Non thermal phenomena in galaxy clusters

Gianfranco Brunetti

Institute of Radioastronomy – INAF, Bologna, ITALY

Outline

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

Physics and dynamics of CR in galaxy clusters

Present constraints on CR protons and B

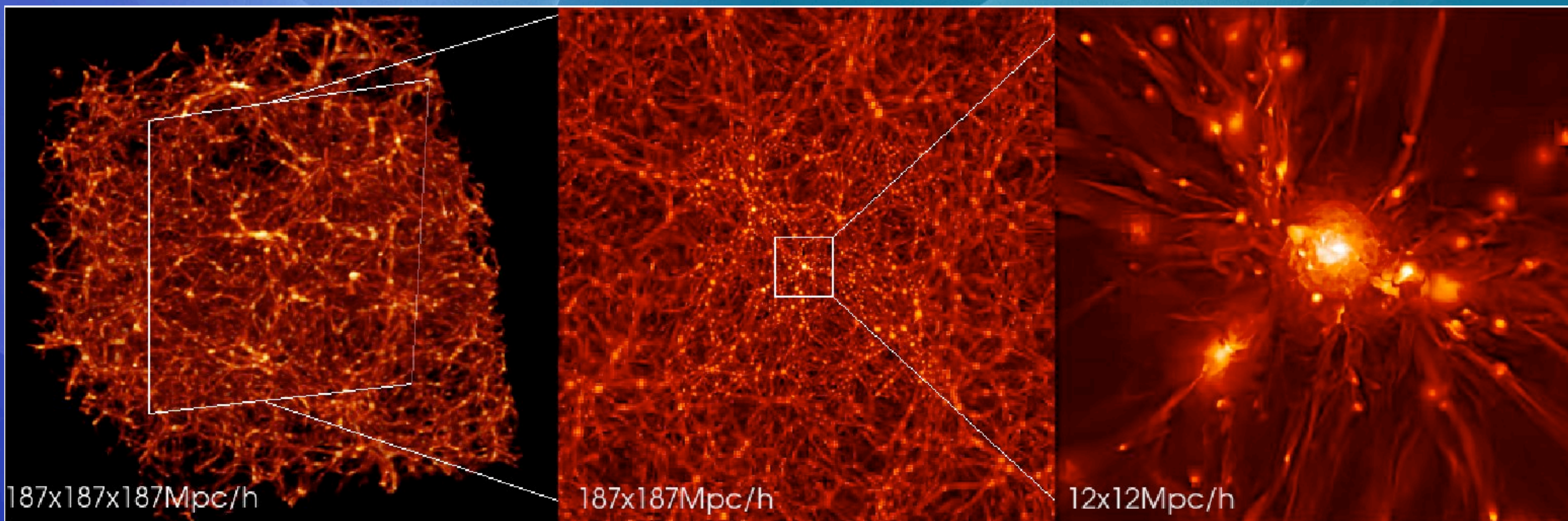
Mpc scale diffuse radio emission from galaxy clusters : mergers induced particle acceleration

(Radio Relics) : Shocks and shock acceleration in clusters

(Radio Halos) : Turbulence and turbulent acceleration

High energy emission from turbulent (merging) clusters

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

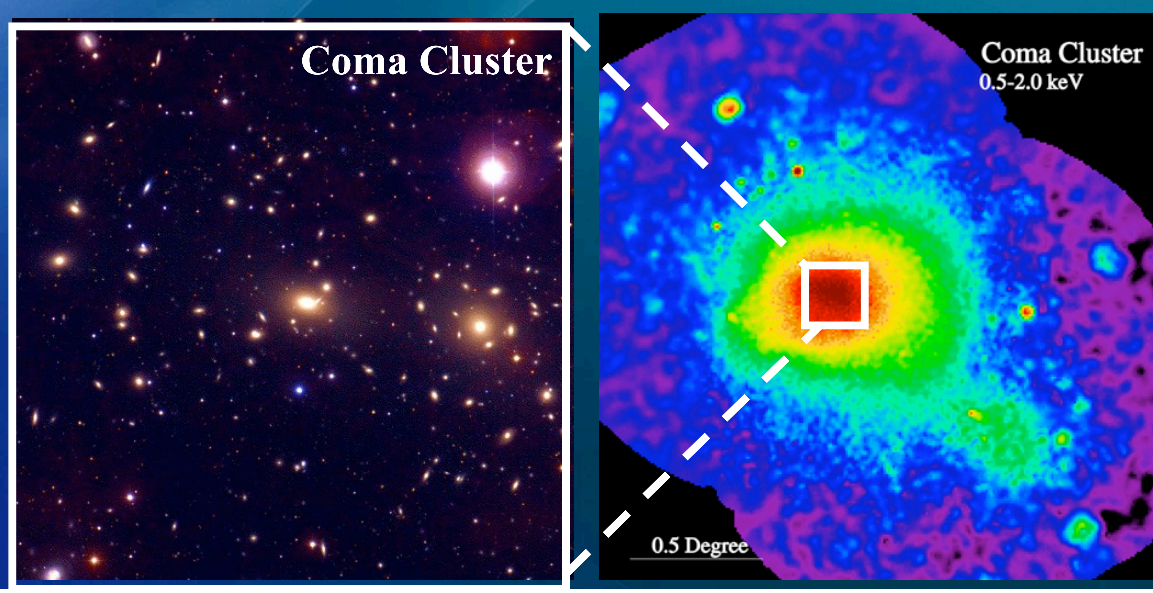


Galaxy cluster mass:

Barions **10%** of stars in galaxies

15-20% of hot diffuse gas

Dark Matter **70%**



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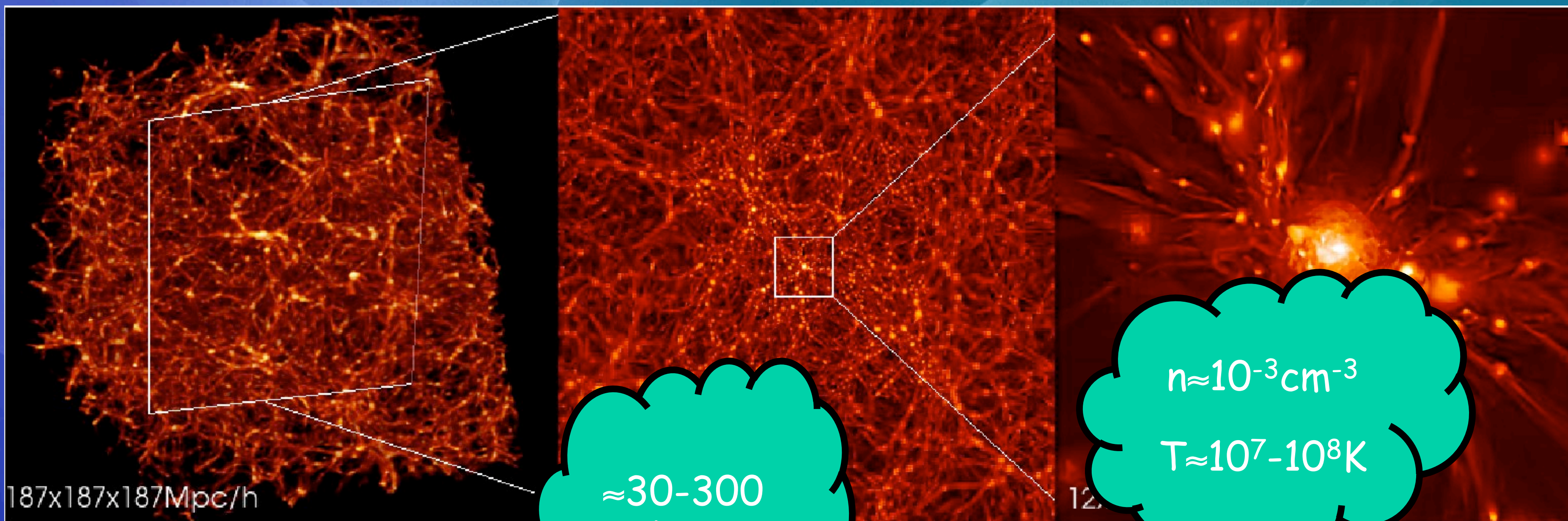

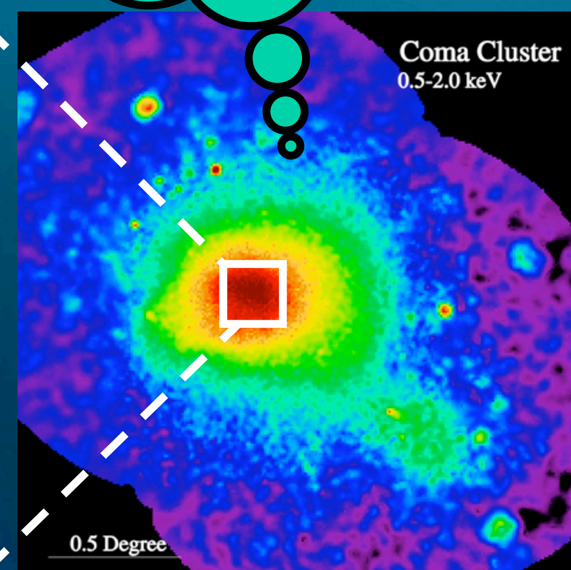

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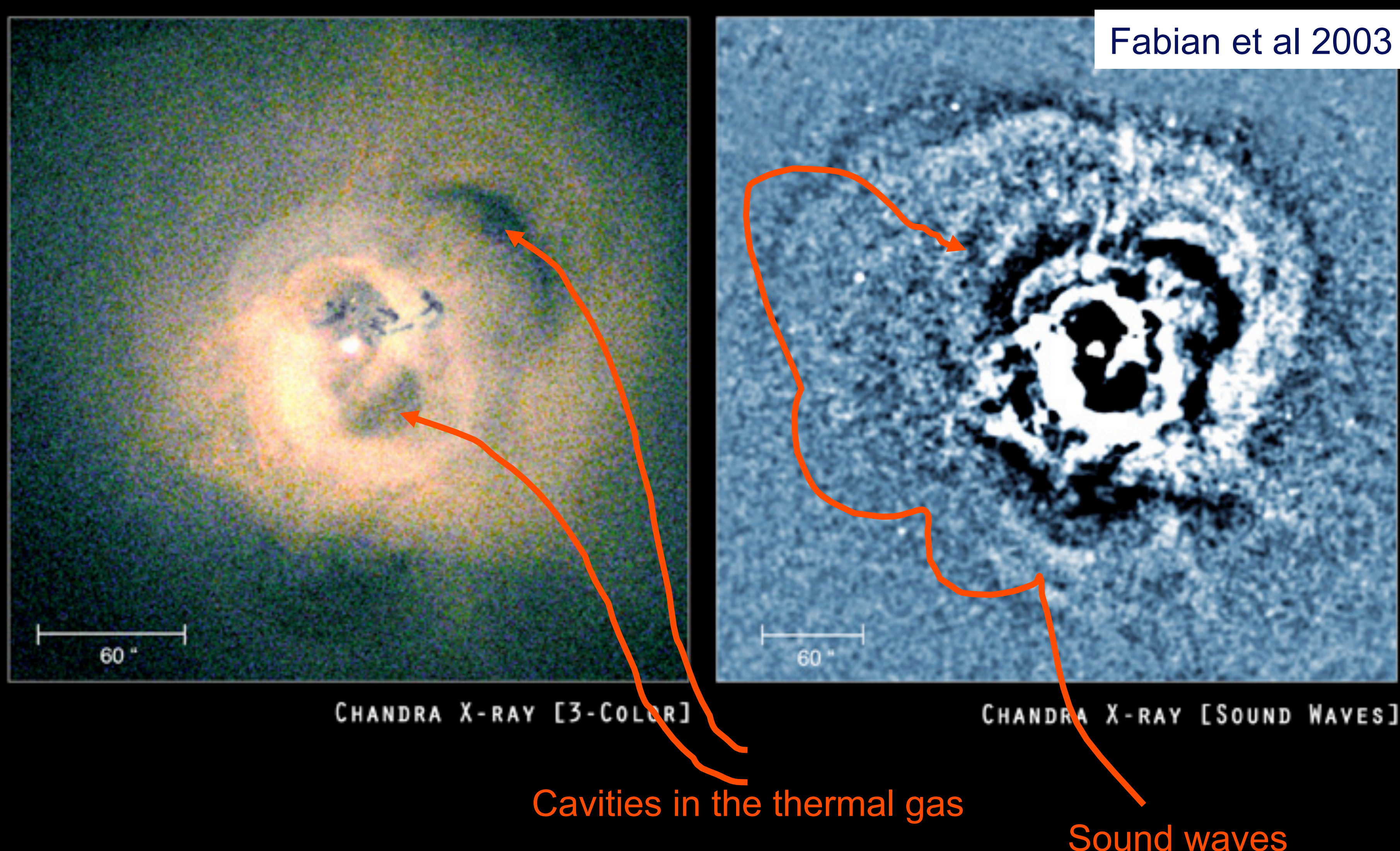
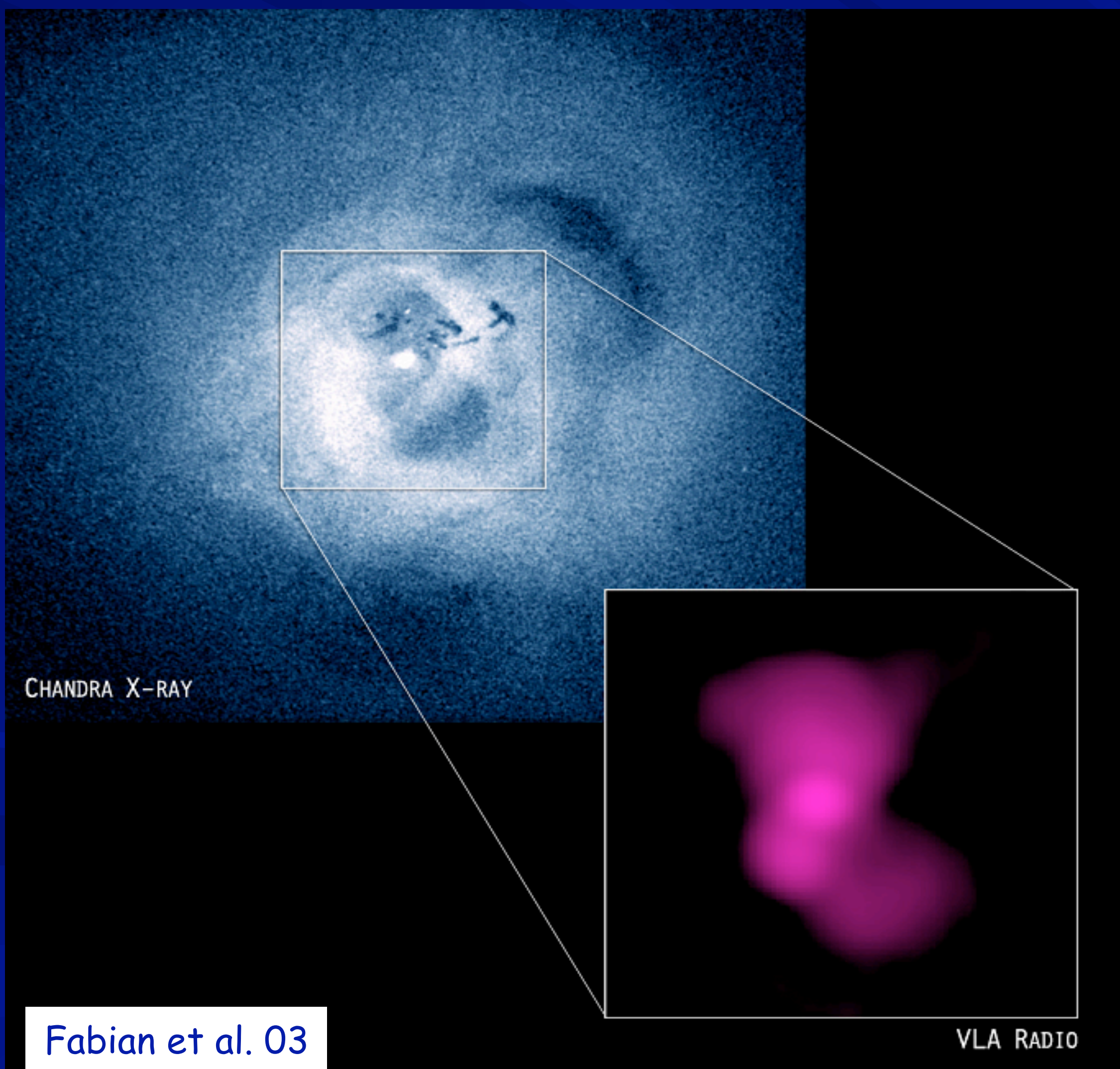
Non-thermal components in Galaxy Clusters



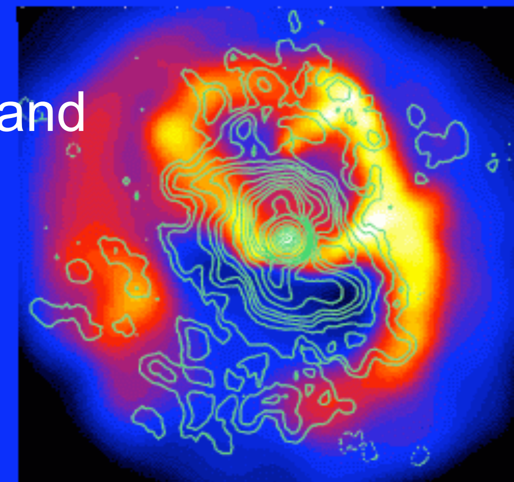
Cavities on small scales (~ 100 kpc):

evidence of dynamical interaction between thermal and non thermal components in GC

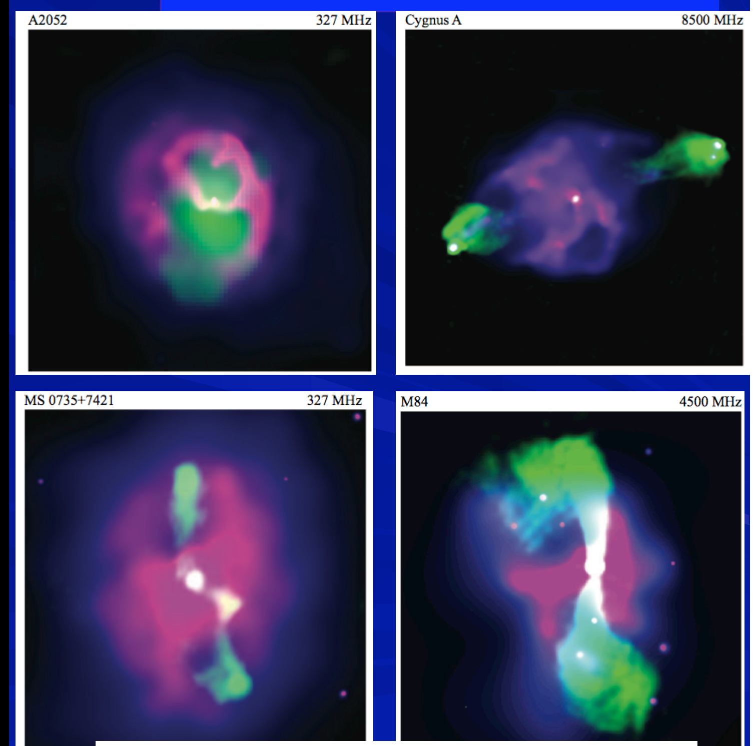


Fabian et al. 03

A2052 (Chandra)



Blanton et al.



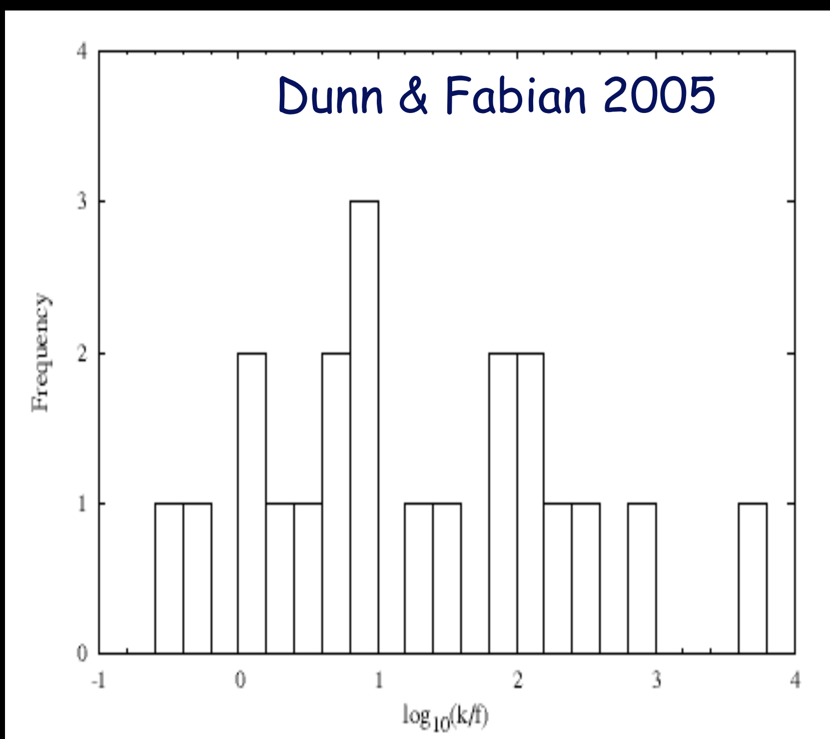
Raferty et al 06, Birzan et al. 07

NT energy and CRptotons

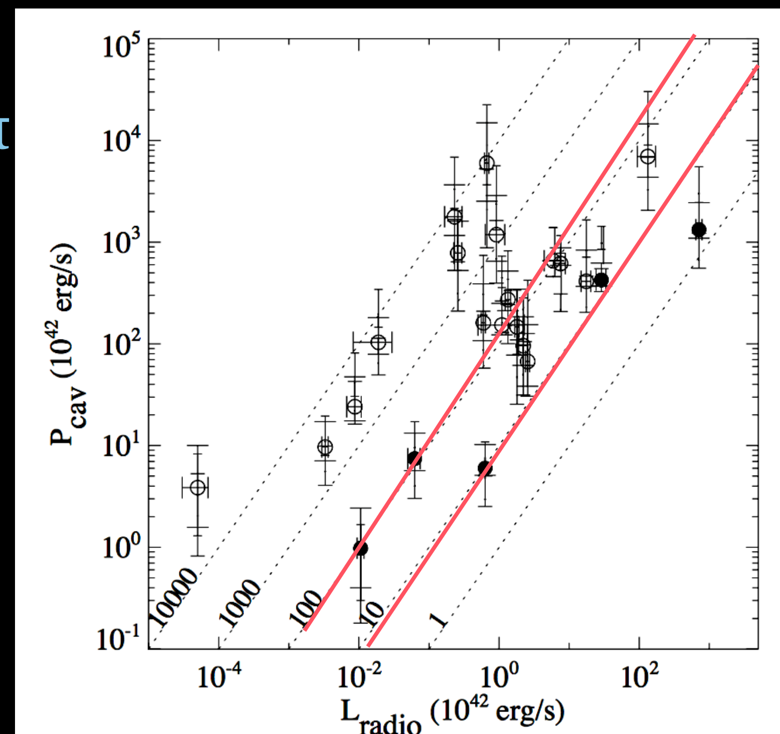
$U_{NT} = U_e + U_p + U_B = (1+k)\, U_e + U_B$ (Longair lecture)

L_{rad} -> $(U_e\ ,\, U_B)$ -> $K_e B^{(\delta+1)/2}$

$p_{th} \approx 2 n_{th} k_B T \approx p_{NT} \approx 1/3(1+k)U_e + B^2/8\pi$



Jet/Cavity Power



Syn Luminosity

Most of the energy extracted from the BH is "accumulated" in the cavities/bubbles

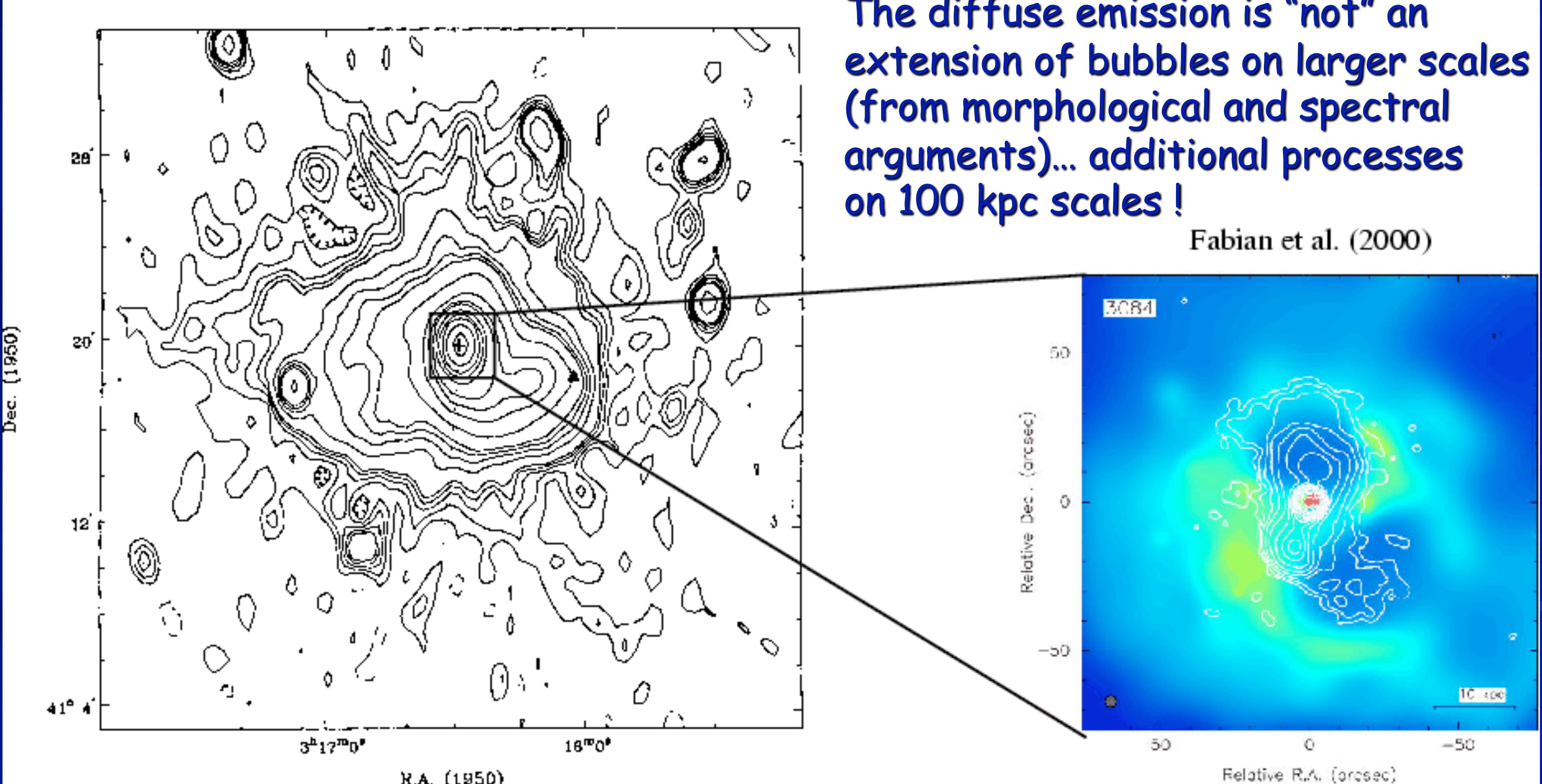
Mini-Halos on core scales (~ 100-300 kpc):

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

Sijbring (1993)

The diffuse emission is "not" an extension of bubbles on larger scales (from morphological and spectral arguments)... additional processes on 100 kpc scales !

Fabian et al. (2000)



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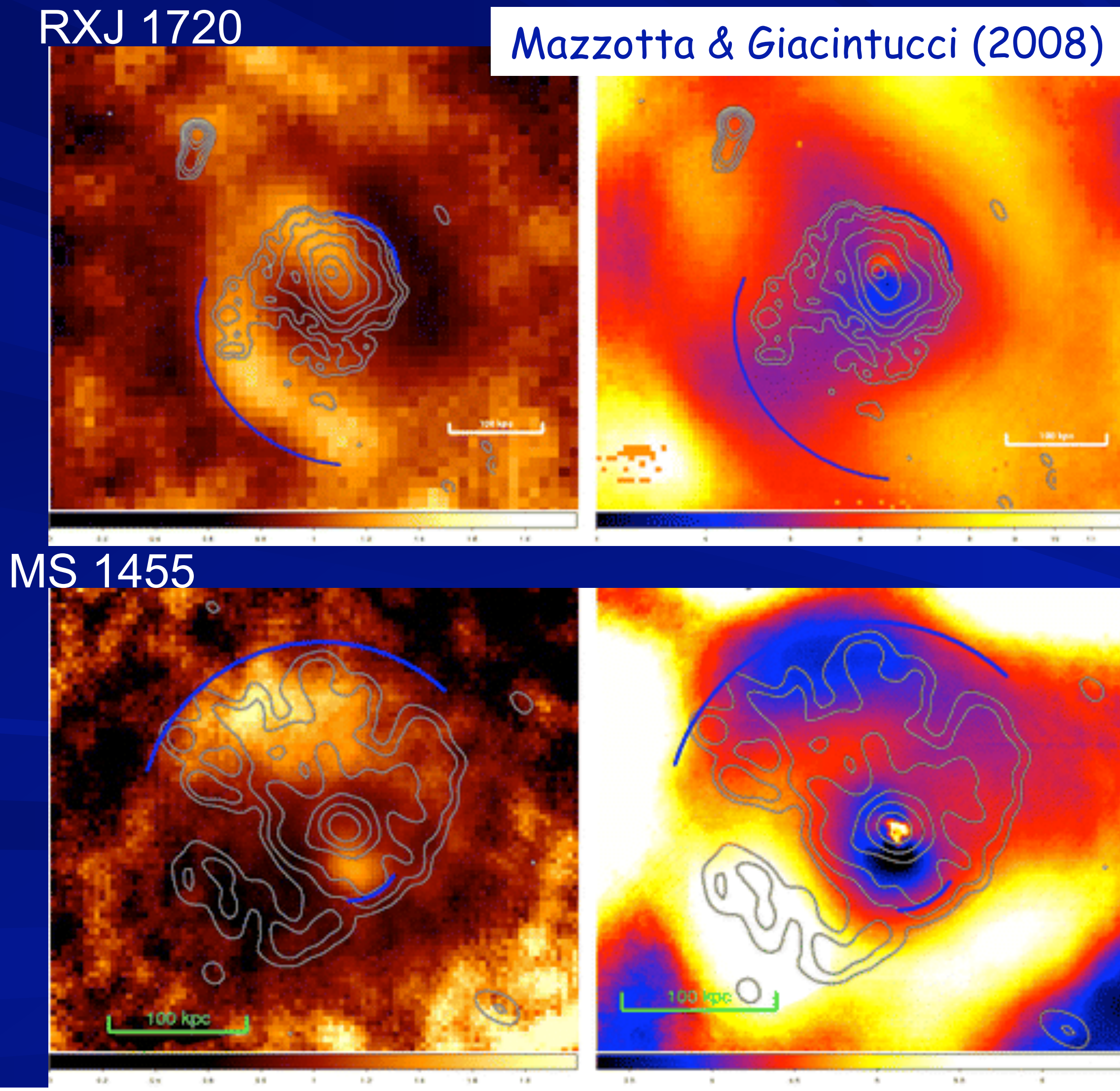
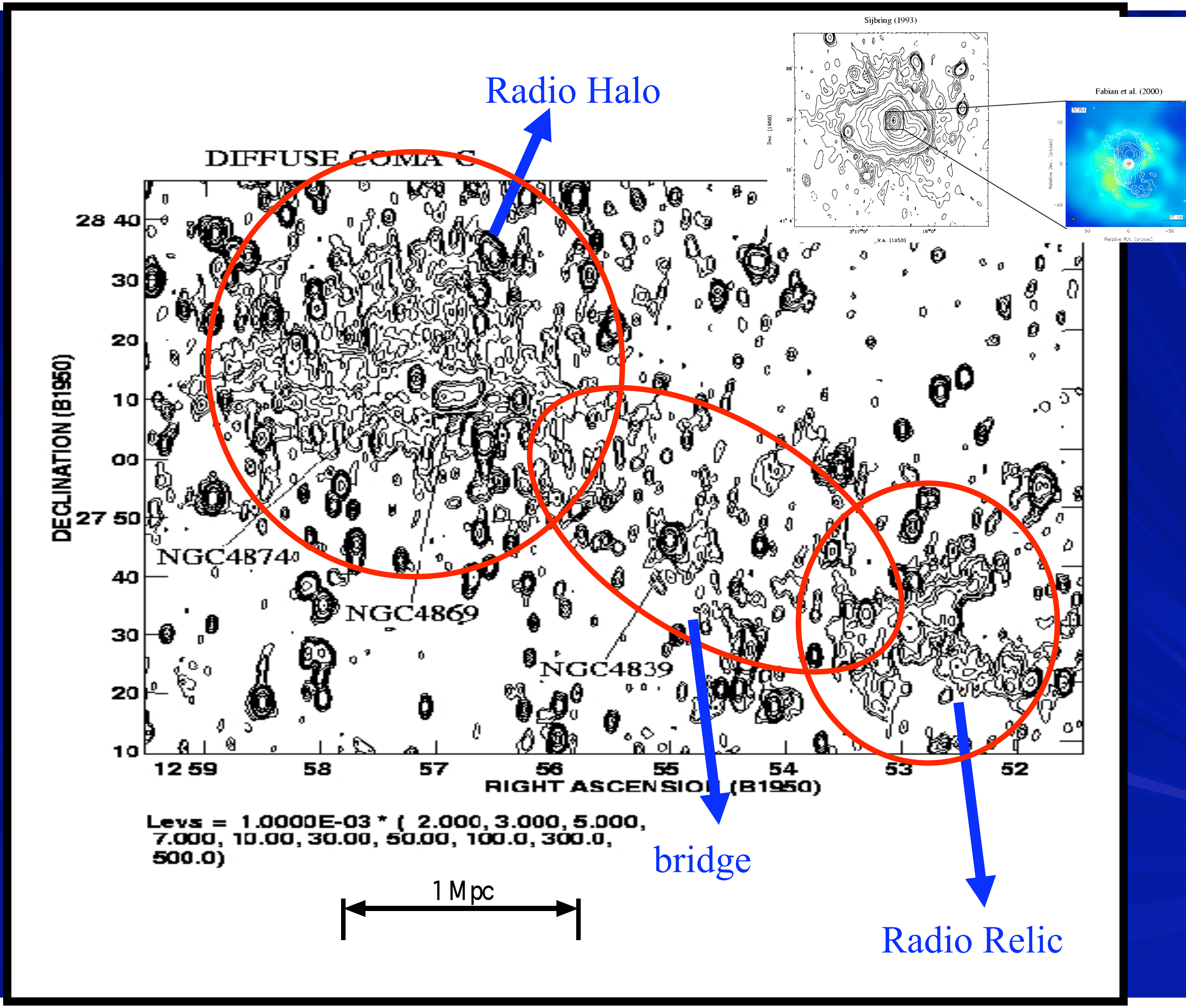


New sources of CR
in connection with the central AGN activity and core-sloshing

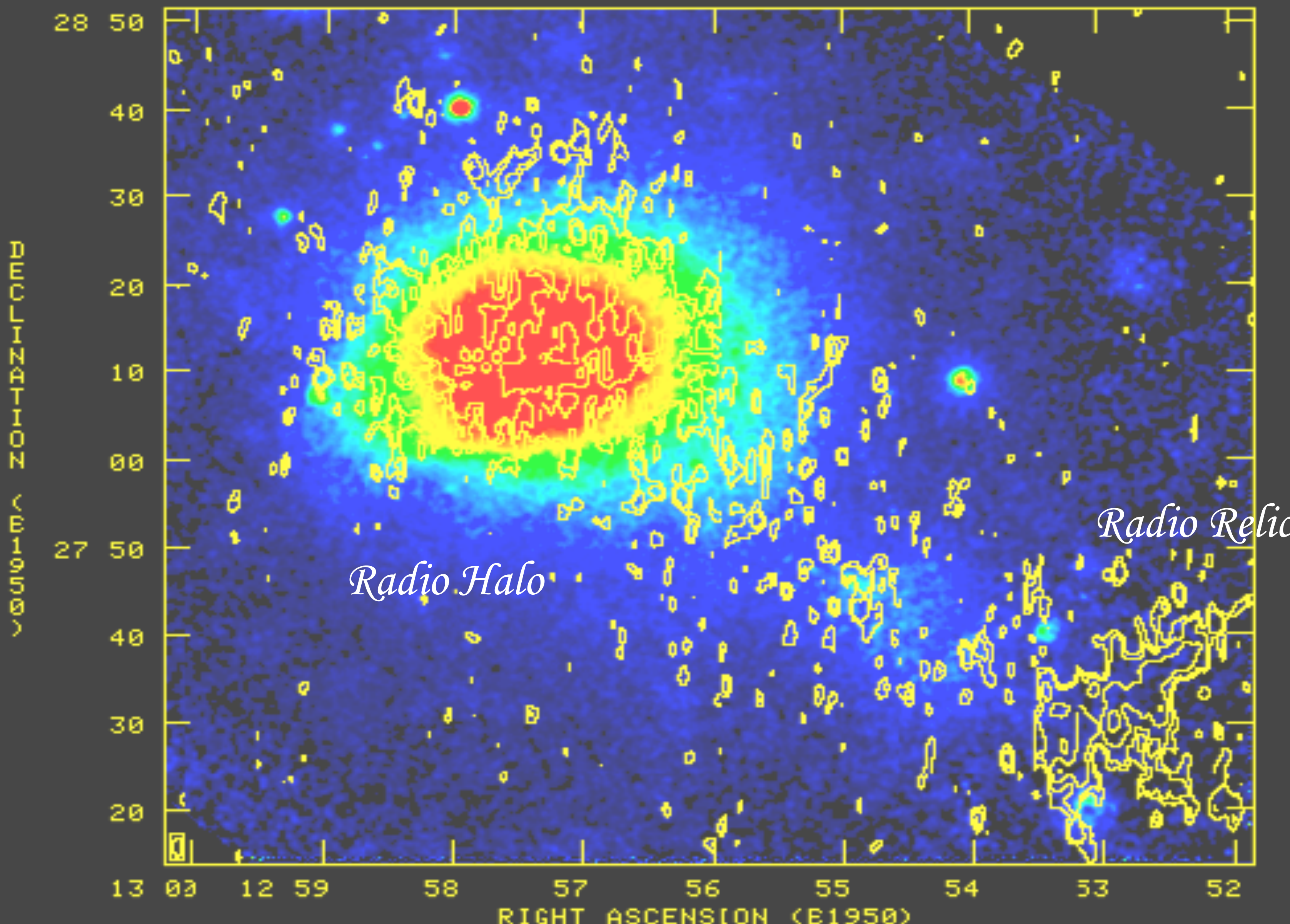
Turbulence,

Hadronic collisions,
(Gitti et al 2002, Pfrommer & Ensslin 2004, ZuHone et al 2011)

Reconnection ?
(Lazarian lecture)

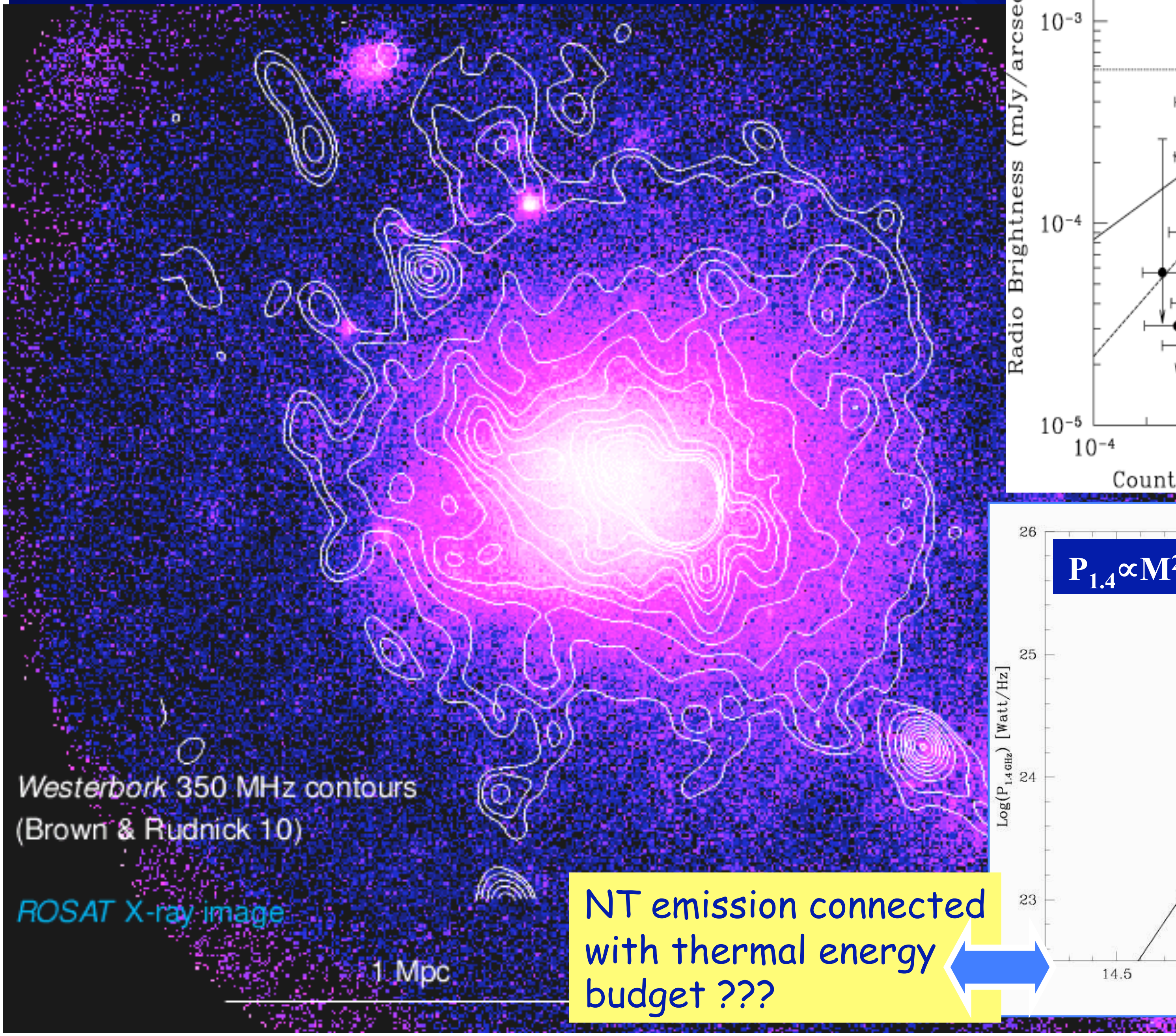

Radio Halo
DIFFUSE COMA C
Sijbring (1993)
Fabian et al. (2000)
DECLINATION (B1950)
28 40
30
20
10
00
27 50
40
30
20
10
NGC4874
NGC4869
NGC4839
12 59
58
57
56
55
54
53
52
RIGHT ASCENSION (B1950)
Levs = 1.0000E-03 * (2.000, 3.000, 5.000, 7.000, 10.00, 30.00, 50.00, 100.0, 300.0, 500.0)
bridge
1 Mpc
Radio Relic

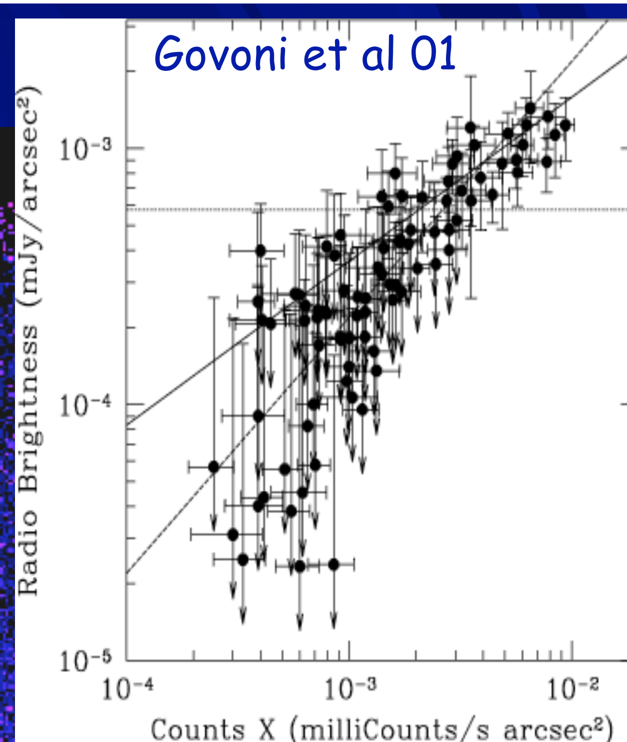
Coma Cluster

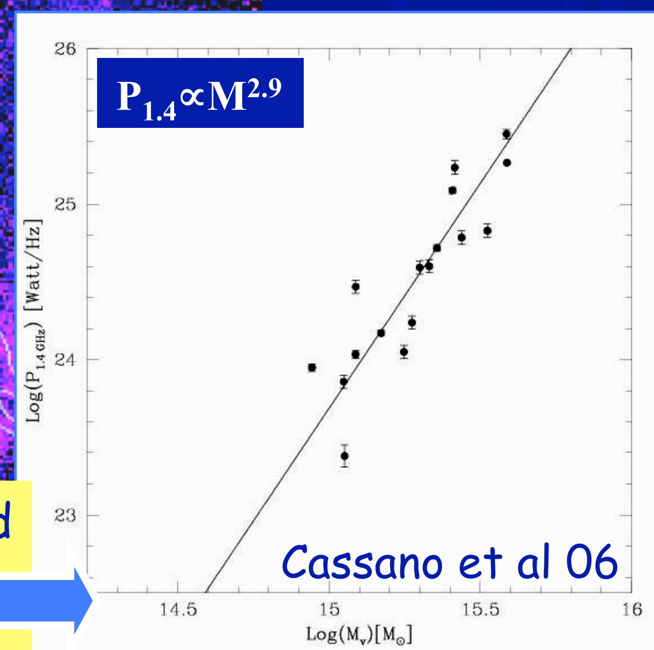


Feretti +al.1998

Connection with the hot IGM

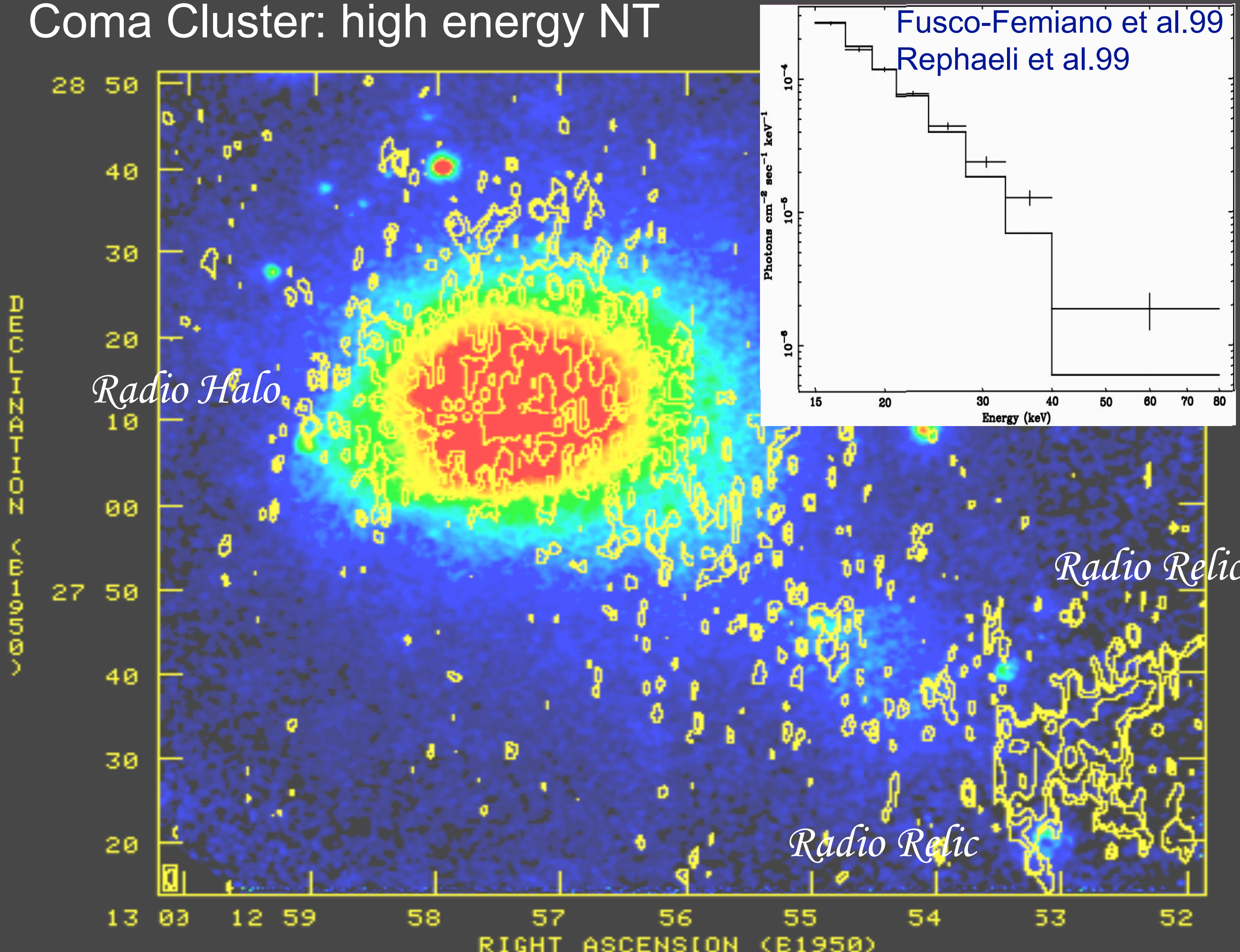




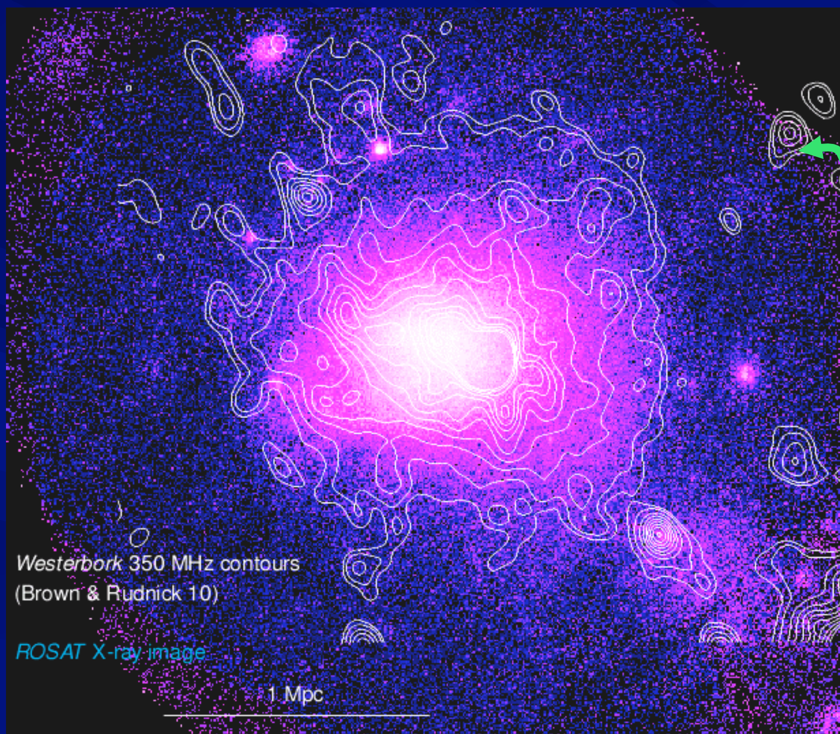


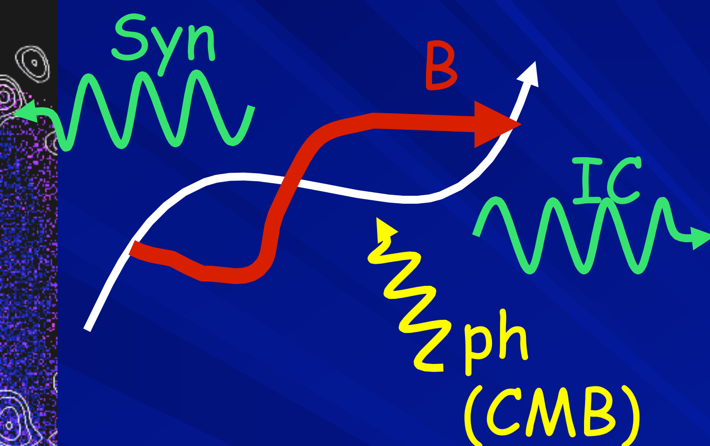
NT emission connected with thermal energy budget ???

Coma Cluster: high energy NT



Inverse Compton Emission from GC ??



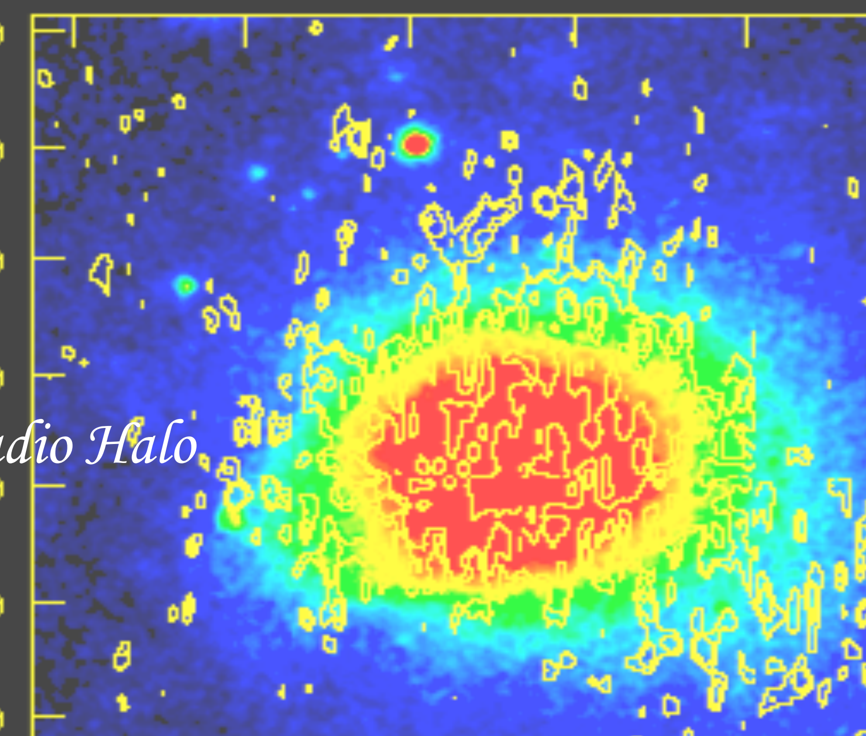


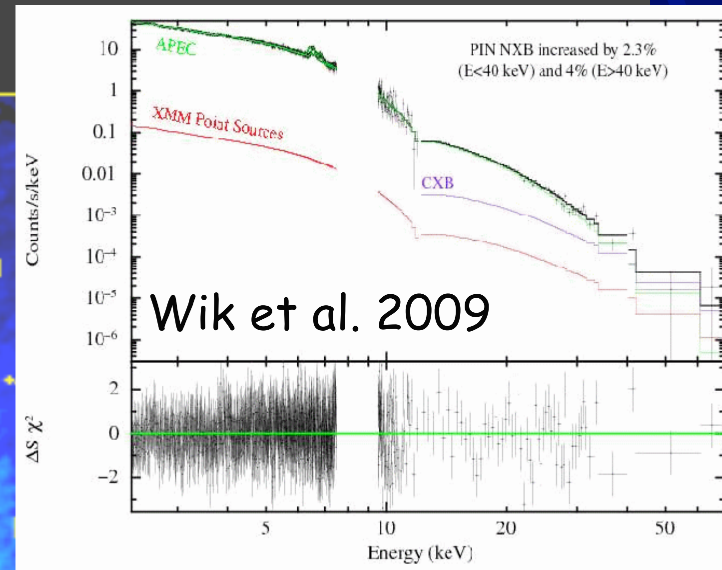
L_{rad} -> $(U_e\ ,\ U_B)$ -> $K_e B^2$ (Longair lecture)

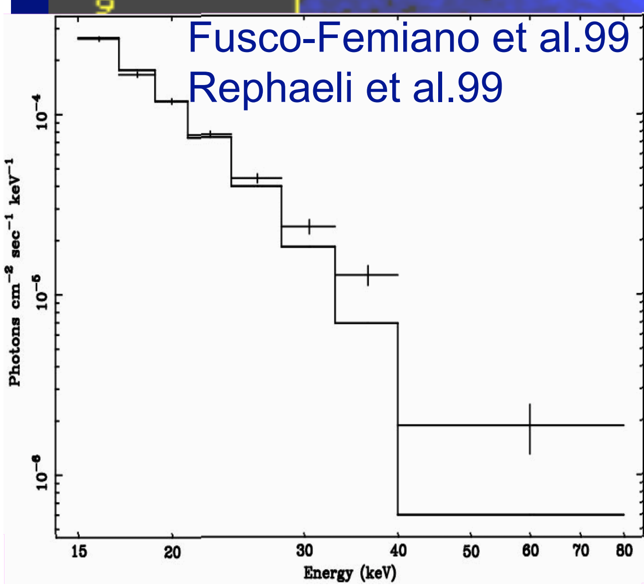
L_{HE} -> $(U_e\ ,\ U_{ph})$ -> $K_e U_{ph}$

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

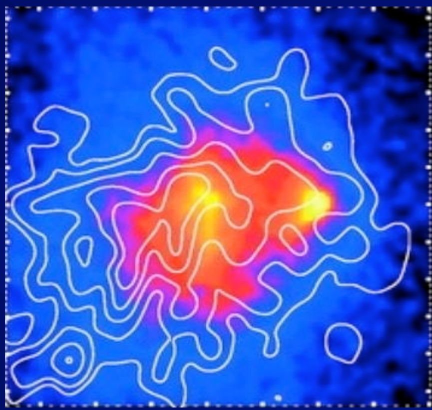
Coma Cluster: high energy NT







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, Wik et al 2011

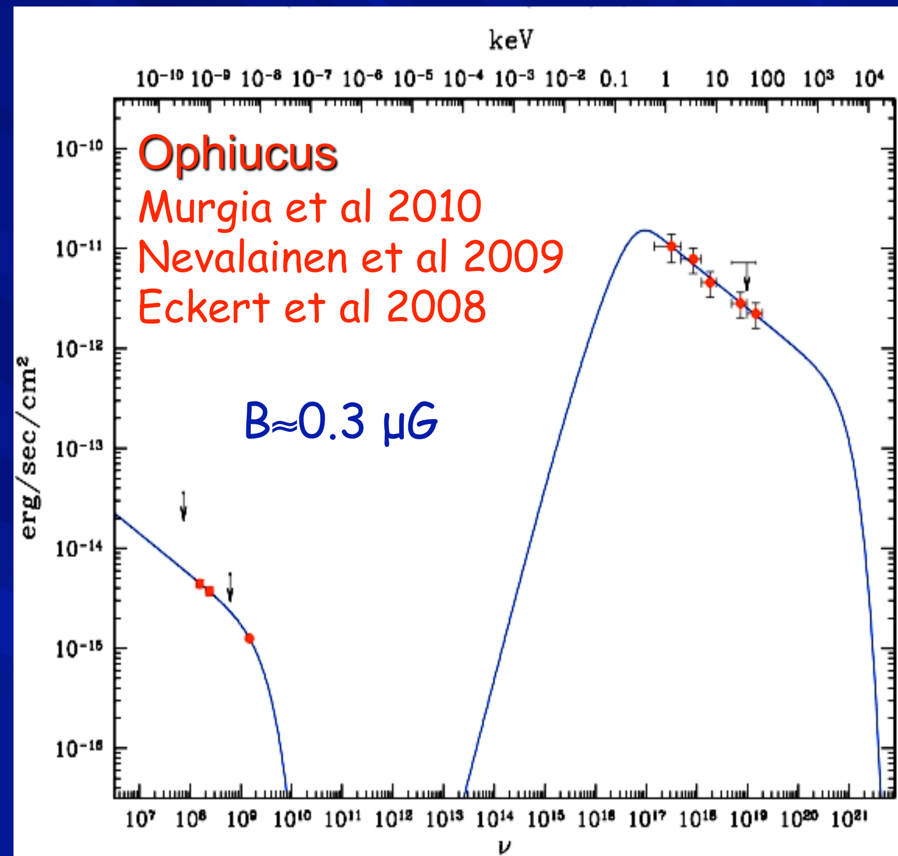


Controversial… but (at least!) lower limits on B

Ajello et al 2010

om Combined *XMM-Newton* and BAT Data

Name	$F_{50-100\,keV}$[a] (10^{-12} erg cm^2 s^{-1})	B[b] (μG)
A85	<2.51	~0.6
A401	<0.22	~0.4
Bullet	$1.58^{+0.43}_{-0.47}$	~0.16
PKS 0745-19	<1.6	~0.5
A1795	<1.38	/
A1914	<1.08	~0.3
A2256	<0.19	~0.6
A3667	$2.98^{+4.17}_{-0.73}$	/
A2390	<0.25	~0.8

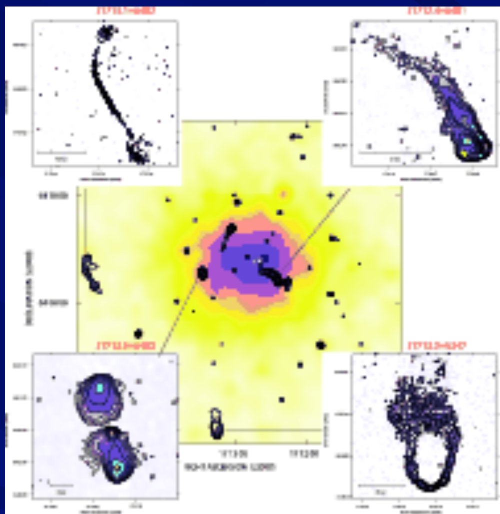


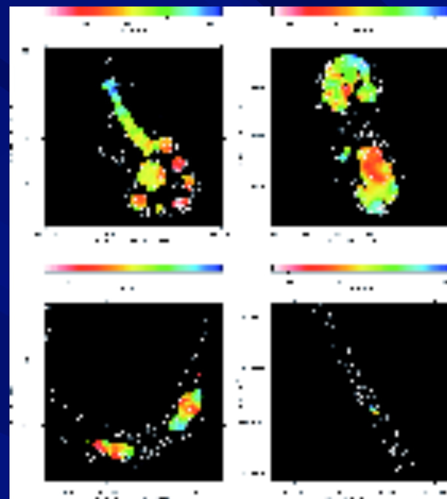
$E_B \approx E_{tur} \approx 0.1\ E_{th}$ … B≈1-10 μG

B ≈ 0.1 μG may suggest magnetic field dissipation on time scale << clusters life-time (few Gyrs)

B in Galaxy Clusters

(also Neronov lecture)





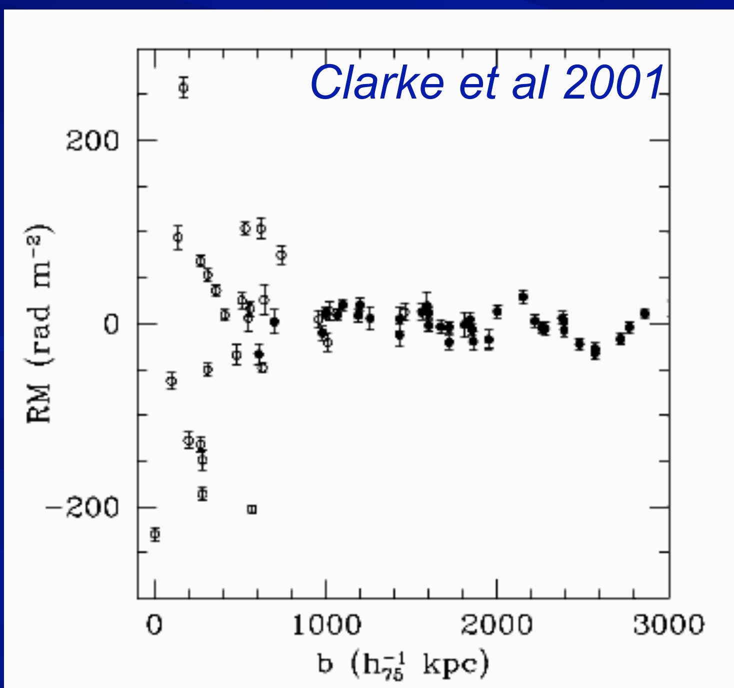
B ≈ few μG

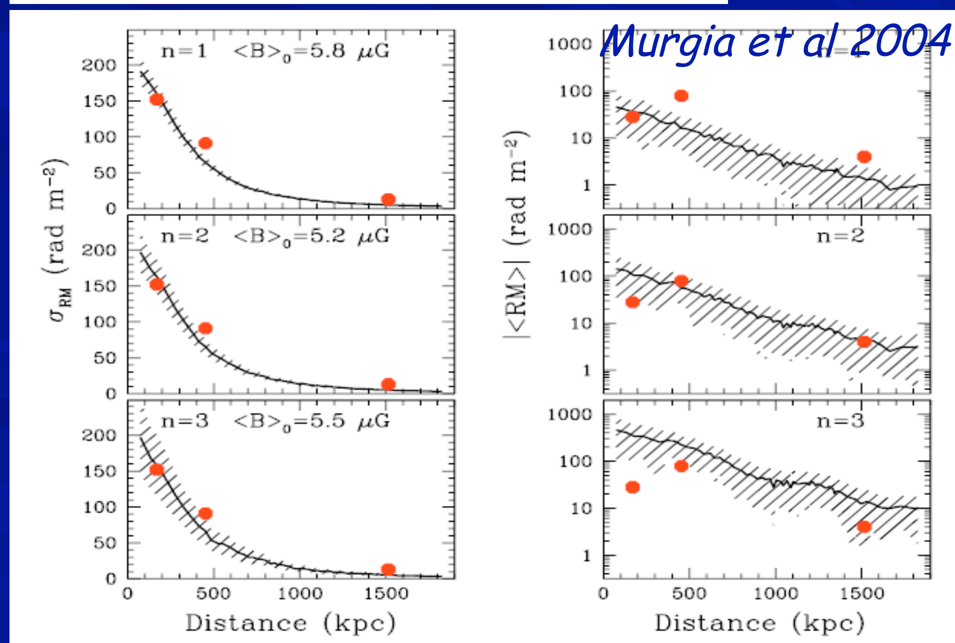
Λc ≈ few-50 kpc

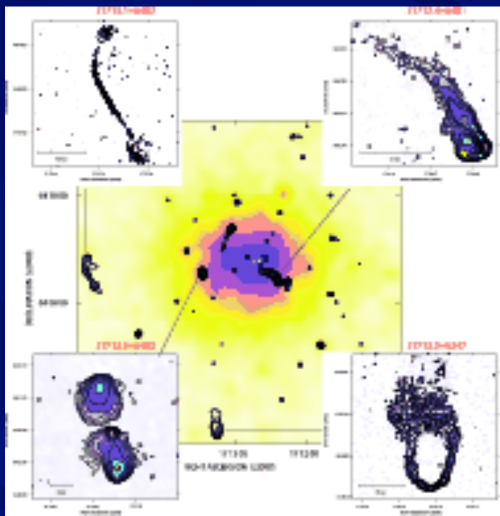
RM probe turbulent motions in the IGM

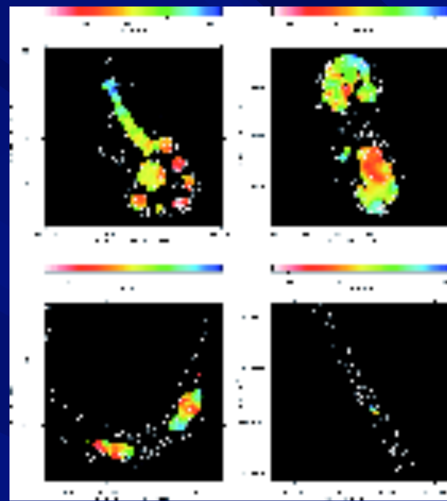
$$\mathrm{RM} = \frac{\Delta\chi}{\Delta\lambda^2} = 811.9 \int_0^L n_e B_{\|} d\ell \;\; \mathrm{rad\;\; m^{-2}},$$

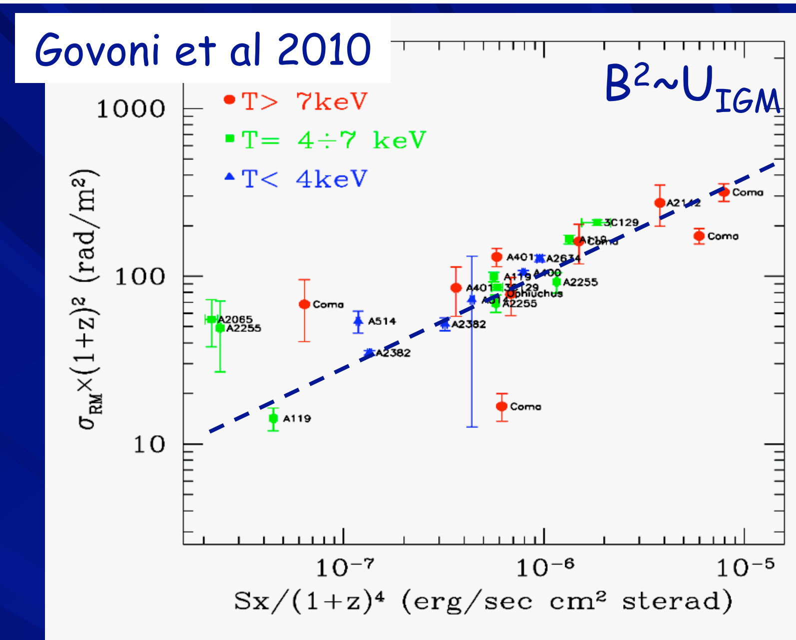
$$\sigma_{RM}^2 = \langle RM^2 \rangle = 812^2 \Lambda_c \int (n_e B_{\|})^2 dl \; .$$











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

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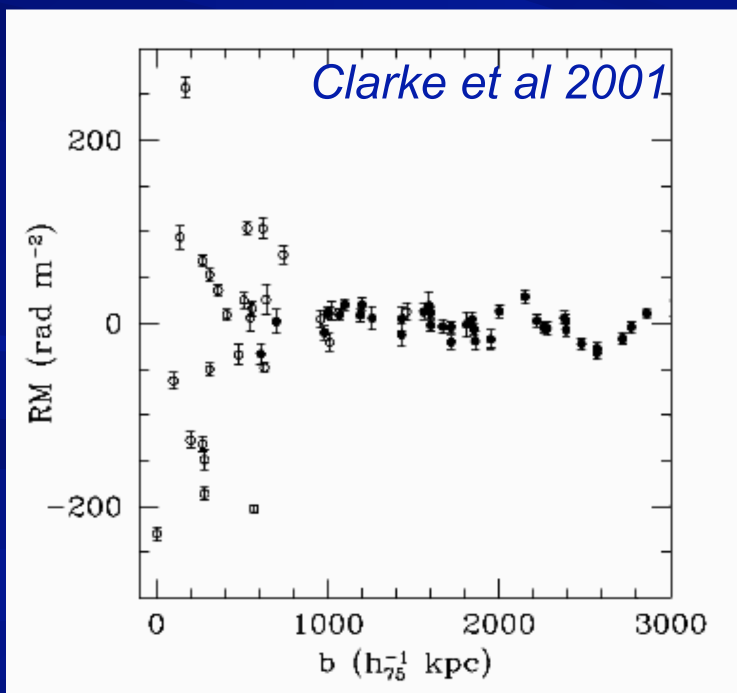
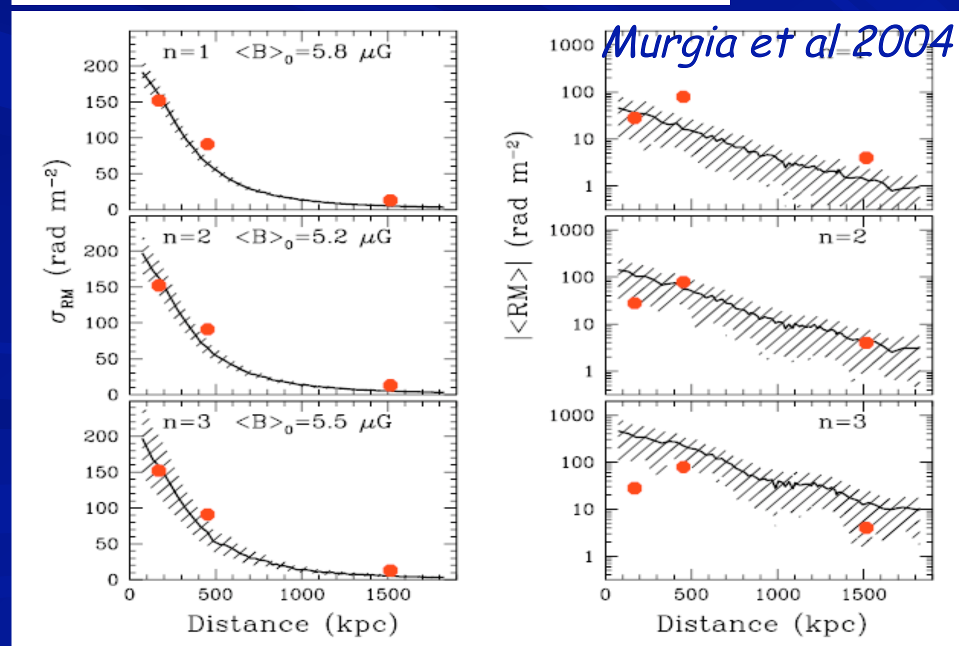




CR+B : important not only for particle acceleration ….

Thermal conduction, kin. Viscosity, collisionality in the ICM

(e.g., Schekochihin et al 05,08, Lazarian 2006, Brunetti+Lazarian 11)

Heating of the ICM and "cooling flow" problem

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

Diffusion and transport of metals in the ICM

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

B-Amplification from Cosmological seed fields

(e.g., Dolag +al. 1999,02, Subramanian et al. 2006, Ryu et al. 08)

Diffusion and scattering of HE & UHECR in the Universe

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

Injection & Dynamics of Cosmic Rays in GC

Cosmological Shocks

(e.g. Sarazin 1999, *Miniati et al. 2001, Blasi 2001, Gabici & Blasi 2003, Ryu et al. 2003, Pfrommer et al. 2006, 2008, Skillman et al. 2008, Vazza, Brunetti, Gheller 2009, 2010, etc..*)

AGN, Galactic Winds

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

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

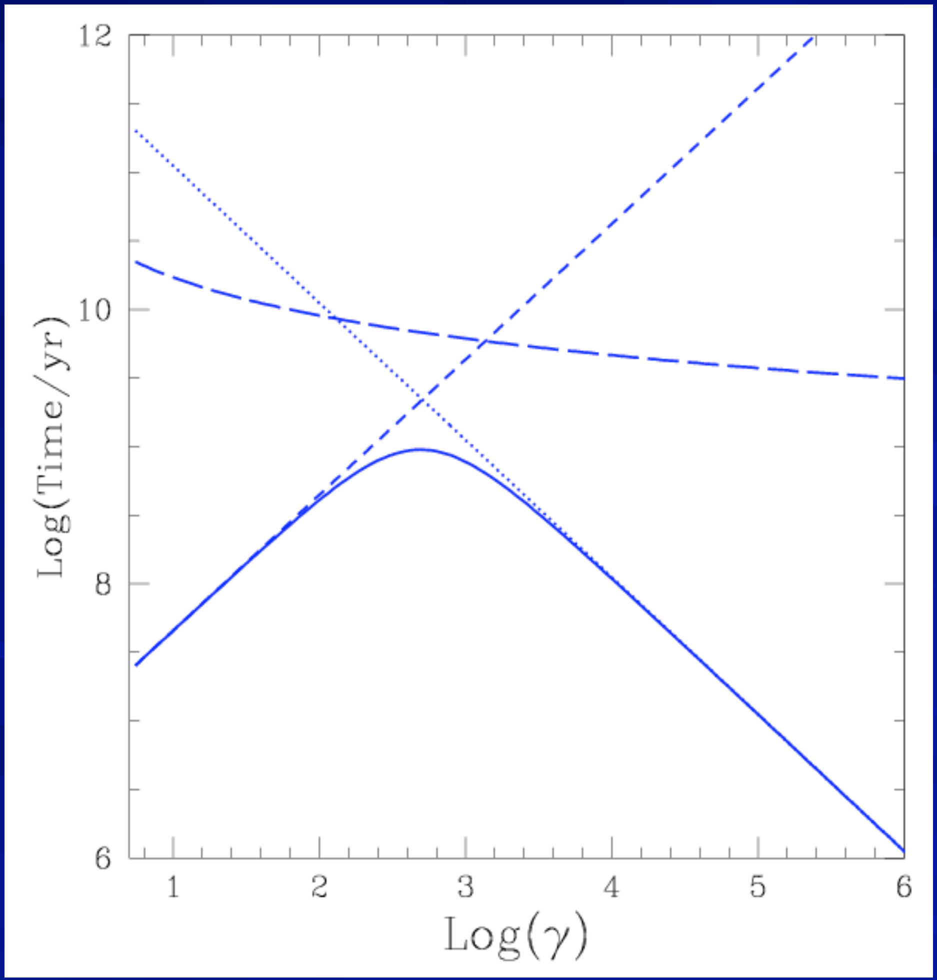
$$b_{\rm Coul}(\gamma) \approx 1.2 \times 10^{-12} n_e\left[1.0 + \frac{\ln(\gamma/n_e)}{75}\right]\ {\rm s}^{-1}\ ,$$

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

Particle Collisions

Physics of CR Leptons

$(dE/dt) \sim E\ /\ \underline{Time} \sim m_e c^2\, b$



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

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

Physics of CR Hadrons

CR protons more energetics than thermal electrons: Coulomb scattering

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

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

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

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

like leptons

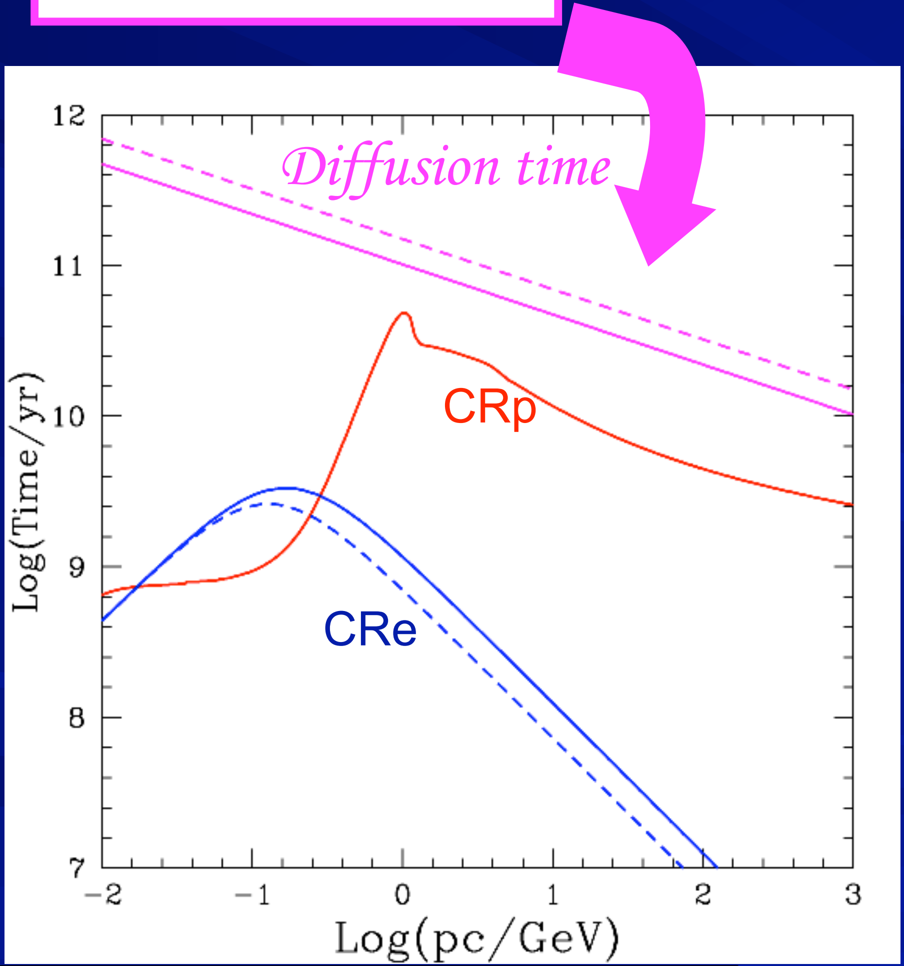
$$\tau_{pp} = \frac{1}{n_{\rm th}\sigma_{\rm pp}c} \sim 10^{18} \left(\frac{n_{\rm th}}{10^{-3}}\right)^{-1} s.$$

Collisions between CR & thermal protons

~30 Gyrs !

Physics of Cosmic Rays

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



Blasi, Gabici, Brunetti 07

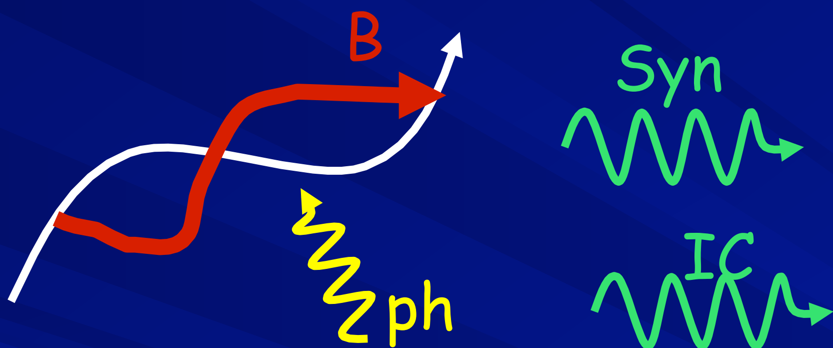
D(GeV) ≈10^{28}-10^{29} cm^2/s << $10^{31} cm^2/s$

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

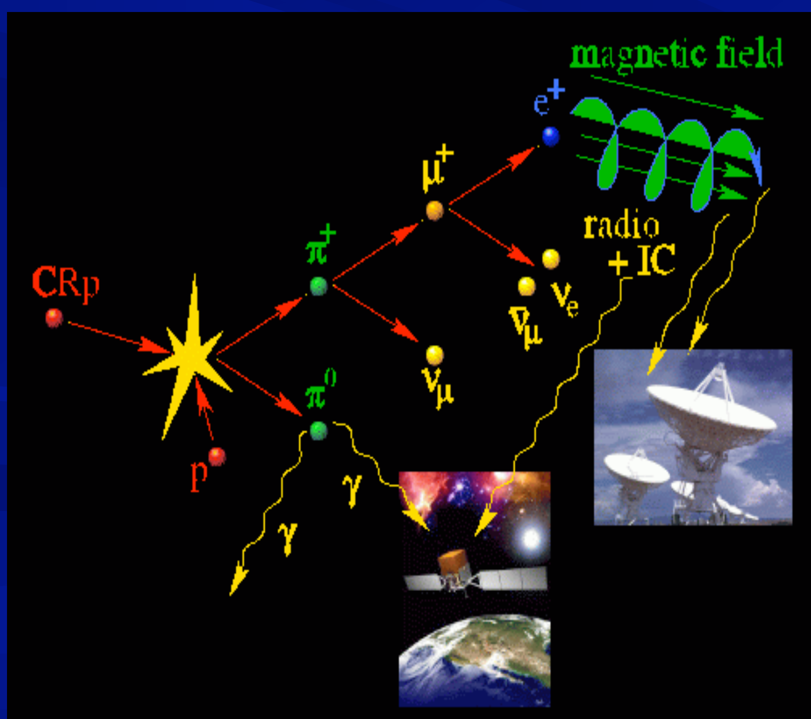
- CR are ***confined*** in GC
  Voelk et al 1996;
  Berezinsky, Blasi, Ptuskin 1997; …
- CR protons are ***long living*** and ***accumulated***
  Voelk et al 1996;
  Berezinsky, Blasi, Ptuskin 1997;
  Ensslin et al 1998; …
- CR electrons are ***short living*** particles and ***accumulated*** at $\gamma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

Radiation from Cosmic Rays in GC

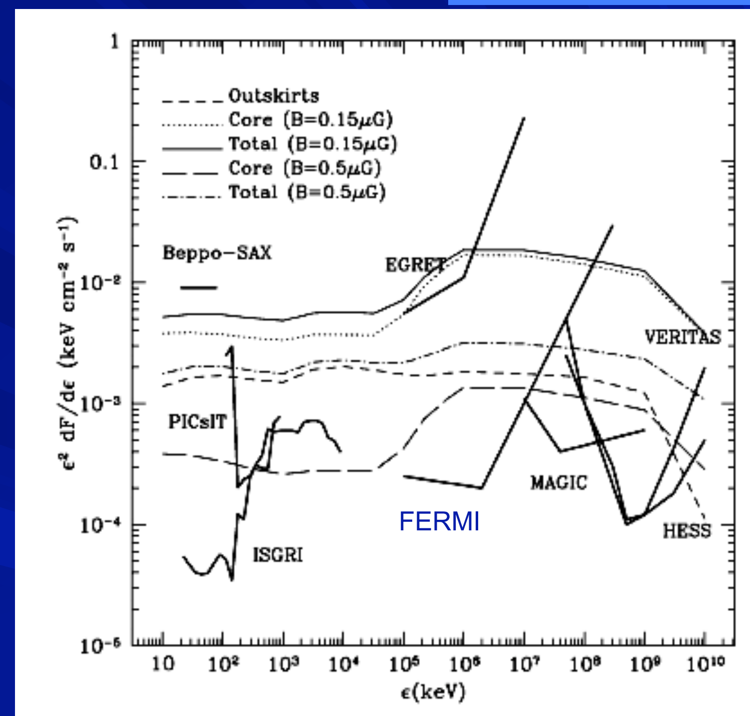
CRe



CRp

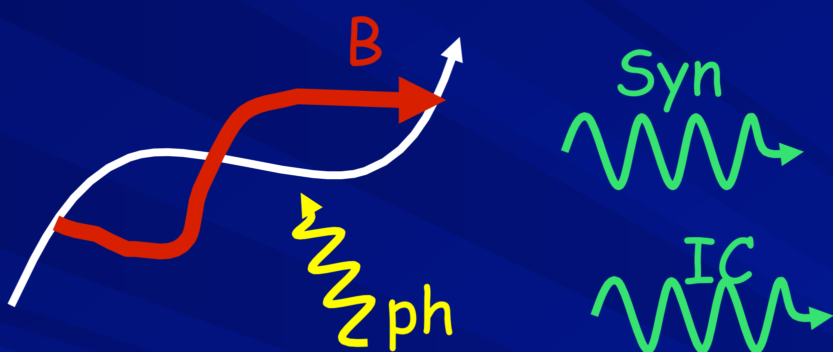


Miniati 2003

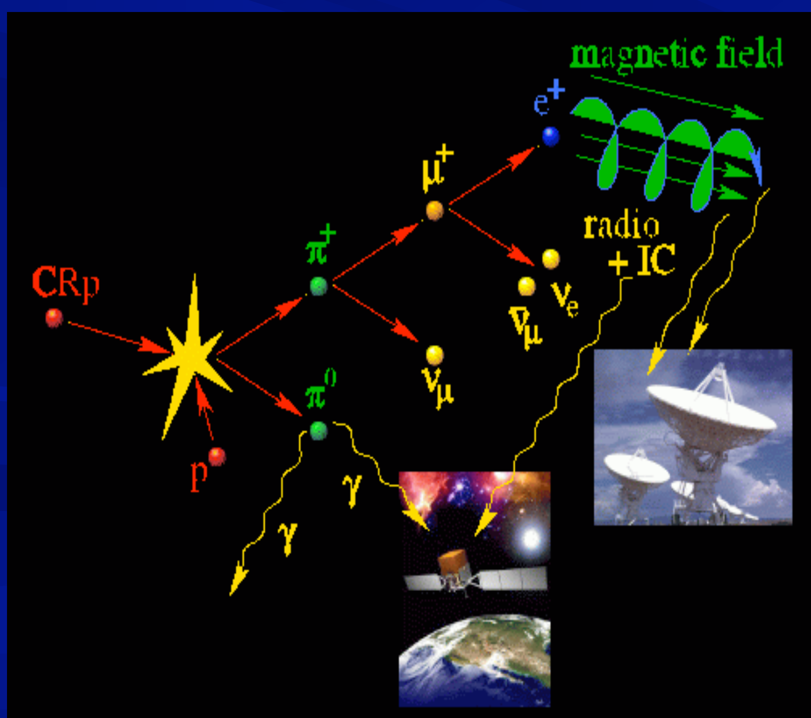


Radiation from Cosmic Rays in GC

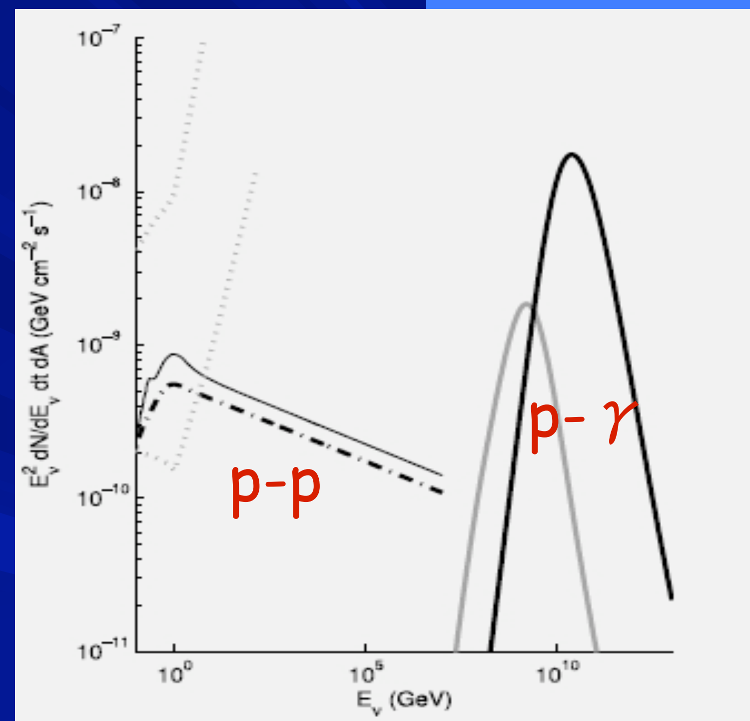
CRe



CRp

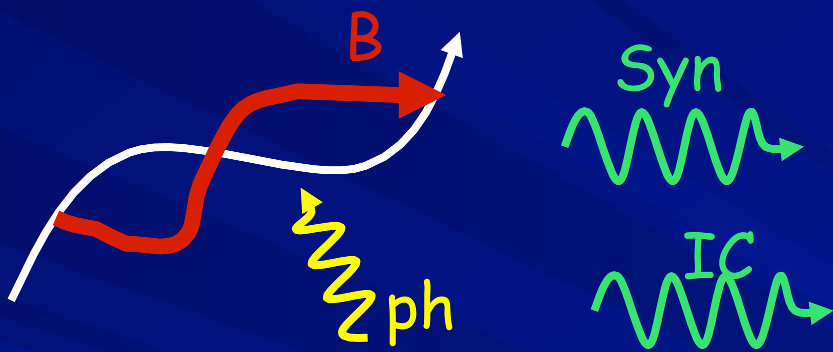


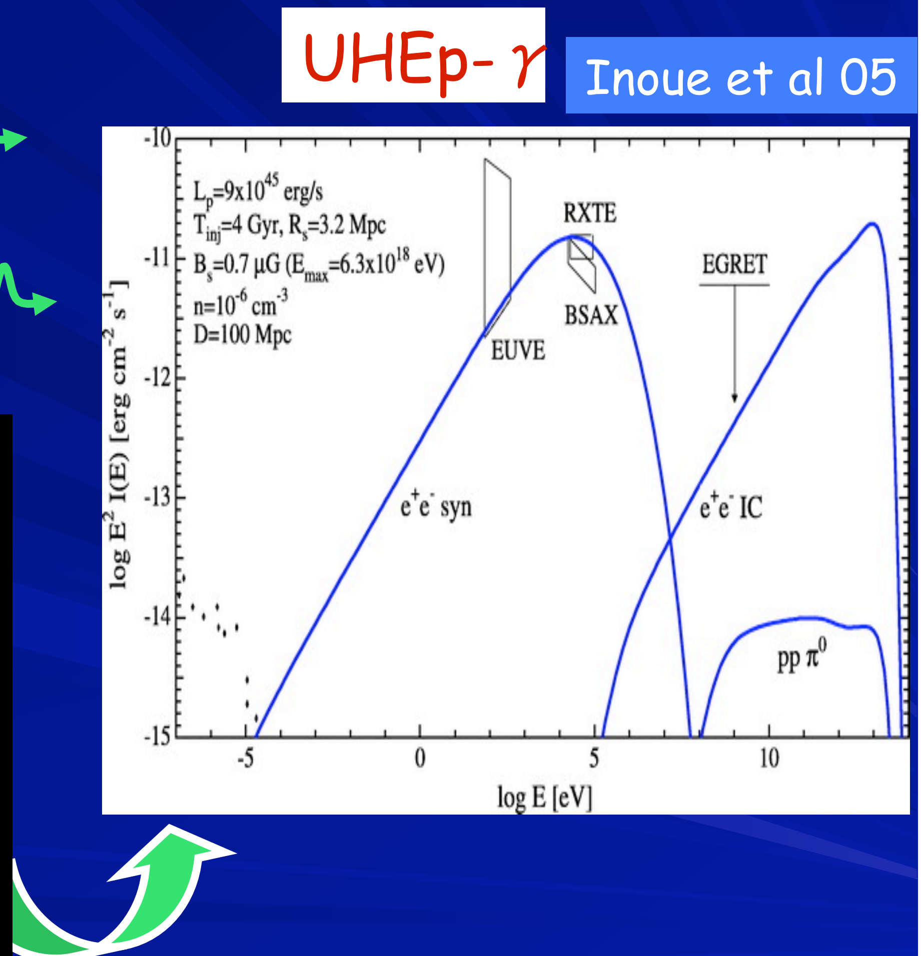
Wolfe +al 2008



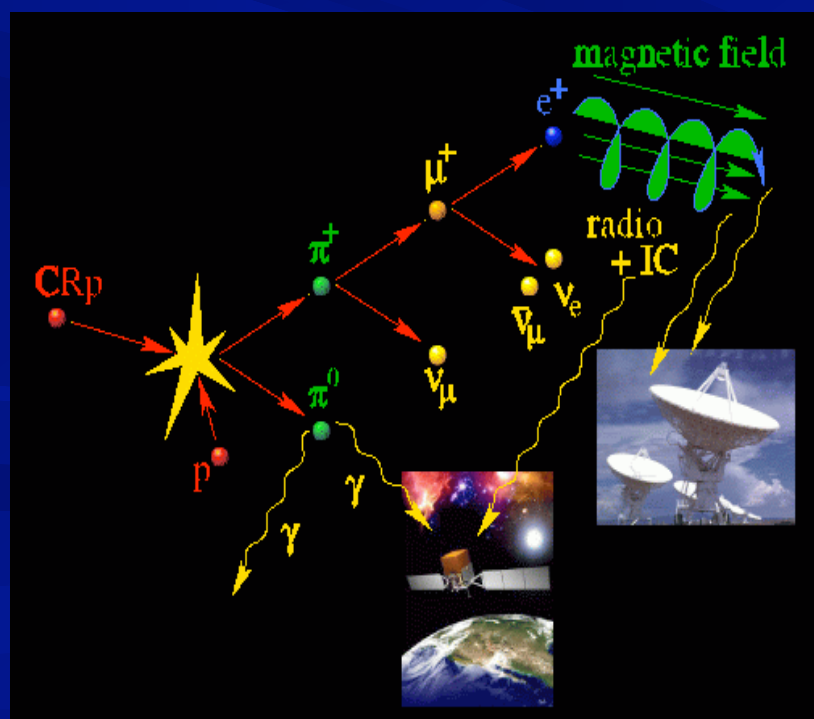
Radiation from Cosmic Rays in GC

CRe



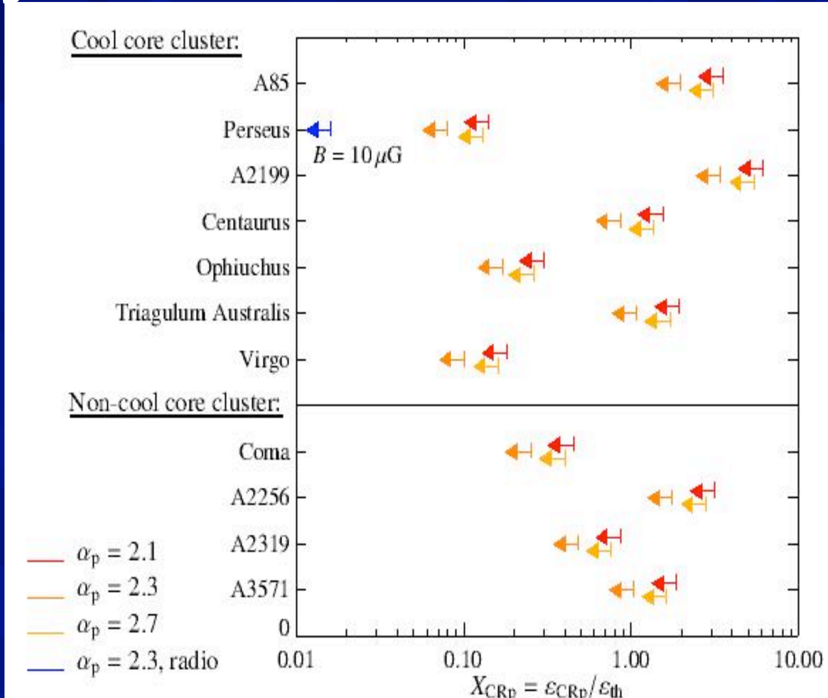


CRp



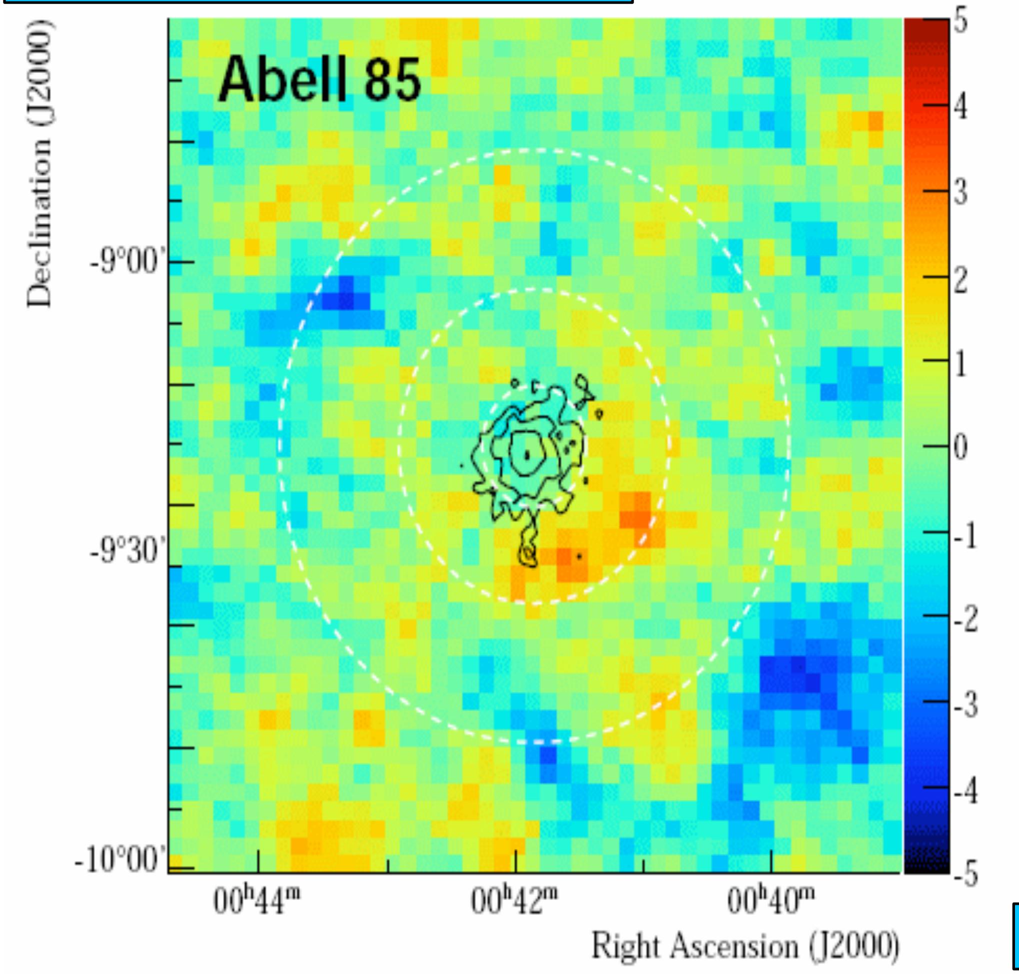
Limits from gamma rays

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)

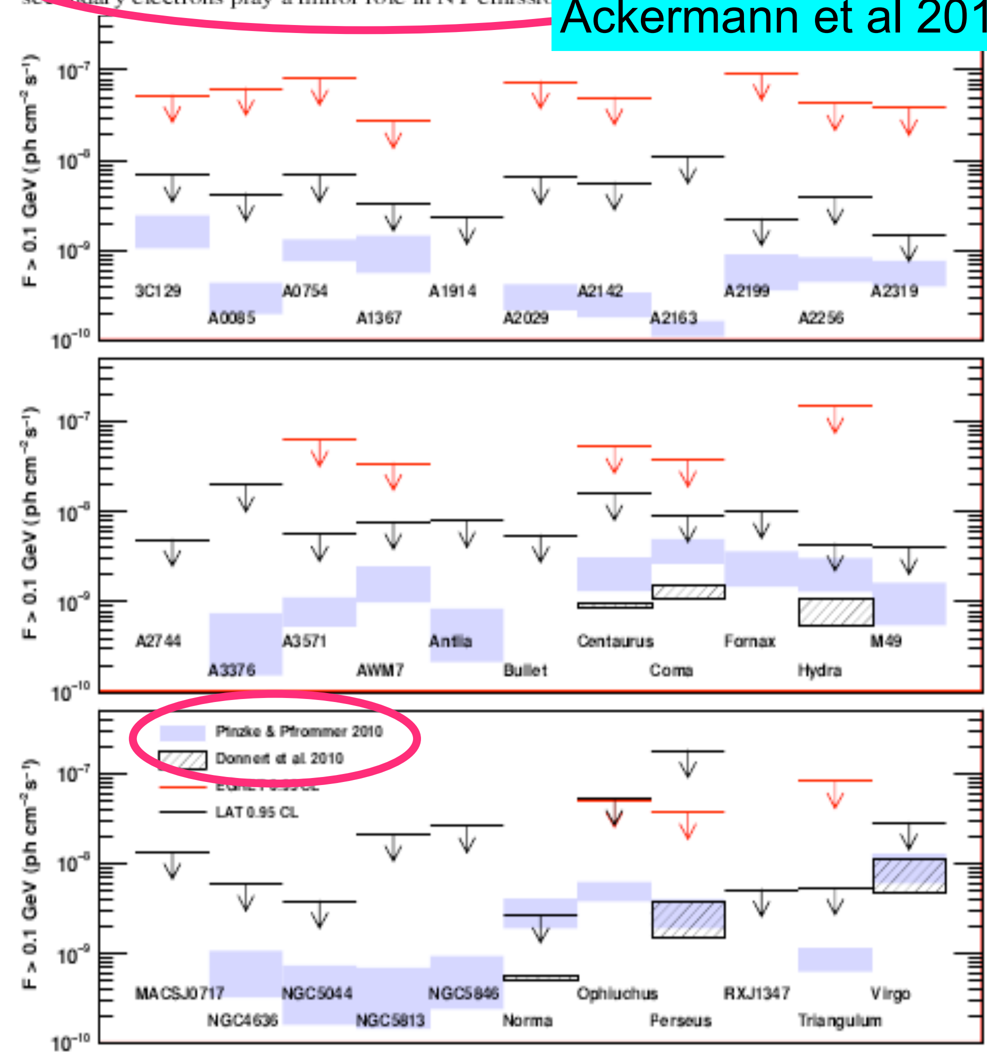
Perseus : Ecr/Eth < 4% (hard spectra)

Gamma rays : energy content of CRp

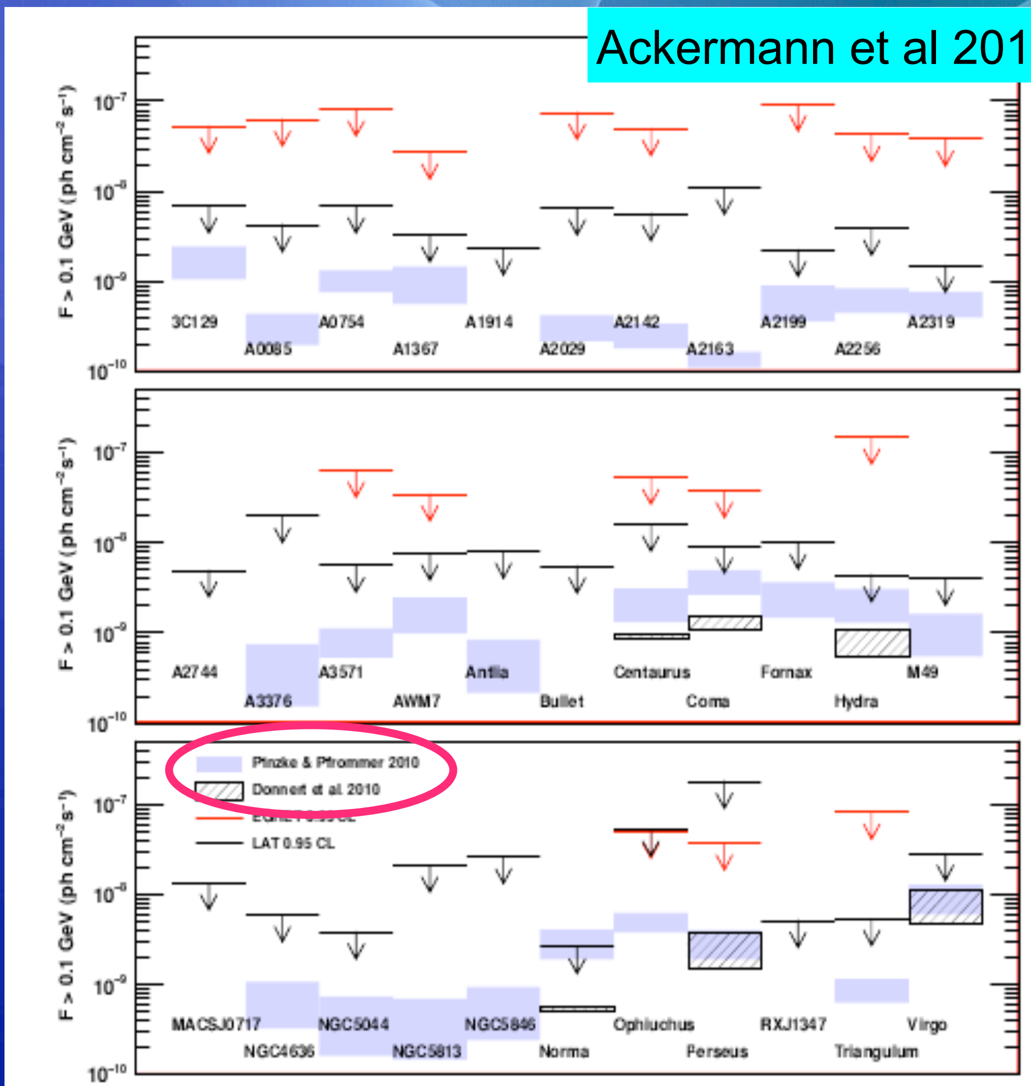
$\langle\epsilon_\gamma F(\epsilon_\gamma)\rangle$ 10–100	$\langle\epsilon_{CR}/\epsilon_{Th}\rangle$ $\alpha_p = 2.1$	$\langle\epsilon_{CR}/\epsilon_{Th}\rangle$ $\alpha_p = 2.4$	Cluster	Spatial Model (R_{68}) (deg)	f_{iso}	N 0.2–100	$\langle\epsilon_\gamma F(\epsilon_\gamma)\rangle$ 0.2–100	$\langle\epsilon_\gamma F(\epsilon_\gamma)\rangle$ 0.2–1
2.61	0.16	0.12	3C 129	King	0.56	3.93	1.26	1.84
2.35	0.06	0.04	A0085	King	0.46	2.23	0.71	1.17
2.03	0.35	0.27	A0754	King	0.54	3.31	1.06	1.65
2.18	0.26	0.16	A1367	King	0.48	1.83	0.59	1.03†
1.86	0.38	0.24	A1914	King	0.54	1.18	0.38†	0.72
2.16	0.11	0.09	A2029	King	0.49	3.18	1.02	1.72
1.95	0.07	0.05	A2142	King	0.52	2.75	0.88	1.59
1.99†	0.81	0.61	A2163	King	0.54	5.50	1.76†	2.32
1.95	0.14	0.11	A2199	King	0.51	1.18	0.76	…
1.79	0.16	0.12	A2256	King	0.47	1.83	0.59	0.81
2.82	0.03	0.02	A2319	King	0.54	0.73	0.23†	0.54
1.89	1.21	0.93	A3376	King	0.57	9.69	3.11	5.18
2.17	0.05	0.04	A3571	King	0.50	3.26	1.04	1.85
2.09	1.52	1.19	Antlia	King	0.52	4.84	1.55	2.86
1.82	0.10	0.08	AWM7	King	0.55	3.95	1.27	1.92
2.13	0.09	0.07	Centaurus	King	0.51	8.15	2.61	3.90
3.03	…	…	Coma	Gauss (0.2)	0.53	4.84	1.55	2.28
3.08	…	…	Coma	Gauss (0.4)	0.52	4.86	1.56	2.36
4.97	…	…	Coma	Gauss (0.6)	0.58	5.12	1.64	2.38
4.88	…	…	Coma	Gauss (0.8)	0.56	4.93	1.58	2.73
2.92	0.05	0.04	Coma	King	0.55	5.14	1.65	2.18
2.12	…	…	Fornax	Gauss (0.2)	0.51	4.77	1.53	2.61
2.72	…	…	Fornax	Gauss (0.4)	0.62	5.40	1.73	2.73
2.68	…	…	Fornax	Gauss (0.6)	0.59	5.73	1.84	3.02
2.28	…	…	Fornax	Gauss (0.8)	0.62	5.39	1.73	2.61
2.30	…	…	Fornax	Gauss (1.0)	0.60	5.03	1.61	2.87
2.81	0.75	0.59	Fornax	King	0.60	5.64	1.81	2.80
2.83	0.28	0.21	Hydra	King	0.60	2.24	0.72†	0.94
2.05	5.09	3.98	M49	King	0.52	2.08	0.67	1.14
2.34	3.89	3.04	NGC 4636	King	0.46	2.67	0.86	1.28
2.18	1.58	1.24	NGC 5044	King	0.50	1.87	0.60	0.81
2.06	25.59	20.03	NGC 5813	King	0.52	10.57	3.39	4.25
1.94	13.82	10.82	NGC 5846	King	0.55	13.01	4.17	5.38
3.84	0.03	0.02	Norma	King	0.54	1.21	0.39†	0.94
1.95	0.05	0.04	Ophiuchus	King	0.54	26.22	8.41	14.18
17.95†	0.27	0.32	Perseus	King	0.70	87.36	28.01	28.11
1.93	0.07	0.05	Triangulum	King	0.54	2.39	0.77†	0.91
4.35	…	…	Virgo	Gauss (0.2)	0.62	14.49	4.65	4.93
5.13	…	…	Virgo	Gauss (0.4)	0.61	15.27	4.90	5.26
4.48	…	…	Virgo	Gauss (0.6)	0.64	14.97	4.80	5.62
4.48	…	…	Virgo	Gauss (0.8)	0.64	15.76	5.05	5.62
4.35	…	…	Virgo	Gauss (1.0)	0.66	16.01	5.13	5.71
4.48	…	…	Virgo	Gauss (1.2)	0.64	17.03	5.46	5.62
5.26	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 emissio…

Ackermann et al 2010



Gamma rays : limits on B …



Ackermann et al 2010

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

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

$L_{rad} / L_{IC} \approx U_B / U_{Oph}$ _-> B

B > 0.15 μG

Agreement with RM, possible disagreement with IC detections…

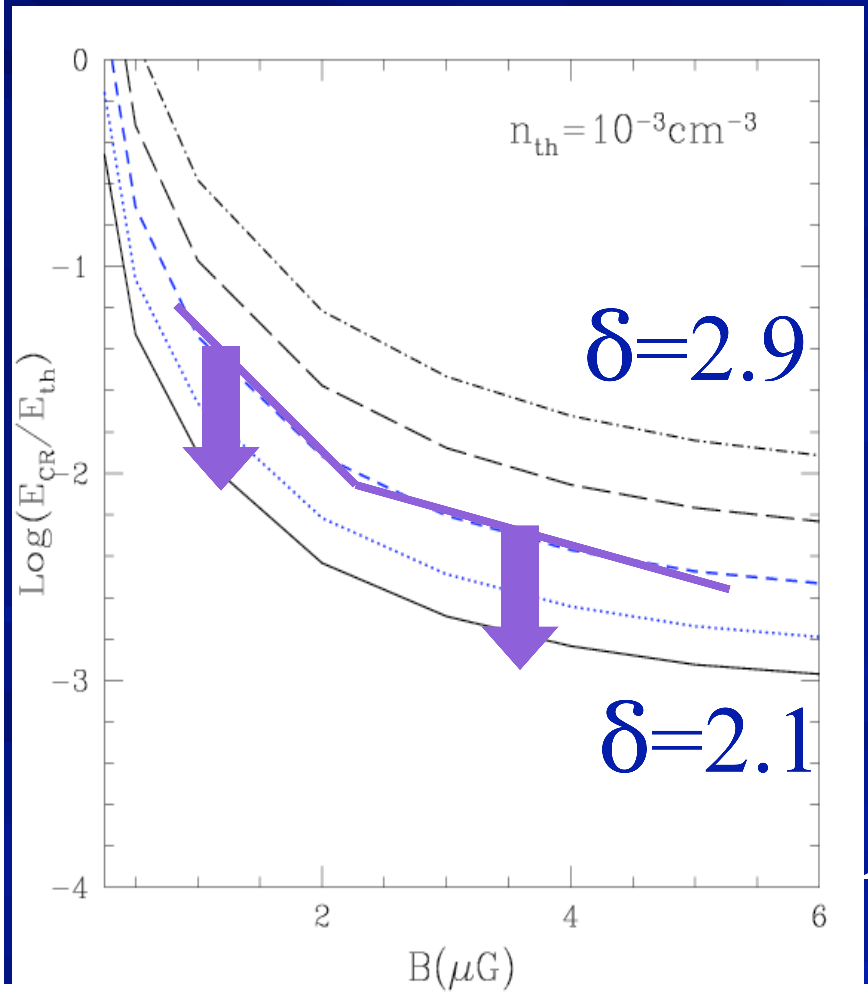
CRp: limits from Radio

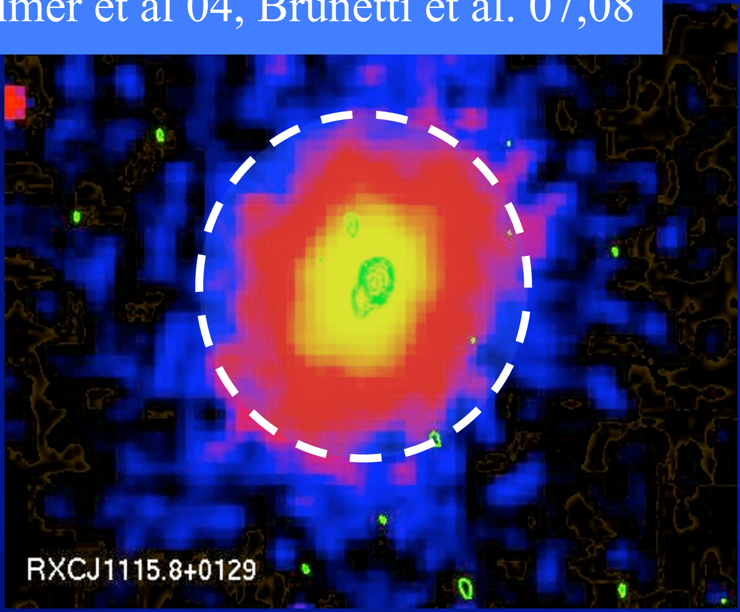
Reimer et al 04, Brunetti et al. 07,08

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

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

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



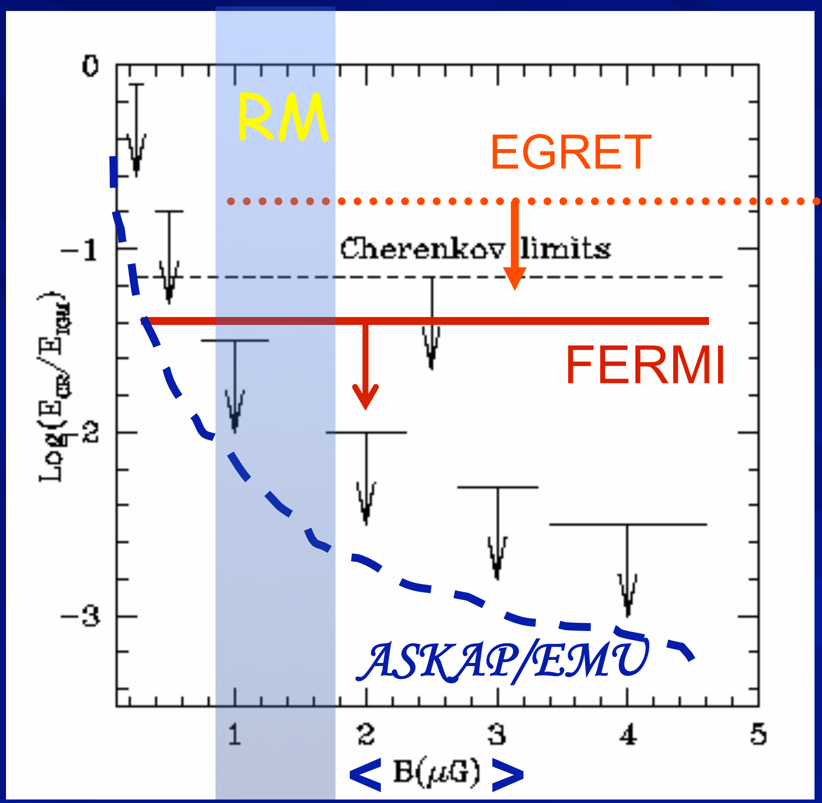


Assuming that secondary particles are injected in the IGM, their synchrotron emission should be smaller than upper limits to the diffuse radio emission.

limits on : $(\mathcal{B}, \mathcal{E}_{CRp})$, δ

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

Energy content of CRp



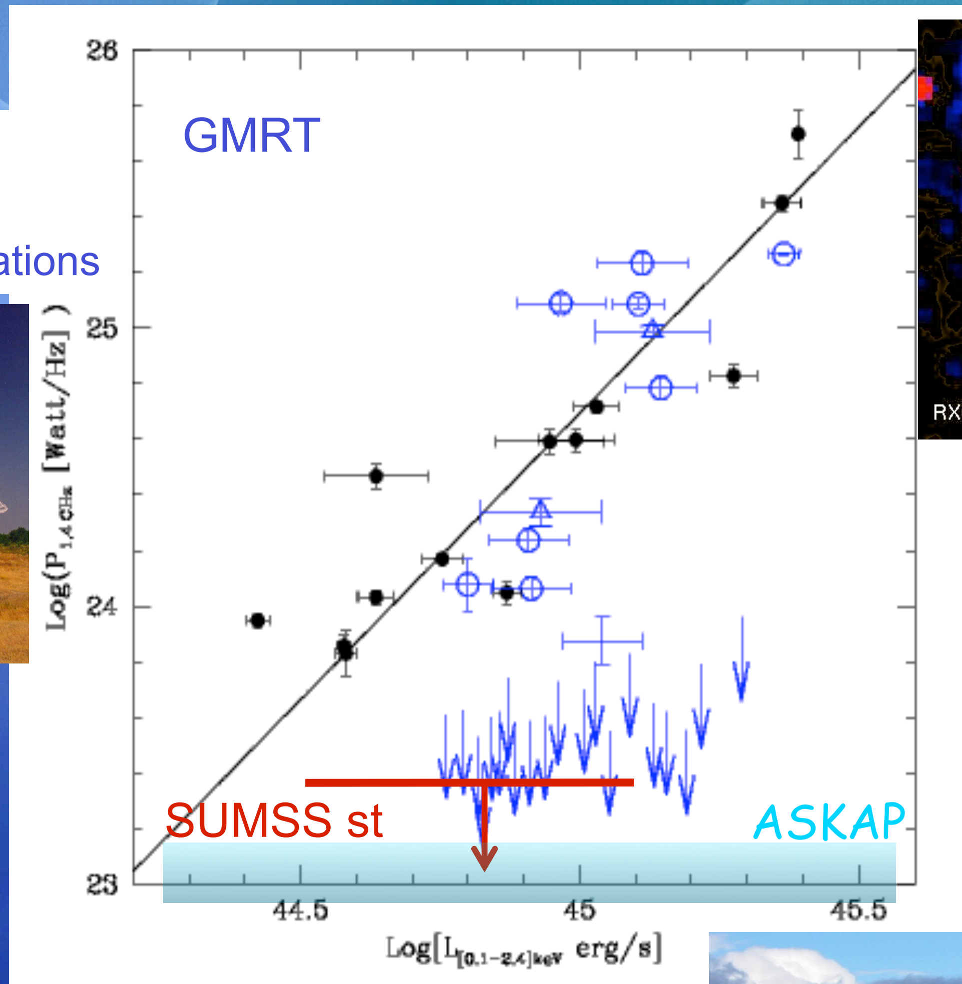
Reimer et al. (2003)
Reimer et al. (2004)
Pfrommer & Ensslin (2004)
Perkins et al. (2006)
Brunetti et al. (2007)
Brunetti et al. (2008)
Perkins et al. (2008)
Aharonian et al. (2008 a,b)
Aleksic et al. (2009)
Ackermann et al (2010)

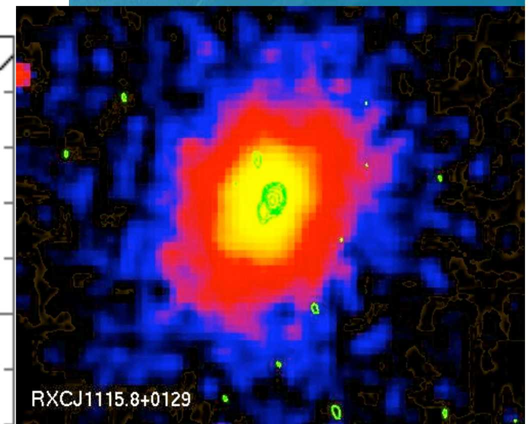
Gamma + Radio observations independently suggest that non-thermal components are dynamically NOT important (% level)

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.

Deeper limits… sic !

Venturi et al 2007,08
610 MHz GMRT
35 deep pointed observations



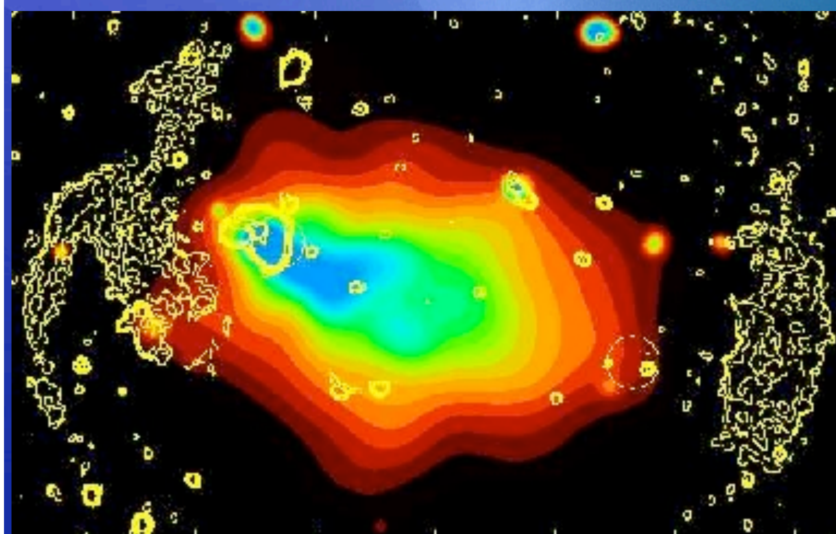


Brown, Emerick, Rudnick, GB, 2011…

843 MHz SUMSS
108 clusters stacked

Non-thermal emission from GC

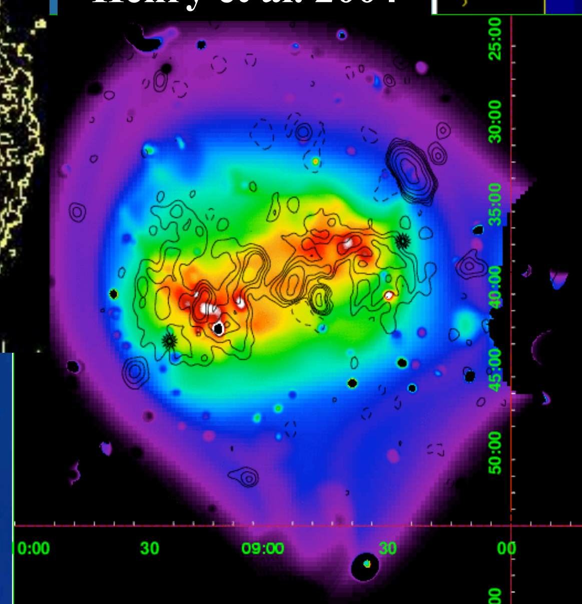
Both **Halos** & **Relics** have **steep spectrum**, $F(\nu)=F_o\nu^{-}$, with ≈1.3

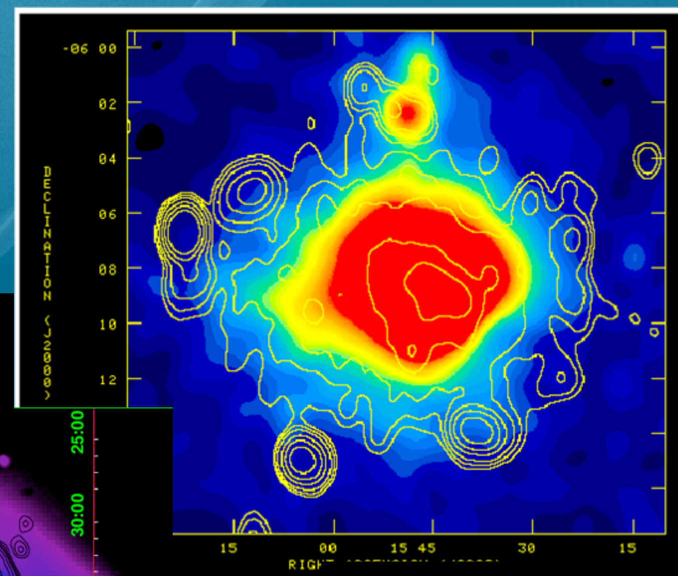


Abell 3376
Bagchi et al. 2005

Radio Relics

Abell 754
Henry et al. 2004





Abell 2163
Feretti et al. 2001

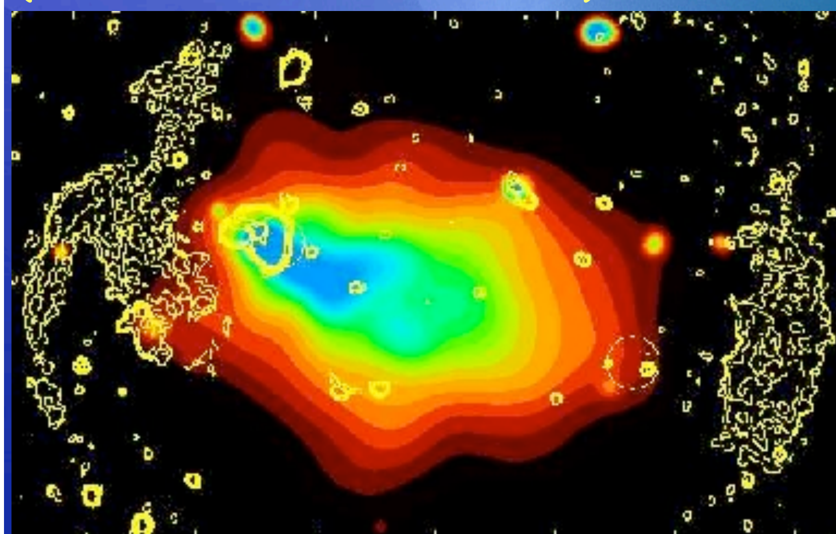
Radio Halos

Non-thermal emission from GC

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

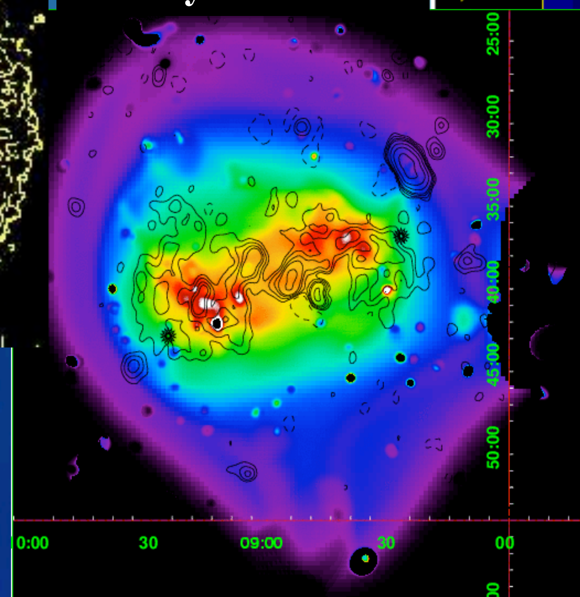
Unpolarised, follow the X-ray brightness
(originate from cluster central regions)

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

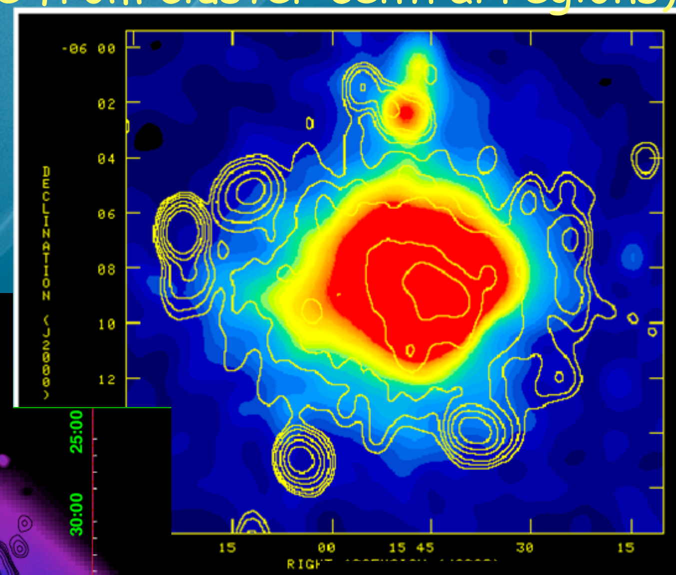


Abell 3376
Bagchi et al. 2005

Radio Relics



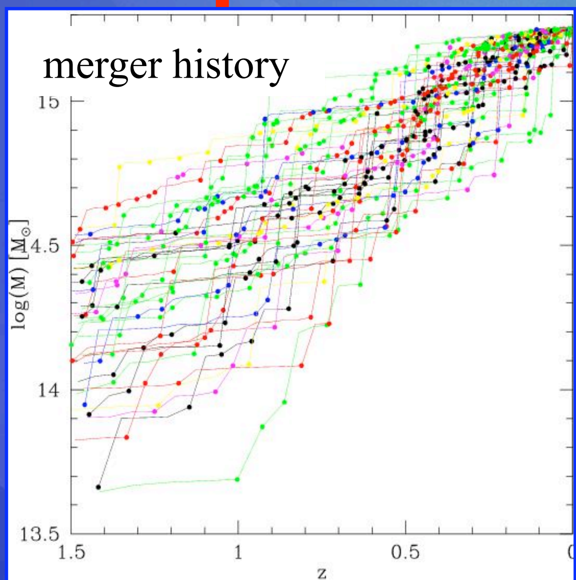
Abell 754
Henry et al. 2004



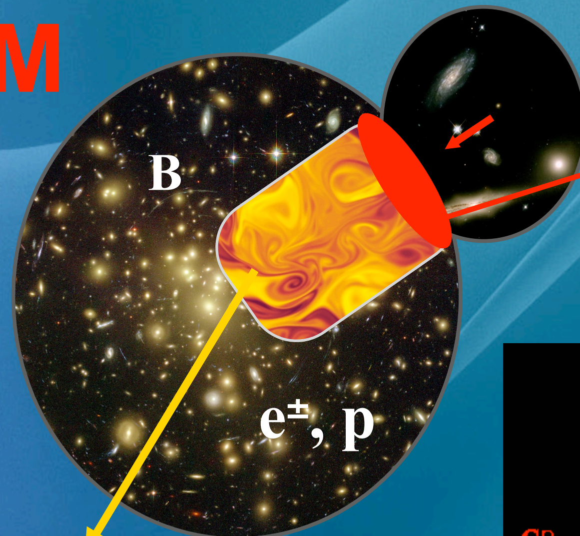
Abell 2163
Feretti et al. 2001

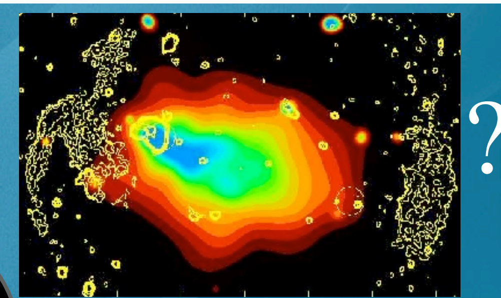
Radio Halos

Connecting LSS formation
.. NT-physics
of IGM

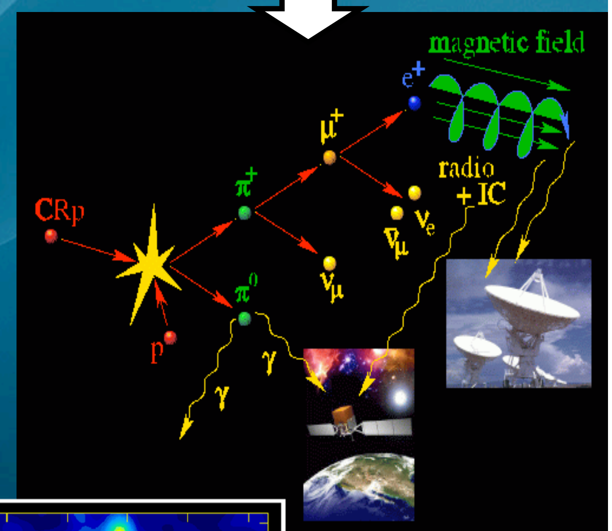


clusters increase their mass via merger with smaller subclusters

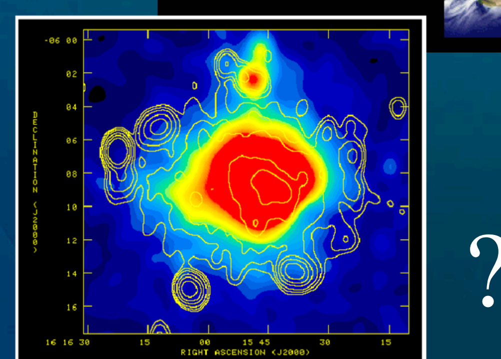




SHOCKS accelerate $e^{\pm}$, p_{cr}

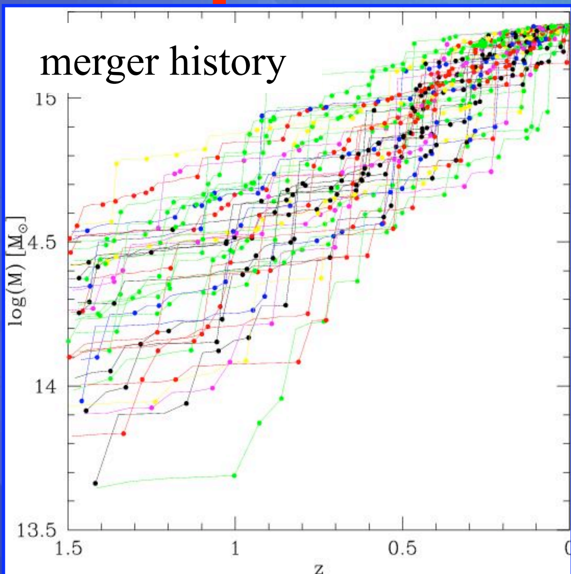


TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scales



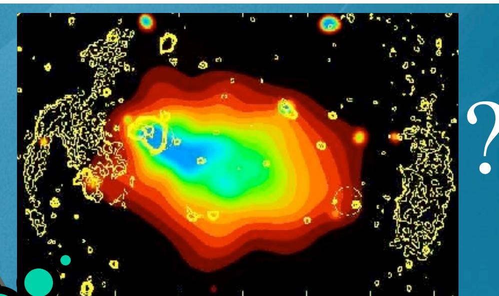
(eg., Brunetti et al. 2001, 2004, 2009; Petrosian 2001; Miniati et al. 2001; Fujita et al. 2003; Ryu et al. 2003; Gabici & Blasi 2003; Berrington & Dermer 2003; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Cassano et al. 2006; Brunetti & Lazarian 2007; Hoeft & Bruggen 2007;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

Connecting LSS formation .. NT-physics of IGM



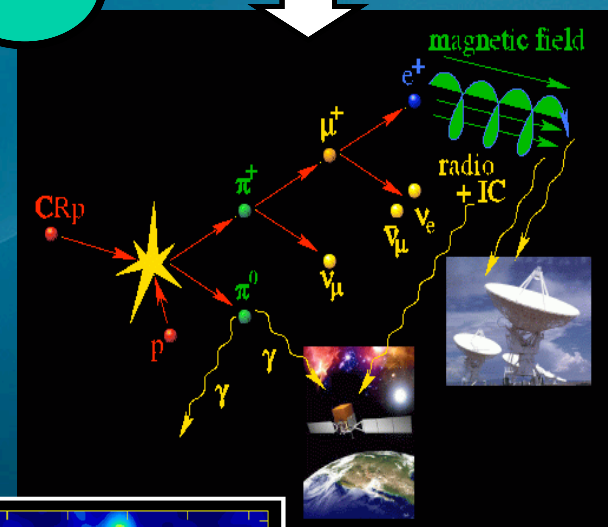
clusters increase their mass via merger with smaller subclusters

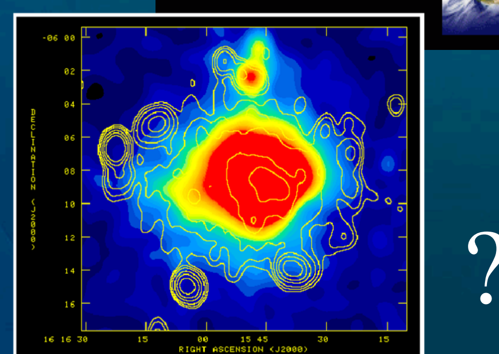
TURBULENCE reaccelerates fossil $e^\pm$ and secondaries $e^\pm$ on Mpc scales



SHOCKS

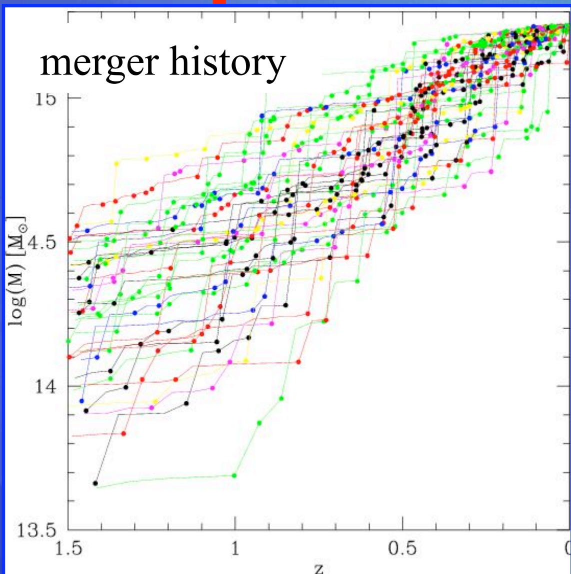
accelerate $e^\pm$, p_{cr}



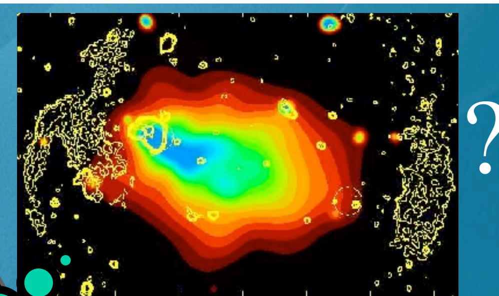


(eg., Brunetti et al. 2001, 2004, 2009; Petrosian 2001; Miniati et al. 2001; Fujita et al. 2003; Ryu et al. 2003; Gabici & Blasi 2003; Berrington & Dermer 2003; Pfrommer & Ensslin 2004; Brunetti & Blasi 2005; Cassano & Brunetti 2005; Cassano et al. 2006; Brunetti & Lazarian 2007; Hoeft & Bruggen 2007;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

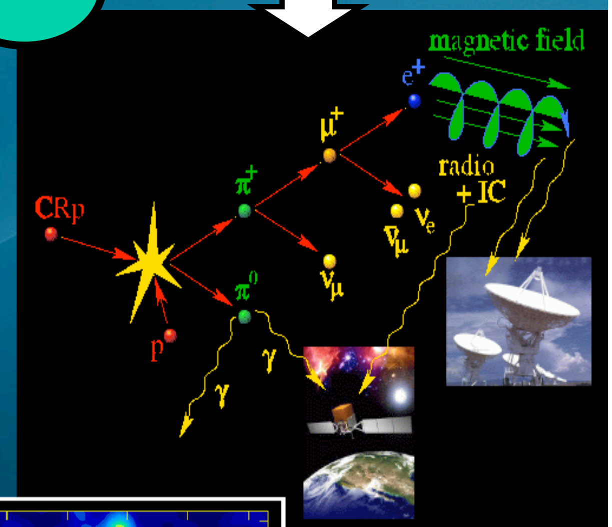
Connecting LSS formation .. NT-physics of IGM



clusters increase their mass via merger with smaller subclusters



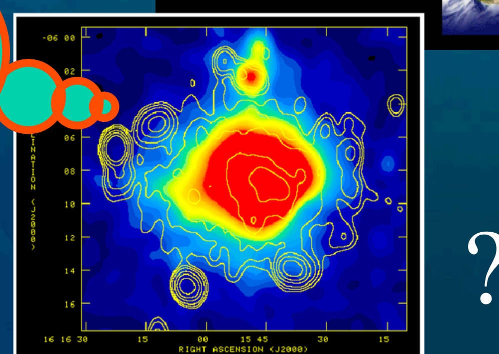
SHOCKS accelerate $e^{\pm}$, p_{cr}



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

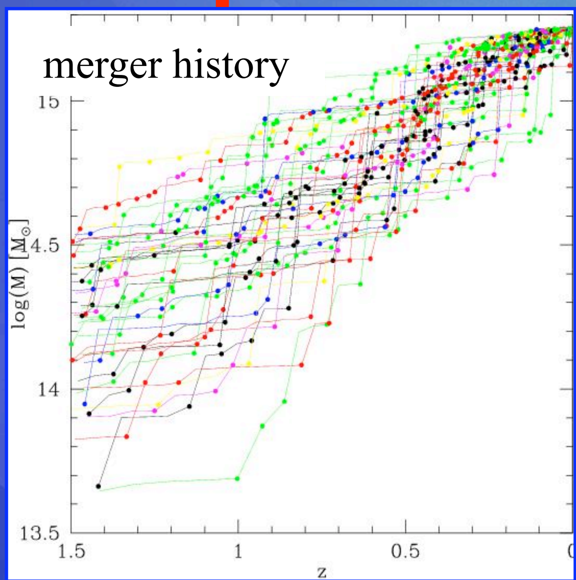
Turbulence?

Contribution by secondaries ?

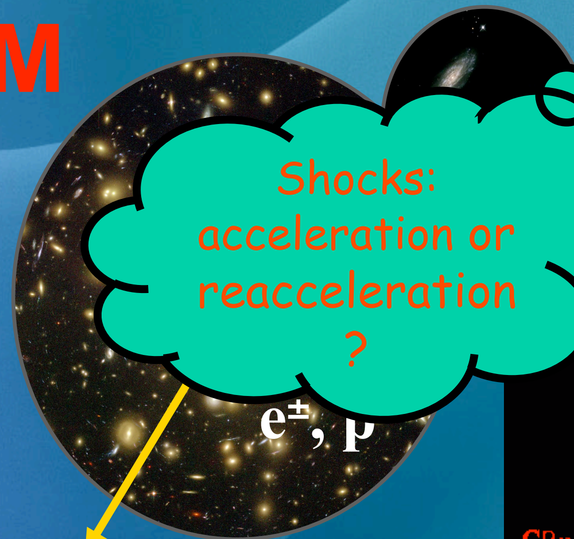


(eg., Brunetti et al. 2001, 2004, 2
Miniati et al. 2001; Fujita et al.
Gabici & Blasi 2003; Berringto
Pfrommer & Ensslin 2004; Brune
Cassano & Brunetti 2005; Cassano et al. 2
Brunetti & Lazarian 2007; Hoeft & Bruggen 2007;
Pfrommer et al. 2008; Petrosian & Bykov 2008)

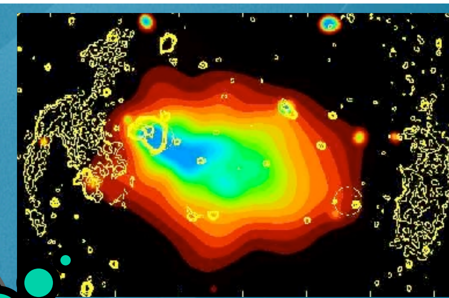
Connecting LSS formation ... NT-physics of IGM



clusters increase their mass via merger with smaller subclusters

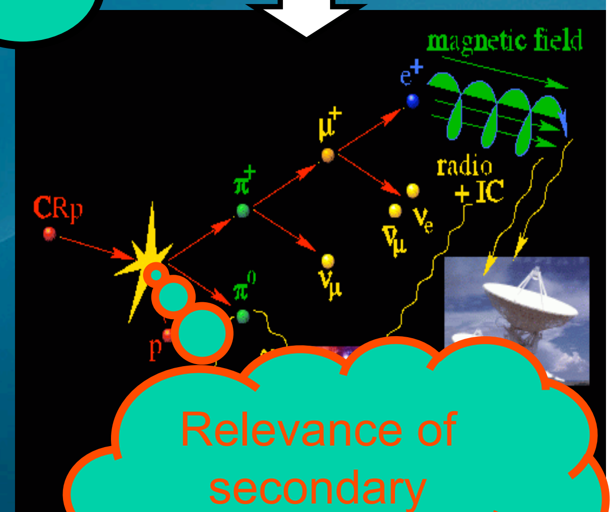


Shocks: acceleration or reacceleration ?



?

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

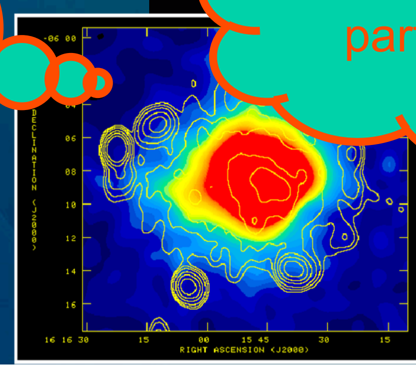


TURBULENCE reaccelerates fossil $e^{\pm}$ and secondaries $e^{\pm}$ on Mpc scal...

Turbulence?

Contribution by secondaries ?

Relevance of secondary particles ?

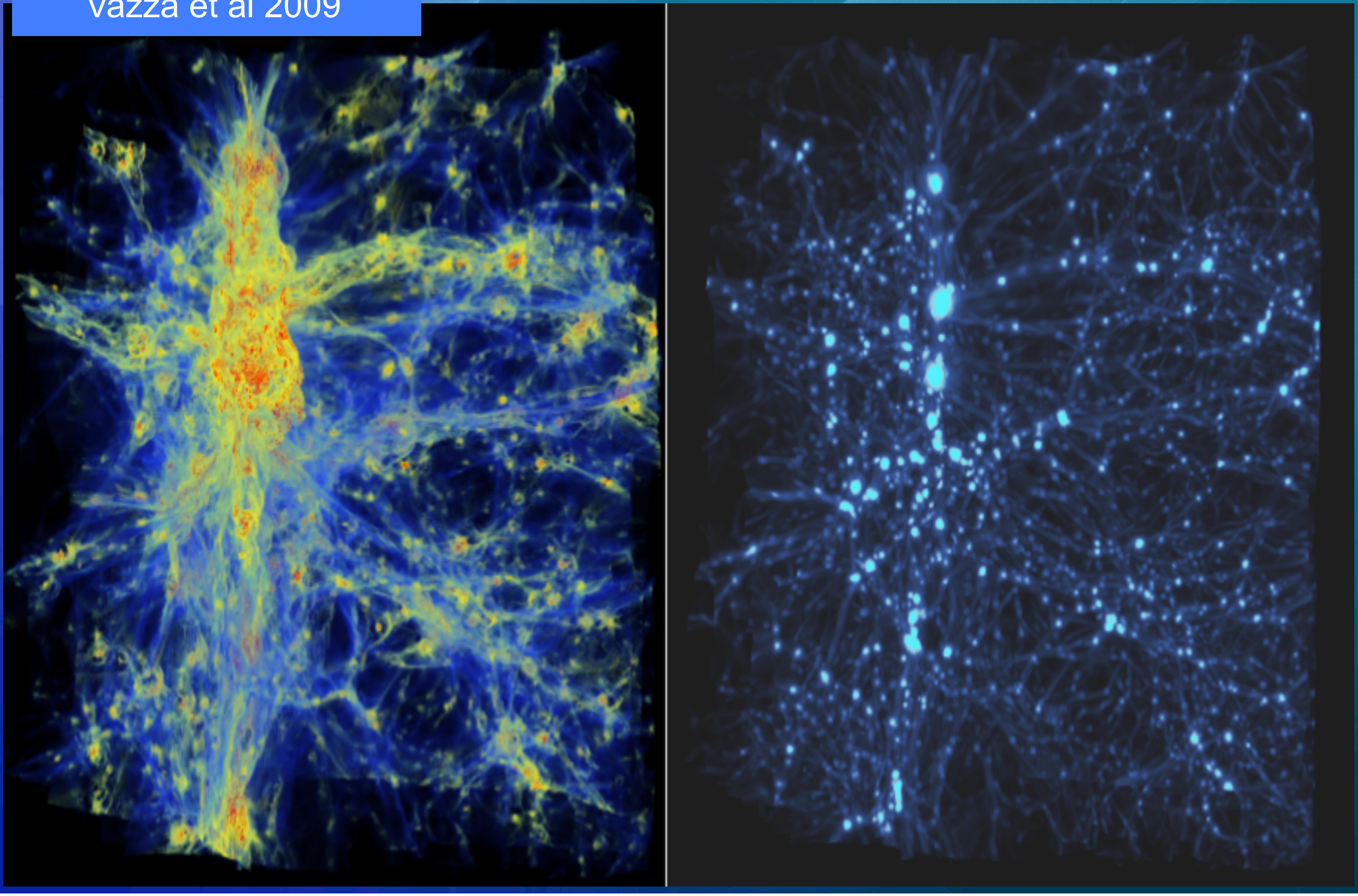


?

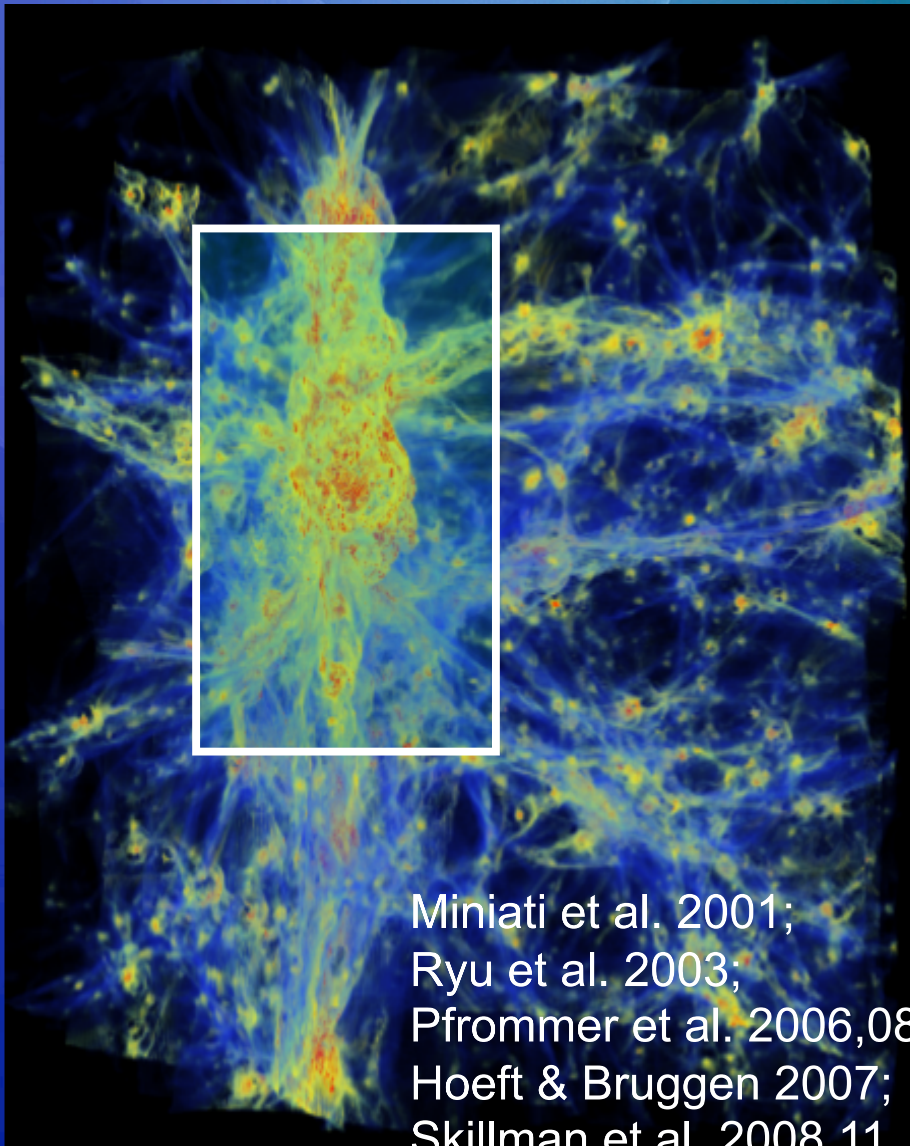
(eg., Brunetti et al. 2001, 2004, 2... Miniati et al. 2001; Fujita et al... Gabici & Blasi 2003; Berringto... Pfrommer & Ensslin 2004; Brun... Cassano & Brunetti 2005; Cassano et al. 2... Brunetti & Lazarian 2007; Hoeft & Bruggen 2007; Pfrommer et al. 2008; Petrosian & Bykov 2008)

Cosmological Shocks

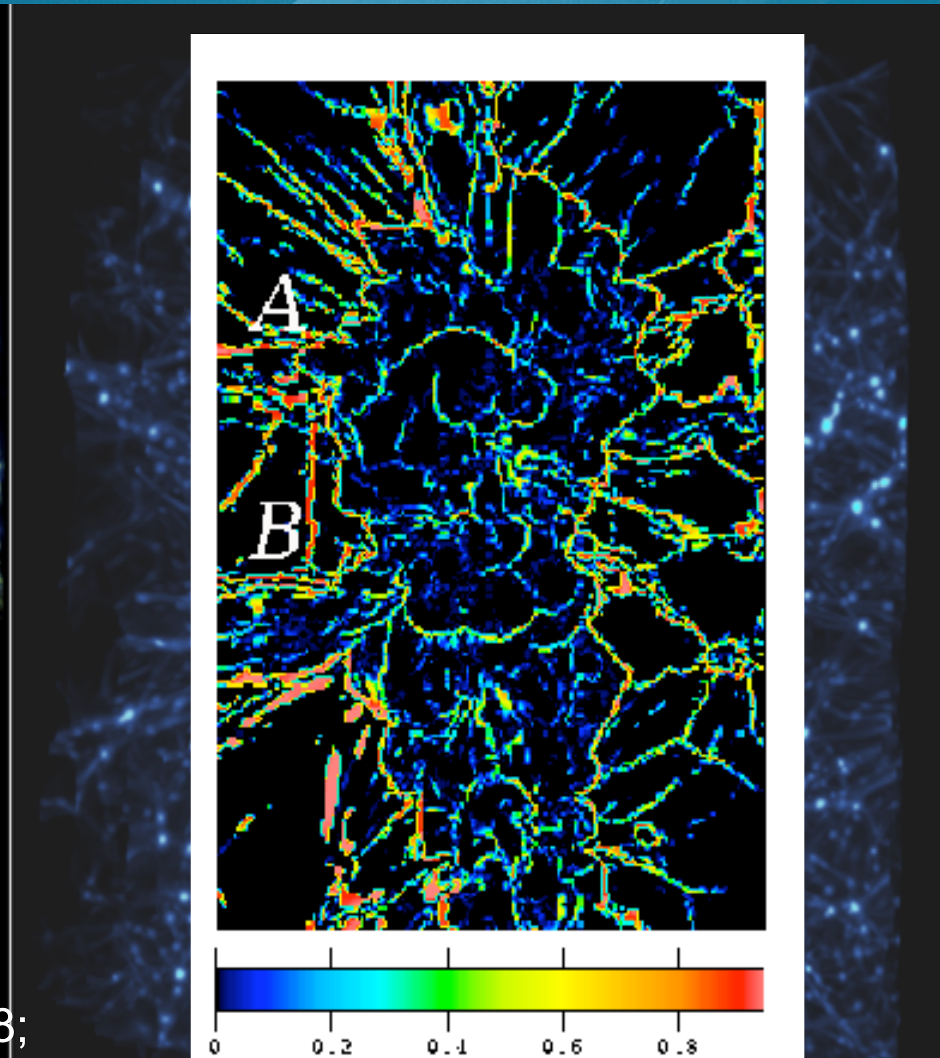
Vazza et al 2009



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

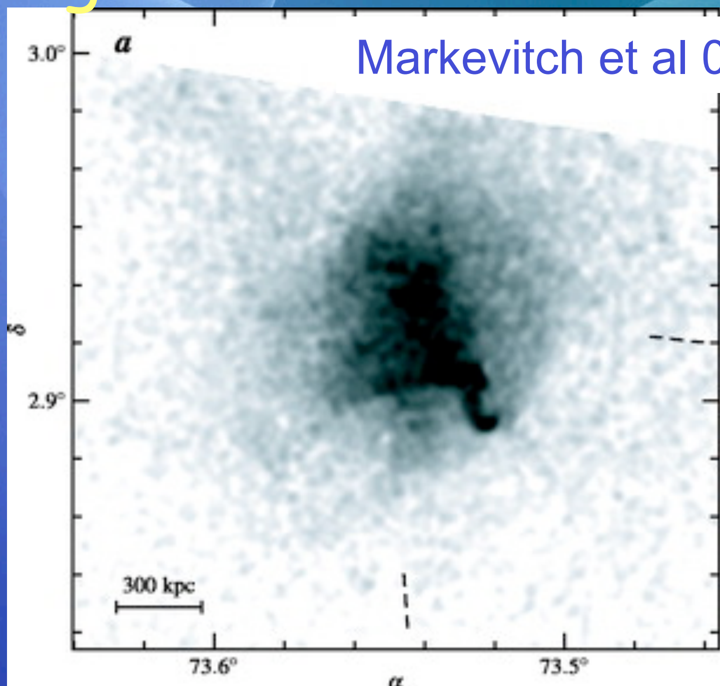


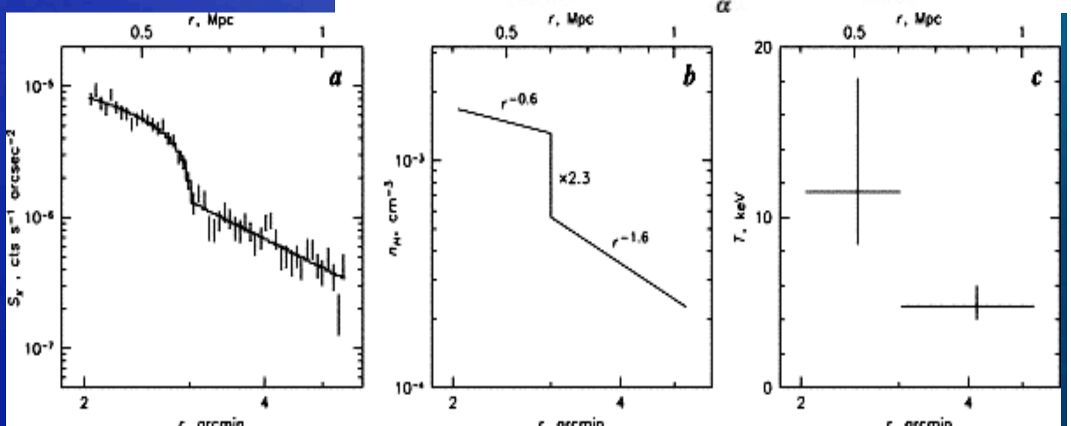
Vazza, Brunetti, Gheller 2009

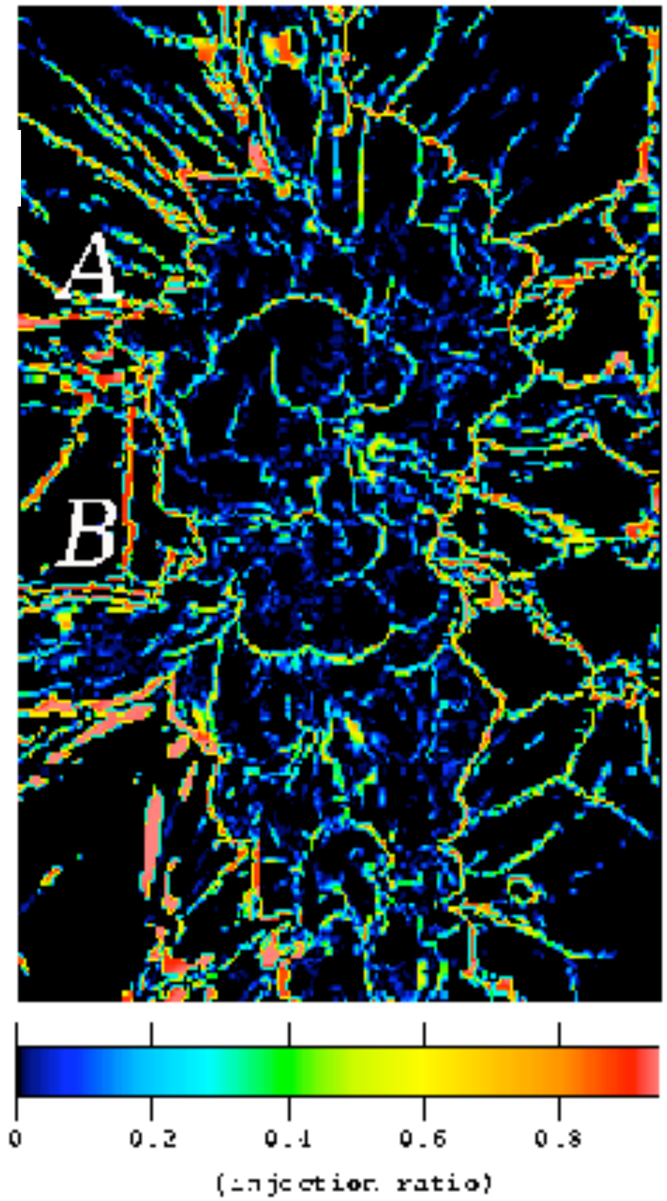
Shocks in Galaxy Clusters

Shocks are responsible for the heating of the IGM

Markevitch et al 05

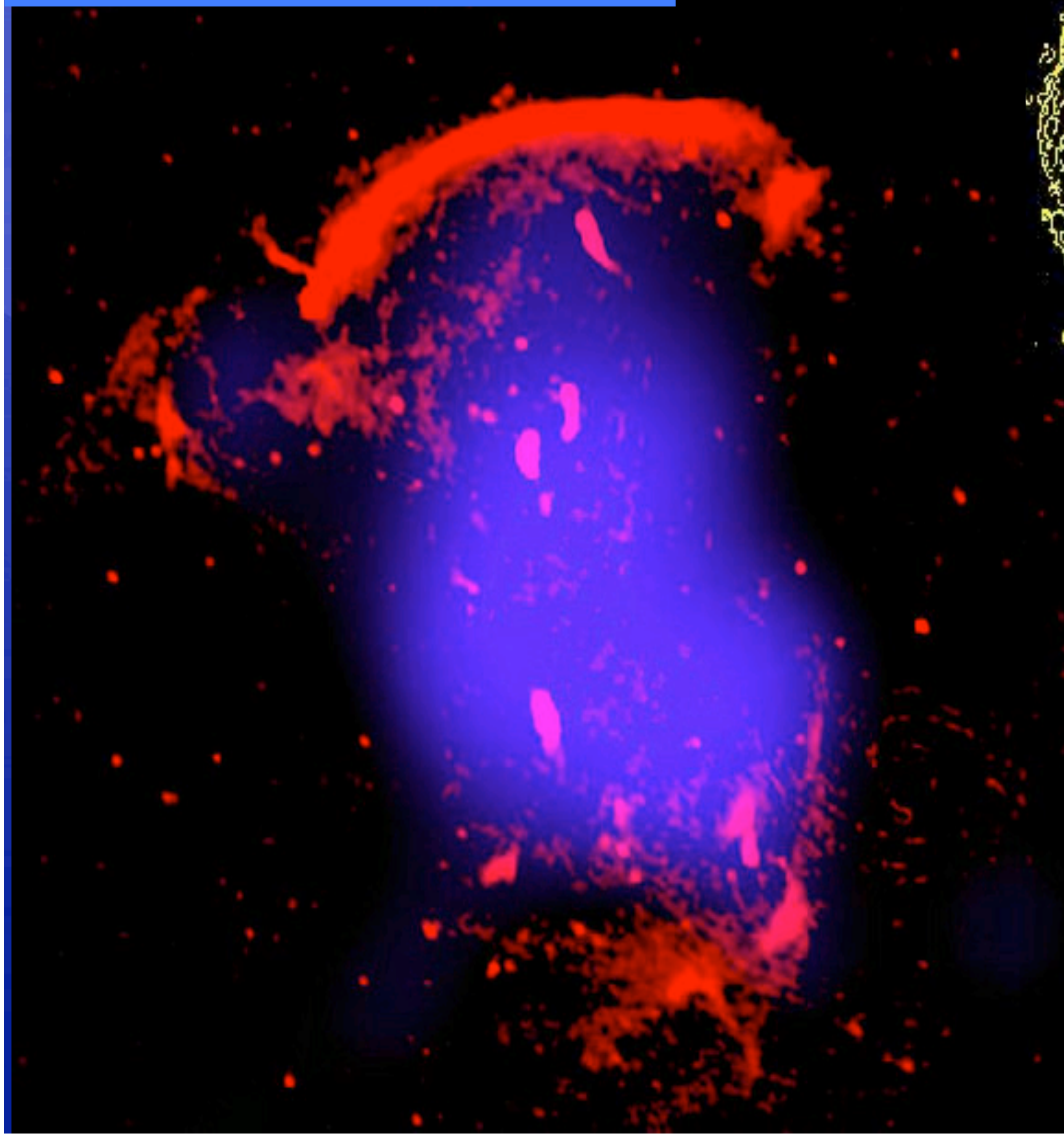




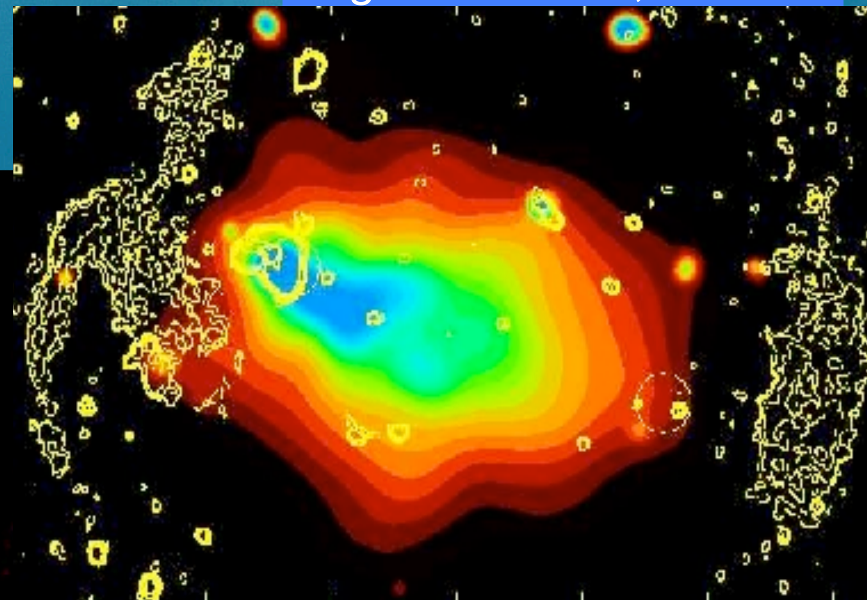


Shock–Relic connection

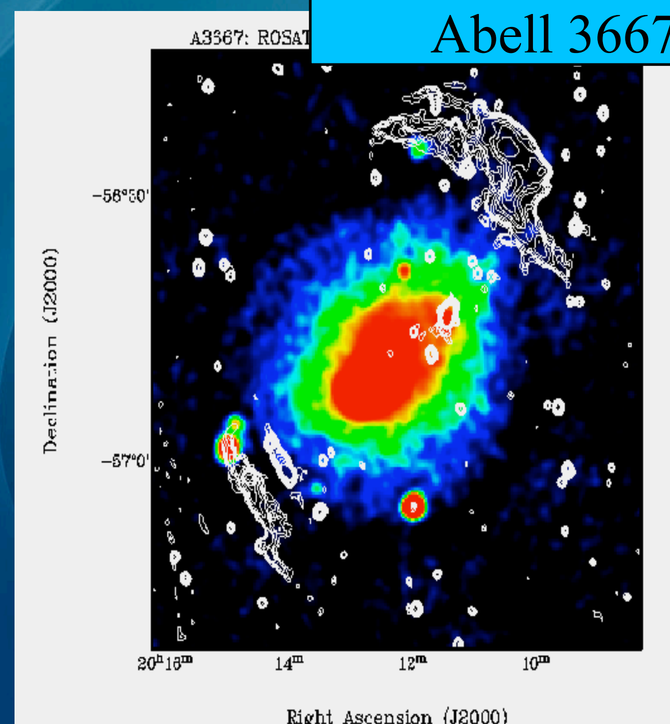
van Weeren+al. 2010, *Science*



Bagchi+al. 2002, *Science*



Abell 3667

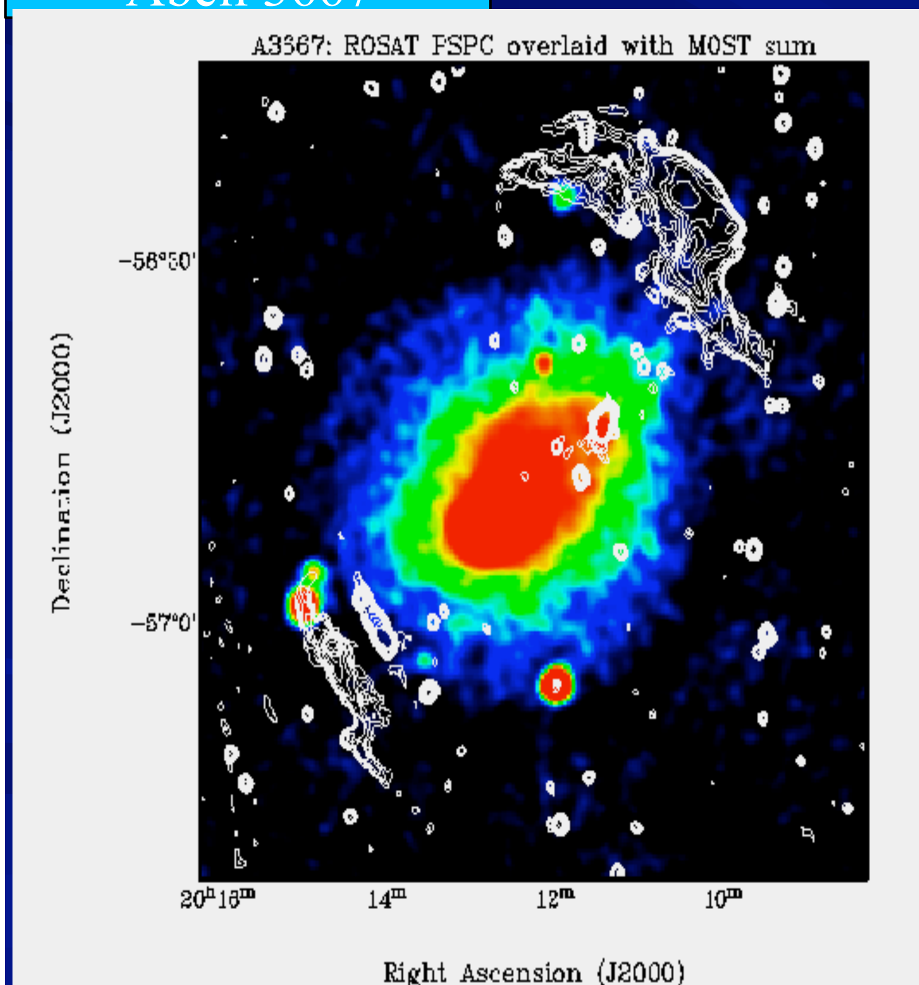


Shock Acceleration: Radio Relics

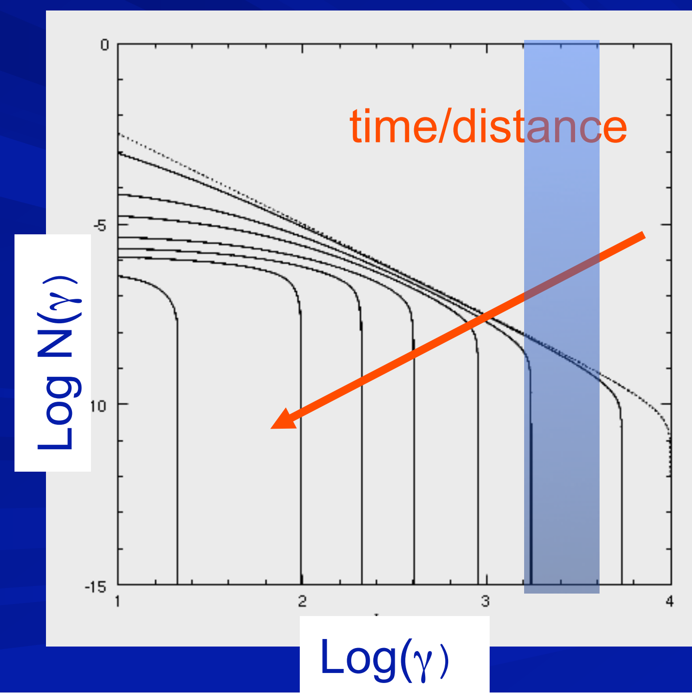
(Ensslin et al 1998, Roettiger et al. 1999, Sarazin 1999)

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

Abell 3667



$L_R \approx V_d \; \tau \; e(\nu) \approx 100$ kpc

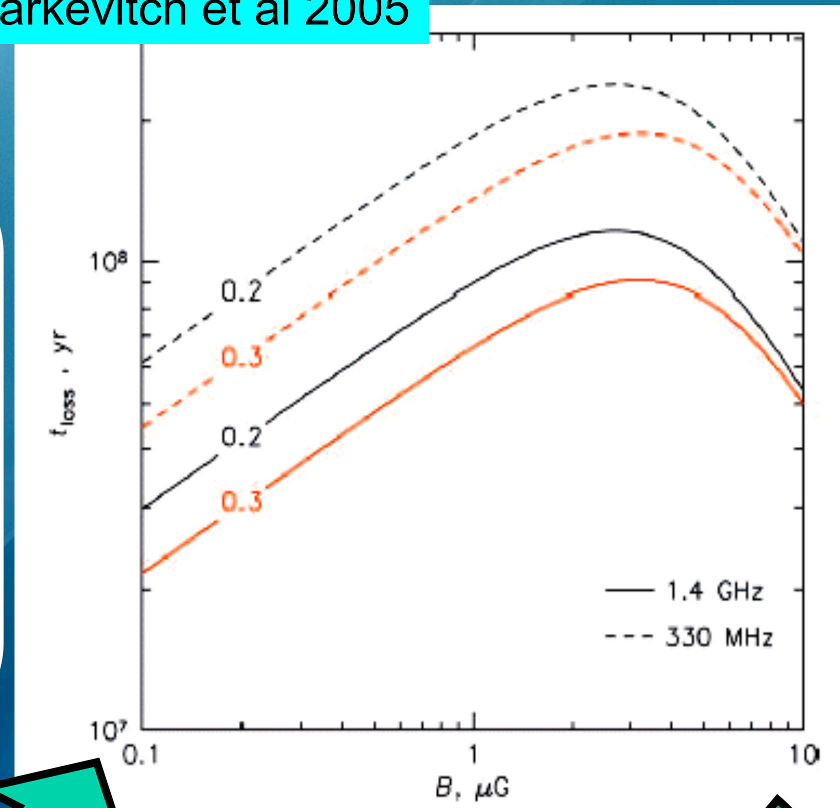


Width of Relics & constraints on B

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

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

Markevitch et al 2005

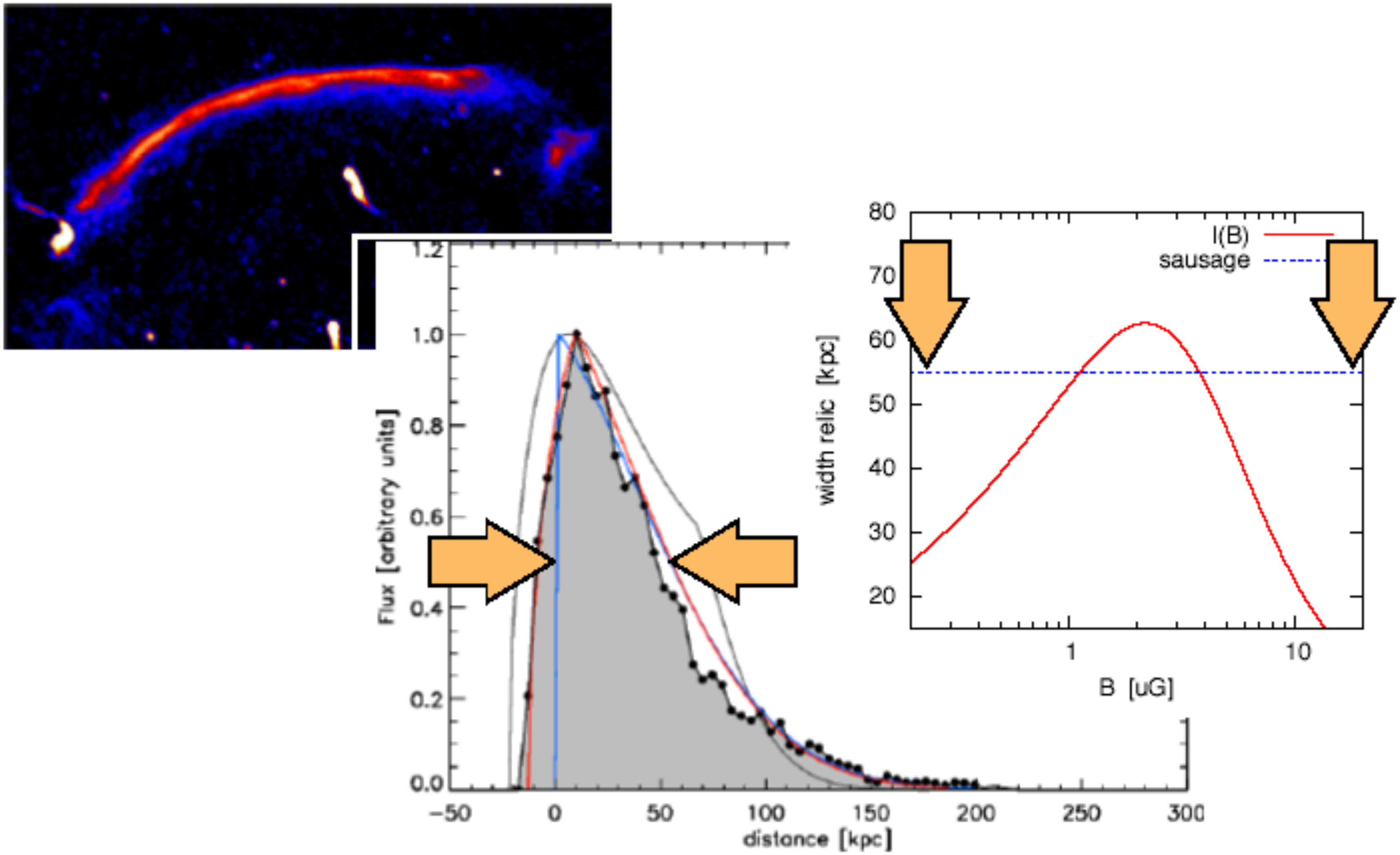


$$V_d \approx c_s M(M^2+3)/4M^2$$

Width of Relic

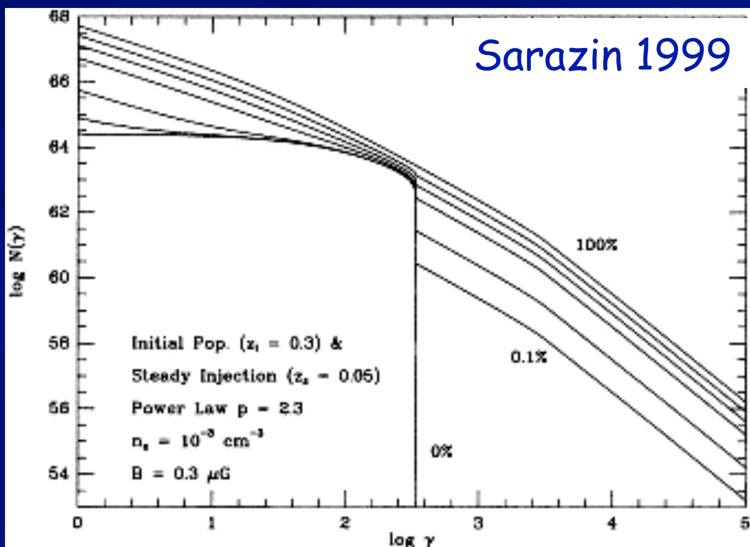
The width of the `sausage' (CIZA 2242)

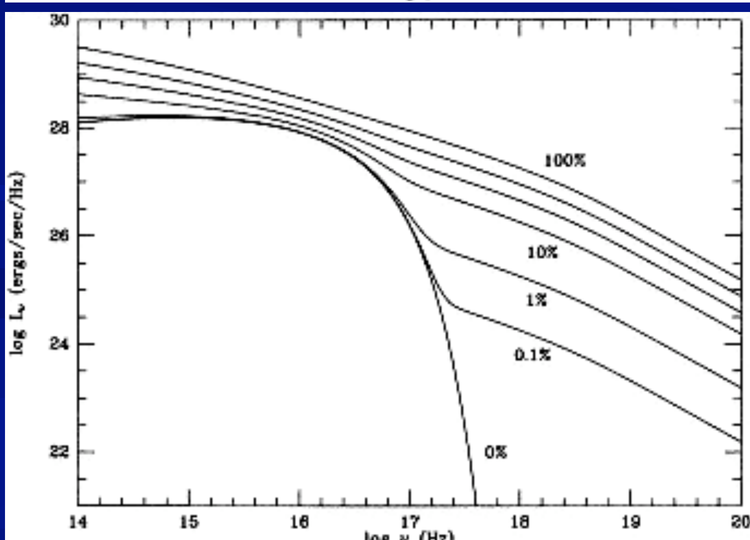
Van Weeren et al., 10

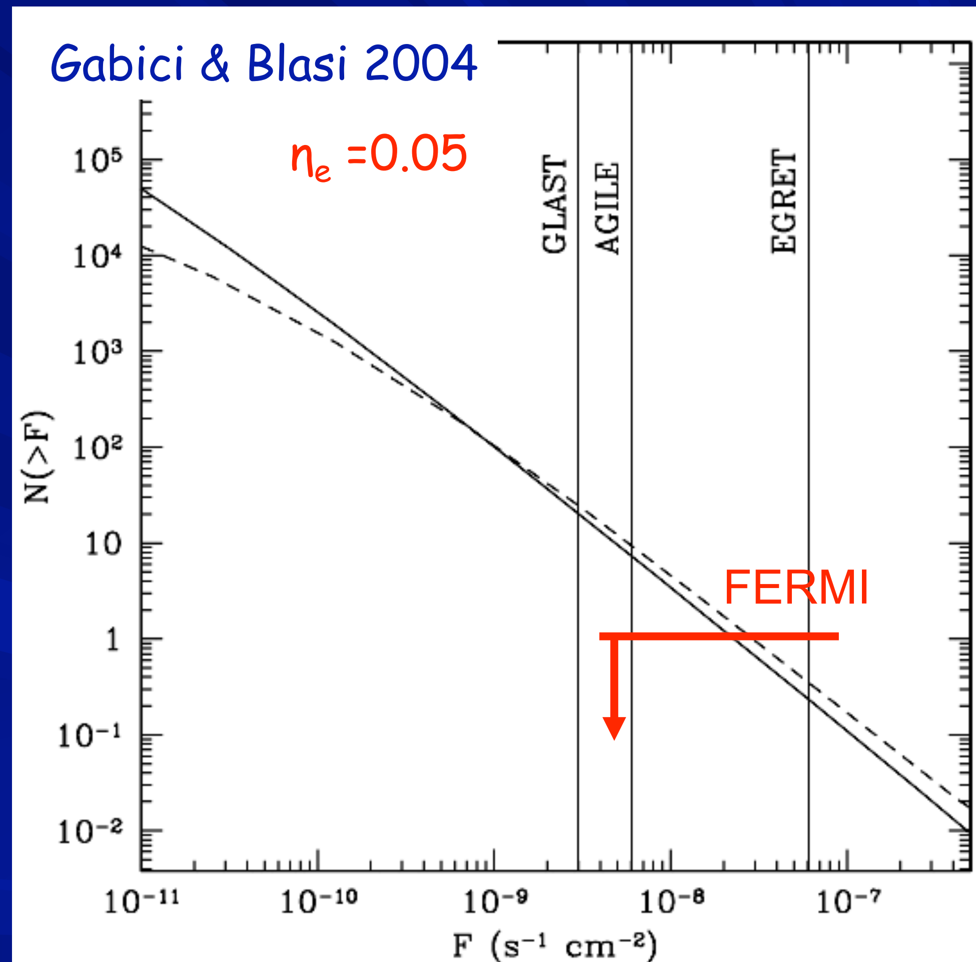


Shock Acceleration: IC

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



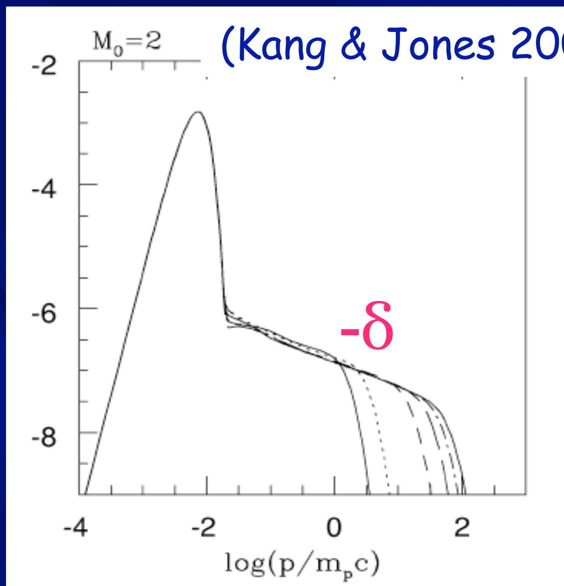


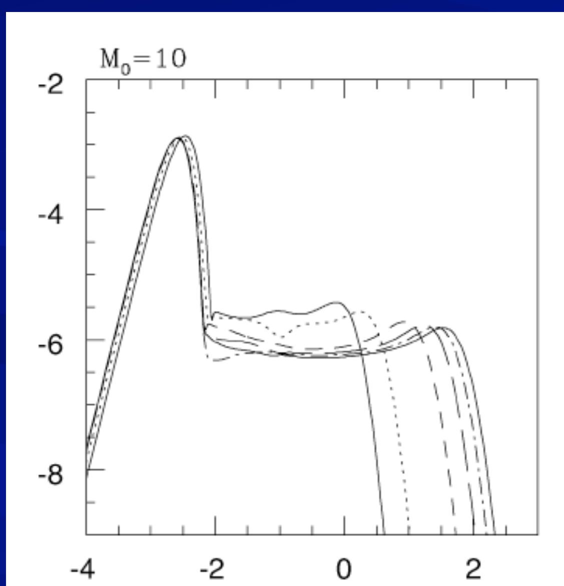


FERMI upper limits constrain the efficiency of electrons acceleration at shocks in galaxy clusters η_e < 0.001

Acceleration of CRp at shocks

(Kang & Jones 2002)





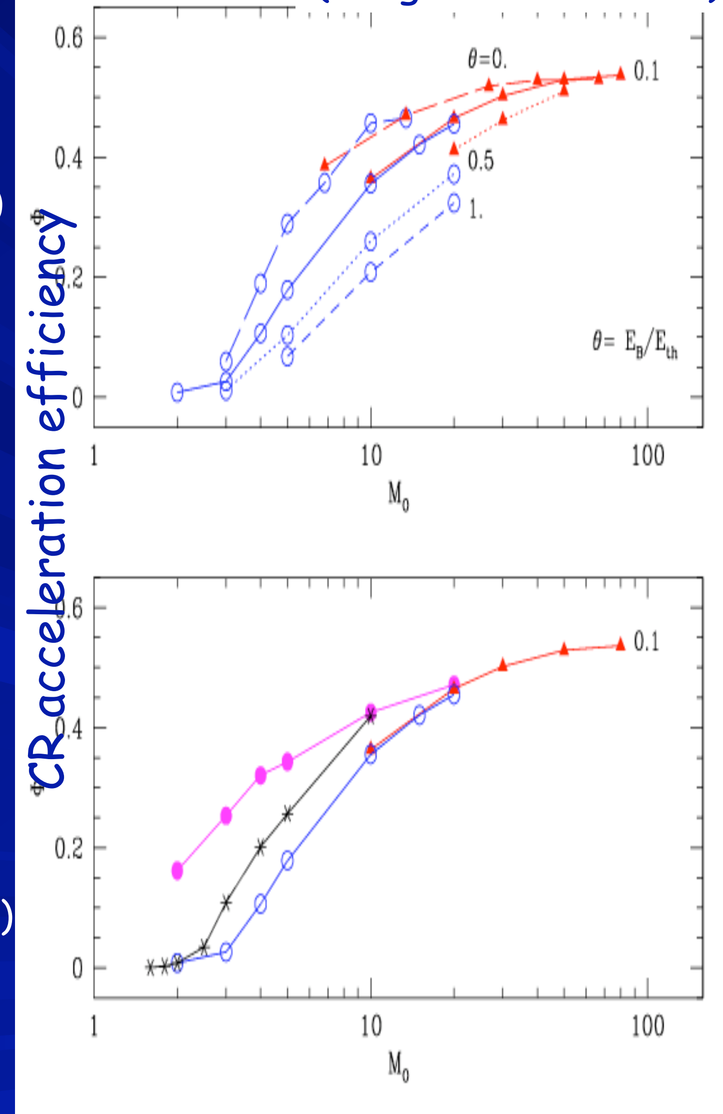
Linear Theory
(e.g.,Blandford & Eichler 1987)

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

Non Linear Theory
(Bell 1987, Ellison, Blasi, Kang..)

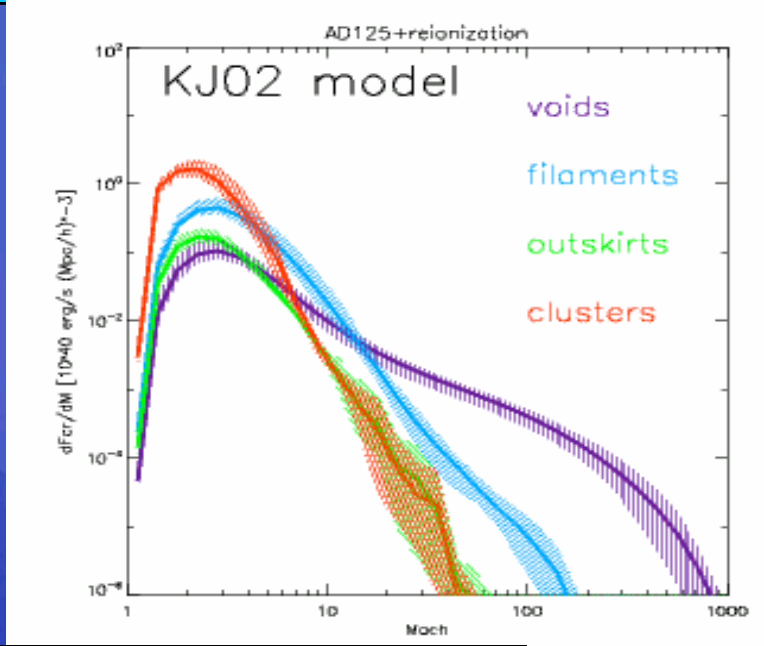
Vink lecture

(Kang & Jones 2007)

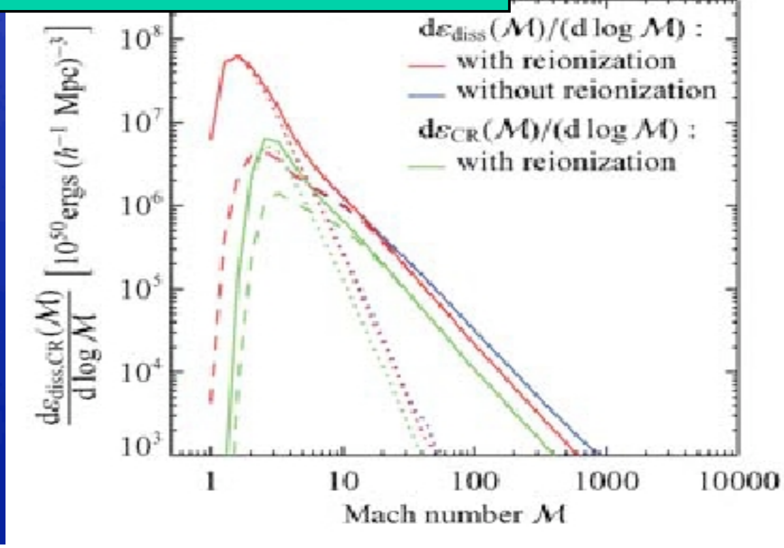


Mach numbers in galaxy clusters

Vazza, Brunetti, Gheller 2009



Pfrommer et al. 2008

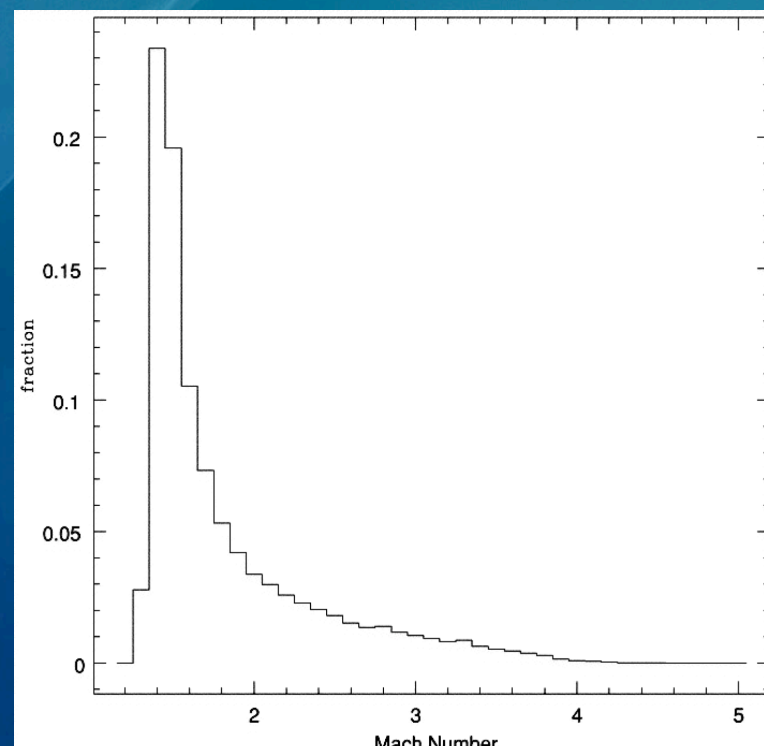


Semi-analytics :

Gabici & Blasi 2003

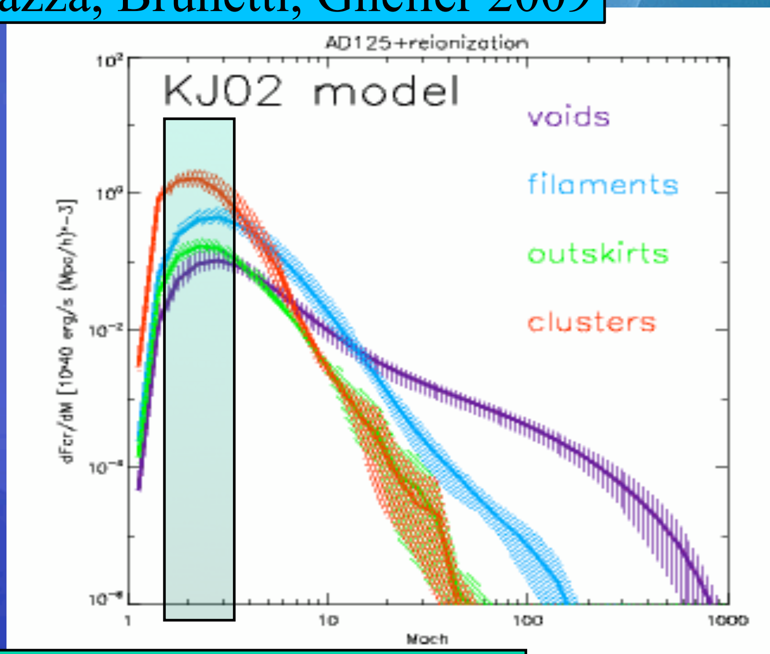
Berrington & Dermer 2003

some agreement…

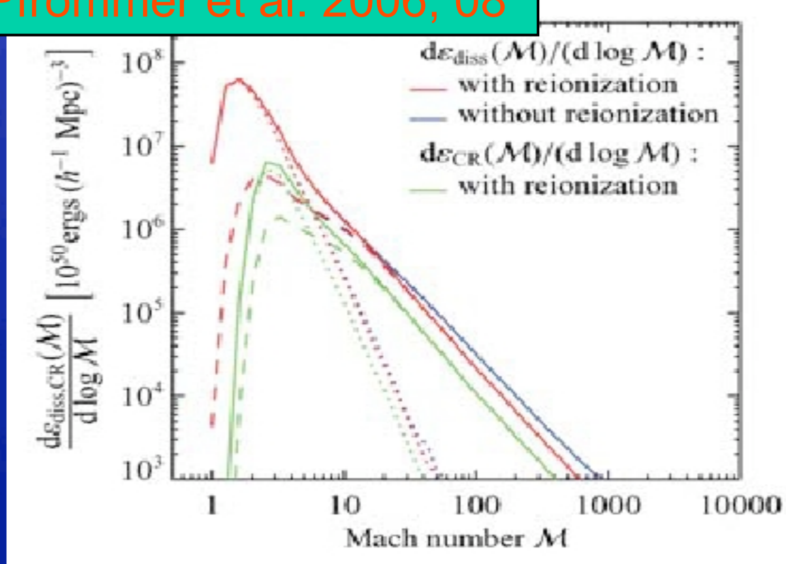


Uncertainties in CR acceleration

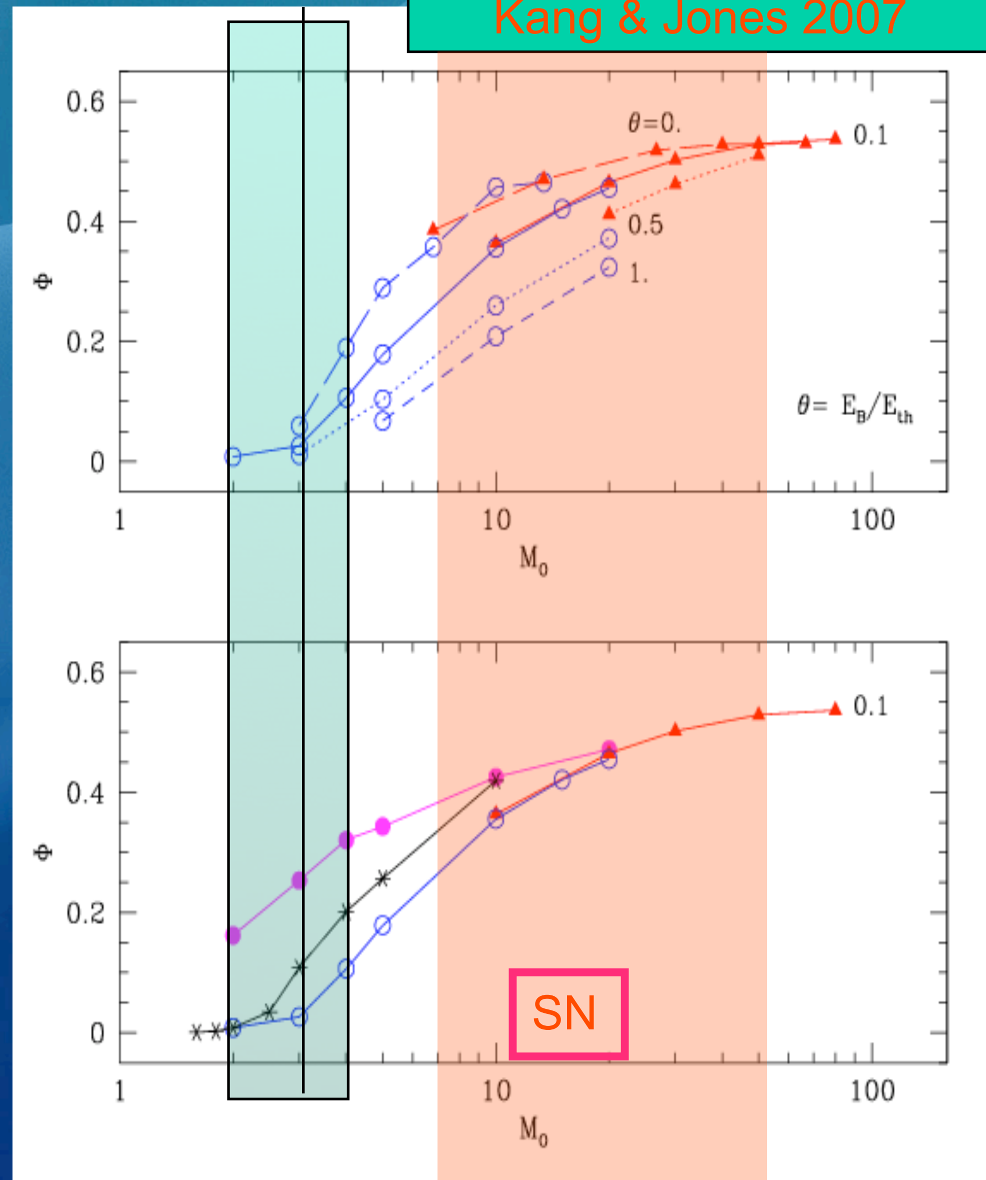
Vazza, Brunetti, Gheller 2009



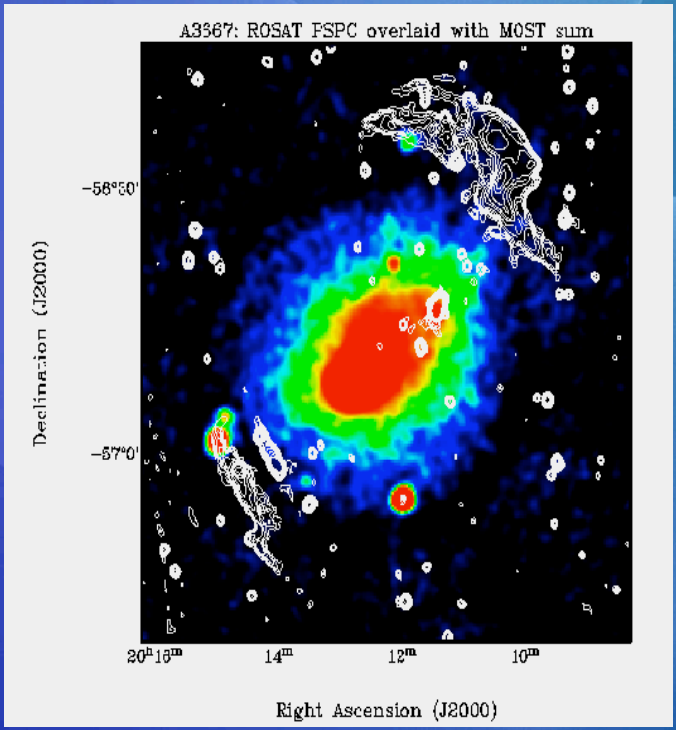
Pfrommer et al. 2006, 08

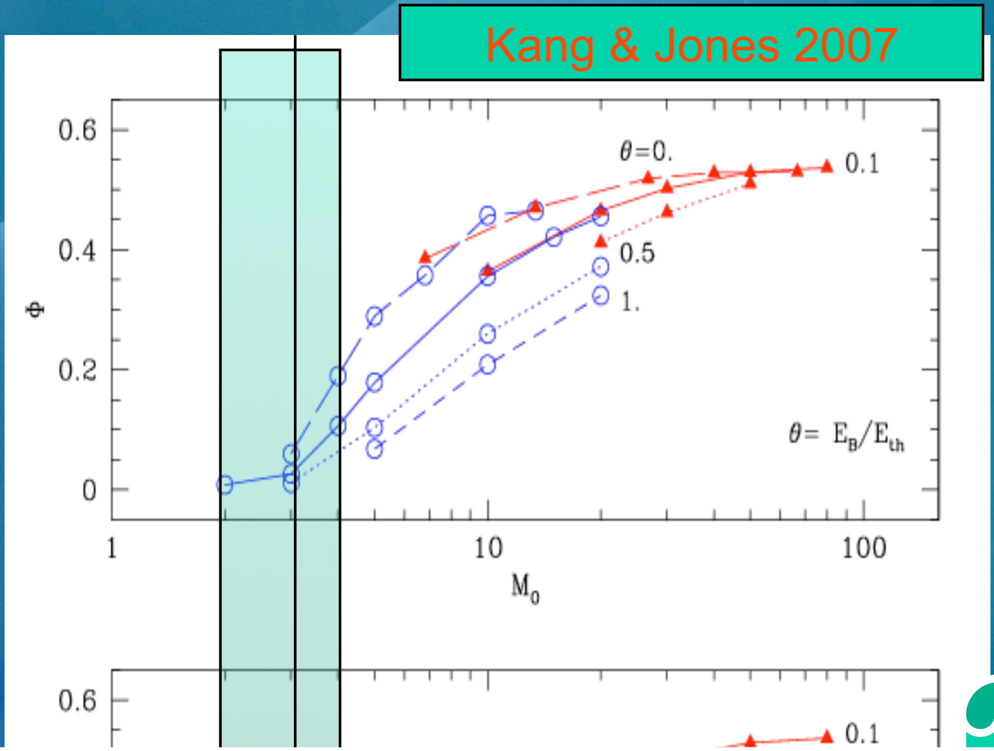


Kang & Jones 2007



CR acceleration or REacceleration?





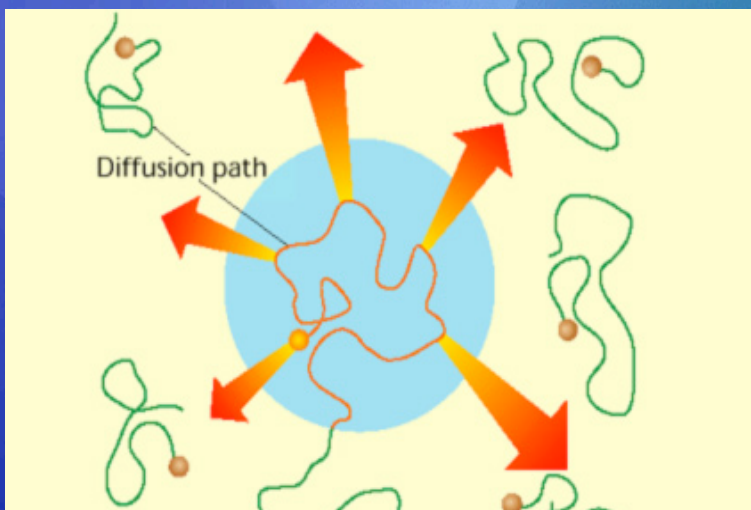
Merger shocks have M=1.5-3. Reacceleration of pre-existing relativistic electrons at these shocks is efficient (eg. Kang & Ryu 11)

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

Radio Halos as "labs" for CR acceleration in GC

$L^2 \sim D \times t$

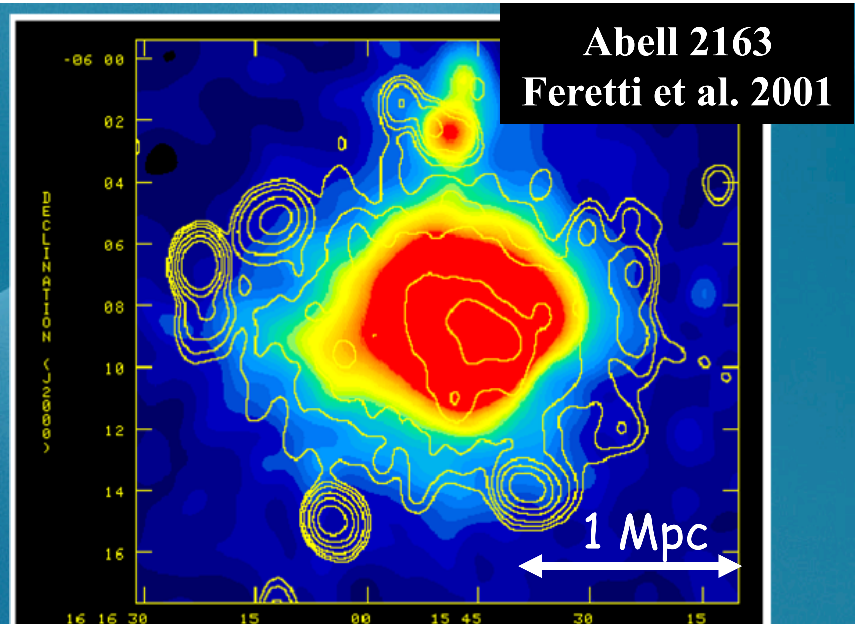
$$D(E_p) = \frac{1}{3} r_L c \frac{B^2}{\int_{1/r_L}^{\infty} dk P(k)}$$

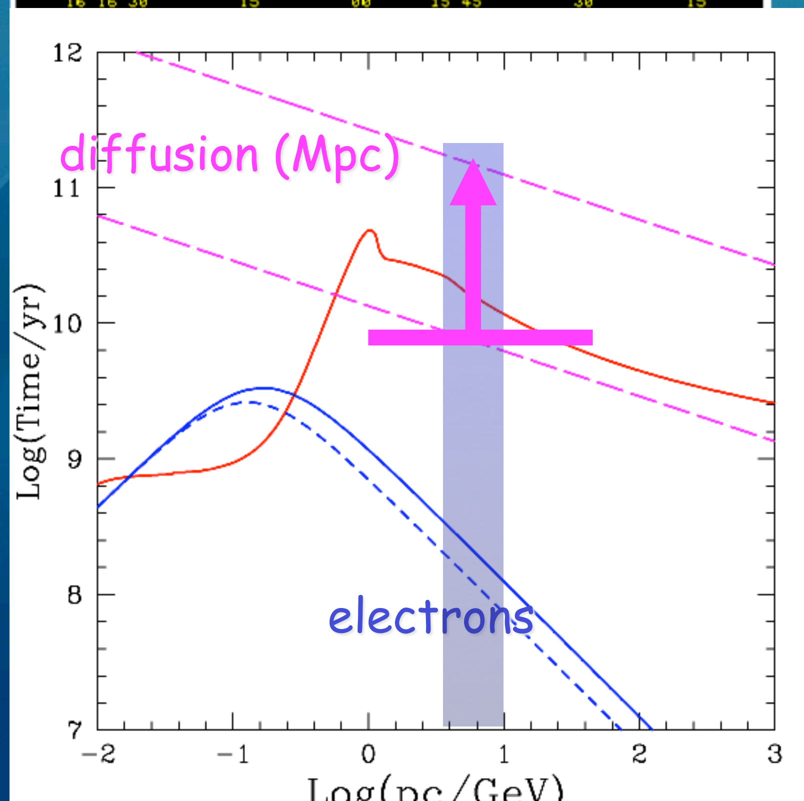


T_{diff} $(\sim 10^{10}$ yr$)$ >> T_{cool} $(\sim 10^{8}$ yr$)$

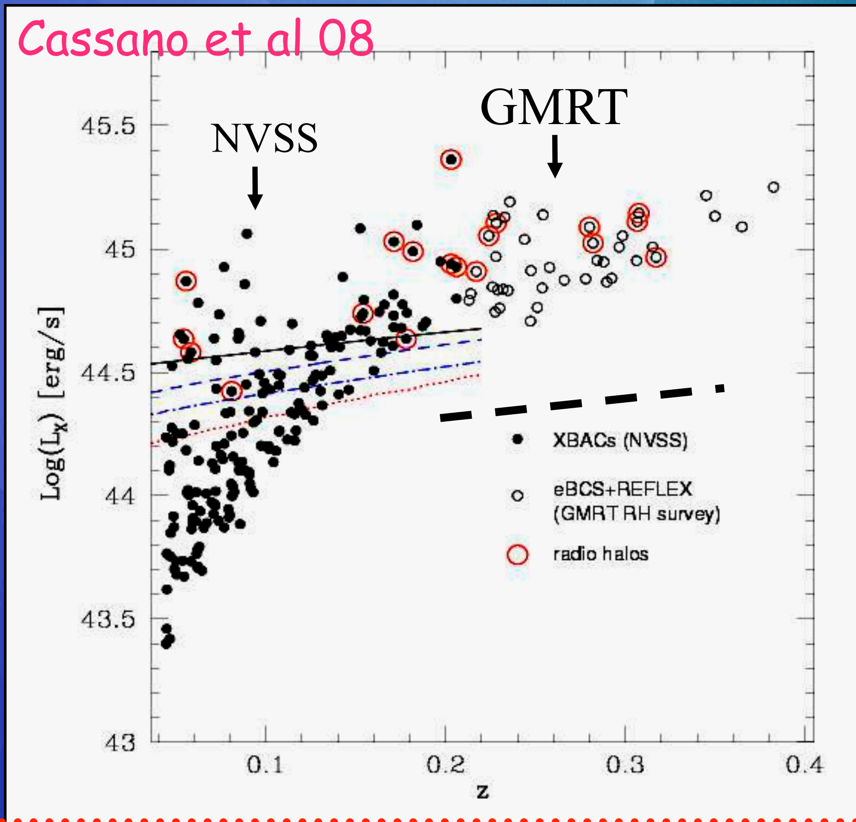
(eg. Jaffe 1977)

"in situ" (re)acceleration or injection of CR electrons ...





Statistics of Radio Halos

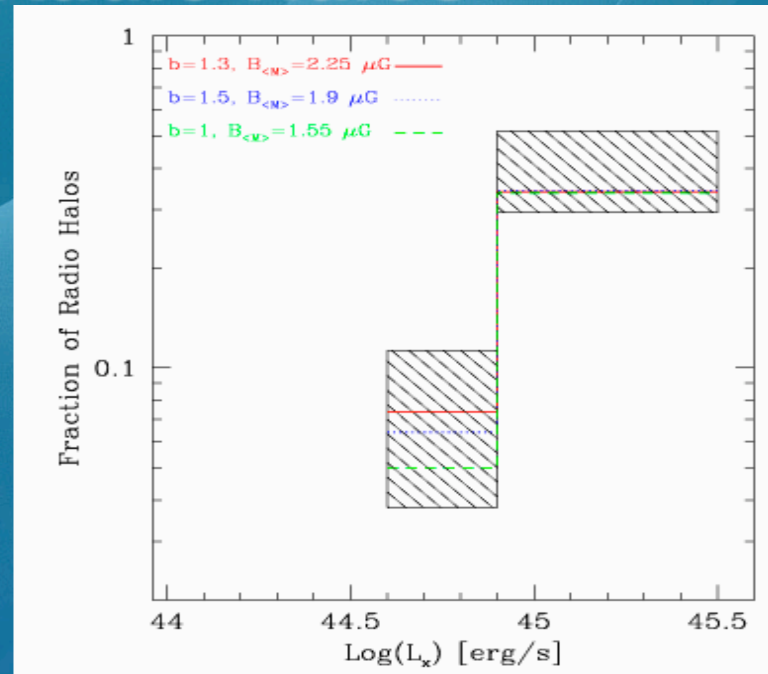


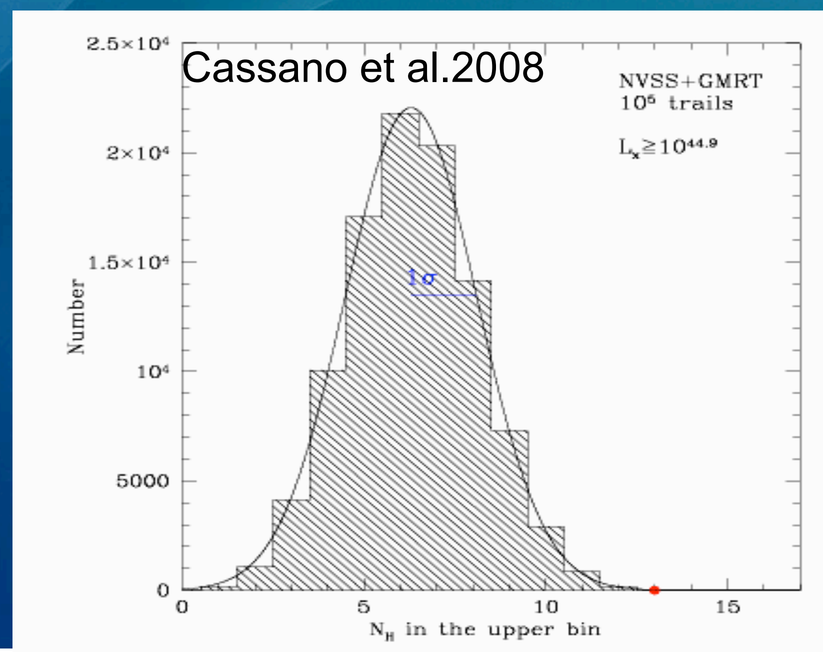
NVSS data (from *Giovannini et al. 1999)*
and deep **GMRT observations.**

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

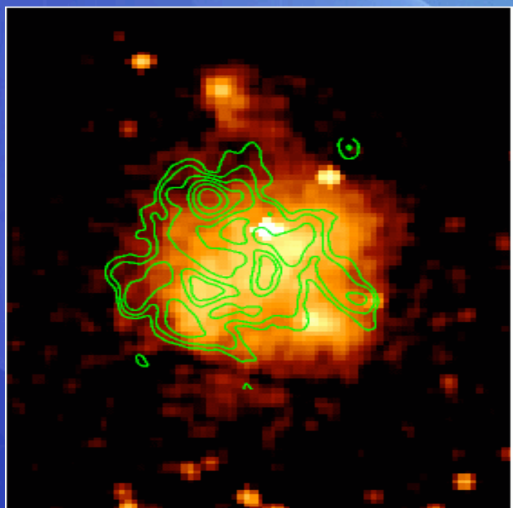
0.08±0.04 for $L_x < 10^{44.9}$ erg/s ≈ 1/10

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

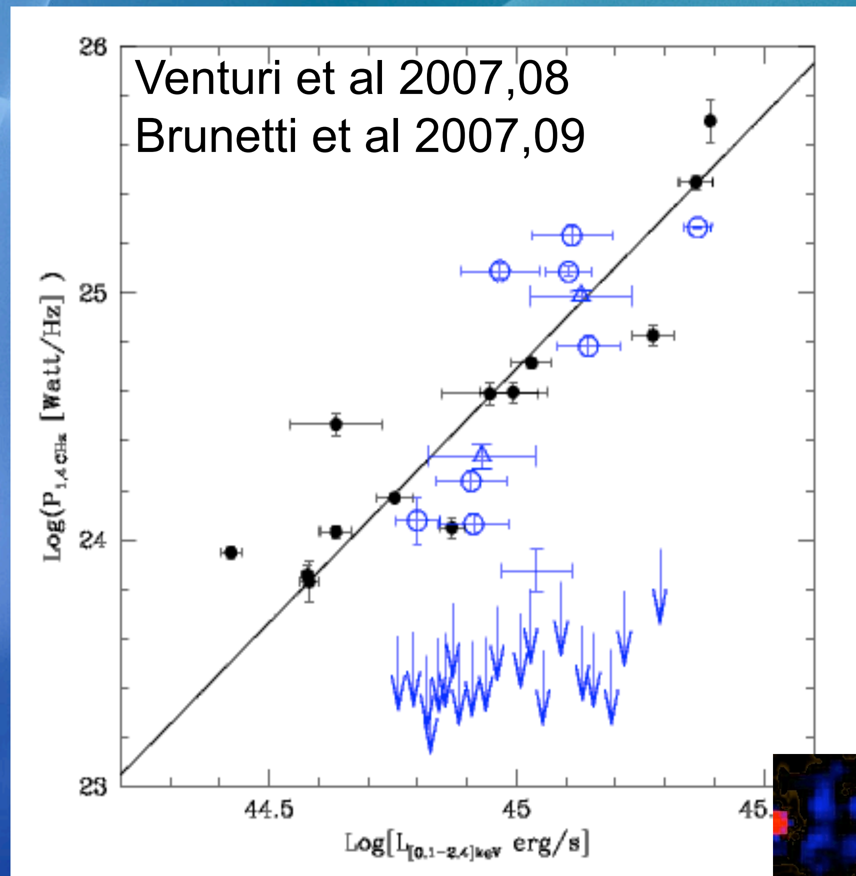




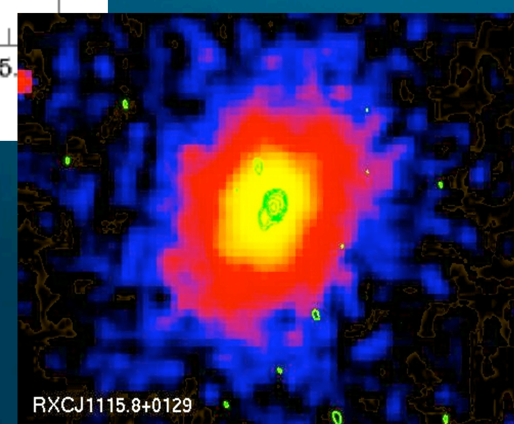
The radio bimodality of galaxy clusters



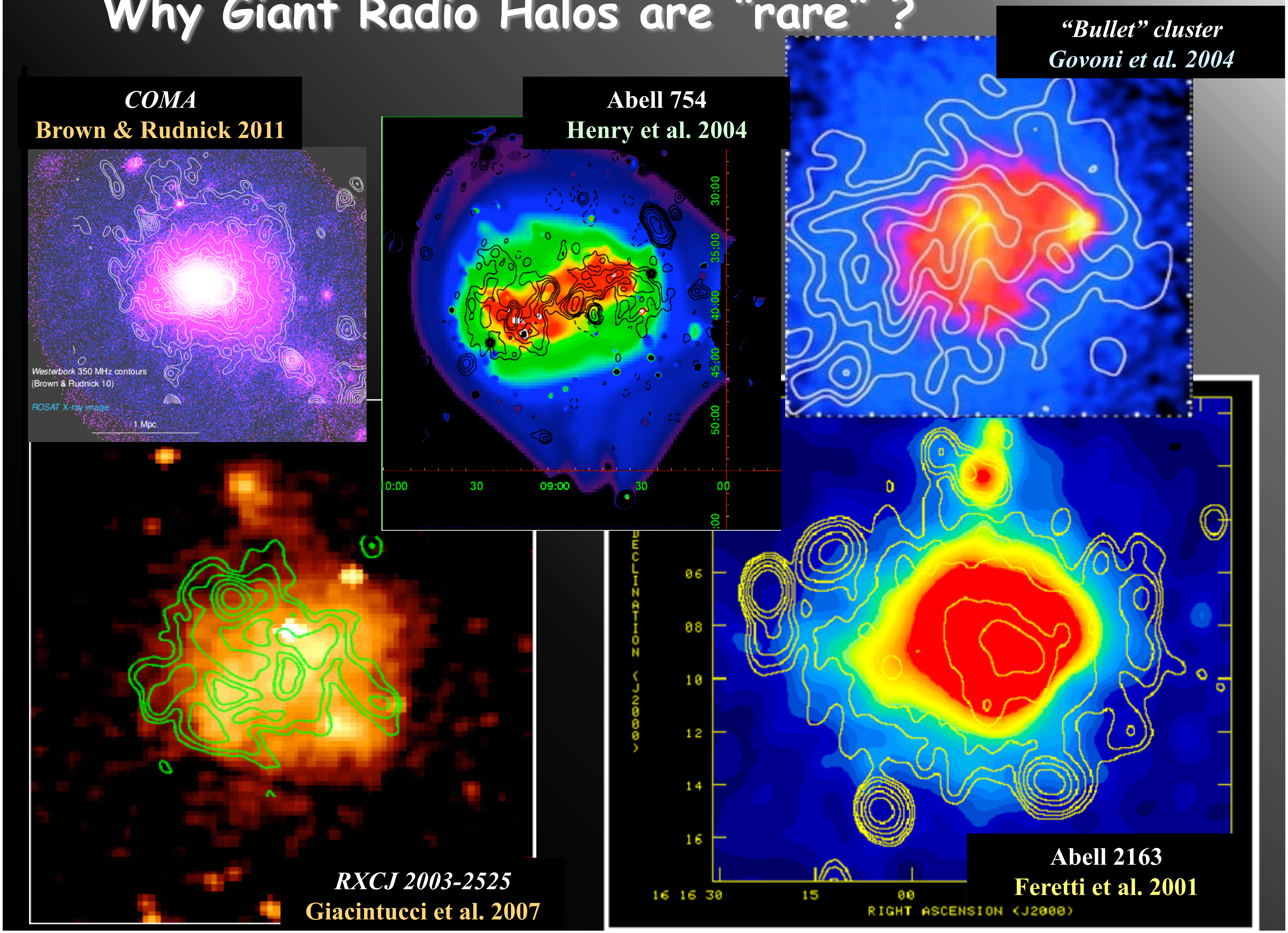
Synchrotron Luminosity



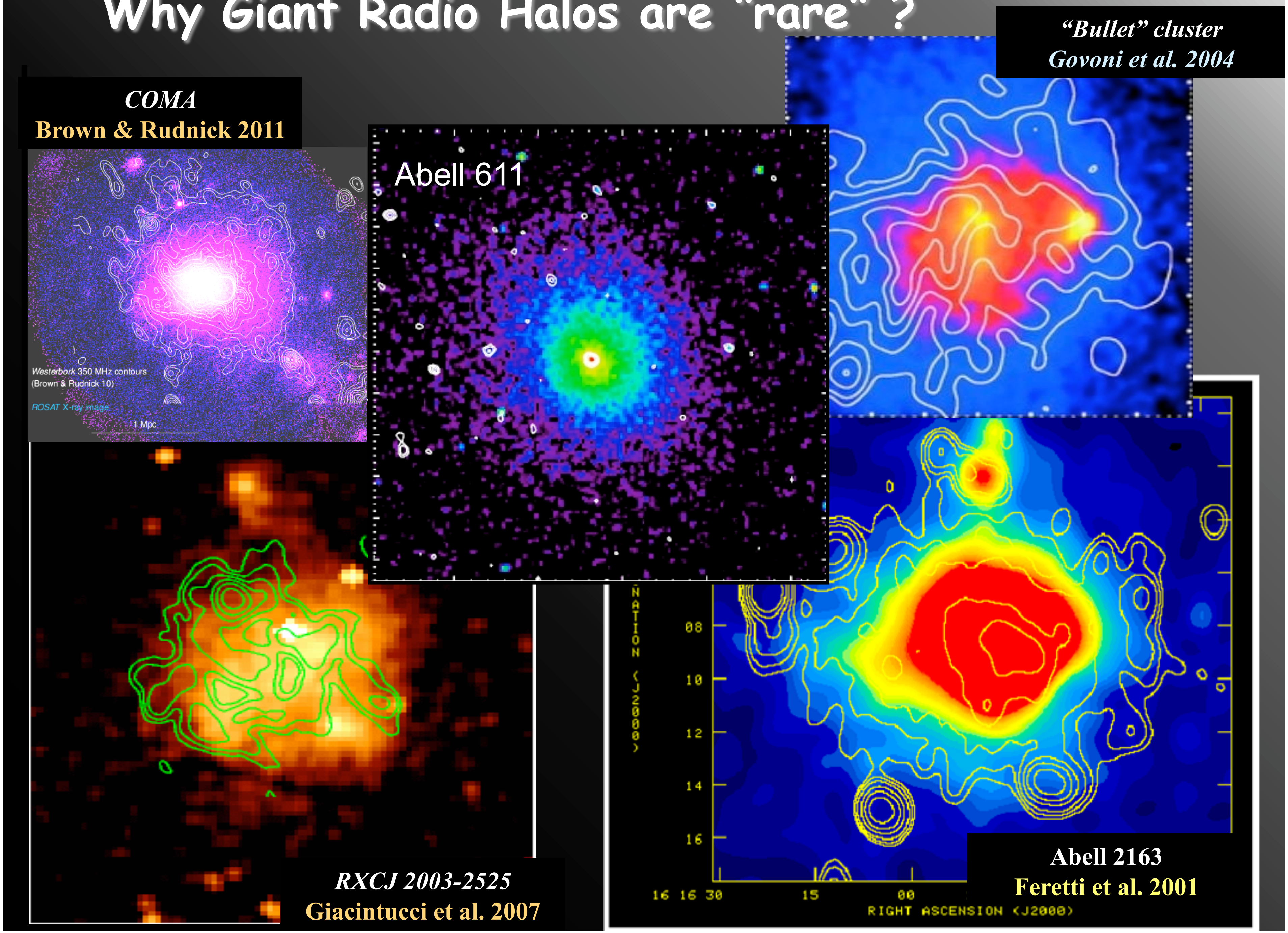
Thermal X-ray Luminosity



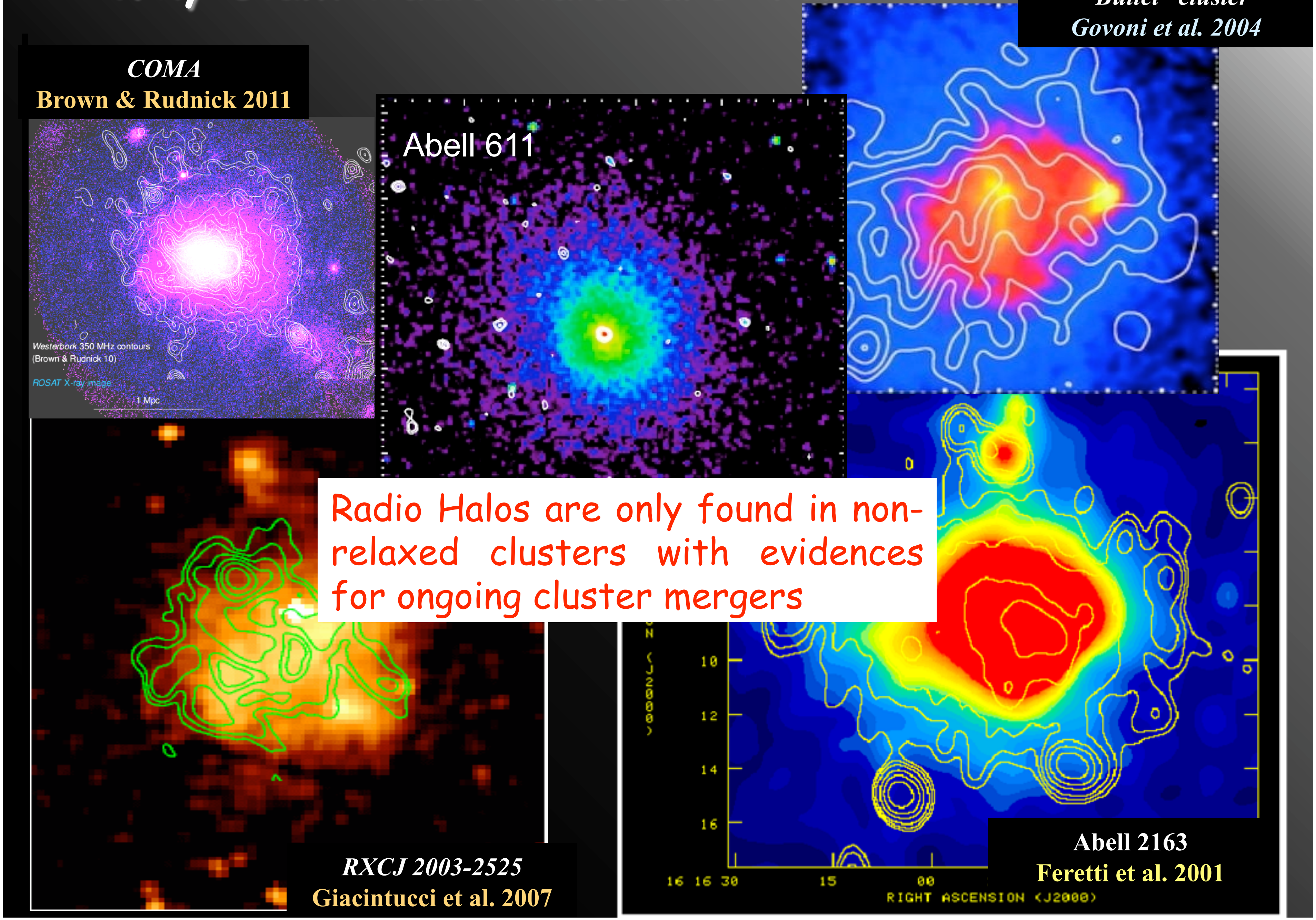
Why Giant Radio Halos are “rare” ?



Why Giant Radio Halos are "rare" ?

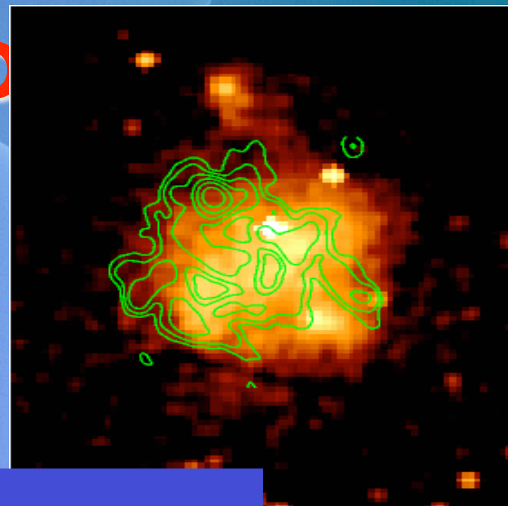


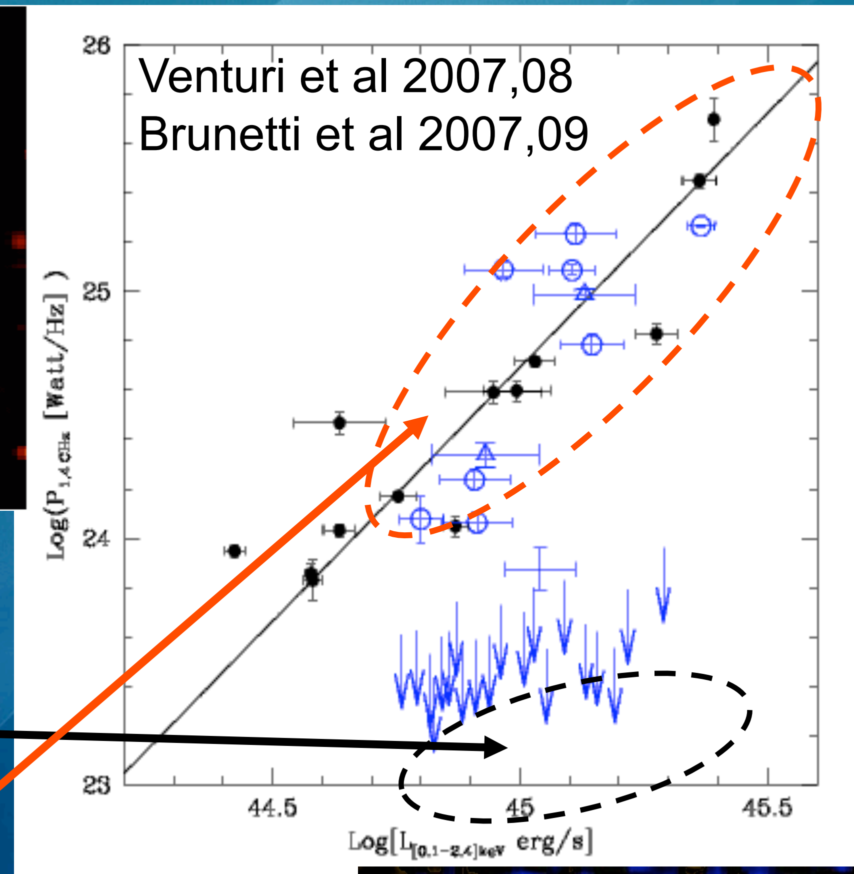
Why Giant Radio Halos are "rare" ?



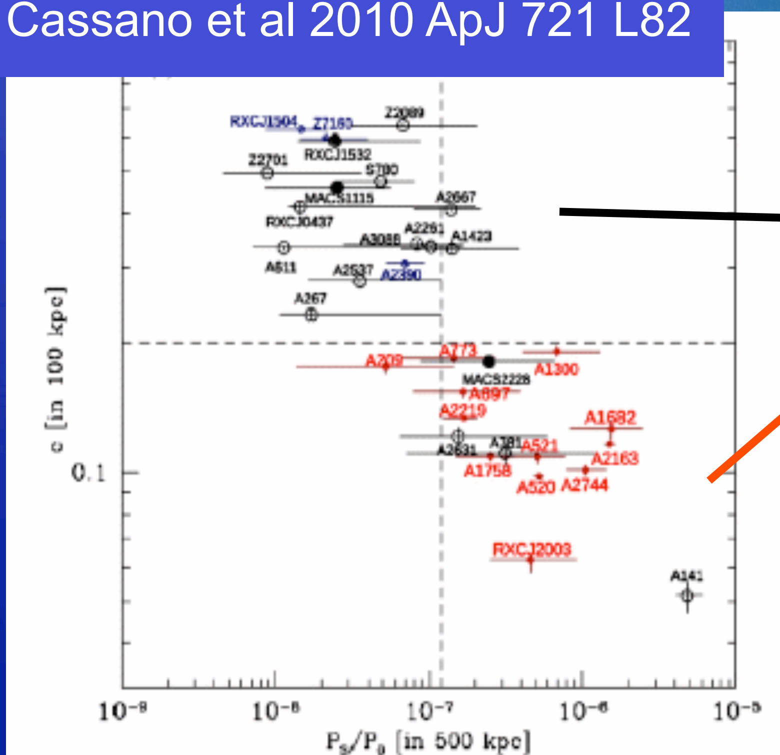
Radio Halos are only found in non-relaxed clusters with evidences for ongoing cluster mergers

Cluster mergers - radio halos connectio

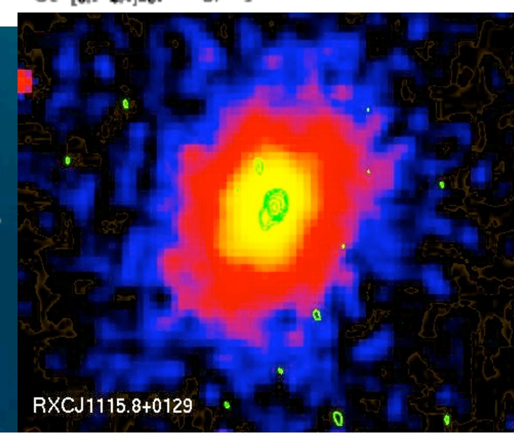




Cassano et al 2010 ApJ 721 L82



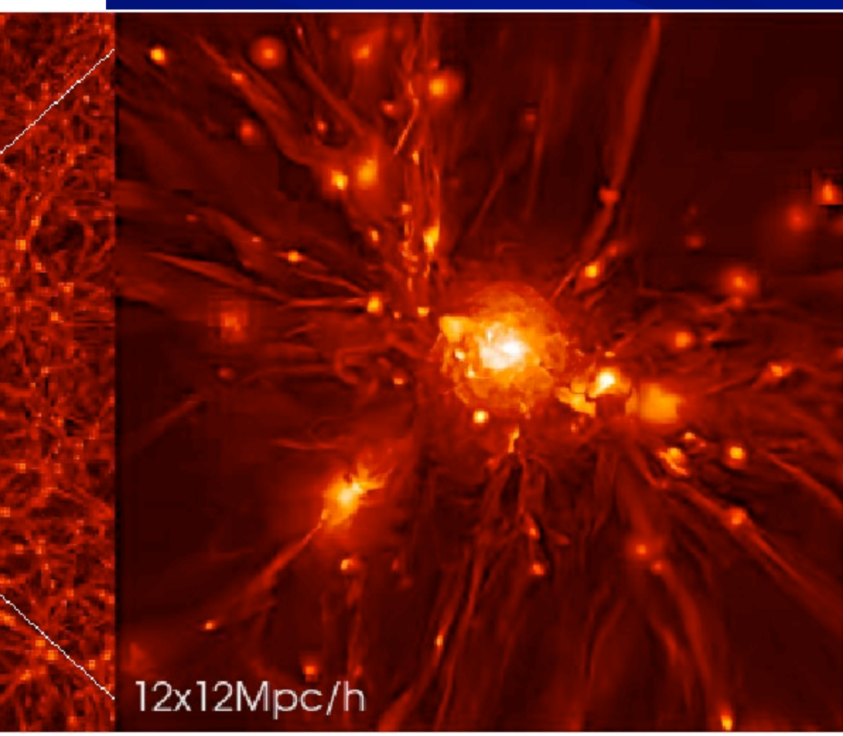
The radio bimodality has a correspondence in terms of dynamical segregation



Merger-Energy Budget

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

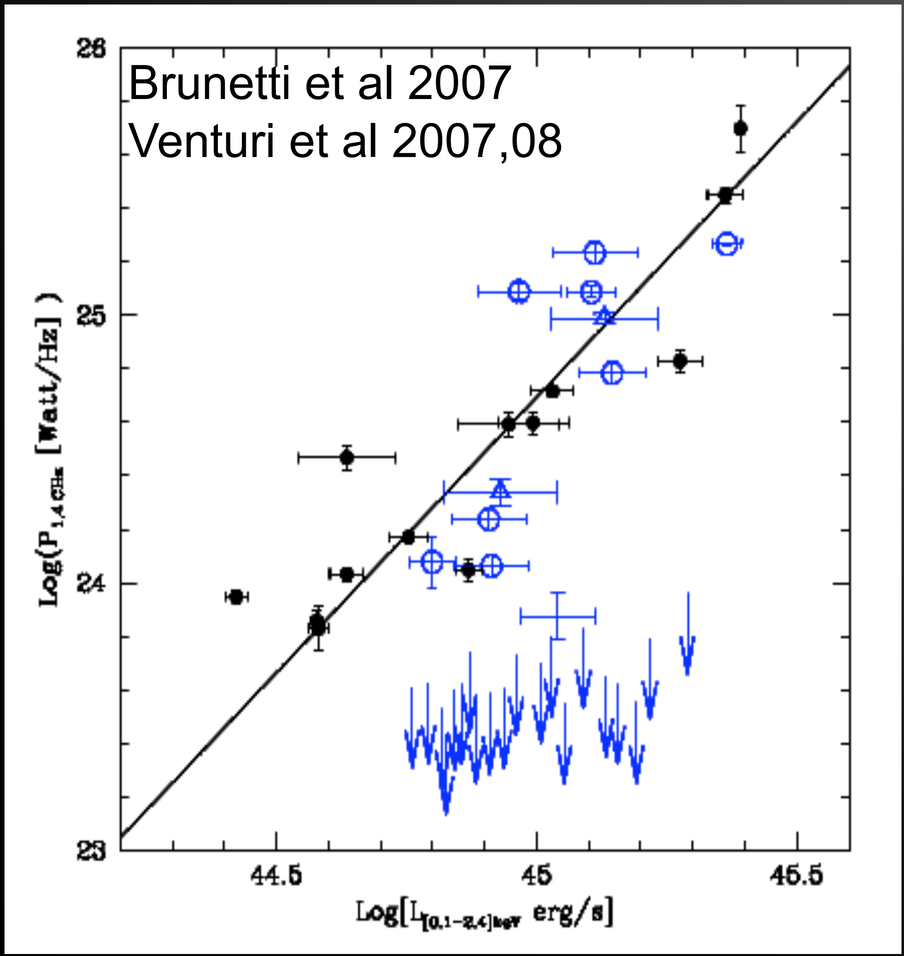
$$\tau_{cross} \longrightarrow 10^{9}\,\mathrm{yrs}$$

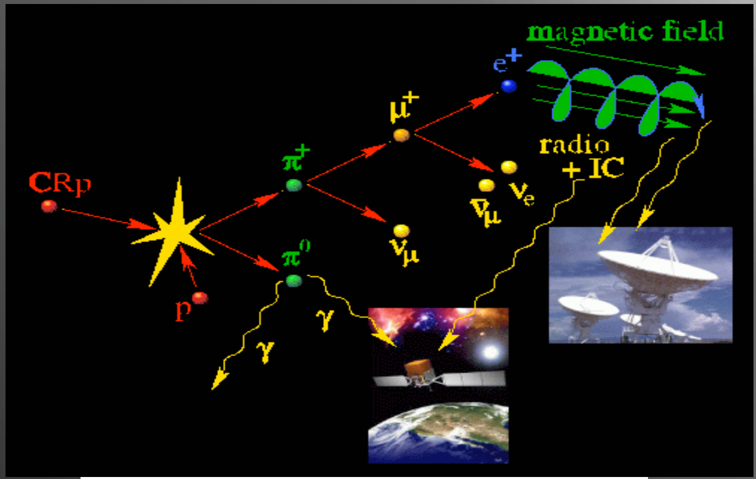


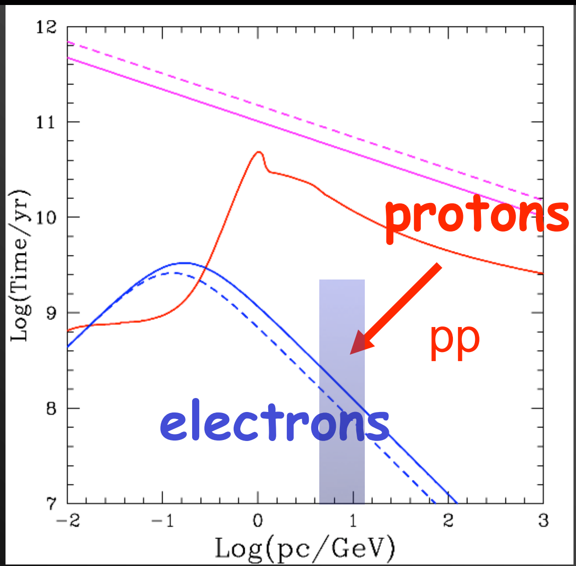
How to extract non-thermal energy?

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

Implications of radio bimodality







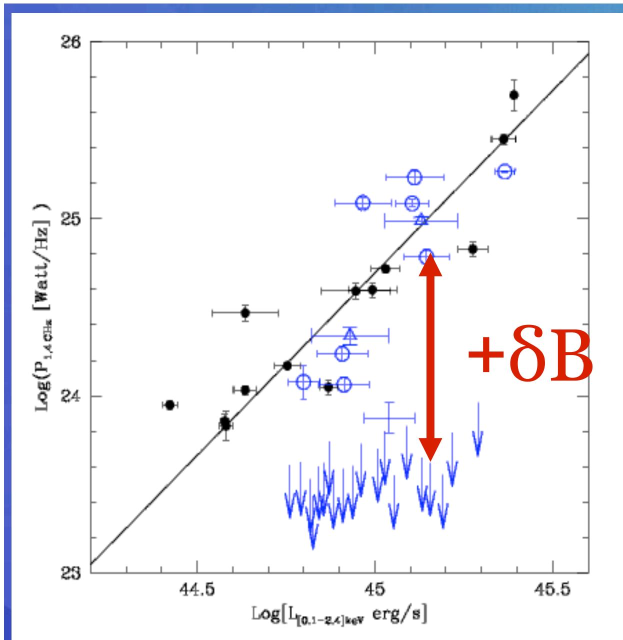
Hadronic models (eg Dennison 1980, Blasi & Colafrancesco 1999, Pfrommer & Enslin 2004)

"all" clusters with Radio Halos, unless B is amplified in clusters with Radio Halos (mergers) (eg Kushnir et al 09, Keshet & Loeb 10)

(or CRp stream out/in clusters, Ensslin et al 2011 ..)

"RM" analysis do not show magnetic bimodality

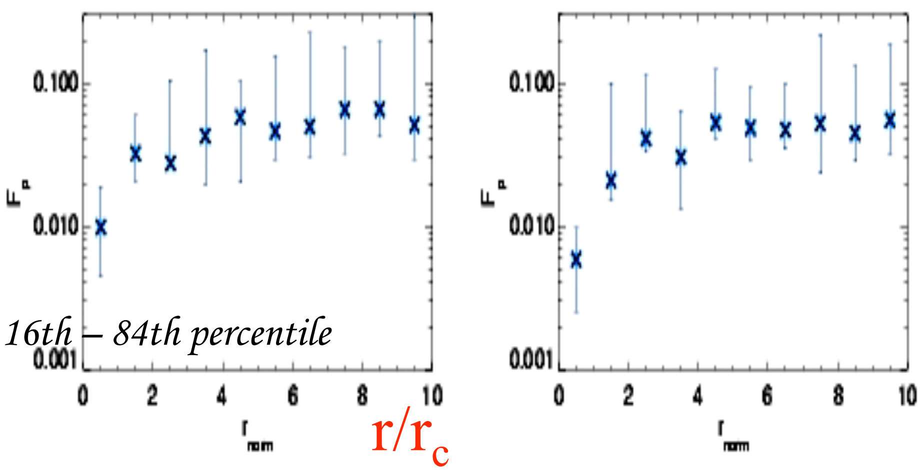
Govoni et al 2010 AA 522, 105



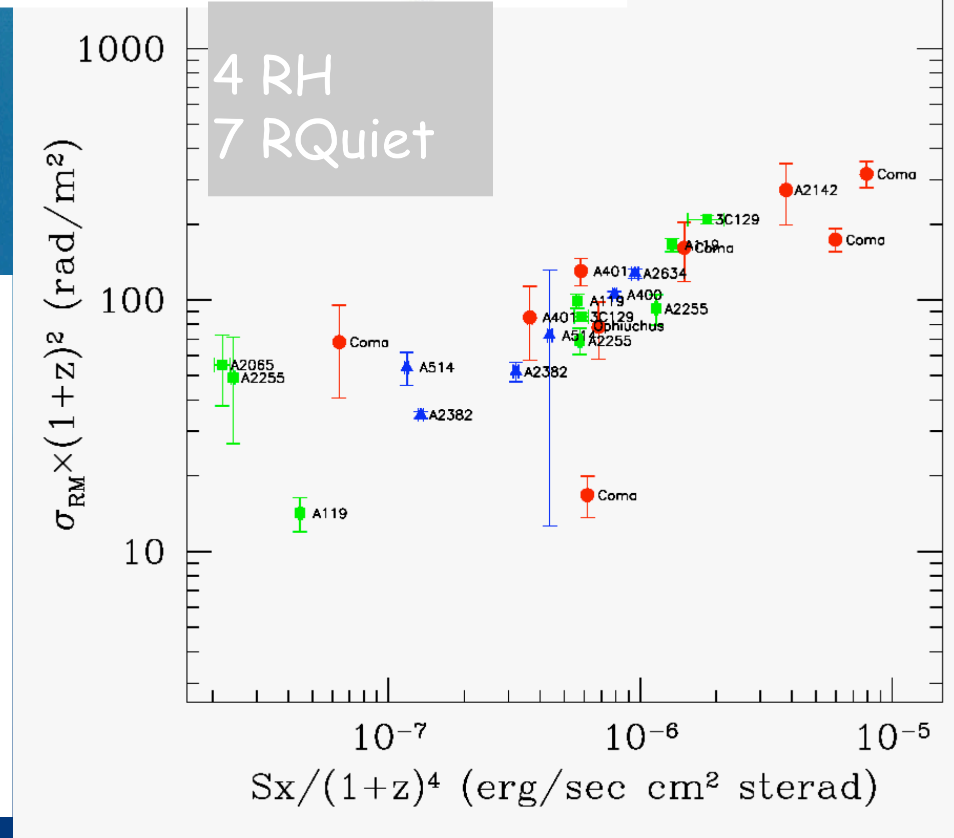
Bonafede +al 2011

Radio Halos

Non Halos

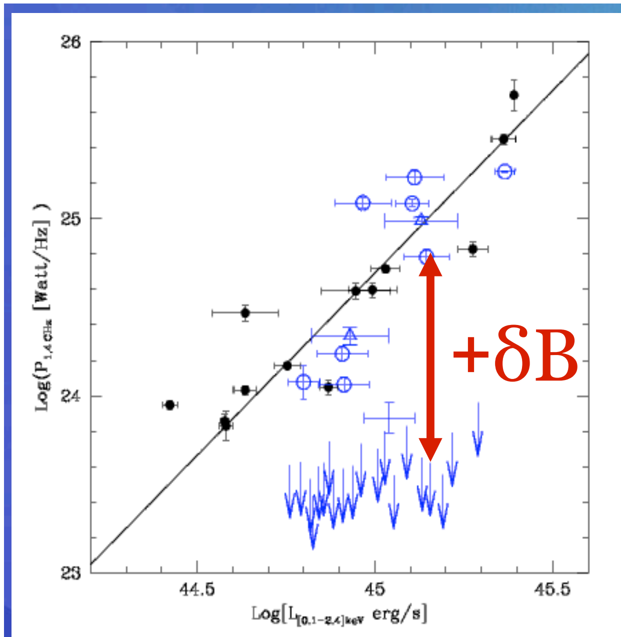


$$\sigma^2_{\rm RM} = \langle {\rm RM}^2 \rangle = 812^2 \Lambda_c \int (n_e B_{\|})^2 dl.$$

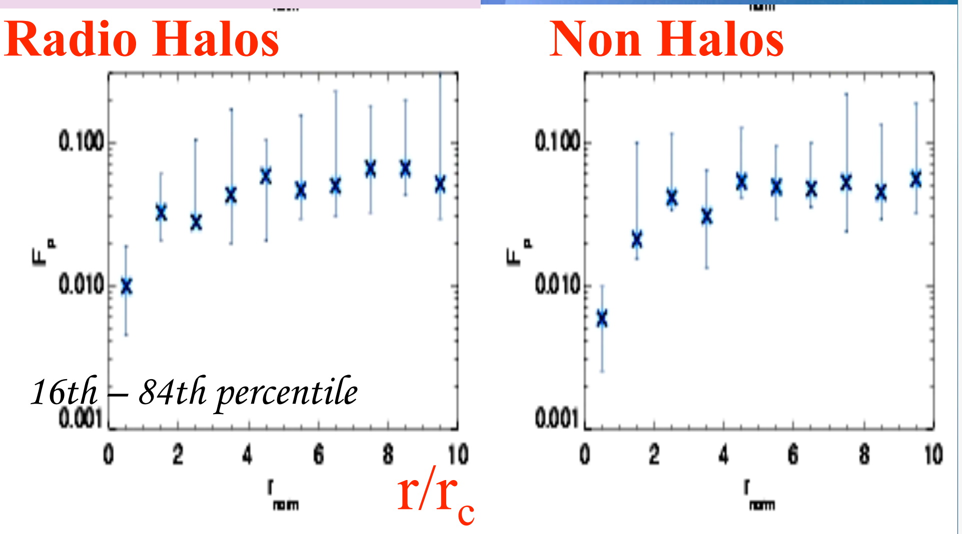


HIFLUGCS + NVSS … 33 clusters
at z = 0.023-0.2..

"RM" analysis do not show magnetic bimodality



Bonafede +al 2011



Govoni et al 2010 AA 522, 105

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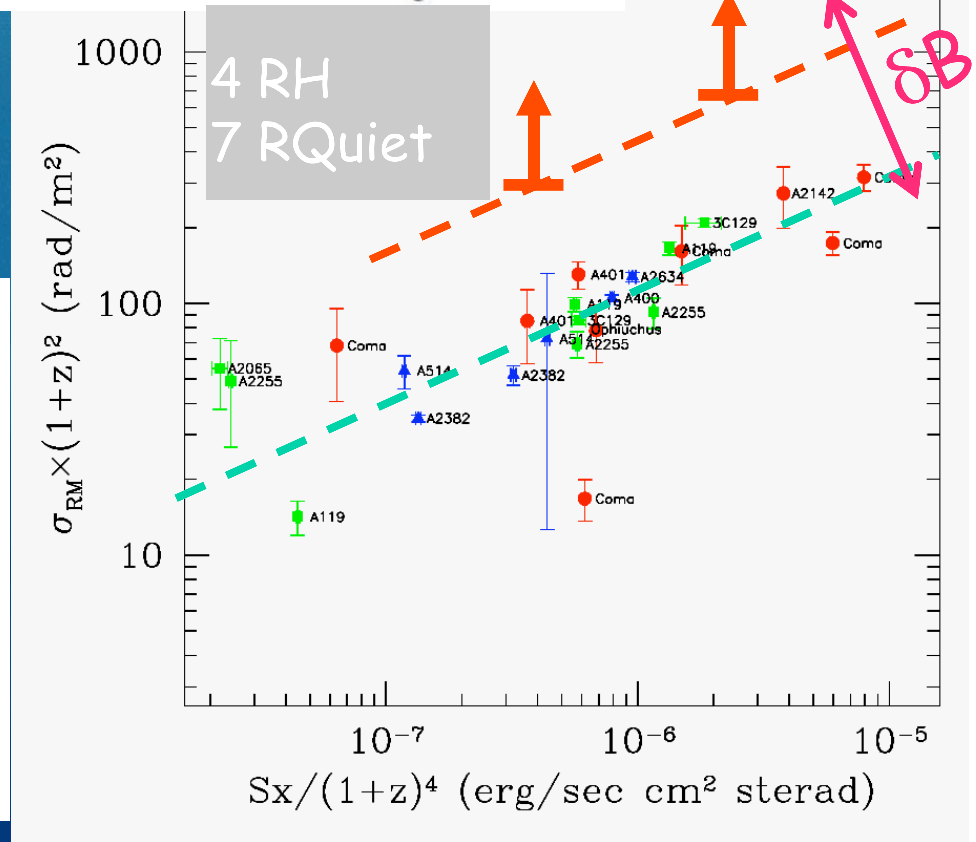

HIFLUGCS + NVSS … 33 clusters
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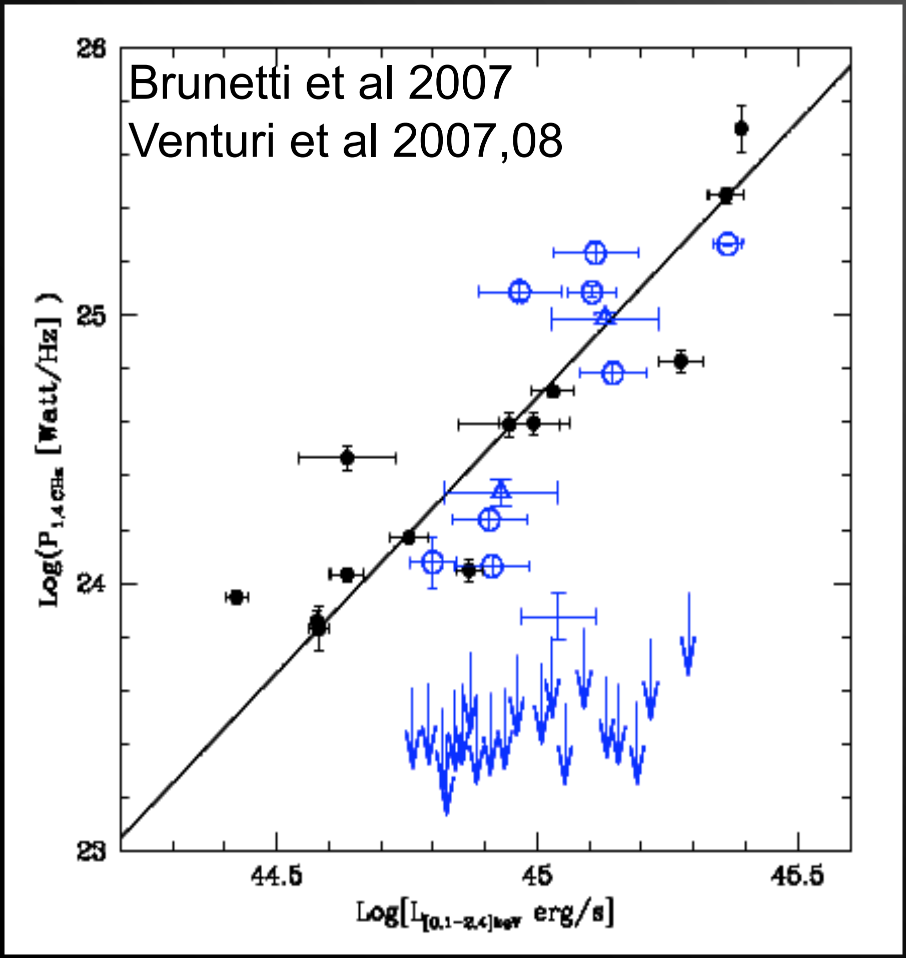
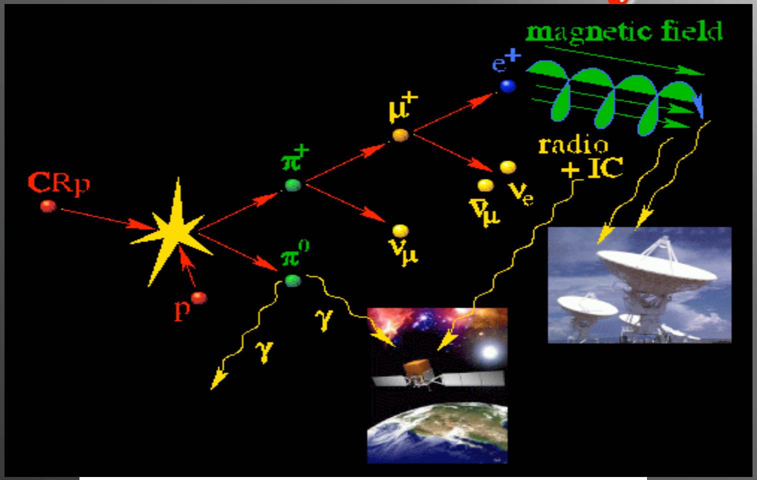
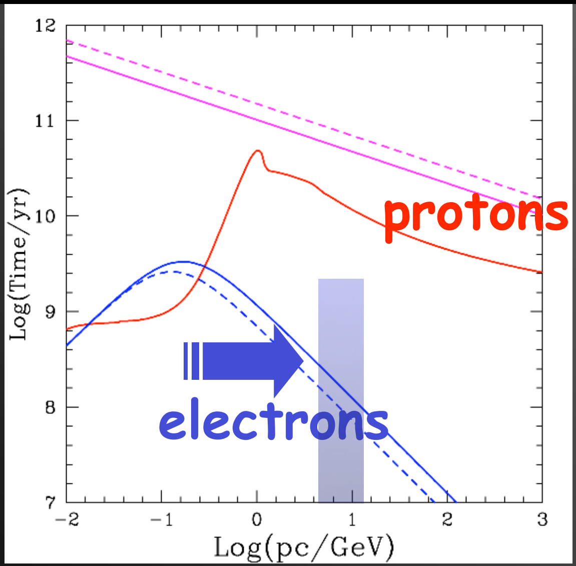
Implications of radio bimodality





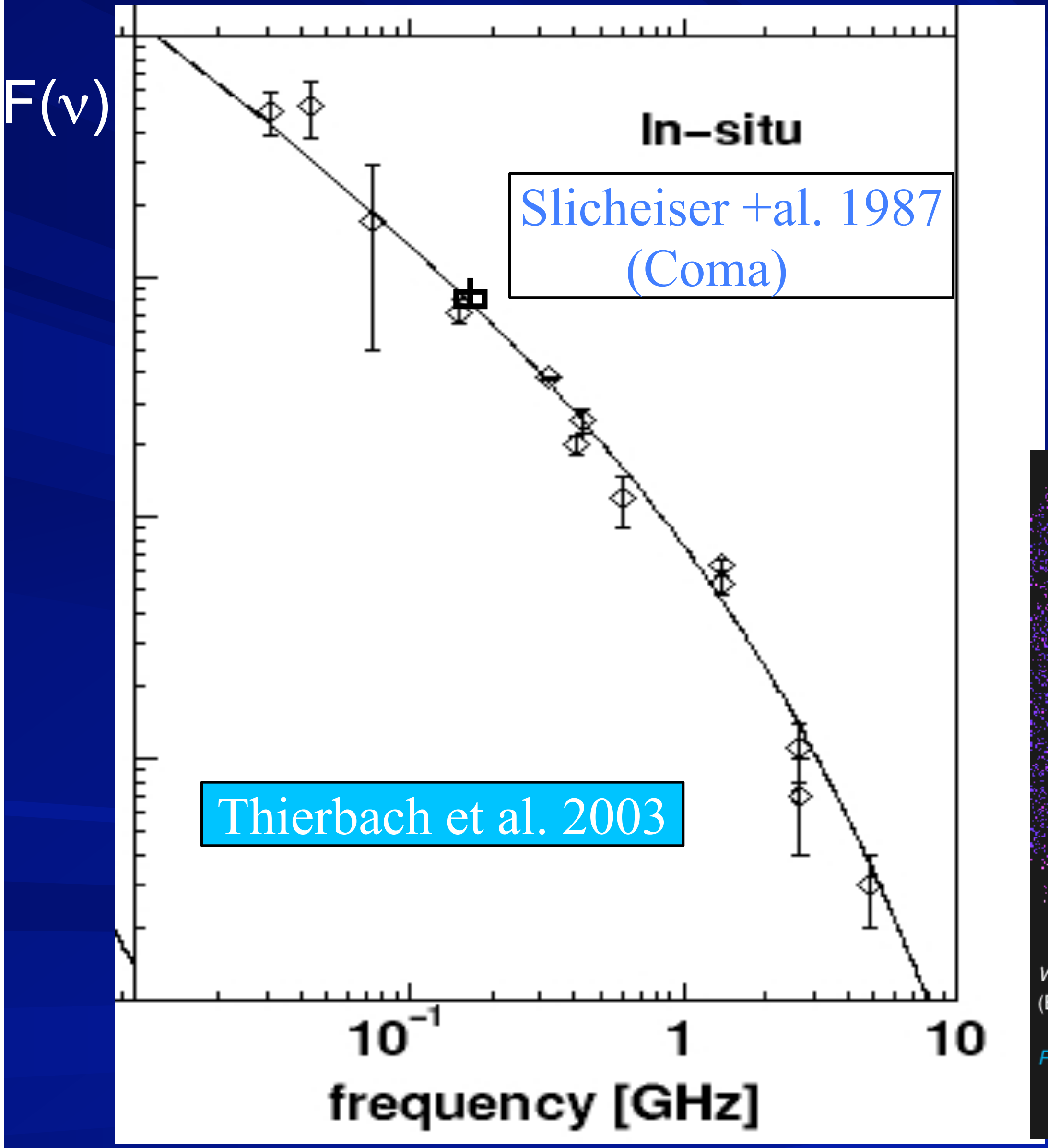


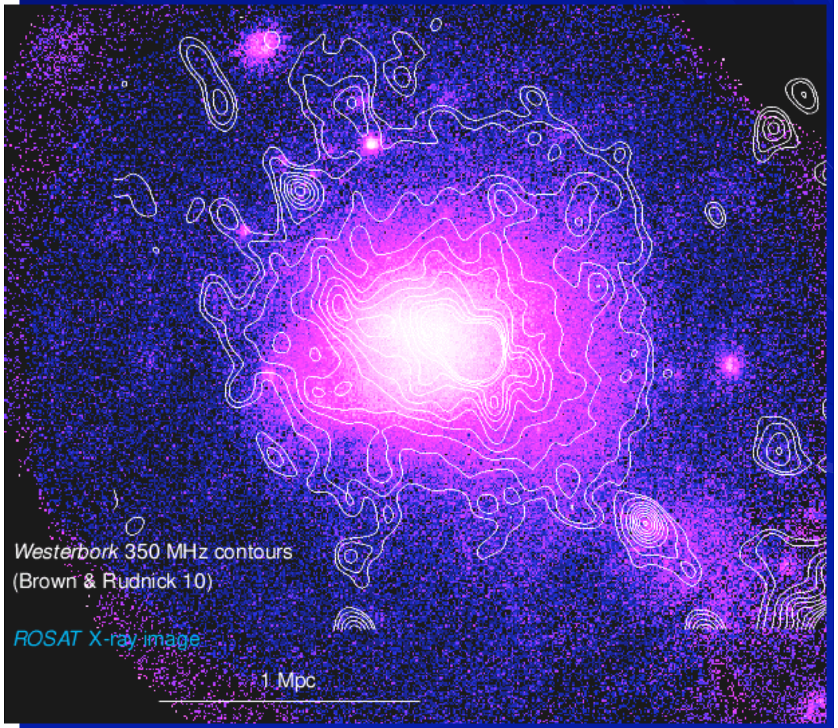
REacceleration models (eg Brunetti et al 01, Petrosian 01, …)

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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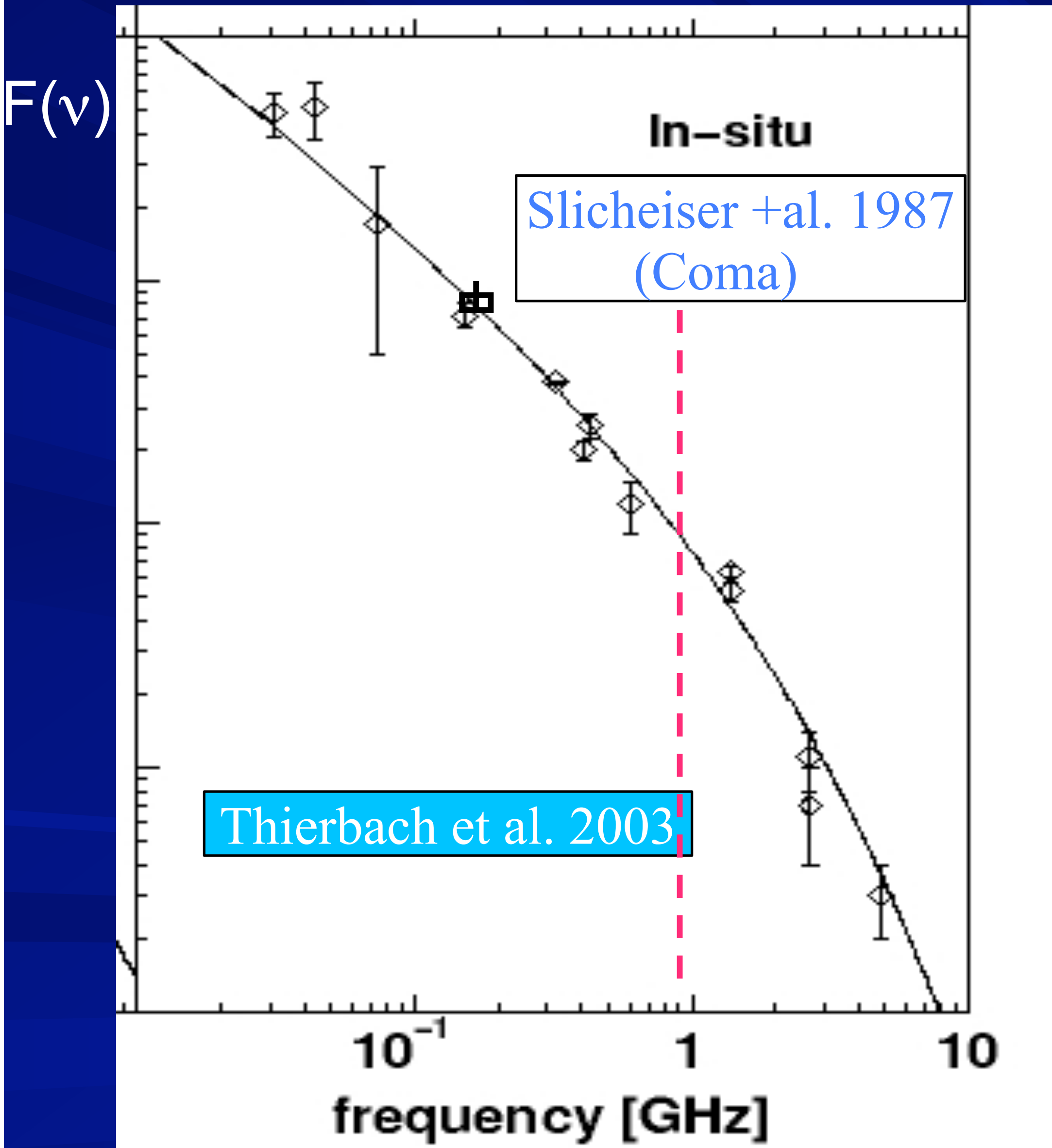
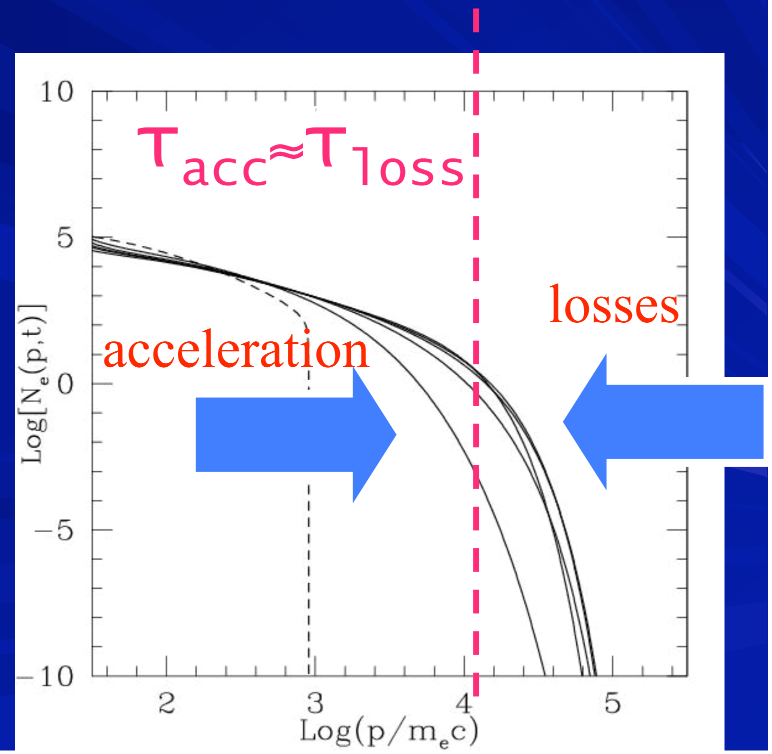


Evidence of break in the spectrum of the emitting electrons at energies of few GeV



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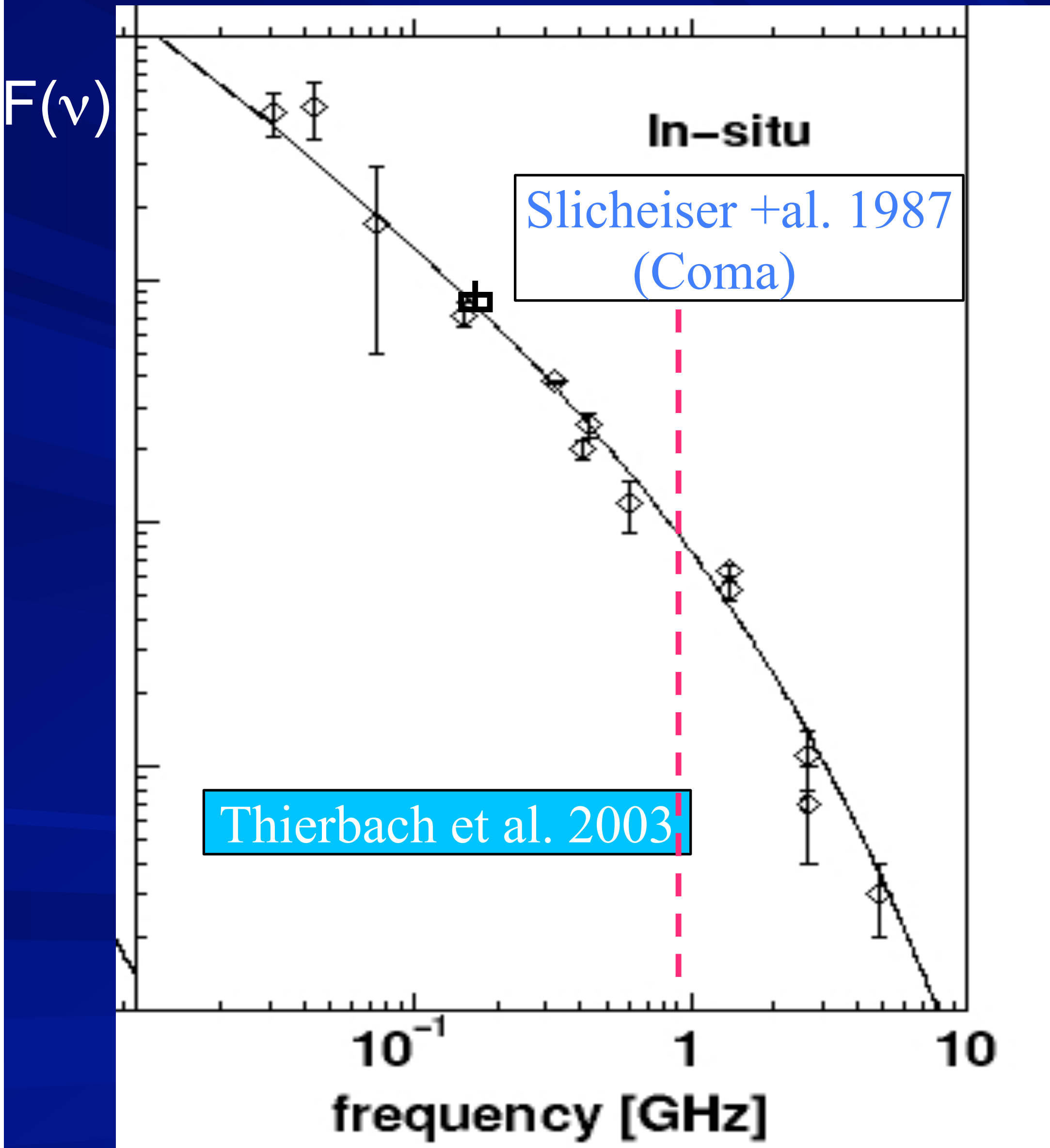
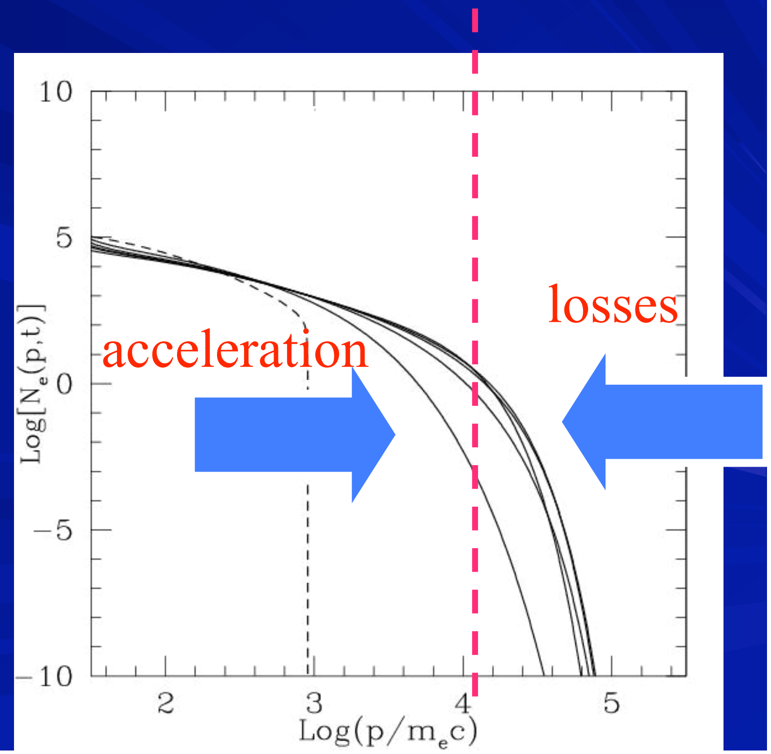


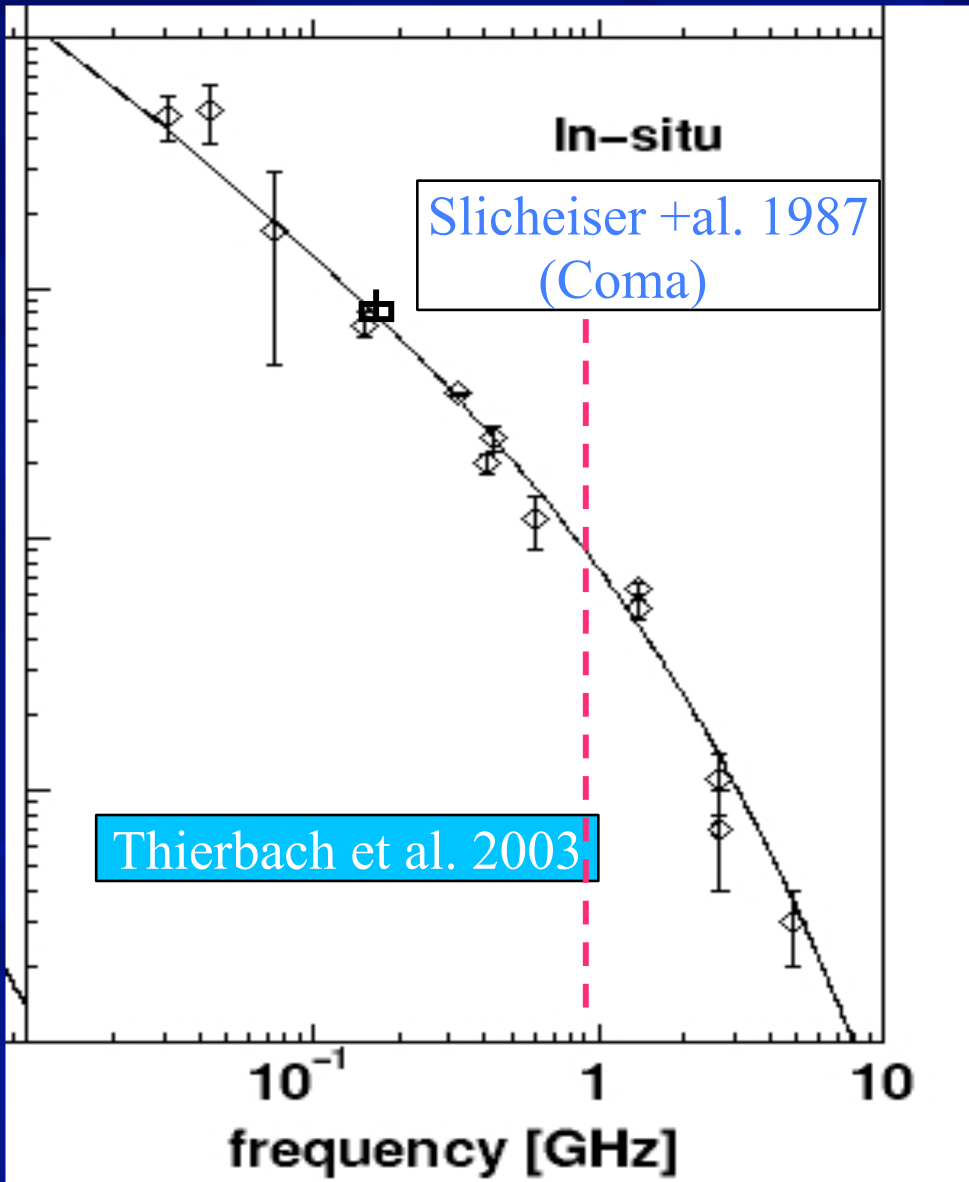
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm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

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



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

F(ν)



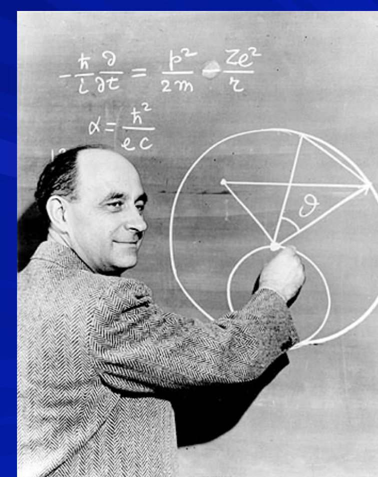
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm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

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

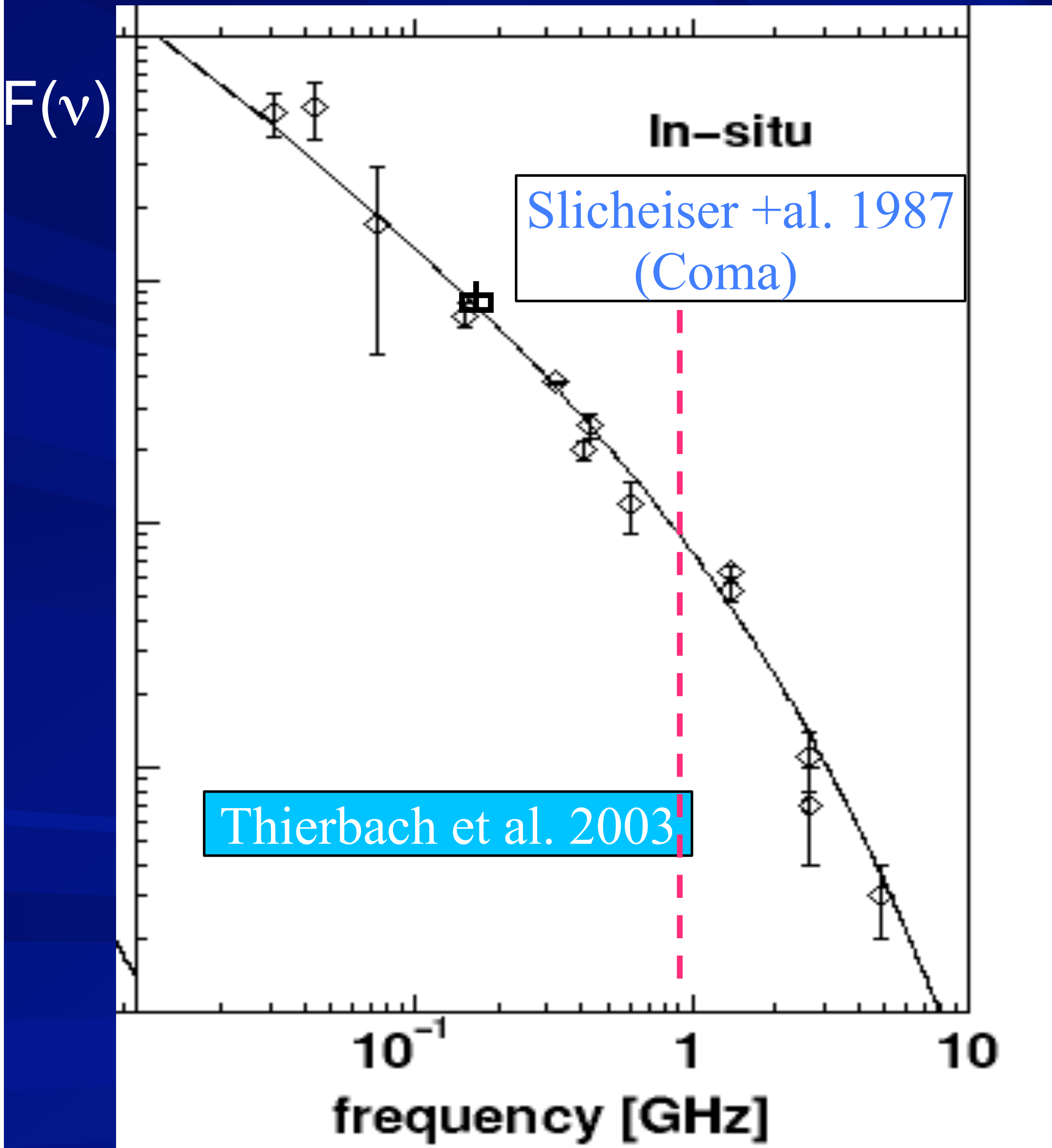
eg., “classical” Fermi II

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

> 10^7yrs



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



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

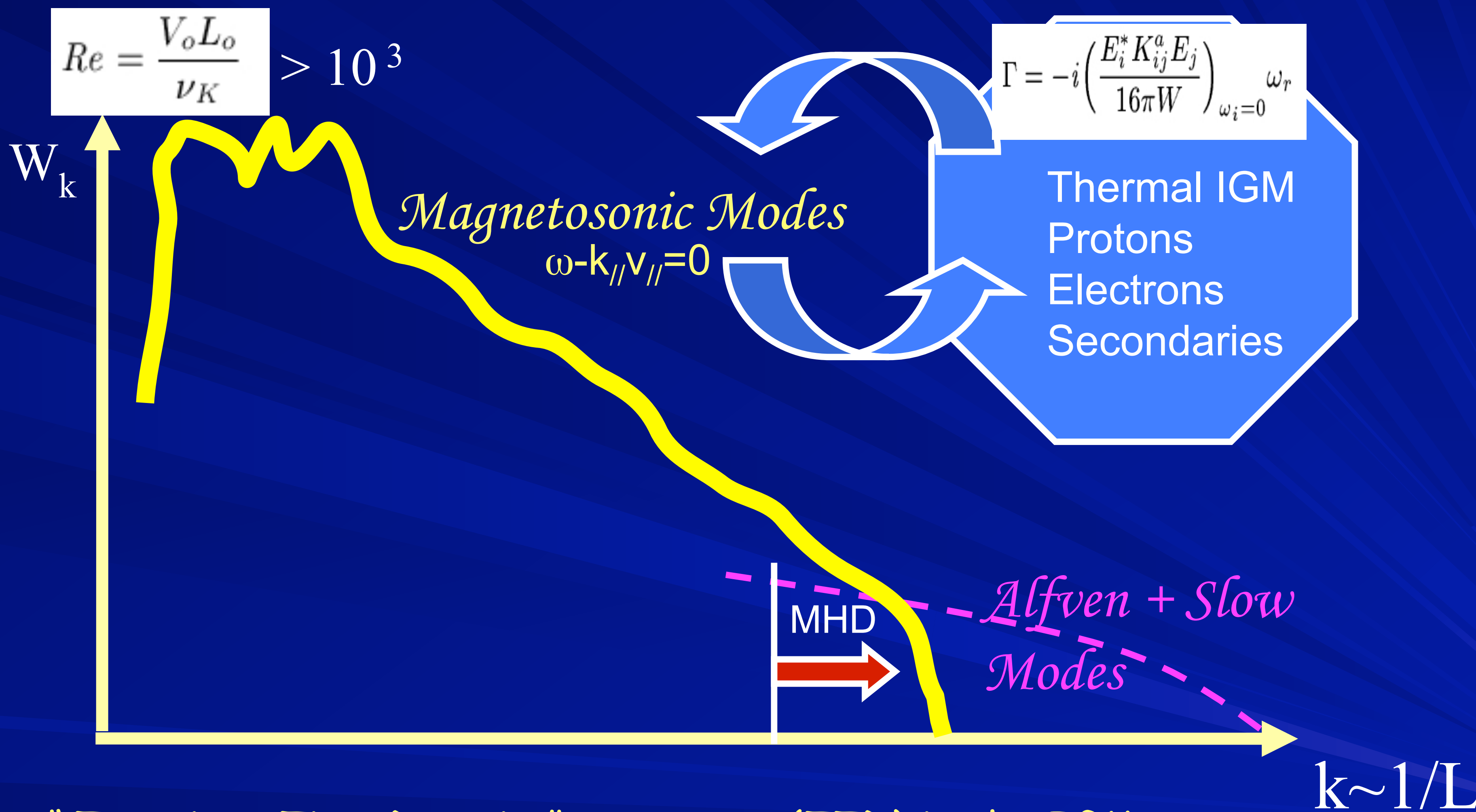
Acceleration time-scale $\approx 10^8$ years

Which is the fraction of turbulent energy that goes into CR accel ??

Properties and energy density of MHD turbulence in galaxy clusters ?

This mechanism is potentially efficient enough ...
(eg. Fujita et al 03, Cassano & Brunetti 05, Brunetti & Lazarian 07,11)

CRp/e (re)acceleration by turbulence



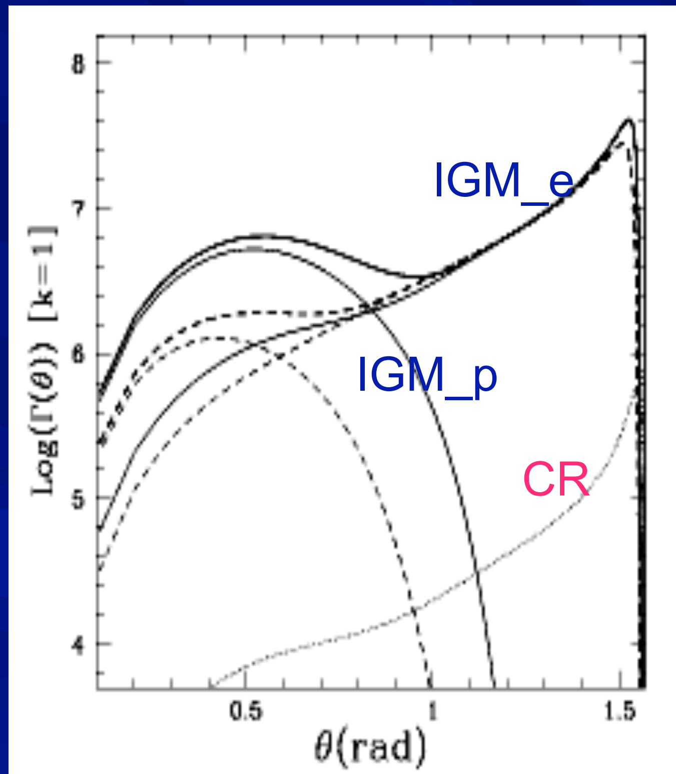
"*Transient Time Damping*" resonance (TTD) in the IGM
(Cassano & Brunetti 2005, Brunetti & Lazarian 2007, 2011a)

Dissipation of turbulence in the ICM

(from Brunetti & Lazarian 2007)

QLTheory

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



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

At least if the turbulence interacts with IGM in a collisionless way …

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

$□_{bb}(k)^{-1} \sim V_{lA} / l_A$ $\quad$ $□_d^{-1} = \Gamma(k)$

Isotropic Effective Damping

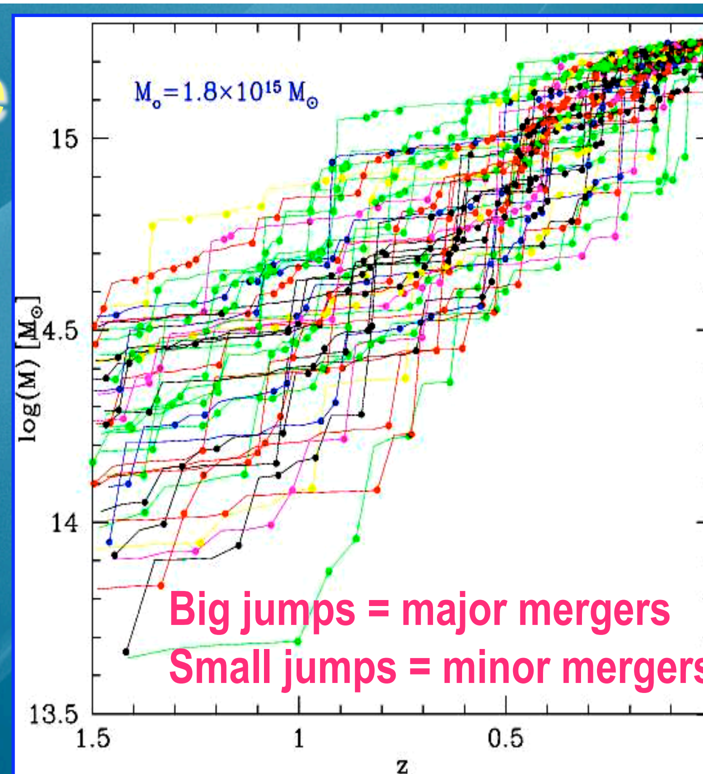
$$l_{diss} \approx 100 \text{ pc}$$

Spectra of radio halos & turbulence

Steepening frequency

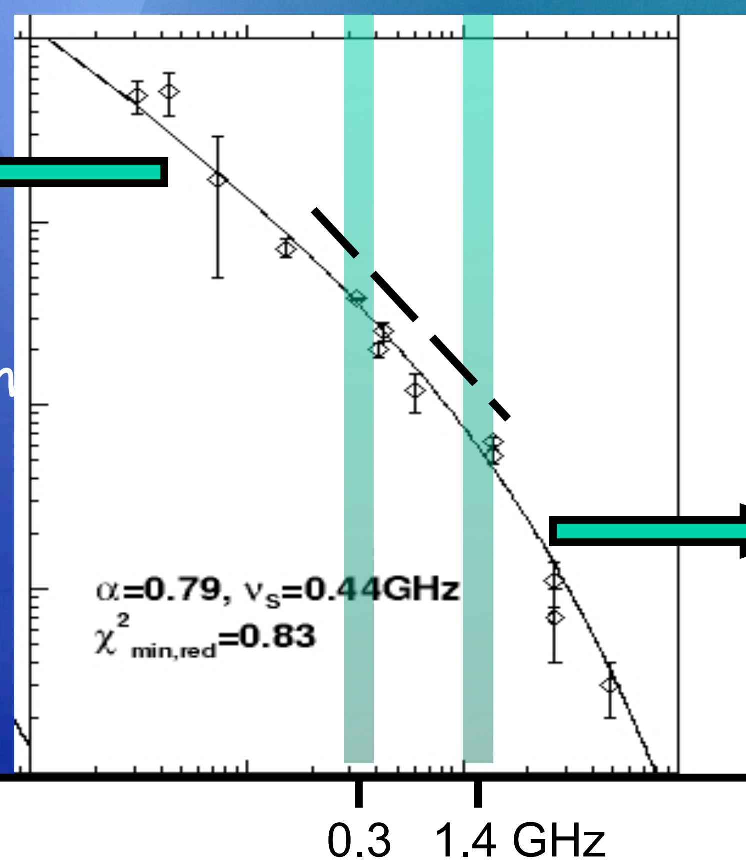
$$\nu_b \propto \langle B \rangle \gamma_{max}^2 \propto \frac{\langle B \rangle \chi^2}{\left(\langle B \rangle^2 + B_{cmb}^2\right)^2}$$

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



less efficient

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



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

more efficient

Observed spectra of radio halos & turbulence

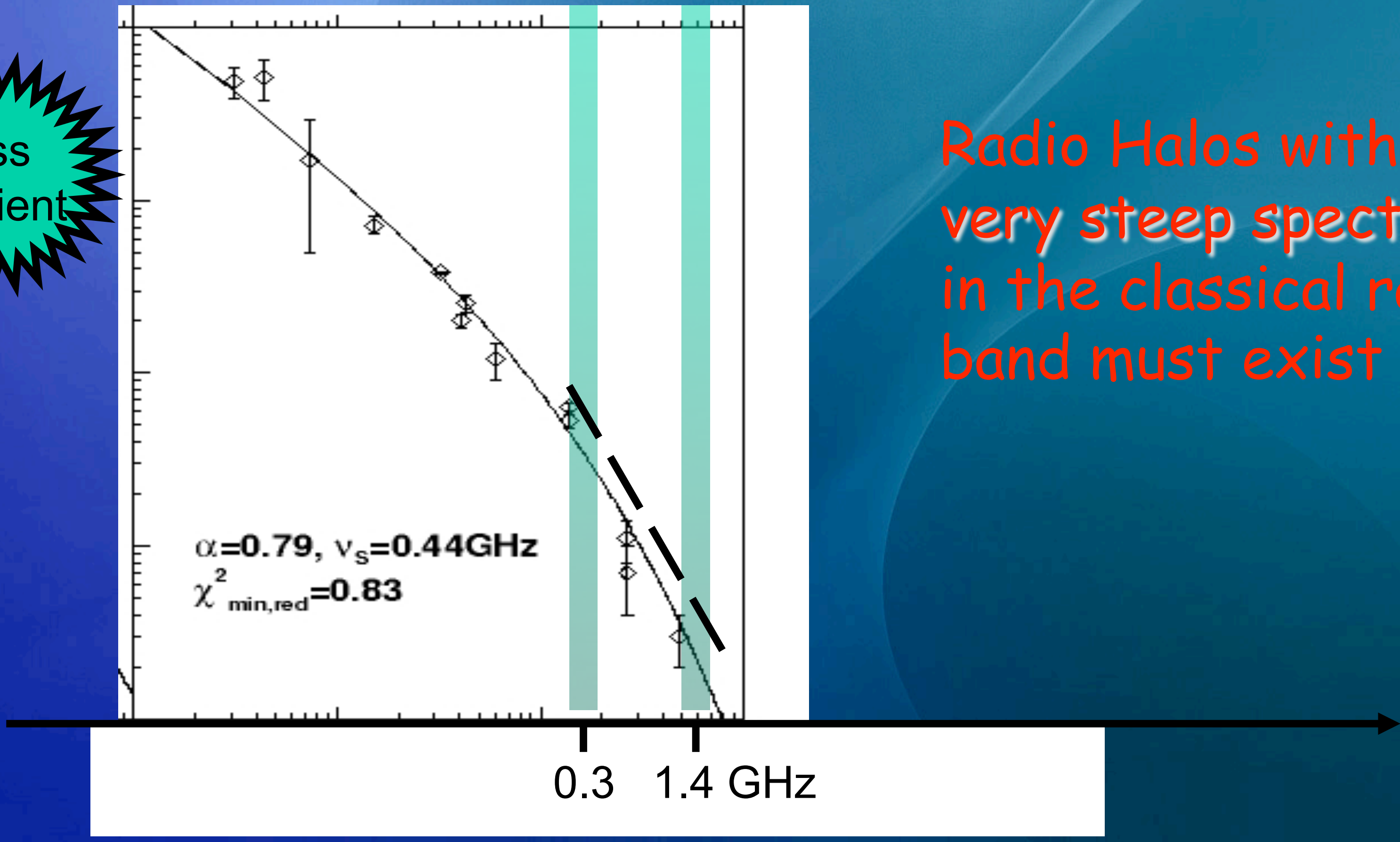
Cassano, GB, Setti (2006)

Steepening frequency

$$\nu_b \propto \langle B \rangle \gamma^2_{max} \propto \frac{\langle B \rangle \chi^2}{(\langle B \rangle^2 + B^2_{cmb})^2}$$

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

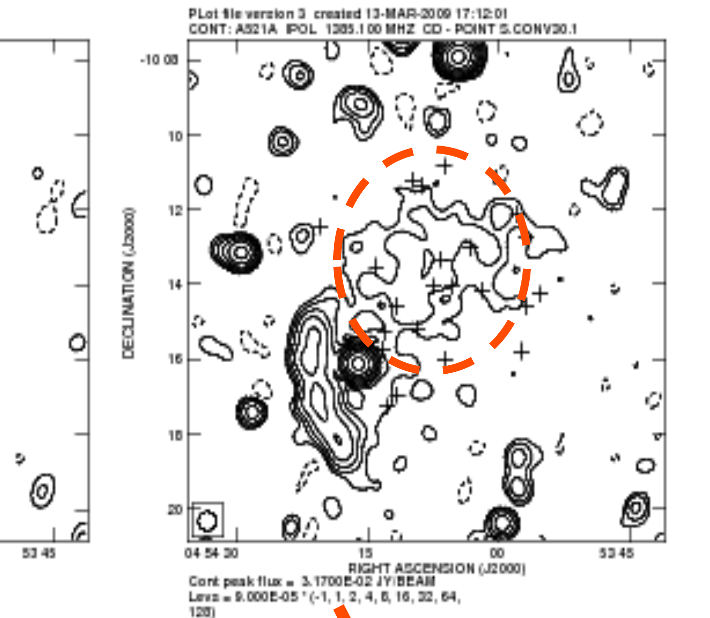
less efficient

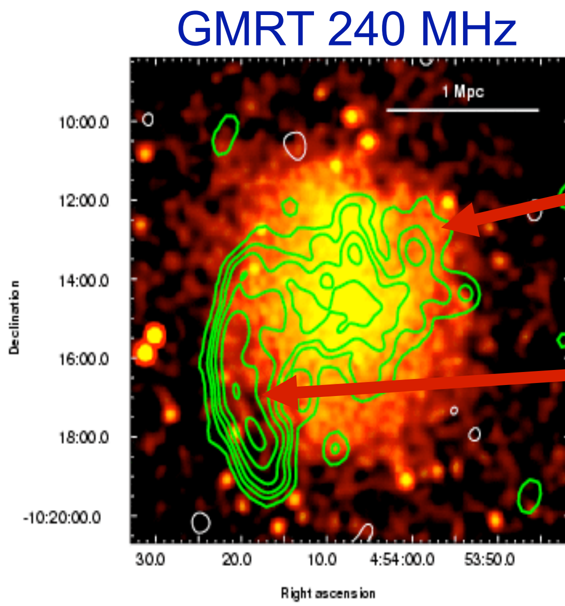


Radio Halos with very steep spectrum in the classical radio band must exist

Turbulent acceleration?

Brunetti +al 2008, *Nature 455, 944*

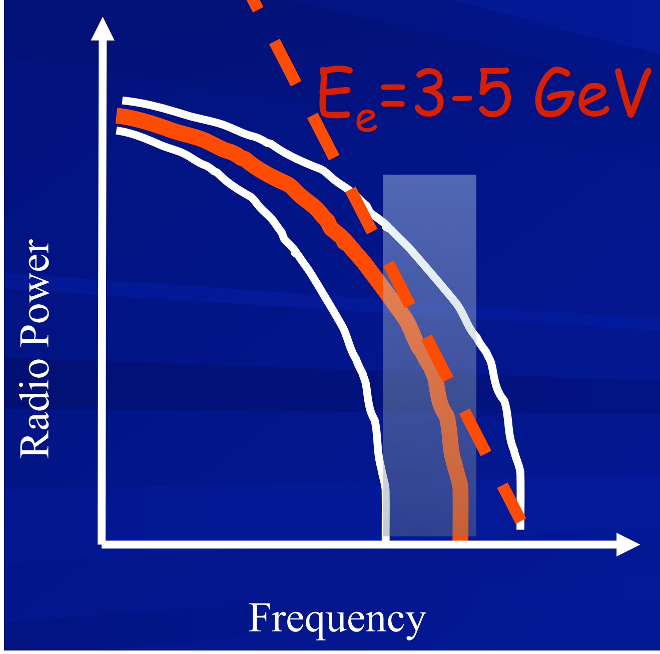


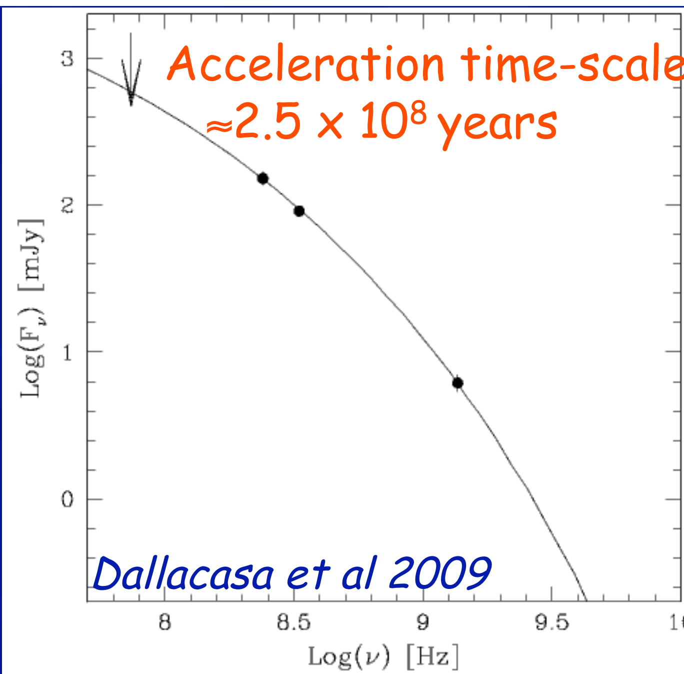


=1.9

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

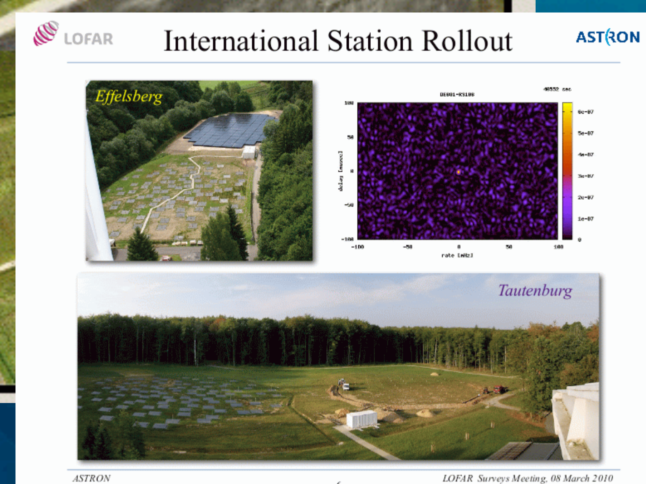
=1.5



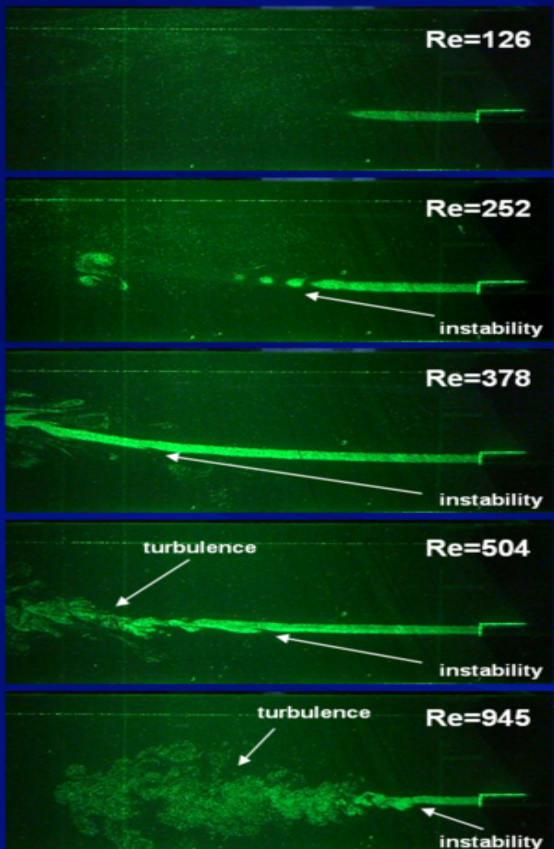


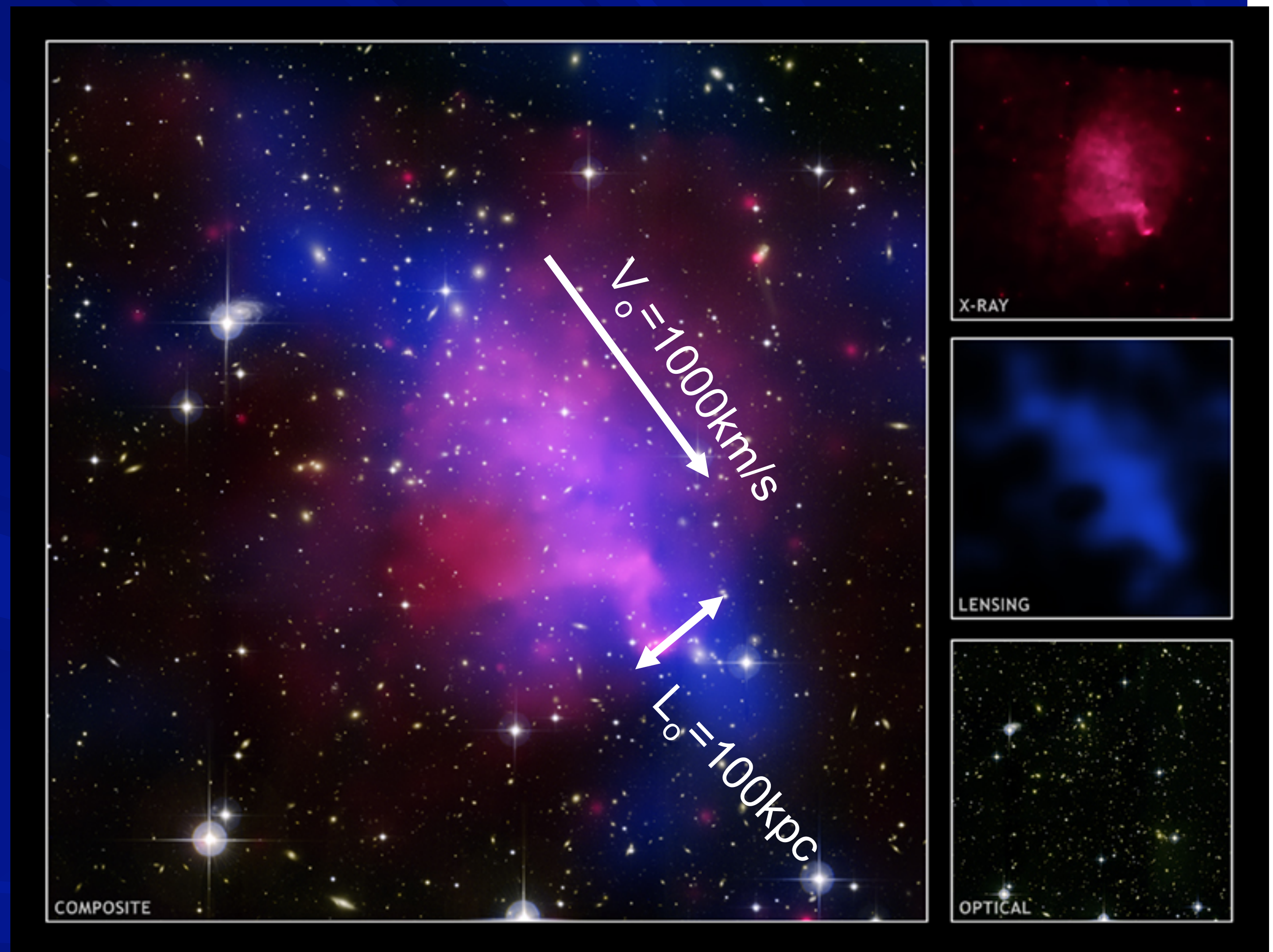
LOFAR ...

(Scaife lecture)



Turbulence in the IGM





$$Re = \frac{V_o L_o}{\nu_K}$$

$\nu_K \approx 1/3\ V_i\ l_{mfp}$

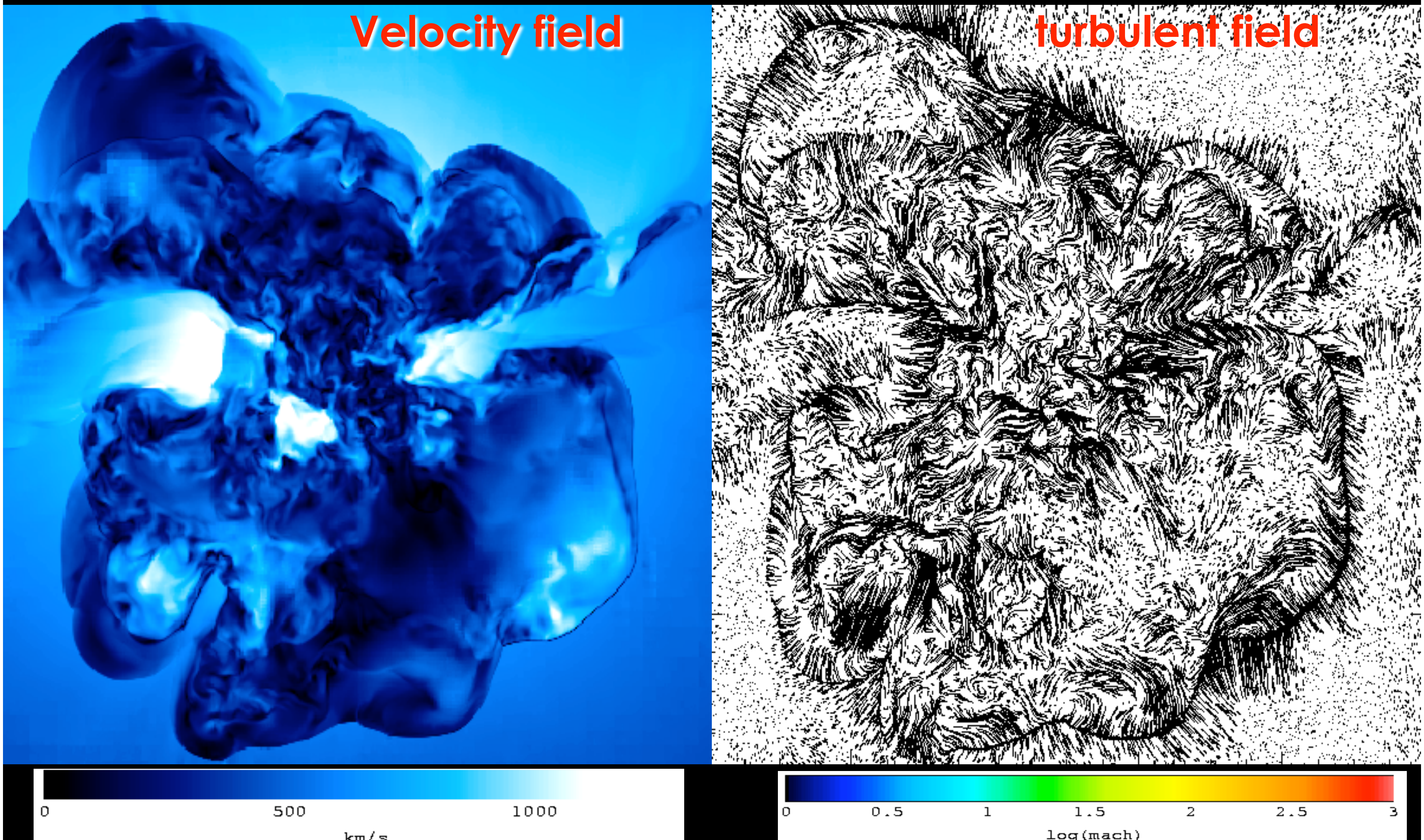
$l_{mfp} = L_{Coul} \approx 10\text{kpc}$

$Re \approx 100$

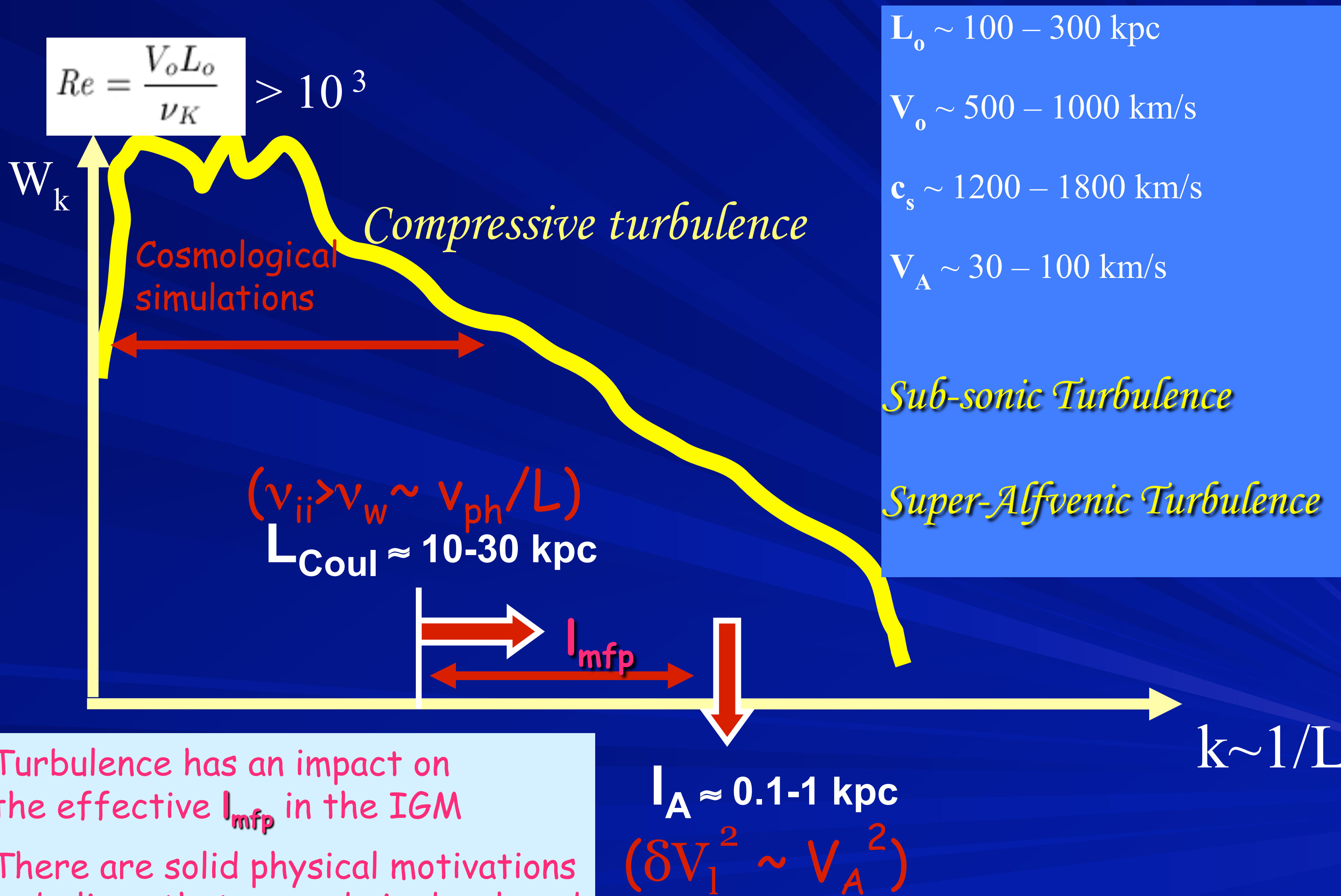
Turbulence in the IGM

(Vazza, GB, et al 2010)

Bryan & Norman 1998; Ricker & Sarazin 2001 Dolag et al. 2005; Takizawa 2005; Nagai et al. 2007; Iapichino & Niemeyer 2008, Ryu et al. 2008 Paul et al. 2010, Iapichino 2011



Turbulence in the IGM … more complex



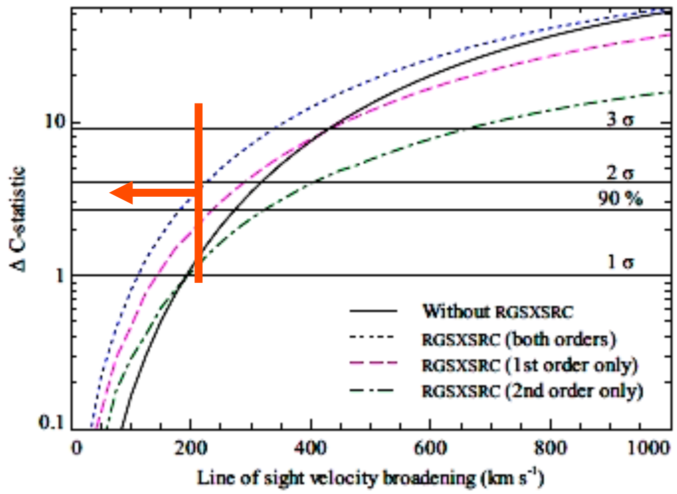
Turbulence has an impact on the effective l_{mfp} in the IGM

There are solid physical motivations to believe that cascade is developed

Turbulence in clusters… future

Present :

Sanders et al 2010



Schueker et al 2004;
Henry & Finoguenov 2004

Future :

$$\Delta v^2=(2k_BT/m)+\delta v^2$$

Line broadening

(eg., Sunyaev, Norman,Bryan 2003; Dolag et al 2005..)

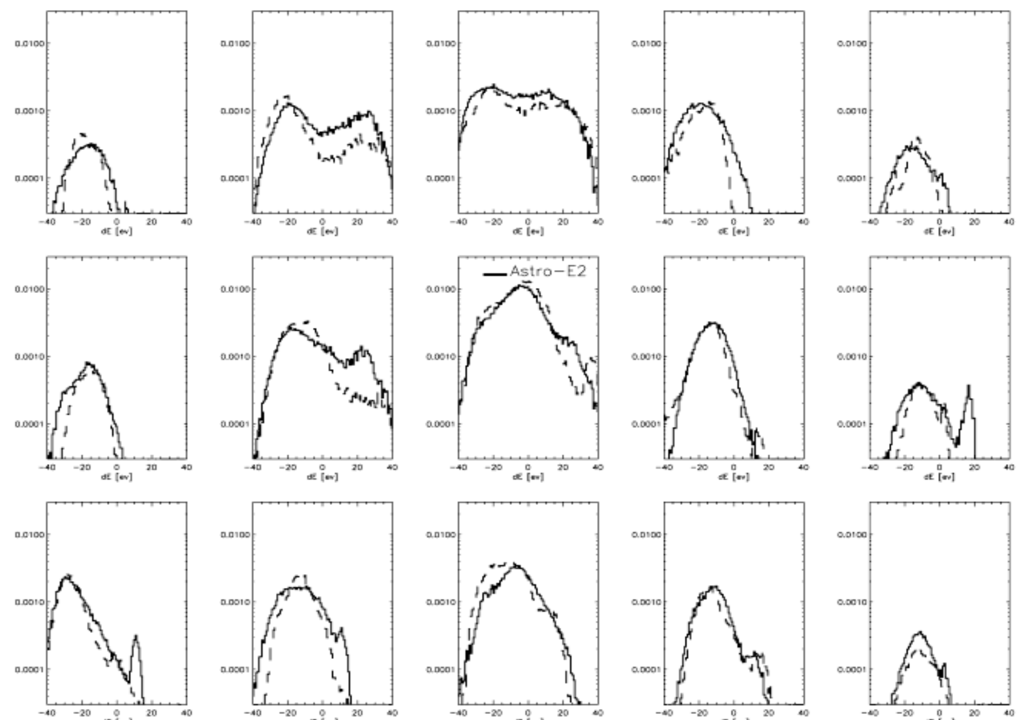
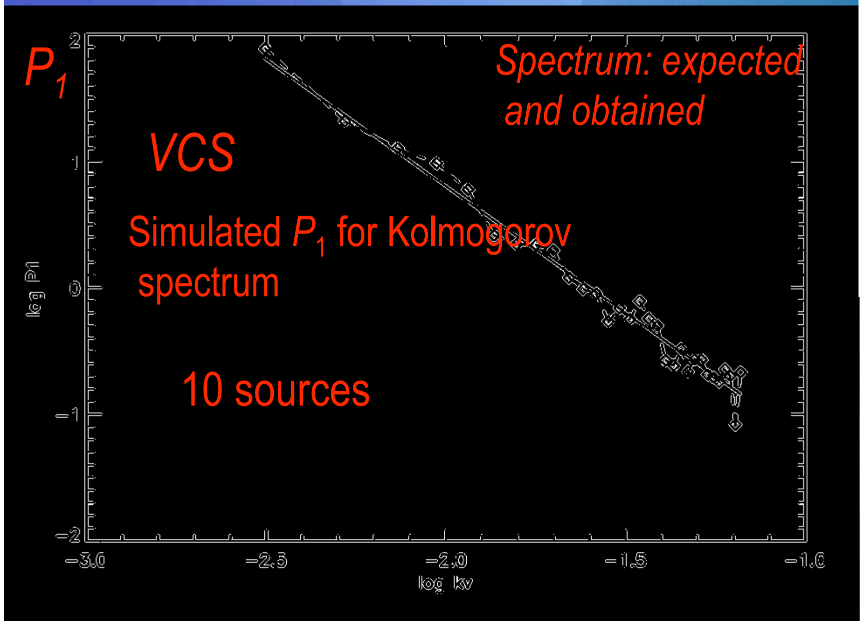
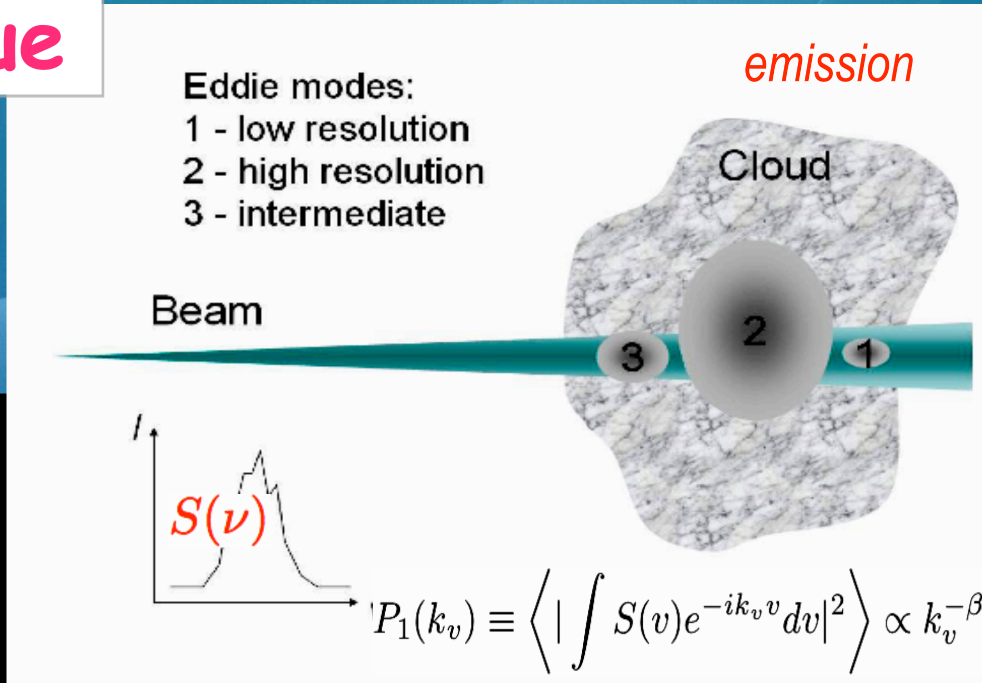


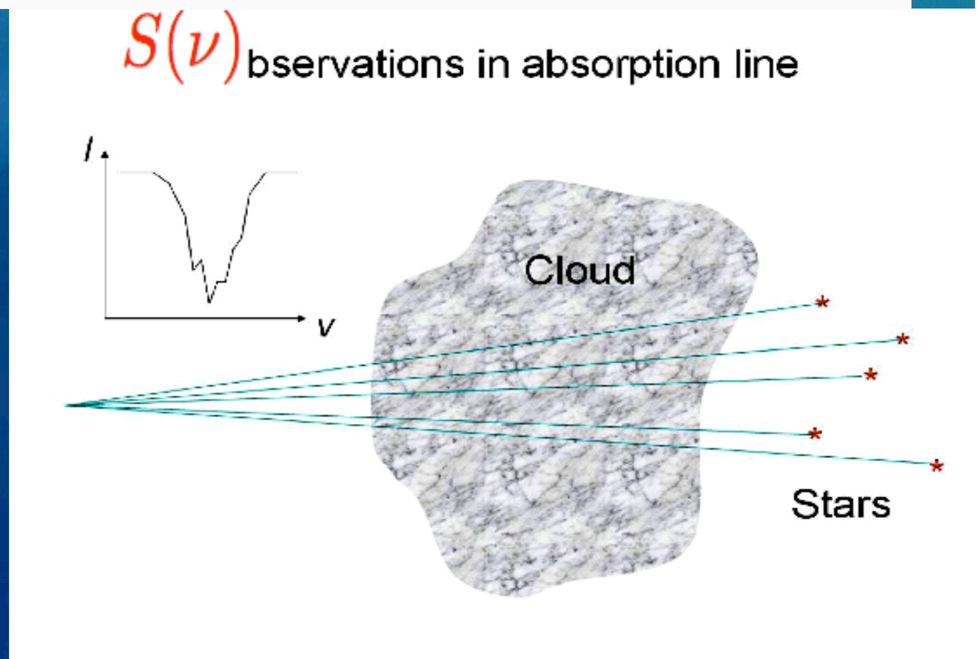
Figure 18. Distribution of the Doppler-shifted emission of the iron 6.702-keV line for 15 lines of sight through the cluster g72. Every panel corresponds to a column of side length 300 h^{-1} kpc through the virial region of the cluster. This roughly corresponds to 1-arcmin resolution (comparable to the *ASTRO-E2* specifications) at the distance of the Coma cluster. The columns from left to right correspond to −500, −250, 0, 250 and 500 h^{-1} kpc impact parameter in the *x*-direction, and the rows correspond to −250, 0 and 250, h^{-1} kpc impact parameter in the *y*-direction. The dashed lines give results for the original viscosity run, while the solid line is for the low-viscosity run. The thick bar in the centre panel marks the expected energy resolution of 12 eV as an indication for a

The VCA/S technique

Lazarian & Pogosyan 2006, 2008

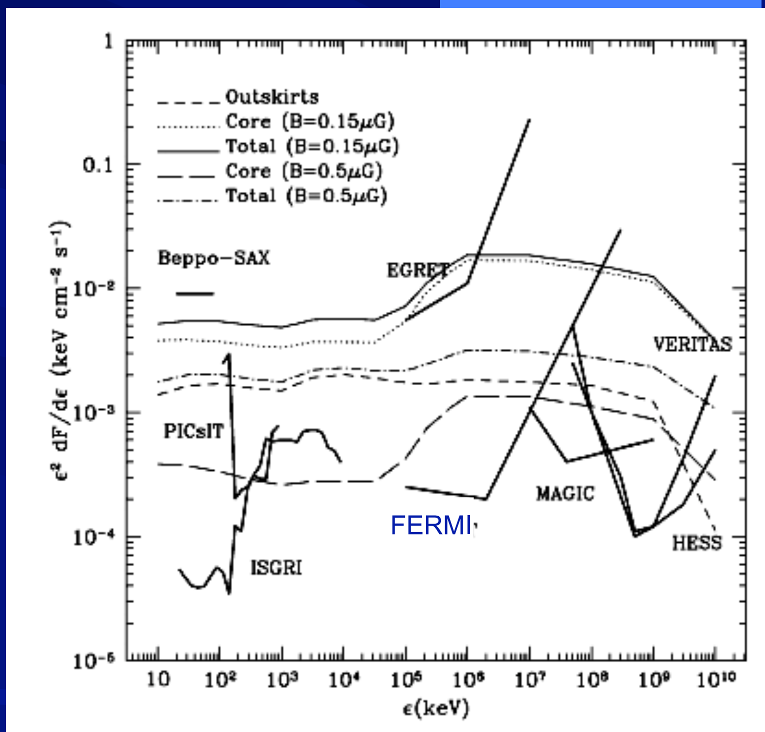




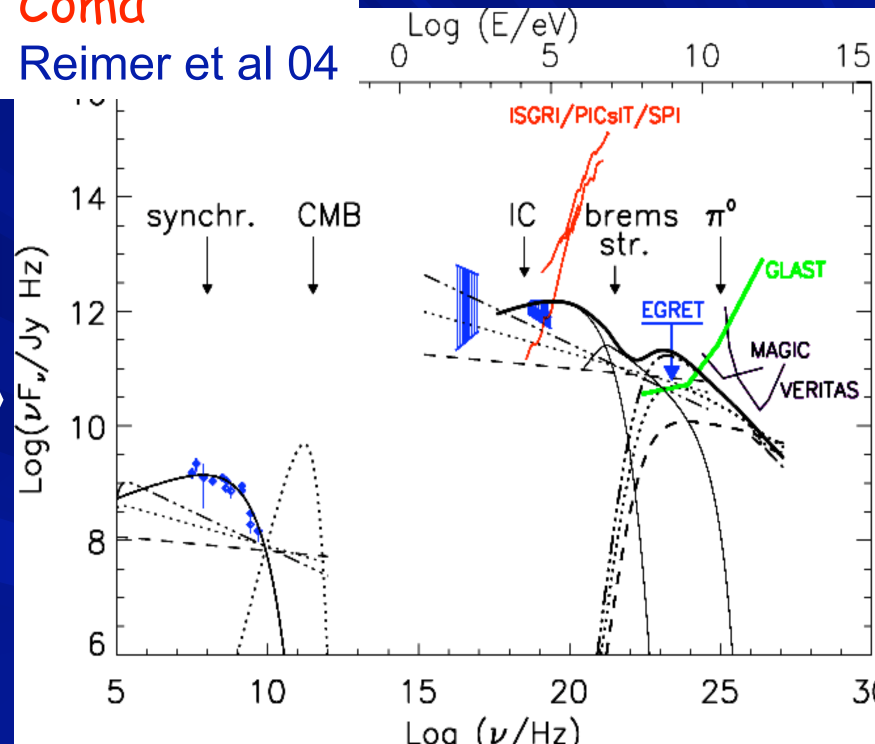


High Energy emission from galaxy clusters

Miniati 2003



Coma
Reimer et al 04



First predictions…

"constrained" predictions…

The properties of the diffuse radio (synchrotron) emission on Mpc scales (eg Radio Halos) and the present estimates of B in galaxy clusters (RM) may impose useful constraints on the predictions at high energies

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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

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

I(k)

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

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

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

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

I(k)

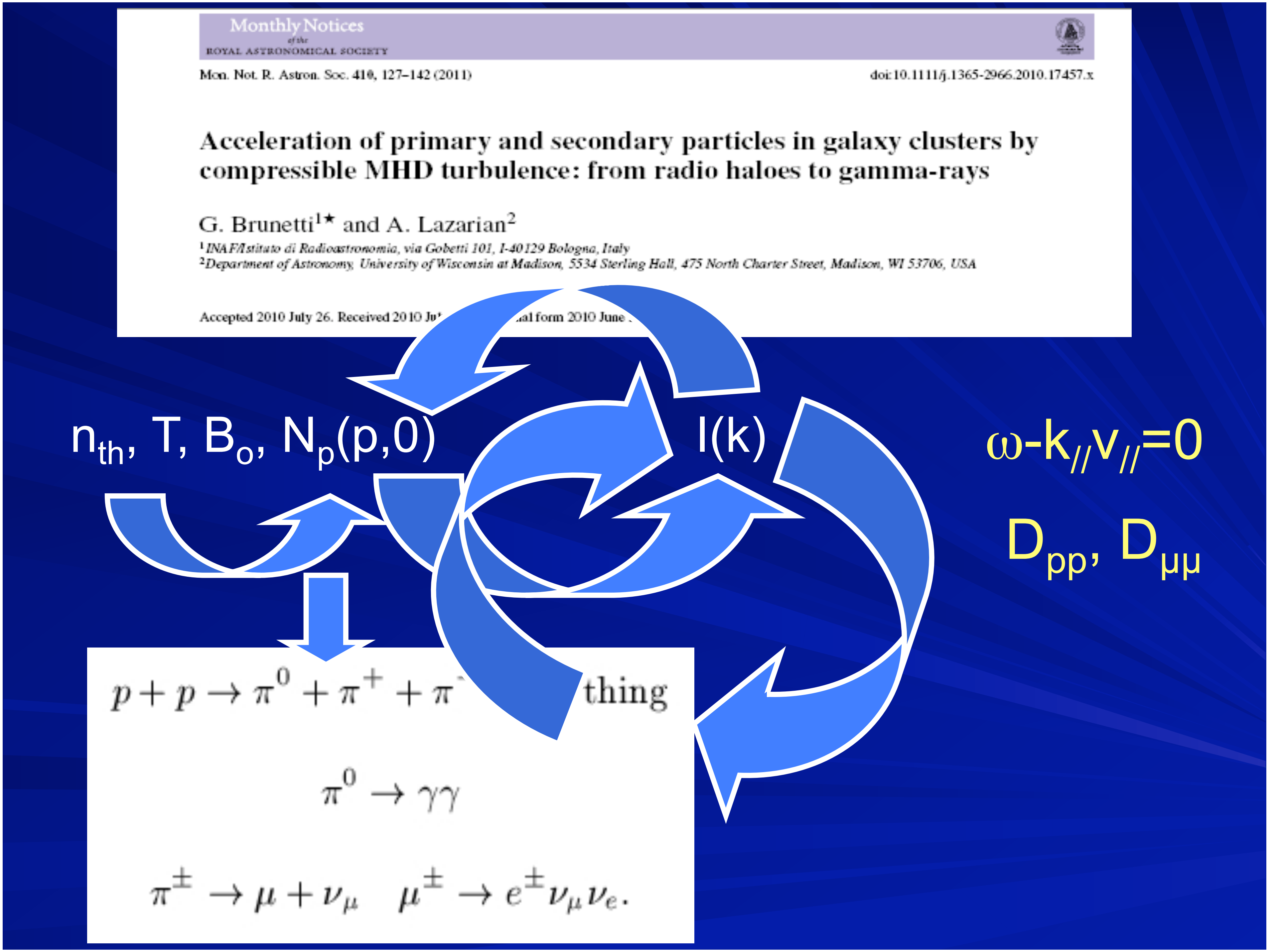
$\omega - k_{//} v_{//} = 0$

D_{pp}, $D_{\mu\mu}$

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

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

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



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n_{th}, T, B_o, $N_p(p,0)$
I(k)
$\omega - k_{//} v_{//} = 0$
D_{pp}, $D_{\mu\mu}$
$p + p \rightarrow \pi^0 + \pi^+ + \pi^-$ thing
$\pi^0 \rightarrow \gamma\gamma$
$\pi^{\pm} \rightarrow \mu + \nu_\mu \quad \mu^{\pm} \rightarrow e^{\pm} \nu_\mu \nu_e .$

Stochastic Particle Acceleration (formalism)

Electrons/Positrons

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

Q_e: secondaries from (CR)p-p collisions

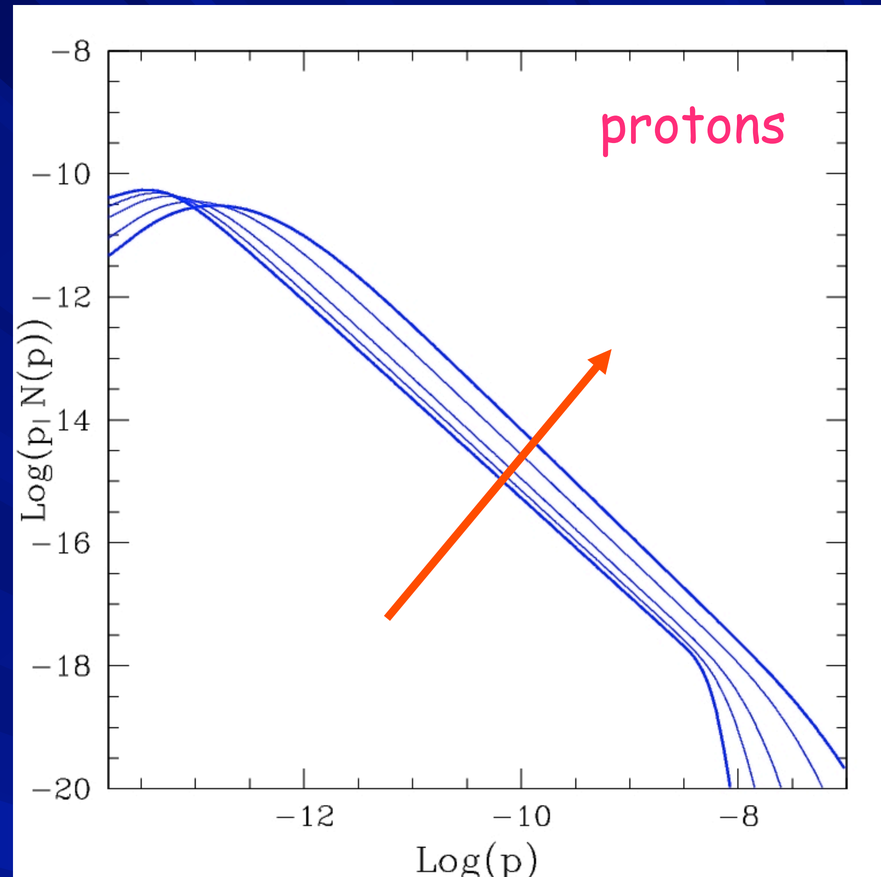
Protons

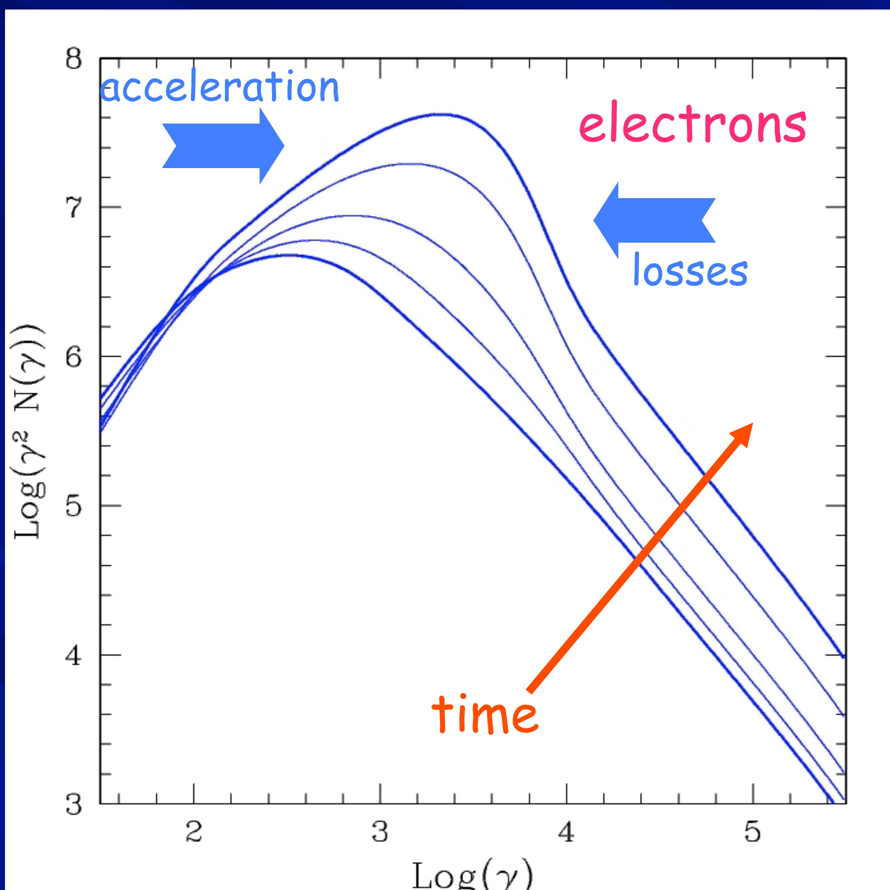
$$\frac{\partial N_p(p,t)}{\partial t} = \frac{\partial}{\partial p}\left(N_p(p,t)\left[\left(\frac{dp}{dt}\right)_i - \frac{2}{p}D_{pp}\right]\right) + \frac{\partial}{\partial p}\left(D_{pp}\frac{\partial N_p(p,t)}{\partial p}\right) + Q_p(p,t)$$

Turb. Modes

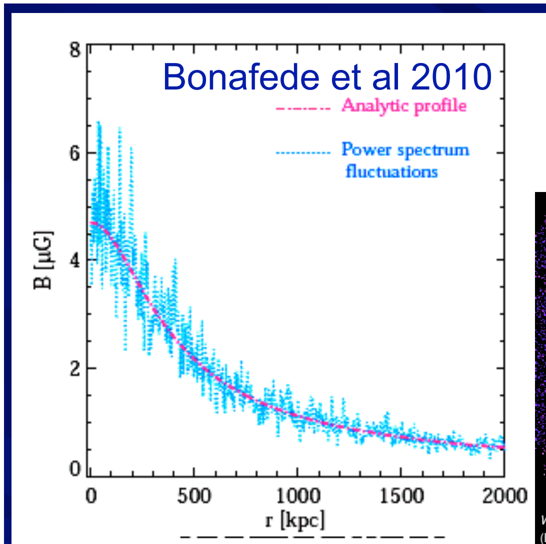
$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

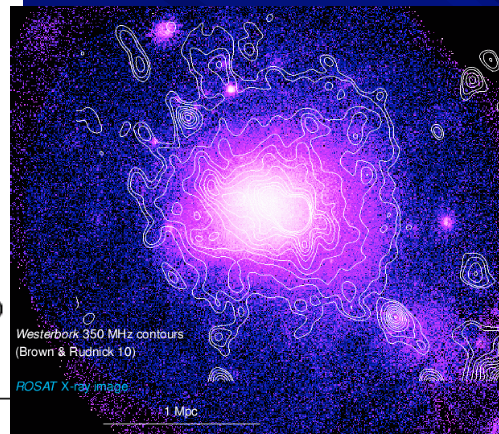
most could be with IGM
or with CR protons


protons
Log(p)
Log(p N(p))
−8
−10
−12
−14
−16
−18
−20
−12
−10
−8


acceleration
electrons
losses
time
Log(γ)
Log(γ² N(γ))
8
7
6
5
4
3
2
3
4
5

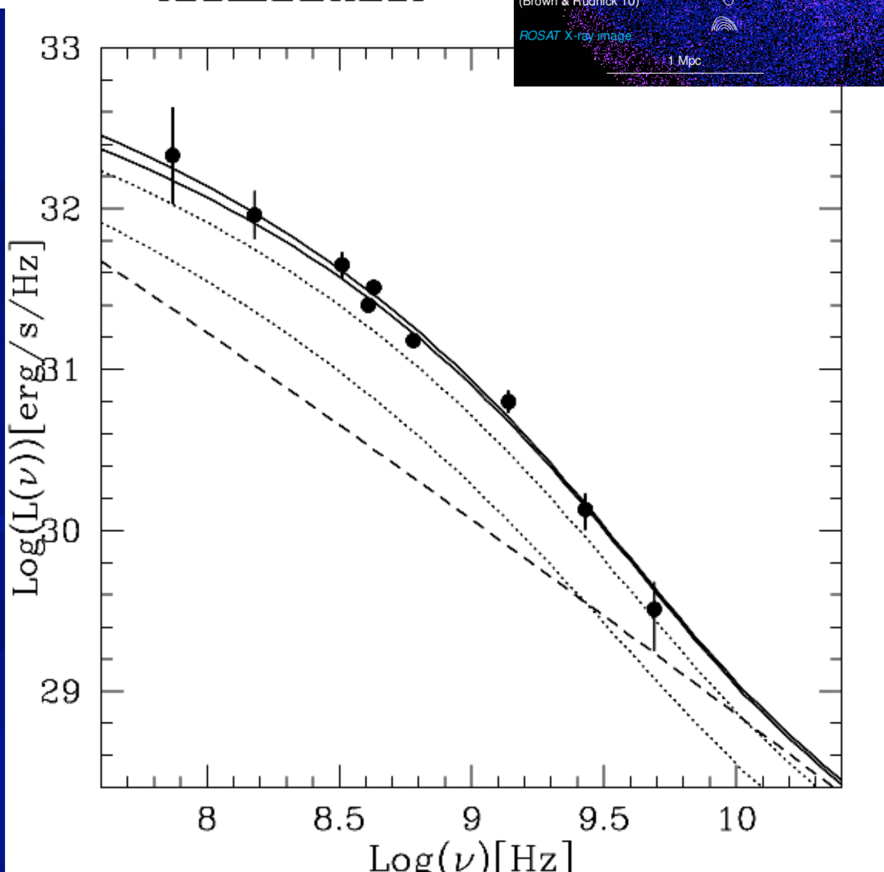
Application : Coma cluster

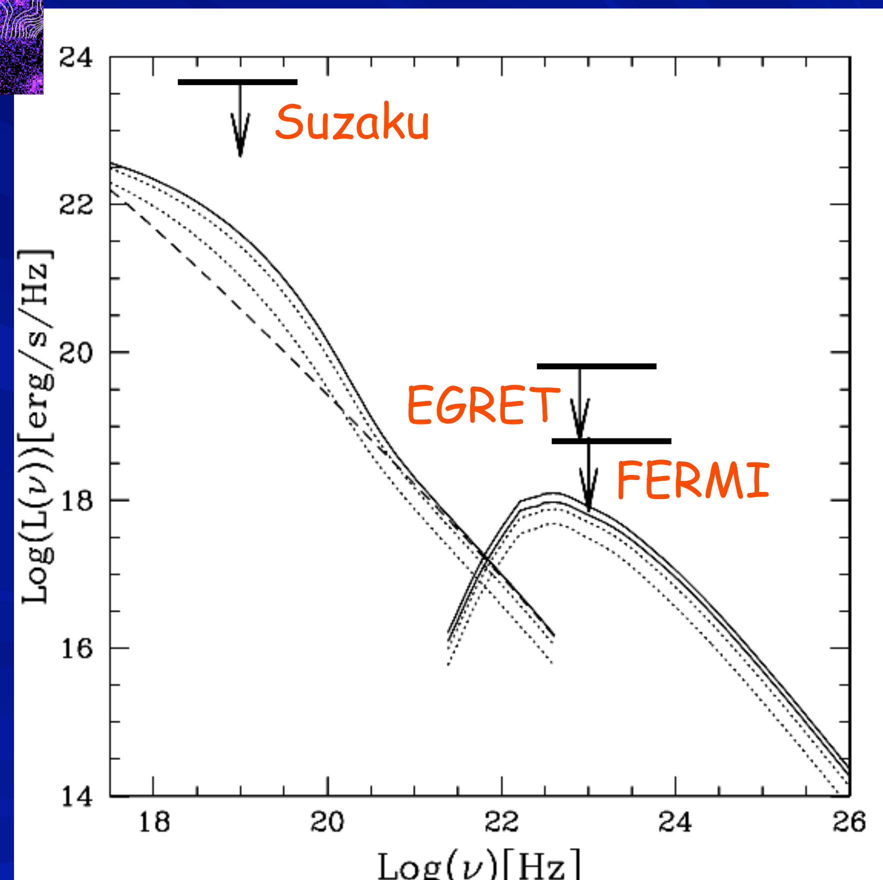




$E_{tur} \approx 10\ \%\ E_{th}$ @k^{-1}~100 kpc

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





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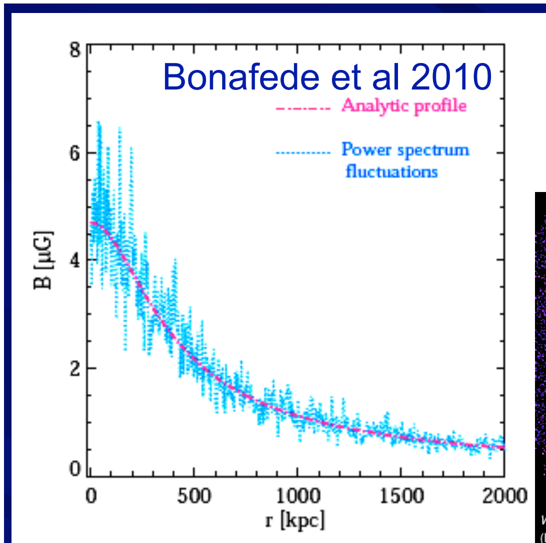

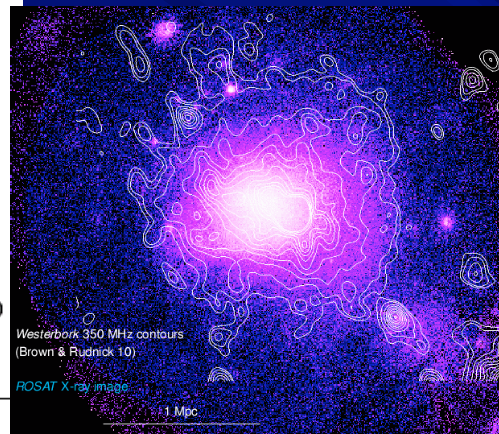

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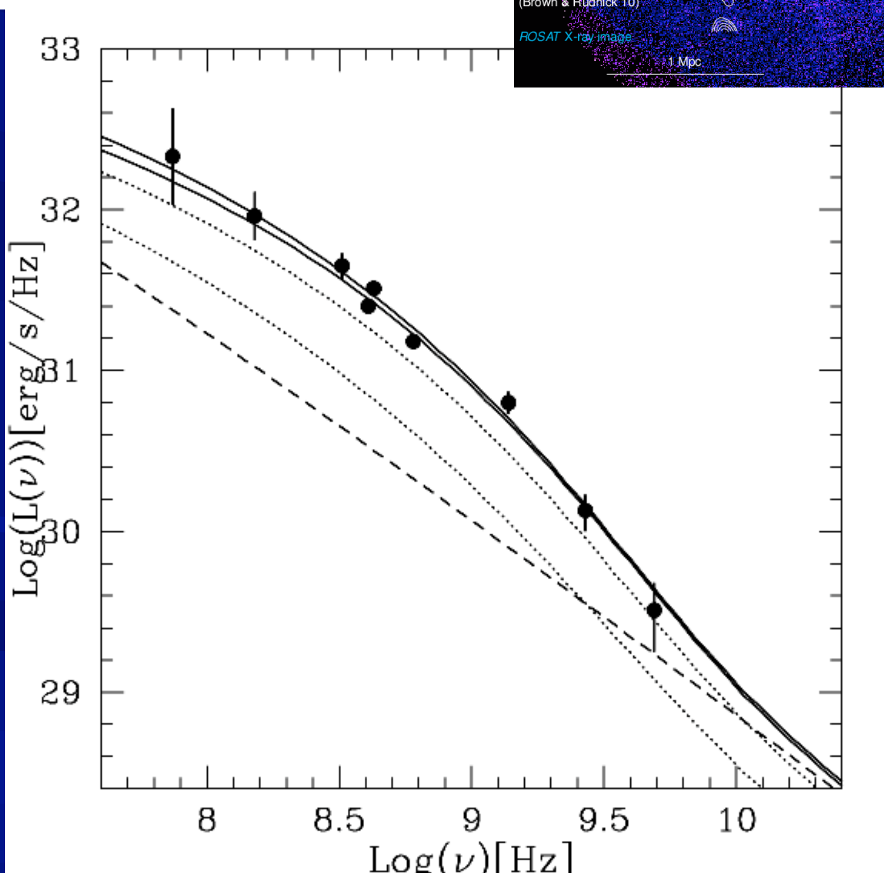
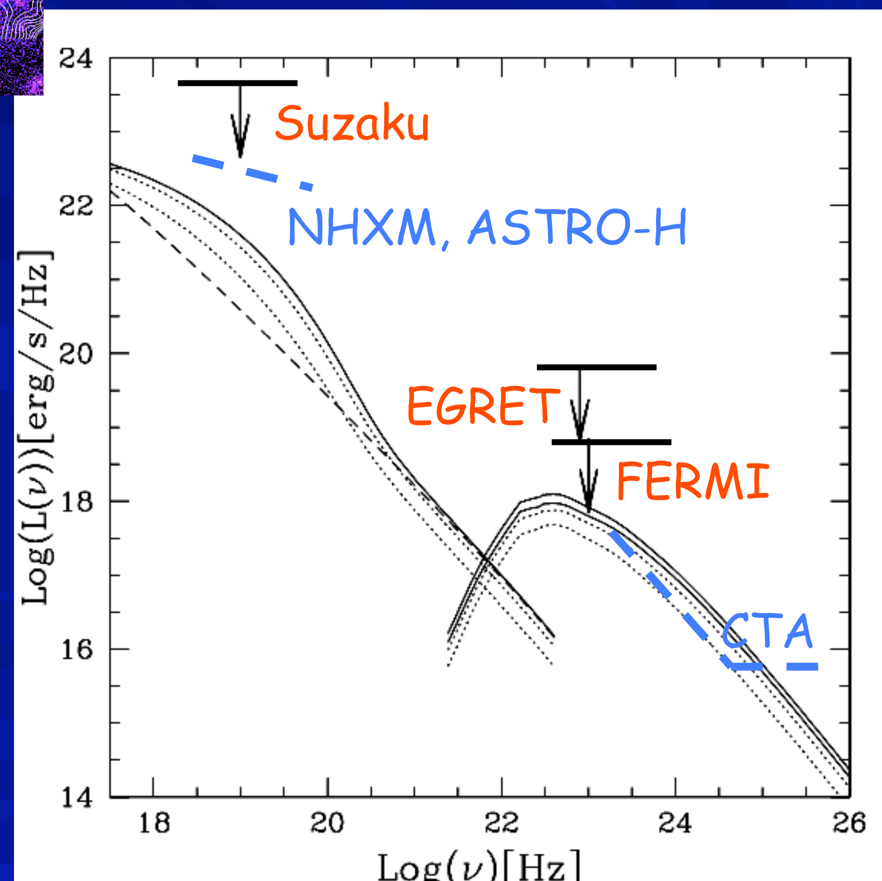
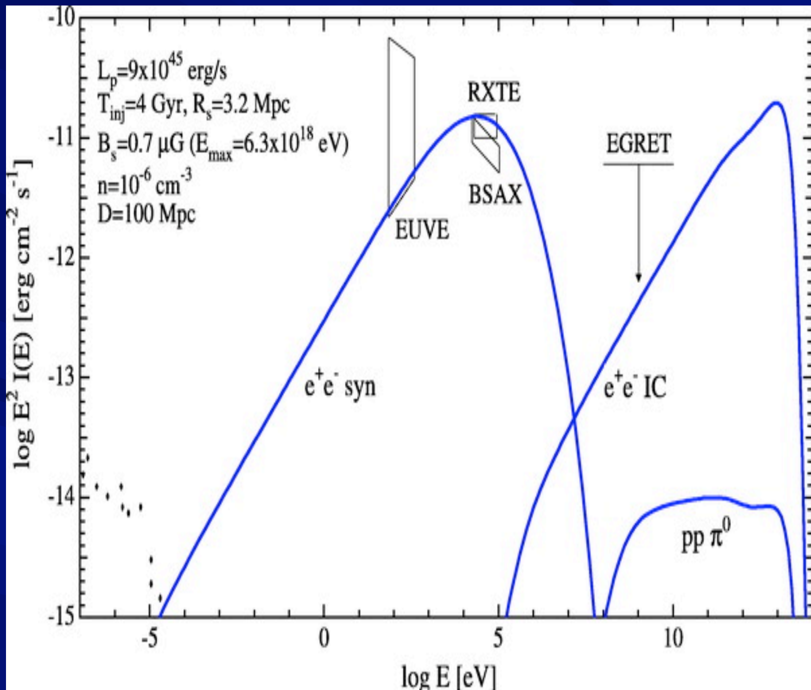
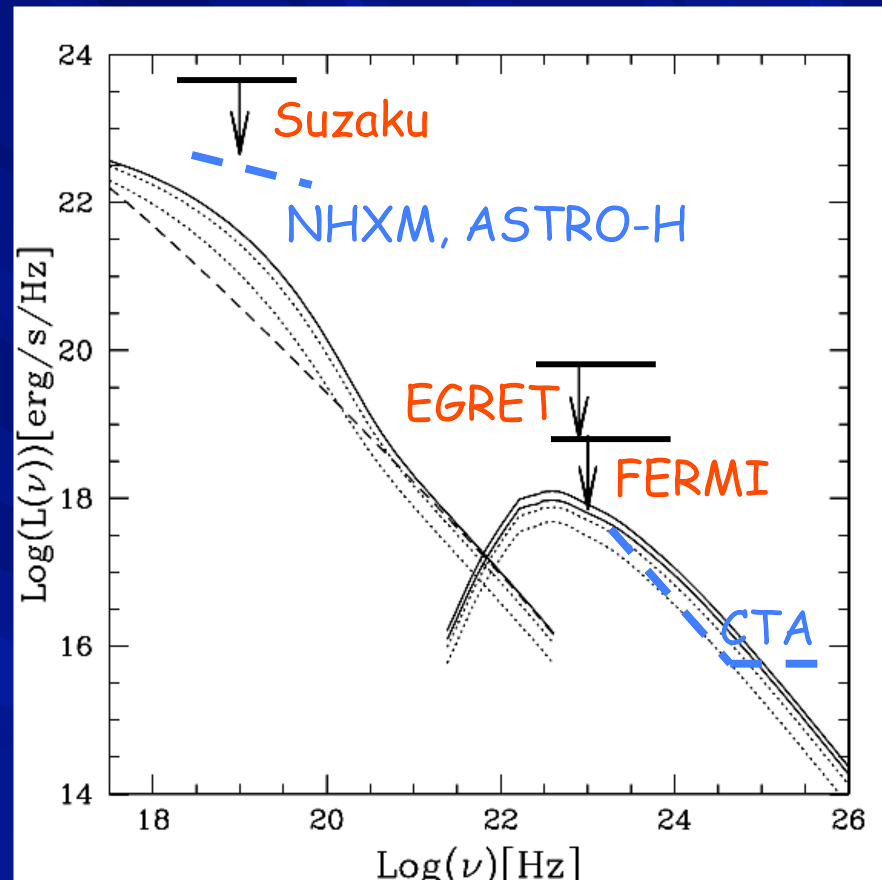


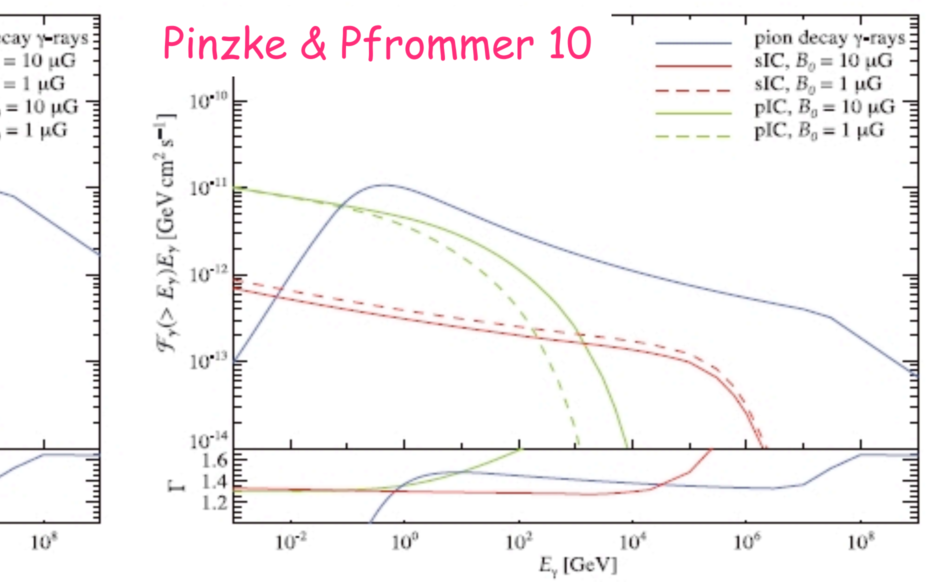


Additional processes

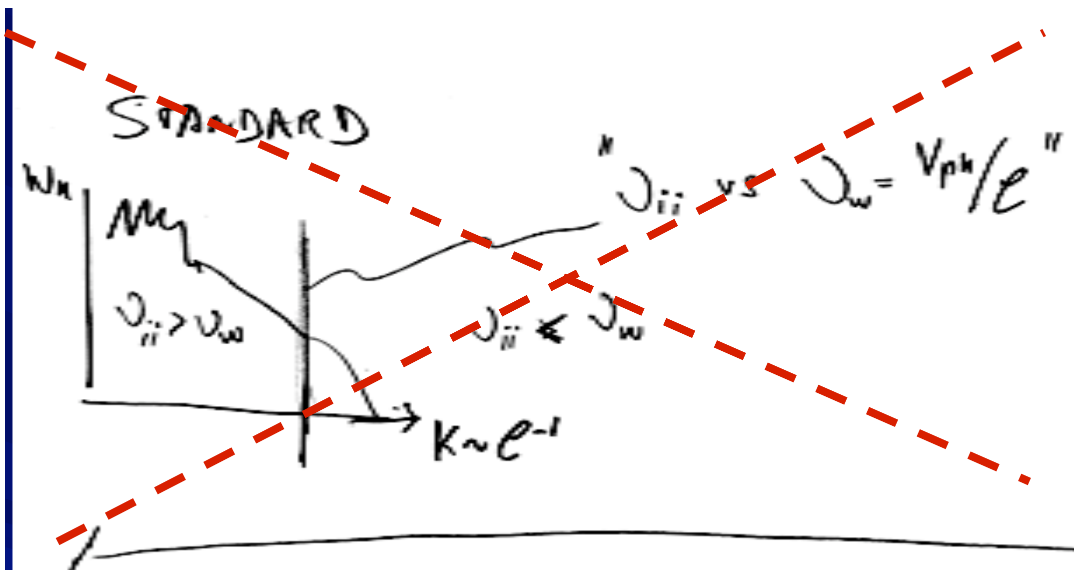
UHEp-γ Inoue et al 05







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

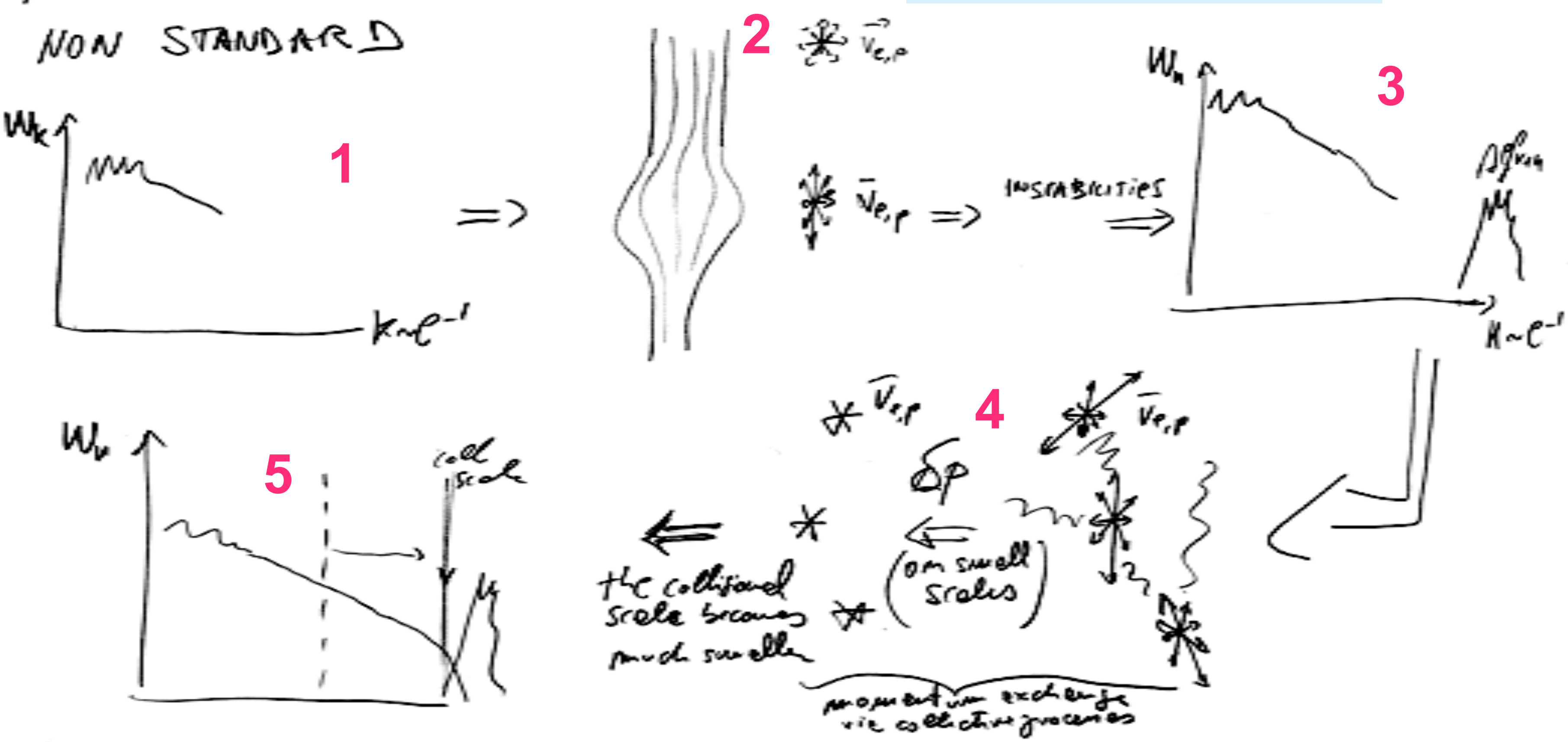


Mon. Not. R. Astron. Soc. 000, 000–000 (0000) Printed 5 November 2010 (MN LaTeX style file v1.4)

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

G. Brunetti,[1] 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

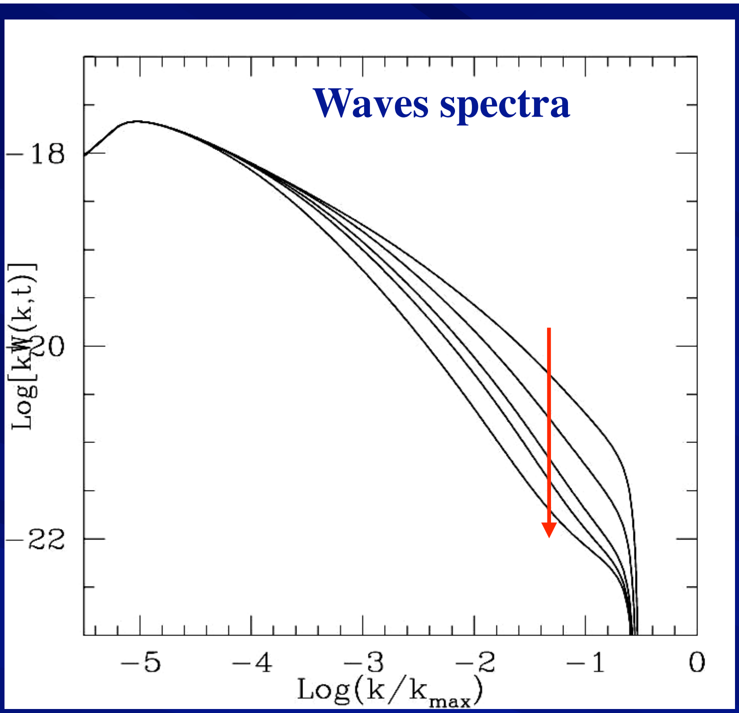
Brunetti & Lazarian 2011b

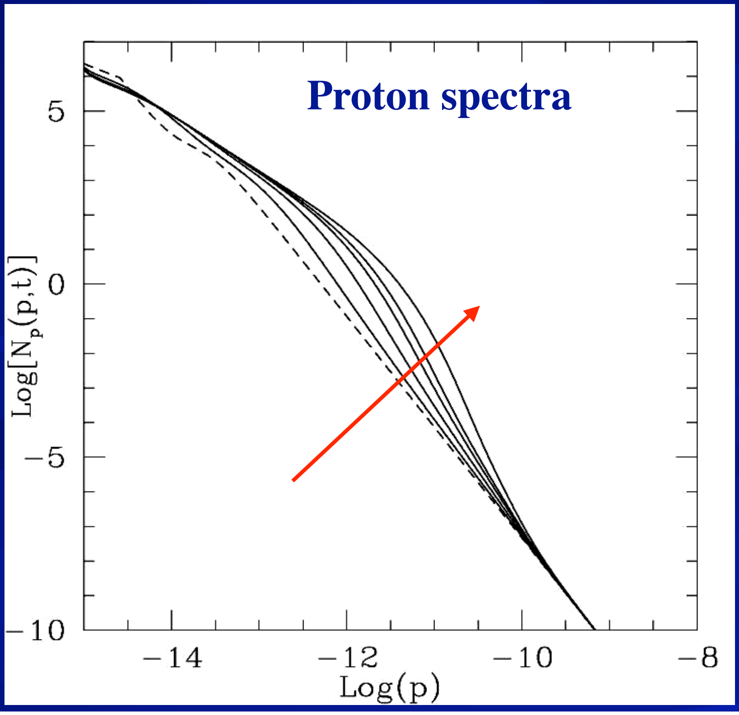


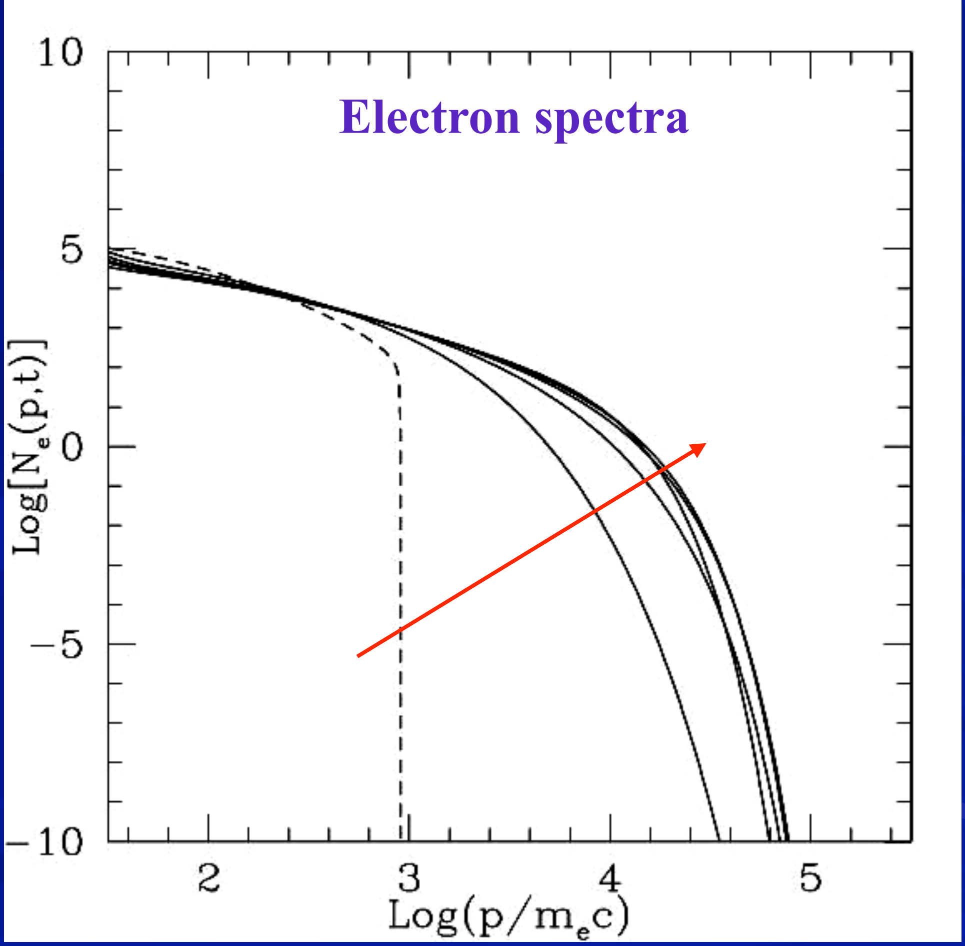
“generic” example of CR-dominated damping …

Alfven-Wave--Particle Coupling

(Brunetti et al. 2004, Brunetti & Blasi 2005)



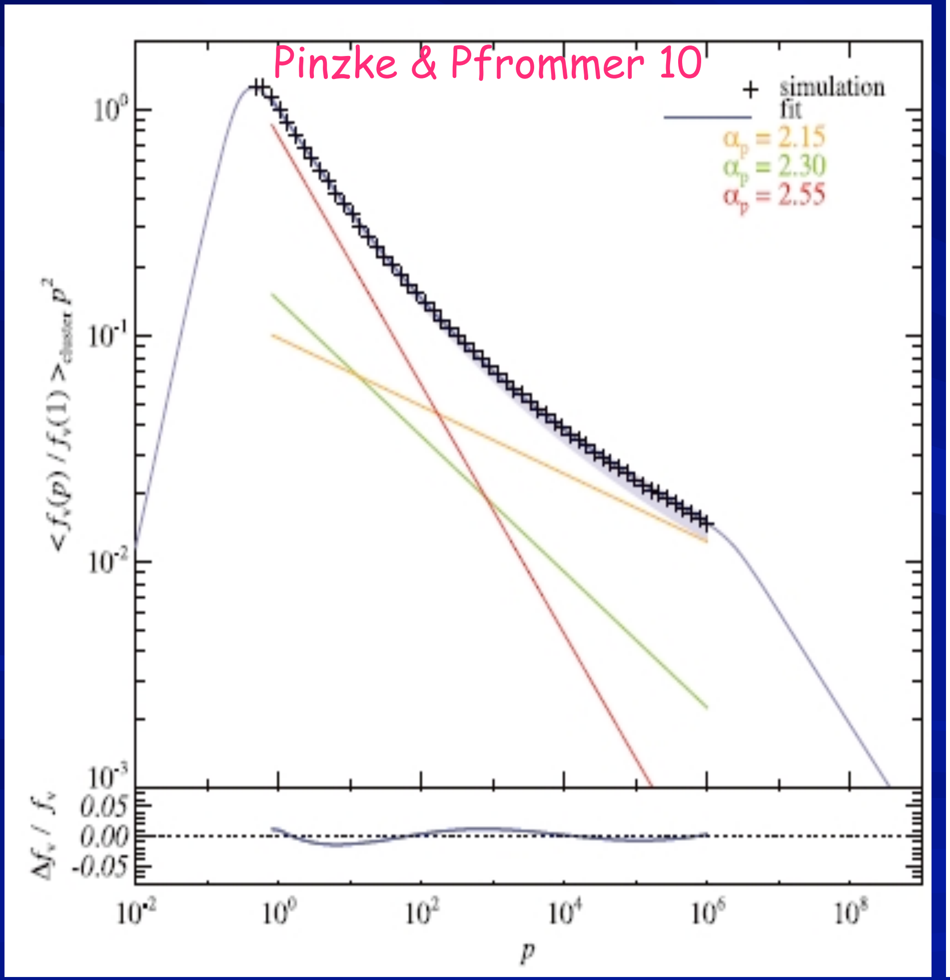


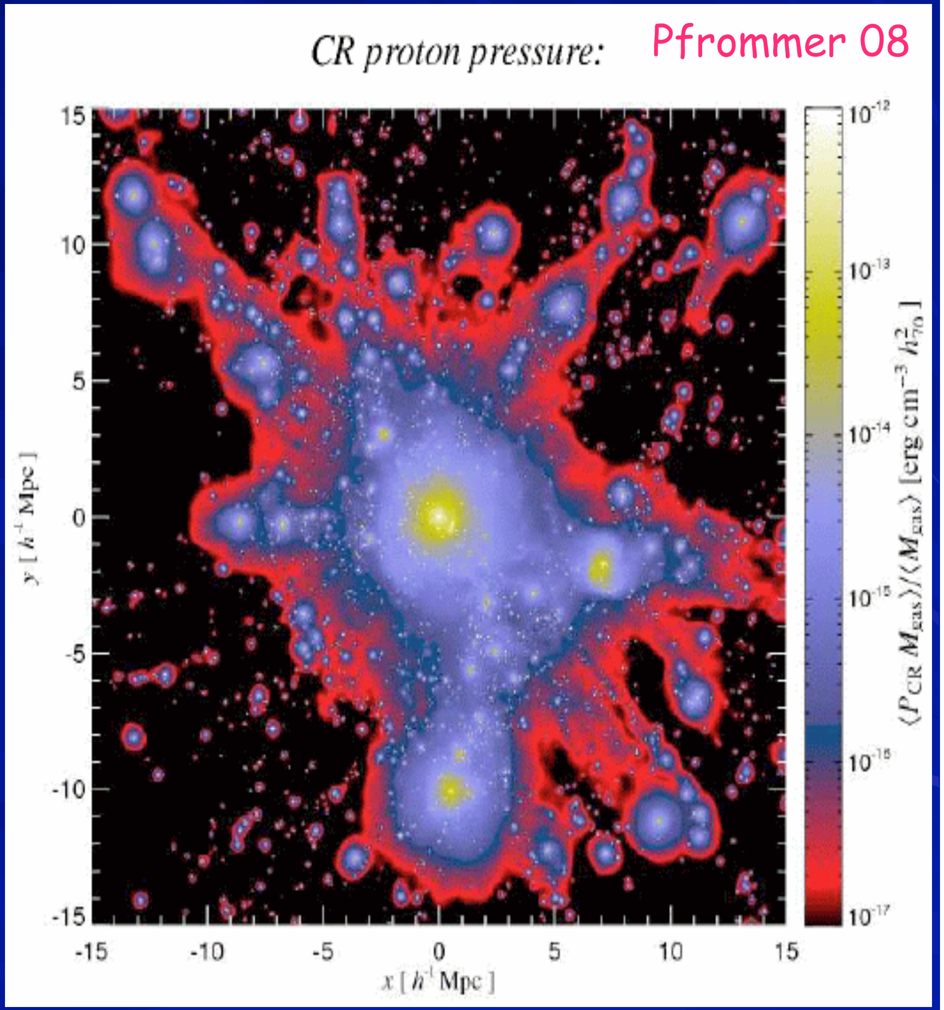


Waves + CRp + CRe

Spectrum of CR in clusters

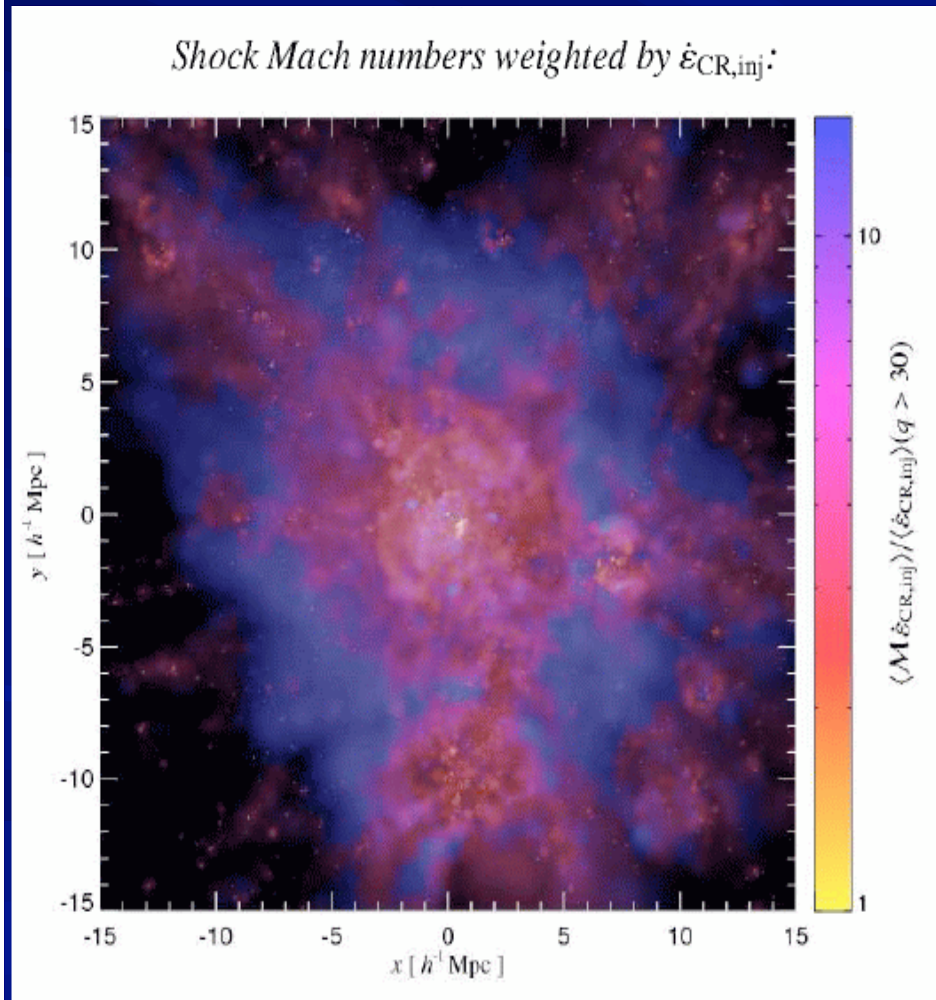
Pfrommer et al. 2007, 08 : first "self-consistent" simulations of CR+IGM
Acceleration efficiency is the "free" parameter

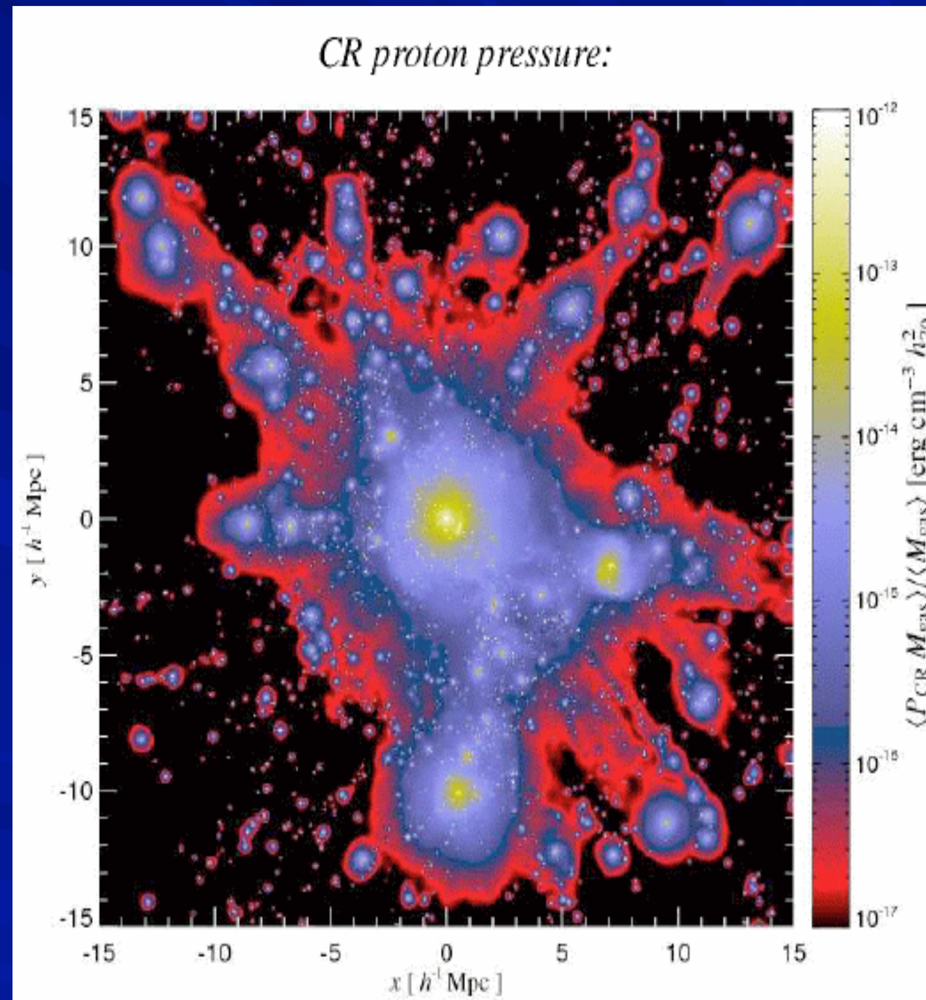




Acceleration of CR at shocks

Pfrommer et al. 2007, 08 : first “self-consistent” simulations of CR+IGM
Acceleration efficiency is the “free” parameter



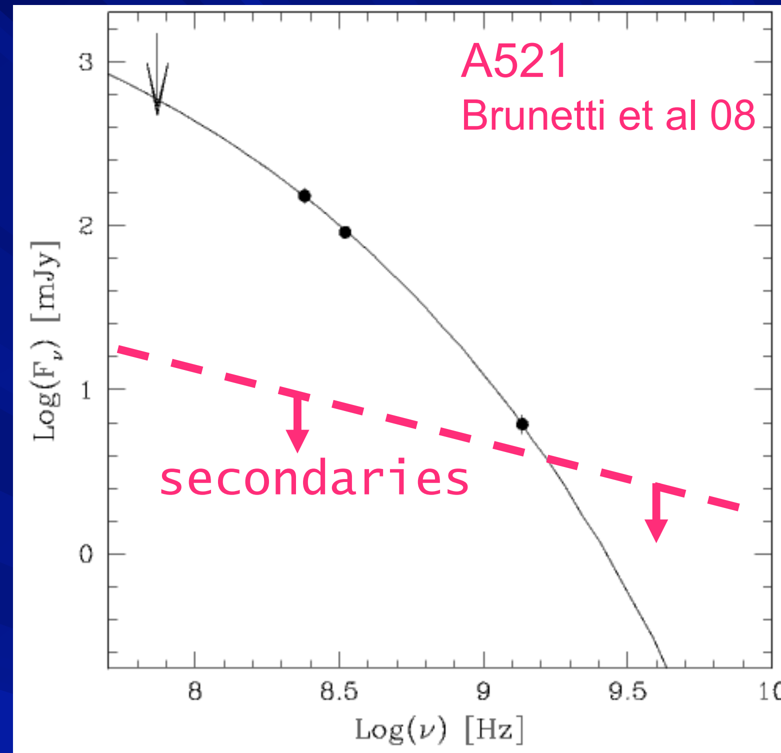


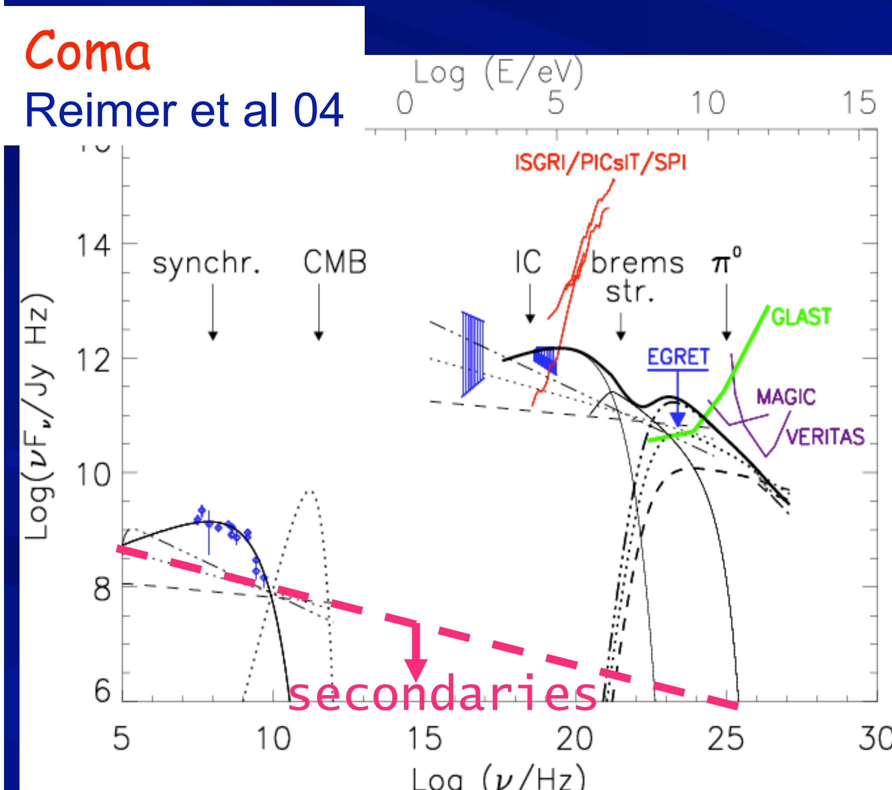
Constraining secondaries & CRp

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

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

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

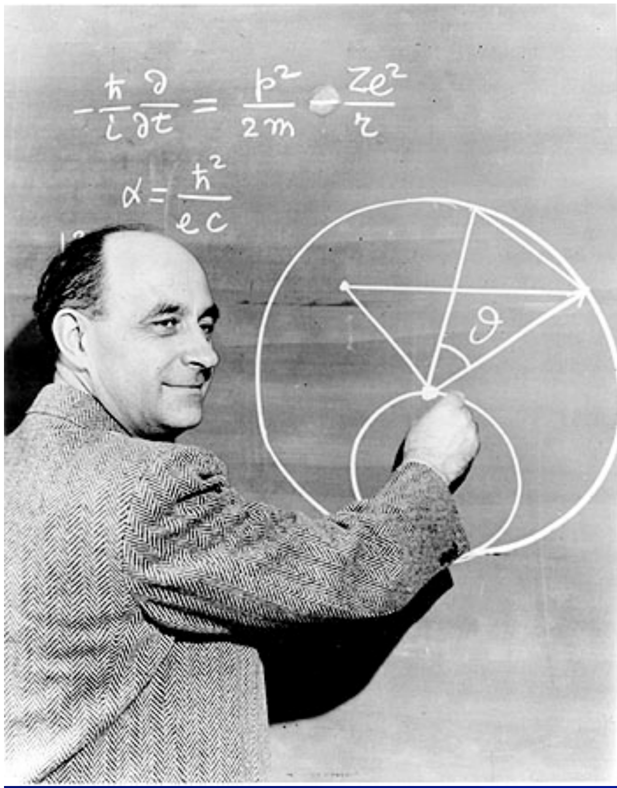




Synchrotron from secondaries should be smaller than the flux of the halo.

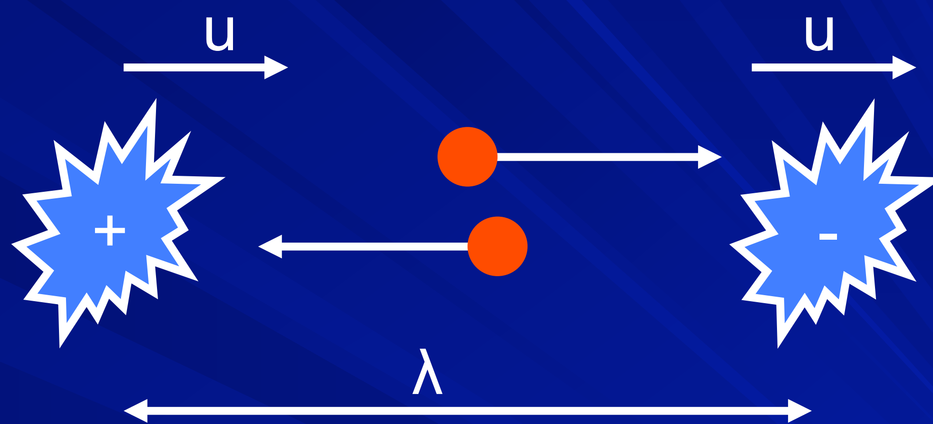
limits on : $(\mathcal{B}\ ,\ \mathcal{E}_{CRp})\ ,\ \delta$

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



Second order Fermi Mechanisms

(Fermi 1949)



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

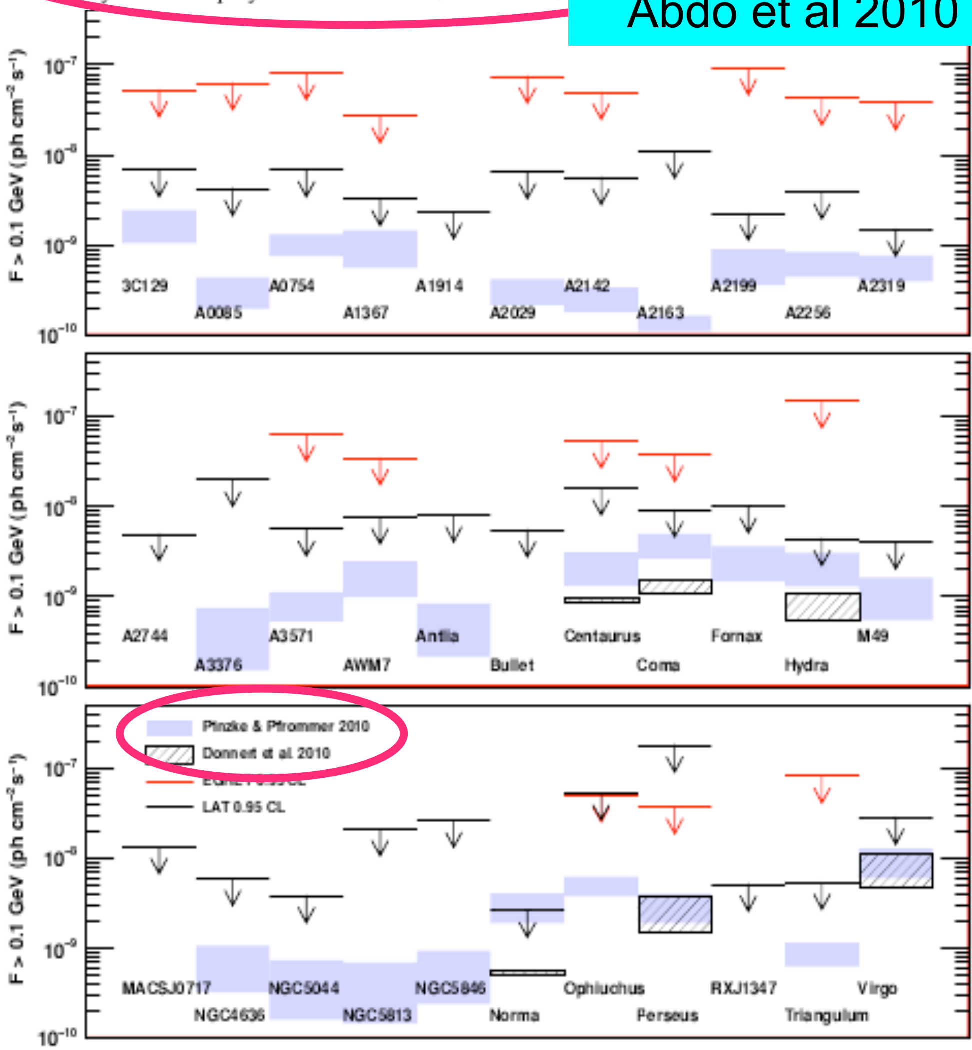
Energy gain per collisions: $\Delta p_\pm \approx \pm 2p\frac{u}{c}$

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

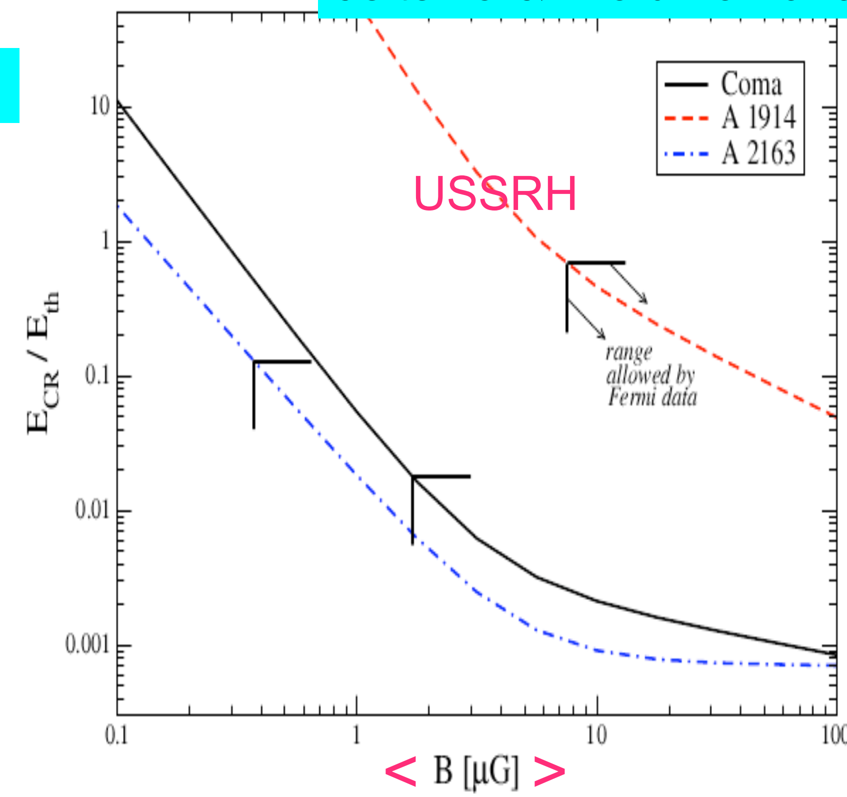
Gamma rays : energy content of CRp & origin of Radio Halos

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 emission.

Abdo et al 2010



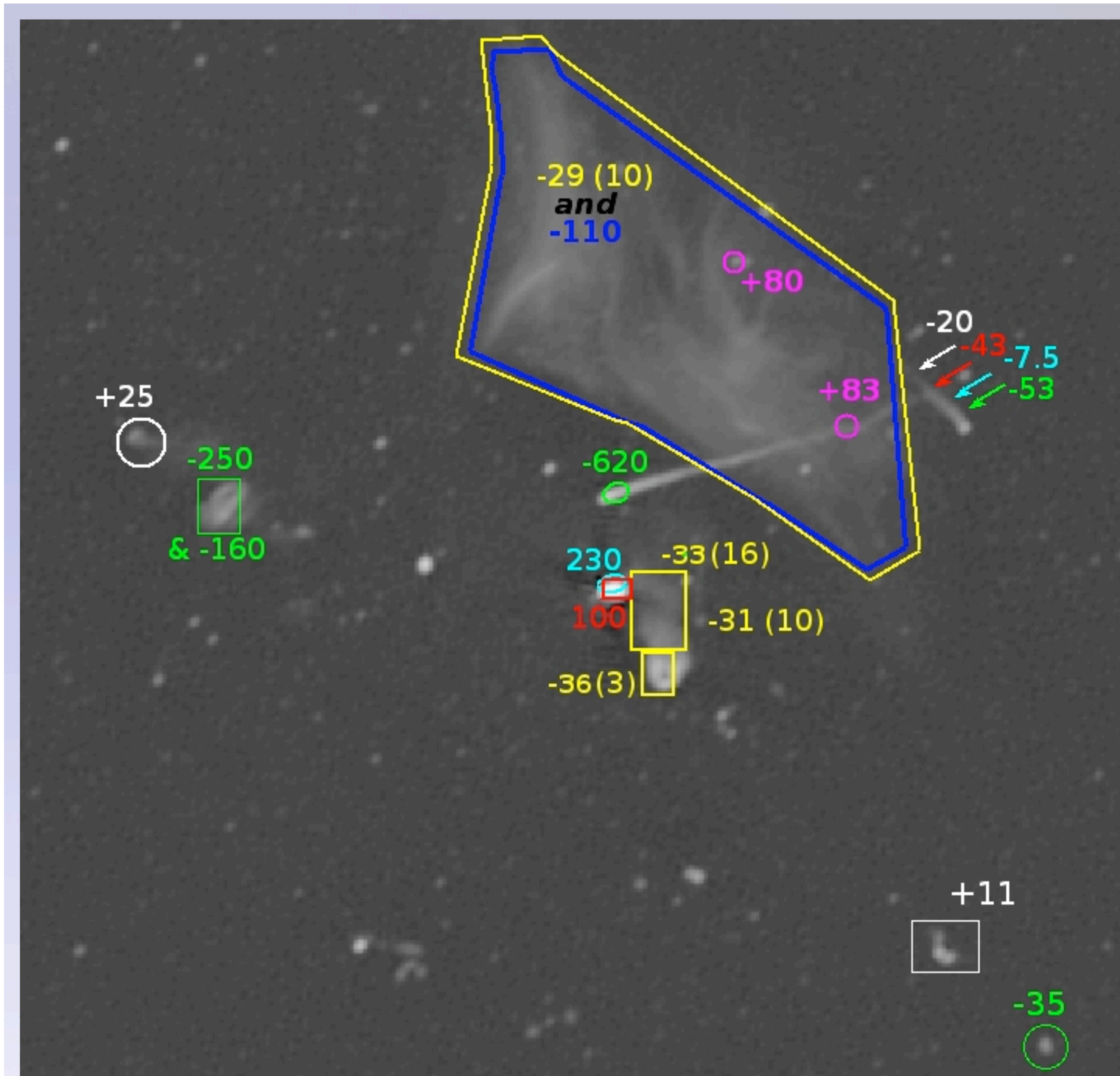
Jeltema & Profumo 2010

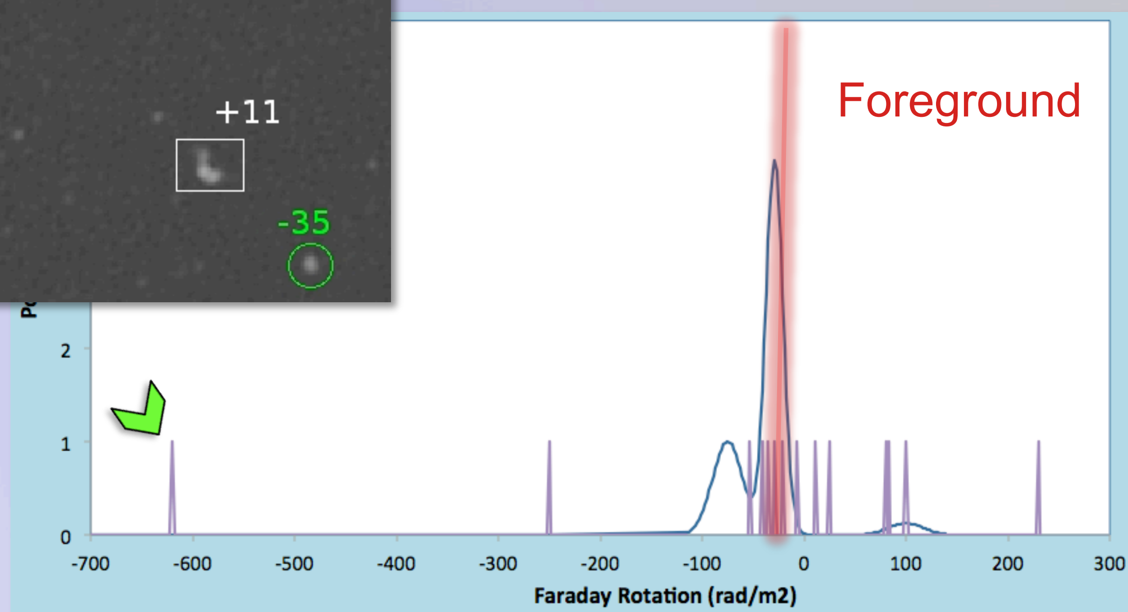


observationally most interesting cases correspond to clusters with large radio emissivities featuring soft spectra. Estimates of the central magnetic field values for those clusters are larger than, or close, to the largest magnetic field values inferred from Faraday rotation measures of clusters, placing tension on the hadronic origin of radio halos. In most cases, however, we find that the *Fermi* data do not *per se* rule out hadronic models for cluster radio halos as the expected gamma-ray flux can be pushed below the *Fermi* sensitivity for asymptotically large magnetic fields. We also find that cosmic rays do not contribute significantly to the cluster energy budget for nearby radio halo clusters.

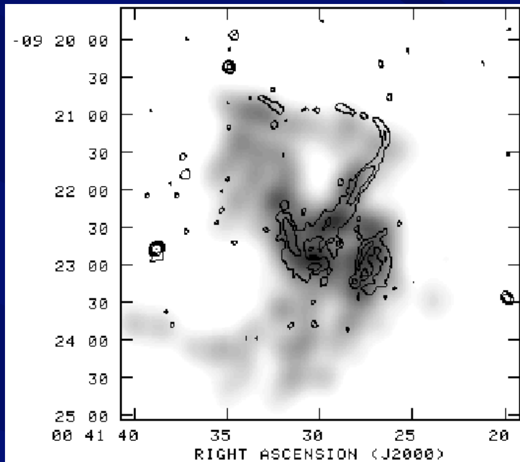
A2256 RMs

- NOT a single/simple distribution



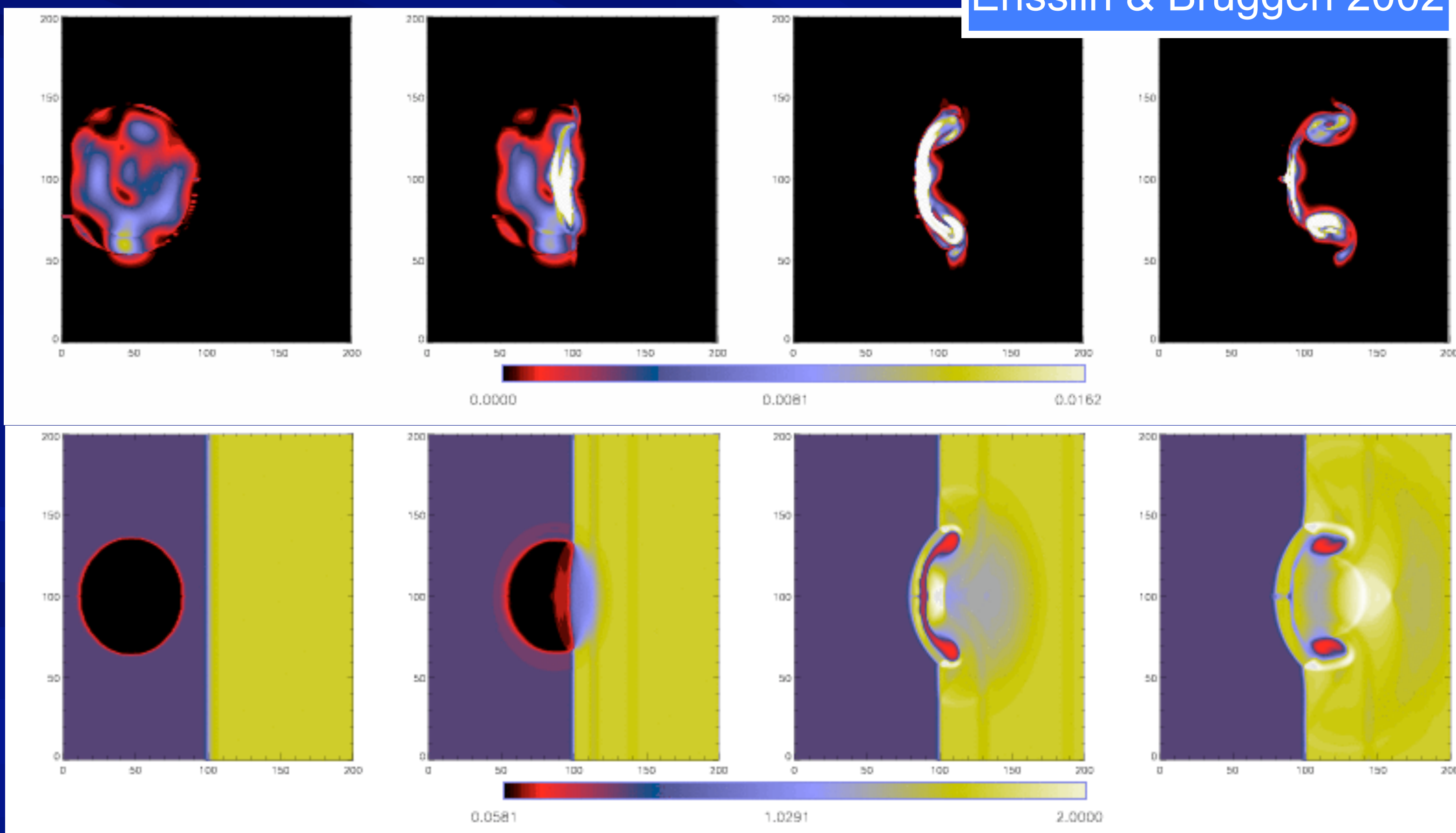


(from L.Rudnick)

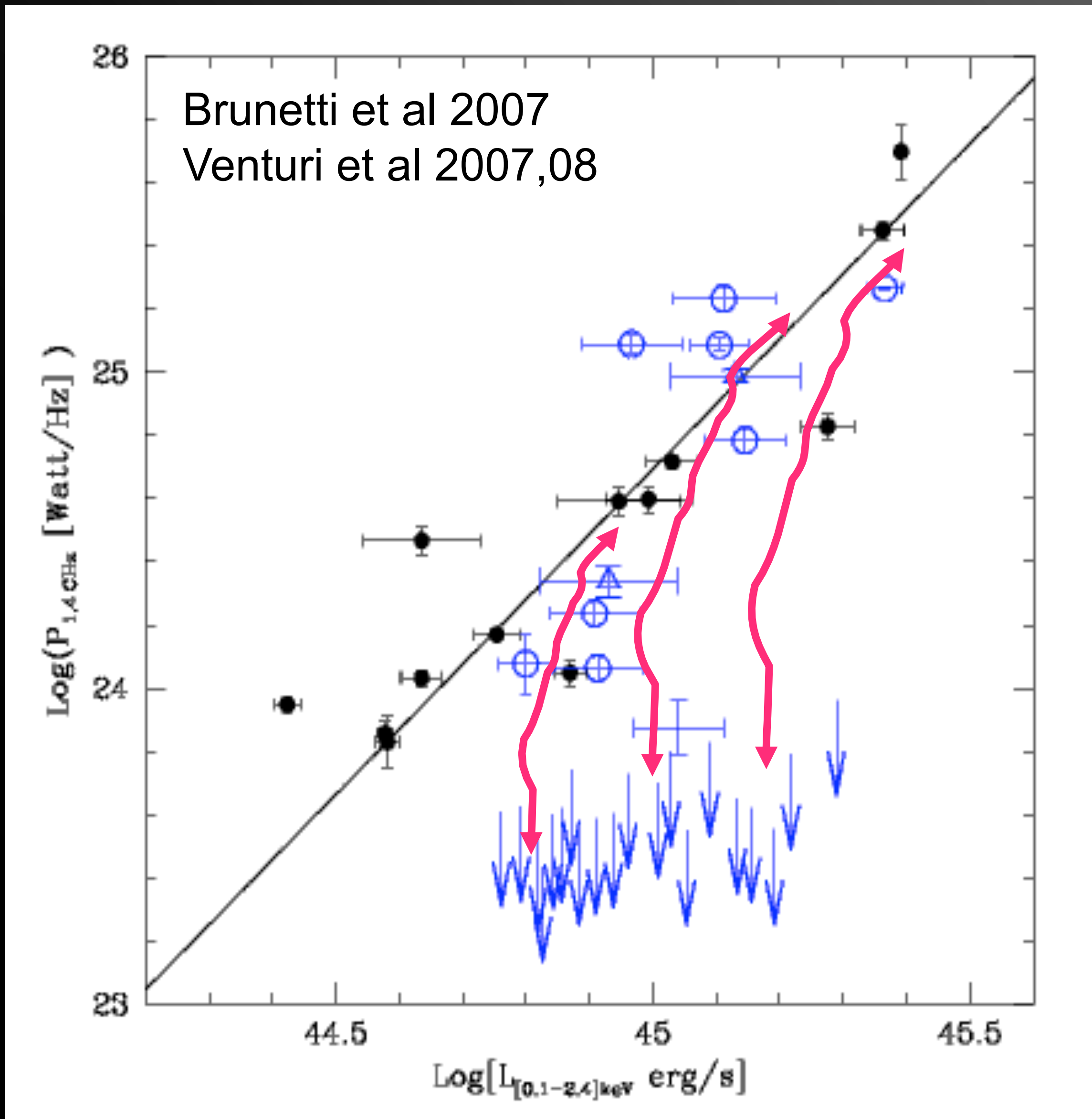


Large Scale Shocks may efficiently boost up Ghost-radio plasma via ***adiabatic compression*** in case this plasma is not efficiently mixed with the IGM (Ensslin & Gopal-Krishna 2001)

Ensslin & Bruggen 2002



Cluster's radio evolution !



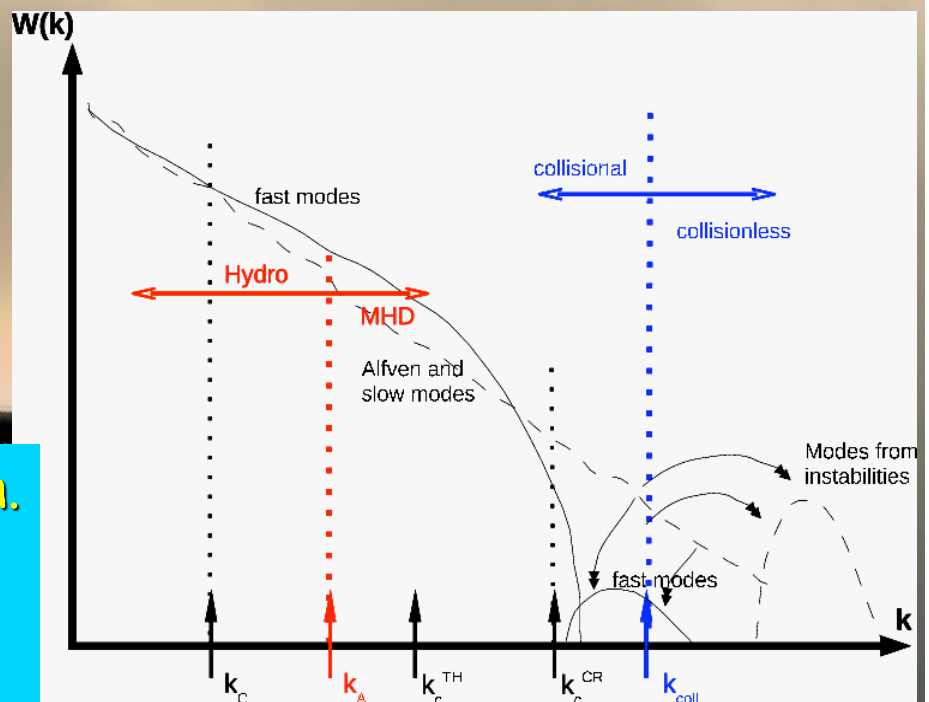
Constraints on :

- CRe evolution
- B evolution

Brunetti +al 2007, 09
Kushnir +al 2009
Keshet & Loeb 2010

Collisionless OR collisional ??

Which is the fraction of E_{tur} available for CR acceleration ?



It does not imply stronger acceleration.
$T_{acc} \approx 10^{7-8}$yrs due to back-reaction of CR on turbulence.
$T_{acc} \approx 10^{8}$yrs at equipartition $E_{tur} \approx E_{CR}$

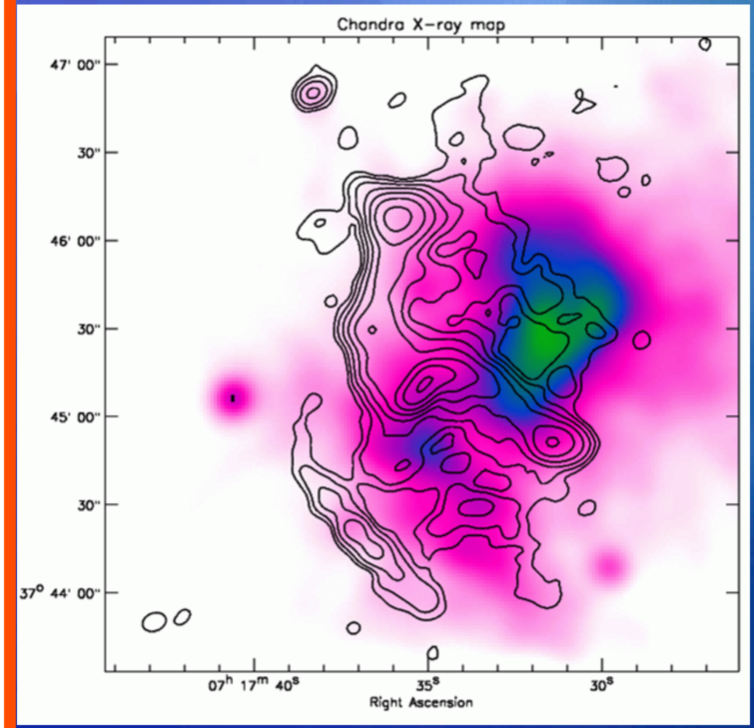
Eventually gamma-ray limits may be used to constrain turbulent energy

Dominant damping : CR
Large fraction to CR

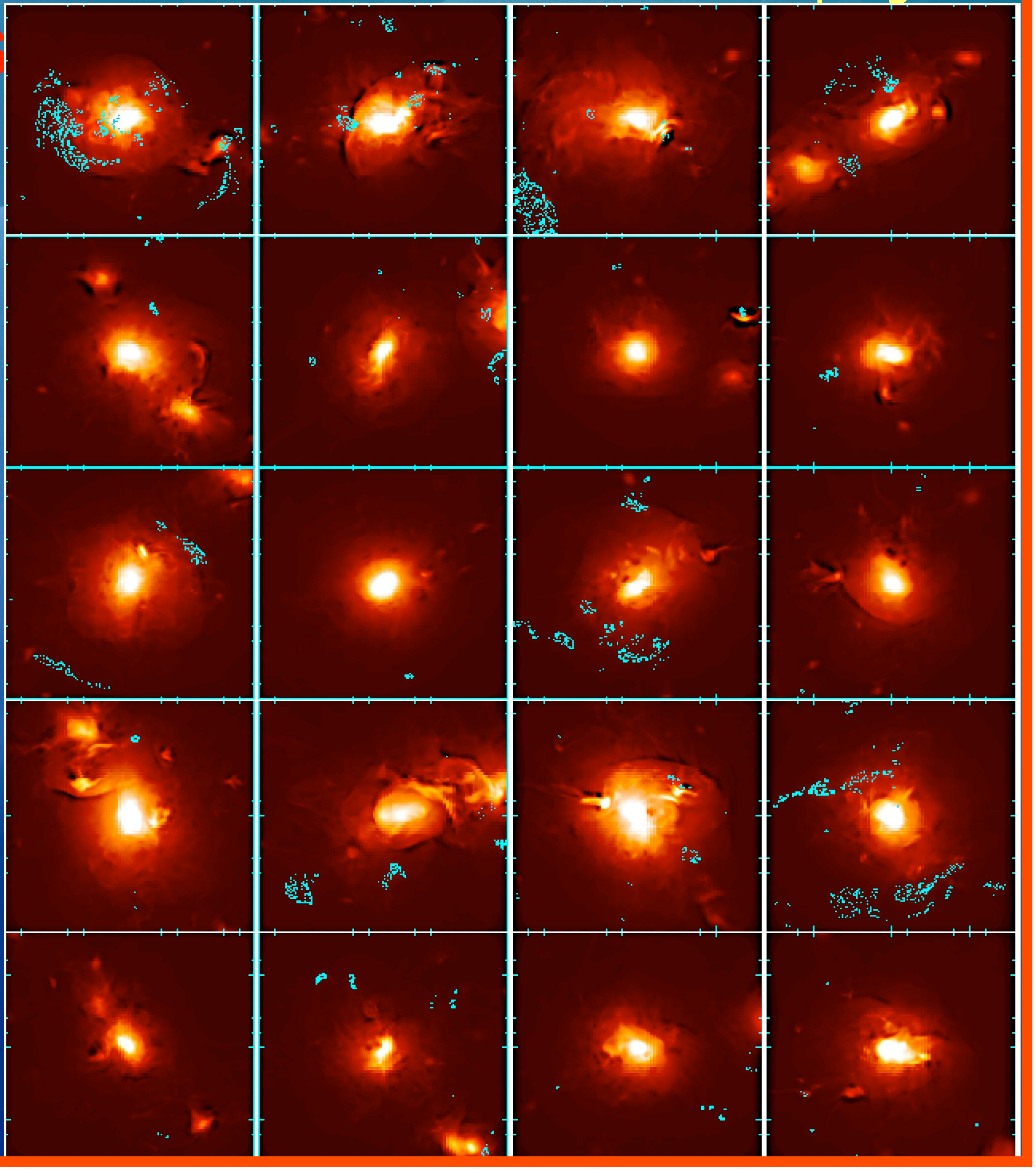
Contamination by shocks

Sarazin 1999
Berrington & Dermer 2003
Hoeft & Bruggen 2007

Vazza, GB +al in progress



van Weeren et al. 2009
Bonafede et al. 2009



Hypothesis for formation of radio relics (Hoeft)

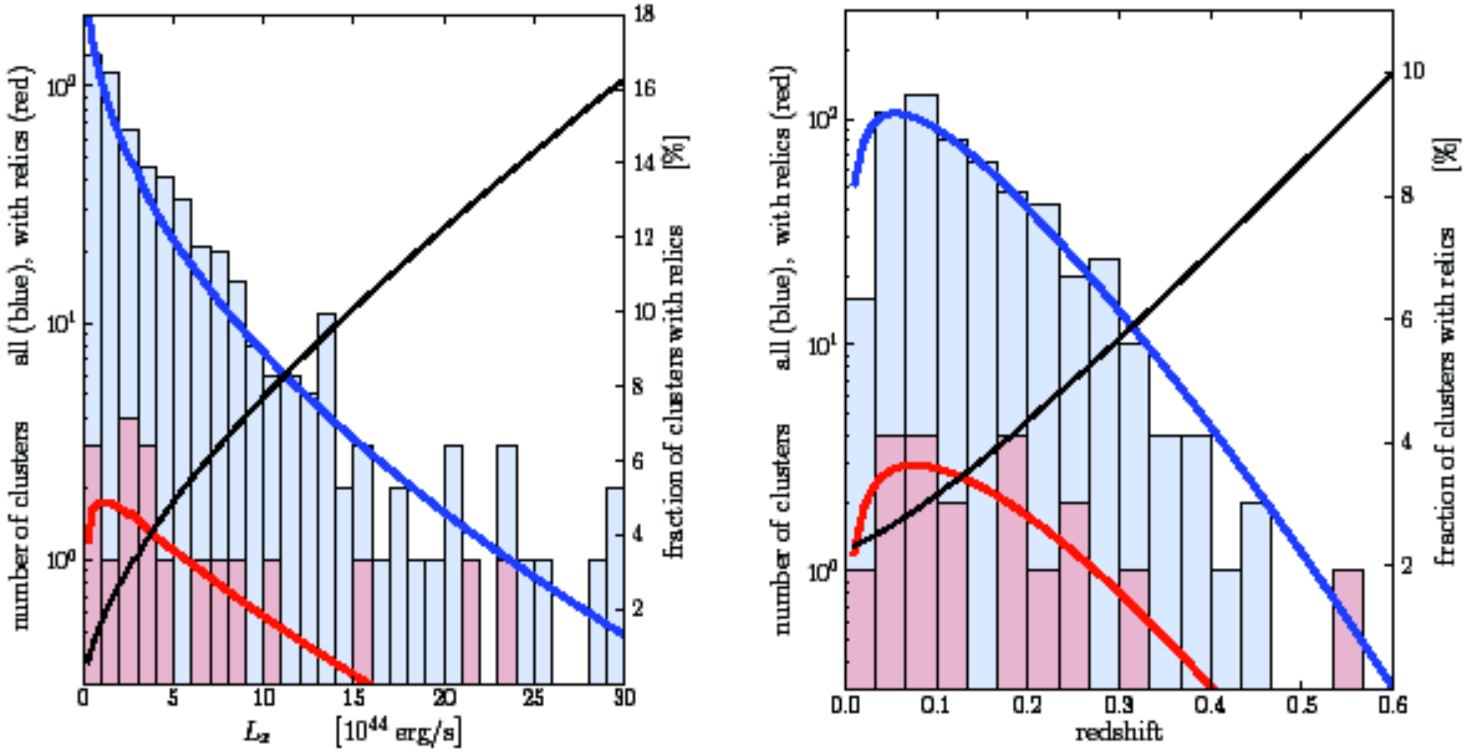
[Ensslin et al. 98]

- radio relics trace cosmological shock waves

- acceleration of thermal electron
  - Alternative: re-acceleration of fossil plasma ('phoenix')
- DSA is applicable (-> slopes -1.0 - 1.5)
- downstream aging due to synchrotron and Inverse Compton losses (-> spectral index variations)
- shock compresses plasma including B-field (-> polarization)

X-ray limited cluster sample

(Hoeft)



- NORAS + REFLEX sample
- fraction of clusters with relic: 3.6%
- S_{thres} = 15 mJy

??

Efficiency constrained from the comparison between observations and simulations

Hypothesis for formation of radio relics (Hoeft)

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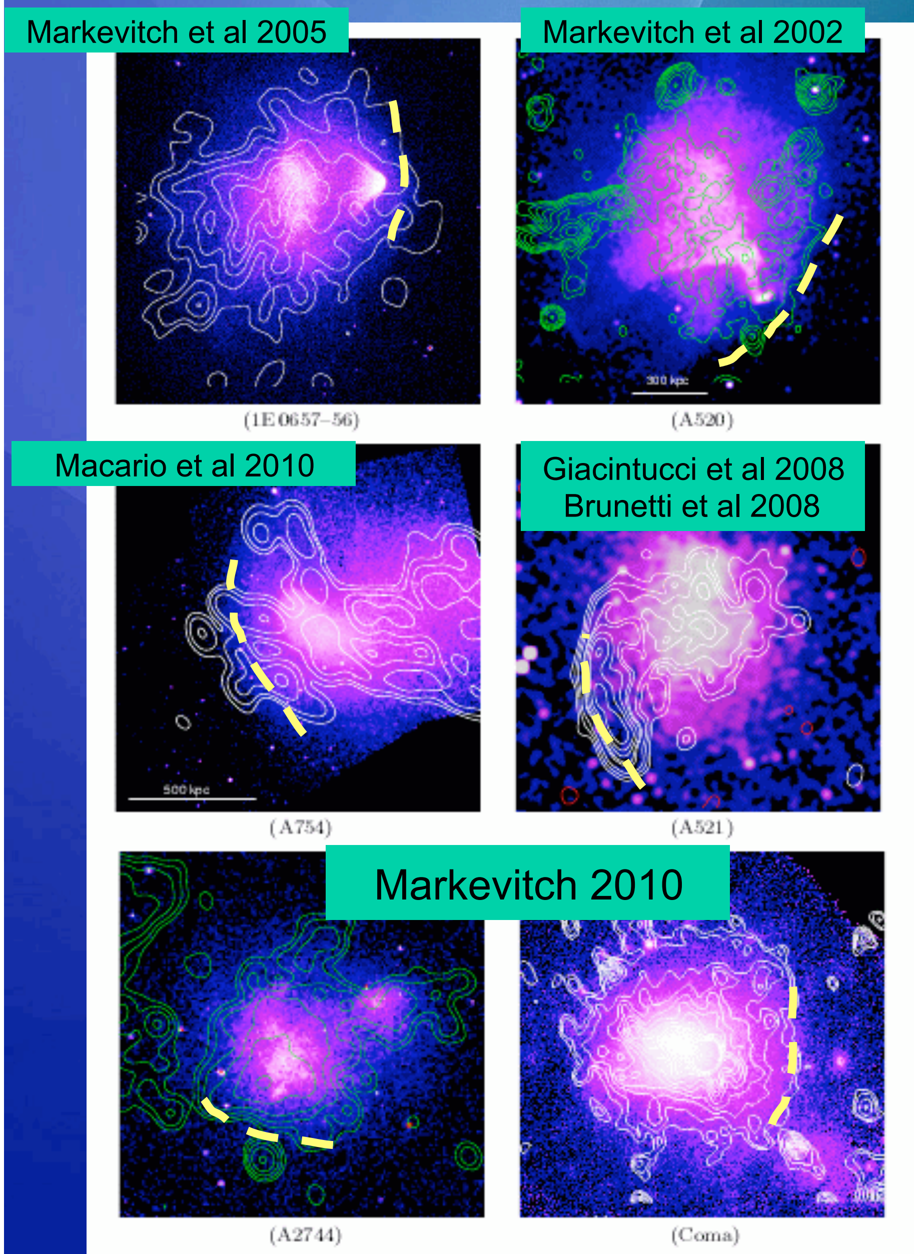
The efficiency of CRe acceleration is probably < 0.0001 !
Why not REacceleration ?
We may need clear-cut cases where the Syn+IC luminosity is >> Energy (rate) dissipated at shocks (see Sarazin talk at Nice)

Relic—Halo connection : direct or "in"direct ??



Not direct :

e.g. both halos (turbulence?) and relics (shocks?) are generated in connection with mergers

Direct :

e.g. the passage of a shock affects the micro-physics of the ICM and trigger particle acceleration mechanisms