Particle acceleration in Galaxy Clusters & connection with cluster mergers

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Outline

- Galaxy Clusters & non thermal phenomena

- Physics & dynamics of CR in galaxy clusters

- CR protons (limits)

- CR electrons : Radio Halos (turbulence?)

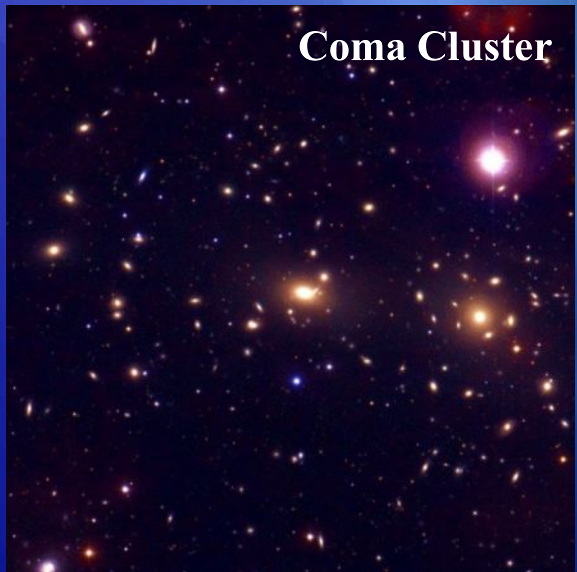
- General Picture of non-thermal clusters
  (calculations of broad band non thermal emission)

- Expectations : … steep spectrum diffuse radio
  emission & LOFAR+LWA

Clusters of galaxies:

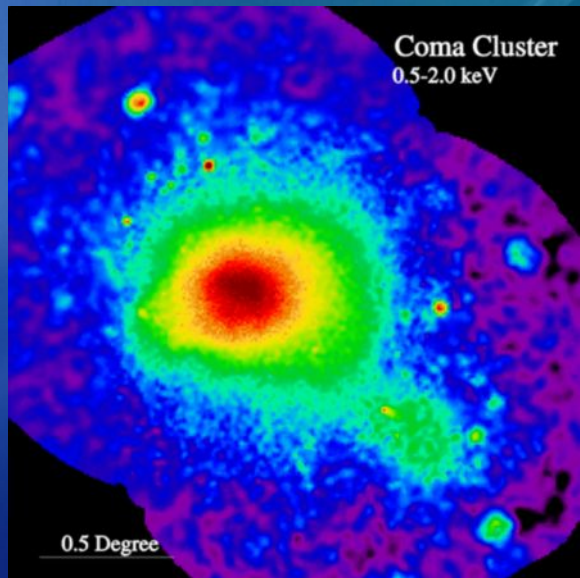
- Galaxy Clusters are the largest concetrations of matter in our Universe.
- They form by accretion & mergers between sub-units
- They extend over **2-4 Mpc** and have a total mass of **~ 10^{14}-10^{15} M_{sol}**
- They contain thousands of galaxies, hot diffuse gas and expecially dark matter

Optical



stars + dark matter

X- ray



hot diffuse gas

Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

Dark Matter 70%

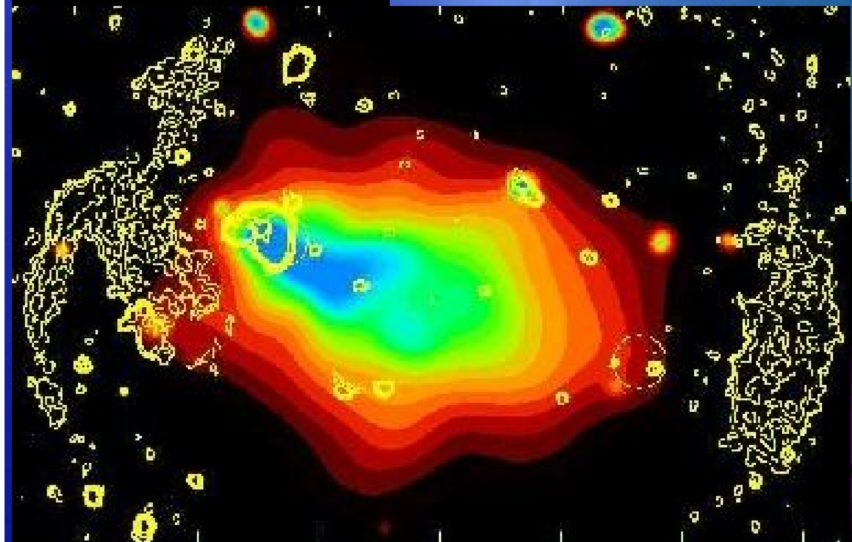
Non-thermal components

& cluster mergers

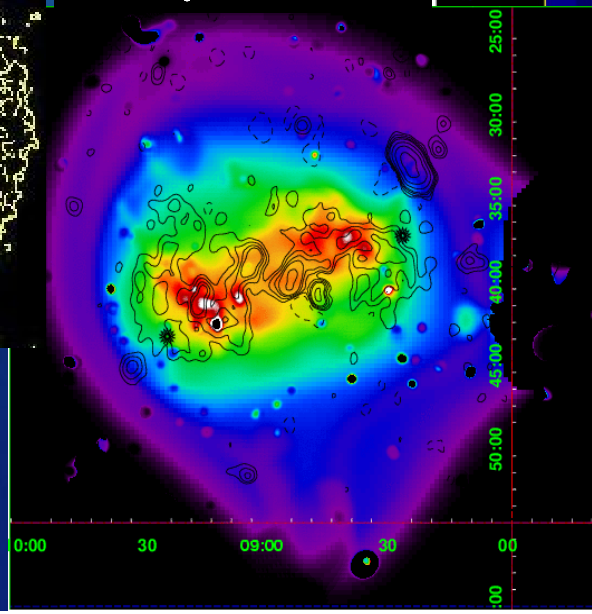
Radio Halos and **Radio Relics** are only found in **non-relaxed** clusters with **recent /ongoing cluster mergers** (e.g. Buote 2001)

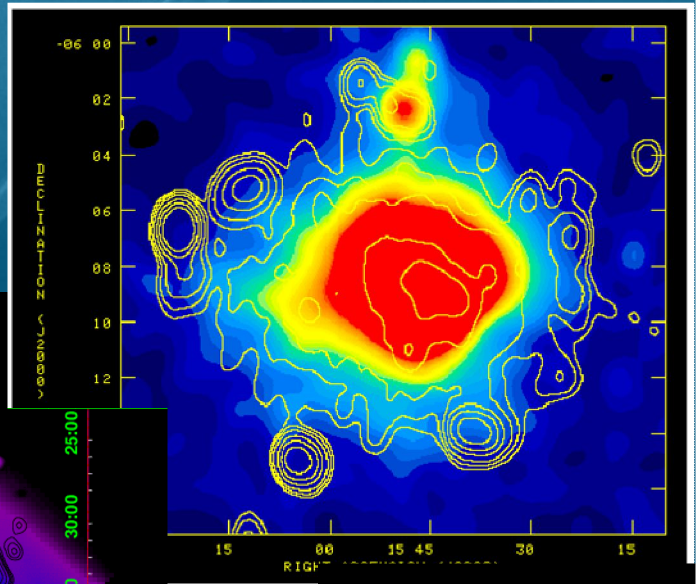
Mergings are the most **energetic events** in the Universe ≈ **few 10^{63}ergs** in a **crossing time!**

Abell 3376
Bagchi et al. 2005



Abell 754
Henry et al. 2004

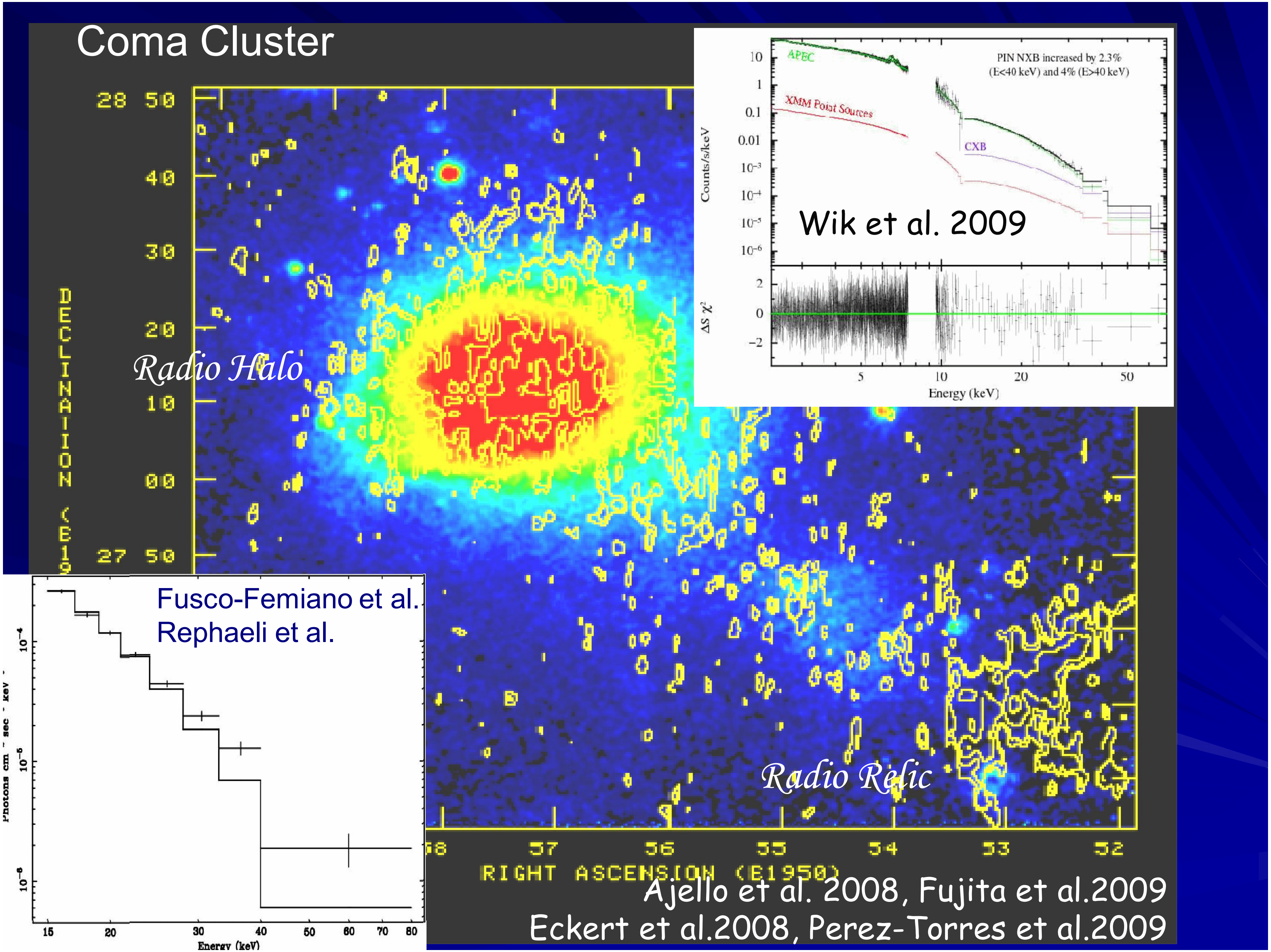




Abell 2163
Feretti et al. 2001

Radio Relics

Radio Halos



Coma Cluster
28 50
40
30
20
10
00
27 50
DECLINATION (B19
Radio Halo
Radio Relic
58
57
56
55
54
53
52
RIGHT ASCENSION (B1950)
Ajello et al. 2008, Fujita et al.2009
Eckert et al.2008, Perez-Torres et al.2009
Wik et al. 2009
APEC
XMM Point Sources
CXB
PIN NXB increased by 2.3%
(E<40 keV) and 4% (E>40 keV)
Counts/s/keV
ΔS χ²
Energy (keV)
Fusco-Femiano et al.
Rephaeli et al.
Photons cm⁻² sec⁻¹ keV⁻¹
Energy (keV)

Injection & Dynamics of Cosmic Rays in GC

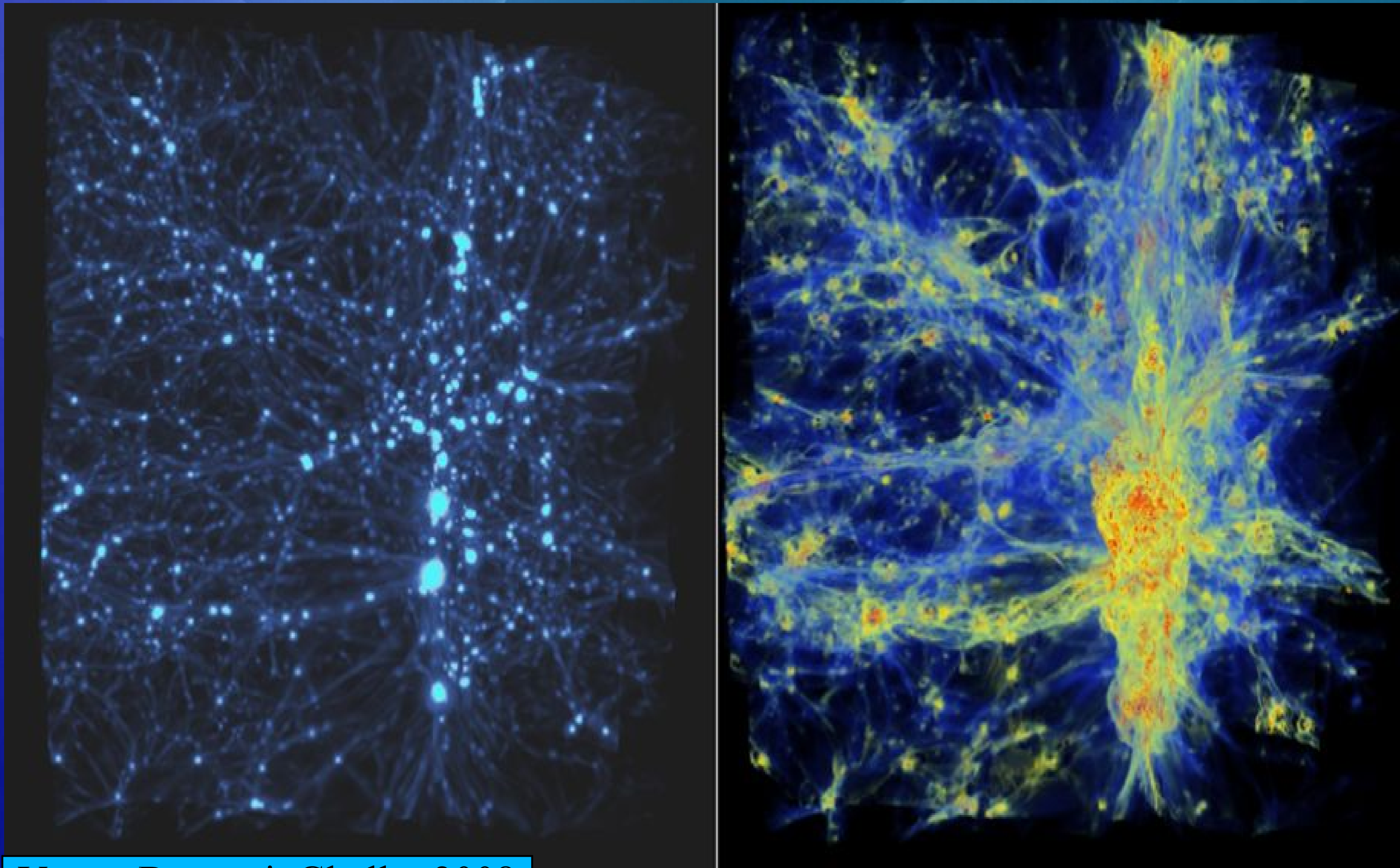
Cosmological Shocks

(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

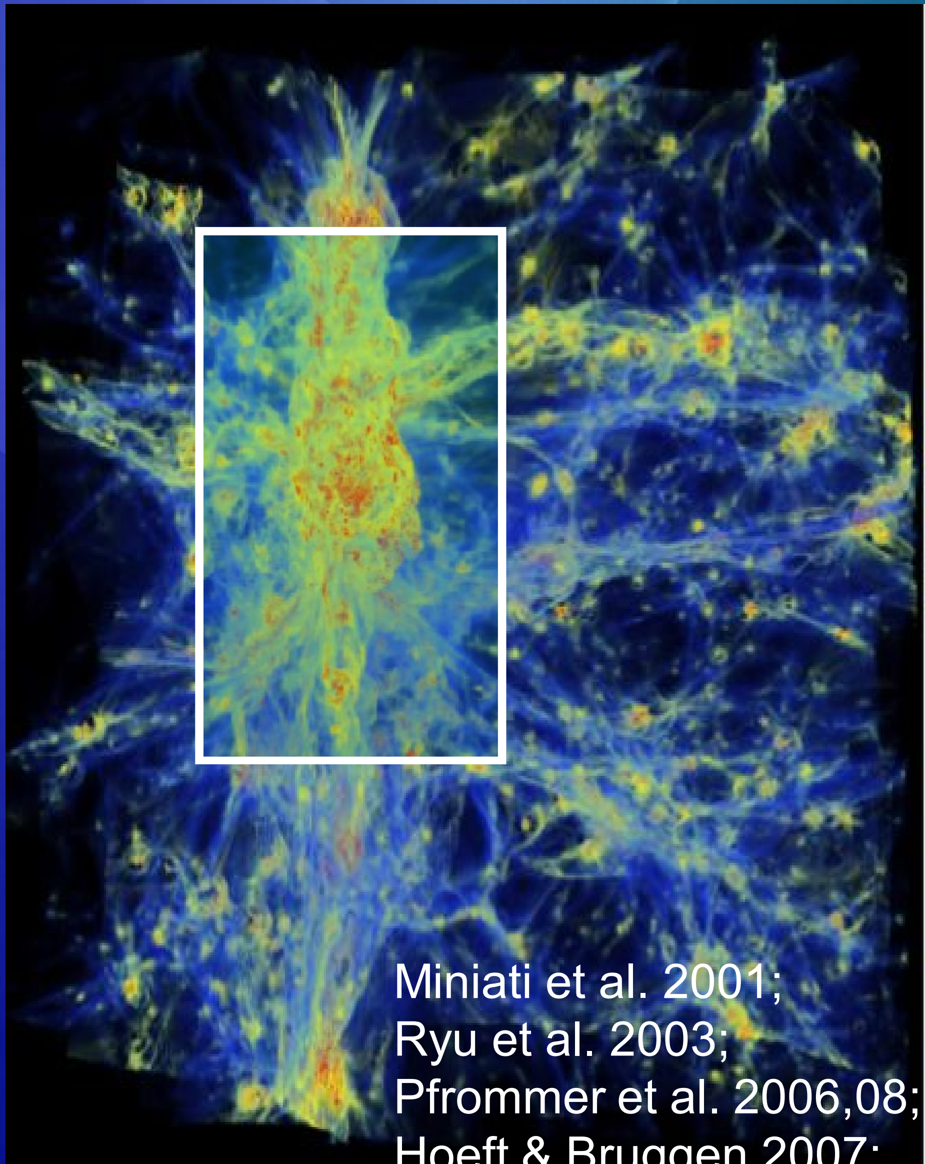
(e.g. Ensslin et al. 1998; Voelk & Atoyan 1999)

Simulations : Shocks in Galaxy Clusters

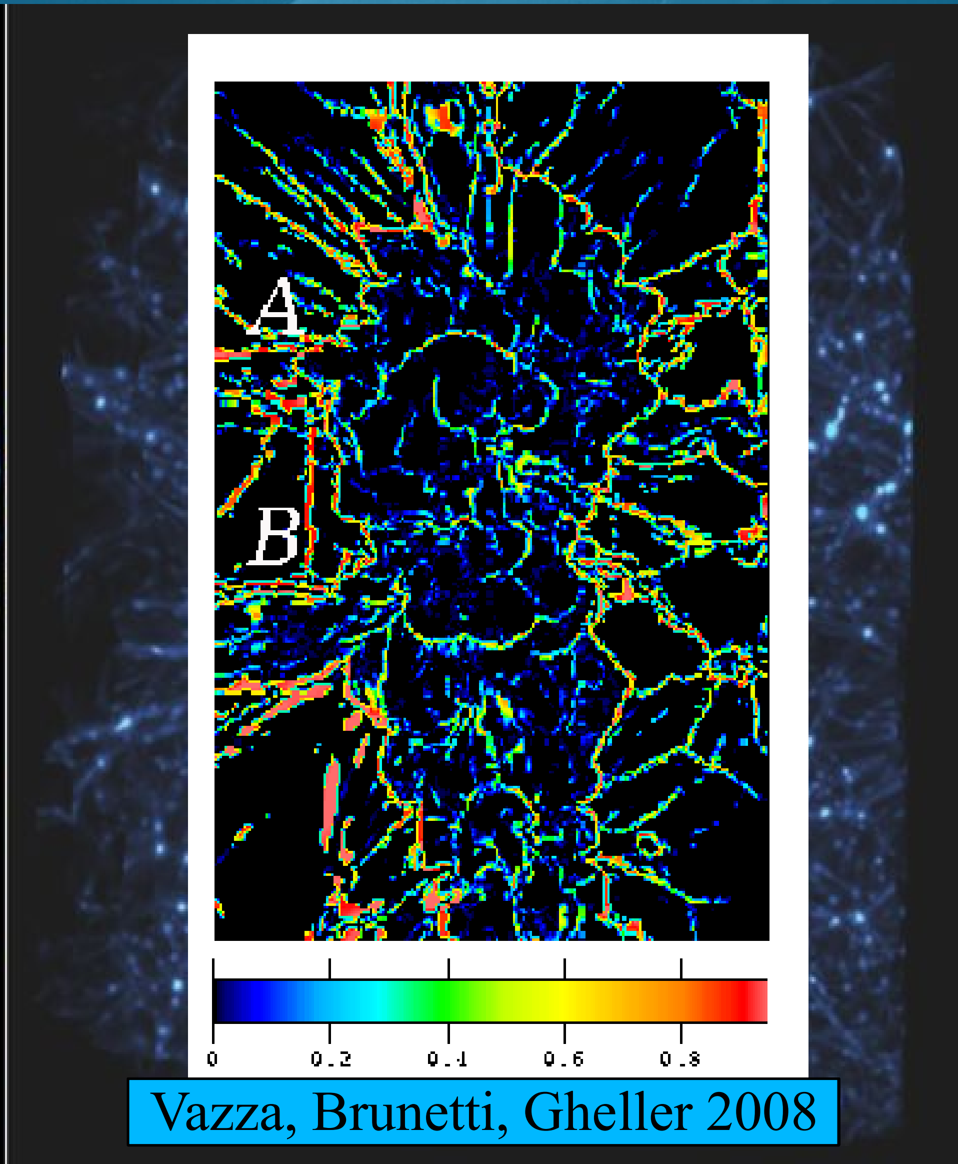


Vazza, Brunetti, Gheller 2008

Shocks in Galaxy Clusters



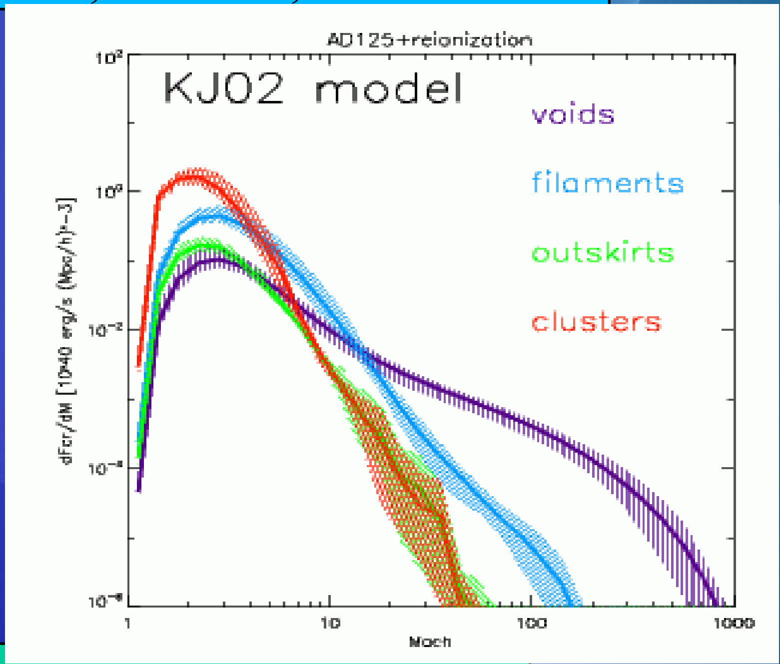
Miniati et al. 2001;
Ryu et al. 2003;
Pfrommer et al. 2006,08;
Hoeft & Bruggen 2007;
Skillman et al. 2008



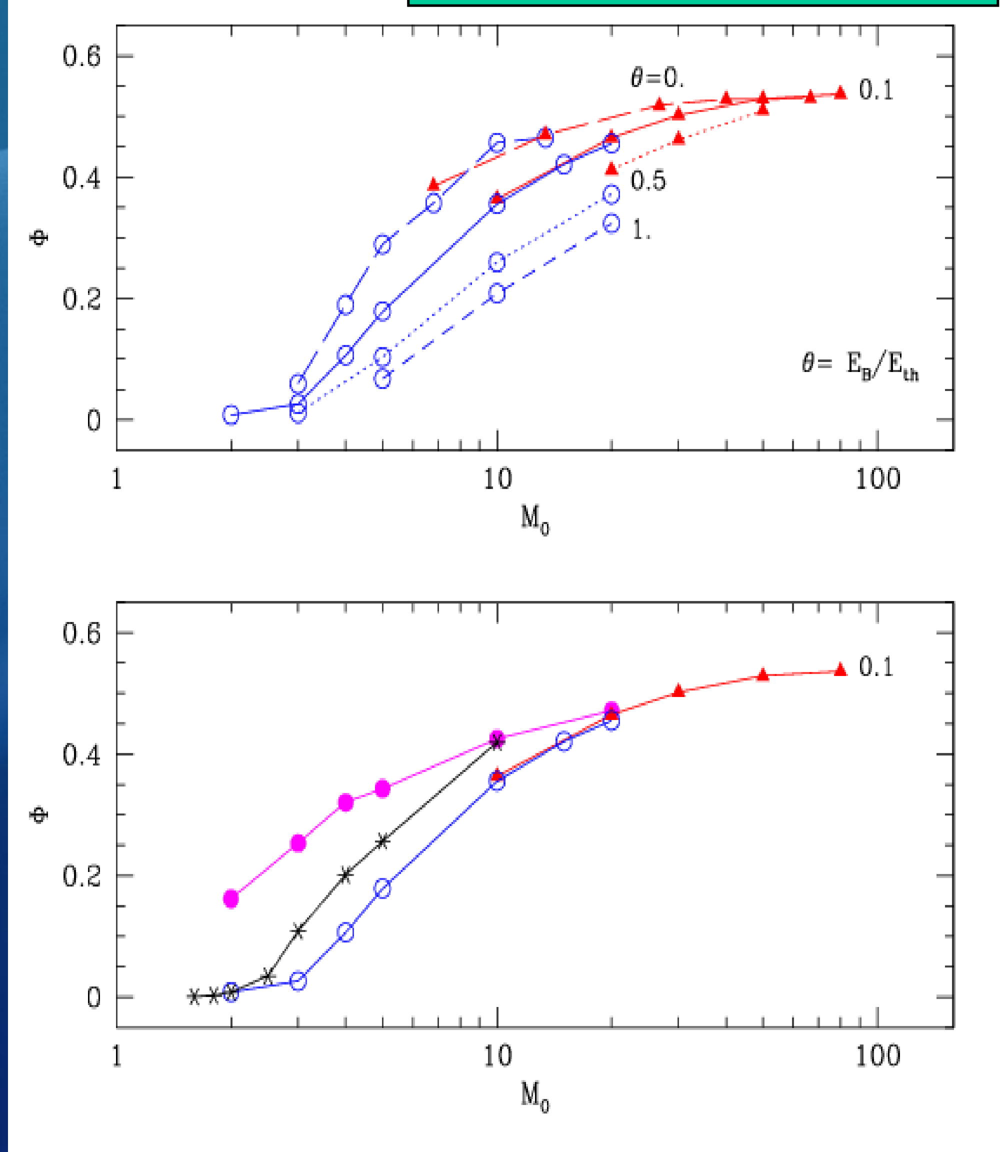
Vazza, Brunetti, Gheller 2008

Uncertainties in CR acceleration

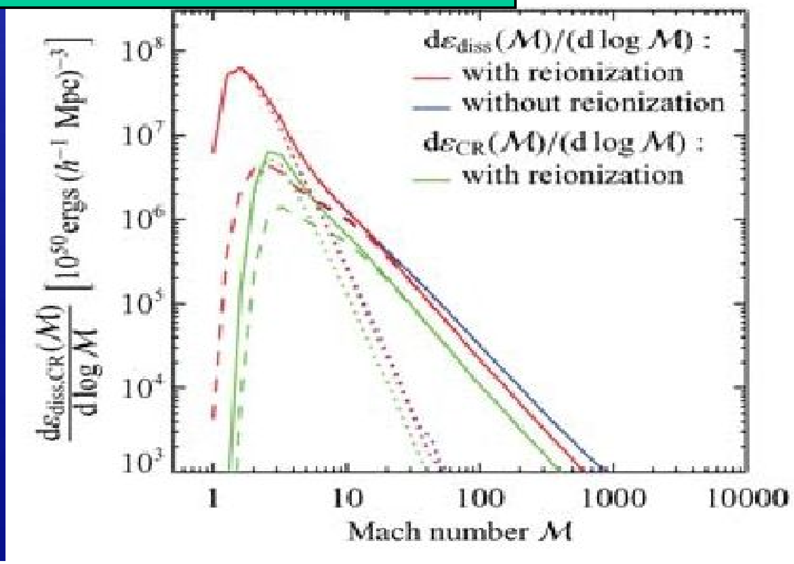
Vazza, Brunetti, Gheller 2008



Kang & Jones 2007



Pfrommer et al. 2008



Uncertainties in CR acceleration

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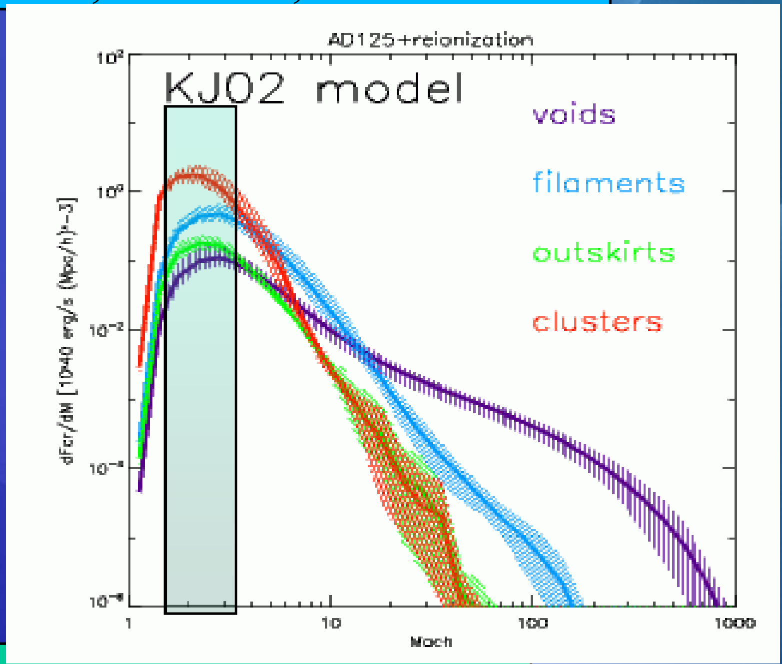

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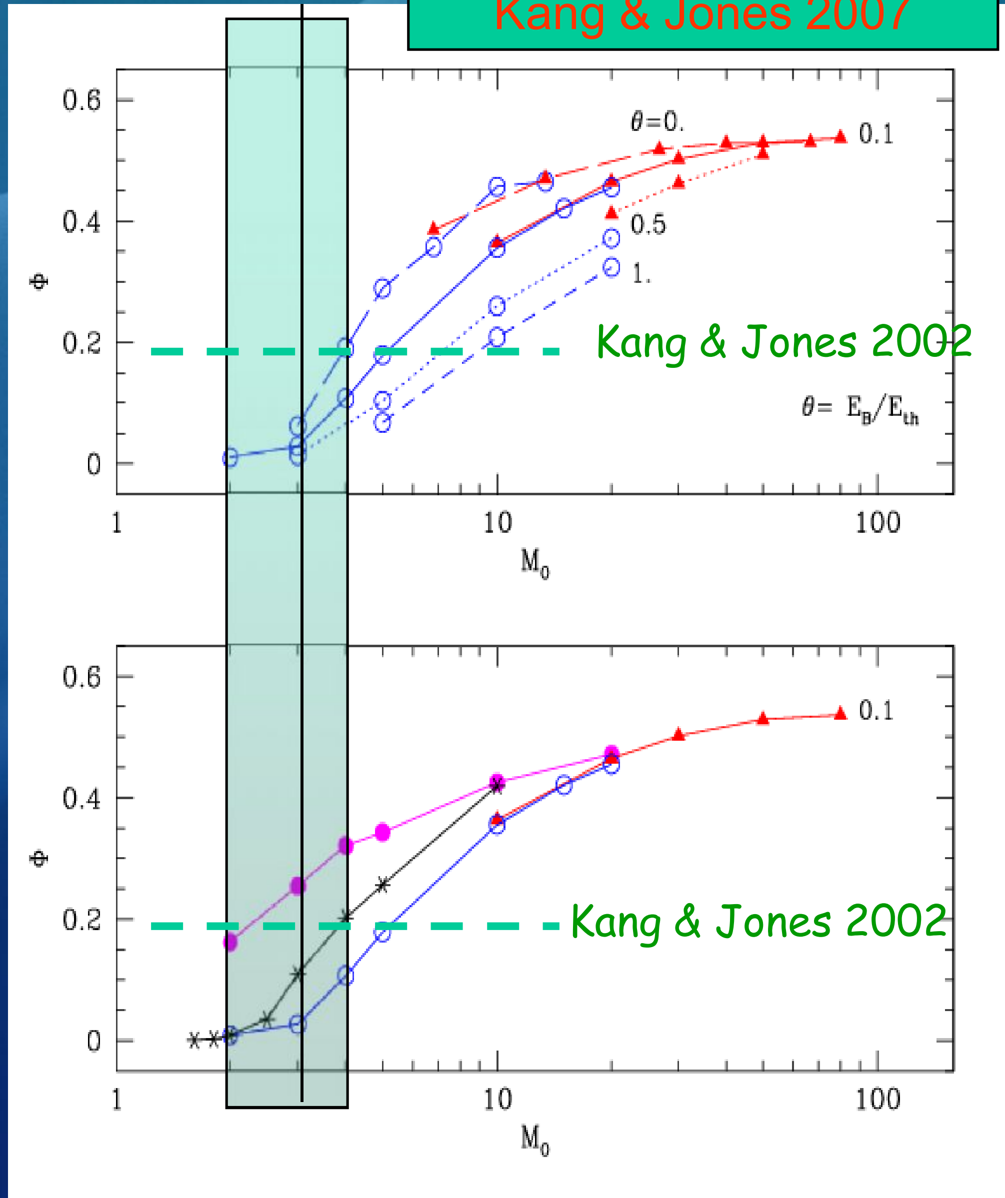
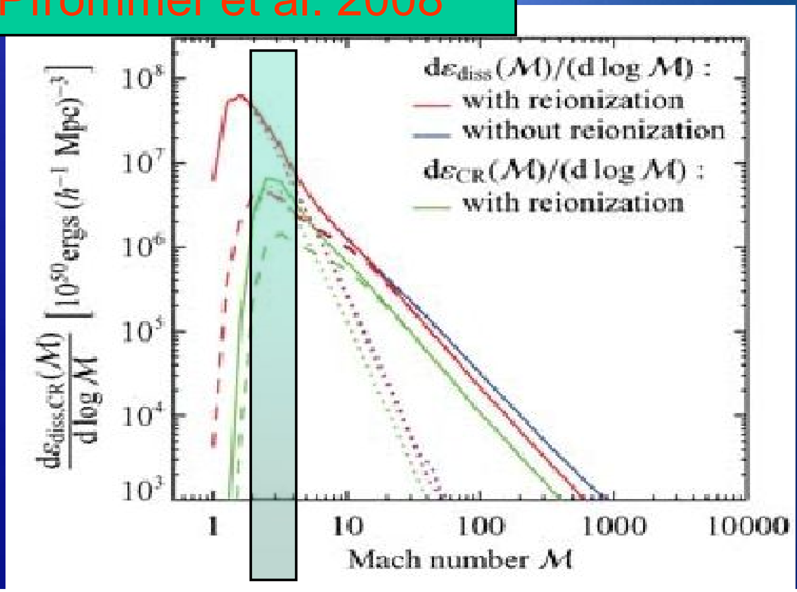
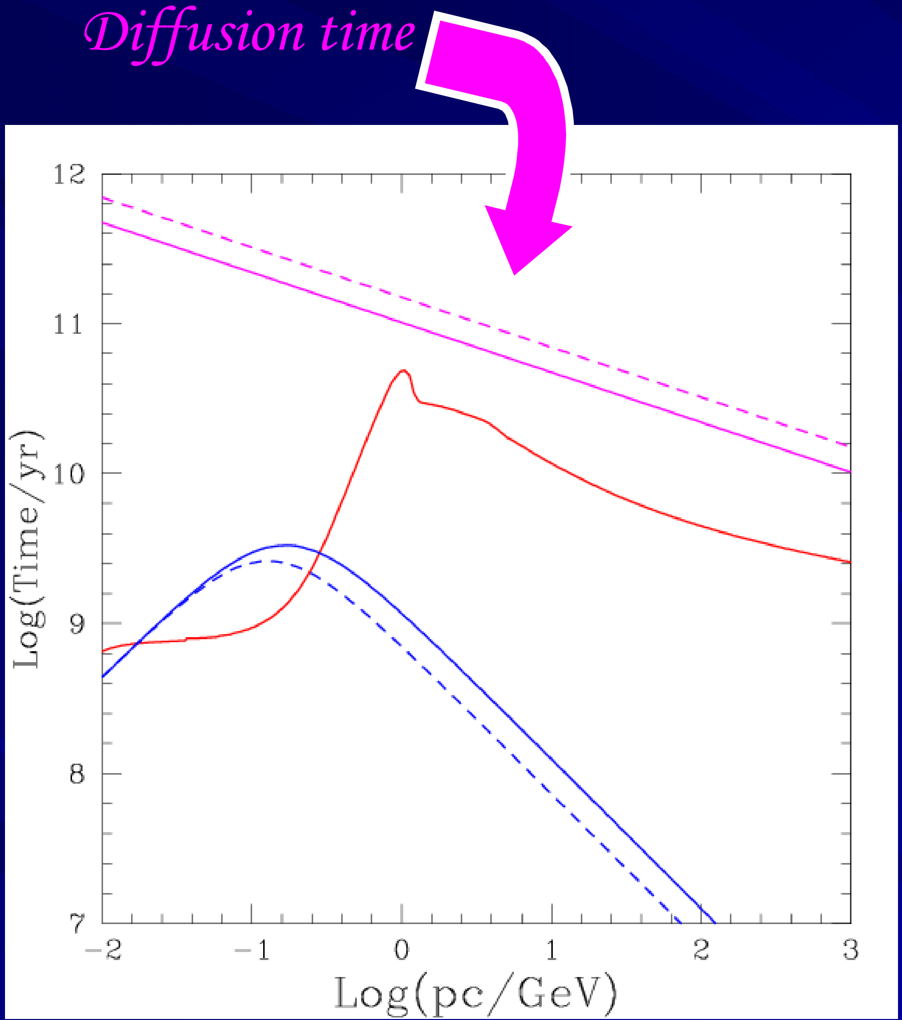


Pfrommer et al. 2008



Cosmic Ray Physics & Confinment



Blasi, Gabici, Brunetti 2007

- CR protons are ***long living*** particles and are ***confined***
  (Voelk et al 1996;
  Berezinsky, Blasi, Ptuskin 1997)

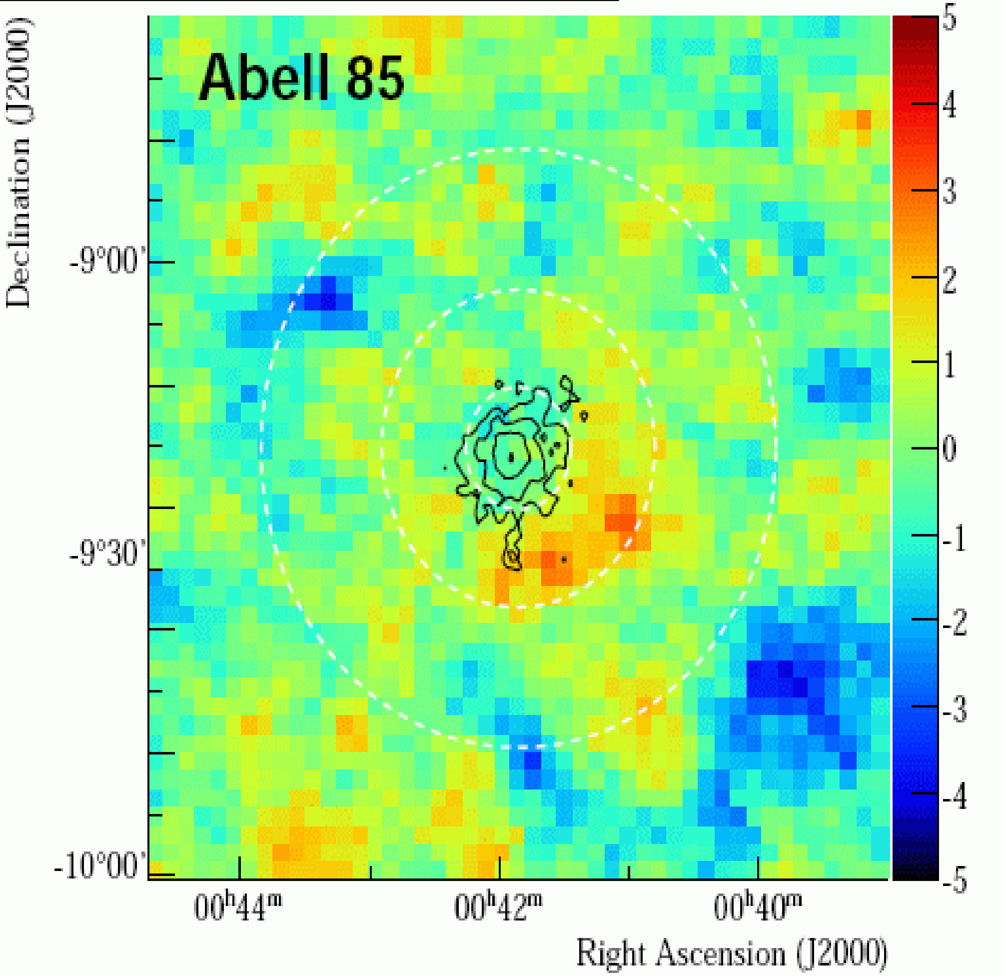
- CR electrons are ***short living*** particles and ***accumulated*** at $\gamma \approx 100\text{-}300$
  (e.g., Sarazin 1999)

Secondary Particles in the IGM

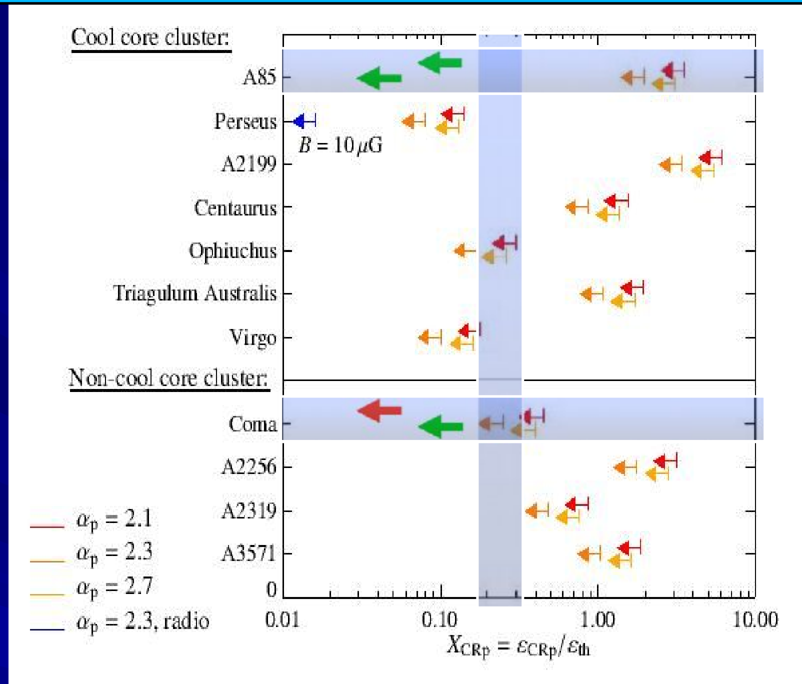
Dennison 1980; Blasi & Colafrancesco 1999; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Wolfe & Melia 2007; Brunetti 2008

CRp: 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%

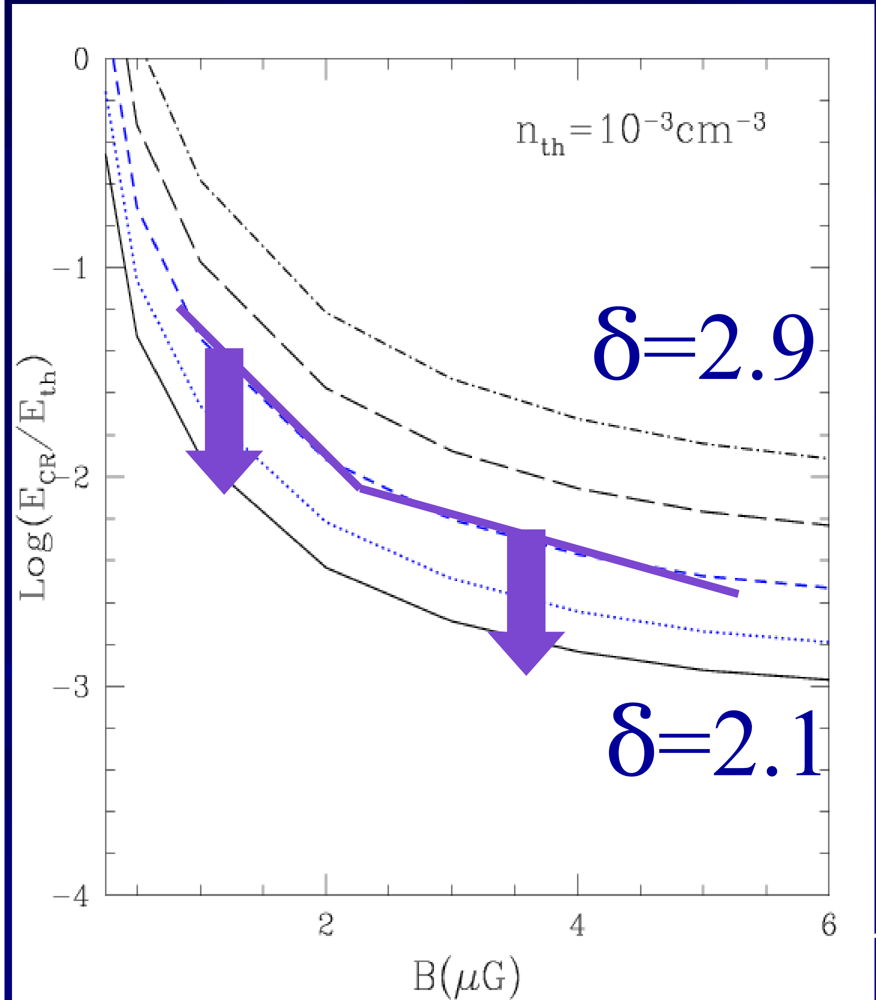
VERITAS (Perkins +al. 2008)

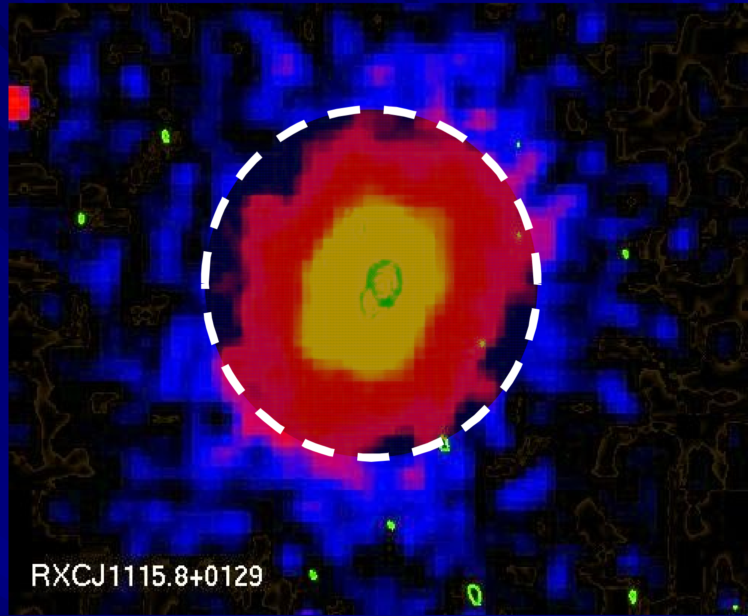
Coma : Ecr/Eth < 5% (hard spectra)

CRp: limits from Radio

Brunetti +al. 2007

Making use of clusters in the GMRT survey





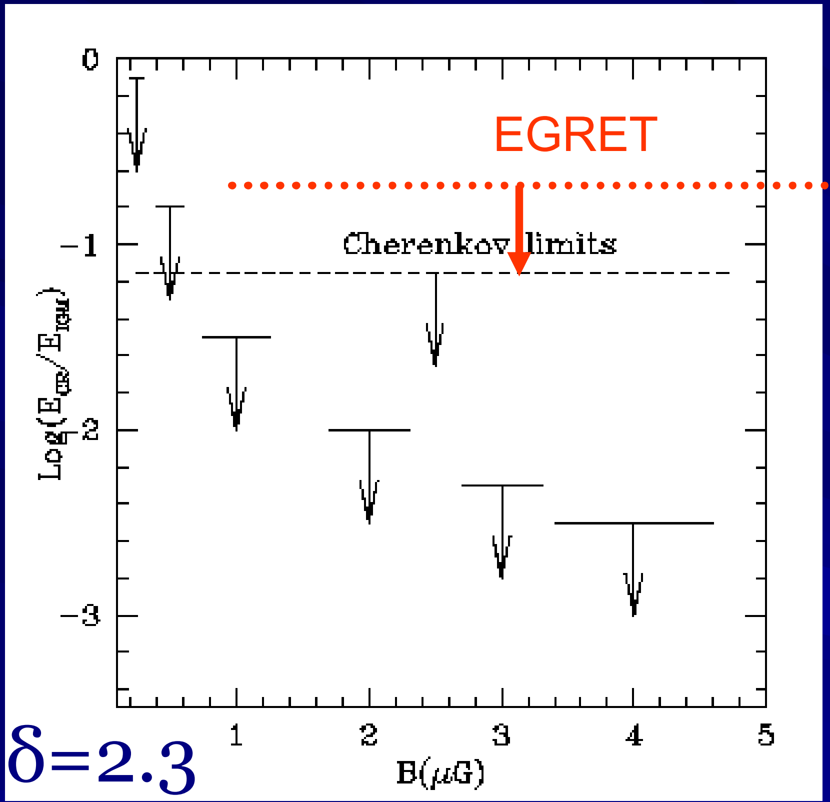
Assuming that secondary particles are injected in the IGM, their synchrotron emission should be smaller than upper limits to the diffuse radio emission.

limit on : B , E_{CRp} , δ

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

Limits for CR protons

Brunetti, Blasi, Cassano, Gabici 2008



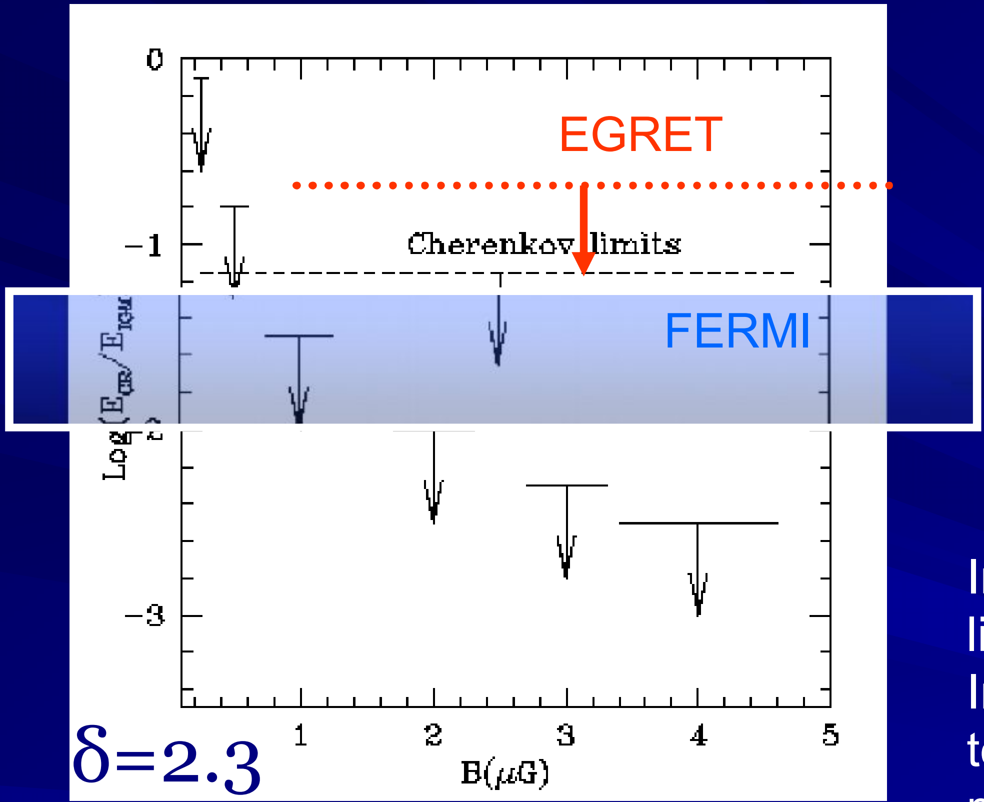
Reimer et al. 2003
Reimer et al. 2004
Pfrommer & Ensslin 2004
Perkins et al. 2006
Brunetti et al. 2007
Brunetti et al. 2008
Perkins et al. 2008
Aharonian et al. 2008

In case of flat proton spectrum present limits constrain E_{CR}< few % Ethermal

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

Limits for CR protons

Brunetti, Blasi, Cassano, Gabici 2008



Reimer et al. 2003
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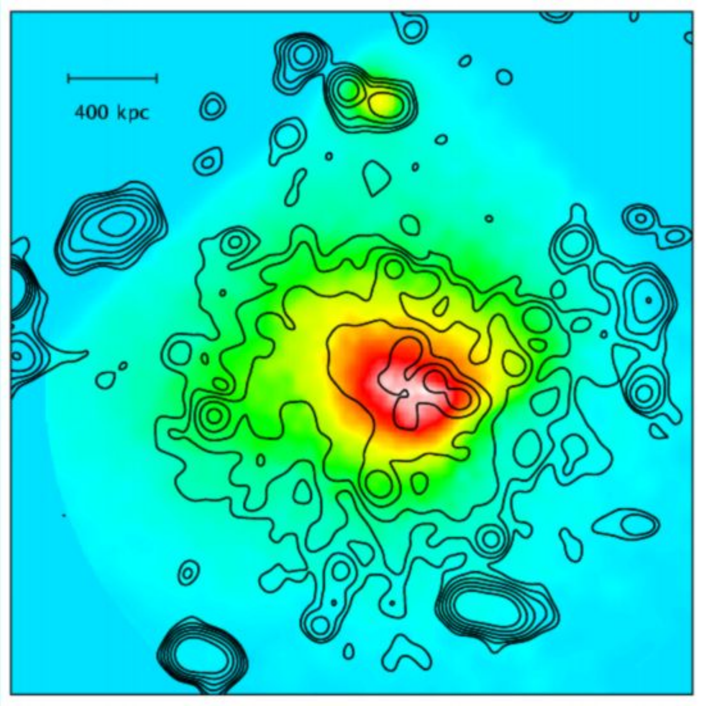
Perkins et al. 2006
Brunetti et al. 2007
Brunetti et al. 2008
Perkins et al. 2008
Aharonian et al. 2008

In case of flat proton spectrum present limits constrain E_{CR}< few % Ethermal.
In case of flat spectra FERMI is expected to step into the region of the Radio limits, providing better constraints in case of steeper spectra.

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

Radio Halos as LABs for particle acceleration



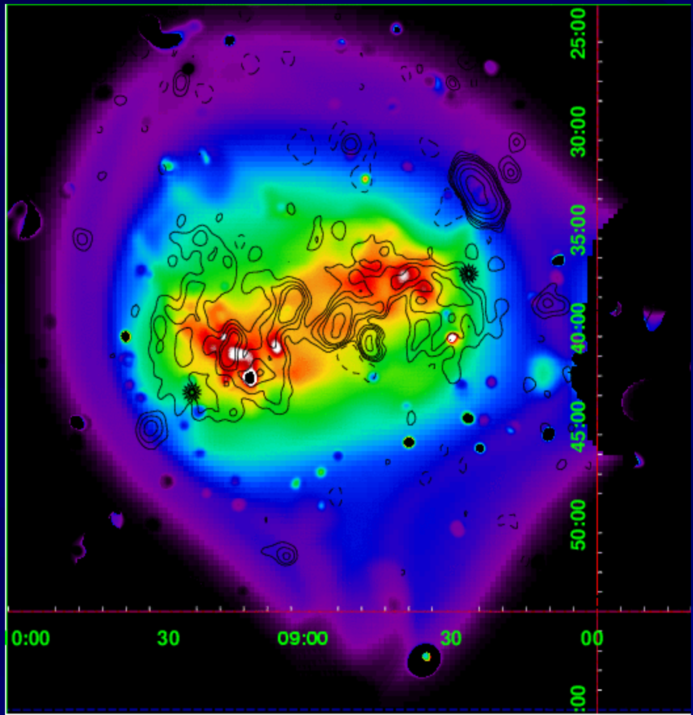
- **GeV electrons on Mpc scales**
- **μG magnetic fields on Mpc scales**
- T_{diff} (~10^{10} yr) >> T_{cool} (~10^{8} yr)

(Jaffe 1977)

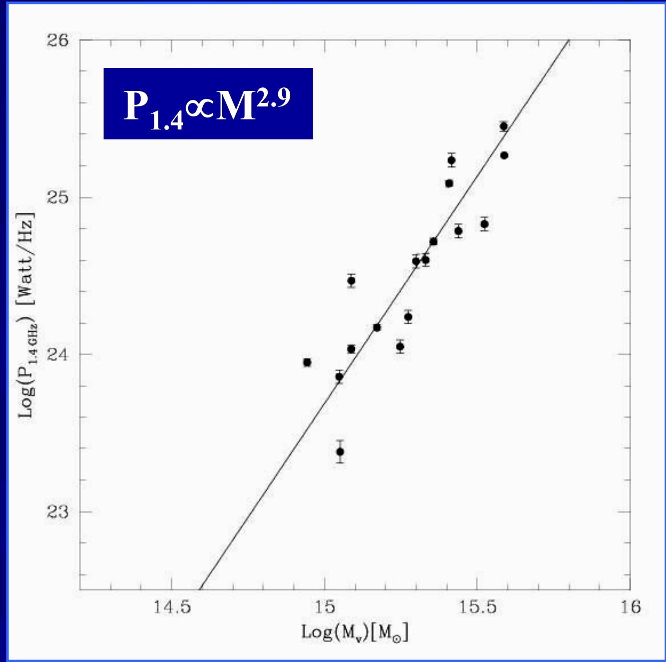
Looking at new physical processes

Labs to study GC as particle accelerators

Radio Halos and cluster-cluster mergers



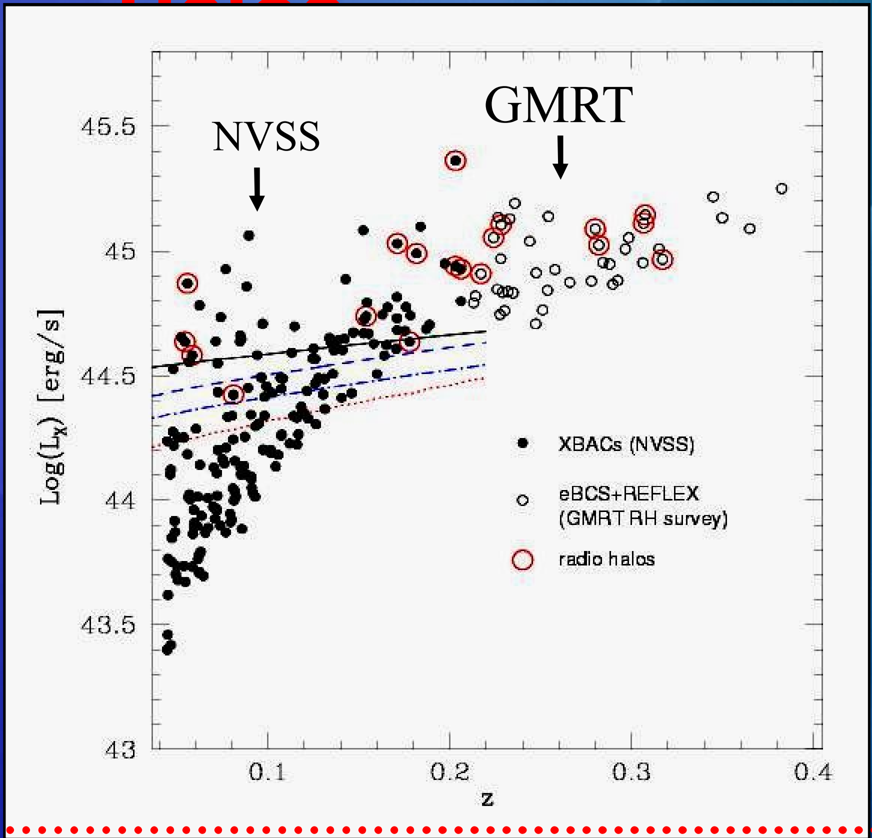
Connection with cluster mergers (e.g. *Buote 2001, Schuecher et al. 2001, Markevitch et al. 2002, Boschin et al. 2003 Govoni et al. 2004*)



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 ?

The complex statistics of Radio Halos

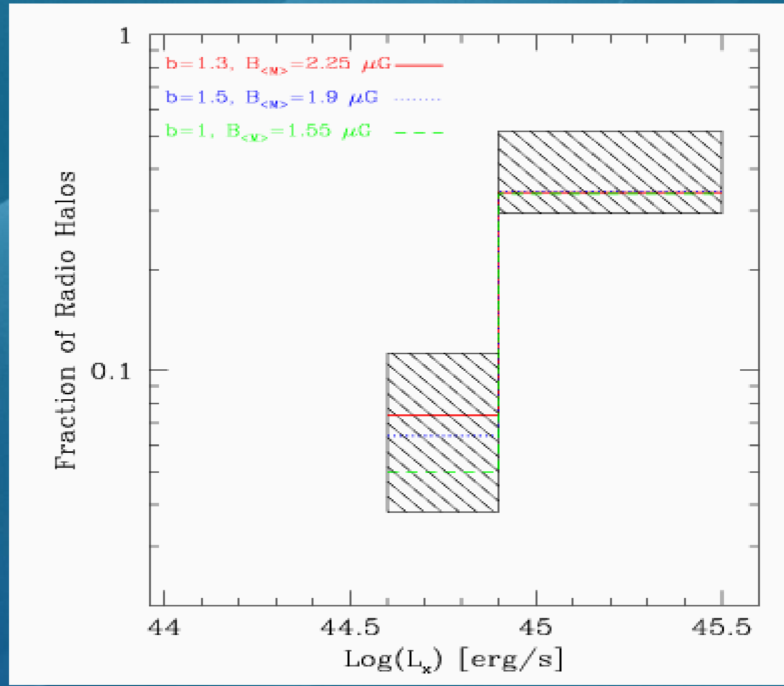


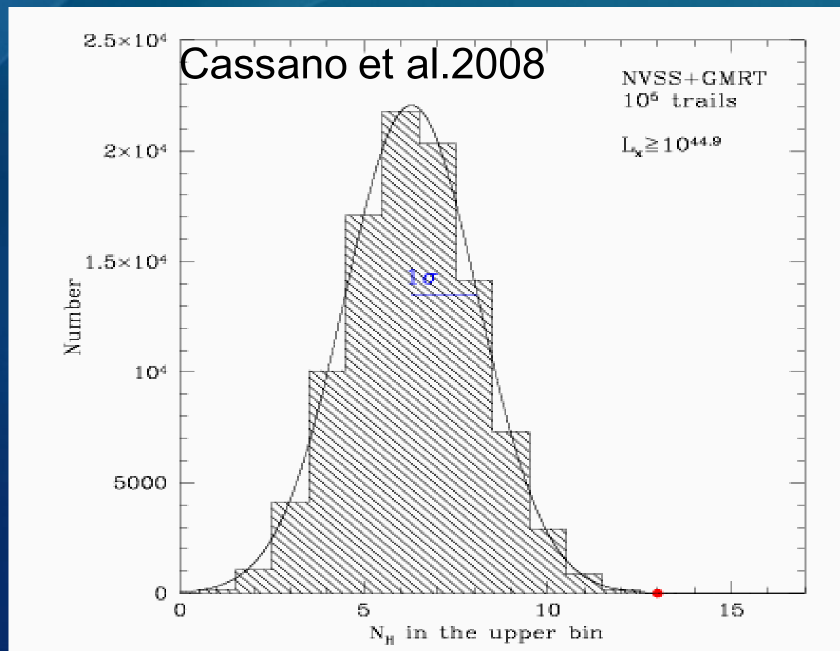
NVSS data (from *Giovannini et al. 1999)* and deep **GMRT observations.**

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)





The complex statistics of Radio Halos

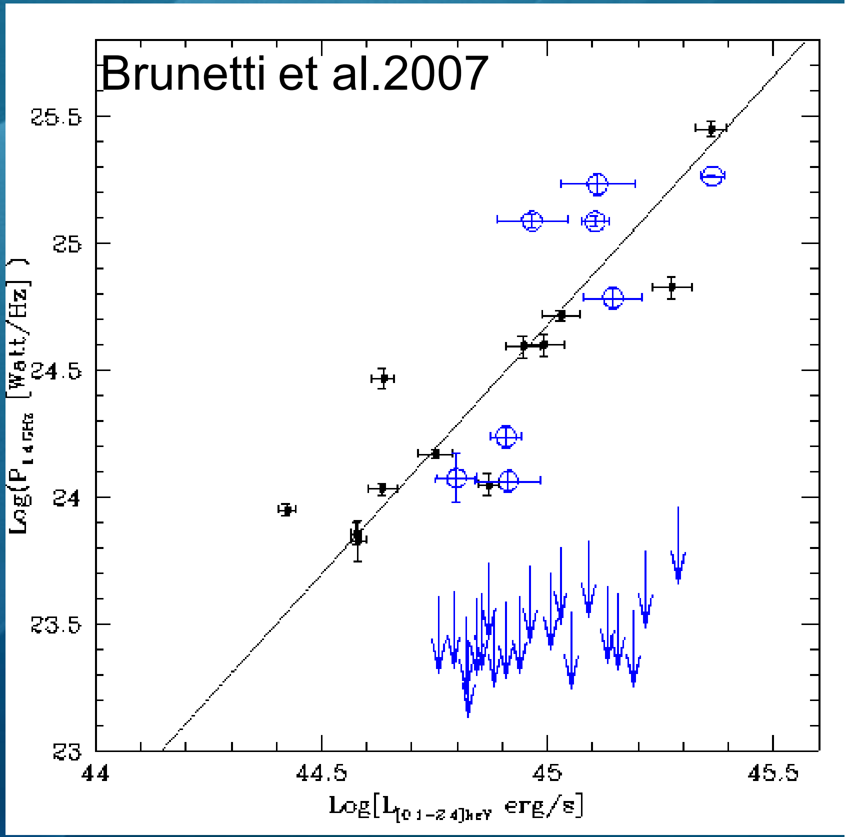
Connection with cluster mergers

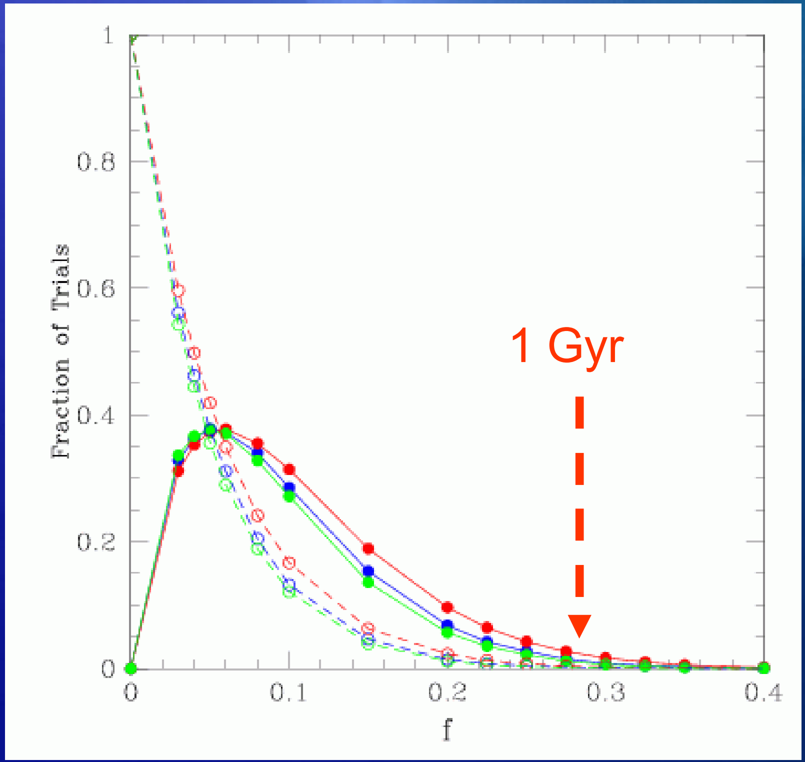
(e.g. *Schuecher et al. 2001, Markevitch et al. 2002, Boschin et al. 2003 Govoni et al. 2004*)

Which is the difference between RH-clusters and ULimits ?

Does non thermal emission evolve ?

Which time-scale ?





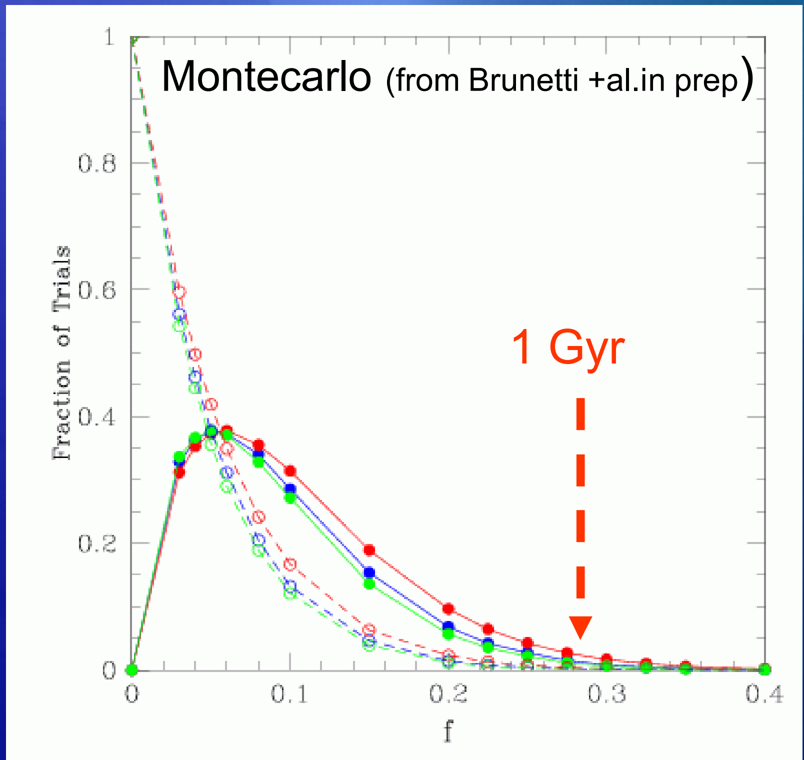
Magnetic field dissipation ?

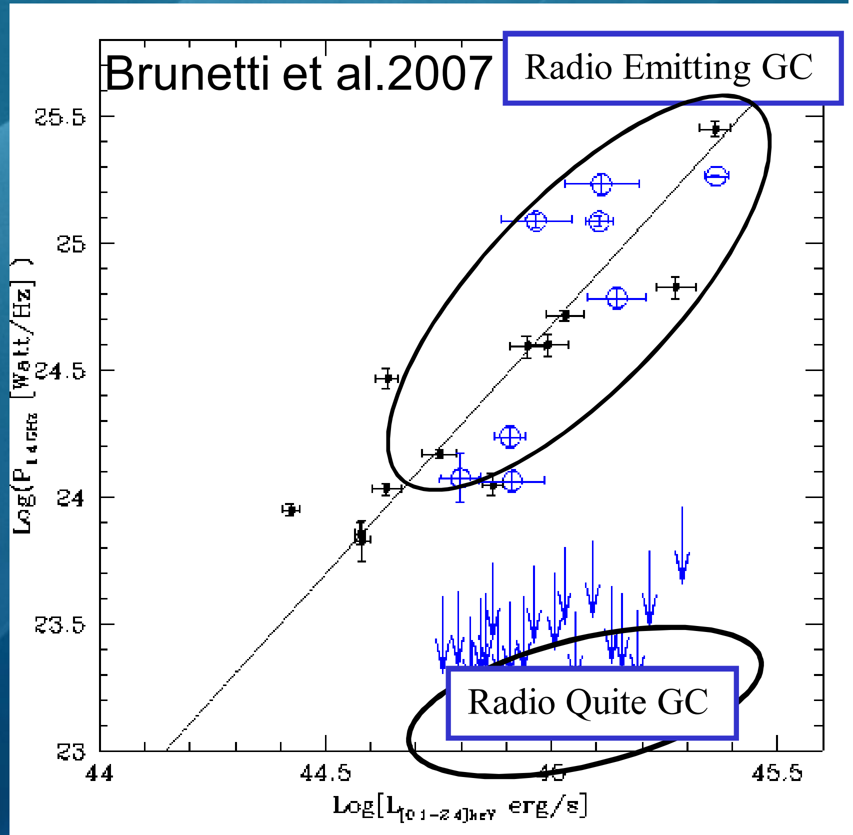
The complex statistics of Radio Halos

Connection with cluster mergers

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

Does non thermal emission evolve ?
Which time-scale ?





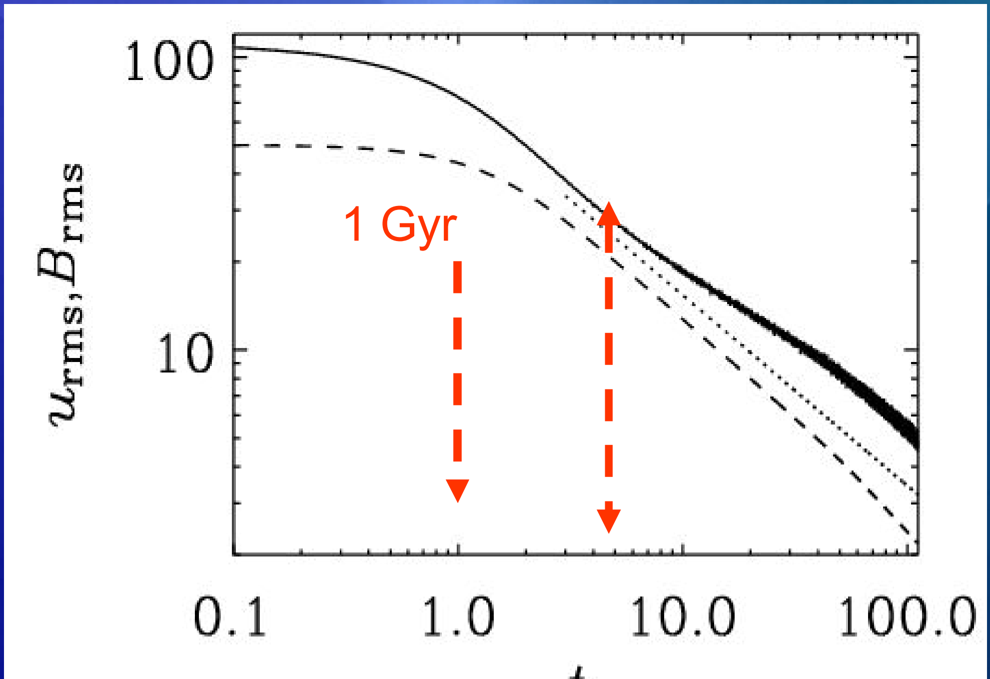
Magnetic field dissipation in the IGM must happen in << 1 Gyr

The complex statistics of Radio Halos

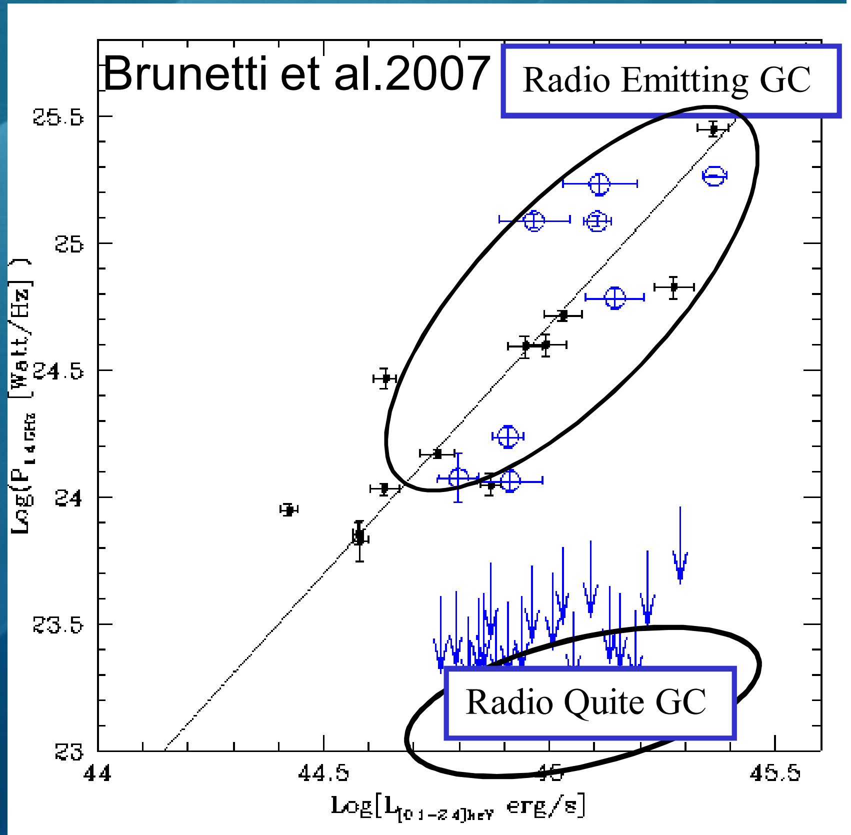
Connection with cluster mergers

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

Does non thermal emission evolve ?
Which time-scale ?

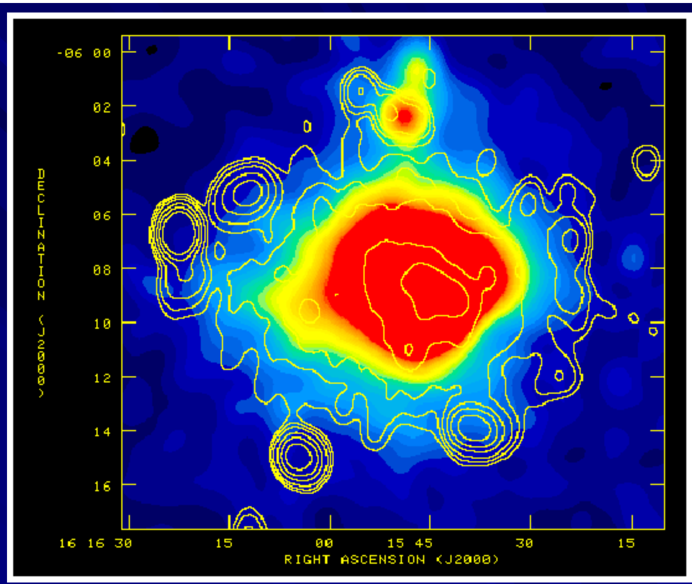


Subramanian et al.2006



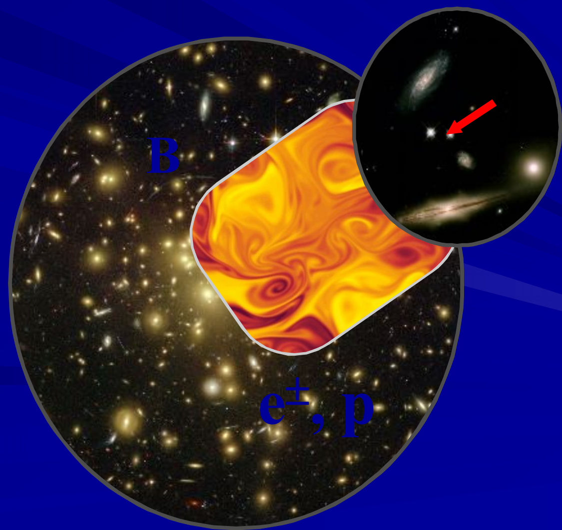
Thus the "bi-modality" is due to the evolution (acceleration and cooling) of the **emitting electrons**

Origin of the emitting electrons

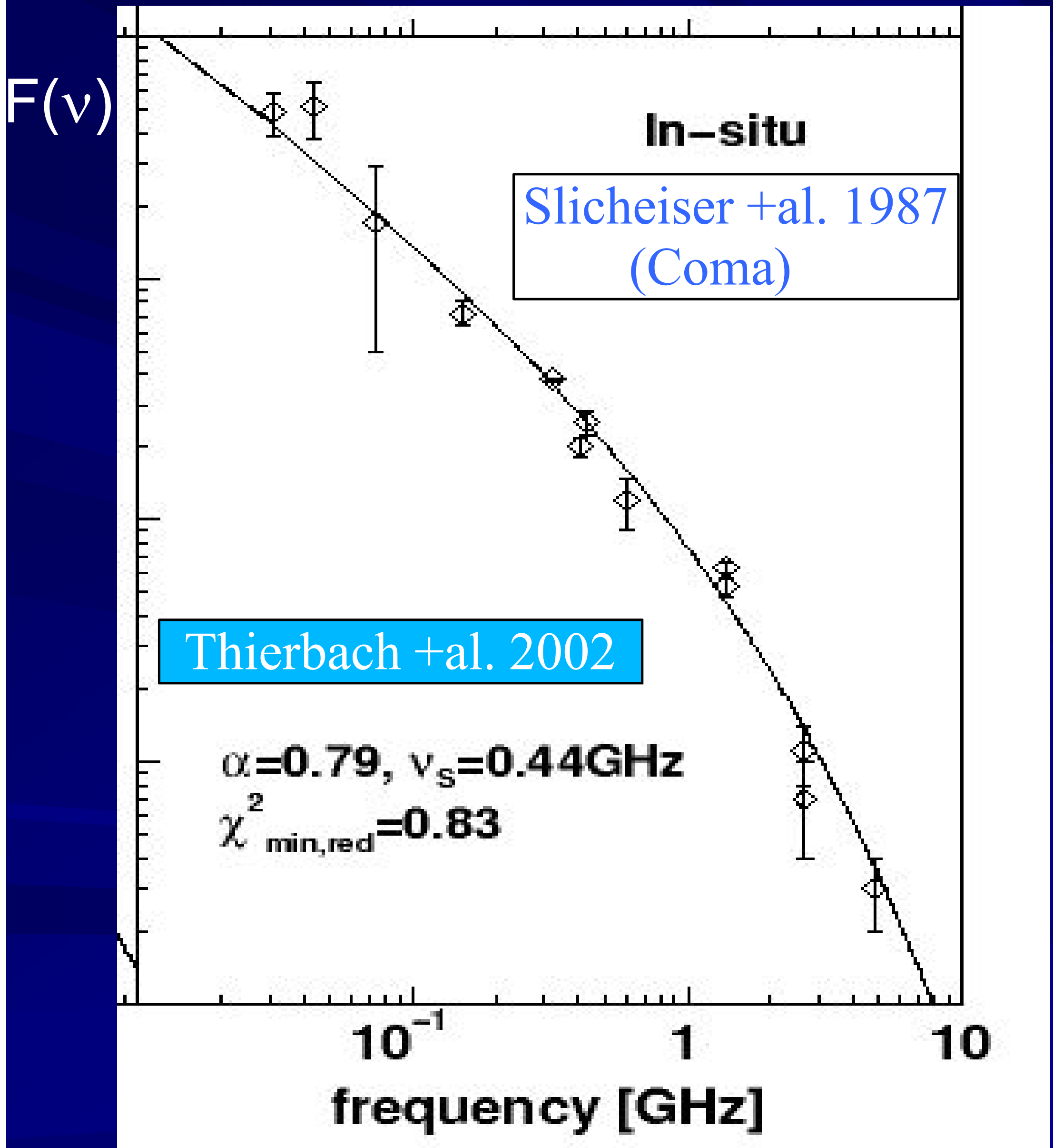


***In situ* re-acceleration of primary & secondary particles by cluster MHD turbulence** (e.g., *Brunetti et al. 2001, 2004; Petrosian 2001; Ohno et al. 2002; Fujita et al. 2003; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Brunetti & Lazarian 2007; Petrosian & Bykov 2008*)

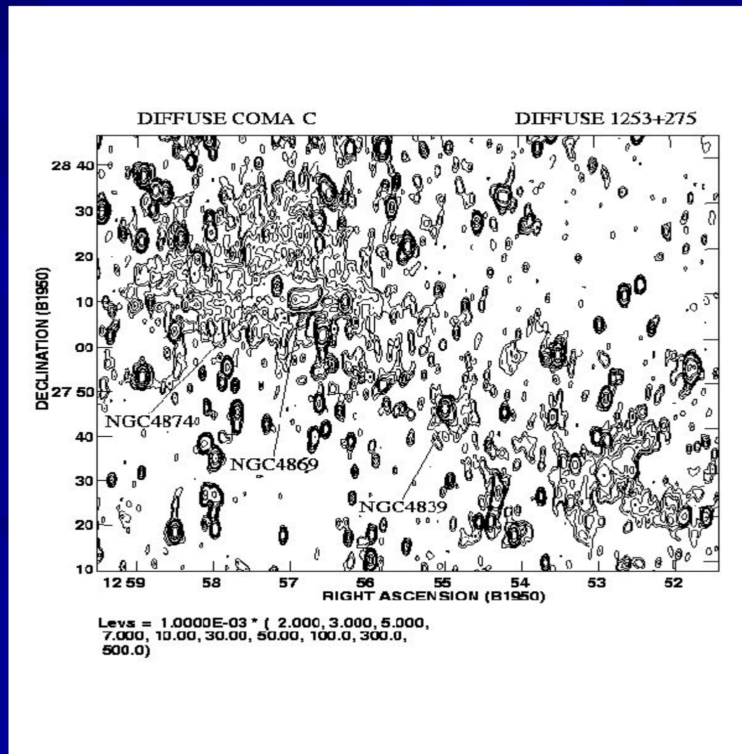
- *Radio halo – merger connection*
- *Fast dissipation (evolution) of synchrotron emission (CRe cooling)*



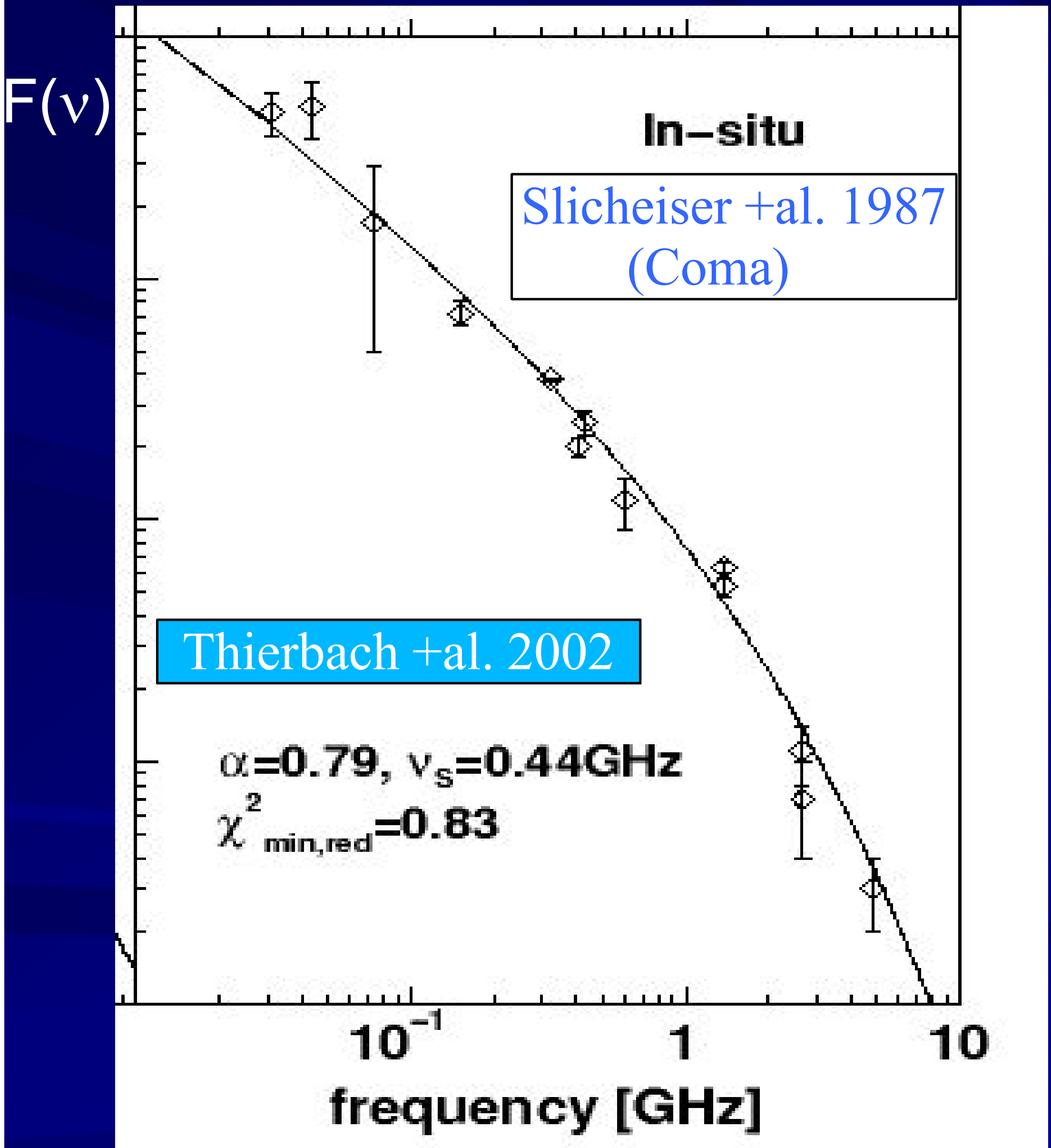
Radio Halos : are they generated by “inefficient” mechanism of CRe acceleration ?



Evidence of break in the synchrotron spectrum

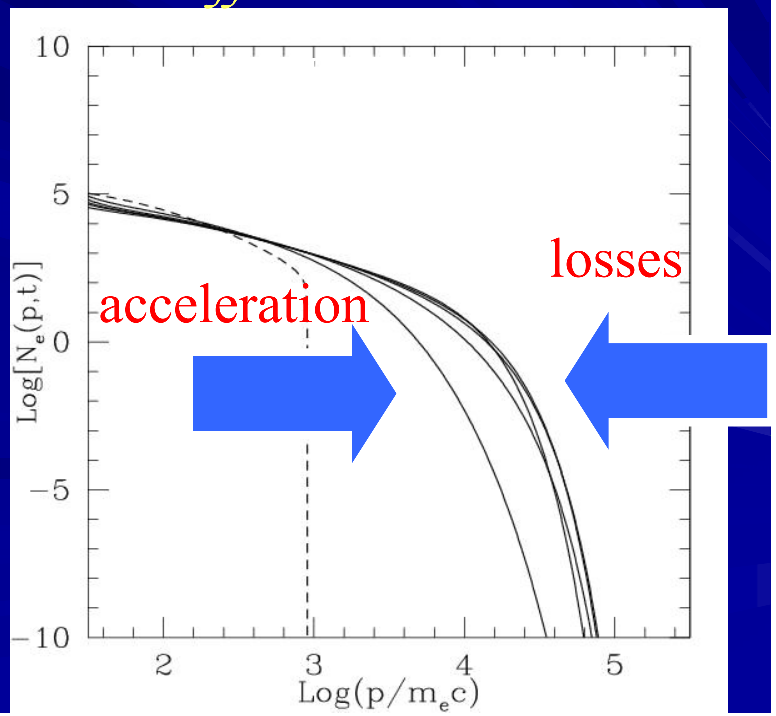


Radio Halos : are they generated by "inefficient" mechanism of CRe acceleration ?

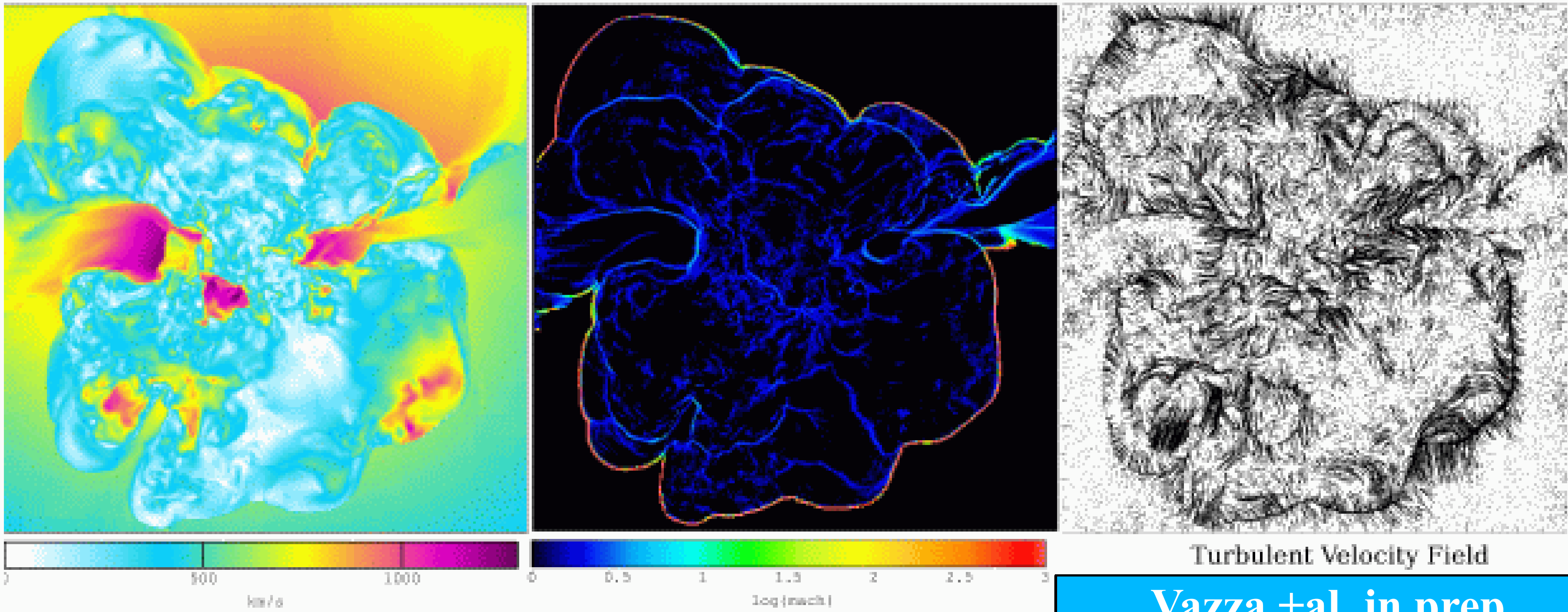


Evidence of break in the spectrum of the emitting electrons at energies of few GeV

Acceleration mechanism not efficient !

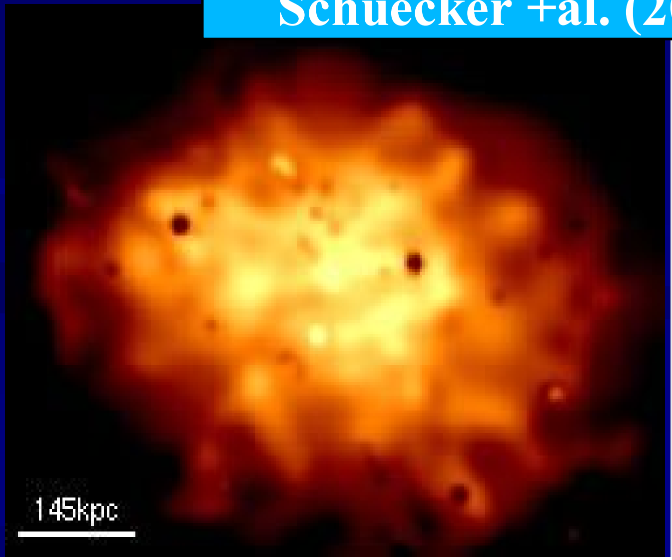


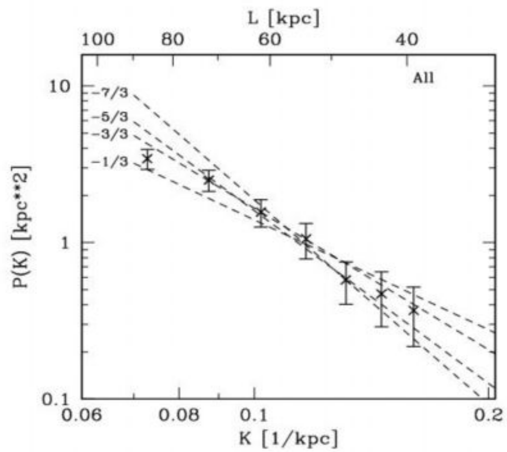
Turbulence in galaxy clusters & cluster-mergers



Vazza +al. in prep.

Schuecker +al. (2004)

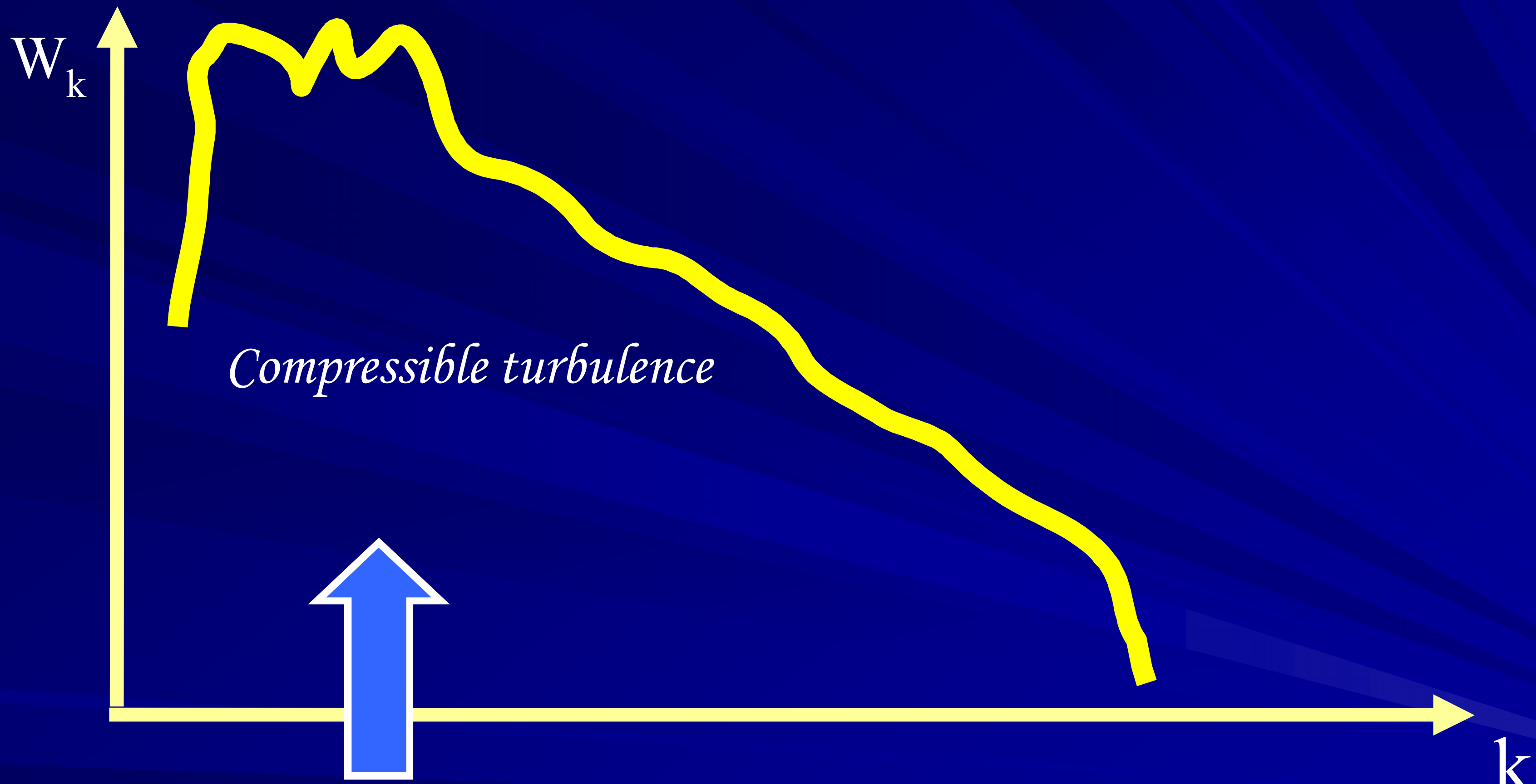




Bryan & Norman 1998;
Ricker & Sarazin 2001;
Sunyaev et al.2003;
Cassano & Brunetti 2005
Dolag et al. 2005;
Vazza et al. 2006;
Nagai et al. 2007;
Brunetti & Lazarian 2007;
Iapichino & Niemeyer 2008

Basics of turbulence in the ICM

Brunetti & Lazarian 2007



L_o ~ 100 – 300 kpc

Basics of turbulence in the ICM

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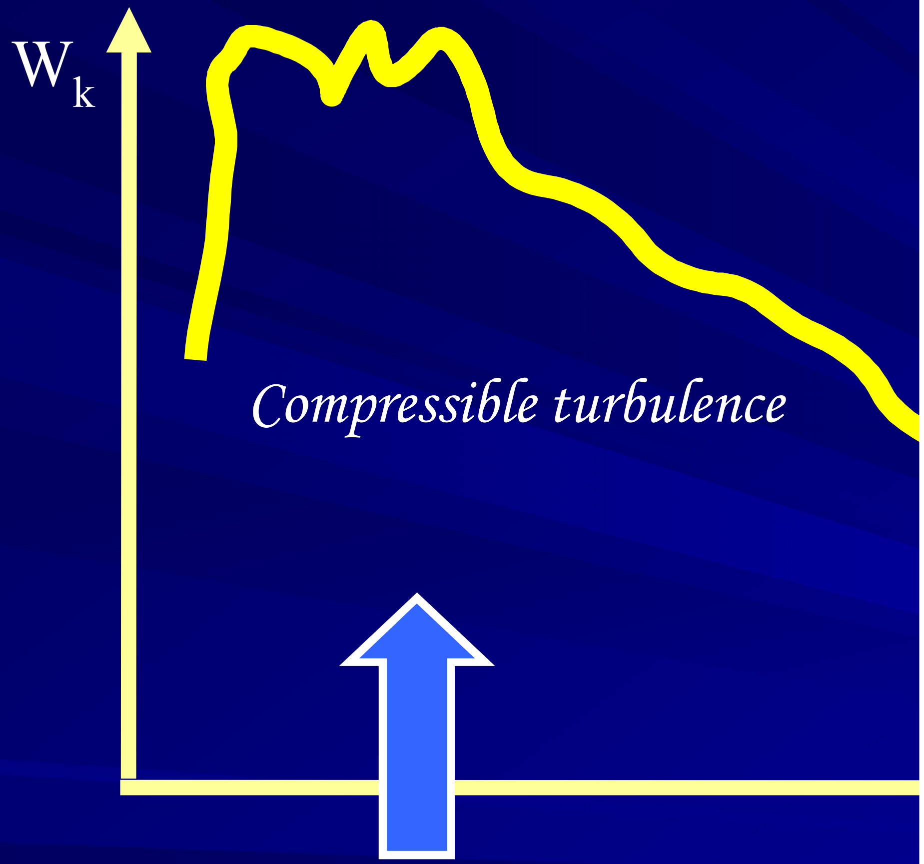


$L_o \sim 100 - 300$ kpc

$L_o \sim 100 - 300$ kpc

$V_o \sim 500 - 1000$ km/s

$c_s \sim 1200 - 1800$ km/s

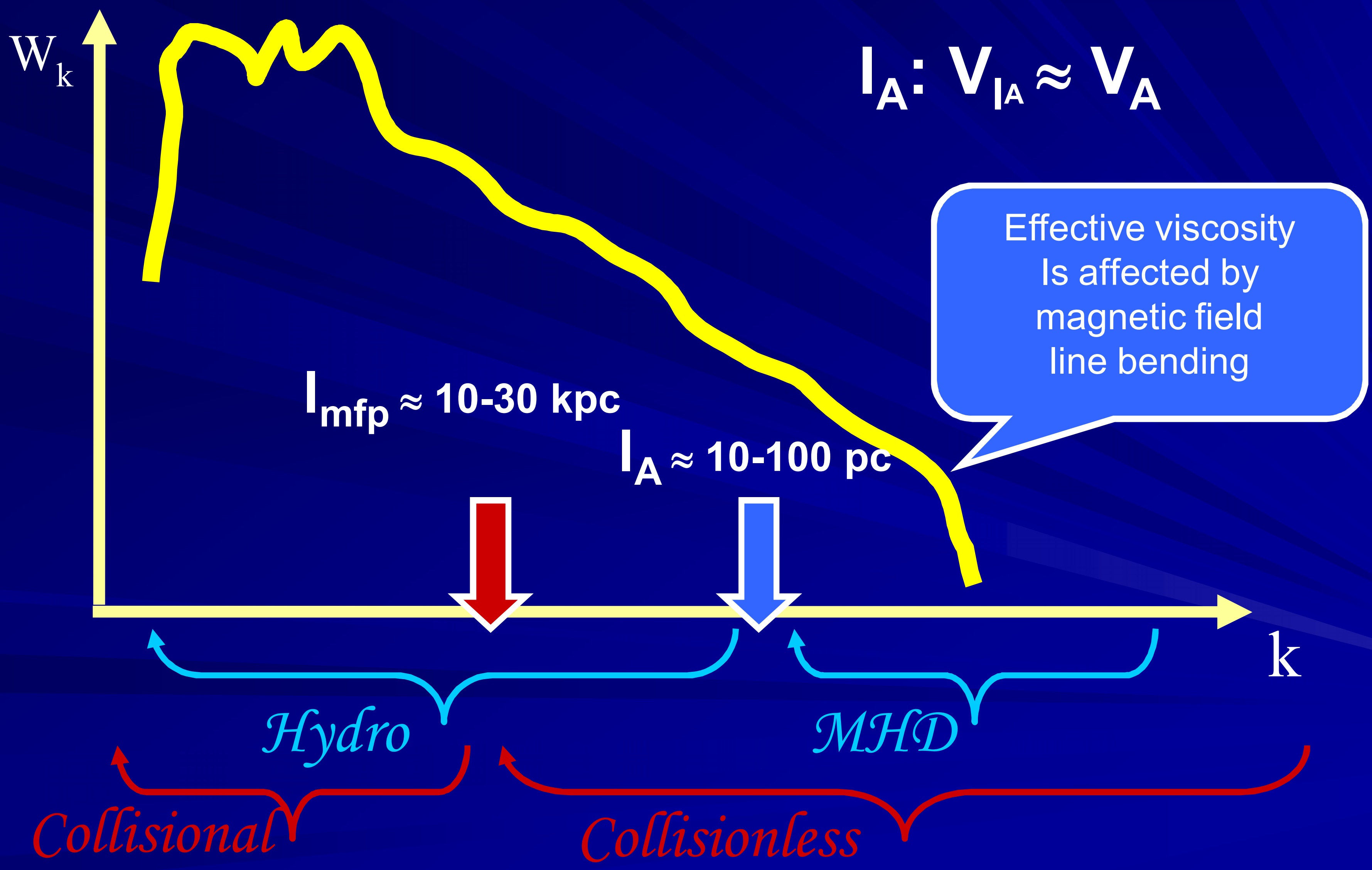
$V_A \sim 30 - 100$ km/s

Sub-sonic Turbulence

Super-Alfvenic Turbulence

Basics of turbulence in the ICM

Brunetti & Lazarian 2007



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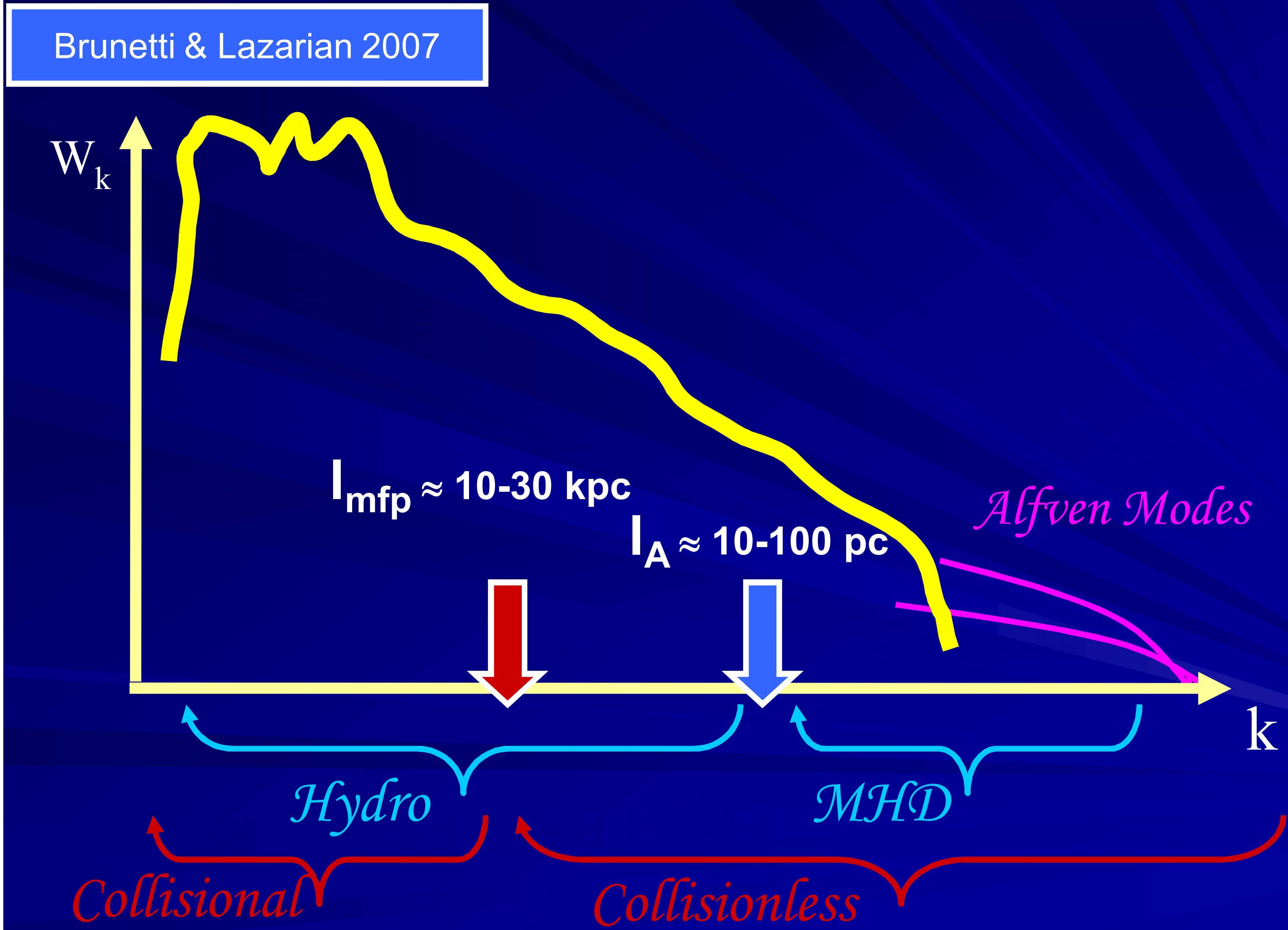

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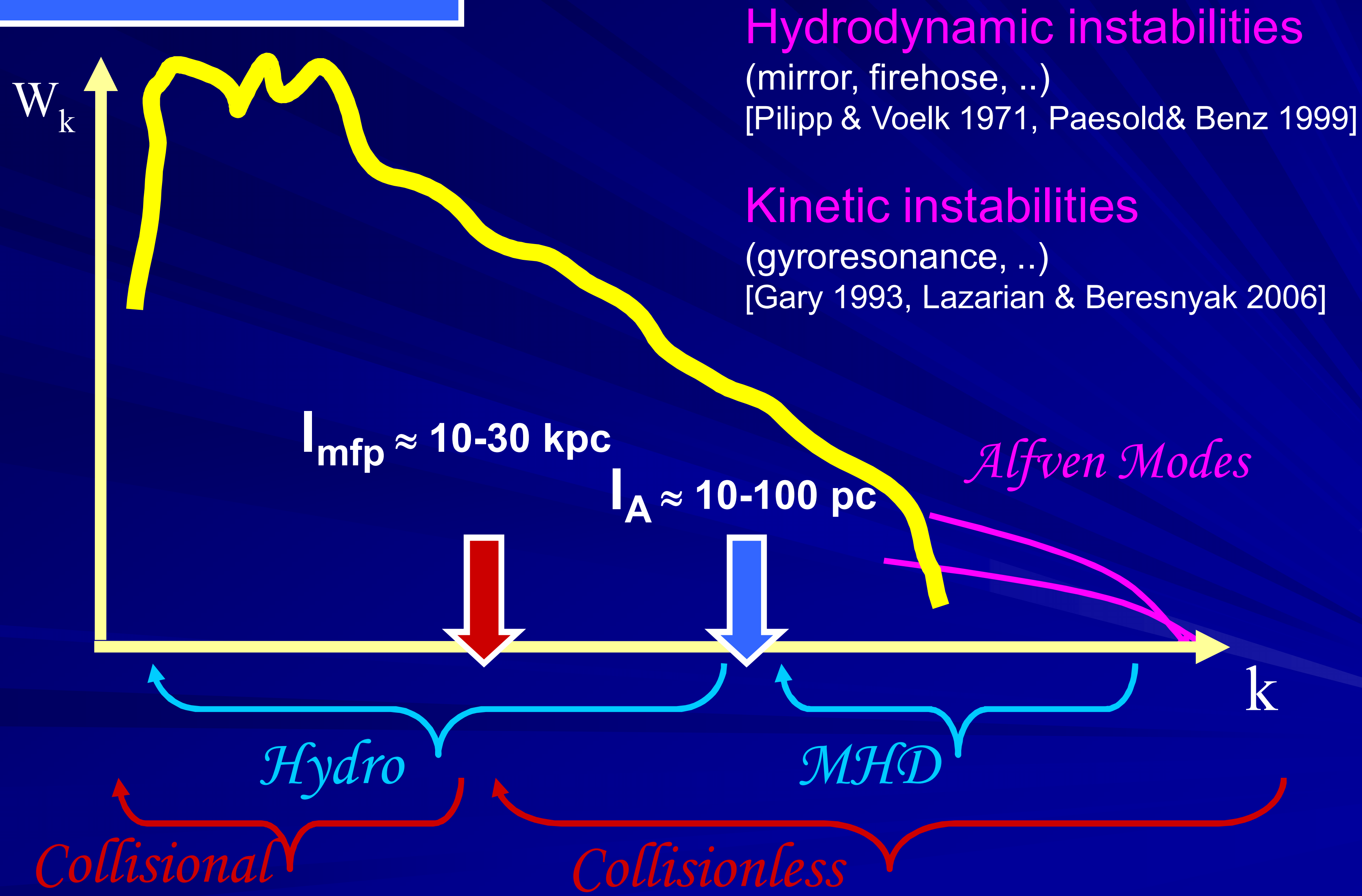
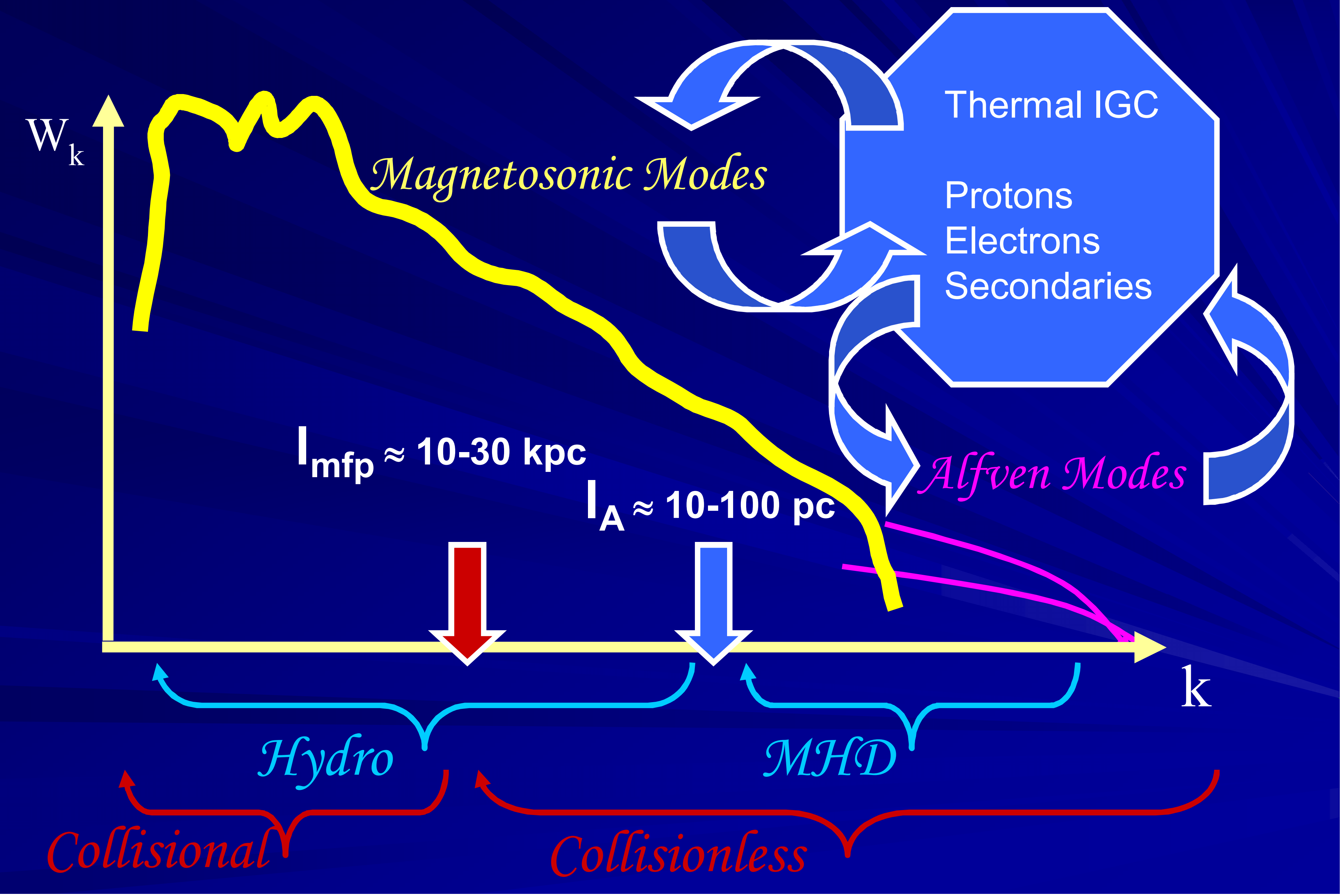
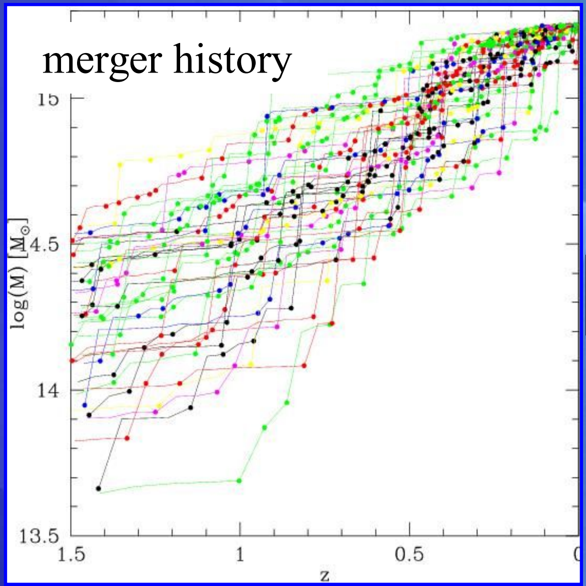


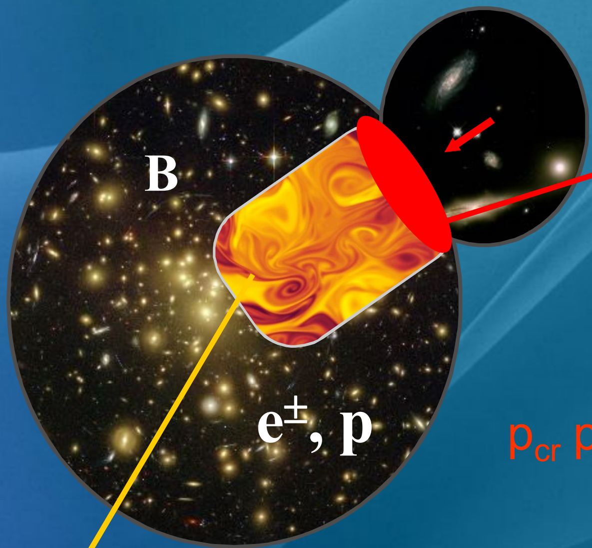
Basics of turbulence in the ICM



The general picture



clusters increase their mass via merger with smaller subclusters



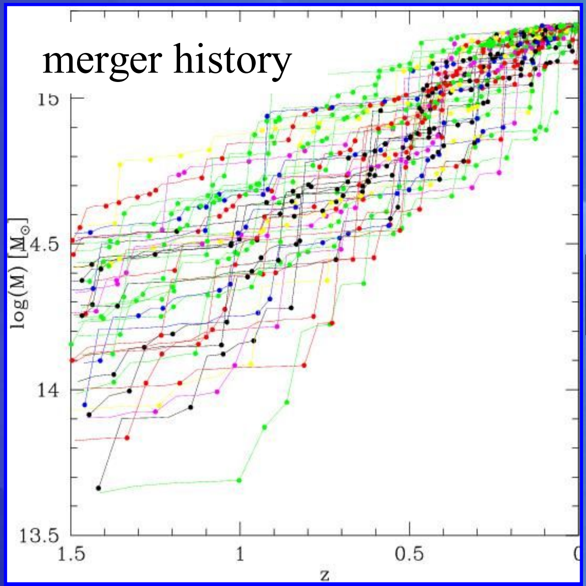
SHOCKS

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

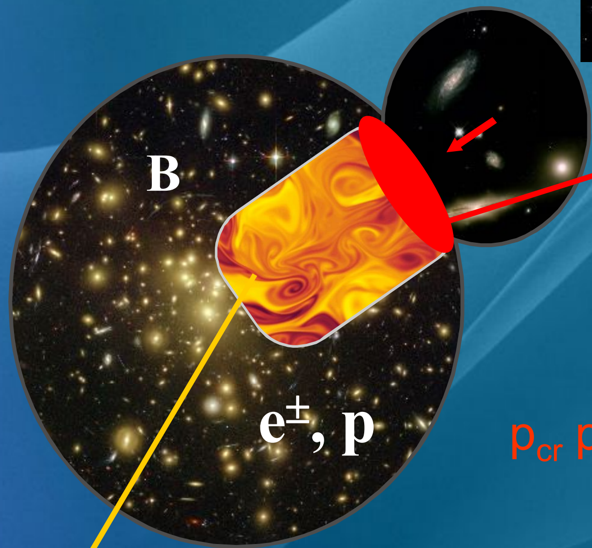
$p_{cr}\ p_{th}\ \rightarrow$ { $\pi^0 \rightarrow \gamma$ rays ; $\pi^{\pm} \rightarrow e^{\pm}$ }

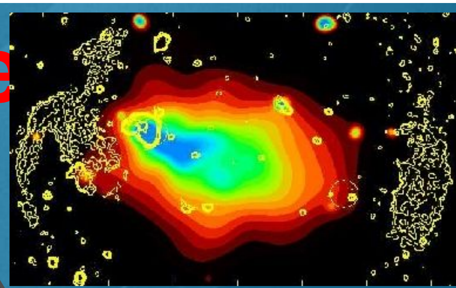
TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scales

The general picture



clusters increase their mass via merger with smaller subclusters





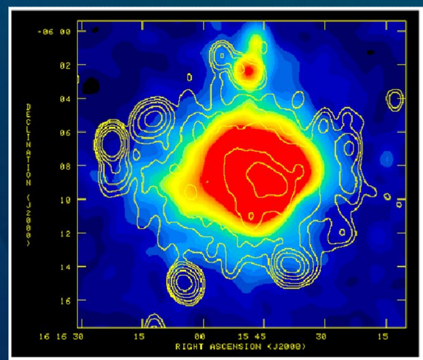
?

SHOCKS

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

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

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



?

Alfvenic: results

n_{th}, T, B_o, $N_p(p,0)$ $\quad$ I(k)

Alfvenic: results

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

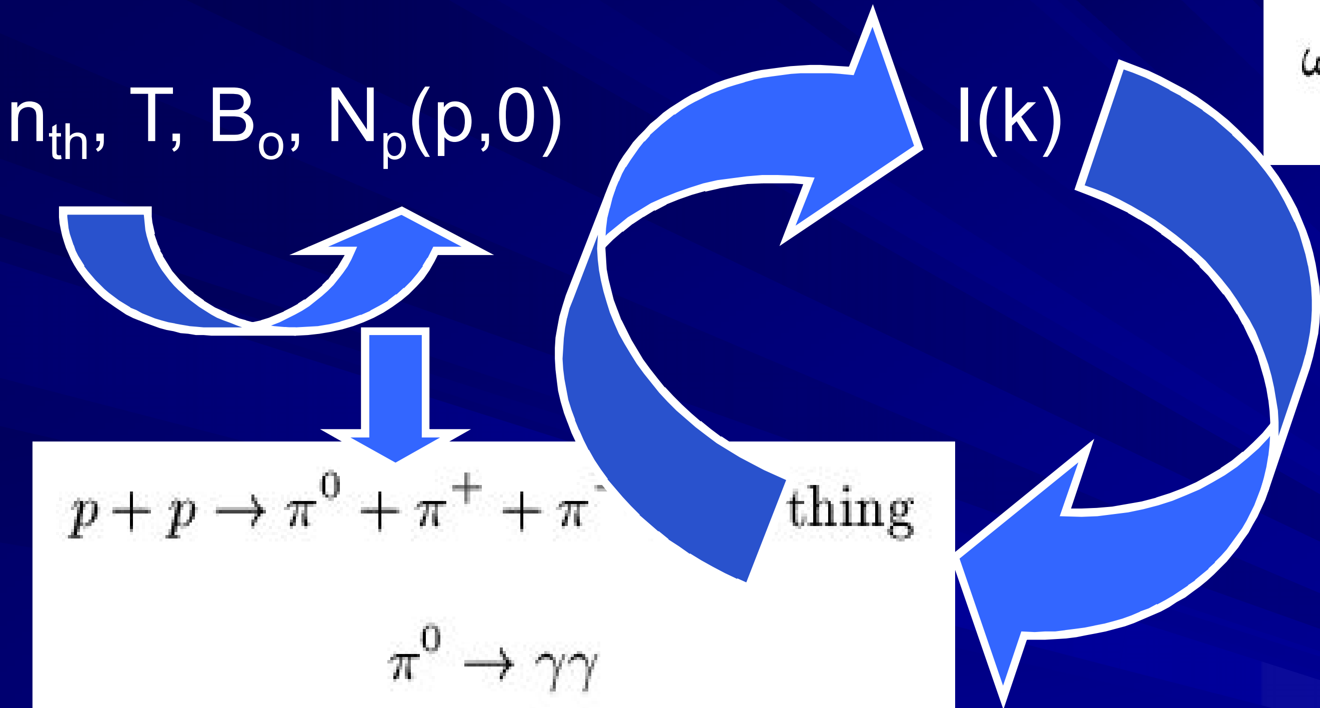
I(k)

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

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

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

Alfvenic: results



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

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

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

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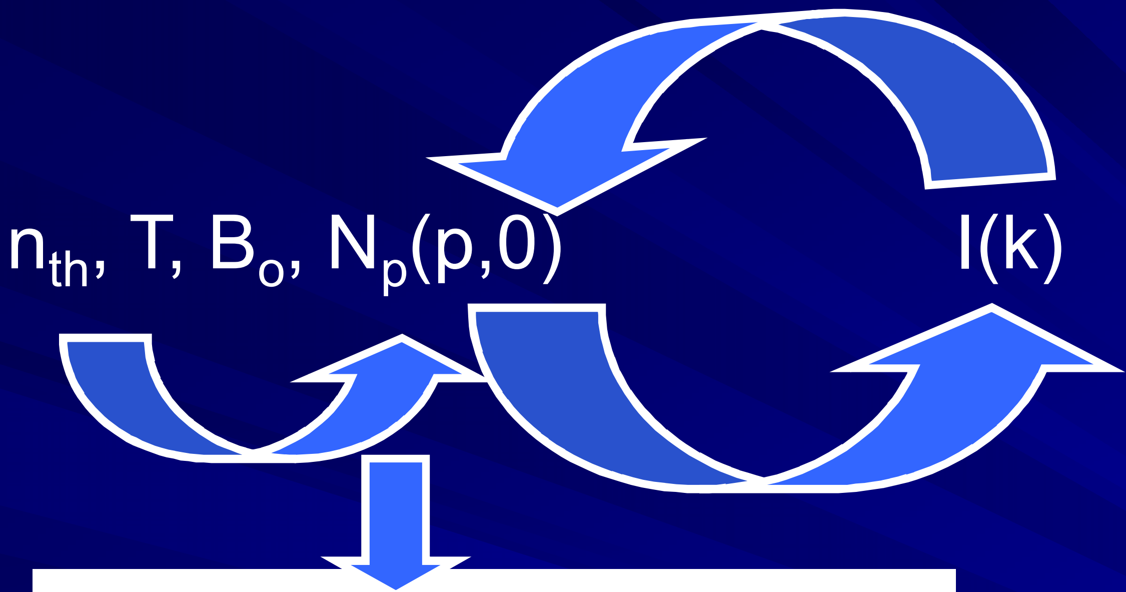

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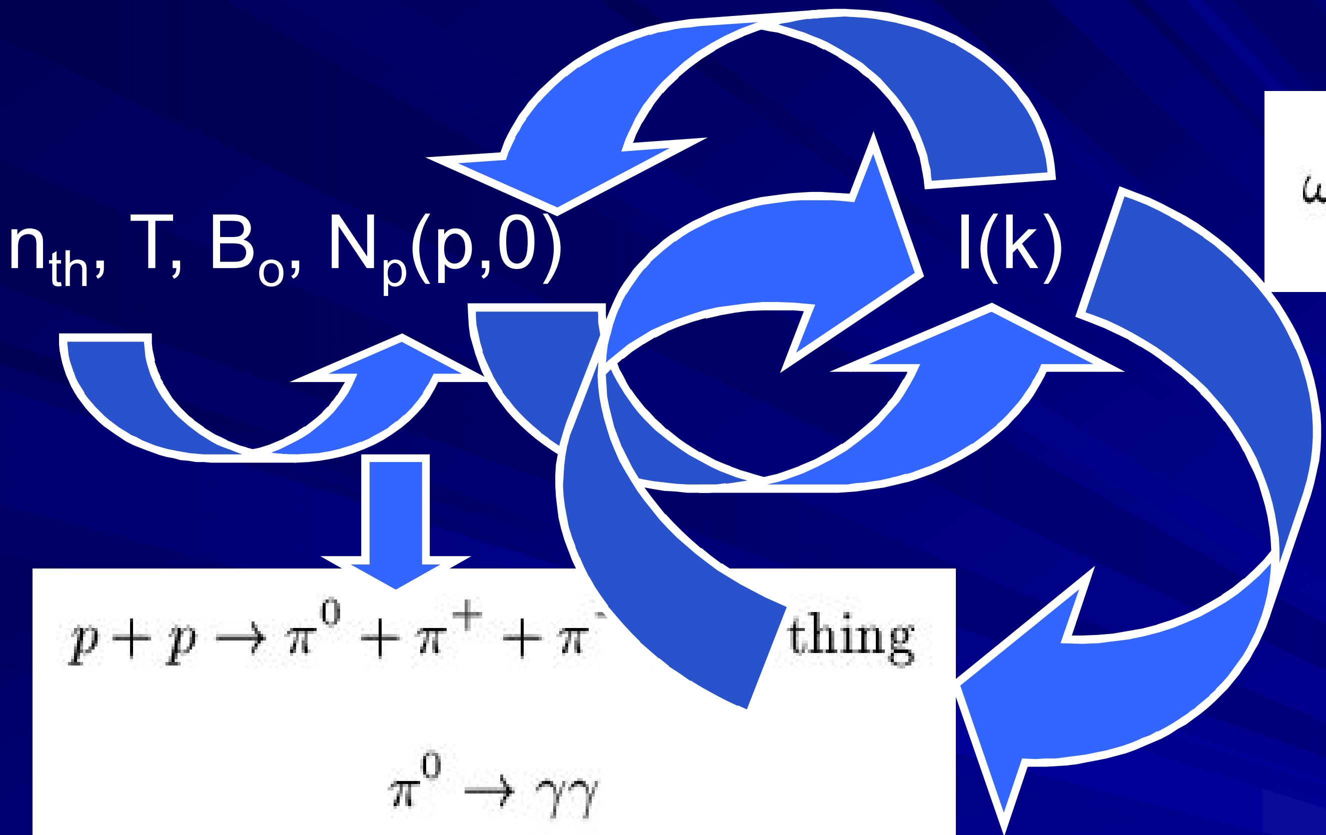

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$$\pi^0 \to \gamma\gamma$$

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

Stochastic Particle Acceleration (formalism)

Brunetti +al. 2004, Brunetti & Blasi 2005, Brunetti +al. 2009

Electrons/Positrons

$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_e(p,t)\left[\left(\frac{dp}{dt}\right)_{rad} + \left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_e(p,t)}{\partial p}\right) + Q_e(p,t)$$

Q_e: secondaries from (CR)p-p collisions

Protons

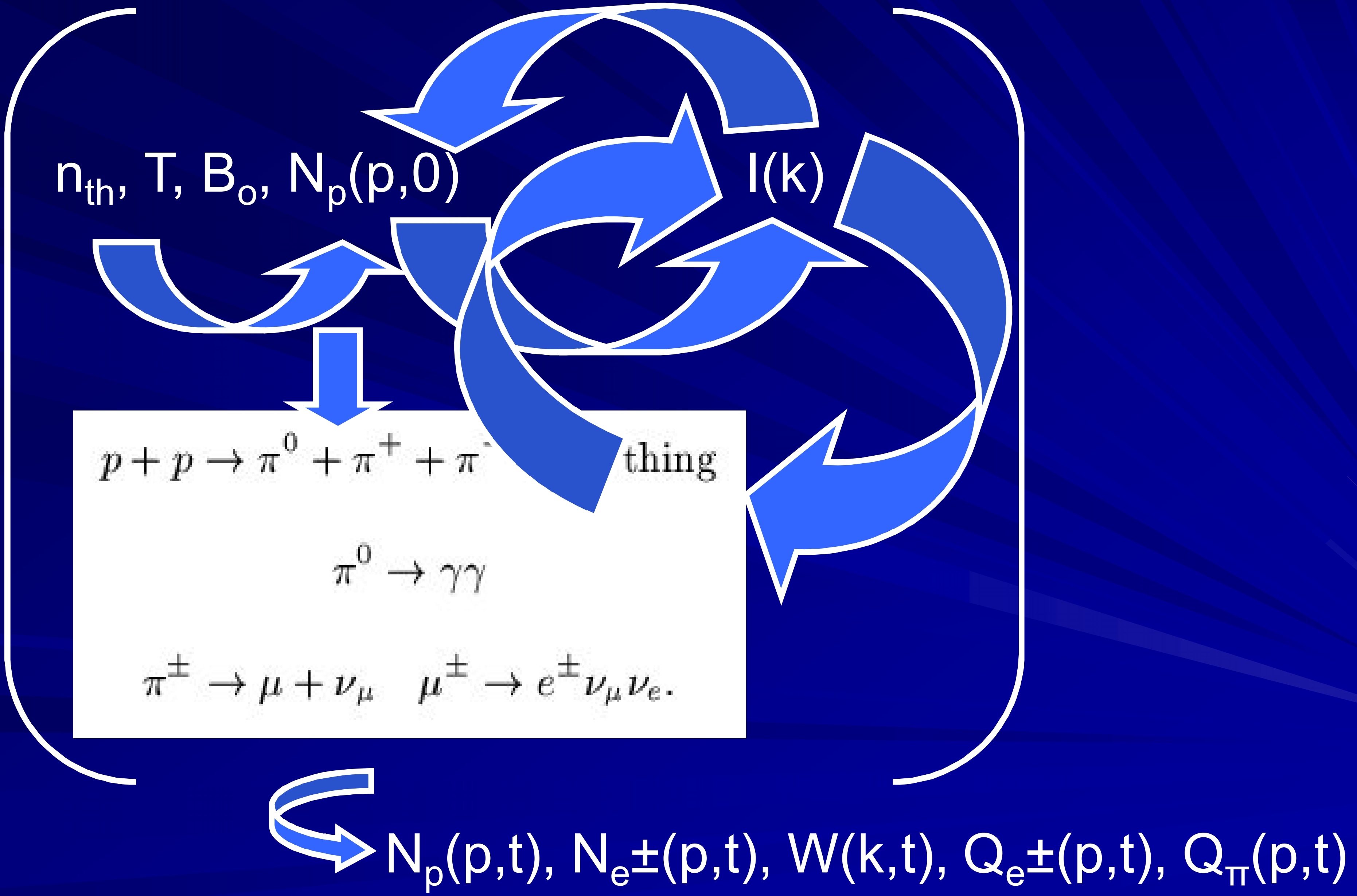
$$\frac{\partial N_p(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_p(p,t)\left[\left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_p(p,t)}{\partial p}\right) + Q_p(p,t)$$

Waves

$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

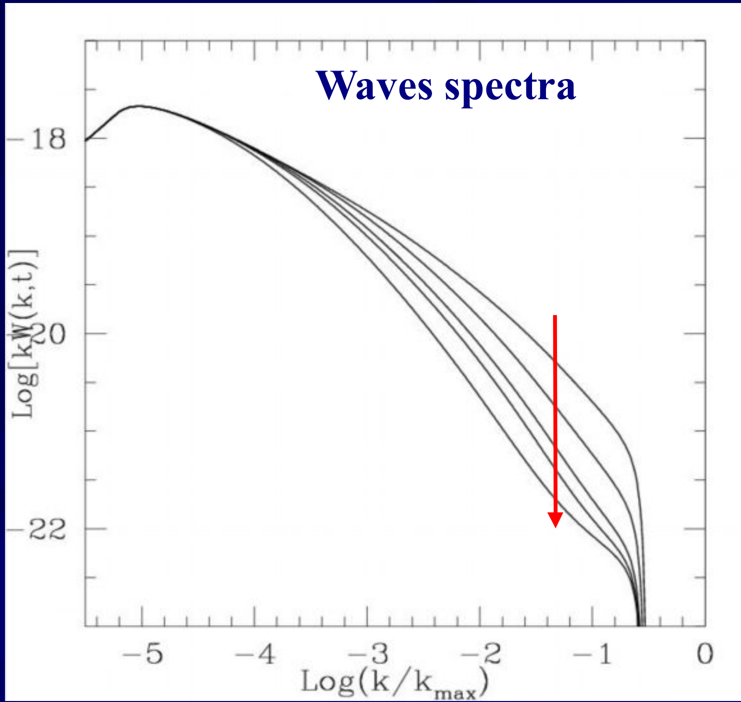
most could be with CR protons

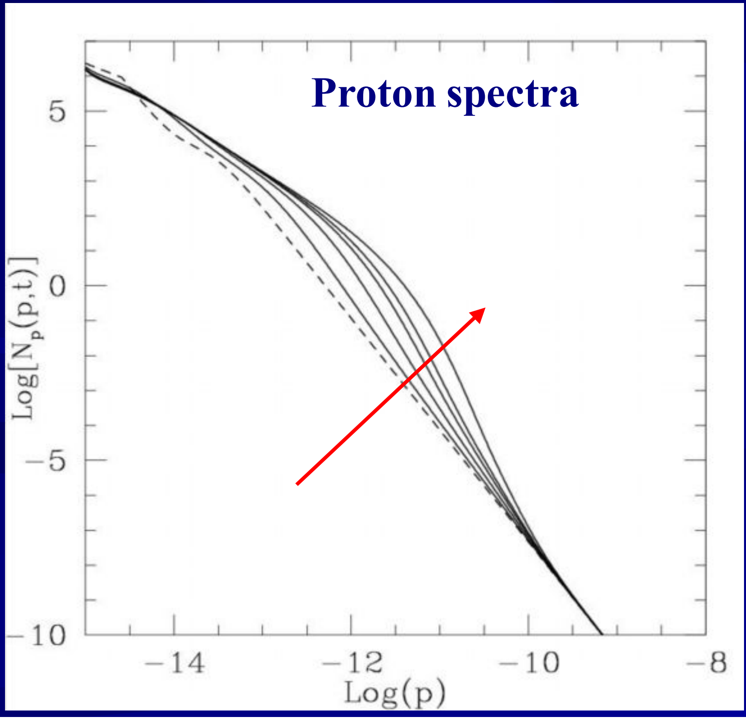
Alfvenic: results

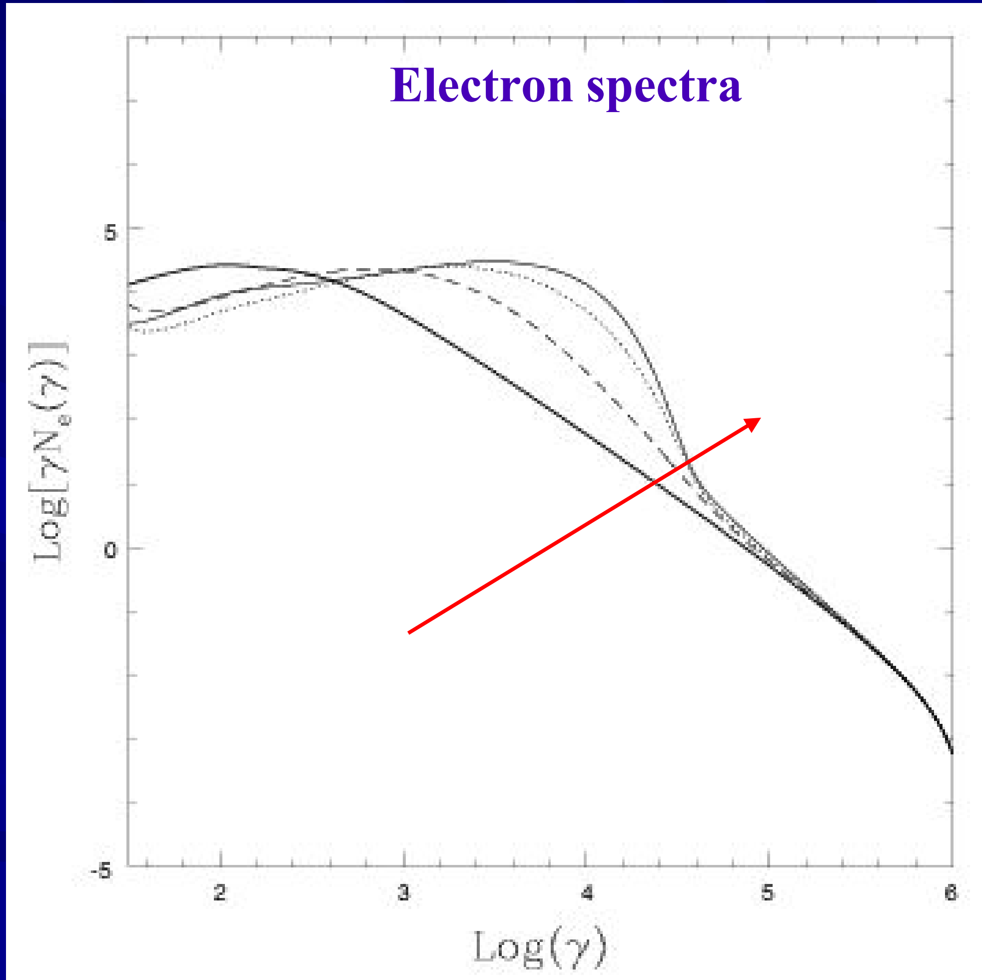


Full Alfven-Wave--Particle Coupling

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

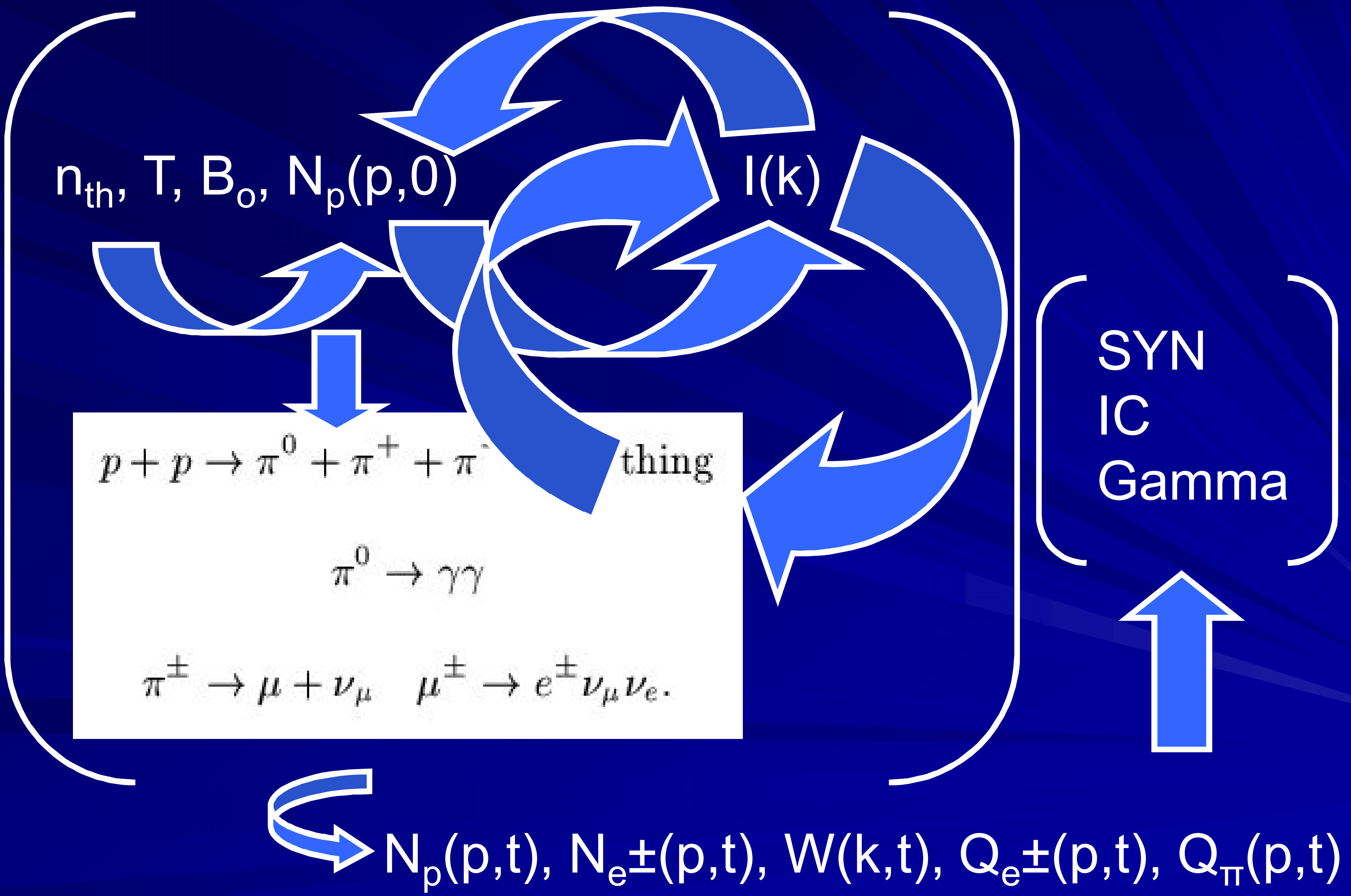






Waves + Protons + Secondaries

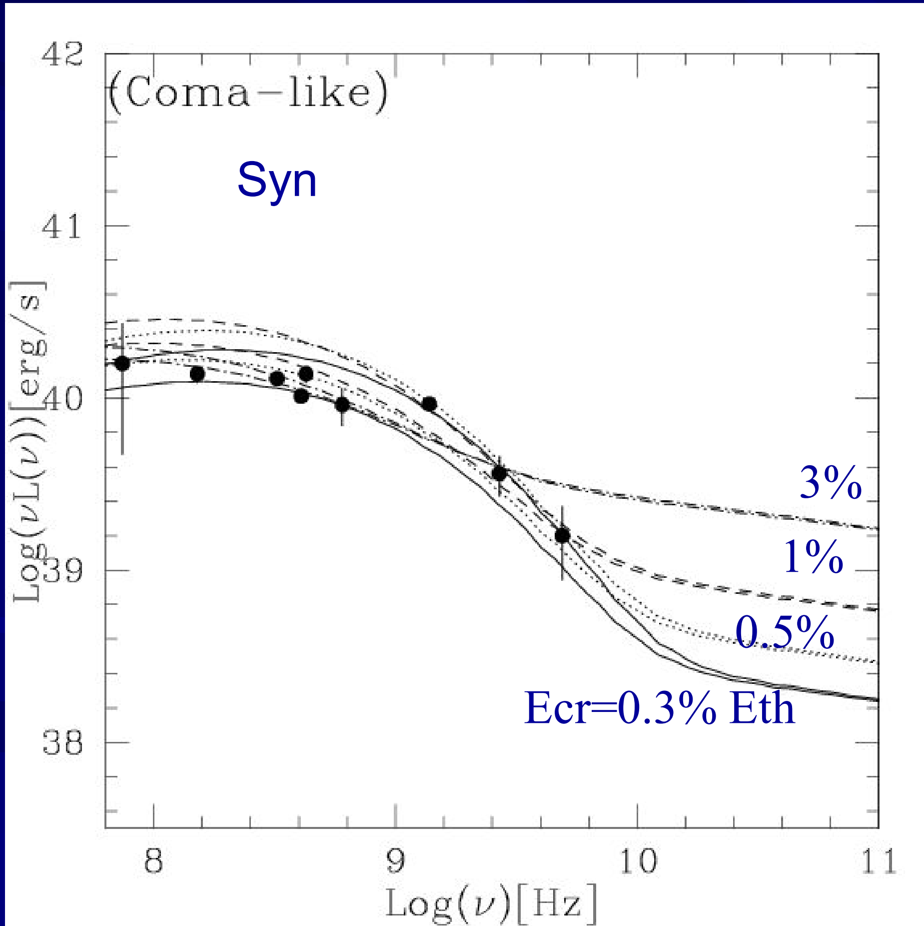
Alfvenic: results

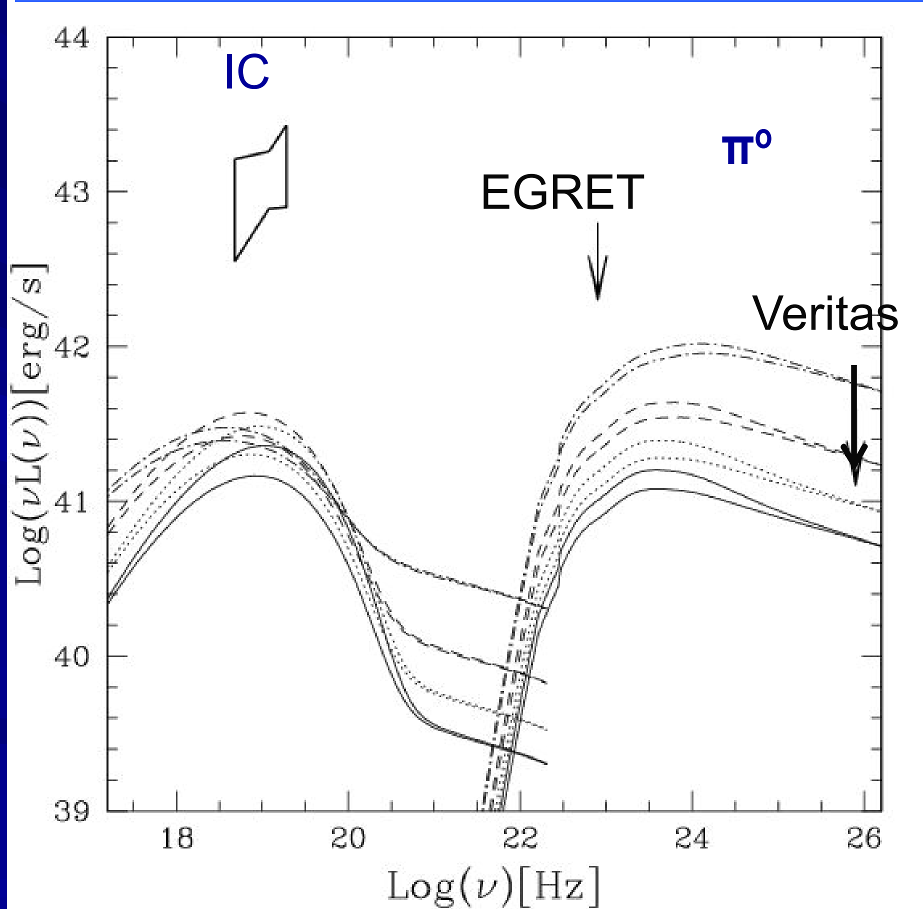


Alfvenic: results

Toy Model: β-profile, $B_o \approx A\, n_{th}$, $B_o(0)$=2μG, $W_{CR} \approx f\, W_{th}$, $P_A \approx Q\;\; n_{th}^{5/6}$

Brunetti, et al. 2009





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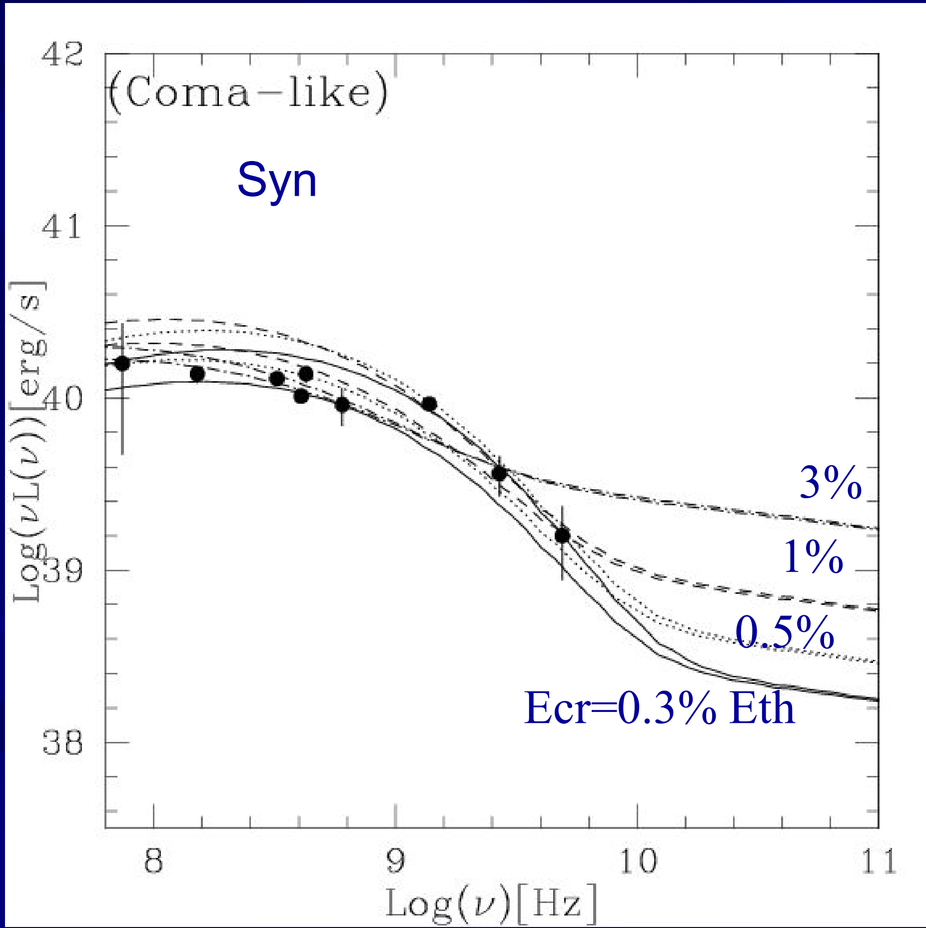
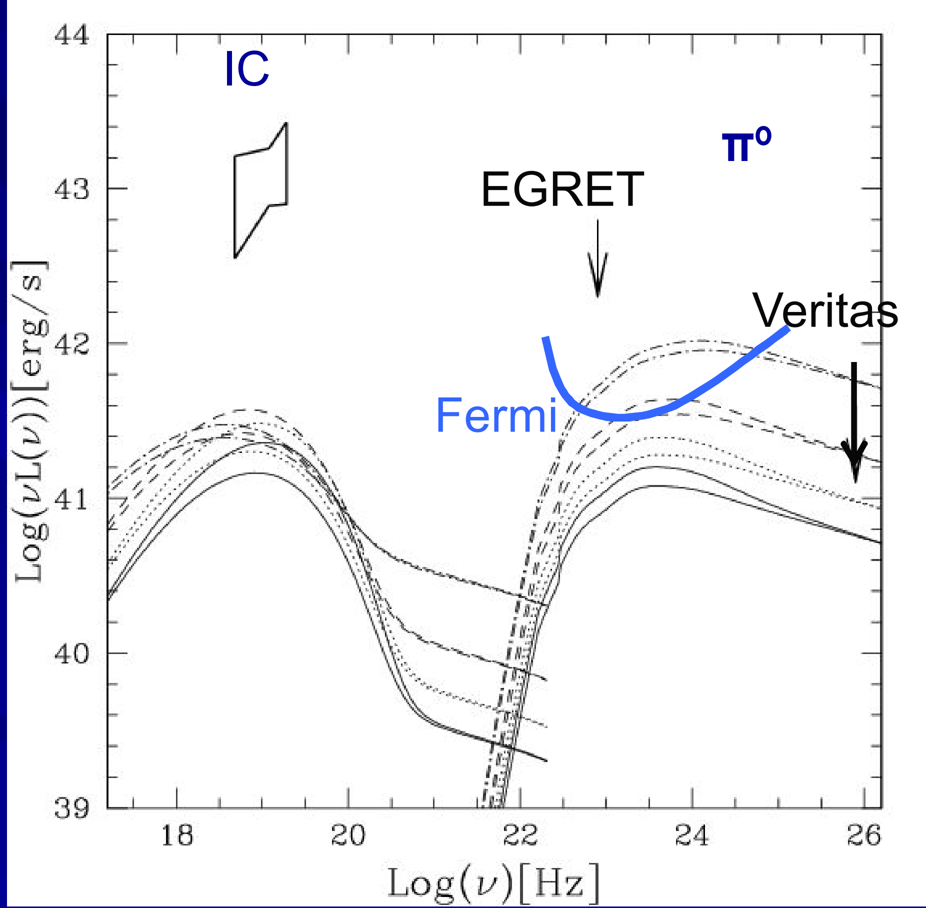
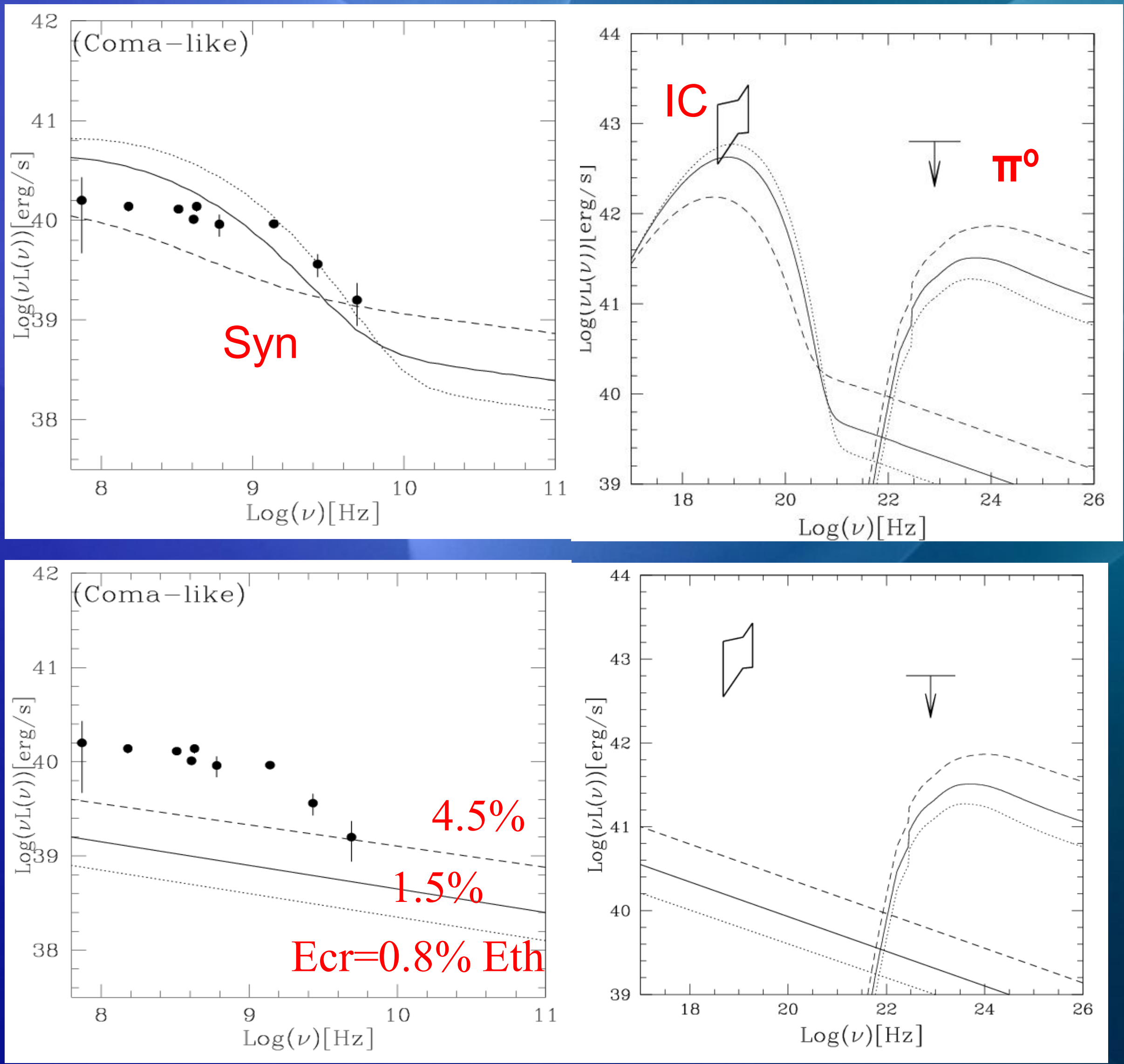
Brunetti, et al. 2009

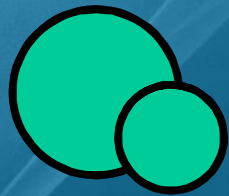




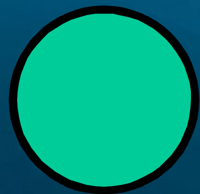
General multiwavelength expectations

Brunetti 2008; Brunetti +al. 2009



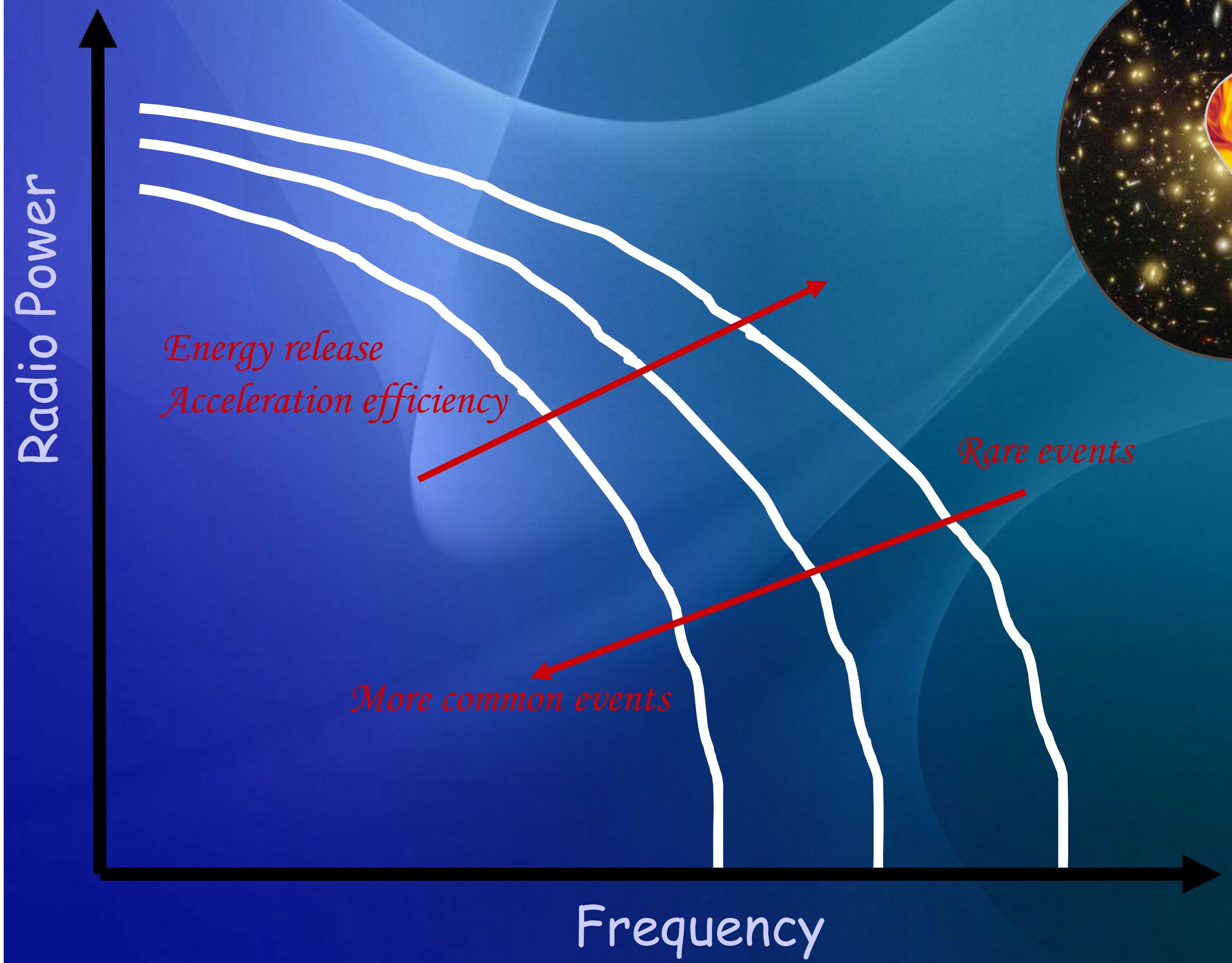


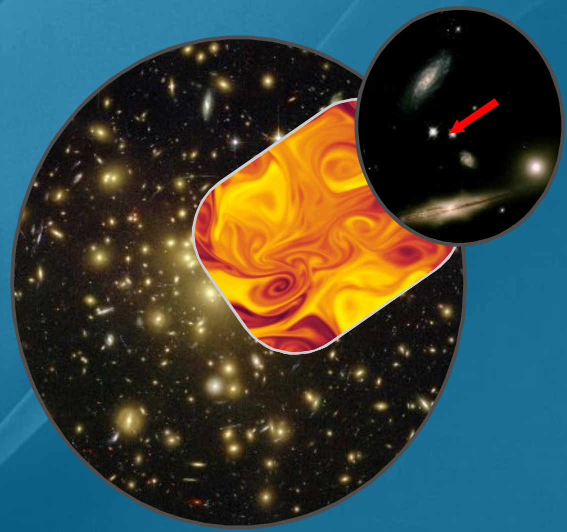
MERGING CLUSTERS



ALL CLUSTERS

The case of the “ultra steep” spectrm radio halos





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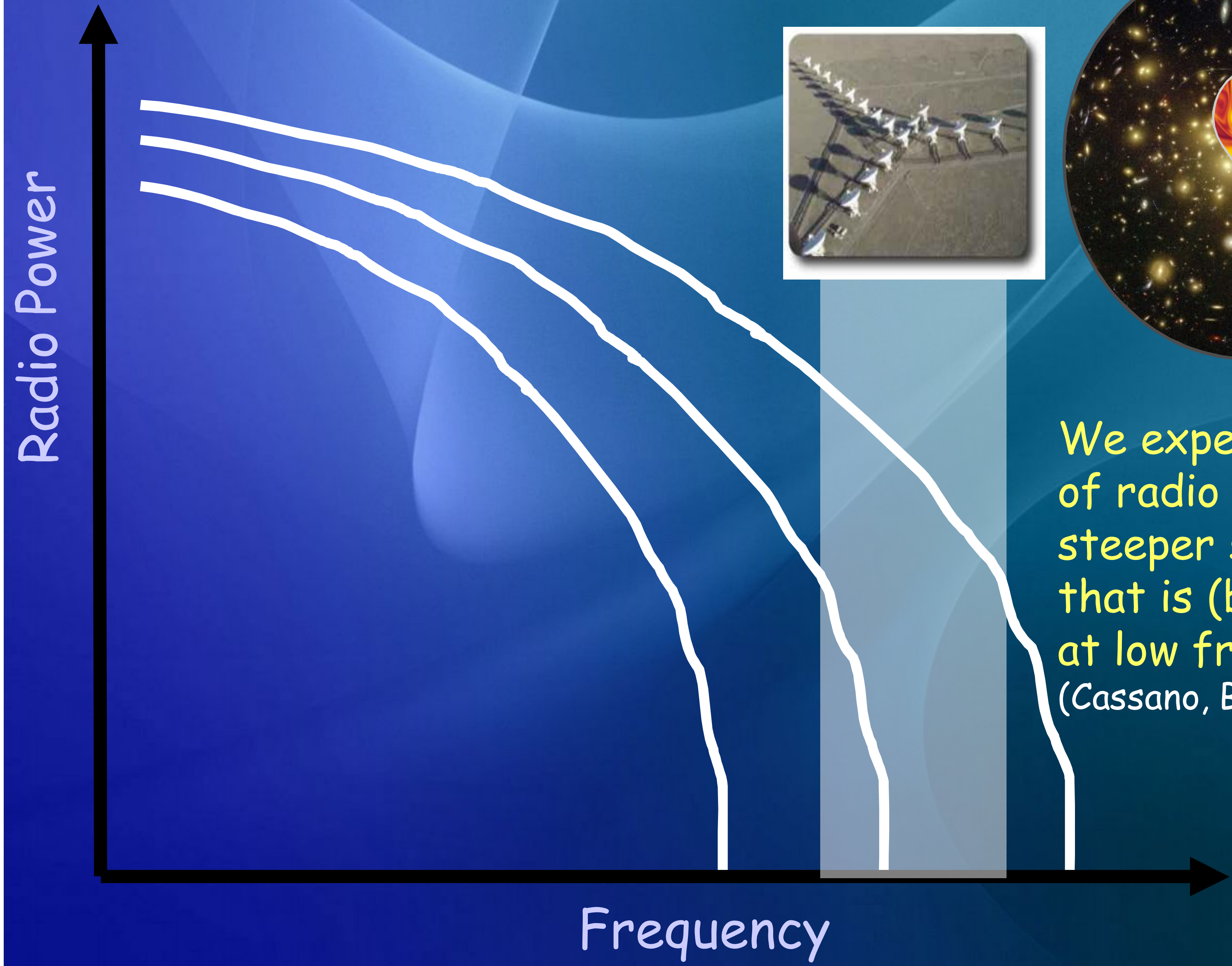
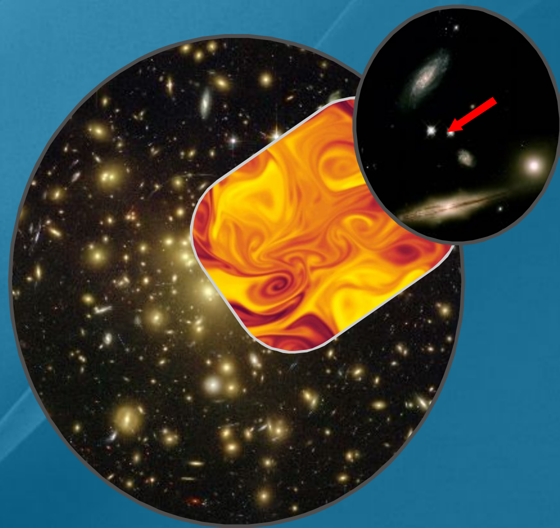
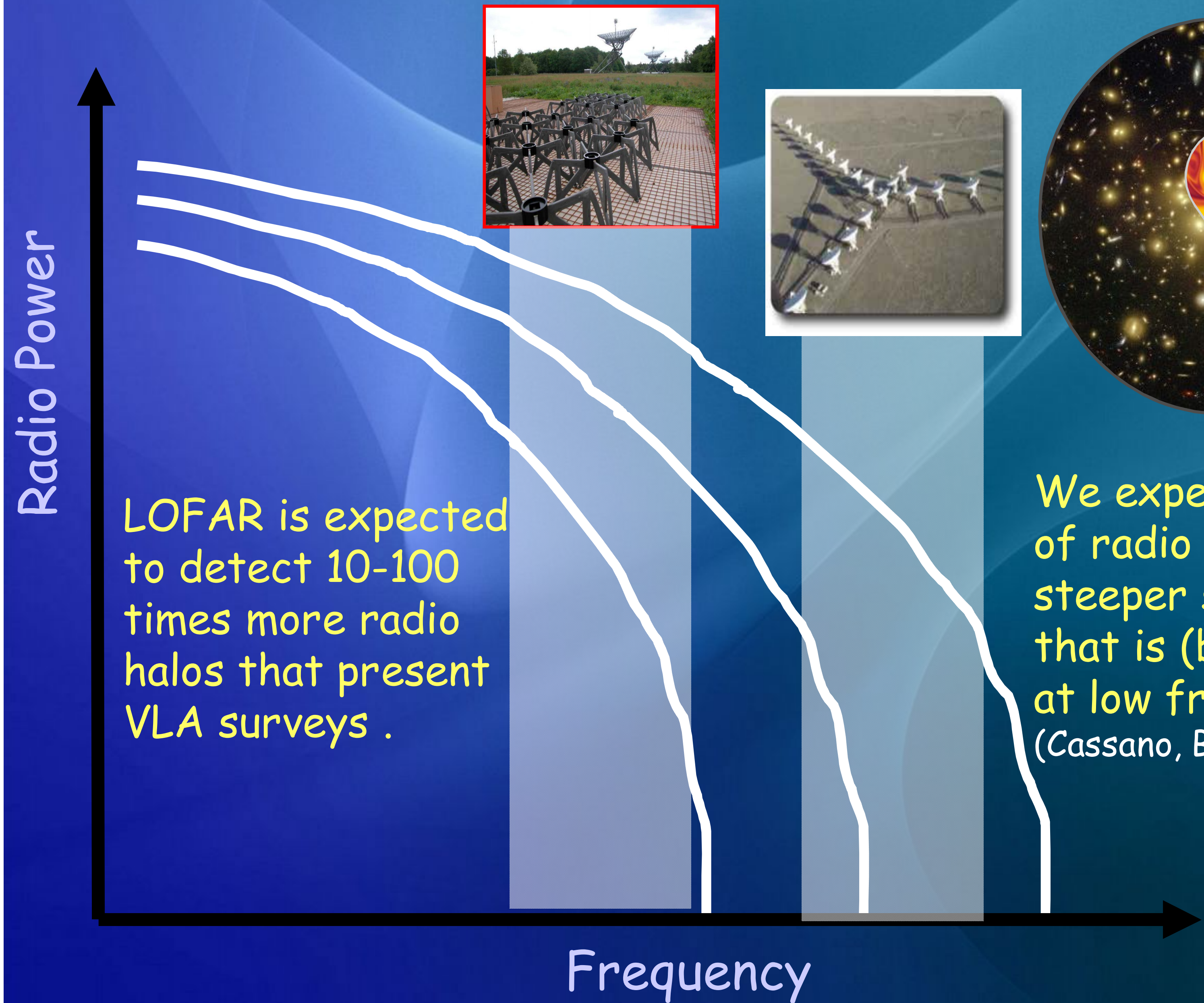


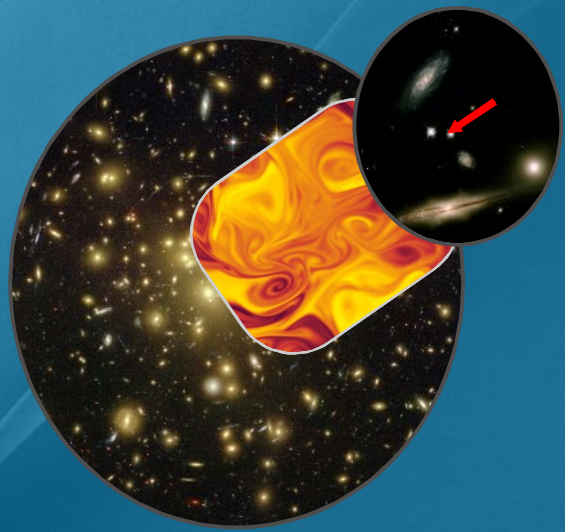


We expect a populations of radio halos with steeper spectrum that is (better) visible at low frequencies
(Cassano, Brunetti, Setti 2006)

The case of the “ultra steep” spectrm radio halos

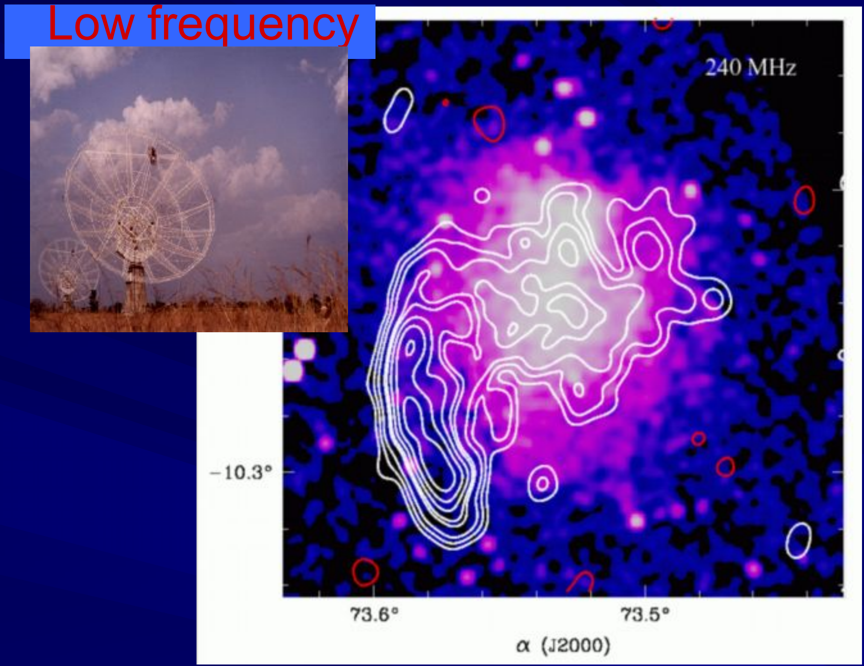


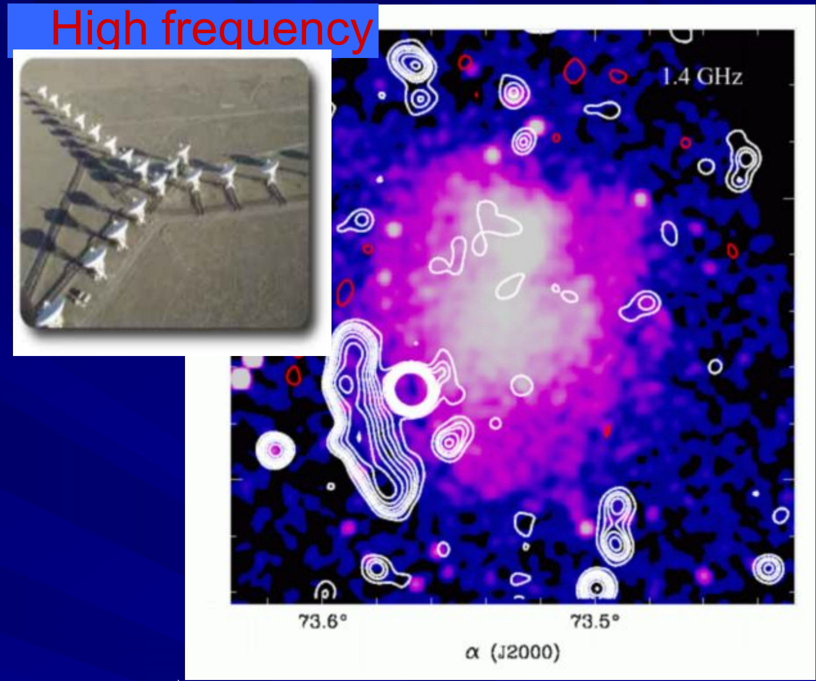
LOFAR is expected to detect 10-100 times more radio halos that present VLA surveys .



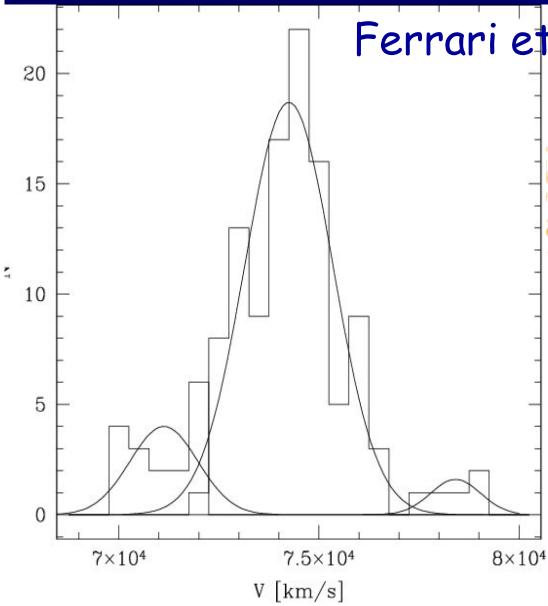
We expect a populations of radio halos with steeper spectrum that is (better) visible at low frequencies (Cassano, Brunetti, Setti 2006)

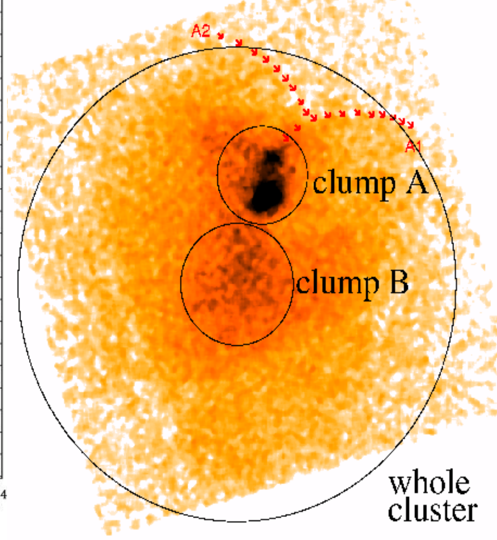
Do they exist ? (Brunetti +al. 2008, Nature 455,944)

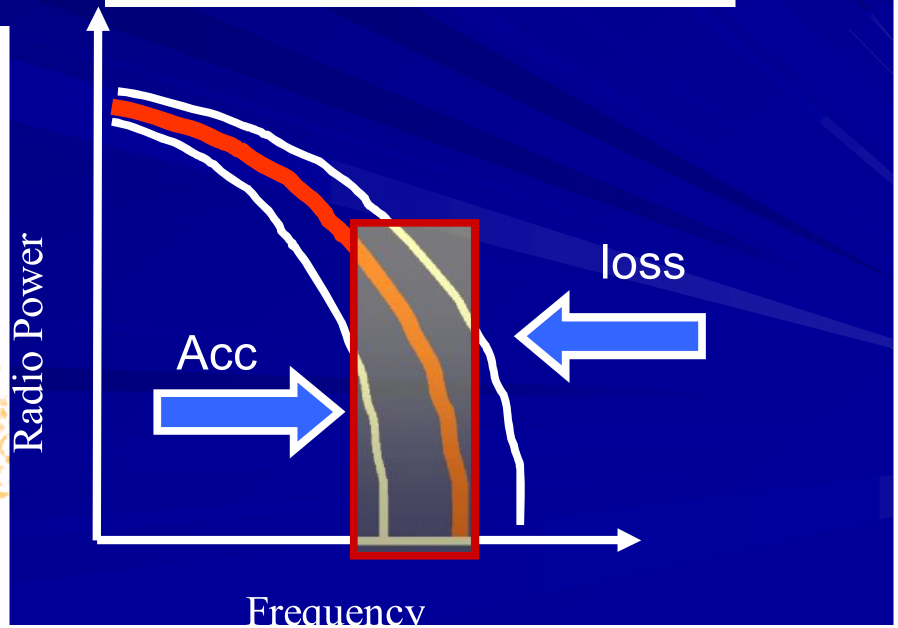




Ferrari et al.2003,06

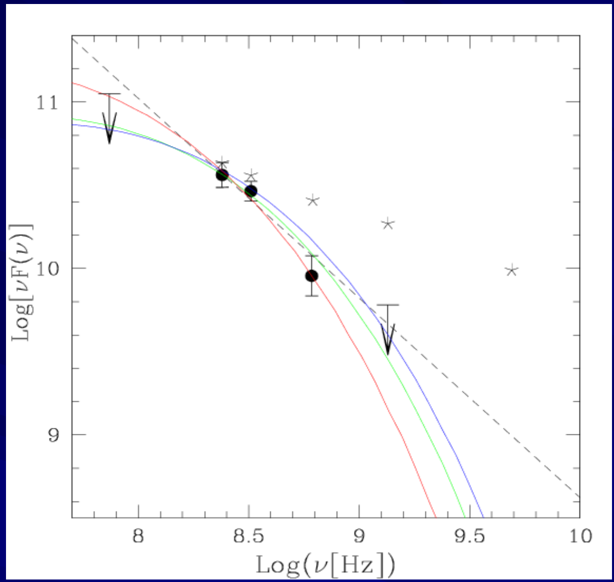


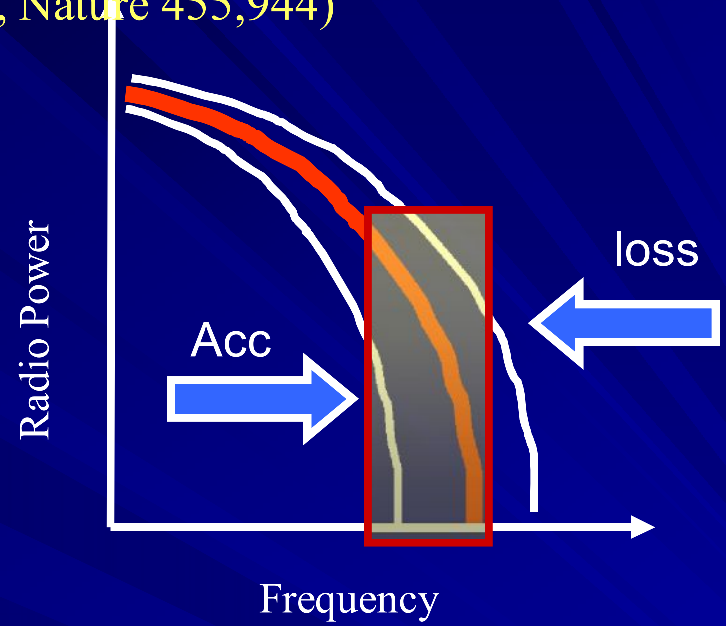


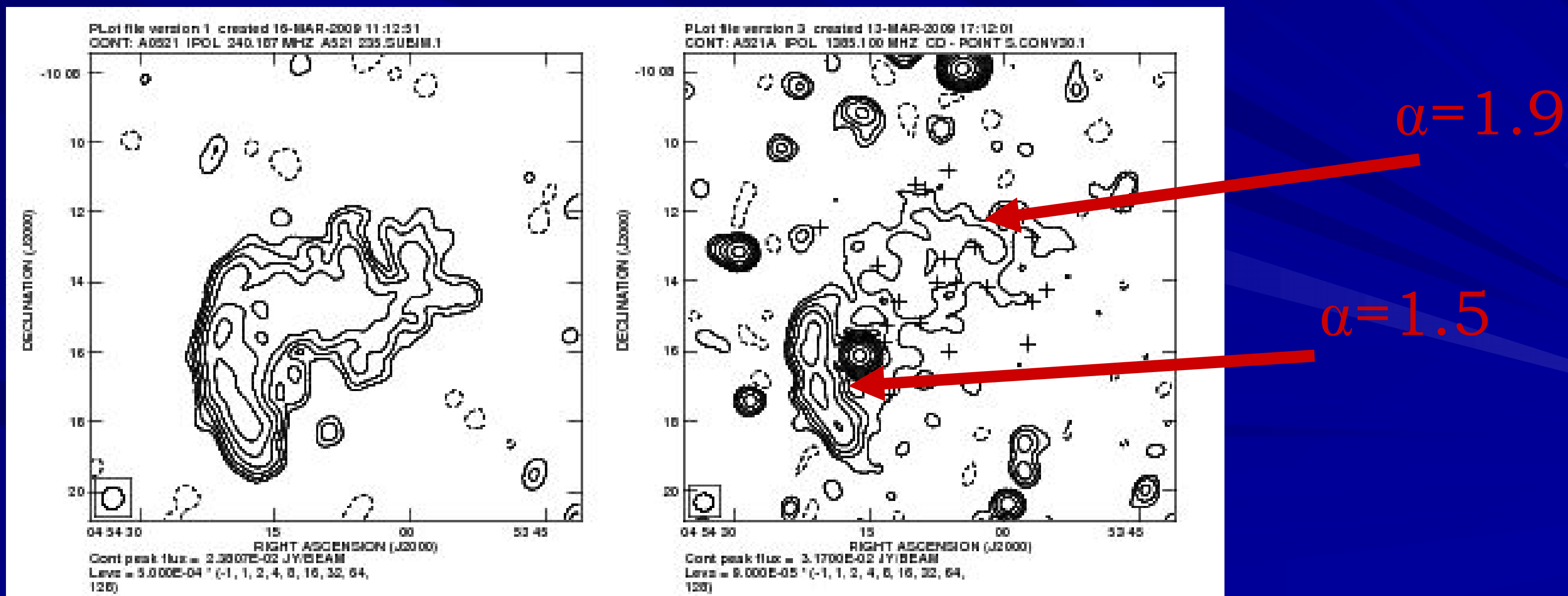


(indirect) evidence for turbulent acceleration

(Brunetti +al. 2008, Nature 455,944)







Dallacasa, Brunetti, et al. 2009

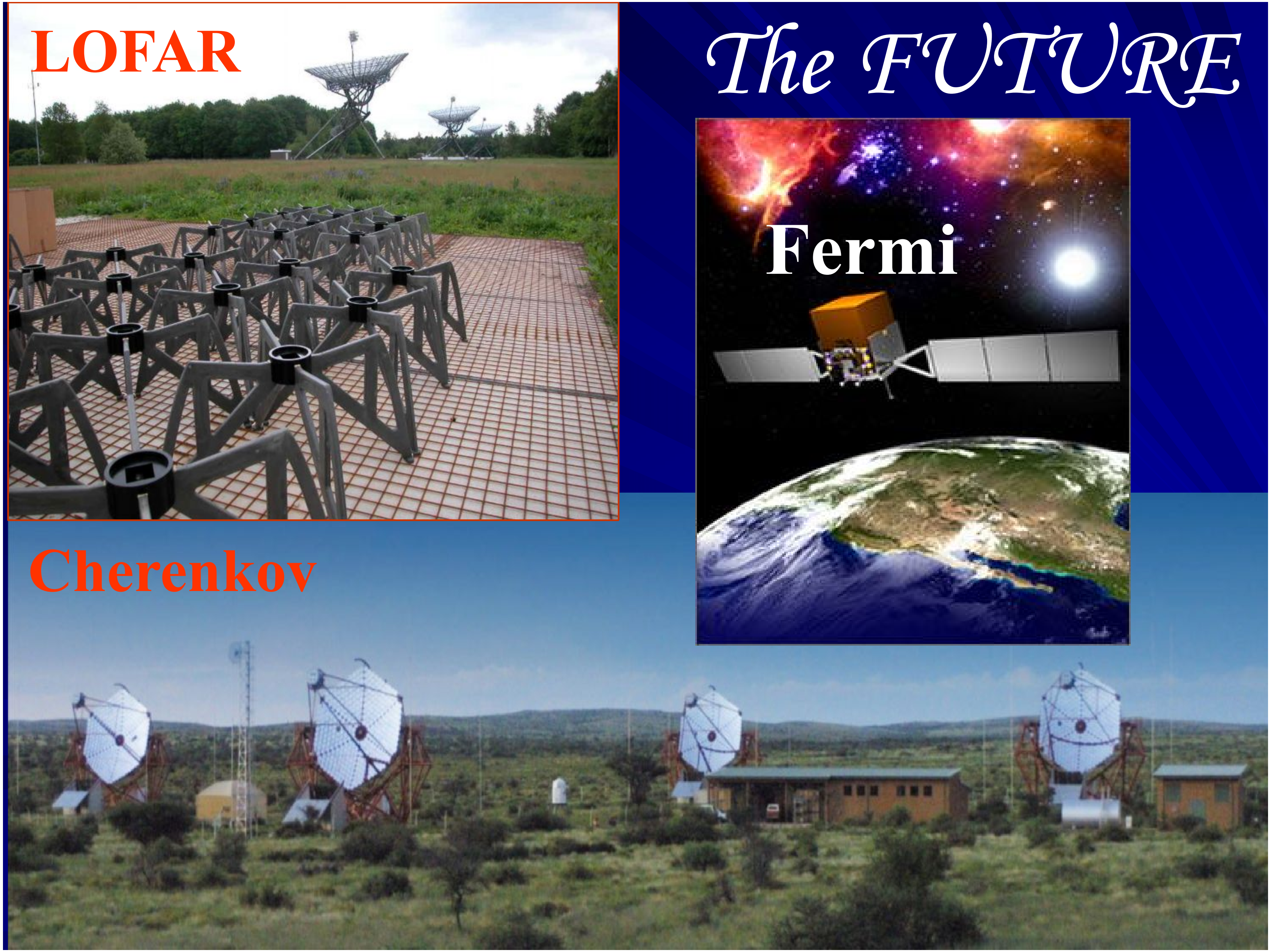
Conclusions

Theoretically protons should be the dominant non thermal particle-component in the IGM (yet only limits)

Theoretically shocks may be an important source of non thermal particles in the IGM, in addition present data suggest that turbulence plays a role in the acceleration of particles in galaxy clusters

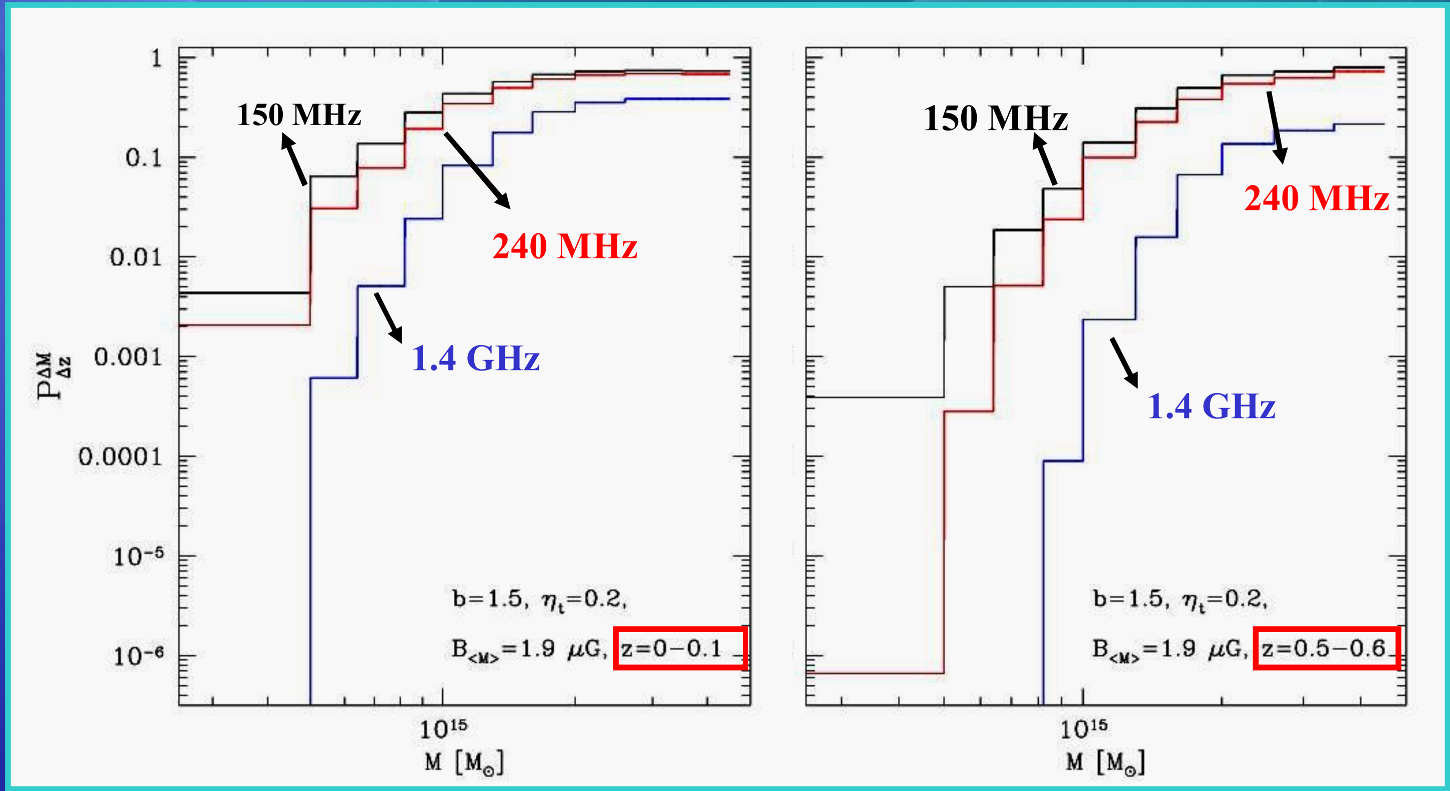
The non-thermal emission from galaxy clusters is a mixture of a transient (turbulnce) and long-living component

LOFAR & FERMI will step into an essentially unexplored territory where theories can be tested (eg "ultra steep halos")


The FUTURE
LOFAR
Fermi
Cherenkov

Fraction of galaxy clusters with radio halos at low ν

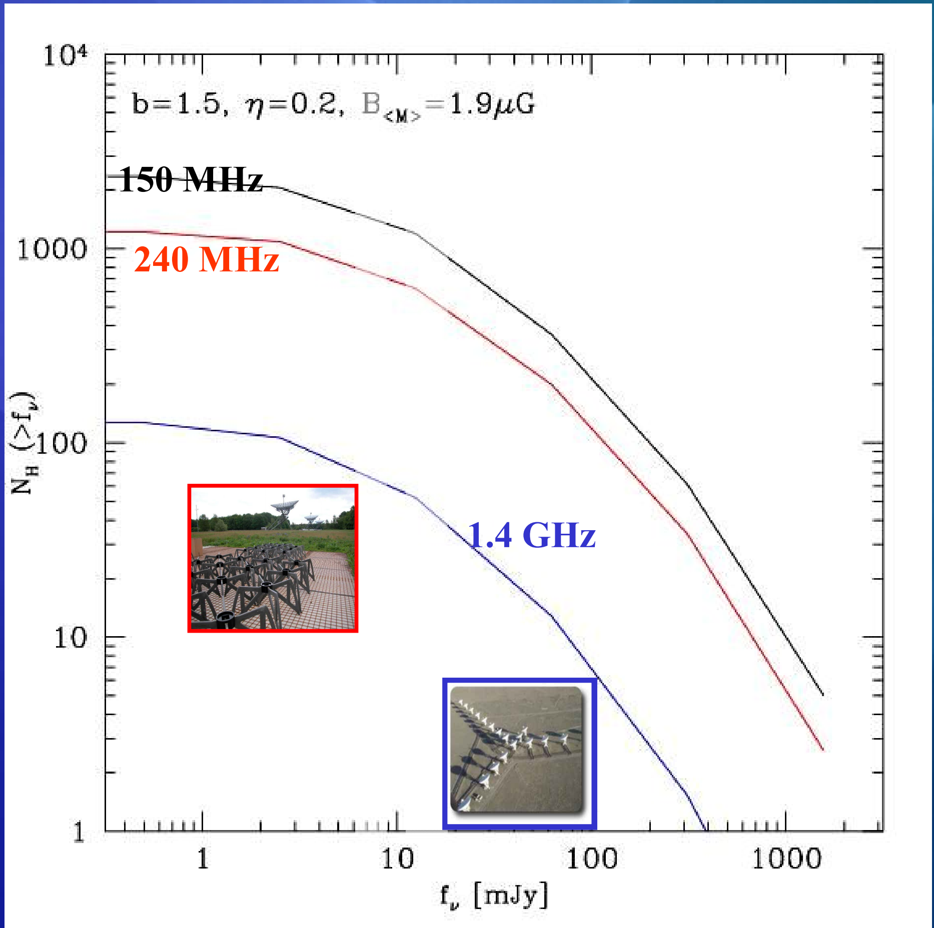
Cassano et al. 2008

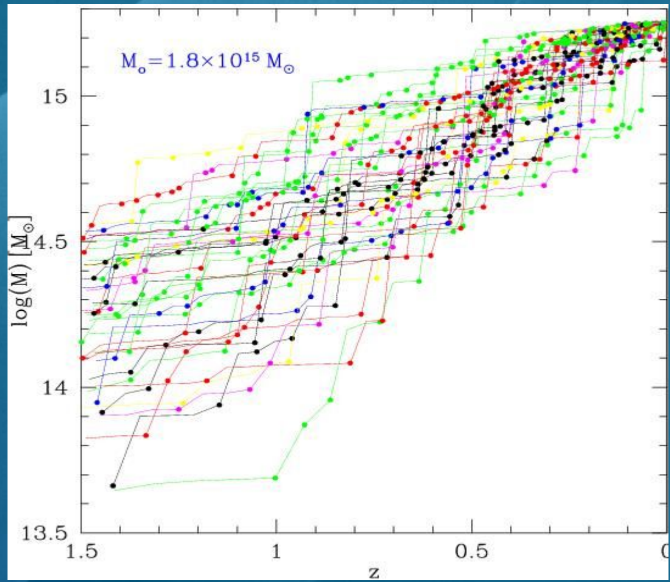


❖ The expected fraction of clusters with radio halos increases at low **ν**

❖ This increase is even stronger for **smaller clusters** ($M<10^{15} M_{\odot}$)

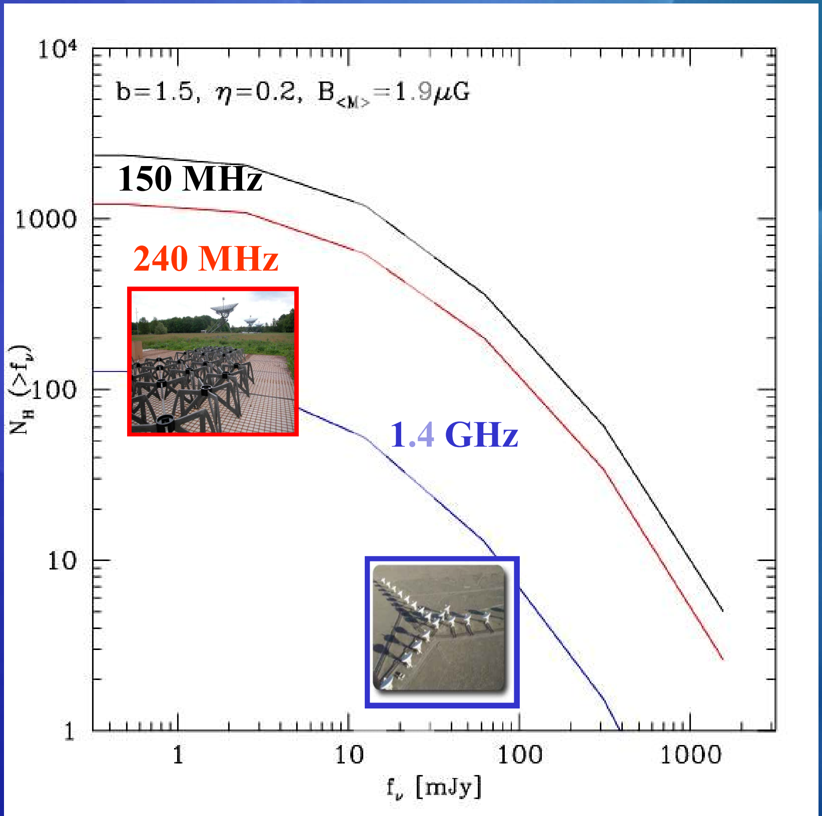
Radio halos in the LOFAR era …



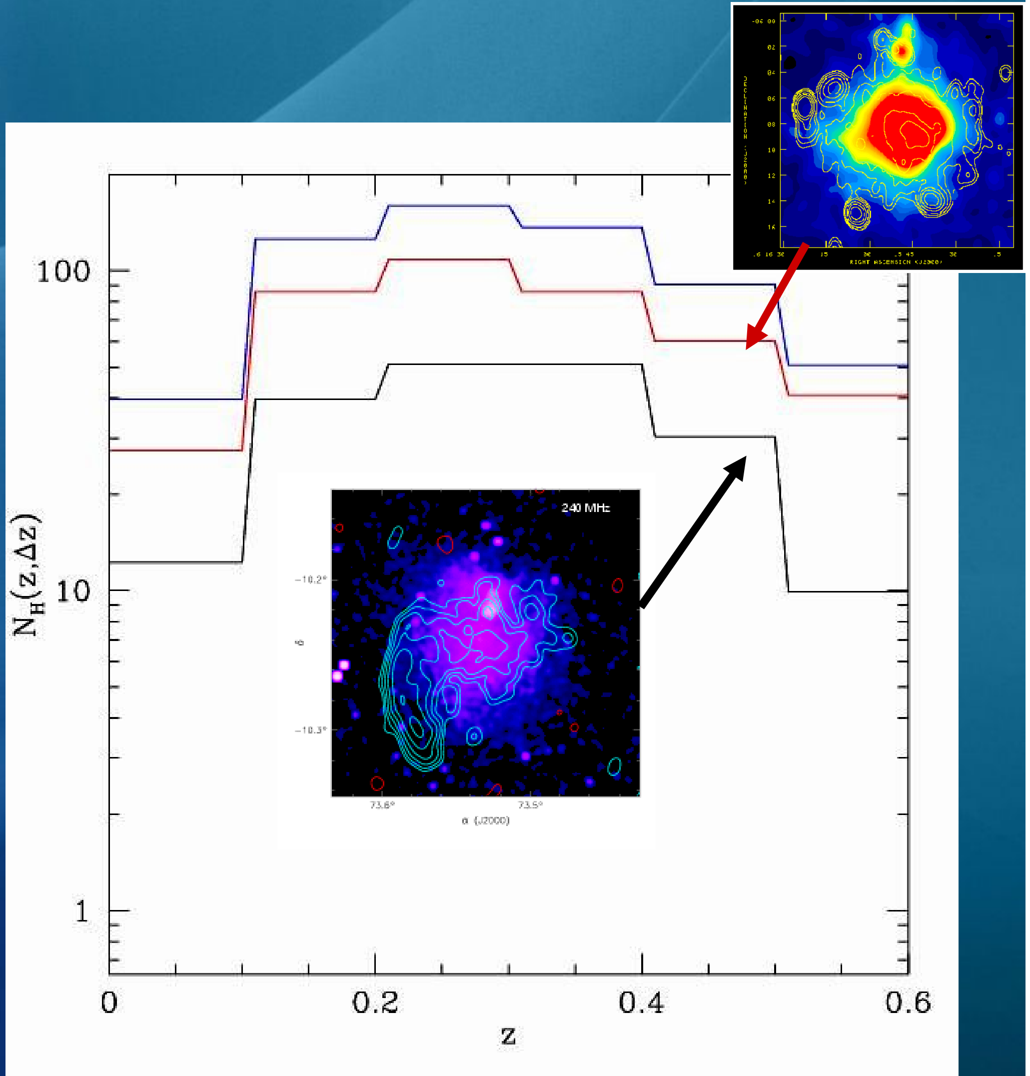


The number of radio halos detectable by deep low frequency observations is expected 10 times larger than that from present VLA observations at 1.4 GHz : **LOFAR** and LWA will catch these sources !

Radio halos in the LOFAR era ...



We expect that the number of RHs detectable by deep low frequency observations is 10 times larger than that from present VLA observations at 1.4 GHz : **LOFAR** and LWA would catch these RHs !



LOFAR "20" beam=25"x 25" Number counts at 120 MHz (Cassano et al., in prep.).

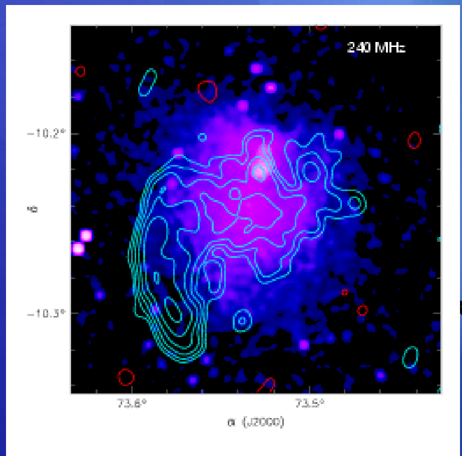
Radio halos at lower radio frequencies

Radio Power

LOFAR

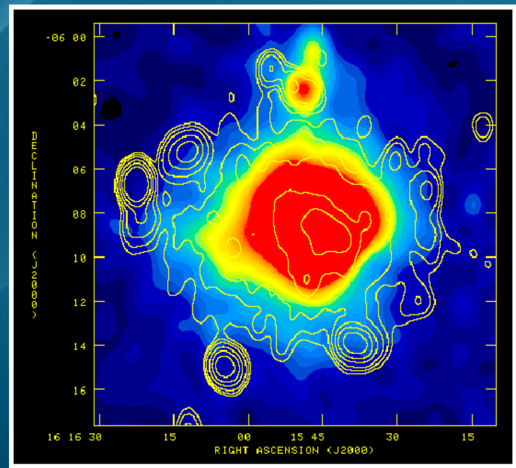
LWA

NOW



LOFAR should discover those RH associated with the most common and less energetic phenomena!

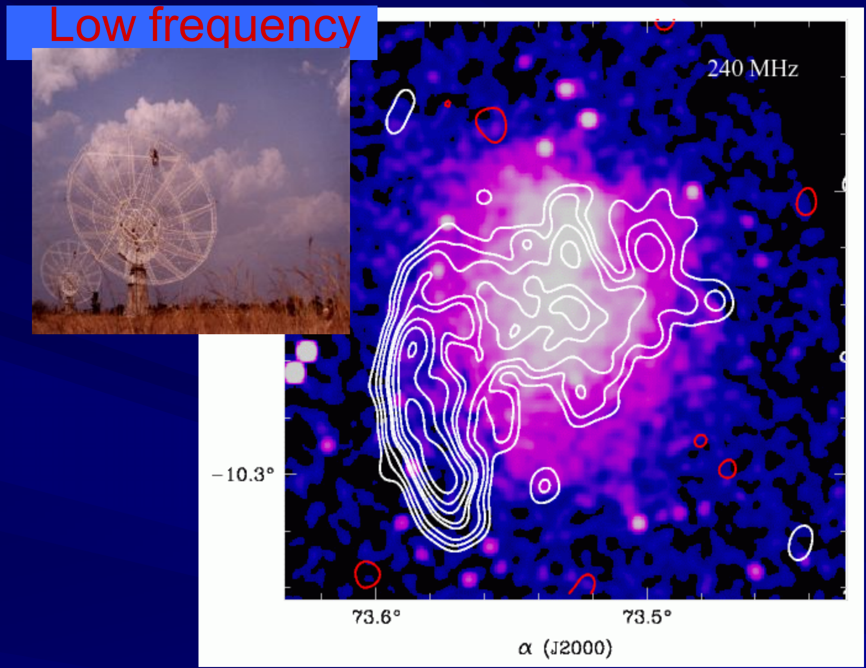
NOW we see RH associated with the most energetic phenomena!

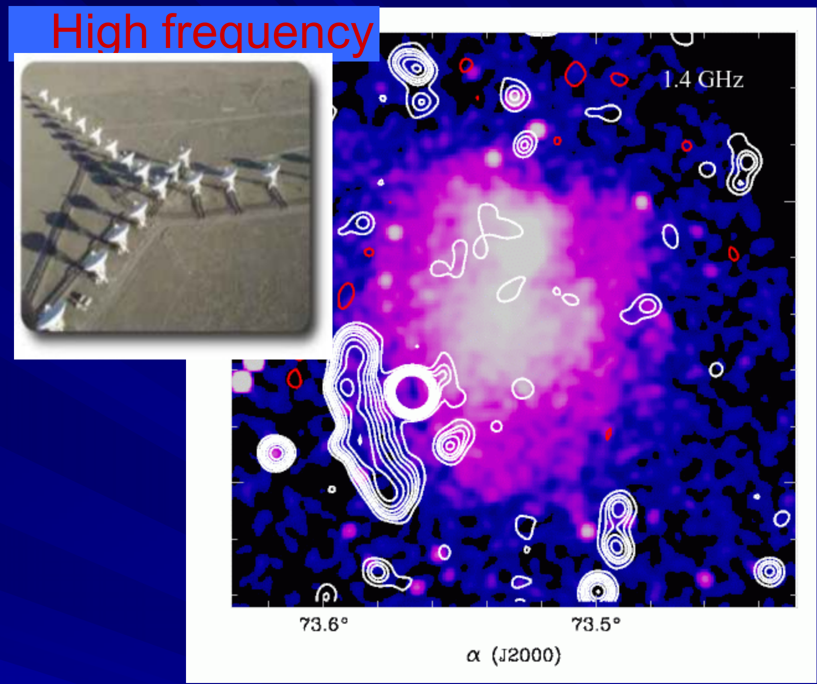


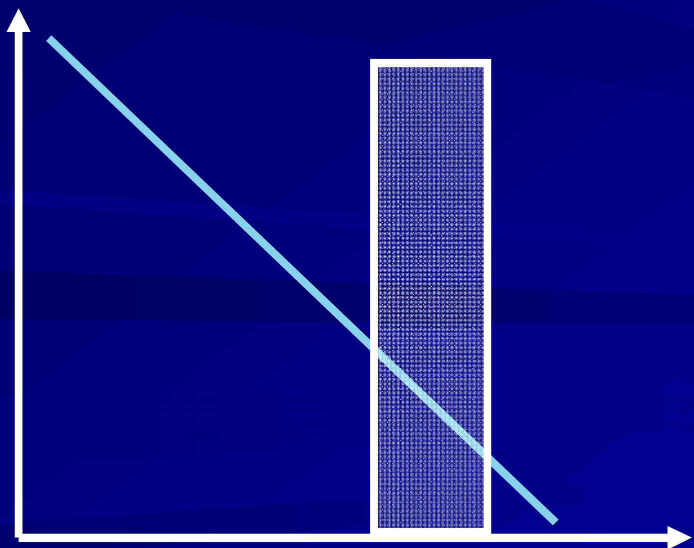
Frequency

~ GHz

Do they exist ? (Brunetti +al. 2008, Nature 455,944)



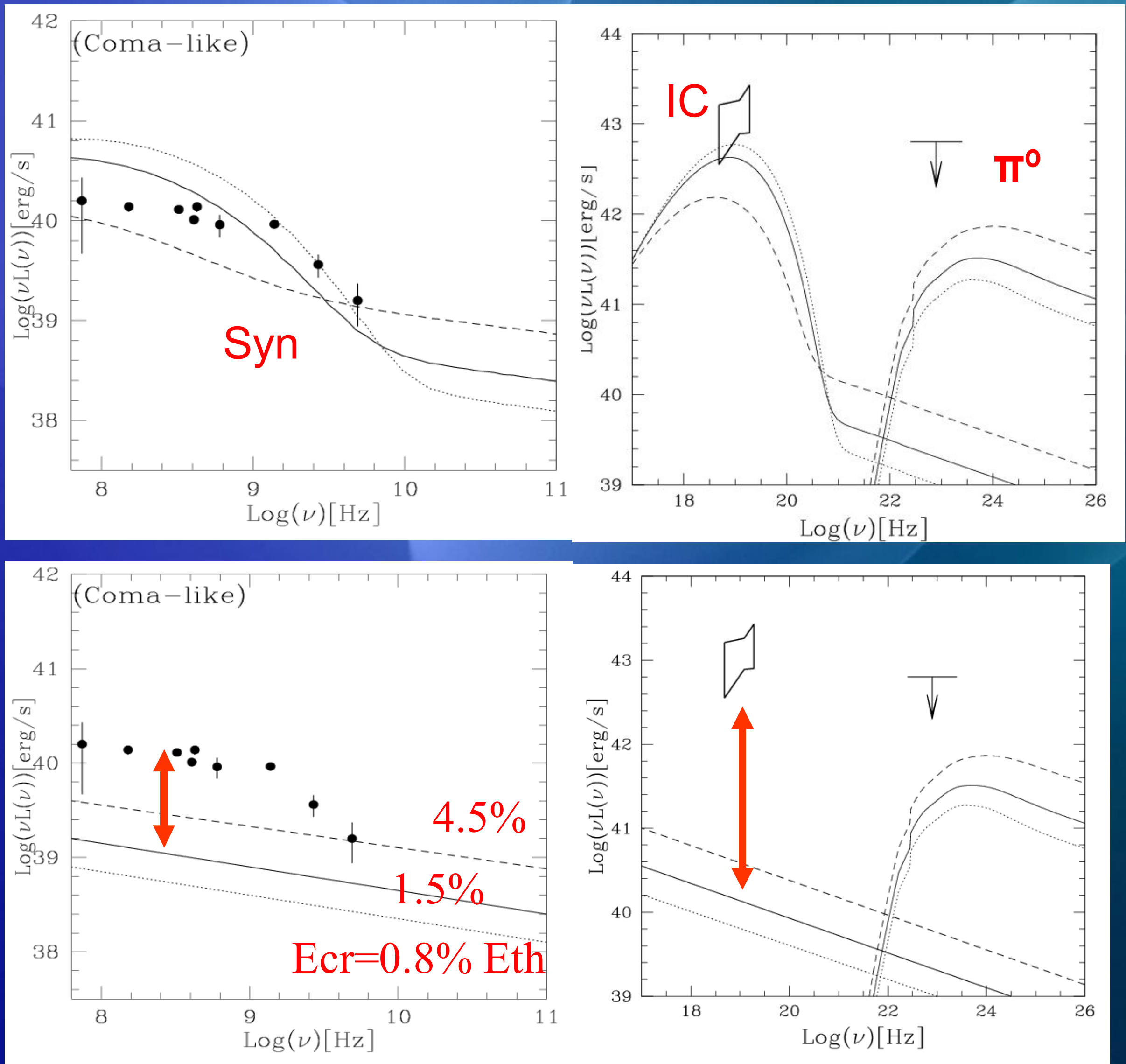


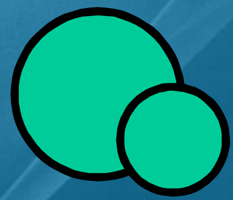


Supposing that the observed synchrotron radiation is from secondary electrons generated during p-pcolisions in theIGM
.. we arrive at the untenable scenario of a relativistic proton population whose energy density exceeds that of the thermal IGM

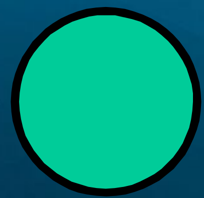
General multiwavelength expectations

Brunetti 2008; Brunetti +al. 2009





MERGING CLUSTERS



ALL CLUSTERS

General multiwavelength expectations

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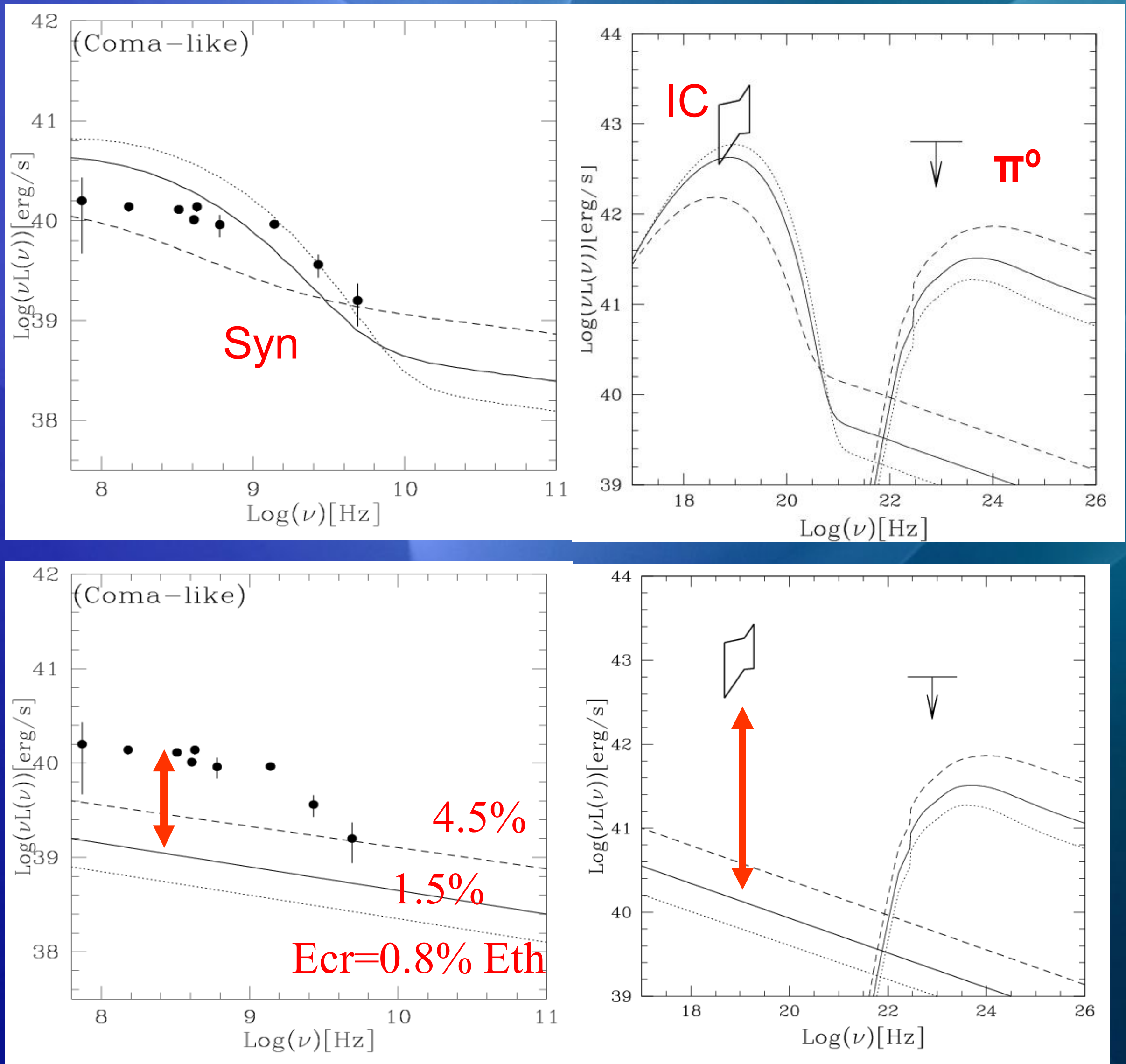
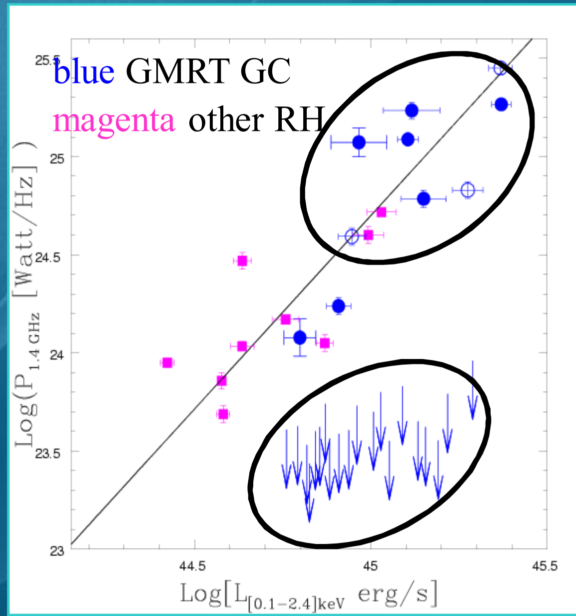
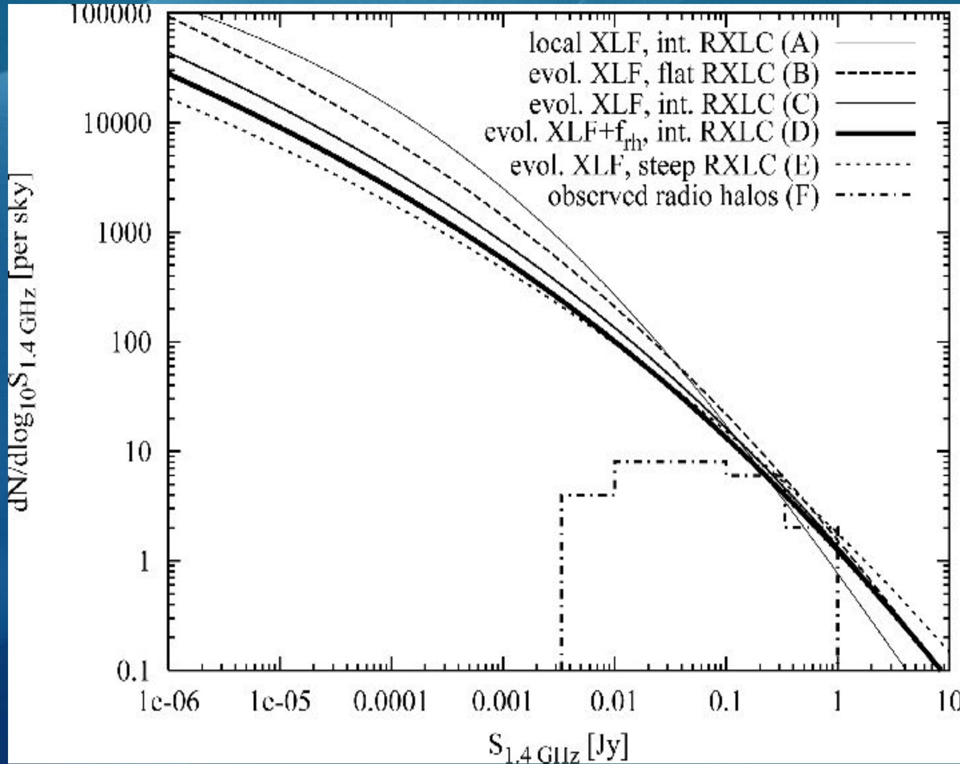




TRANSIENT PHENOMENA

Why low frequency ?

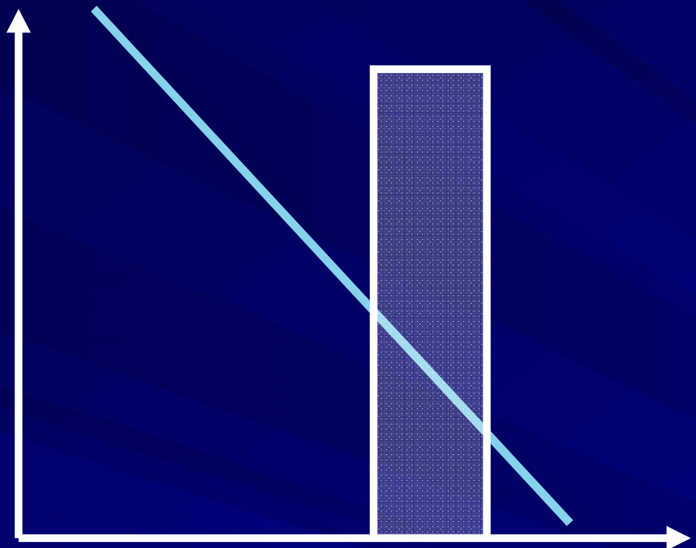
Ensslin & Roettgering 2002

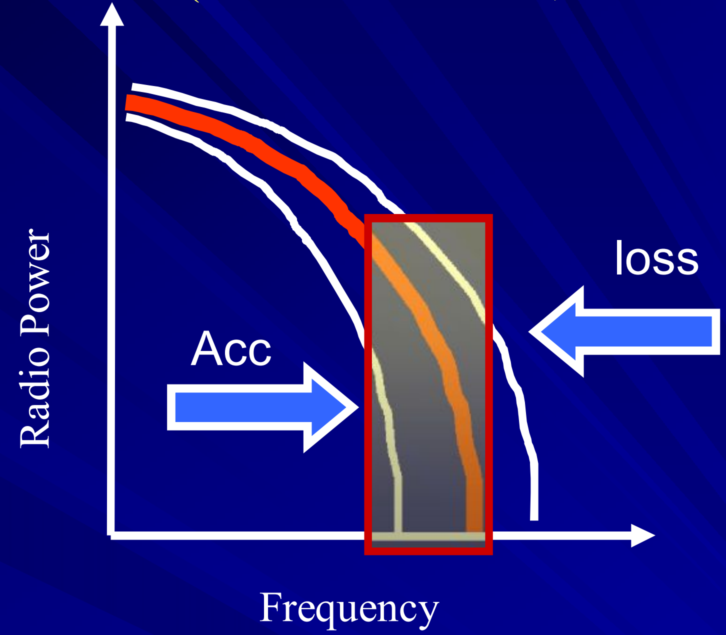


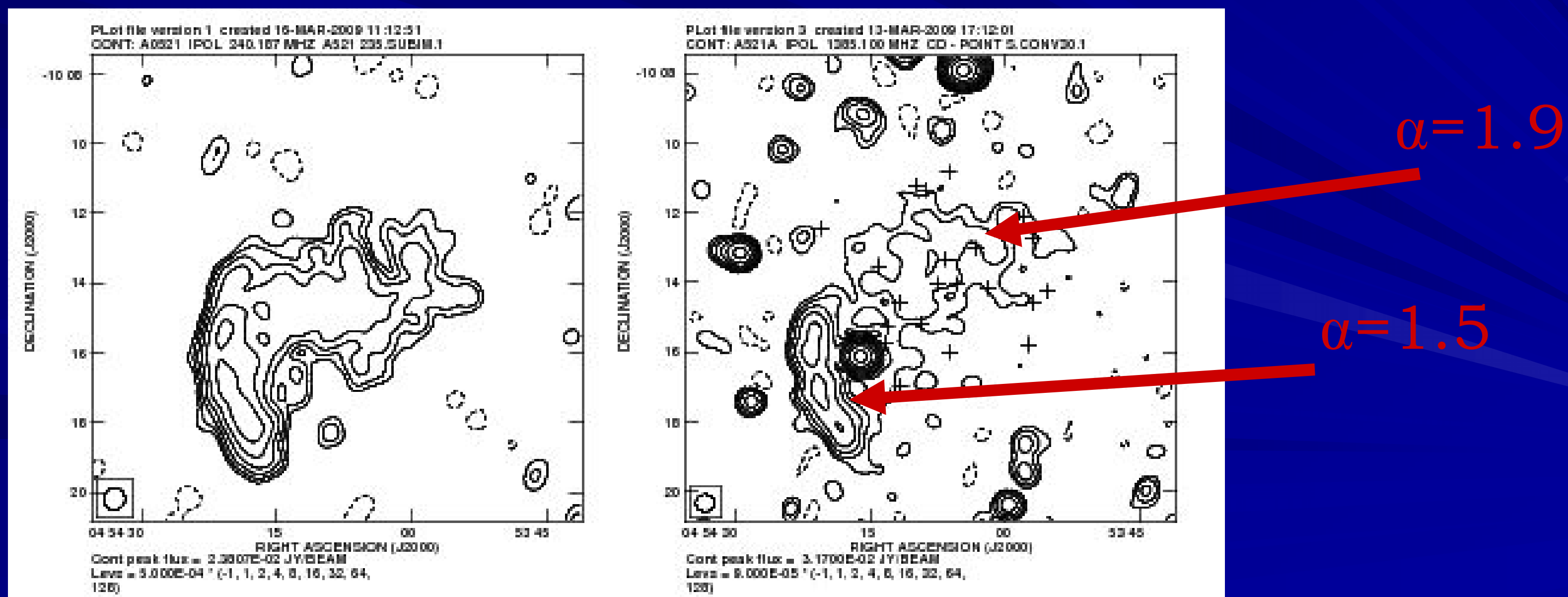
Regardless of the origin of Radio Halos, extrapolations of their number counts at 1.4 GHz based on the Radio-X ray correlation observed for Radio Halos suggest that a large fraction of these Halos is at faint fluxes.

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.

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







Dallacasa + al. ApJL sumbitted

The LOFAR Array

- Core area - 2 km around Exloo
  - Min. 18 stations
- Remote stations - 100 km
  - Min. 18 stations
- International stations
  - Min. 8 stations

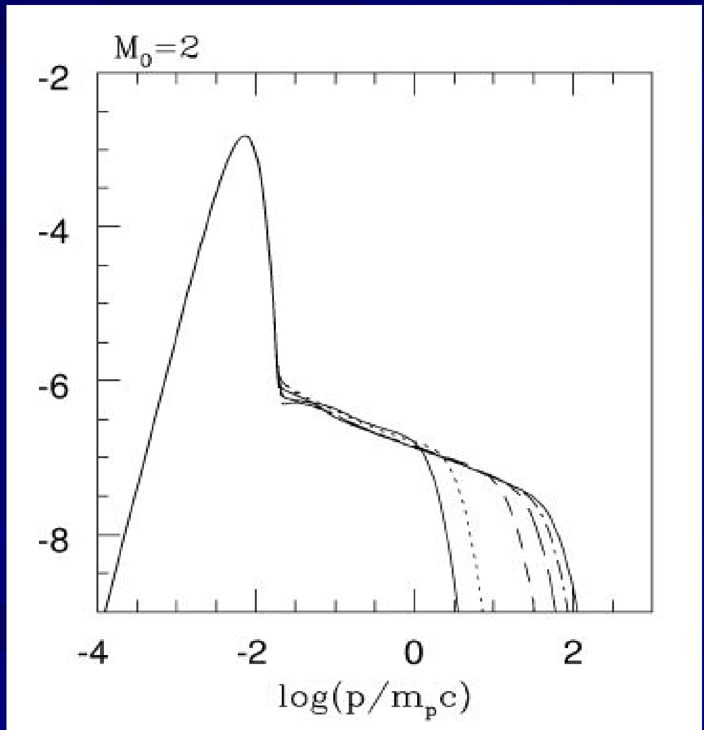
Acceleration of CRp at shocks

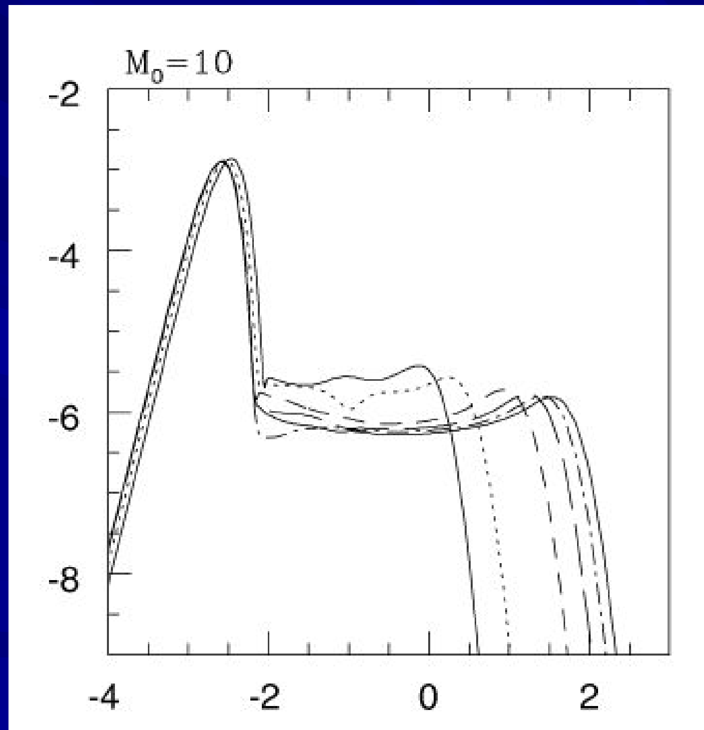
$N(p) \propto p^{-\delta}$

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

Linear Theory
(e.g.,Blandford & Eichler 1987)

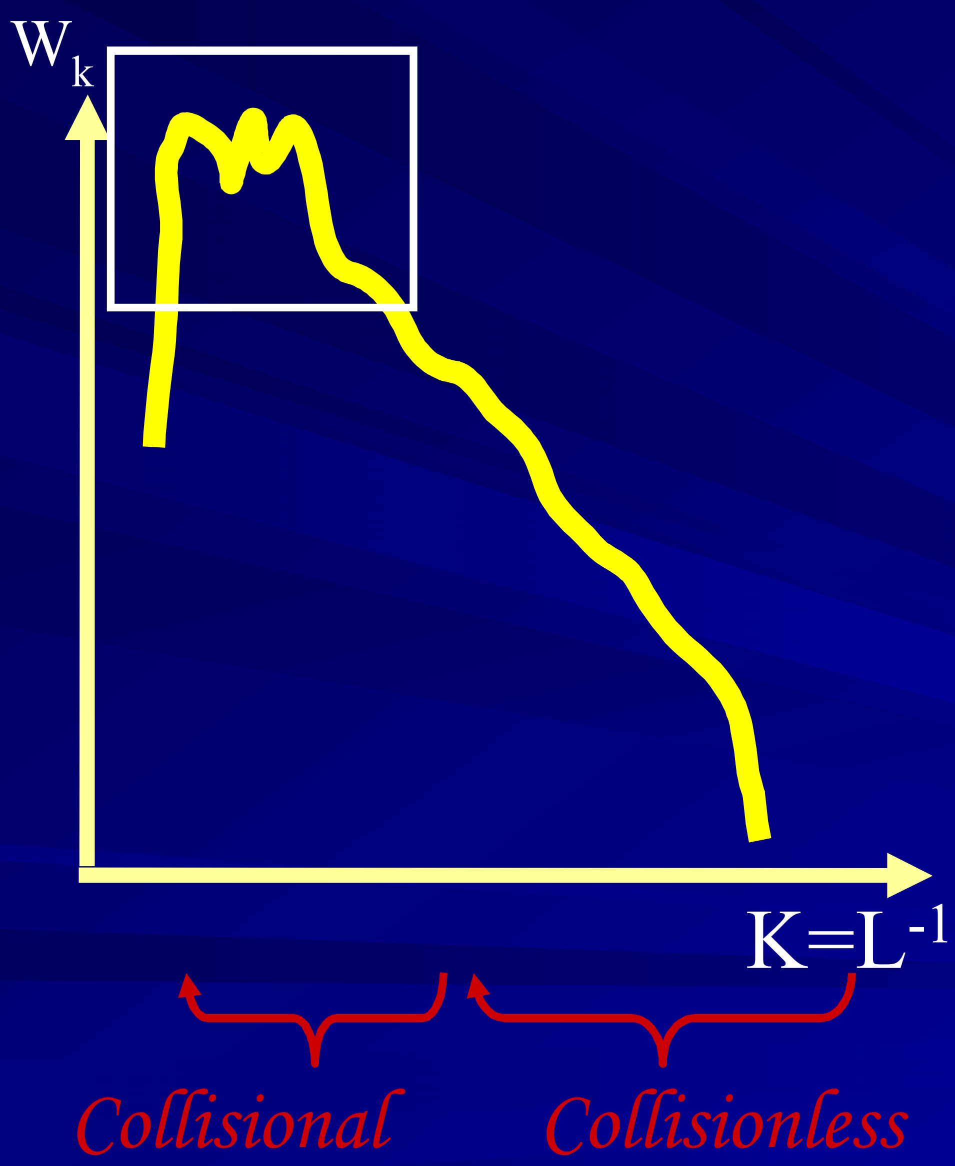
Np^2

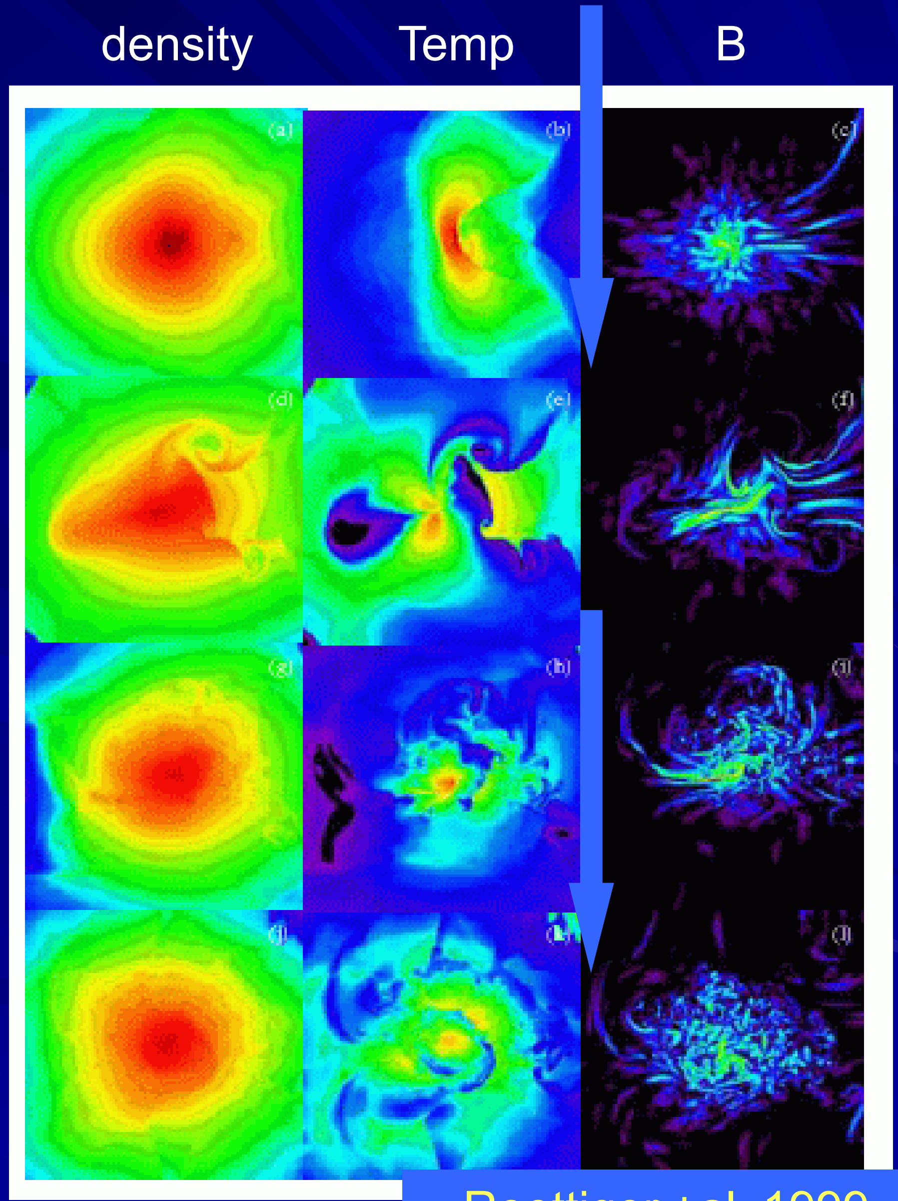




(Kang & Jones 2002; **Malkov 1997, Kang & Jones 2005, 07, Amato & Blasi 2006)**

Turbulence in the ICM

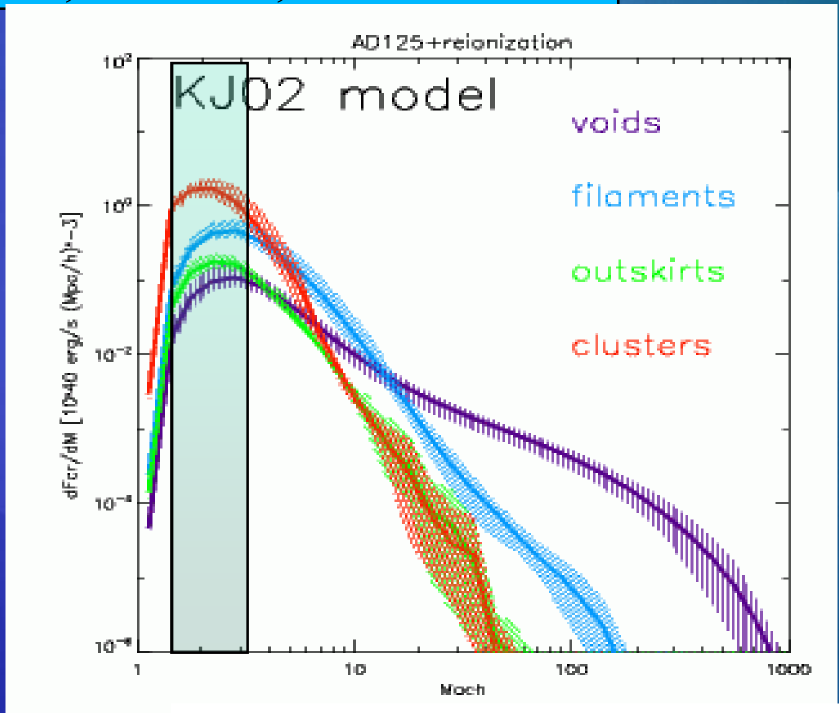




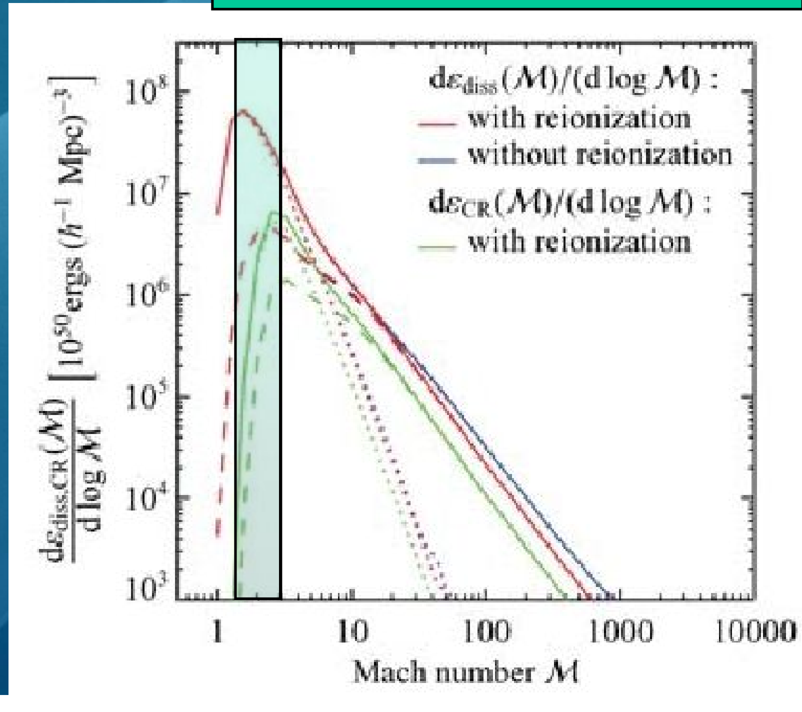
Roettiger +al. 1999

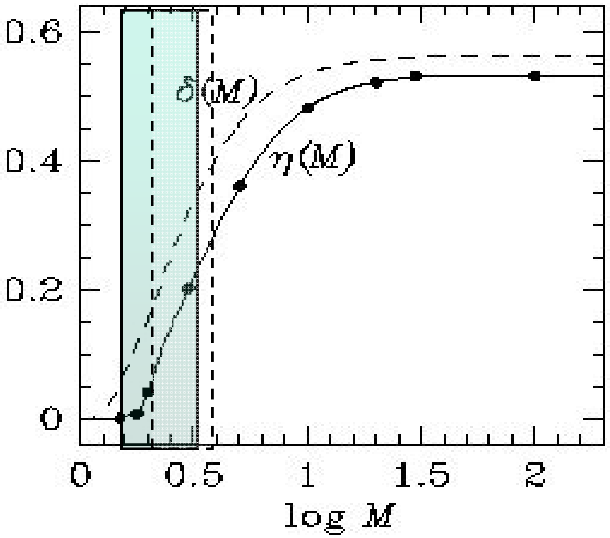
Shocks in Galaxy Clusters (I)

Vazza, Brunetti, Gheller 2008

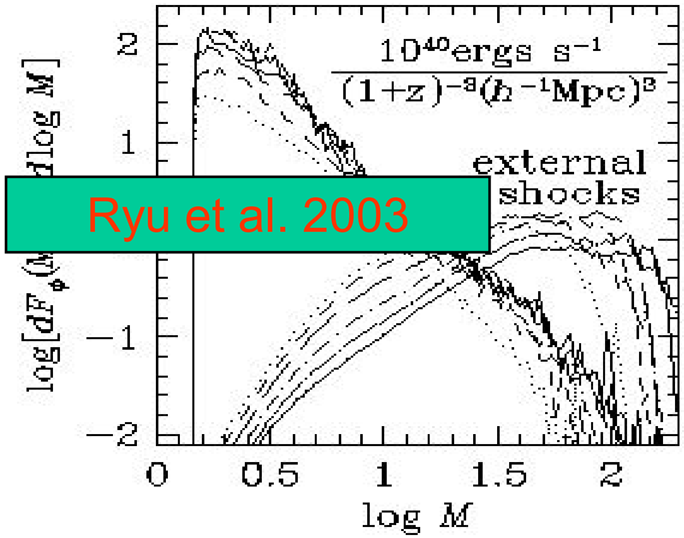


Pfrommer et al. 2008

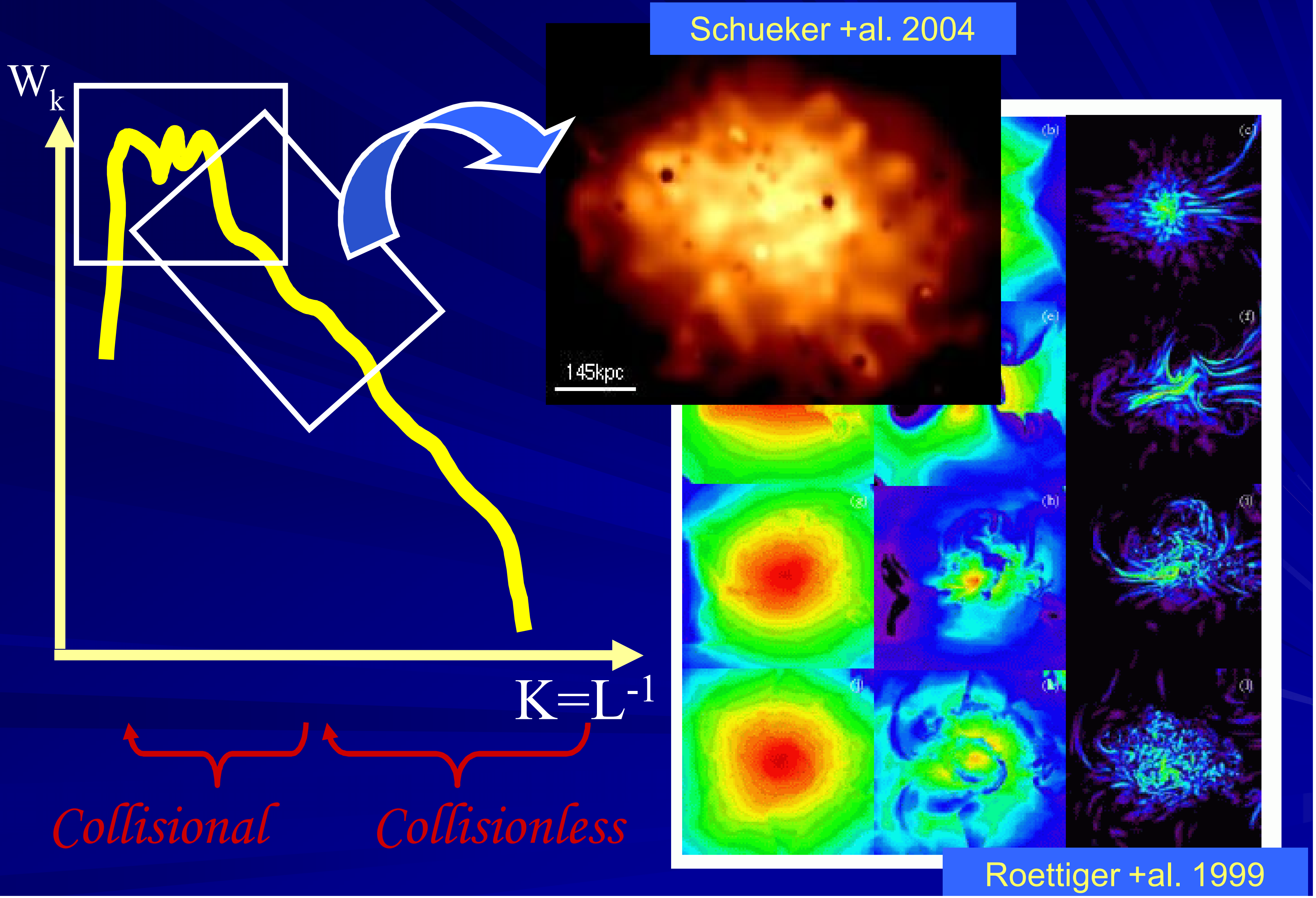




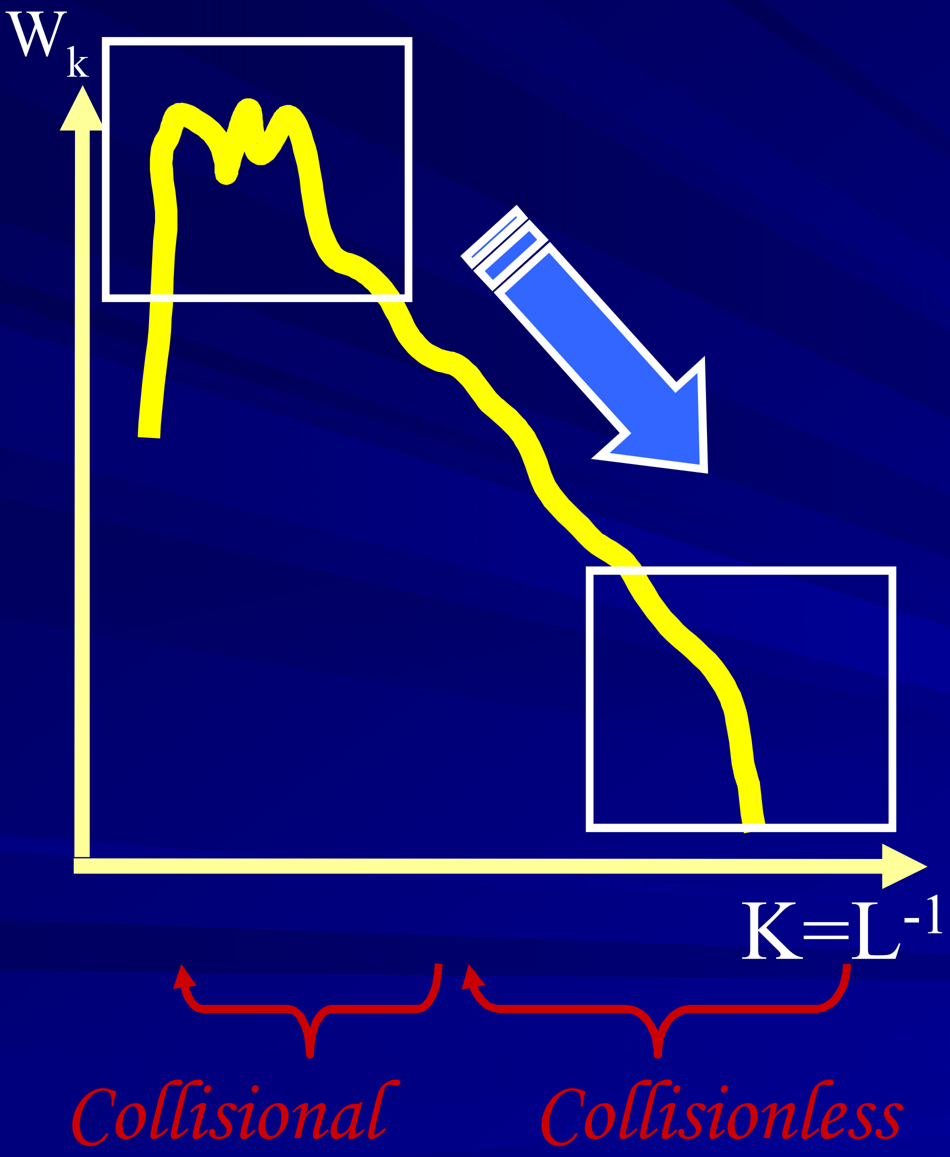
Ryu et al. 2003

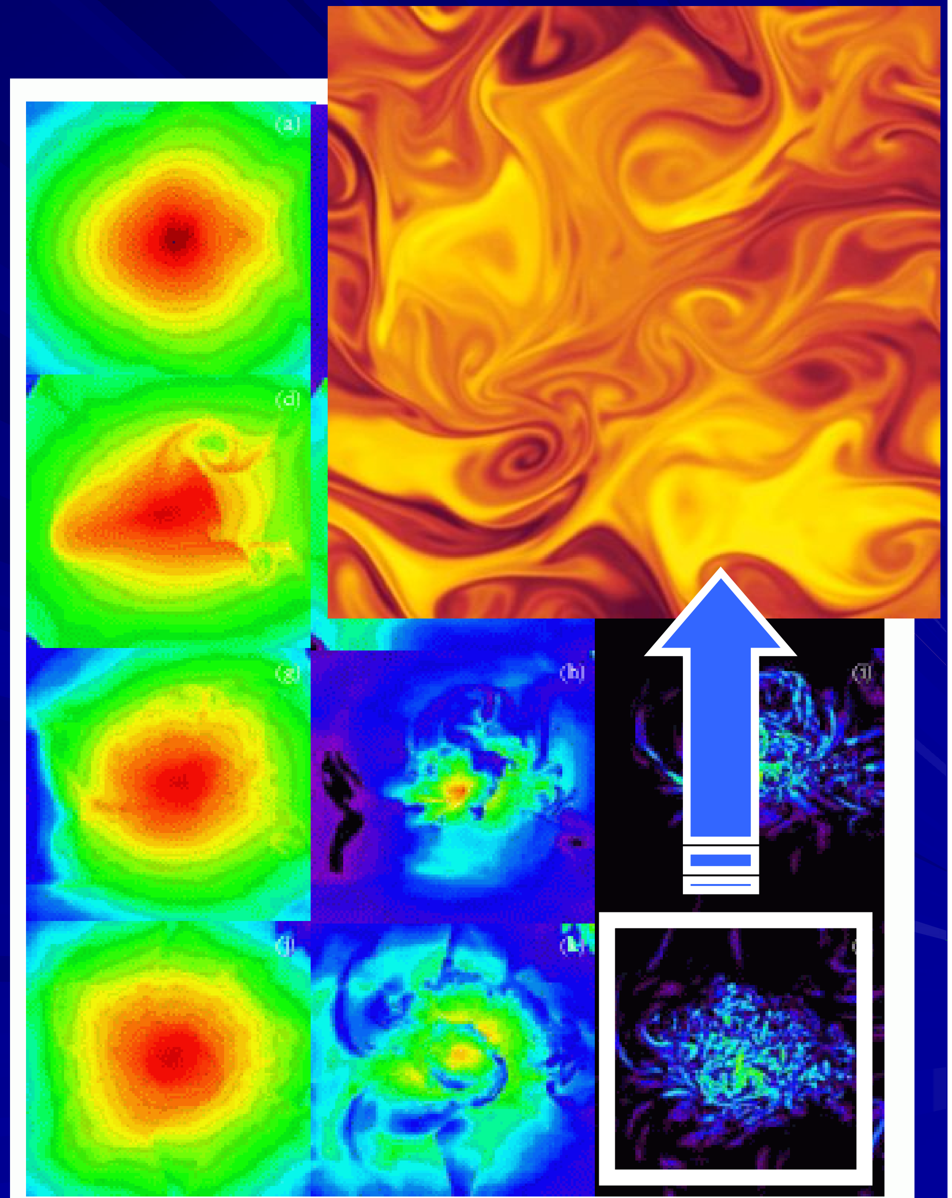


Turbulence in the ICM

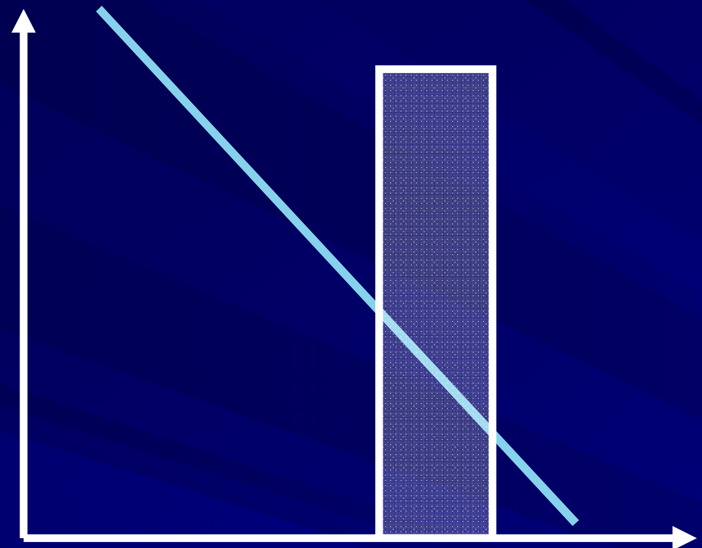


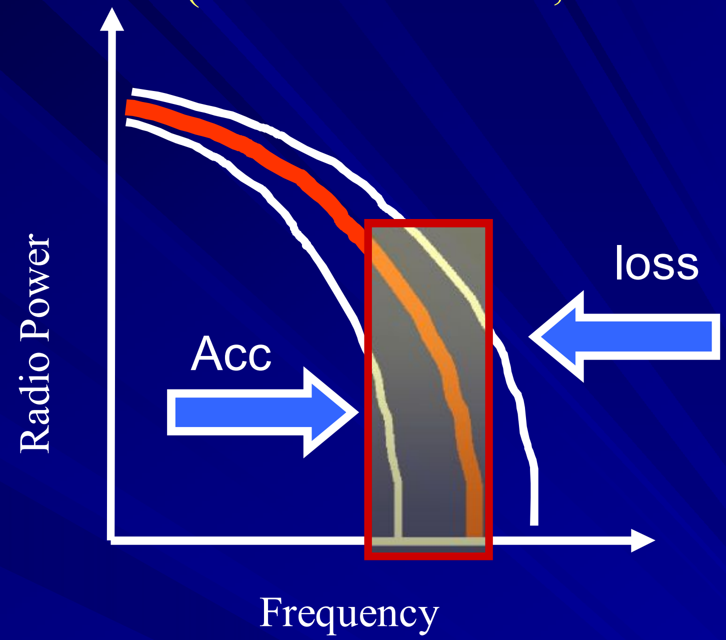
Turbulence in the ICM

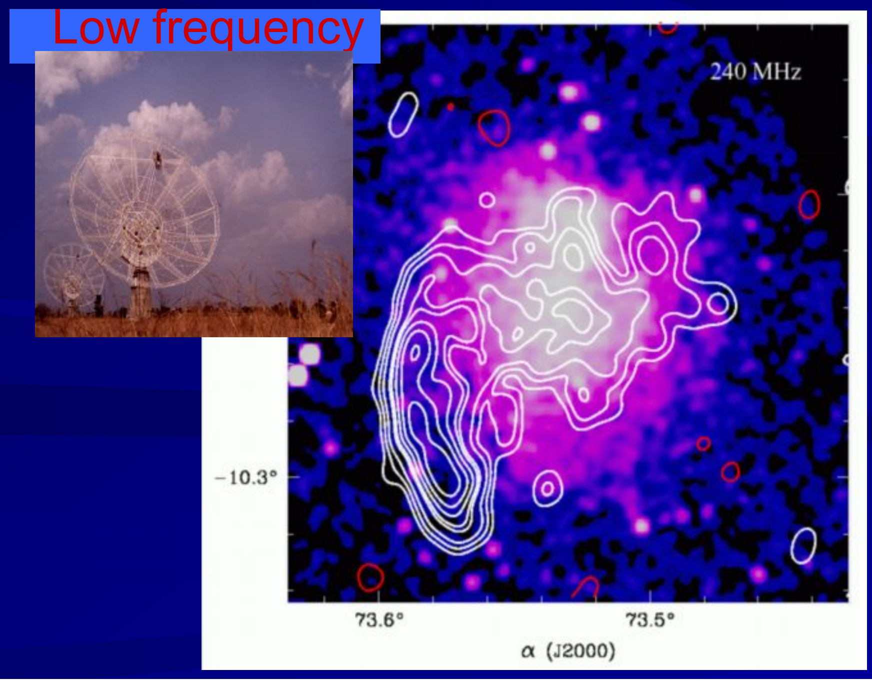


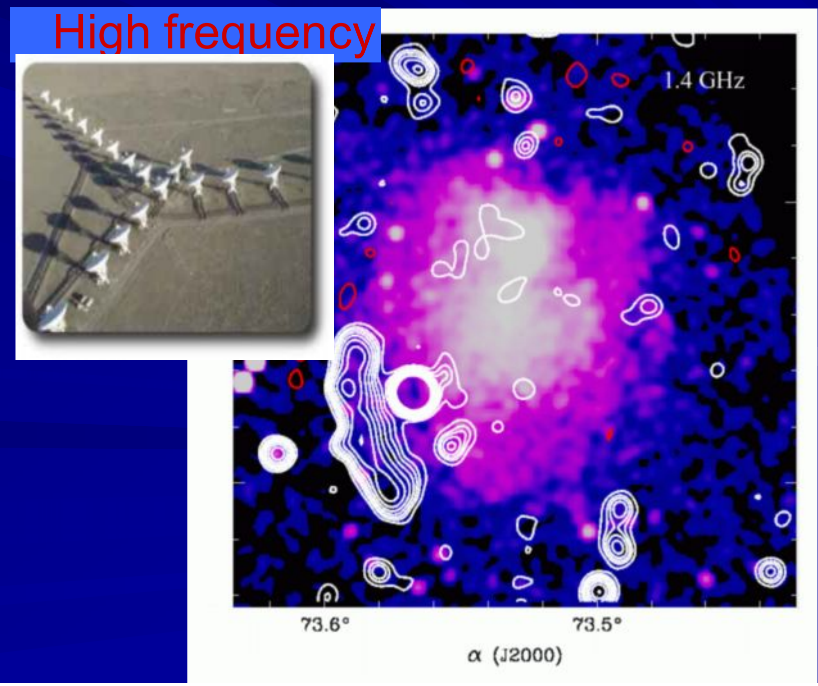


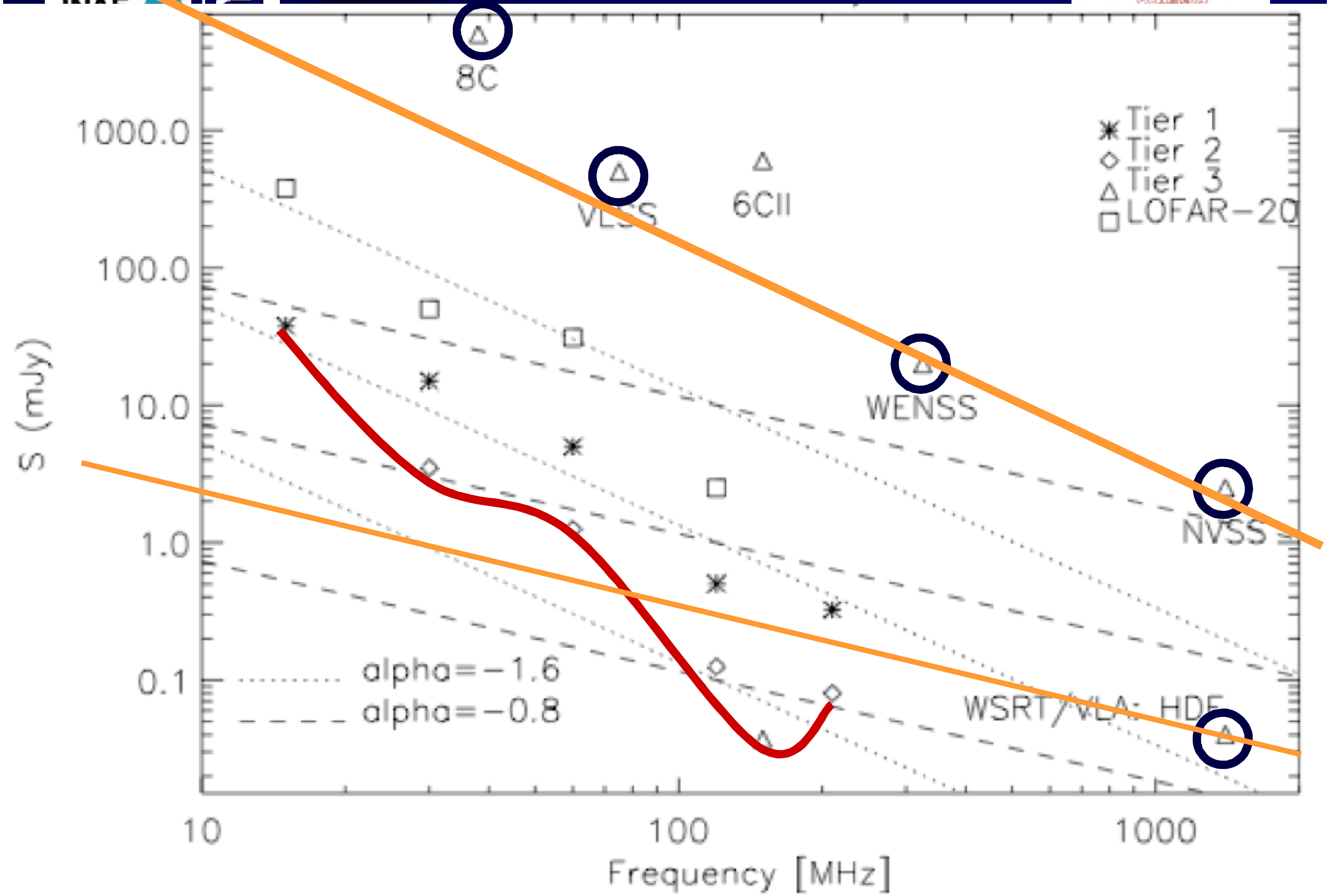
Turbulent acceleration in GC (Brunetti +al. 2008, Nature 455,944)





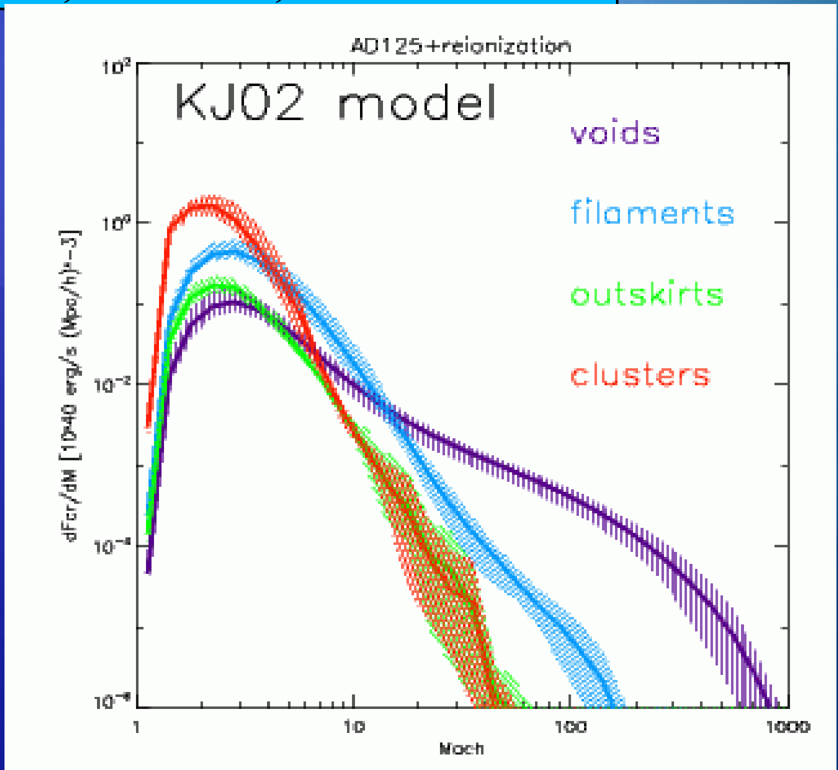




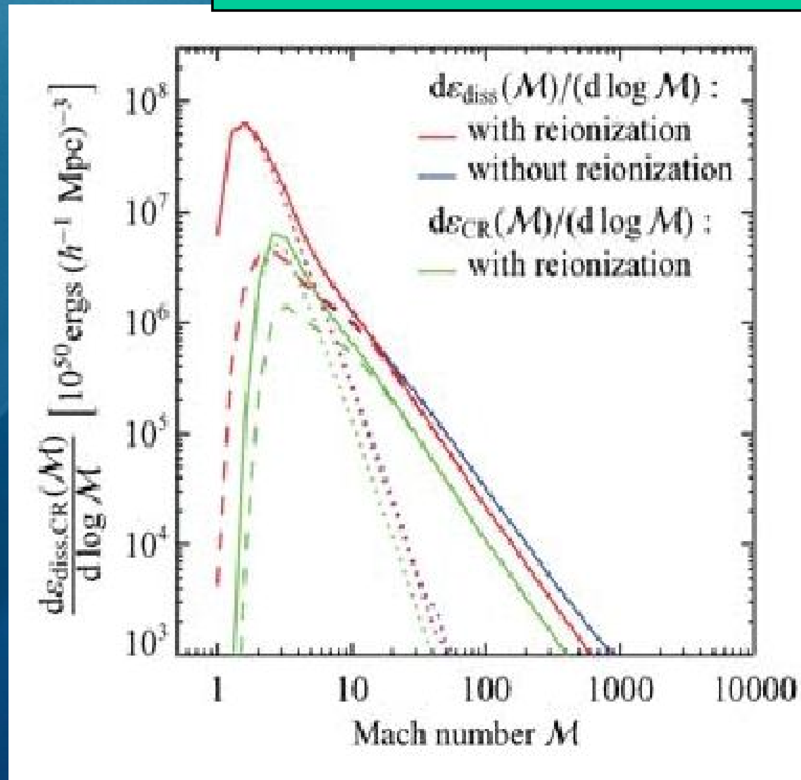

8C
1000.0
100.0
10.0
1.0
0.1
S (mJy)
Tier 1
Tier 2
Tier 3
LOFAR−20
VLSS
6CII
WENSS
NVSS
alpha=−1.6
alpha=−0.8
WSRT/VLA: HDF
10
100
1000
Frequency [MHz]

Shocks in Galaxy Clusters

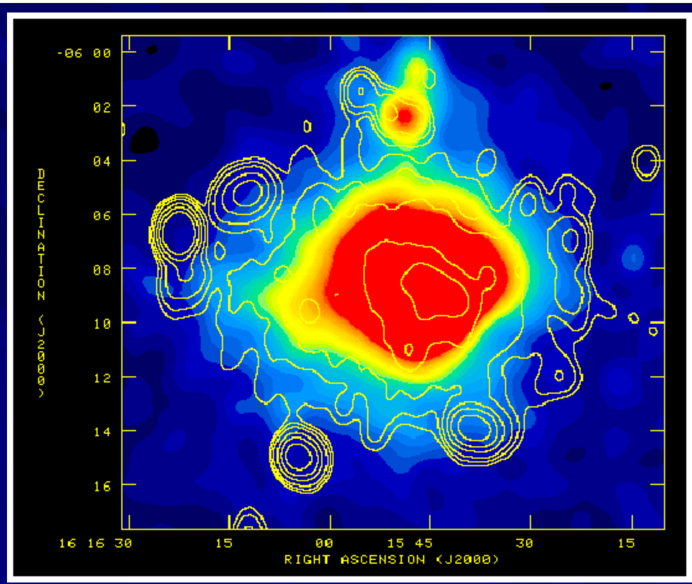
Vazza, Brunetti, Gheller 2008



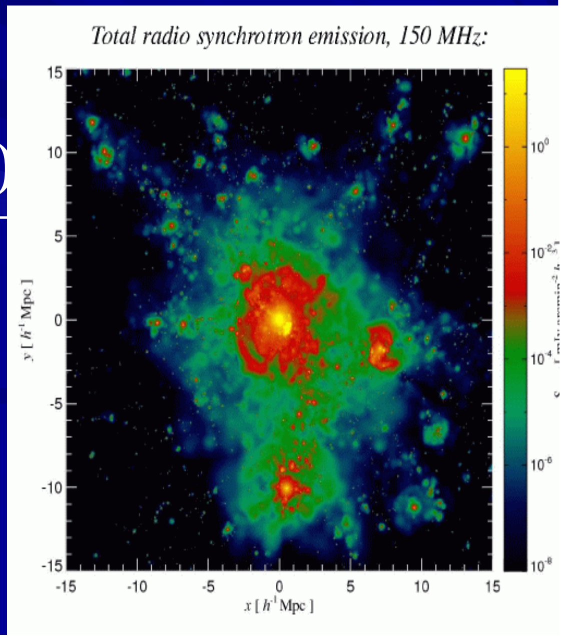
Pfrommer et al. 2008



Origin of the emitting electrons



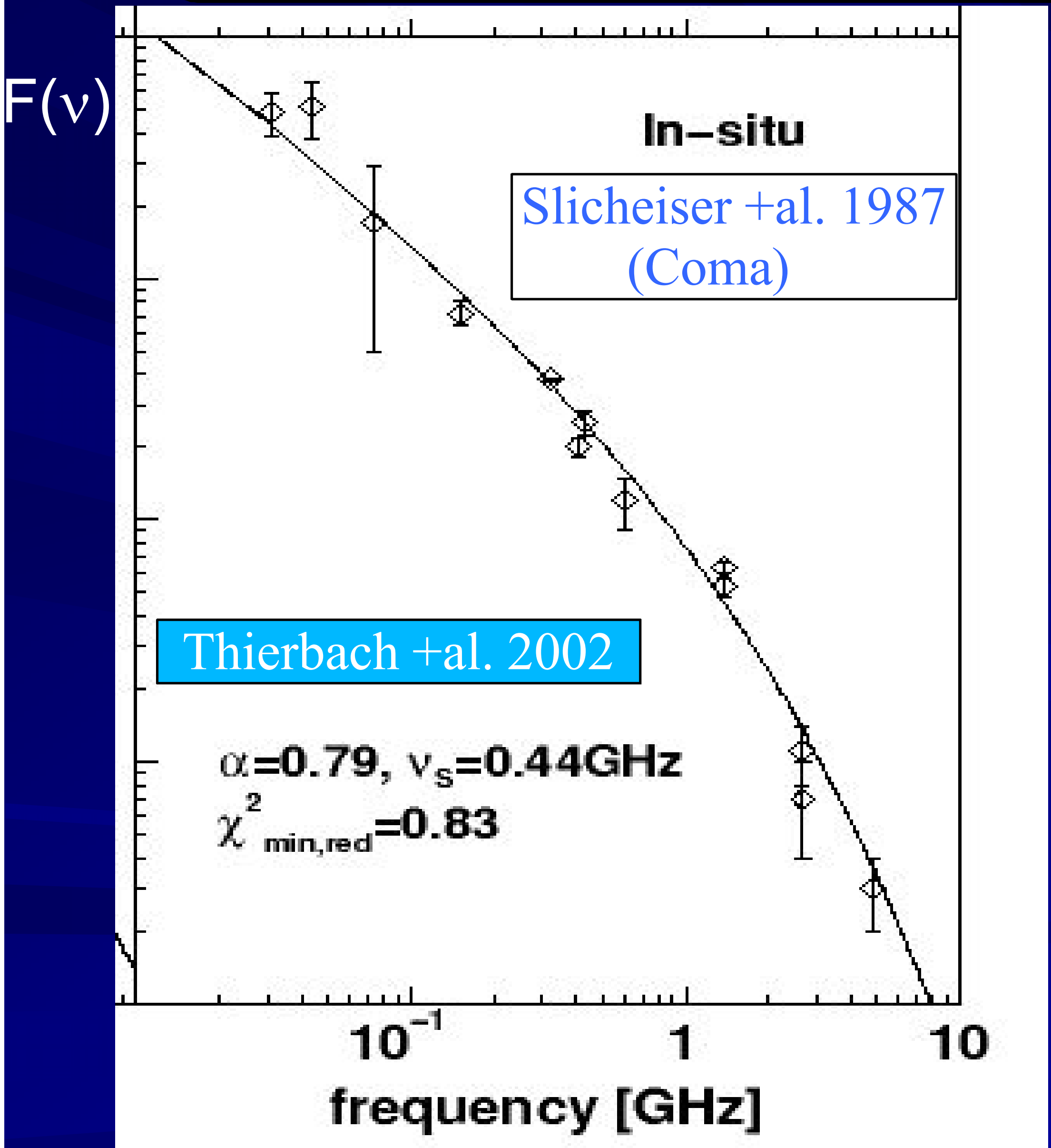
First possibility: *secondary models,* **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions (e.g.,** *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004,08***)**



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 ?

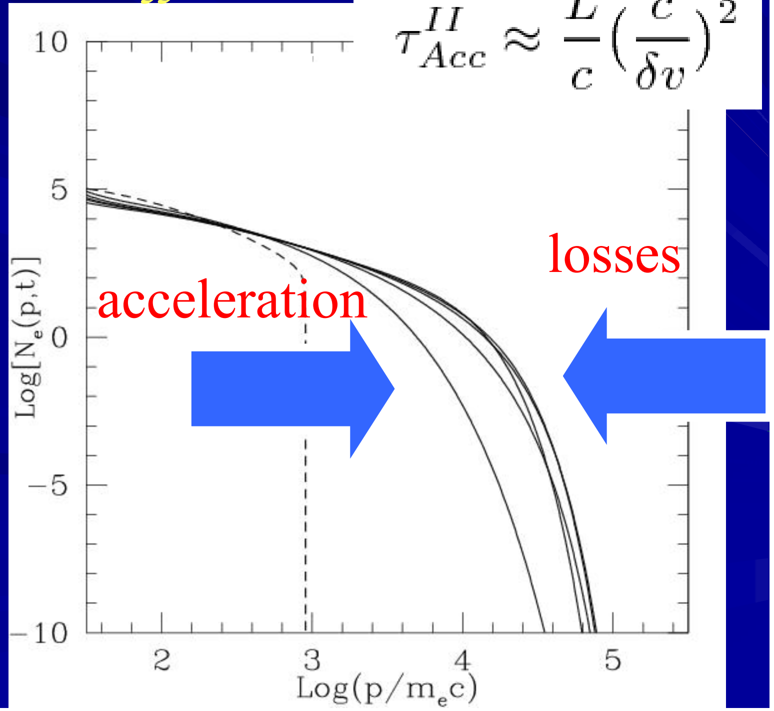
Observations: Spectral Cut-Off



We expect a break in the spectrum of the emitting electrons at energies of few GeV

Acceleration mechanism not efficient !

$$\tau^{II}_{Acc} \approx \frac{L}{c}\left(\frac{c}{\delta v}\right)^2$$



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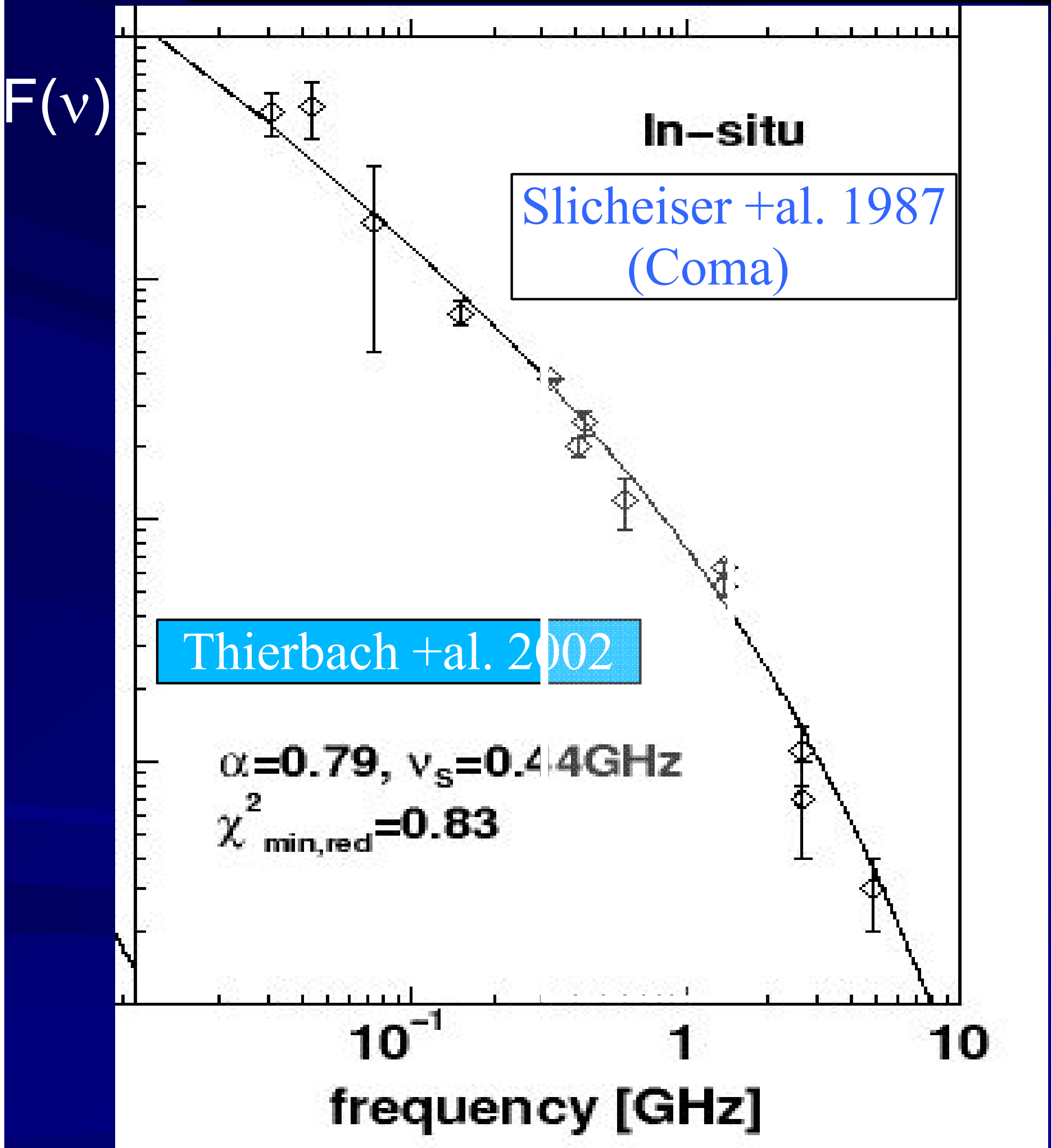

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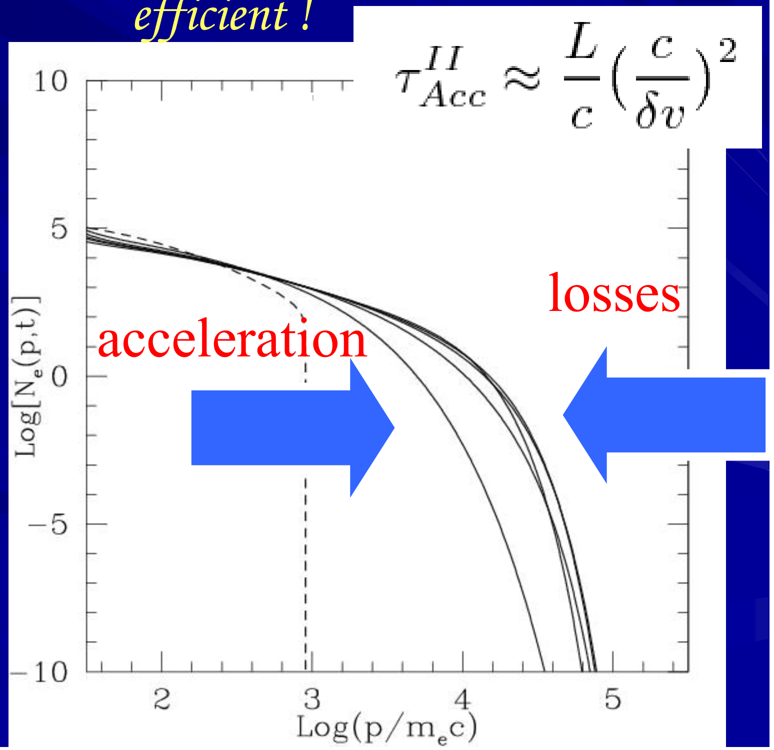

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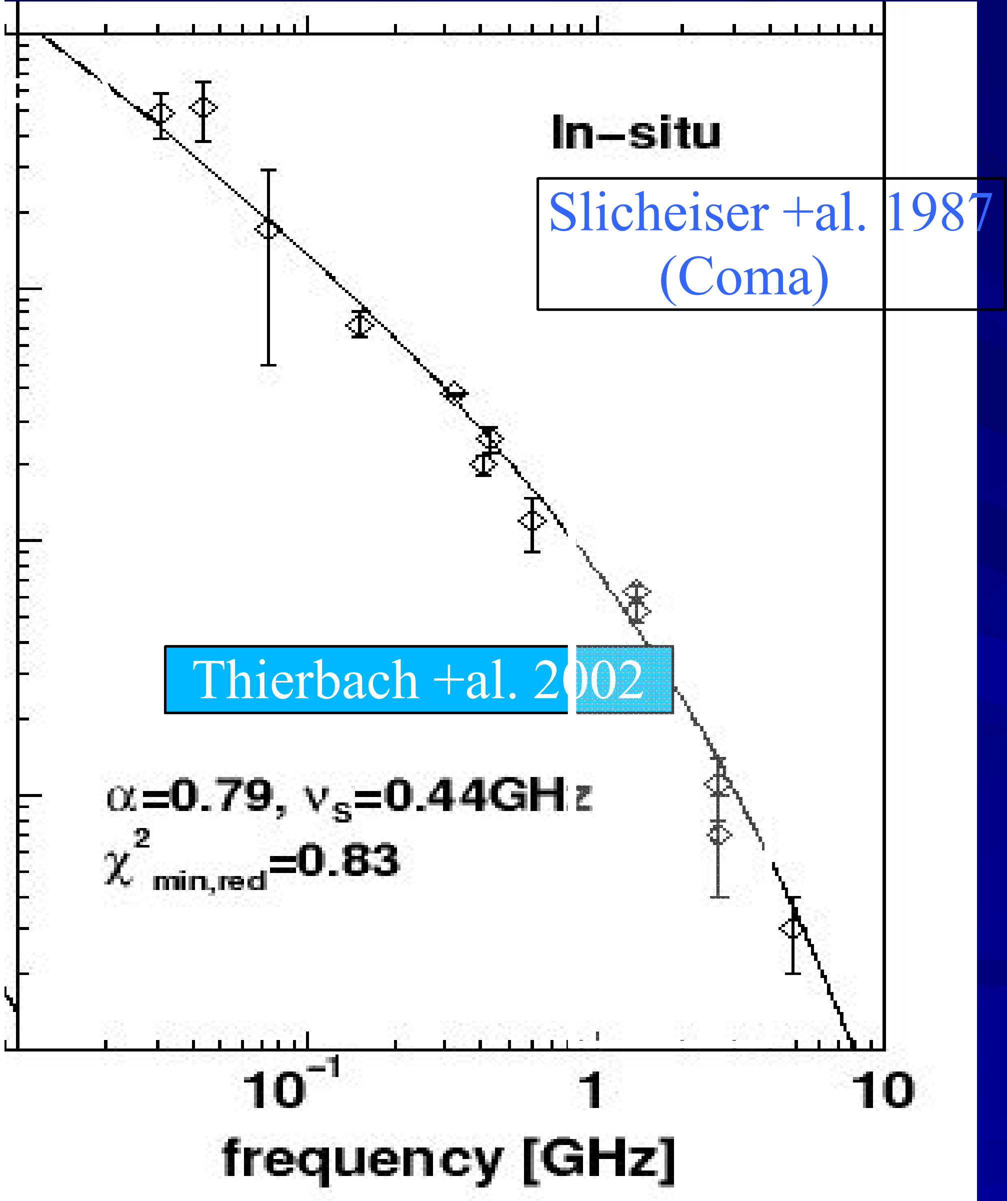

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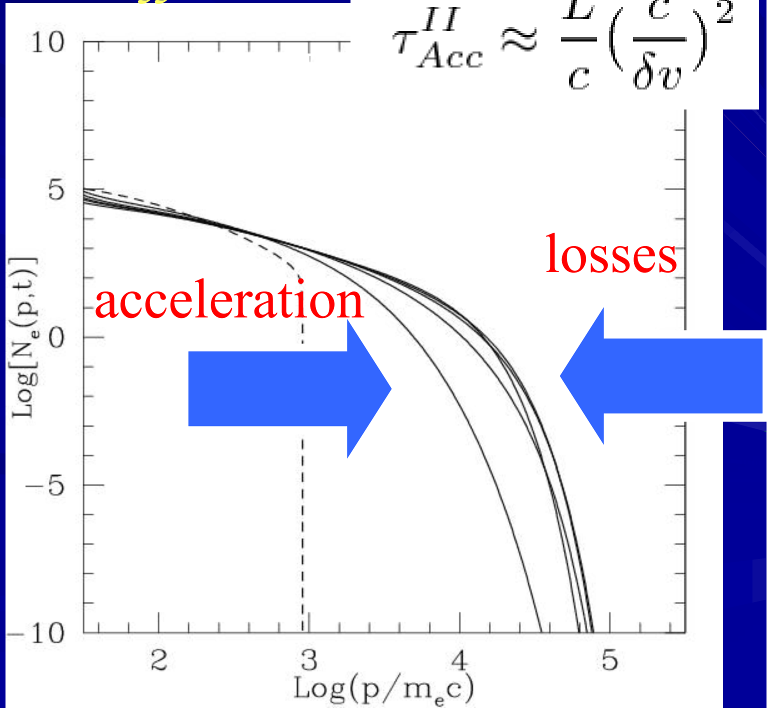
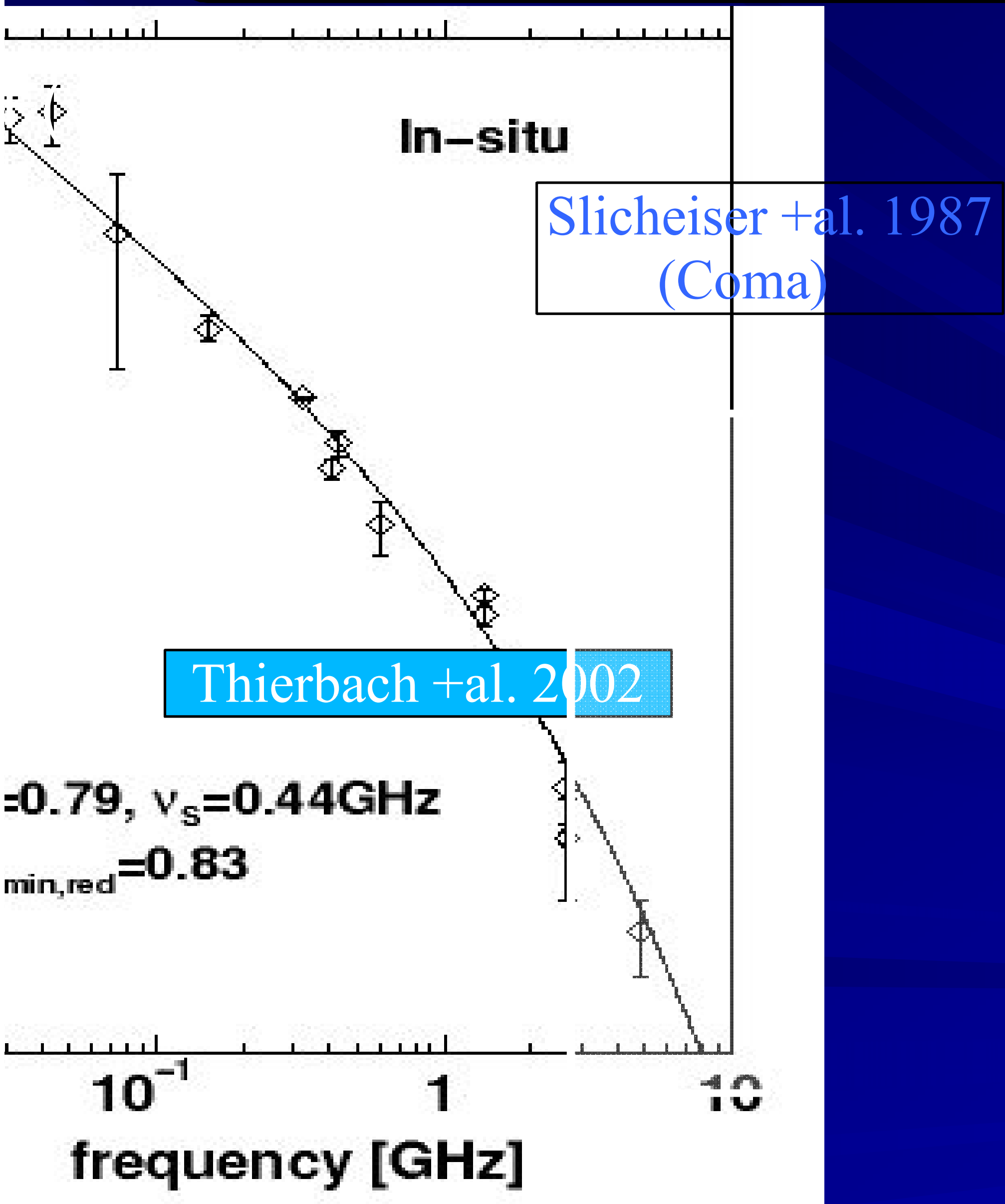


Observations: Spectral Cut-Off



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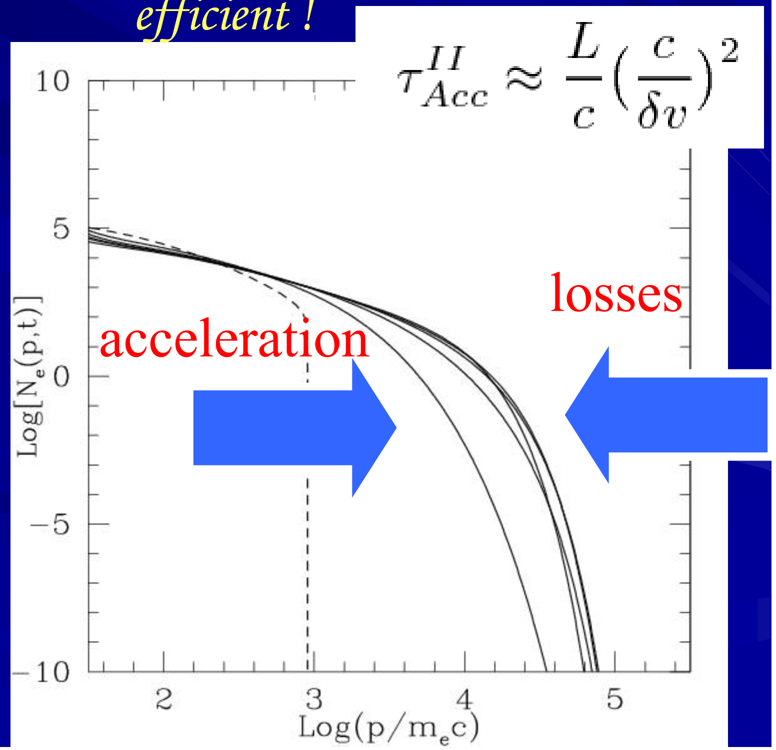
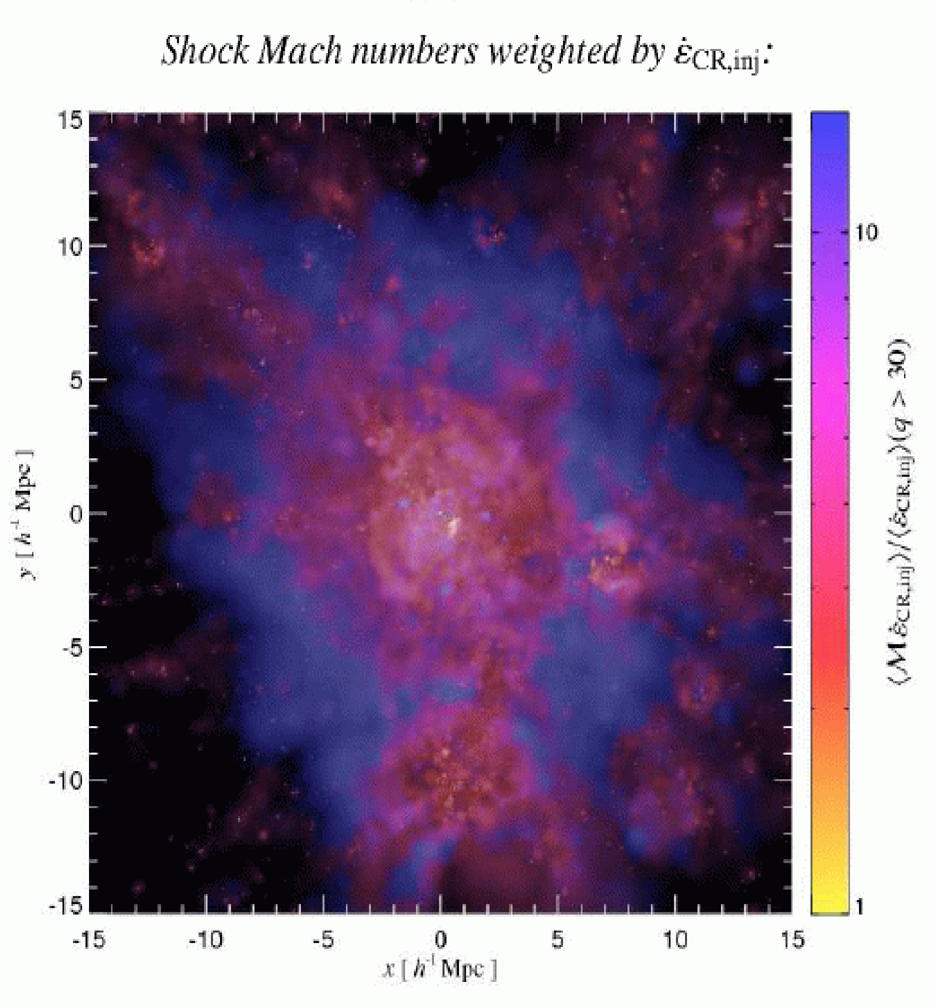
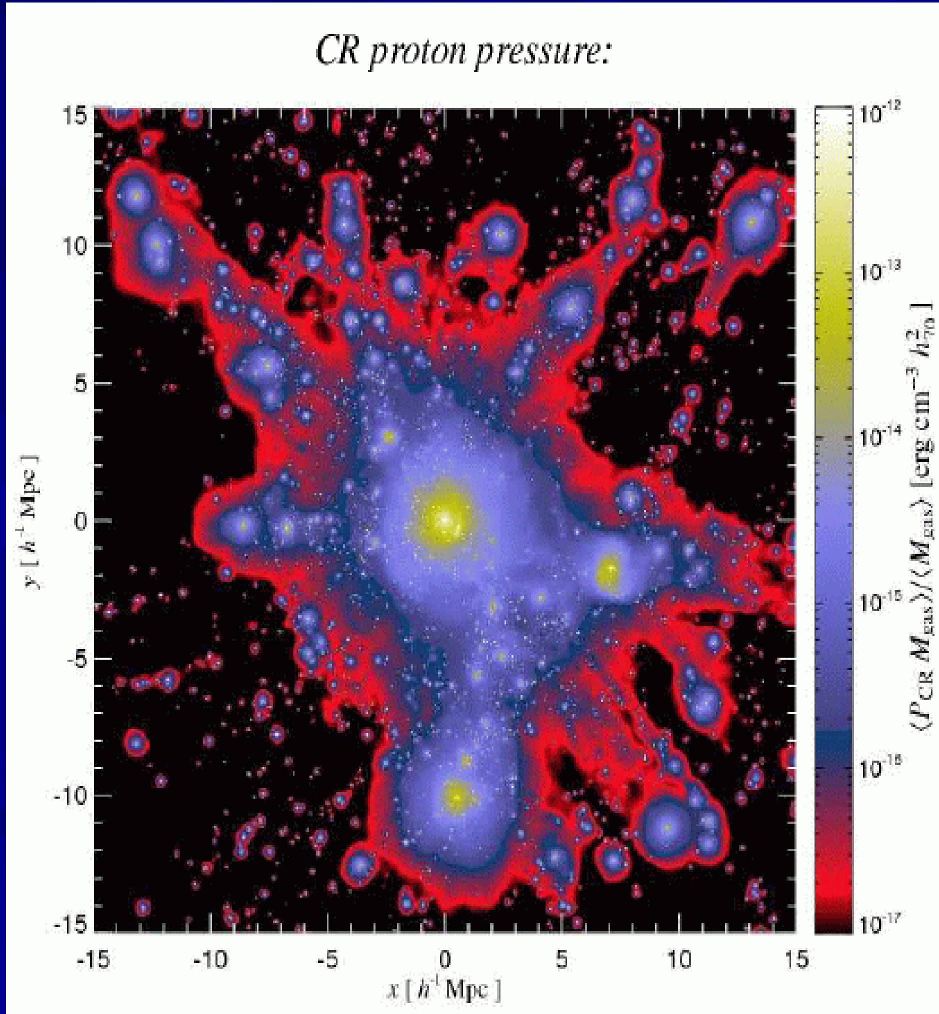


Acceleration of CR at shocks

Pfrommer et al. 2007, 08





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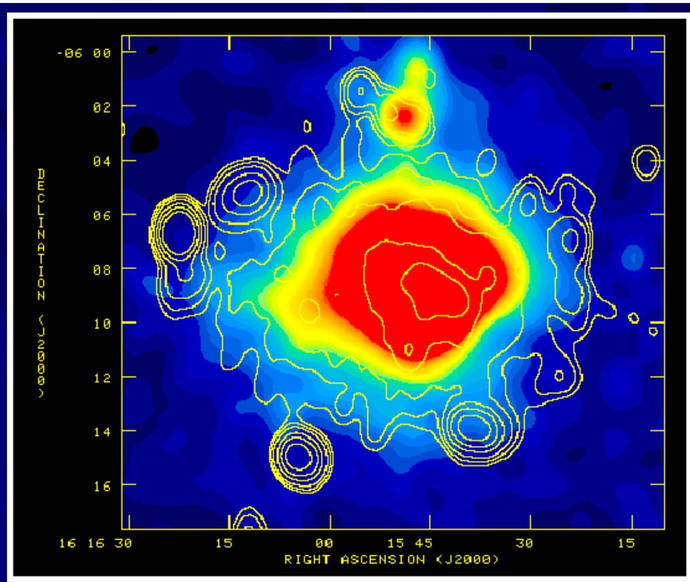

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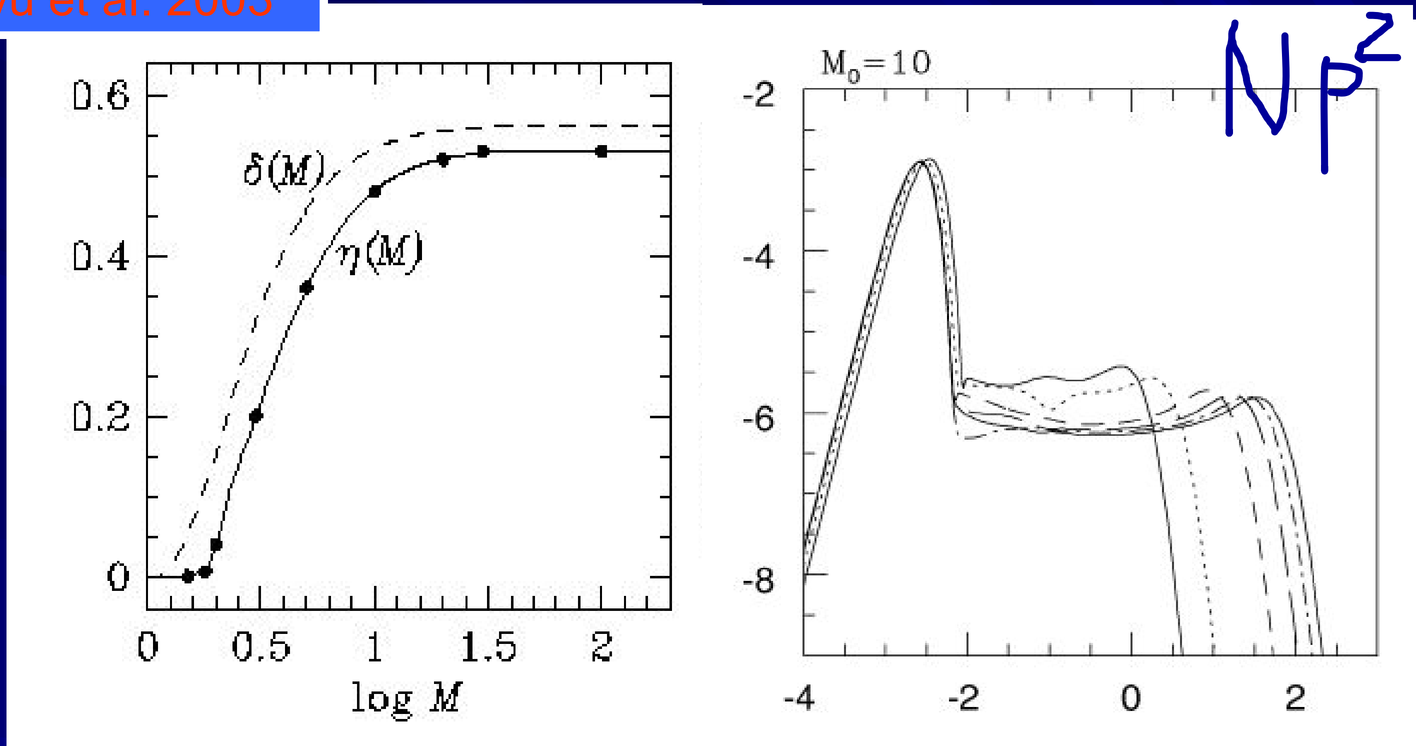
(e.g., *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004***)**

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***)**

Acceleration of CRp at shocks

Ryu et al. 2003

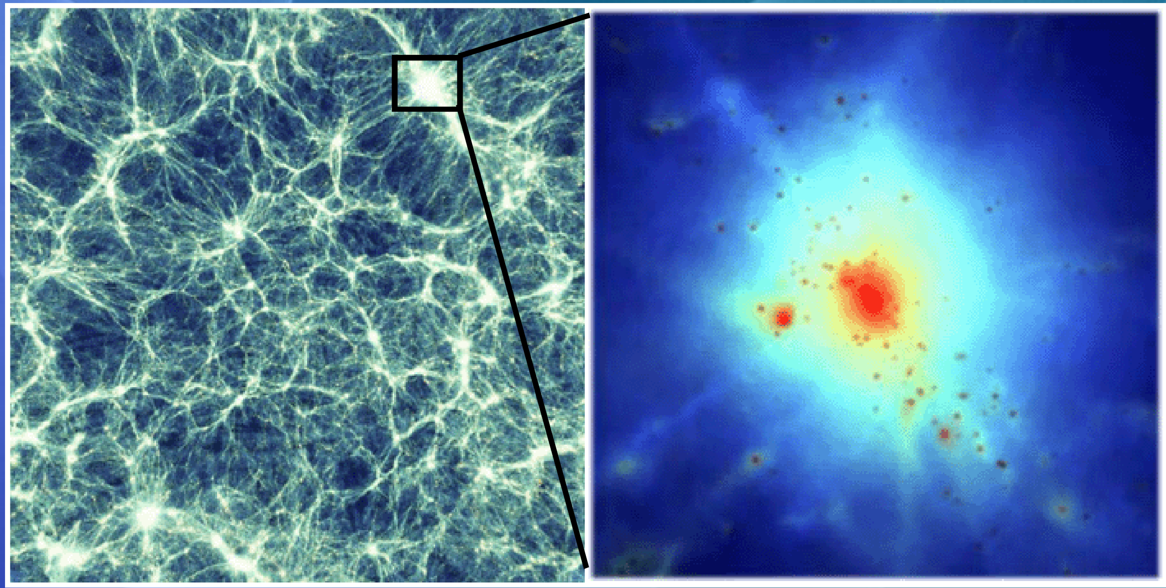


$$E_{CR} \simeq \eta(M)\,\rho\,V_{sh}^{3}$$

From SN and our Galaxy electrons take 1-10% of the proton energy.

Clusters of galaxies

How galaxy clusters form?

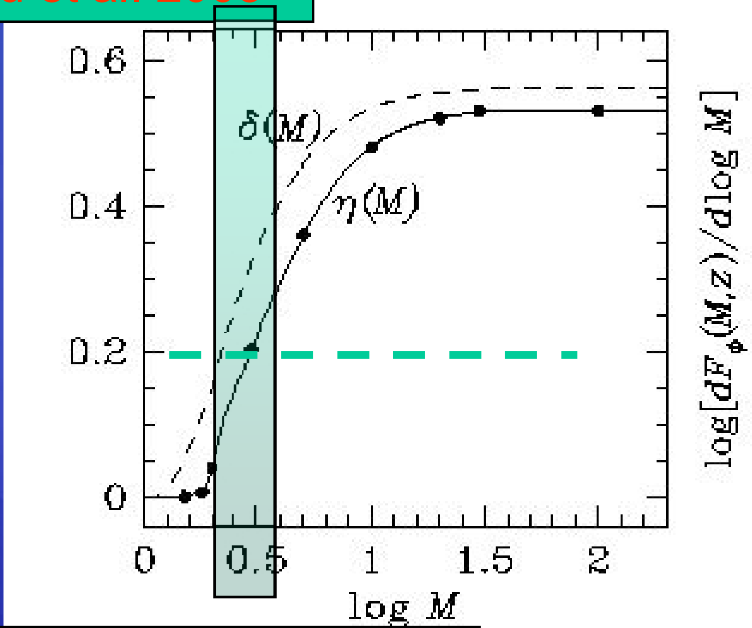


Borgani et al. 2004

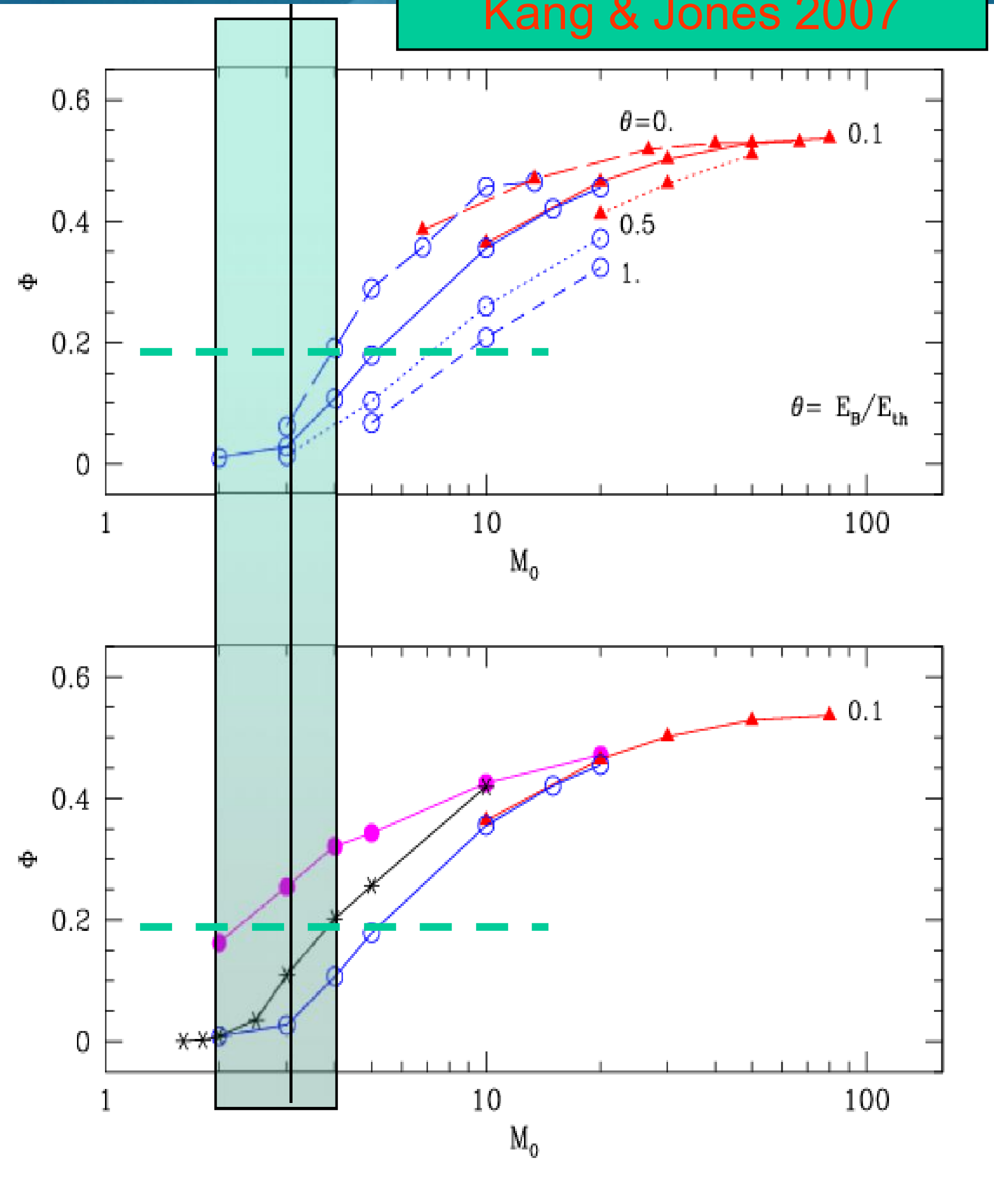
- Cosmic structures forms as a result of the gravitational amplification of primordial density fluctuations.
- Clusters form by accretion of matter and mergers between sub-units at the intersection of filaments which make up the 'cosmic web'.
- Gas falling into deep potential wells is heated to ~10^7-10^8 °K by shocks (and adiabatic compression)

Acceleration of CRp at shocks

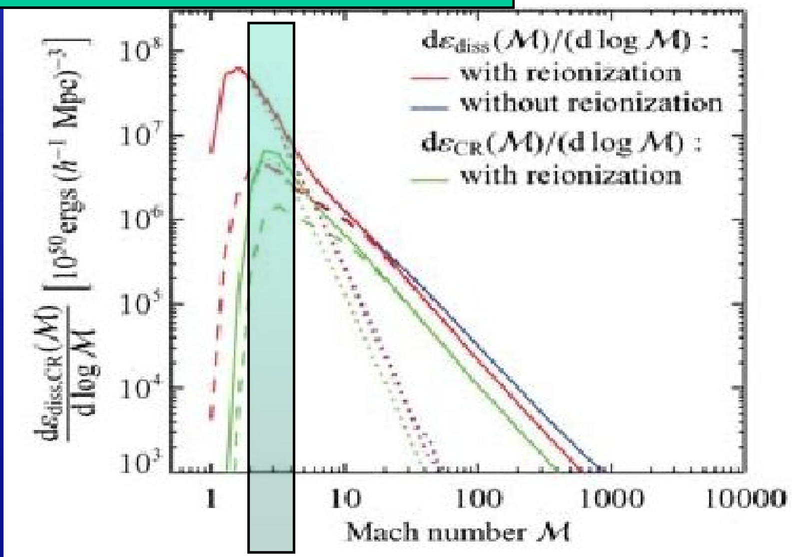
Ryu et al. 2003



Kang & Jones 2007



Pfrommer et al. 2008



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

Not only particle acceleration ….

Thermal conduction and kin. viscosity in the ICM

(e.g., Lazarian 2006)

Heating of the ICM and “cooling flow” problem

(e.g., Fujita , Matsumoto, Weda 2004)

Diffusion and transport of metals in the ICM

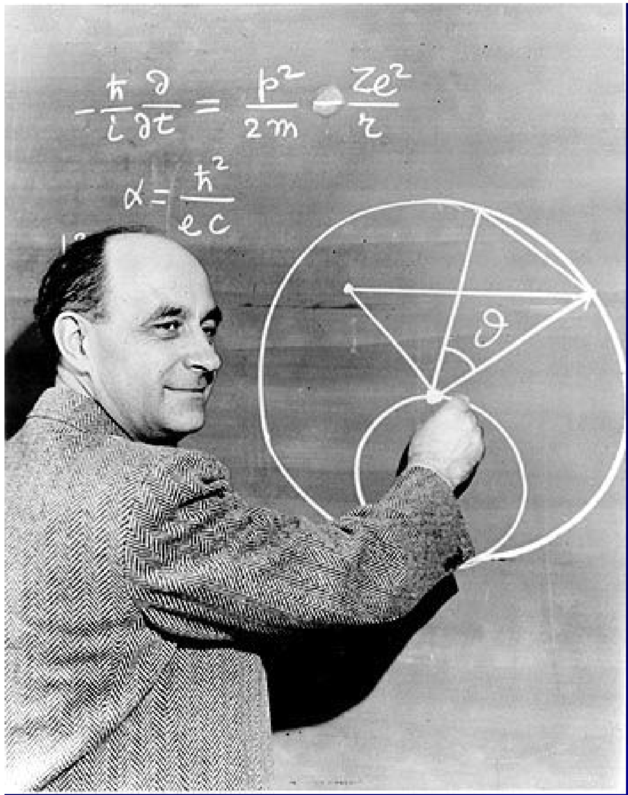
(e.g., Voigt & Fabian 2004; Rebusco +al. 2005)

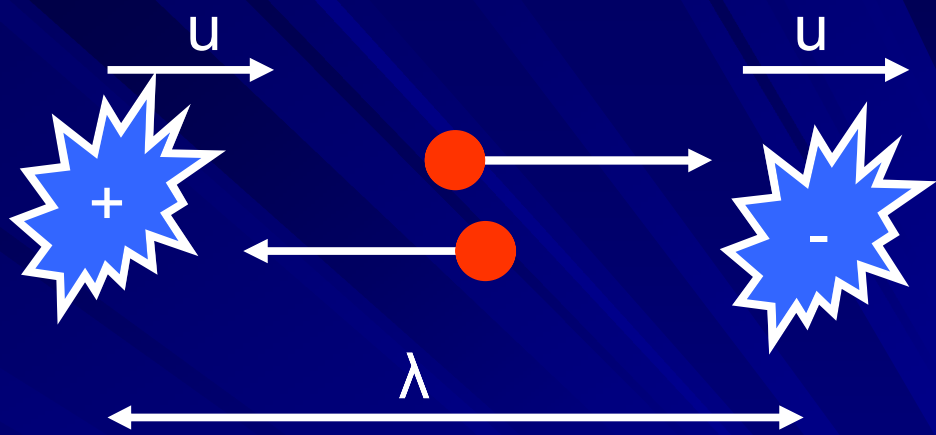
B-Amplification from Cosmological seed fields

(e.g., Dolag +al. 1999,02; Subramanian +al. 2006)

Diffusion and scattering of HE & UHECR in the Universe

(e.g., Sigl +al. 2005; Dolag +al. 2005)





$$\Delta p_{\pm} \approx \pm 2\, p\, \frac{u}{c}$$

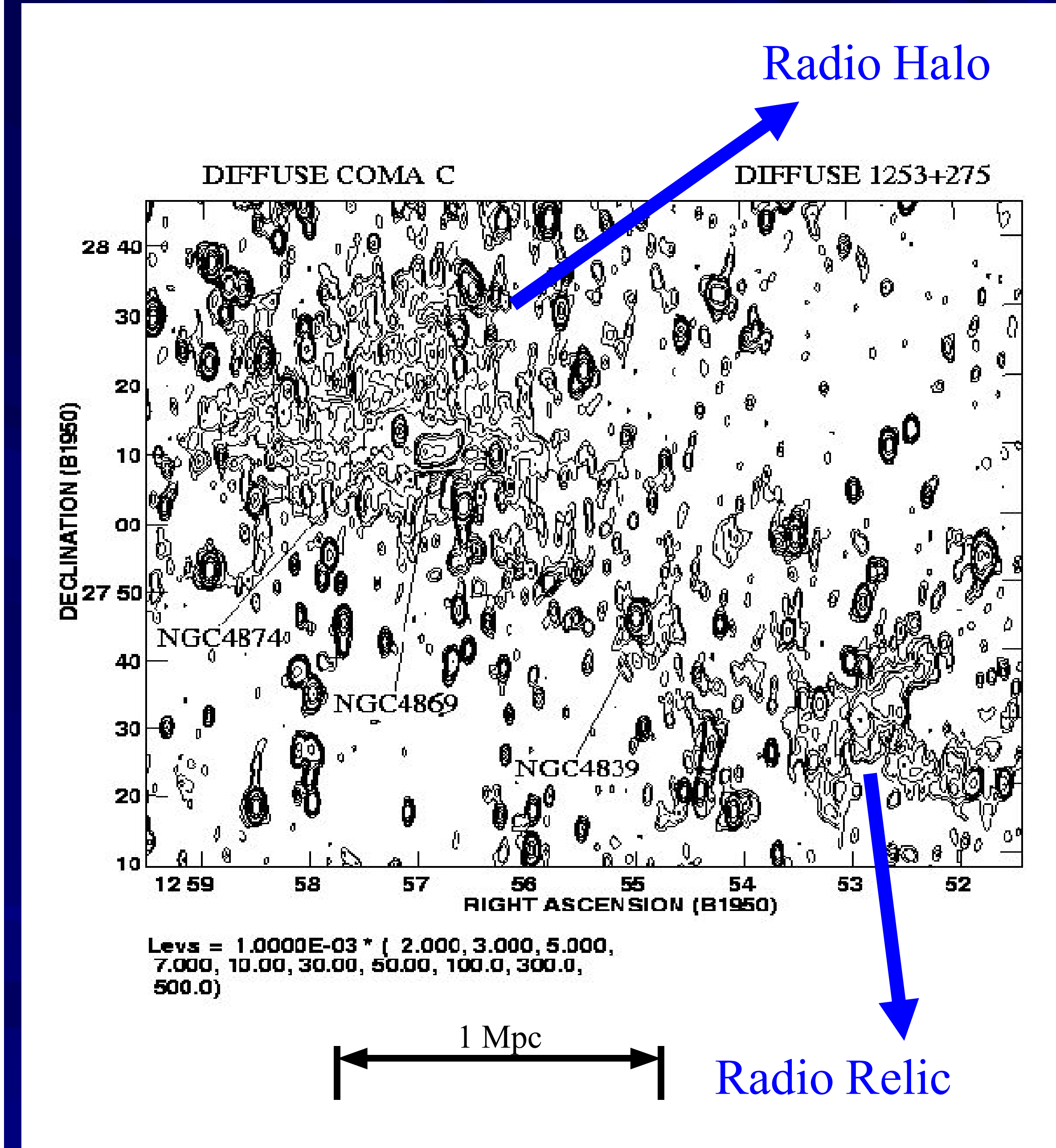
$$\nu_{+} = \frac{u + c}{\lambda} \qquad \nu_{-} = \frac{c - u}{\lambda}$$

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

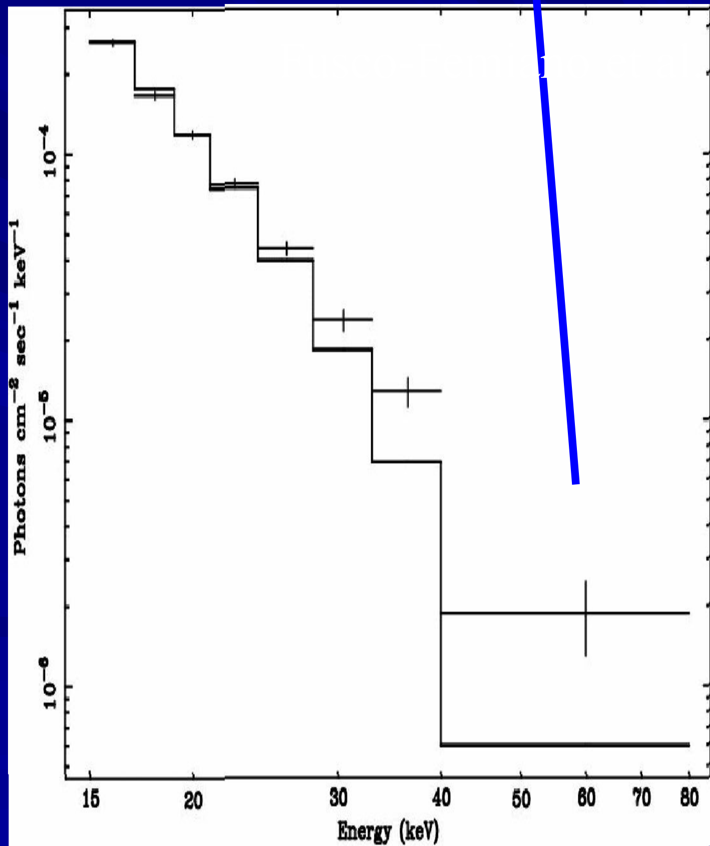
$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle \approx 2p\, \frac{u}{c}\, \frac{c}{\lambda}$$

COMA

Hard X-ray Excess (HXR)



it may be due to IC emission from the same radio emitting electrons



Fusco-Femiano +al. 1999,04; Rephaeli +al. 1999

CR populations in GC

- Long living population of CR protons

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

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

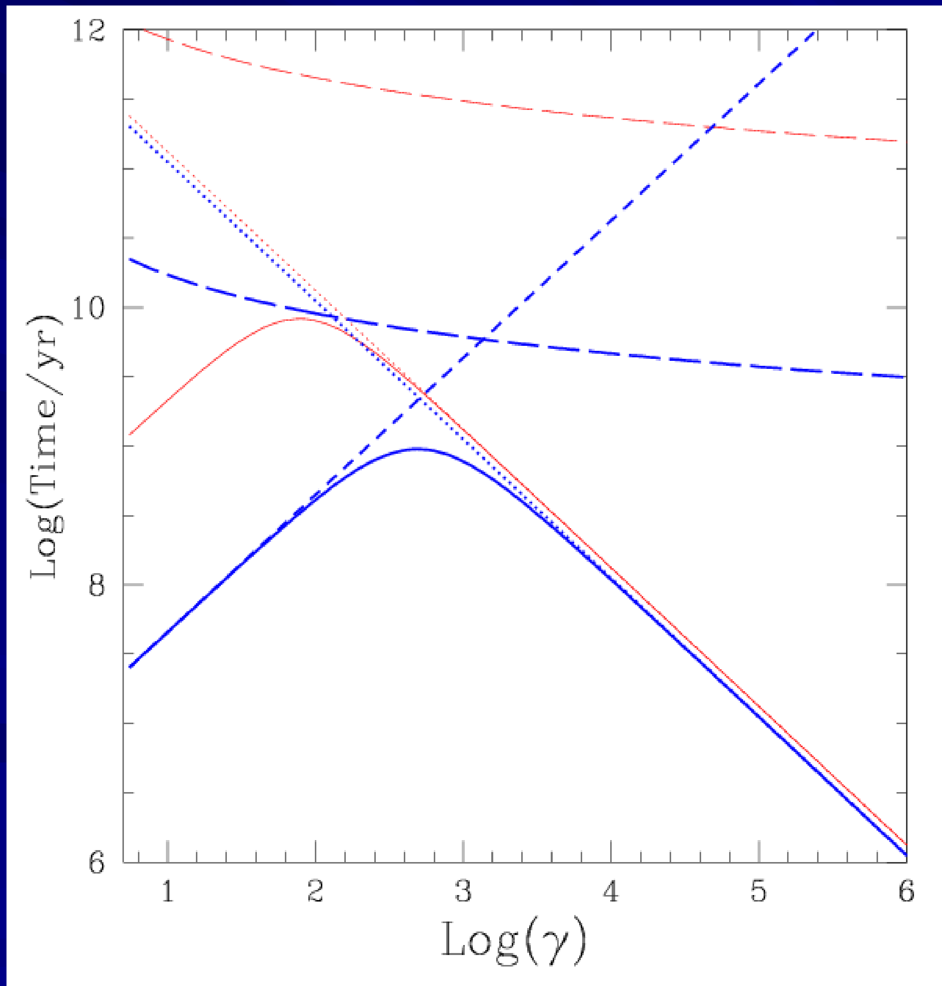
$$\pi^\pm \to \mu + \nu_\mu \quad \mu^\pm \to e^\pm \nu_\mu \nu_e.$$

- Stationary (continuous injection) population of CR (secondary) electrons

- Transient population of CR electrons (< 1 Gyr)

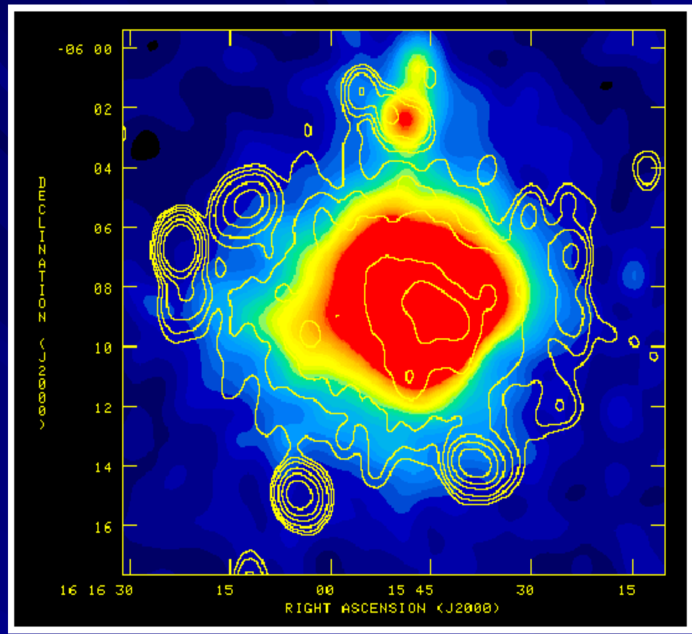
Physics of CR Leptons

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



Diffuse Radio Emission & origin of emitting electrons

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

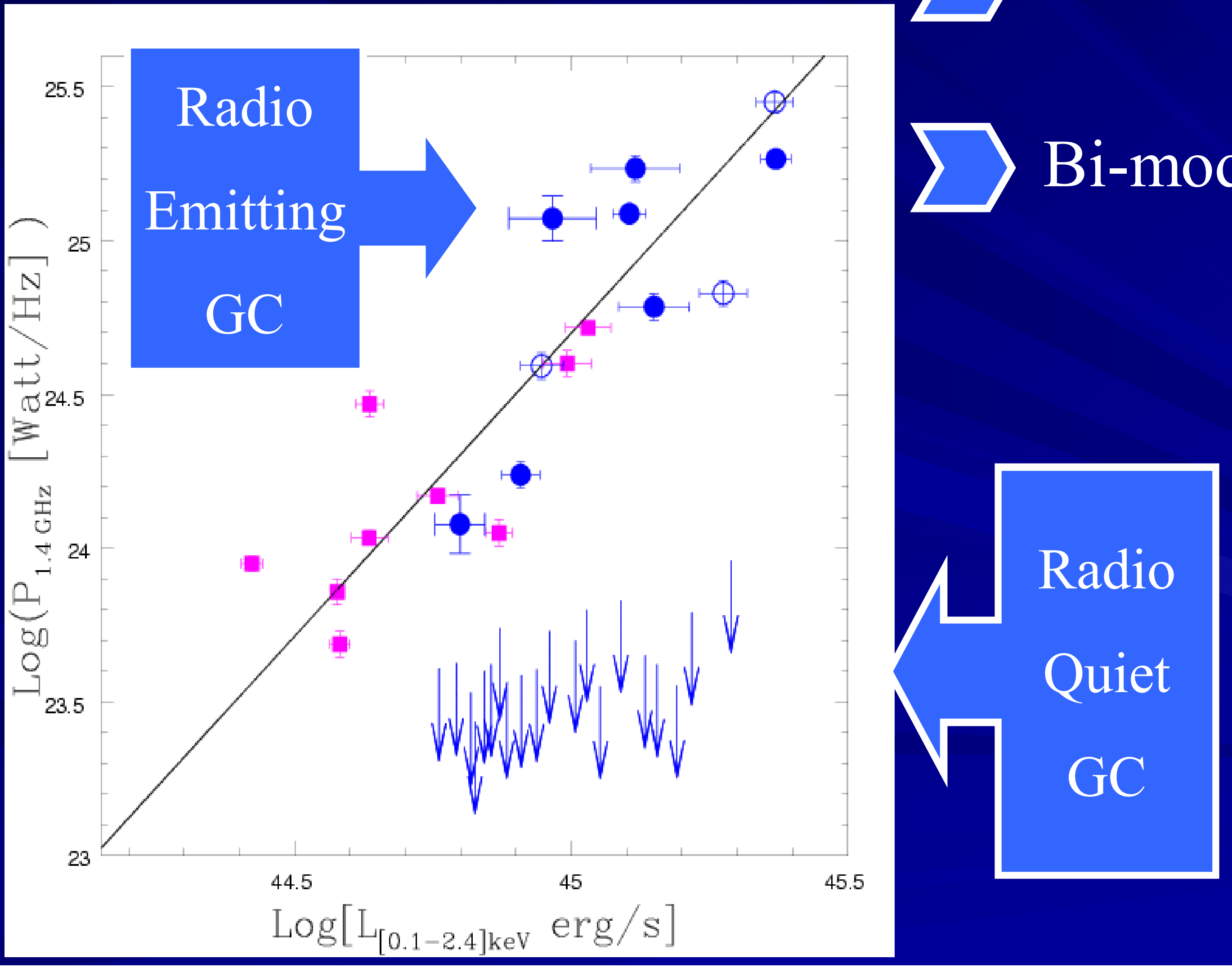


Sample of
50 massive GC z=0.2-0.4
(REFLEX + eBCS)

Similar z
Similar X-luminosities

Radio- Statistical properties of GC

Brunetti +al. 2007

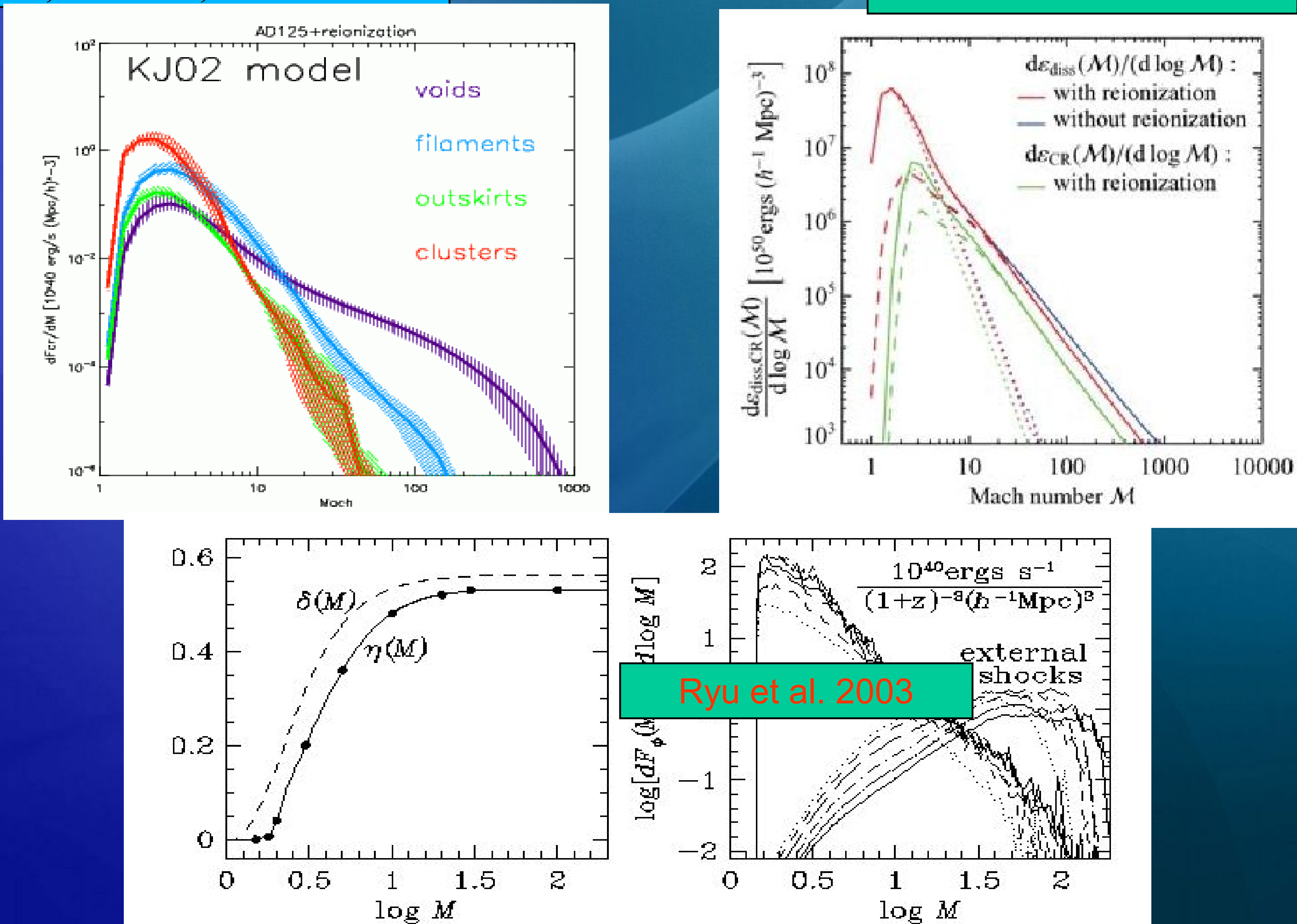


- RH are not common
- Bi-modality of GC

Shocks in Galaxy Clusters (I)

Vazza, Brunetti, Gheller 2008

Pfrommer et al. 2008

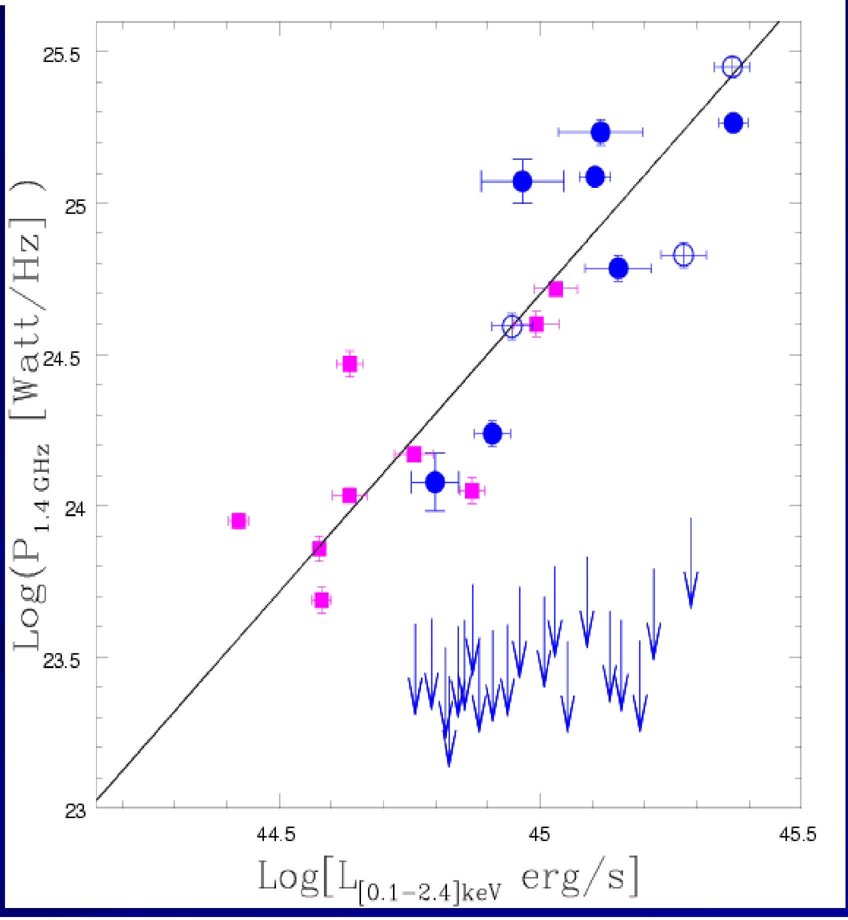


Ryu et al. 2003

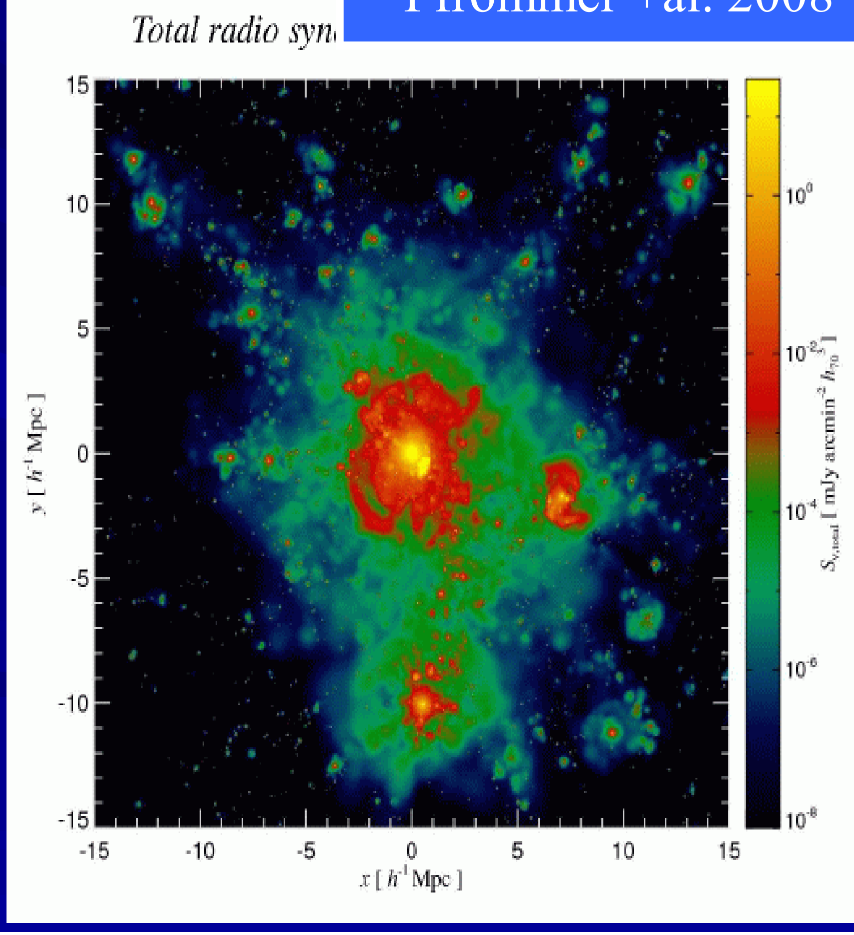
Radio- Statistical properties of GC

Disagreement with shock+secondary models

Brunetti +al. 2007



Pfrommer +al. 2008



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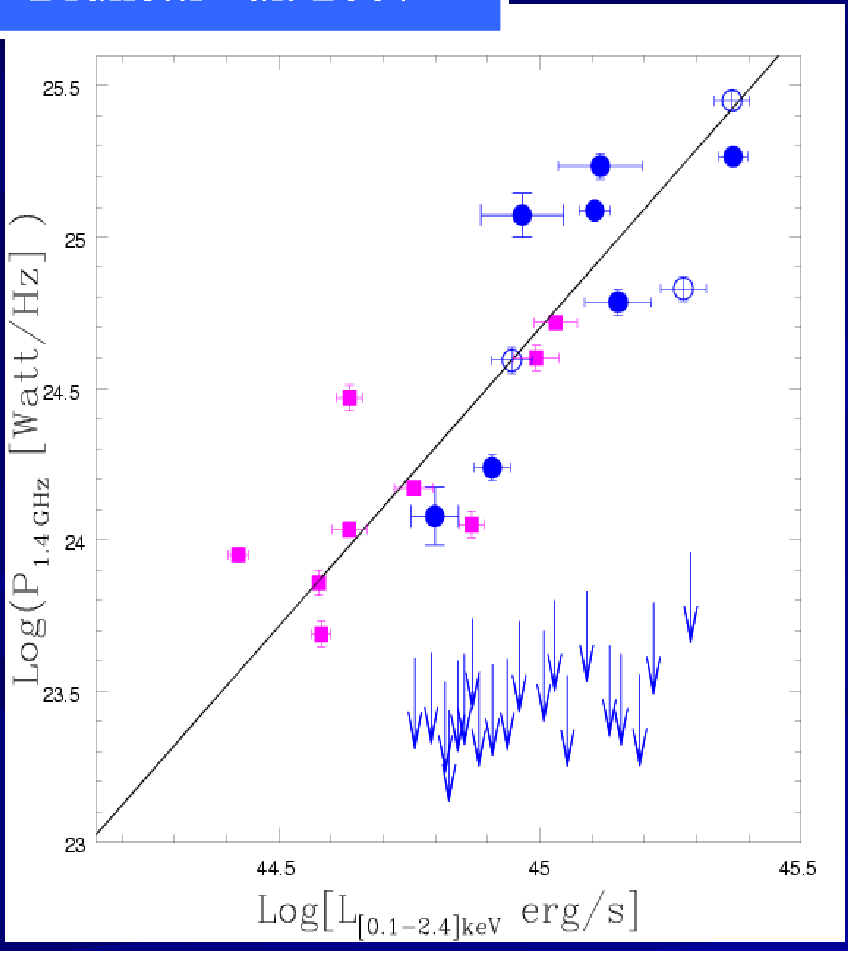
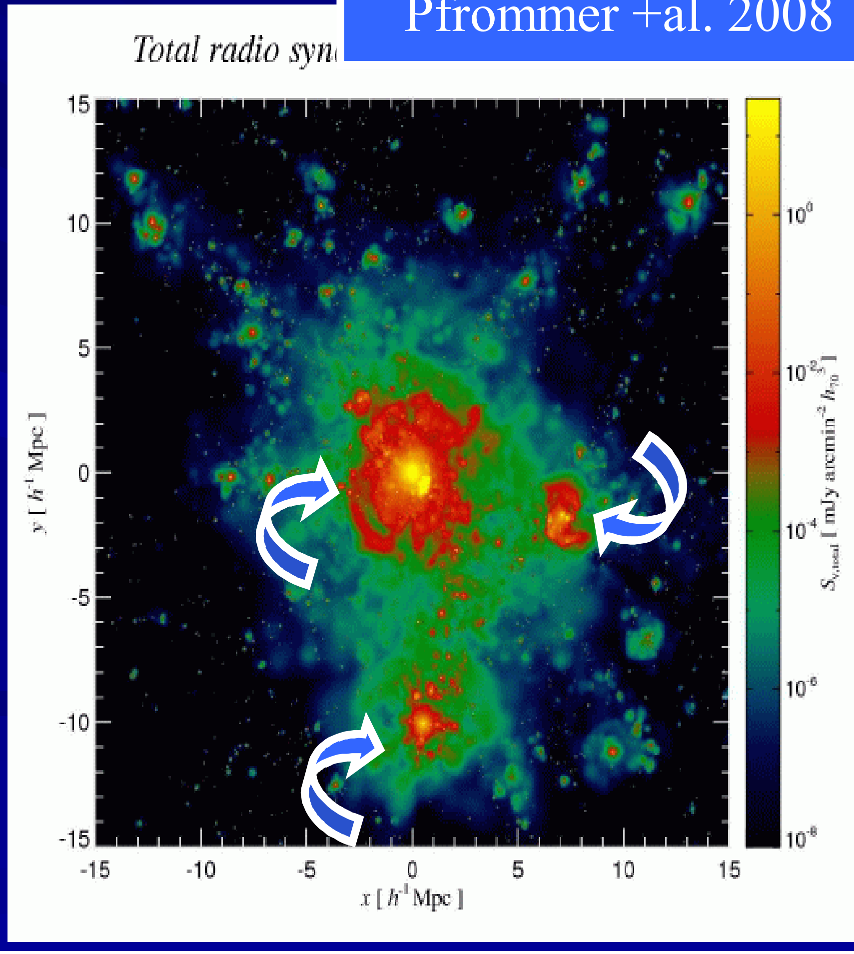


Pfrommer +al. 2008



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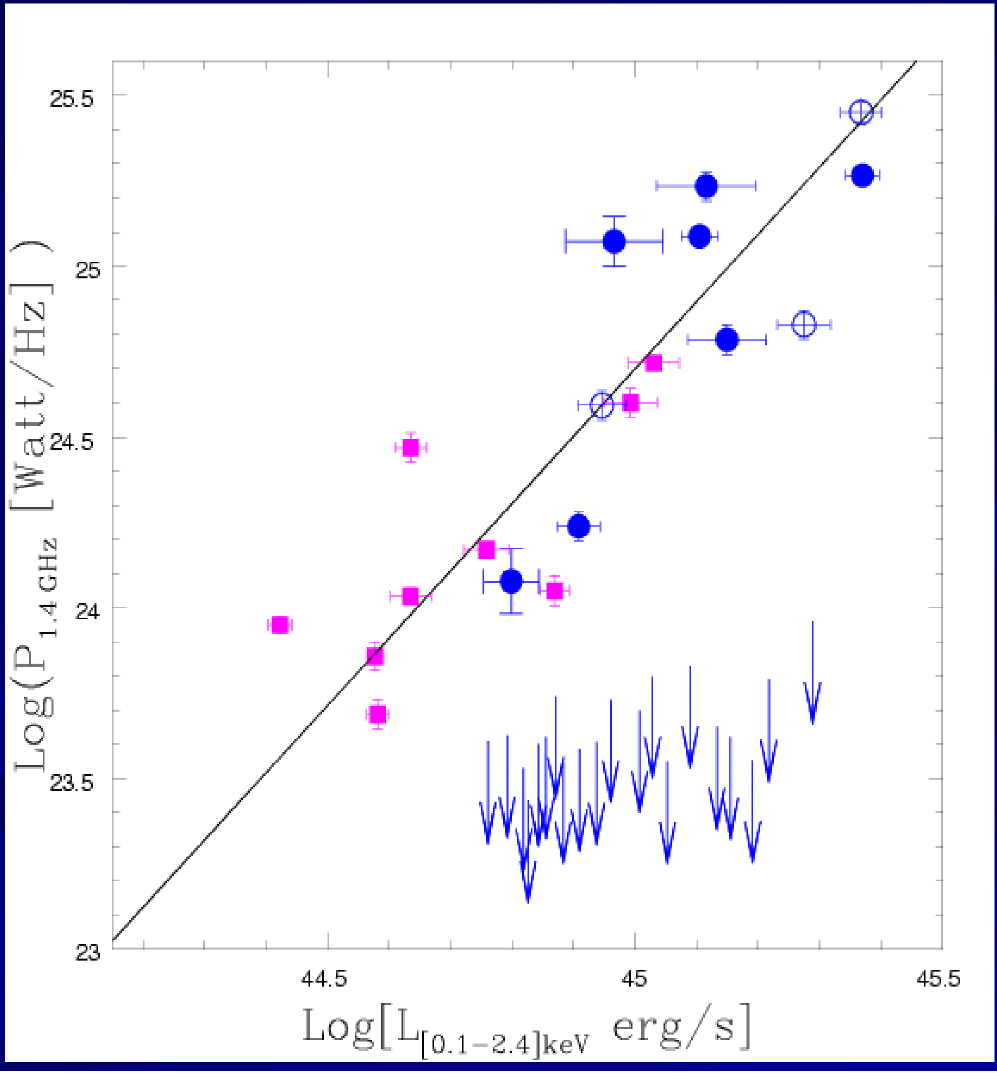

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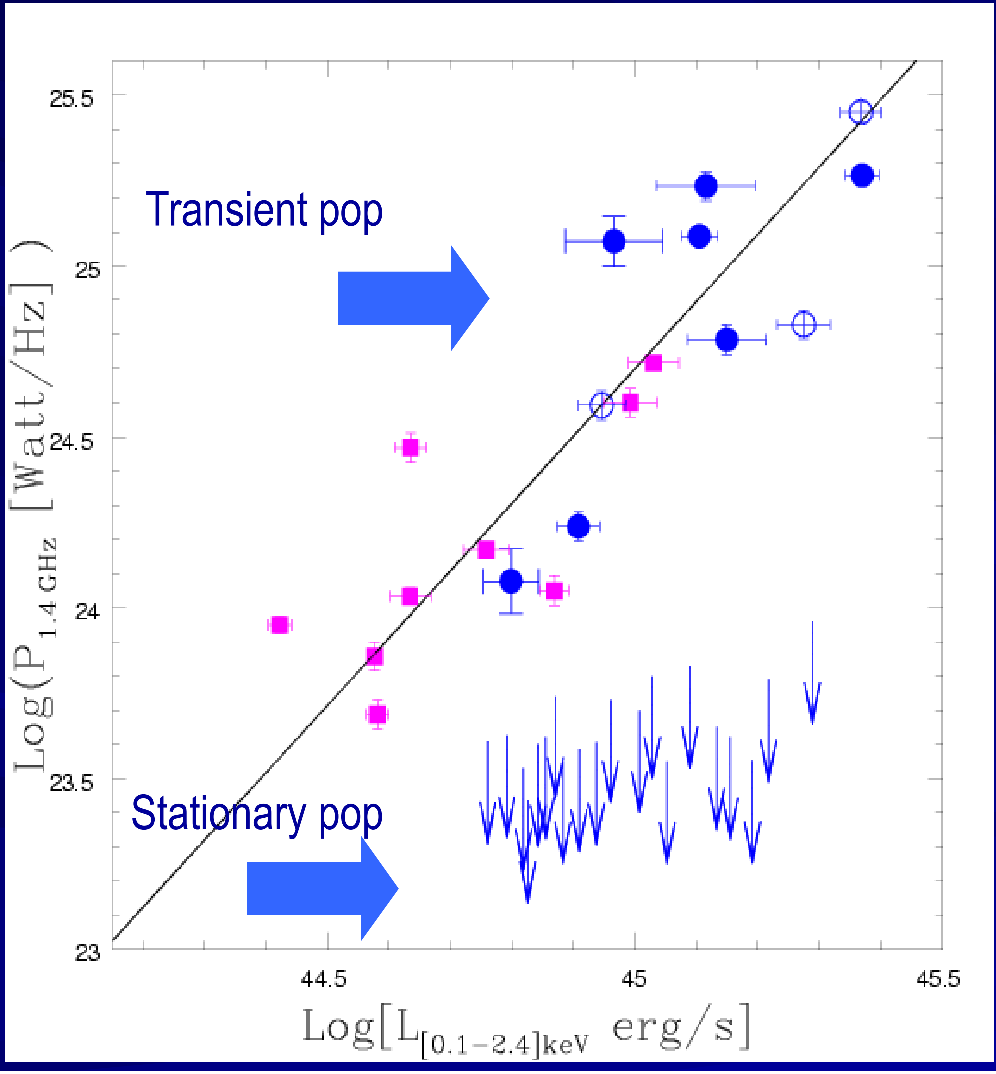
$\gamma \approx 10^4$ $e^{\pm}$ are not common in GC (on-off mechanism)

Radio- Statistical properties of GC

Brunetti +al. 2007



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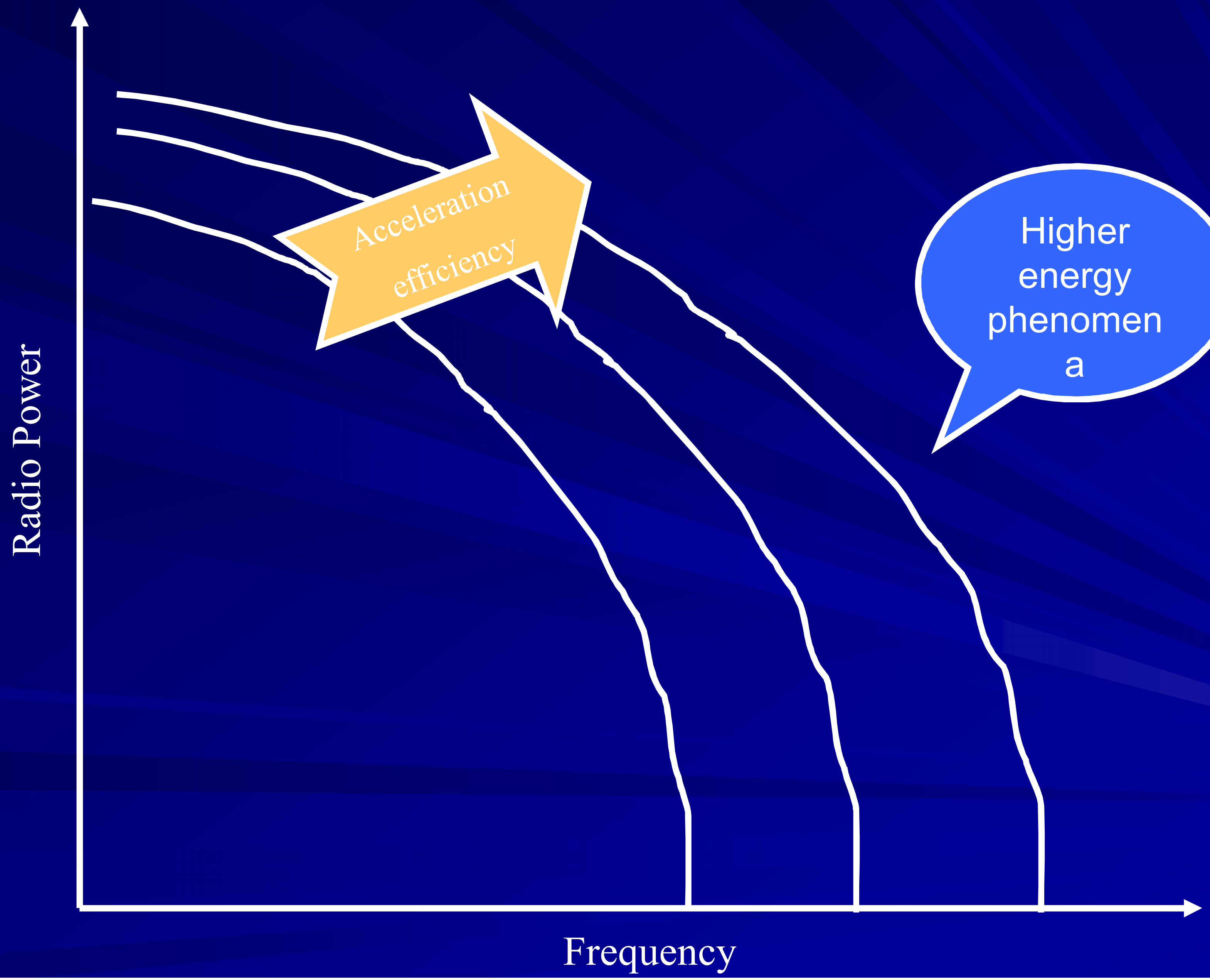
Request: Extending the frequency range



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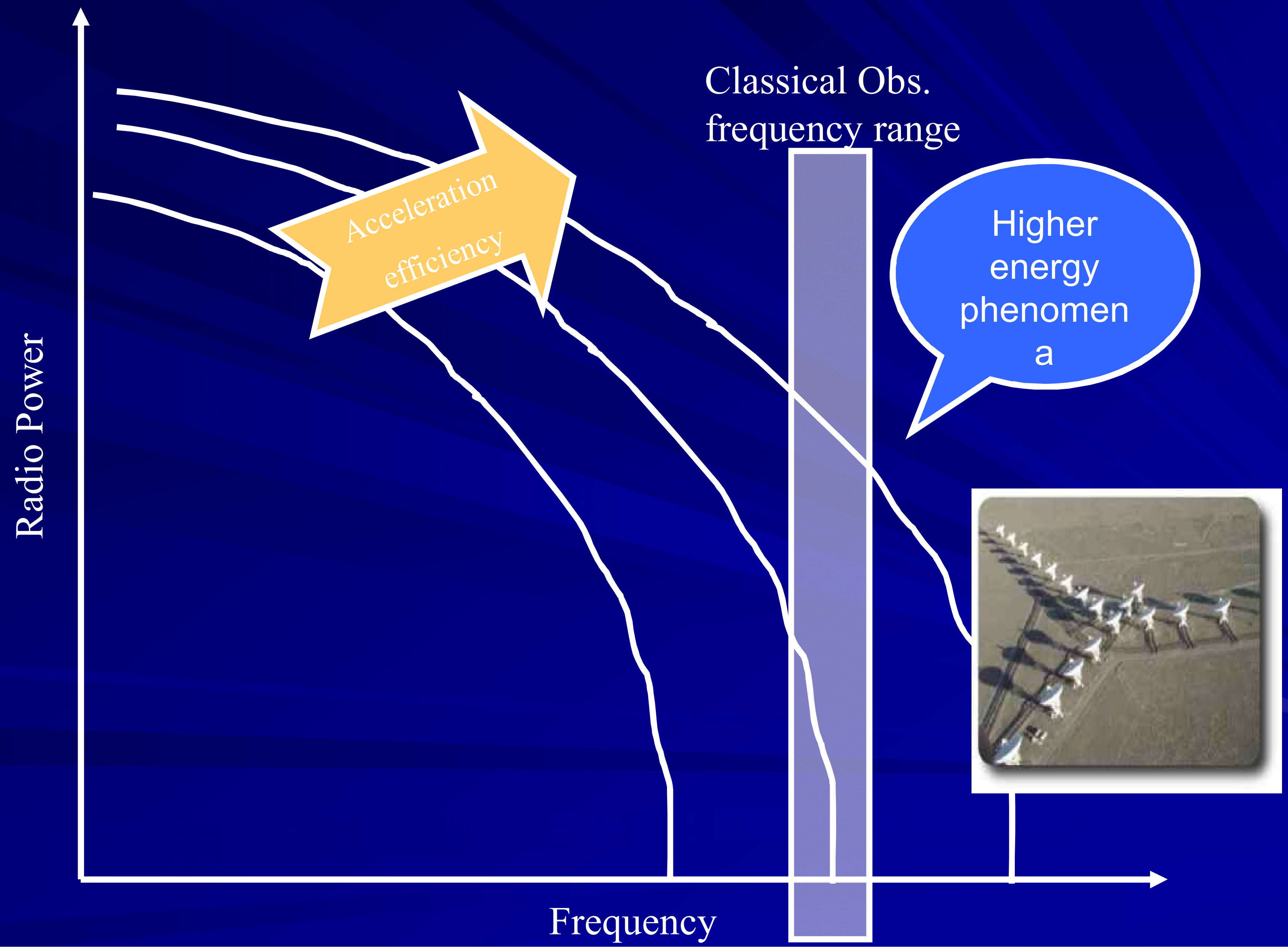

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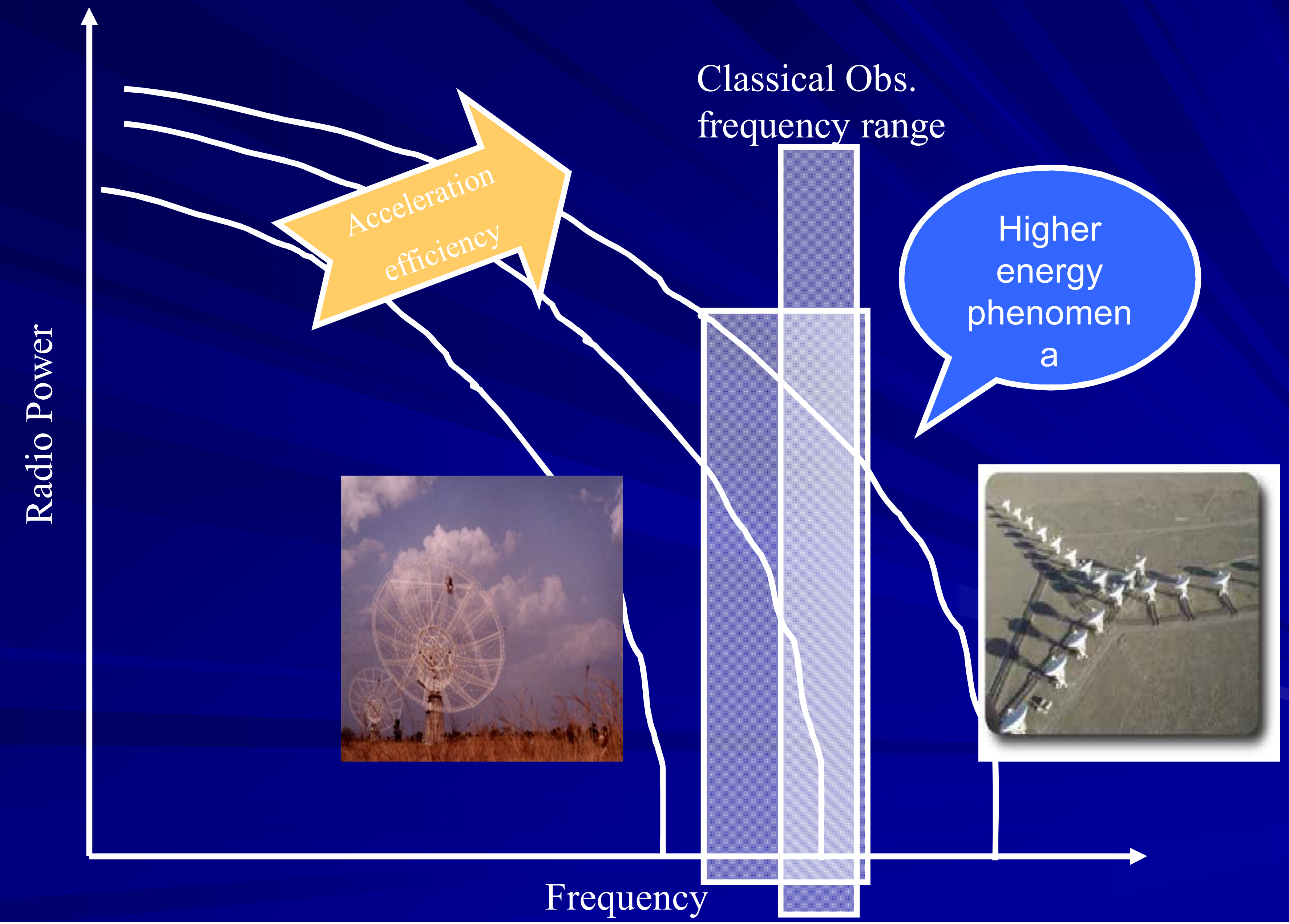
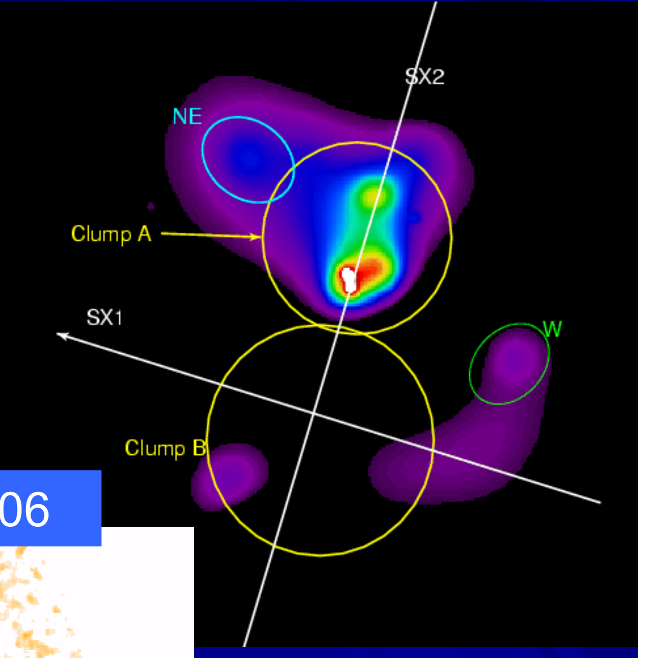
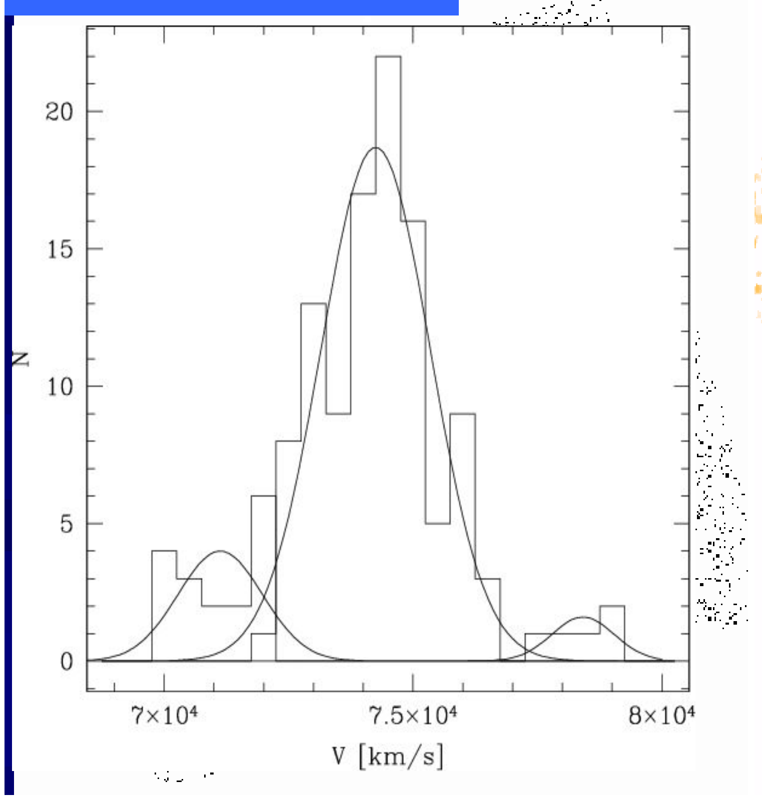


Abell 521: a big surprise !

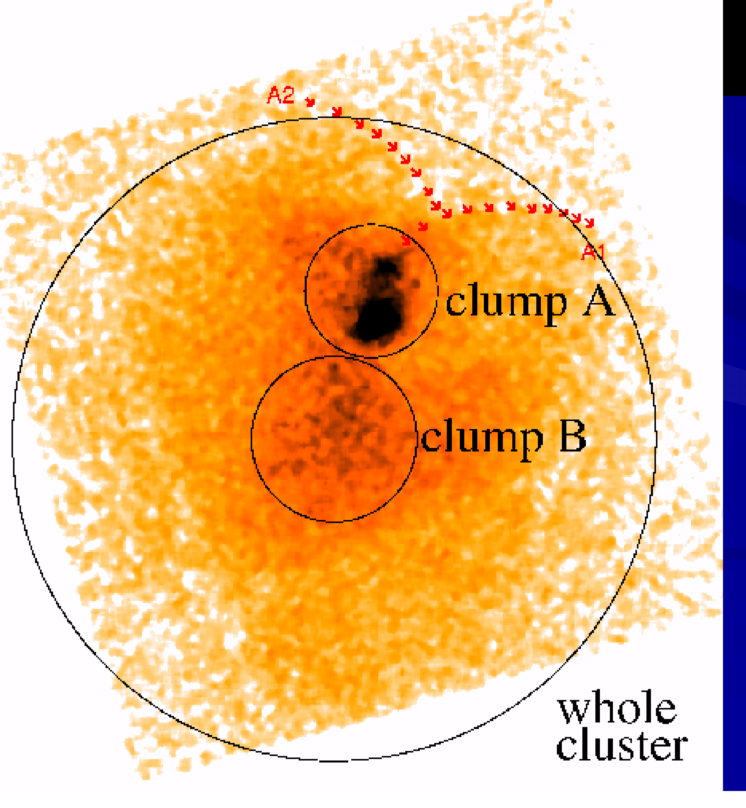
$z=0.247$
$L_x[0.1\text{-}2.4]=8.2\ 10^{44}$ erg/s
$M\approx 2\ 10^{15}$ Msun



Ferrari +al. 2003



Ferrari +al. 2006



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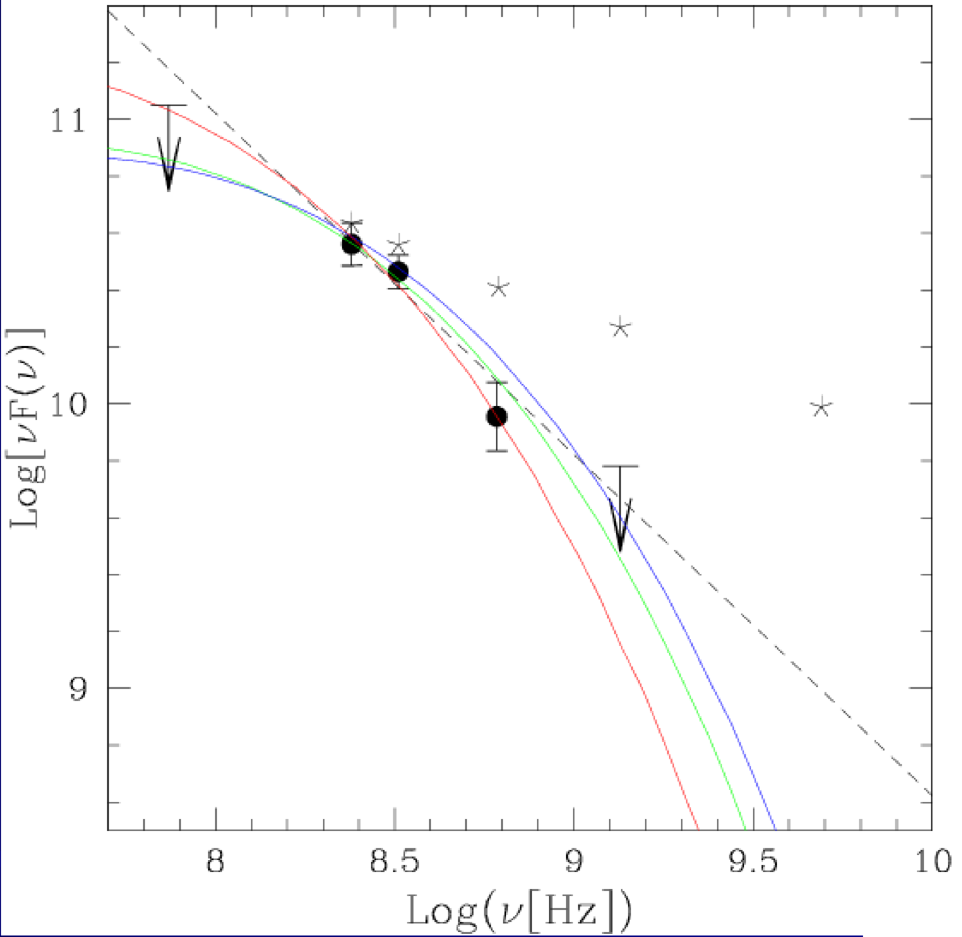
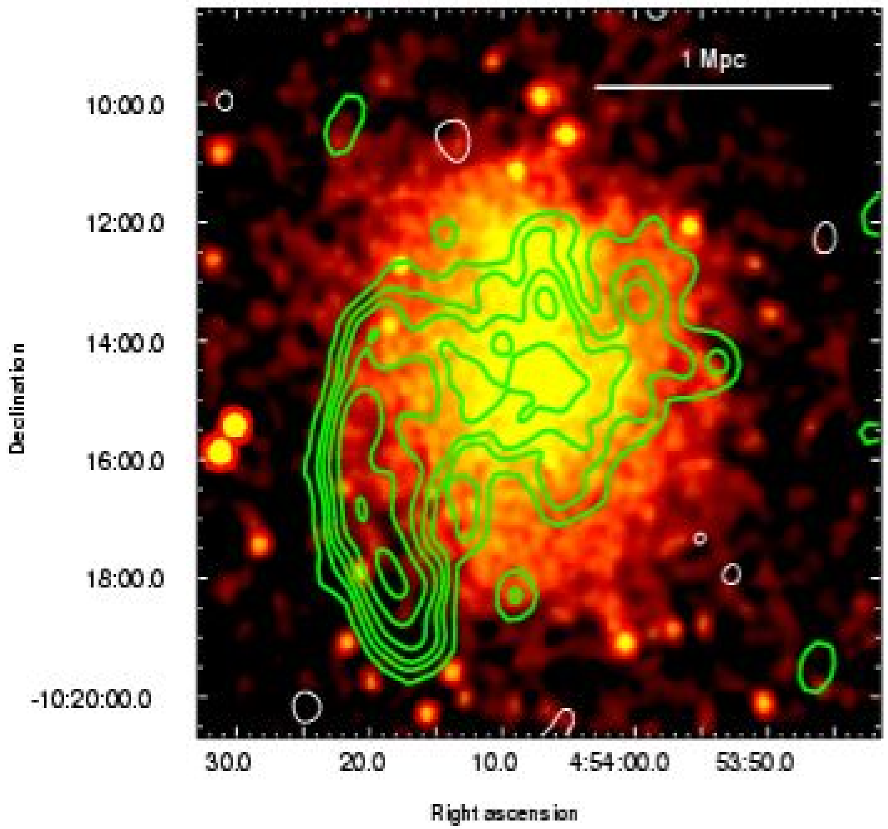
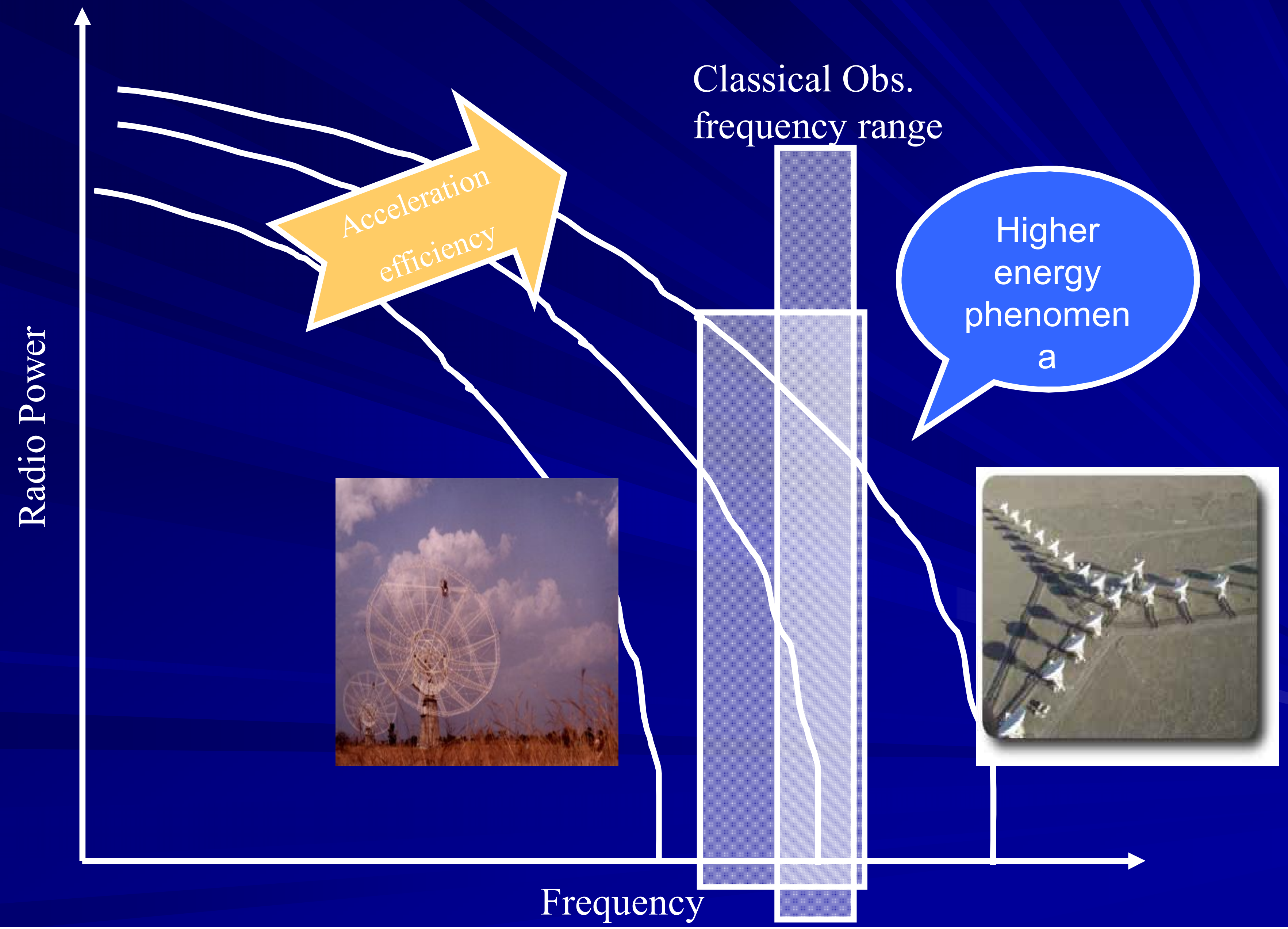


The first low frequency Radio Halo !

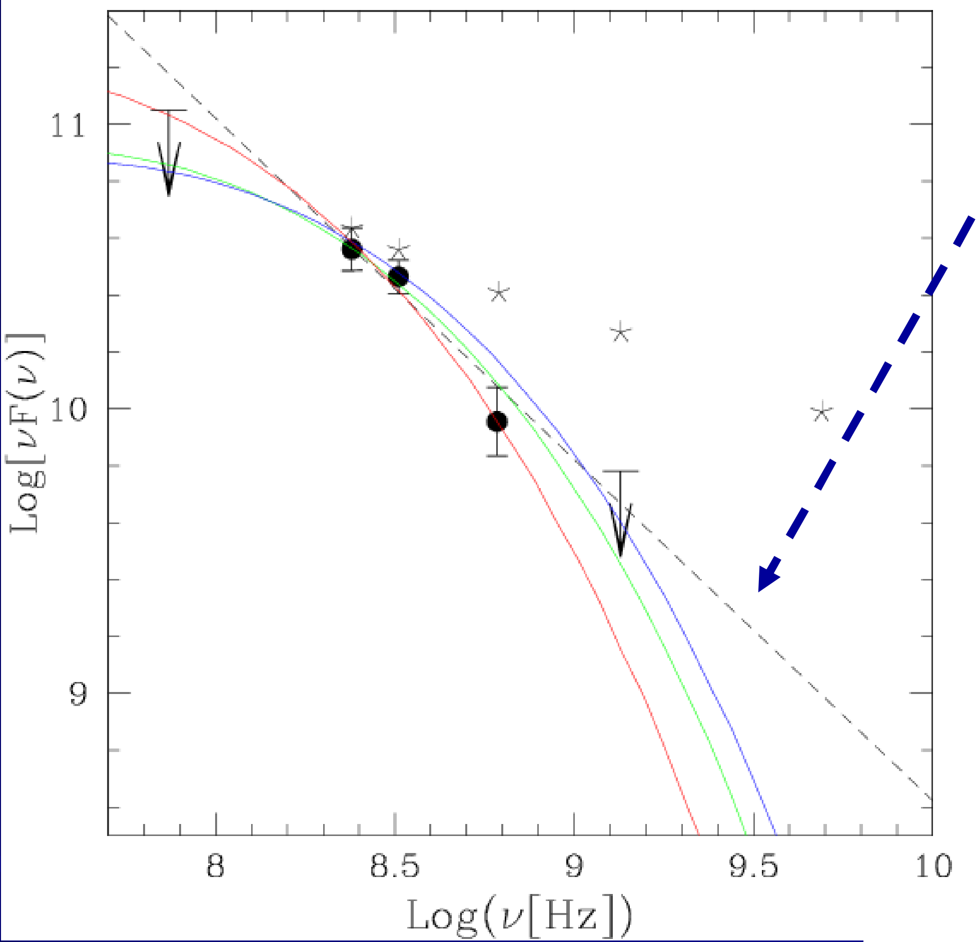


The first Radio Halo with ultra steep spectrum

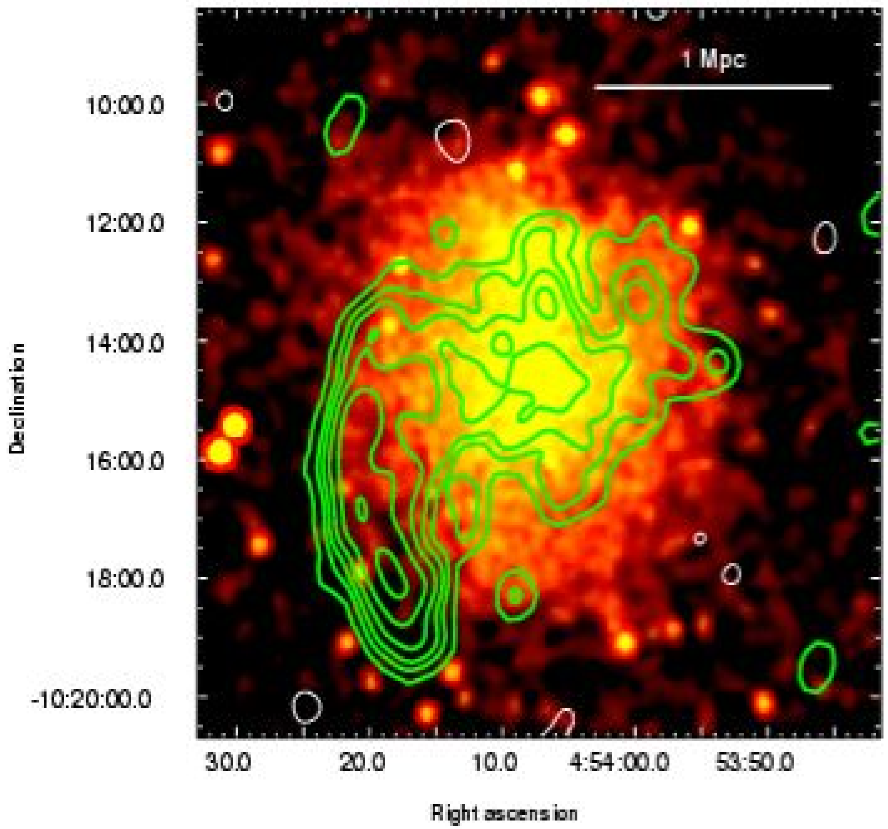
Request: Extending the frequency range



Abell 521: a big surprise !

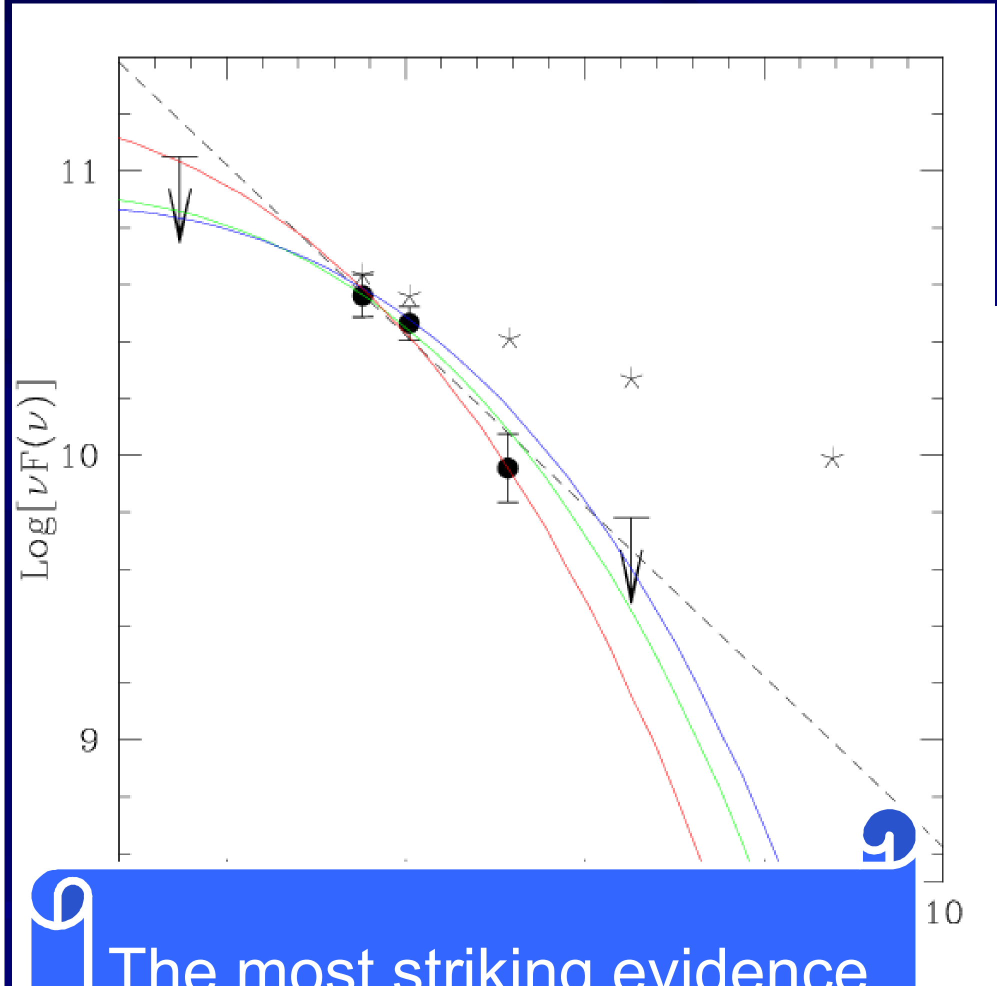


Secondary models require energy in CR protons larger than the cluster thermal energy



The first Radio Halo with ultra steep spectrum

Abell 521: a big surprise !



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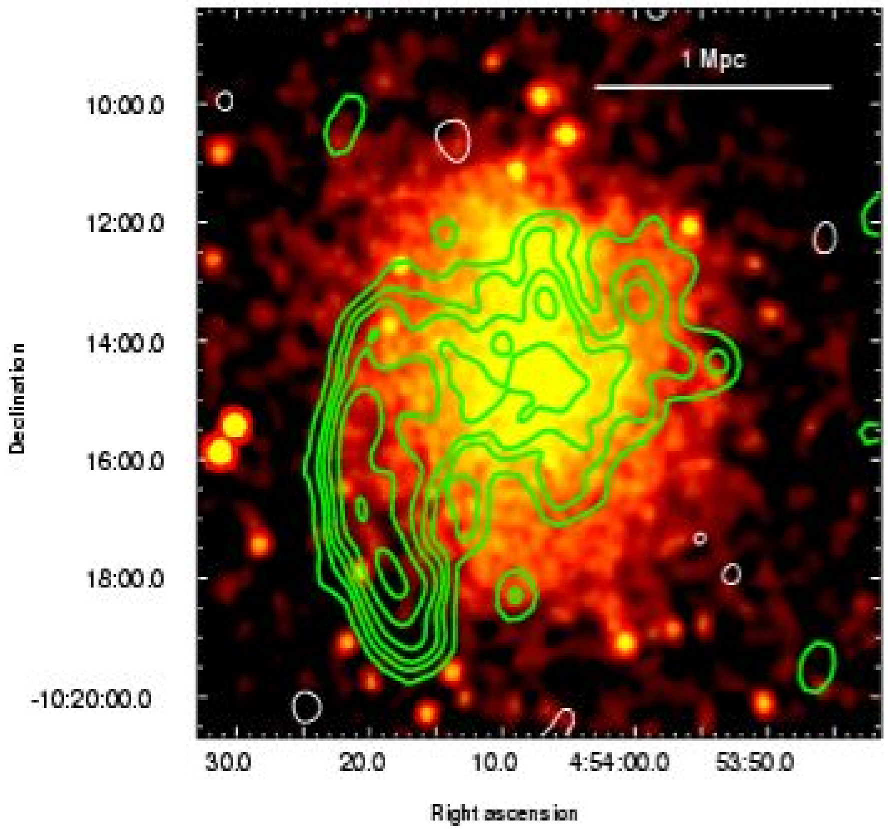
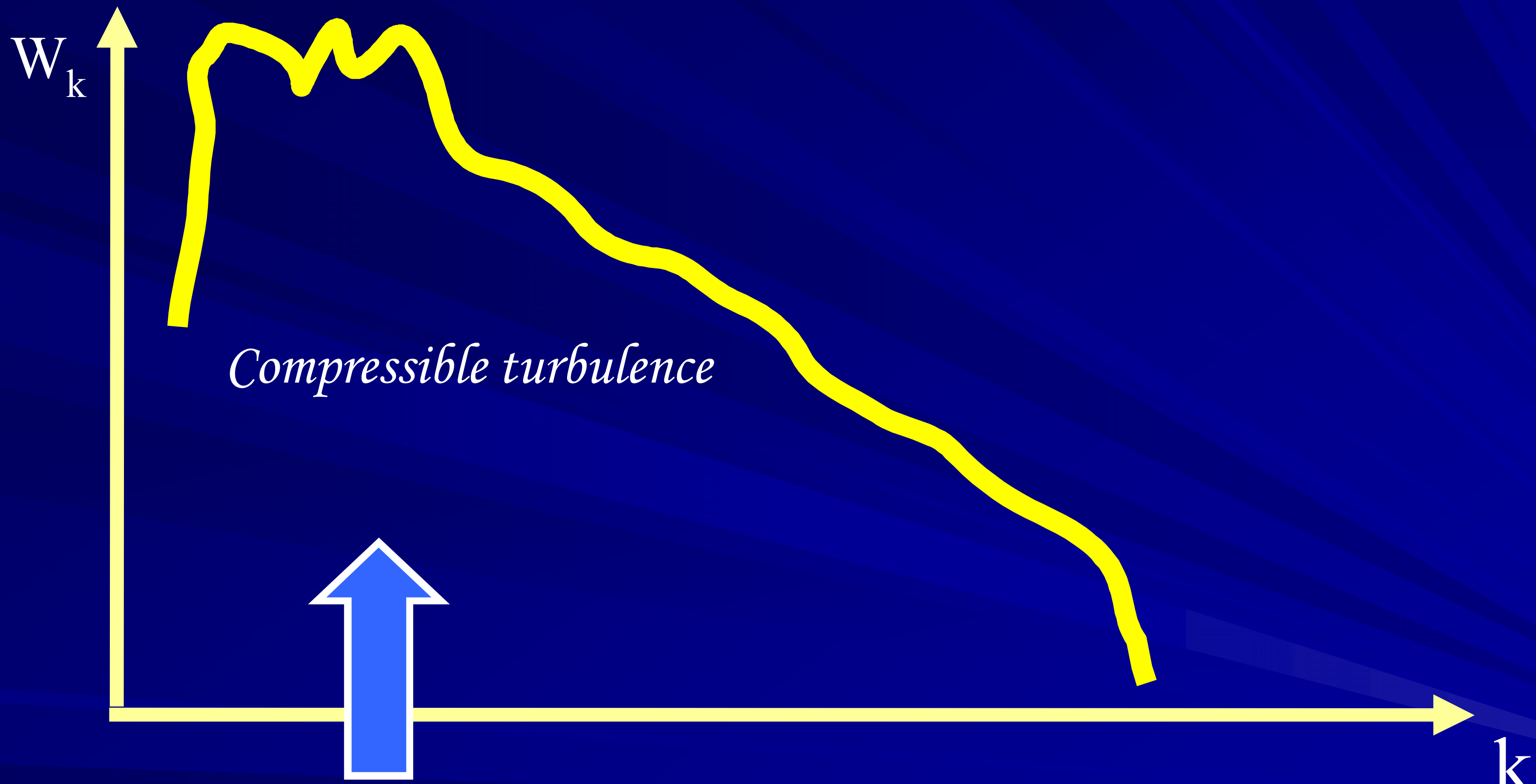


The most striking evidence that turbulence accelerates particles in the IGM

Basics of turbulence in the ICM

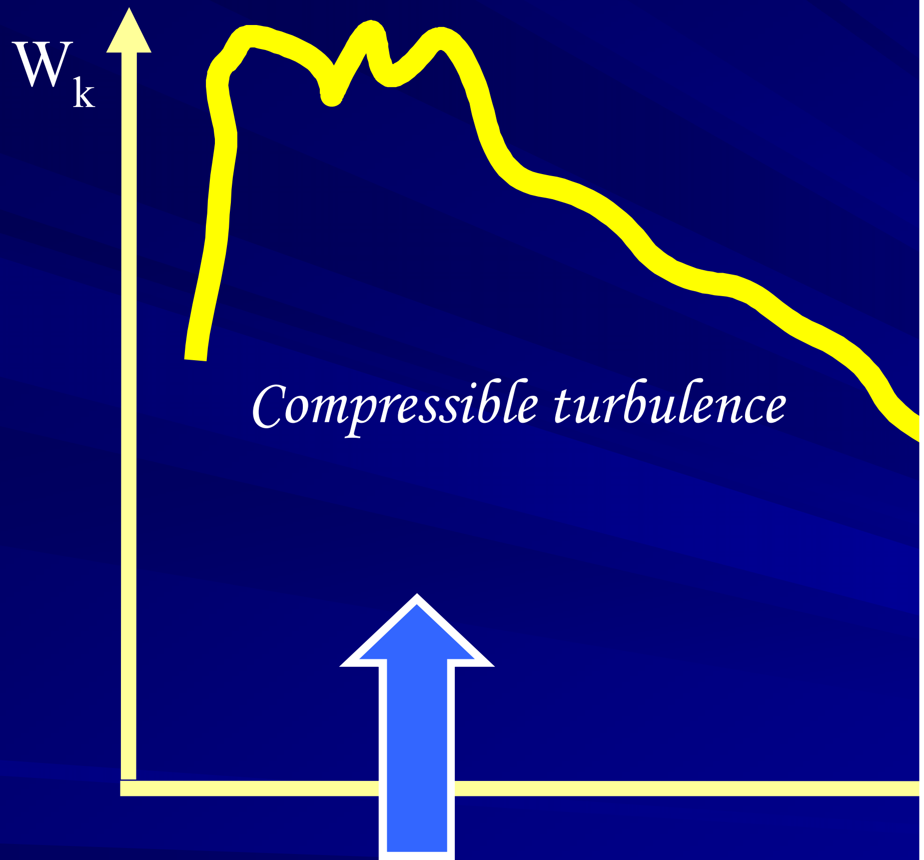
Brunetti & Lazarian 2007



$L_o \sim 100 – 300$ kpc

Basics of turbulence in the ICM

Brunetti & Lazarian 2007



$L_o \sim 100 – 300$ kpc

$L_o \sim 100 – 300$ kpc

$V_o \sim 500 – 1000$ km/s

$c_s \sim 1200 – 1800$ km/s

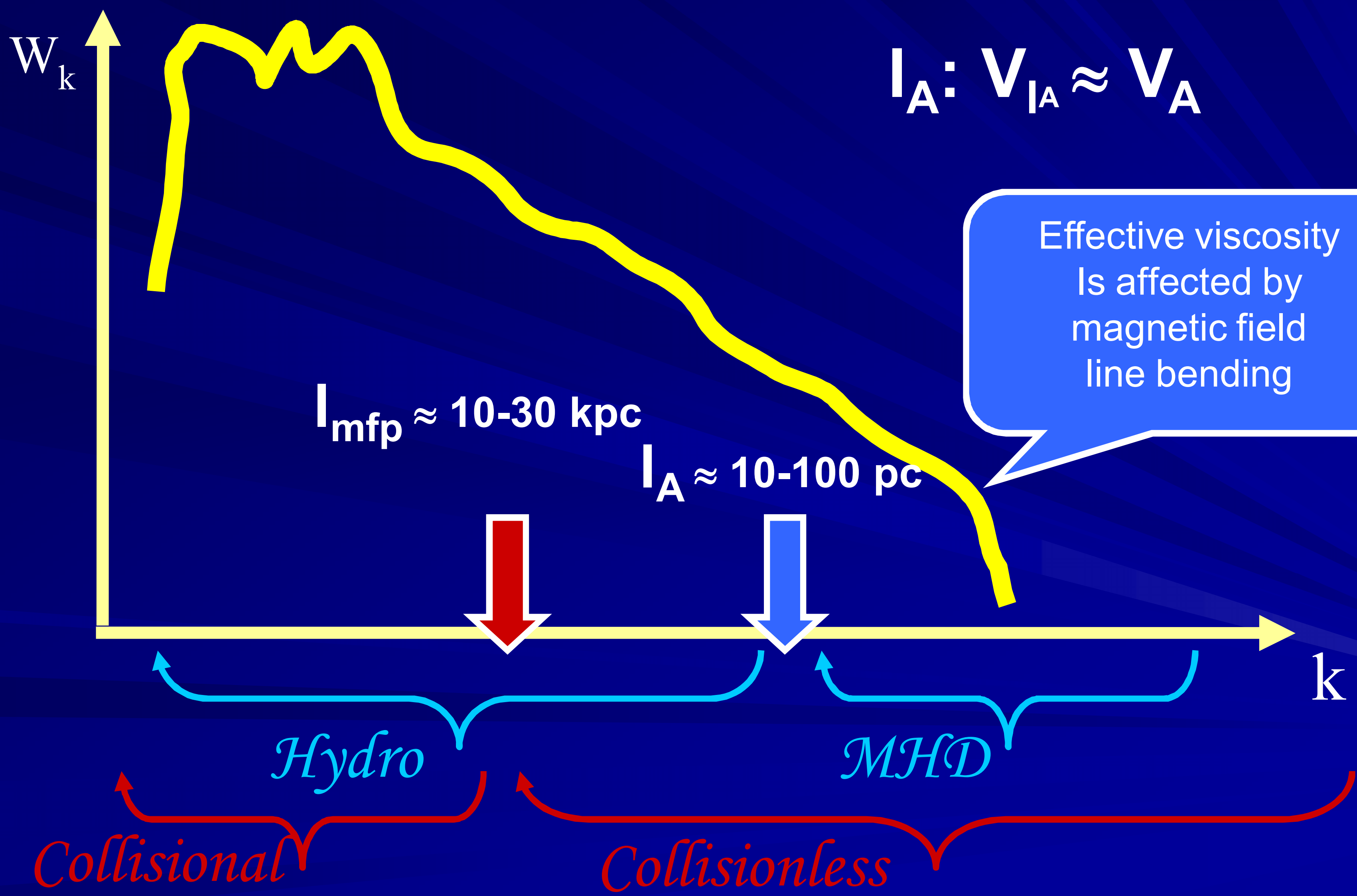
$V_A \sim 30 – 100$ km/s

Sub-sonic Turbulence

Super-Alfvenic Turbulence

Basics of turbulence in the ICM

Brunetti & Lazarian 2007



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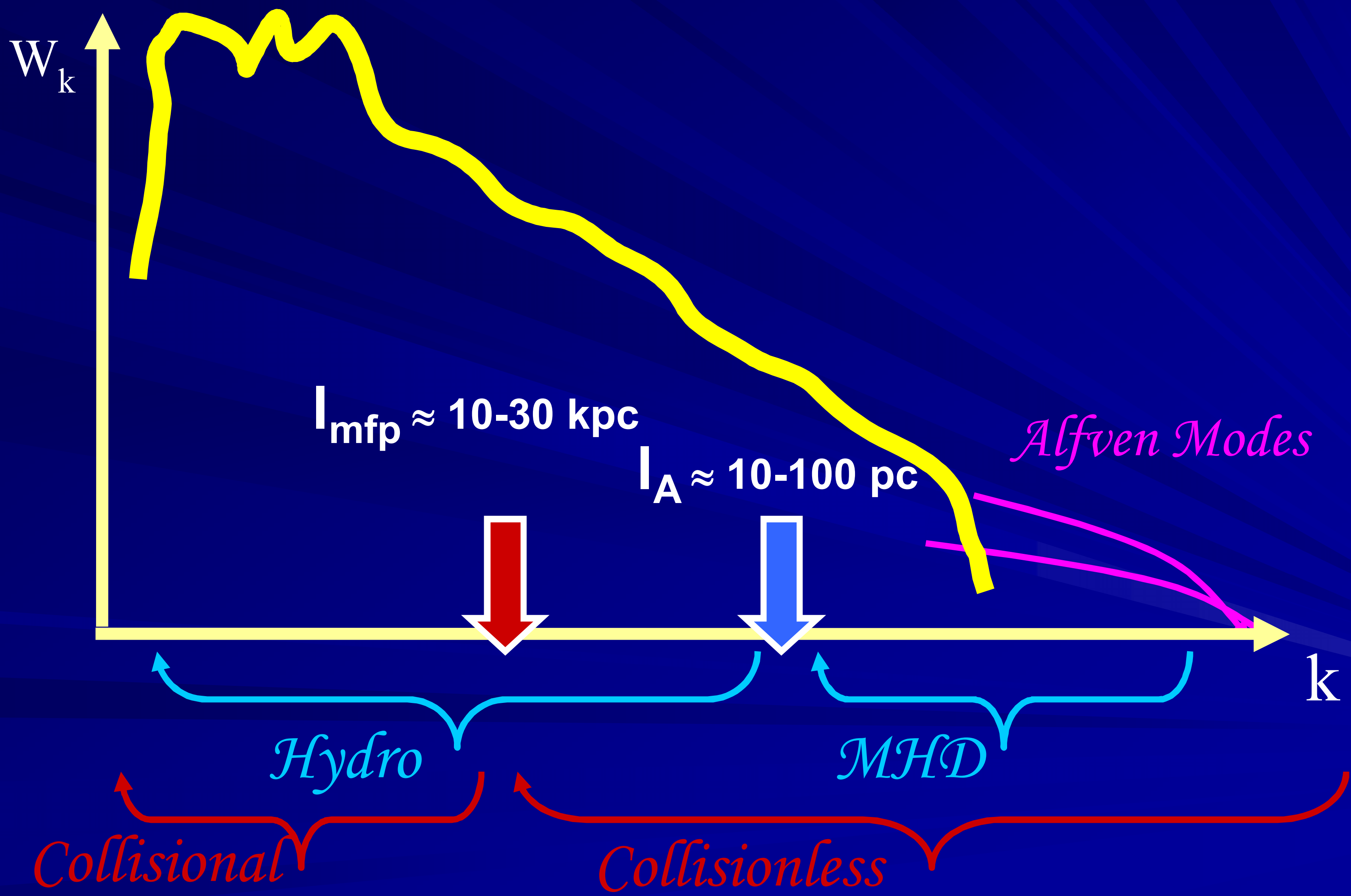
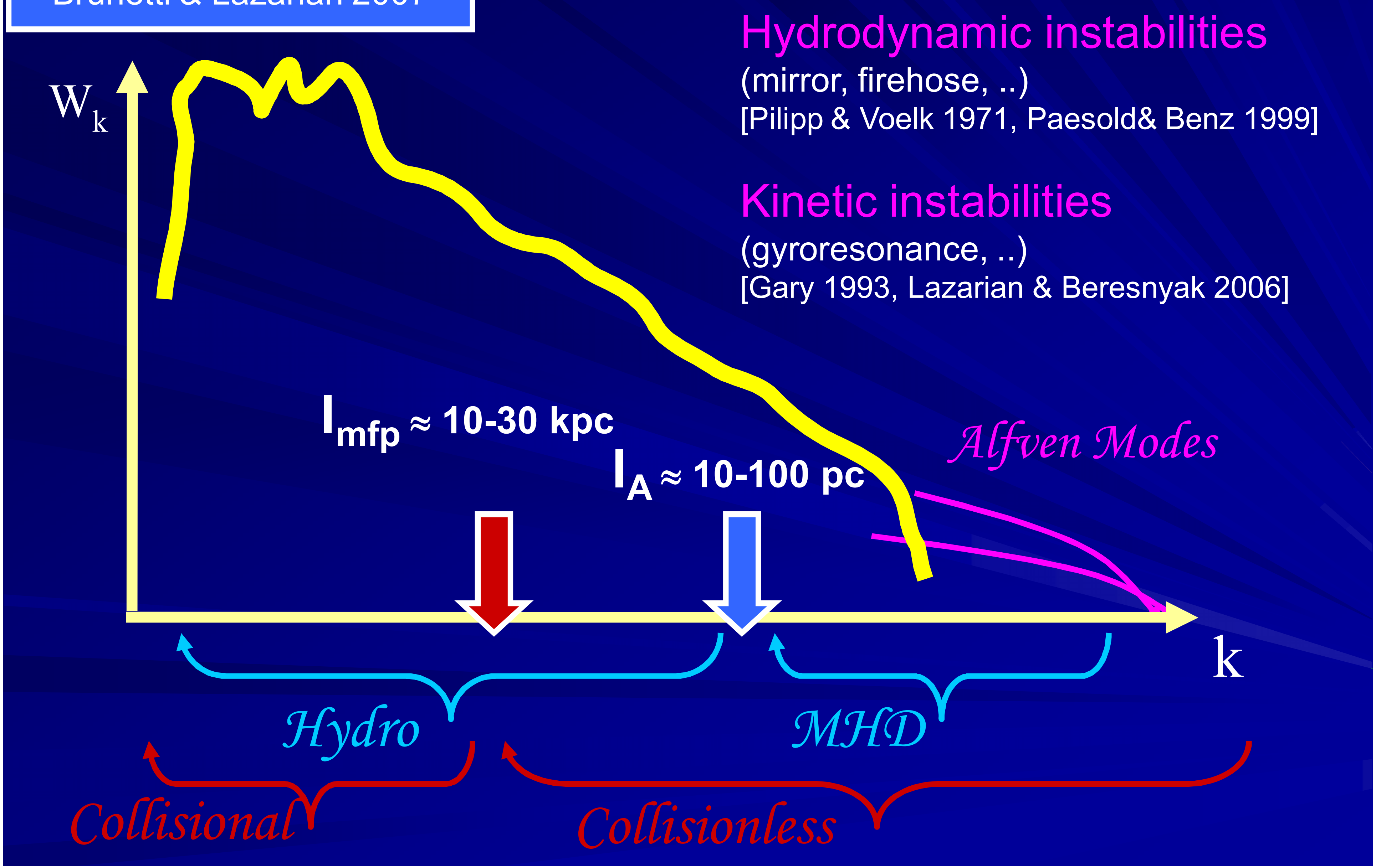


Basics of turbulence in the ICM

Brunetti & Lazarian 2007



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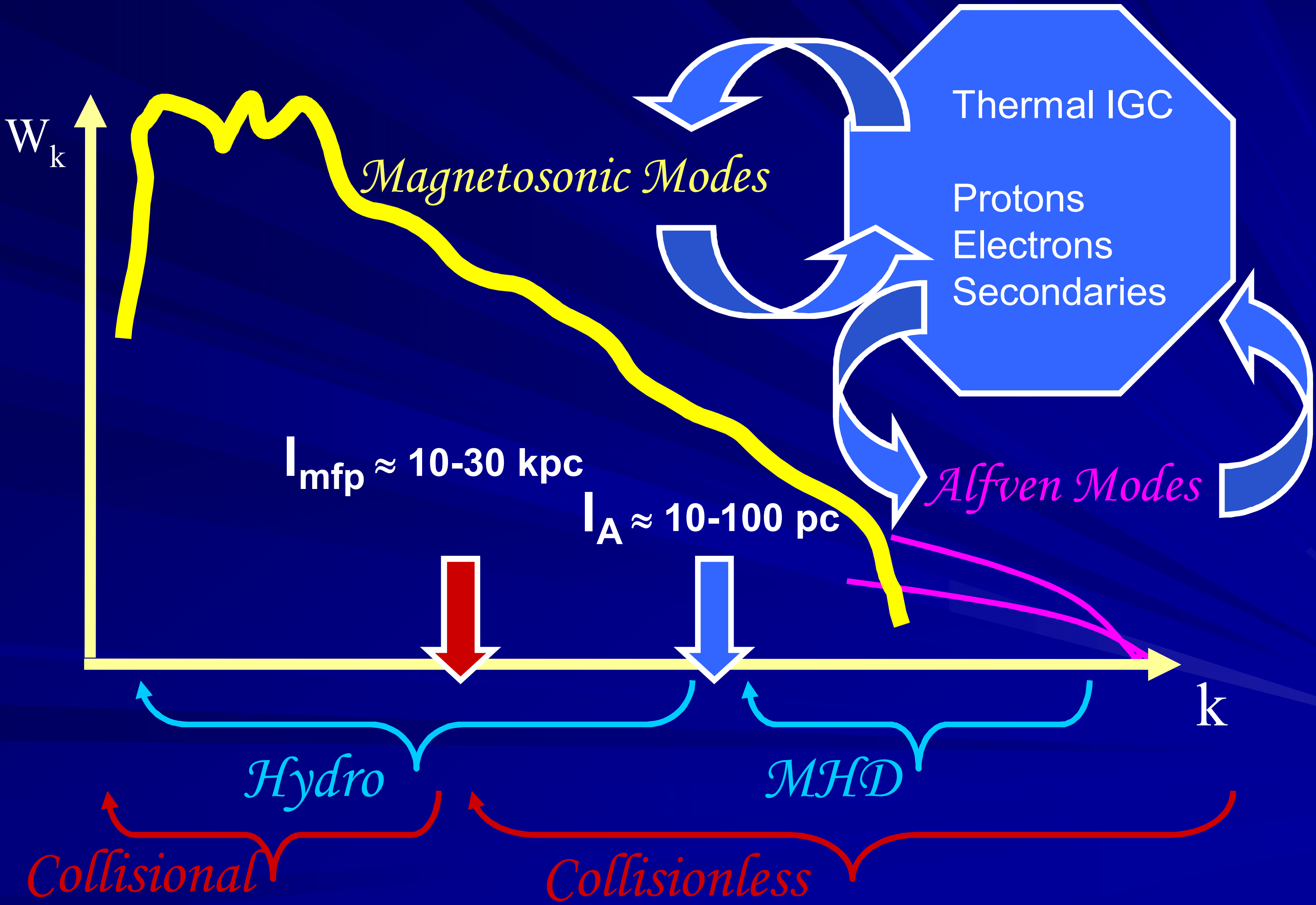


Alfvenic: results

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

Alfvenic: results

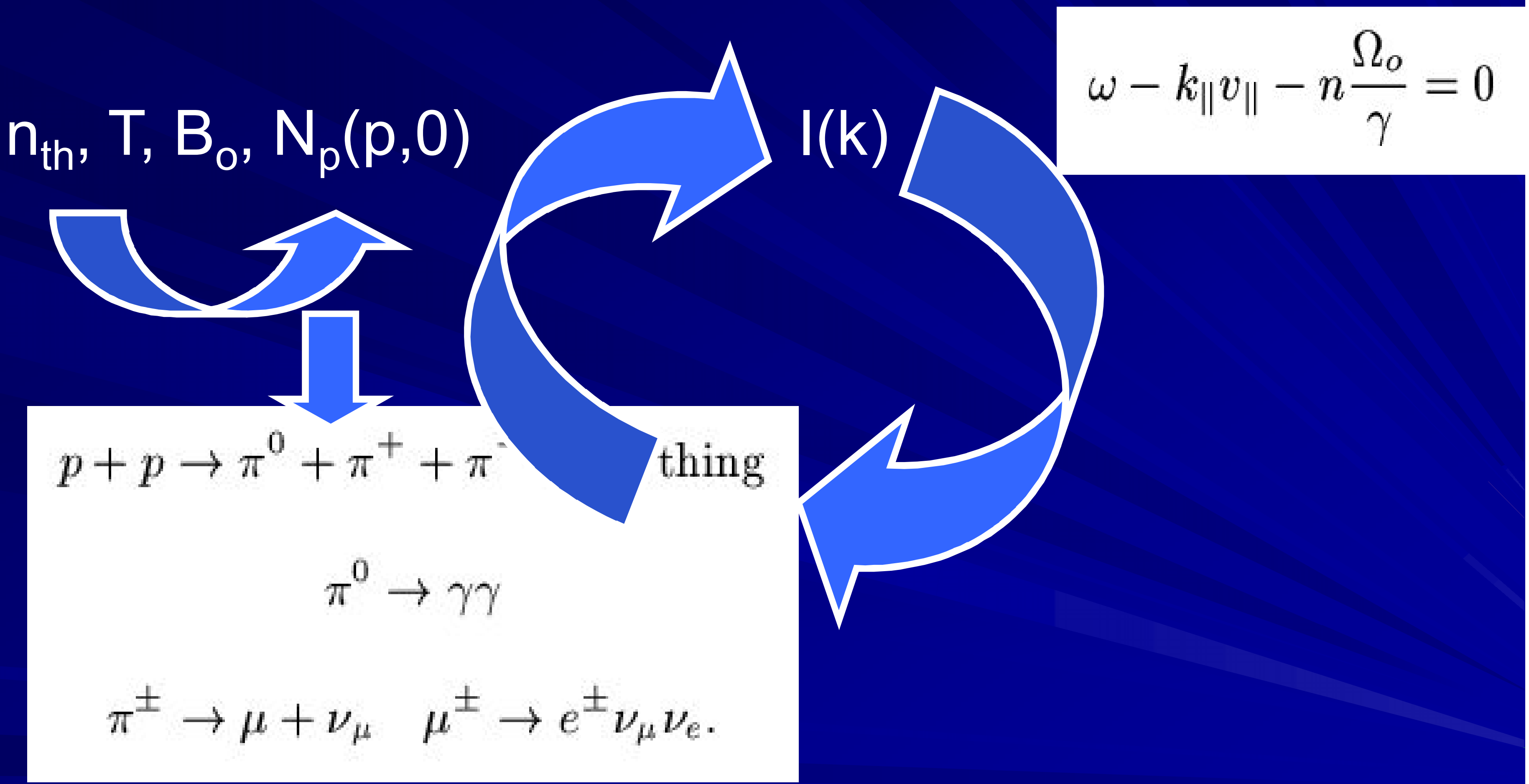
n_{th}, T, B_o, $N_p(p,0)$ I(k)

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

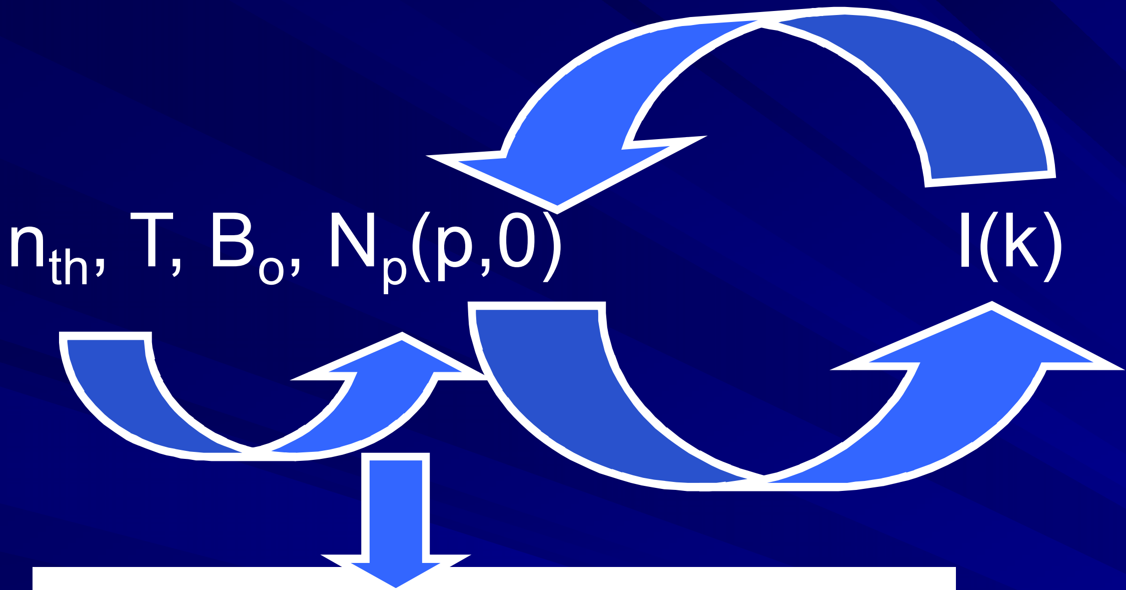
$$\pi^0 \rightarrow \gamma\gamma$$

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

Alfvenic: results



Alfvenic: results



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

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

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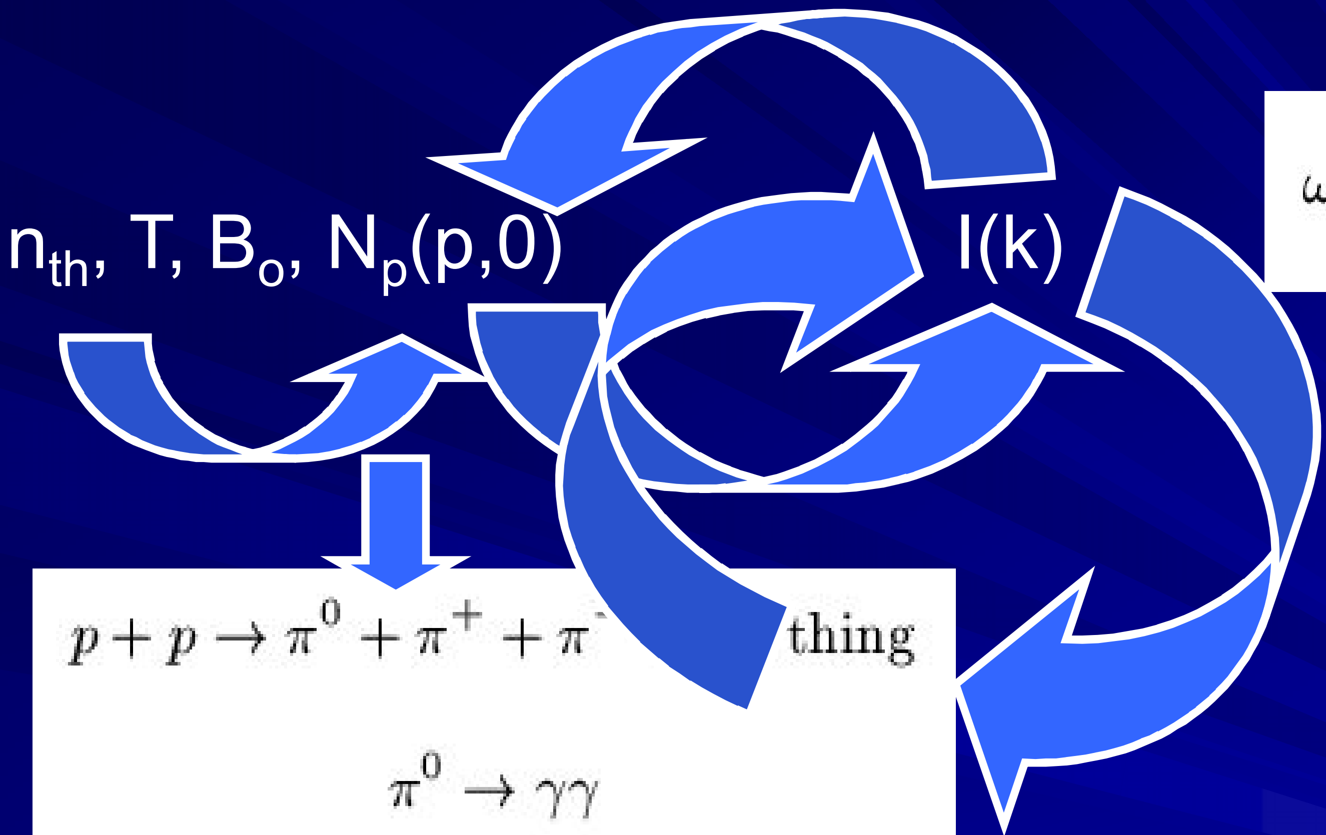
Alfvenic: results



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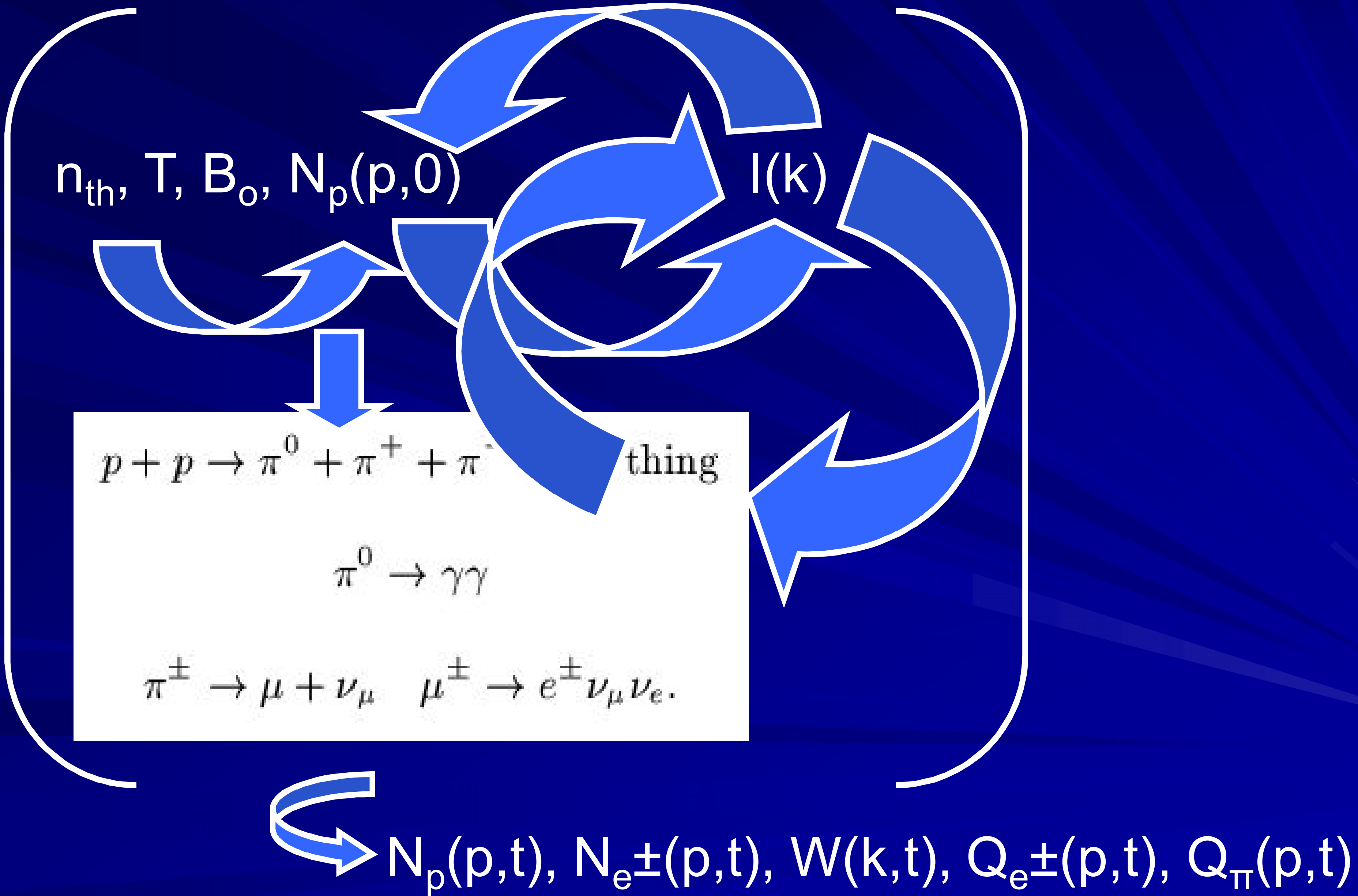

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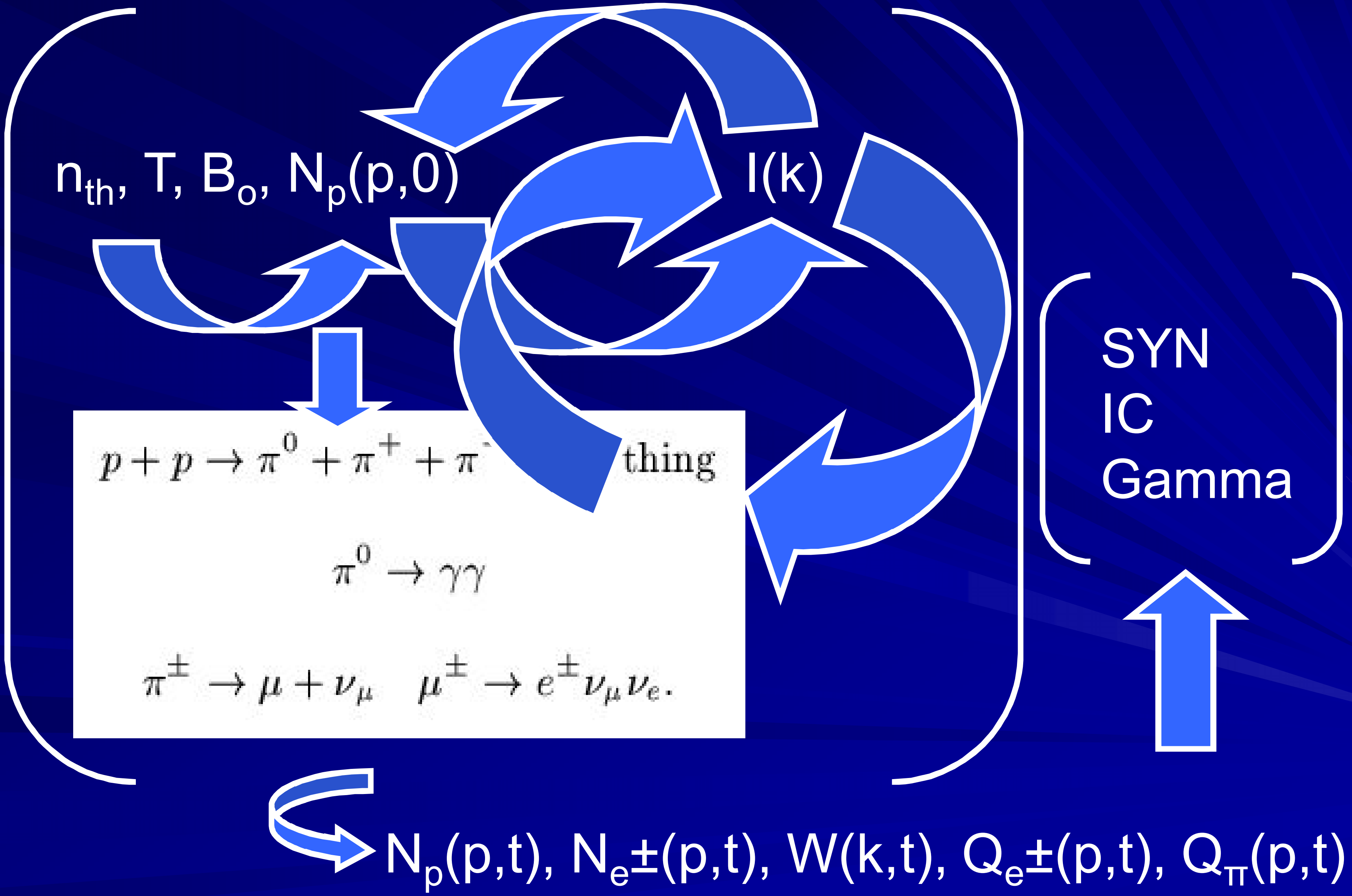
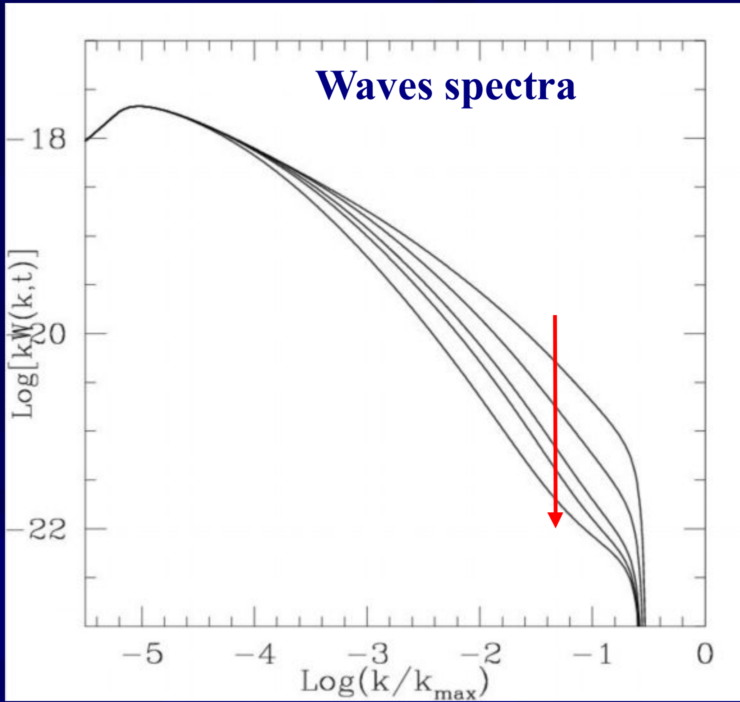
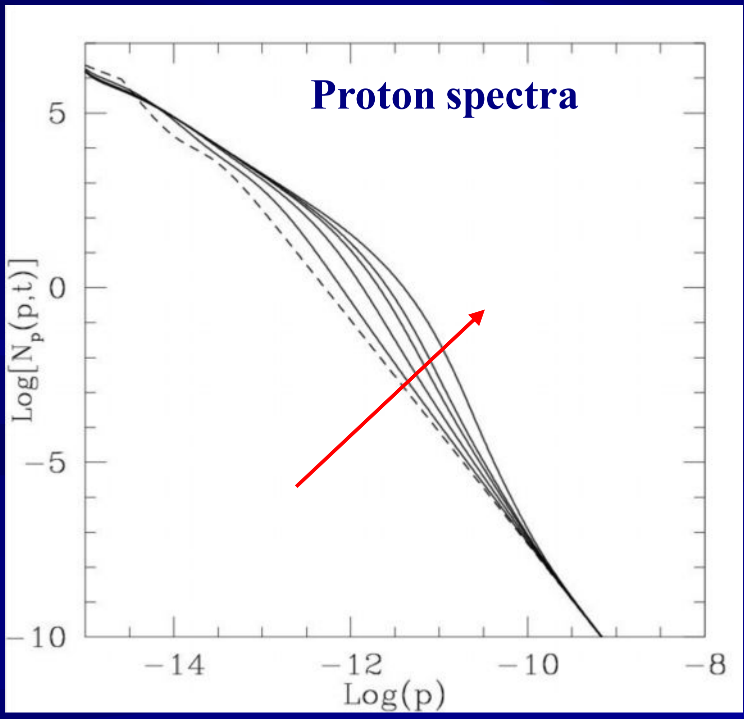
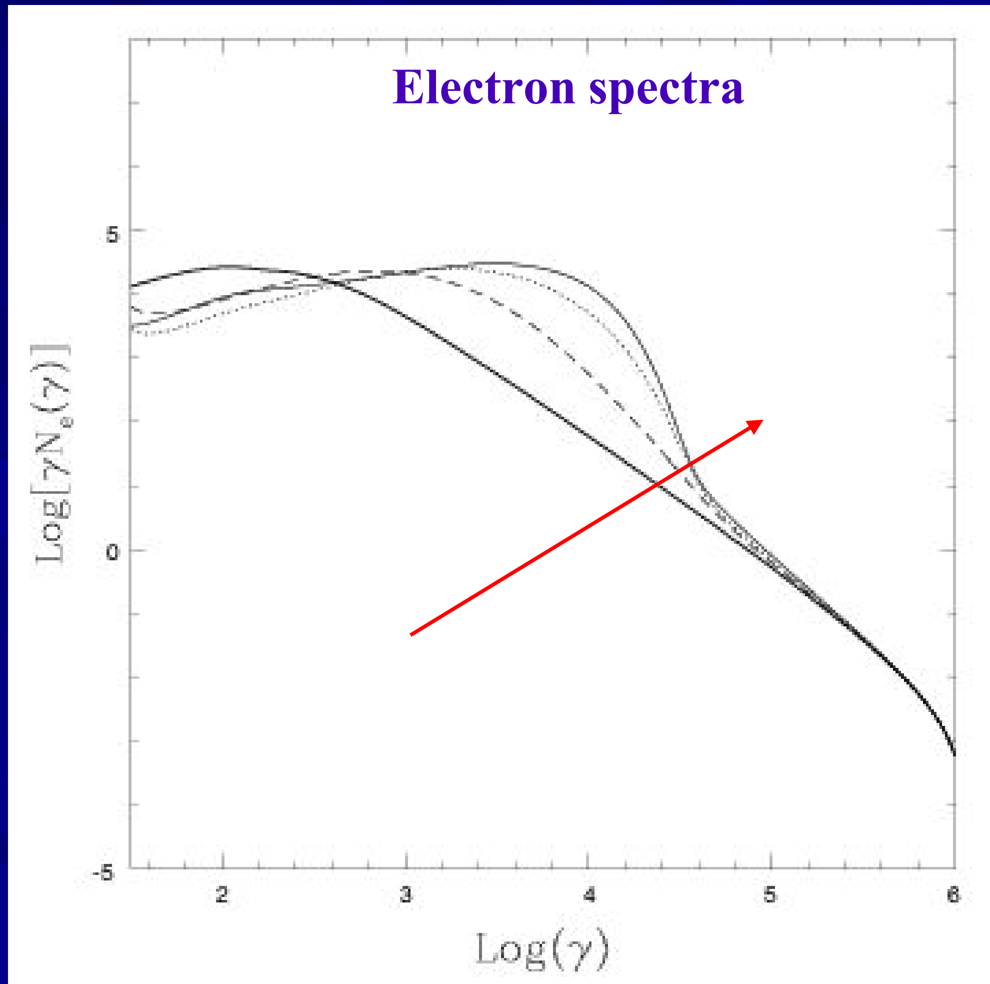


Full Alfven-Wave--Particle Coupling

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







Waves + Protons + Secondaries

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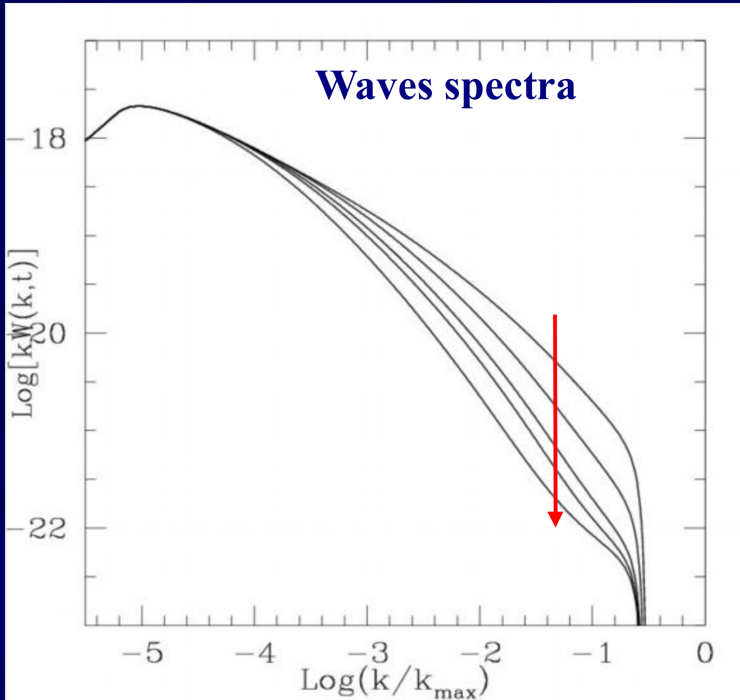
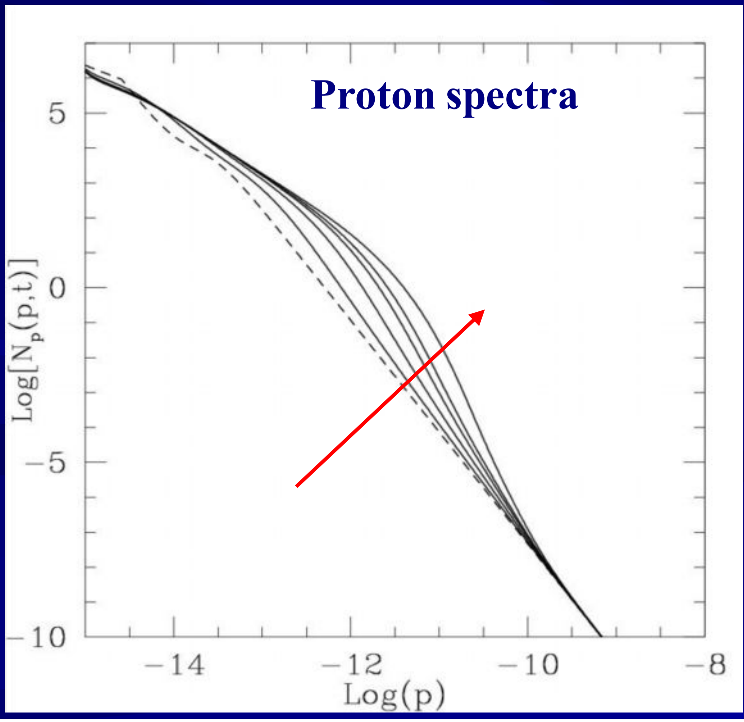
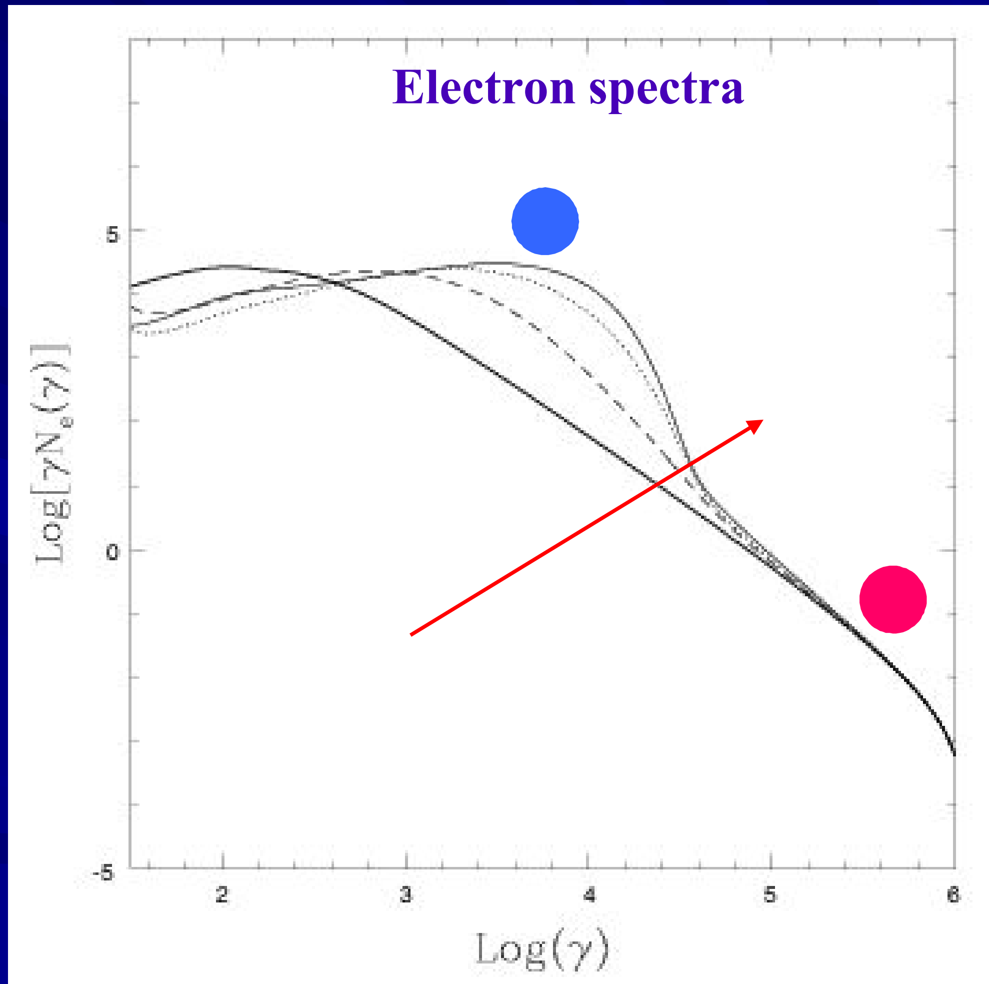
(Brunetti +al. 2004; Brunetti & Blasi 2005)





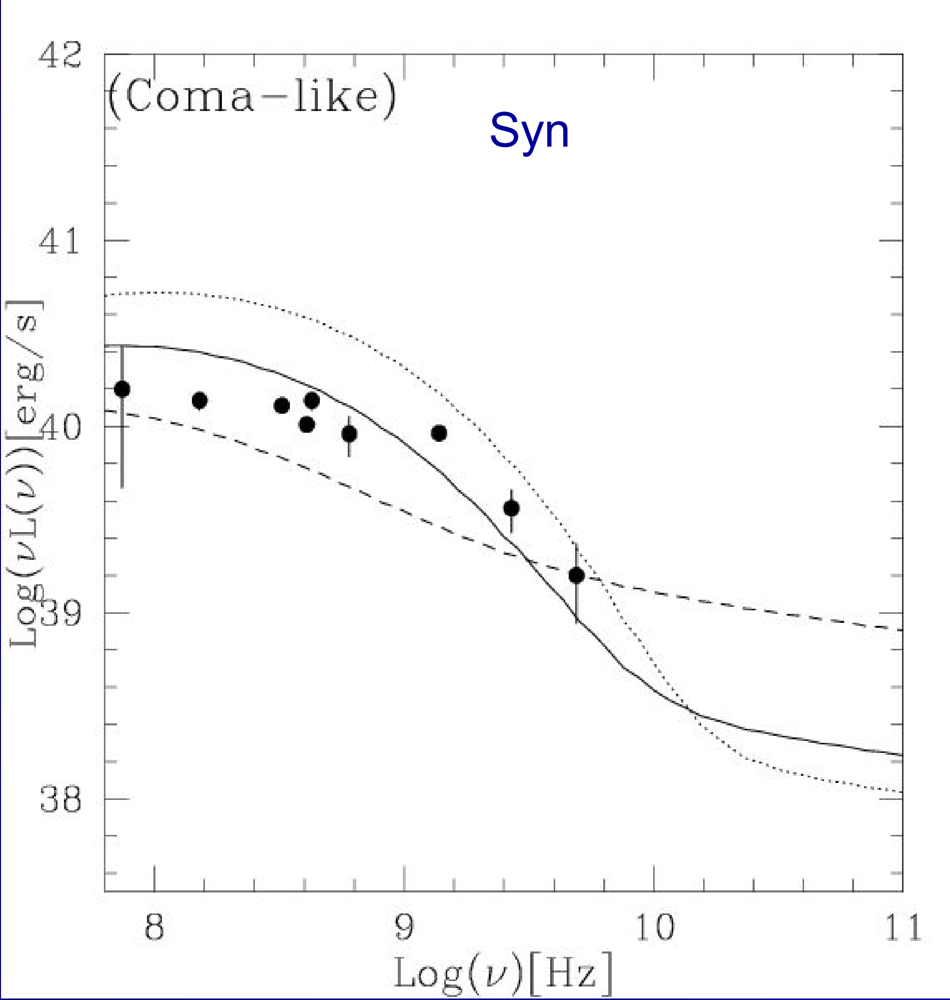


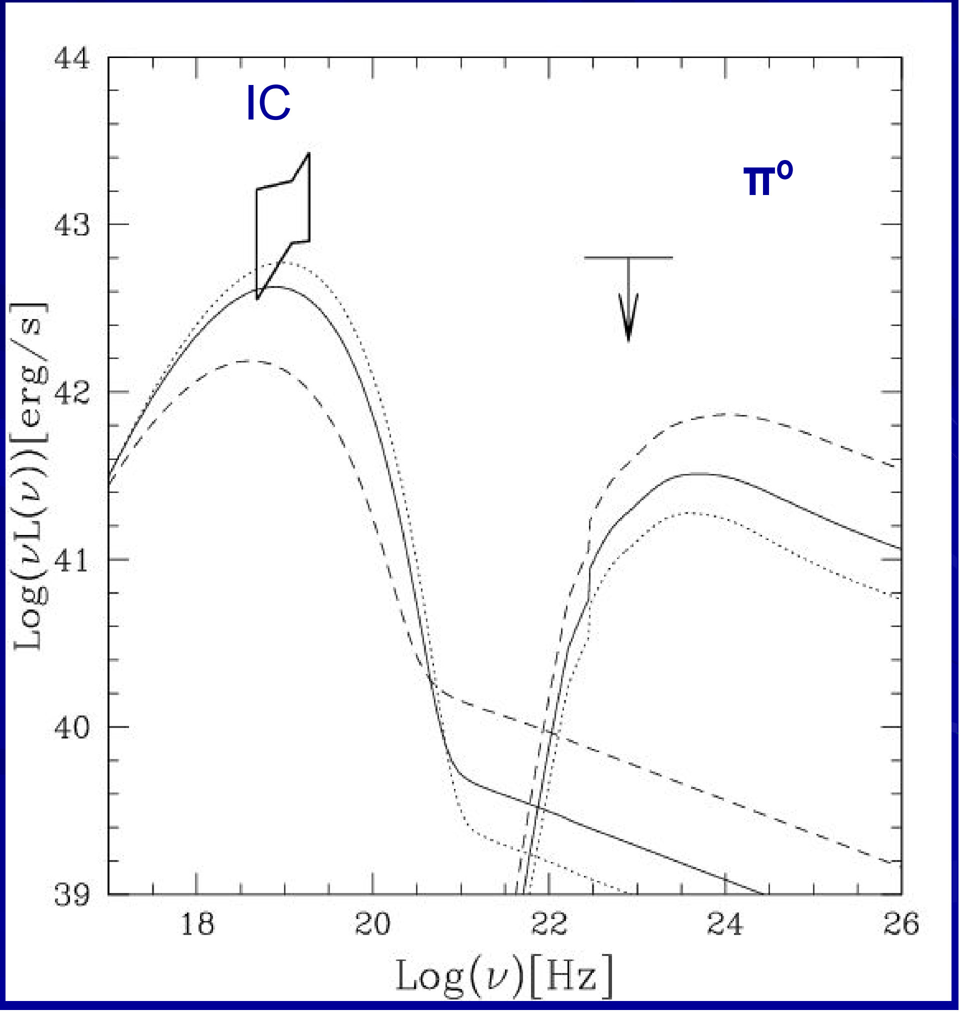
Waves + Protons + Secondaries

Alfvenic: results

Brunetti, Blasi, Gabici, Cassano, in prep

Toy Model: β-profile, $B_o \approx A\, n_{th}^{2/3}$, $B_o(0)=1.5\mu G$, $W_{CR} \approx f\, W_{th}$, $P_A \approx Q\, n_{th}^{5/6}$





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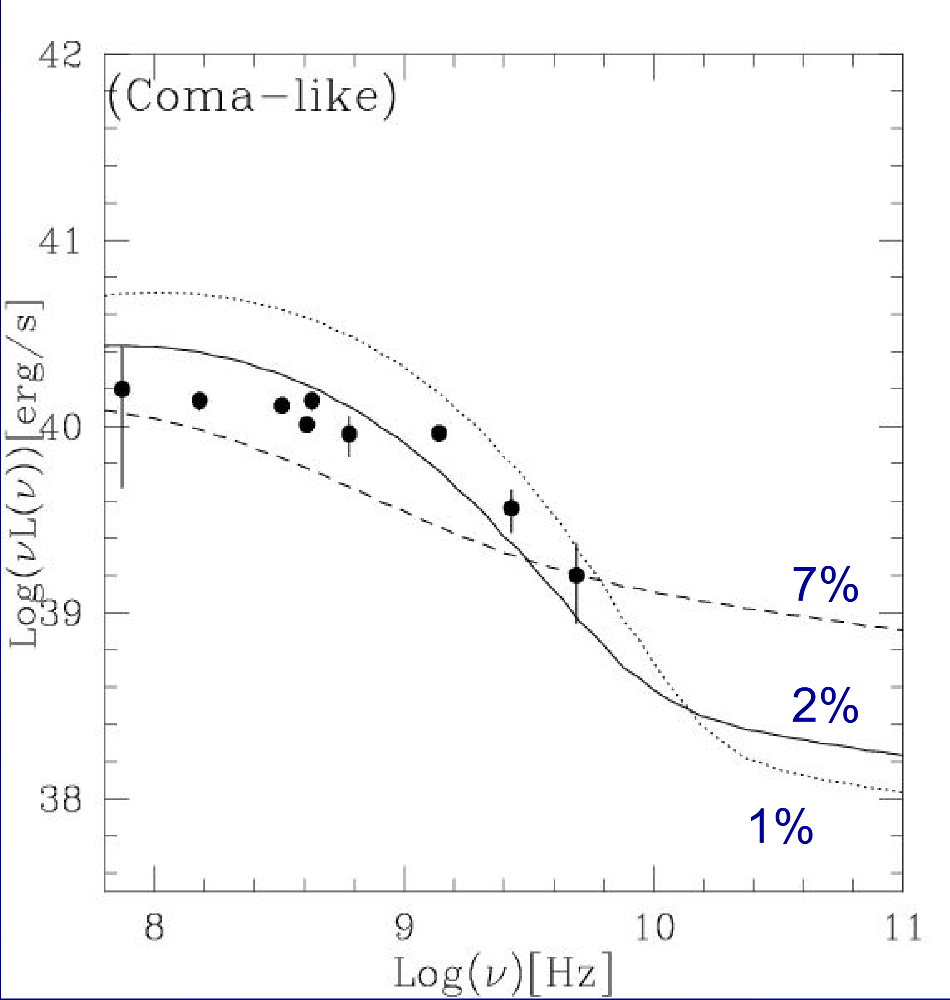

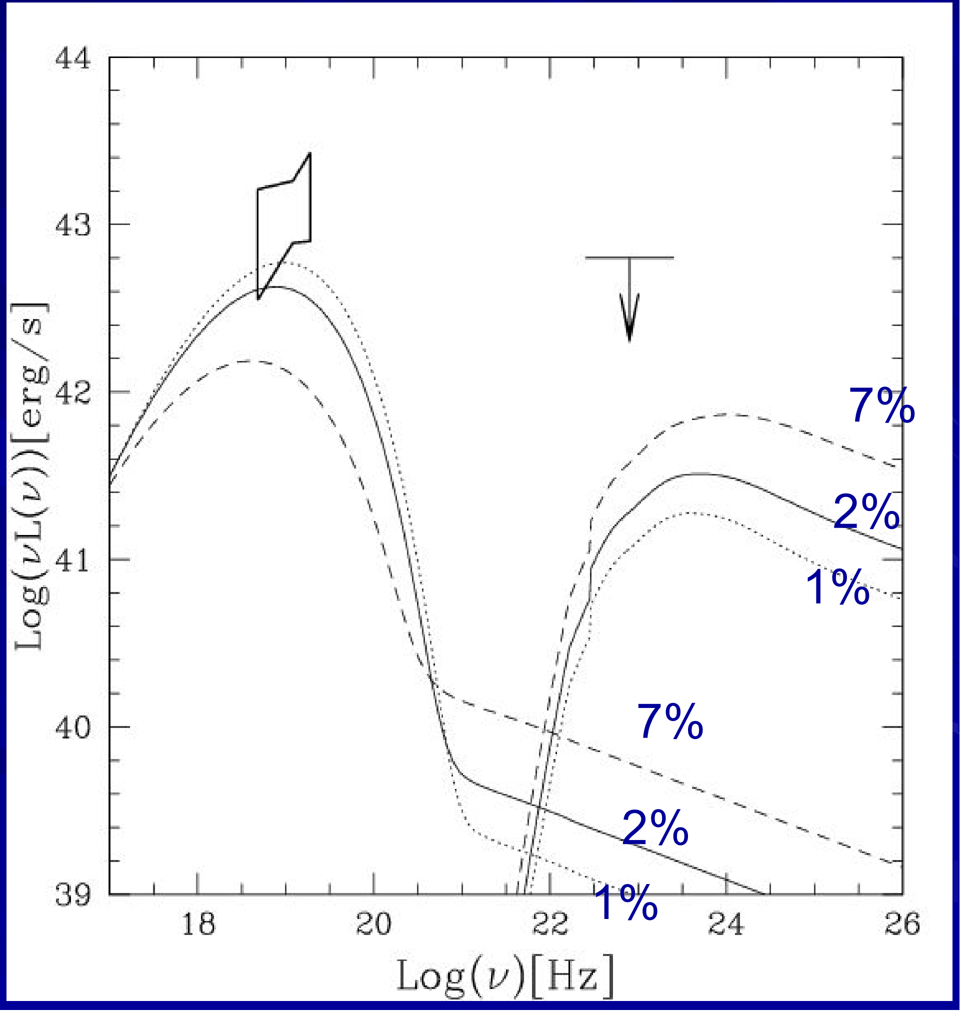

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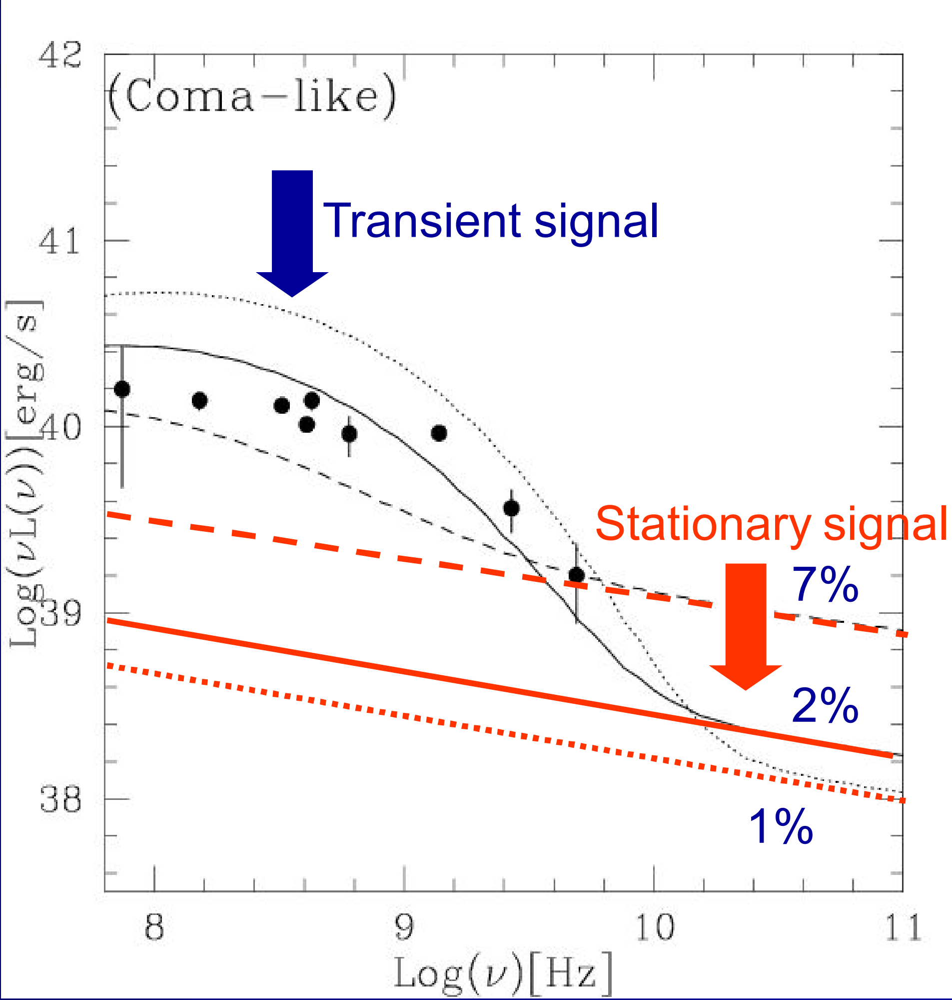

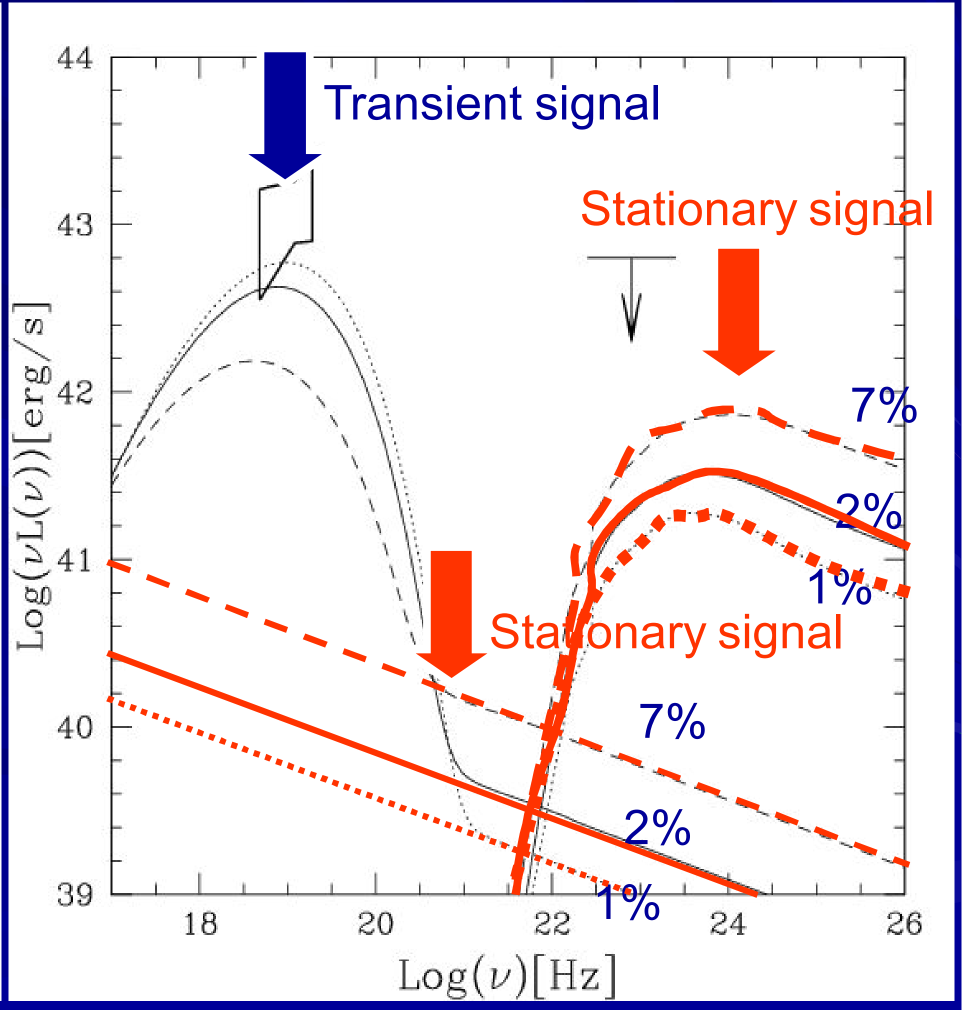

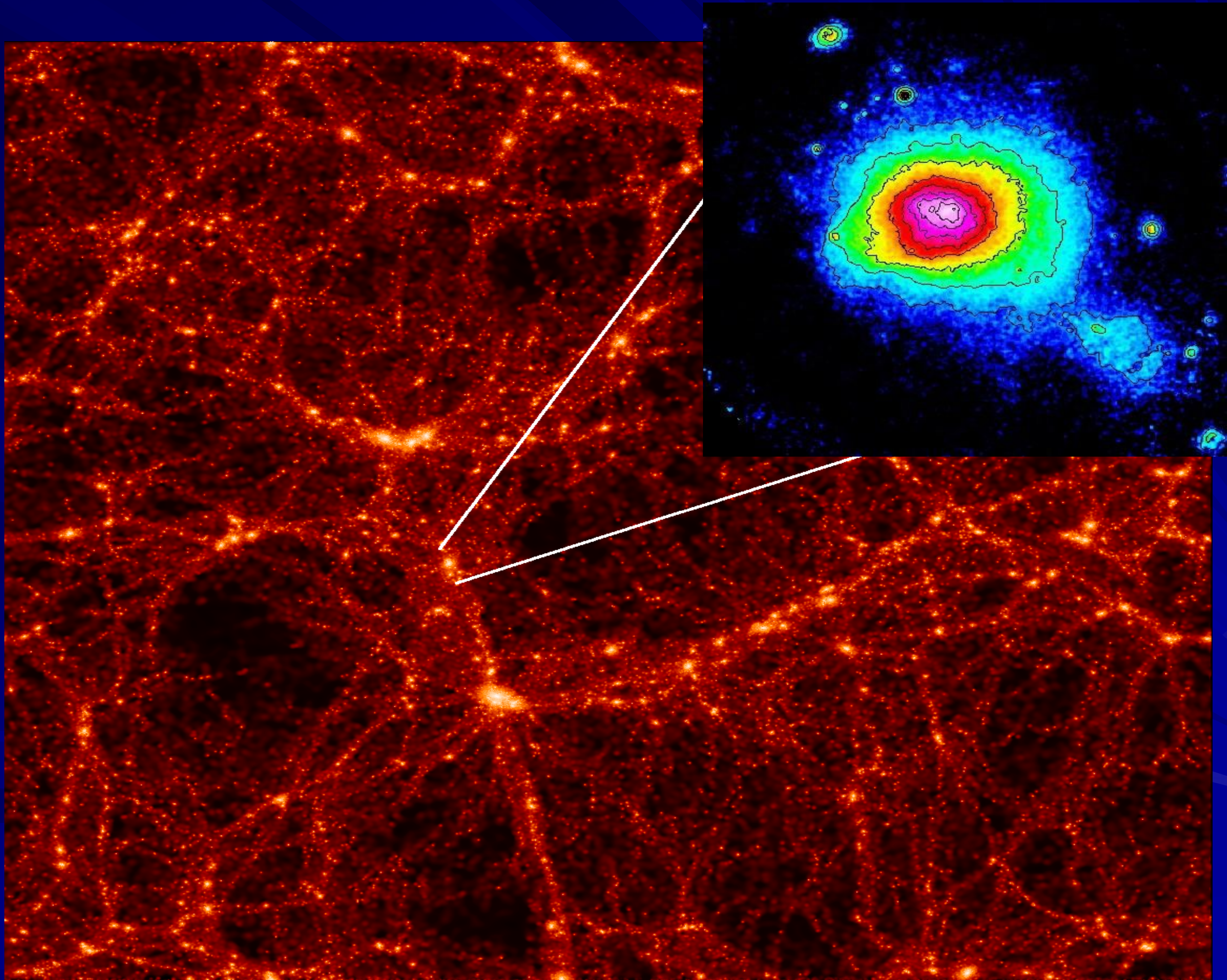

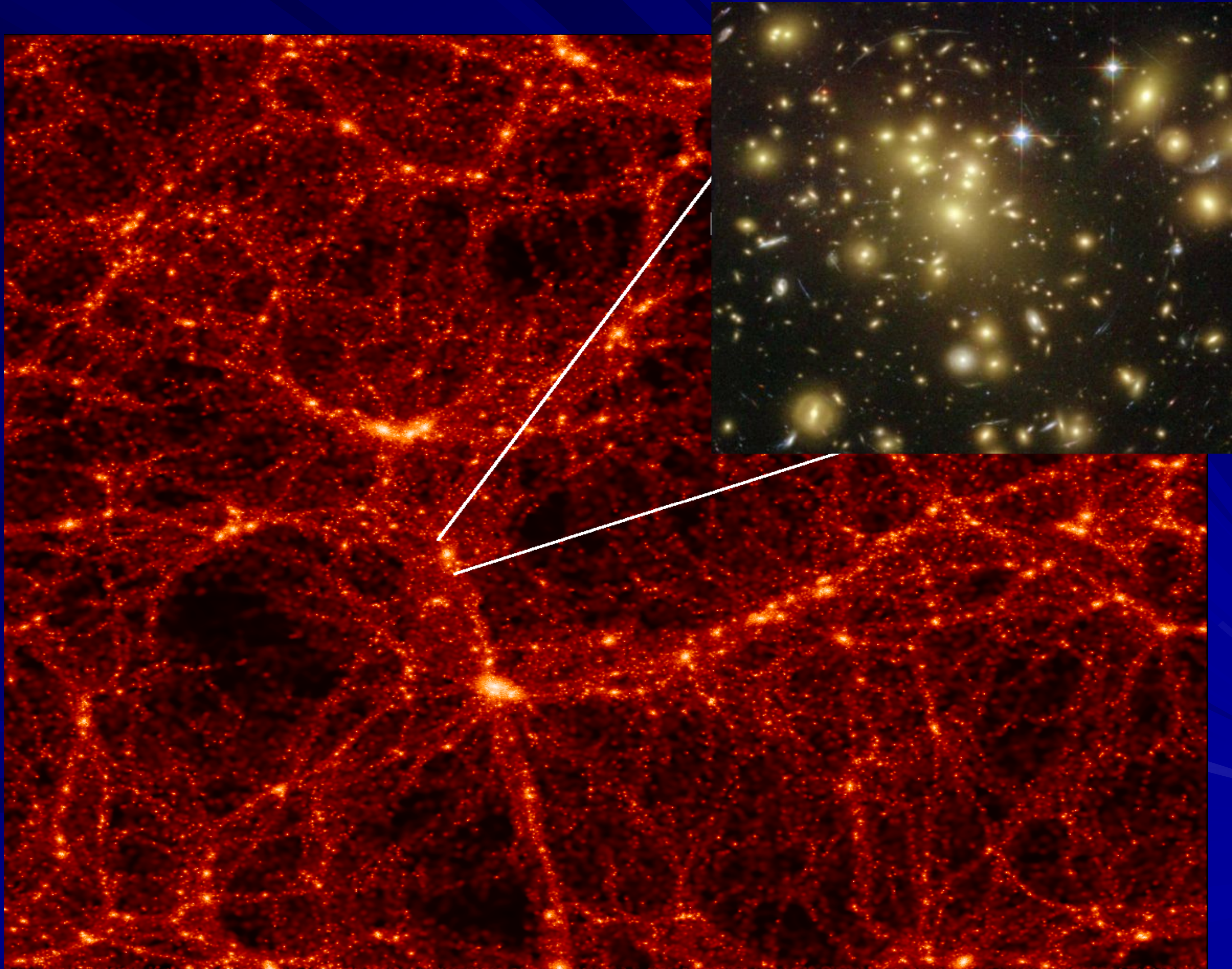

Alfvenic: results

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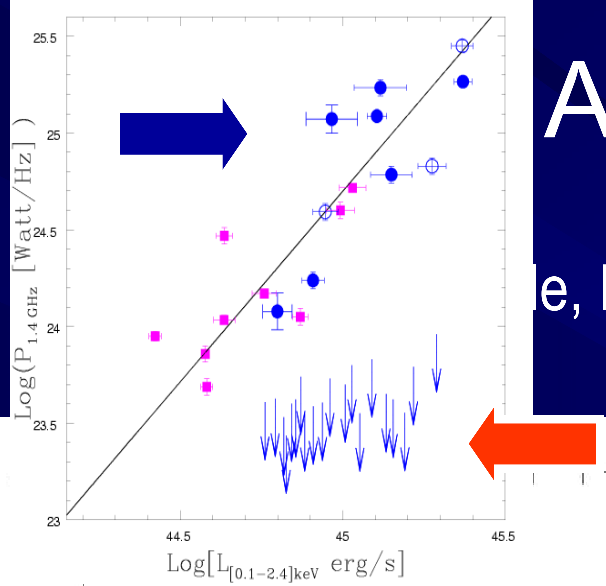
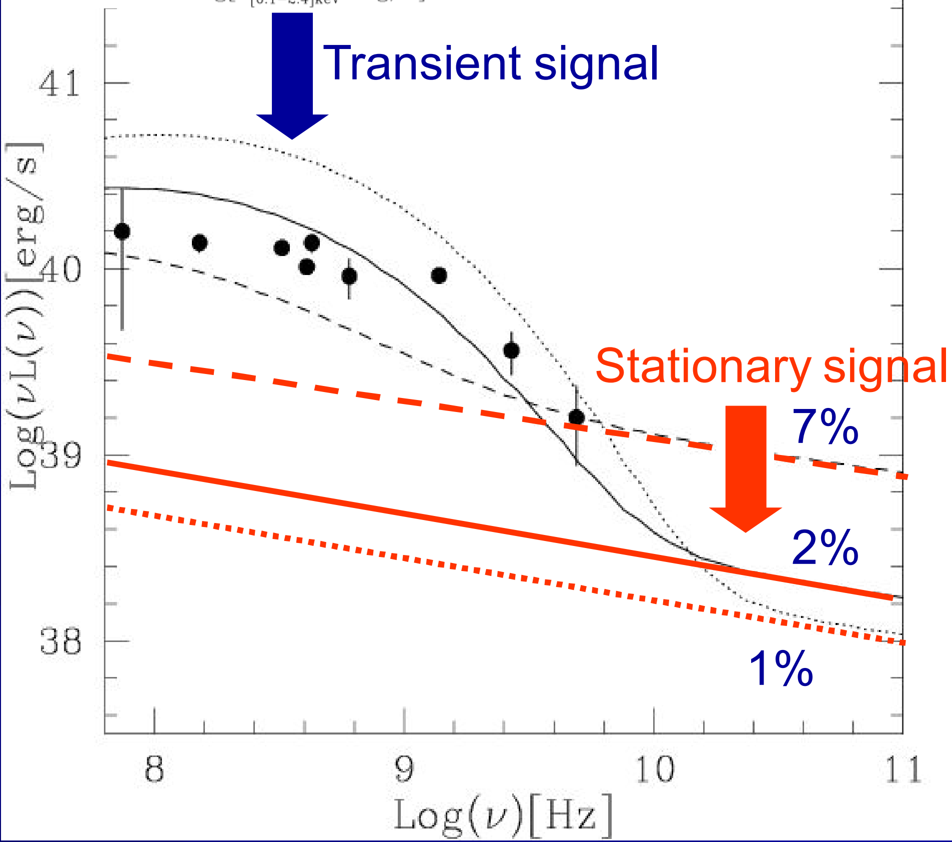
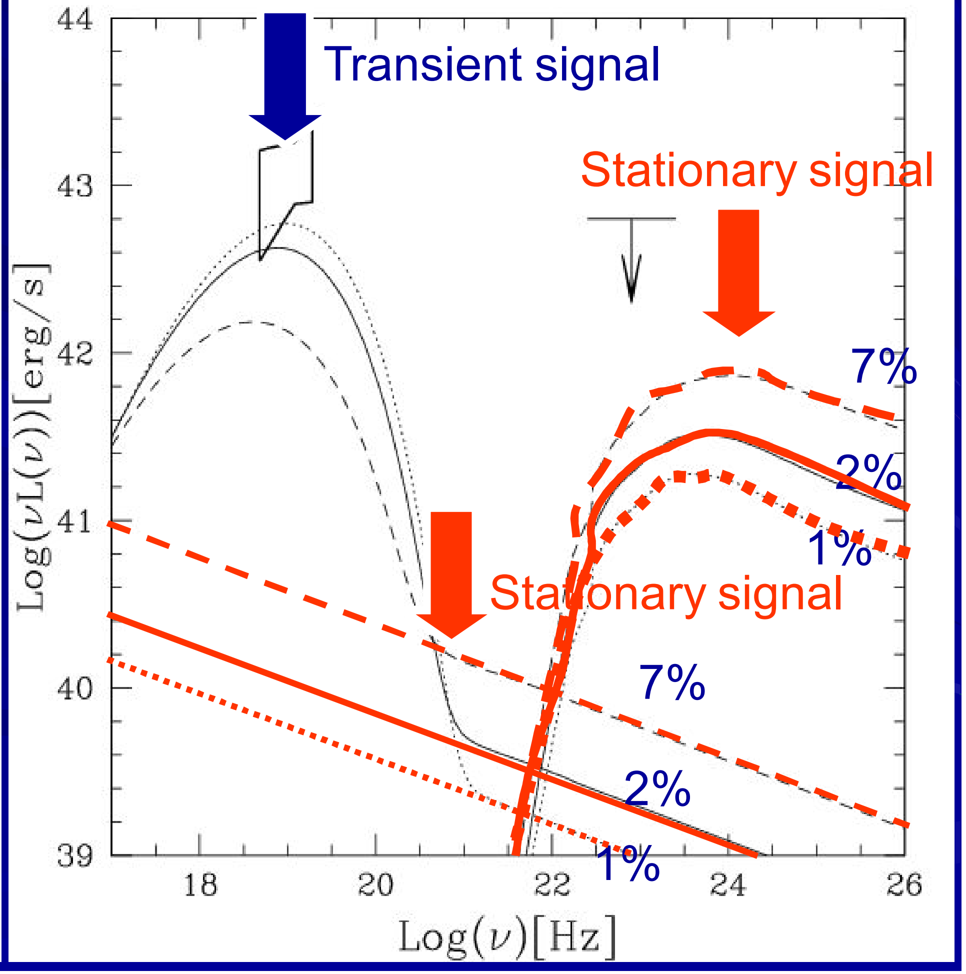
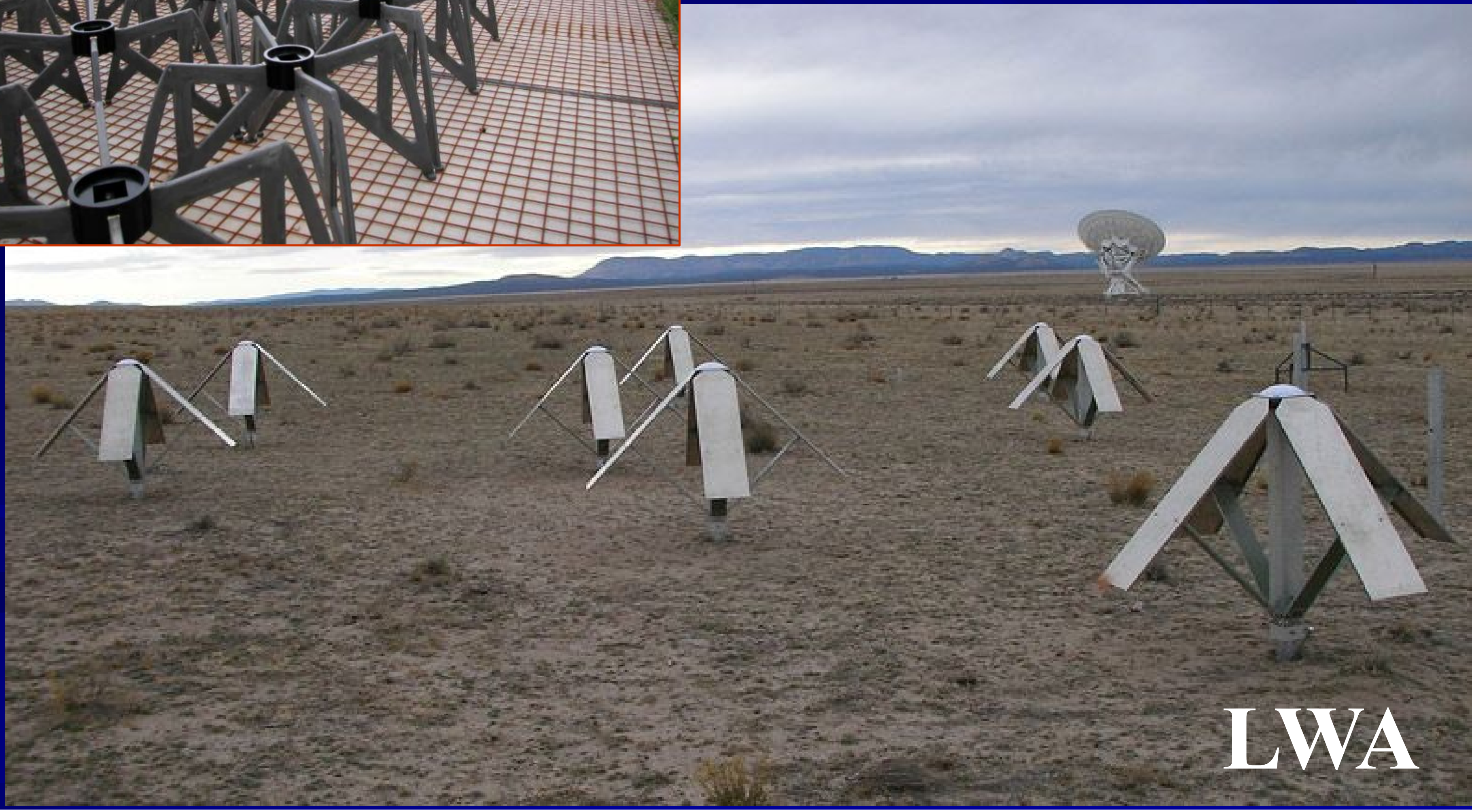


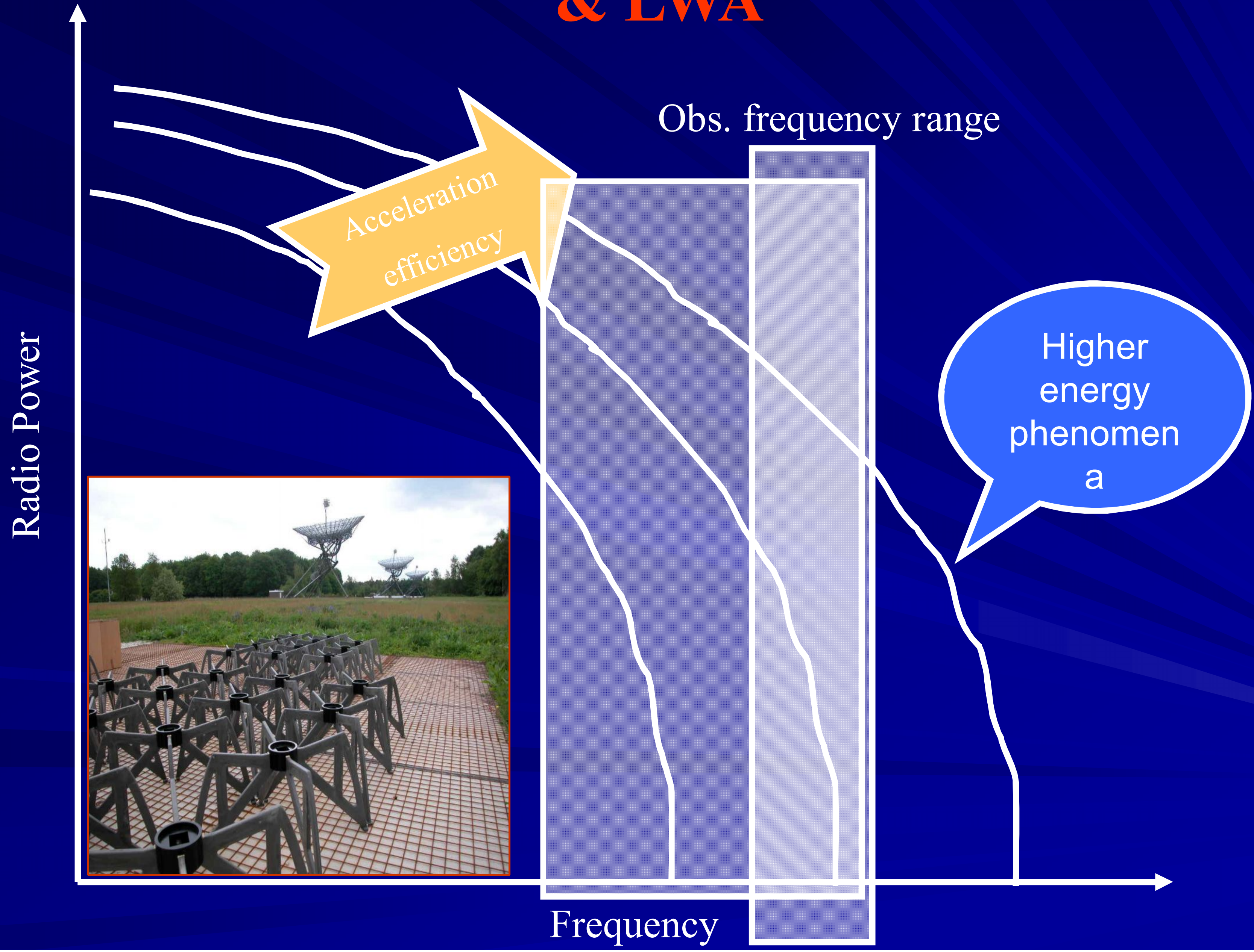




FUTURE

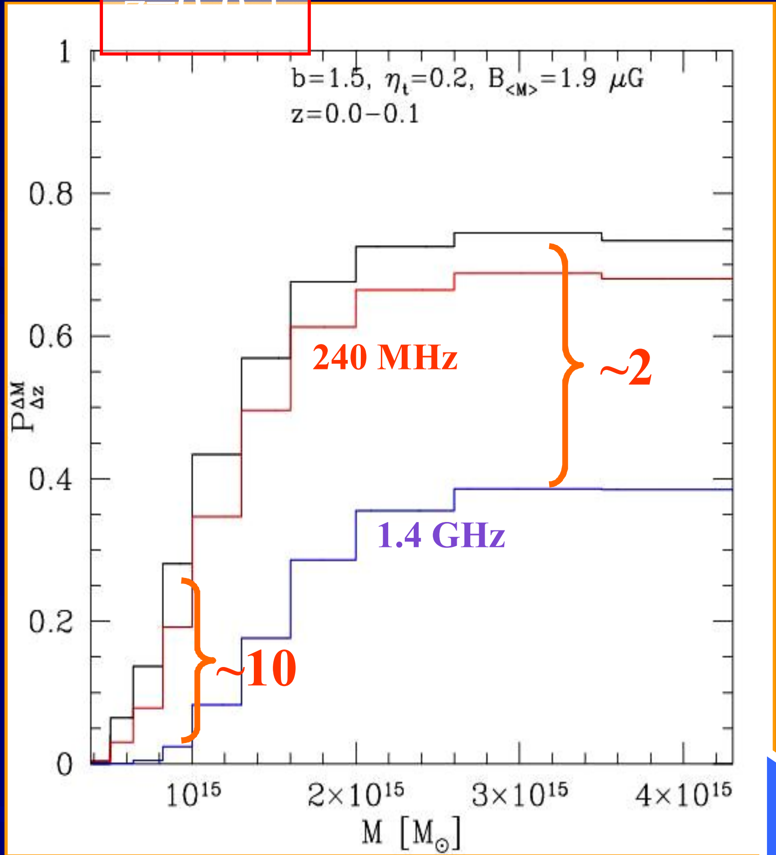


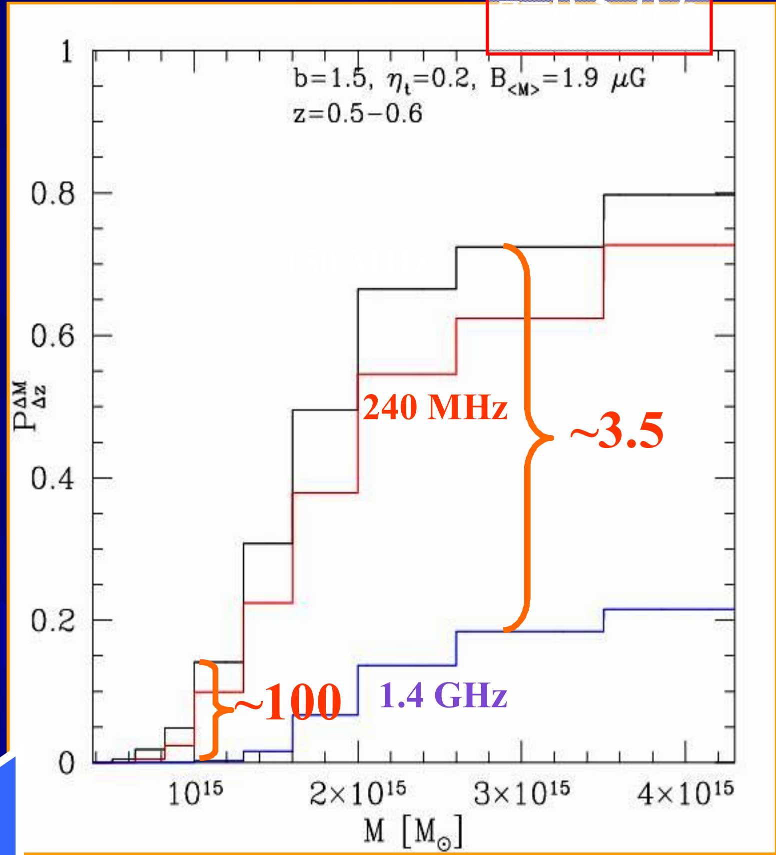
LOW freq observations: LOFAR & LWA



Fraction of GC with RHs at lower frequencies

(Cassano et al., 2006,08)



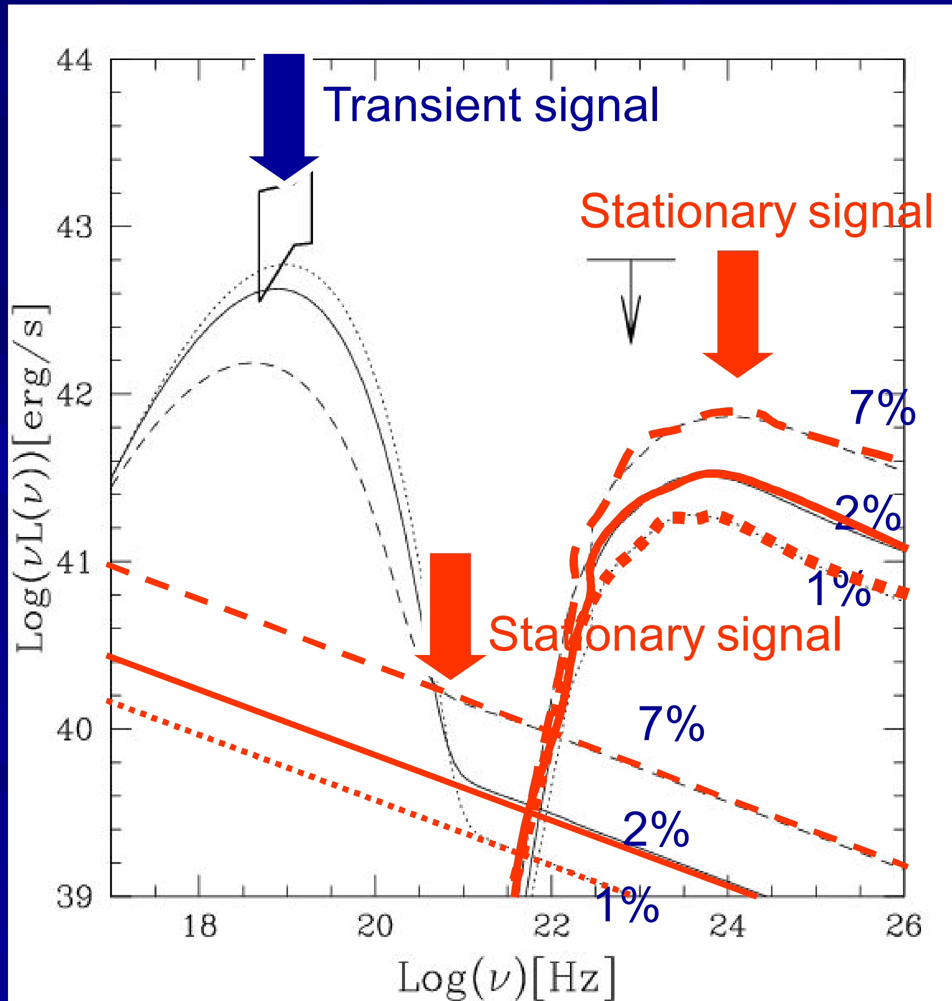


Expectation : Ultra-Steep-Spectrum Radio Halos

FUTURE

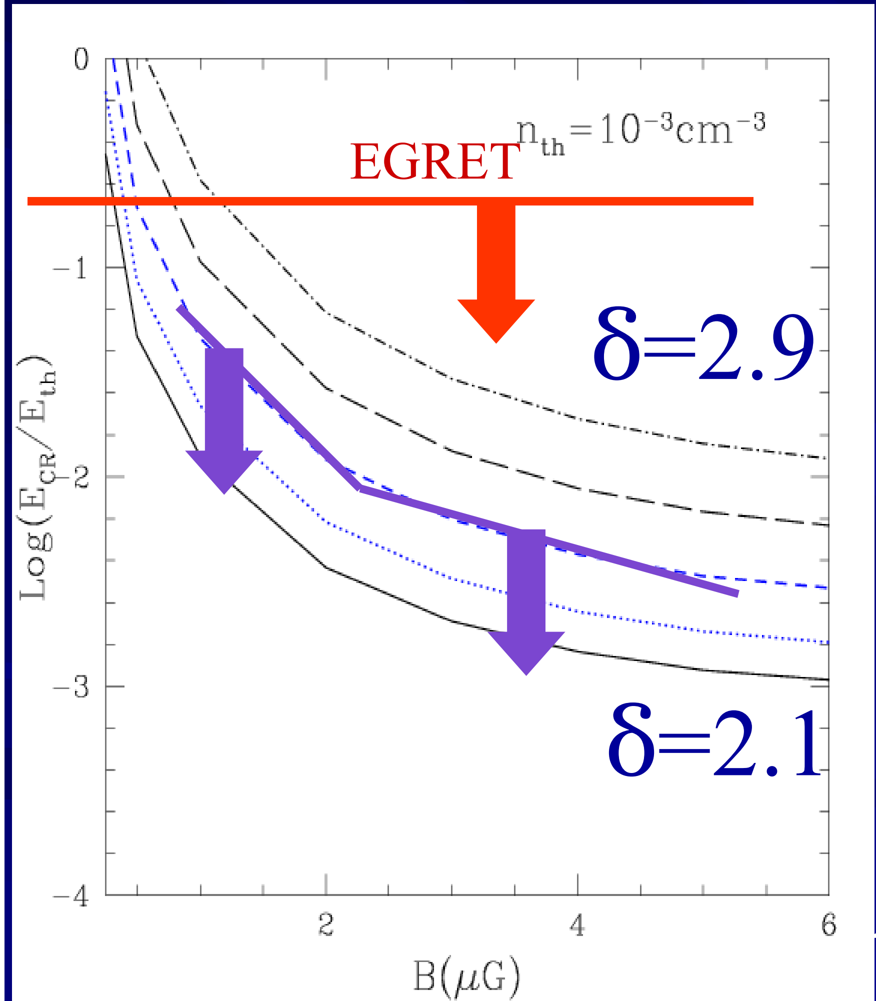
Alfvenic: results

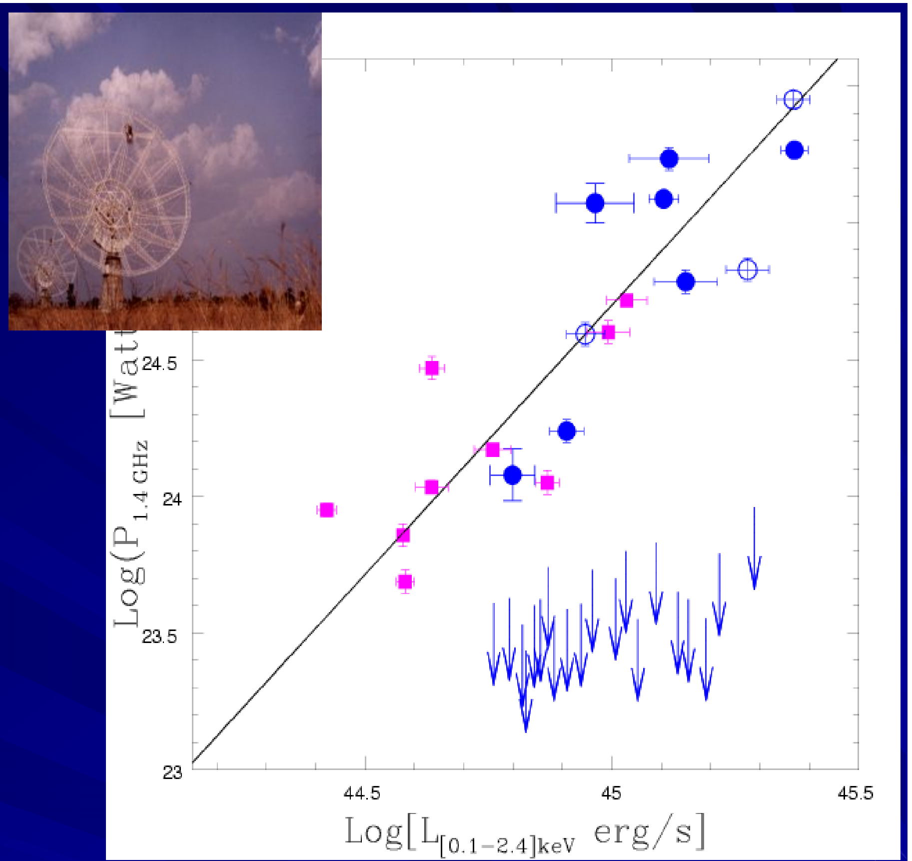
The gamma ray signal yields a direct estimate of CR protons



.. limits on CR protons

Brunetti +al. 2007

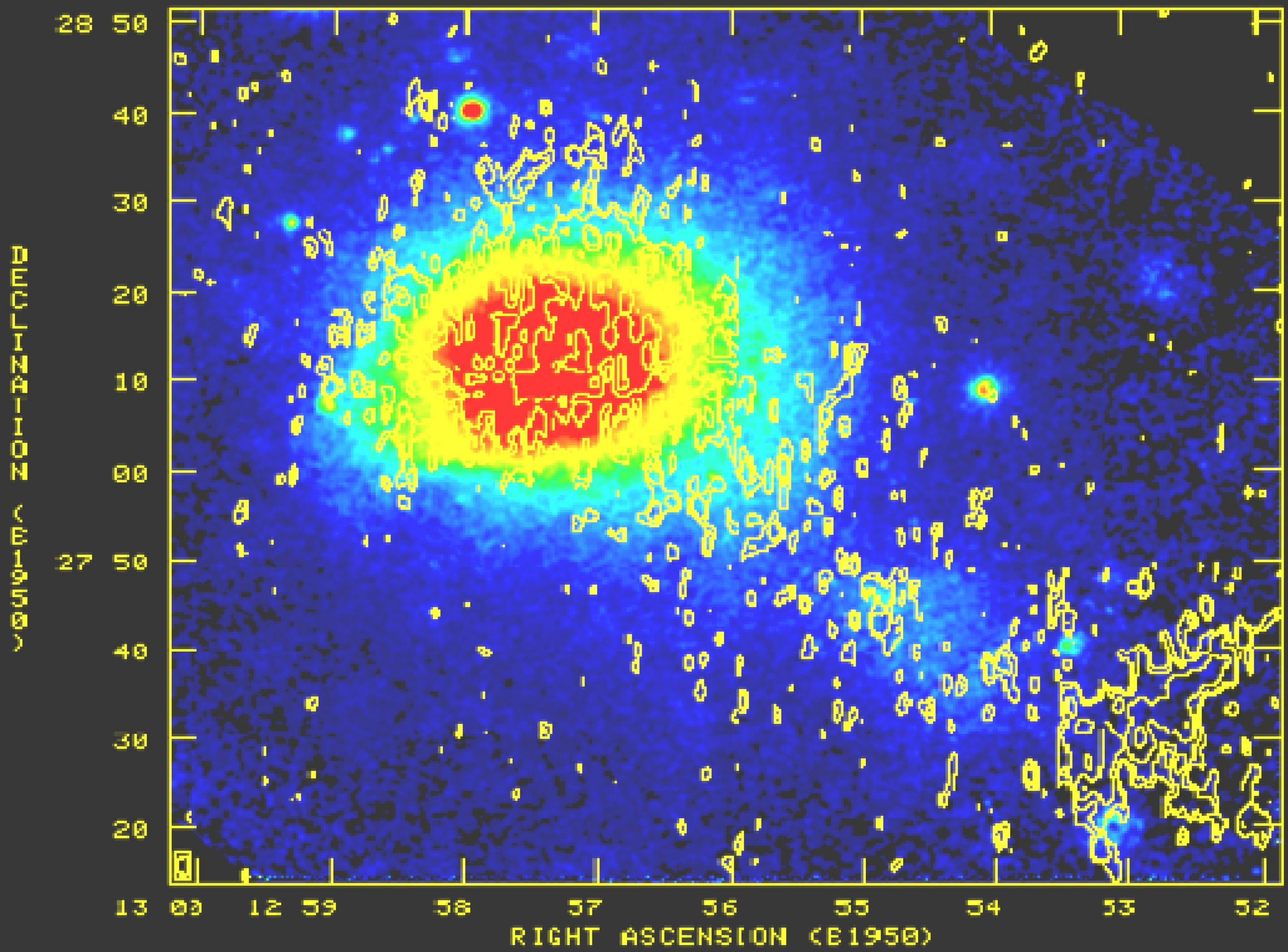




Synchrotron emission from secondaries should be smaller than upper limits .

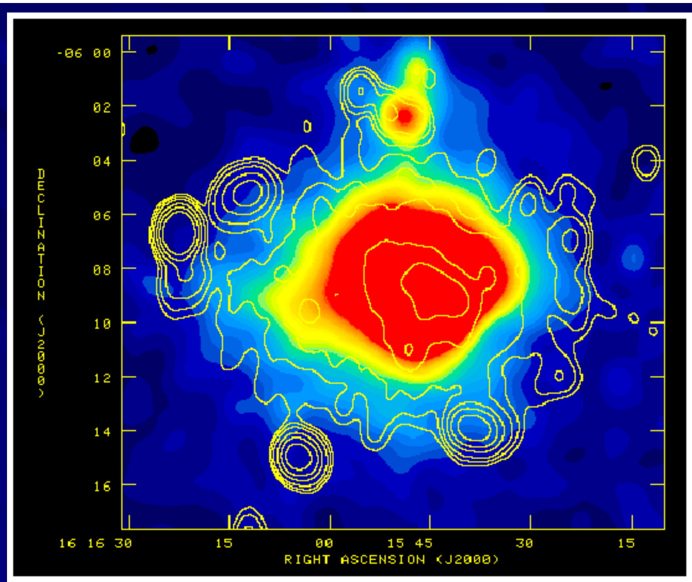
limit on : B , E_{CRp} , δ

Coma Cluster



Feretti +al.1998

Origin of the emitting electrons

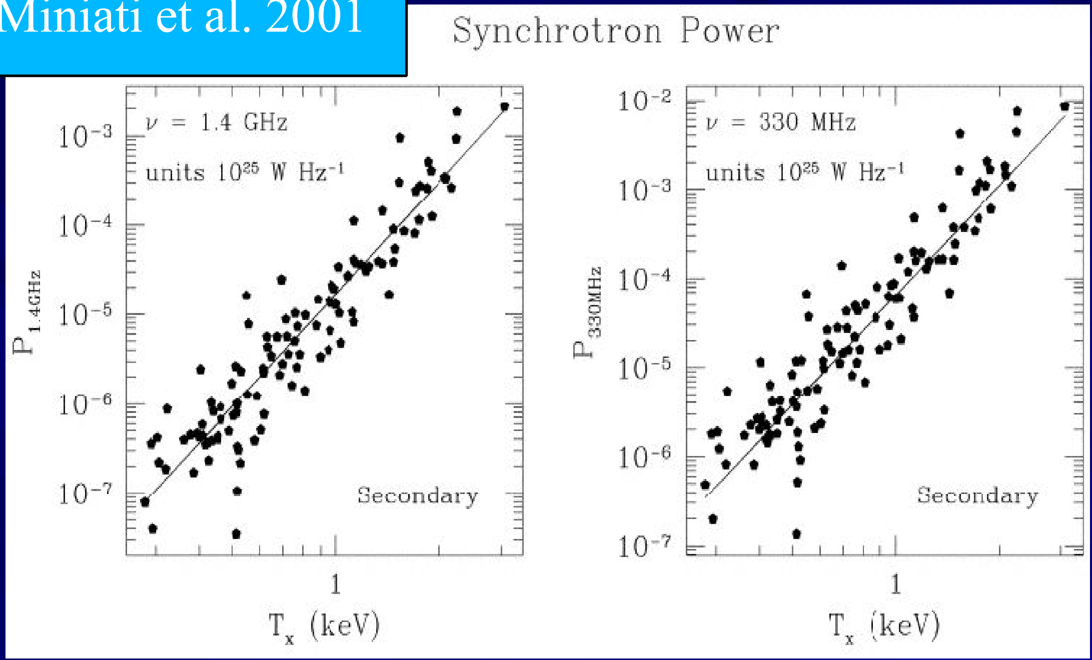


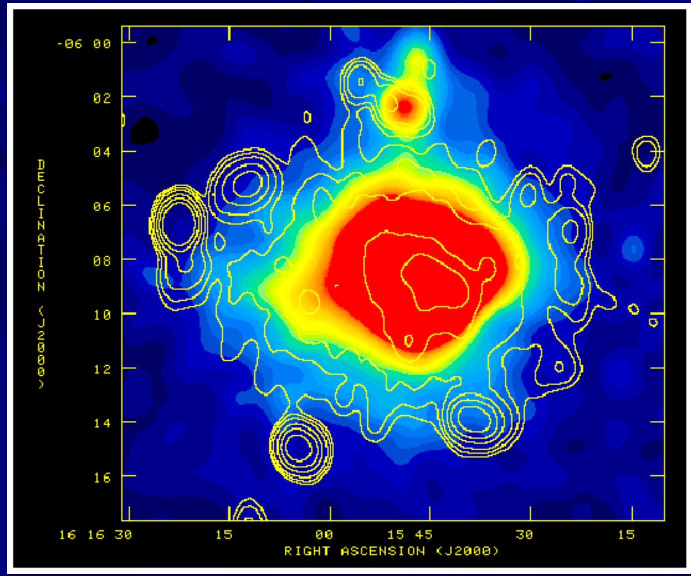
First possibility: *secondary models,* **relativistic electrons continuously injected in the ICM by inelastic proton-proton collisions through productions and decay of charged pions**
(e.g., *Dennison 1980, Blasi & Colafrancesco 1999, Dolag & Ensslin 2000; Pfrommer & Ensslin 2004***)**

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***)**

Drawback of secondary models

Miniati et al. 2001



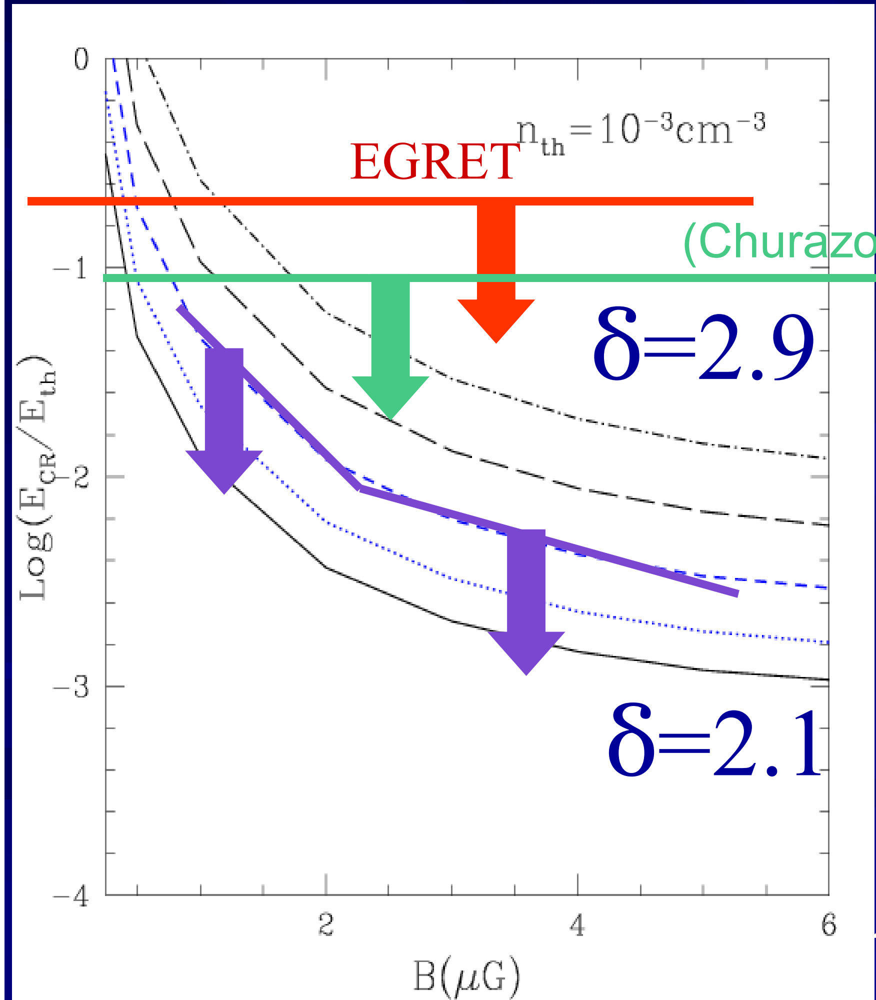


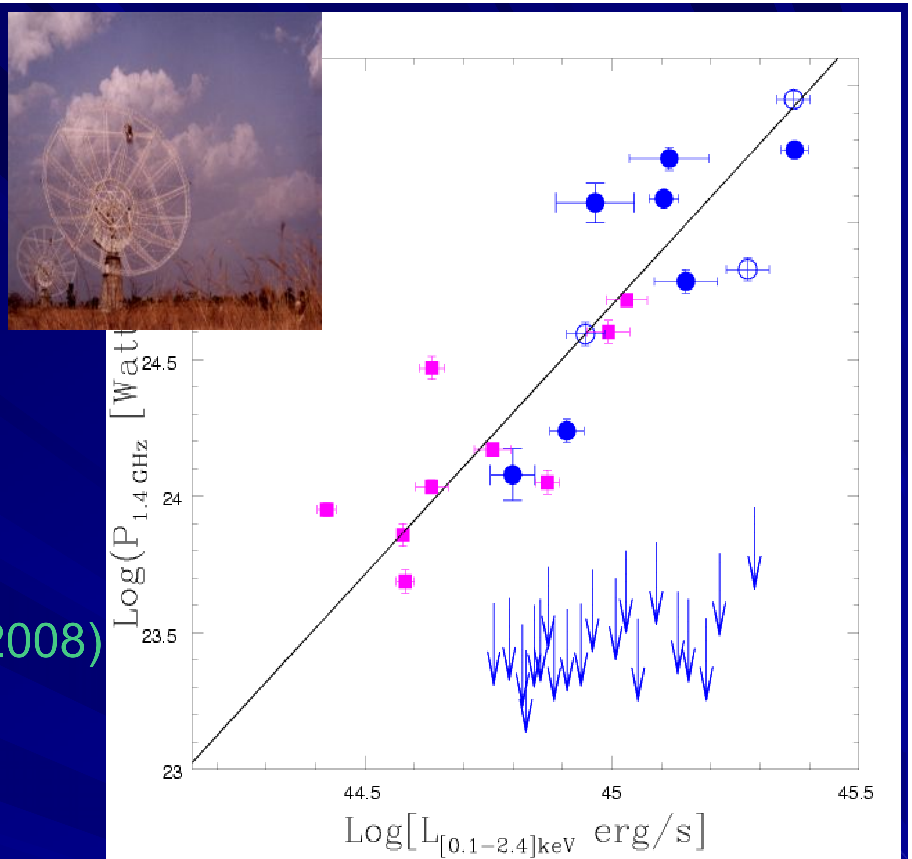
In case clusters have similar magnetic fields :

- Radio Halos are long living (cluster “life-time”) phenomena (difficult to understand connection with mergers)
- Clusters with similar thermal properties have similar radio halos

.. limits on CR protons

Brunetti +al. 2007



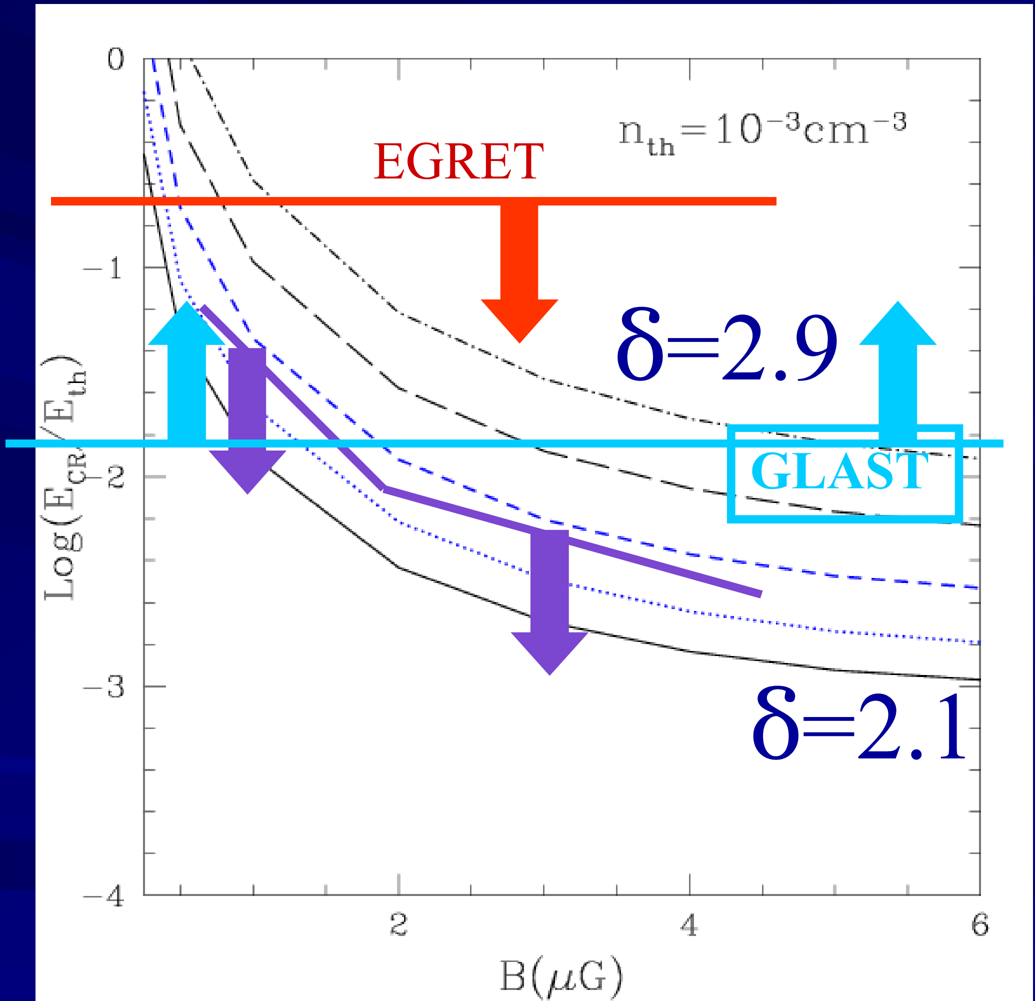


Synchrotron emission from secondaries should be smaller than upper limits .

limit on : B , E_{CRp} , δ

GLAST: CR & B in GC

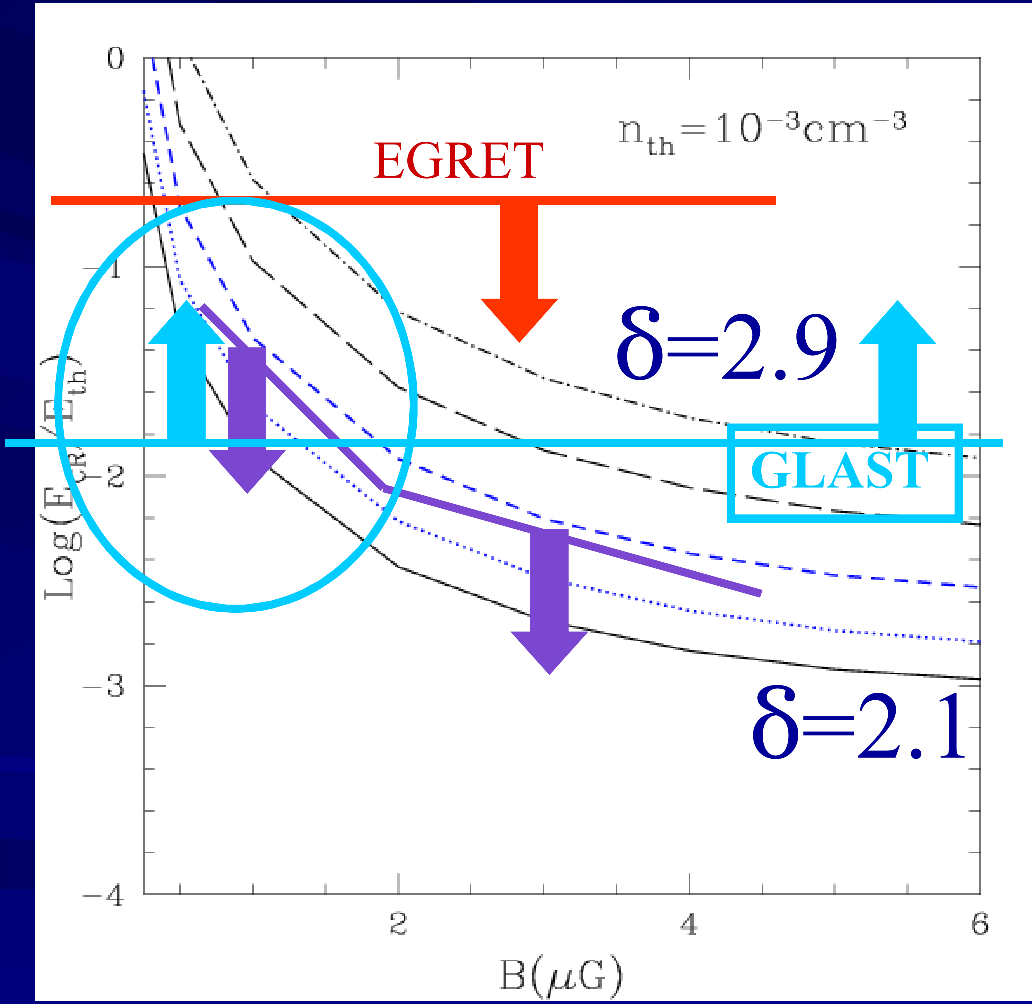
Brunetti +al. 2007



The combination of synchrotron observations (limits) of clusters without RHs with GLAST observations will constrain also B !

GLAST: CR & B in GC

Brunetti +al. 2007



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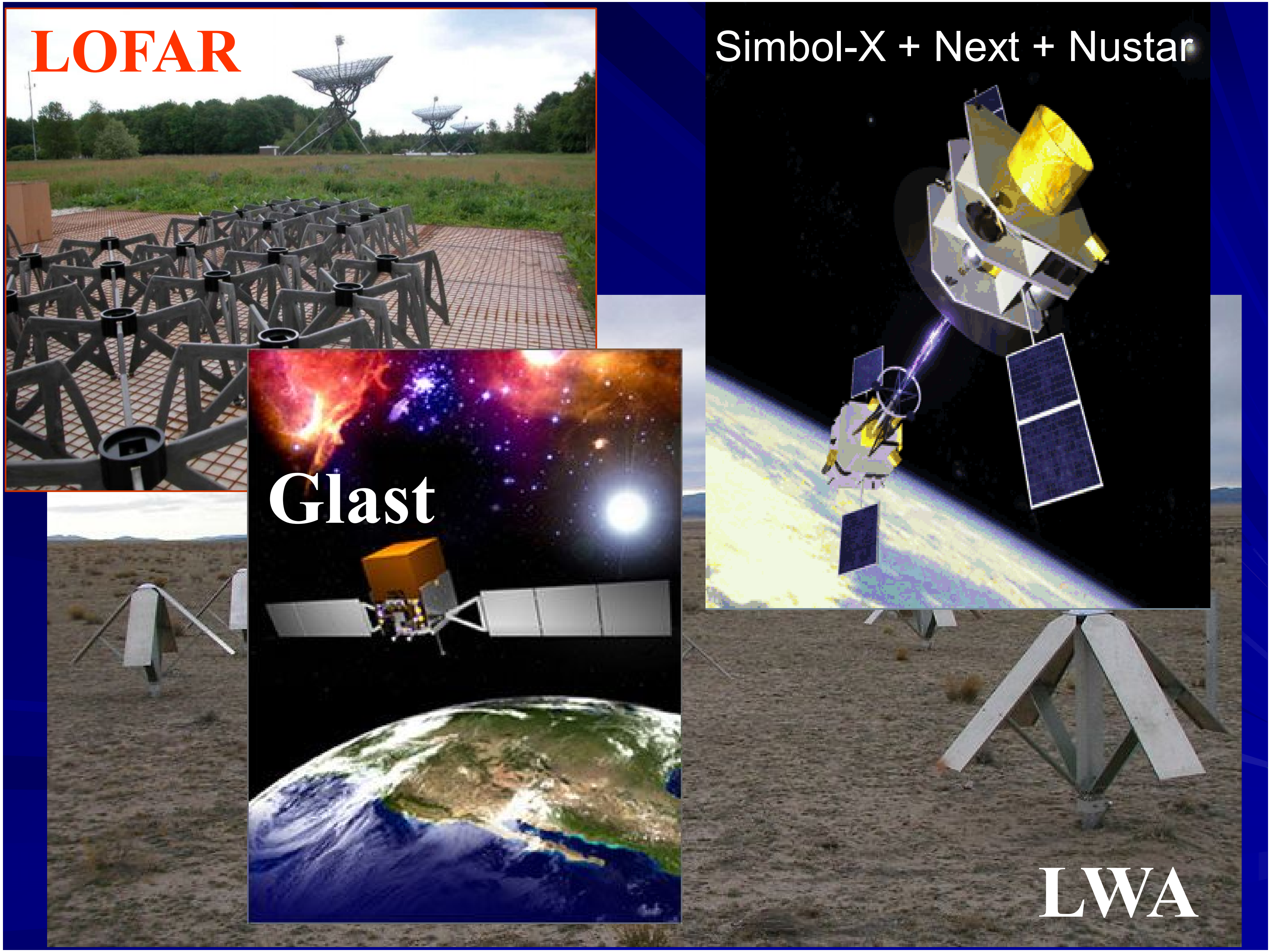
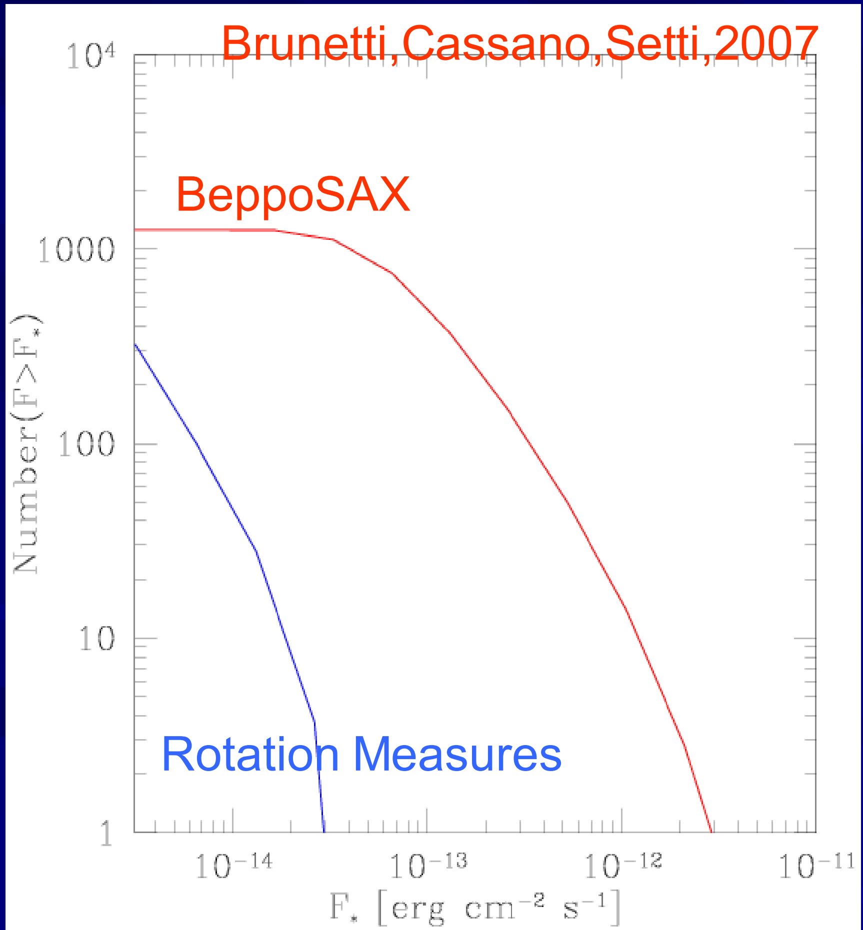
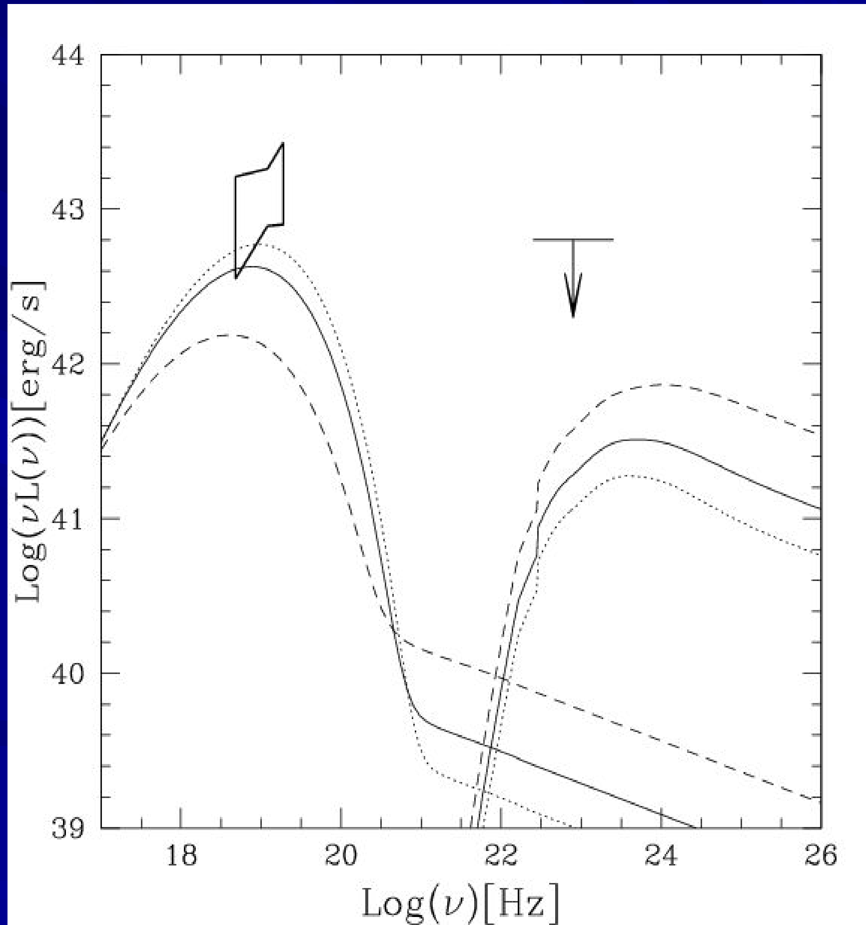

LOFAR
Simbol-X + Next + Nustar
Glast
LWA

Simbol-X + Next + Nustar

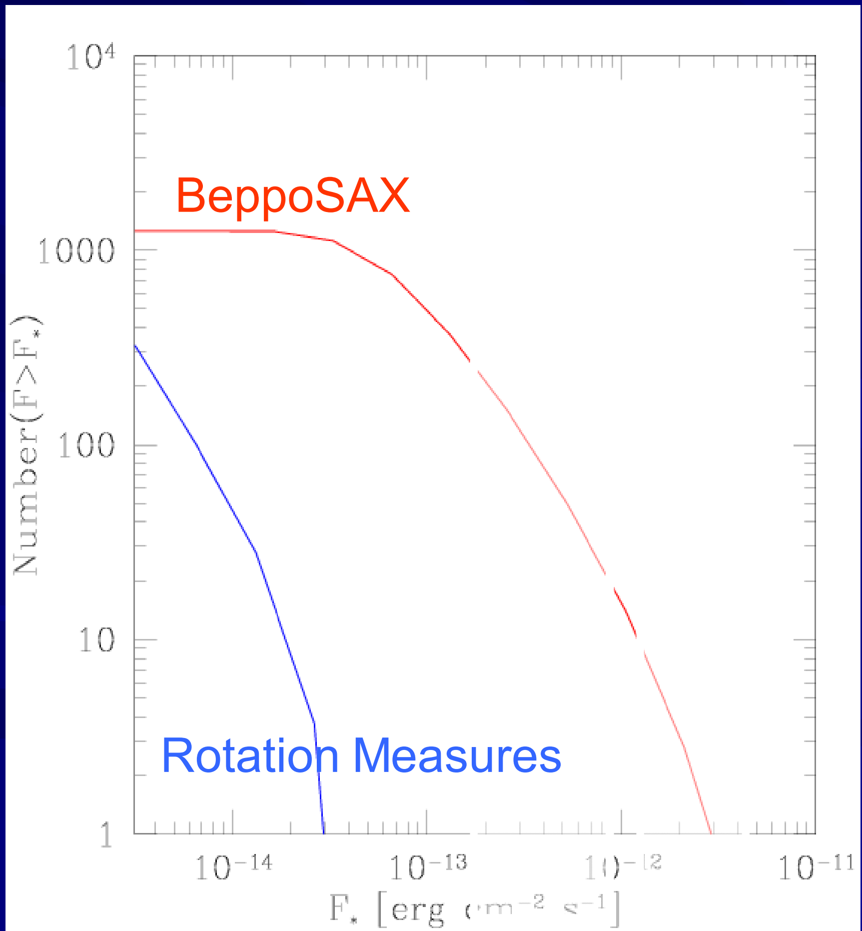
The level of IC emission from the radio emitting regions in Radio Halos depends on the magnetic field.

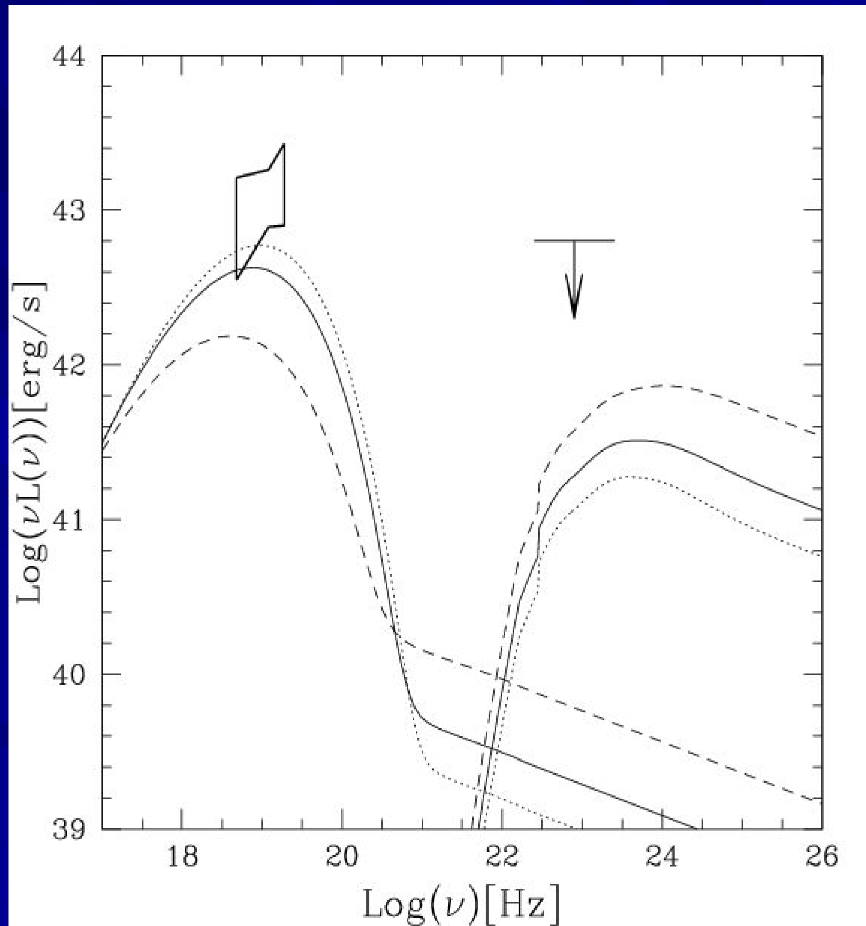




Simbol-X + Next + Nustar

Future hard X-ray telescopes will give a final(?) answer on the strength of the magnetic field in the IGM





Summary

Turbulent
acceleratio
n

Observations: bi-modality of GC (radio “quiet” & radio “loud”)

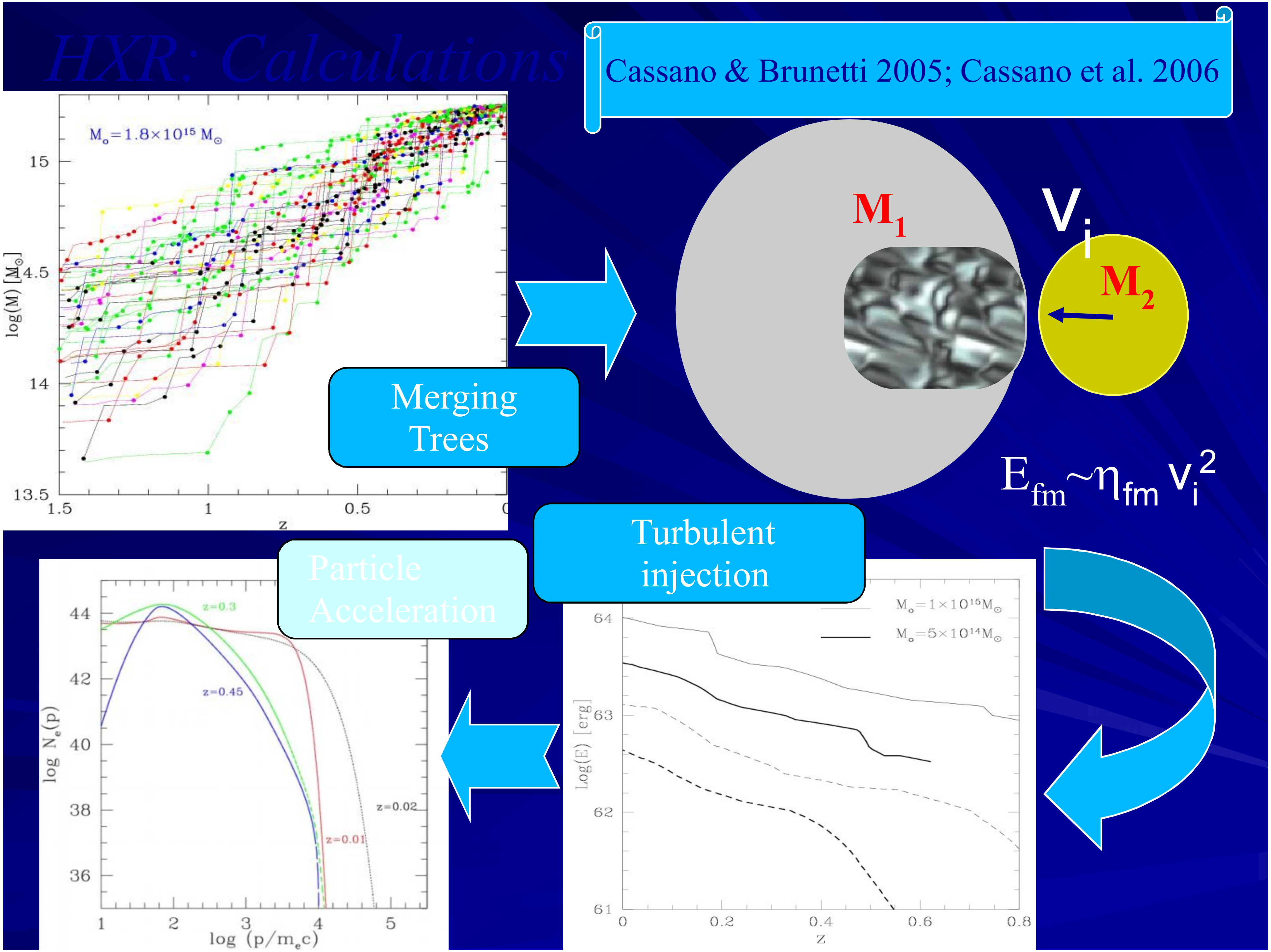
Observations: break/cut-off in the synchrotron spectrum of RH

Observations: new class of RH (USSRH)

Models: magnetosonic acceleration (… need pitch angle scattering)
(… need really turbulent media)

Models: Alfvenic acceleration (… need injection driven by KPIns)

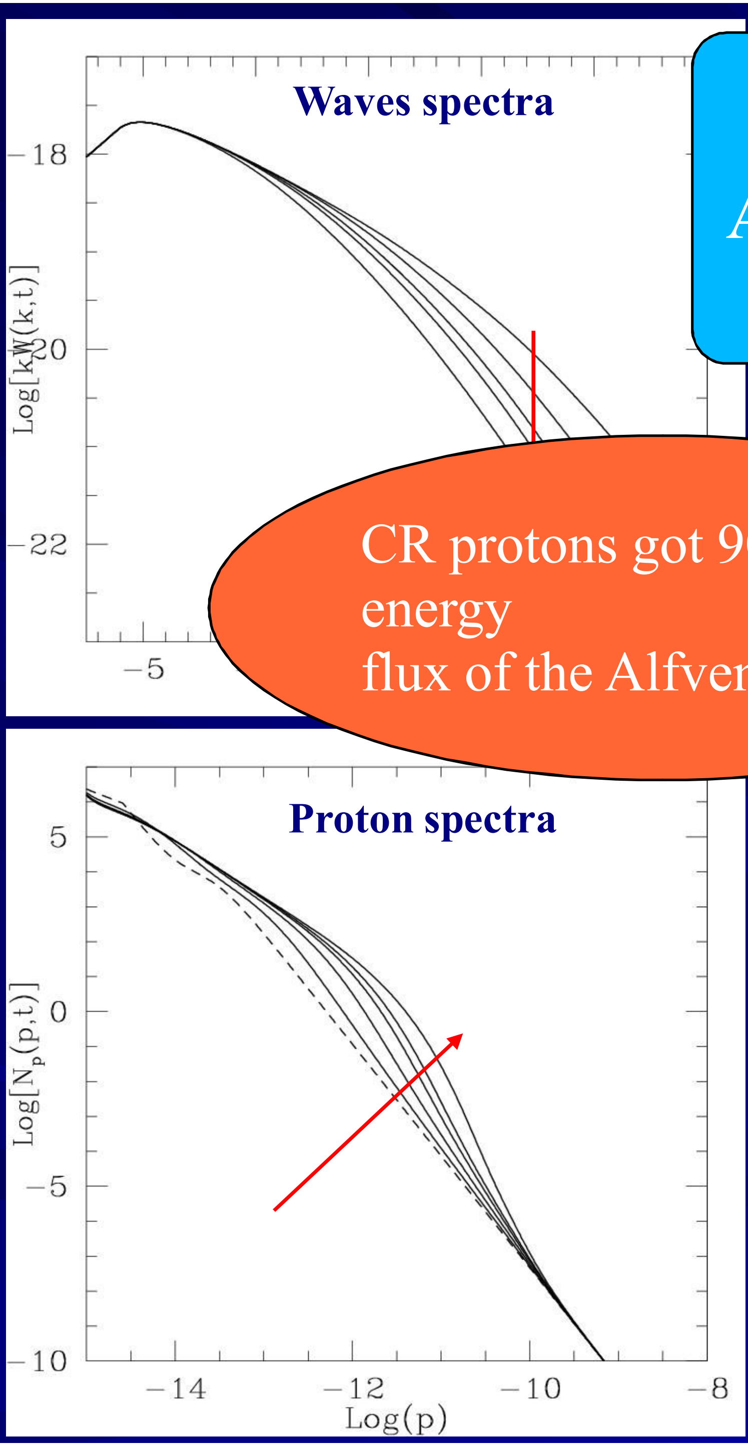
Future: USSRH and spectral studies of RH (LOFAR, LWA)
Hard-X-rays (Simbol-X,Nustar,Next)
Gamma-rays (GLAST, Cerenkov)

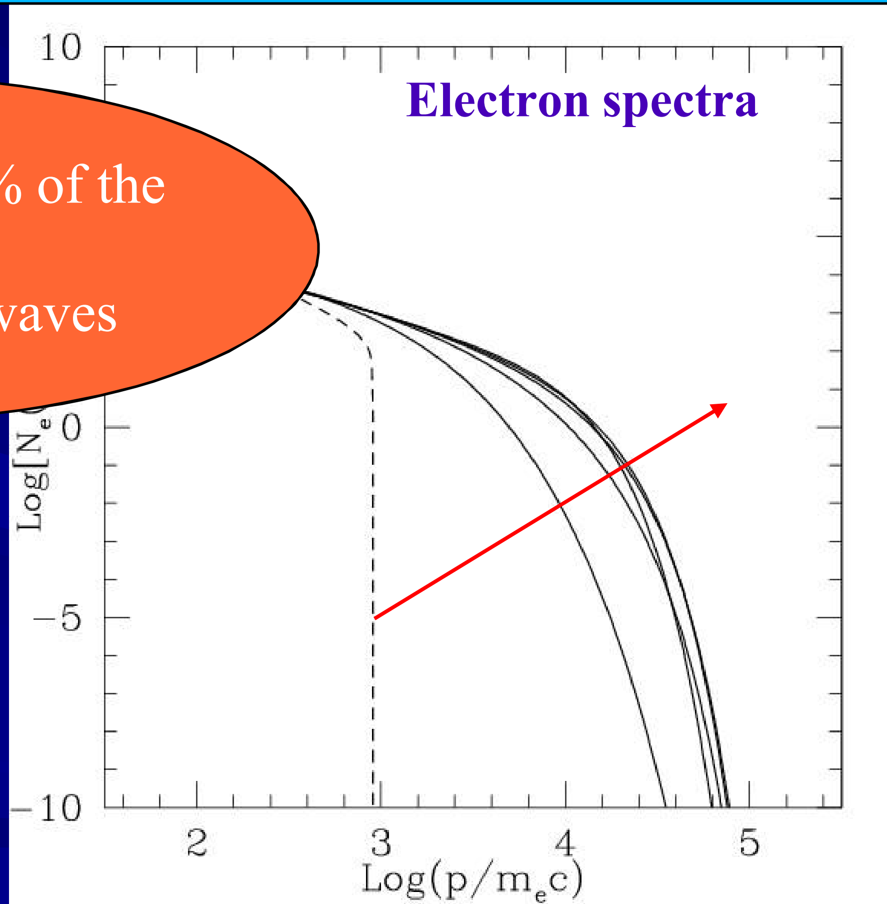


HXR: Calculations
Cassano & Brunetti 2005; Cassano et al. 2006
M$_o$=1.8×10^{15} M$_⊙$
log(M) [M$_⊙$]
z
Merging Trees
M$_1$
V$_i$
M$_2$
E$_{fm}$~η$_{fm}$ v$_i^2$
Turbulent injection
Particle Acceleration
z=0.3
z=0.45
z=0.02
z=0.01
log N$_e$(p)
log (p/m$_e$c)
M$_o$=1×10^{15}M$_⊙$
M$_o$=5×10^{14}M$_⊙$
Log(E) [erg]
z

Full Alfven-Wave--Particle Coupling

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





CR protons got 90% of the energy
flux of the Alfven waves

Waves + electrons + Protons

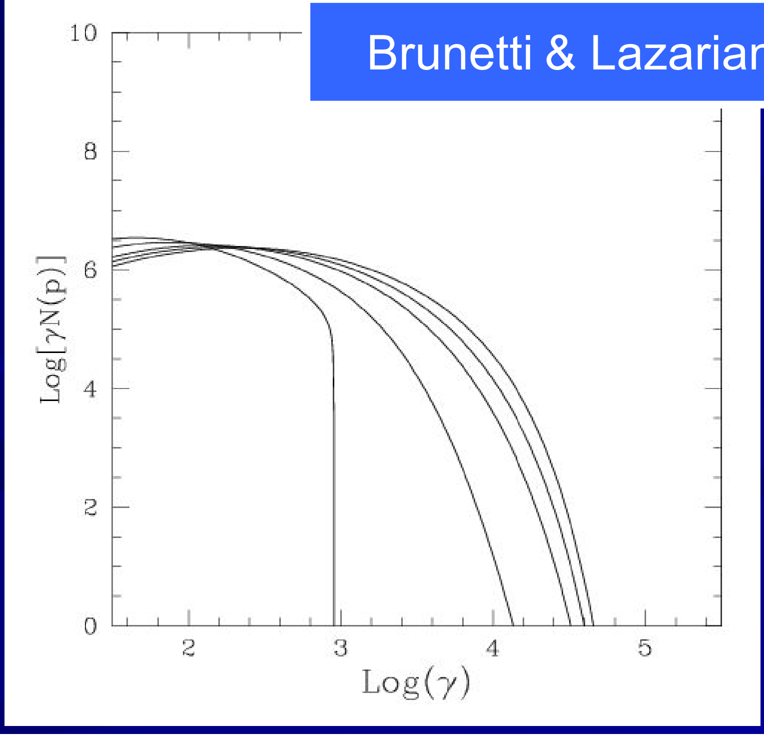
Stochastic Particle Acceleration (formalism)

$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_e(p,t)\left[\left(\frac{dp}{dt}\right)_{rad} + \left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_e(p,t)}{\partial p}\right)$$

$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

with thermal particles

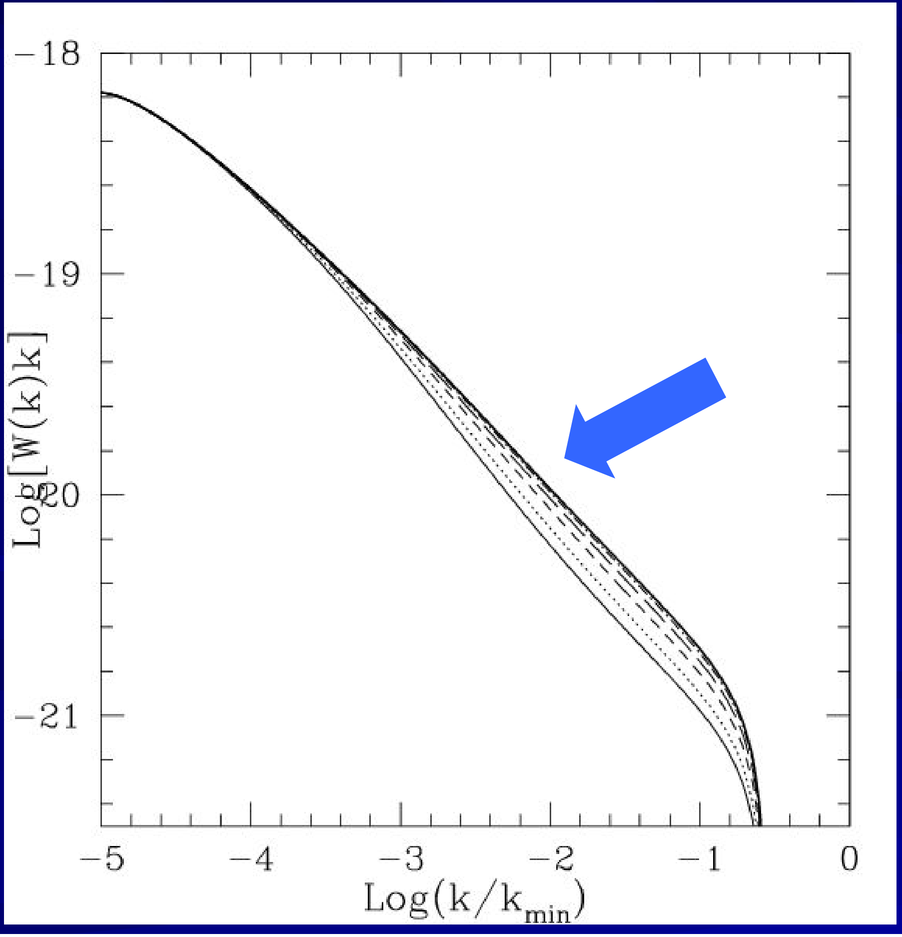
Brunetti & Lazarian 2007

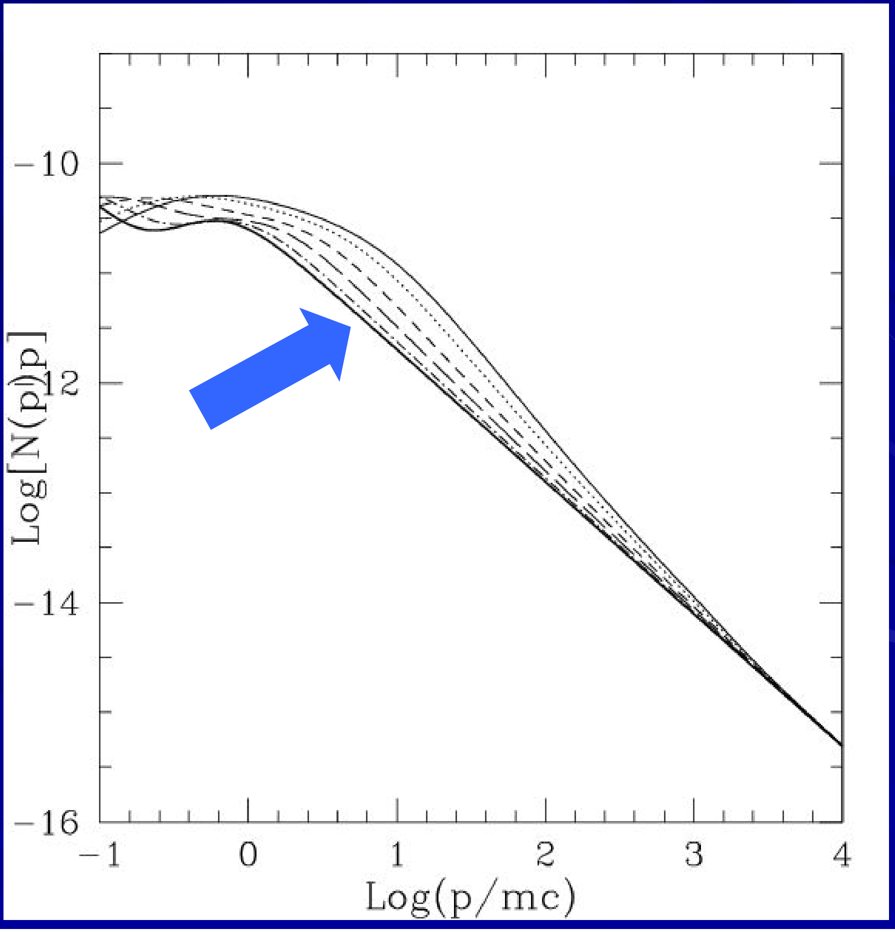


Alfvenic: results

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

$N_p(p,t)$, $N_e\pm(p,t)$, W(k,t), $Q_e\pm(p,t)$, $Q_\pi(p,t)$





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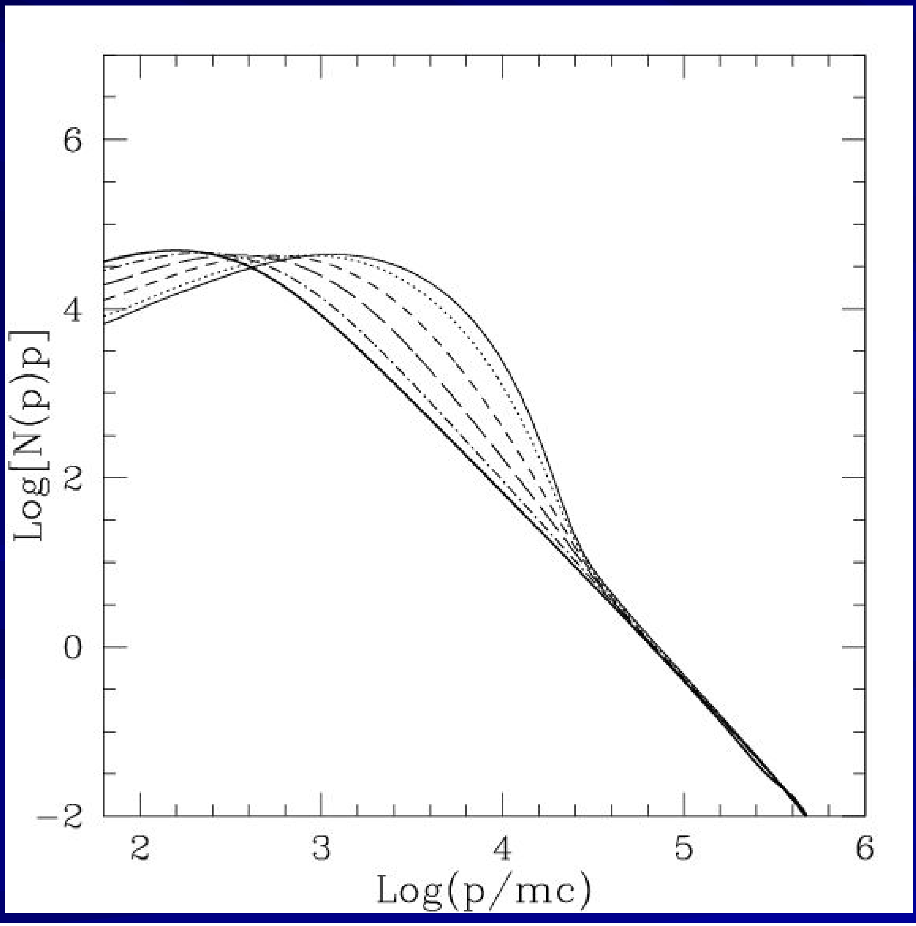

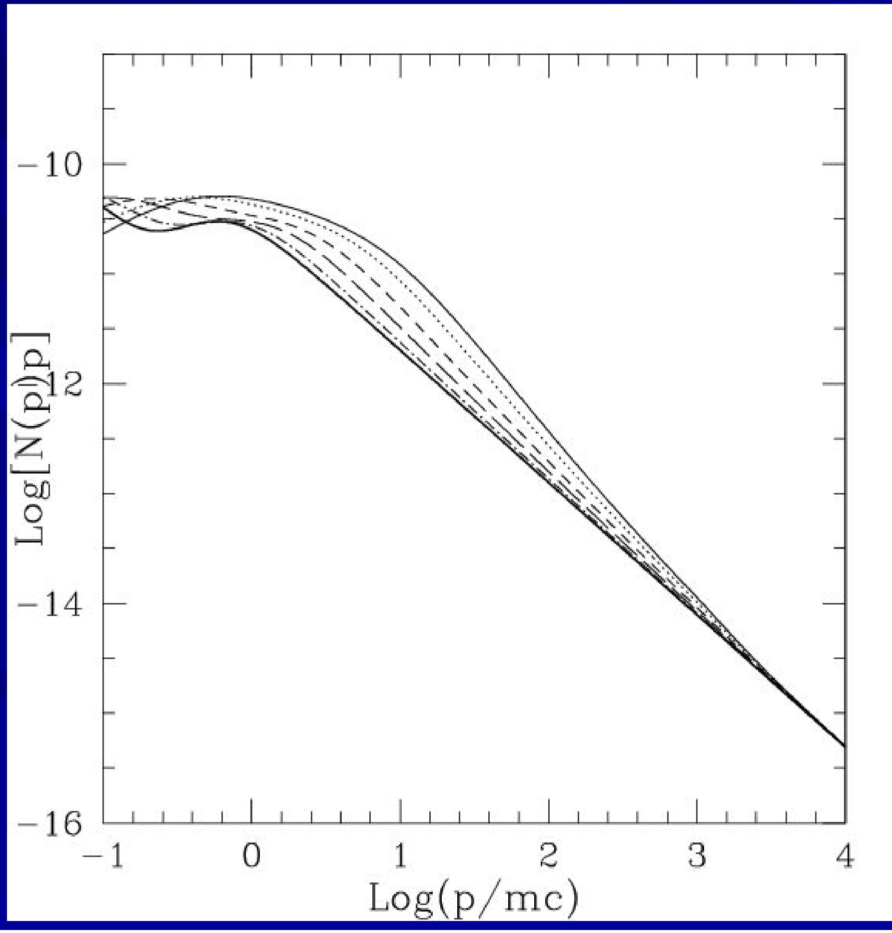

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n_{th}, T, B_o, $N_p(p,0)$, I(k)

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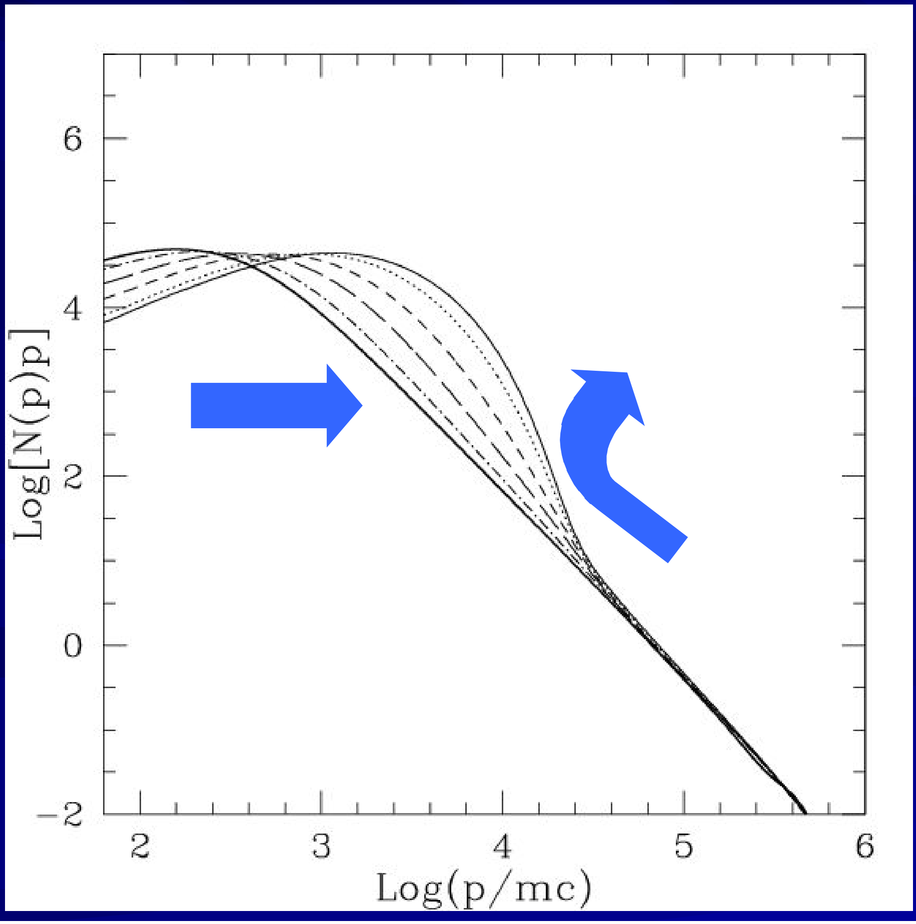

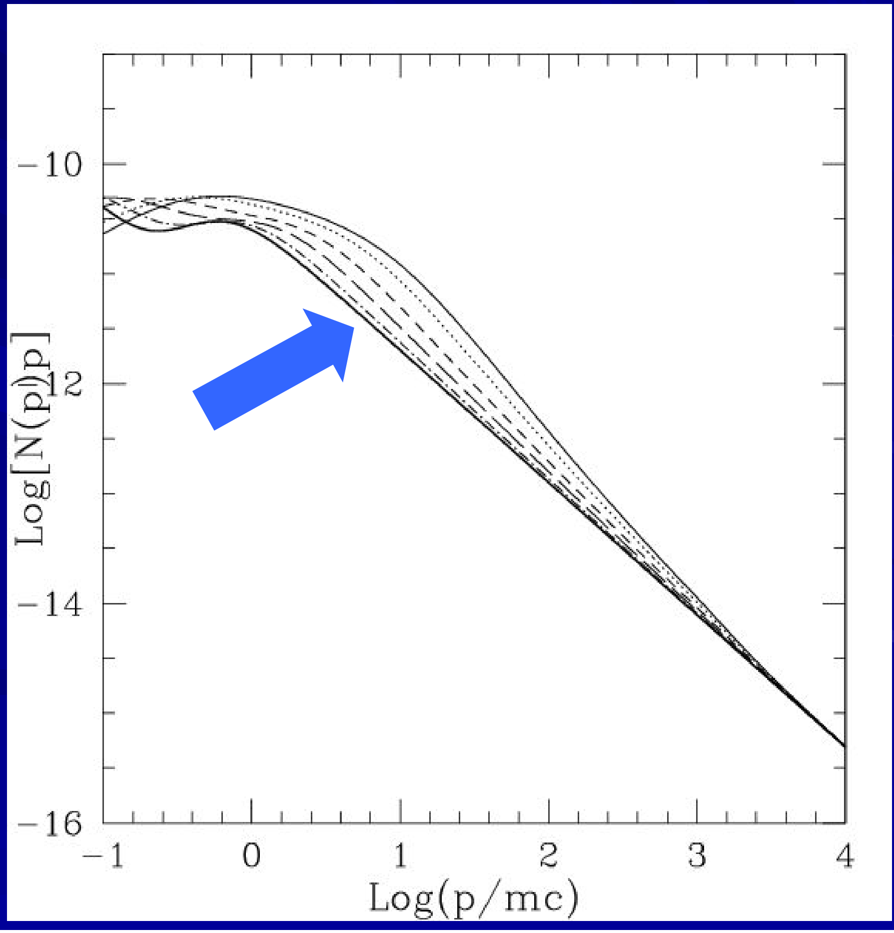

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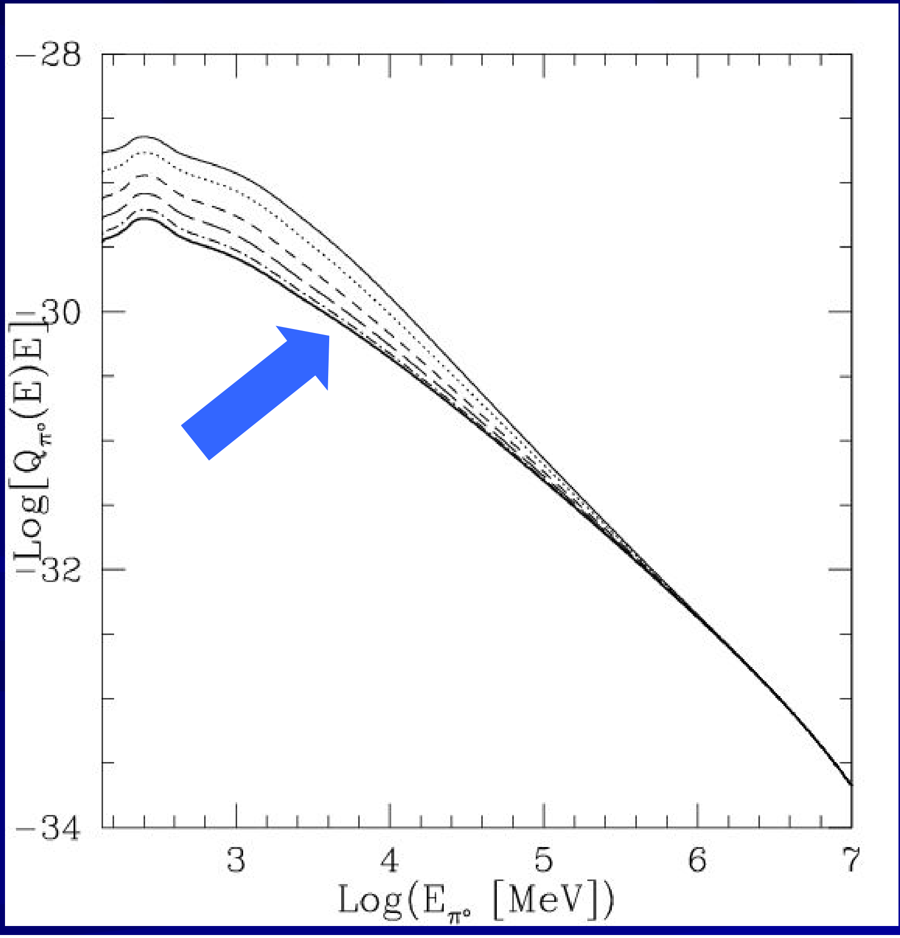
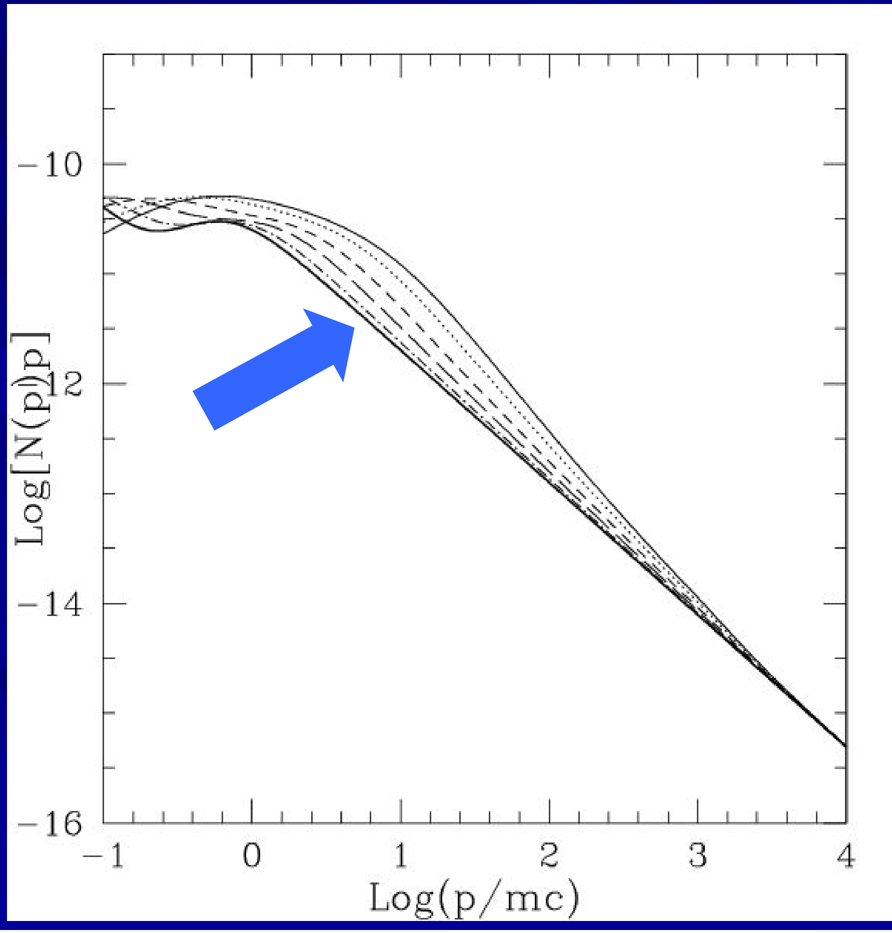




Dissipation of turbulence in the ICM

Brunetti & Lazarian 2007

(quasi-linear theory)

- TTD Resonant acceleratio

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

(provided there is an additional source of pitch angle scattering)

Damping-rate

$$\Gamma = -i \left(\frac{E_i^* K_{ij}^a E_j}{16 \pi W} \right)_{\omega_i = 0} \omega_r$$

Energy changing-rate

$$\int d^3 p E_\alpha \left(\frac{\partial f_\alpha(p)}{\partial t} \right) = \int d\mathbf{k} \Gamma^\alpha (k, \theta) W(\mathbf{k})$$

Energy damping-rate

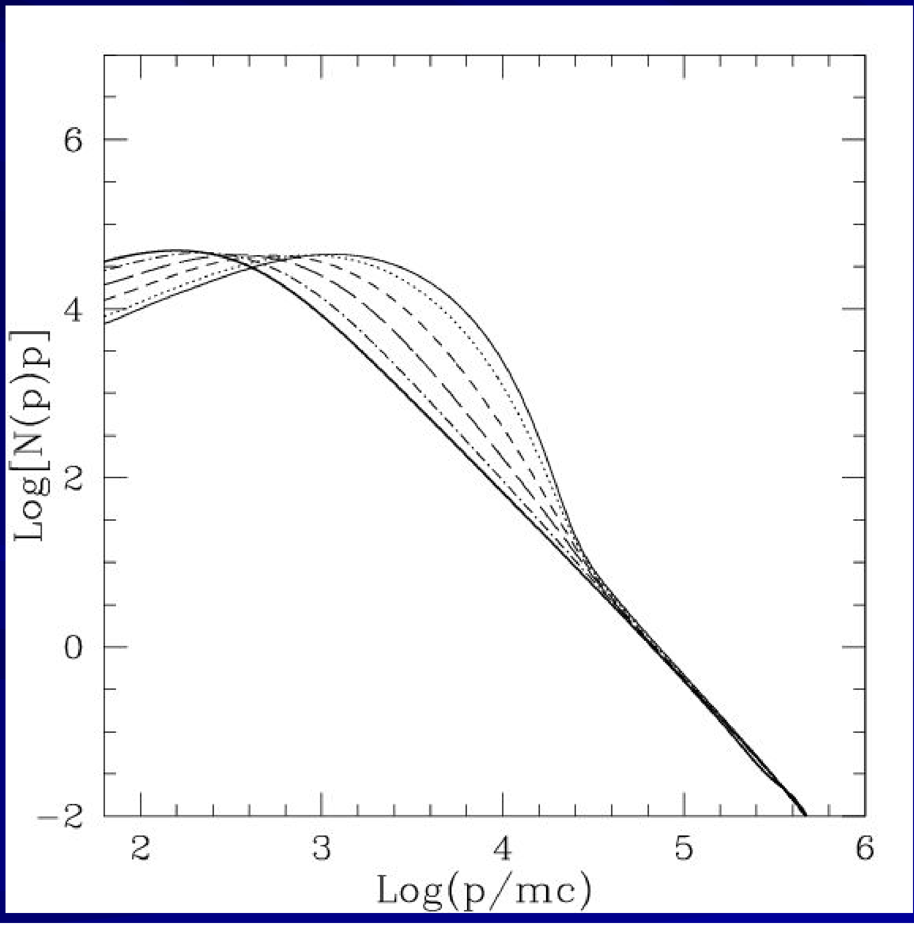
Diffusion coeff. In momentum space

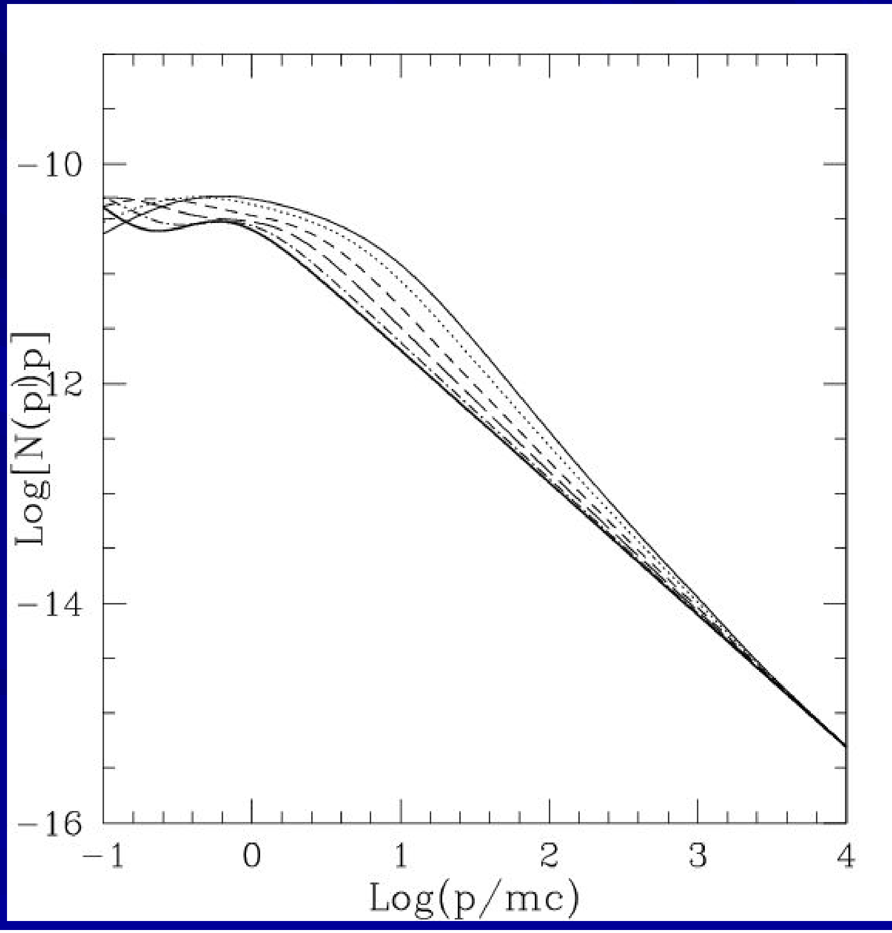
$$D_{pp}(p) = \frac{\pi^2}{2} \frac{p^2}{c} \frac{1}{B_o^2} \int_0^{\pi/2} d\theta V_{ph}^2 \frac{\sin^3(\theta)}{|\cos(\theta)|} \mathcal{H} \left(1 - \frac{V_{ph}/c}{\cos\theta} \right) \left(1 - (\frac{V_{ph}/c}{\cos\theta})^2 \right)^2 \int dk W_B(k) k$$

Alfvenic: results

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

$N_p(p,t)$, $N_e\pm(p,t)$, W(k,t), $Q_e\pm(p,t)$, $Q_\pi(p,t)$





Alfvenic: results

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

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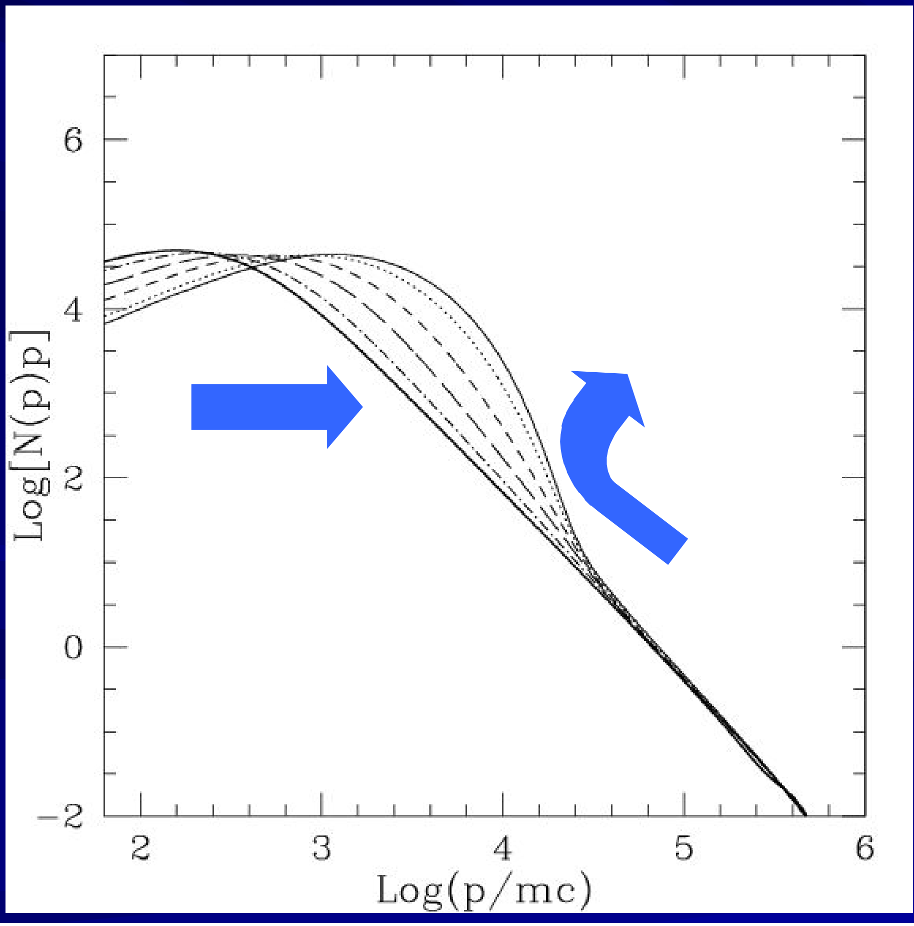
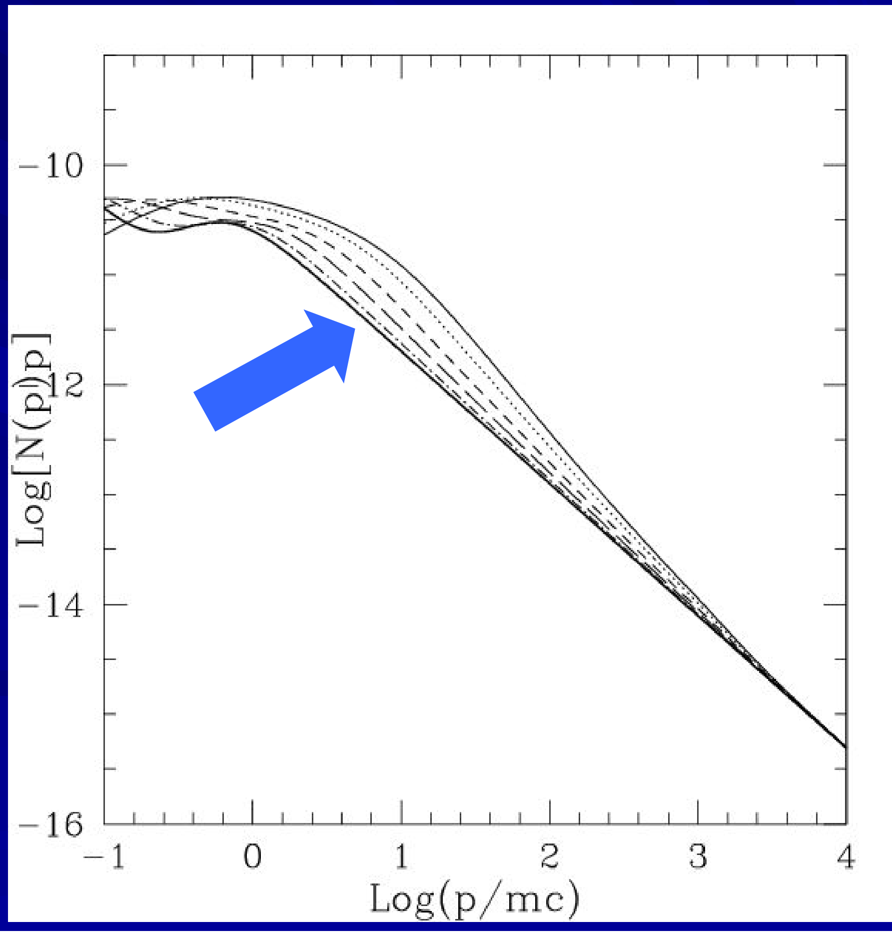
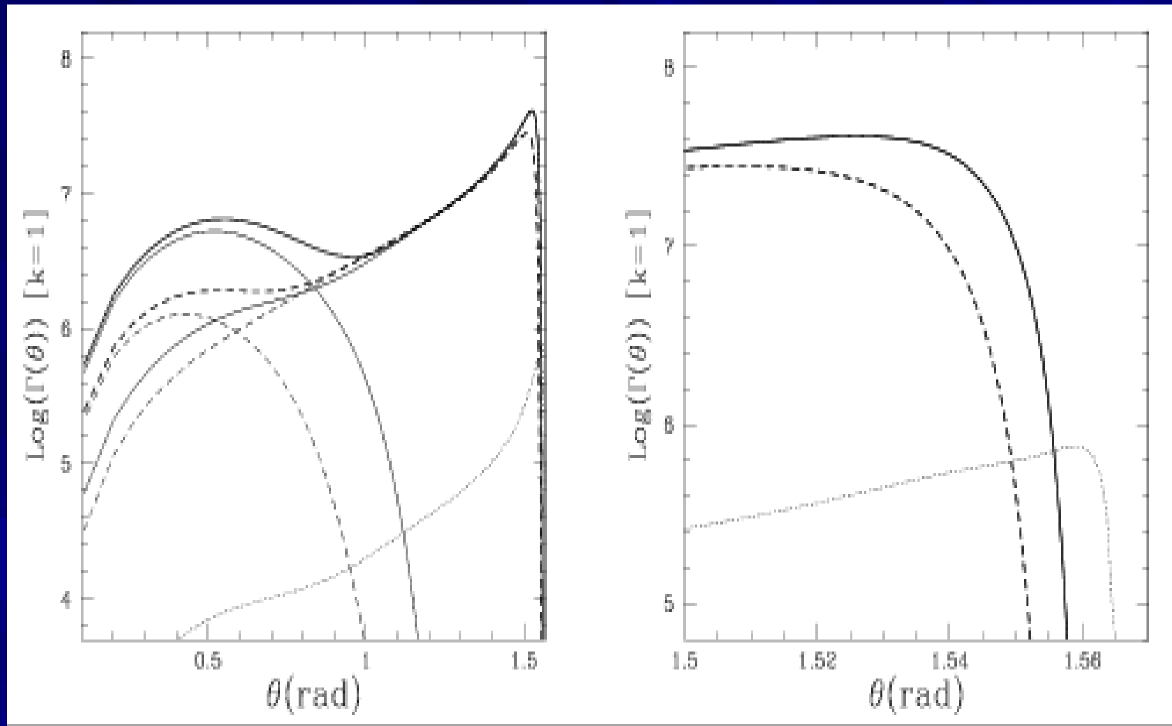




Dissipation of turbulence in the ICM
(quasi-linear theory)

$$\Gamma = -i\left(\frac{E_i^* K_{ij}^a E_j}{16\pi W}\right)_{\omega_i=0}\omega_r$$



Line-bending *efficiency* >> *damping efficiency*

$\tau_{bb}(k)^{-1} \sim V_{lA} / l_A$ $\tau_d^{-1} = \Gamma(k)$

Isotropic Effective Damping

$l_{diss} \approx 100$ pc

Dissipation of turbulence in the ICM
(Hydro-turbulence)

Dissipation cut-off developes at scale :

$\tau_{kk}(l) \geq \tau_{vis}(l) = l^2/\nu_K$

$$\nu_K \sim \frac{1}{3} v_i \times \min\left\{l_A, l_{mfp}\right\}$$

(e.g., Lazarian 2006)

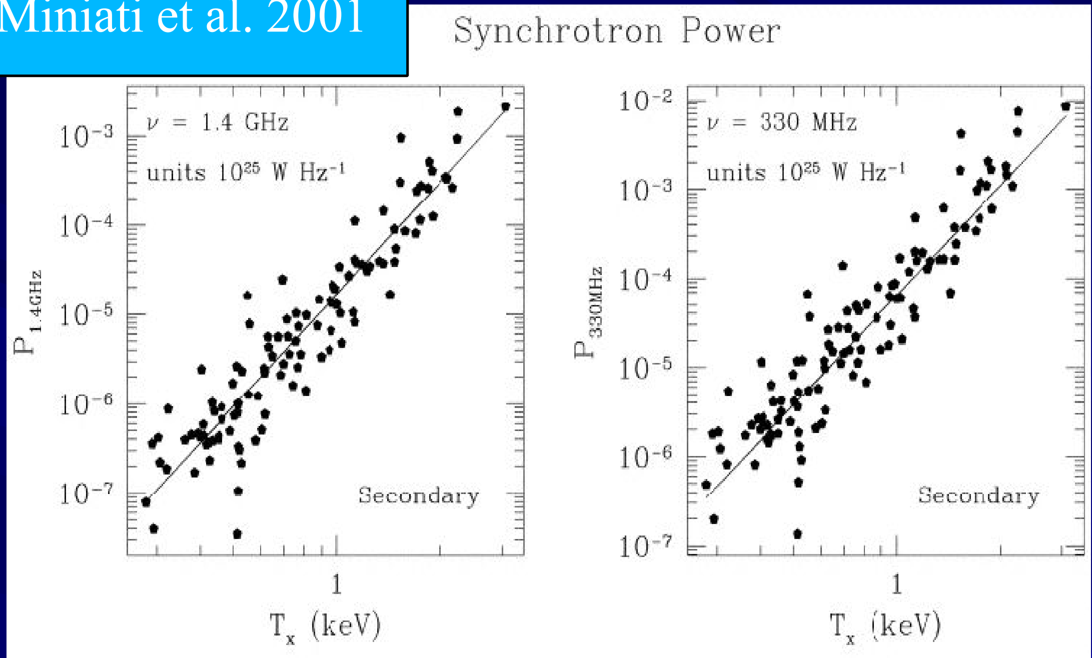
$$Re = \frac{V_o L_o}{\nu_K} > 10^3$$

$$l_{diss} \sim L_o (Re)^{-\frac{3}{4}} < l_{mfp}$$

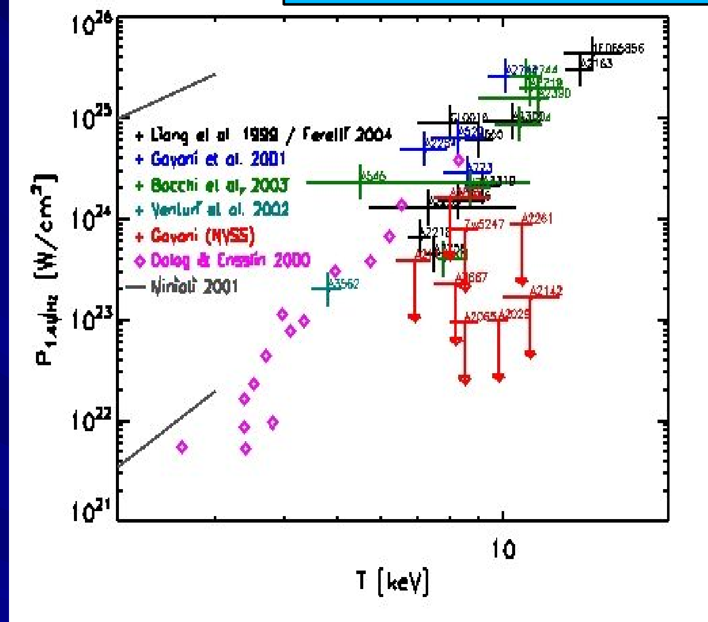
Collisionless dissipation !

Statistical properties of RH

Miniati et al. 2001



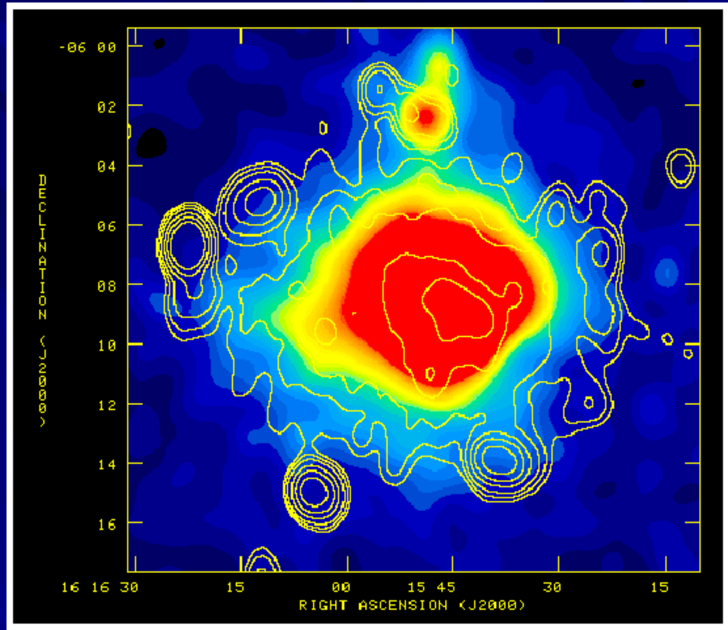
Dolag 2005



In case electrons are secondaries :

- RH are not transient phenomena
- GC with similar thermal properties have similar radio properties

Diffuse Radio Emission & origin of emitting electrons



Aims:

- Statistical properties of RH
- Spectral studies of RH
- Connection with mergers

Stochastic Particle Acceleration (formalism)

Brunetti +al. 2004, Brunetti & Blasi 2005, Brunetti +al. In prep

Electrons/Positrons

$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_e(p,t)\left[\left(\frac{dp}{dt}\right)_{rad} + \left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_e(p,t)}{\partial p}\right) + Q_e(p,t)$$

Q_e: secondaries from (CR)p-p collisions

Protons

$$\frac{\partial N_p(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_p(p,t)\left[\left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_p(p,t)}{\partial p}\right) + Q_p(p,t)$$

Waves

$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

most could be with CR protons

Stochastic particle RE- acceleration

- Stochastic turbulent compression (e.g. Ptuskin 1988)

(provided $l \gg l_{mfp}$ & $V_l^2 \ll c_s^2$)

$$D_{pp} \simeq \frac{2}{9} D p^2 \frac{V_o^2}{L_o^{2/3}} \int_{1/L_o}^{1/l_{cut}} \frac{dy\, y^{1/3}}{c_s^2 + D^2 y^2}$$

With

$$D \sim \frac{c}{3} \max\left\{ l_{cut} \, , \, \min\{l_A \, , \, l_{mfp}\} \right\}$$

Also ...
efficient source of particle pitch-angle isotropization

Dissipation of turbulence in the ICM

(quasi-linear theory)

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

Small scale $n = +/-1, +/-2, +/-\ 3, ...$

Large scale $n = 0$

Transit-Time-Damping **n = 0** (e.g. Schlickeiser & Miller 1998)

$$\omega = k_{\|} v_{\|}$$

&

$$V_{\rm ph}^2 = \frac{c_s^2}{2} \frac{\beta_{pl}+1}{\beta_{pl}} \left\{ 1 + \sqrt{1 - 4 \left(\frac{k_{\|}}{k} \right)^2 \frac{\beta_{pl}}{(1+\beta_{pl})^2}} \right\}$$

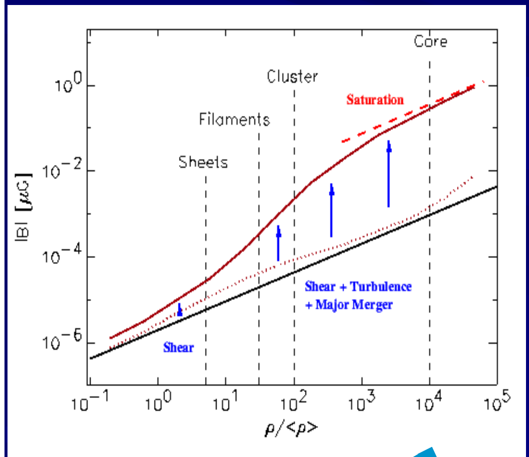
Brunetti & Lazarian 20

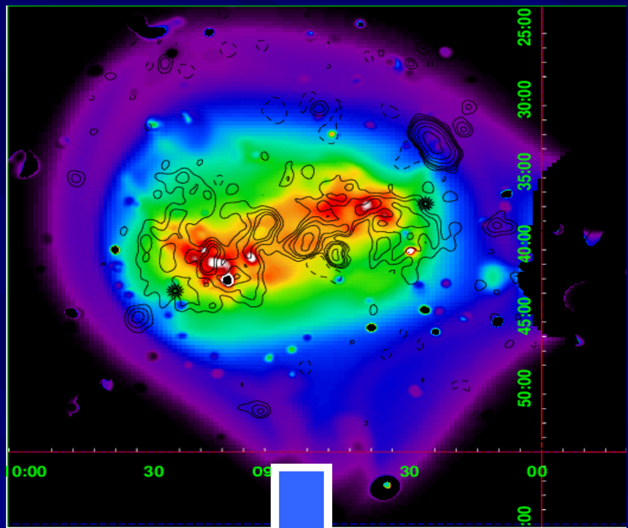
Fermi II RE-Acceleration Models

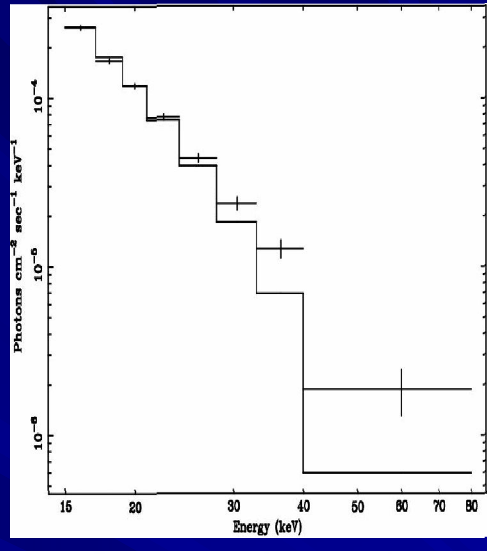
(Brunetti et al. 2001, Petrosian 2001,…++ al.)

Dolag & Bruggen talks

MF Amplification

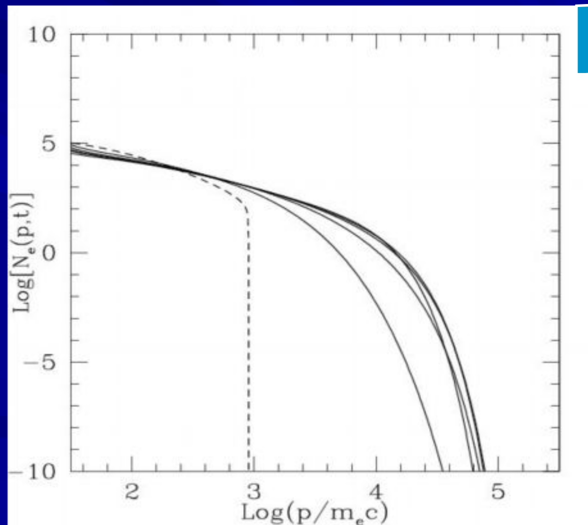


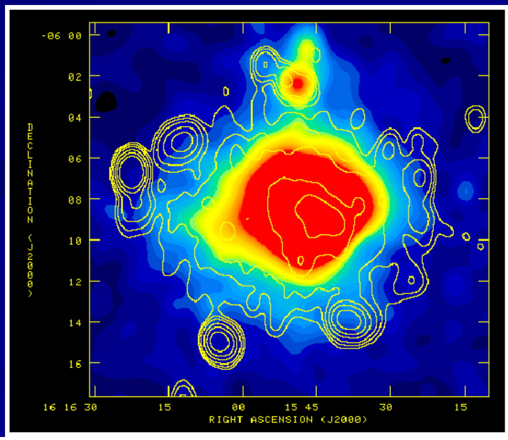




IC

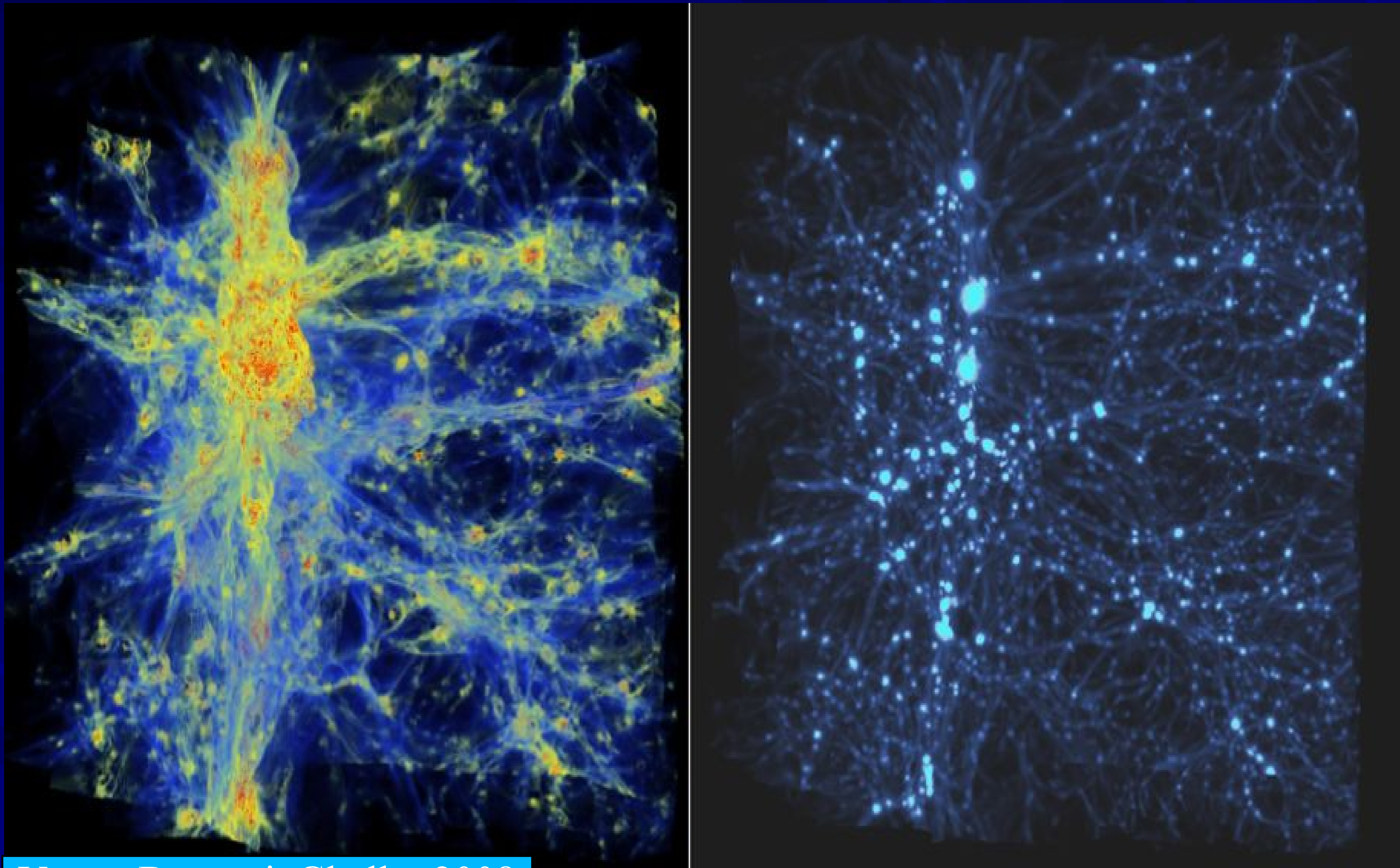
Turbulence





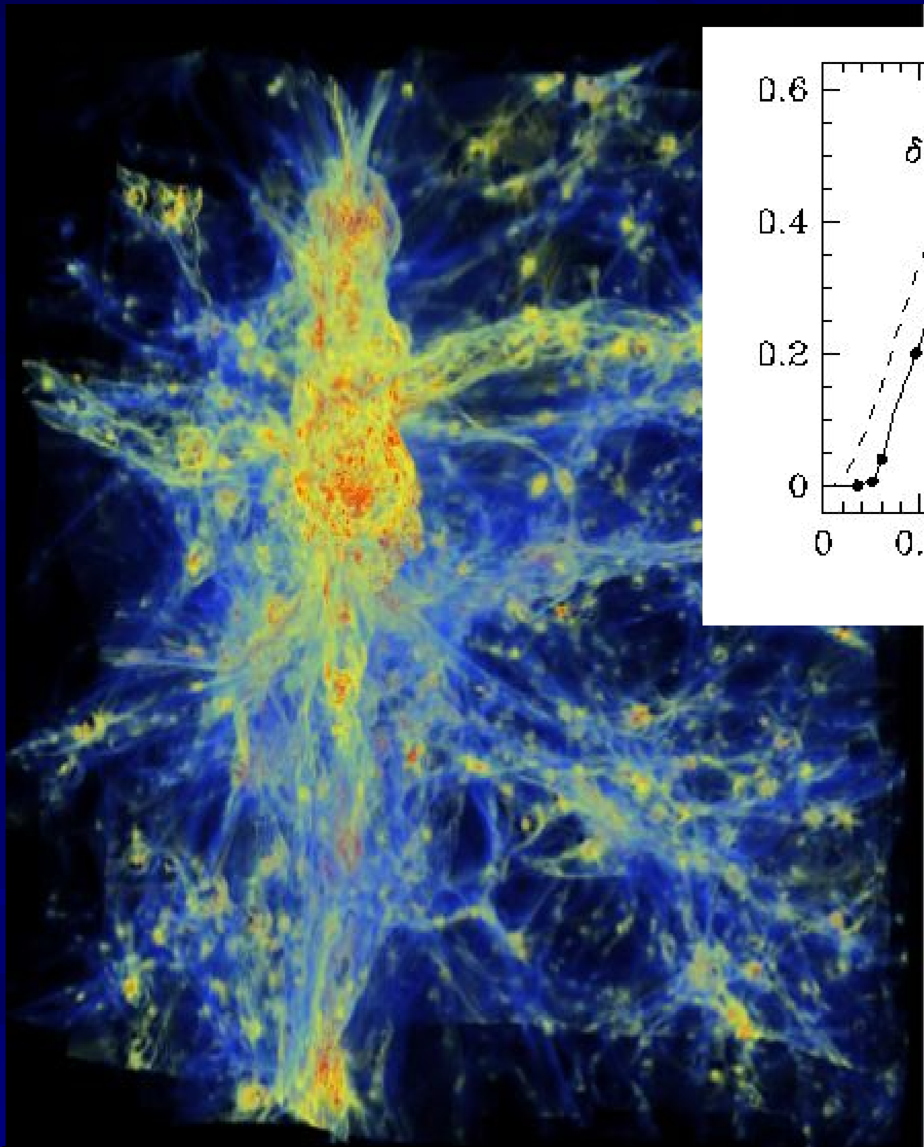
Synchrotron

Shocks in Galaxy Clusters

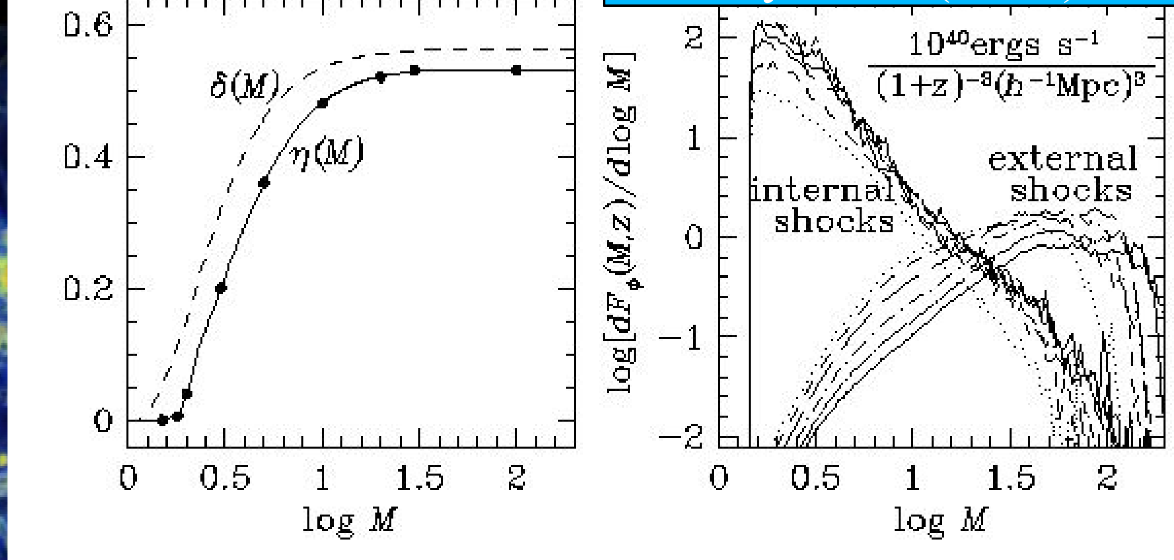


Vazza, Brunetti, Gheller 2008

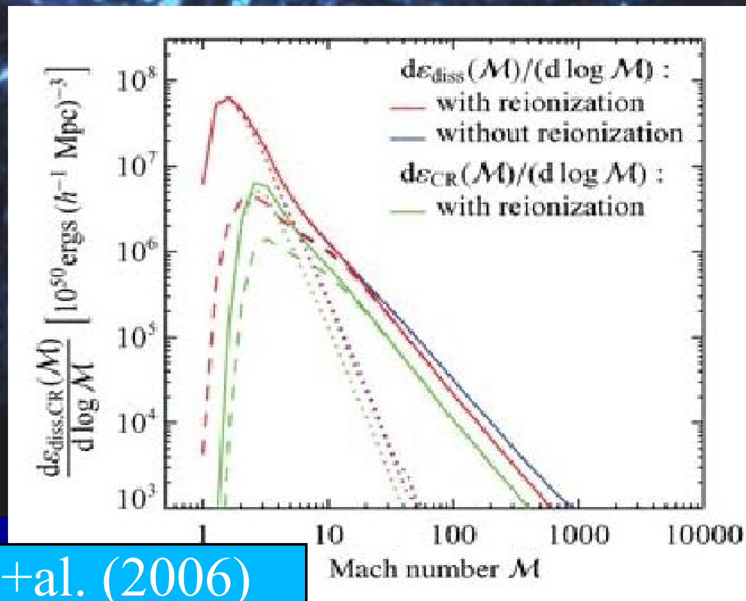
Shocks in Galaxy Clusters



Vazza, Brunetti, Gheller 2008

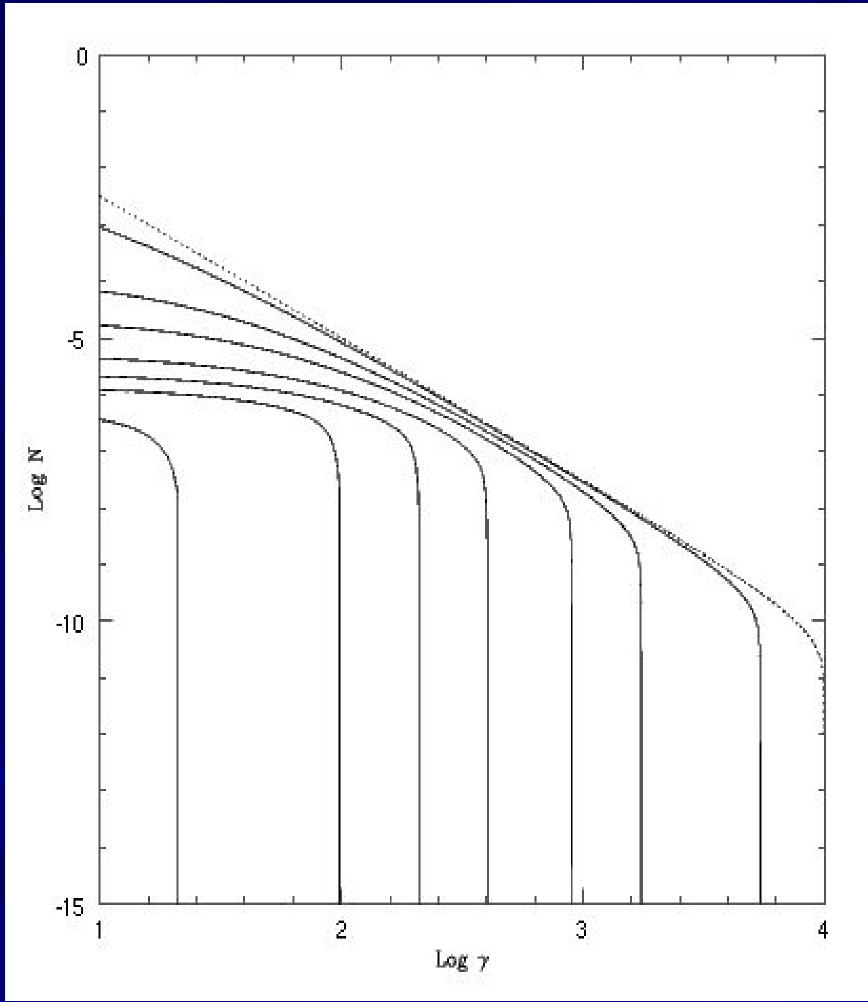


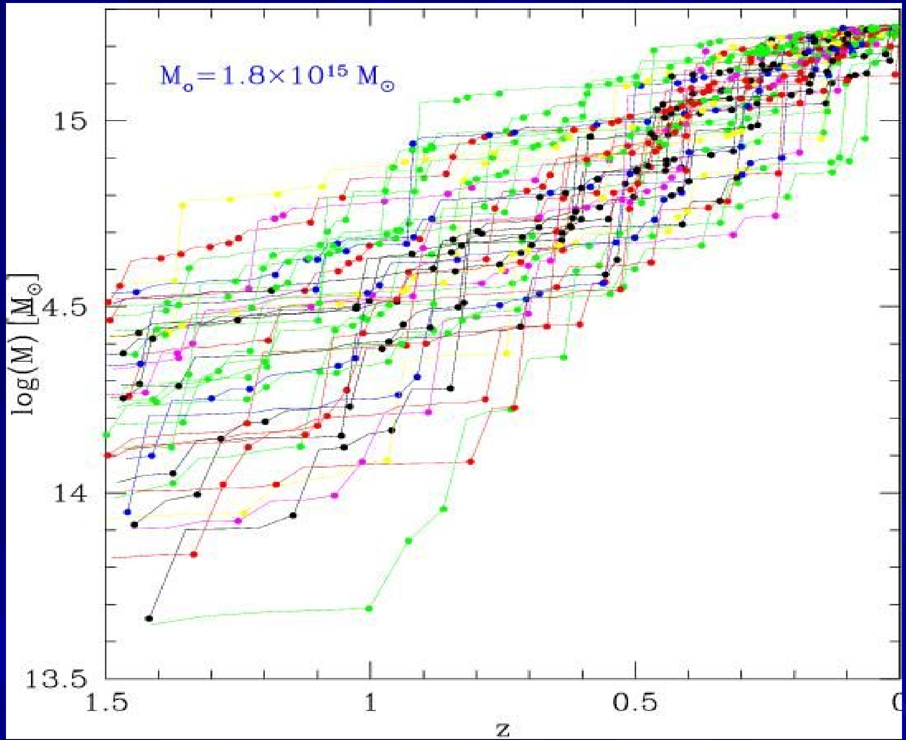
Ryu +al. (2003)



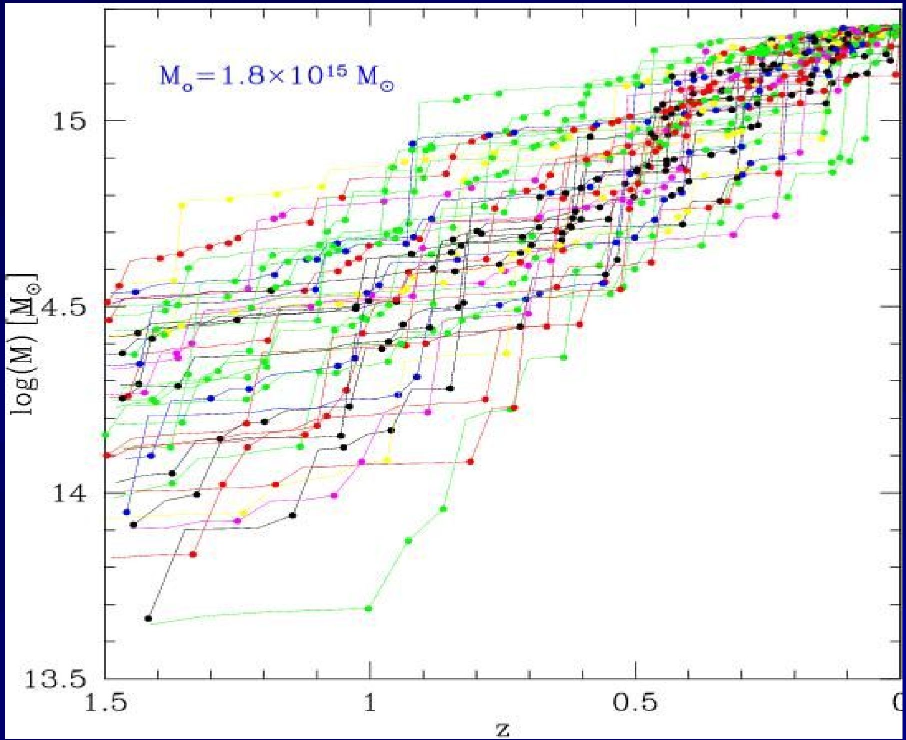
Pfrommer +al. (2006)

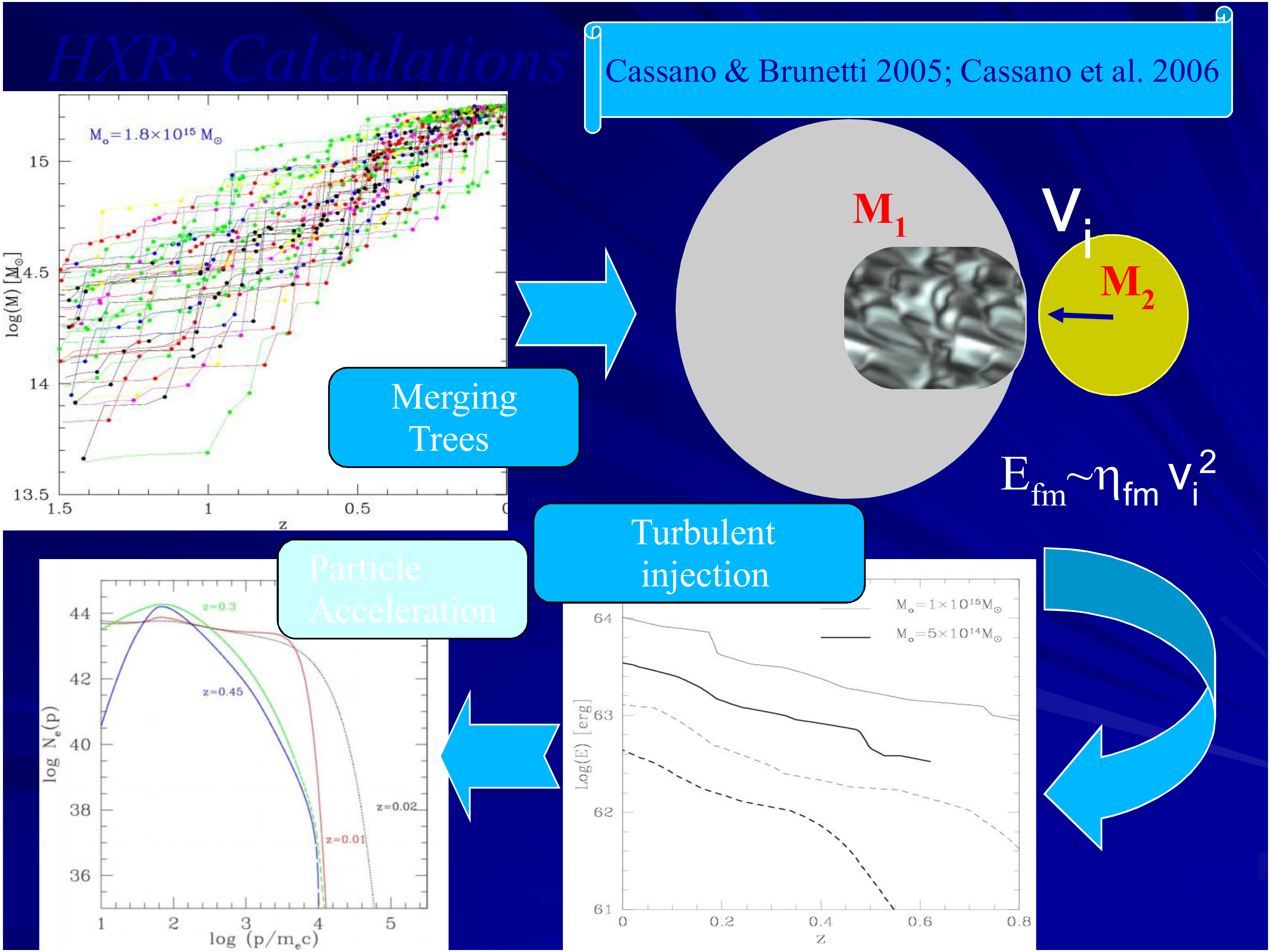
CR Emission


0
-5
-10
-15
1
2
3
4
Log N
Log γ

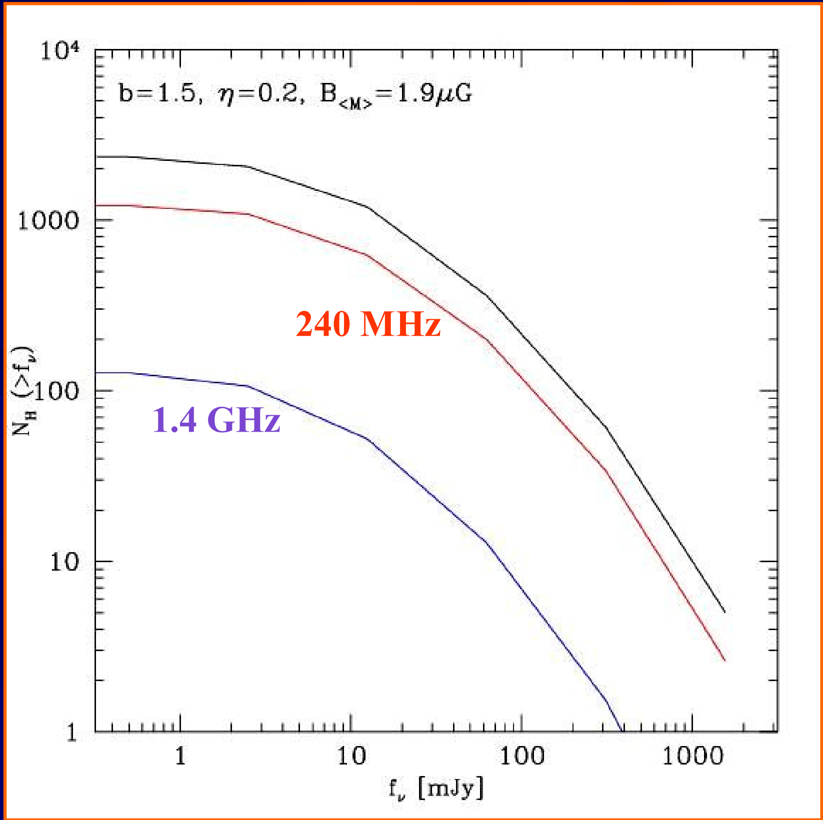

M$_o$=1.8×10^{15} M$_\odot$
15
14.5
14
13.5
1.5
1
0.5
0
log(M) [M$_\odot$]
z

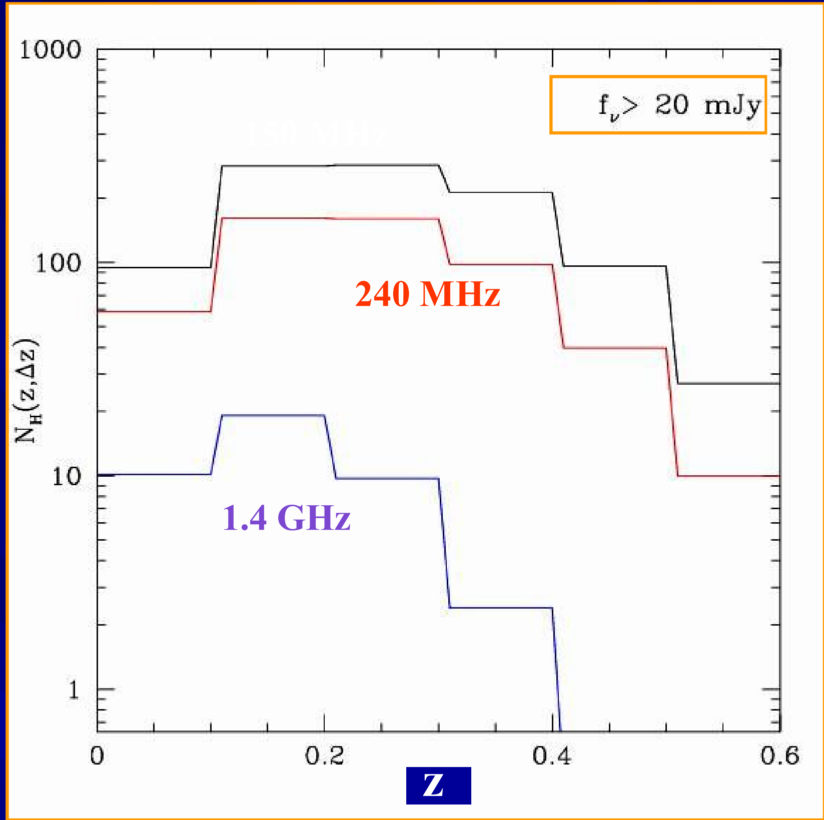
CR Emission




HXR: Calculations
Cassano & Brunetti 2005; Cassano et al. 2006
$M_o=1.8\times10^{15}\,M_\odot$
Merging Trees
M_1
v_i
M_2
$E_{fm}\sim\eta_{fm}\,v_i^2$
Turbulent injection
Particle Acceleration
$M_o=1\times10^{15}M_\odot$
$M_o=5\times10^{14}M_\odot$
z=0.3
z=0.45
z=0.02
z=0.01
log $N_e(p)$
log (p/m_ec)
log(M) $[M_\odot]$
Log(E) [erg]
z

Number Counts of RHs at lower radio frequencies





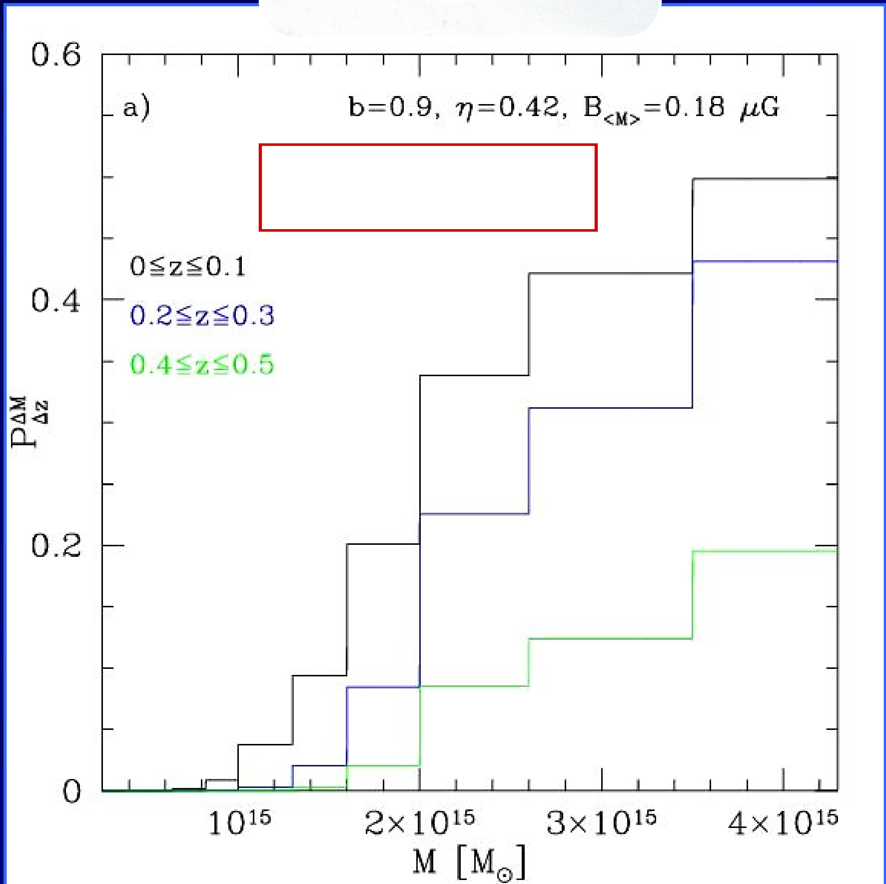
The number of expected RHs increases at lower frequencies by about a factor 10!

LOFAR should be able to catch the bulk of RHs!

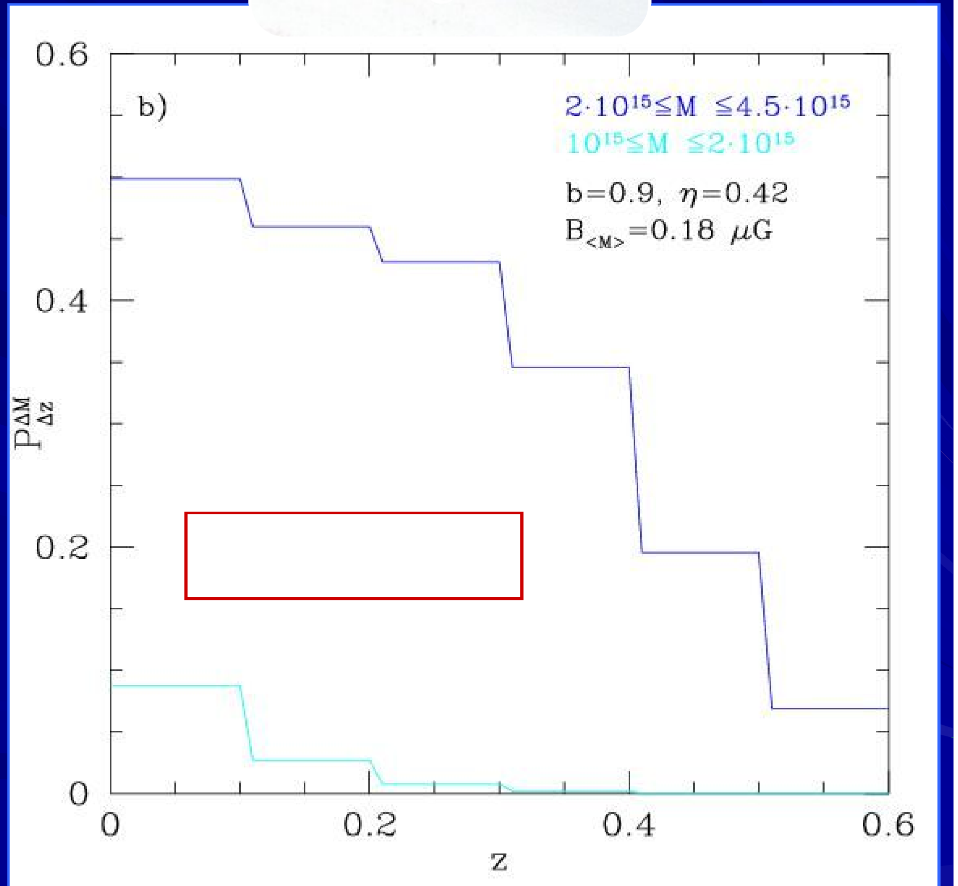
The bulk of RHs emitting at GHz frequencies is expected at relatively low redshift: 0.1-0.3.
At lower radio frequencies a number of RHs is expected to be discovered at relatively higher redshifts z>0.4.

Expected probabilities to form GRHs versus M & z

sub-linear scaling **b=0.9**



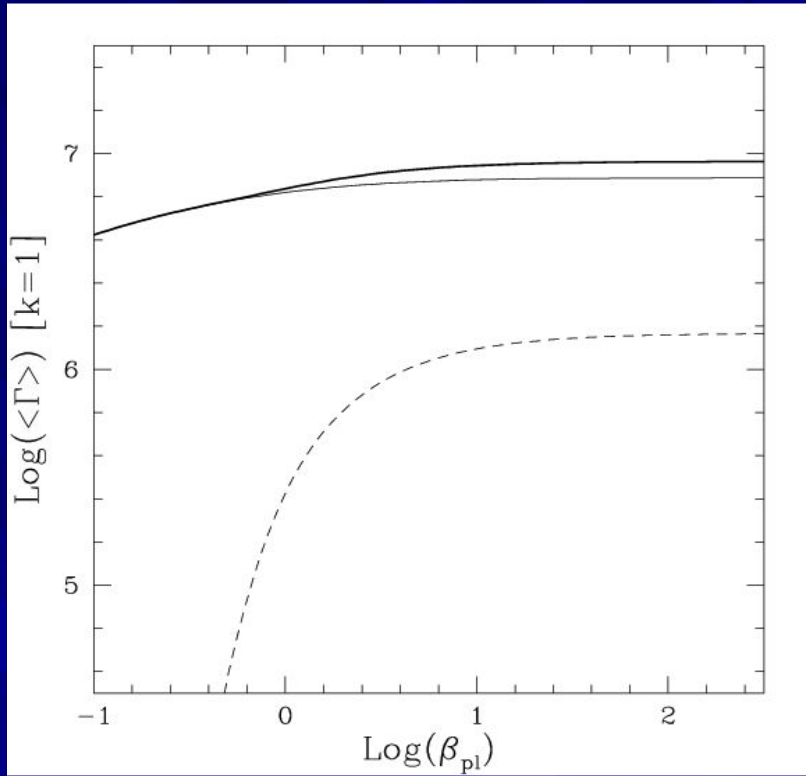
sub-linear scaling **b=0.9**



Dissipation of turbulence in the ICM
(quasi-linear theory)

(e.g., Melrose 1968; Barnes 1969;
Barnes & Scargle 1973)

$$\Gamma = -i \left(\frac{E_i^* K_{ij}^a E_j}{16\pi W} \right)_{\omega_i = 0} \omega_r$$



L ... ency

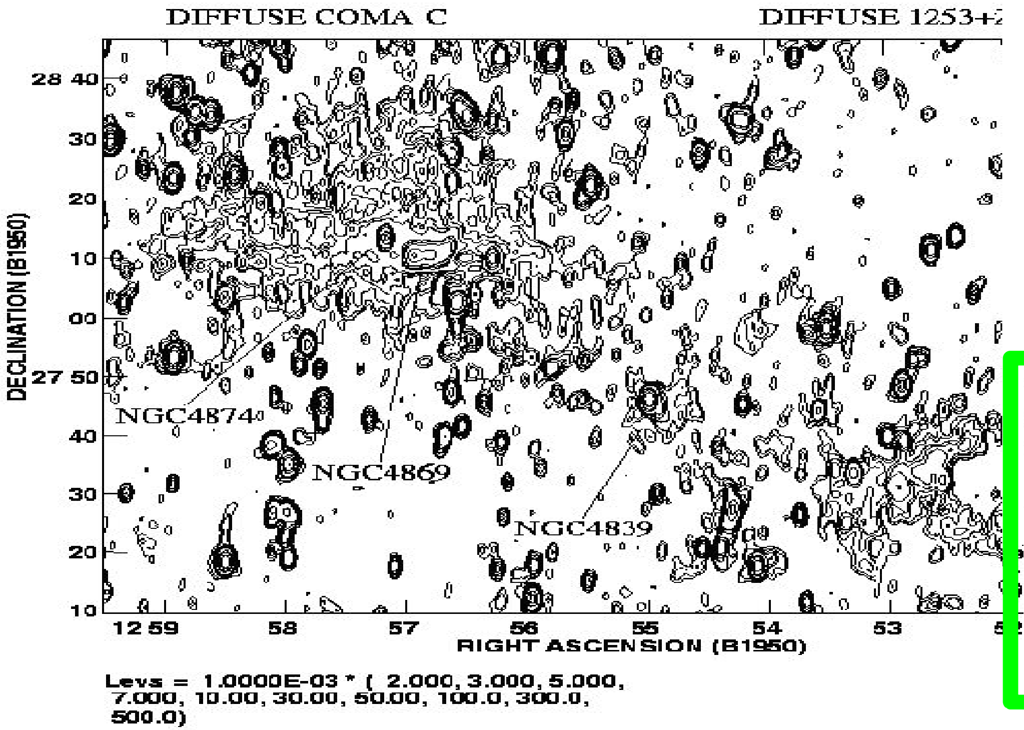
(k)

Damping is dominated by thermal electrons since they are faster than the phase velocity of the modes . CR are not important provided they are not a dominant component in the ICM

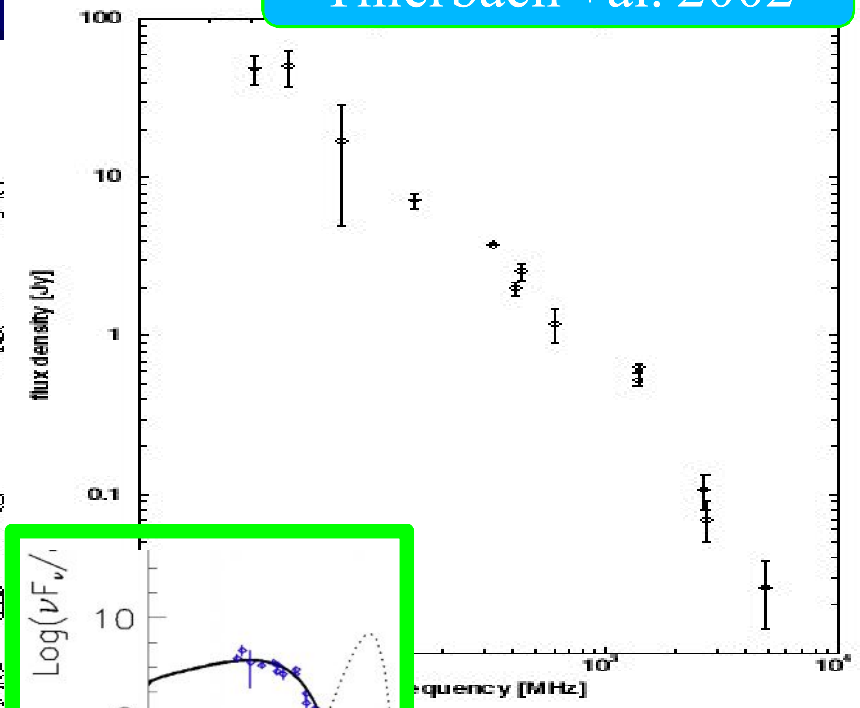
Damping is simple !

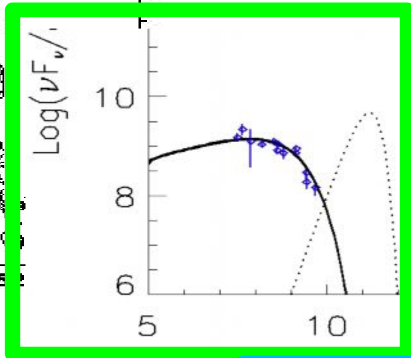
Brunetti & Lazarian 20

RADIO



Thierbach +al. 2002



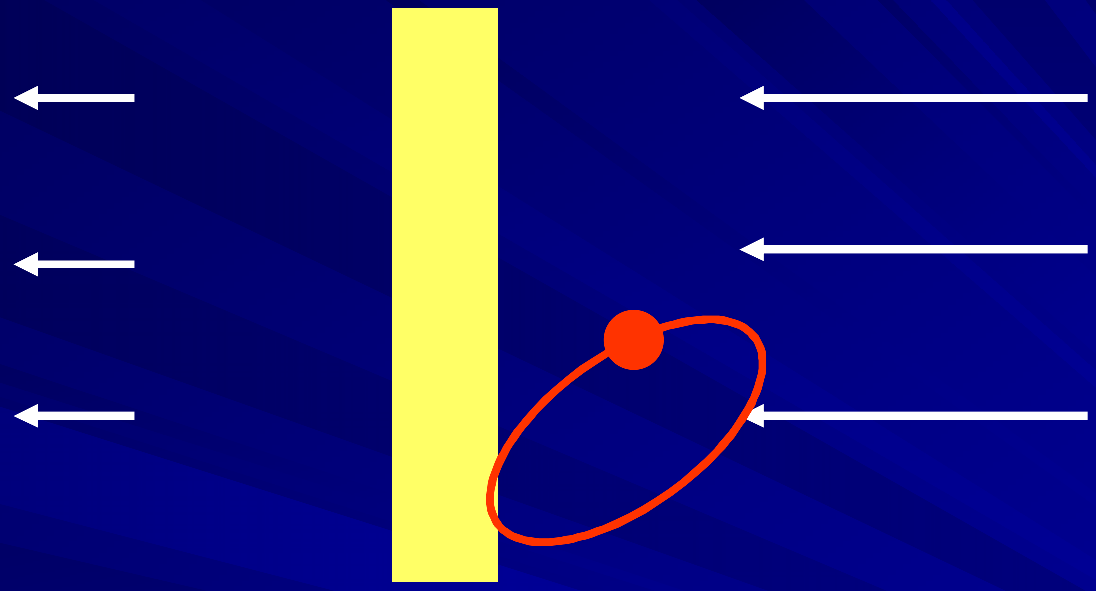


Reimer +al. 2004

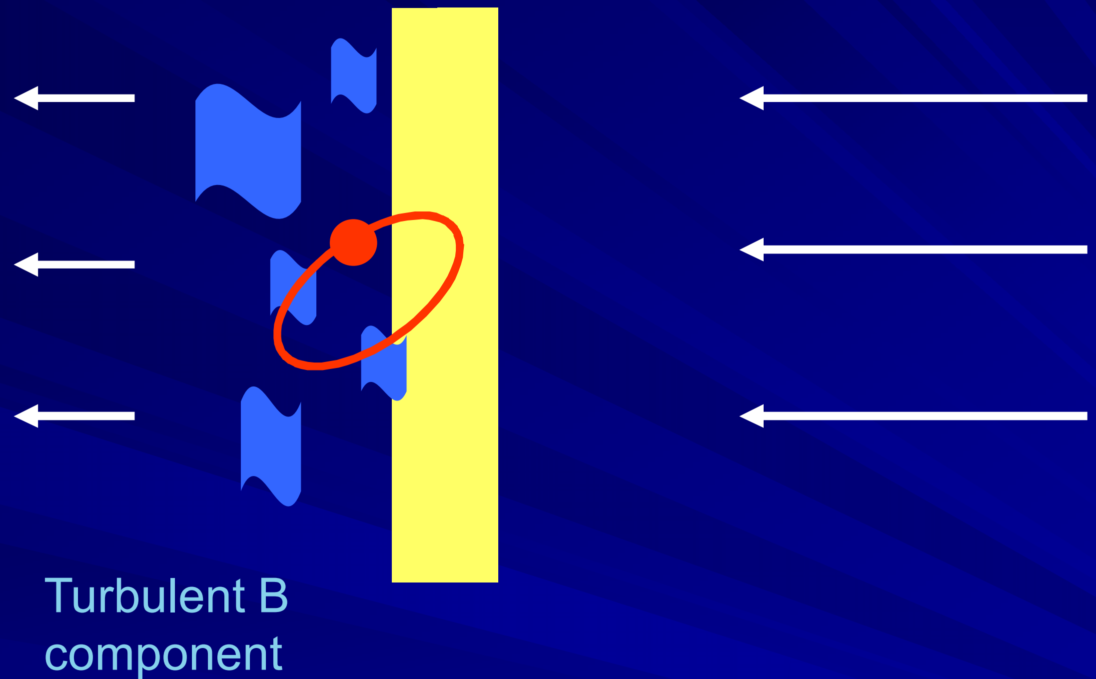
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\mathrm{th}}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\mathrm{th}}/10^{-3}}\right)\right]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

< 0.1 Gyrs

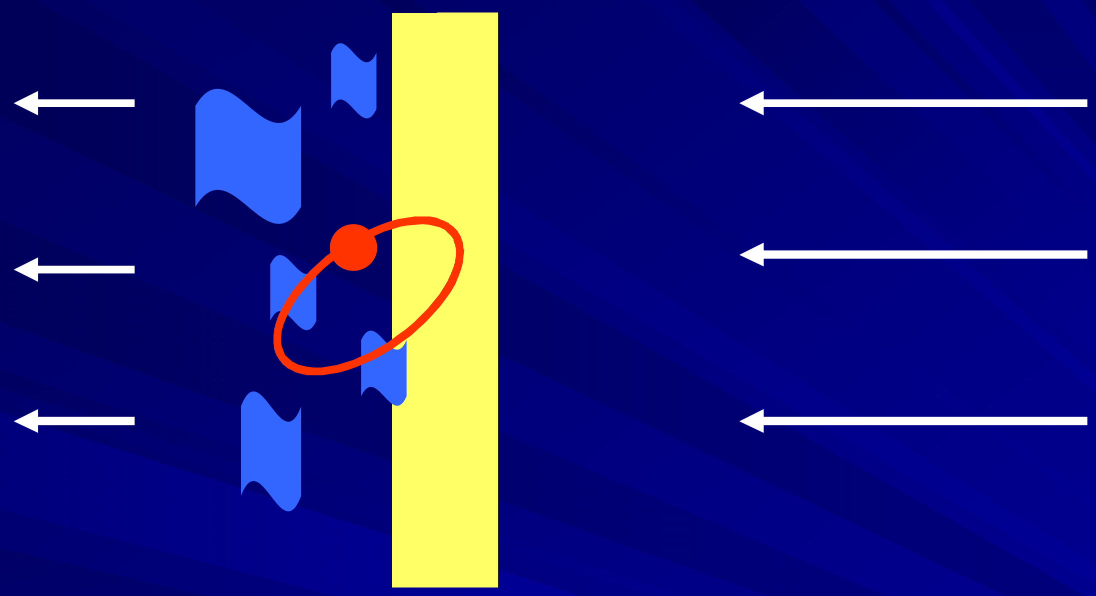
Acceleration of CR at shocks



Acceleration of CR at shocks



Acceleration of CR at shocks

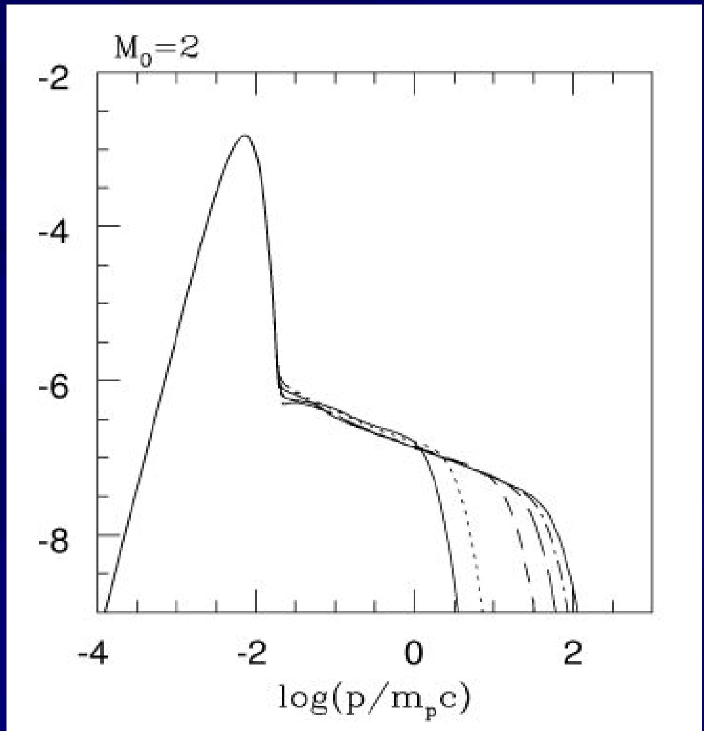


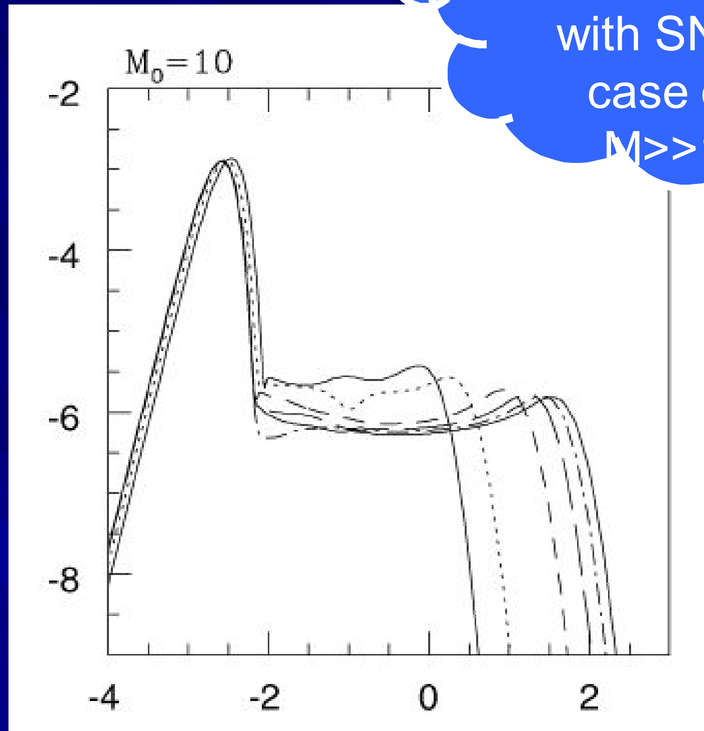
The level of amplification of the turbulent field in the post shock region is necessary to calculate the efficiency of particle acceleration & the minimum momentum of particles that can be accelerated at the shock.
This physics is not yet under control !

Acceleration of CRp at shocks

p_{inj} is a “free parameter” … it’s a *guess* !

Pinj is calibrated with SN in case of M>>1





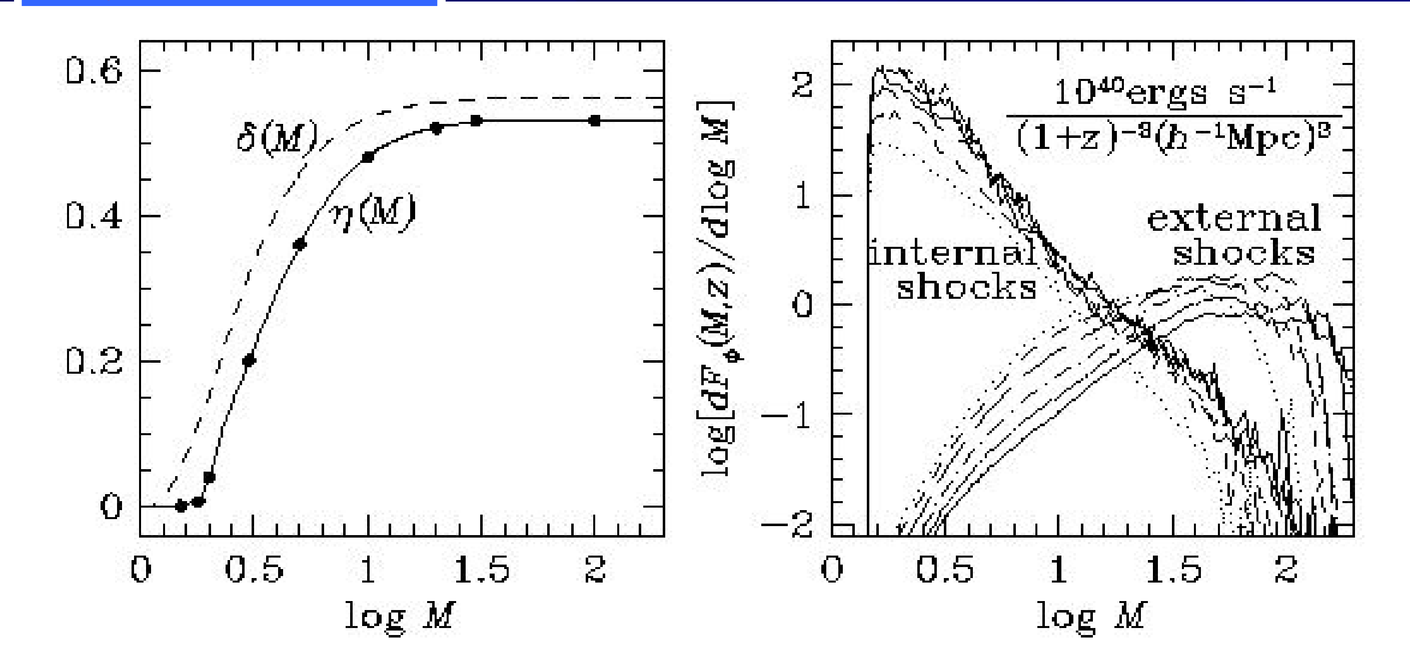
(Kang & Jones 2002; **see also Malkov 1997, Kang & Jones 2005, 07, Amato & Blasi 2006)**

However going from $p_{inj} = 3.5\ p_{th}$ to 3.8 reduces the acceleration efficiency by a factor of 10 !

Acceleration of CRp at shocks

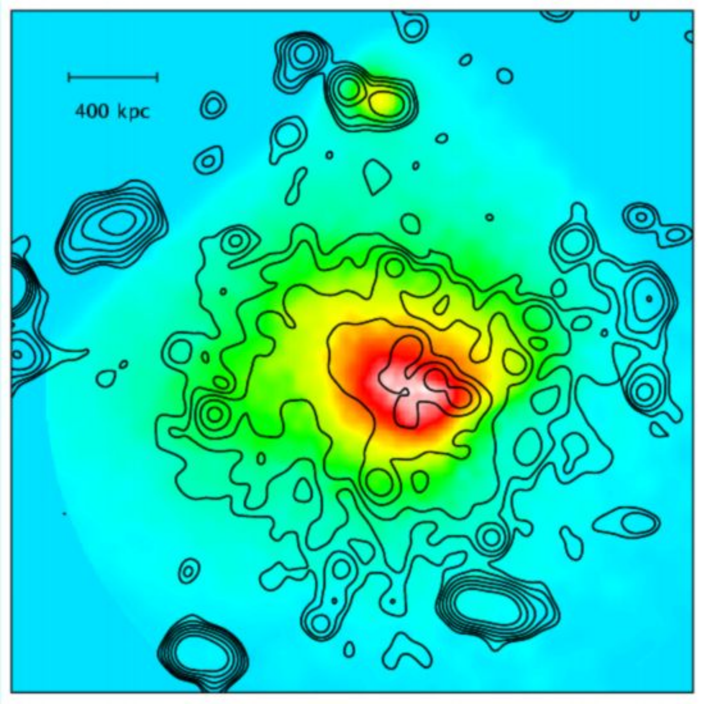
The efficiency strongly depends on Mach number !!!

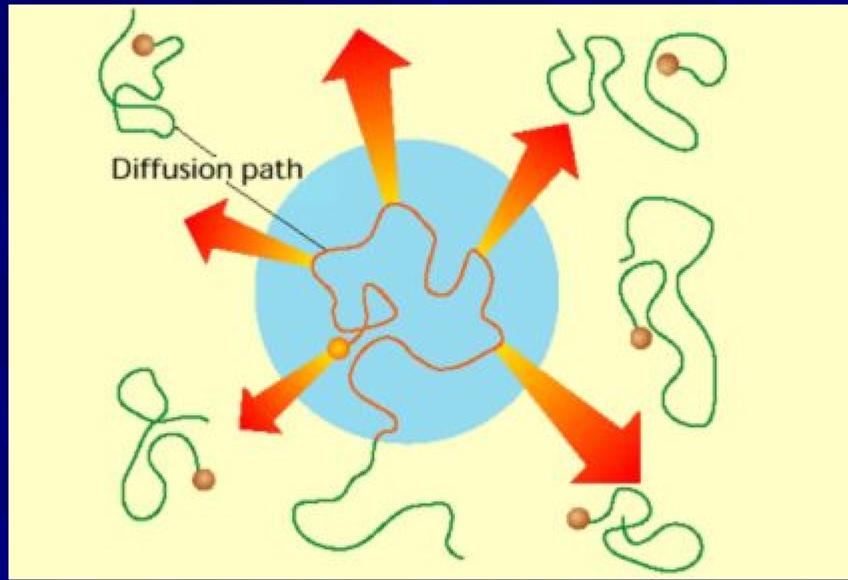
Ryu et al. 2003



Having M=2 or M=2.5 implies a difference of 10 in terms of acceleration efficiency

Origin of Radio Halos





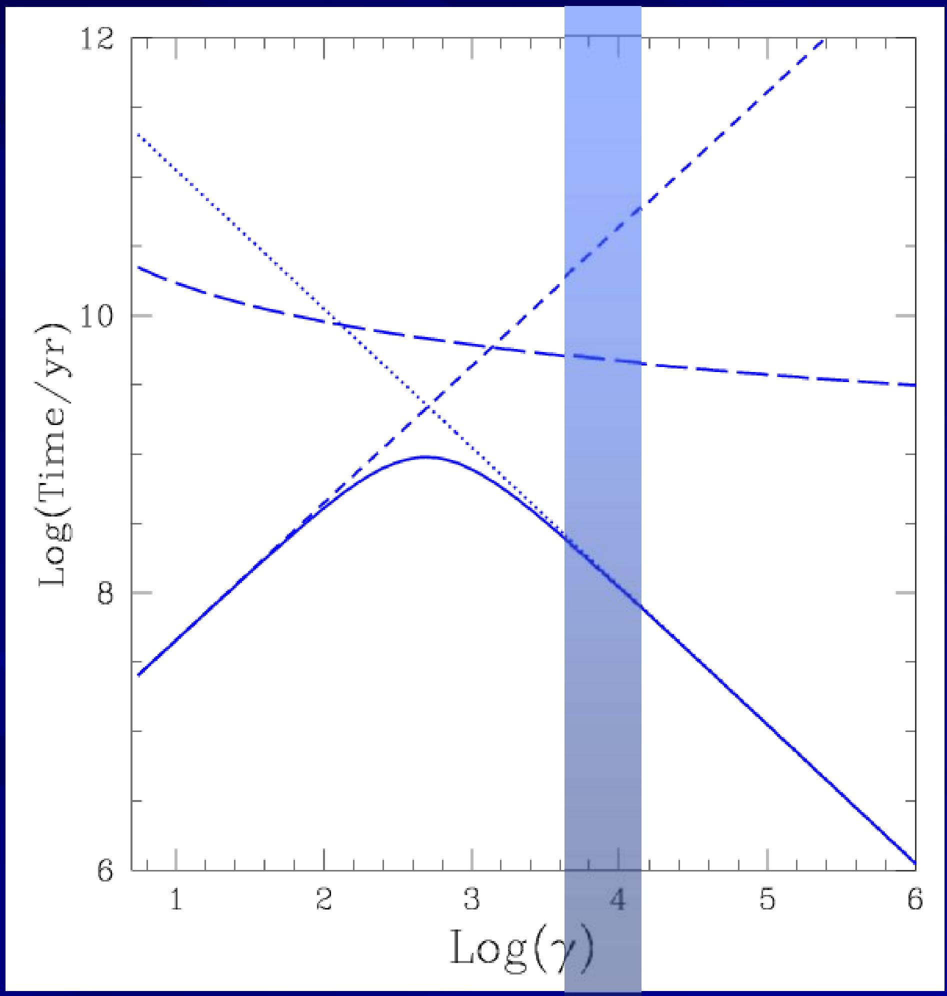
$$\frac{\partial n_p(E_p, r, t)}{\partial t} - D(E)\nabla^2 n_p(E_p, r, t)$$

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

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

Physics of CR Leptons

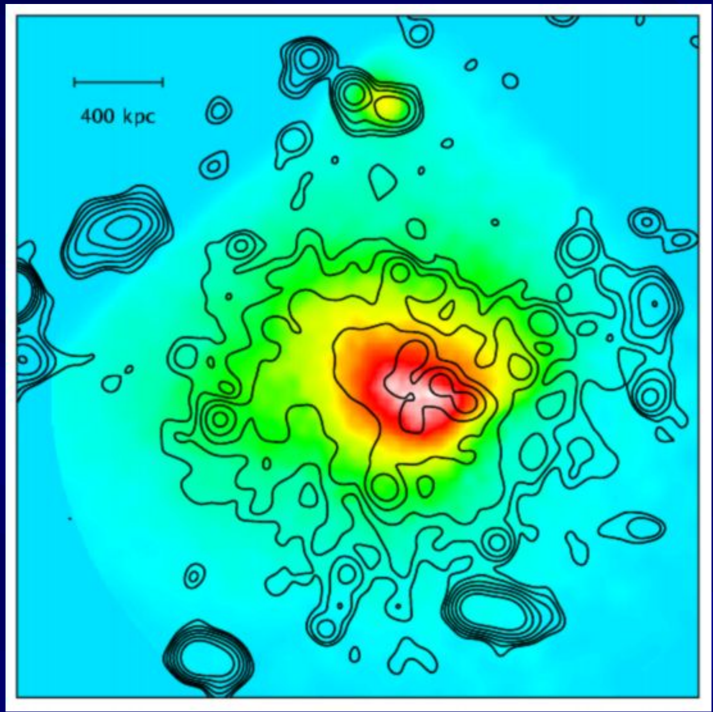
(dE/dt) ~ E / <u>Time</u>



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

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

Radio Halos



$$\tau = \tau_E$$

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

Brunetti 2003

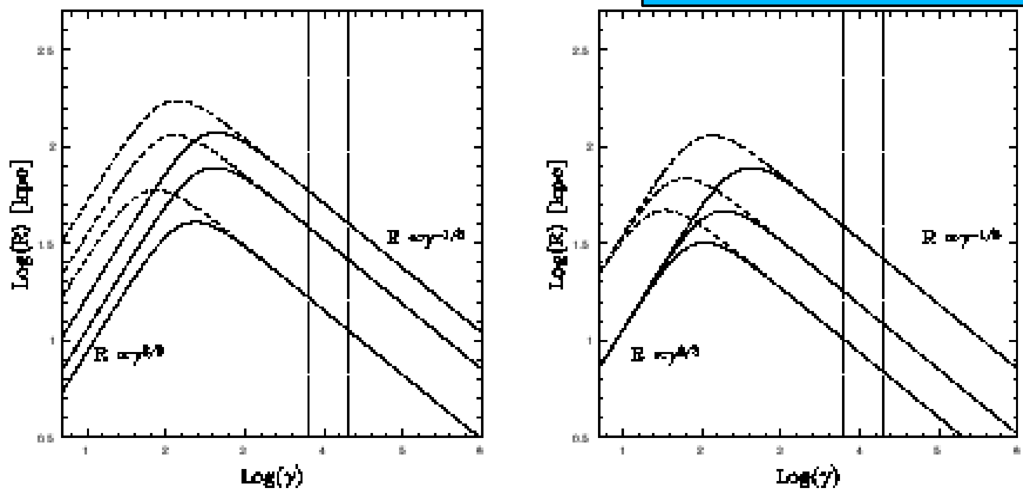
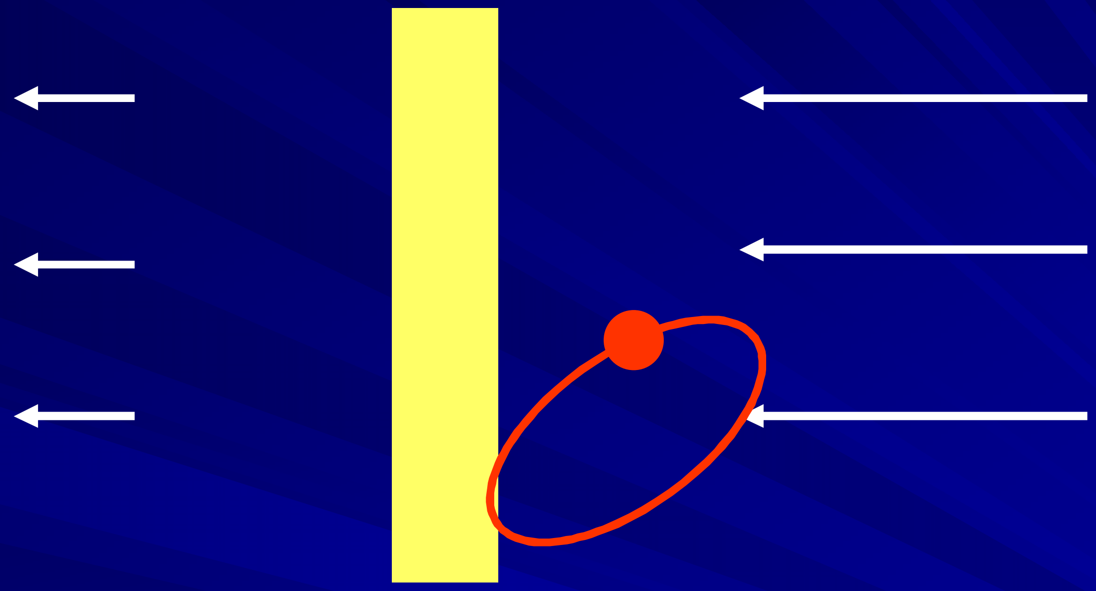


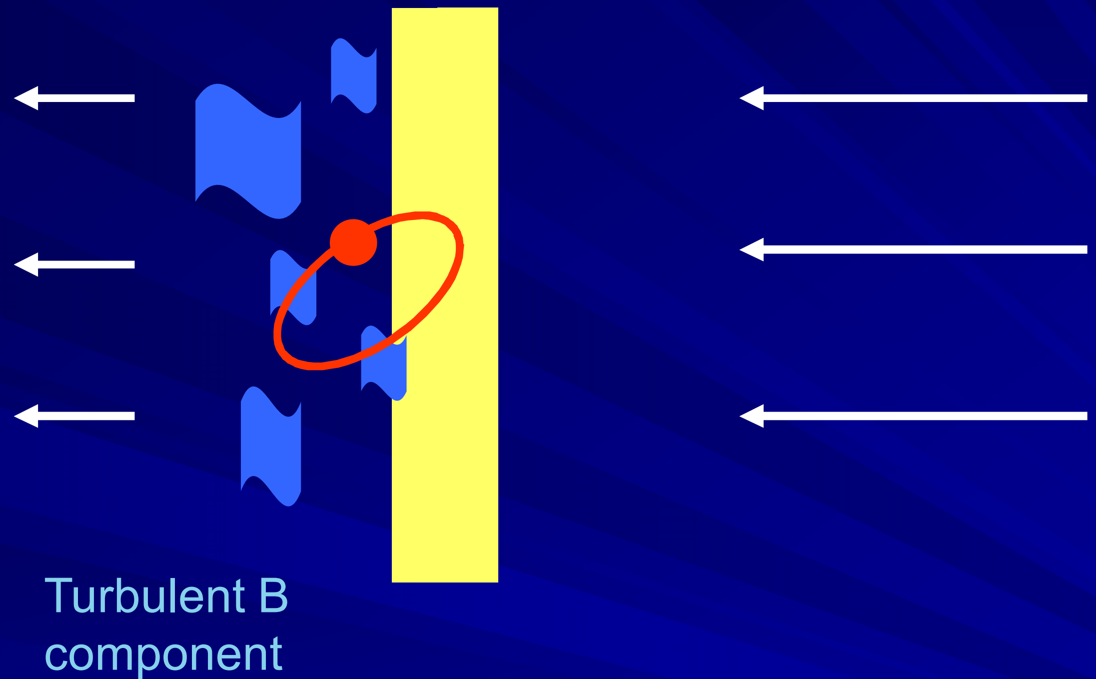
Figure 2. **Panel a)** : Diffusion lengths are reported as a function of γ of the electrons. Calculations are performed at $z = 0$, for $n_{th} = 10^{-3}$ cm^{-3} (solid lines) and 10^{-4} cm^{-3} (dashed lines) assuming (from the bottom) B=5, 1, and 0.1 μG. **Panel b)** : Diffusion lengths as in panel 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

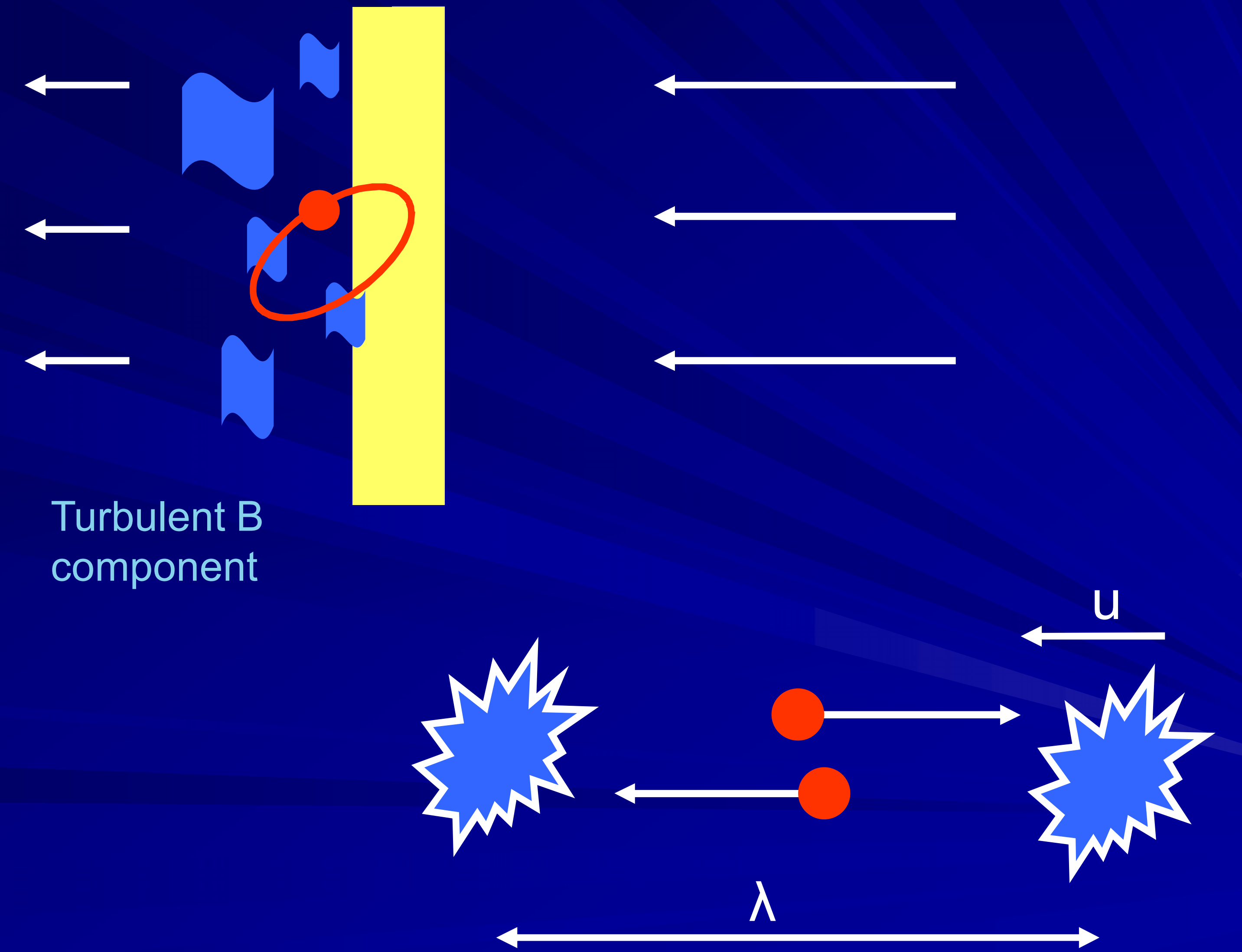
Acceleration of CR at shocks

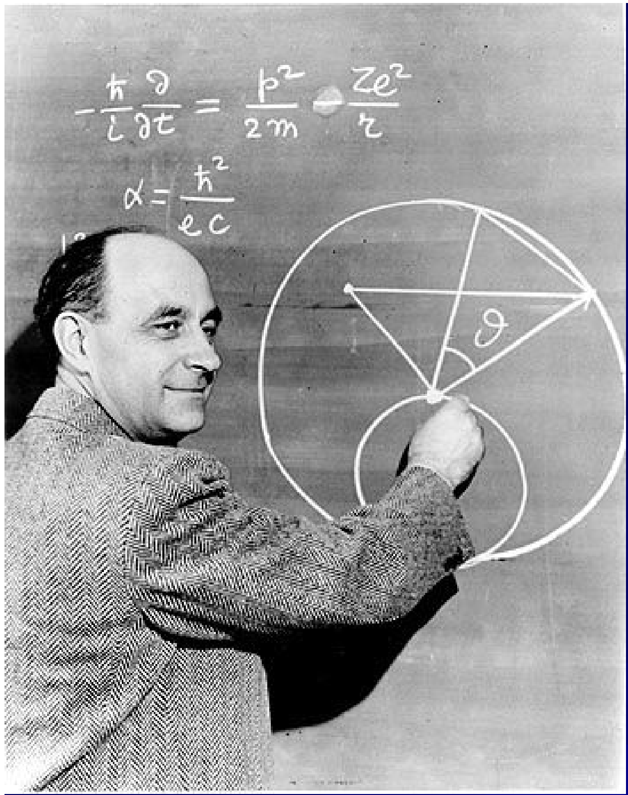


Acceleration of CR at shocks



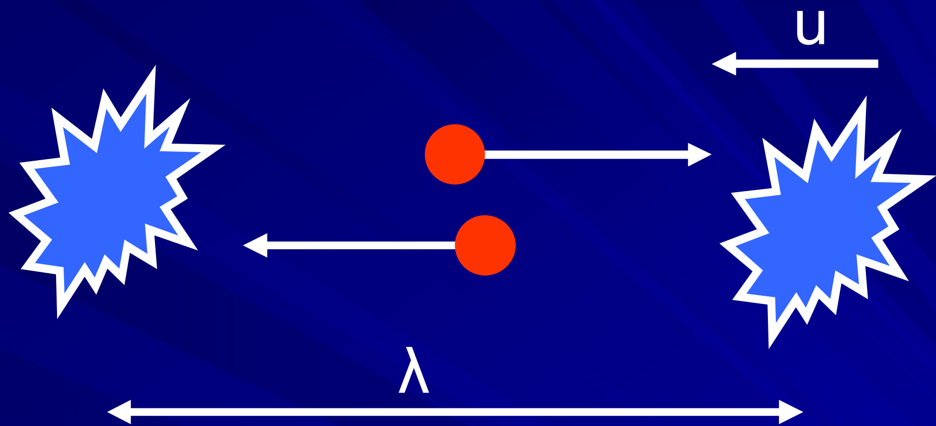
Acceleration of CR at shocks





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: $$\left\langle \frac{\Delta p}{\Delta t} \right\rangle \simeq 2p\,\frac{u}{c}\,\frac{c}{\lambda}$$

Physics of CR Leptons

Sarazin 1999 ; Brunetti 2003 for reviews

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

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

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

Photon Collisions

Particle Collisions

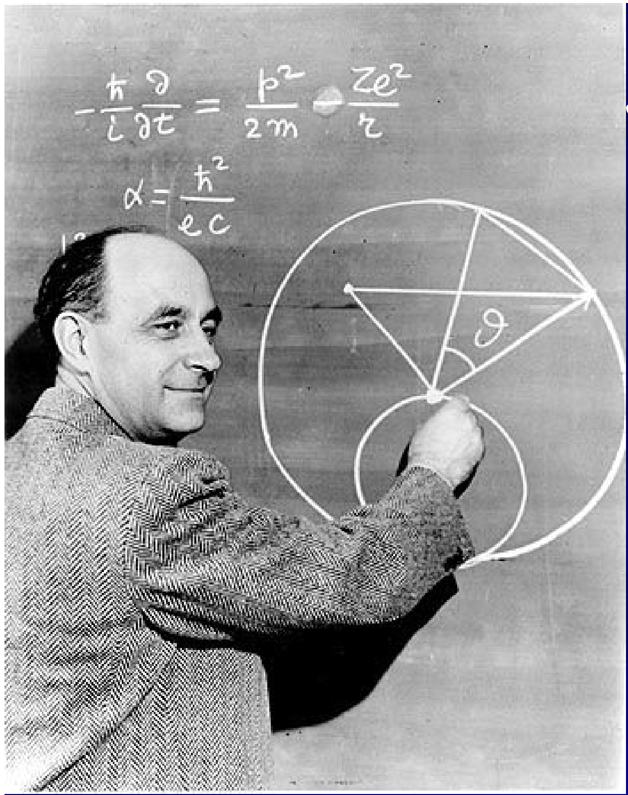
$$b_{Coul}(\gamma) \approx 1.2 \times 10^{-12} n_e\left[1.0 + \frac{\ln(\gamma/n_e)}{75}\right] \text{ s}^{-1},$$

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

IV - Conclusion

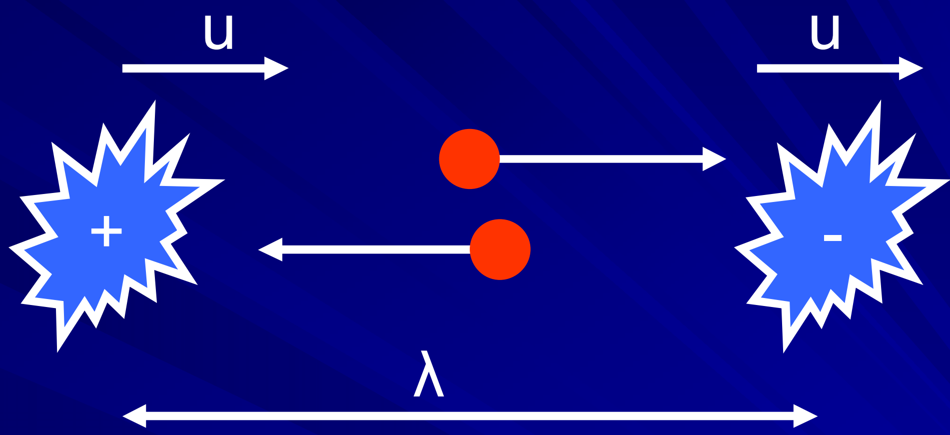
(a) Synchrotron emission from secondaries is an unavoidable process in the IGM

(b) Still this is probably not the (unique) process at the origin of Radio Halos … the level of CR protons is below that necessary to explain Radio Halos



Second order Fermi Mechanisms

(Fermi 1949)



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

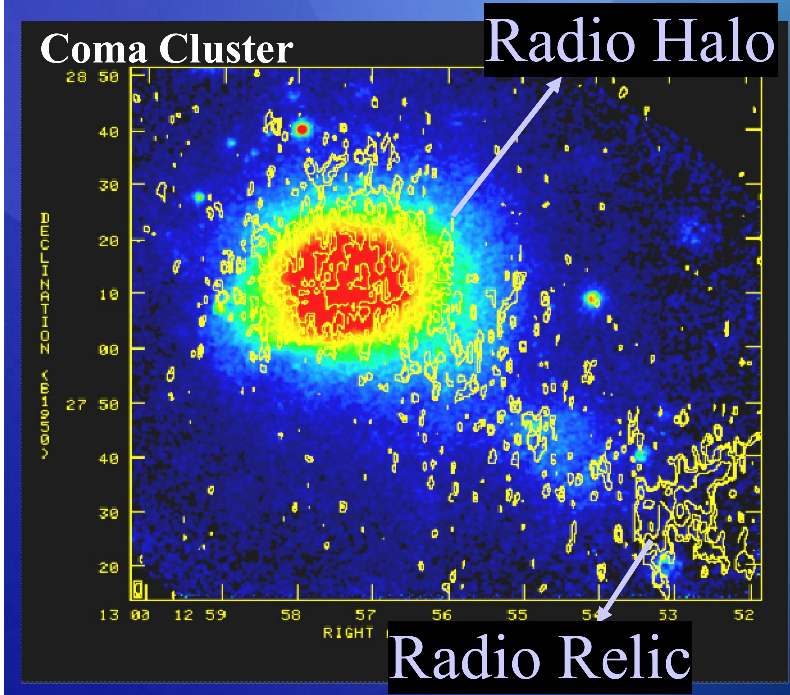
Energy gain per collisions: $\Delta p_\pm \approx \pm 2p\frac{u}{c}$

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

Non-thermal components

Observational evidences

Diffuse synchrotron radio sources from the ICM (not associated with any individual galaxy):



Radio Halos ($L_{1.4GHz} \sim 10^{24}$-10^{26} h_{70}^{-2} Watt/Hz)

- steep spectrum sources ($\alpha \sim 1.1$-1.5)
- low surface brightness (μJy arcsec^{-2} at 1.4 GHz)
- at the cluster centre
- generally regular shape (mimic the X-ray morphology) (~Mpc size)

Radio Relics ($L_{1.4GHz} \sim 10^{23}$-10^{25} h_{70}^{-2} Watt/Hz)

- steep spectrum sources ($\alpha \sim 1.1$-1.5)
- at the cluster outskirts
- elongated morphology + polarised

Halos and **Relics** prove the presence of non-thermal componenets, **GeV** electrons **($\gamma \sim 10^4$)** and μG magnetic field, mixed with the thermal ICM on Mpc scales

CR+B : important not only for particle acceleration ….

Thermal conduction and kin. viscosity in the ICM

(e.g., Lazarian 2006)

Heating of the ICM and "cooling flow" problem

(e.g., Fujita , Matsumoto, Weda 2004; Guo & Oh 2008)

Diffusion and transport of metals in the ICM

(e.g., Voigt & Fabian 2004; Rebusco +al. 2005)

B-Amplification from Cosmological seed fields

(e.g., Dolag +al. 1999,02; Subramanian +al. 2006)

Diffusion and scattering of HE & UHECR in the Universe

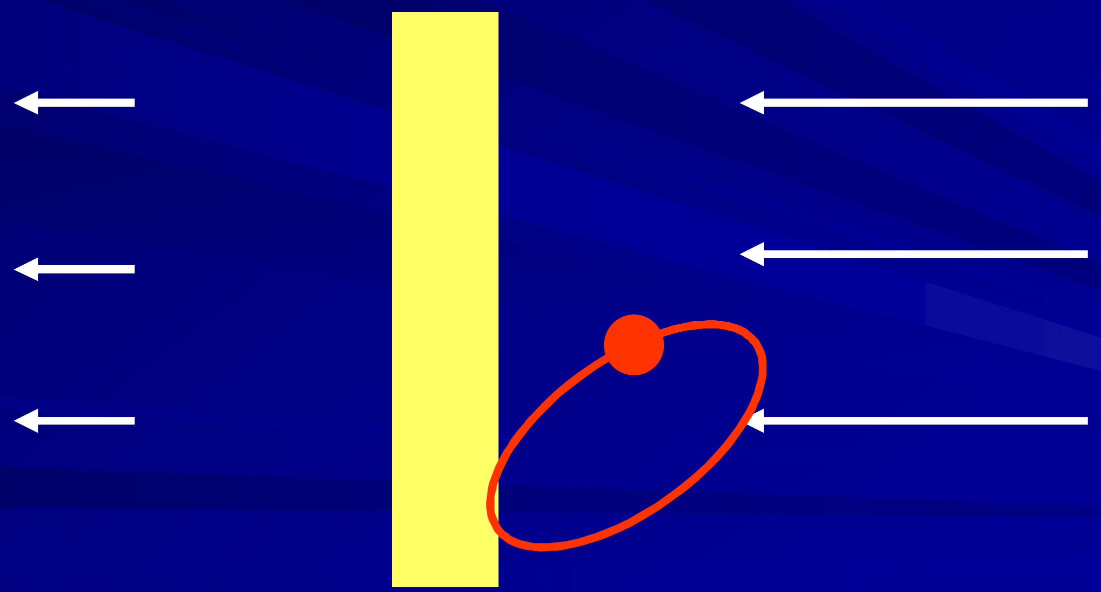
(e.g., Sigl +al. 2005; Dolag +al. 2005)

Acceleration of CRp at shocks

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

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

Linear Theory
(e.g.,Blandford & Eichler 1987)



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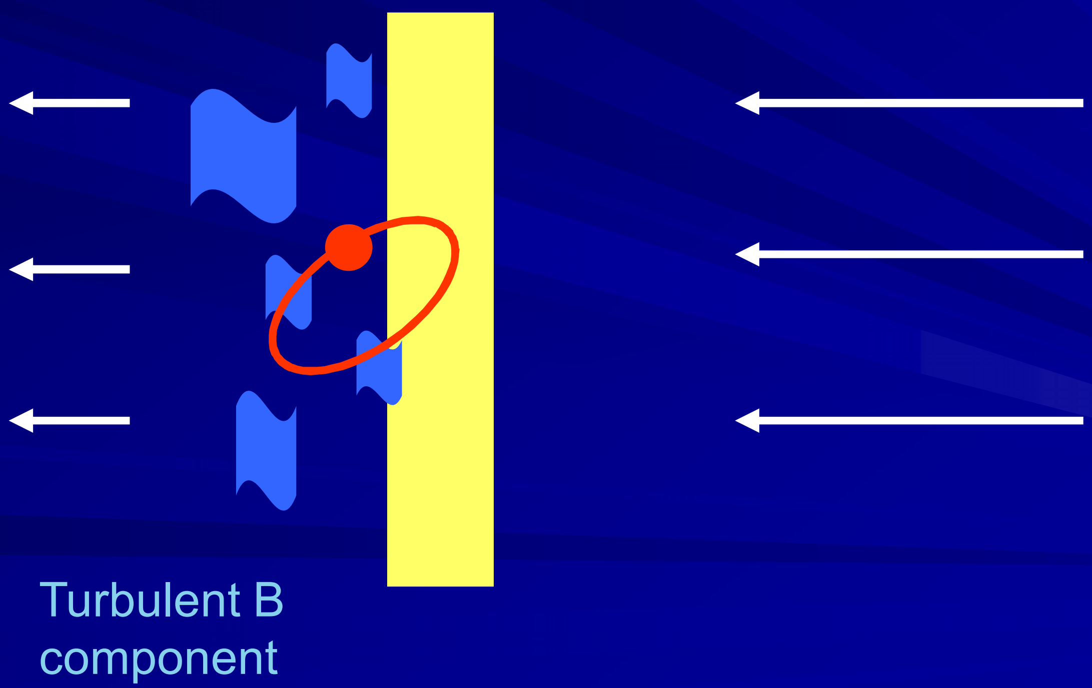
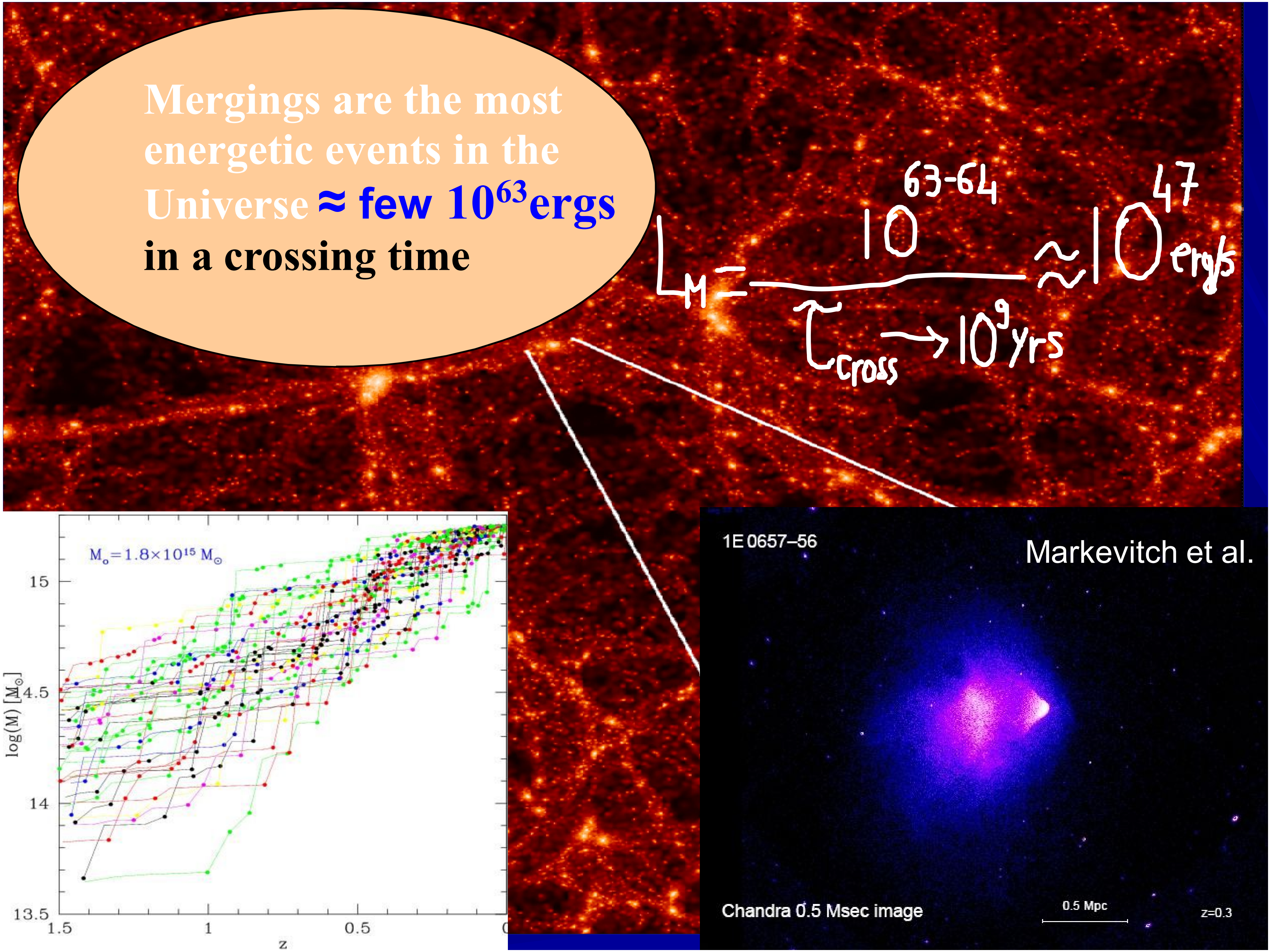
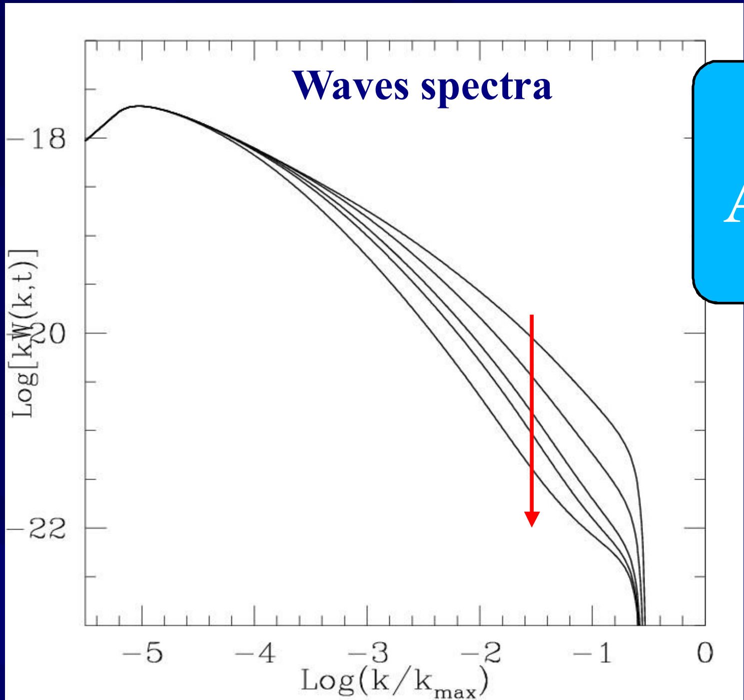
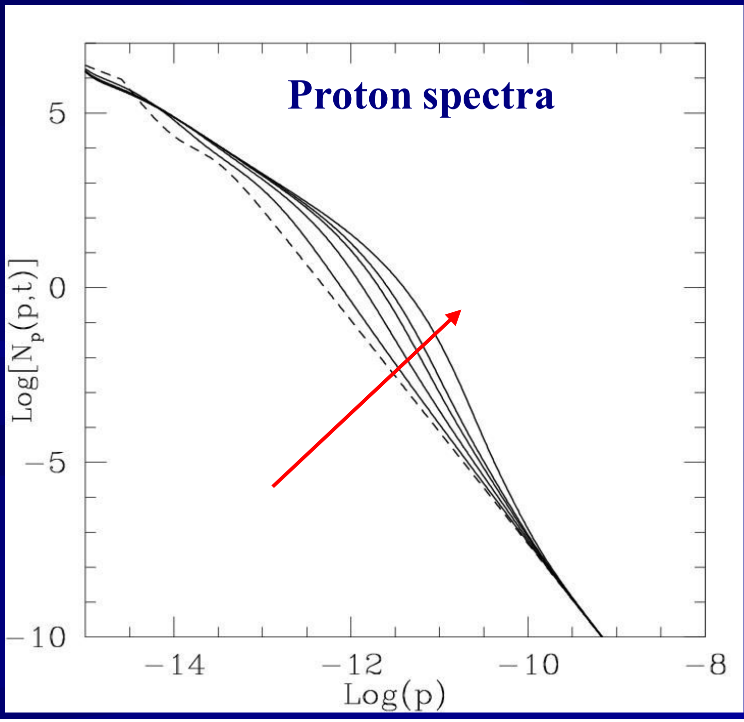


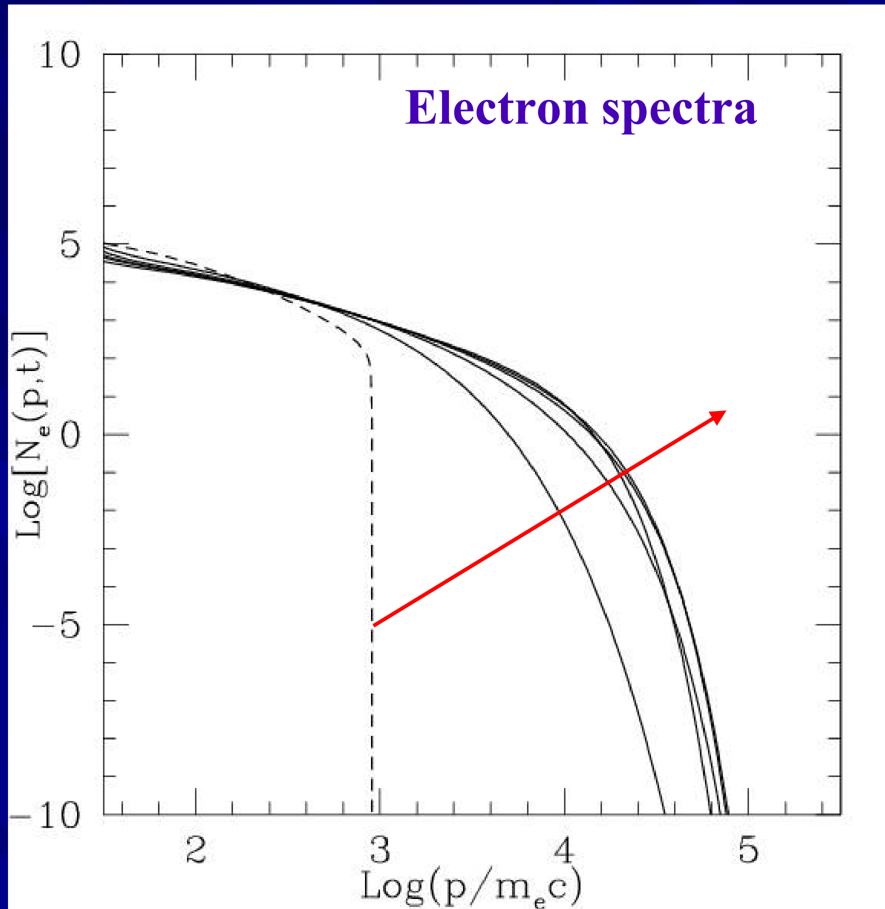

Mergings are the most energetic events in the Universe ≈ few 10^{63}ergs in a crossing time
$L_M = \frac{10^{63-64}}{\tau_{cross}} \approx 10^{47}$ erg/s
$\tau_{cross} \rightarrow 10^9$ yrs
$M_o = 1.8 \times 10^{15} M_\odot$
log(M) [$M_\odot$]
15
14.5
14
13.5
1.5
1
0.5
0
z
1E 0657–56
Markevitch et al.
Chandra 0.5 Msec image
0.5 Mpc
z=0.3

Full Alfven-Wave--Particle Coupling

(Brunetti et al. 2004)







Waves + electrons + Protons