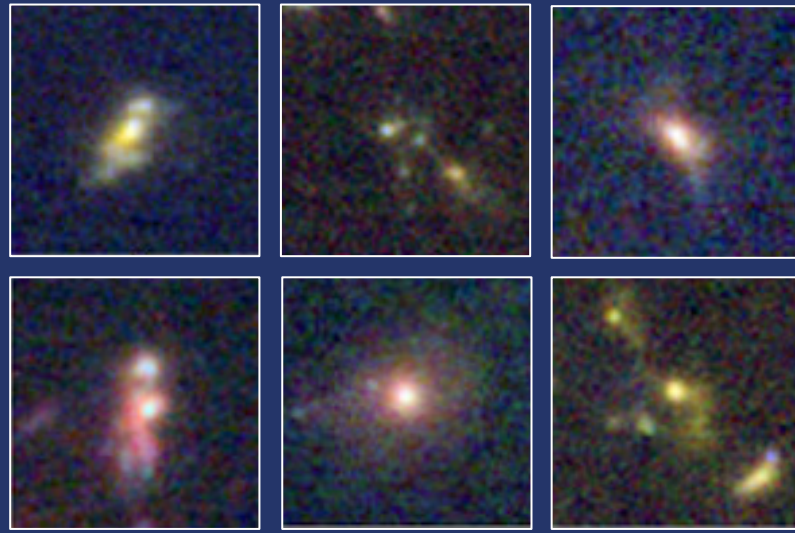


🕒 13.6 Gyr

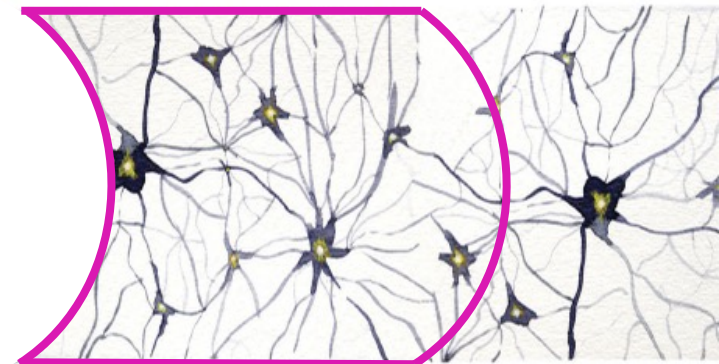
🌡️ 3 K

↗️ 5×10^{10} ly

Galaxy evolution over 100s of million yrs



© NASA
& JWST



🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

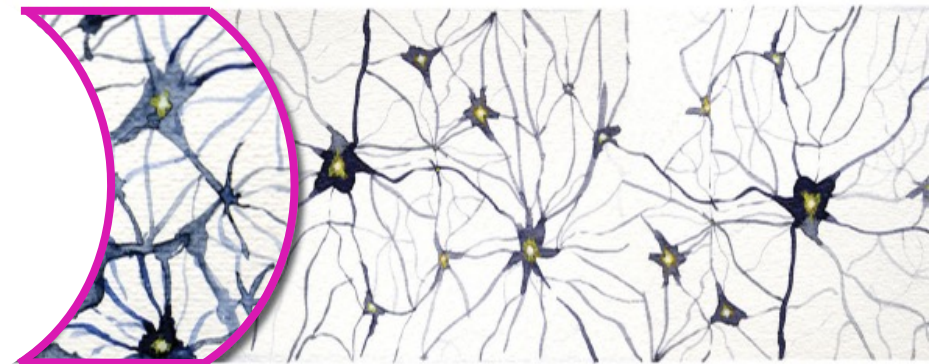
🌡️ 3 K

↗️ 5×10^{10} ly

Brief history of the Universe

Nordita program
25/05/2026

Formation of the first stars,
when the Universe has cooled
down enough for gravitational
collapse.



🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

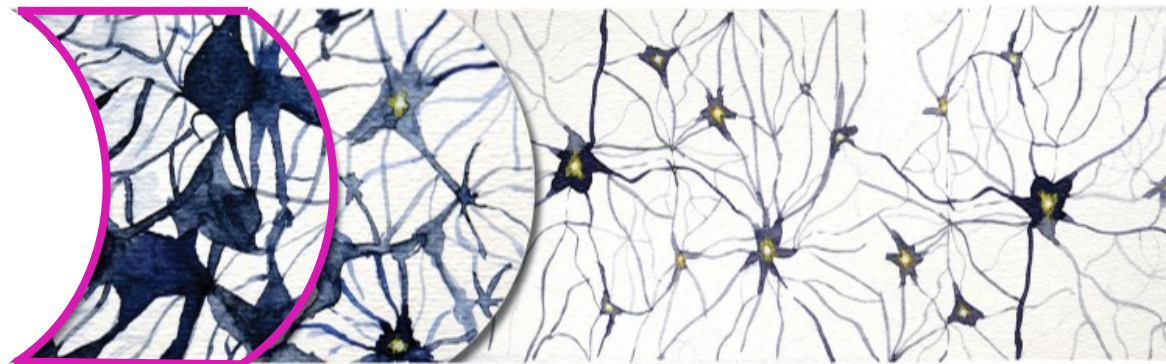
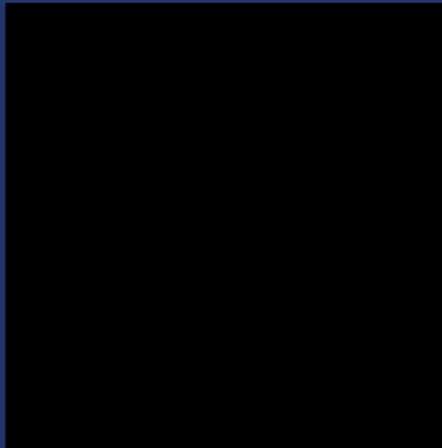
🌡️ 3 K

↗️ 5×10^{10} ly

Brief history of the Universe

Nordita program
25/05/2026

Dark ages:
No stars that emit light.



🕒 300–500 Myr

🌡️ 30 K

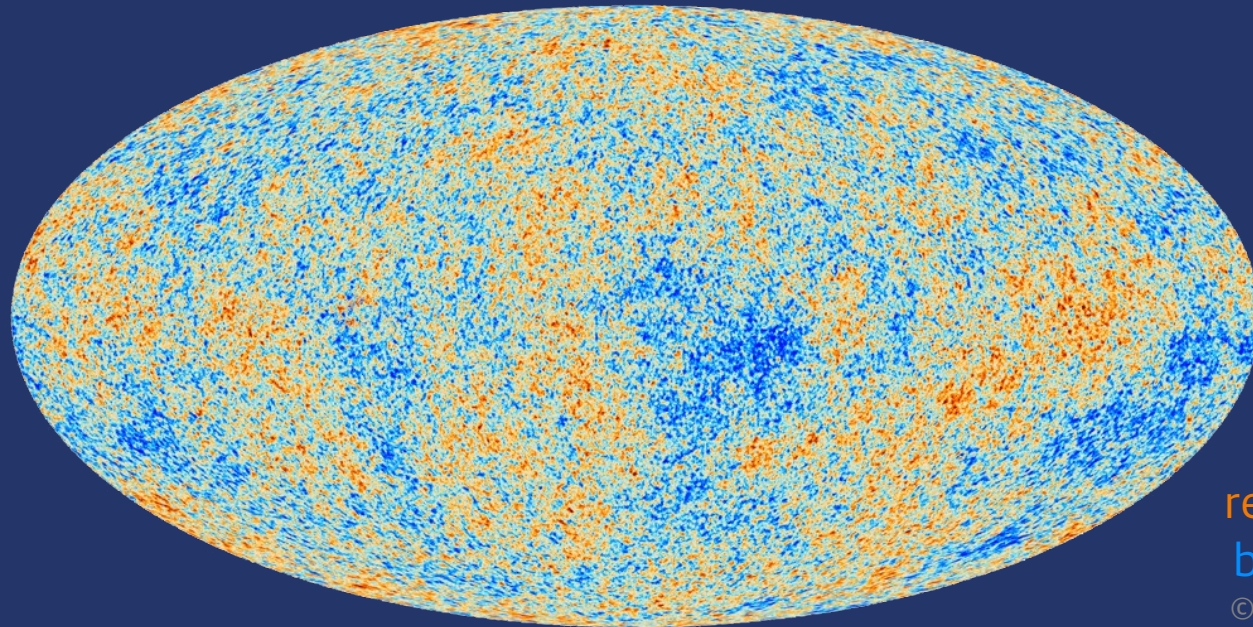
↗️ 3×10^9 ly

🕒 13.6 Gyr

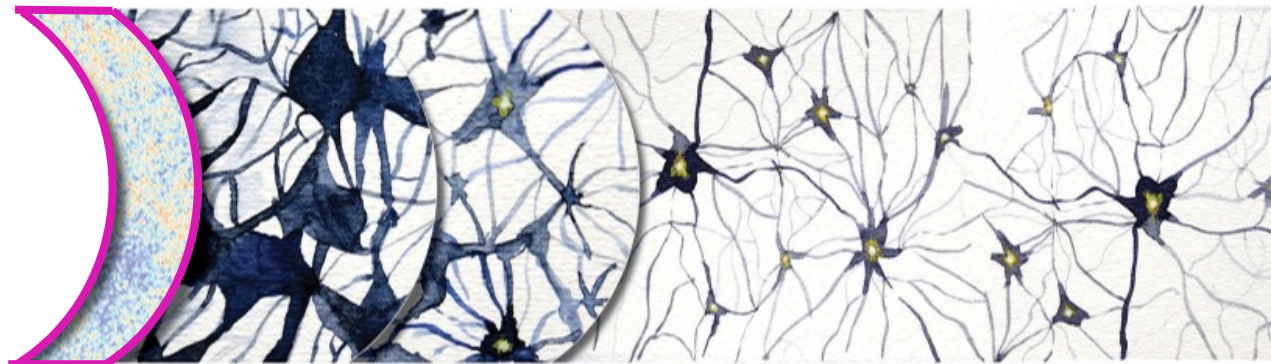
🌡️ 3 K

↗️ 5×10^{10} ly

Cosmic background radiation



Temperature
fluctuations
red: slightly warmer
blue: slightly colder
© ESA & Planck Collaboration



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

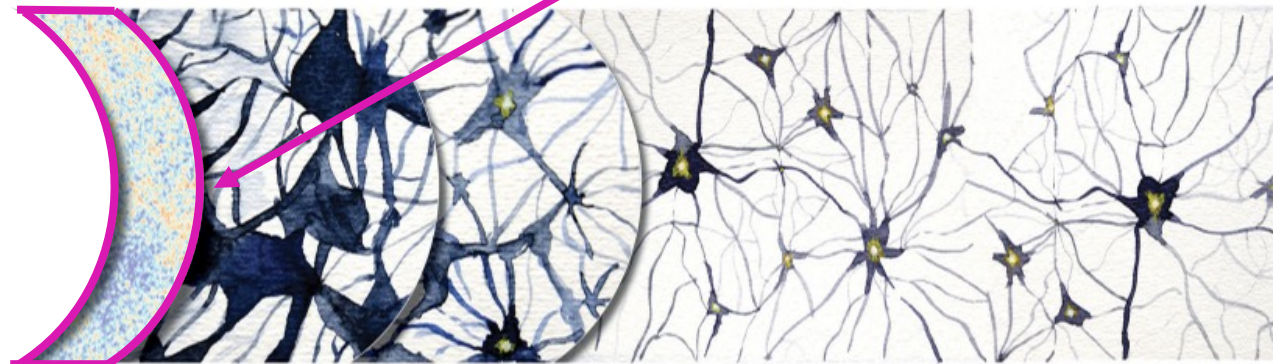
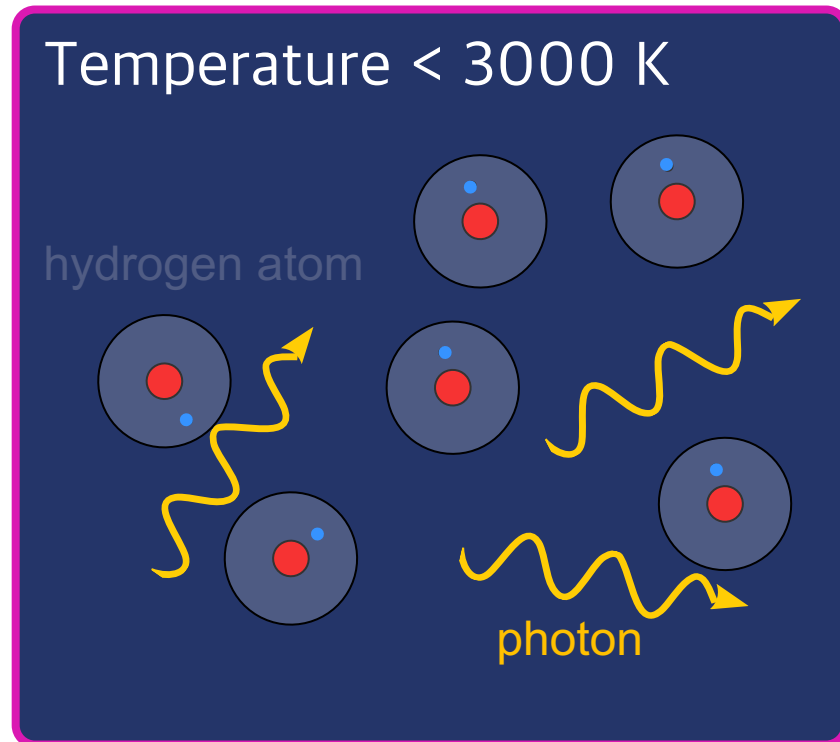
🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Brief history of the Universe

Nordita program
25/05/2026



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

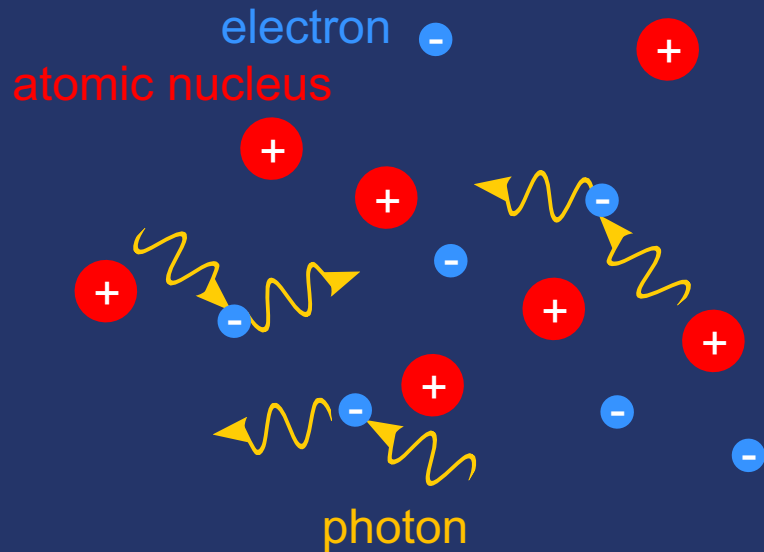
🌡️ 3 K

↗️ 5×10^{10} ly

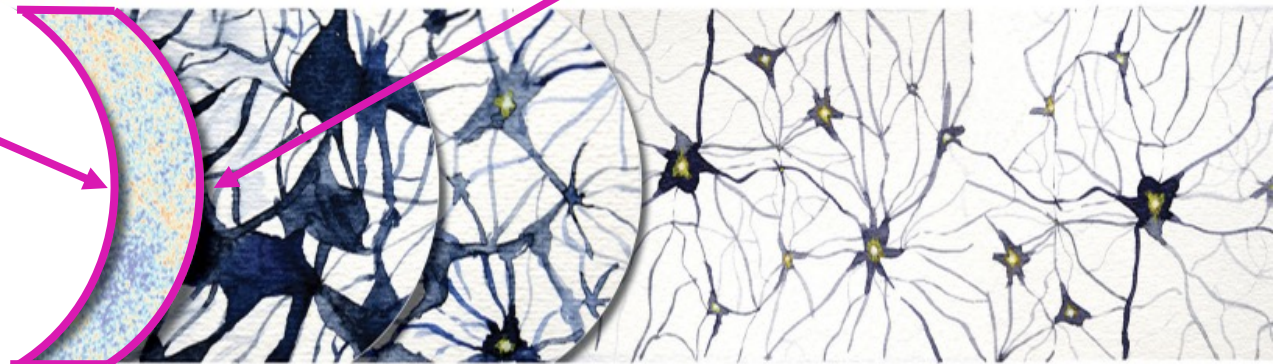
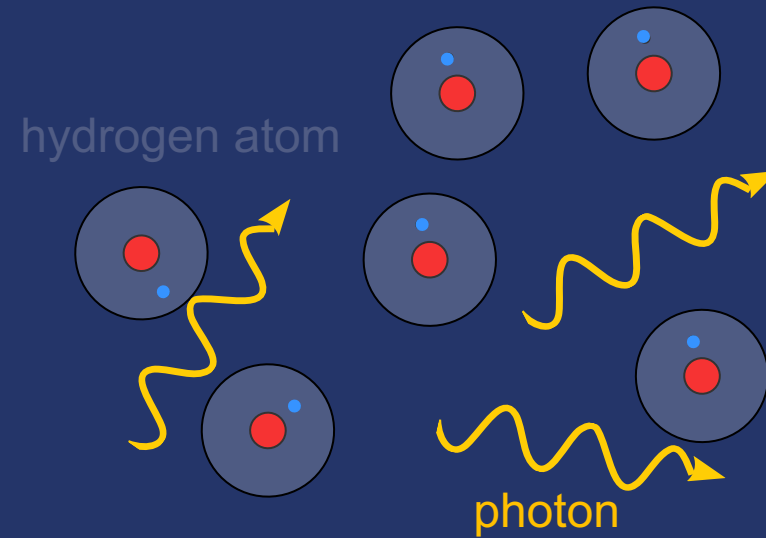
Brief history of the Universe

Nordita program
25/05/2026

Temperature > 3000 K



Temperature < 3000 K



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

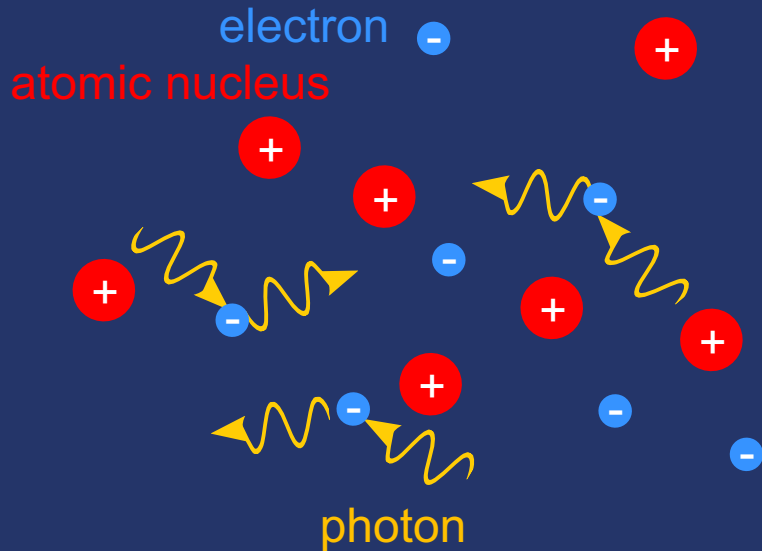
🌡️ 3 K

↗️ 5×10^{10} ly

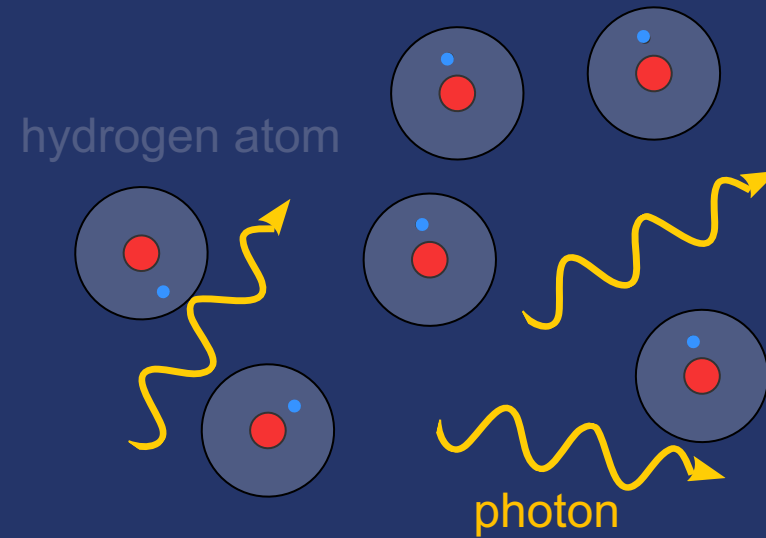
Brief history of the Universe

Nordita program
25/05/2026

Temperature > 3000 K



Temperature < 3000 K



Big Bang

Optically thick

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

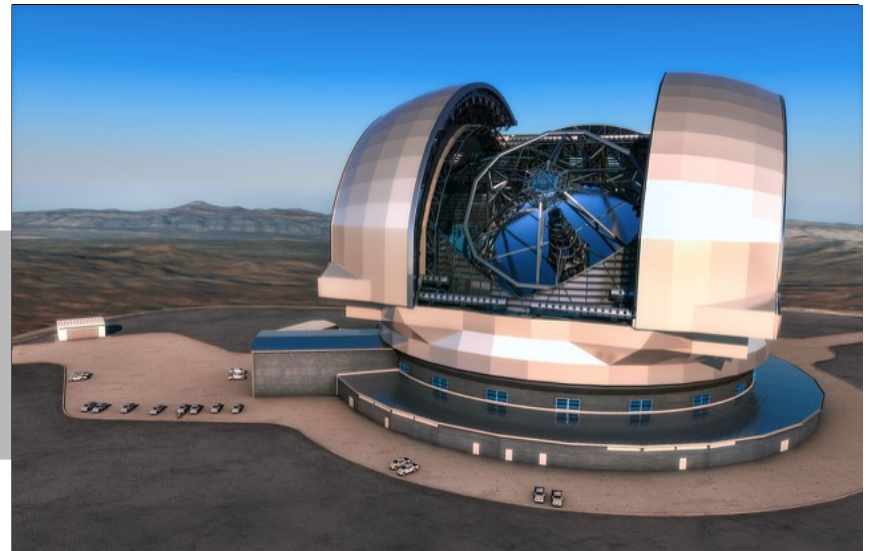
🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Brief history of the Universe

Nordita program
25/05/2026



European Extremely Large Telescope © ESO

Optically thick

Big Bang

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

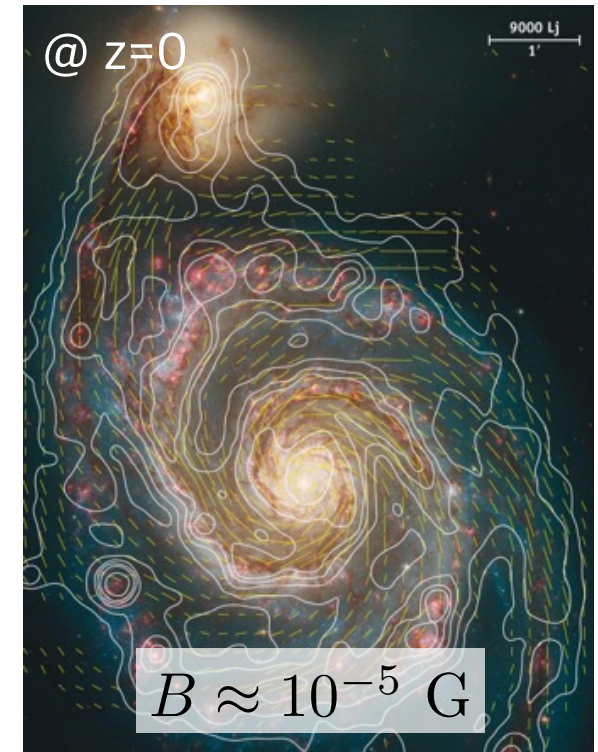
🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic fields of the past

Nordita program
25/05/2026



Big Bang



🕒 $4 \times 10^5 \text{ yr}$

🌡️ 3000 K

↗️ $3 \times 10^7 \text{ ly}$

🕒 300-500 Myr

🌡️ 30 K

↗️ $3 \times 10^9 \text{ ly}$

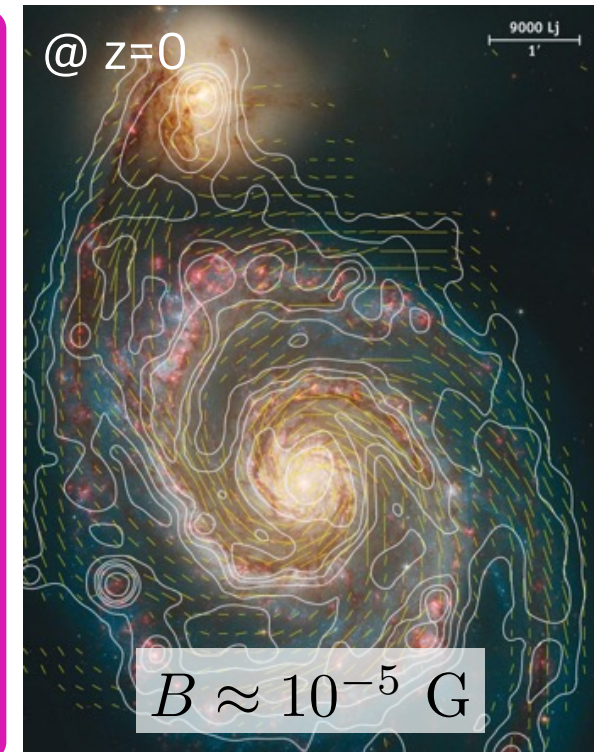
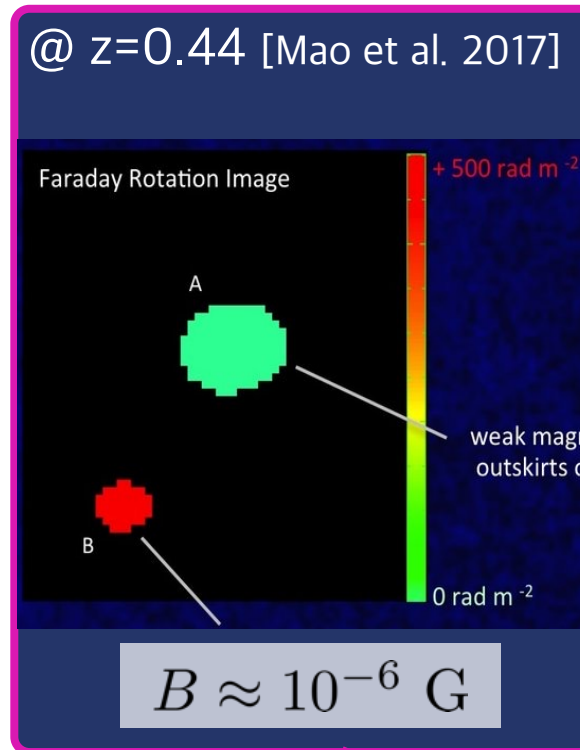
🕒 13.6 Gyr

🌡️ 3 K

↗️ $5 \times 10^{10} \text{ ly}$

Magnetic fields of the past

Nordita program
25/05/2026



Big Bang

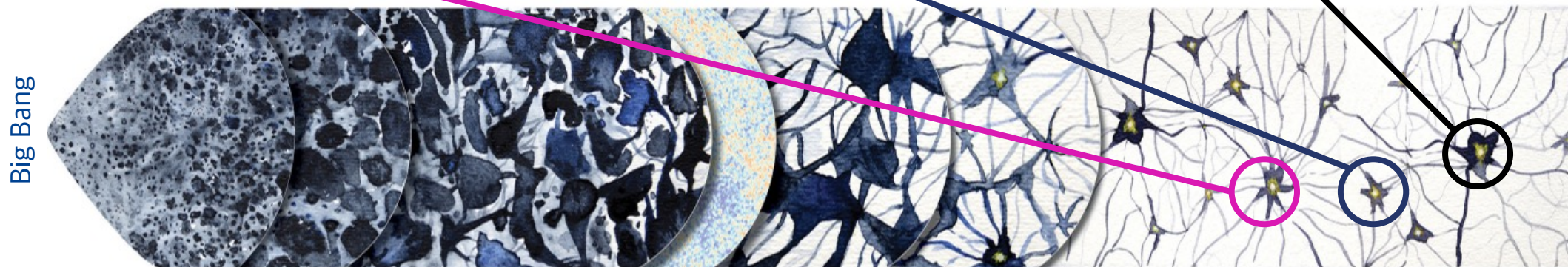
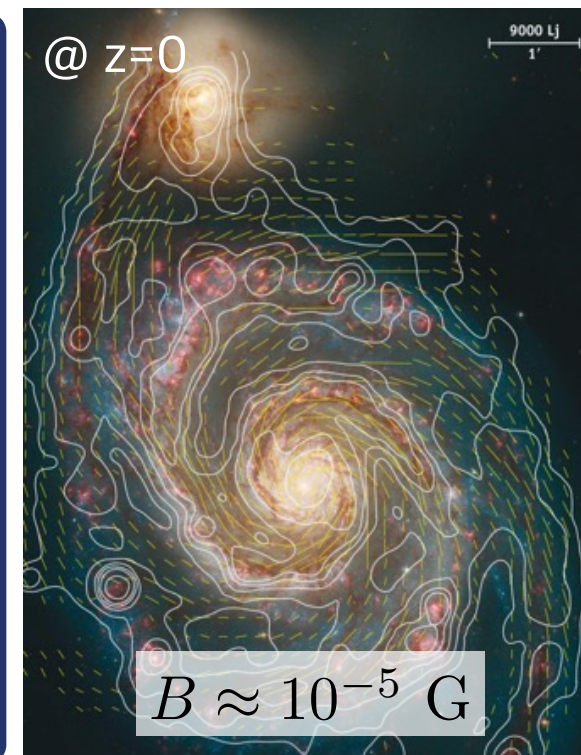
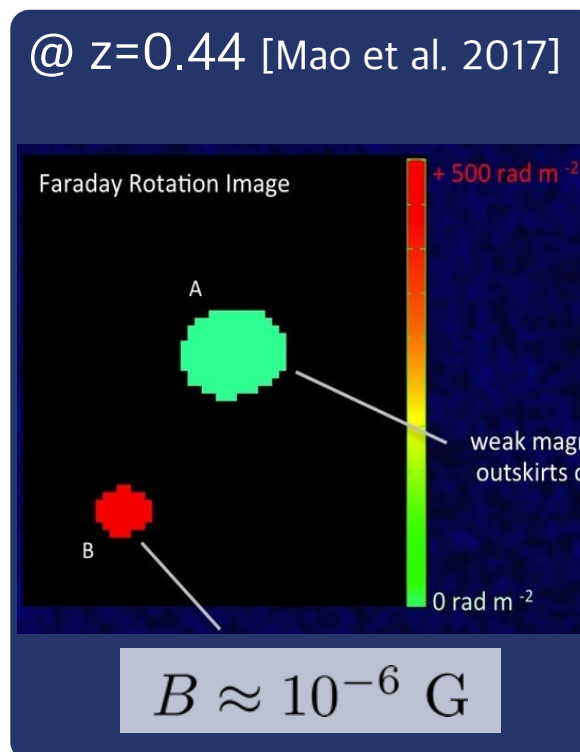
🕒 $4 \times 10^5 \text{ yr}$
 🌡️ 3000 K
 ↗️ $3 \times 10^7 \text{ ly}$

🕒 300-500 Myr
 🌡️ 30 K
 ↗️ $3 \times 10^9 \text{ ly}$

🕒 13.6 Gyr
 🌡️ 3 K
 ↗️ $5 \times 10^{10} \text{ ly}$

Magnetic fields of the past

Nordita program
25/05/2026



🕒 $4 \times 10^5 \text{ yr}$

🌡️ 3000 K

↗️ $3 \times 10^7 \text{ ly}$

🕒 300-500 Myr

🌡️ 30 K

↗️ $3 \times 10^9 \text{ ly}$

🕒 13.6 Gyr

🌡️ 3 K

↗️ $5 \times 10^{10} \text{ ly}$

Seed magnetic fields

Nordita program
25/05/2026

How strong can magnetic fields be when they are generated from first principles, starting from zero?



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Astrophysical seed fields

- **Biermann battery**

[Biermann 1950]

$$B_0 \approx 10^{-21} - 10^{-19} \text{ G}$$

- **Radiation-driven battery**

[Durrive & Langer 2015]

$$B_0 \approx 10^{-23} - 10^{-19} \text{ G}$$

- **Weibel instability**

[Zhou et al. 2024]

$$B_0 \approx 10^{-9} \text{ G}$$

Big Bang



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Seed magnetic fields

Nordita program
25/05/2026

Cosmological seed fields

- **Inflation**

[Turner & Widrow 1988,
Ratra 1992]

$$B_0 \approx 10^{-65} - 10^{-9} \text{ G}$$

- **(1st-order) phase transitions**

[Hogan 1983, Sigl et al.
1997]

$$B_0 \approx 10^{-29} - 10^{-20} \text{ G}$$

Astrophysical seed fields

- **Biermann battery**

[Biermann 1950]

$$B_0 \approx 10^{-21} - 10^{-19} \text{ G}$$

- **Radiation-driven battery**

[Durrive & Langer 2015]

$$B_0 \approx 10^{-23} - 10^{-19} \text{ G}$$

- **Weibel instability**

[Zhou et al. 2024]

$$B_0 \approx 10^{-9} \text{ G}$$

Big Bang



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

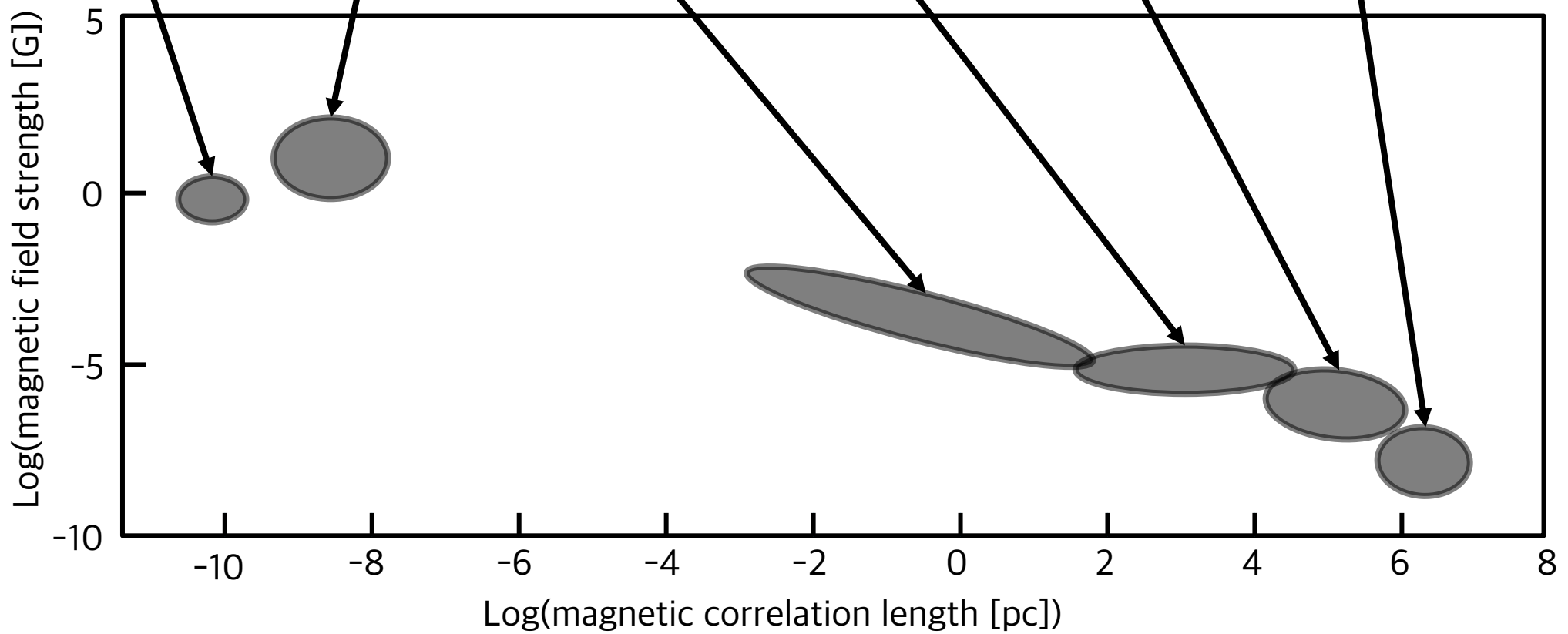
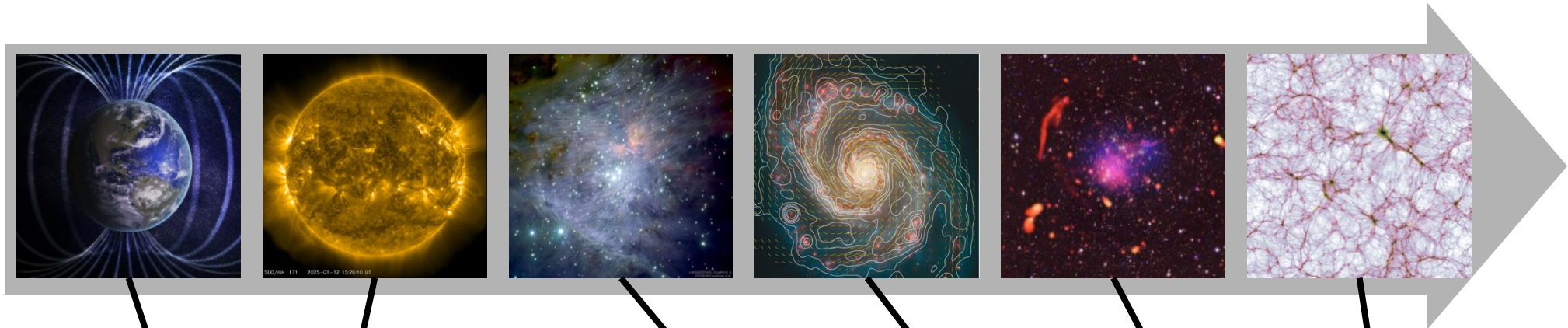
🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

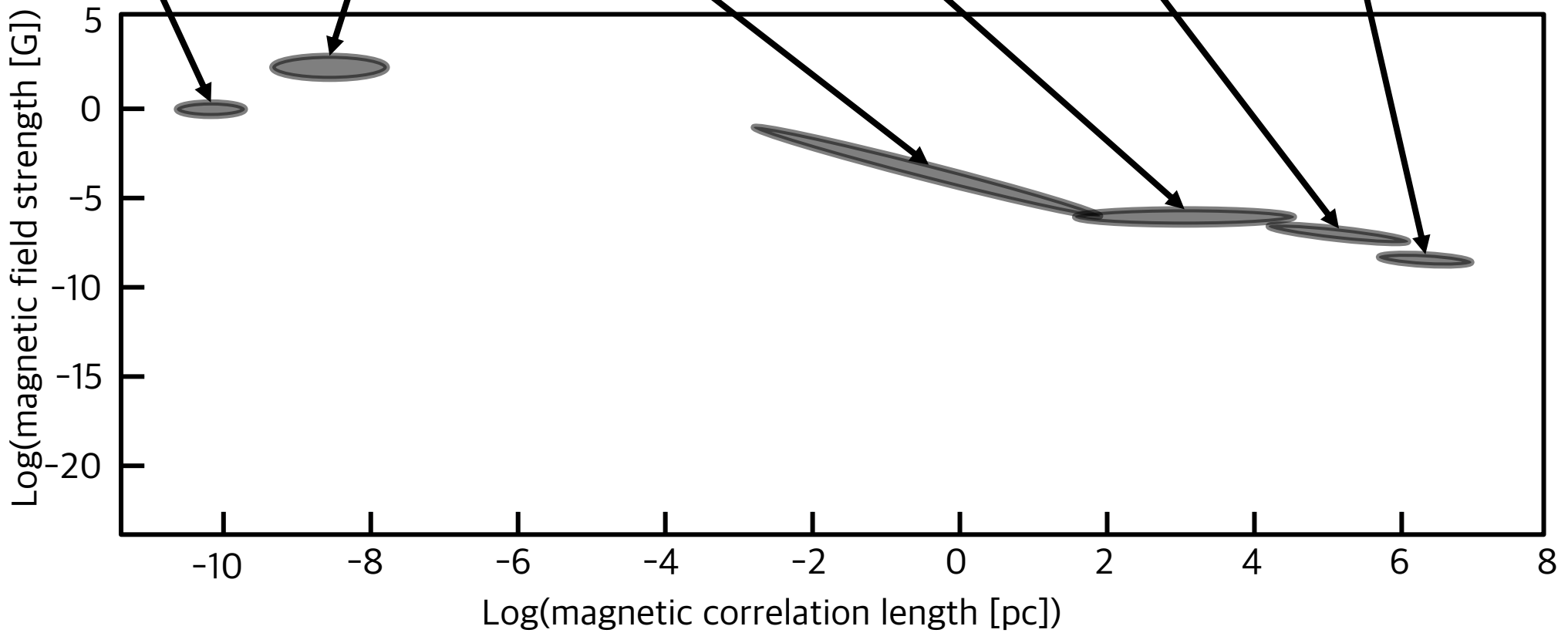
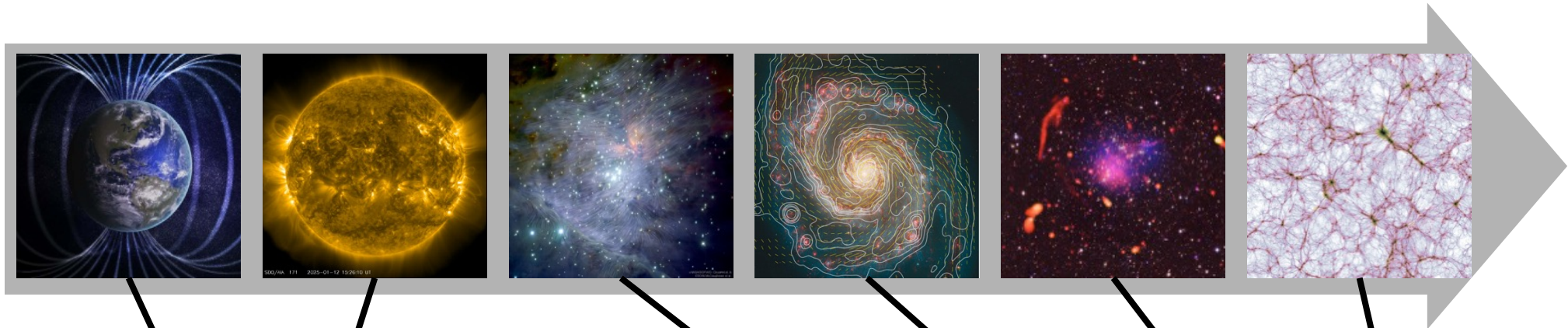
The magnetic Universe

Nordita program
25/05/2026



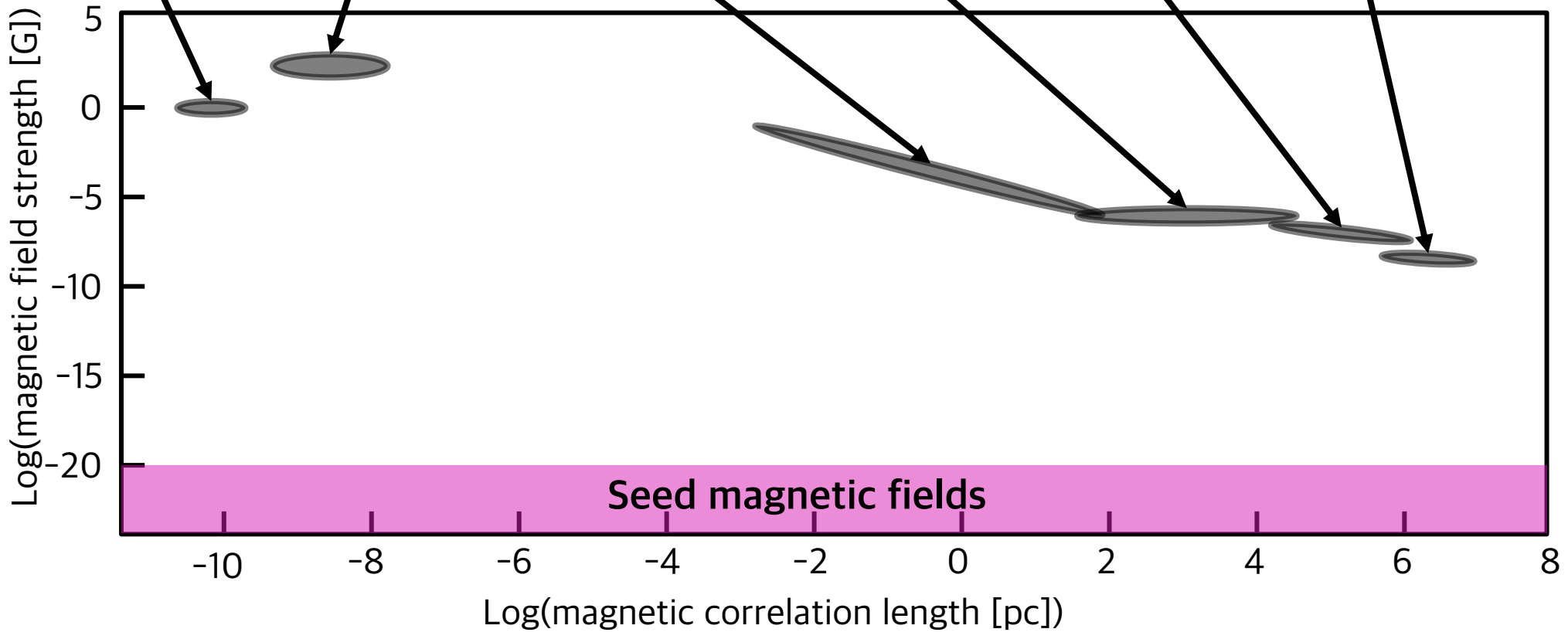
The magnetic Universe

Nordita program
25/05/2026



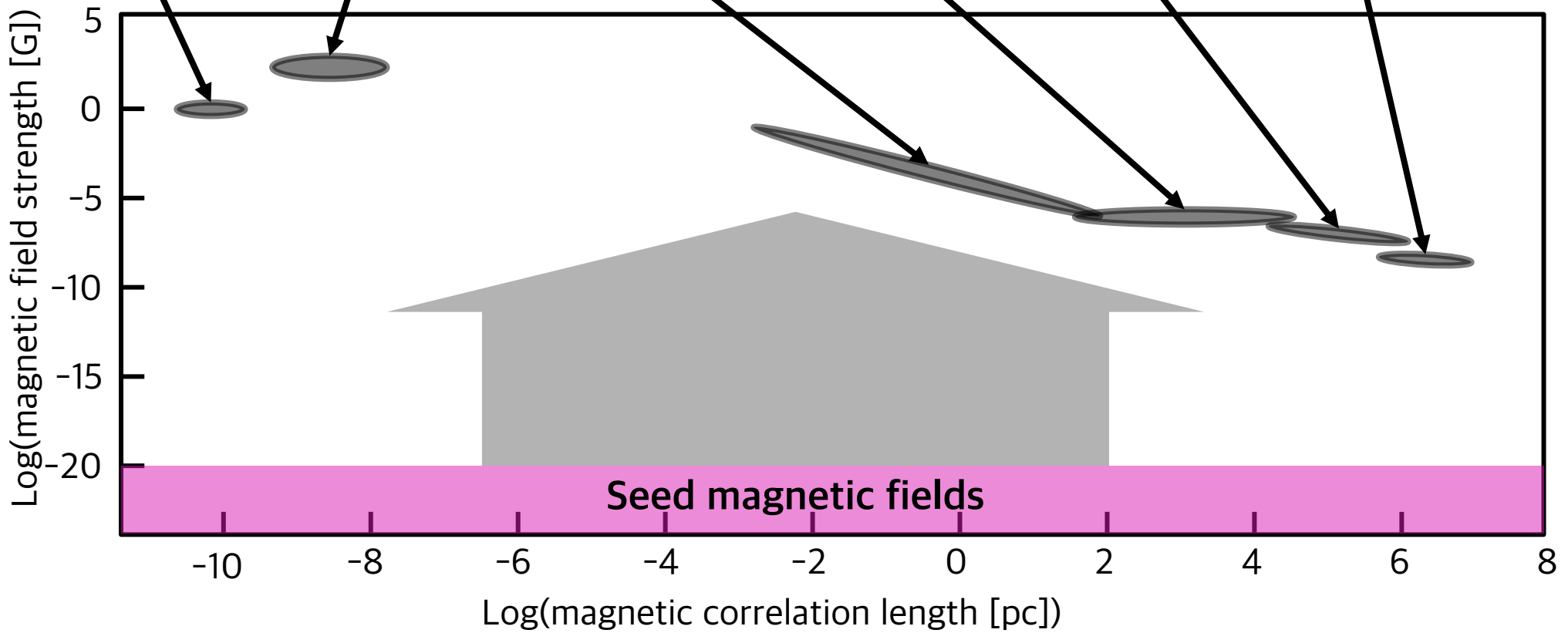
The magnetic Universe

Nordita program
25/05/2026



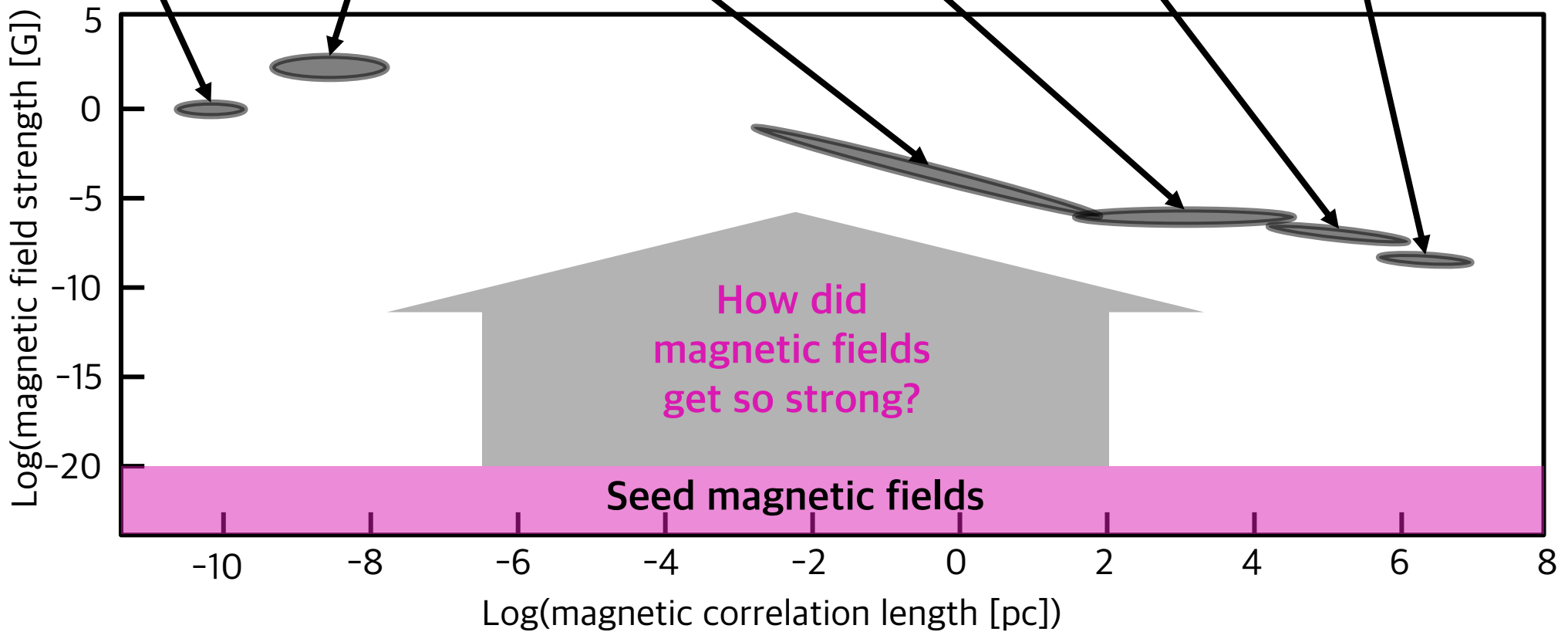
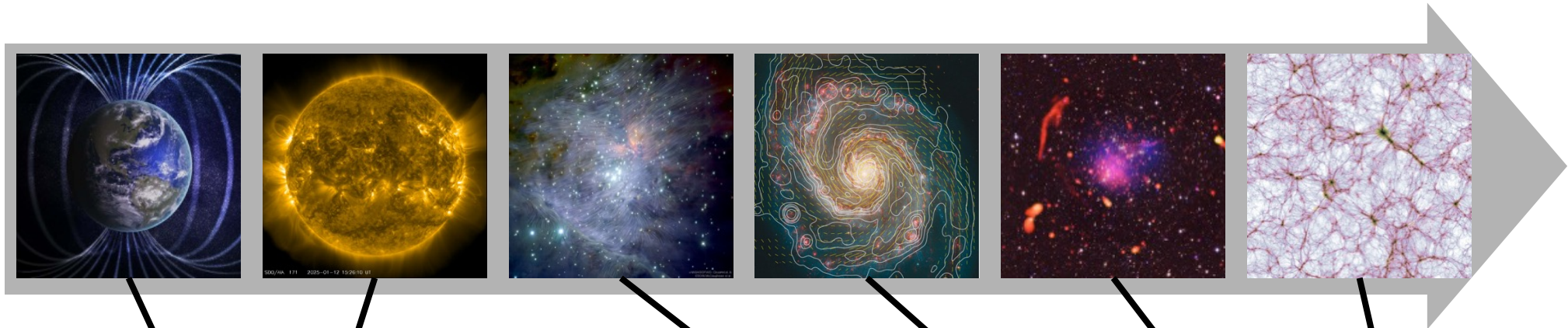
The magnetic Universe

Nordita program
25/05/2026



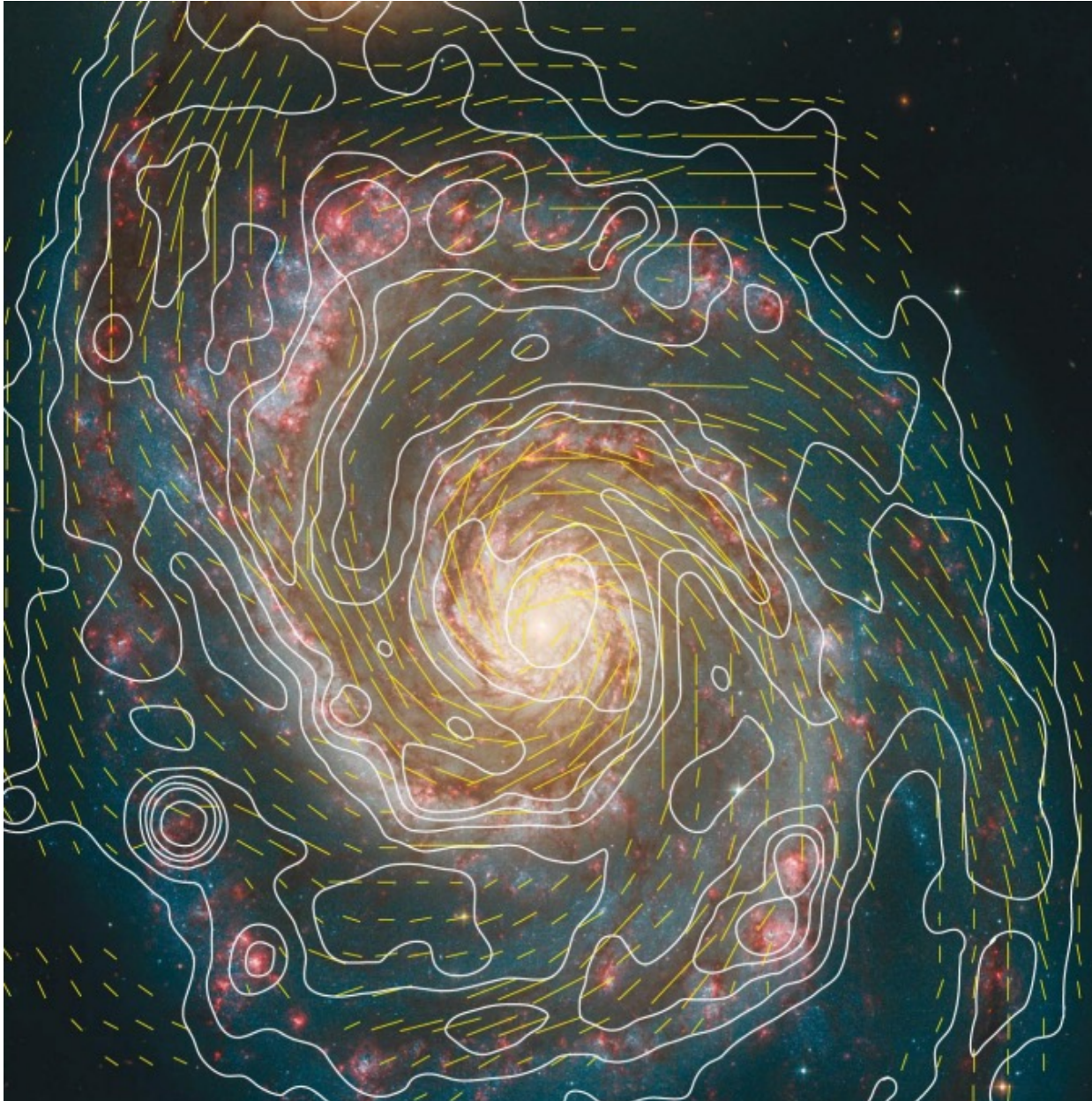
The magnetic Universe

Nordita program
25/05/2026



Modelling astrophysical fluids

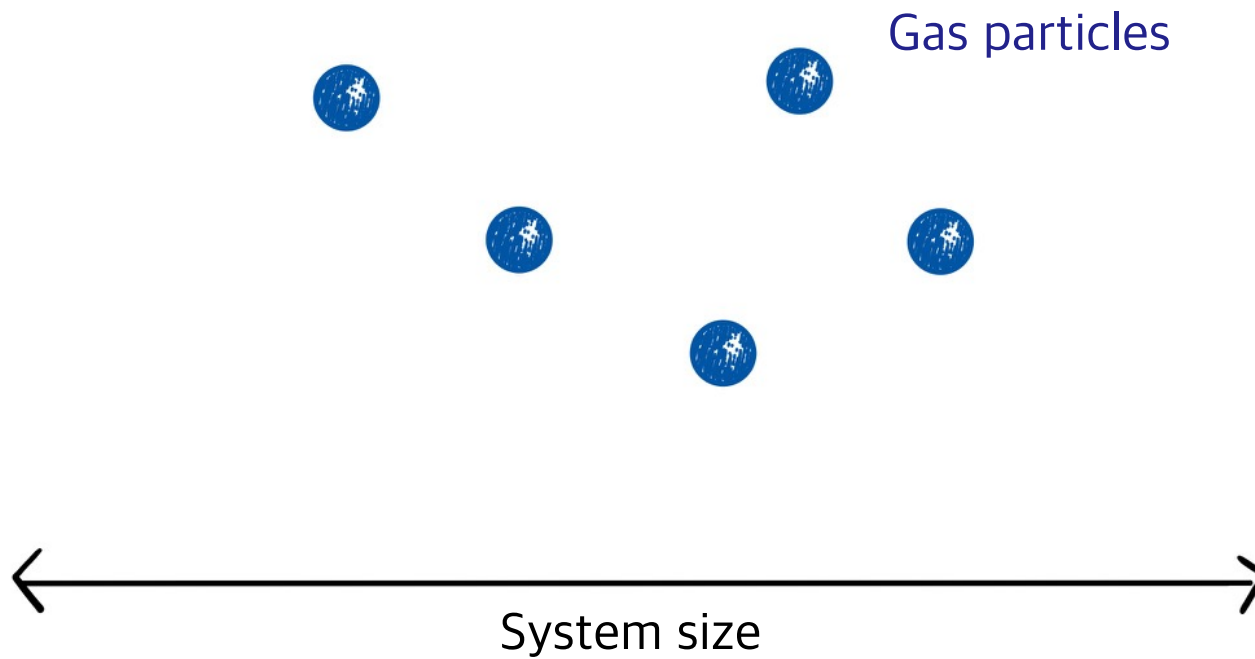
Nordita program
25/05/2026



How to model this?

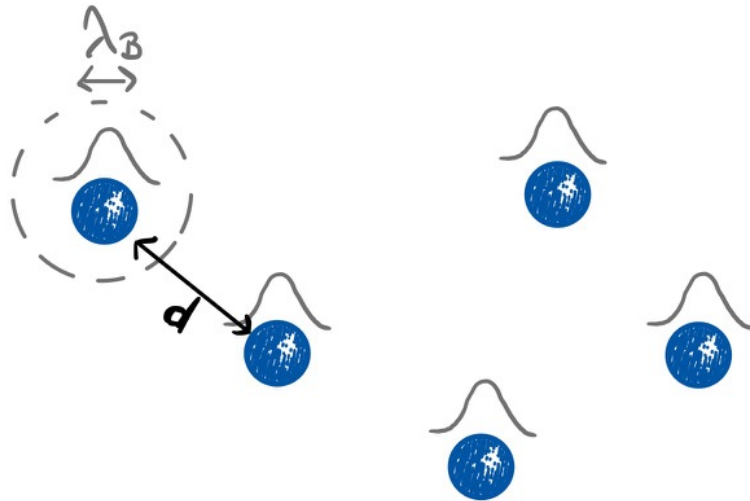
Modelling astrophysical fluids

Nordita program
25/05/2026



Modelling astrophysical fluids

Nordita program
25/05/2026



Model

Description:

positions + velocities

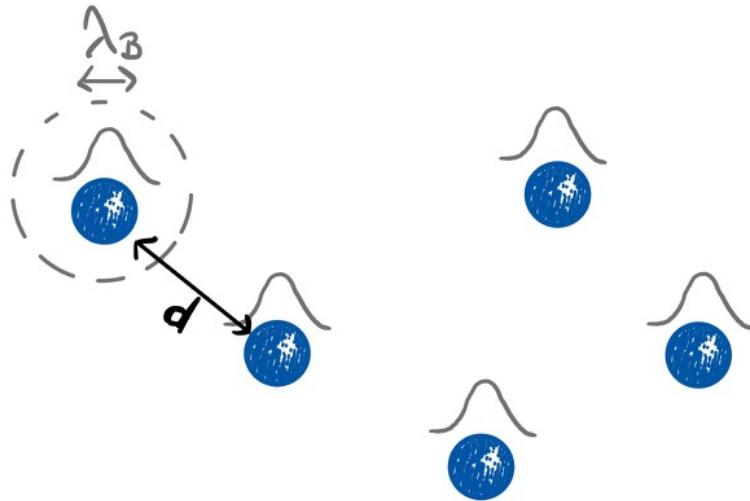
Equations:

Newtonian,
Lagrangian, or
Hamiltonian mechanics

← System size →

Modelling astrophysical fluids

Nordita program
25/05/2026



Model

Description:

positions + velocities

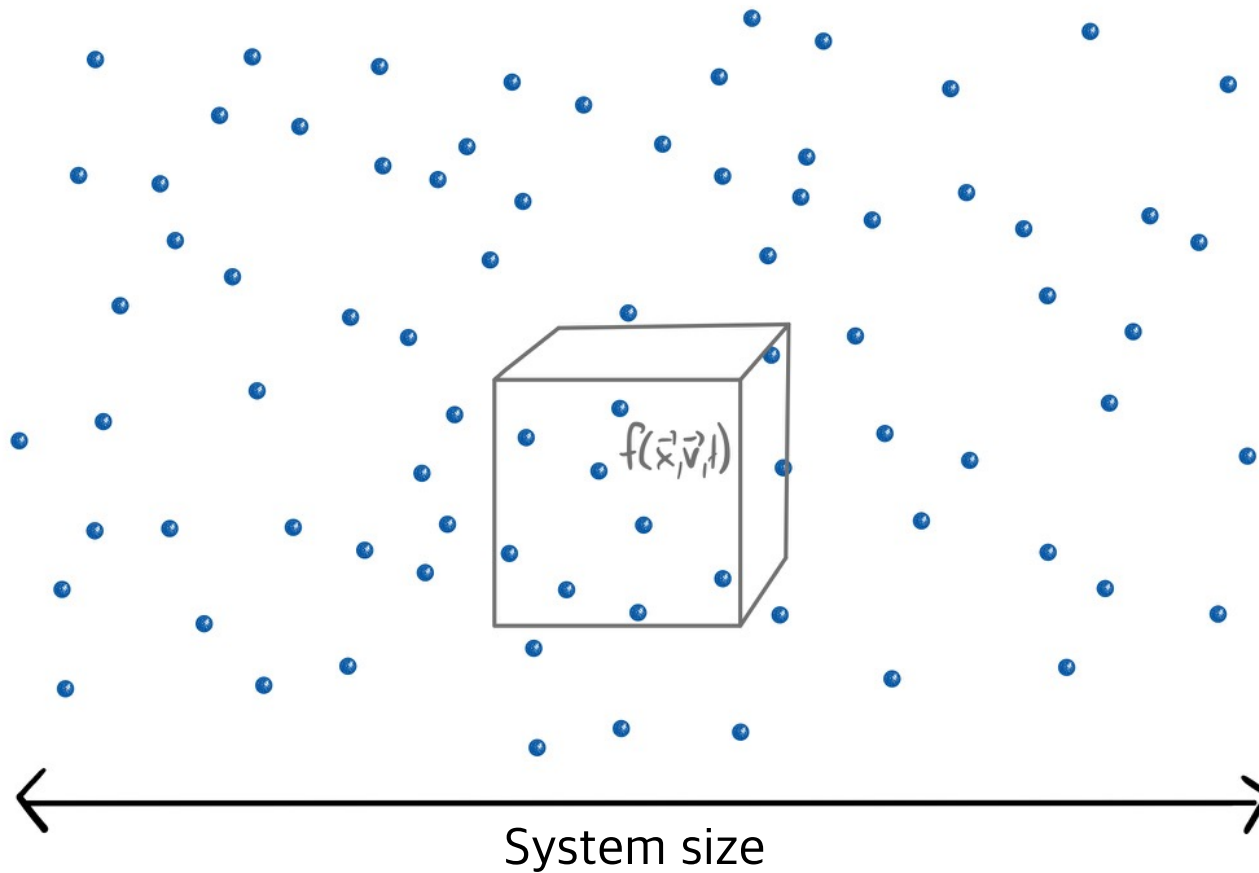
Equations:

Newtonian,
Lagrangian, or
Hamiltonian mechanics

For a large number of particles, we can
move to a statistical description.

Modelling astrophysical fluids

Nordita program
25/05/2026



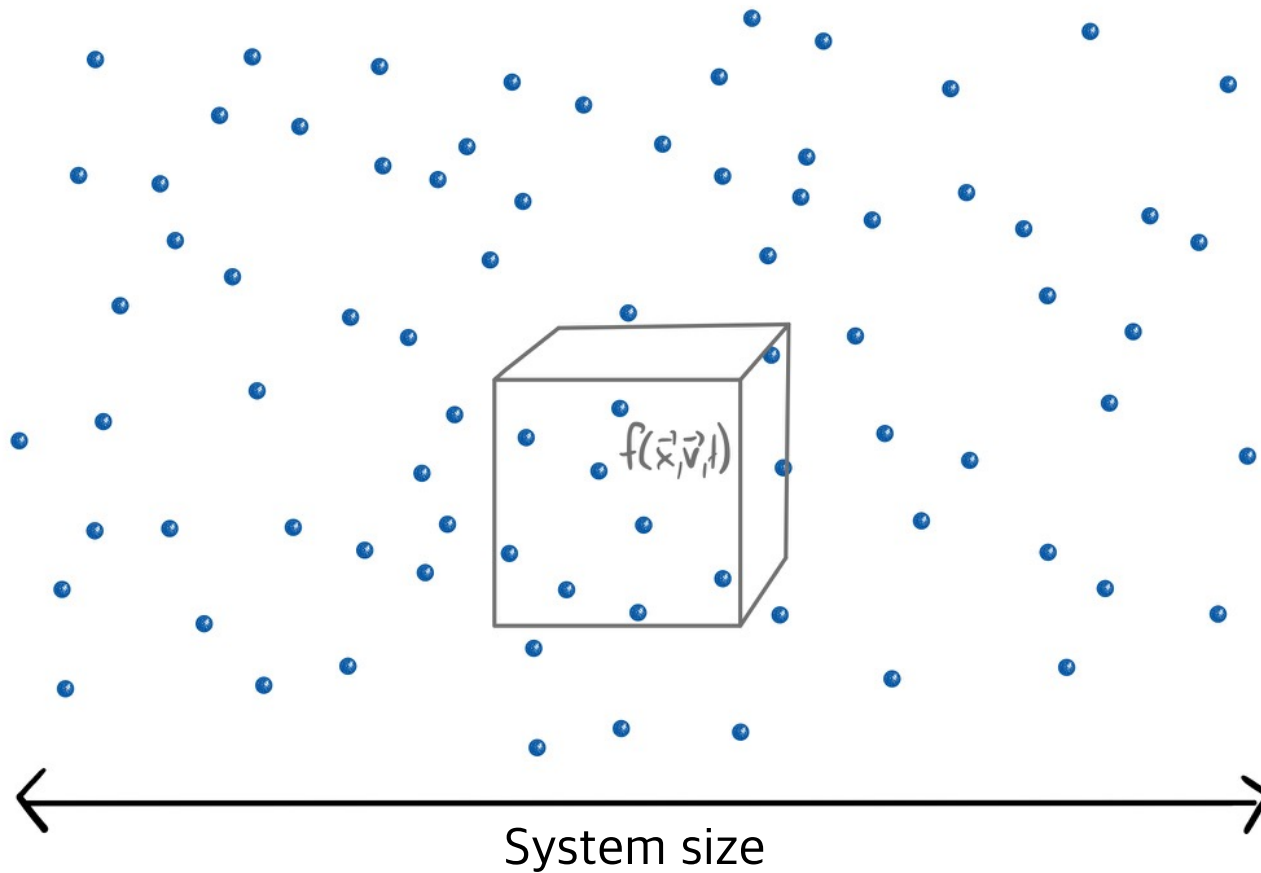
Model

Description:
distribution function

Equations:
Boltzmann eq.

Modelling astrophysical fluids

Nordita program
25/05/2026



Model

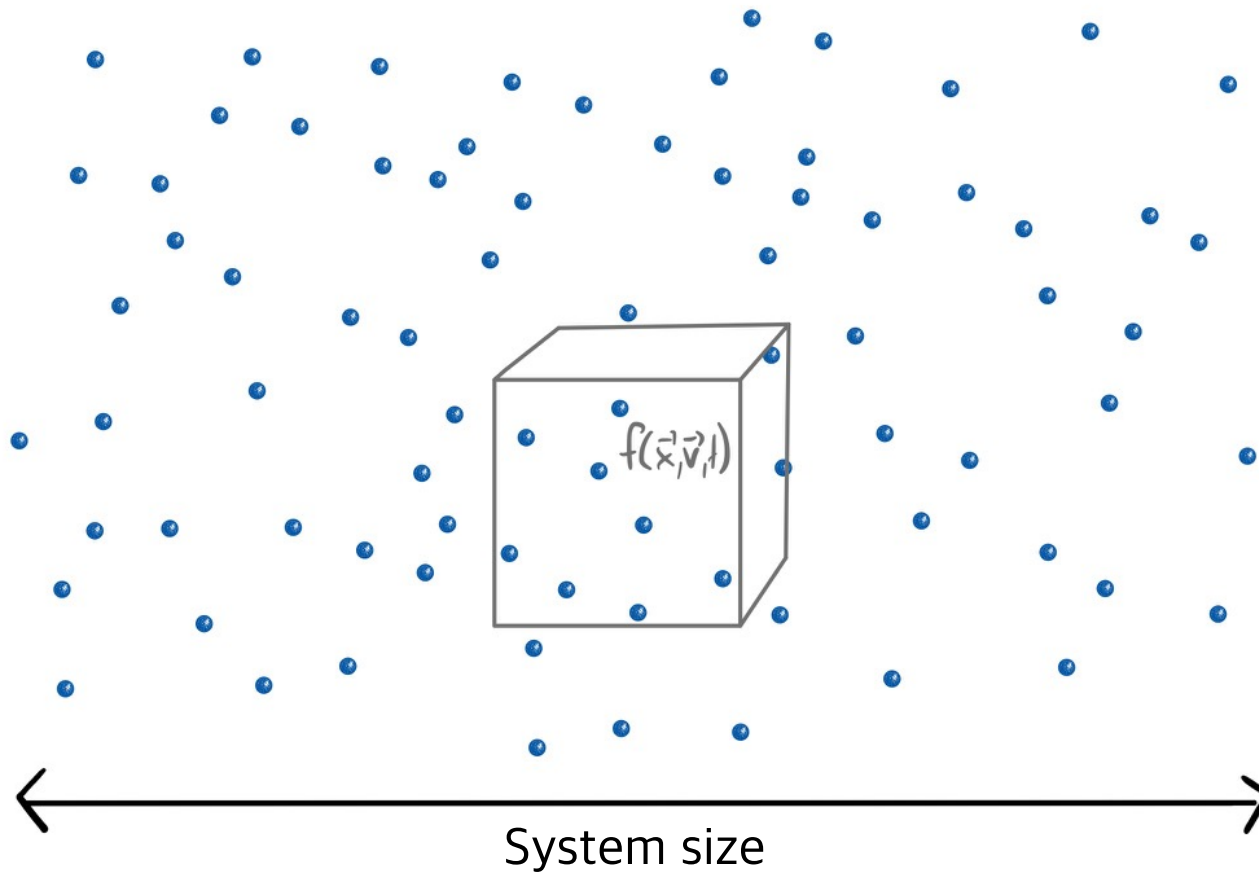
Description:
distribution function

Equations:
Boltzmann eq.

If collisions are frequent enough to build up a Maxwellian distribution, a continuum model is possible.

Modelling astrophysical fluids

Nordita program
25/05/2026



Model

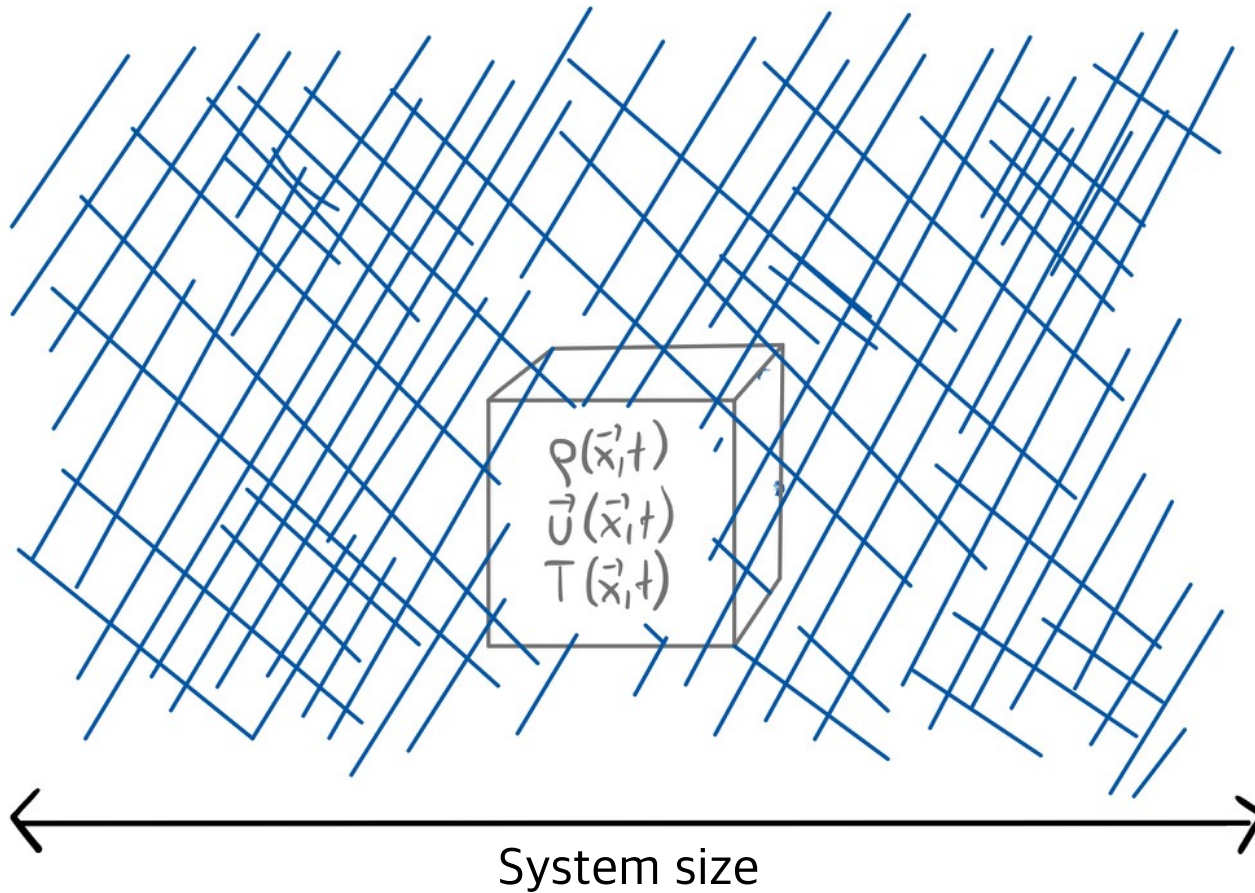
Description:
distribution function

Equations:
Boltzmann eq.

If **collisions** are frequent enough to build up a Maxwellian distribution, a continuum model is possible.

Modelling astrophysical fluids

Nordita program
25/05/2026



Model

Description:

two thermodynamic
variables
+ velocity field

Equations:

hydrodynamic eqns.

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Conservation of momentum:

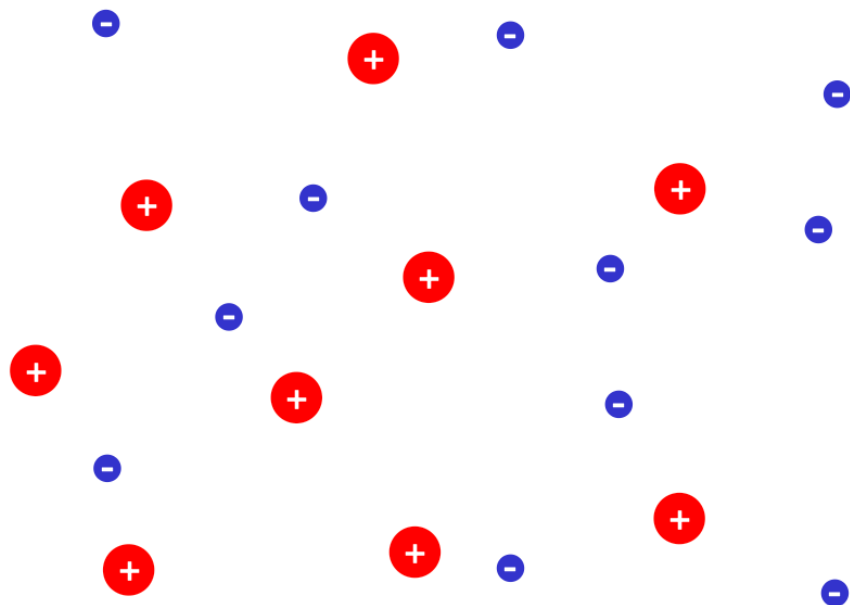
$$\frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} = -\frac{1}{\rho} \nabla p + \frac{1}{m} \mathbf{F} + \frac{\mu}{\rho} \left(\nabla^2 \mathbf{U} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{U}) \right)$$

Conservation of energy:

$$\rho \left(\frac{\partial \epsilon}{\partial t} + \mathbf{U} \cdot \nabla \epsilon \right) = \nabla \cdot (K \nabla T) - p \nabla \cdot \mathbf{U}$$

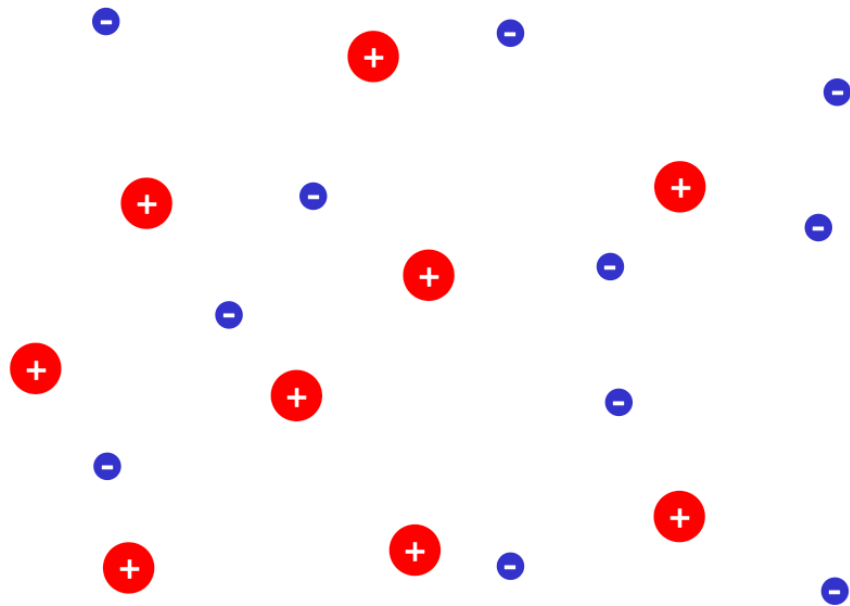
Adding electromagnetic fields

Nordita program
25/05/2026

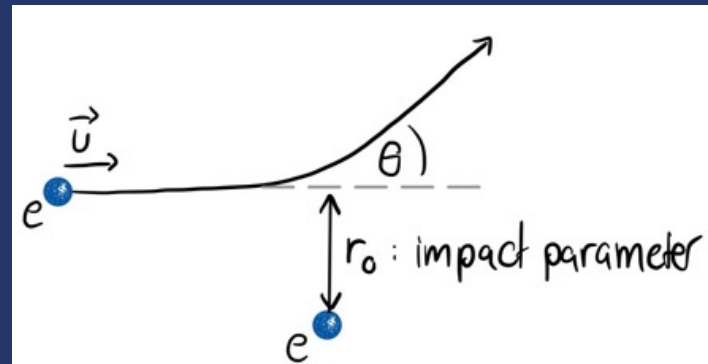


Adding electromagnetic fields

Nordita program
25/05/2026

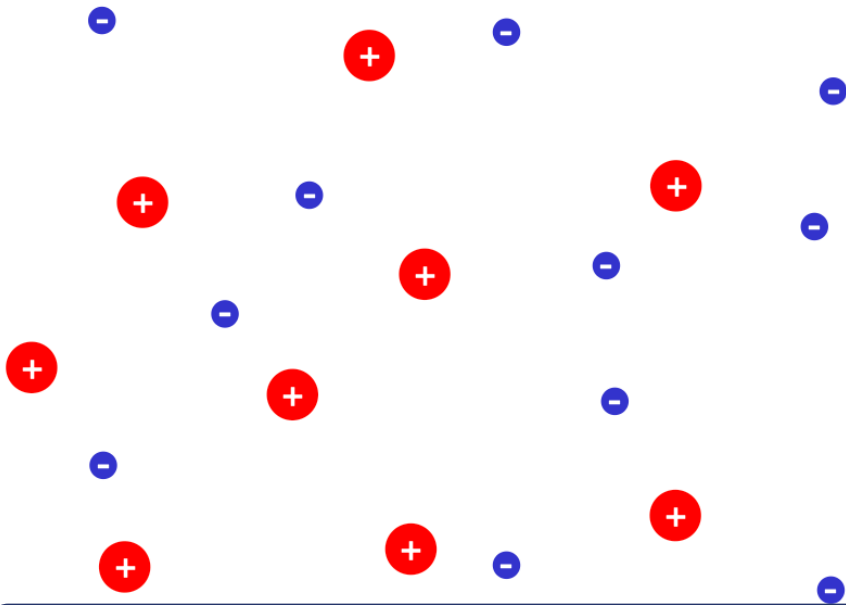


"Collisions" in a plasma:

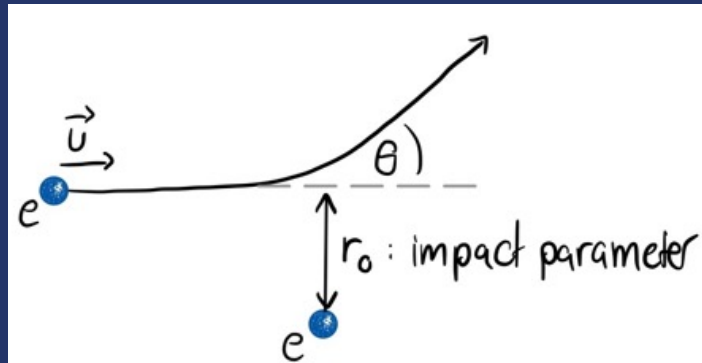


Adding electromagnetic fields

Nordita program
25/05/2026



"Collisions" in a plasma:



Combine Maxwell equations

$$\nabla \cdot \mathbf{E} = 4\pi\rho_{el} \quad \nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{B} - \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = \frac{4\pi}{c} \mathbf{J}$$

with the **electric current** [here: given by **Ohm's law** that emerges in transition from 2-fluid to 1-fluid description]:

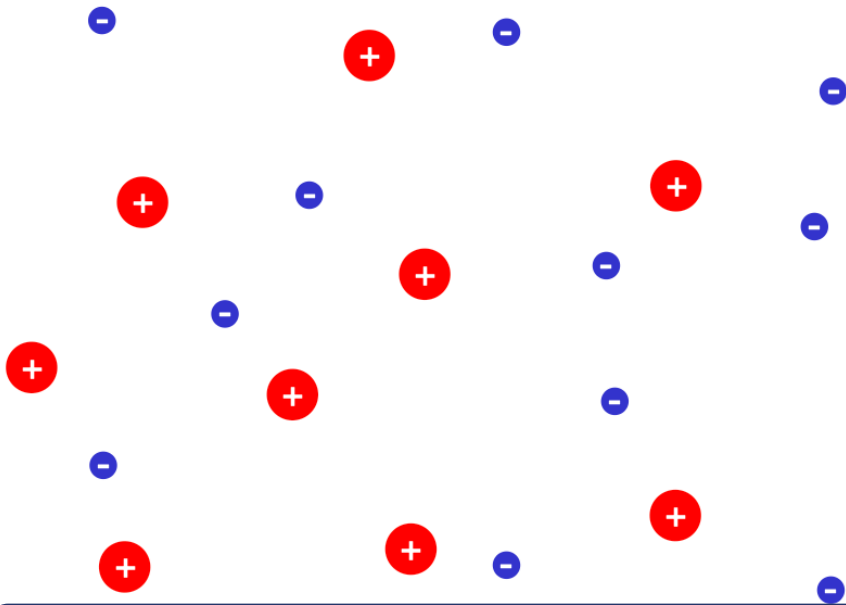
$$\mathbf{J} = \sigma \left(\mathbf{E} + \frac{1}{c} \mathbf{U} \times \mathbf{B} \right)$$

Induction equation

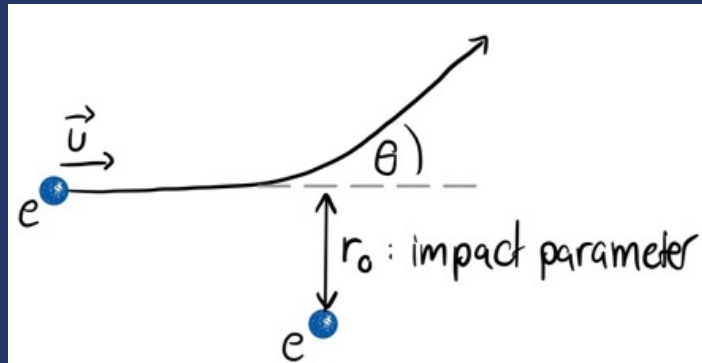
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Adding electromagnetic fields

Nordita program
25/05/2026



"Collisions" in a plasma:



Combine Maxwell equations

$$\nabla \cdot \mathbf{E} = 4\pi\rho_{el} \quad \nabla \times \mathbf{E} + \frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} = 0$$

$$\nabla \cdot \mathbf{B} = 0 \quad \nabla \times \mathbf{B} - \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} = \frac{4\pi}{c} \mathbf{J}$$

with the **electric current** [here: given by **Ohm's law** that emerges in transition from 2-fluid to 1-fluid description]:

$$\mathbf{J} = \sigma \left(\mathbf{E} + \frac{1}{c} \mathbf{U} \times \mathbf{B} \right)$$

Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Plasma
velocity

Magnetic diffusivity

$$\eta = \frac{c^2}{4\pi\sigma}$$

Equations of magnetohydrodynamics

Nordita program
25/05/2026

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Conservation of momentum:

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} &= -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{1}{m} \mathbf{F} + \frac{1}{4\pi\rho} (\mathbf{B} \cdot \nabla) \mathbf{B} \\ &+ \frac{\mu}{\rho} \left(\nabla^2 \mathbf{U} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{U}) \right) \end{aligned}$$

Conservation of energy:

$$\rho \left(\frac{\partial \epsilon}{\partial t} + \mathbf{U} \cdot \nabla \epsilon \right) = \nabla \cdot (K \nabla T) + \frac{J^2}{\sigma} - p \nabla \cdot \mathbf{U}$$

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Equations of magnetohydrodynamics

Nordita program
25/05/2026

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Conservation of momentum:

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} &= -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{1}{m} \mathbf{F} + \frac{1}{4\pi\rho} (\mathbf{B} \cdot \nabla) \mathbf{B} \\ &+ \frac{\mu}{\rho} \left(\nabla^2 \mathbf{U} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{U}) \right) \end{aligned}$$

Conservation of energy:

$$\rho \left(\frac{\partial \epsilon}{\partial t} + \mathbf{U} \cdot \nabla \epsilon \right) = \nabla \cdot (K \nabla T) + \frac{J^2}{\sigma} - p \nabla \cdot \mathbf{U}$$

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Magnetic history of galaxies

Nordita program
25/05/2026

Initial condition

(Tiny) fluctuations in the density field seen in the cosmic microwave background.

Big Bang



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

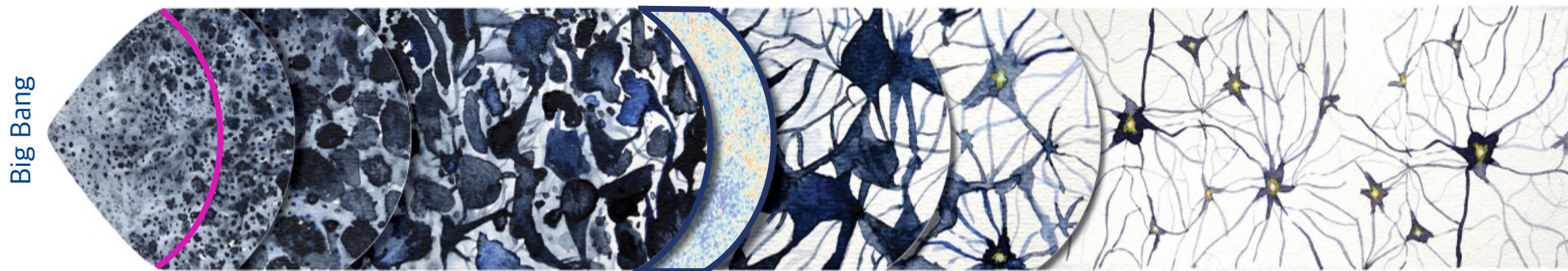
Nordita program
25/05/2026

Origin of initial condition

Quantum fluctuations are blown up during inflation.

Initial condition

(Tiny) fluctuations in the density field seen in the cosmic microwave background.



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

Nordita program
25/05/2026

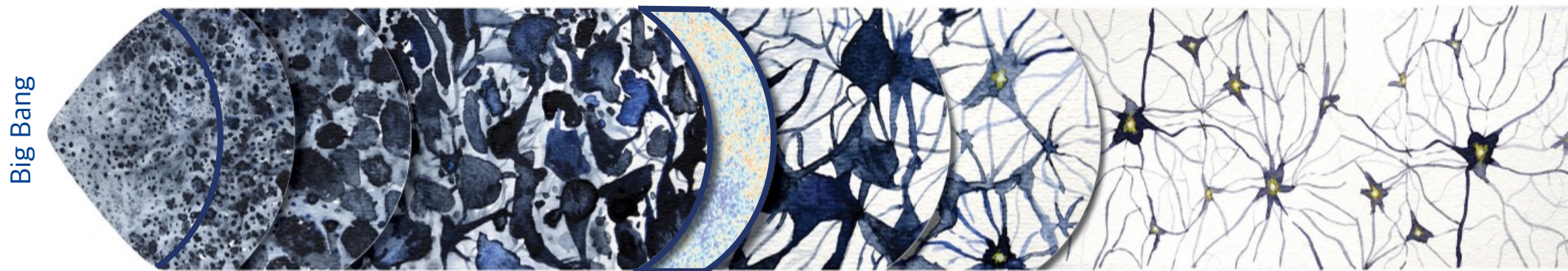
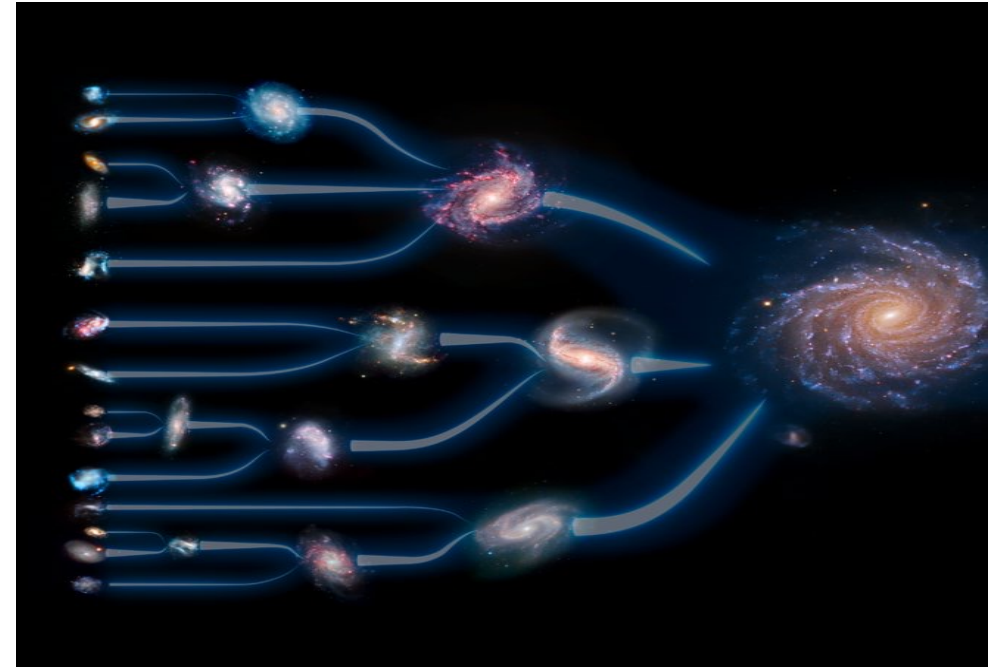
Origin of initial condition

Quantum fluctuations are blown up during inflation.

Initial condition

(Tiny) fluctuations in the density field seen in the cosmic microwave background.

Hierarchical structure formation



Big Bang

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

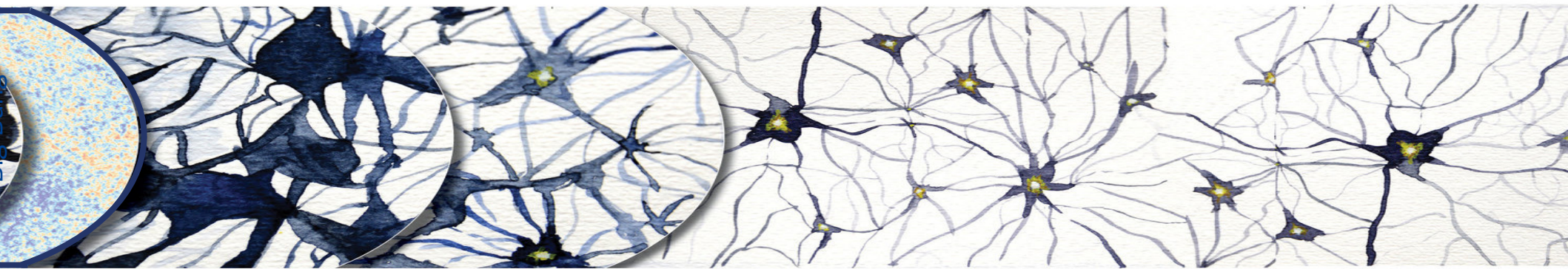
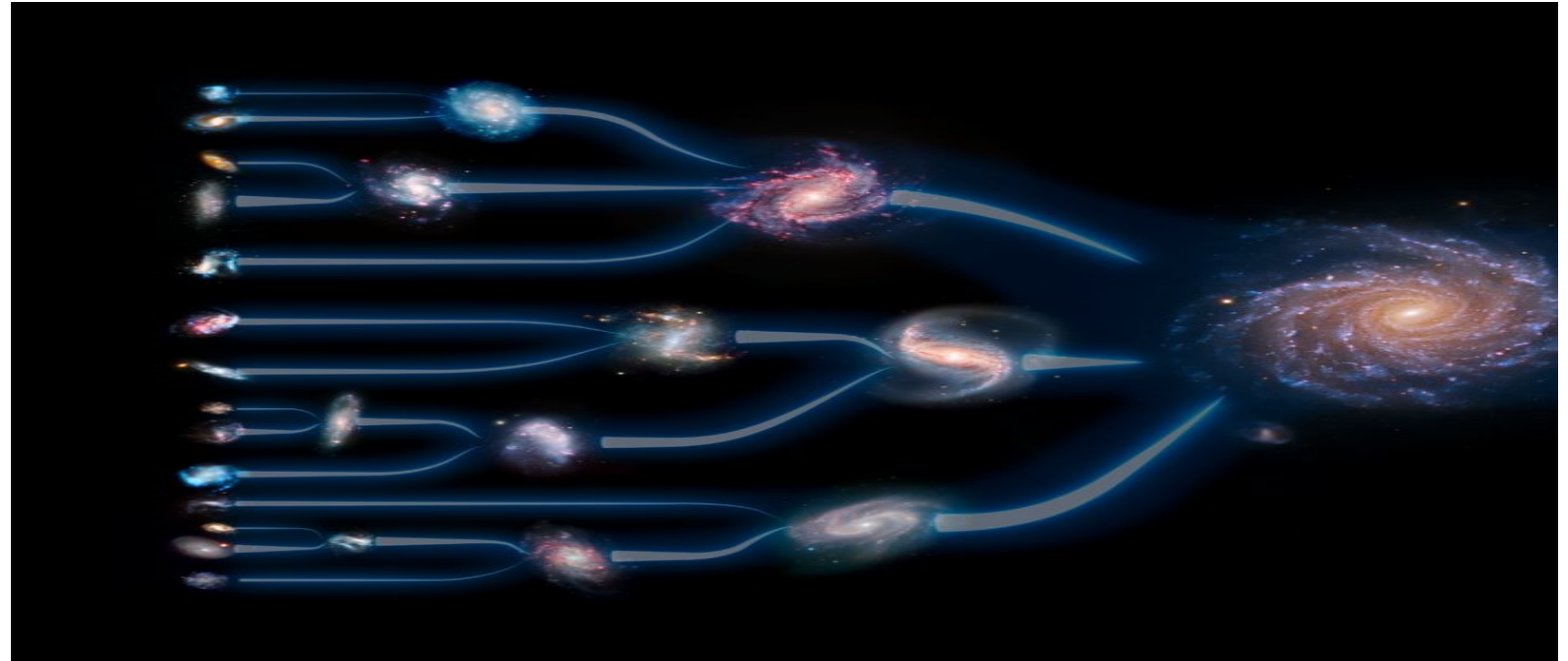
Magnetic history of galaxies

Nordita program
25/05/2026

Initial condition

(Tiny) fluctuations in the density field seen in the cosmic microwave background.

Hierarchical structure formation



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

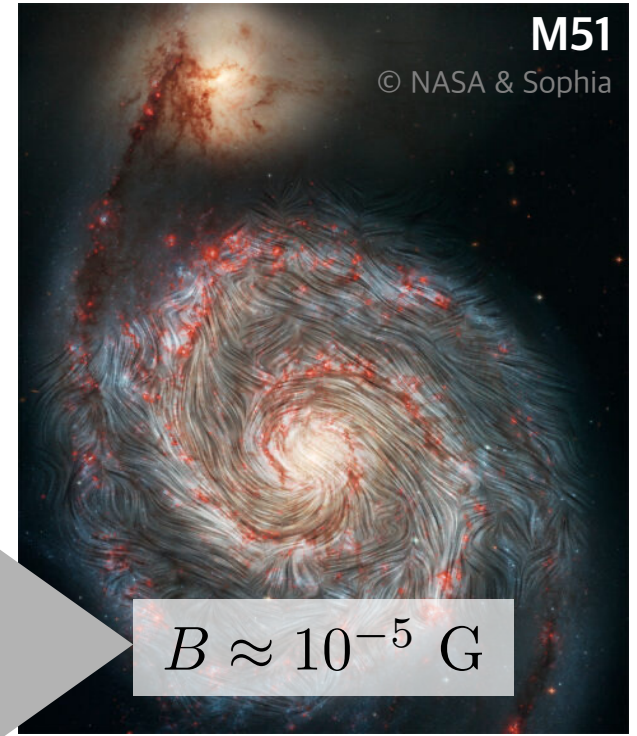
↗️ 5×10^{10} ly

Magnetic history of galaxies

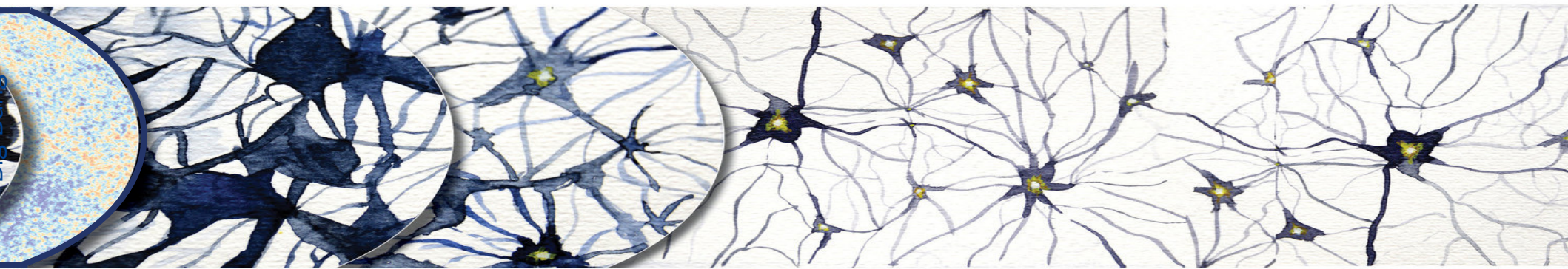
Nordita program
25/05/2026

Seed
magnetic
field

$$B_0 \approx 10^{-20} \text{ G}$$



$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

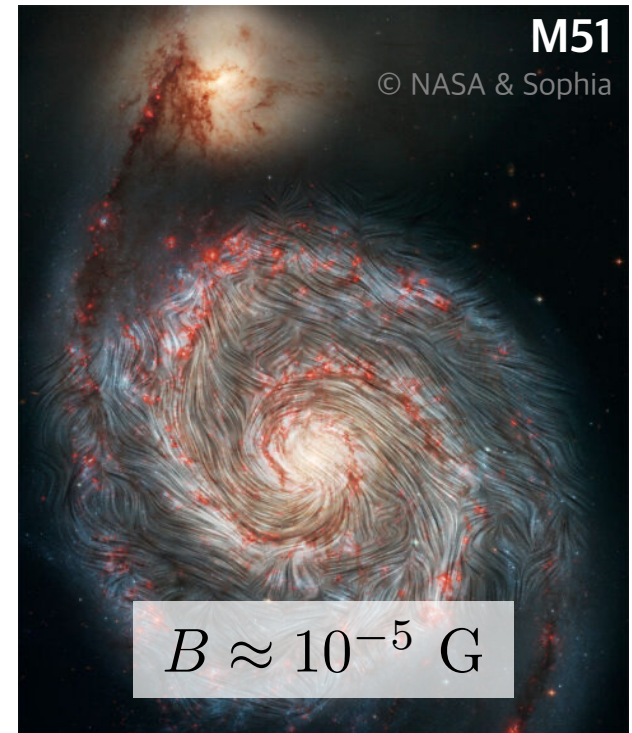
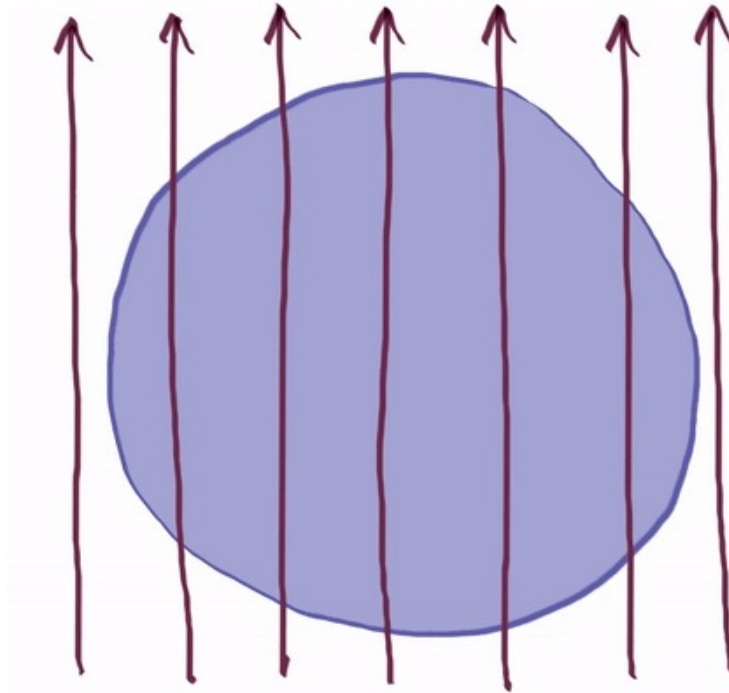
↗️ 5×10^{10} ly

Magnetic history of galaxies

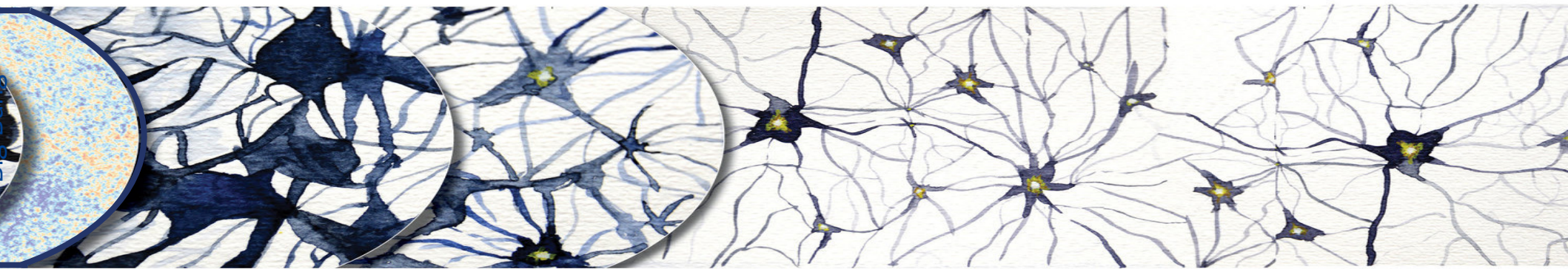
Nordita program
25/05/2026

Seed
magnetic
field

$$B_0 \approx 10^{-20} \text{ G}$$



$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

Nordita program
25/05/2026

Seed
magnetic
field

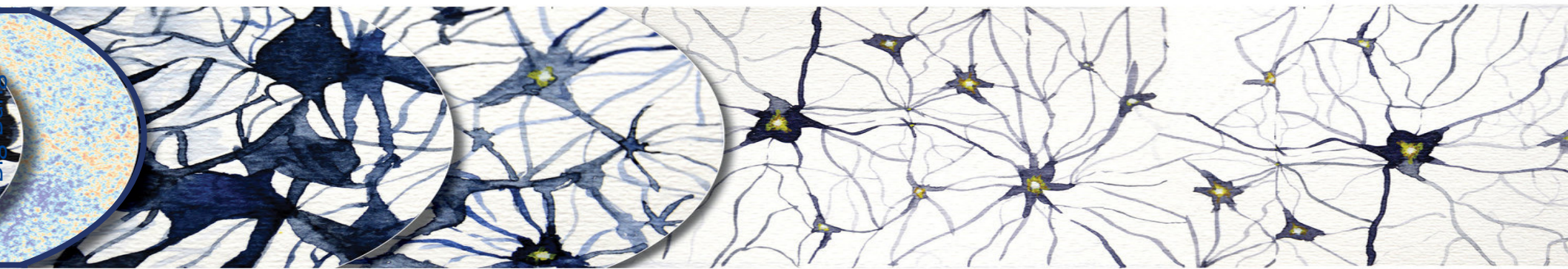
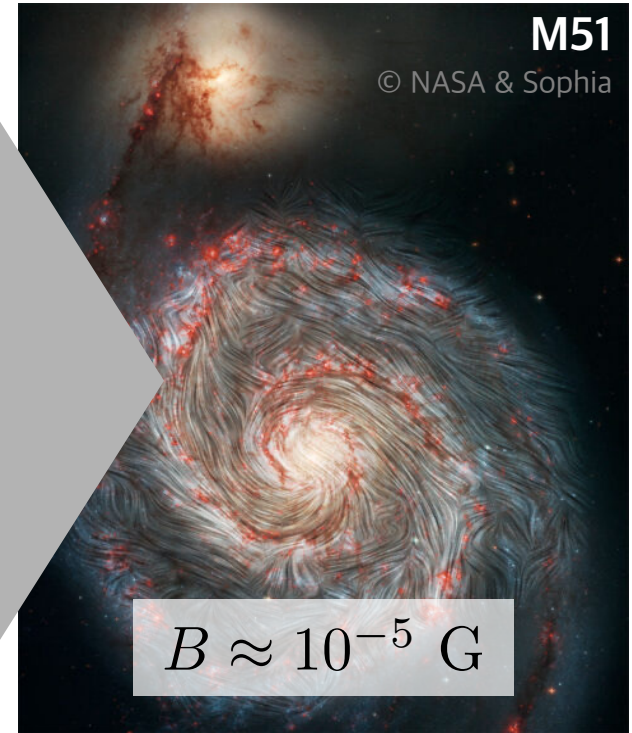
Gravitational compression

$$B \propto n^{2/3}$$

(spherical symmetry)

$$B_0 \approx 10^{-20} \text{ G}$$

$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

Nordita program
25/05/2026

Seed
magnetic
field

$$n_0 \approx 10^{-6} \frac{1}{\text{cm}^3}$$

$$B_0 \approx 10^{-20} \text{ G}$$

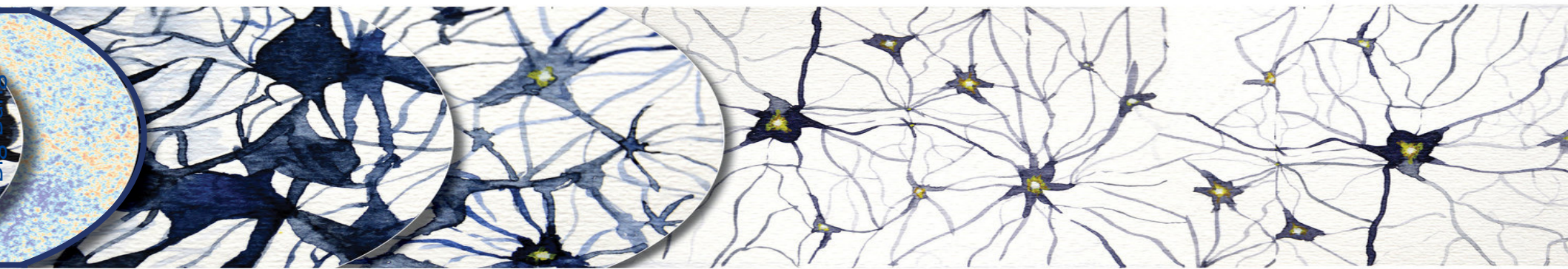
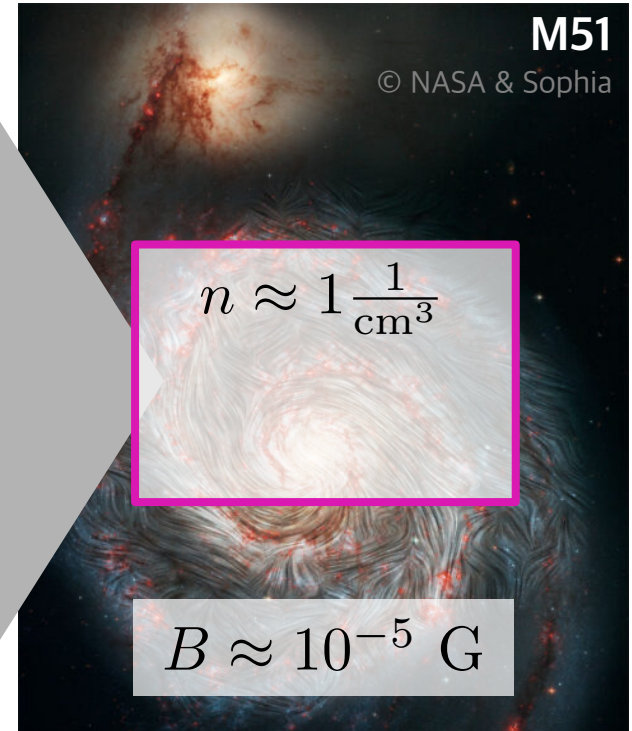
Gravitational compression

$$B \propto n^{2/3}$$

(spherical symmetry)

$$n \approx 1 \frac{1}{\text{cm}^3}$$

$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

Nordita program
25/05/2026

Seed
magnetic
field

$$n_0 \approx 10^{-6} \frac{1}{\text{cm}^3}$$

$$B_0 \approx 10^{-20} \text{ G}$$

Gravitational compression

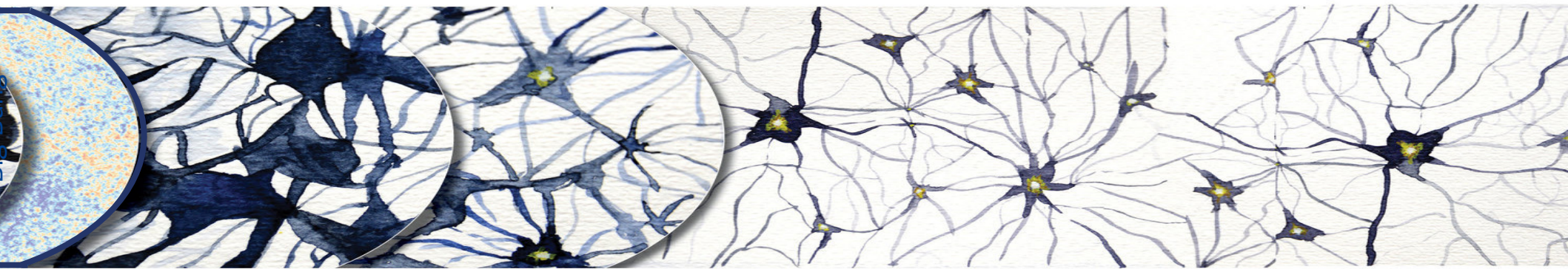
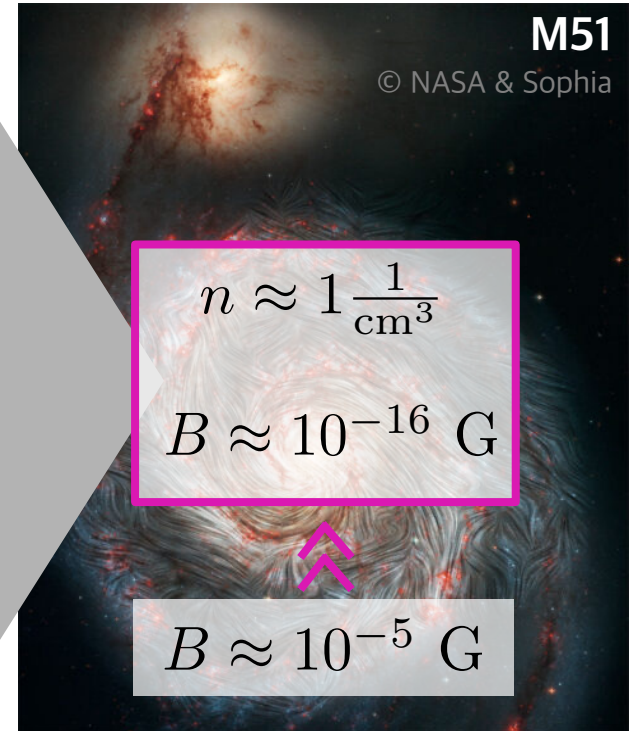
$$B \propto n^{2/3}$$

(spherical symmetry)

$$n \approx 1 \frac{1}{\text{cm}^3}$$

$$B \approx 10^{-16} \text{ G}$$

$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of galaxies

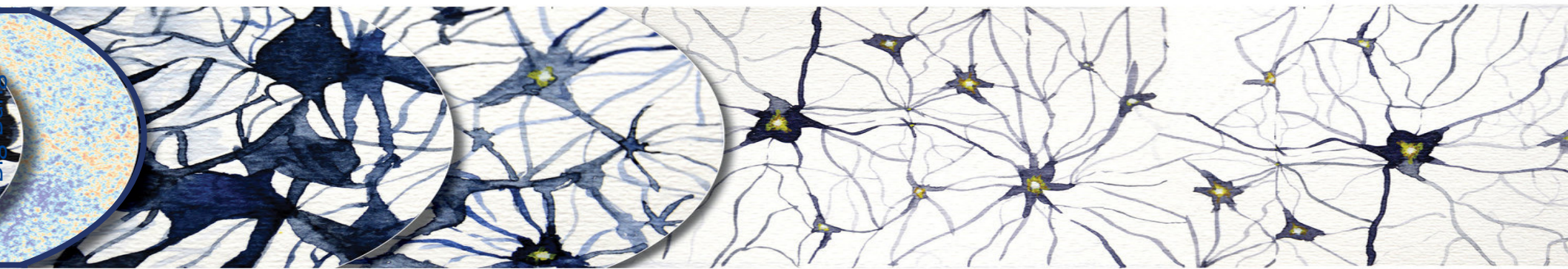
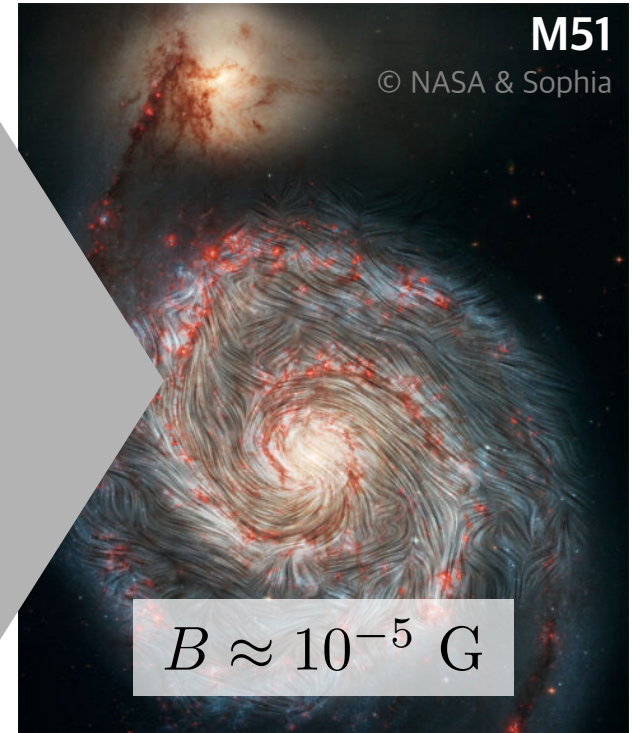
Nordita program
25/05/2026

Seed
magnetic
field

Magnetohydrodynamical
(MHD) dynamos can
bridge this gap.

$$B_0 \approx 10^{-20} \text{ G}$$

$$B \approx 10^{-5} \text{ G}$$



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Equations of magnetohydrodynamics

Nordita program
25/05/2026

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Conservation of momentum:

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} &= -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{1}{m} \mathbf{F} + \frac{1}{4\pi\rho} (\mathbf{B} \cdot \nabla) \mathbf{B} \\ &+ \frac{\mu}{\rho} \left(\nabla^2 \mathbf{U} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{U}) \right) \end{aligned}$$

Conservation of energy:

$$\rho \left(\frac{\partial \epsilon}{\partial t} + \mathbf{U} \cdot \nabla \epsilon \right) = \nabla \cdot (K \nabla T) + \frac{J^2}{\sigma} - p \nabla \cdot \mathbf{U}$$

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Equations of magnetohydrodynamics

Nordita program
25/05/2026

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$$

Conservation of momentum:

$$\begin{aligned} \frac{\partial \mathbf{U}}{\partial t} + (\mathbf{U} \cdot \nabla) \mathbf{U} &= -\frac{1}{\rho} \nabla \left(p + \frac{B^2}{8\pi} \right) + \frac{1}{m} \mathbf{F} + \frac{1}{4\pi\rho} (\mathbf{B} \cdot \nabla) \mathbf{B} \\ &+ \frac{\mu}{\rho} \left(\nabla^2 \mathbf{U} + \frac{1}{3} \nabla (\nabla \cdot \mathbf{U}) \right) \end{aligned}$$

Conservation of energy:

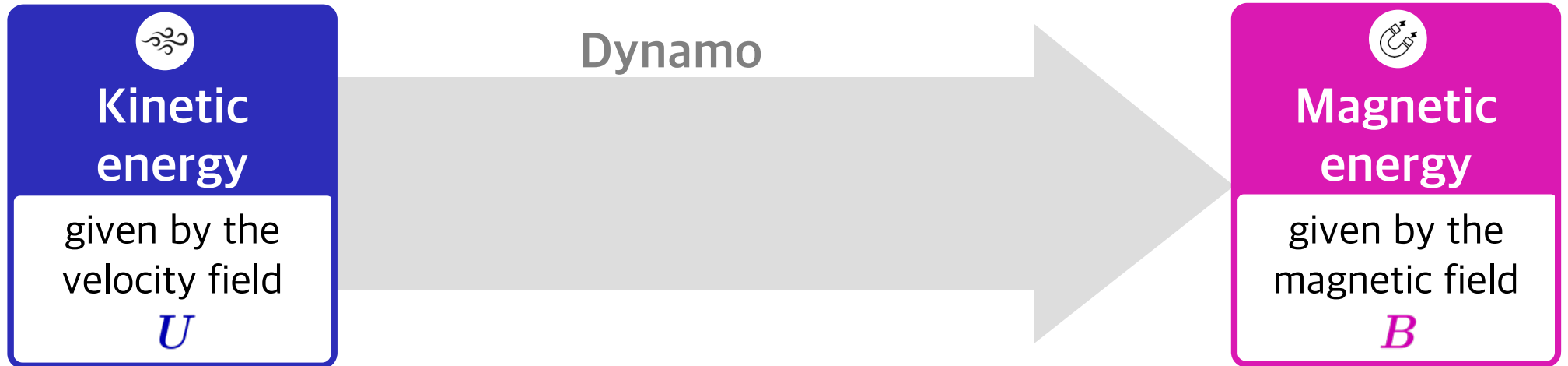
$$\rho \left(\frac{\partial \epsilon}{\partial t} + \mathbf{U} \cdot \nabla \epsilon \right) = \nabla \cdot (K \nabla T) + \frac{J^2}{\sigma} - p \nabla \cdot \mathbf{U}$$

Induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

MHD dynamos

Nordita program
25/05/2026



MHD dynamos

Nordita program
25/05/2026



**Kinetic
energy**

given by the
velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$



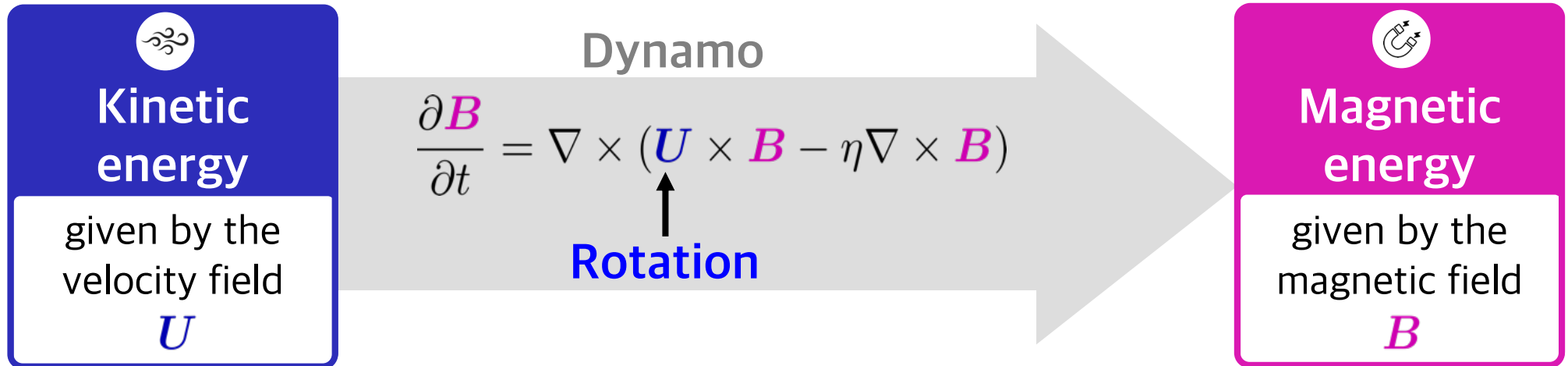
**Magnetic
energy**

given by the
magnetic field

B

MHD dynamos

Nordita program
25/05/2026



MHD dynamos

Nordita program
25/05/2026



Kinetic energy

given by the velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

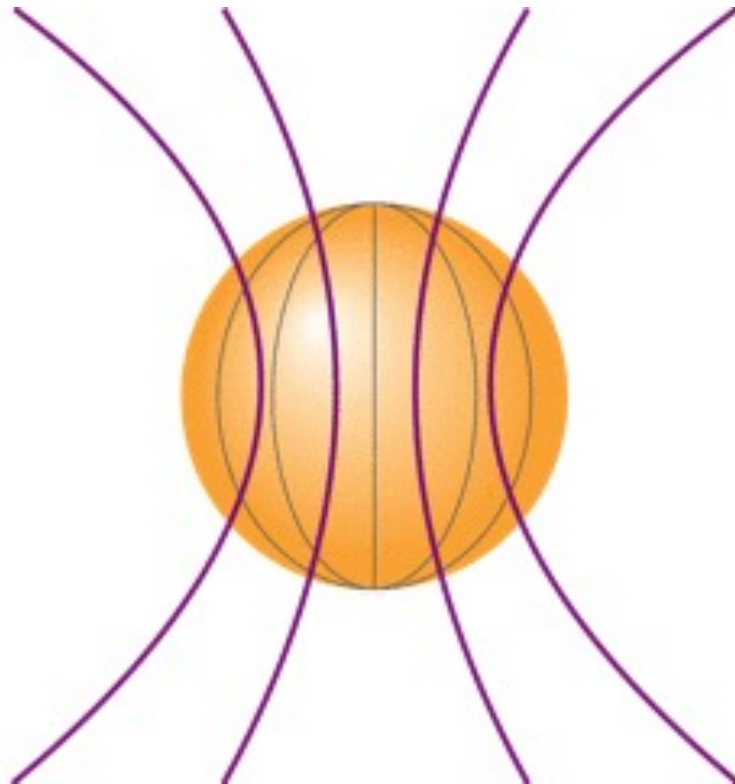
Rotation



Magnetic energy

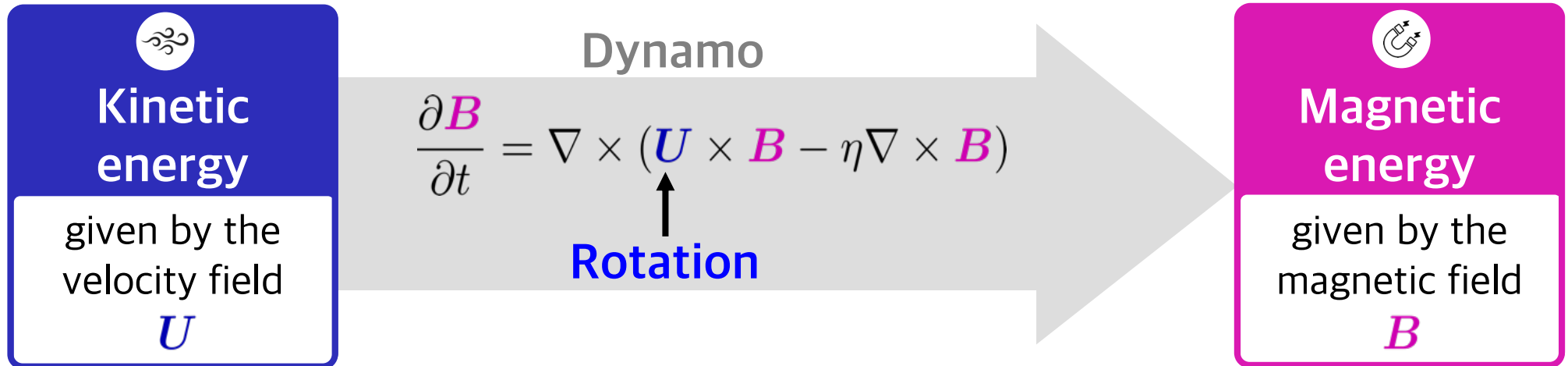
given by the magnetic field

B



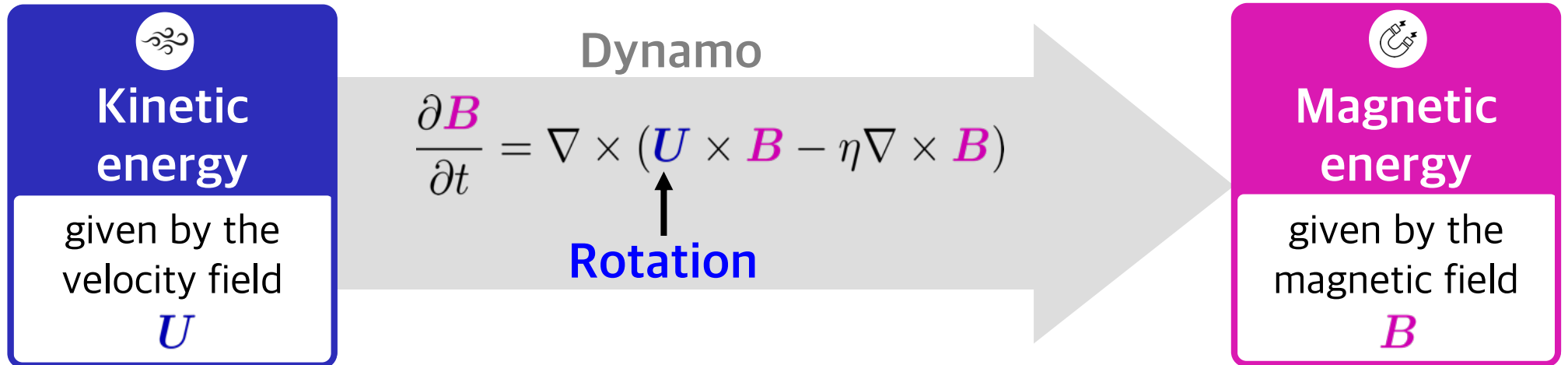
MHD dynamos

Nordita program
25/05/2026



MHD dynamos

Nordita program
25/05/2026

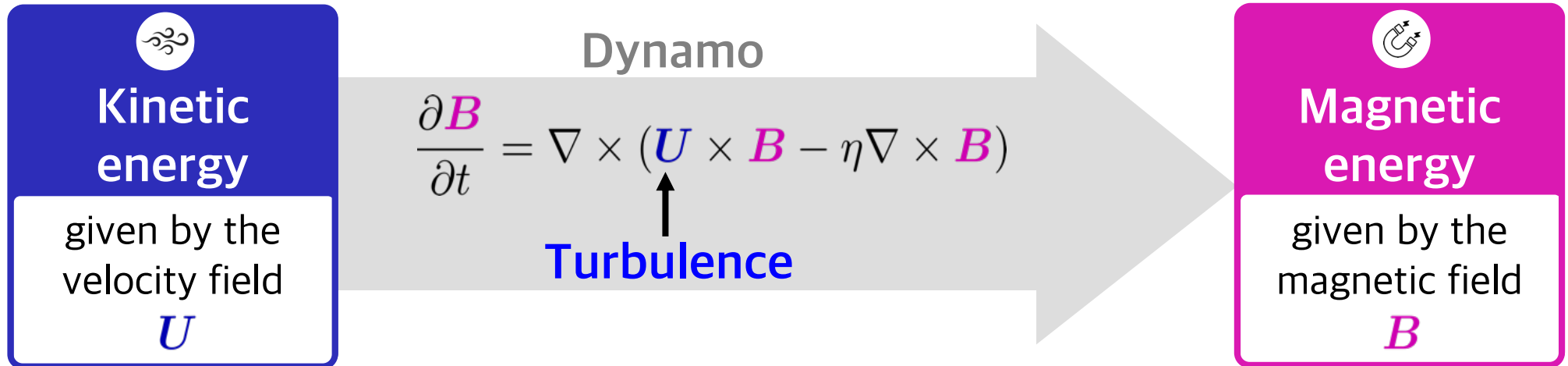


“Omega dynamo”

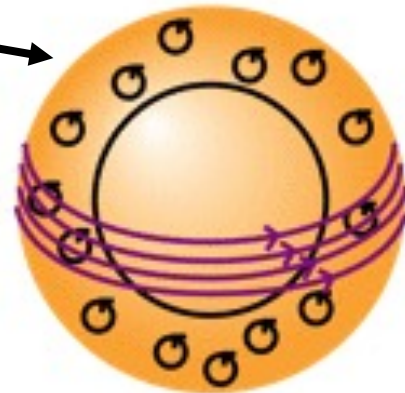
Dynamo driven by rotation.

MHD dynamos

Nordita program
25/05/2026

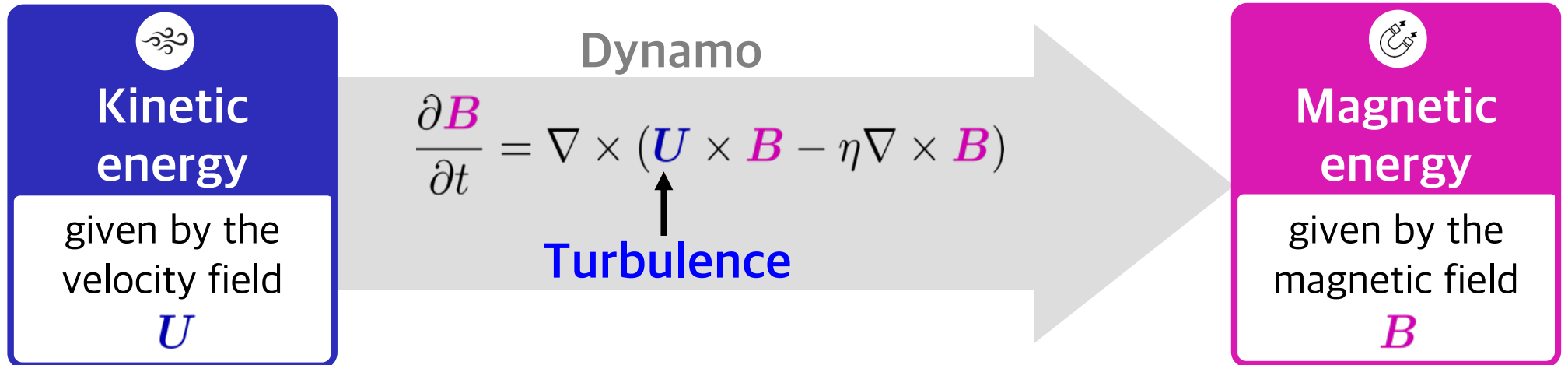


Convection zone
of the Sun

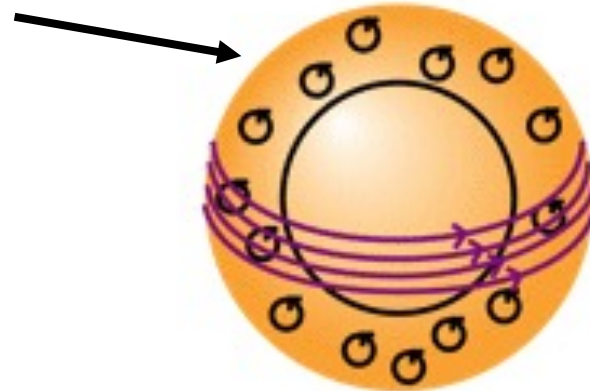


MHD dynamos

Nordita program
25/05/2026



Convection zone
of the Sun



MHD dynamos

Nordita program
25/05/2026



Kinetic energy

given by the velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

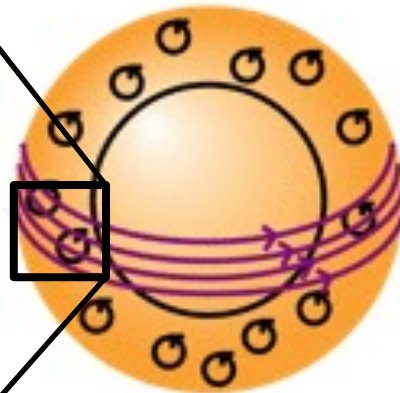
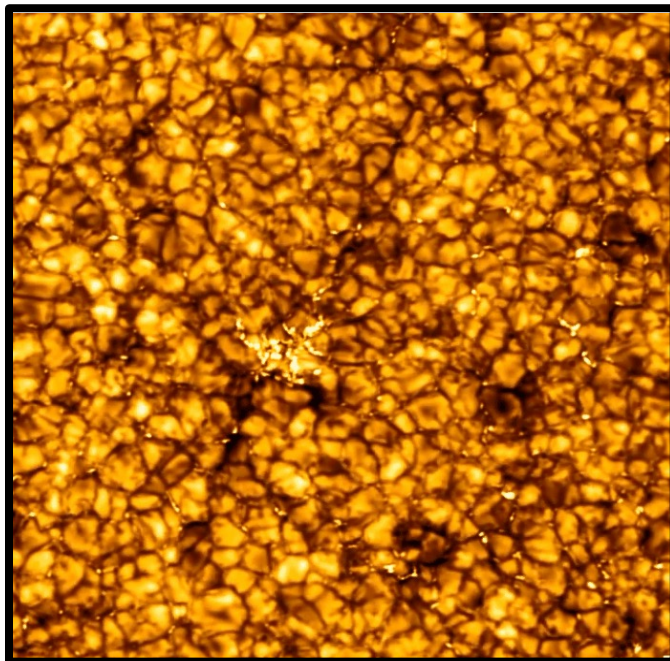
Turbulence



Magnetic energy

given by the magnetic field

B

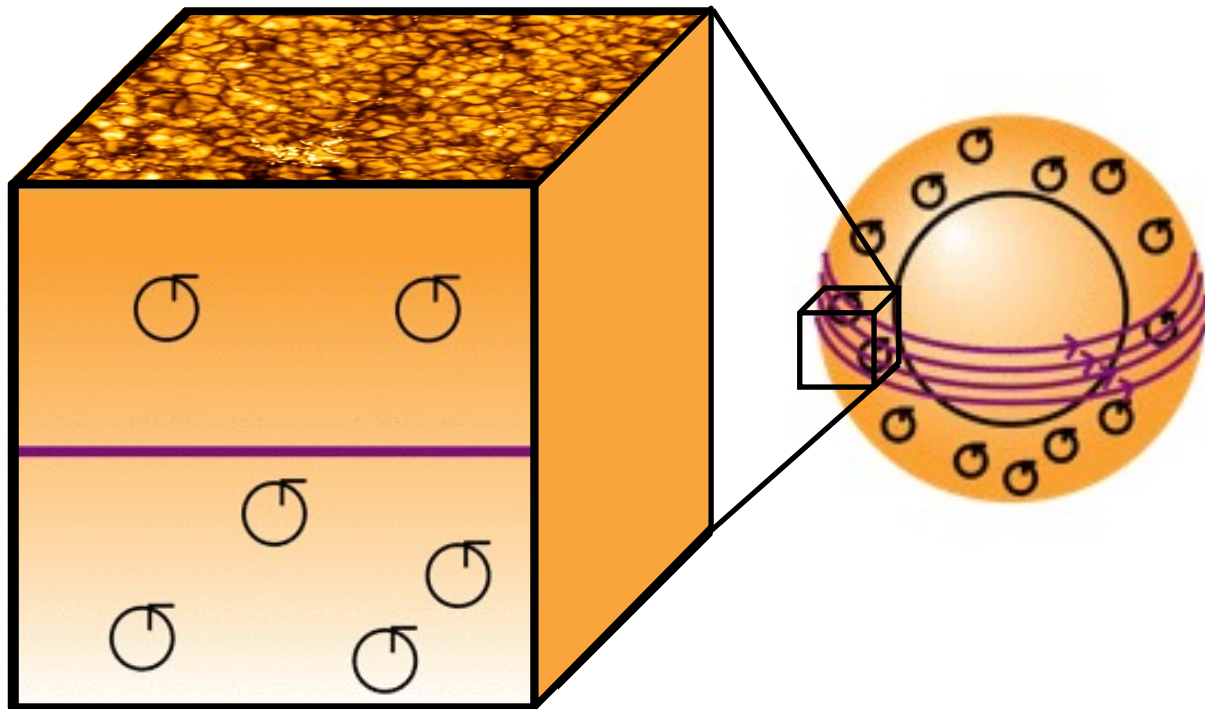
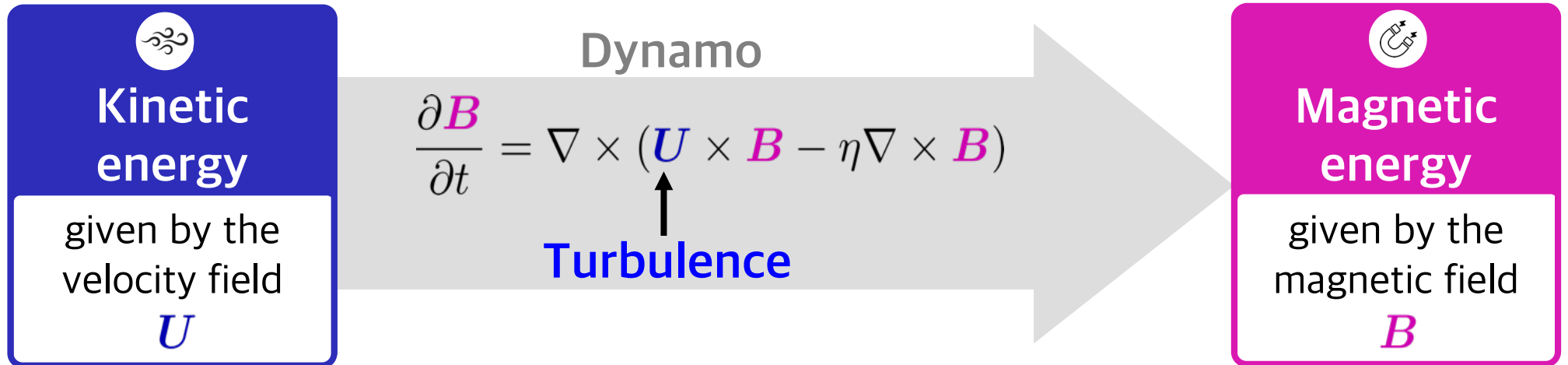


Granulation on Solar surface

© Swedish 1-m Solar Telescope

MHD dynamos

Nordita program
25/05/2026



MHD dynamos

Nordita program
25/05/2026



Kinetic energy

given by the velocity field
 U

Dynamo

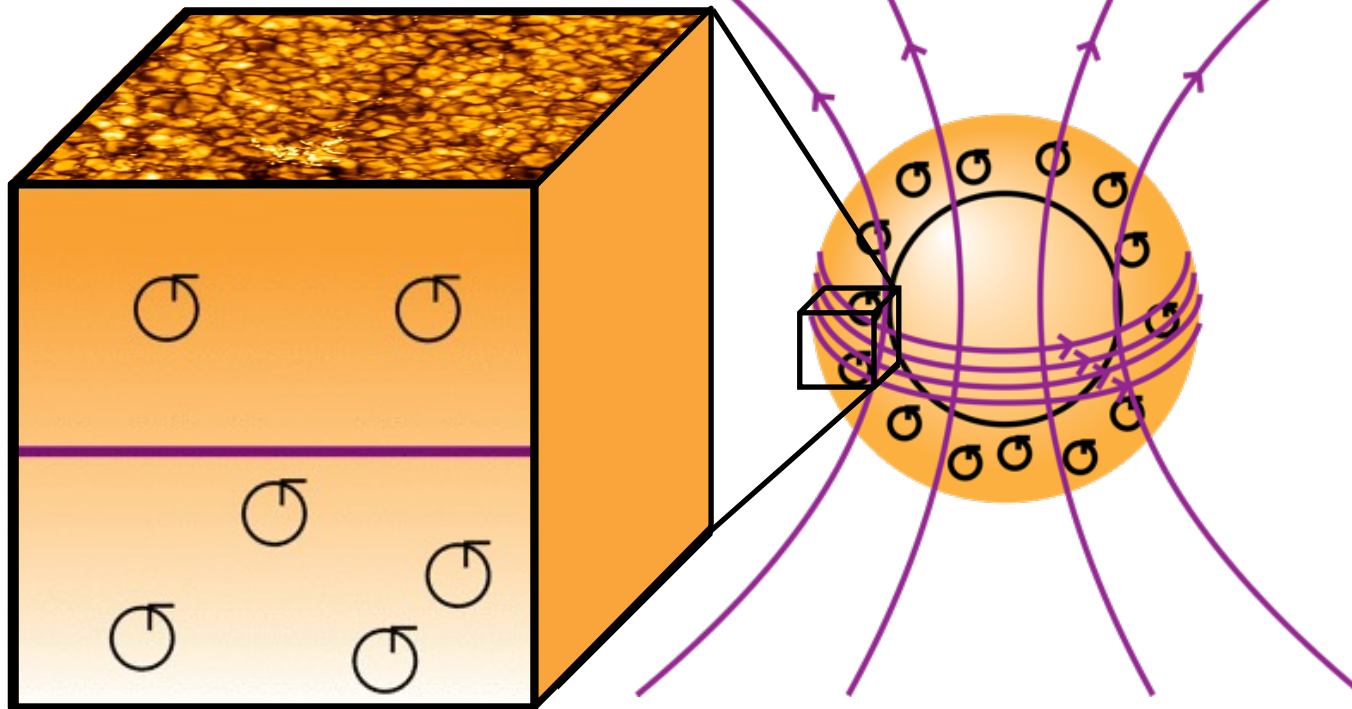
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Turbulence



Magnetic energy

given by the magnetic field
 B



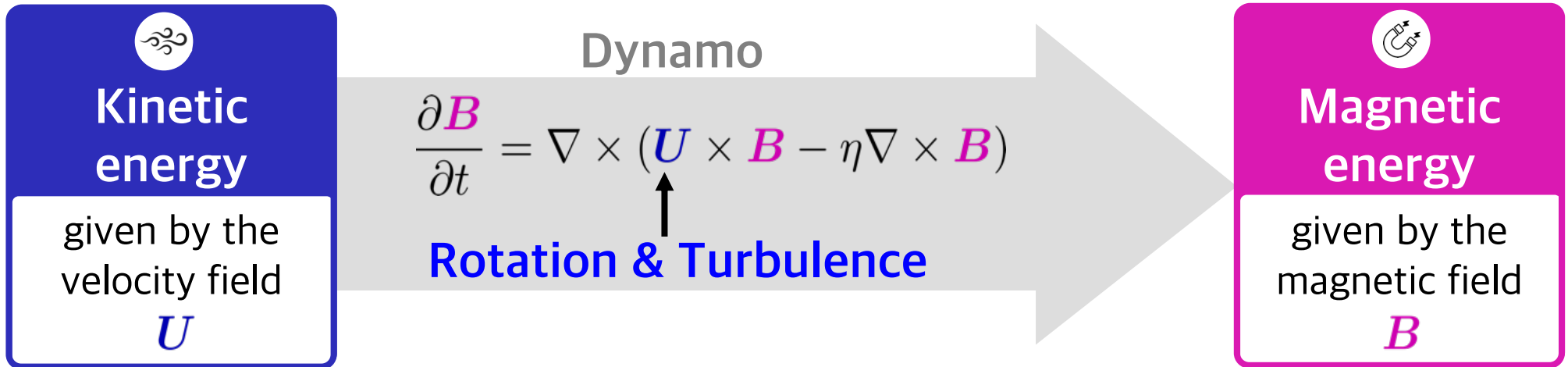
“Alpha dynamo”

Dynamo driven by a
(helical) **turbulent velocity field**

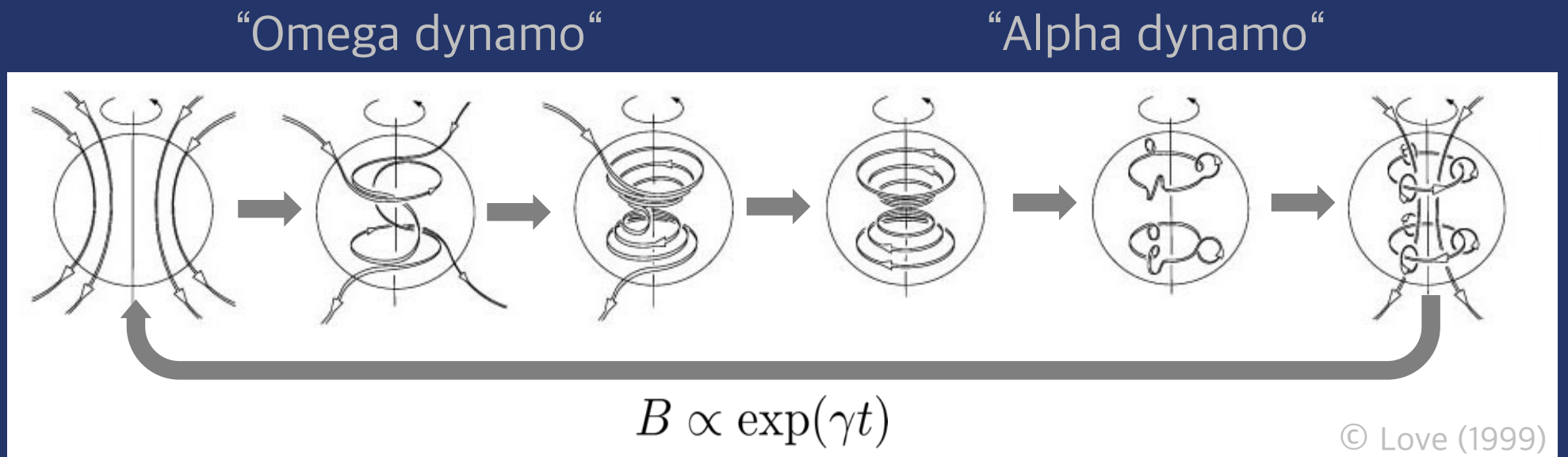
[Parker 1955].

MHD dynamos

Nordita program
25/05/2026



Combined effects: „Alpha-Omega dynamo“



© Love (1999)

MHD dynamos

Nordita program
25/05/2026



**Kinetic
energy**

given by the
velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Rotation & Turbulence



**Magnetic
energy**

given by the
magnetic field

B

**Dynamos in the
laboratory:**

Dresden
Dynamo-Experiment
“DRESDYN”

© HZDR/Frank Stefani



MHD dynamos

Nordita program
25/05/2026



**Kinetic
energy**

given by the
velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Rotation & Turbulence



**Magnetic
energy**

given by the
magnetic field

B

**Dynamos in the
laboratory:**

Liquid
sodium
inside!

Dresden
Dynamo-Experiment
“DRESDYN”

© HZDR/Frank Stefani



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

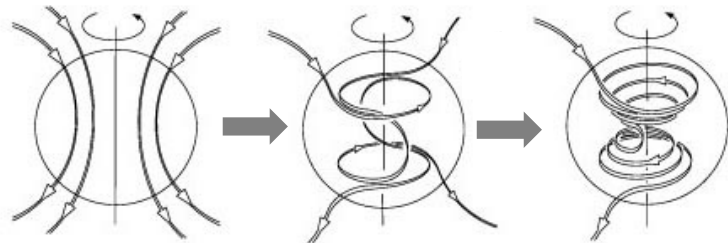
Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Omega dynamo



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

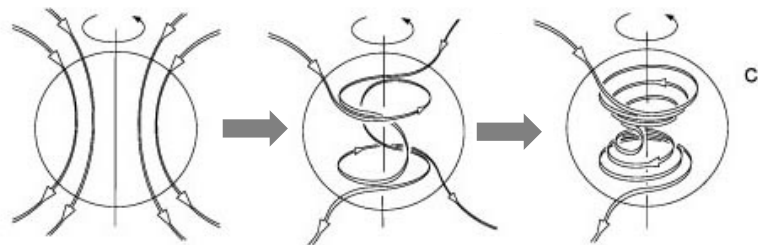
$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Mean EMF

Omega dynamo



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Moffatt 1978

Closure through ansatz:

$$\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle = \text{func}(\langle \mathbf{B} \rangle)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Moffatt 1978

Closure through ansatz:

$$\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle = \text{func}(\langle \mathbf{B} \rangle)$$

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\alpha \langle \mathbf{B} \rangle) + (\eta + \eta_T) \nabla^2 \langle \mathbf{B} \rangle$$

Alpha dynamo

Turbulent diffusivity

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Moffatt 1978

Closure through ansatz:

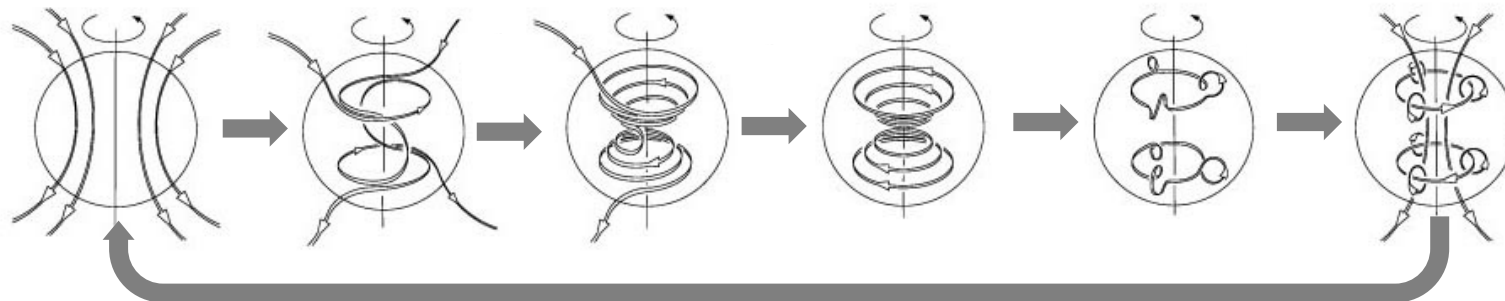
$$\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle = \text{func}(\langle \mathbf{B} \rangle)$$

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\alpha \langle \mathbf{B} \rangle) + (\eta + \eta_T) \nabla^2 \langle \mathbf{B} \rangle$$

Omega dynamo

Alpha dynamo

Turbulent diffusivity



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Moffatt 1978

Closure through ansatz:

$$\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle = \text{func}(\langle \mathbf{B} \rangle)$$

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\alpha \langle \mathbf{B} \rangle) + (\eta + \eta_T) \nabla^2 \langle \mathbf{B} \rangle$$

Steenbeck, Krause &
Rädler 1966

First-order smoothing
approximation (FOSA)

$$\alpha = -\frac{1}{3} \langle \delta \mathbf{U} \cdot (\nabla \times \delta \mathbf{U}) \rangle \tau$$

$$\eta_T = \frac{1}{3} \langle \delta \mathbf{U} \cdot \delta \mathbf{U} \rangle \tau$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Separation ansatz

$$\mathbf{B} = \langle \mathbf{B} \rangle + \delta \mathbf{B}, \quad \mathbf{U} = \langle \mathbf{U} \rangle + \delta \mathbf{U}$$

and averaging

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle) + \eta \nabla^2 \langle \mathbf{B} \rangle$$

Closure through ansatz:

$$\langle \delta \mathbf{U} \times \delta \mathbf{B} \rangle = \text{func}(\langle \mathbf{B} \rangle)$$

$$\frac{\partial \langle \mathbf{B} \rangle}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \langle \mathbf{B} \rangle) + \nabla \times (\alpha \langle \mathbf{B} \rangle) + (\eta + \eta_T) \nabla^2 \langle \mathbf{B} \rangle$$

Other methods

- τ -approximation: Relaxation-time closure [Blackman & Field 2002, Rogachevskii & Kleeorin 2000, 2004]
- Test-field method: Auxiliary induction equations [Schrinner et al. 2005, 2007]
- IROS method: Iterative EMF deconvolution [Bendre et al. 2024]
- ...

Mean-field dynamos: open questions

Nordita program
25/05/2026

- How to determine transport coefficients reliably? Mean-field models depend entirely on them...
- How does nonlinear saturation work? Sets magnetic field strength and cycle behavior...
- How important are nonlocality and memory effects? Standard local closures may fail...
- ...

MHD dynamos

Nordita program
25/05/2026



**Kinetic
energy**

given by the
velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$



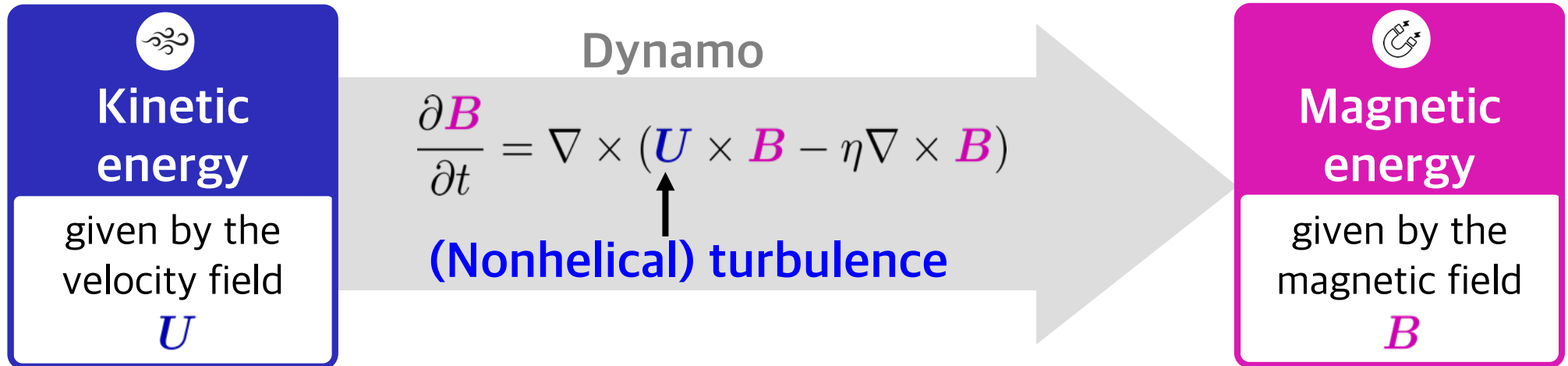
**Magnetic
energy**

given by the
magnetic field

B

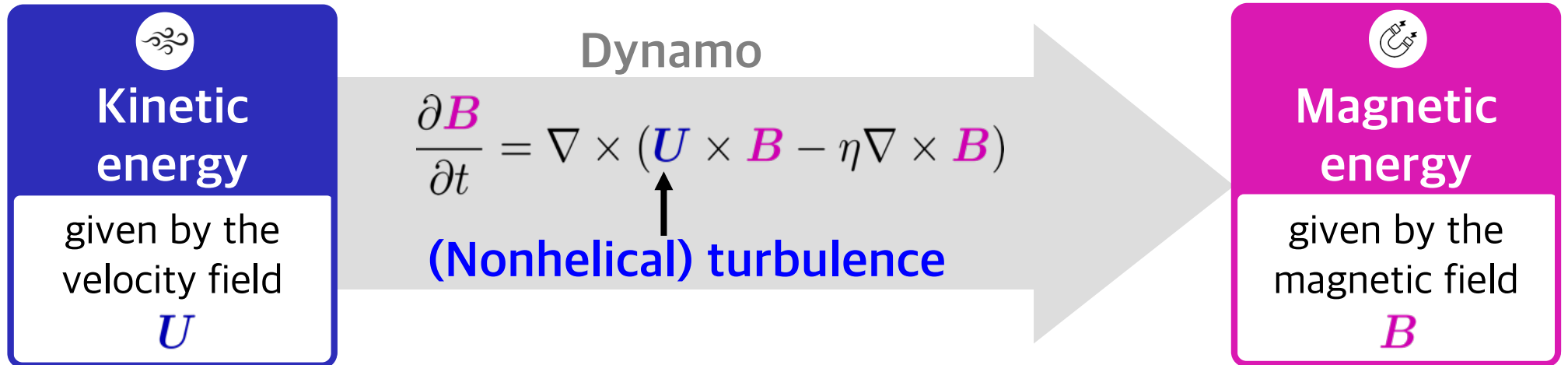
MHD dynamos

Nordita program
25/05/2026

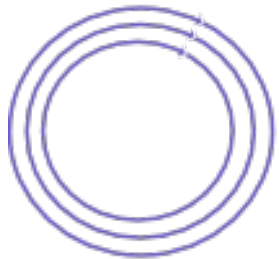


MHD dynamos

Nordita program
25/05/2026



Small-scale dynamo



MHD dynamos

Nordita program
25/05/2026



Kinetic energy

given by the velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

(Nonhelical) turbulence

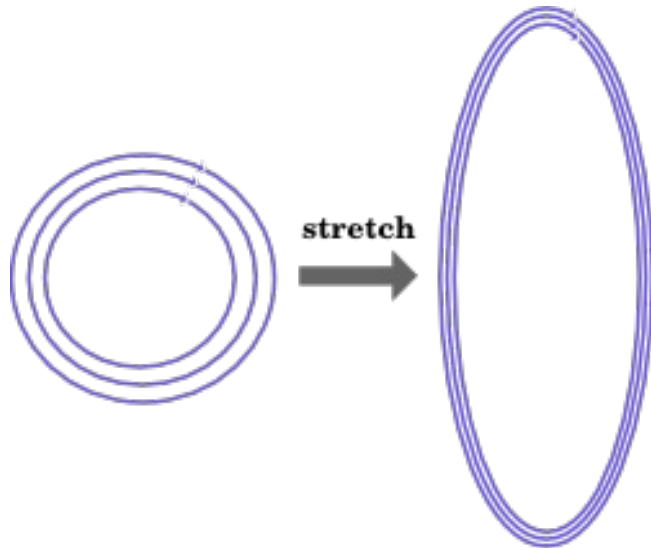


Magnetic energy

given by the magnetic field

B

Small-scale dynamo



MHD dynamos

Nordita program
25/05/2026



Kinetic energy

given by the velocity field

U

Dynamo

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

(Nonhelical) turbulence

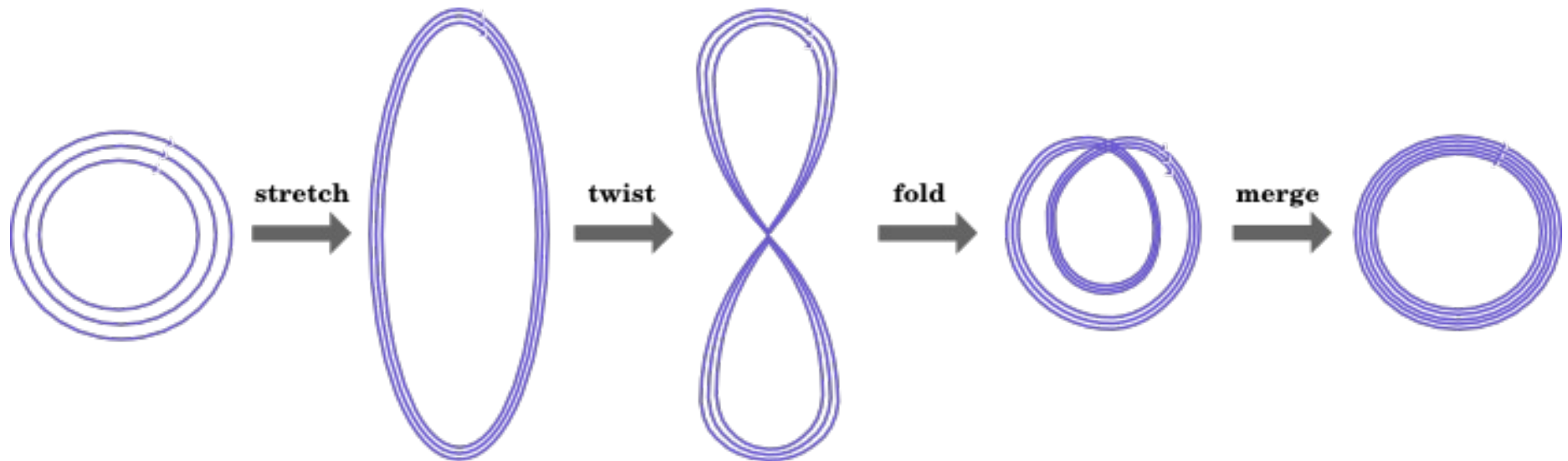


Magnetic energy

given by the magnetic field

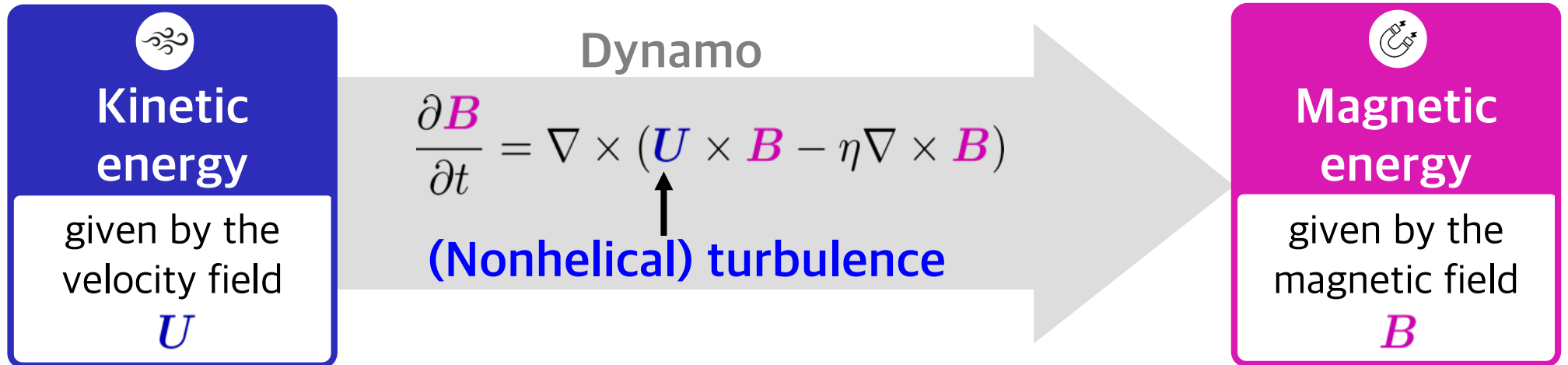
B

Small-scale dynamo

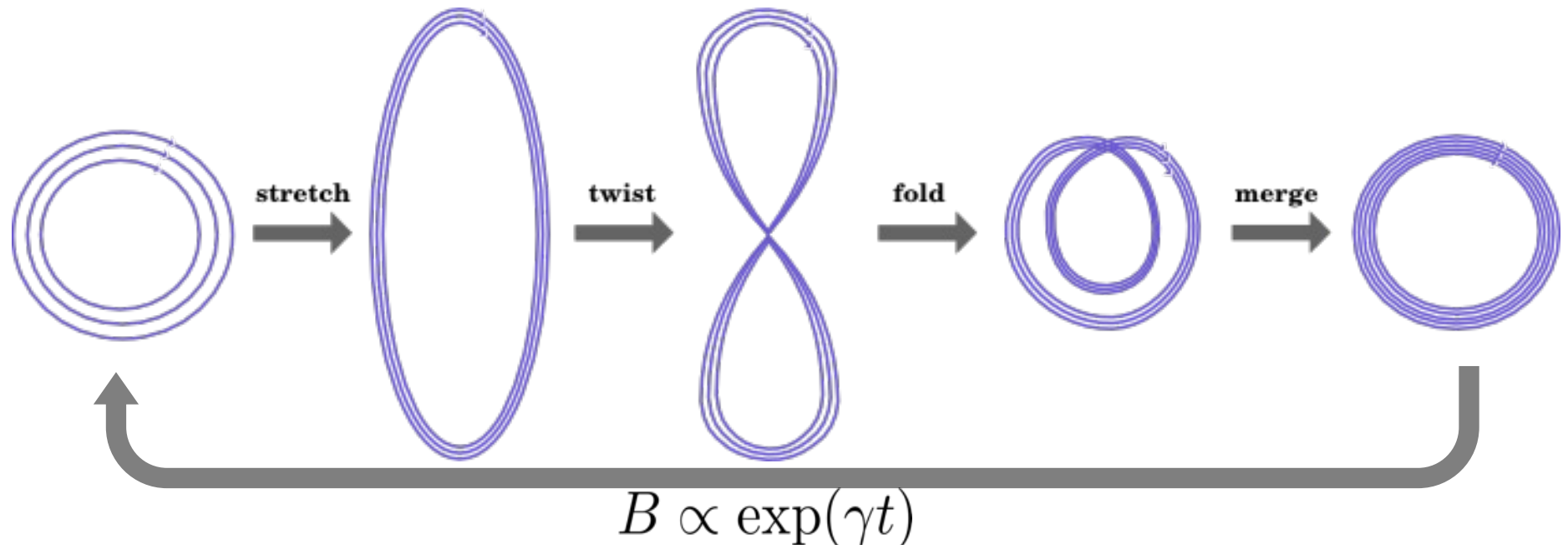


MHD dynamos

Nordita program
25/05/2026

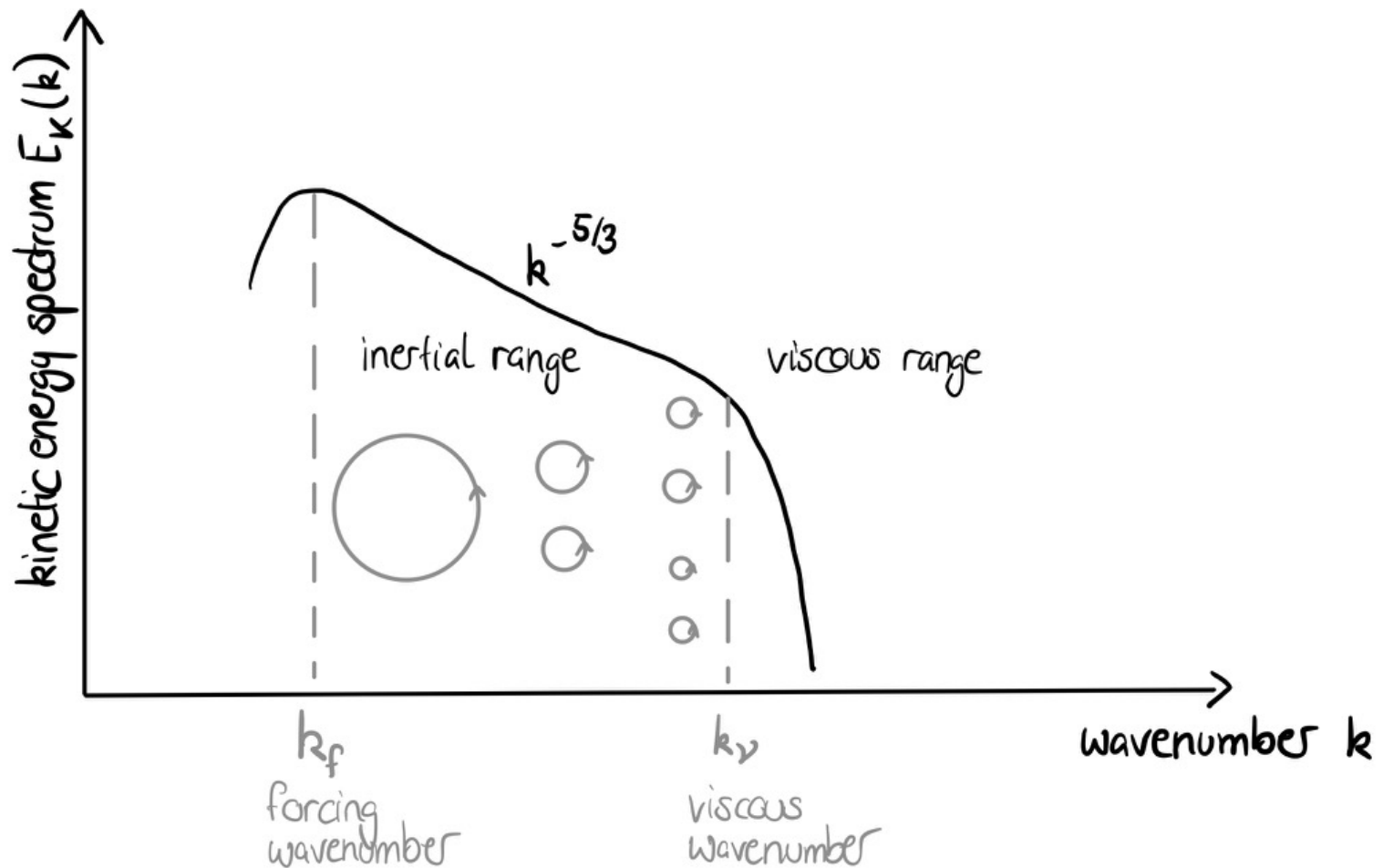


Small-scale dynamo



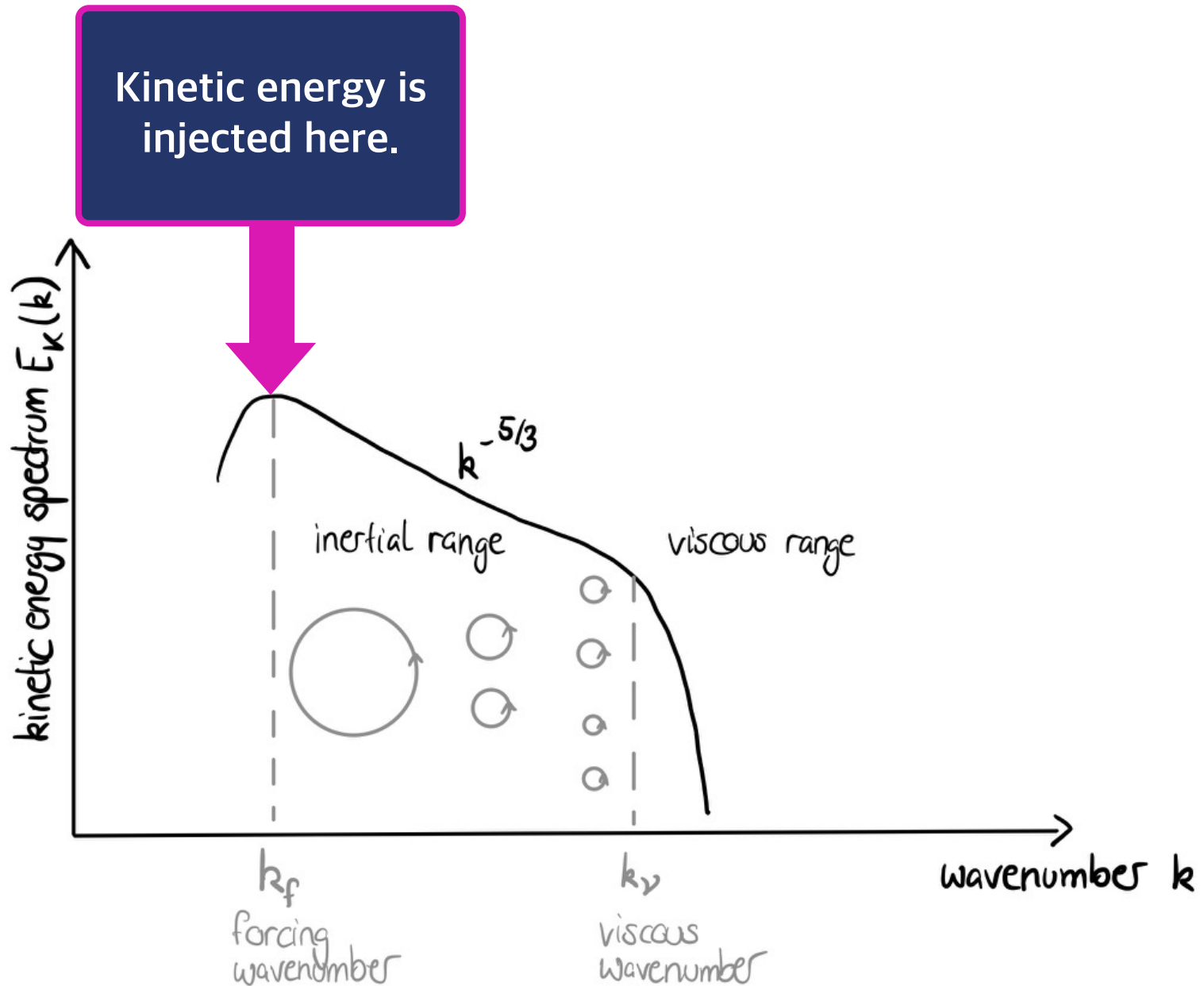
Small-scale dynamos

Nordita program
25/05/2026



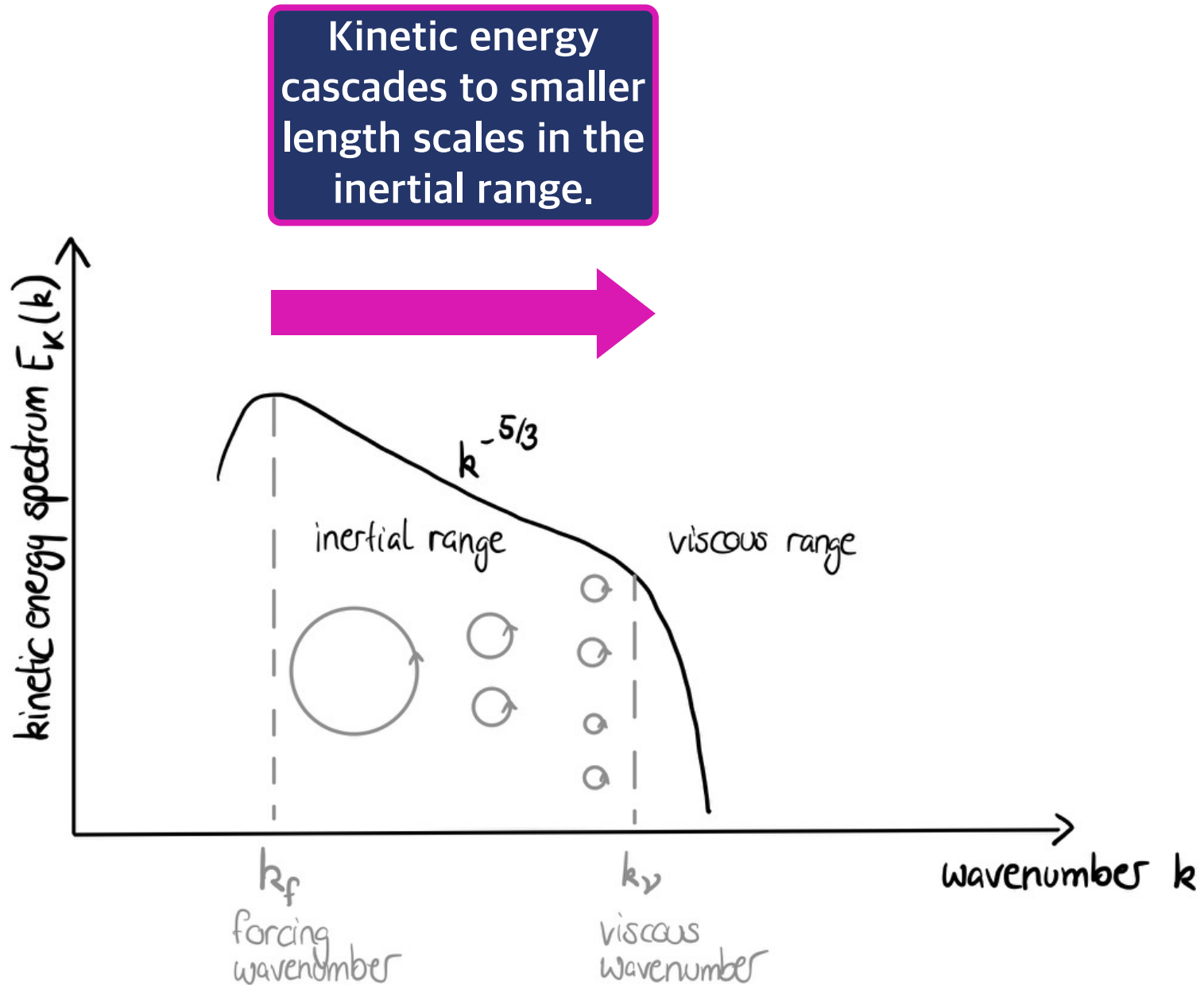
Small-scale dynamos

Nordita program
25/05/2026



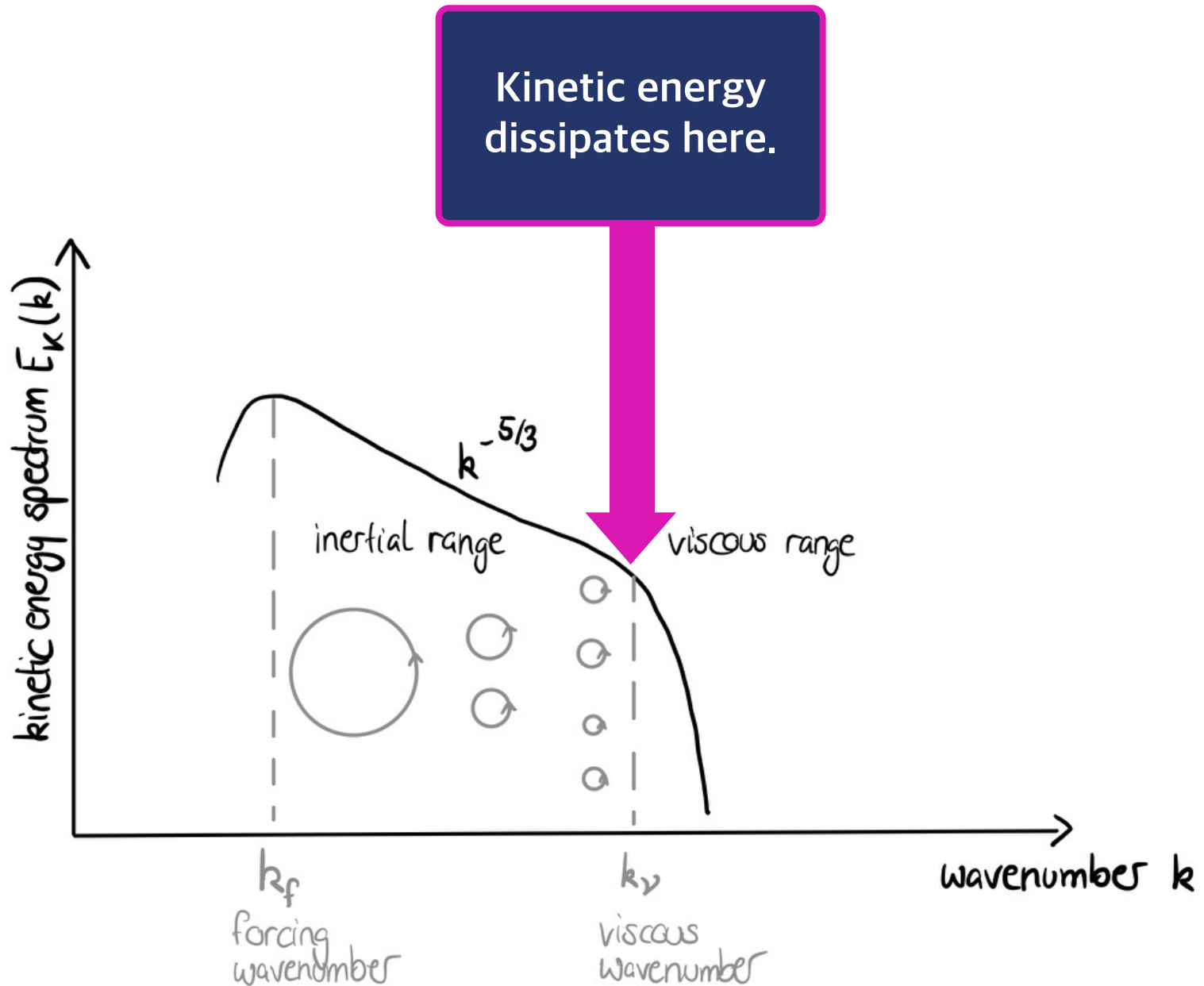
Small-scale dynamos

Nordita program
25/05/2026



Small-scale dynamos

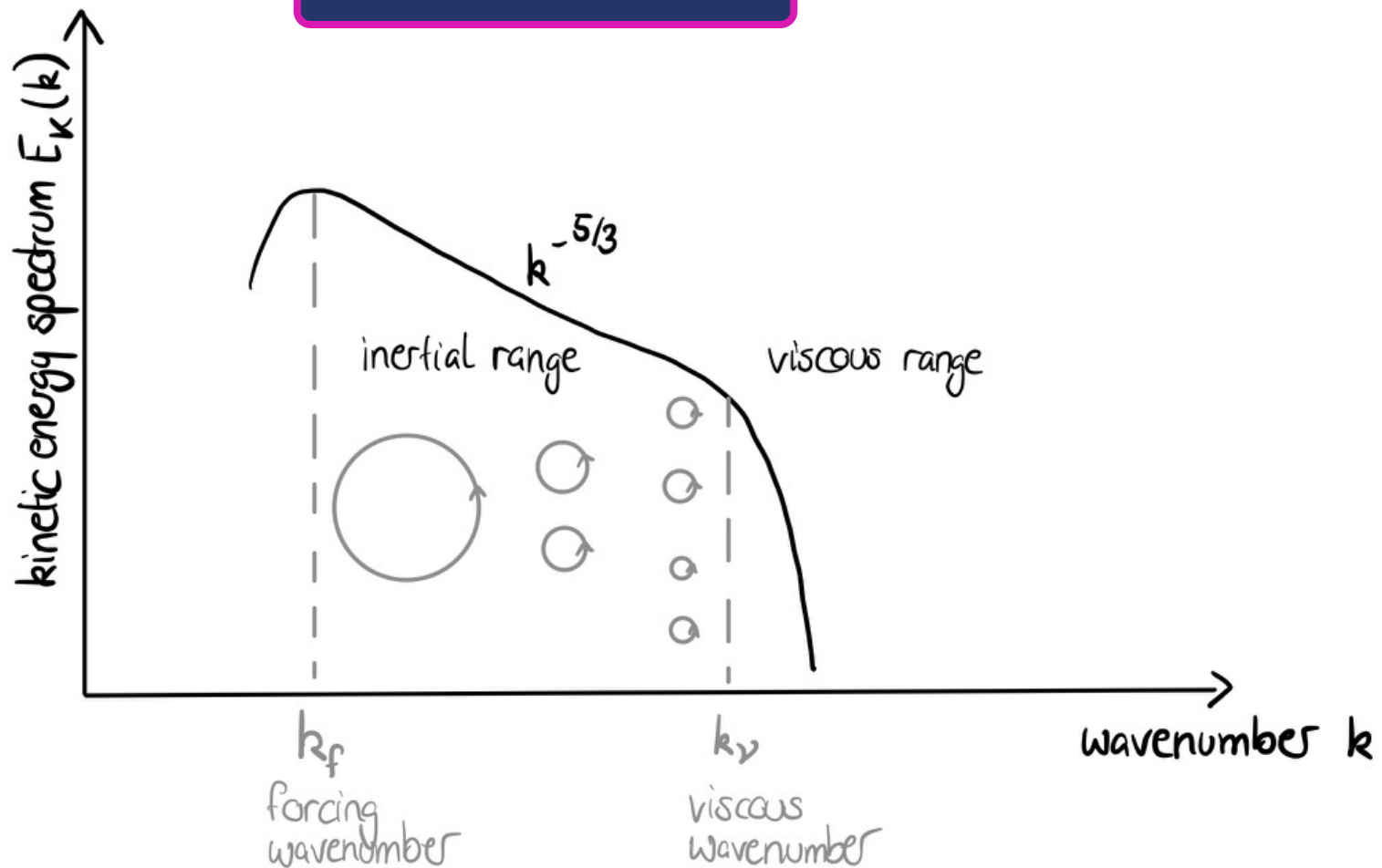
Nordita program
25/05/2026



Small-scale dynamos

Nordita program
25/05/2026

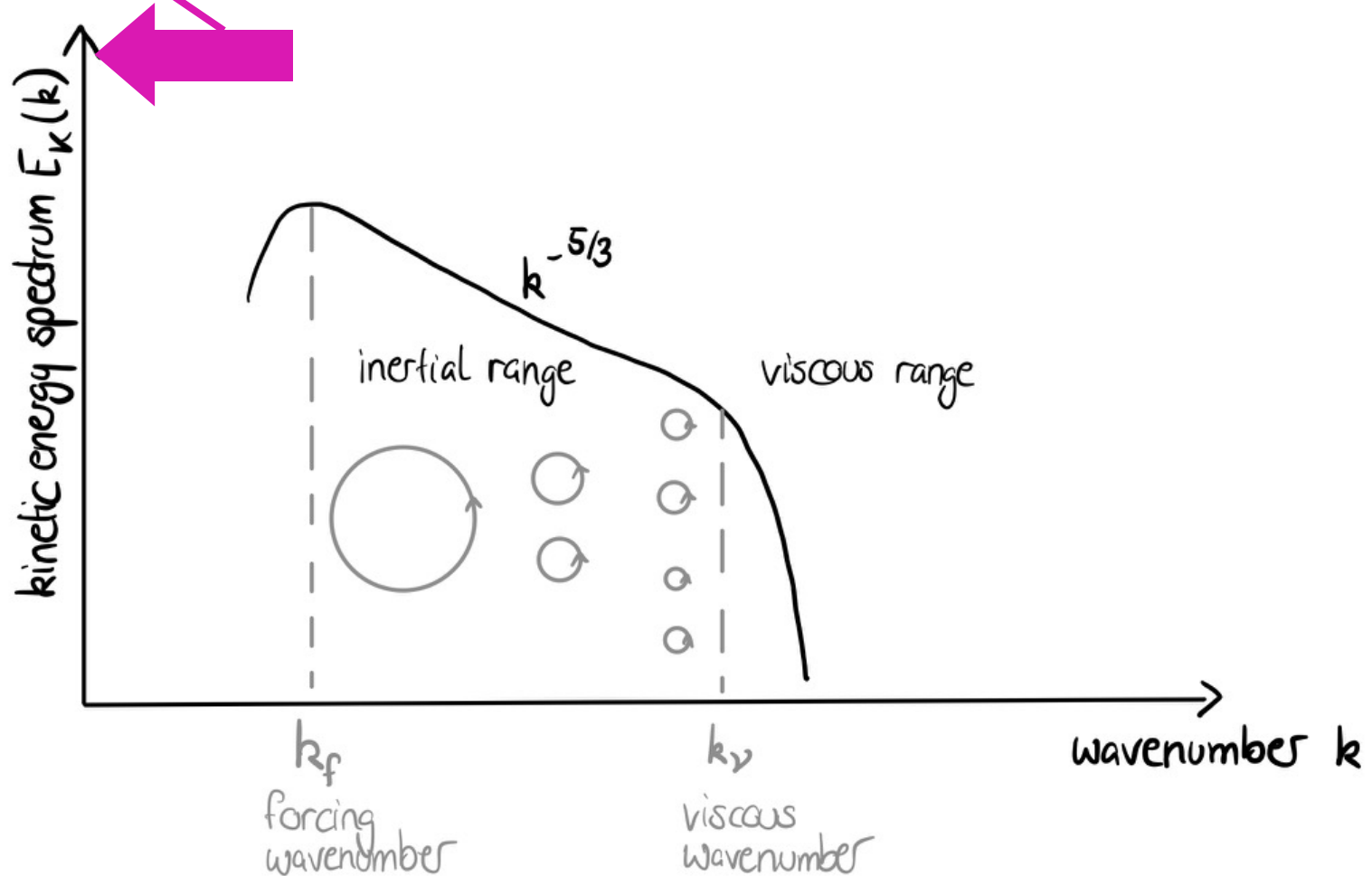
“More turbulence”
= larger inertial range
= larger Reynolds
number Re



Small-scale dynamos

Nordita program
25/05/2026

Large-scale dynamo
(mean-field dynamo)

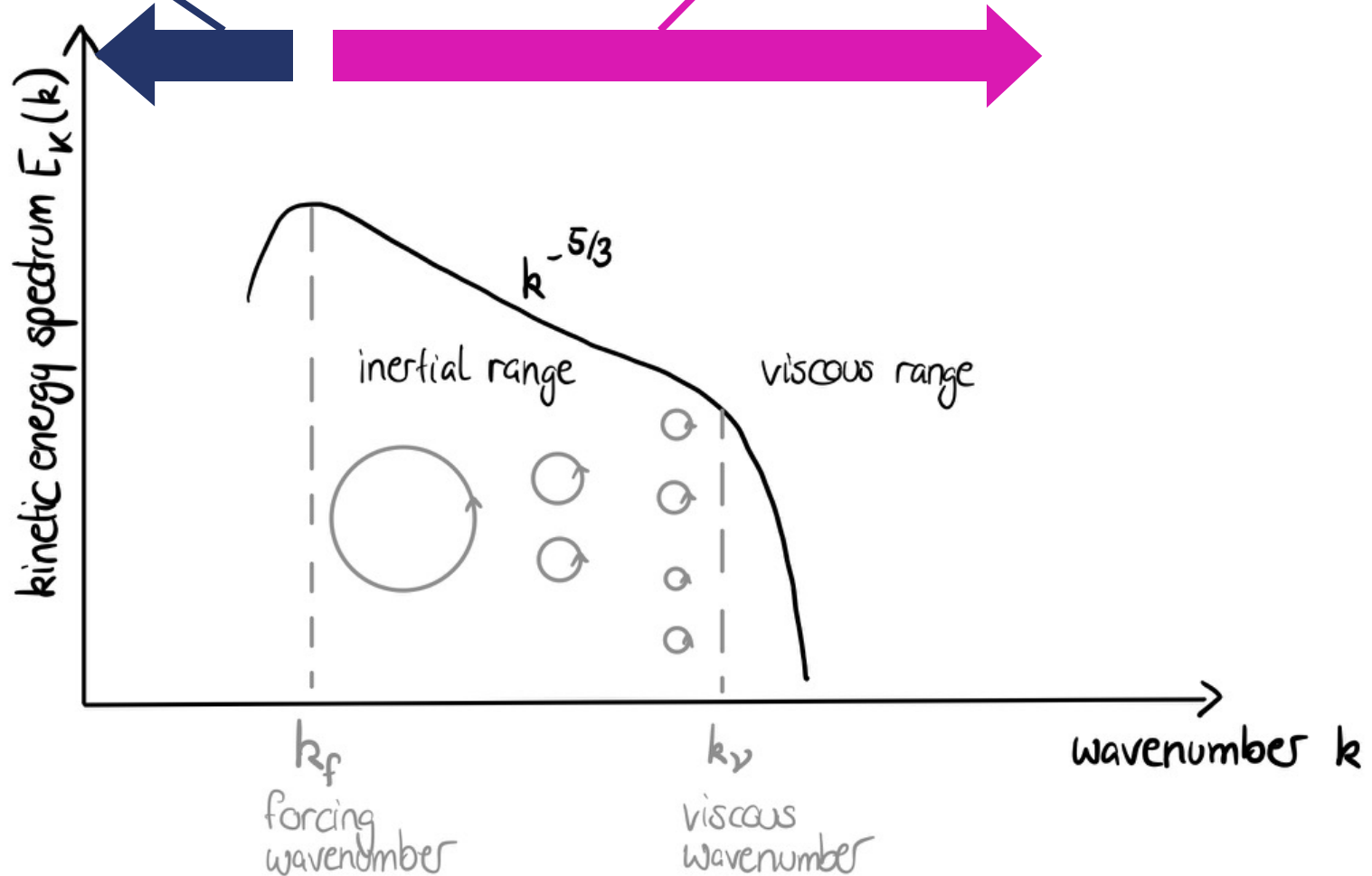


Small-scale dynamos

Nordita program
25/05/2026

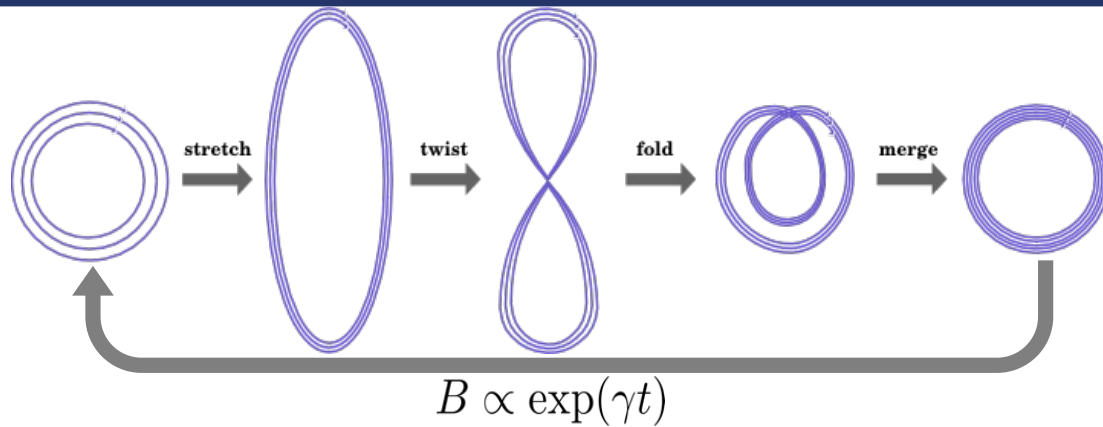
Large-scale dynamo
(mean-field dynamo)

Small-scale dynamo
(fluctuation dynamo)

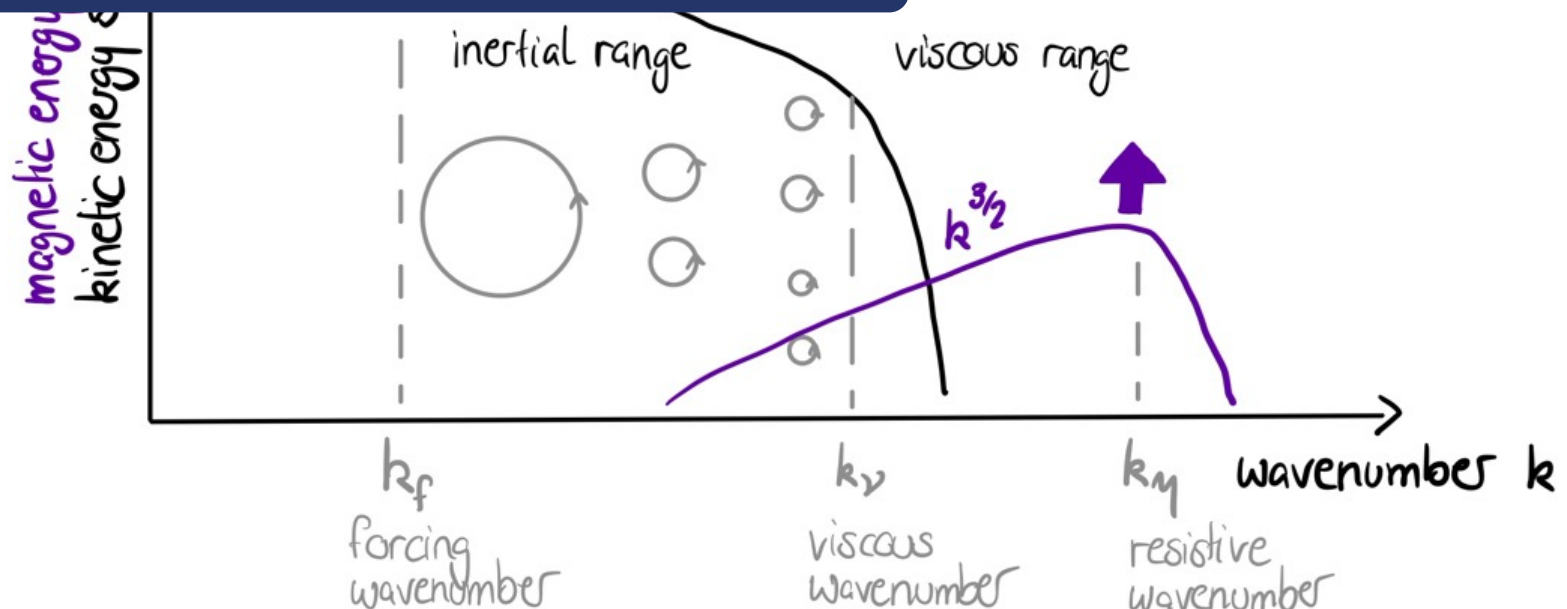


Small-scale dynamos

Time scale: determined by fastest eddies



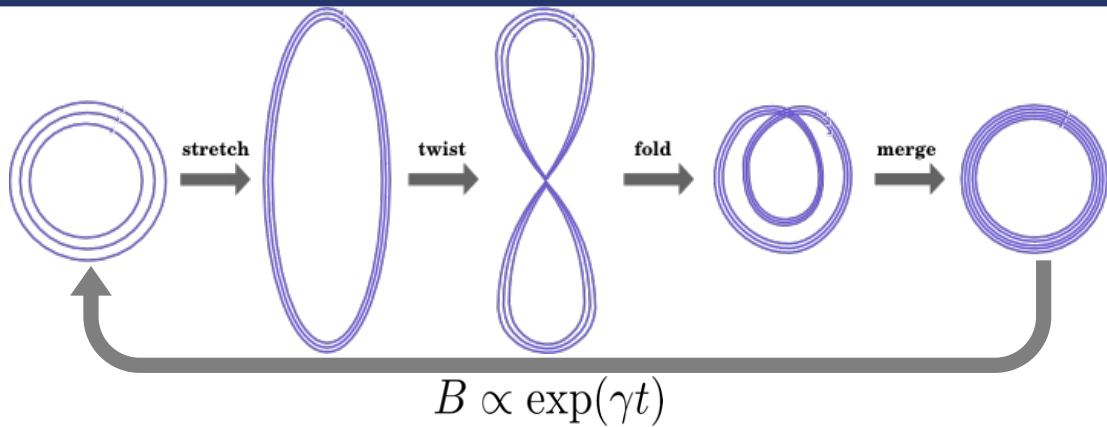
The growth rate scales with the Reynolds number Re as $\gamma \propto Re^{1/2}$ [Kazantsev 1968].



Small-scale dynamos

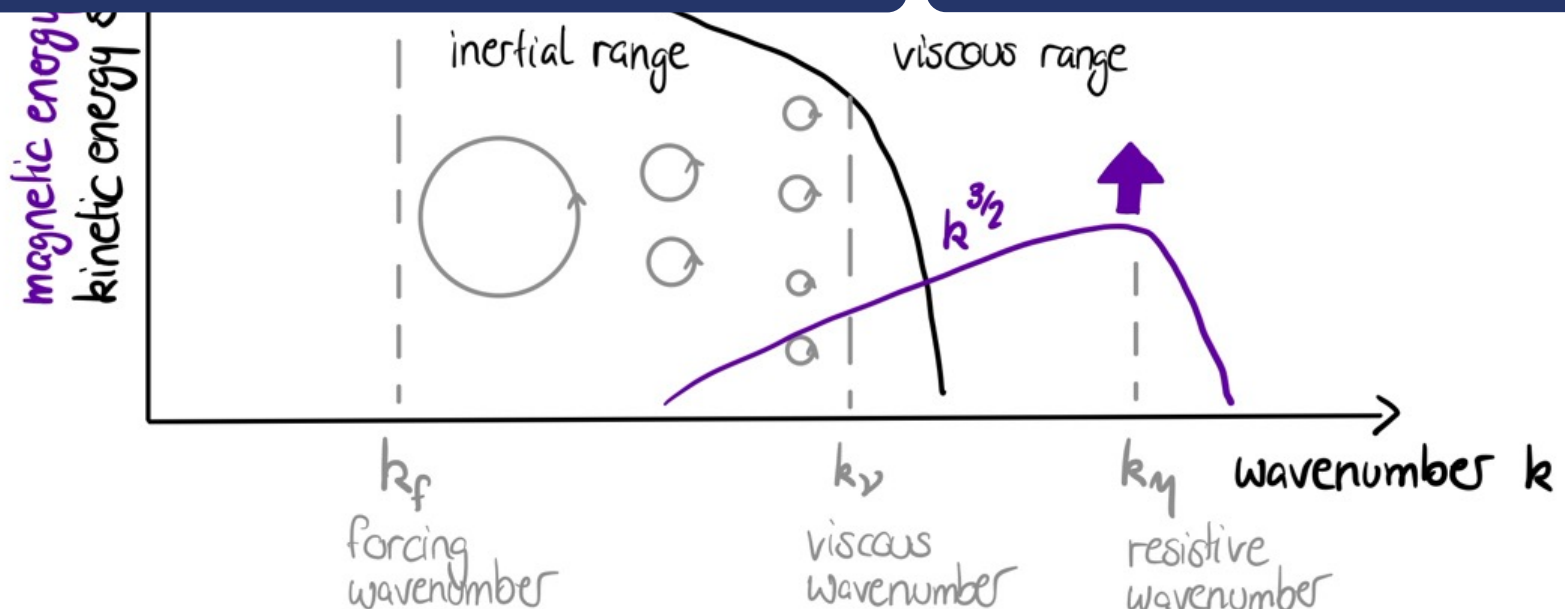
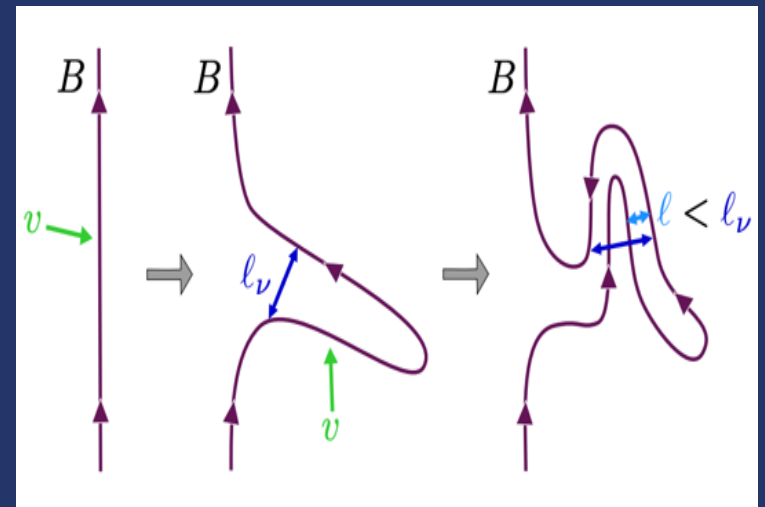
Nordita program
25/05/2026

Time scale: determined by fastest eddies

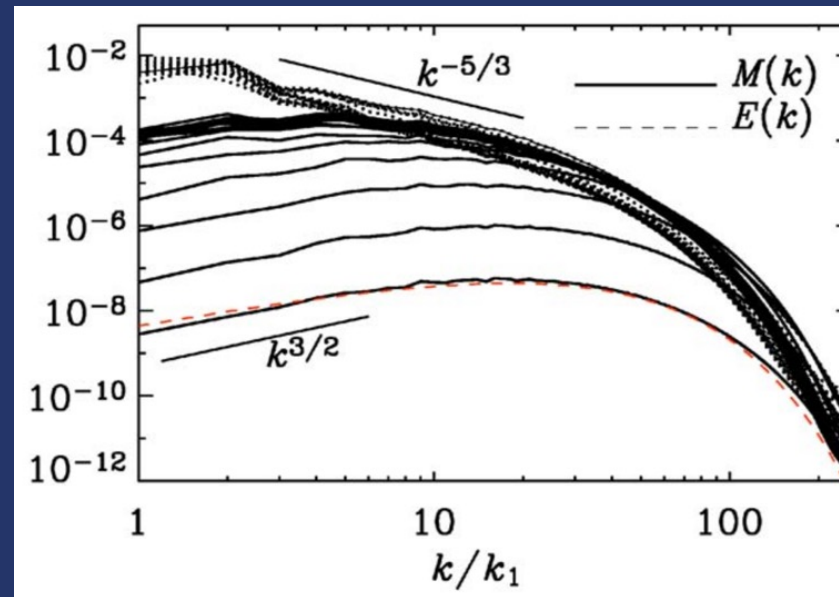


The growth rate scales with the Reynolds number Re as $\gamma \propto Re^{1/2}$ [Kazantsev 1968].

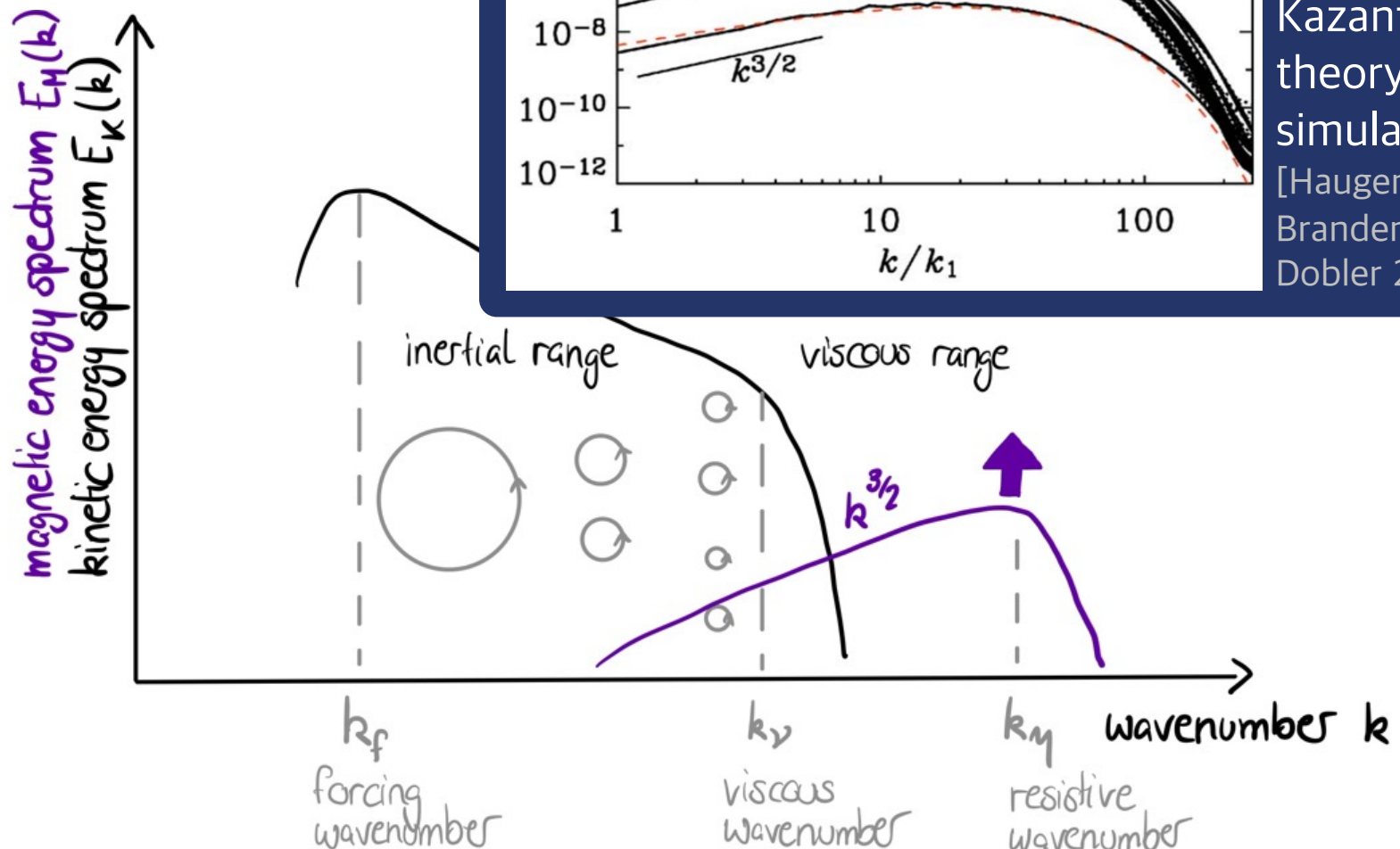
Length scale: determined by resistive effects



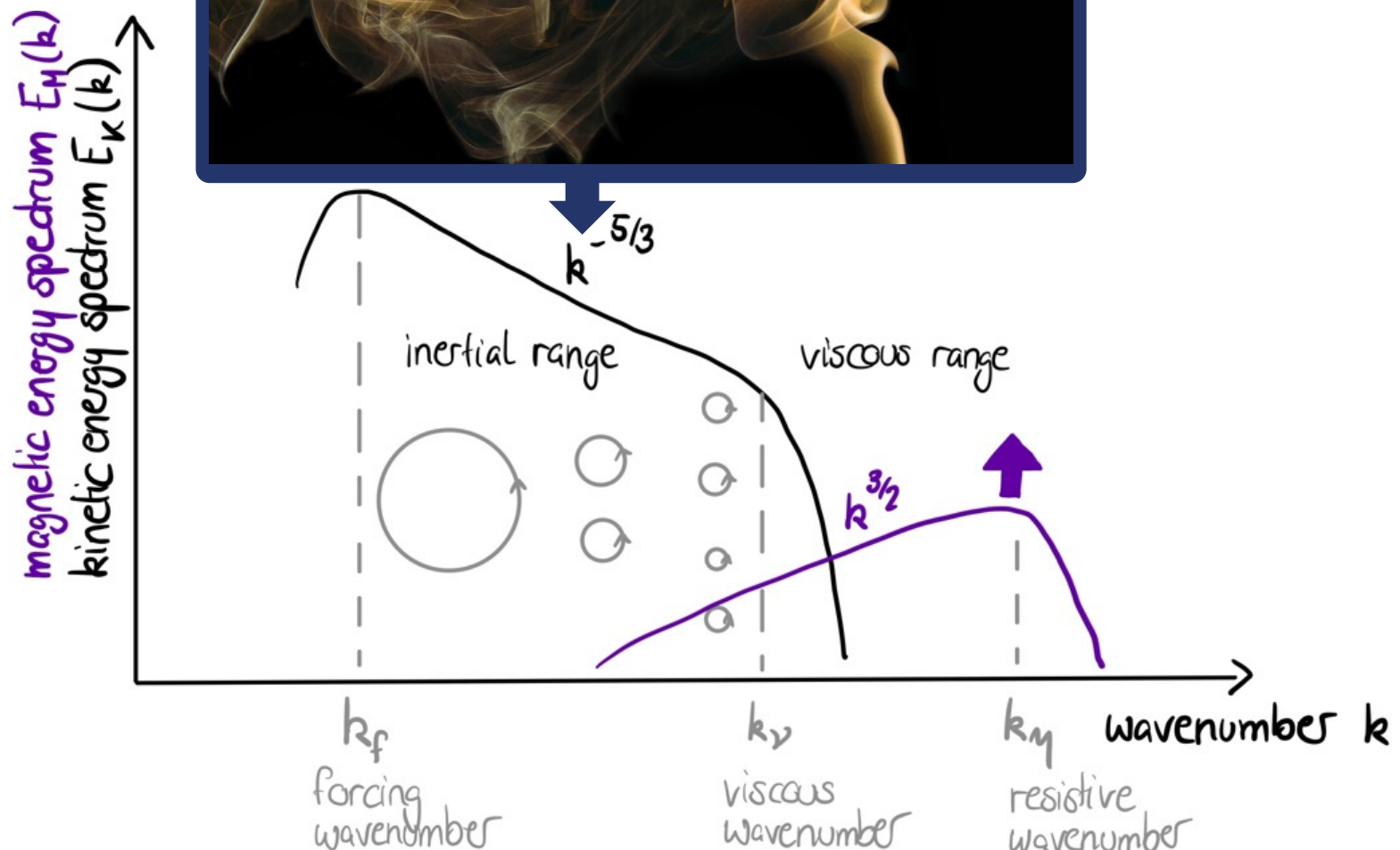
Numerical simulations of forced turbulence



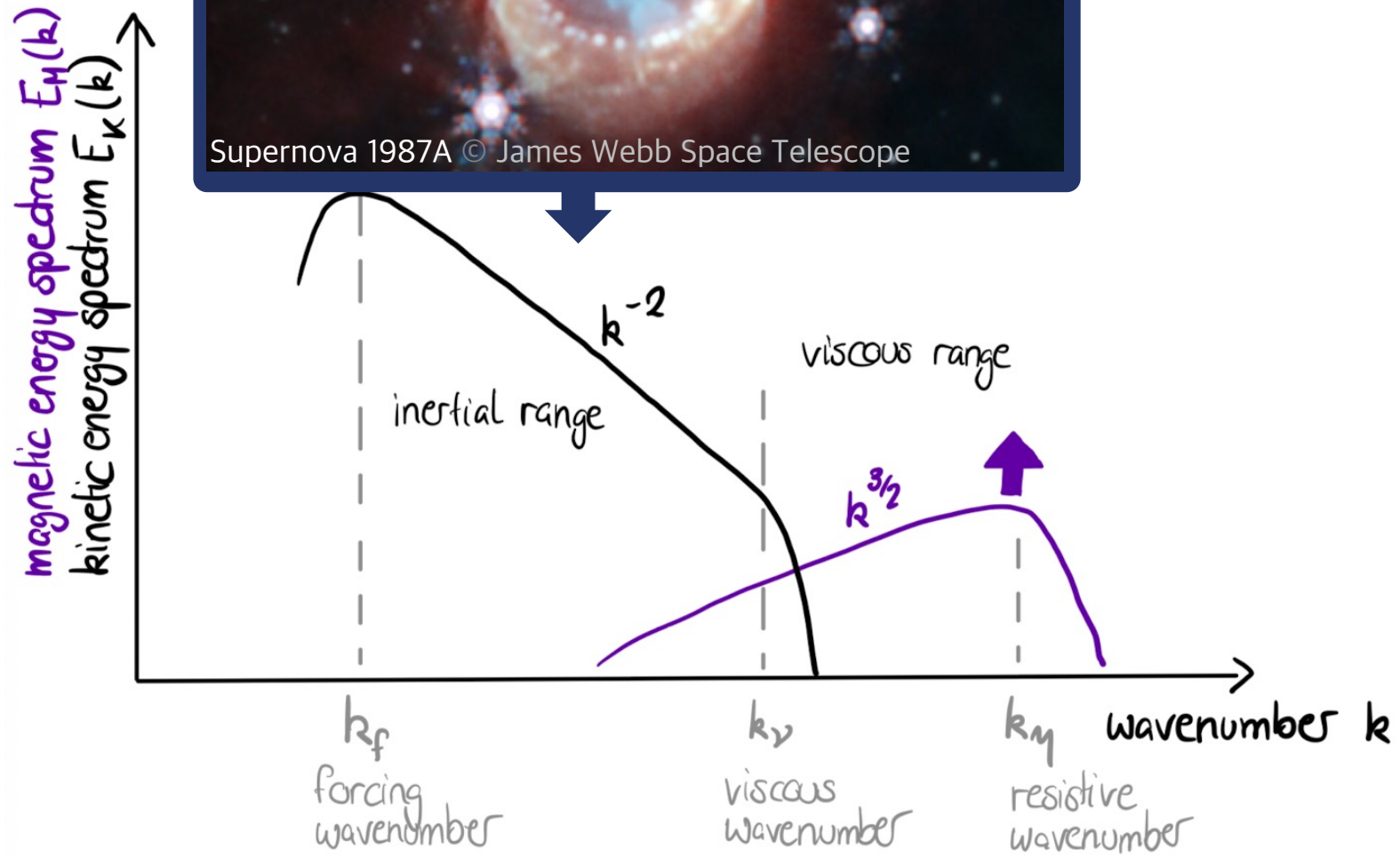
Agreement between Kazantsev theory and simulations [Haugen, Brandenburg, Dobler 2004]



Incompressible turbulence (Kolmogorov)

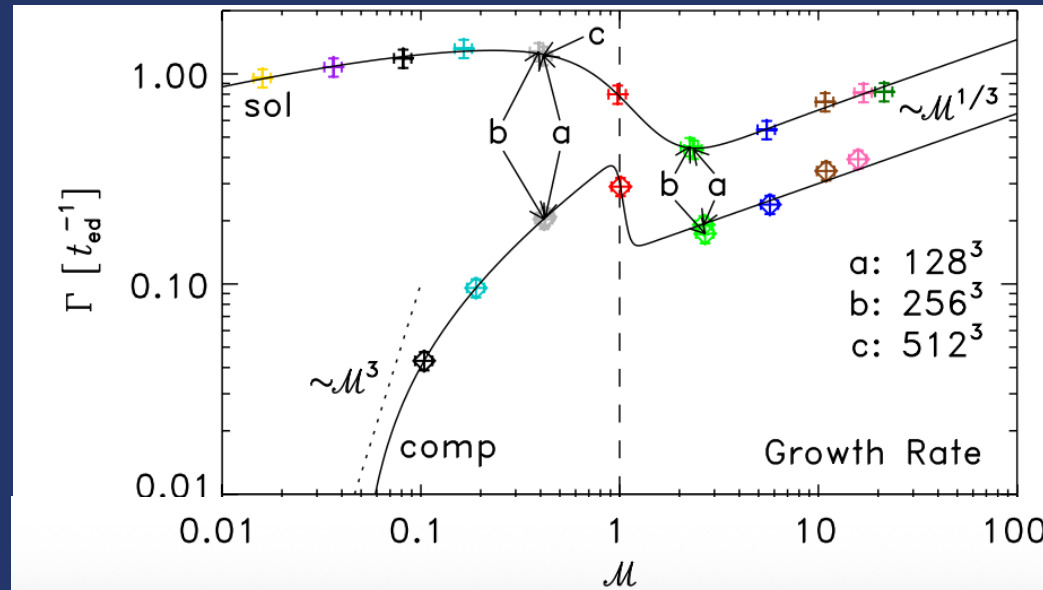


Compressible turbulence (Burgers)



From incompressible ($E_K \propto k^{-5/3}$) to compressible ($E_K \propto k^{-2}$) turbulence

magnetic energy spectrum $E_H(k)$
kinetic energy spectrum $E_K(k)$



Lower dynamo growth rates in compressible turbulence

[Federrath et al. 2011]

inertial range

$k^{3/2}$

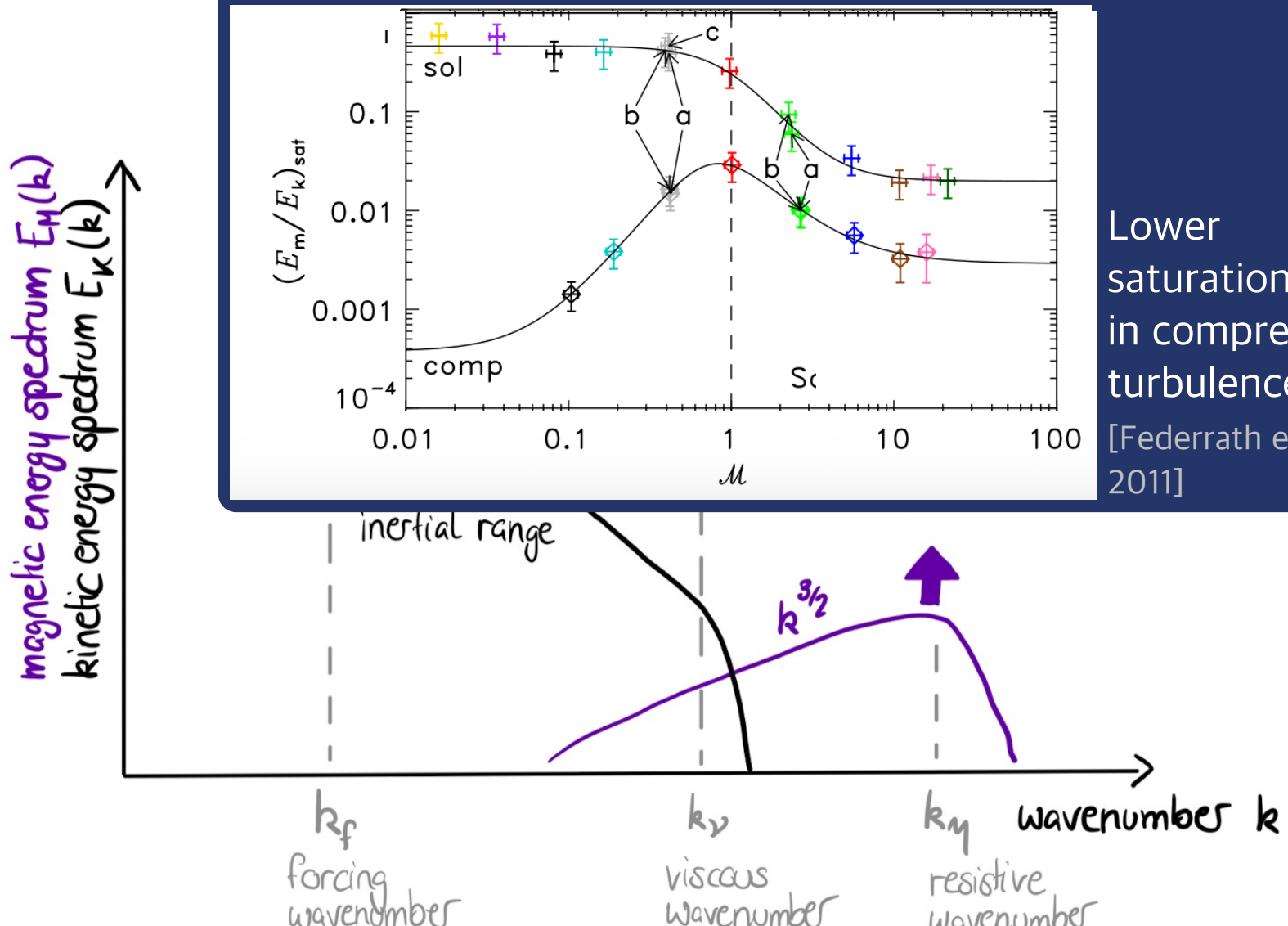
k_f
forcing wavenumber

k_v
viscous wavenumber

k_η
resistive wavenumber

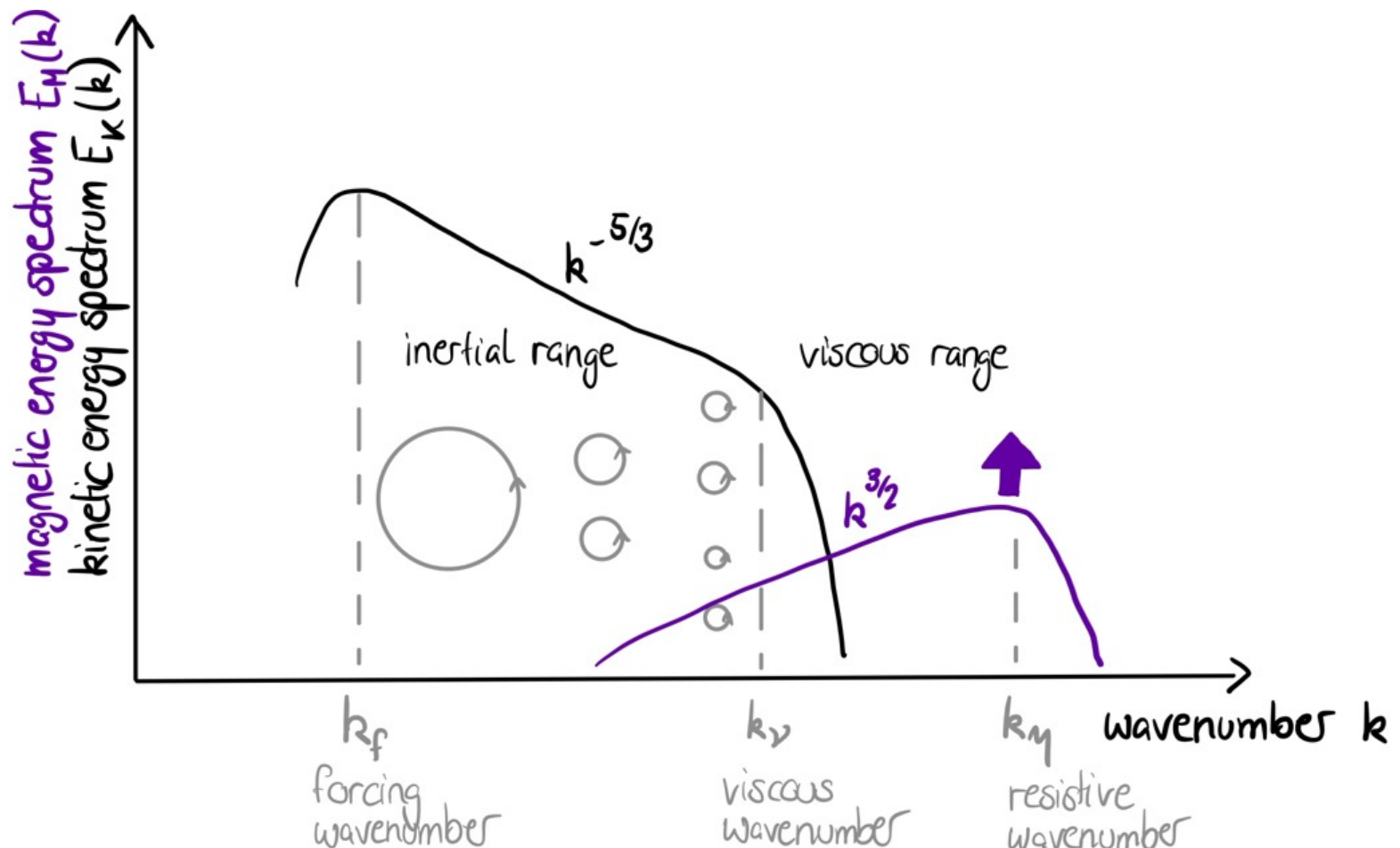
wavenumber k

From incompressible ($E_K \propto k^{-5/3}$) to
compressible ($E_K \propto k^{-2}$) turbulence

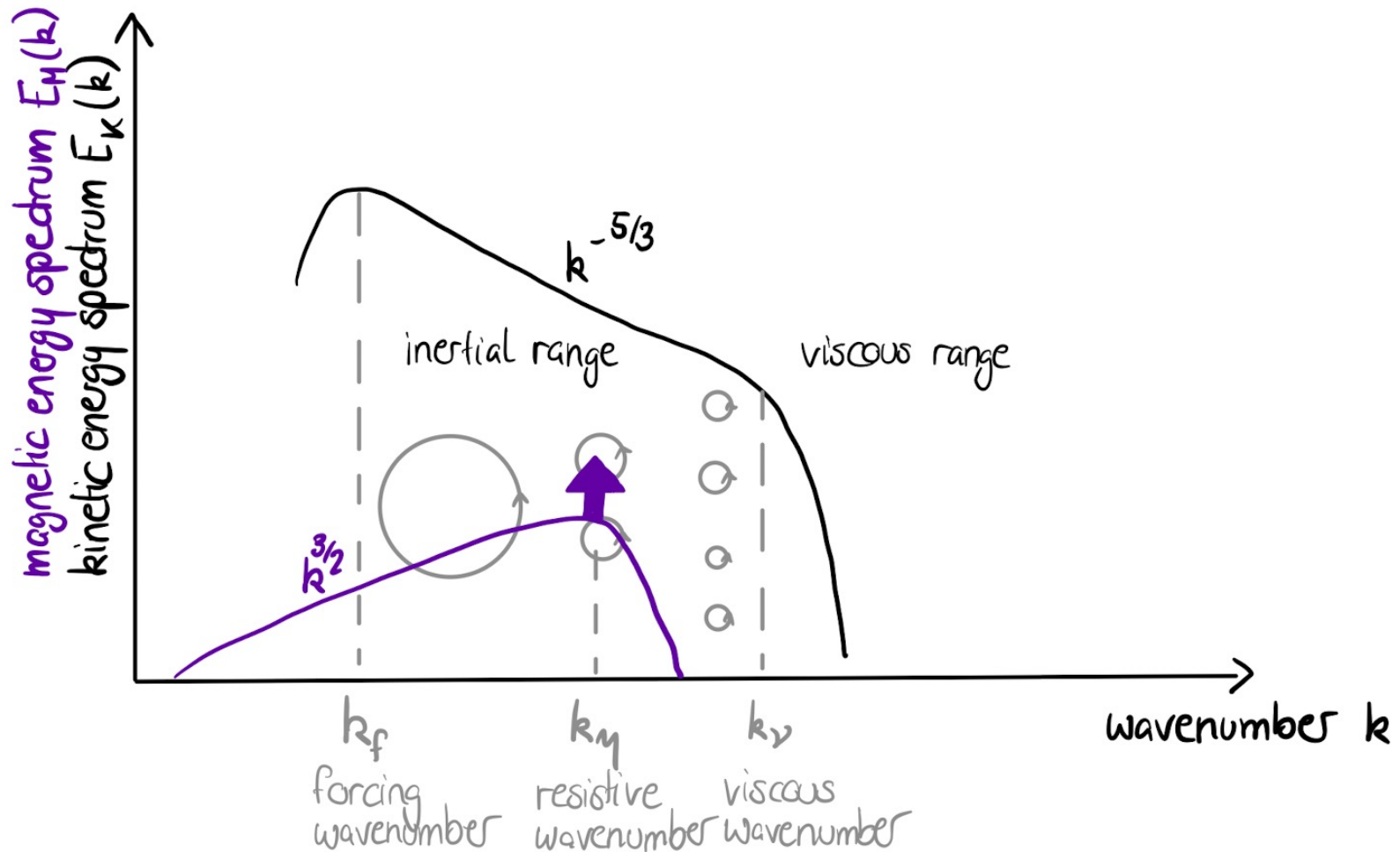


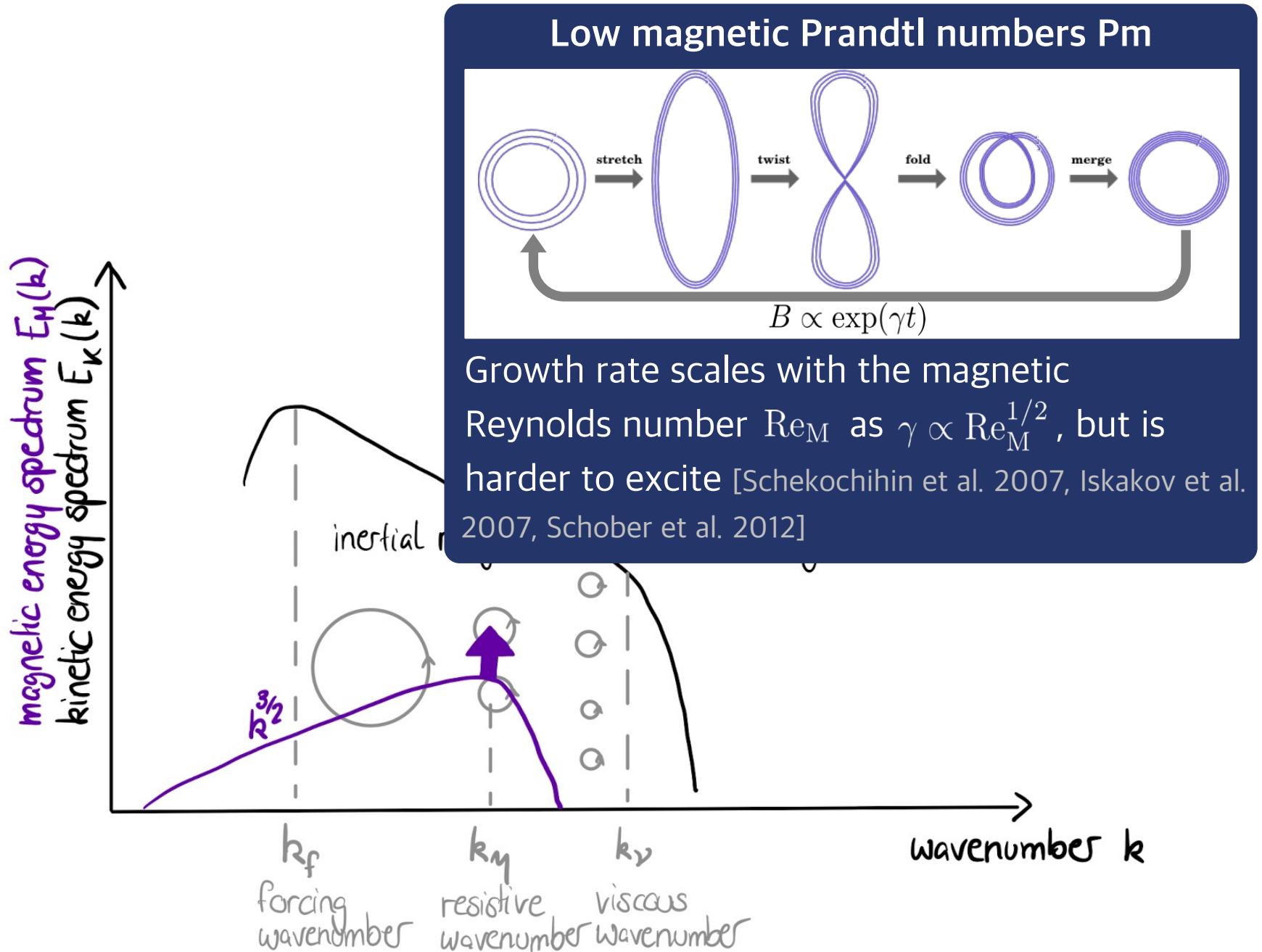
Lower
saturation levels
in compressible
turbulence
[Federrath et al.
2011]

High magnetic Prandtl numbers P_m



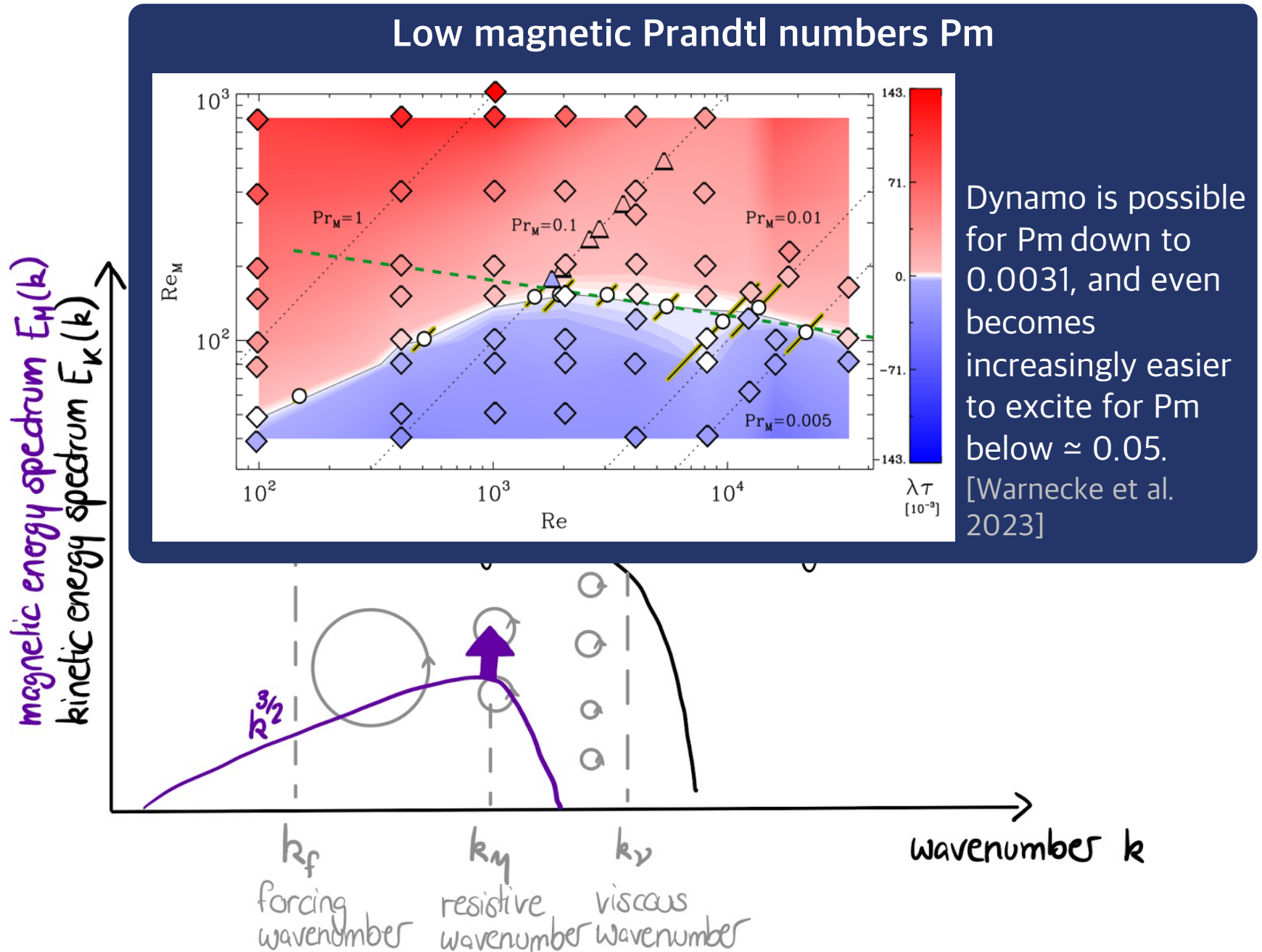
Low magnetic Prandtl numbers P_m





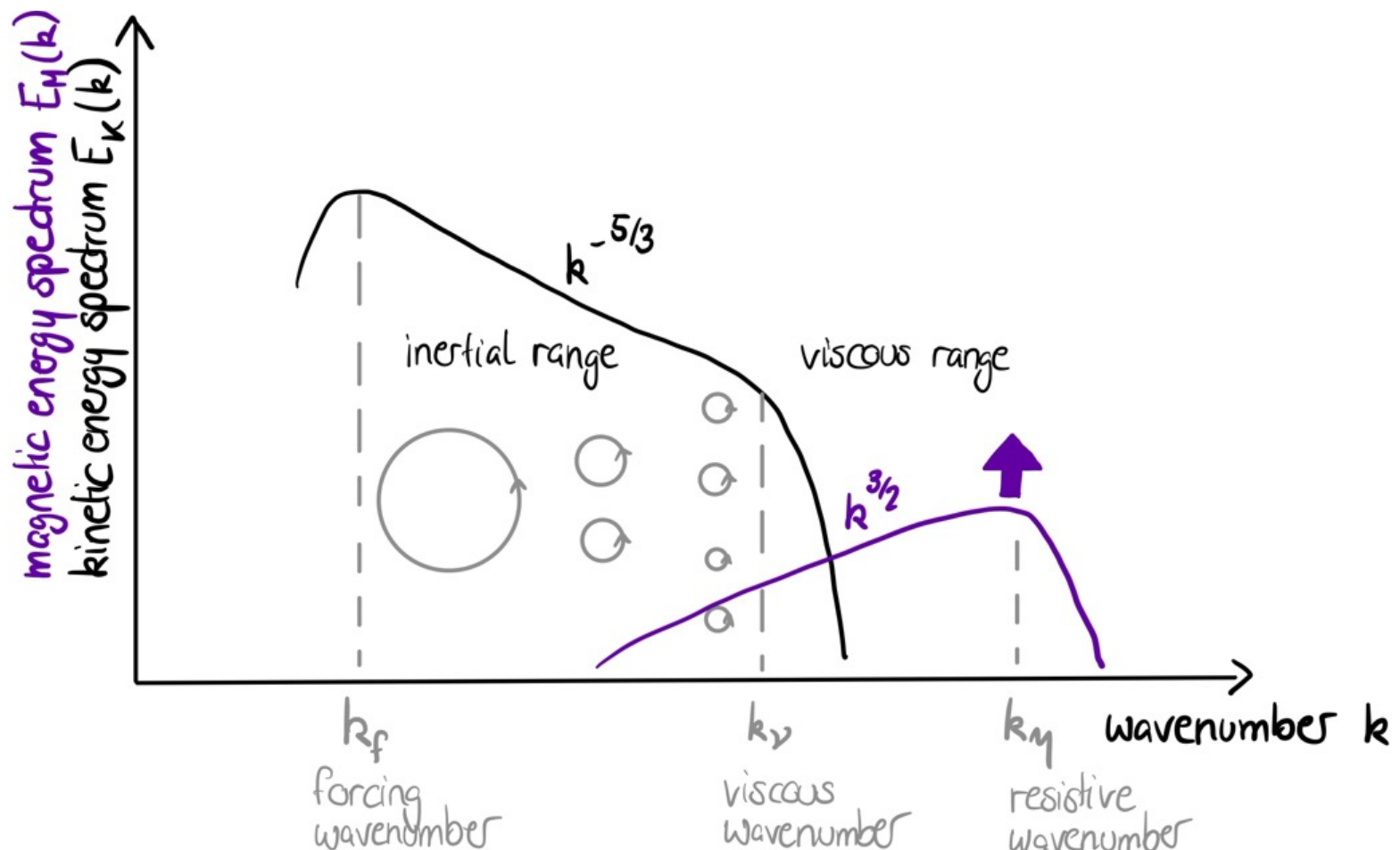
Small-scale dynamos

Nordita program
25/05/2026

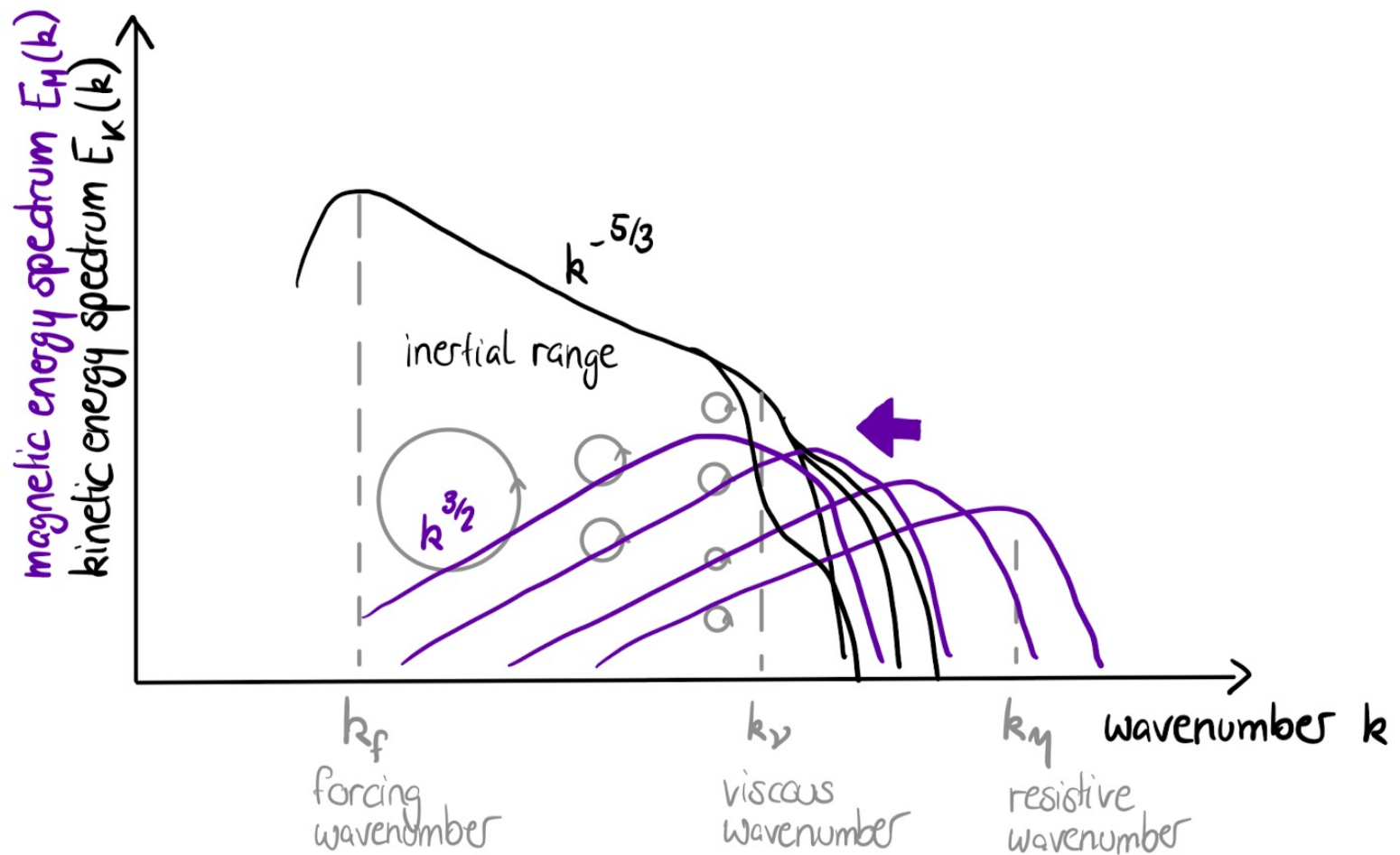


Small-scale dynamos

Nordita program
25/05/2026



Nonlinear small-scale dynamo

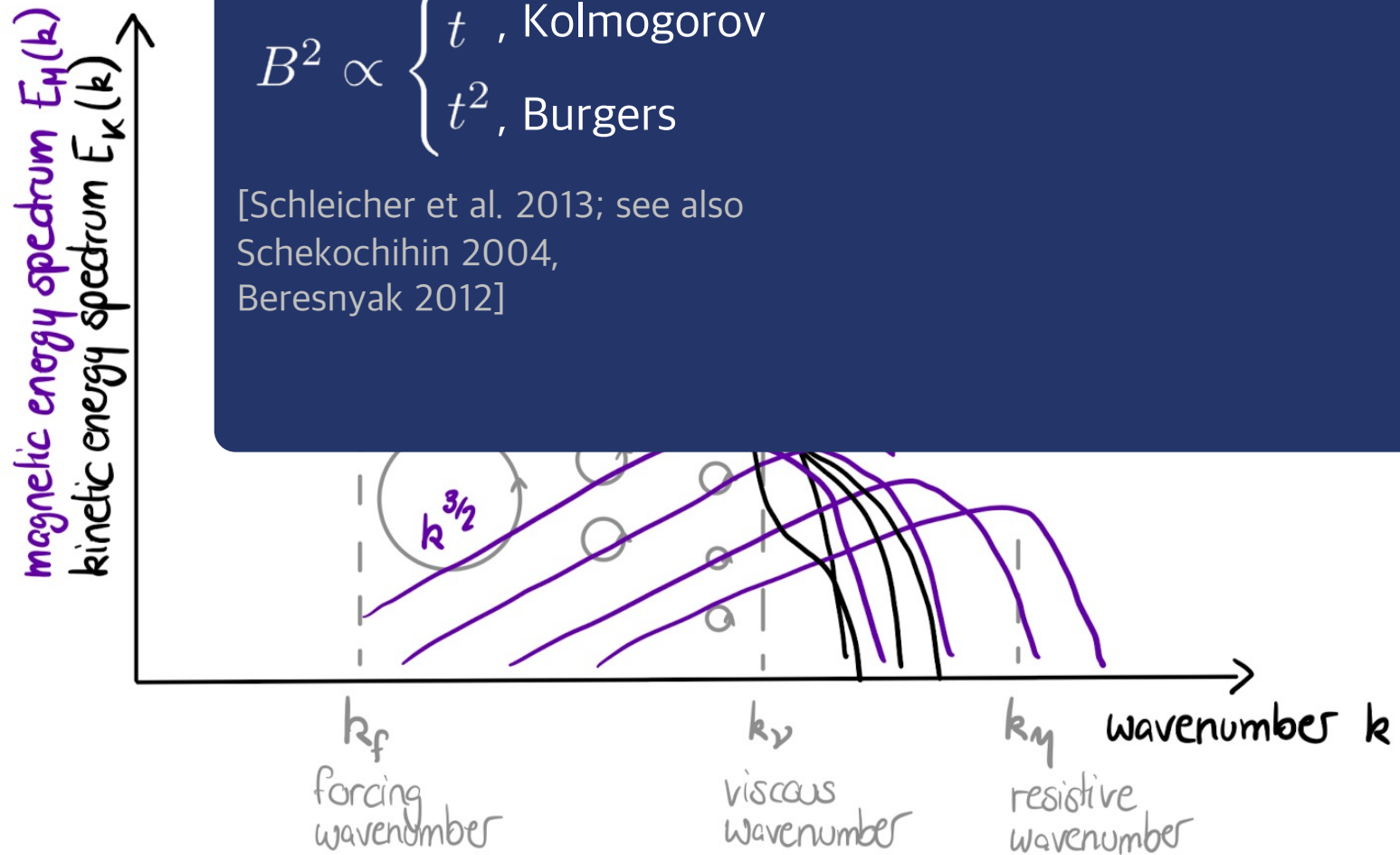


Nonlinear small-scale dynamo

Shift of magnetic energy
from small to large
spatial scales with

$$B^2 \propto \begin{cases} t, & \text{Kolmogorov} \\ t^2, & \text{Burgers} \end{cases}$$

[Schleicher et al. 2013; see also
Schekochihin 2004,
Beresnyak 2012]



Nonlinear small-scale dynamo

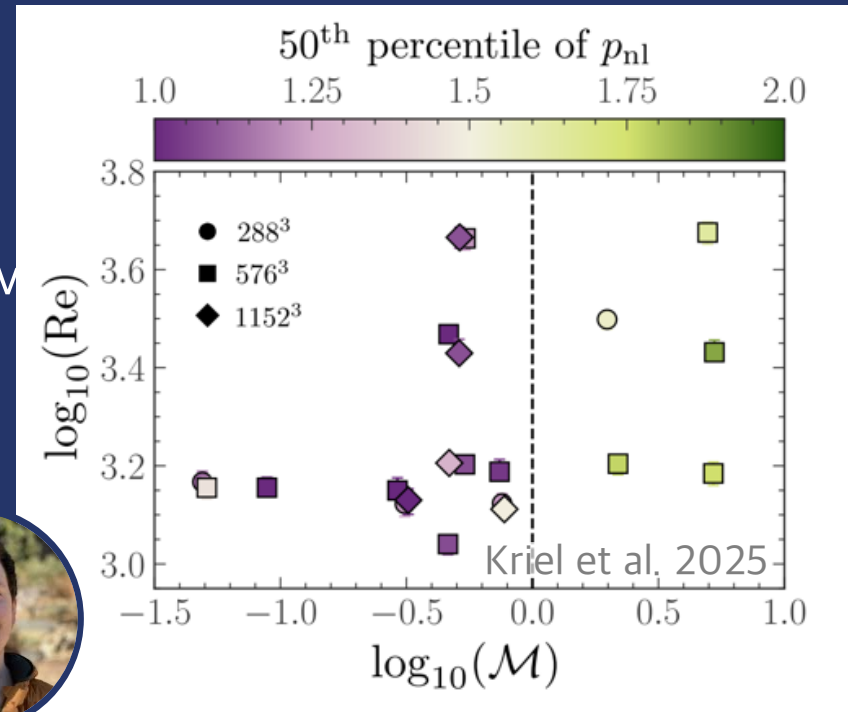
Shift of magnetic energy from small to large spatial scales with

$$B^2 \propto \begin{cases} t, & \text{Kolmogorov} \\ t^2, & \text{Burgers} \end{cases}$$

[Schleicher et al. 2013; see also Schekochihin 2004, Beresnyak 2012]



Neco Kriel

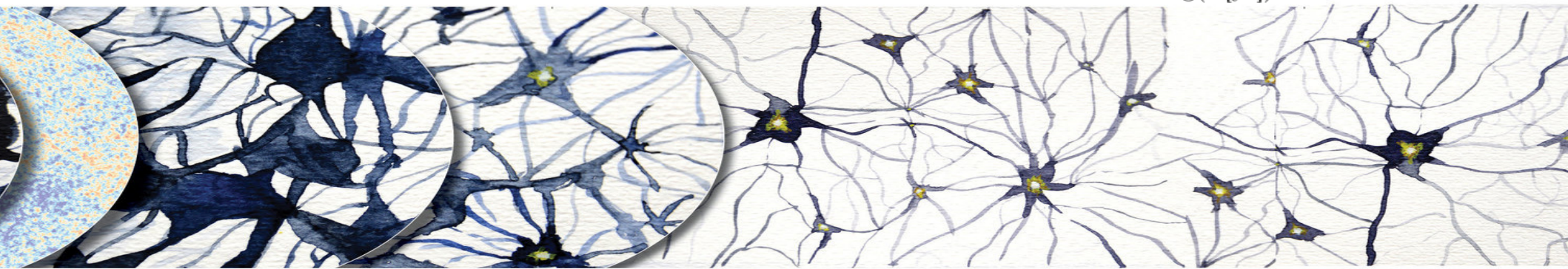
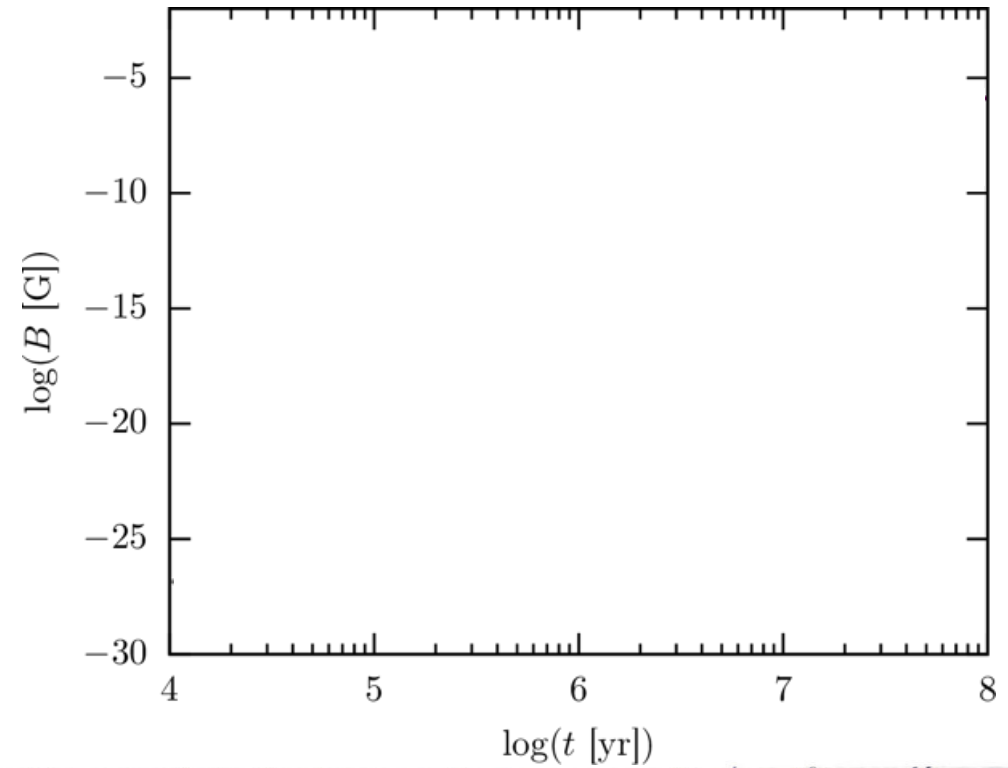


magnetic energy spectrum $E_M(k)$
kinetic energy spectrum $E_K(k)$



Dynamos during galaxy formation

Nordita program
25/05/2026



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

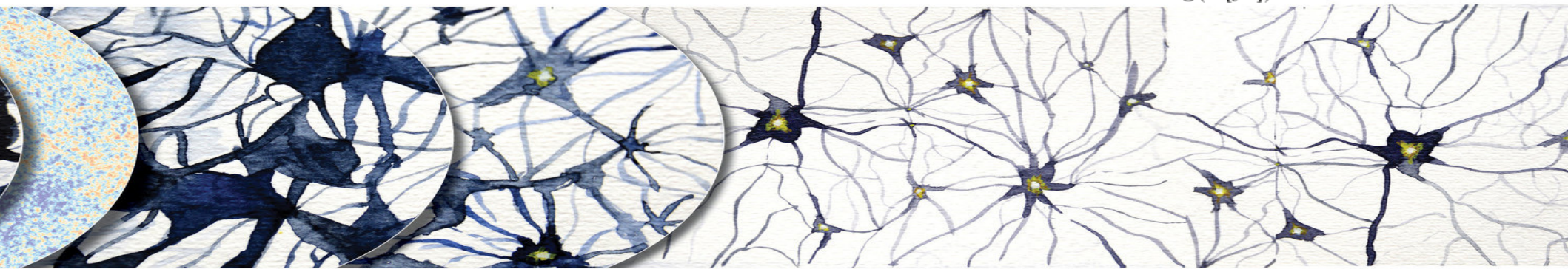
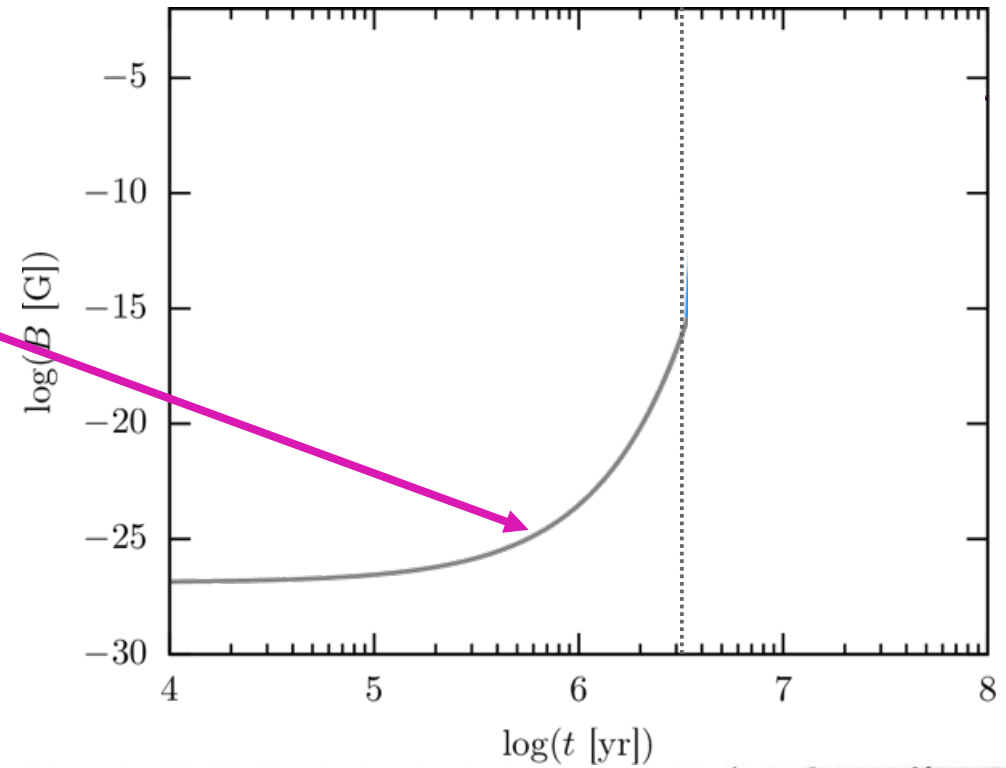
Dynamos during galaxy formation

Nordita program
25/05/2026

Kinematic phase

$$B \propto \exp(\gamma t)$$

[using a model for turbulence to estimate growth rate]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Dynamamos during galaxy formation

Nordita program
25/05/2026

Kinematic phase

$$B \propto \exp(\gamma t)$$

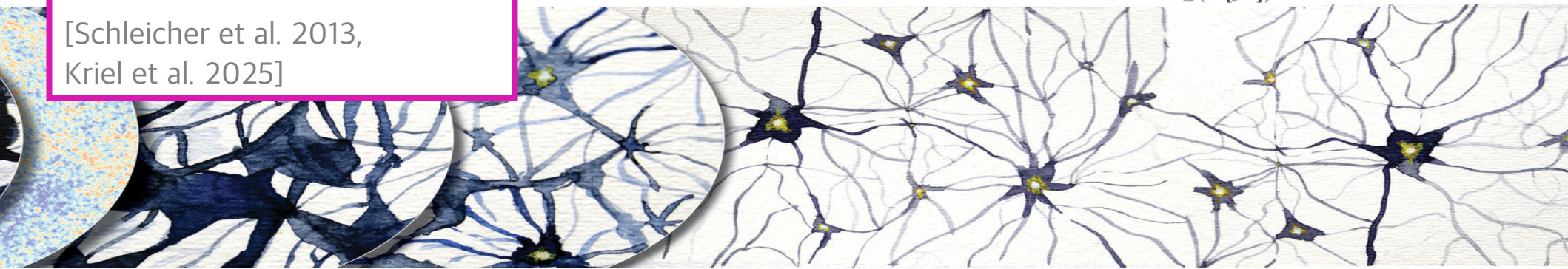
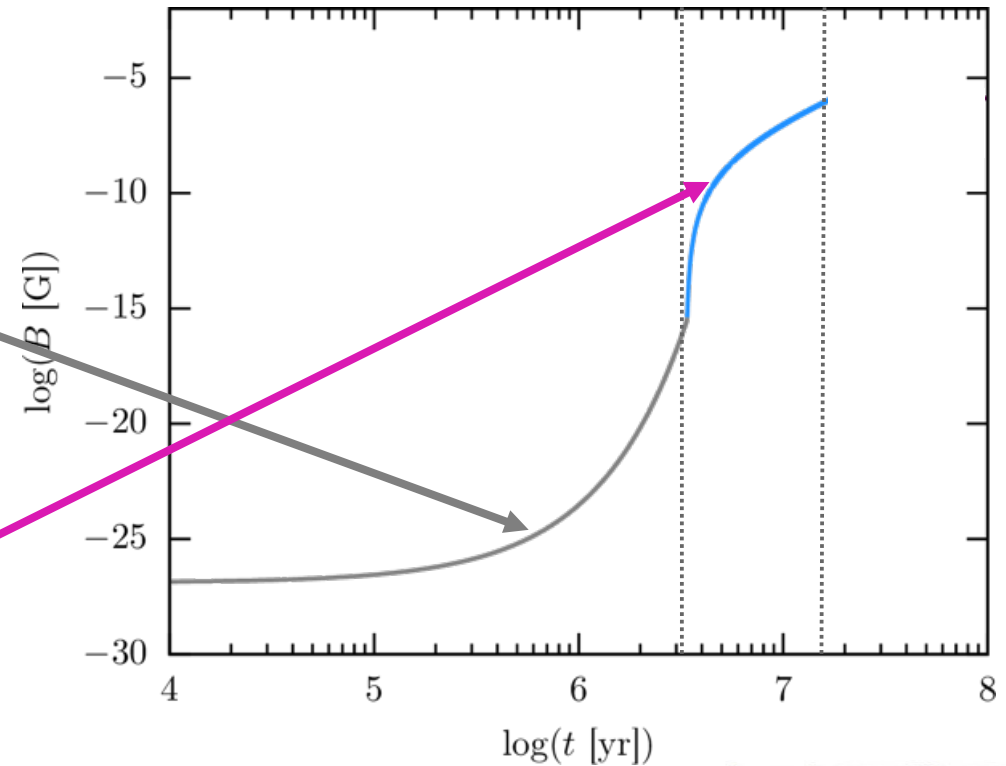
[using a model for turbulence to estimate growth rate]

Non-linear phase

→ shift of magnetic energy from small to large spatial scales with

$$B(t) \propto t$$

[Schleicher et al. 2013,
Kriel et al. 2025]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Dynamamos during galaxy formation

Nordita program
25/05/2026

Kinematic phase

$$B \propto \exp(\gamma t)$$

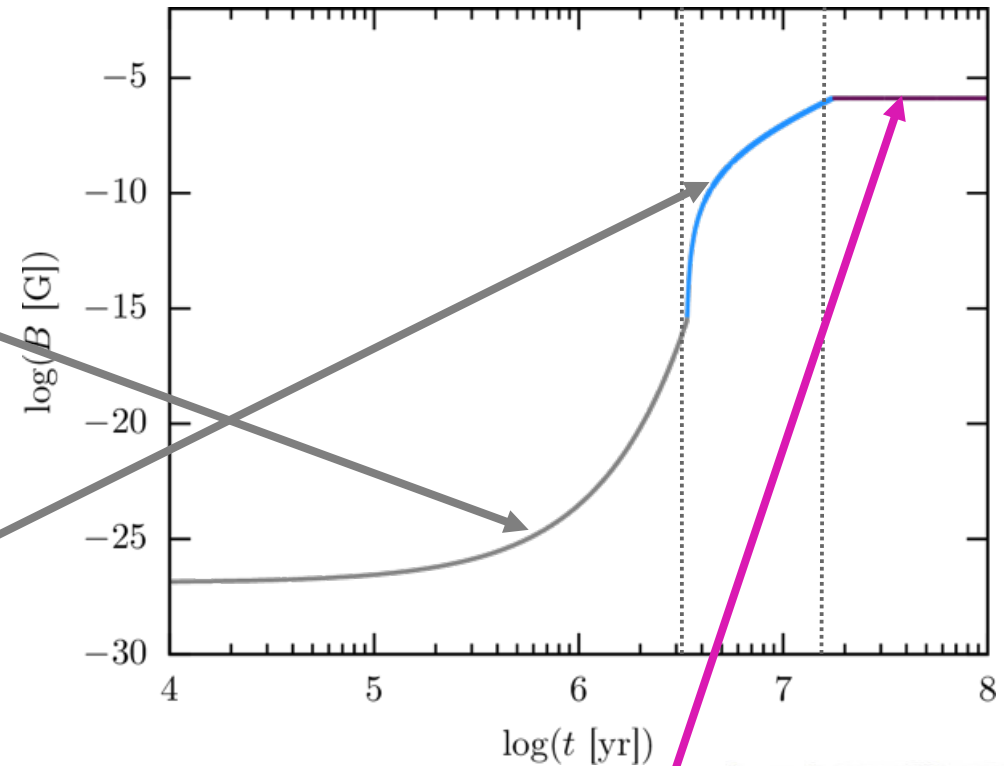
[using a model for turbulence to estimate growth rate]

Non-linear phase

→ shift of magnetic energy from small to large spatial scales with

$$B(t) \propto t$$

[Schleicher et al. 2013,
Kriel et al. 2025]



Saturation

→ no further growth due to strong Lorentz force on turbulent eddies once

$$E_{\text{mag,sat}} \approx 0.01 - 0.4 E_{\text{kin}}$$

[Federrath et al. 2014, Schober et al. 2015]

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 yr

🌡️ 30 K

↗️ 3×10^9 ly

🌡️ 3 K

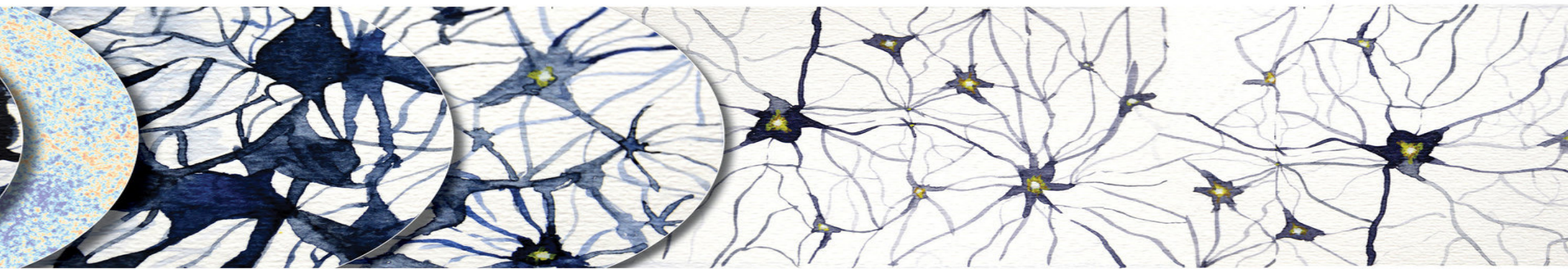
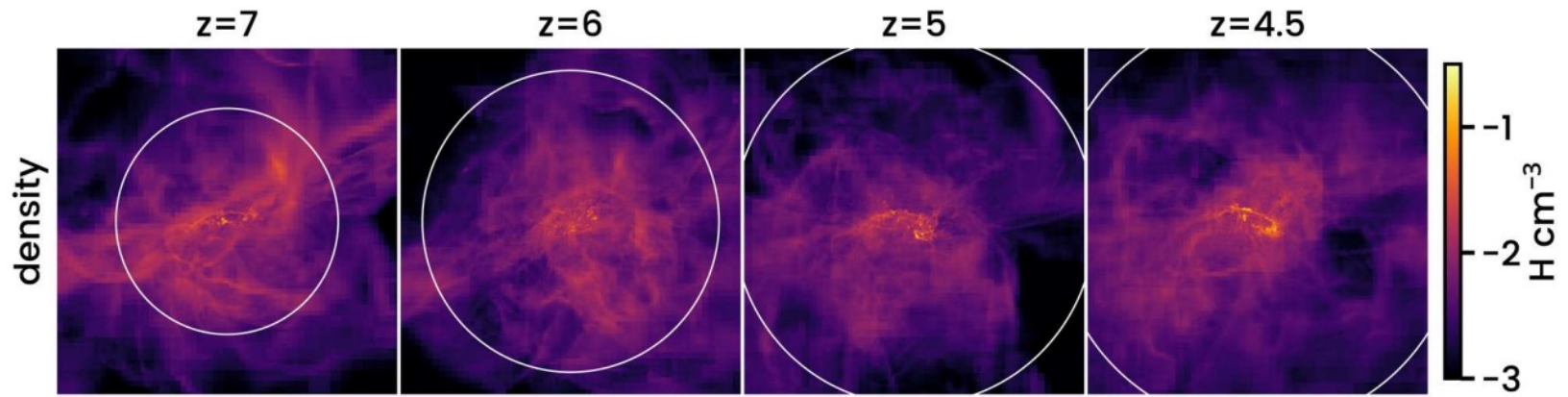
↗️ 5×10^{10} ly

Dynamamos during galaxy formation

Nordita program
25/05/2026

The small-scale dynamo in non-cosmological simulations of isolated haloes.

[Rieder & Teyssier 2016]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

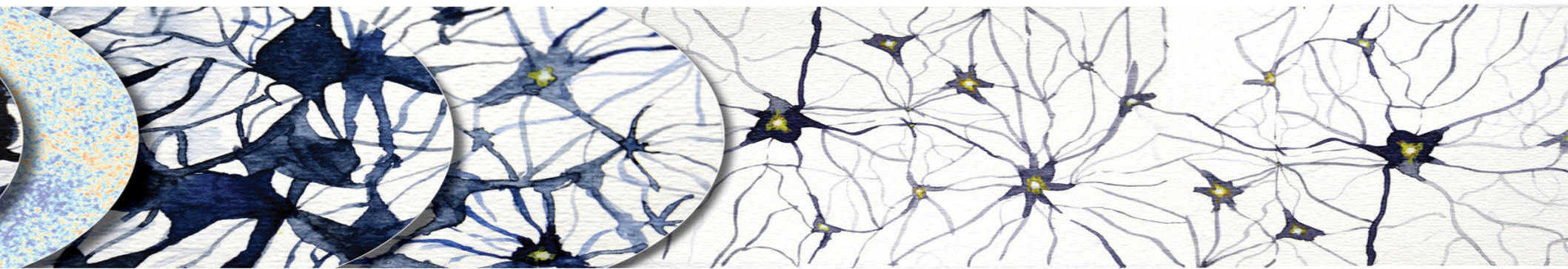
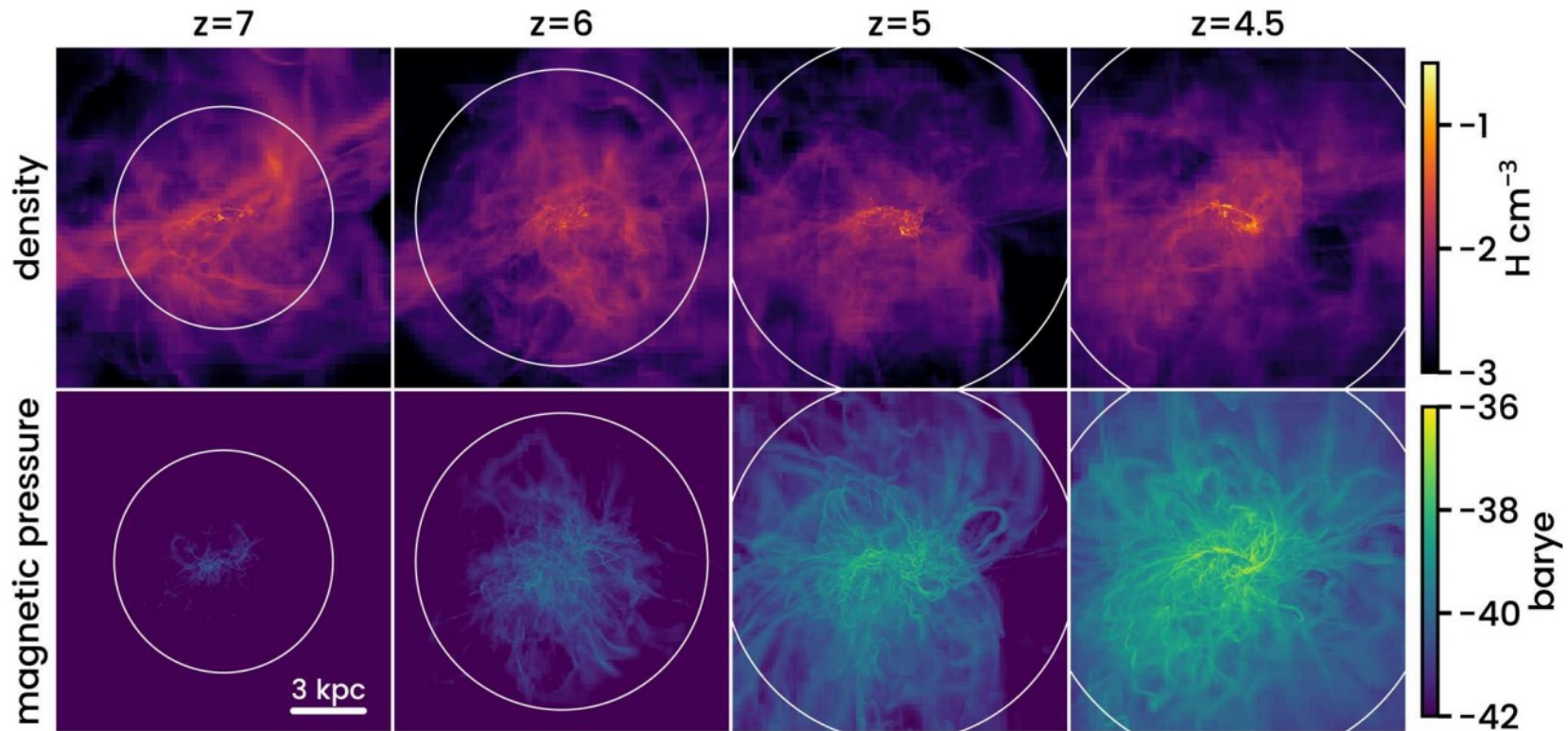
↗️ 5×10^{10} ly

Dynamamos during galaxy formation

Nordita program
25/05/2026

The small-scale dynamo in non-cosmological simulations of isolated haloes.

[Riederer & Teyssier 2016]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

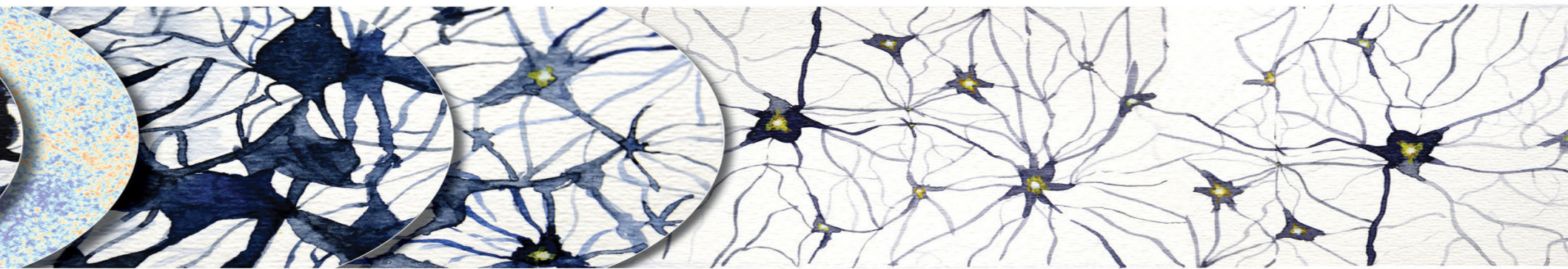
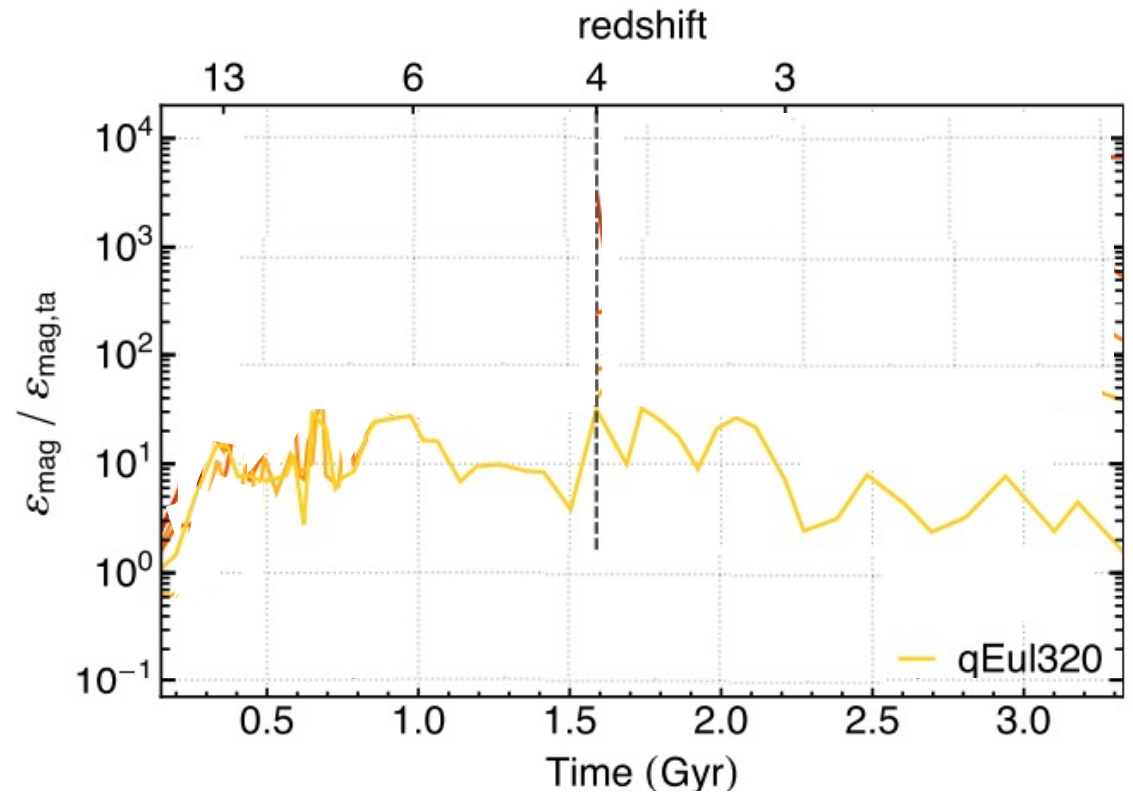
Dynamos during galaxy formation

Nordita program
25/05/2026

The small-scale dynamo can now also be seen in cosmological boxes.

[Pakmor et al. 2017,
Rieder & Teyssier 2017b,
Martin-Alvarez et al. 2018]

low resolution
[Martin-Alvarez
et al. 2022]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

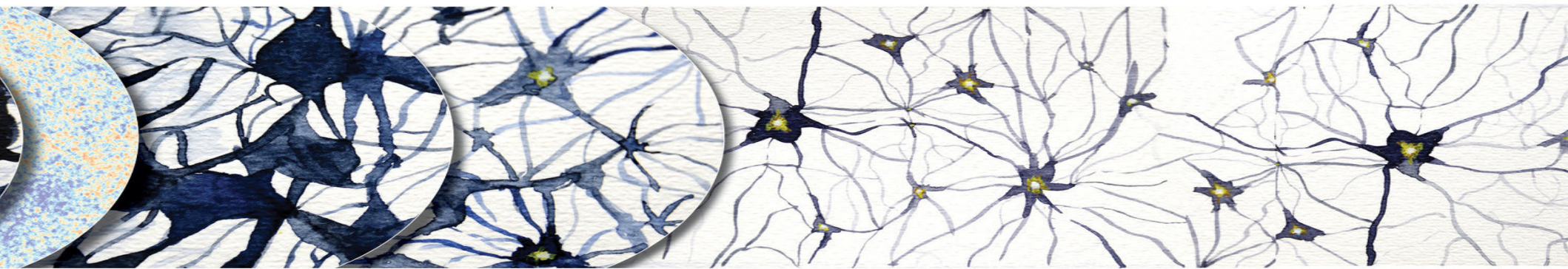
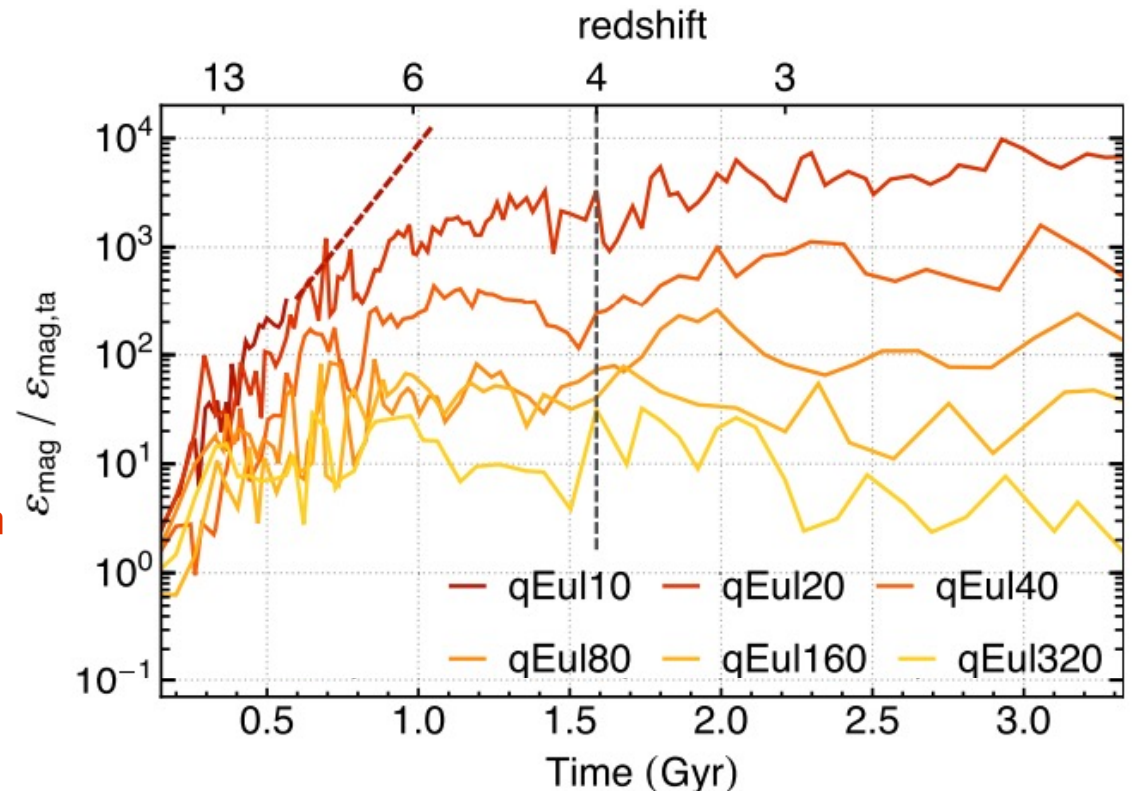
Dynamamos during galaxy formation

Nordita program
25/05/2026

The small-scale dynamo can now also be seen in cosmological boxes.

[Pakmor et al. 2017,
Rieder & Teyssier 2017b,
Martin-Alvarez et al. 2018]

high resolution
low resolution
[Martin-Alvarez
et al. 2022]



🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

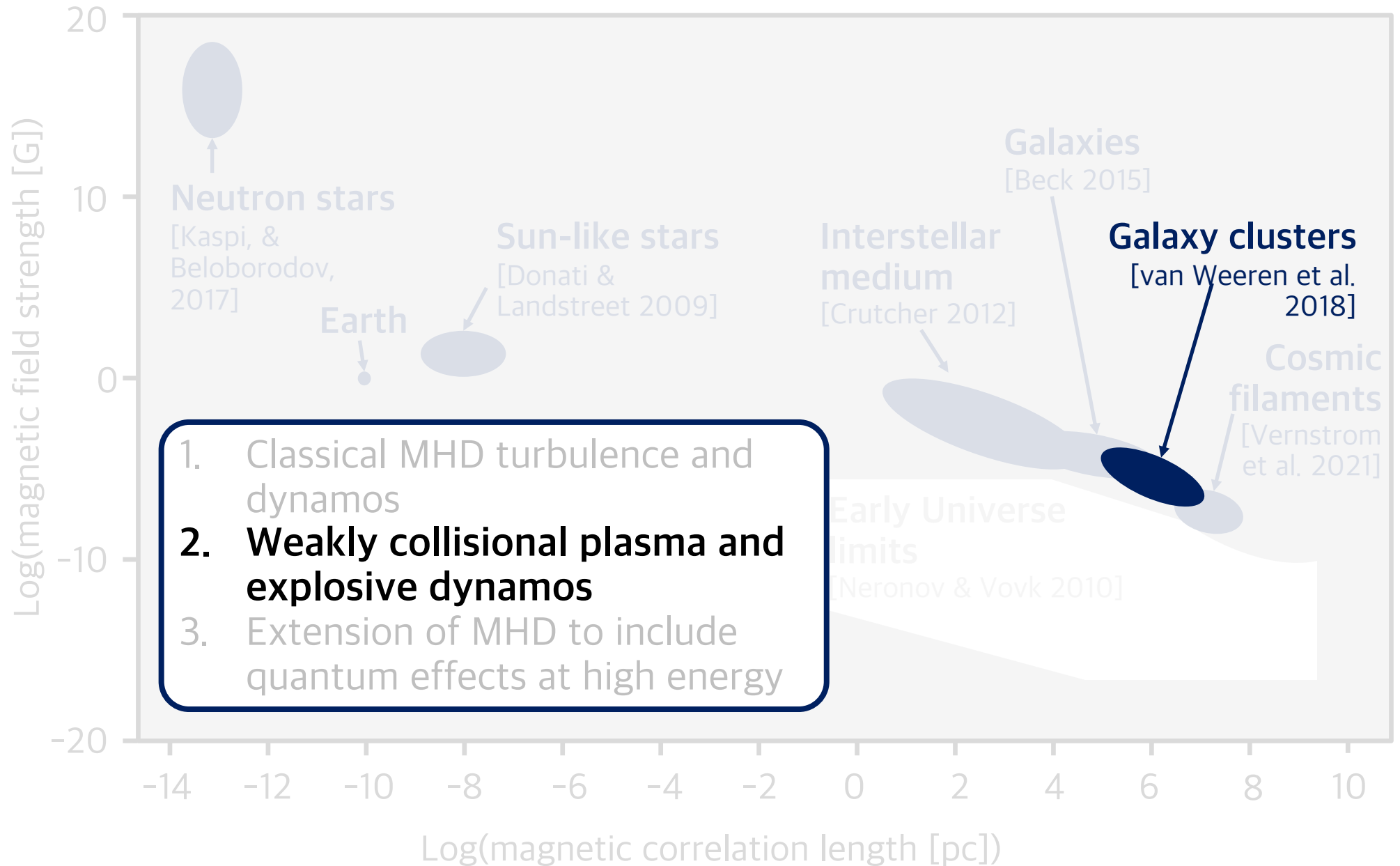
🌡️ 3 K

↗️ 5×10^{10} ly

- How does the small-scale dynamo operate in the collisionless regime?
We observe strong magnetic fields in the intracluster medium...
- What is the connection between the small-scale dynamo and reconnection? A small amount of reconnection is needed for closing the dynamo loop...
- How to design suitable subgrid models of the small-scale dynamo for astrophysical/cosmological simulations? The true nature of the dynamo can never be modeled due to limited scale separation...
- ...

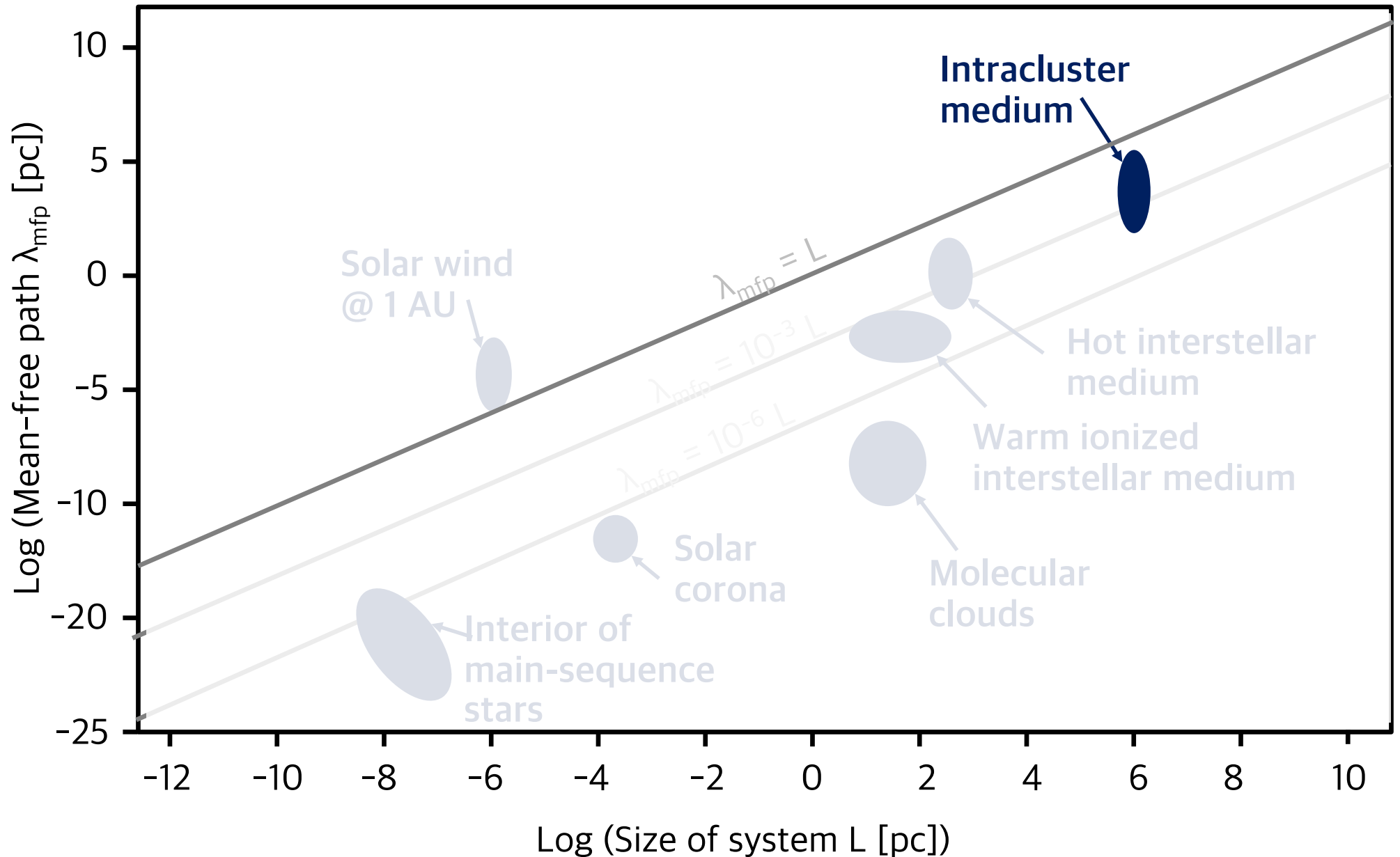
Overview of this talk

Nordita program
25/05/2026



Plasma Universe: collisionality

Nordita program
25/05/2026



Galaxy clusters lack collisions

Nordita program
25/05/2026

Schekochihin & Cowley (2006)



© X-ray: NASA/CXC/U.Waterloo/C.Kirkpatrick et al.;

Radio: NSF/NRAO/VLA;

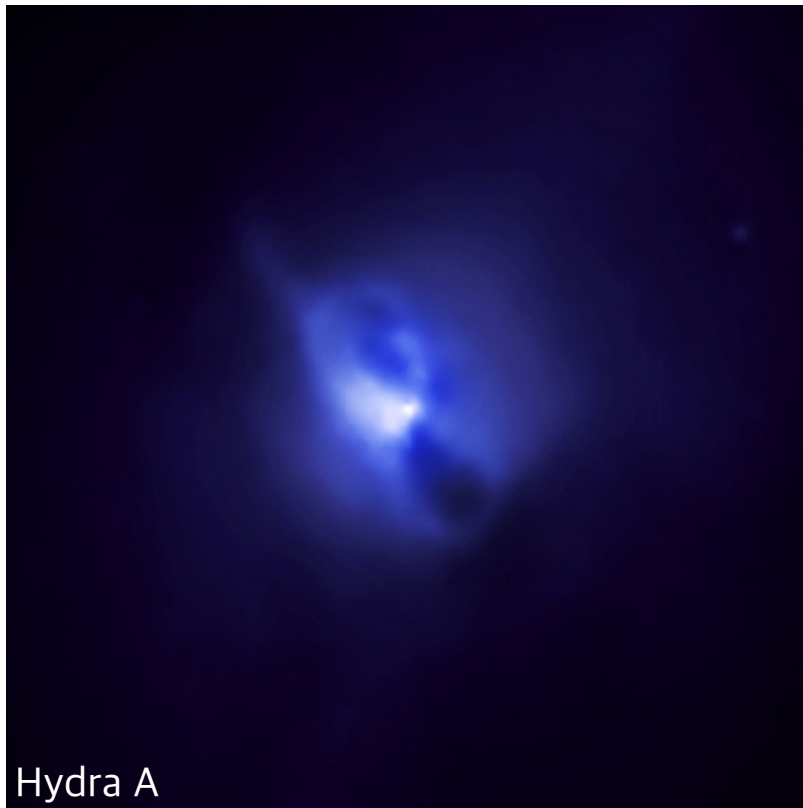
Optical: Canada-France-Hawaii-Telescope/DSS

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

Galaxy clusters lack collisions

Nordita program
25/05/2026

Schekochihin & Cowley (2006)



© X-ray: NASA/CXC/U. Waterloo/C. Kirkpatrick et al.;

Radio: NSF/NRAO/VLA;

Optical: Canada-France-Hawaii-Telescope/DSS

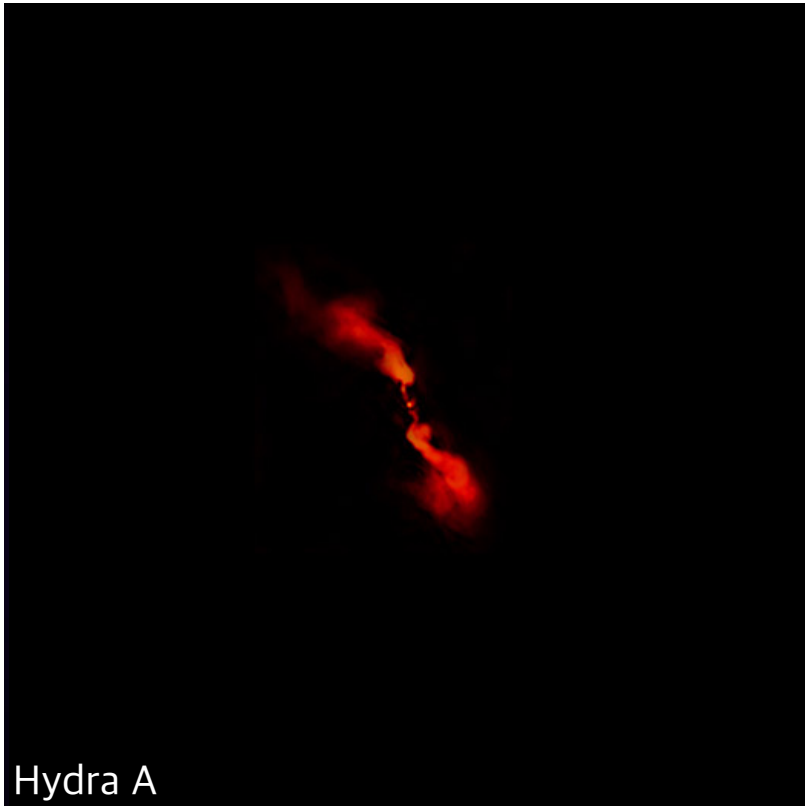
Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}



Galaxy clusters lack collisions

Nordita program
25/05/2026

Schekochihin & Cowley (2006)



© X-ray: NASA/CXC/U. Waterloo/C. Kirkpatrick et al.;

Radio: NSF/NRAO/VLA;

Optical: Canada-France-Hawaii-Telescope/DSS

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}



Galaxy clusters lack collisions

Nordita program
25/05/2026



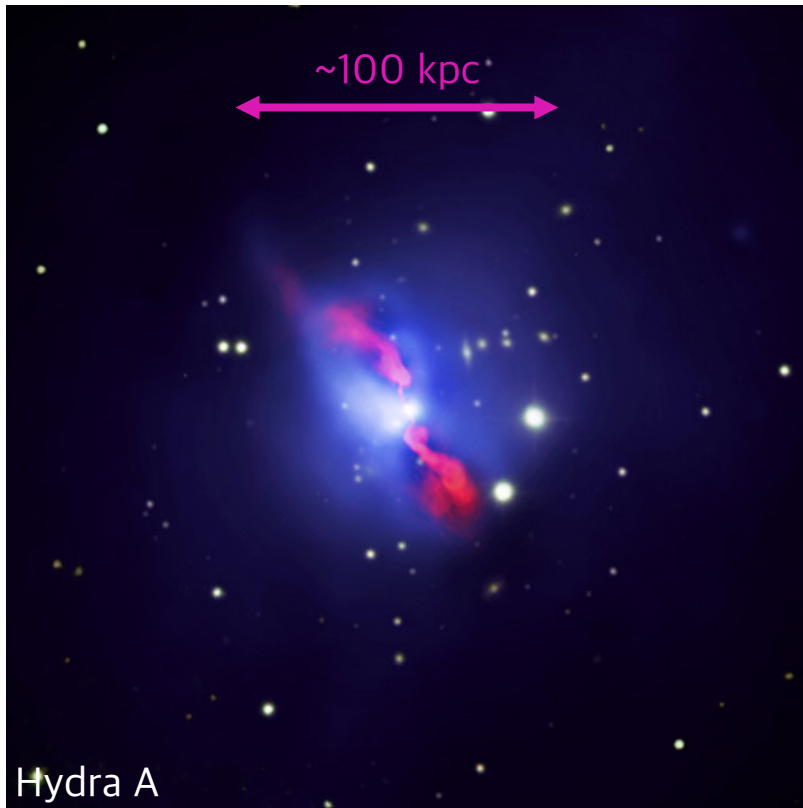
© X-ray: NASA/CXC/U.Waterloo/C.Kirkpatrick et al.;
Radio: NSF/NRAO/VLA;
Optical: Canada-France-Hawaii-Telescope/DSS

Schekochihin & Cowley (2006)

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

Galaxy clusters lack collisions

Nordita program
25/05/2026



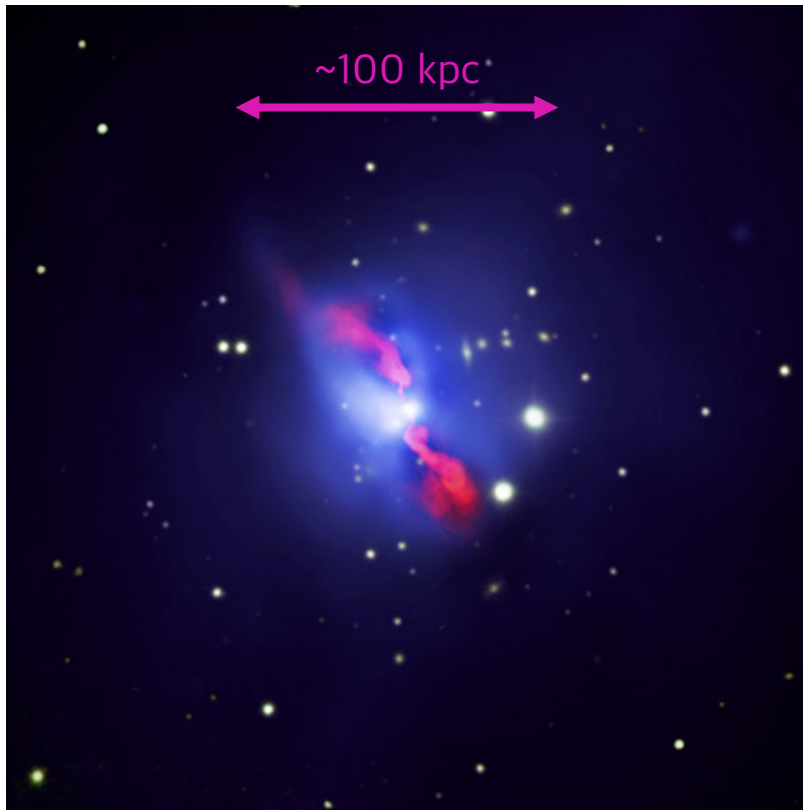
Schekochihin & Cowley (2006)

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
$\mu_{ }$	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	$UL/\mu_{ }$	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

The intracluster medium plasma is only **weakly collisional.**

Galaxy clusters lack collisions

Nordita program
25/05/2026



Schekochihin & Cowley (2006)

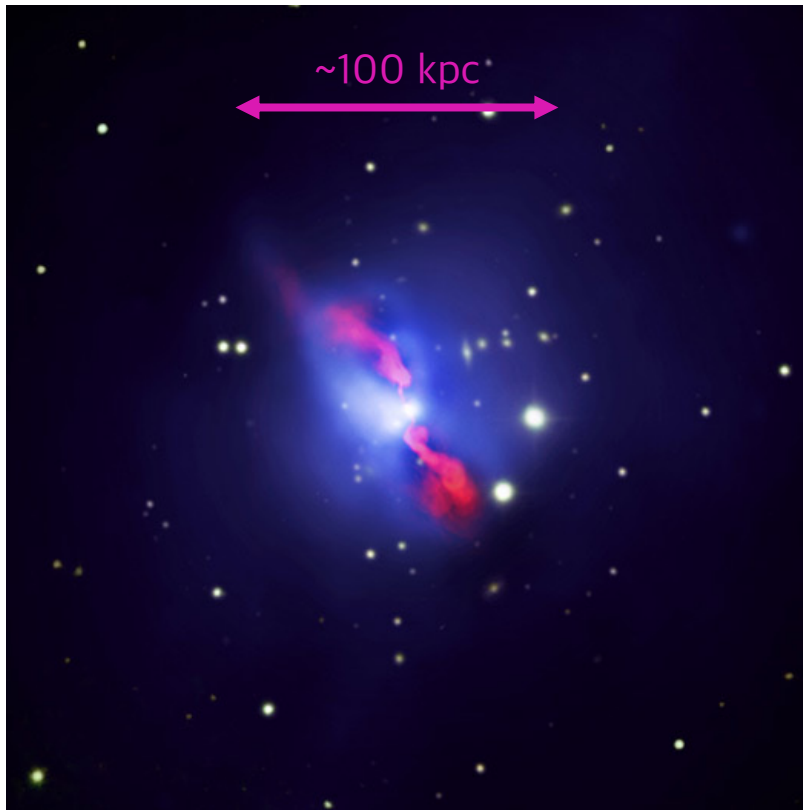
Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

The intracluster medium plasma is only **weakly collisional**.

Therefore, classical MHD cannot (in principle) be used to model the evolution of magnetic fields.

Galaxy clusters lack collisions

Nordita program
25/05/2026



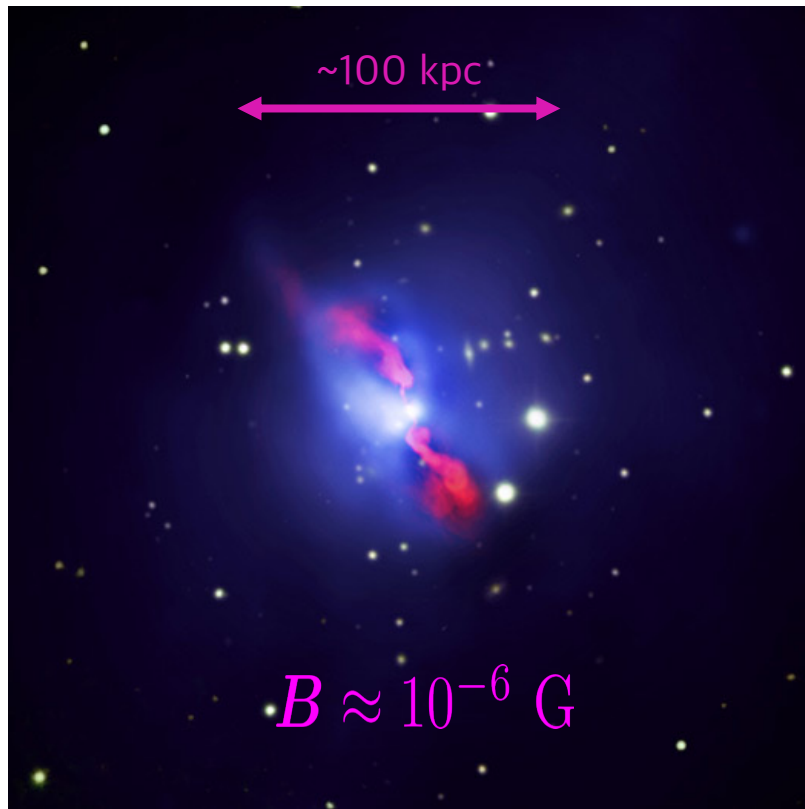
Schekochihin & Cowley (2006)

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	3×10^7 K	10^8 K
n	observed	6×10^{-2} cm ⁻³	10^{-3} cm ⁻³
$v_{th,i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	5×10^{-13} s ⁻¹	2×10^{-15} s ⁻¹
λ_{mfp}	$v_{th,i}/\nu_{ii}$	0.05 kpc	30 kpc
$\mu_{ }$	$v_{th,i} \lambda_{mfp}$	10^{28} cm ² /s	10^{31} cm ² /s
η	$3 \times 10^{13} T^{-3/2b}$	200 cm ² /s	30 cm ² /s
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	4×10^7 yr	7×10^8 yr
Re	$UL/\mu_{ }$	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

The intracluster medium plasma is **not turbulent.**

Galaxy clusters lack collisions

Nordita program
25/05/2026



Therefore, magnetic field amplification via dynamos seems impossible.

Schekochihin & Cowley (2006)

Parameter	Expression	Cool cores ^a	Hot ICM
T	observed	$3 \times 10^7 \text{ K}$	10^8 K
n	observed	$6 \times 10^{-2} \text{ cm}^{-3}$	10^{-3} cm^{-3}
$v_{\text{th},i}$	$(2T/m_i)^{1/2}$	700 km/s	1300 km/s
ν_{ii}	$1.5 n T^{-3/2b}$	$5 \times 10^{-13} \text{ s}^{-1}$	$2 \times 10^{-15} \text{ s}^{-1}$
λ_{mfp}	$v_{\text{th},i}/\nu_{ii}$	0.05 kpc	30 kpc
μ_{\parallel}	$v_{\text{th},i} \lambda_{\text{mfp}}$	$10^{28} \text{ cm}^2/\text{s}$	$10^{31} \text{ cm}^2/\text{s}$
η	$3 \times 10^{13} T^{-3/2b}$	$200 \text{ cm}^2/\text{s}$	$30 \text{ cm}^2/\text{s}$
U	inferred	250 km/s	300 km/s
L	inferred	10 kpc	200 kpc
L/U	inferred	$4 \times 10^7 \text{ yr}$	$7 \times 10^8 \text{ yr}$
Re	UL/μ_{\parallel}	70	2
Rm	UL/η	4×10^{27}	6×10^{29}

The intracluster medium plasma is **not turbulent.**

Modelling weakly collisional plasma

Nordita program
25/05/2026

MHD

Momentum equation with isotropic pressure:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla p$$

Lower collision rate

MHD

Momentum equation with isotropic pressure:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla p$$

Lower collision rate

Weakly collisional MHD

When the collision rate is low, no isotropy is established:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla \cdot \left[p_{\perp} (\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}) + p_{\parallel} \hat{\mathbf{b}}\hat{\mathbf{b}} \right]$$

Now, the pressure parallel and perpendicular to the magnetic field is different.

MHD

Momentum equation with isotropic pressure:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla p$$

Lower collision rate

Weakly collisional MHD

When the collision rate is low, no isotropy is established:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla \cdot \left[p_{\perp} (\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}) + p_{\parallel} \hat{\mathbf{b}}\hat{\mathbf{b}} \right]$$

Now, the pressure parallel and perpendicular to the magnetic field is different.

Pressure-anisotropy-induced instabilities (firehose and mirror) regulate the pressure anisotropy by **changing the effective collisionality of the system.**

MHD

Momentum equation with isotropic pressure:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla p$$

Lower collision rate

Weakly collisional MHD

When the collision rate is low, no isotropy is established:

$$\frac{DU}{Dt} = \mathbf{J} \times \mathbf{B} - \frac{1}{\rho} \nabla \cdot \left[p_{\perp} (\mathbf{I} - \hat{\mathbf{b}}\hat{\mathbf{b}}) + p_{\parallel} \hat{\mathbf{b}}\hat{\mathbf{b}} \right]$$

Now, the pressure parallel and perpendicular to the magnetic field is different.

Pressure-anisotropy-induced instabilities (firehose and mirror) regulate the pressure anisotropy by **changing the effective collisionality of the system.**

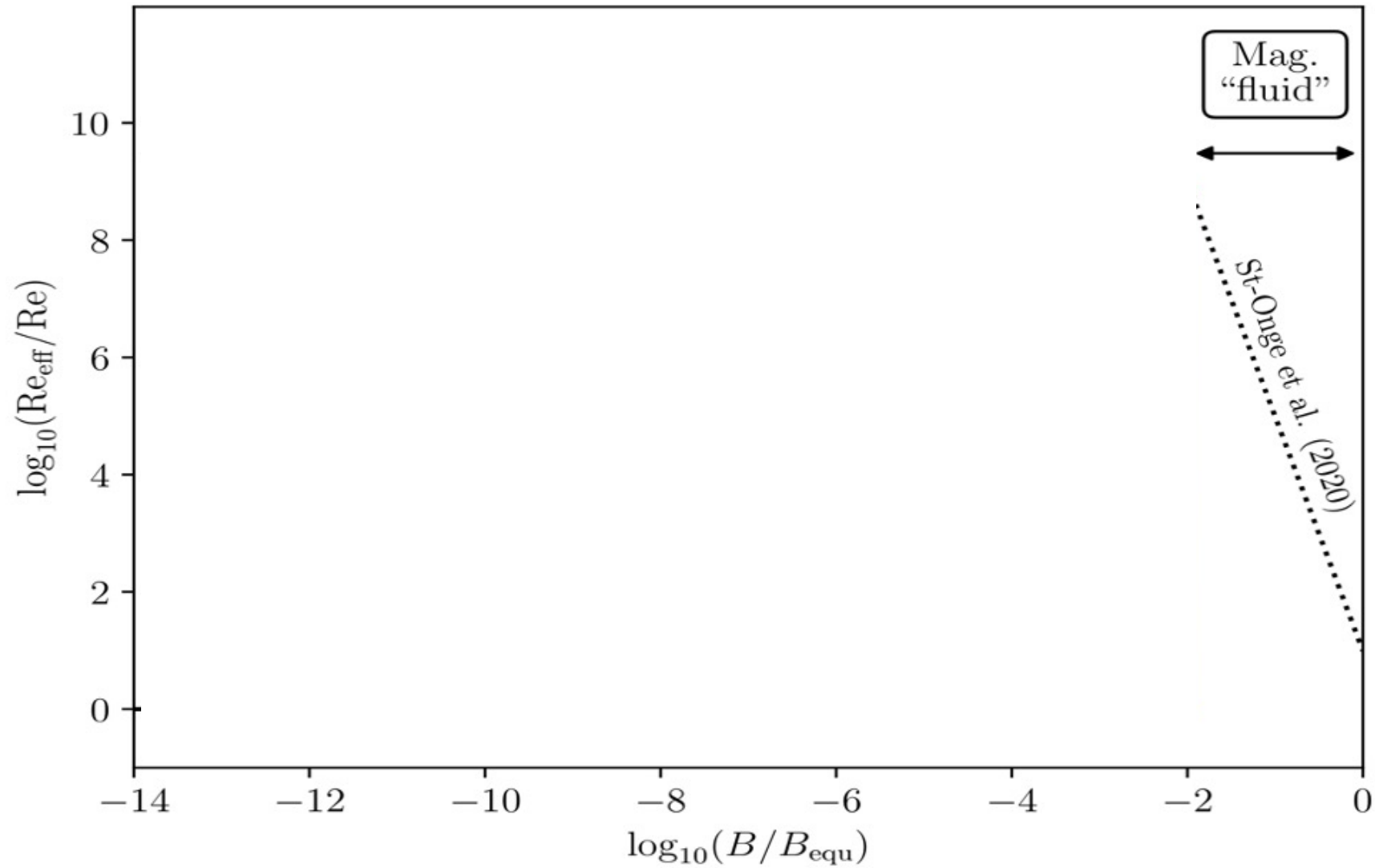
The effective Reynolds number is **B-dependent:**

$$\text{Re} \rightarrow \text{Re}_{\text{eff}}(B)$$

[St-Onge et al. 2020].

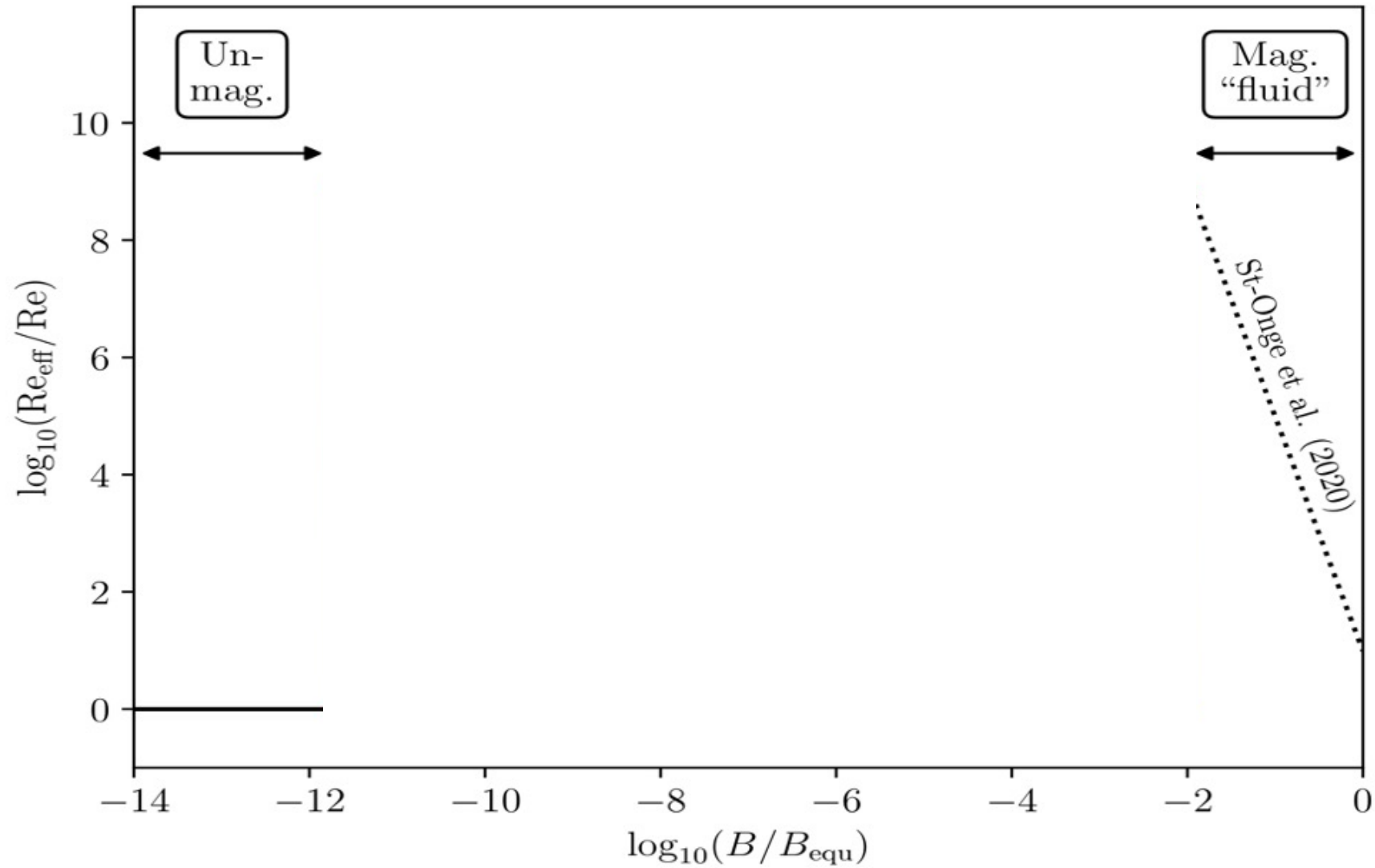
Effective Reynolds number

Nordita program
25/05/2026



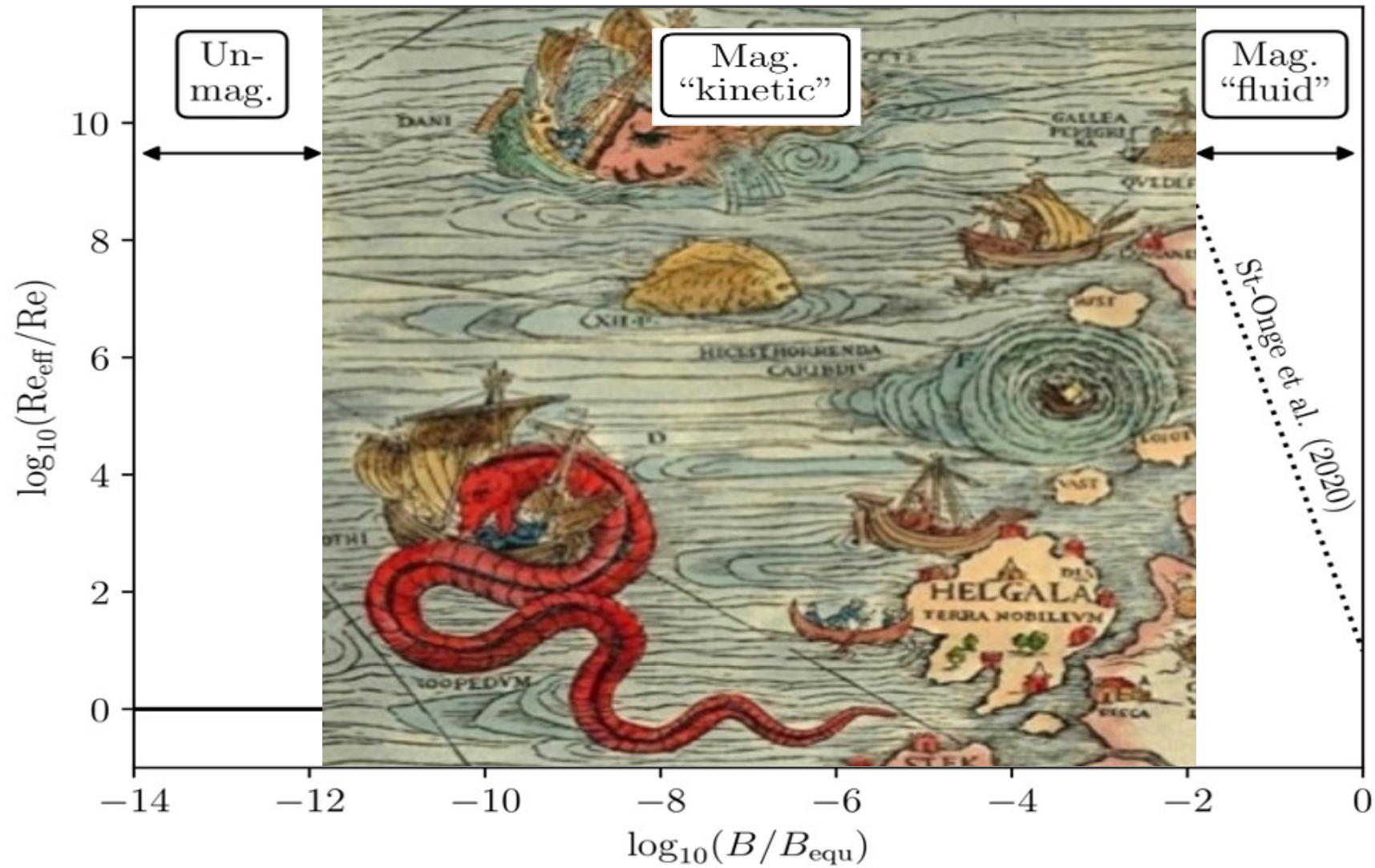
Effective Reynolds number

Nordita program
25/05/2026



Effective Reynolds number

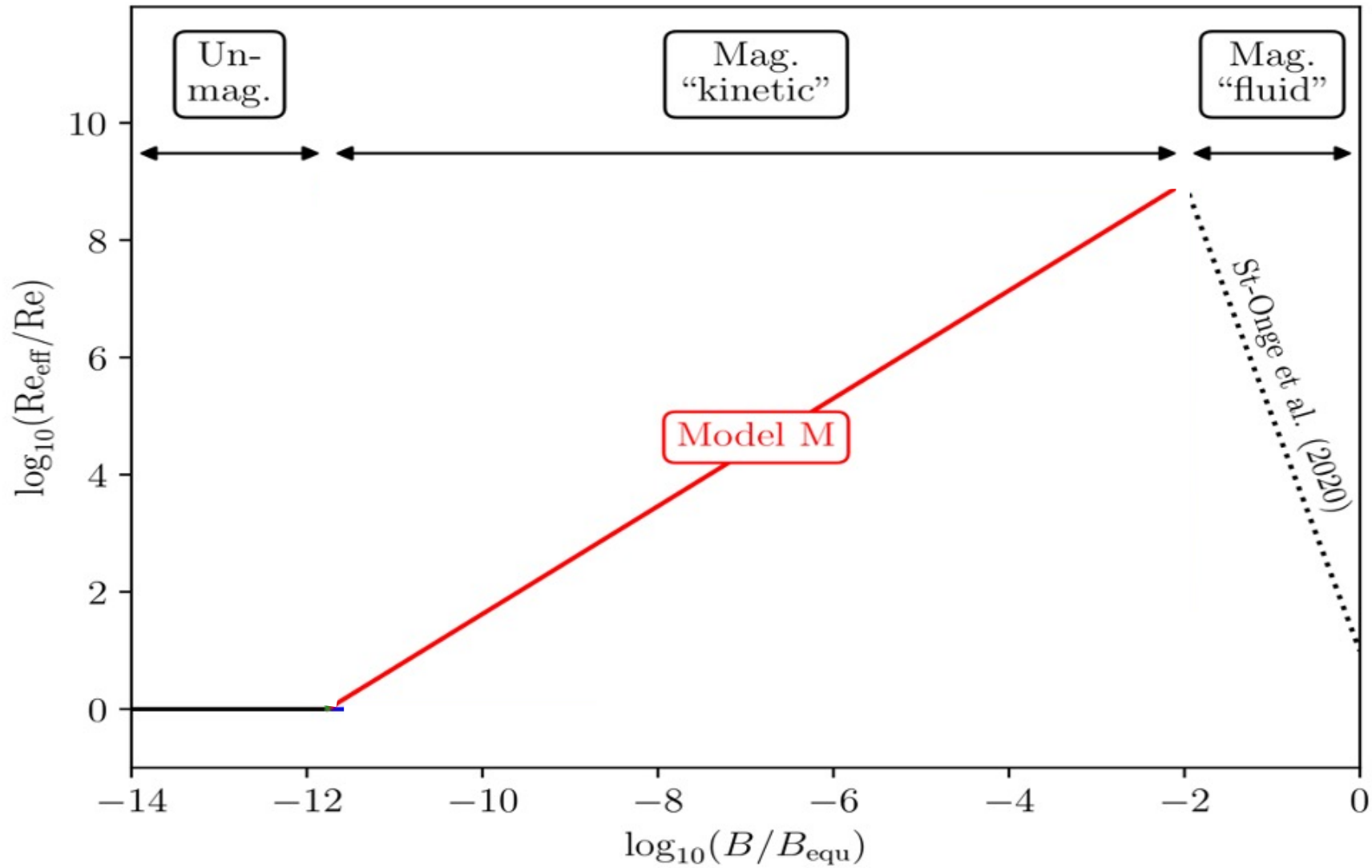
Nordita program
25/05/2026



Yoan Rappaz

Effective Reynolds number

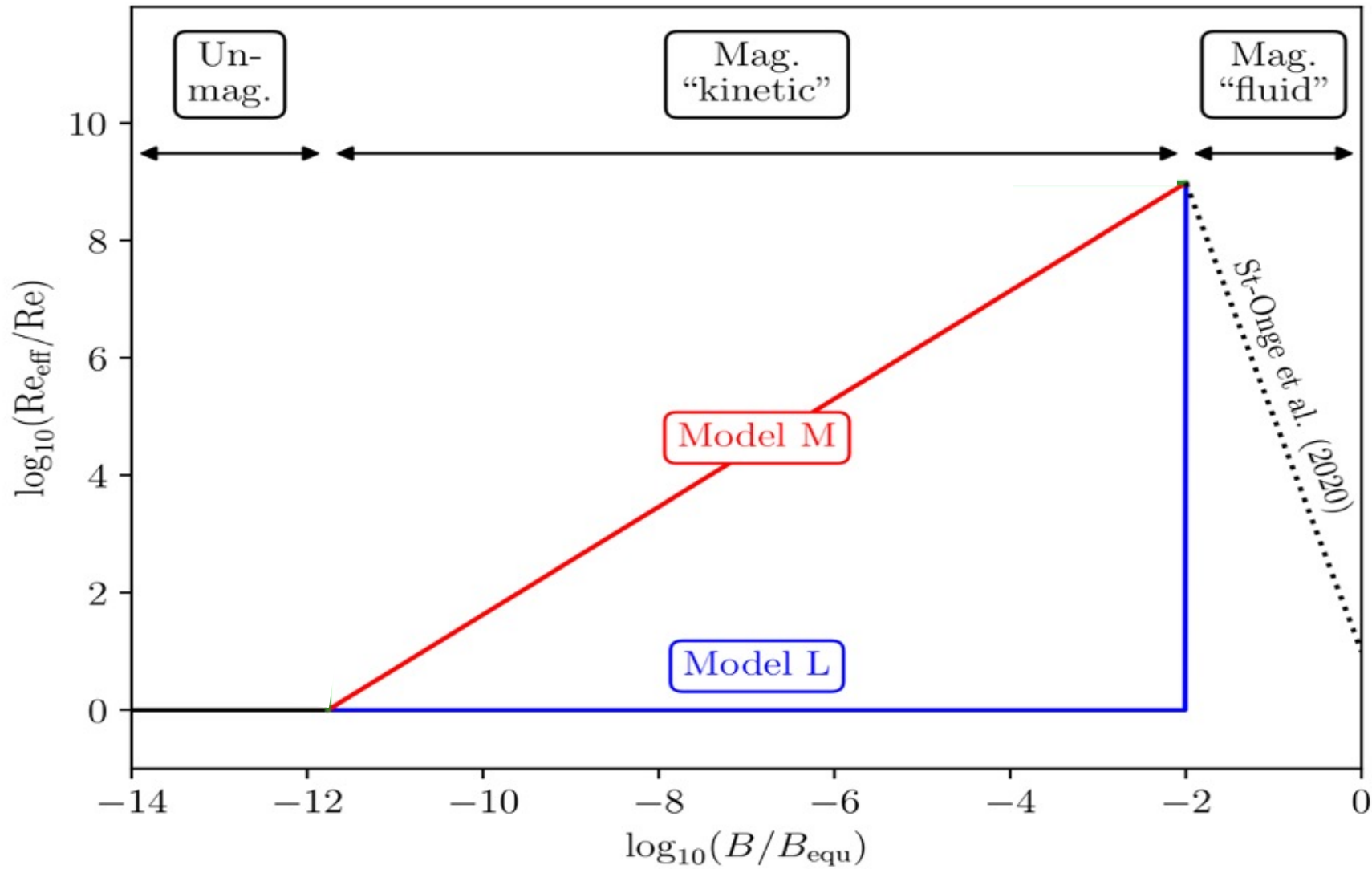
Nordita program
25/05/2026



Yoan Rappaz

Effective Reynolds number

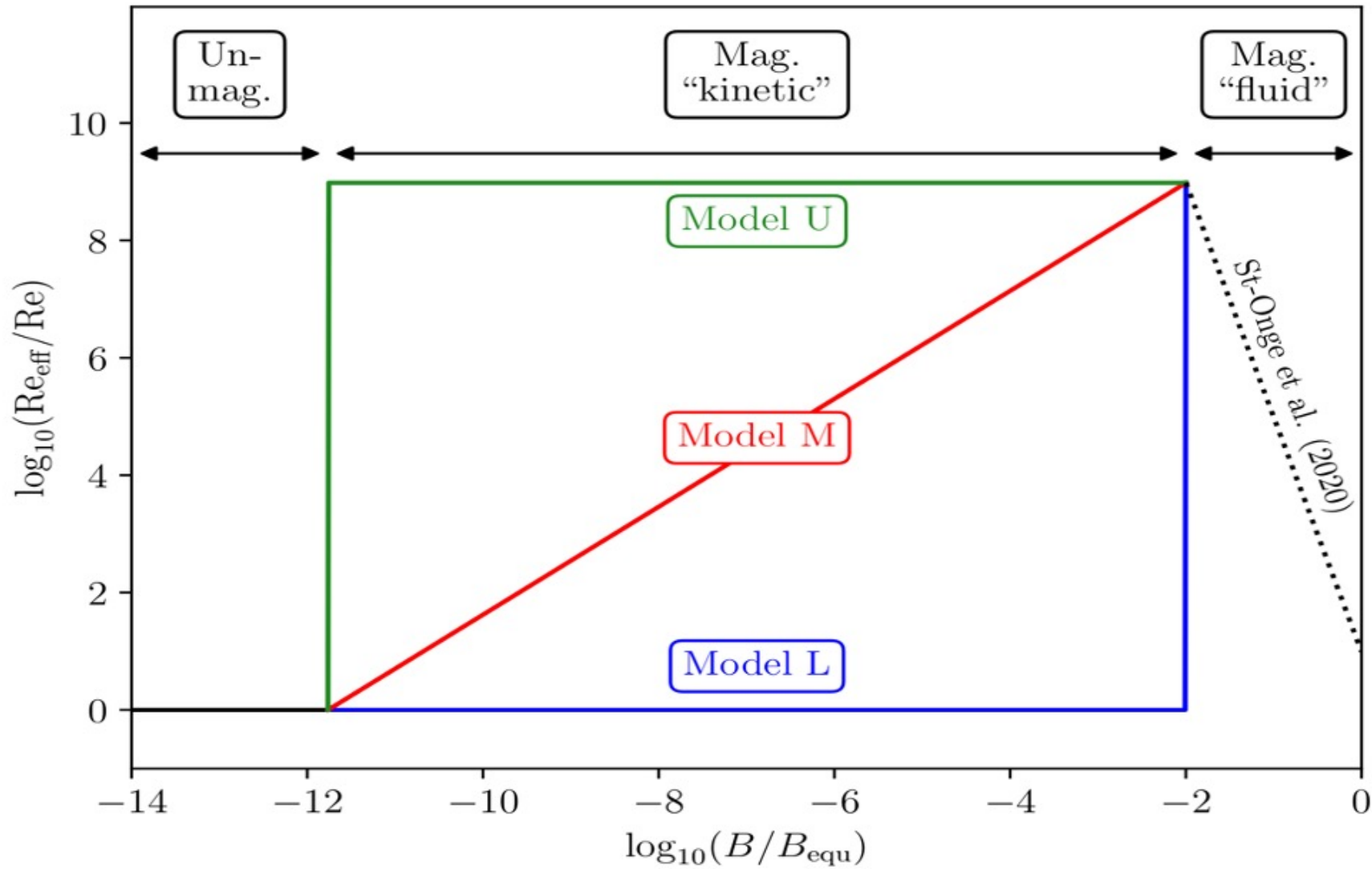
Nordita program
25/05/2026



Yoan Rappaz

Effective Reynolds number

Nordita program
25/05/2026



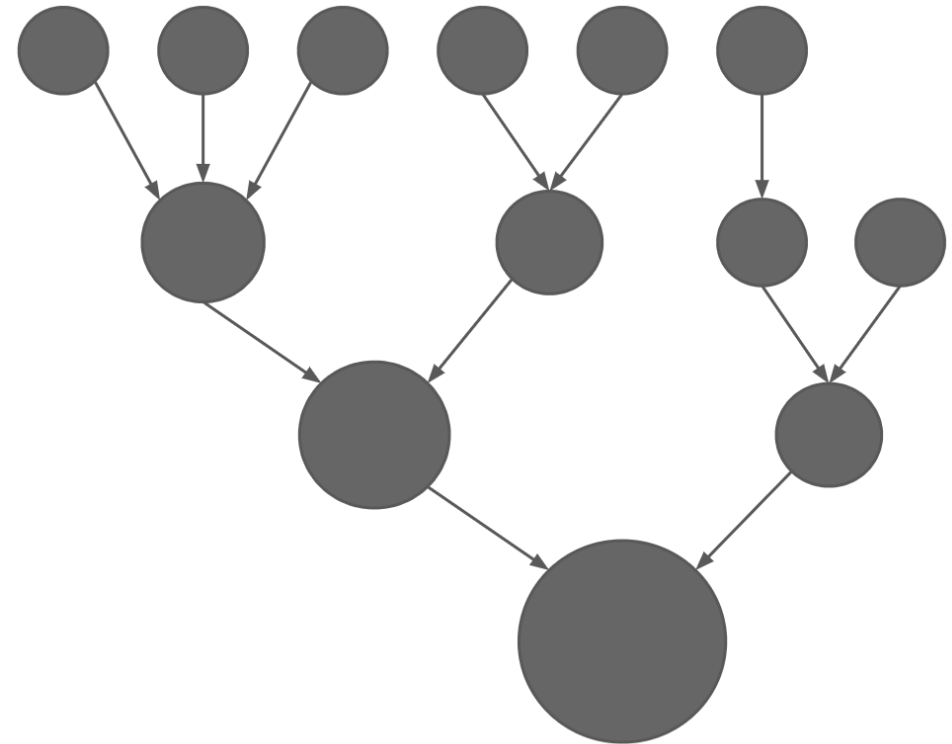
Yoan Rappaz

Modelling a cluster dynamo

Nordita program
25/05/2026

Model cluster evolution via **merger trees**

[Modified Galform Algorithm, Parkinson et al 2008]



Modelling a cluster dynamo

Nordita program
25/05/2026

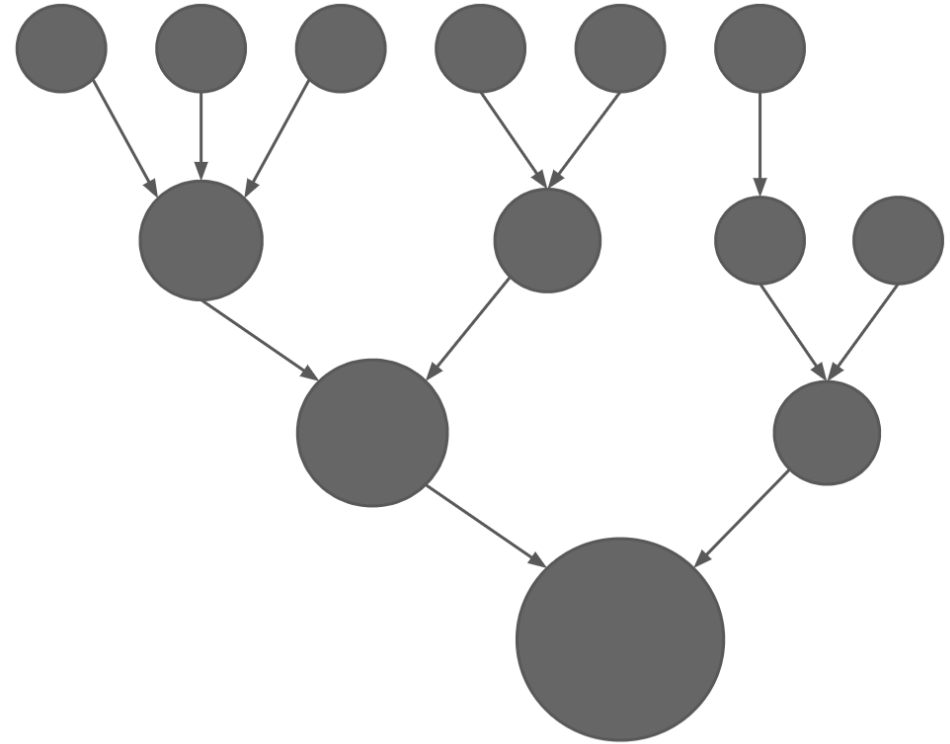
Model cluster evolution via **merger trees**

[Modified Galform Algorithm, Parkinson et al 2008]

Model gas density and temperature distributions, assuming a **hydrostatic equilibrium** of a polytropic gas in a dark matter halo:

$$T(r) = T_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]$$

$$\rho_g(r) = \rho_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]^\xi$$



Modelling a cluster dynamo

Nordita program
25/05/2026

Model cluster evolution via **merger trees**

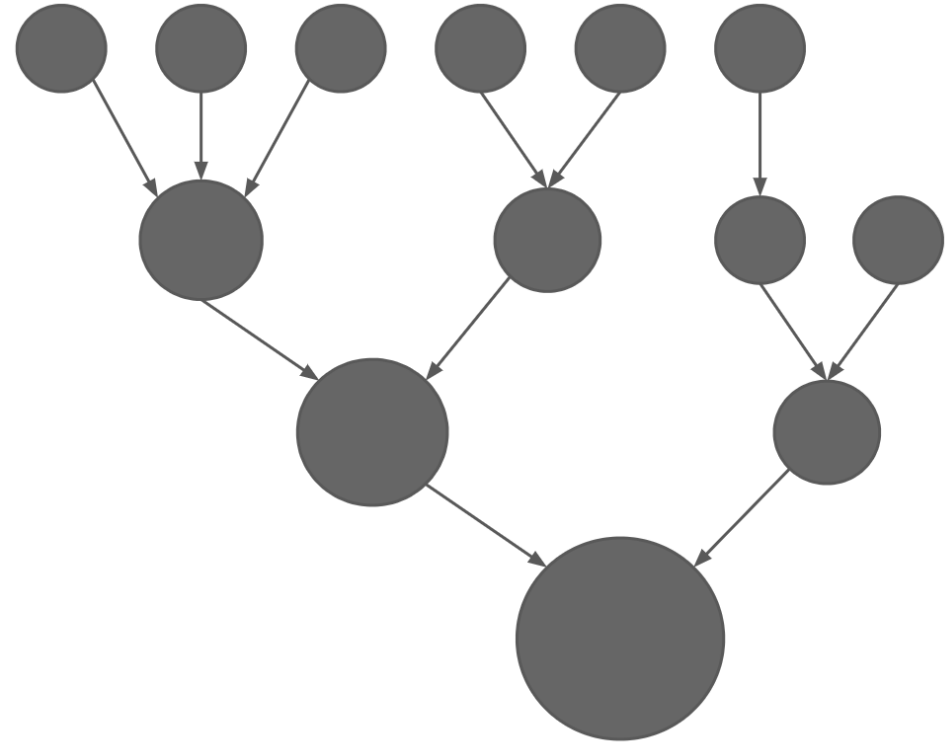
[Modified Galform Algorithm, Parkinson et al 2008]

Model gas density and temperature distributions, assuming a **hydrostatic equilibrium** of a polytropic gas in a dark matter halo:

$$T(r) = T_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]$$

$$\rho_g(r) = \rho_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]^\xi$$

Average over all halos and over 1000s of merger trees to find Reynolds number $\text{Re}_{\text{eff}}(z, B)$



Modelling a cluster dynamo

Nordita program
25/05/2026

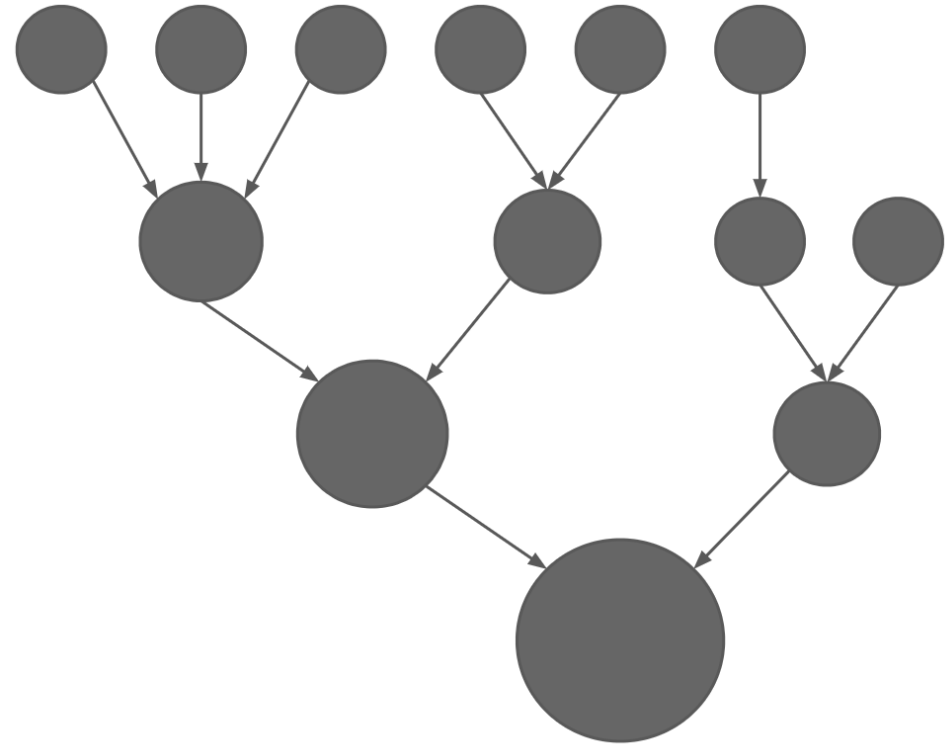
Model cluster evolution via **merger trees**

[Modified Galform Algorithm, Parkinson et al 2008]

Model gas density and temperature distributions, assuming a **hydrostatic equilibrium** of a polytropic gas in a dark matter halo:

$$T(r) = T_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]$$

$$\rho_g(r) = \rho_0 \left[1 - \frac{\Lambda}{1 + \xi} \left(1 - \frac{\ln(1 + r/r_s)}{r/r_s} \right) \right]^\xi$$

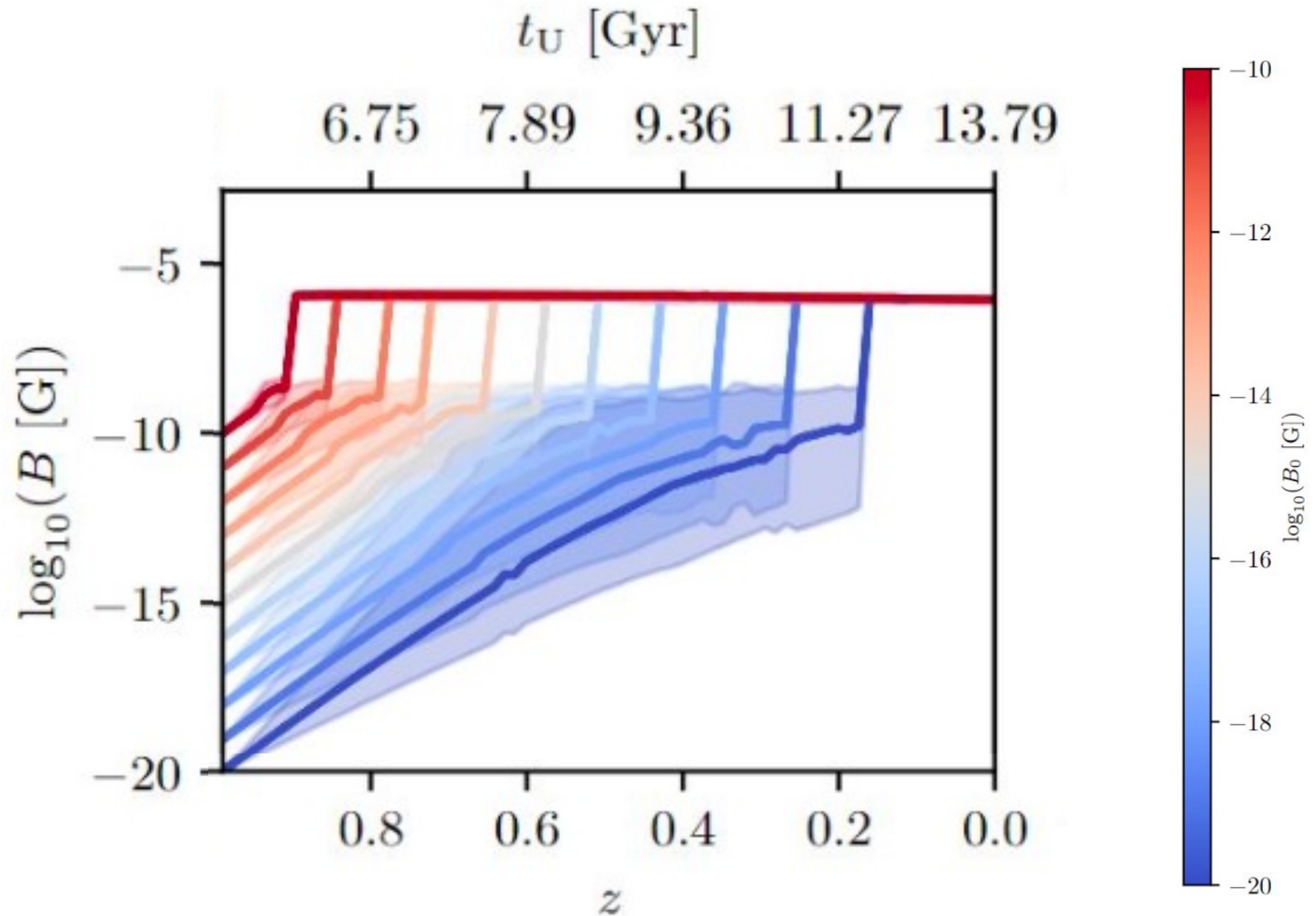


Average over all halos and over 1000s of merger trees to find Reynolds number $\text{Re}_{\text{eff}}(z, B)$

Solve the dynamo equation: $\frac{d \ln B}{dt} \approx \frac{v_{\text{turb}}}{L_{\text{turb}}} \text{Re}_{\text{eff}}(z, B)^{1/2}$

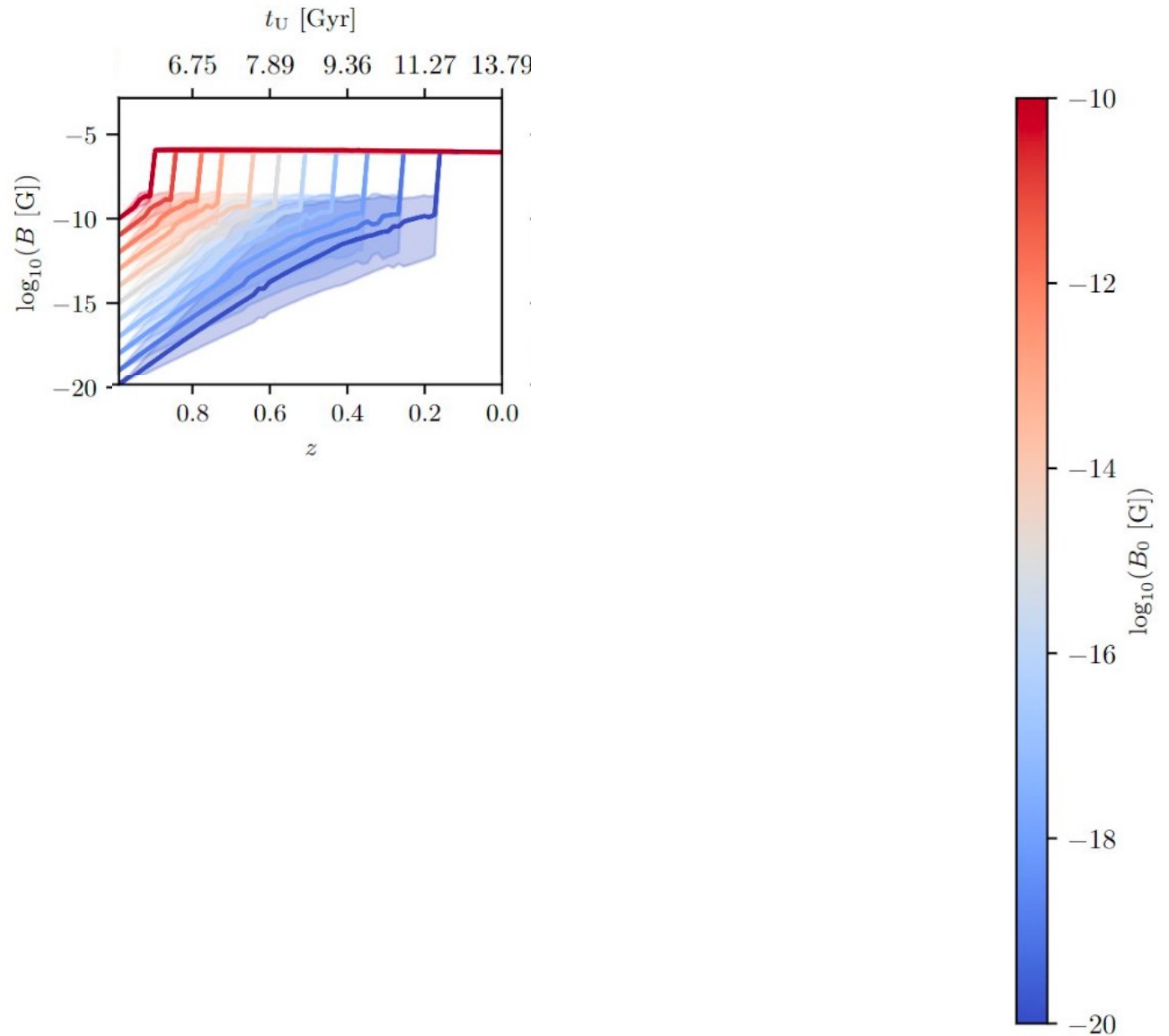
Explosive dynamos in galaxy clusters

Nordita program
25/05/2026



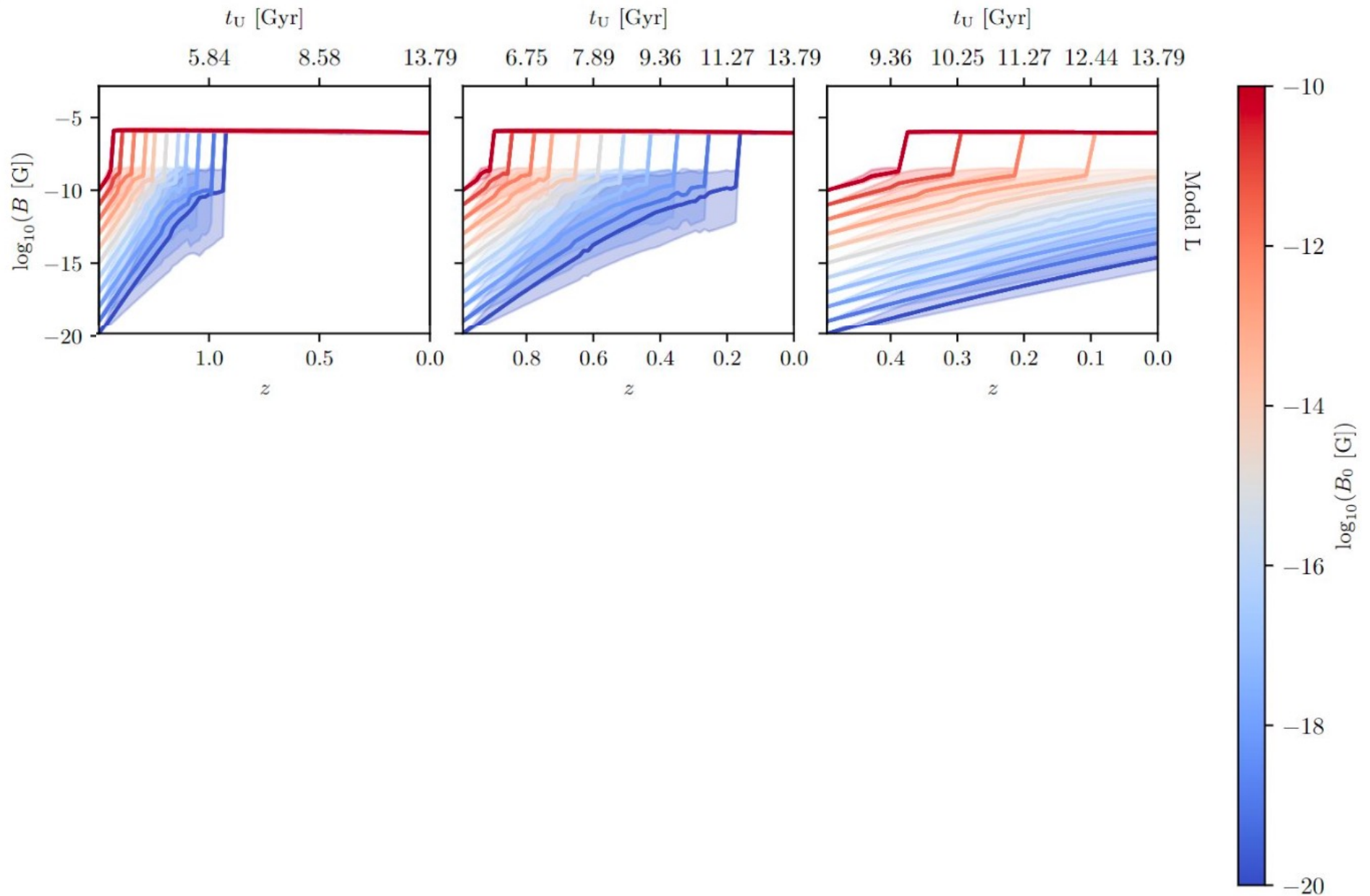
Explosive dynamos in galaxy clusters

Nordita program
25/05/2026



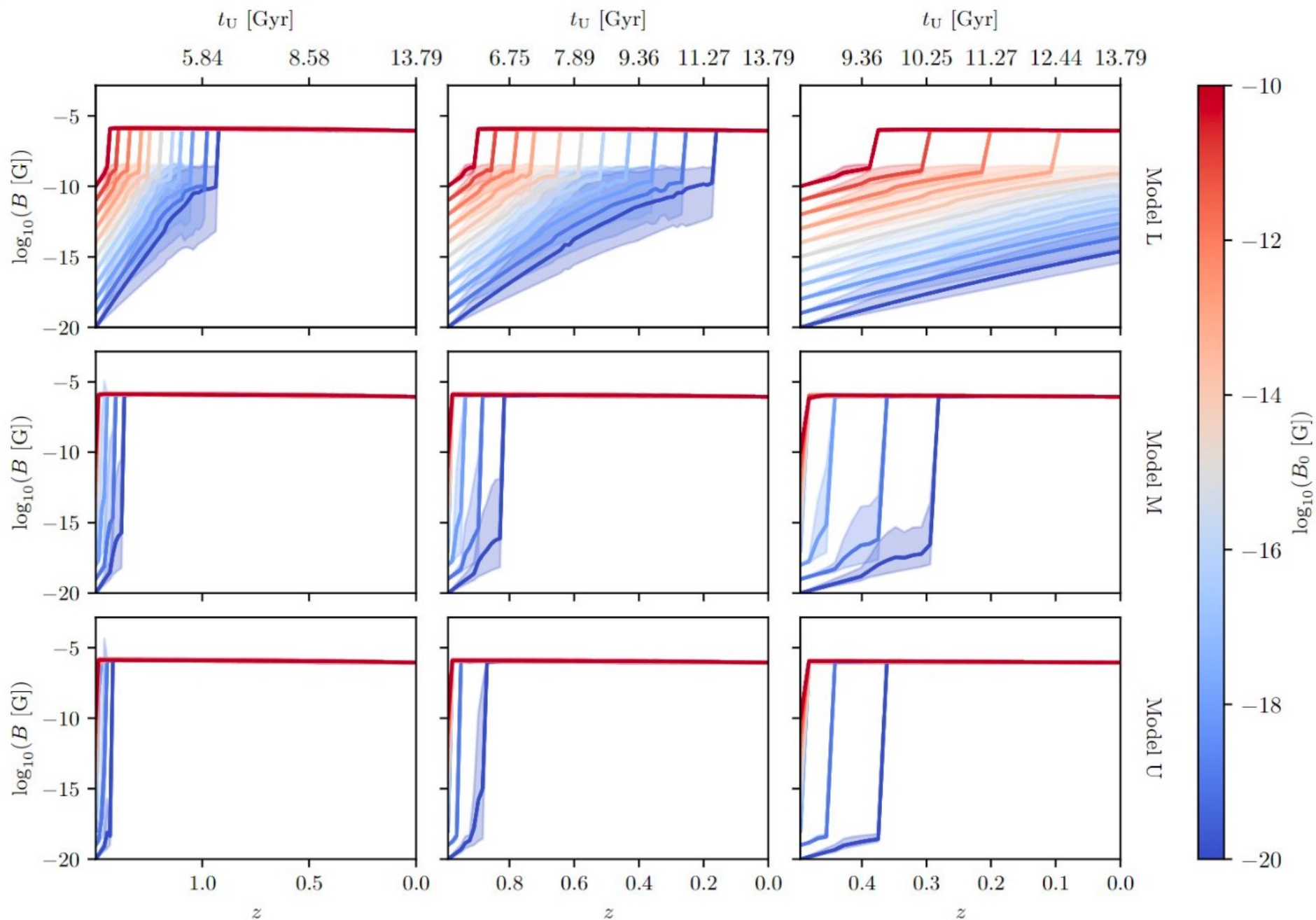
Explosive dynamos in galaxy clusters

Nordita program
25/05/2026



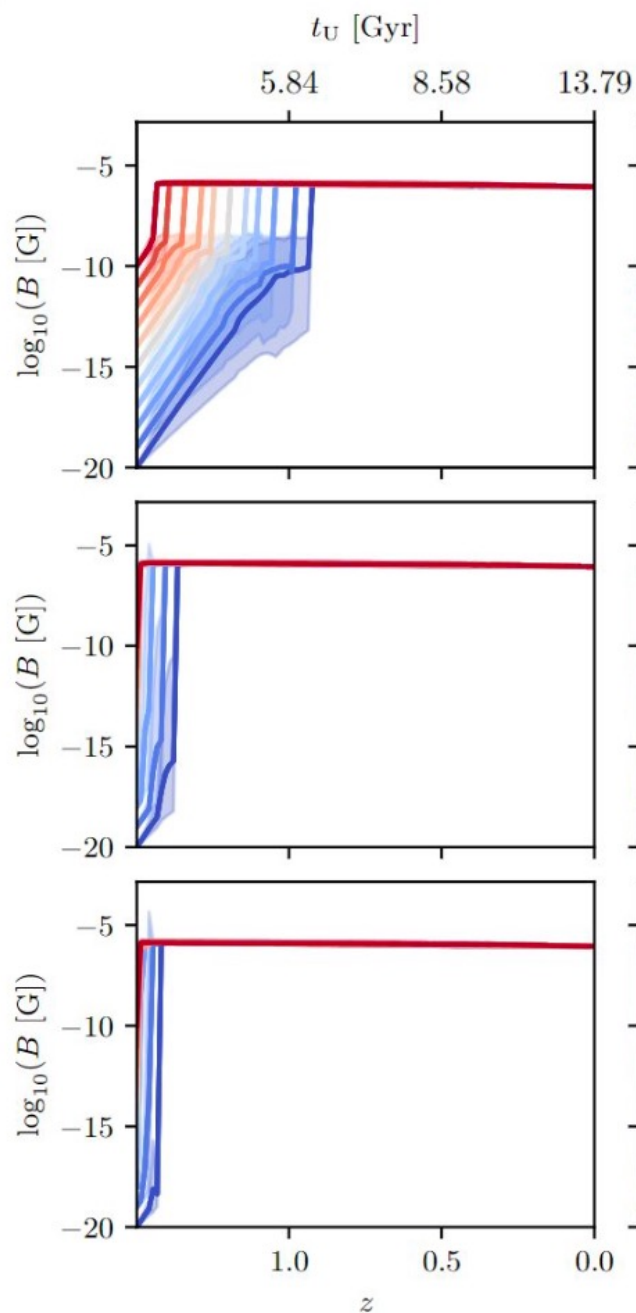
Explosive dynamos in galaxy clusters

Nordita program
25/05/2026

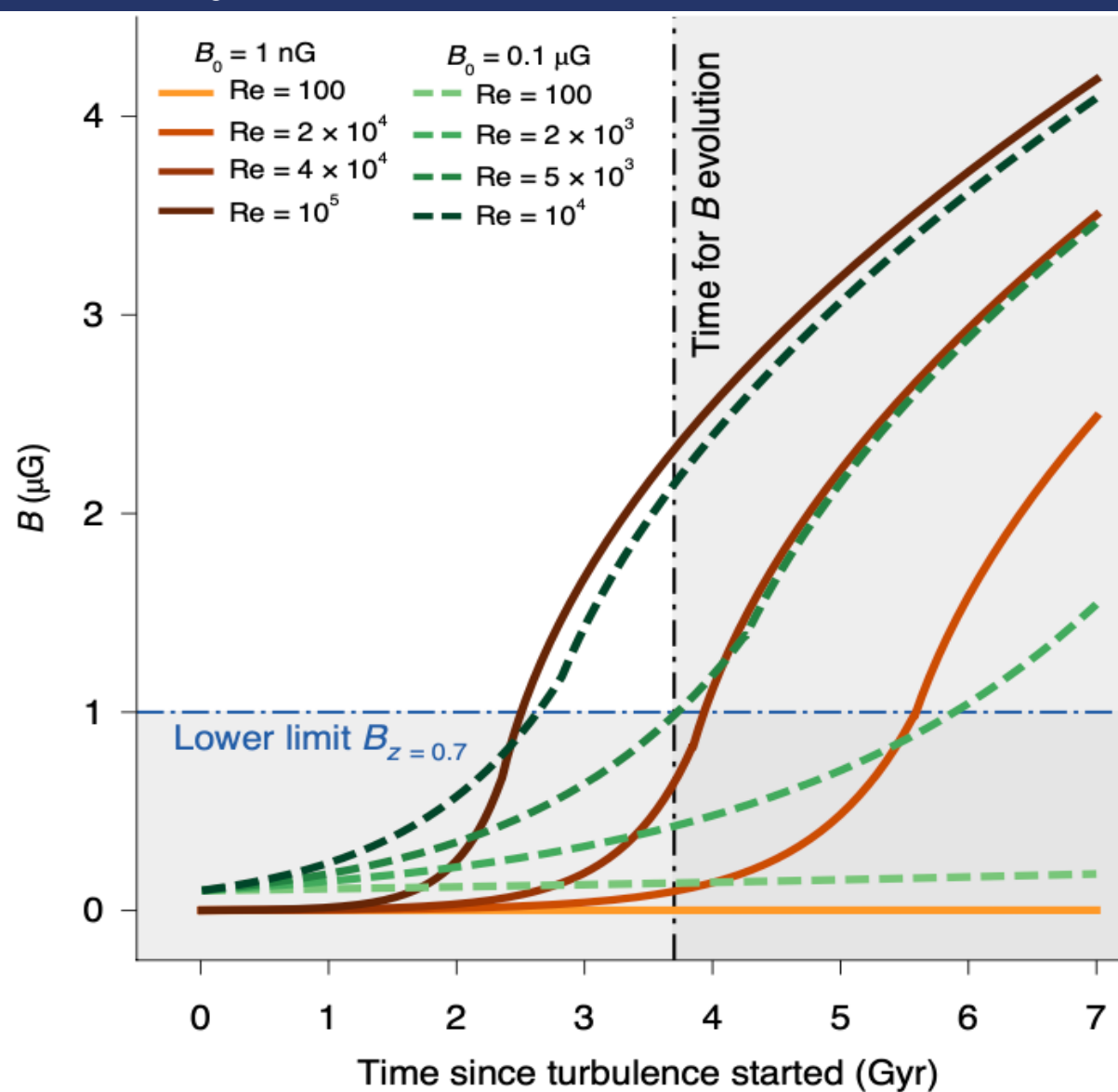


Explosive dynamos in galaxy clusters

Nordita program
25/05/2026



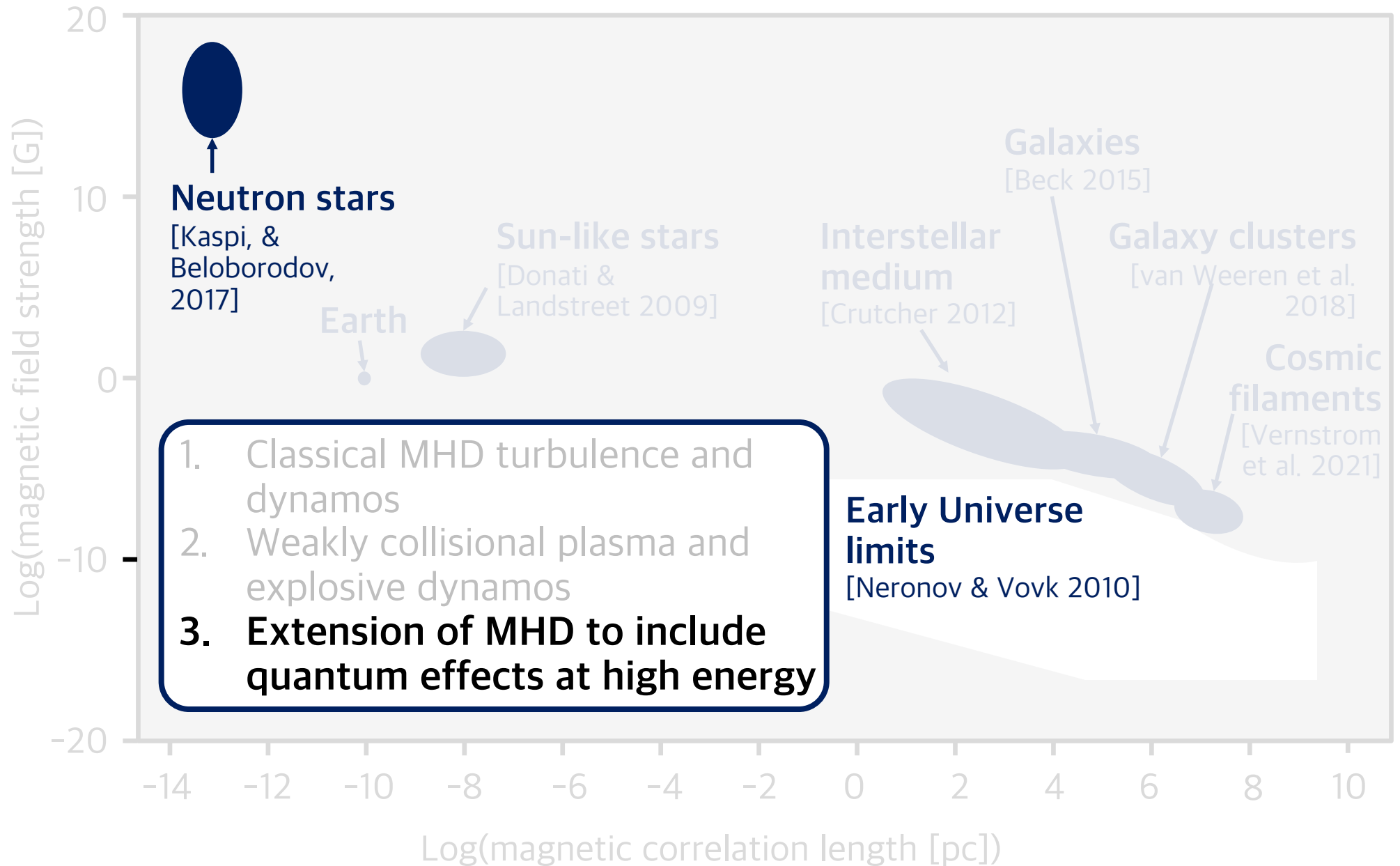
Observational evidence for high-Reynolds number dynamos in clusters [Di Gennaro et al. 2021]



- What sets the effective Reynolds number of the ICM? How do kinetic instabilities regulate viscosity and collisionality?)
- Does weakly collisional turbulence have a MHD-like inertial range?
- How is turbulent energy dissipated in high- β plasma? Pressure anisotropy, Landau damping, reconnection, kinetic cascades?
- How does the fluctuation dynamo operate in weakly collisional plasma? Growth rates, saturation, magnetic topology?
- Why does weakly collisional turbulence often appear macroscopically MHD-like despite kinetic microphysics?
- ...

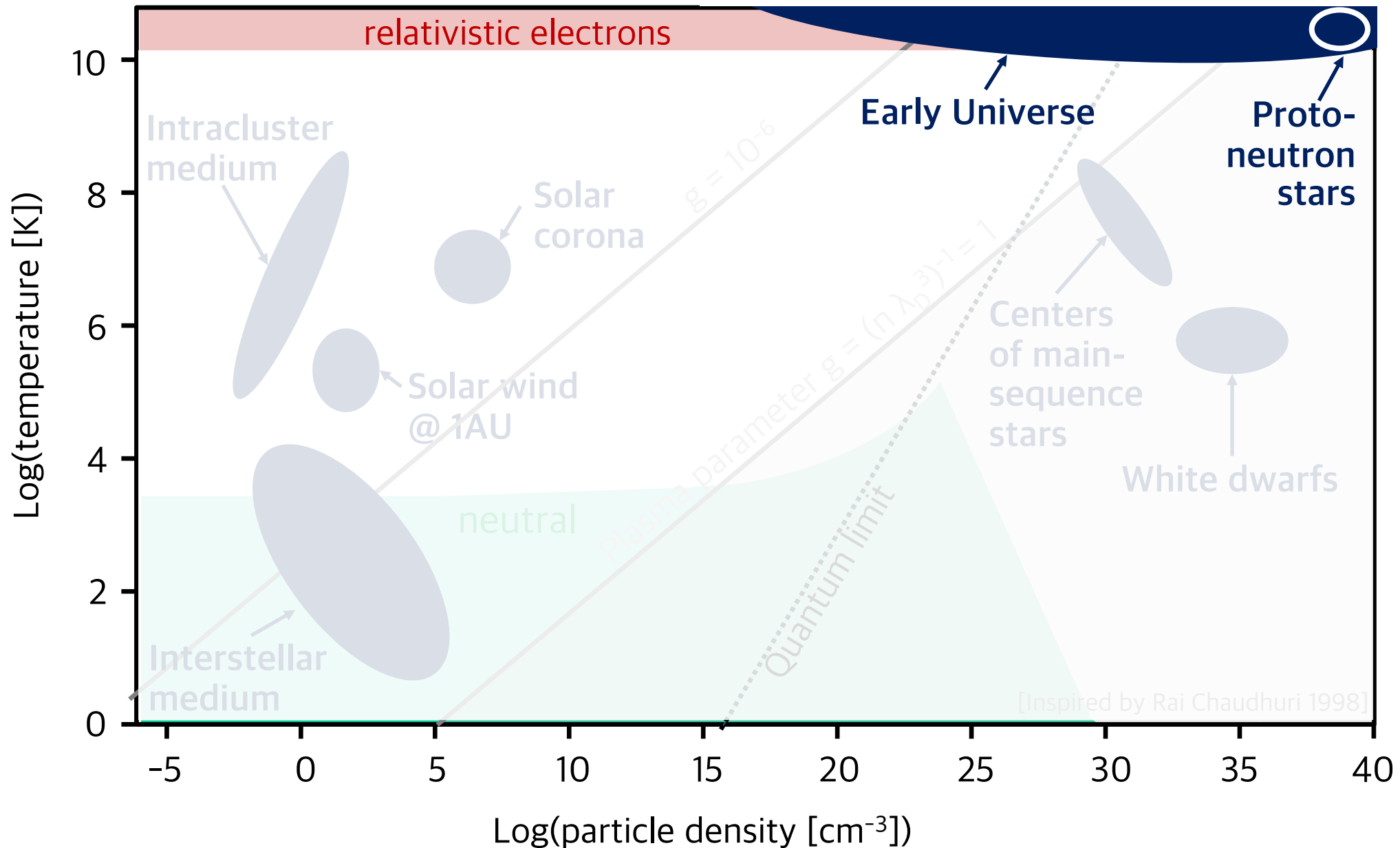
Overview of this talk

Nordita program
25/05/2026



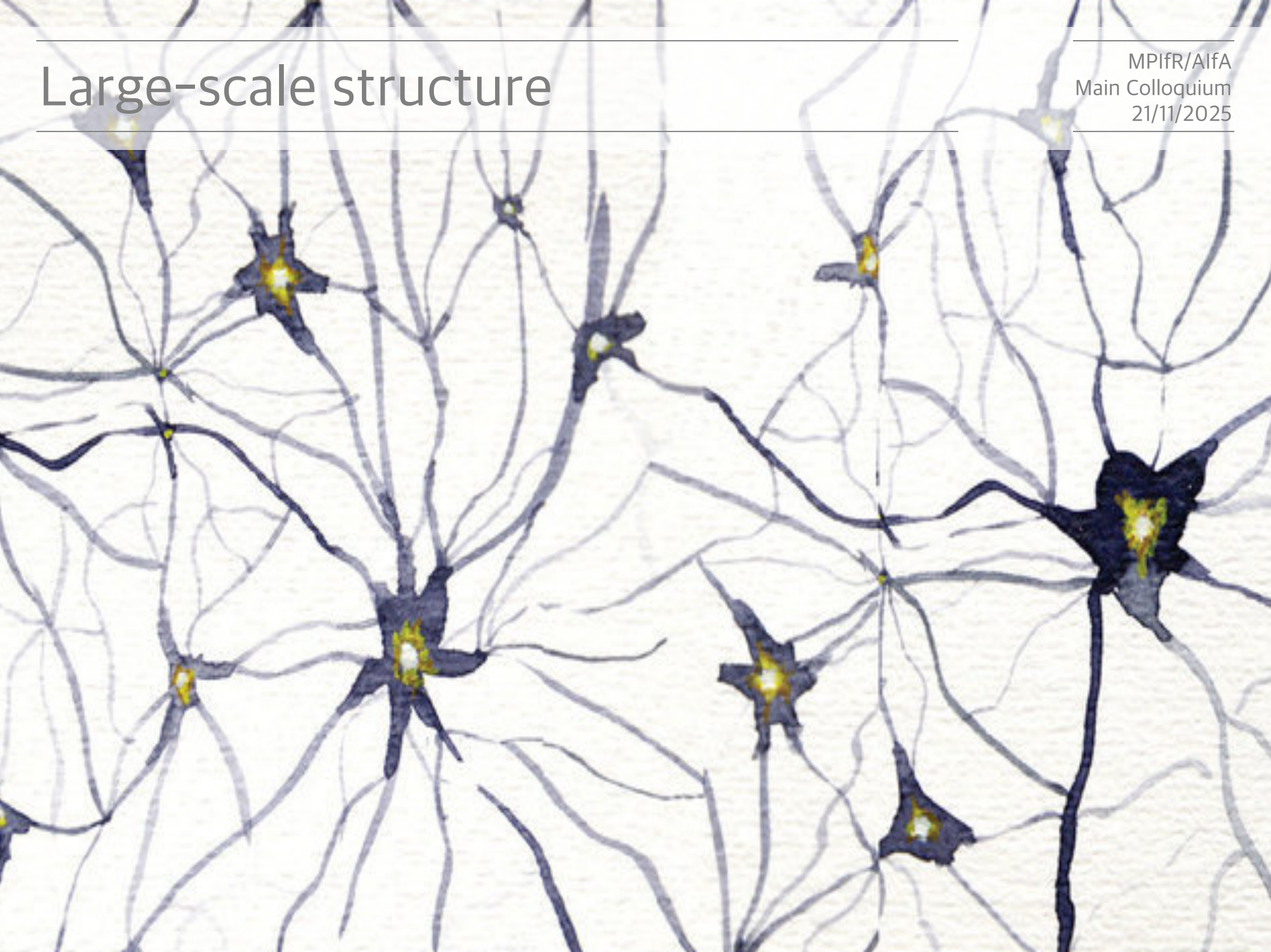
Plasma Universe: types

Nordita program
25/05/2026



Large-scale structure

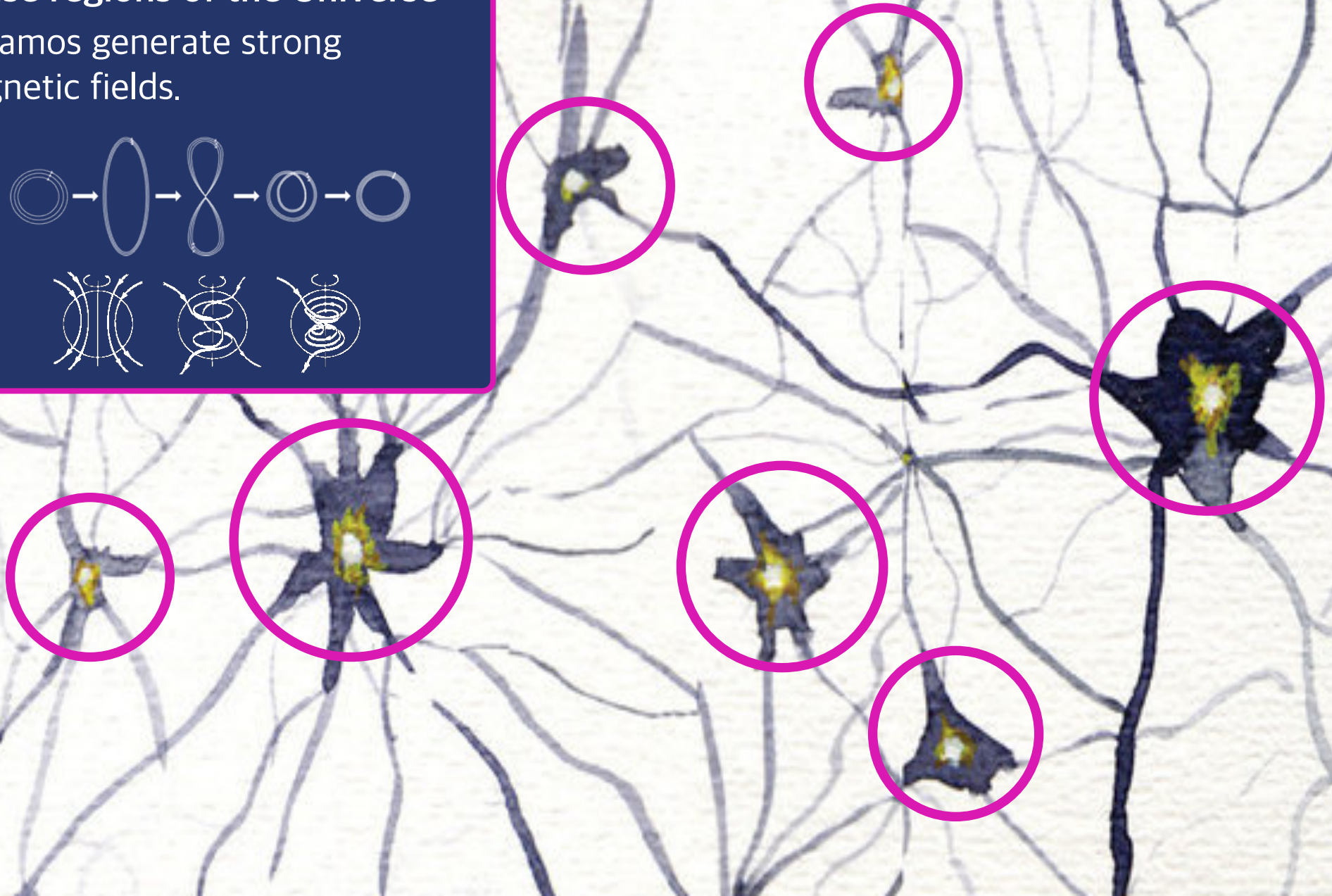
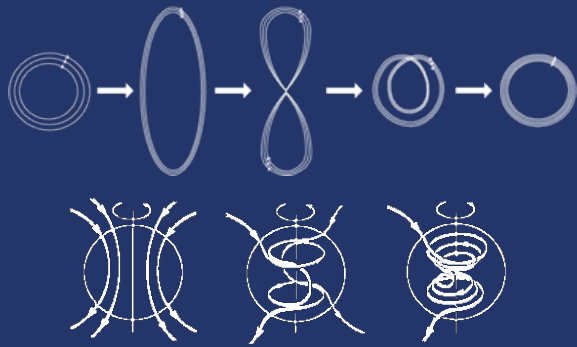
MPIfR/Alfa
Main Colloquium
21/11/2025



Large-scale structure

MPIfR/Alfa
Main Colloquium
21/11/2025

Dense regions of the Universe:
Dynamoes generate strong
magnetic fields.

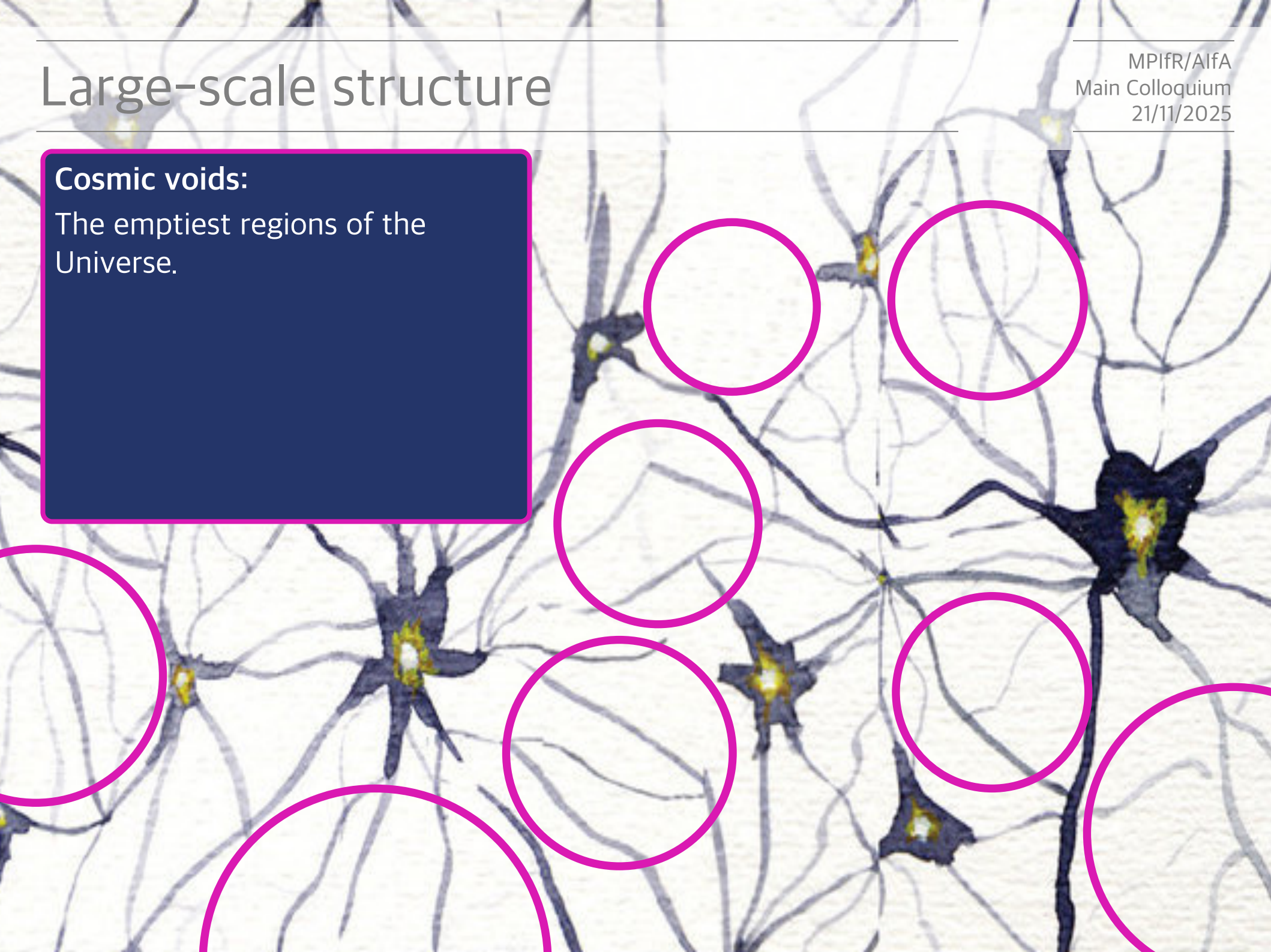


Large-scale structure

MPIfR/AlfA
Main Colloquium
21/11/2025

Cosmic voids:

The emptiest regions of the Universe.



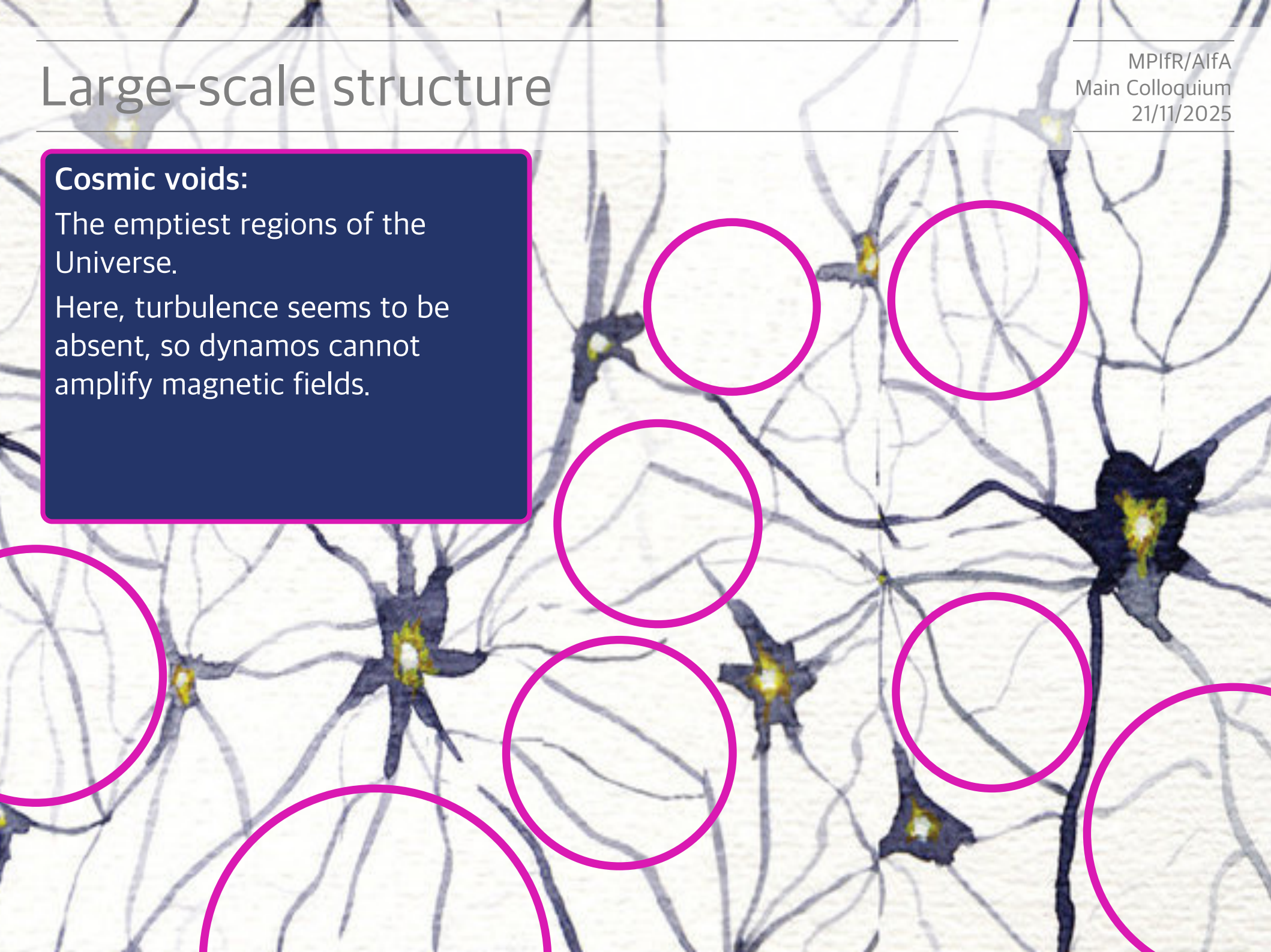
Large-scale structure

MPIfR/AlfA
Main Colloquium
21/11/2025

Cosmic voids:

The emptiest regions of the Universe.

Here, turbulence seems to be absent, so dynamos cannot amplify magnetic fields.



Large-scale structure

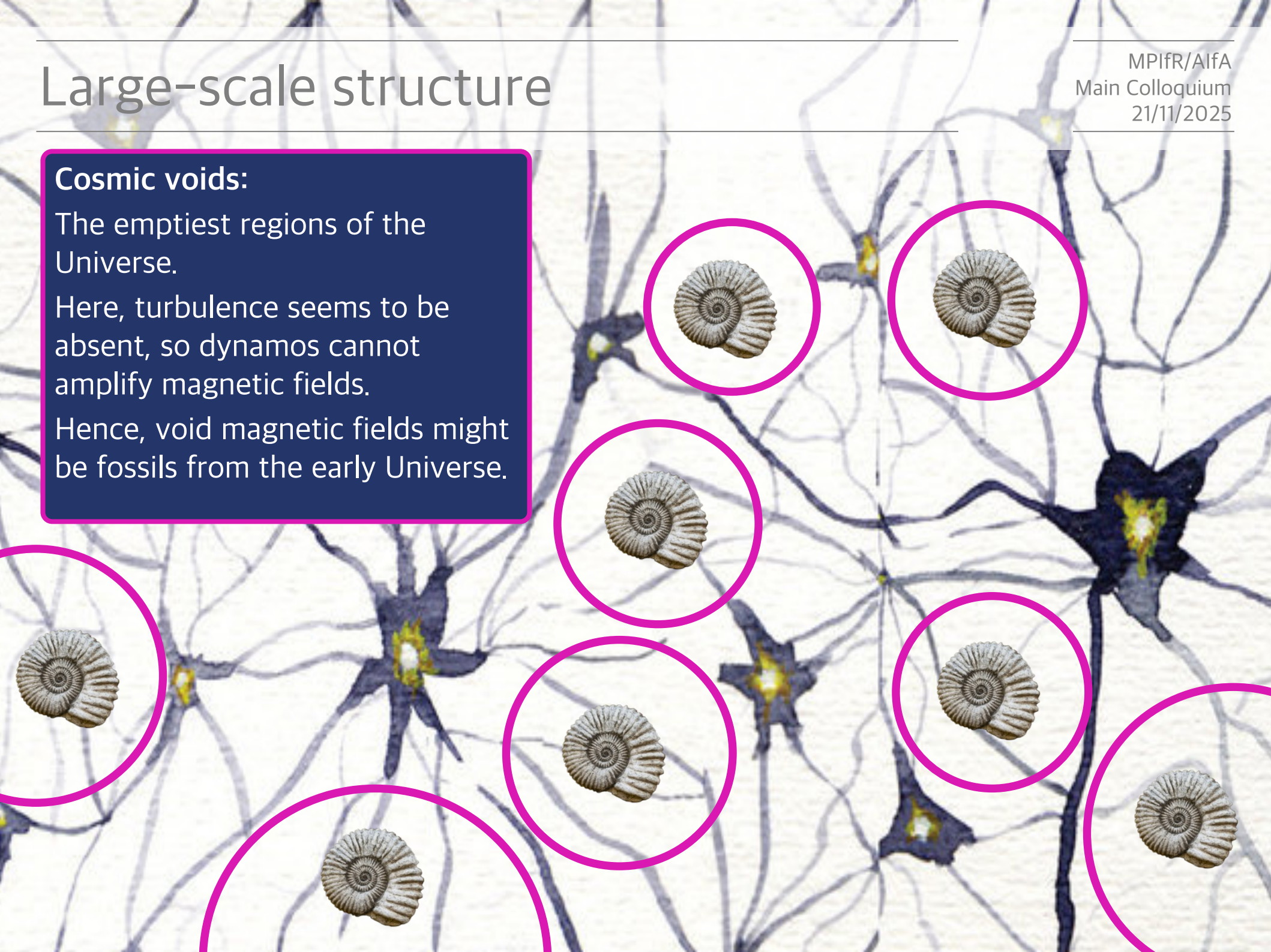
MPIfR/AlfA
Main Colloquium
21/11/2025

Cosmic voids:

The emptiest regions of the Universe.

Here, turbulence seems to be absent, so dynamos cannot amplify magnetic fields.

Hence, void magnetic fields might be fossils from the early Universe.



Large-scale structure

MPIfR/AlfA
Main Colloquium
21/11/2025

Cosmic voids:

The emptiest regions of the Universe.

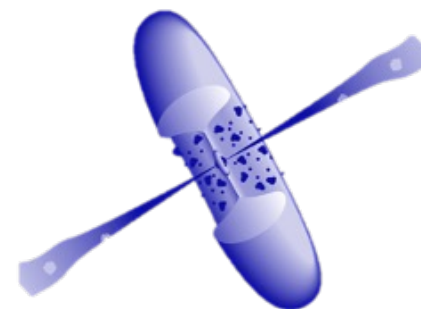
Here, turbulence seems to be absent, so dynamos cannot amplify magnetic fields.

Hence, void magnetic fields might be fossils from the early Universe.

Observer



TeV blazer



Void magnetic fields

MPIfR/AiFA
Main Colloquium
21/11/2025

Observer



TeV blazar



Void magnetic fields

MPIfR/AiFA
Main Colloquium
21/11/2025

Observer



few 10s Mpc

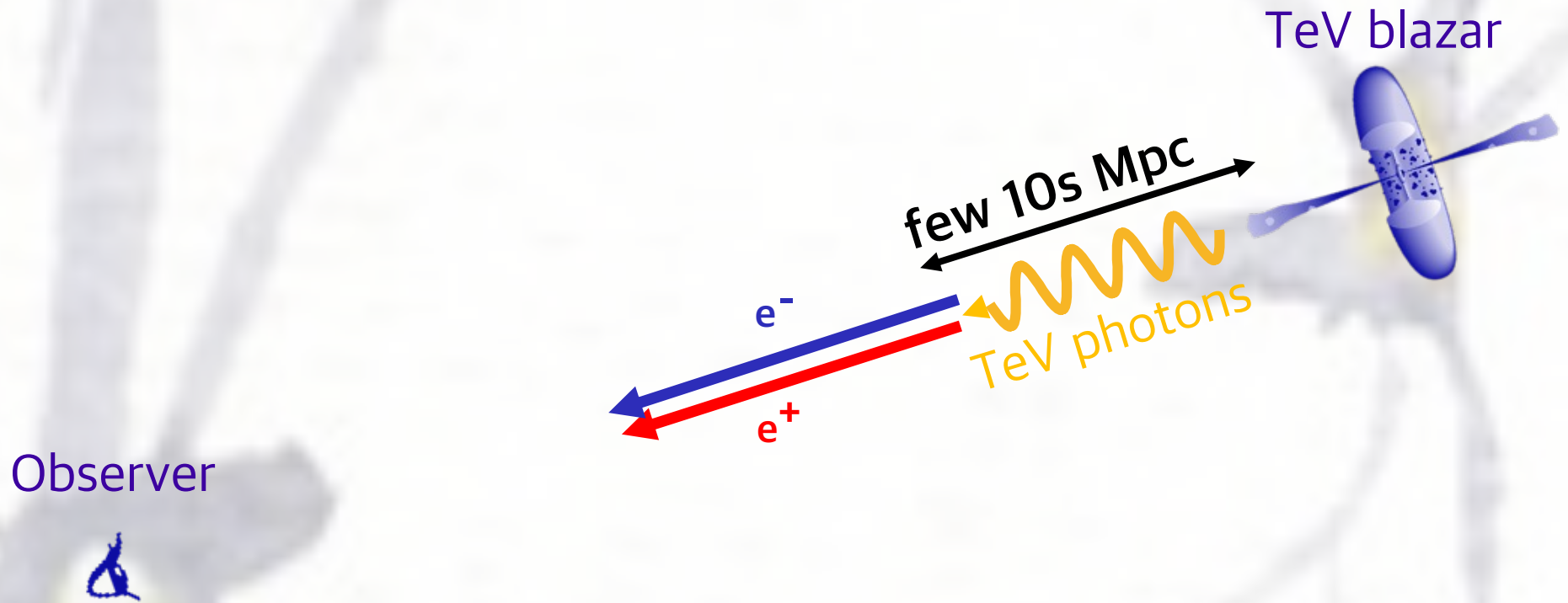
TeV photons

TeV blazar



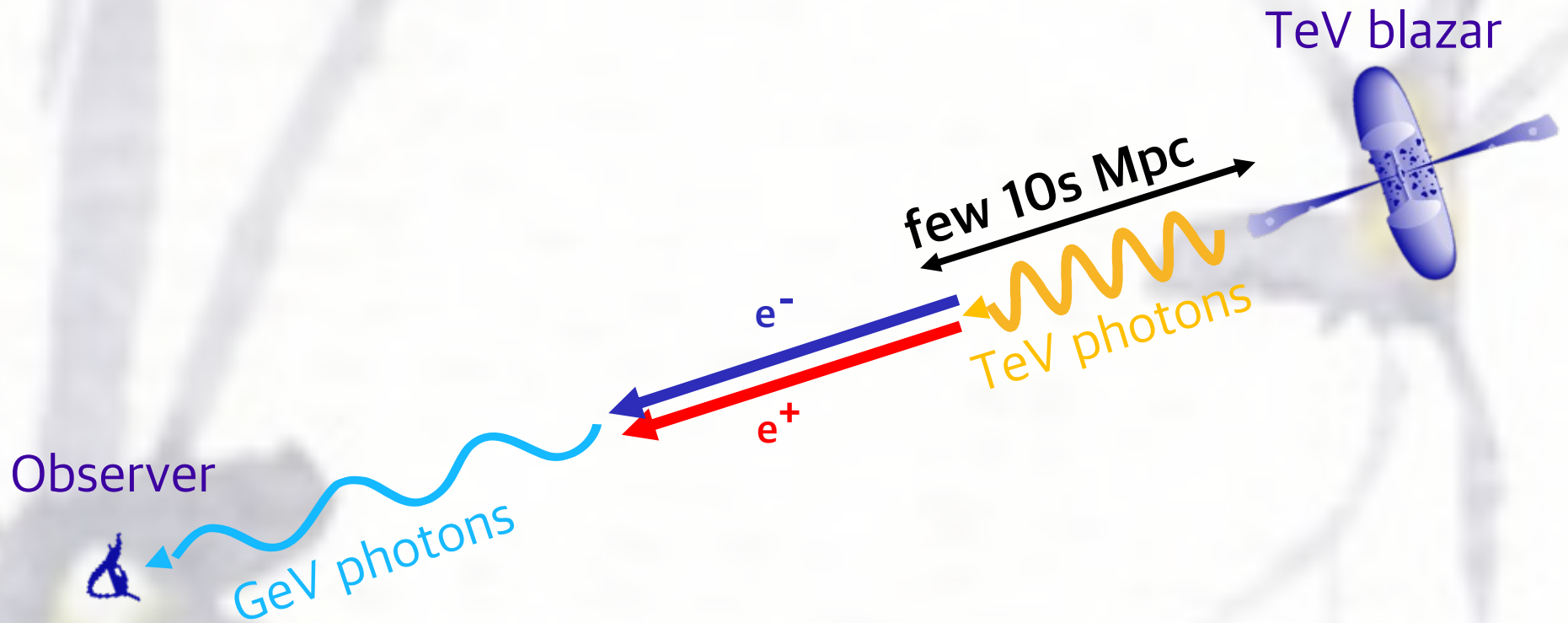
Void magnetic fields

MPIfR/AiFA
Main Colloquium
21/11/2025

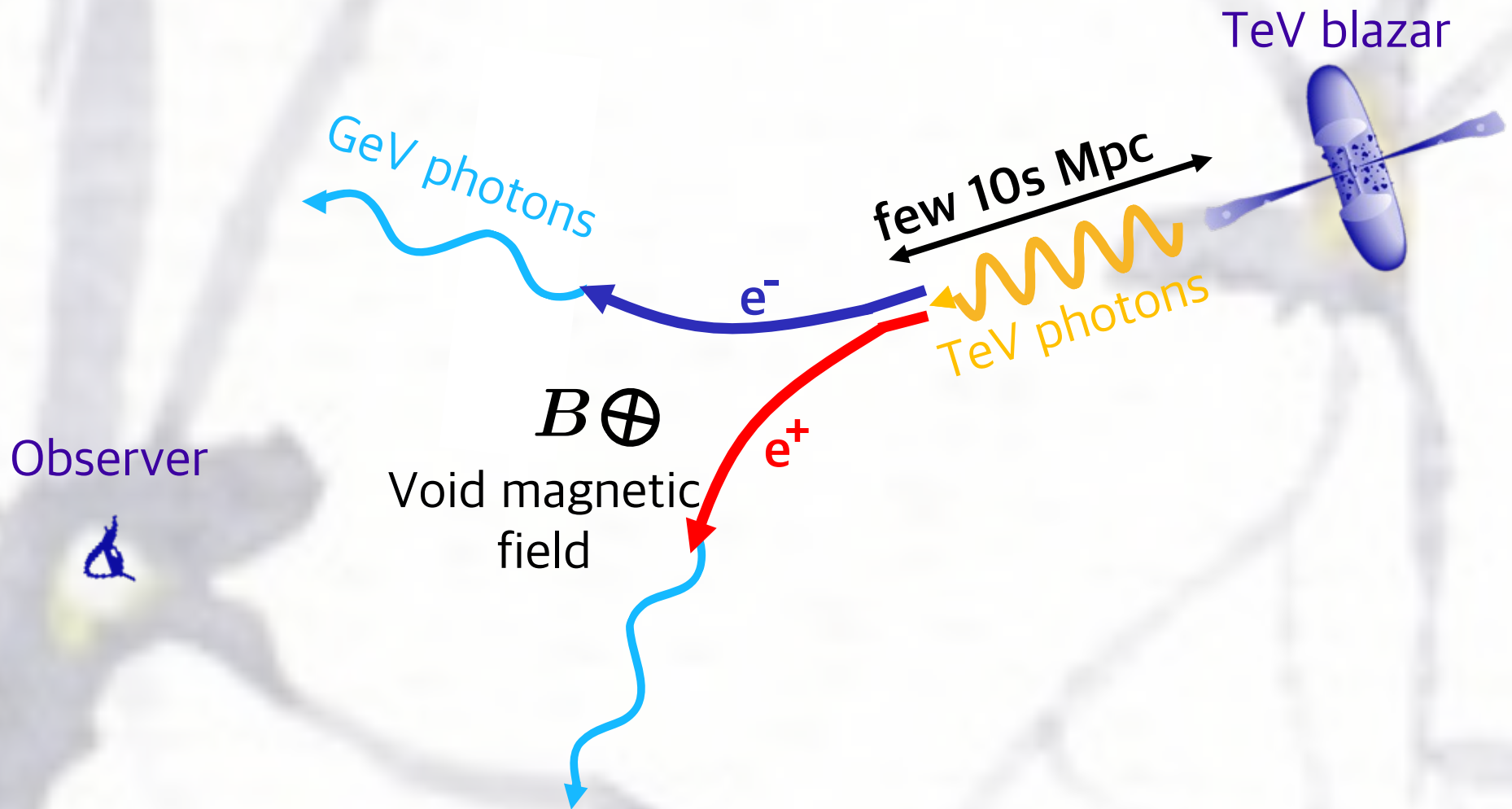


Void magnetic fields

MPIfR/AiFA
Main Colloquium
21/11/2025

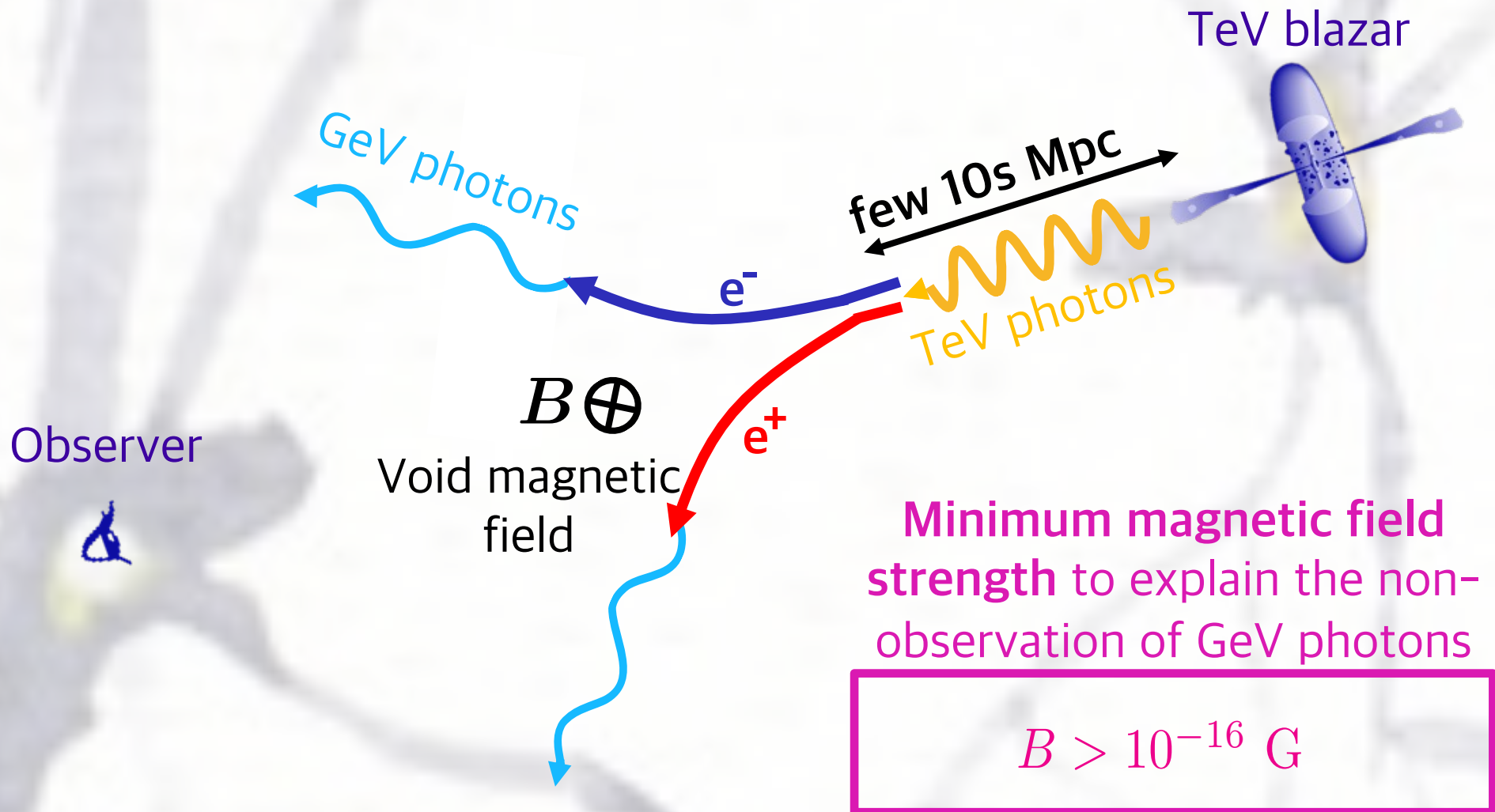


Void magnetic fields



Void magnetic fields

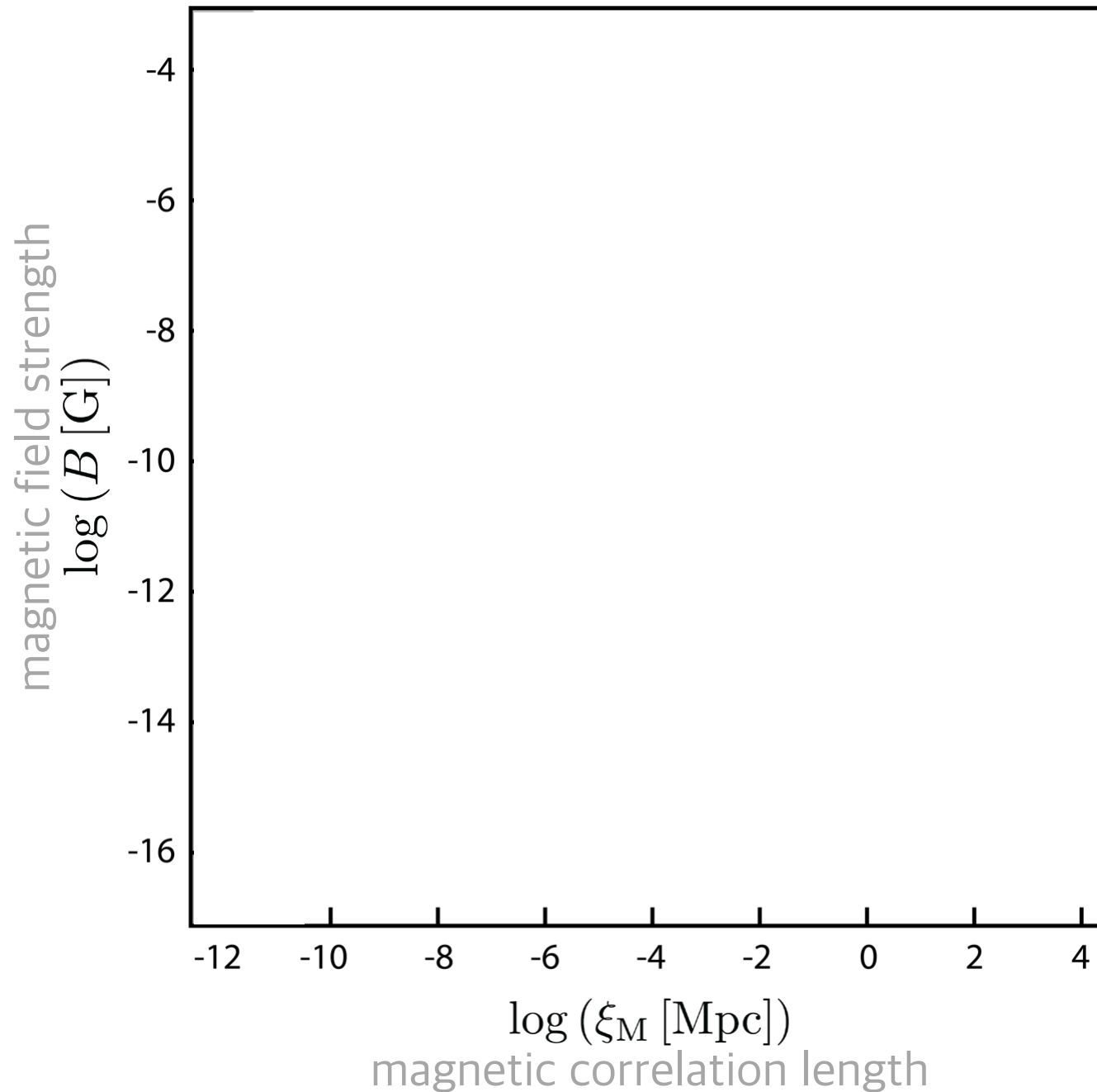
MPIfR/AiFA
Main Colloquium
21/11/2025



[Neronov & Vovk 2010]

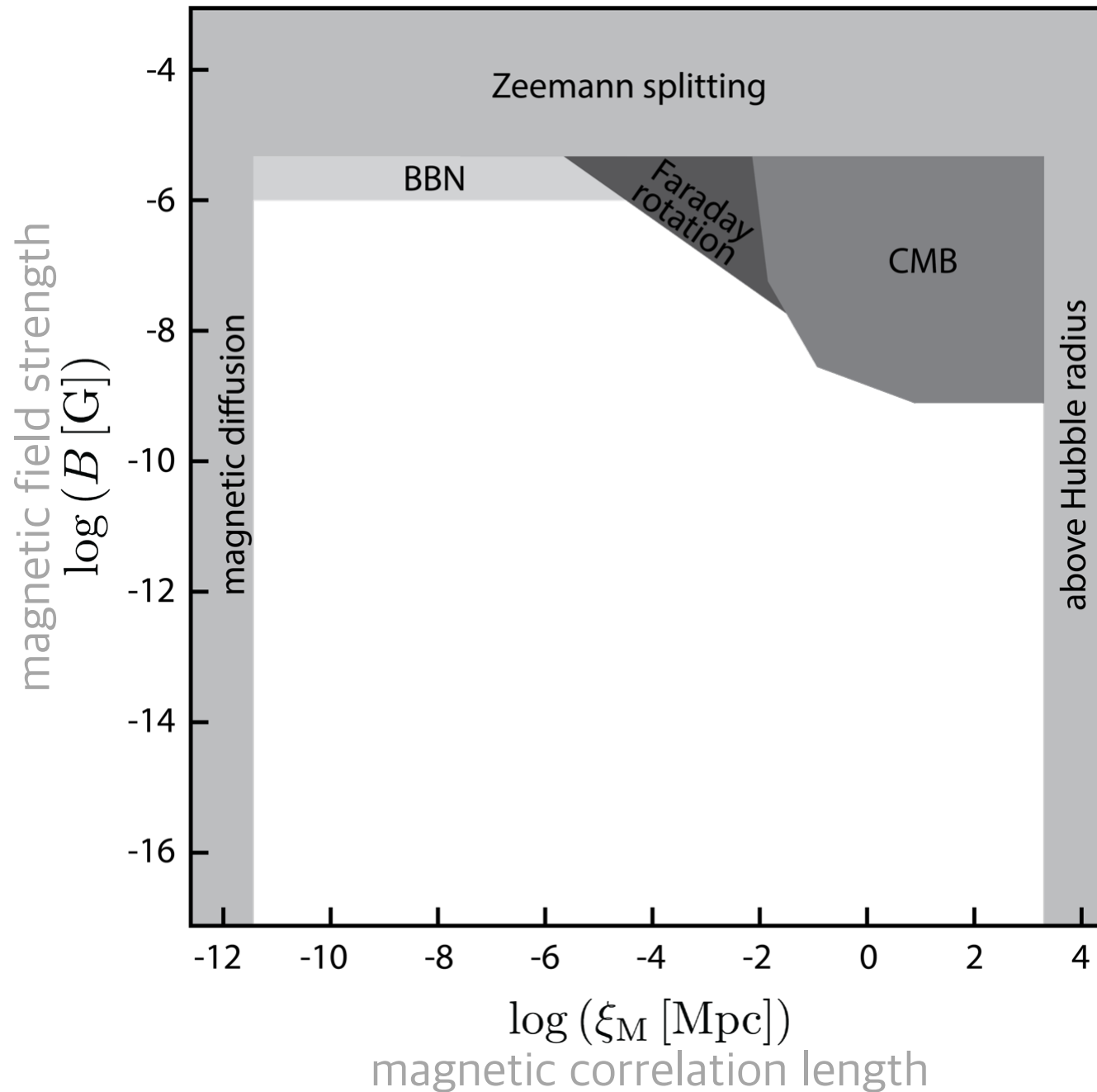
Constraints on void magnetic fields

Nordita program
25/05/2026



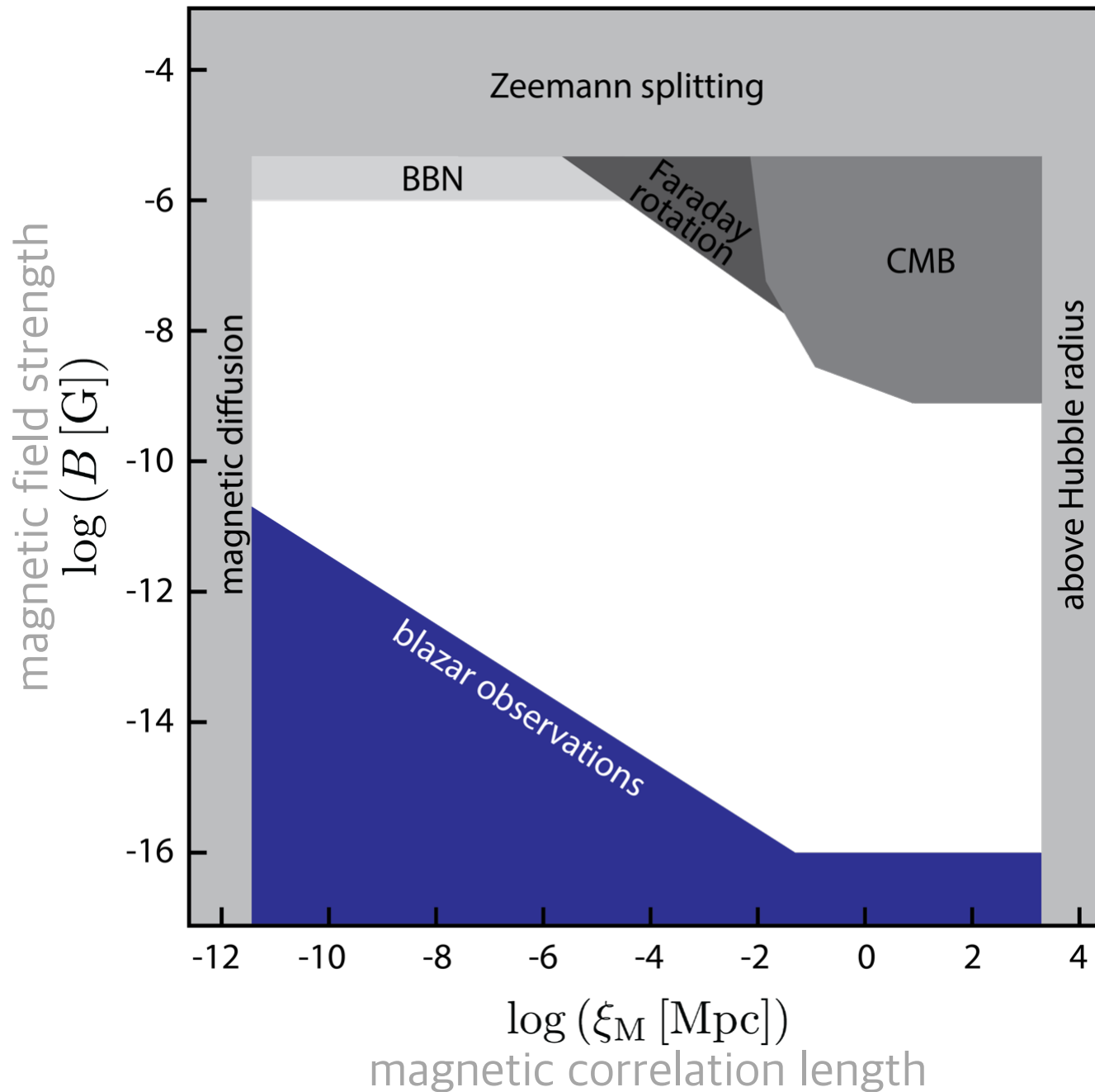
Constraints on void magnetic fields

Nordita program
25/05/2026



Constraints on void magnetic fields

Nordita program
25/05/2026



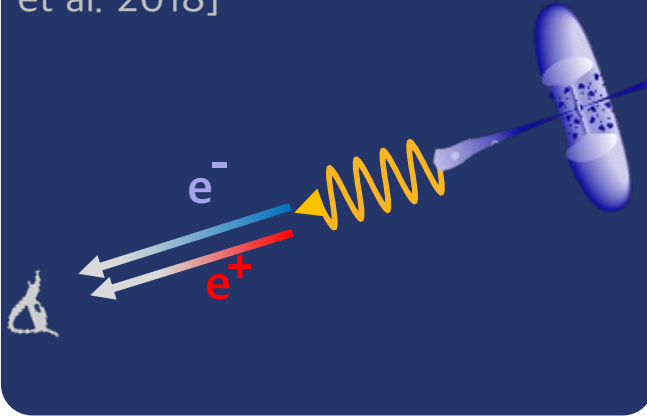
Neronov & Vovk,
Science, 2010

Reliability of fossil magnetic fields

Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]

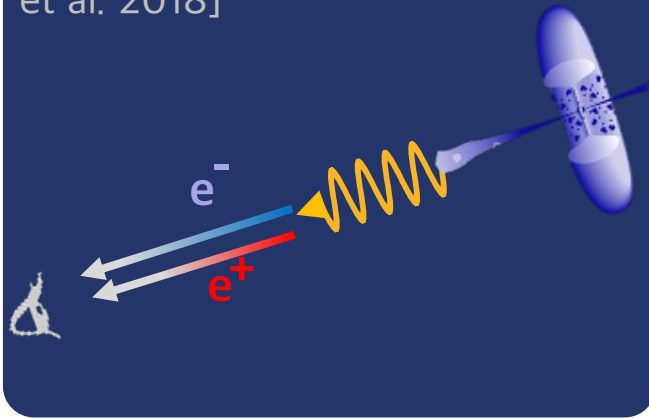


Reliability of fossil magnetic fields

Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



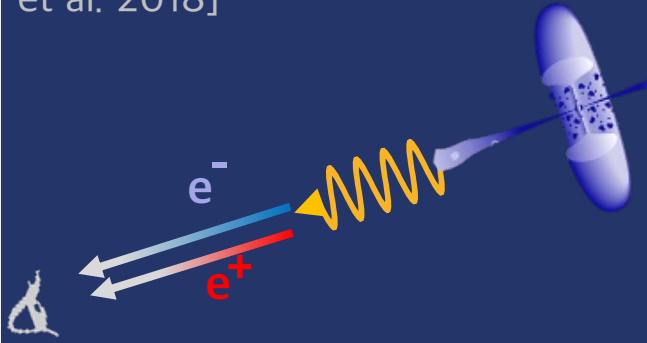
This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Reliability of fossil magnetic fields

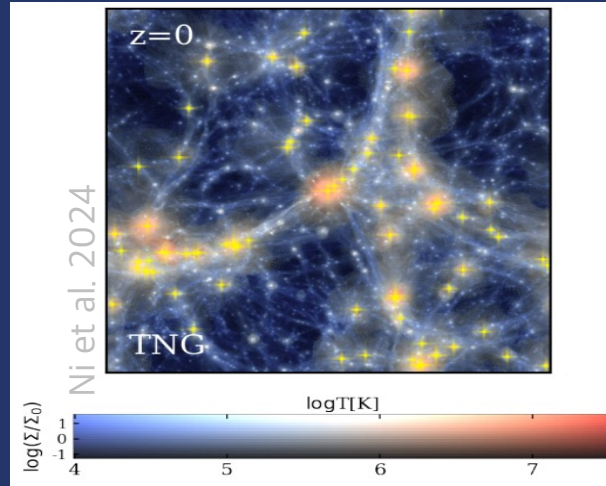
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields



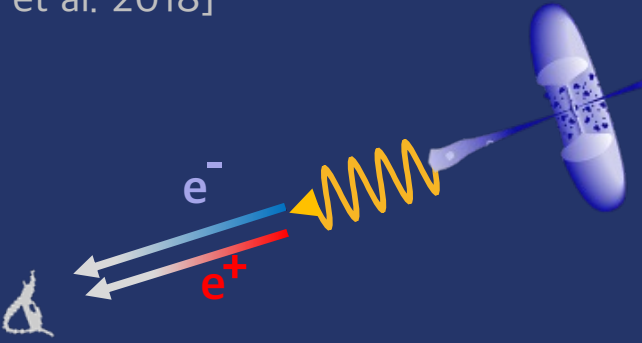
This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Reliability of fossil magnetic fields

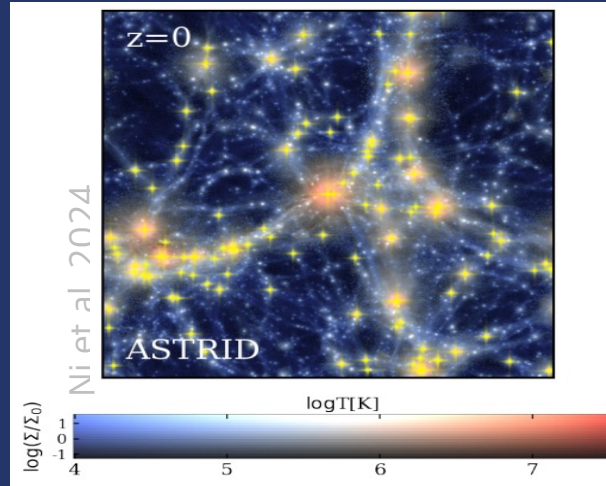
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields



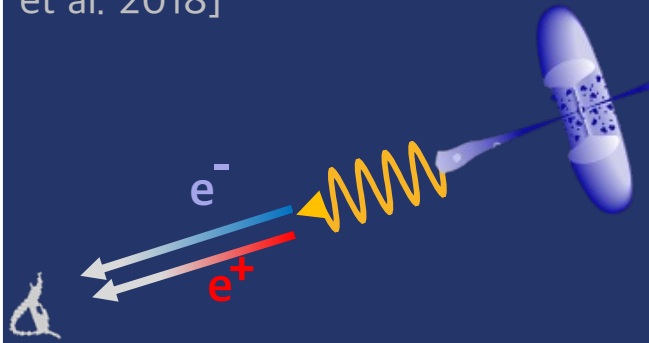
This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Reliability of fossil magnetic fields

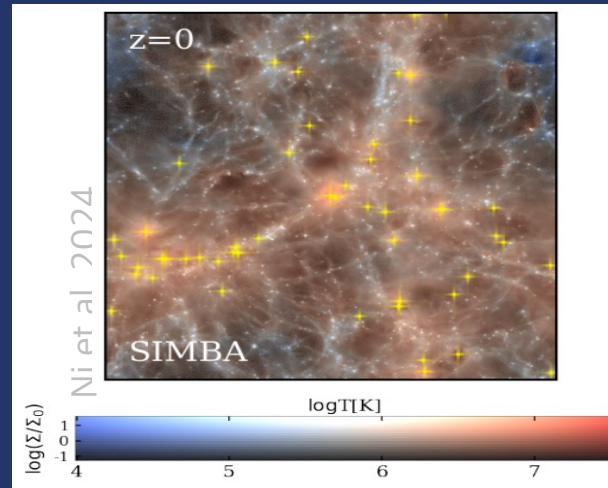
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields



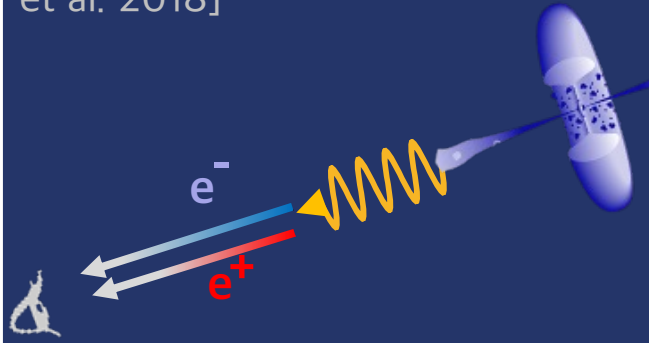
This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Reliability of fossil magnetic fields

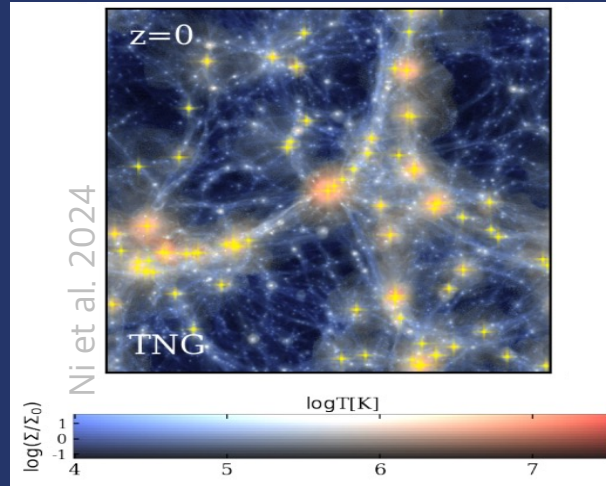
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields



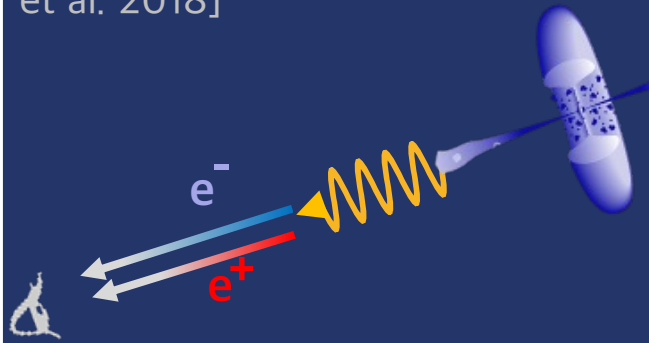
This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Reliability of fossil magnetic fields

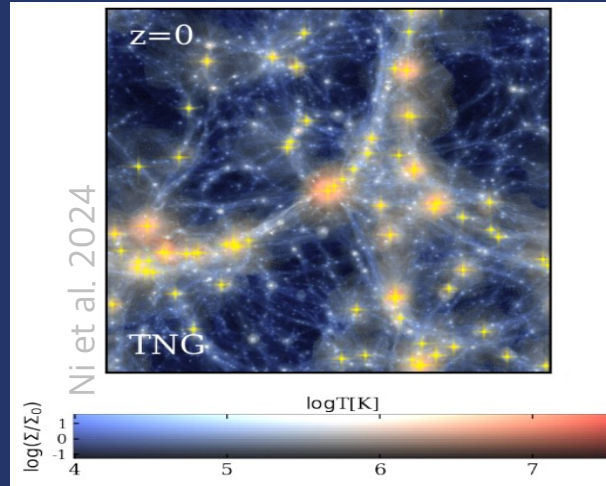
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]

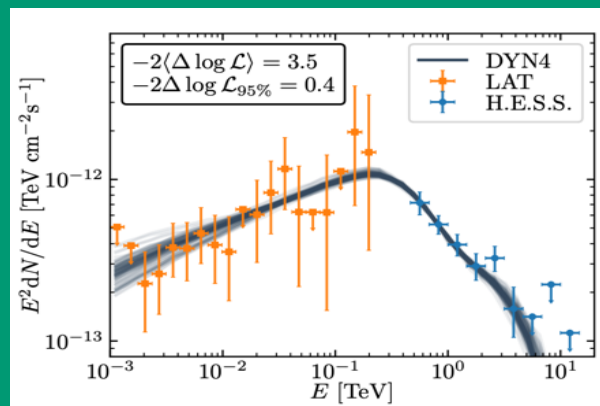


Pollution of voids by galactic magnetic fields



This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Not volume filling enough [Tjemsland et al. 2024].

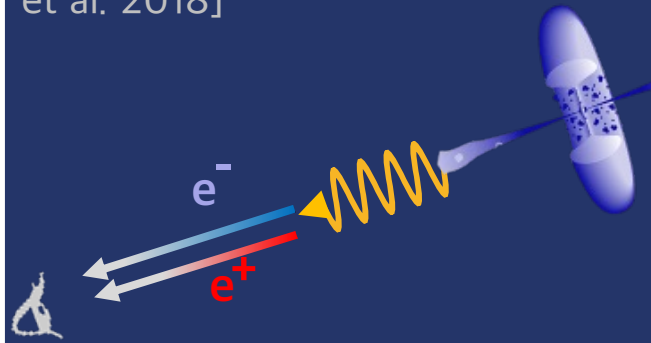


Reliability of fossil magnetic fields

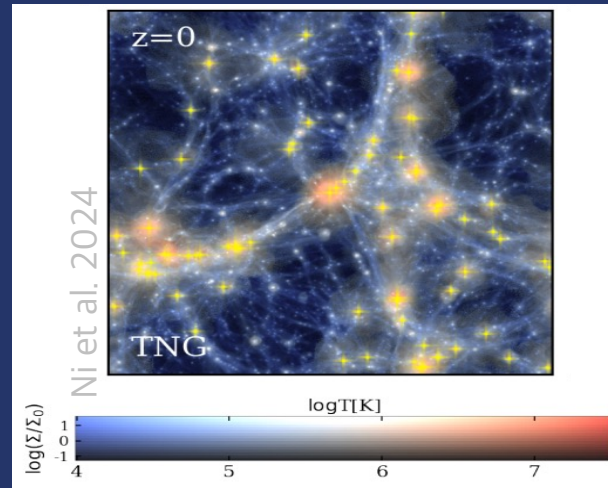
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields

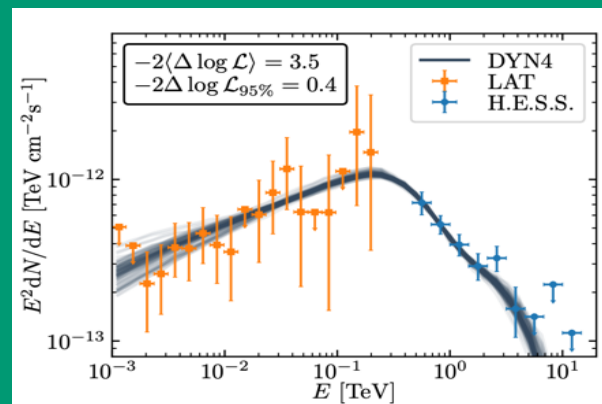


Galactic dipoles add up to fill voids [Garg, Durrer, & Schober 2025]



This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Not volume filling enough [Tjemsland et al. 2024].

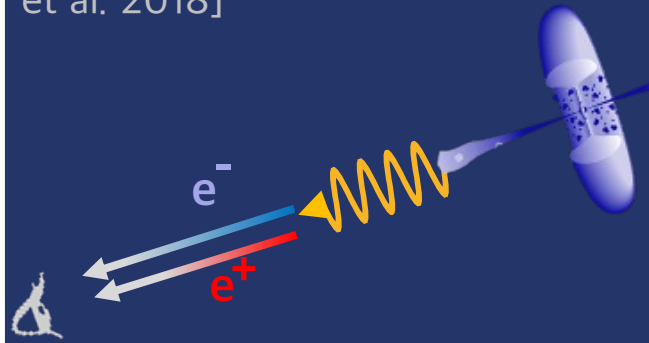


Reliability of fossil magnetic fields

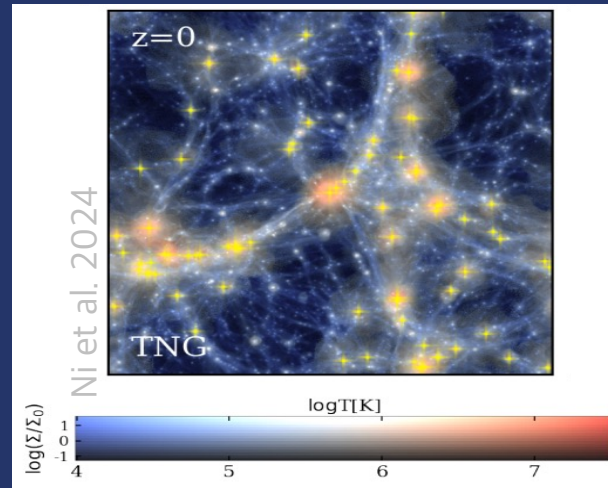
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

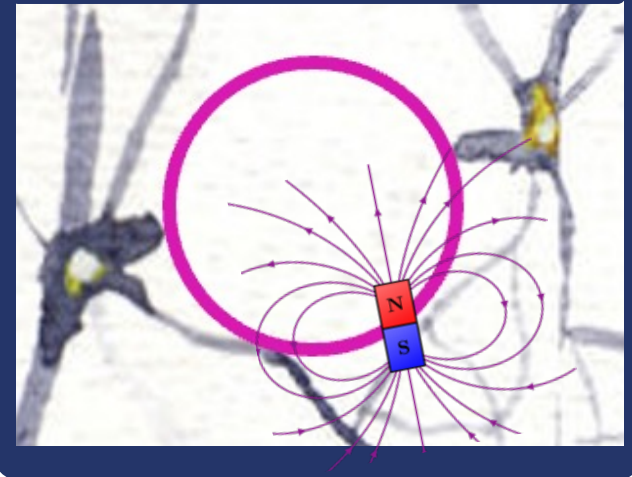
[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields

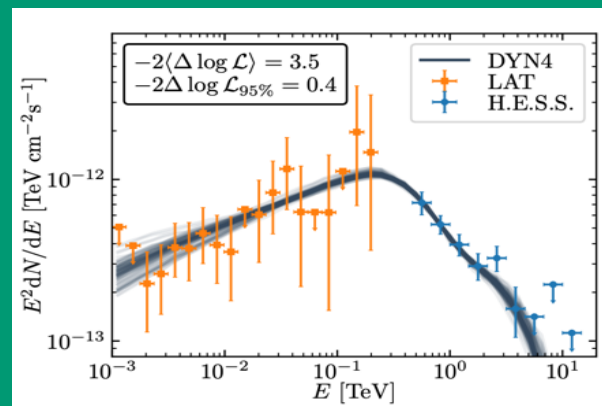


Galactic dipoles add up to fill voids [Garg, Durrer, & Schober 2025]



This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Not volume filling enough [Tjemsland et al. 2024].

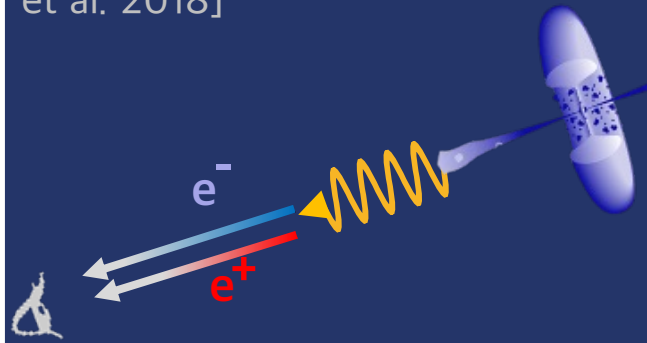


Reliability of fossil magnetic fields

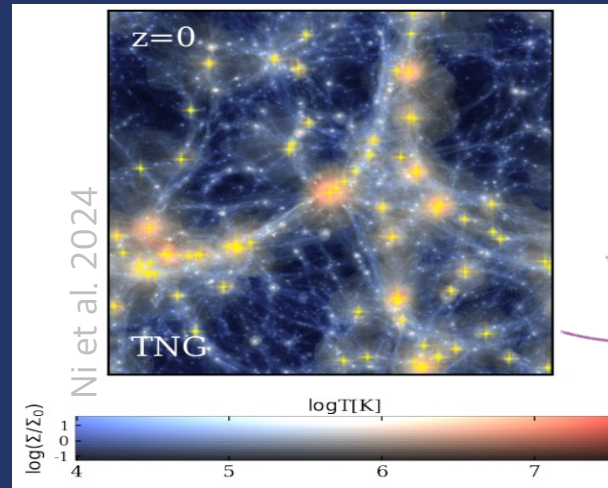
Nordita program
25/05/2026

Plasma instabilities cause non-detection of GeV emission

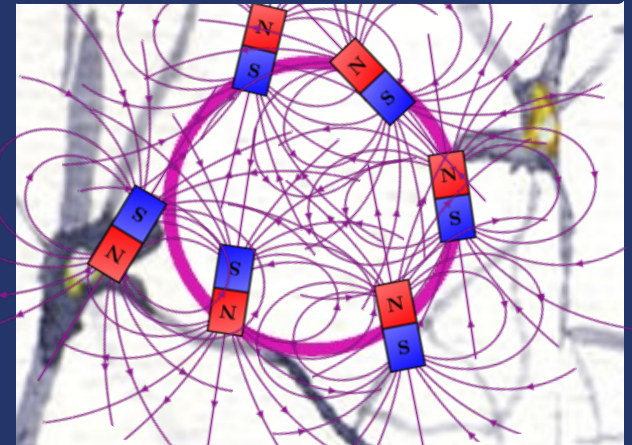
[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields

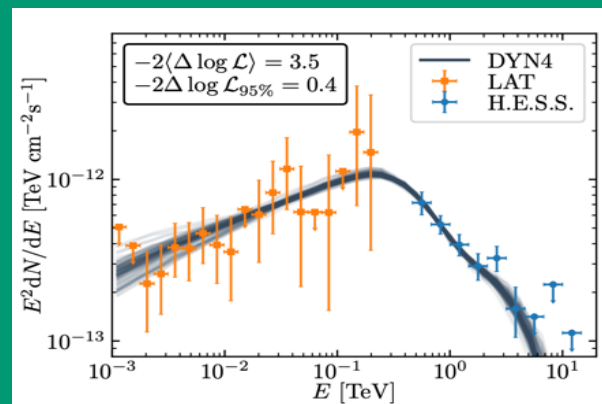


Galactic dipoles add up to fill voids [Garg, Durrer, & Schober 2025]



This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

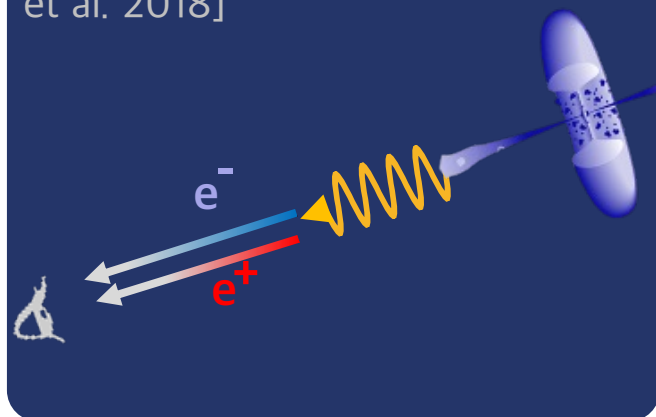
Not volume filling enough [Tjemsland et al. 2024].



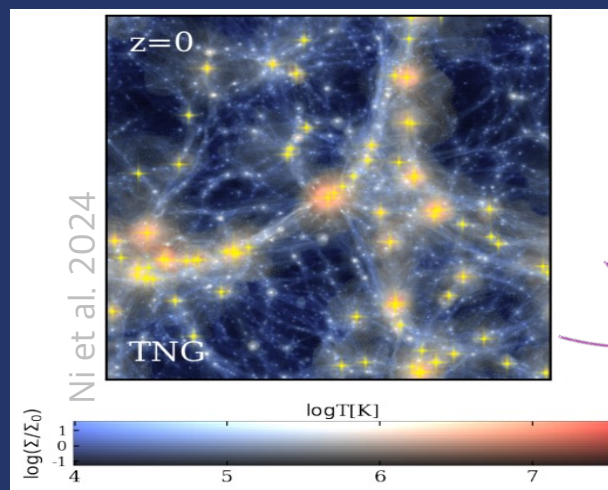
Reliability of fossil magnetic fields

Plasma instabilities cause non-detection of GeV emission

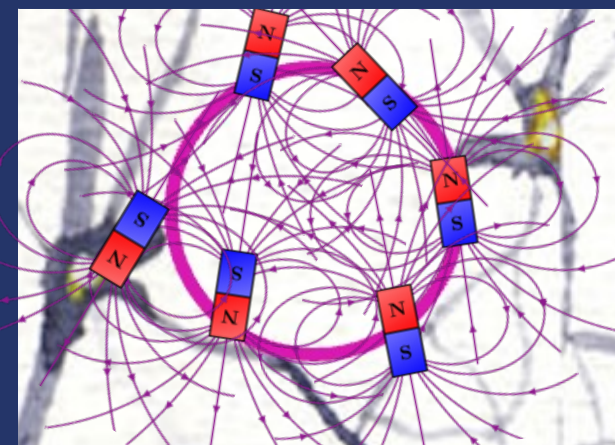
[Schlickeiser et al. 2012, Broderick et al. 2018]



Pollution of voids by galactic magnetic fields

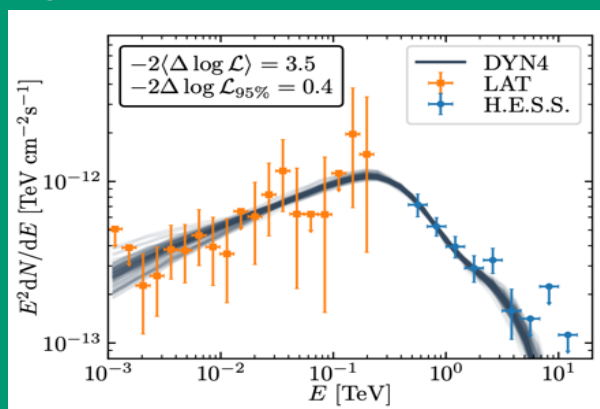


Galactic dipoles add up to fill voids [Garg, Durrer, & Schober 2025]

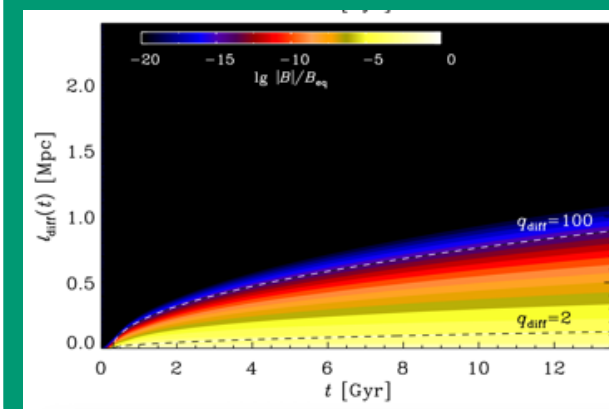


This effect seems not to be significant for the characteristic IGM parameters [Alves Batista, Saveliev, & de Gouveia Dal Pino 2019] and is absent in the lab [Arrowsmith et al 2025].

Not volume filling enough [Tjemsland et al. 2024].



Spreading seems too slow [Ghosh et al. 2026].



Large-scale structure

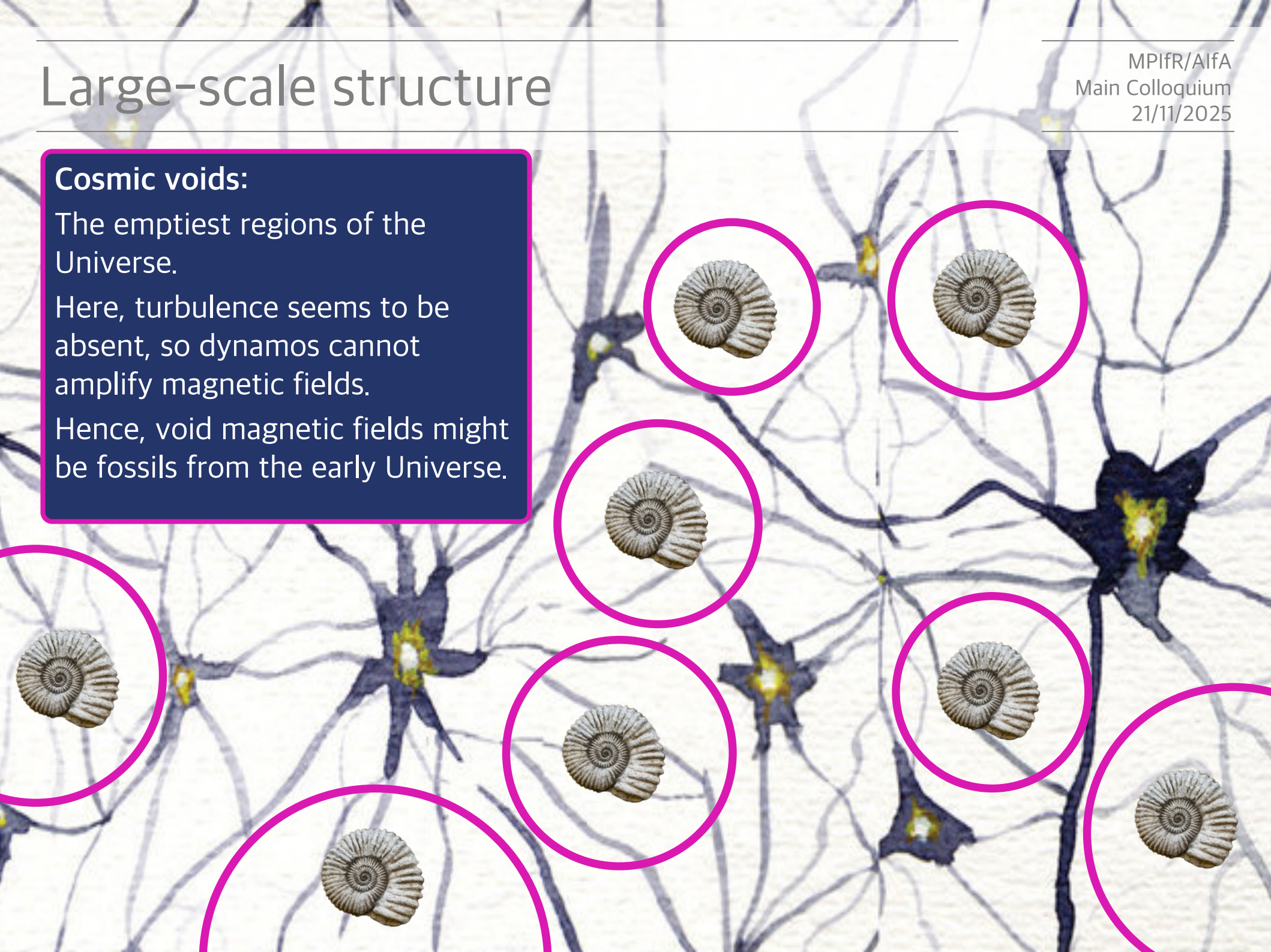
MPIfR/AlfA
Main Colloquium
21/11/2025

Cosmic voids:

The emptiest regions of the Universe.

Here, turbulence seems to be absent, so dynamos cannot amplify magnetic fields.

Hence, void magnetic fields might be fossils from the early Universe.



Early Universe & fundamental physics

Nordita program
25/05/2026



Optically thick

🕒 4×10^5 yr
🌡️ 3000 K
↗️ 3×10^7 ly

🕒 300–500 Myr
🌡️ 30 K
↗️ 3×10^9 ly

🕒 13.6 Gyr
🌡️ 3 K
↗️ 5×10^{10} ly

Big Bang

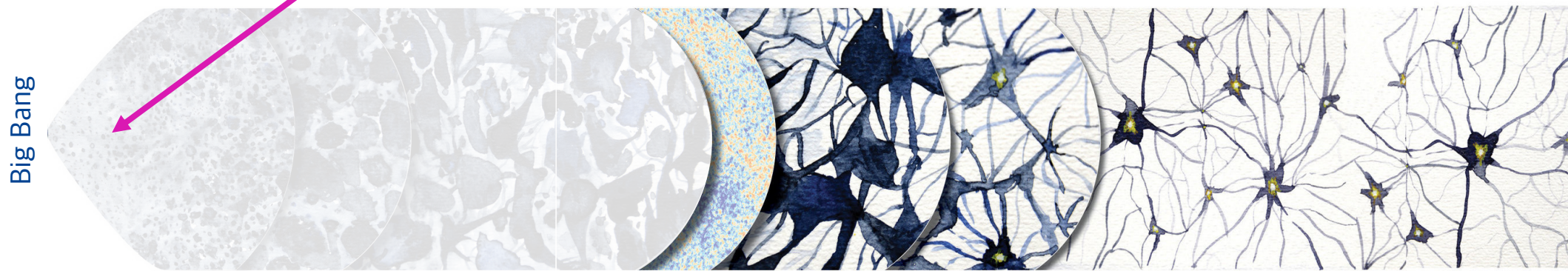
Early Universe & fundamental physics

Nordita program
25/05/2026

Inflation:

Extremely fast expansion of space

[Increase by a factor of 10^{26}]



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

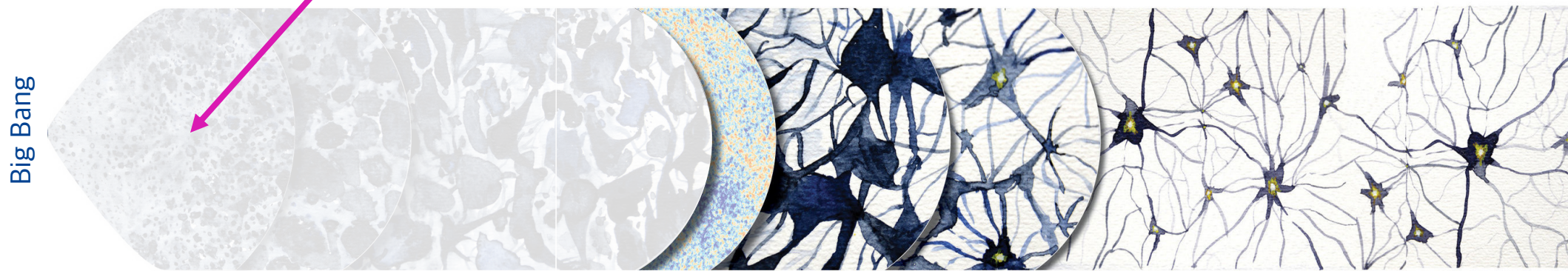
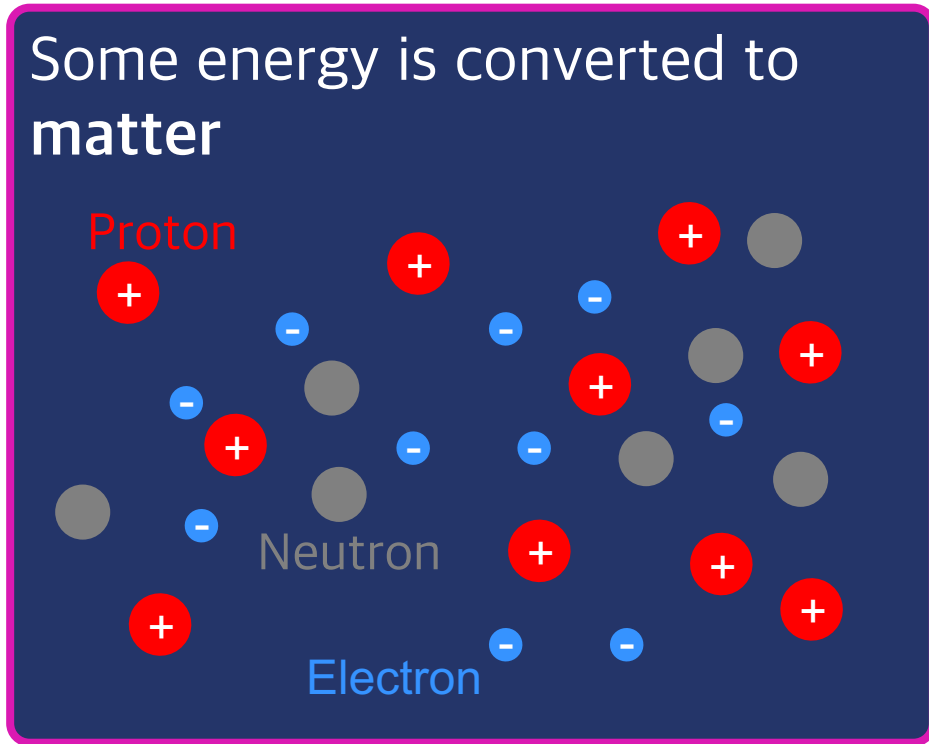
🌡️ 3 K

↗️ 5×10^{10} ly

Early Universe & fundamental physics

Nordita program
25/05/2026

Some energy is converted to
matter



Big Bang

🕒 10^{-32} s
🌡️ 10^{27} K
📏 0.01 ly

🕒 4×10^5 yr
🌡️ 3000 K
📏 3×10^7 ly

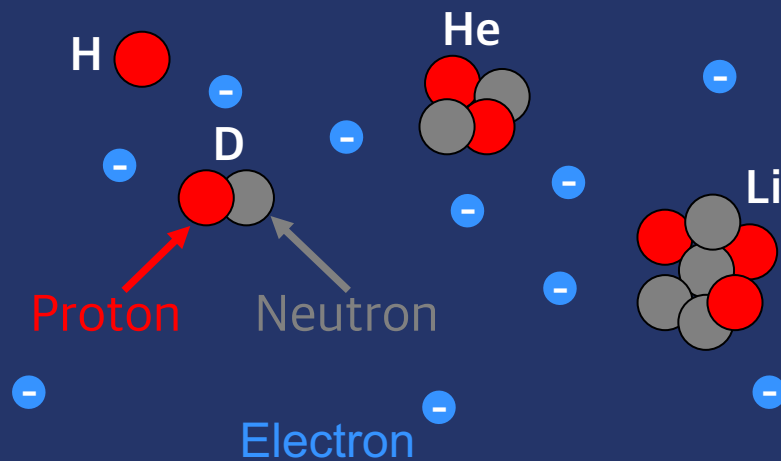
🕒 300–500 Myr
🌡️ 30 K
📏 3×10^9 ly

🕒 13.6 Gyr
🌡️ 3 K
📏 5×10^{10} ly

Early Universe & fundamental physics

Nordita program
25/05/2026

Primordial nucleosynthesis



Big Bang



🕒 10^{-32} s
🌡️ 10^{27} K
↗️ 0.01 ly

🕒 3 min
🌡️ 10^9 K
↗️ 1 ly

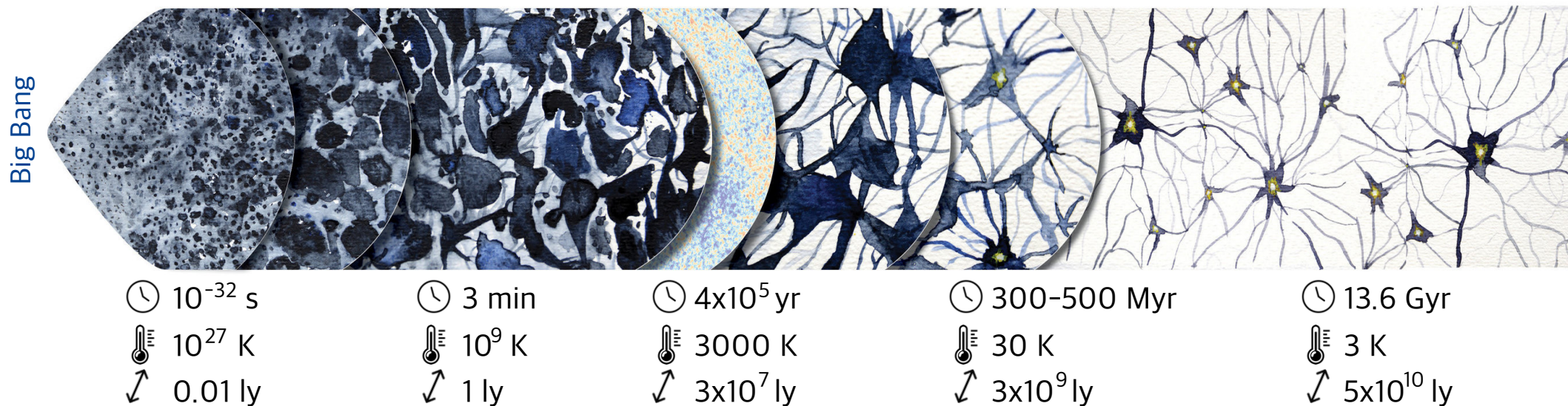
🕒 4×10^5 yr
🌡️ 3000 K
↗️ 3×10^7 ly

🕒 300–500 Myr
🌡️ 30 K
↗️ 3×10^9 ly

🕒 13.6 Gyr
🌡️ 3 K
↗️ 5×10^{10} ly

The early Universe might hold answers to the biggest questions:

- How can gravity and quantum physics be combined?
- Why inflation?
- Why did the Big Bang produce a tiny bit more matter than anti-matter?
- What is dark matter?



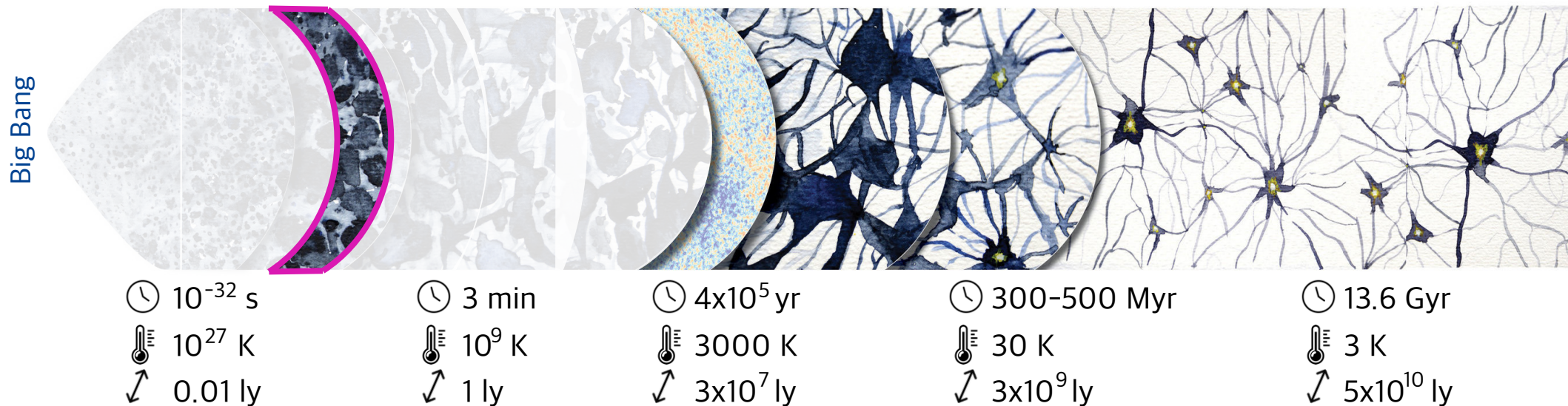
Early Universe & fundamental physics

Nordita program
25/05/2026



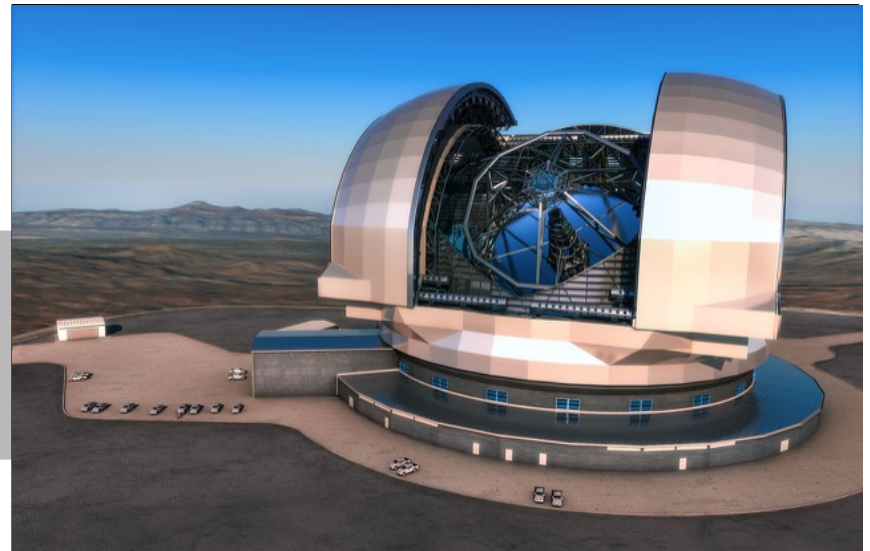
Large-Hadron Collider (LHC) © N. S. J. Hertzog, CERN

This physics is tested at particle accelerators.



Early Universe & fundamental physics

Nordita program
25/05/2026



European Extremely Large Telescope © ESO

Optically thick

🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Big Bang

Early Universe & fundamental physics

Nordita program
25/05/2026



Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

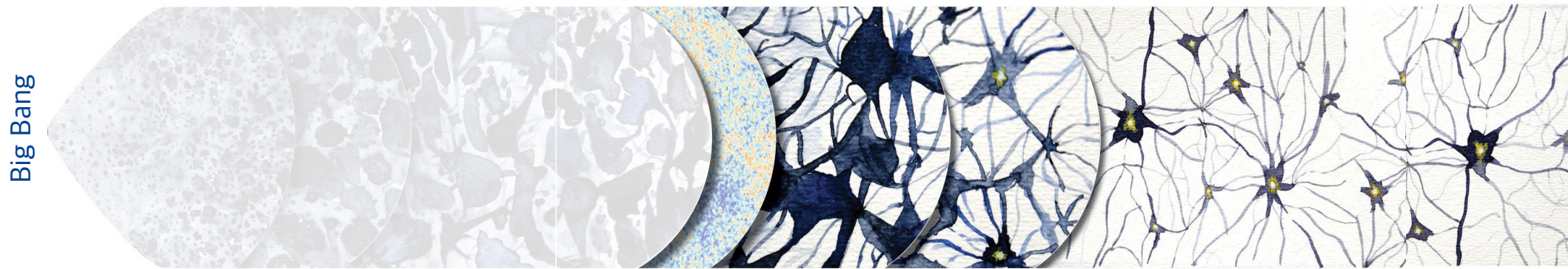
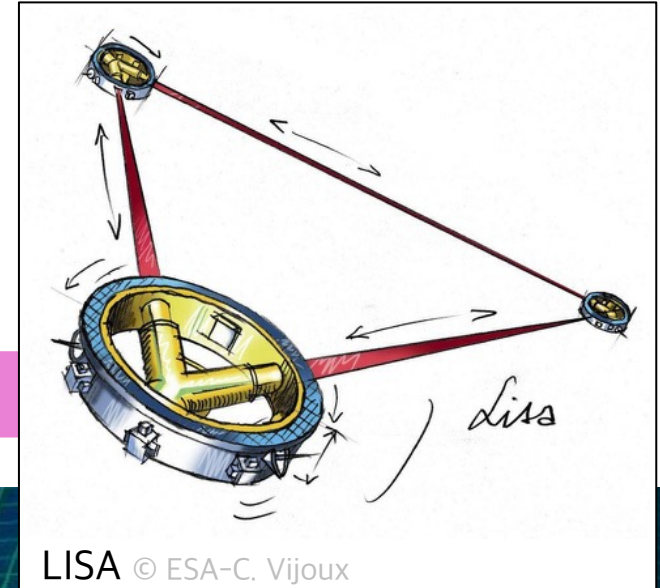
🌡️ 3 K

↗️ 5×10^{10} ly

Early Universe & fundamental physics

Nordita program
25/05/2026

One way to directly probe the early Universe:
Gravitational waves



Big Bang

🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

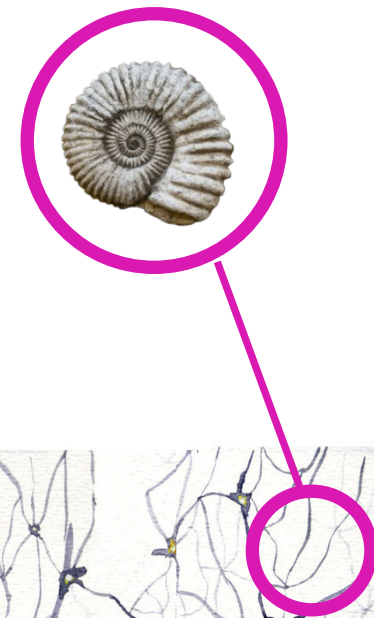
↗️ 5×10^{10} ly

Early Universe & fundamental physics

Nordita program
25/05/2026

Our approach to test early
Universe physics:
Primordial magnetic fields

Fossiles of
primordial
magnetic fields in
today's voids.



Big Bang



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

↗️ 3×10^7 ly

↗️ 3×10^9 ly

↗️ 5×10^{10} ly

Early Universe & fundamental physics

Nordita program
25/05/2026

Our approach to test early
Universe physics:
Primordial magnetic fields

Fossiles of
primordial
magnetic fields in
today's voids.



Big Bang



🕒 10^{-32} s
🌡️ 10^{27} K
📏 0.01 ly

🕒 3 min
🌡️ 10^9 K
📏 1 ly

🕒 4×10^5 yr
🌡️ 3000 K
📏 3×10^7 ly

🕒 300–500 Myr
🌡️ 30 K
📏 3×10^9 ly

🕒 13.6 Gyr
🌡️ 3 K
📏 5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026

Primordial magnetogenesis

- **Inflation**

[Turner & Widrow 1988,
Ratra 1992]

$$B_0 \approx 10^{-65} - 10^{-9} \text{ G}$$

- **(1st-order) phase transitions**

[Hogan 1983, Vachaspati
1991, Sigl et al. 1997]

$$B_0 \approx 10^{-29} - 10^{-20} \text{ G}$$

Fossiles of
primordial
magnetic fields in
today's voids.



Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

📏 3×10^9 ly

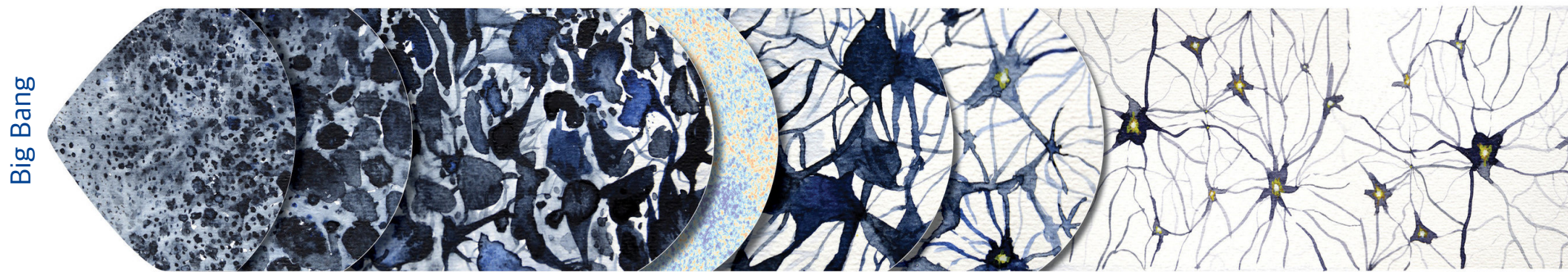
🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

↗️ 3×10^7 ly

↗️ 3×10^9 ly

↗️ 5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026

Magnetic field strength ↑

Fundamental physics:
Different theories predict different magnetic field strengths.

Time →

Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

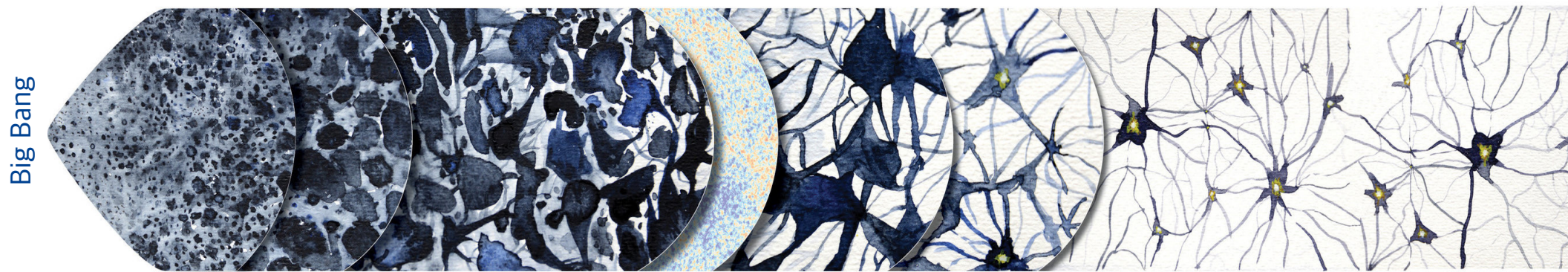
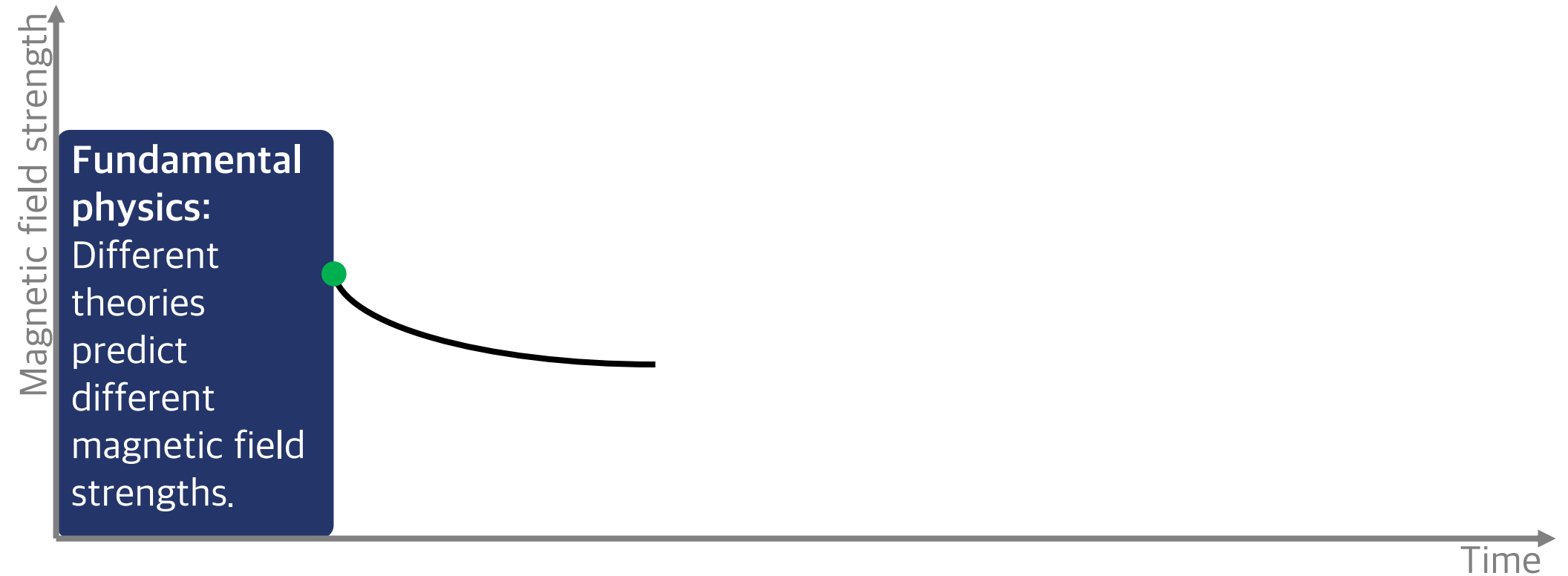
🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

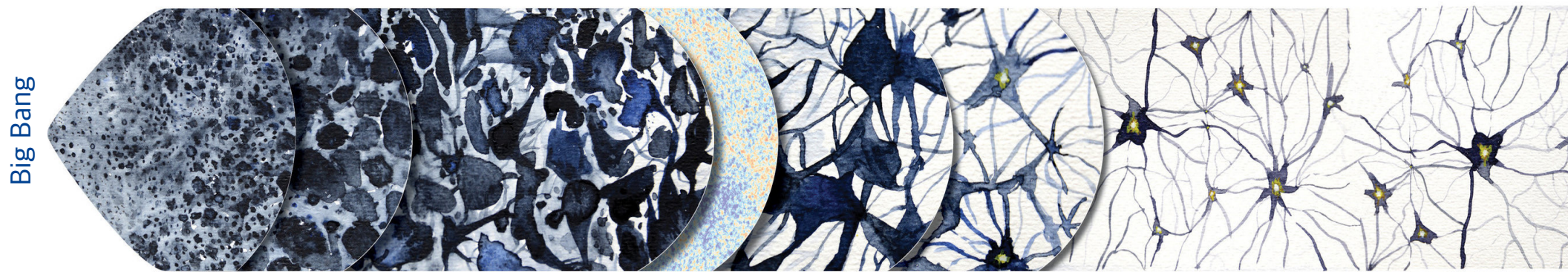
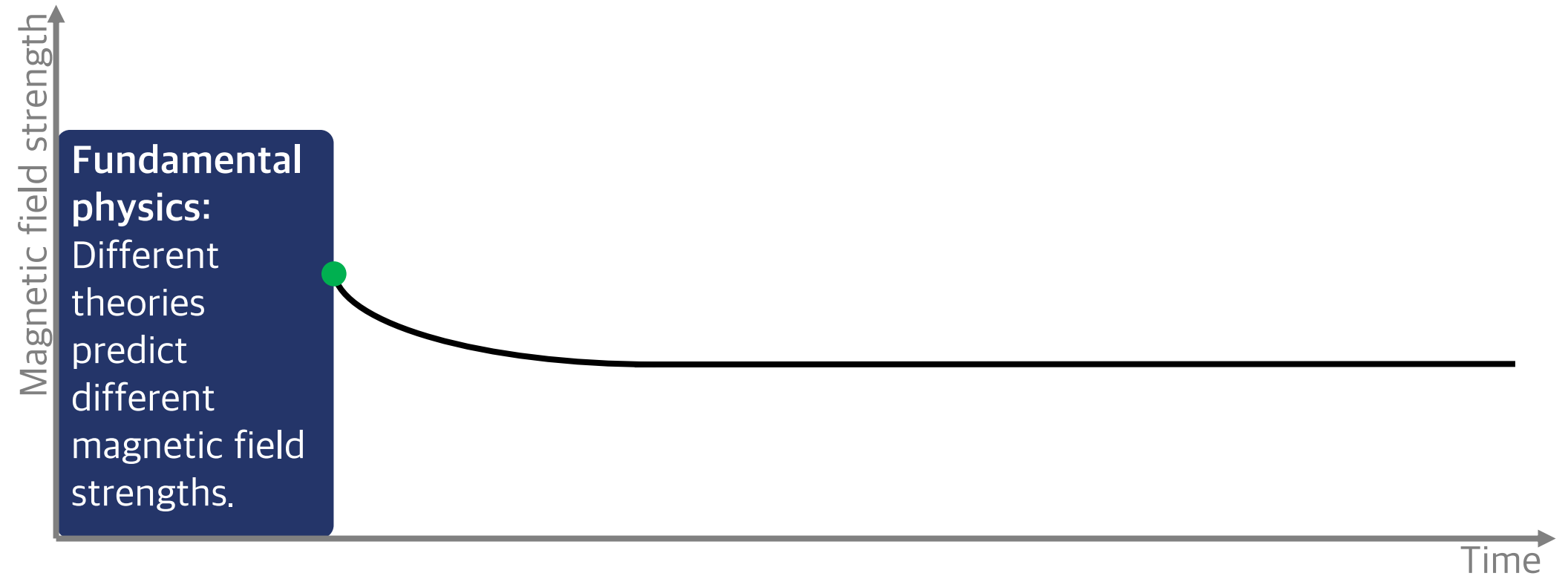
↗️ 3×10^7 ly

↗️ 3×10^9 ly

↗️ 5×10^{10} ly

Magnetic fields & fundamental physics

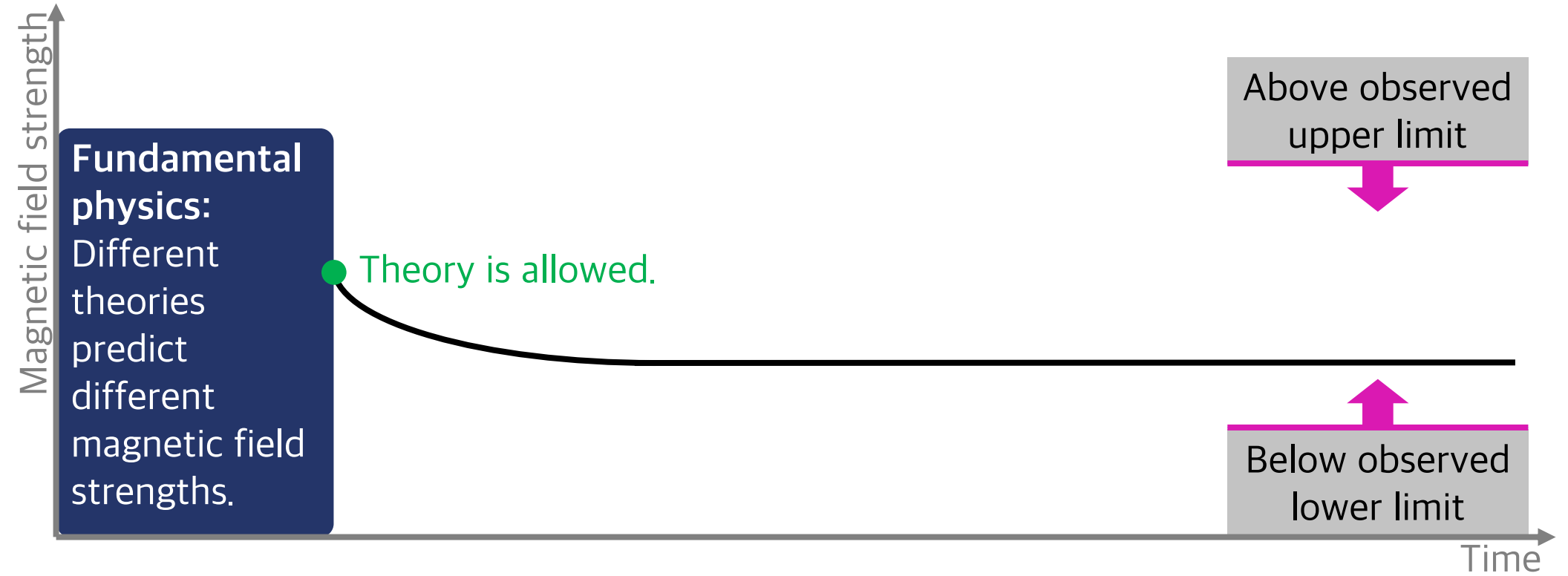
Nordita program
25/05/2026



🕒 10^{-32} s	🕒 3 min	🕒 4×10^5 yr	🕒 300–500 Myr	🕒 13.6 Gyr
🌡️ 10^{27} K	🌡️ 10^9 K	🌡️ 3000 K	🌡️ 30 K	🌡️ 3 K
↗️ 0.01 ly	↗️ 1 ly	↗️ 3×10^7 ly	↗️ 3×10^9 ly	↗️ 5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026



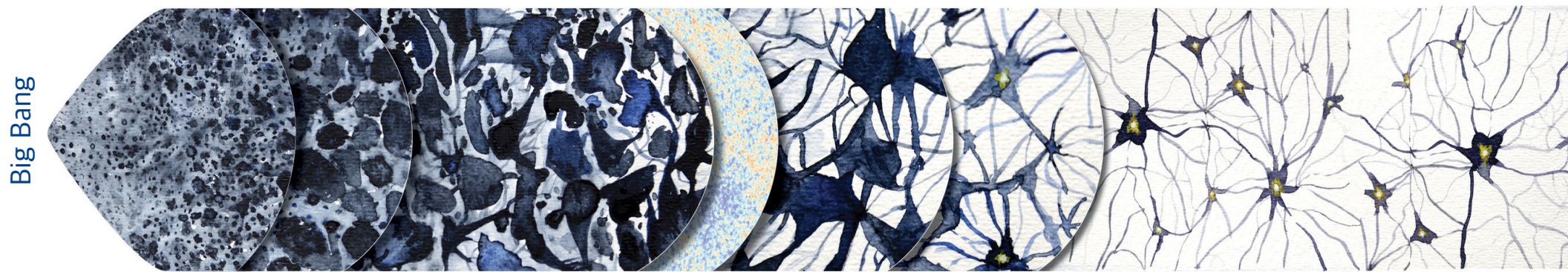
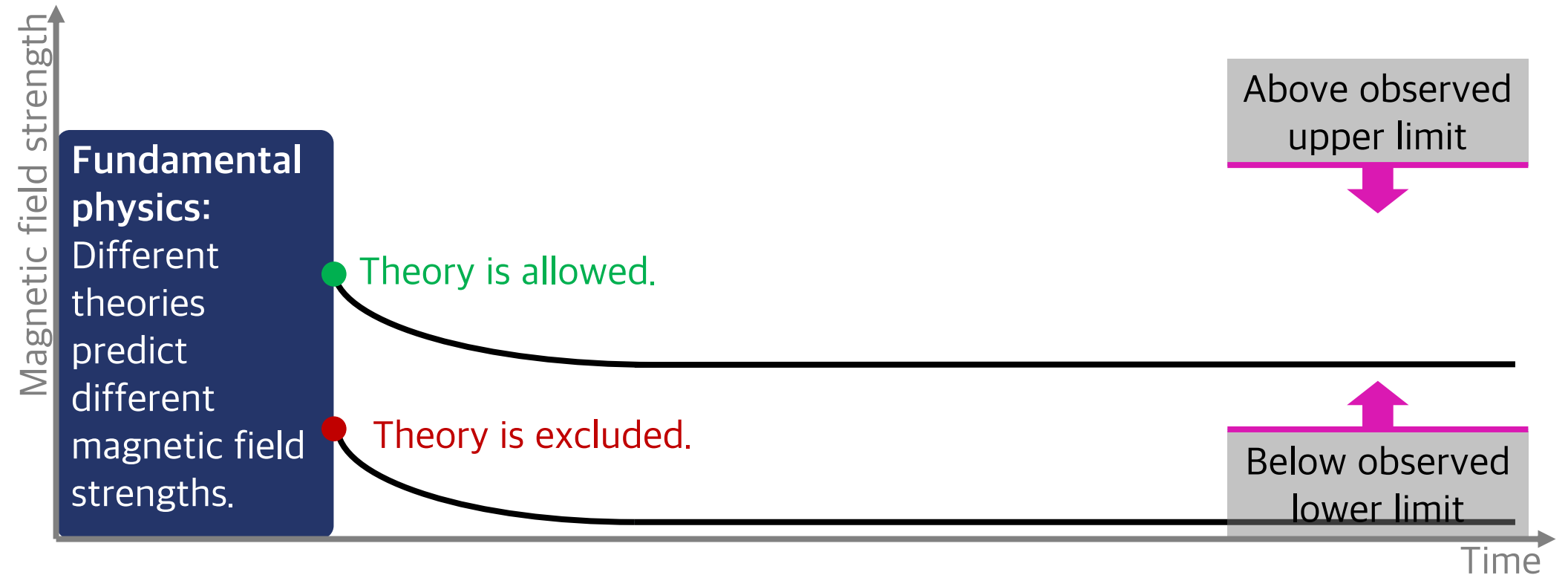
Fundamental physics:
Different theories predict different magnetic field strengths.



10^{-32} s	3 min	4×10^5 yr	300–500 Myr	13.6 Gyr
10^{27} K	10^9 K	3000 K	30 K	3 K
0.01 ly	1 ly	3×10^7 ly	3×10^9 ly	5×10^{10} ly

Magnetic fields & fundamental physics

Nordita program
25/05/2026



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

↗️ 3×10^7 ly

↗️ 3×10^9 ly

↗️ 5×10^{10} ly

Magnetic history of the Universe

Nordita program
25/05/2026

Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of the Universe

Nordita program
25/05/2026

Seed
magnetic
fields

Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Dynamical variables: magnetic field B , velocity field U , density ρ + equation of state

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Dynamical variables: magnetic field B , velocity field U , density ρ + equation of state
- Evolution equations:

Fully general
relativistic MHD
equations

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Dynamical variables: magnetic field B , velocity field U , density ρ + equation of state
- Evolution equations:

Fully general relativistic MHD equations

Use comoving quantities like $\tilde{B} \equiv a^2 B$ and conformal time $d\tilde{t} \equiv a^{-1} dt$ [$ds^2 = c^2 dt^2 - a(t)^2 d\Sigma$].

MHD equations

Brandenburg et al. 1996

Seed magnetic fields



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Magnetic field evolution is governed by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B}]$$

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly


Decaying magnetohydrodynamical (MHD) turbulence

- Magnetic field evolution is governed by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B}]$$

- It implies that **magnetic helicity** \mathcal{H} is conserved [for $\eta \rightarrow 0$]:

$$\mathcal{H} = \int_V \mathbf{A} \cdot \mathbf{B} \, dV = \text{const}$$



vector potential



Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Magnetic field evolution is governed by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B}]$$

- It implies that **magnetic helicity** \mathcal{H} is conserved [for $\eta \rightarrow 0$]:

$$\mathcal{H} = \int_V \mathbf{A} \cdot \mathbf{B} \, dV \approx \xi_M B^2 = \text{const}$$

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Decaying magnetohydrodynamical (MHD) turbulence

- Magnetic field evolution is governed by the induction equation:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B}]$$

- It implies that **magnetic helicity** \mathcal{H} is conserved [for $\eta \rightarrow 0$]:

$$\mathcal{H} = \int_V \mathbf{A} \cdot \mathbf{B} \, dV \approx \xi_M B^2 = \text{const}$$

This implies an **inverse cascade** of magnetic energy:

$$B \searrow \rightarrow \xi_M \nearrow$$



Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

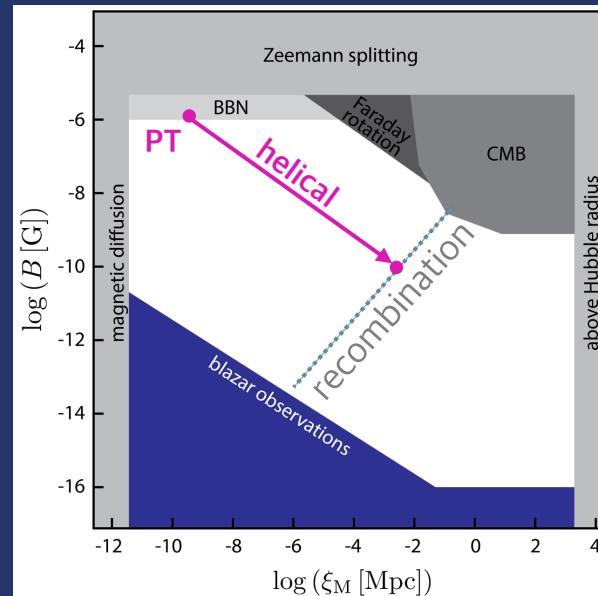
🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of the Universe

Nordita program
25/05/2026

Decaying magnetohydrodynamical (MHD) turbulence



[Kahniashvili et al. 2013 ,
Brandenburg et al. 2017]

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

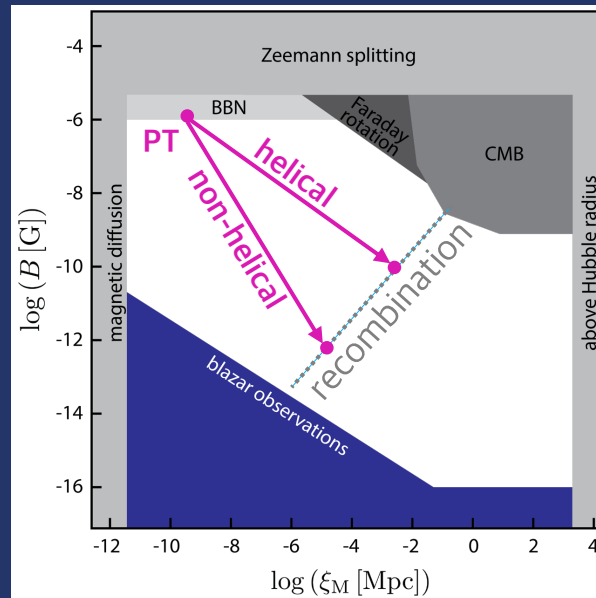
↗️ 5×10^{10} ly

Big Bang

Magnetic history of the Universe

Nordita program
25/05/2026

Decaying magnetohydrodynamical (MHD) turbulence



[Kahniashvili et al. 2013 ,
Brandenburg et al. 2017,
Hosking & Schekochihin 2021]

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

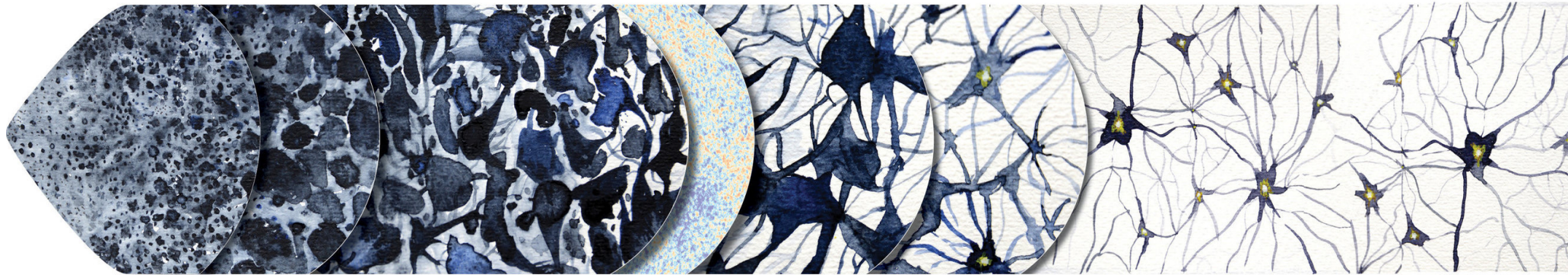
Big Bang

Magnetic history of the Universe

Nordita program
25/05/2026

Seed
magnetic
fields

Decaying MHD
turbulence



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Big Bang

Magnetic history of the Universe

Nordita program
25/05/2026

Seed
magnetic
fields

Decaying MHD
turbulence

Passive evolution

Magnetic field is frozen in Hubble
expansion



Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of the Universe

Nordita program
25/05/2026

Reviews:

Durrer & Neronov 2013

Subramanian 2016

Vachaspati 2020

Seed
magnetic
fields

Decaying MHD
turbulence

Passive
evolution



Big Bang

🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of the Universe

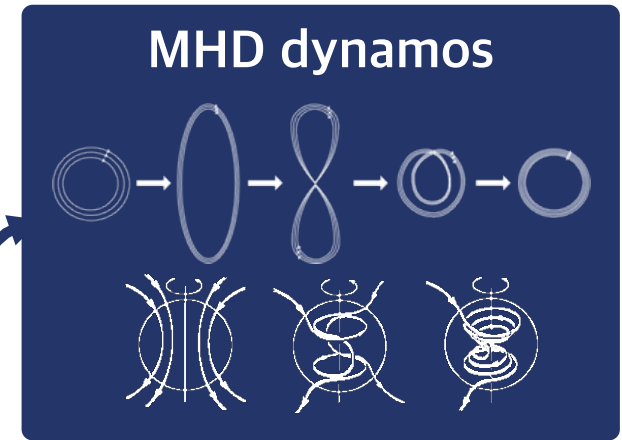
Nordita program
25/05/2026

Reviews:

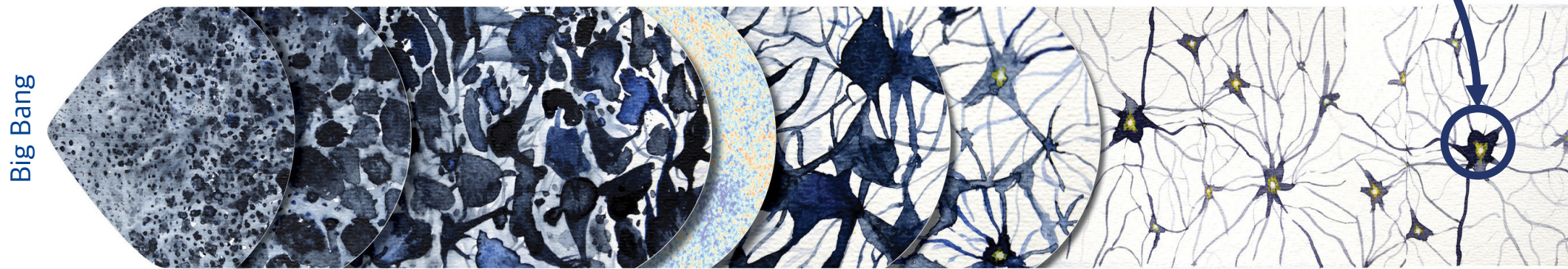
Durrer & Neronov 2013

Subramanian 2016

Vachaspati 2020



Memory of primordial fields lost



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

📏 0.01 ly

📏 1 ly

📏 3×10^7 ly

📏 3×10^9 ly

📏 5×10^{10} ly

Magnetic history of the Universe

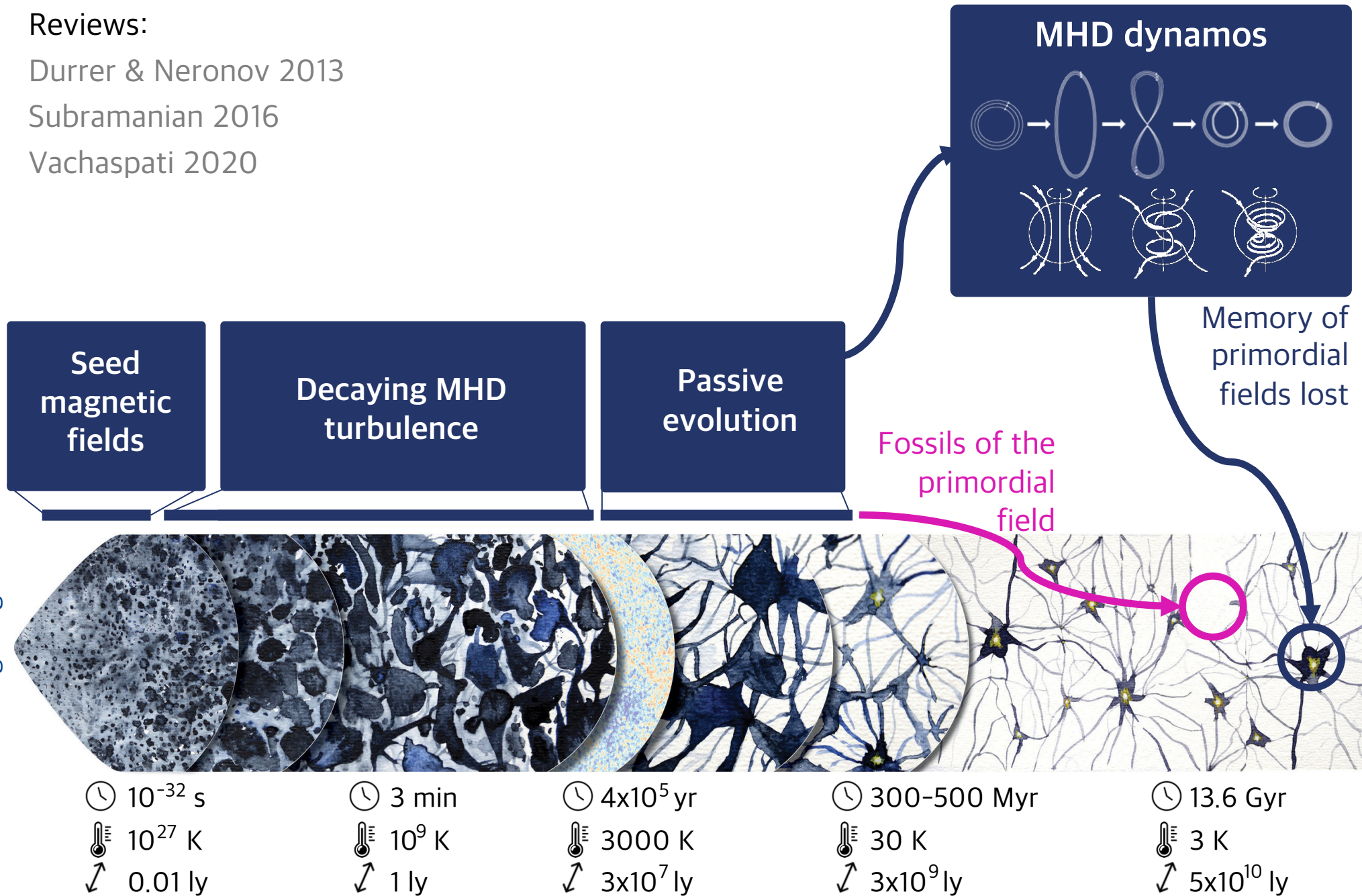
Nordita program
25/05/2026

Reviews:

Durrer & Neronov 2013

Subramanian 2016

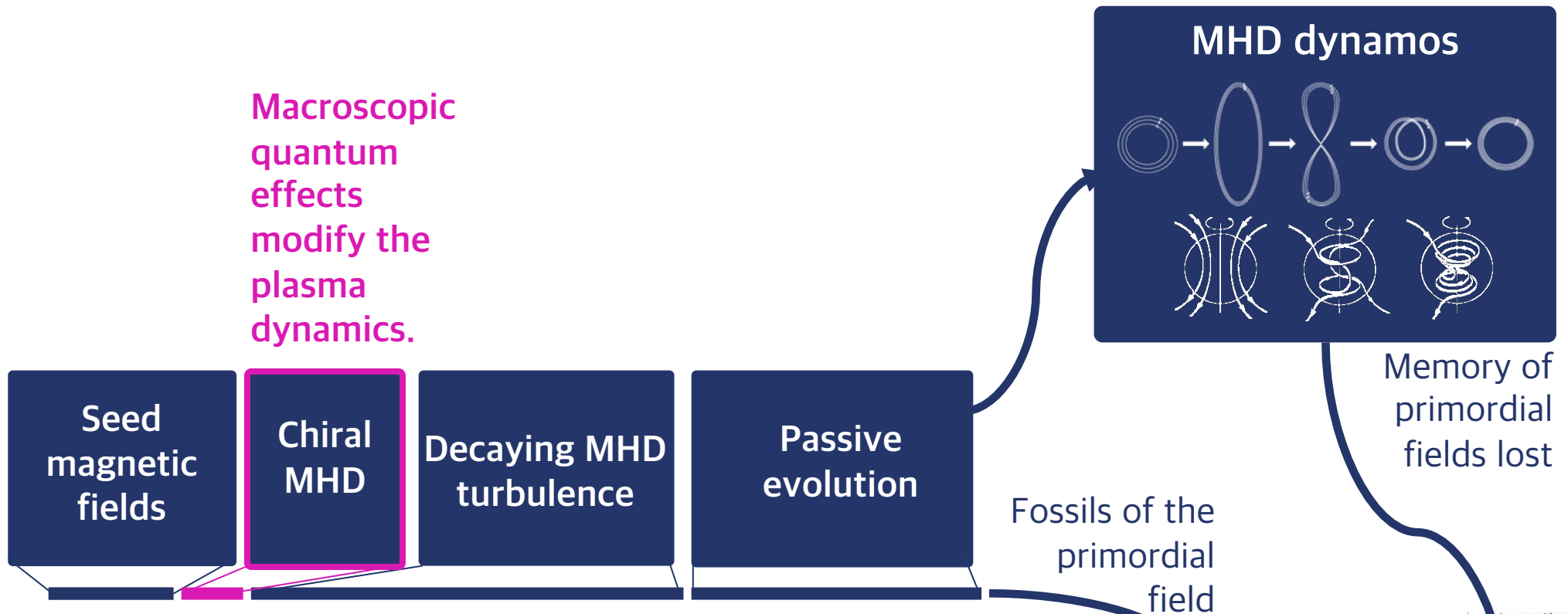
Vachaspati 2020



Magnetic history of the Universe

Nordita program
25/05/2026

Macroscopic quantum effects modify the plasma dynamics.



Big Bang



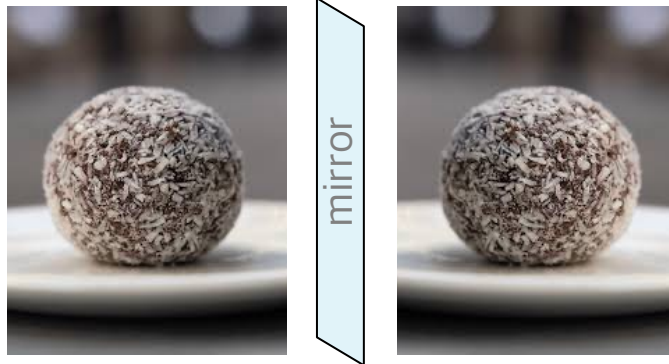
🕒 10^{-32} s	🕒 3 min	🕒 4×10^5 yr	🕒 300–500 Myr	🕒 13.6 Gyr
🌡️ 10^{27} K	🌡️ 10^9 K	🌡️ 3000 K	🌡️ 30 K	🌡️ 3 K
📏 0.01 ly	📏 1 ly	📏 3×10^7 ly	📏 3×10^9 ly	📏 5×10^{10} ly

Magnetic history of the Universe

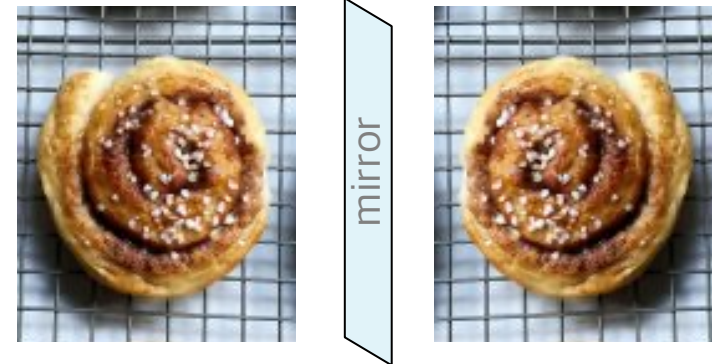
Nordita program
25/05/2026

Chirality

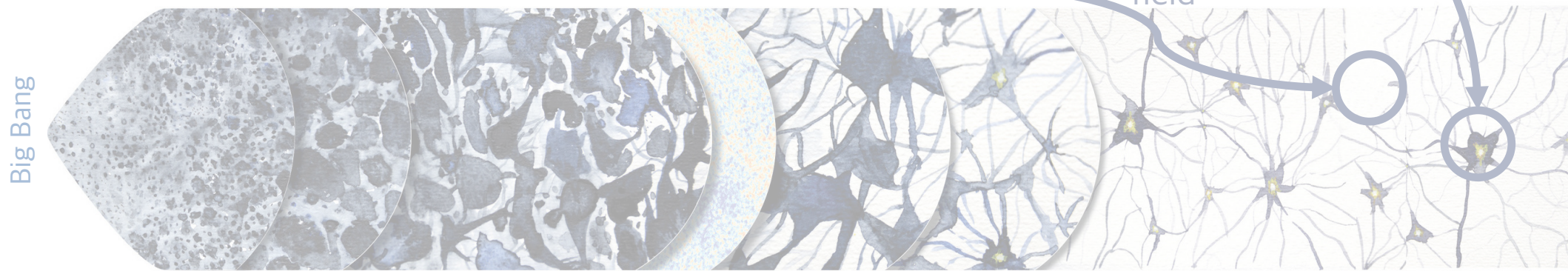
Achiral objects can be superimposed with mirrored version.



Chiral objects cannot be superimposed with mirrored version.



Seed
magnetic
fields



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

📏 0.01 ly

📏 1 ly

📏 3×10^7 ly

📏 3×10^9 ly

📏 5×10^{10} ly

Chirality

Achiral objects include **scalars**, e.g.

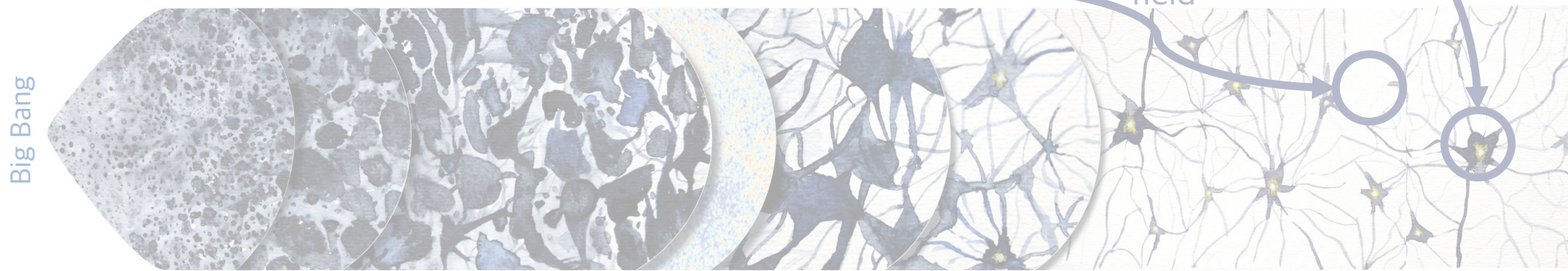
- electric charge q_{el}
 - particle density n
- and **vectors**, e.g.
- velocity \mathbf{U}
 - vector potential \mathbf{A}

Chiral objects cannot be superimposed with mirrored version.



mirror

Seed magnetic fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

↗️ 5×10^{10} ly

Chirality

Achiral objects include **scalars**, e.g.

- electric charge q_{el}
 - particle density n
- and **vectors**, e.g.
- velocity \mathbf{U}
 - vector potential \mathbf{A}

Chiral objects include **pseudo-scalars**, e.g.

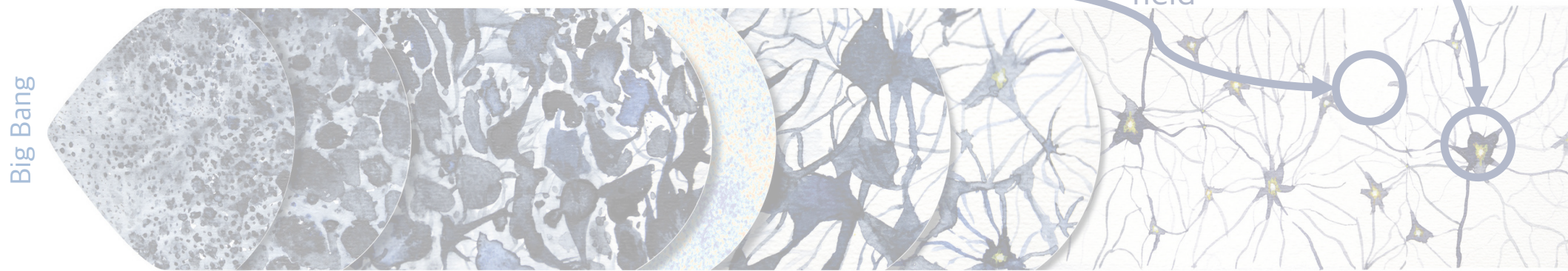
- magnetic charge q_{mag}
- chiral density

$$n_5 = n_L - n_R$$

and **pseudo/axial vectors**, e.g.

- vorticity $\boldsymbol{\omega} = \nabla \times \mathbf{U}$
- magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$

Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300-500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Chirality

Achiral objects include **scalars**, e.g.

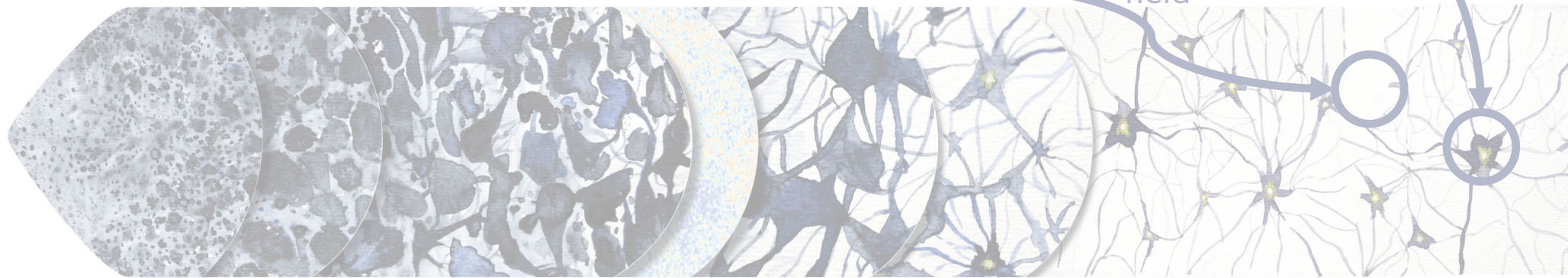
- electric charge q_{el}
 - particle density n
- and **vectors**, e.g.
- velocity \mathbf{U}
 - vector potential \mathbf{A}

Chiral objects include **pseudo-scalars**, e.g.

- magnetic charge q_{mag}
 - **chiral chemical potential**
 $\mu_5 = \mu_L - \mu_R$
- and **pseudo/axial vectors**, e.g.
- vorticity $\omega = \nabla \times \mathbf{U}$
 - magnetic field $\mathbf{B} = \nabla \times \mathbf{A}$

Seed magnetic fields

Big Bang



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

📏 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

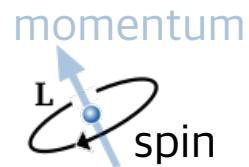
🌡️ 3 K

📏 5×10^{10} ly

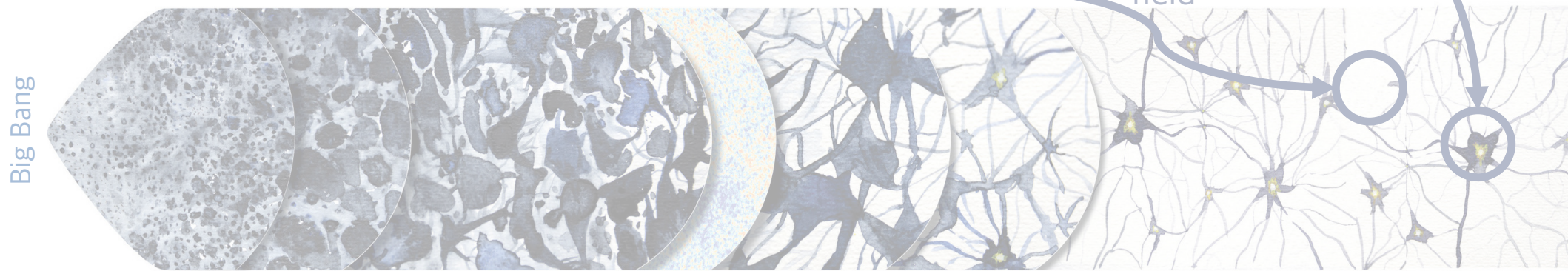
Magnetic history of the Universe

Nordita program
25/05/2026

Chiral magnetic effect (CME)



Seed
magnetic
fields



🕒 10^{-32} s
🌡️ 10^{27} K
📏 0.01 ly

🕒 3 min
🌡️ 10^9 K
📏 1 ly

🕒 4×10^5 yr
🌡️ 3000 K
📏 3×10^7 ly

🕒 300–500 Myr
🌡️ 30 K
📏 3×10^9 ly

🕒 13.6 Gyr
🌡️ 3 K
📏 5×10^{10} ly

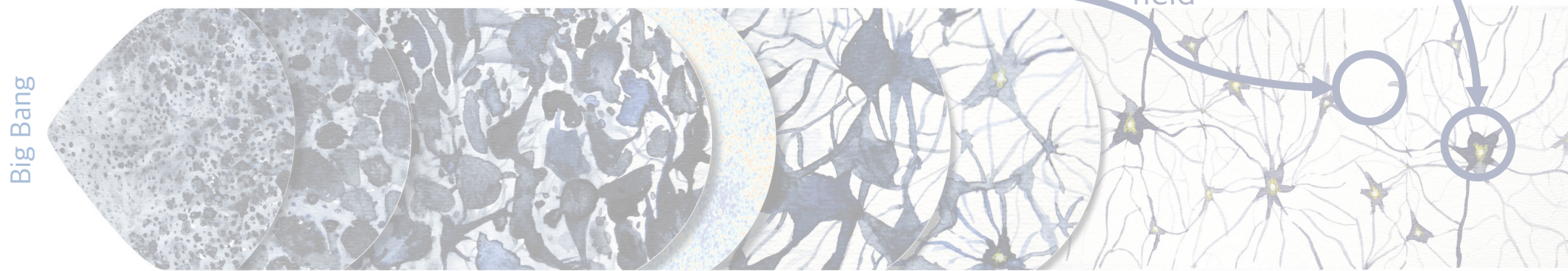
Magnetic history of the Universe

Nordita program
25/05/2026

Chiral magnetic effect (CME)



Seed
magnetic
fields



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 a

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

↗️ 3×10^7 ly

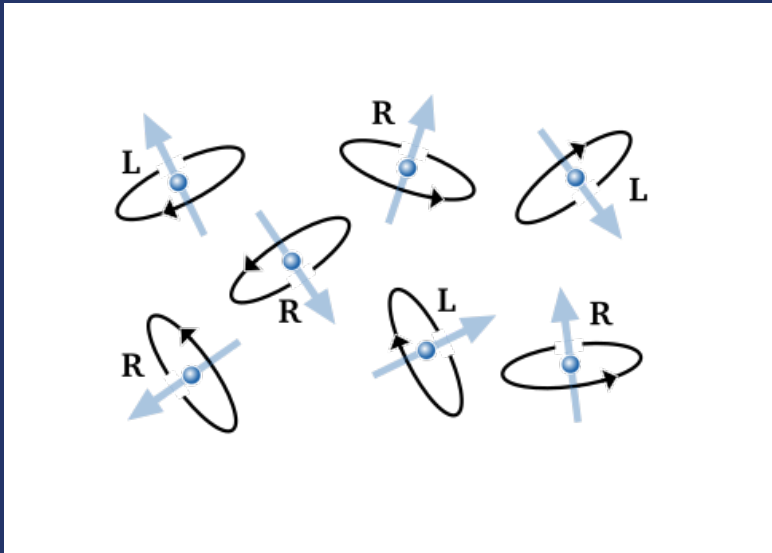
↗️ 3×10^9 ly

↗️ 5×10^{10} ly

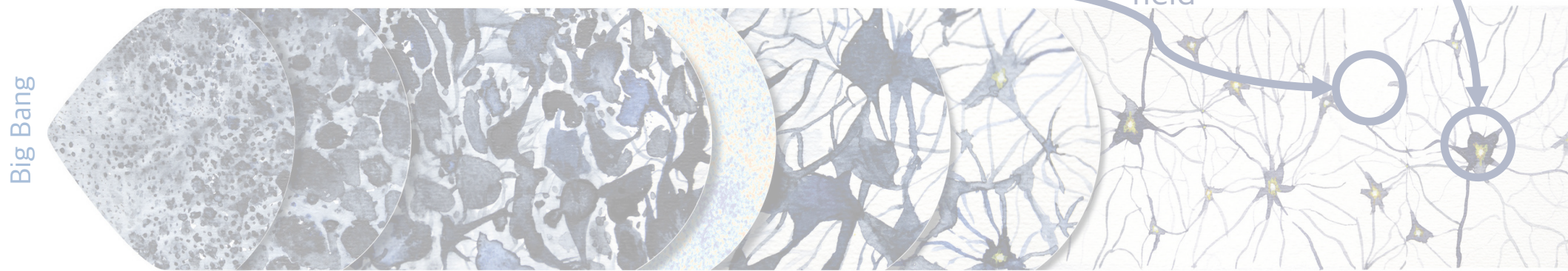
Magnetic history of the Universe

Nordita program
25/05/2026

Chiral magnetic effect (CME)



Seed
magnetic
fields



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

↗️ 3×10^7 ly

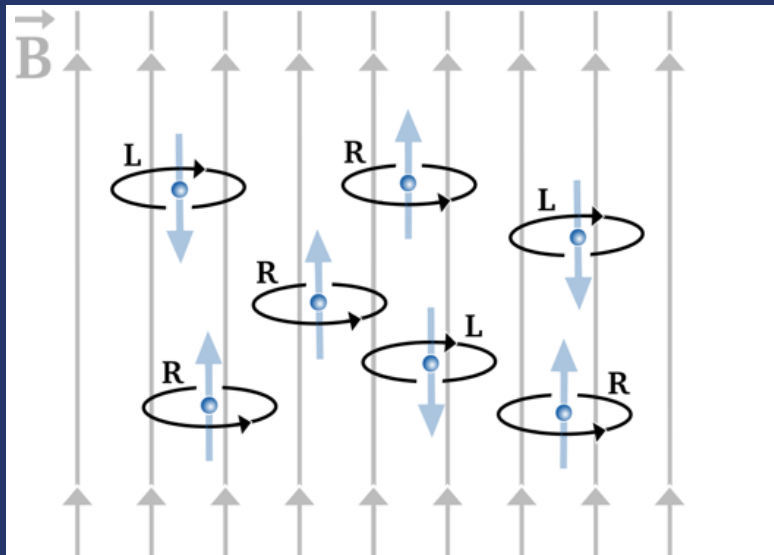
↗️ 3×10^9 ly

↗️ 5×10^{10} ly

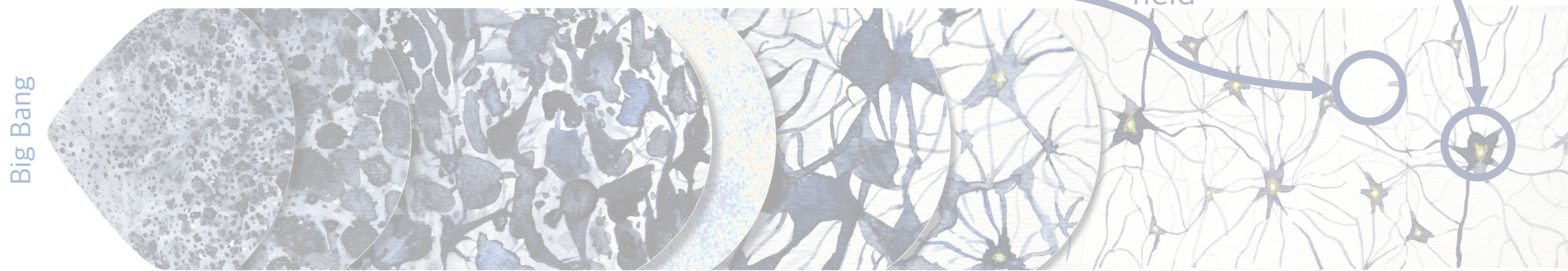
Magnetic history of the Universe

Nordita program
25/05/2026

Chiral magnetic effect (CME)



Seed
magnetic
fields



🕒 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

🕒 3 min

🌡️ 10^9 K

↗️ 1 ly

🕒 4×10^5 yr

🌡️ 3000 K

↗️ 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

↗️ 3×10^9 ly

🕒 13.6 Gyr

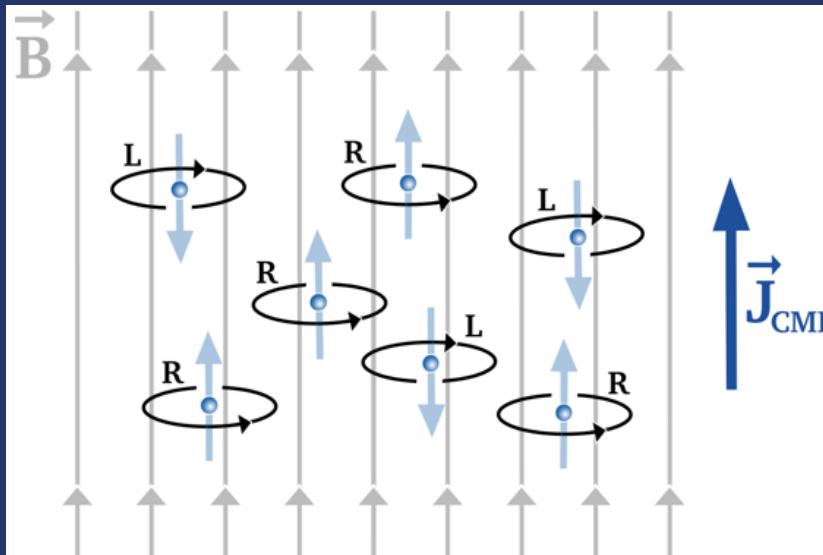
🌡️ 3 K

↗️ 5×10^{10} ly

Magnetic history of the Universe

Nordita program
25/05/2026

Chiral magnetic effect (CME)

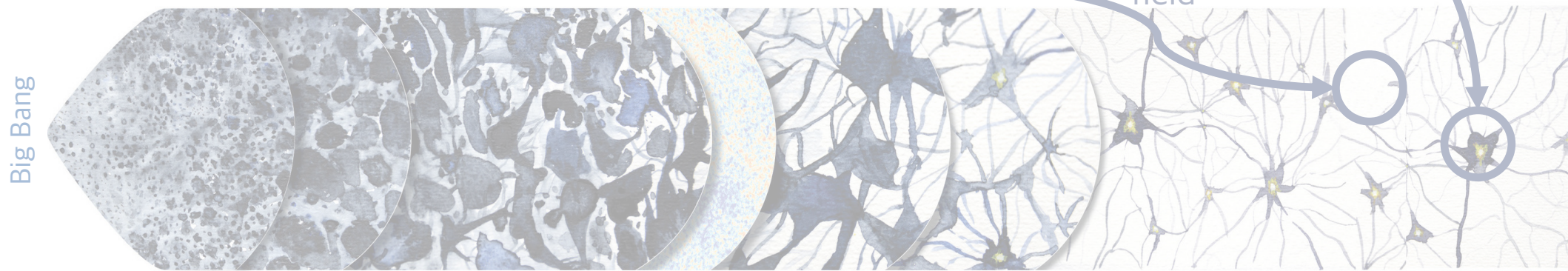


A chiral chemical potential
 $\mu_5 \equiv \mu_L - \mu_R$
leads to an electric current

$$\mathbf{J}_{\text{CME}} \propto \mu_5 \mathbf{B}$$

[Vilenkin 1980], which can be
relevant in cosmology [Joyce &
Shaposhnikov 1997; Fröhlich & Pedrini
2000; Semikoz & Sokoloff 2004;
Boyarsky et al. 2012; Pavlovic et al 2017].

Seed
magnetic
fields



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300-500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

📏 0.01 ly

📏 1 ly

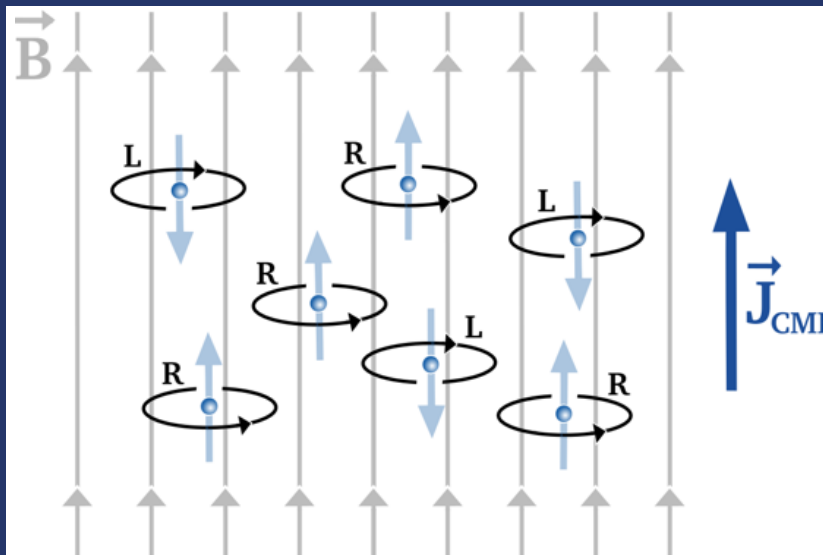
📏 3×10^7 ly

📏 3×10^9 ly

📏 5×10^{10} ly

Big Bang

Chiral magnetic effect (CME)



A chiral chemical potential
 $\mu_5 \equiv \mu_L - \mu_R$
leads to an electric current

$$\mathbf{J}_{\text{CME}} \propto \mu_5 \mathbf{B}$$

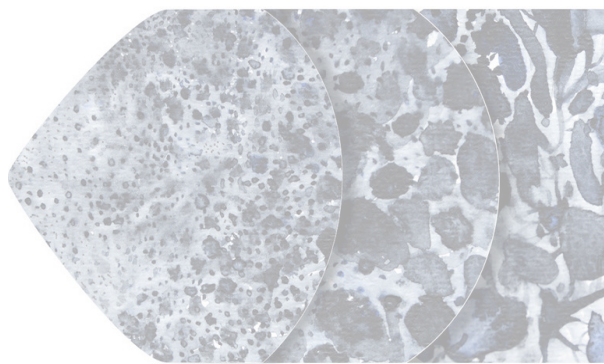
[Vilenkin 1980], which can be
relevant in cosmology [Joyce &
Shaposhnikov 1997; Fröhlich & Pedrini
2000; Semikoz & Sokoloff 2004;
Boyarsky et al. 2012; Pavlovic et al 2017].

Seed
magnetic
fields

The CME is part of the Standard Model of particle physics and may also be important for

- (proto-)neutron stars [Dvornikov & Semikoz 2015; Grabowska et al. 2015; Sigl & Leite 2016; Yamamoto 2016]
- heavy-ion collisions [ALICE collaboration, 2013; Hirono, Hirano, & Kharzeev 2014],
- and Dirac and Weyl semimetals [Li et al. 2016; Galitski, Kargarian, & Syzranov 2018].

Big Bang



⌚ 10^{-32} s

🌡️ 10^{27} K

↗️ 0.01 ly

⌚ 3 min

🌡️ 10^9 K

↗️ 1 ly

↘️ 3×10^7 ly

↘️ 3×10^9 ly

↘️ 5×10^{10} ly

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations
yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

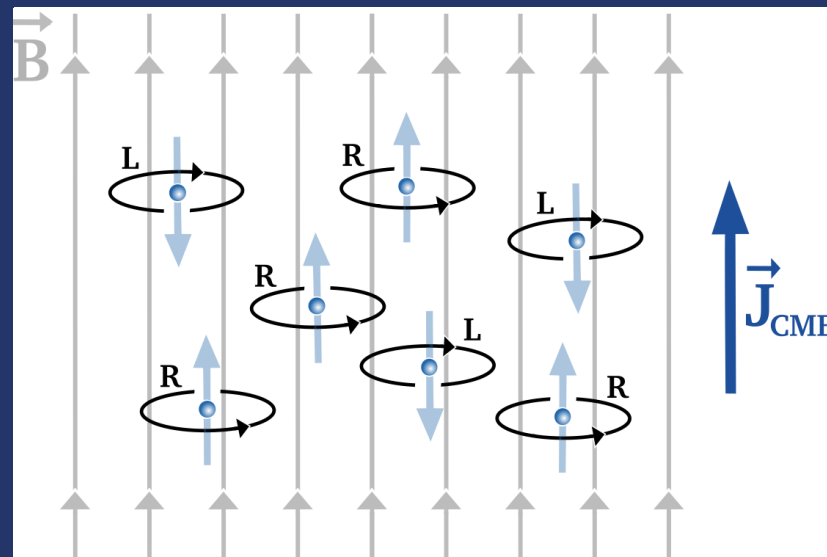
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$



A chiral chemical potential

$$\mu_5 \equiv \mu_L - \mu_R$$

leads to an electric current

$$\mathbf{J}_{\text{CME}} \propto \mu_5 \mathbf{B}$$

[Vilenkin 1980].

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the **chiral induction eq:**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the chiral induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Conservation law

(valid for $\eta \rightarrow 0$)

$$\frac{\partial}{\partial t} \langle \mathbf{A} \cdot \mathbf{B} \rangle = 0$$



leads to inverse cascade:

$$B \searrow \rightarrow \xi_M \nearrow$$

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the chiral induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Conservation law

(valid for $\eta \rightarrow 0$)

$$\frac{\partial}{\partial t} \langle \mathbf{A} \cdot \mathbf{B} \rangle = 0$$



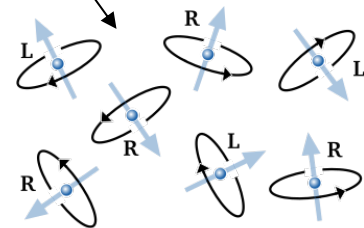
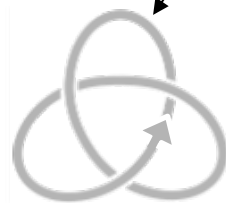
leads to inverse cascade:

$$B \searrow \rightarrow \xi_M \nearrow$$

Conservation law

(valid for any η):

$$\frac{\partial}{\partial t} \left(\langle \mathbf{A} \cdot \mathbf{B} \rangle + \frac{2 \langle \mu_5 \rangle}{\lambda} \right) = 0$$



leads to new dynamics.

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the **chiral induction eq:**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Formally similar to the mean-field induction equation in classical MHD!

$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \nabla \times (\langle \mathbf{U} \rangle \times \bar{\mathbf{B}} + \alpha \langle \mathbf{B} \rangle - (\eta + \eta_{\text{T}}) \nabla \times \langle \mathbf{B} \rangle)$$

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the **chiral induction eq:**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Linear theory
with ansatz

$$\mathbf{B} \propto e^{\gamma_5 t}$$

Extension of MHD to high energies

Nordita program
25/05/2026

MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}}$$

and Maxwell's equations yield the induction eq:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Higher temperature

Chiral MHD

The electric current

$$\mathbf{J} = \mathbf{J}_{\text{Ohm}} + \mathbf{J}_{\text{CME}}$$

and Maxwell's equations yield the **chiral induction eq:**

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} + \eta \mu_5 \mathbf{B} - \eta \nabla \times \mathbf{B})$$

Linear theory
with ansatz
 $B \propto e^{\gamma_5 t}$

The maximum growth rate is given by

$$\gamma_5 = \frac{\eta \mu_5^2}{4}$$

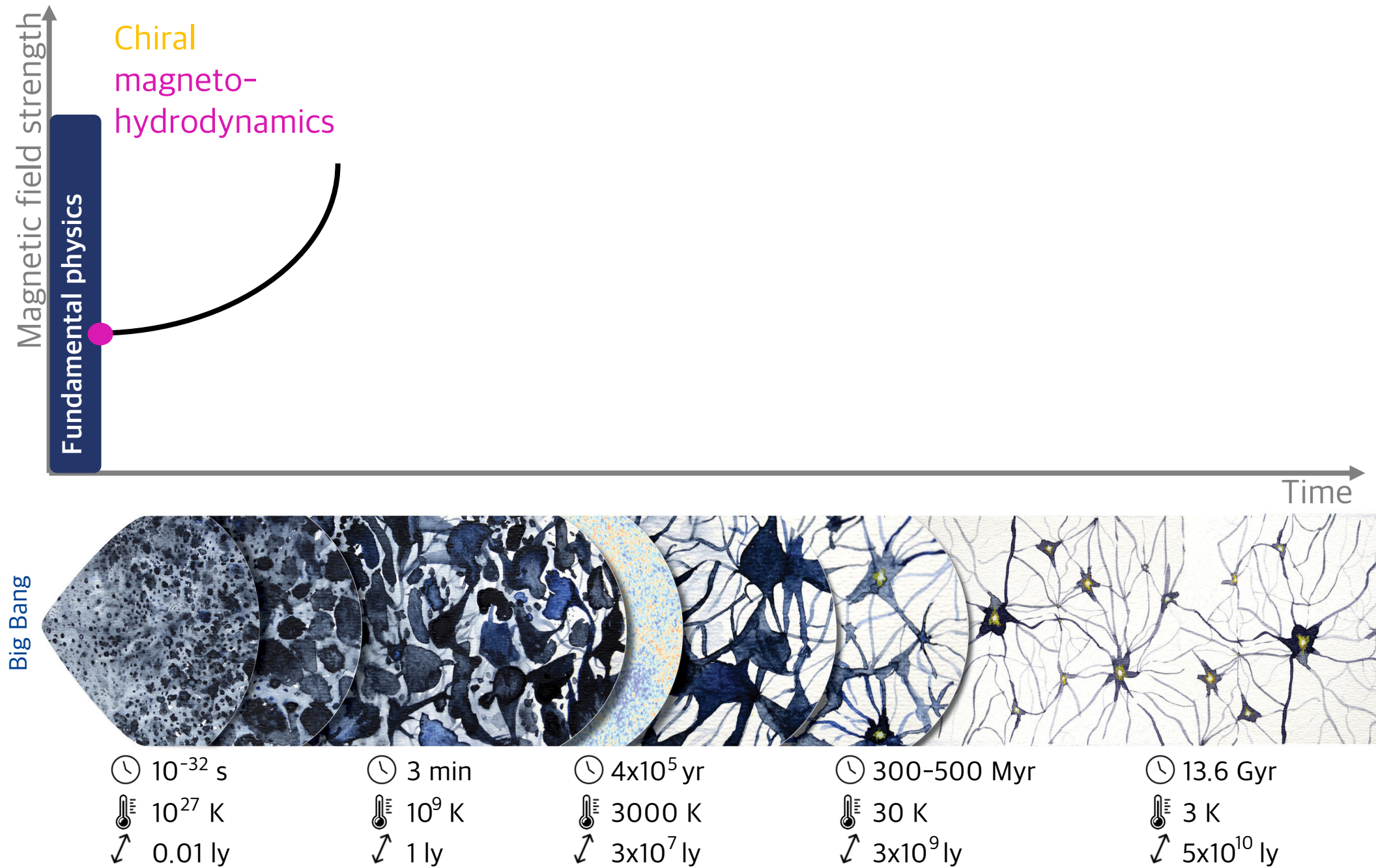
and attained on the wavenumber:

$$k_5 = \frac{\mu_5}{2}$$

[Joyce & Shaposhnikov 1997].

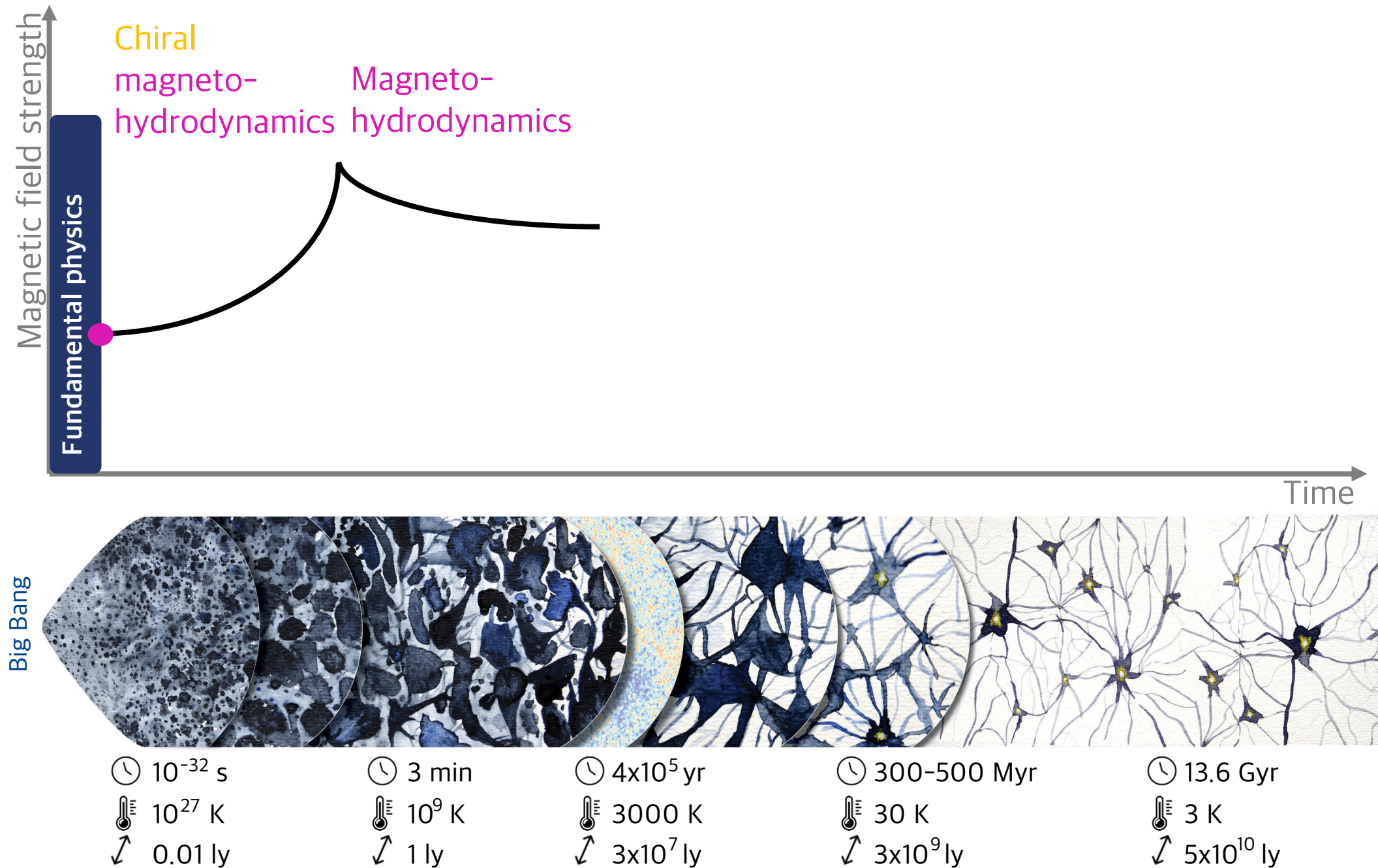
Primordial magnetic fields

Nordita program
25/05/2026



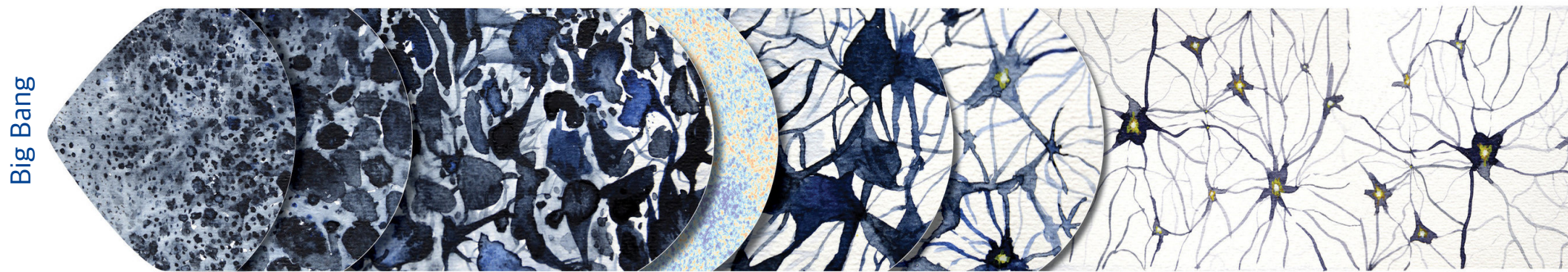
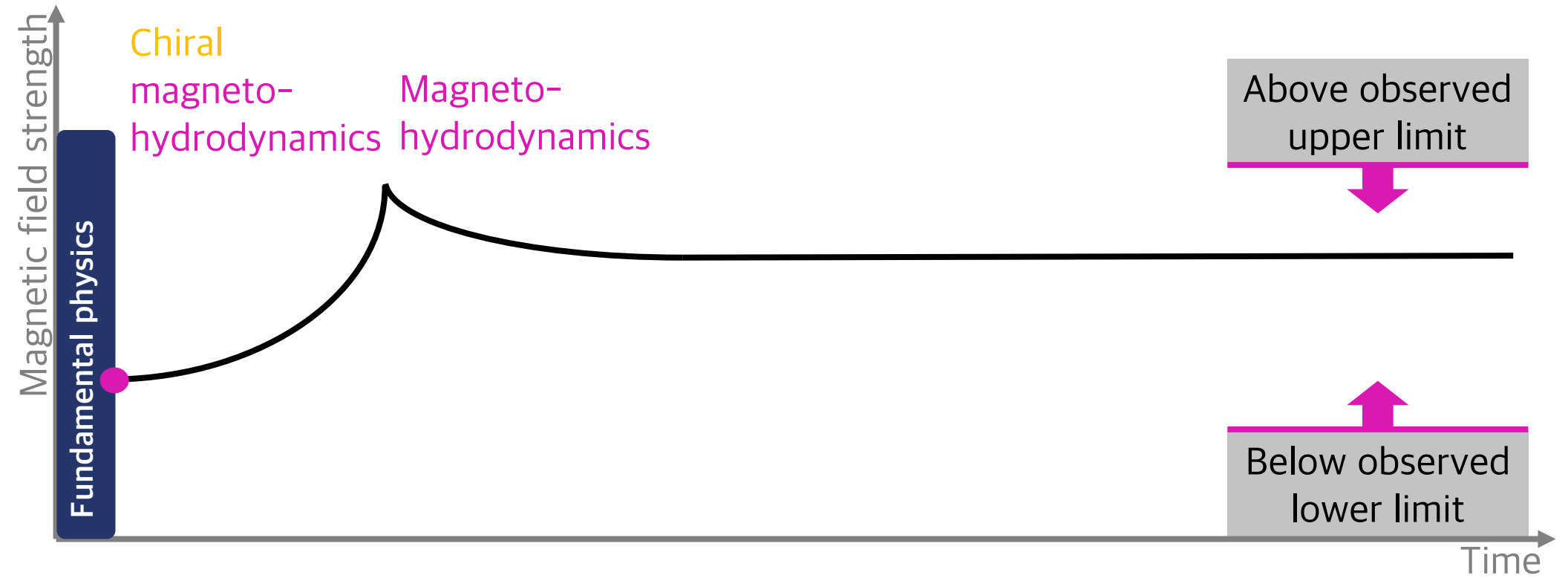
Primordial magnetic fields

Nordita program
25/05/2026



Primordial magnetic fields

Nordita program
25/05/2026



🕒 10^{-32} s

🕒 3 min

🕒 4×10^5 yr

🕒 300–500 Myr

🕒 13.6 Gyr

🌡️ 10^{27} K

🌡️ 10^9 K

🌡️ 3000 K

🌡️ 30 K

🌡️ 3 K

↗️ 0.01 ly

↗️ 1 ly

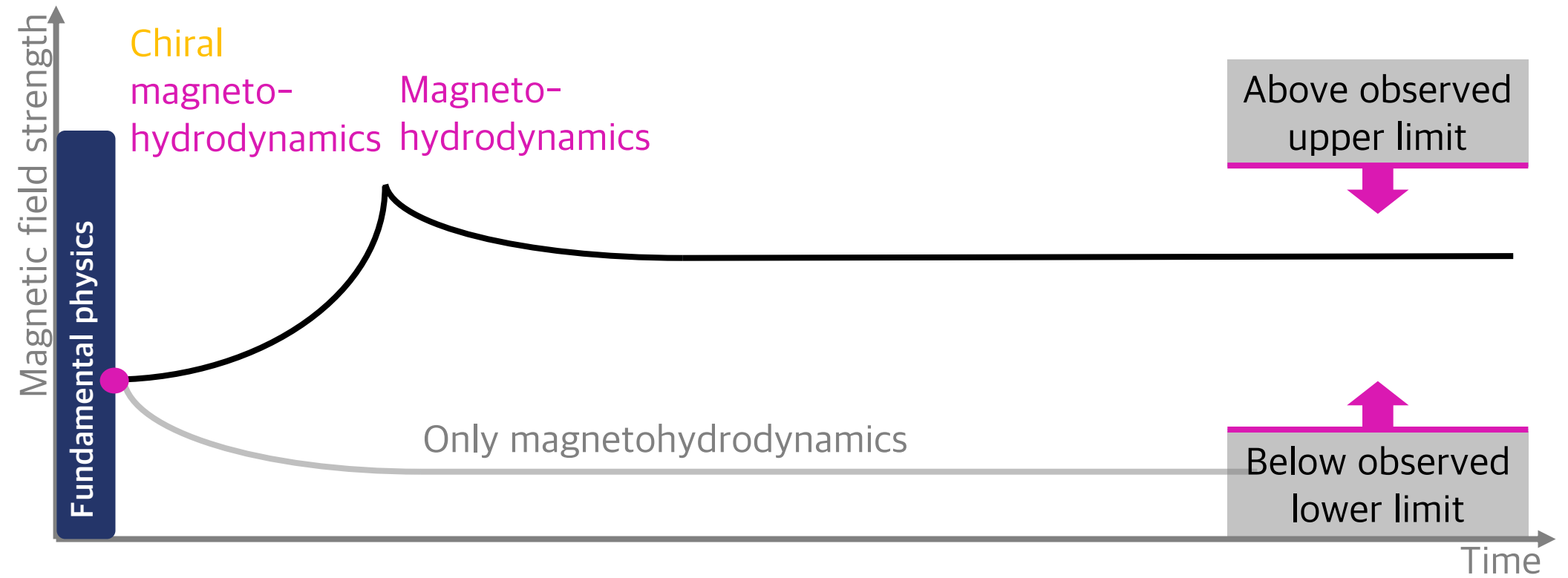
↗️ 3×10^7 ly

↗️ 3×10^9 ly

↗️ 5×10^{10} ly

Primordial magnetic fields

Nordita program
25/05/2026



🕒 10^{-32} s	🕒 3 min	🕒 4×10^5 yr	🕒 300–500 Myr	🕒 13.6 Gyr
🌡️ 10^{27} K	🌡️ 10^9 K	🌡️ 3000 K	🌡️ 30 K	🌡️ 3 K
📏 0.01 ly	📏 1 ly	📏 3×10^7 ly	📏 3×10^9 ly	📏 5×10^{10} ly

Chiral MHD equations:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})] \\ \rho \frac{D\mathbf{U}}{Dt} &= (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S}) \\ \frac{D\rho}{Dt} &= -\rho \nabla \cdot \mathbf{U} \\ \frac{D\mu_5}{Dt} &= \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]\end{aligned}$$

Rogachevskii et al. 2017

Chiral MHD equations:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})] \\ \rho \frac{D\mathbf{U}}{Dt} &= (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S}) \\ \frac{D\rho}{Dt} &= -\rho \nabla \cdot \mathbf{U} \\ \frac{D\mu_5}{Dt} &= \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]\end{aligned}$$

Rogachevskii et al. 2017

Chiral MHD equations:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})] \\ \rho \frac{D\mathbf{U}}{Dt} &= (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S}) \\ \frac{D\rho}{Dt} &= -\rho \nabla \cdot \mathbf{U} \\ \frac{D\mu_5}{Dt} &= \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]\end{aligned}$$

Rogachevskii et al. 2017

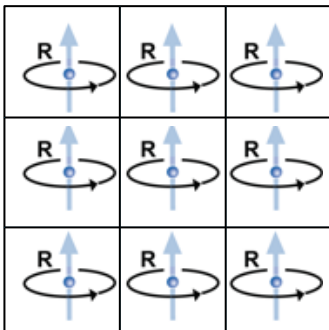
Direct numerical
simulations



PENCIL CODE
[pencil-code.nordita.org]

Initial conditions:

- Weak seed magnetic field
- No initial velocity
- Large initial $\mu_5(x, y, z)$



Chiral MHD equations:

$$\begin{aligned}\frac{\partial \mathbf{B}}{\partial t} &= \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})] \\ \rho \frac{D\mathbf{U}}{Dt} &= (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S}) \\ \frac{D\rho}{Dt} &= -\rho \nabla \cdot \mathbf{U} \\ \frac{D\mu_5}{Dt} &= \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]\end{aligned}$$


Rogachevskii et al. 2017


Direct numerical
simulations




PENCIL CODE

[pencil-code.nordita.org]

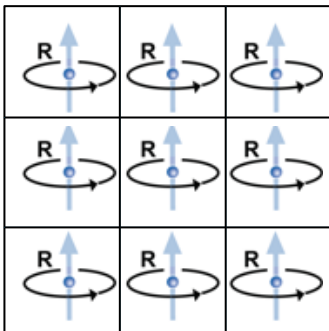
 Public code for modelling compressible flows with magnetic fields

 High-order finite difference methods [6th-order explicit in space; 3rd-order accurate time-stepping]

 Highly modular with diverse applications [turbulent flows, combustion, Solar and galactic physics, gravitational waves, ...]

Initial conditions:

- Weak seed magnetic field
- No initial velocity
- Large initial $\mu_5(x, y, z)$



Chiral MHD equations:

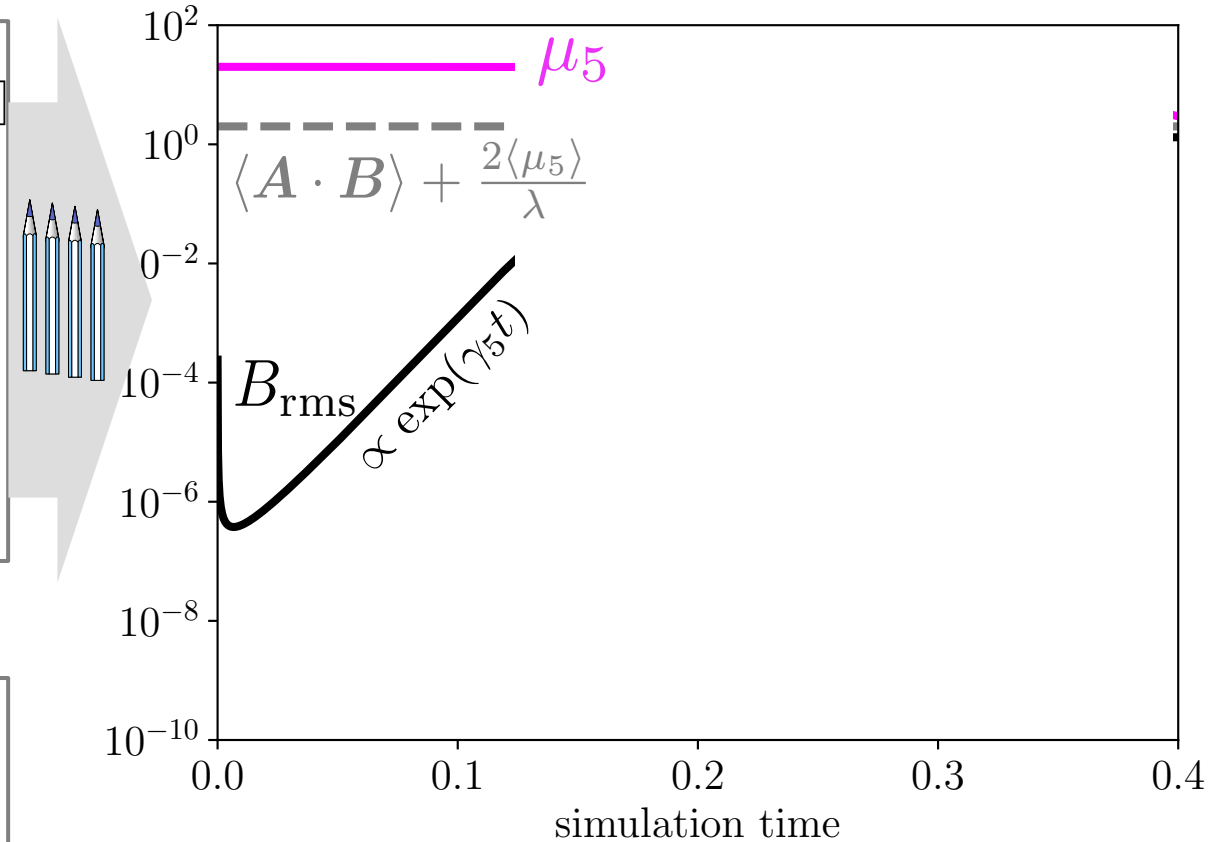
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

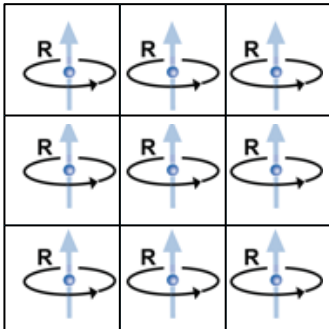
$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017



Initial conditions:

- Weak seed magnetic field
- No initial velocity
- Large initial $\mu_5(x, y, z)$



Chiral MHD equations:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

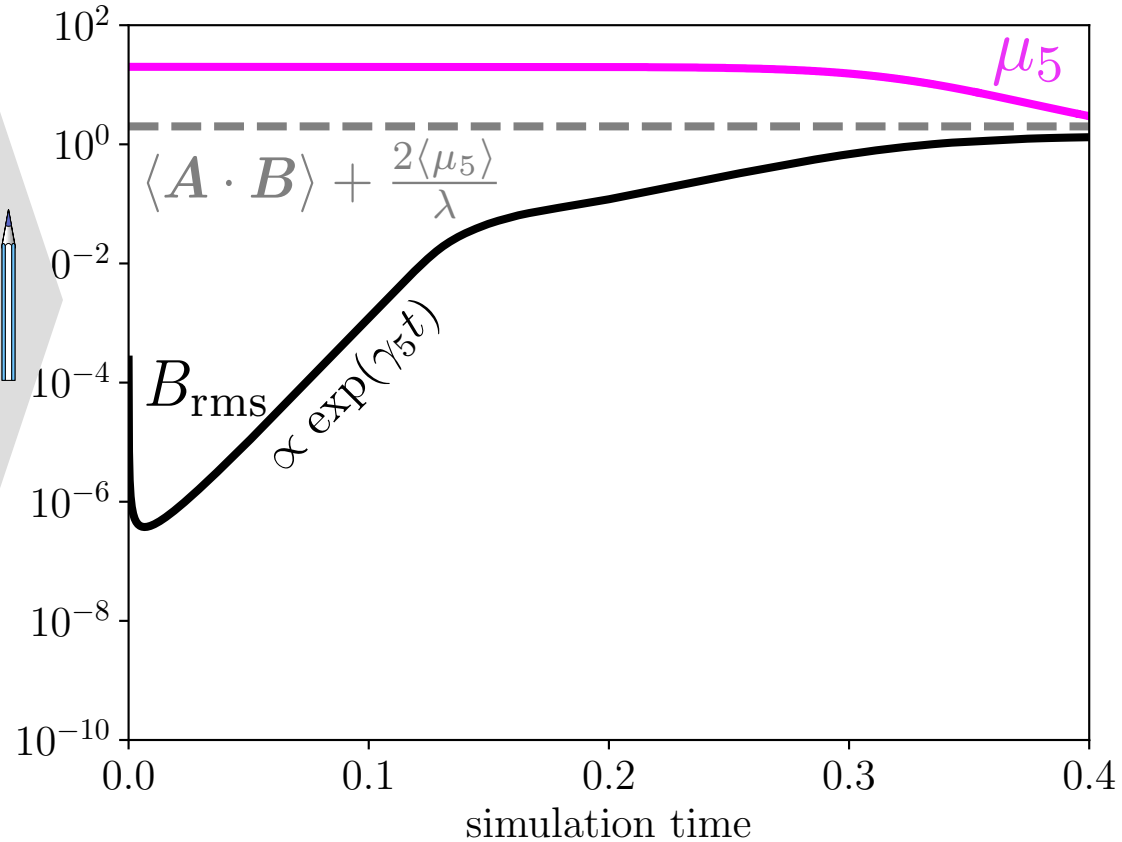
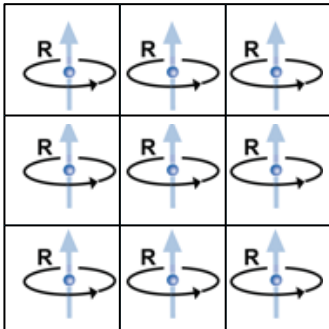
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017

Initial conditions:

- Weak seed magnetic field
- No initial velocity
- Large initial $\mu_5(x, y, z)$



Chiral MHD equations:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

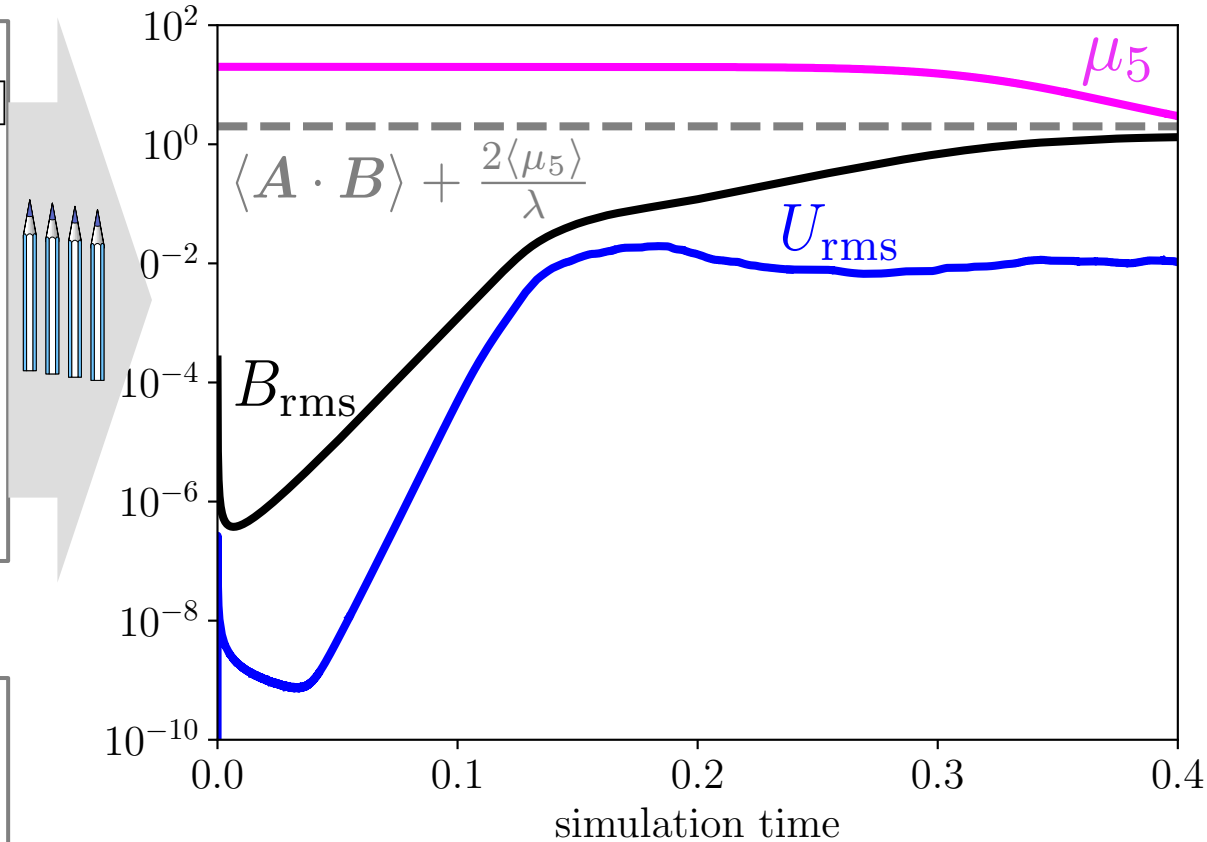
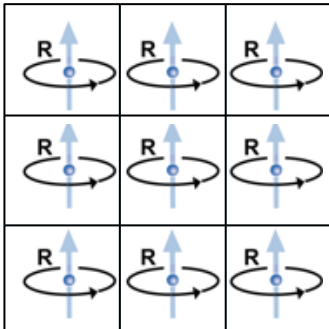
$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017

Initial conditions:

- Weak seed magnetic field
- No initial velocity
- Large initial $\mu_5(x, y, z)$



Chiral MHD equations:

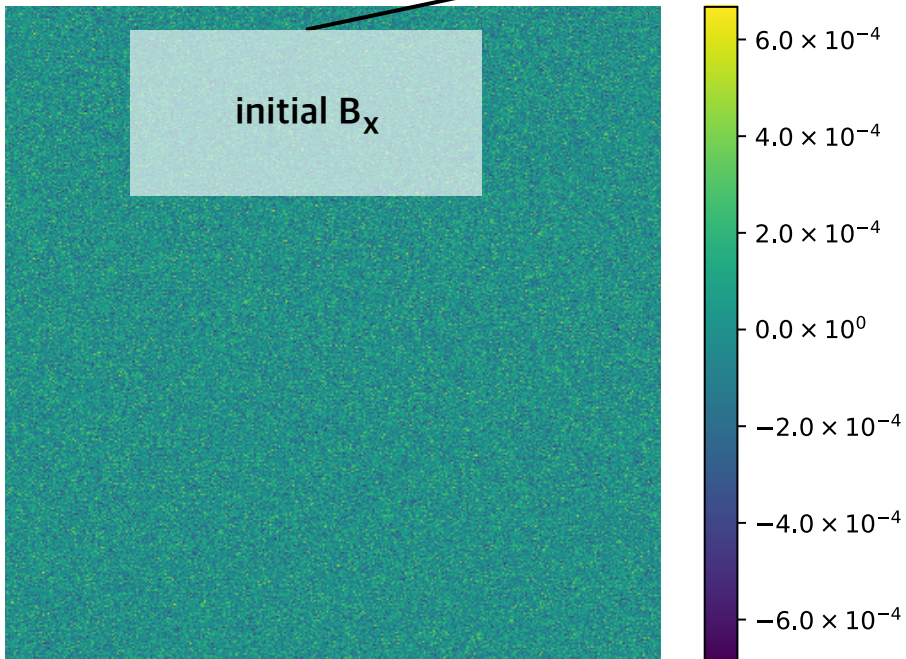
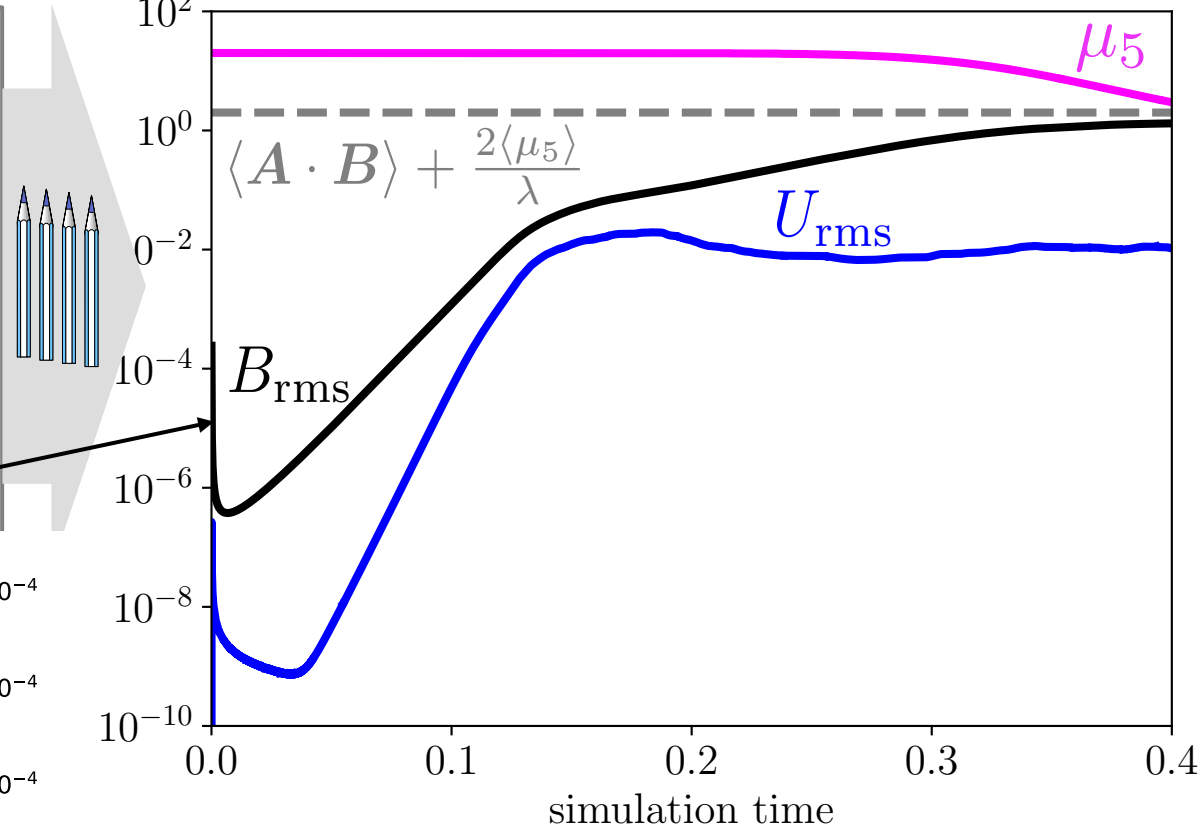
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017



Chiral MHD equations:

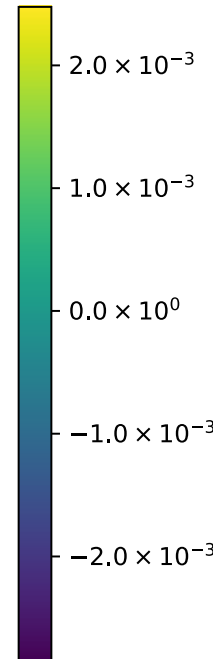
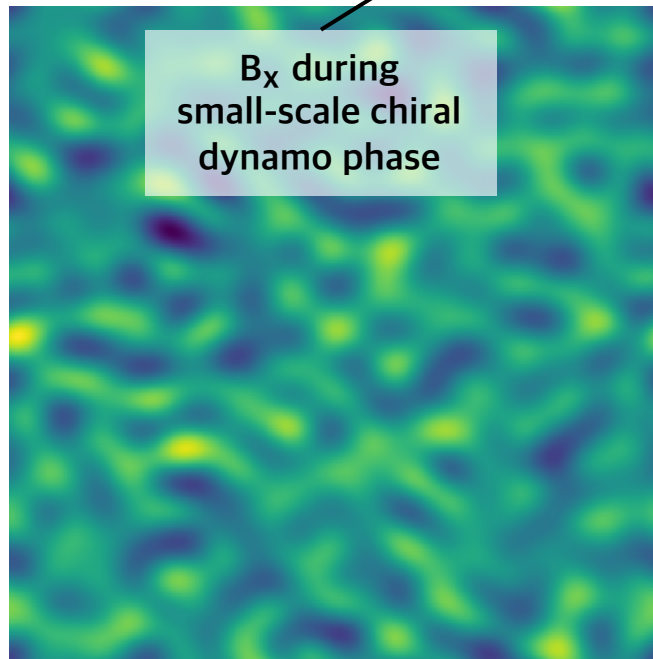
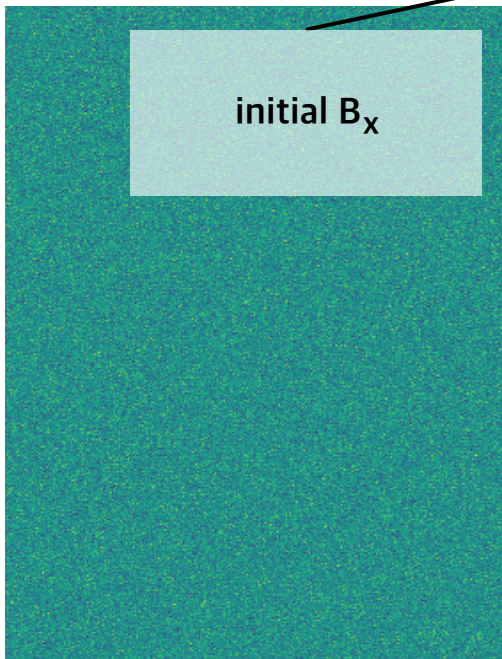
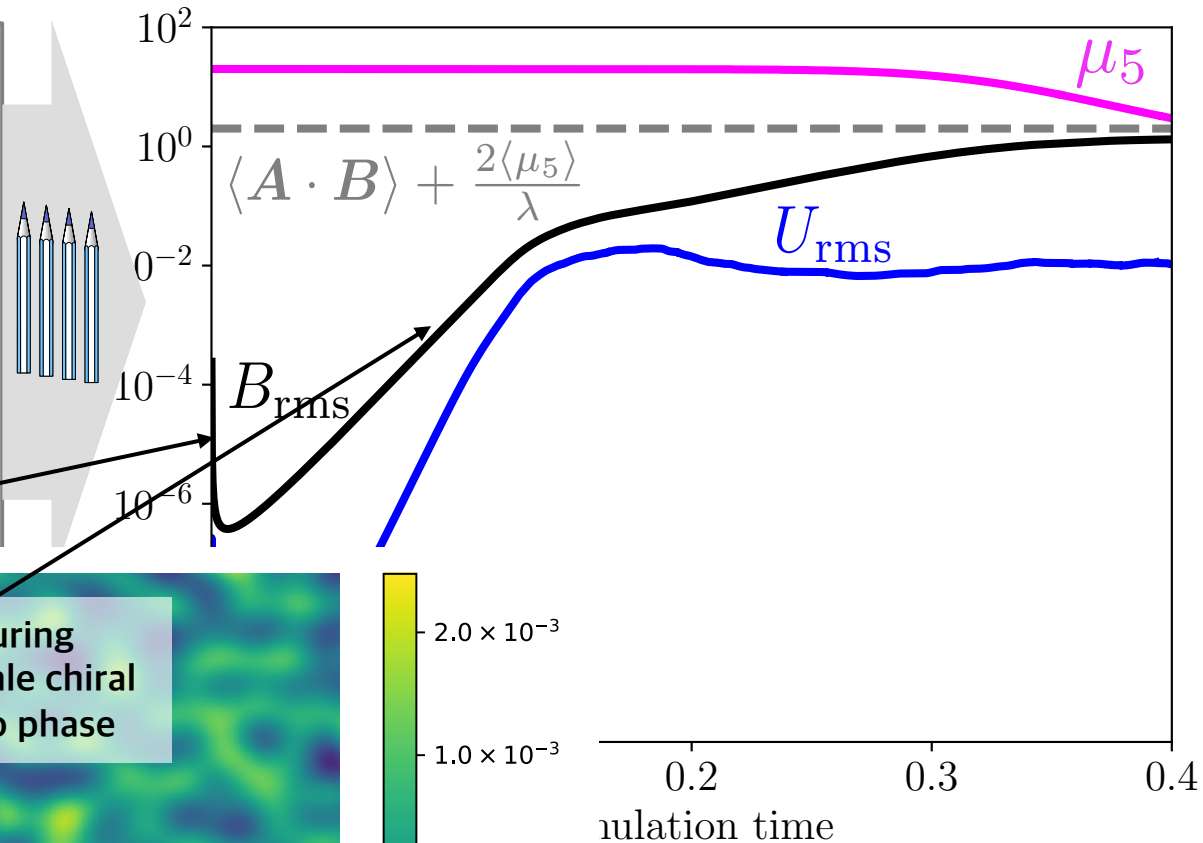
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017



Chiral MHD dynamos

Nordita program
25/05/2026

Chiral MHD equations:

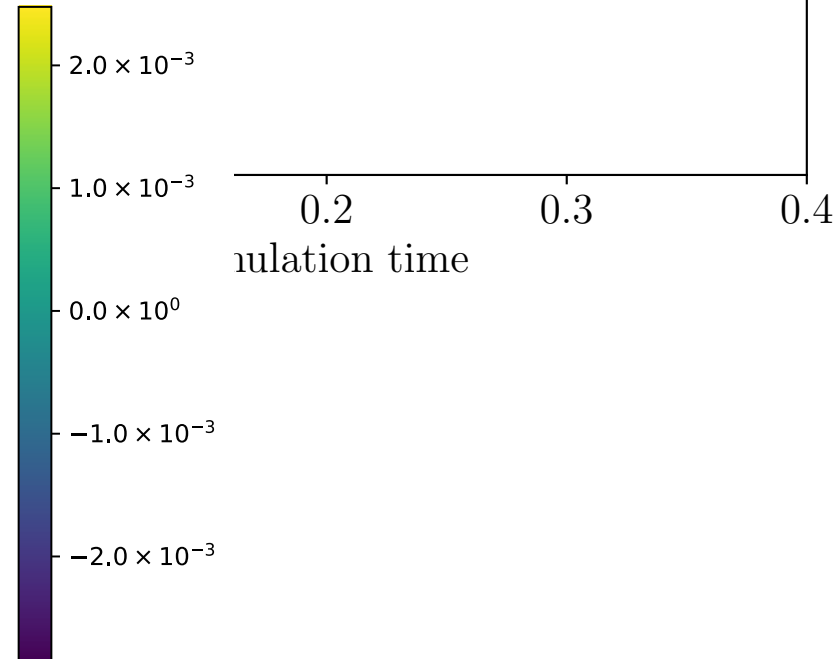
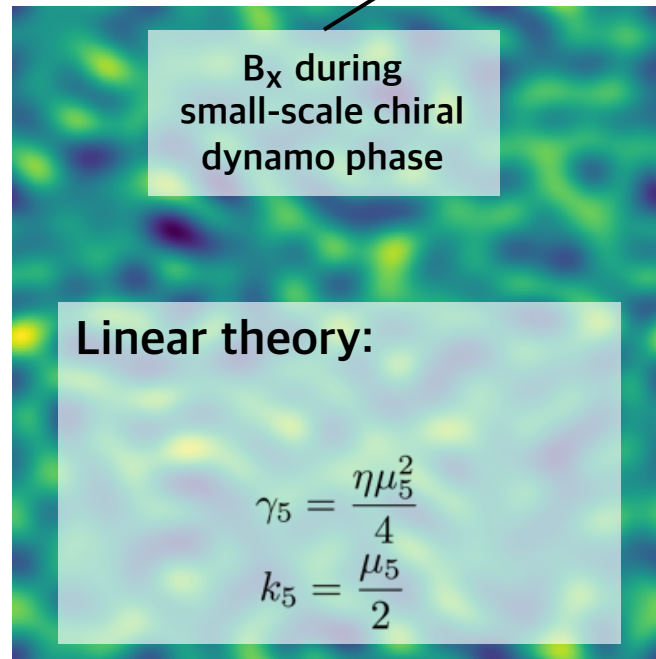
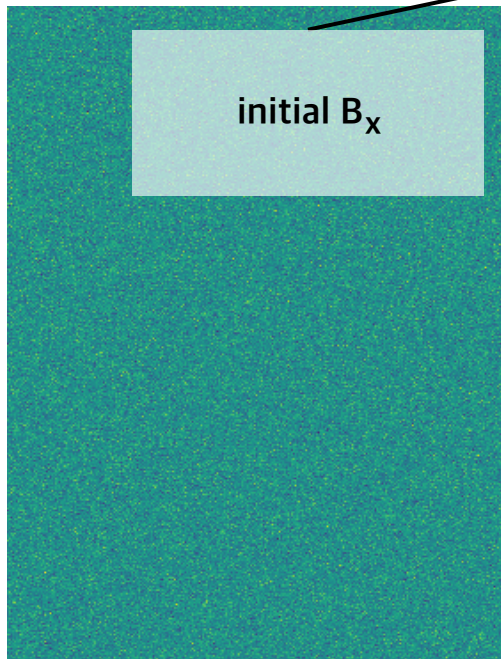
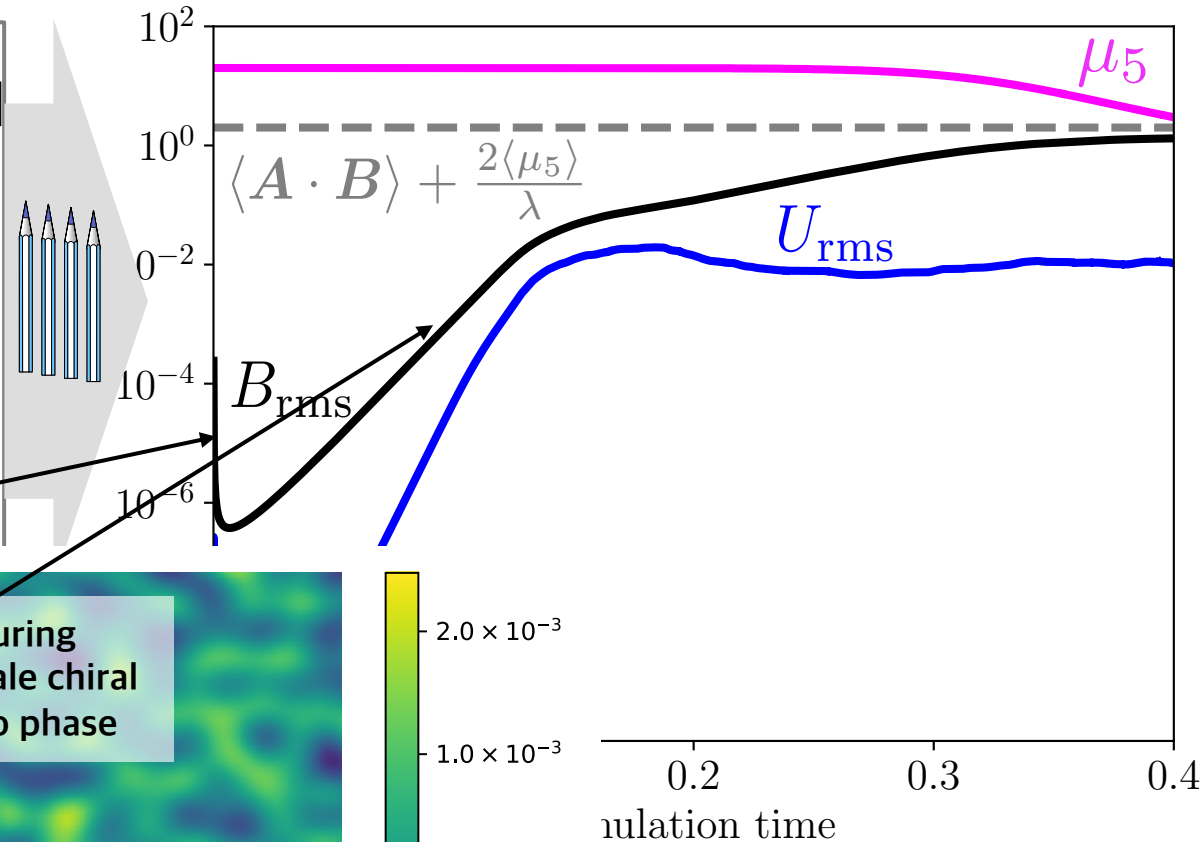
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017



Chiral MHD equations:

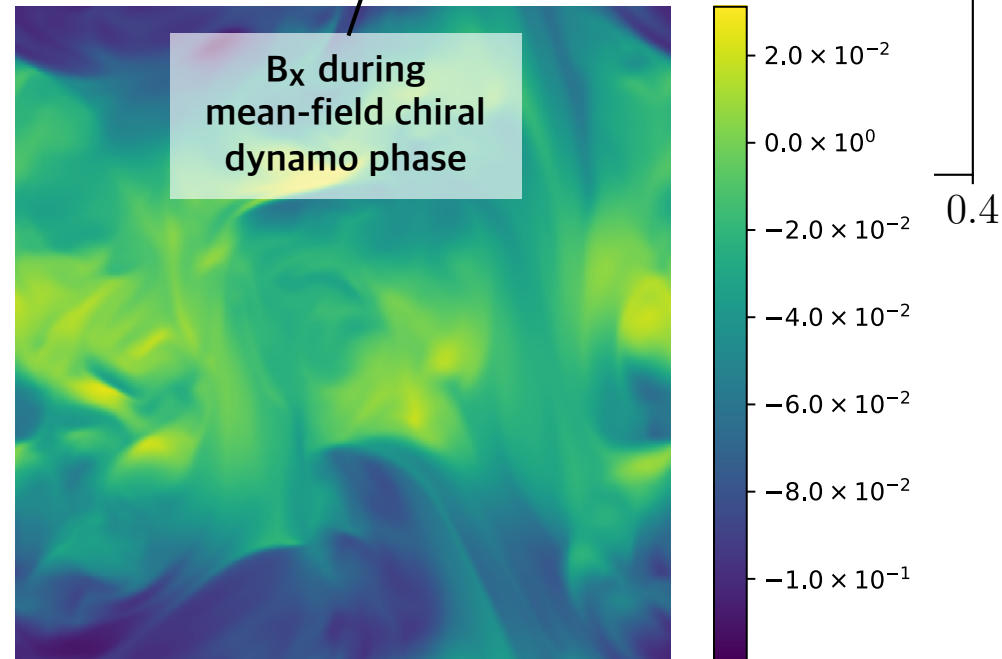
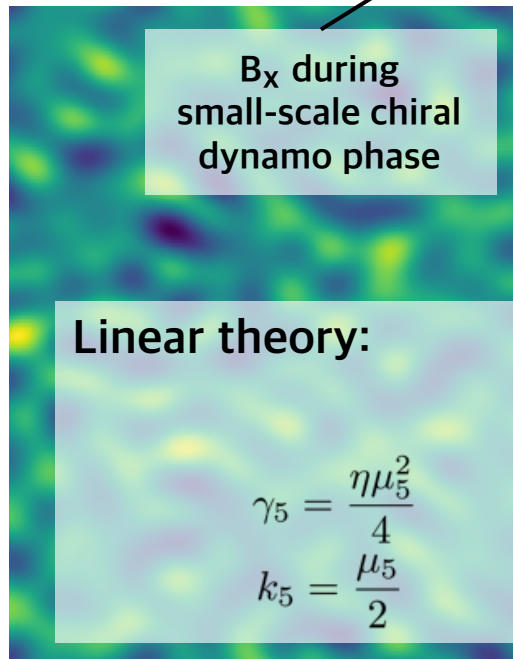
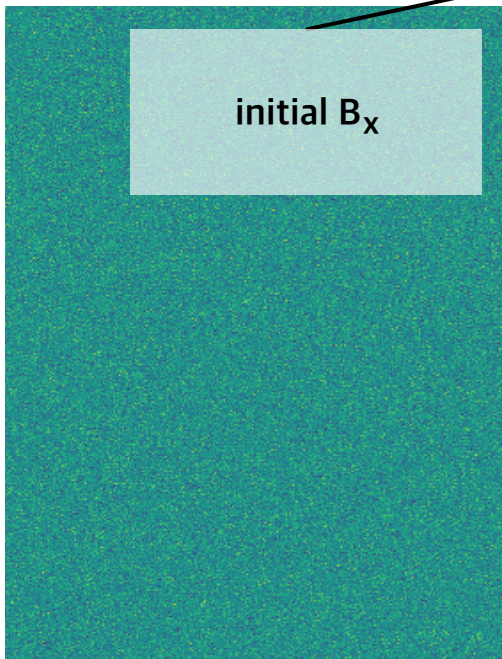
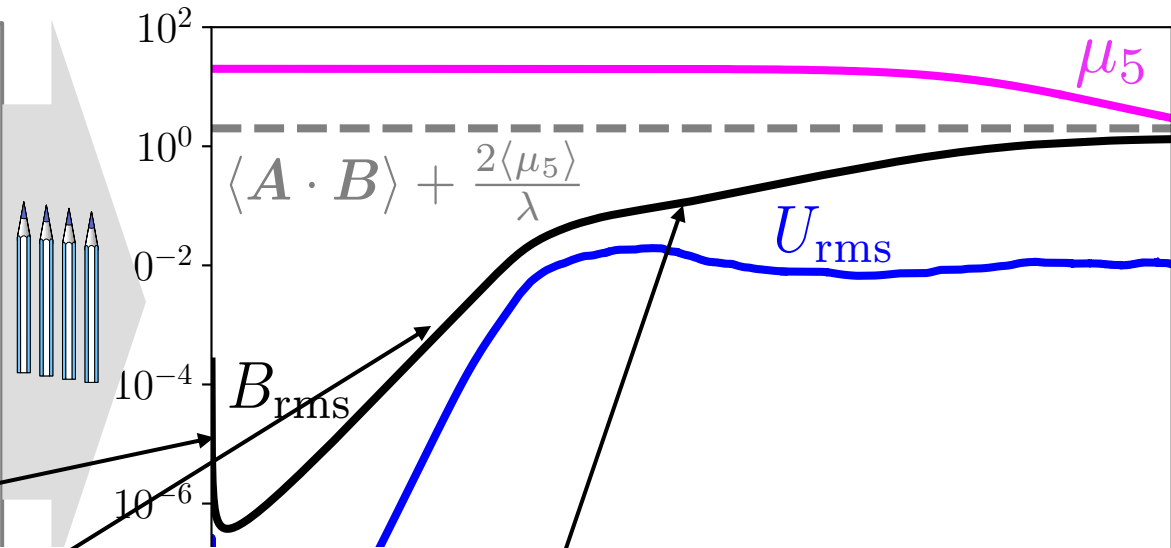
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017



Chiral MHD equations:

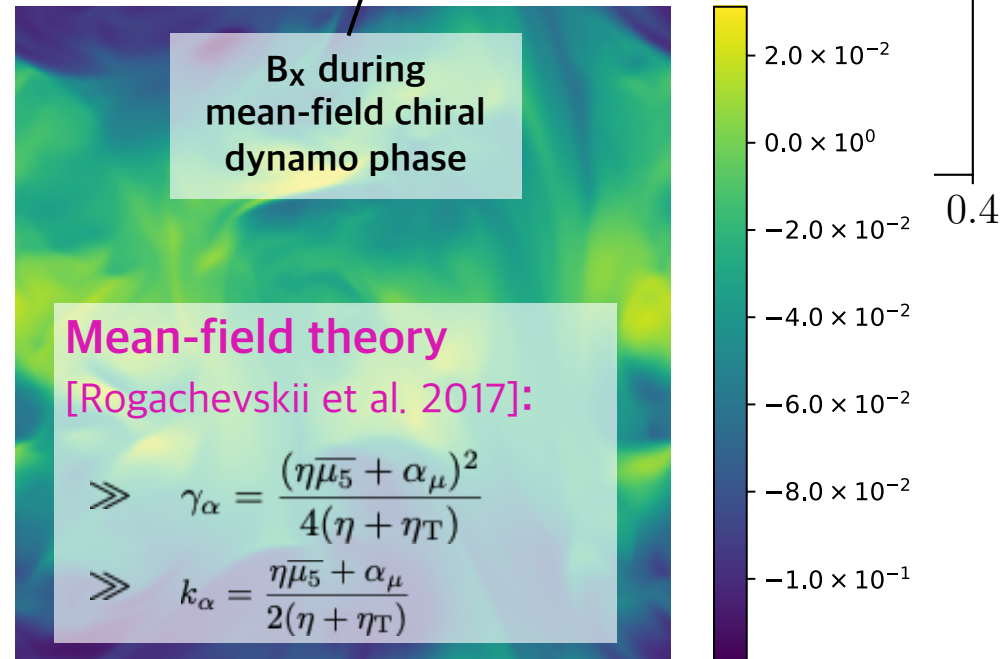
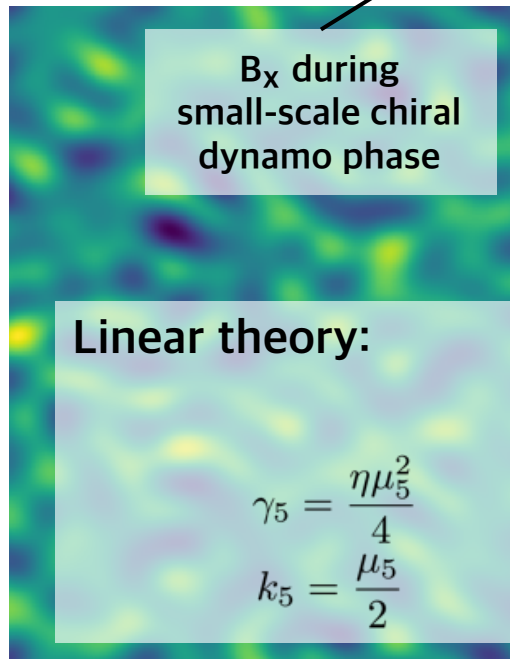
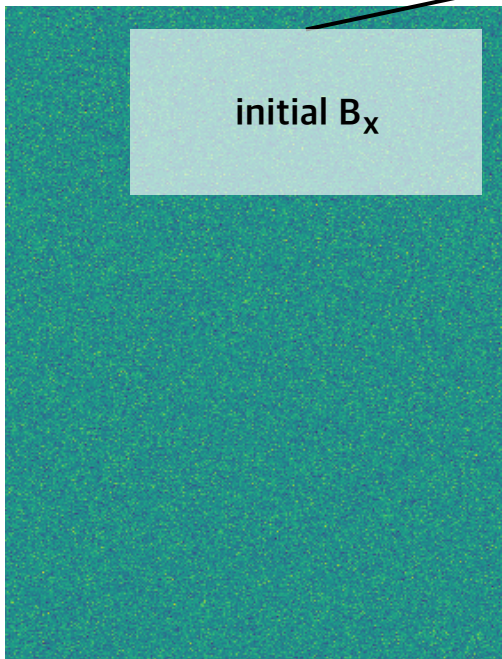
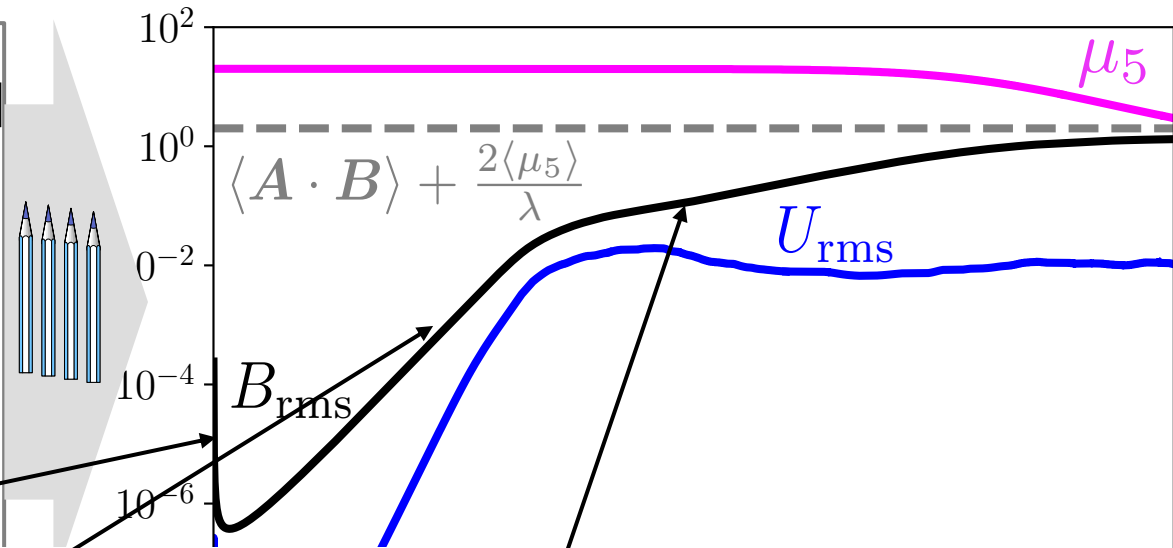
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times [\mathbf{U} \times \mathbf{B} + \eta (\mu_5 \mathbf{B} - \nabla \times \mathbf{B})]$$

$$\rho \frac{D\mathbf{U}}{Dt} = (\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p + \nabla \cdot (2\nu \rho \mathbf{S})$$

$$\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{U}$$

$$\frac{D\mu_5}{Dt} = \lambda \eta [\mathbf{B} \cdot (\nabla \times \mathbf{B}) - \mu_5 \mathbf{B}^2]$$

Rogachevskii et al. 2017

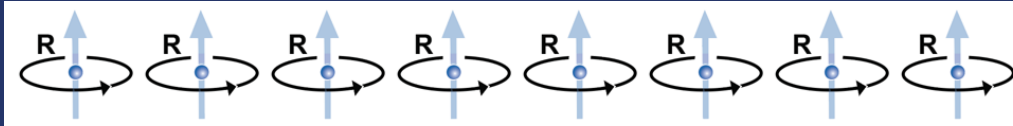


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t = 0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

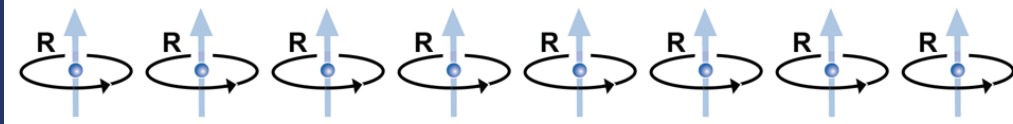
Why should the Big Bang have produced more right-handed than left-handed fermions?

Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

Generalization 1

Non-uniform chiral chemical potential, i.e.
 $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.

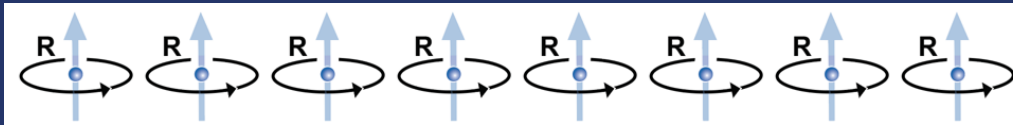


Towards more realistic scenarios

Nordita program
25/05/2026

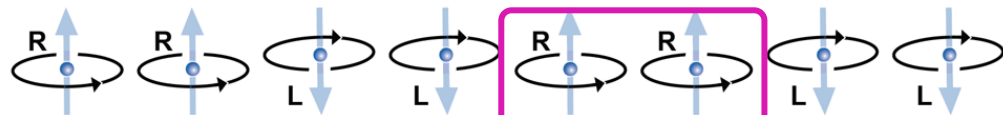
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



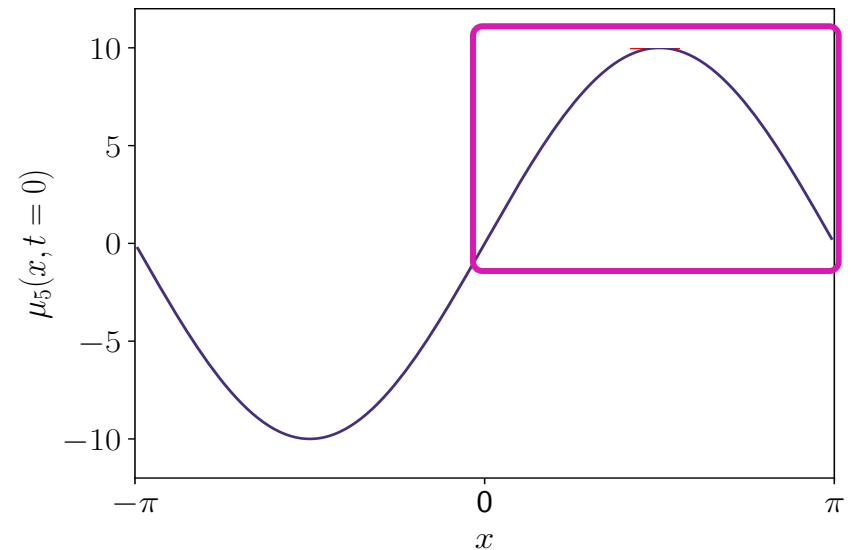
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Islands with
 $\langle \mu_5 \rangle \neq 0$

Initial distribution in numerical domain:

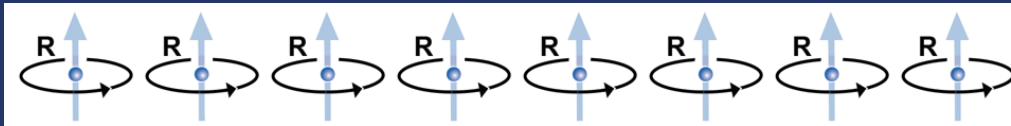


Towards more realistic scenarios

Nordita program
25/05/2026

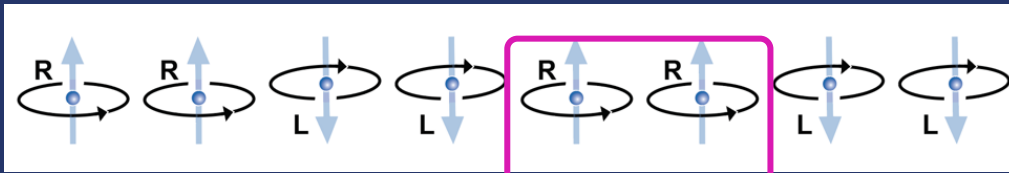
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



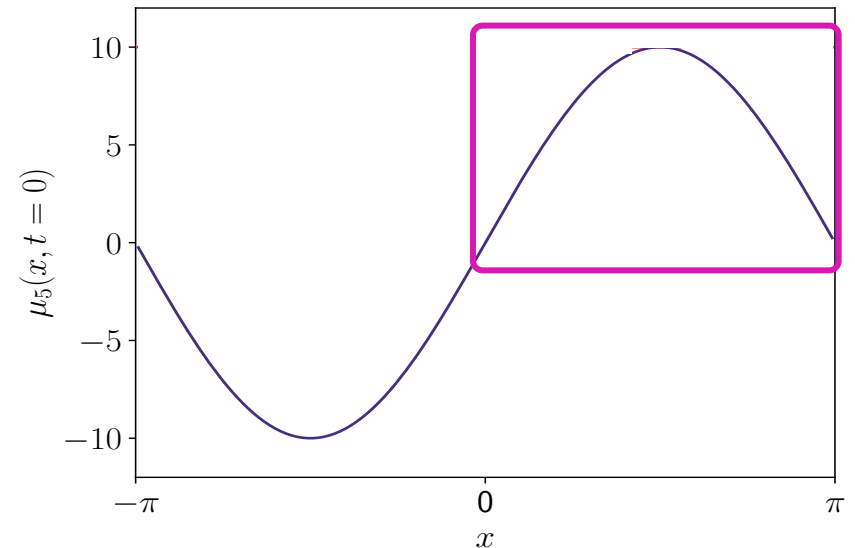
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.

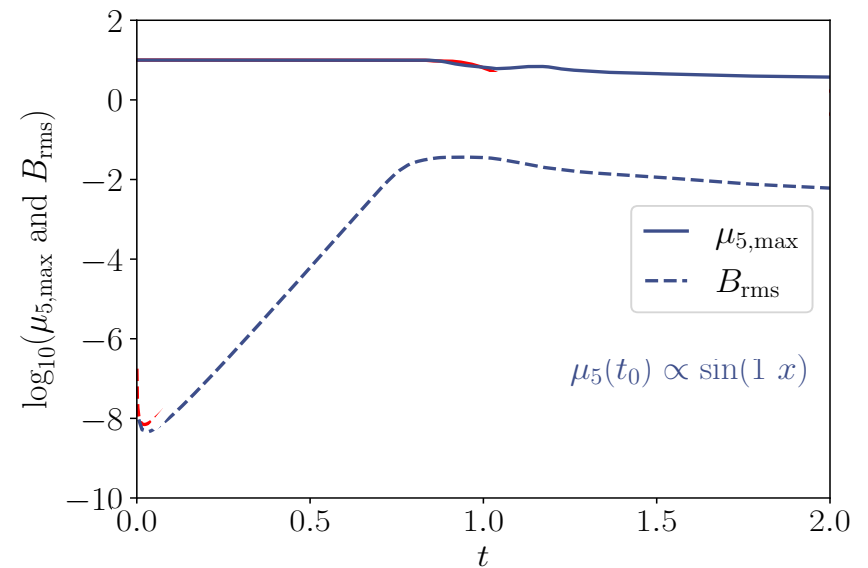


Islands with
 $\langle \mu_5 \rangle \neq 0$

Initial distribution in numerical domain:



Resulting time evolution:

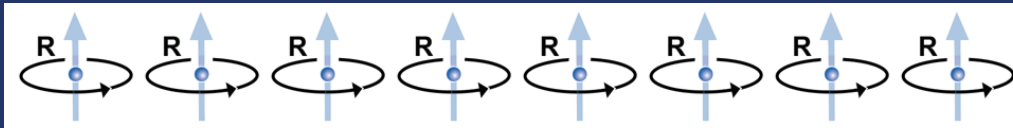


Towards more realistic scenarios

Nordita program
25/05/2026

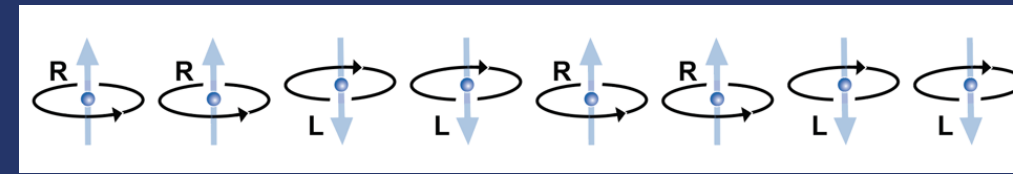
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.

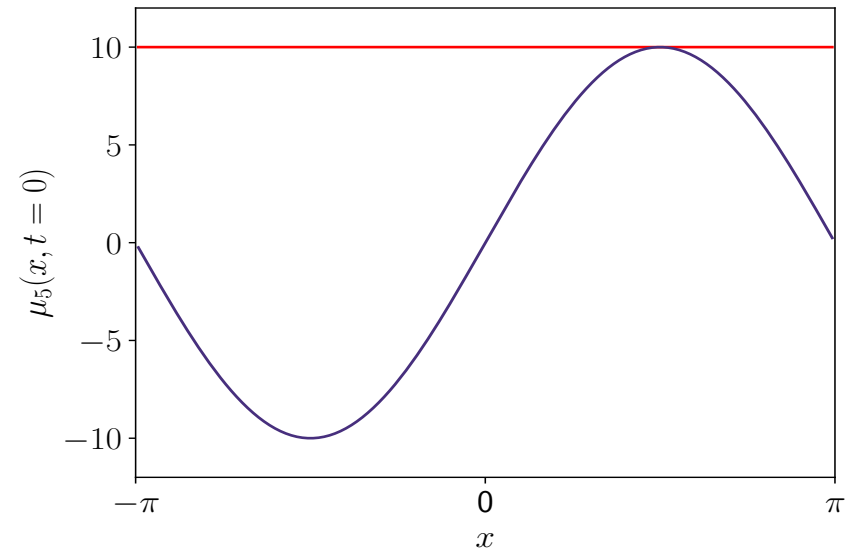


Generalization 1

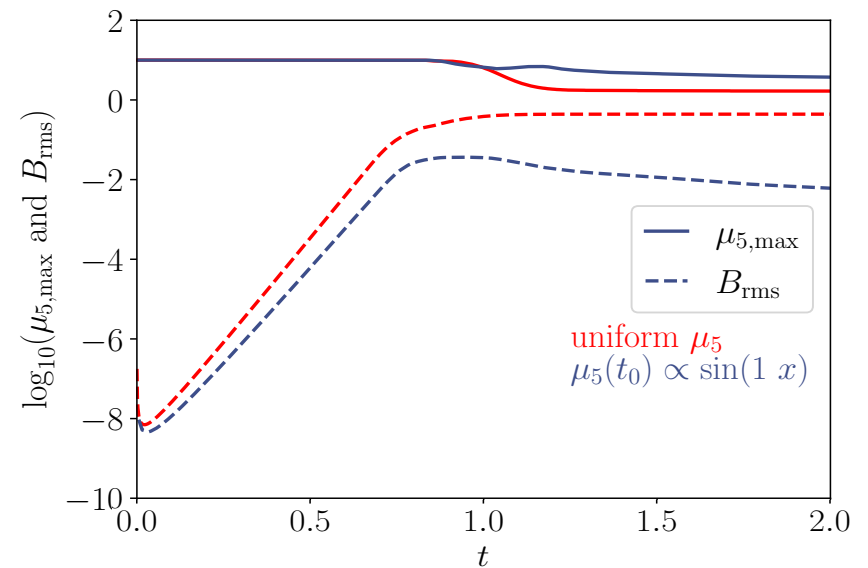
Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Initial distribution in numerical domain:



Resulting time evolution:

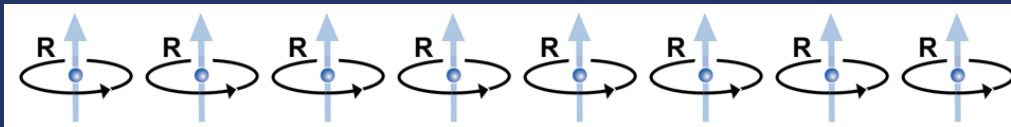


Towards more realistic scenarios

Nordita program
25/05/2026

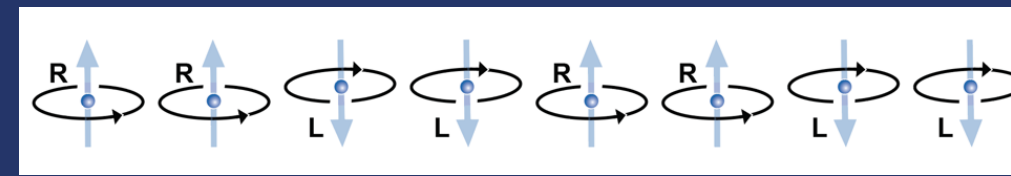
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.

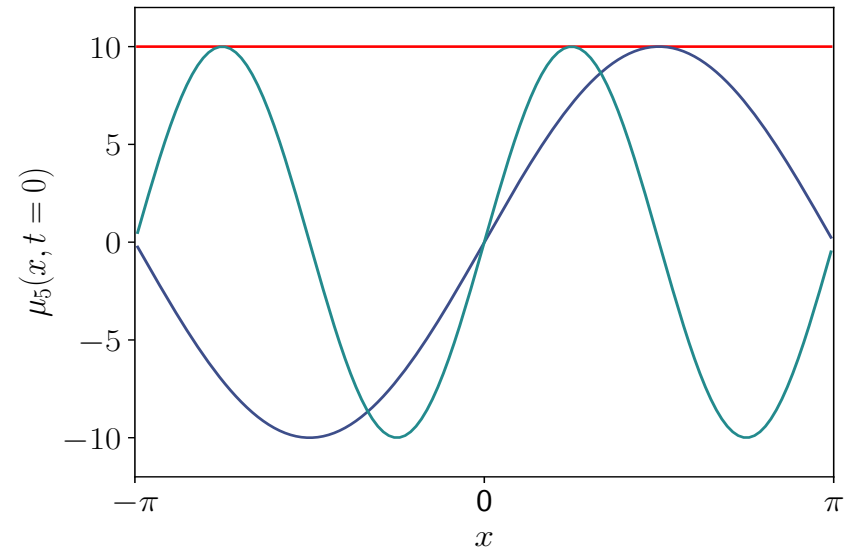


Generalization 1

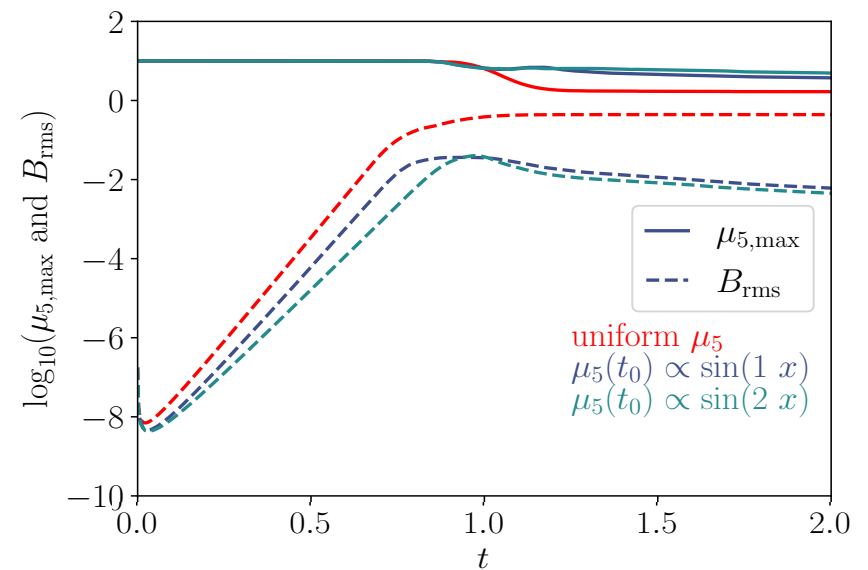
Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Initial distribution in numerical domain:



Resulting time evolution:

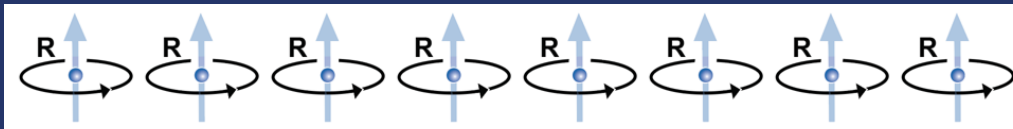


Towards more realistic scenarios

Nordita program
25/05/2026

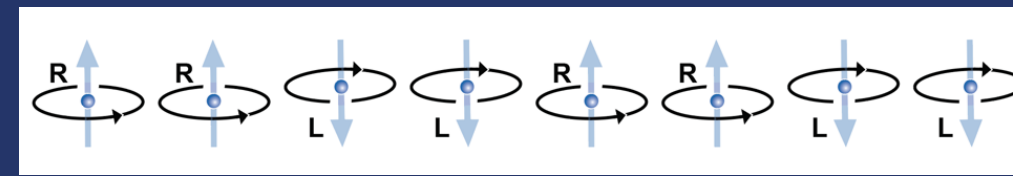
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.

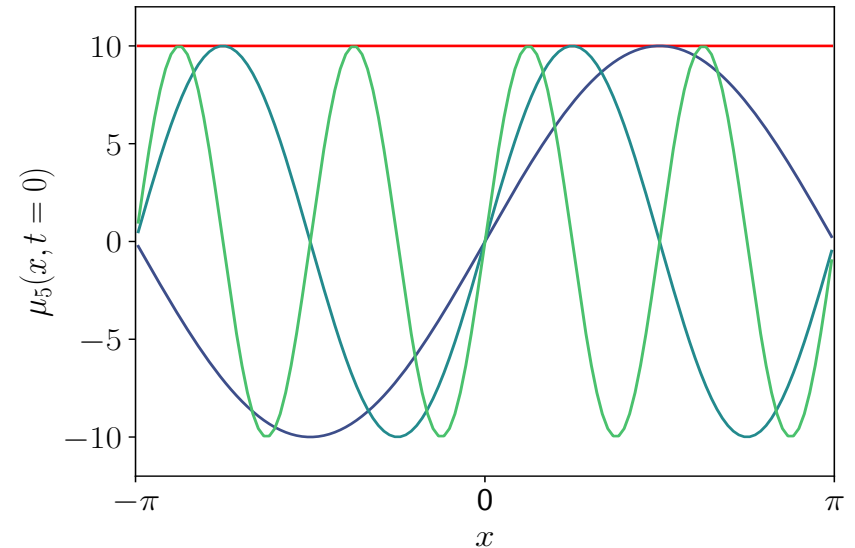


Generalization 1

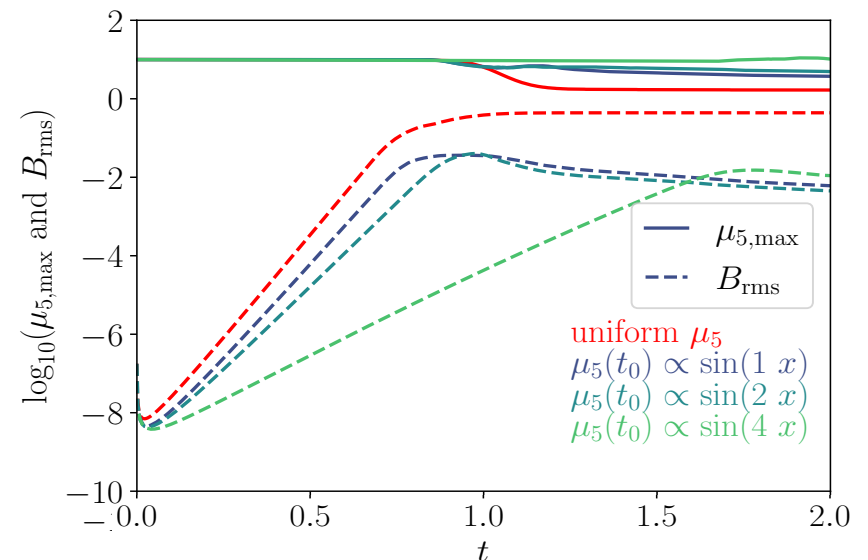
Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Initial distribution in numerical domain:

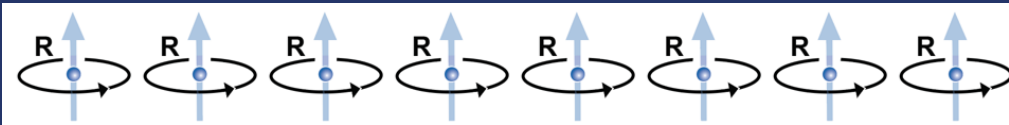


Resulting time evolution:



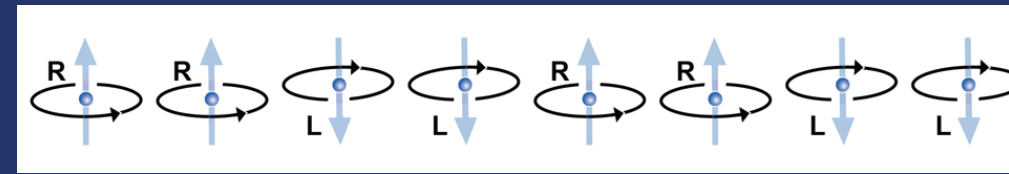
Ideal case

Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Generalization 1

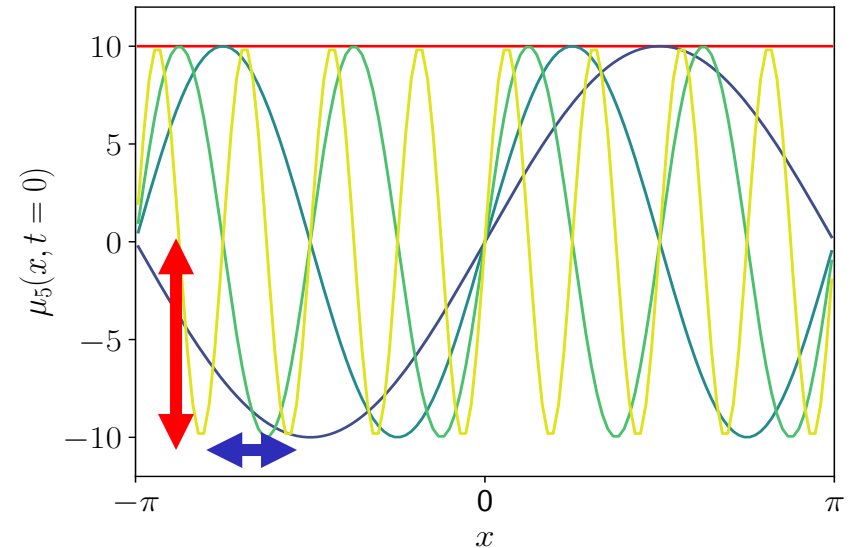
Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



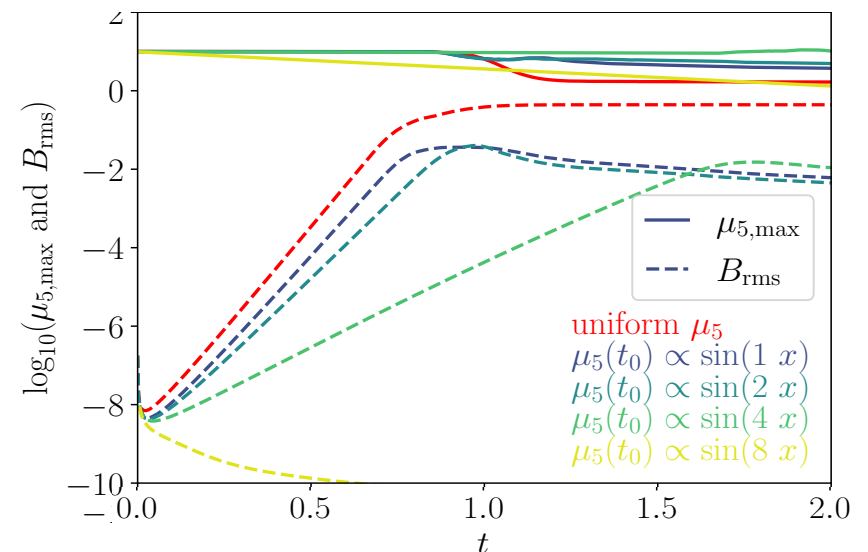
→ Minimum separation between the correlation length of μ_5 and the dynamo instability scale ($= \mu_5/2$) needed.

[Schober et al. 2022]

Initial distribution in numerical domain:



Resulting time evolution:

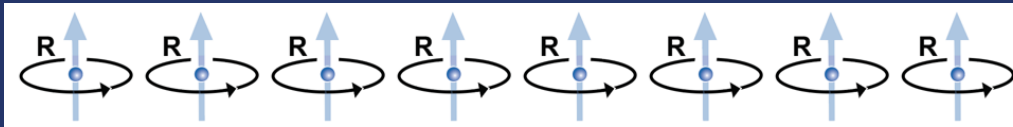


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

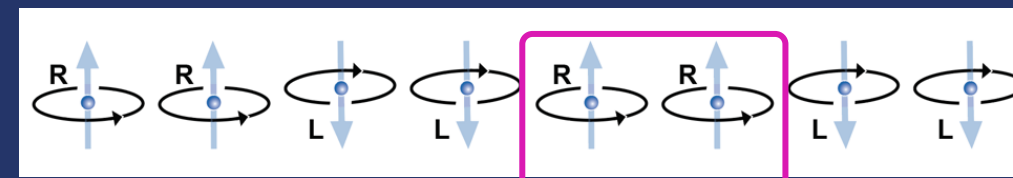
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

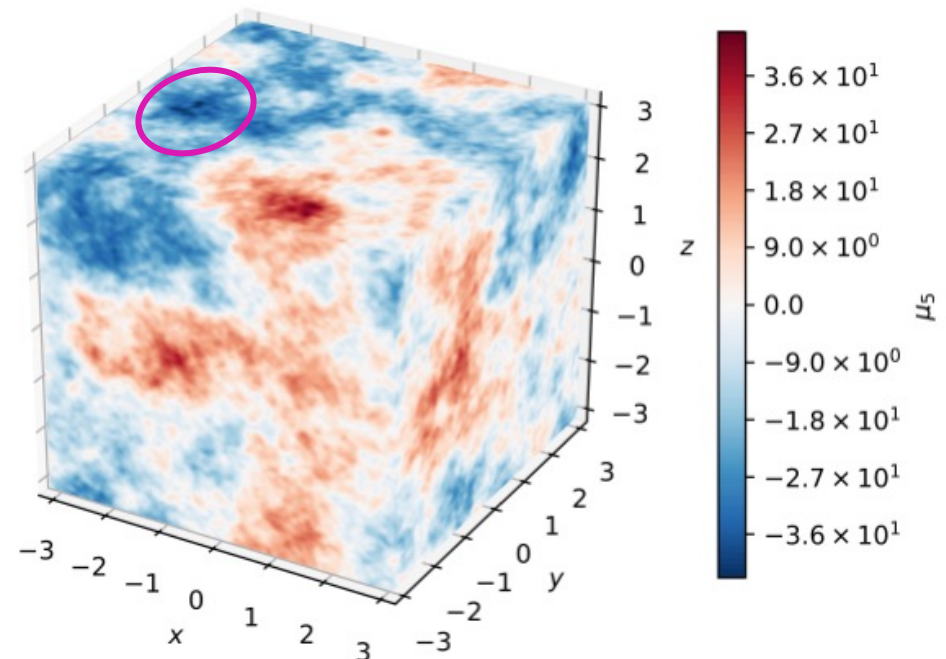
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Islands with
 $\langle \mu_5 \rangle \neq 0$

Schober et al., PRL, 2022

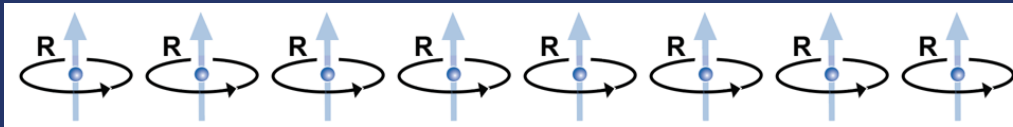


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

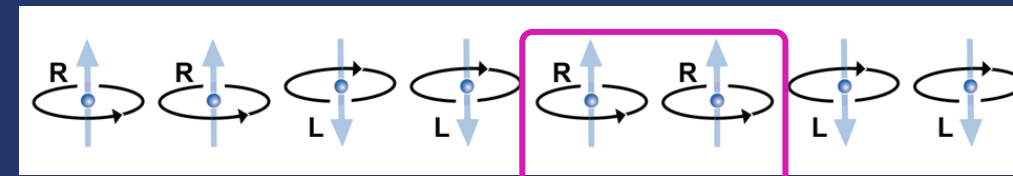
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

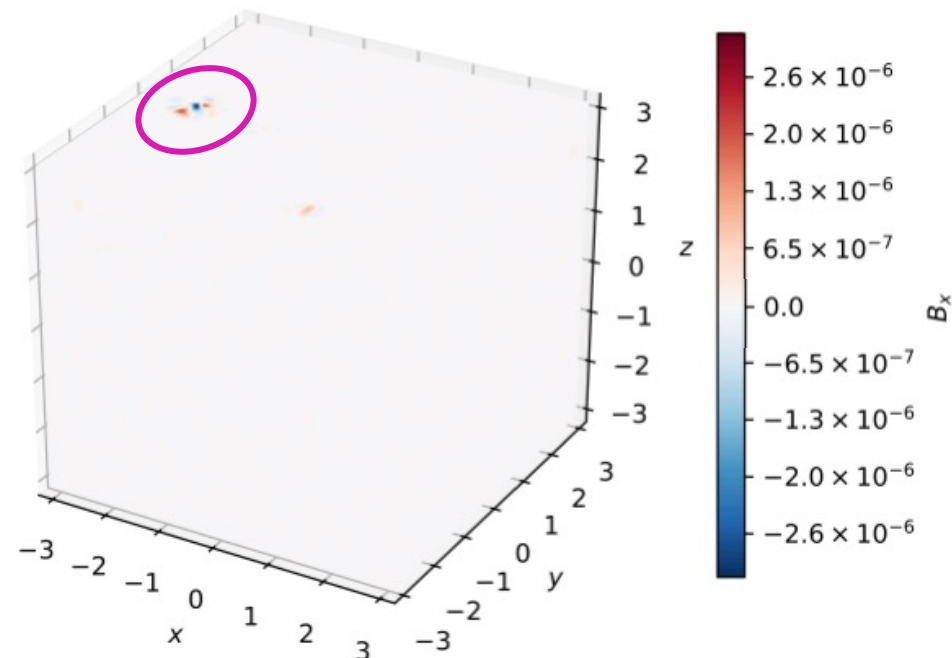
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Islands with
 $\langle \mu_5 \rangle \neq 0$

Schober et al., PRL, 2022

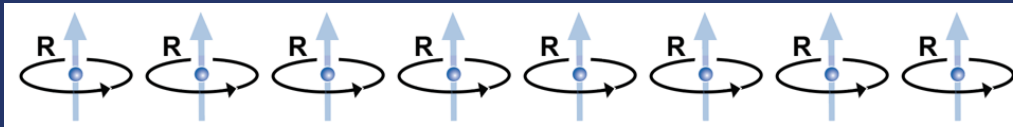


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

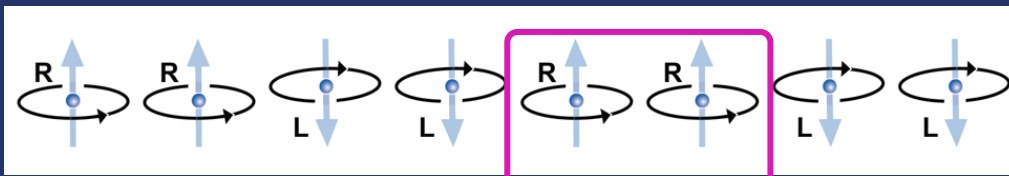
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

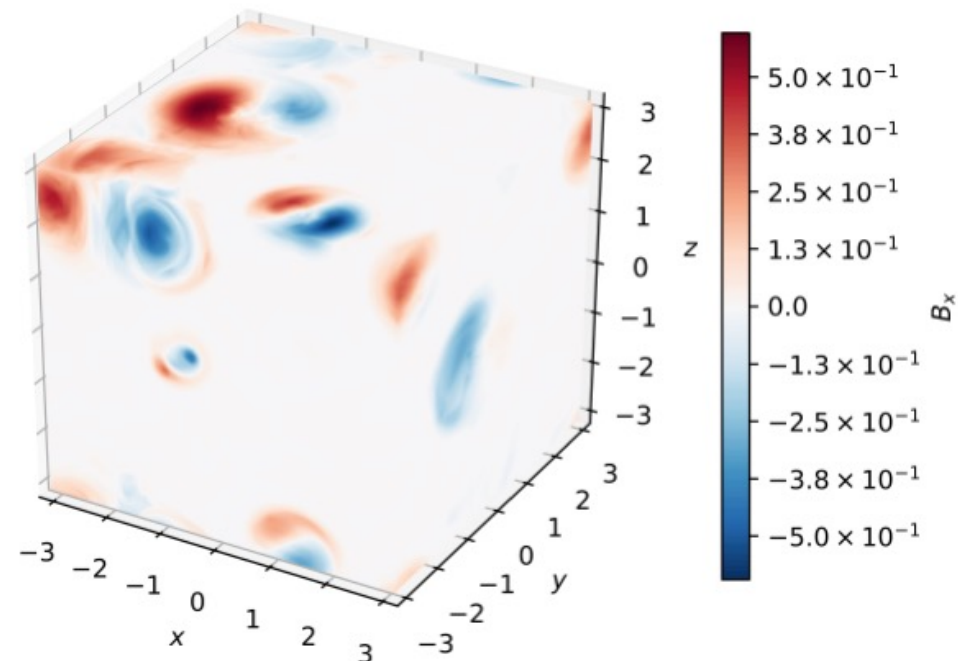
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Islands with
 $\langle \mu_5 \rangle \neq 0$

Schober et al., PRL, 2022

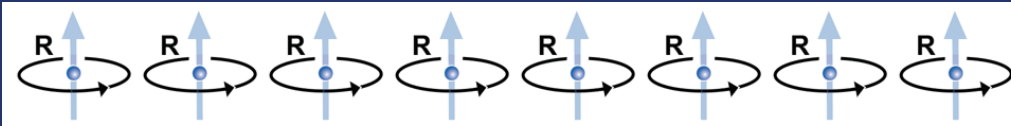


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

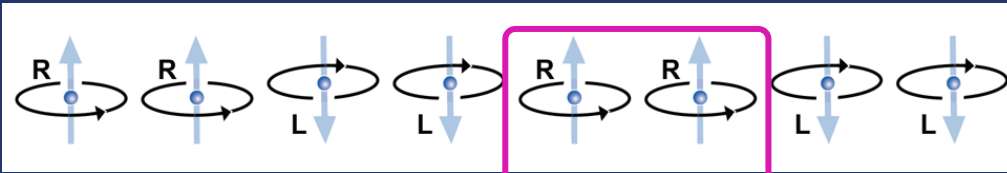
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

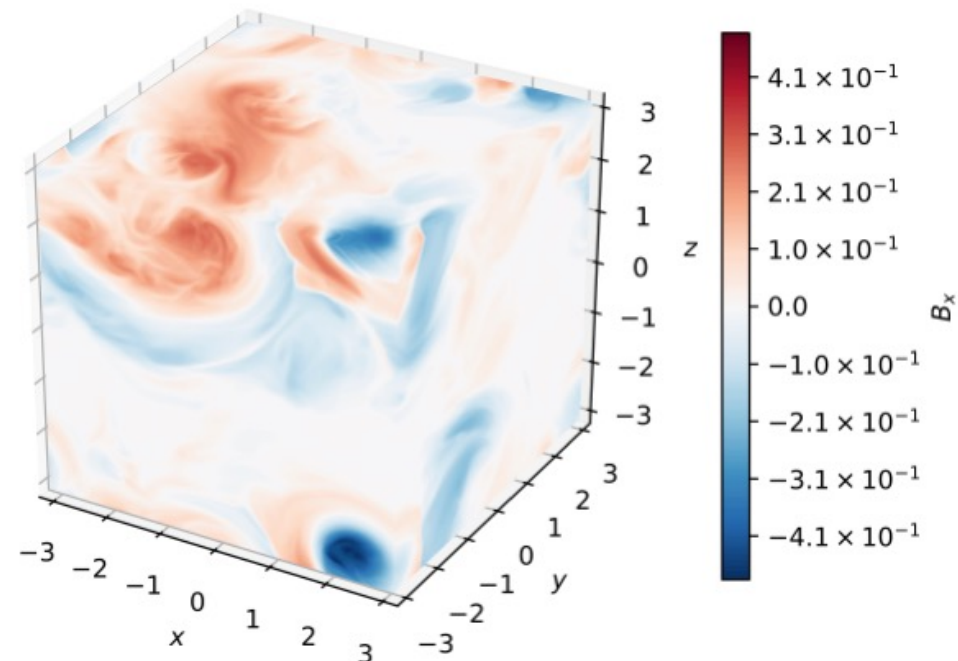
Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Islands with
 $\langle \mu_5 \rangle \neq 0$

Schober et al., PRL, 2022

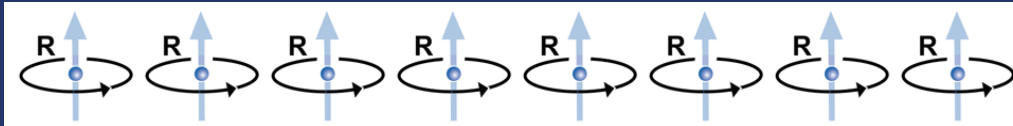


Towards more realistic scenarios

Nordita program
25/05/2026

Ideal case

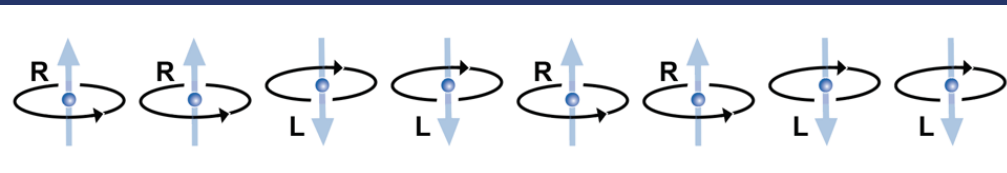
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

Generalization 1

Non-uniform chiral chemical potential, i.e.
 $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Schober et al., PRL, 2022

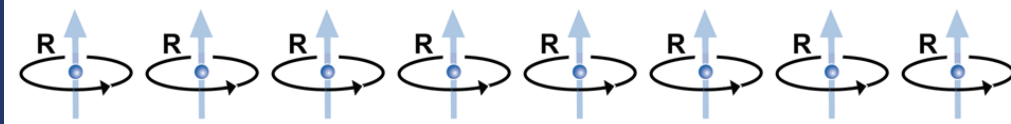
Generalization 2

No initial chiral chemical potential, i.e.
 $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) = 0$,
but autonomous generation via chiral magnetic waves.

Schober et al., PRL, 2024

Ideal case

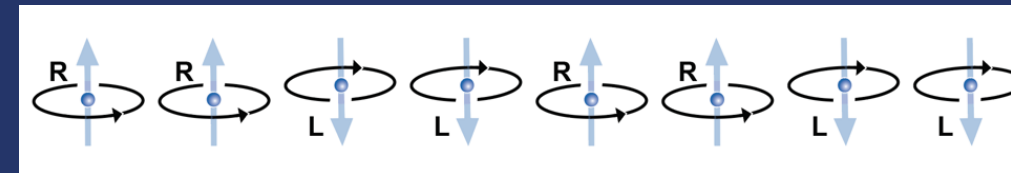
Uniform chiral chemical potential in the entire Universe, i.e. $\langle \mu_5 \rangle(t=0) \neq 0$.



Brandenburg et al., 2017
Rogachevskii et al., 2017
Schober et al., 2018

Generalization 1

Non-uniform chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) \neq 0$.



Schober et al., PRL, 2022

Generalization 2

No initial chiral chemical potential, i.e. $\langle \mu_5 \rangle(t=0) = 0$ & $\mu_{5,\text{rms}}(t=0) = 0$, but autonomous generation via chiral magnetic waves.

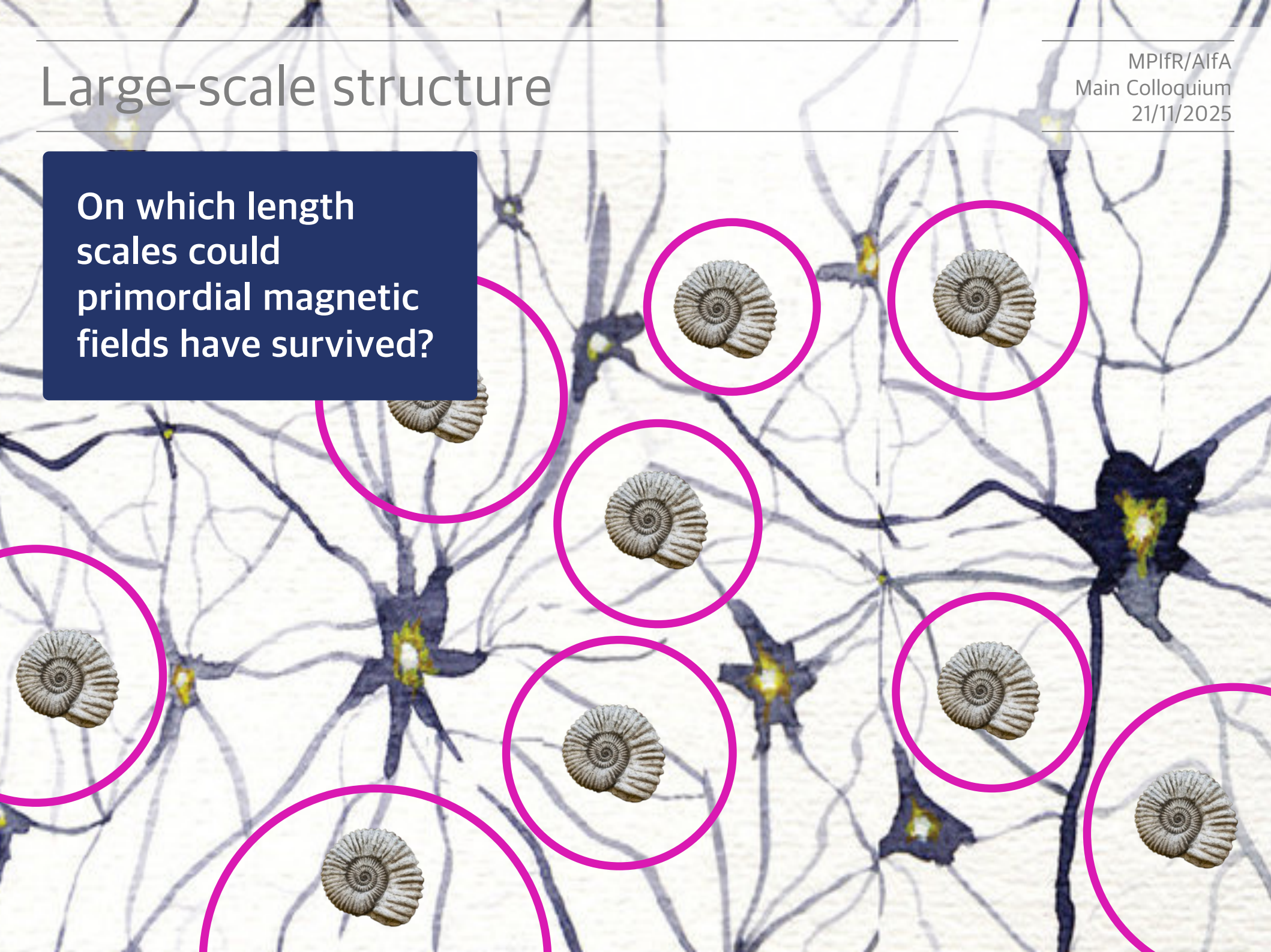
Schober et al., PRL, 2024

Mean-field chiral dynamos are a universal mechanism to generate large-scale magnetic fields!

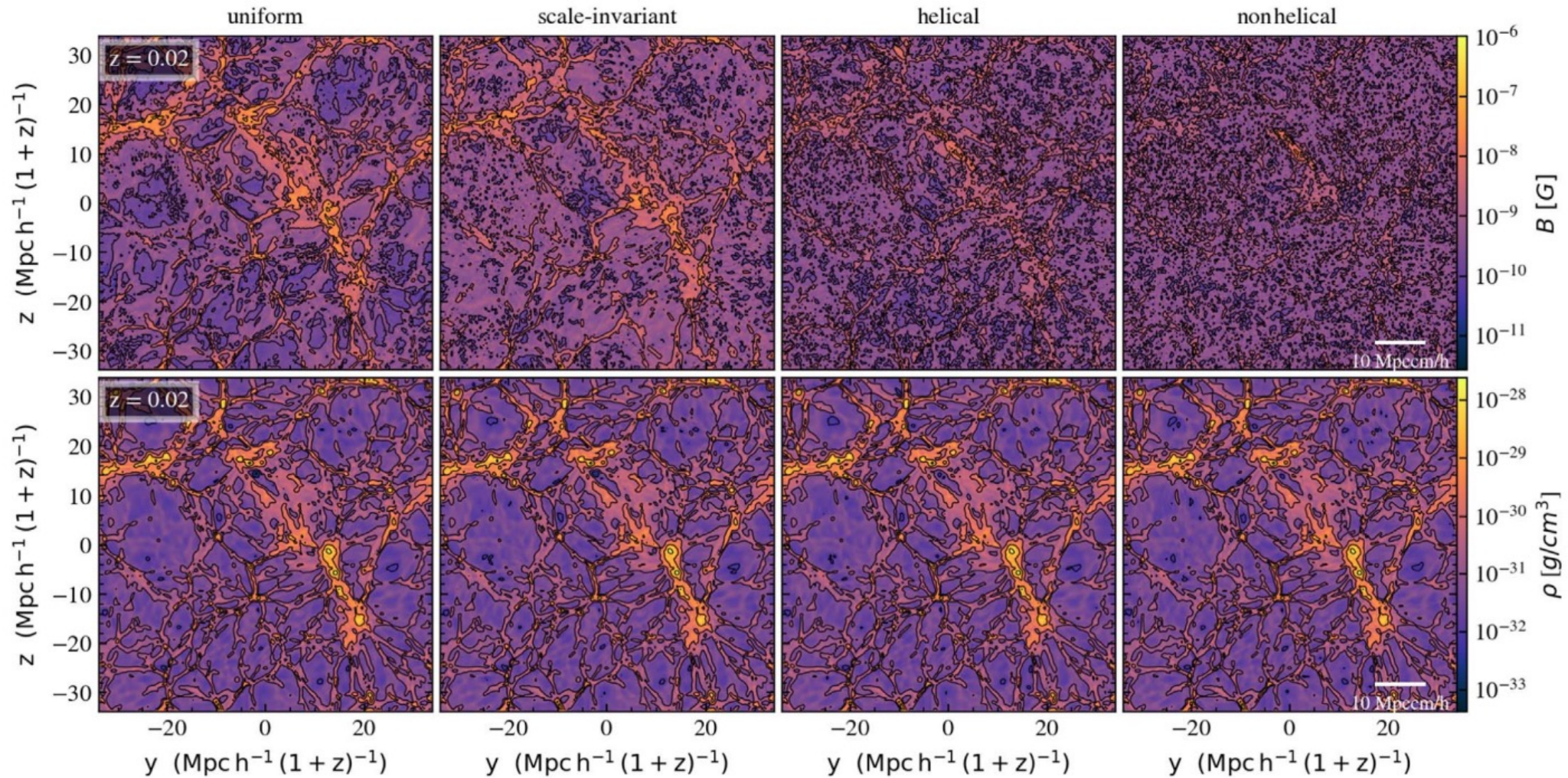
Large-scale structure

MPIfR/AlfA
Main Colloquium
21/11/2025

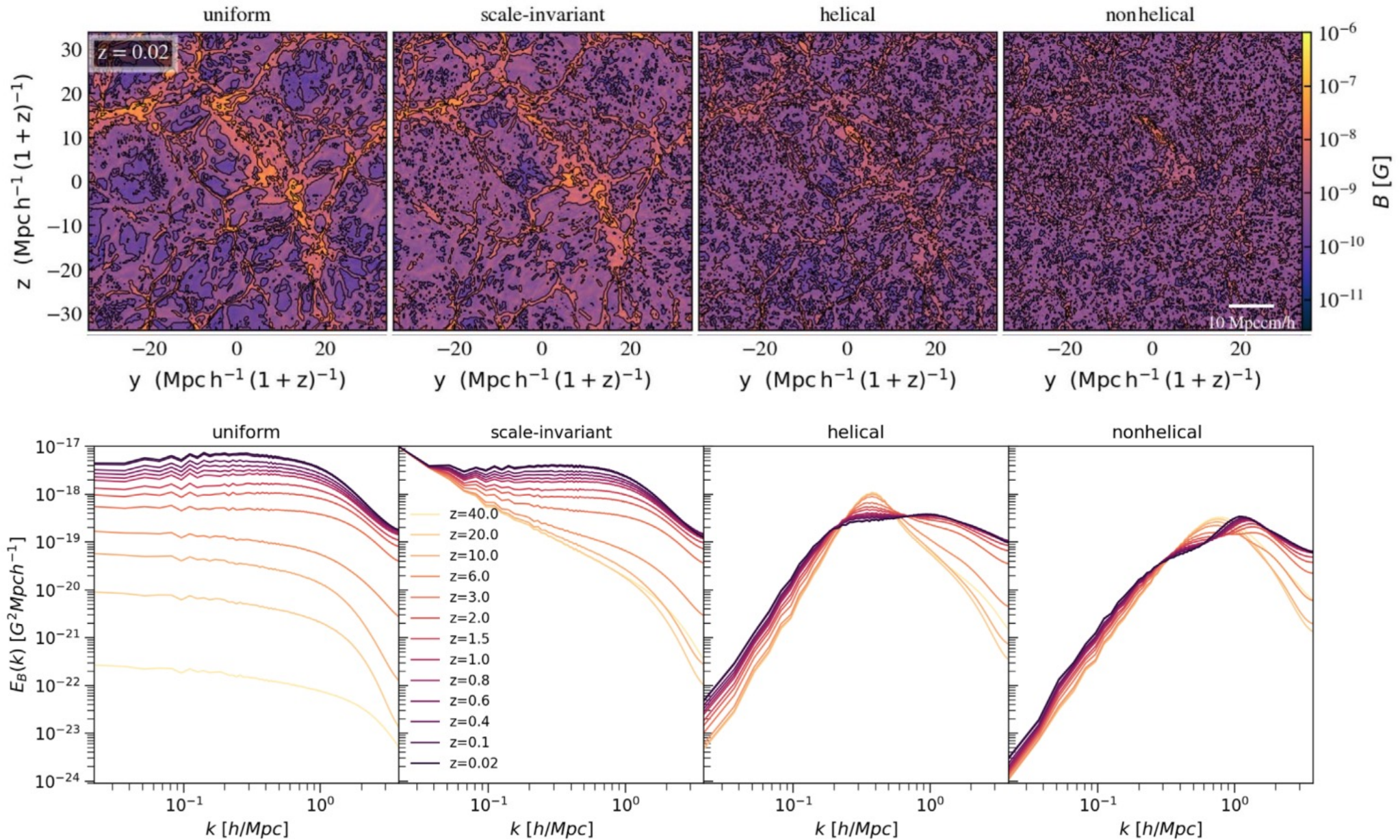
On which length
scales could
primordial magnetic
fields have survived?



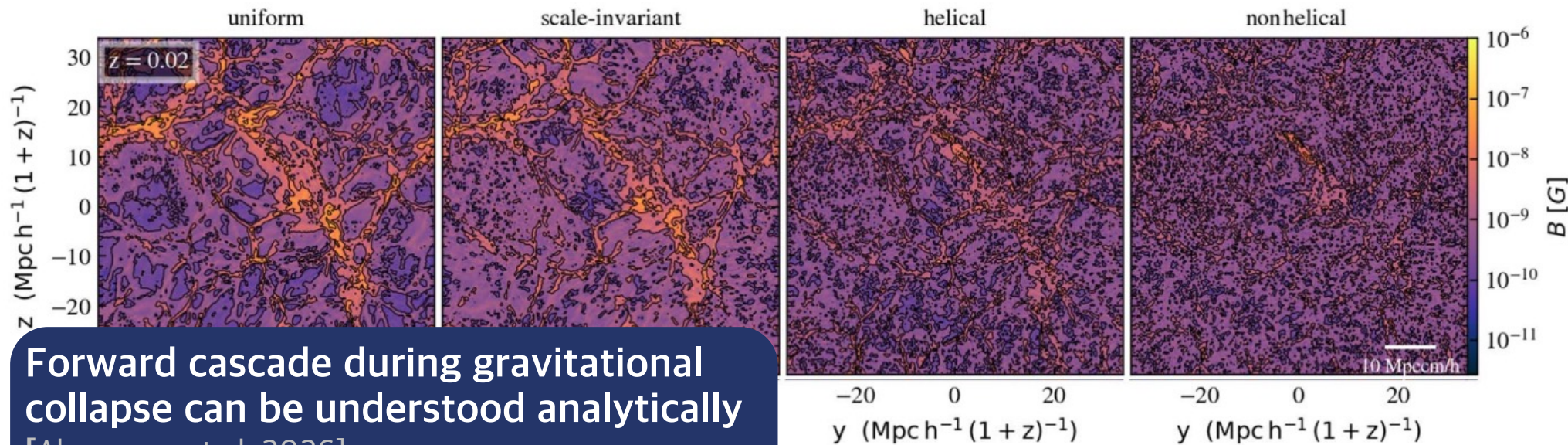
PMFs during structure formation



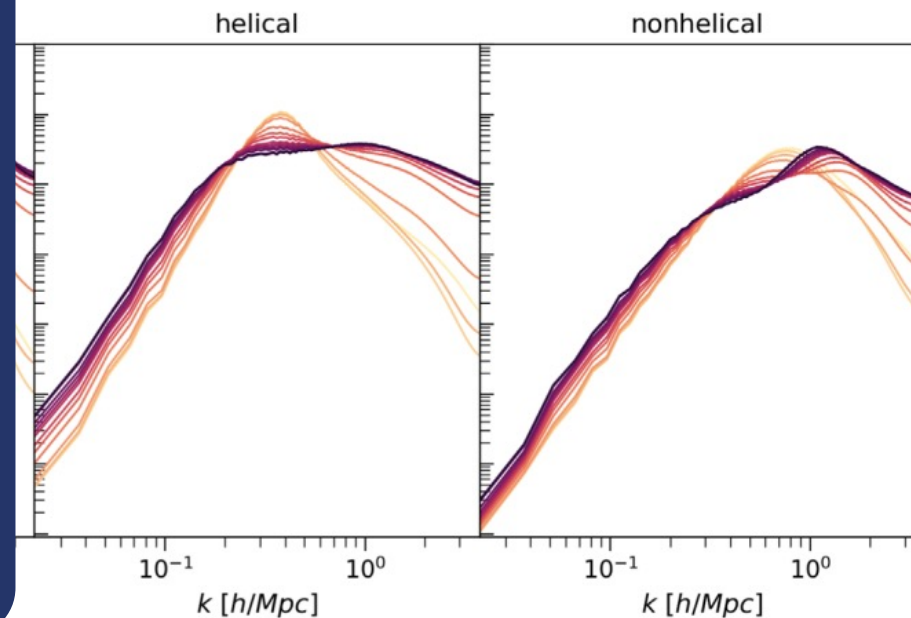
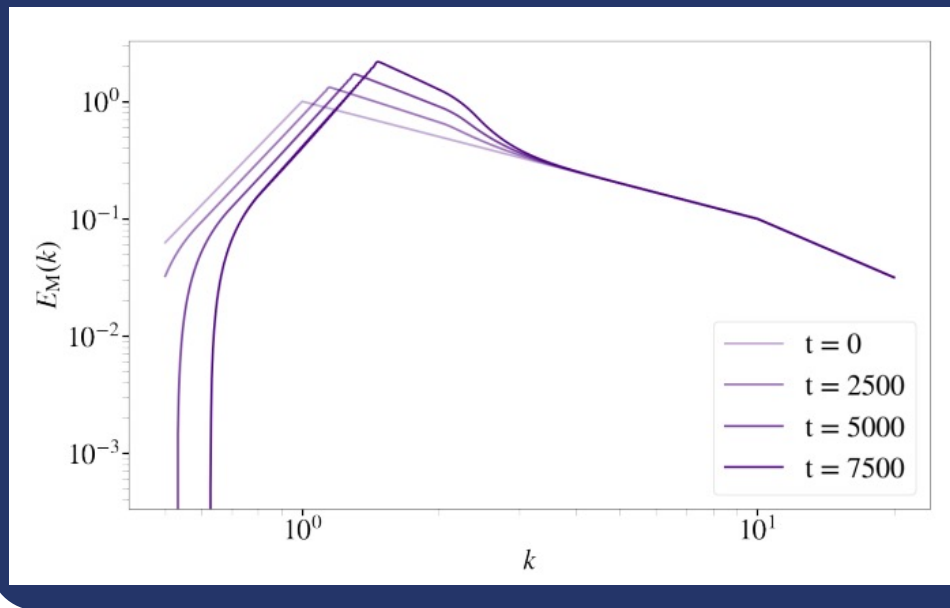
PMFs during structure formation



PMFs during structure formation

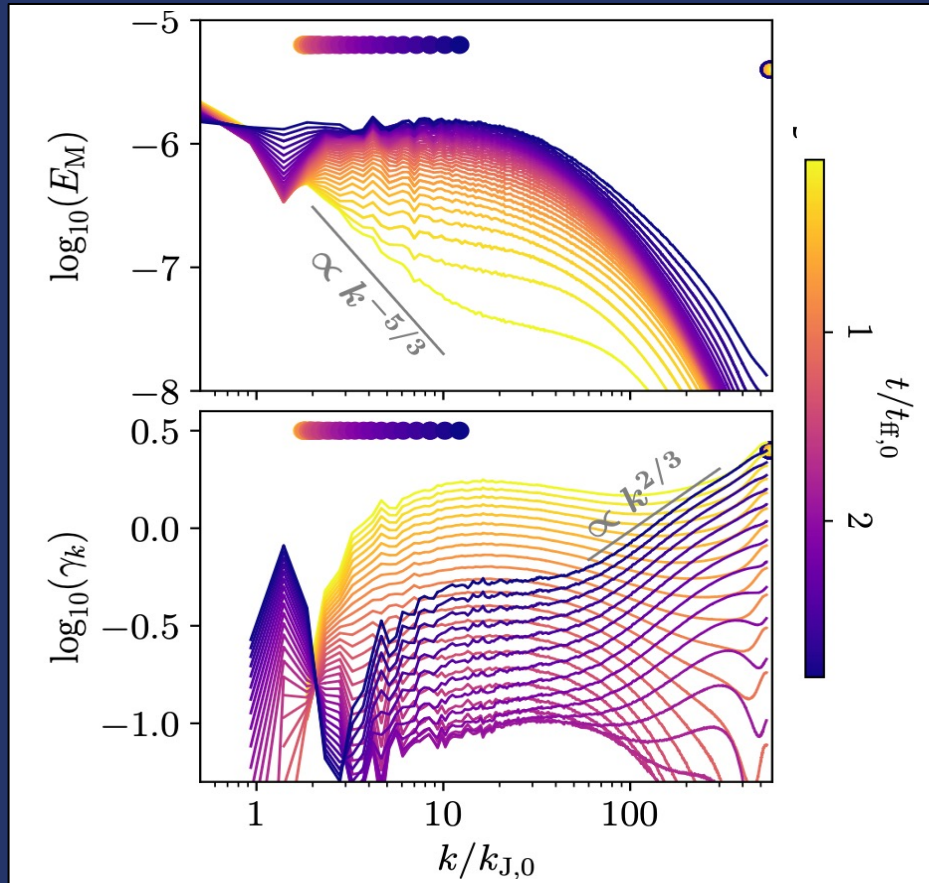


Forward cascade during gravitational collapse can be understood analytically [Abramson et al. 2026].

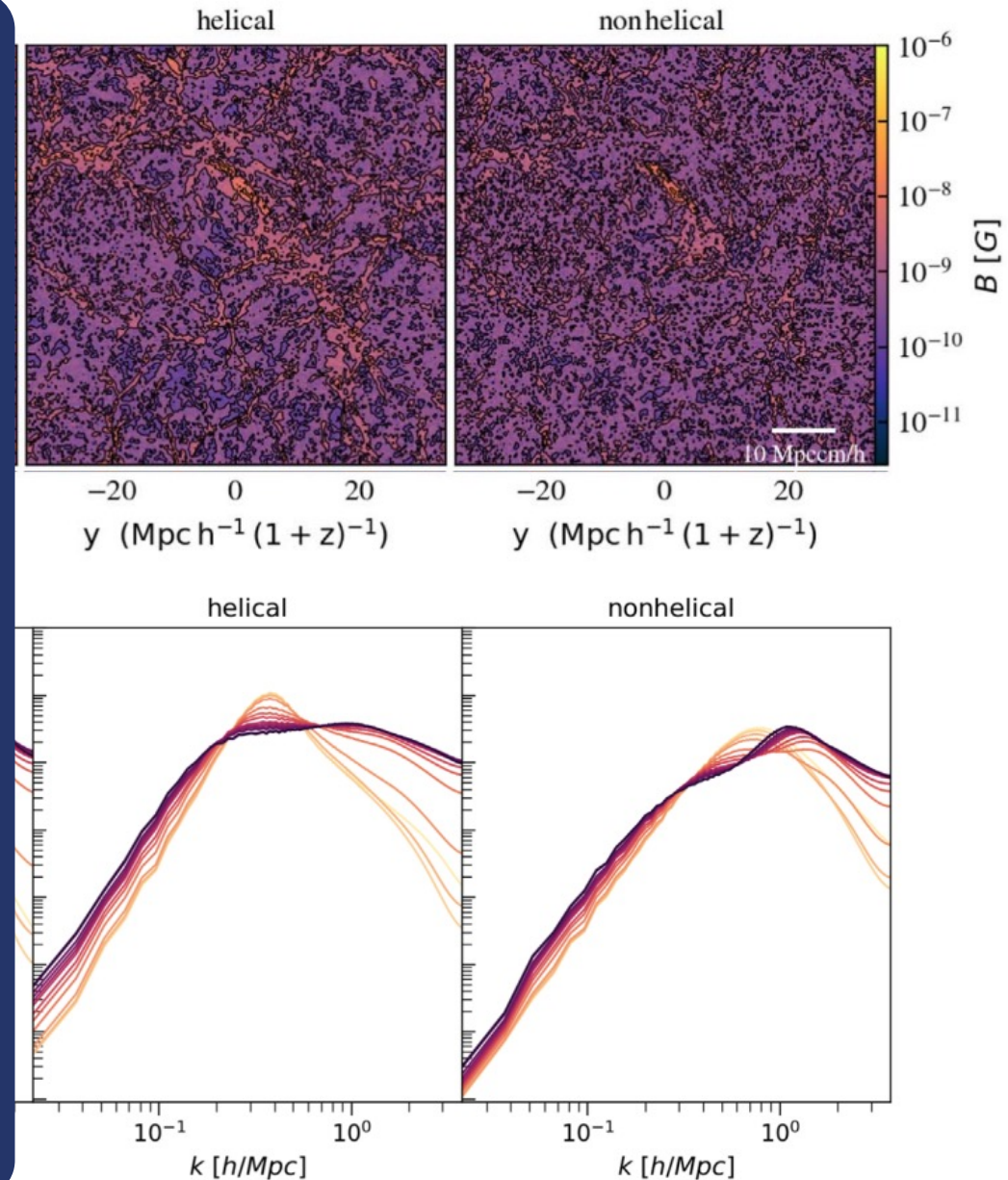


PMFs during structure formation

Below the Jeans scale, a small-scale dynamo washes out the memory on PMFs [Schober et al. 2026]



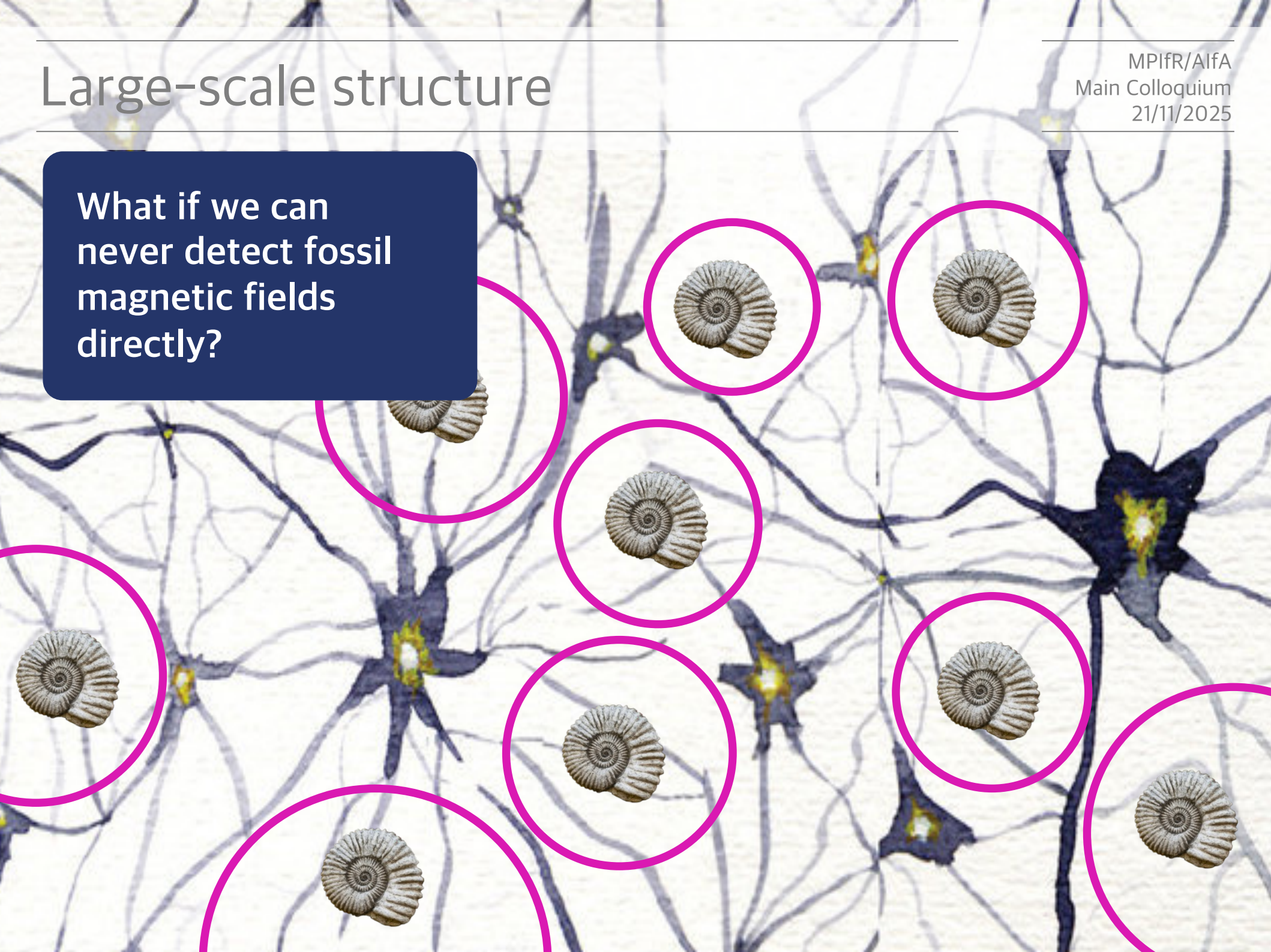
[see also Federrath et al. 2011, Sur et al. 2012, Brandenburg & Ntormousi 2025]



Large-scale structure

MPIfR/AlfA
Main Colloquium
21/11/2025

What if we can
never detect fossil
magnetic fields
directly?



Primordial magnetic fields...

Nordita program
25/05/2026

... help to explain the **baryon asymmetry**

Kamada 2018

... produce relic **gravitational waves**

Caprini et al.
2009, Roper
Pol et al. 2020

... help to relieve the **Hubble tension**

Jedamzik &
Pogosian 2020

... modify the **CMB statistics**

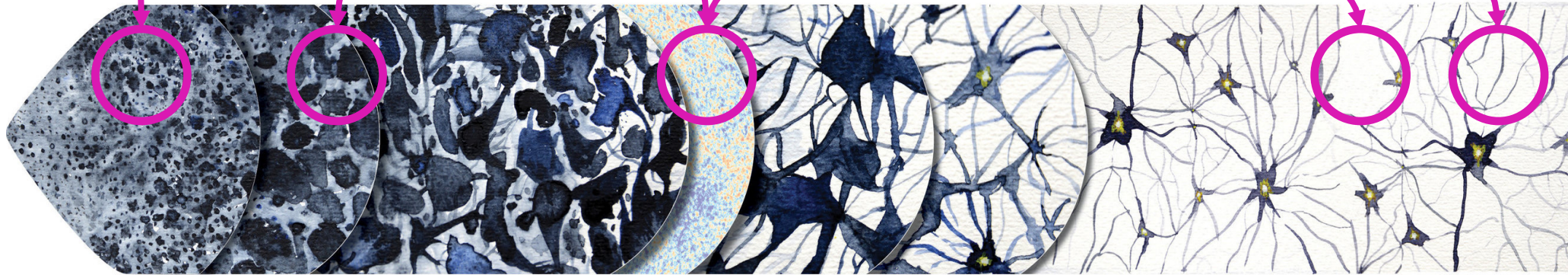
Durrer 2007

... affect the **21 cm signal**

Kunze 2019

... modify the evolution of **dwarf galaxies**

Sanati et al.
2019, 2024



🕒 10^{-32} s

🌡️ 10^{27} K

📏 0.01 ly

🕒 3 min

🌡️ 10^9 K

📏 1 ly

🕒 4×10^5 a

🌡️ 3000 K

📏 3×10^7 ly

🕒 300–500 Myr

🌡️ 30 K

📏 3×10^9 ly

🕒 13.6 Gyr

🌡️ 3 K

📏 5×10^{10} ly

Big Bang

Conclusions

Nordita program
25/05/2026



Thanks for
your
attention!

Contact:

✉ schober@uni-bonn.de
🌐 jennifer-schober.com

Conclusions

Nordita program
25/05/2026

Magneto-
hydrodynamical
turbulence is
everywhere in
the Universe.



Thanks for
your
attention!

Contact:

✉ schober@uni-bonn.de
🌐 jennifer-schober.com

Conclusions

Nordita program
25/05/2026

Magneto-
hydrodynamical
turbulence is
everywhere in
the Universe.

Often, **MHD**
provides an
effective
framework to
model magnetic
fields.

MHD dynamos
convert turbulent
kinetic energy in
to magnetic
energy in planets,
stars, the
interstellar
medium, and
galaxies.



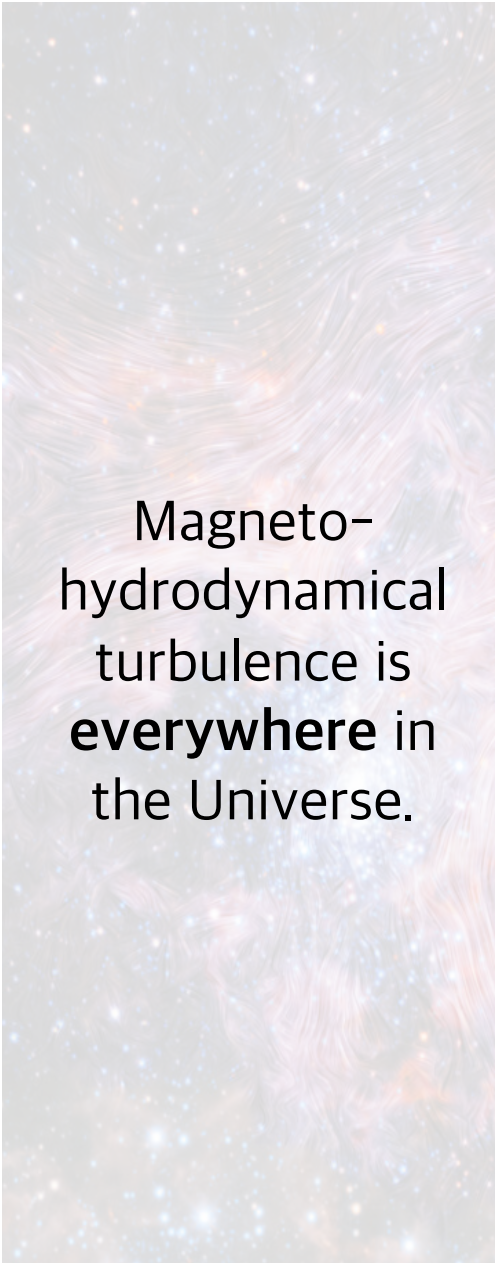
Thanks for
your
attention!

Contact:

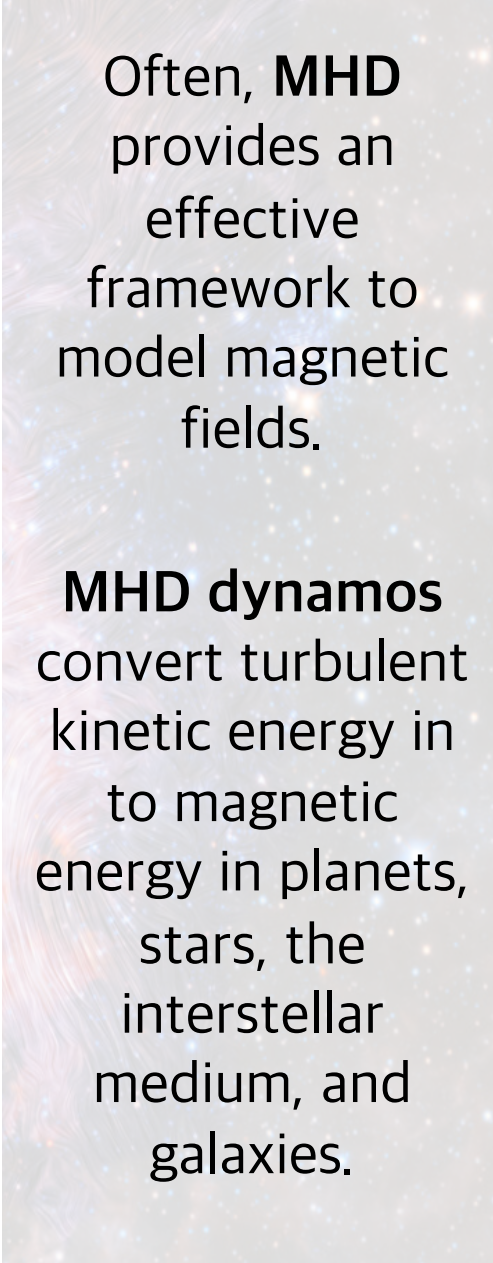
✉ schober@uni-bonn.de
🌐 jennifer-schober.com

Conclusions

Nordita program
25/05/2026

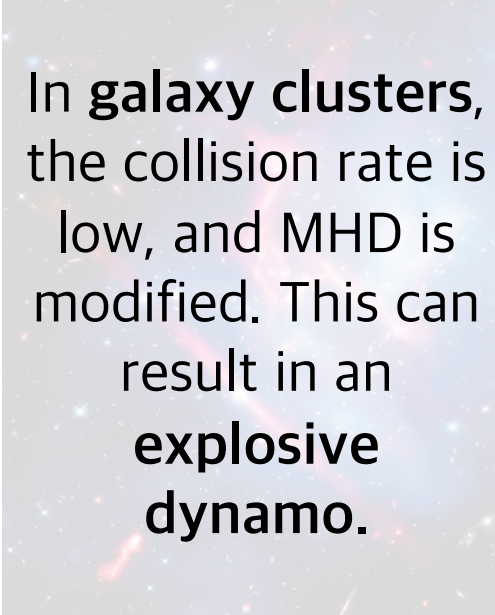


Magneto-
hydrodynamical
turbulence is
everywhere in
the Universe.



Often, **MHD**
provides an
effective
framework to
model magnetic
fields.

MHD dynamos
convert turbulent
kinetic energy in
to magnetic
energy in planets,
stars, the
interstellar
medium, and
galaxies.



In **galaxy clusters**,
the collision rate is
low, and MHD is
modified. This can
result in an
**explosive
dynamo.**



Thanks for
your
attention!

Contact:

✉ schober@uni-bonn.de
🌐 jennifer-schober.com

Conclusions

Nordita program
25/05/2026

Magneto-
hydrodynamical
turbulence is
everywhere in
the Universe.

Often, **MHD**
provides an
effective
framework to
model magnetic
fields.

MHD dynamos
convert turbulent
kinetic energy in
to magnetic
energy in planets,
stars, the
interstellar
medium, and
galaxies.

In **galaxy clusters**,
the collision rate is
low, and MHD is
modified. This can
result in an
**explosive
dynamo.**

In the **early
Universe**, MHD
needs to be
extended to **chiral
MHD**, leading to
new dynamos.

Thanks for
your
attention!

Contact:

✉ schober@uni-bonn.de
🌐 jennifer-schober.com