Cosmic rays and magnetic field in the early universe

with examples from laser-plasmas

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How cosmic rays might be responsible for the primordial magnetic field

Magnetic field in early universe

Must be generated from zero field

Universe at time of reionization, first stars/galaxies: t <1 Gyr, z ~ 6 - 10

Distance between galaxies: ~ 1 Mpc

Thermal plasma: n_e~10^{-4}cm^{-3}, T~1K (>100kpc from galaxies), ionisation fraction ~ 10^{-4}

968 *R. J. McLure et al.*

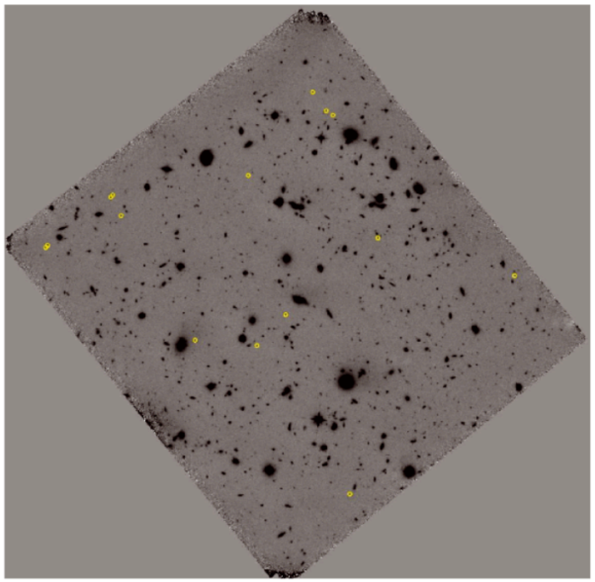
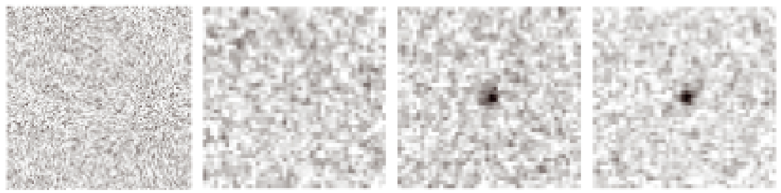


Figure 4. The positions of the 15 galaxies in our sample with primary photometric redshift solutions at $z > 7$ overplotted on the new WFC3/IR H_{160}-band image of the HUDF (north is up and east is to the left). The four most distant galaxies in the sample (at $z > 7.8$) are confined to the groups at the north and north-east of the image.

Hubble deep field:
galaxies at time of formation

McClure et al (MNRAS 2010)



z = 8.45

Ways of producing magnetic field from nothing

1. Biermann battery (baroclinic source)
2. Weibel instability
3. Resistive field generation

Biermann battery (baroclinic source)

Field produced by gradients in density and temperature as structure forms

Quasi-neutrality maintained by $n_e e E = -\nabla P_e$ where $P_e = n_e e T$

$$\Longrightarrow \quad E = -\frac{\nabla P_e}{n_e e}$$

At constant density

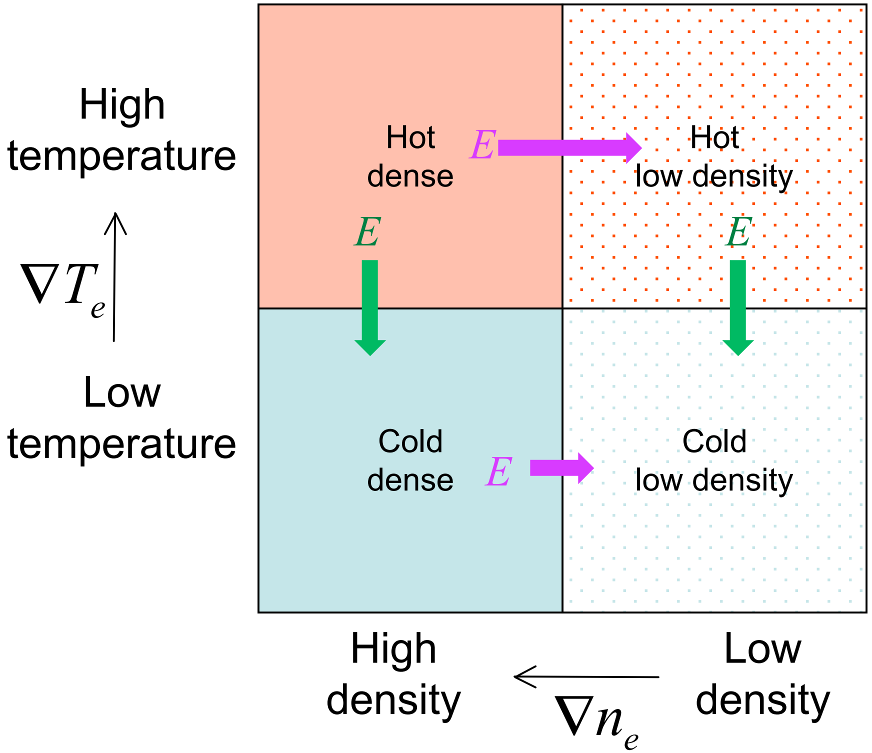
$$\boxed{E = -\nabla T_e}$$

At constant temperature

$$\boxed{E = -T_e \frac{\nabla n_e}{n_e}}$$

Integrate around centre

$$\oint E.dl \neq 0$$



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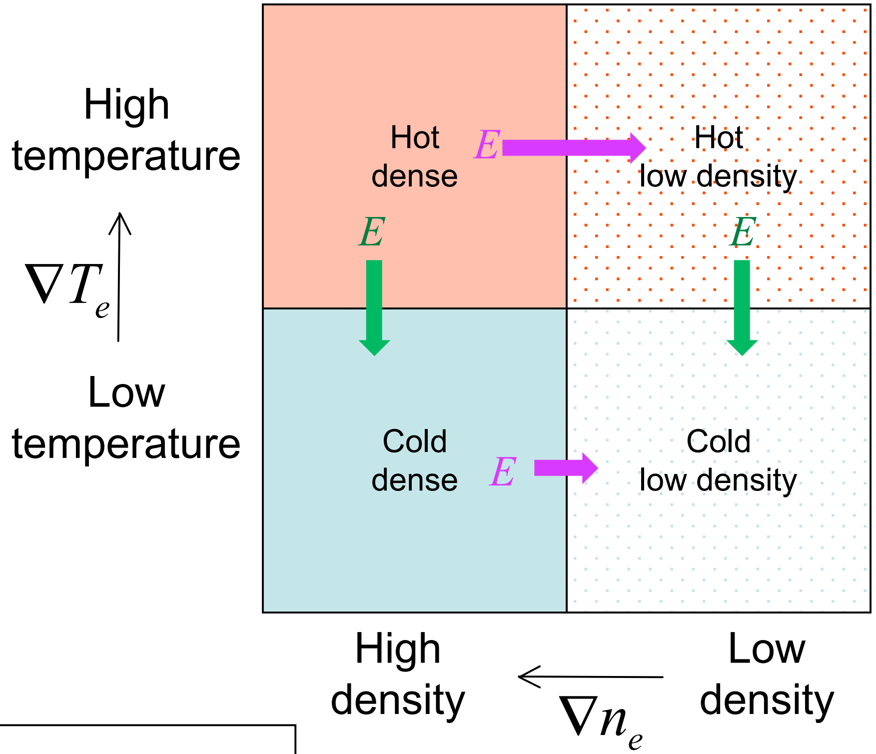
Integrate around centre

$$\oint E.dl \neq 0$$

$$\boxed{\frac{\partial B}{\partial t} = \frac{1}{n_e} \nabla n_e \times \nabla T}$$



Magnetic field in laser-plasma experiments

Borghesi et al 1998

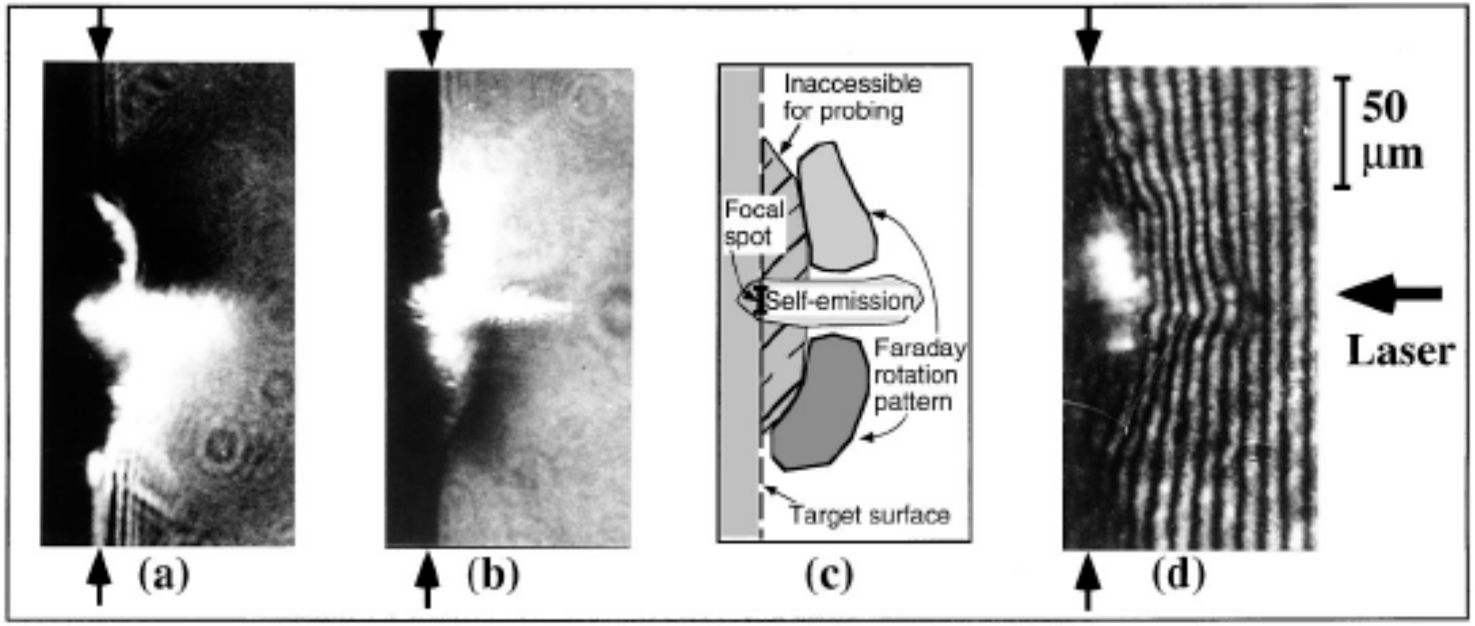
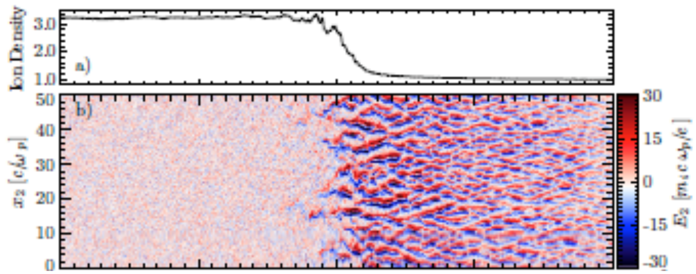


FIG. 1. (a), (b) Polarigrams taken 12 ps after the interaction of a 10 TW, 1.5 ps laser pulse with a solid Al target, with the two polarizers $-9°$ and $+12°$ off crossed. The position of the target surface is indicated by the arrows. (c) Schematic showing the main features of the polarigrams. (d) Interferogram recorded 15 ps after the interaction.

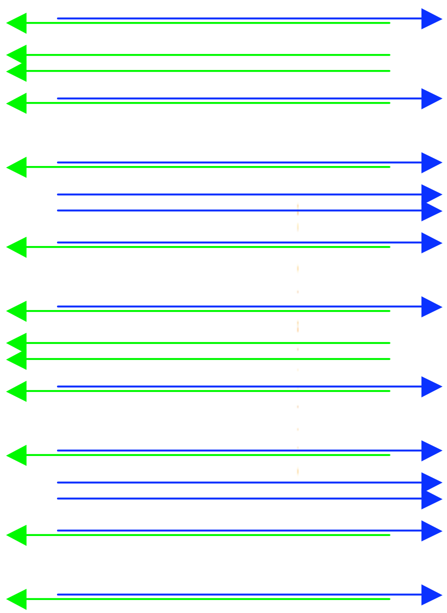
Weibel instability: opposing energetic electron beams

Produces field on small scale near shocks

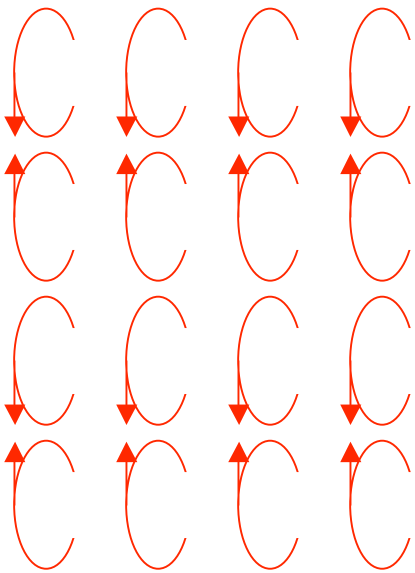


Martins et al 2009, electron ion plasma

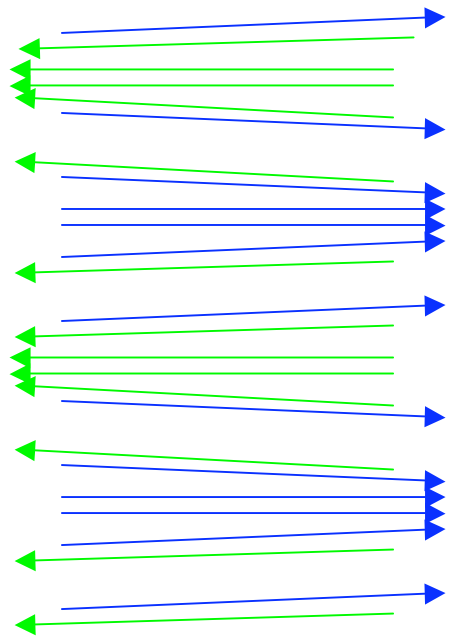
1) Perturbed beam density



2) Magnetic field

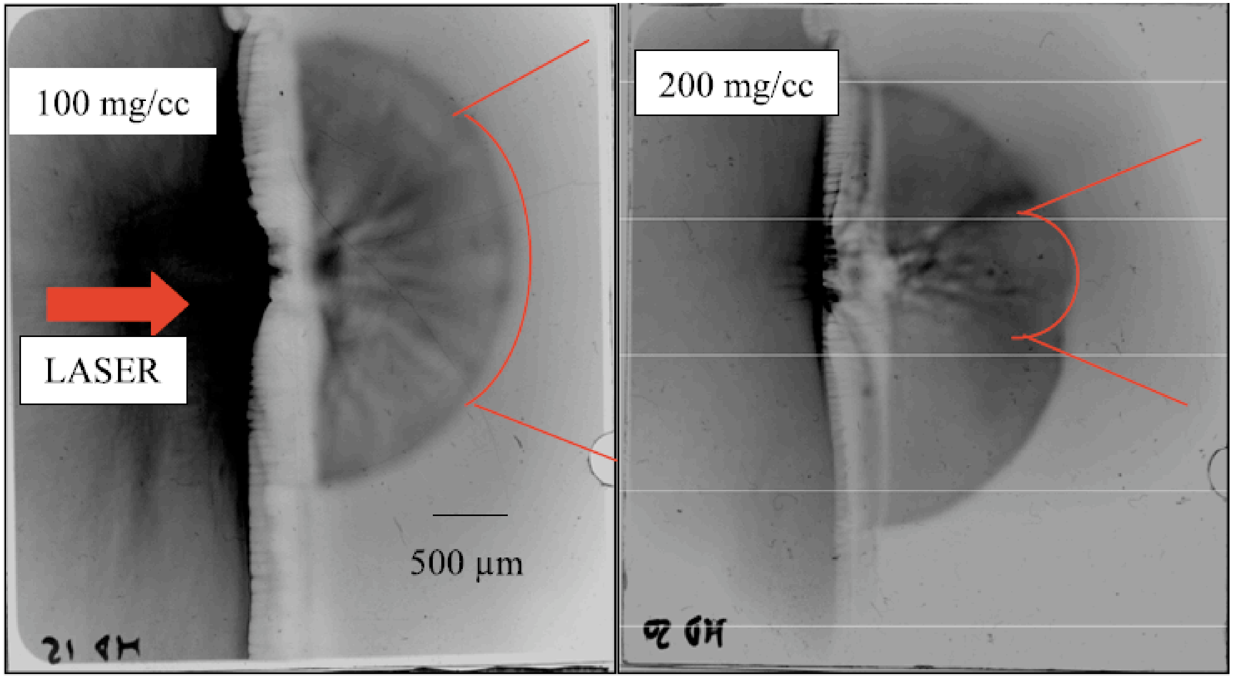


3) Focus currents



Electron beam filamentation

Ramakrishna et al (2009)



T= 2ps T=2ps

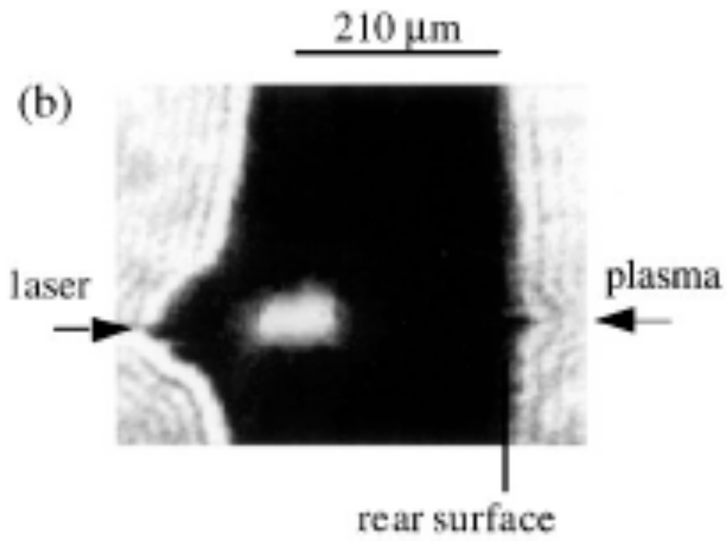
Fig. 3 RCF images of foam targets following CPA interaction. The density of the foam is indicated in figure. Timing relative to the interaction is indicated below the figures. The hemi-circular shadow on the right side of the images is due to the half-washer enclosing the foam (see Fig. 2), while the *vertical white band* at the centre of the images corresponds to the foam-vacuum interface. Beside plasma expansion from the interface into the vacuum, the images clearly show filamentary structures appearing inside the bulk of the target. The cone containing the filaments expanding from the interaction point is indicated by the *red lines* on the right of the figure

Resistive field generation

Produced by charge energetic particle currents in a resistive plasma

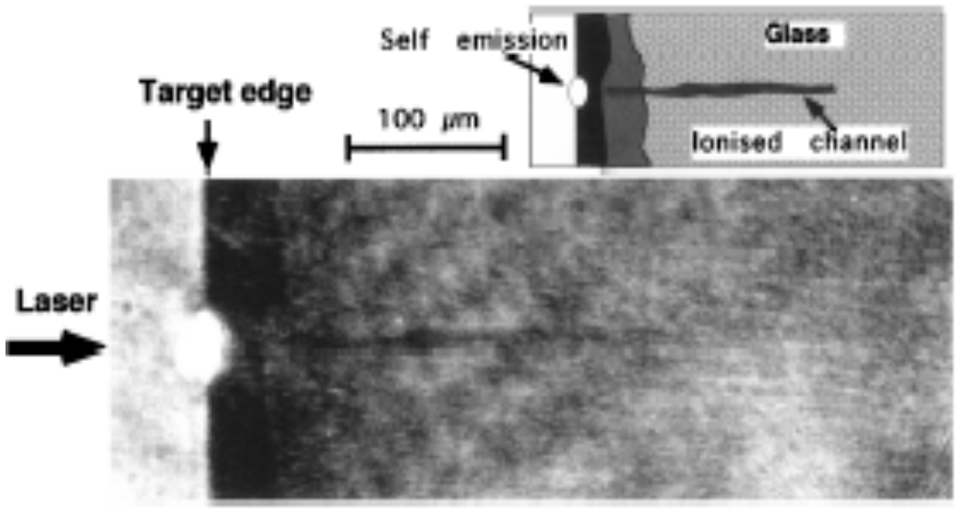
Laser incident on this solid foil
Produces energetic electrons

Tatarakis et al, PRL 81, 999 (1998)

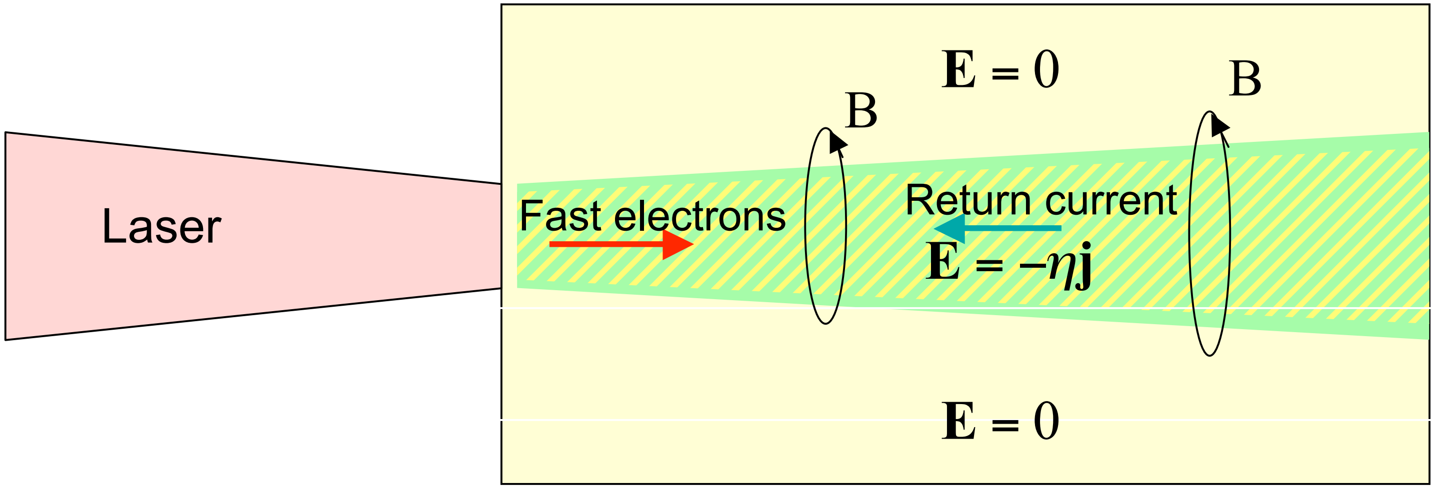


Electrons self-collimate into beam in glass target

Borghesi et al PRL 83, 4309 (1999)



Resistive field generation



Laser produces fast electrons carrying current **j**

Neutrality/induction: Thermal electrons carry return current **-j**

Collisional return current drawn by field: **E** = - η **j**

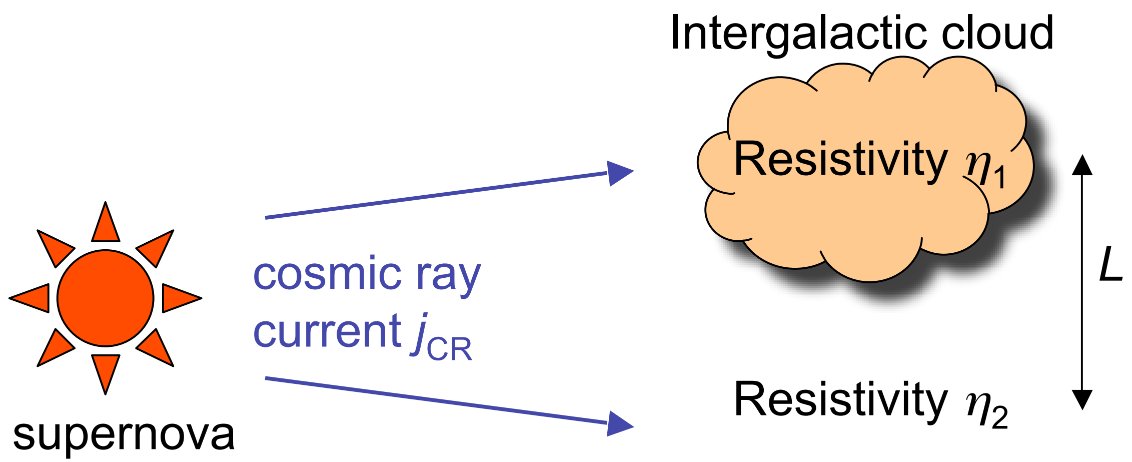
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E} \quad \Longrightarrow \quad \frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\eta \mathbf{j})$$

Resistive magnetic field generation

in the early universe

Resistive field generation in the early universe

from megaGauss/psec to attoGauss/Gyr



Need stronger E to draw return current through dense cold cloud

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\eta \mathbf{j}) \quad \Longrightarrow \quad \frac{\partial B}{\partial t} \sim \frac{j_{CR}}{L}(\eta_1 - \eta_2)$$

Uniform current j_{CR}

Magnetic field for constant CR current

$$\frac{\partial B}{\partial t} \sim \frac{\eta j_{CR}}{L_T}$$

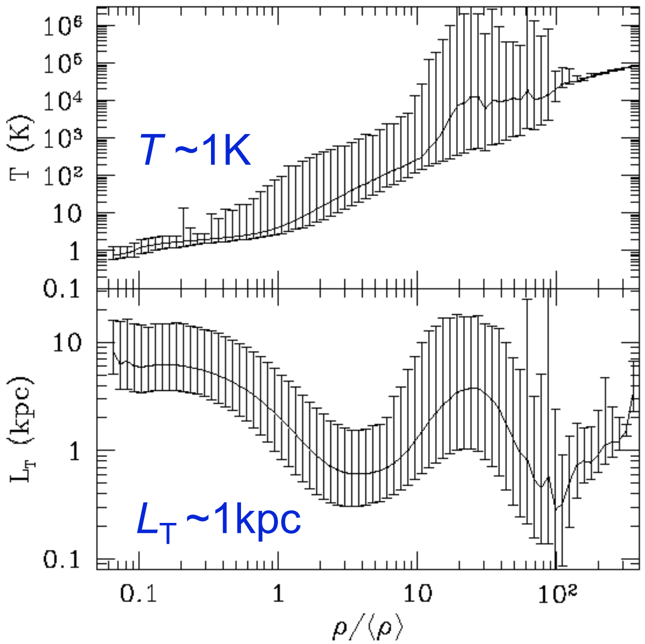
$$j_{CR} = 5.3\times 10^{-20}\left(\frac{L}{L_*}\right)\left(\frac{R}{\mathrm{Mpc}}\right)^{-2}\left(\frac{p_{\min}}{m_p c}\right)^{-0.3}\left(1+\frac{p_{\min}}{m_p c}\right)^{-1}\ \mathrm{Amp\,m^{-2}}$$

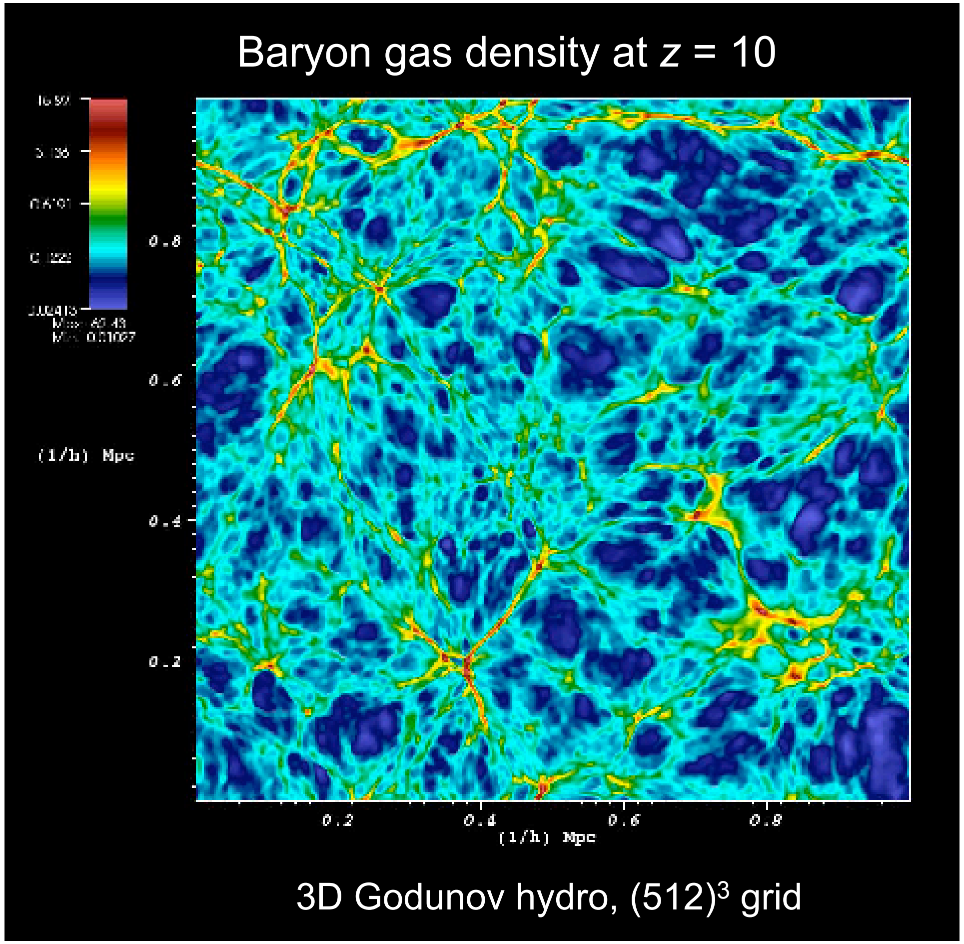
where: L is the galaxy luminosity
L_*= luminosity of typical bright galaxy
R is the distance from the galaxy
p_{min} is the minimum CR momentum
CR energy spectrum ~$p^{-2.3}$
CR energy production assumed to be 30% efficient

Produces an electric field

$$E = \eta j_{CR} = 0.2\left(\frac{L}{L_*}\right)\left(\frac{R}{\mathrm{Mpc}}\right)^{-2}\left(\frac{p_{\min}}{m_p c}\right)^{-0.3}\left(1+\frac{p_{\min}}{m_p c}\right)^{-1}\left(\frac{T}{K}\right)^{-3/2}\ \mathrm{Volt\ parsec^{-1}}$$

Cosmological simulation
(Miniati)





Baryon gas density at z = 10

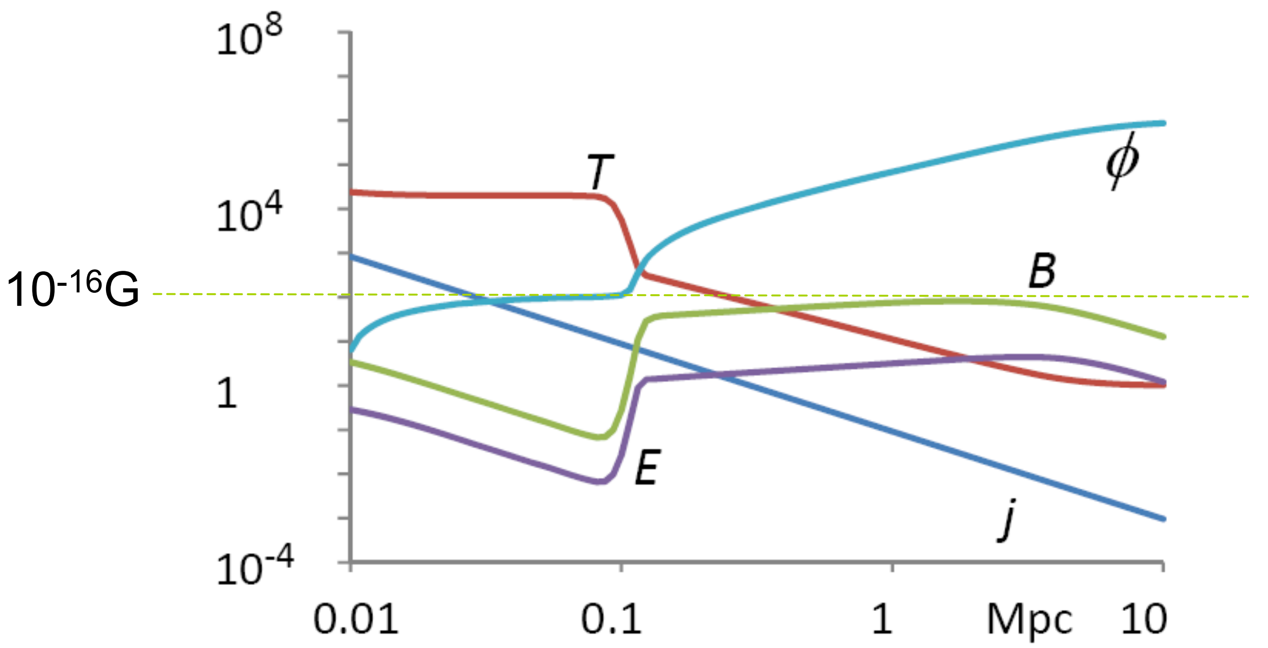
3D Godunov hydro, $(512)^3$ grid

140kpc

$$\Rightarrow B = 2\times10^{-16}\left(\frac{L}{L_*}\right)\left(\frac{R}{\mathrm{Mpc}}\right)^{-2}\left(\frac{p_{\min}}{m_p c}\right)^{-0.3}\left(1+\frac{p_{\min}}{m_p c}\right)^{-1}\left(\frac{T}{K}\right)^{-3/2}\left(\frac{L_T}{\mathrm{kpc}}\right)^{-1}\left(\frac{t}{\mathrm{Gyr}}\right)\mathrm{Gauss}$$

Determine self-consistently from Ohmic heating

Magnetic field around bright galaxy



Units

j: 10^{-18}Am^{-2}

T: K

B: 10^{-22}T (10^{-18}G)

E: 10^{-18}Vm^{-1}

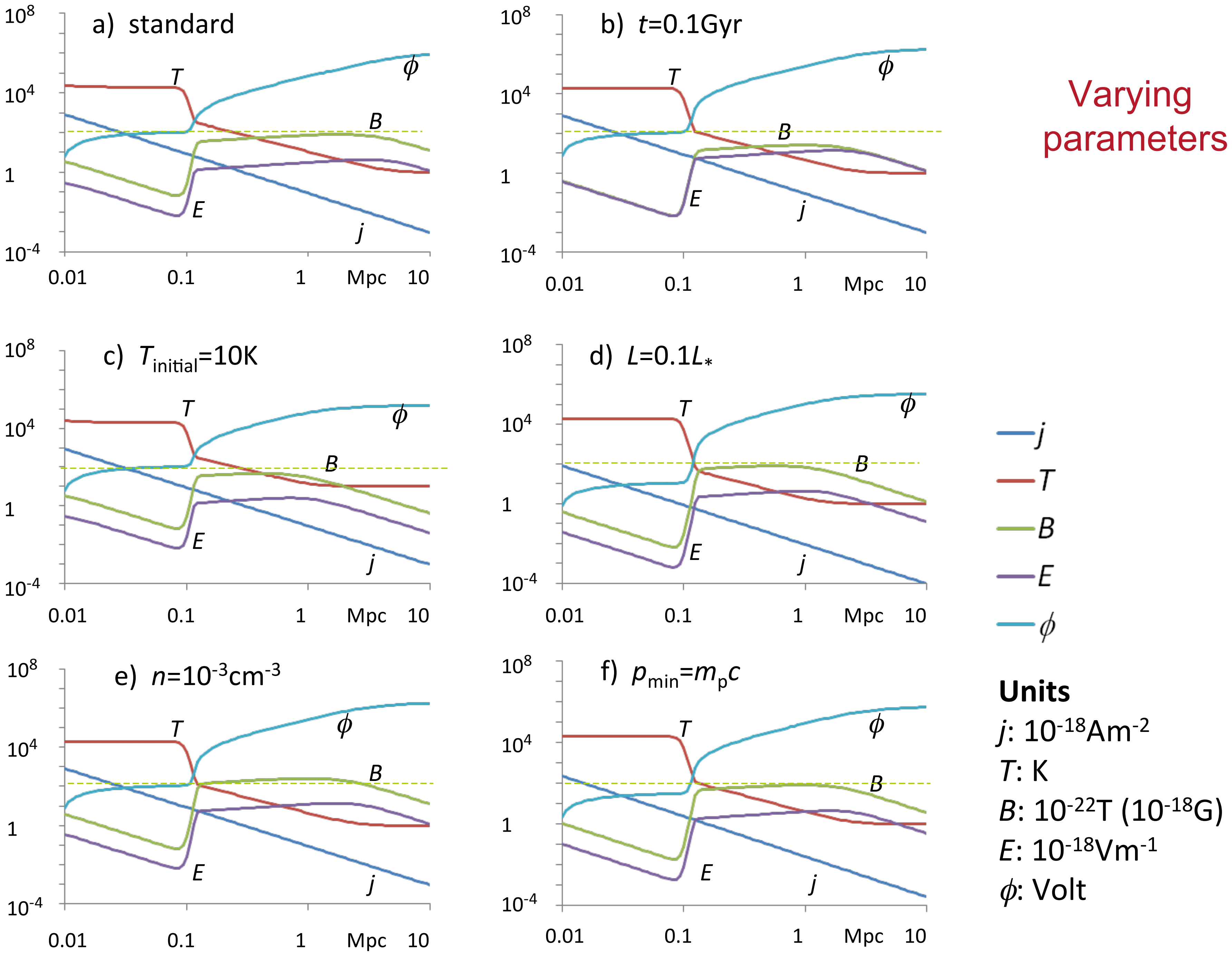
ϕ: Volt

Maximum magnetic field

$$B_{\max} = 8\times10^{-17}\left(\frac{L_T}{\mathrm{kpc}}\right)^{-1}\left(\frac{T_1}{\mathrm{K}}\right)^{-1/4}\left(\frac{n}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{t}{\mathrm{Gyr}}\right)^{1/2}\ \mathrm{Gauss}$$

at distance from galaxy

$$R_{\max} = 1.9\left(\frac{n}{10^{-4}\,\mathrm{cm}^{-3}}\right)^{-1/4}\left(\frac{T_1}{\mathrm{K}}\right)^{-5/8}\left(\frac{L}{L_*}\right)^{1/2}\left(\frac{p_{\min}}{0.1m_p c}\right)^{-0.15}\left(1+\frac{p_{\min}}{0.1m_p c}\right)^{-1/2}\left(\frac{t}{\mathrm{Gyr}}\right)^{1/4}\ \mathrm{Mpc}$$



a) standard
b) t=0.1Gyr
c) T_initial=10K
d) L=0.1L*
e) n=10^-3cm^-3
f) p_min=m_pc
10^8
10^4
1
10^-4
0.01
0.1
1
Mpc
10
T
B
E
j
ϕ
Varying parameters
Units
j: 10^-18Am^-2
T: K
B: 10^-22T (10^-18G)
E: 10^-18Vm^-1
ϕ: Volt

How do different processes contribute?

Weibel instability (large B but on small scale)

- Requires strong anisotropy: stress tensor, diffusion insufficient
- Occurs near shocks (eg Medvedev et al 2006)
- Grows on small scale c/ω_{pe}

Biermann battery (up to $B \sim 10^{-18}$ G eg Gnedin et al 2006)

- Grows on large scale
- Field limited by small thermal energy T_e

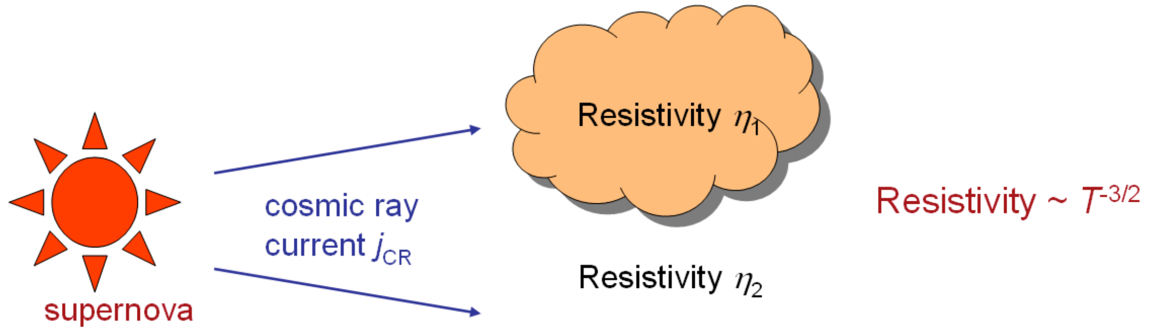
$$\partial B / \partial t = -\nabla \times E \qquad E = -\nabla P_e / n_e e \approx T_e / L$$

Resistive generation ($B \sim 10^{-16}$G on kpc scale)

- Grows on large scale of cluster/galaxy formation
- Large B because E determined by cosmic ray energy ($\gg T_e$)
- Requires low temperature for high resistivity

Compton drag (Harrsion 1970, Ichiki etal 2006)

Conclusion



First cosmic rays from first supernovae

may account for primordial magnetic field