Intergalactic Magnetogenesis at the Epoch of Reionization by photoionization

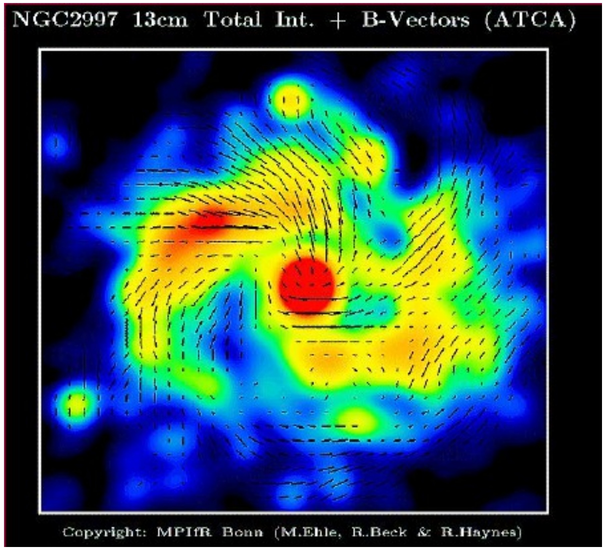
Durrive & Langer 2014, to be submitted

Jean-Baptiste Durrive & Mathieu Langer

Institut d'Astrophysique Spatiale, Orsay, France

Cosmic Magnetic Fields, Cracow Oct20–24, 2014

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

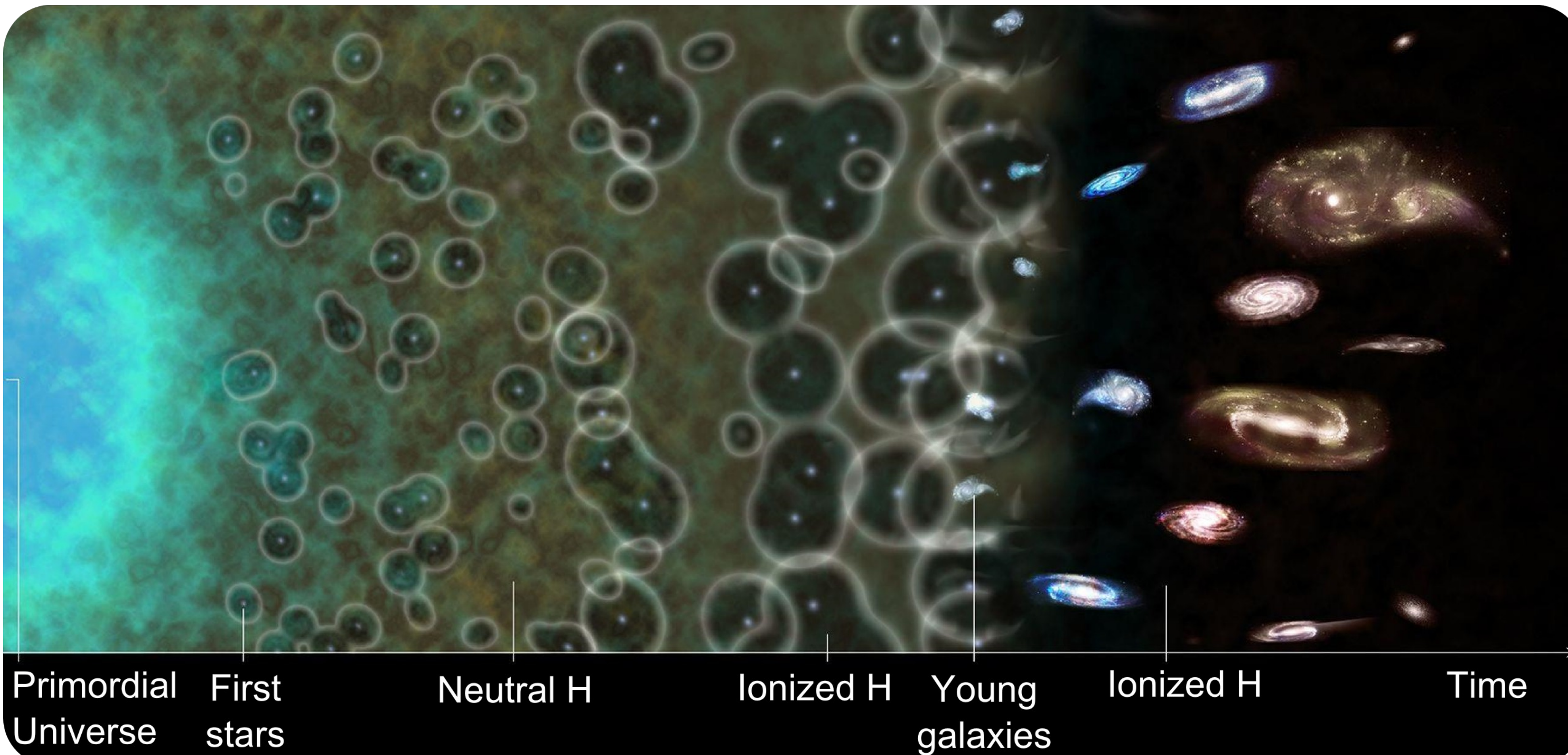
(Neronov&Vovk 2010, Taylor et al 2011, Takahashi et al 2011, ...)

Here: **astrophysical mechanism generating intergalactic magnetic fields at the Epoch of Reionization**

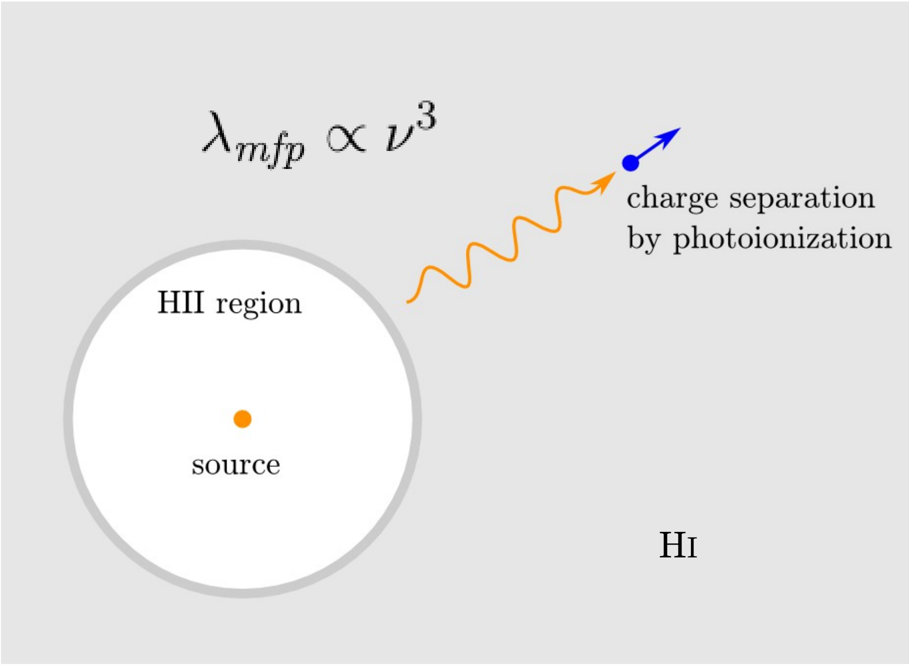
Cosmological context

Epoch of Reionization

30	⟷	6	redshift
0.10		0.93	time (Gyrs)



Magnetogenesis at the Epoch of Reionization

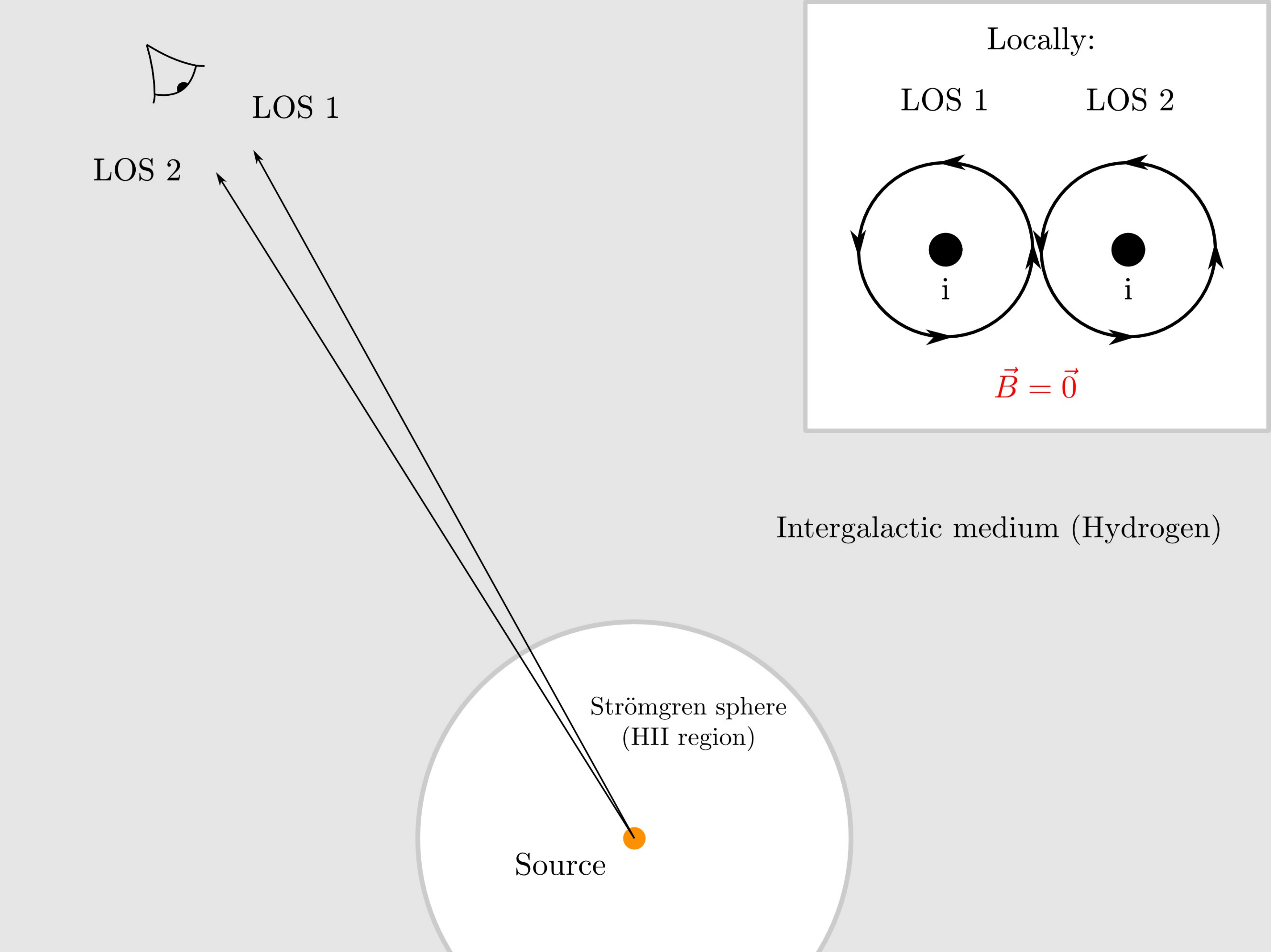


Maxwell-Faraday equation: $\partial_t \vec{B} = -c\vec{\nabla} \times \vec{E}$

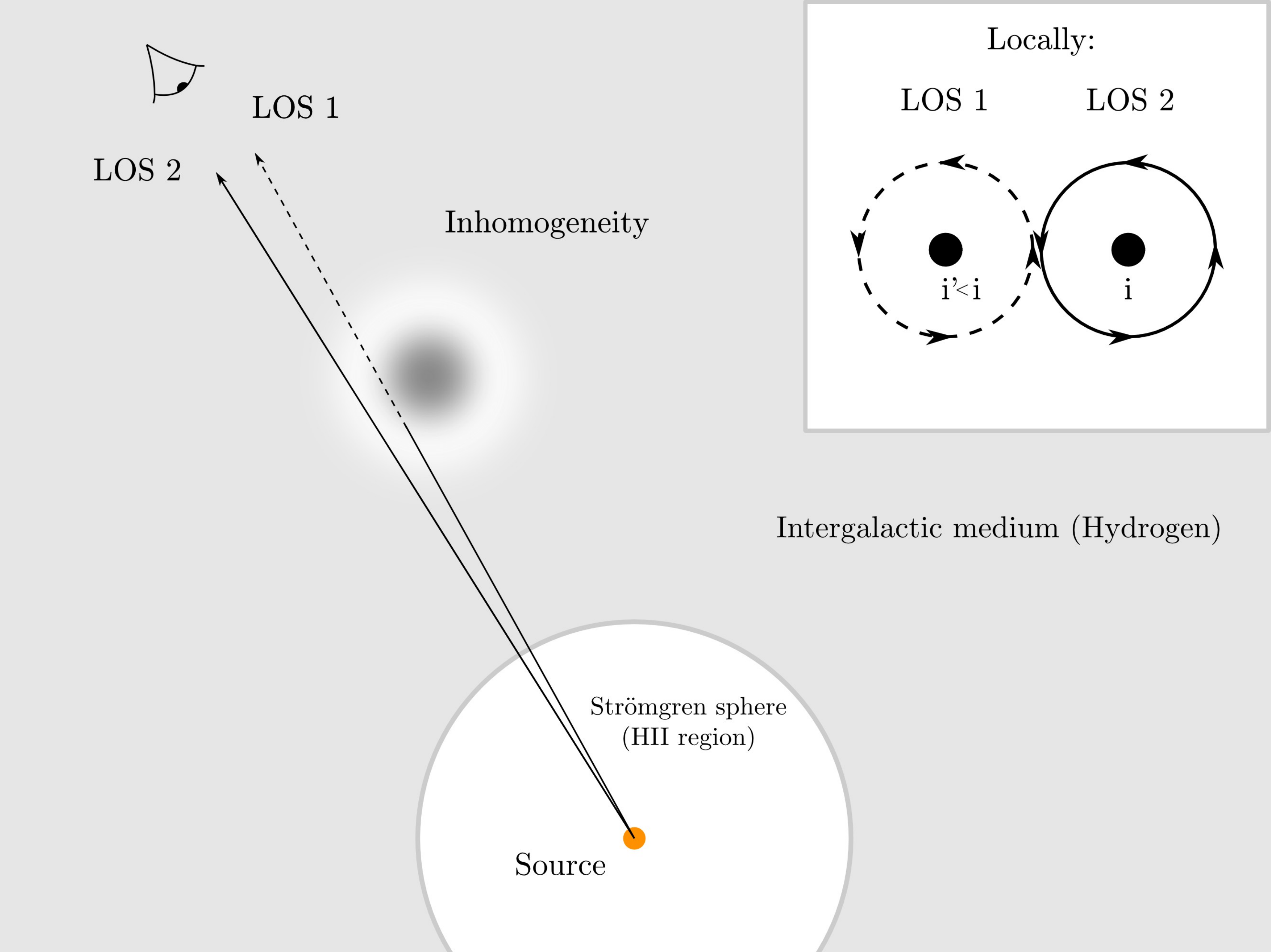
B field generation needs **charge separation** that induces a **rotational *E* field**

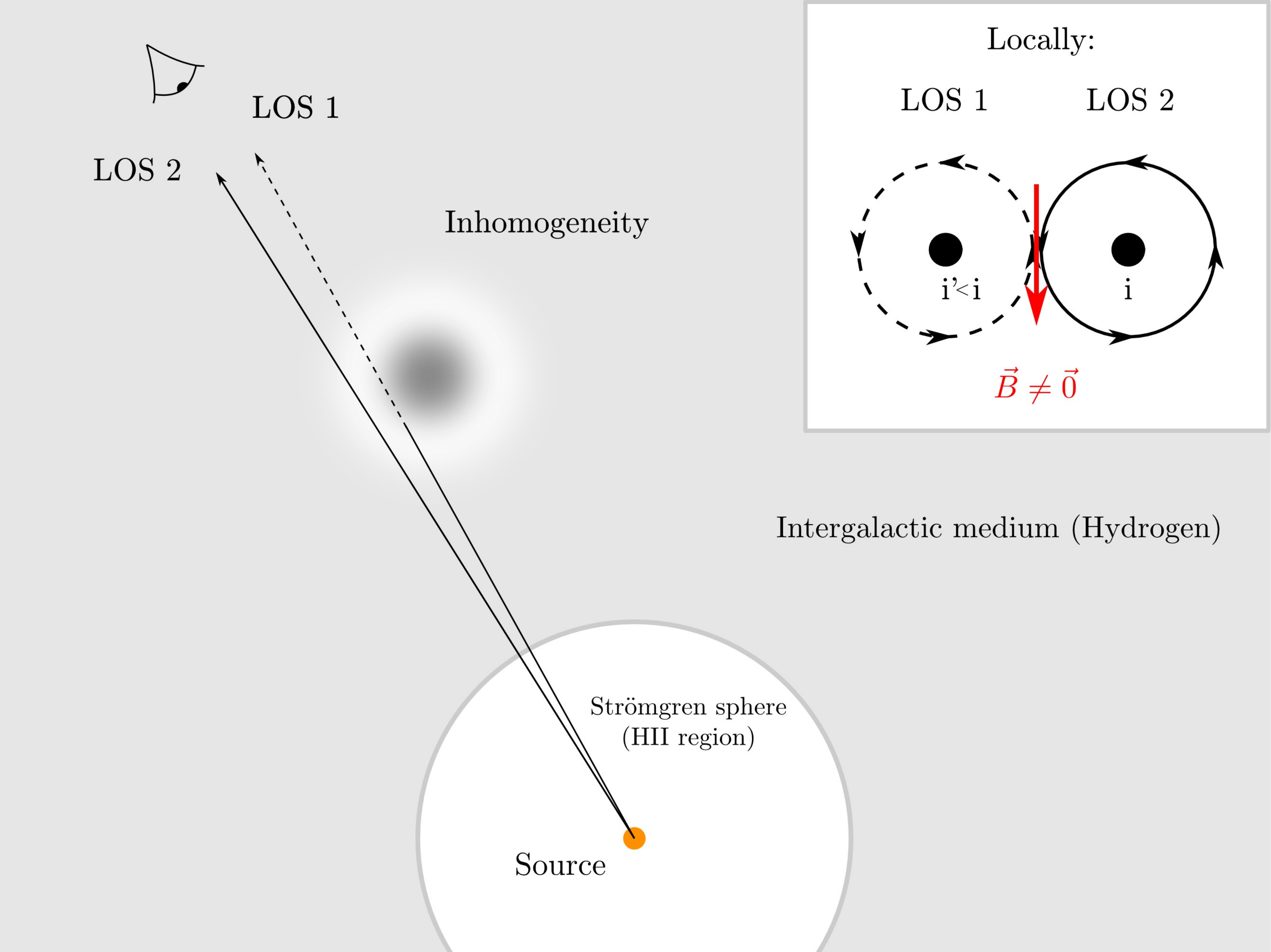
(Langer et al 2005)

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



LOS 1
LOS 2
Locally:
LOS 1
LOS 2
i
i
$\vec{B} = \vec{0}$
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source


Locally:
LOS 1
LOS 2
i'<i
i
LOS 1
LOS 2
Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source



Locally:
LOS 1
LOS 2
i'<i
i
$\vec{B} \neq \vec{0}$
LOS 1
LOS 2
Inhomogeneity
Intergalactic medium (Hydrogen)
Strömgren sphere
(HII region)
Source

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:

kinetic description: electrons, ions, neutrals, photons $\longrightarrow$ monofluid description $\vec{J}$

Generalized Ohm's law:

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

$\vec{P}$ = 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

Absorption along the line of sight

So that explicitely:

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

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:

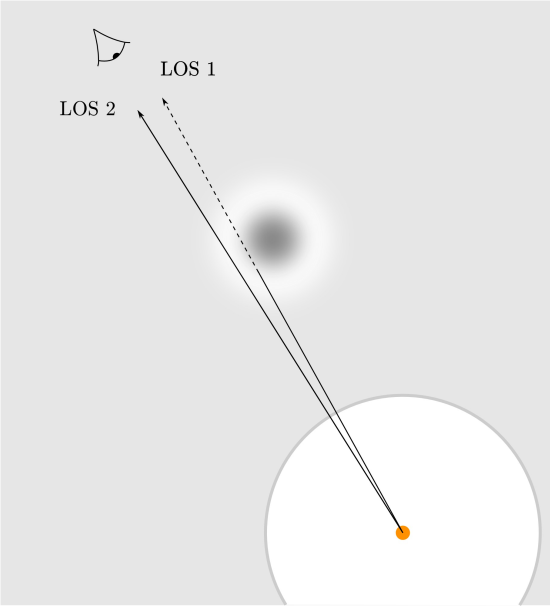
$$\boxed{\partial_t\vec{B} = -\frac{c}{e}\frac{\vec{\nabla}n_e \times \vec{\nabla}p_e}{n_e^2} - \frac{c}{e}\vec{\nabla} \times \frac{\dot{\vec{p}}_e}{n_e}}$$

Biermann **Photoionization**

Resulting magnetic field

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

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

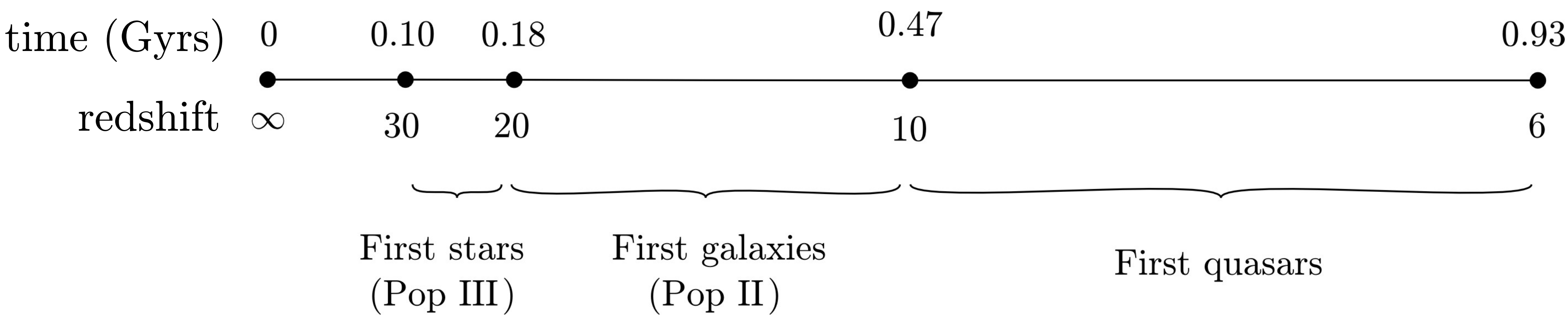


Source of B:
Anisotropy of the column density
(non radial gradients) as expected

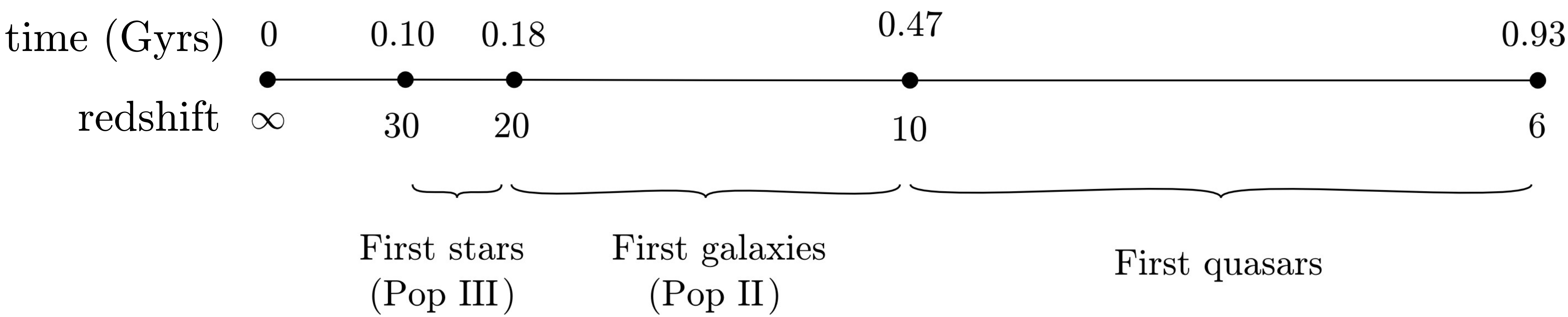
Where: $N(t,\vec{r}) = \frac{1}{4\pi r^2}\int_{\nu_0}^{\infty} f_{mt}\sigma_\nu^2 L_\nu e^{-\tau_\nu}\,d\nu$

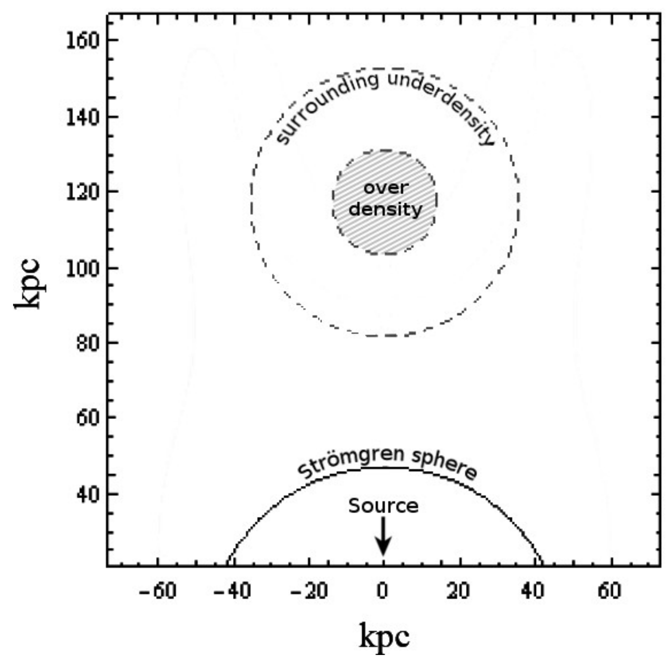
Source spectrum

Illustrative examples

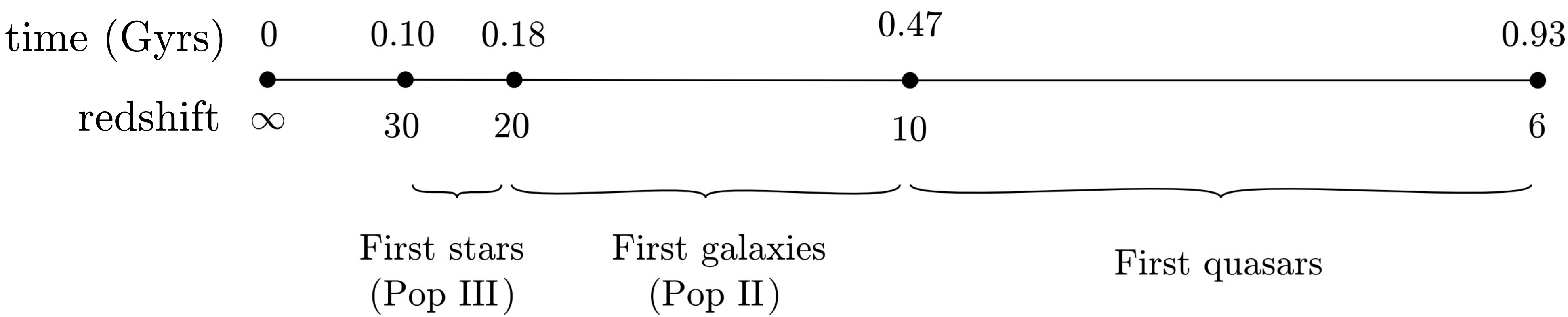


Illustrative examples





Illustrative examples

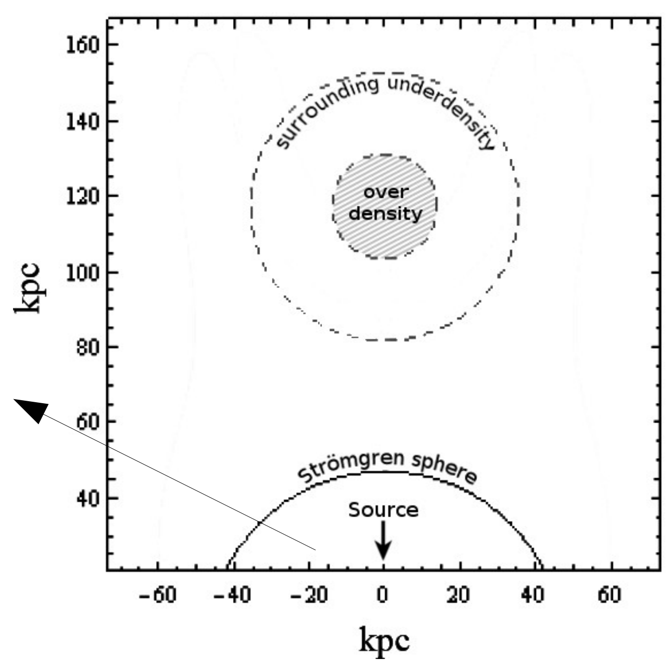


Sources:

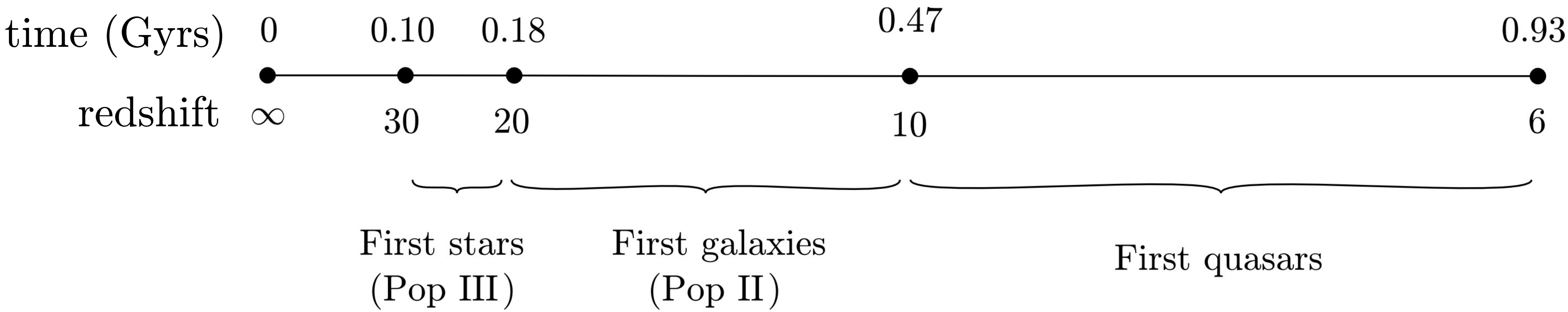
$$L_\nu = L_0 \left(\frac{\nu}{\nu_0}\right)^\alpha$$ from:

- QSO : α = -1.7
  (Shang et al, 2011)

- Synthetic spectra for Pop III and Pop II (various IMFs)
  (Zackrisson et al, 2011)



Illustrative examples

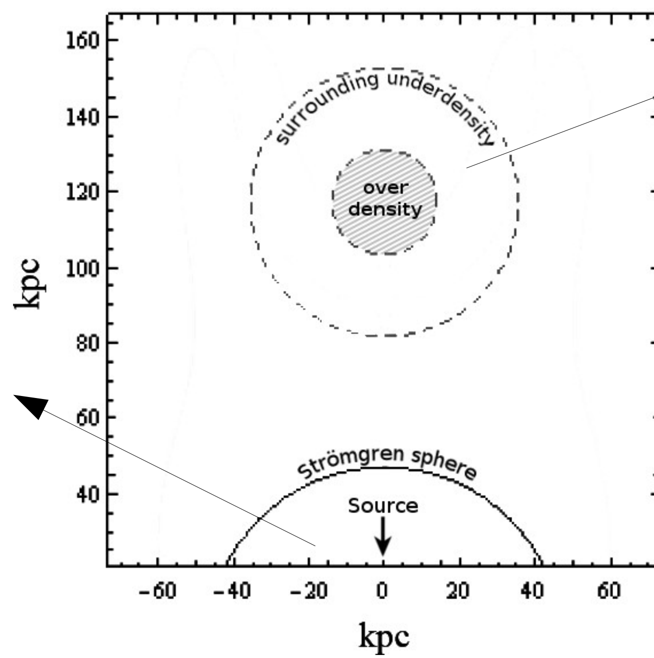


<u>Sources:</u>

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

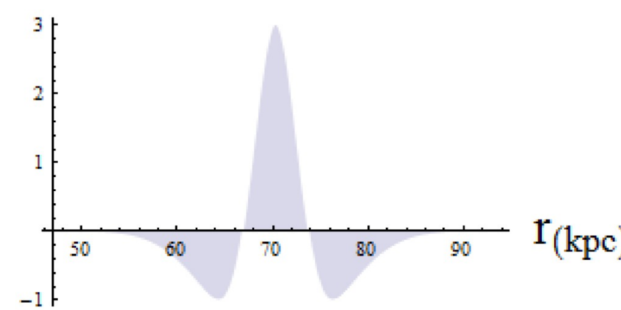
- QSO : α = -1.7
  (Shang et al, 2011)

- Synthetic spectra for Pop III and Pop II (various IMFs)
  (Zackrisson et al, 2011)



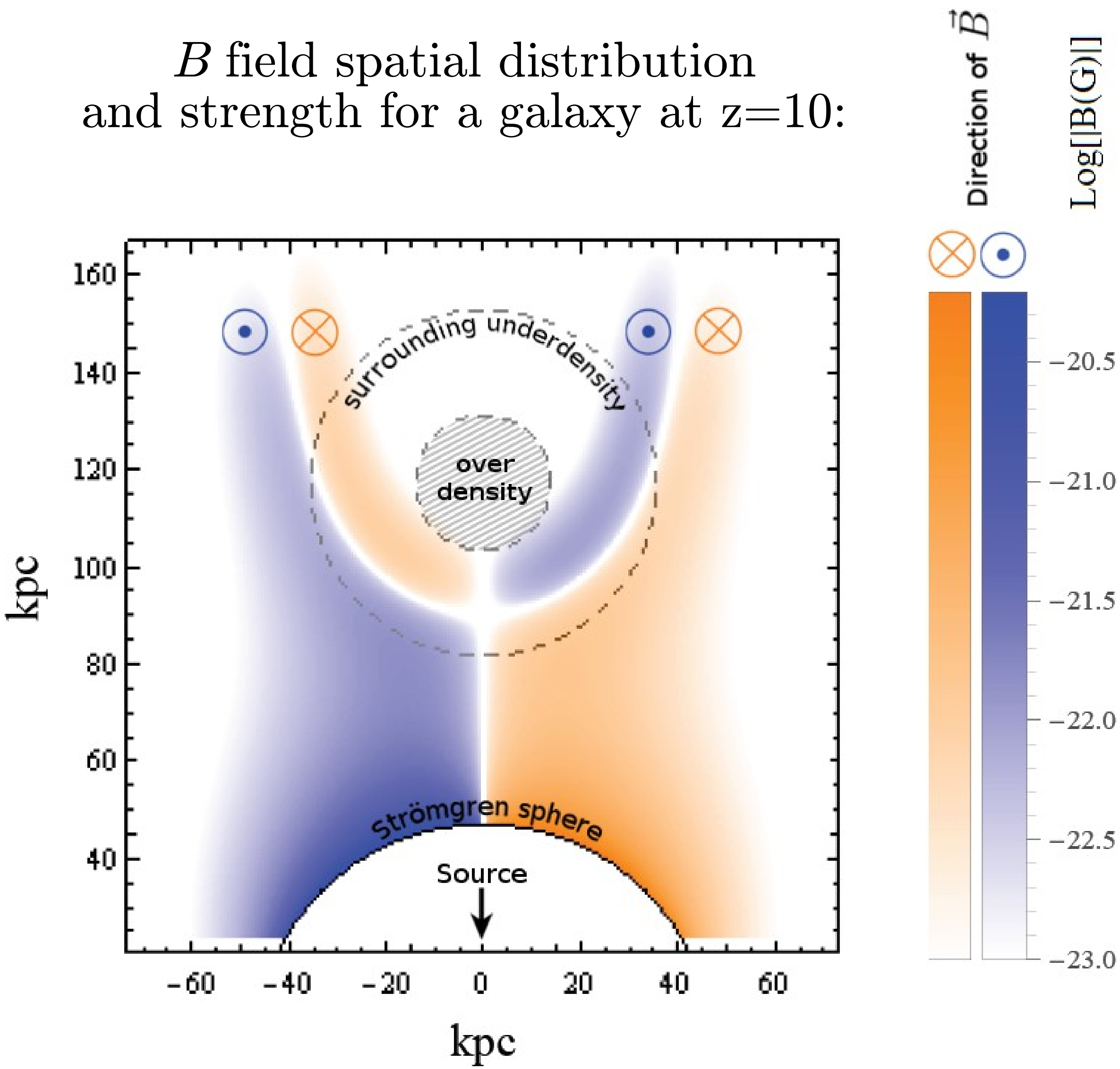
<u>Inhomogeneity:</u>

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

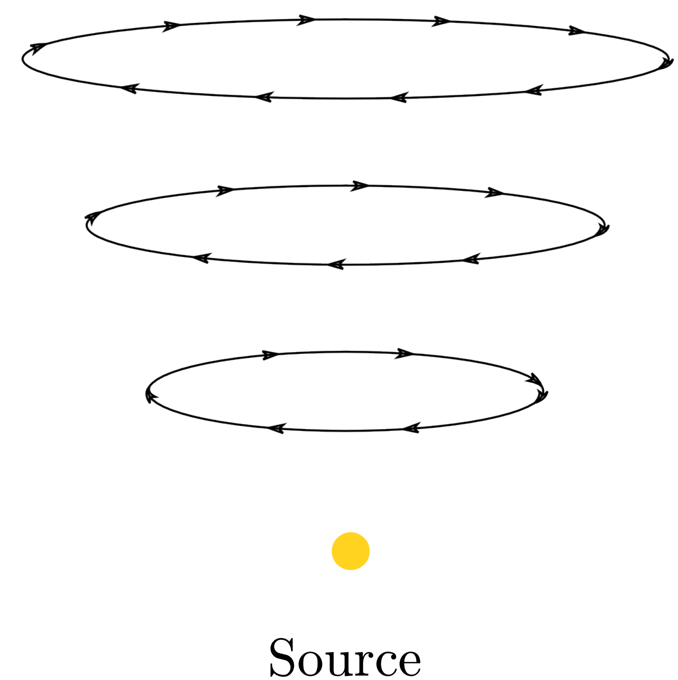


Examples of results

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

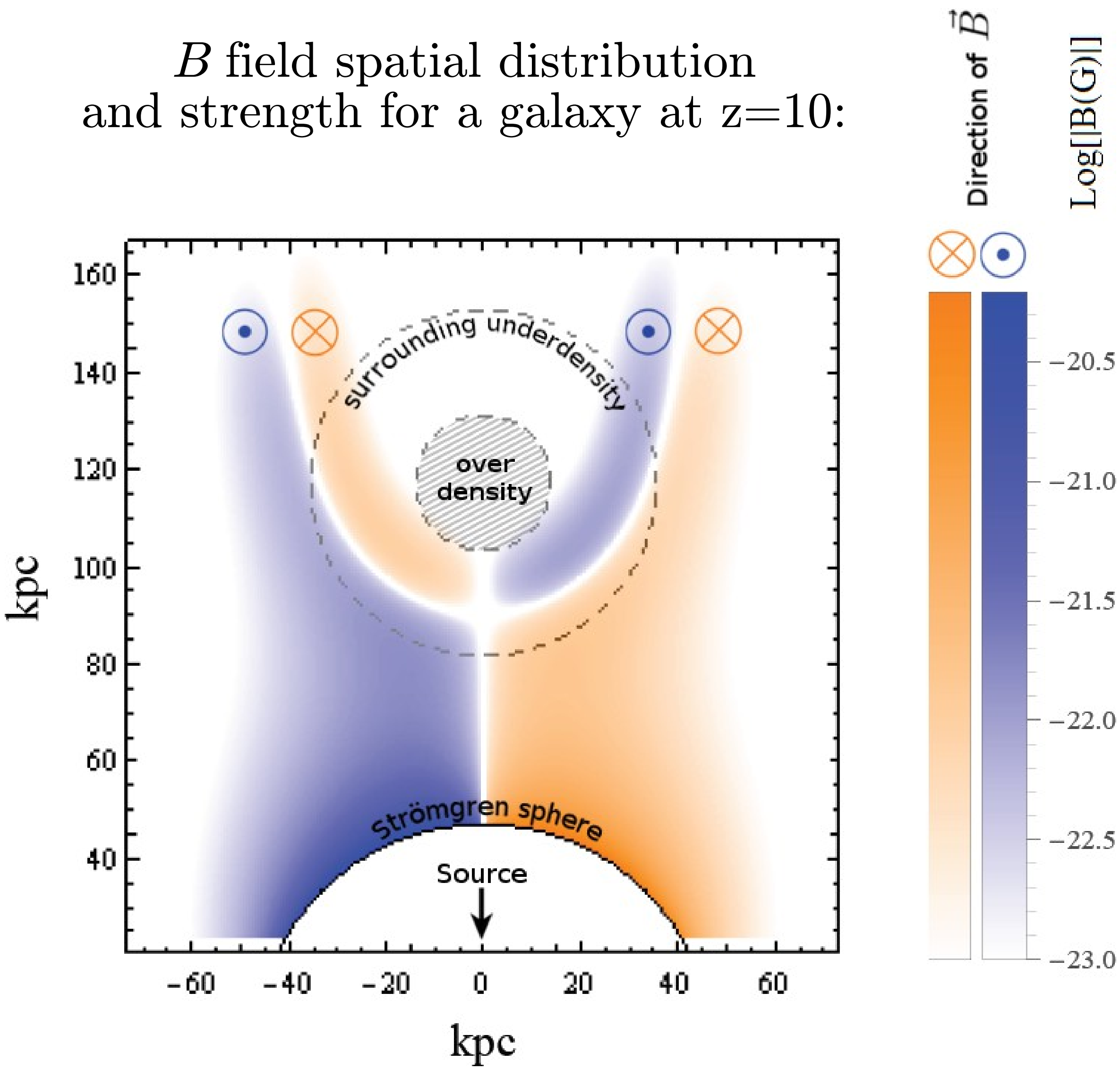


Field lines:

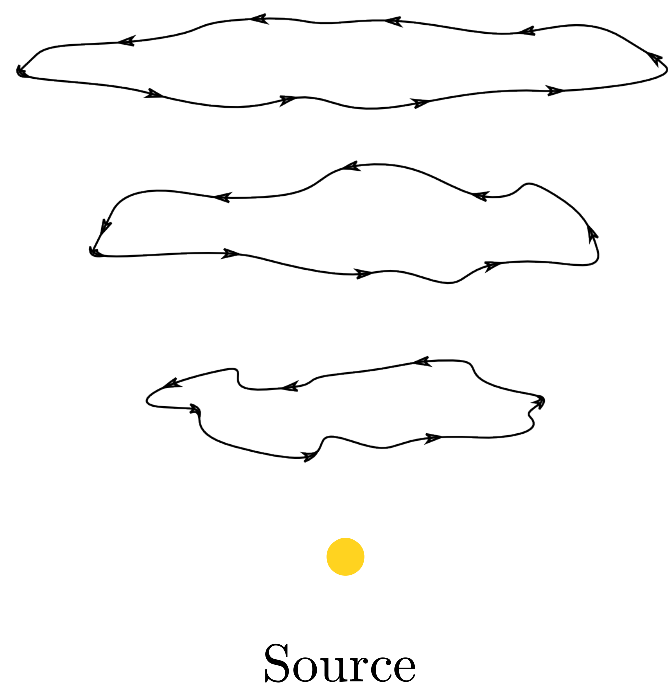


Examples of results

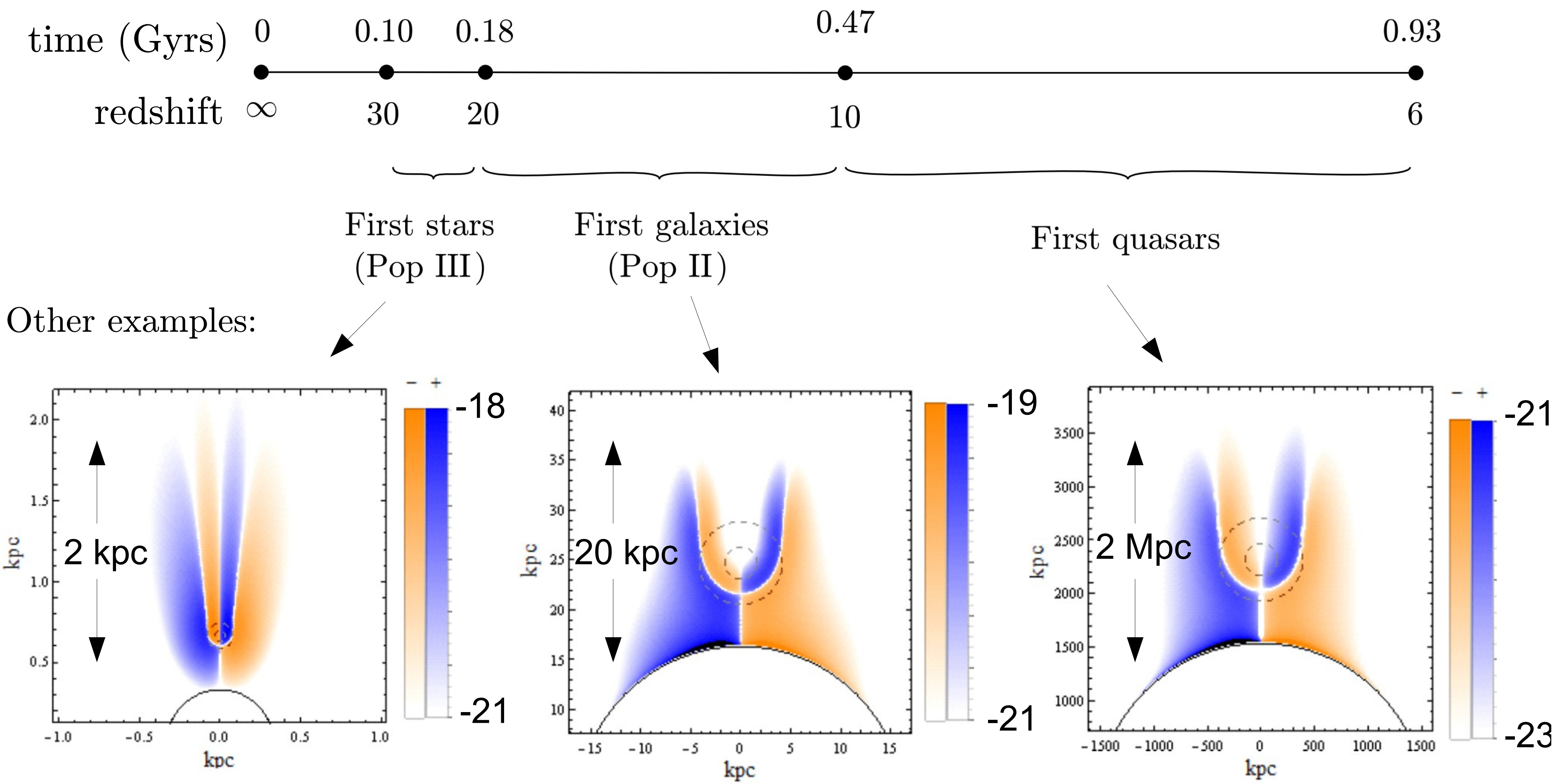
B field spatial distribution
and strength for a galaxy at z=10:



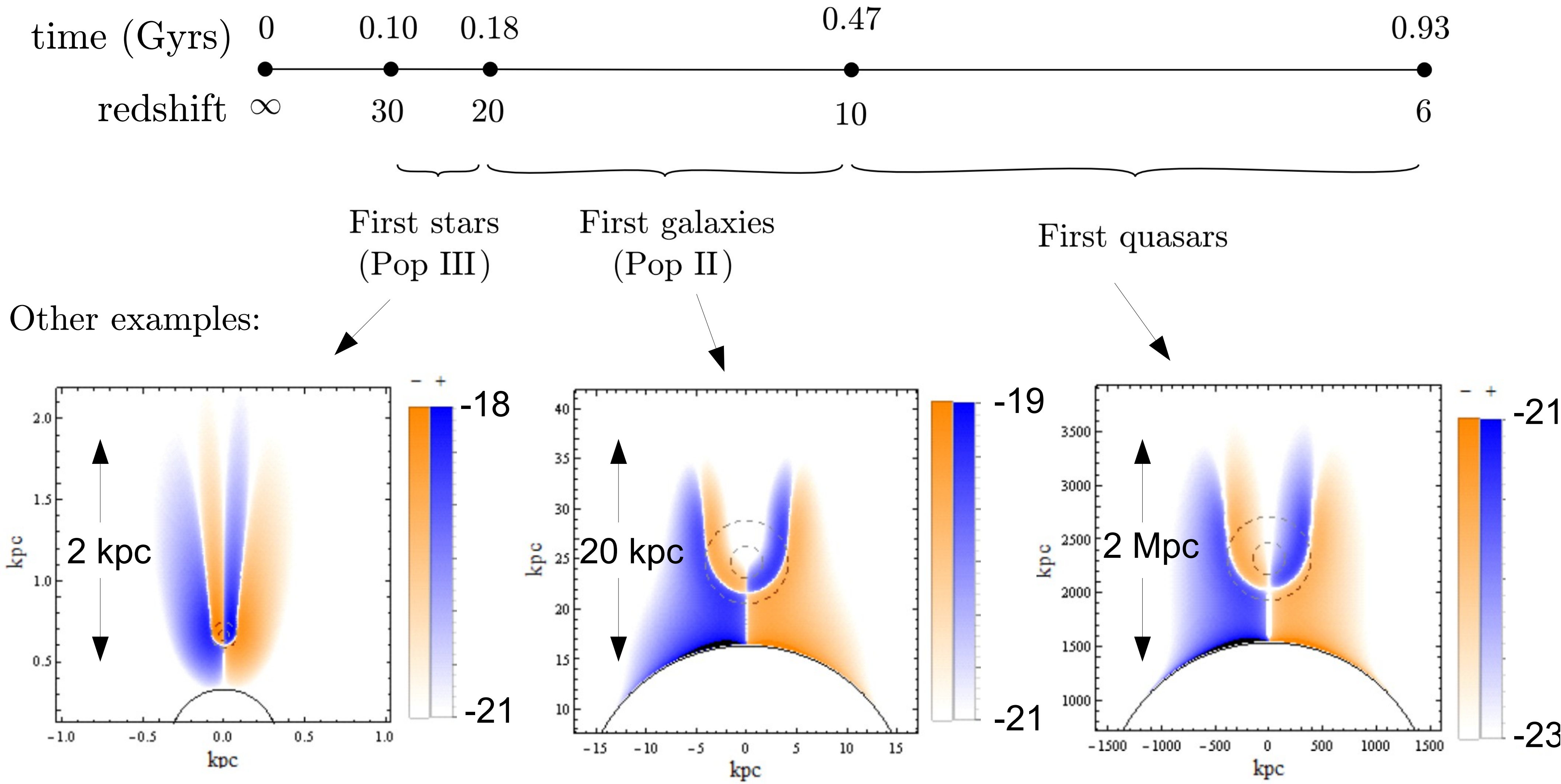
Field lines:
(in a less symmetric situation)



Typical spatial distributions and scales



Typical spatial distributions and scales



Estimates of half intersource distances:

~10 kpc ~ tens kpc ~ Few Mpc

⟹ Participates to the **premagnetization 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

$\Rightarrow$ Contributes to **premagnetization of the whole Intergalactic medium**

- **Specific spatial configuration**: may help discriminate the seeds from other mechanisms

<u>Prospects:</u>

- 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