Non-thermal emission, CR and turbulence in galaxy clusters

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Outline

(1) Galaxy clusters, clusters mergers and non-thermal particles/emission in the ICM

(2) Gamma ray emission from galaxy clusters and limits on CRp energy content

(3) Origin of diffuse Mpc-scale syn emission in galaxy clusters, turbulence?, turbulence+hadronic?, ??

(4) A unvisible population of Mpc-scale very-steep spectrum emissions to be discovered in galaxy clusters ?

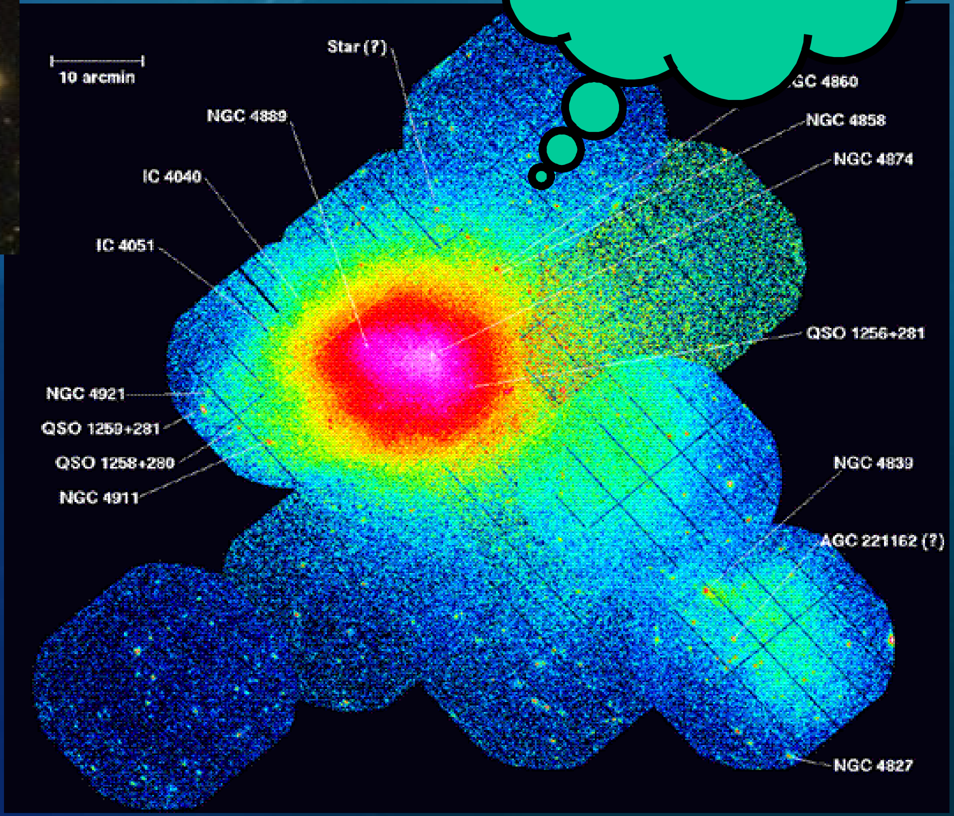
(5) LOFAR : expectations and first results

Clusters of galaxies: the largest gravitational structures in the Universe ($M \approx 10^{14}-10^{15} M_{sun}$, $R_V \approx$ 2-3 Mpc)

≈30-300 galaxies

$n \approx 10^{-3} cm^{-3}$

$T \approx 10^{7}-10^{8} K$



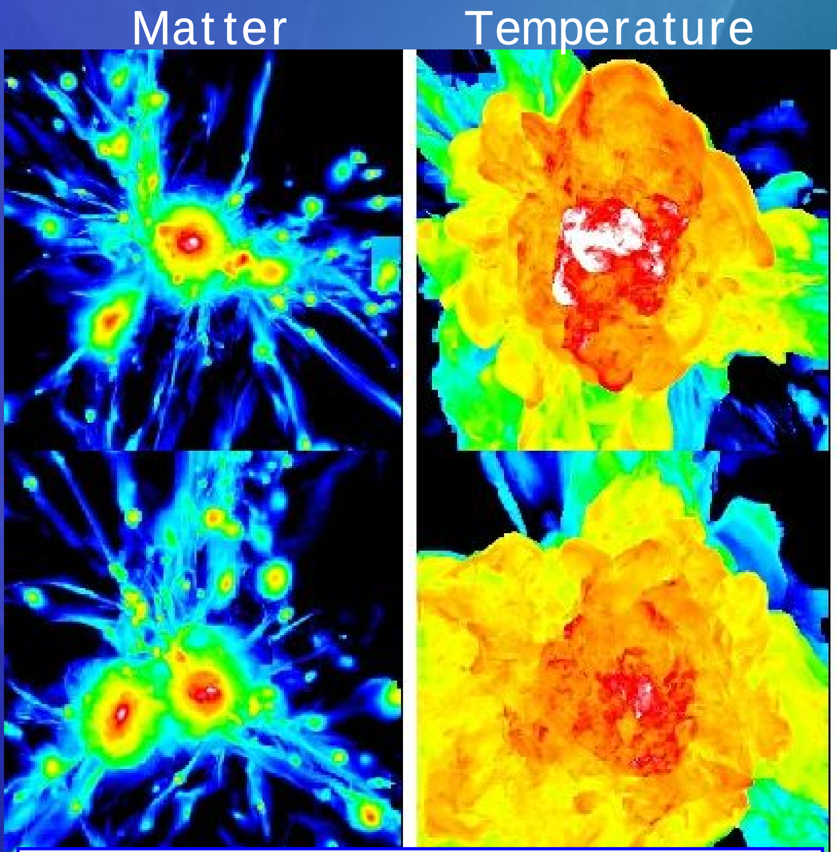
Galaxy cluster mass:

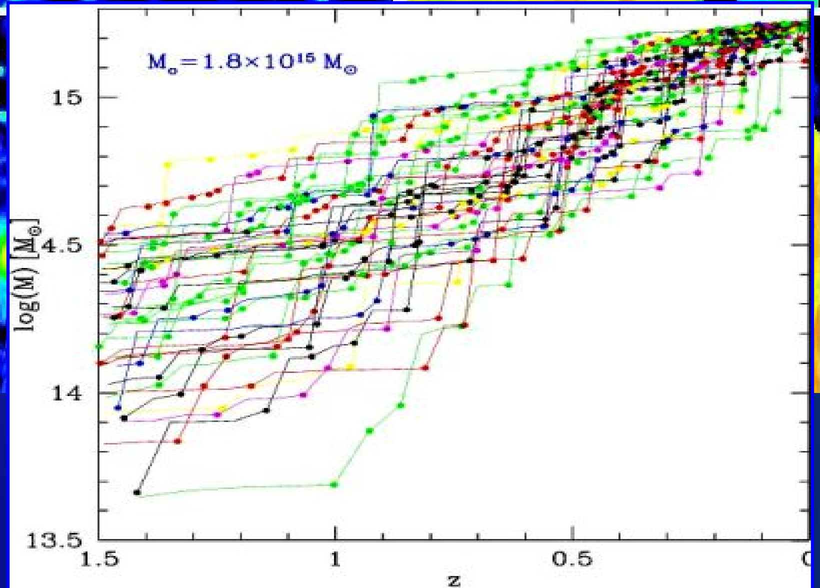
Barions **10%** of stars in galaxies

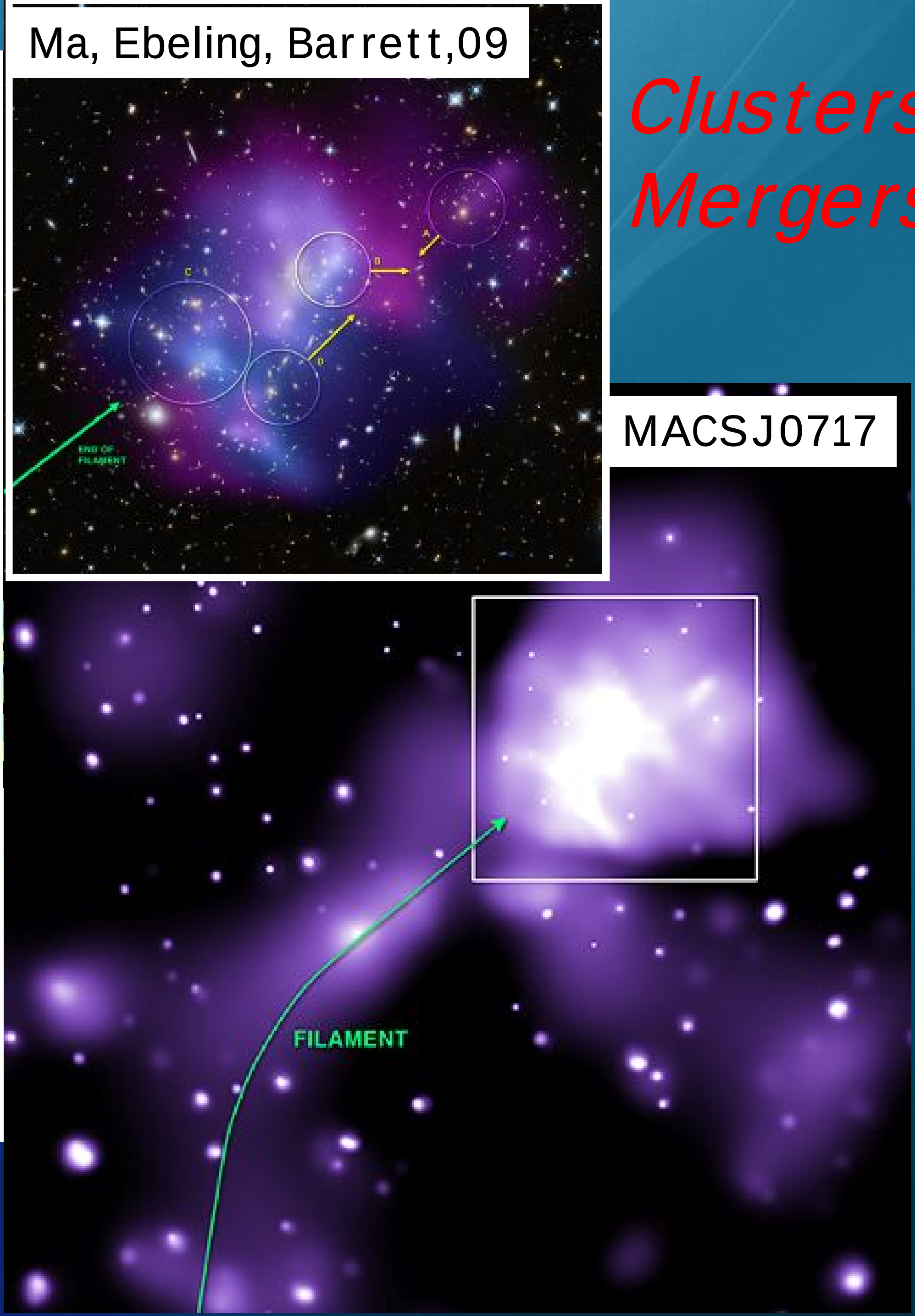
15-20% of hot diffuse gas

Dark Matter **70%**

Clusters Mergers






Ma, Ebeling, Barrett,09

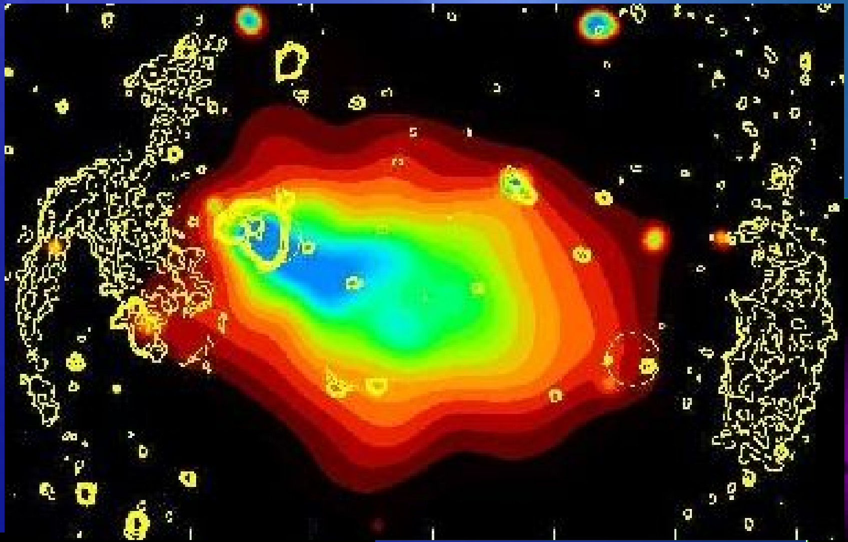
MACSJ0717

Cosmic rays in galaxy clusters

Diffuse synchrotron emission is detected in a fraction of galaxy clusters.
This demonstrates the presence of (at least) CRe and B.

Unpolarised, follow the X-ray brightness
(originate from cluster central regions)

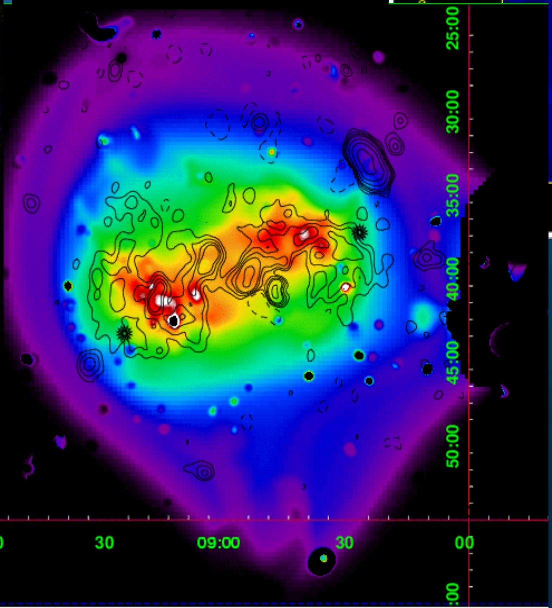
Polarised, no correlation with X-ray brightness
(form in cluster outskirts)

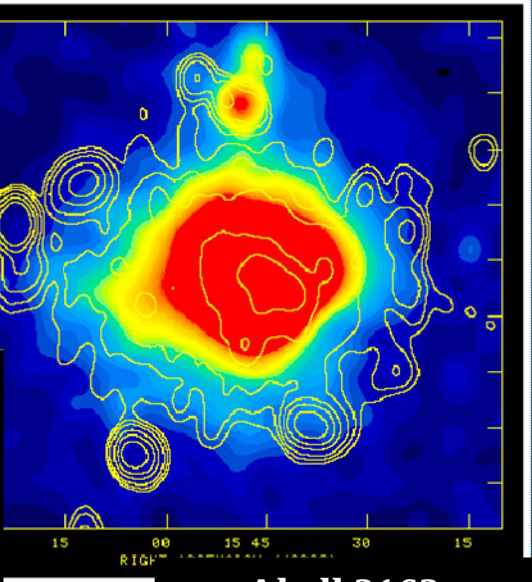


Abell 3376
Bagchi et al. 2005

Radio Relics

Abell 754
Henry et al. 2004

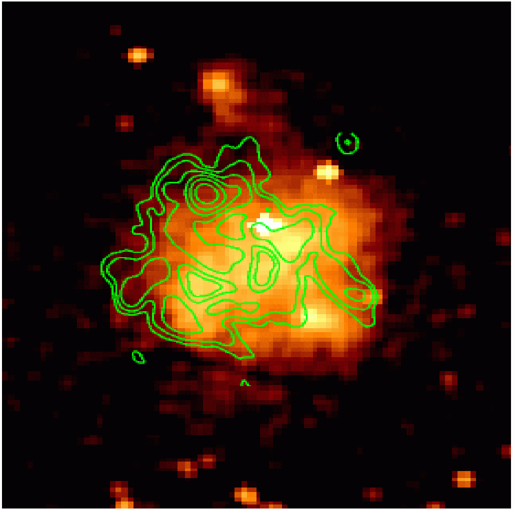


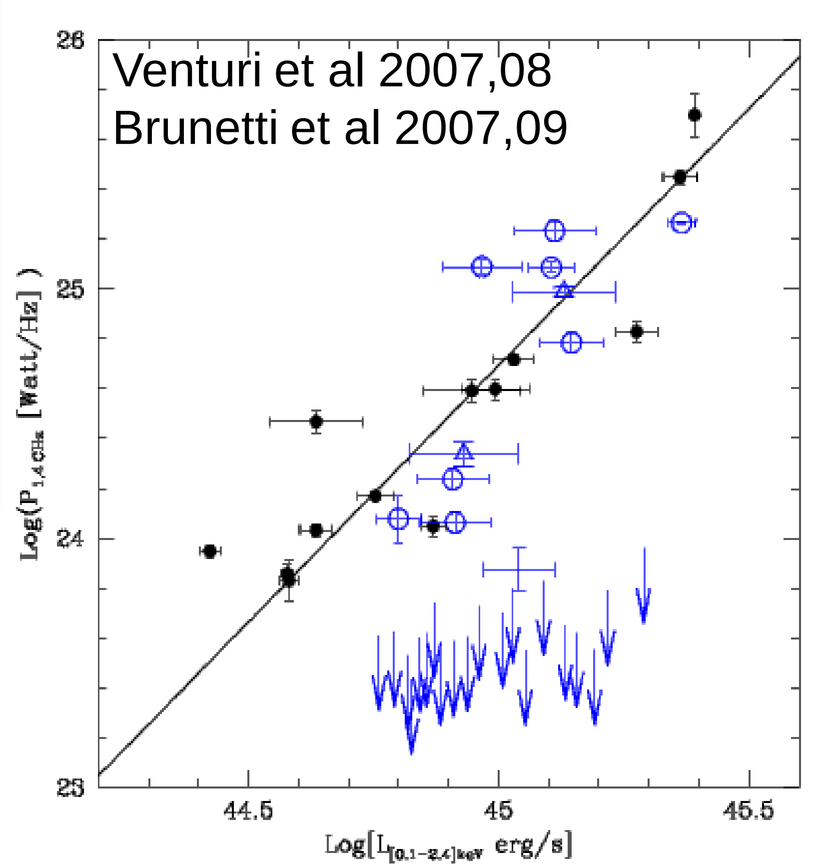


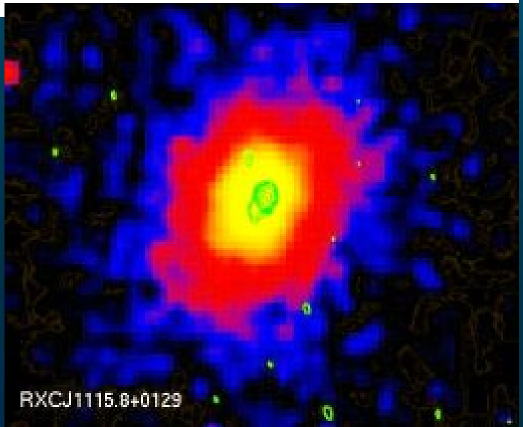
Abell 2163
Feretti et al. 2001

Radio Halos

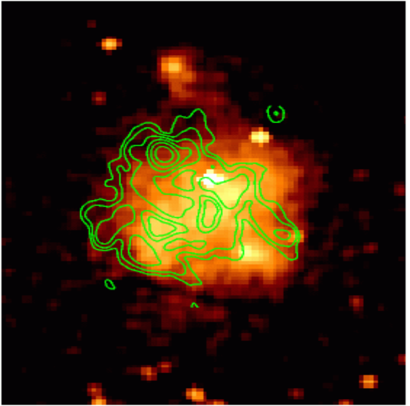
Cluster mergers - radio halos connectio

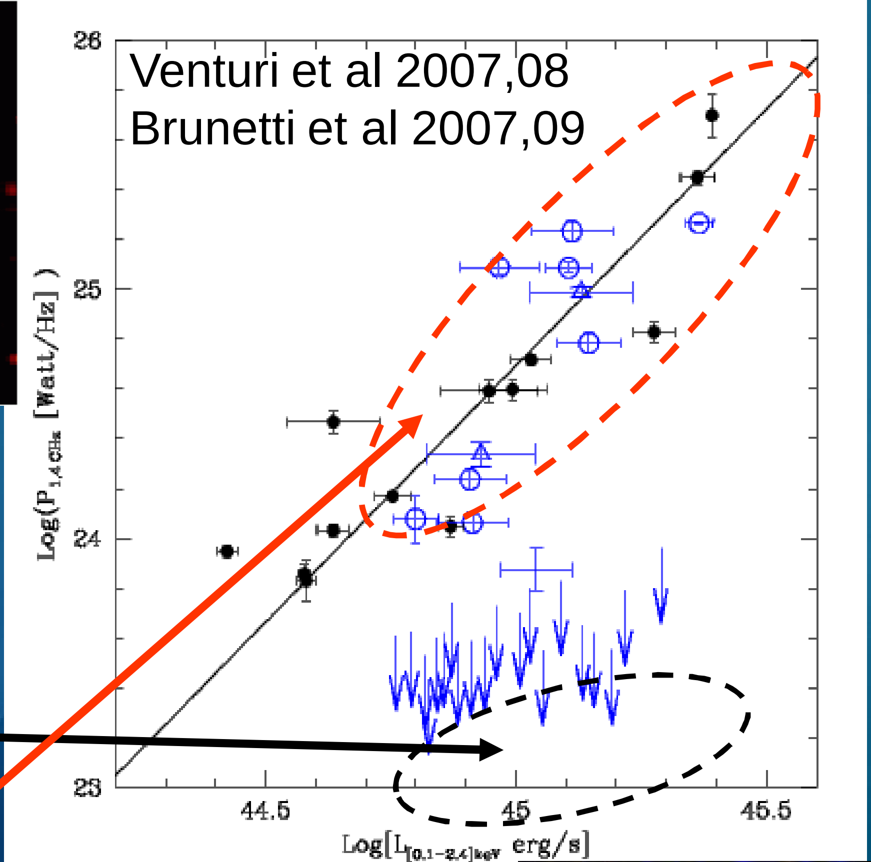



Venturi et al 2007,08
Brunetti et al 2007,09



Cluster mergers - radio halos connection

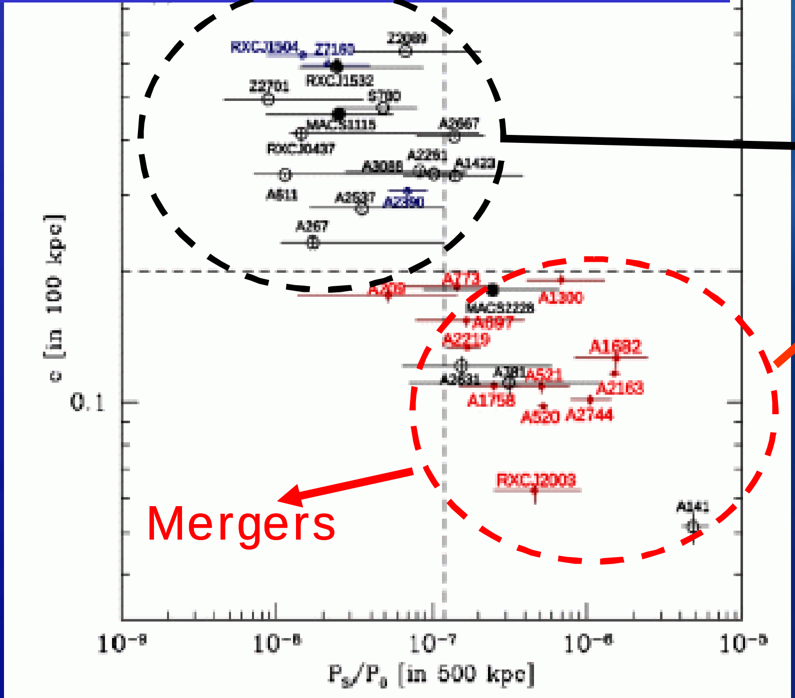




Venturi et al 2007,08
Brunetti et al 2007,09

Relaxed

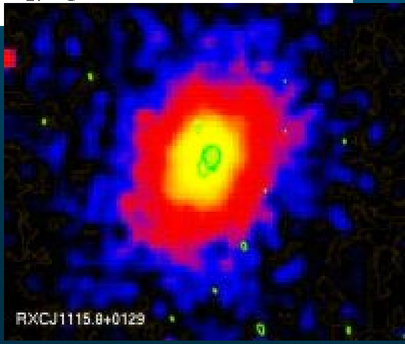
Cassano et al 2010 ApJ 721 L82



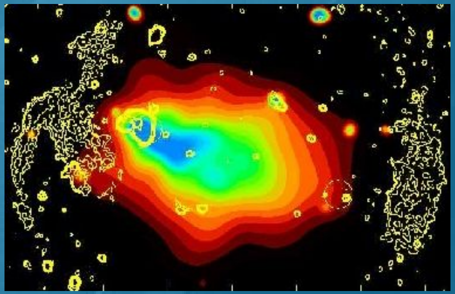
Mergers

The radio bimodality has a correspondence in terms of dynamical segregation : particle acceleration and B amplification in meregrs

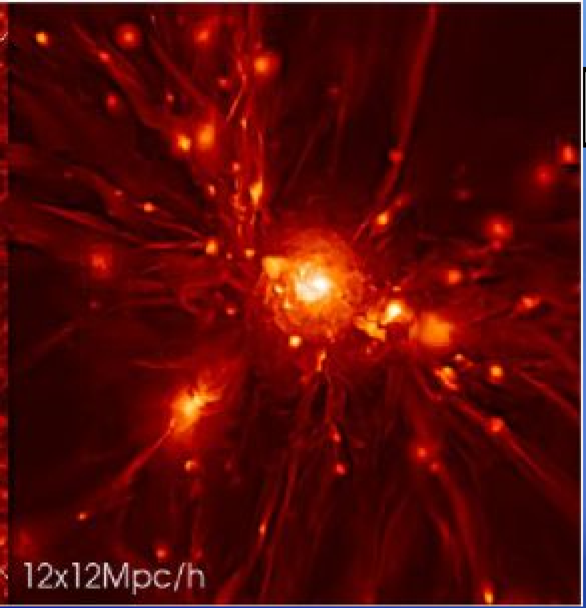
(Brunetti et al 07, 09, Kushnir et al09, Keshet & Loeb 10)

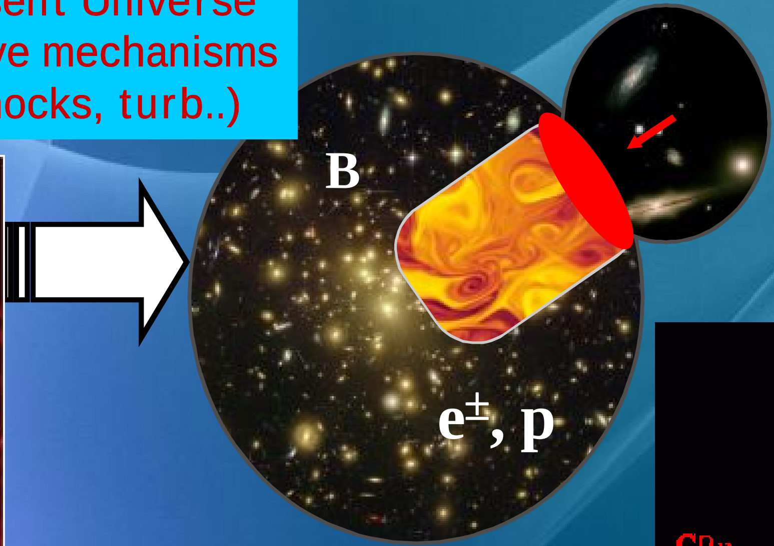


Mergers & CR-acceleration



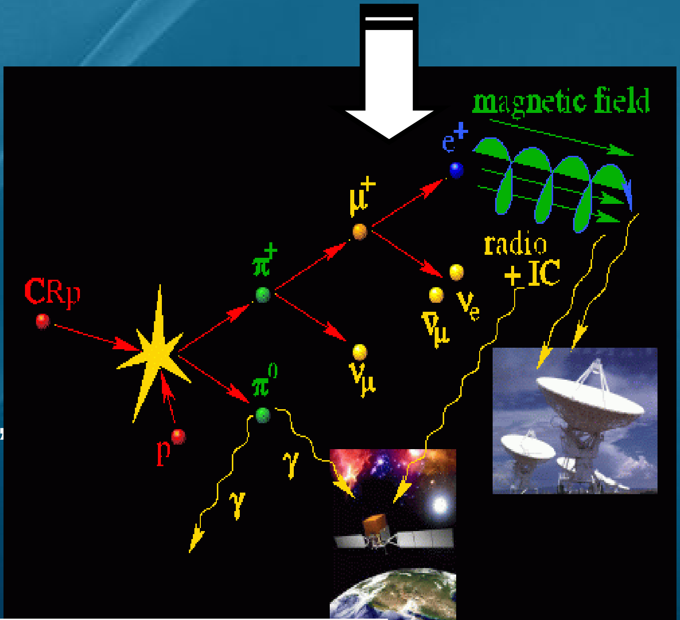
Cluster-cluster mergers are the most energetic events in the present Universe (10^{64}erg/Gyr). They can drive mechanisms for particle acceleration (shocks, turb..)





SHOCKS

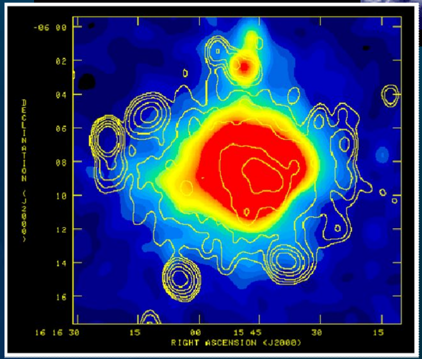
accelerate CRe±,CRp



TURBULENCE

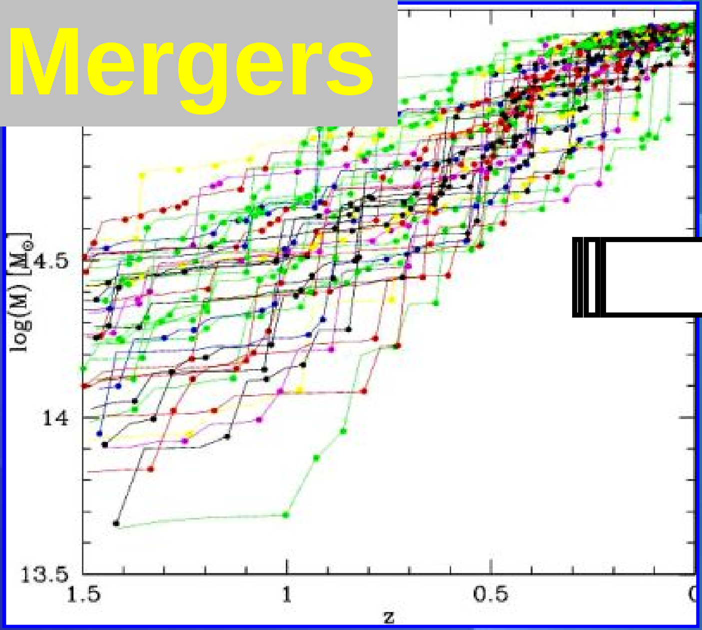
reaccelerates fossil CRe± , CRp and secondaries CRe±

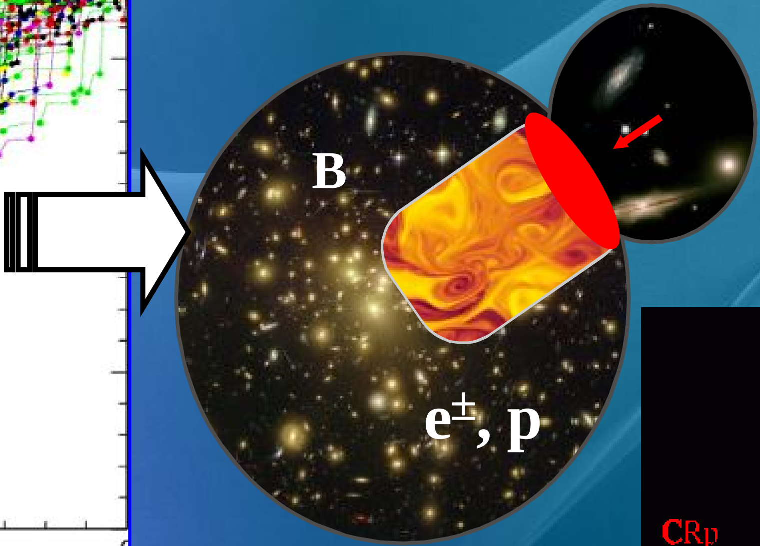
(Brunetti et al. 01, 04, 09; Petrosian 01; Blasi 01; Miniati et al. 01,03; Fujita et al. 03; Ryu et al. 03; Berrington & Dermer 03; Pfrommer & Ensslin 04; Brunetti & Blasi 05; Cassano & Brunetti 05; Marchegiani et al 07; Brunetti & Lazarian 07, 2011; Hoeft & Bruggen 07; Colafrancesco & Marchegiani 08; Pfrommer et al. 08; Wolfe et al. 08; Kushnir et al 09; Keshet & Loeb 10…)

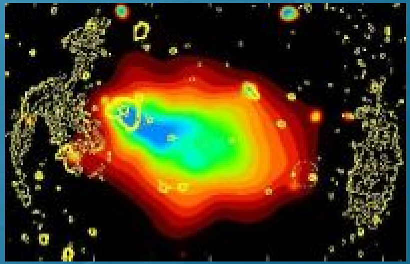


Mergers & CR-acceleration

Mergers

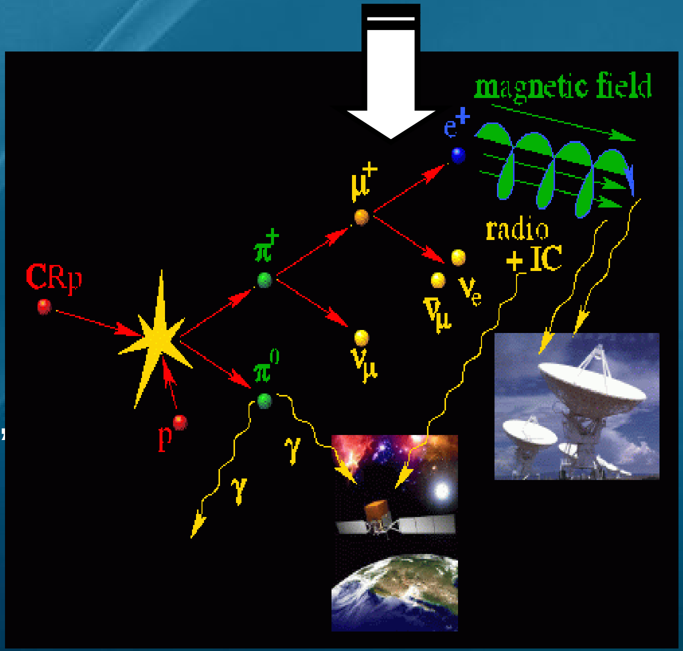






SHOCKS

accelerate CRe$^\pm$,CRp

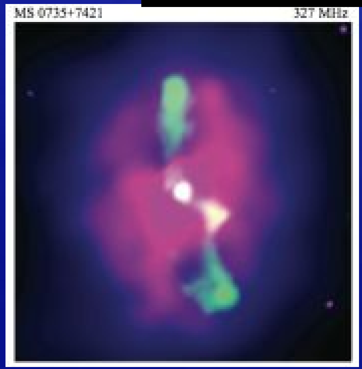


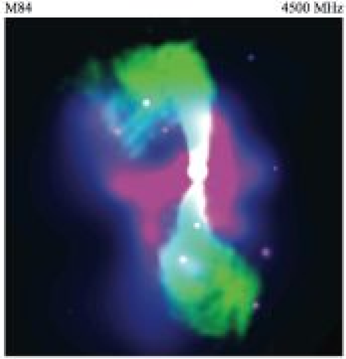
TURBULENCE

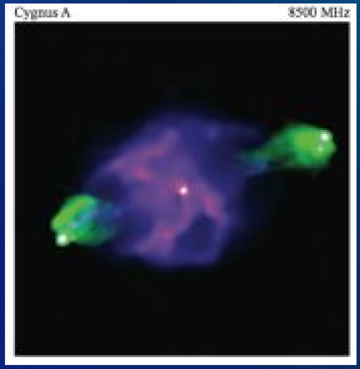
reaccelerates fossil CRe$^\pm$, CRp and secondaries CRe$^\pm$

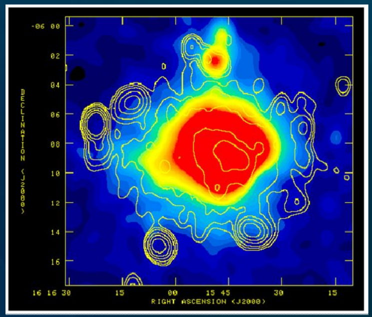
AGN/GW

Voelk et al 96, 99



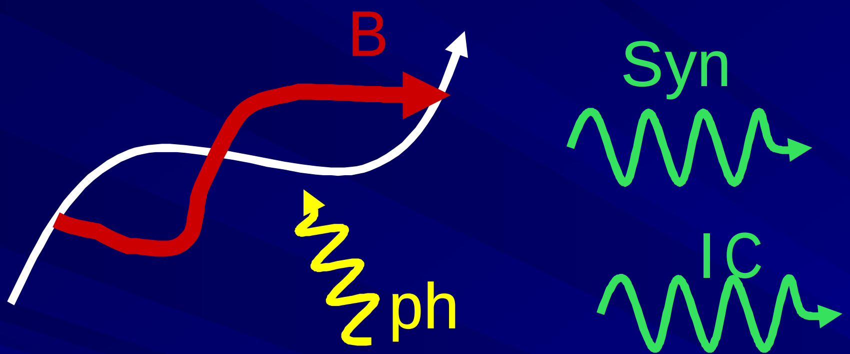




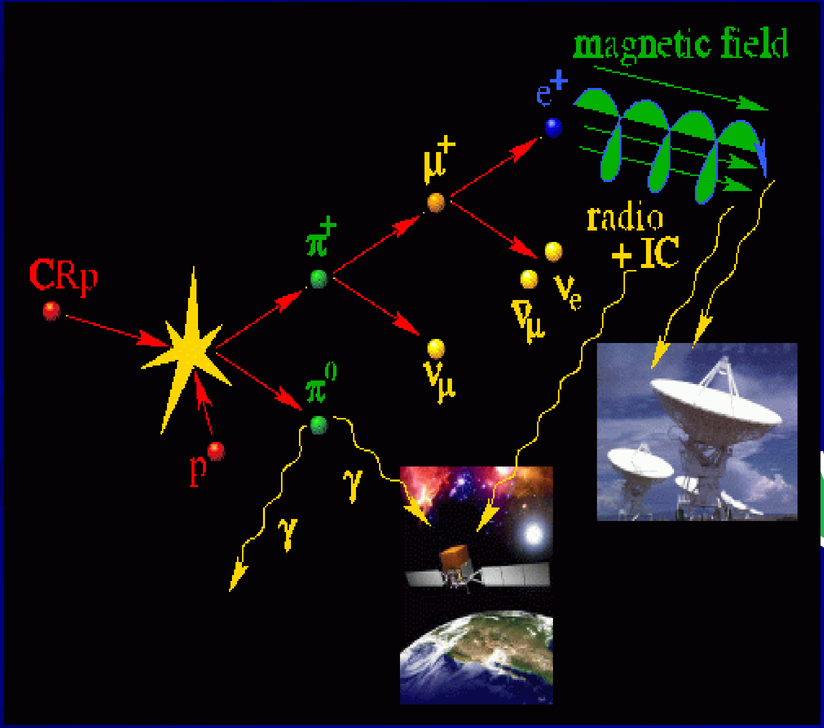


High energy emission from GC

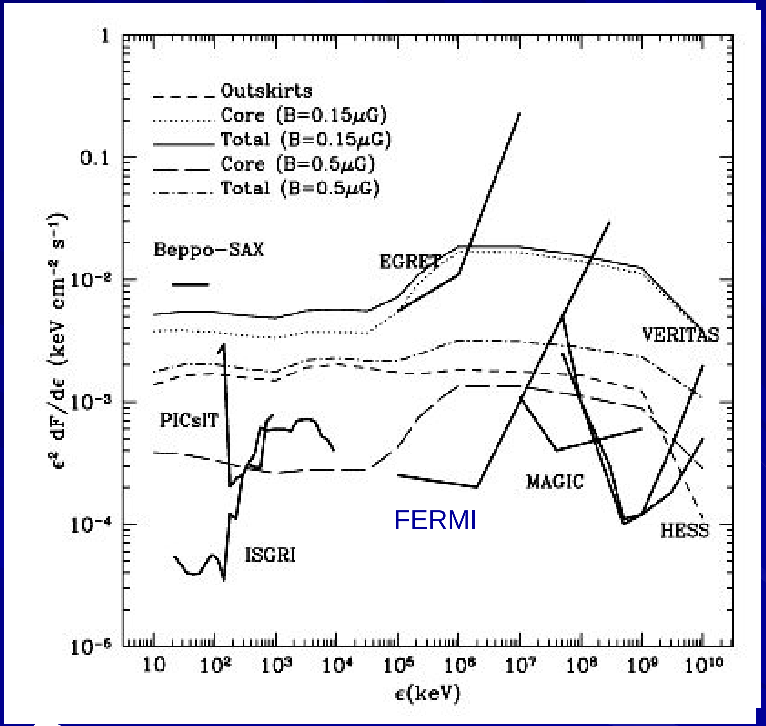
CRe



CRp

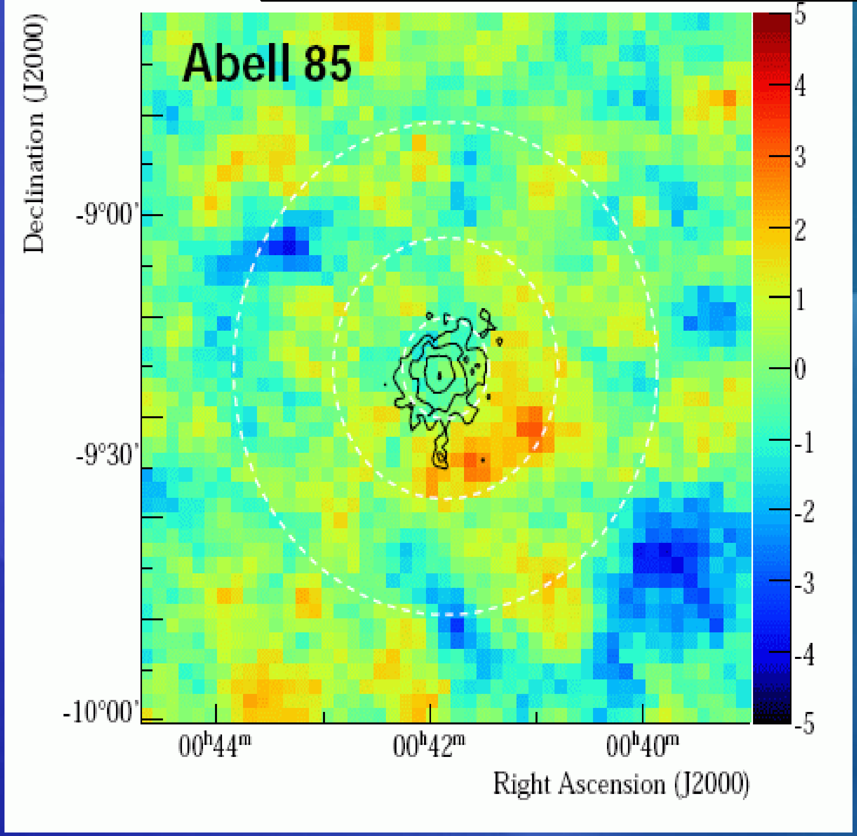


Miniati 2003



Limits & CRp content

Aharonian et al. 2009



H.E.S.S.

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

Coma : Ecr/Eth < 12%

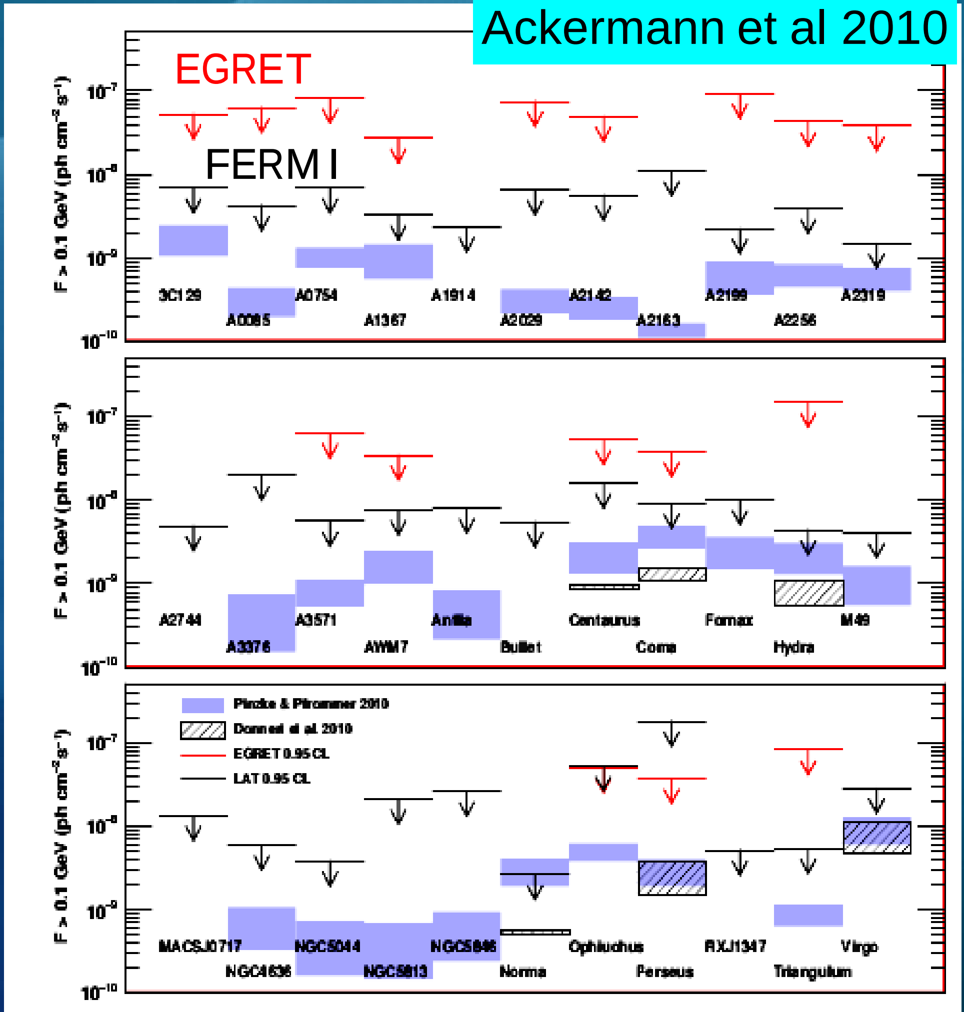
VERITAS (Perkins +al. 2008)

Coma : Ecr/Eth < 5-10% (hard spectra)

MAGIC (Aleksic +al. 10, 12)

Perseus : Ecr/Eth < 3% (hard spectra)

Ackermann et al 2010

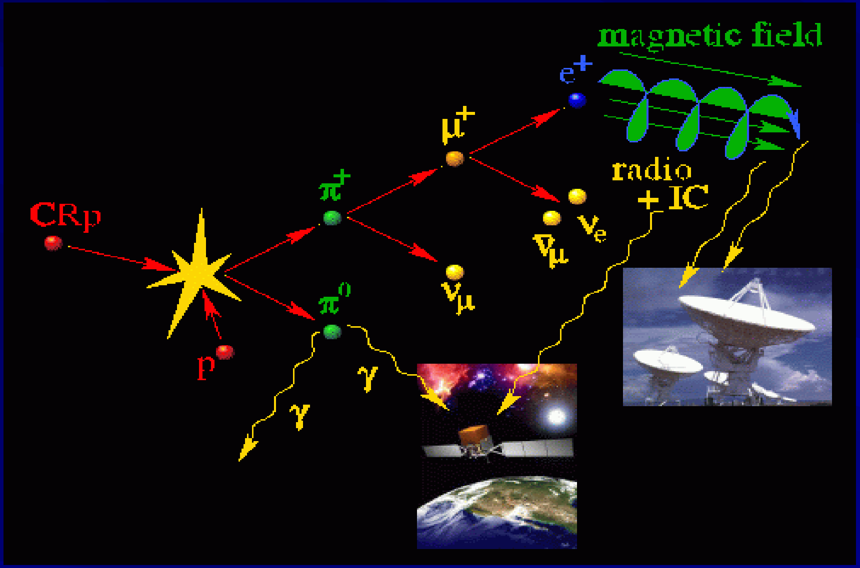


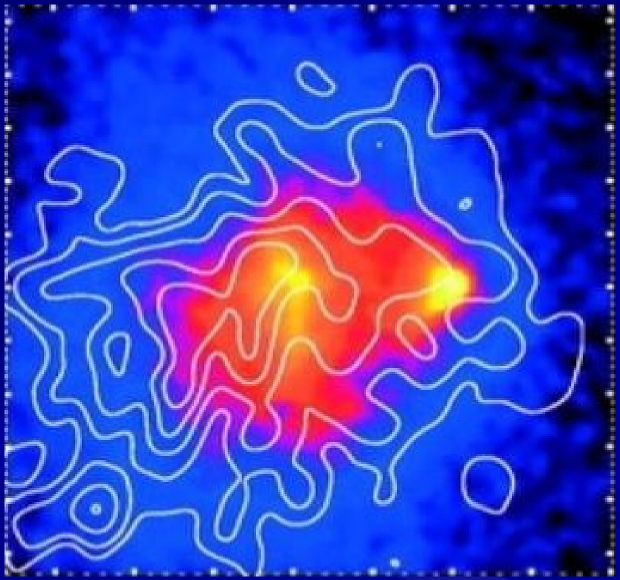
FERMI-LAT u.l. imply Ecr/Eth < 5%
(assuming Ecr~Eth)

Do CRp generate Radio Halos ?

(Dennison 80, Blasi & Colafrancesco 99, Ensslin & Pfrommer 04, ...)

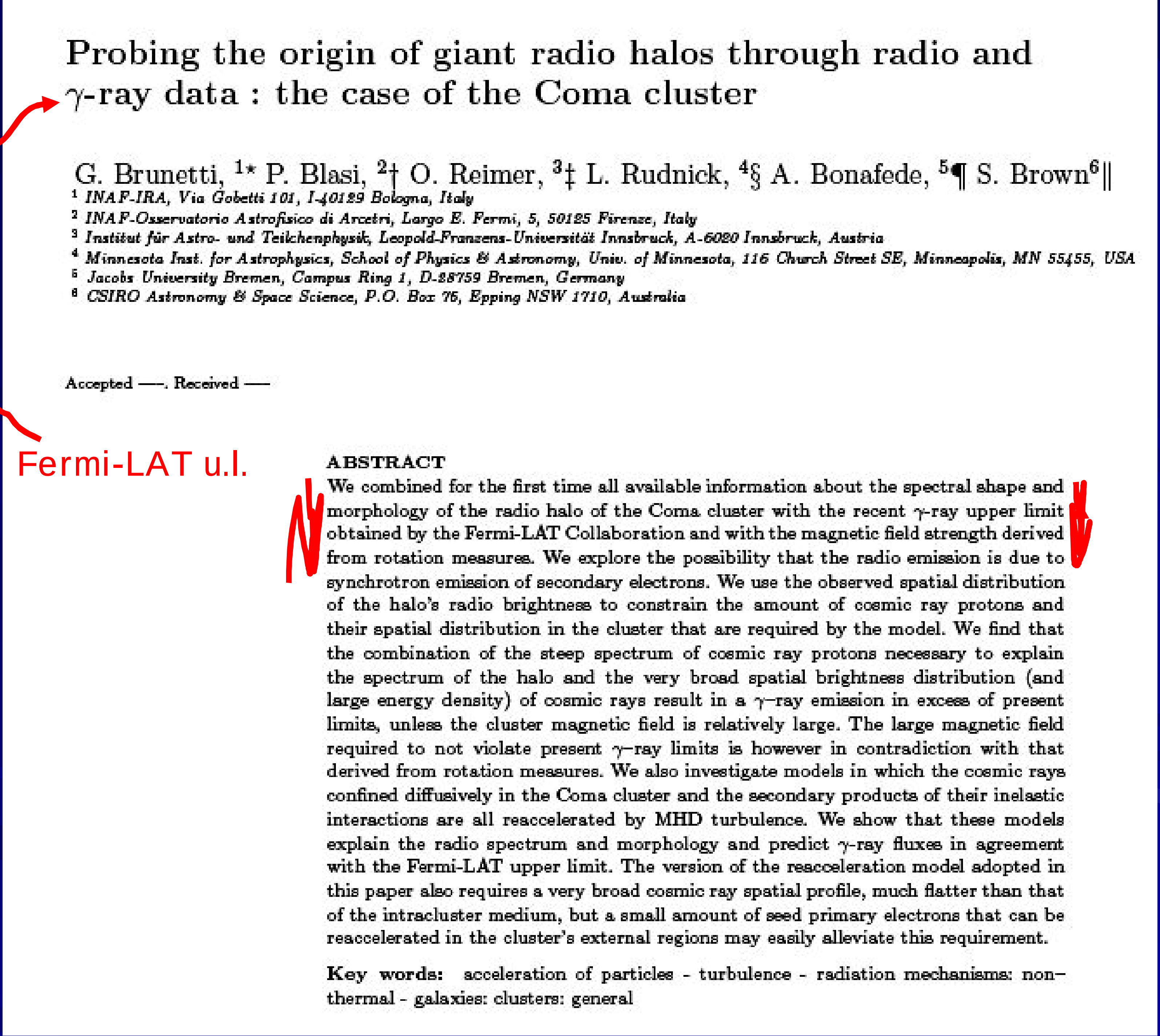
$$L_{\gamma,\pi} \sim f_{\gamma}(\delta) \langle E_{CR}\rangle \langle E_{th}/T\rangle V_{\gamma}$$





$$L_{syn} \sim f_{1}(\delta) \langle E_{CR}\rangle \langle E_{th}/T\rangle V_{syn}\, B^{(1+\delta/2)}(B^{2}+B_{cmb}^{2})^{-1}$$

$L_{Syn}/L_{\gamma,\pi}$ --> $\langle B^{\delta/2+1}/(B^{2}+B_{cmb}^{2})\rangle$_(emission weighted)



Probing the origin of giant radio halos through radio and γ-ray data : the case of the Coma cluster

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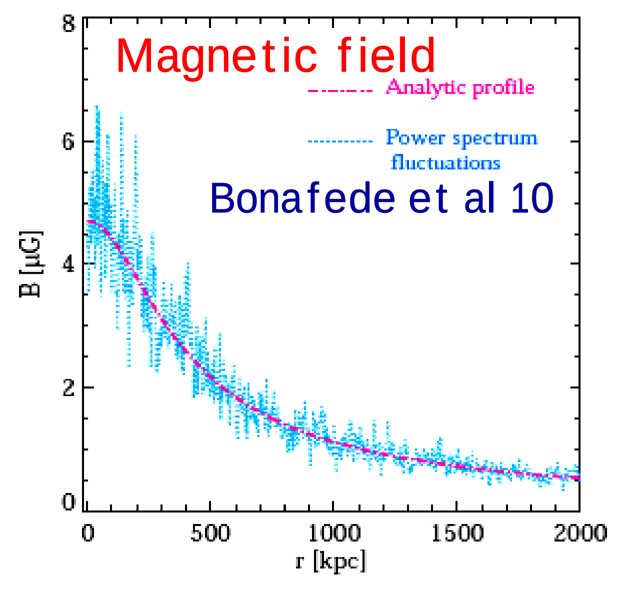
Accepted —. Received —

Fermi-LAT u.l.

ABSTRACT

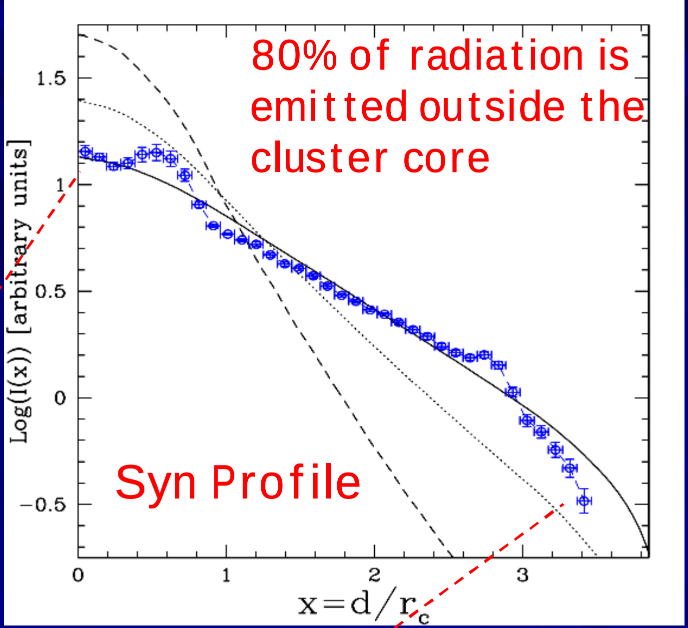
We combined for the first time all available information about the spectral shape and morphology of the radio halo of the Coma cluster with the recent γ-ray upper limit obtained by the Fermi-LAT Collaboration and with the magnetic field strength derived from rotation measures. We explore the possibility that the radio emission is due to synchrotron emission of secondary electrons. We use the observed spatial distribution of the halo's radio brightness to constrain the amount of cosmic ray protons and their spatial distribution in the cluster that are required by the model. We find that the combination of the steep spectrum of cosmic ray protons necessary to explain the spectrum of the halo and the very broad spatial brightness distribution (and large energy density) of cosmic rays result in a γ−ray emission in excess of present limits, unless the cluster magnetic field is relatively large. The large magnetic field required to not violate present γ−ray limits is however in contradiction with that derived from rotation measures. We also investigate models in which the cosmic rays confined diffusively in the Coma cluster and the secondary products of their inelastic interactions are all reaccelerated by MHD turbulence. We show that these models explain the radio spectrum and morphology and predict γ-ray fluxes in agreement with the Fermi-LAT upper limit. The version of the reacceleration model adopted in this paper also requires a very broad cosmic ray spatial profile, much flatter than that of the intracluster medium, but a small amount of seed primary electrons that can be reaccelerated in the cluster's external regions may easily alleviate this requirement.

Key words: acceleration of particles - turbulence - radiation mechanisms: non–thermal - galaxies: clusters: general



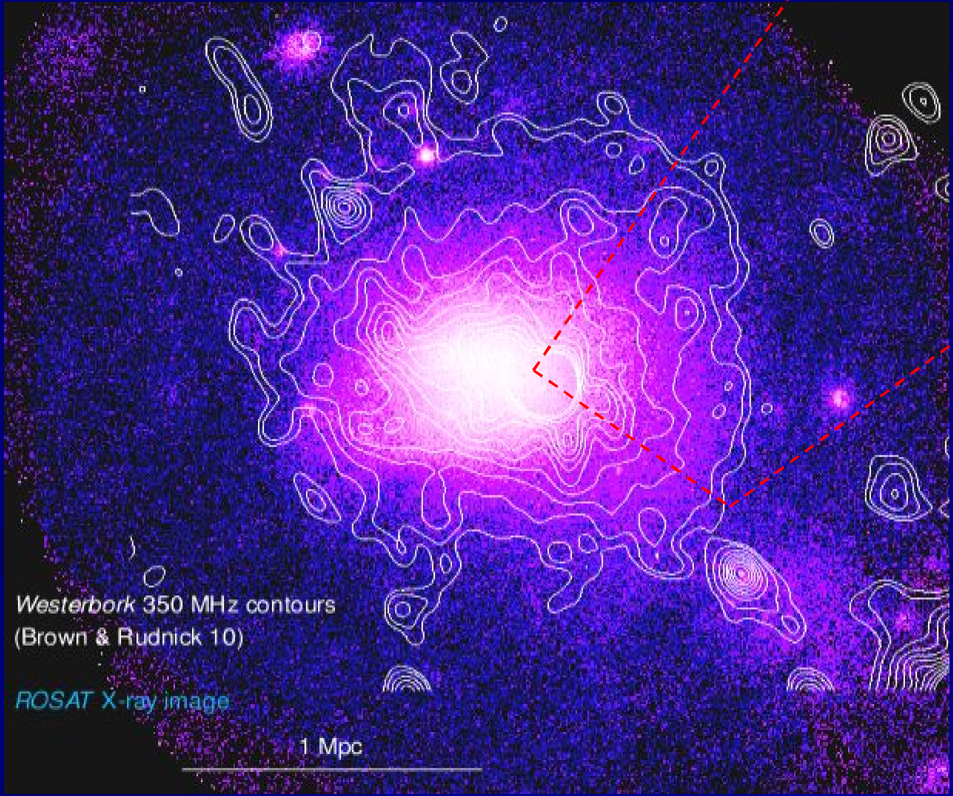
Magnetic field

Bonafede et al 10



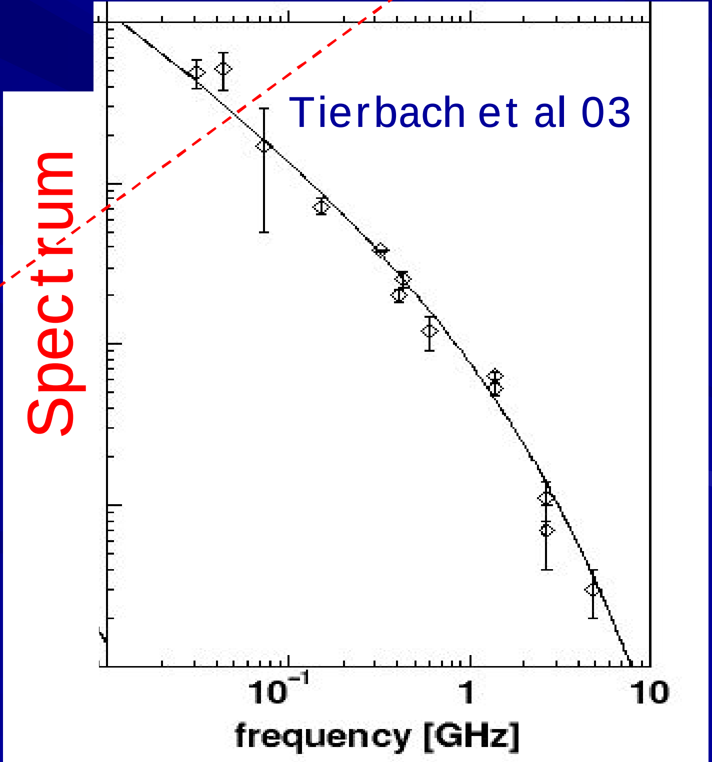
80% of radiation is emitted outside the cluster core

Syn Profile



Westerbork 350 MHz contours
(Brown & Rudnick 10)

ROSAT X-ray image



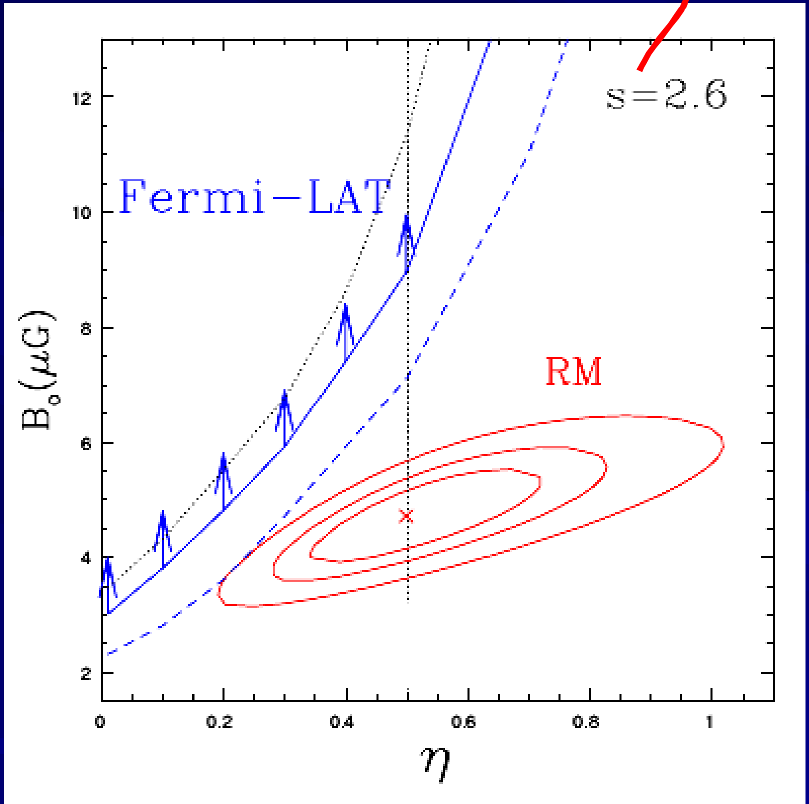
Spectrum

Tierbach et al 03

A hadronic origin for the Coma halo ? (GB +al 2012)

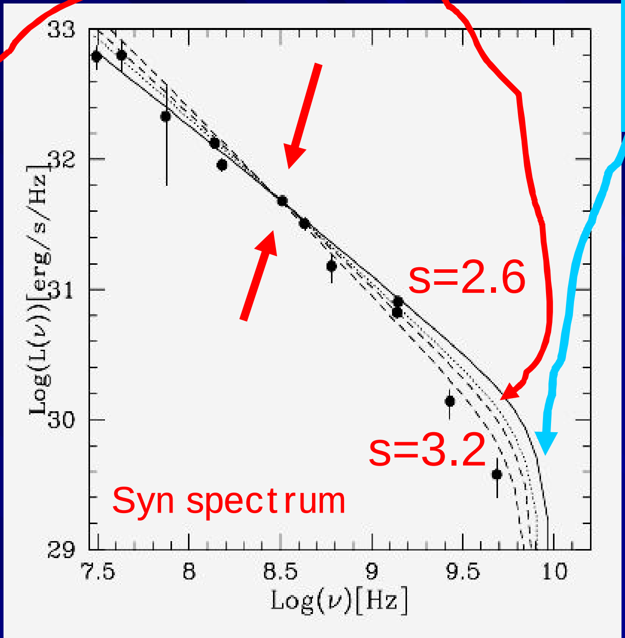
$$N_{cr}(p,r)=K(r)\,p^{-s}$$

$$B(r)=B_o(\epsilon_{TH}/\epsilon_o)^{\eta}$$



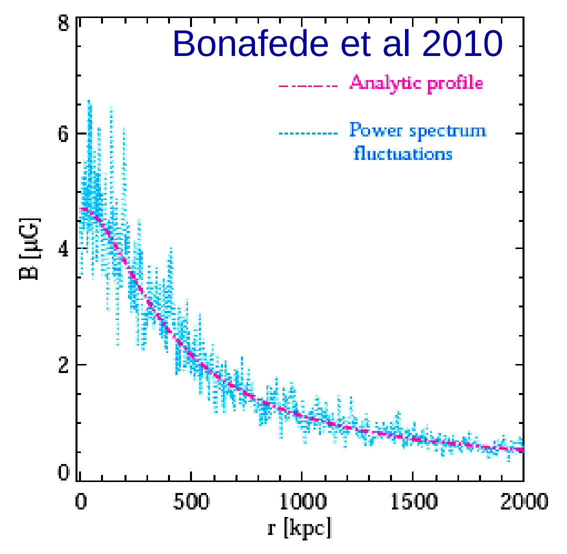
$$\sigma^2_{\rm RM}=\langle {\rm RM}^2\rangle = 812^2\Lambda_c\int (n_e B_{\parallel})^2 dl.$$

A signal ≈3 times larger would be expected in RM to reconcile Fermi-LAT limits with a "pure" hadronic origin of the RH



Cut-off in the observed spectrum due to SZ-decrement

Combining all (including RM) radio and γ-ray constraints we conclude that a scenario based on "pure"hadronic models appears disfavoured…..



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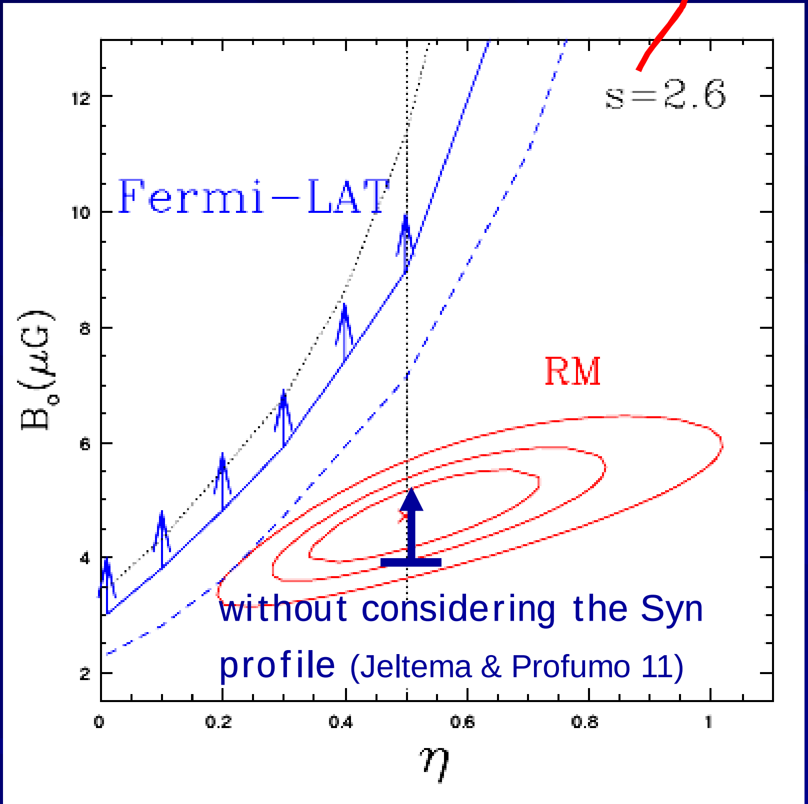
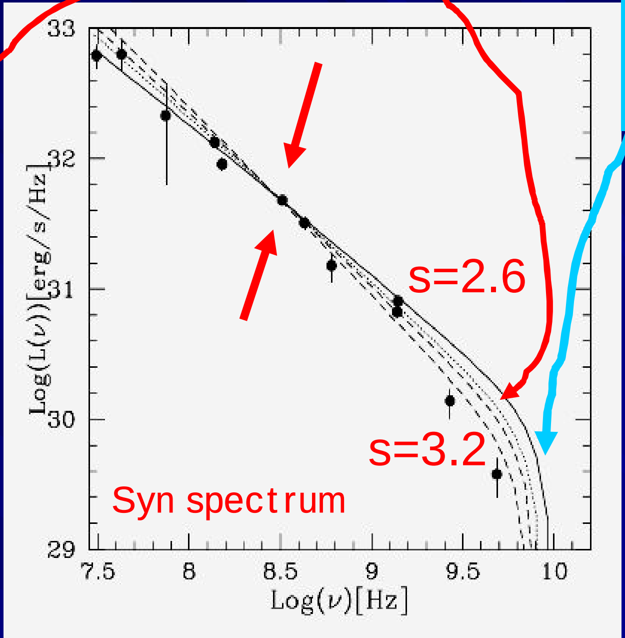


without considering the Syn profile (Jeltema & Profumo 11)

$$\sigma_{RM}^2=\langle RM^2\rangle = 812^2\Lambda_c\int (n_e B_{\|})^2\,dl.$$



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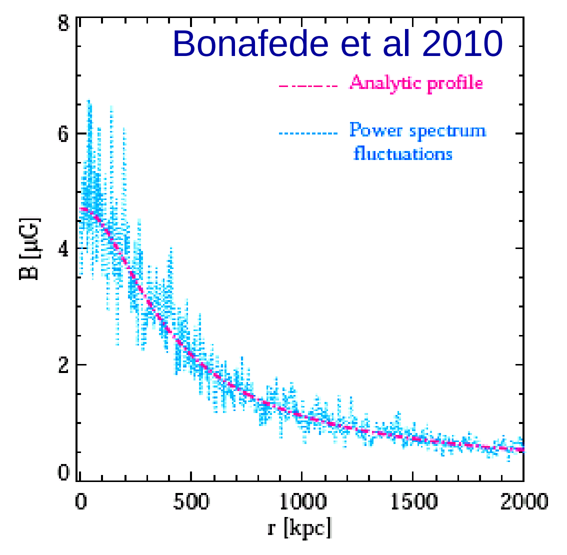

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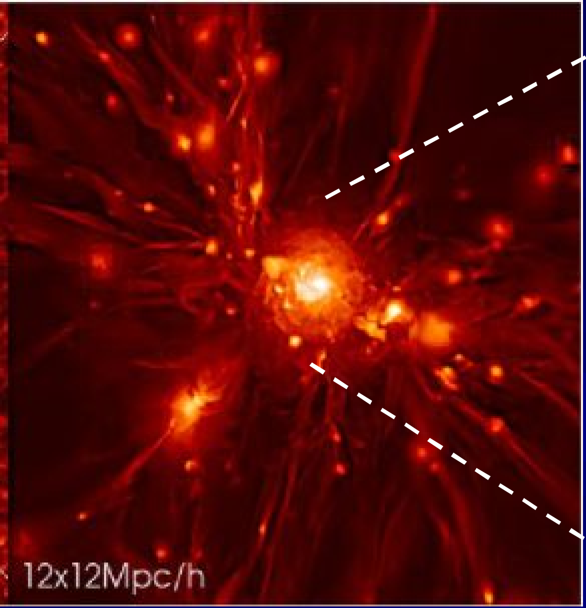
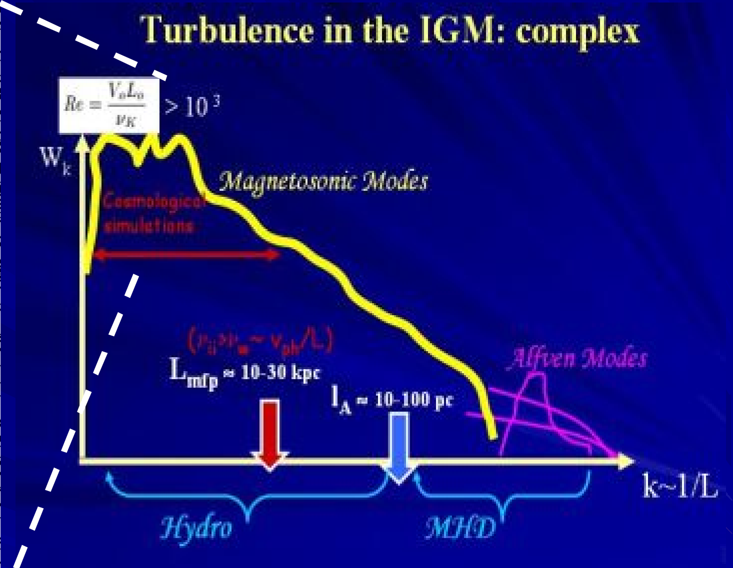
Does "merger-turbulence" generates Radio Halos?

(Brunetti et al. 01, 04, Petrosian 01, Liang et al 02, Kuo et al 02, Fujita et al. 03, Cassano & . Brunetti 05,Brunetti & Lazarian 07, 11, Petrosian & Bykov 08, ZuHone et al 12)



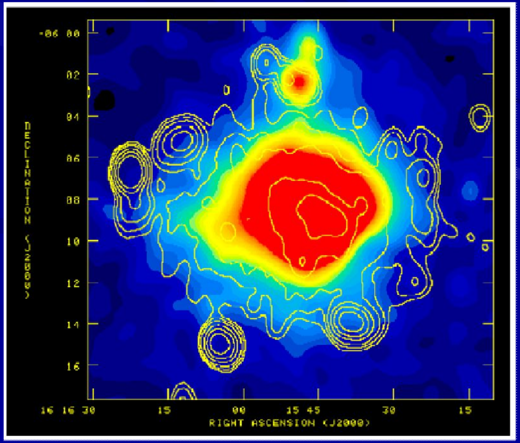


Turbulent properties & fraction of turbulent energy-flux in CR ?
(dampings & effective plasma collisionality...)

Back reaction of CR on turbulence ?
(properties of micro-turbulence/kinetic instabilities..)

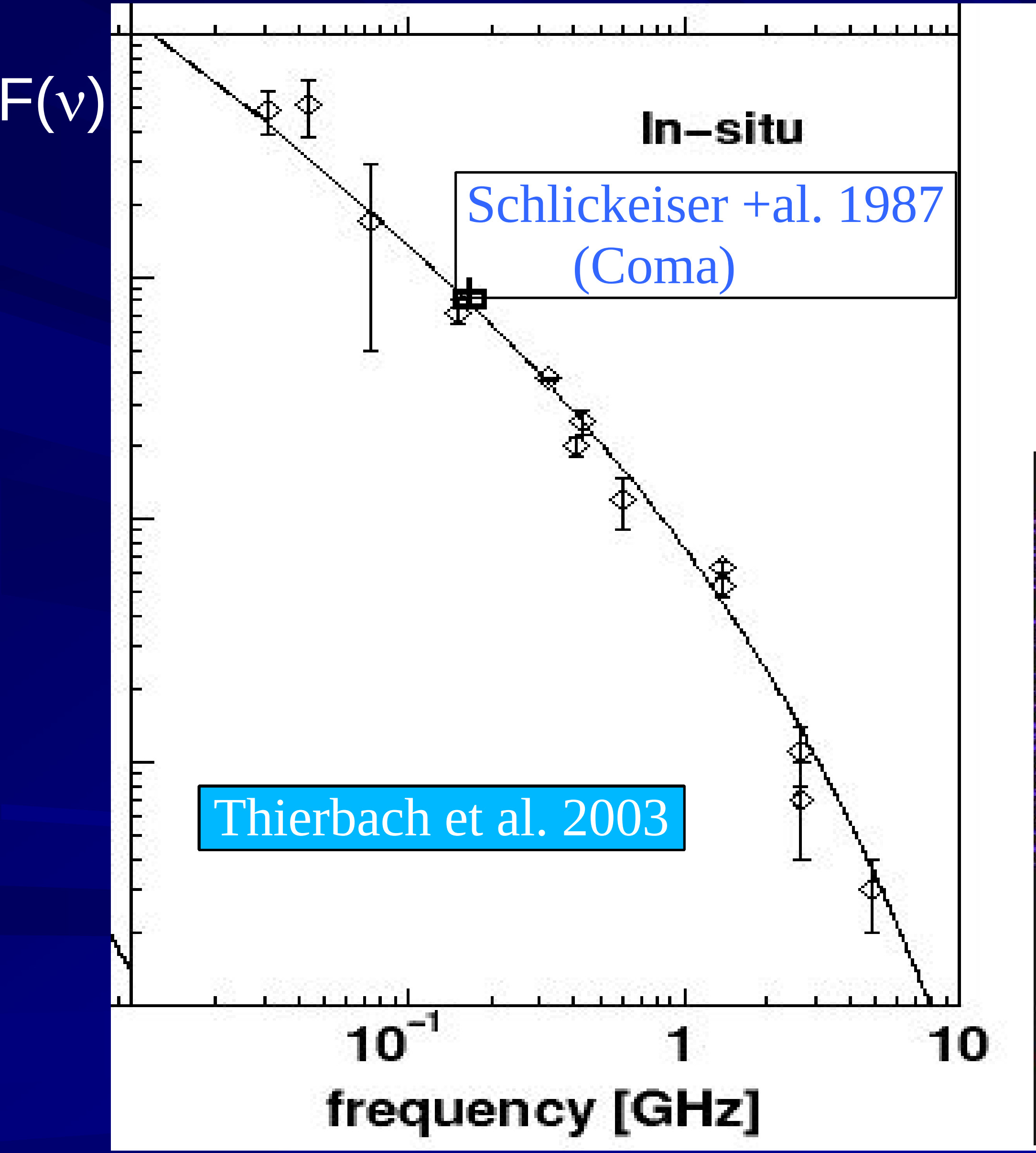
Seeds particles to reaccelerate ?
(difficulty in accelerating thermal ICM)

Role of reconnection in the ICM ?



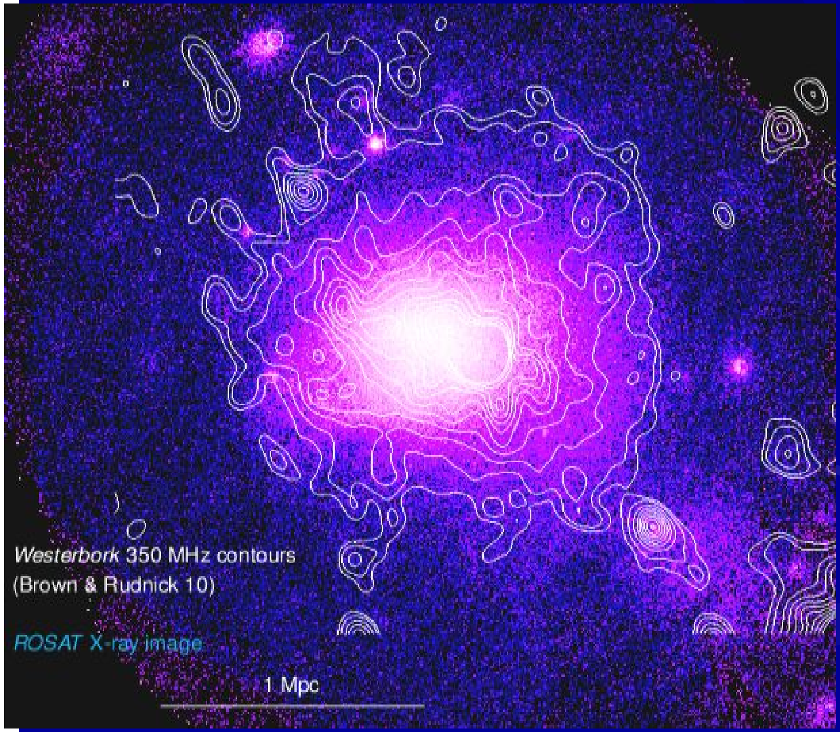
rev. Petrosian & Bykov 08, Brunetti 11,12, Lazarian & Brunetti 11

Original “phenomenological” motivation for turbulence

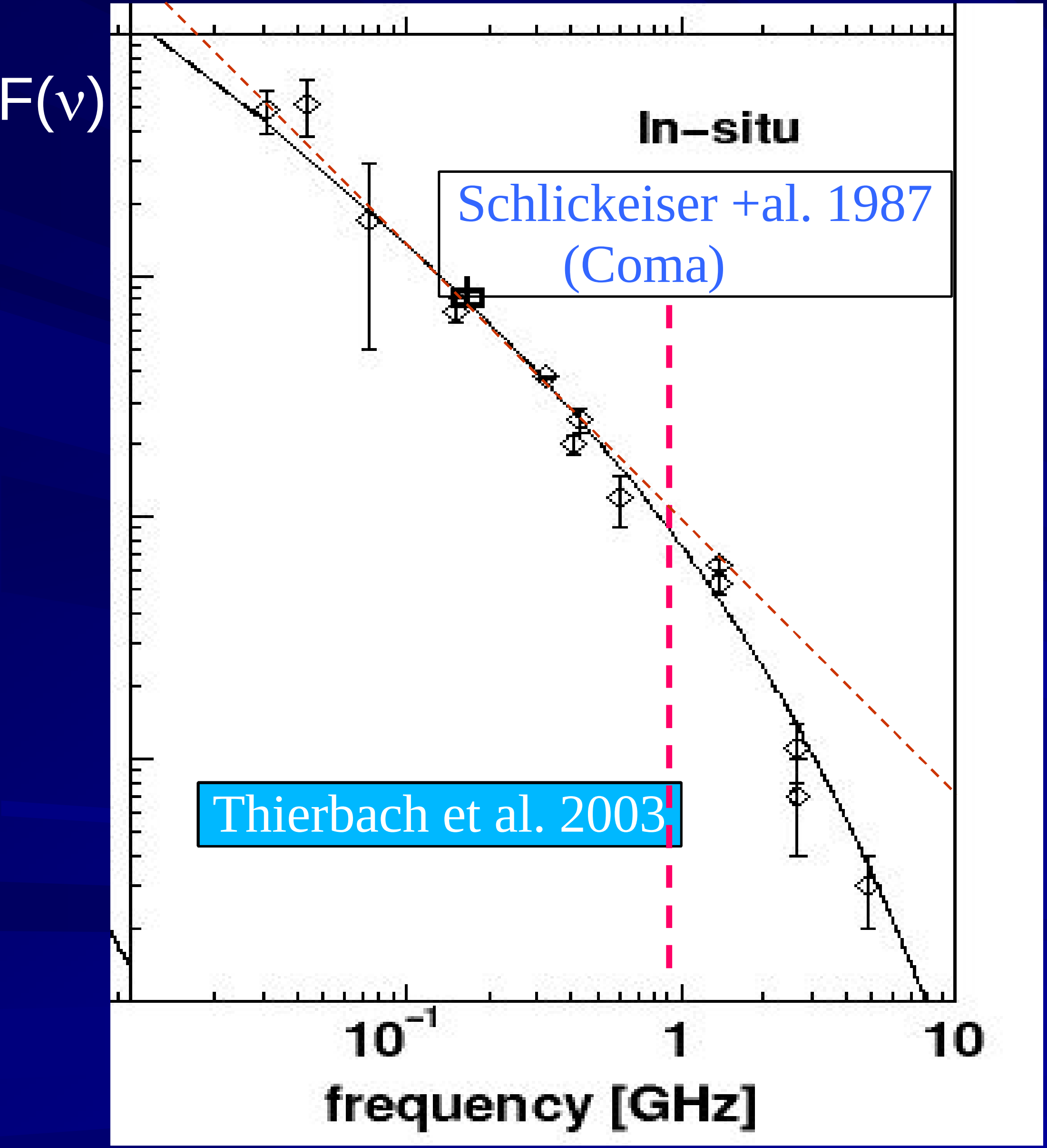


Schlickeiser +al. 1987
(Coma)

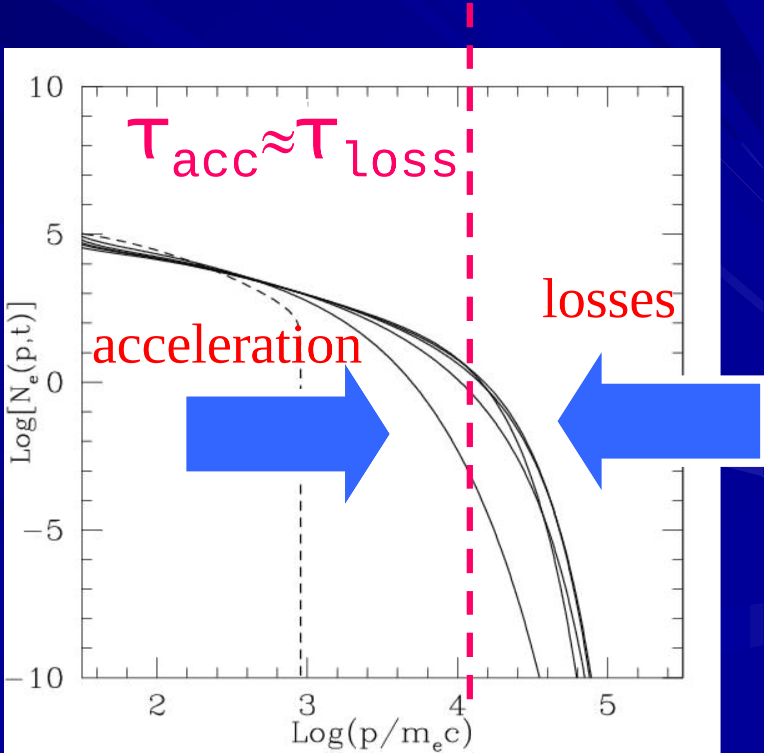
Thierbach et al. 2003



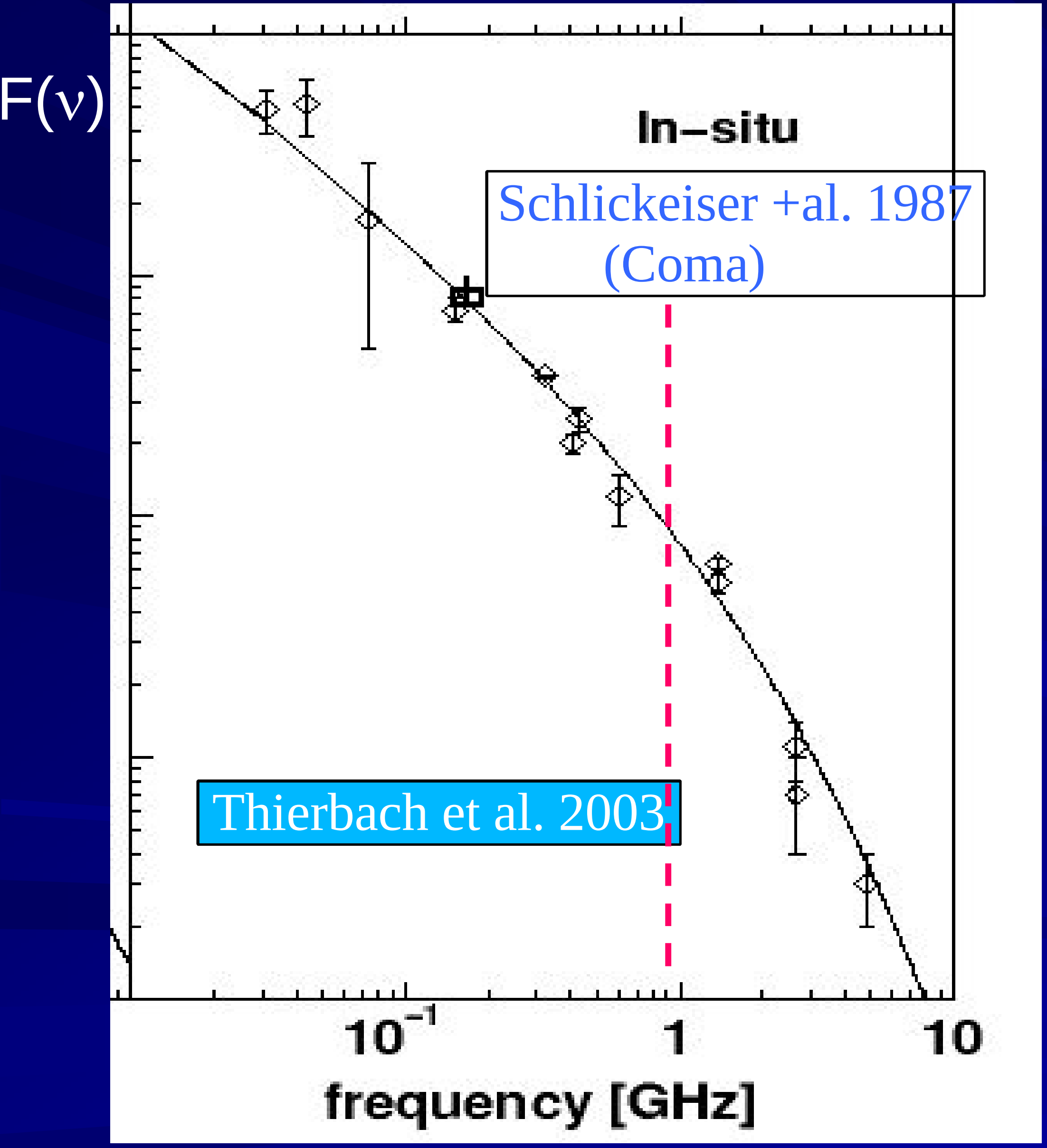
Radio Halos : are they generated by “inefficient” mechanism of CRe acceleration ?



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



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

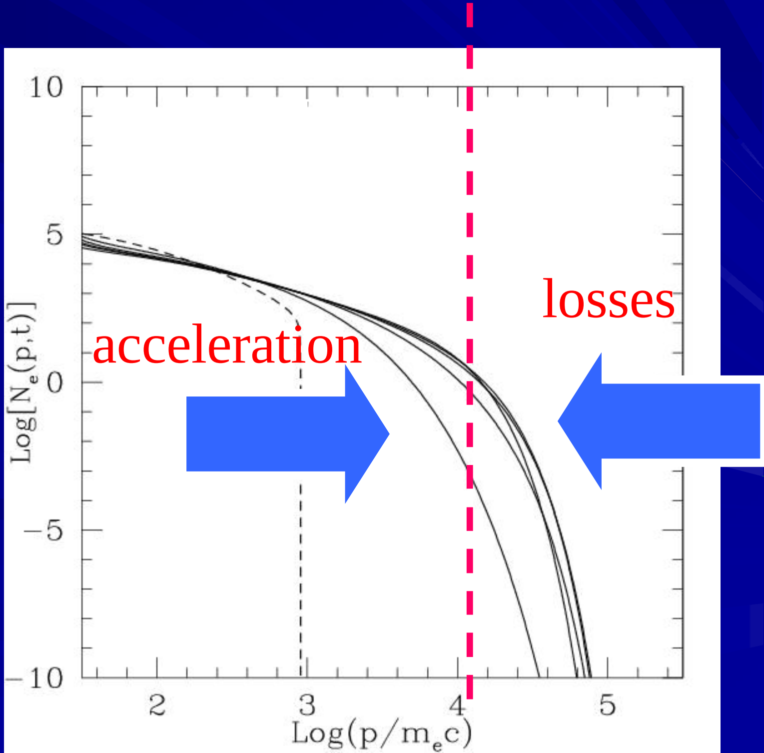


Schlickeiser +al. 1987 (Coma)

Thierbach et al. 2003

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

Acceleration time-scale $\approx 10^8$ years



acceleration

losses

Does turbulence alleviate problems with γ-rays in a “hadronic-based” scenario ?

Monthly Notices
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Mon. Not. R. Astron. Soc. 410, 127–142 (2011) doi:10.1111/j.1365-2966.2010.17457.x

Acceleration of primary and secondary particles in galaxy clusters by compressible MHD turbulence: from radio haloes to gamma-rays

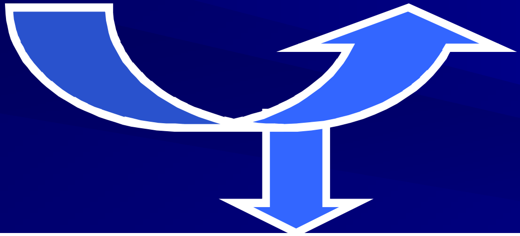
G. Brunetti[1]★ and A. Lazarian[2]

[1] INAF/Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
[2] Department of Astronomy, University of Wisconsin at Madison, 5534 Sterling Hall, 475 North Charter Street, Madison, WI 53706, USA

Accepted 2010 July 26. Received 2010 July 26; in original form 2010 June 29

see also GB+Blasi 2005 MNRAS 363 1173

n_{th}, T, B_o + $N_p(p)$ + I(k) *driven by cluster-cluster mergers*



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

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

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

This “hybrid” approach uses the physics insight behind the concept of CRp confinement and production of secondary CRe in the ICM and calculates the energization and modification of the spectrum of both CRp and CRe due to stochastic reacceleration in the presence of MHD turbulence.

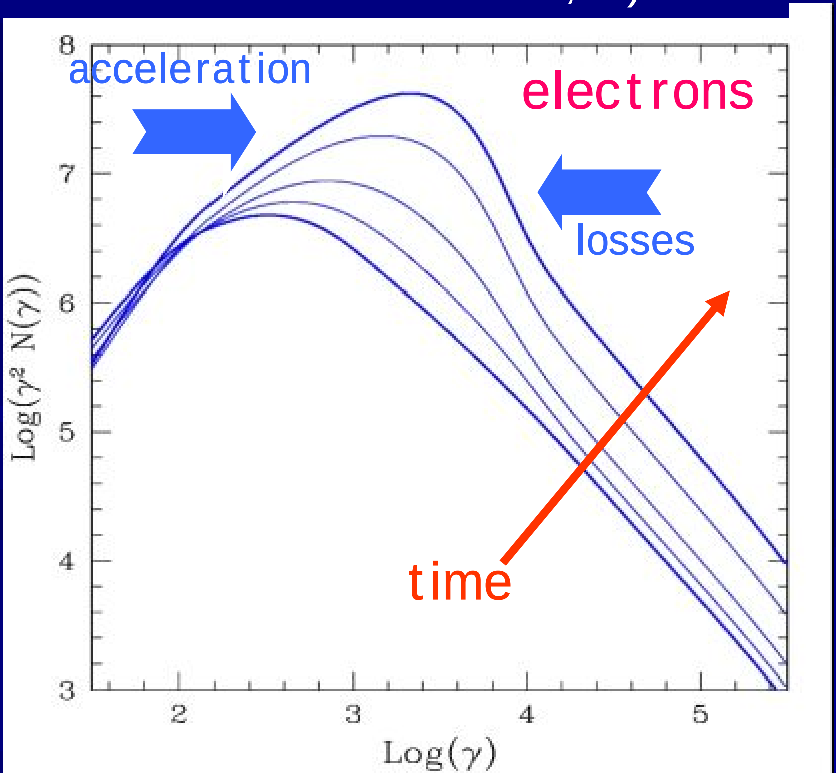
For I(k)=0 this is a “pure” secondary model.

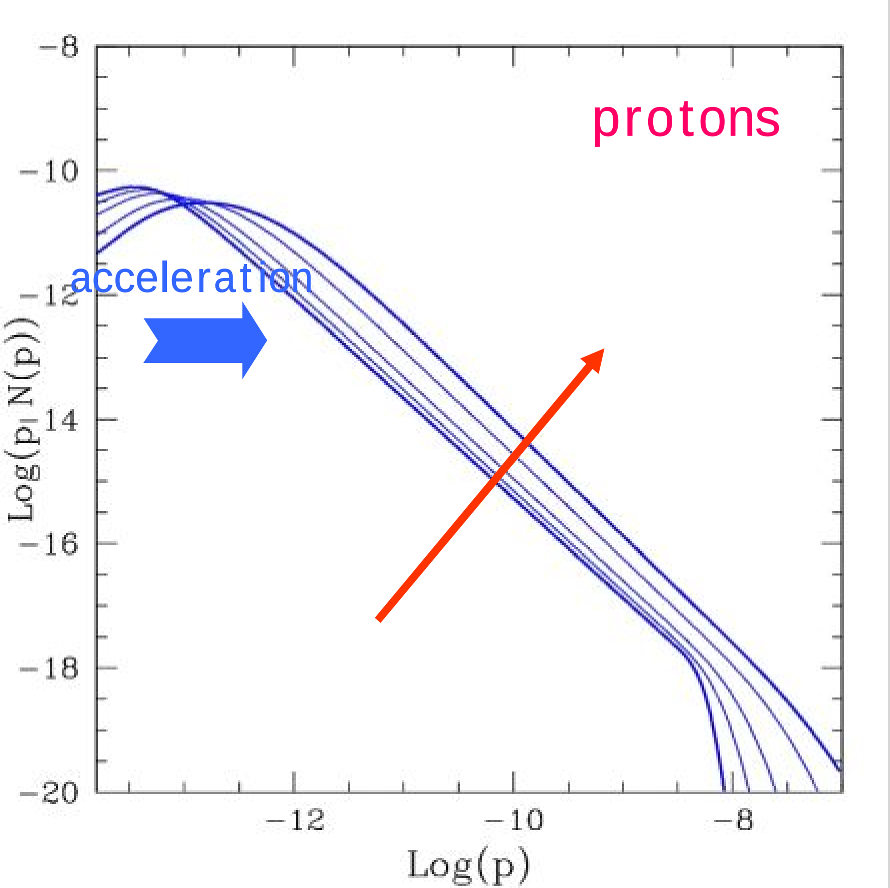
Transit Time Damping (TTD)

$$\omega - k_{//} v_{//} = 0$$

Interaction btw magnetic moment of particle and parallel gradient of B

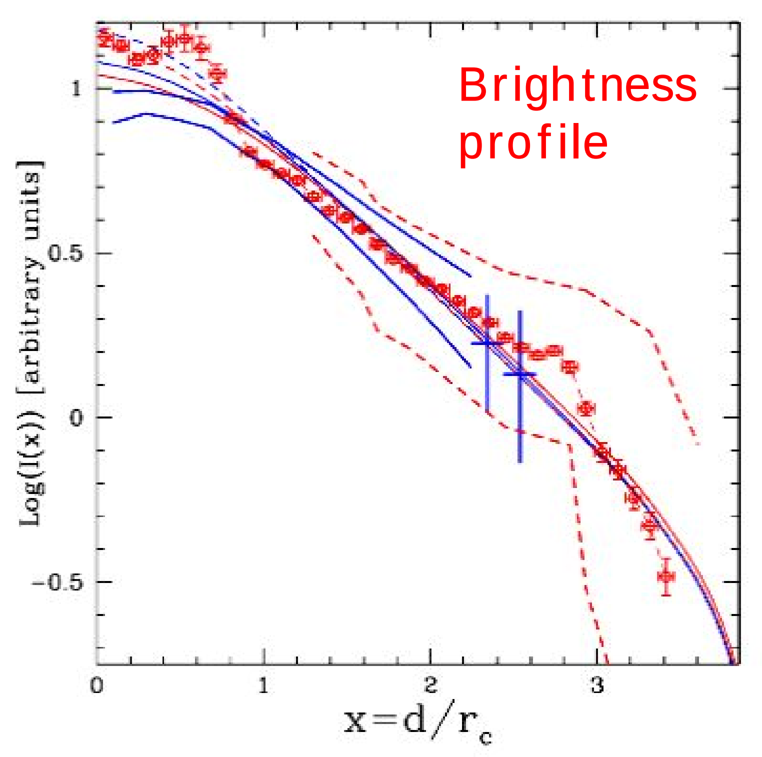
Suitable for ICM !
Isotropic fast modes
(Cassano & Brunetti 05, Yan et al 10, Brunetti & Lazarian 07, 11)

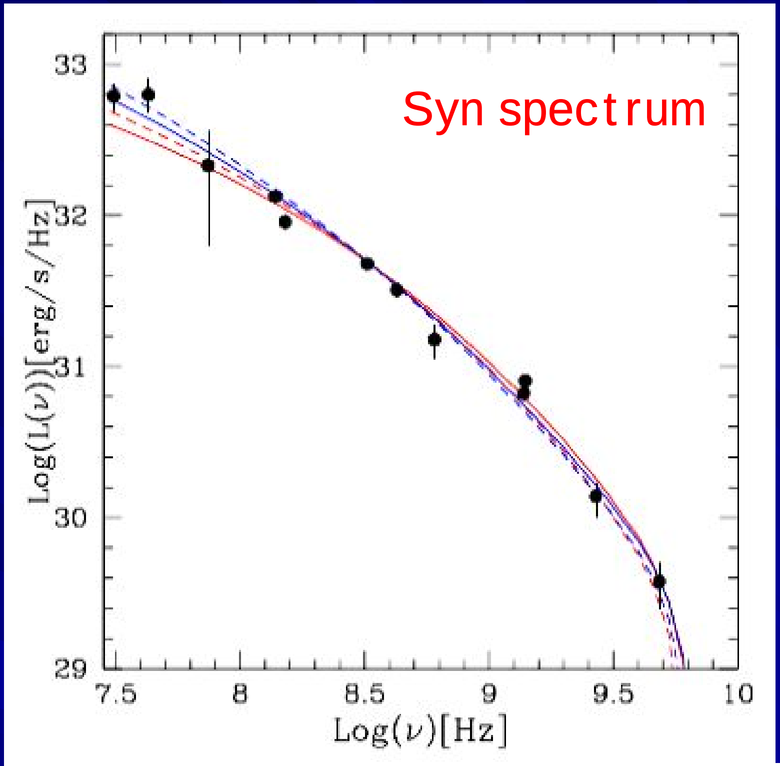




The modification of the electrons spectrum at energies of few GeV increases the ratio Syn/gamma and creates a curvature in the Syn spectrum at higher radio frequencies

Results from reacceleration (GB +al 2012, sub)



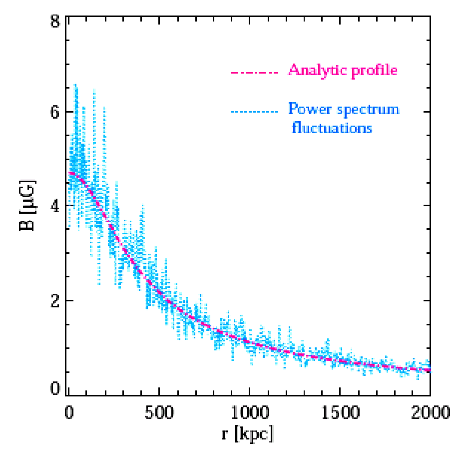


$\varepsilon_{CRp}/\varepsilon_{TH} \approx 0.05$

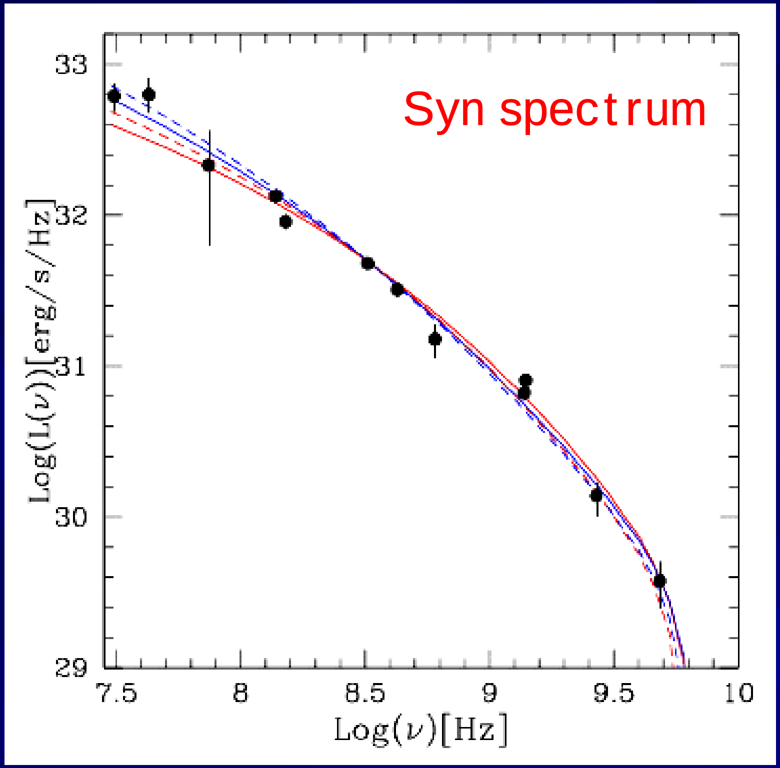
(flat CRp profile on RH-scale)

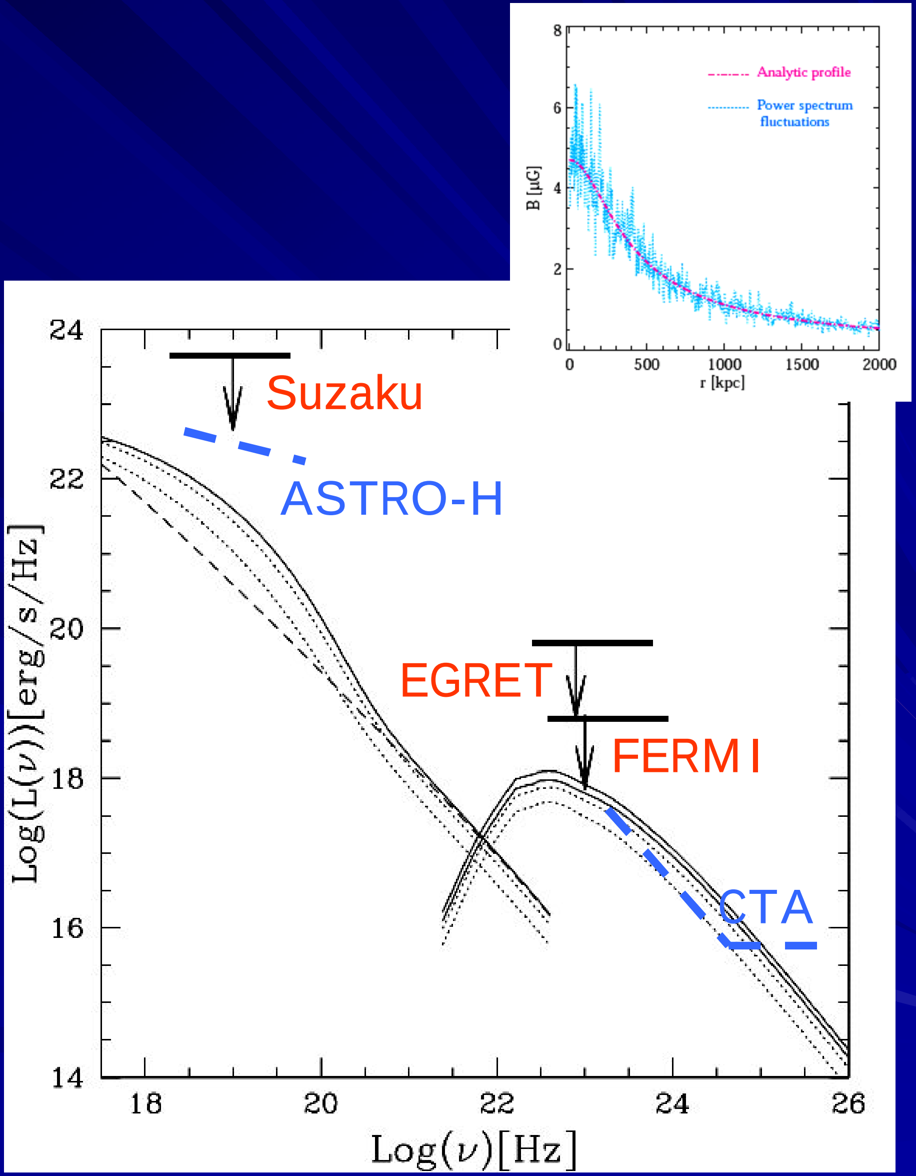
$(\delta V_l)^2 / c_s^2 \approx 0.05$

(on l=30 kpc scale, 0.15-0.2 on RH-scale)



Results from reacceleration (GB +al 2012, sub)





$\varepsilon_{CRp}/\varepsilon_{TH} \approx 0.05$

(flat CRp profile on RH-scale)

$(\delta V_l)^2/c_s^2 \approx 0.05$

(on l=30 kpc scale, 0.15-0.2 on RH-scale)

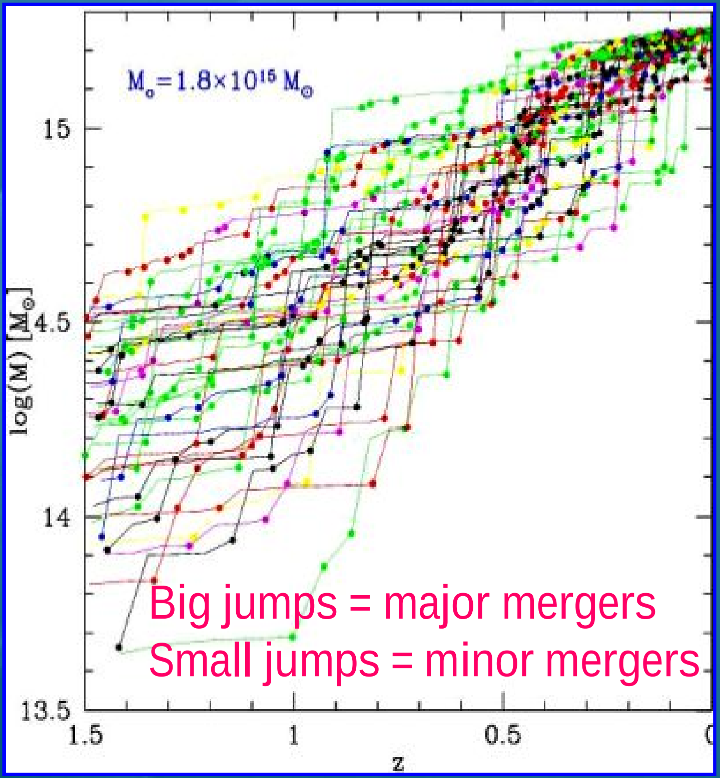
Testing turbulent models ??

Acceleration efficiency

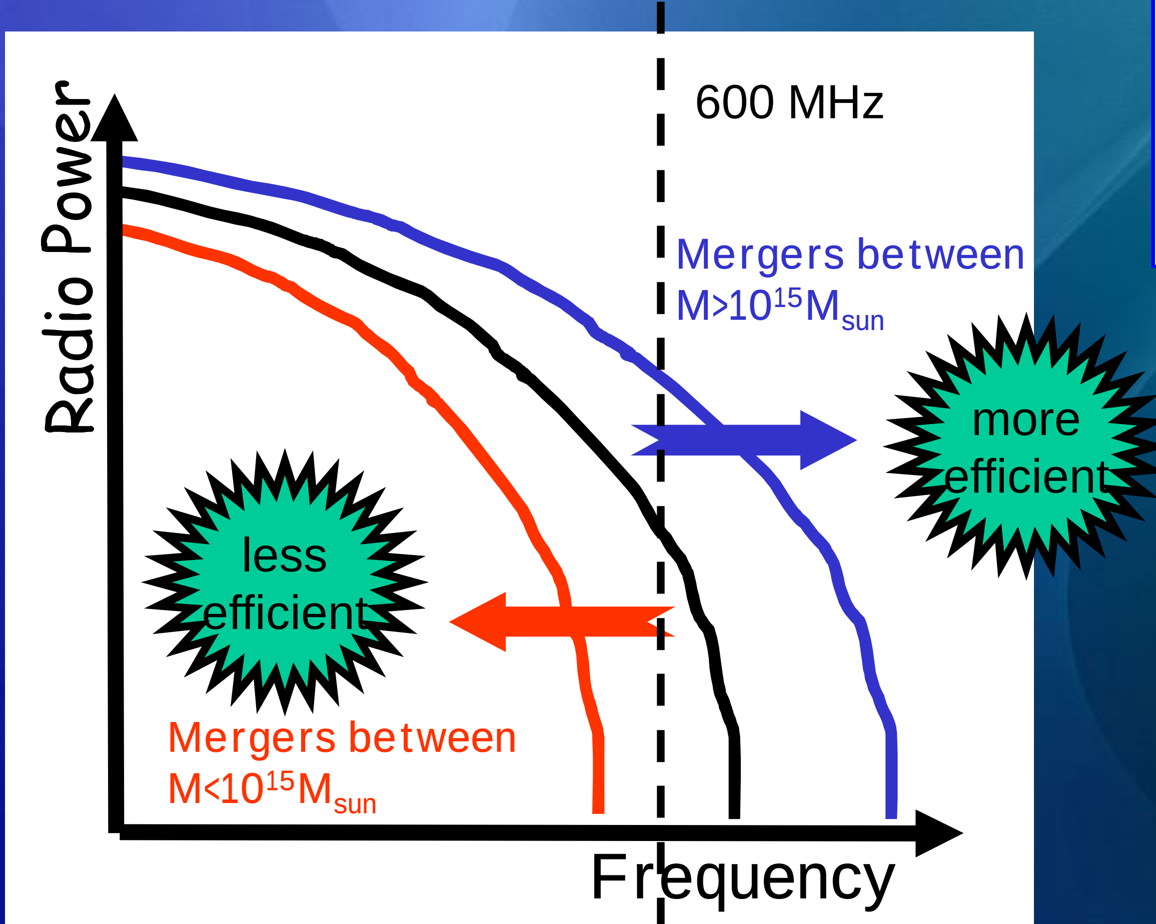
$$\chi \approx 1/\tau_{acc}$$

Steepening frequency

$$\nu_b \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$



Big jumps = major mergers
Small jumps = minor mergers

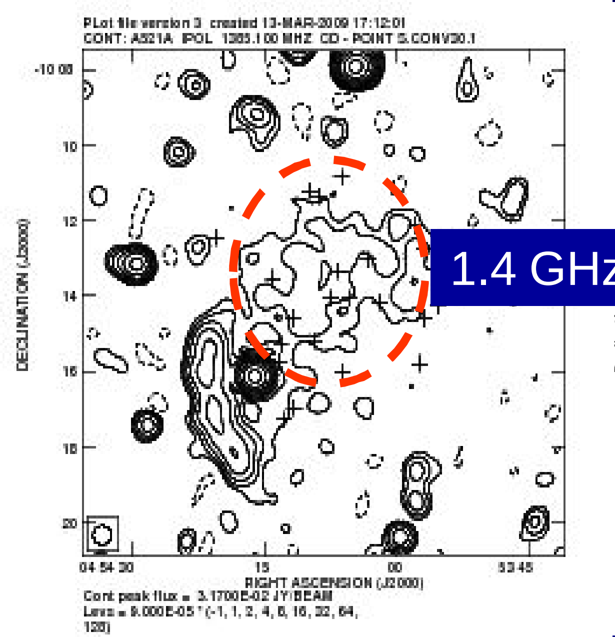


Radio Halos with very steep spectrum in the classical radio band must exist

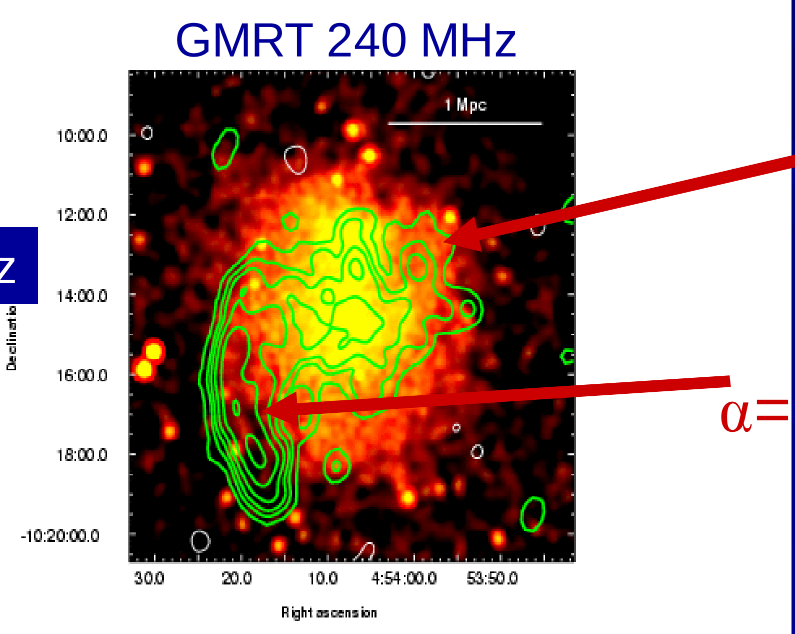
(Cassano, GB, Setti 06)

Turbulent acceleration?

Brunetti +al 2008, *Nature 455, 944*



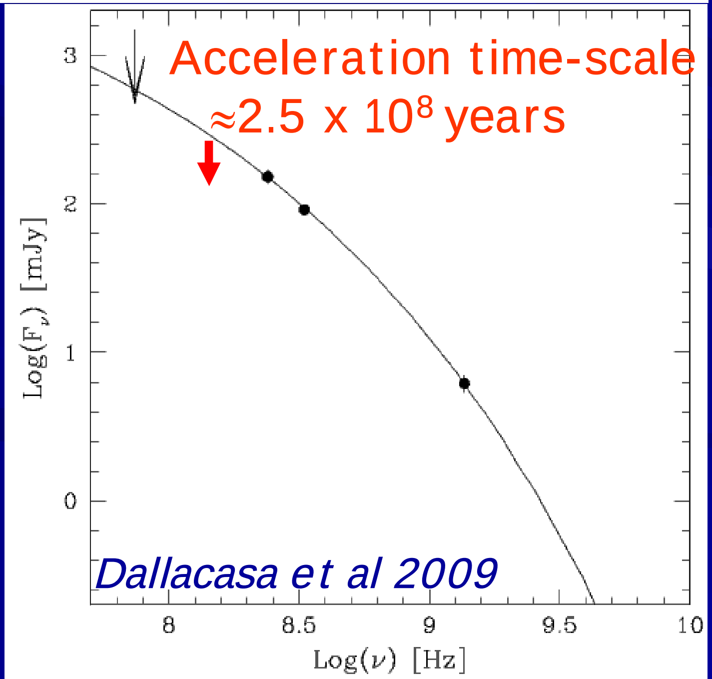
1.4 GHz



$\alpha=1.9$

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

$\alpha=1.4$



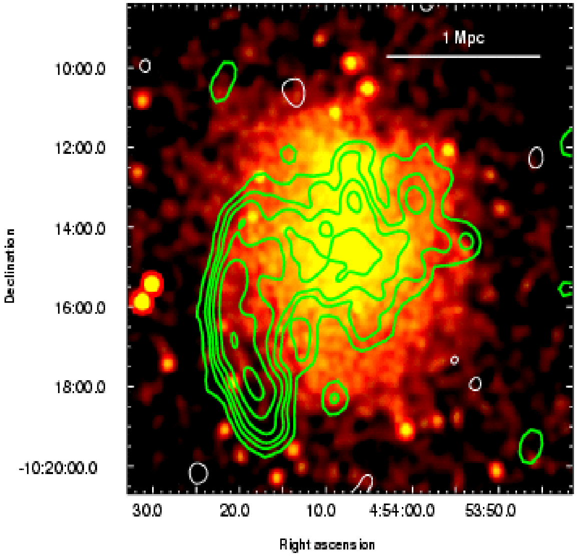
Acceleration time-scale $\approx 2.5 \times 10^8$ years

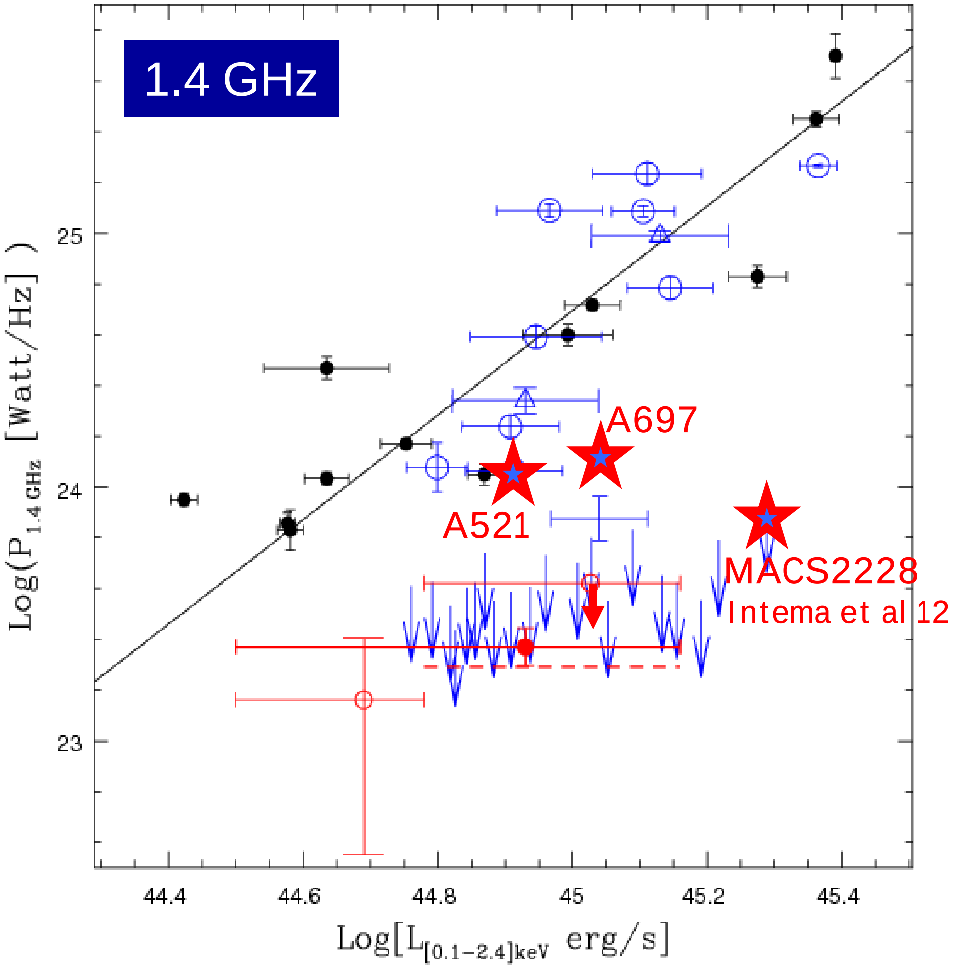
Dallacasa et al 2009

Turbulent acceleration?

Brunetti +al 2008, *Nature 455, 944*

GMRT 240 MHz

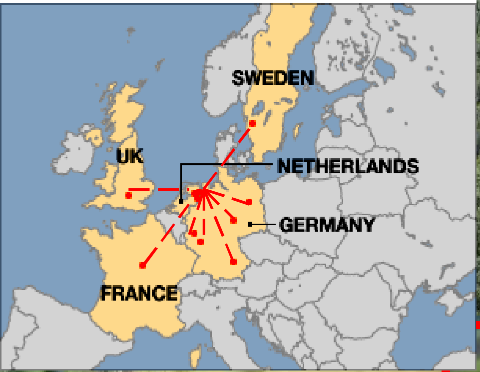




Several giant radio halos with ultra-steep spectrum have been discovered so far, they fill the transition region in the Psyn-Px diagram as expected by the reacceleration model

(see Cassano 10 A&A 517, 10).

International Lofar Stations




Tautemburg, Germany


Effelsberg, Germany

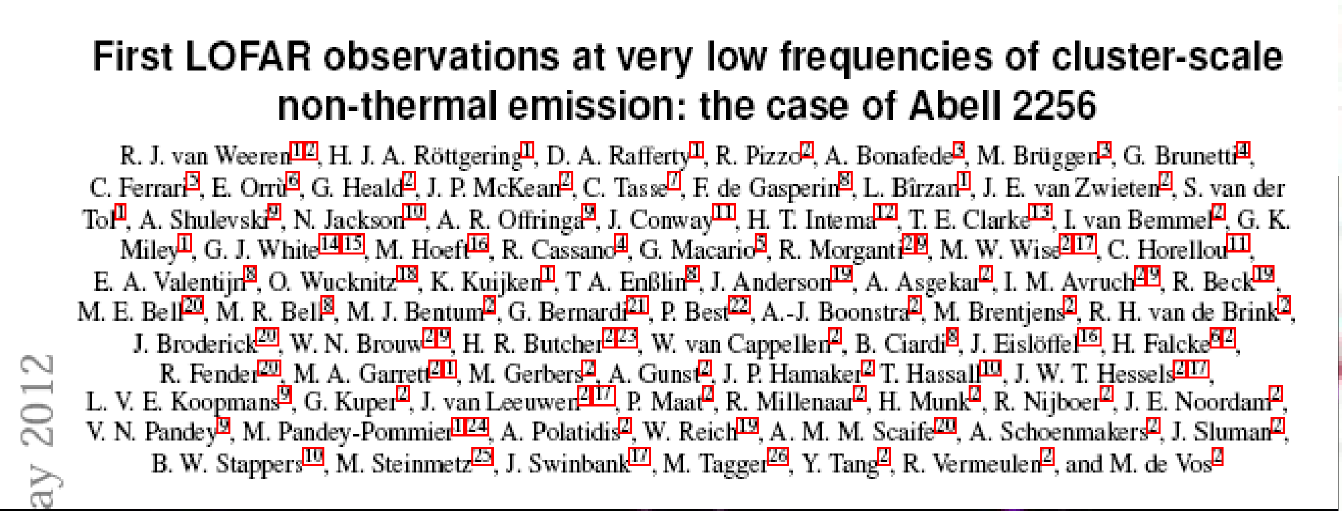

Onsala, Sweden


Chilbolton, UK


Receivers 15-80 MHz

LOFAR Core, Exloo, NL

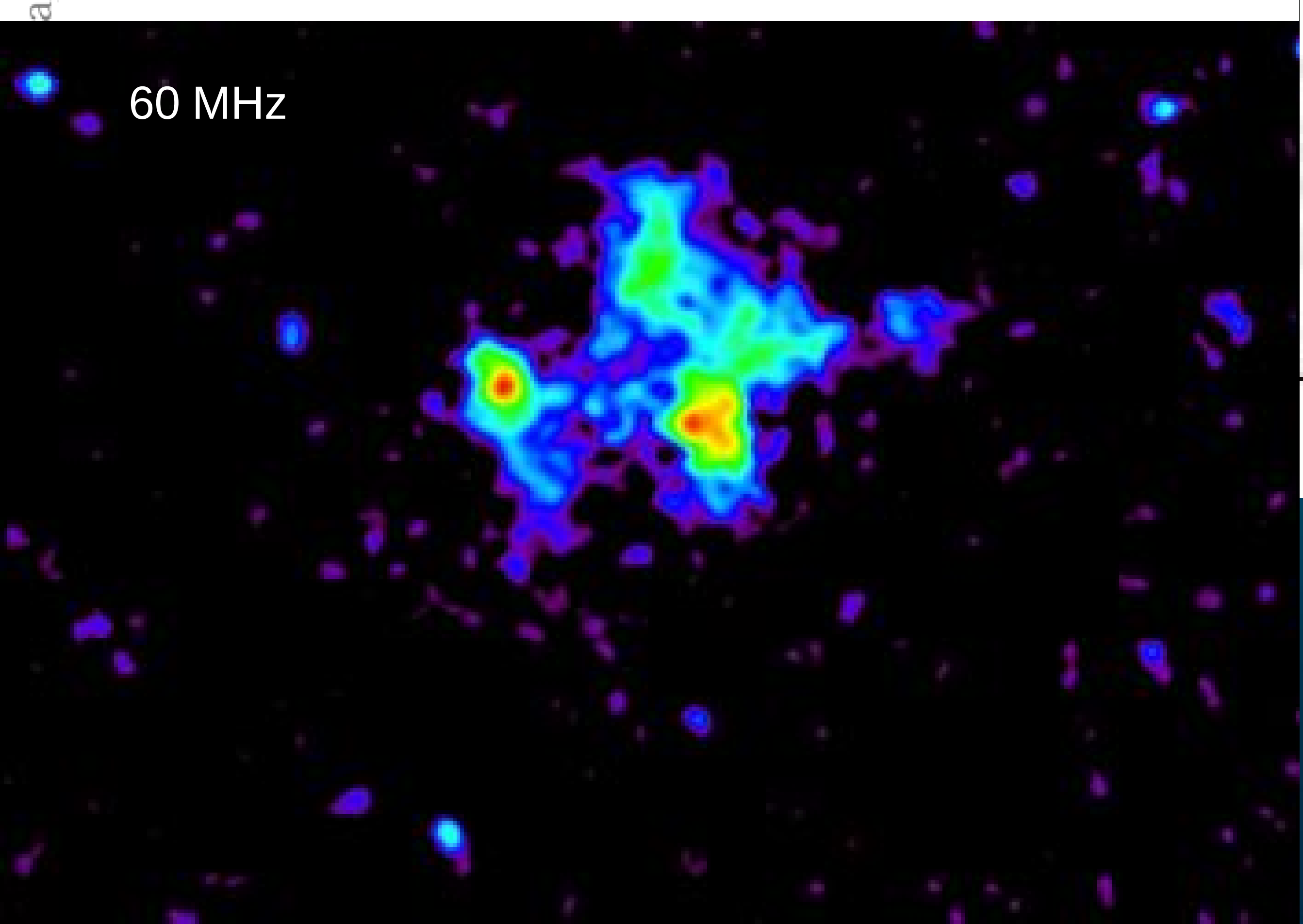
Receivers 110-240 MHz



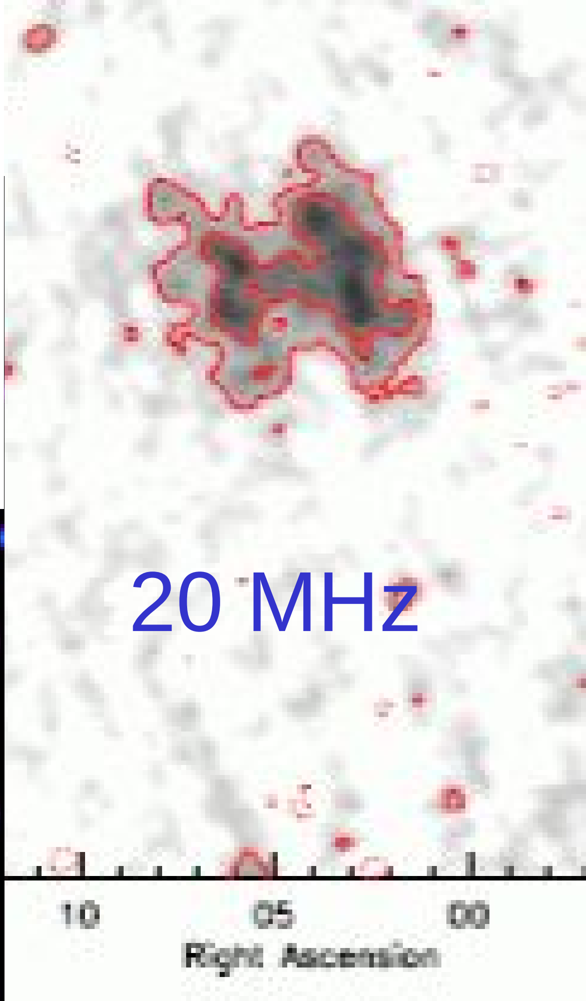
First LOFAR observations at very low frequencies of cluster-scale non-thermal emission: the case of Abell 2256

R. J. van Weeren[1,2], H. J. A. Röttgering[1], D. A. Rafferty[1], R. Pizzo[2], A. Bonafede[3], M. Brüggen[3], G. Brunetti[4], C. Ferrari[5], E. Orrù[6], G. Heald[2], J. P. McKean[2], C. Tasse[7], F. de Gasperin[8], L. Bîrzan[1], J. E. van Zwieten[2], S. van der Tol[1], A. Shulevski[9], N. Jackson[10], A. R. Offringa[9], J. Conway[11], H. T. Intema[12], T. E. Clarke[13], I. van Bemmel[2], G. K. Miley[1], G. J. White[14,15], M. Hoeft[16], R. Cassano[4], G. Macario[5], R. Morganti[2,9], M. W. Wise[2,17], C. Horellou[11], E. A. Valentijn[8], O. Wucknitz[18], K. Kuijken[1], T A. Enßlin[8], J. Anderson[19], A. Asgekar[2], I. M. Avruch[2,9], R. Beck[19], M. E. Bell[20], M. R. Bell[8], M. J. Bentum[2], G. Bernardi[21], P. Best[22], A.-J. Boonstra[2], M. Brentjens[2], R. H. van de Brink[2], J. Broderick[20], W. N. Brouw[2,9], H. R. Butcher[2,23], W. van Cappellen[2], B. Ciardi[8], J. Eislöffel[16], H. Falcke[6,2], R. Fender[20], M. A. Garrett[2,1], M. Gerbers[2], A. Gunst[2], J. P. Hamaker[2] T. Hassall[10], J. W. T. Hessels[2,17], L. V. E. Koopmans[9], G. Kuper[2], J. van Leeuwen[2,17], P. Maat[2], R. Millenaar[2], H. Munk[2], R. Nijboer[2], J. E. Noordam[2], V. N. Pandey[9], M. Pandey-Pommier[1,24], A. Polatidis[2], W. Reich[19], A. M. M. Scaife[20], A. Schoenmakers[2], J. Sluman[2], B. W. Stappers[10], M. Steinmetz[25], J. Swinbank[17], M. Tagger[26], Y. Tang[2], R. Vermeulen[2], and M. de Vos[2]

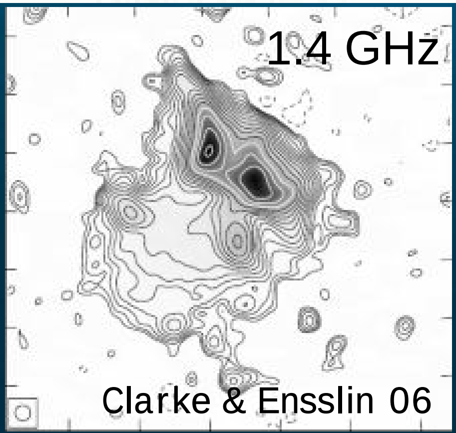
ay 2012



60 MHz



20 MHz



1.4 GHz

Clarke & Ensslin 06

Summary

(i) Clusters host many sources of CRp and CRe, evidence for (at least) CRe come from radio observations.
Clusters mergers (formation!) have a major impact on the non-thermal components and emission.

(ii) Gamma-ray u.l. and limits in the radio band constrain the energy content of CRp to few % of the clusters thermal ICM.

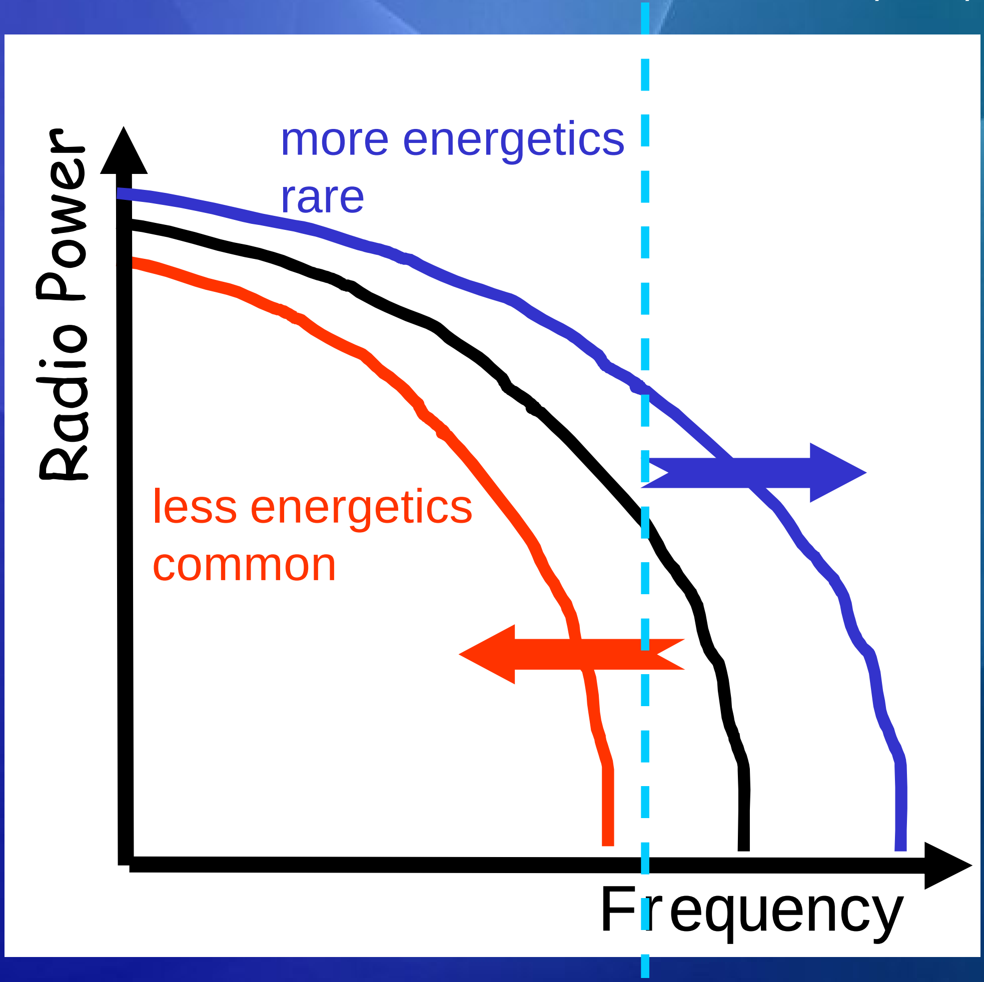
(iii) Gamma ray u.l. provide new constraints for the origin of giant radio halos. When combined with radio observations (including RM) they disfavour a "pure" hadronic origin of giant radio Halos

(iv) In principle turbulent reacceleration of seed particles (including secondaries) may explain "all" available data under reasonable conditions.
Important prediction of these models is the existence of ultra-steep spectrum emission ("all" models using non-efficient mechanisms)

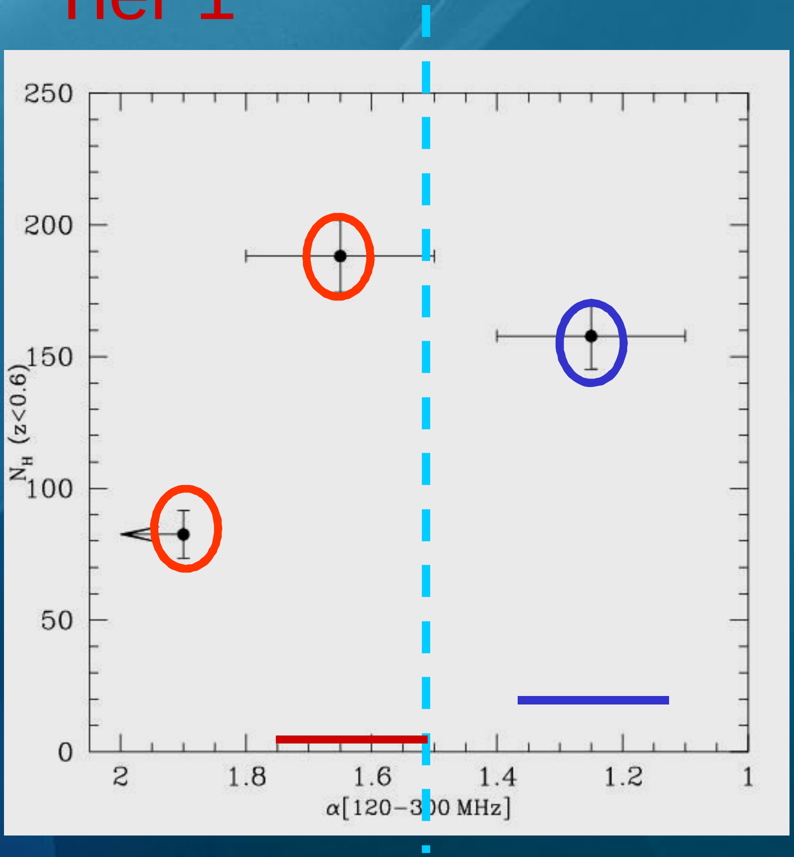
(v) LOFAR is the ideal radiotelescope to test, first results are coming……..

Spectral properties of Radio Halos

Cassano, GB, Rottgering, Bruggen, 2010 A&A 509 68

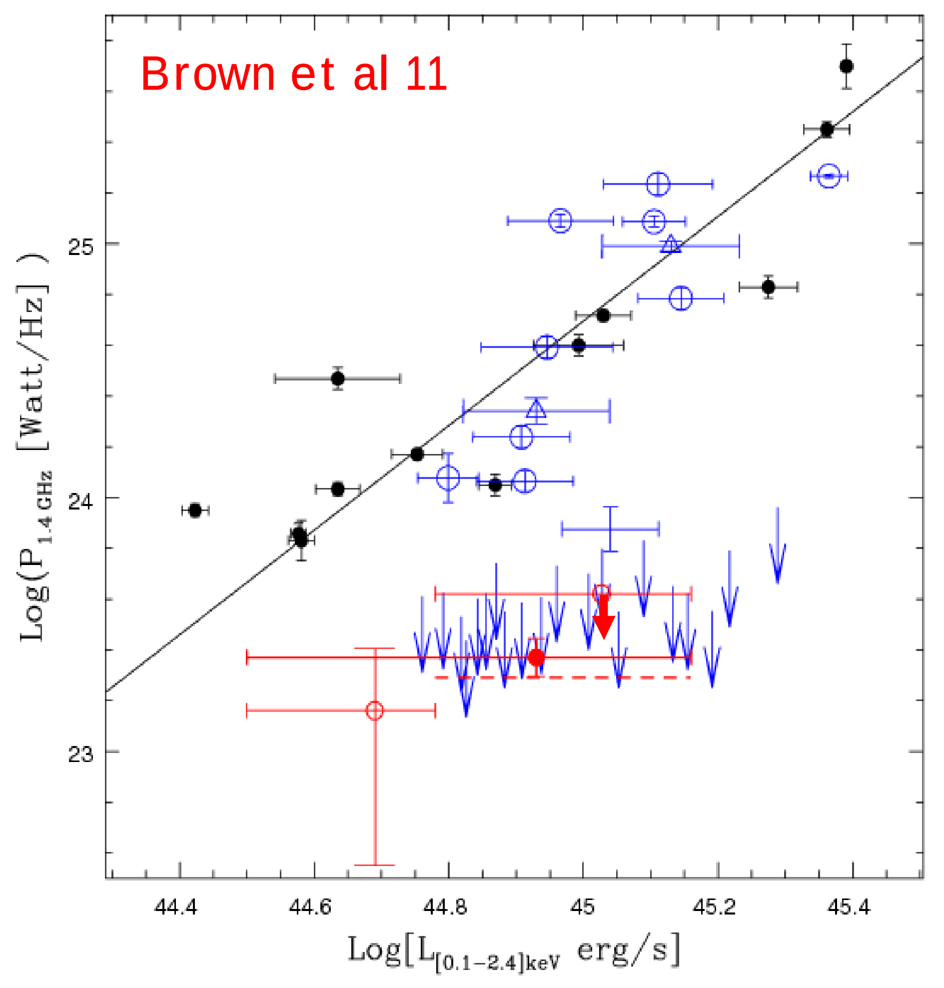


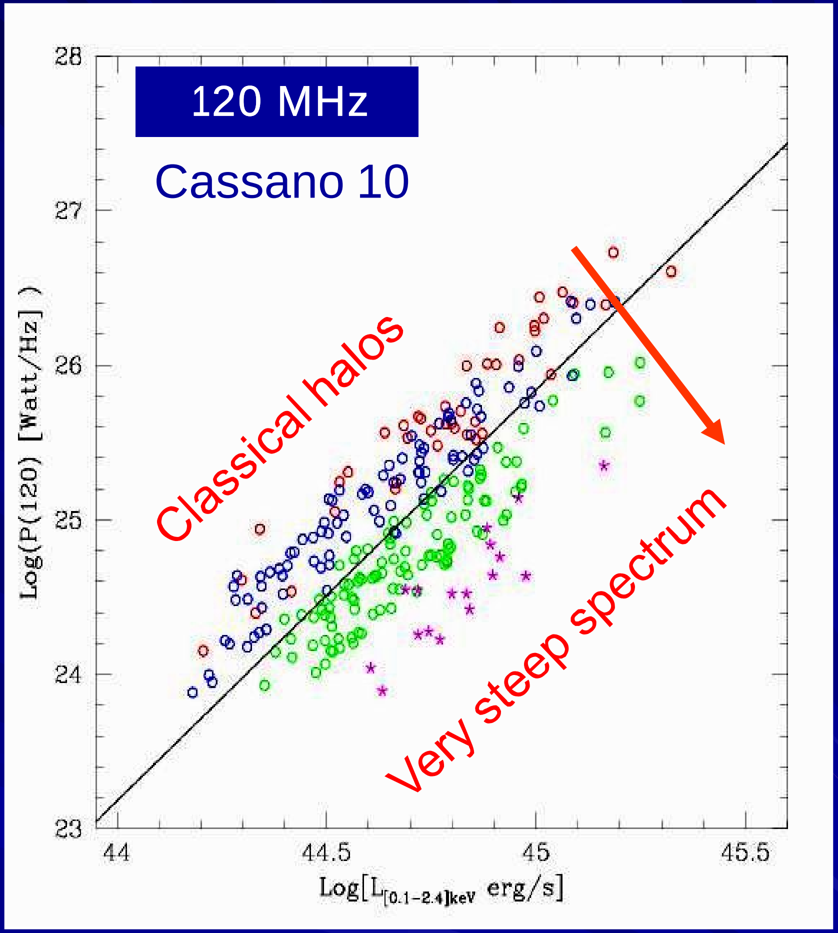
Tier 1



LOFAR is expected to discover 300-400 giant radio halos at z<1.0, a large fraction of them with very steep-spectrum (from less energetics cluster-cluster mergers)

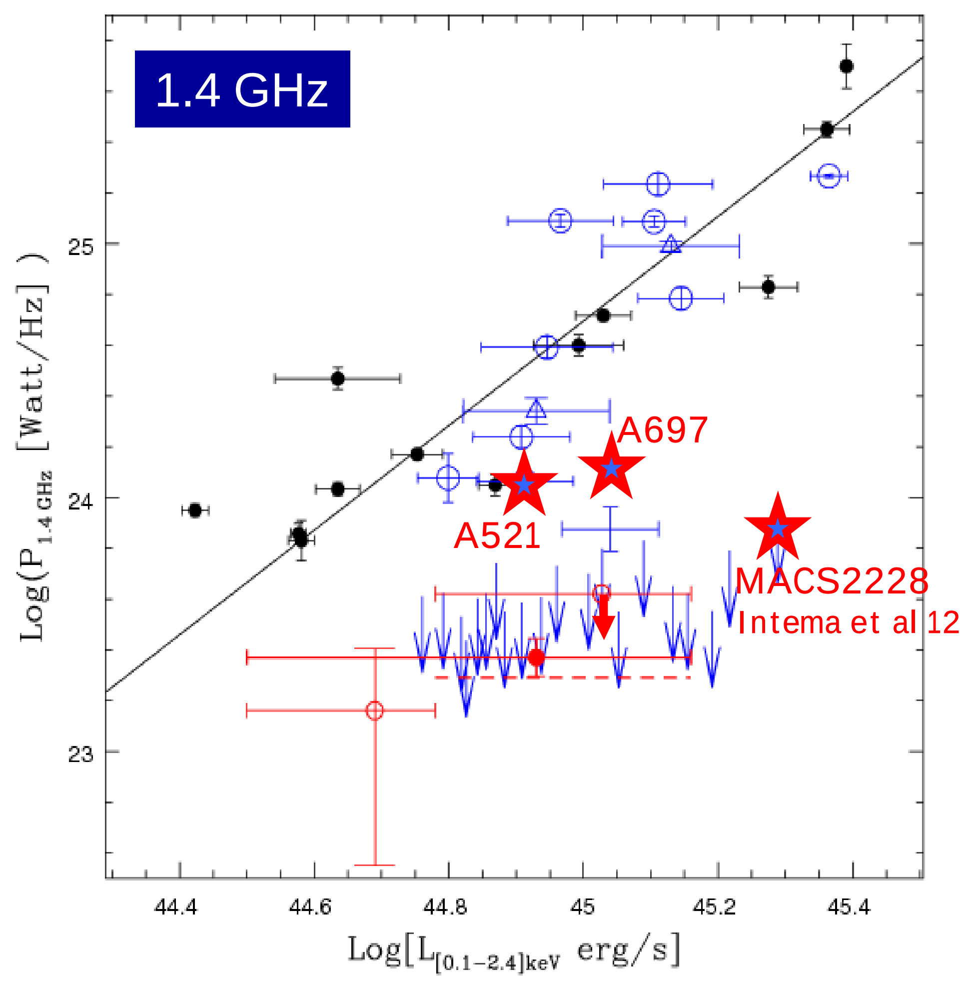
Where are steep-halos?

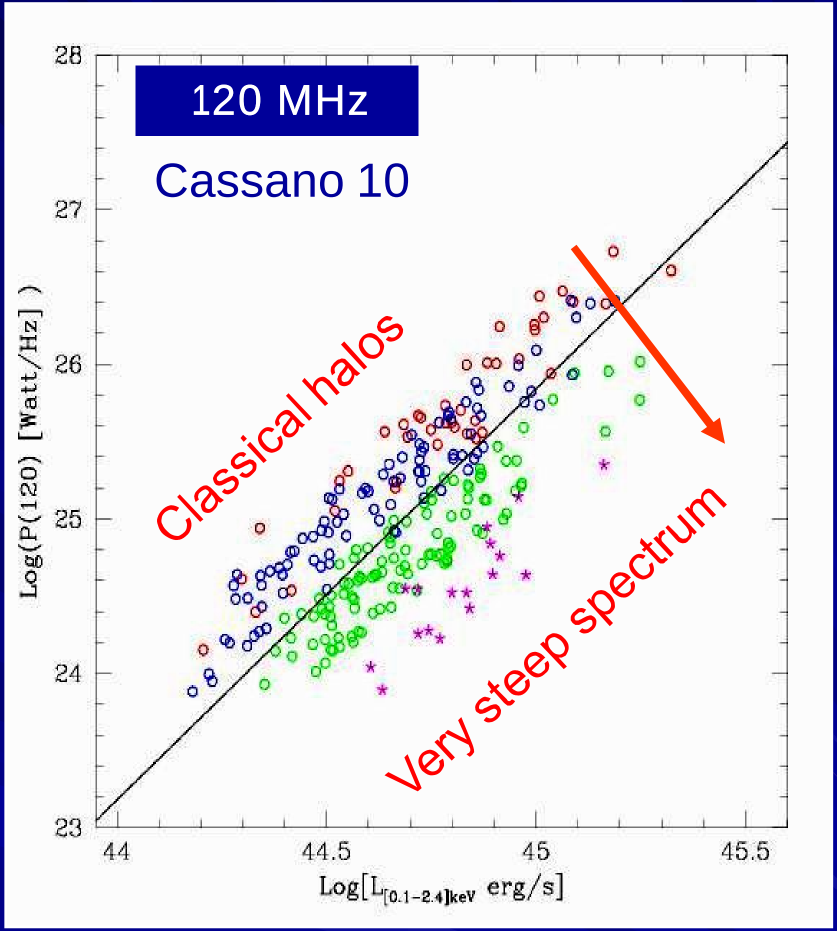




The relatively small dispersion of the correlation at 1.4 GHz is mainly driven by the difficulty to detect very-steep spectrum halos at higher radio frequencies

Present Situation



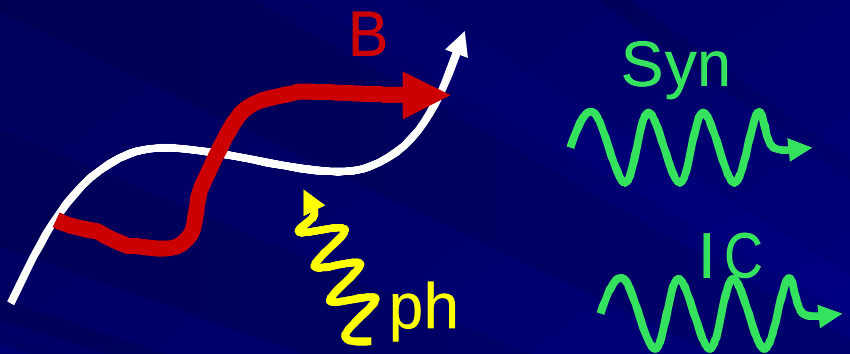


★ are very-steep spectrum halos discovered in clusters of the GMRT (blue!) sample

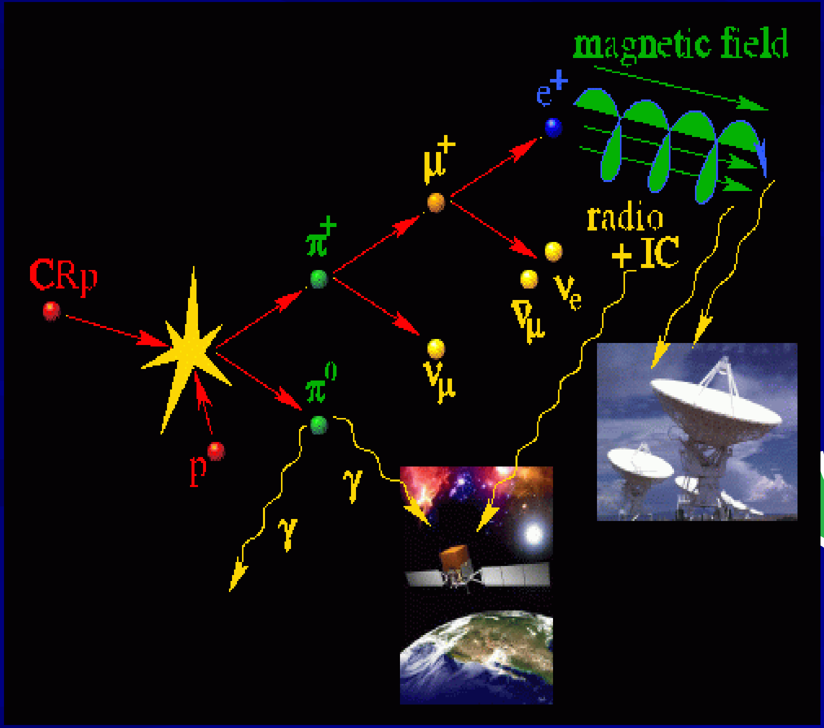
The relatively small dispersion of the correlation at 1.4 GHz is probably driven by the difficulty to detect very-steep spectrum halos at higher radio frequencies

High energy emission from GC

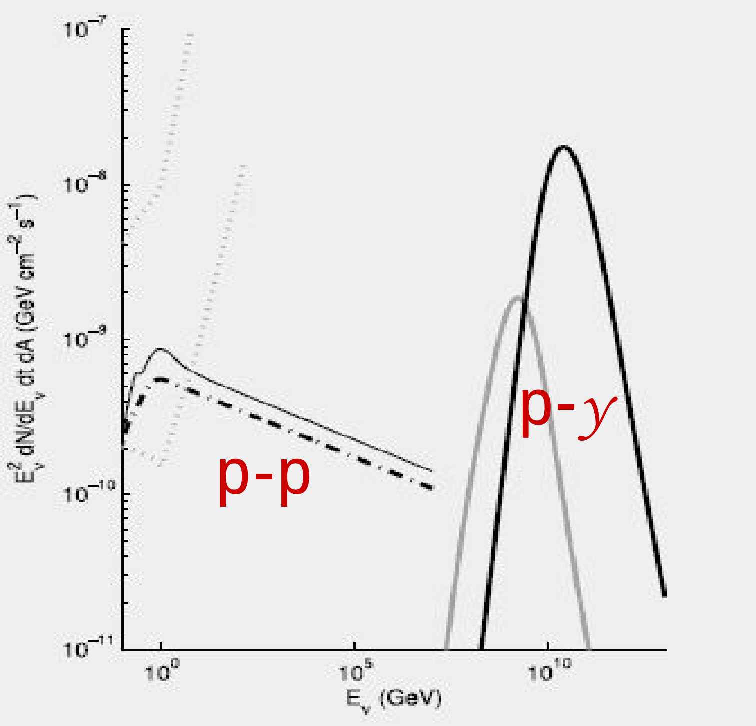
CRe



CRp

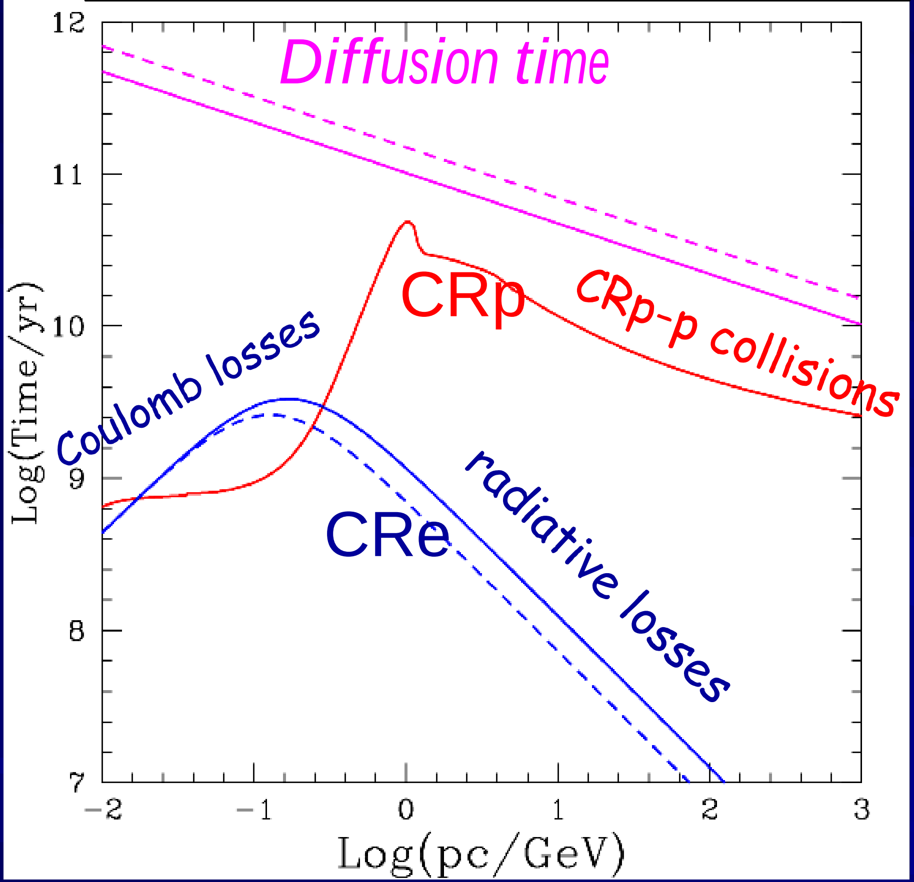


Wolfe +al 2008



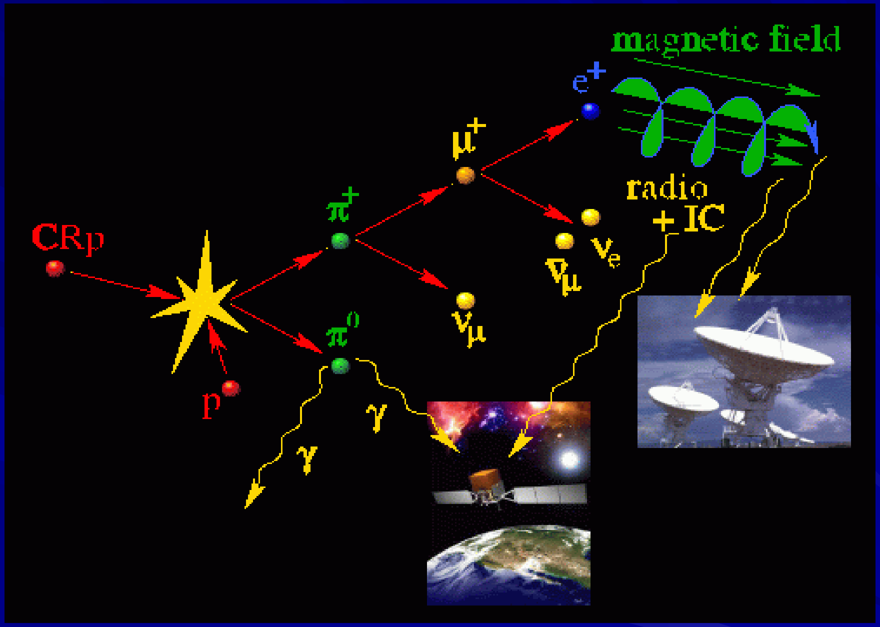
Cosmic rays confinement

review: Blasi, Gabici, Brunetti 07



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

Galaxy clusters contain several sources of CRp : Starbursts, Galaxies, AGN, LS Shocks, reconnection(?), turbulence



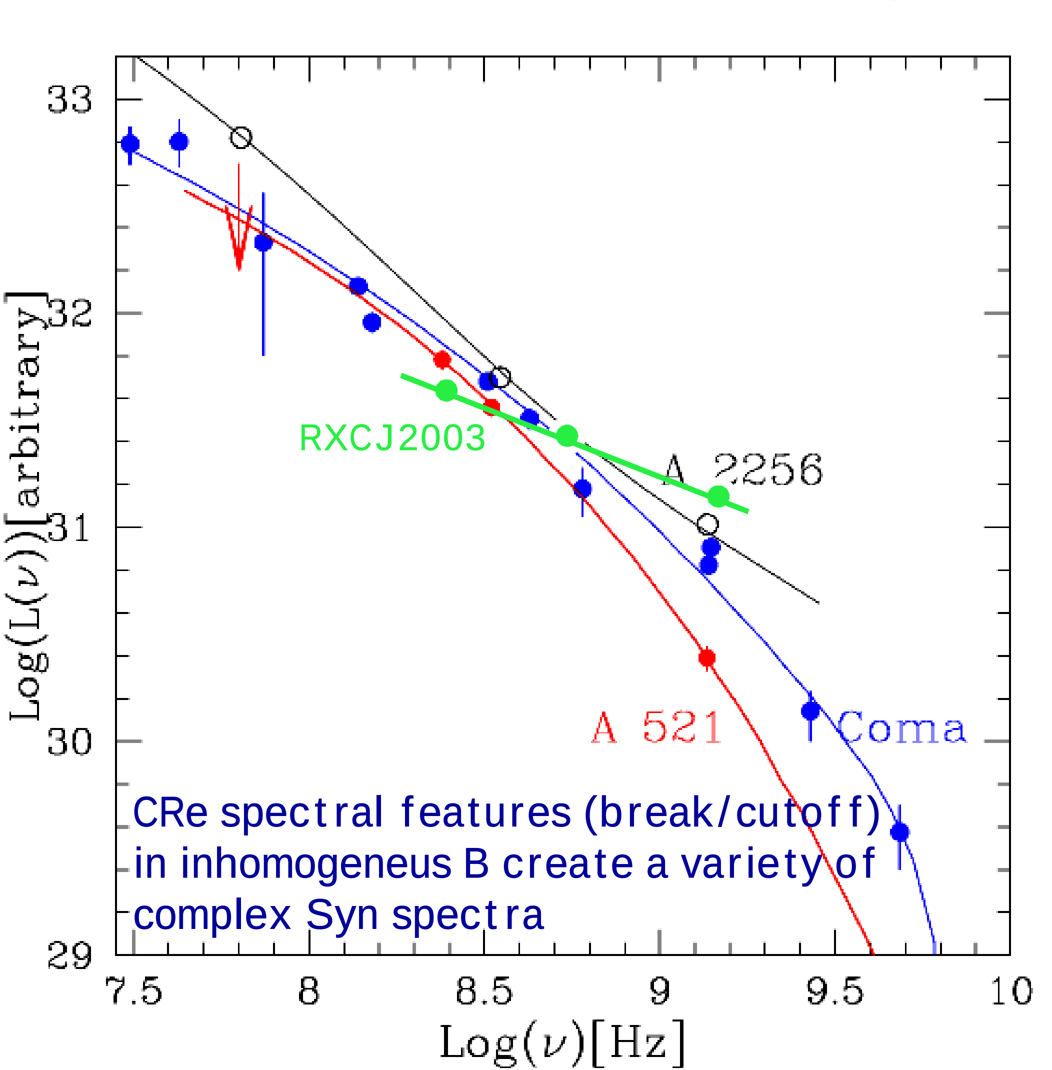
Voelk et al. 96, Berezinsky et al 97, Ensslin et al 97, Sarazin 99, …

Cosmic ray protons “must” be present in galaxy clusters and gamma-rays are unavoidable…
at what level ? This constraints CRp energy content !

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

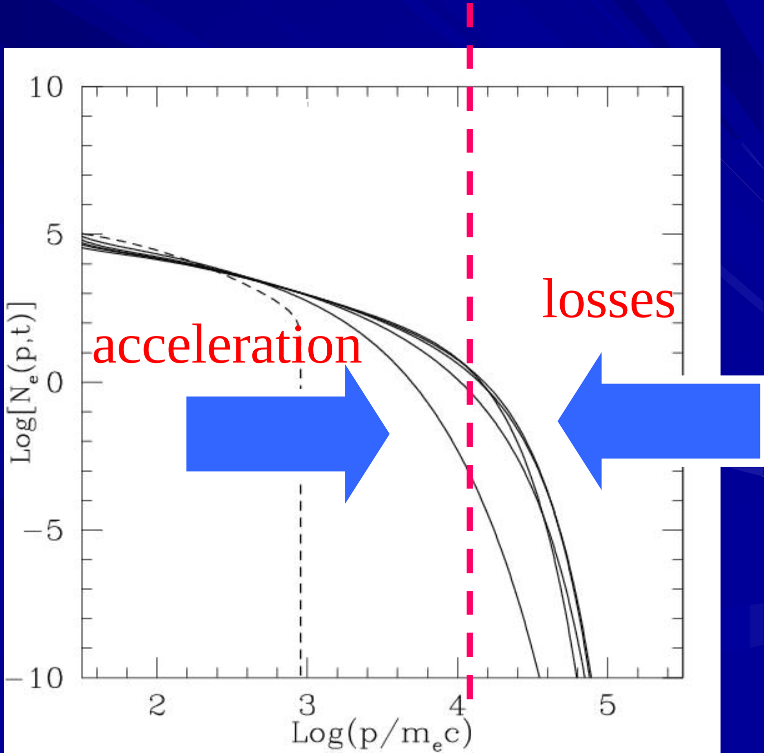
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\mathrm{th}}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\mathrm{th}}/10^{-3}}\right)\right]\right\}^{-1}.$$

Radio halos do not have universal spectra

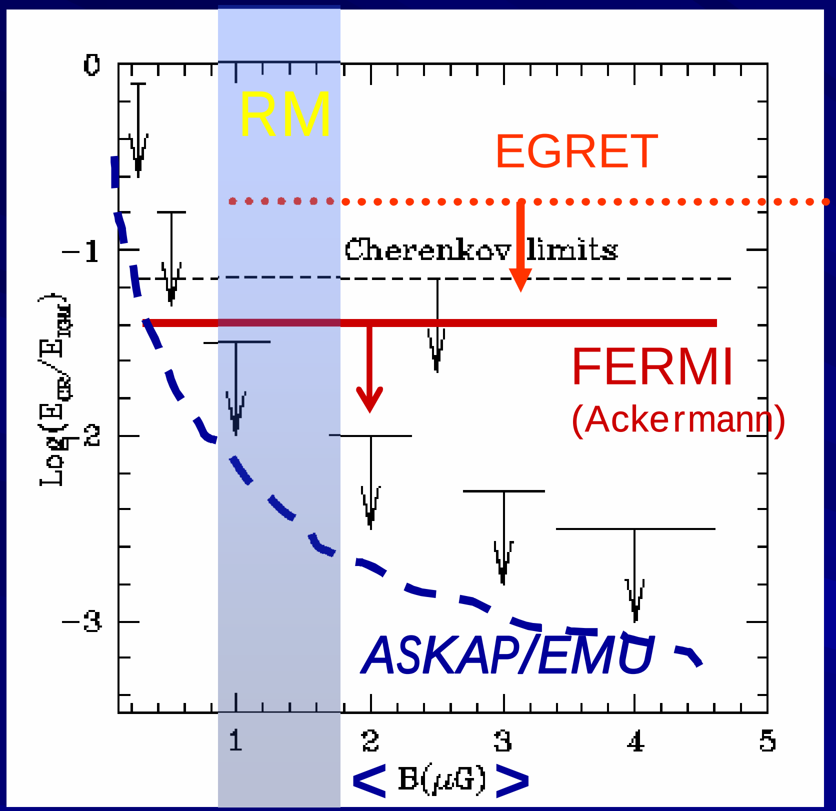


CRe spectral features (break/cutoff) in inhomogeneus B create a variety of complex Syn spectra

Acceleration time-scale $\approx 10^8$ years



Energy content of CRp



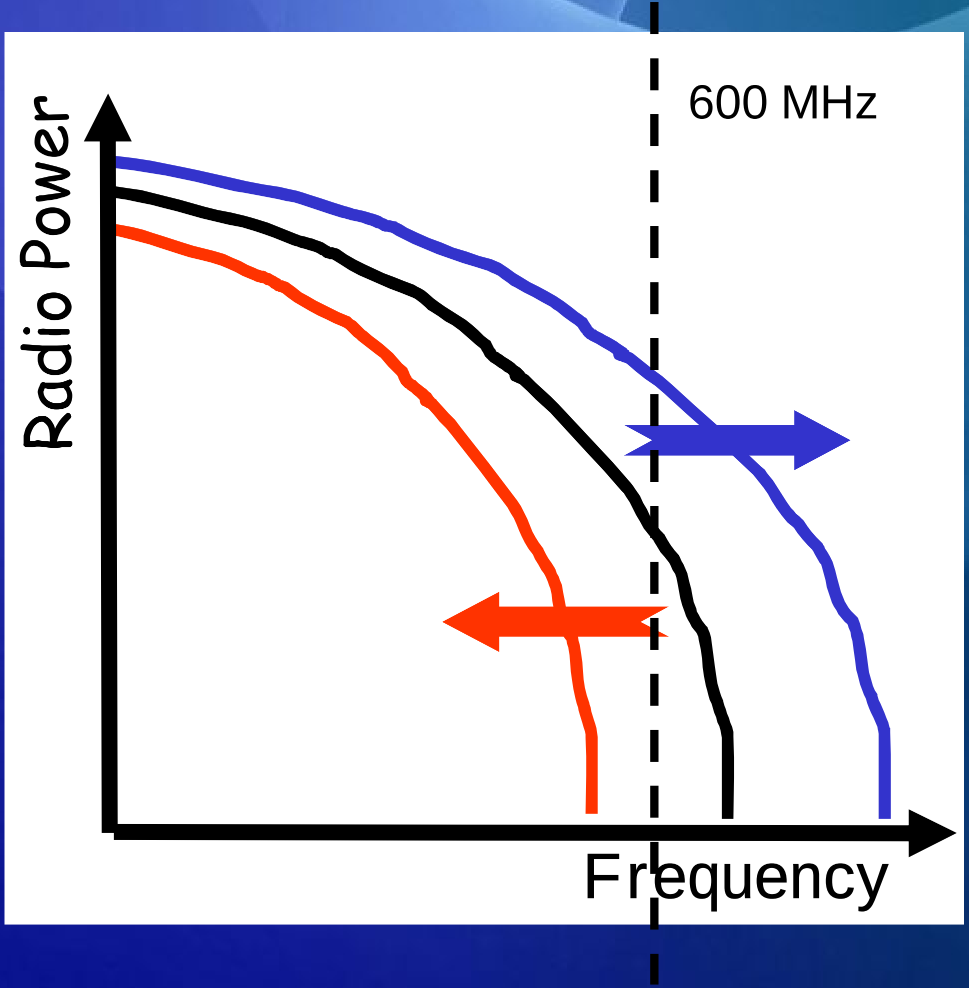
Reimer et al. (2003)
Reimer et al. (2004)
Pfrommer & Ensslin (2004)
Perkins et al. (2006)
Brunetti et al. (2007)
Brunetti et al. (2008)
Perkins et al. (2008)
Aharonian et al. (2008 a,b)
Aleksic et al. (2009)
Ackermann et al (2010)

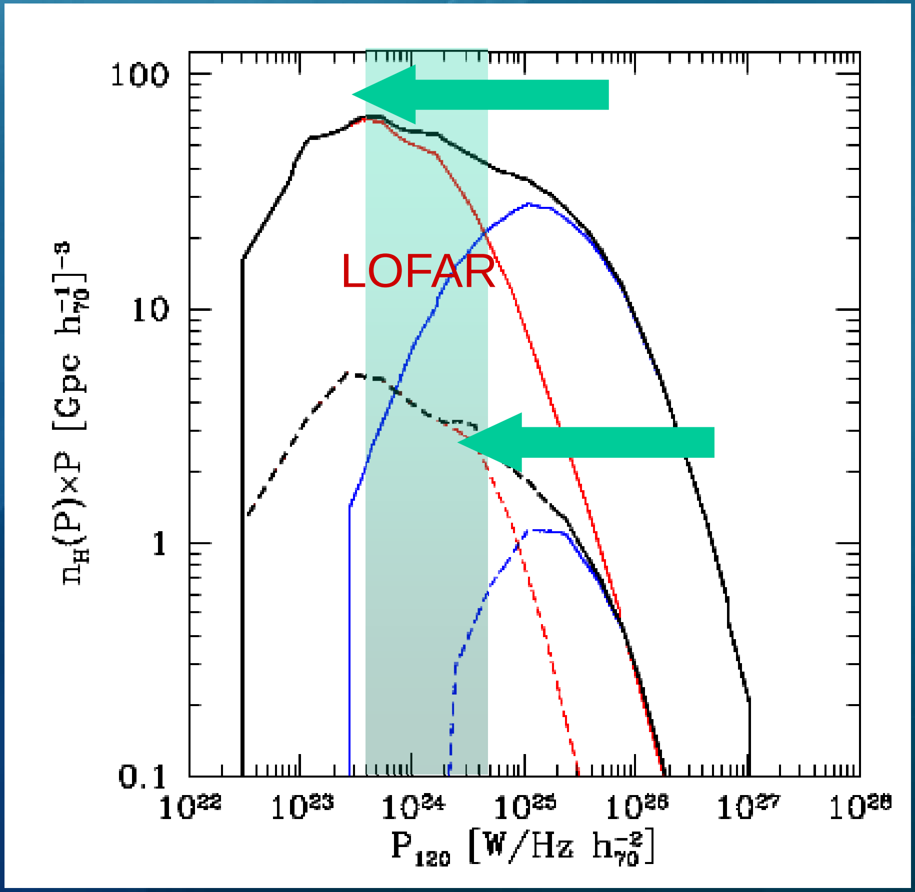
Gamma + Radio observations independently suggest that non-thermal components are dynamically NOT important (% level) … at least in the central Mpc-scale regions

Additional limits from cluster dynamics (e.g. Churazov et al. 2008; Lagana et al 2009) constrain $E_{CR}+E_{B}+E_{turb}$ below 10% (< 30%) Ethermal.

Montecarlo calculations

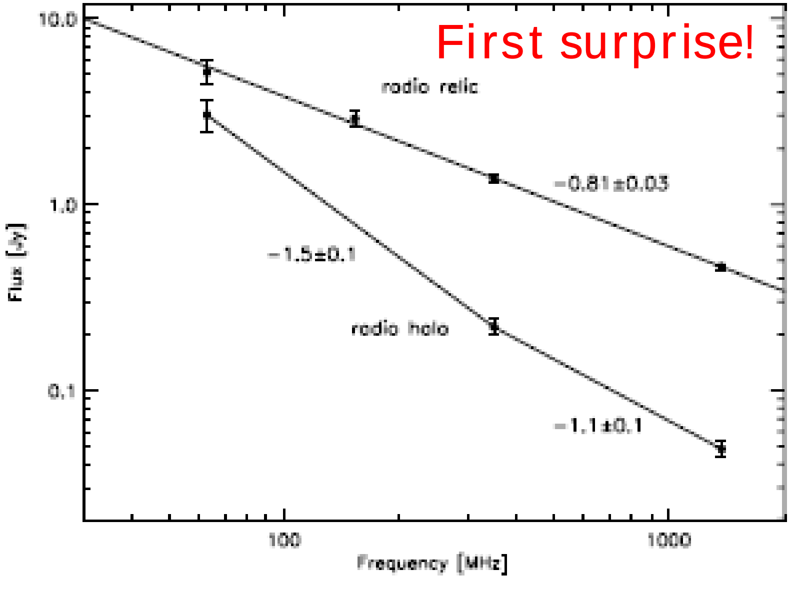
(Cassano, **GB**, Rottgering, Bruggen 2010)



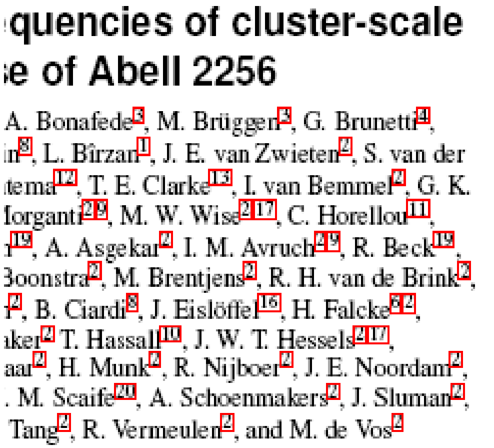


─── z=0-0.1

– – – – z=0.5-0.6

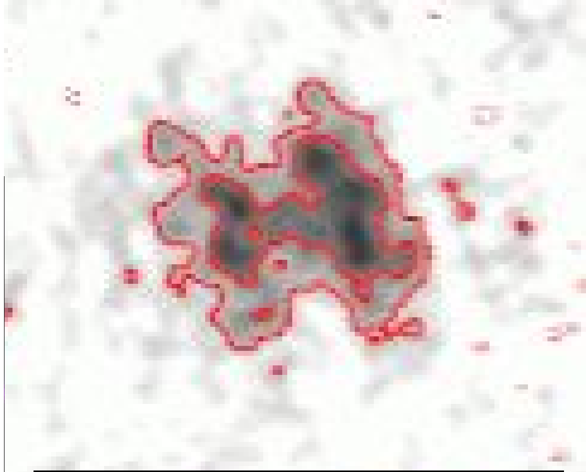


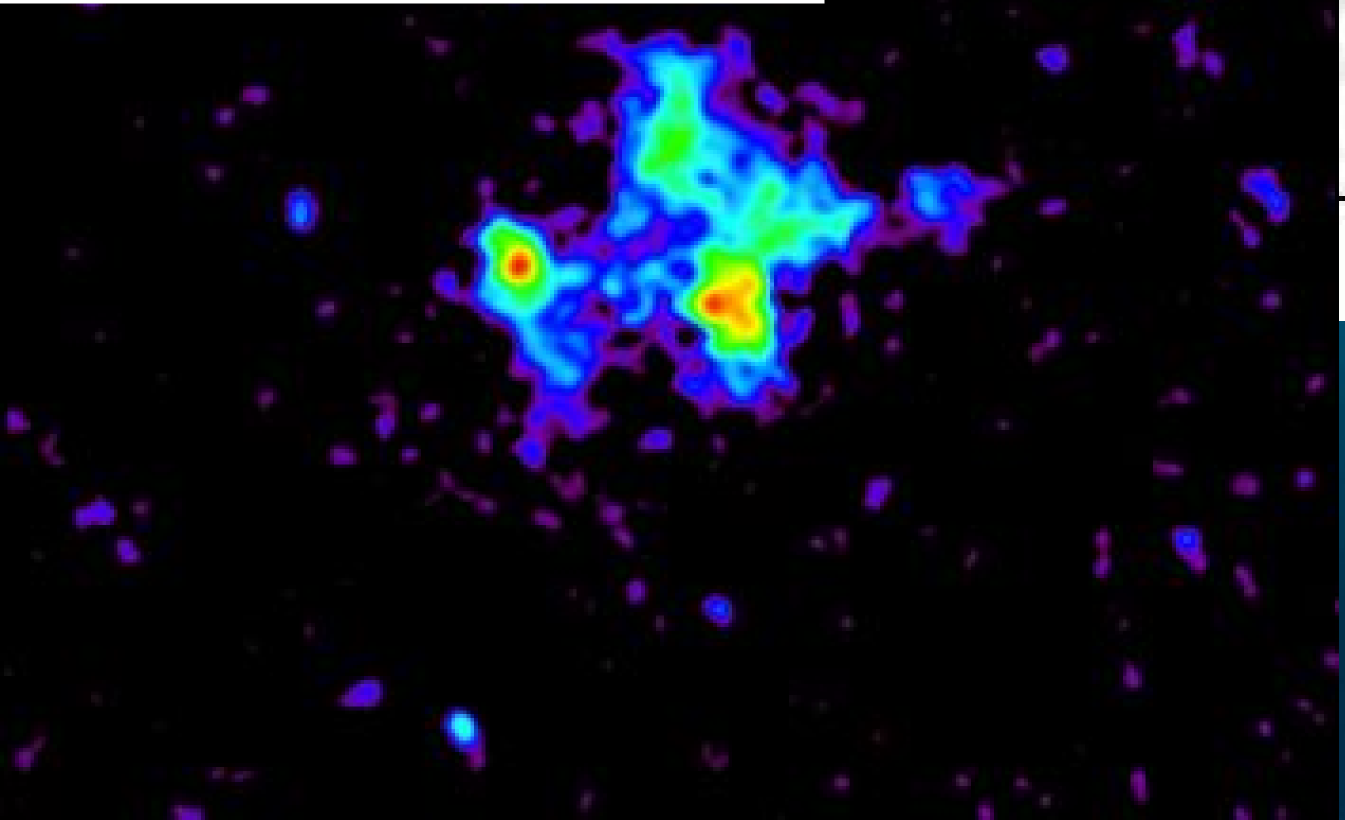
First surprise!

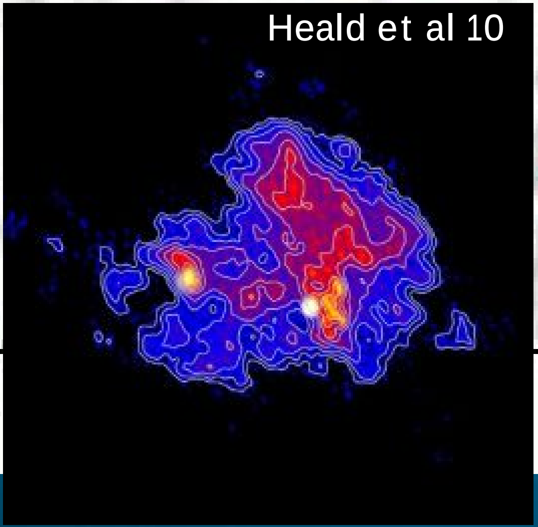


quencies of cluster-scale e of Abell 2256

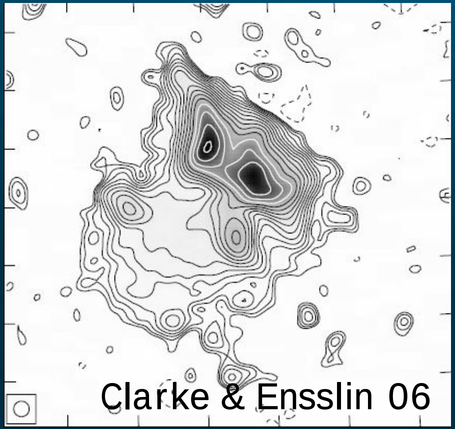
A. Bonafede[3], M. Brüggen[3], G. Brunetti[4], in[8], L. Bîrzan[1], J. E. van Zwieten[2], S. van der tema[12], T. E. Clarke[13], I. van Bemmel[2], G. K. Iorganti[2][9], M. W. Wise[2][17], C. Horellou[11], r[19], A. Asgekar[2], I. M. Avruch[4][9], R. Beck[19], Boonstra[2], M. Brentjens[2], R. H. van de Brink[2], r[2], B. Ciardi[8], J. Eislöffel[16], H. Falcke[6][2], aker[2] T. Hassall[10], J. W. T. Hessels[2][17], aar[2], H. Munk[2], R. Nijboer[2], J. E. Noordam[2], . M. Scaife[20], A. Schoenmakers[2], J. Sluman[2], Tang[2], R. Vermeulen[2], and M. de Vos[2]







Heald et al 10

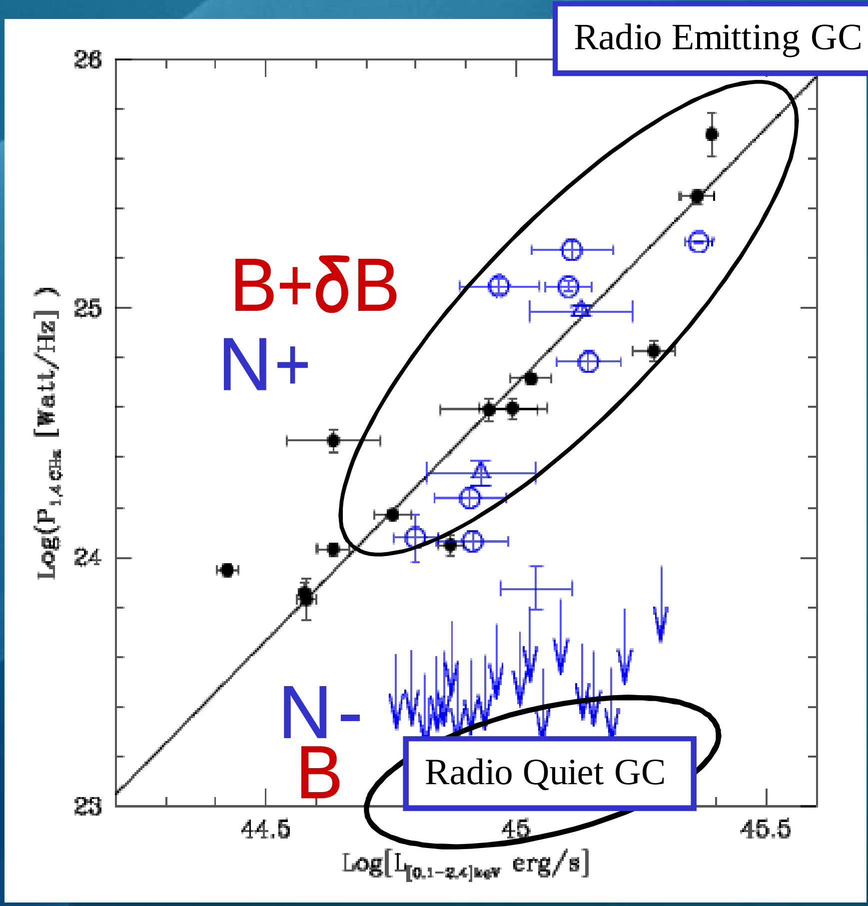


Clarke & Ensslin 06

Cluster mergers - radio halos connection

Magnetic field is amplified *(CRe are accelerated)* during mergers, $B+\delta B$ (N+), and is dissipated *(CRe cool)* when clusters become dynamically “relaxed”, B (N-).

- Brunetti et al 07
- Kushnir et al 09
- Brunetti et al 09
- Keshet & Loeb 10
- Cassano & Brunetti 10
- Ensslin et al 11
- Bonafede et al 11



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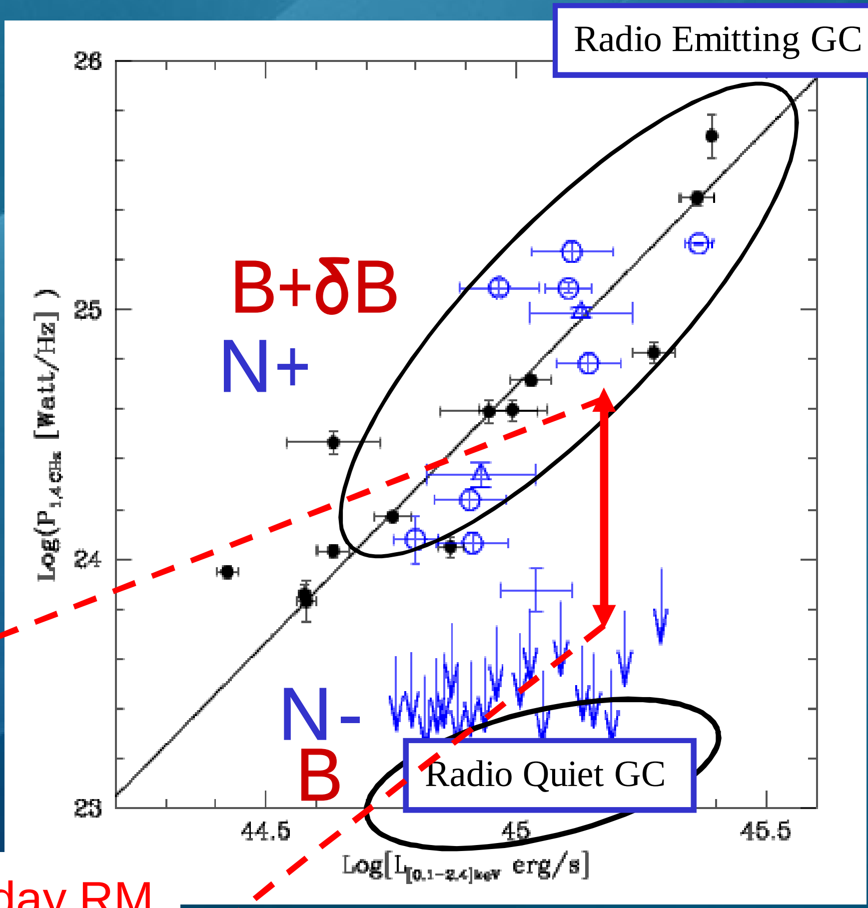
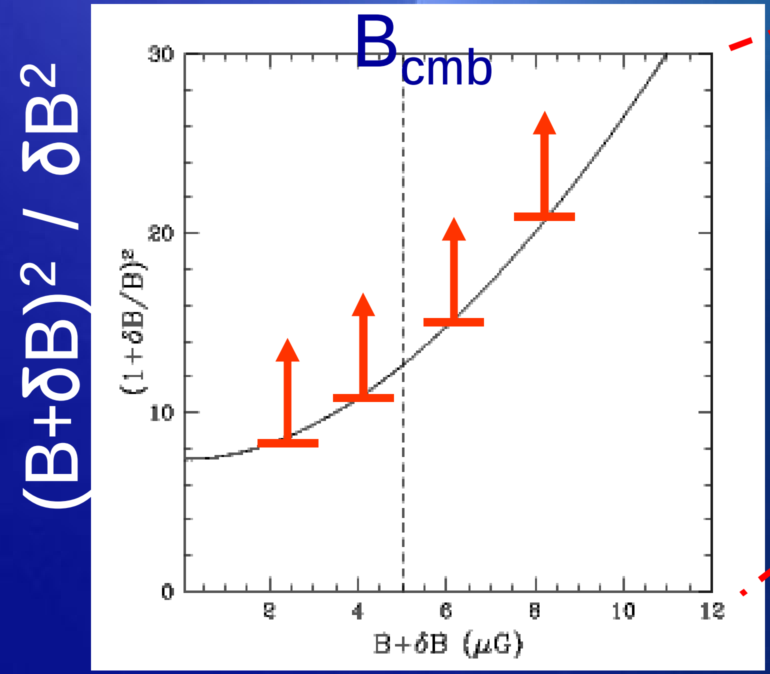
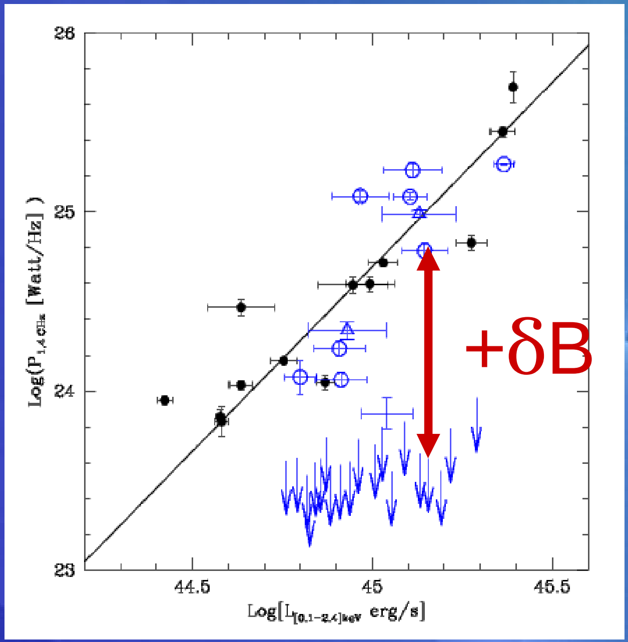




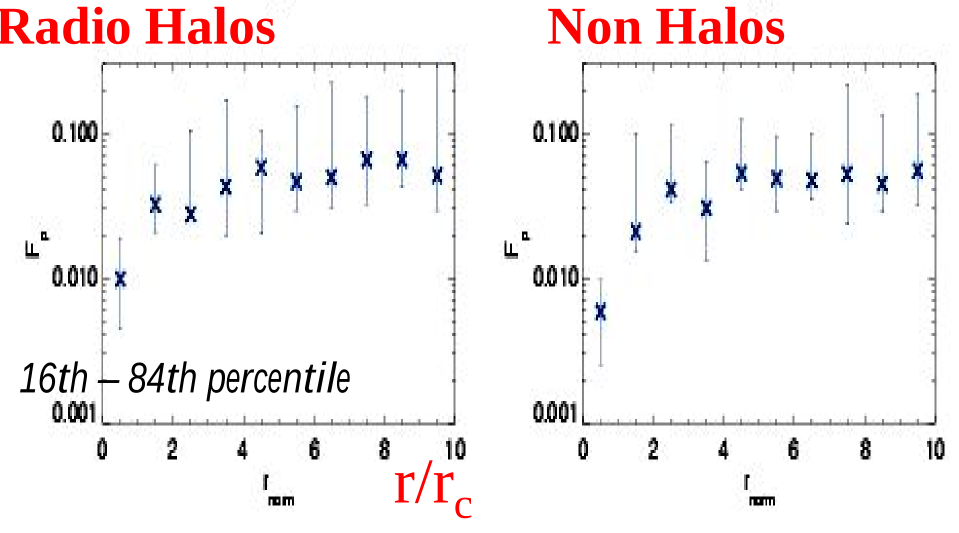
Faraday RM

However no differences are found between B in radio halos and radio "quiet" clusters (Clarke et al 01, Govoni et al 10, Bonafede et al 11). Also in many "relaxed" and radio "quiet" clusters B is significantly larger than that in radio halo clusters (Murgia et al 04, Ensslin & Vogt 05, Vacca et al 12)

"RM" analysis inconsistent with magnetic bimodality

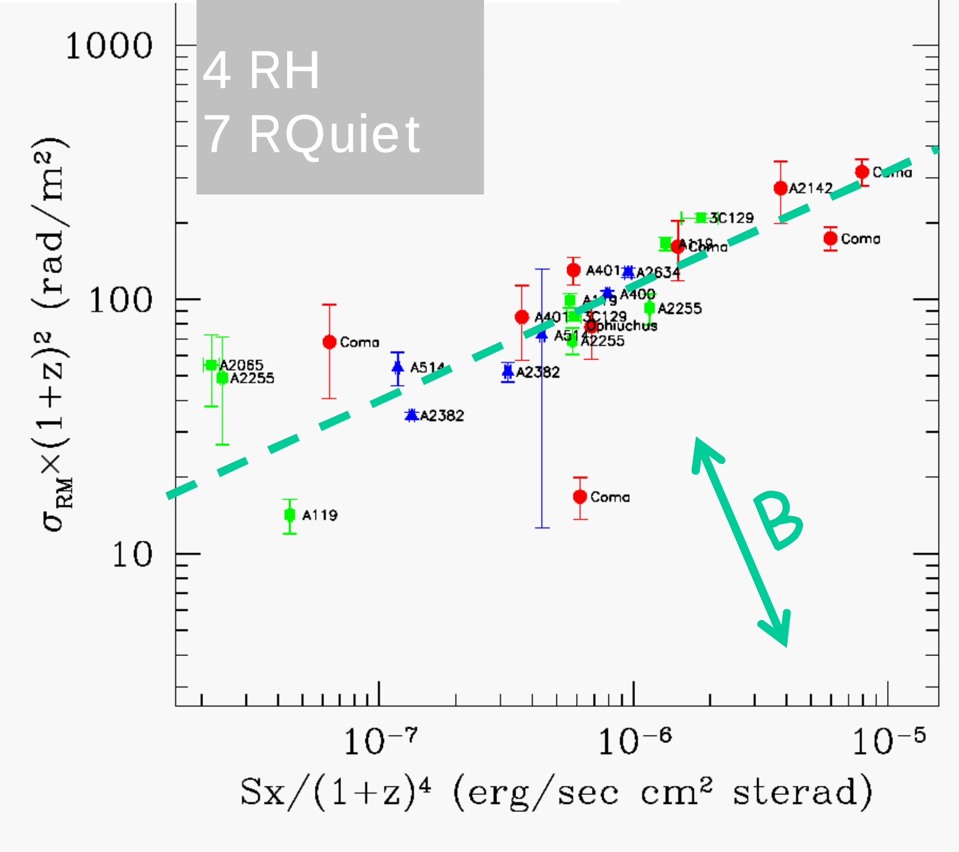


Bonafede +al 2011



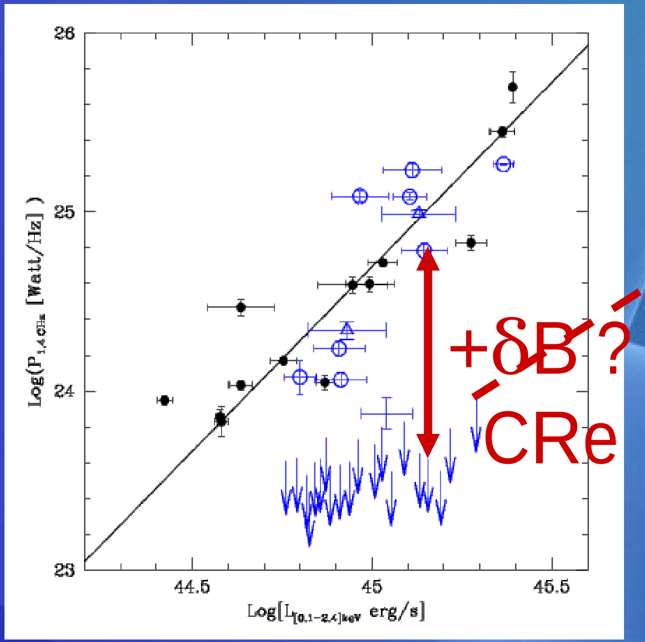
Govoni et al 2010 AA 522, 105

$$\sigma^2_{\mathrm{RM}} = \langle \mathrm{RM}^2 \rangle = 812^2 \Lambda_c \int (n_e B_{\|})^2 \mathrm{d}l.$$


4 RH
7 RQuiet

HIFLUGCS + NVSS … 33 clusters at z = 0.023-0.2..

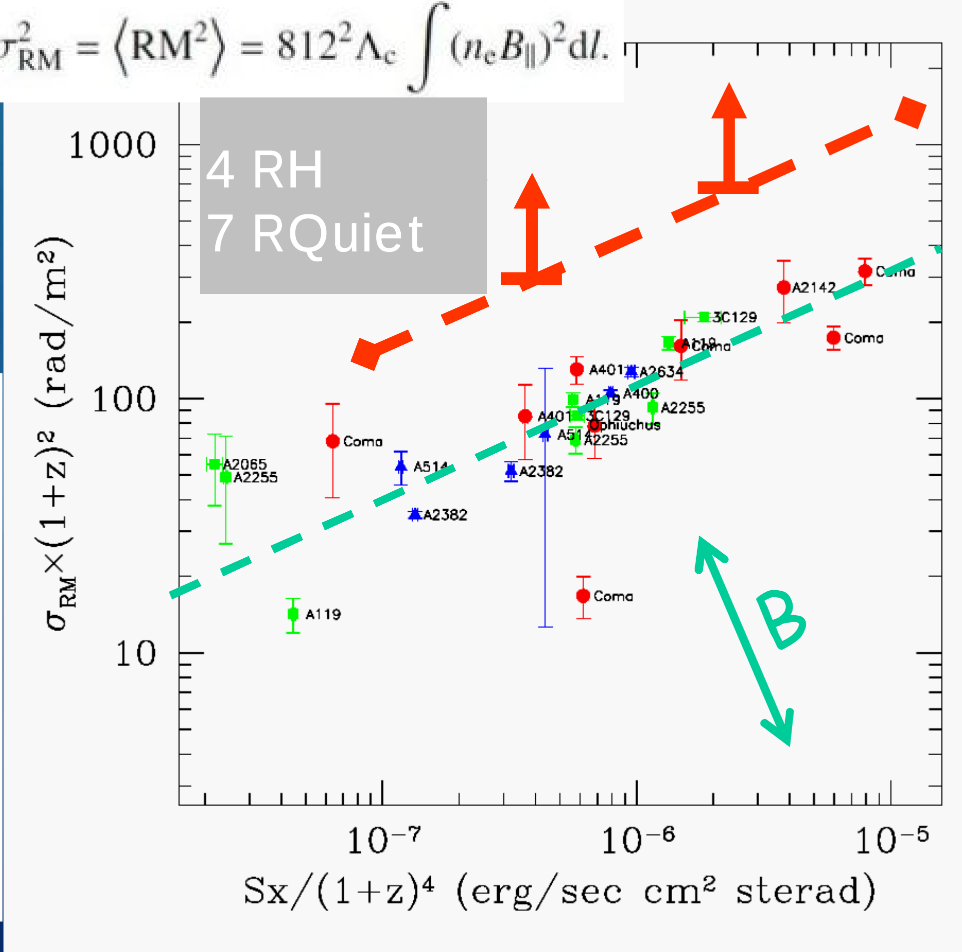
“RM” analysis inconsistent with magnetic bimodality



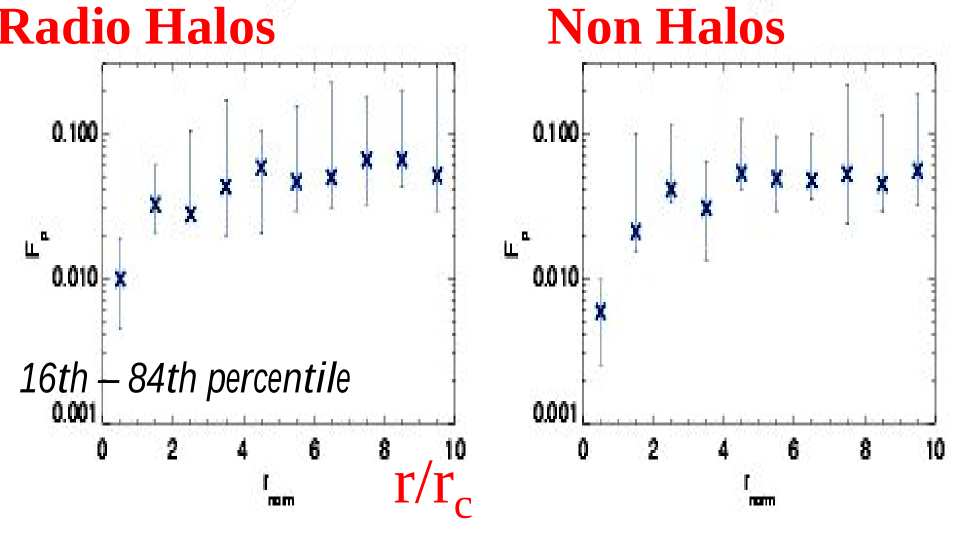
Govoni et al 2010 AA 522, 105

GB + Cassano 2010

$$\sigma^2_{\mathrm{RM}} = \langle \mathrm{RM}^2 \rangle = 812^2 \Lambda_c \int (n_e B_\parallel)^2 \mathrm{d}l.$$



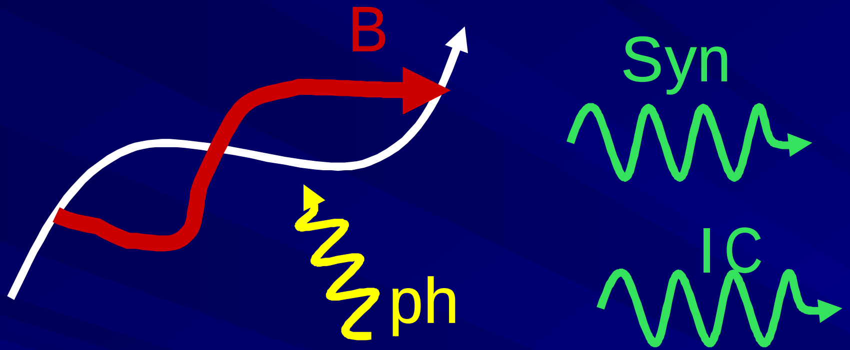
Bonafede +al 2011



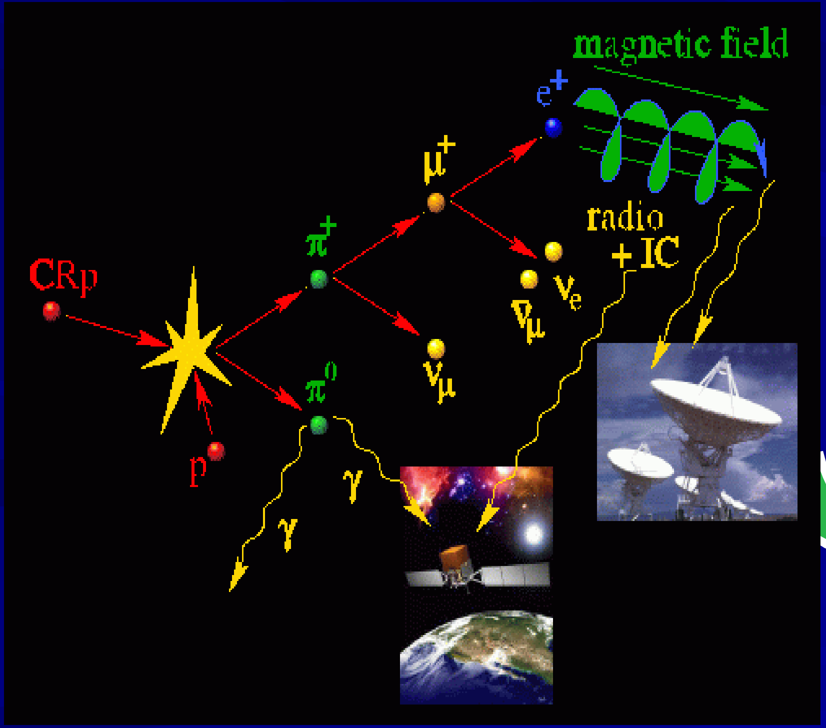
HIFLUGCS + NVSS ... 33 clusters at z = 0.023-0.2..

Radiation from Cosmic Rays in GC

CRe

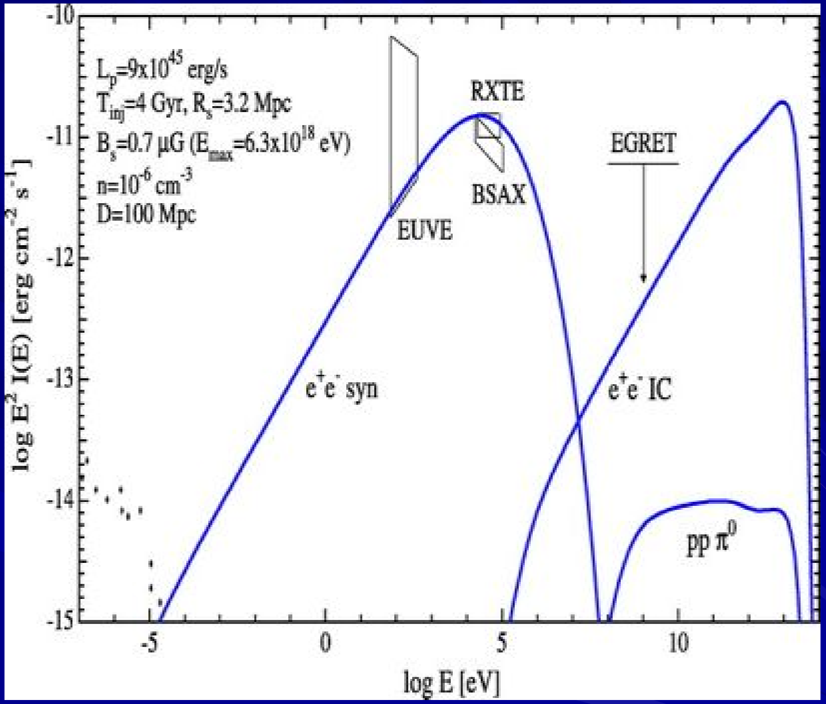


CRp



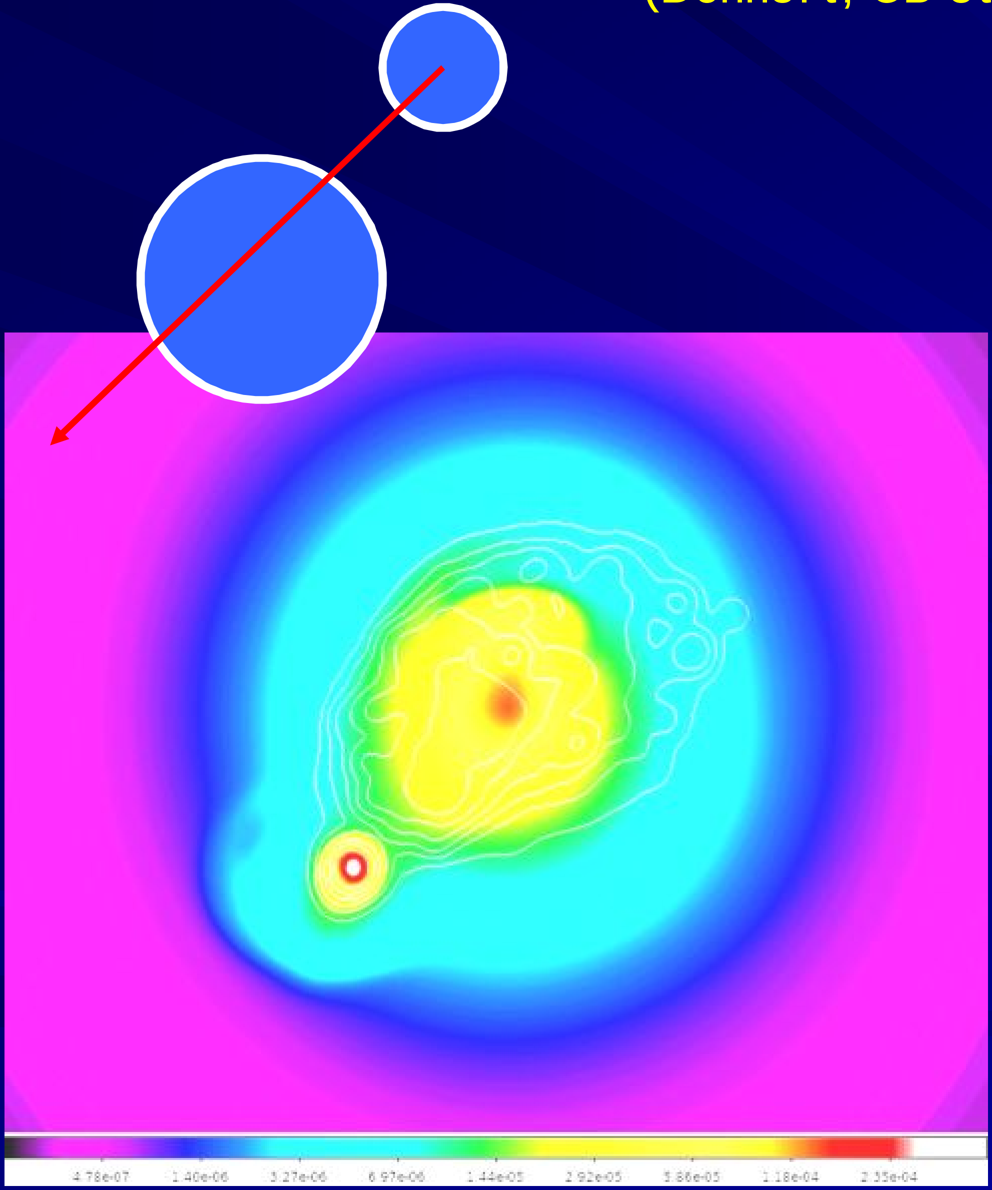
UHEp-γ

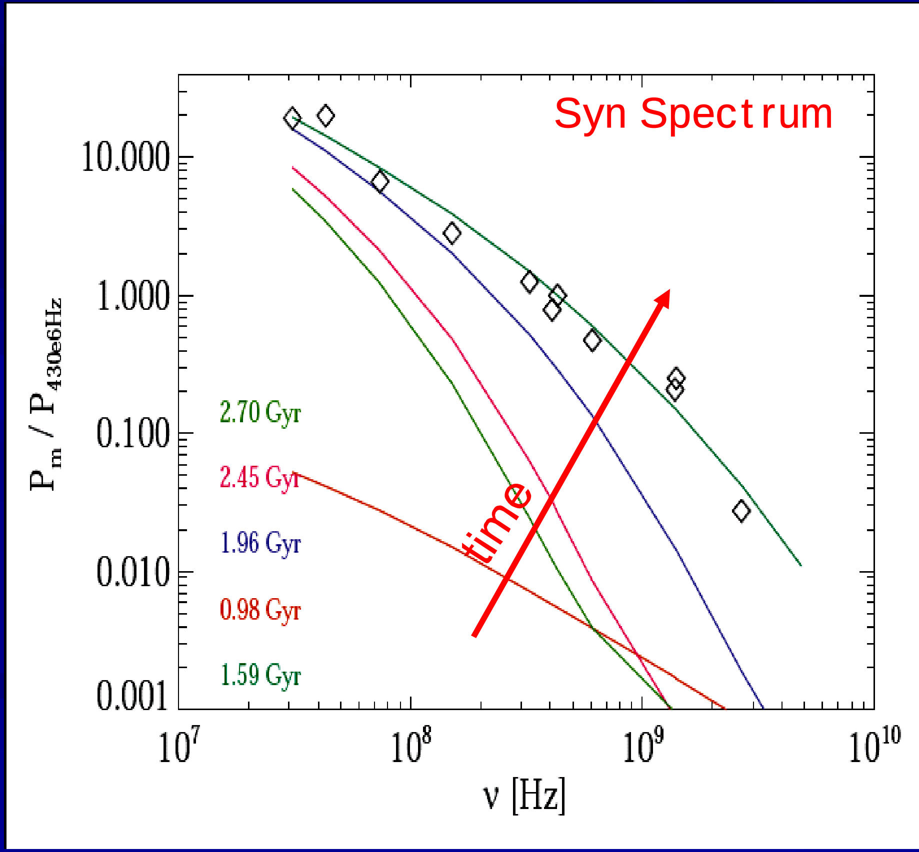
Inoue et al 05



Direct Fokker-Planck (+MHD) simulations in galaxy clusters

(Donnert, GB et al in prep)

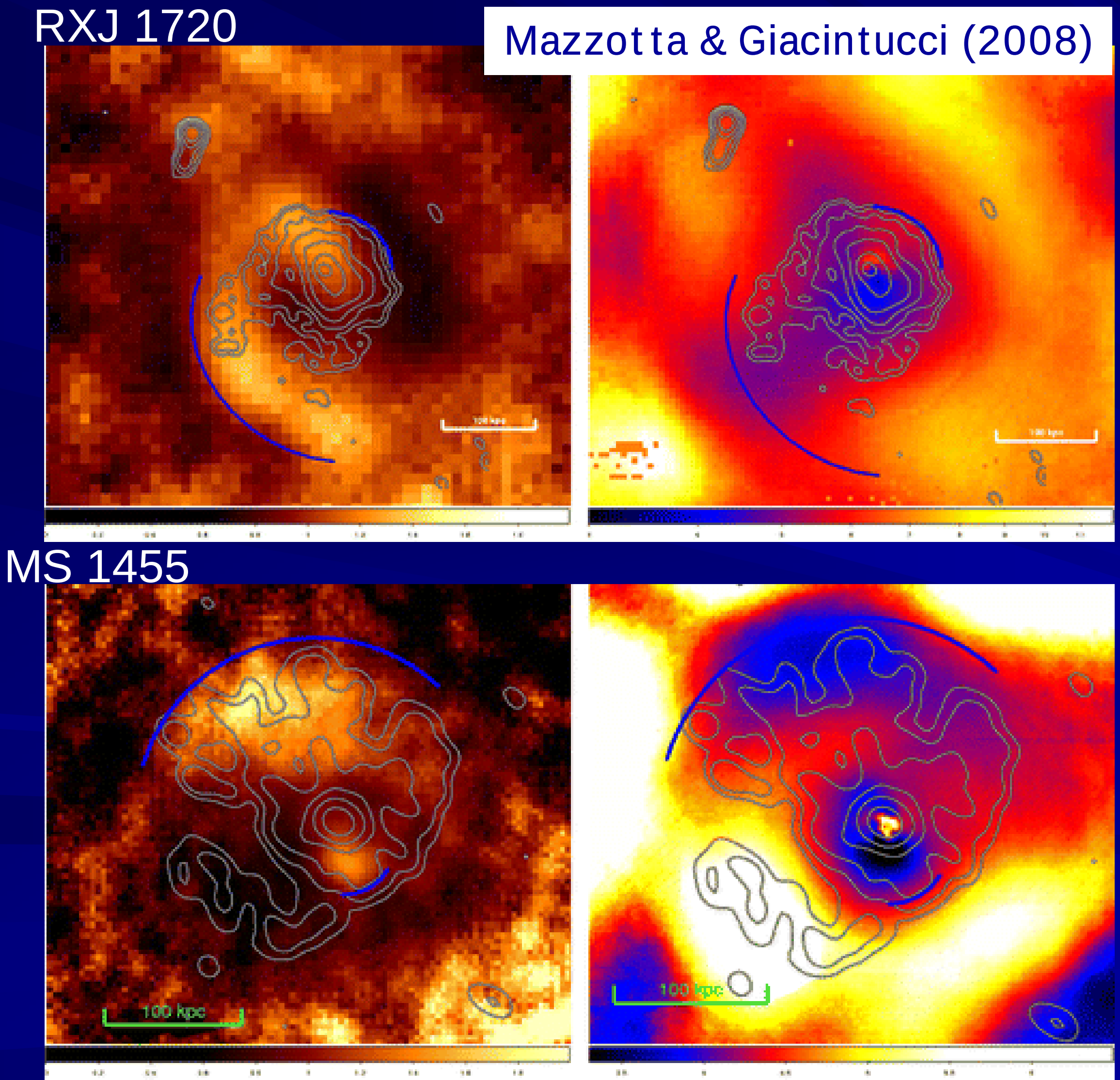




X-ray emission (color) radio emission (contours)

Radio “mini”-Halos on core scales (~ 100-300 kpc):

evidence of GeV electrons (γ= 2000-10000) and
B = 1-10 μG mixed in the thermal ICM



Mazzotta & Giacintucci (2008)

New mechanisms of CR acceleration in connection with the core-sloshing

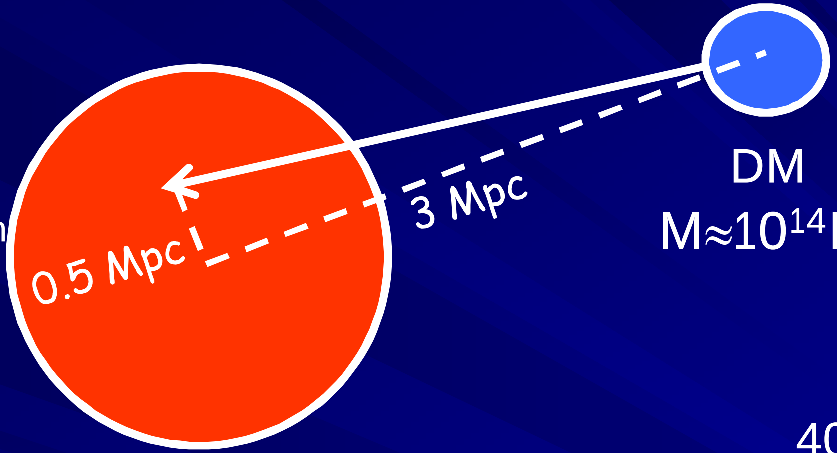
Turbulence ?

(Gitti, GB, Setti 2002, ZuHone et al 2011)

Reconnection ?

Simulations of core-sloshing driven turbulence & CR acceleration

(ZuHone, Markevitch, GB, Giacintucci 2012..)



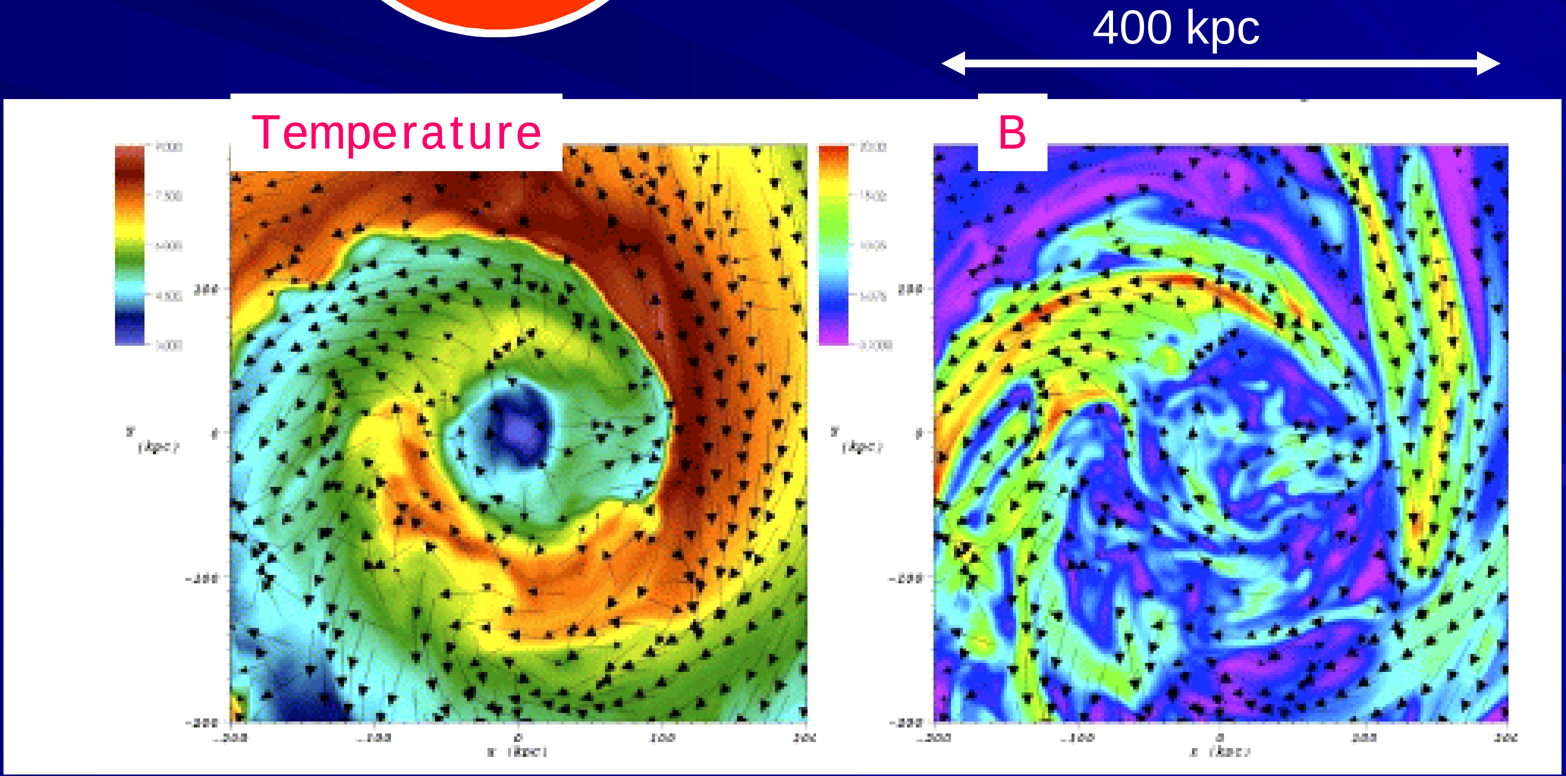
DM+gas

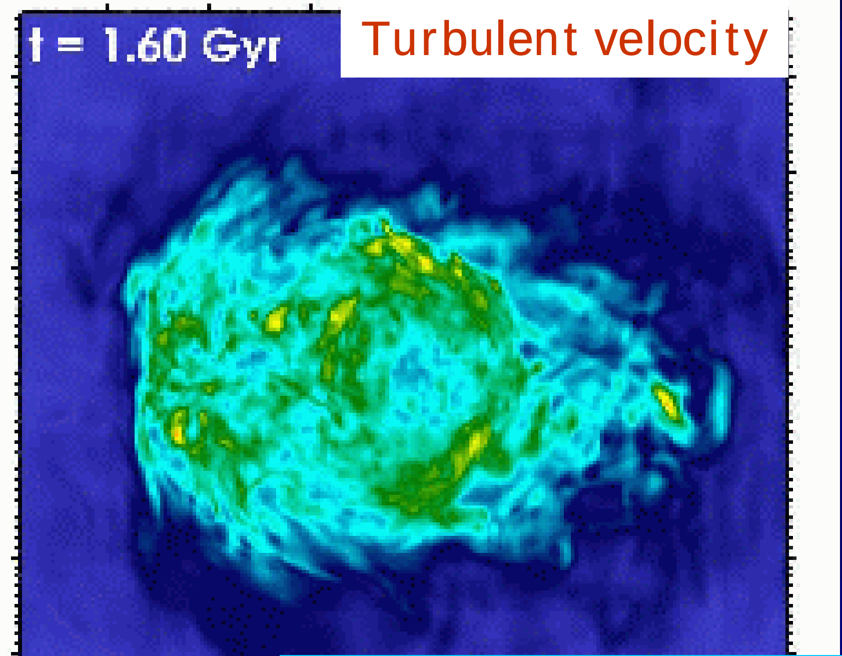
M≈$10^{15}$$M_{sun}$

DM

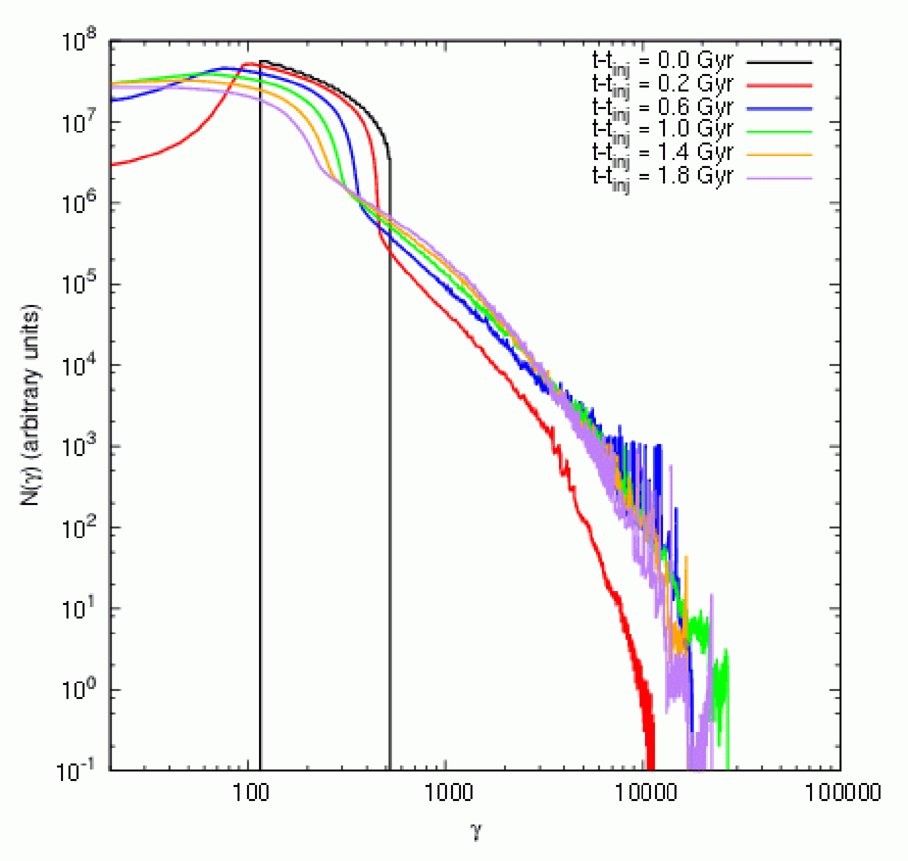
M≈$10^{14}$$M_{sun}$

Flash 3 – AMR
1 kpc resolution





$(\delta V_l)^2 \sim 1\%\ c_s^2$

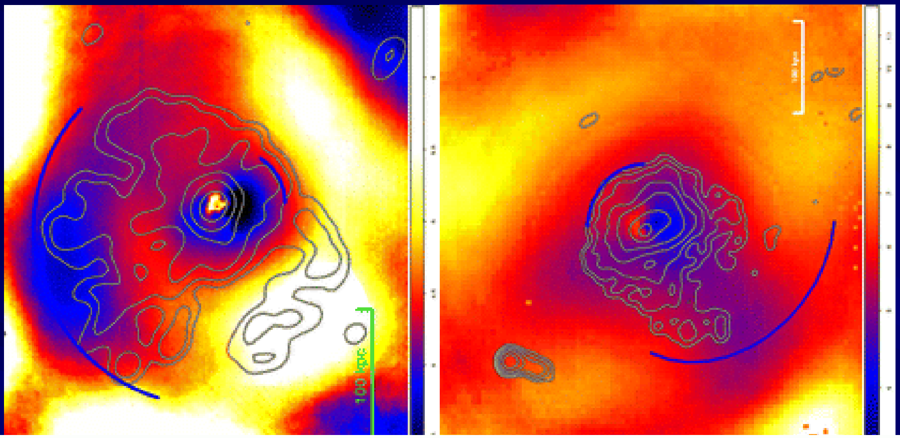


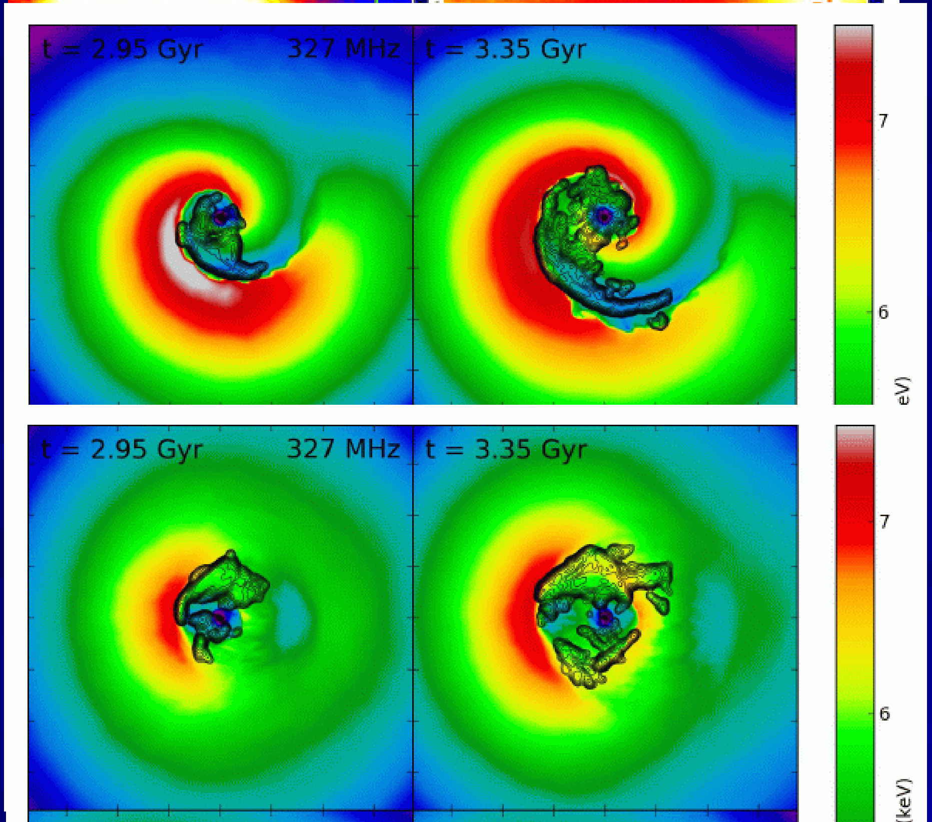
$$d\gamma/dt = -(d\gamma/dt)_r - (d\gamma/dt)_C + \underbrace{(4D_{pp}/p^2)\gamma}_{(V_{tur}\ ,\ l)}$$

MonteCarlo + Tracers

Morphology & Connection with temperature

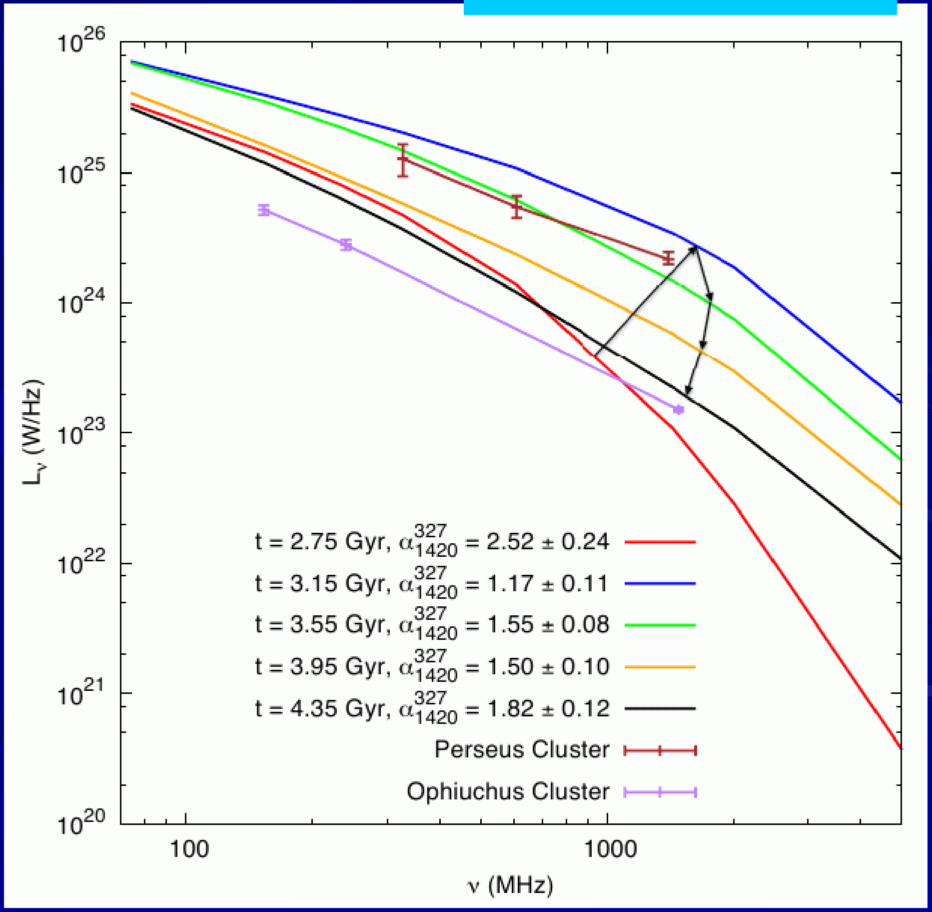
RESULTS



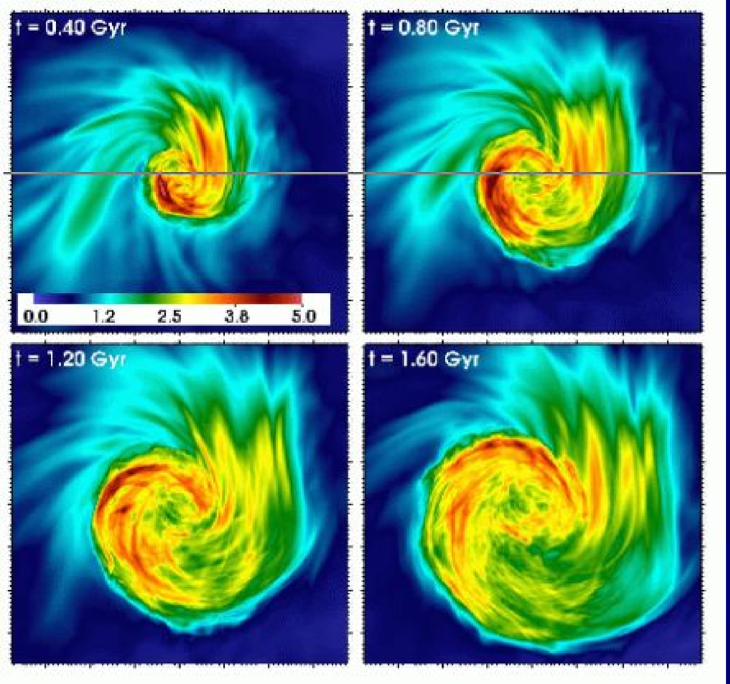


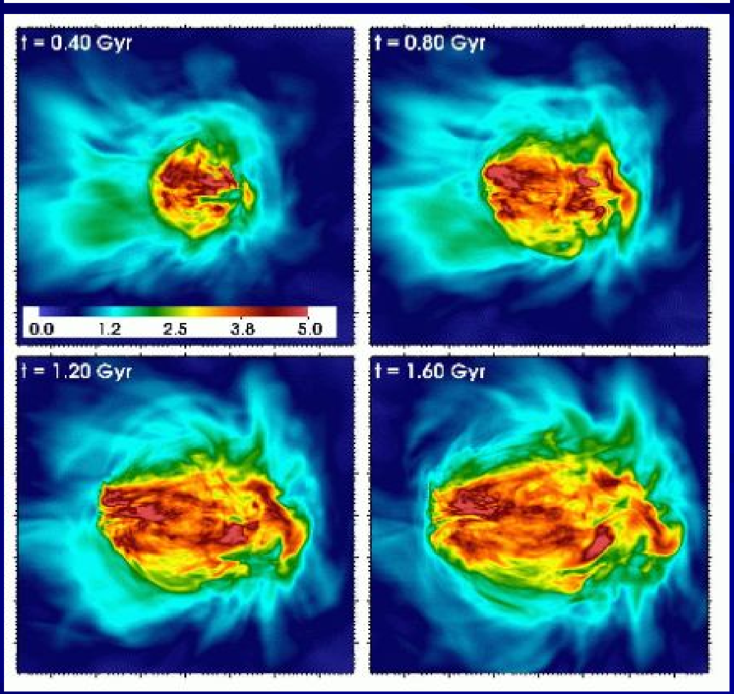
Temporal evolution & spectrum

ZuHone et al 2012

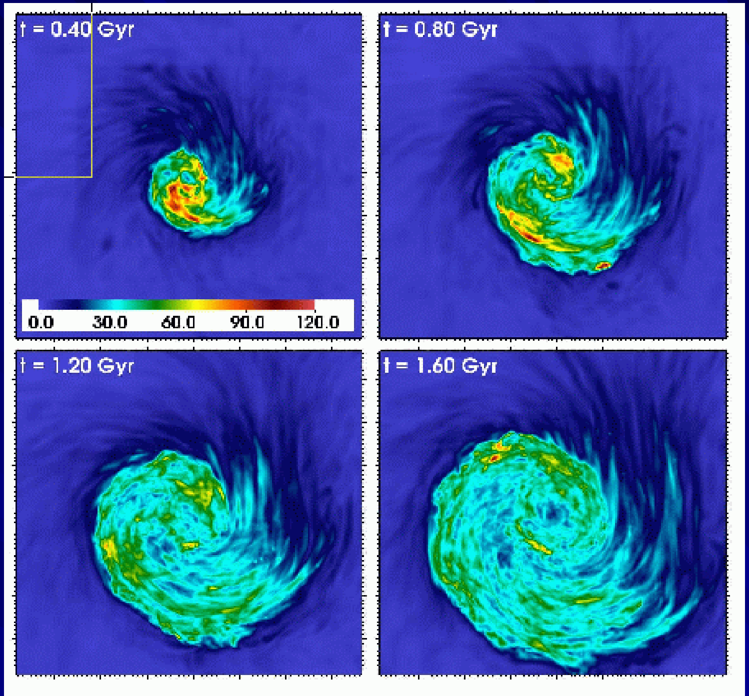


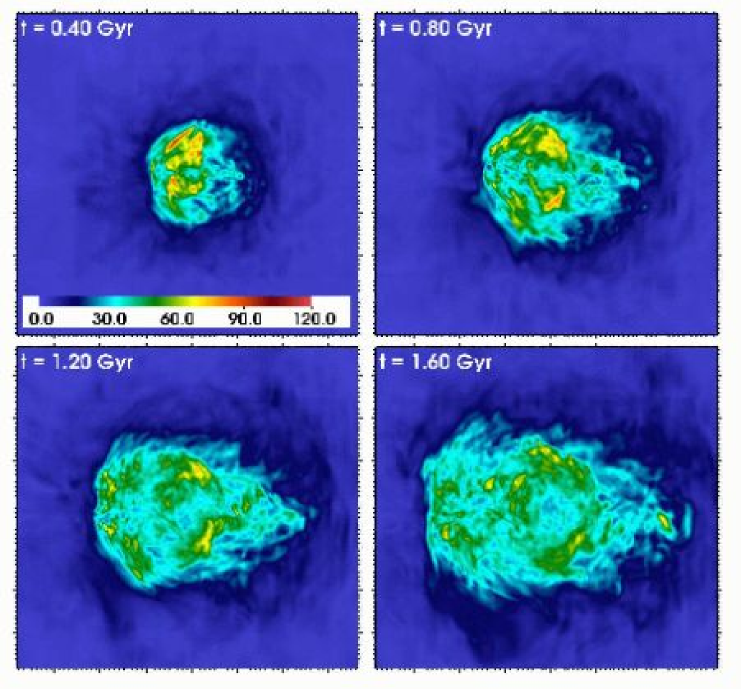
Magnetic field





Turbulence (δv)





Turbulence in the IGM

(from Brunetti & Lazarian 2007, 2011)

$L_o \sim 100 – 300$ kpc

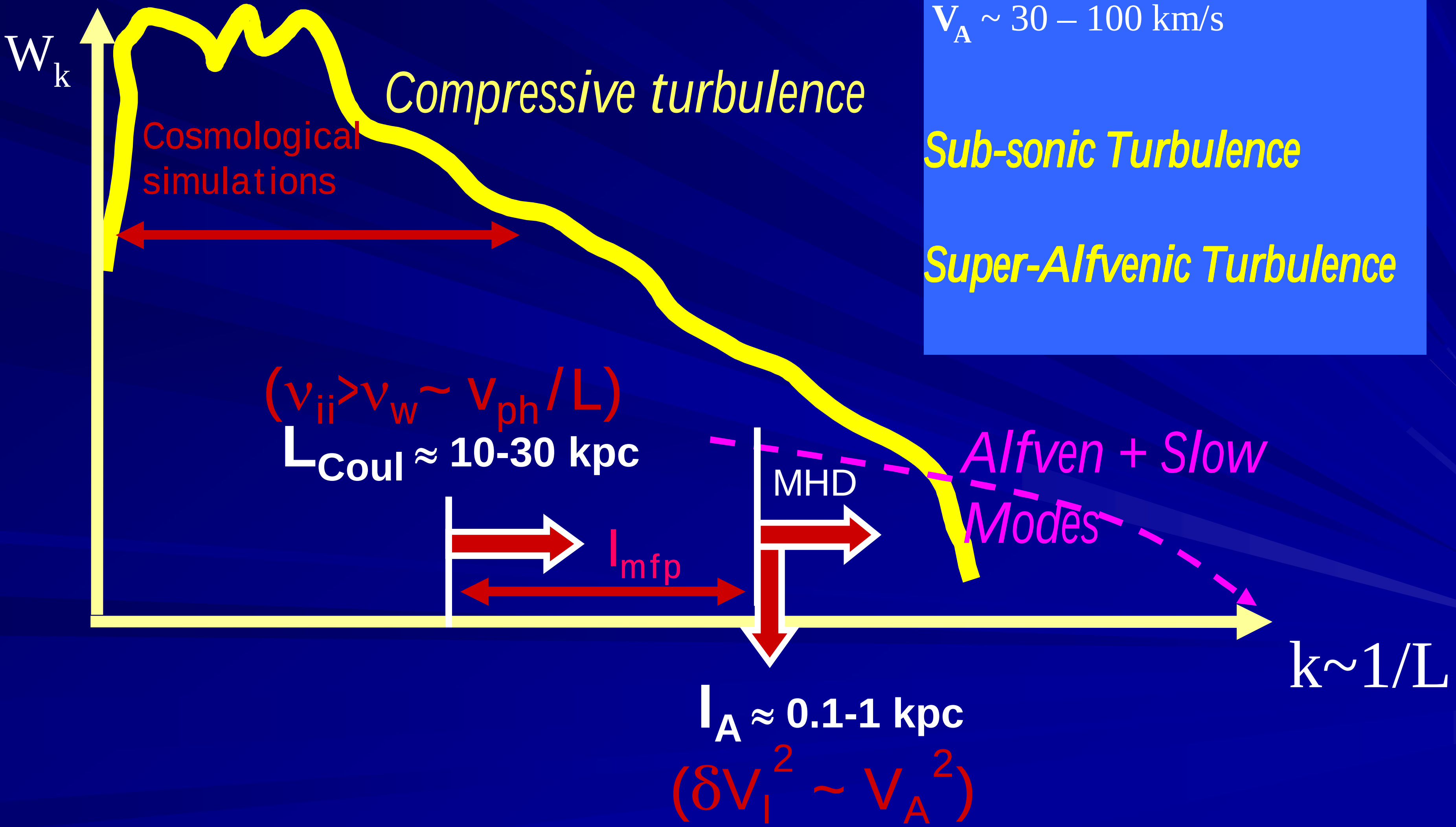
$V_o \sim 200 – 700$ km/s

$c_s \sim 1200 – 1800$ km/s

$V_A \sim 30 – 100$ km/s

Sub-sonic Turbulence

Super-Alfvenic Turbulence



W_k

Compressive turbulence

Cosmological simulations

$(\nu_{ii} > \nu_w \sim v_{ph}/L)$

$L_{Coul} \approx$ **10-30 kpc**

MHD

l_{mfp}

Alfven + Slow Modes

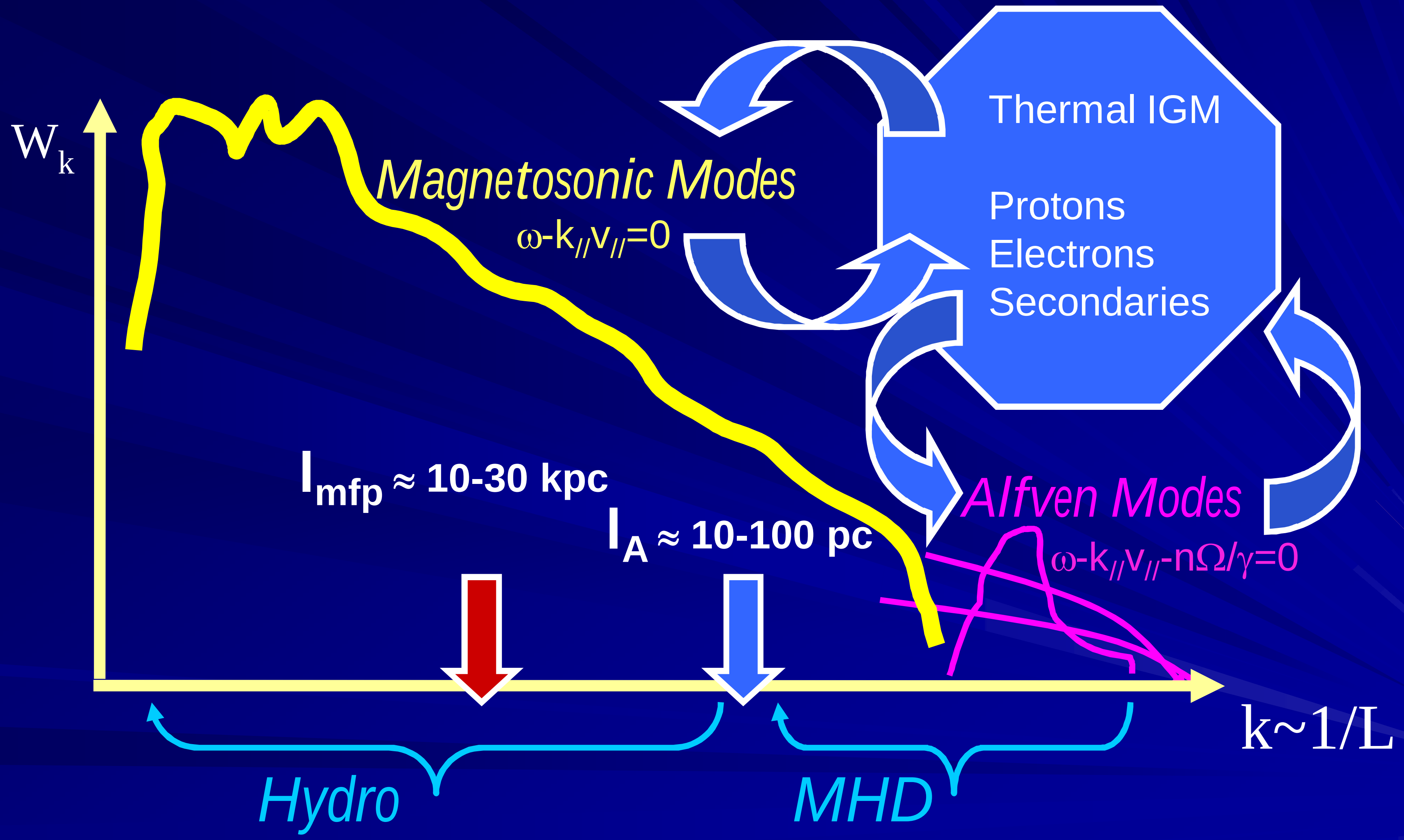
$l_A \approx$ **0.1-1 kpc**

$(\delta V_l^2 \sim V_A^2)$

k~1/L

Turbulence in the ICM: complex

Subramanian +al 2006; Schekochihin +al 2005,09; Brunetti & Lazarian 2007,11; Sharma +al 2010; Kunz +al 2010



Thermal IGM

Protons
Electrons
Secondaries

Magnetosonic Modes

$\omega - k_{//} v_{//} = 0$

Alfven Modes

$\omega - k_{//} v_{//} - n\Omega/\gamma = 0$

$l_{mfp} \approx$ 10-30 kpc

$l_A \approx$ 10-100 pc

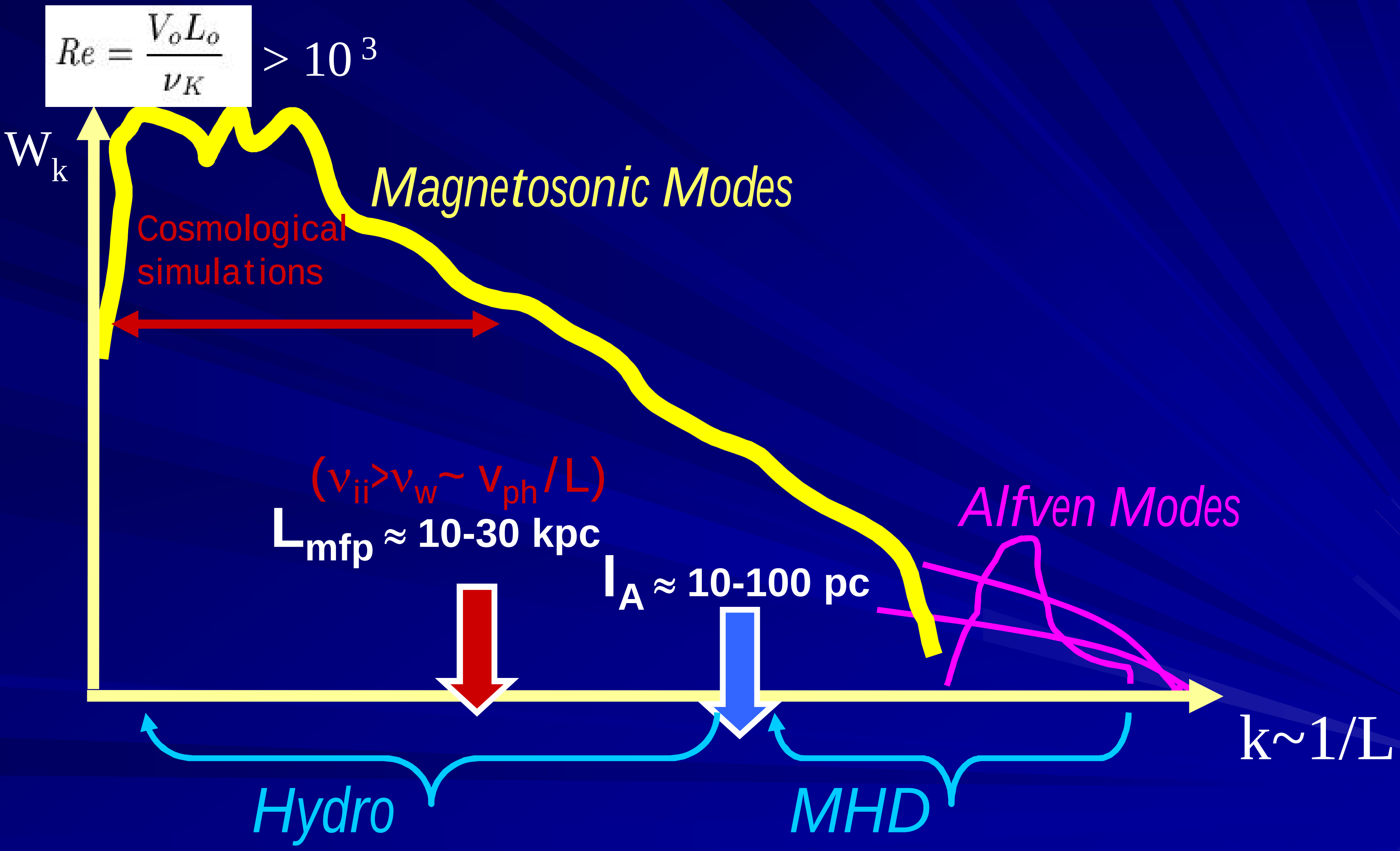
Hydro

MHD

The generation of small scale MHD modes in the ICM is a totally open issue

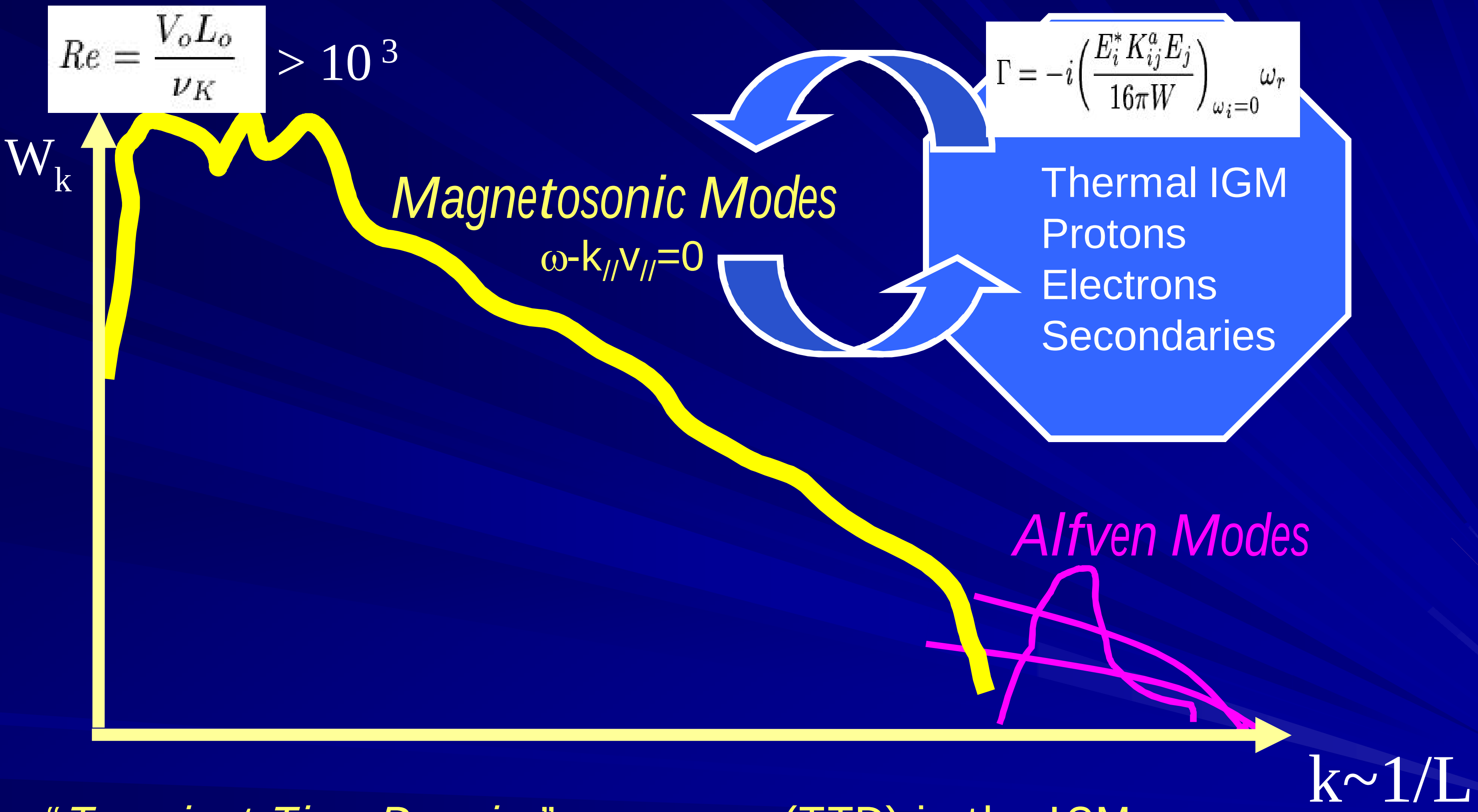
(see Schekochihin et al 2005, 09, Lazarian & Beresnyak 2009, Yan & Lazarian 2010, Brunetti & Lazarian 11)

Turbulence in the IGM: complex



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

Turbulence in the IGM: complex

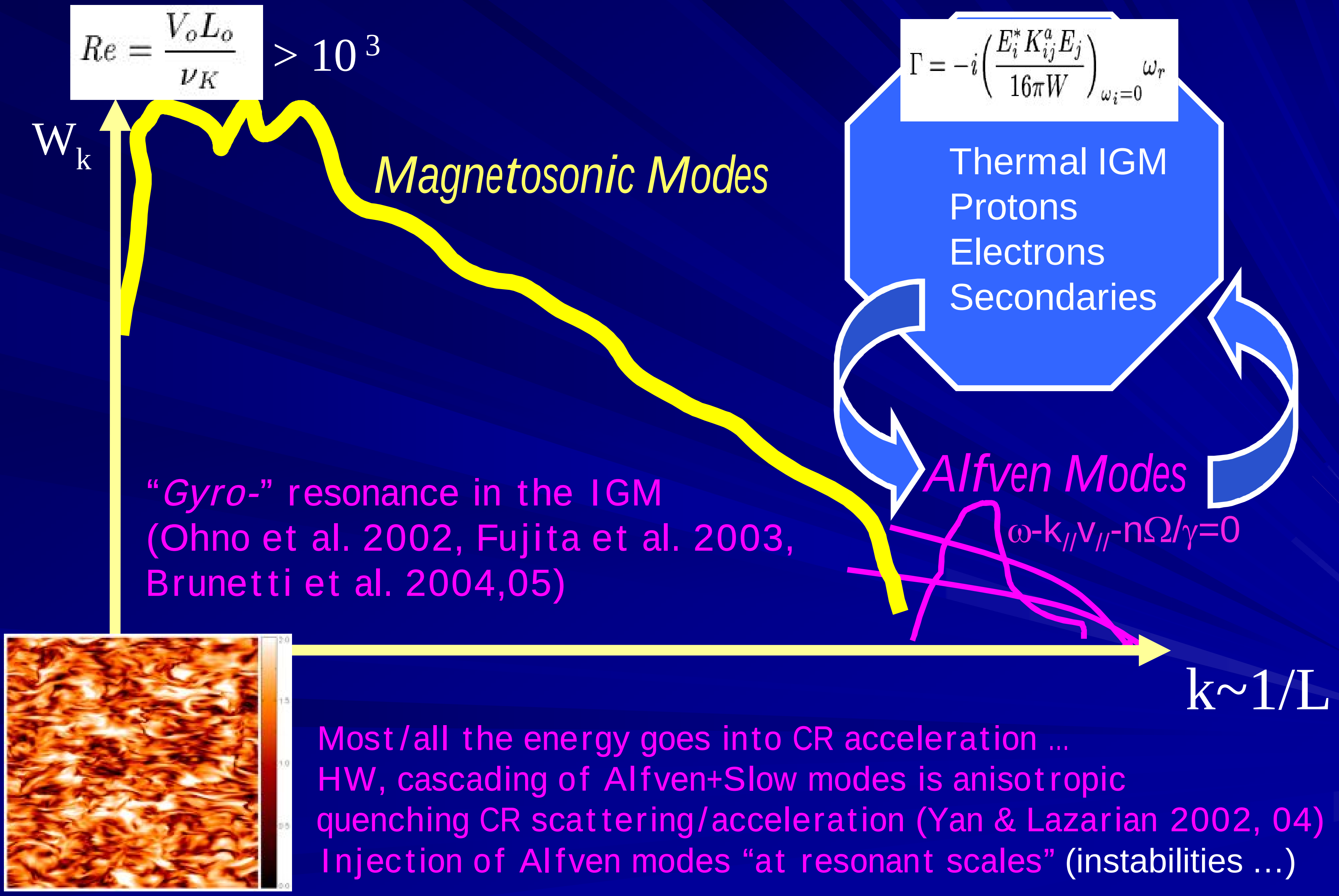


$$Re = \frac{V_o L_o}{\nu_K} > 10^3$$

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

"*Transient Time Damping*" resonance (TTD) in the IGM
(Cassano & Brunetti 2005, Brunetti & Lazarian 2007,11a)
Which is the fraction of turbulent-energy in CR acceleration ?
(see Brunetti & Lazarian 2011b)

Turbulence in the IGM: complex



"*Gyro-*" resonance in the IGM
(Ohno et al. 2002, Fujita et al. 2003,
Brunetti et al. 2004,05)

Most/all the energy goes into CR acceleration …
HW, cascading of Alfven+Slow modes is anisotropic
quenching CR scattering/acceleration (Yan & Lazarian 2002, 04)
Injection of Alfven modes "at resonant scales" (instabilities …)

Effects of the NL interaction of particles-waves on CR evolution

(Book reviews : Melrose 1980, Berezinskii et al 1990, Schlickeiser 2002)

The diffusion coefficients define characteristics of particle propagation and acceleration

Propagation $\nu = 2D_{\mu\mu}/(1-\mu^2)$ $\quad \lambda_{\|} = \frac{3}{4}\int d\mu \frac{v(1-\mu^2)^2}{D_{\mu\mu}}$

Stochastic Acceleration $A(E) = \frac{\partial[vp^2 D(p)]}{4p^2 \partial p}, \; D(p) = \frac{1}{2}\int_{-1}^{1} D_{pp} d\mu$

$D_{\mu\mu} \longleftrightarrow \delta B,$

$D_{pp} \longleftrightarrow \delta E = \delta v \times B_0/c$

Acceleration is sensitive to our model of turbulence

Where do δB, δv come from? MHD turbulence!

- The diffusion coeffecients are determined by the statistical properties of turbulence

Stochastic acceleration of fast particles diffusing in turbulence (Fermi 1949, ... Ptuskin 1988)

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

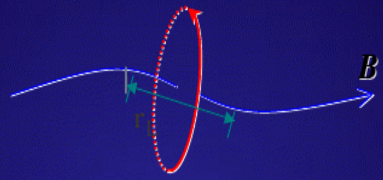
Gyroresonance scattering depends on the properties of turbulence

Gyroresonance

$\omega - k_{\|} v_{\|} = n\Omega$, $(n = \pm 1, \pm 2 \ldots)$,

Which states that the MHD wave frequency (Doppler shifted) is a multiple of gyrofrequency of particles ($v_{\|}$ is particle speed parallel to **B**).

So, $k_{\|,res} \sim \Omega/v = 1/r_L$



Transit Time Damping (TTD)

$$\omega - k_{//} v_{//} = 0$$

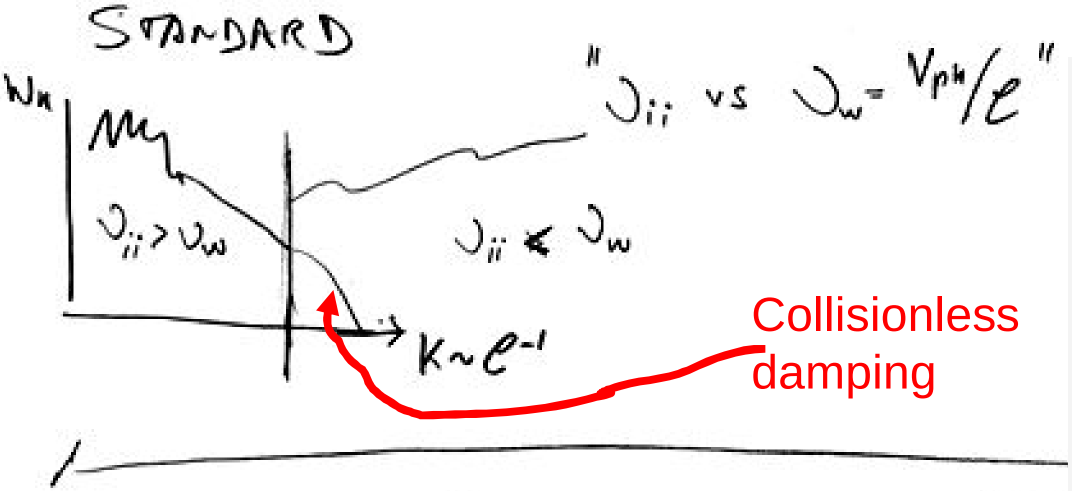
Interaction btw magnetic moment of particle and parallel gradient of B

Suitable for ICM !

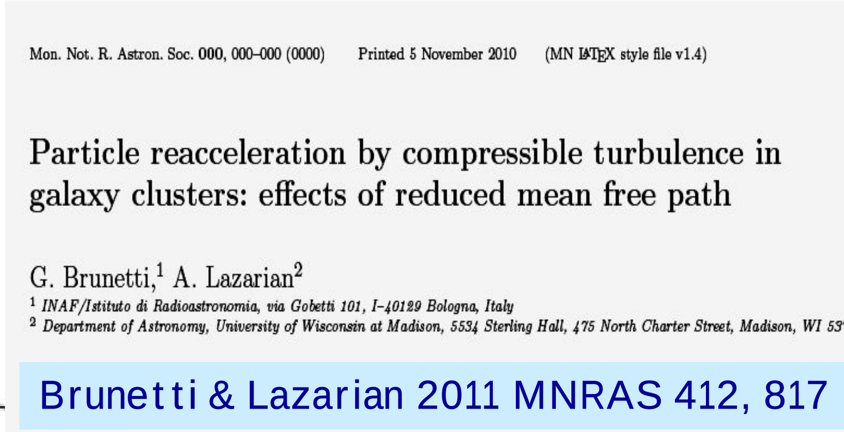
Isotropic fast modes

(Cassano & Brunetti 05, Yan et al 10, Brunetti & Lazarian 07, 11)

Comment on turbulent acceleration efficiency in ICM



Collisionless damping



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Particle reacceleration by compressible turbulence in galaxy clusters: effects of reduced mean free path

G. Brunetti,[1] A. Lazarian[2]

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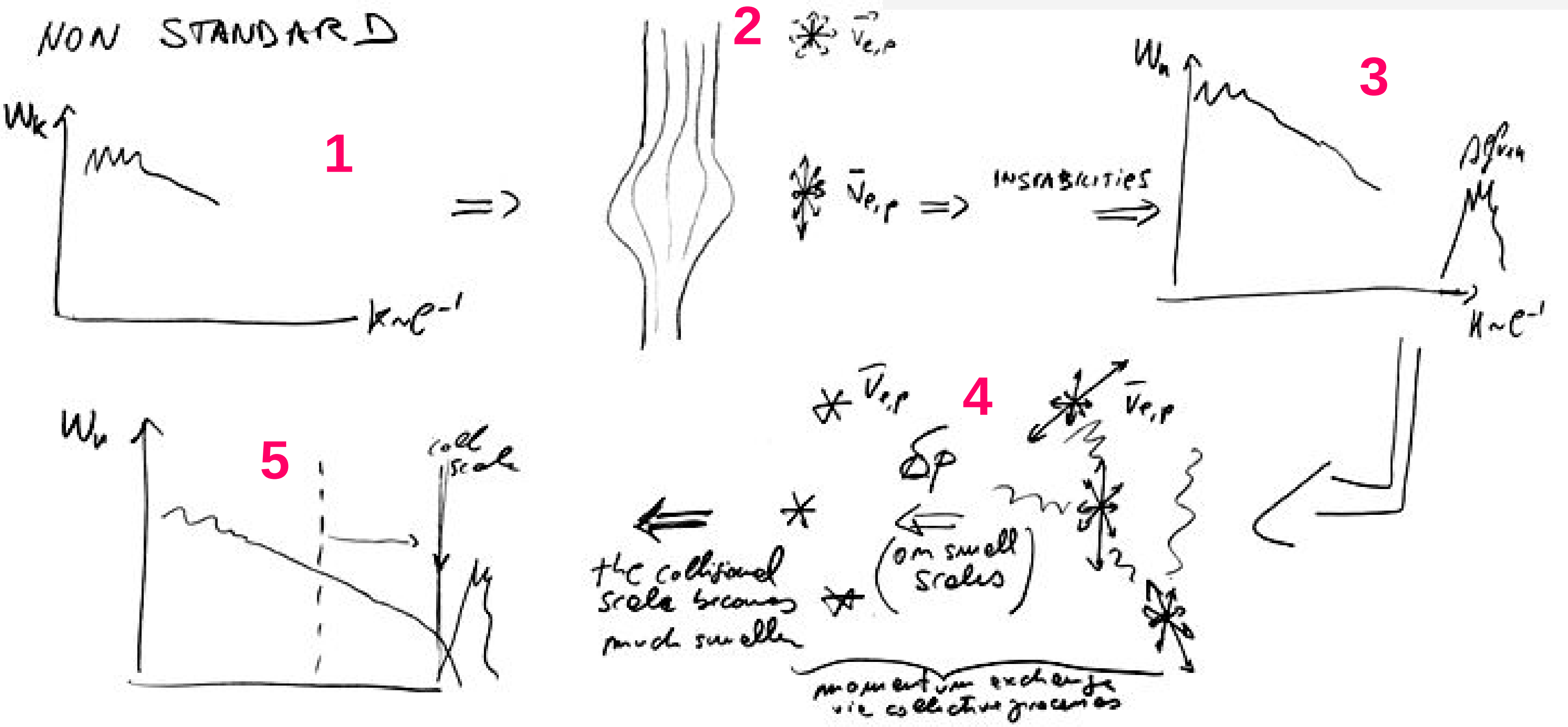
[2] Department of Astronomy, University of Wisconsin at Madison, 5534 Sterling Hall, 475 North Charter Street, Madison, WI 53

Brunetti & Lazarian 2011 MNRAS 412, 817

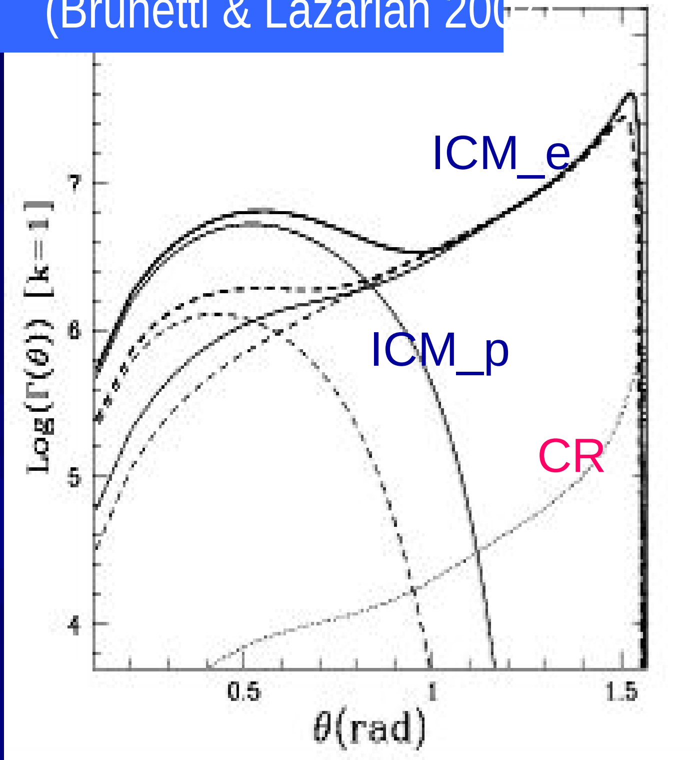


Heating of ICM & CR-acceleration by compressible turbulence in the ICM

QLTheory

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

(Brunetti & Lazarian 200



The most important damping of compressive (fast) modes in the ICM is via "magnetic Landau" damping (n=0 resonance, Transit Time Damping) with thermal electrons and protons (CR contribute for < 10%).

Thermal ICM back-reacts on the turbulence, modifies its spectrum and affects CR acceleration...

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

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

Isotropic Effective Damping

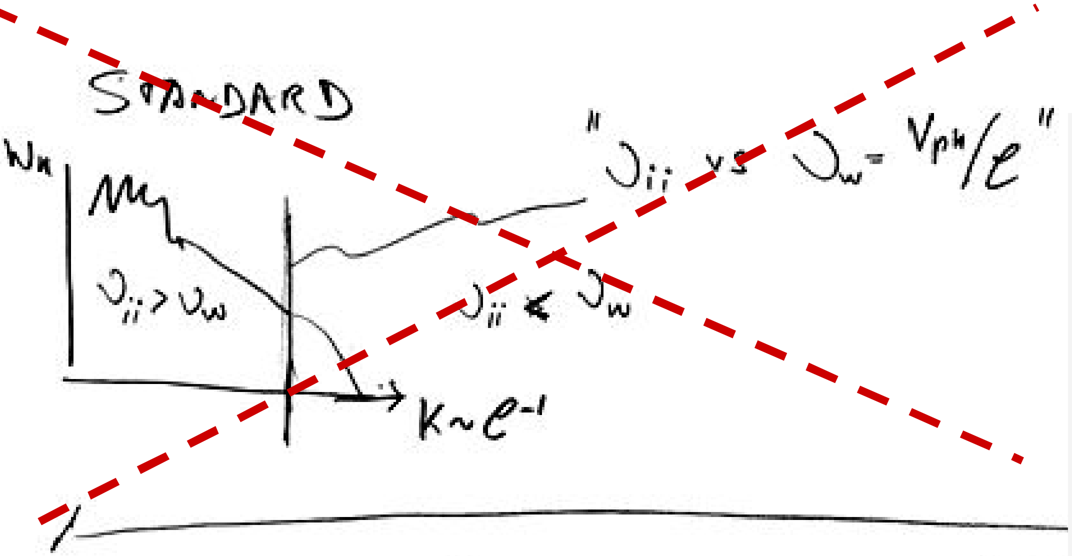
$l_{diss} \approx 100$ pc

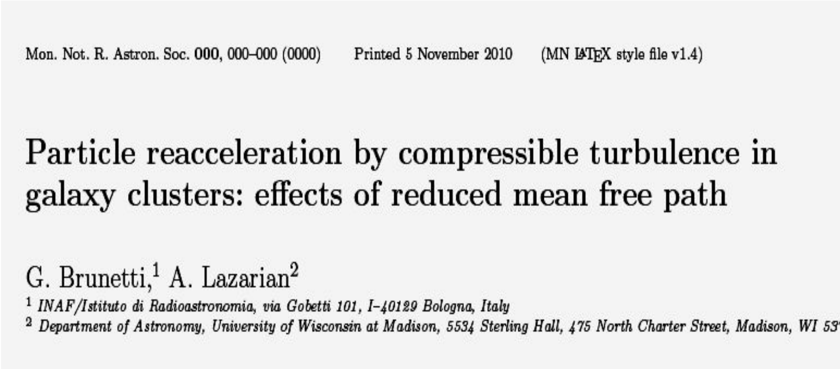
CRp/e

$D_{pp} \sim V_L^4 L^{-1}$

+ observables

STANDARD





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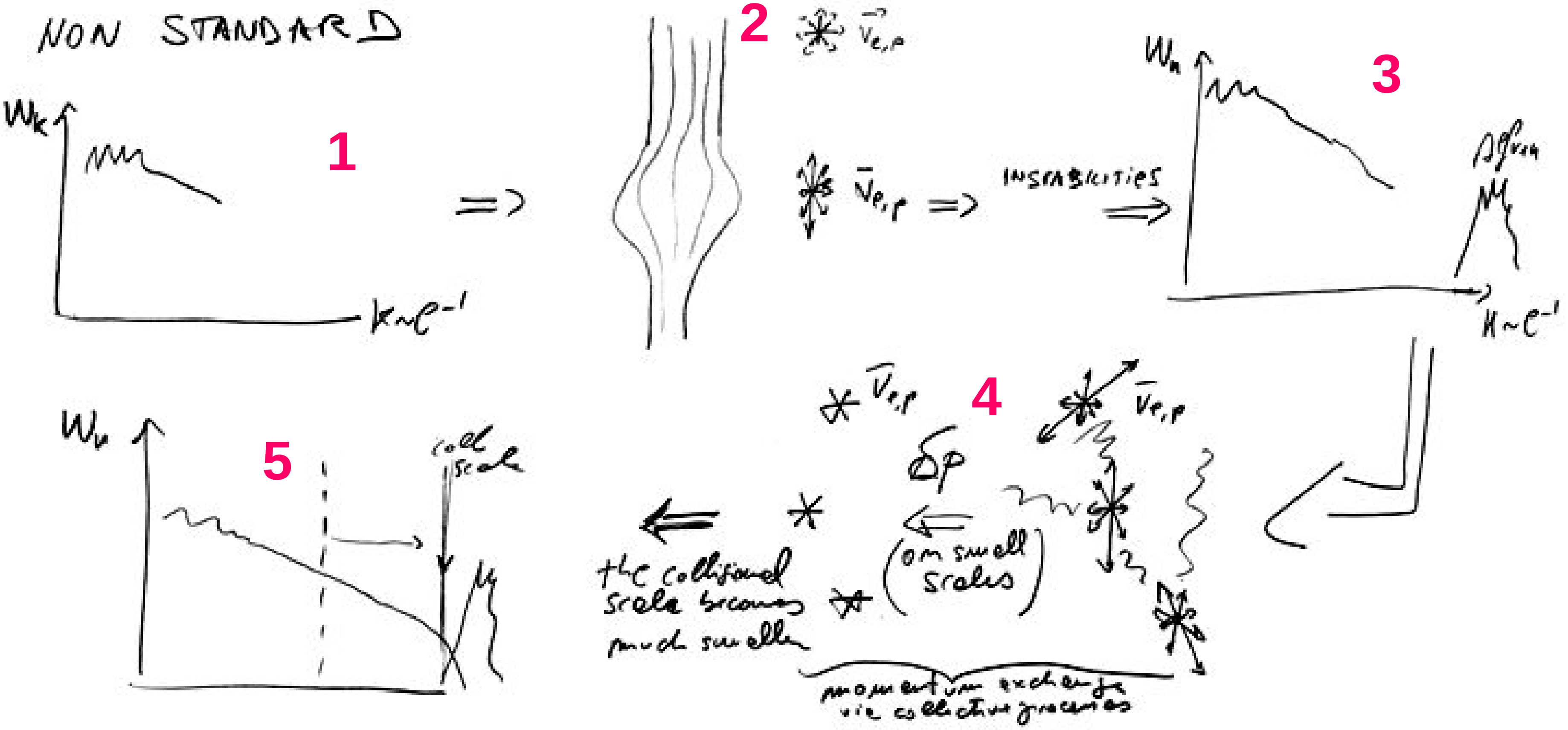
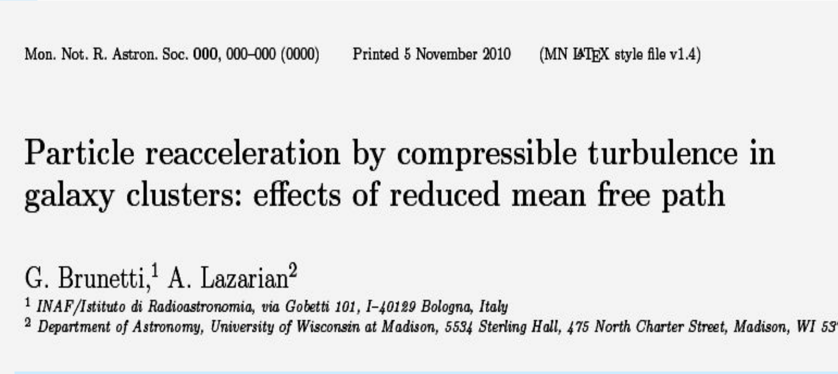
Brunetti & Lazarian 2011 MNRAS 412, 817

NON STANDARD



Damping of turbulence is dominated by CR that back react on turbulence as their energy density increases

$$D_{pp} \simeq 2 c_w c_k^{1/2} \frac{p^2 I_o^f}{\sum_{e,p} \int dp p^2 c \left| \frac{\partial N}{\partial p} - 2\frac{N}{p} \right|} \sim I_o E_{cr}^{-1}$$



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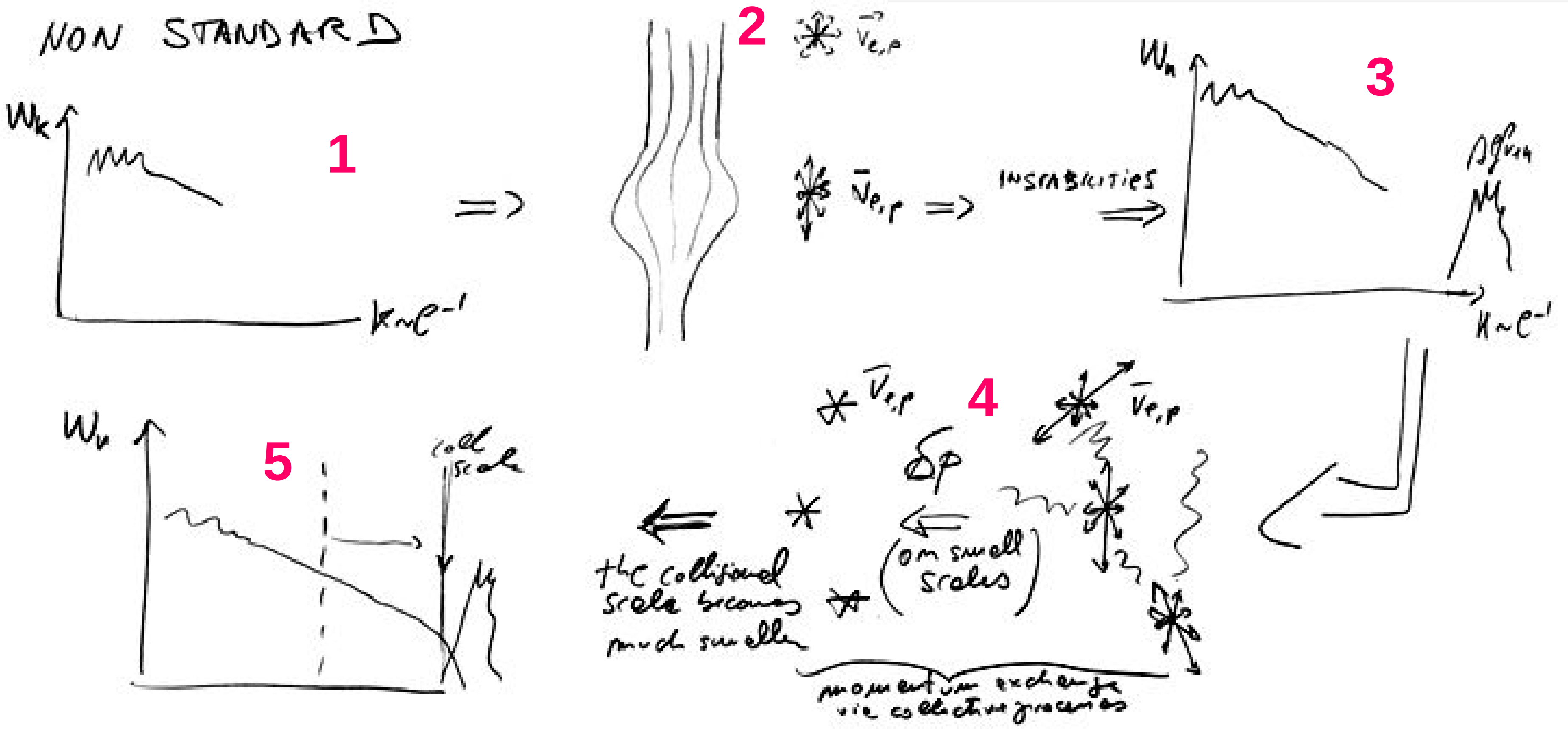

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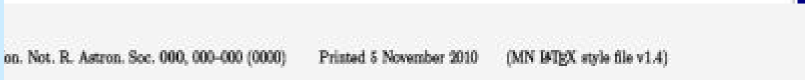
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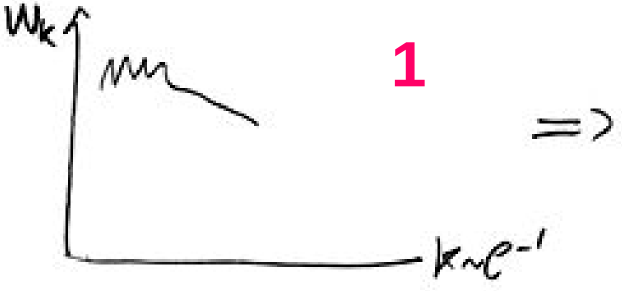
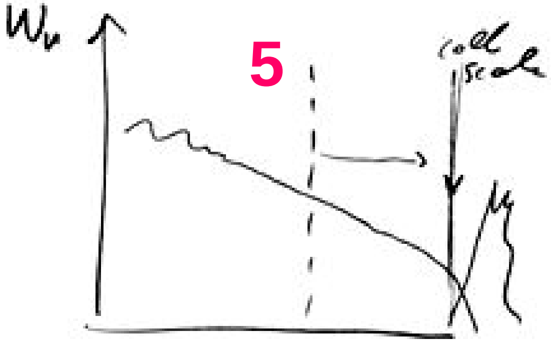
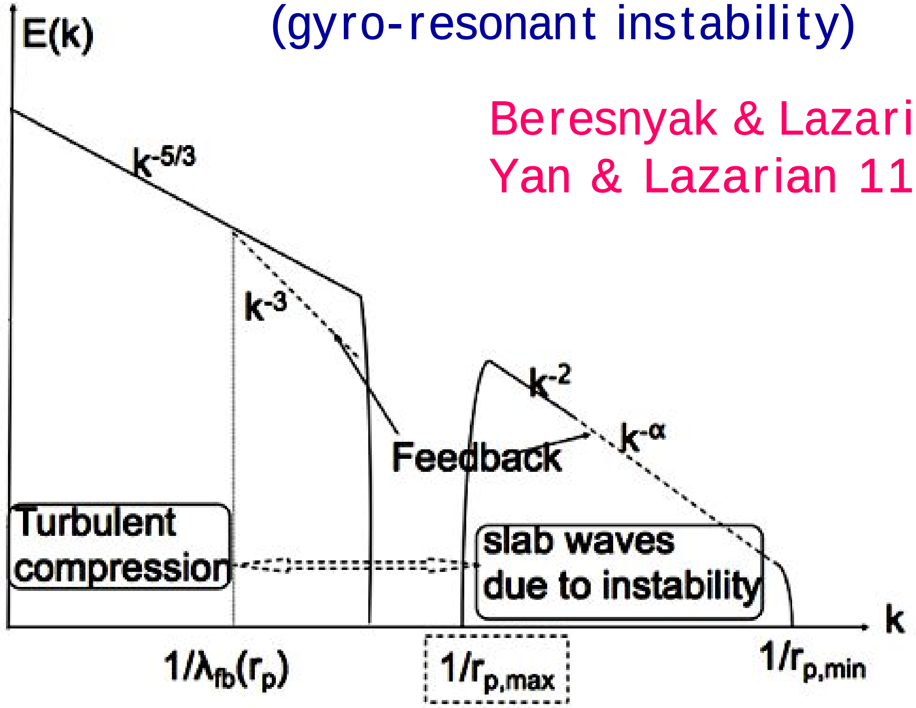




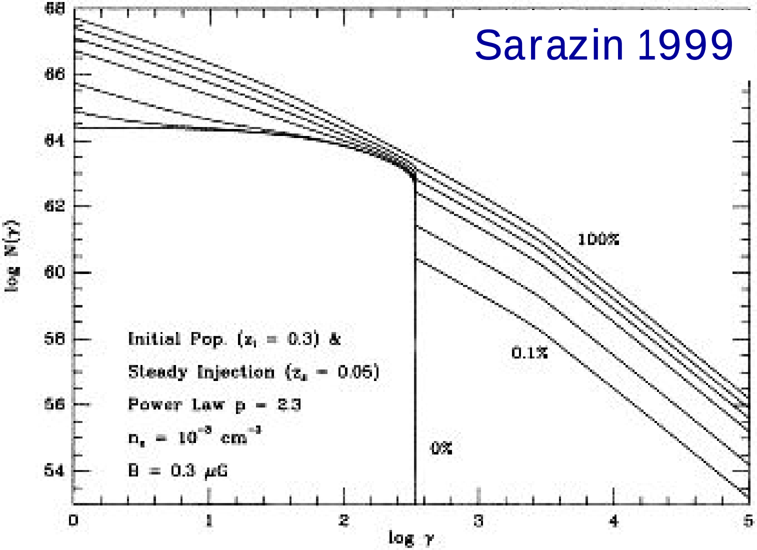
Feedback by CR
(gyro-resonant instability)

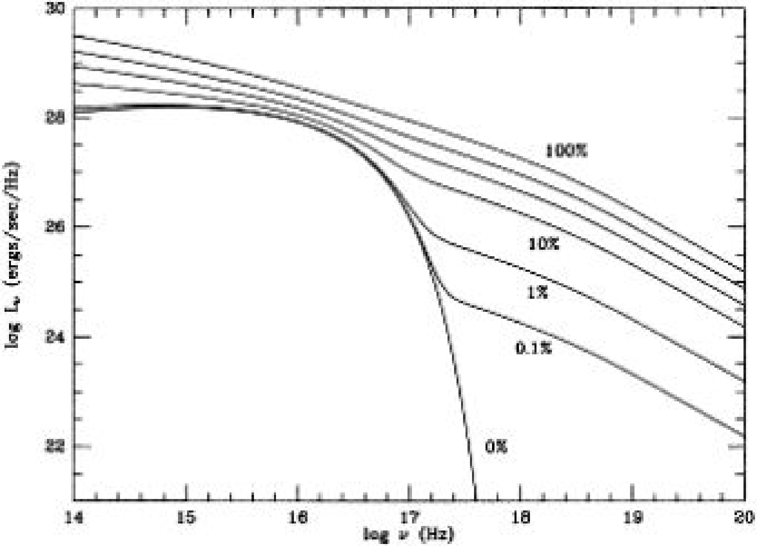
Beresnyak & Lazarian 06
Yan & Lazarian 11

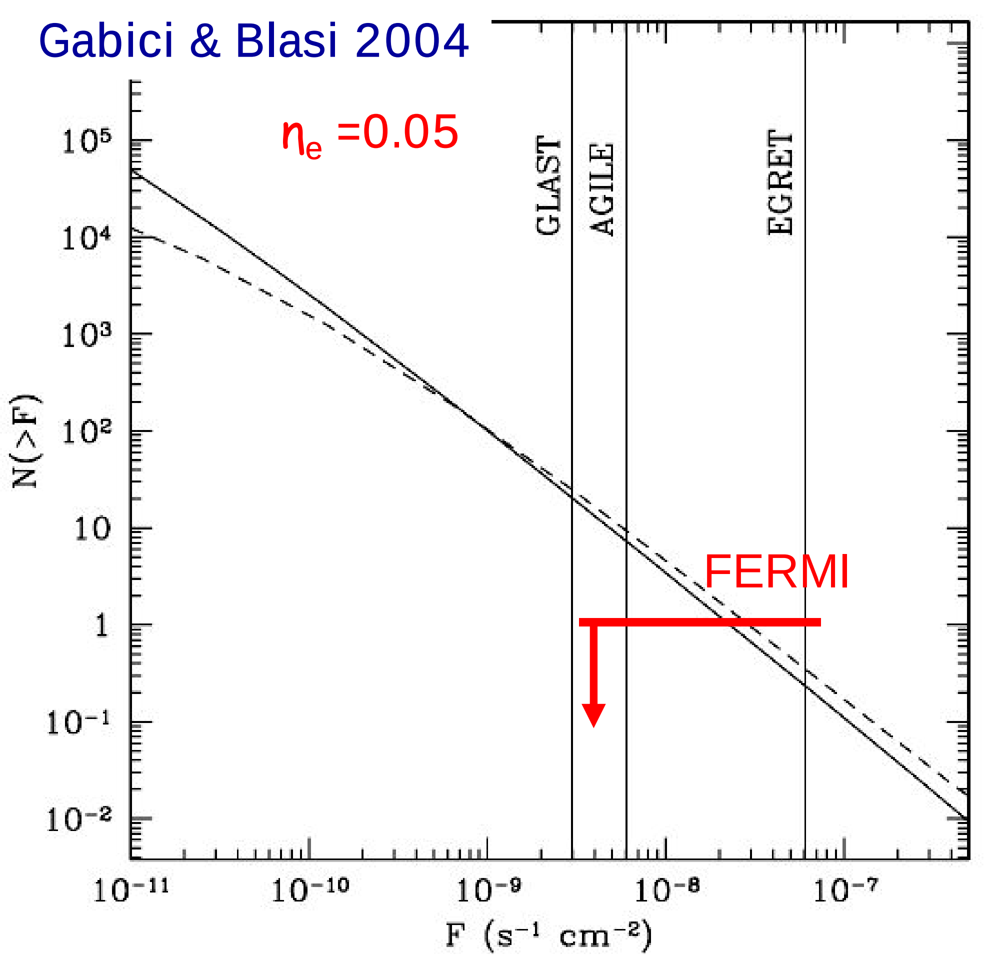


Shock Acceleration CRe : ICS

(Sarazin 1999, Waxman & Loeb 2000, Blasi 2001, ..)


Sarazin 1999




Gabici & Blasi 2004

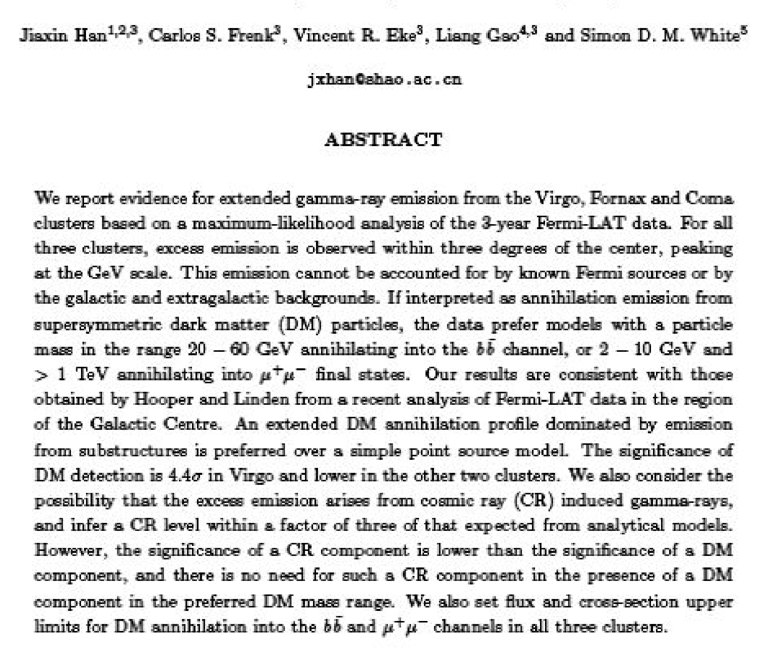
η_e =0.05

FERMI

FERMI upper limits constrain the efficiency of electrons acceleration at shocks in galaxy clusters $\eta_e < 0.005$

Better constraints with FERMI ??

Han et al 2012, arXiv



Evidence for extended gamma-ray emission from galaxy clusters

Jiaxin Han[1,2,3], Carlos S. Frenk[3], Vincent R. Eke[3], Liang Gao[4,3] and Simon D. M. White[5]

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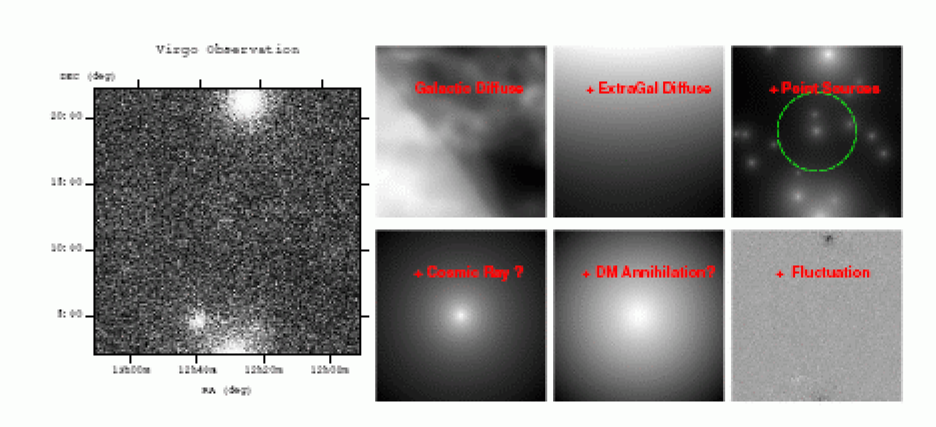
ABSTRACT

We report evidence for extended gamma-ray emission from the Virgo, Fornax and Coma clusters based on a maximum-likelihood analysis of the 3-year Fermi-LAT data. For all three clusters, excess emission is observed within three degrees of the center, peaking at the GeV scale. This emission cannot be accounted for by known Fermi sources or by the galactic and extragalactic backgrounds. If interpreted as annihilation emission from supersymmetric dark matter (DM) particles, the data prefer models with a particle mass in the range 20 – 60 GeV annihilating into the $b\bar{b}$ channel, or 2 – 10 GeV and > 1 TeV annihilating into $\mu^+\mu^-$ final states. Our results are consistent with those obtained by Hooper and Linden from a recent analysis of Fermi-LAT data in the region of the Galactic Centre. An extended DM annihilation profile dominated by emission from substructures is preferred over a simple point source model. The significance of DM detection is 4.4σ in Virgo and lower in the other two clusters. We also consider the possibility that the excess emission arises from cosmic ray (CR) induced gamma-rays, and infer a CR level within a factor of three of that expected from analytical models. However, the significance of a CR component is lower than the significance of a DM component, and there is no need for such a CR component in the presence of a DM component in the preferred DM mass range. We also set flux and cross-section upper limits for DM annihilation into the $b\bar{b}$ and $\mu^+\mu^-$ channels in all three clusters.



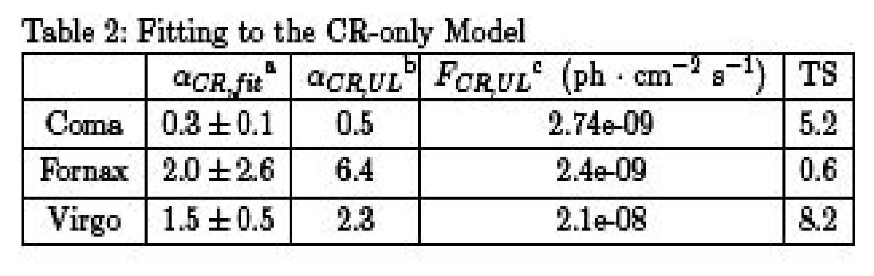
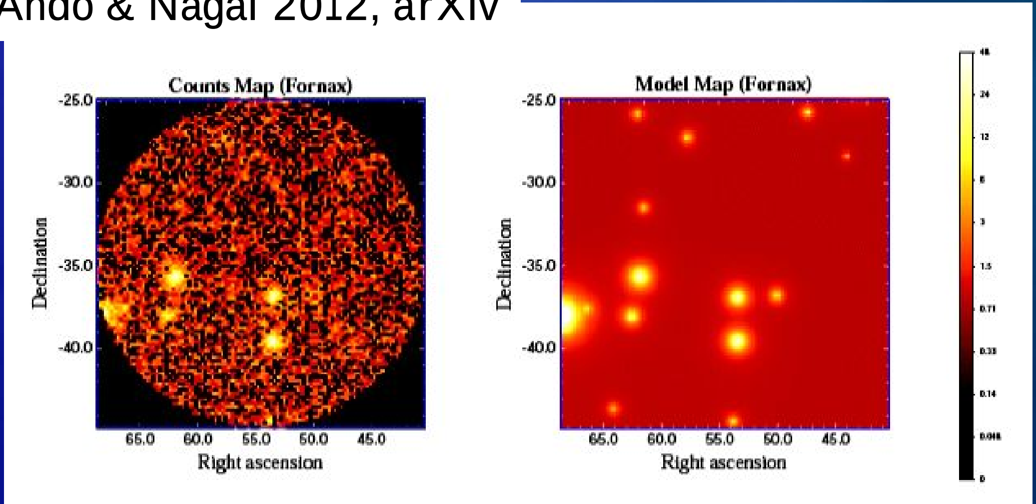


Table 2: Fitting to the CR-only Model

	$\alpha_{CR,fit}$[a]	$\alpha_{CR,UL}$[b]	$F_{CR,UL}$[c] (ph · cm^{-2} s^{-1})	TS
Coma	0.3 ± 0.1	0.5	2.74e-09	5.2
Fornax	2.0 ± 2.6	6.4	2.4e-09	0.6
Virgo	1.5 ± 0.5	2.3	2.1e-08	8.2

5e-09
5e-09
15e-09

Ando & Nagai 2012, arXiv



Similar u.l. for Coma and Fornax have been derived by Han et al and Ando & Nagai (3+ years)… These limits are more than 2 times deeper than those derived by Ackermann et al. (18 months)

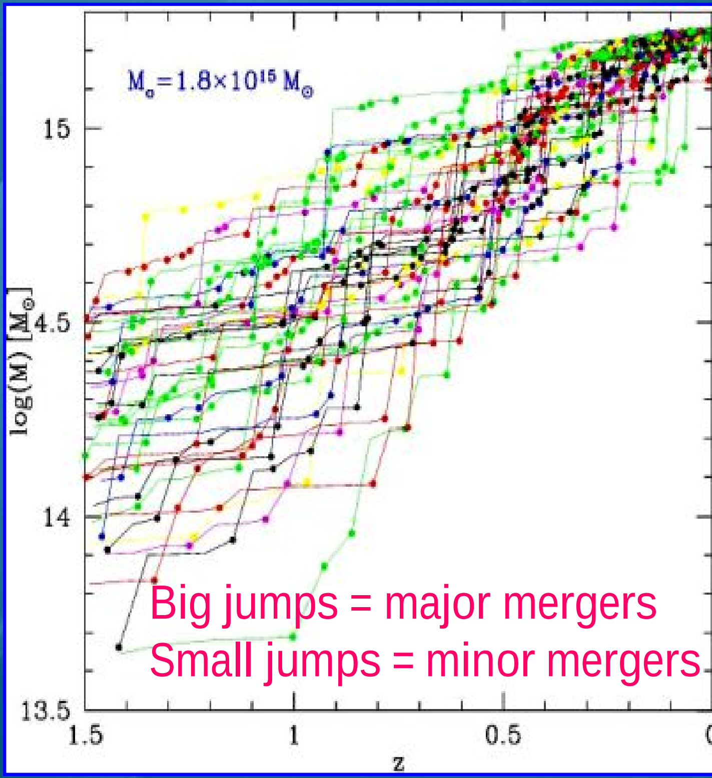
Testing turbulent models ??

Acceleration efficiency

$\chi \approx 1/\tau_{acc}$

Steepening frequency

$$\nu_b \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$

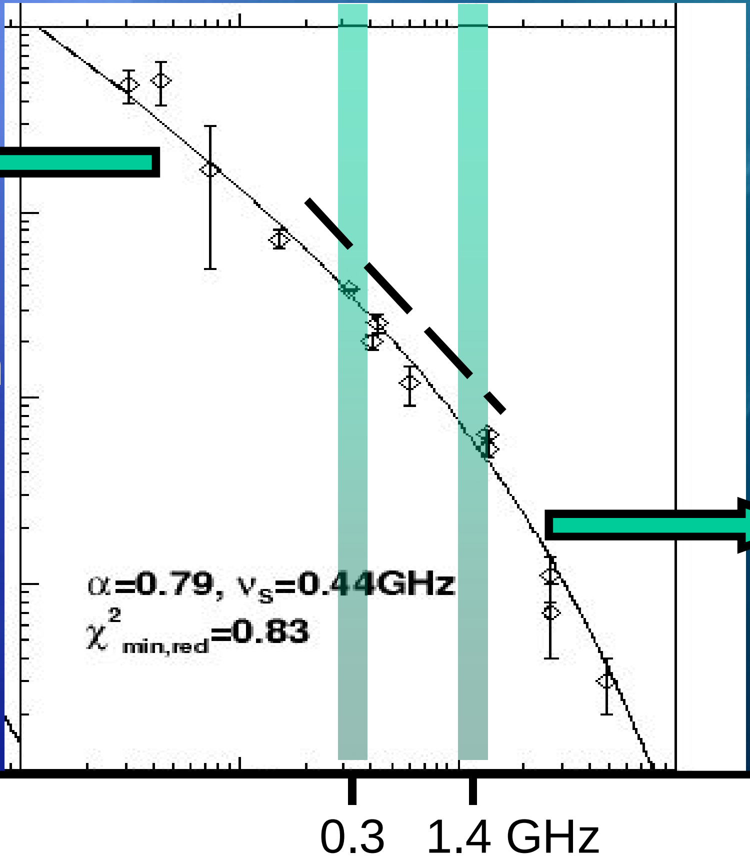


Big jumps = major mergers

Small jumps = minor mergers

less efficient

Mergers between $M<10^{15}M_{sun}$



Mergers between $M>10^{15}M_{sun}$

more efficient

Testing turbulent models ??

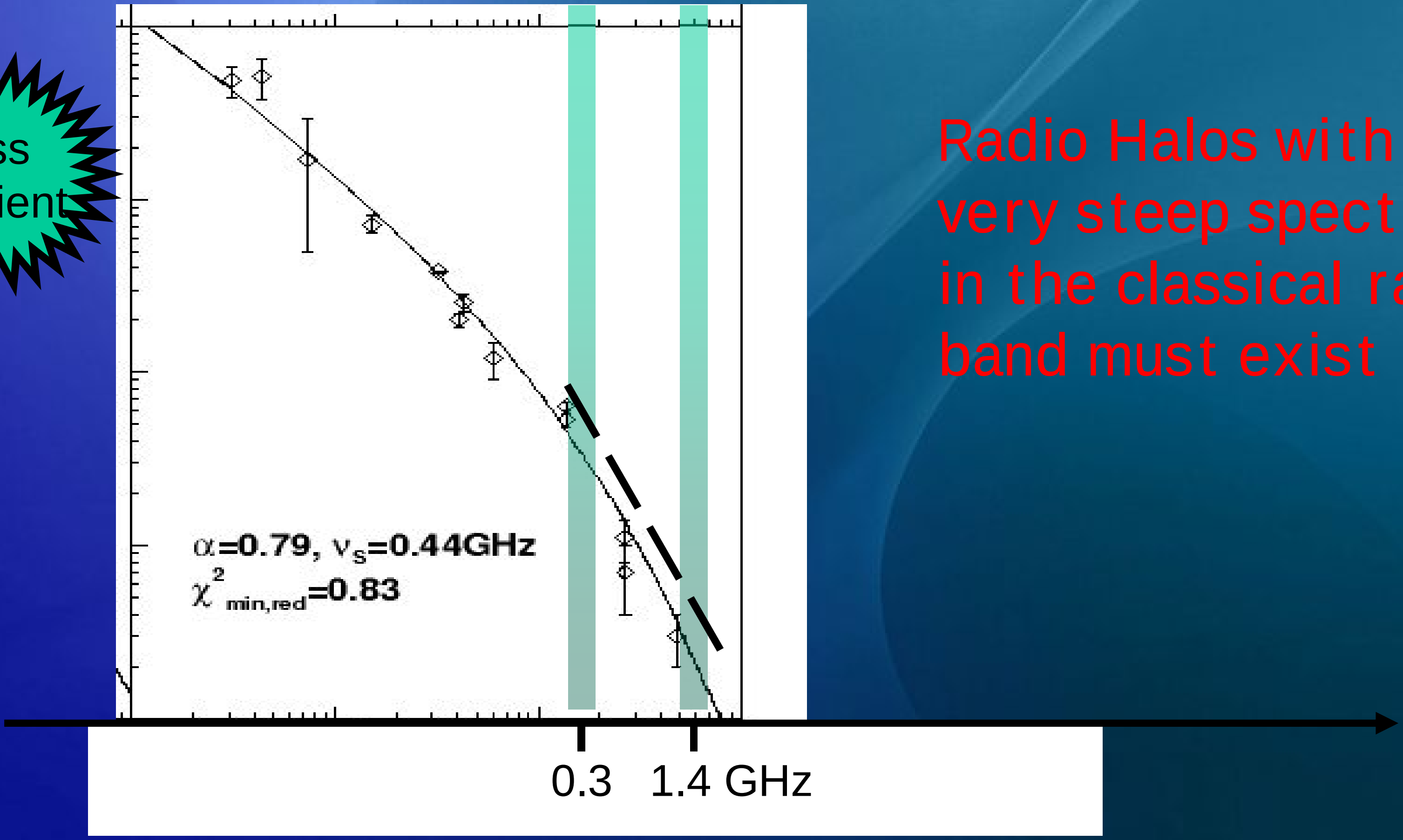
Cassano, GB, Setti (2006)

Steepening frequency

$$\nu_b \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$

$$\chi \approx 1/\tau_{acc}$$

less efficient



Radio Halos with very steep spectrum in the classical radio band must exist

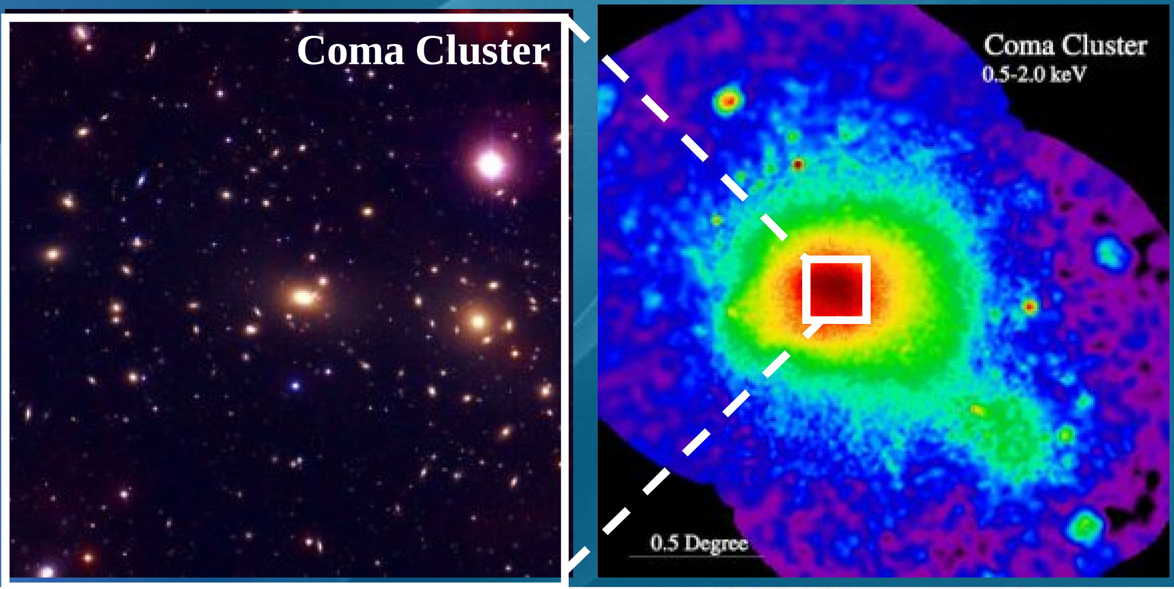
Clusters of galaxies: the largest gravitational structures in the Universe ($M \approx 10^{14}$-$10^{15} M_{sun}$, $R_V \approx$ 2-3 Mpc)

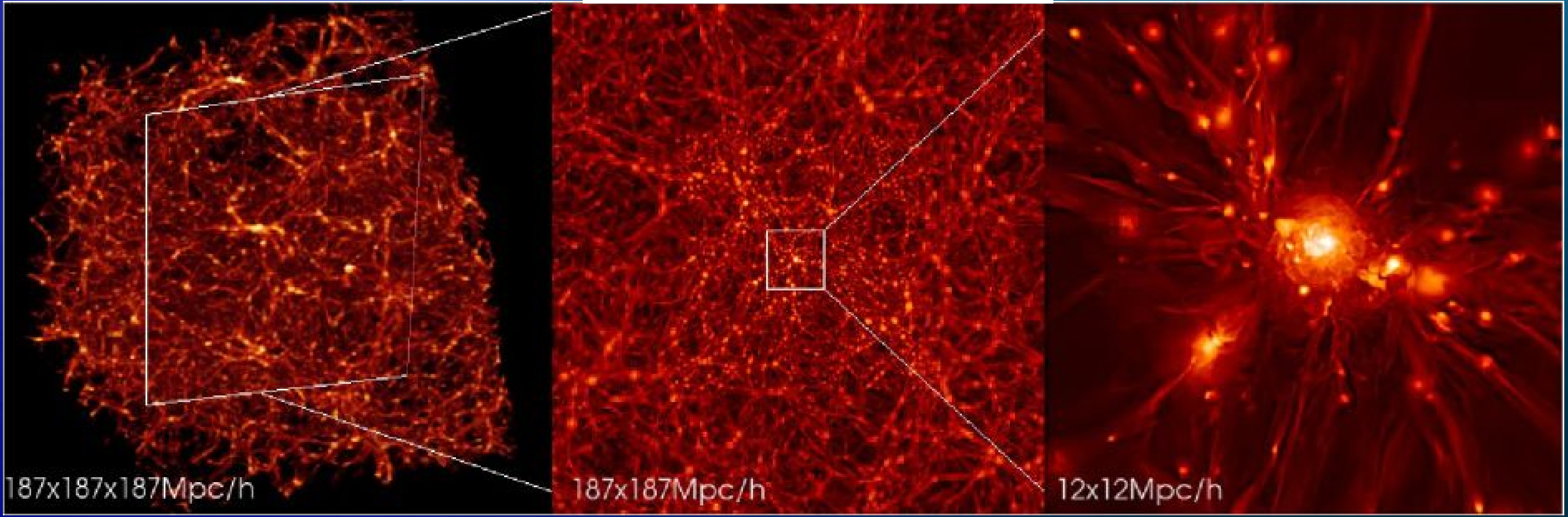
Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

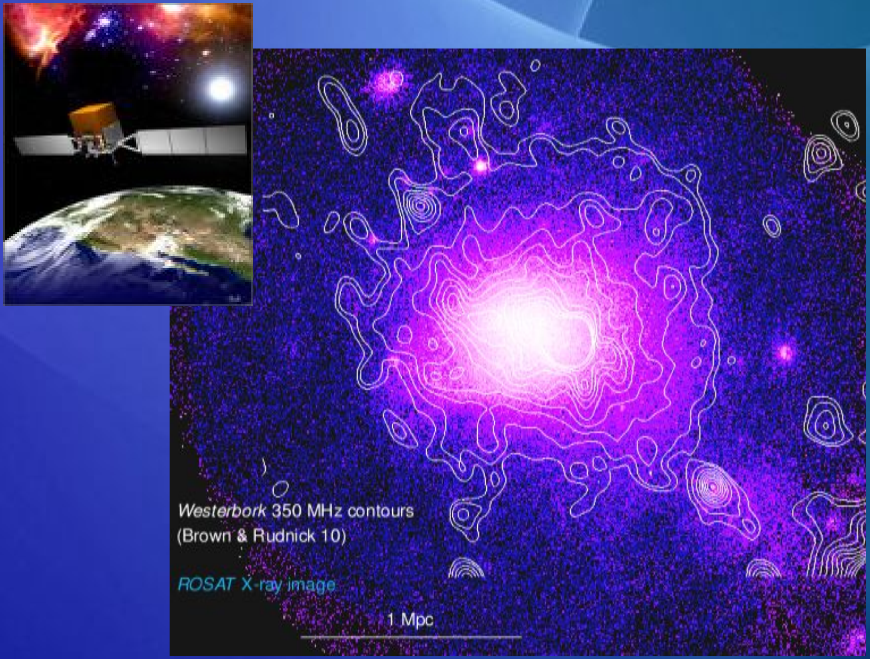
Dark Matter **70%**

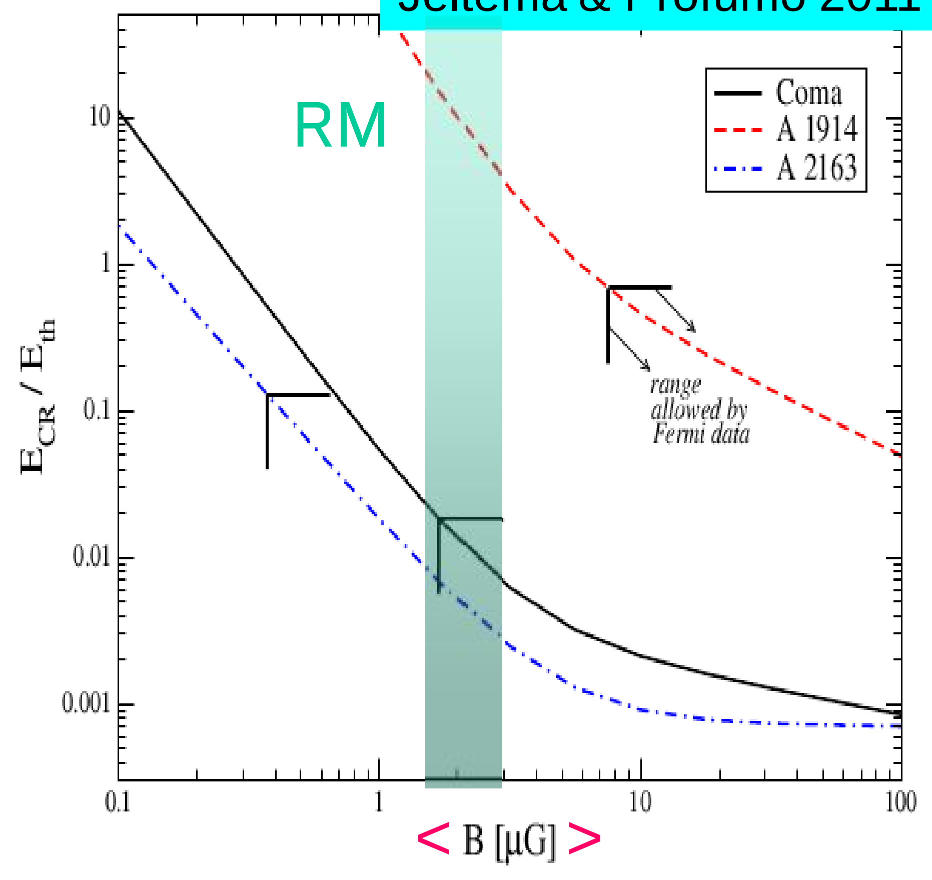




Testing hadronic models for Halos

also Marchegiani et al 07,
Brunetti 09, Donnert et al 10



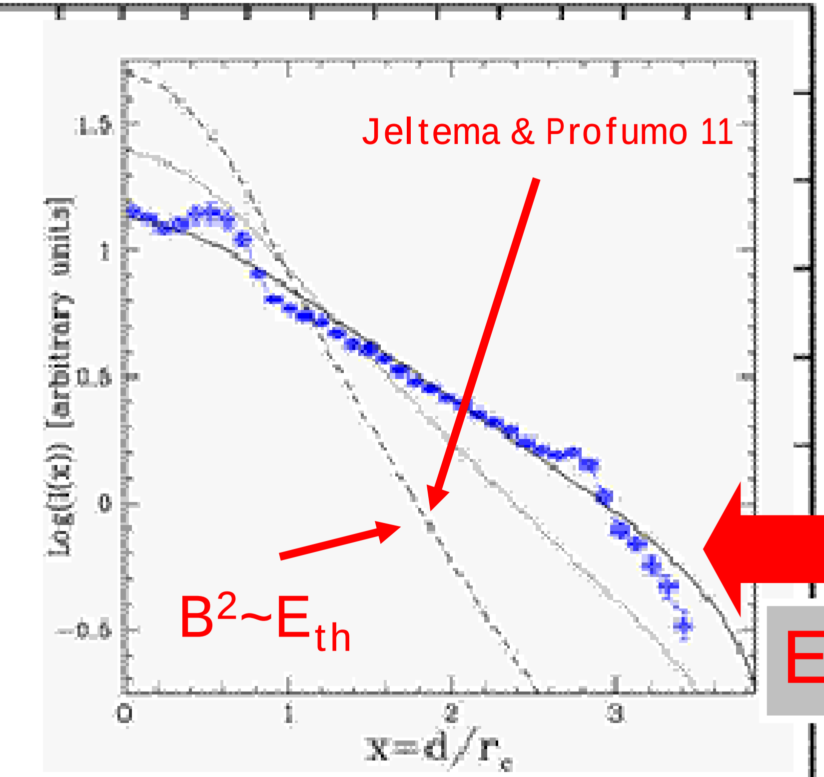

Jeltema & Profumo 2011

$L_{\gamma,\pi} \sim f_{\gamma}(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{\gamma}$

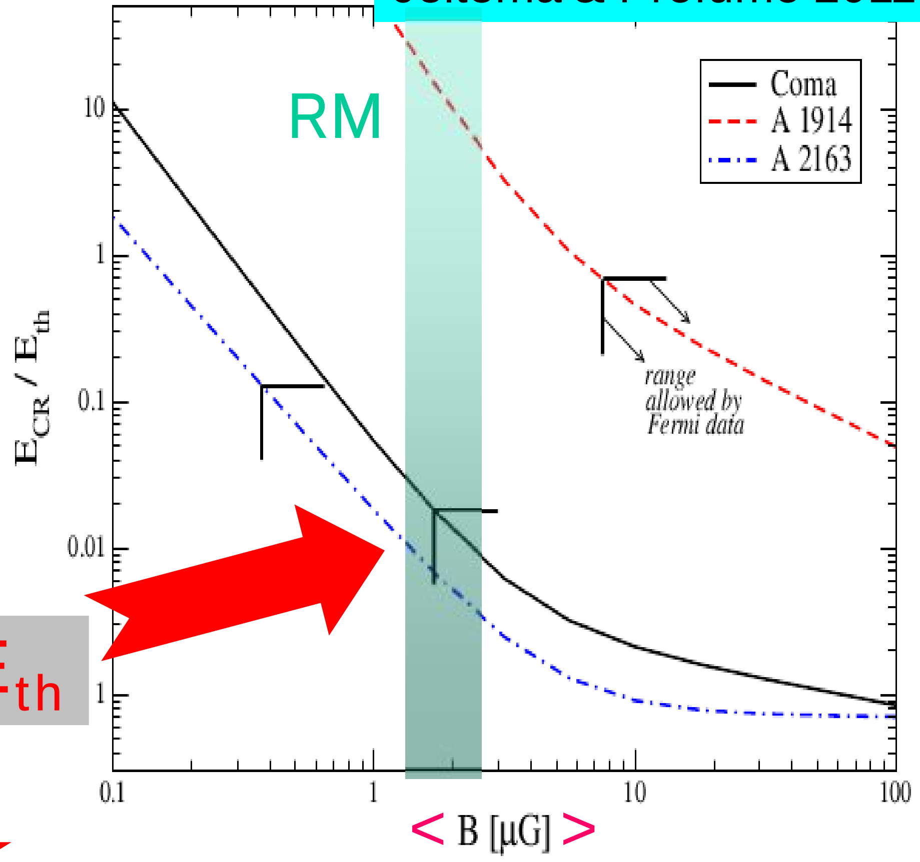
$L_R \sim f_R(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle \langle B^{\delta/2+1}/(B^2+B_{cmb}^2) \rangle V_R$

$L_R / L_{\gamma,\pi} \to \langle B^{\delta/2+1}/(B^2+B_{cmb}^2) \rangle\_$(emission weighted)

Testing hadronic models for Halos



Jeltema & Profumo 2011



E_{CR} ~E_{th}

$L_{\gamma,\pi} \sim f_{\gamma}(\delta) \langle E_{CR}\rangle \langle E_{th}/T\rangle V_{\gamma}$

$L_R \sim f_R(\delta)\langle E_{CR}\rangle \langle E_{th}/T\rangle \langle B^{\delta/2+1}/(B^2+B_{cmb}^2)\rangle V_R$

$L_R/L_{\gamma,\pi}$ -> $\langle B^{\delta/2+1}/(B^2+B_{cmb}^2)\rangle$_(emission weighted)