Cosmic rays in galaxy clusters & non-thermal emission

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OUTLINE

- Intro & physics of CRs in galaxy custers
- Magnetic CRs confinement & gamma-rays
- Radio Relics
- Radio Halos

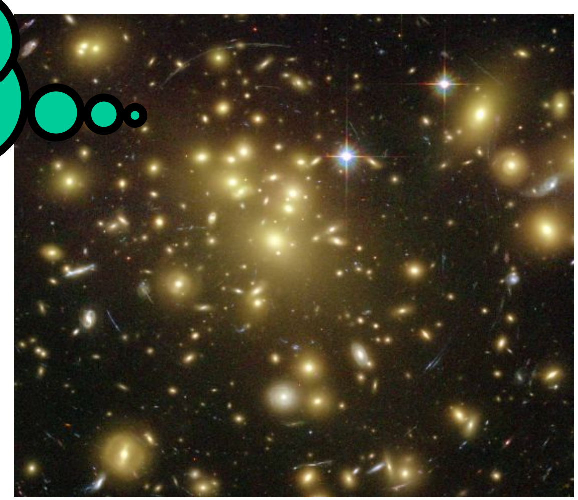
Clusters scale radio sources as probes of CRs physics

- Beyond radio : nonthermal emission on "18 decades" in frequency

Clusters of galaxies:

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

≈30-300 galaxies

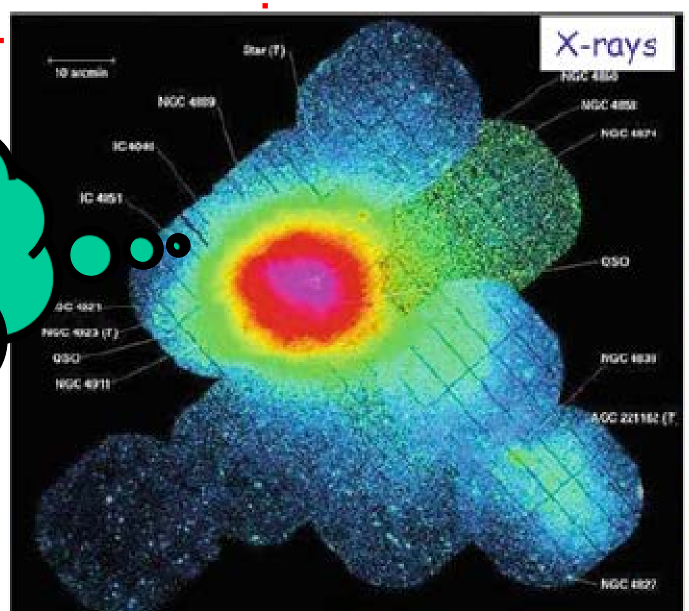


Galaxy cluster matter :

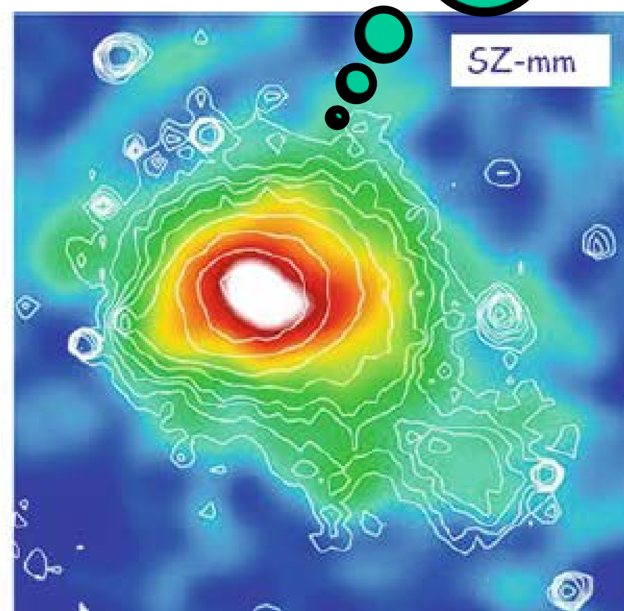
Barions
- 10% of stars in galaxies
- 15-20% of hot diffuse gas

Dark Matter 70%

$\sim \int n_e T dl$



$\sim \int n_e^2 dl$



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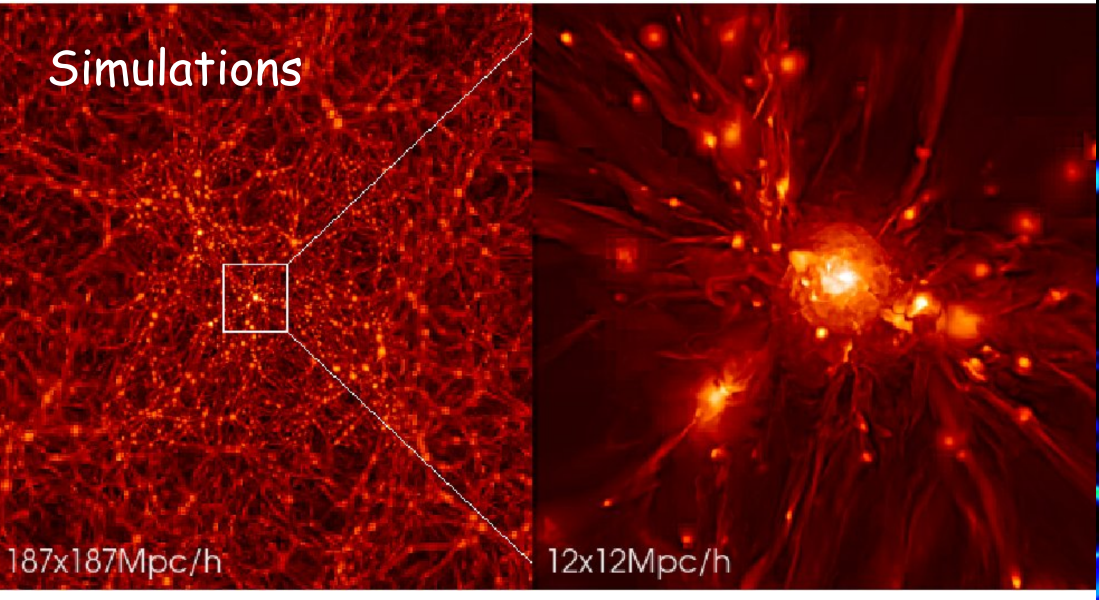
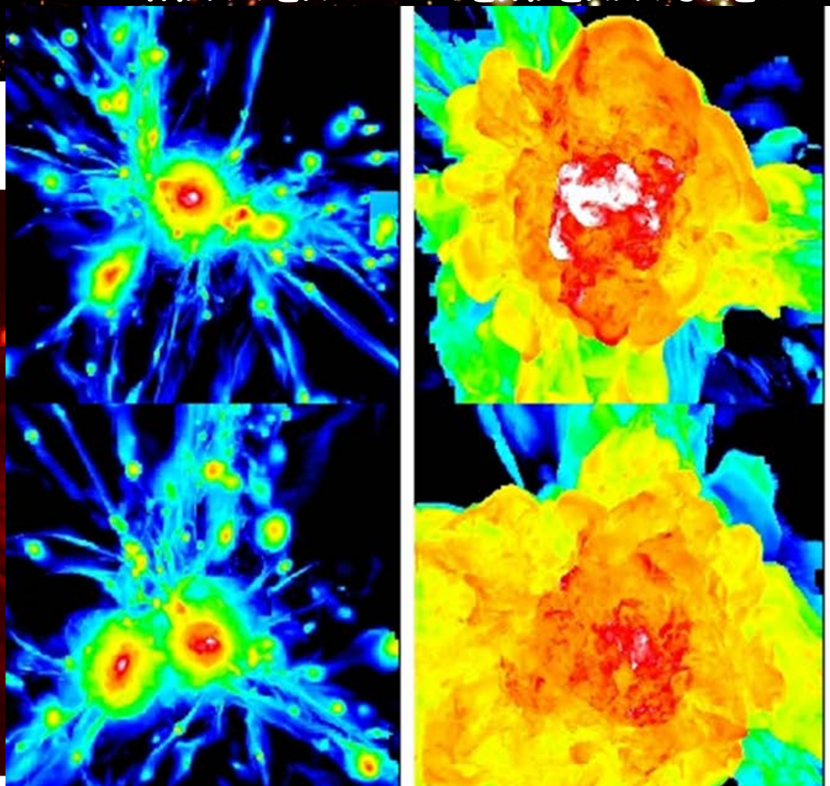
Clowe et al. 06



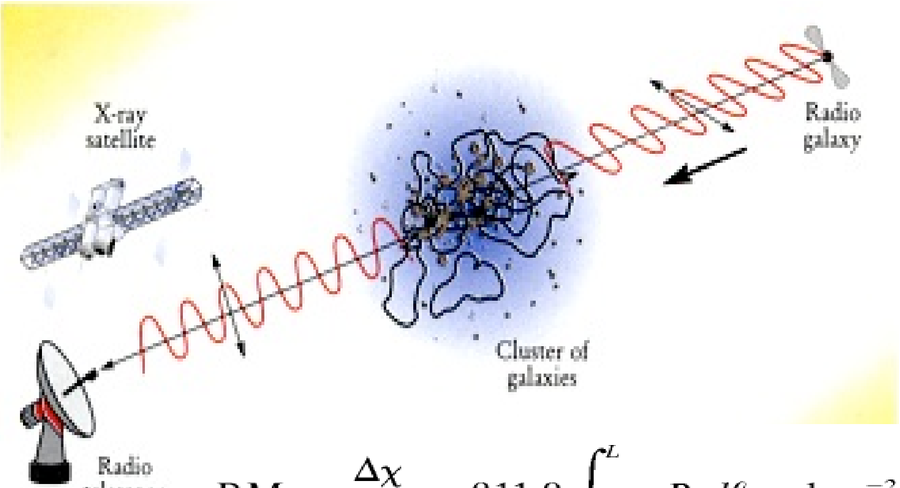


The ICM is magnetised

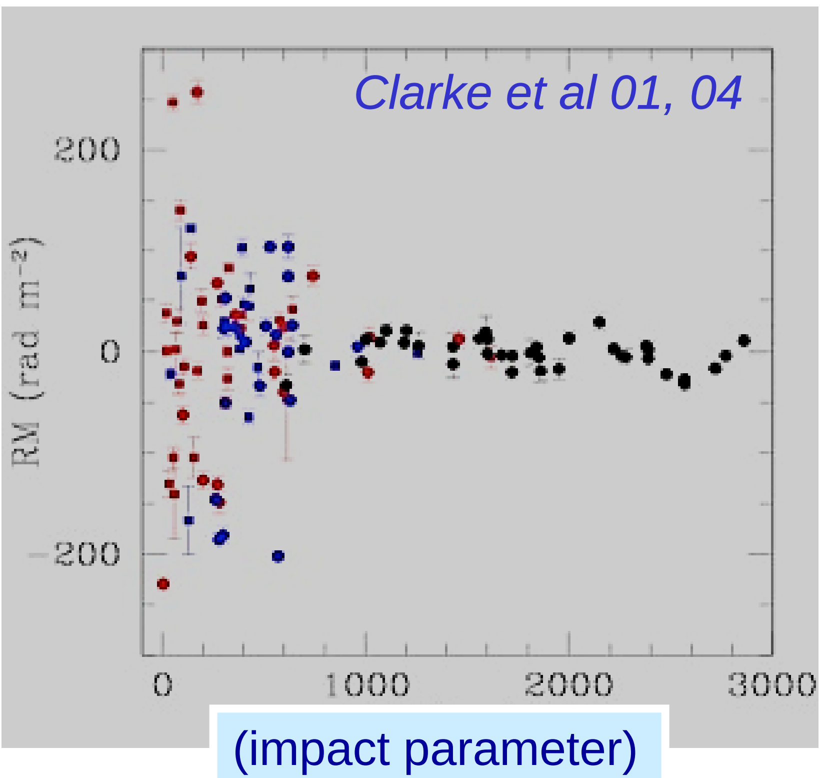
- $B \approx$ few μG
- scales $\approx$ 0.3/few-100 kpc

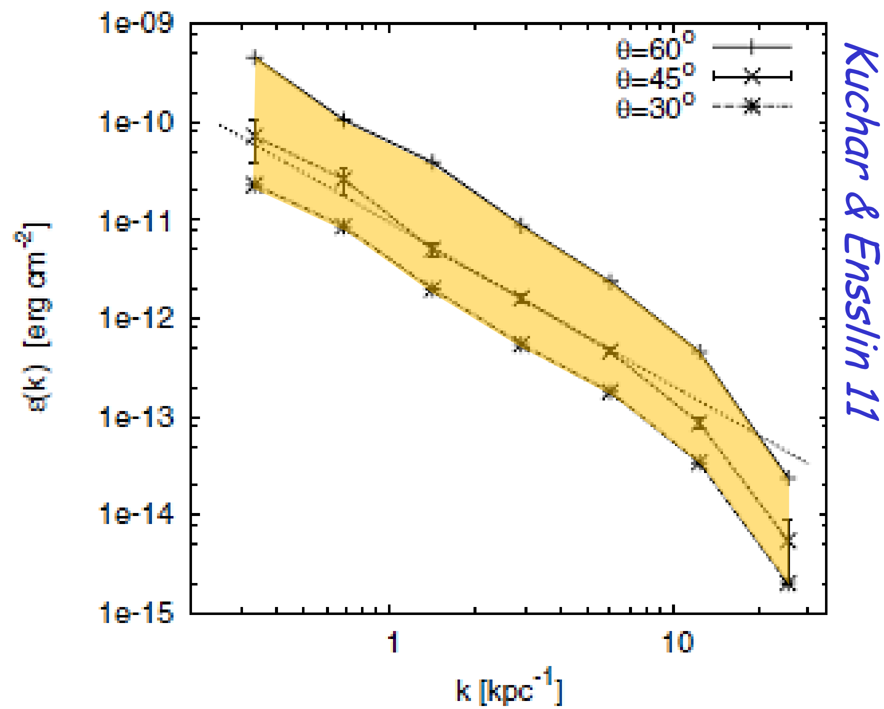
Magnetic field in the ICM is advected by super-Alfvenic (sub-sonic) motions.
(Subramanian et al 06, Brunetti & Lazarian 07, …)

RM are probes of ICM turbulence
(Murgia et al 04, Govoni et al 05, Bonafede et al 10, …)



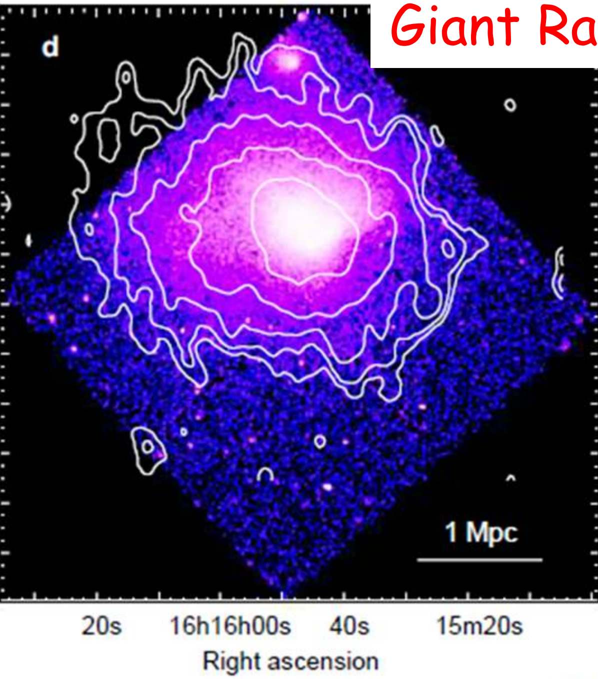
$$\mathrm{RM} = \frac{\Delta\chi}{\Delta\lambda^2} = 811.9 \int_0^L n_e B_\parallel d\ell \ \mathrm{rad\ m^{-2}},$$

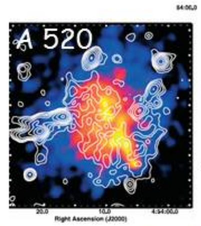


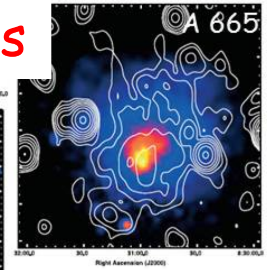


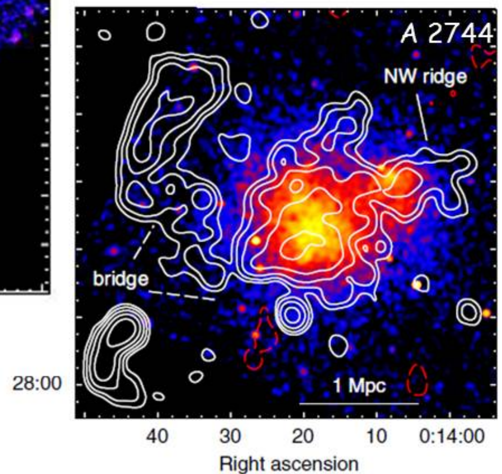
Cluster-scale radio emission

Giant Radio Halos







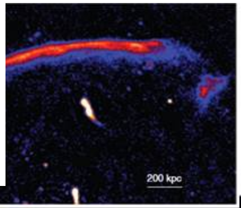


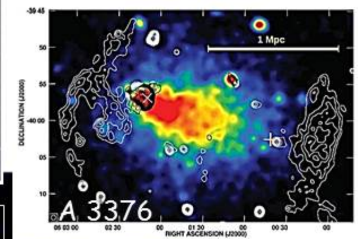
- ❑ Steep spectrum sources
- ❑ Low brightness

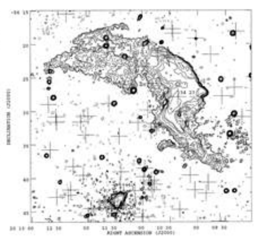
Synchrotron radiation FROM the ICM

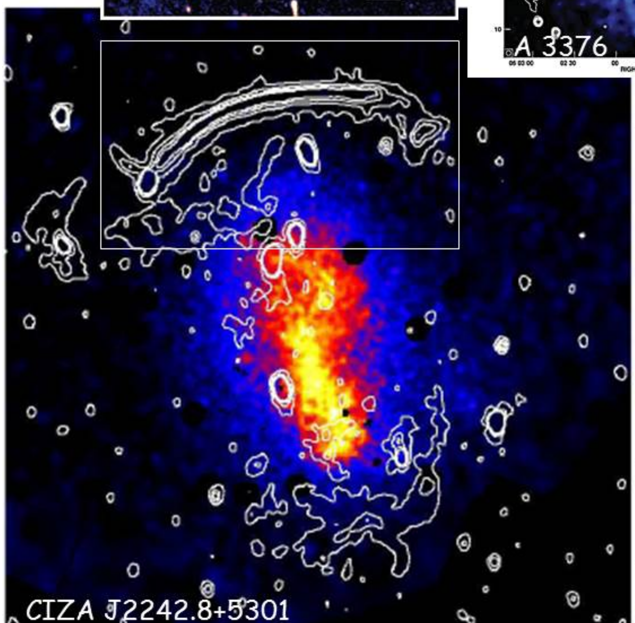
Relativistic electrons (protons?) and B distributed on Mpc-scales…

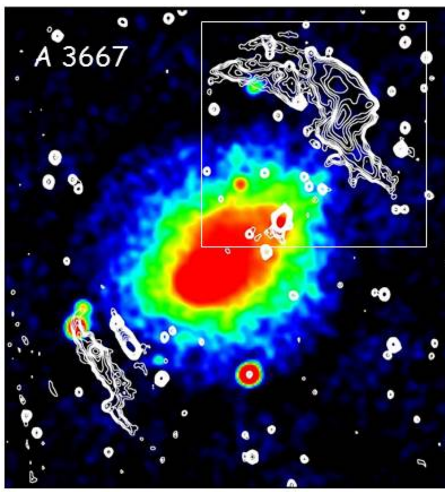
Giant Radio Relics











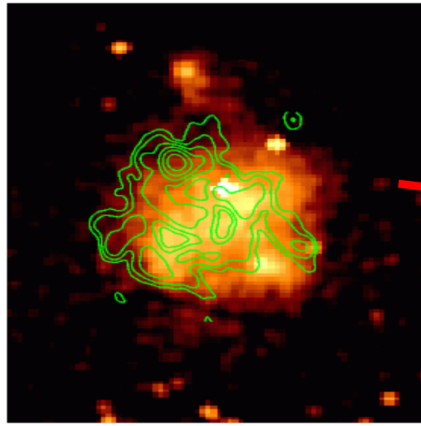
Mechanisms operating within clusters drain energy into relativistic particles and magnetic field

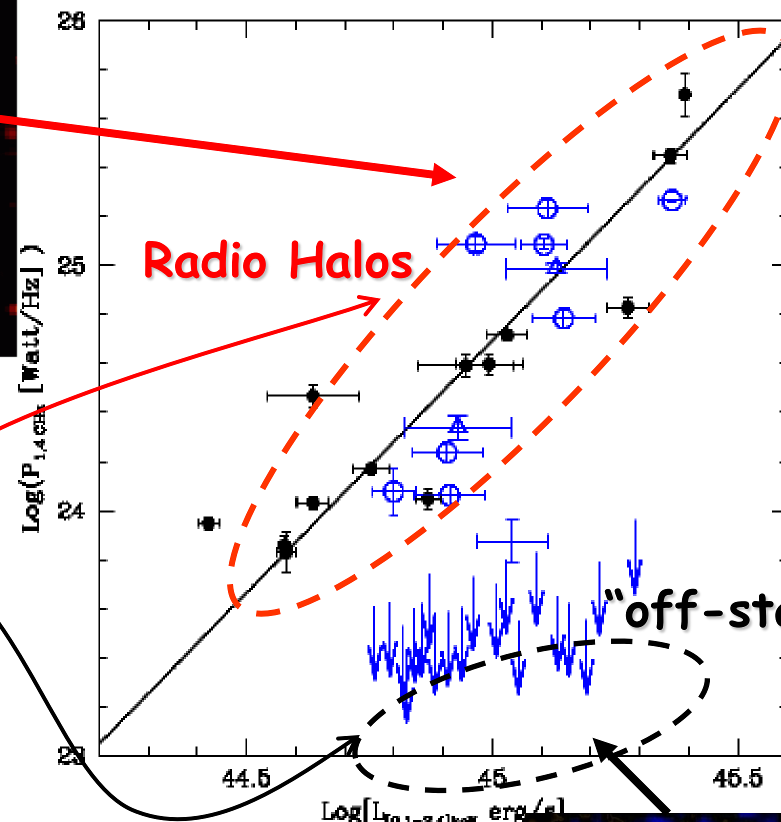
- ➢ IMPACT on thermal ICM ?? (microphysics & dynamics)
- ➢ ORIGIN & Physics ??

Cluster mergers – NT connection

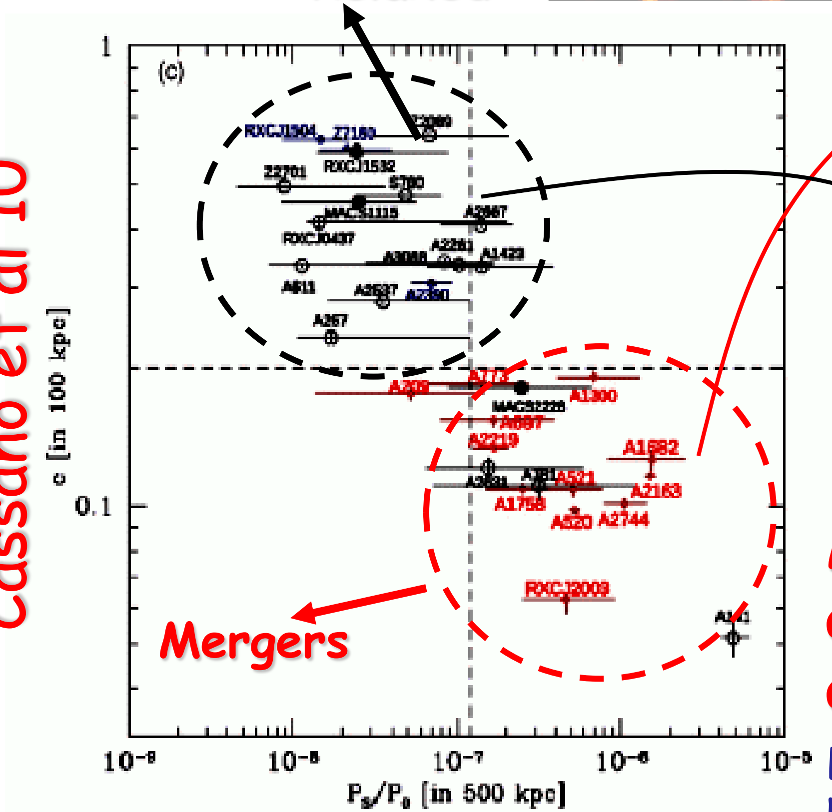
Venturi et al 08, Brown et al 11
Basu 12, Cassano et al 13,
Sommer & Basu 14

Radio halos probe the dissipation of kin energy in the DM-driven merger events into CRs and B

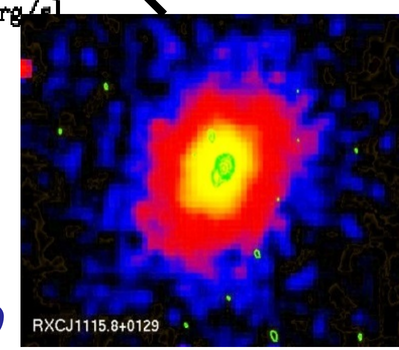




Brunetti et al 07,09

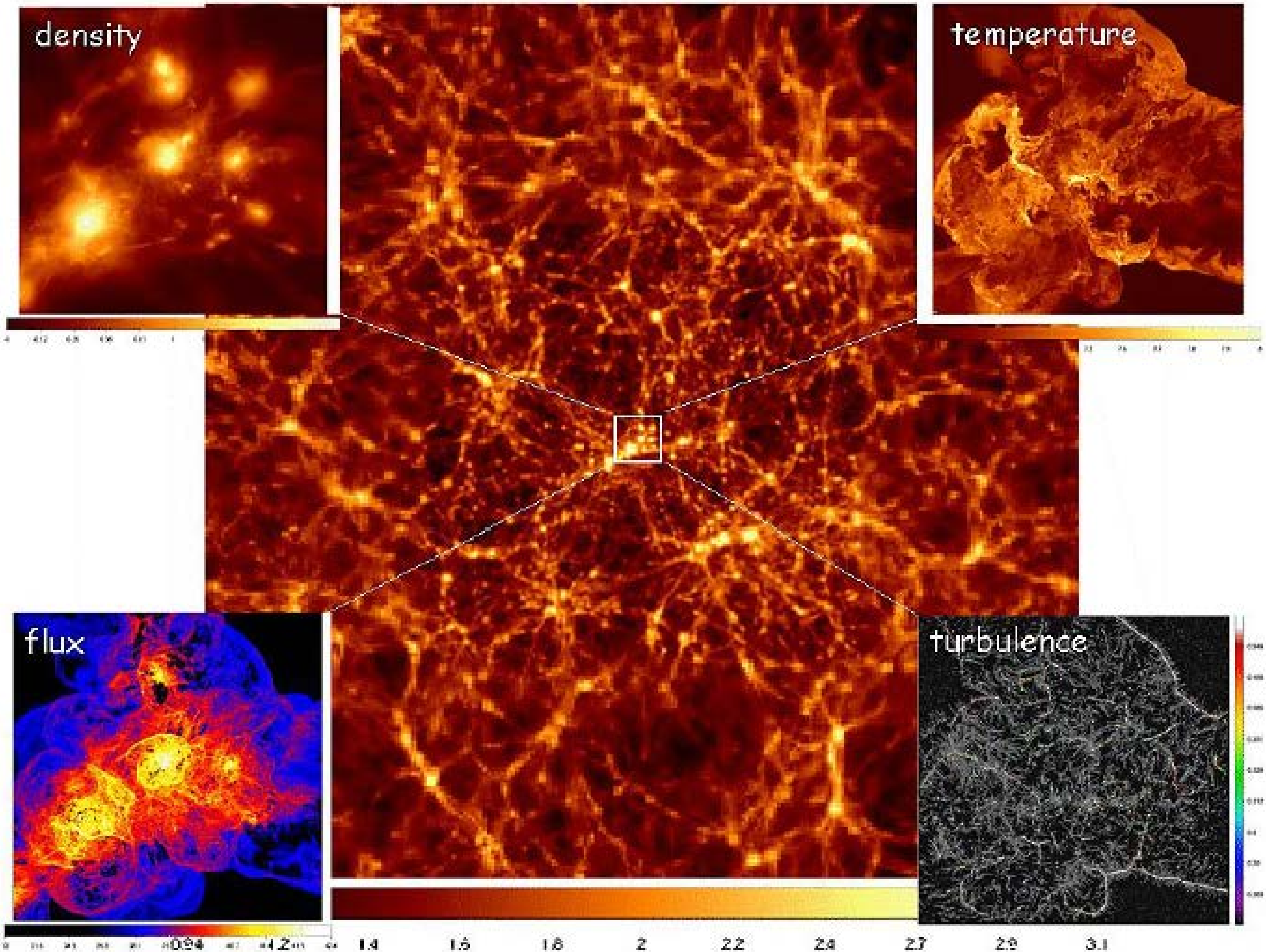


Cassano et al 10



Mergers guide CRe acceleration/dynamics and/or amplify B

Brunetti 07, 09 Kushnir et al 09
Ensslin et al 11 Wiener et al 13


density
temperature
flux
turbulence
0.94
1.2
1.4
1.6
1.8
2
2.2
2.4
2.7
2.9
3.1

Turbulence

Pitch-angle scattering

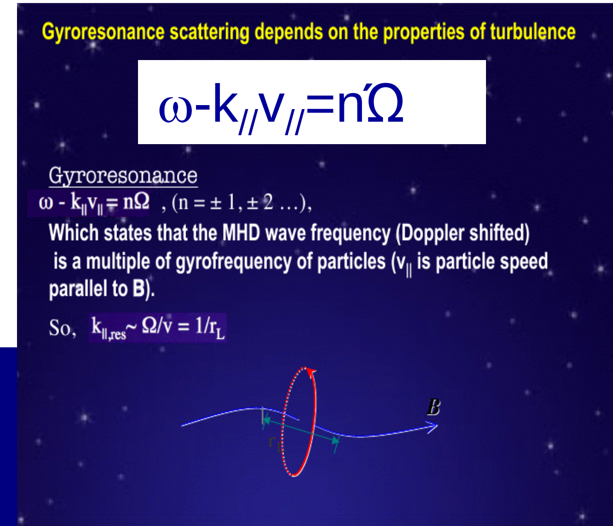
$$D_{\mu\mu} \equiv \lim_{t\to\infty} \frac{1}{2t}\langle \Delta\mu(t)\Delta\mu^*(t+\tau)\rangle = \Re\int_0^\infty d\tau \langle \dot\mu(t)\dot\mu^*(t+\tau)\rangle \Leftrightarrow \delta B^2$$

$$\tau scatt \approx \frac{\mu^2}{D_{\mu\mu}} \Rightarrow D = \frac{V_{CR}^2}{8}\int_{-1}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}}$$

Acceleration

$$D_{pp} \equiv \lim_{t\to\infty} \frac{1}{2t}\langle \Delta p(t)\Delta p^*(t+\tau)\rangle = \Re\int_0^\infty d\tau \langle \dot p(t)\dot p^*(t+\tau)\rangle \Leftrightarrow \delta E^2$$

$$\tau_{acc} \approx \frac{p^2}{D_{pp}} \quad \overset{\delta E \sim \frac{V_{ph}}{c}\delta B}{\Longleftrightarrow} \quad \tau_{acc} \sim \tau scatt \left(\frac{c}{V_{ph}}\right)^2$$

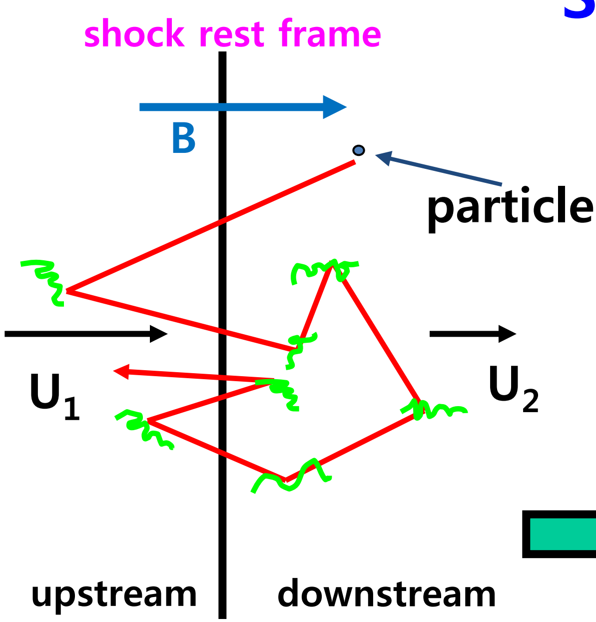


Transit Time Damping (TTD)

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

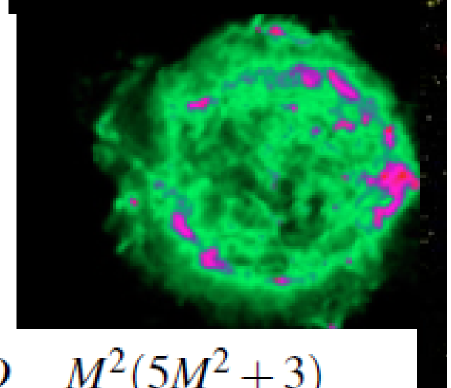
Interaction btw magnetic moment of particles and parallel gradient of B

Shocks

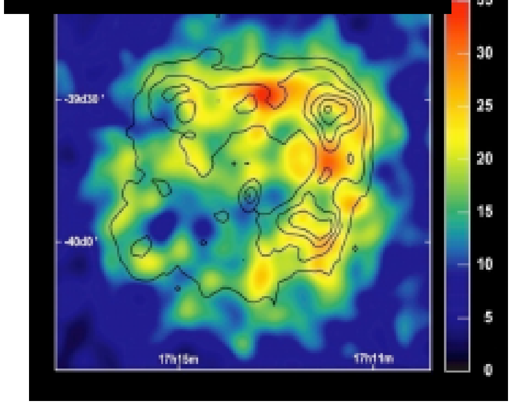


$$\Rightarrow \tau_{acc} \simeq \frac{4D}{V_{sh}^2}\frac{M^2(5M^2+3)}{(M^2+3)(M^2-1)}$$

CRe with E≈GeV

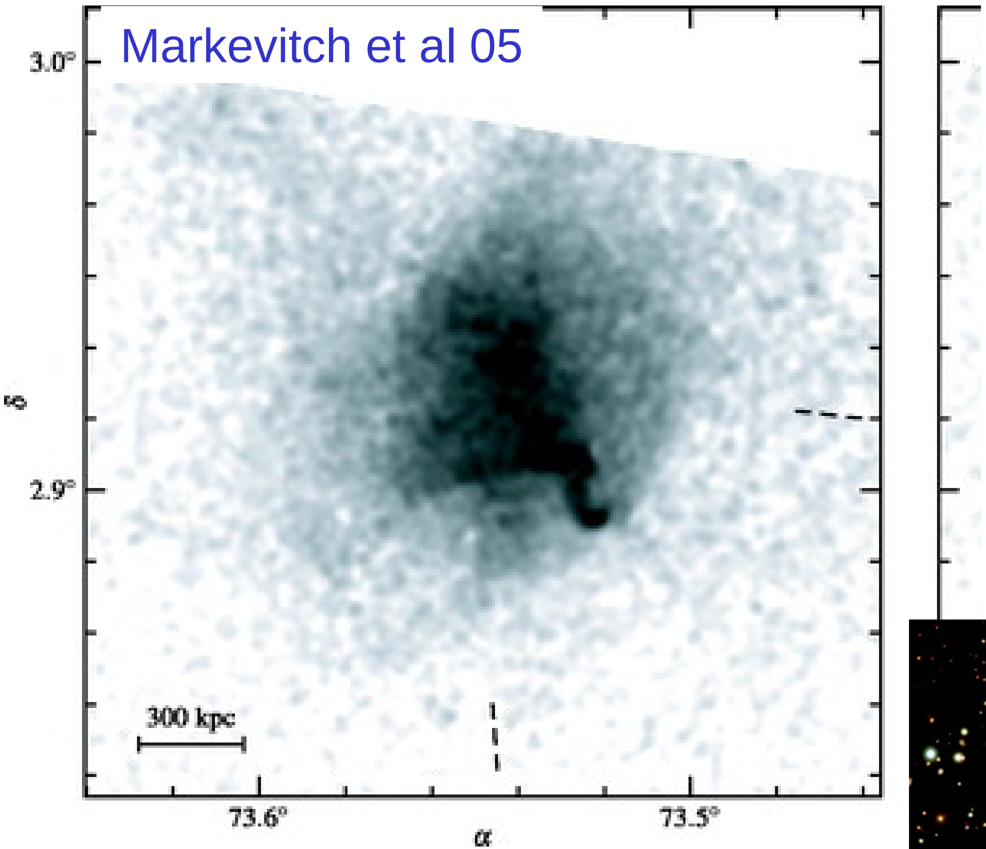


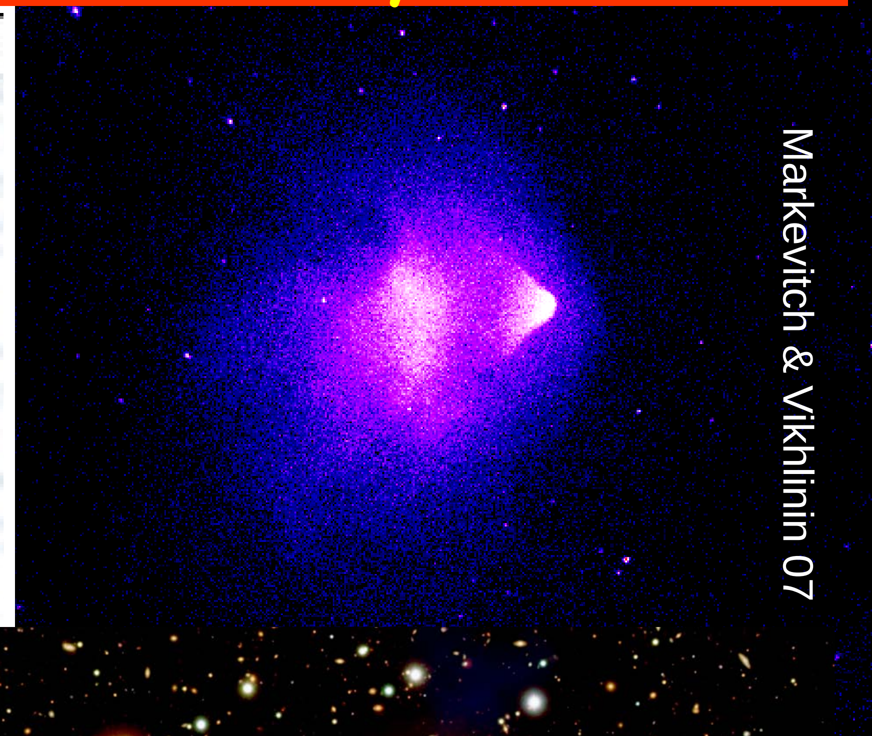
CRs with E≈TeV++

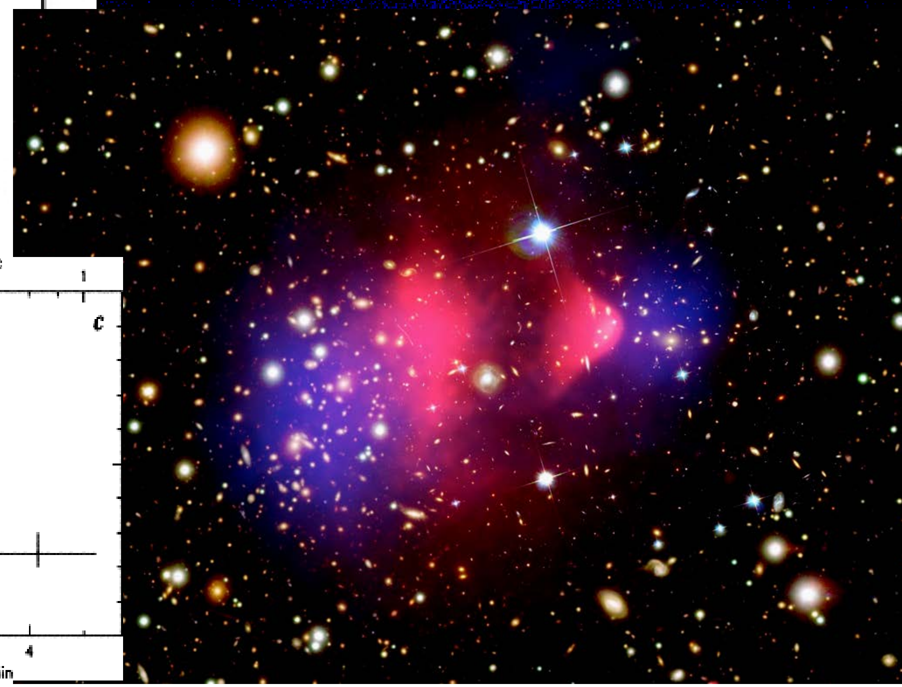


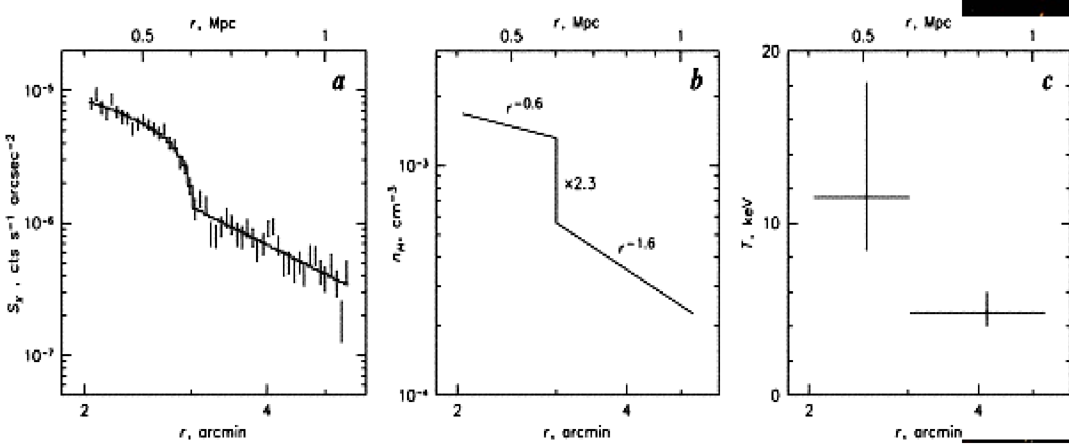
Aharonian et al
Nature (2004)

Shocks “are observed” in Galaxy Clusters



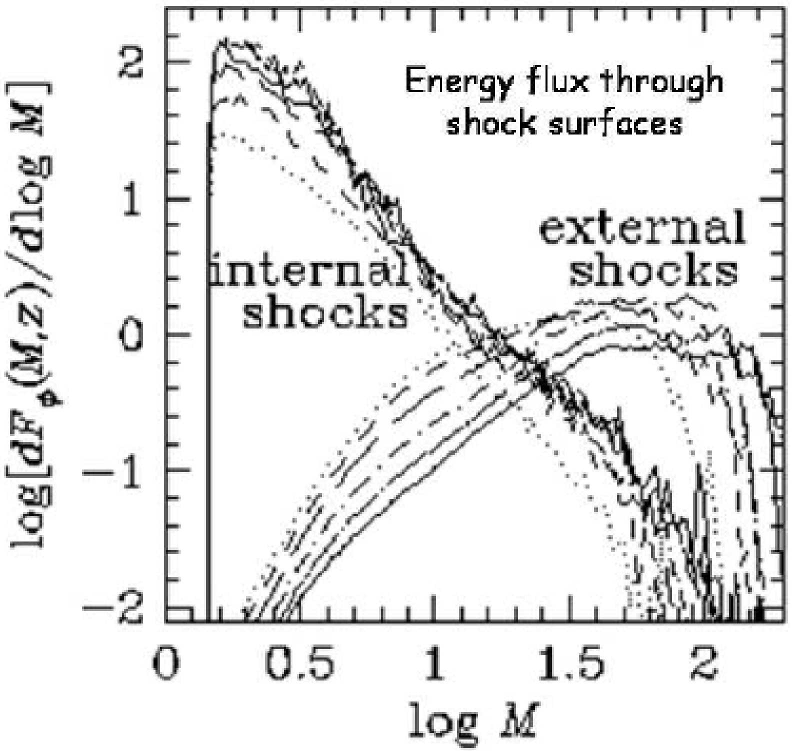




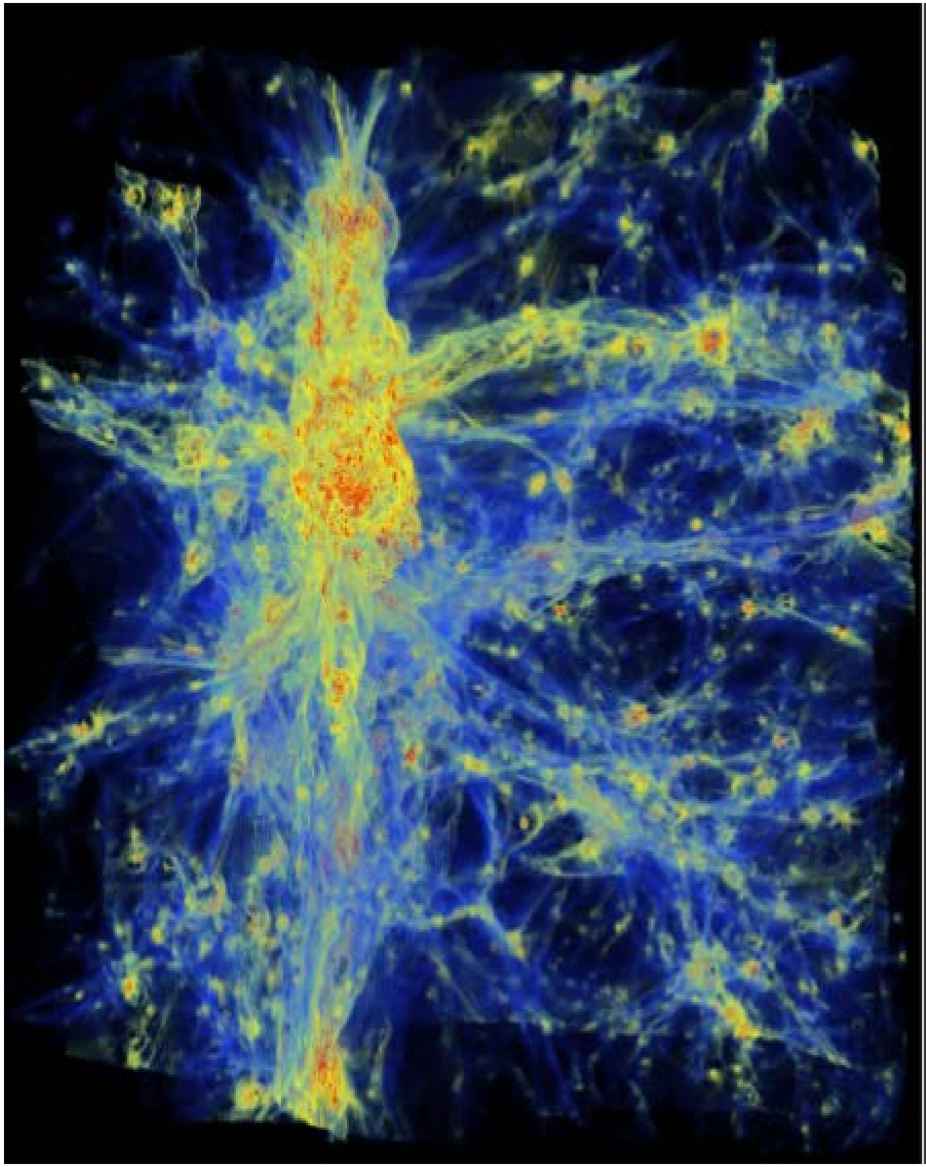


Cosmological Shocks as CRs accelerators

Ryu et al 03



Vazza, Brunetti et al 09

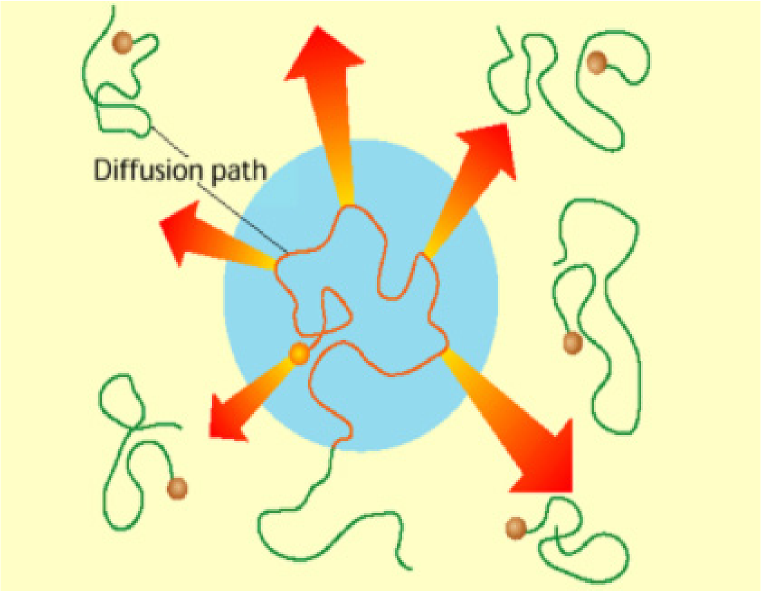


The bulk of ICM heating is due to shocks, so if shock acceleration in the ICM is 10% the resulting CRs would have ..up to.. 0.1 E_{TH}

Cosmic rays confinement

(Voelk et al. 96, Berezinsky et al 97) ...

The size of galaxy clusters allows confinement of CRs… up to very high energies



$$\tau_{diff} \approx \frac{1}{4}\frac{L^2}{D}$$

Time necessary to diffuse on scale = L

$$D \sim \frac{1}{3} c \lambda_{mfp}$$

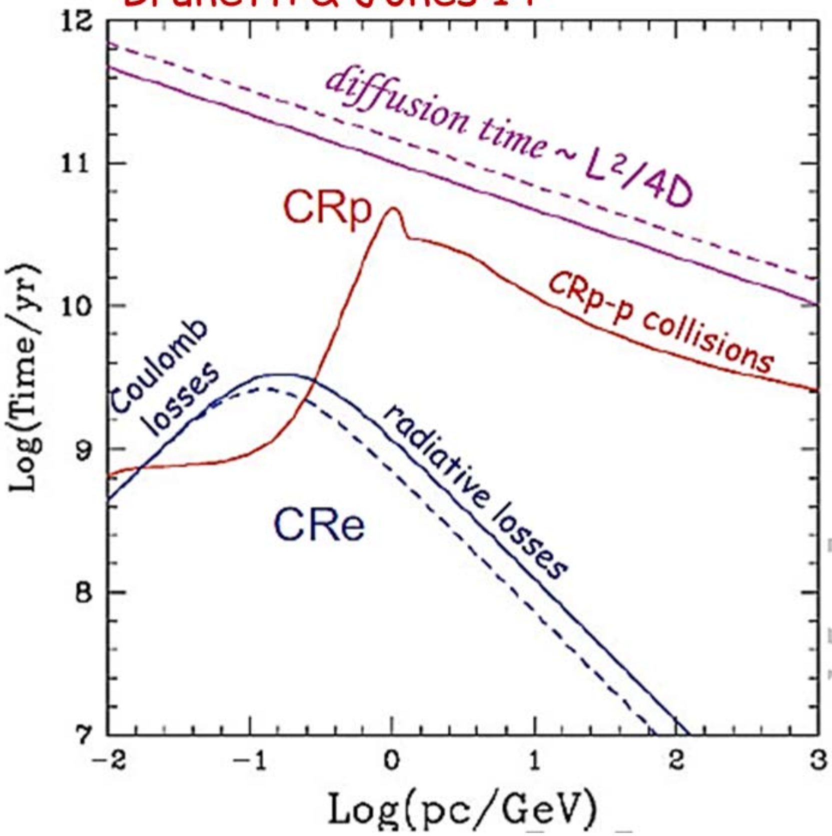
Spatial diffusion coefficient

Escaping from 1 Mpc in few Gyr requires a particles mfp ~ kpc (in our Galaxy the mfp of GeV CRs is 0.01 pc !)

CRs diffusion is mediated by scattering with magnetic field fluctuations and the diffusion coefficient depends on the turbulent properties (see Brunetti & Jones 14 for a rev on the ICM)

Quest for CRp in GC

Blasi, Gabici, Brunetti 07
Brunetti & Jones 14

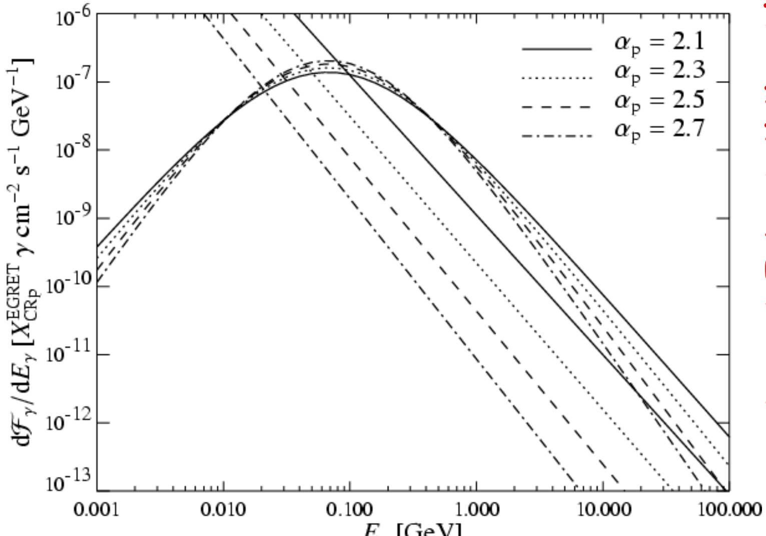


$$X_g \sim n_{ICM} m_p c \tau \sim 1.6 \times \frac{n_{ICM}}{10^{-3}} \times \frac{\tau}{\mathrm{Gyr}} \,\mathrm{g\,cm^{-2}}$$

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

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

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$



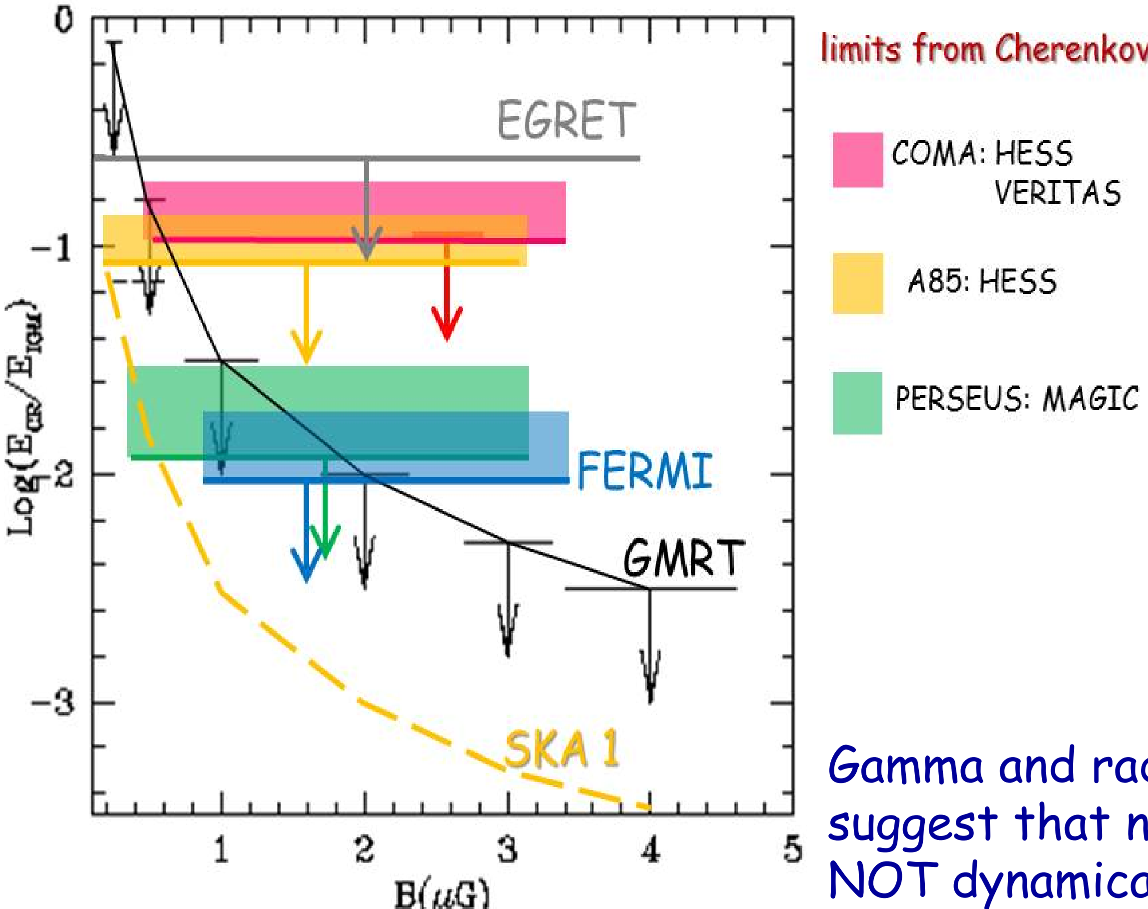
Pfrommer & Ensslin 04

- CRp have LONG life-times in the ICM
- CRp take Hubble+ time to diffuse on Mpc

Cosmic ray protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times

No gamma-rays from GC: limits on CRp

Brunetti & Jones 14



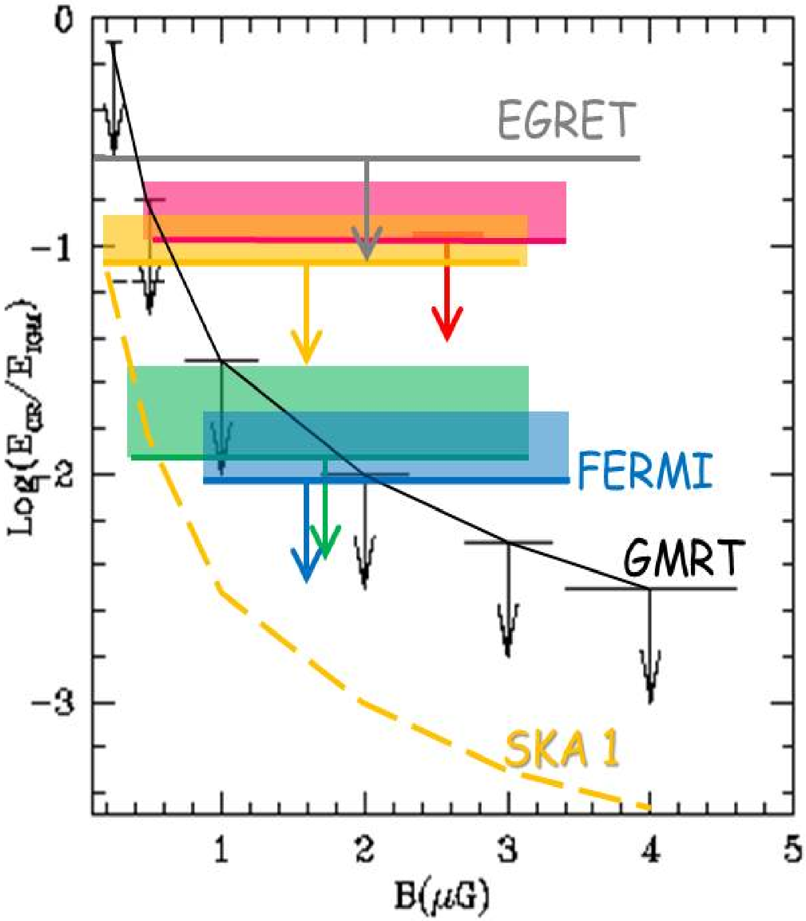
Reimer et al. 03
Reimer et al. 04
Pfrommer & Ensslin 04
Perkins et al. 06, 08
Brunetti et al. 07
Brunetti et al. 08
Aharonian et al. 08 a,b
Aleksic et al. 09,12
Ackermann et al 10,14
Arlen et al 12
Huber et al 13
Prokorov & Churazov 13
Zandanel & Ando 14
Griffin et al 14

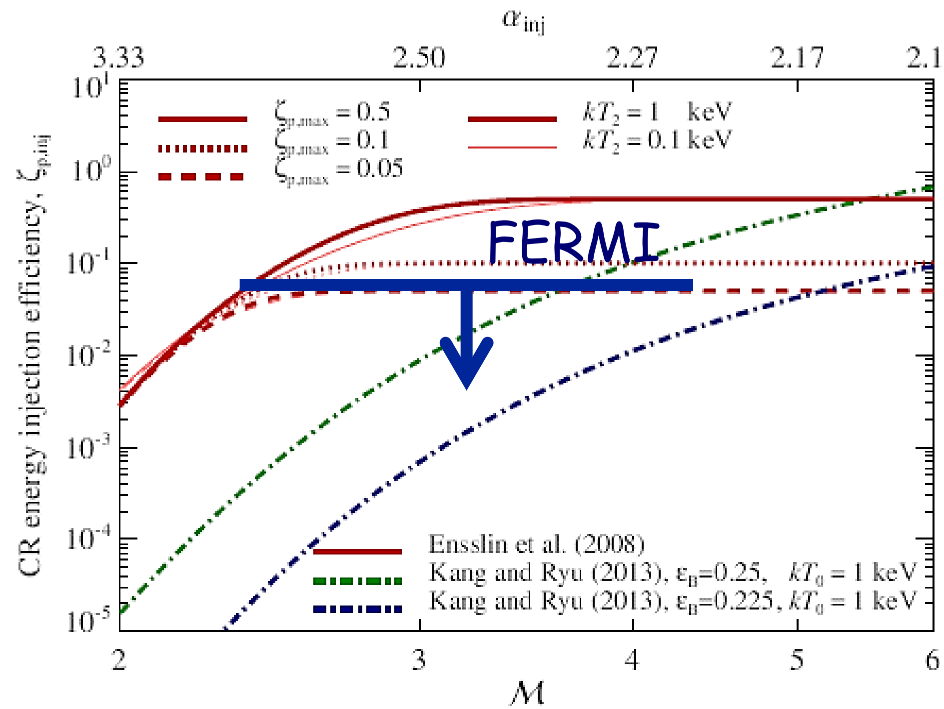
Gamma and radio observations independently suggest that non-thermal components are NOT dynamically important (% level) … at least in the central Mpc-scale regions

This poses fundamental questions/constraints on the efficiency of CRs acceleration in the ICM and on the dynamics of CRs (Brunetti & Jones 14 for review)

No gamma-rays from GC: limits on CRp

Brunetti & Jones 14



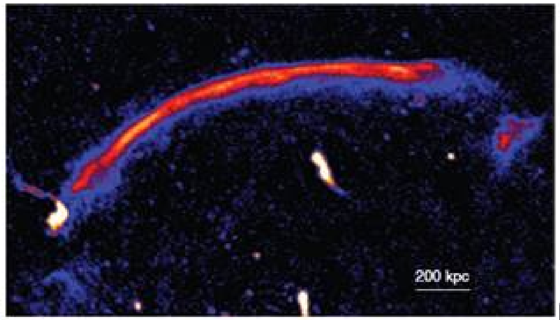


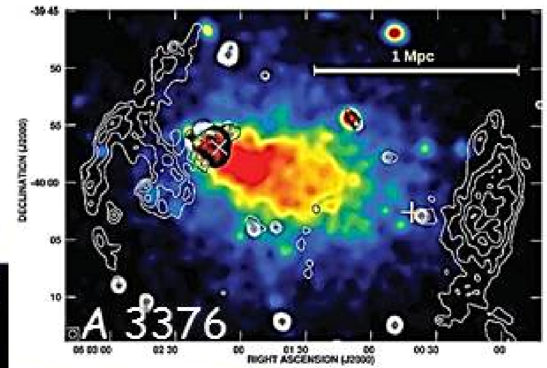
Ackerman et al 14

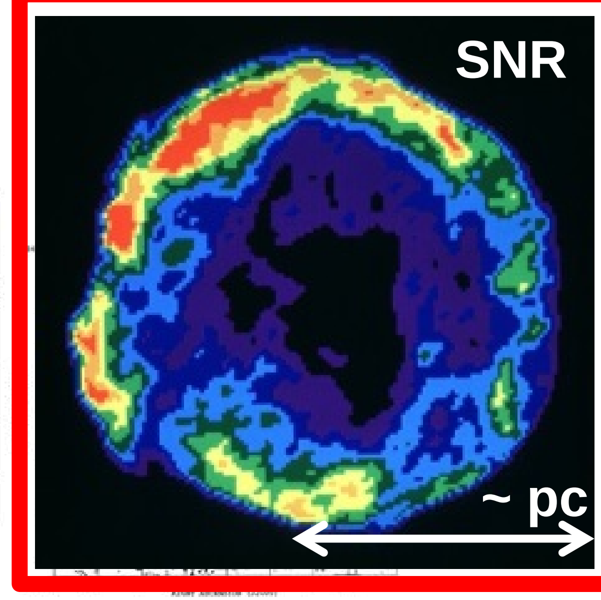
The max acceleration efficiency that is constrained by current Fermi-LAT limits is 3x smaller than that «expected» by «optimistic» models and «boarder line» with more «pessimistic» models.

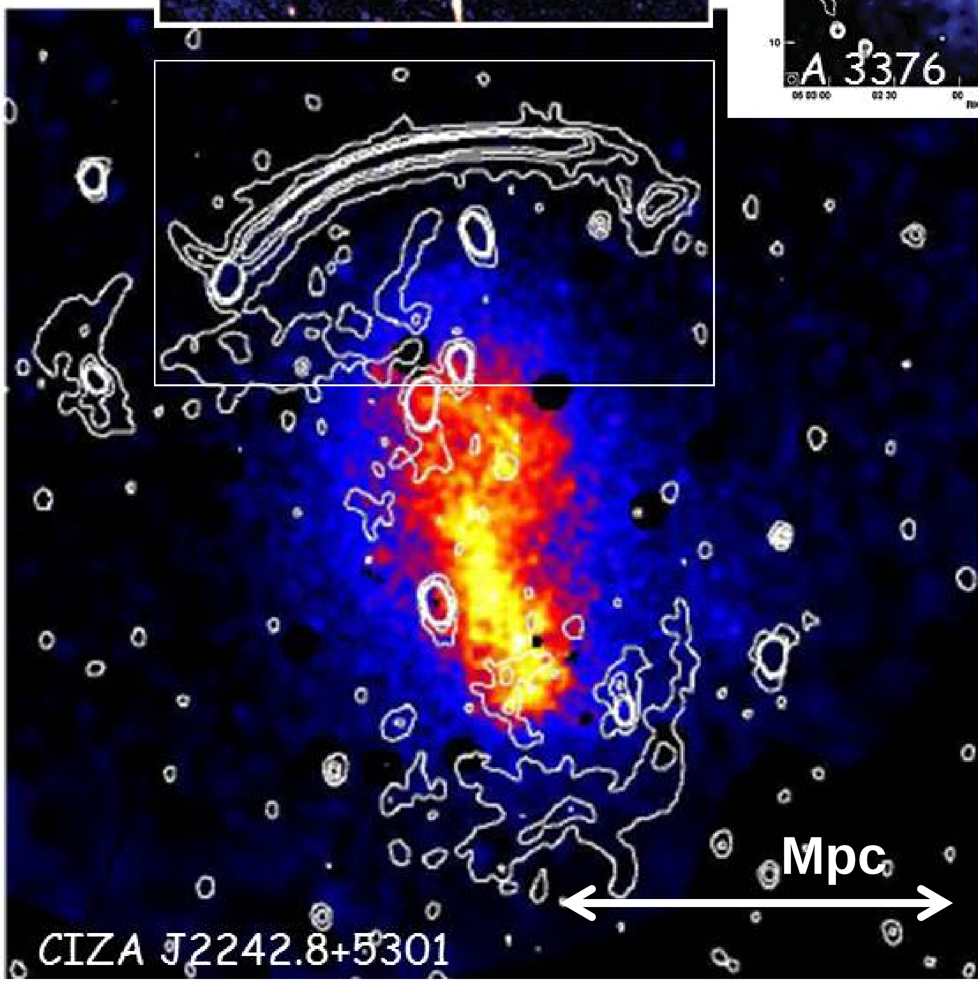
This poses fundamental questions/constraints on the efficiency of CRs acceleration in the ICM and on the dynamics of CRs (Brunetti & Jones 14 for review)

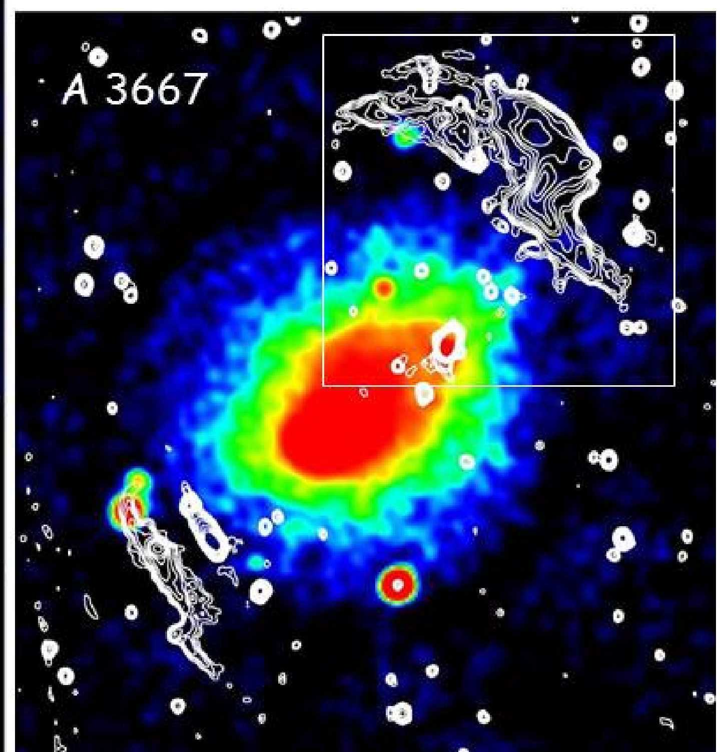
CRe: Giant Radio Relics







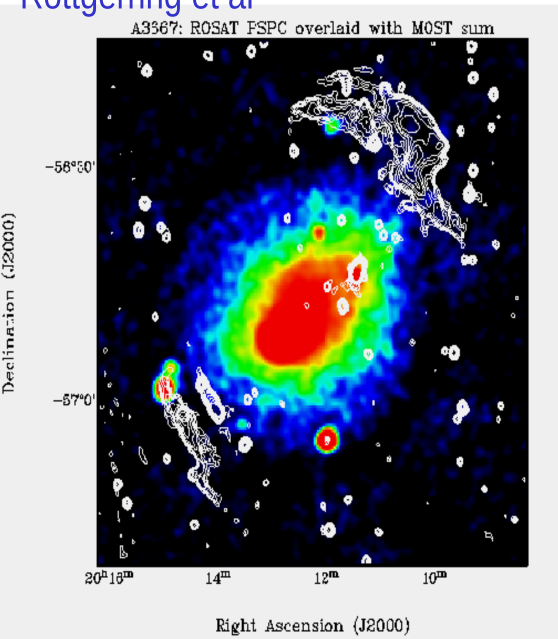


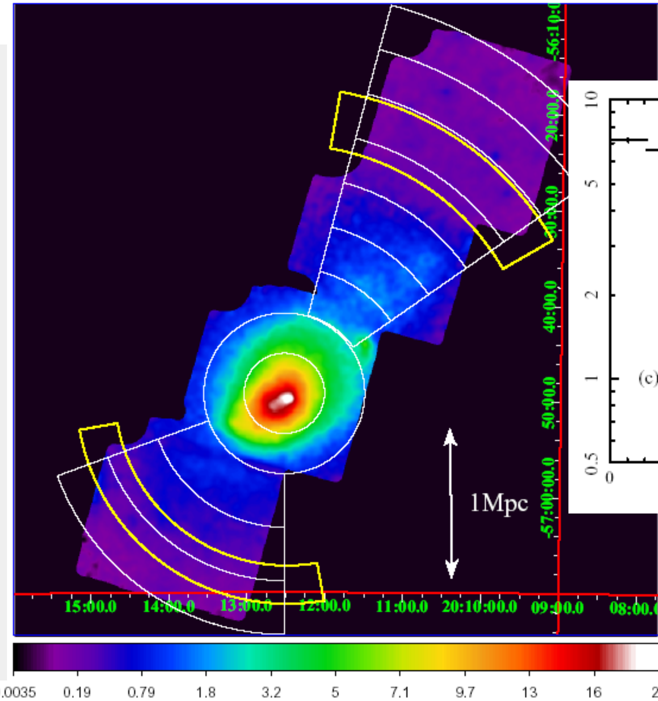


Relics -- Shocks connection

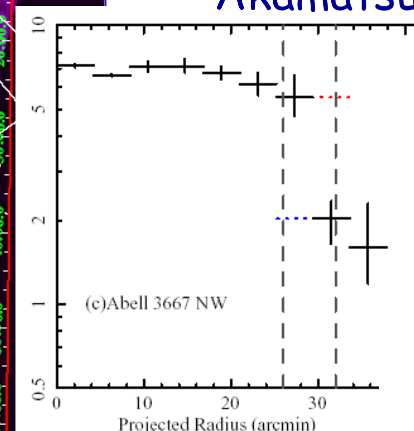
Ensslin et al 98, Rottgering et al 99, Sarazin 99, Takizawa et al 00, etc

Rottgerring et al



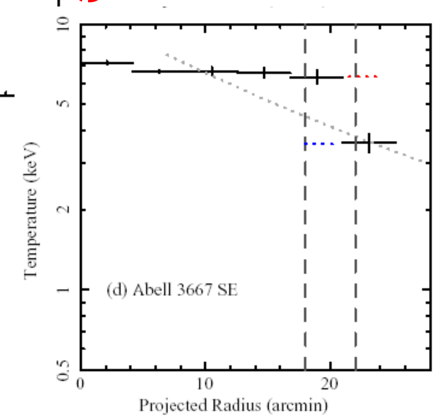


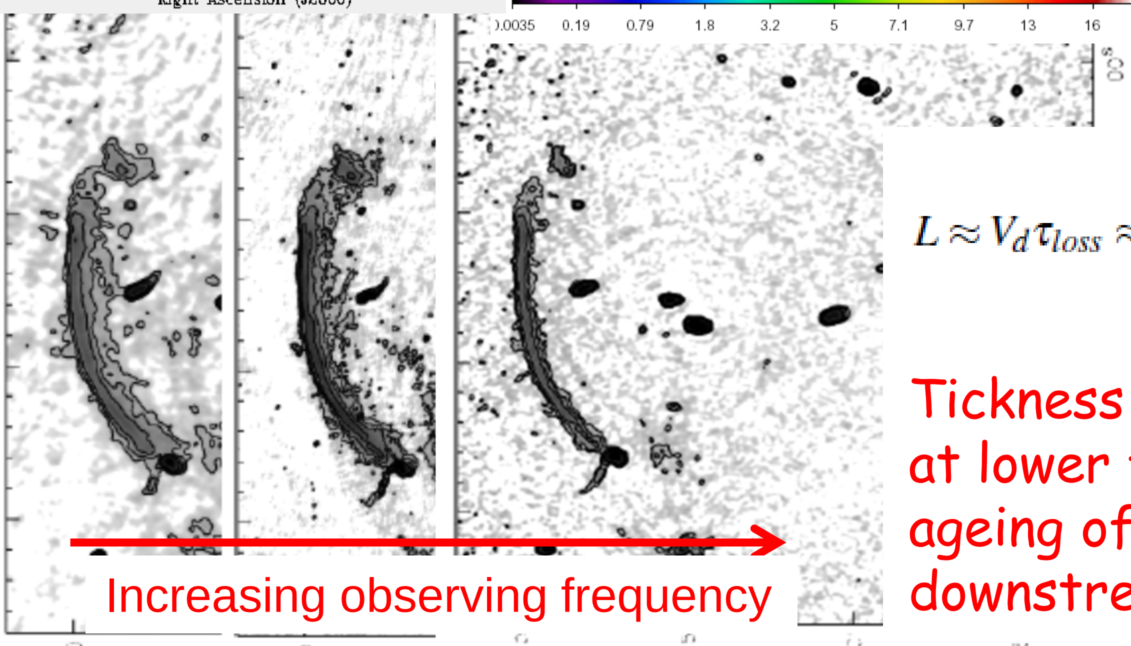
Akamatsu & Kawahara 12



temperature

Mach=2 - 4





Increasing observing frequency

$$L \approx V_d \tau_{loss} \approx \frac{M^2+3}{4M^2} V_{sh} \tau_{loss}(E \rightarrow \nu_{ph})$$

$$\tau_{loss} \approx \frac{4\pi}{\sigma_T} \frac{m^2 c^3}{B_\perp^2 + B_{IC}^2} \frac{1}{E}$$

$$\nu_{ph} \simeq \frac{3}{4\pi} \frac{eB}{m^3 c^5} E^2$$

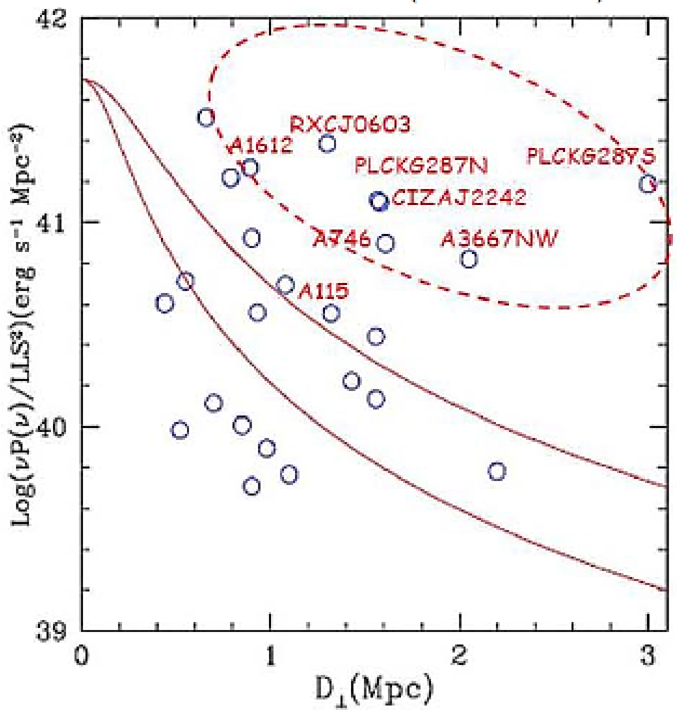
Tickness increases at lower frequencies: ageing of CRe downstream

Open problems… (Brunetti & Jones 14 for rev)

1) Discrepancies between 'X-rays' prop. and radio spectral properties
(Akamatsu et al 13, Ogrean et al 13, Stroe et al 14)

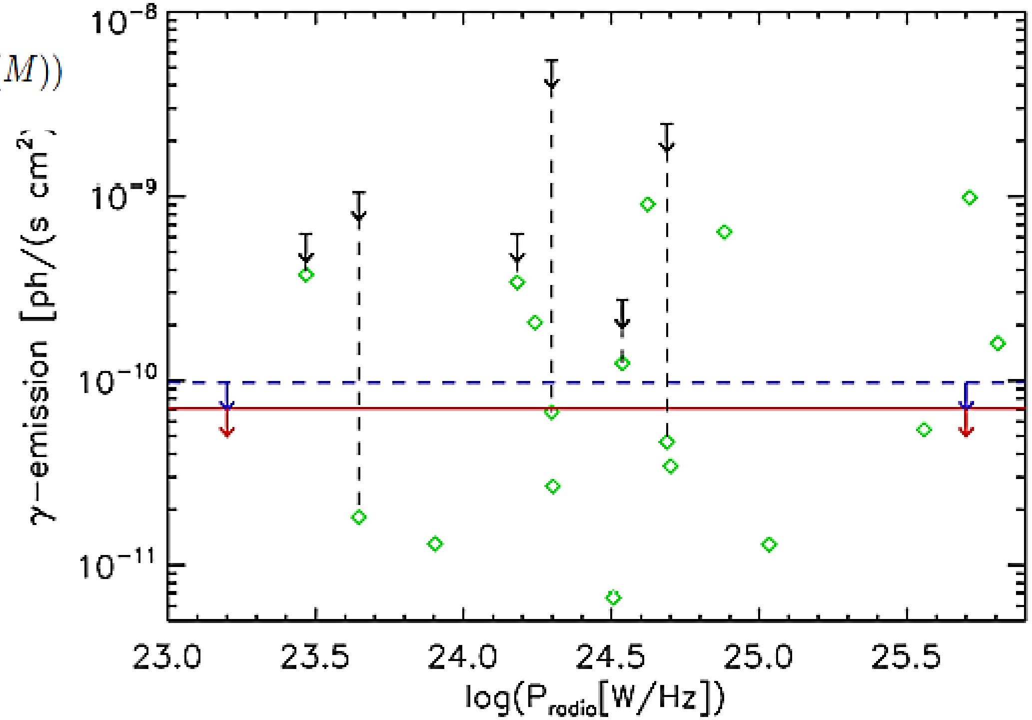
energy flux

$$\nu_o P_{\rm Syn}(\nu_o) \sim 1/2\rho_u V_{\rm sh}^3 \eta_{\rm CRe} S \left(1 + \left(\frac{B_{\rm IC}}{B}\right)^2\right)^{-1} \mathscr{F}^{-1}(\alpha(M))$$



2) The efficiency of CRe acceleration that is required to explain a fraction of radio relics is … big..
(Kang et al 05, 11, 12, … Brunetti & Jones 14)

3) Assuming SNRs as reference if you explain radio relics you over-produce gamma-rays (Vazza & Bruggen 14…)

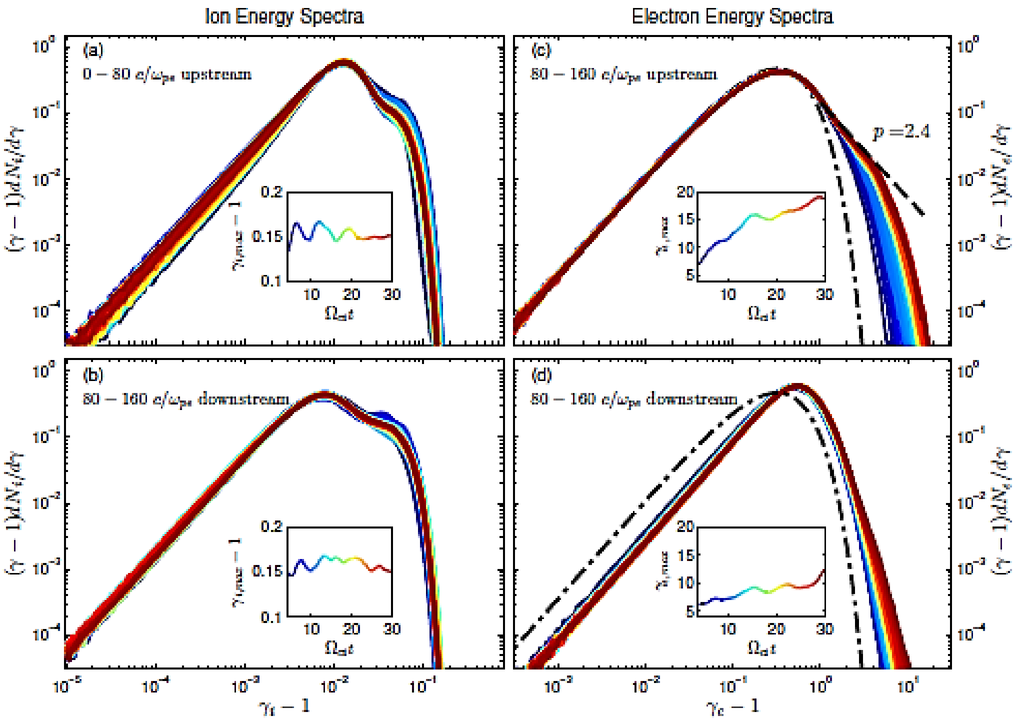


Griffin et al 14

I. REacceleration of CRe ?

II. Anomalous (high vs SNR) CRe/CRp ?

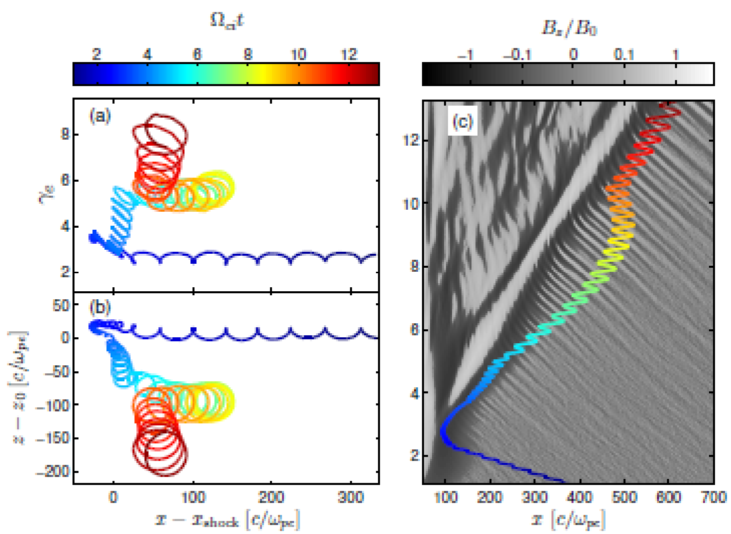
First PIC of «clusters» shock acceleration

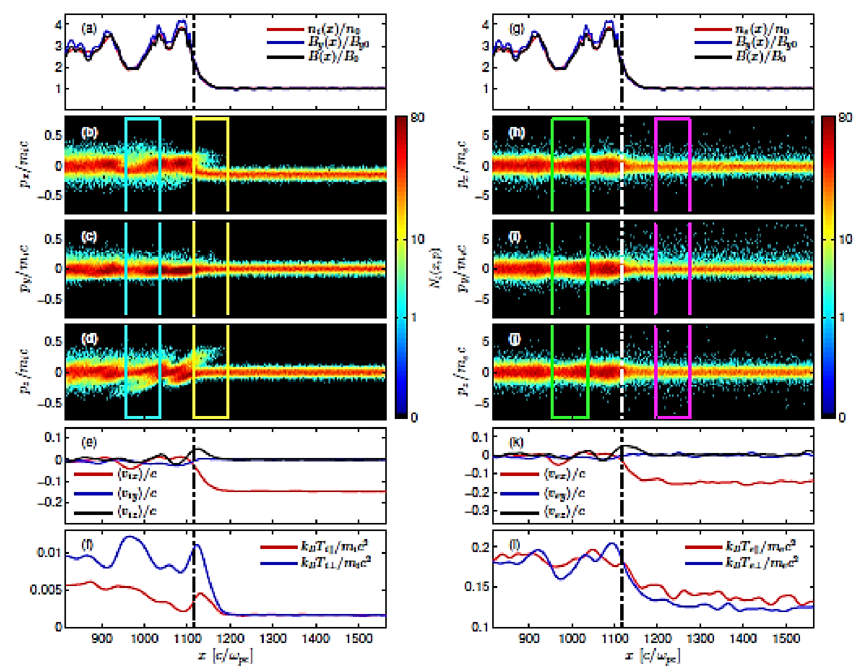


Low Mach number perpendicular shock in high-beta plasma (Guo, Sironi, Narayan 14)

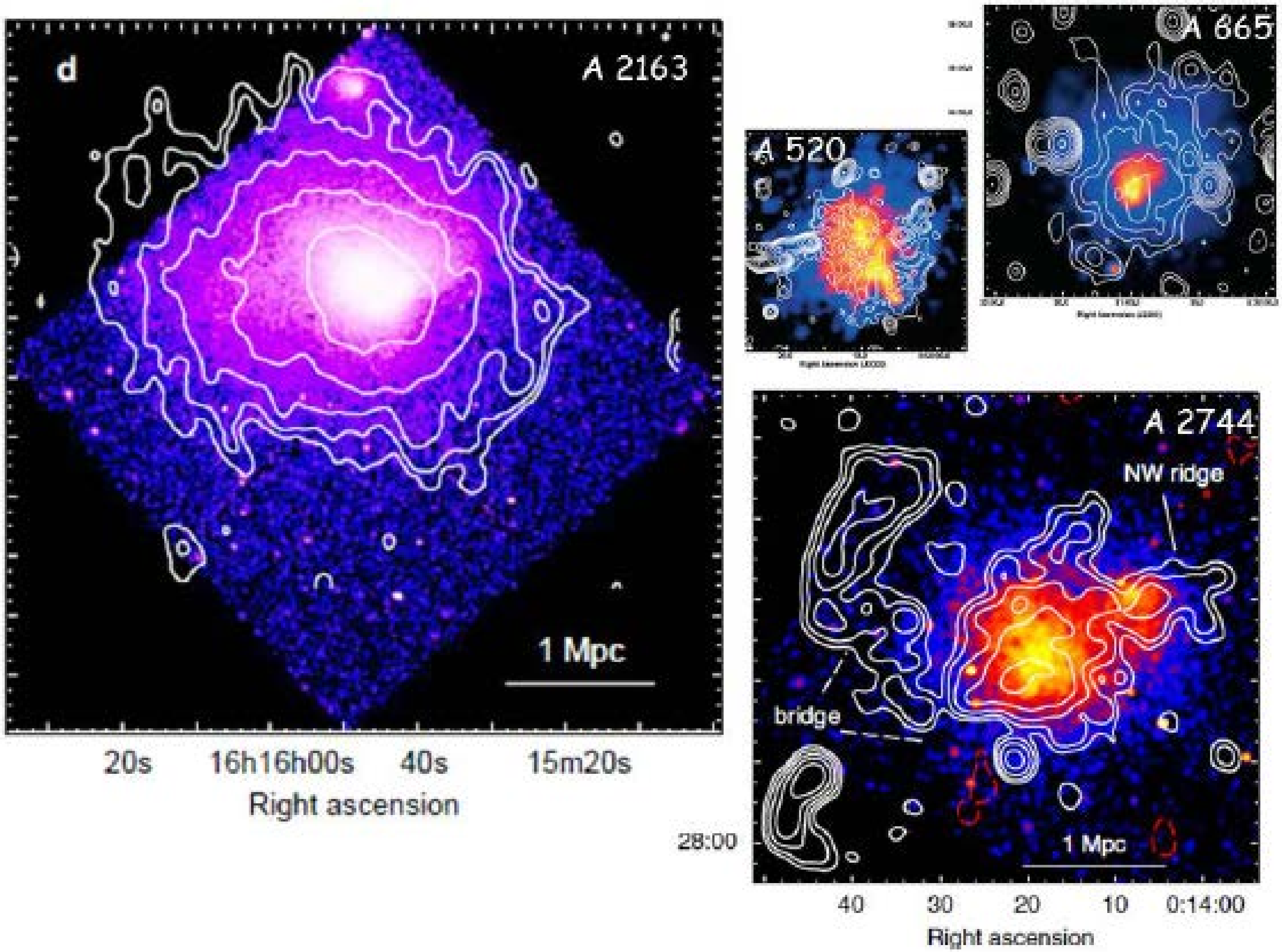
Efficient CRe acceleration.

Shock drift acceleration + Fermi-like via scattering upstream-downstream mediated by self-generated waves .





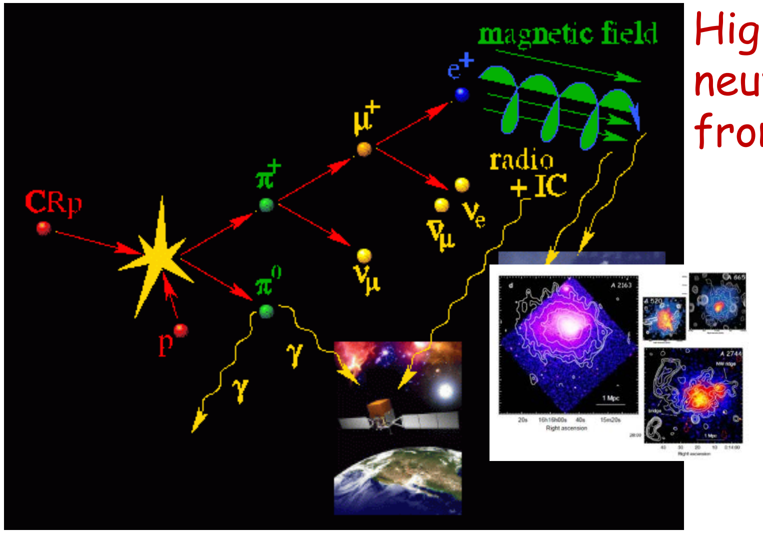
CRe : Giant Radio Halos



Giant Radio Halos

Hadronic interactions

(Dennison 1980, Blasi & Colafrancesco 99, ...)

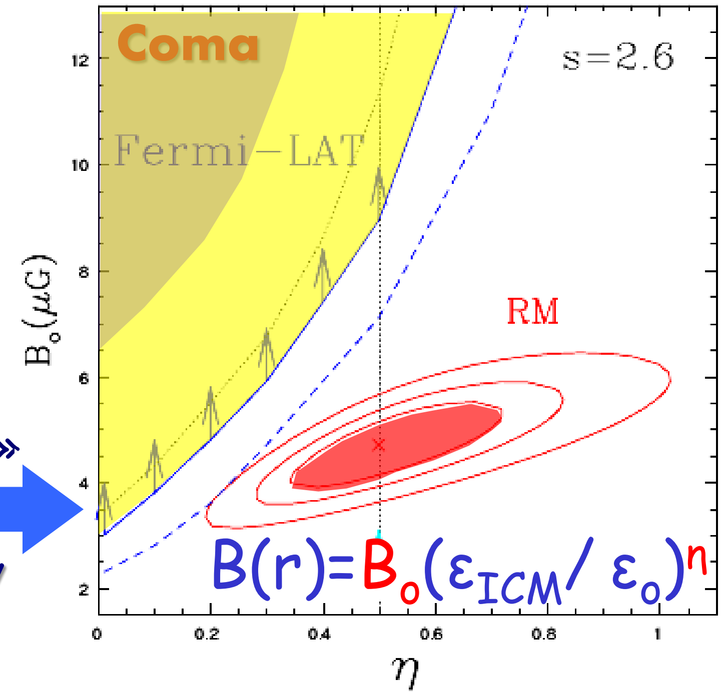


High energy and neutrino emission from galaxy clusters

ratio Fsyn/Fγ depends on «B»

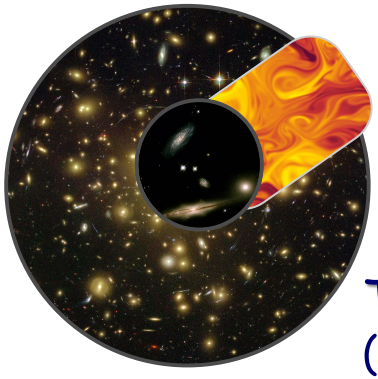
disfavoured by gamma-ray u.l.

Brunetti et al 12



Turbulence + stochastic (re)acceleration

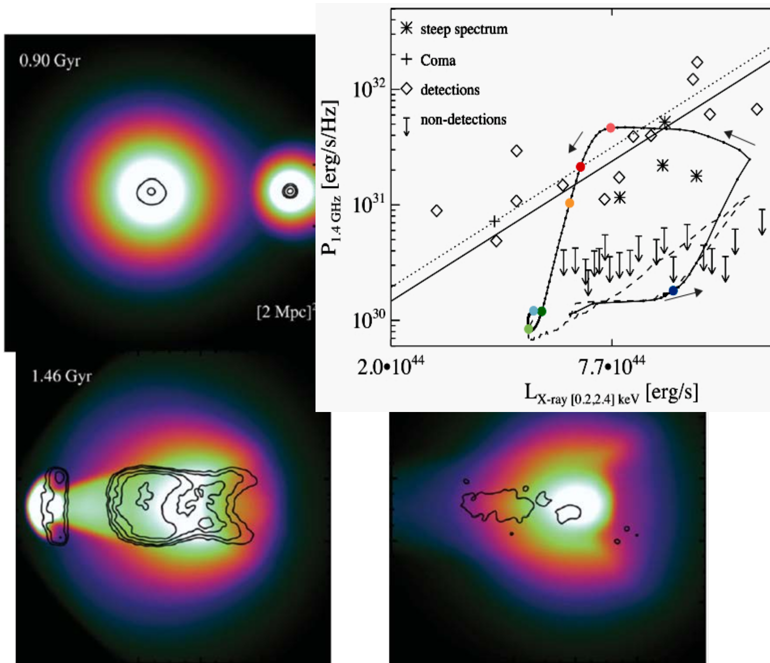
(Brunetti et al 01, Petrosian 01, ... ++)



Radio halos probe the dissipation of energy in dark-matter driven collisions between clusters

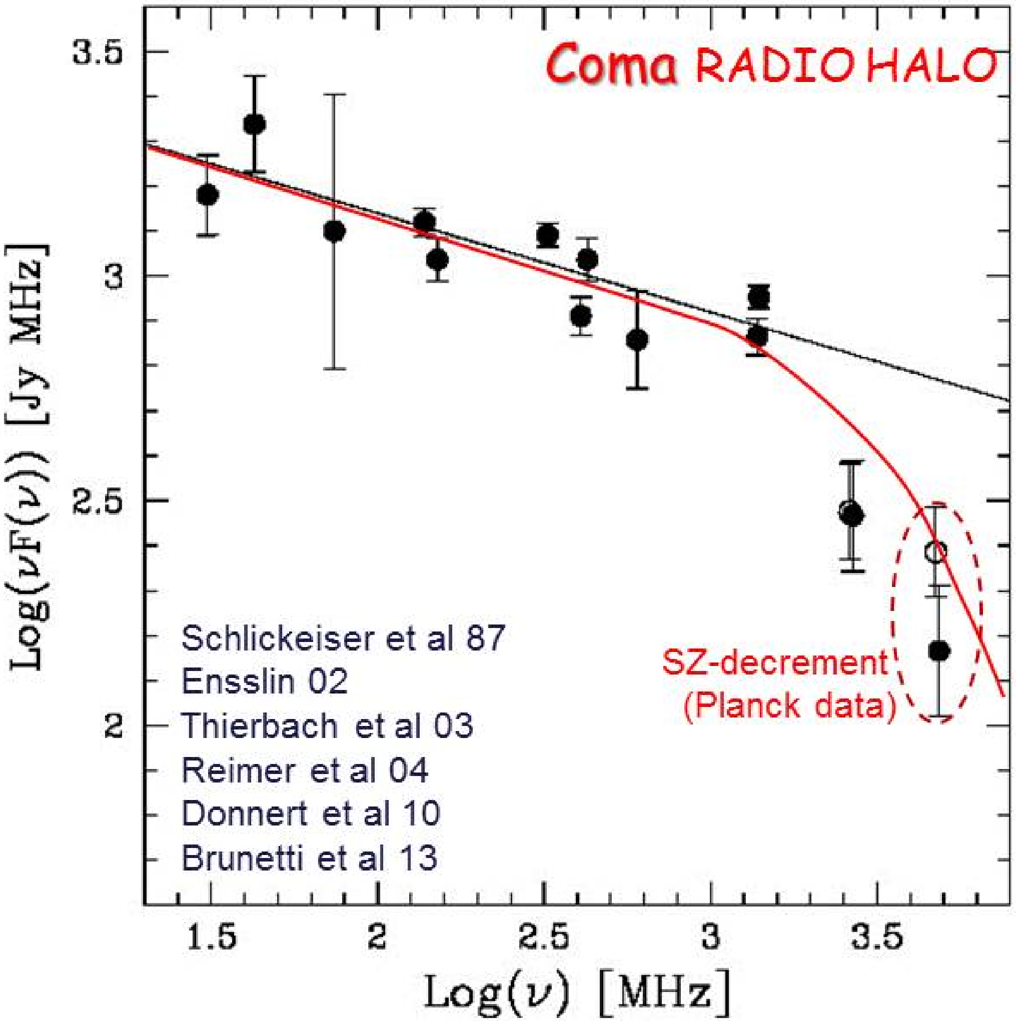
Theoretical CHALLENGE !

(Brunetti & Lazarian 07, 11a,b, Beresnyak et al 13, Miniati 14)

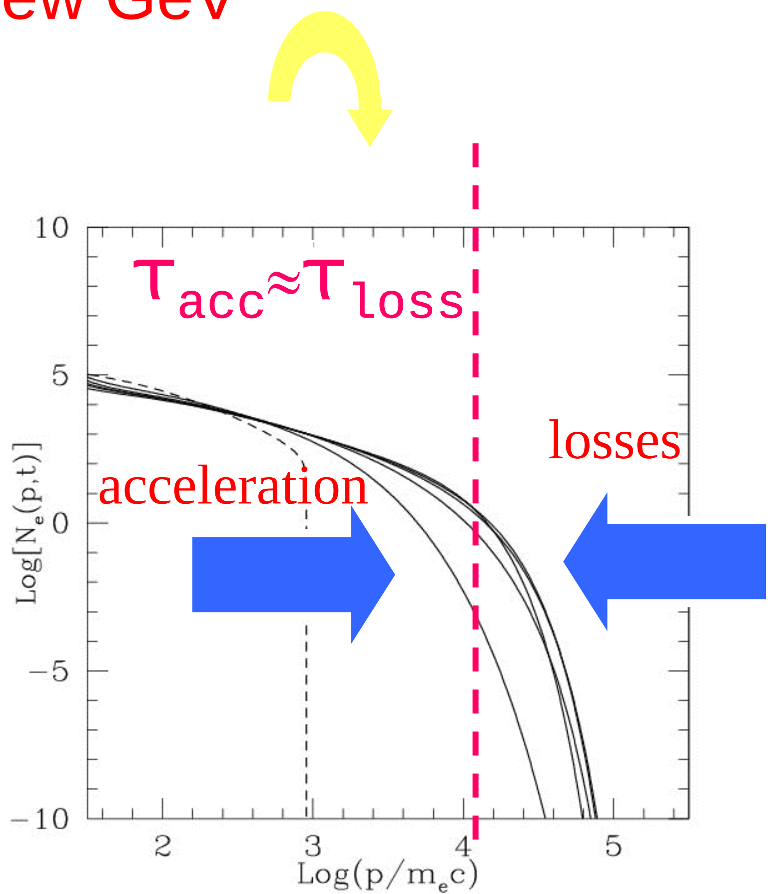


Donnert et al 13

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

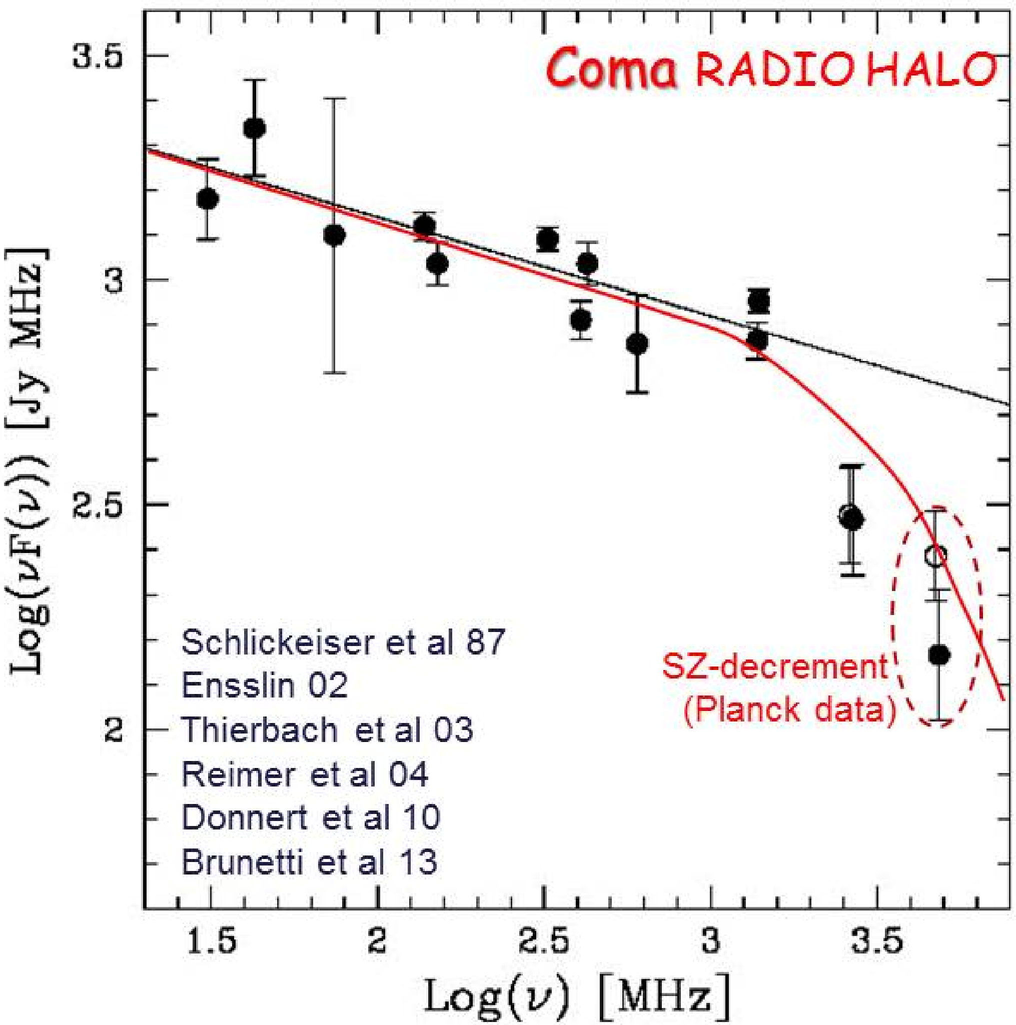


Evidence of break in the spectrum of the emitting electrons at energies of few GeV

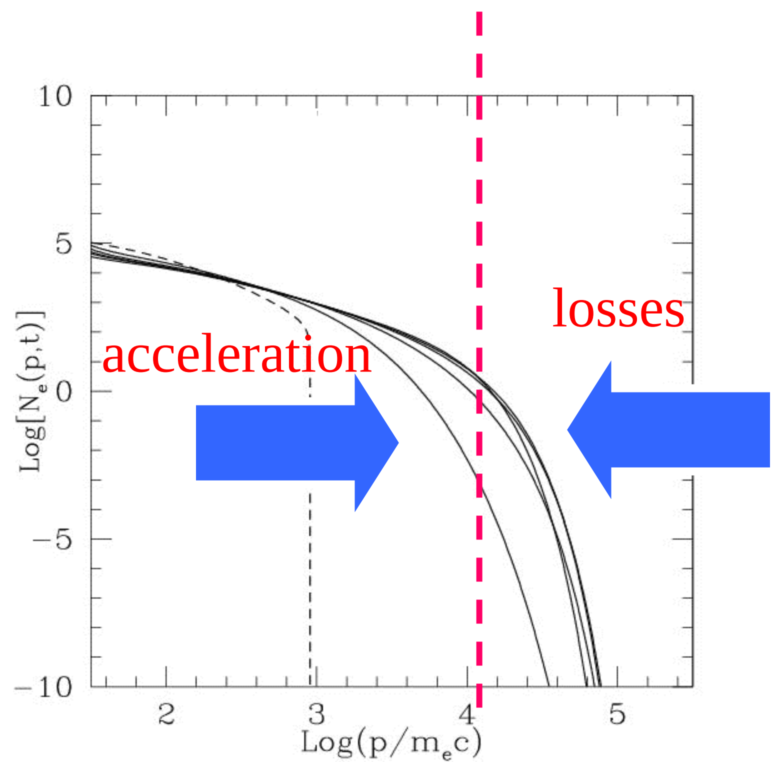


Radio Halos : are they generated by "inefficient" mechanism of CRe acceleration ?

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

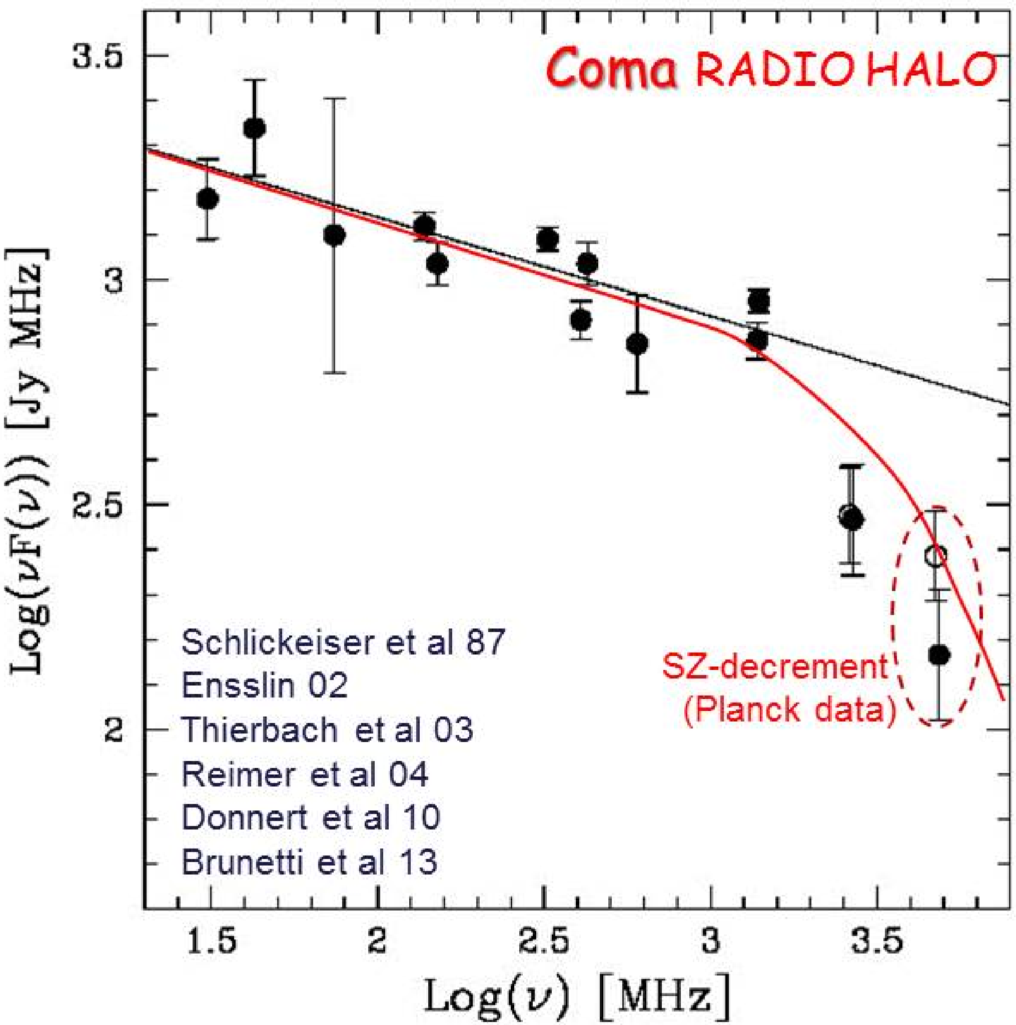


Acceleration time-scale
$\approx 10^8$ years



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

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

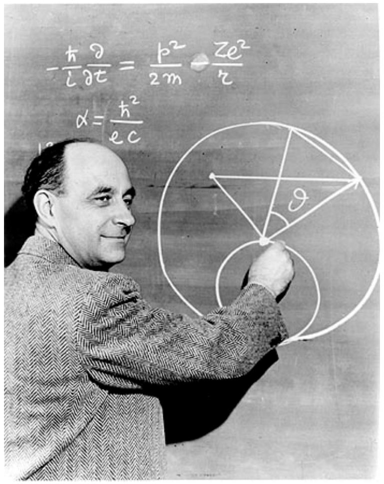


Acceleration time-scale $\approx 10^8$ years

eg., "classical" Fermi II

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

> 10^7yrs



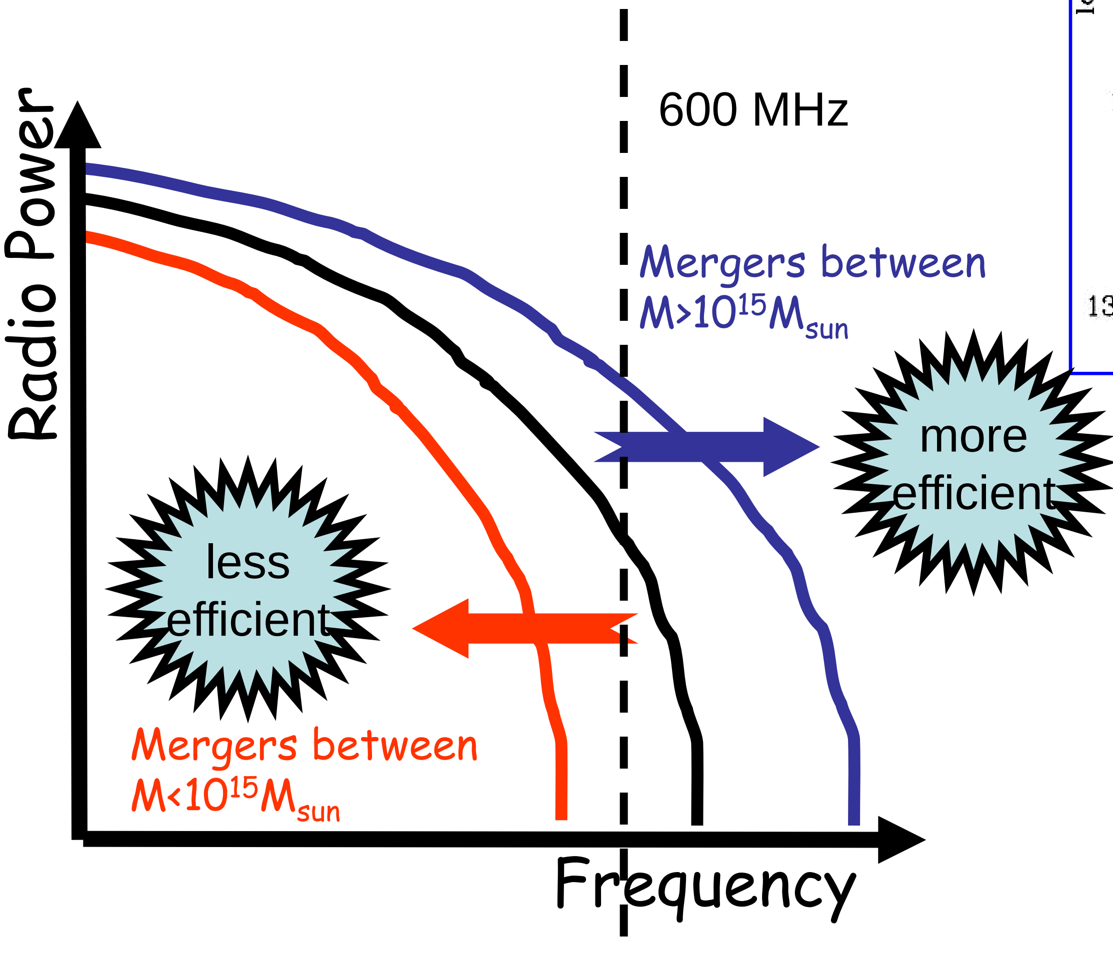
Expectations for Radio Halos

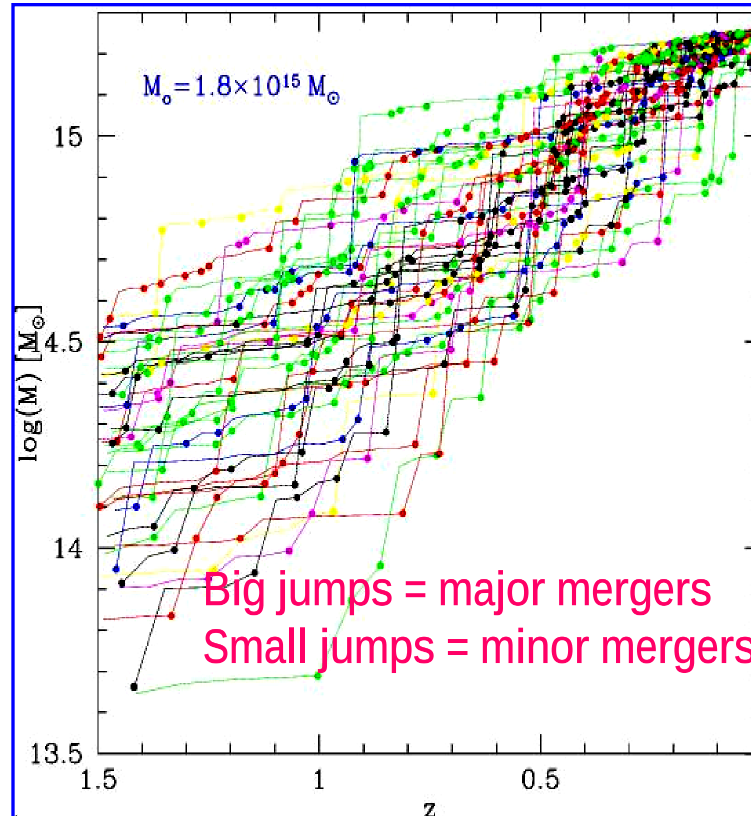
Acceleration efficiency

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

Steepening frequency

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



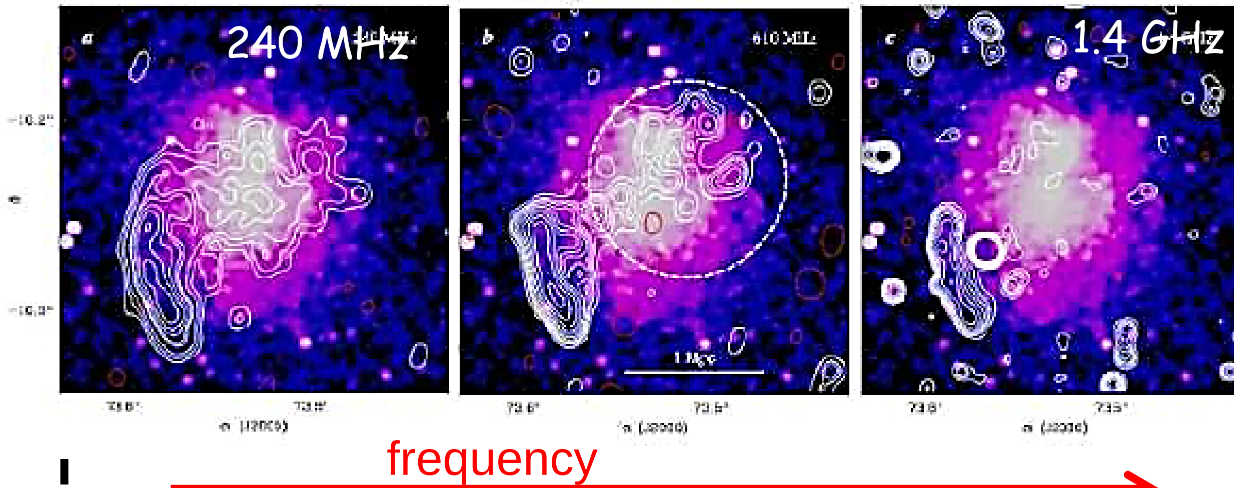


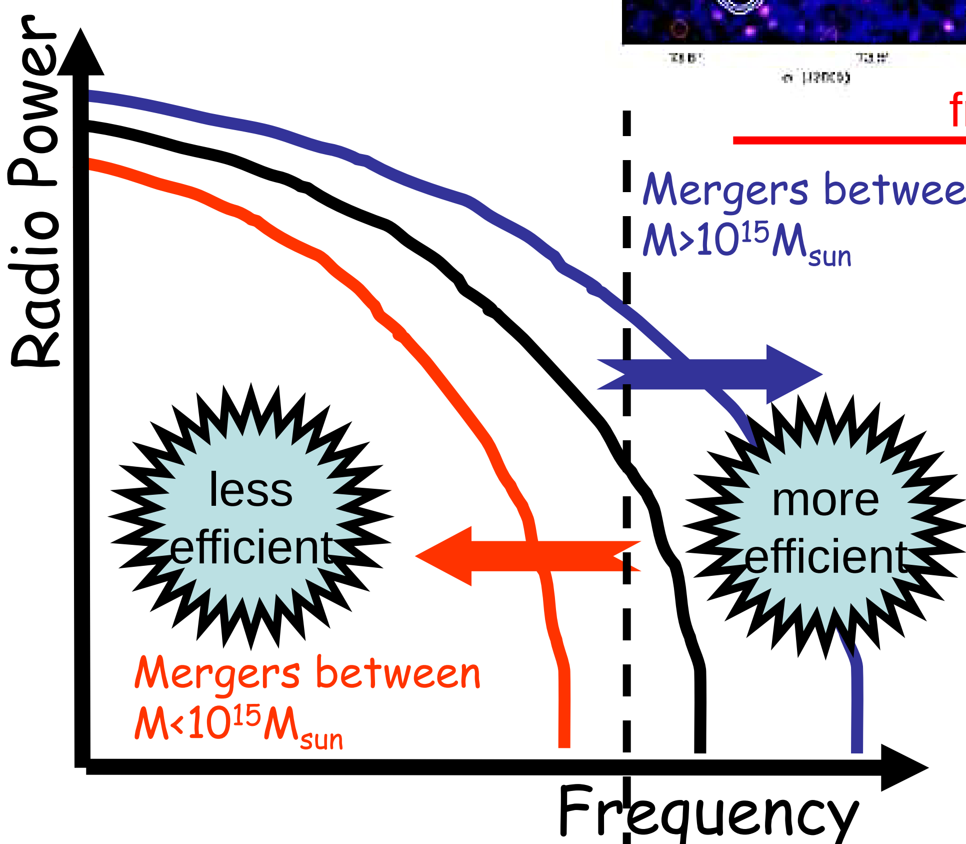
Radio Halos with very steep spectrum in the classical radio band must exist

(Cassano, Brunetti, Setti 06)

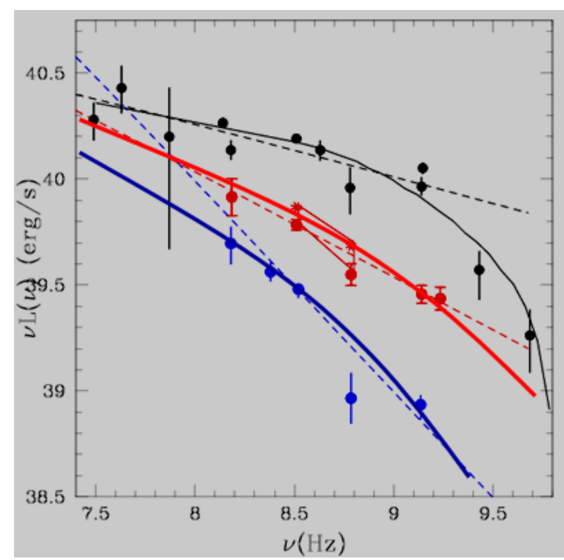
OBS: Syn spectra of Radio Halos

Brunetti et al 08 Nature 455, 944





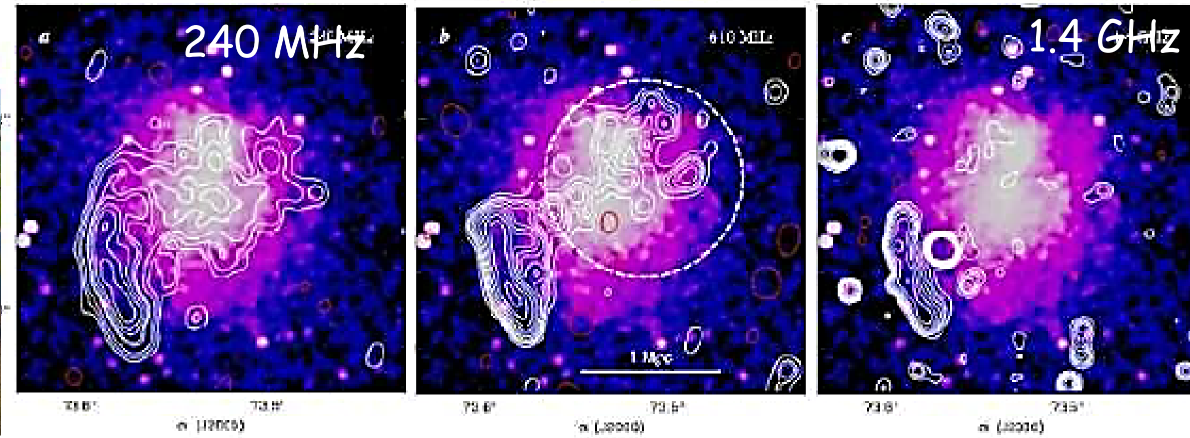
Venturi 11,13, Macario 13



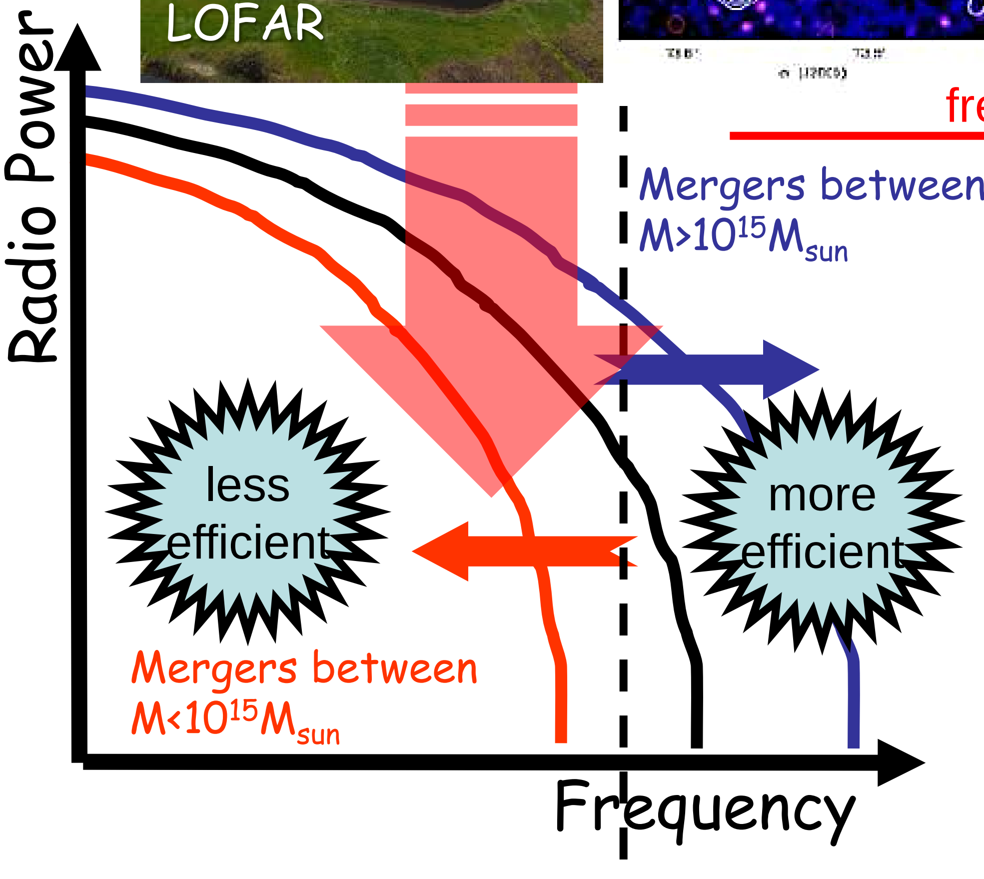
OBS: Syn spectra of Radio Halos

Brunetti et al 08 Nature 455, 944

quantitative predictions in
Cassano, GB et al 10,12



frequency



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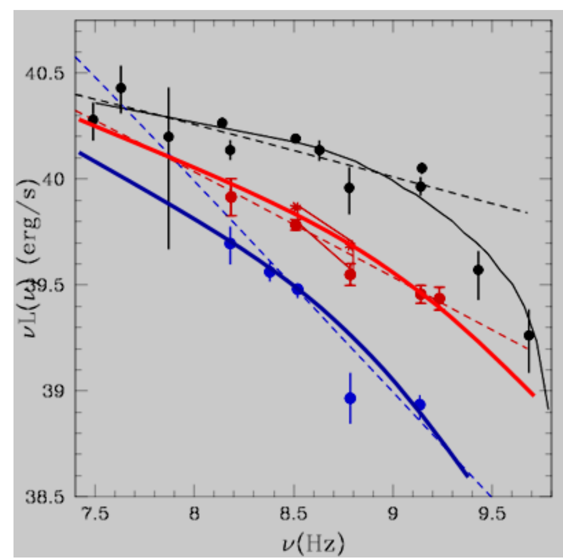


Stochastic REacceleration of primaries & secondaries
(Brunetti & Lazarian 11)

Transit Time Damping (TTD)

ICM, B, CRp ⇔ $\omega - k_{//} v_{//} = 0$

Pitch-angle isotropy

Electrons/Positrons

Q_e: secondaries from CRp-p collisions

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

losses + sys acceleration — p-diffusion

Protons

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

losses + sys acceleration — p-diffusion — injection

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

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

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

Turb. Modes

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

mode coupling — collisionless dampings — injection

dampings

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

Radio & high energies

(Brunetti & Lazarian 11)

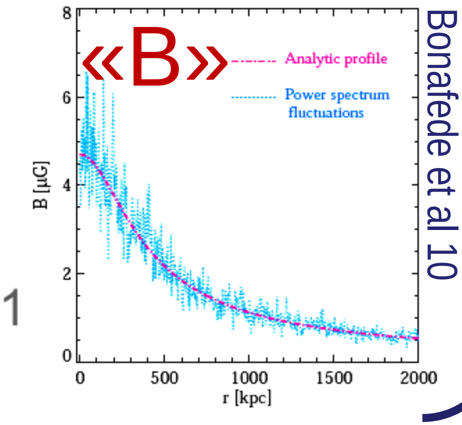
Calculations that consider the general case where both primaries (CRp,CRe) and secondaries (CRe) interact with turbulence (reaccelerated)

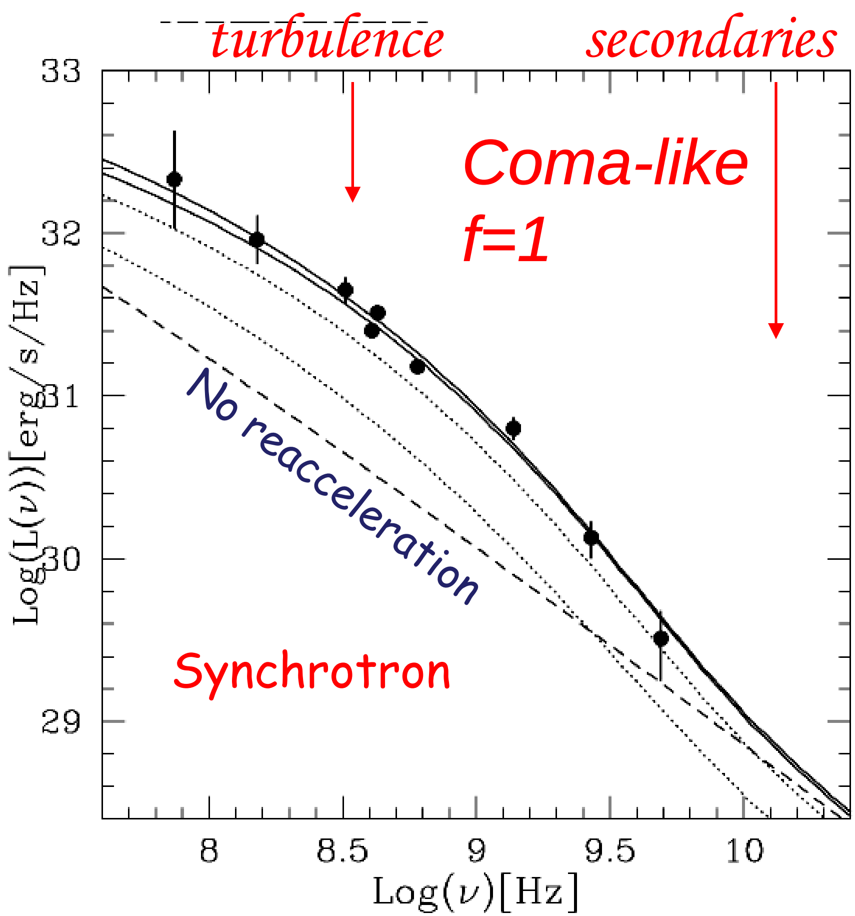
assumptions

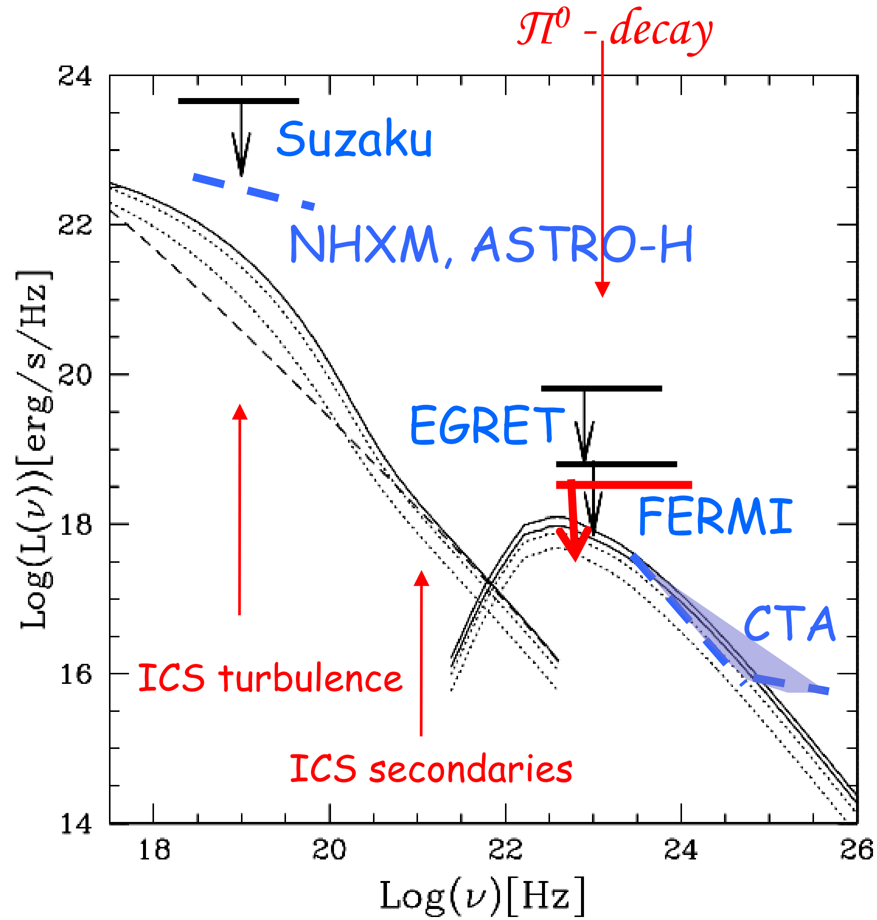
$E_{tur} \approx 10\ \%\ E_{th}$

$E_{CRp} = \sim\ \%\ E_{th}$

$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

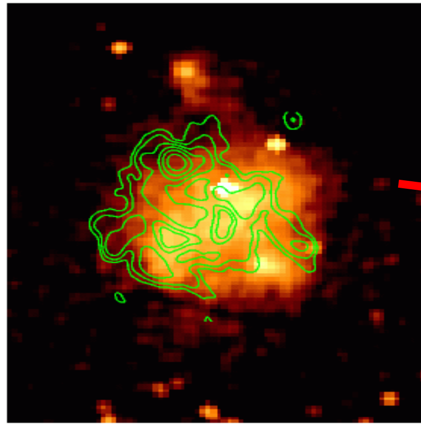




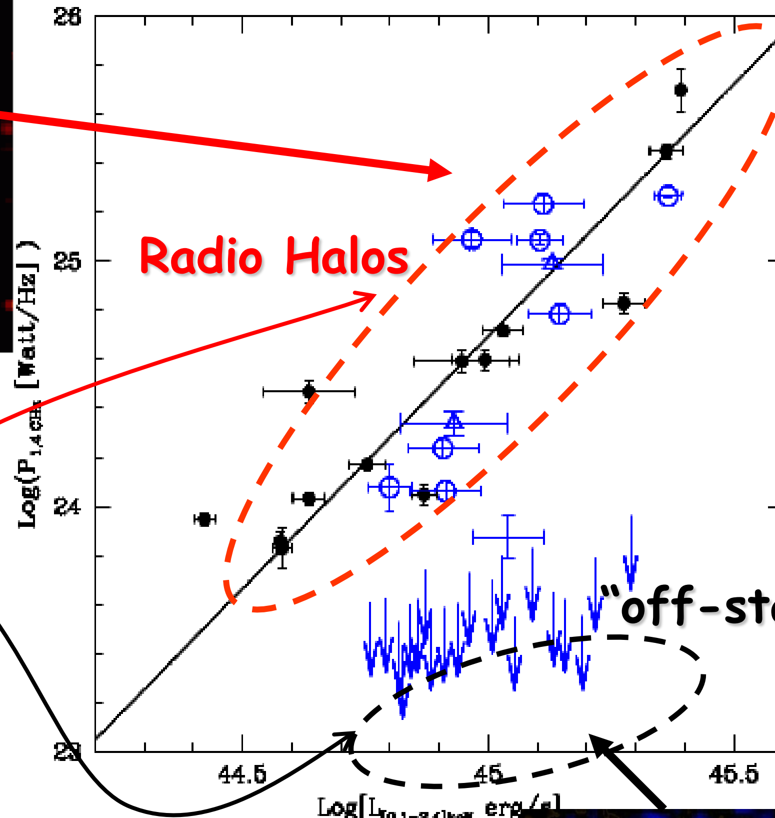


Cluster mergers – NT connection

Radio halos probe the dissipation of kin energy in the DM-driven merger events into CRs and B

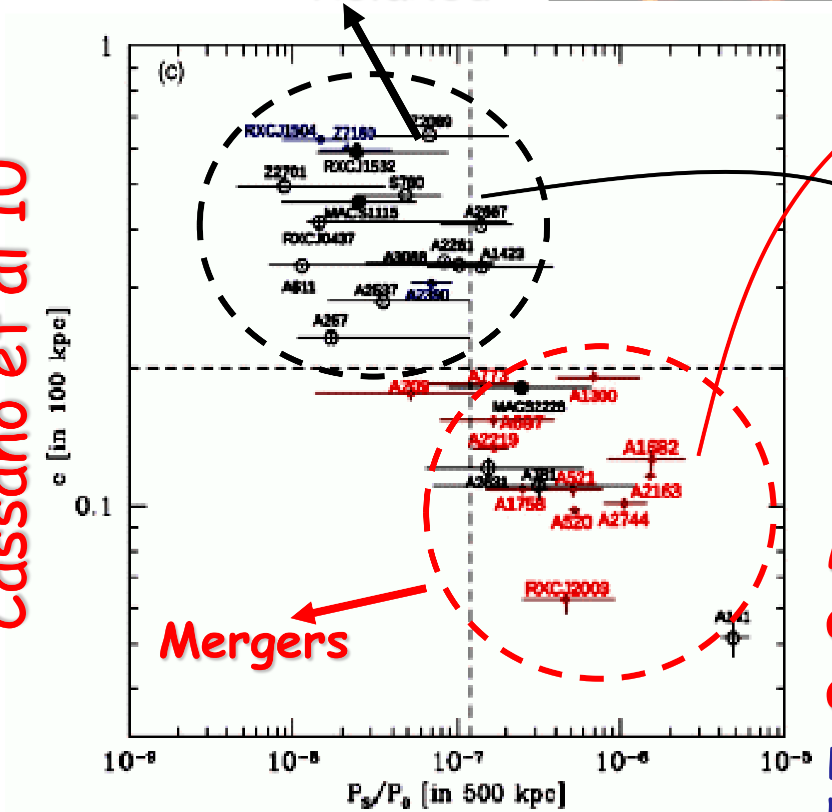


Venturi et al 08, Brown et al 11
Basu 12, Cassano et al 13,
Sommer & Basu 14



Brunetti et al 07,09

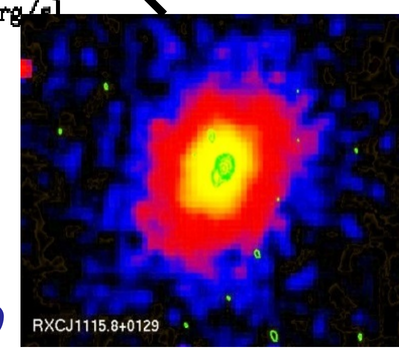
Relaxed



Cassano et al 10

Mergers guide CRe acceleration/dynamics and/or amplify B

Brunetti 07, 09 Kushnir et al 09
Ensslin et al 11 Wiener et al 13



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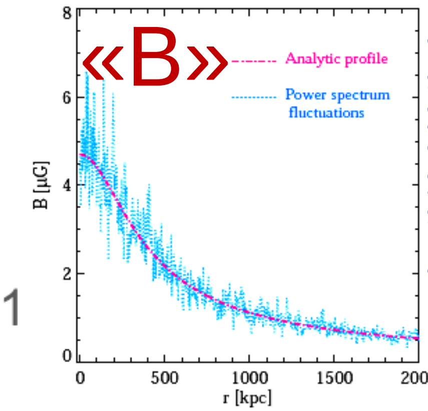
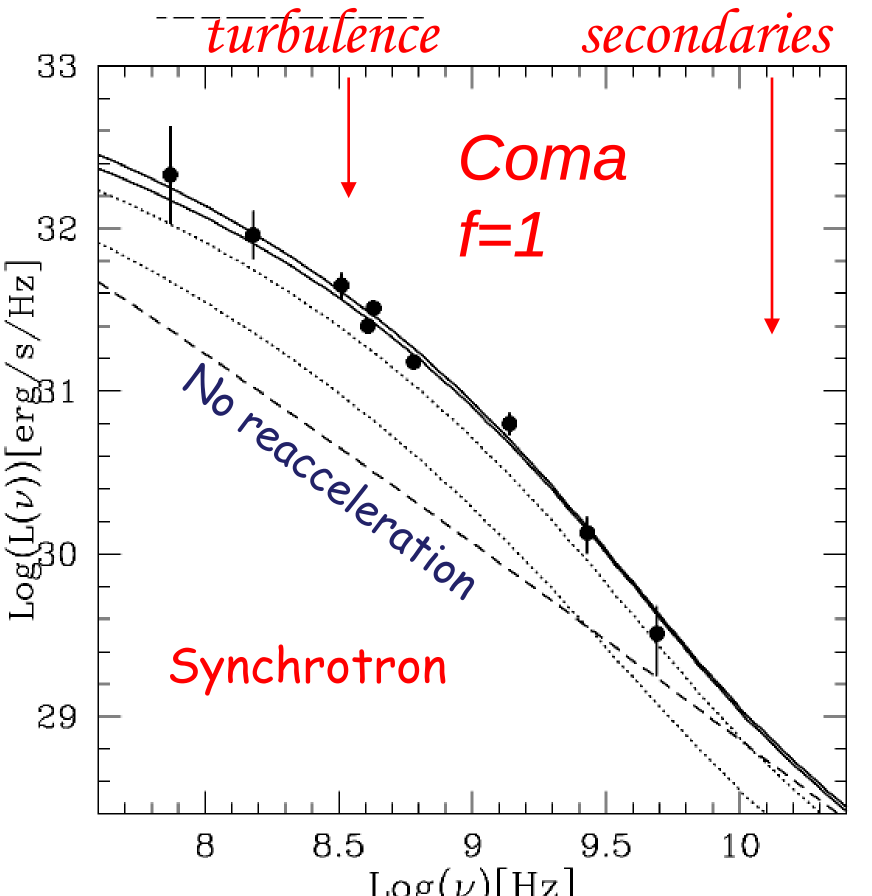
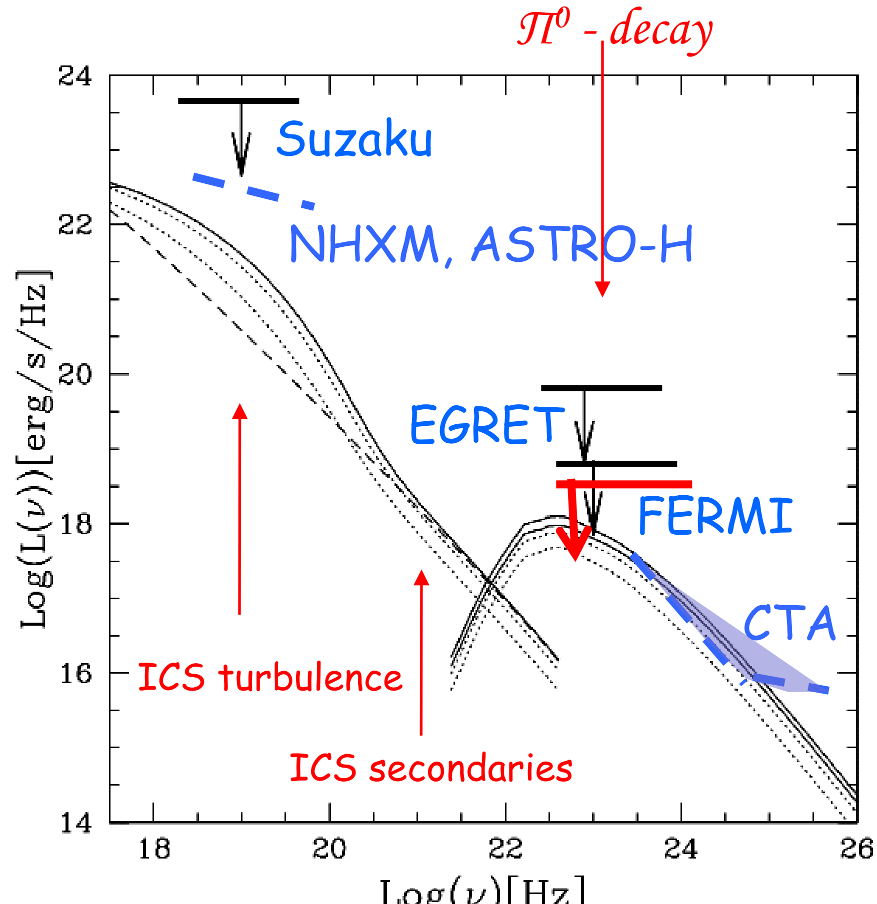


Bonafede et al 10





Constraining phys parameters

$$\frac{L_{ICS}}{L_\gamma} \propto F(\delta)\frac{I_{tu}B_{IC}^2}{B^2+B_{IC}^2}f$$

$$L_\gamma \propto \epsilon_{CRp} n_{TH} V_\gamma$$

$$L_{SYN} \propto I_{tu}\Gamma_{CRe}\frac{B^2}{B^2+B_{IC}^2}V_{SYN}$$

Turb energy flux

$$L_{ICS} \propto I_{tu}\Gamma_{CRe}\frac{B_{IC}^2}{B^2+B_{IC}^2}V_{ICS}$$

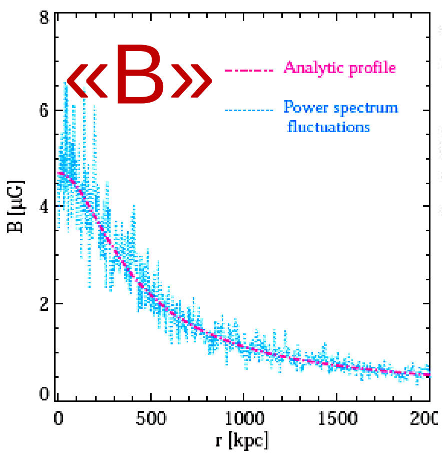
$$\frac{L_{SYN}}{L_\gamma} \propto F(\delta)\frac{I_{tu}B^2}{B^2+B_{IC}^2}f$$

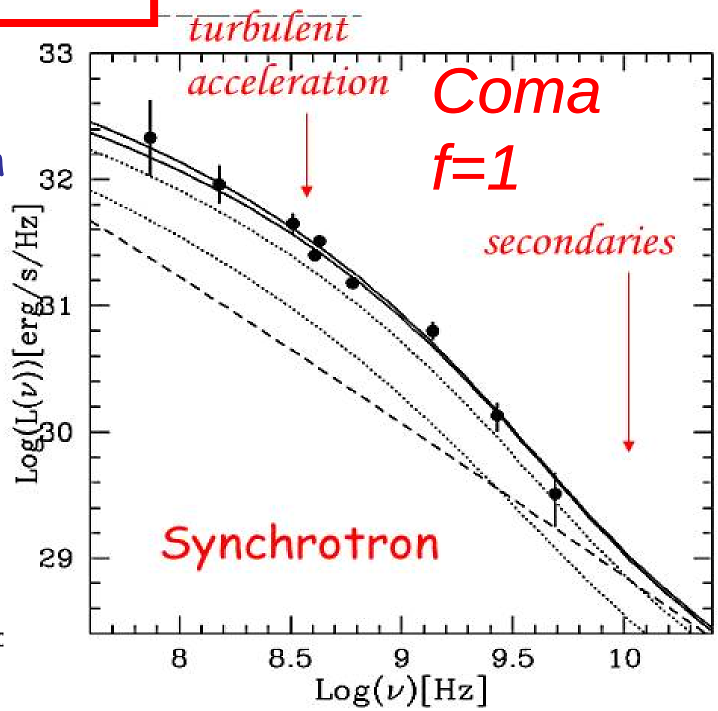
$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B_{IC}^2}$$

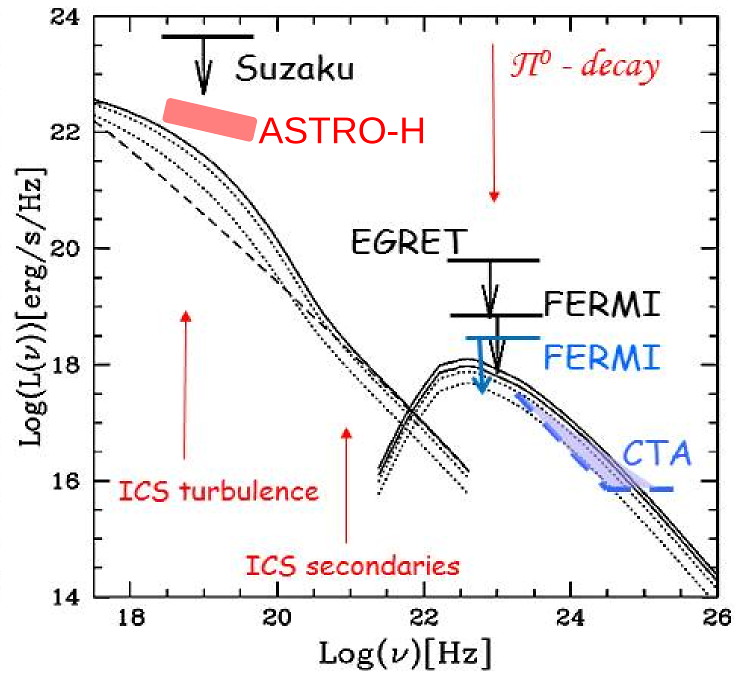
$$f = \frac{PRIMARY\, e^\pm}{SECONDARY\, e^\pm} + 1$$

$$\Gamma \propto \int d^3k A(k) \int d^3p B(p,k) p^2 \frac{\partial f_e}{\partial p} \approx \epsilon_{CRe} \int d^3k A(k) B(<p>, k)$$

$E_{tur} \approx 10\ \%\ E_{th}$







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Turb energy flux

$$L_{ICS} \propto I_{tu}\Gamma_{CRe}\frac{B_{IC}^2}{B^2+B_{IC}^2}V_{ICS}$$

$$\frac{L_{SYN}}{L_\gamma} \propto F(\delta)\frac{I_{tu}B^2}{B^2+B_{IC}^2} f$$

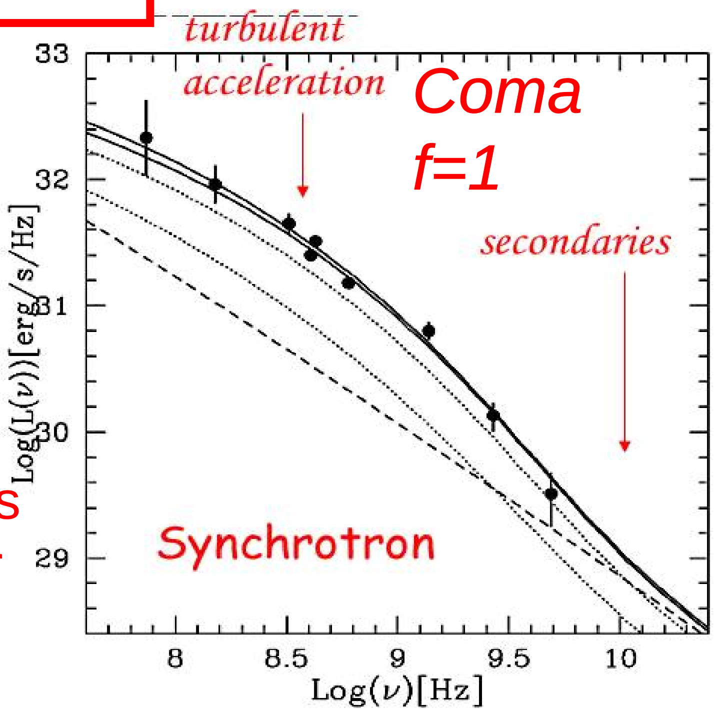
$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B_{IC}^2}$$

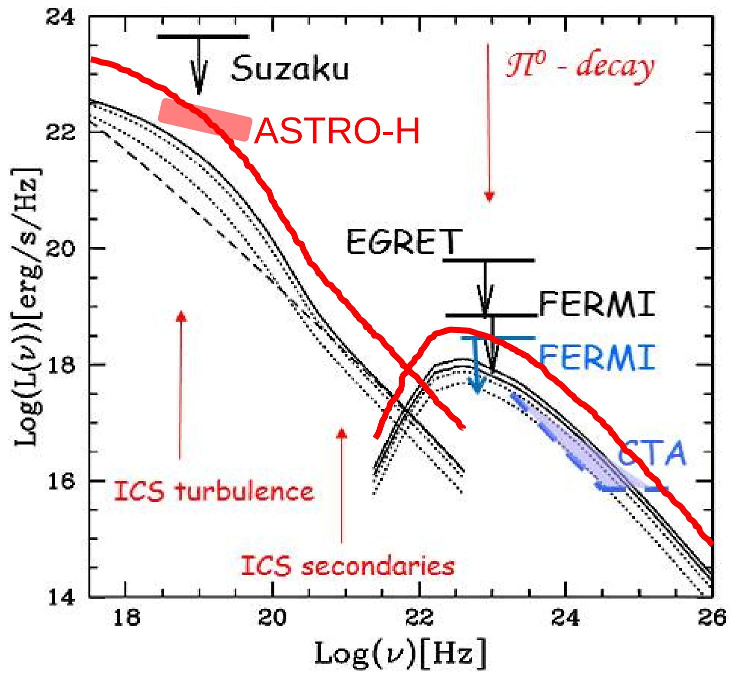
$$f = \frac{PRIMARY\,e^\pm}{SECONDARY\,e^\pm} + 1$$

$$\Gamma \propto \int d^3k A(k) \int d^3p B(p,k) p^2 \frac{\partial f_e}{\partial p} \approx \epsilon_{CRe} \int d^3k A(k) B(<p>, k)$$

0.4xB

ICS & gamma-rays are boosted up for smaller «B»





Constraining phys parameters

$$L_\gamma \propto \epsilon_{CRp} n_{TH} V_\gamma$$

$$L_{SYN} \propto I_{tu} \Gamma_{CRe} \frac{B^2}{B^2 + B^2_{IC}} V_{SYN}$$

Turb energy flux

$$L_{ICS} \propto I_{tu} \Gamma_{CRe} \frac{B^2_{IC}}{B^2 + B^2_{IC}} V_{ICS}$$

$$\frac{L_{ICS}}{L_\gamma} \propto F(\delta) \frac{I_{tu} B^2_{IC}}{B^2 + B^2_{IC}} f$$

$$\frac{L_{SYN}}{L_\gamma} \propto F(\delta) \frac{I_{tu} B^2}{B^2 + B^2_{IC}} f$$

$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B^2_{IC}}$$

$$f = \frac{PRIMARY\, e^\pm}{SECONDARY\, e^\pm} + 1$$

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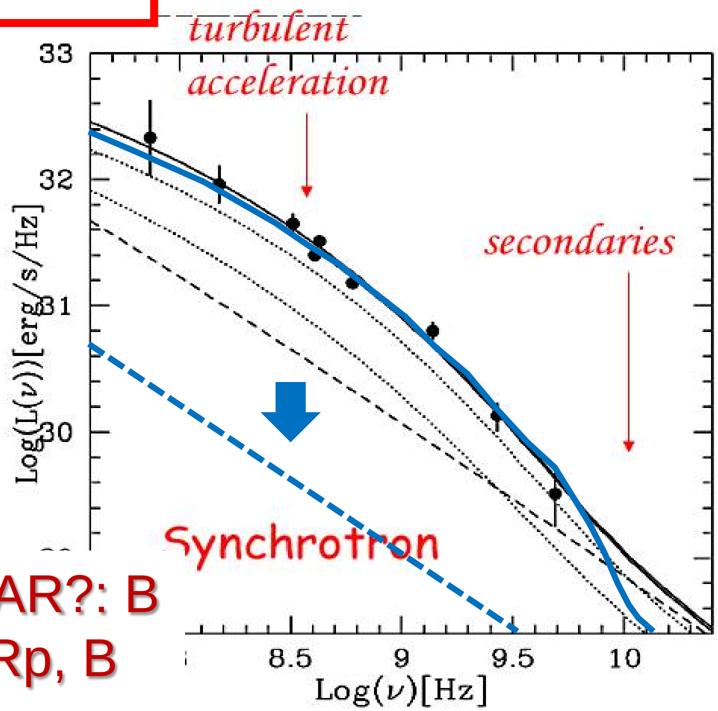
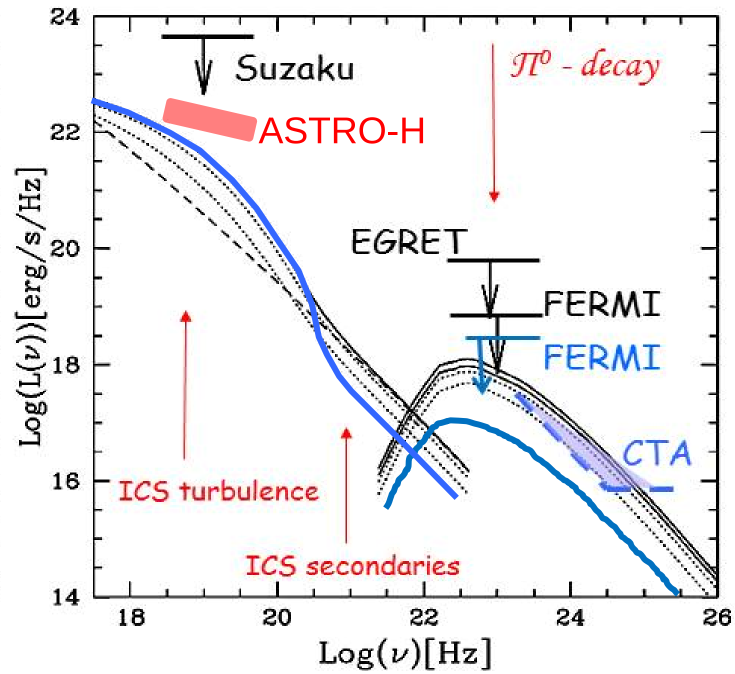
f=10





ASTRO-H, NuSTAR?: B

CTA, Fermi10: CRp, B

SUMMARY

- ❑ Magnetic fields have a fundamental role in CRs diffusion & acceleration
- ❑ CRs have a role in magnetic field amplification
- ❑ CRs (e) emission is a probe of magnetic field properties

- CRs and B in galaxy clusters are probed by radio observations: impact on the physics of ICM & evolution of clusters
- CRs Origin : Shocks, turbulence (reconnection?) and generation of secondaries are the fundamental players in the current theoretical picture

In the last decade :

I. Connection between Mpc-scale radio sources and mergers : cosmological probes ?

II. CR protons constrained by gamma-rays !

III. Relics : from standard DSA … to REacceleration & new parameter space (different from SNRs)

IV. Halos : from hadronic vs turbulence … to turbulent models : beautiful.. but theoretical challenge

- ➢ LOFAR is (hopefully..) providing a revolution in the field
- ➢ High energies (X-rays and gamma-rays) remain fundamental for CRs physics