IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

MAGNETIZED UNIVERSE

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ACP SEMINAR (ASTRONOMY - COSMOLOGY - PARTICLE PHYSICS)

CNPq
Conselho Nacional de Desenvolvimento Científico e Tecnológico

Why Magnetic Fields?

Few decades ago cosmic magnetic fields were generally regarded as unimportant.

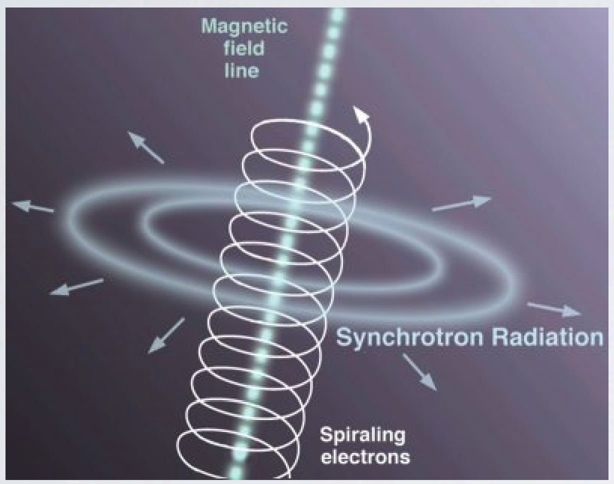
Now, we know that most of the visible matter in the Universe is in a plasma state permeated by magnetic fields.

Magnetic fields play a crucial role in: star formation, solar and stellar activity, pulsars, accretion disks, formation and stability of jets, formation and propagation of cosmic rays, and stability of galactic disks.

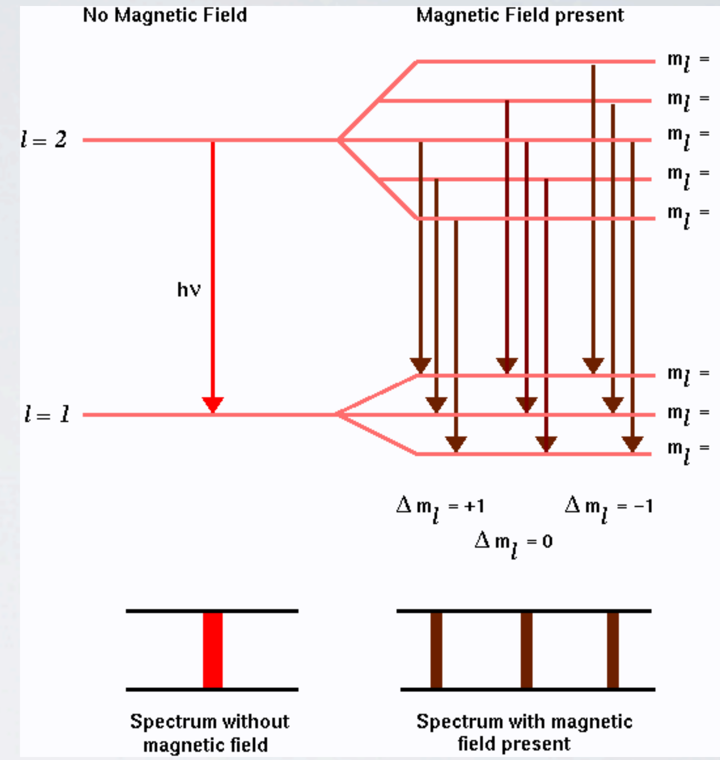
They are also probably crucial in: the interstellar medium (ISM) dynamical evolution, in molecular clouds, supernova remnants, proto-planetary disks, and planetary nebulae, stellar evolution, halos of galaxies, galaxy evolution, and structure formation in the early Universe

OBSERVATIONAL METHODS

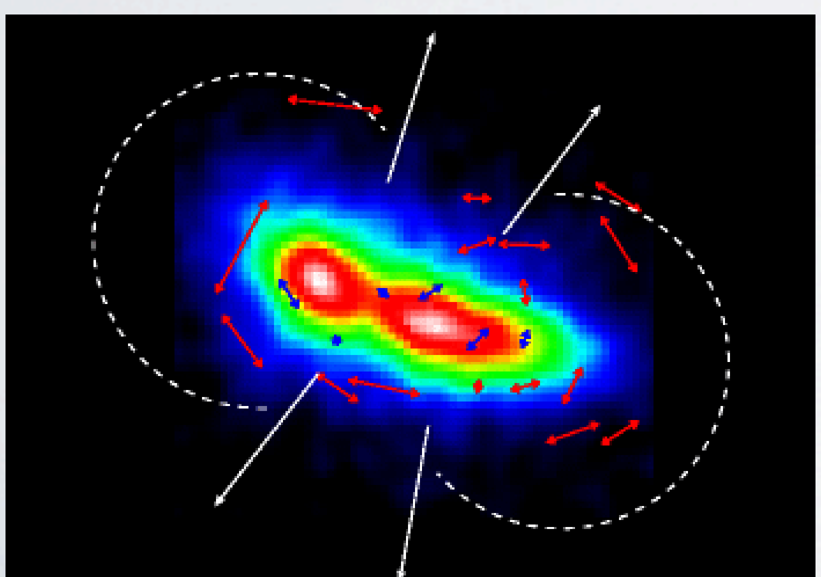
Synchrotron Emission



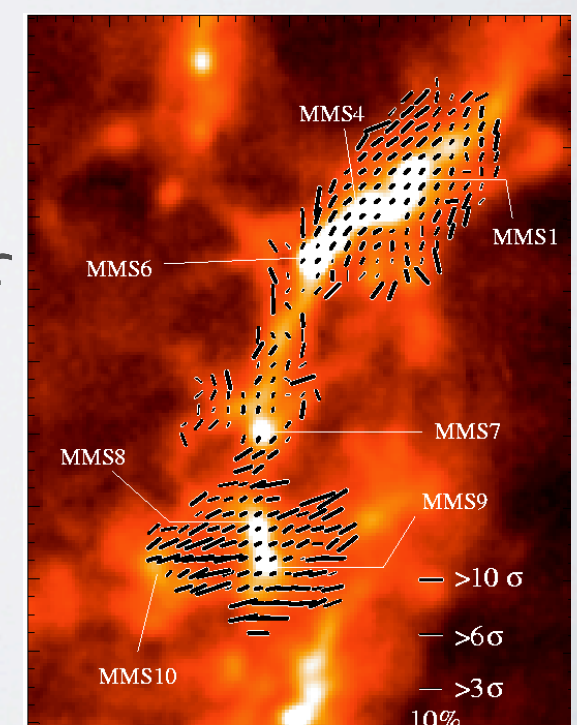
Zeeman Effect



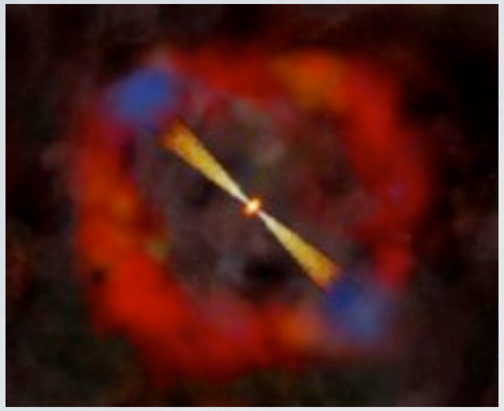
Faraday Rotation



Polarization of Diffuse Light



MAGNETIC FIELDS EVERYWHERE

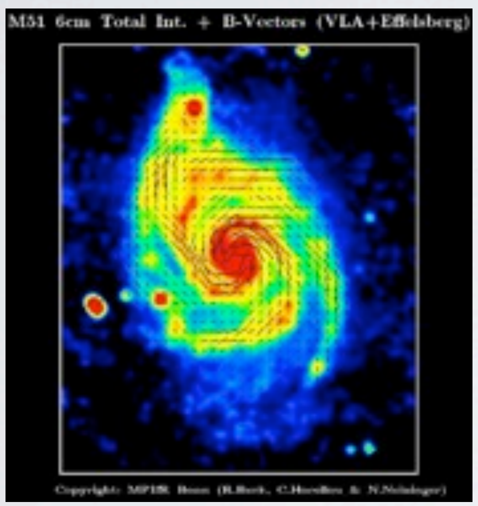


de Souza, R. S. and Opher, R., JCAP, 02, 022 (2010)

Gamma ray bursts

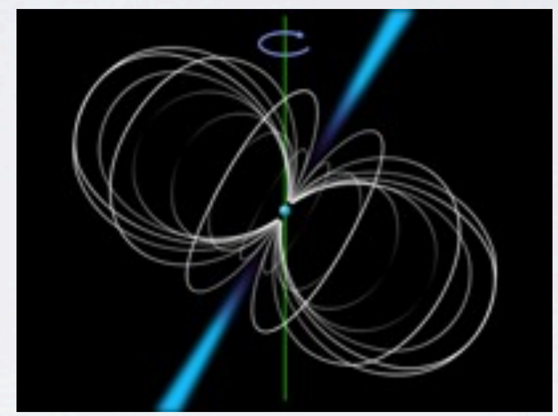
Laganá, T. F., **de Souza, R.S.** and Keller, G. R. A&A, 510, A76 (2010)

Clusters of galaxies



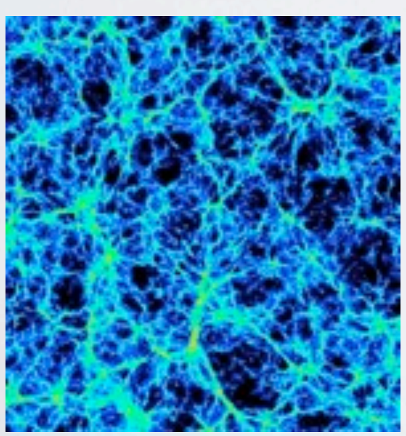
de Souza, R.S. and Opher, R., PRD, 81, 6, 067301 (2010)

Galaxies



de Souza, R. S. and Opher, R., Ap&SS, 212D (2010)

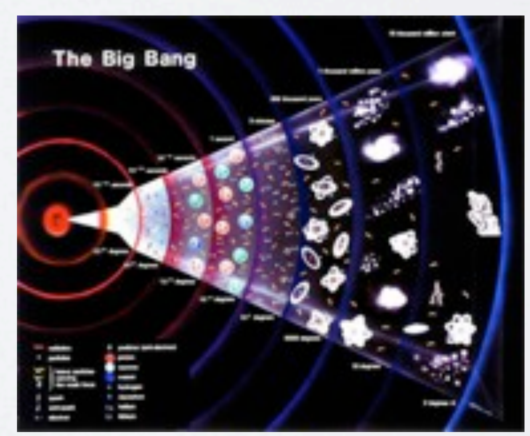
Pulsars



e Souza, R. S. et al. MNRAS, 2010, early view

Rodrigues, L. F. S., **de Souza, R. S.** and Opher, R., MNRAS, 406, 1 (2010)

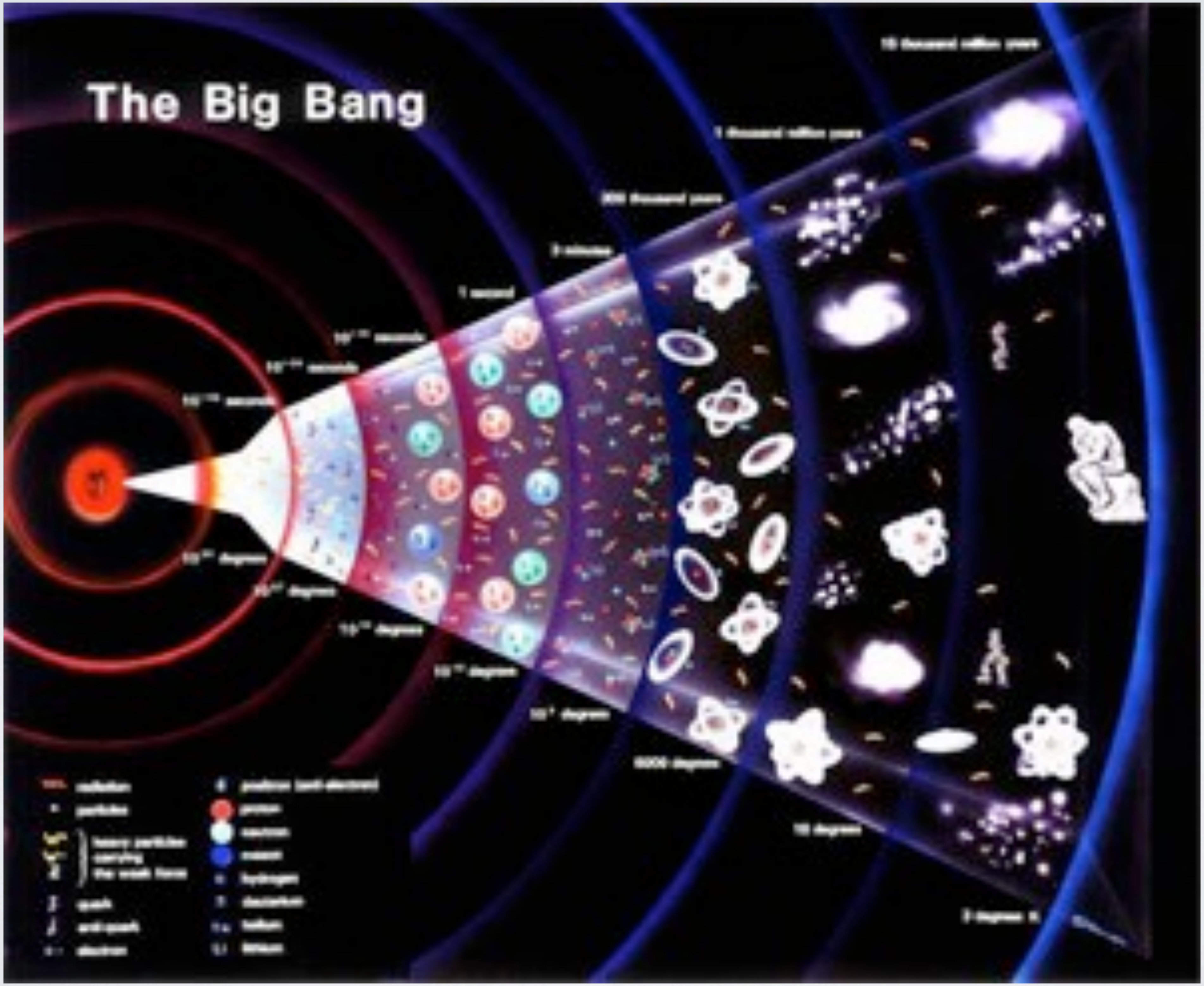
Large scale structures



de Souza, R.S. and Opher, R., PRD, 77, 043529 (2008)

Early Universe

EARLY UNIVERSE



CANDIDATES FOR SEED FIELDS

Astrophysical Mechanisms	Primordial Mechanisms
Biermann Battery	Quark hadron phase transition
Primordial Supernovas	Electroweak phase transition
Extragalactic Jets	Inflation
Evolution of electromagnetic fluctuation created in the primordial plasma	

ELECTROMAGNETIC FLUCTUATIONS

- We can estimate intensity of magnetic fields for a wavelength λ,

$$\langle B^2 \rangle_\lambda / 8\pi = (k_B T/2)(4\pi/3)\lambda^{-3}$$

At z = 10^{11}, the strength of the fluctuations were B ~10^{16}, however with small coherence scale size 10^{-12} cm.

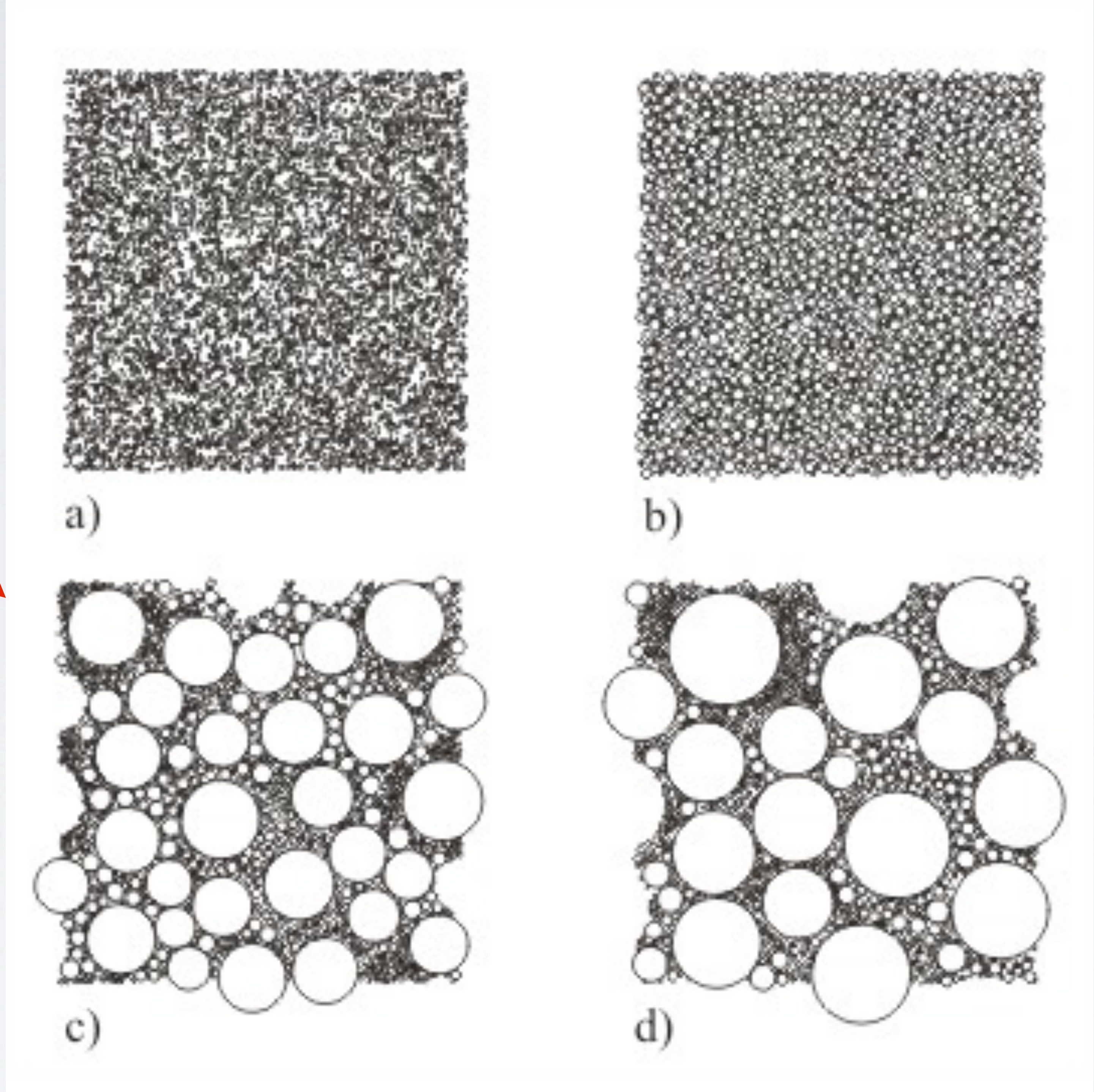
de Souza, R.S. and Opher, R., PRD, 77, 043529 (2008)

Mean size

$$\bar{\lambda}$$

Lifetime

$$\tau \propto \lambda^2$$

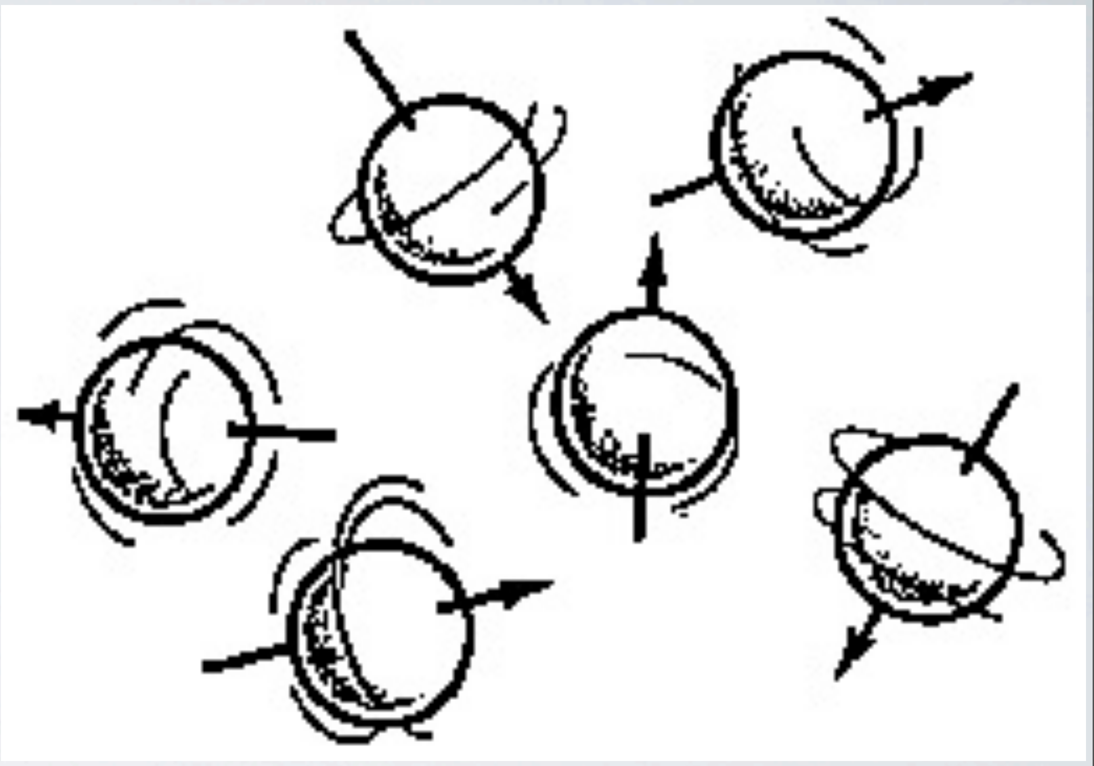


We start our calculations at z ~10^{11} and follow the evolution up to z ~10, when first galaxies form.

We can analyze this process in the point of view of the Bolztmann equation for in comoving coordinates.

$$\frac{\partial n_i}{\partial t} = -\frac{n_i}{\tau i^2} + 3Hn_i + n_{i-1}\langle n_1 v\sigma\rangle$$

$$H(z) = H_0\sqrt{\Omega_{m0}(1+z)^3 + \Omega_\Lambda + \Omega_{r0}(1+z)^4}$$



Magnetic bubbles tend to align, yielding bigger structures.

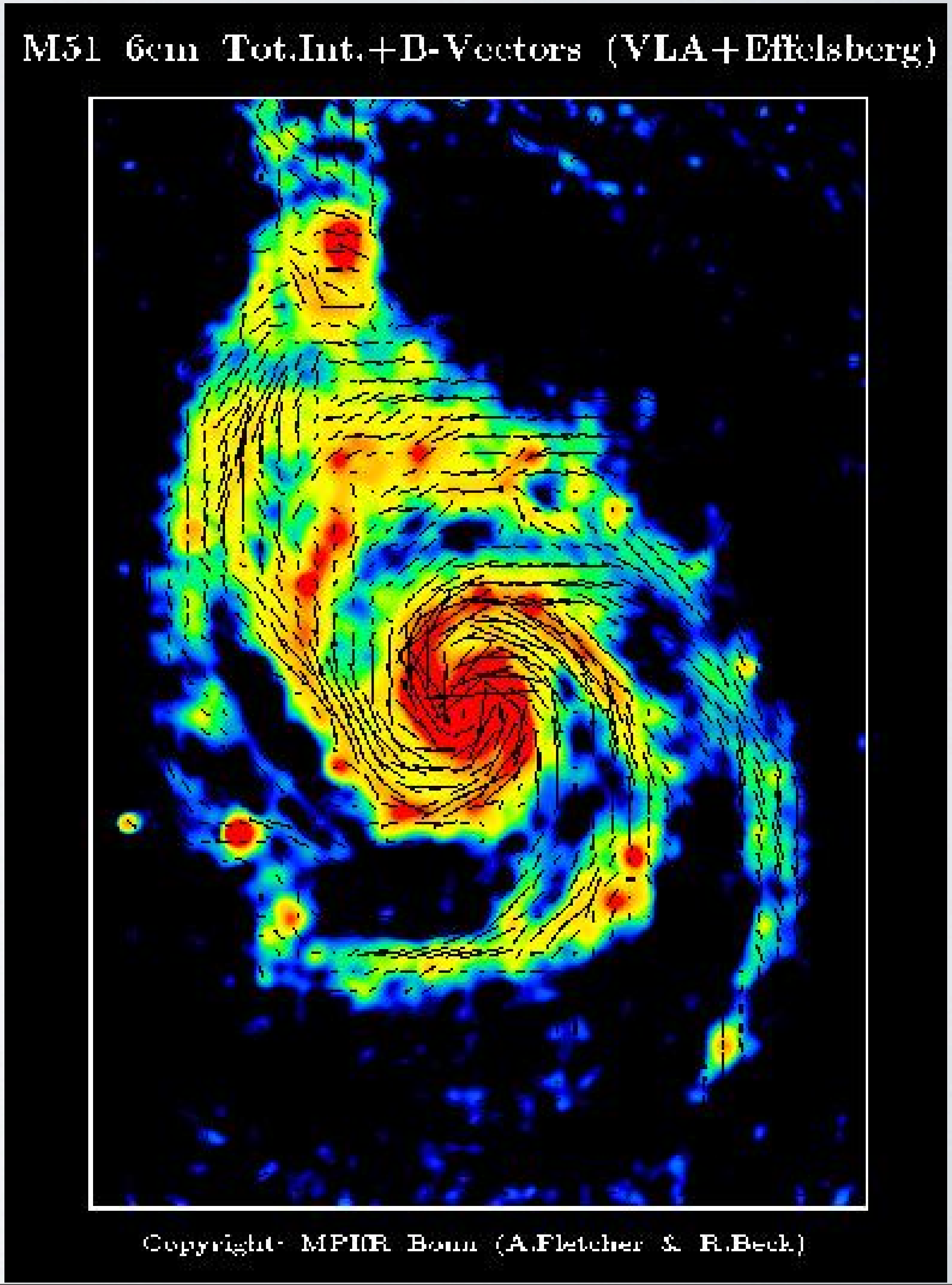
EVOLUTION OF THE MAGNETIC FIELDS

Table 1: Size and Strength of Magnetic Fields in Bubbles

Epoch	Magnetic Field (μG)	Redshift	Time (sec)	Size (cm)
Immediately after the QHPT	10^{22}	6×10^{11}	10^{-4}	10^{-12}
Electron positron annihilation era	10^{18}	10^{10}	1	10^{8}
Nucleosynthesis era	10^{15}	$10^{8} - 10^{9}$	$1 - 500$	10^{10}
Equipartition era	2×10^{5}	3600	10^{12}	3×10^{14}
Recombination era	2×10^{2}	1100	8×10^{12}	10^{15}
Galaxy formation era	9	~ 10	10^{16}	10^{17}

GALACTIC MAGNETIC FIELDS

- We observe magnetic fields in galaxies of intensities ~ μG, over regions of kpc.
- We also observe intense magnetic fields of 84 μG, in galaxies at z=0.692.



HOW TO AMPLIFY THESE SEED FIELDS?

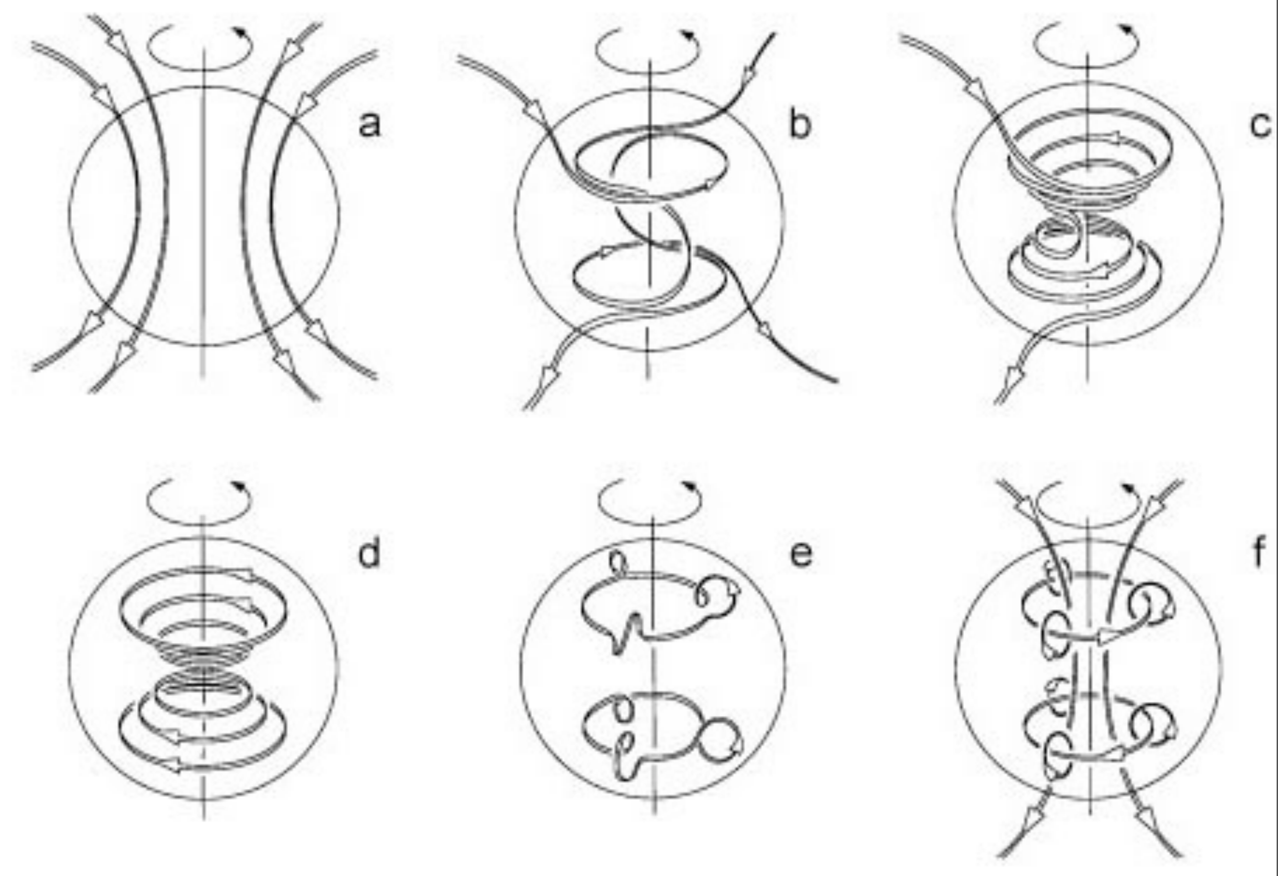
- We expect that pre galactic seed fields will be amplified during galaxy formation and evolution,
- The most popular mechanism to amplify seed fields in galaxy disks is the α-**Ω dynamo**.

GALACTIC DYNAMO

$$\frac{\partial \bar{\mathbf{B}}}{\partial t} = \nabla \times (\mathbf{U} \times \bar{\mathbf{B}}) + \nabla \times (\alpha \bar{\mathbf{B}}) + \beta \nabla^2 \bar{\mathbf{B}}$$

$$\alpha = -\frac{\tau}{3} < \mathbf{v} \cdot \nabla \times \mathbf{v} >,$$

$$\beta = \frac{\tau}{2} < \mathbf{v}^2 >$$



Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

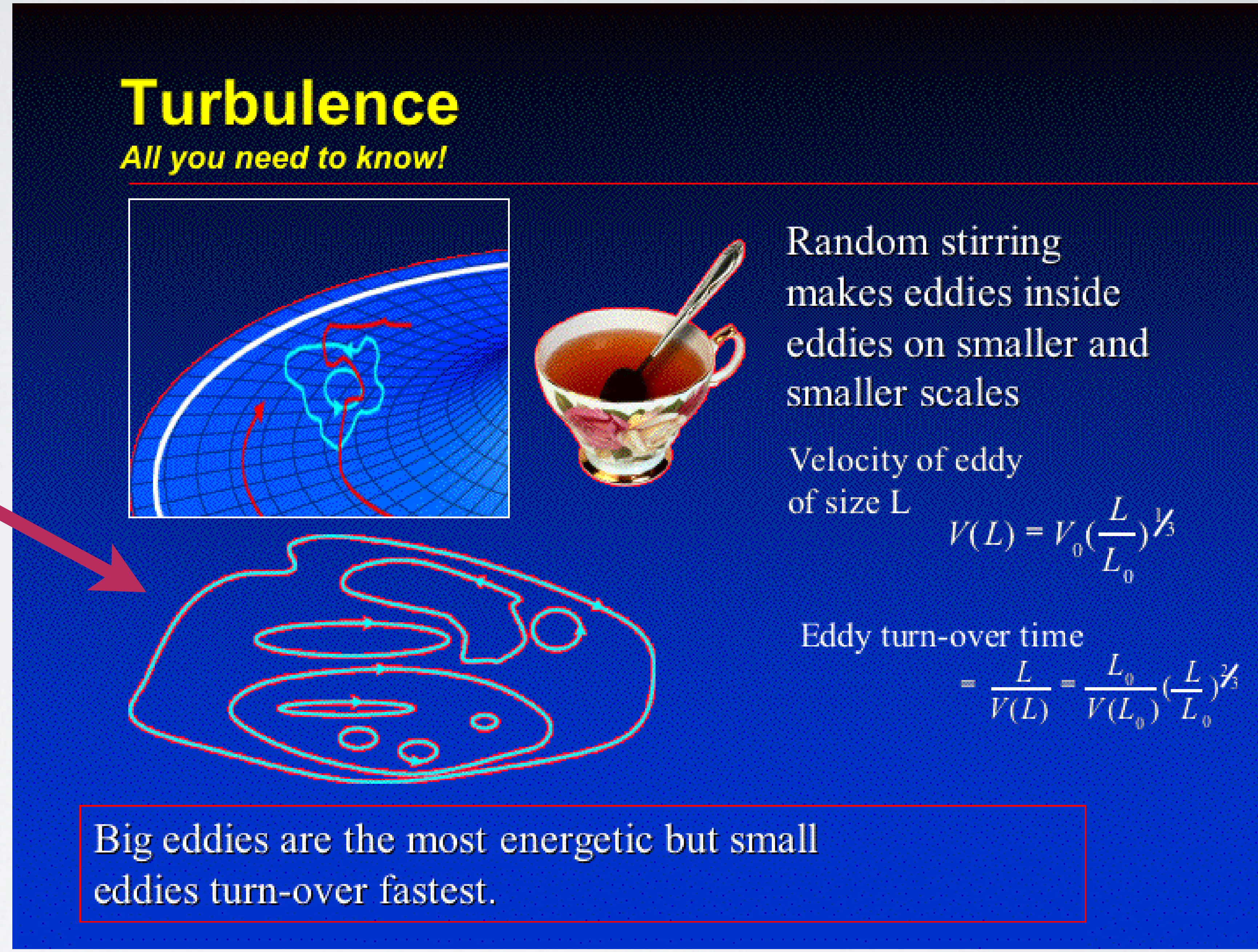
In order to obtain microgauss magnetic fields during ~10 billion years, we need a seed fields ~10^{-13} G. Observations indicate the presence of magnetic fields of microgauss in clusters of galaxies and in galaxies at high redshift. Therefore is difficult to explain these high fields with classic alpha-omega dynamo.

PROTOGALACTIC TURBULENCE

- Kolmogorov Turbulence.

$$v_l \propto l^{1/3}$$

$$\Gamma_l \sim v_l/l \propto l^{-2/3}$$



de Souza, R.S. and Opher, R., PRD, 81, 6, 067301 (2010)

EQUATIONS FOR EVOLUTION OF MAGNETIC FIELDS

$$
\begin{aligned}
\frac{\partial M_L}{\partial t}(r,t) &= \frac{2}{r^4}\frac{\partial}{\partial r}\left(r^4\kappa_N(r,t)\,\frac{\partial M_L(r,t)}{\partial r}\right) \\
&+ G(r)M_L(r,t) + 4\,\alpha_N H(r,t)\,,
\end{aligned}
$$

$$\kappa_N(r,t) = \eta + T_{LL}(0) - T_{LL}(r) + 2\,a\,M_L(0,t)$$

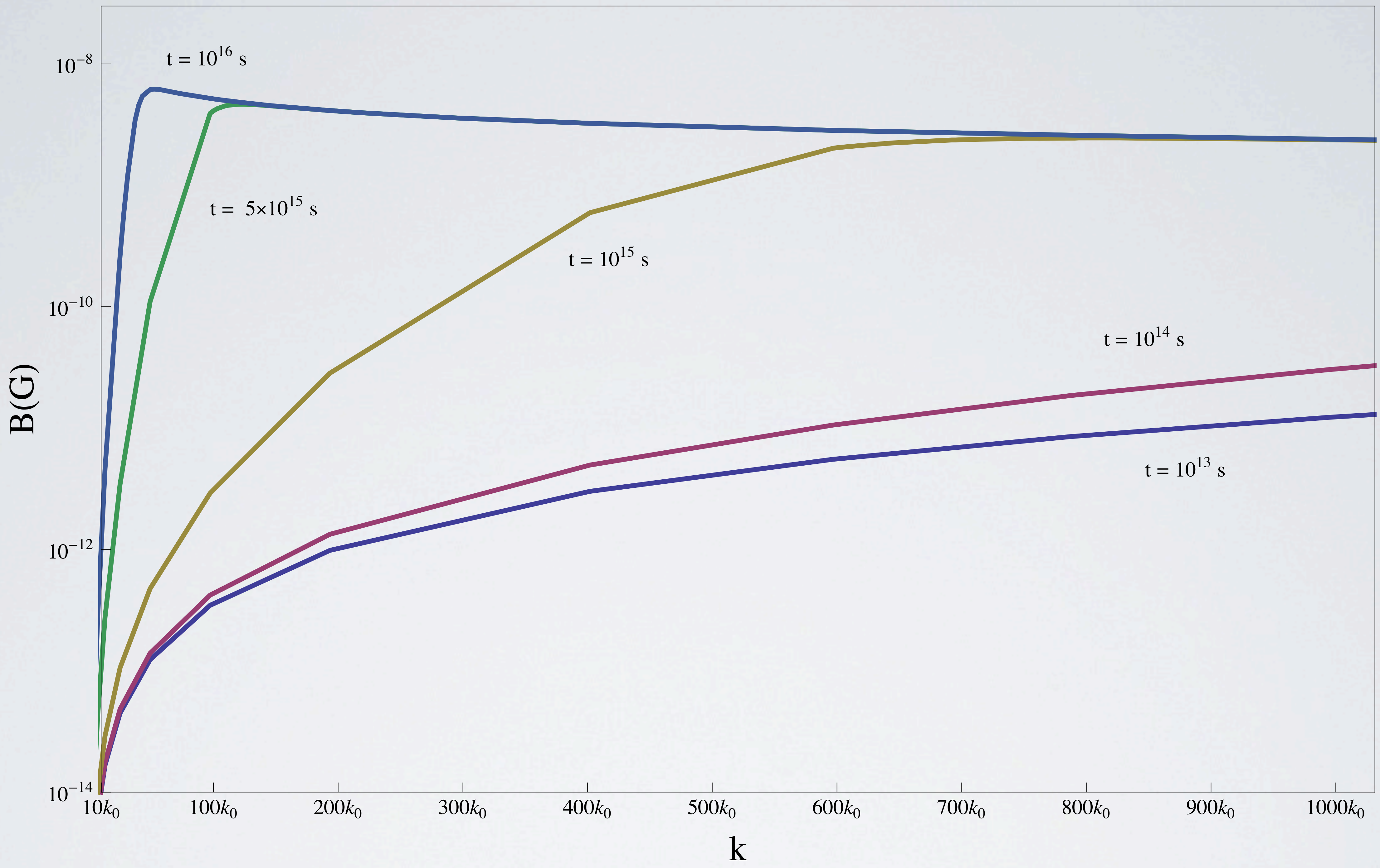
$$\alpha_N(r,t) = 2\,C(0) - 2\,C(r) - 4\,a\,H(0,t)$$

$$G(r) = -4\left\{\frac{d}{d\,r}\left[\frac{T_{NN}(r)}{r}\right] + \frac{1}{r^2}\frac{d}{d\,r}\left[r\,T_{LL}(r)\right]\right\}$$

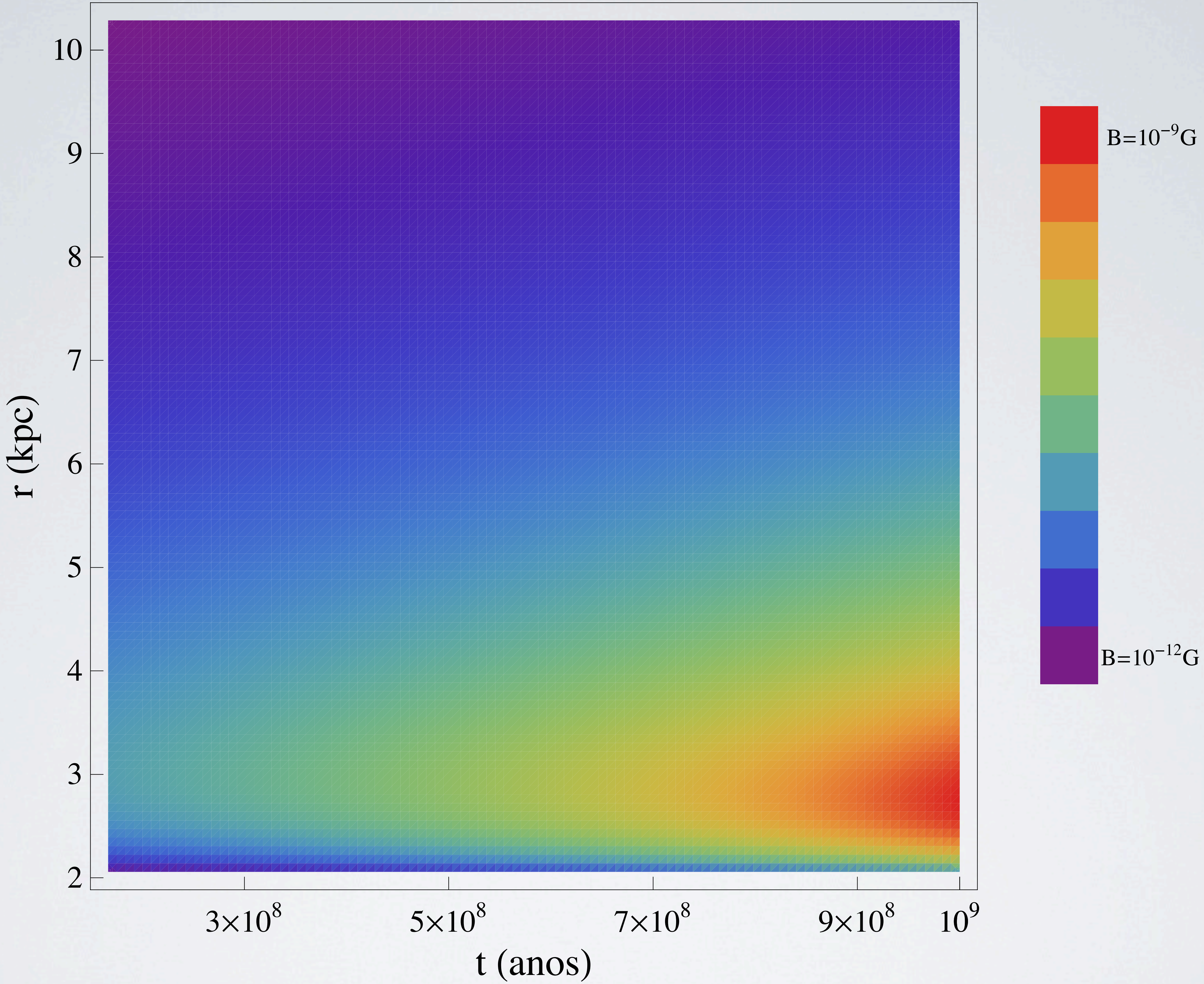
$$T_{LL}(r) = \frac{V_c L_c}{3}\left[1 - R_e^{1/2}\left(\frac{r}{L}\right)^2\right] \qquad 0 < r < l_c$$

$$T_{LL}(r) = \frac{V_c L_c}{3}\left[1 - \left(\frac{r}{L}\right)^{4/3}\right] \qquad l_c < r < L,$$

$$T_{LL}(r) = 0 \qquad r > L$$



B(k) as a function of wavenumber k_0 ($k_0=2\pi/L_{PG}$)



Values of magnetic fields B(G) as a function of time (years) and coherence lenght r (kpc)

COMMENTS

We show that in principle, electromagnetic fluctuations present in primordial plasma could create seed magnetic fields,

These seed fields can be amplified by Kolmogorov turbulence present during galaxy formation,

GOOD!!! Our model can explain the origin of magnetic fields in galaxies!!!?????

Take it easy man!!! Any model capable to predict seed fields > 10^{-20} G can be a candidate to be amplified by galactic turbulence.

HOW DISCRIMINATE BETWEEN MODELS?

- Cosmic Rays (Good for IGM, but only in low z)
- Nucleosynthesis (Good to constraint a upper limit)
- Faraday Rotation Measurements (Good for clusters, difficult to use for IGM)
- CMB polarization (Good for upper limits in high z, but cannot constraint the evolution of the field)
- SKA, LOFAR? In principle will be able to follow evolution of cosmic fields through 3D Faraday Rotation maps.
- Next slide, we will discuss another approach.

LARGE SCALE STRUCTURES

Jeans Mass $$M_J = \left(\frac{5kT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

FILTER MASS $$M_{\mathrm{F}}^{2/3} = \frac{3}{a}\int_0^a \mathrm{d}a' \; M_{\mathrm{J}}^{2/3}(a')\left[1 - \left(\frac{a'}{a}\right)^{1/2}\right].$$

A very important result, obtained by Gnedin (2000), through the study of cosmological hydrodynamical simulations, is that the filter mass still characterizes the scale of suppression of the formation of baryonic structures even in the non-linear regime.

de Souza, R. S. et al. MNRAS, 2010, astro-ph/1005.0639v2

Rodrigues, L. F. S., **de Souza, R. S.** and Opher, R., MNRAS, 406, 1 (2010)

MAGNETIC FILTER MASS

$$\langle B^2 \rangle = f_T^2(z) B_0^2 \left(\frac{L_0}{L}\right)^{2p} (1+z)^4 \qquad \text{for } L > L_0 \ ,$$

$$\langle B^2 \rangle = f_T^2(z) B_0^2 \, (1+z)^4 \qquad \text{for } L < L_0 \ .$$

Turbulence

$$f_T(t) \simeq e^{t/\tau}$$

$$M_J^2 = \frac{3}{4\pi G^3 \bar{\rho}} \left(\frac{B_{rms}^2}{4\pi \bar{\rho}} + \frac{3}{2} \frac{k_B T}{m_H \mu} \right)^3$$

$$L_m^6 = \left(\frac{\kappa}{G}\right)^3 \left[\frac{\kappa\, f_T^2(z) B_0^2}{3} \left(\frac{L_0}{L_m}\right)^{2p} + \frac{3}{2} \frac{k_B T(z)}{\mu m_H} (1+z)^{-1} \right]^3$$

$$M_J^2 = \frac{\kappa}{G^3} \left[\frac{\kappa^{\left(1-\frac{2}{3}p\right)}}{3} \frac{f_T^2(z)\, B_0^2 L_0^{2p}}{M_J^{\frac{2}{3}p}} + \frac{3}{2} \frac{k_B T(z)}{\mu m_H (1+z)} \right]^3$$

Filter mass as a function of z

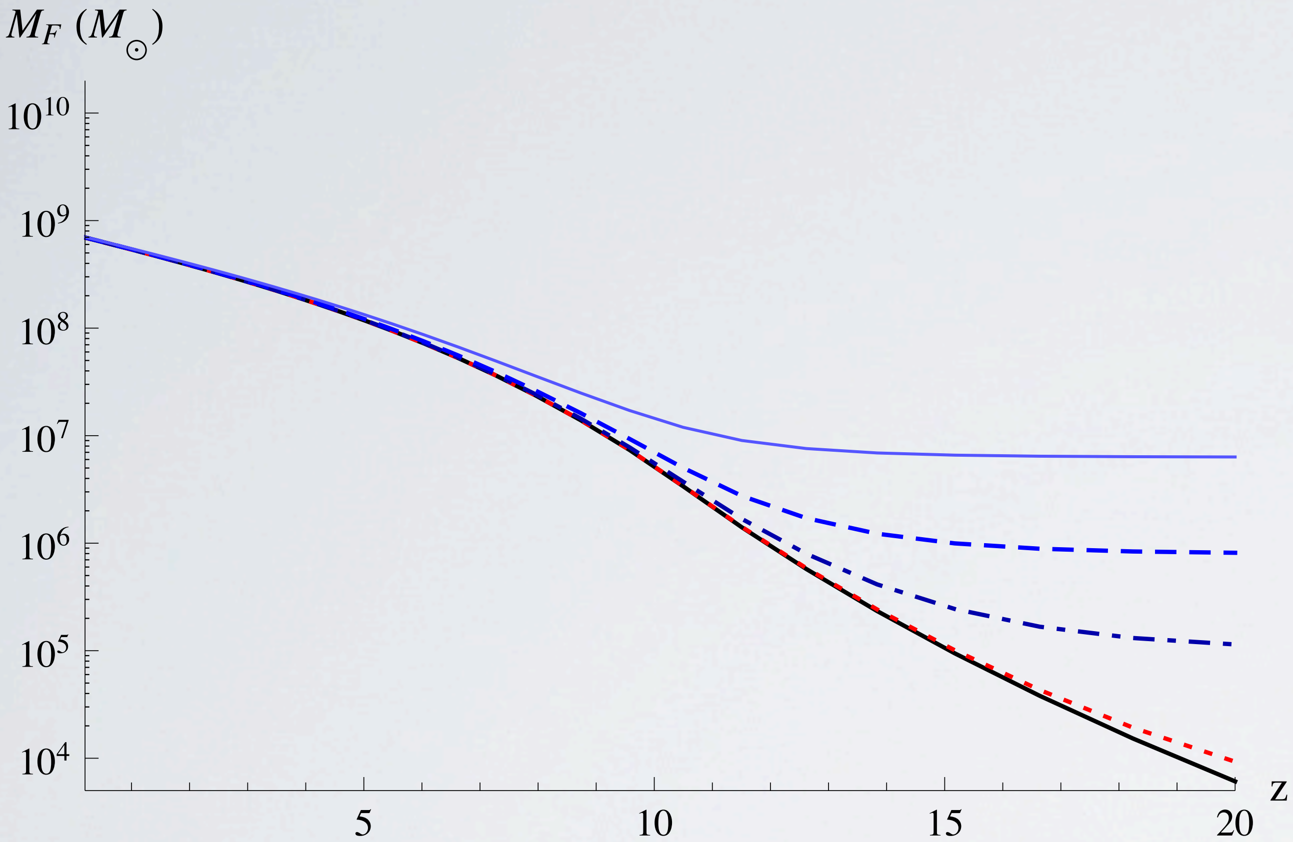


Figure 1. Variation of the filtering mass with redshift in the presence of a dipole-like ($p = 3/2$) random magnetic field, for $z_s = 11$ and $z_r = 8$. The continuous (*black*) curve corresponds to the $B_0 = 0$ case. The other curves have $B_0 = 0.1\,\mu$G and, from bottom to top, $L_0 = 10$ pc for the dotted (*red*) curve; $L_0 = 10^2$ pc for the dash-dotted (*dark-blue*) curve; $L_0 = 10^{2.5}$ pc for the dashed (*blue*) curve; $L_0 = 10^3$ pc for the thin (*light-blue*) curve.

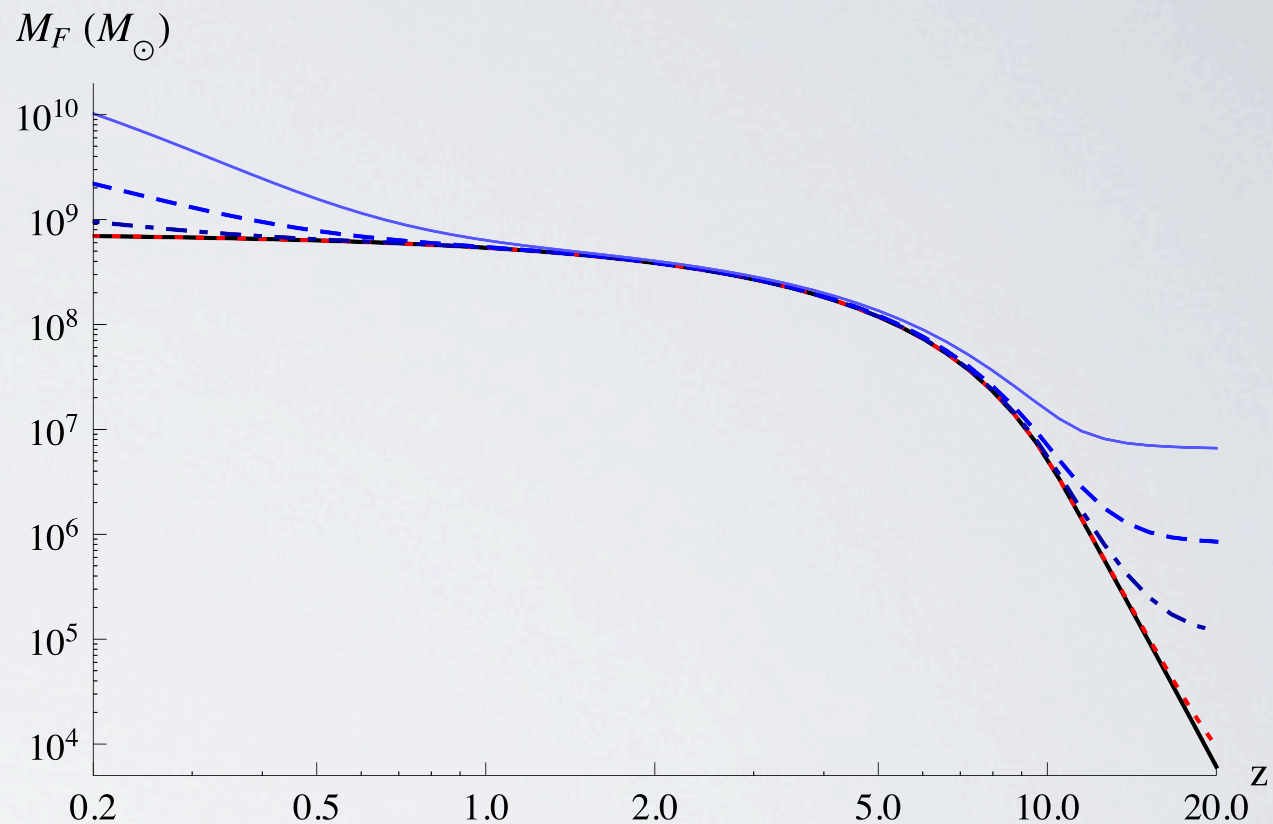


Figure 3. Variation of the filtering mass with redshift in the presence of a dipole-like ($p = 3/2$) random magnetic field, taking into account amplification of the seed fields by IGM turbulence, for $z_s = 11$ and $z_r = 8$. The continuous (*black*) curve corresponds to the $B_0 = 0$ case. The other curves have $B_0 = 0.1\,\mu$G and, from bottom to top, $L_0 = 10$ pc for the dotted (*red*) curve; $L_0 = 10^2$ pc for the dash-dotted (*dark-blue*) curve; $L_0 = 10^{2.5}$ pc for the dashed (*blue*) curve; $L_0 = 10^3$ pc for the thin (*light-blue*) curve.

GAS FRACTION CONTENT

$$f_g \approx \frac{f_b}{[1 + 0.26 M_F(t)/M]^3}$$

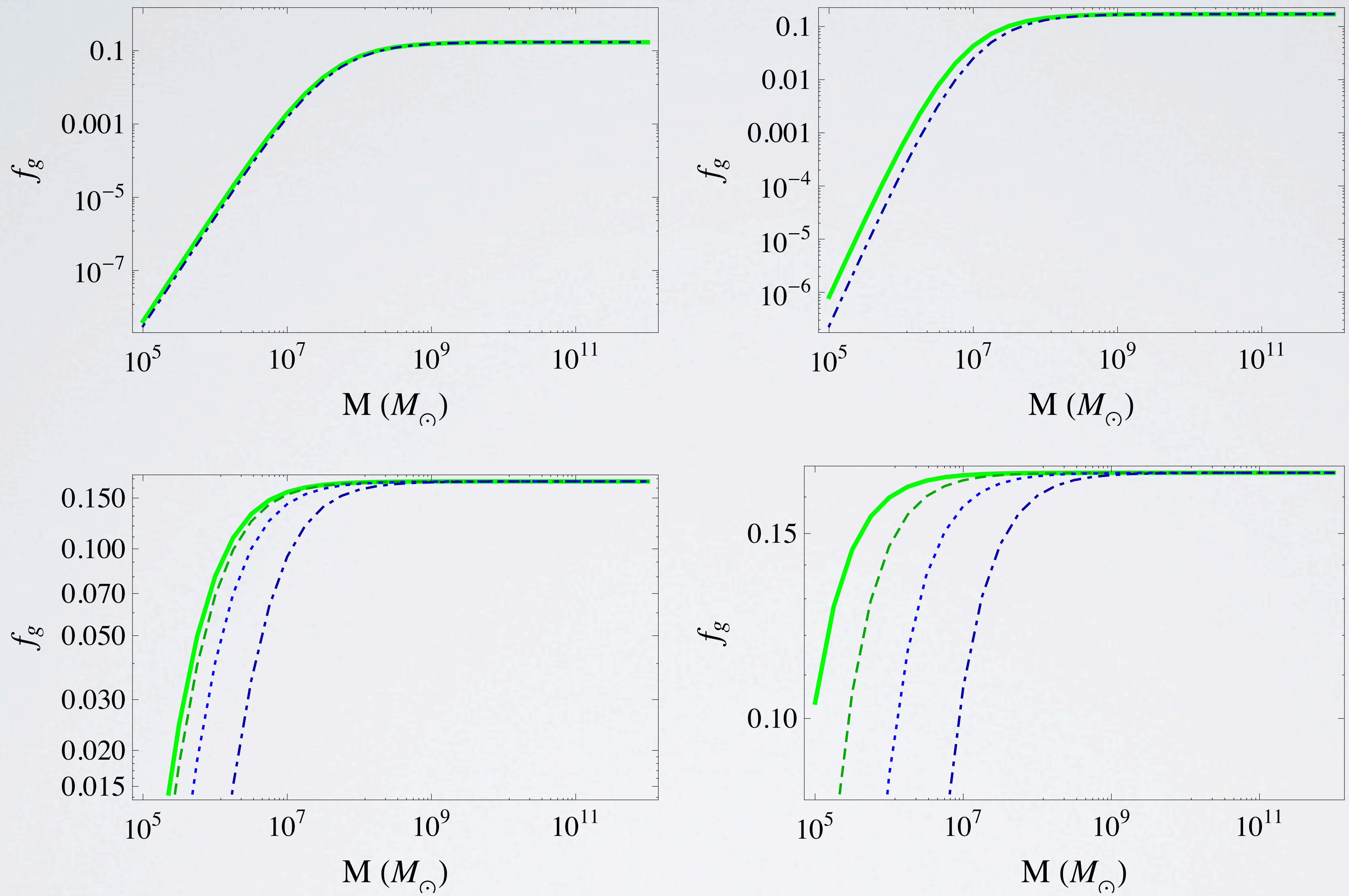


Figure 9. Halo gas fraction, in the presence of a dipole-like field ($p = 3/2$), as a function of halo mass at $z = 3$, $z = 6$, $z = 9$ and $z = 12$, in the *top-left*, *top-right*, *bottom-left* and *bottom-right* panels, respectively. The thick (*green*) curve corresponds to $B_0 = 0$. For all other curves, $B_0 = 10^{-7}$ G. For the dashed (*dark-green*) curve we have $L_0 = 10$ pc, for the dotted (*blue*) curve, $L_0 = 10^2$ pc, for the dash-dotted (*dark-blue*) curve, $L_0 = 10^3$ pc.

COMMENTS

- We show that each magnetogenesis model can affect the caractheristic mass that can collapse as function z as well as the gas content of the objects.
- We propose to use this values as alternative approach to discriminate between models.
- In the next slide we will discuss how magnetic fields can affect the mass determination of galaxy clusters.

CLUSTER OF GALAXIES

Clusters of galaxies are powerful tools for investigations of cosmological interests. The evolution of the mass function of a cluster is highly sensitive to cosmological models since the matter density controls the rate at which structures grow

In order to use clusters of galaxies as observational probes of dark energy in the Universe and to investigate the structure formation history including baryonic hydrodynamics, the non-thermal contribution must be well understood and quantified.

Cluster	RA (J2000)	Dec (J2000)	z	r_{500} h_{70}^{-1} kpc
A496	04 33 37.1	–13 14 46	0.033	1480
A2050	15 16 21.6	+00 05 59	0.1183	2172
A1689	13 11 34.2	–01 21 56	0.1823	1785
A2667	23 51 47.1	–26 00 18	0.23	2153
A2631	23 37 39.7	+00 17 37	0.273	1976

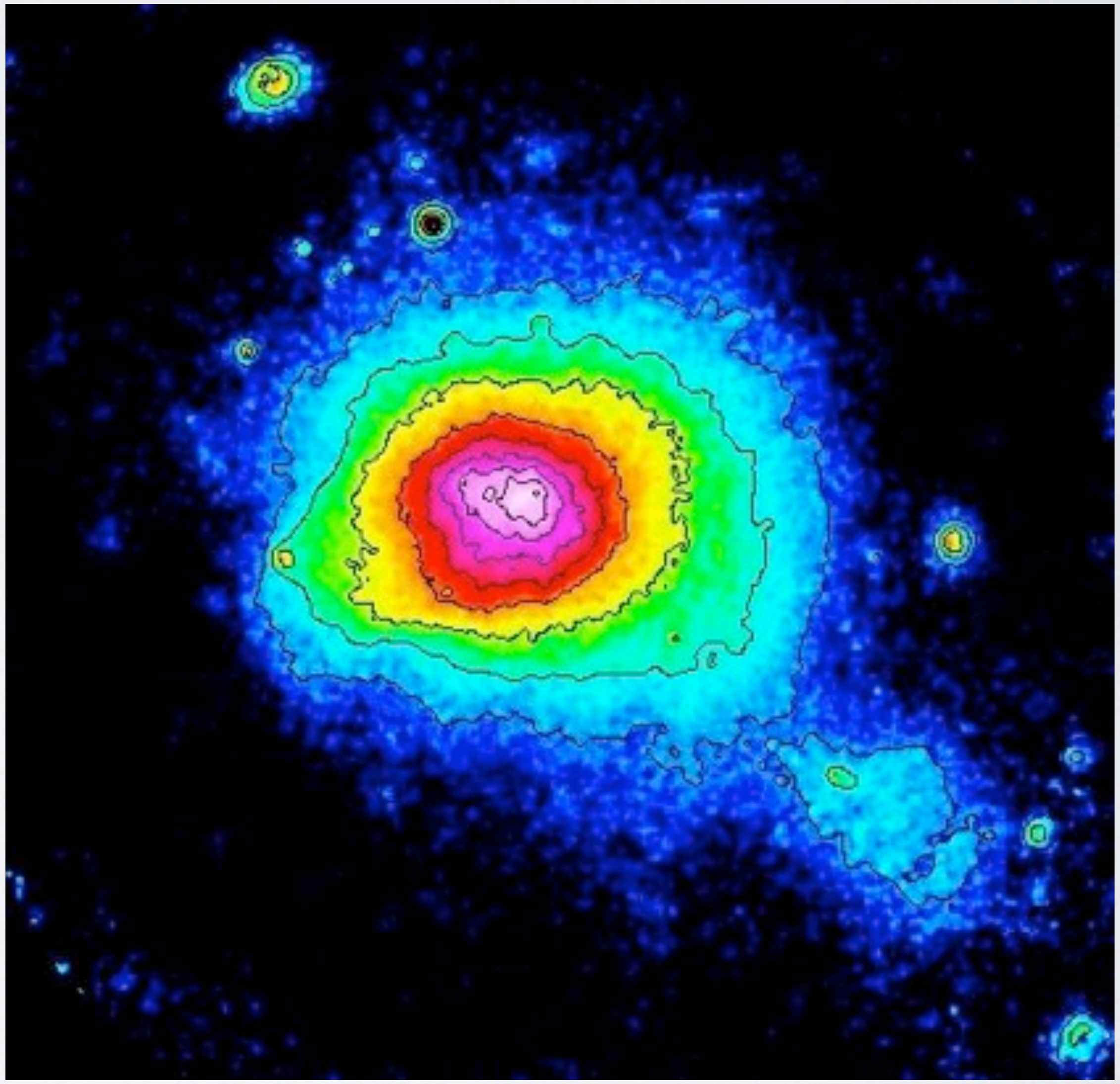
X-RAY MASS DETERMINATION

Hydrostatic equilibrium

$$\frac{GM(r)}{r^2} = -\frac{k_B T}{\mu m_H}\left[\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right]$$

beta model:

$$\rho = \rho(0)(1 + r^2/r_c^2)^{-3\beta/2}$$



EFFECTS OF NON-THERMAL COMPONENTS

$$\frac{\mathrm{d}(P_\mathrm{g} + P_\mathrm{B} + P_\mathrm{turb} + P_{cr})}{\mathrm{d}r} = -\rho_\mathrm{g}\frac{GM_\mathrm{NTP}(r)}{r^2},$$

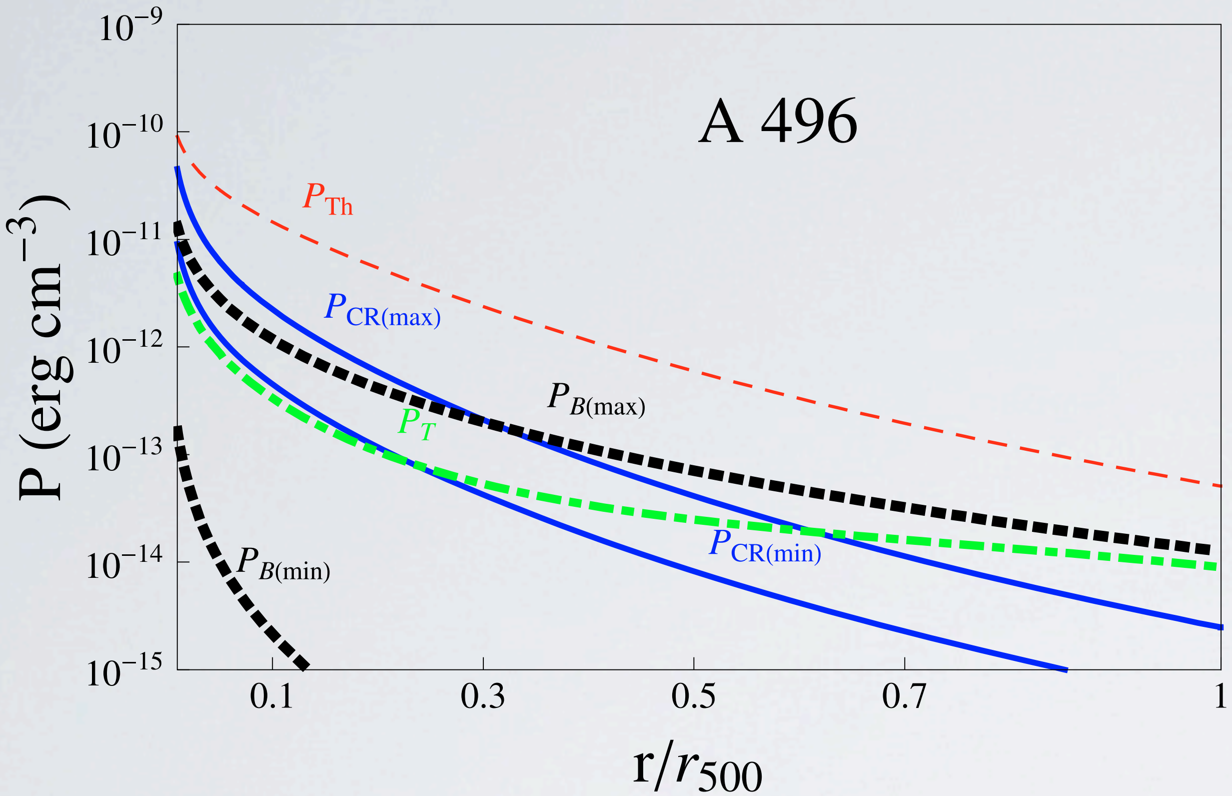
$$\begin{aligned} M_\mathrm{PNT}(r) &= -\frac{k_B T(r)}{G\mu m_\mathrm{H}} r \left(\frac{\mathrm{d}\ln\rho_\mathrm{g}(r)}{\mathrm{d}\ln r} + \frac{\mathrm{d}\ln T(r)}{\mathrm{d}\ln r}\right) \\ &\quad - \frac{r^2}{8\pi\rho_\mathrm{g}(r)G}\frac{\mathrm{d}B(r)^2}{\mathrm{d}r} - \frac{r^2}{2\rho_\mathrm{g}(r)G}\frac{\mathrm{d}}{\mathrm{d}r}(\rho_\mathrm{g}(r)\sigma_\mathrm{r}^2(r)) \\ &\quad - \frac{r}{G}(2\sigma_\mathrm{r}^2(r) - \sigma_\mathrm{t}^2(r)) - \frac{r^2}{G\rho_\mathrm{g}(r)}\frac{\mathrm{d}P_\mathrm{cr}(r)}{\mathrm{d}r}, \end{aligned}$$

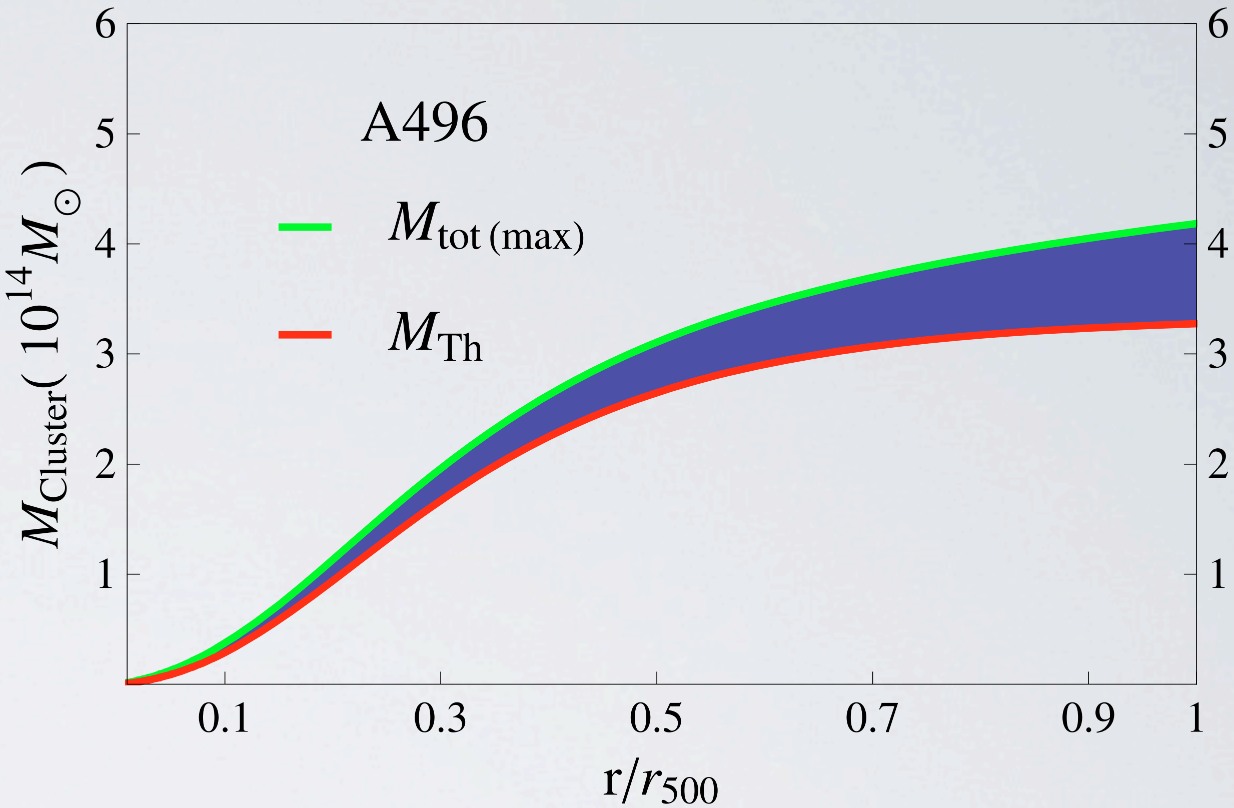
EFFECTS OF NON-THERMAL COMPONENTS

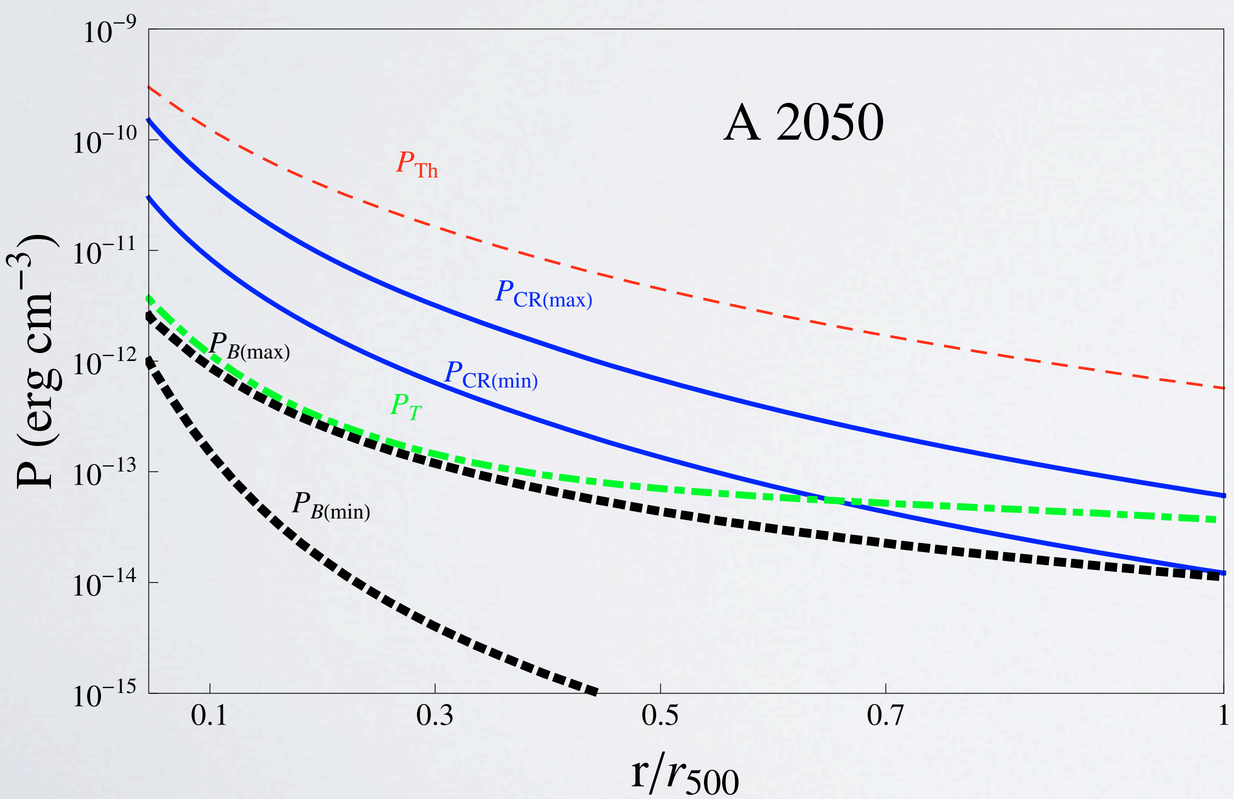
Magnetic Pressure $P_B = \frac{B^2(r)}{8\pi}$ $B(r) = B_0 \left(\frac{\rho_{\rm g}(r)}{\rho_0} \right)^{\alpha}$

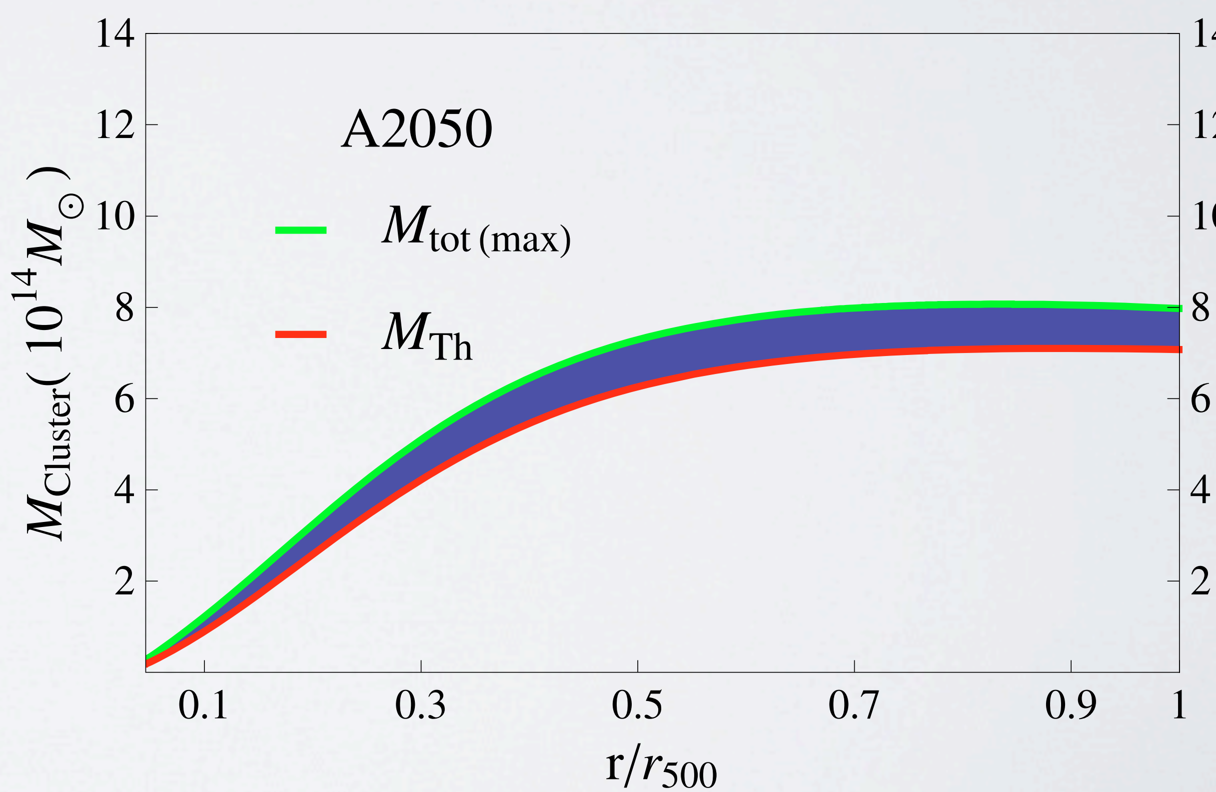
Turbulent Pressure $P_{\rm turb} = \frac{1}{3}\rho_{\rm g}(\sigma_{\rm r}^2 + \sigma_{\rm t}^2)$

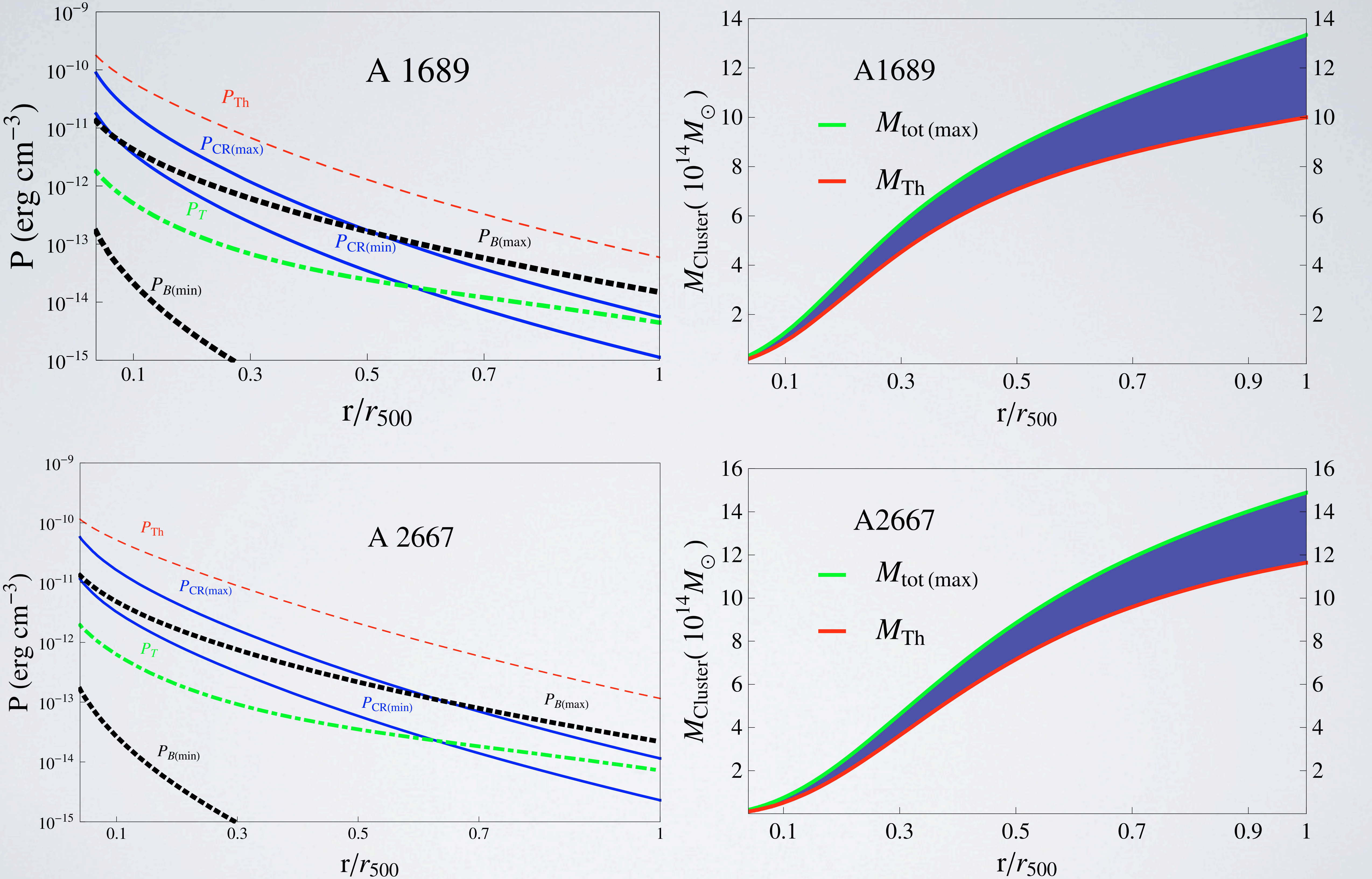
Cosmic Ray Pressure $Y_p \equiv \frac{P_{\rm cr}}{P_{\rm g}}$ $Y_p(r) = Y_{p0} \left(\frac{r}{r_0} \right)^{\Psi}$


A 496
P (erg cm^-3)
r/r500
P_Th
P_CR(max)
P_B(max)
P_T
P_CR(min)
P_B(min)
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
0.1
0.3
0.5
0.7
1


A496
M_tot (max)
M_Th
M_Cluster(10^14 M_⊙)
r/r500
0.1
0.3
0.5
0.7
0.9
1
1
2
3
4
5
6


A 2050
P (erg cm^-3)
r/r500
P_Th
P_CR(max)
P_CR(min)
P_B(max)
P_T
P_B(min)
10^-9
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
0.1
0.3
0.5
0.7
1


A2050
M_tot (max)
M_Th
M_Cluster(10^14 M_⊙)
r/r500
0.1
0.3
0.5
0.7
0.9
1
2
4
6
8
10
12
14



A 1689
P (erg cm^-3)
r/r500
PTh
PCR(max)
PCR(min)
PB(max)
PT
PB(min)
A1689
MCluster(10^14 M⊙)
Mtot (max)
MTh
A 2667
A2667

Systematic erros

Cluster	σ_B(max)	$\sigma_{\rm turb}$(max)	$\sigma_{\rm cr}$(max)	$\sigma_{\rm total}$(max)
A496	17.33%	5.52%	4.87%	27.72%
A1689	20.07%	3.87%	9.47%	33.40%
A2050	1.24%	0.82%	10.69%	12.74%
A2631	0.59%	0.77%	9.79%	11.15%
A2667	14.92%	3.06%	9.93%	27.90%

$$\sigma M_{\rm NTP} = \frac{M_{\rm NTP}(r) - M(r)}{M(r)}$$

FINAL REMARKS

- We show that magnetic fields can be important during early phase of the universe as well as during their evolution;
- It is important to be better understood in order to avoid possible systematic erros;
- We hope that future experiments, Lofar, SKA can help to discriminate between magnetogenesis models.

"Magnetic fields are important for cosmology and should be investigated in more details"

Erik Magnus, **Magneto**