Generating magnetic fields at reionisation

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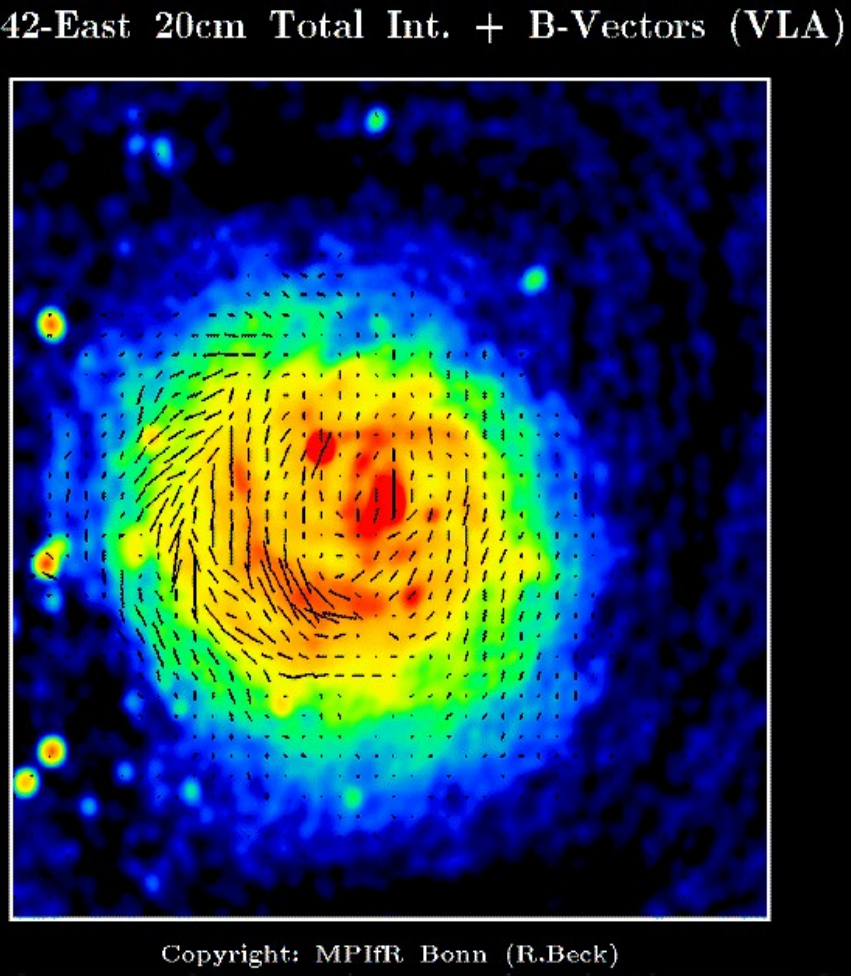
Measured magnetic fields in the Universe

- In galaxies
  - Zeeman splitting
  - Synchrotron emission
  - Faraday Rotation Measure

$$B \sim 1 - 10\,\mu\mathrm{G}$$

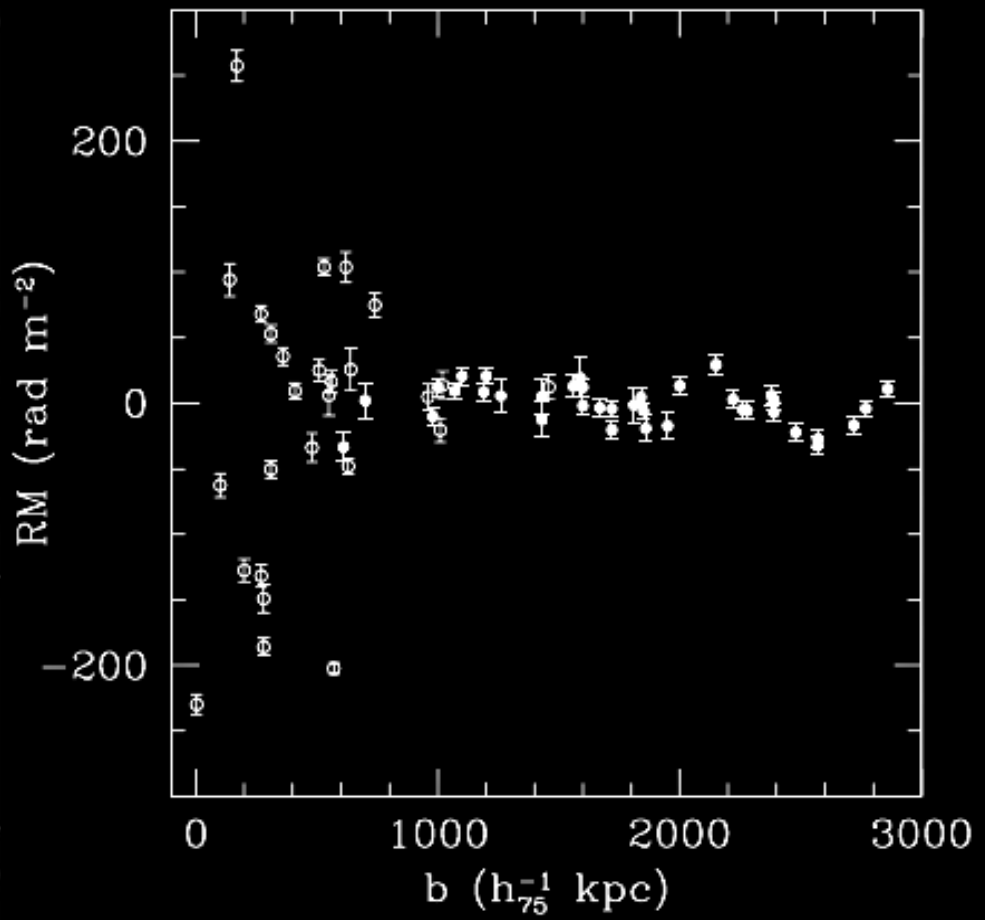


Note : large B in galaxies even at high redshift

(84 μG @ z ~ 0.7, Wolfe et al. 2008 // ~10 μG up to z = 3, Kronberg et al. 2008)

Measured magnetic fields in the Universe

- In galaxy clusters
  - Faraday Rotation Measure of background radio sources
  - Clear excess up to 500 kpc
  - $B \sim 5\,\mu$G at $L \sim 10$ kpc

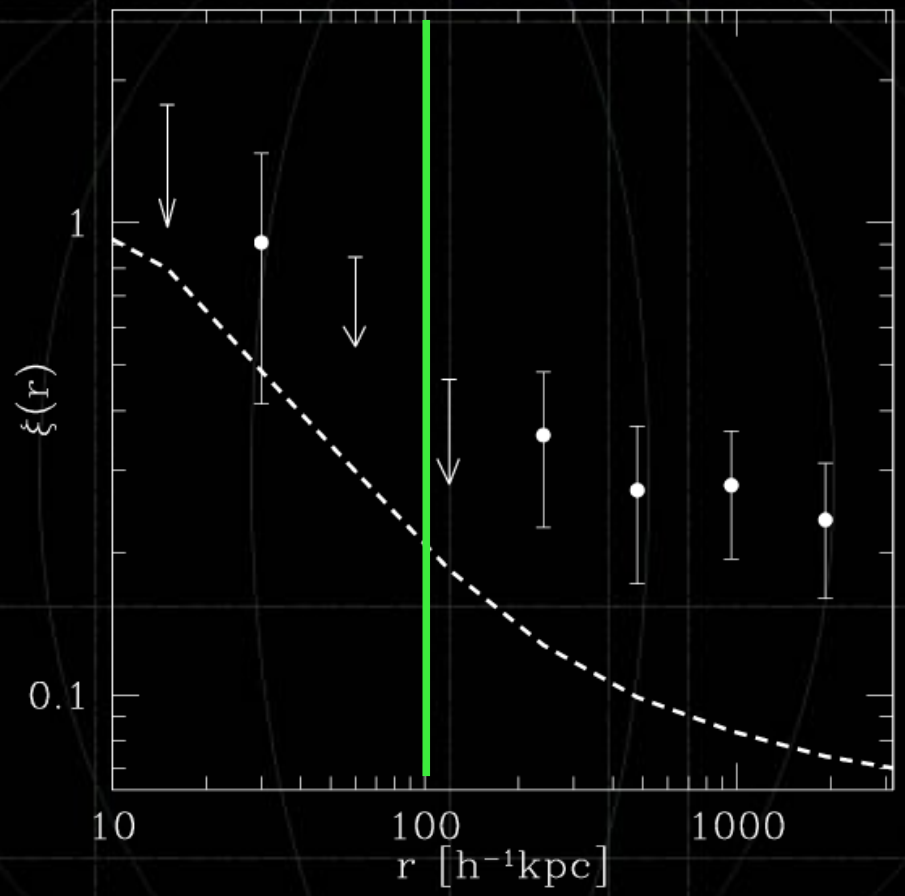


(Clarke et al. 2001)

Measured magnetic fields in the Universe

- On larger scales
  - Cross-correlation of |RM| and galaxy density field
  - Significant excess detected at large distances
  - $B \sim 30$ nG

    $L \sim 1$ Mpc



(Lee et al. 2009)

Where do those fields come from? Most likely scenario in two steps :

- Amplification and organisation (build-up of coherence)
  - Adiabatic compression (frozen-in flux)
  - Galactic $\alpha - \Omega$ dynamo
  - Turbulent dynamo (small scales, Intra-Cluster Medium)

- *Ex nihilo* generation of non-zero fields

The need of weak seeds

Linearised fluid equations

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\frac{\dot{a}}{a}\mathbf{v}+\frac{\mathbf{v}\cdot\nabla\mathbf{v}}{a}\right) = -\frac{\nabla \mathrm{p}}{a}-\rho\frac{\nabla\phi}{a}+\frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi a}$$

$$\frac{\partial\delta}{\partial t}+3\frac{\dot{a}}{a}\rho+\frac{\nabla\cdot(\rho\mathbf{v})}{a} = 0\,,$$

$$\nabla^2\phi = 4\pi G a^2\left(\rho-\rho_0(t)\right)\,.$$

The need of weak seeds

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- $\boldsymbol{B}$ as a source of density fluctuations (Rees & Reinhardt 1975, Wasserman 1978, Kim et al. 1996, ⋯)

  → modifies structure formation history

- In particular, $\boldsymbol{B}$ ~ 1 nG, on $L \lesssim 10$ ckpc, → additional power on scales M ~ 10^6 $M_\odot$ → enhances Pop III star formation

  → early reionisation completed by z ~ 15

  (Sethi & Subramanian 2003 ; Tashiro & Sugiyama 2006)

Seed field generation mechanisms

- Primordial Universe
  - Inflation
  - Phase transitions
- Recombination
  - Second order perturbations
- Post-recombination Universe
  - Plasma instabilities (e.g. Weibel)
  - Biermann Battery
  - Photon drag of charged particles

Seed field generation mechanisms

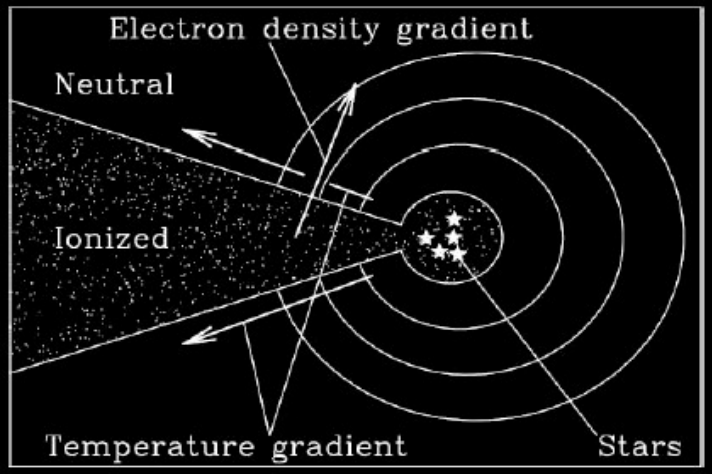
- Primordial Universe
  - Inflation — Ridiculously weak seeds
  - Phase transitions — Too small scales
- Recombination
  - Second order perturbations — Small fields, needs vorticity & tight coupling breaking
- Post-recombination Universe
  - Plasma instabilities (e.g. Weibel) — Too small scales
  - Biermann Battery
  - Photon drag of charged particles

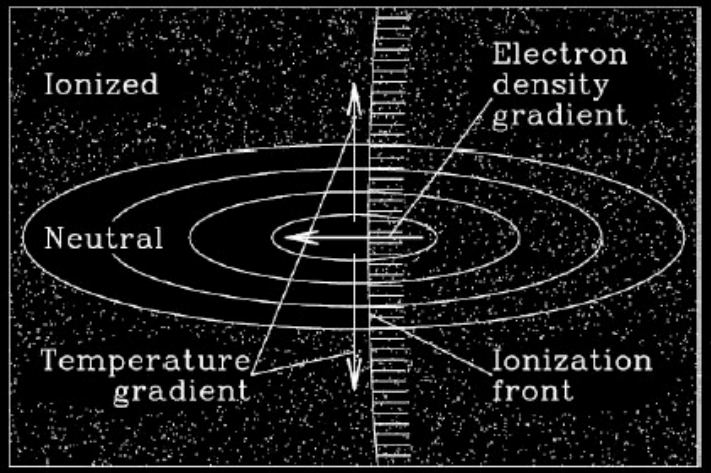
Biermann battery at reionisation

Subramanian et al. 1994, Gnedin et al. 2000

Induction : source term

$$\frac{d\vec{B}}{dt} = -\frac{c\,k_B}{q_e}\frac{\vec{\nabla}T\times\vec{\nabla}n_e}{n_e}$$





$B \sim 10^{-20} - 10^{-18}$ G @ $L \sim$ a few kpc

B fields from radiation drag at reionisation

Langer, Aghanim, Puget 2005

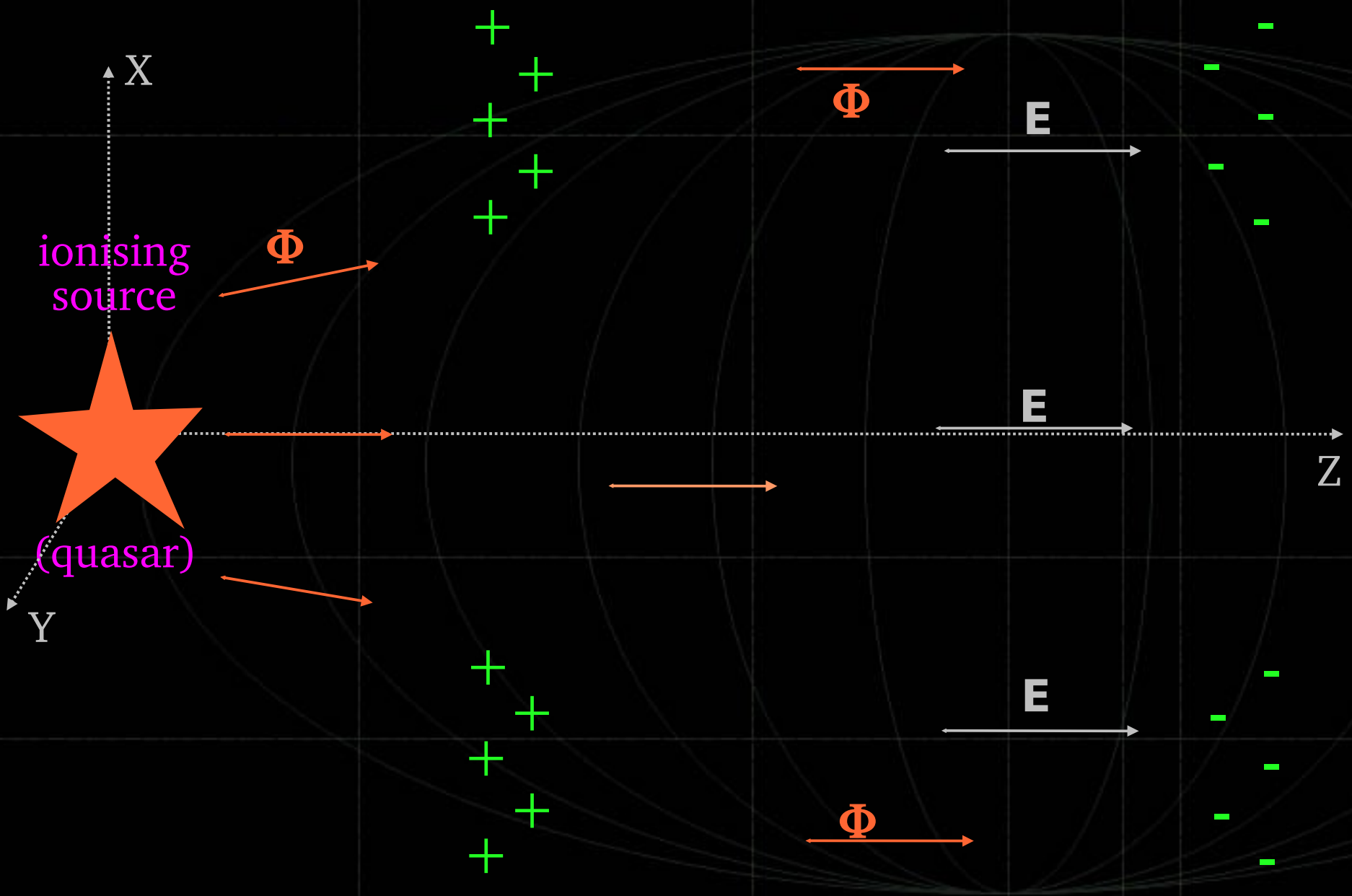
- Maxwell equations

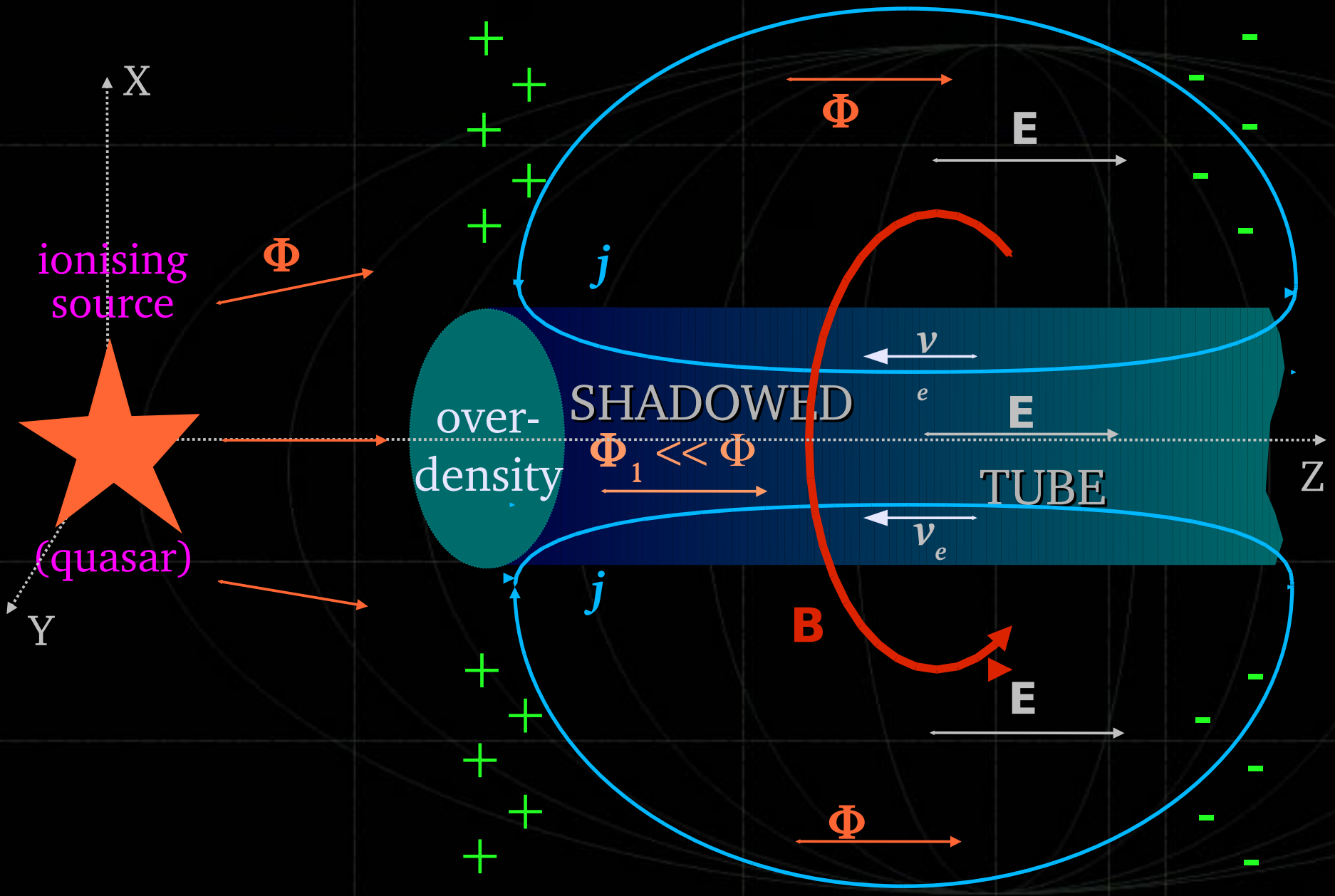
- Generalised Ohm's law

$$\frac{d\vec{j}}{dt} = \frac{\omega_p^2}{4\pi}\left(\vec{E} + \frac{\vec{u}\times\vec{B}}{c}\right) + \frac{q_e}{m_e c}\vec{j}\times\vec{B} - \nu_c\vec{j} + \nu_\gamma\vec{I}$$

- Radiation drag source term
  - Photon-electron interaction : photoionisation $\nu_\gamma = \sigma_{ion}\phi$
  - Source current : momentum transferred to bound electrons

$$I = f_{mt}\frac{h\nu}{m_e c^2} q_e n_H c \qquad \text{where} \qquad f_{mt} = \frac{8}{5}\frac{\nu - \nu_0}{\nu}$$


X
Φ
E
ionising
source
Φ
E
Z
(quasar)
Y
E
Φ


X
Y
Z
ionising source
(quasar)
Φ
over-density
SHADOWED
$\Phi_1 \ll \Phi$
TUBE
E
E
E
j
j
B
v_e
v_e
Φ
Φ

B fields from radiation drag at reionisation

Langer, Aghanim, Puget 2005

- Ionising source : quasar
- Amplitude of the generated field

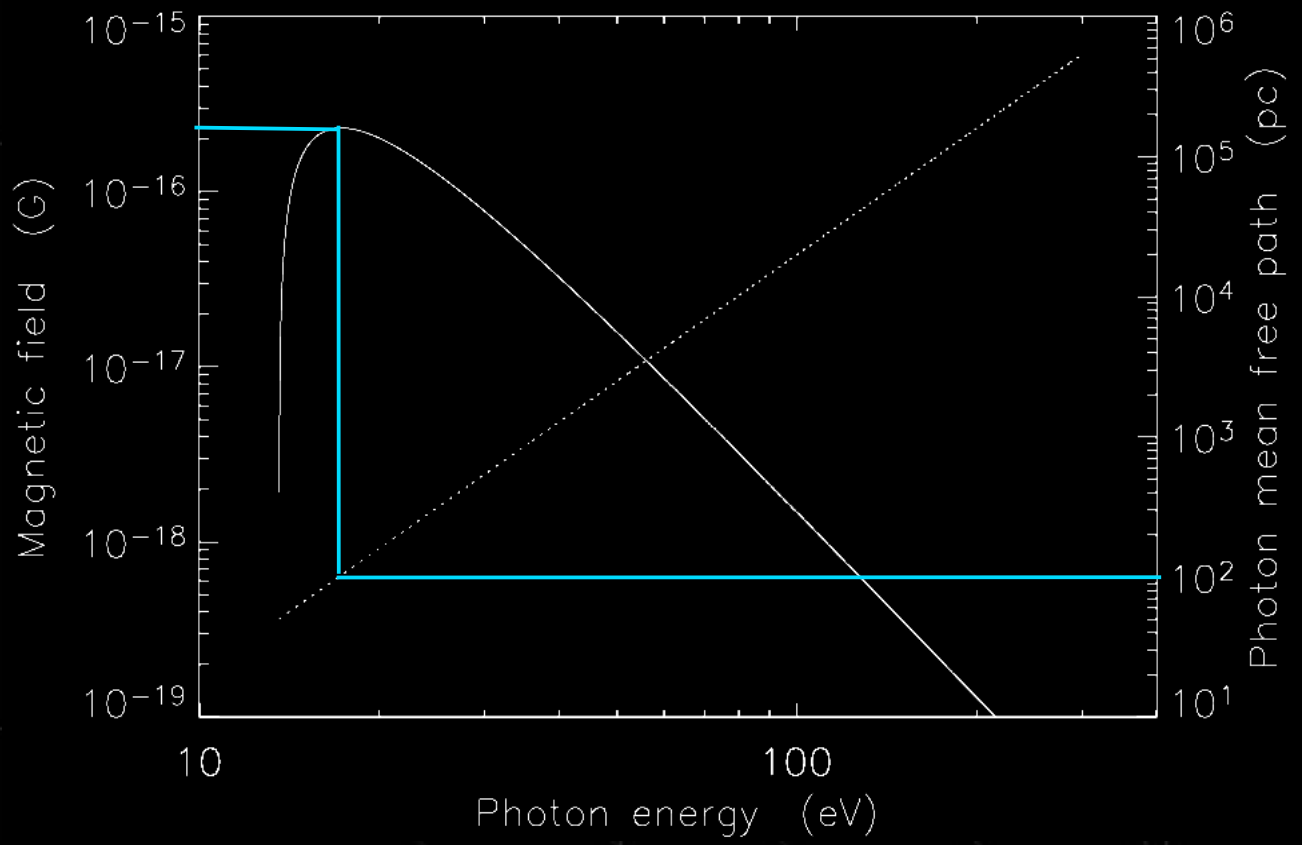
$$\vec{B} = 4\pi \frac{c\,\nu_\gamma}{\omega_p^2} \vec{\nabla} \times \vec{I}\, t$$

$$B \sim 1.6 \times 10^{-15} F(\nu)\, C_{10}^{2/3} \frac{n_H / n_e}{10^4} \frac{L_{12}^{1/3}}{R_2} \frac{t_S}{10^8\, yrs} \left(\frac{1+z}{16} \right)^4 \quad \text{Gauss}$$

- Mean free path of ionising photons outside Strömgren sphere

$$l_{mfp} \approx 50 \left(\frac{\nu}{\nu_0} \right)^3 \left(\frac{1+z}{16} \right)^{-3} \quad \text{parsecs}$$

B fields from radiation drag at reionisation



Langer, Aghanim, Puget 2005

$B \sim 2 \times 10^{-16}$ G @ $L \sim 100$ pc

B fields from radiation drag at reionisation

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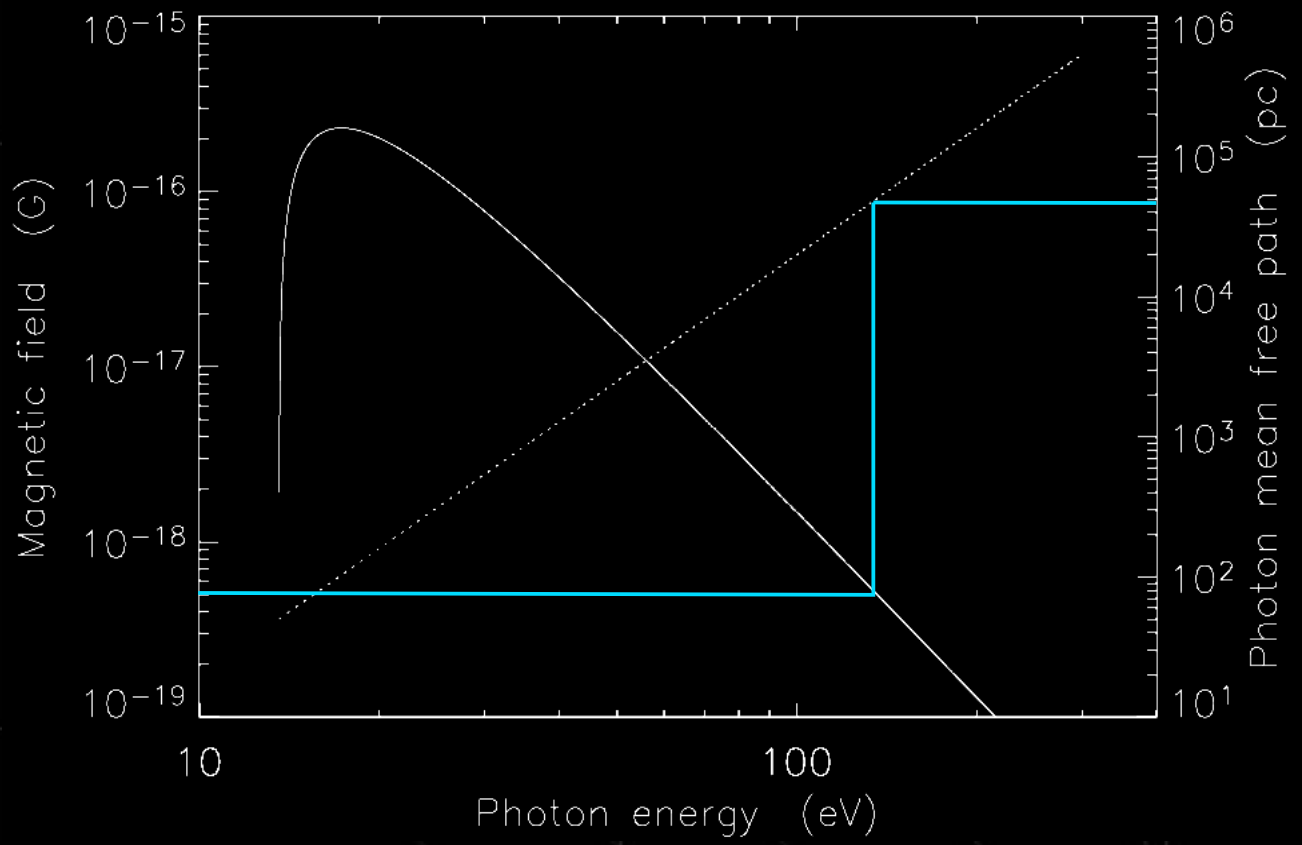
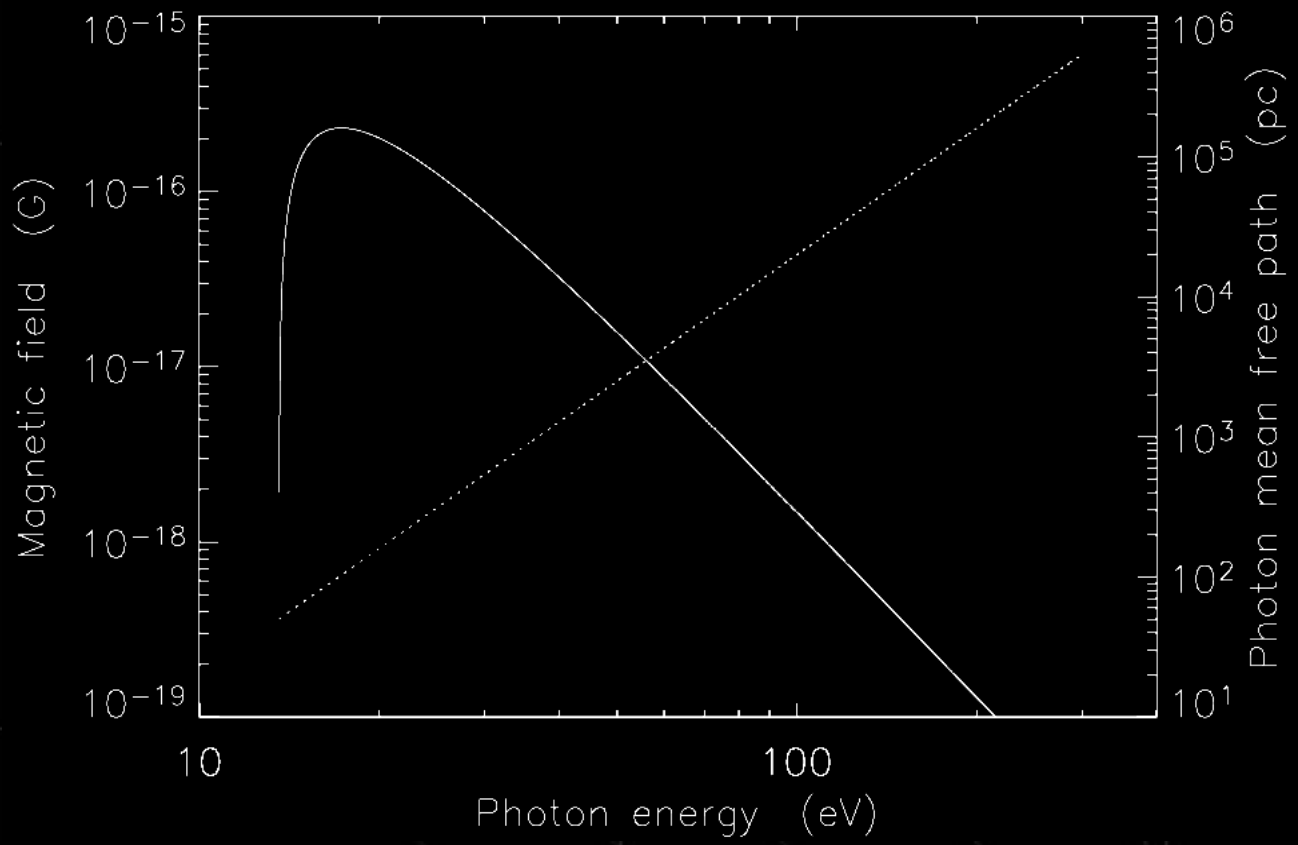


$B \sim 2 \times 10^{-16}$ G @ $L \sim 100$ pc

$B \sim 5 \times 10^{-19}$ G @ $L \sim 50$ kpc

B fields from radiation drag at reionisation

Langer, Aghanim, Puget 2005



$B \sim 2 \times 10^{-16}$ G @ $L \sim 100$ pc

$B \sim 5 \times 10^{-19}$ G @ $L \sim 50$ kpc

Distance between 3.9 σ sources :
880 kpc @ z ~ 15

$B \sim 4 \times 10^{-20}$ G

⇒ **Pre-magnetisation of the Universe**

Eventual statistics of the produced seeds?

Langer, Puget, Aghanim 2003

- ***B*** field power spectrum :

  $P_B(k) \sim k^{-4}$ on cluster scales

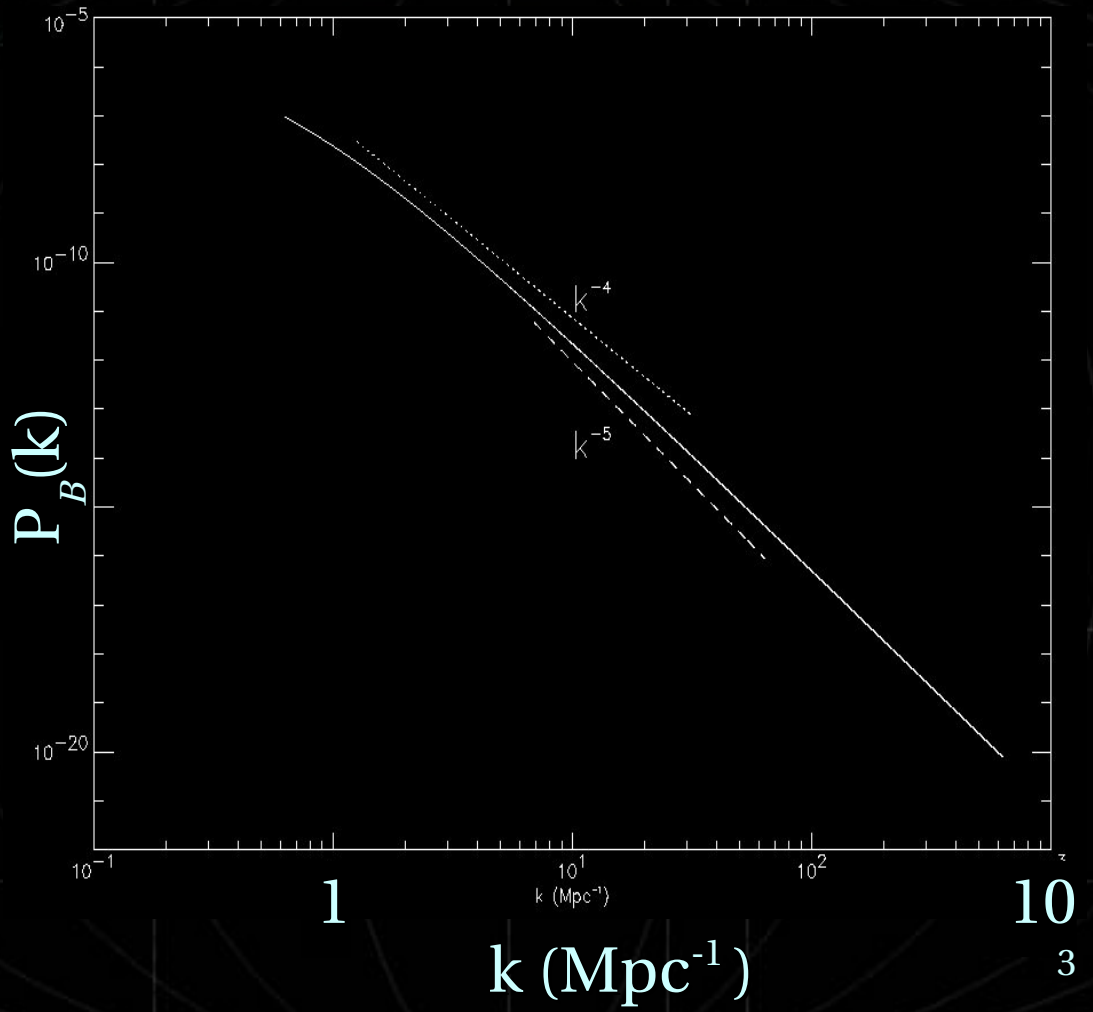
  $P_B(k) \sim k^{-4.7}$ on galactic scales

- But there's not enough time :

  $$t_{nl} \sim 4 \times 10^8 \, \delta_k^{-1} \; yrs$$

  $$t_S \sim t_E \sim 4 \times 10^8 \; yrs$$

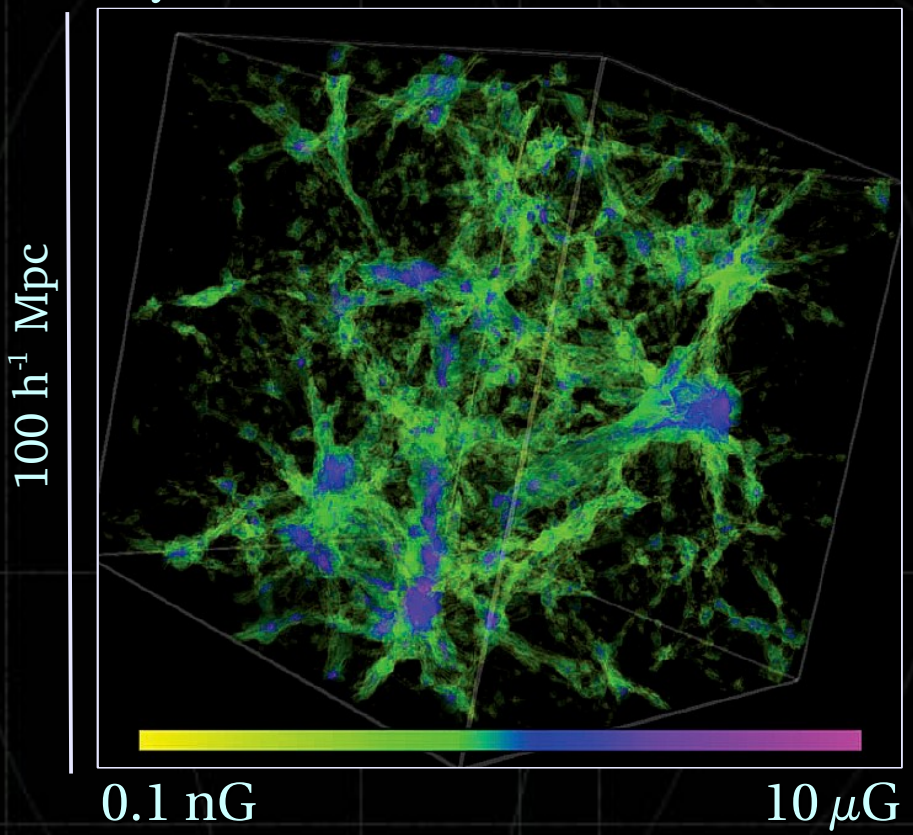
  Non-linear effects (turbulence) set in!



Subsequent evolution

- Turbulence from structure formation
  - Vorticity generation
  - Magnetic field amplification
- Results @ z = 0 independent of initial conditions !
  - Seed field strength
  - Coherence

(Ryu et al. 2008)



Memory of generation mechanism is lost !

(cf. also Dolag et al. 2002)

Summary

- Origin of cosmological magnetic fields still unsettled
- Radiation drag at reionisation : promising mechanism

  $\boldsymbol{B}$ generation inherent to reionisation, IGM pre-magnetisation

- Turbulent amplification efficient on large scales

  Loss of memory of $\boldsymbol{B}$ seed production mechanism

- Need for detailed observations, esp. in low density regions