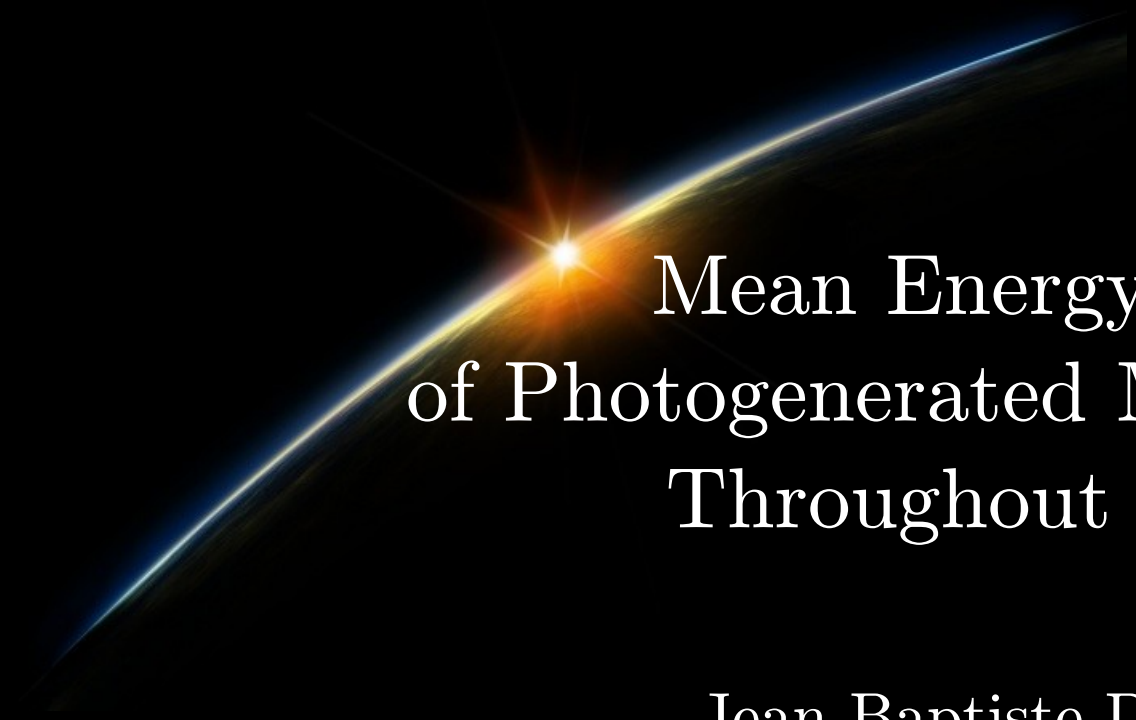


Mean Energy Density of Photogenerated Magnetic Fields Throughout the EoR

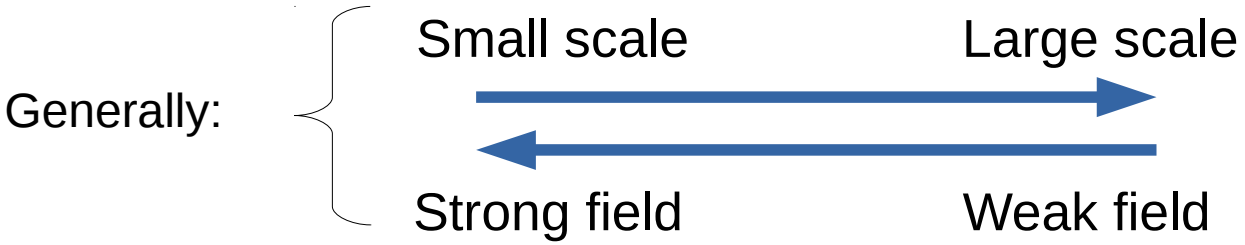
Jean-Baptiste Durrive

Nagoya University, Japan

Durrive & Langer, 2015, MNRAS, arXiv:1506.08177
→ Durrive, Tashiro, Langer, Sugiyama 2017, MNRAS, 472, 1649
Durrive & Aubert, 2017, in prep

Peering towards Cosmic Dawn, IAU Symposium 333, 2-6/10/17, Dubrovnik

• 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

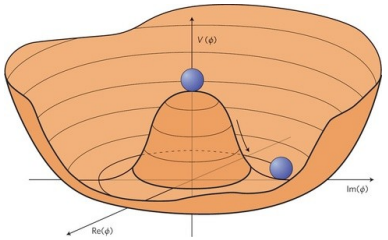
• Turbulence in structures → B fields lost their initial properties

→ 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

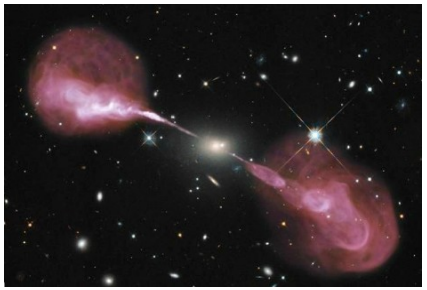
- Numerous mechanisms:
  (Reviews see e.g. Ryu et al 2012, Widrow et al 2012, Durrer & Neronov 2013, ...)



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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- Numerous mechanisms:
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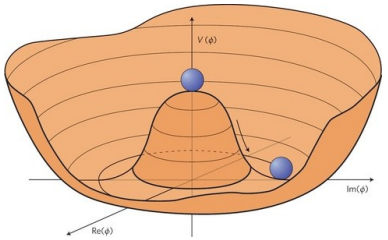


I) Primordial Universe mechanisms

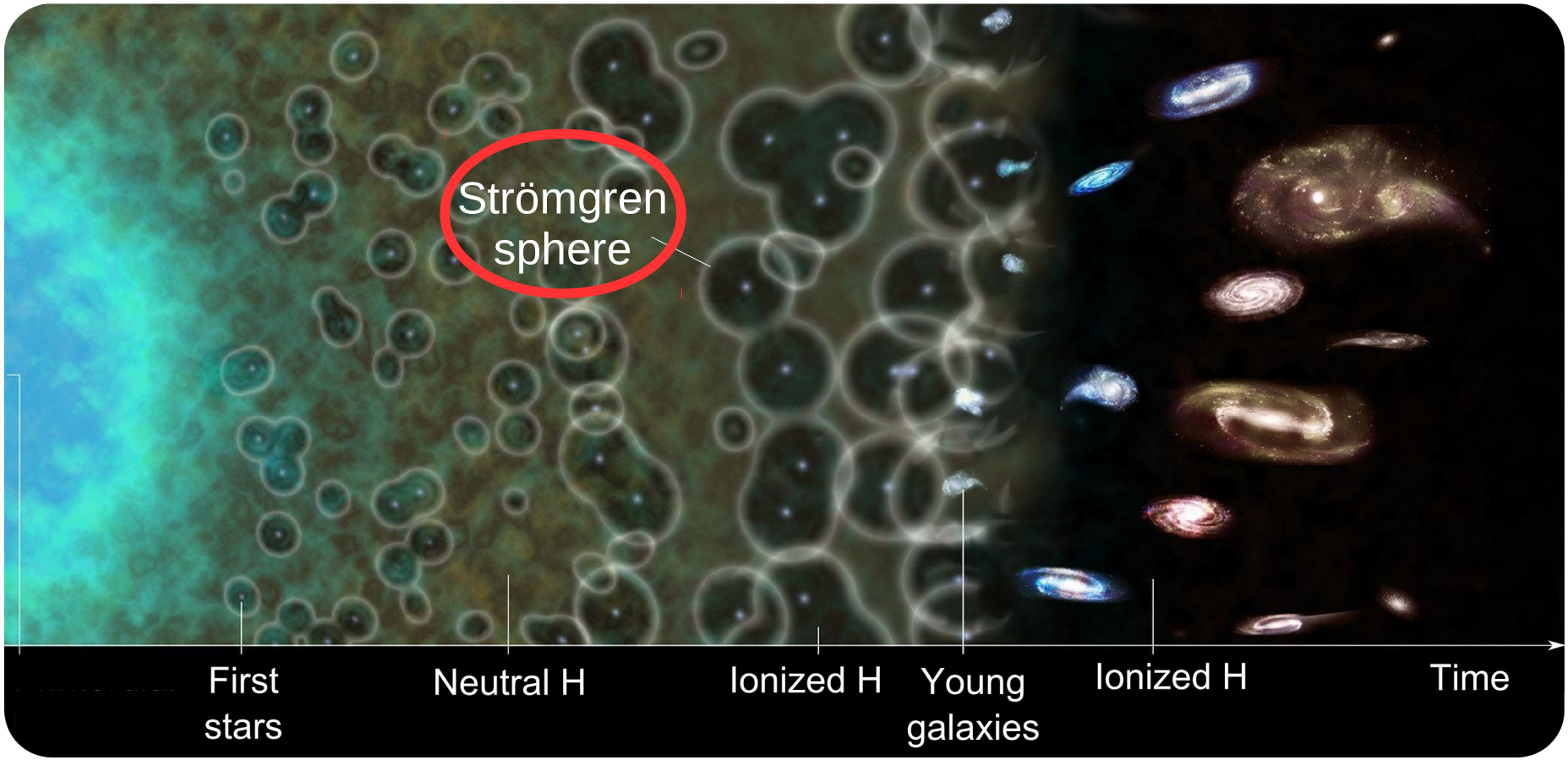
- Inflation: quantum fluctuations of electromagnetic field, but need non-standard electromagnetism
- Phase transitions: electroweak and quark-hadron
- Recombination: rotating plasma blobs interacting

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



neutral

neutral → ionized
'Epoch of Reionization'

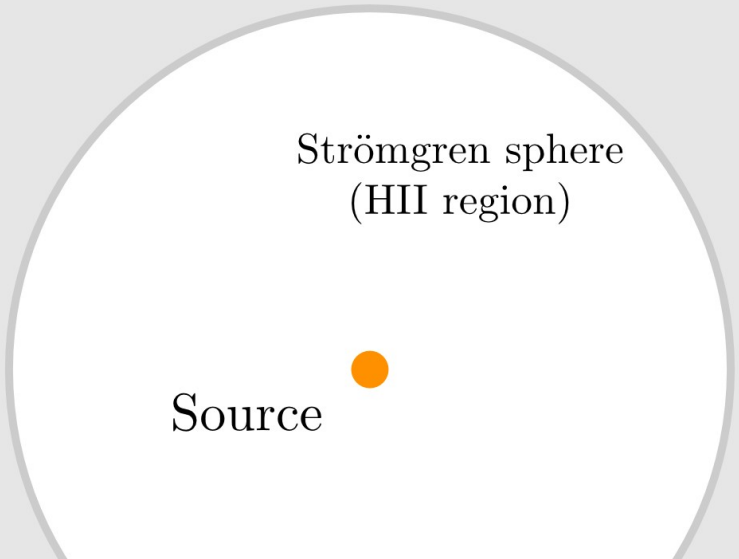
ionized

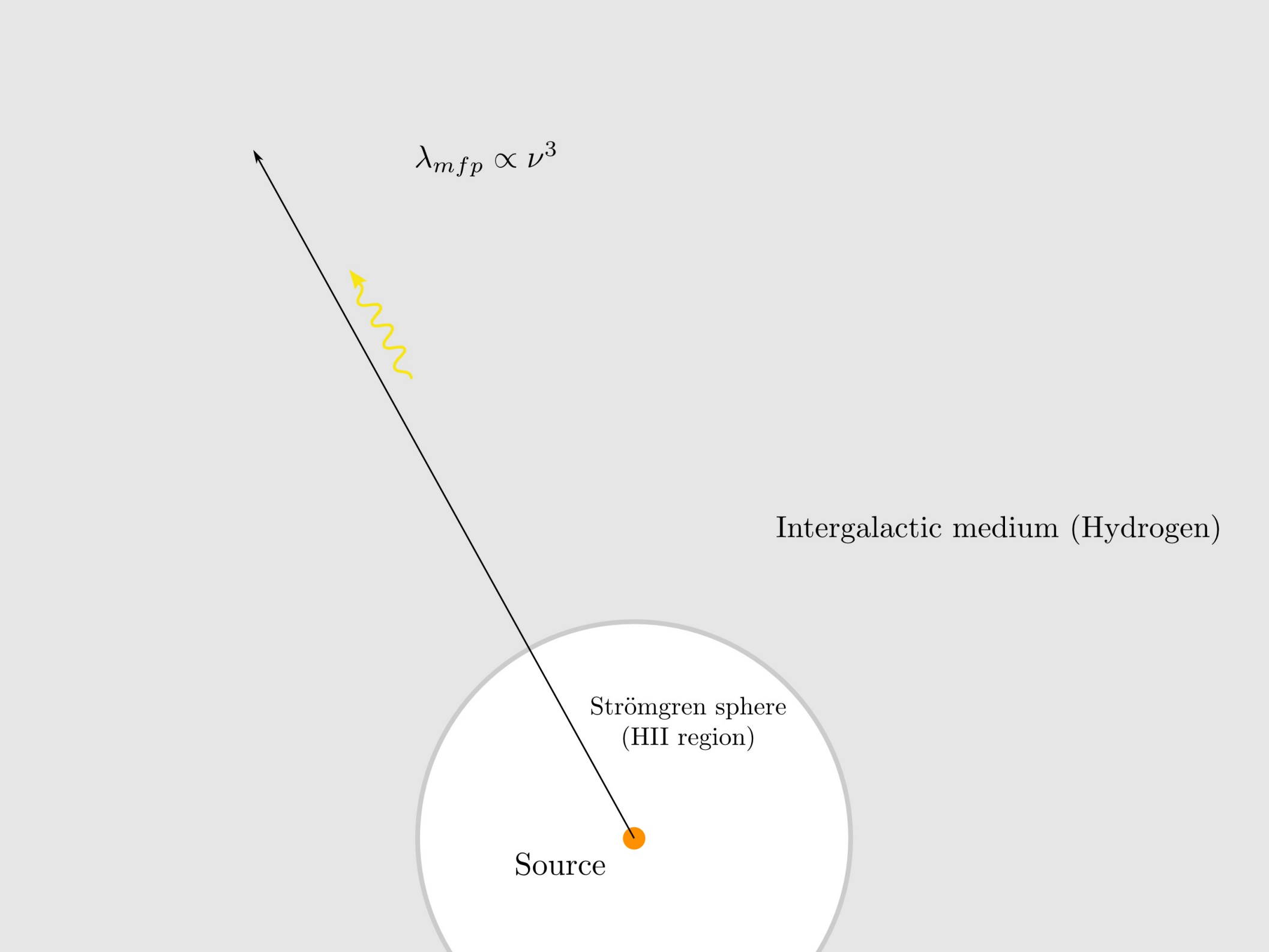
Recombination
(380 000 years)

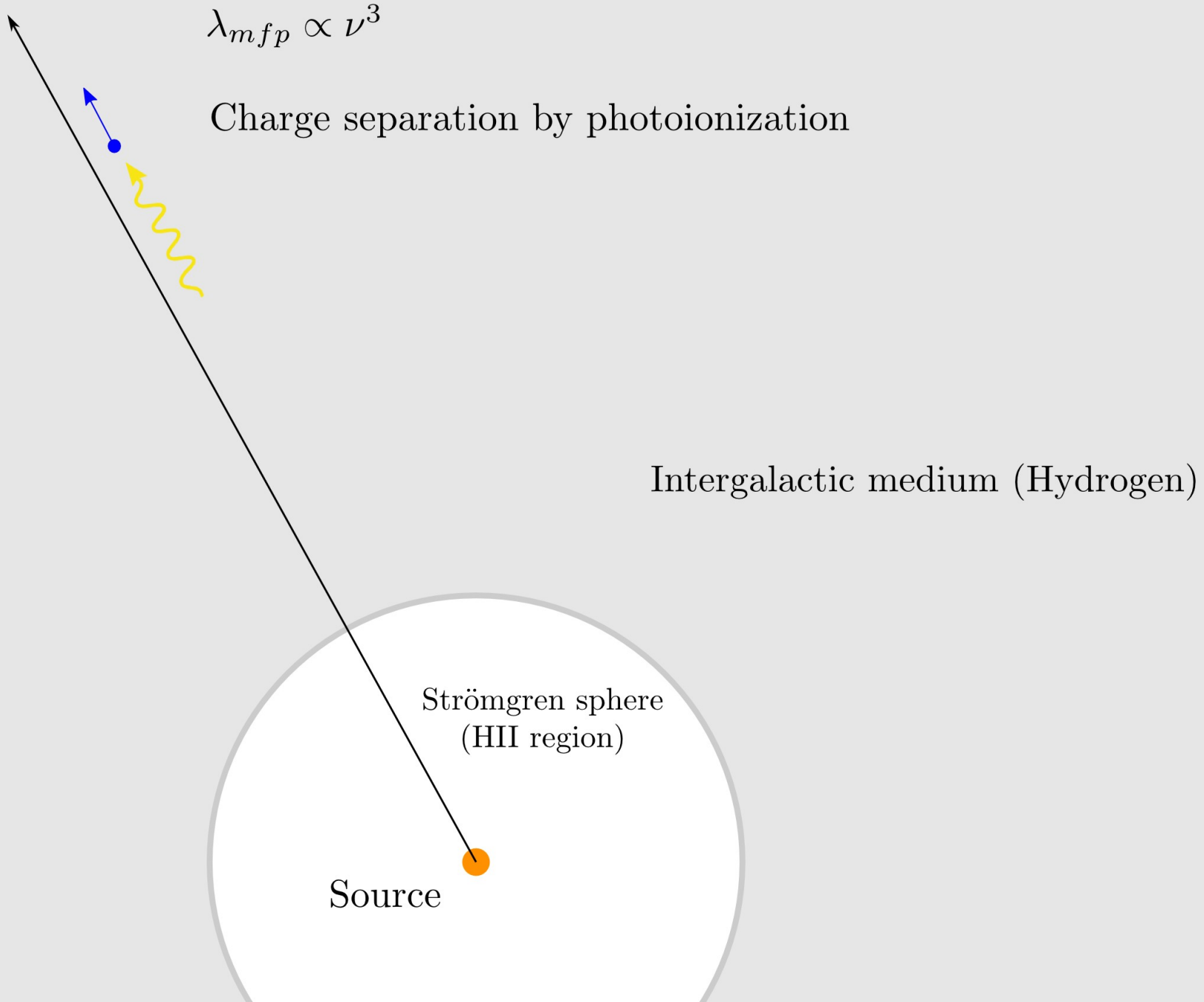
Reionization
(~ 1 billion years)

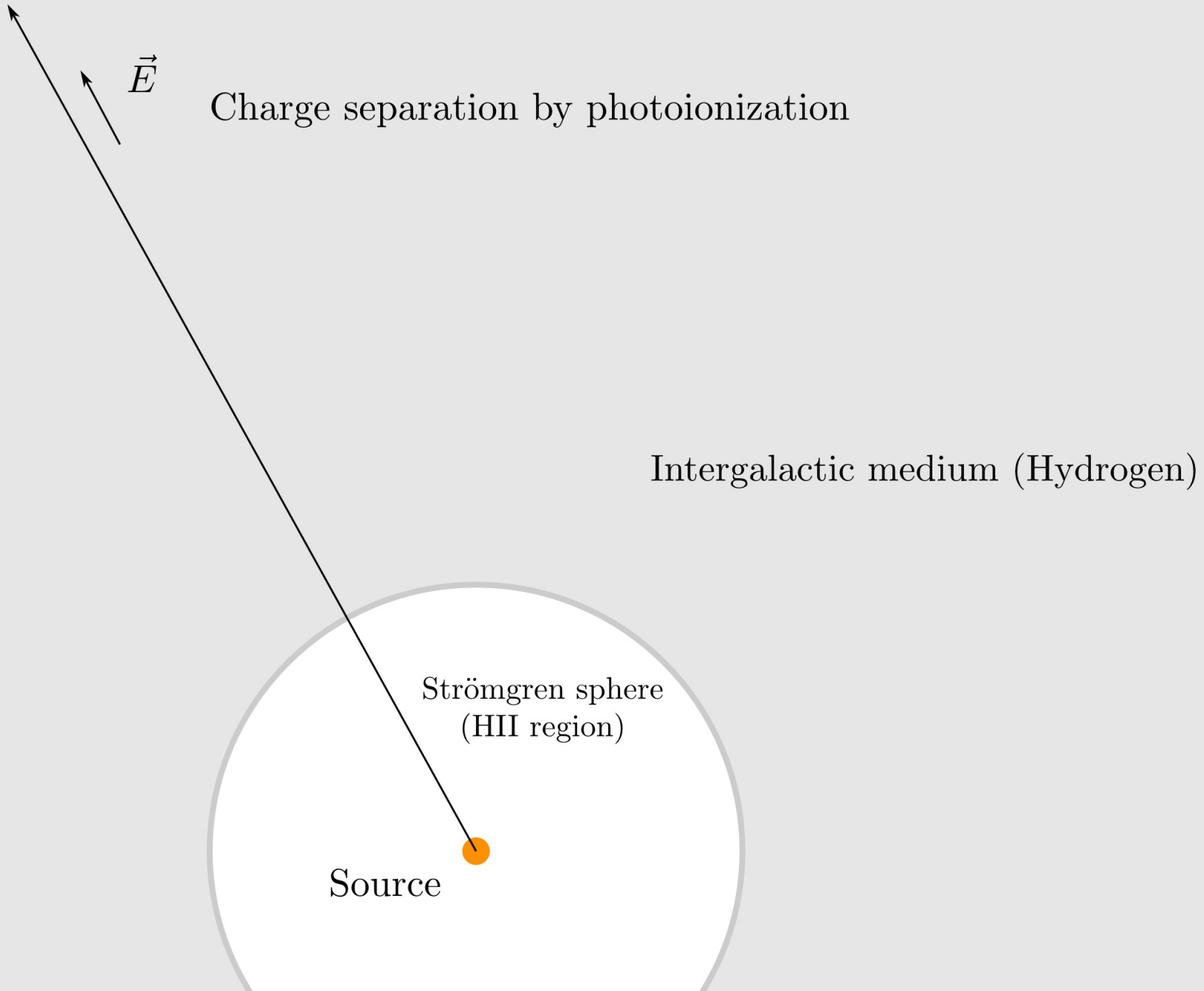
Today
(~ 14 billion years)

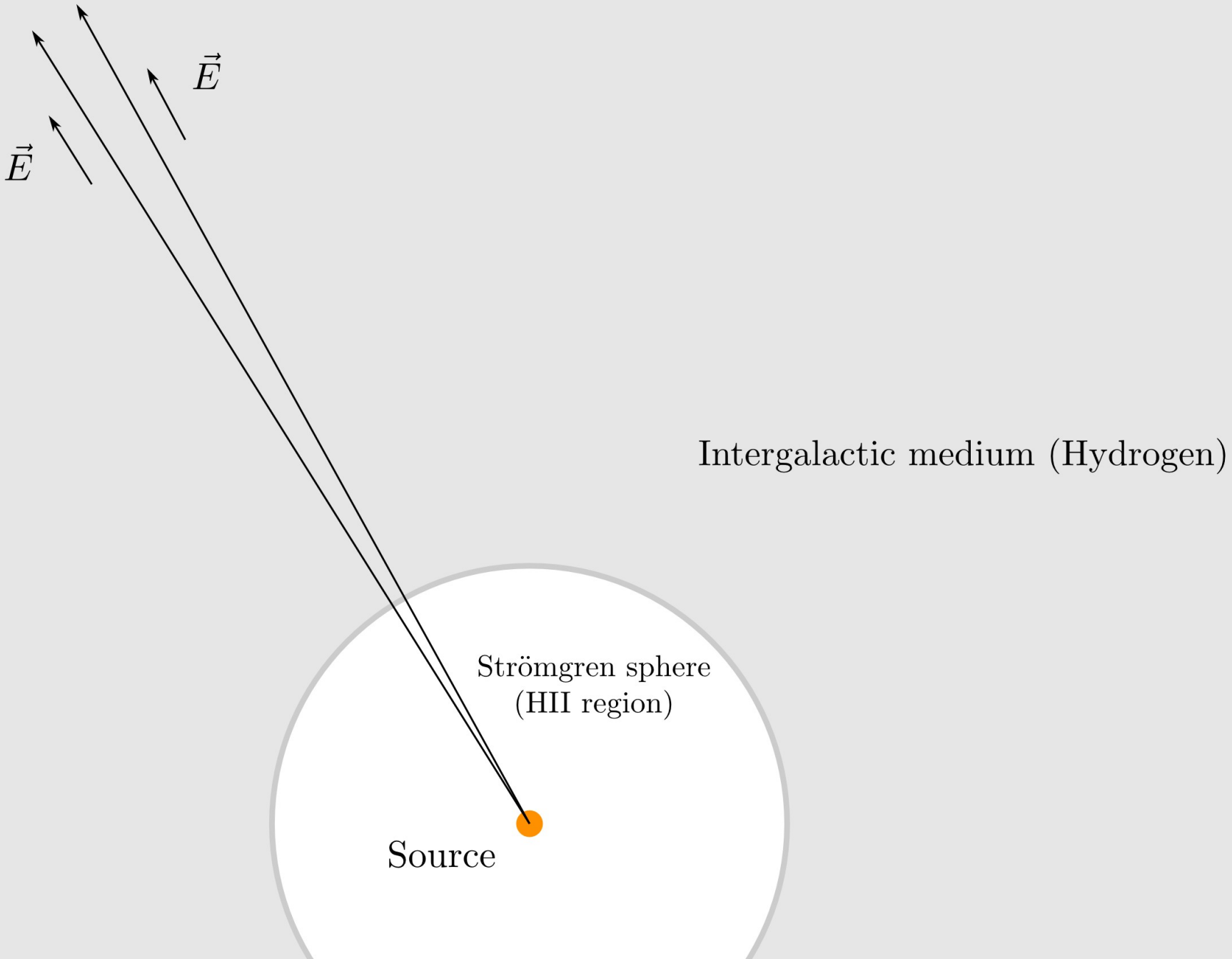
Intergalactic medium (Hydrogen)



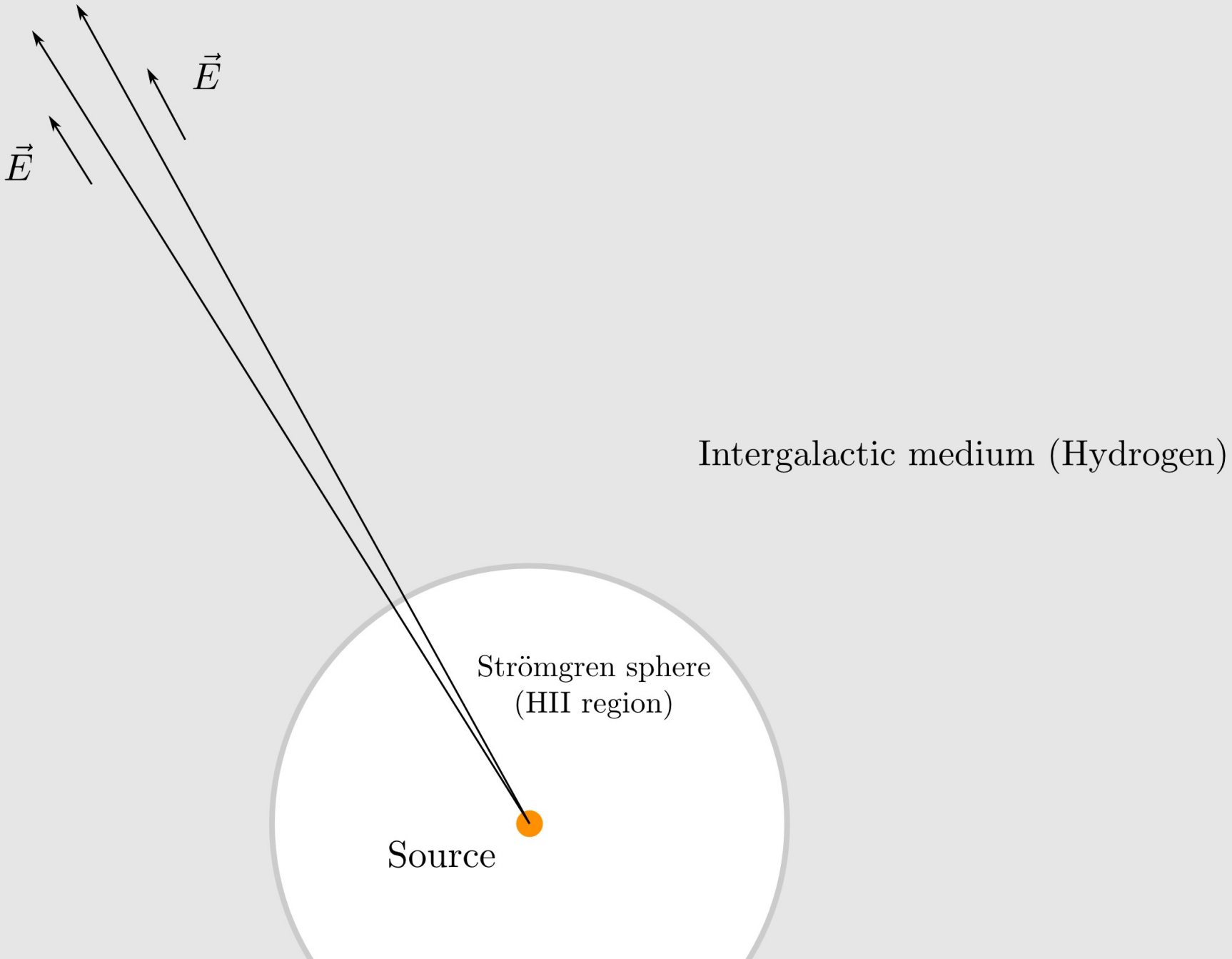

$\lambda_{mfp} \propto \nu^3$
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


$\lambda_{mfp} \propto \nu^3$
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

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

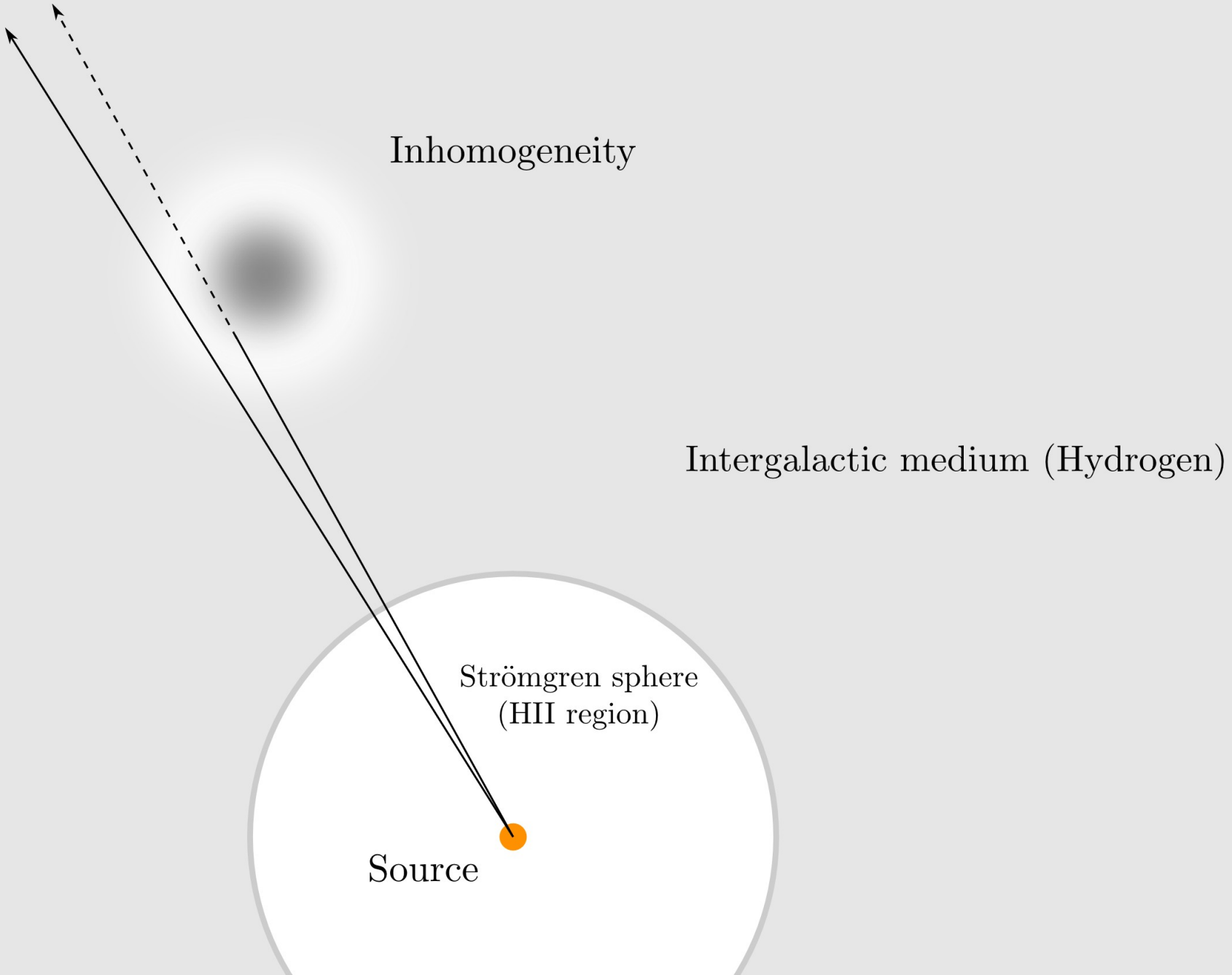


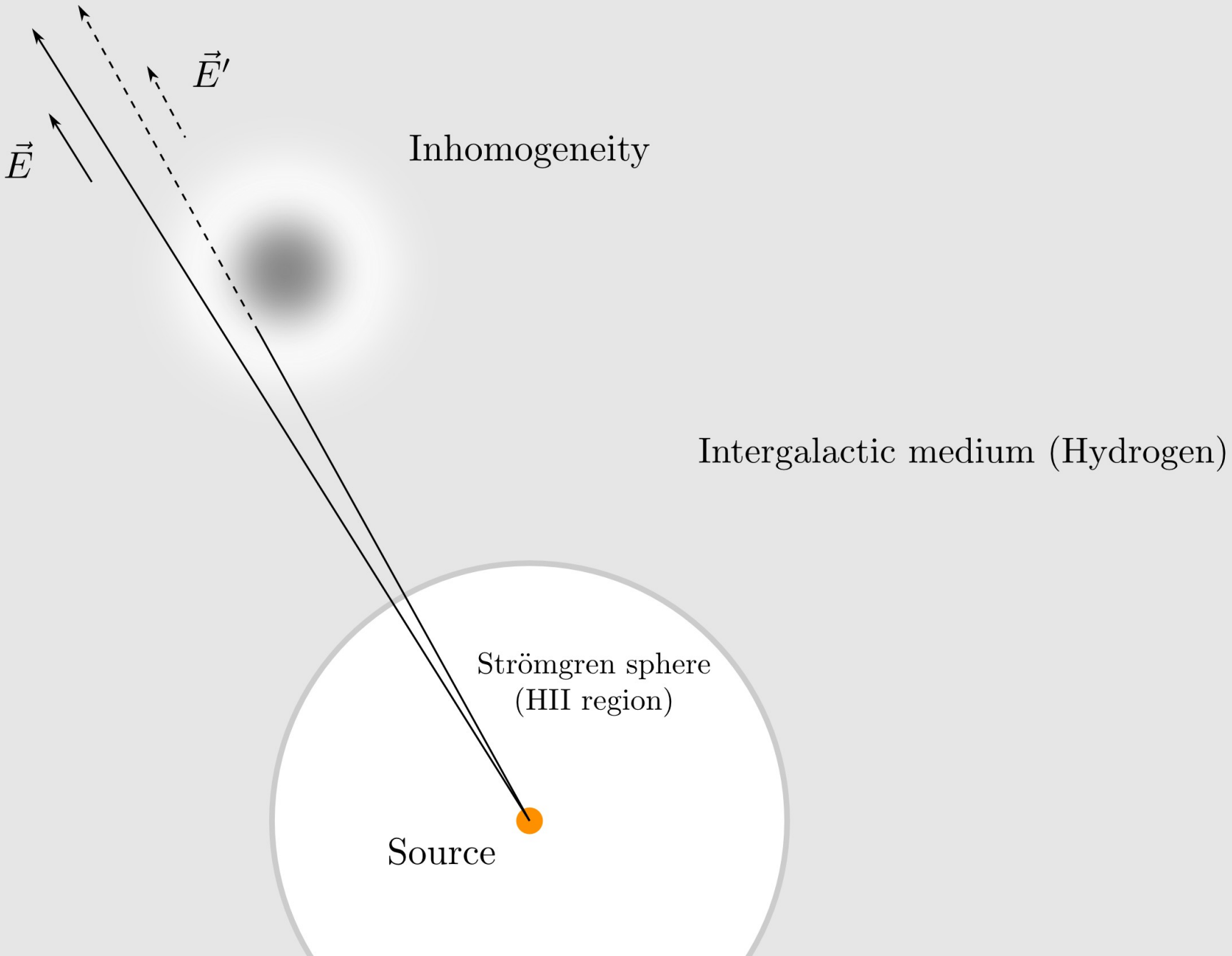
Maxwell-Faraday equation: $$\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E}$$

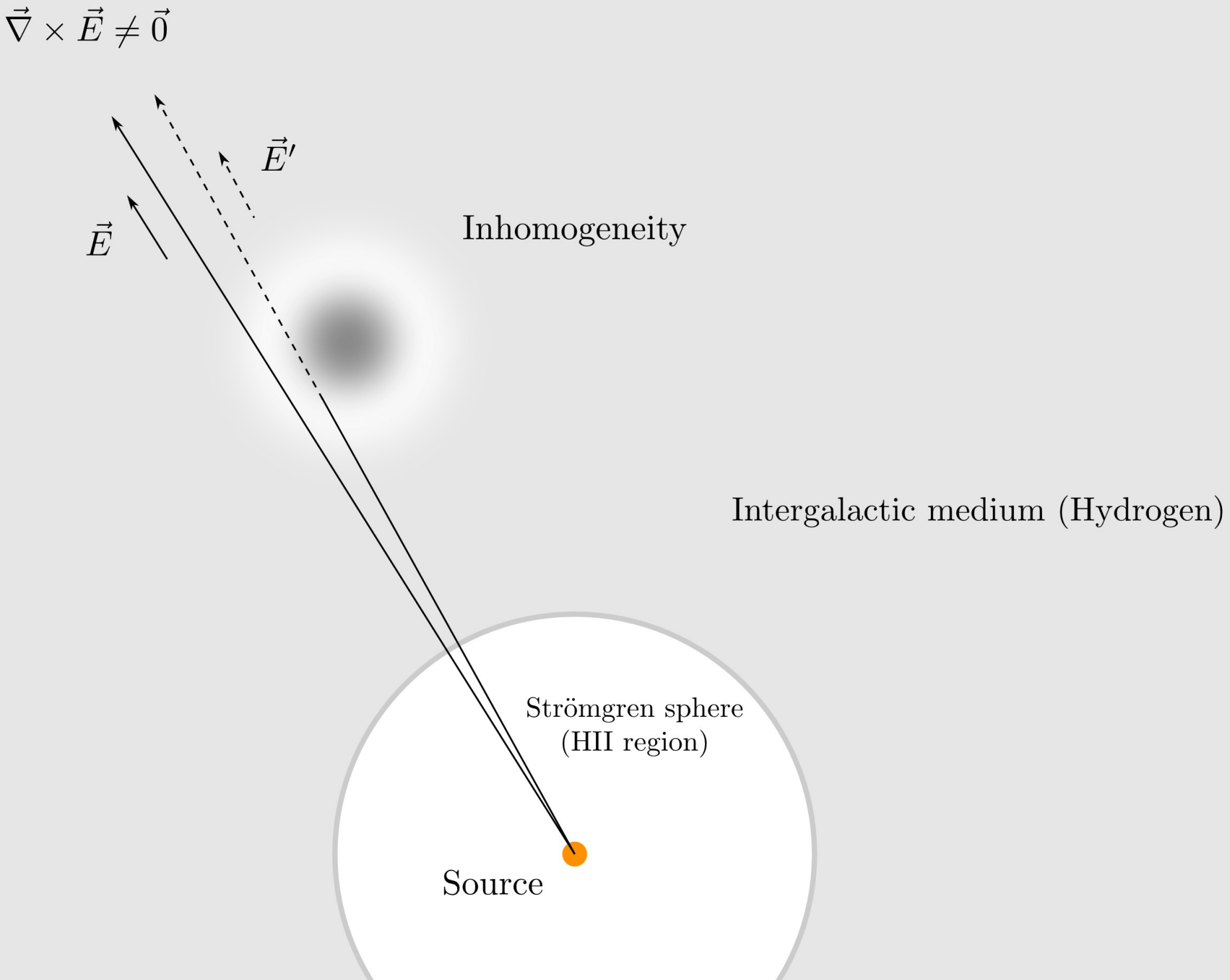
→ Need **rotational *E* field** to generate B

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)
Strömgren sphere
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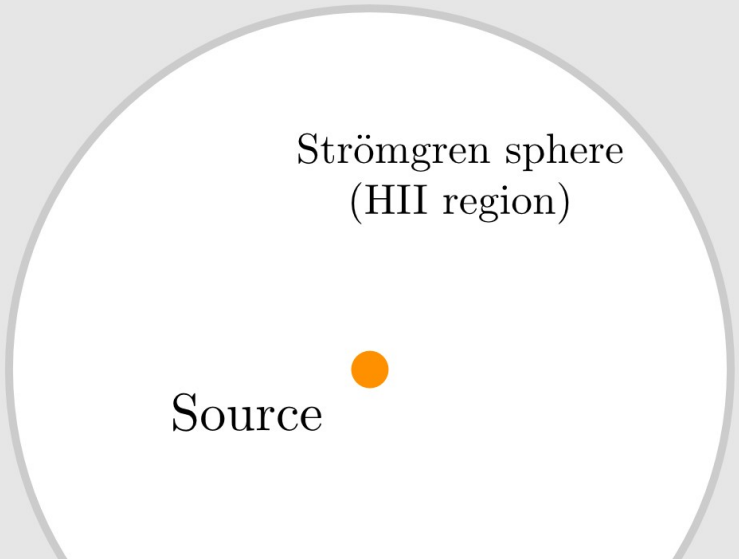
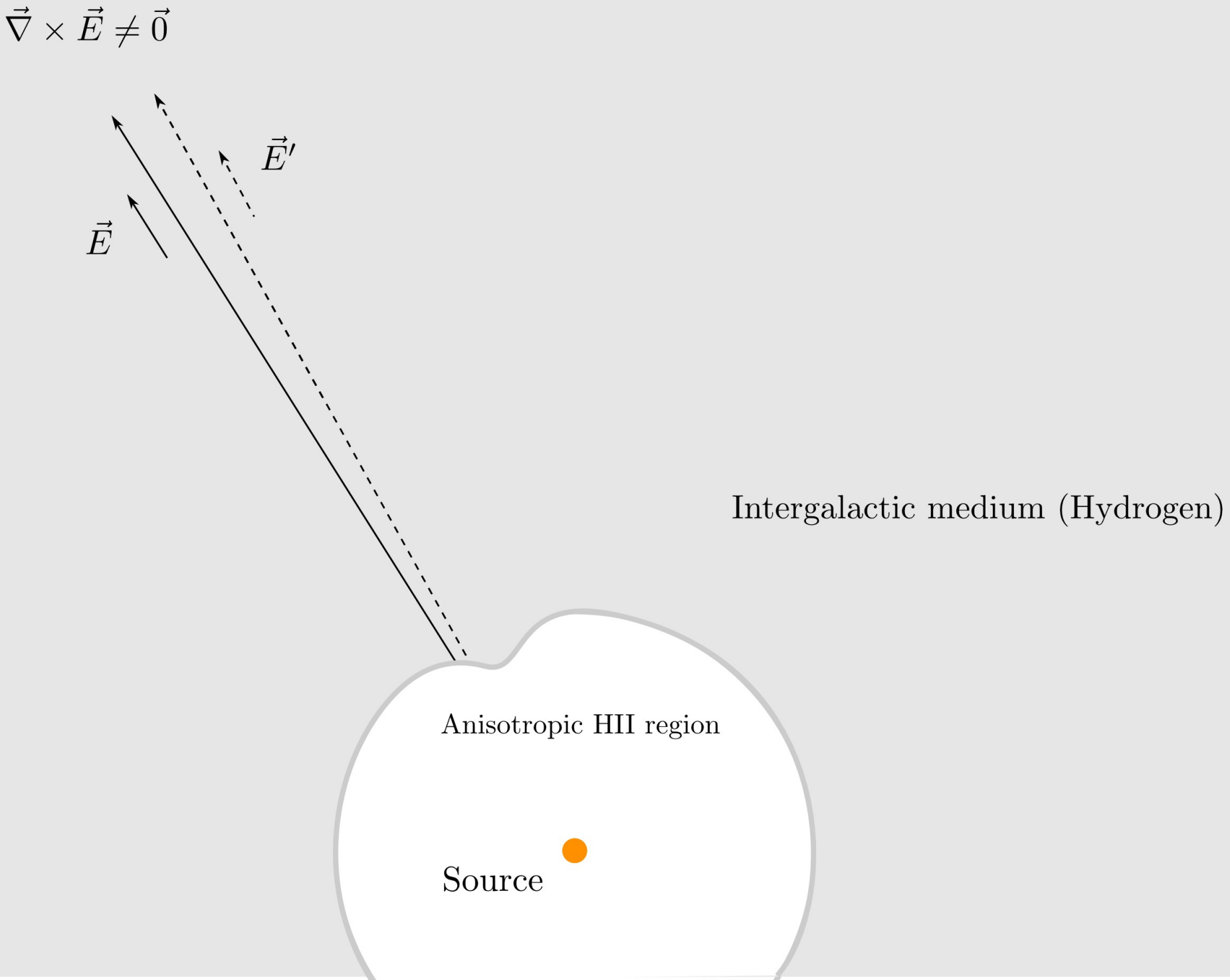
Intergalactic medium (Hydrogen)



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

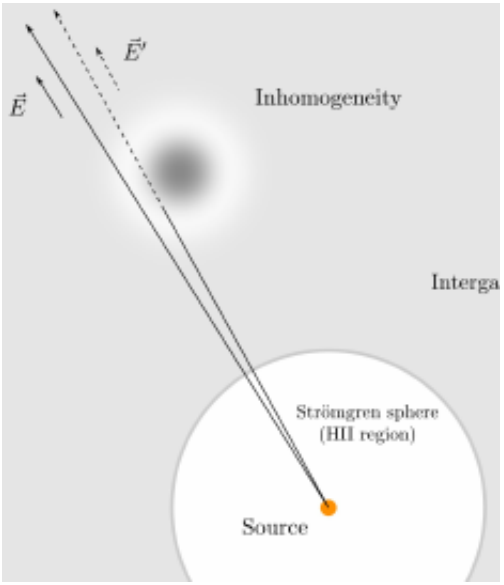
Ionizing photons

Fraction of momentum transferred

Resulting magnetic field

(Durrive & Langer, 2015, MNRAS)

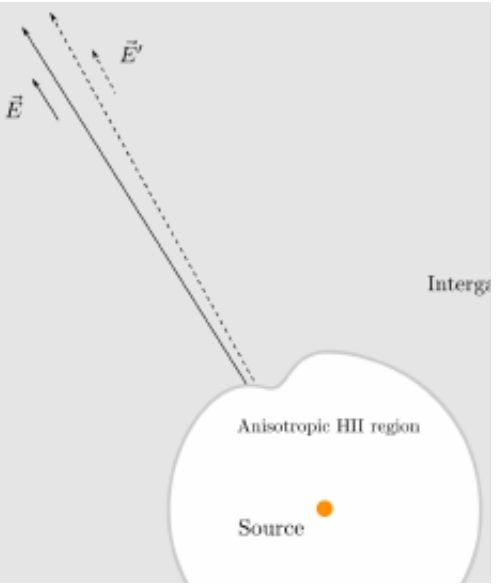
Source of *B* :
Anisotropy of the column density



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



Previously: Study for various isolated sources at various epochs:

PopIII clusters: B ~ 10^{-21}G to 10^{-18}G on ~ 2 kpc

First galaxies: B ~ 10^{-21}G to 10^{-19}G on ~ 20 kpc

Quasars: B ~ 10^{-23}G to 10^{-21}G on ~ 2 Mpc

New work: In the cosmological context of EoR:

Analytic approach:
Durrive,Tashiro,Langer, Sugiyama, 2017

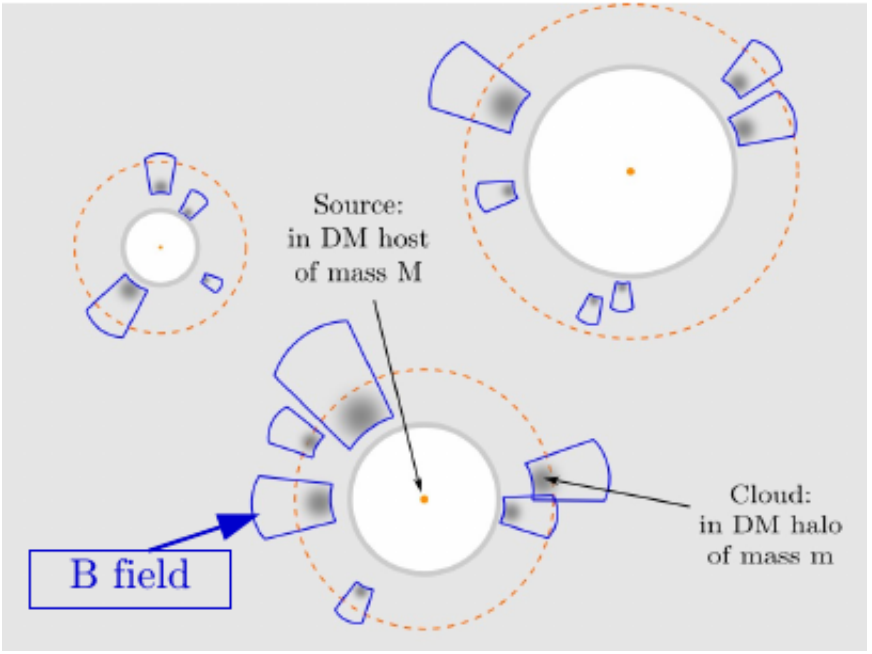
Numerical approach:
Durrive,Aubert, in prep

Global magnetization level of the Universe

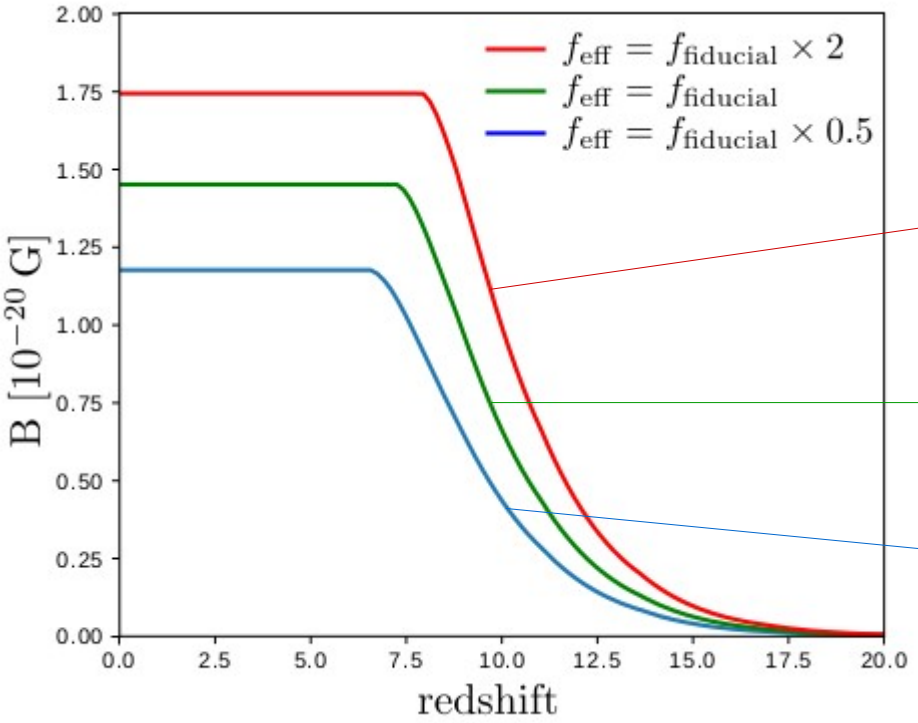
(Durrive, Tashiro, Langer, Sugiyama 2017, MNRAS)

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)

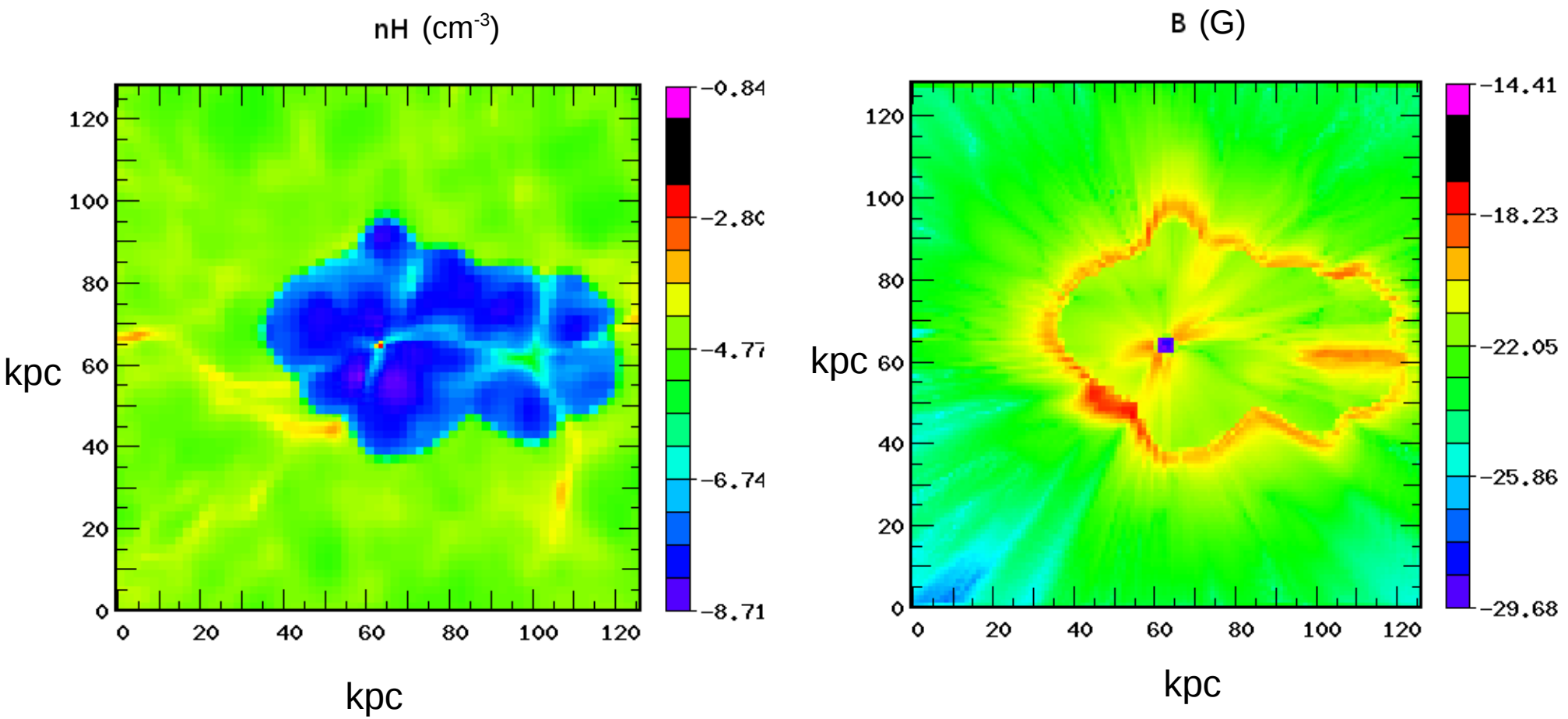
Fiducial model

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!

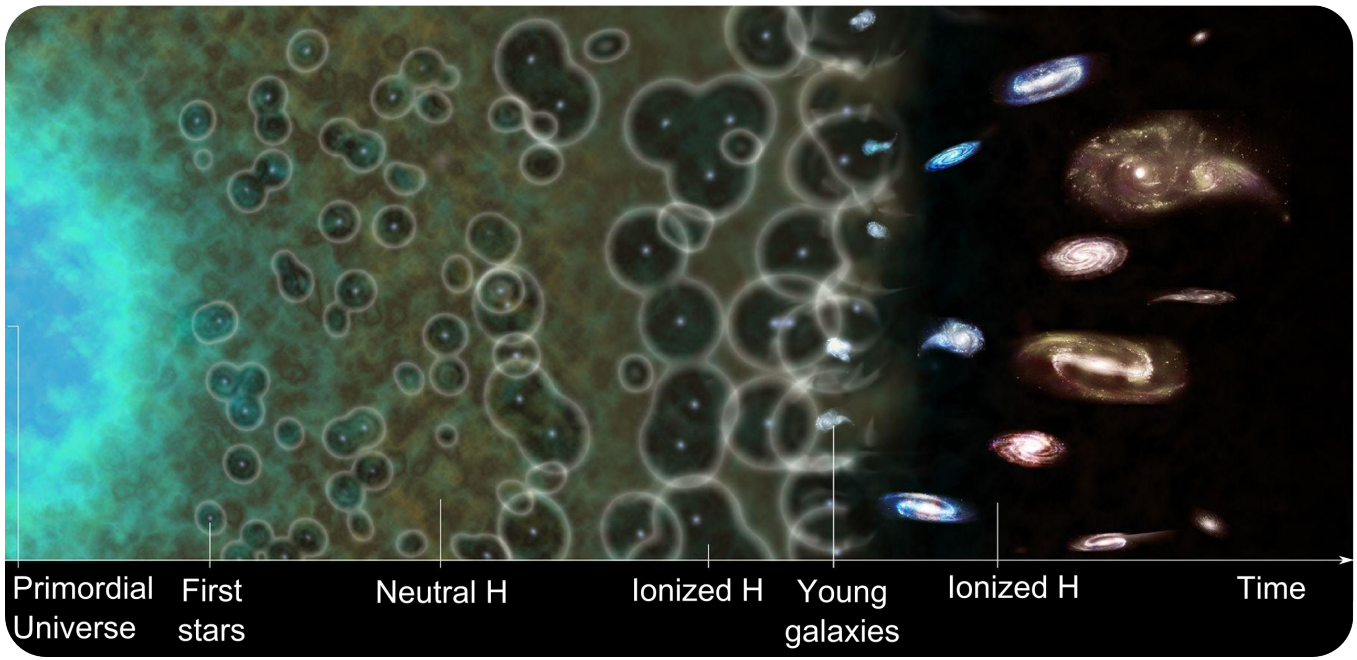
Evolution in the cosmic web?

B field **generated** early

?

→

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



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

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 f elds prior and during EoR

  (Venumadhav et al 2017, Gluscevic et al 2017)

  → SKA

- Evolution of cosmological B fields in the cosmic web?

  (e.g. Vazza et al 2014)

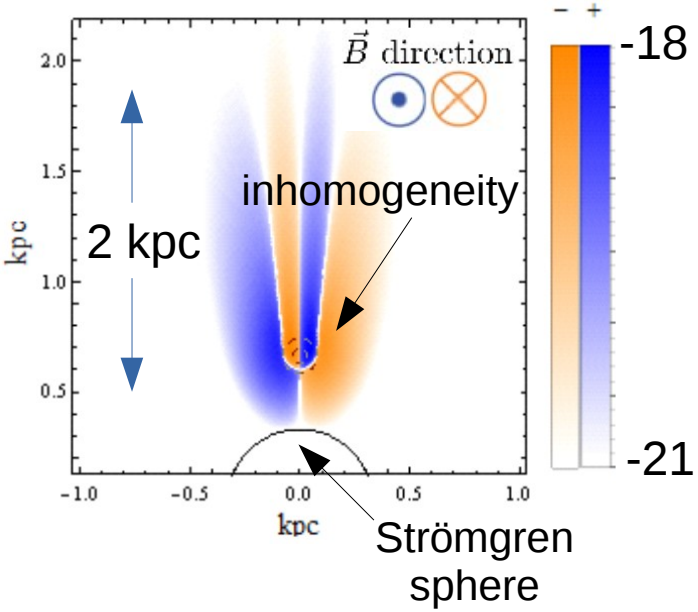
Thank you for your attention

Typical spatial distributions and scales

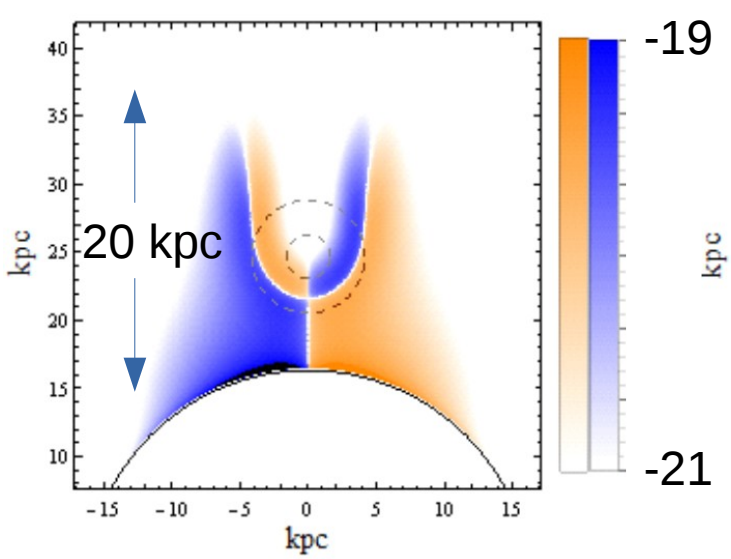
(Durrive & Langer, 2015, MNRAS)

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

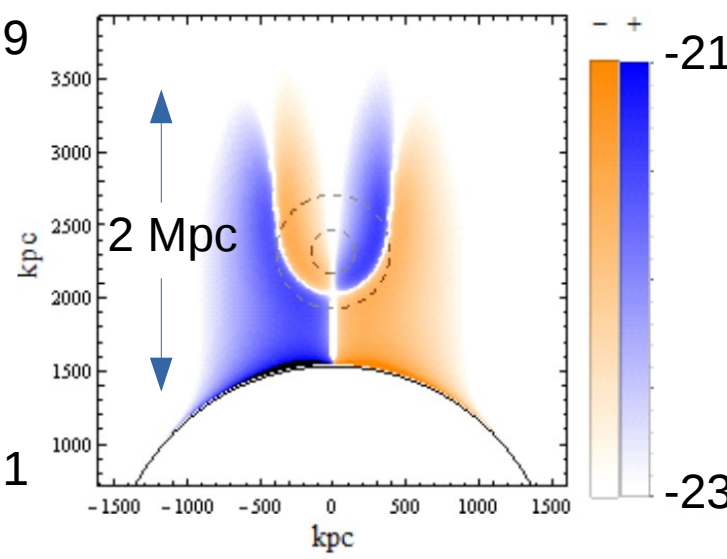
Pop III clusters



First galaxies

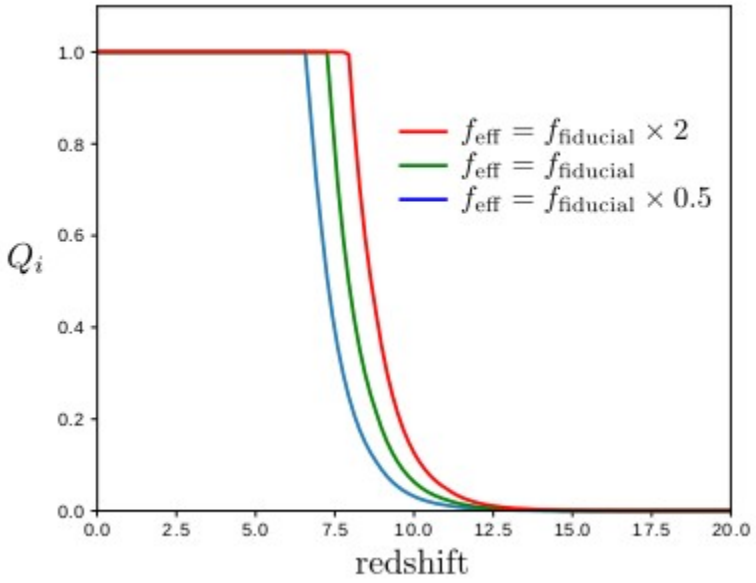


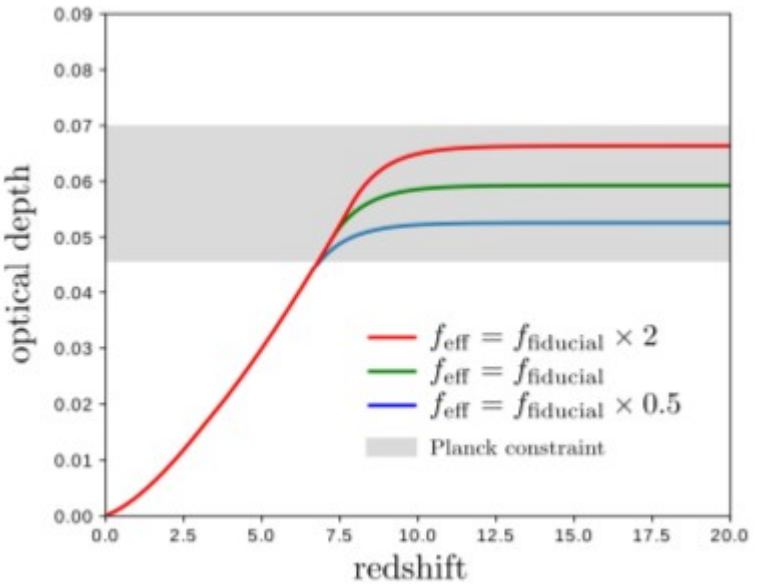
Quasars

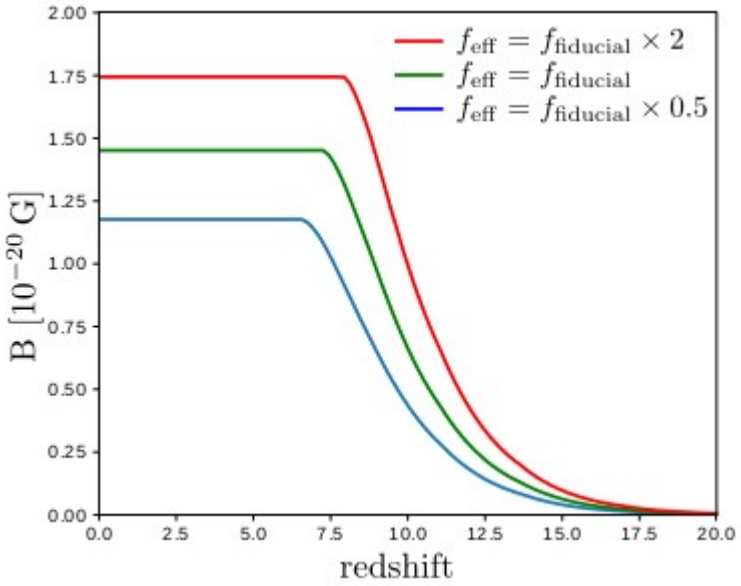


→ Best compromise power/dilution

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


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