

Intergalactic Magnetogenesis at the Epoch of Reionization

Durrive & Langer 2014, to be submitted

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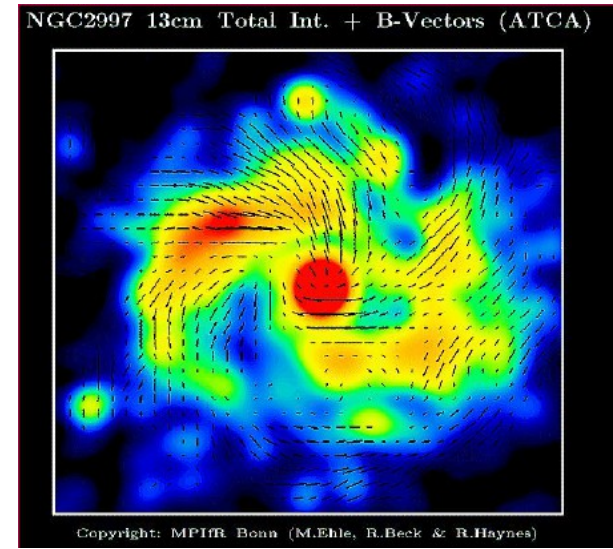


Origin of cosmological magnetic fields ?

Structures are magnetized at all scales
and at every stage of evolution → origin ?

High energy gamma rays:

a significant fraction of the Intergalactic Medium might be magnetized
(Neronov&Vovk 2010, Taylor et al 2011, Takahashi et al 2011, ...)

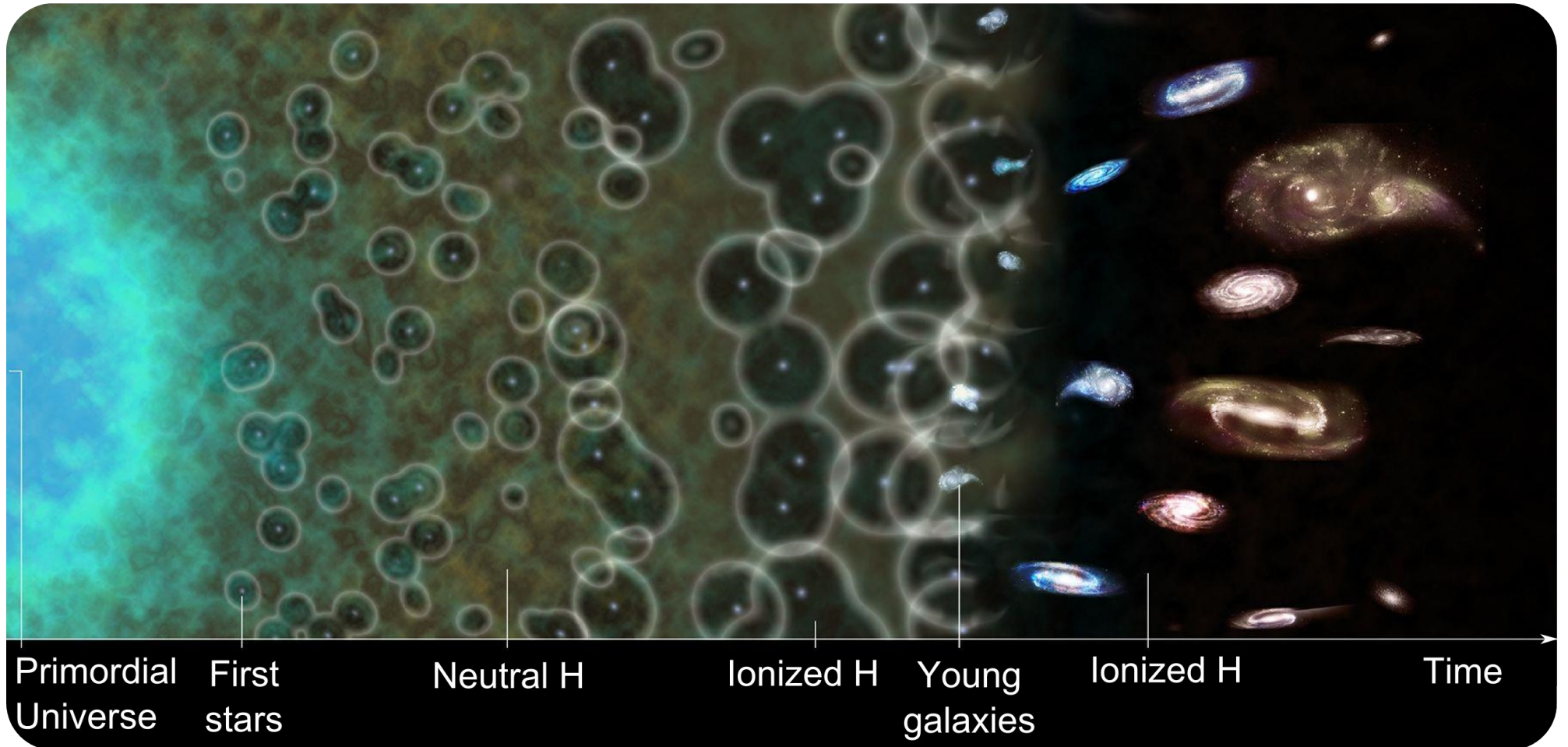
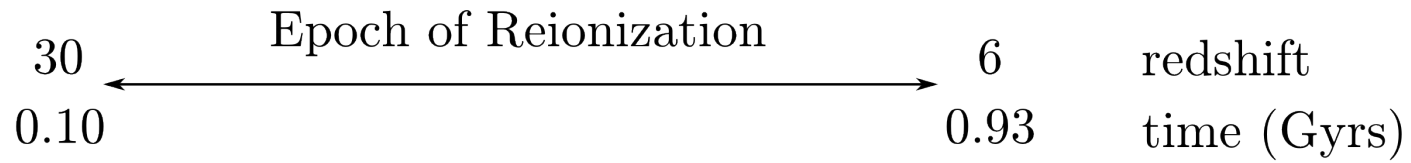


astrophysical mechanism

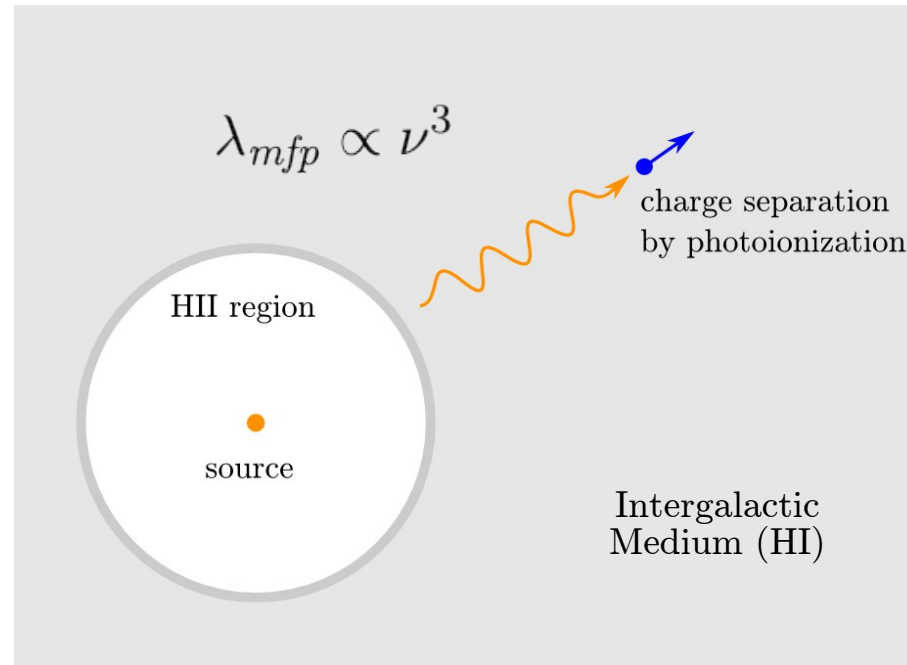
Here: generating intergalactic magnetic fields

at the Epoch of Reionization

Cosmological context



Magnetogenesis at the Epoch of Reionization



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

B field generation needs **charge separation** that induces a **rotational E field**

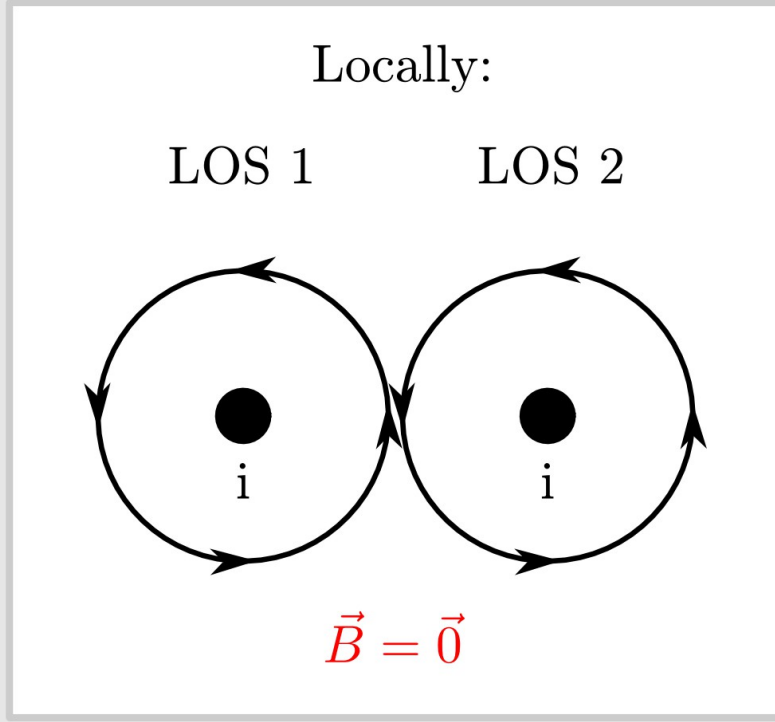
(Langer et al 2005)

This can be done by photoionization in the **inhomogeneous** Intergalactic medium during the Epoch of Reionization

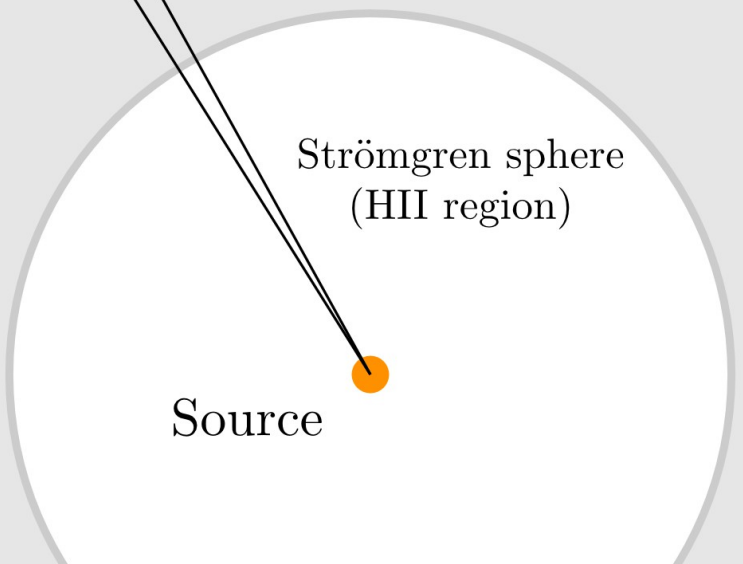


LOS 2

LOS 1

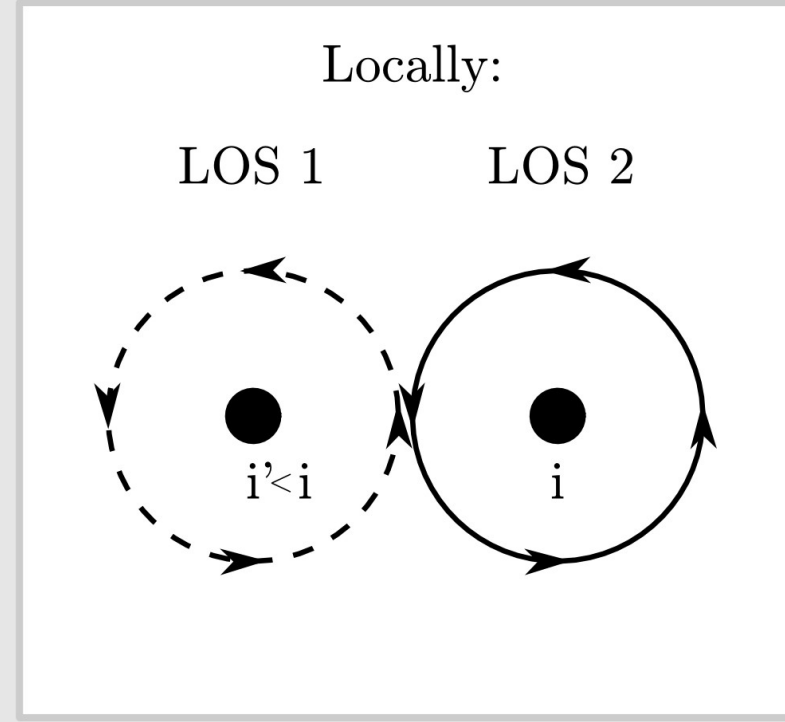
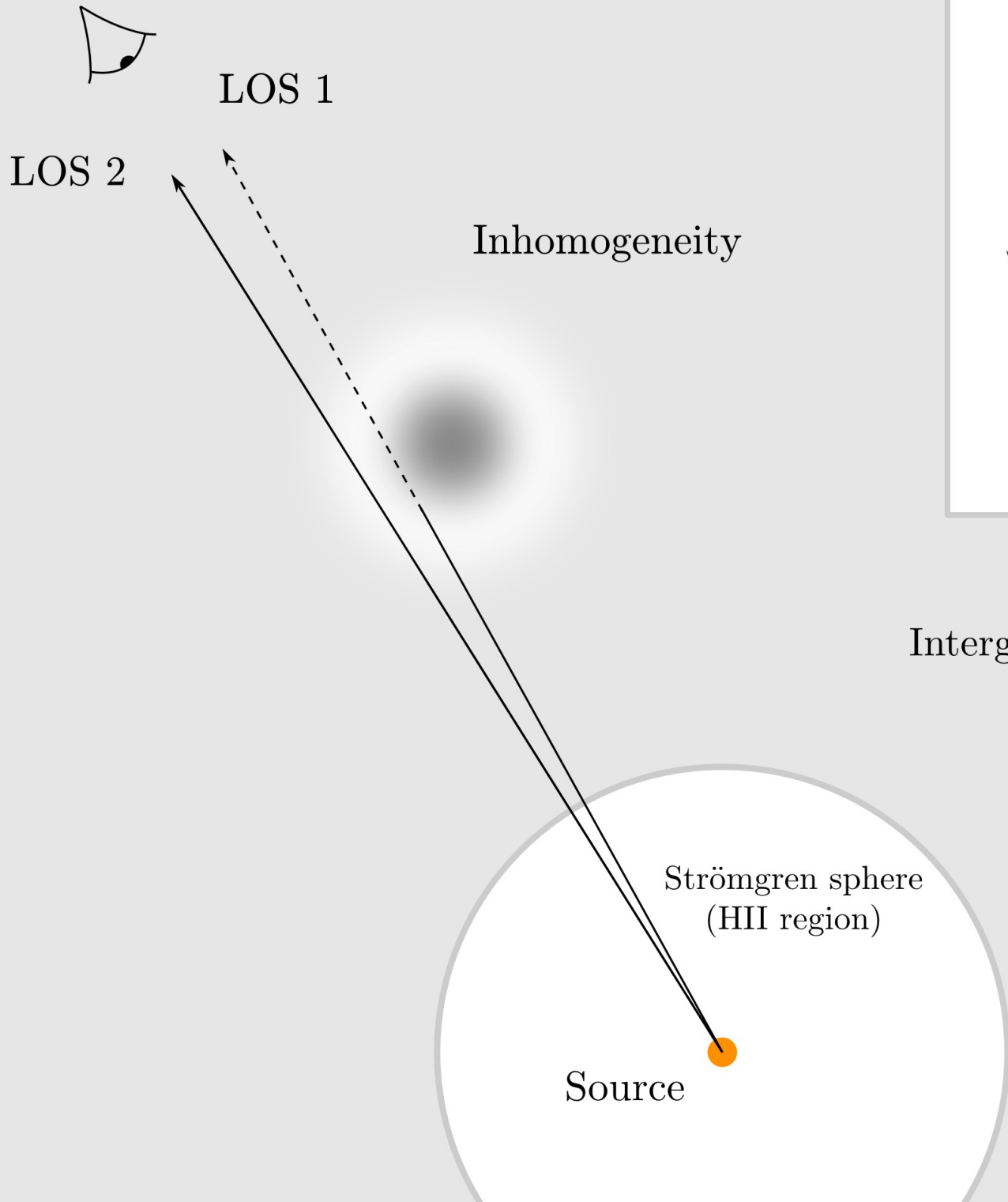


Intergalactic medium (Hydrogen)



Strömgren sphere
(HII region)

Source

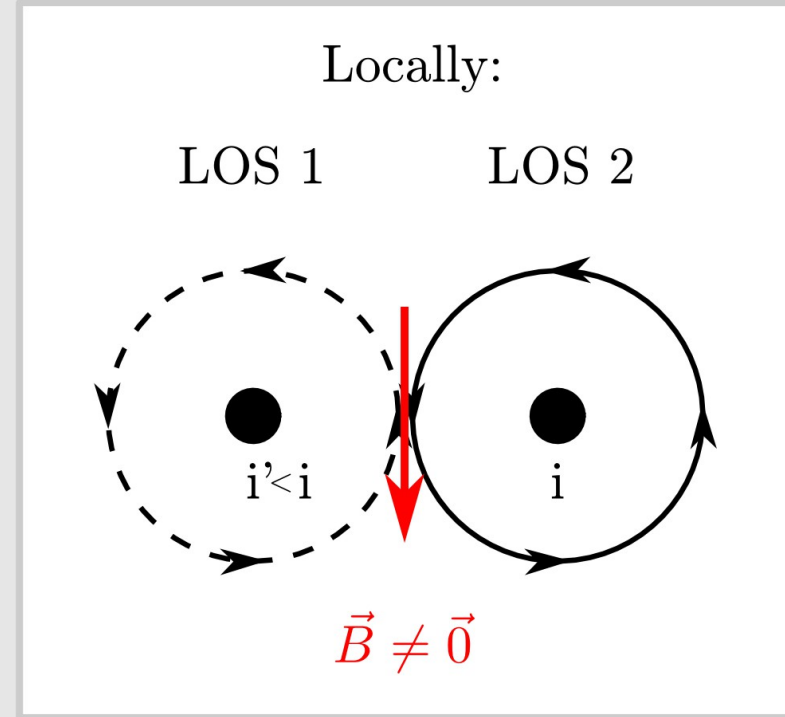


Intergalactic medium (Hydrogen)

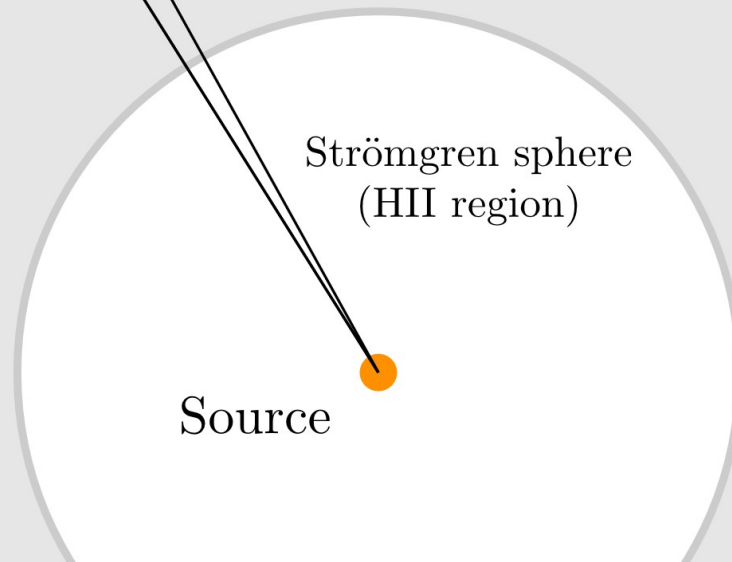
LOS 1

LOS 2

Inhomogeneity



Intergalactic medium (Hydrogen)

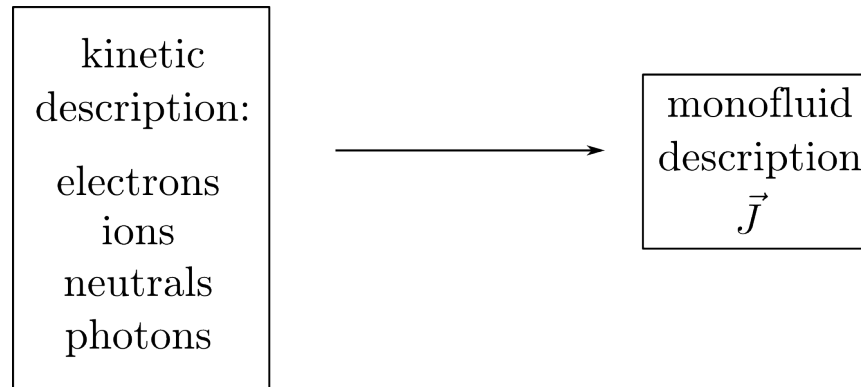


Formalism

Photoionization = local modification of the number and the velocity distribution of electrons
 \Rightarrow source term in Vlasov equation

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

Hence the procedure:



Generalized Ohm's law:

$$\partial_t \vec{J} + (\vec{V} \cdot \vec{\nabla}) \vec{J} + (\vec{\nabla} \cdot \vec{J}) \vec{V} - \vec{V} \vec{V} \cdot \vec{\nabla} \rho = \Sigma_{\alpha} \frac{q_{\alpha}^2 n_{\alpha}}{m_{\alpha}} \left(\vec{E} + \frac{\vec{V}_{\alpha} \times \vec{B}}{c} \right) - \vec{P} + \vec{C} + \underbrace{\Sigma_{\alpha} \frac{q_{\alpha}}{m_{\alpha}} \dot{\vec{p}}_{\alpha}}_{\text{Current source term}}$$

\vec{P} = pressure term

\vec{C} = collision term

Current source term
 as photons transfer
 their momentum

\longrightarrow Induction equation

The source term

Electron momentum creation rate:

$$\dot{\vec{p}}_e = \int m_e \vec{v} \partial_t f_{pi} d^3 v$$

Momentum transferred from photons to electrons:

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

Fraction of momentum transferred

So that explicitly:

$$\dot{\vec{p}}_e = \frac{n_{HI}}{c} \int_{\nu_0}^{\infty} f_{mt} \sigma_{\nu} L_{\nu} \frac{e^{-\tau_{\nu}}}{4\pi r^2} d\nu \hat{r}$$

Absorption along the
line of sight

Geometric dilution

Cross section

Source spectrum

Simplified generalized Ohm's law

In our situation:

Initially vanishing B , E and J
Neutrals at rest

} Keep first order terms only

Generalized Ohm's law reduces to:

$$\vec{0} = -en_e\vec{E} - \vec{\nabla}p_e + \dot{\vec{p}}_e$$

Taking the curl:

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

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Biermann **Photoionization**

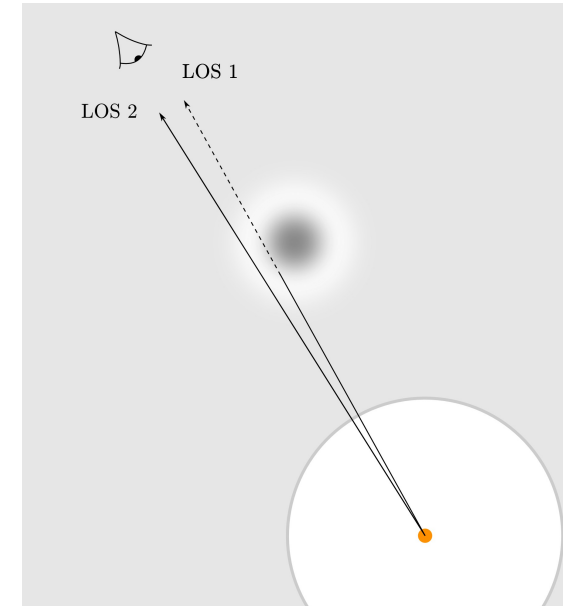
Resulting magnetic field

Expliciting the source term, the magnetic field generated by photoionization reads:

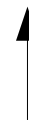
$$\vec{B}(t, \vec{r}) = t \frac{N}{ex_e} \vec{\nabla} \int_{\tau_s}^r n_{HI} dr \times \hat{r}$$



Source of B :
Anisotropy of the column density
(non radial gradients) as expected

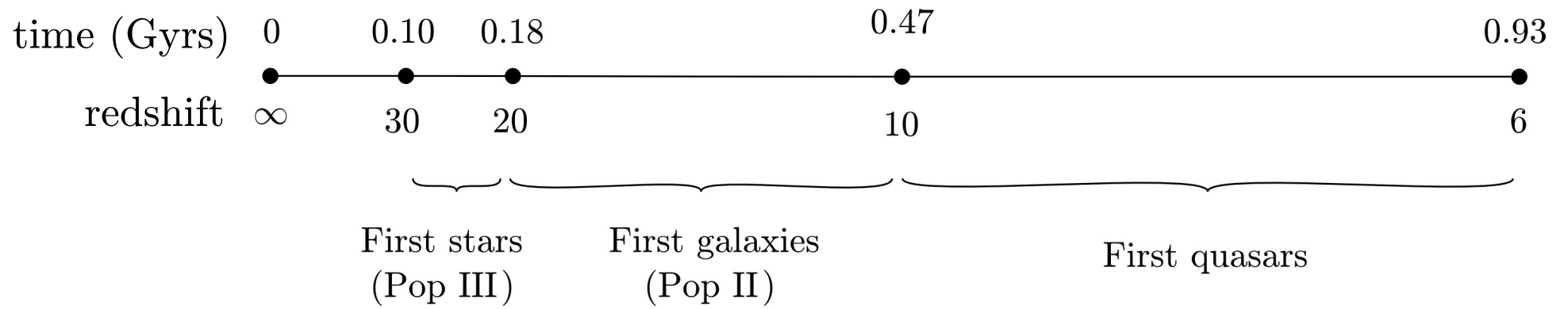


Where:
$$N(t, \vec{r}) = \frac{1}{4\pi r^2} \int_{\nu_0}^{\infty} f_{mt} \sigma_{\nu}^2 L_{\nu} e^{-\tau_{\nu}} d\nu$$

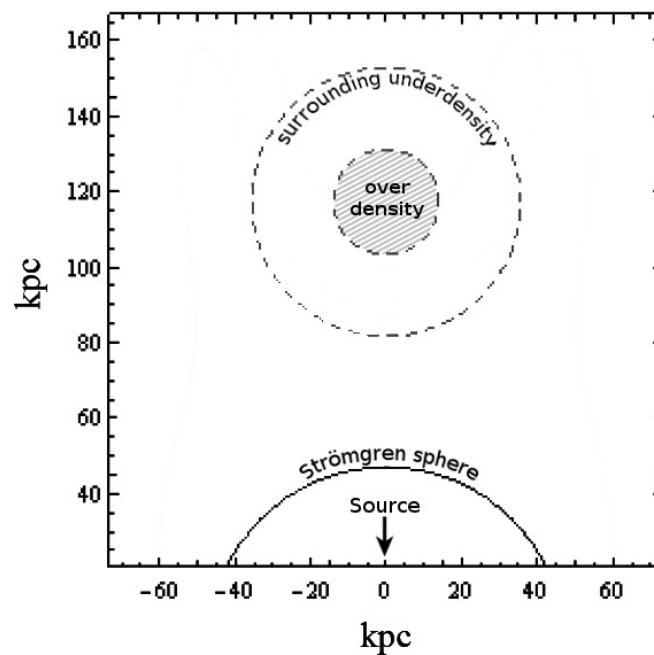
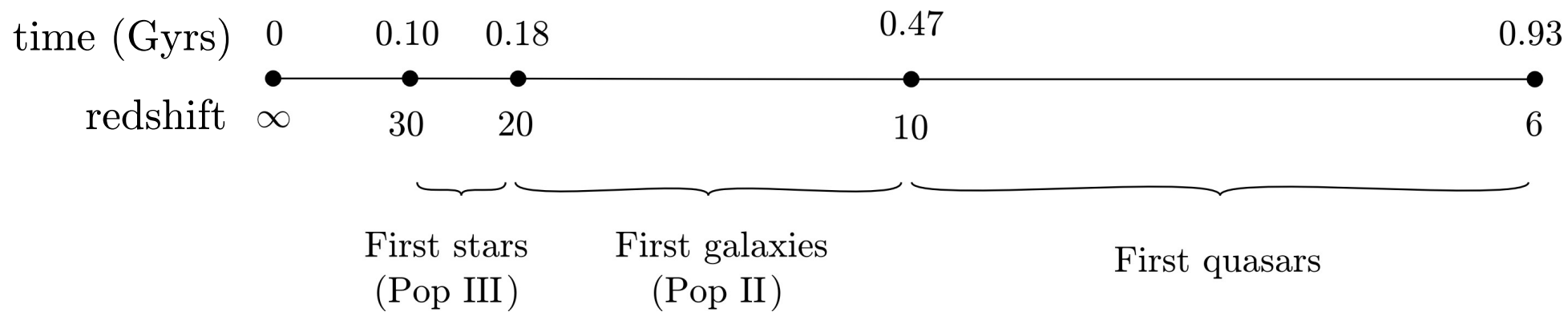


Source spectrum

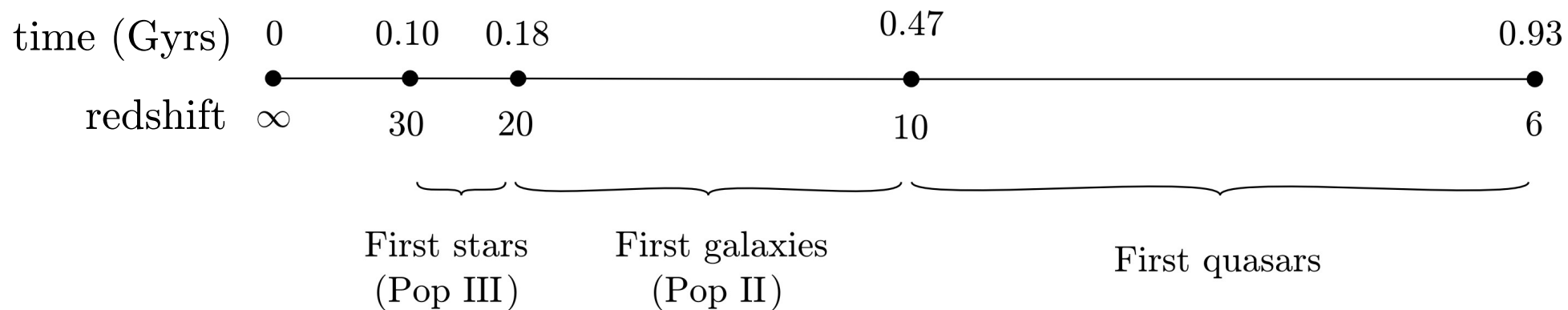
Illustrative examples



Illustrative examples



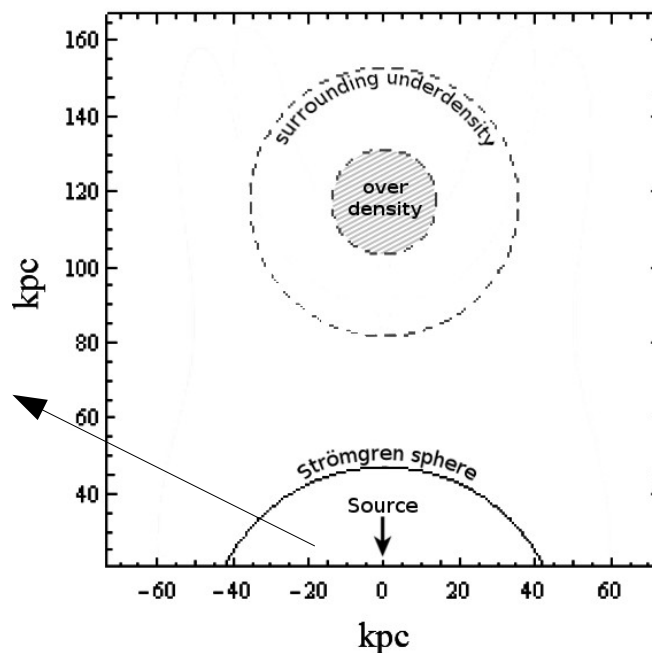
Illustrative examples



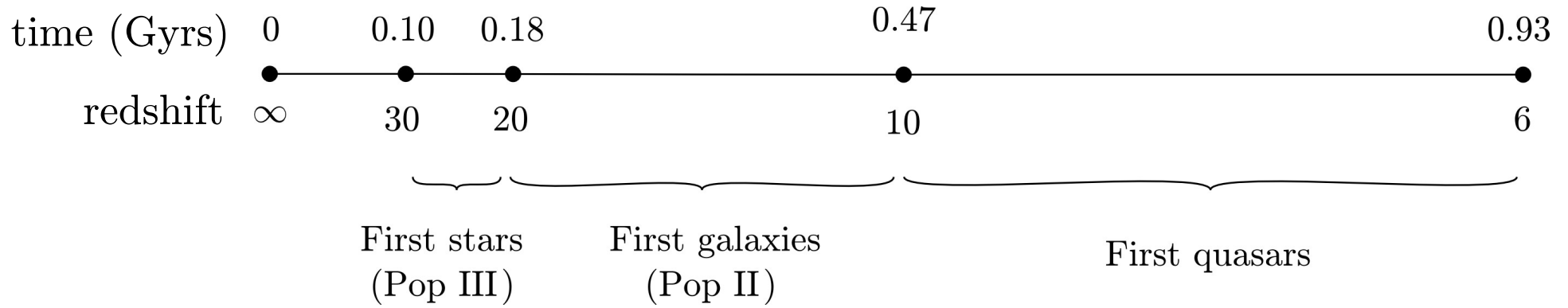
Sources:

$$L_\nu = L_0 \left(\frac{\nu}{\nu_0} \right)^\alpha \quad \text{from:}$$

- QSO : $\alpha = -1.7$
(Shang et al, 2011)
- Synthetic spectra for Pop III
and Pop II (various IMFs)
(Zackrisson et al, 2011)



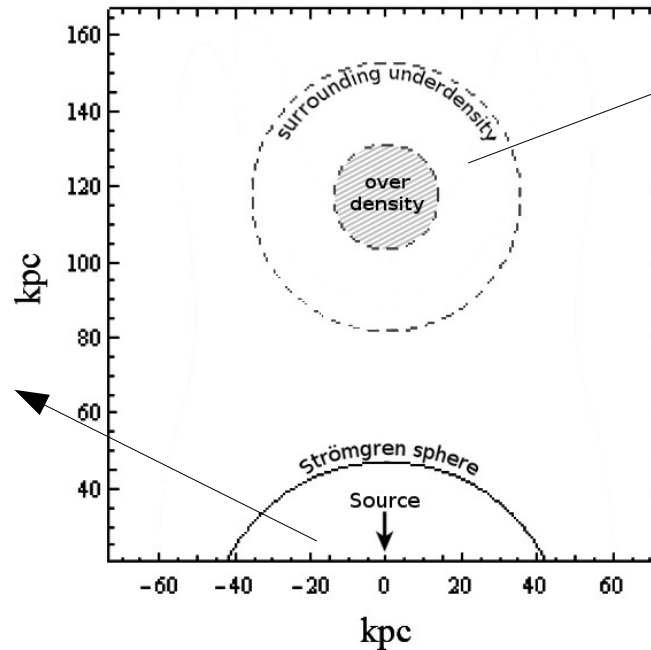
Illustrative examples



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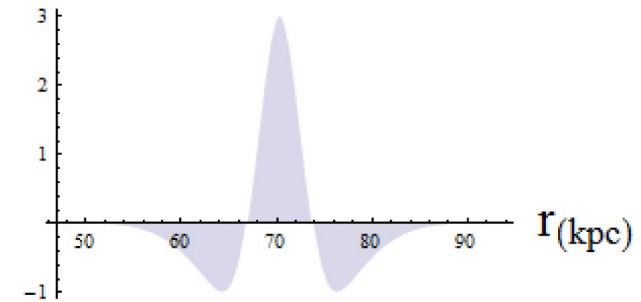
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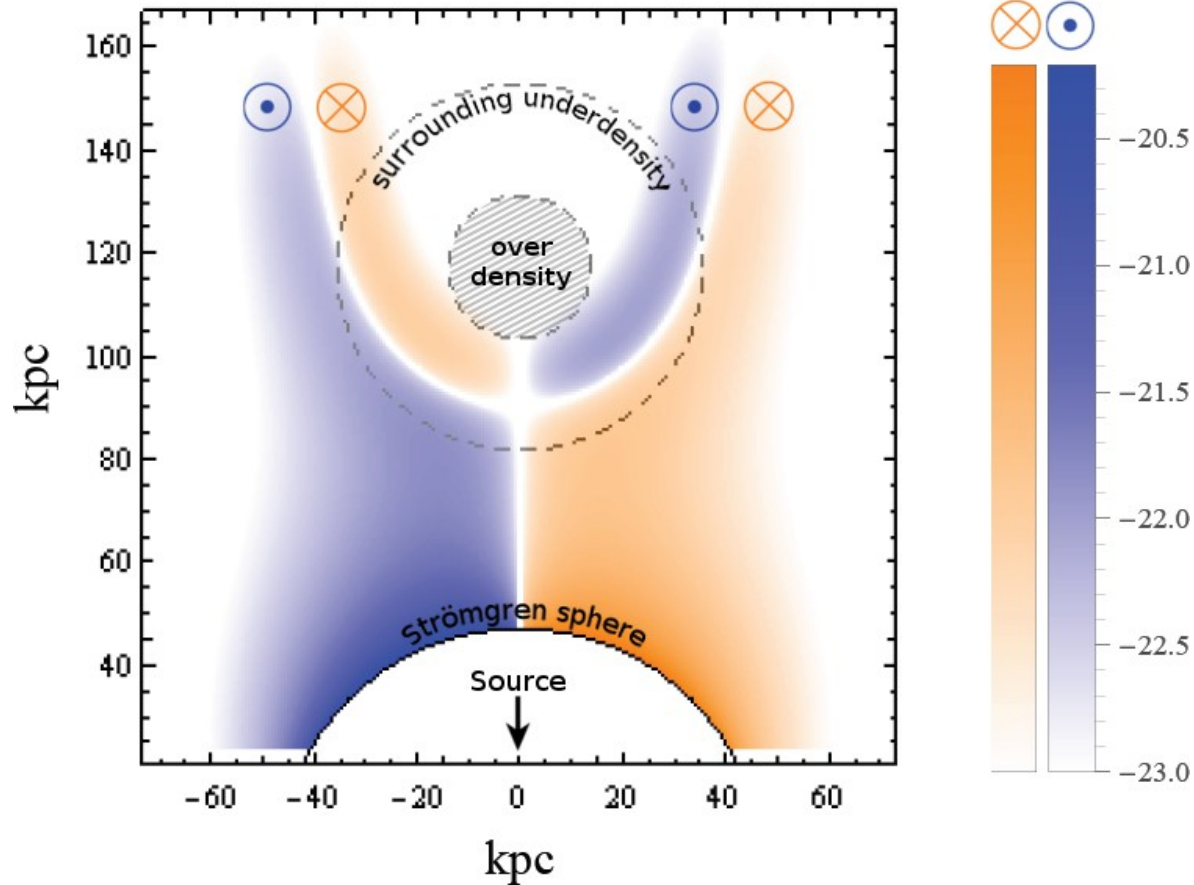
Inhomogeneity:

$$\delta = \frac{n_{HI} - \bar{n}}{\bar{n}} \quad (\theta = 0)$$

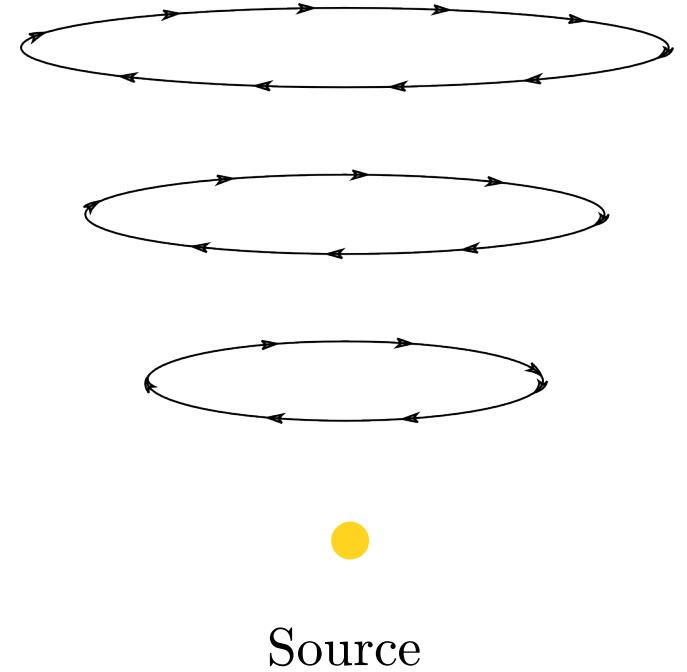


Example of a result

B field spatial distribution
and strength for a galaxy at $z=10$:

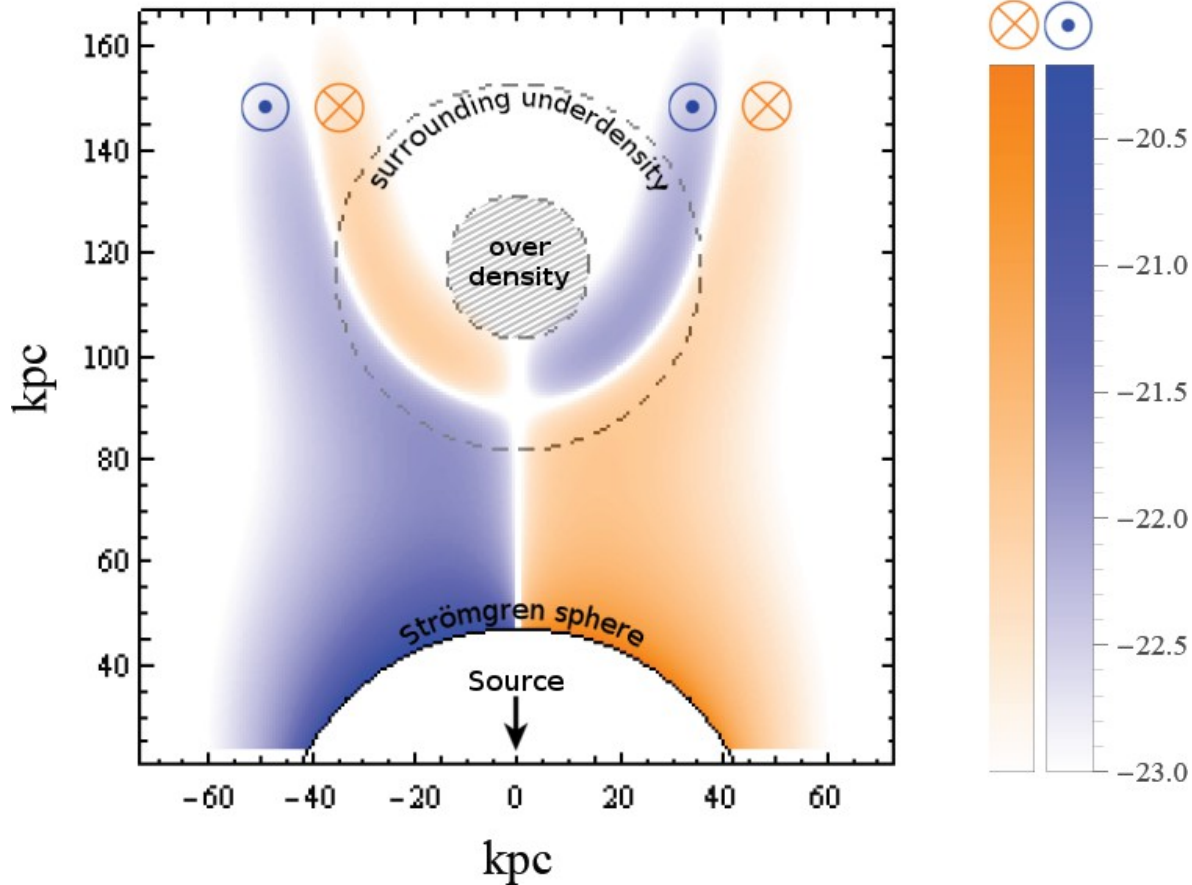


Field lines:

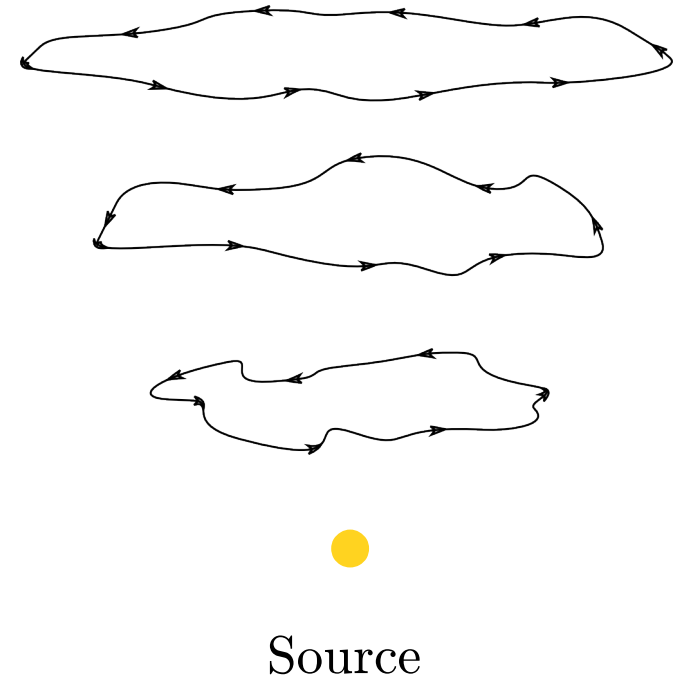


Example of a result

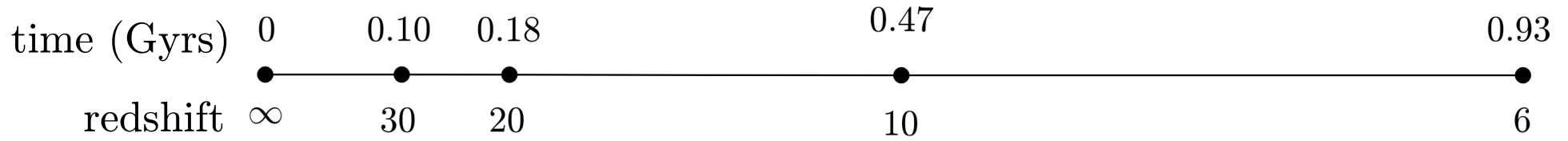
B field spatial distribution
and strength for a galaxy at $z=10$:



Field lines:
(in a less symmetric situation)



Typical spatial distributions and scales

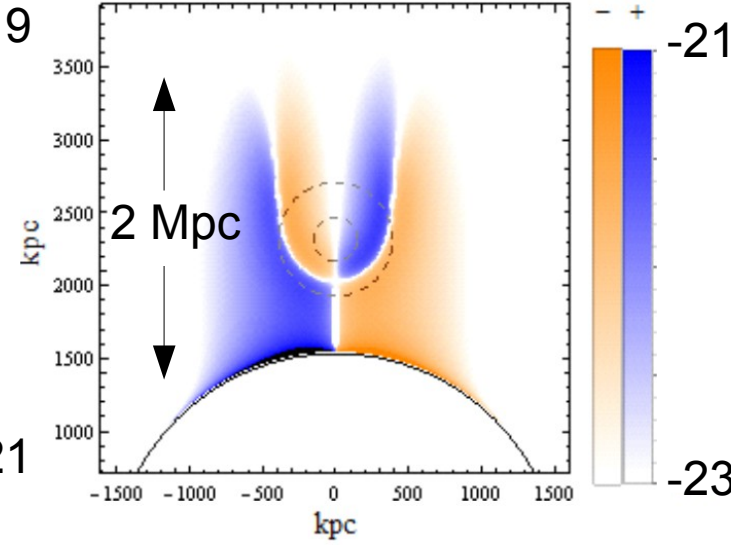
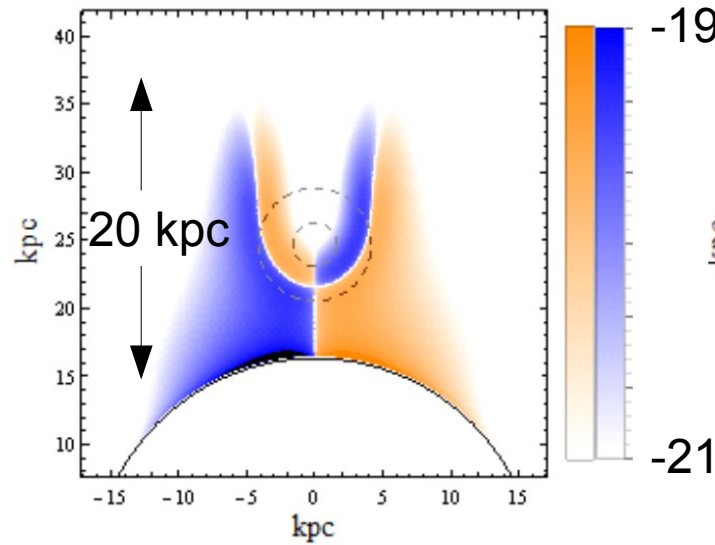
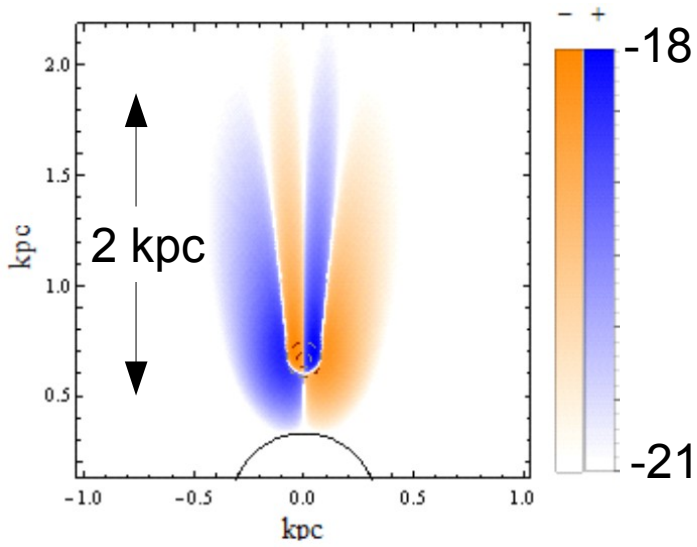


First stars
(Pop III)

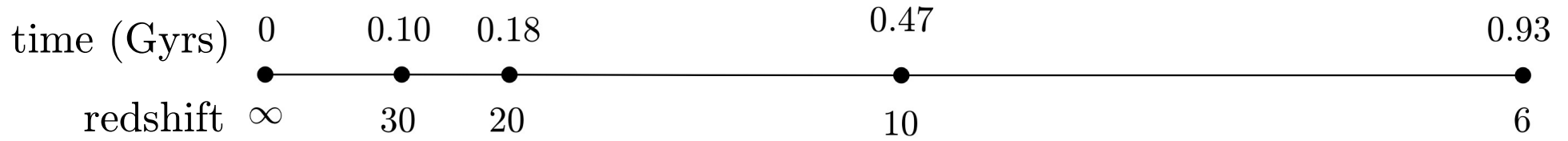
First galaxies
(Pop II)

First quasars

Other examples:



Typical spatial distributions and scales

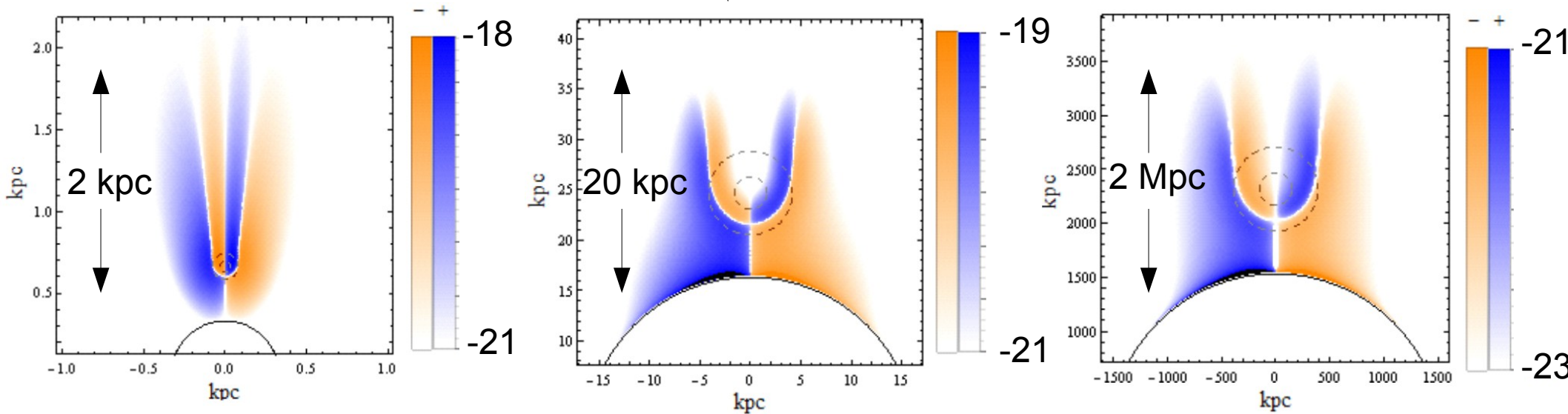


First stars
(Pop III)

First galaxies
(Pop II)

First quasars

Other examples:



Estimates of half intersource distances:

~10 kpc

~ tens kpc

~ Few Mpc

⇒ Participates to the **magnetization of the whole Intergalactic medium**

Conclusion

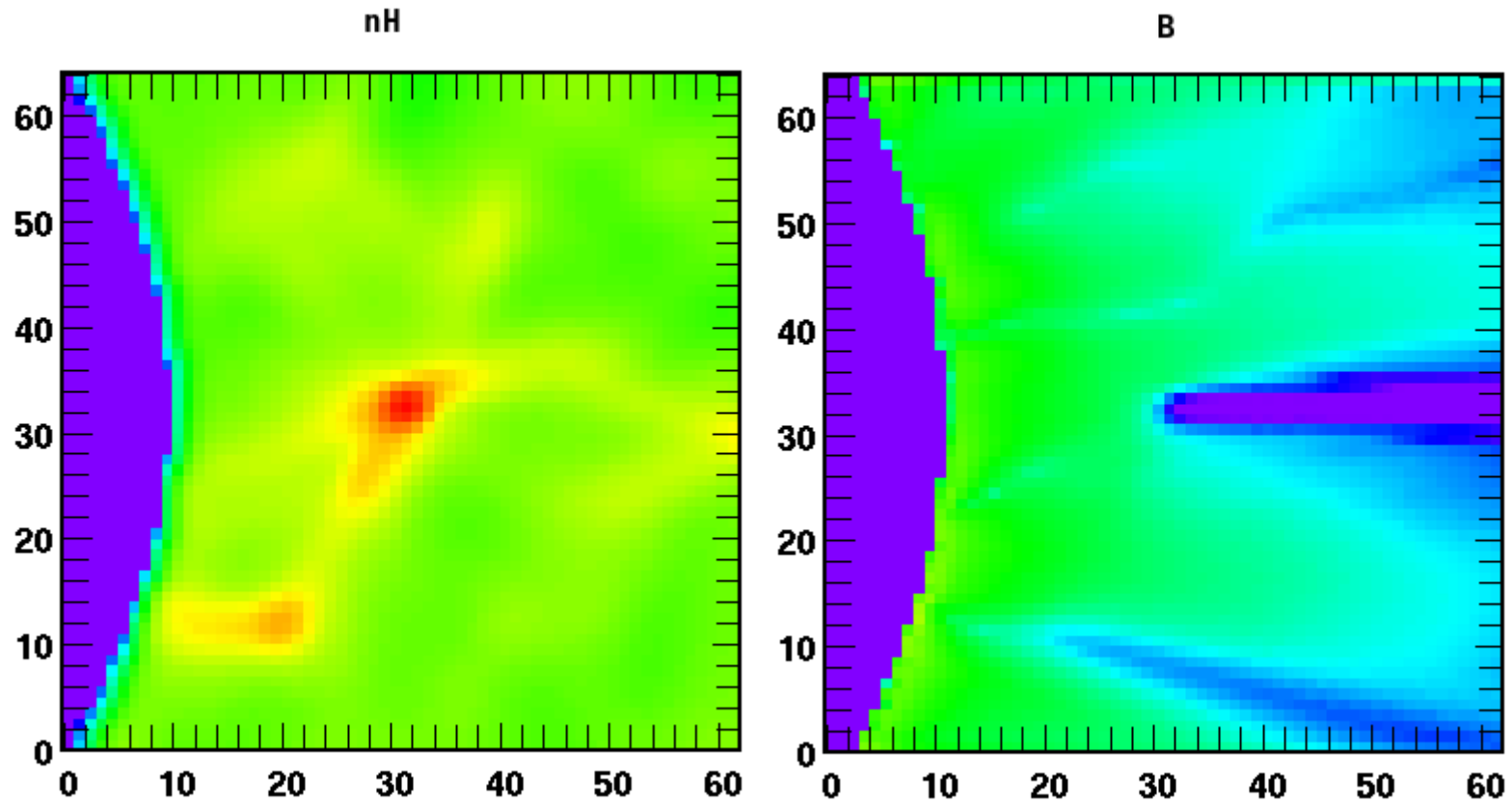
- Astrophysical mechanism: operating for any source, **all along the Epoch of Reionization**
- Strengths comparable to Biermann battery, but on entire intersource scales
 - ⇒ Contributes to **magnetization of the whole Intergalactic medium**
- **Specific spatial configuration:** may help discriminate the seeds from other mechanisms

Prospects:

- Realistic Strömgren sphere → stronger fields?
- Processing by large scale turbulence from structure formation → sufficient seeds?
- Large scale statistical properties?
 - ▶ numerical simulations (with Dominique Aubert, Strasbourg)

Thank you for your attention

Numerical approach with Dominique Aubert (Strasbourg)
Example with an H distribution from a Reionization simulation



Example of B field distribution with a gaussian inhomogeneity

