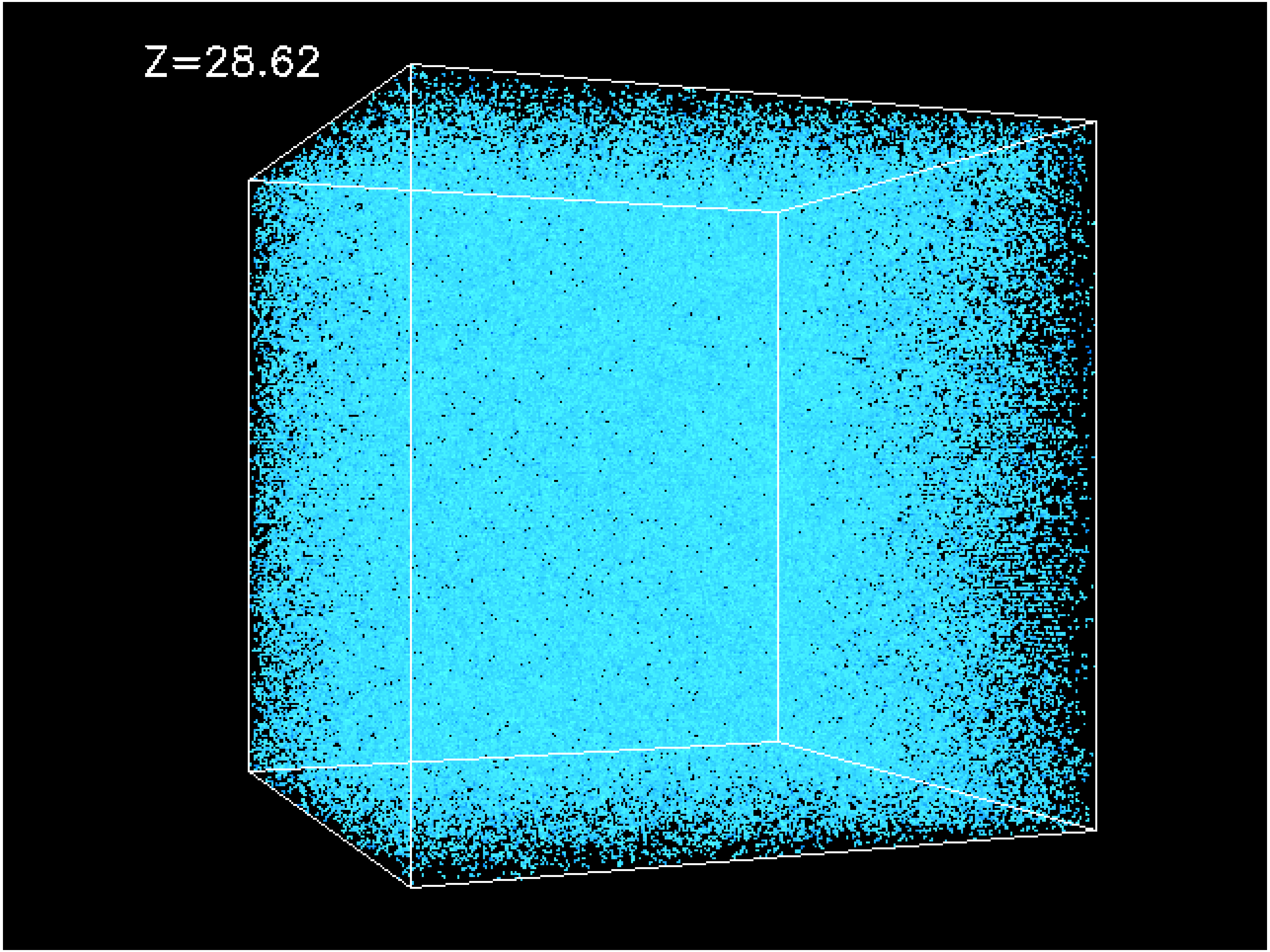
Particle acceleration in Galaxy Clusters

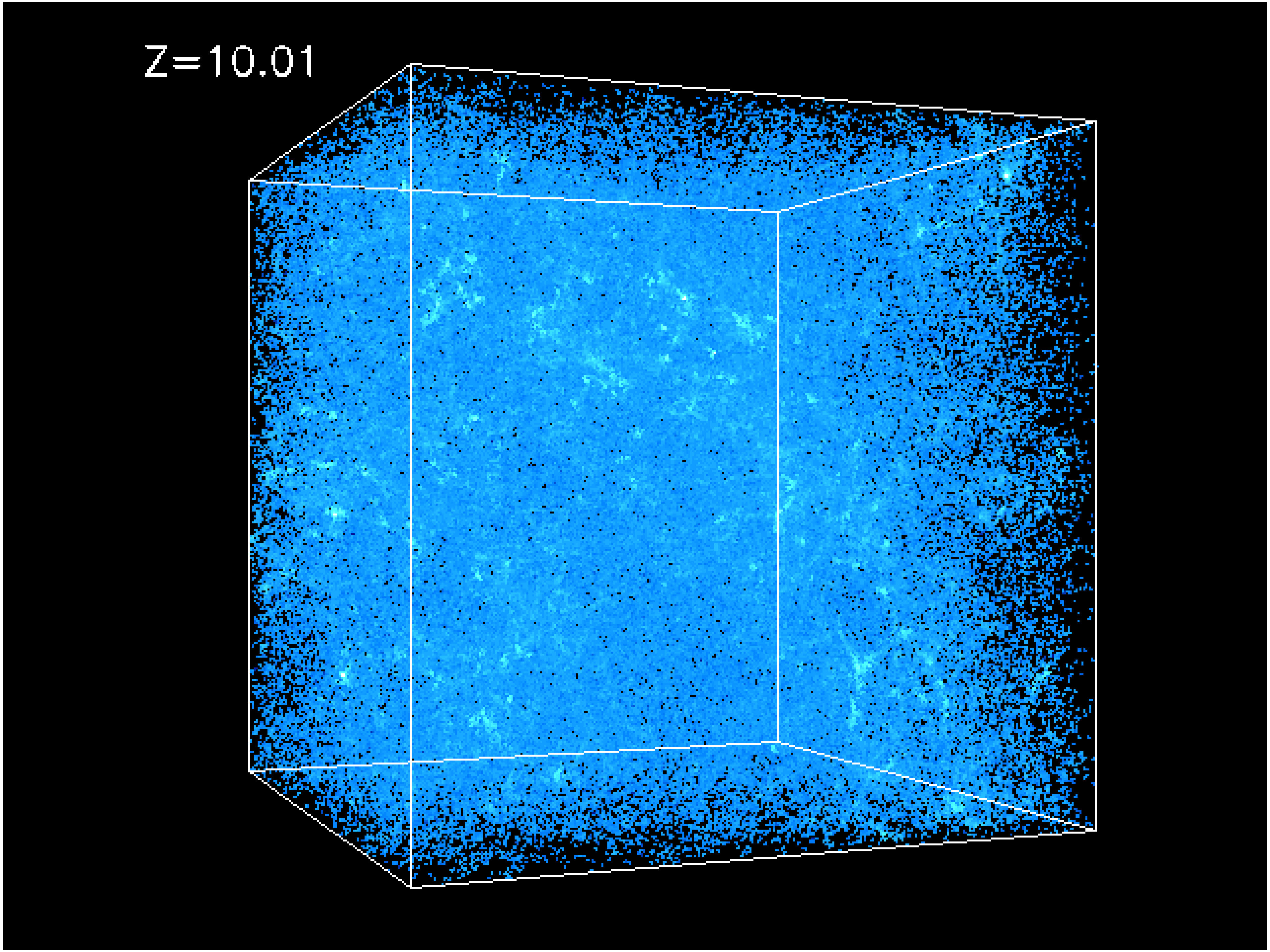
Gianfranco Brunetti

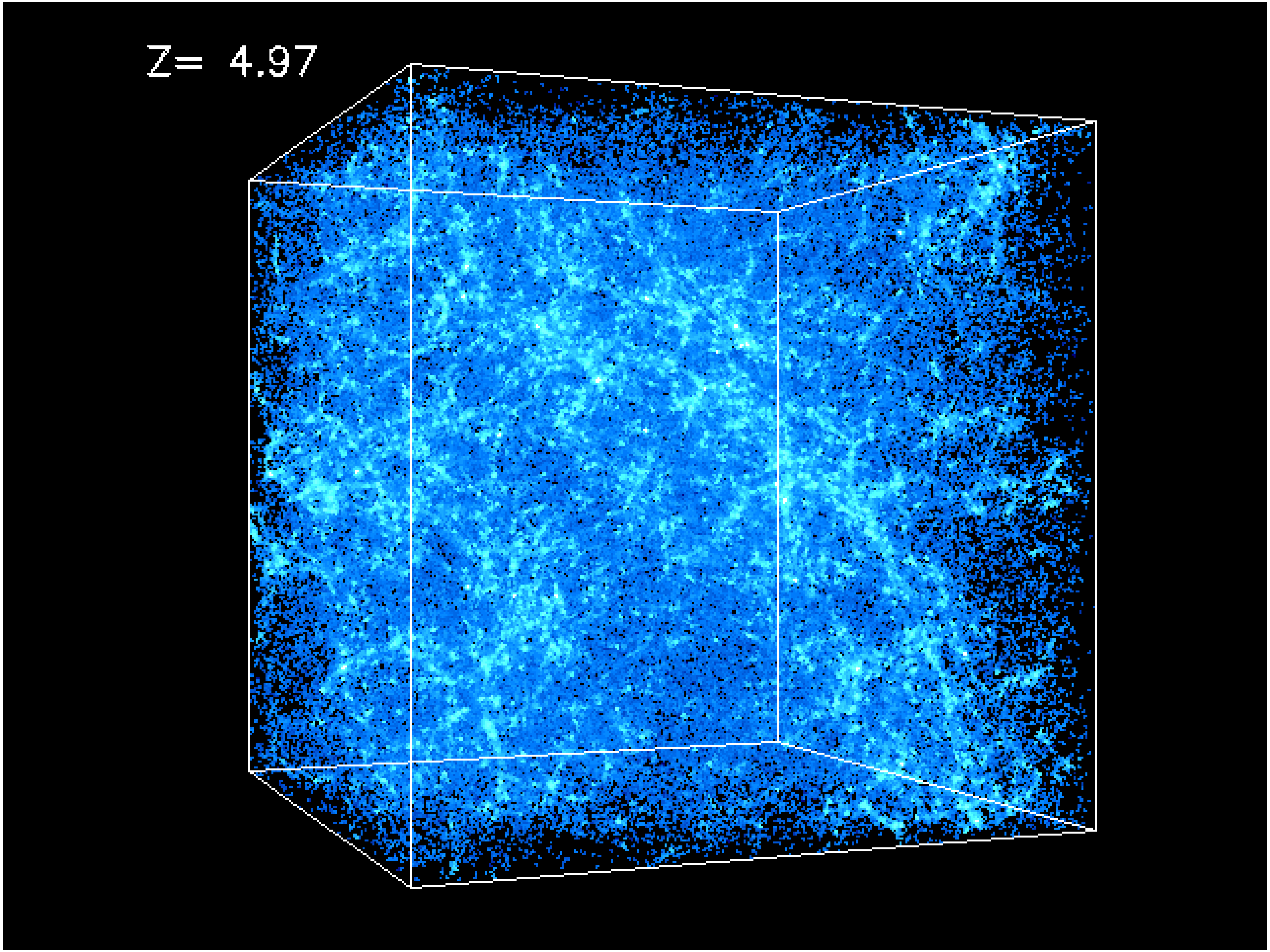
Institute of Radioastronomy –INAF, Bologna, ITALY

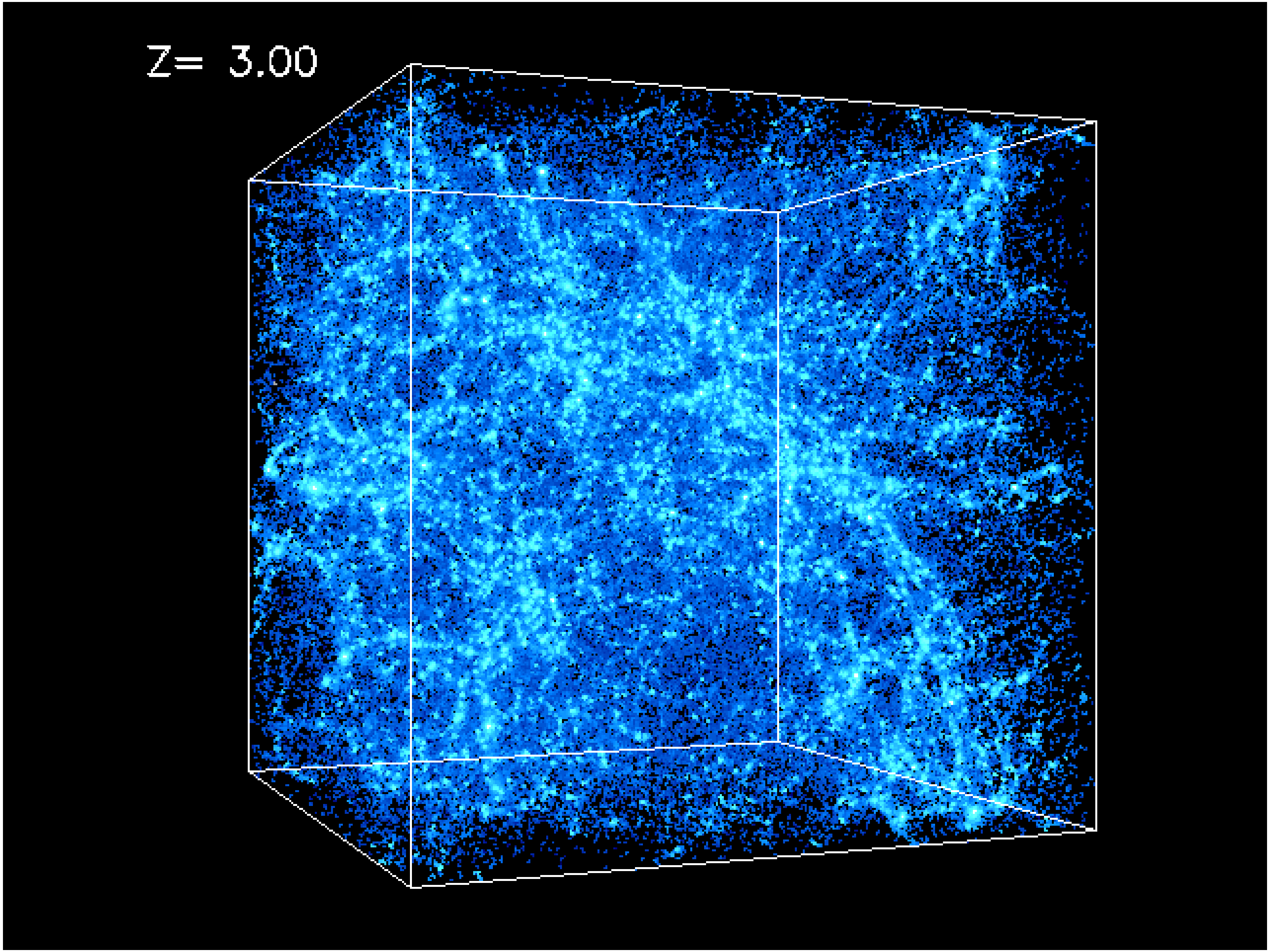
Outline

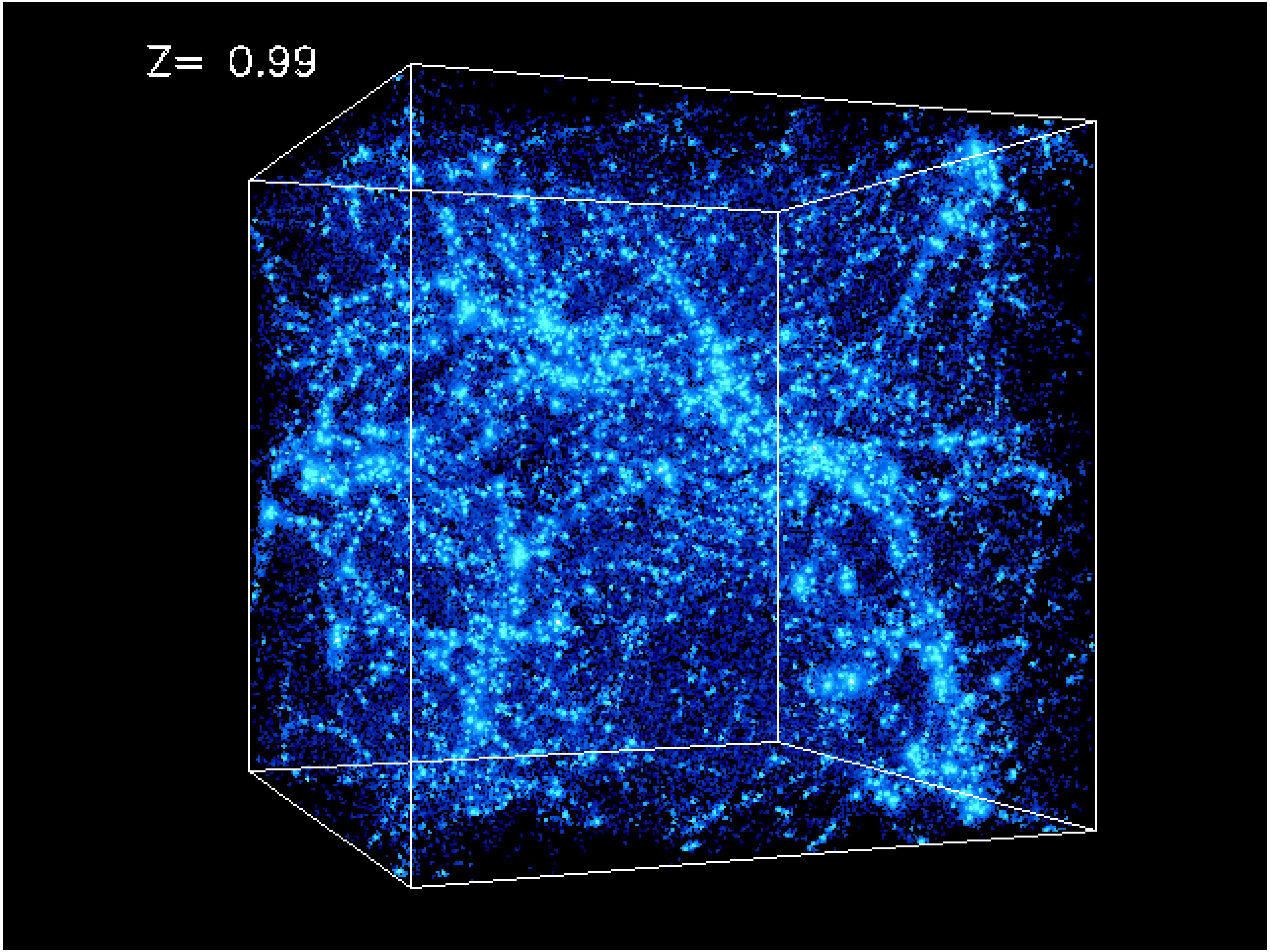
- Introduction : Galaxy Clusters
- Introduction : Non thermal emission
- Physics of non thermal components
- Models of particle acceleration

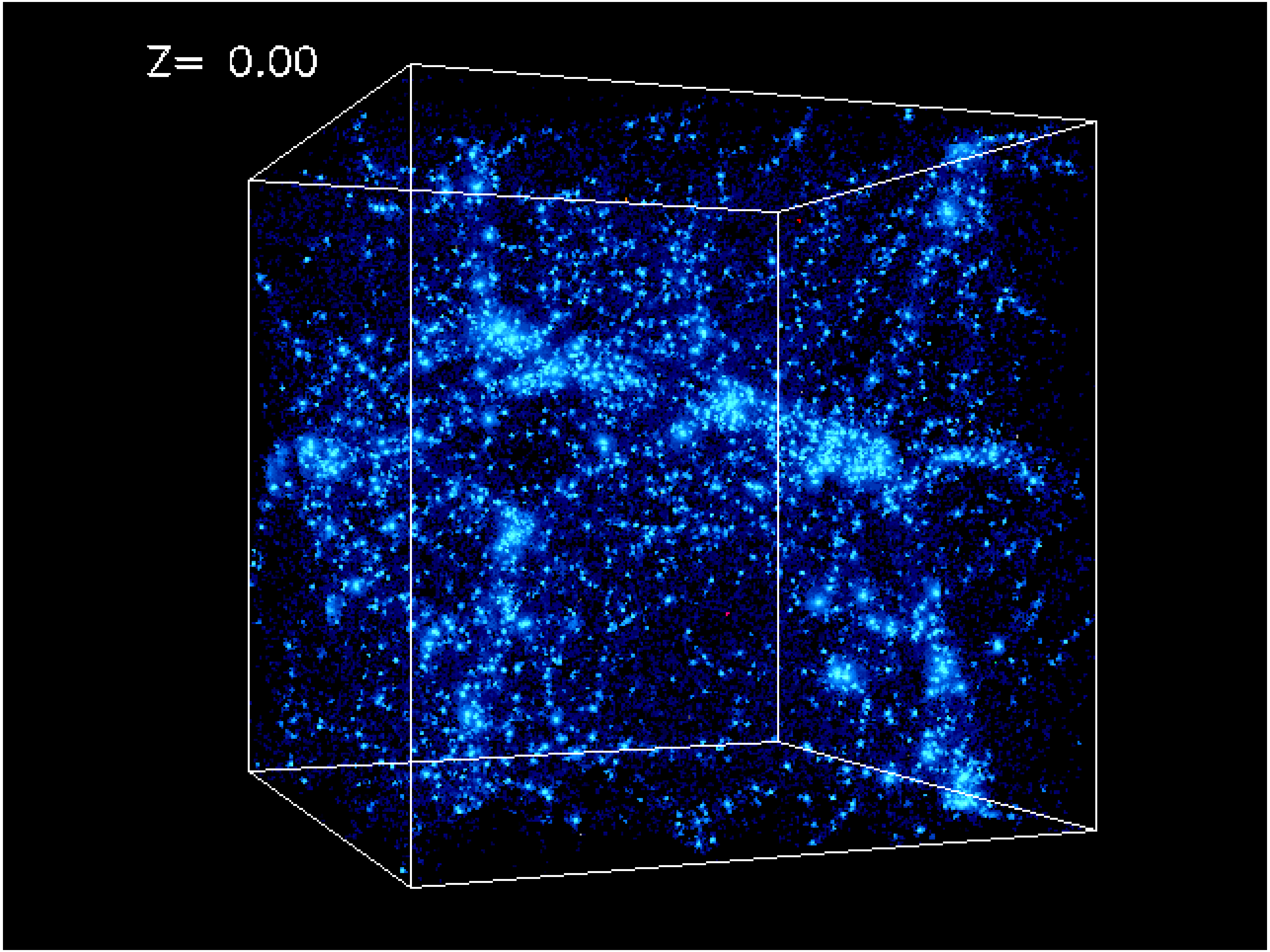

Z=28.62

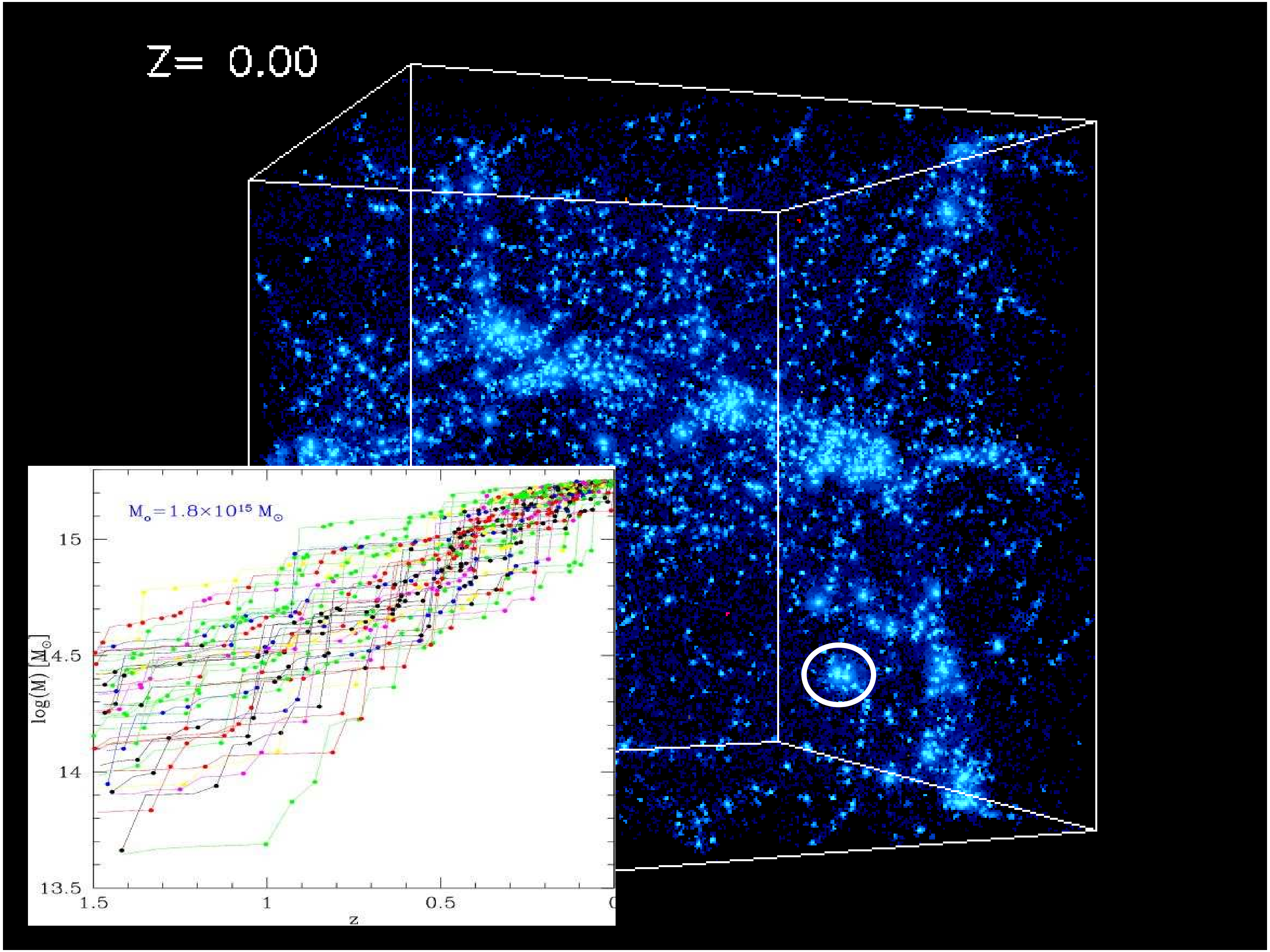

Z=10.01


Z= 4.97

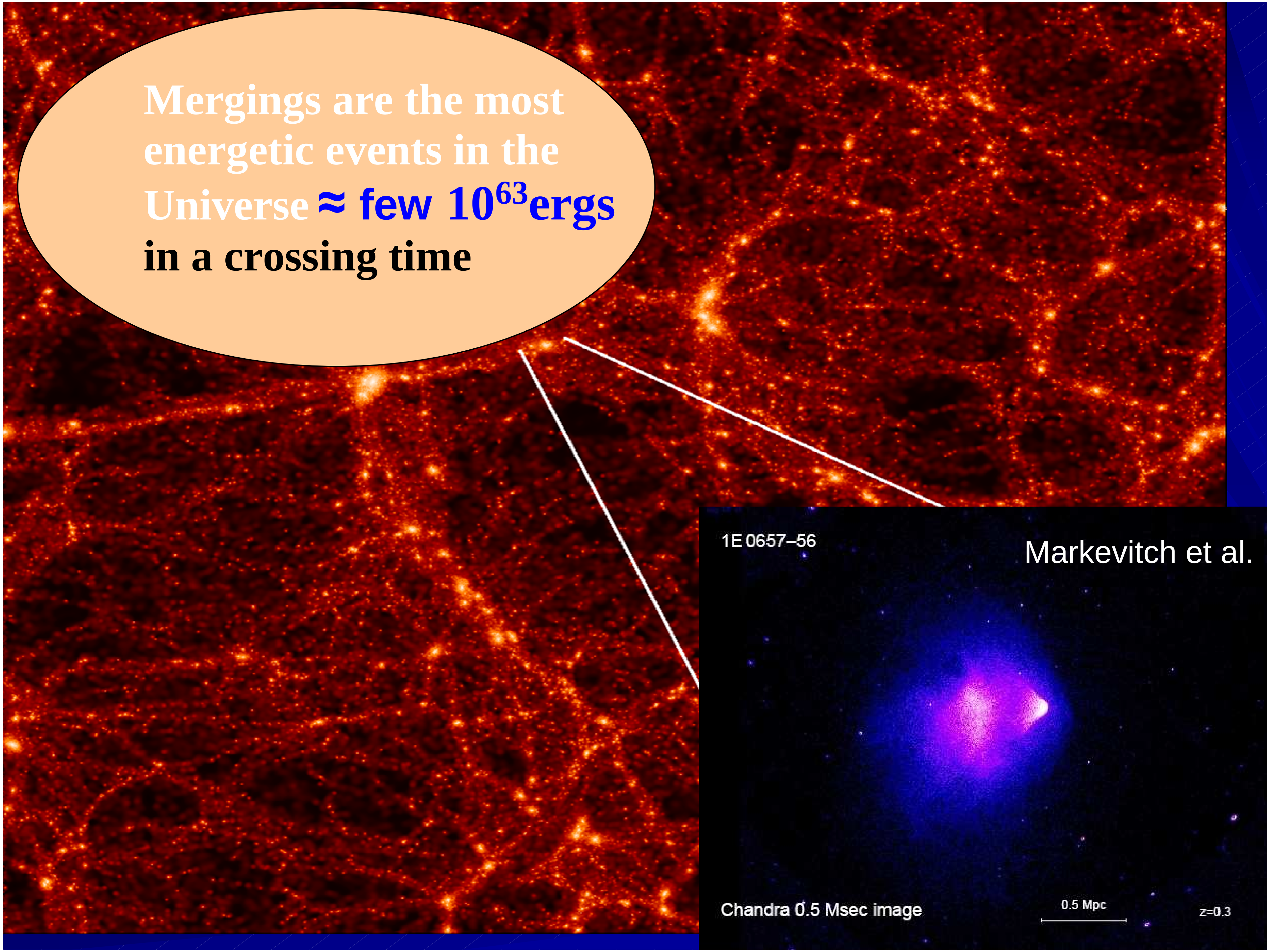

Z= 3.00


Z= 0.99


Z= 0.00



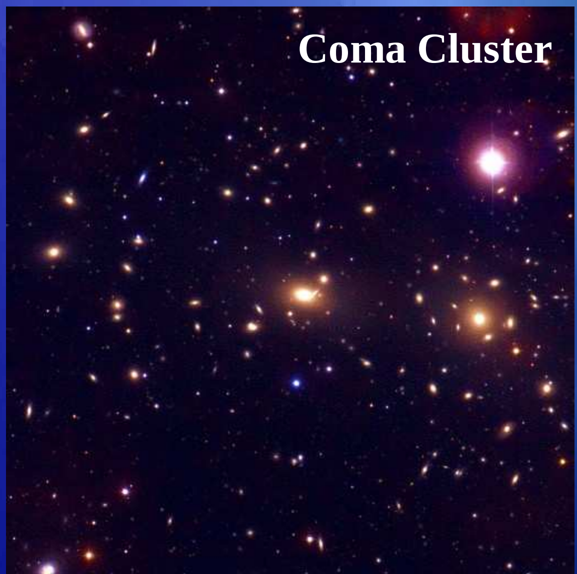
Z= 0.00
$M_o=1.8\times10^{15}\ M_\odot$
log(M) [$M_\odot$]
z
15
14.5
14
13.5
1.5
1
0.5
0


Mergings are the most energetic events in the Universe ≈ few 10^{63}ergs in a crossing time
1E 0657–56
Markevitch et al.
Chandra 0.5 Msec image
0.5 Mpc
z=0.3

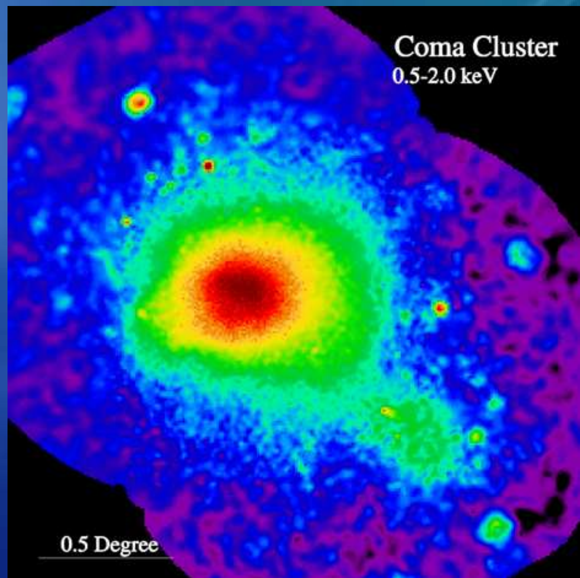
Clusters of galaxies: what is a galaxy cluster made of ?

- Galaxy Clusters are the largest concetrations of matter in our Universe.
- They extend over **2-4 Mpc** and have a total mass of **~ 10^{14}-10^{15} $M_\odot$**
- They contain thousands of galaxies, hot diffuse gas and expecially dark matter

Optical



X- ray



stars + dark matter

hot diffuse gas

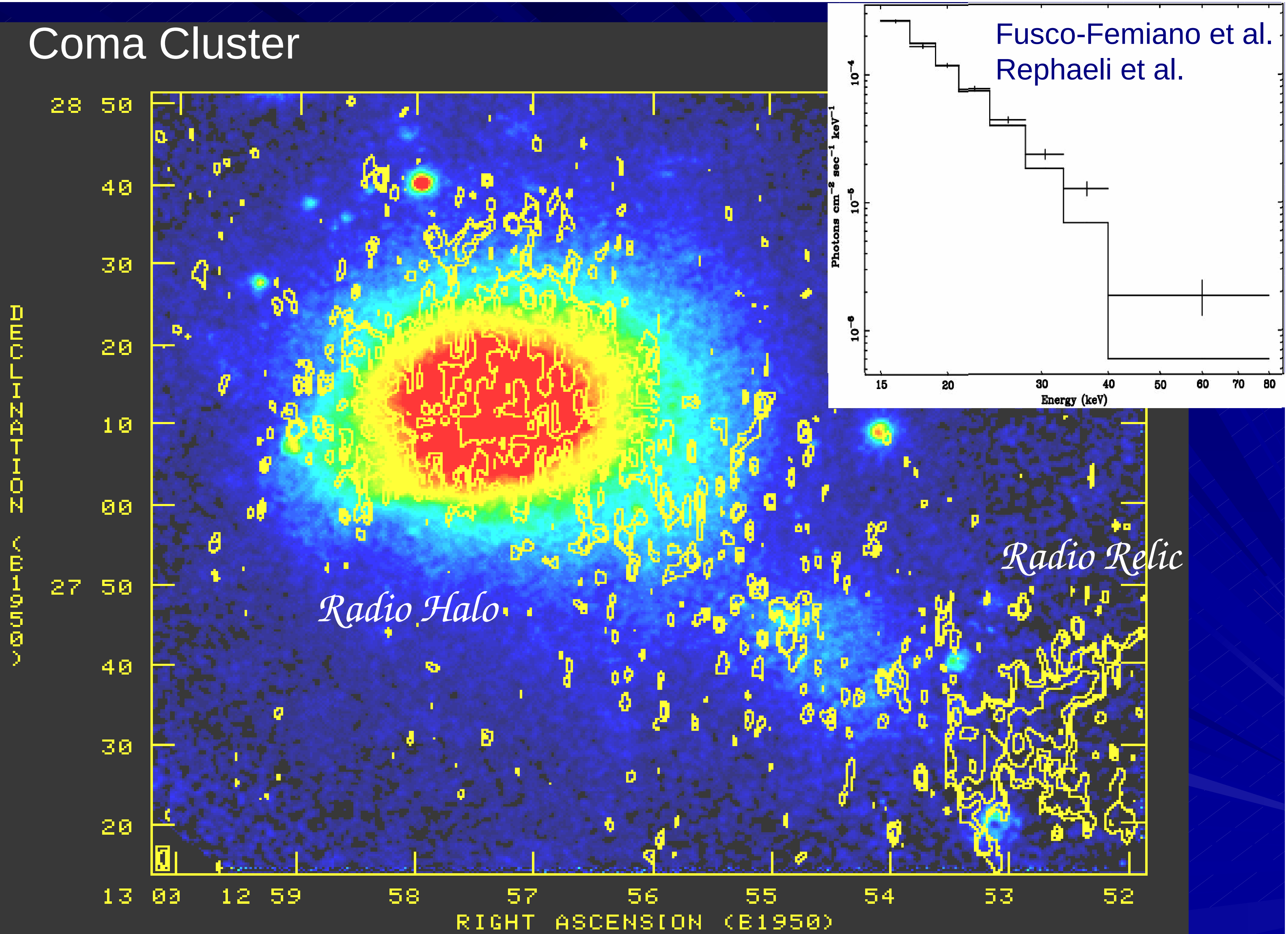
Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

Dark Matter **70%**

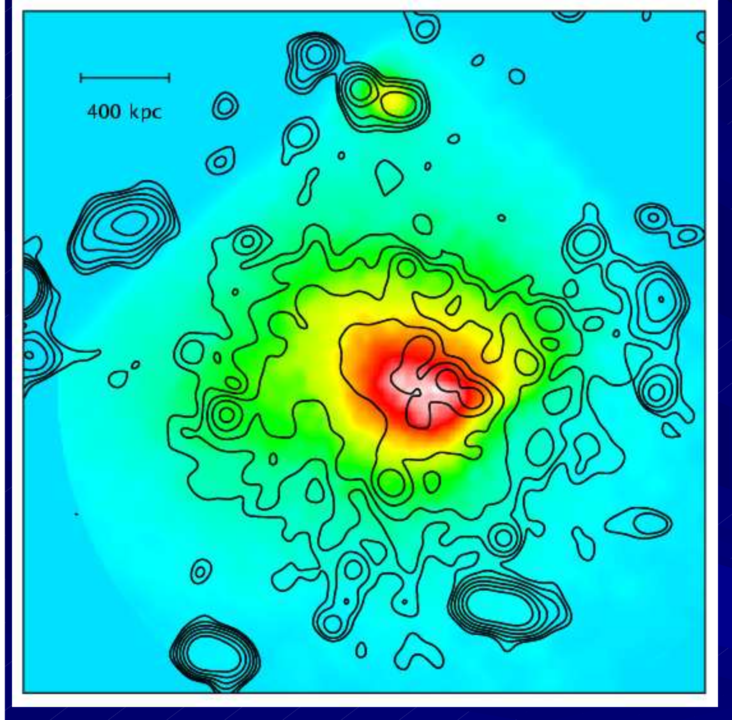
Coma Cluster



Feretti +al.1998

Radio Halos

A2163, Govoni +al.2004



$$\nu(\mathrm{Hz}) \approx 4.2\, B_{\mu G}\, \gamma^2$$

- **GeV electrons on Mpc scales**
- **μG magnetic fields on Mpc scales**

Cosmic Rays in GC

Cosmological Shocks

(e.g. Sarazin 1999, *Miniati et al. 2001, Blasi 2001,*
Gabici & Blasi 2003, Ryu et al. 2003,
Pfrommer et al. 2006, 2008, Vazza, Brunetti, Gheller 2008)

AGN, Galactic Winds

(e.g. Ensslin et al. 1998; Voelk & Atoyan 1999)

Merger-Energy Budget

$$L_M = \frac{10^{63-64}}{\tau_{cross}} \approx 10^{47}\ \mathrm{erg/s}$$

$$\tau_{cross} \longrightarrow 10^{9}\ \mathrm{yrs}$$

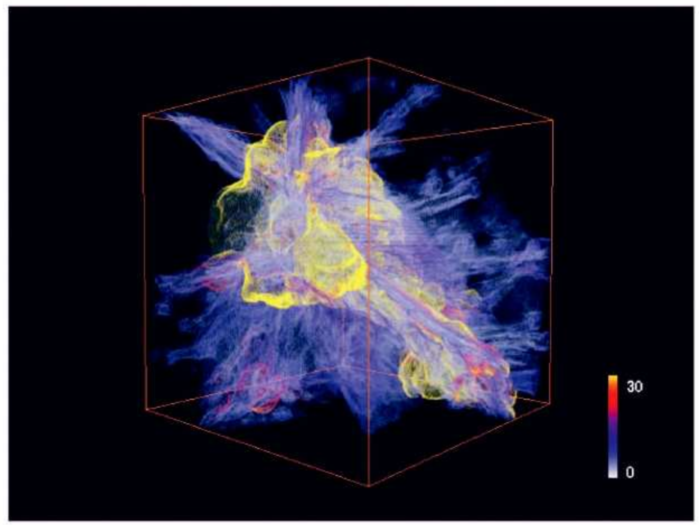
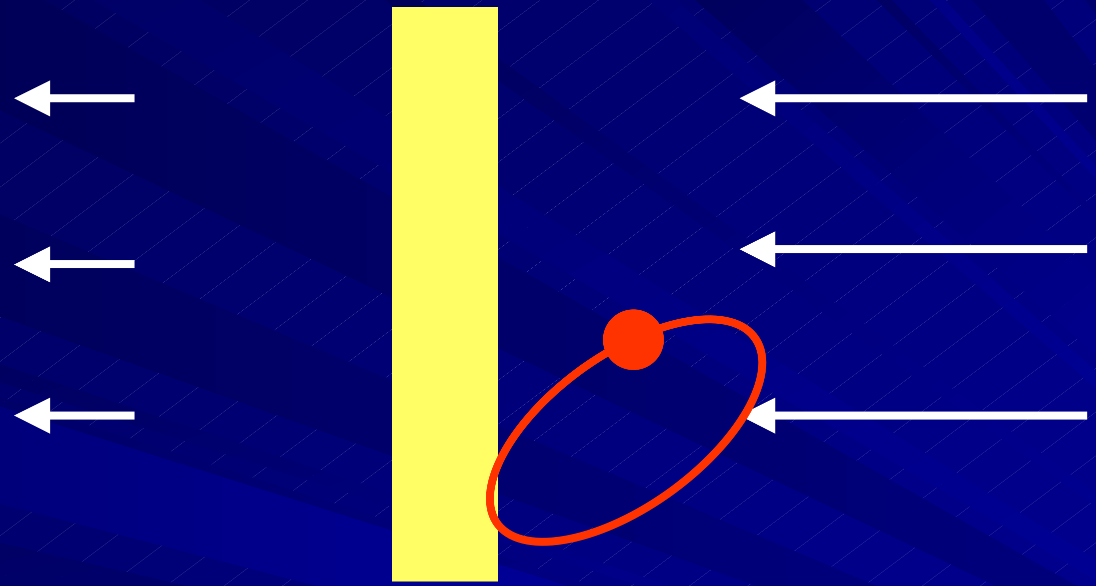


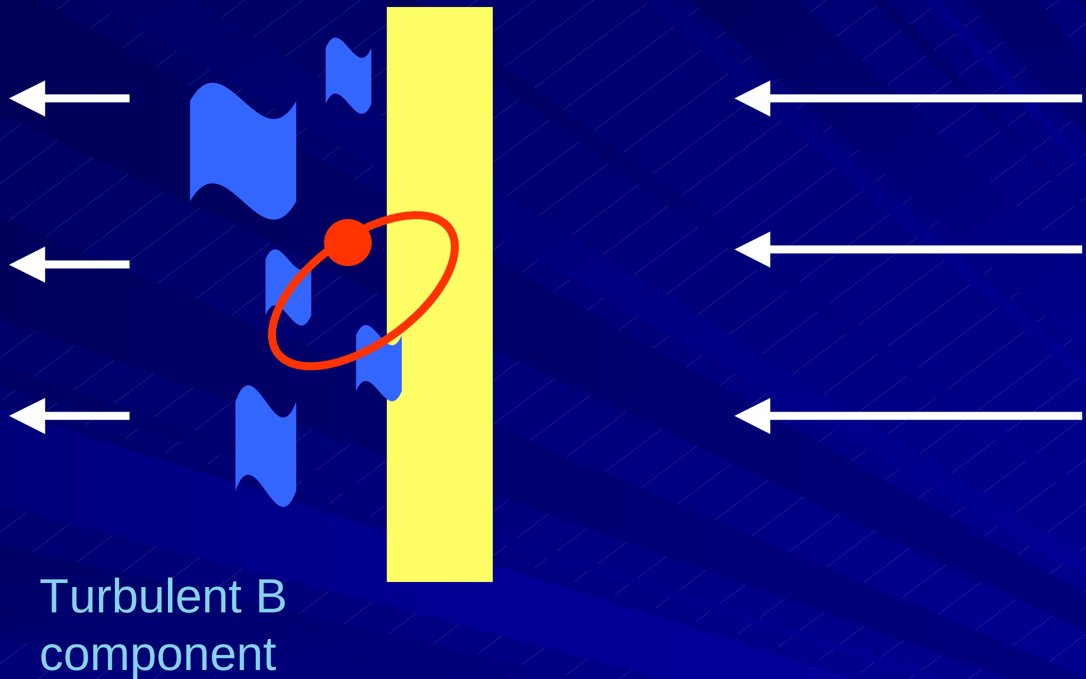
FIG. 4.—Three-dimensional shock surfaces in a volume of $(25\ h^{-1}\ \mathrm{Mpc})^3$ around the same complex as in Fig. 3. The color bar shows the values of Mach numbers of shock surfaces.

$$\eta L_M \longleftrightarrow L_{NTh}$$

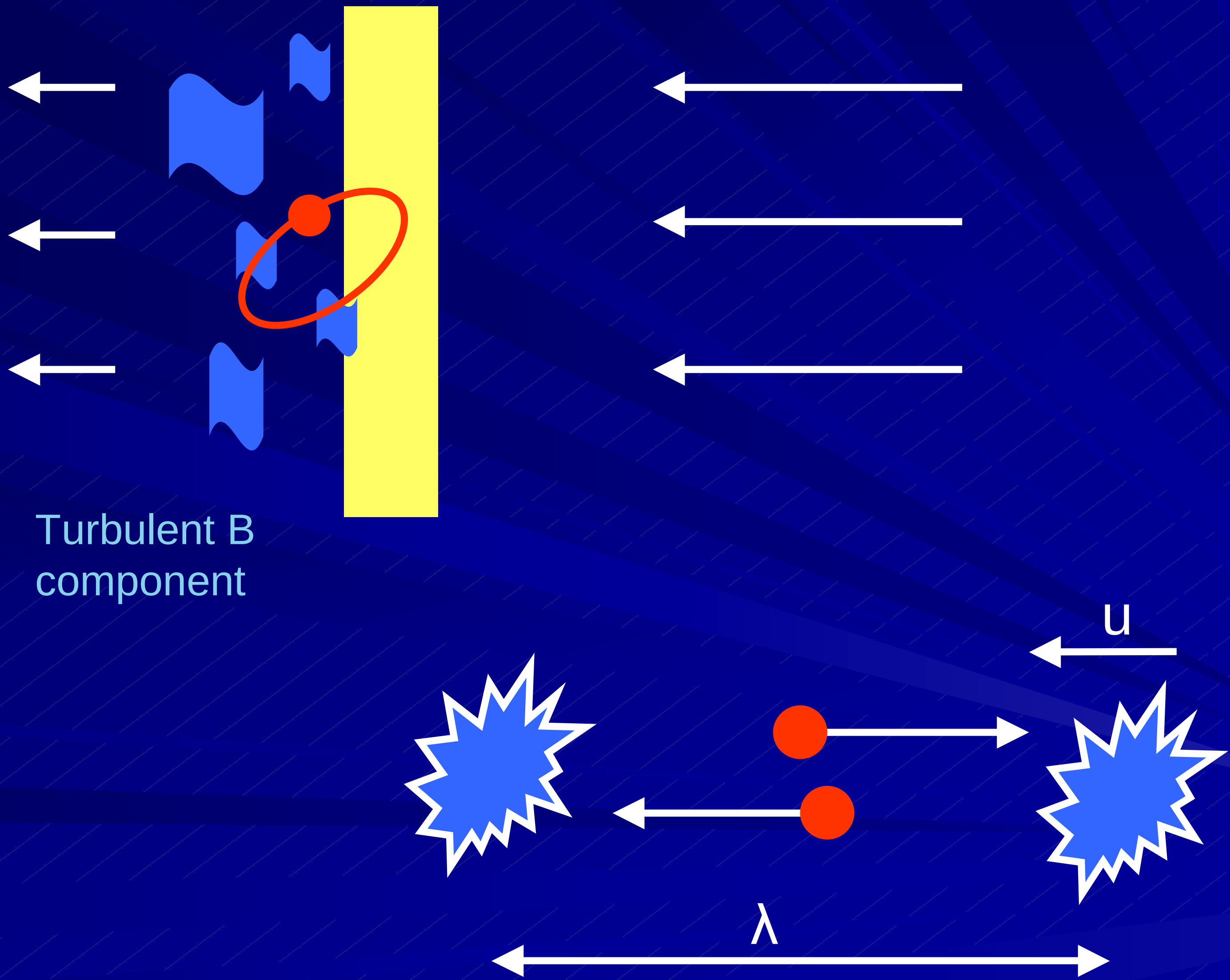
Acceleration of CR at shocks

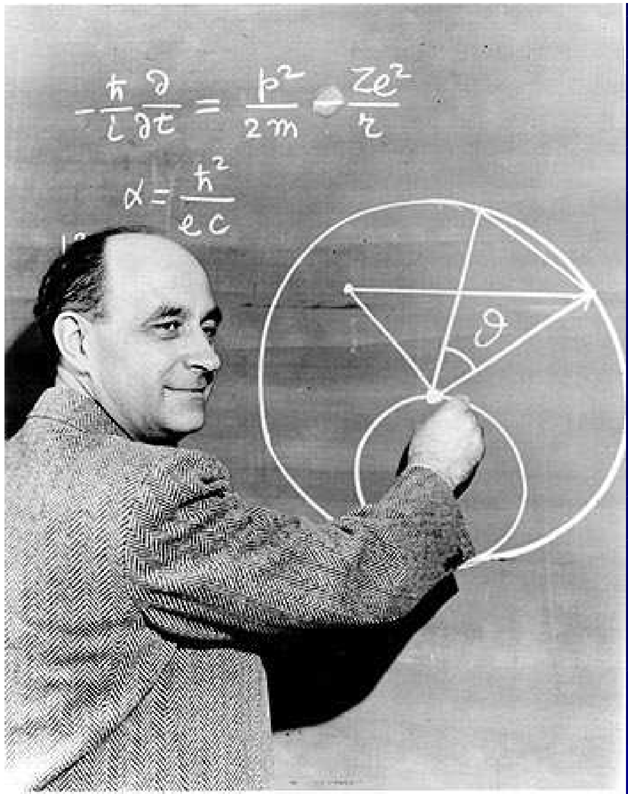


Acceleration of CR at shocks



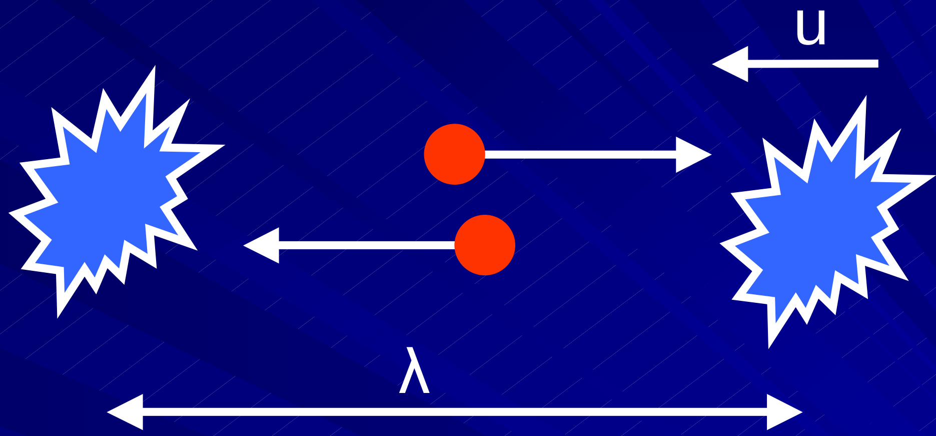
Acceleration of CR at shocks





First order Fermi Mechanisms

(Fermi 1949)



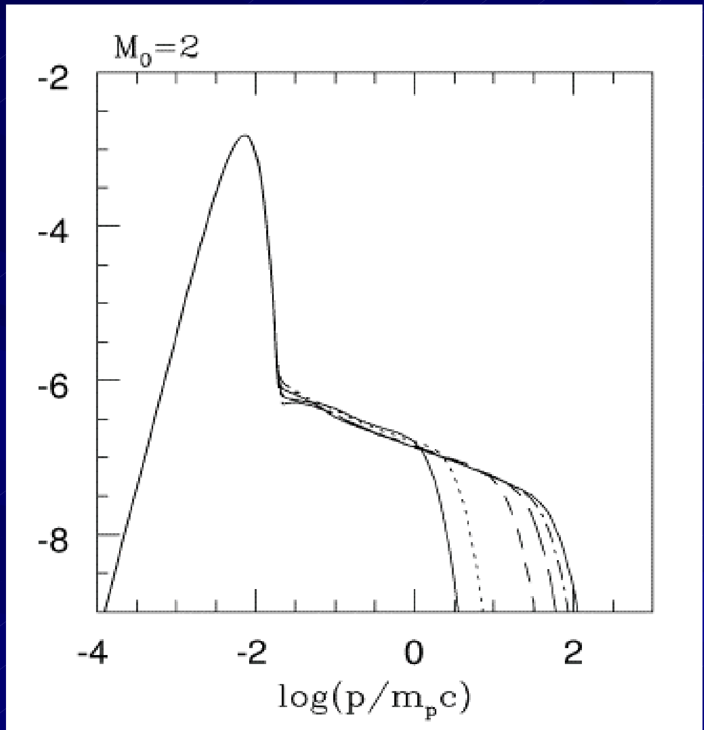
Frequency of collisions: $\nu_+ = \frac{u+c}{\lambda}$

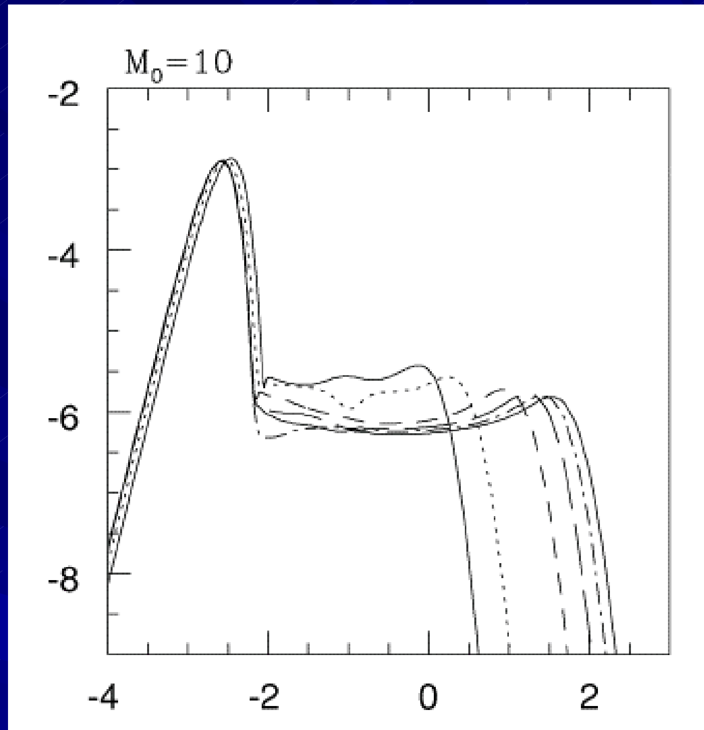
Energy gain per collisions: $\Delta p_+ = 2p\frac{u}{c}$

Energy gain per second: $\left\langle \frac{\Delta p}{\Delta t} \right\rangle \simeq 2p\frac{u}{c}\frac{c}{\lambda}$

Acceleration of CRp at shocks

Np^2





(Kang & Jones 2002; **Malkov 1997, Kang & Jones 2005, 07, Amato & Blasi 2006)**

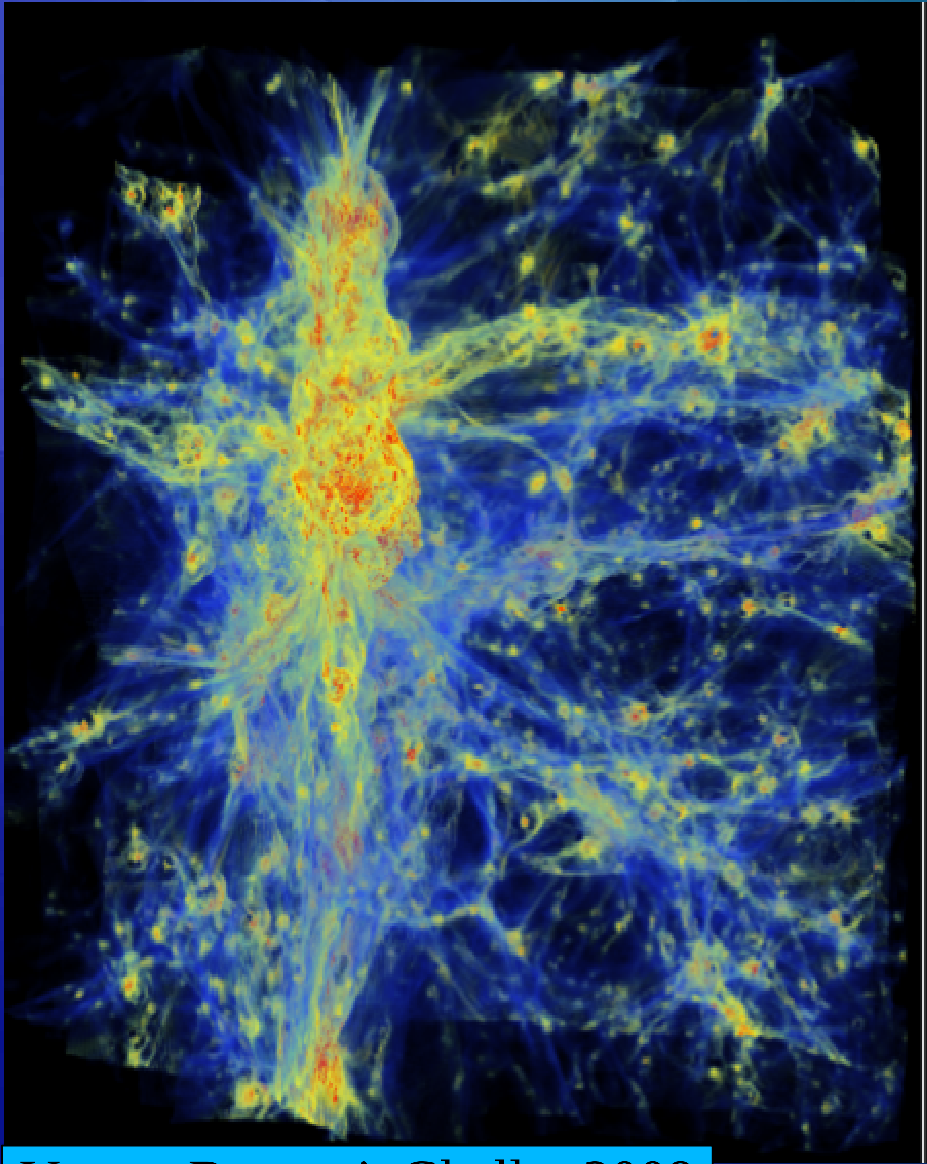
$N(p) \propto p^{-\delta}$

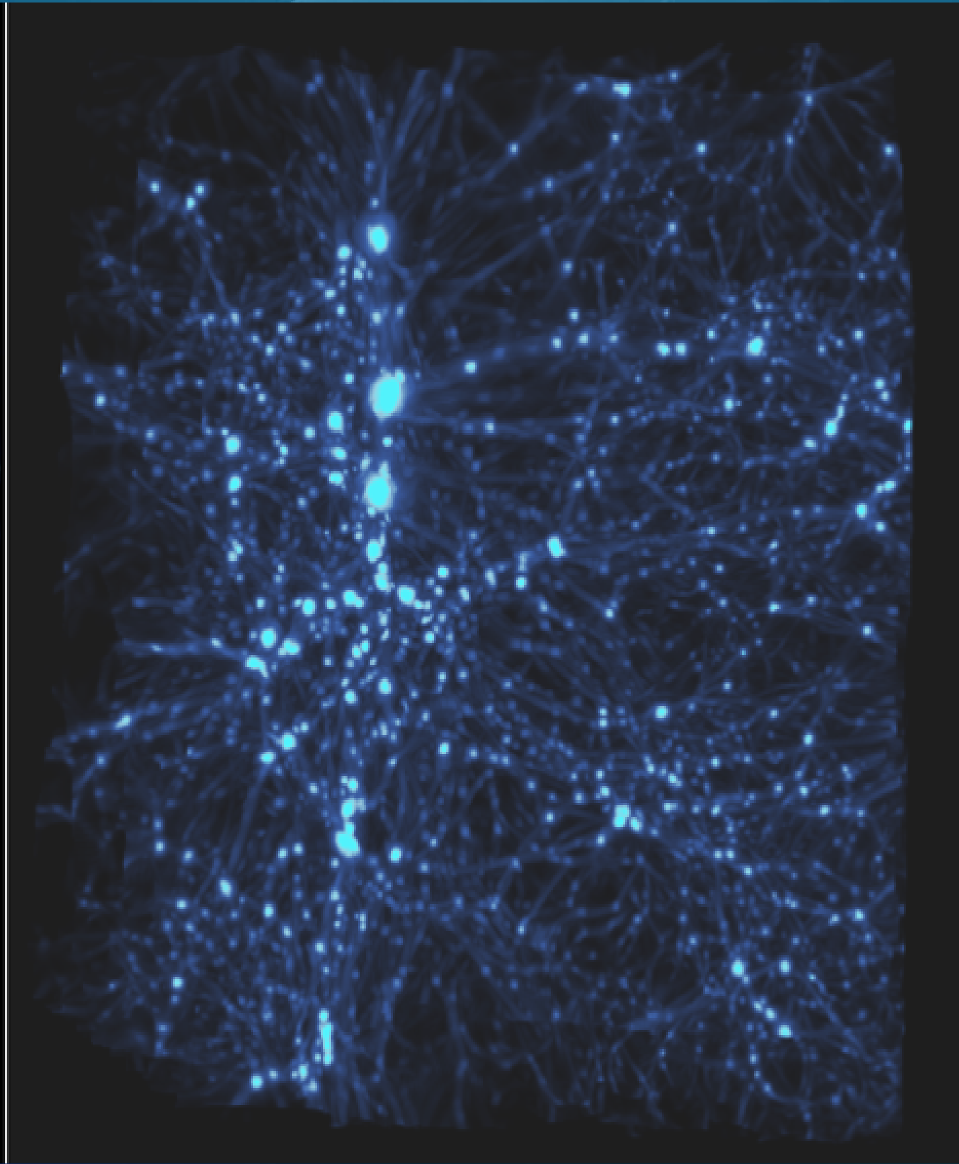
$$\delta = 2\frac{\mathcal{M}^2+1}{\mathcal{M}^2-1}.$$

Linear Theory

(e.g.,Blandford & Eichler 1987)

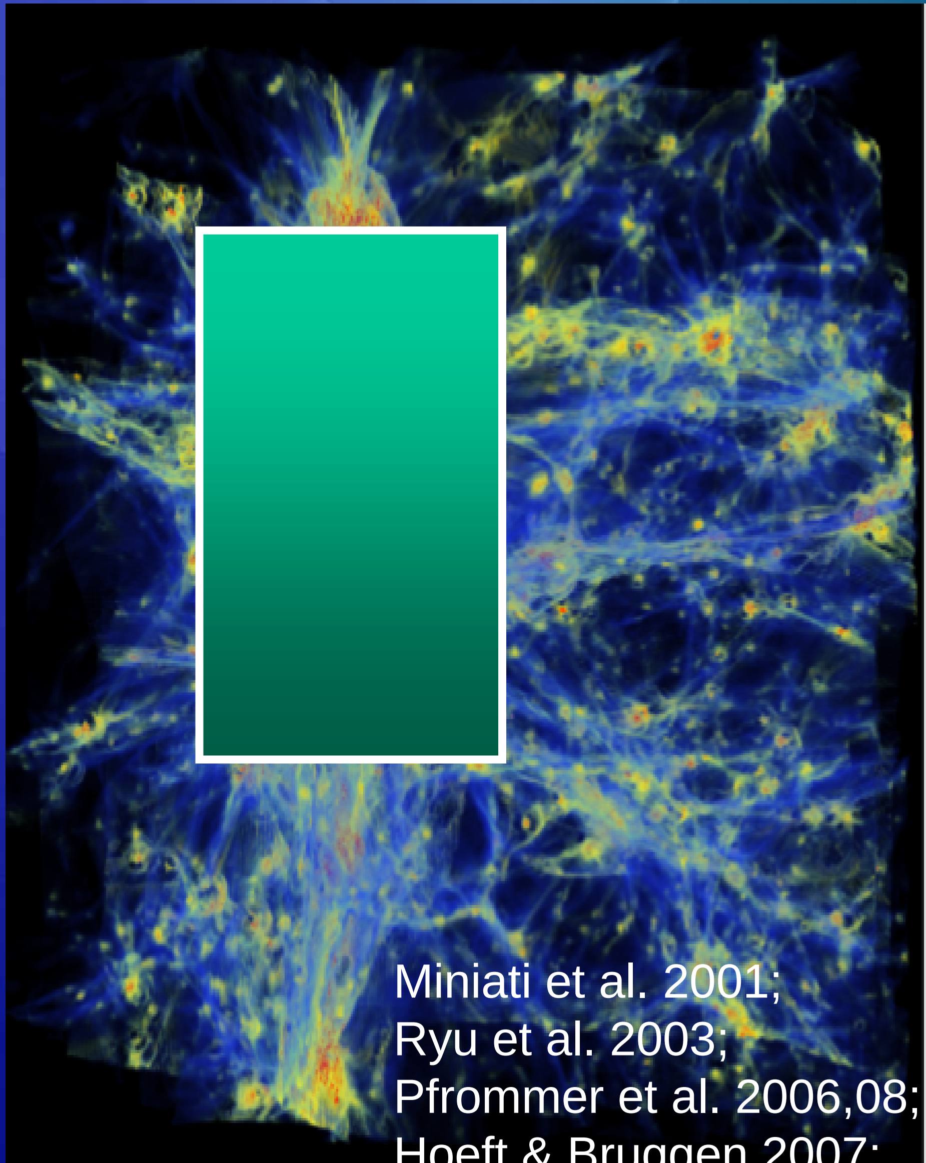
Simulations : Shocks in Galaxy Clusters

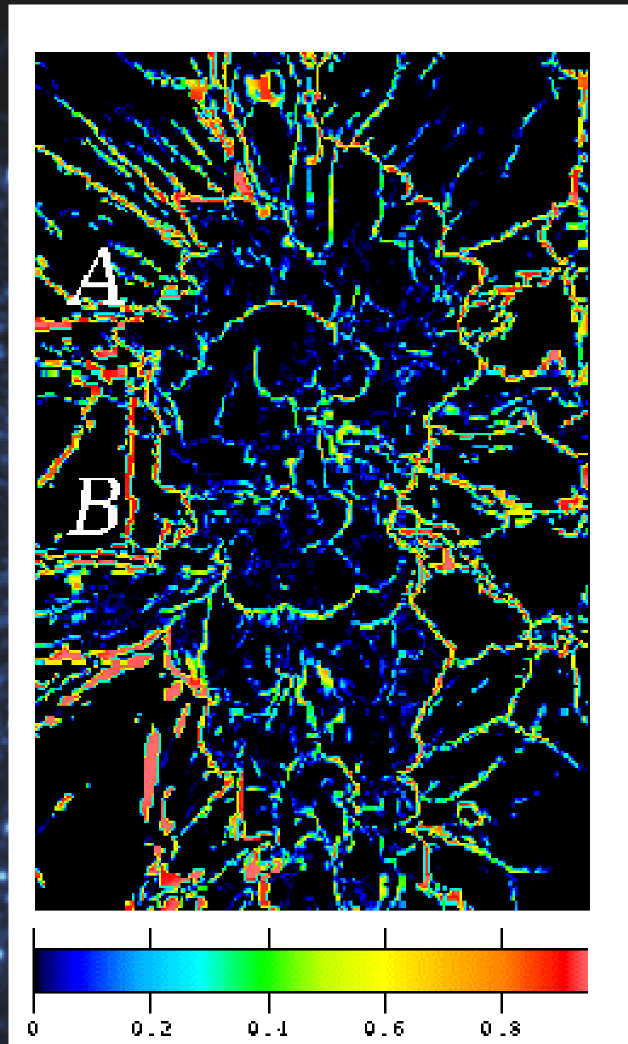




Vazza, Brunetti, Gheller 2008

Shocks in Galaxy Clusters





Vazza, Brunetti, Gheller 2008

Miniati et al. 2001;
Ryu et al. 2003;
Pfrommer et al. 2006,08;
Hoeft & Bruggen 2007;
Skillman et al. 2008

Physics of CR Leptons

Sarazin 1999 ; Brunetti 2003 for reviews

$(dE/dt) / m_e c^2$ = b = rate of energy losses in units of $m_e c^2$

$$b_{IC}(\gamma) = \frac{4}{3}\frac{\sigma_T}{m_e c}\gamma^2 U_{CMB} = 1.37\times 10^{-20}\gamma^2(1+z)^4 \text{ s}^{-1},$$

$$b_{syn}(\gamma) = \frac{4}{3}\frac{\sigma_T}{m_e c}\gamma^2 U_B = 1.30\times 10^{-21}\gamma^2\left(\frac{B}{1\ \mu\text{G}}\right)^2 \text{ s}^{-1},$$

Photon Collisions

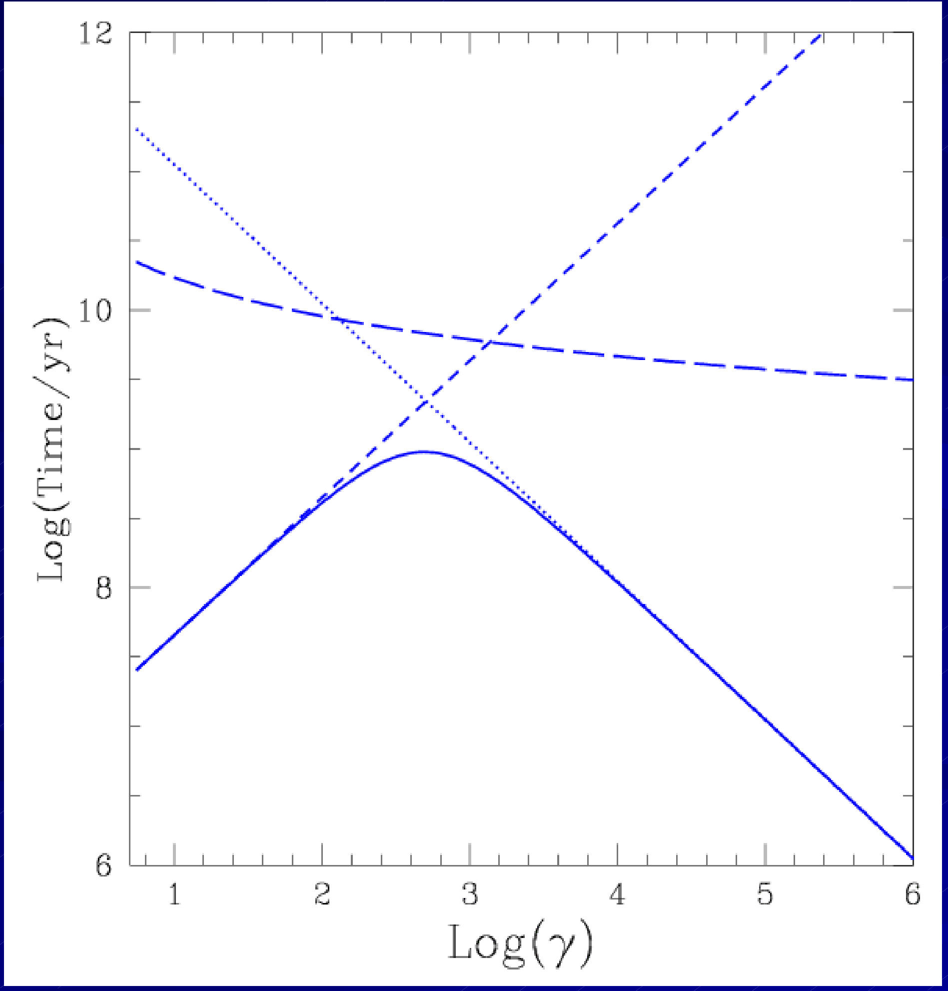
$$b_{Coul}(\gamma) \approx 1.2\times 10^{-12} n_e\left[1.0 + \frac{\ln(\gamma/n_e)}{75}\right] \text{ s}^{-1},$$

$$b_{brem}(\gamma) \approx 1.51\times 10^{-16} n_e \gamma[\ln(\gamma) + 0.36] \text{ s}^{-1},$$

Particle Collisions

Physics of CR Leptons

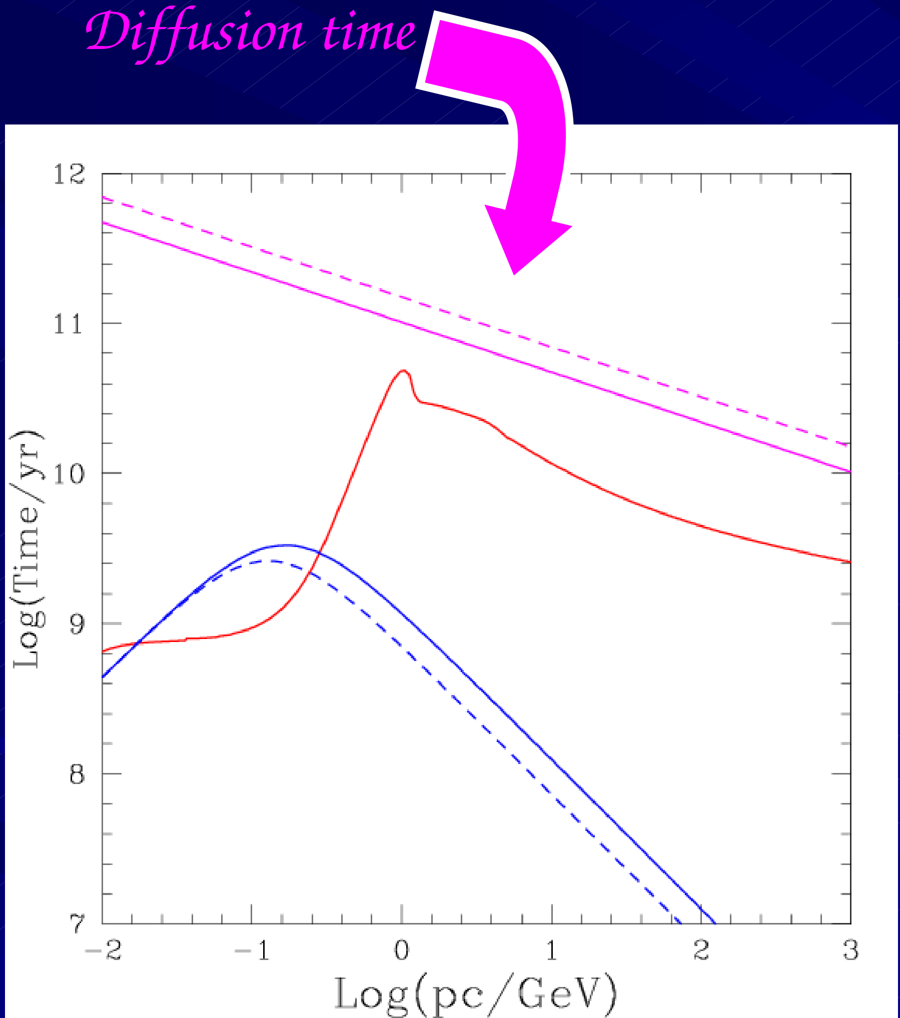
(dE/dt) ~ E / Time ~ $m_e c^2 b$



$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm th}/10^{-3}}\right)\right]\right\}^{-1}.$$

The life-time of electrons depends on quantities that are well measured

I - Cosmic Ray Confinment in GC



Blasi, Gabici, Brunetti 2007

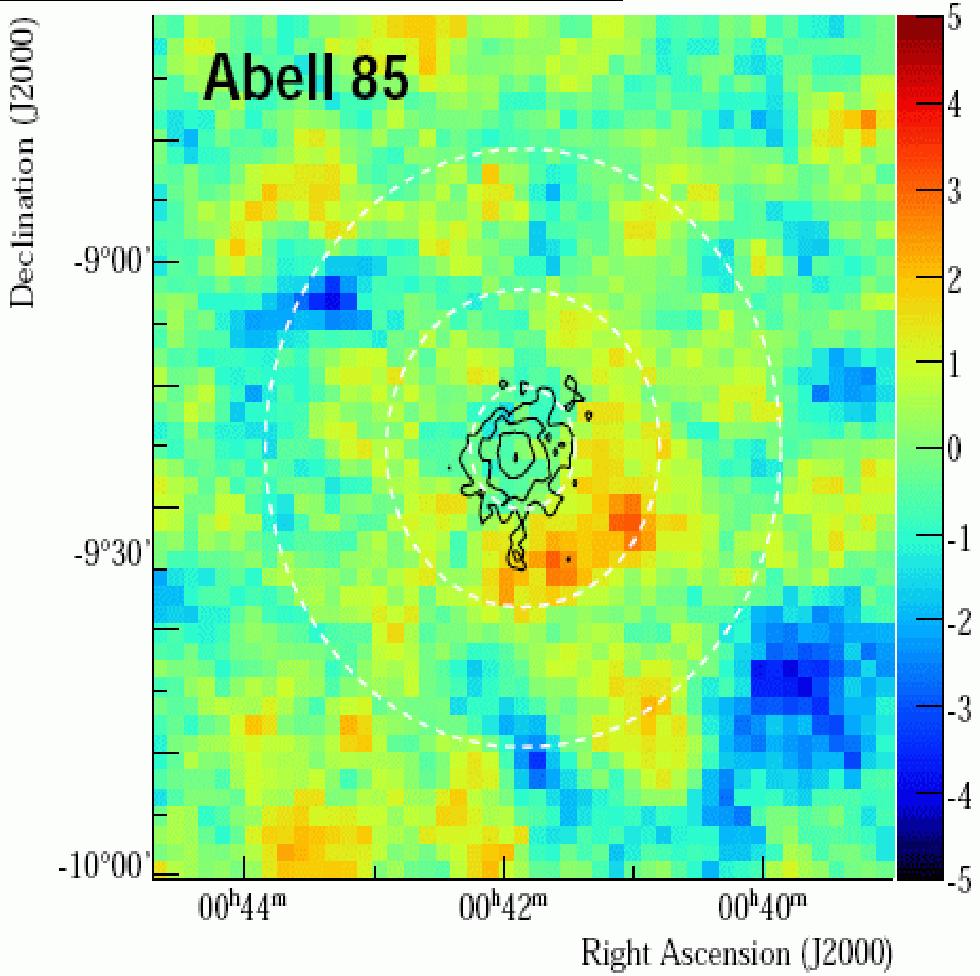
- CR protons are ***long living*** particles and are ***confined*** (Voelk et al 1996; Berezinsky, Blasi, Ptuskin 1997)
- CR electrons are ***short living*** particles and ***accumulated*** at $\gamma \approx 100$-300 (e.g., Sarazin 1999)

Secondary Particles in the IGM

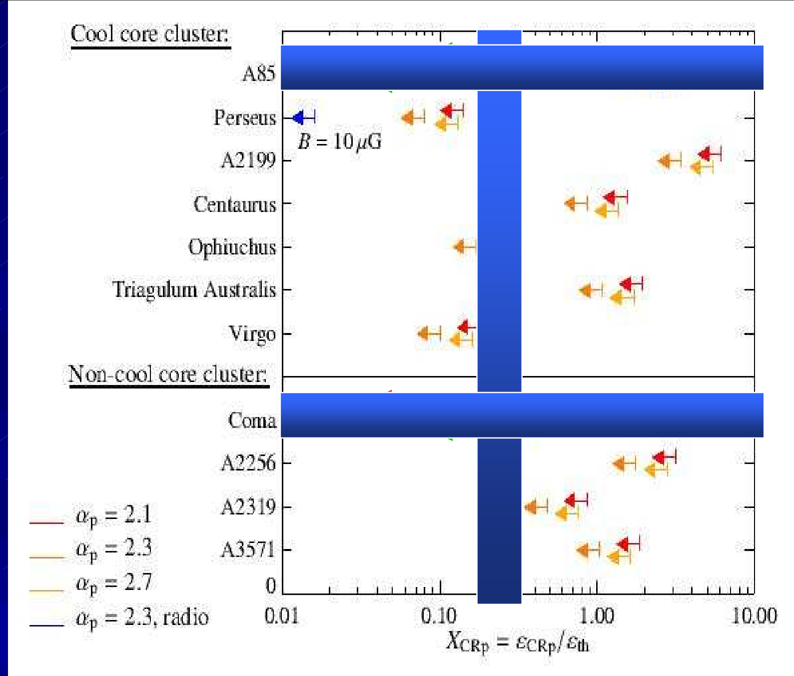
Dennison 1980; Blasi & Colafrancesco 1999; Pfrommer & Ensslin 2004;
Brunetti & Blasi 2005; Wolfe & Melia 2007; Brunetti 2008

Limits from gamma rays

Aharonian + al. 2008



Reimer +al. 2003; Pfrommer & Ensslin 2004



H.E.S.S.

A 85 : Ecr/Eth < 6-15% (hard spectra)

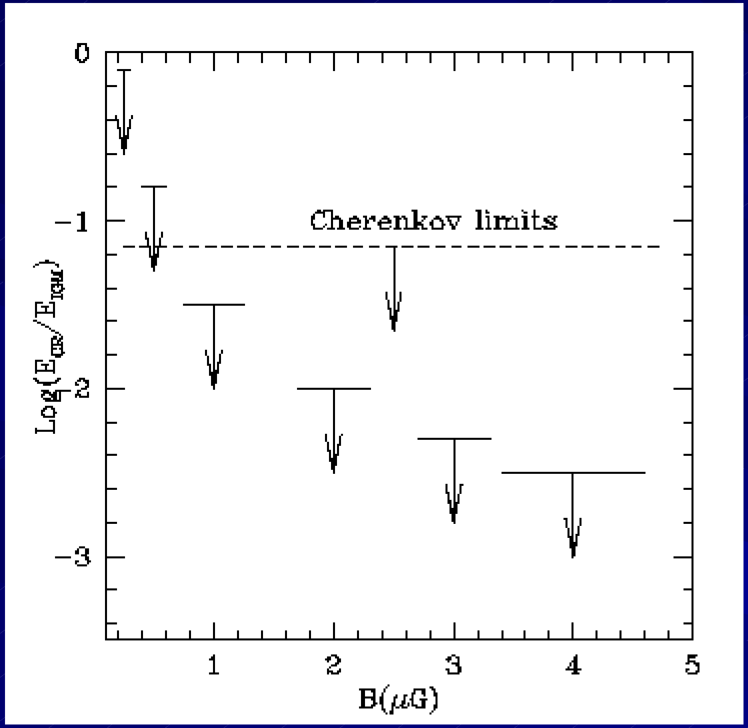
Coma : Ecr/Eth < 12%

VERITAS (Perkins +al. 2008)

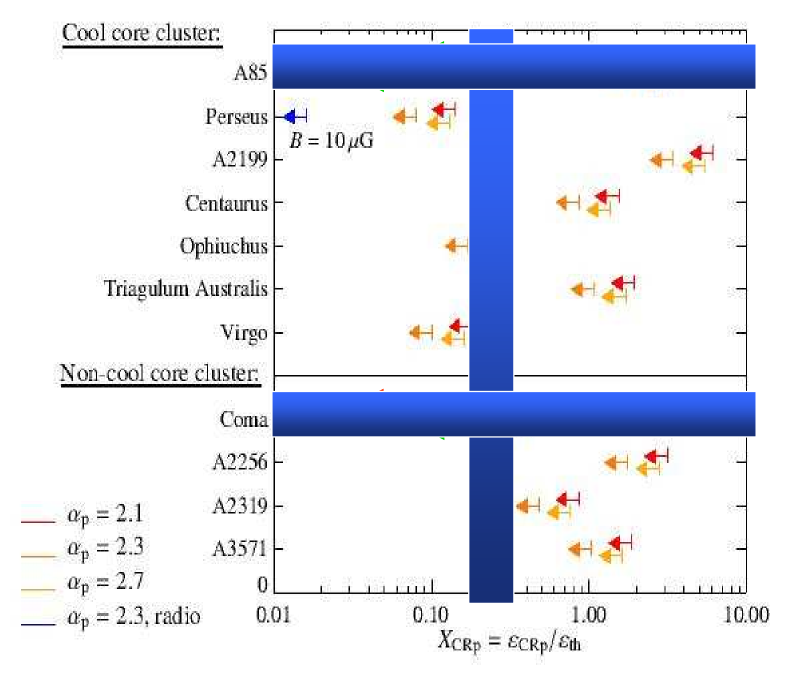
Coma : Ecr/Eth < 5% (hard spectra)

Limits for CR protons

Brunetti, Blasi, Cassano, Gabici 2008



Reimer +al. 2003; Pfrommer & Ensslin 2004



Limits from radio observations are obtained from the constraints to secondary electrons in galaxy clusters Without Radio Halos

H.E.S.S.

A 85 : Ecr/Eth < 6-15% (hard spectra)

Coma : Ecr/Eth < 12%

VERITAS (Perkins +al. 2008)

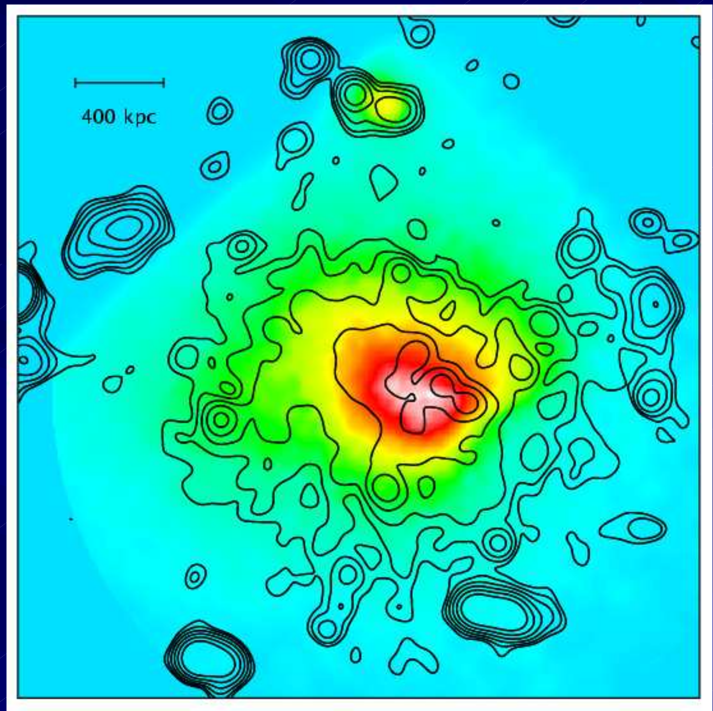
Coma : Ecr/Eth < 5% (hard spectra)

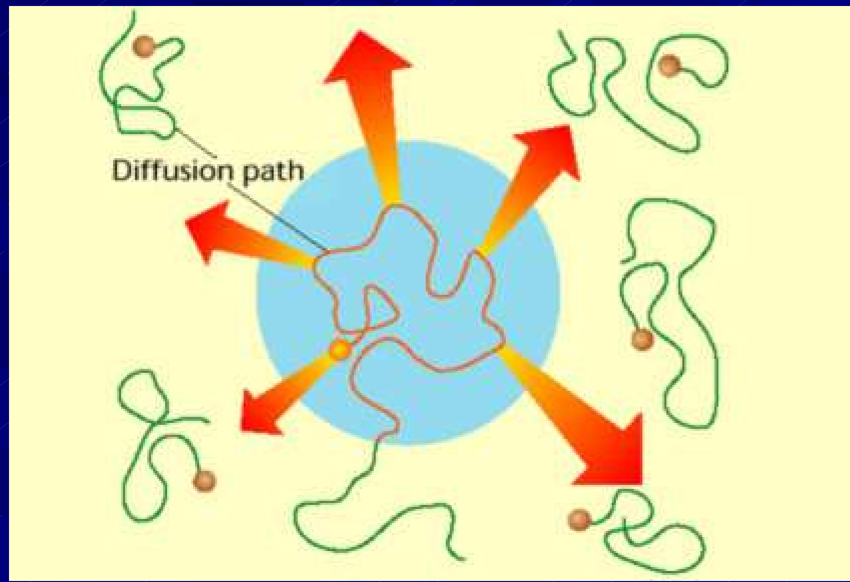
II - Conclusion

(a) Protons are expected the dominant CR population in the IGM : they result from the accumulation of CR from the epoch of formation of galaxy clusters

(b) Despite (a) we have only upper limits to the energy content in the form of CR protons

Origin of Radio Halos



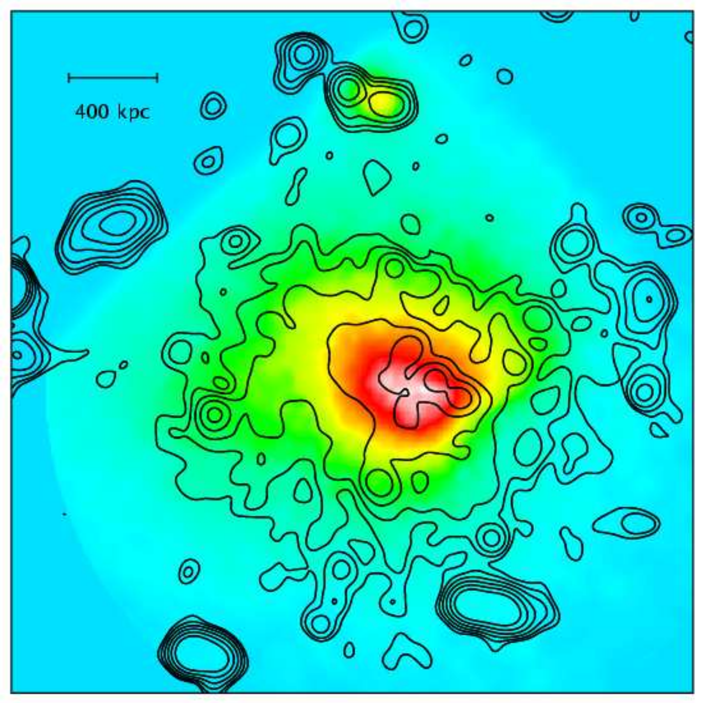


$$\frac{\partial n_p(E_p, r, t)}{\partial t} - D(E)\nabla^2 n_p(E_p, r, t)$$

$$D(E_p) = \frac{1}{3} r_L c \frac{B^2}{\int_{1/r_L}^{\infty} dk P(k)}$$

$$R \approx 2\sqrt{\tau D}$$

Radio Halos



$$\tau = \tau_E$$

$$R \approx 2\sqrt{\tau D}$$

Brunetti 2003

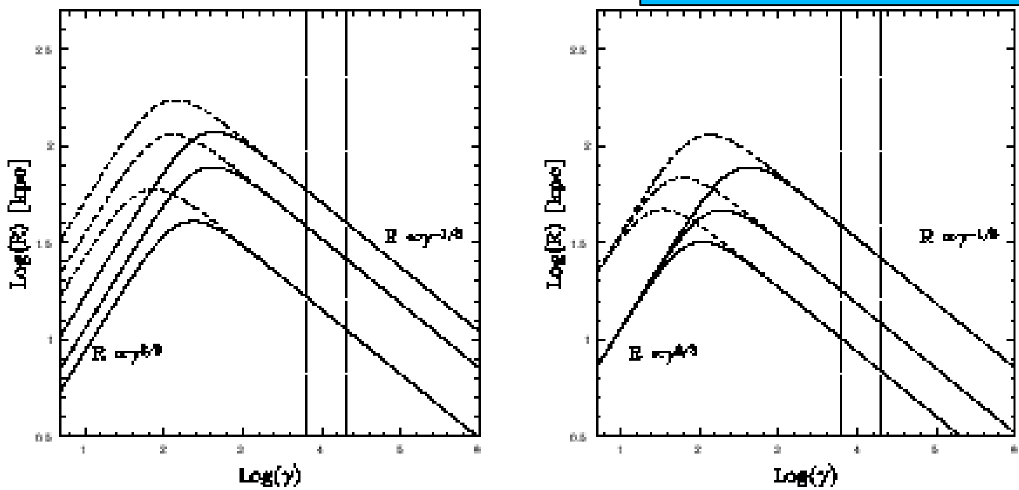
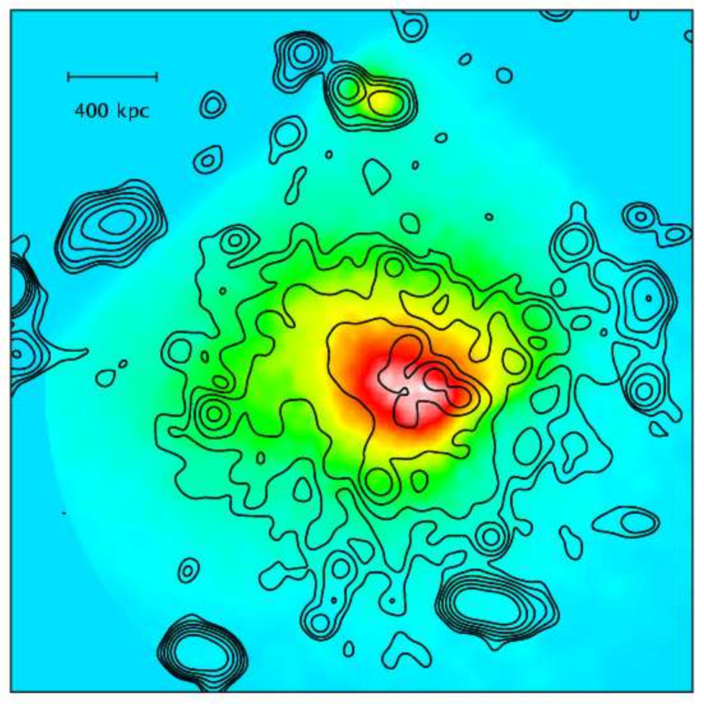


Figure 2. **Panel a)** : Diffusion lengths are reported as a function of γ of the electrons. Calculations are performed at $z = 0$, for $n_{th} = 10^{-3}$ cm^{-3} (solid lines) and 10^{-4} cm^{-3} (dashed lines) assuming (from the bottom) B=5, 1, and 0.1 μG. **Panel b)** : Diffusion lengths as in panel a), but assuming $B = 1\mu G$, and $z = 0$, 0.5, and 1.0 (from the top). The energy range of the radio emitting electrons is reported in both panels (vertical dotted lines).

The diffusion time of the emitting electrons necessary to cover Mpc distances is 100 times larger than their radiative life-time

III – Conclusion : no diffusion !



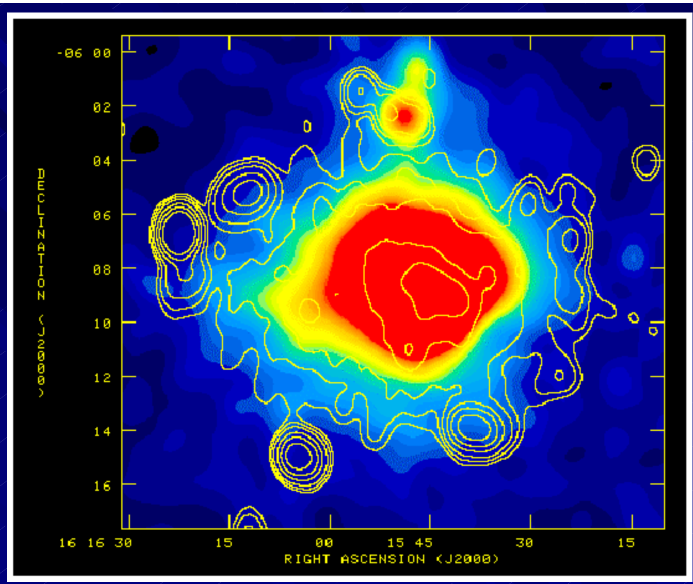
- **GeV electrons on Mpc scales**
- **μG magnetic fields on Mpc scales**
- T_{diff} (~10^{10} yr) >> T_{cool} (~10^{8} yr)

(Jaffe 1977)

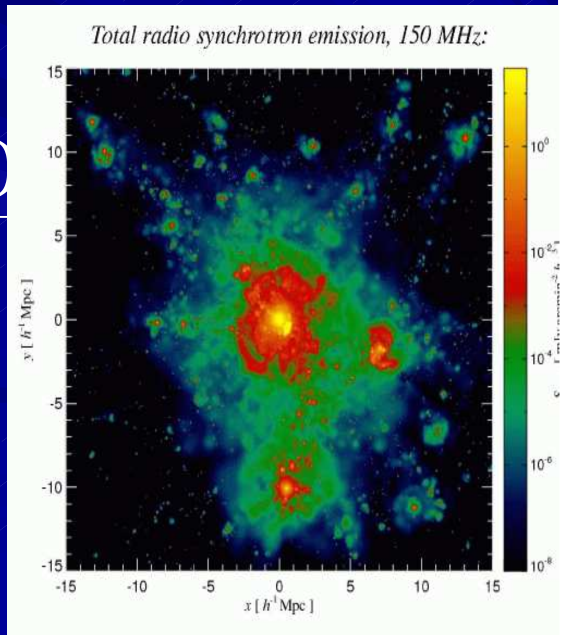
Looking at new physical processes

Labs to study GC as particle accelerators

Origin of the emitting electrons



First possibility: *secondary models*, **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions (e.g.,** *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004,08)*

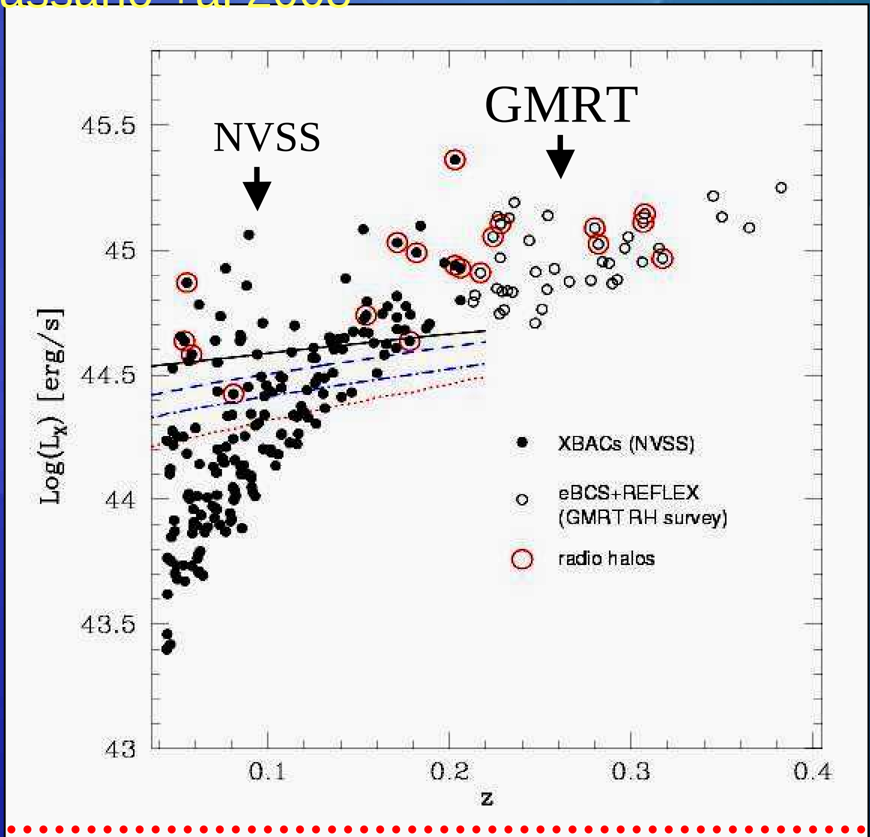


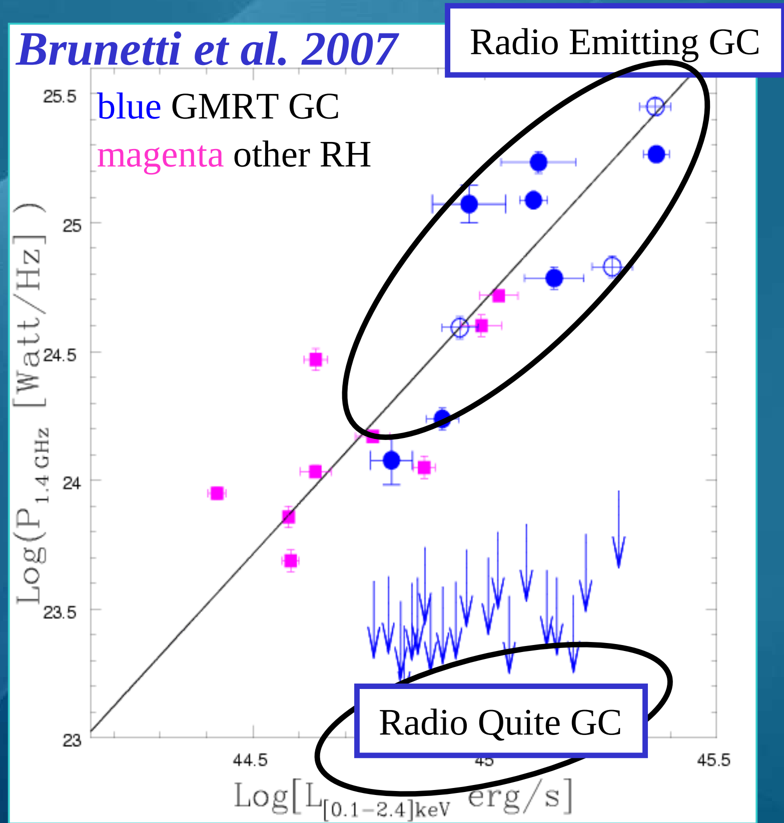
Since protons accumulate in galaxy clusters and clusters are magnetised at muG level, we expect that the synchrotron emission from secondary electrons in the IGM should be common.

- Which is the level of this emission ?
- Are Radio Halos due to secondary emission ?

The complex statistics of Radio Halos

Cassano +al 2008





NVSS data (from *Giovannini et al. 1999)* and deep **GMRT observations.**

0.41±0.11 for $L_x > 10^{44.9}$ erg/s

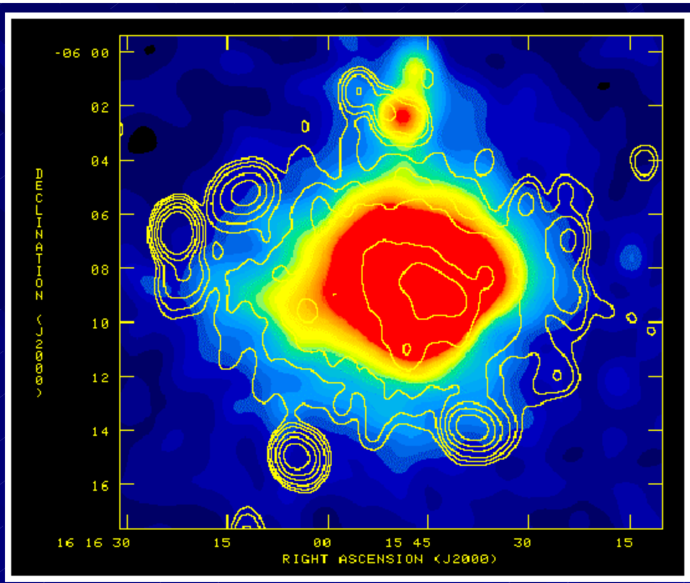
0.08±0.04 for $L_x < 10^{44.9}$ erg/s

(Venturi et al. 2007, 2008; Cassano et al.2008)

Evidence for "on-off" phenomena ??
(Brunetti et al. 2007)

Connection with cluster mergers
(e.g. *Schuecher et al. 2001, Markevitch et al. 2002, Boschin et al. 2003 Govoni et al. 2004*)

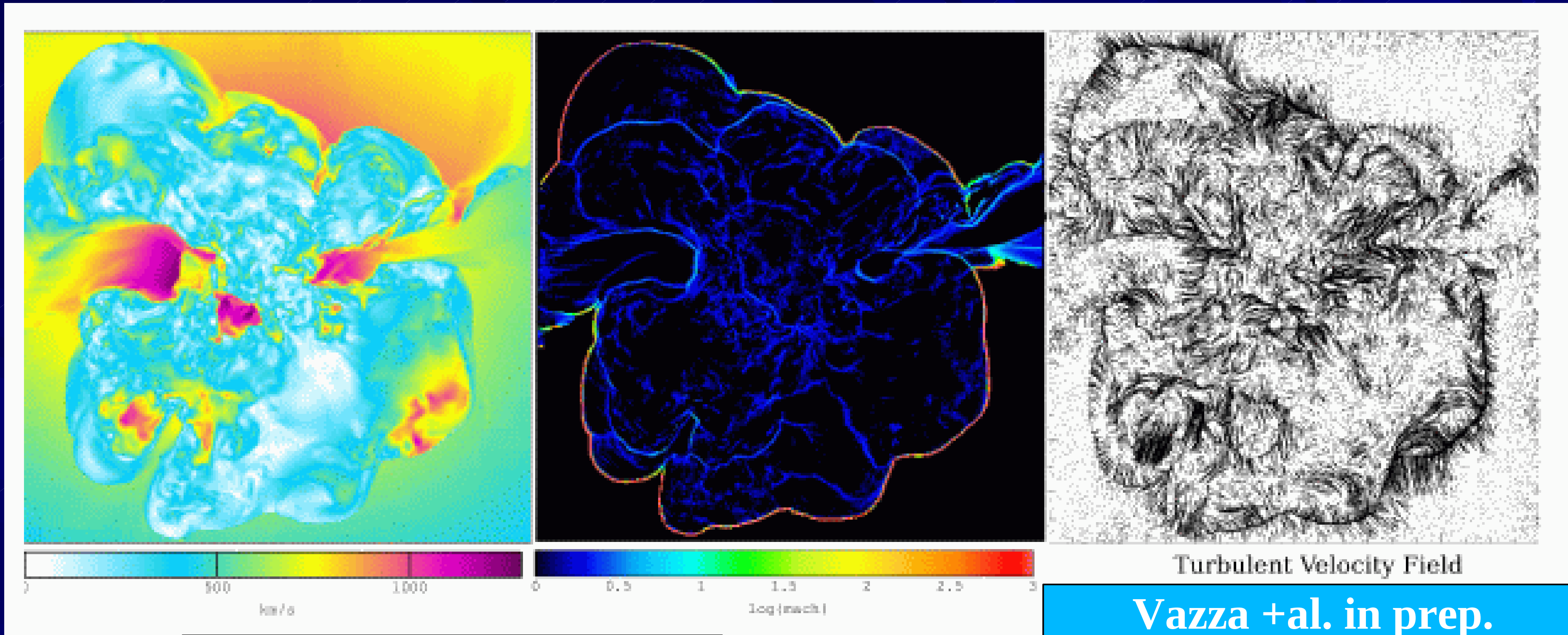
Origin of the emitting electrons



First possibility: *secondary models*, **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions**
(e.g., *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004*)

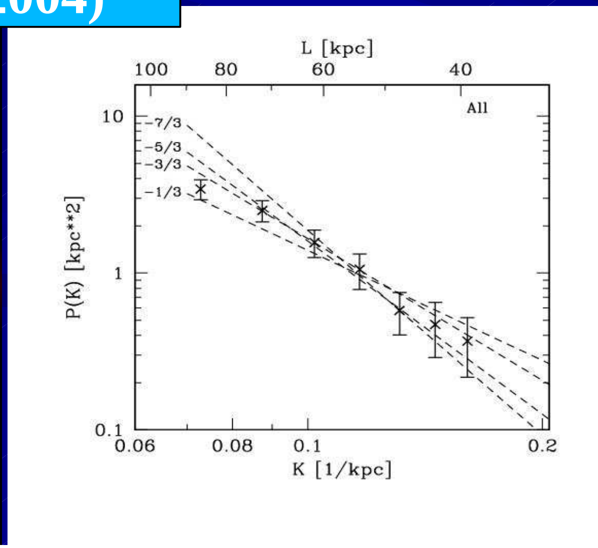
Second possibility : ***in situ* re-acceleration by MHD turbulence developed in the cluster volume during the merger events**
(e.g., *Brunetti et al. 2001, 2004; Petrosian 2001; Ohno et al. 2002; Fujita et al. 2003; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Brunetti & Lazarian 2007; Petrosian & Bykov 2008*)

Turbulence in galaxy clusters

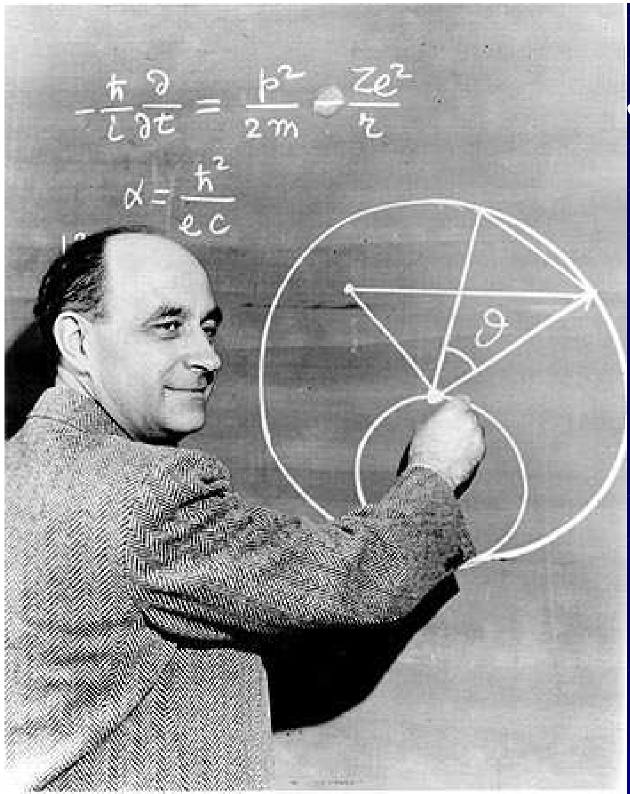


Vazza +al. in prep.

Schuecker +al. (2004)

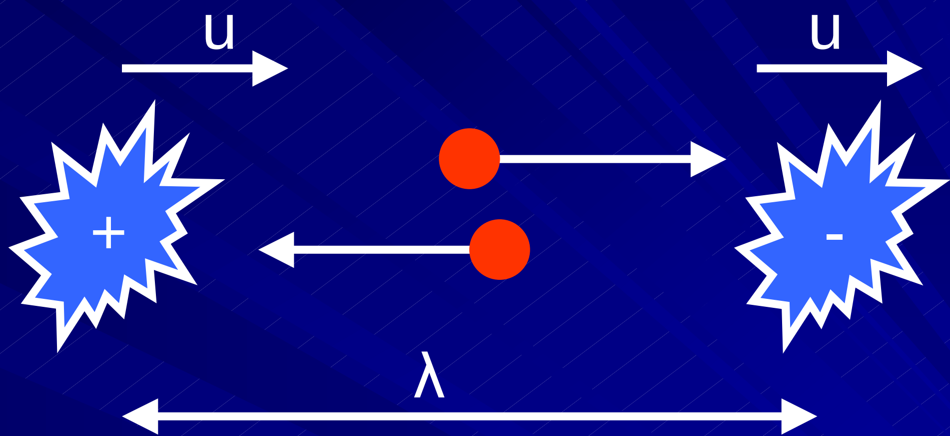


Bryan & Norman 1998;
Ricker & Sarazin 2001;
Sunyaev et al.2003;
Cassano & Brunetti 2005
Dolag et al. 2005;
Vazza et al. 2006;
Nagai et al. 2007;
Brunetti & Lazarian 2007;
Iapichino & Niemeyer 2008



Second order Fermi Mechanisms

(Fermi 1949)



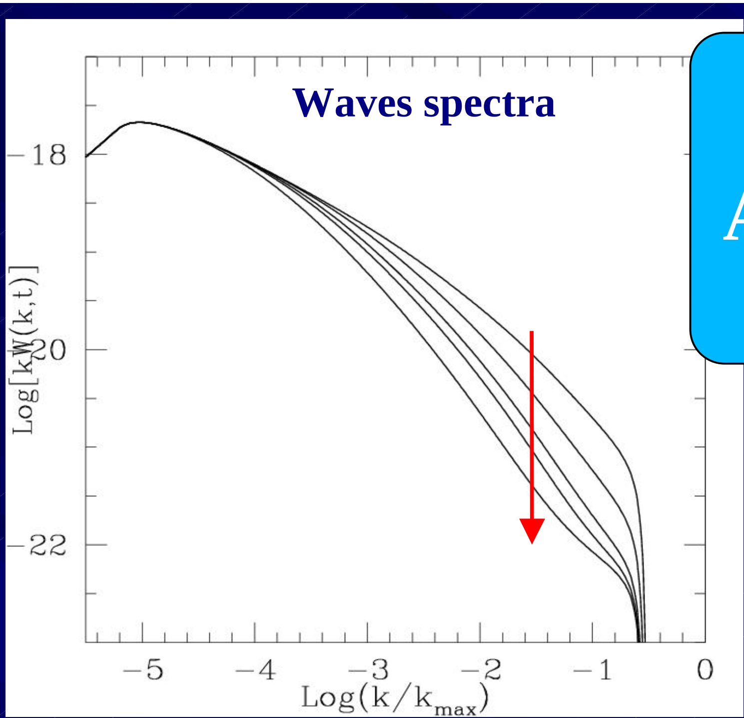
Frequency of collisions: $\nu_+ = \frac{u+c}{\lambda}$ $\nu_- = \frac{c-u}{\lambda}$

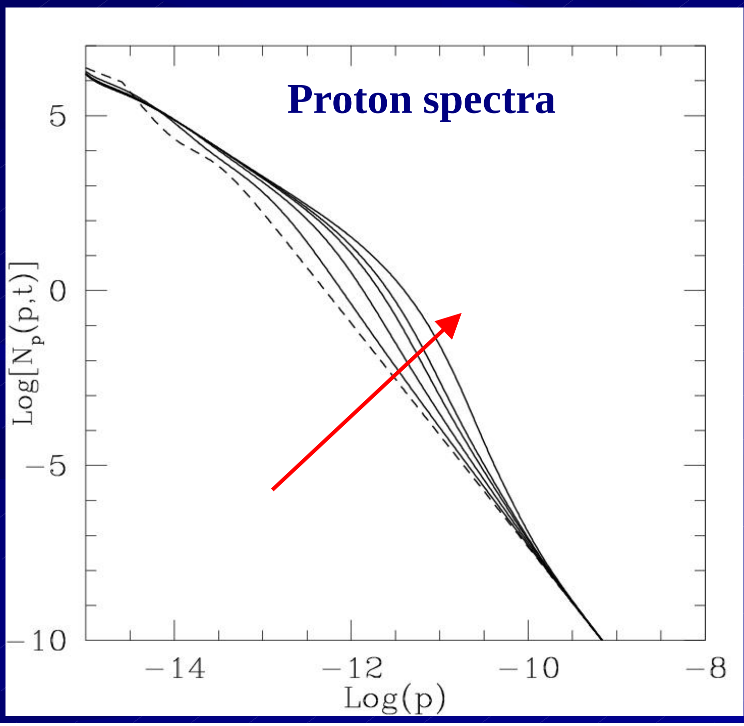
Energy gain per collisions: $\Delta p_\pm \approx \pm 2\, p\, \frac{u}{c}$

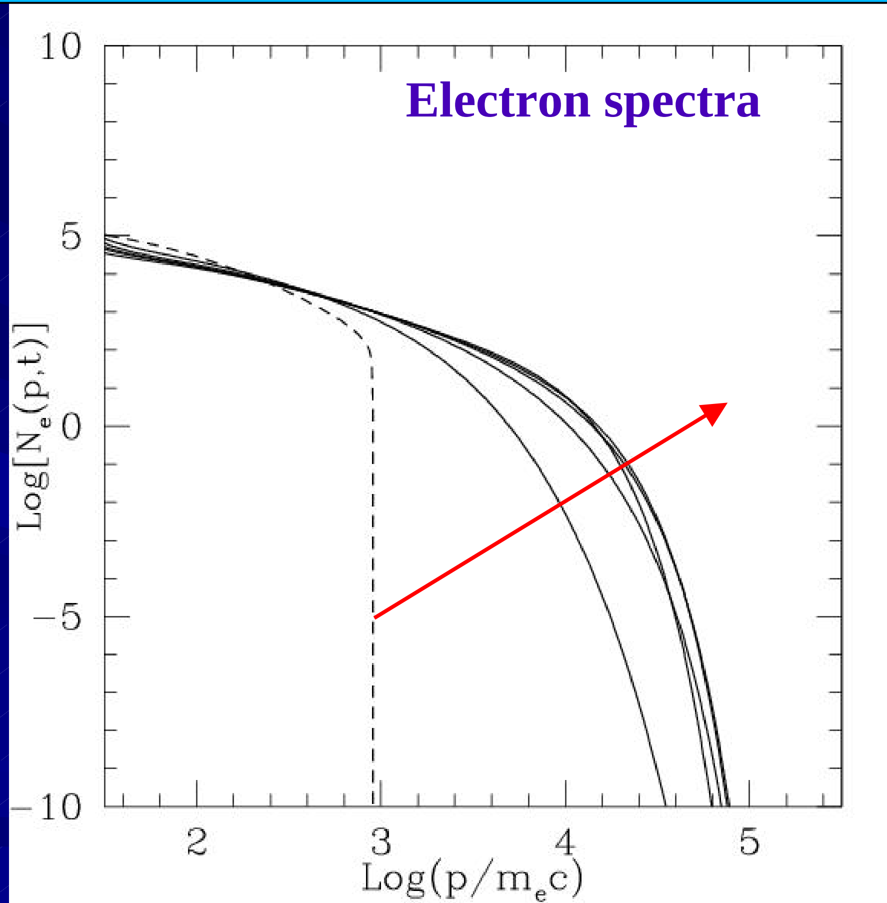
$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle = \nu_+ \Delta p_+ + \nu_- \Delta p_- \approx 2p\, \frac{u^2}{c^2}\, \frac{c}{\lambda}$$

Full
Alfven-Wave--Particle Coupling

(Brunetti +al. 2004; Brunetti & Blasi 2005)

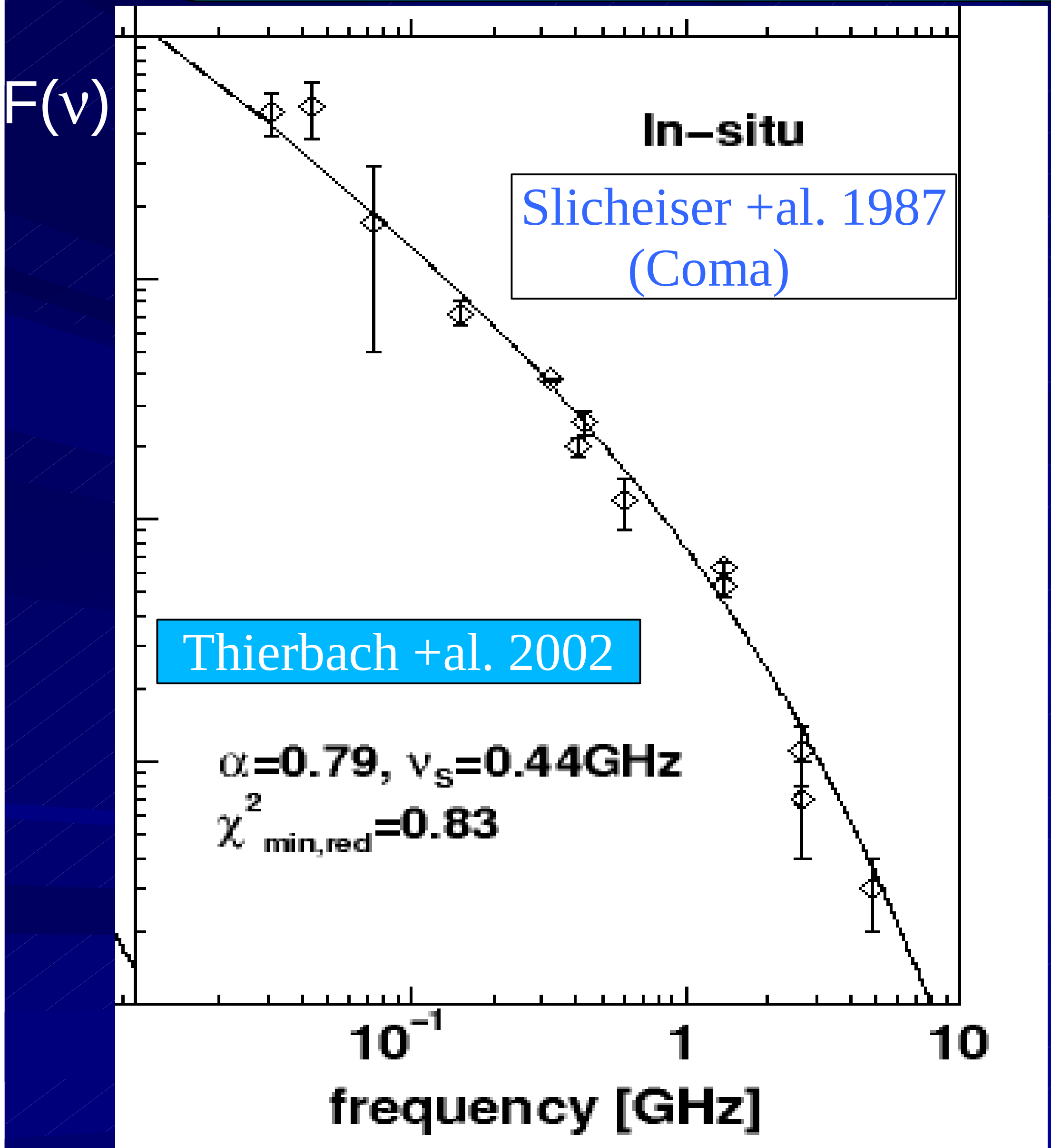




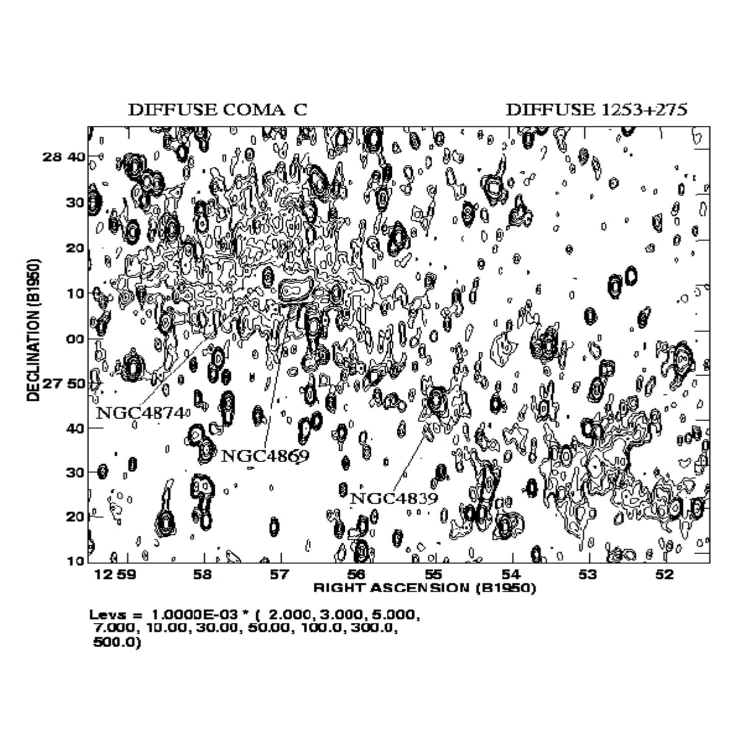


Waves + electrons + Protons

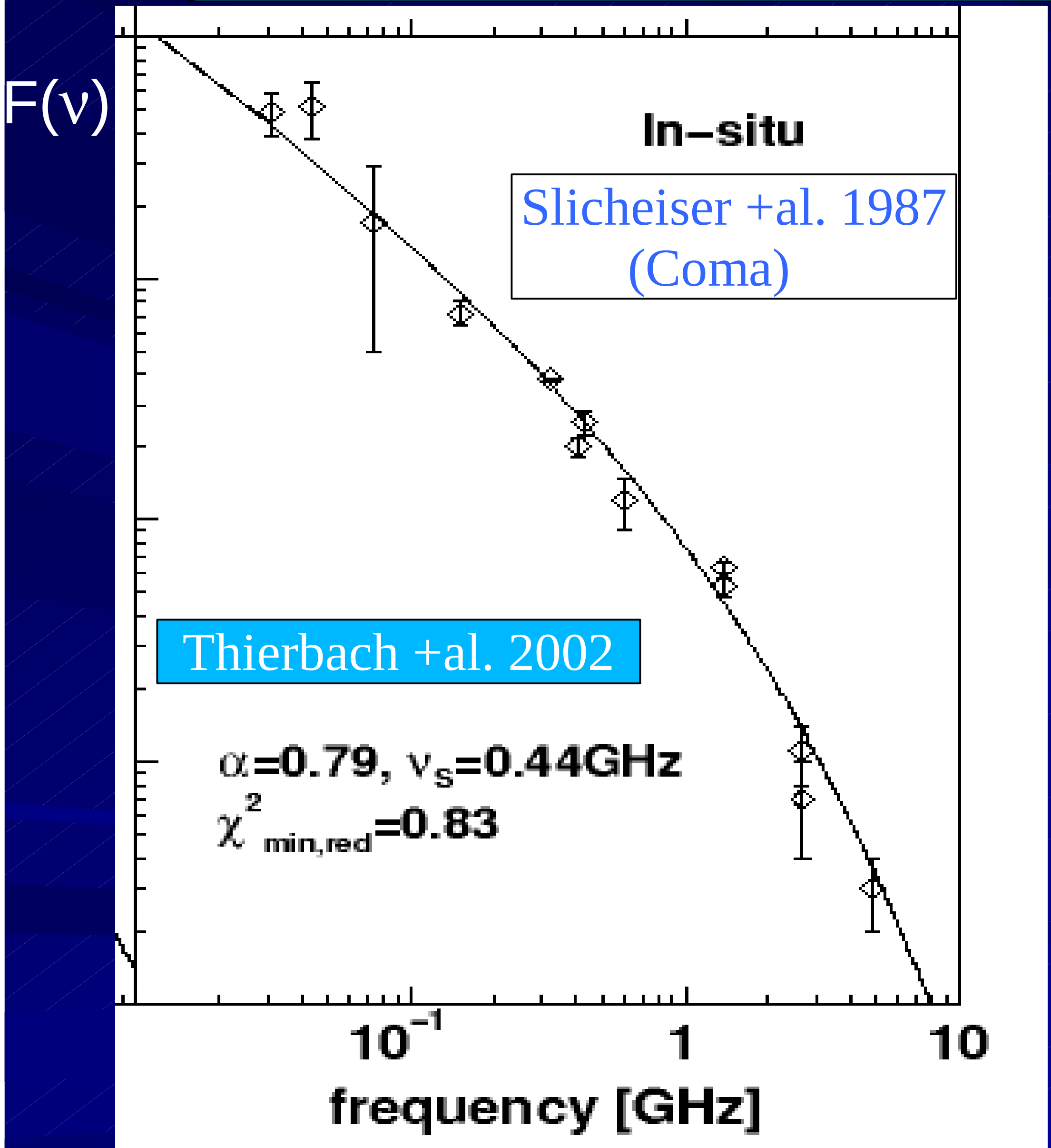
Observations: Spectral Cut-Off



Evidence of break in the synchrotron spectrum

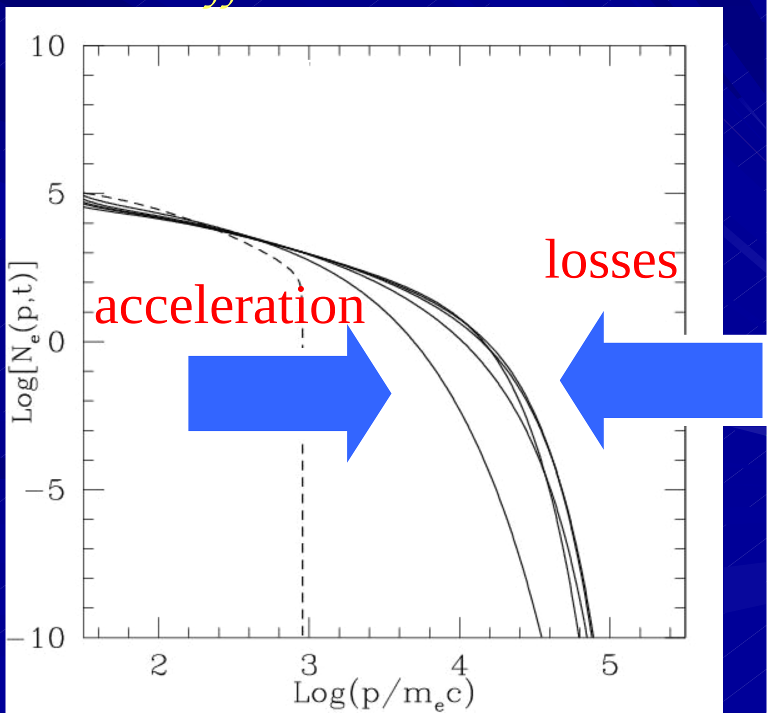


Observations: Spectral Cut-Off

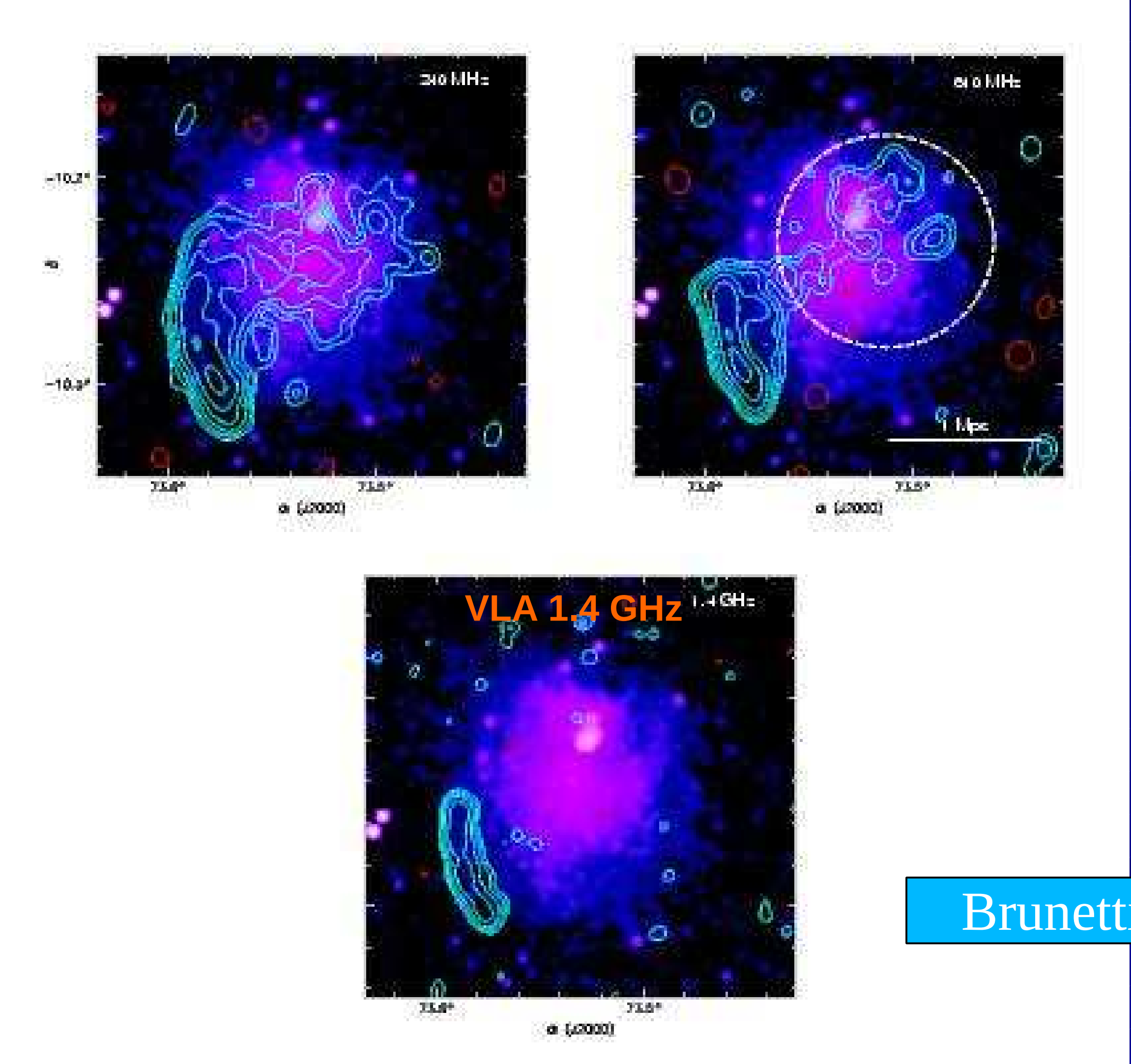


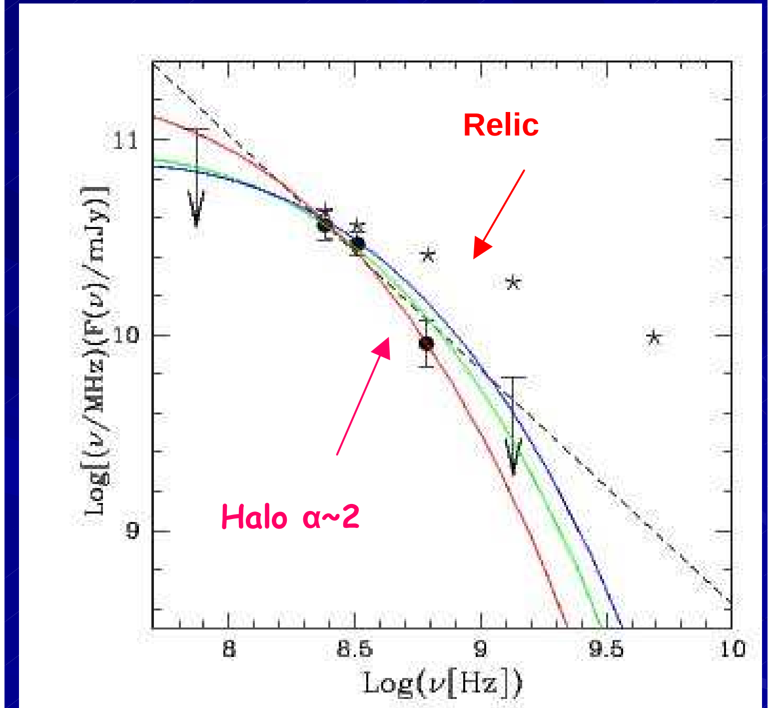
Evidence of break in the spectrum of the emitting electrons at energies of few GeV

Acceleration mechanism not efficient !



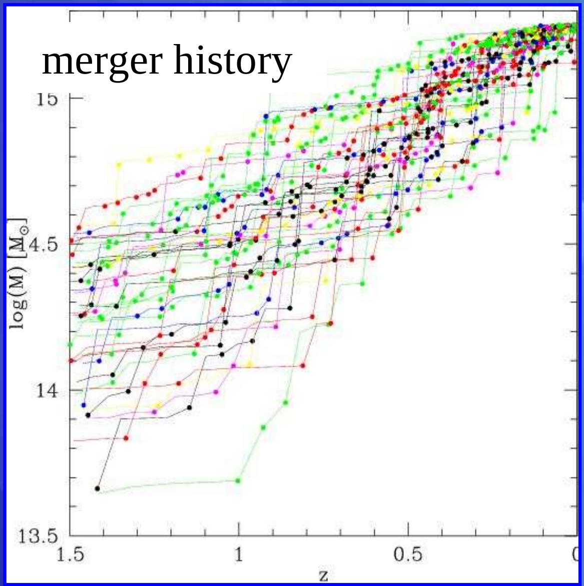
Evidence for steep spectra : turbulent acceleration



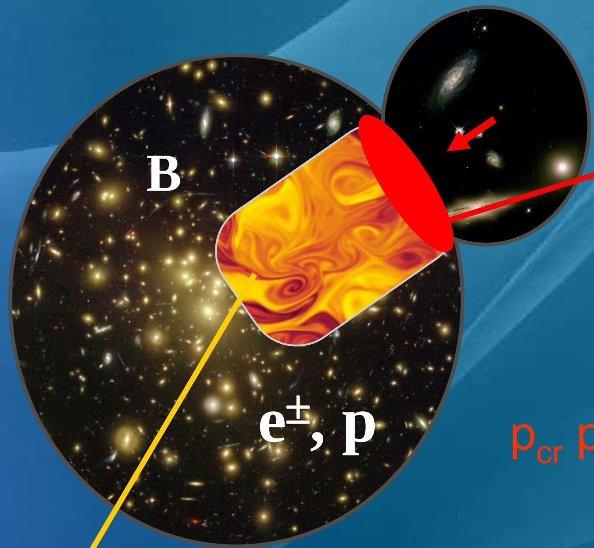


Brunetti et al. 2008, Nature 455, 944

The general picture



clusters increase their mass via merger with smaller subclusters

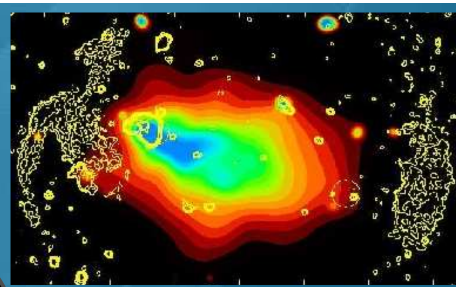


SHOCKS
accelerate $e^{\pm}$, p_{cr}

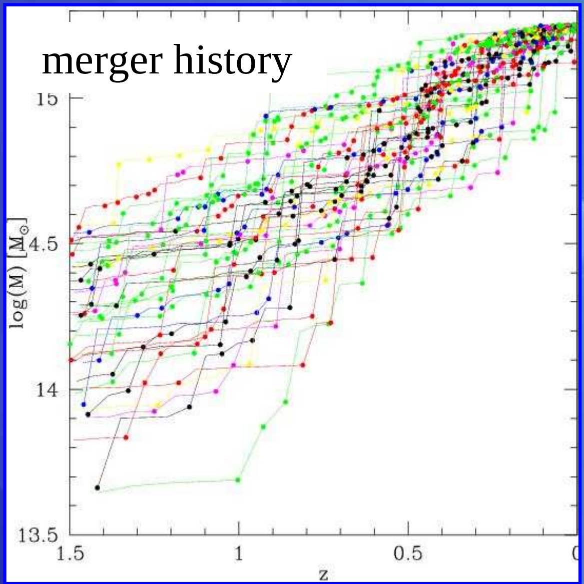
p_{cr} p_{th} → π^0 → γ rays
$\pi^{\pm}$ → $e^{\pm}$

TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scales

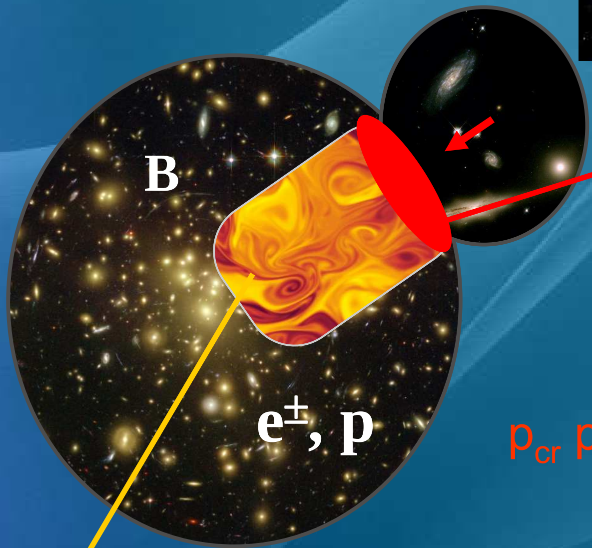
The general picture



?



clusters increase their mass via merger with smaller subclusters

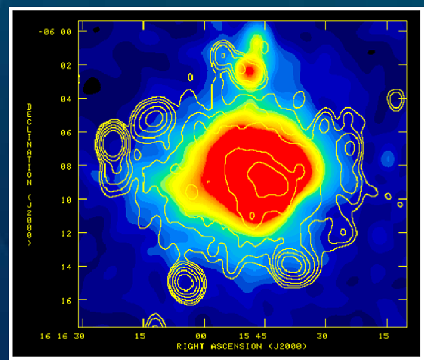


SHOCKS

accelerate $e^{\pm}$, p_{cr}

$p_{cr}\ p_{th} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma \text{ rays} \\ \pi^{\pm} \rightarrow e^{\pm} \end{cases}$

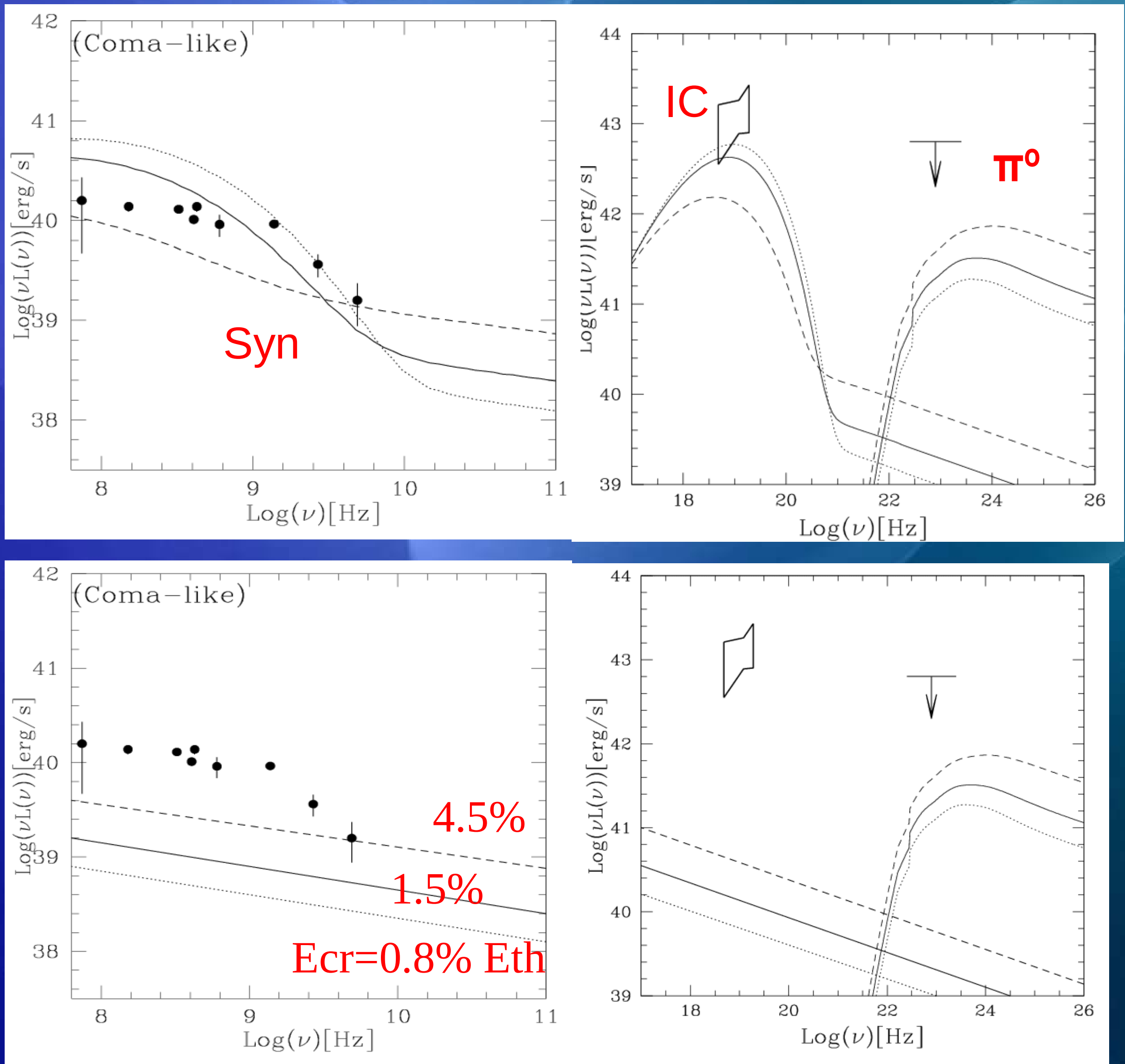
TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scales

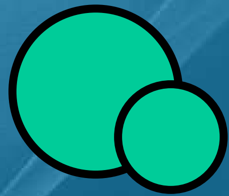


?

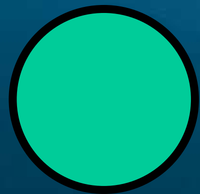
General multiwavelength expectations

Brunetti, 2008





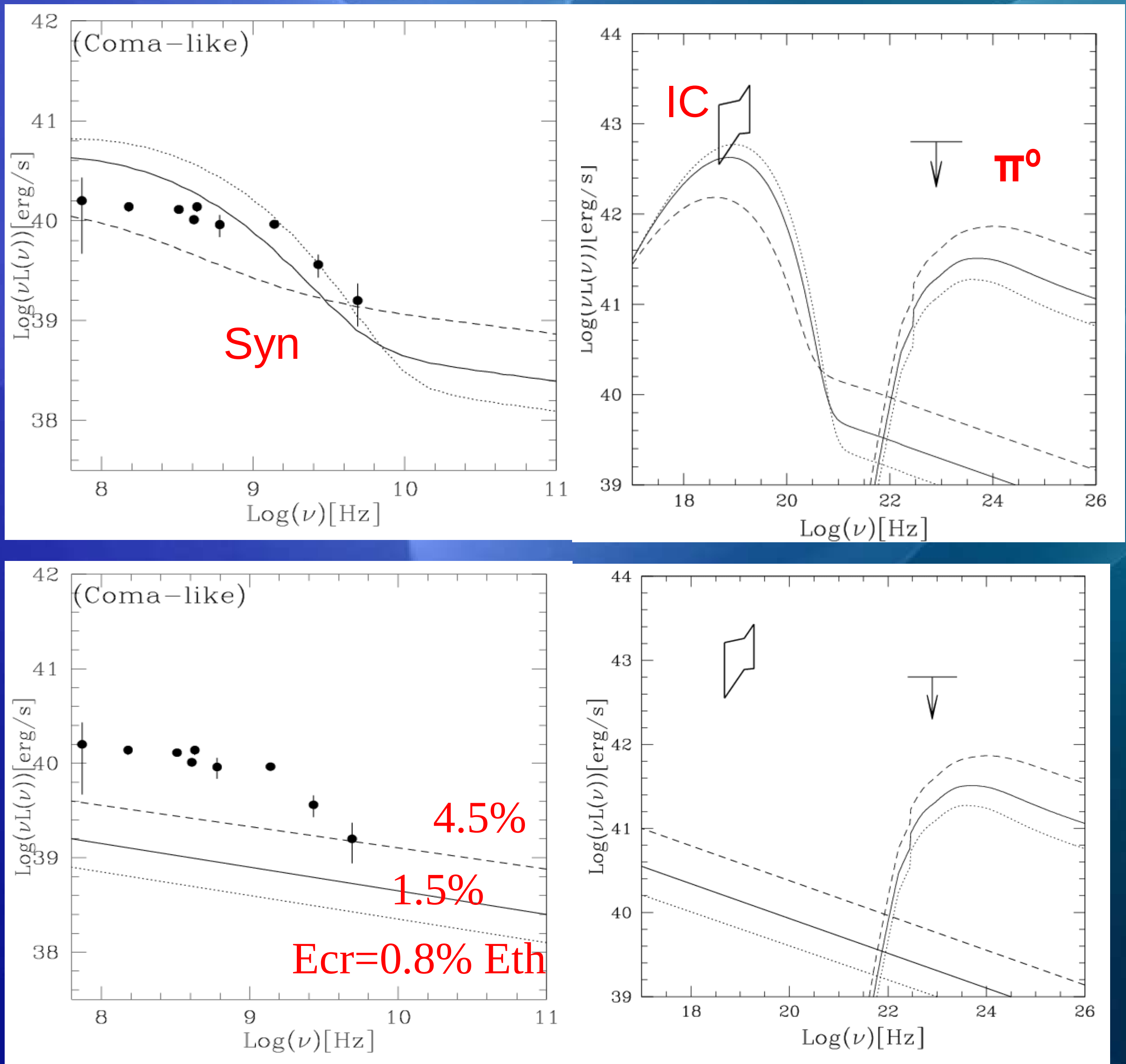
MERGING CLUSTERS

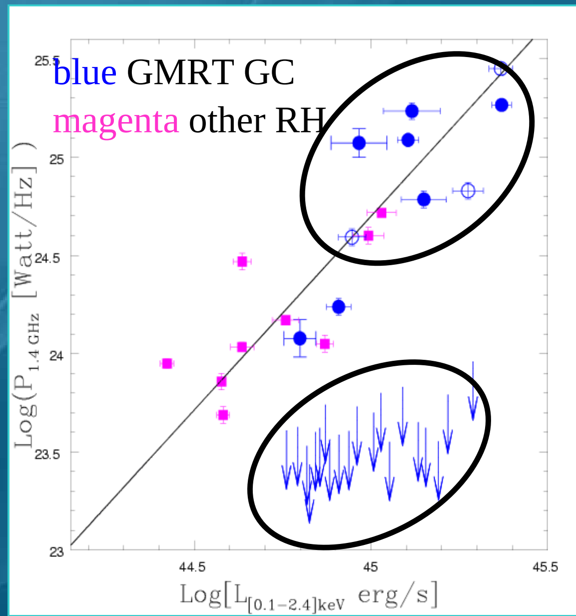


ALL CLUSTERS

General multiwavelength expectations

Brunetti, 2008





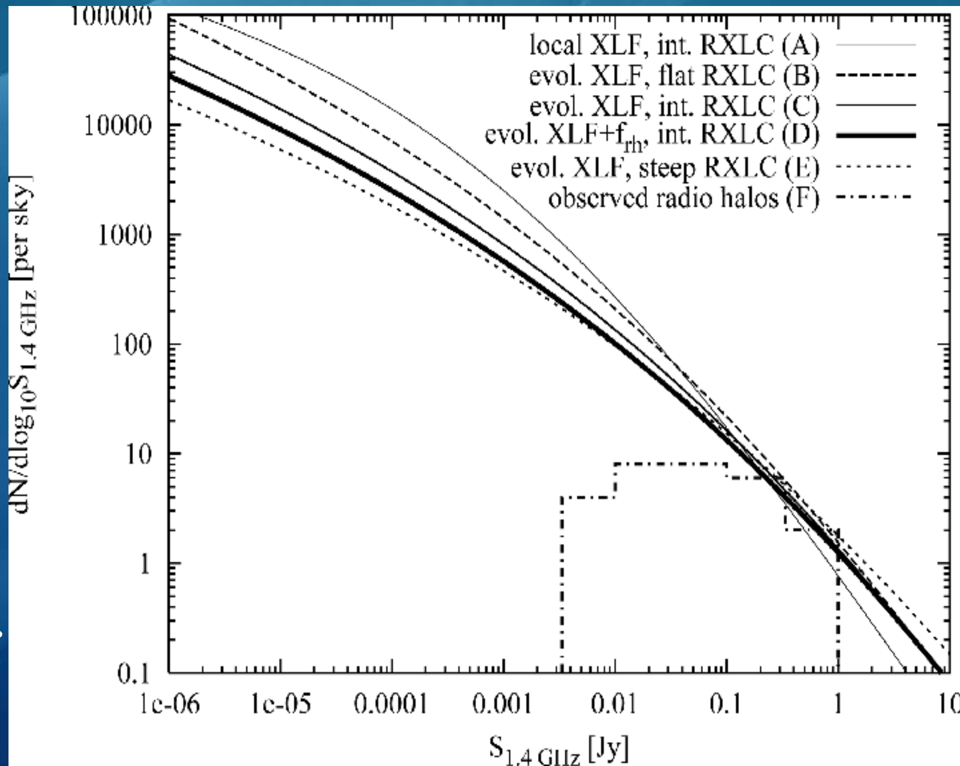
TRANSIENT PHENOMENA

The FUTURE

Why low frequency ?

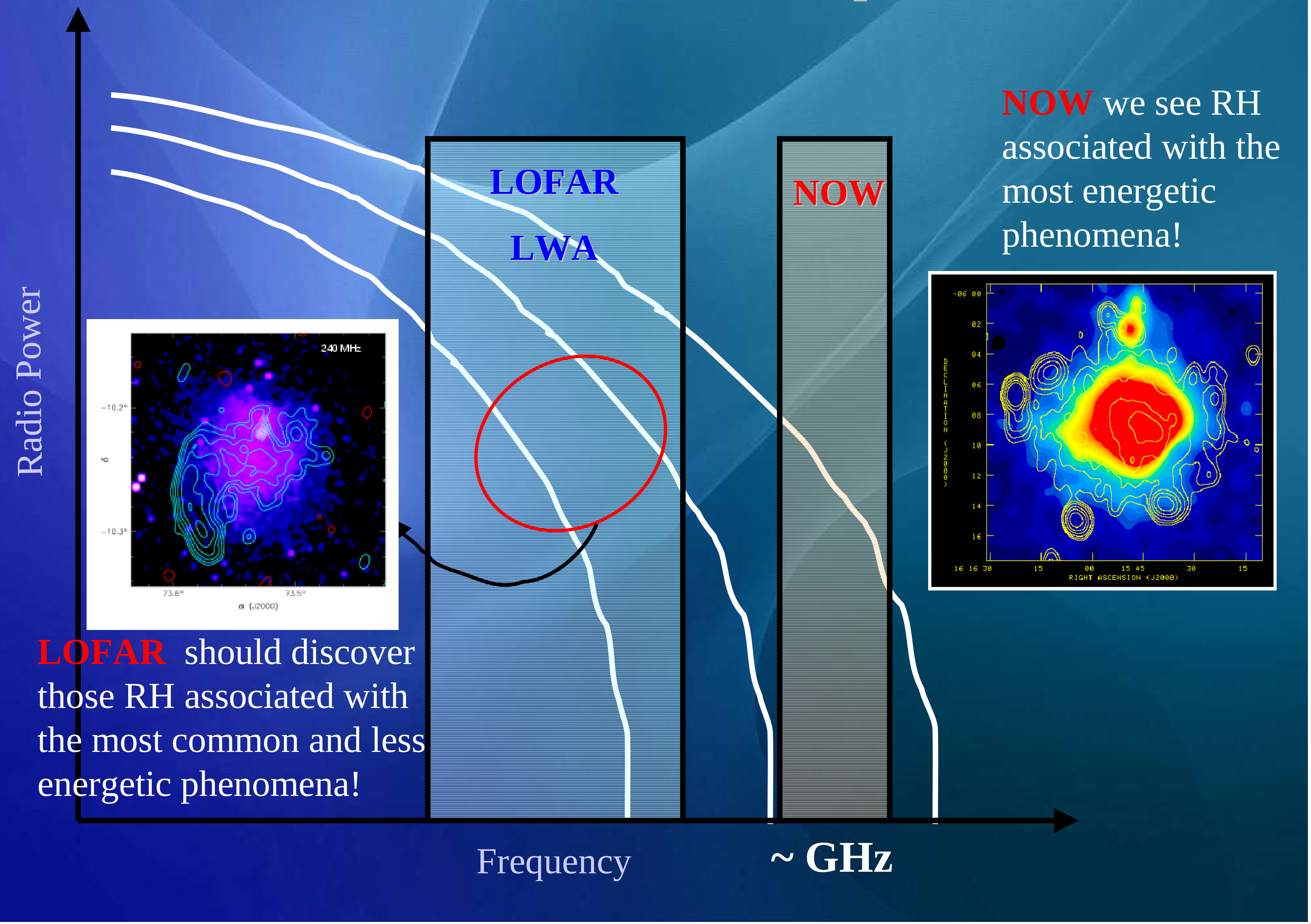
Ensslin & Roettgering 2002

Regardless of the origin of Radio Halos, extrapolations of their number counts at 1.4 GHz based on the Radio-X ray correlation observed for Radio Halos suggest that a large fraction of these Halos is at faint fluxes.



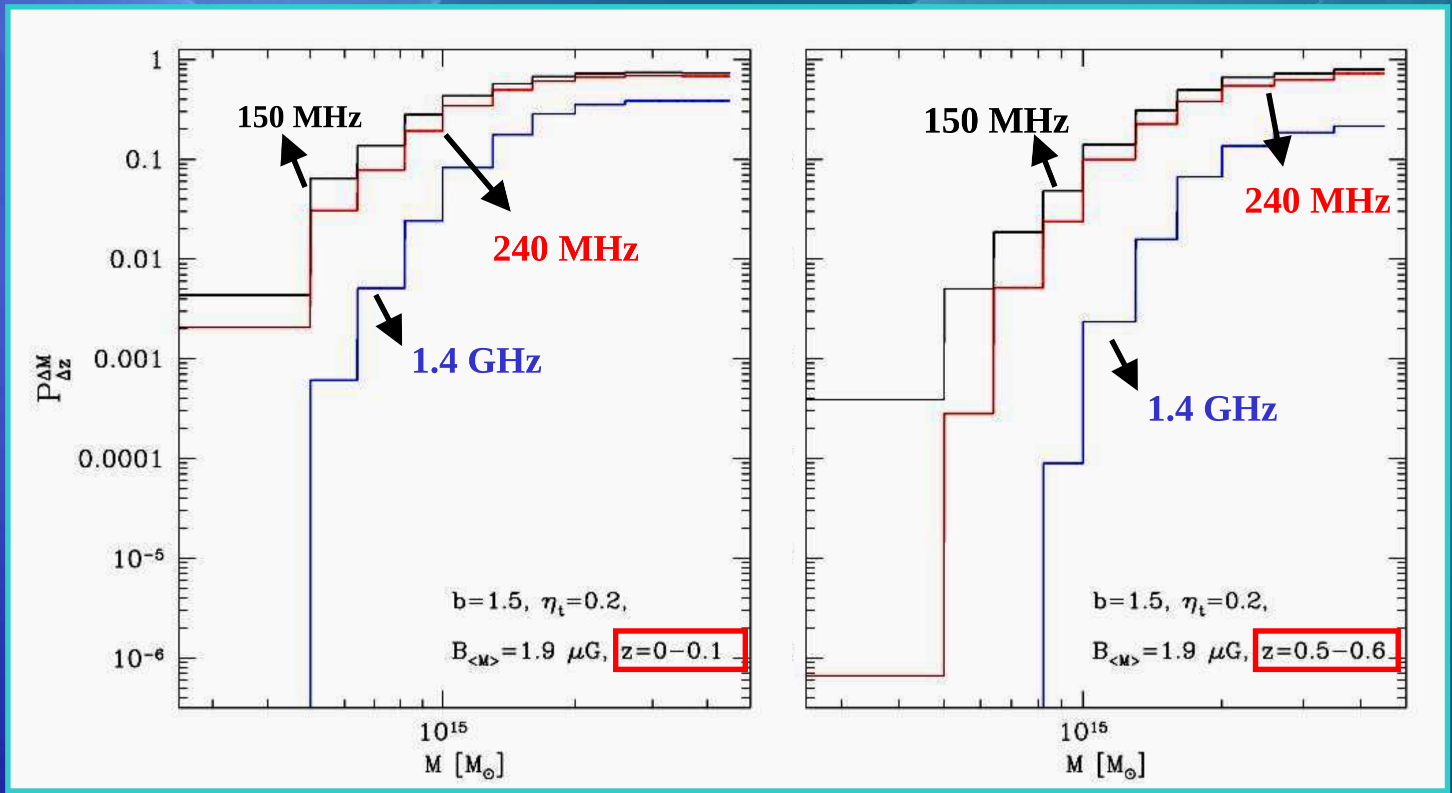
Due to their steep synchrotron spectrum, faint Radio Halos should appear more luminous at low frequencies and thus LOFAR and LWA are expected to discover a large number of these objects.

Radio halos at lower radio frequencies



Fraction of galaxy clusters with radio halos at low ν

Cassano et al. 2008



- ❖ The expected fraction of clusters with radio halos increases at low **ν**
- ❖ This increase is even stronger for **smaller clusters** ($M<10^{15}\,M_\odot$)

Main Conclusions

- Connection between non thermal emission and cluster mergers
- Shocks and turbulence accelerate particles in the IGM
- Protons are accumulated in the IGM and inject secondary particles
- Electrons are short living particles : re-acceleration / injection
- The non thermal spectrum is complex and extends from radio to gamma
  Radio : Radio Halos = turbulence? Radio relics = shocks ?
- Future : Low radio frequency & high energies
  LOFAR will detect hopefully 1000 Radio Halos testing present models