Particle acceleration in galaxy clusters and Mpc-scale non-thermal emission

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Outline

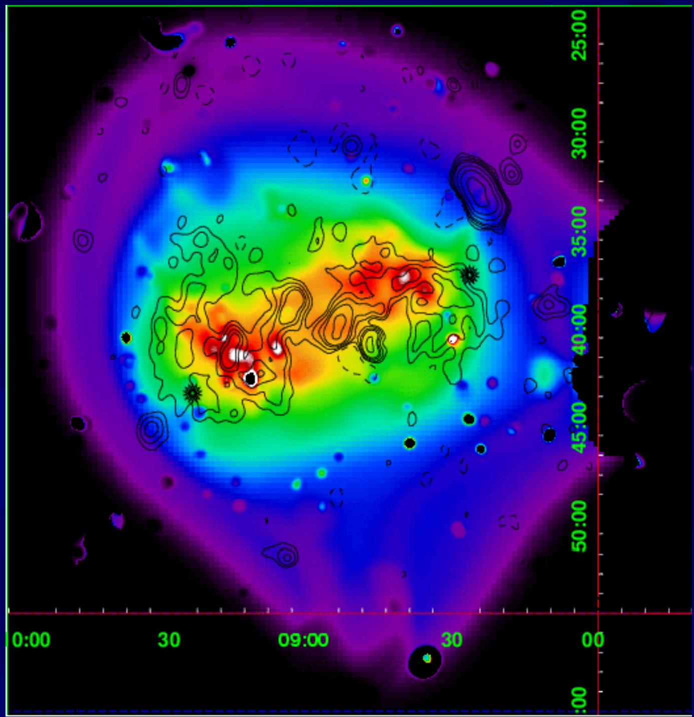
- (i) Non thermal components & connection with mergers

- (ii) Stochastic particle acceleration : Radio Halos

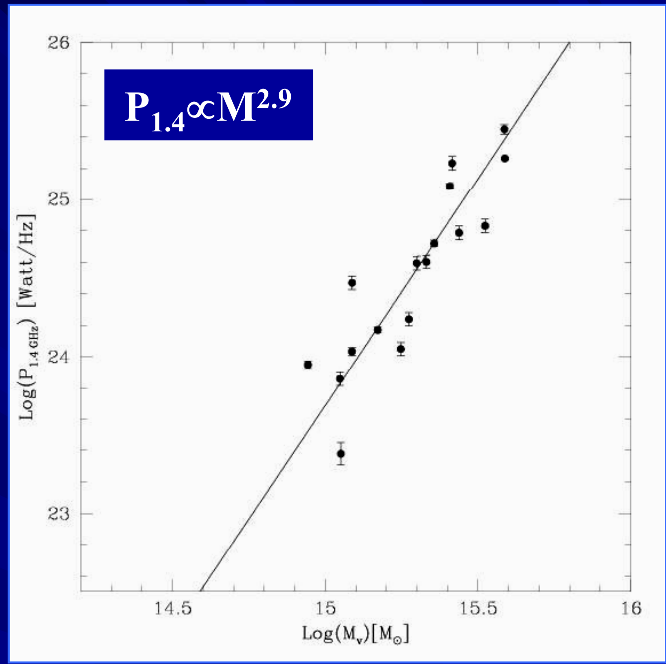
- (iii) Clusters non-thermal spectrum & evolution

- (iv) Constraints on CR acceleration in clusters

Non-thermal sources & cluster mergers



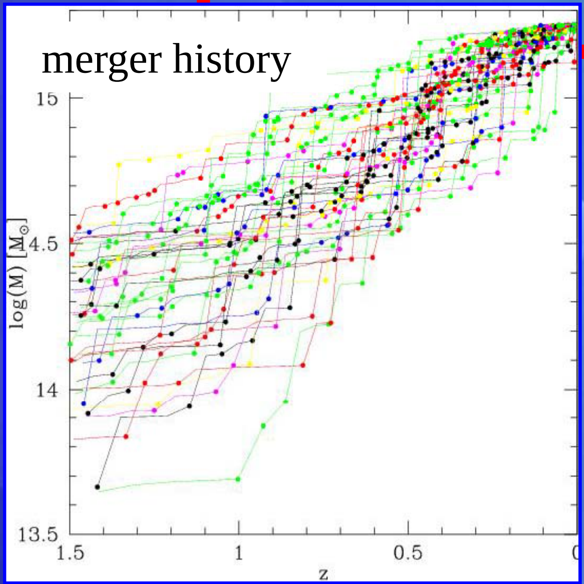
Connection with cluster mergers (e.g. *Buote 2001, Schuecher et al. 2001, Markevitch et al. 2002, Boschin et al. 2003 Govoni et al. 2004, Venturi et al. 2008*)



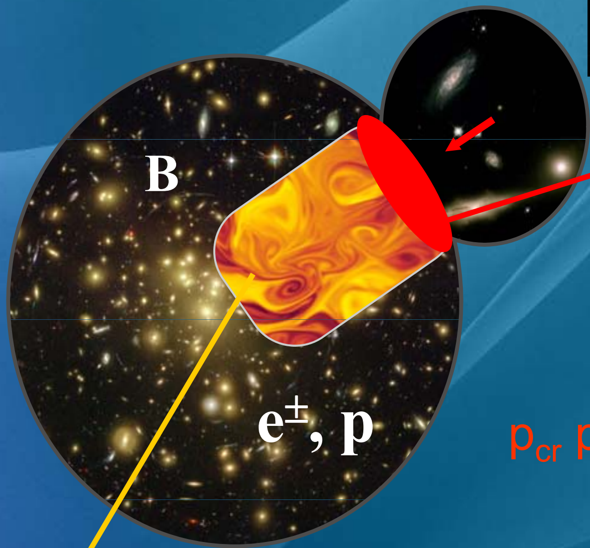
The 1.4 GHz synchrotron radio power of GRH increases with the cluster mass (L_X,T) (e.g. *Liang 1999, Bacchi et al. 2003, Cassano et al. 2006*)

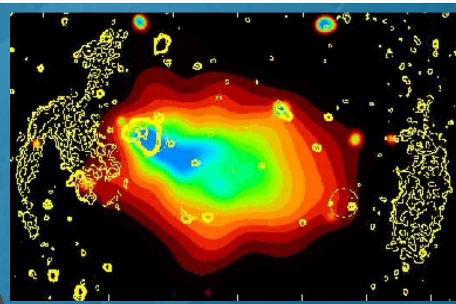
Gravitational - driven processes ?

Connecting LSS formation … physics of IGM



clusters increase their mass via merger with smaller subclusters





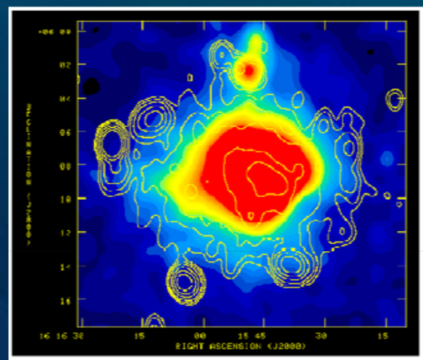
?

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

$p_{cr}\ p_{th}$ → { $\pi^0 \rightarrow \gamma$ rays ; $\pi^\pm \rightarrow e^\pm$ }

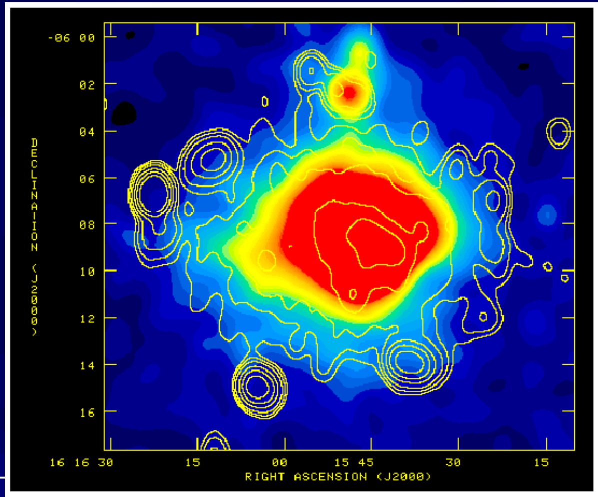
TURBULENCE reaccelerates fossil $e^\pm$ and secondaries $e^\pm$ on Mpc scales

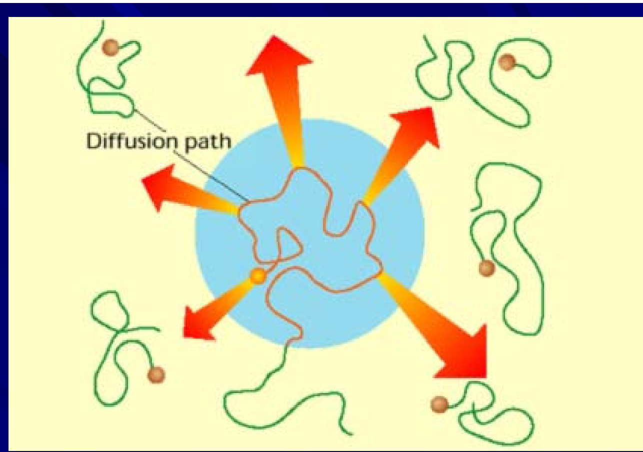
(eg., Sarazin 1999; Blasi & Colafrancesco 1999; Takizawa & Naito 2000; Brunetti et al. 2001, 2004, 2009; Petrosian 2001; Miniati et al. 2001; Fujita et al. 2003; Ryu et al. 2003; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Cassano et al. 2006; Brunetti & Lazarian 2007; Hoeft & Bruggen 2007; Pfrommer et al. 2008; Petrosian & Bykov 2008)



?

(ii) Origin of Halos





(Jaffe 1977)

T_{diff} (~10^{10} yr) >> T_{cool} (~10^{8} yr)

First possibility: *hadronic models*, **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions**

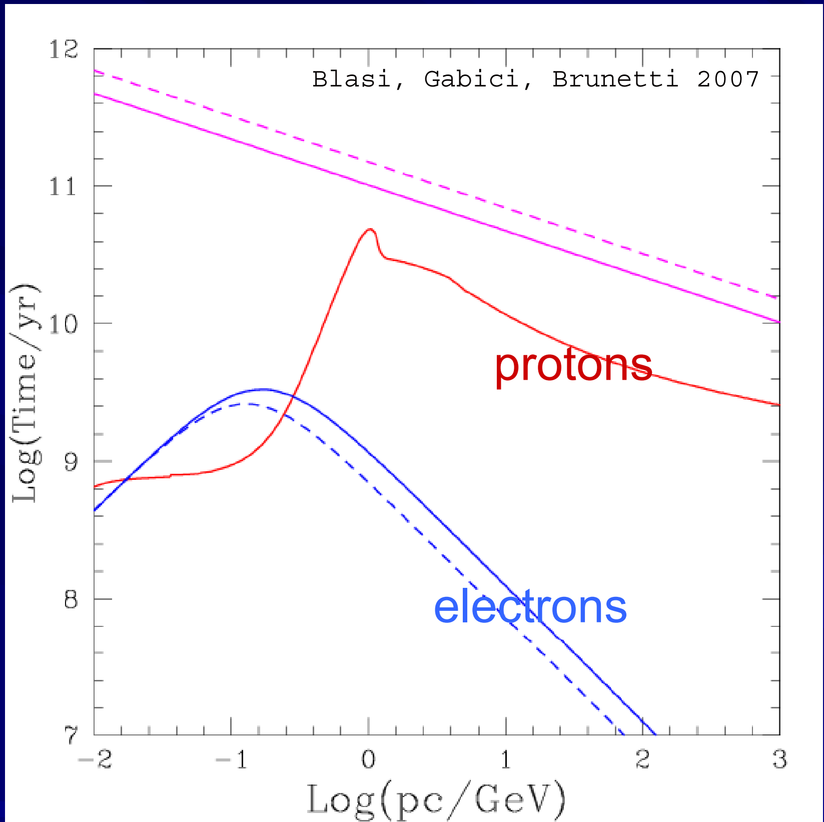
(e.g., *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004*)

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*)

Hadronic (secondary) models

Dennisnon 1980, Blasi & Colafrancesco 1999,
Dolag & Ensslin 2000, Pfrommer & Ensslin 2004

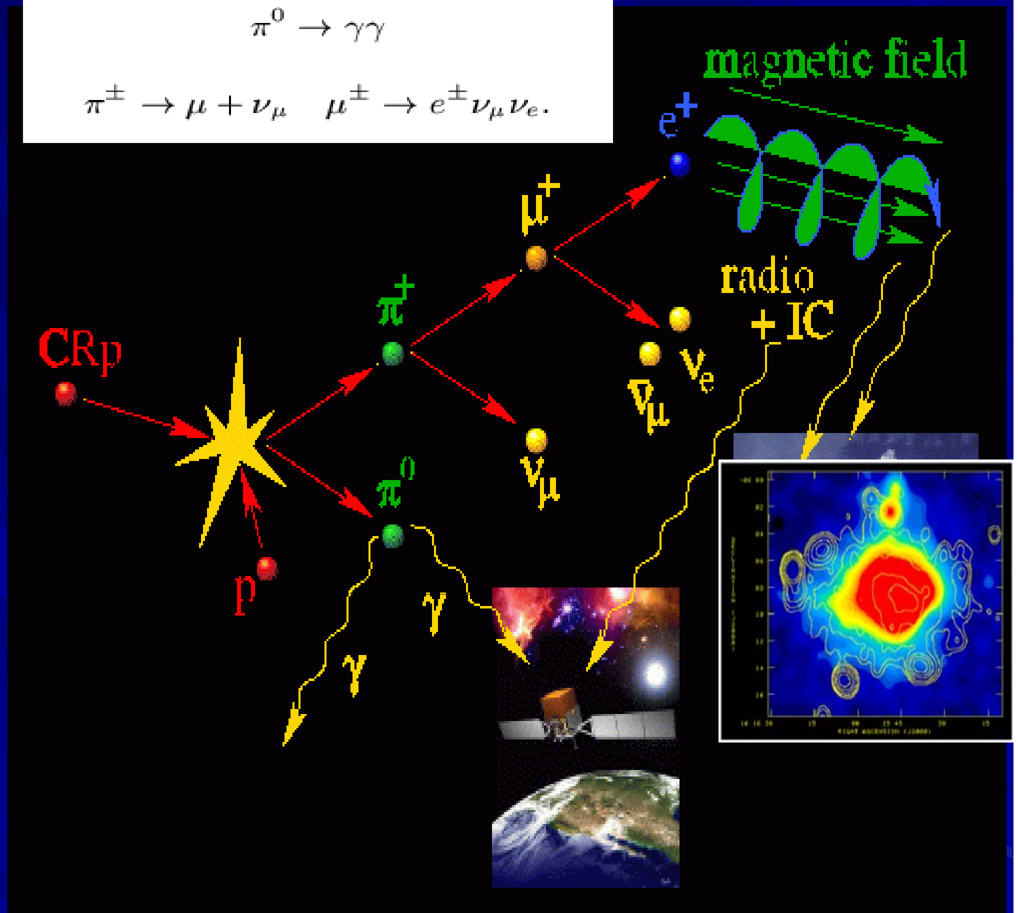


Voelk et al 1996
Berezinsky et al 1997

$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

$$\pi^0 \rightarrow \gamma\gamma$$

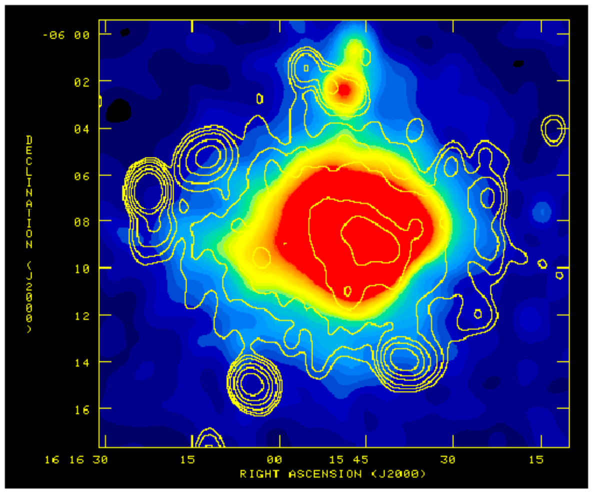
$$\pi^\pm \rightarrow \mu + \nu_\mu \quad \mu^\pm \rightarrow e^\pm \nu_\mu \nu_e.$$

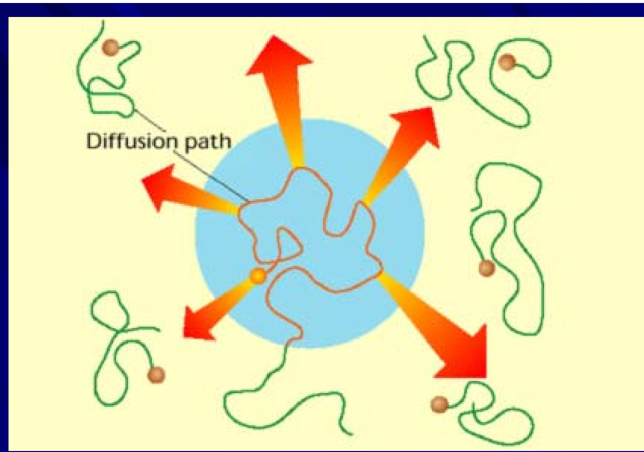


.. seem to be inconsistent with a number of key-observed properties of Radio Halos that came out in the last 5-7 years

(see also Donnert talk..)

Origin of Halos





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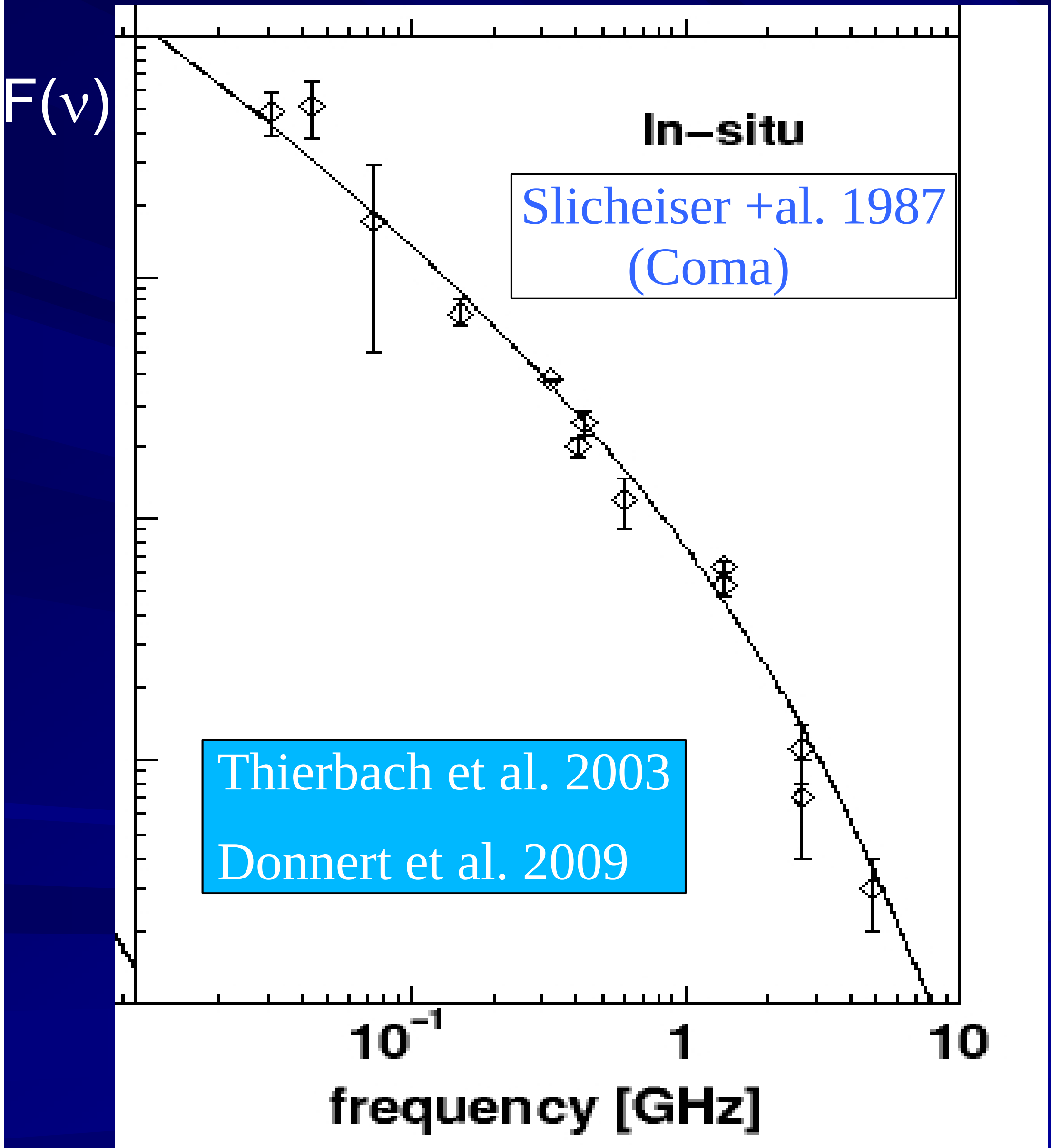
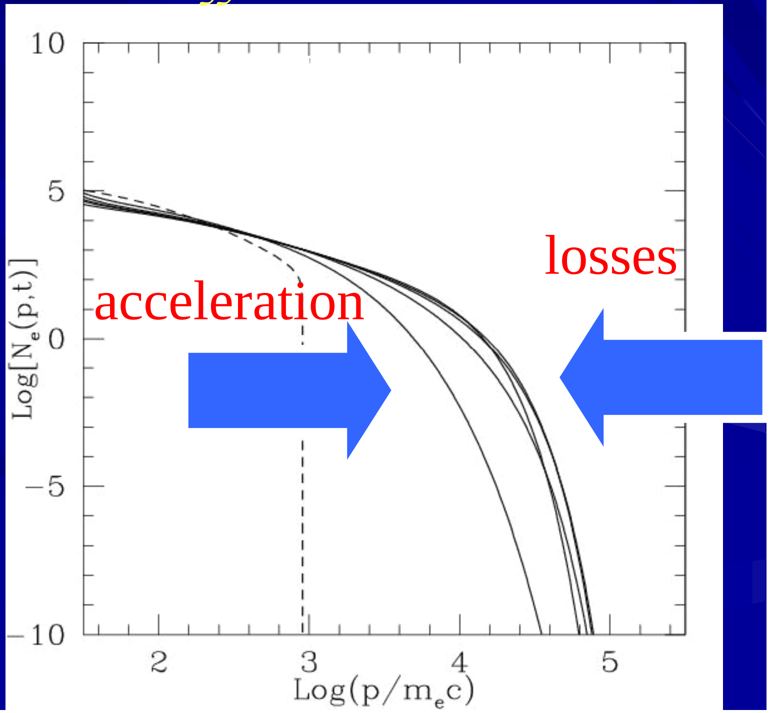
Radio Halos : are they generated by “inefficient” mechanism of CRe acceleration ?



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

Acceleration mechanism not efficient !



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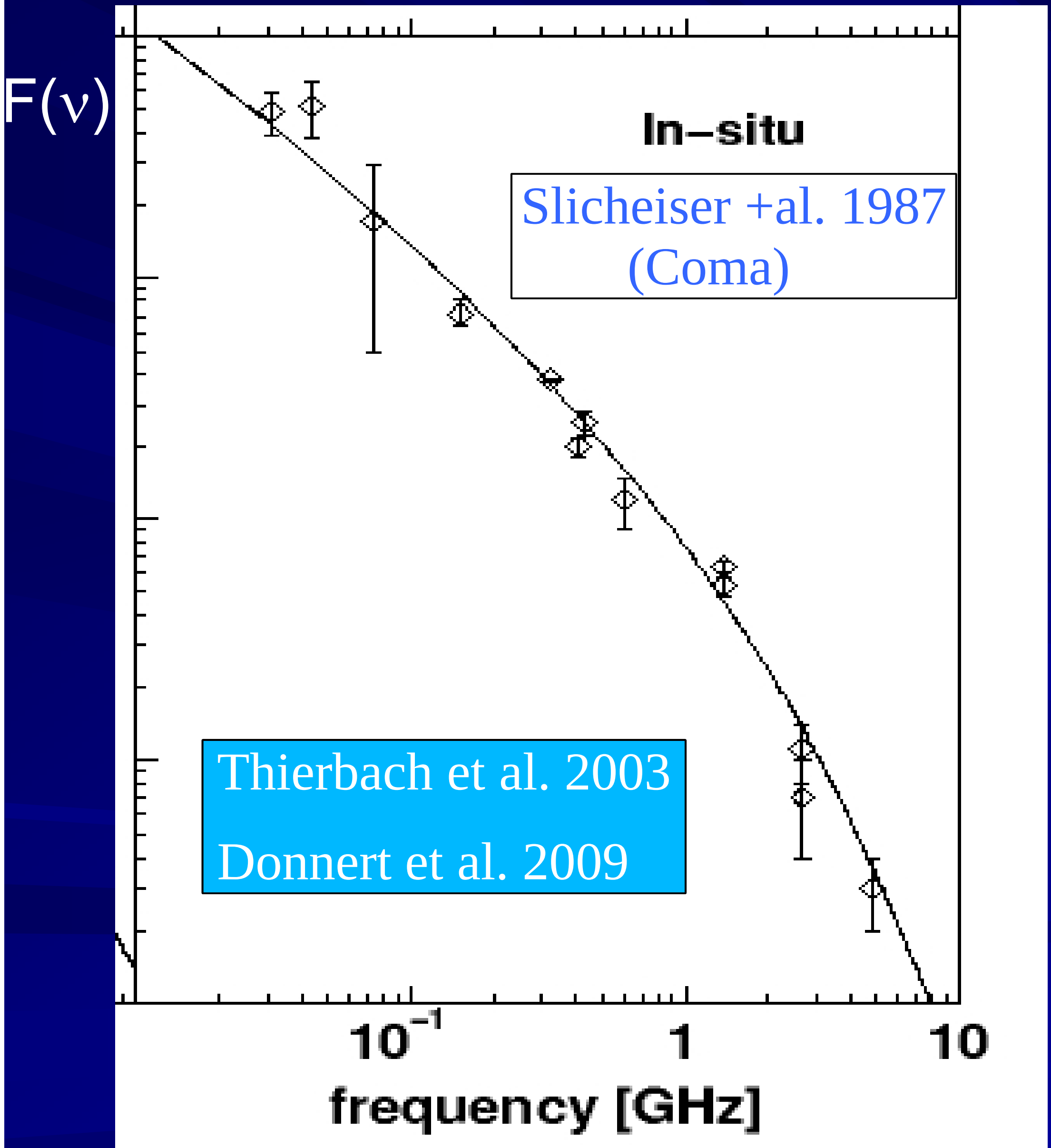

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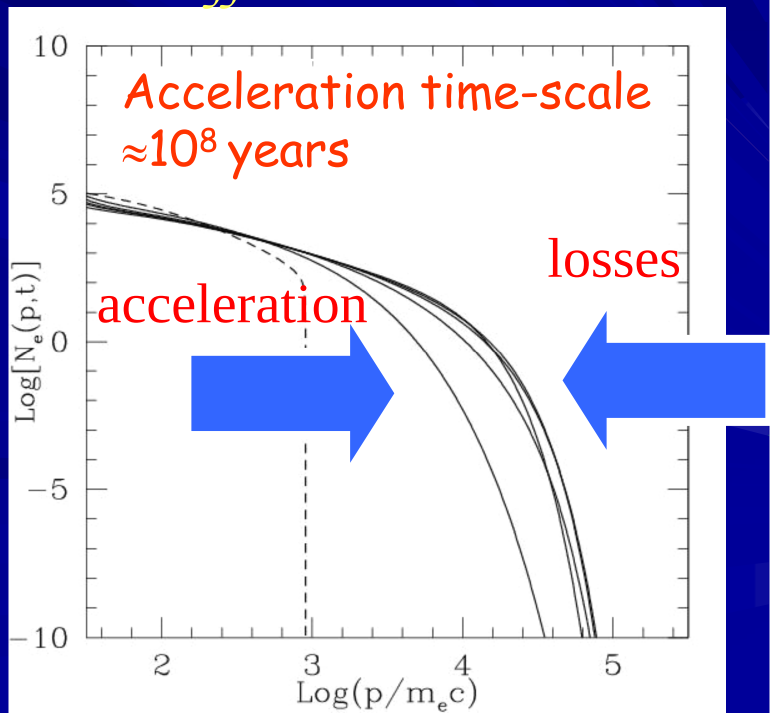
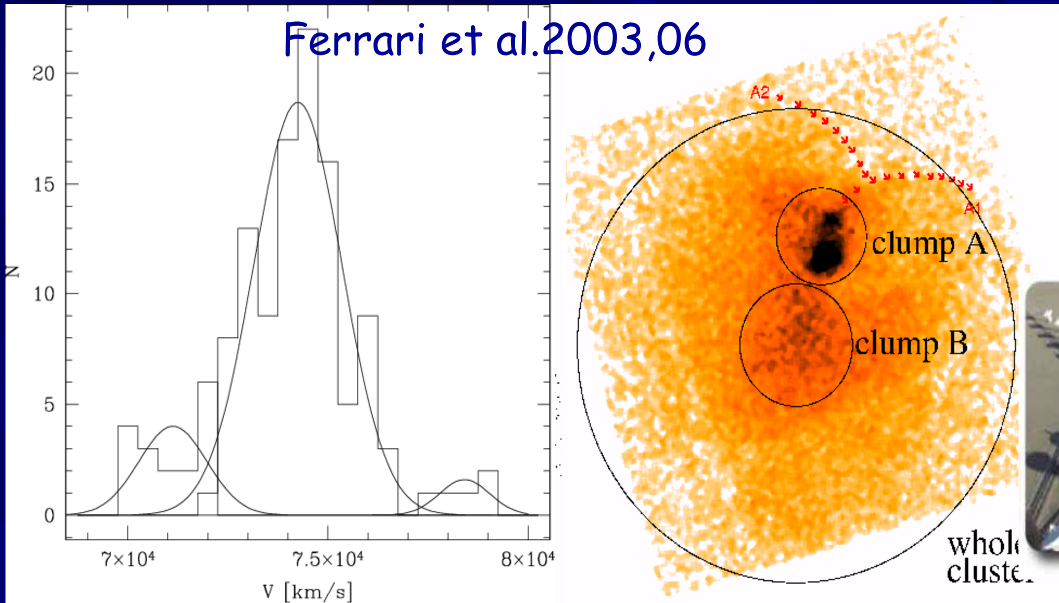
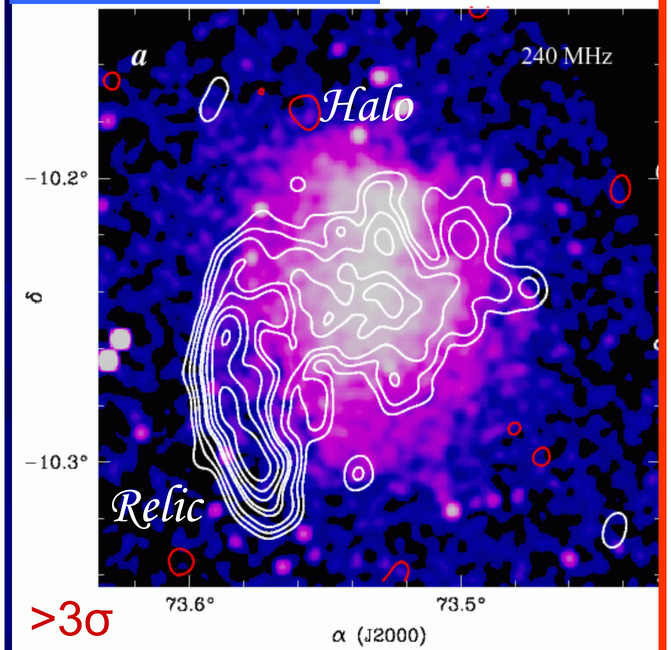


Turbulent acceleration? (Brunetti +al. 2008, Nature 455,944)

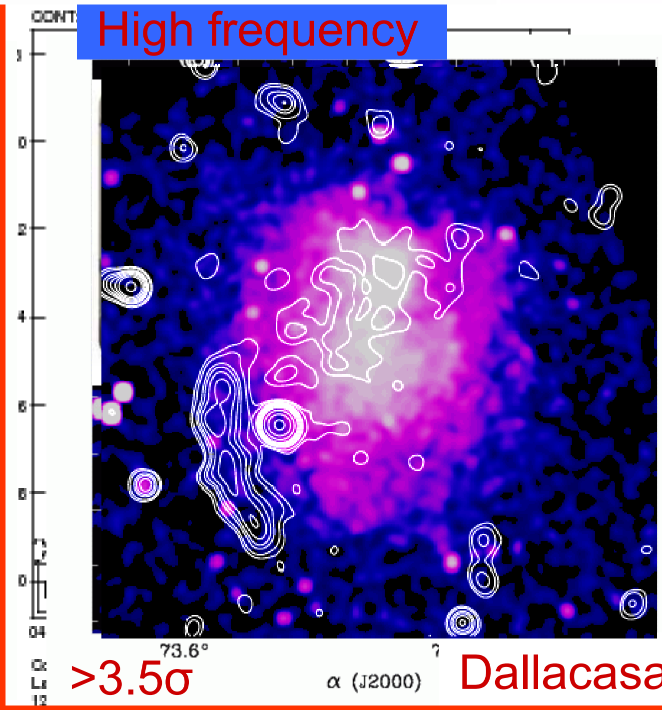


Low frequency

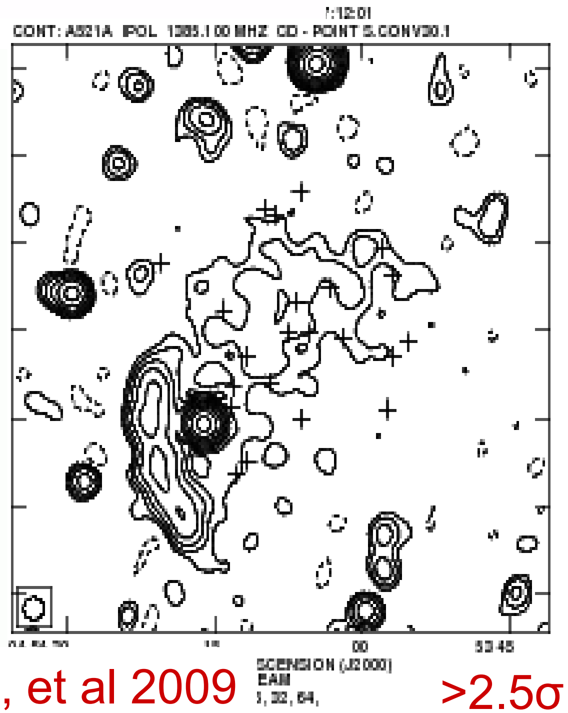


>3σ

High frequency



>3.5σ

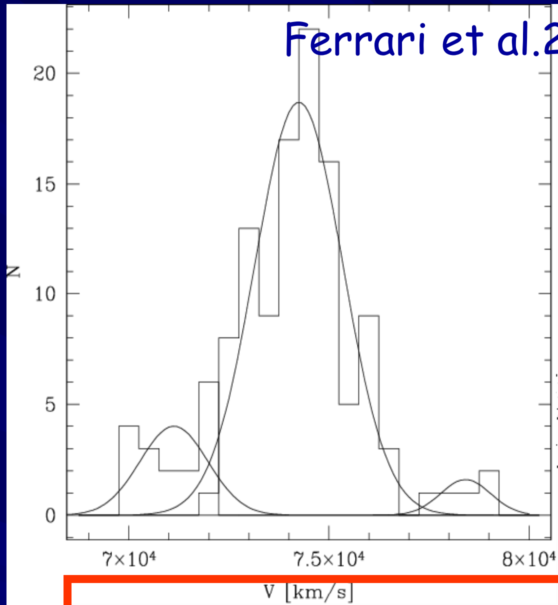


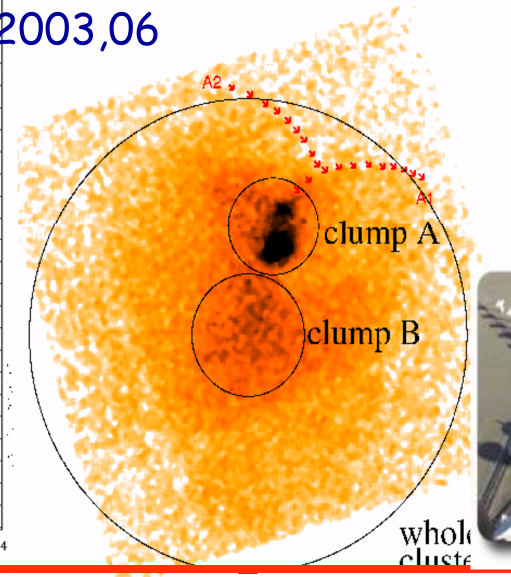
Dallacasa, et al 2009

>2.5σ

Turbulent acceleration? (Brunetti +al. 2008, Nature 455,944)

Ferrari et al.2003,06





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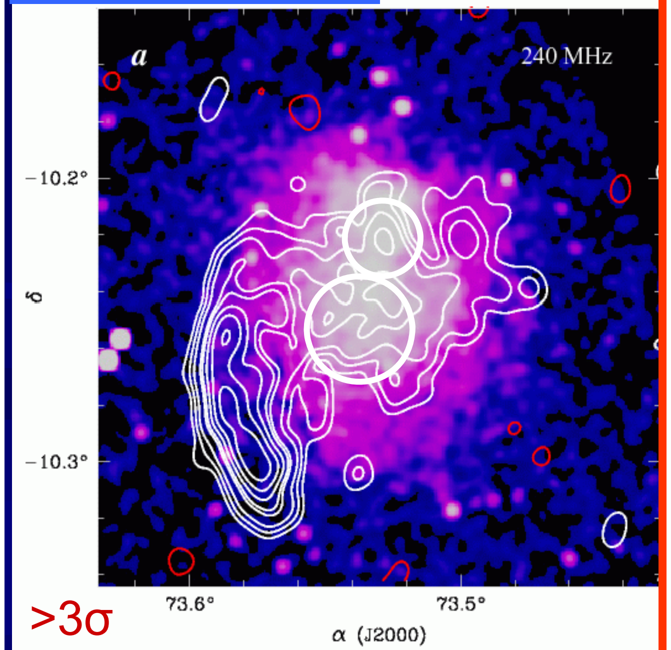

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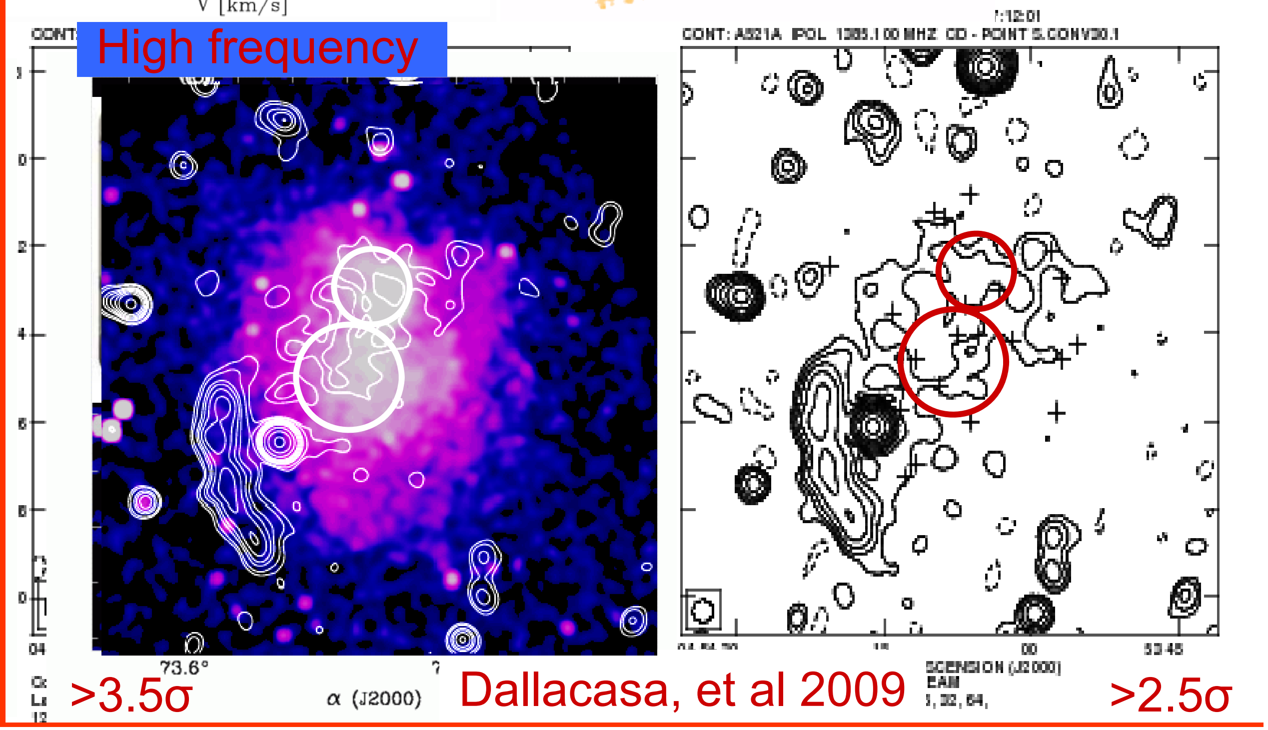

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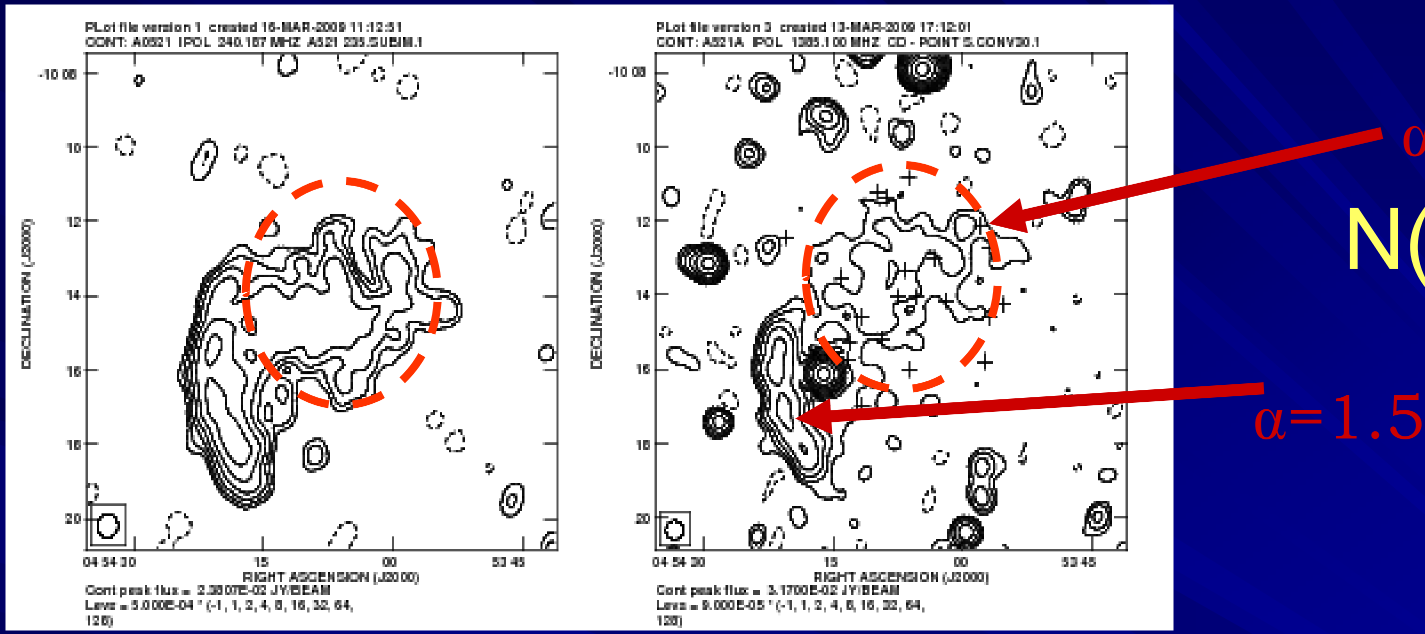
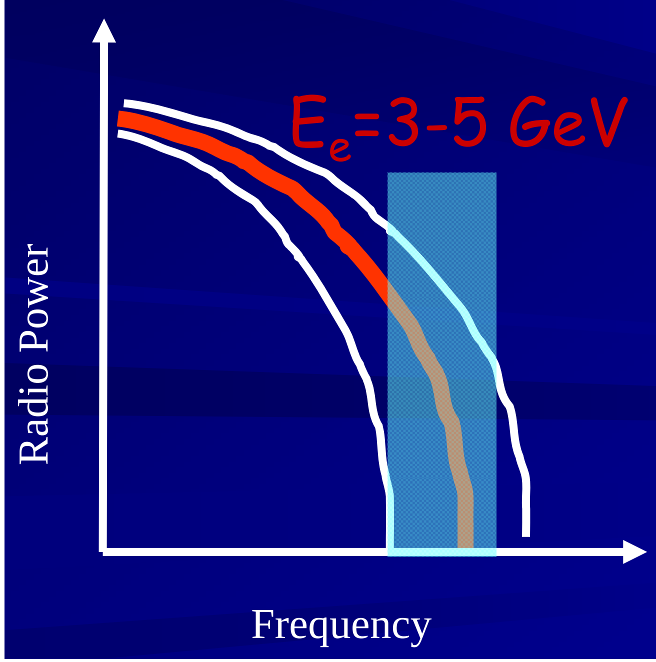
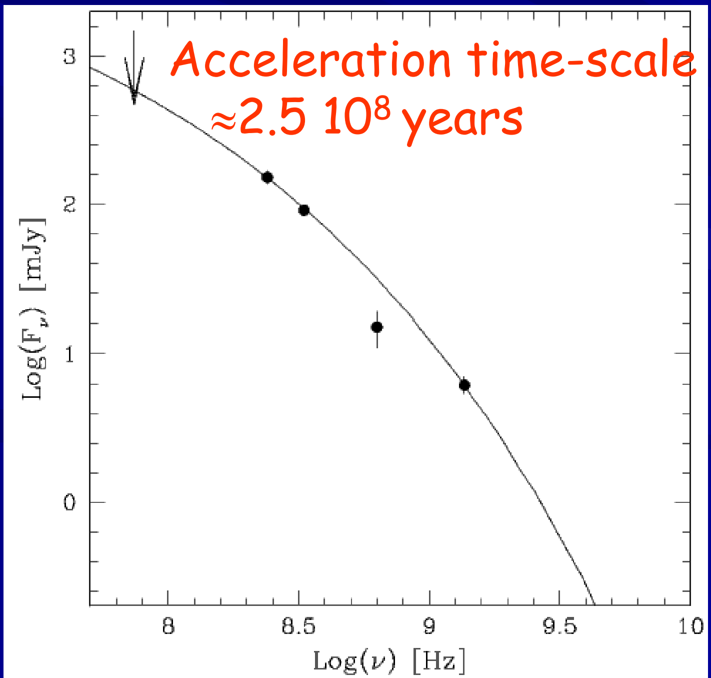
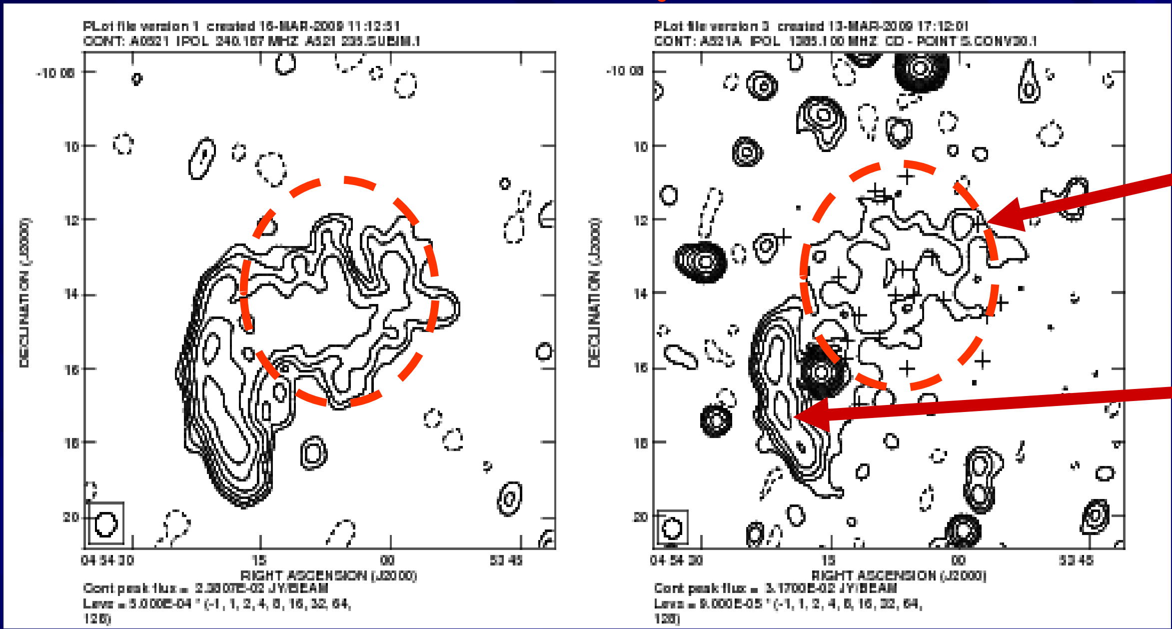


$N(E)=k\,E^{-4.8}$





Drawback of alternatives (Brunetti +al. 2008)



α=1.9

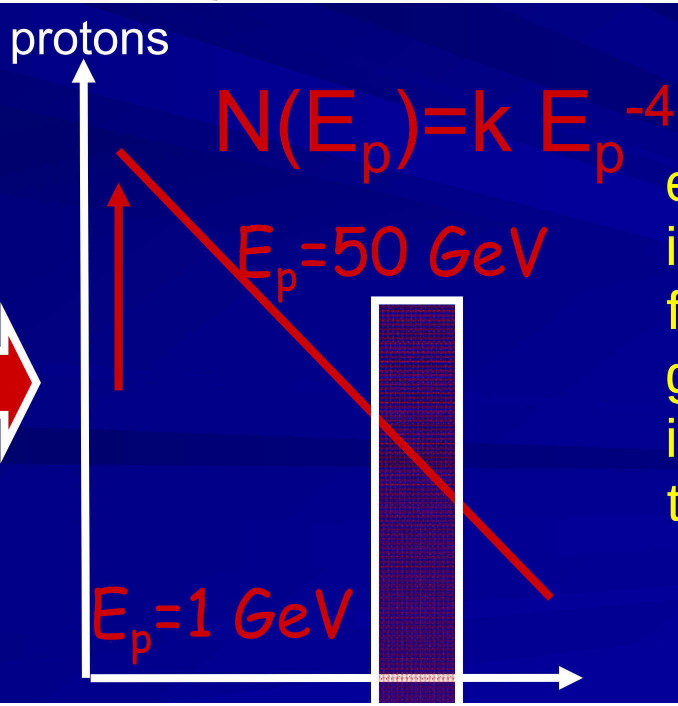
$N(E)=k\,E^{-4.8}$

α=1.5

$$p+p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^\pm \rightarrow \mu + \nu_\mu \quad \mu^\pm \rightarrow e^\pm \nu_\mu \nu_e .$$



Hadronic fails for $\alpha > 1.5$-1.6!

(eg. Brunetti 2004)

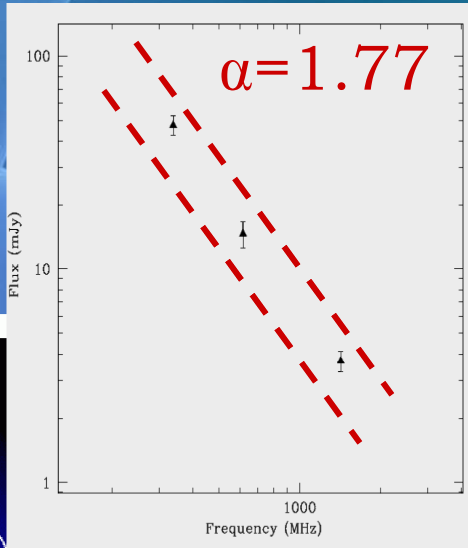
e.g. if the synchrotron radiation is from secondary $e^\pm$ electrons generated during p-p colisions in the IGM we would arrive at the untenable scenario

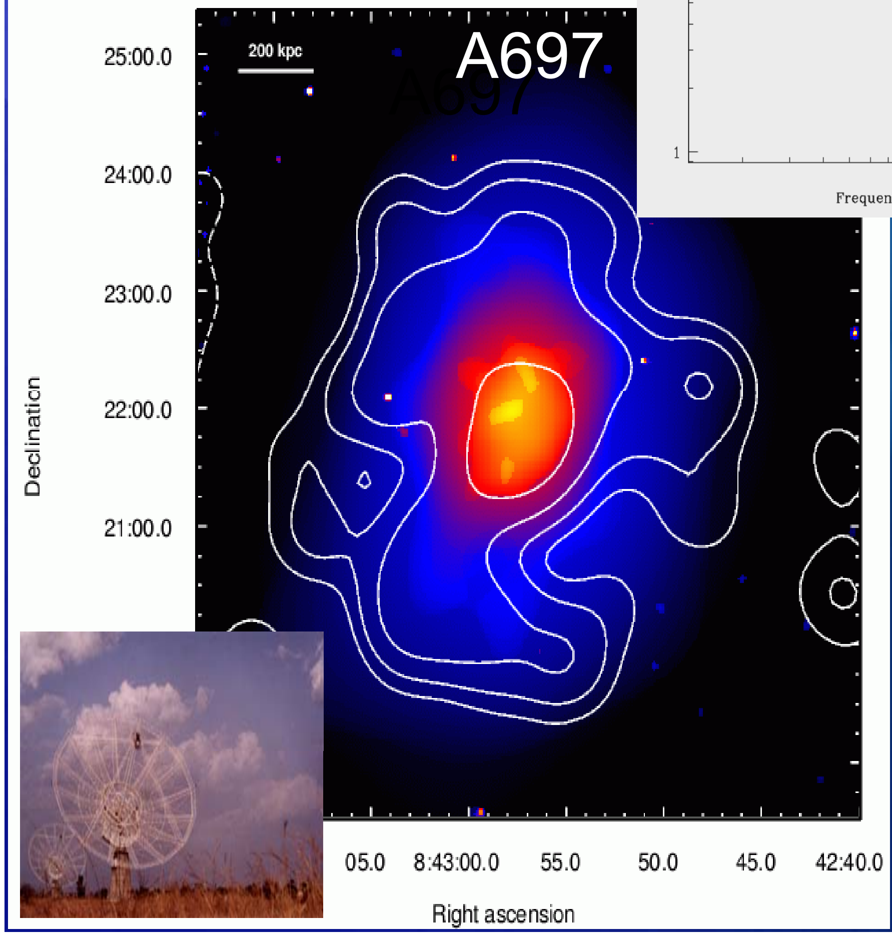
$$\omega_{CR} + B^2/8\pi > \omega_{Th}$$

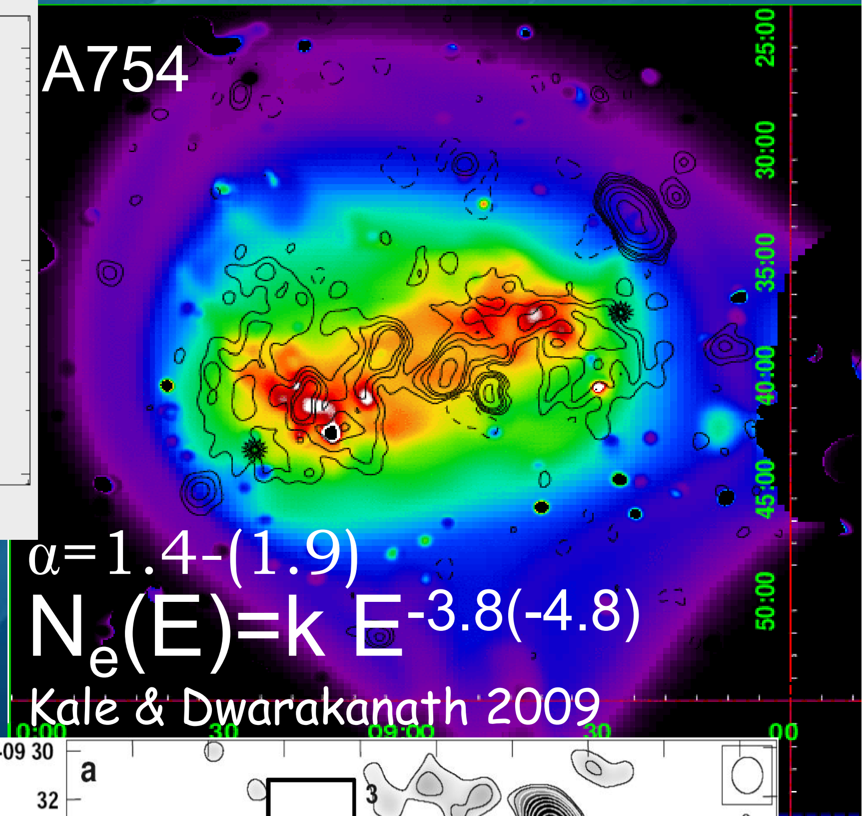
Other very-steep spectrum Radio Halos
(α > 1.5-1.6, about 15 % of Radio Halos)

$N_e(E) = k\,E^{-4.5}$

Macario et al 2009+



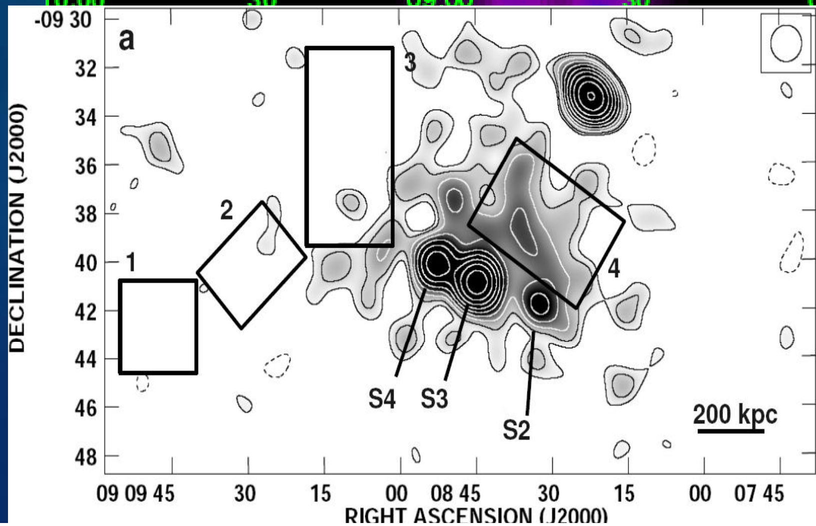




α=1.4-(1.9)

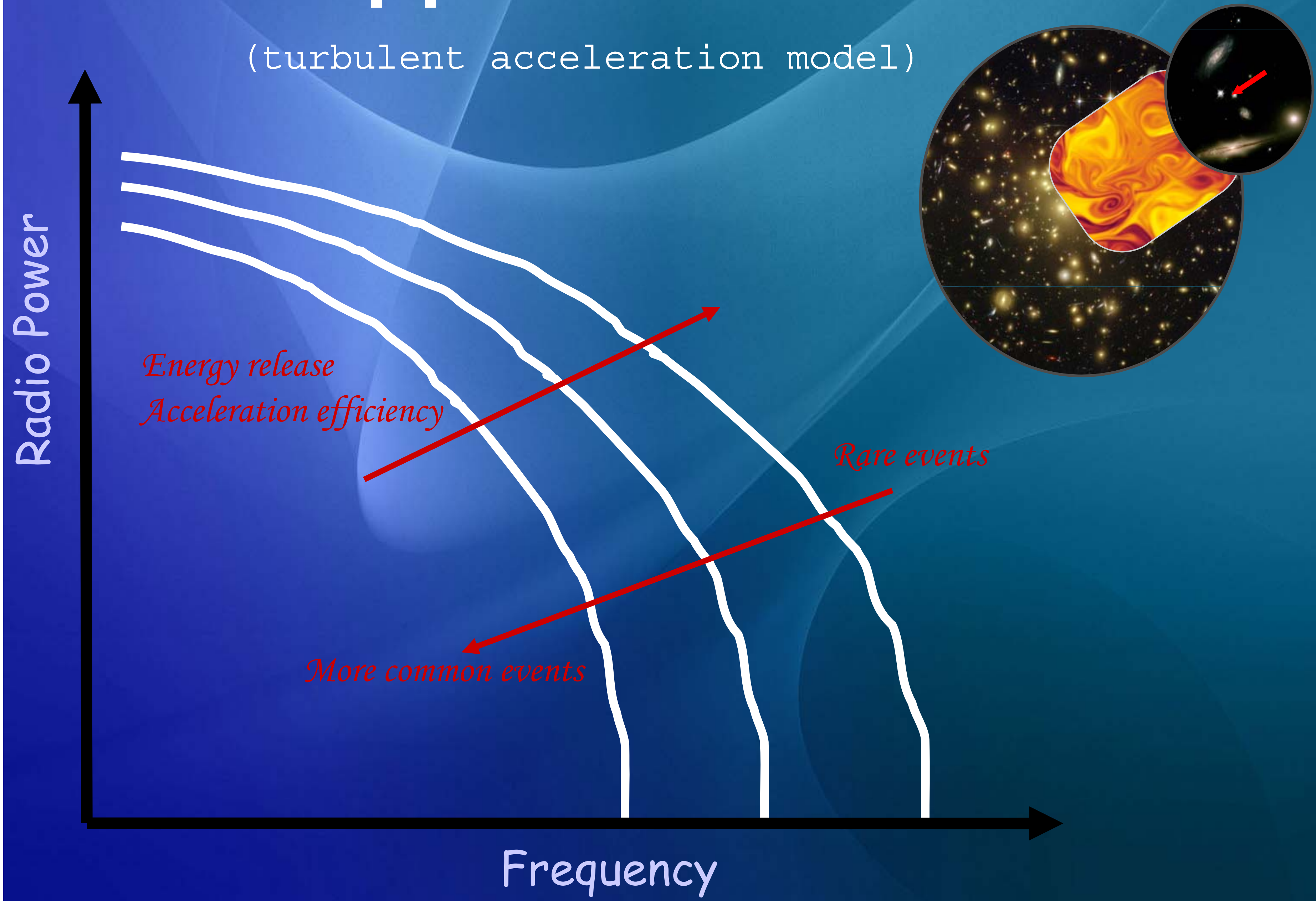
$N_e(E) = k\,E^{-3.8(-4.8)}$

Kale & Dwarakanath 2009



On the population of radio halos

(turbulent acceleration model)



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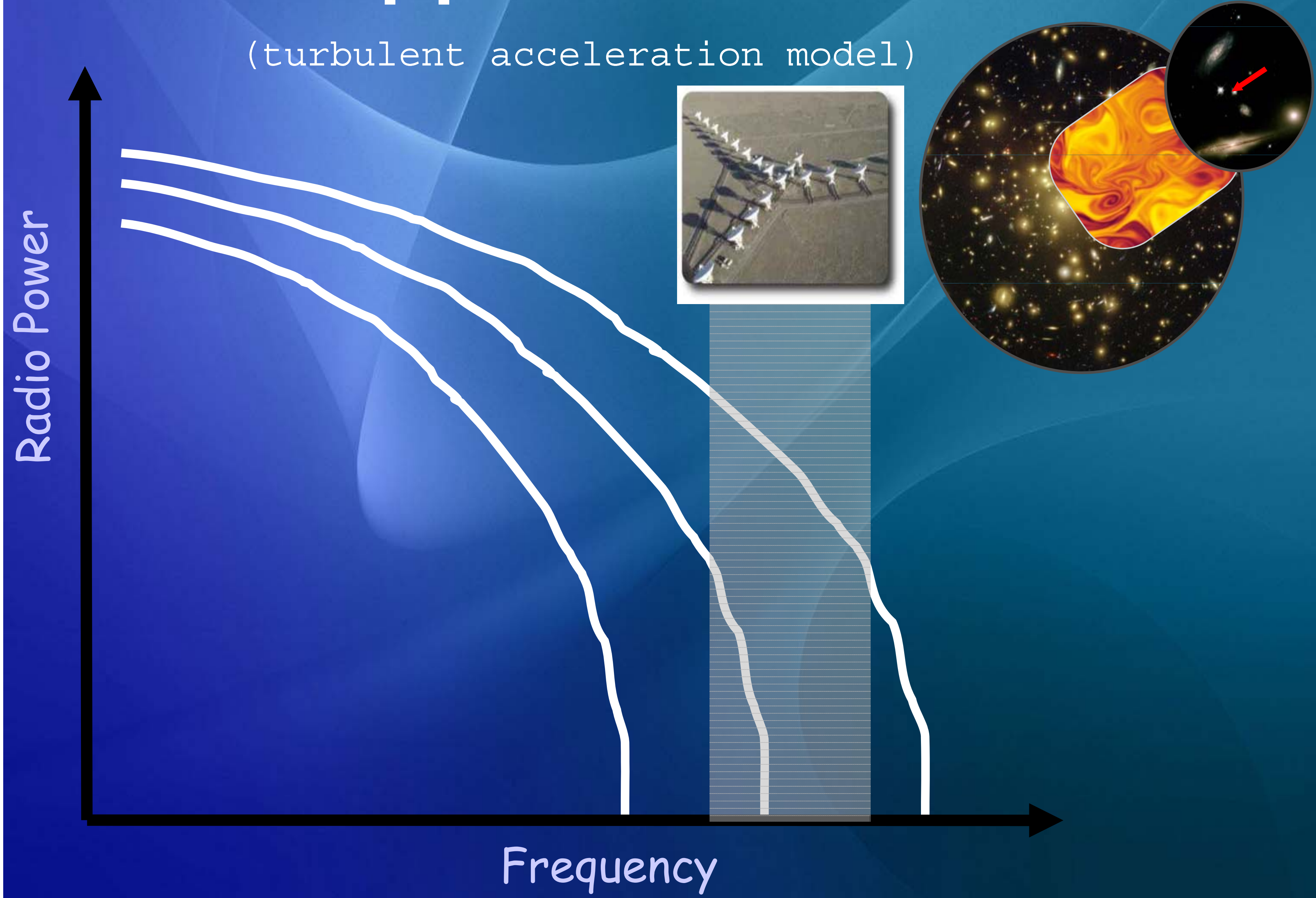

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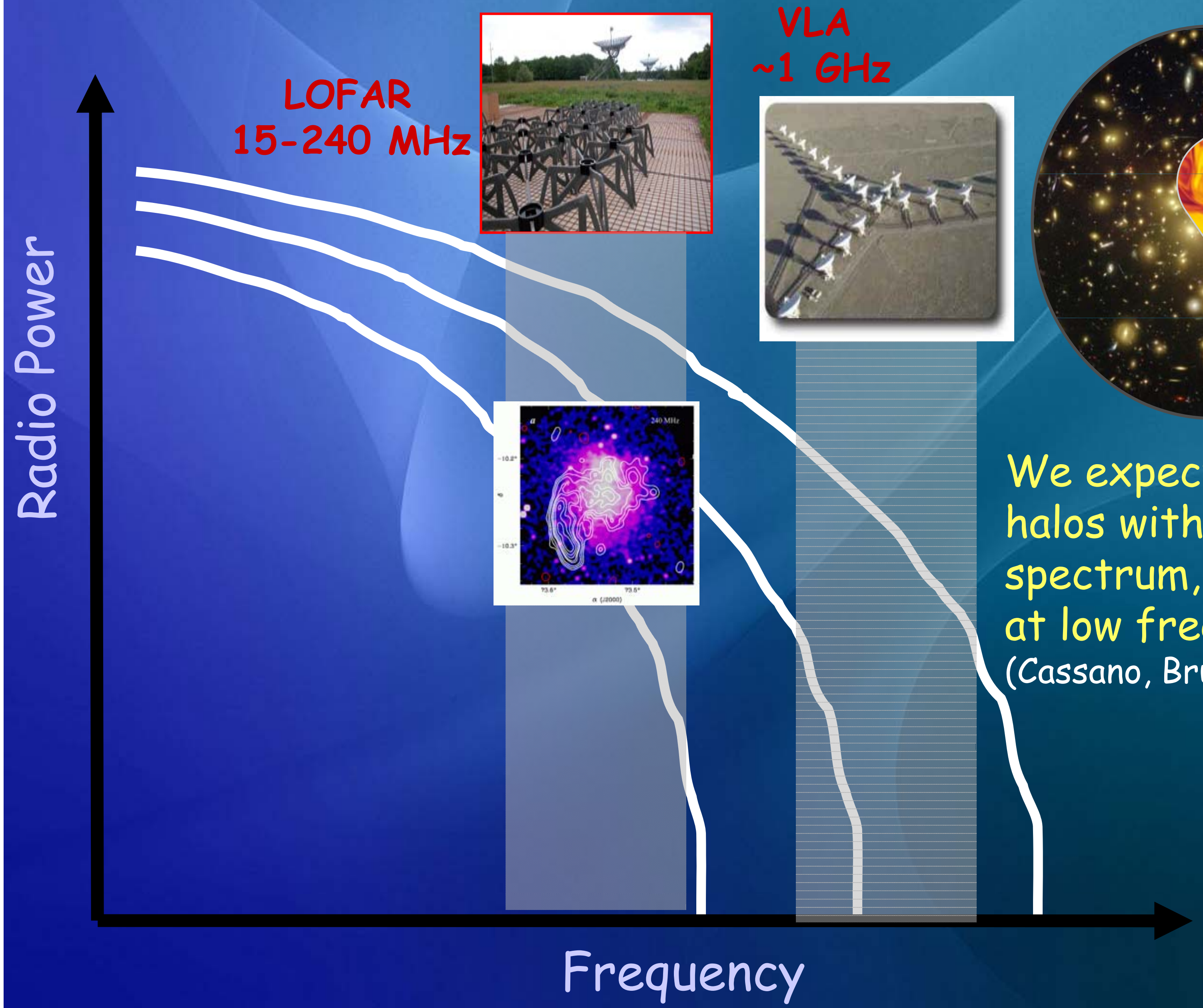
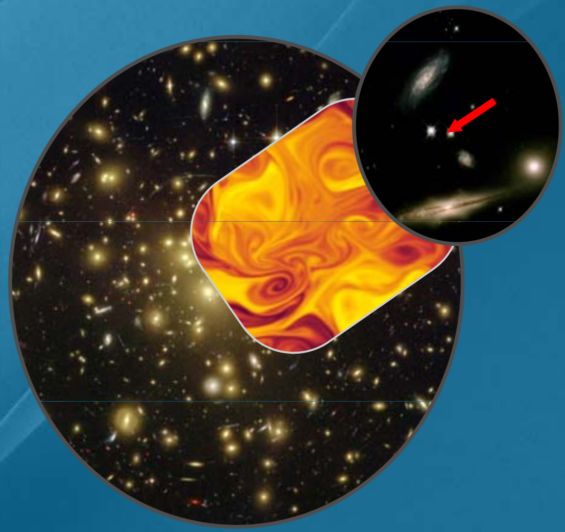


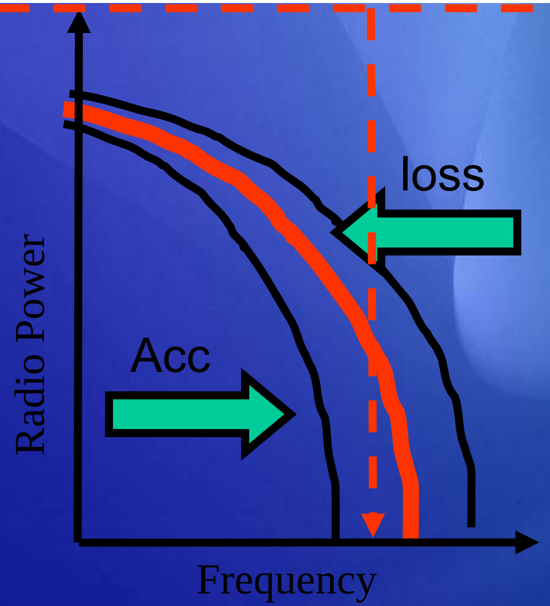


We expect many radio halos with very steep spectrum, (better) visible at low frequencies
(Cassano, Brunetti, Setti 2006)

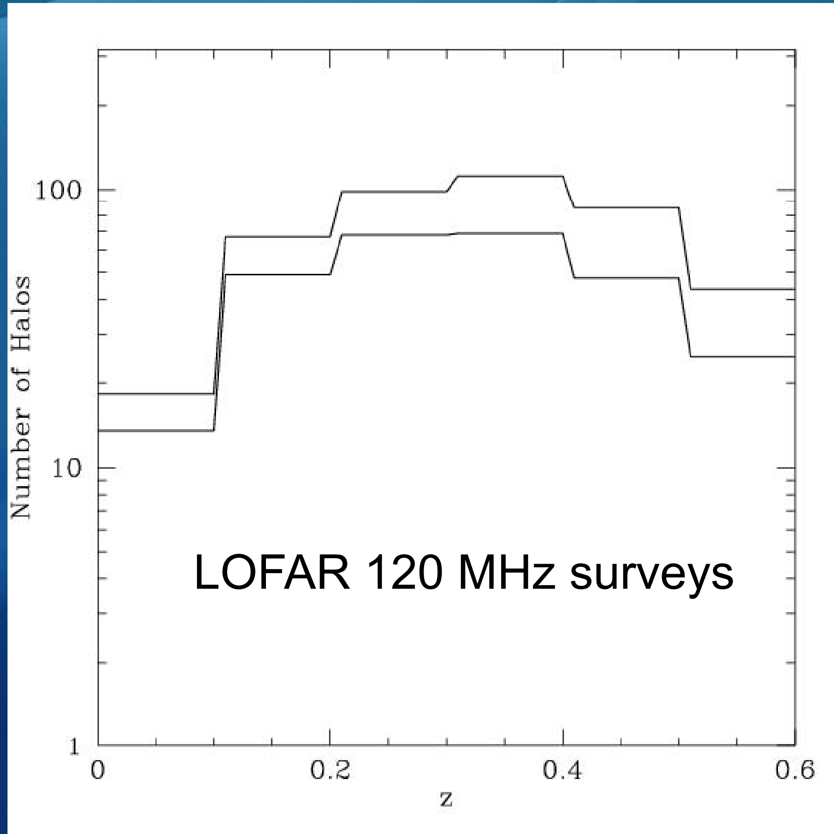
How many radio halos at low ν ?

Cassano, Brunetti, Rottgering, Bruggen, 2009

$$\nu_b(z) \propto \frac{B\chi^2}{(B^2+B_{cmb}^2)^2} \propto \frac{B\,\eta_t^2}{R_H^6\,(B^2+B_{cmb}^2)^2} \sum_j \left[\left(\frac{M_v+\Delta M}{R_v} \right)^3 \times \frac{r_s^4}{kT} \right]_j \times \left\{ \begin{array}{ll} 1 & \text{if } r_s \le R_H \\ (R_H/r_s)^2 & \text{if } r_s > R_H \end{array} \right\}_j$$



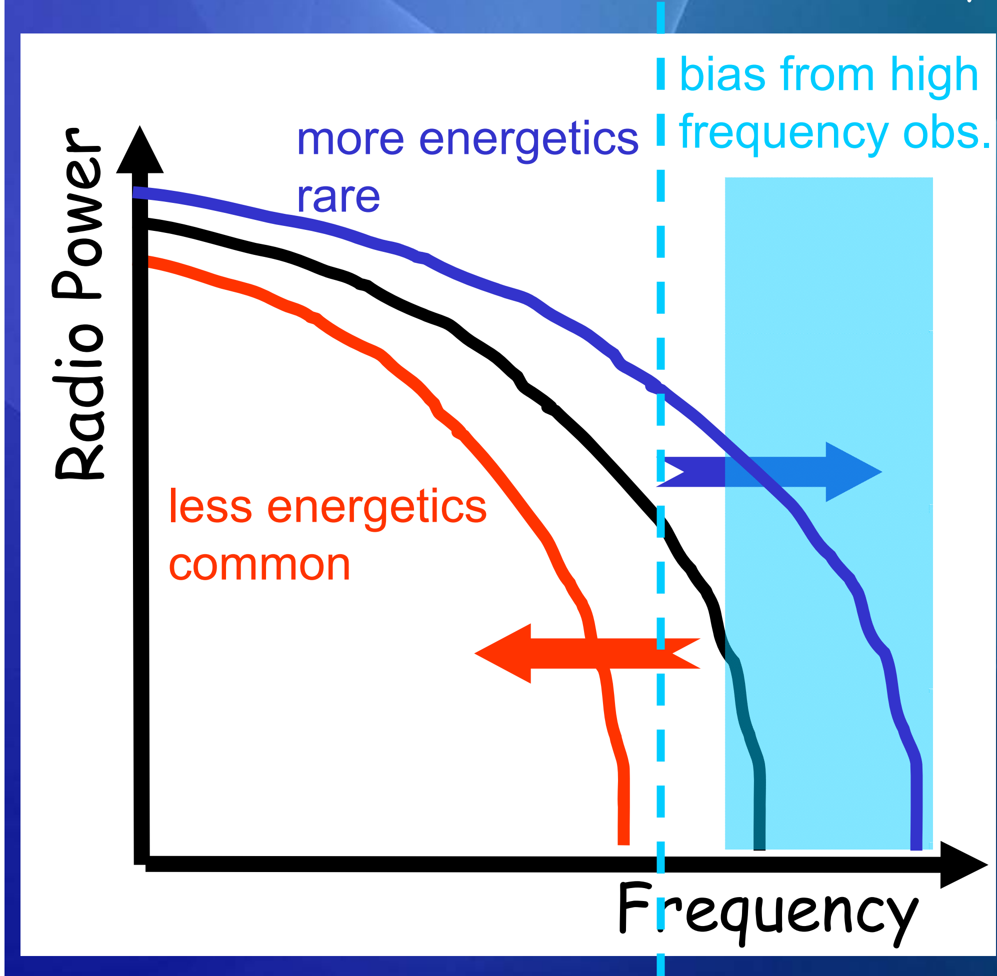
Cosmological / Monte Carlo calculations

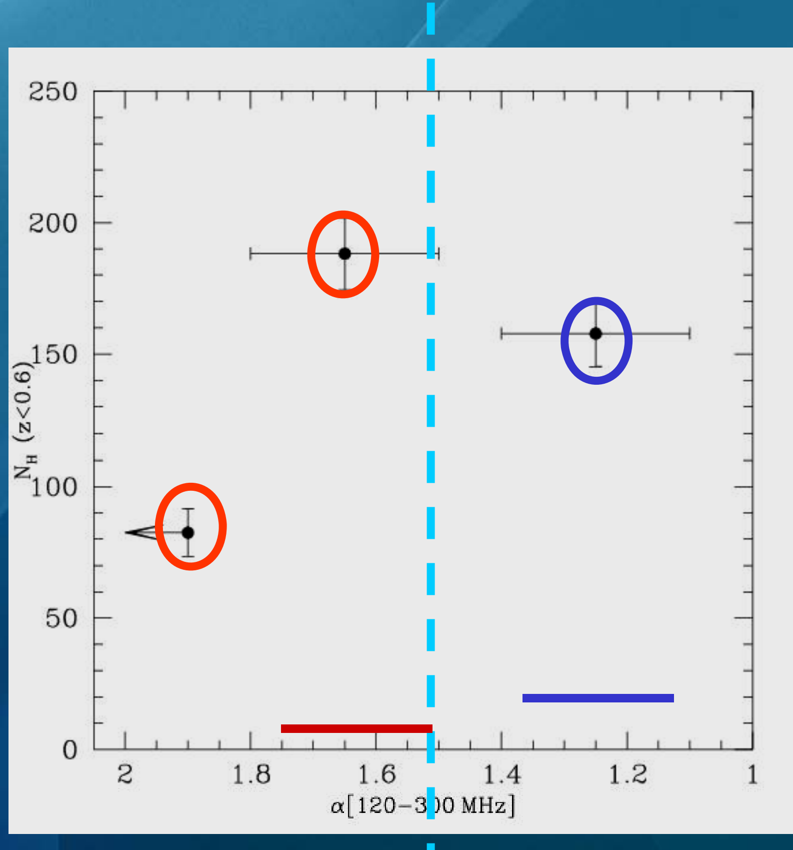


- ❖ LOFAR surveys should detect about 350-400 giant radio halos
- ❖ Increase by about 20 times present statistics ➡ cosmological probes ?

Spectral properties of Radio Halos

Cassano, Brunetti, Rottgering, Bruggen, 2009





LOFAR is expected to discover a large fraction of steep-spectrum Radio Halos

(iii)

Alfvenic: results

(Brunetti & Blasi 2005; Brunetti et al. 2009)

n_{th}, T, B_o, $N_p(p,0)$

I(k)

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(Brunetti & Blasi 2005; Brunetti et al. 2009)

n_{th}, T, B_o, $N_p(p,0)$

I(k)

$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

$$\pi^0 \rightarrow \gamma\gamma$$

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Alfvenic: results

(Brunetti & Blasi 2005; Brunetti et al. 2009)

n_{th}, T, B_o, $N_p(p,0)$

I(k)

$$\omega - k_{||} v_{||} - n \frac{\Omega_o}{\gamma} = 0$$

$$p + p \to \pi^0 + \pi^+ + \pi^- \ \ldots \text{thing}$$

$$\pi^0 \to \gamma\gamma$$

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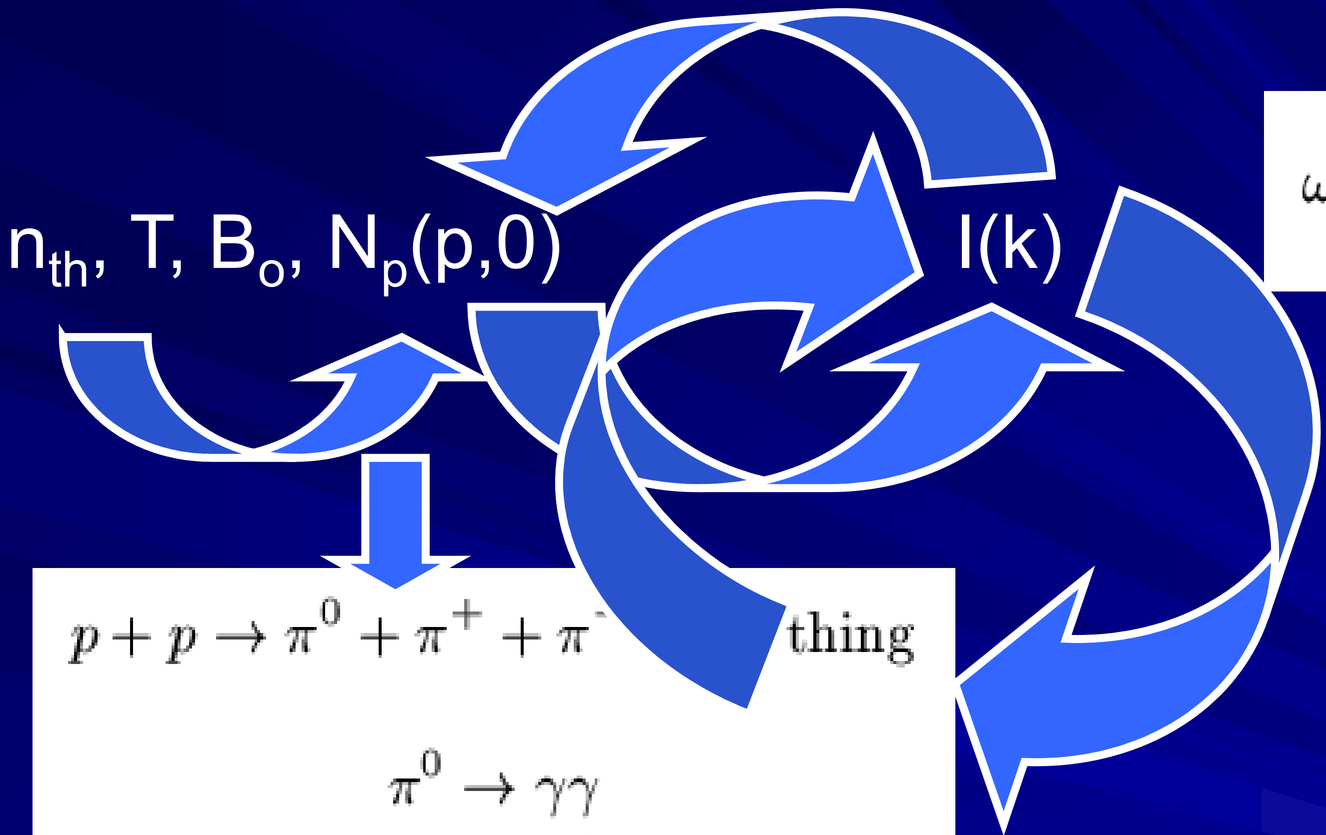

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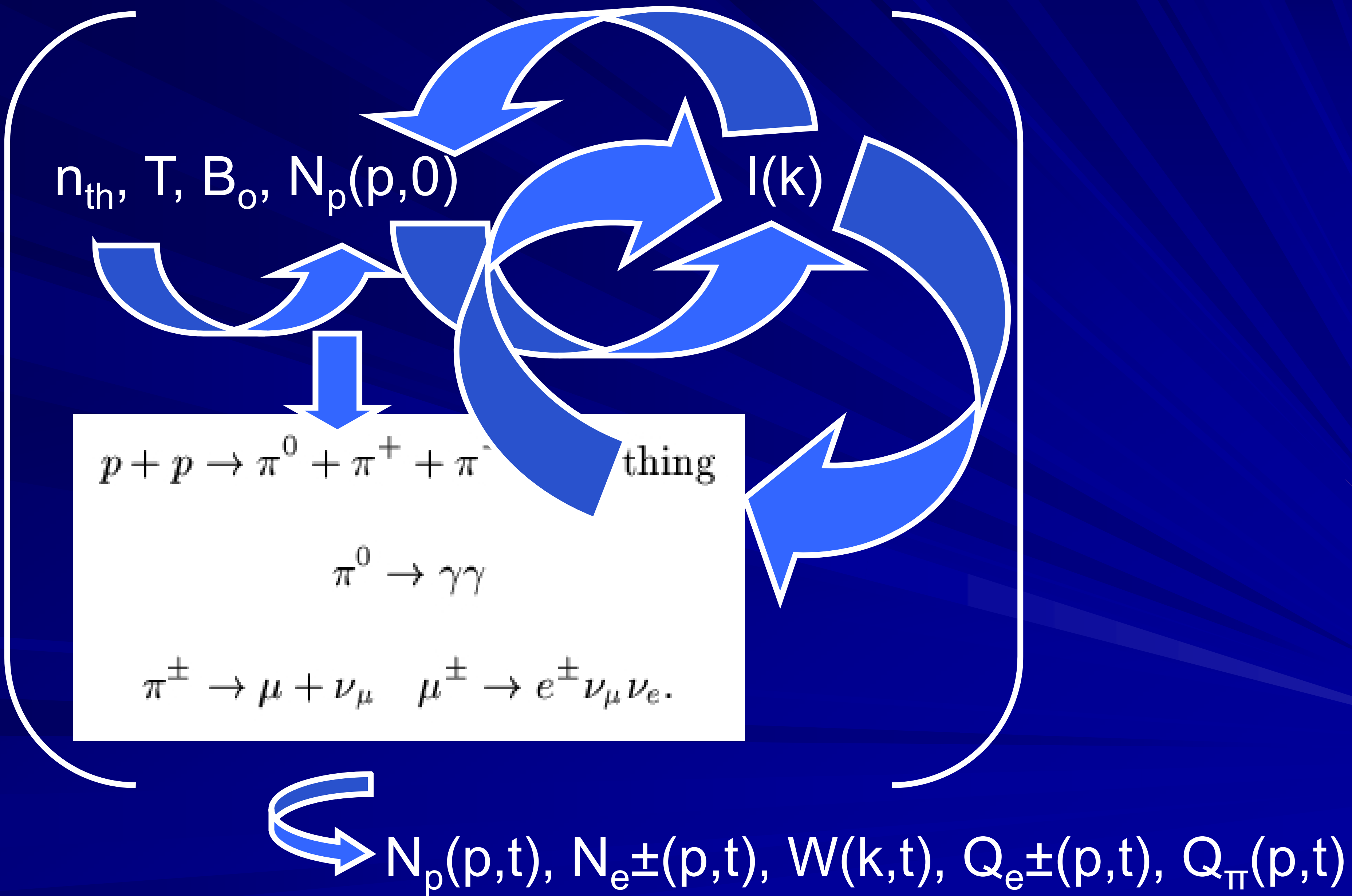
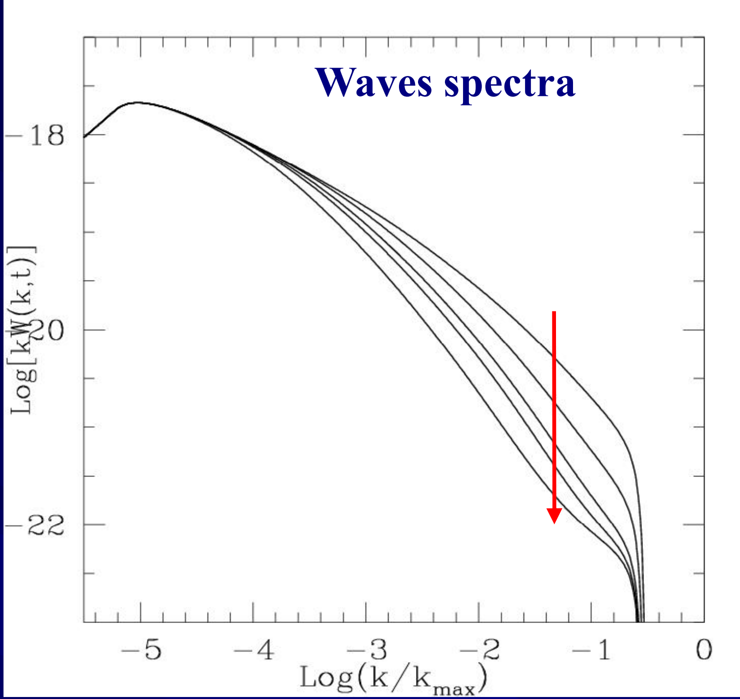
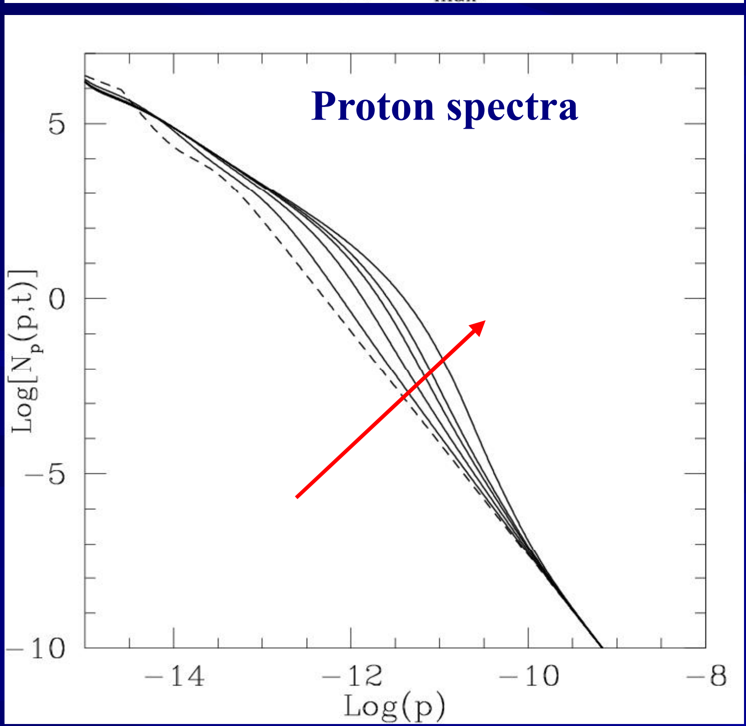
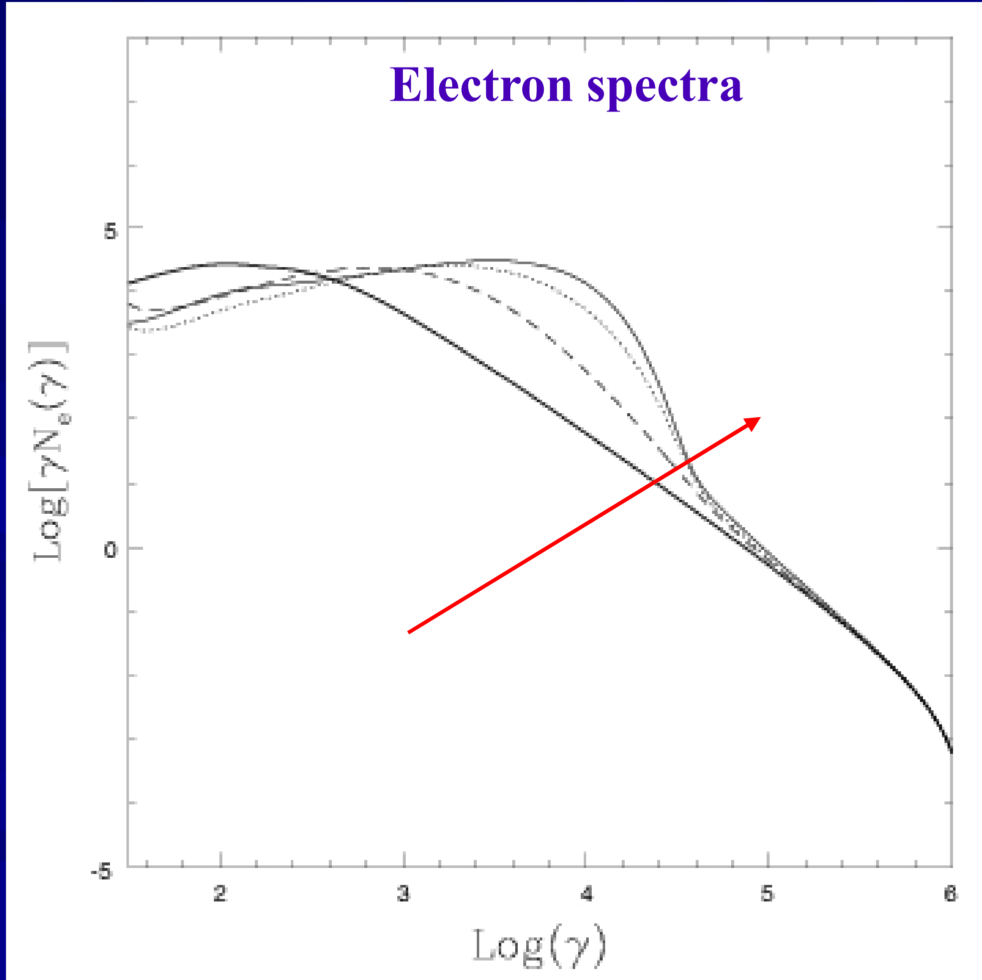


Alfven-Wave--Particle Coupling

(Brunetti & Blasi 2005; Brunetti et al. 2009)





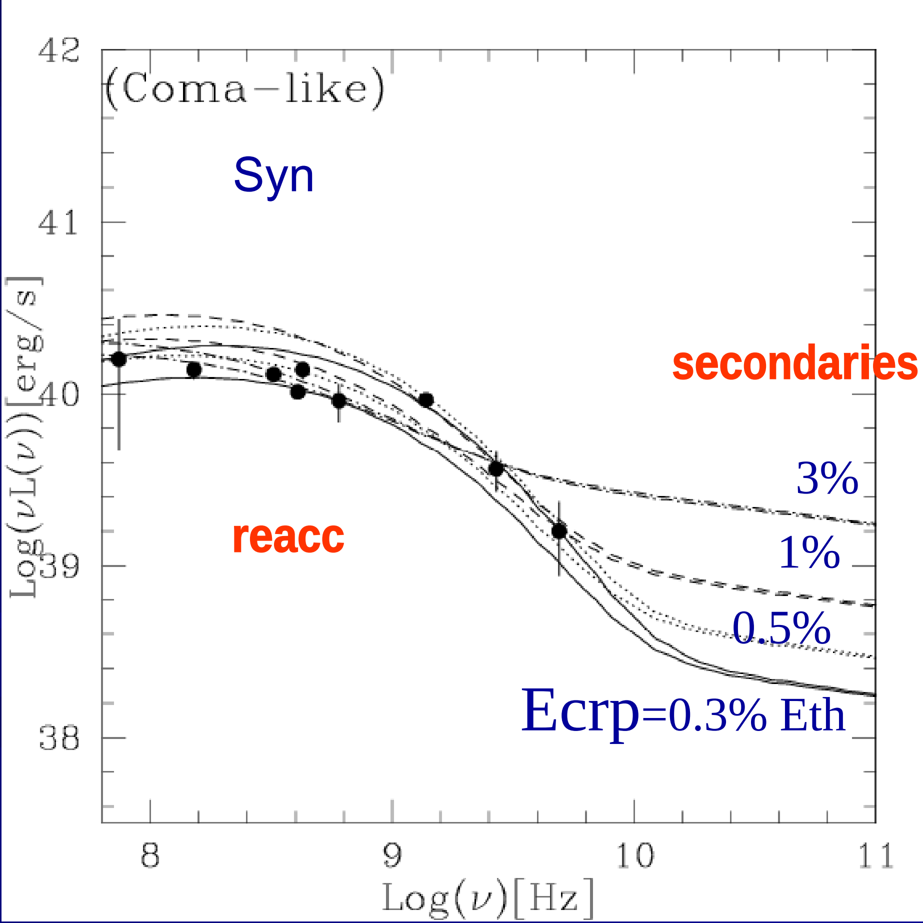


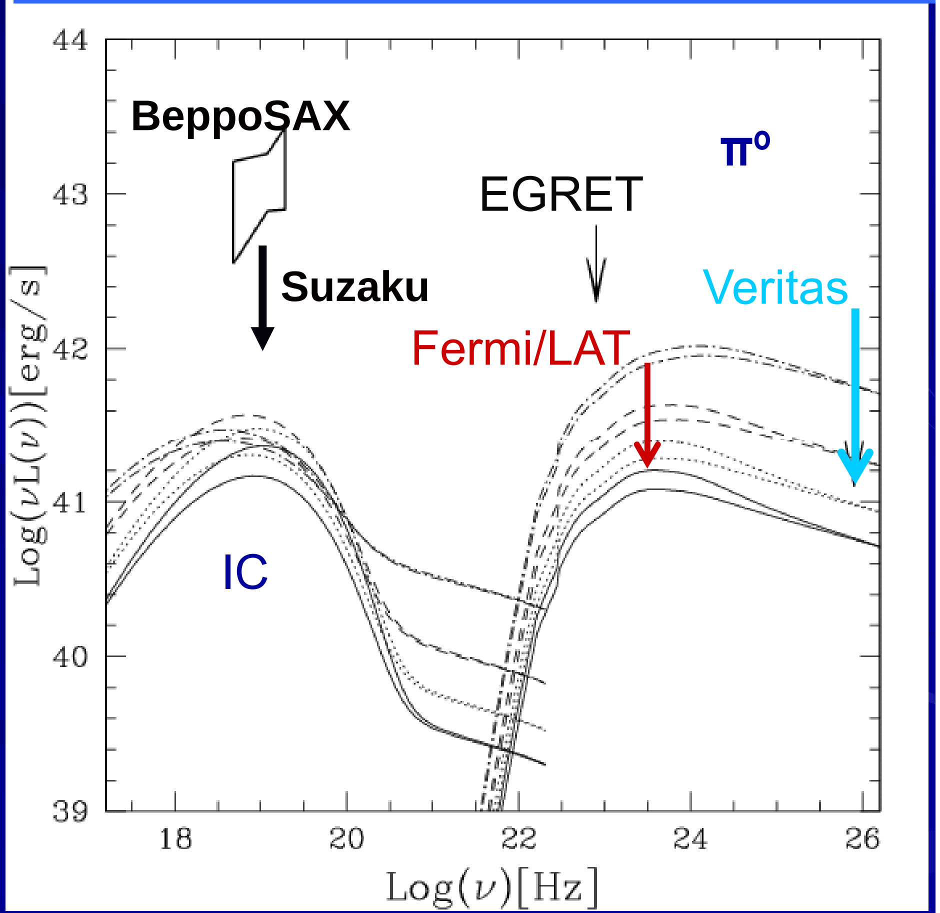
Waves + Protons + Secondaries

Alfvenic: results

Toy Model: β-profile, $B_o \approx A\, n_{th}$, $B_o(0)$=3 μG, $W_{CR} \approx f\, W_{th}$, $P_A \approx Q\ n_{th}^{5/6}$

Brunetti, et al. 2009





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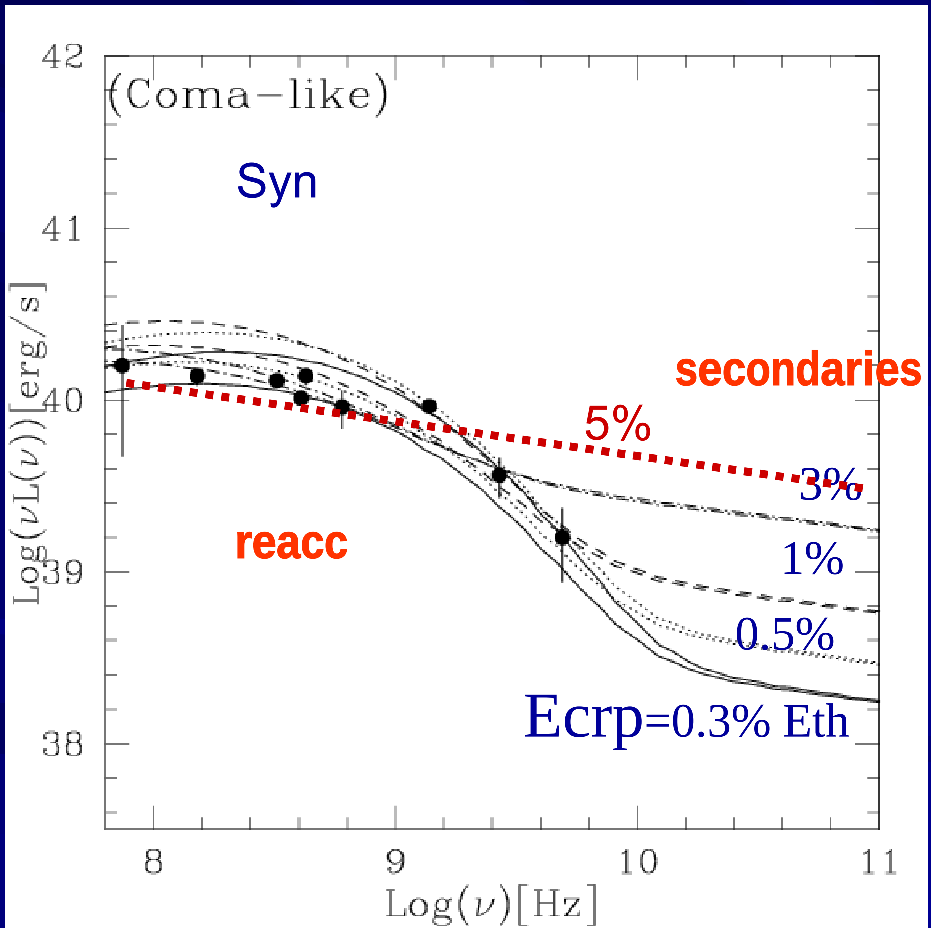
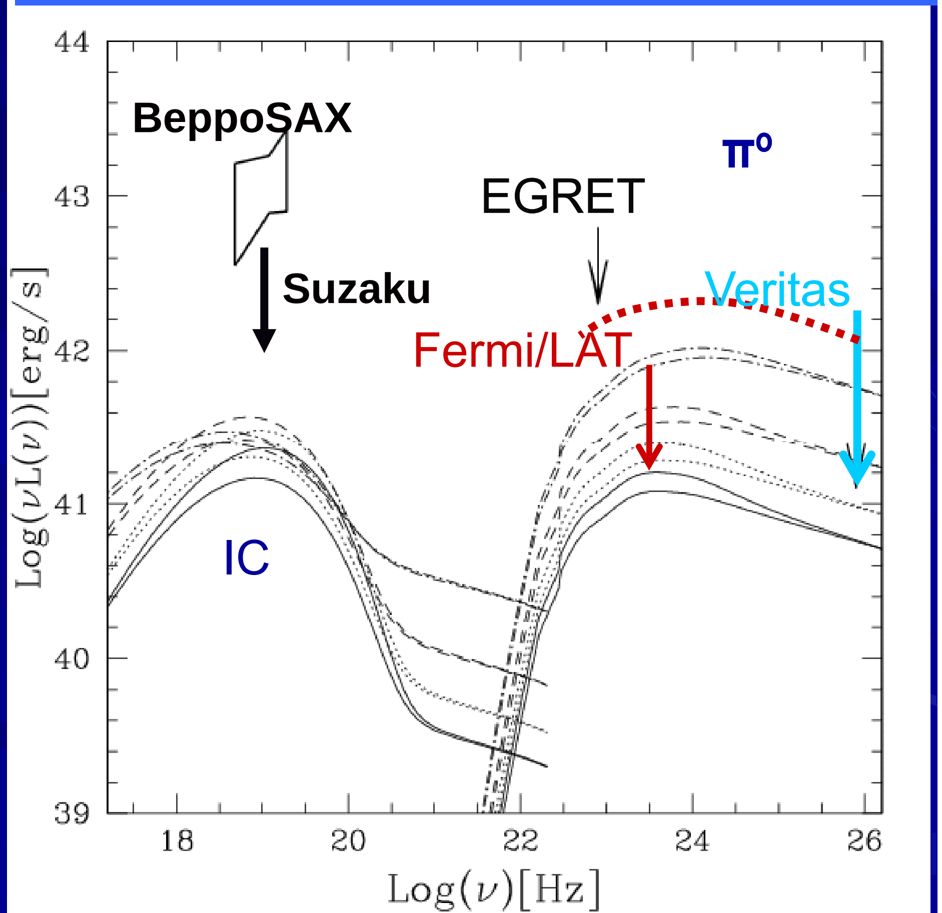
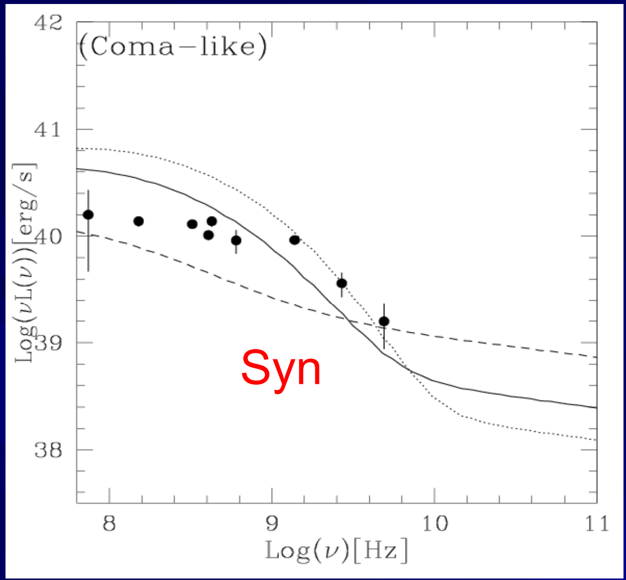
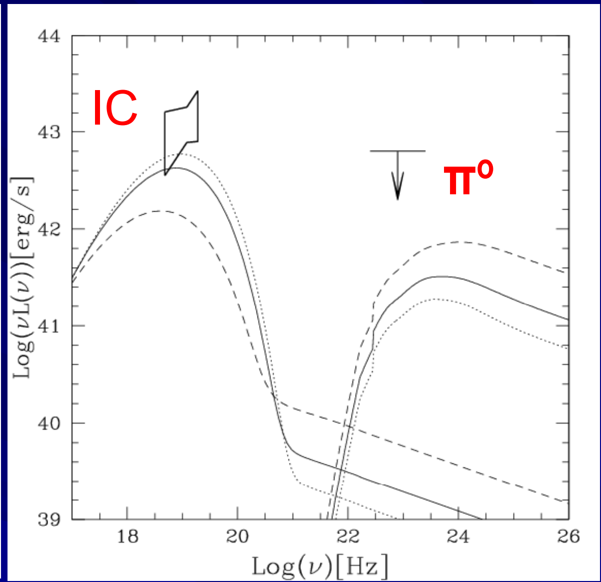


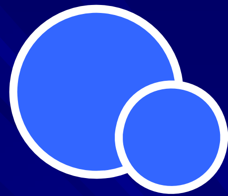


Connection with mergers & radio-bimodality

Brunetti 2008; Brunetti +al. 2009

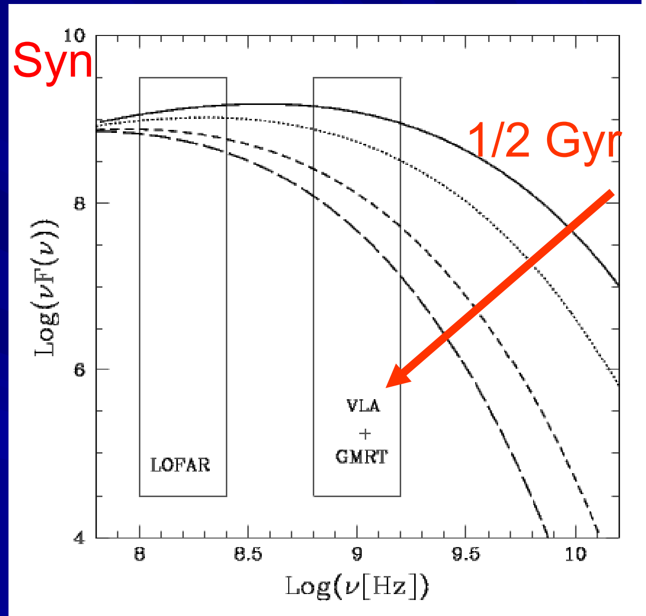


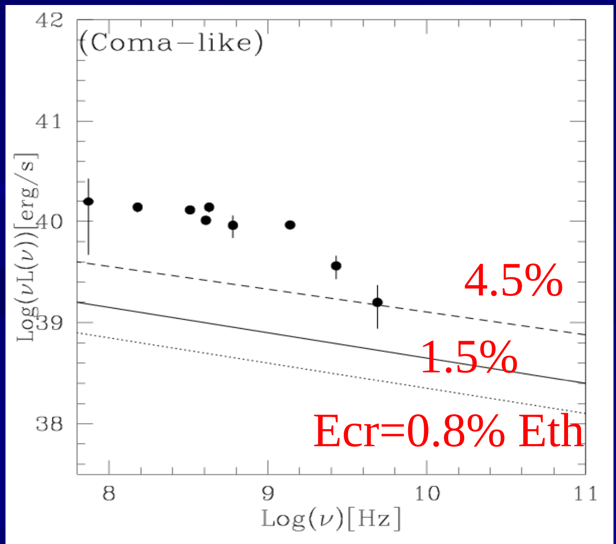


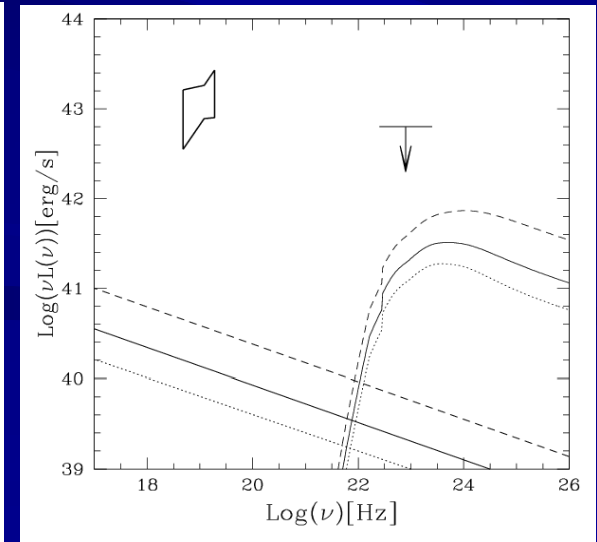


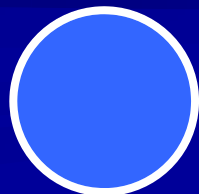
MERGING CLUSTERS

Brunetti +al. 2009



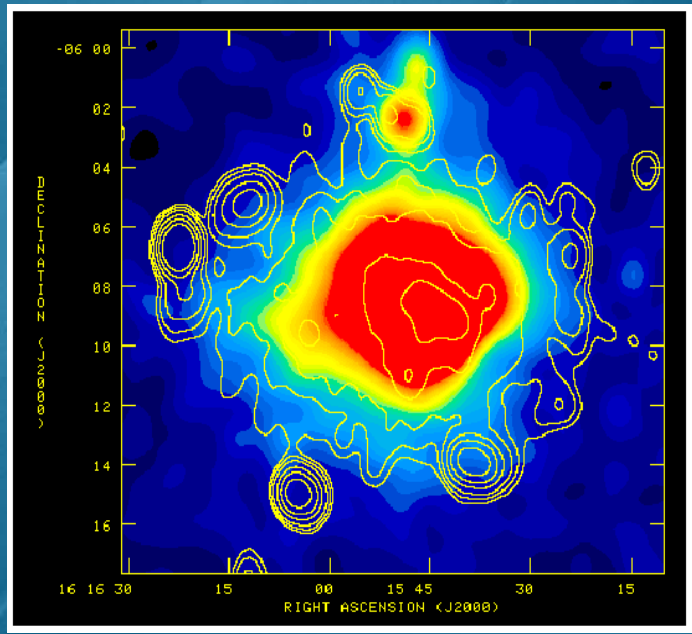






ALL CLUSTERS

The “GMRT Radio Halo Survey”

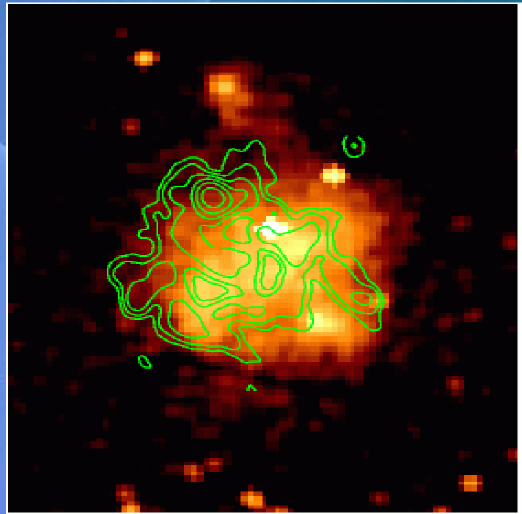


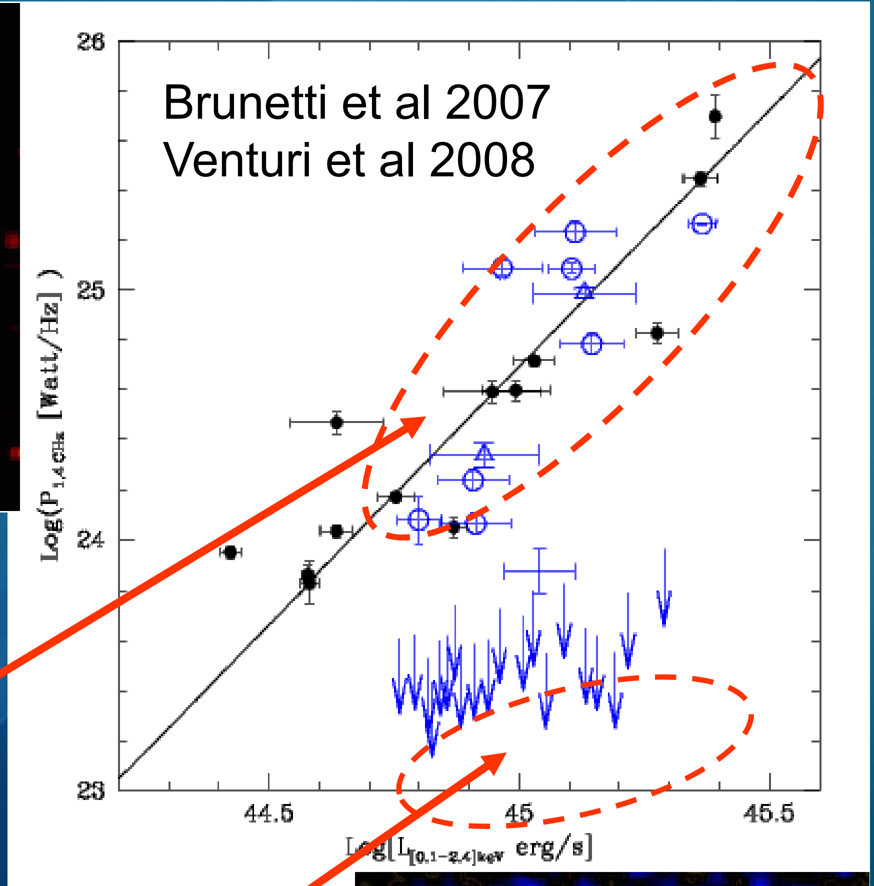
R.Cassano, T.Venturi
S.Giacintucci, G.Brunetti, D.Dallacasa, R.Athreya, G.Macario, N.Kassim, W.Lane, K.Dolag, S.Bardelli, G.Setti, B.Cotton, P.Mazzotta, M.Markevitch

Sample of
50 massive GC z=0.2-0.4
(REFLEX + eBCS)

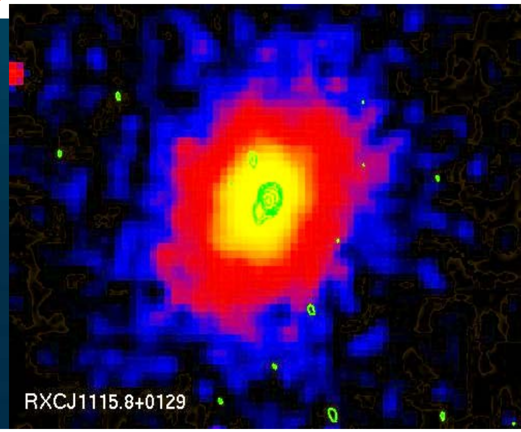
Similar z
Similar X-luminosities

Cluster's radio bimodality





Merging clusters



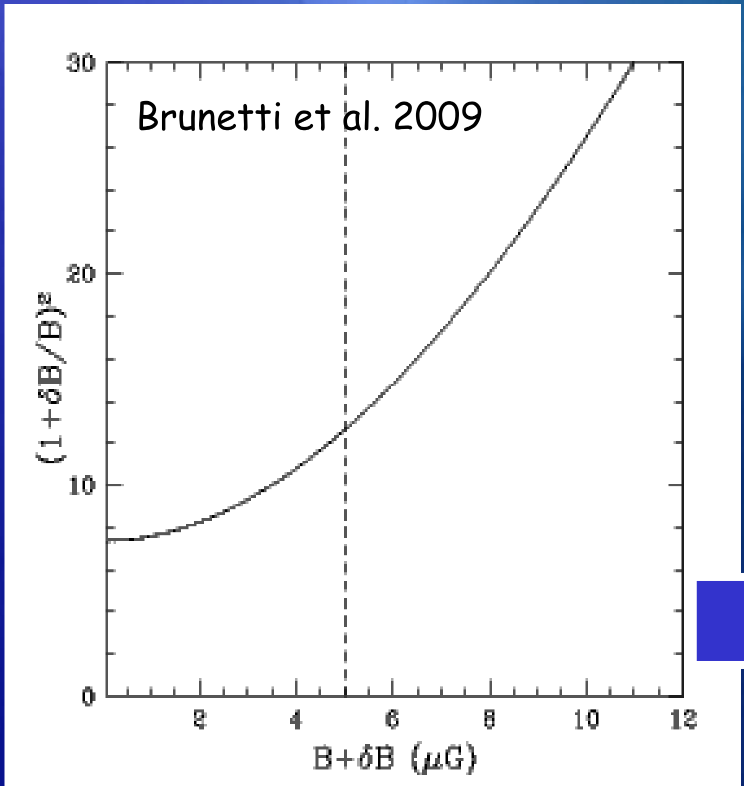
Connection with cluster mergers
(e.g. Buote 2001; *Schuecher et al. 2001; Boschin et al. 2003 Govoni et al. 2004; Venturi et al. 2007, 08*)

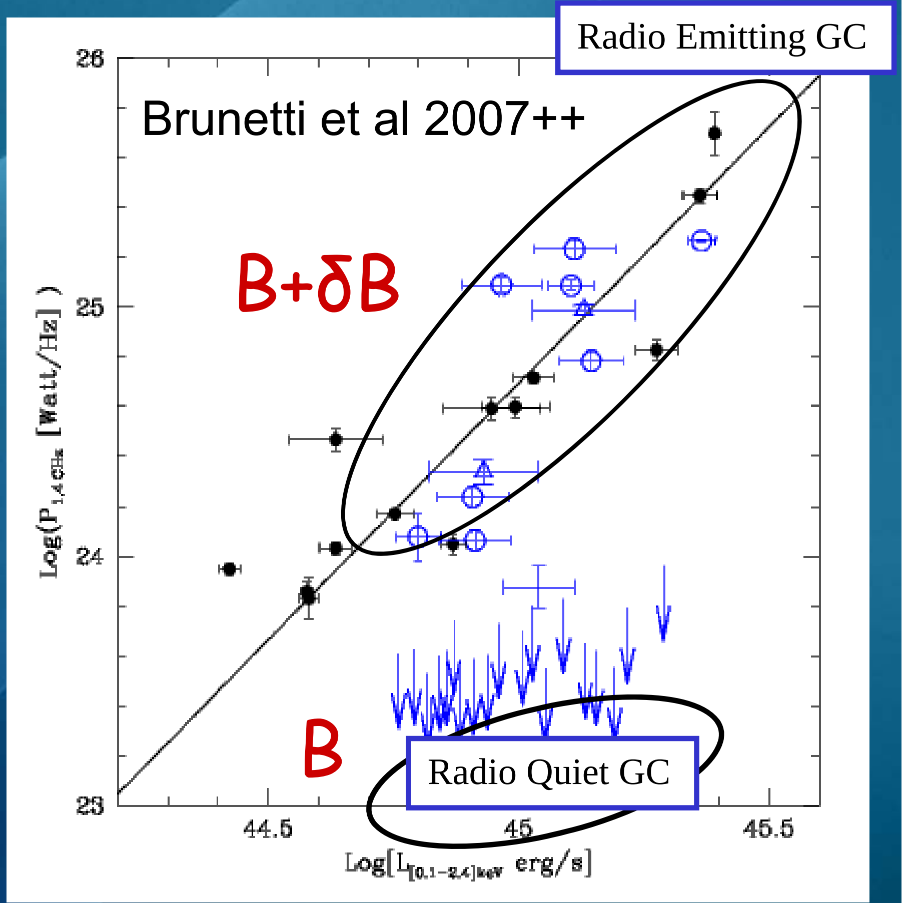
Typically relaxed

"Magnetic" evolution of Radio Halos ?

Brunetti, Cassano, Dolag, Setti, (2009)

Magnetic field is amplified during mergers, B+δB, and is dissipated when clusters become dynamically "relaxed", B





90% of the magnetic field energy must be dissipated when clusters become more relaxed.

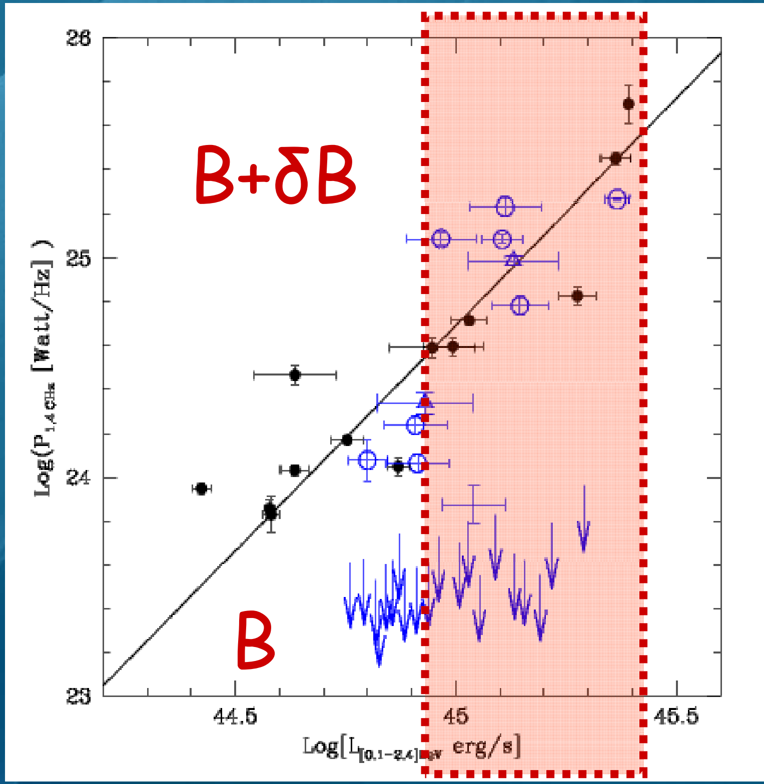
Which time scale ?

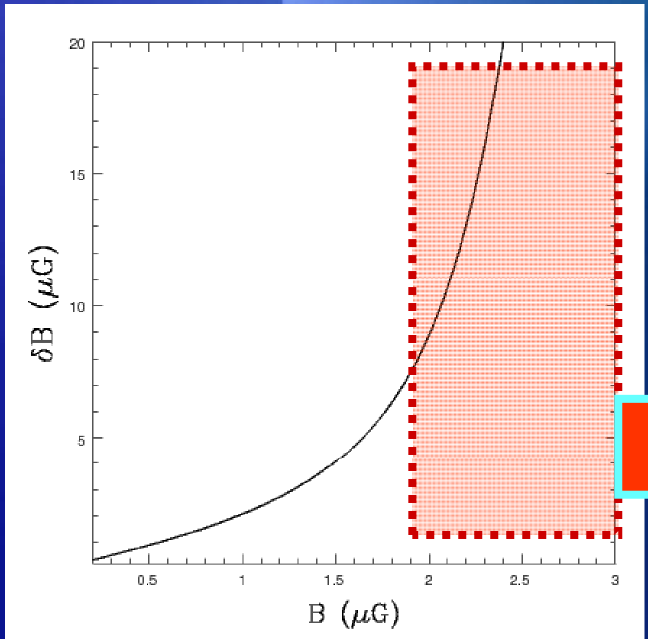
“Magnetic” evolution of Radio Halos ?

Brunetti, Cassano, Dolag, Setti, (2009)

According to Monte Carlo simulations δB must be dissipated in τ_{diss} << 1 Gyr

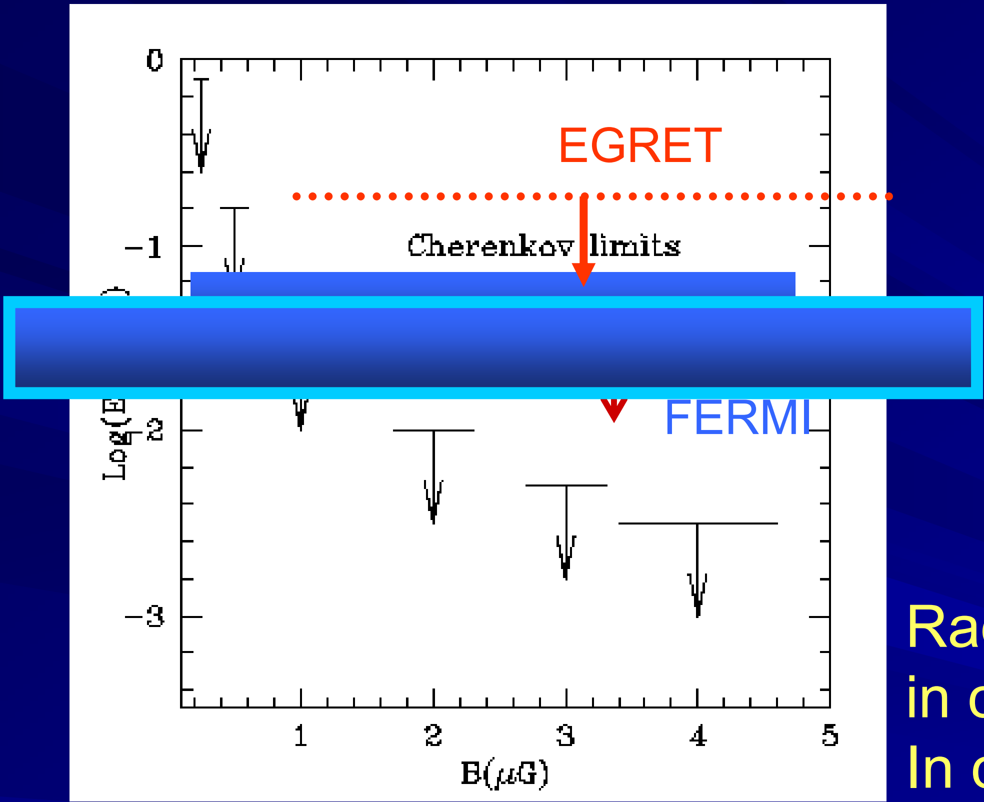
- Too fast assuming typical coherence scales for B
- If we “postulate” small scale δB





energetics “run-away”: energy dissipated similar to cluster thermal budget

(iv) Limits for CR protons



Reimer et al. (2003)
Reimer et al. (2004)
Pfrommer & Ensslin (2004)
Perkins et al. (2006)
Brunetti et al. (2007)
Brunetti et al. (2008)
Perkins et al. (2008)
Aharonian et al. (2008 a,b)
Aleksic et al. (2009)

Radio & Cherenkov upper limits are e
in case of "flat" CRp spectrum $N(E_p)$=
In case of "steeper" spectra FERMI is
expected to provide the best constrai

Additional limits from cluster dynamics (e.g. Churazov et al. 2008; Lagana et a
constrain $E_{CR}+E_B+E_{turb}$ below 10% (< 30%) Ethermal.

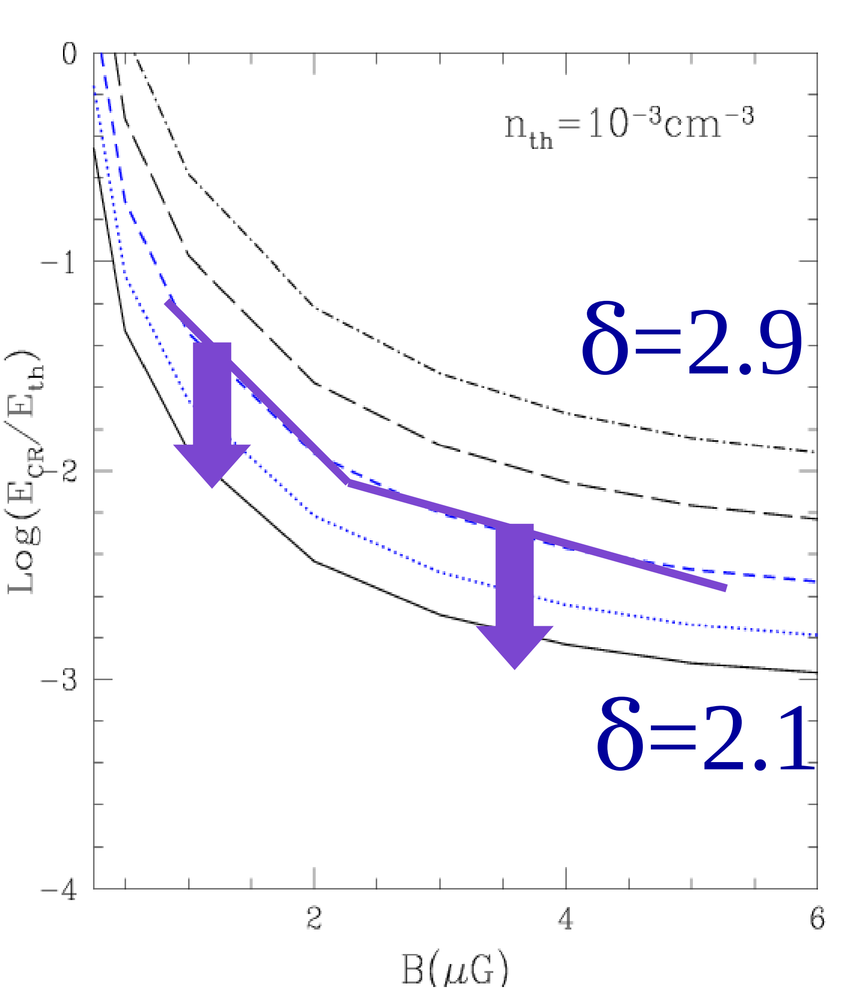
CRp: limits from Radio

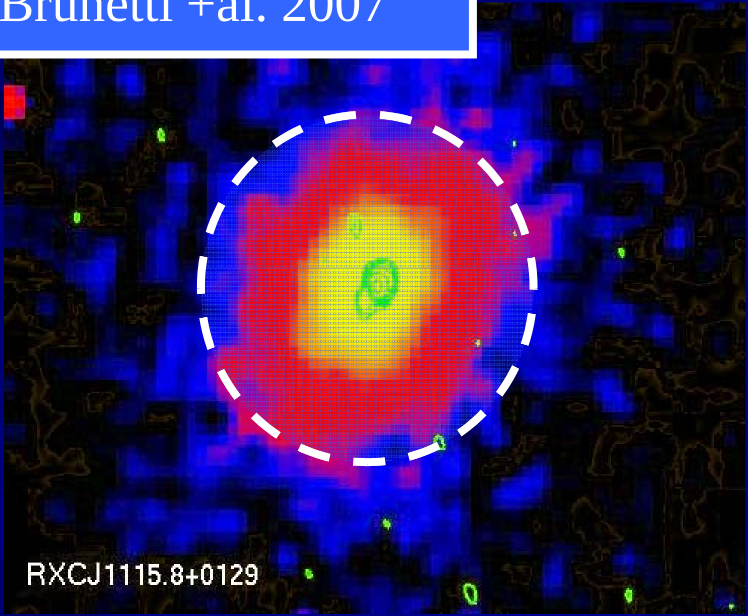
Brunetti +al. 2007

$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

$$\pi^0 \rightarrow \gamma\gamma$$

$$\pi^\pm \rightarrow \mu + \nu_\mu \quad \mu^\pm \rightarrow e^\pm \nu_\mu \nu_e.$$



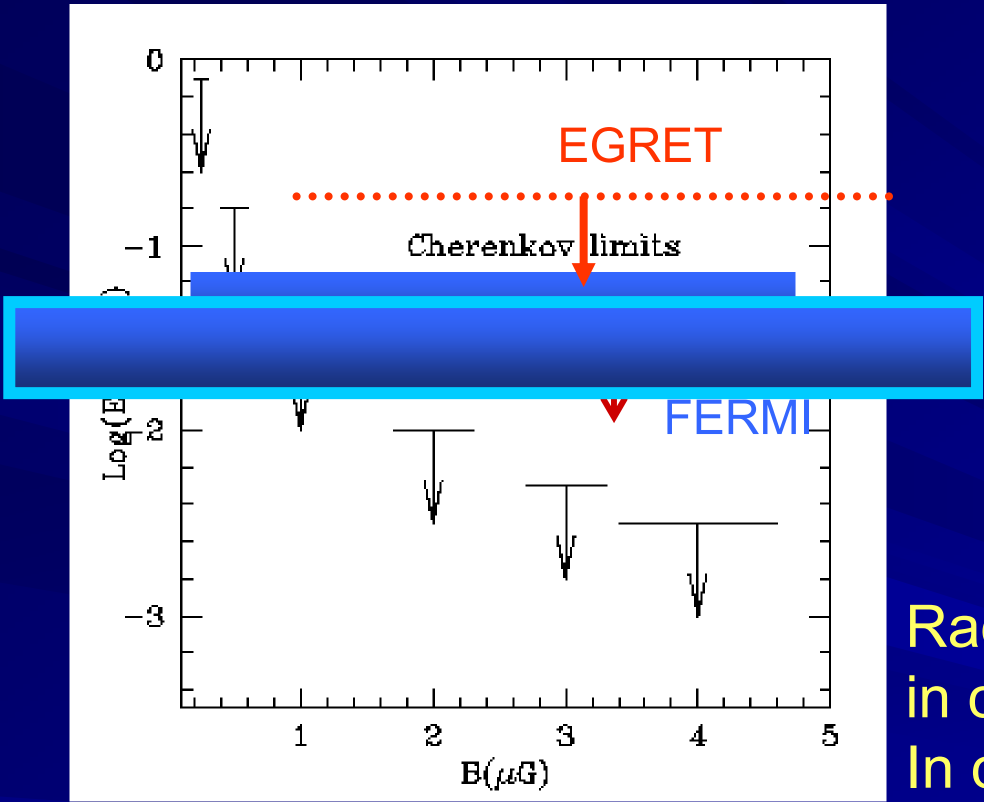


Assuming that secondary particles are injected in the IGM, their synchrotron emission should be smaller than upper limits to the diffuse radio emission.

limit on : B , E_{CRp} , δ

$N(p)=K\,p^{-\delta}$

Limits for CR protons



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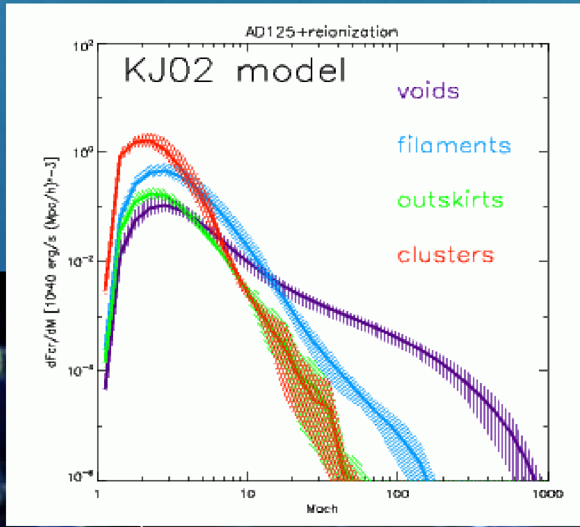
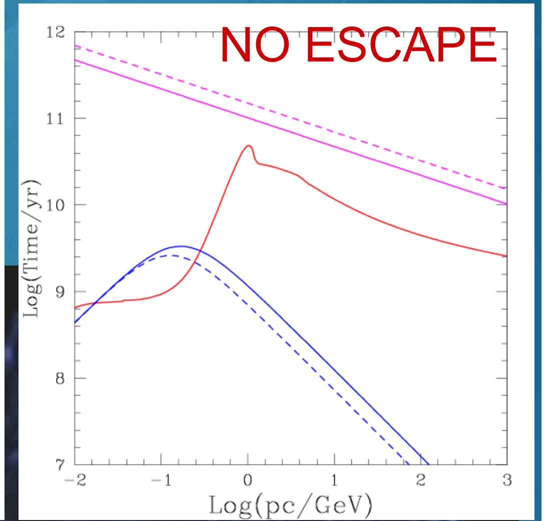
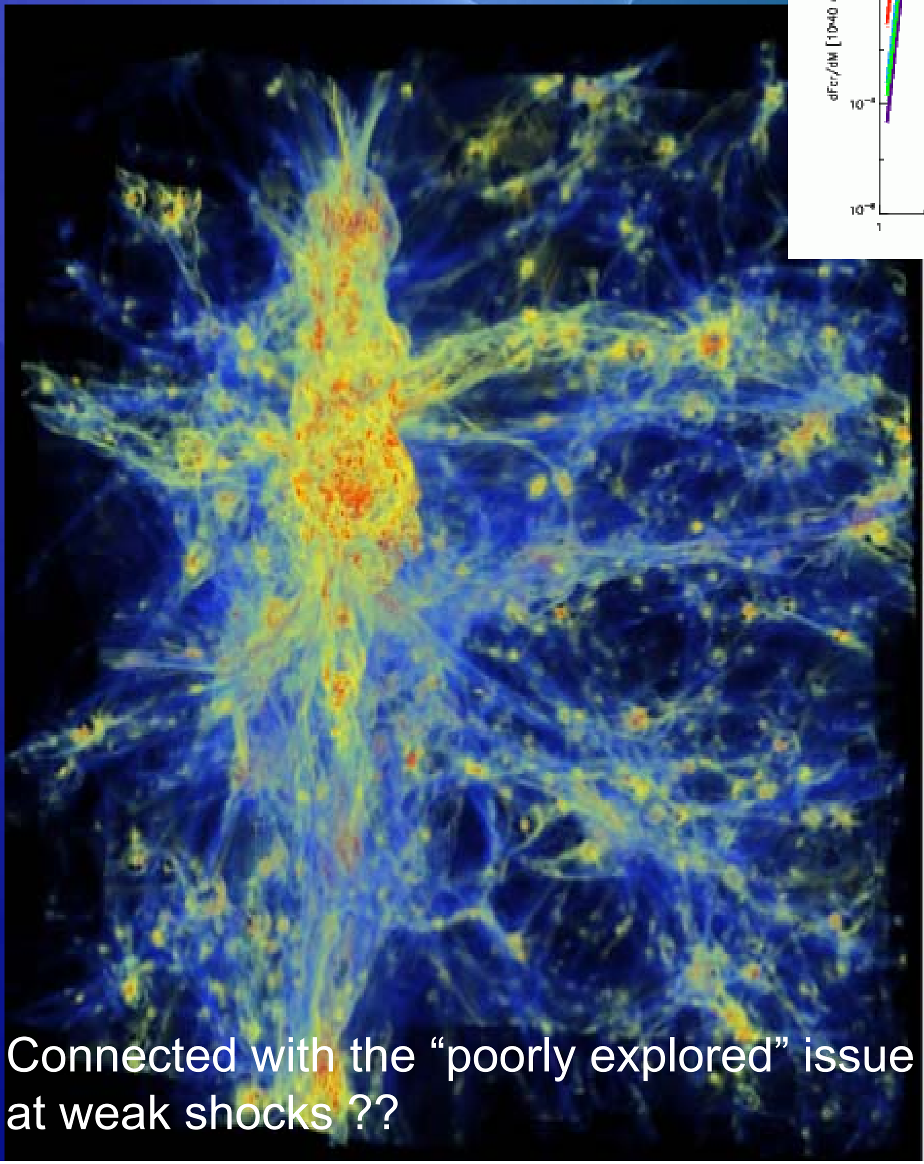
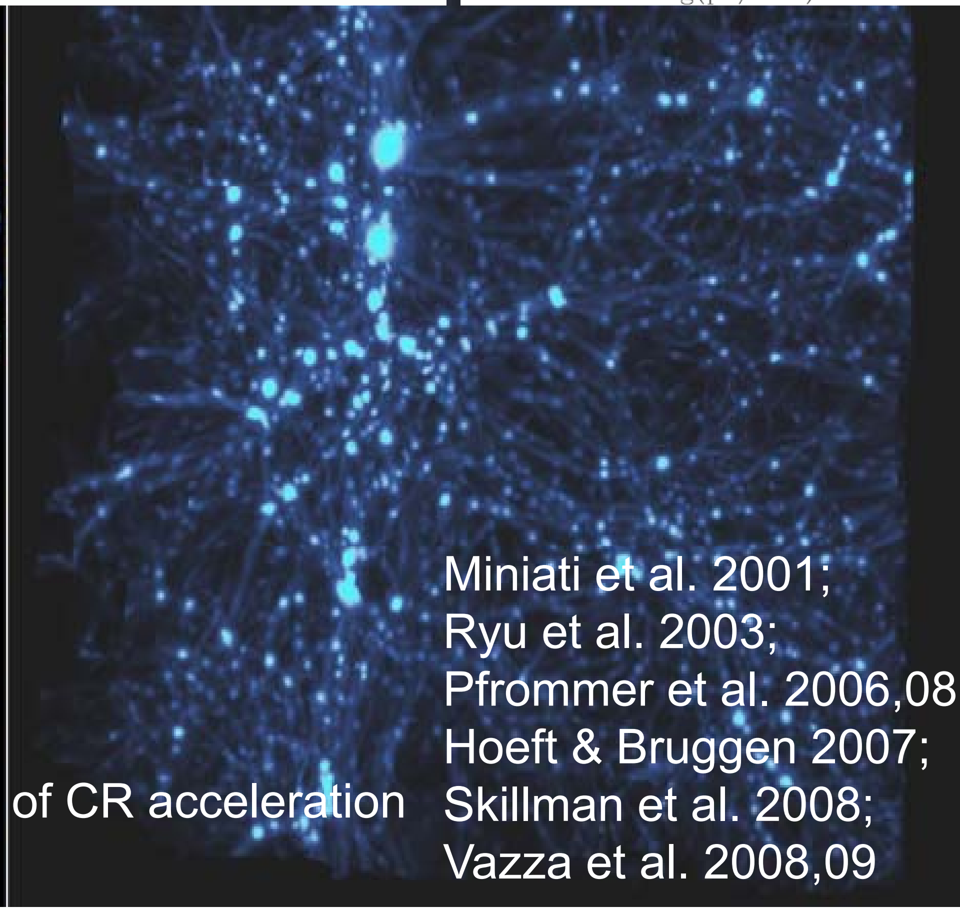
Shocks in Clusters









Connected with the “poorly explored” issue of CR acceleration at weak shocks ??

Miniati et al. 2001;
Ryu et al. 2003;
Pfrommer et al. 2006,08;
Hoeft & Bruggen 2007;
Skillman et al. 2008;
Vazza et al. 2008,09

Conclusions

- **A fraction of the energy dissipated during cluster formation is channelled into non thermal components (shocks + turbulence)**

- **Mpc-scale diffuse radio sources suggest that turbulence plays a role ("gentle" acceleration mechanims..)**
  - we are probably **missing the bulk** of these Halos !
  - calculations suggest that LOFAR will detect several 100+ of these Radio Halos: **test of turbulent models**

- **Non-thermal cluster emission consists of transient (turbulnce+shocks) and long-living component**
  - Cluster **radio-bimodality is consistent** with this picture
  - γ-ray observations are now **contributing to test models**

- **CR protons "apparently" do not contribute to +few % of the energy of the ICM (Mpc-scale)**
  - Probing CR acceleration at **weak shocks** ?