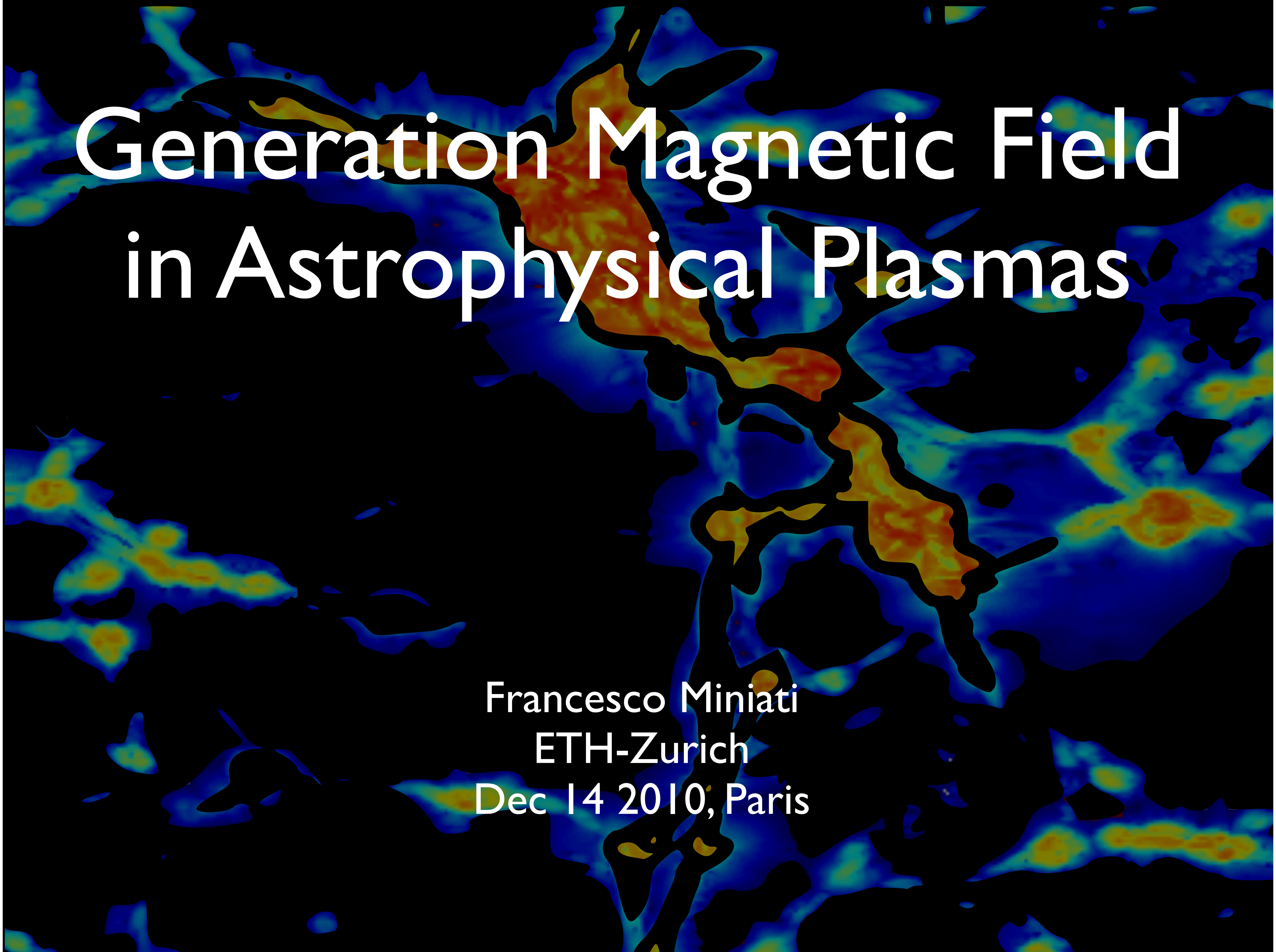

Generation Magnetic Field in Astrophysical Plasmas

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Dec 14 2010, Paris

Outline

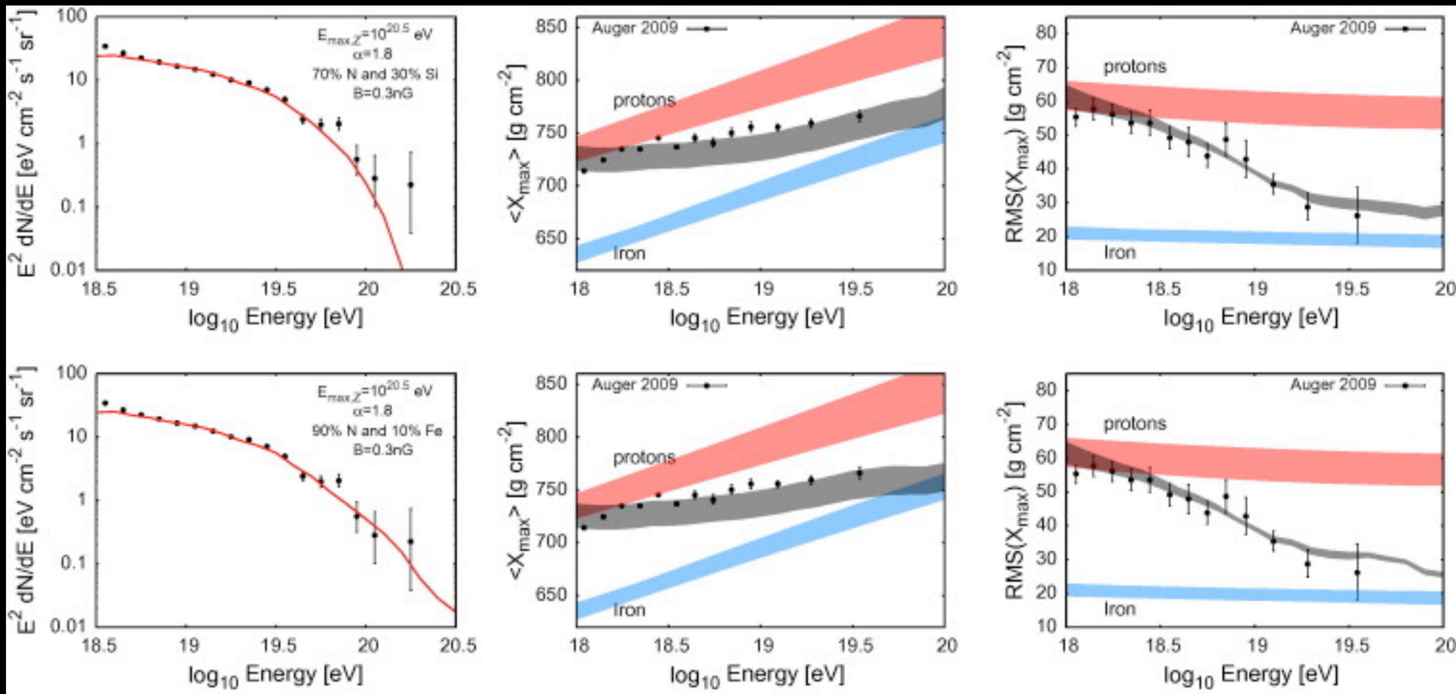
- Introduction
- Viable mechanisms for the generation of magnetic fields.
- Outfows, Biermann, Weibel
- Resistive mechanism
- Summary

Cosmic Magnetism

- Galaxy, nearby galaxies and “high-redshift” galaxies: B~1-10 μG
- Clusters of Galaxies: B ~ 0.1-10 μG
- Filament of Galaxies: B ~ nG (?)
- Cosmic Voids: B ~ 0.1-0.01 fG

Magnetism in Galaxy Filaments

nG strong B-fields ordered on Mpc scales in the low density IGM (f~10%) can cause large deflections Sigl, Miniati, Ensslin (2004, 2005). [see also Dolag et al (2005), Ryu et al. (2008)]



70% nitrogen and 30% silicon

90% nitrogen and 10% iron

Hooper and Taylor Astropart. Phys 33, 3 (2010)

B~0.3 nG, λ_B~1Mpc

Mechanisms

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla} \times \vec{E} = \vec{\nabla} \times \vec{u} \times \vec{B} + \frac{\eta c^2}{4\pi} \nabla^2 \vec{B}$$

- Plasma processes: return currents (Miniati & Bell 2010) Biermann's battery (Subramanian et al 1992, Kulsrud et al. 1997, Gnedin et al. 2000), Weibel's instability (Schlickeiser & Shukla 2003).
- Galactic outflows (Kronberg et al. 1999, Bertone et al. 2006, Donnert et al.2009, Dubois & Teyssier 2010)
- Jets from radiogalaxies (e.g., Furlanetto & Loeb 2001)
- Early Universe (Ichiki et al. 2006)
- Inflationary processes (see talks by Caprini, Durrer, Fenu)

Galactic Outflows

- hydrodynamics is difficult to model (see Bertone et al. 2006), in fact numerical models based on analytic treatment.
- we see MgII absorption lines are magnetized, they extend out to 50-100 kpc for 0.1-3 L_* galaxies, still within virial radius though (Bernet et al 2008).
- required filling factor of metals to reproduce statistics of absorption lines systems at z~3 is about 10% (Booth, Schaye et al 2010 arxiv:1011.5502)

Biermann

E.g., thermoelectric effects induce a current, which stops when enough charge has built up.

E-Gradient $\Rightarrow \nabla \times E$

n_{high} ,P_{high} n_{high} ,P_{low}

\+ −
\+ −
\+ −
\+ −

charge imbalance $\Rightarrow$ $$\frac{\vec{\nabla} P}{n_e} = -e\vec{E}\,'$$

\+ −
\+ −

n_{low} ,P_{high} n_{low} ,P_{low}

Biermann

$$\vec{E} + \frac{\vec{u}}{c} \times \vec{B} = -\frac{\vec{\nabla} P_e}{e n_e}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \vec{u} \times \vec{B} + \frac{m_p c}{e} \frac{\vec{\nabla} P \times \vec{\nabla} \rho}{\rho^2}$$

vorticity follows a similar equation

$$\frac{\partial \vec{\omega}}{\partial t} = \vec{\nabla} \times \vec{u} \times \vec{\omega} - \frac{\vec{\nabla} P \times \vec{\nabla} \rho}{\rho^2}$$

the same as proton gyro-frequency: $\vec{\Omega}_p = -\frac{e\vec{B}}{m_p c}$

Biermann at shock fronts

So without dissipation terms:

$$\omega=\Omega_p$$

and assuming rotational energy ~ gravitational energy

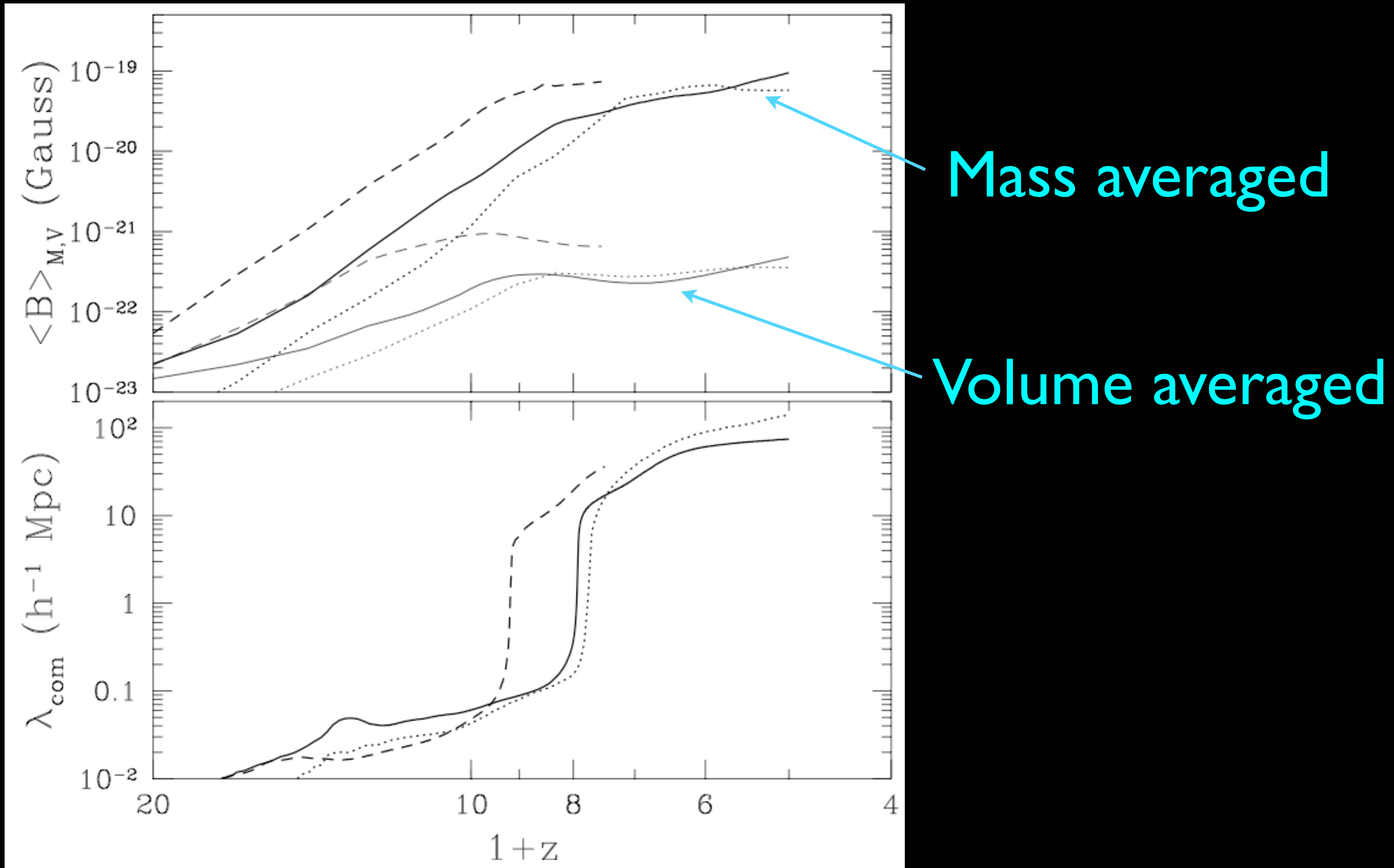
$$\Omega_p=\omega=(4\pi G\rho)^{1/2}$$

$10^4\,\mathrm{s\,G}^{-1}$ → $\frac{m_p c}{e}$

$$B_{Gauss} = -\frac{m_p c}{e}\left(4\pi G\rho\right)^{1/2} = 10^{-19}\,n^{1/2}$$

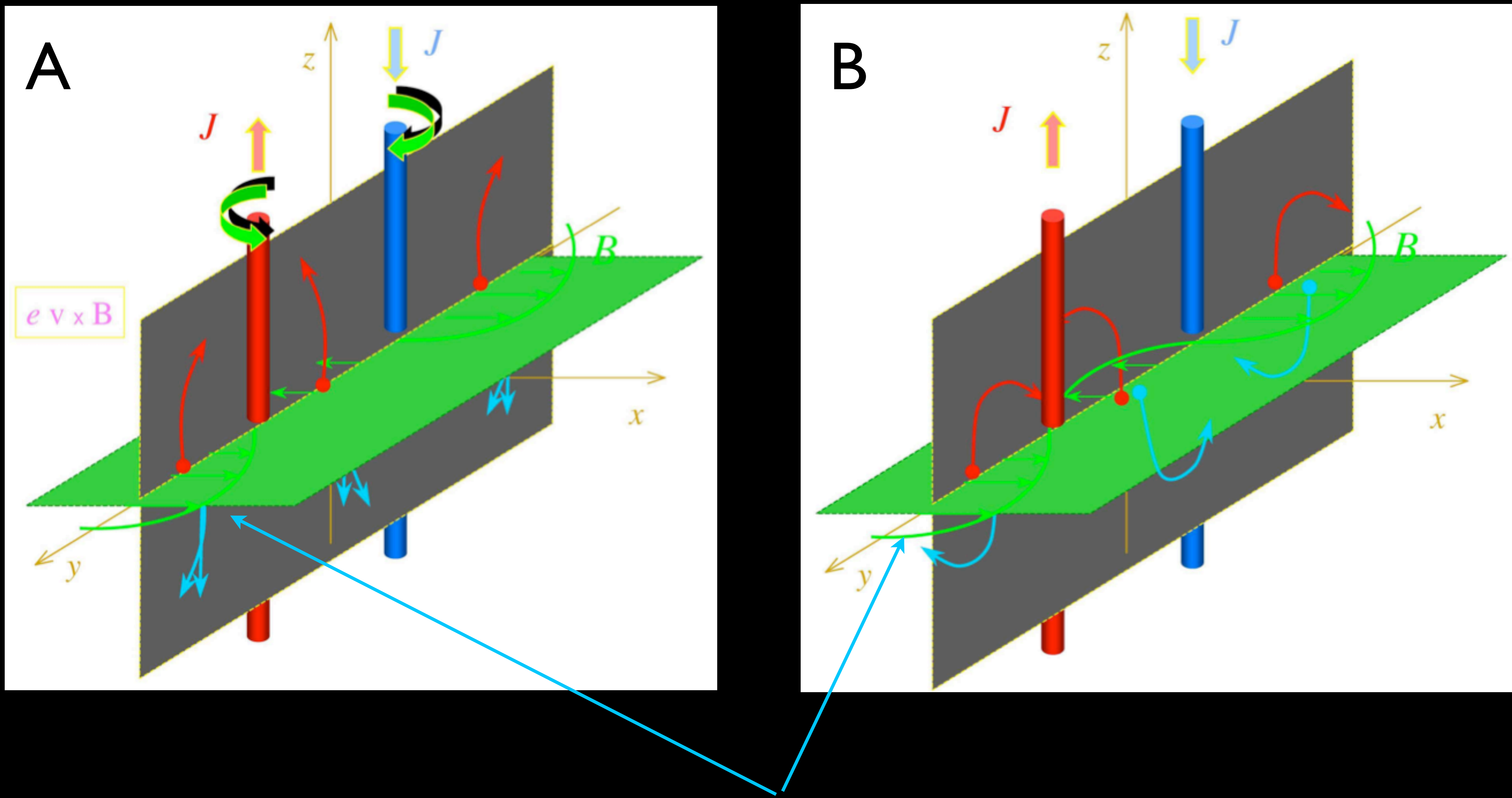
Kulsrud et al ApJ 480, 481 (1997)

Biermann at reionization fronts



Gnedin, Ferrara, Zweibel, ApJ 539 505 (2000)

Weibel



$$\vec{B} = B_x \cos(ky)\hat{x}$$

Medvedev et al. JKAS, 37, 533 (2004)

Scales

$$\frac{\lambda}{\mathrm{cm}} \sim 2\pi \frac{c}{\omega_e} \sim 3\times 10^9 \left(\frac{n_{IGM}}{10^{-6}\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

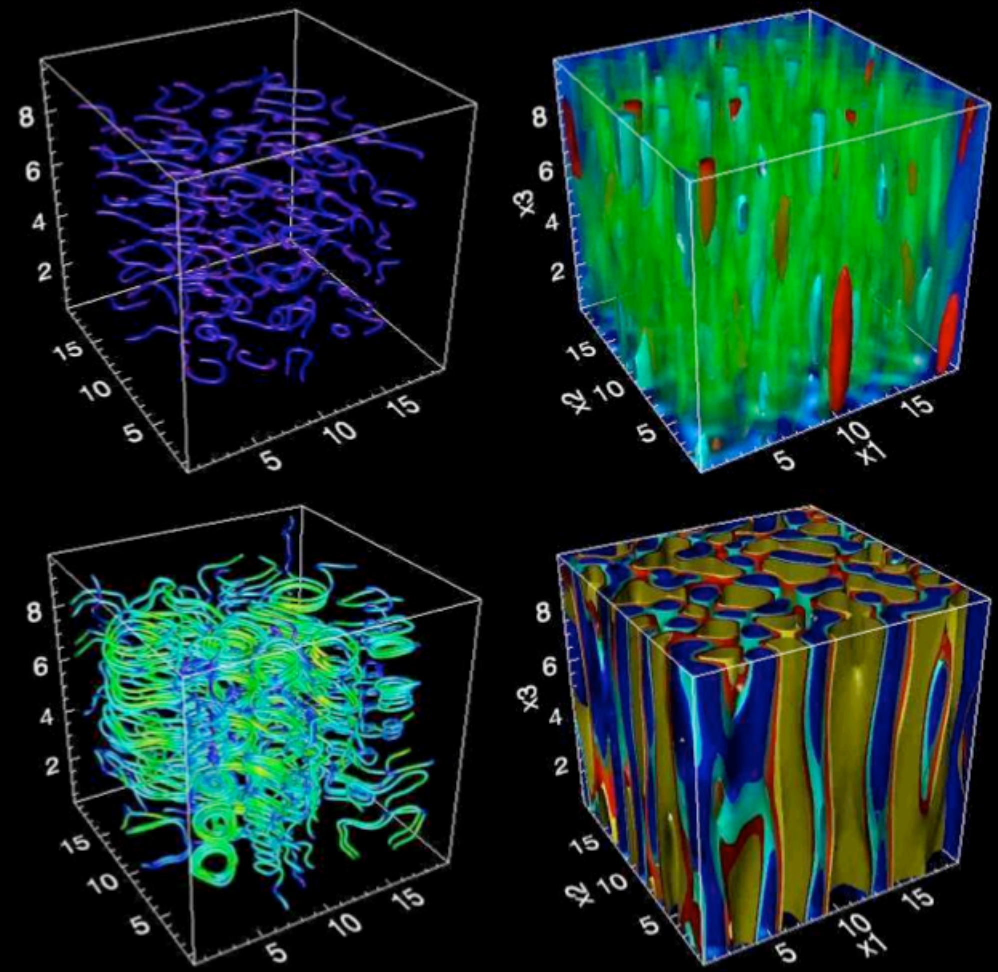
$$\frac{\tau}{\mathrm{sec}} \sim \frac{c}{\omega_e}\frac{1}{u_{sh}} \sim 10^2 \left(\frac{u_{sh}}{10^7\,\mathrm{cm/s}}\right)^{-1}\left(\frac{n_{IGM}}{10^{-6}\,\mathrm{cm}^{-3}}\right)^{-1/2}$$

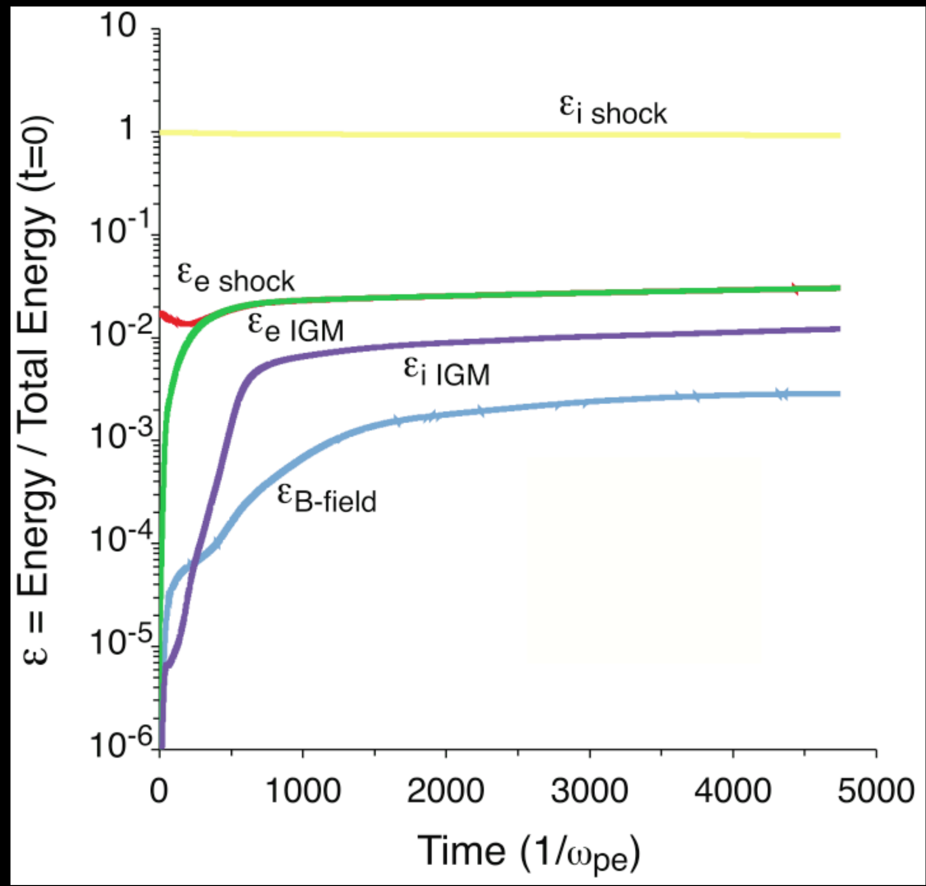
Saturation

$$\lambda \sim r_L = \frac{u_{sh}}{\Omega_e} \quad \Rightarrow \quad \mathrm{B} \sim 10^{-9}\left(\frac{u_{sh}}{10^7\,\mathrm{cm/s}}\right)\left(\frac{n_{IGM}}{10^{-6}\,\mathrm{cm}^{-3}}\right)^{1/2}$$

Medvedev, Silva, Kamionkowski ApJL, 642, 1 (2006)

Weibel





ε = Energy / Total Energy (t=0)
Time ($1/\omega_{pe}$)
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
0
1000
2000
3000
4000
5000
$\varepsilon_{i\ shock}$
$\varepsilon_{e\ shock}$
$\varepsilon_{e\ IGM}$
$\varepsilon_{i\ IGM}$
$\varepsilon_{B\text{-}field}$

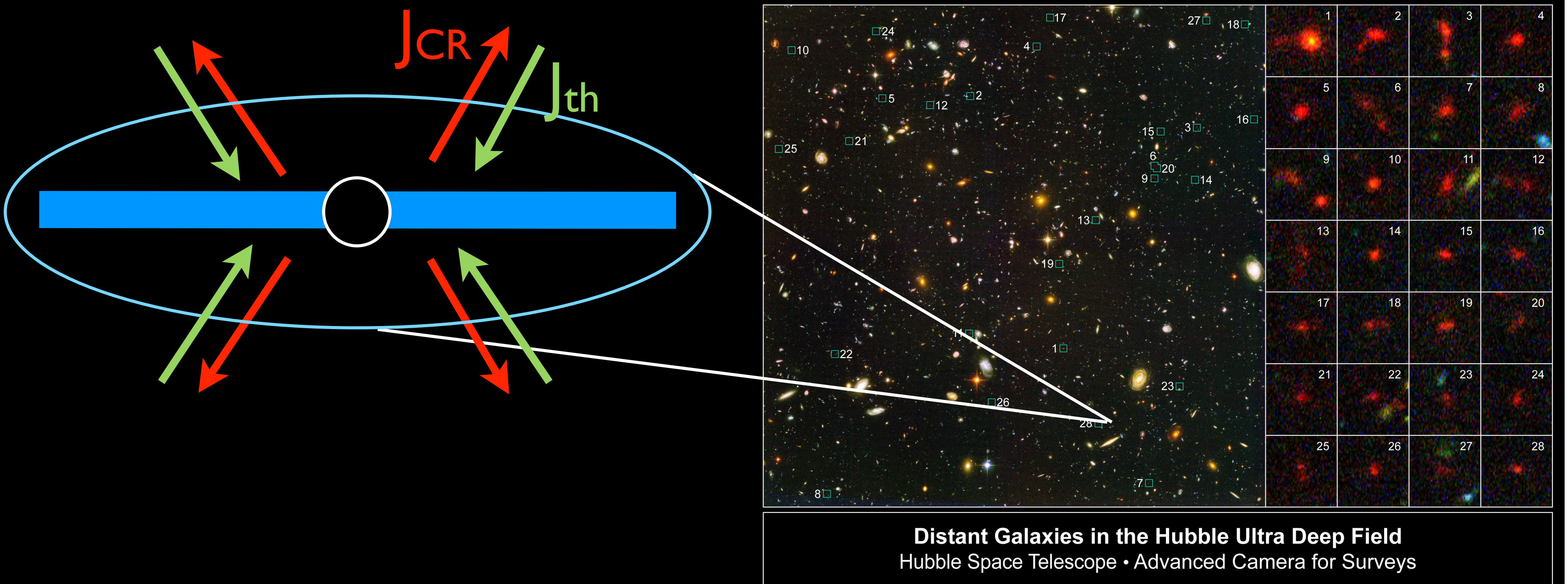
Remarks

- Biermann seed is quite low and requires remarkable amplification to match the observed magnetic fields in galaxy clusters. Perhaps turbulent amplification is sufficient (Ryu et al 2008), but this is in tension with LSS numerical simulation (which predict ampl. factors $\sim 10^3$.)
- Weibel's field is they survive resistive dissipation, are unlikely to affect propagation of UHECRs, unless there is a way to stretch them out by some 15 orders of magnitude.
- Neither Wiebel nor Biermann, as they operate at shocks (at least the way they are being currently modeled), can generate magnetic fields in voids because.

Resistive Mechanism

(FM & Bell, arXiv:1001.2011)

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



NASA, ESA, R. Bouwens and G. Illingworth (University of California, Santa Cruz)

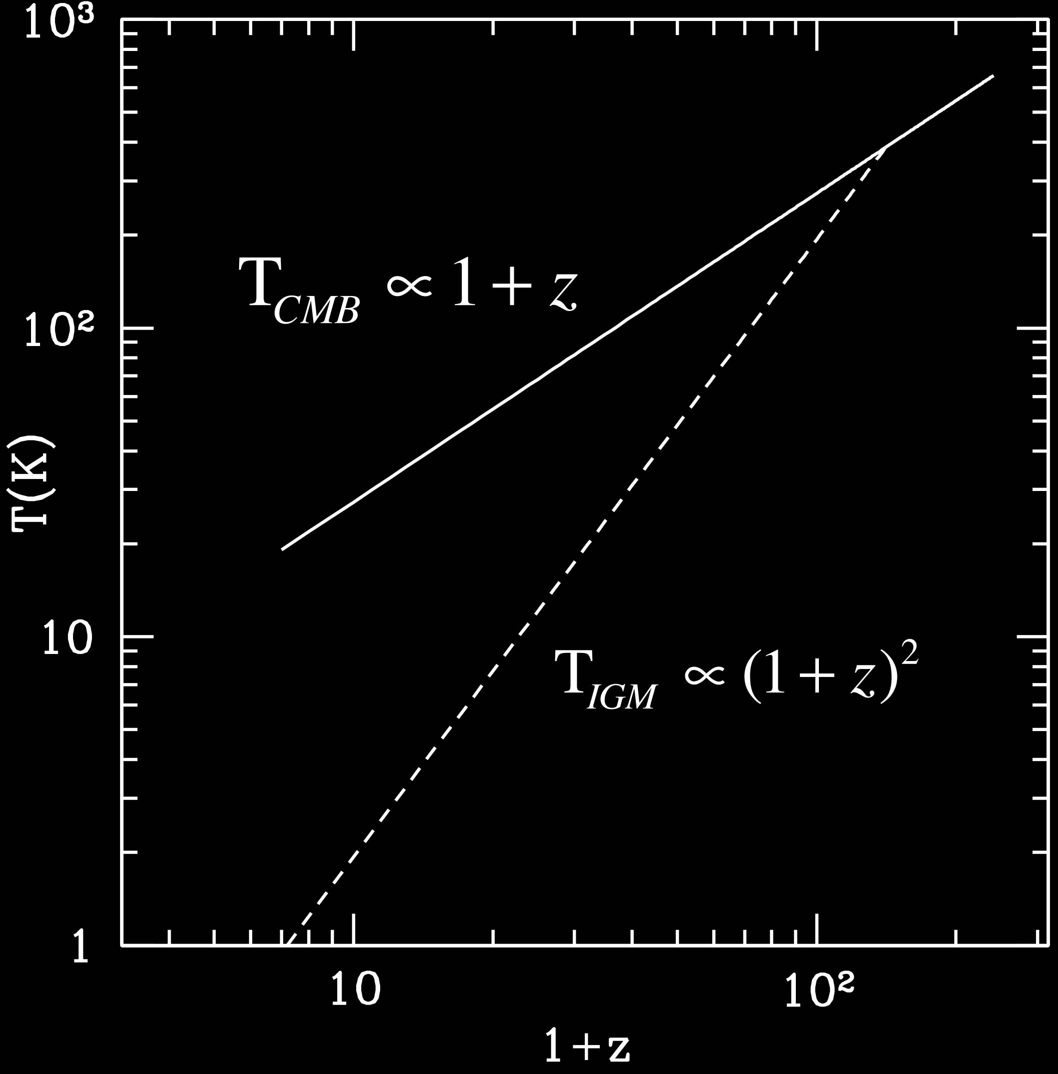
Basics

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

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

- the Electric field is due to charge imbalance and induction.

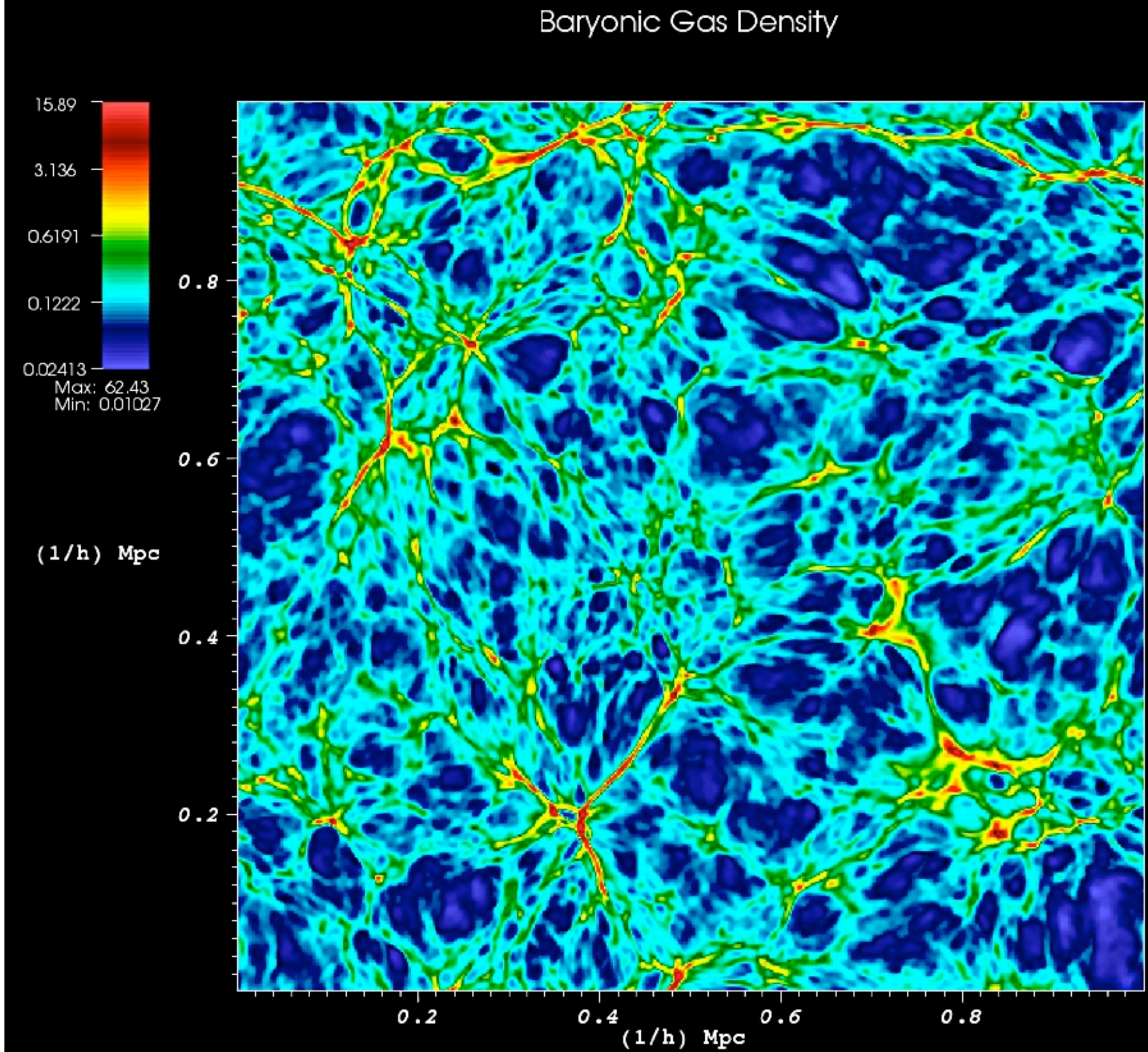
Temperature evolution

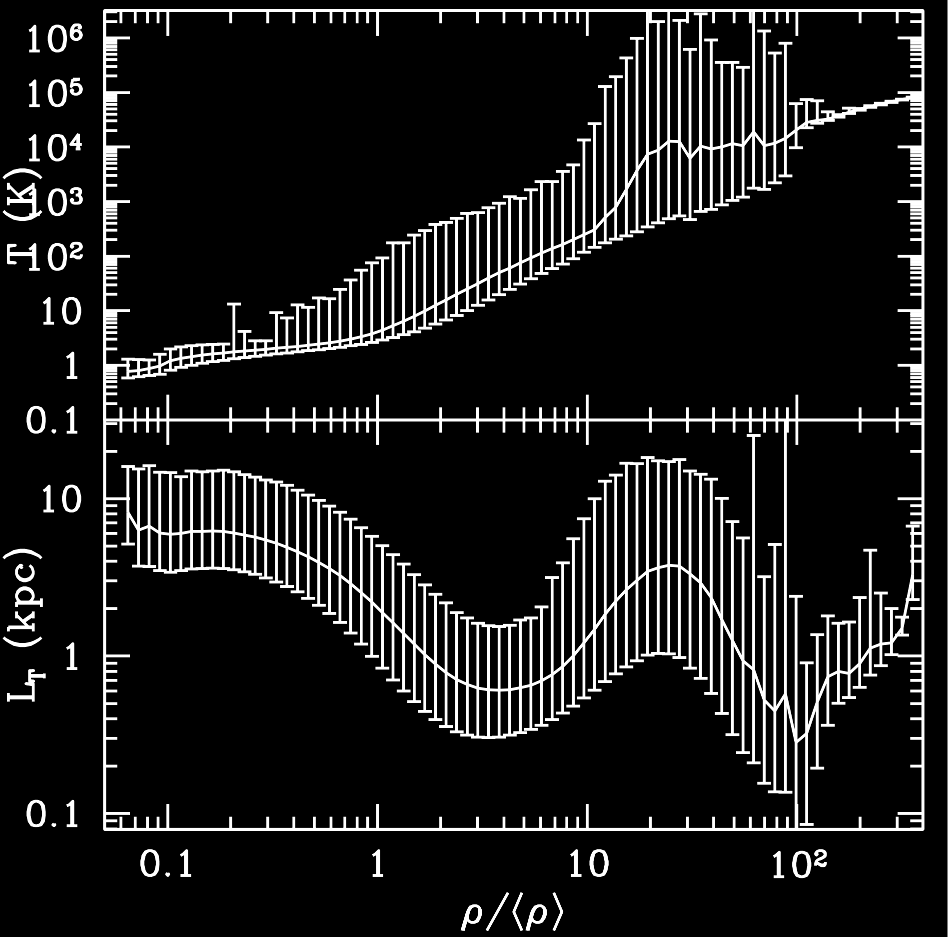


Compton scattering efficiently couples T_{IGM} and T_{CMB} only for z>140.

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

IGM at z≈6





Miniati & Bell (2010)

Governing Equations

Ampere: $$\vec{\nabla} \times \vec{B} = \frac{c}{4\pi}\left(\vec{j}_{cr} + \vec{j}_{th}\right)$$

Ohm: $$\vec{E} + \frac{\vec{u}}{c} \times \vec{B} = \frac{c}{4\pi\sigma}\vec{\nabla} \times \vec{B} - \frac{\vec{j}_{cr}}{\sigma}$$

Faraday: $$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \vec{u} \times \vec{B} - \frac{c^2}{4\pi\sigma}\vec{\nabla} \times \vec{\nabla} \times \vec{B} + c\vec{\nabla} \times \frac{\vec{j}_{cr}}{\sigma}$$

Ohmic Heating: $$\frac{3}{2}nk_{B}\frac{dT}{dt} = \frac{1}{\sigma}j_{cr}^2$$

Growth rate around bright galaxies

$$\dot{B} \approx c\vec{j}_{cr} \times \vec{\nabla}\frac{1}{\sigma} \approx \frac{cj_{cr}}{\sigma \ell_T}$$

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

CR-current density

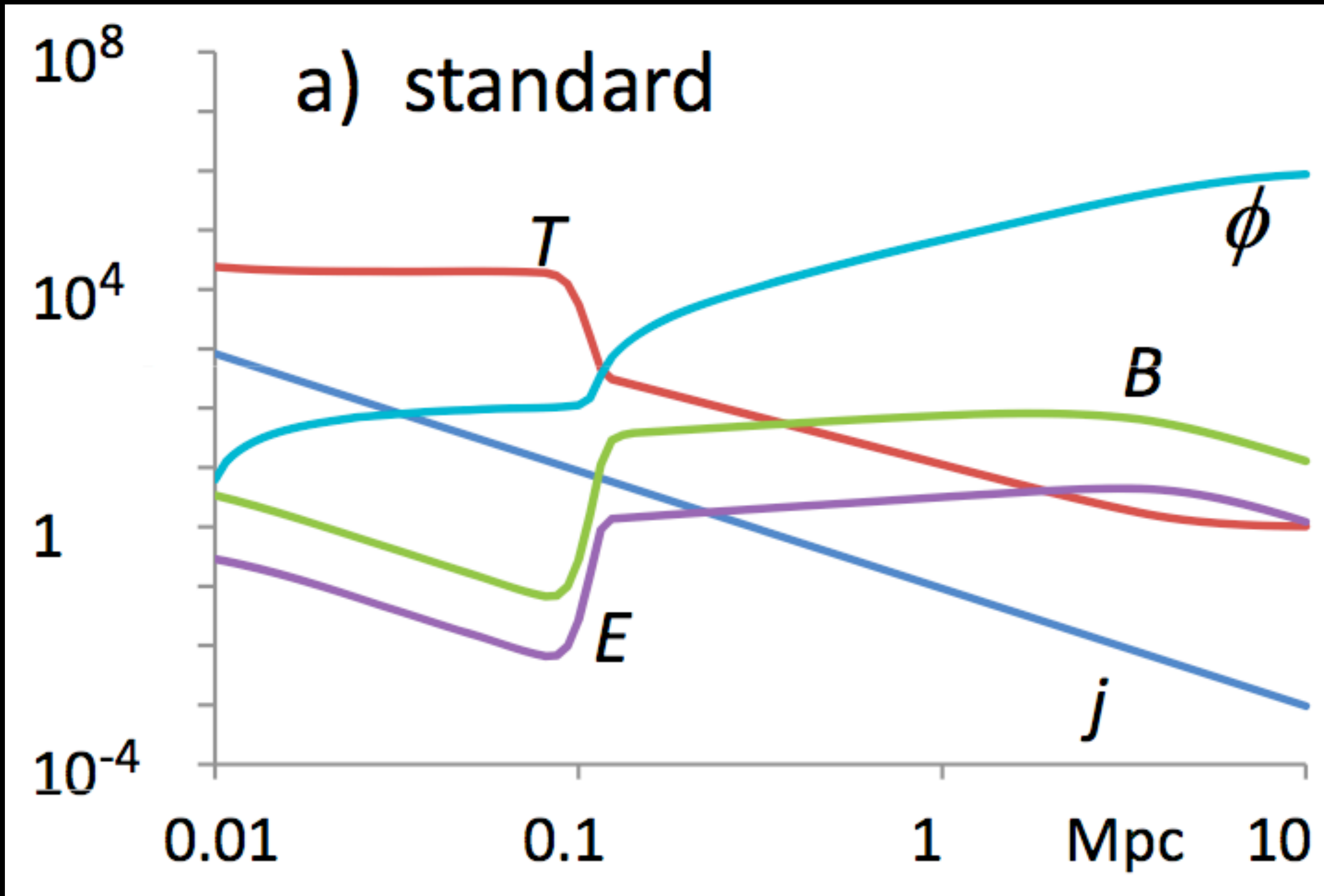
$$j_{cr} \simeq \frac{e\varepsilon_{cr}L}{2\pi R^2 p_{\min} c\Lambda_{cr}}\left(\frac{\theta d}{R}\right)^{-2}$$

Temperature scale-length

$$\ell_T \equiv \frac{T}{|\nabla T|}$$

Ohmic heating increases the temperature, i.e. conductivity, so after one Gyr B~10^{-16} Gauss.

Solution Profile



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

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

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

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

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

Galaxy luminosity function at high z

Luminosity Function

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

Luminosity of bright galaxies

$$L_* = 5.2 \times 10^{21}\,\mathrm{W\ Hz}^{-1}$$

Number density of bright galaxies

$$\Phi_* = 10^{-3}\,\mathrm{Mpc}^{-3}$$

Faint slope end

$$\alpha = 1.77$$

Growth rate in the IGM

Luminosity Function

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

Mean distance between L-galaxies

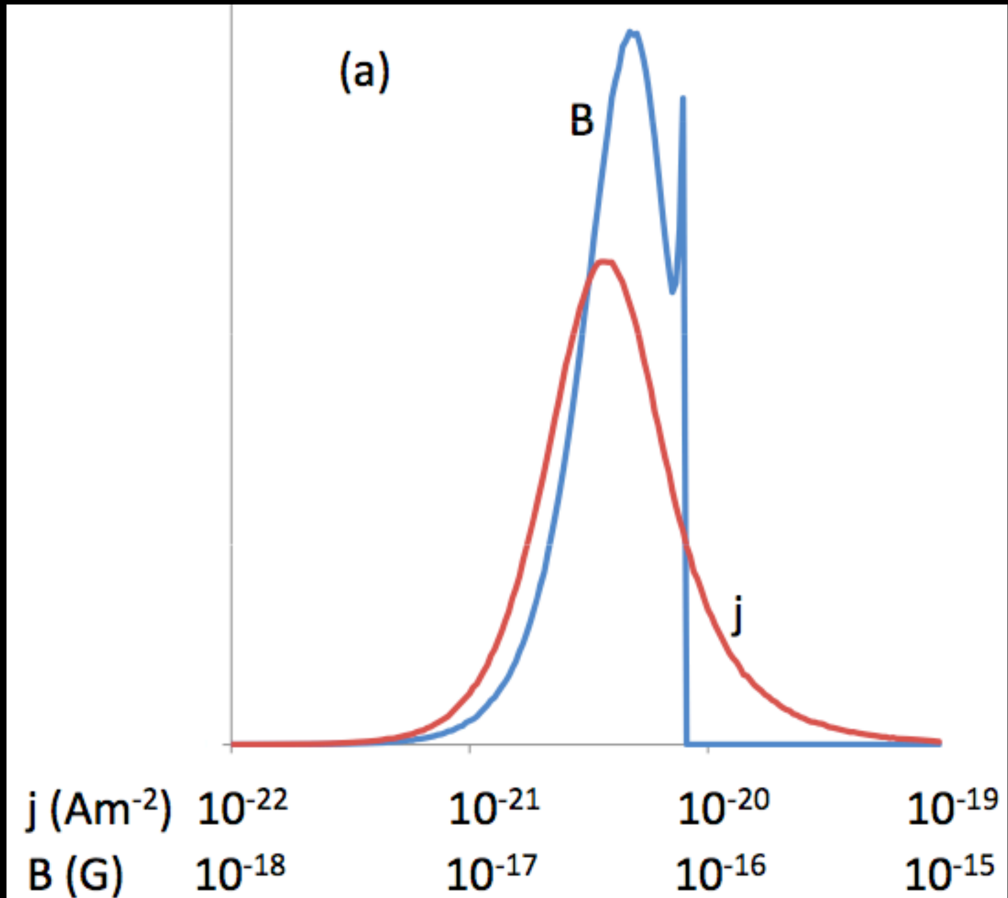
$$\langle d_L \rangle = \left[\frac{L}{L_*}\Phi(L)\right]^{-1/3} \propto L^{(\alpha-1)/3}$$

Magnetization around L-galaxies

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

Prior to reionization the universe is magnetized with fields $B \sim 10^{-16}$-10^{-17} G

IGM MC Solution



Prior to reionization the universe is magnetized with fields $B \sim 10^{-16}$-10^{-17} G

Summary

- Magnetic fields are ubiquitous and various mechanisms likely responsible for their origin.
- Interesting recent developments to measure magnetic fields in filaments and voids
- Resistive mechanism provides suitable seeds for effects observed in filaments and voids, with fields $B \sim 10^{-16}$-10^{-17} G at $z \sim 6$.