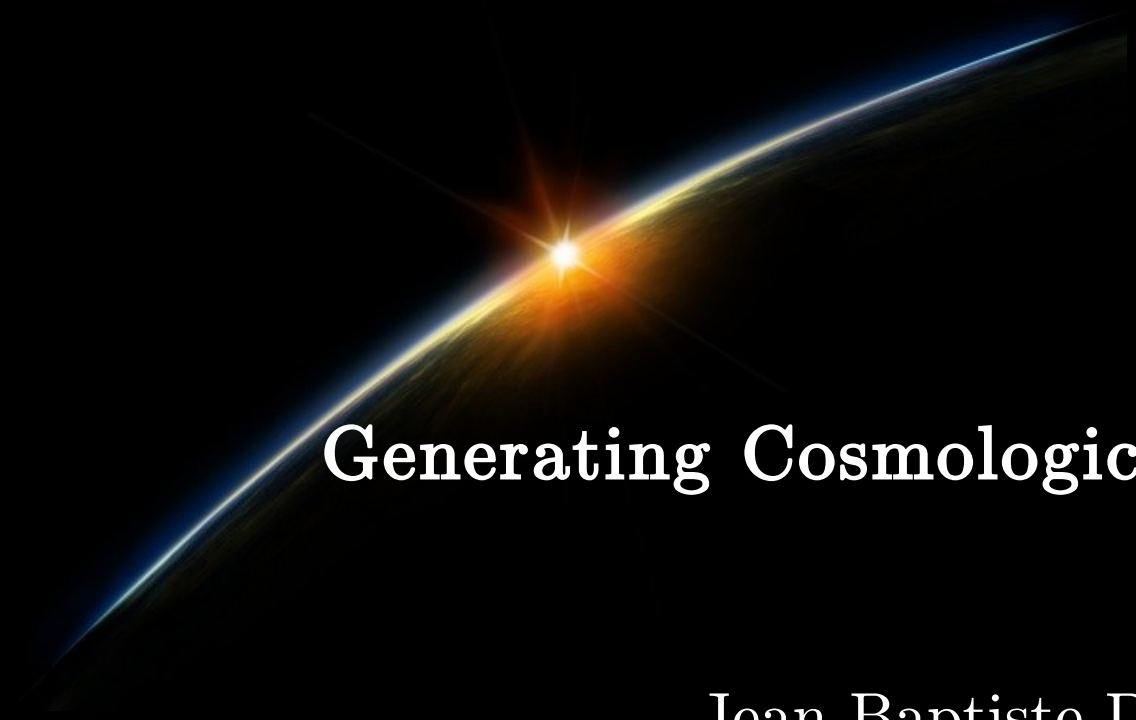


Generating Cosmological Magnetic Fields

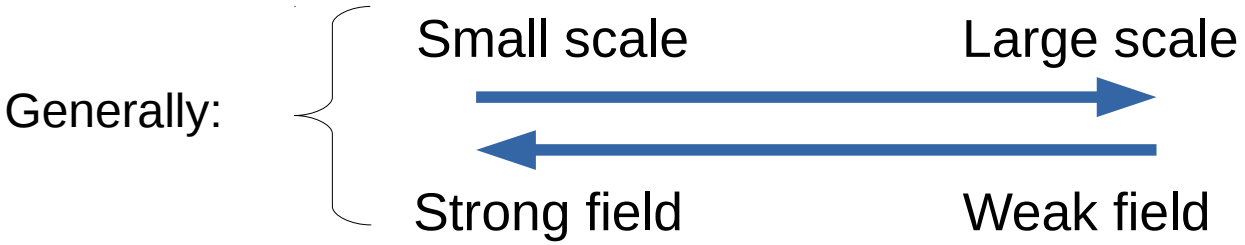
Jean-Baptiste Durrive

Nagoya University, Japan

Durrive & Langer, 2015, MNRAS, arXiv:1506.08177
Durrive, Tashiro, Langer, Sugiyama 2017, MNRAS, accepted
Durrive & Aubert, 2017, in prep

Workshop 'Advances in Theoretical Cosmology in the Light of Data'
Nordita, July 2017, Stockholm

• Magnetic fields **everywhere**: from stars to galaxies to cosmic voids



• **Cosmological** Magnetic fields:

Observational upper bounds:

CMB: B < 5 nG (comoving) at 1 Mpc (Planck results 2015: XIX)

Constraints from structure formation B < nG at protogalactic scales (Wasserman 1978, Kim et al 1996)

Observational **lower** bounds:

High energy gamma rays (Fermi and HESS): B > 10^{-16} or 10^{-18} G (?) in a significant fraction of the IGM (Neronov&Vovk 2010, Taylor et al 2011, Takahashi et al 2011, …)

Origin(s)?

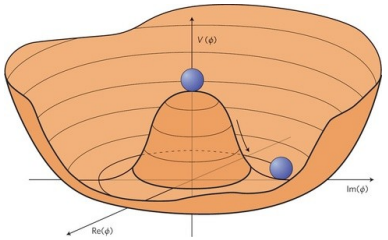
• Current paradigm:
1) Generate **weak seeds**
2) **Amplified**: compression during structure formation (flux freezing) + dynamos

• Turbulence in structures → B fields lost their initial properties
→ look at the **Intergalactic medium** where seeds did not evolve too much

- Current status of amplification process studies:

→ we need ~ 10^{-22} to 10^{-12} G seeds

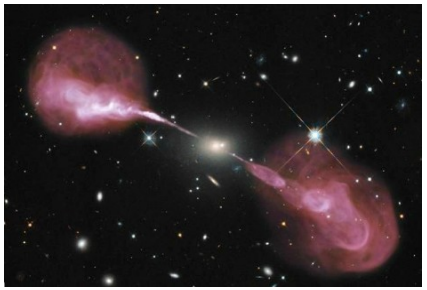
- Numerous mechanisms:
  (Reviews see e.g. Ryu et al 2012, Widrow et al 2012, Durrer & Neronov 2013, ...)



I) Primordial Universe mechanisms

- Inflation: quantum fluctuations of electromagnetic field, but need non-standard electromagnetism
- Phase transitions: electroweak and quark-hadron
- Recombination: rotating plasma blobs interacting with background radiation

II) Post recombination mechanisms



- Thermal (Biermann) battery: in stars, from cosmological shocks during cosmic web formation, from propagating ionization fronts at EoR in large structures
- Plasma instabilities: many, but e.g. Weibel instability
- Radiation: Thomson scattering In protogalaxies, **Photoionization** at EoR in the IGM or around first stars
- Outflows: Galactic winds from galaxies in clusters, from void galaxies, AGN outflows

- Current status of amplification process studies:

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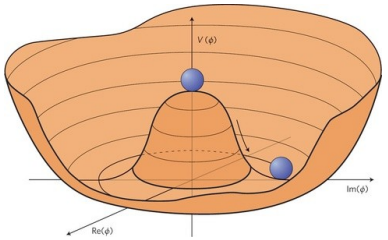


I) Primordial Universe mechanisms

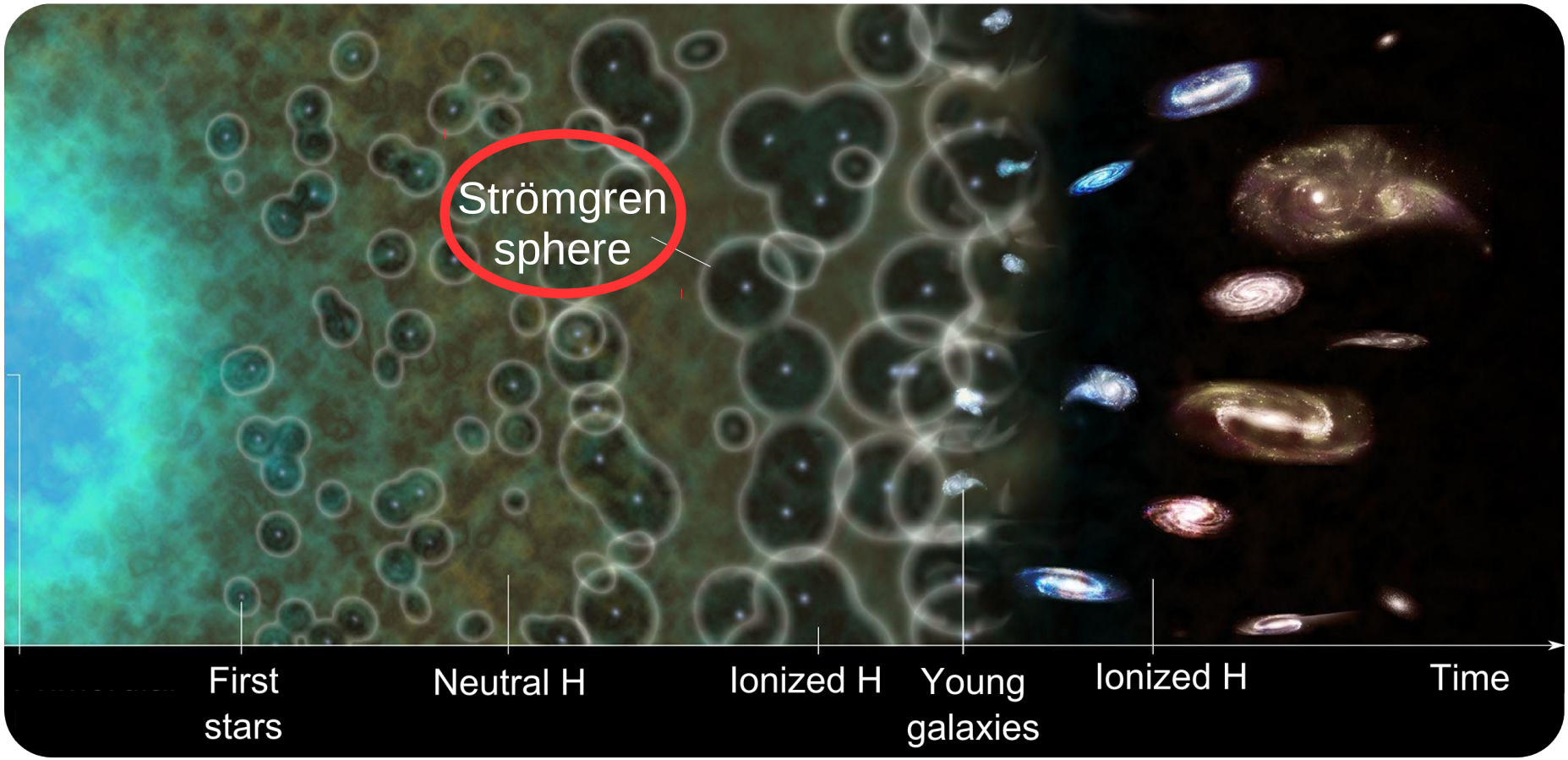
- Inflation: quantum fluctuations of electromagnetic field, but need non-standard electromagnetism
- Phase transitions: electroweak and quark-hadron
- Recombination: rotating plasma blobs interacting

No preferred mechanism so far.
Fields not strong enough on intergalactic scales

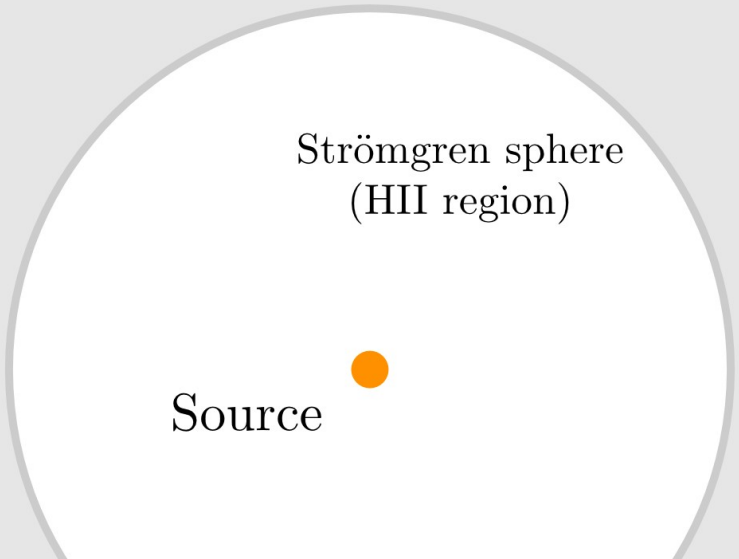
II) Post recombination

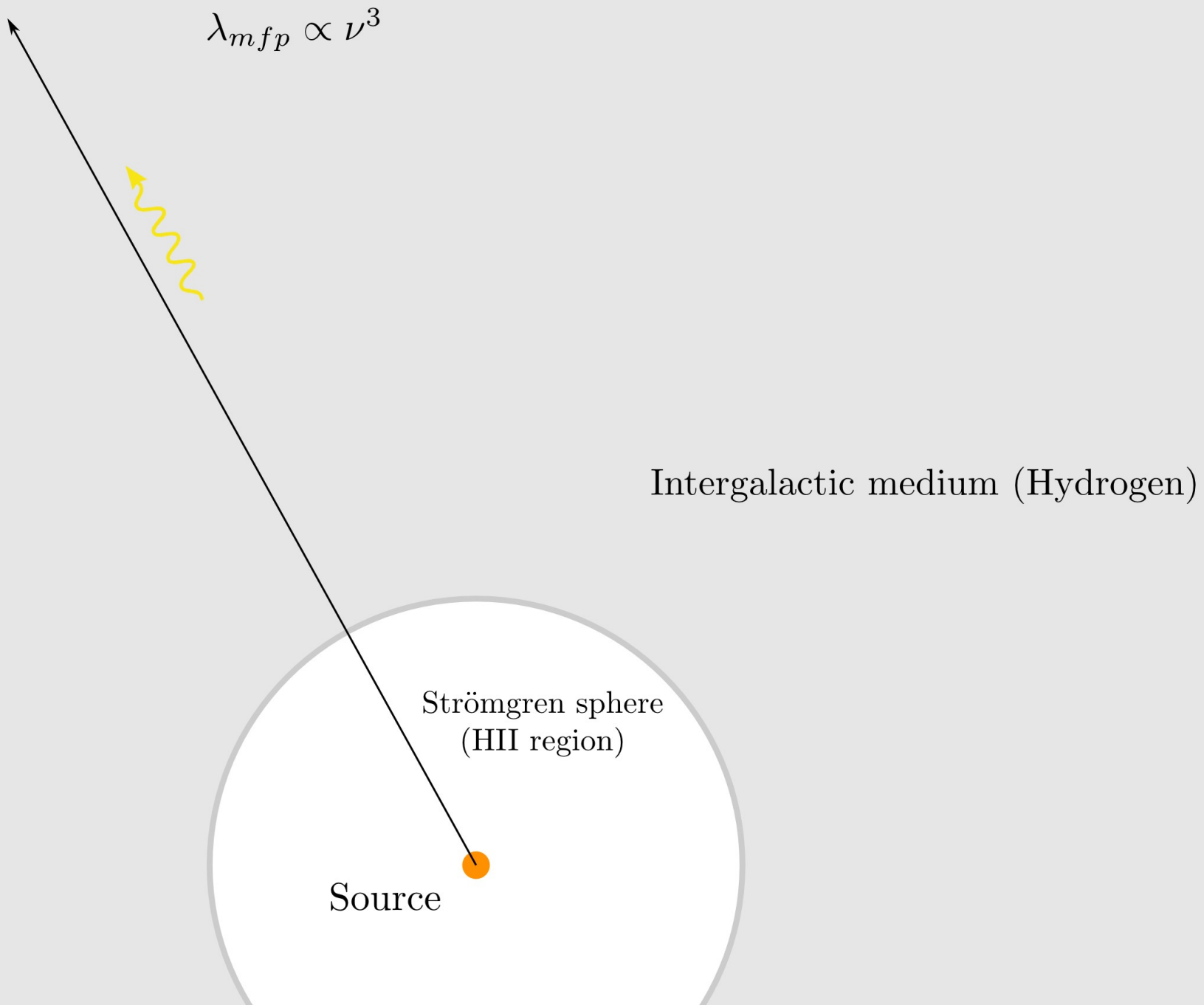
- ionization fronts
- Plasma instabilities: many, but e.g. Weibel instability
- Radiation: Thomson scattering In protogalaxies, **Photoionization** at EoR in the IGM or around first stars
- Outflows: Galactic winds from galaxies in clusters, from void galaxies, AGN outflows

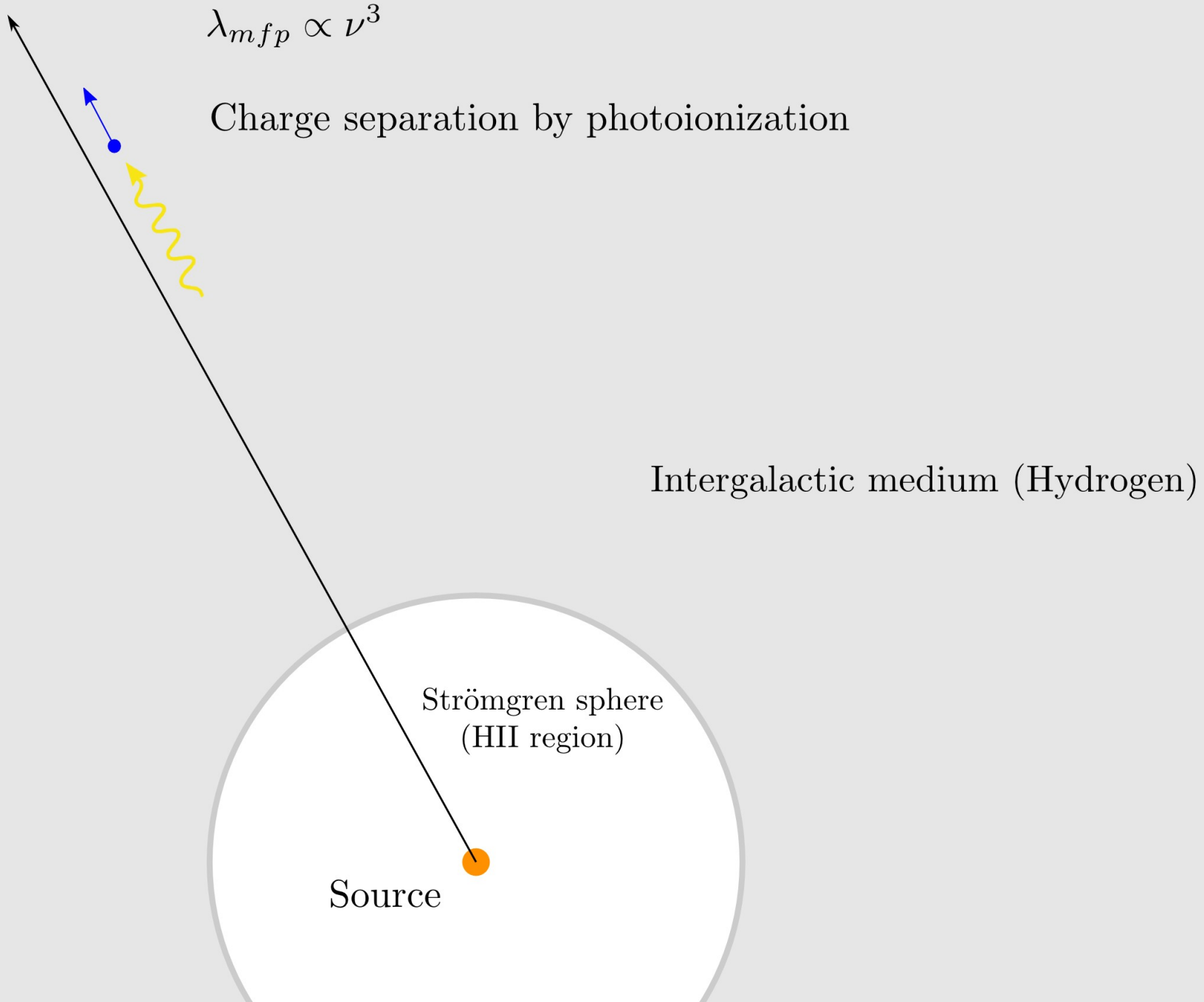
Astrophysical mechanism generating **intergalactic** magnetic fields at the Epoch of Reionization

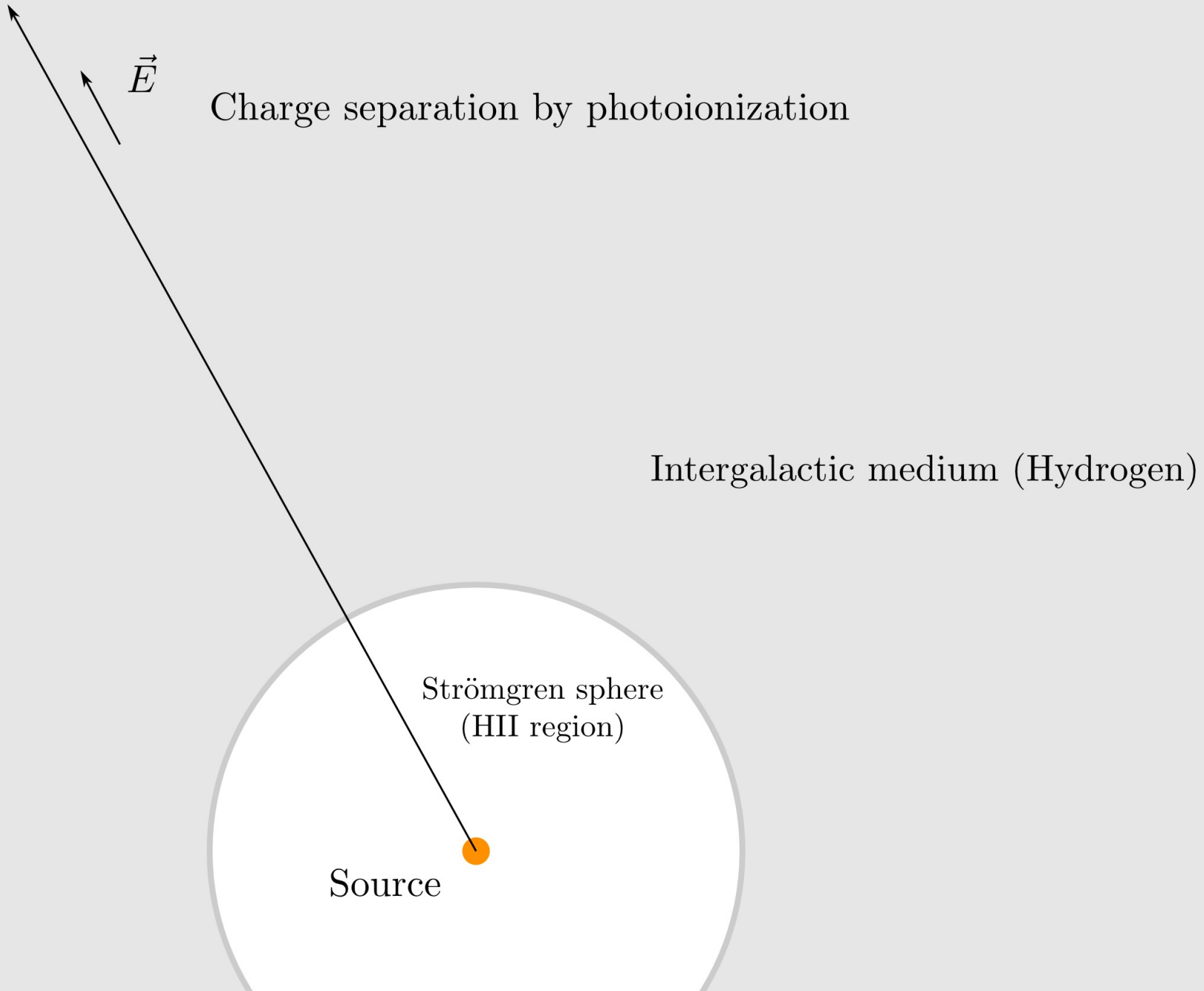


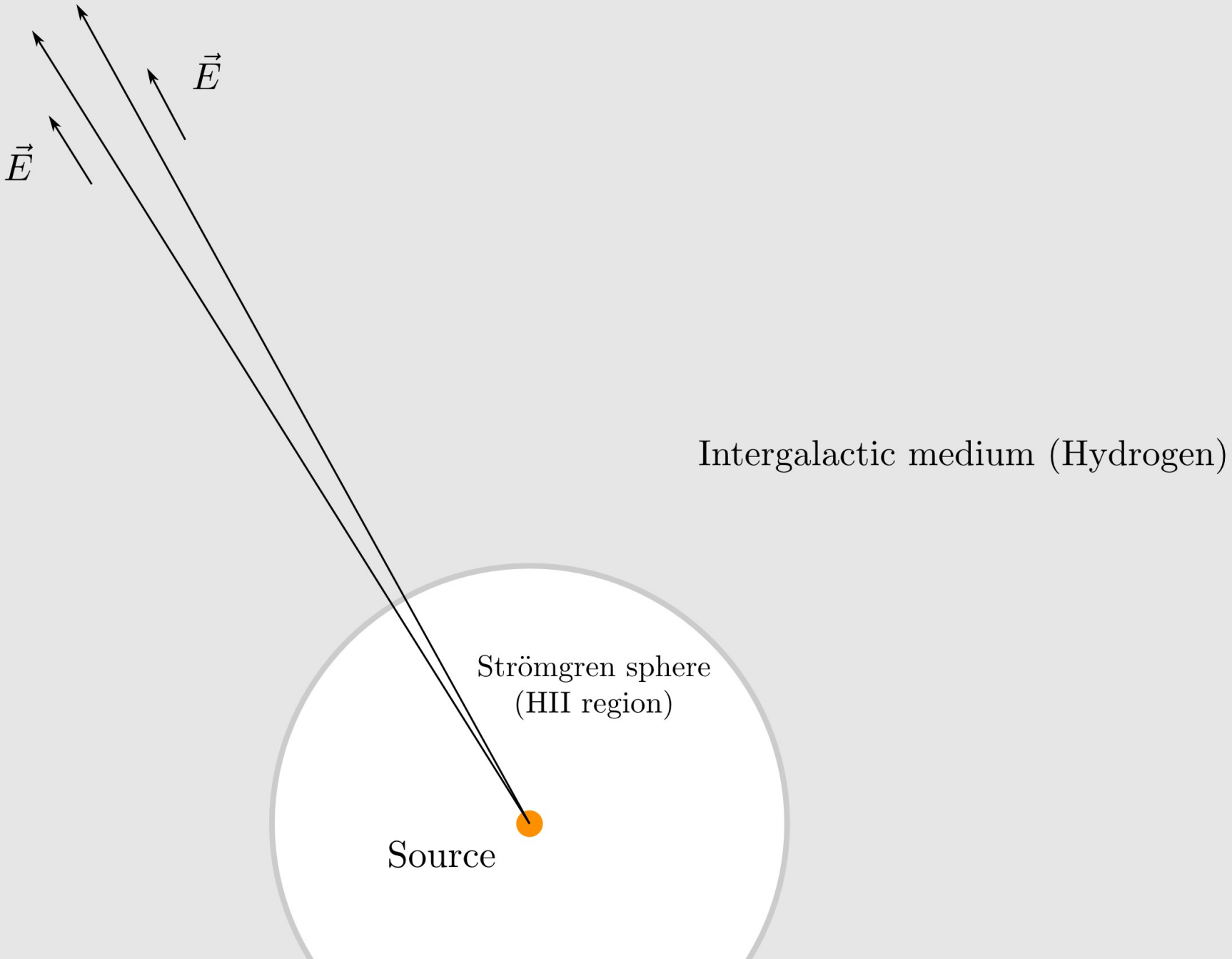
Intergalactic medium (Hydrogen)



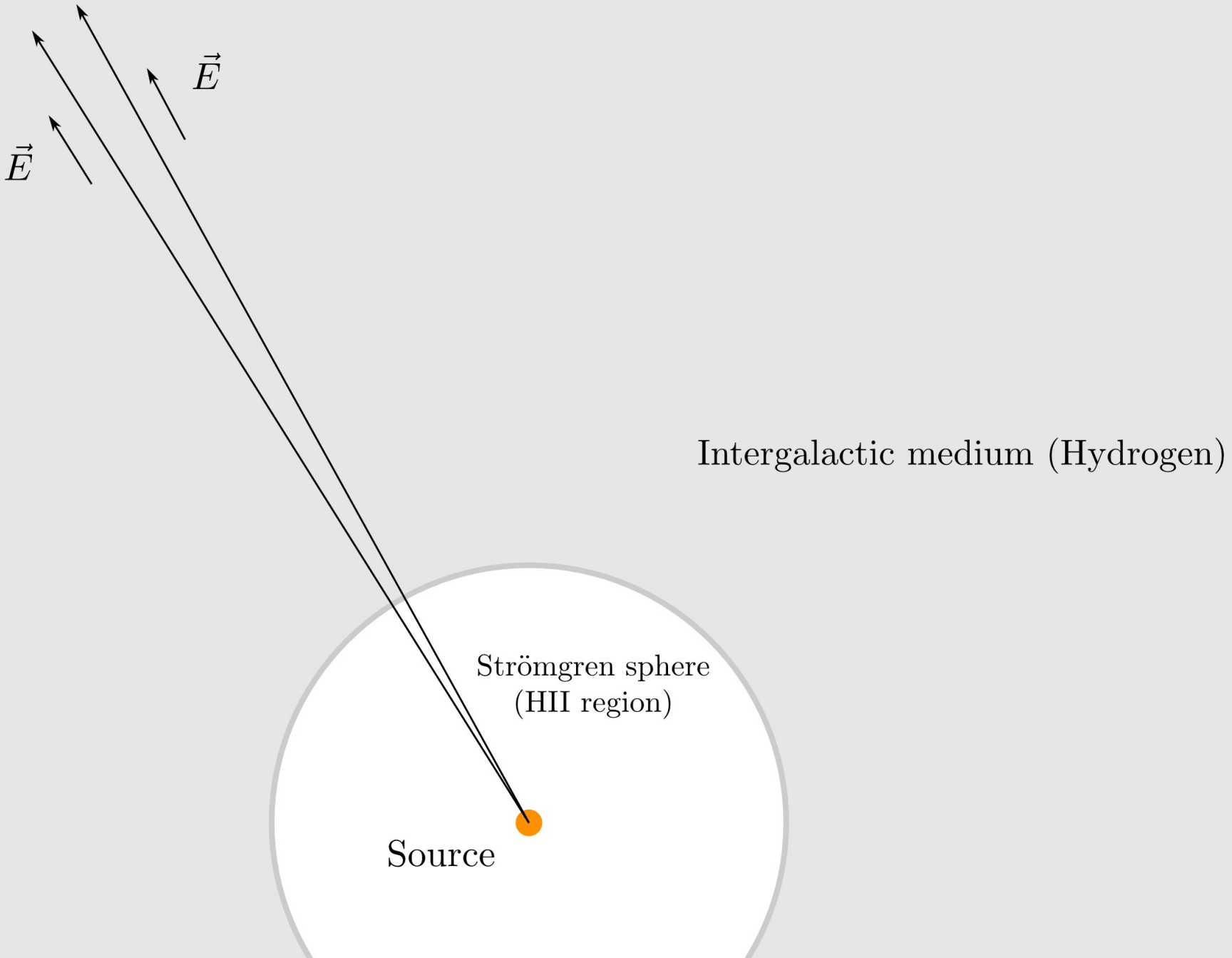

$\lambda_{mfp} \propto \nu^3$
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\lambda_{mfp} \propto \nu^3$
Charge separation by photoionization
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\vec{E}$
Charge separation by photoionization
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\vec{E}$
$\vec{E}$
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source

$$\vec{\nabla} \times \vec{E} = \vec{0}$$

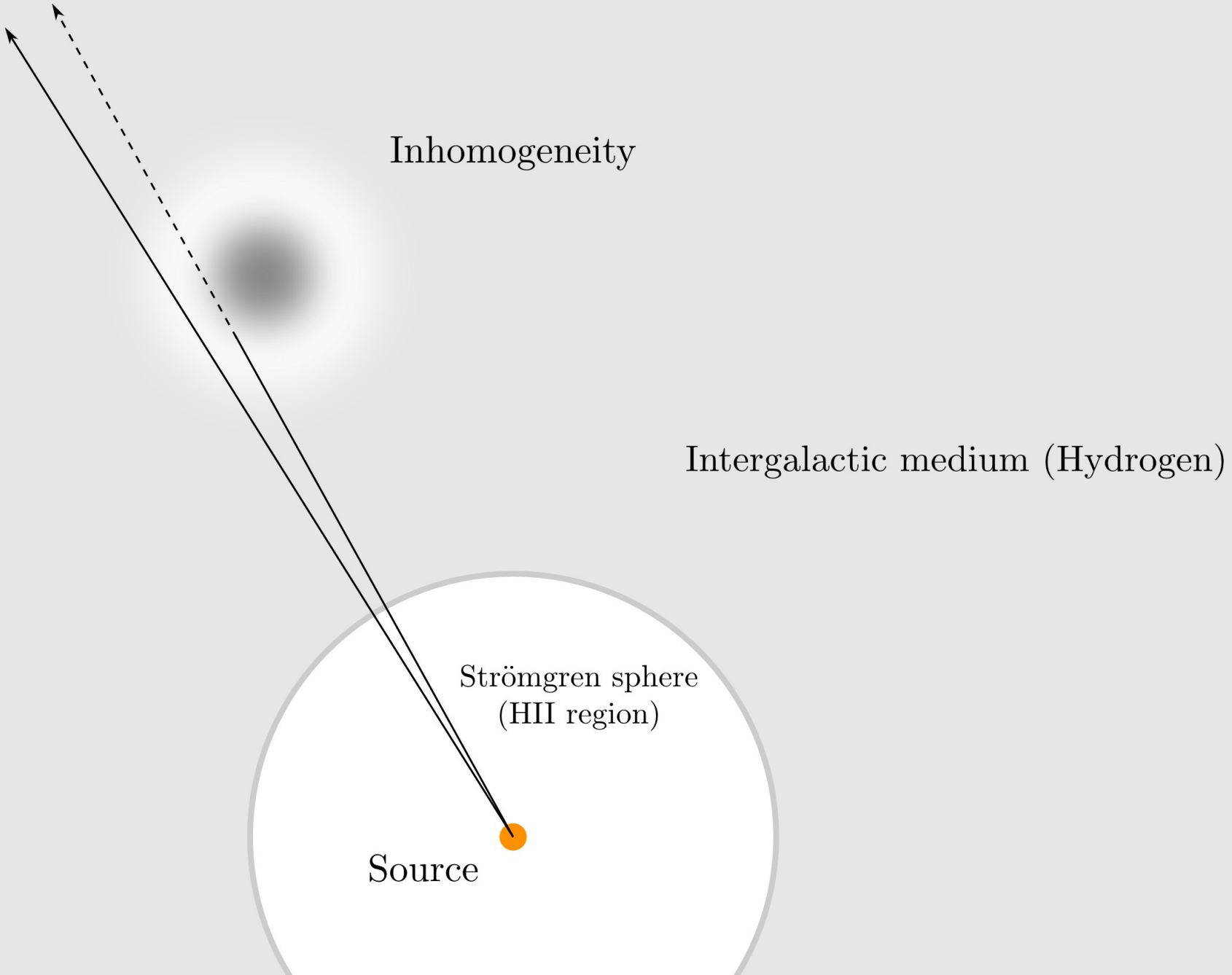


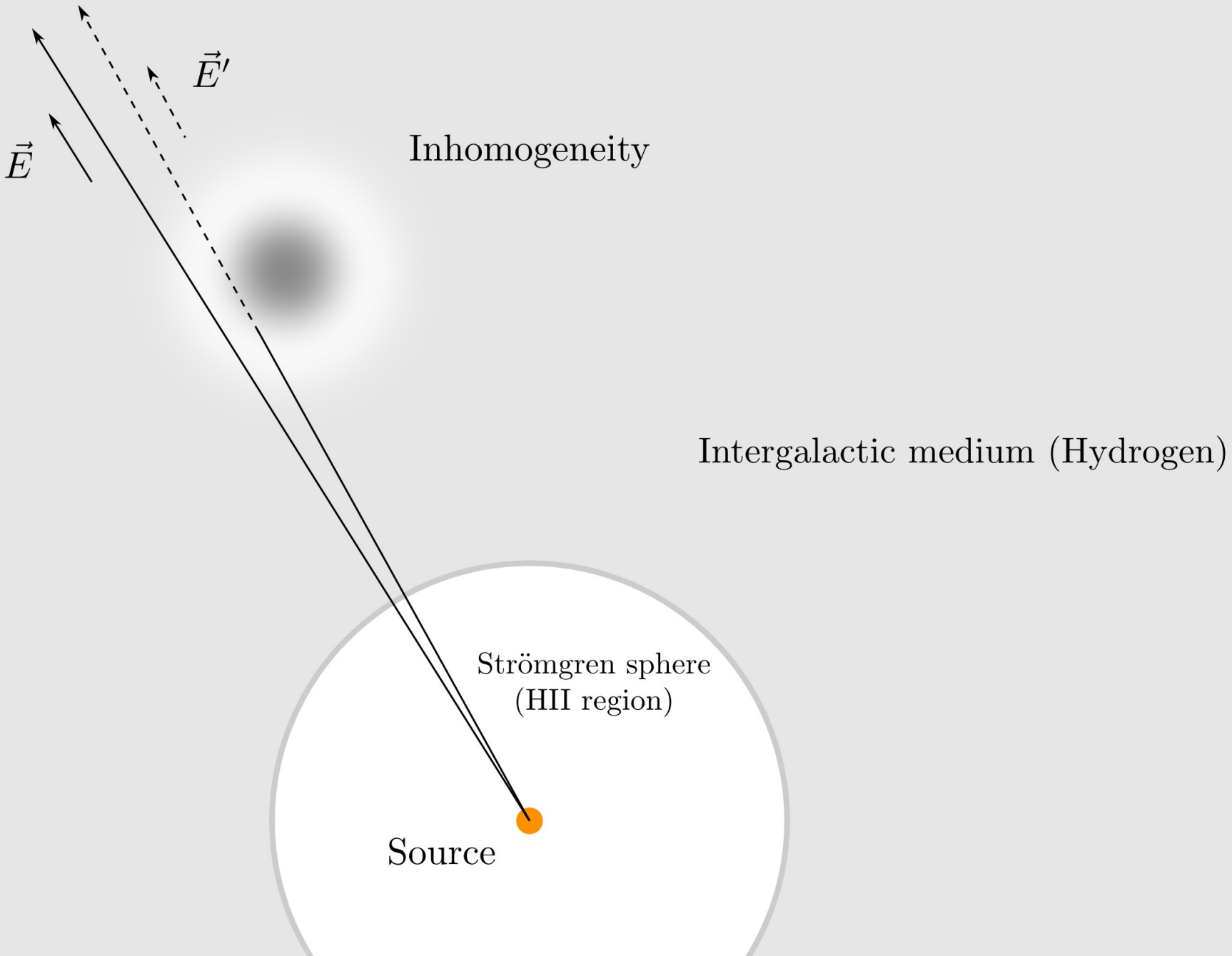
Maxwell-Faraday equation: $$\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E}$$

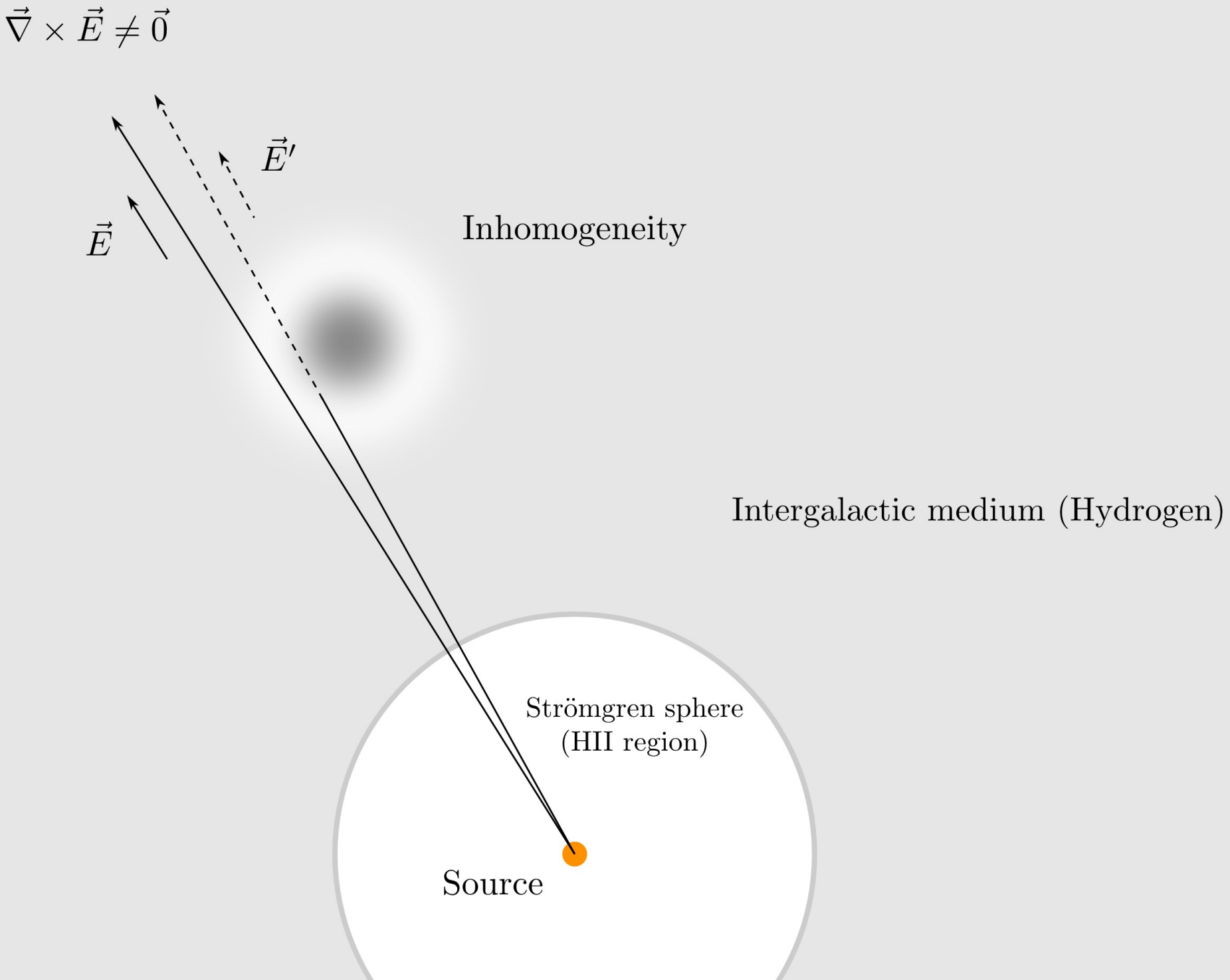
→ Need **rotational *E* field** to generate B

Inhomogeneities of Intergalactic medium enable this

(Langer et al 2005)


Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\vec{E}'$
$\vec{E}$
Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\vec{\nabla} \times \vec{E} \neq \vec{0}$
$\vec{E}'$
$\vec{E}$
Inhomogeneity
Intergalactic medium (Hydrogen)
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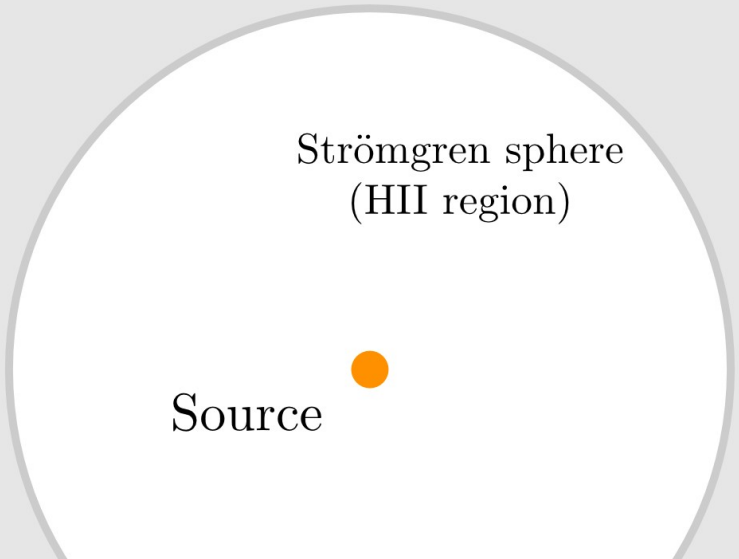
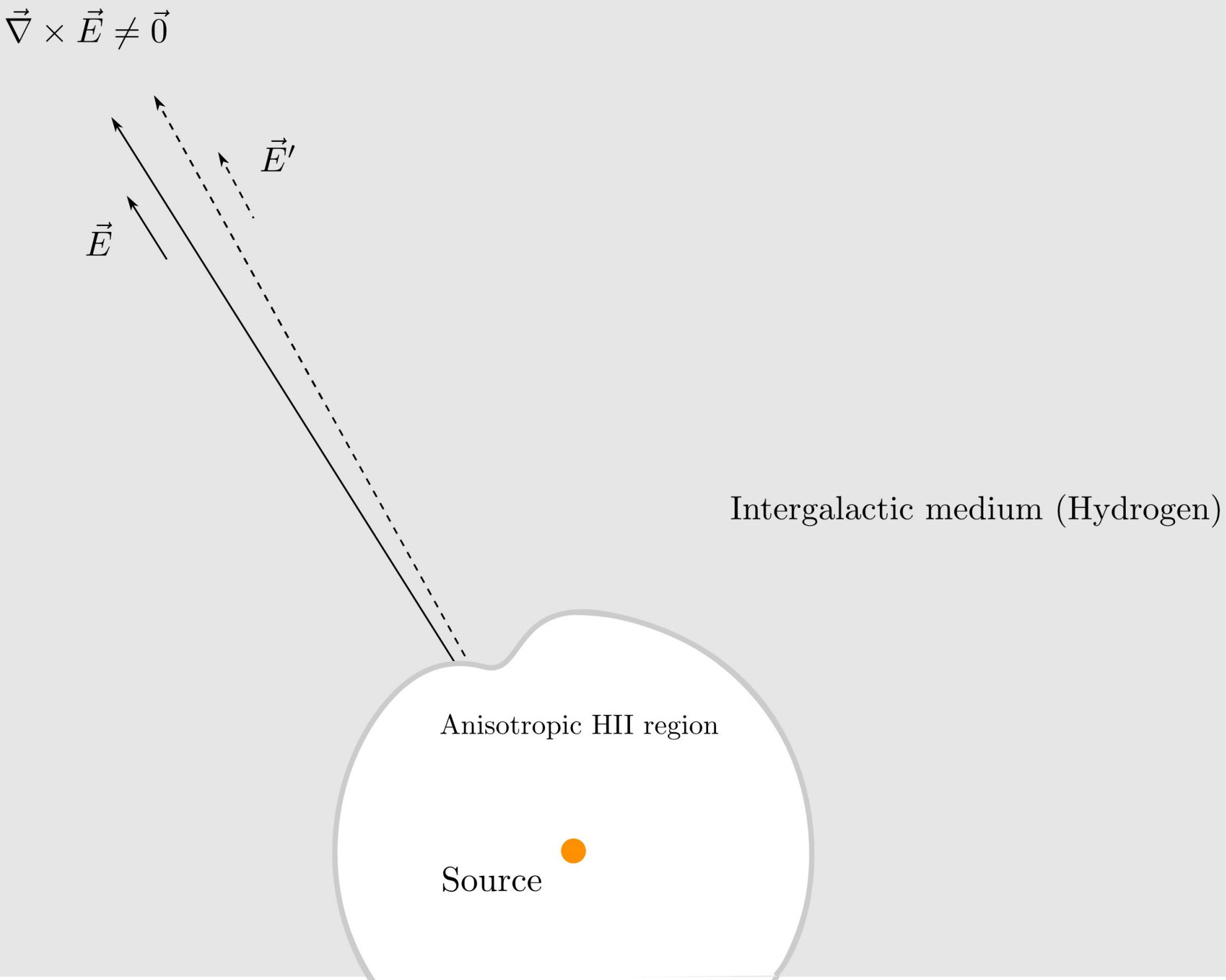
Intergalactic medium (Hydrogen)




Intergalactic medium (Hydrogen)
Anisotropic HII region
Source


$\vec{\nabla} \times \vec{E} \neq \vec{0}$
$\vec{E}'$
$\vec{E}$
Intergalactic medium (Hydrogen)
Anisotropic HII region
Source

Formally

(Durrive & Langer, 2015, MNRAS)

Photoionization = local modification of the number of electrons and of their **velocity distribution**

$\Rightarrow$ Kinetic theory!
Source term in Boltzmann equation of electron distribution function:

$$\frac{df}{dt} = \partial_t f\big|_{\text{photoionization}}$$

Momentum transferred from photons to electrons:

$$m_e \vec{v} = f_{mt}(\nu)\frac{h\nu}{c}\hat{r}$$

Fraction of momentum transferred

Induction equation:

$$\partial_t \vec{B} = -\frac{c}{e}\frac{\vec{\nabla} n_e \times \vec{\nabla} p_e}{n_e^2} - \frac{c}{e}\vec{\nabla} \times \frac{\dot{\vec{p}}_e}{n_e}$$

Momentum transfer rate

Biermann

Photoionization: Radiation induces magnetic fields!

Resulting magnetic field

(Durrive & Langer, 2015, MNRAS)

Source of B :
Anisotropy of the column density

$$\vec{B}(t,\vec{r}) = t\frac{N}{ex_e}\vec{\nabla}\int_{r_s}^{r} n_{HI}\,dr \times \hat{r}$$

where $$N = \frac{1}{4\pi r^2}\int_{\nu_0}^{\infty} f_{mt}\sigma_\nu^2 L_\nu e^{-\tau_\nu}\,d\nu$$

Cross section

Absorption along photon path

Geometric dilution

Source spectrum

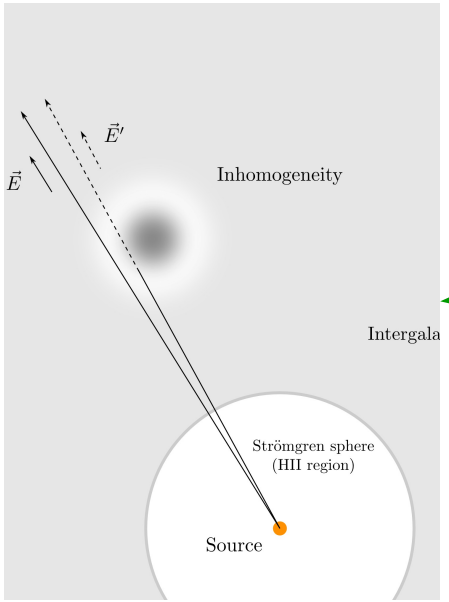
Ionizing photons

Fraction of momentum transferred

Resulting magnetic field

(Durrive & Langer, 2015, MNRAS)

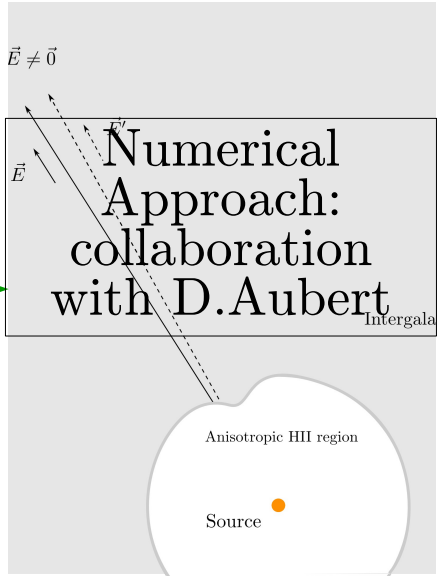
Source of B :
Anisotropy of the column density



Inhomogeneity

$$\vec{B}(t,\vec{r}) = t\frac{N}{ex_e}\vec{\nabla}\int_{r_s}^{r} n_{HI}\, dr \times \hat{r}$$

Strömgren radius



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Cross section

Absorption along photon path

Geometric dilution

Source spectrum

Ionizing photons

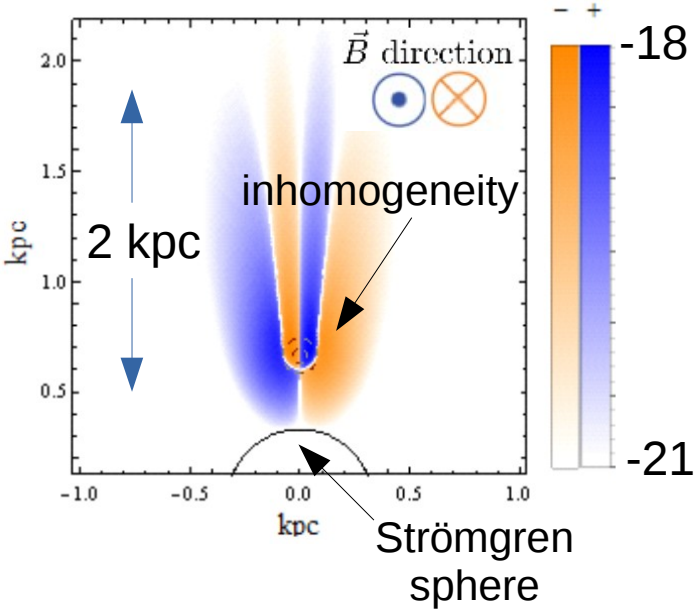
Fraction of momentum transferred

Typical spatial distributions and scales

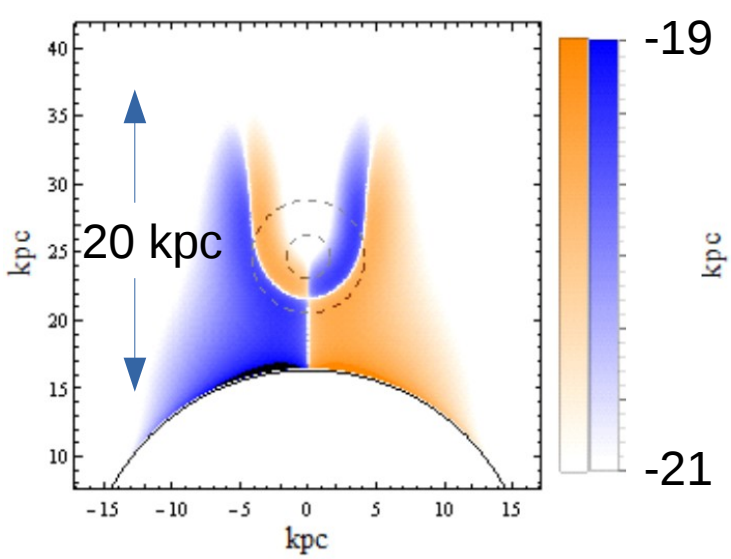
(Durrive & Langer, 2015, MNRAS)

- Gaussian inhomogeneities → analytical expressions
- Explicit lengthscales & magnetized regions
- Studied properties for various sources at various epochs:

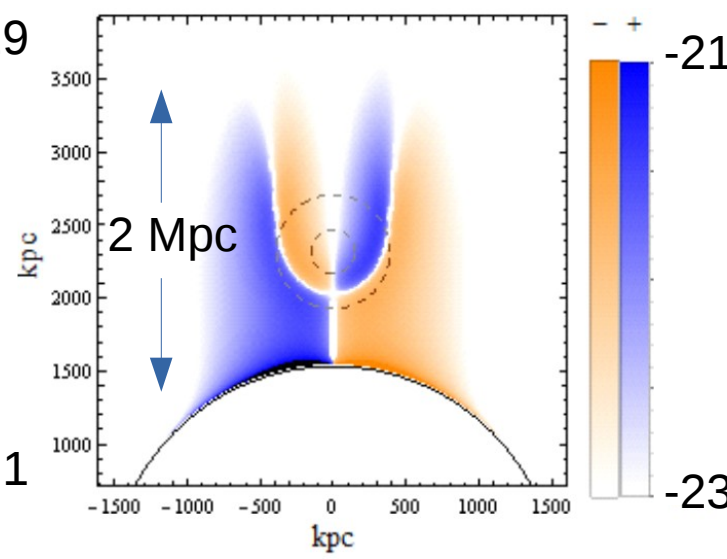
Pop III clusters



First galaxies



Quasars



→ Best compromise power/dilution

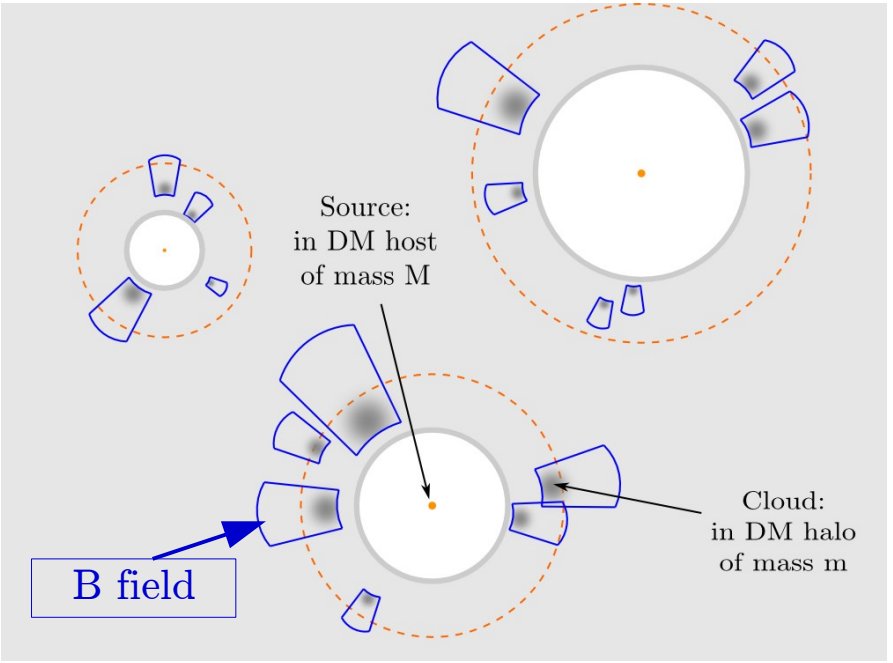
- Compared with intersource distances:
  ⟹ magnetization of the **whole intergalactic medium**

Global magnetization level of the Universe

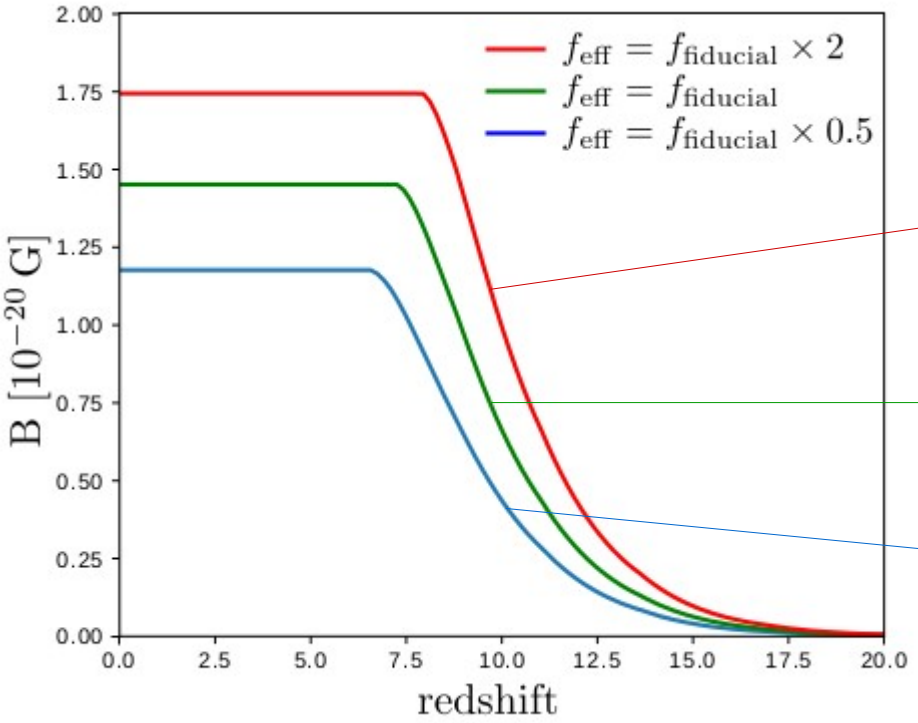
(Durrive, Tashiro, Langer, Sugiyama 2017, MNRAS, accepted)

Case of galaxies:

Distribution of sources & clouds:
Given by underlying **Dark Matter halos**
(Press-Schechter formalism)



Mean magnetic field in the Universe:



Universe with **'strongly ionizing'** galaxies
(**maximal** escape fraction & stars formed
to stay consistent with Planck)

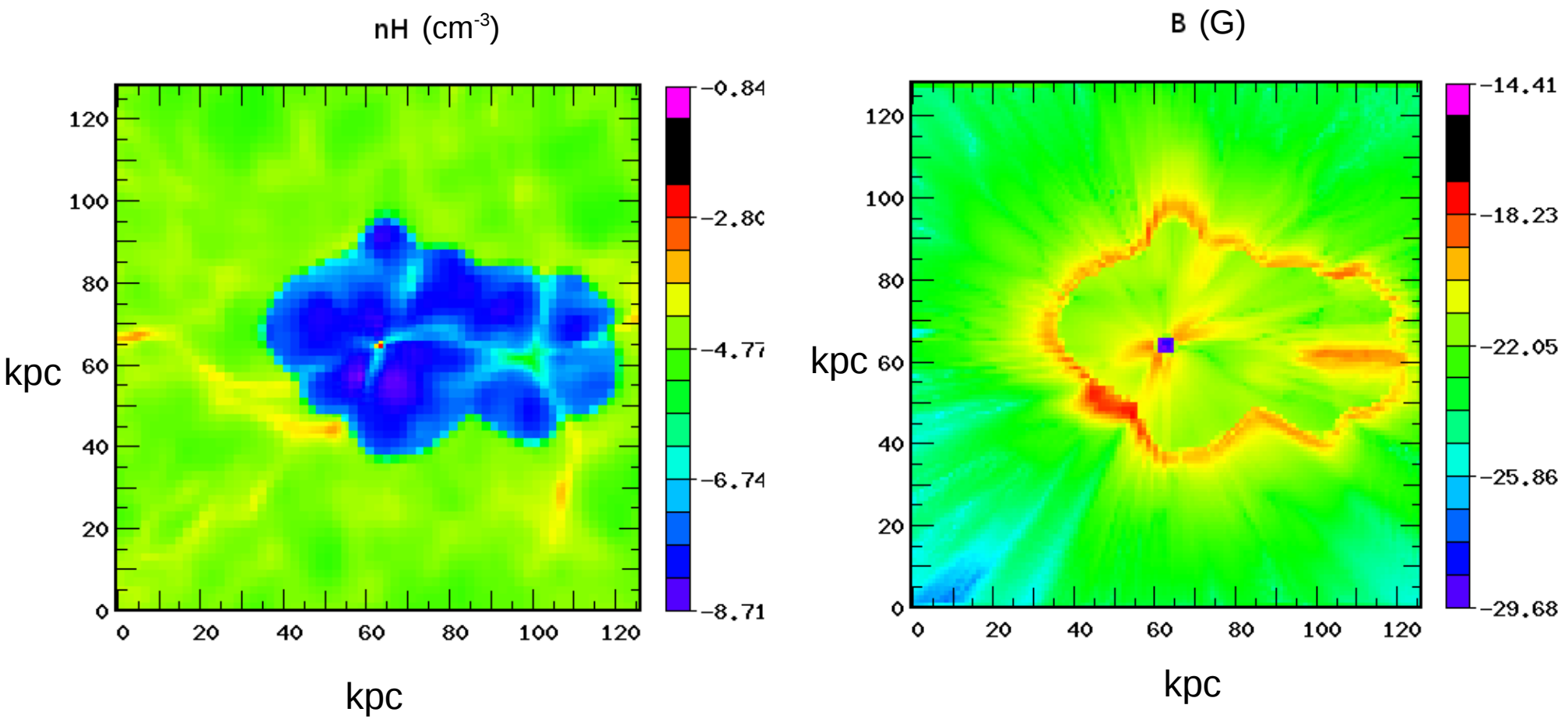
Fiducial model

Universe with **'weakly ionizing'** galaxies
(**minimal** escape fraction & stars formed
to stay consistent with Planck)

Numerical approach

(Durrive & Aubert, 2017, in prep)

Generated B field with realistic profiles from cosmological simulations:



(example of a primordial galaxy at z = 10)

Ongoing work!

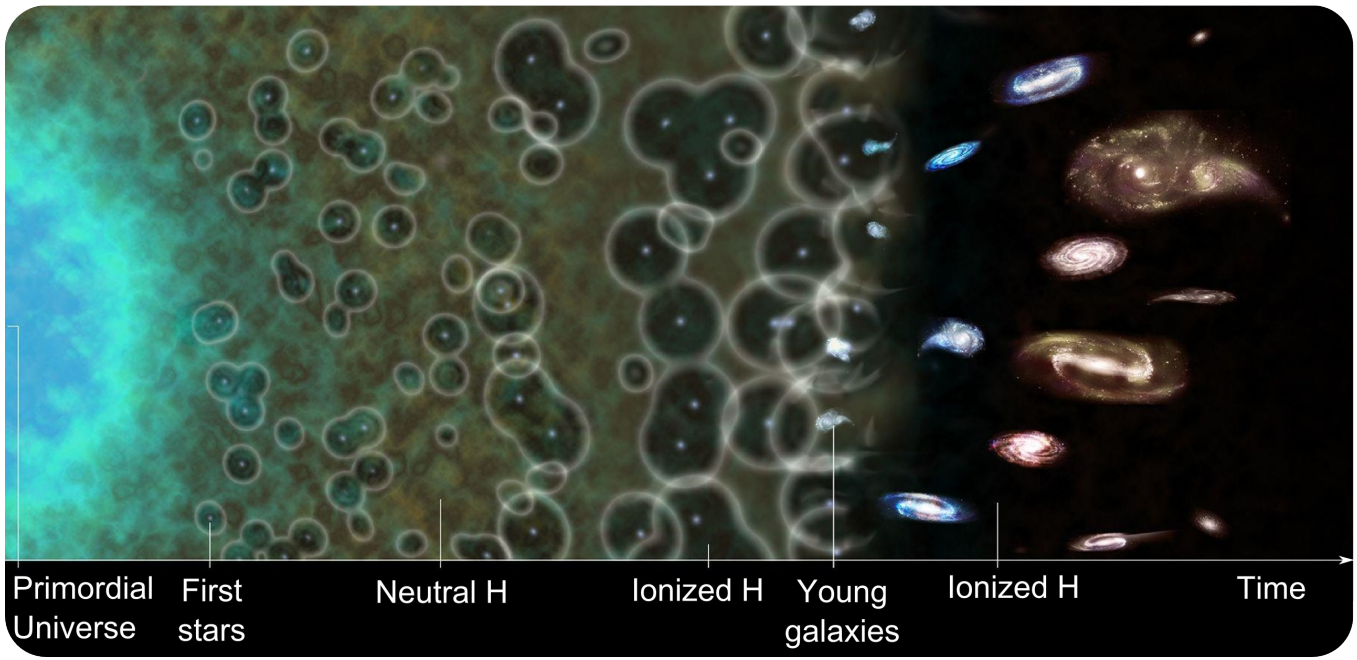
Evolution in the cosmic web?

B field **generated** early

?

→

B **observed** in today's **structured** Universe

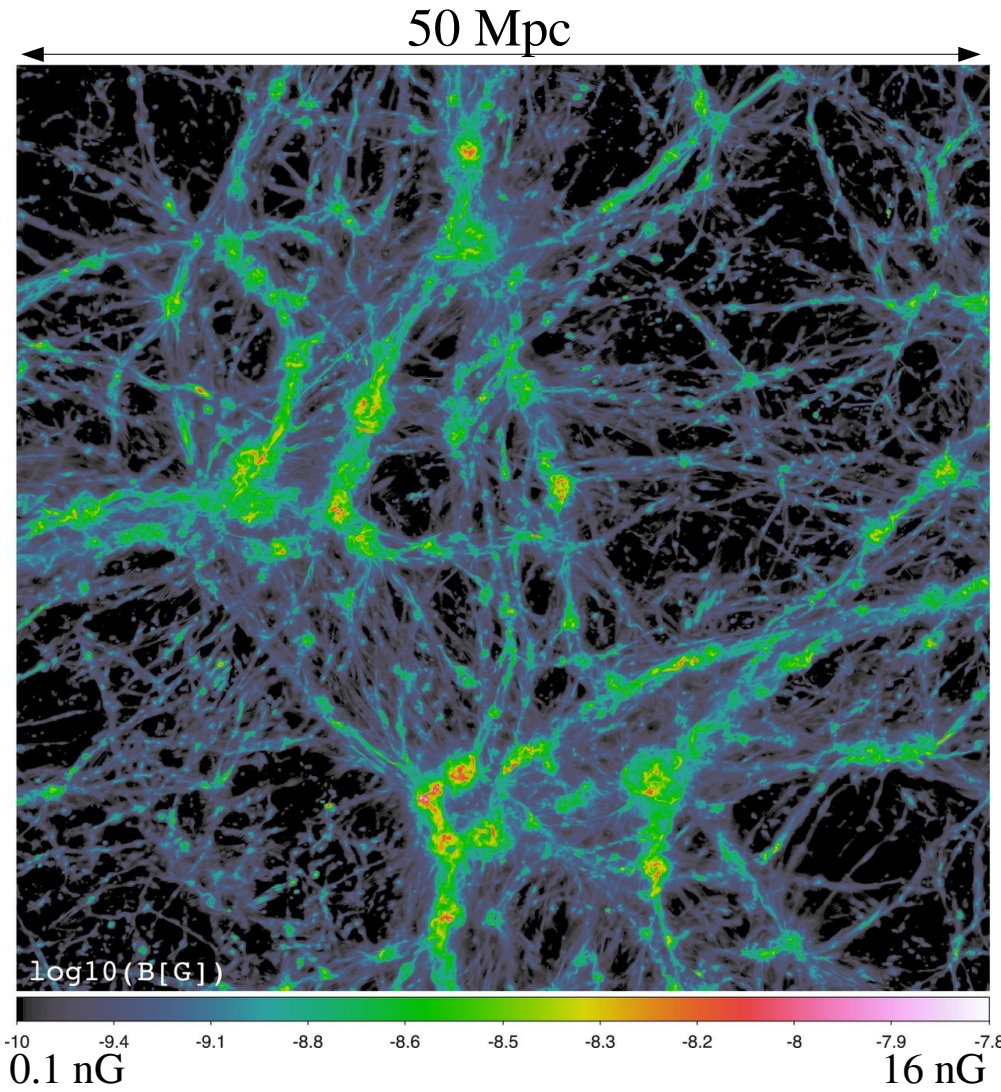


→ Need to study the **evolution** of cosmological magnetic fields

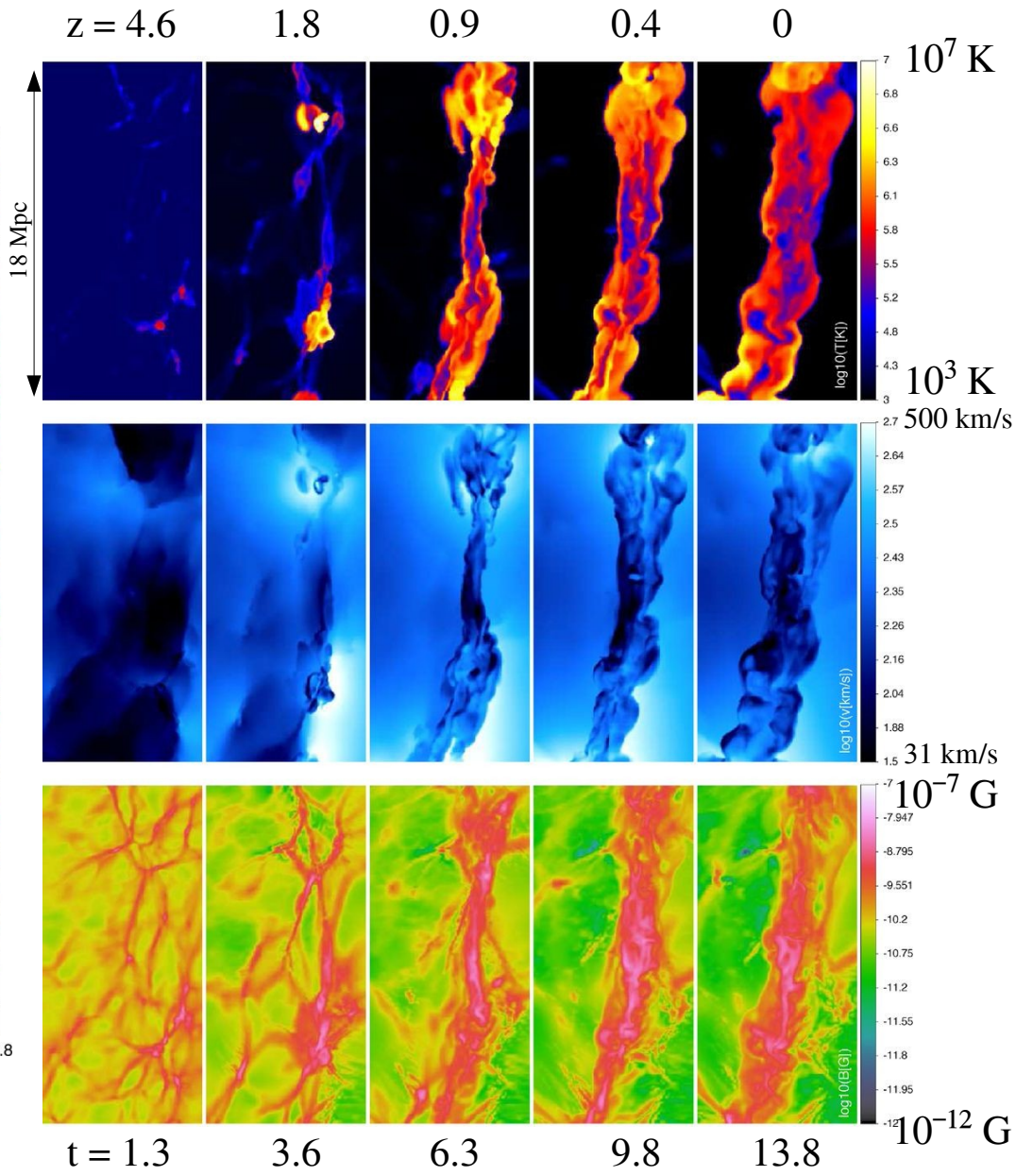
Cosmological evolution of B in the cosmic web?

- Within intergalactic filaments

Vazza et al. 2014



Cosmic web at z = 0



Cosmological evolution of B in the cosmic web?

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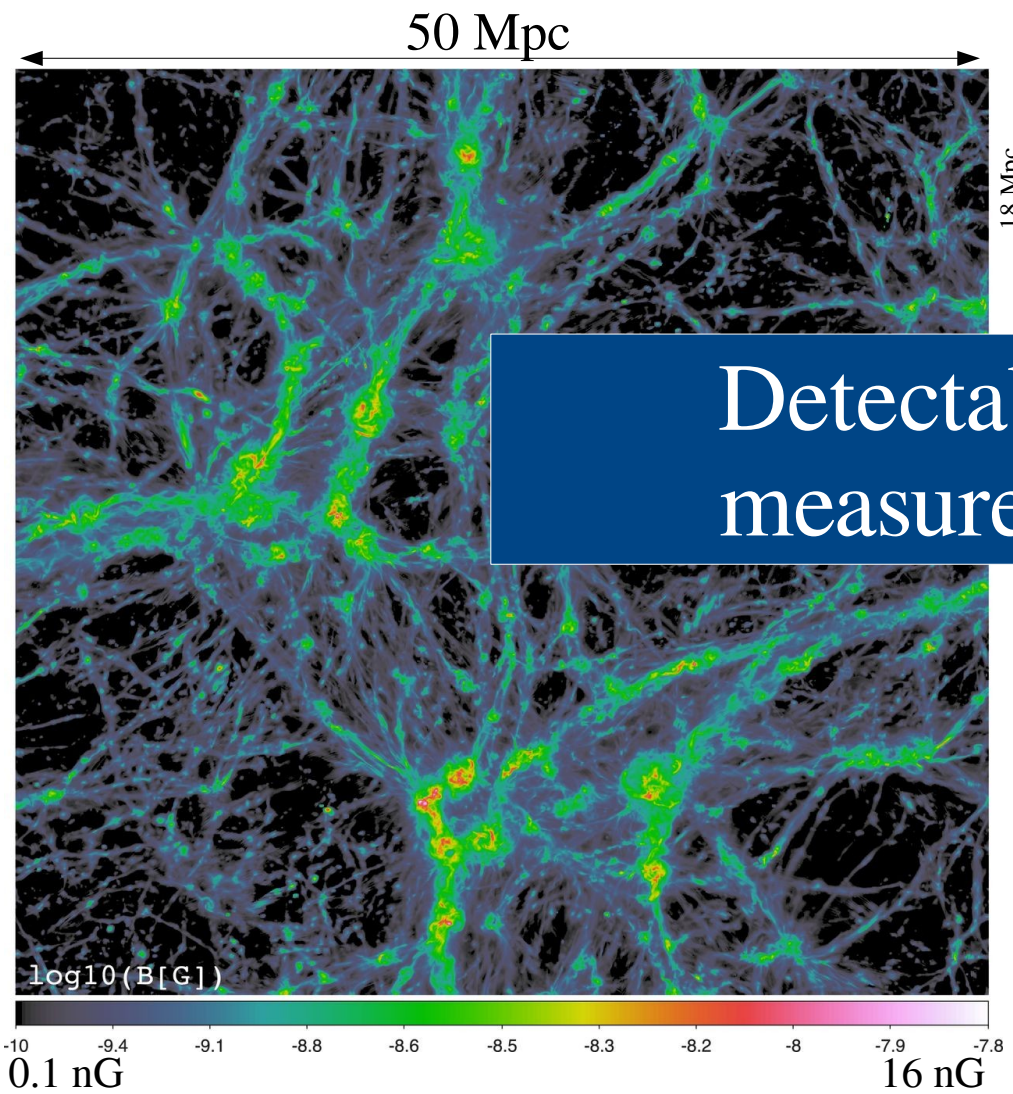
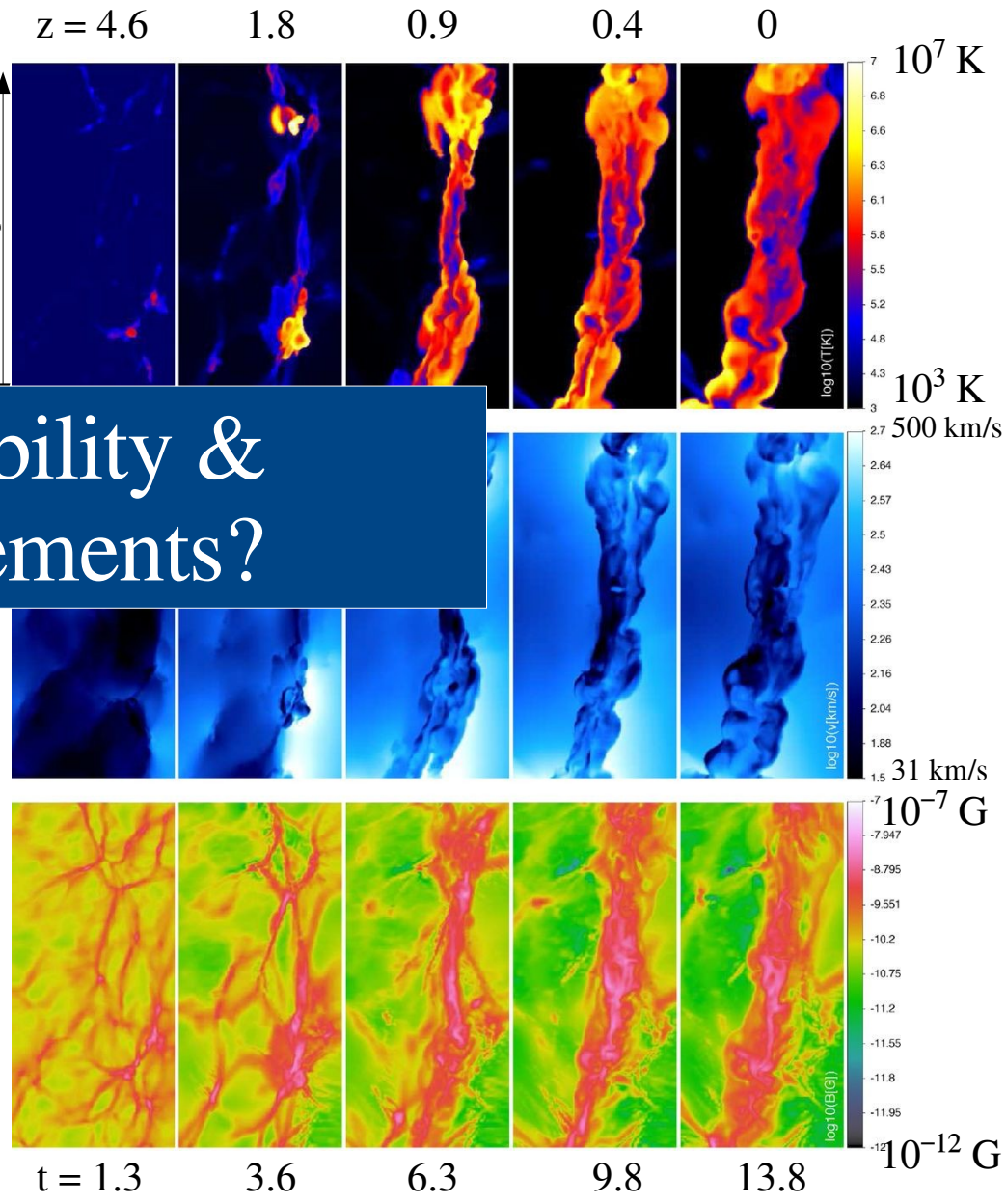
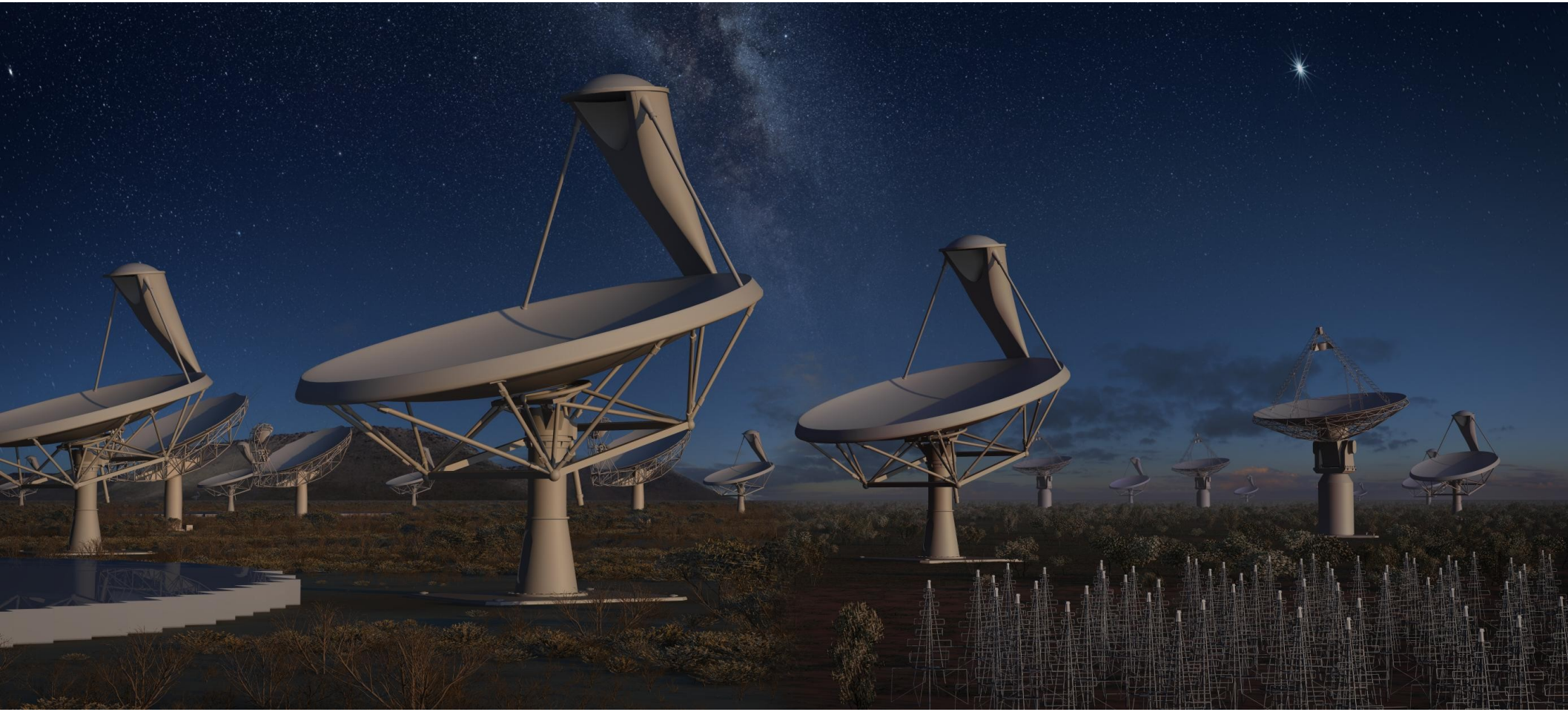


Cosmic web at z = 0



Detectability & measurements?

Square Kilometre Array

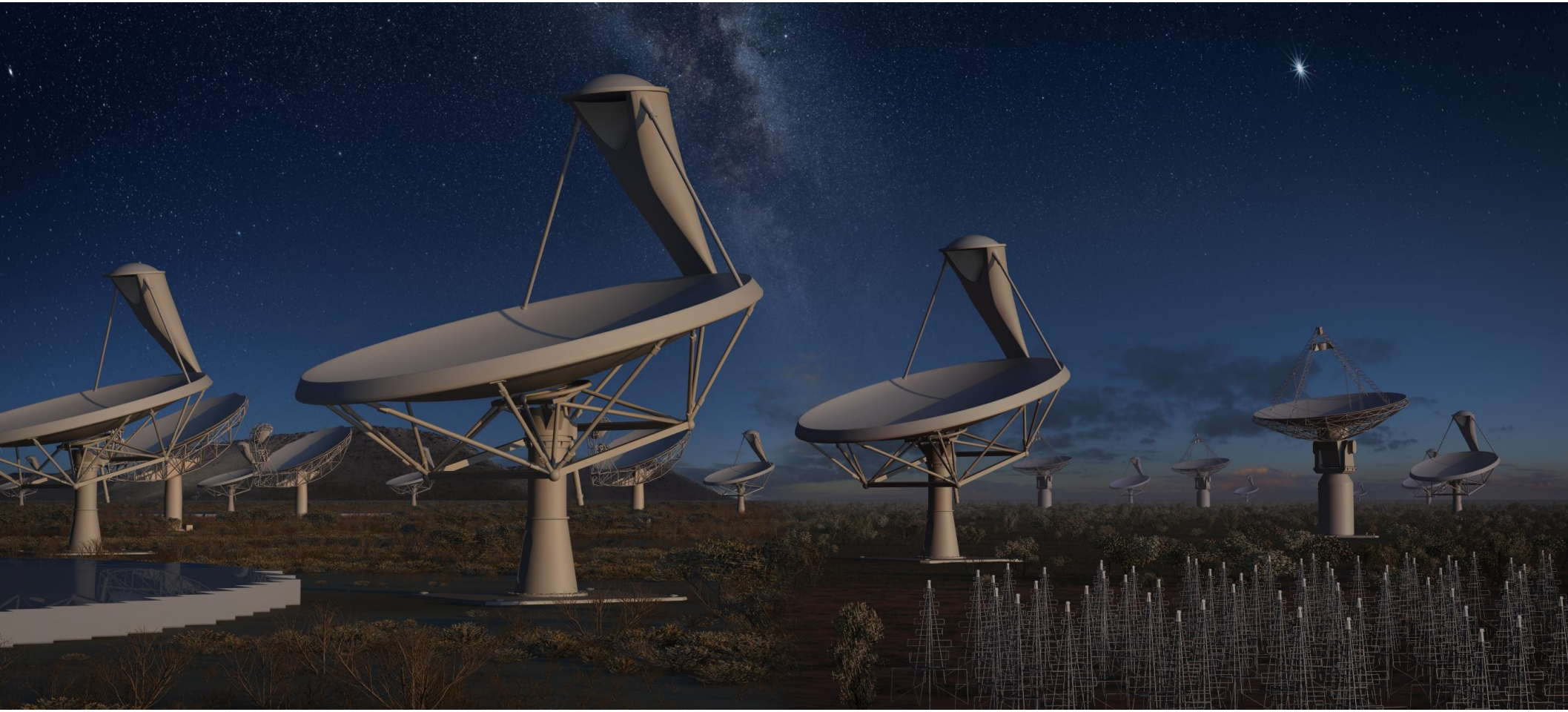


- Galaxy evolution, cosmology and dark energy
- Strong-field test of gravity using pulsars and back holes
- **The origin and evolution of cosmic magnetism**
- Probing the Cosmic Dawn
- The cradle of life
- Exploration of the unknown

Square Kilometre Array

Phase 1 : construction 2018 – 2023
→ SKA1 : 10 % total surface, sc. op. 2020

Phase 2 : design 2018 – 2023, construction 2023 – 2030
→ SKA2



SKA1 mid

- Array on ~150 km in diameter
- 350 MHz – 14 GHz
- 197 dishes: 15 m & 13.5 m (64 MeerKAT)
- Pulsars, 21cm local univ., **galactic B & IGM**,…

SKA1 low

- Array on ~ 40 km in diameter
- 50 MHz – 350 MHz
- 131 000 double-polarization (+ ASKAP)
- Reionization, **galactic B & IGM**, exoplanets,…

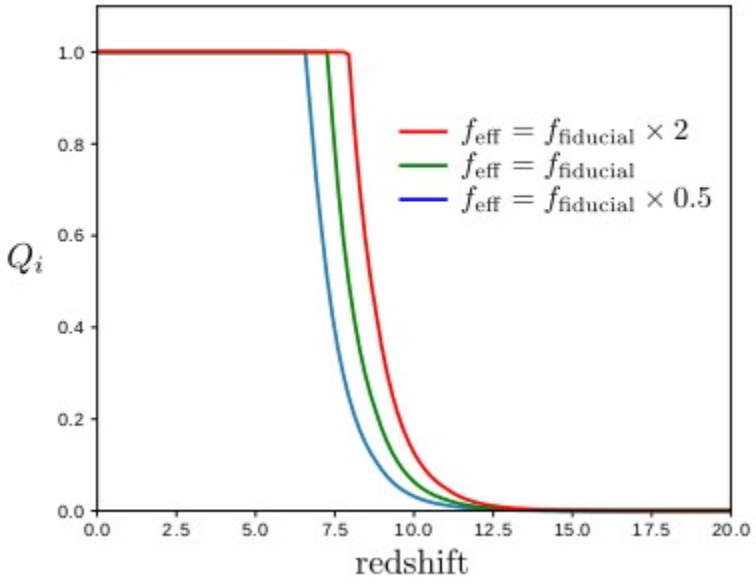
Conclusion and discussion

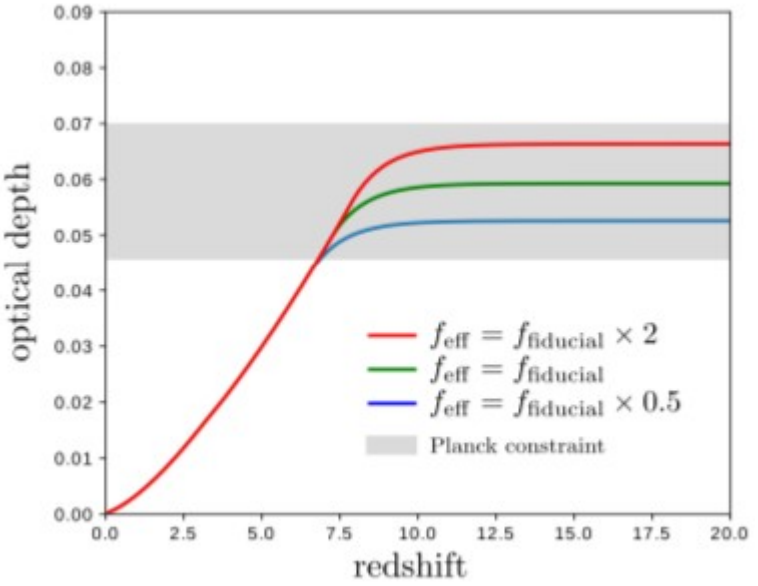
- Astrophysical mechanism, operating for any source, **all along the EoR**
- Strengths comparable to Biermann battery, but on entire inter-source scales

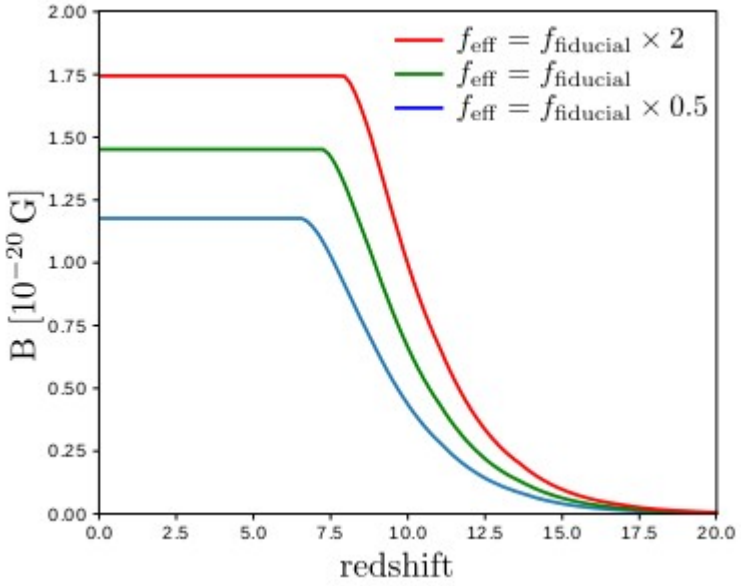
⇒ Contributes to **magnetization of the whole Intergalactic medium**
interesting for voids!

- Specific spatial configuration:
may help discriminate the seeds from other mechanisms
- Directly measurable seeds ?
→ 10^{-19} G fields prior and during EoR !
(Venumadhav et al 2017, Gluscevic et al 2017)

Thank you for your attention


Q_i
redshift
$f_{\rm eff} = f_{\rm fiducial} \times 2$
$f_{\rm eff} = f_{\rm fiducial}$
$f_{\rm eff} = f_{\rm fiducial} \times 0.5$


optical depth
redshift
$f_{\rm eff} = f_{\rm fiducial} \times 2$
$f_{\rm eff} = f_{\rm fiducial}$
$f_{\rm eff} = f_{\rm fiducial} \times 0.5$
Planck constraint


B $[10^{-20}$ G]
redshift
$f_{\rm eff} = f_{\rm fiducial} \times 2$
$f_{\rm eff} = f_{\rm fiducial}$
$f_{\rm eff} = f_{\rm fiducial} \times 0.5$