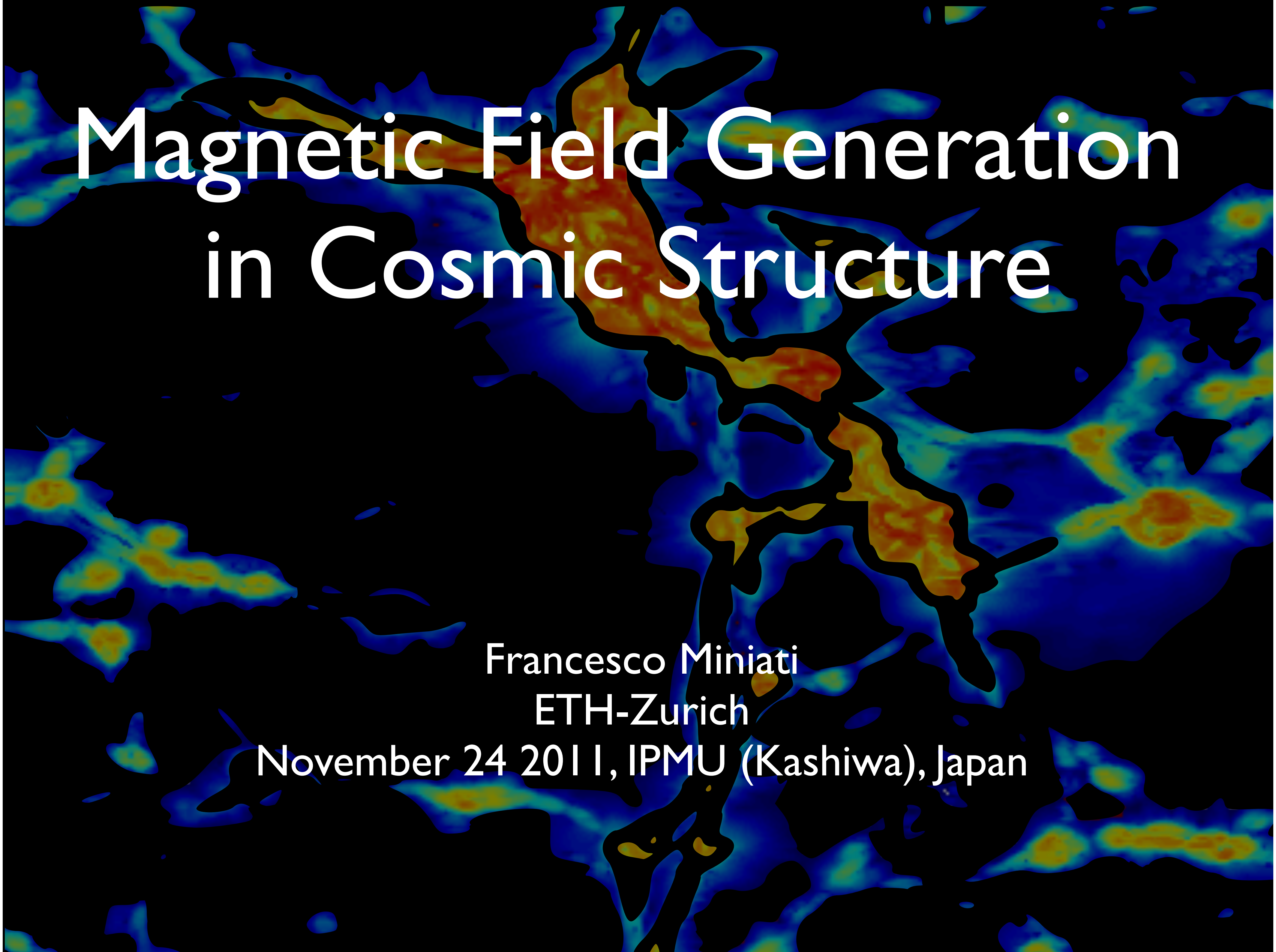

Magnetic Field Generation in Cosmic Structure

Francesco Miniati
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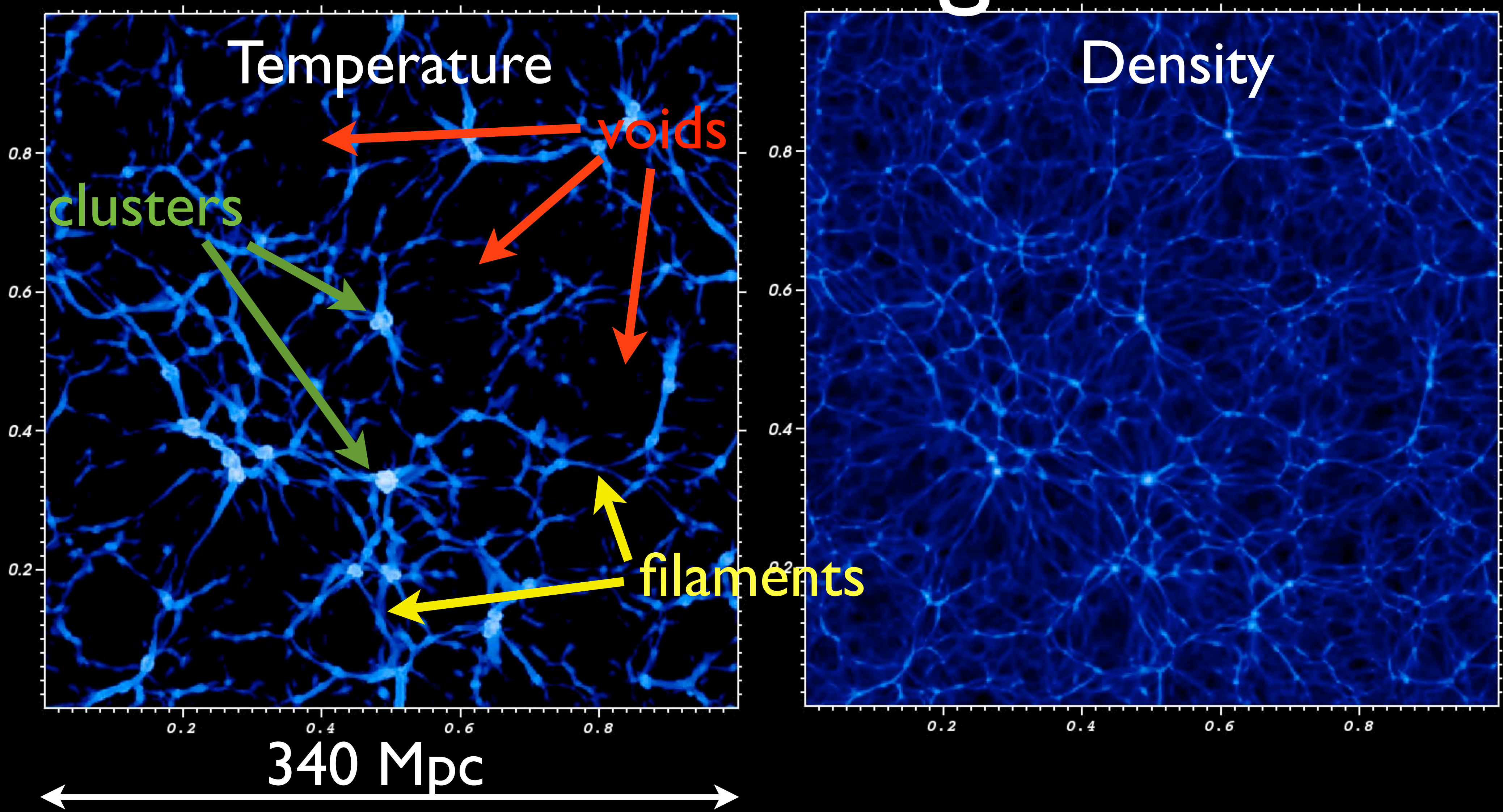
November 24 2011, IPMU (Kashiwa), Japan

Cosmic Magnetism

Most astrophysical bodies are magnetized:

- Main sequence stars 1-100 G.
- Galaxy, nearby galaxies and "high-redshift" galaxies: B~1-10 μG (Beck 1996, Bernet et al 2008)
- Clusters of Galaxies: B ~ 0.1-10 μG
- Filament of Galaxies: B ~ nG (?)
- Cosmic Voids: B ~ 0.1-0.01 fG

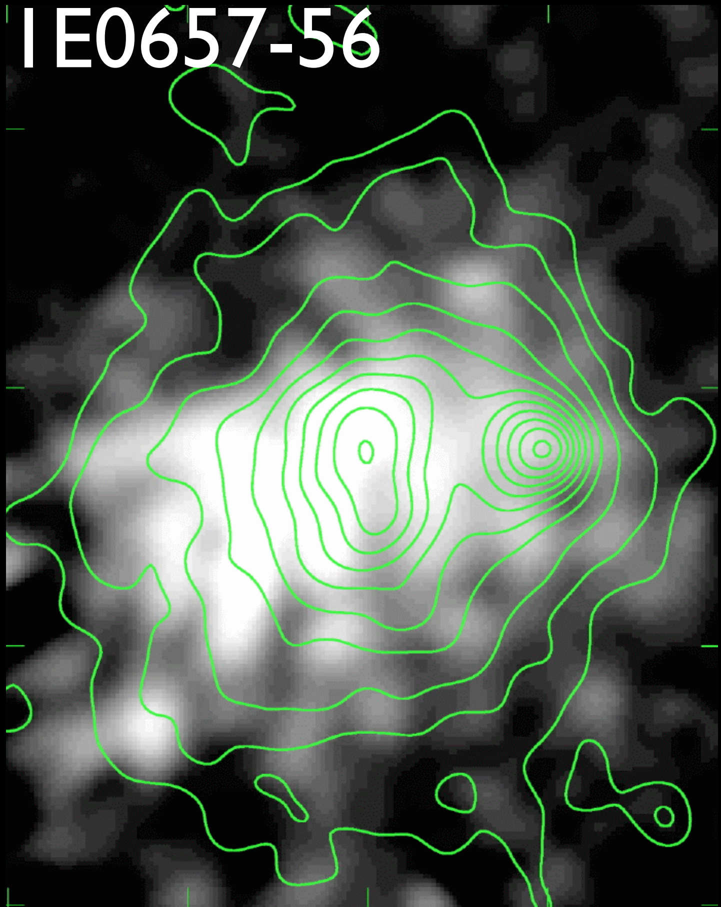
The LSS: voids, filaments and clusters of galaxies



Outline

- measurement of magnetic fields in the LSS, i.e. galaxy clusters, filaments and voids
- resistive generation mechanism
- conclusions

Probes of Magnetism in Galaxy Clusters



Radio Halo

Synchrotron Radiation

relativistic electrons

$$\frac{dN}{dE}(E) = N_0 E^{-s}$$

synchrotron flux

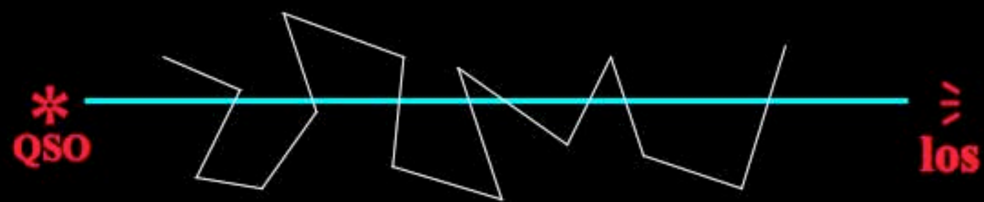
$$F_\nu \propto N_0 \, B^{\frac{1+s}{2}} \, \nu^{-\frac{s-1}{2}}$$

Probes of Magnetism

Rotation Measure

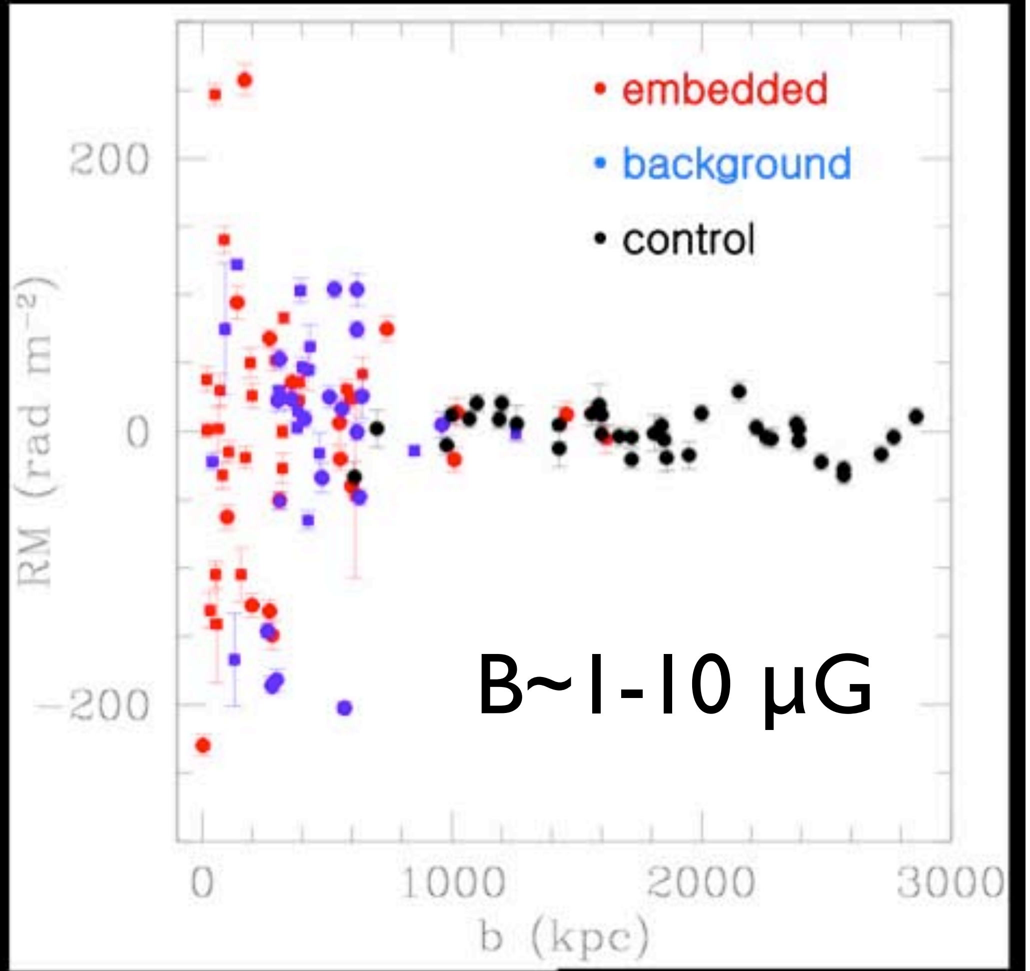
$$\chi = \chi_0 + \mathrm{RM}\,\lambda^2$$

$$\mathrm{RM}=0.8\int n_e \vec{B}\cdot d\vec{l}$$



$$\langle \mathrm{RM} \rangle = 0$$

$$\sigma_{\mathrm{RM}} \propto B\ell_c^{1/2}$$



Clarke et al (2001, 2004)

E.M. cascade in Voids

$\gamma_{Blz}\gamma_{EBL} \rightarrow e^+e^-$

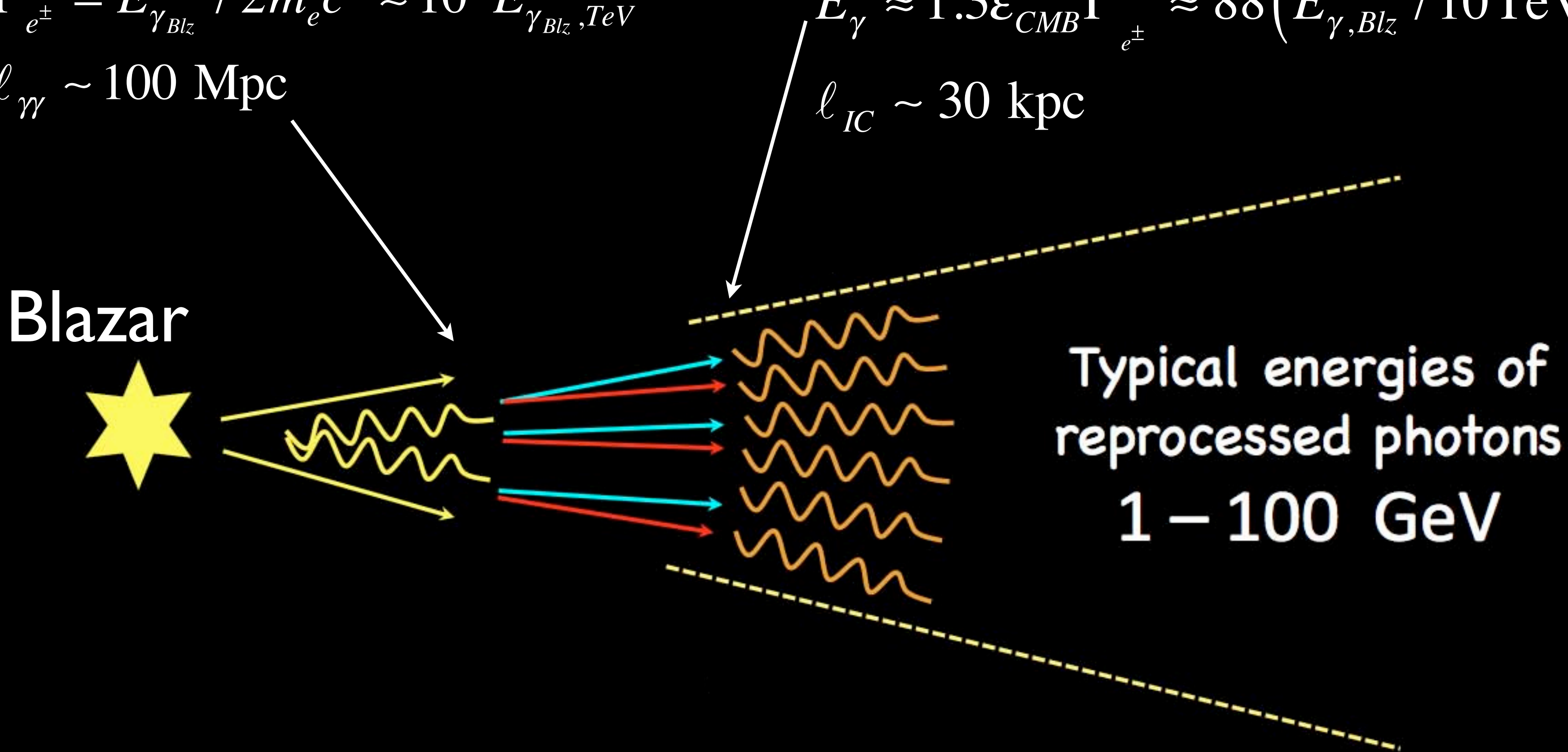
$\Gamma_{e^\pm} = E_{\gamma_{Blz}} / 2m_e c^2 \approx 10^6 E_{\gamma_{Blz},TeV}$

$\ell_{\gamma\gamma} \sim 100$ Mpc

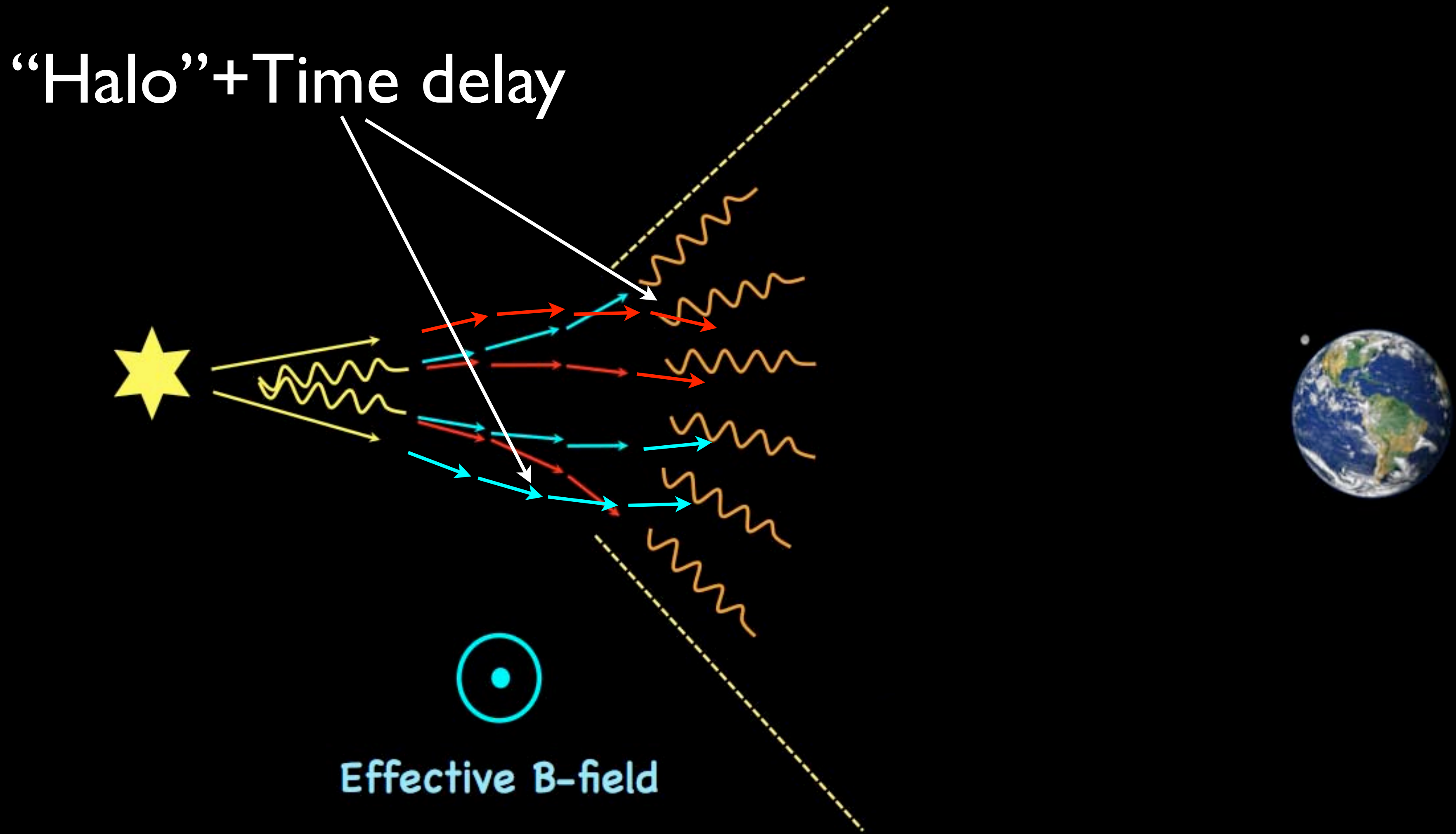
$e^\pm\gamma_{CMB} \rightarrow e^\pm\gamma$

$E_\gamma \approx 1.3\varepsilon_{CMB}\Gamma^2_{e^\pm} \approx 88\left(E_{\gamma,Blz} / 10\text{TeV}\right)^2$ GeV

$\ell_{IC} \sim 30$ kpc

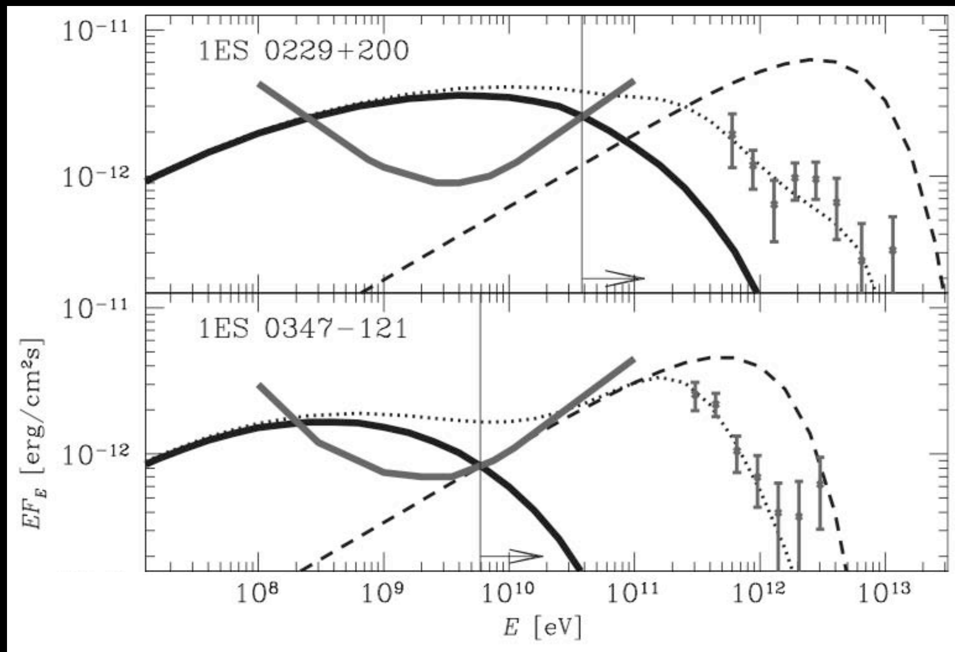


Non vanishing B-field deflects secondary e±



Magnetism in Voids

$$B \geq 10^{-18} - 10^{-17} \text{ Gauss}$$



Neronov and Vovk, Science 328 73 (2010), see also Tavecchio et al (2010), Dermer et al. 2010, Taylor et al. 2011

Evolution of B

Electrostatic fields are weak and negligible!

$$\vec{E}' \approx 0 \Rightarrow \vec{E} = -\frac{\vec{u}}{c} \times \vec{B}$$

Induction equation

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} = \vec{\nabla} \times \left(\vec{u} \times \vec{B} \right) + \dot{\vec{B}}_{Source}$$

Growth timescale of B set by flow $\left(\vec{u} \right)$ geometry.

B evolution in various environments

- In Galaxy Clusters the requirement on the initial seeds is not well constrained because the amplification is not well known
- In filaments the amplification due to turbulence is probably poor
- In voids the flow is divergent, so turbulence, if any, decays and we are most likely seeing are the fields directly seeded by the initial mechanism
- Initial seeds $B_0 \leq 1\ \mathrm{nG}$ (e.g. Schleicher & Miniati 2011)

Generation Mechanisms for B

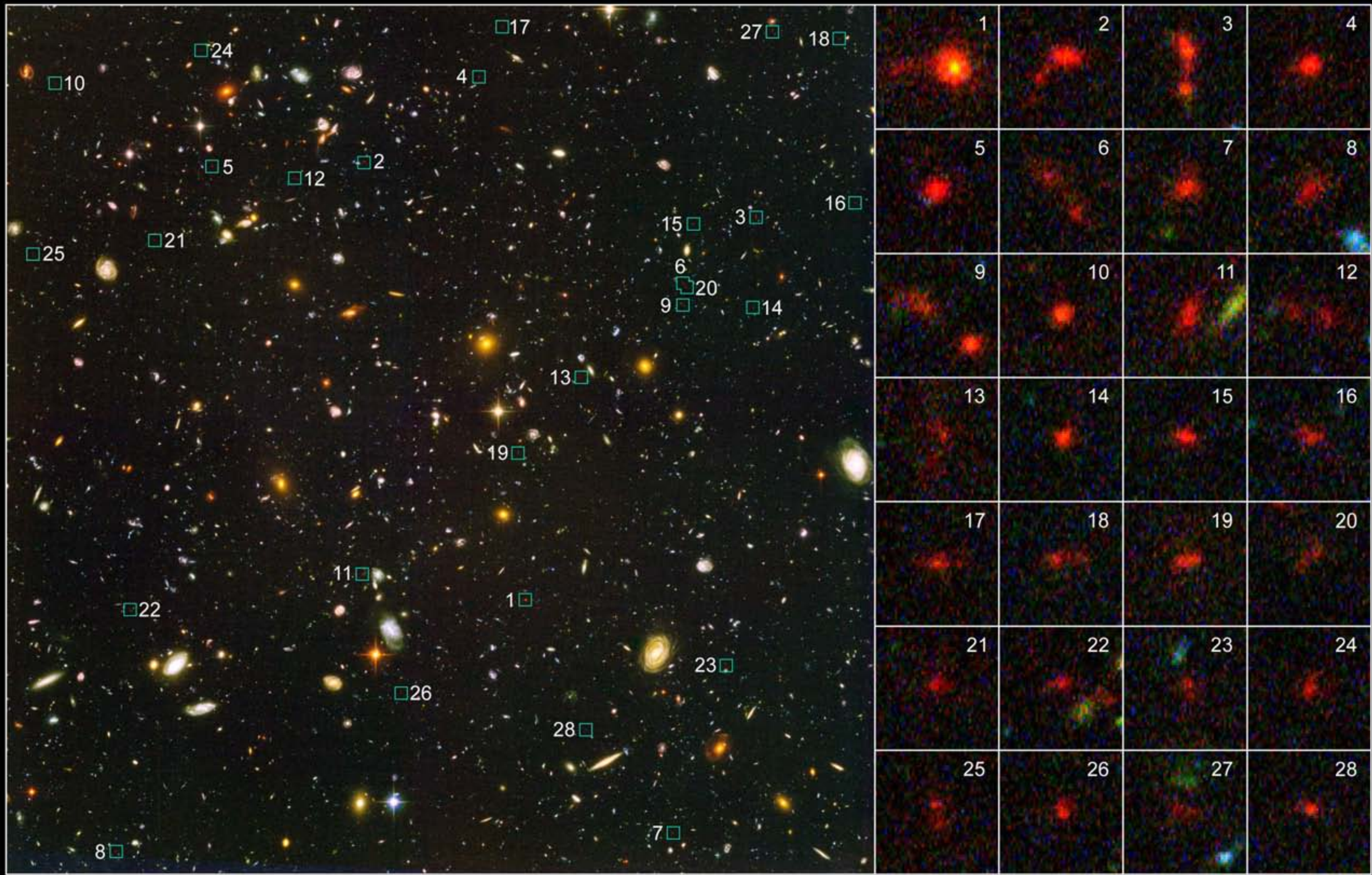
$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} = \vec{\nabla} \times \left(\vec{u} \times \vec{B}\right) + \frac{\eta c^2}{4\pi} \nabla^2 \vec{B} + \dot{\vec{B}}_{Source}$$

- Plasma processes:
  - (i) resistive mechanism (Miniati & Bell 2011)
  - (ii) Biermann's battery (Subramanian et al. 1992, Kulsrud et al. 1997, Gnedin et al. 2000),
  - (iii) Weibel's instability (Schlickeiser & Shukla 2003, Medvedev et al 2004).
- Outflows:
  - (i) Galactic (Kronberg et al. 1999, Bertone et al. 2006, Donnert et al.2009, Dubois & Teyssier 2010)
  - (ii) Jets from radiogalaxies (e.g., Furlanetto & Loeb 2001, Kronberg et al 2001)
- Early Universe (Ichiki et al. 2006)
- Inflationary processes (see work by, e.g., Kanishvili, Rathra, Jedamzik, Sigl)

Remarks

- Weibel can generates large fields in collapsed structures.
- Biermann mostly generates magnetic seeds in collapsed structures which need large amplification (turbulence + adiabatic compression)
- galactic outflows are characterized by strong B field, but their filling factor is quite difficult to predict
- same is true for outflows from AGN

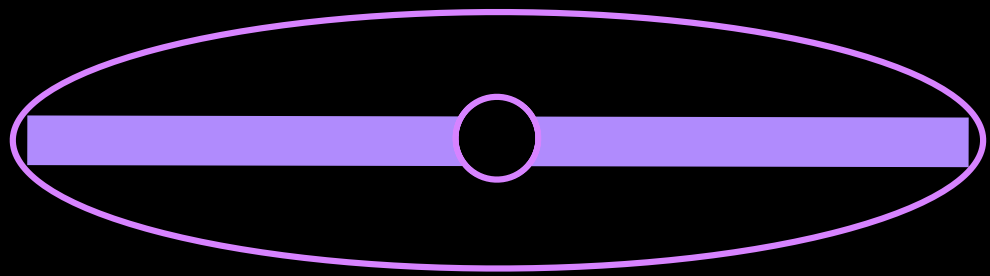
High redshift galaxies reionize the universe



Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

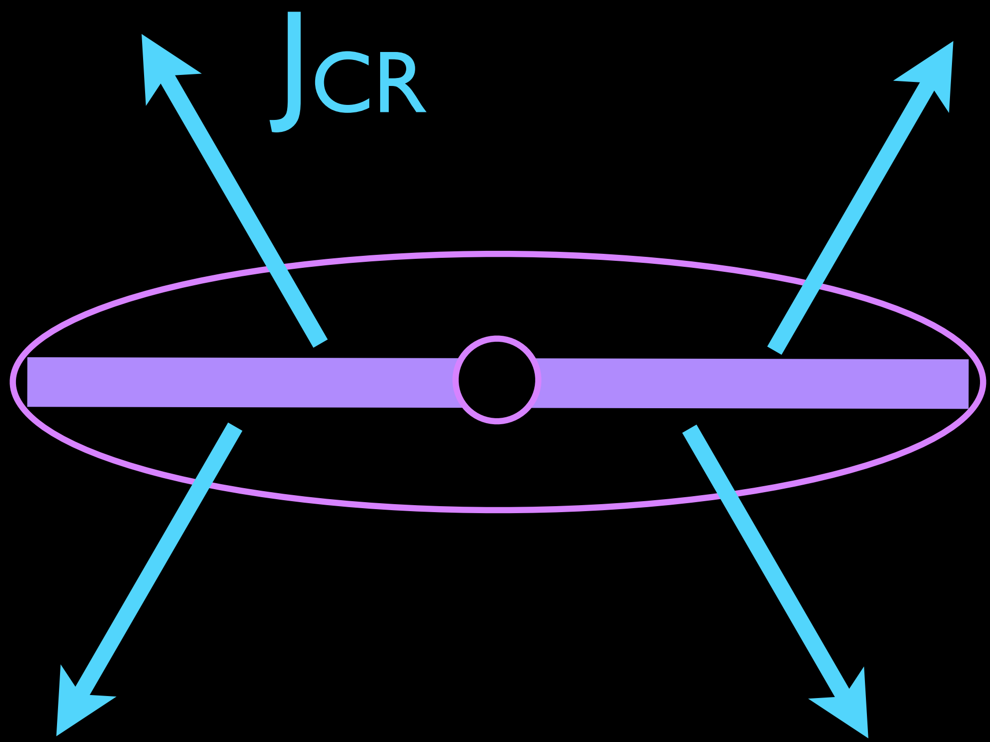
Resistive Mechanism

(FM & Bell, ApJ 2011, 729, 73; arXiv:1001.2011)



Resistive Mechanism

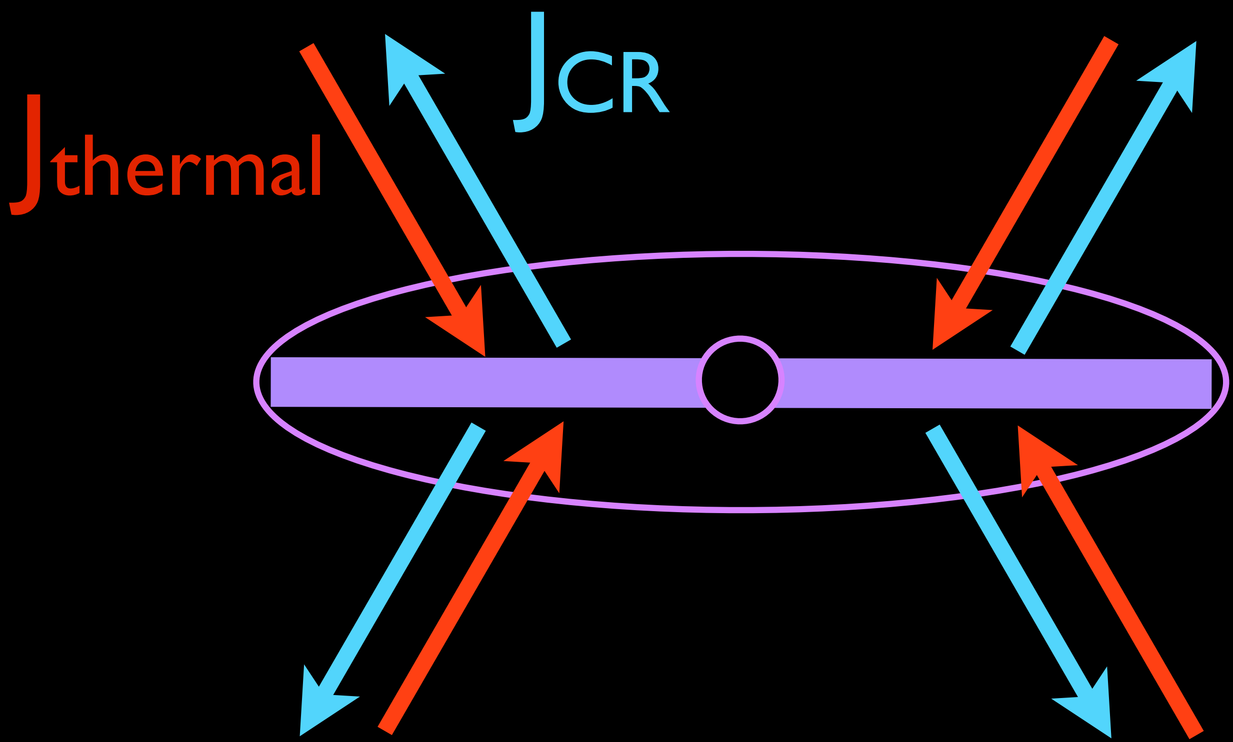
(FM & Bell, ApJ 2011, 729, 73; arXiv:1001.2011)



High-redshift (z>6) star forming galaxies produce copious amount of cosmic-rays which escape into the intergalactic medium.

Resistive Mechanism

(FM & Bell, ApJ 2011, 729, 73; arXiv:1001.2011)



High-redshift (z>6) star forming galaxies produce copious amount of cosmic-rays which escape into the intergalactic medium.

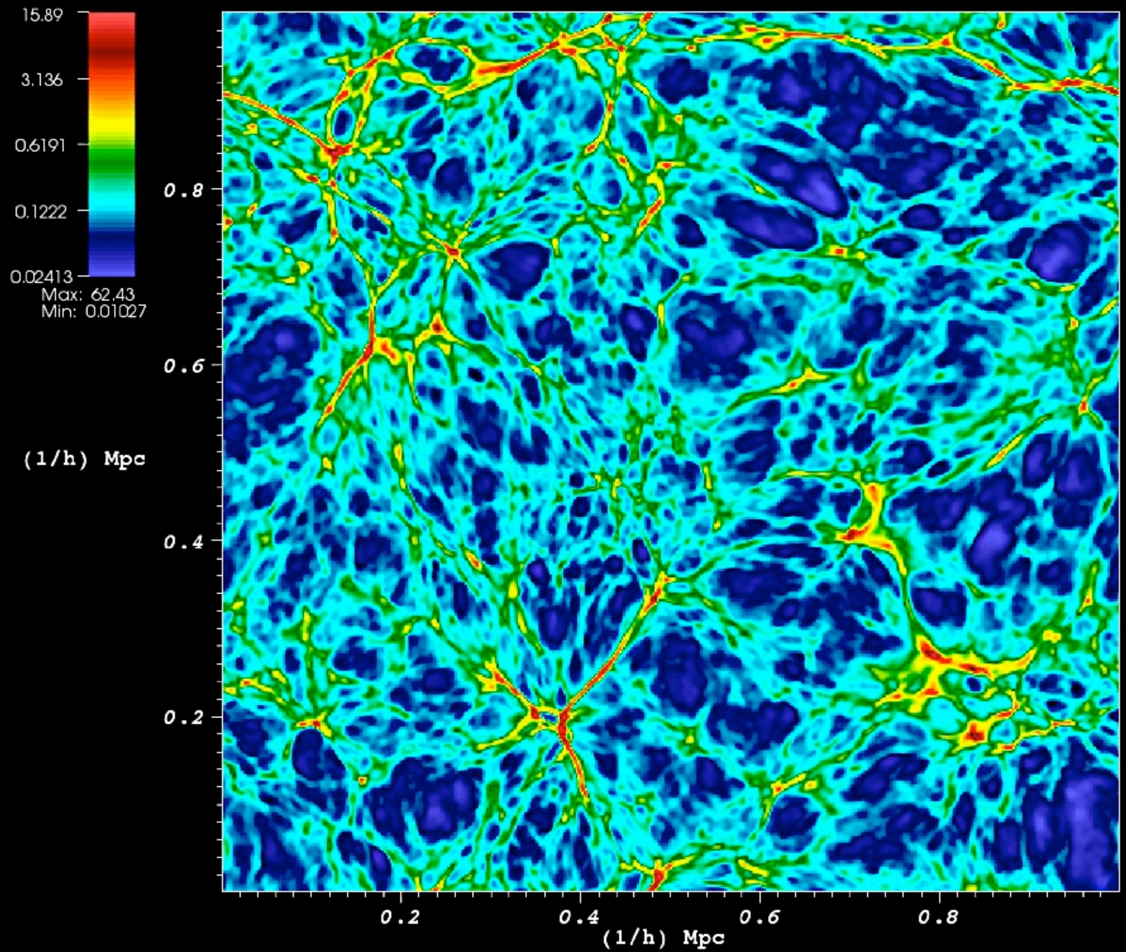
Basics

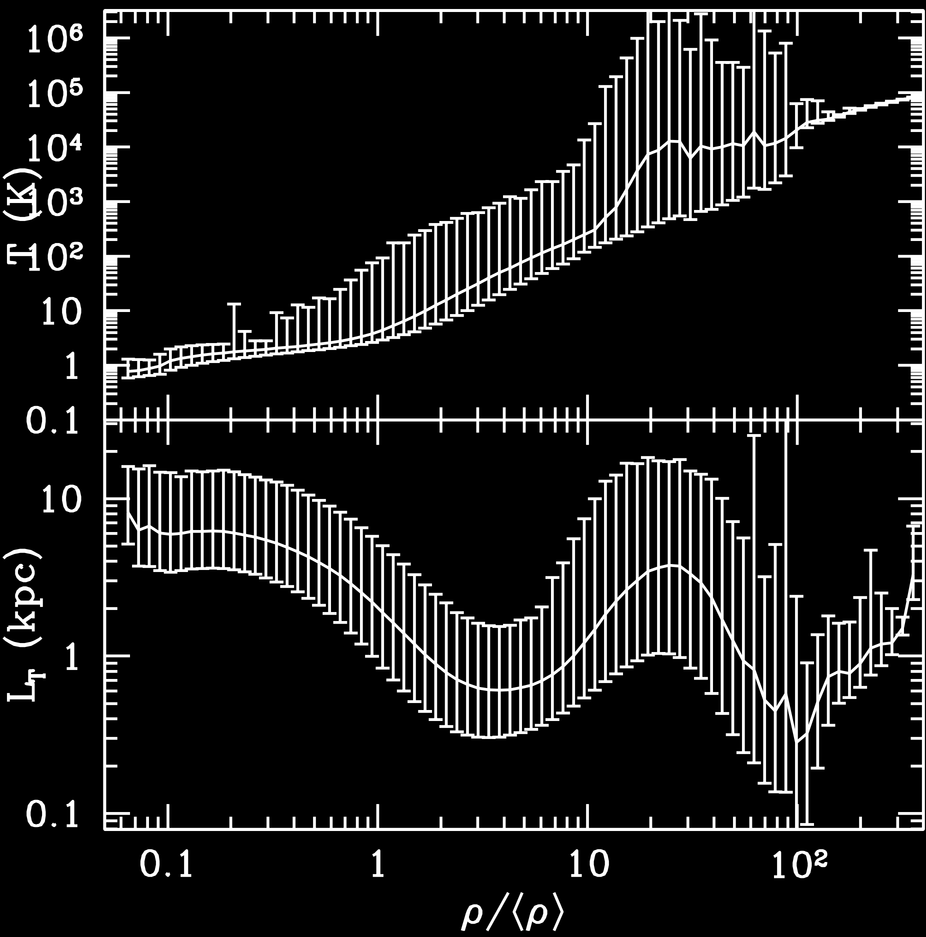
- the CR current, j_{cr}, drives a return current in the plasma, j_{th}, that tends to cancel j_{cr} itself, i.e. $j_{th} \approx -j_{cr}$
- the return current is associated with an electric field:

$$\vec{E}' = \frac{\vec{j}_{th}}{\sigma}, \quad \text{where (Spitzer)} \ \sigma \simeq 10^7 \left(\frac{T}{K} \right)^{3/2} s^{-1}$$

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} \simeq c\frac{\vec{j}_{cr}}{\sigma} \times \frac{\vec{\nabla} T}{T}$$

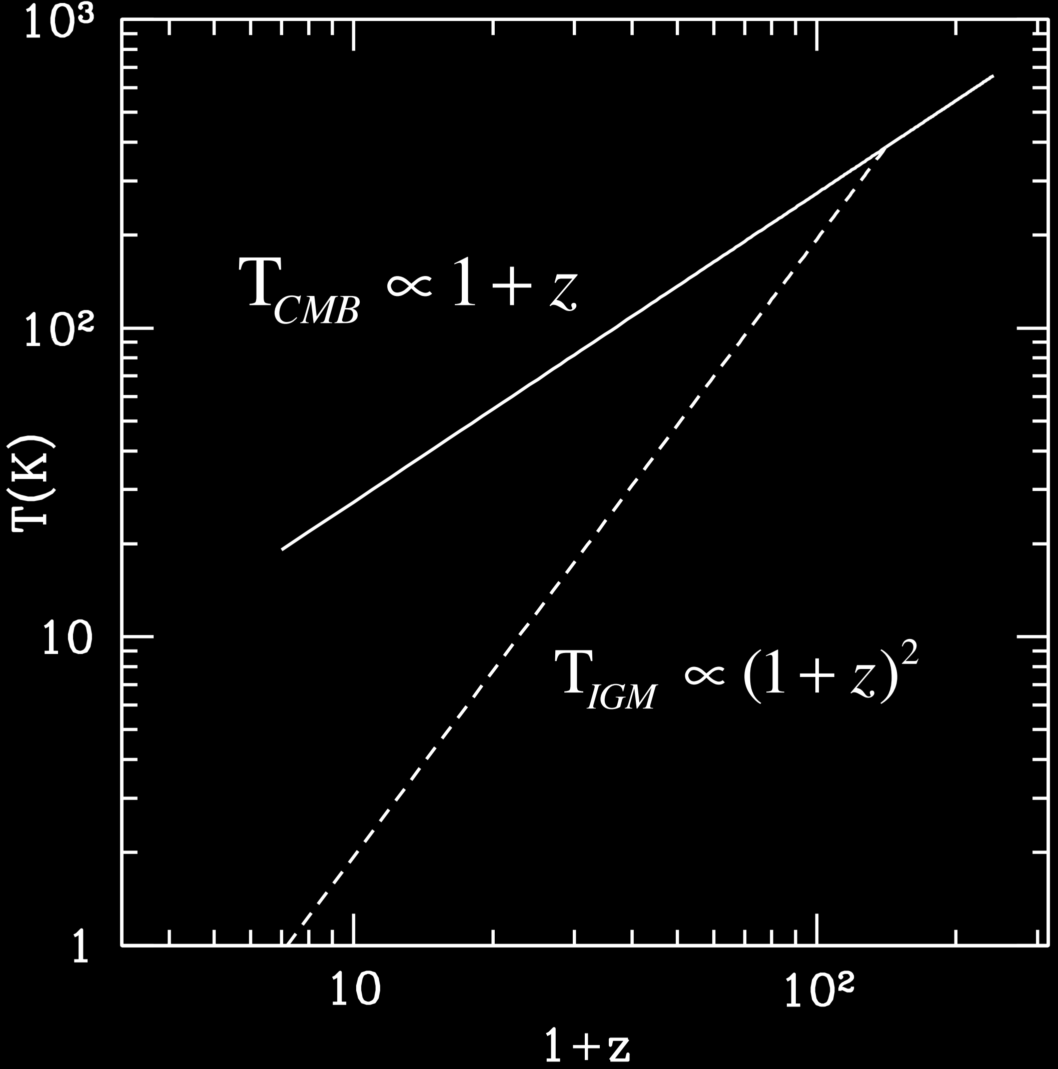
IGM inhomogeneities at z≈6





Miniati & Bell (2011)

IGM Temperature



Compton scattering efficiently couples T_{IGM} and T_{CMB} only for z>140.

Just prior to cosmic reionization the temperature of the IGM was at its lowest point (~1K).

Growth rate around L* galaxies

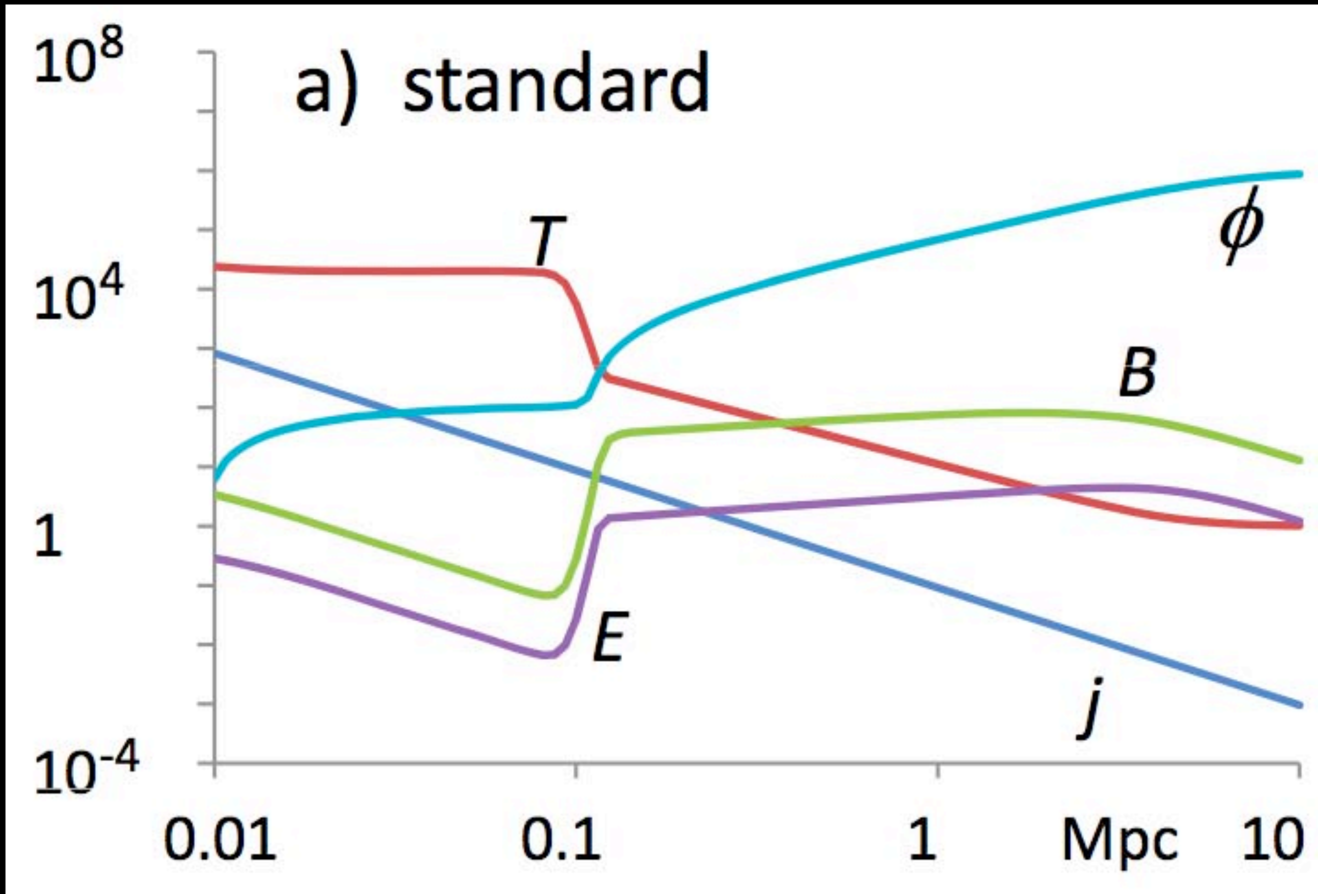
Temperature scale-length $\ell_T \equiv \frac{T}{|\nabla T|} \sim 1 \text{ kpc}$

CR-current density $j_{CR} \simeq \frac{e\varepsilon_{CR} L}{2\pi\theta p_{\min} c\Lambda_{CR}} d^{-2}$

$$\frac{\partial B}{\partial t} \approx \frac{c j_{CR}}{\sigma \ell_T} \approx 10^{-15} \left(\frac{\ell_T}{\text{kpc}}\right)^{-1} \left(\frac{T}{\text{K}}\right)^{-3/2} \left(\frac{L}{L_*}\right) \left(\frac{d}{\text{Mpc}}\right)^{-2} \frac{\text{Gauss}}{\text{Gyr}}$$

+ Ohmic heating: $\frac{3}{2} n k_B \frac{dT}{dt} = j_{cr}^2 / \sigma$

Solution's radial profile



$[j] = 10^{-18}\,\mathrm{Am^{-2}}$

$[\mathrm{T}] = \mathrm{K}$

$[\mathrm{B}] = 10^{-18}\,\mathrm{G}$

$[\mathrm{E}] = 10^{-18}\,\mathrm{Vm^{-1}}$

$[\phi] = \mathrm{Volt}$

Growth rate in the IGM

Luminosity Function

$$\Phi(L) = \Phi_* \left(\frac{L}{L_*} \right)^{-\alpha} e^{-L/L_*} \quad : \quad n(L) \approx \Phi(L) \frac{L}{L_*}$$

Mean distance between L-galaxies

$$\langle d_L \rangle = \left[\frac{L}{L_*} \Phi(L) \right]^{-1/3} \propto L^{(\alpha-1)/3} \approx L^{1/4}$$

Bowens et al. 2009

Magnetization around L-galaxies

$$\dot{B} \propto L \langle d_L \rangle^{-2} \propto L^{1/2}$$

Magnetization of the IGM is dominated by the most luminous galaxies

MHD + Resistive Source

$$\frac{\partial U}{\partial t} + \vec{\nabla} \cdot \vec{F}_{MHD} = \dot{U}_{Cosmol} + \begin{pmatrix} 0 \\ 0 \\ j_{CR}^2 / \sigma \end{pmatrix} \quad \begin{matrix} \text{mass} \\ \text{momentum} \\ \text{energy} \end{matrix}$$

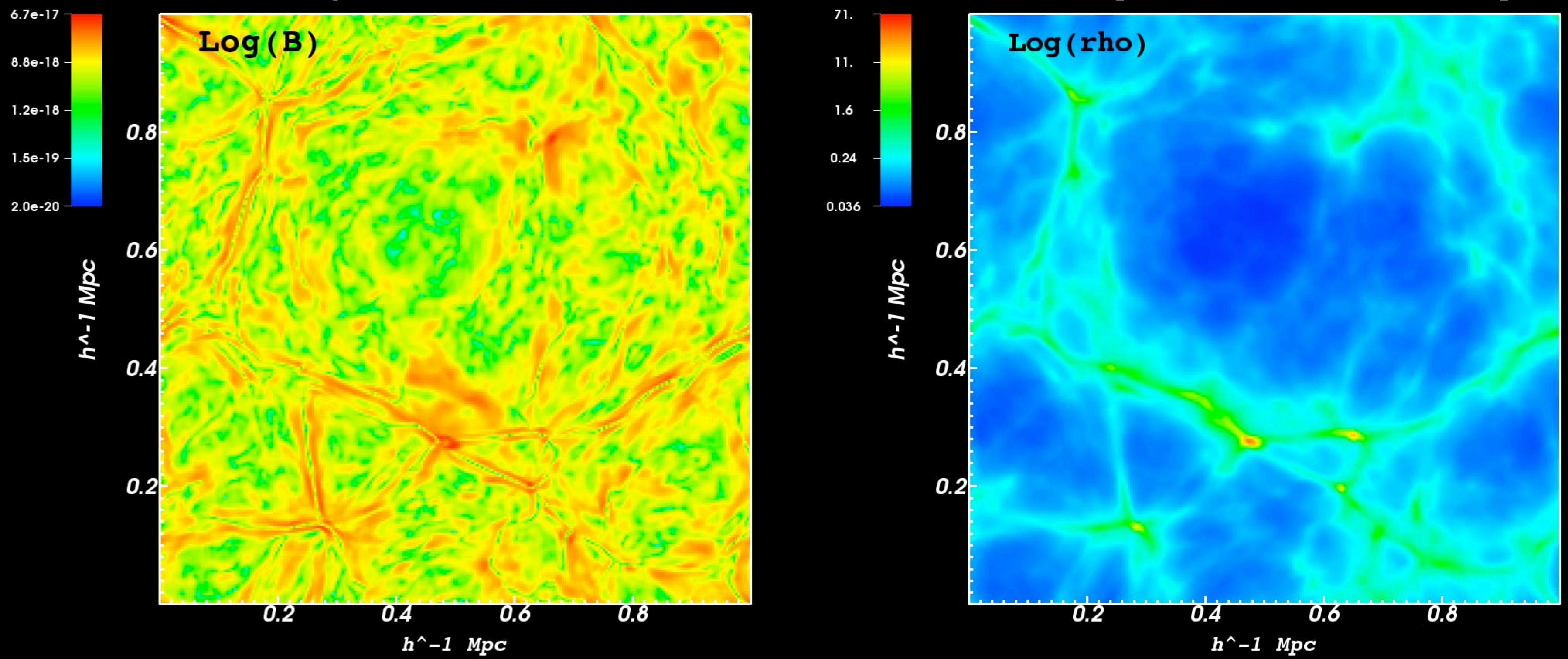
$$\frac{\partial \vec{B}}{\partial t} + \vec{\nabla} \cdot \vec{F}_B = \dot{\vec{B}}_{Cosmol} + c\vec{\nabla} \times \left(\vec{j}_{CR} / \sigma \right)$$

Cosmological MHD code (Miniati & Colella 2007; Miniati & Martin 2011). '$\nabla \cdot B=0$' constraint enforced through Constrained-Transport, hence 'B' is not artificially generated (Brackbill & Barnes, 1980).

Z~10

Box = 100 h^{-1} kpc
ΛCDM (WMAP7)

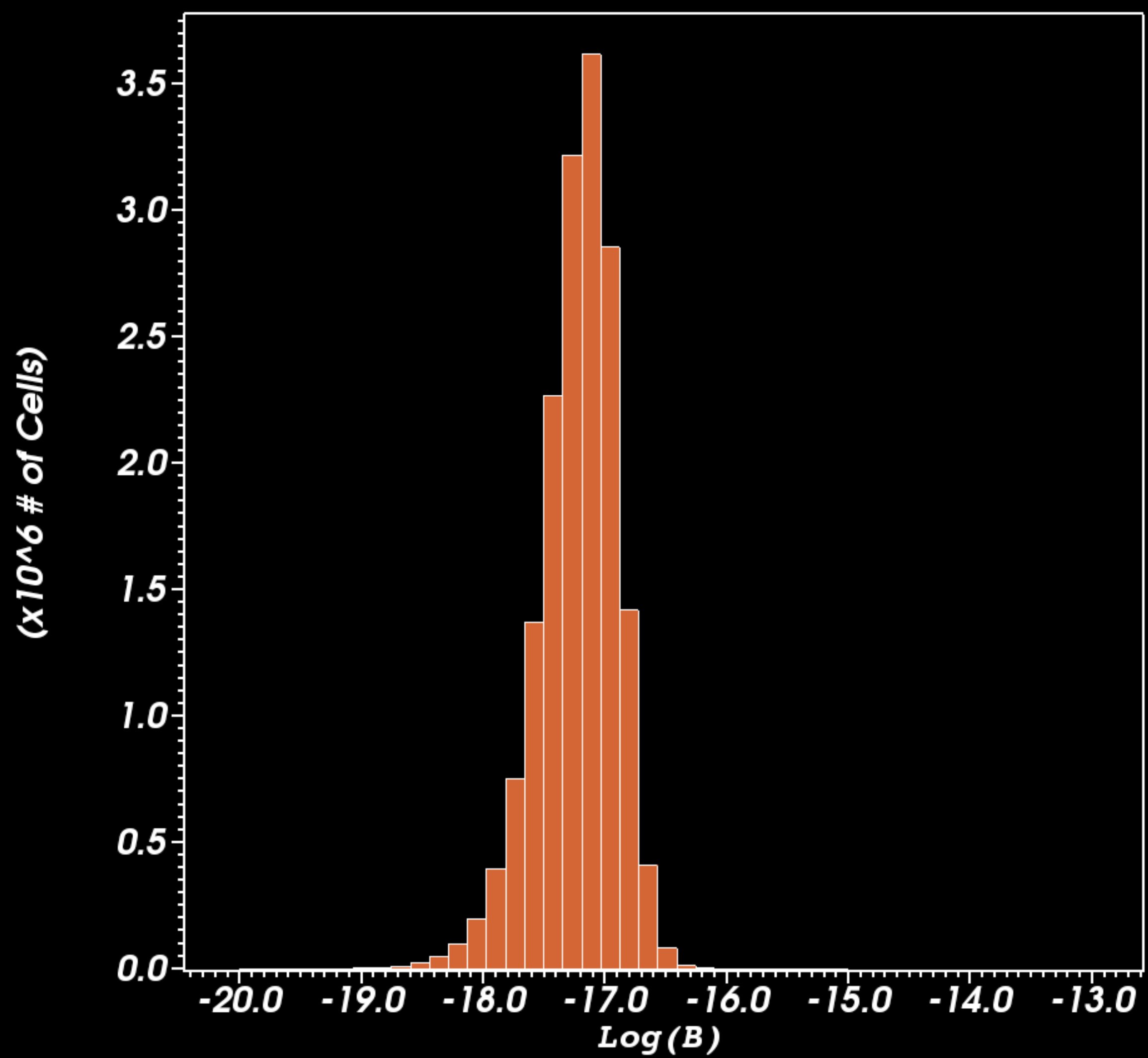
Magnetic Field   Baryonic Density



Miniati & Bell, 2011 (arXiv:1110.4115)

Z~10

Box = 100 h^{-1} kpc
ΛCDM (WMAP7)

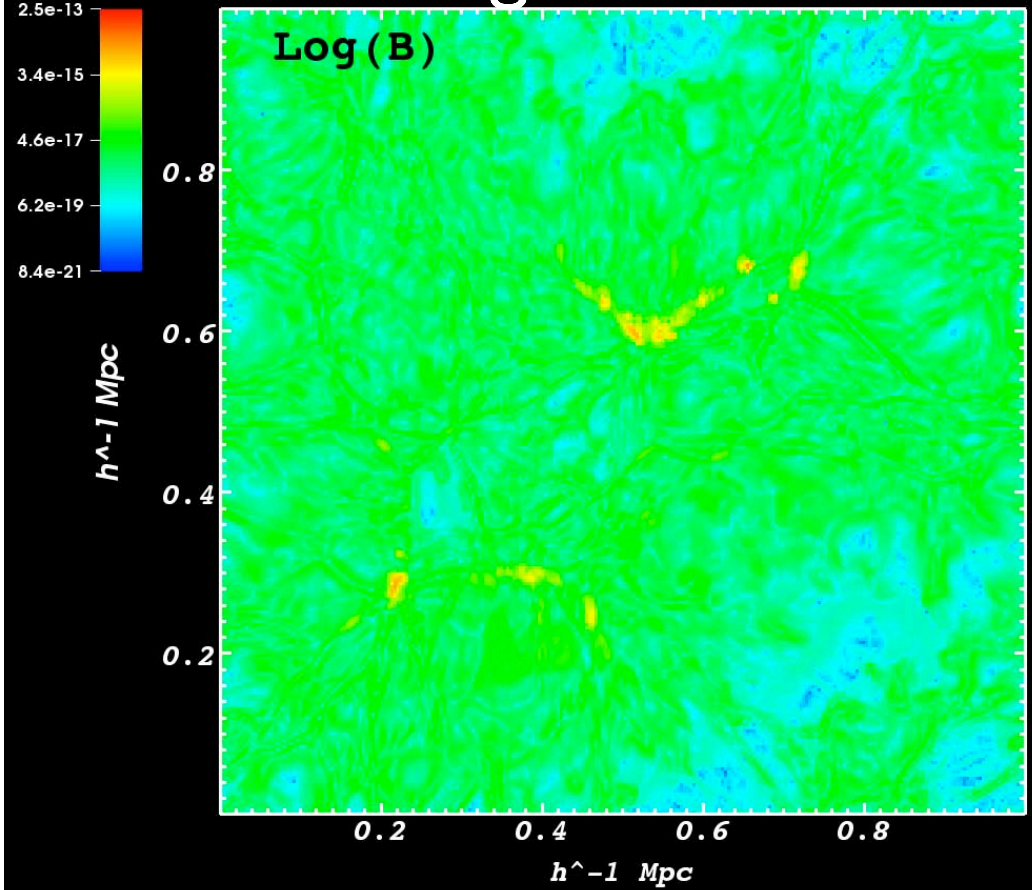


Miniati & Bell, 2011 (arXiv:1110.4115)

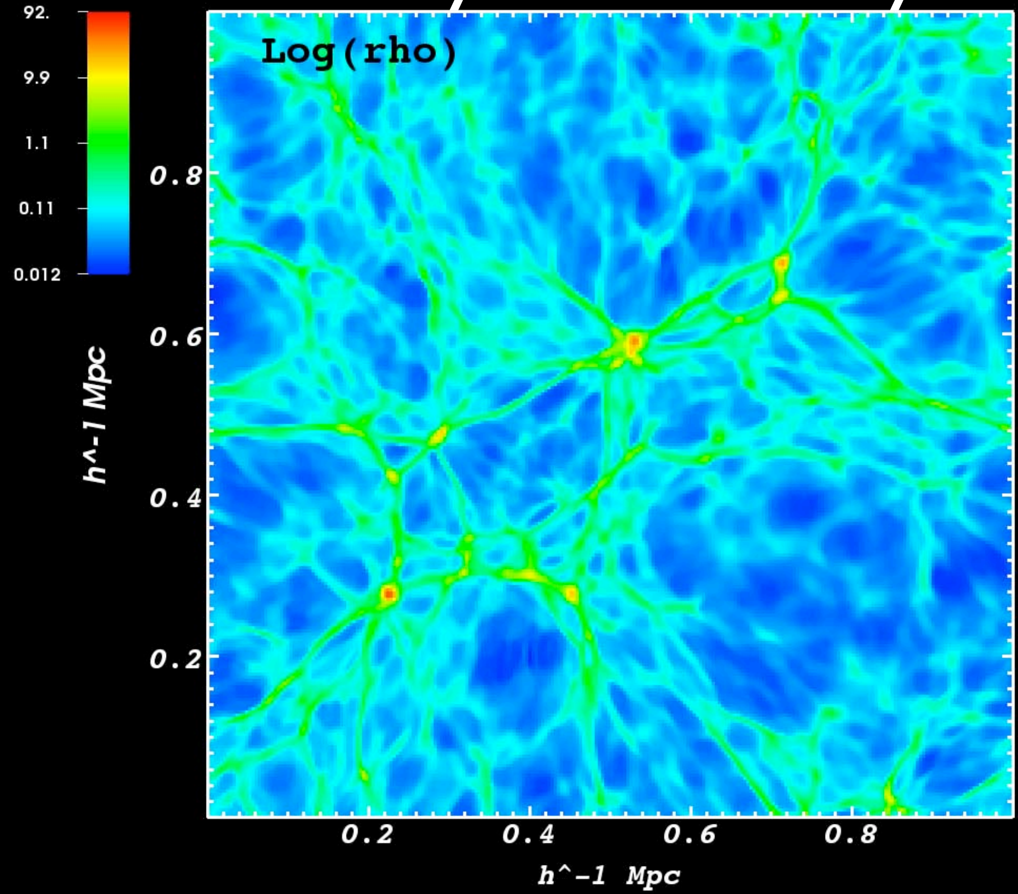
Z~6

Box = 1 h^{-1} Mpc
ΛCDM (WMAP7)

Magnetic Field



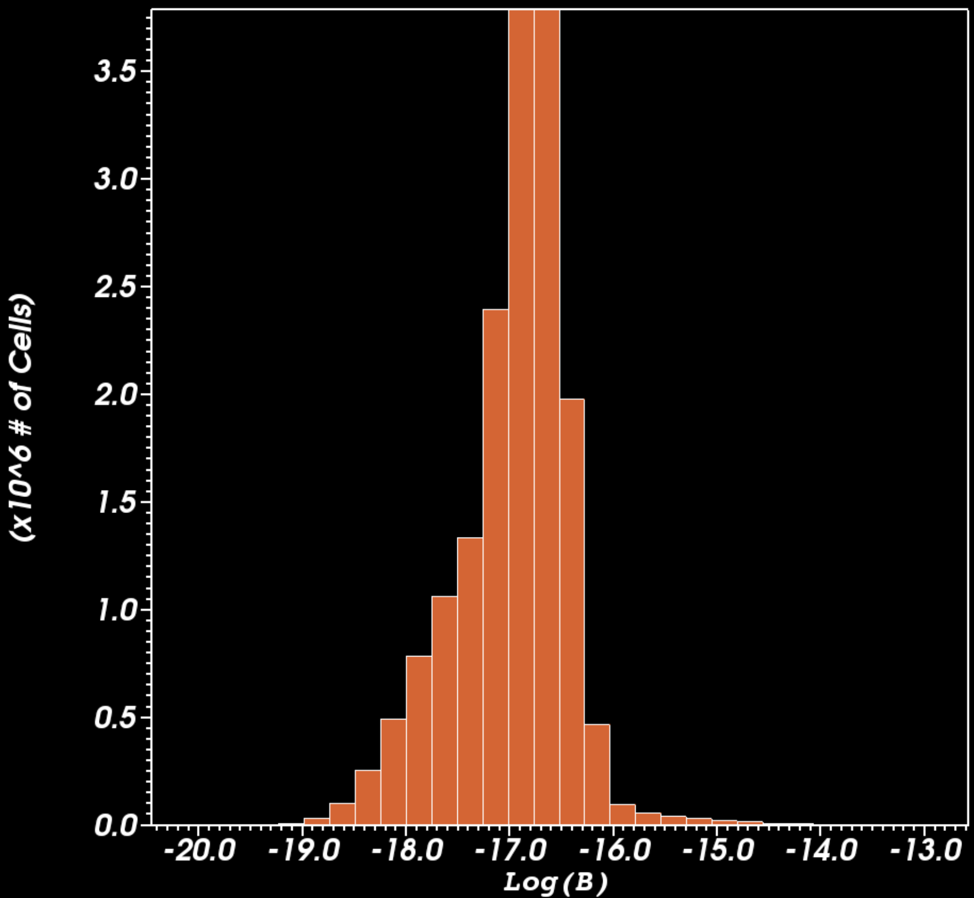
Baryonic Density



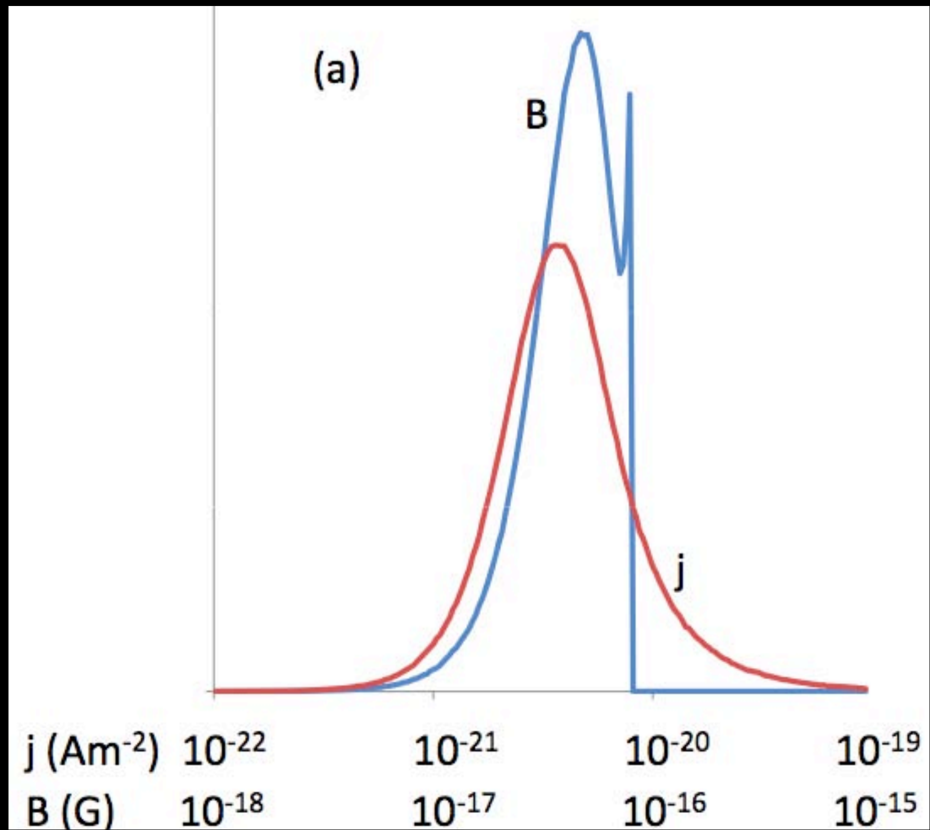
Z~6

Box = 1 h^{-1} Mpc
ΛCDM (WMAP7)

Numerical Simulation



Monte Carlo solution



Non-resonant term

$$\frac{\partial U}{\partial t} + \vec{\nabla} \cdot \vec{F}_{MHD} = S_{Cosmol+Resistive} - \begin{pmatrix} 0 \\ \vec{j}_{CR} \times \vec{B} \\ \vec{u} \cdot \left(\vec{j}_{CR} \times \vec{B} \right) \end{pmatrix} \begin{matrix} \text{mass} \\ \text{momentum} \\ \text{energy} \end{matrix}$$

whence an instability with growth rate (Bell 2005)

$$\gamma = \left(\frac{kBj_{CR}}{\rho} \right)^{\frac{1}{2}} \approx 0.5 \text{ Gyr}^{-1} \left(\frac{\lambda}{kpc} \right)^{-\frac{1}{2}} \left(\frac{B}{5 \times 10^{-17} G} \right)^{\frac{1}{2}} \left(\frac{d}{Mpc} \right)^{-1}$$

important, may be, on 10 Gyr time scales (z~1)

Summary

- Magnetic field are ubiquitous and play several different roles in astrophysical plasma
- Recently discovered in cosmic voids!
- Resistive mechanism provides suitable seed fields $B \sim 10^{-16}$-10^{-17} G at $z \sim 10$-6
- Degree of amplification by the non-resonant instability is not clear yet