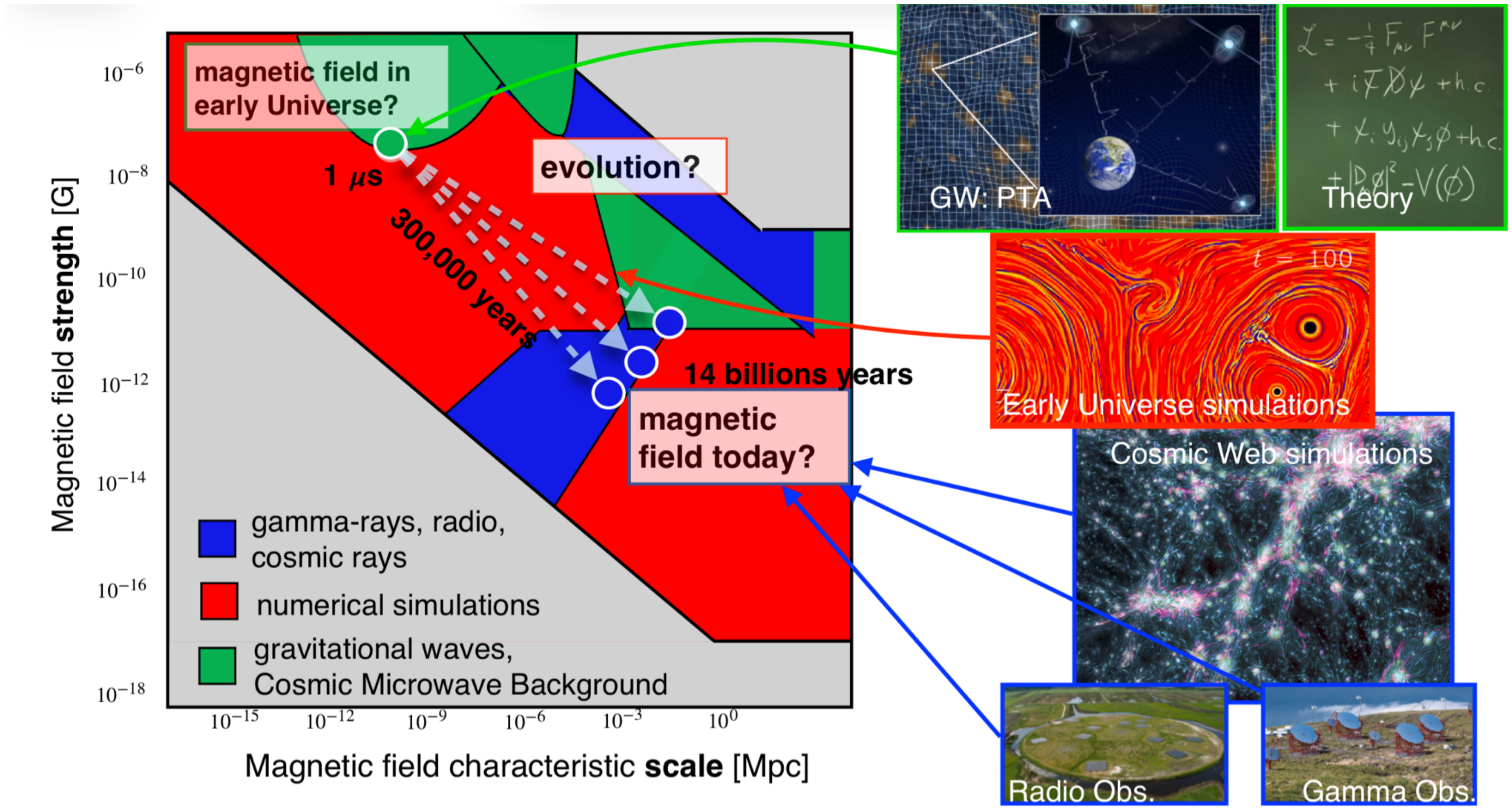
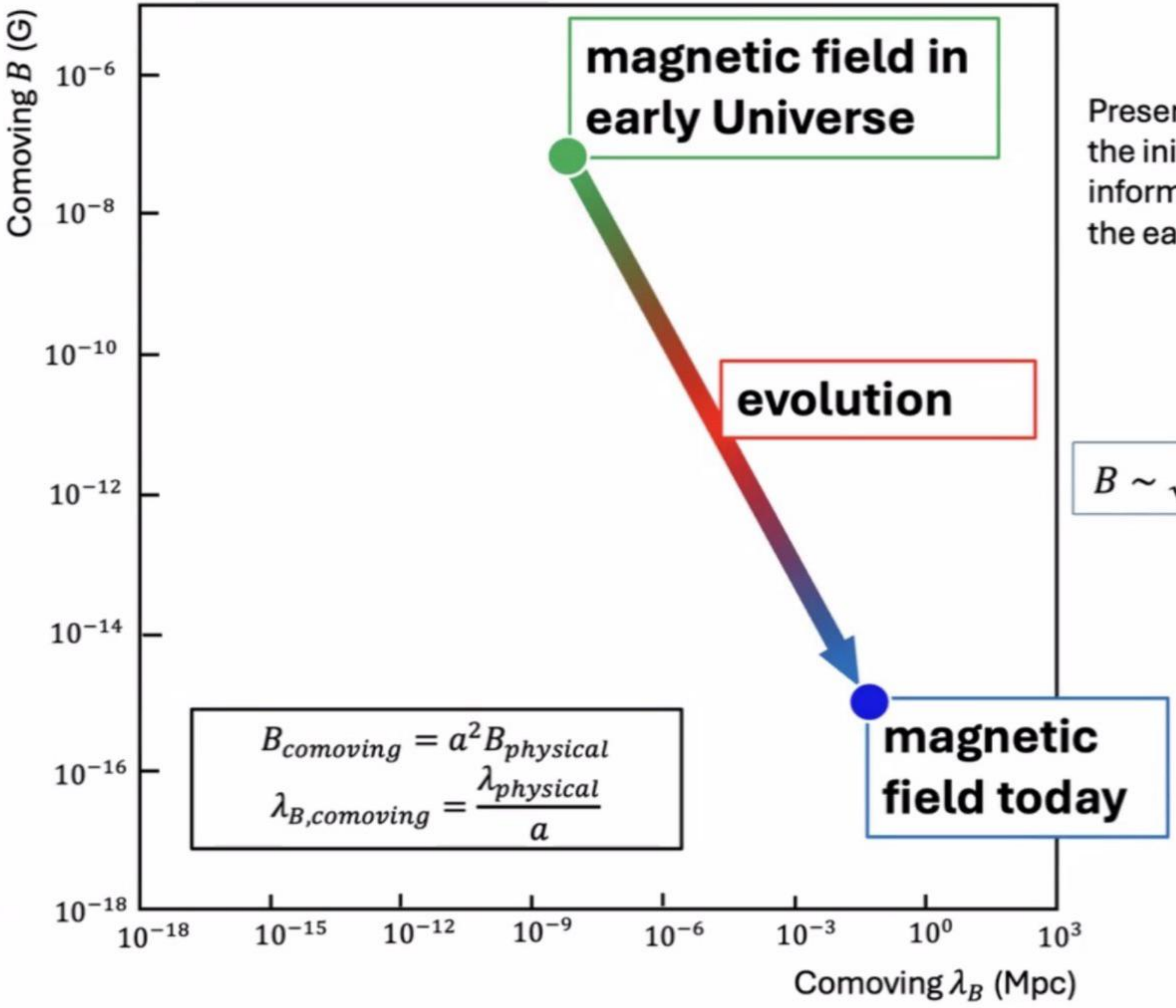
Magnetic fields as probes of the first microseconds

Axel Brandenburg
& Oksana Iarygina

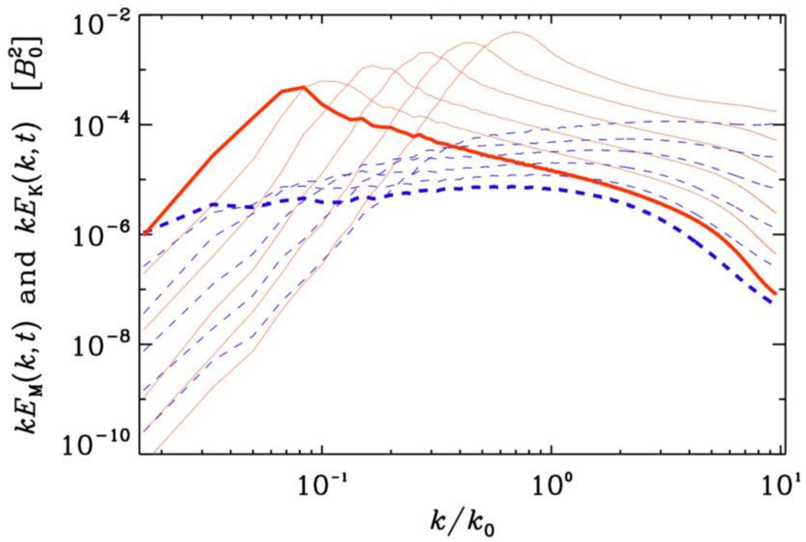




Magnetic field: inversely cascading

Present-day relic magnetic field parameters are related to the initial field characteristics. They potentially provide information on the mechanism of production of the field in the early Universe.

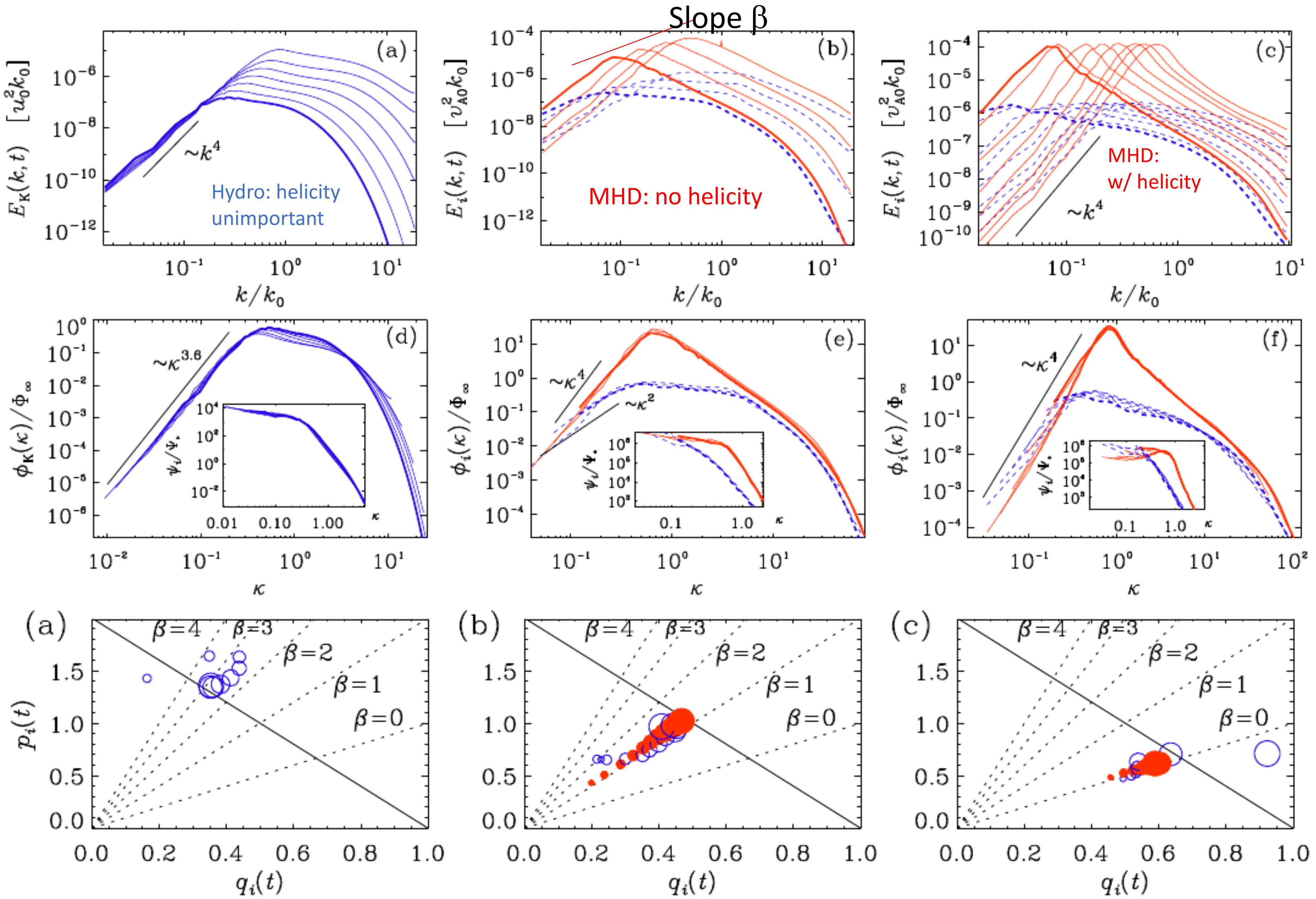
$$B \sim \sqrt{2\rho_B}$$



- Turbulent decay
  - Magnetic field drives gas motions
  - The velocity stirs up the field further
- But: length scale can increase
  - Energy at large scales (small k) can increase!
  - → Inverse cascade

Collapsed spectra and *pq* diagrams

$-p_i(t) = d\ln\mathcal{E}_i/d\ln t, \quad q_i(t) = d\ln\xi_i/d\ln t,$



Brandenburg & Kahniashvili (2017)

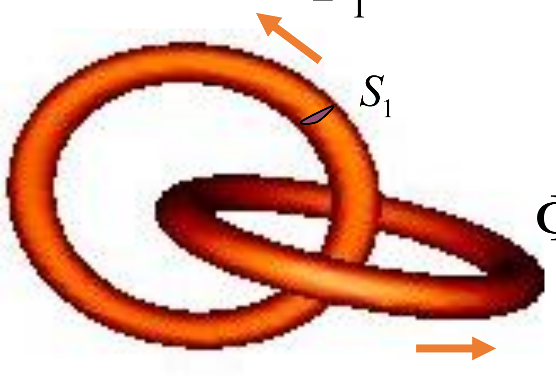
Explanations for slope β

Exponents *p,q*

(Hosking & Schekochihin 2021+2023)

Inverse cascading is unique to magnetic decay

Magnetic helicity



$$H = \int_V \mathbf{A}\cdot\mathbf{B}\,\mathrm{d}V$$

$$\mathbf{B} = \nabla\times\mathbf{A}$$

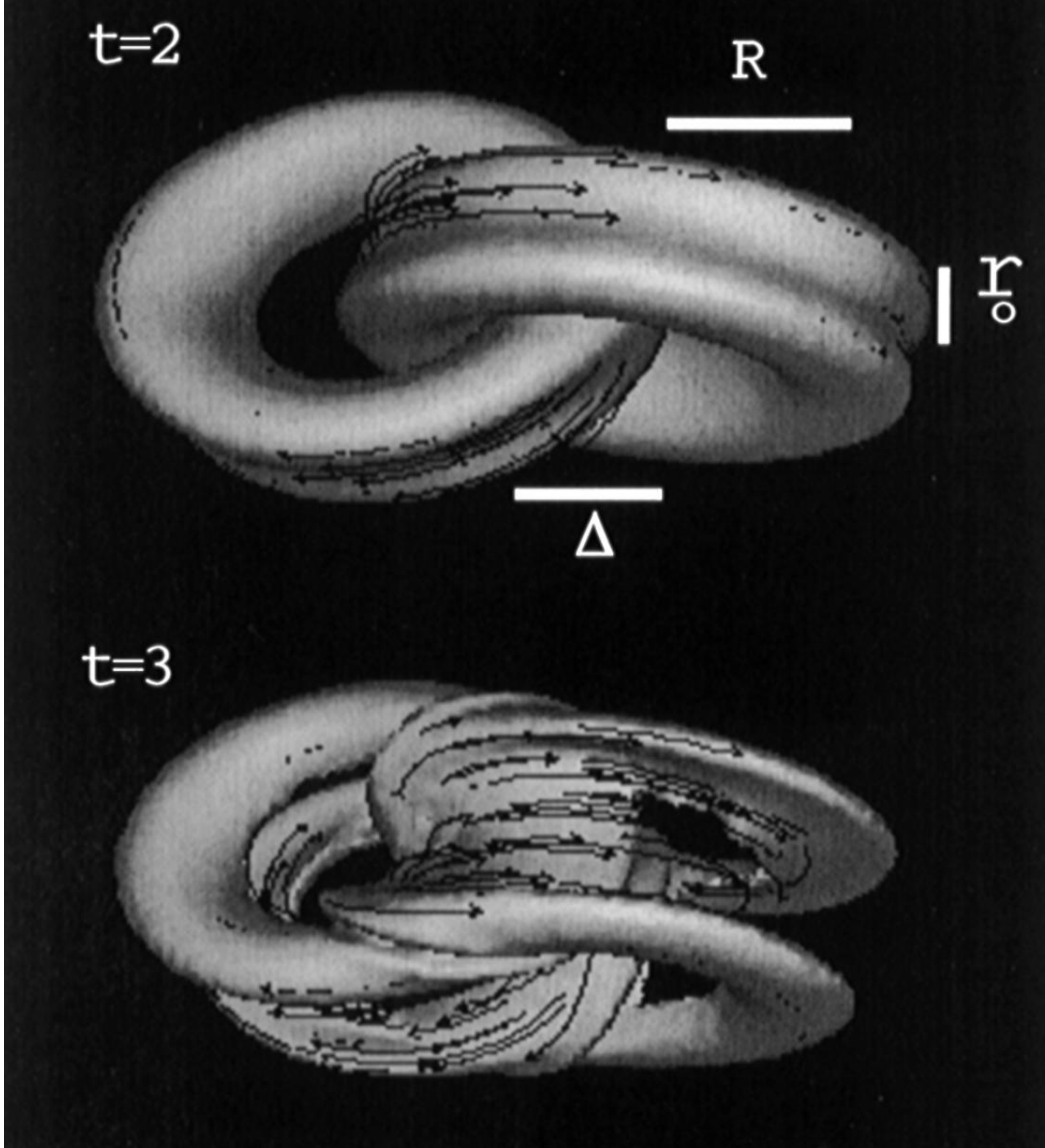
$$H_1 = \int_{L_1} \mathbf{A}\cdot\mathrm{d}\boldsymbol{\ell} \int_{S_1} \mathbf{B}\cdot\mathrm{d}\mathbf{S}$$

$$= \int_{S_2} \nabla\times\mathbf{A}\cdot\mathrm{d}\mathbf{S} = \Phi_2 \qquad = \Phi_1$$

$$H = \pm 2\Phi_1\Phi_2$$

Therefore the unit is Maxwell squared

Kerr & Brandenburg (1999)



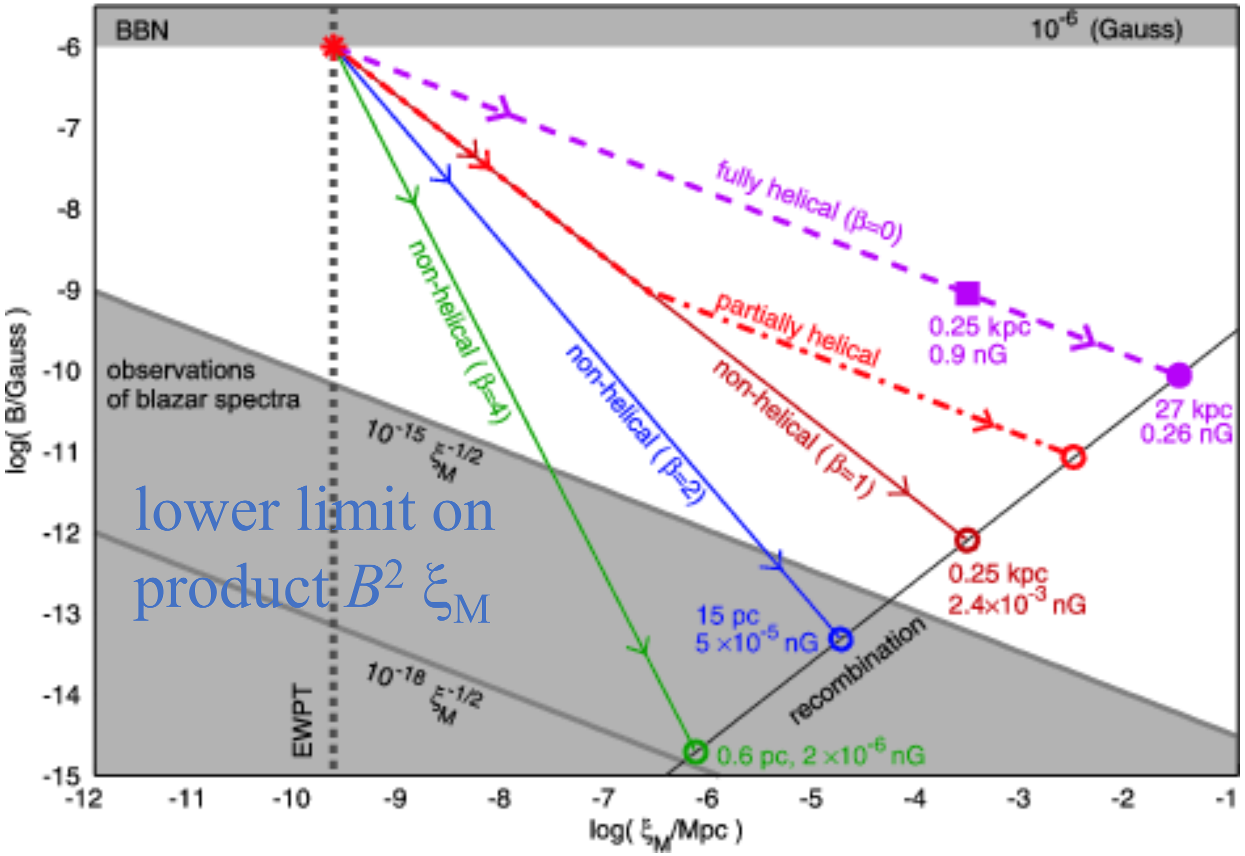
Conservation laws

$\xi_M \sim \langle A.B \rangle\, t^{2/3}$

$\mathrm{cm} \sim (\mathrm{cm}^3/\mathrm{s}^2)^{1/3}\, \mathrm{s}^{2/3}$

Magnetic helicity	$\langle \boldsymbol{A}\cdot\boldsymbol{B}\rangle$	$\mathrm{cm}^3\,\mathrm{s}^{-2}$	$\xi_\mathrm{M}(t) \propto \langle \boldsymbol{A}\cdot\boldsymbol{B}\rangle^{1/3} t^{2/3}$
Anastrophy (2-D)	$\langle A_z^2\rangle$	$\mathrm{cm}^4\,\mathrm{s}^{-2}$	$\xi_\mathrm{M}(t) \propto \langle A_z^2\rangle^{1/4} t^{1/2}$
Hosking integral	I_H	$\mathrm{cm}^9\,\mathrm{s}^{-4}$	$\xi_\mathrm{M}(t) \propto I_\mathrm{H}^{1/9} t^{4/9}$
Saffman integral	I_S	$\mathrm{cm}^5\,\mathrm{s}^{-2}$	$\xi_\mathrm{M}(t) \propto I_\mathrm{S}^{1/5} t^{2/5}$
Loitsyansky integral	I_L	$\mathrm{cm}^7\,\mathrm{s}^{-2}$	$\xi_\mathrm{M}(t) \propto I_\mathrm{S}^{1/7} t^{2/7}$

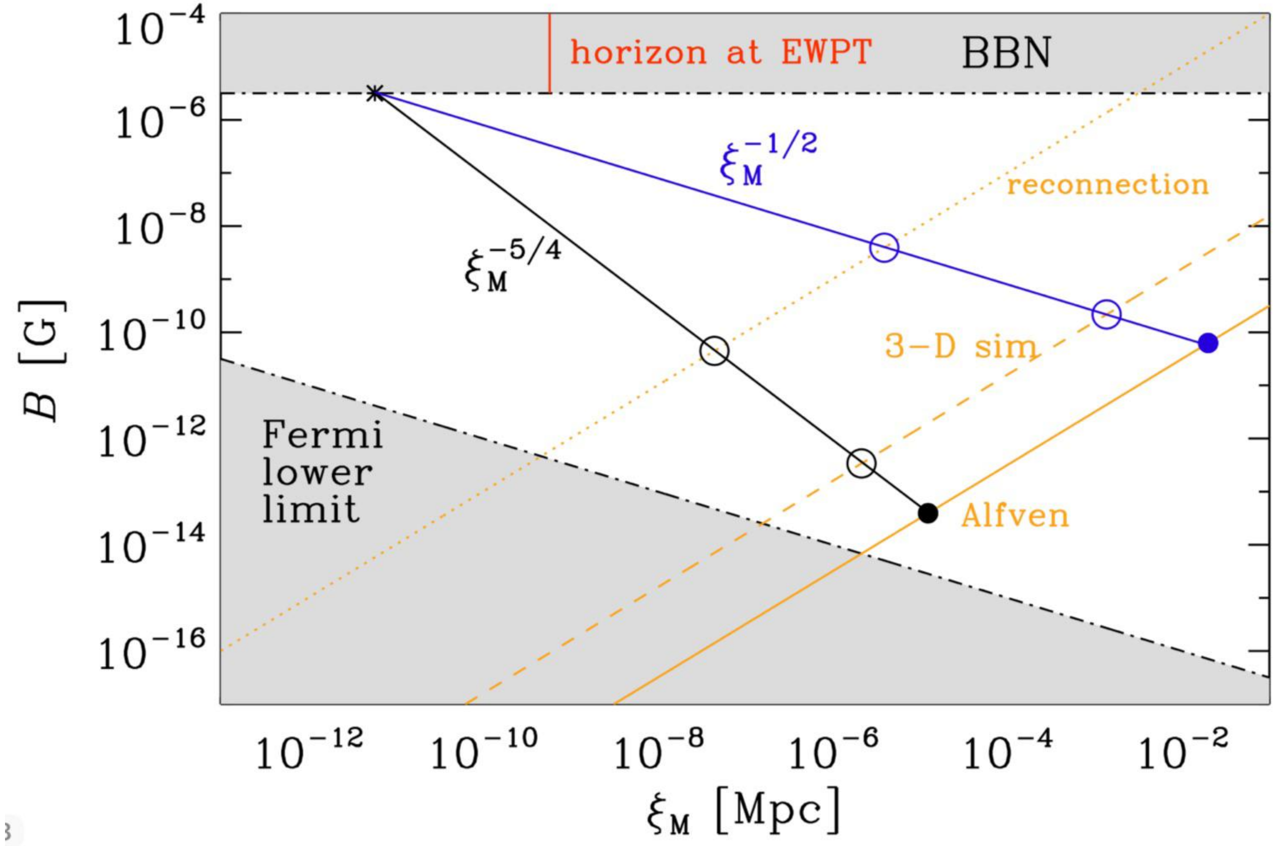
AB, Kahniashvili, ..., Vachaspati (2017)



Magnetic energy dependence
Parametric representation

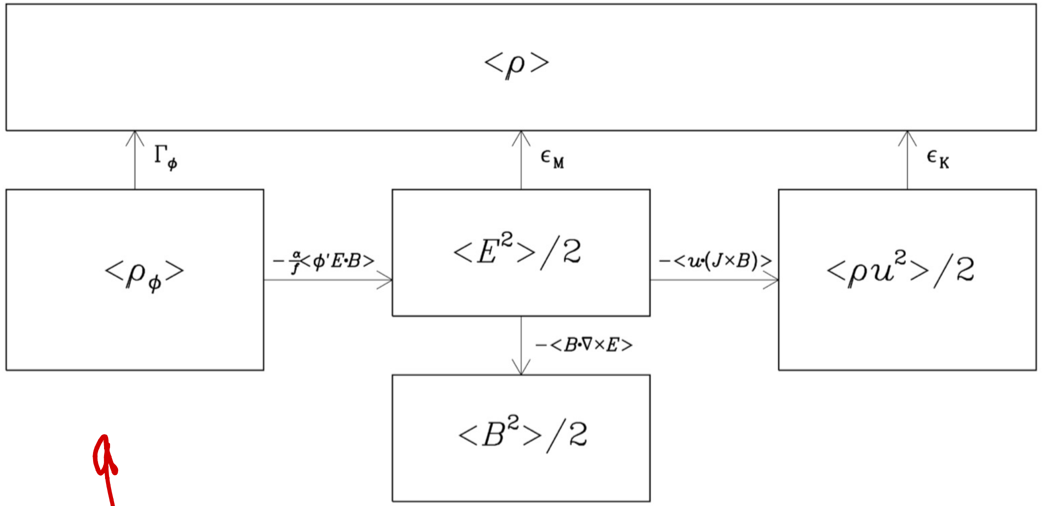
magnetic energy	$\kappa = p/2q$
$\mathcal{E}_\mathrm{M}(t) \propto \langle \boldsymbol{A}\cdot\boldsymbol{B}\rangle^{2/3} t^{-2/3}$	$\propto \xi_\mathrm{M}^{-1/2}$
$\mathcal{E}_\mathrm{M}(t) \propto \langle A_z^2\rangle^{1/2} t^{-1}$	$\propto \xi_\mathrm{M}^{-1}$
$\mathcal{E}_\mathrm{M}(t) \propto I_\mathrm{H}^{2/9} t^{-10/9}$	$\propto \xi_\mathrm{M}^{-5/4}$
$\mathcal{E}_\mathrm{M}(t) \propto I_\mathrm{S}^{2/5} t^{-6/5}$	$\propto \xi_\mathrm{M}^{-3/2}$
$\mathcal{E}_\mathrm{M}(t) \propto I_\mathrm{S}^{2/7} t^{-10/7}$	$\propto \xi_\mathrm{M}^{-5/2}$

Resistive slow-down of turbulent decay



- Endpoints under assumption that decay time = Alfven time
- Use: decay time = recombination time
- Possibility: decay time >> Alfven time
- → Premature endpoint of evolution

Connecting magnetic decay with axion inflation



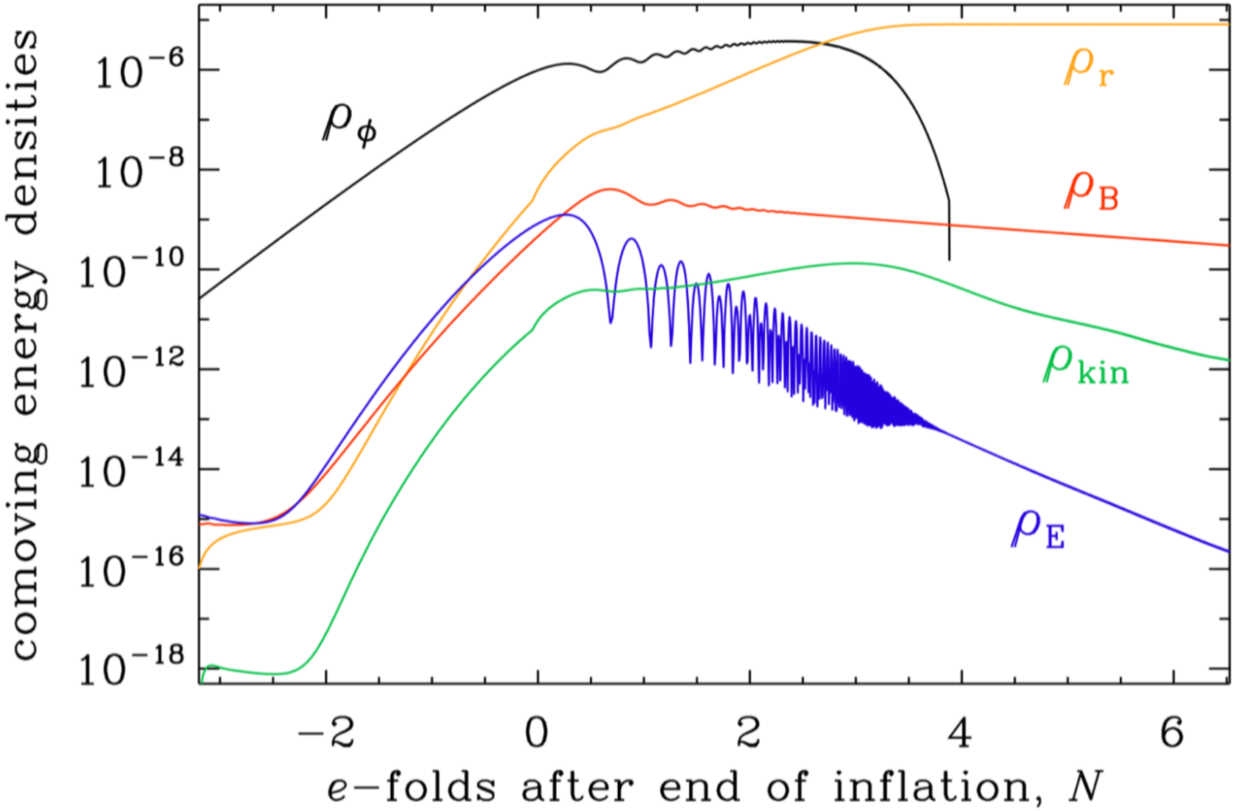
$$\partial_\tau^2\phi + 2\mathcal{H}\partial_\tau\phi - \boldsymbol{\nabla}^2\phi + a^2\frac{dV}{d\phi} = \frac{\alpha}{a^2 f}\boldsymbol{E}\cdot\boldsymbol{B},$$

$$\partial_\tau \boldsymbol{E} - \mathrm{rot}\,\boldsymbol{B} + \frac{\alpha}{f}\left(\partial_\tau\phi\boldsymbol{B} + \boldsymbol{\nabla}\phi\times\boldsymbol{E}\right) + \boldsymbol{J} = 0,$$

$$\boldsymbol{\nabla}\cdot\boldsymbol{E} = -\frac{\alpha}{f}\boldsymbol{\nabla}\phi\cdot\boldsymbol{B}, \quad \boldsymbol{\nabla}\cdot\boldsymbol{B} = 0,$$

$$\partial_\tau\boldsymbol{B} + \mathrm{rot}\,\boldsymbol{E} = 0,$$

$$\mathcal{H}^2 = \frac{8\pi}{3m_{\mathrm{Pl}}^2}a^2\left(\rho_\phi + \rho_E + \rho_B + \rho_\chi\right),$$



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Schwinger effect in axion inflation on a lattice

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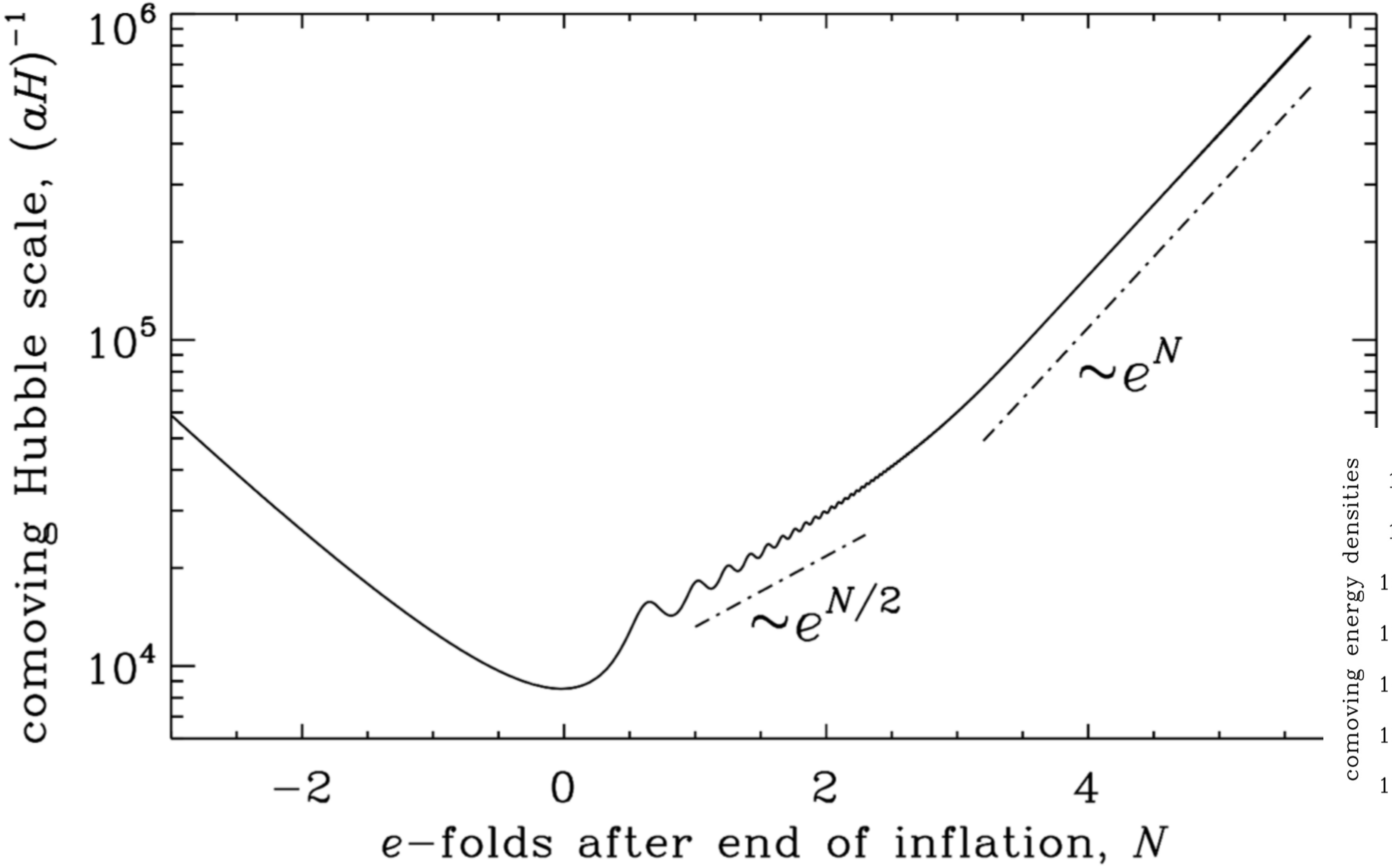
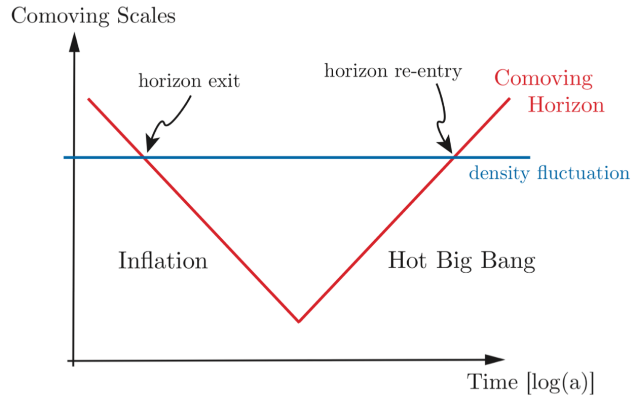
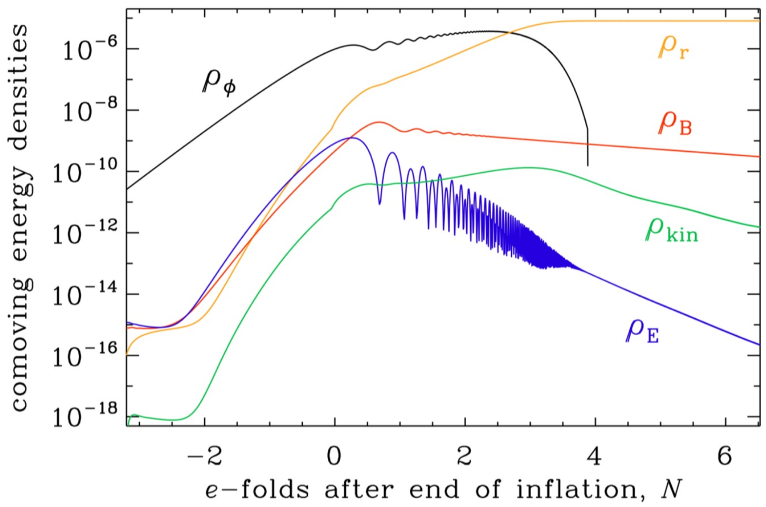
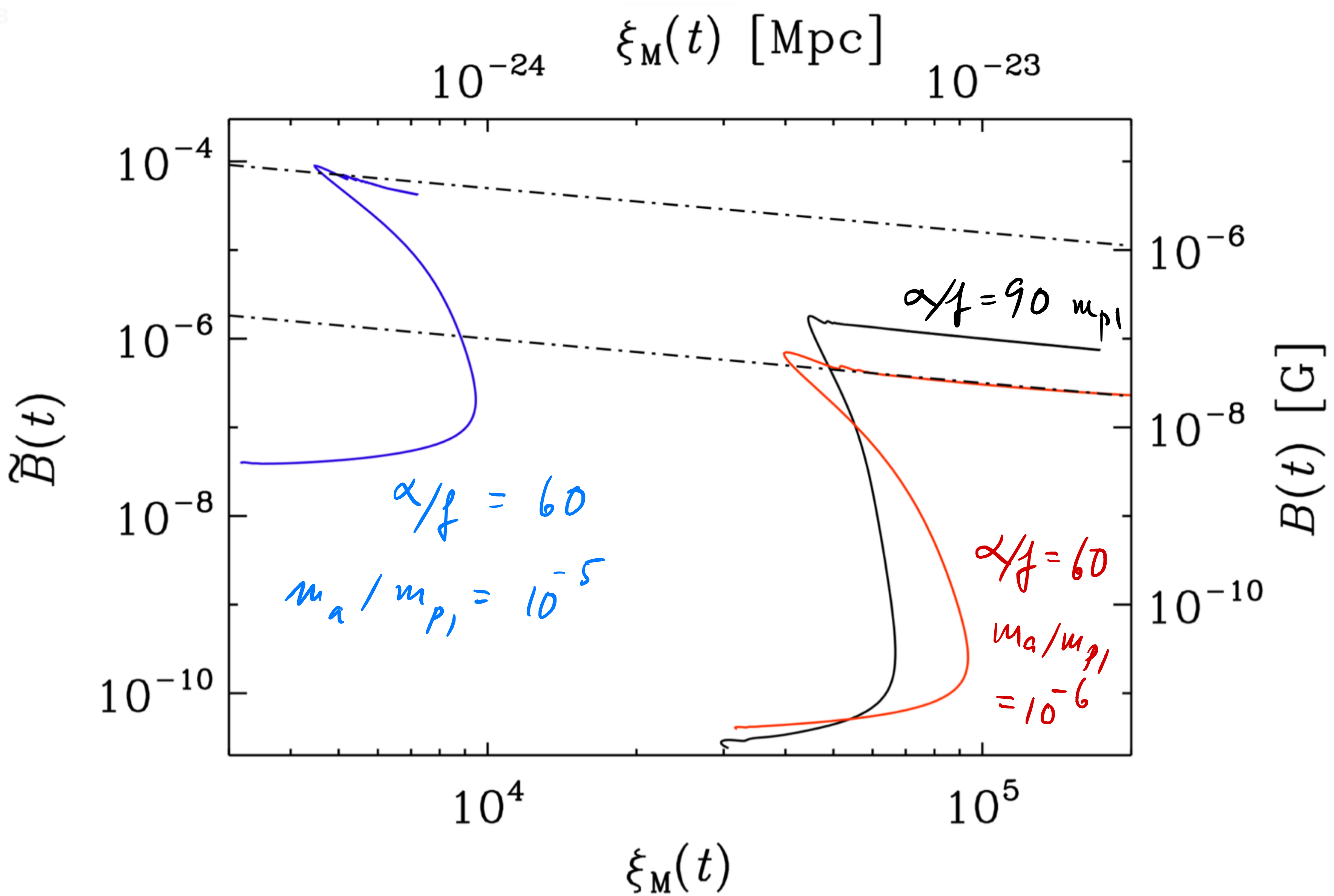
Building a radiation-dominated universe





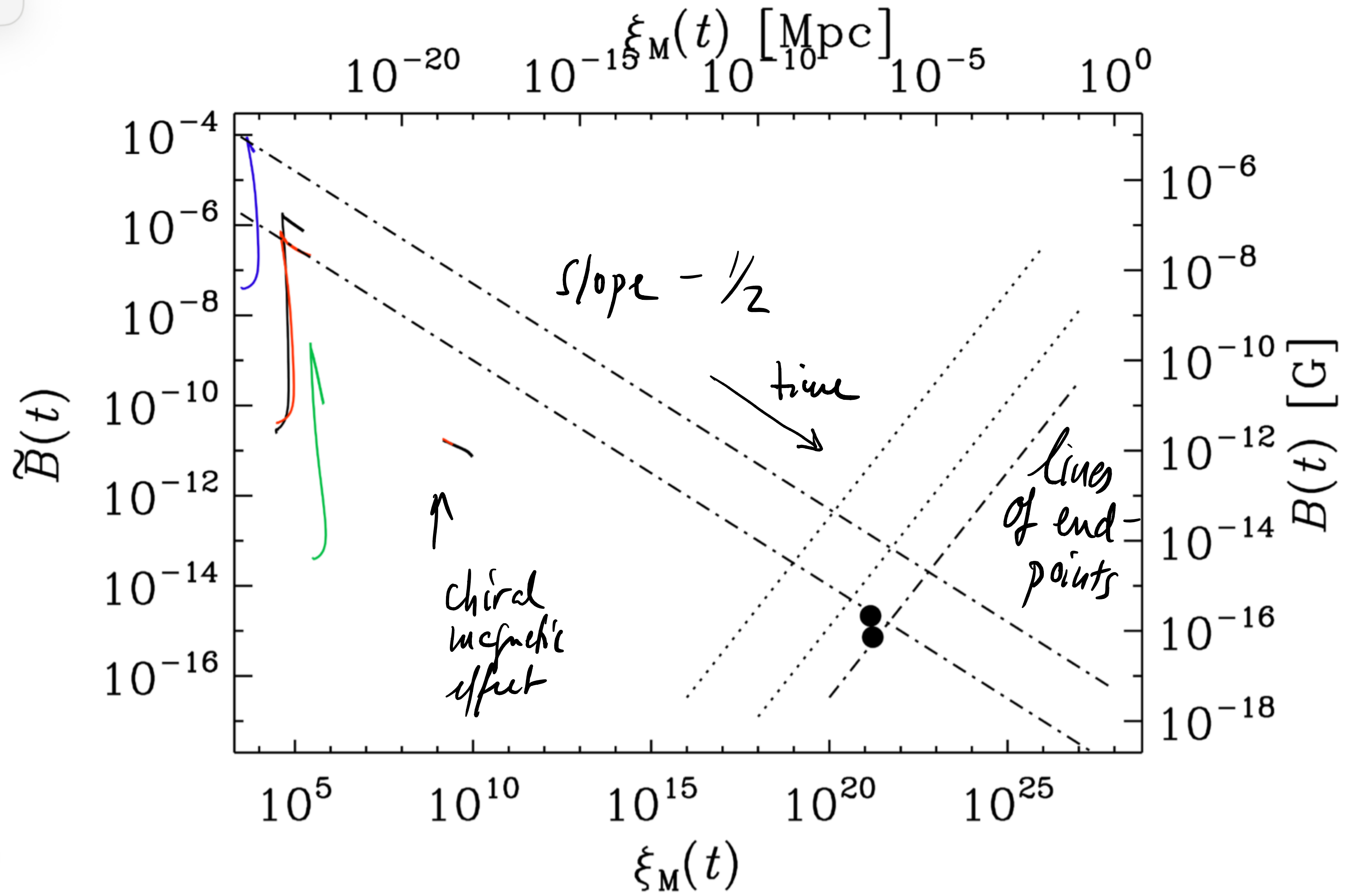


Diagnostic diagram



Complicated evolution before entering inverse cascade

…. until today



$\xi_M(t)$ [Mpc]
10^{-20} 10^{-15} 10^{-10} 10^{-5} 10^{0}
10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16}
$\tilde{B}(t)$
10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}
$B(t)$ [G]
10^{5} 10^{10} 10^{15} 10^{20} 10^{25}
$\xi_M(t)$
slope − 1/2
time
chiral magnetic effect
lines of end-points

Conclusions

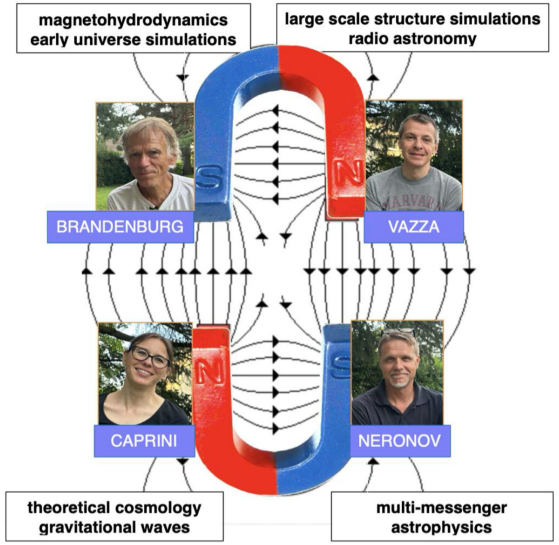
tools are available to explore "full" intergalactic / cosmological magnetic fields parameter space, from the moment of creation to recombination and throughout structure formation up to $z = 0$

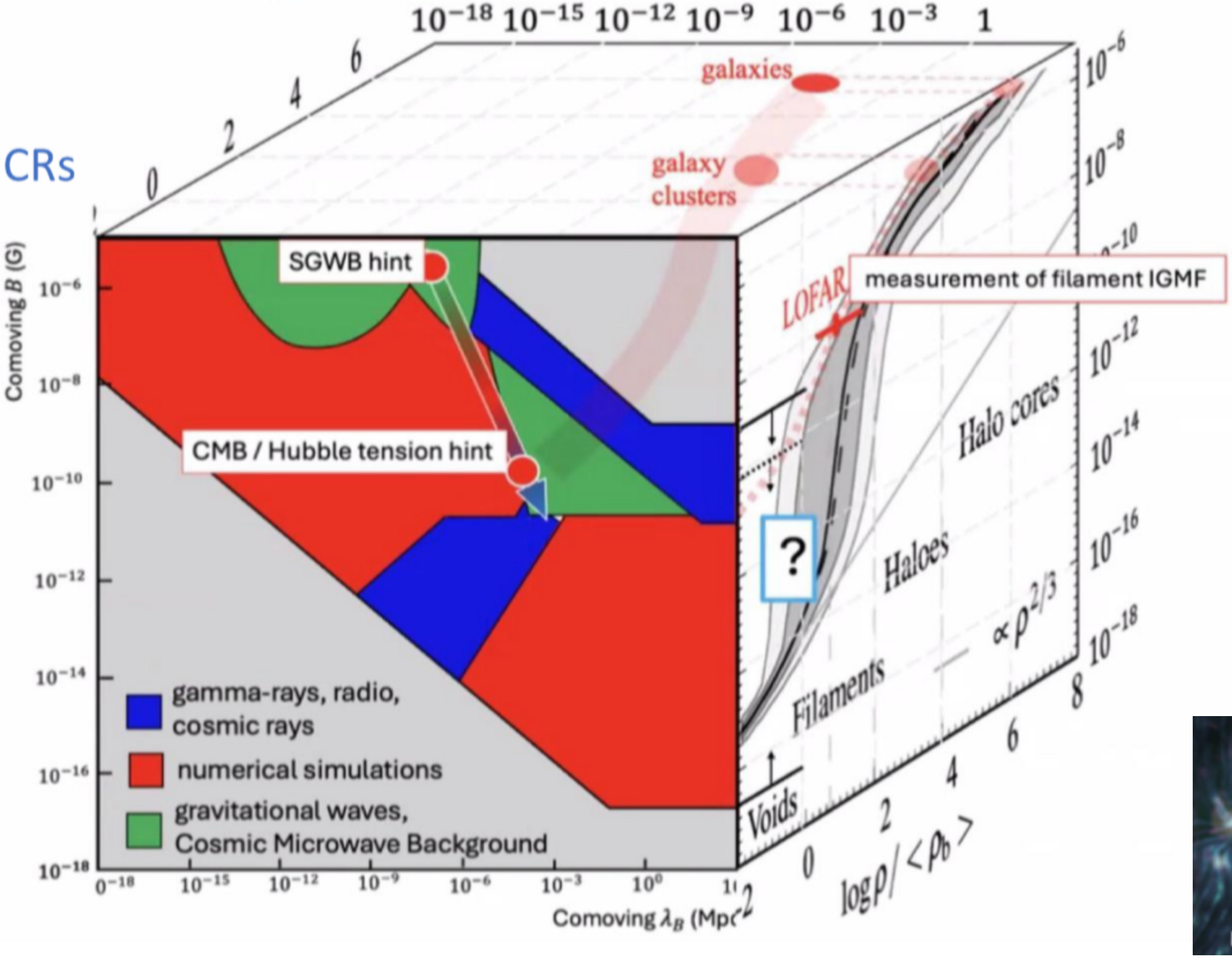
Interplay:

Gamma-ray, radio, CRs

GWs, CMB

simulations





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