Cosmic Ray acceleration in clusters of galaxies

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Outline

NT components (CRe,CRp,B) in galaxy clusters : observations

Physics and dynamics of CR in galaxy clusters

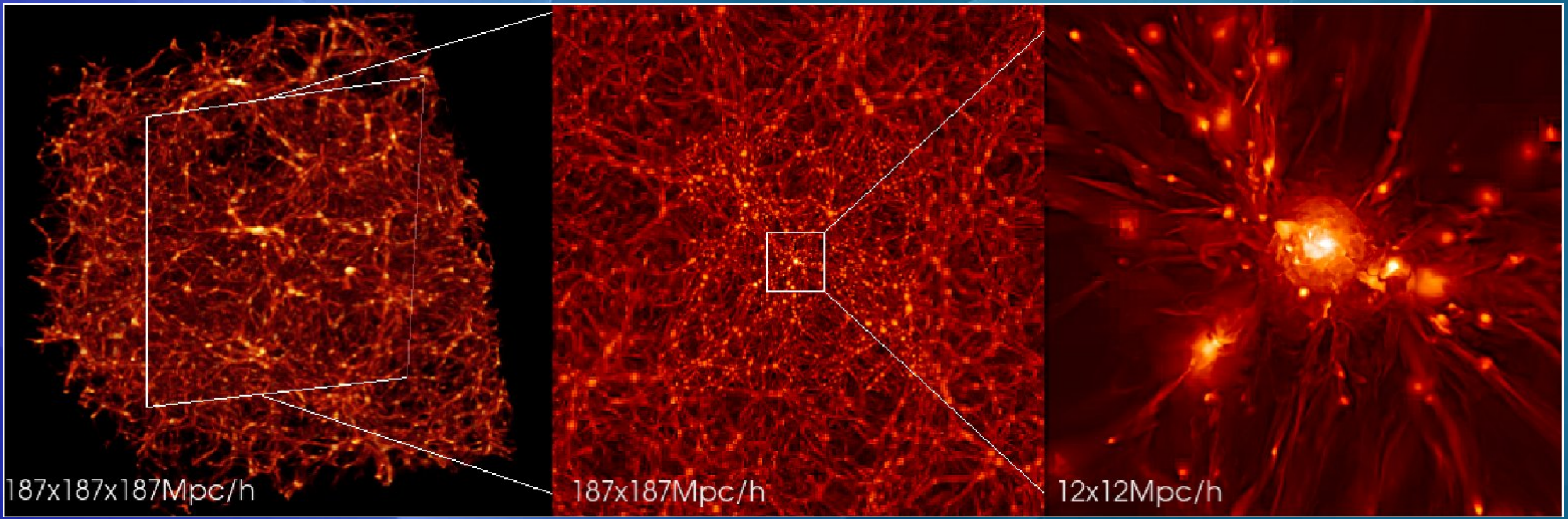
Present constraints on CR protons **new**

Physics of NT Mpc scale diffuse radio emission from galaxy clusters: Relics & Halos

Shocks and turbulent acceleration in clusters

Future at low radio frequencies & gamma rays

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

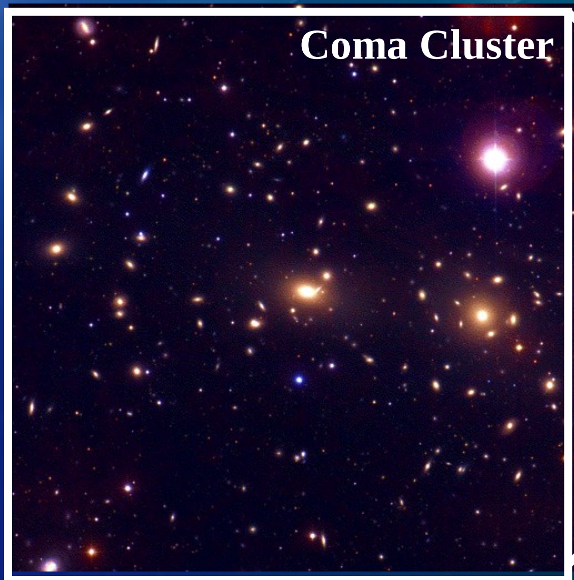


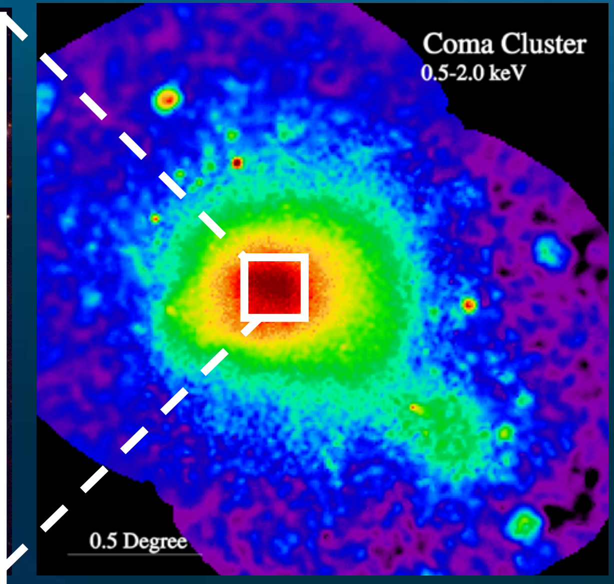
Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

Dark Matter **70%**





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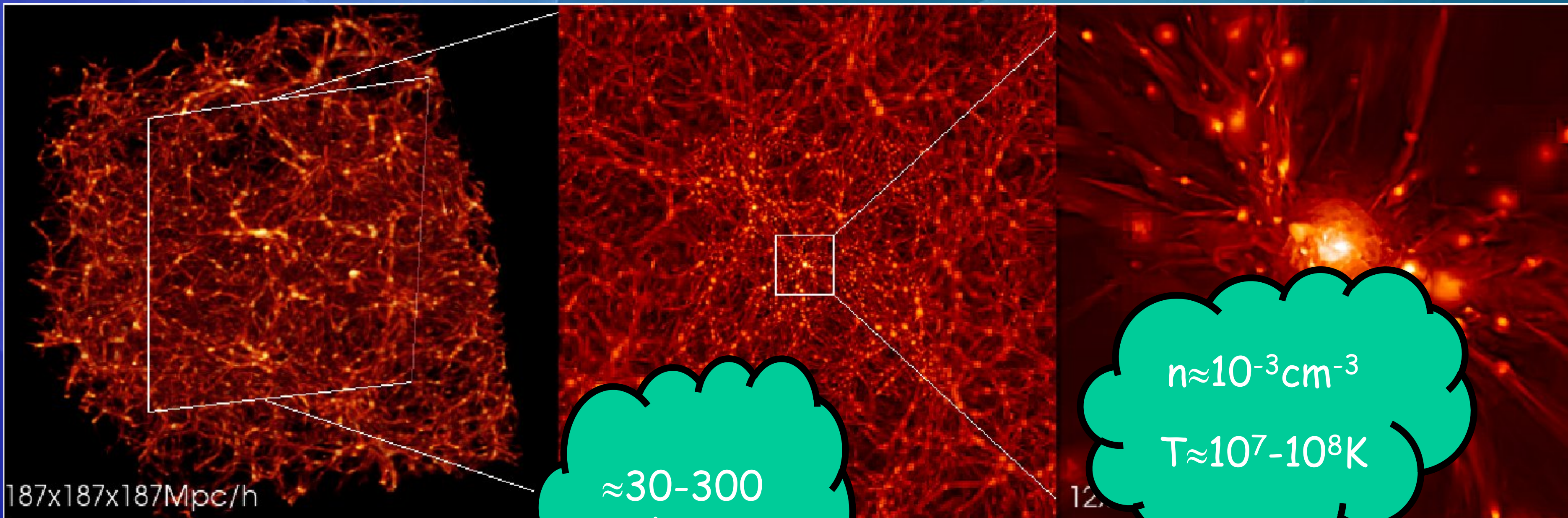

≈30-300 galaxies

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

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

Galaxy cluster mass:

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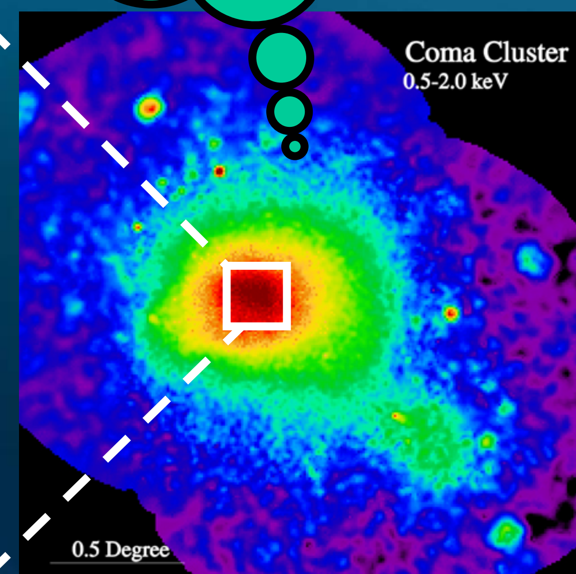
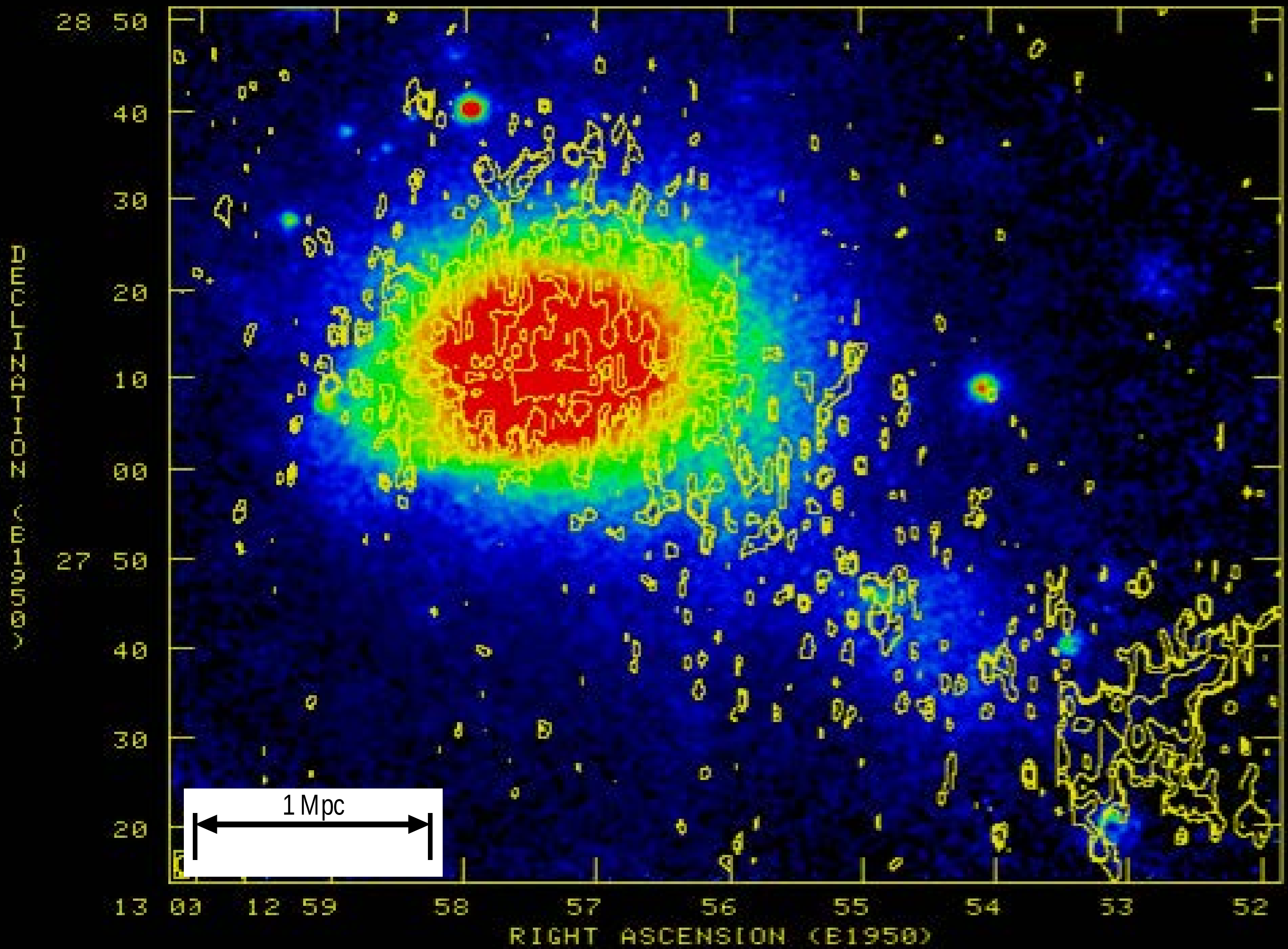
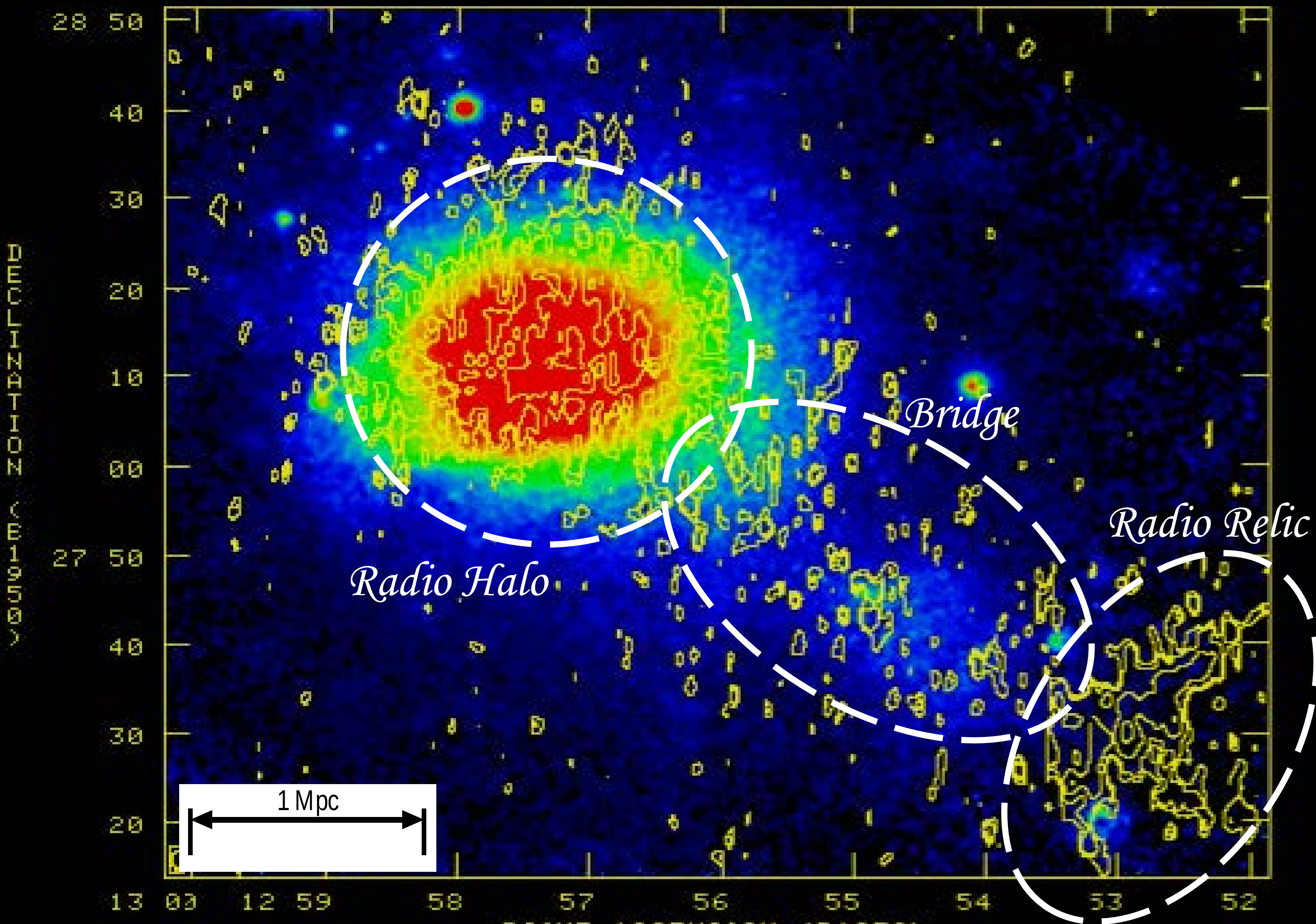


Coma Cluster



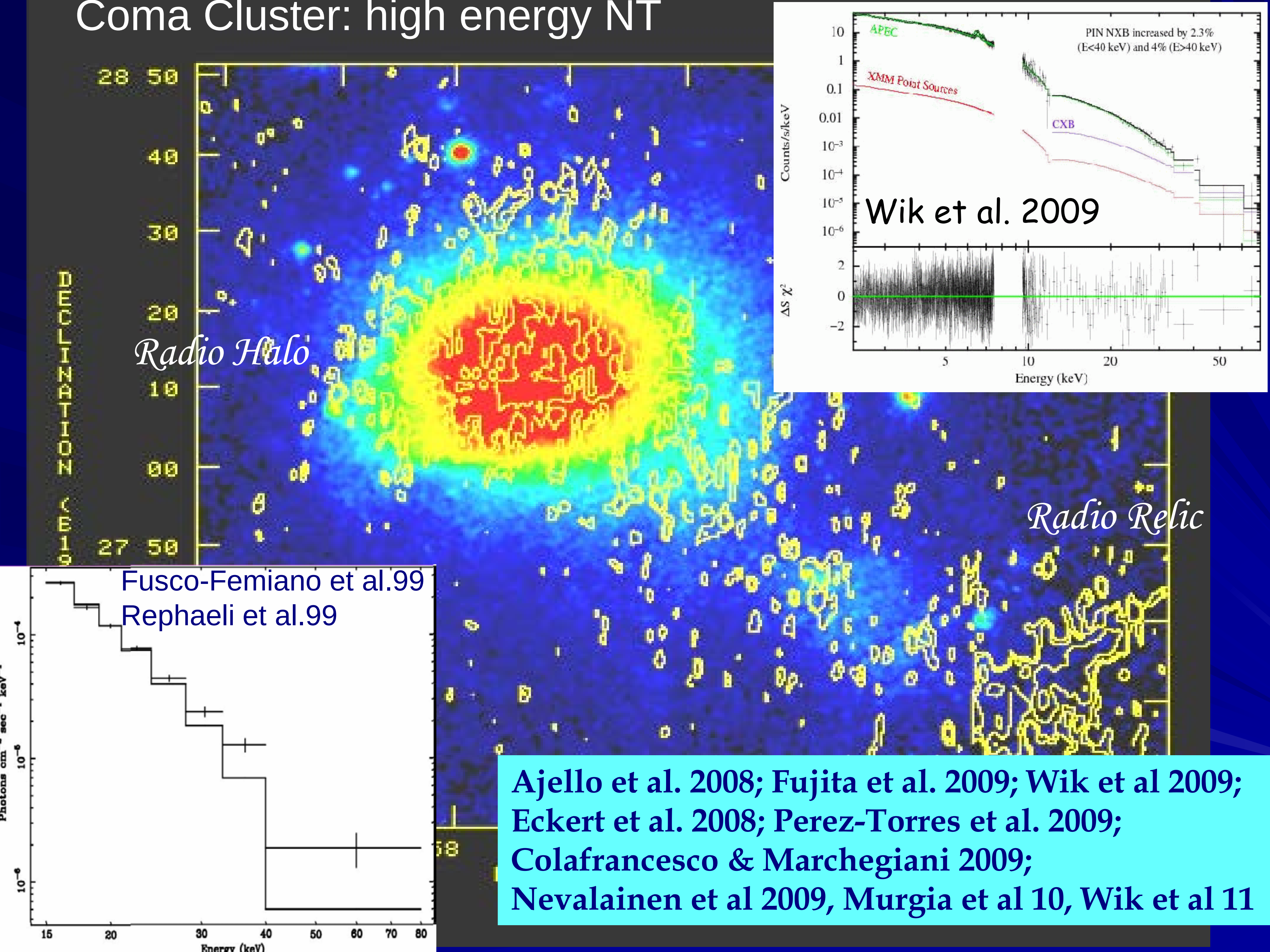
Feretti +al.1998

Coma Cluster



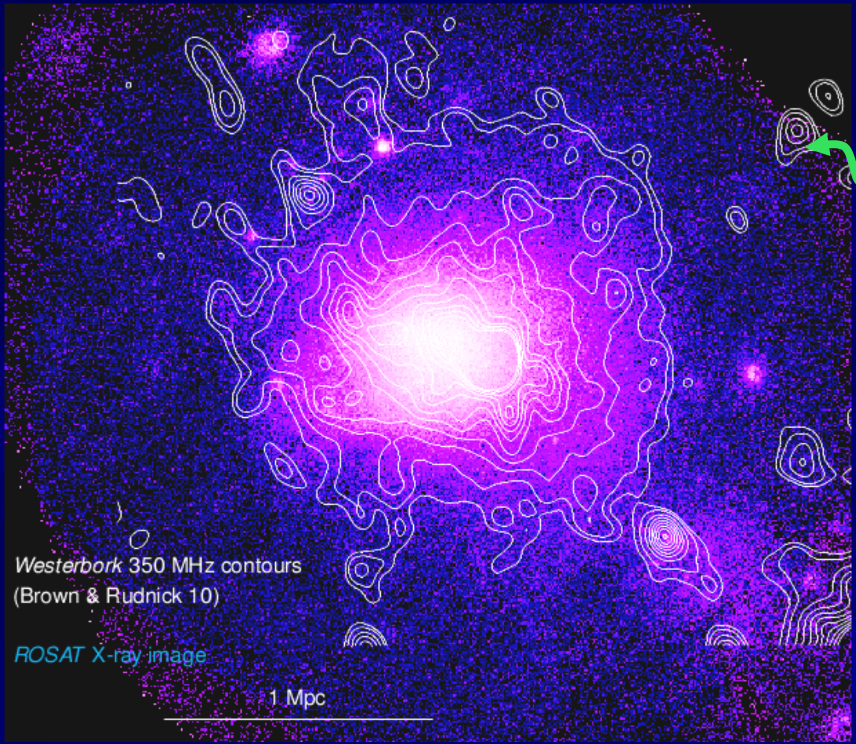
Feretti +al.1998

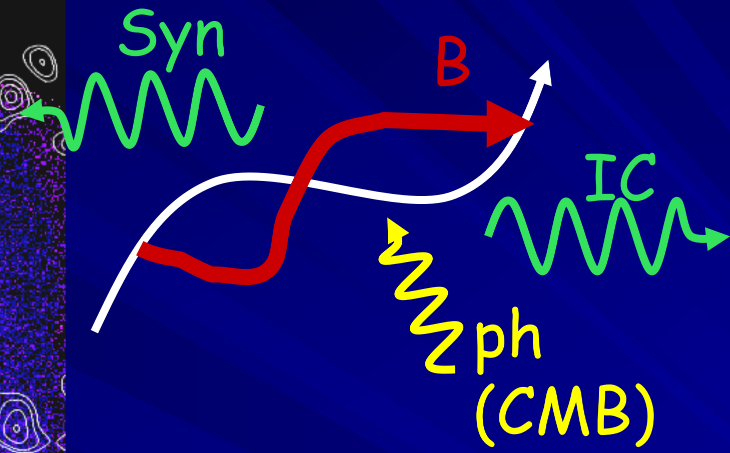
Coma Cluster: high energy NT



Ajello et al. 2008; Fujita et al. 2009; Wik et al 2009; Eckert et al. 2008; Perez-Torres et al. 2009; Colafrancesco & Marchegiani 2009; Nevalainen et al 2009, Murgia et al 10, Wik et al 11

Inverse Compton Emission from GC ??





L_{rad} -> $(U_e\ ,\ U_B)$ -> $K_e B^2$

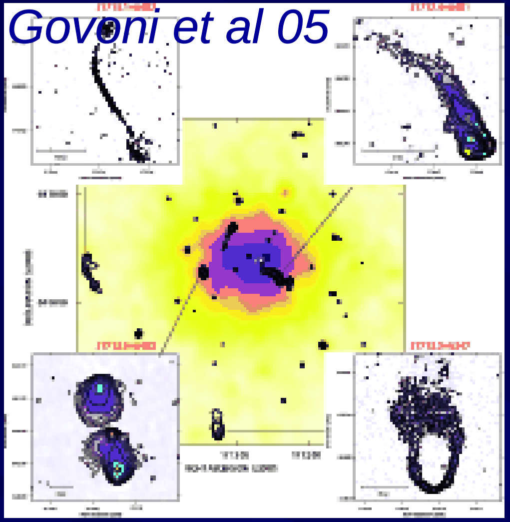
L_{HE} -> $(U_e\ ,\ U_{ph})$ -> $K_e U_{ph}$

$L_{rad} / L_{HE} \approx U_B / U_{ph}$ _-> B ⇨ B > 0.1-0.2 μG

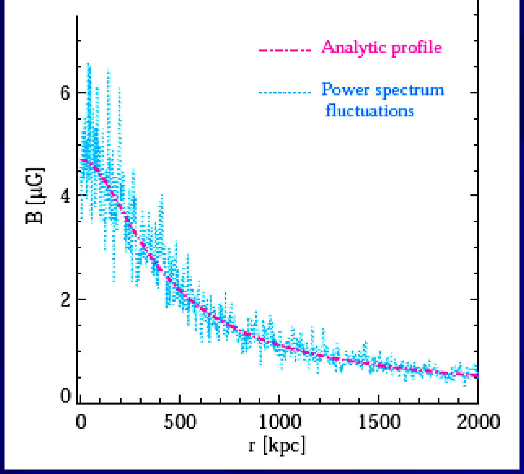
B in Galaxy Clusters

(also Bruggen,Dolag,Neronov lectures)

Govoni et al 05



Bonafede et al 2010



$B \approx$ few μG

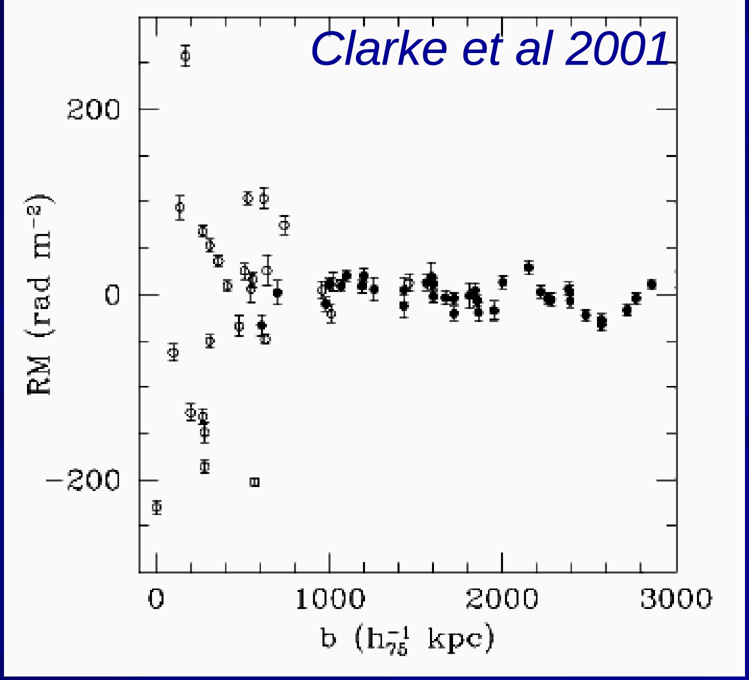
$\Lambda c \approx$ few-50 kpc

RM probe turbulent motions in the IGM

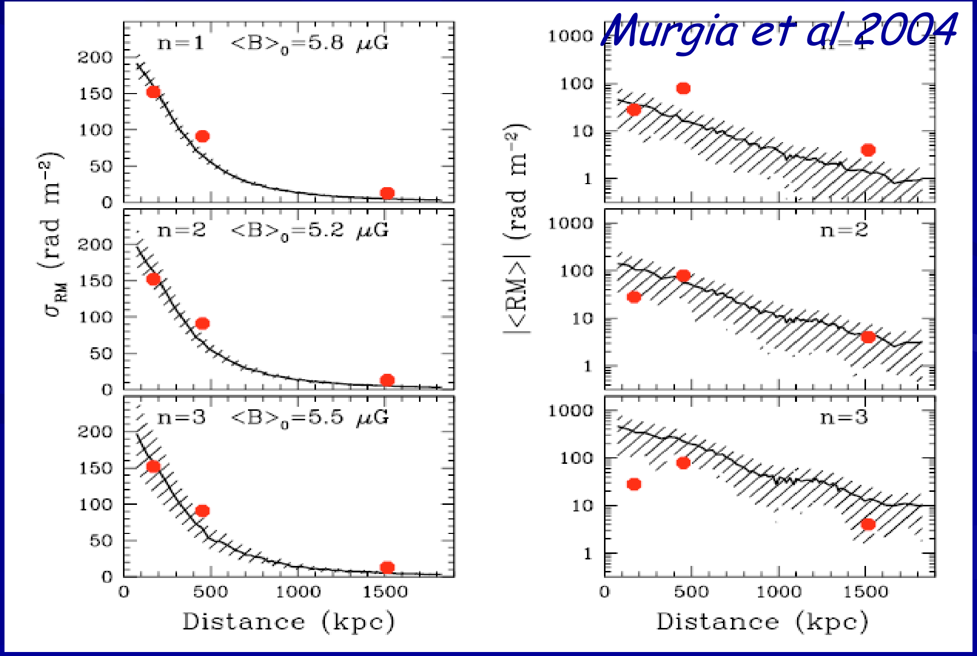
$$\mathrm{RM} = \frac{\Delta\chi}{\Delta\lambda^2} = 811.9 \int_0^L n_e B_{\|} d\ell \ \text{rad m}^{-2},$$

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

Clarke et al 2001



Murgia et al 2004



Injection & Dynamics of CR 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,
Hoeft & Bruggen 2007, Skillman et al. 2008,
Vazza, Brunetti, Gheller 2009, 2010, etc..)

AGN, Galactic Winds

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

Reconnection (turbulent .. Lazarian & Vishniac 99)

(e.g. Brunetti & Lazarian 2011, DeGouveia dal Pino et al 2011,..)

Physics of CR Leptons

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

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

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

Photon Collisions

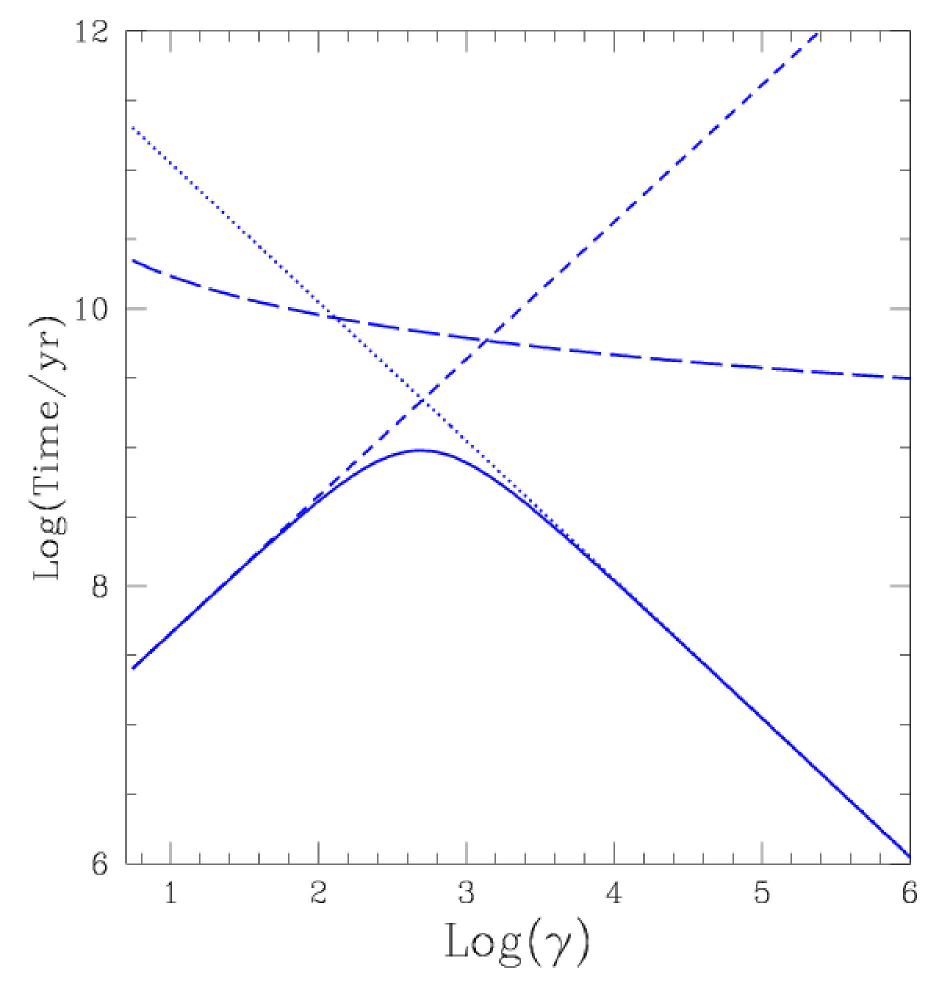
$$b_{\rm Coul}(\gamma) \approx 1.2 \times 10^{-12} n_e\left[1.0 + \frac{\ln\ (\gamma/n_e)}{75}\right]{\rm s}^{-1}\,,$$

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

Particle Collisions

Physics of CR Leptons

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



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

The life-time of electrons depends on quantities that can be measured

Physics of CR Hadrons

CR protons more energetics than thermal electrons: Coulomb scattering

$$\beta_c \equiv (3/2 m_e/m_p)^{1/2} \beta_e$$

$$\frac{dp}{dt} \simeq -1.7 \times 10^{-29} \left(\frac{n_{\rm th}}{10^{-3}}\right) \frac{\beta_p}{x_m^3 + \beta_p^3} \ \text{cgs}$$

$$\frac{dp}{dt} \propto \left(\frac{n_{\rm th}}{10^{-3}}\right) \times \begin{cases} \text{p} & \text{for} \quad mc\beta_c < p < mcx_m \\ p^{-2} & \text{for} \quad mcx_m < p << mc \\ \text{Const.} & \text{for} \quad p >> mc \end{cases}$$

$$X_m = \left(\frac{3\sqrt{\pi}}{4}\right)^{1/3} \beta_e$$

like leptons

$$\tau_{pp} = \frac{1}{n_{\rm th}\sigma_{\rm pp}c} \sim 10^{18} \left(\frac{n_{\rm th}}{10^{-3}}\right)^{-1} s.$$

Collisions between CR & thermal protons

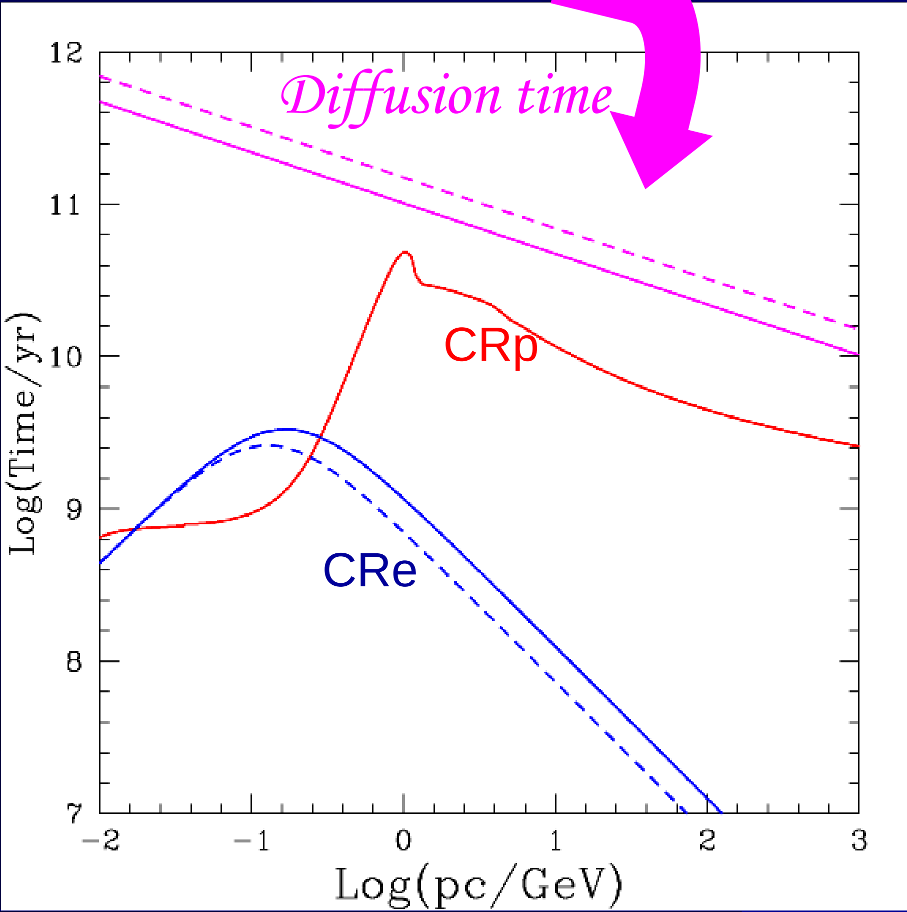
~30 Gyrs !

Physics of Cosmic Rays

$D(GeV) \approx 10^{28}\text{-}10^{29}\ cm^2/s \ll 10^{31} cm^2/s$

(Schlickeiser +al 1987, Blasi+Colafrancesco 1999, GB +al 2011…)

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

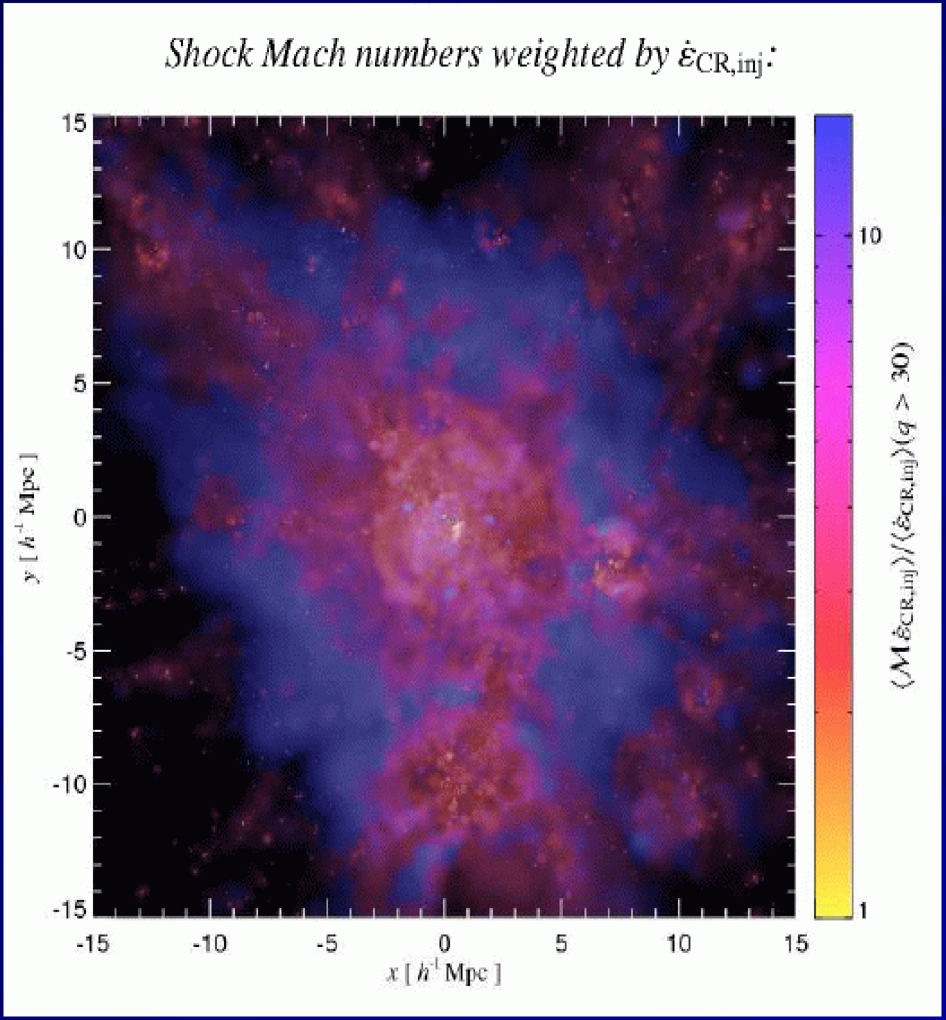


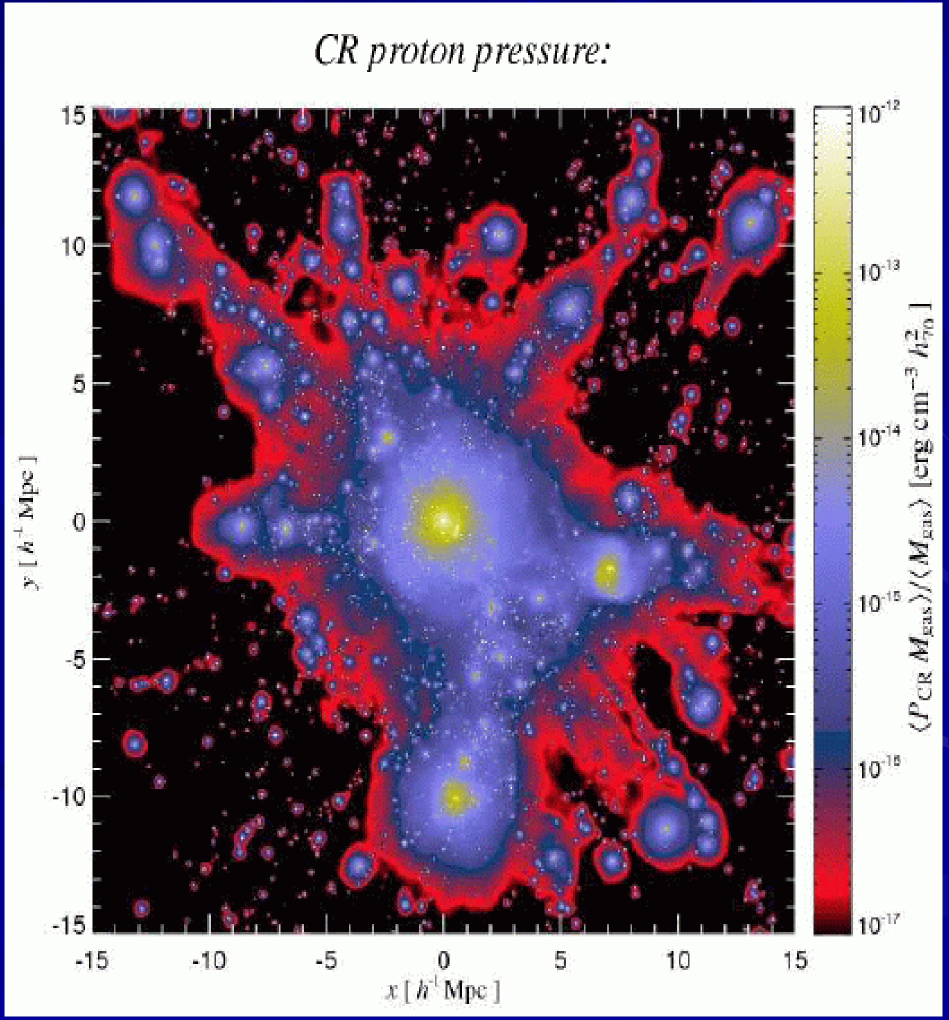
Blasi, Gabici, Brunetti 07

- CR are ***confined*** in GC
  Voelk et al 1996;
  Berezinsky, Blasi, Ptuskin 1997; …
- CR protons are ***long living*** and ***accumulated***
  Voelk et al 1996;
  Berezinsky, Blasi, Ptuskin 1997;
  Ensslin et al 1998; …
- CR electrons are ***short living*** particles and ***accumulated*** at $\gamma \approx 100\text{-}300$
  Sarazin 1999; Petrosian 2001; …

Acceleration & transport of CR : simulations

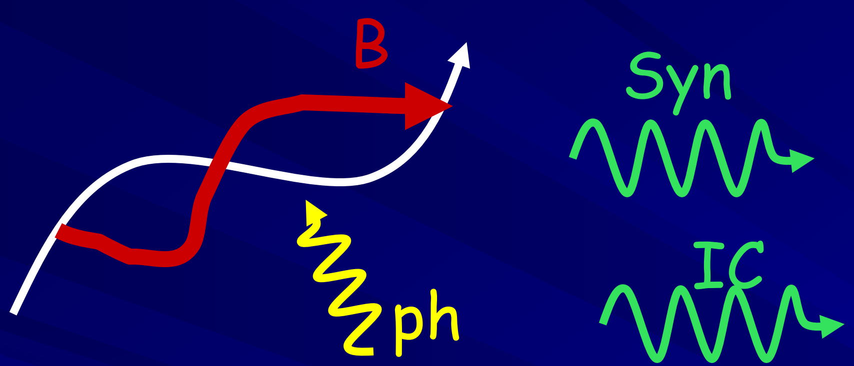
Pfrommer et al. 2007, 08 : simulations of CR+IGM +CR transport/advection
- Acceleration efficiency is the "free" parameter
- Diffusion time >> advection time





Radiation from Cosmic Rays in GC

CRe

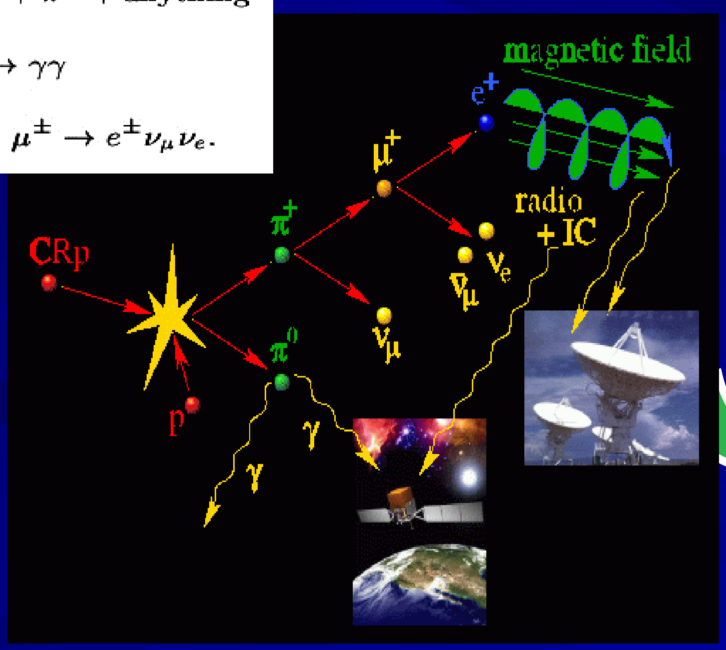


$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

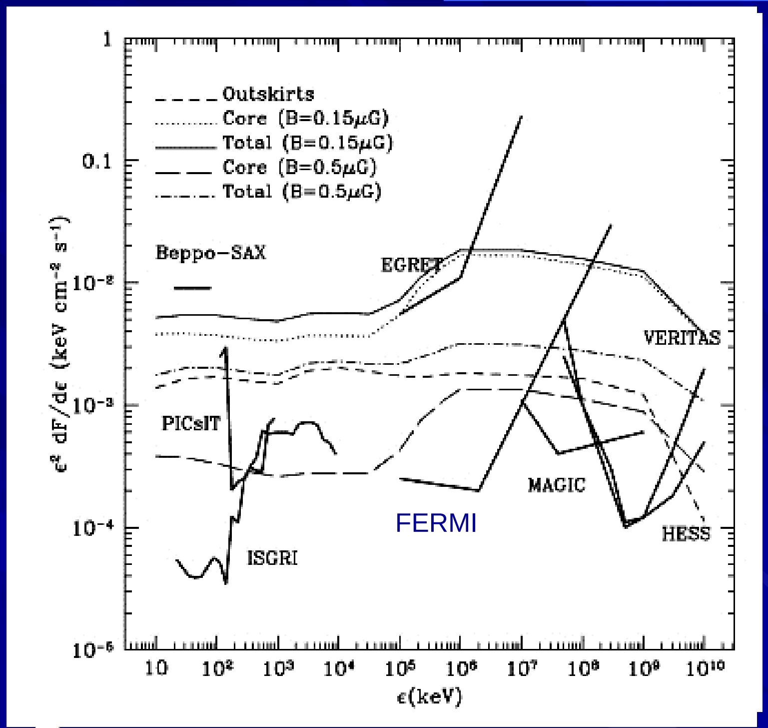
$$\pi^0 \rightarrow \gamma\gamma$$

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

CRp



Miniati 2003



Radiation from Cosmic Rays in GC

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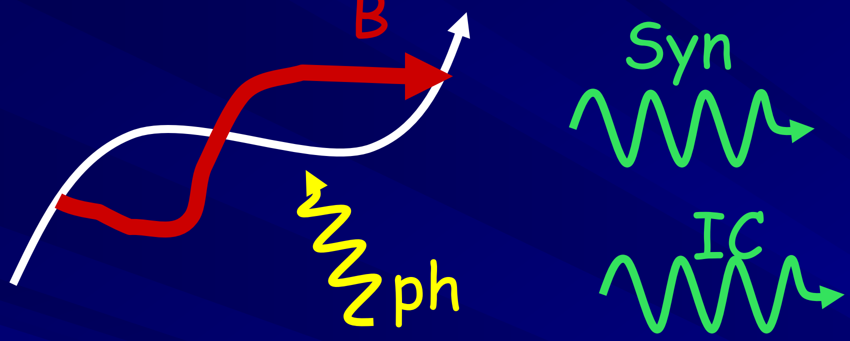
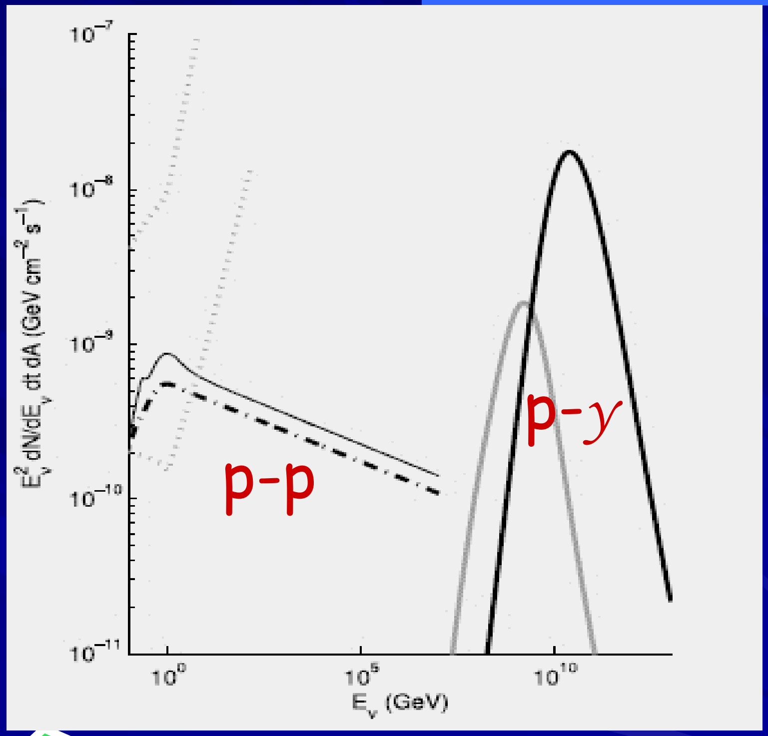


Wolfe +al 2008



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

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

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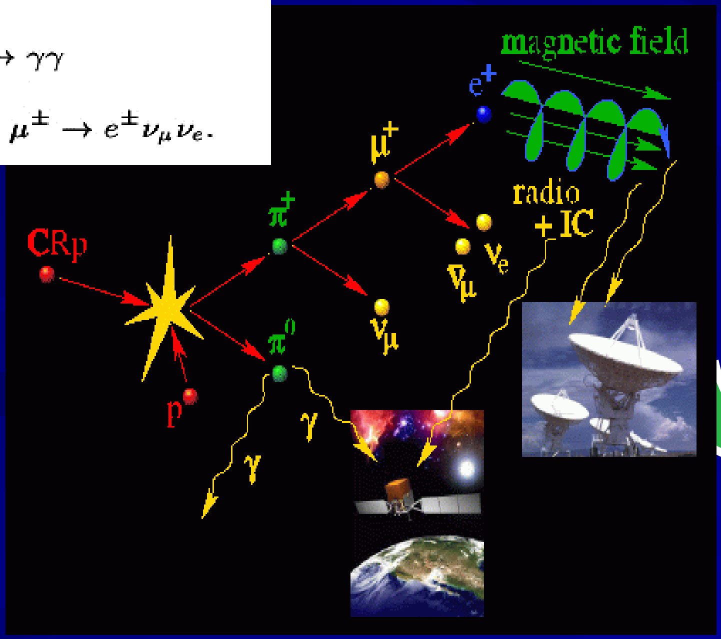
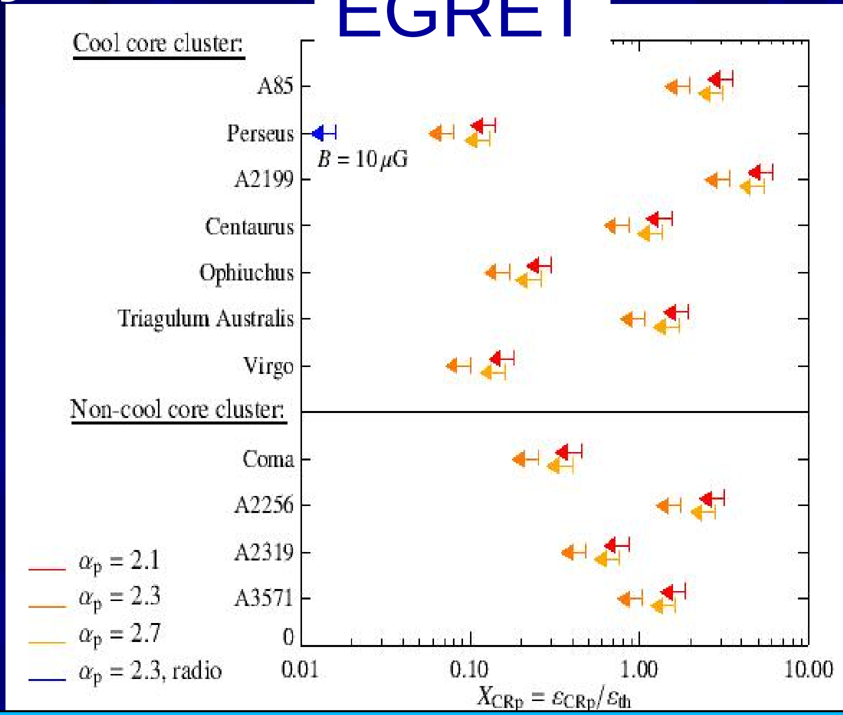
CRp



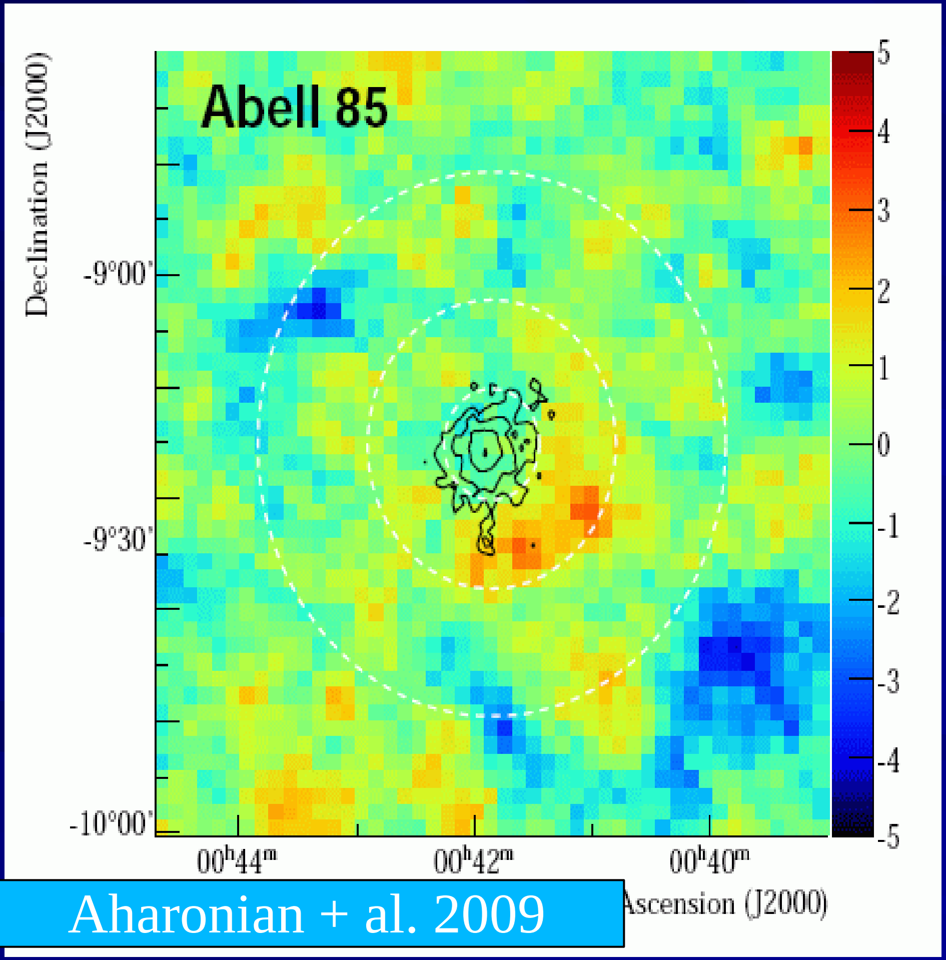
Limits from gamma rays

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

EGRET



Reimer +al. 2003; Pfrommer & Ensslin 2004



Aharonian + 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. 2010)

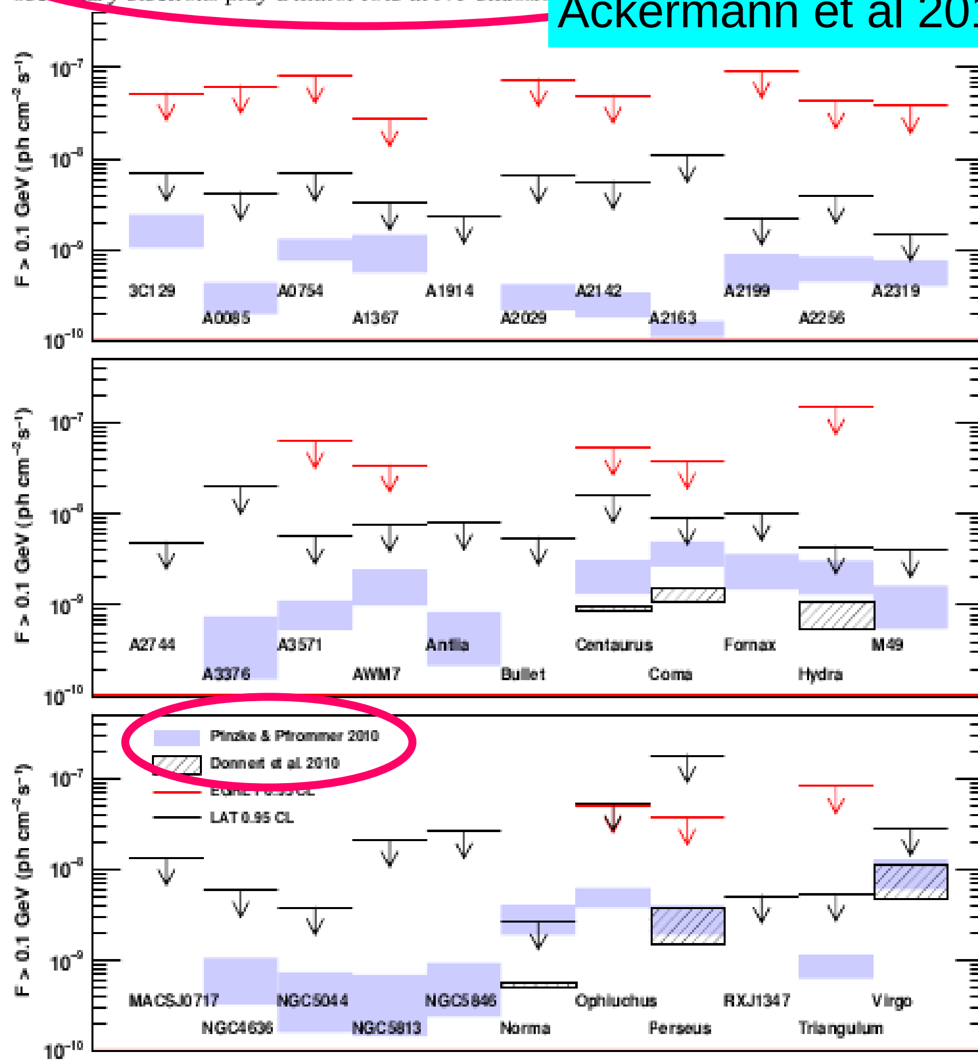
Perseus : Ecr/Eth < 4% (hard spectra)

Gamma rays : energy content of CRp

$\langle \epsilon_{CR}/\epsilon_{Th} \rangle$ $\alpha_p = 2.1$	$\langle \epsilon_{CR}/\epsilon_{Th} \rangle$ $\alpha_p = 2.4$	Cluster	Spatial Model (R_{68}) (deg)	f_{68}	N 0.2–100	$\langle \epsilon_\gamma F(\epsilon_\gamma) \rangle$ 0.2–100	$\langle \epsilon_\gamma F(\epsilon_\gamma) \rangle$ 0.2–1
0.16	0.12	3C 129	King	0.56	3.93	1.26	1.84
0.06	0.04	A0085	King	0.46	2.23	0.71	1.17
0.35	0.27	A0754	King	0.54	3.31	1.06	1.65
0.26	0.16	A1367	King	0.48	1.83	0.59	1.03†
0.38	0.24	A1914	King	0.54	1.18	0.38†	0.72
0.11	0.09	A2029	King	0.49	3.18	1.02	1.72
0.07	0.05	A2142	King	0.52	2.75	0.88	1.59
0.81	0.61	A2163	King	0.54	5.50	1.76†	2.32
0.14	0.11	A2199	King	0.51	1.18	0.76	…
0.16	0.12	A2256	King	0.47	1.83	0.59	0.81
0.03	0.02	A2319	King	0.54	0.73	0.23†	0.54
1.21	0.95	A3376	King	0.57	9.69	3.11	5.18
0.05	0.04	A3571	King	0.50	3.26	1.04	1.85
1.52	1.19	Antlia	King	0.52	4.84	1.55	2.86
0.10	0.08	AWM7	King	0.55	3.95	1.27	1.92
0.09	0.07	Centaurus	King	0.51	8.15	2.61	3.90
…	…	Coma	Gauss (0.2)	0.53	4.84	1.55	2.28
…	…	Coma	Gauss (0.4)	0.52	4.86	1.56	2.36
…	…	Coma	Gauss (0.6)	0.58	5.12	1.64	2.38
…	…	Coma	Gauss (0.8)	0.56	4.93	1.58	2.73
0.05	0.04	Coma	King	0.55	5.14	1.65	2.18
…	…	Fornax	Gauss (0.2)	0.51	4.77	1.53	2.61
…	…	Fornax	Gauss (0.4)	0.62	5.40	1.73	2.73
…	…	Fornax	Gauss (0.6)	0.59	5.73	1.84	3.02
…	…	Fornax	Gauss (0.8)	0.62	5.39	1.73	2.61
…	…	Fornax	Gauss (1.0)	0.60	5.03	1.61	2.87
0.75	0.59	Fornax	King	0.60	5.64	1.81	2.80
0.28	0.21	Hydra	King	0.60	2.24	0.72†	0.94
5.09	3.98	M49	King	0.52	2.08	0.67	1.14
3.89	3.04	NGC 4636	King	0.46	2.67	0.86	1.28
1.58	1.24	NGC 5044	King	0.50	1.87	0.60	0.81
25.59	20.03	NGC 5813	King	0.52	10.57	3.39	4.25
13.82	10.82	NGC 5846	King	0.55	13.01	4.17	5.38
0.03	0.02	Norma	King	0.54	1.21	0.39†	0.94
0.05	0.04	Ophiuchus	King	0.54	26.22	8.41	14.18
0.27	0.32	Perseus	King	0.70	87.36	28.01	28.11
0.07	0.05	Triangulum	King	0.54	2.39	0.77†	0.91
…	…	Virgo	Gauss (0.2)	0.62	14.49	4.65	4.93
…	…	Virgo	Gauss (0.4)	0.61	15.27	4.90	5.26
…	…	Virgo	Gauss (0.6)	0.64	14.97	4.80	5.62
…	…	Virgo	Gauss (0.8)	0.64	15.76	5.05	5.62
…	…	Virgo	Gauss (1.0)	0.66	16.01	5.13	5.71
…	…	Virgo	Gauss (1.2)	0.64	17.03	5.46	5.62
0.17	0.13	Virgo	King	0.61	14.89	4.77	5.24

The constraints on hadronic CR populations derived from LAT data are in agreement with limits placed by indirect methods (Brunetti et al. 2007; Churazov et al. 2008) and with the predictions of theoretical models and numerical simulations pointing out morphological and spectral difficulties (namely, observed radio spectra cutoffs) in explaining large-scale radio halos with purely secondary emission (e.g., Blasi et al. 2007 and references therein; Donnert el al. 2010). For the clusters examined thus far, multiwavelength evidence suggests that secondary electrons play a minor role in NT emissi

Ackermann et al 2010



CRp: limits from Radio

Reimer et al 04, Brunetti et al. 07,08

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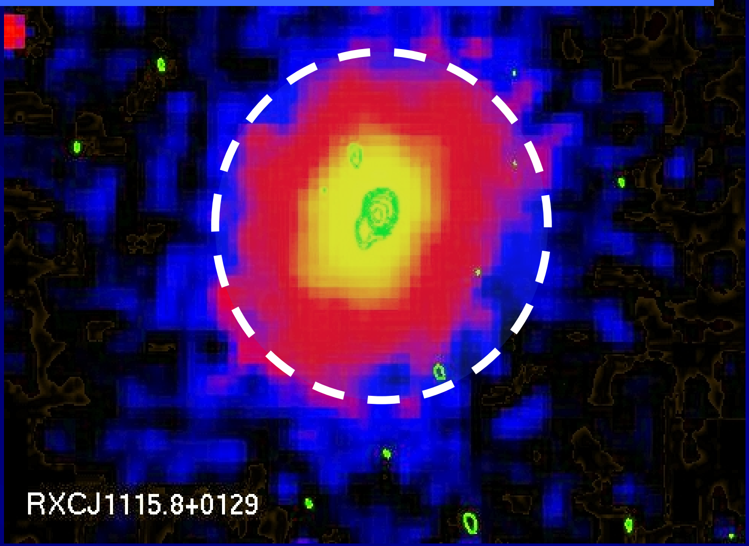
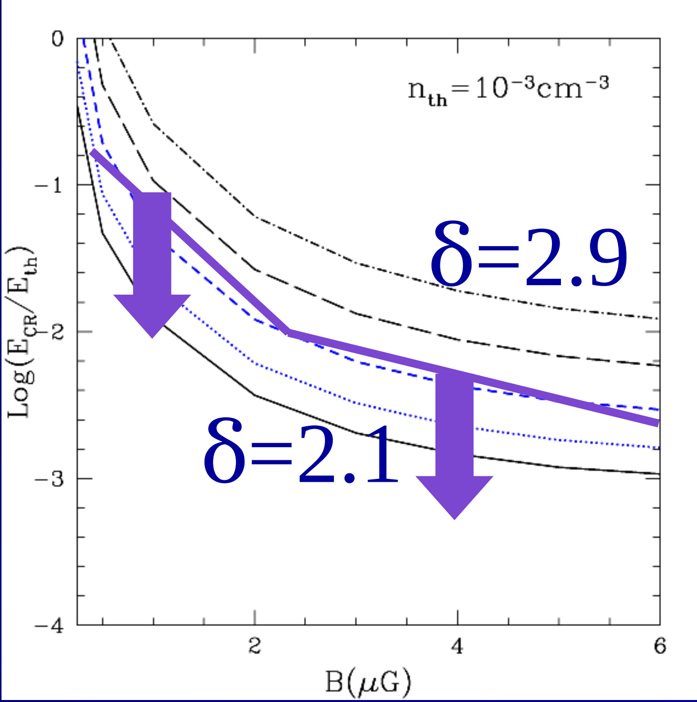


$$L_{\gamma,\pi} \sim f_\gamma(\delta) \langle E_{CR}\rangle \langle E_{th}/T\rangle V_\gamma$$

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



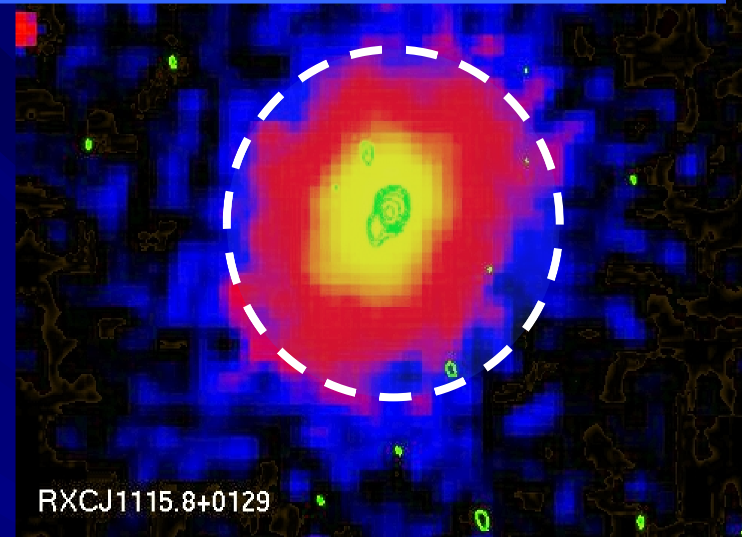
Assuming that secondary particles are injected in the IGM, their synchrotron emission should be smaller than upper limits to the diffuse radio emission.

limits on: (B, E_{CRp}), δ

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

CRp: limits from Radio

Reimer et al 04, Brunetti et al. 07,08



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

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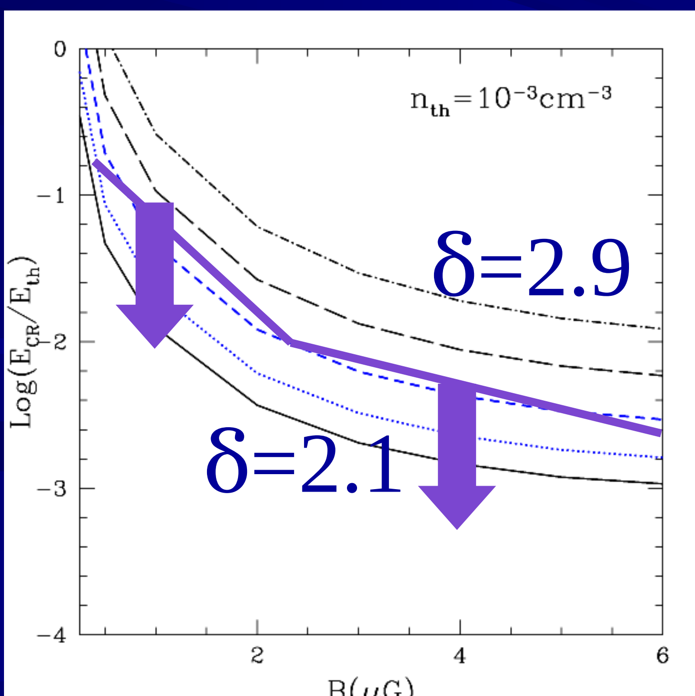
$$L_{\gamma,\pi} \sim f_\gamma(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_\gamma$$

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



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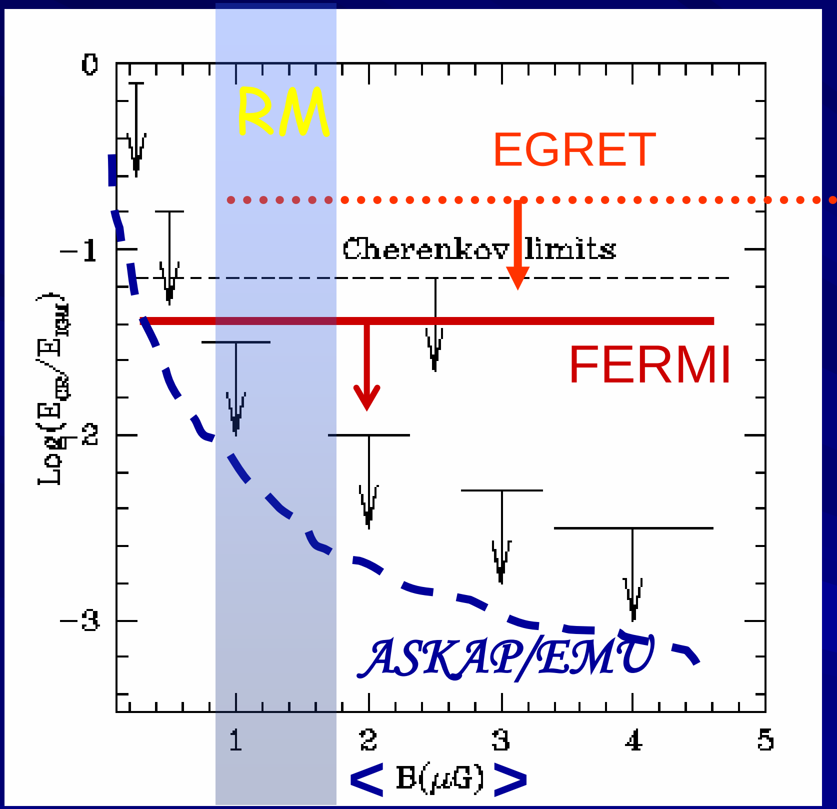
Energy content of CRp



Reimer et al. (2003)
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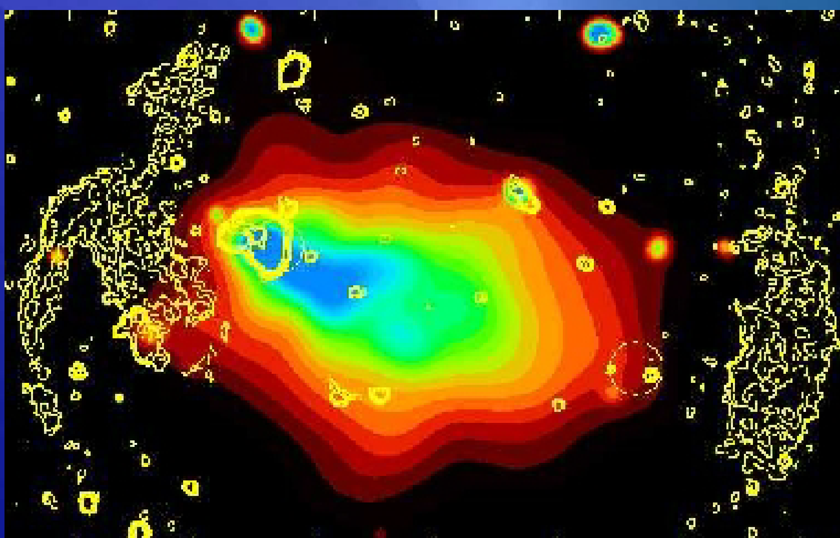
Aharonian et al. (2008 a,b)
Aleksic et al. (2009)
Ackermann et al (2010)

Gamma + Radio observations independently suggest that non-thermal components are dynamically NOT important (% level)

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.

Non-thermal emission from GC

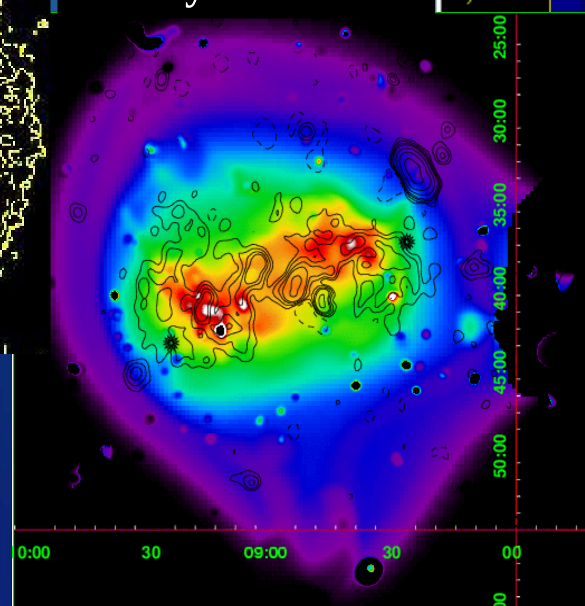
Both **Halos** & **Relics** have **steep spectrum**, $F(\nu)=F_o\nu^{-\alpha}$, with $\alpha \approx 1.3$

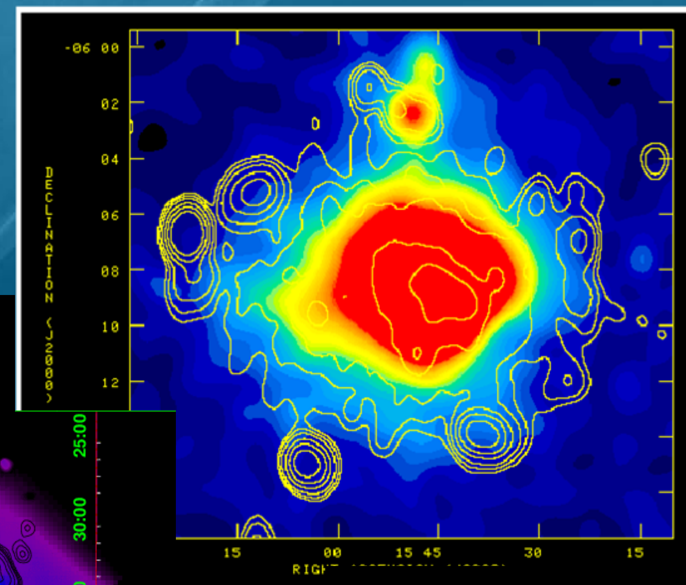


Abell 3376
Bagchi et al. 2005

Radio Relics

Abell 754
Henry et al. 2004





Abell 2163
Feretti et al. 2001

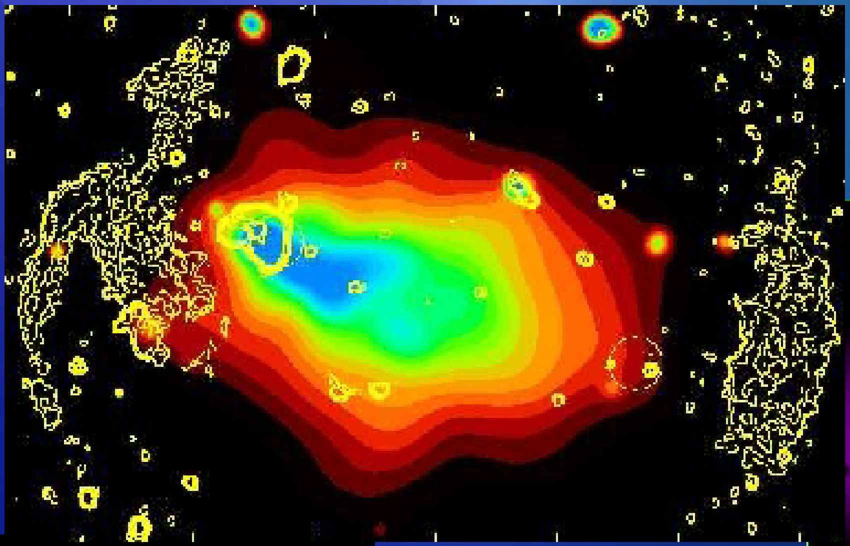
Radio Halos

Non-thermal emission from GC

Both **Halos** & **Relics** have **steep spectrum**, $F(\nu)=F_o\nu^{-\alpha}$, with $\alpha\approx1.3$

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

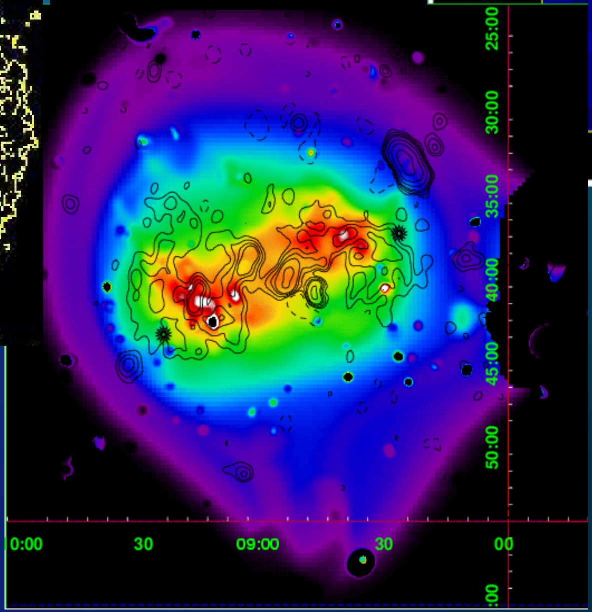
Polarised, no correlation with X-ray brightness (form in cluster outskirts)

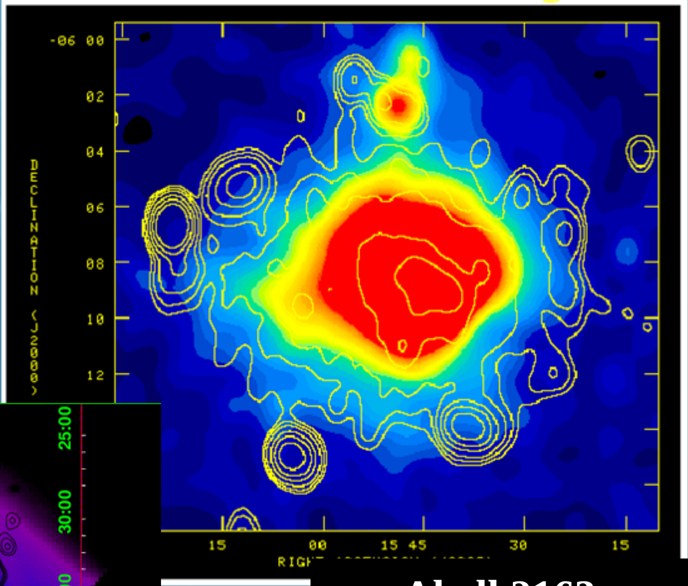


Abell 3376
Bagchi et al. 2005

Radio Relics

Abell 754
Henry et al. 2004

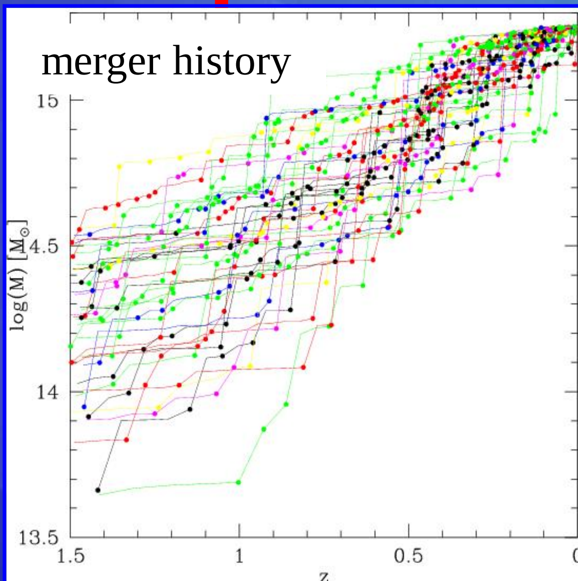




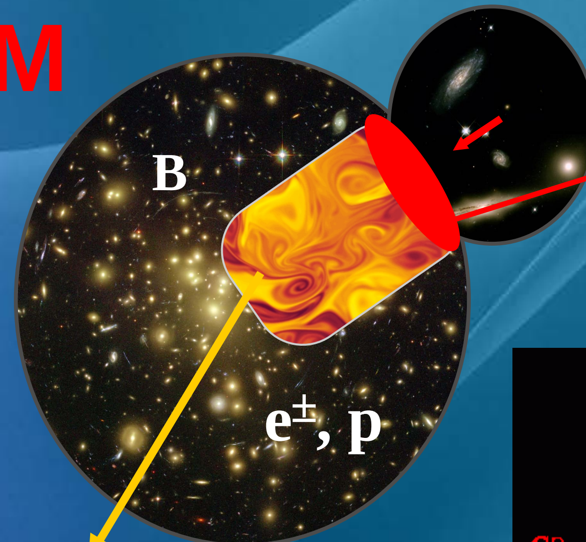
Abell 2163
Feretti et al. 2001

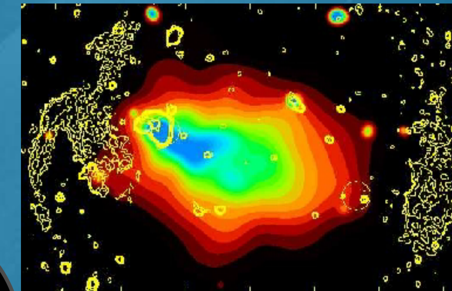
Radio Halos

Connecting LSS formation .. NT-physics of IGM



clusters increase their mass via merger with smaller subclusters

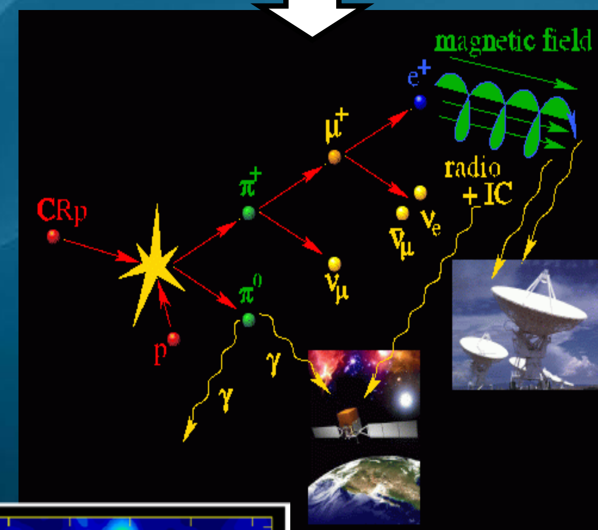




?

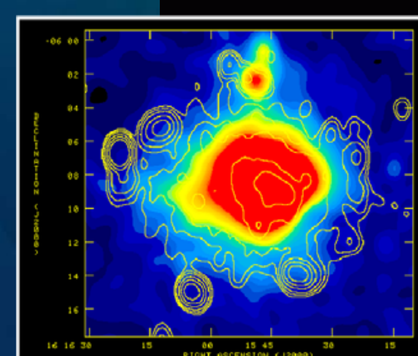
SHOCKS

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



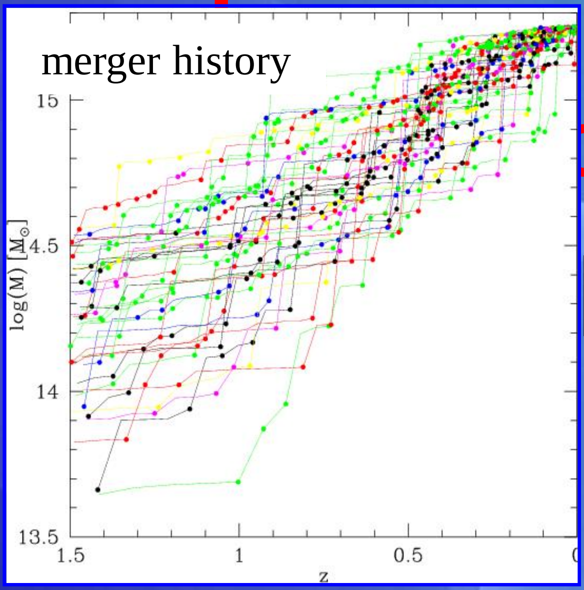
TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scales

(eg., Brunetti et al. 2001, 2004, 2009; Petrosian 2001; Miniati et al. 2001; Fujita et al. 2003; Ryu et al. 2003; Gabici & Blasi 2003; Berrington & Dermer 2003; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Cassano et al. 2006; Brunetti & Lazarian 2007; Hoeft & Bruggen 2007; Pfrommer et al. 2008; Petrosian & Bykov 2008, …)



?

Connecting LSS formation .. NT-physics of IGM



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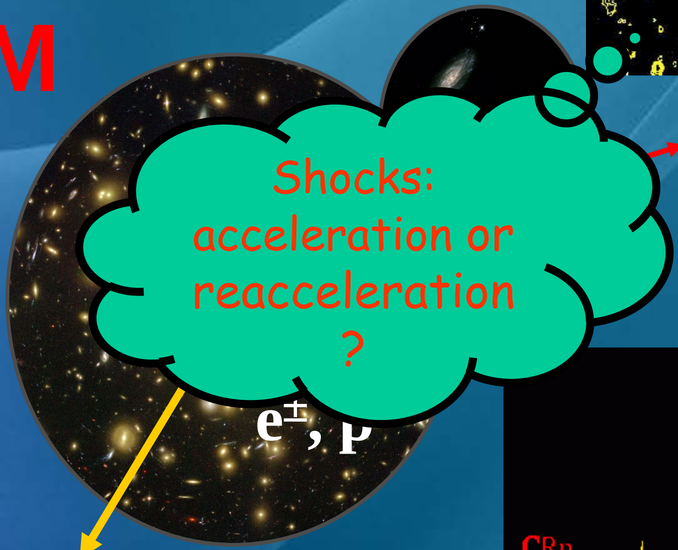

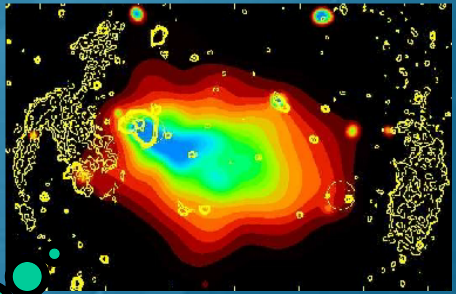

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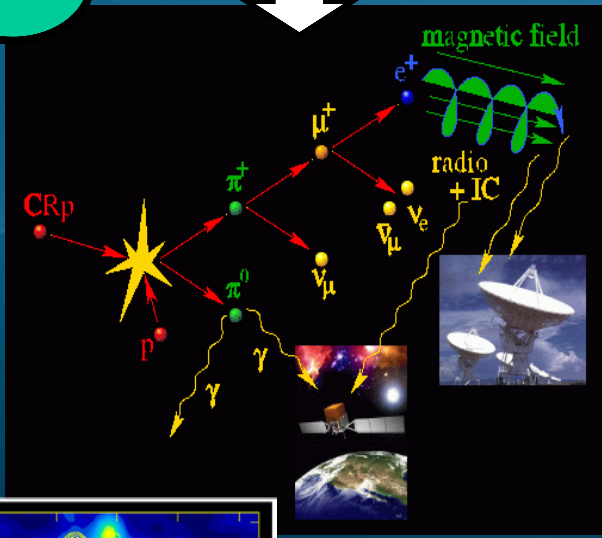

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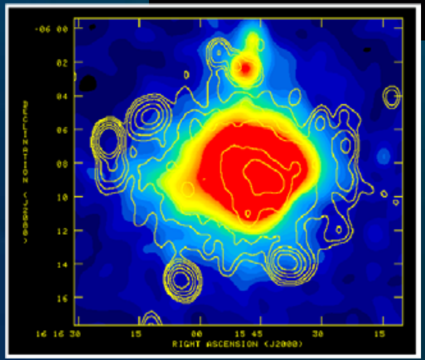
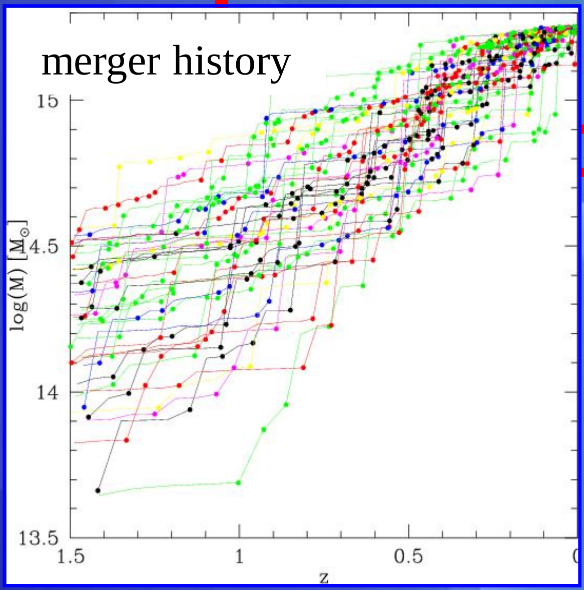


?

Connecting LSS formation .. NT-physics of IGM



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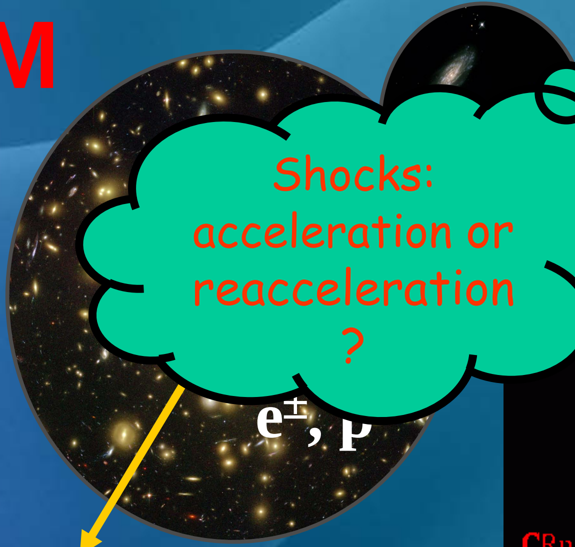
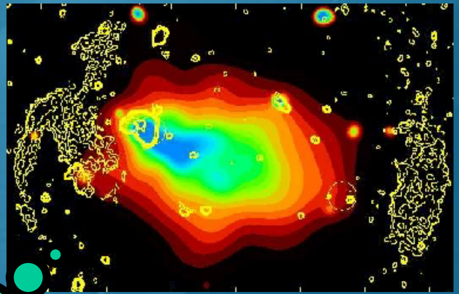
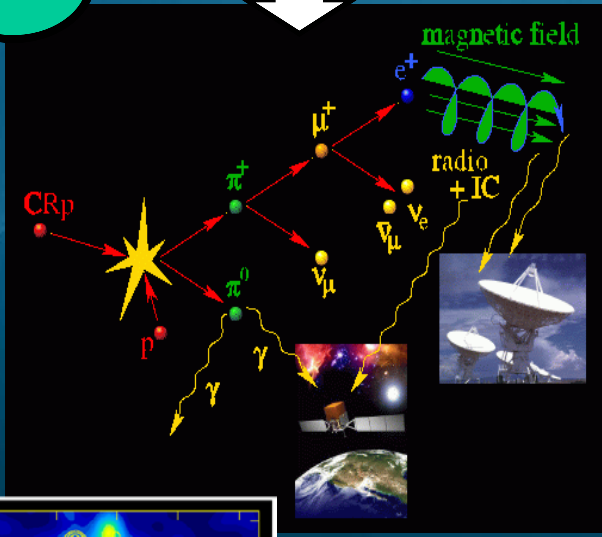


Shocks: acceleration or reacceleration ?



?

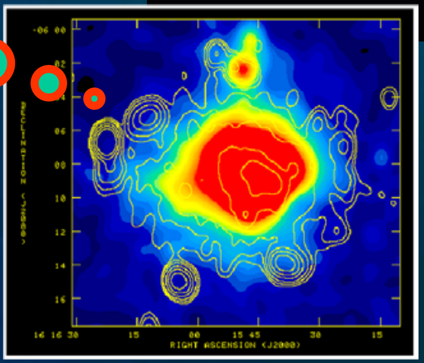
SHOCKS accelerate $e^{\pm}$, p_{cr}



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

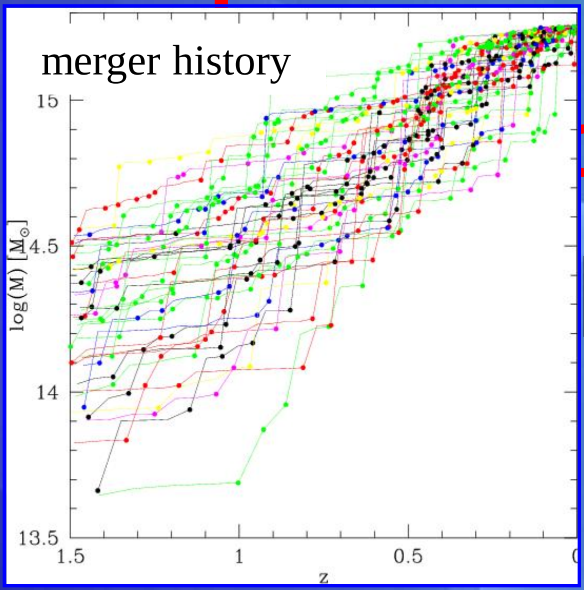
Turbulence?

(eg., Brunetti et al. 2001, 2004, Miniati et al. 2001; Fujita et al. 20 Gabici & Blasi 2003; Berrington & Dermer 2003; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Cassano et al. 2006; Brunetti & Lazarian 2007; Hoeft & Bruggen 2007; Pfrommer et al. 2008; Petrosian & Bykov 2008, …)



?

Connecting LSS formation .. NT-physics of IGM



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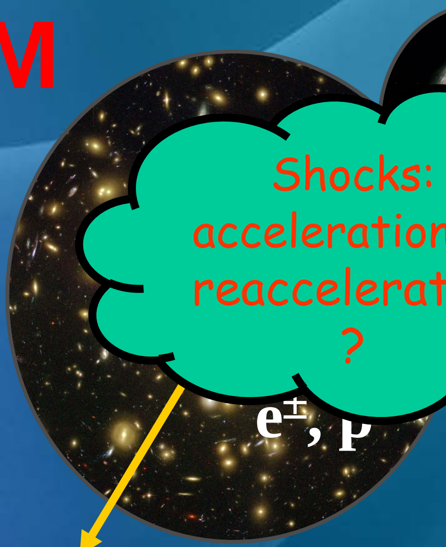

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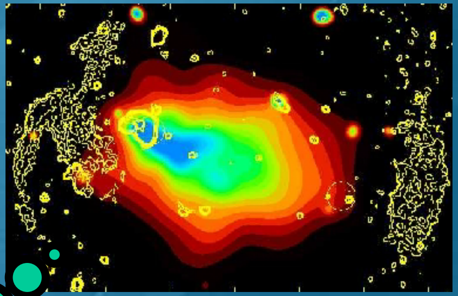
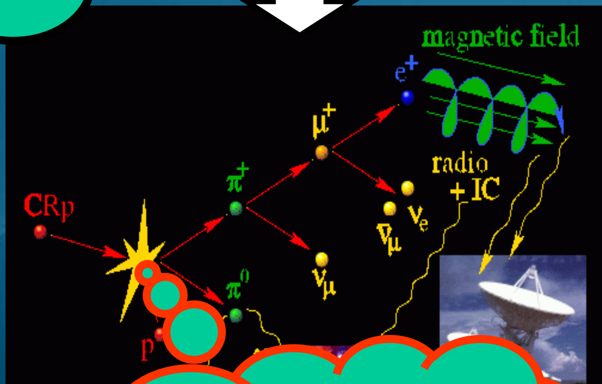


?

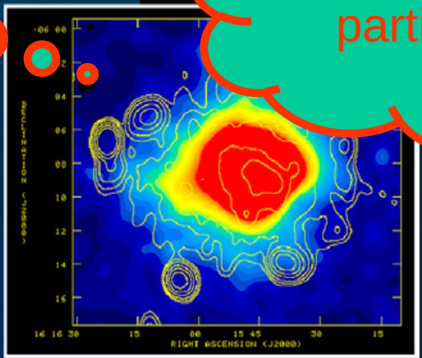
SHOCKS accelerate e±, p_{cr}



TURBULENCE reaccelerates fossil e± and secondaries e± on Mpc

Turbulence?

Relevance of secondary particles ?



?

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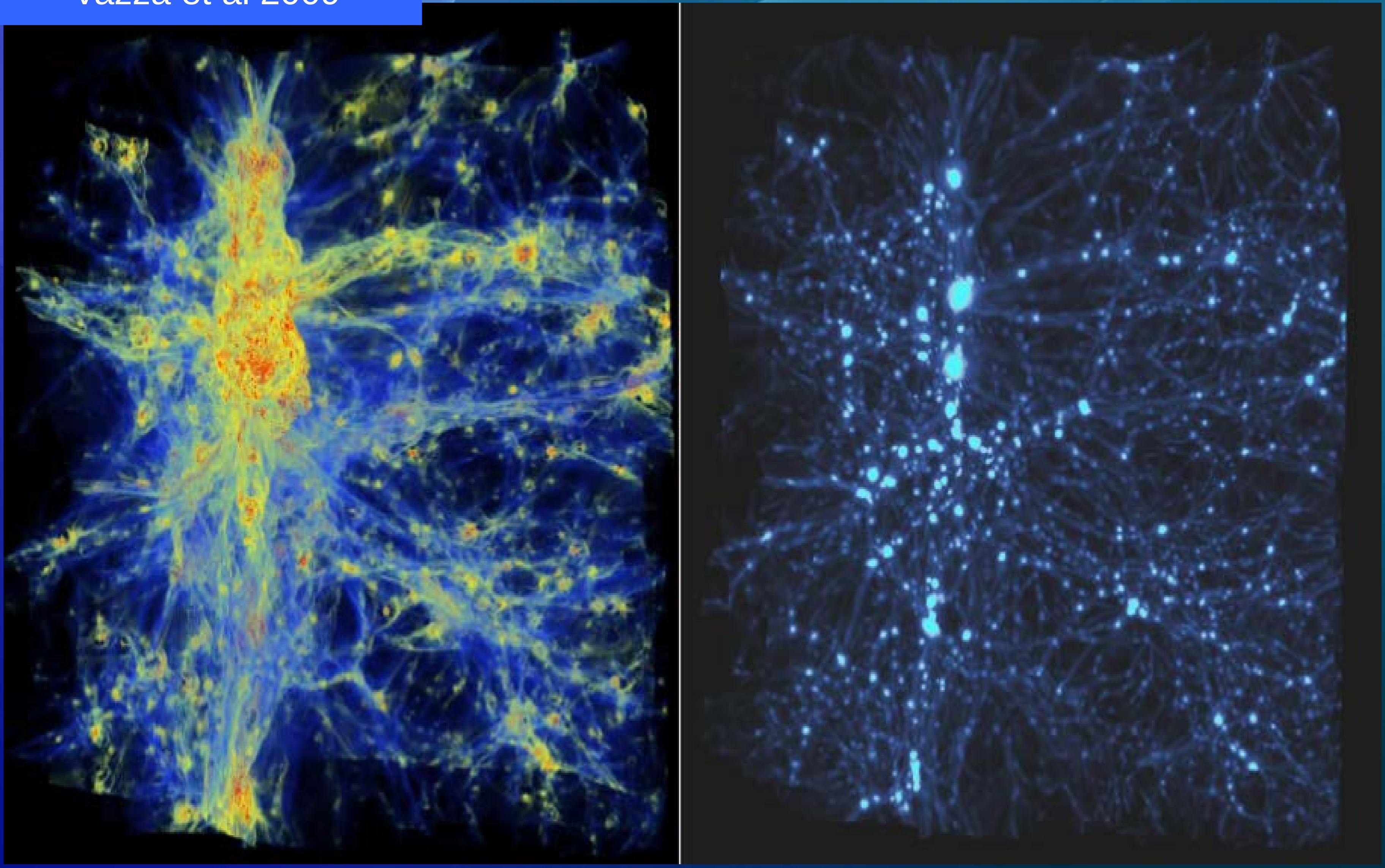
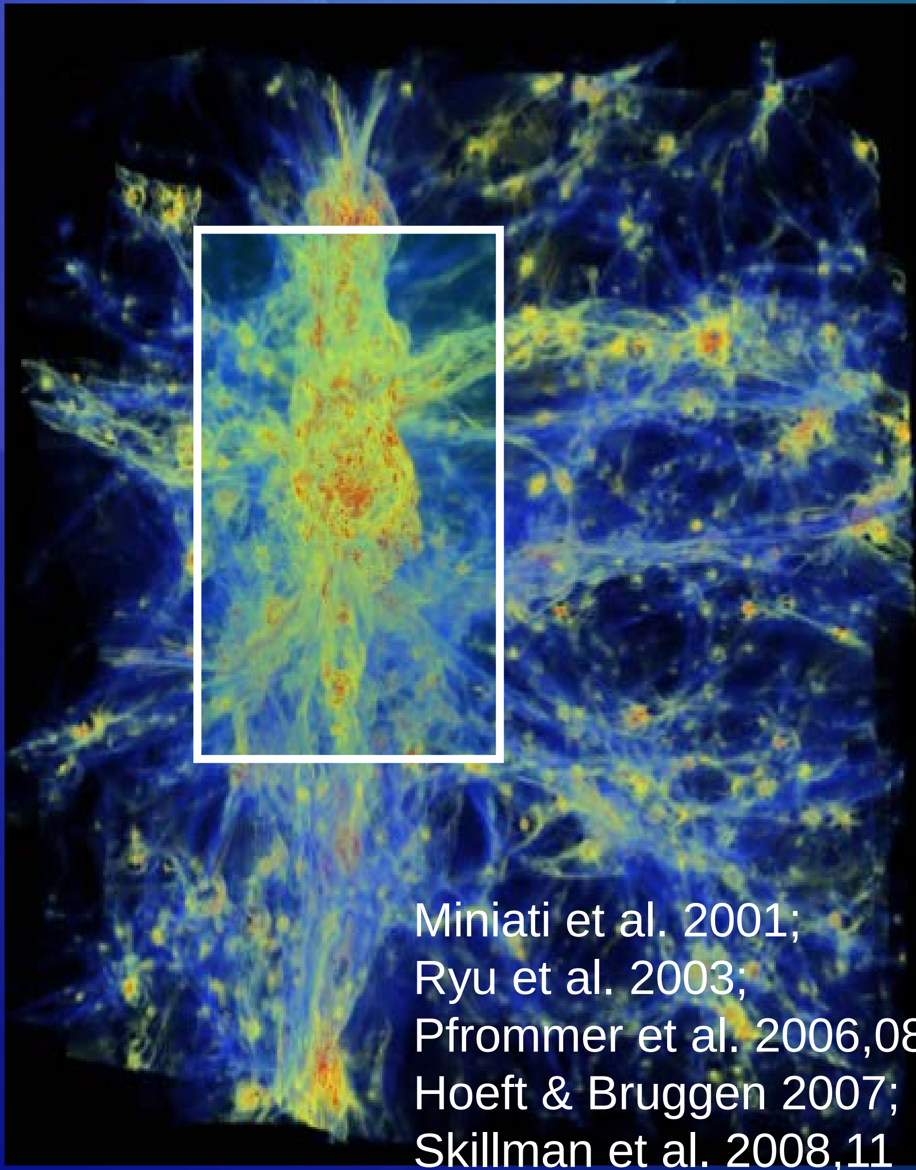
Cosmological Shocks

Natural consequence of the hierarchical process of LSS formation

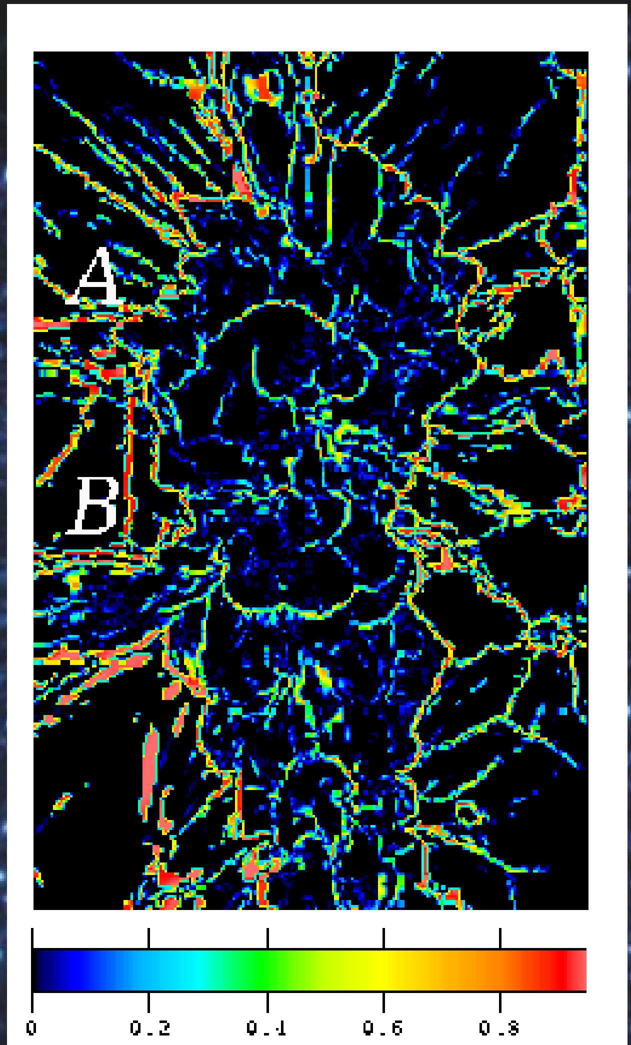
Vazza et al 2009



Shocks in Galaxy Clusters



Miniati et al. 2001;
Ryu et al. 2003;
Pfrommer et al. 2006,08;
Hoeft & Bruggen 2007;
Skillman et al. 2008,11
Vazza et al. 2009, 11

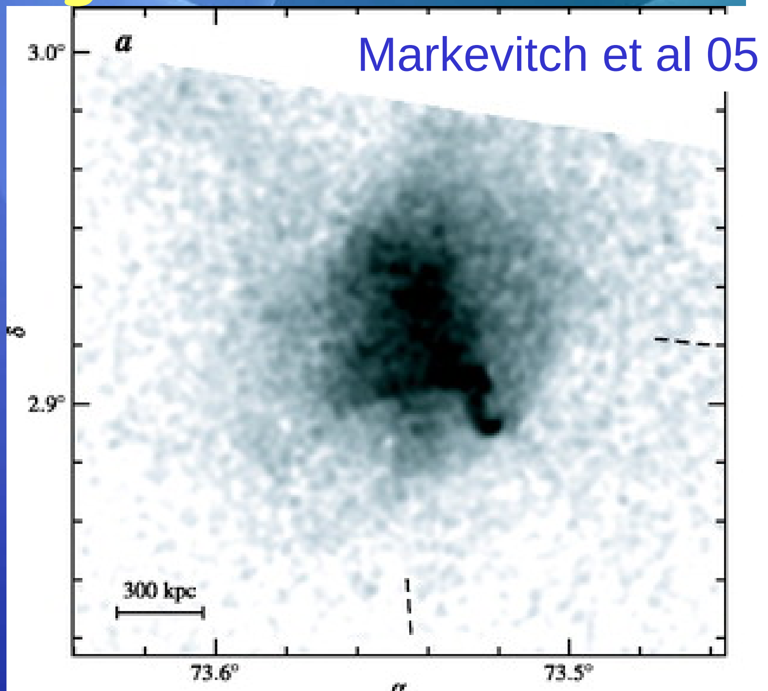


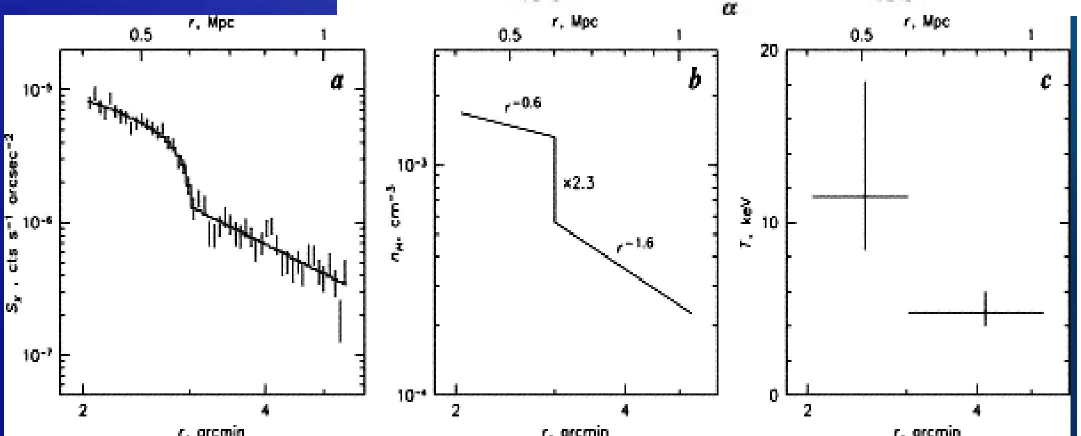
Vazza, Brunetti, Gheller 2009

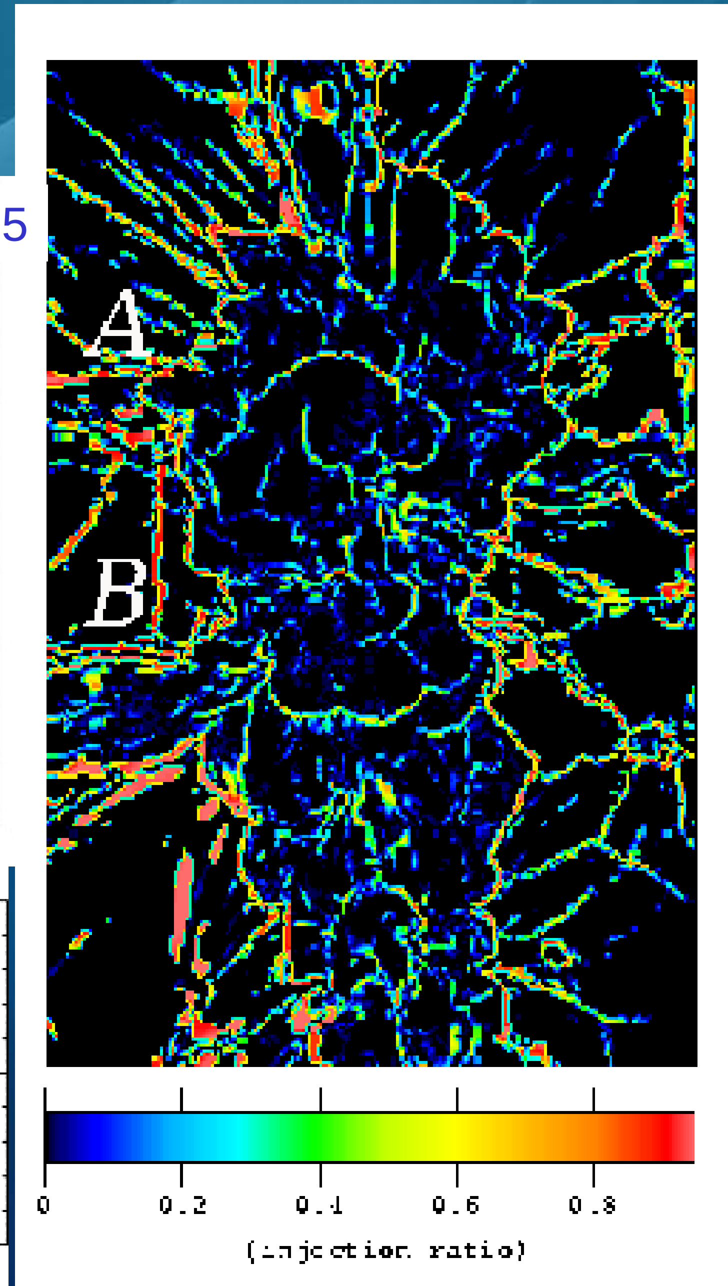
Shocks in Galaxy Clusters

Shocks are responsible for the heating of the IGM

Markevitch et al 05

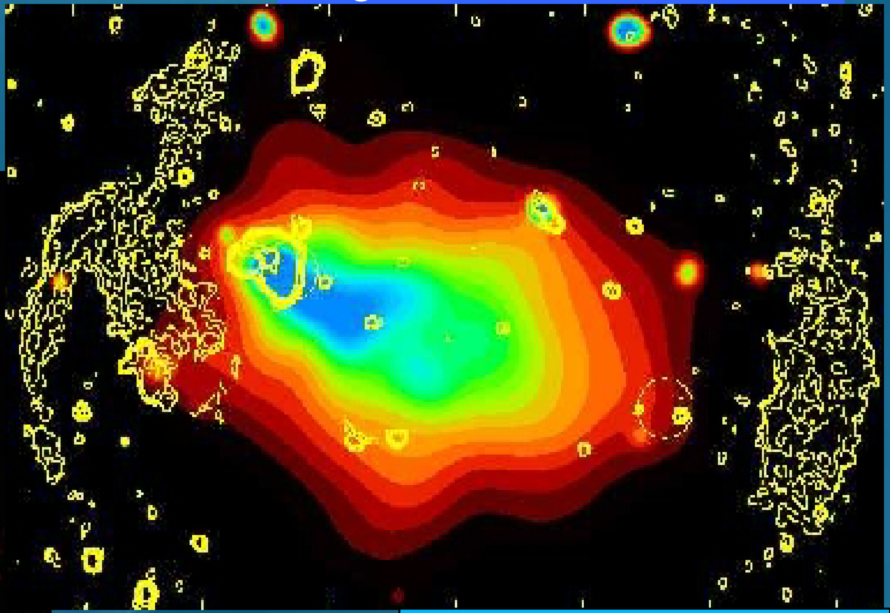




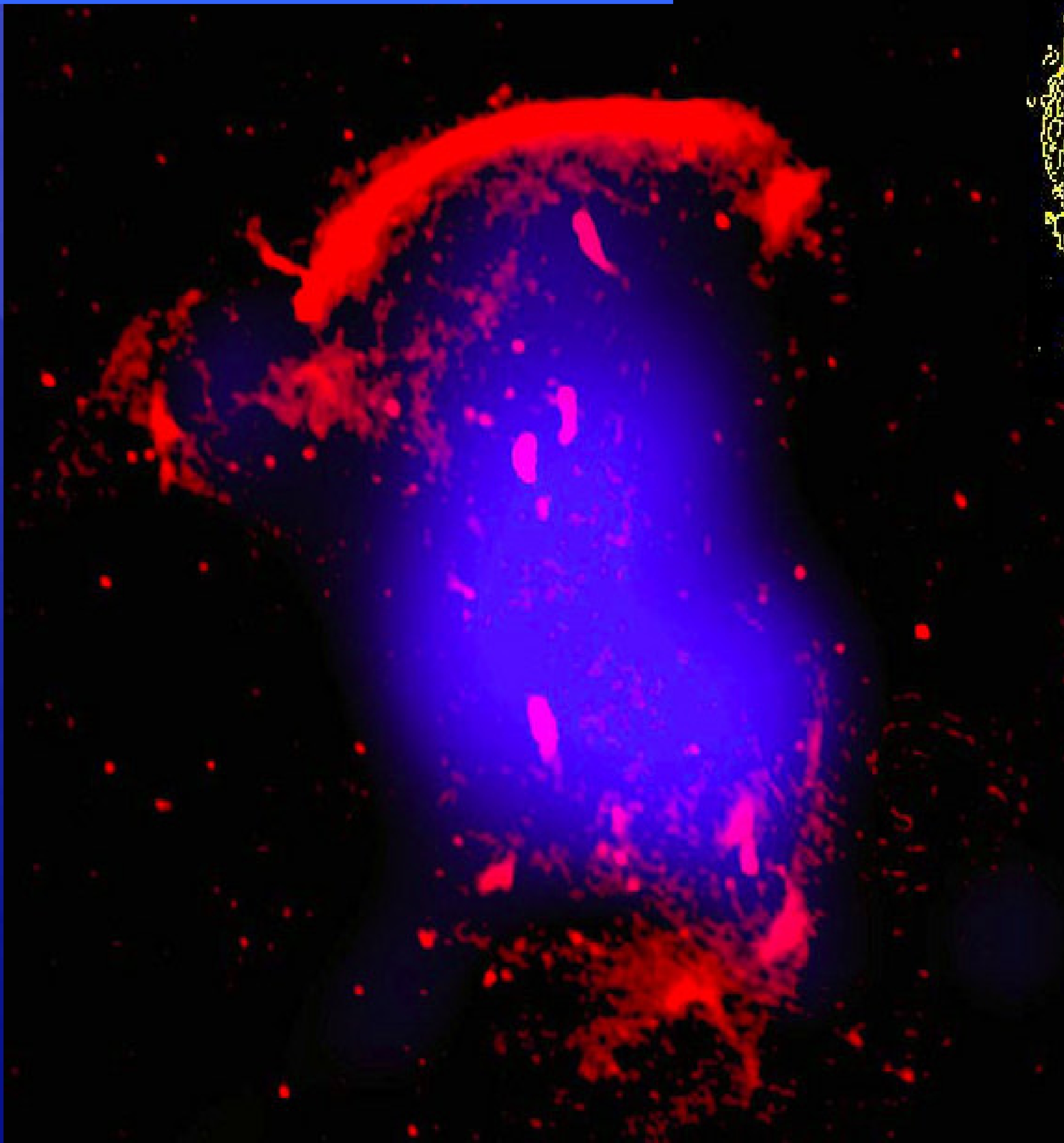


Shock—Relic connection

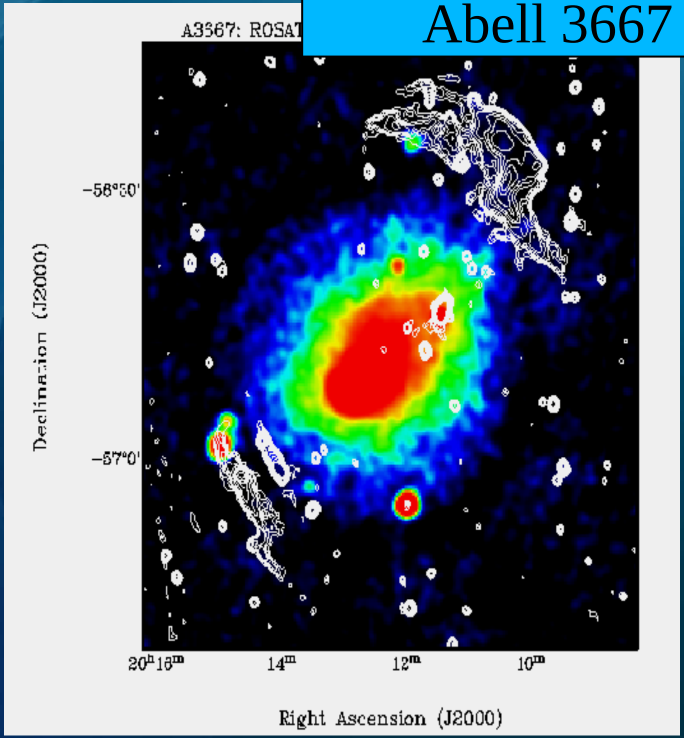
Bagchi+al. 2002, *Science*



van Weeren+al. 2010, *Science*



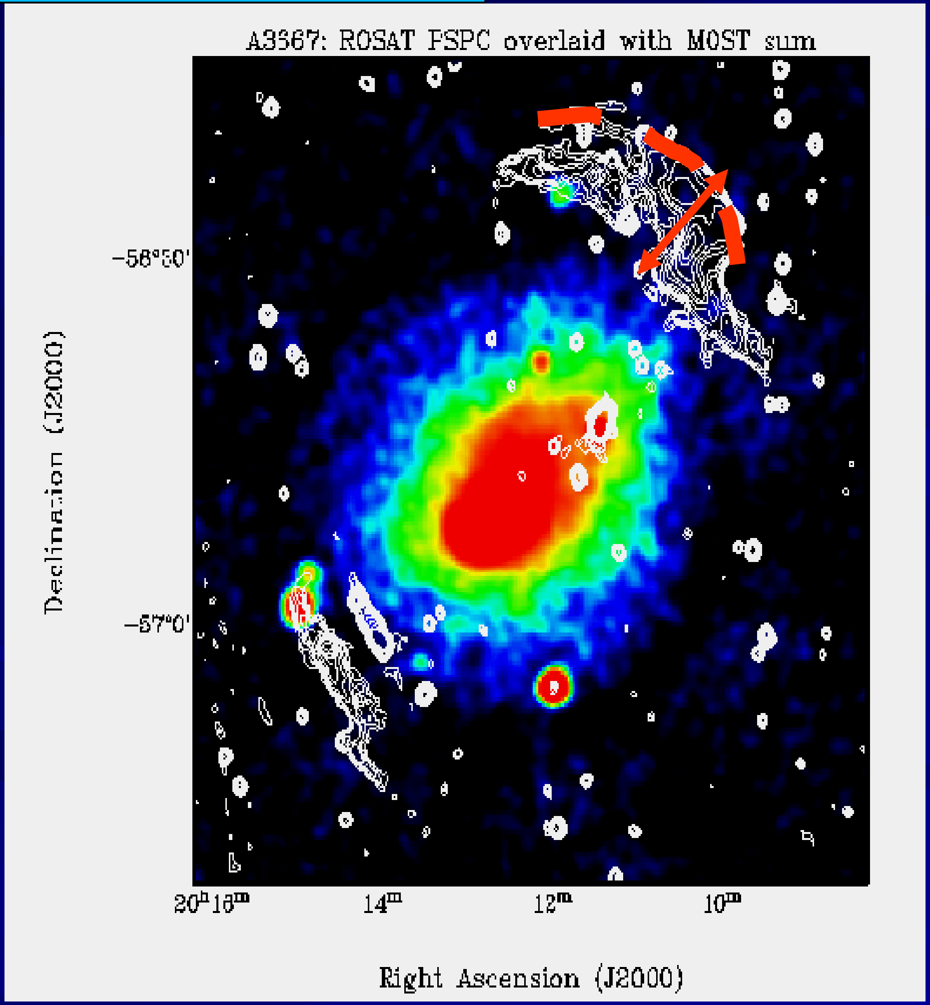
Abell 3667

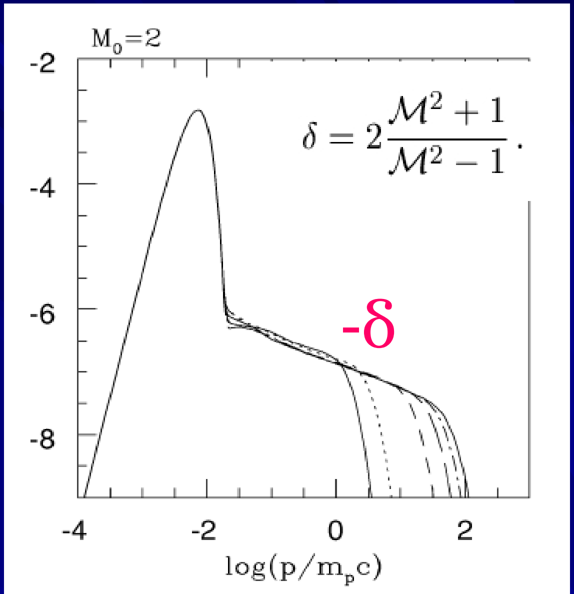


Shock Acceleration: Radio Relics

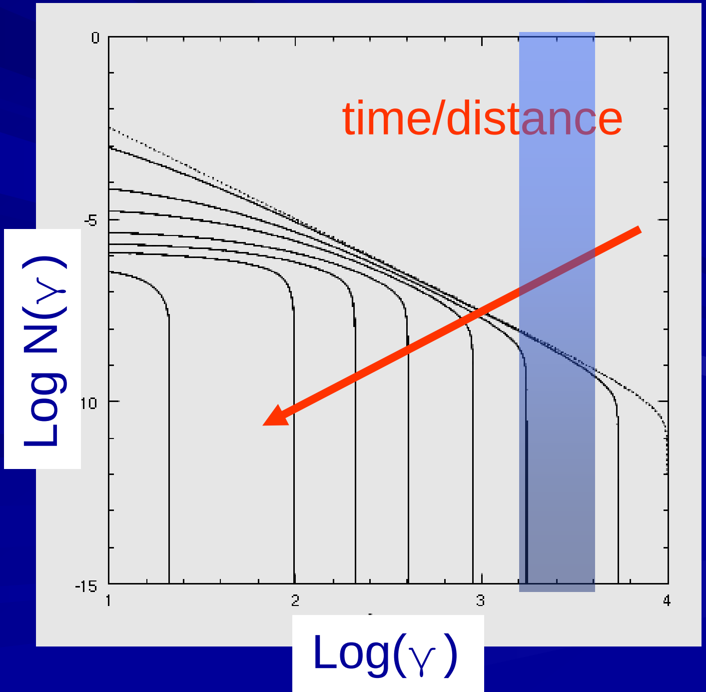
(Ensslin et al 1998, Roettiger et al. 1999, Sarazin 1999, …)

Abell 3667



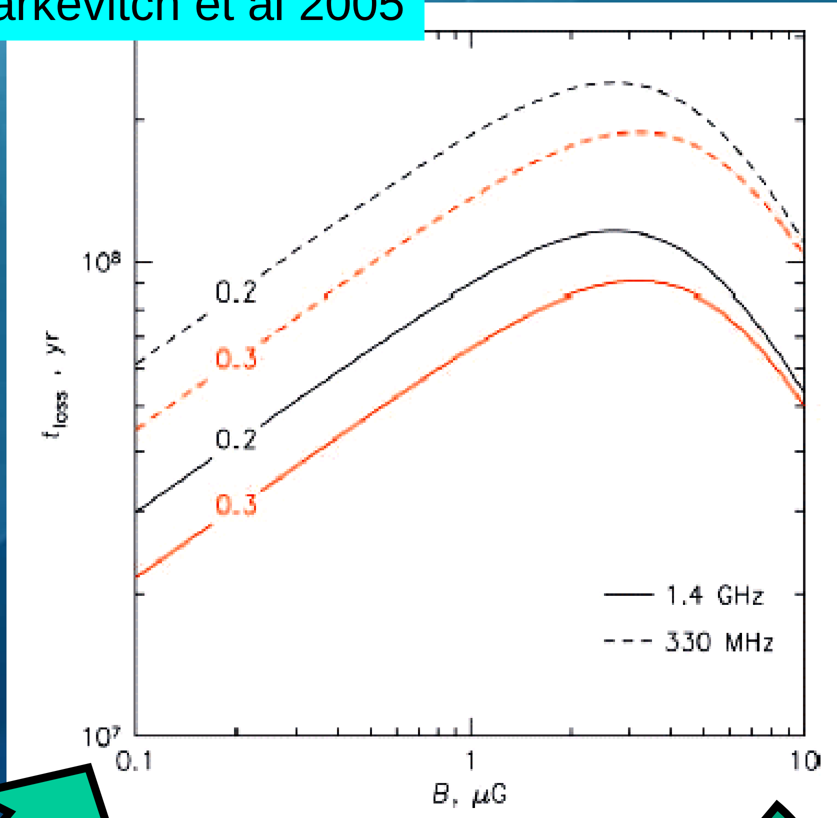


$l_R \approx V_d\, \tau_e(\nu) \approx 100$ kpc



Width of Relics & constraints on B

Markevitch et al 2005



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

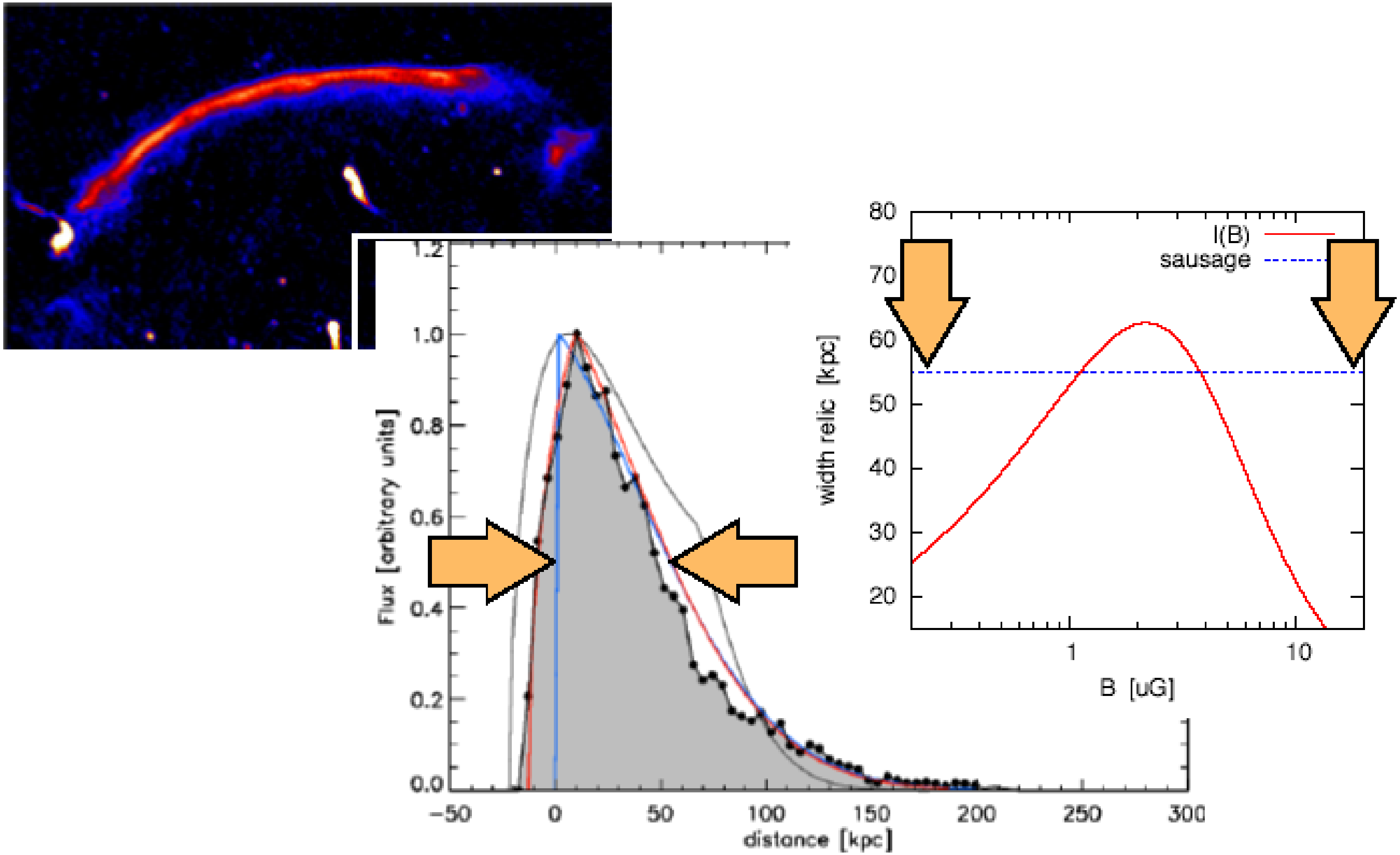
$$\gamma \approx c_{syn} (\nu/B)^{1/2}$$

$$V_d \approx c_s M(M^2+3)/4M^2$$

Width of Relic

The width of the `sausage' (CIZA 2242)

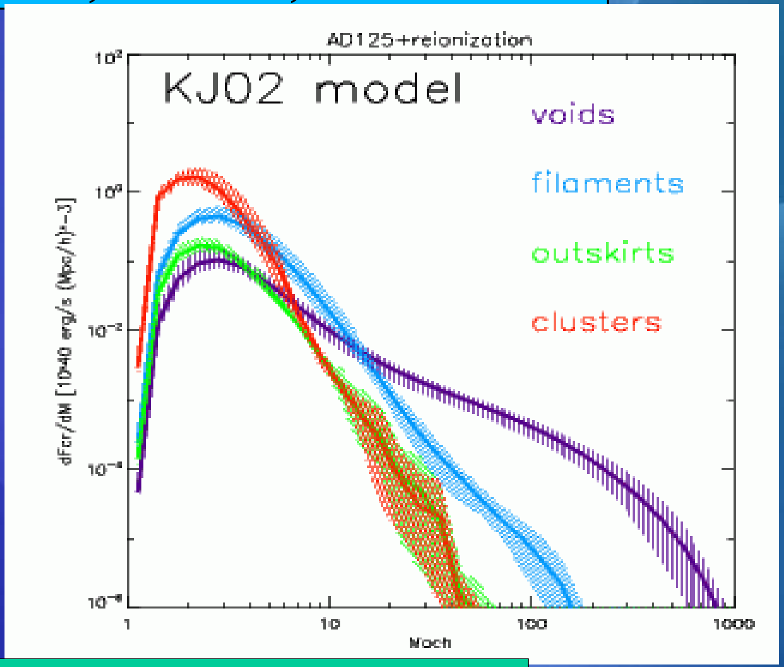
Van Weeren et al., 10



From Heft, conference in Bangalore

Mach numbers in galaxy clusters

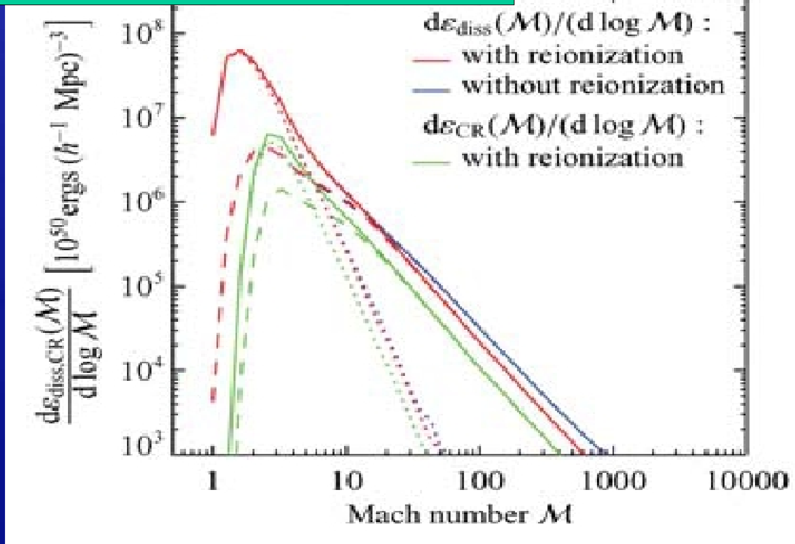
Vazza, Brunetti, Gheller 2009

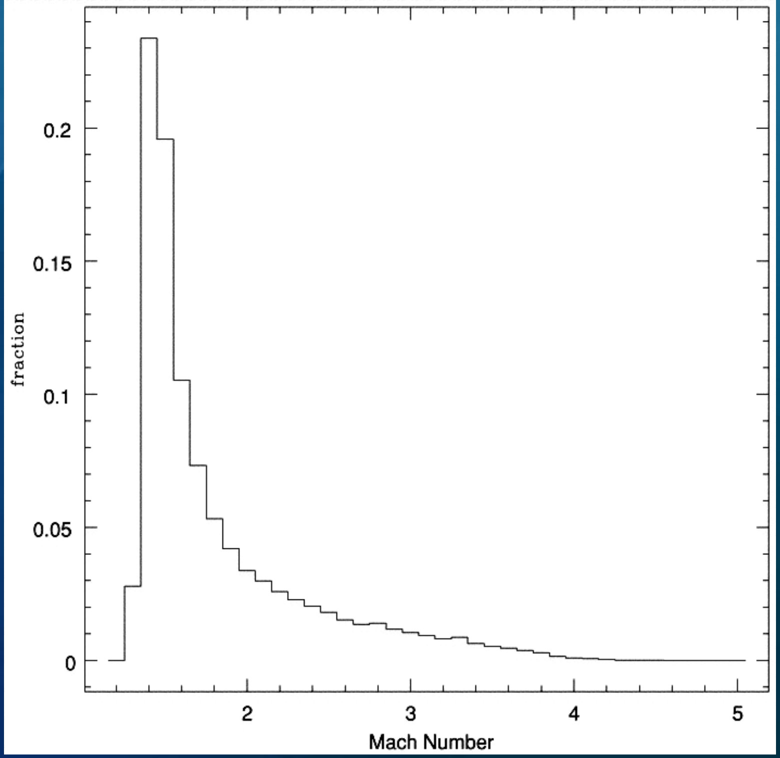


Semi-analytics :
Gabici & Blasi 2003
Berrington & Dermer 2003

some agreement…

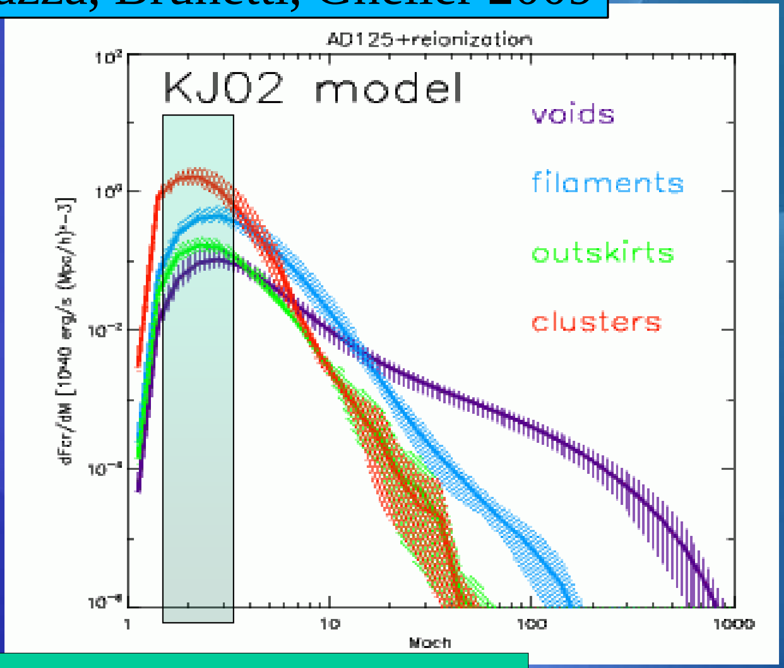
Pfrommer et al. 2008



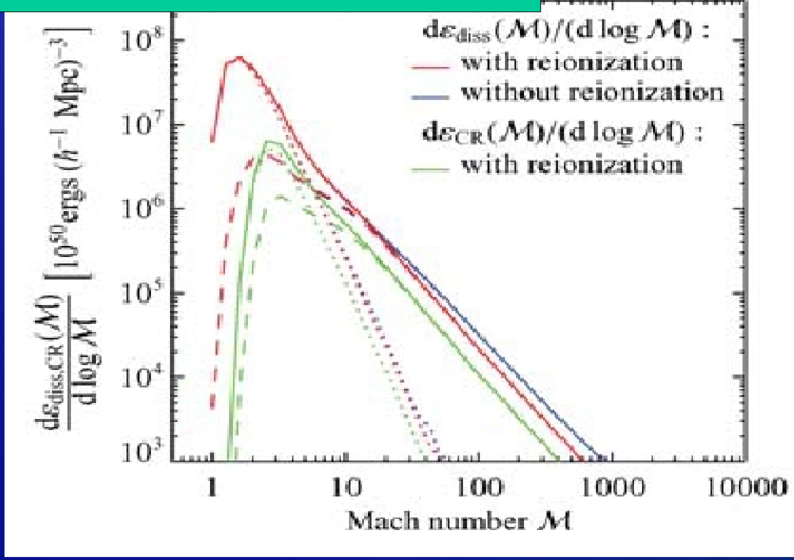


Uncertainties in CR acceleration

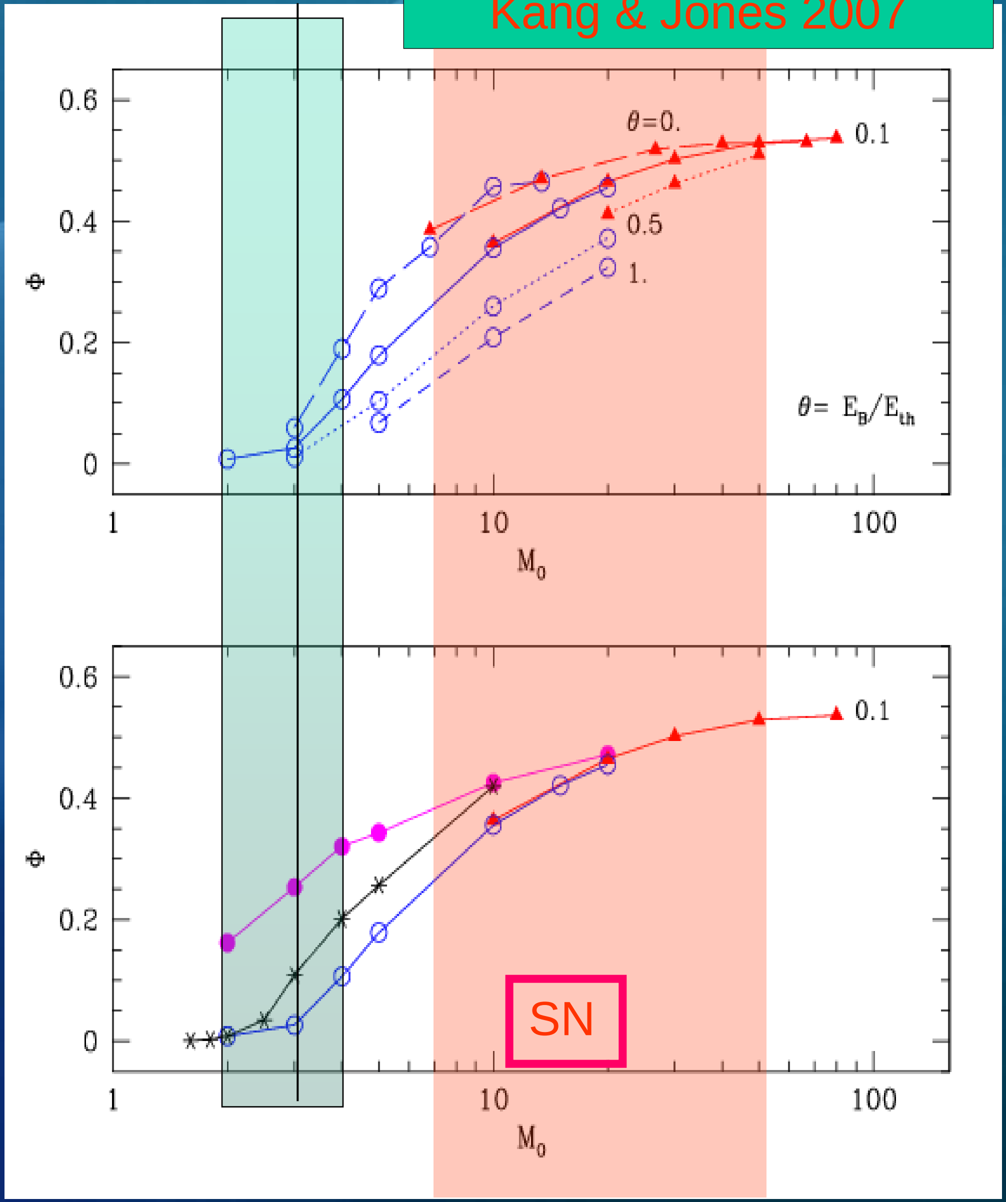
Vazza, Brunetti, Gheller 2009



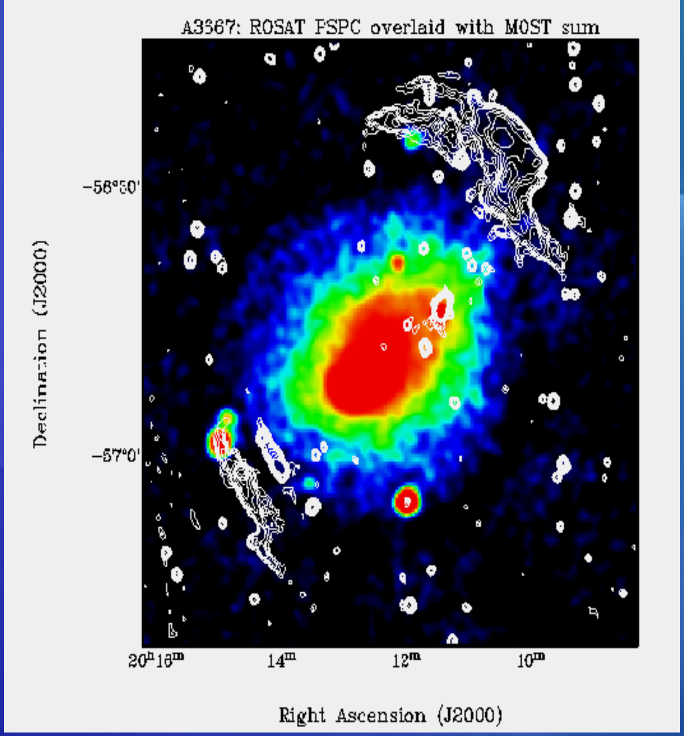
Pfrommer et al. 2006, 08

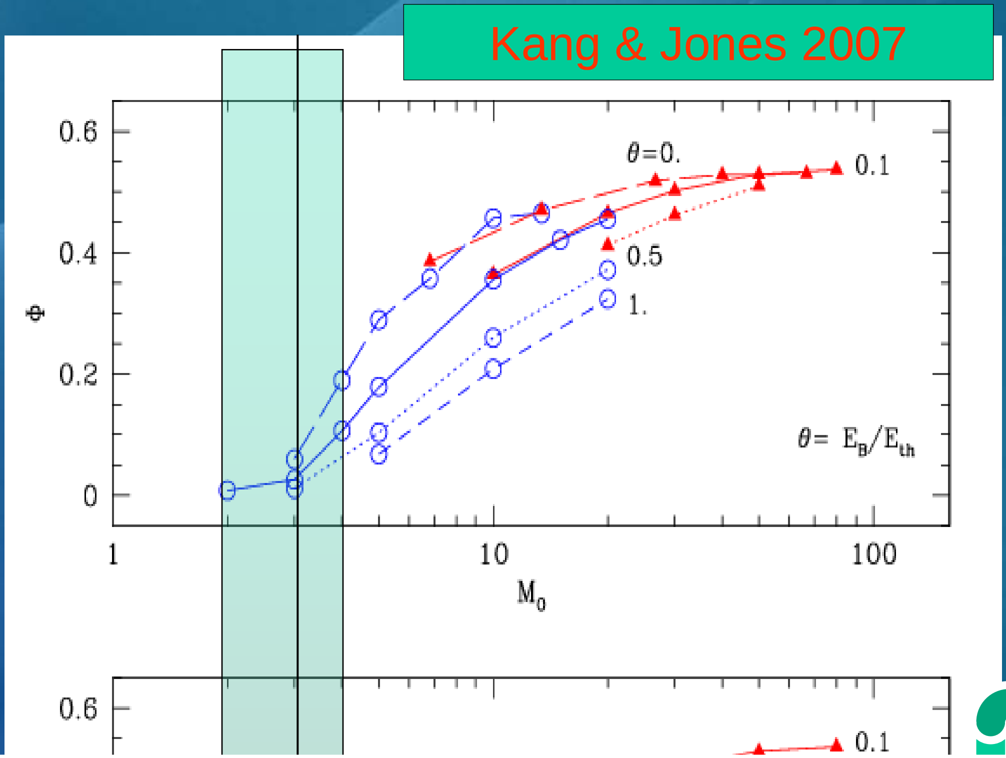


Kang & Jones 2007



CR acceleration or REacceleration?





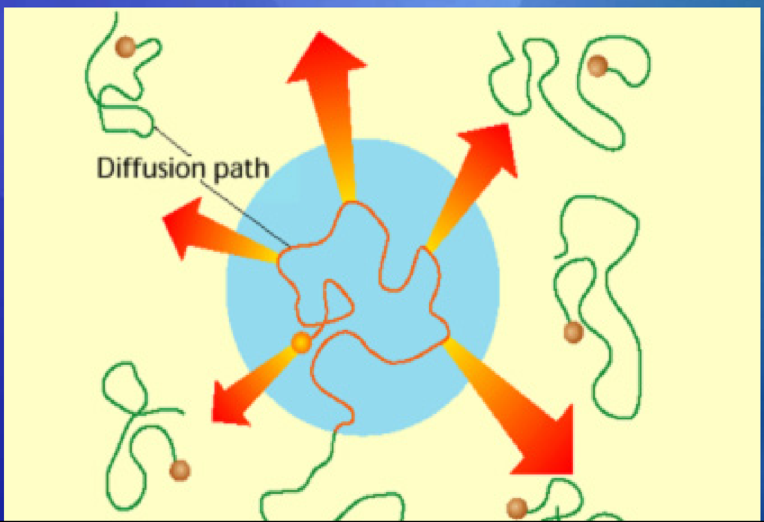
Merger shocks have M=1.5-3.
Reacceleration of pre-existing relativistic electrons at these shocks is efficient (eg. Kang & Ryu 11)

Galaxy clusters are unique labs to study particle acceleration at weak & LS shocks

Radio Halos as “labs” for CR acceleration in GC

$L^2 \sim D \times t$

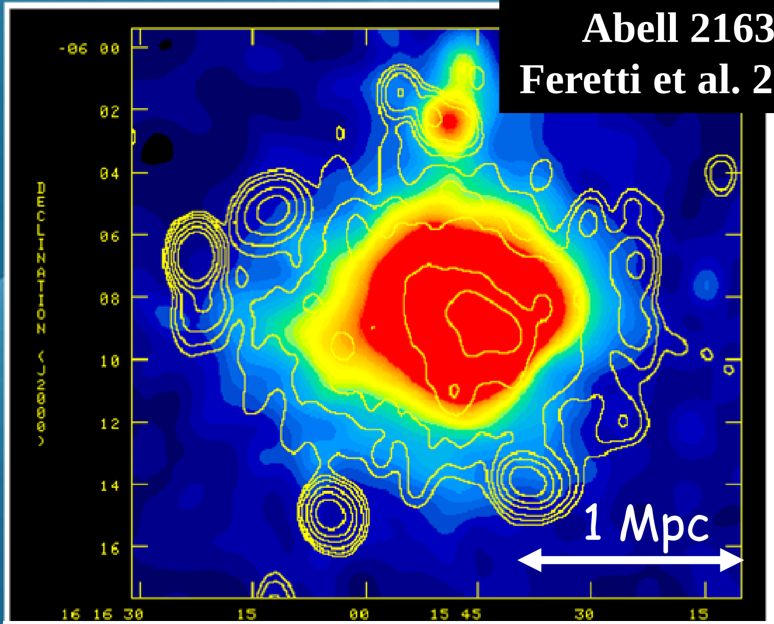
$$D(E_p) = \frac{1}{3} r_L c \frac{B^2}{\int_{1/r_L}^{\infty} dk P(k)}$$



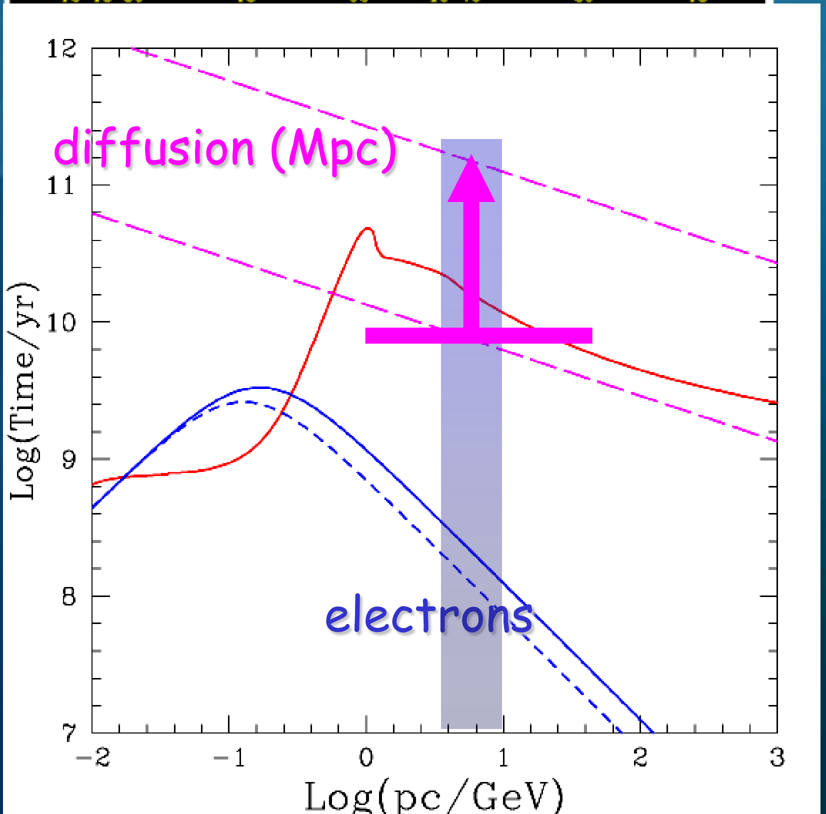
T_{diff} (~10^{10} yr) >> T_{cool} (~10^{8} yr)

(eg. Jaffe 1977)

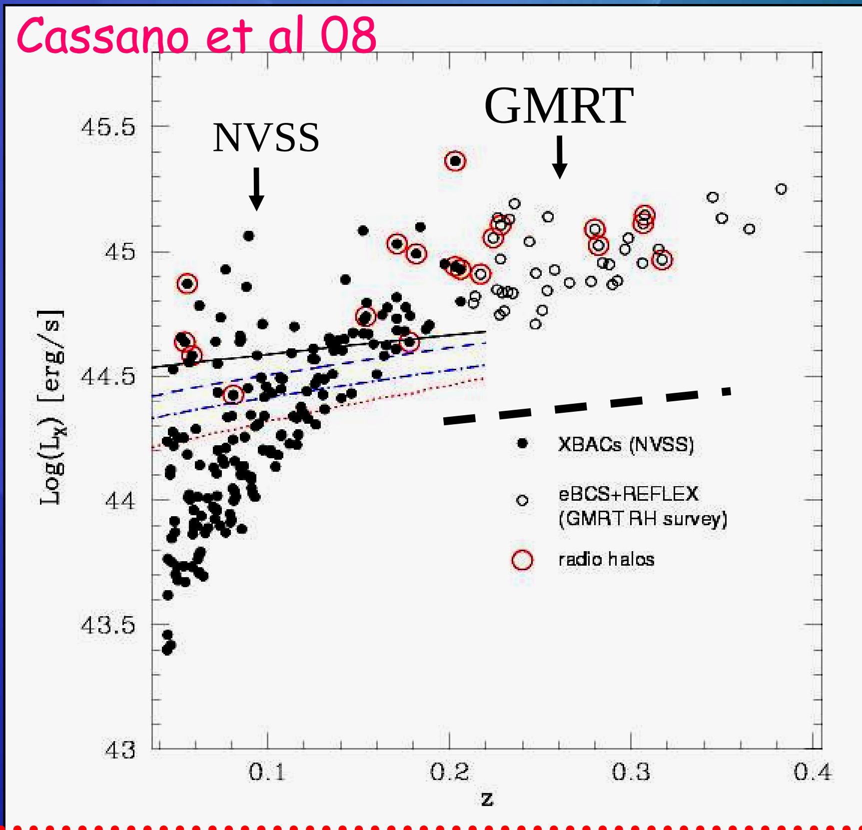
“in situ” (re)acceleration or injection of CR electrons …

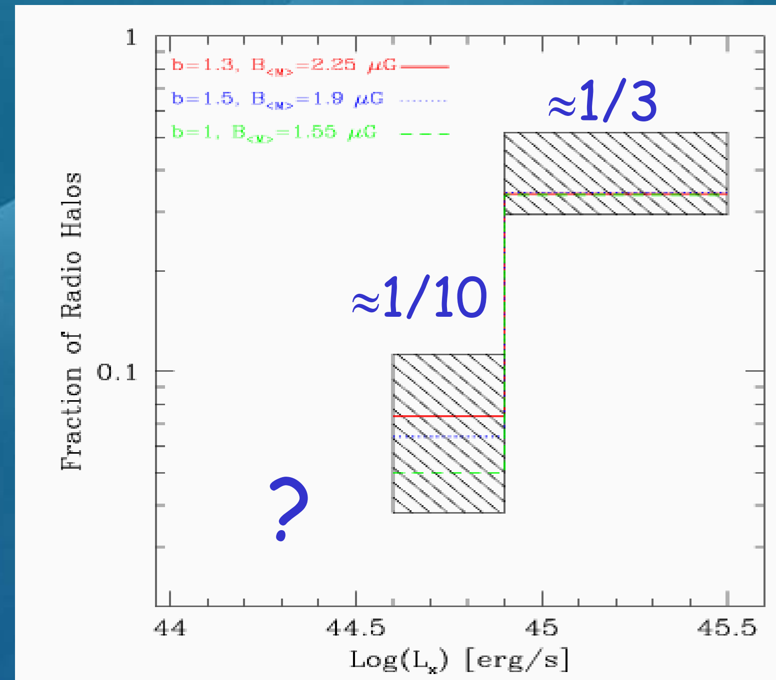


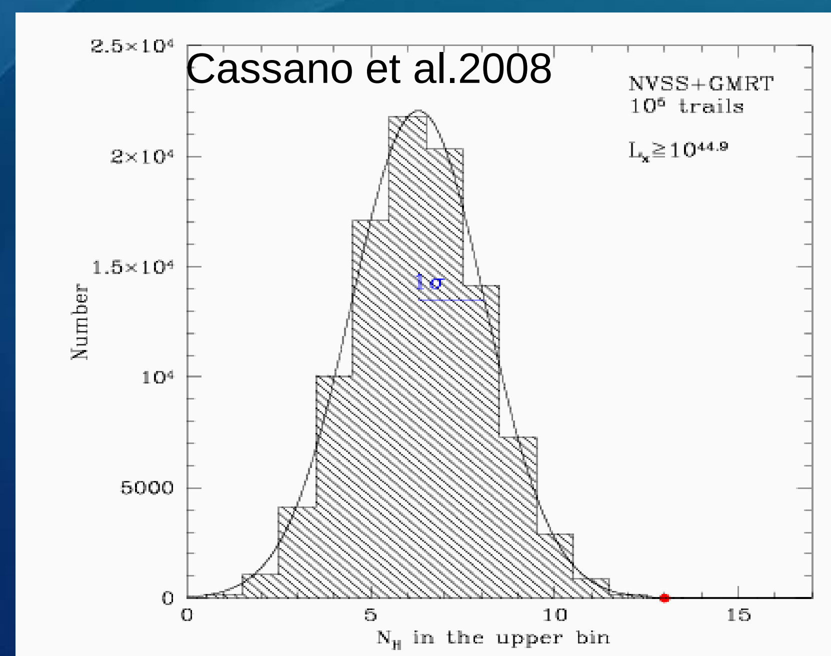
Abell 2163
Feretti et al. 2001



Statistics of Radio Halos







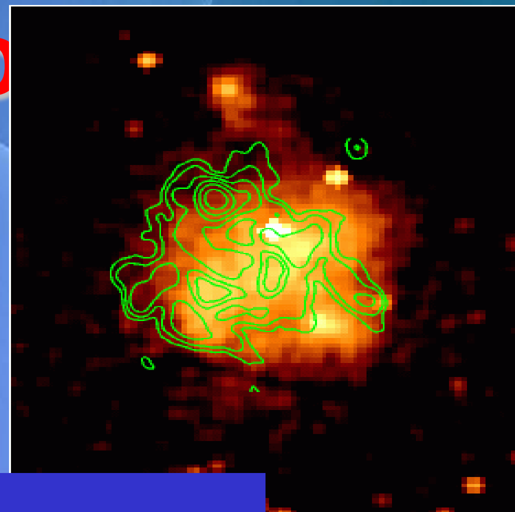
NVSS data (from *Giovannini et al. 1999*) and deep **GMRT observations**.

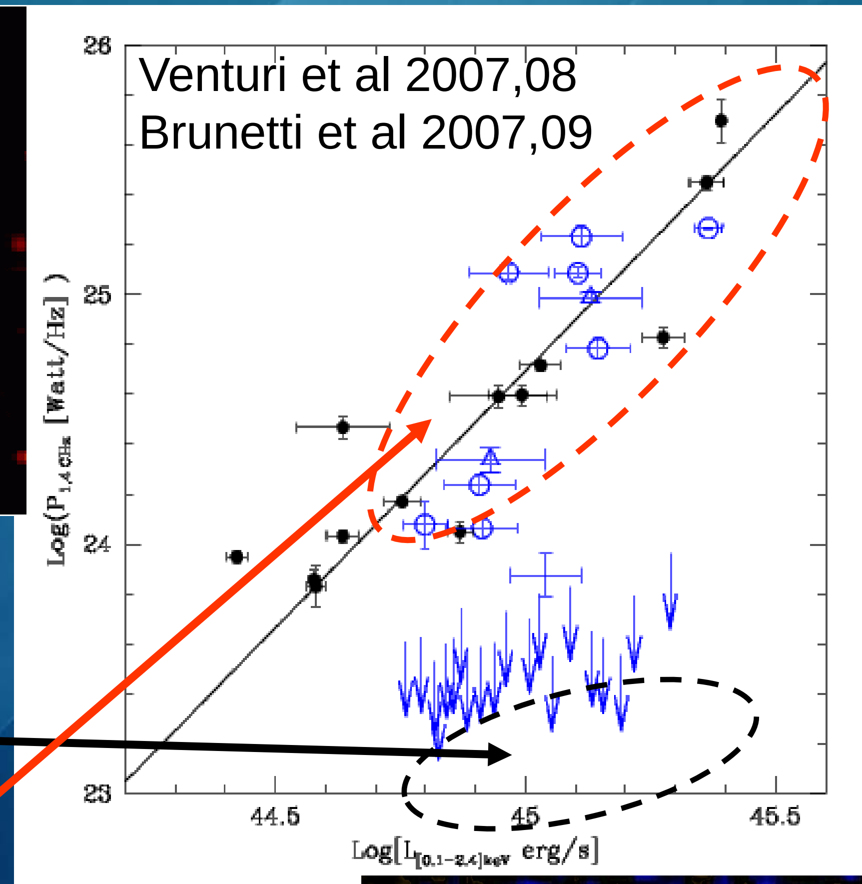
0.41±0.11 for $L_x > 10^{44.9}$ erg/s ≈ 1/3

0.08±0.04 for $L_x < 10^{44.9}$ erg/s ≈ 1/10

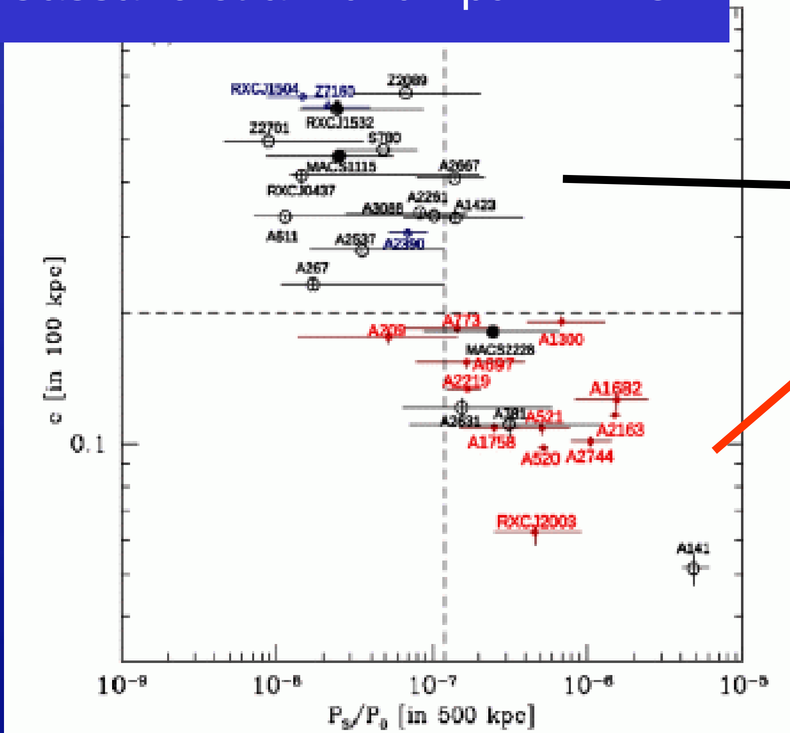
(Venturi et al. 2007, 2008; Cassano et al.2008)

Cluster mergers - radio halos connectio

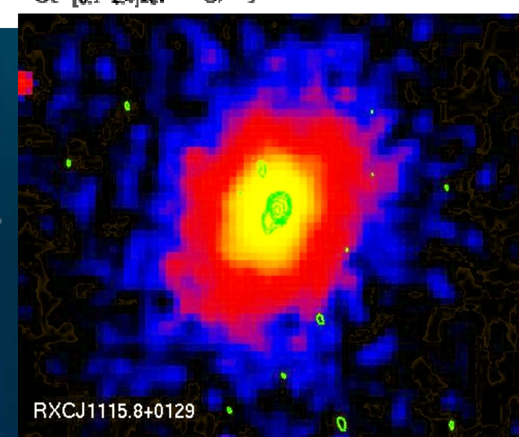




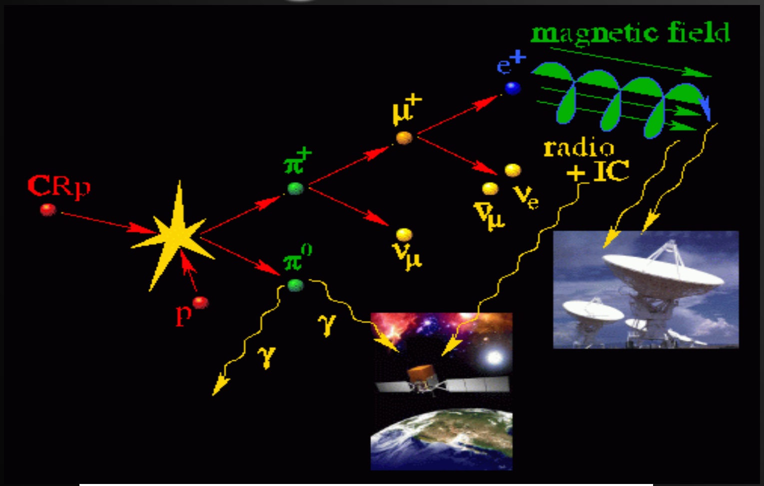
Cassano et al 2010 ApJ 721 L82

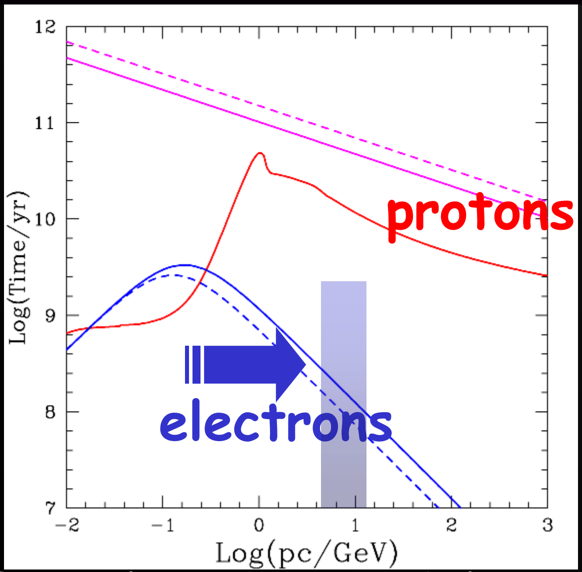


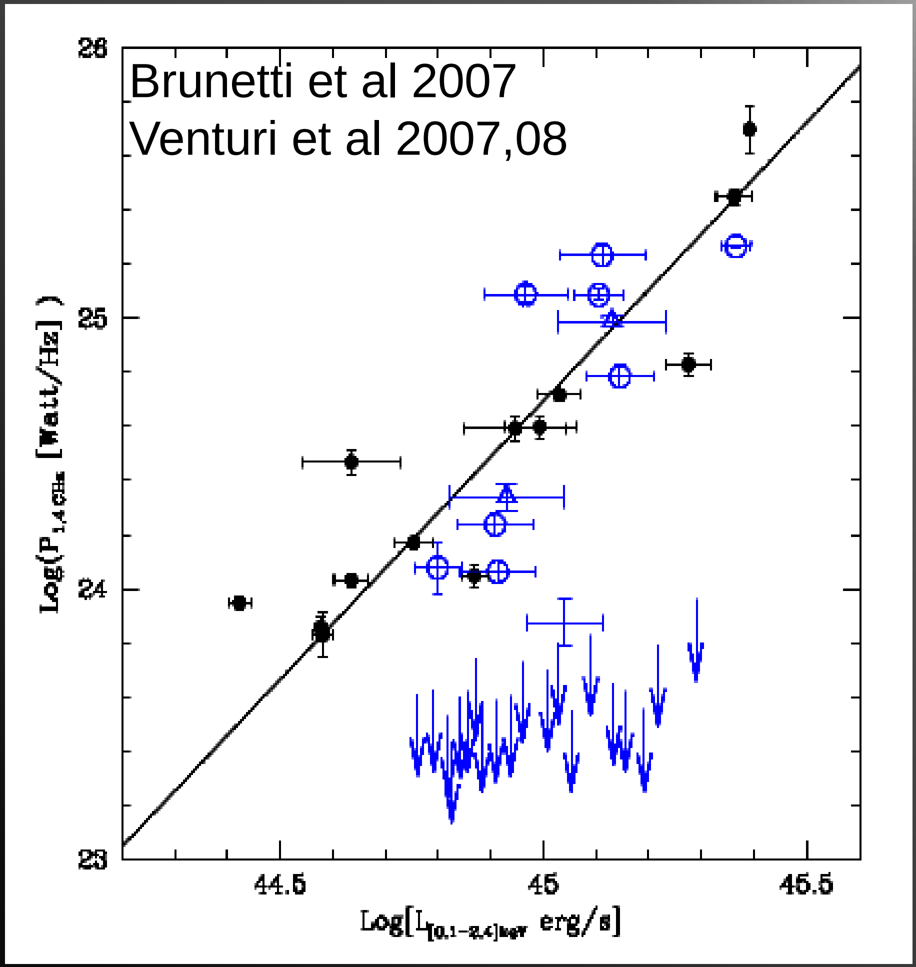
The radio bimodality has a correspondence in terms of dynamical segregation



Origin of Radio Halos: turbulence ?





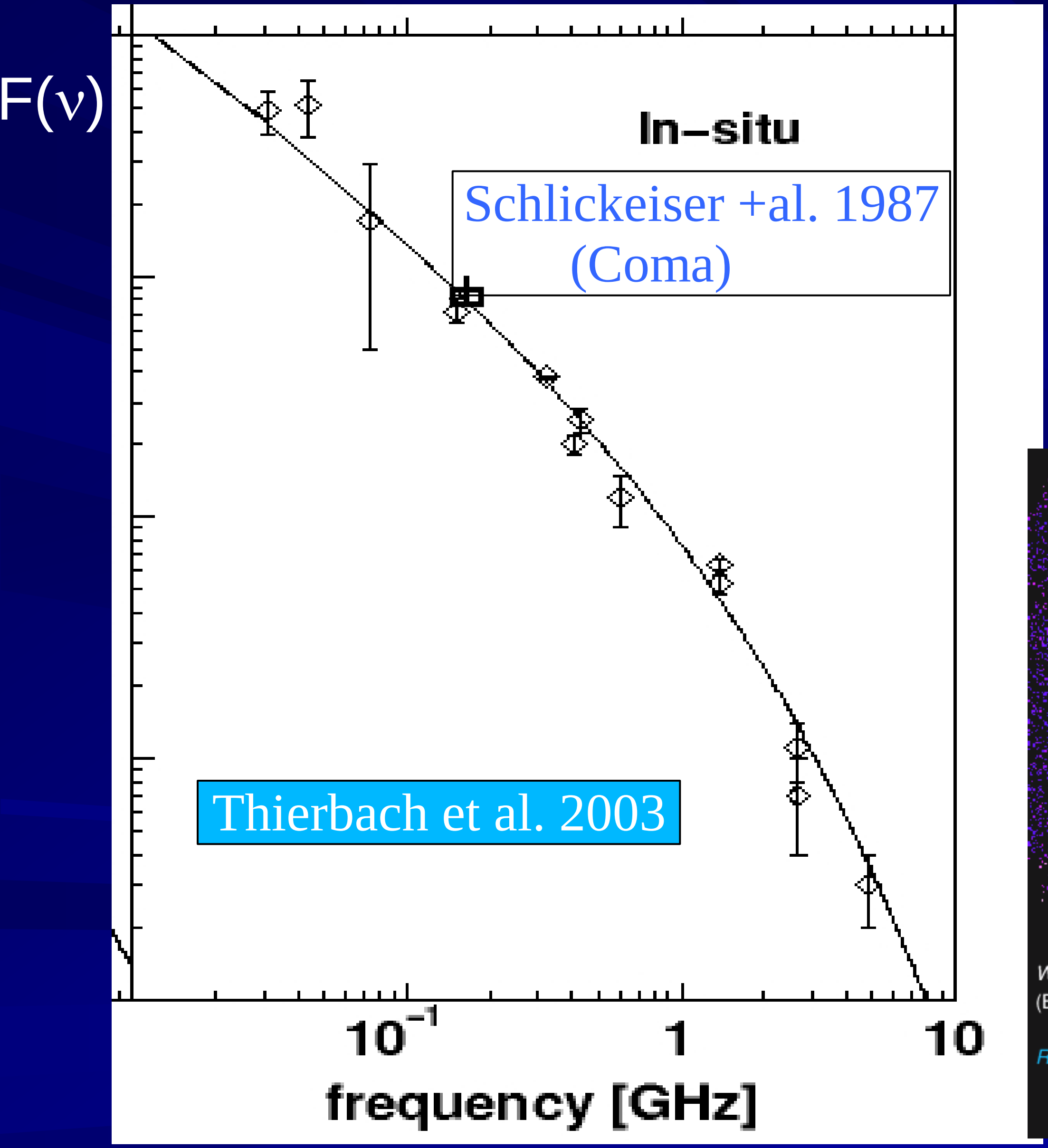


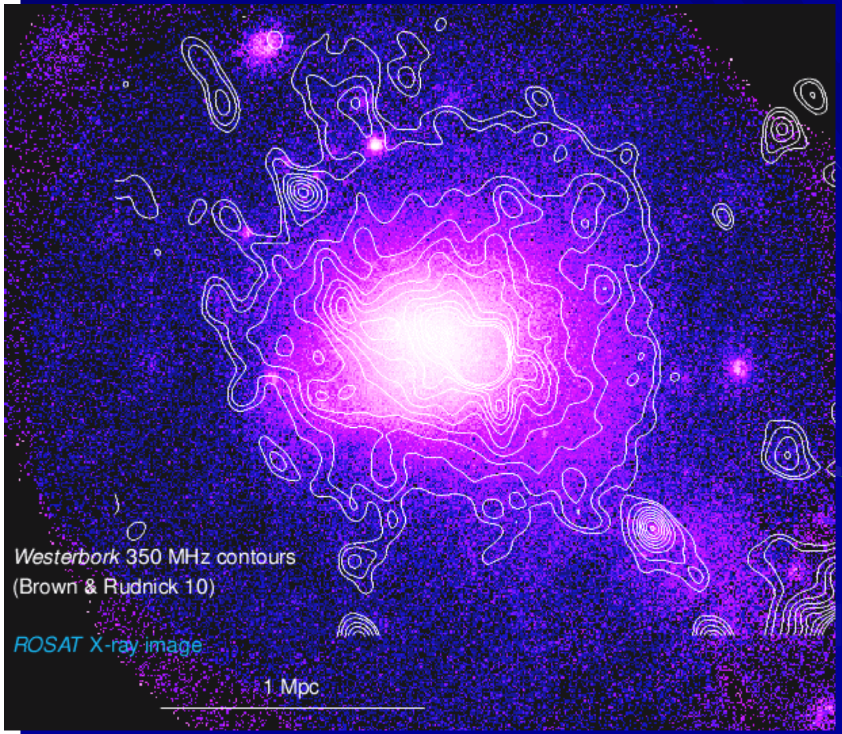
REacceleration models (eg Brunetti et al 01, Petrosian 01, …)

A mechanisms <u>distributed on Mpc scales</u> channels a fraction of the gravitational energy dissipated during mergers into high energy particles

Turbulence ??

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





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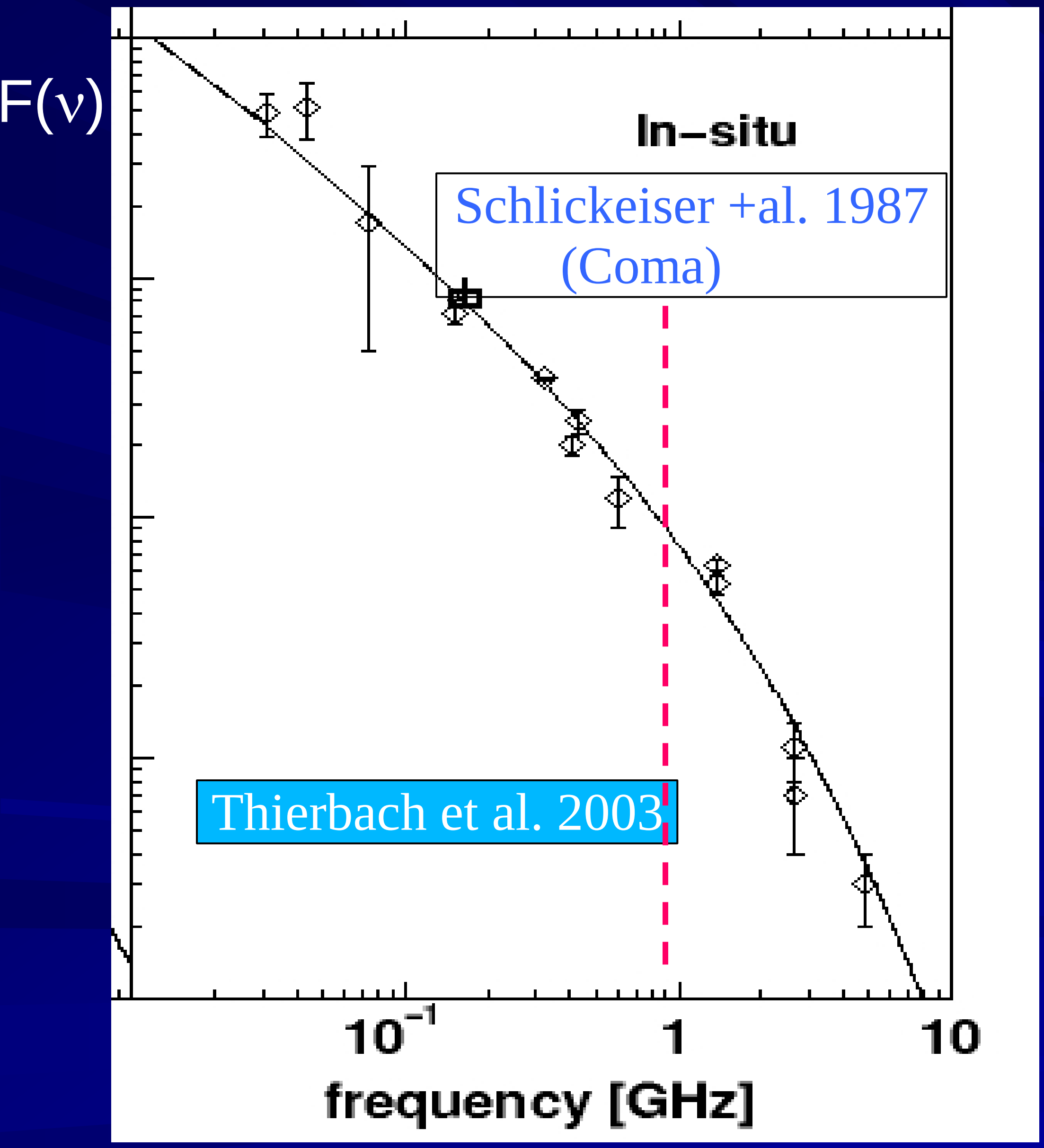
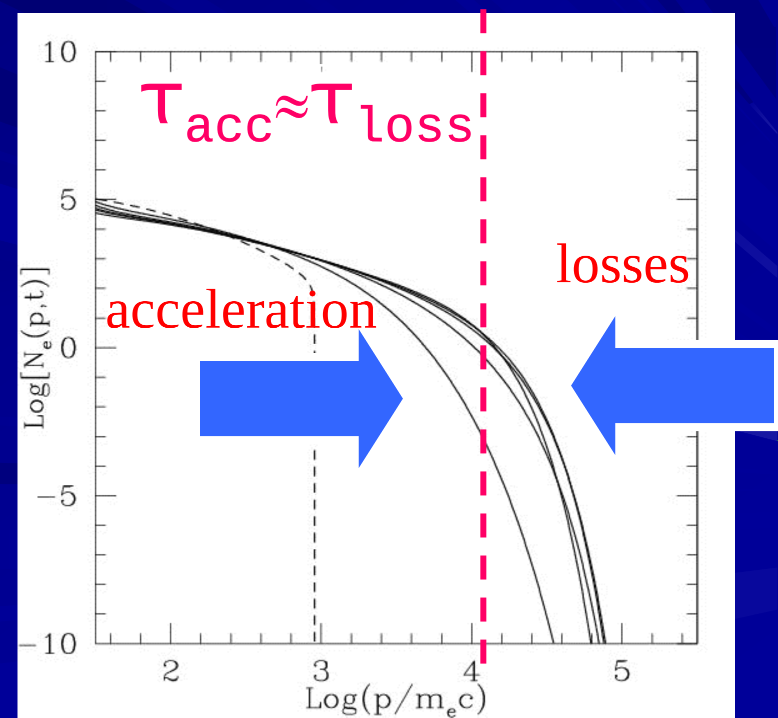


Evidence of break in the spectrum of the emitting electrons at energies of few GeV



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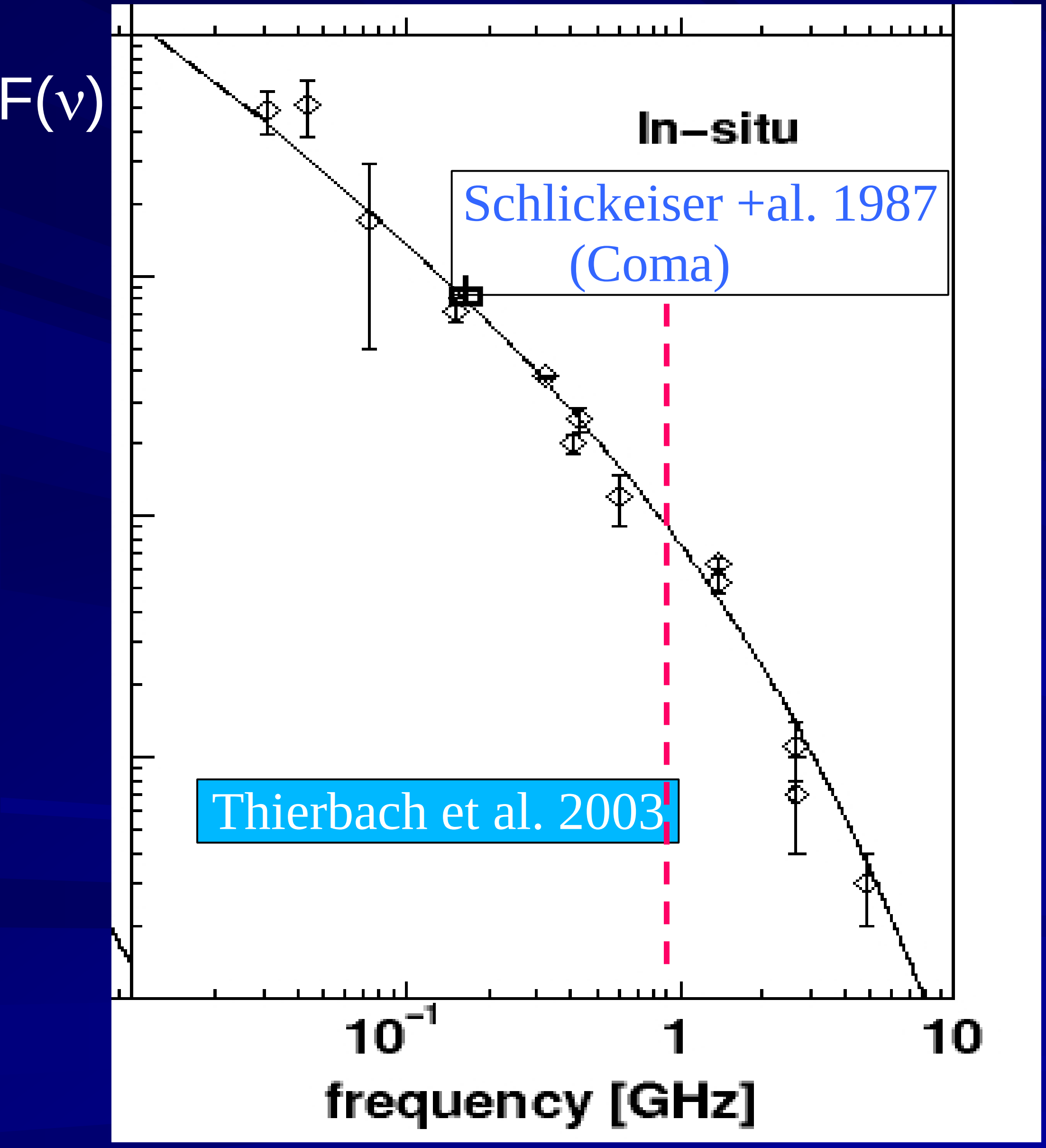
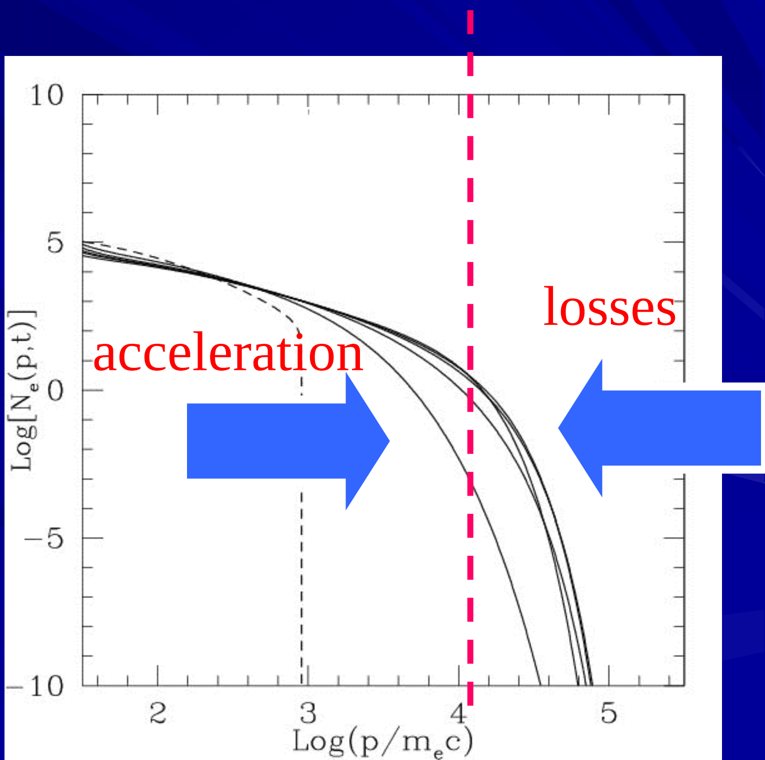


$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm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

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



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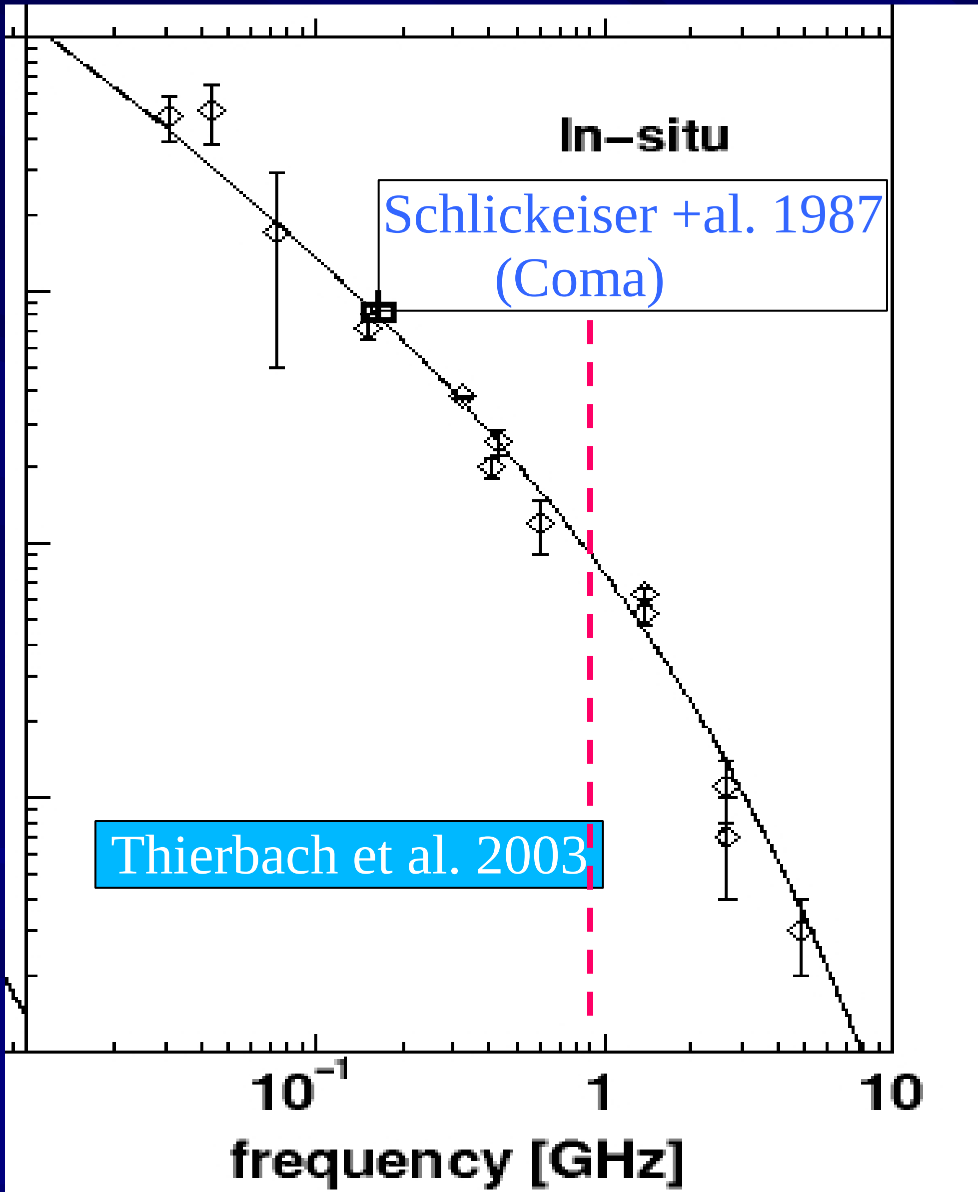

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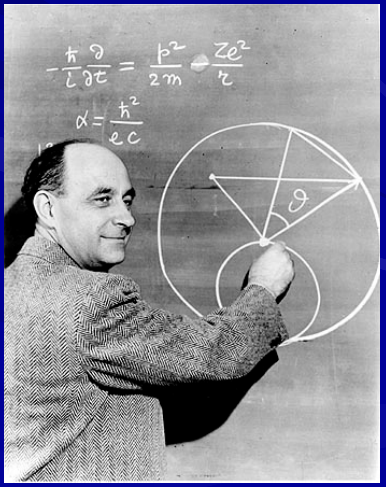
Acceleration time-scale $\approx 10^8$ years

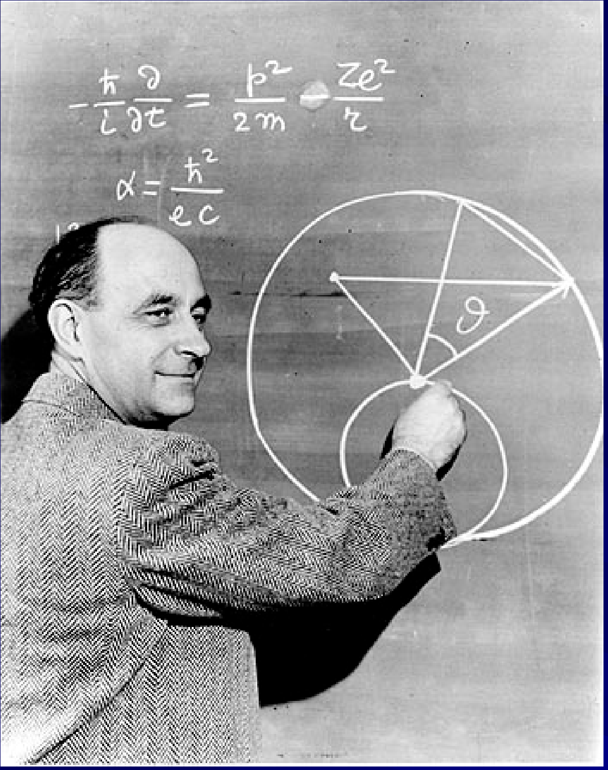
eg., "classical" Fermi II

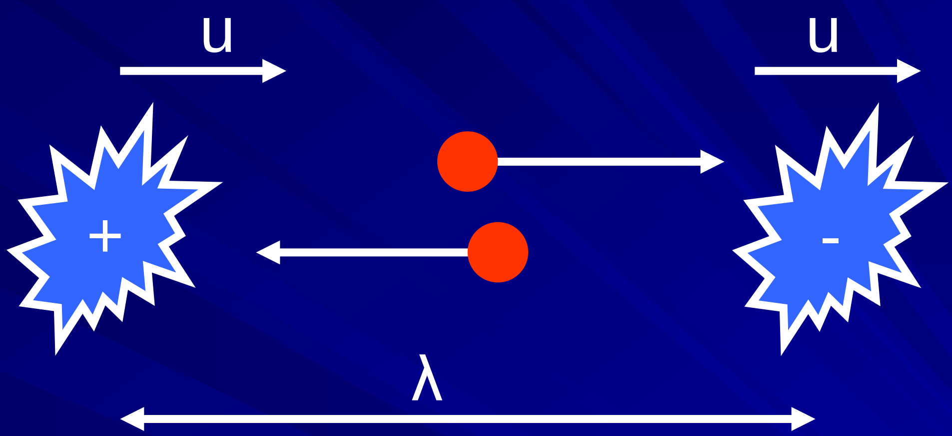
$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2}$$

$> 10^7$yrs



Second order Fermi Mechanisms
(Fermi 1949)





Frequency of collisions:

Energy gain per collisions:

Cosmic rays interact with magnetic turbulence

Cosmic Rays ⟷ **Magnetized medium**

In case of small angle scattering, Fokker-Planck equation can be used to describe the particles' evolution:

$$\frac{\partial F}{\partial t} + \underbrace{v\mu \frac{\partial F}{\partial Z} - \Omega \frac{\partial F}{\partial \phi}}_{\text{transport}} = S + \frac{1}{p^2} \underbrace{\frac{\partial}{\partial x}\left(p^2 D_{xy} \frac{\partial F}{\partial y} \right)}_{\text{diffusion}}$$

S : Sources and sinks of particles

2nd term on rhs: diffusion in phase space specified by Fokker -Planck coefficients D_{xy}

Stochastic particle acceleration due to particle-mode coupling

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

The diffusion coefficients define characteristics of particle propagation and acceleration

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

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 (Ptuskin 1988)

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

Stochastic particle acceleration due to particle-mode coupling

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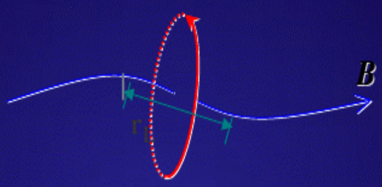
Gyroresonance scattering depends on the properties of turbulence

Gyroresonance

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

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

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

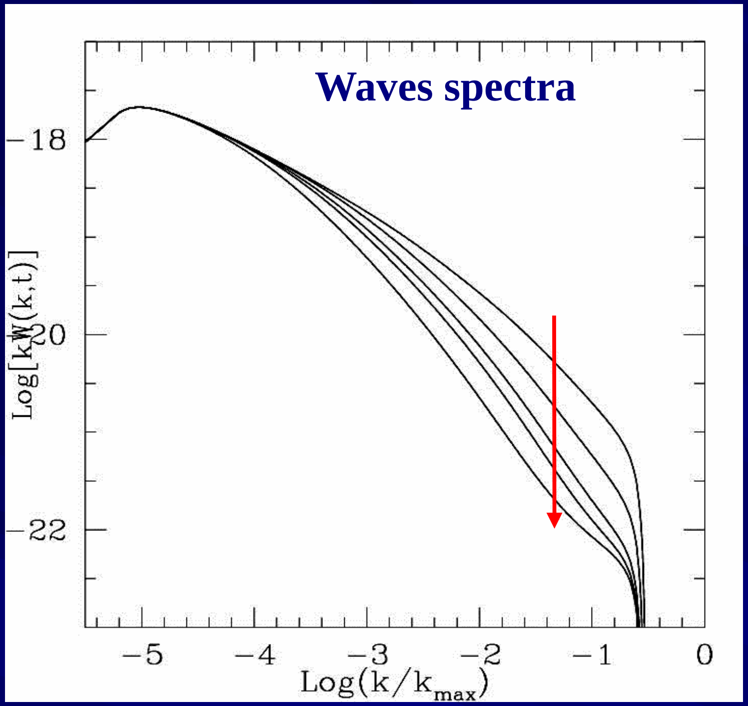


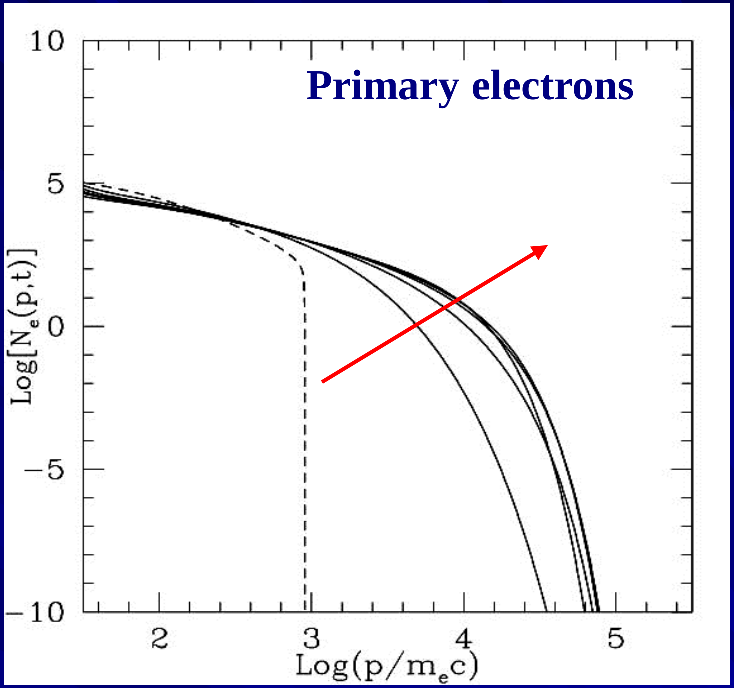
Transit Time Damping (TTD)

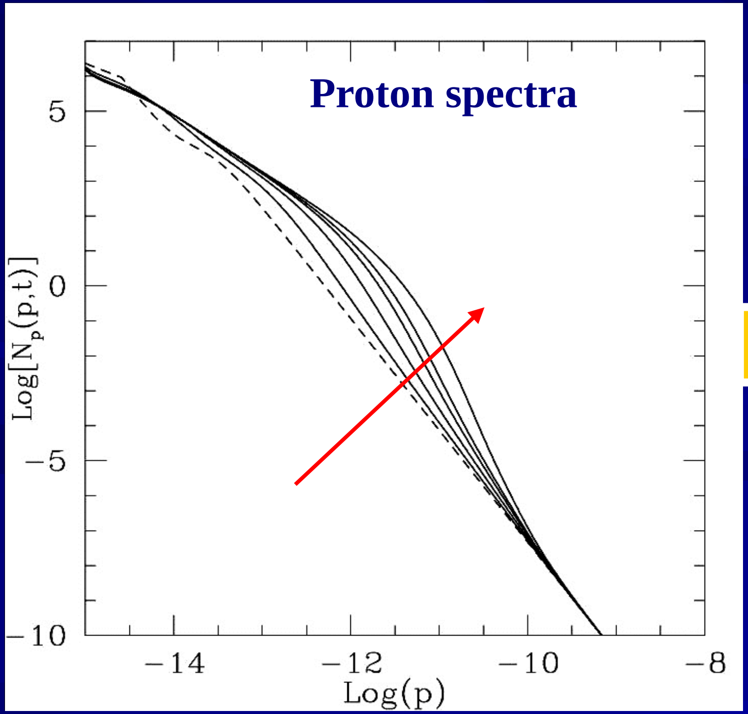
$$\omega - k_{//} v_{//} = 0$$

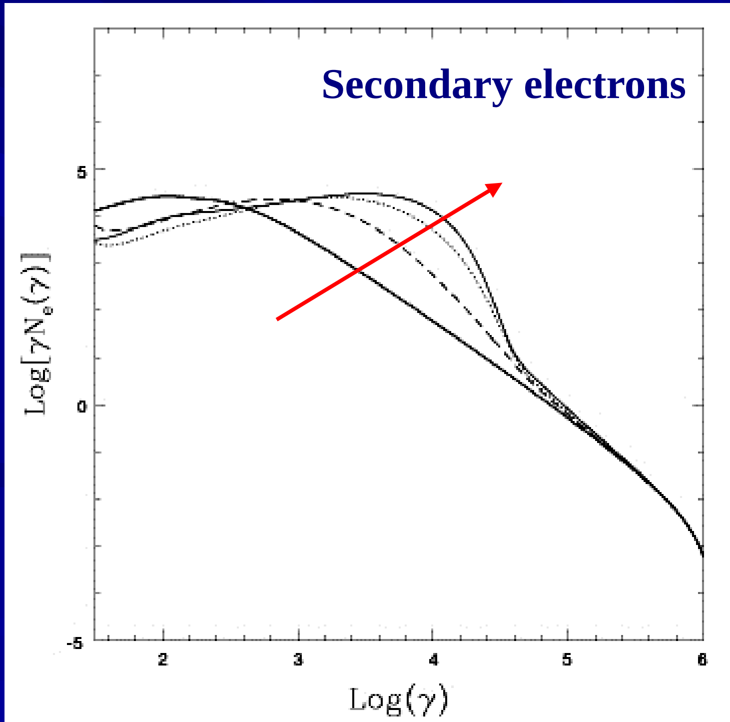
Interaction btw magnetic moment of particle and parallel gradient of B

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


Waves spectra
Log[kW(k,t)]
−18
−20
−22
−5
−4
−3
−2
−1
0
Log(k/k_max)


Primary electrons
Log[N_e(p,t)]
10
5
0
−5
−10
2
3
4
5
Log(p/m_e c)


Proton spectra
Log[N_p(p,t)]
5
0
−5
−10
−14
−12
−10
−8
Log(p)

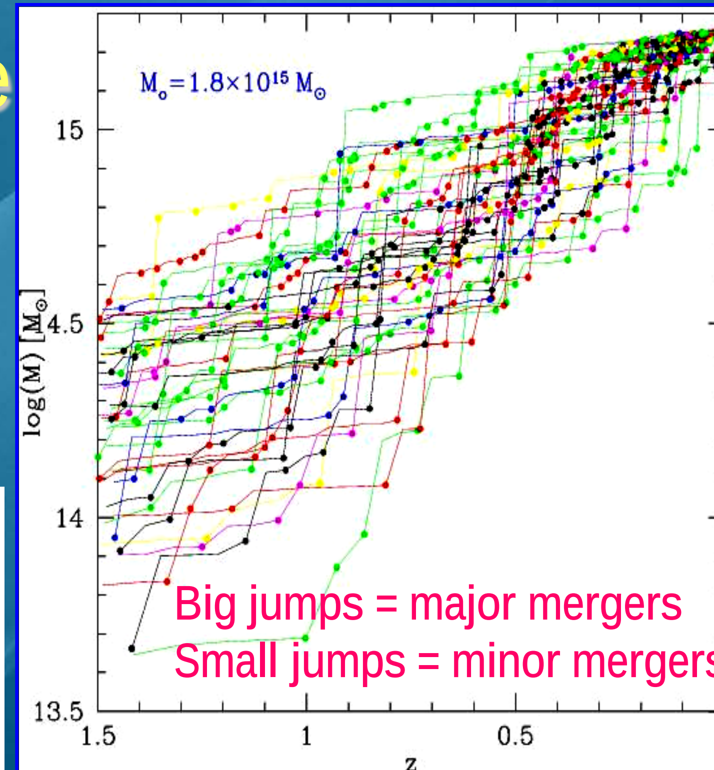

Secondary electrons
Log[γN_e(γ)]
5
0
-5
2
3
4
5
6
Log(γ)

Spectra of radio halos & turbulence

Steepening frequency

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

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

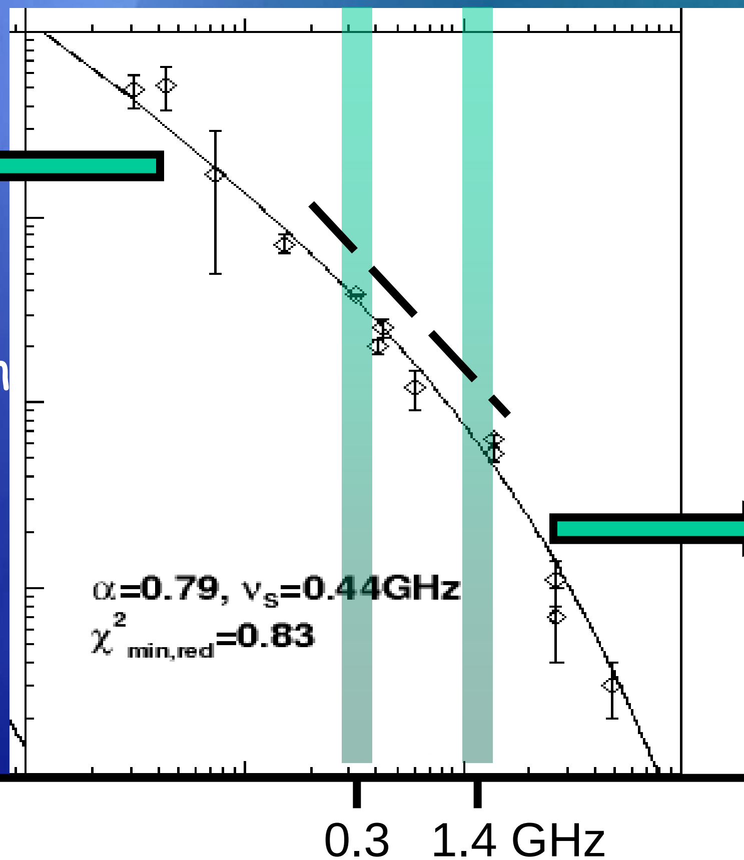


Big jumps = major mergers

Small jumps = minor mergers

less efficient

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



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

more efficient

Observed spectra of radio halos & turbulence

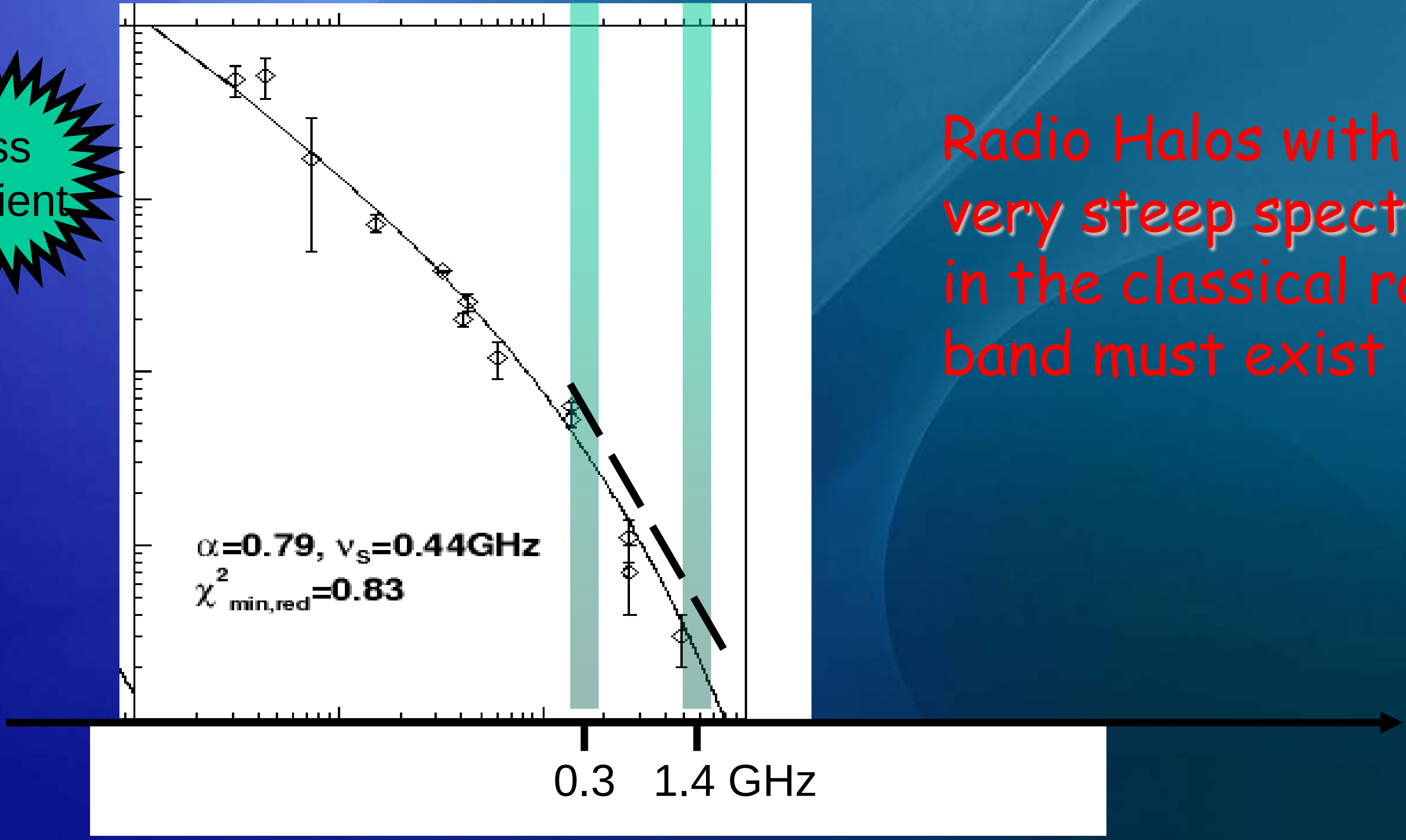
Cassano, GB, Setti (2006)

Steepening frequency

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

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

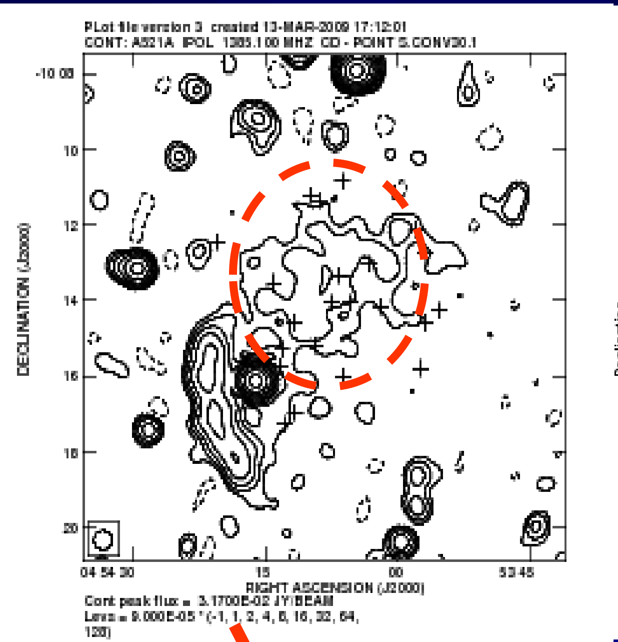
less efficient

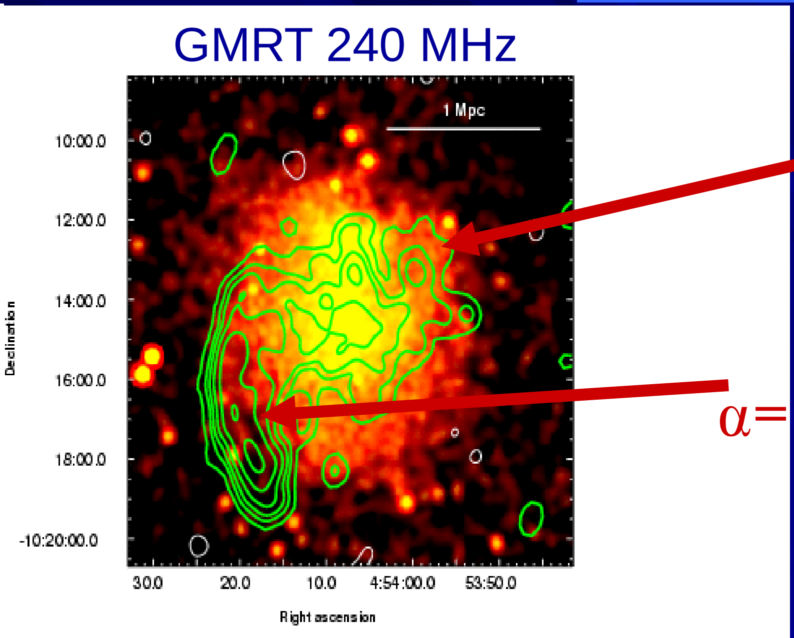


Radio Halos with very steep spectrum in the classical radio band must exist

Turbulent acceleration?

Brunetti +al 2008, *Nature 455, 944*

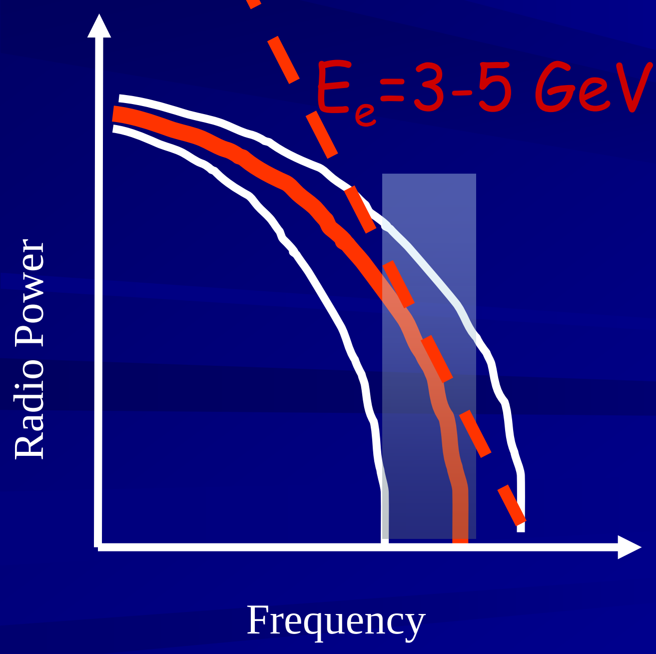


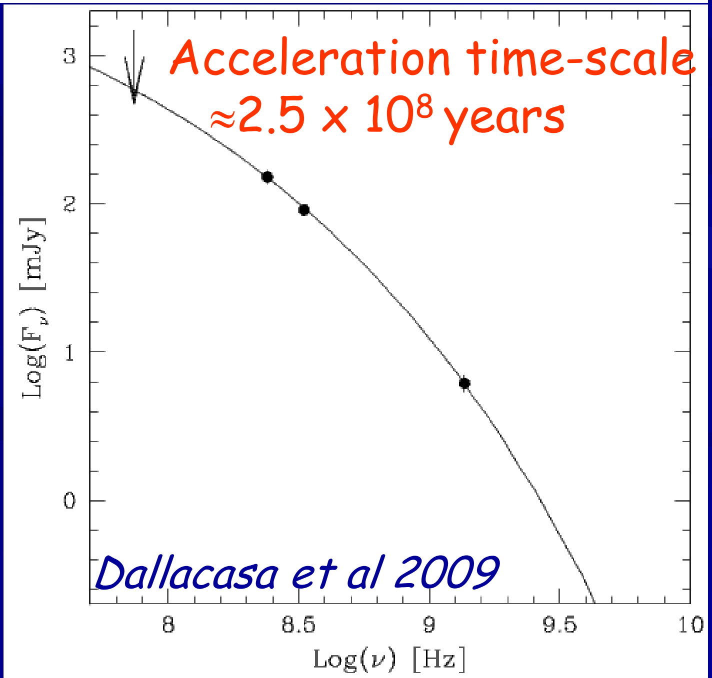


α=1.9

α=1.5

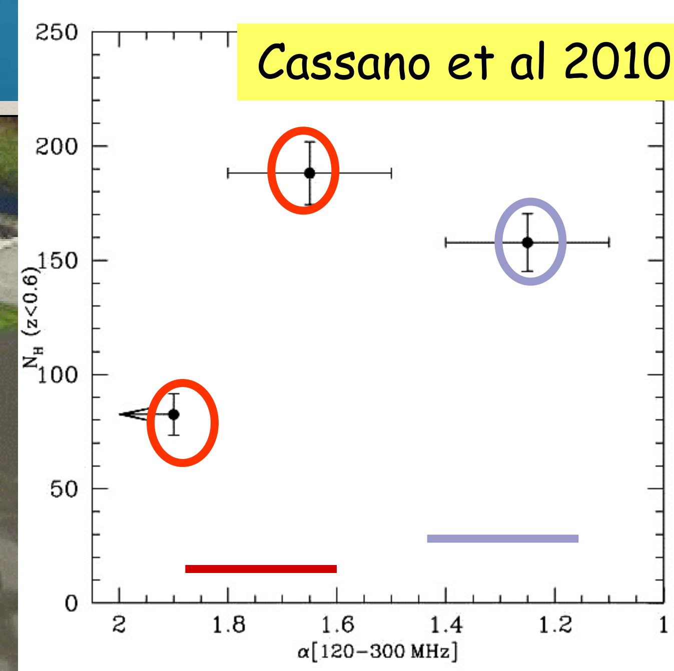
$N(E)=k\,E^{-4.8}$





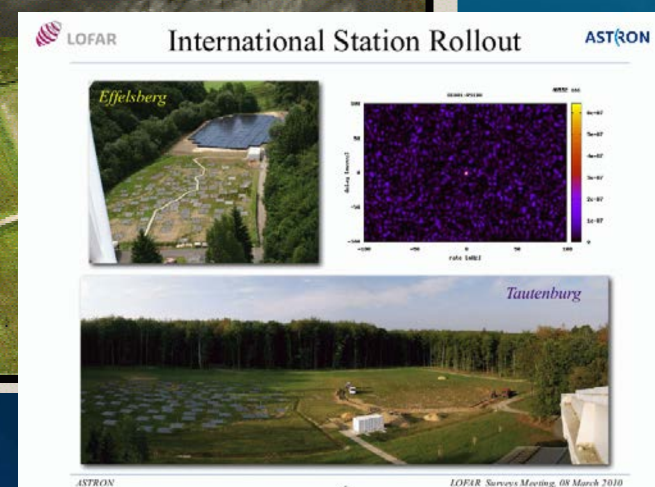
LOFAR ...

LOFAR Superterp



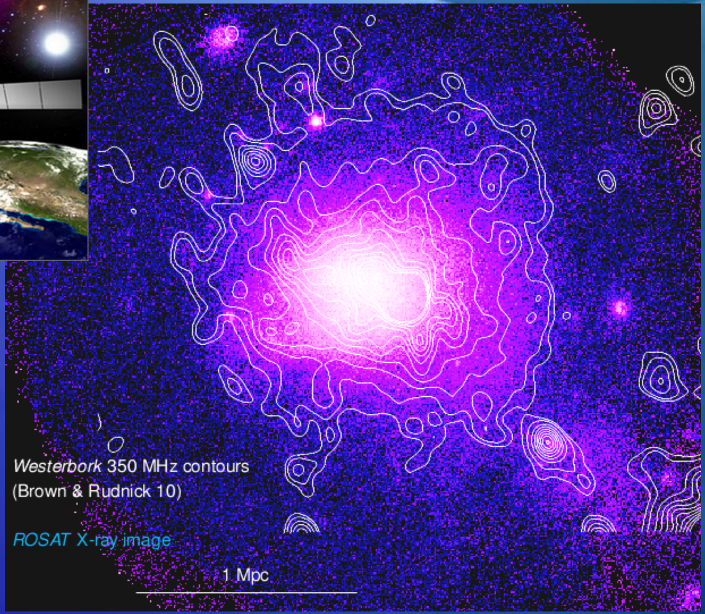
Cassano et al 2010
N_H (z<0.6)
α[120−300 MHz]
0
50
100
150
200
250
2
1.8
1.6
1.4
1.2
1

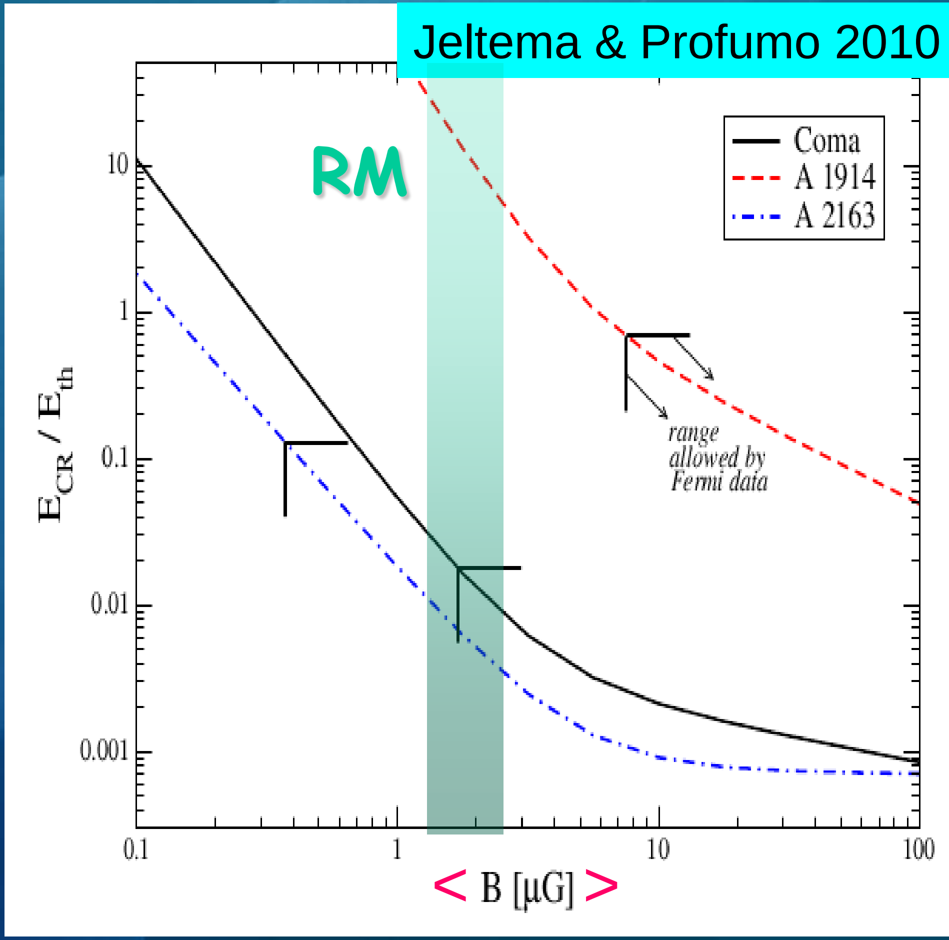
ASTRON
NWO
6



LOFAR
International Station Rollout
ASTRON
Effelsberg
Tautenburg
ASTRON
LOFAR Surveys Meeting, 08 March 2010
6

Gamma rays : energy content of CRp & origin of Radio Halos



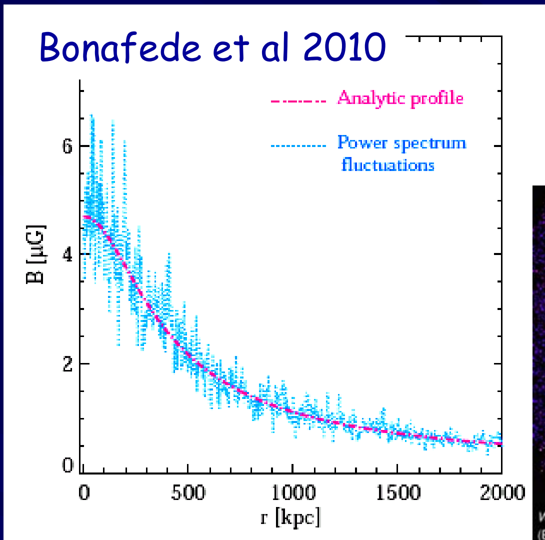


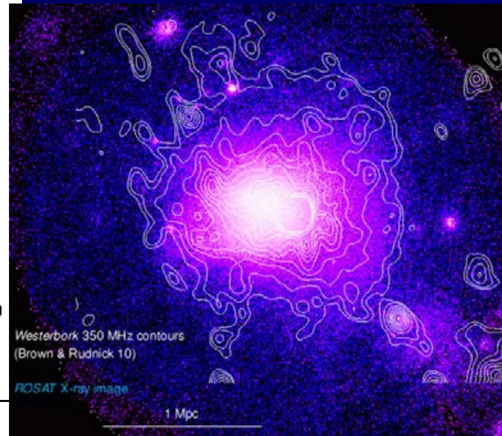
$L_{\gamma,\pi} \sim f_\gamma(\delta) \langle E_{CR}\rangle \langle E_{th}/T\rangle V_\gamma$

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

$L_R / L_{\gamma,\pi} \rightarrow \langle B^{\delta/2+1}/(B^2+B_{cmb}^2)\rangle$ Also Donnert et al 10, Brunetti et al …

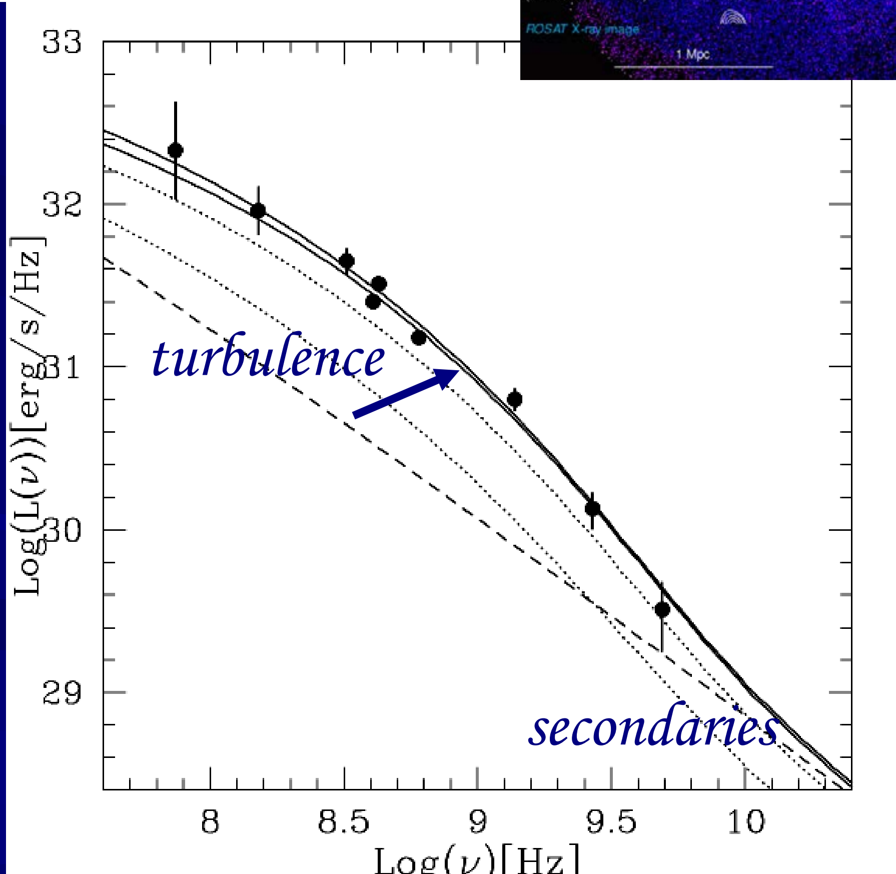
Turbulent models and Coma SED

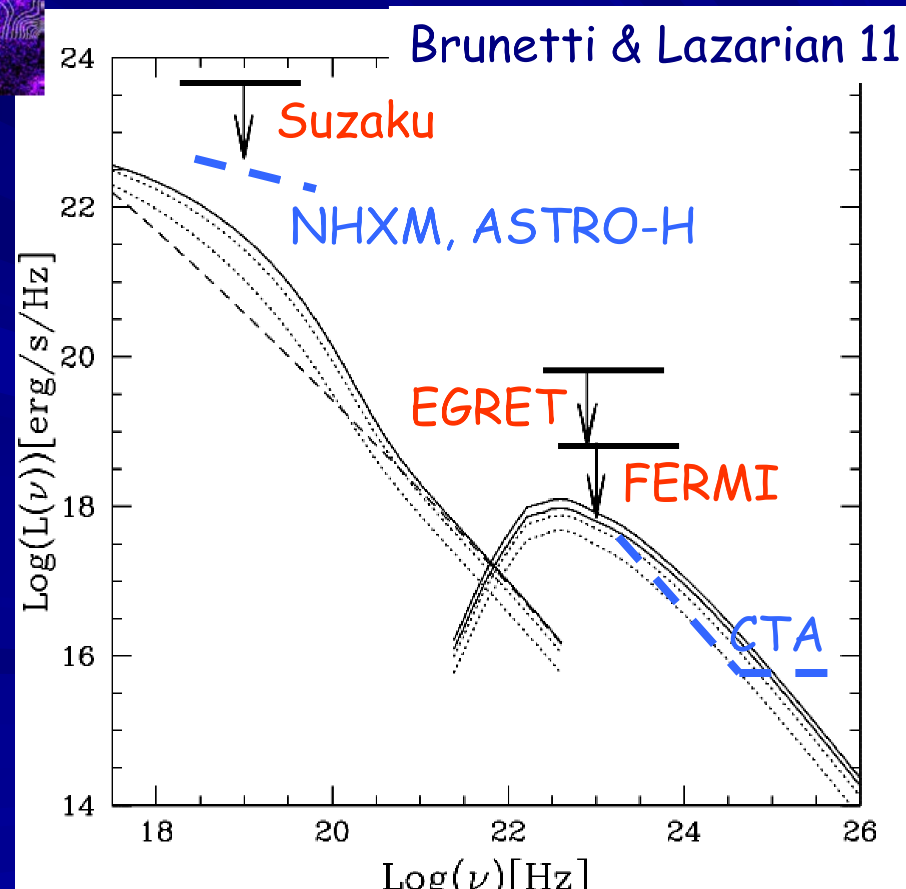




$E_{tur} \approx 10\ \%\ E_{th}$ @k^{-1}~100 kpc

$E_{CR} = 3\ \%\ E_{th}$ (flat profile)

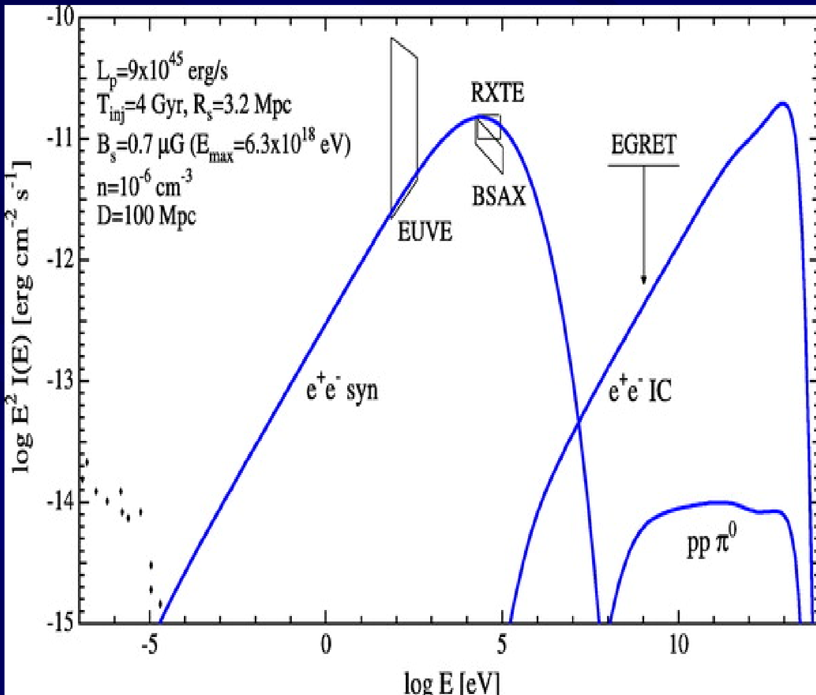




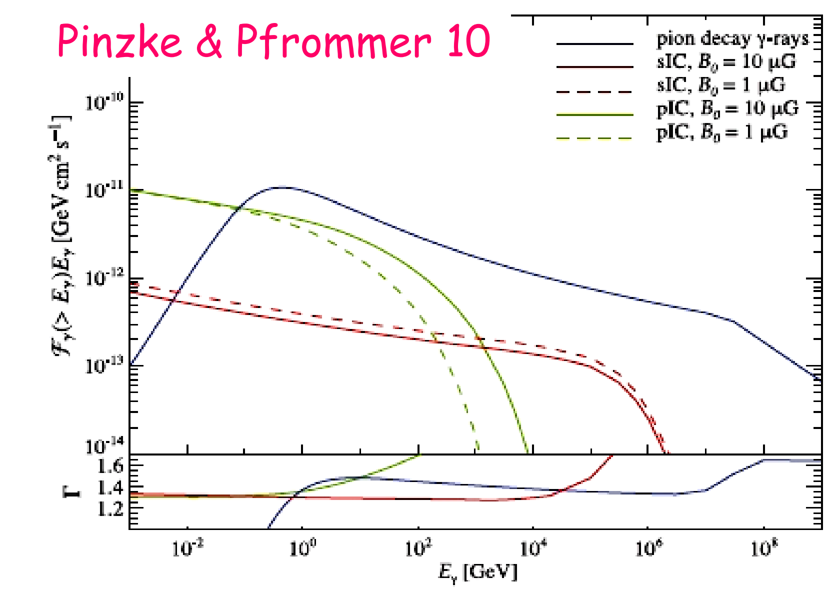
Additional processes

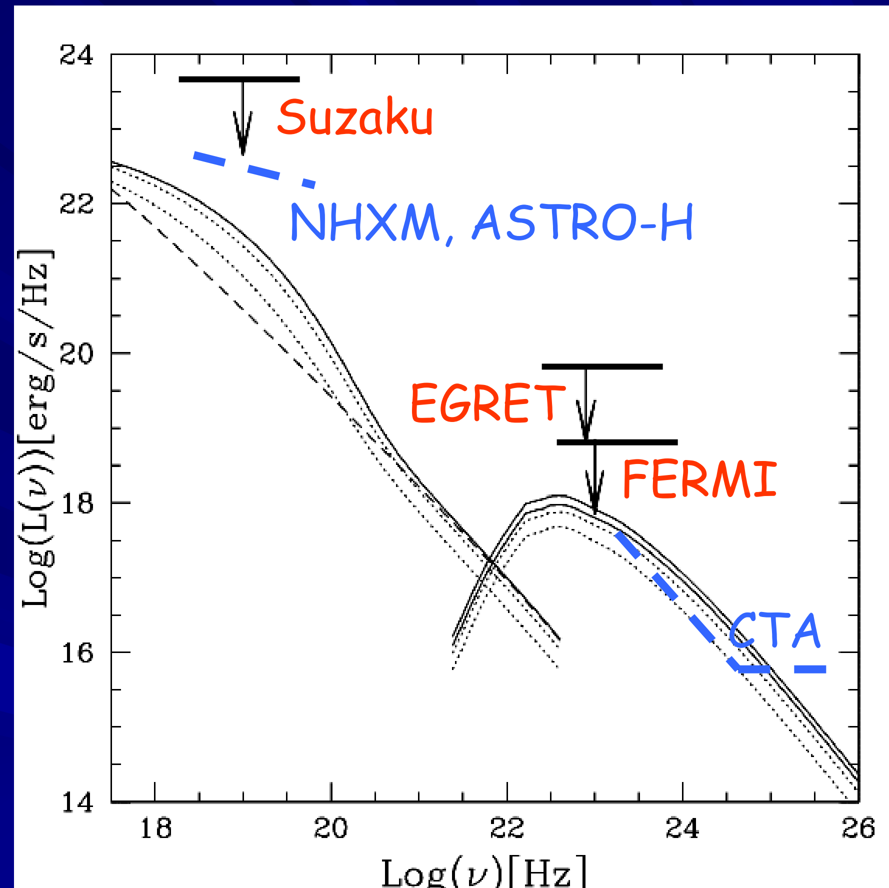
UHEp-γ

Inoue et al 05



Pinzke & Pfrommer 10





If B is smaller than that estimated from RM (reasonable?) … more gamma rays