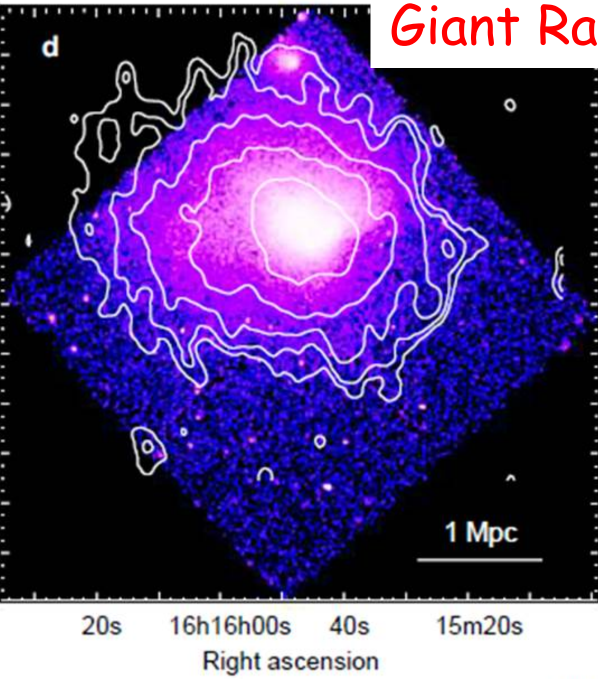
Diffuse radio emission in galaxy clusters: crossroad between astrophysics and cosmology

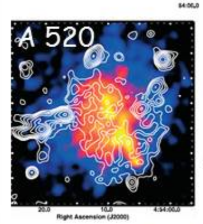
Gianfranco Brunetti

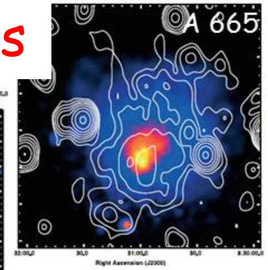
INAF IRA ISTITUTO DI RADIOASTRONOMIA

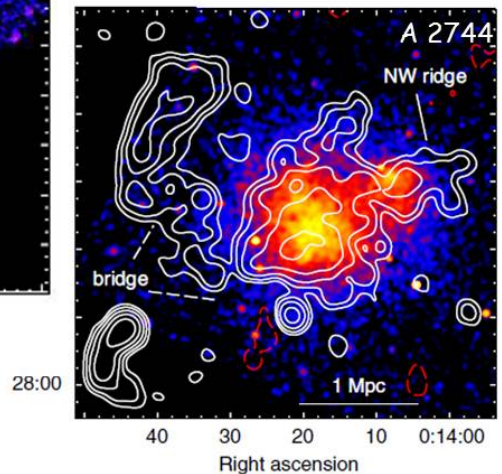
Cluster-scale radio emission

Giant Radio Halos







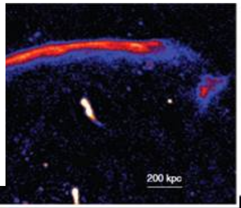


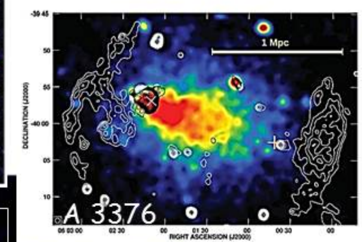
- Steep spectrum sources
- Low brightness

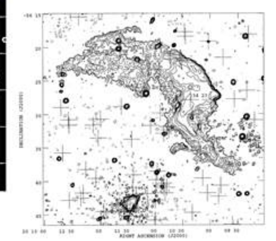
Synchrotron radiation FROM the ICM

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

Giant Radio Relics

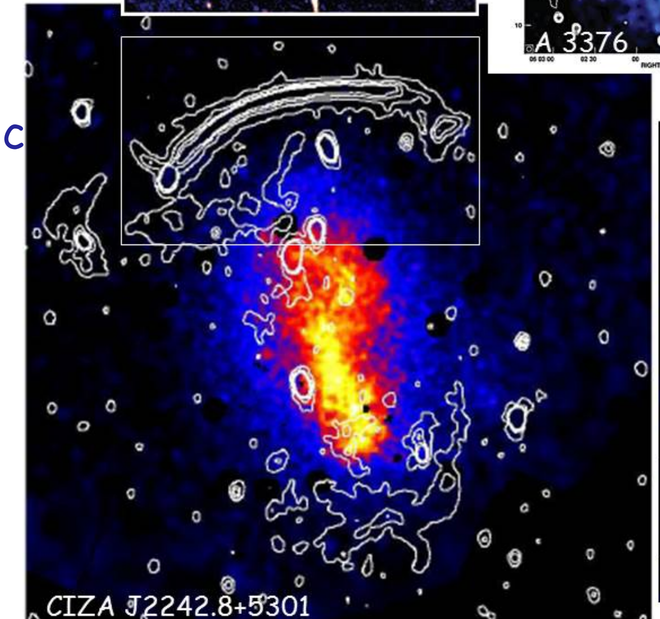


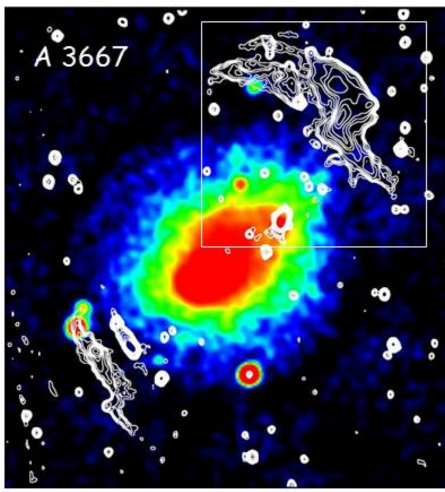




Mechanisms operating within clusters drain gravitational and electromagnetic energy into relativistic particles and magnetic field

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

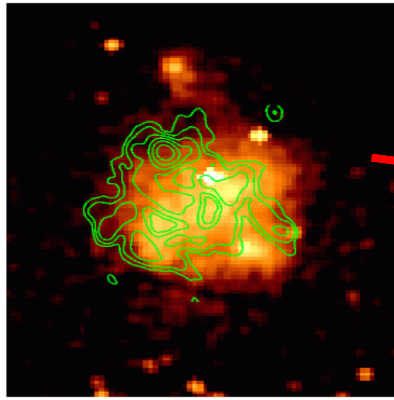


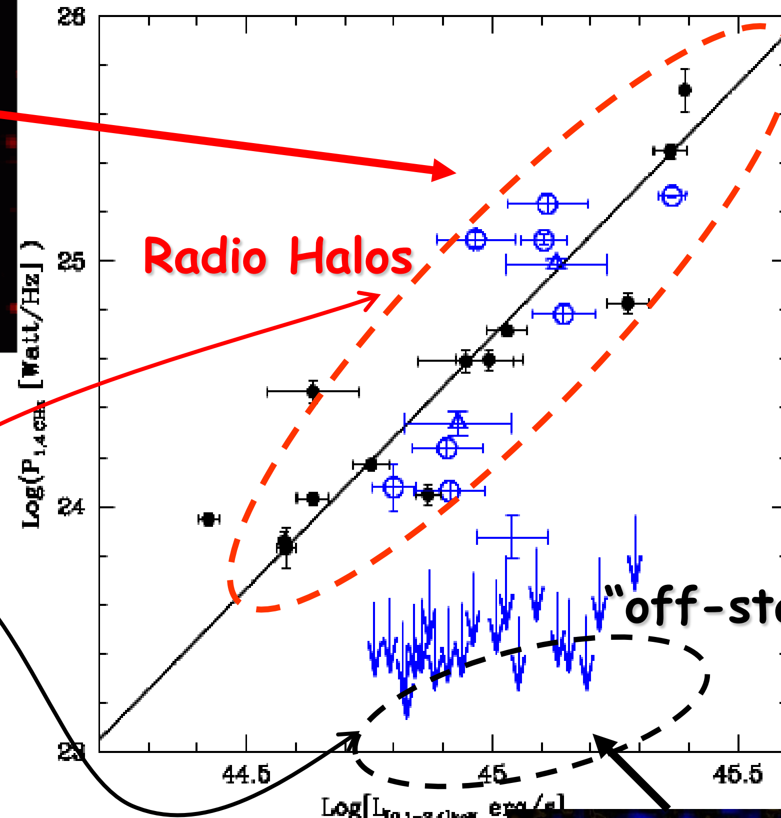


Cluster mergers - NT connection

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

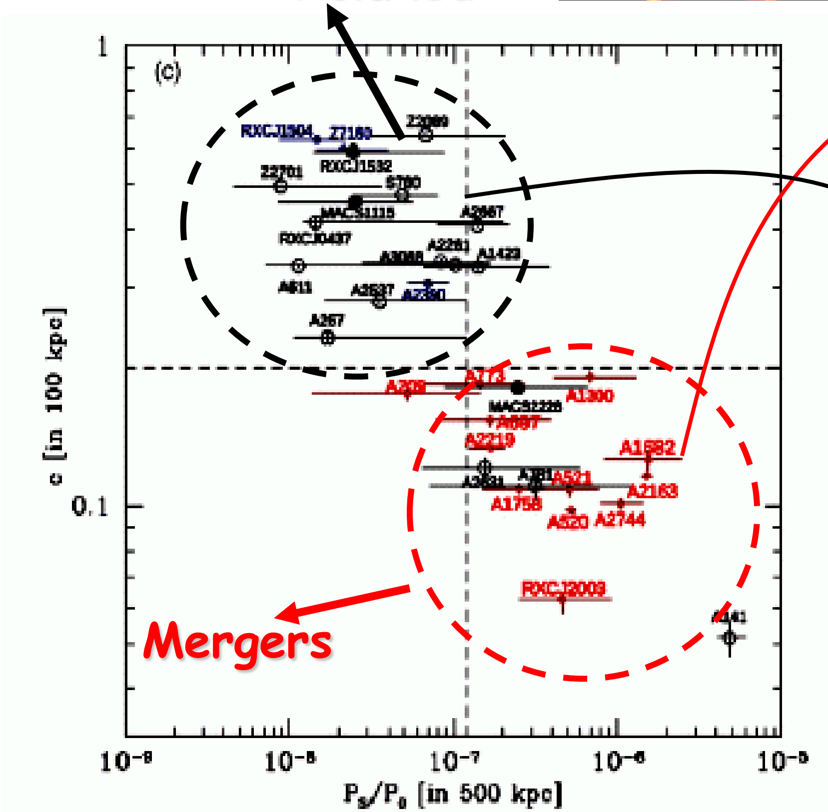
Radio halos probe the dissipation of kin energy in the DM-driven merger events into CRs and B



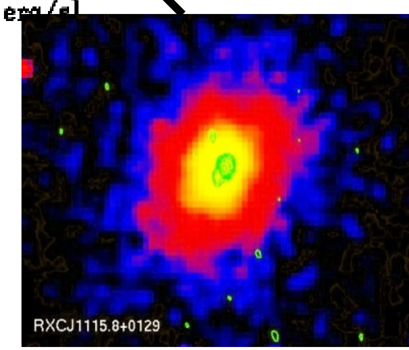


Brunetti et al 07,09

Relaxed



Cassano et al 10

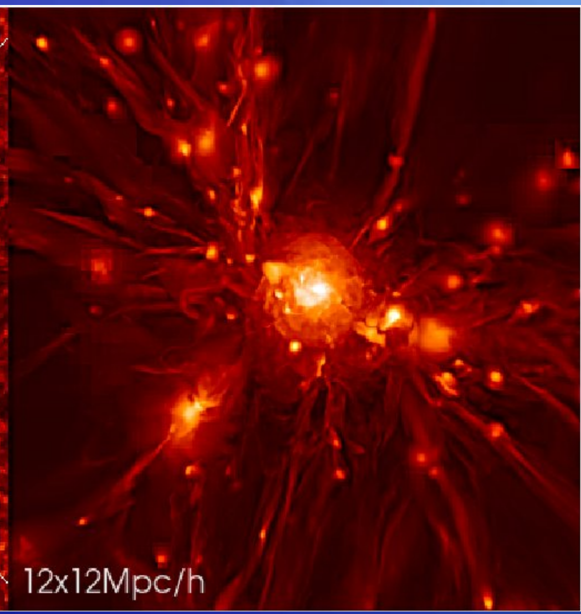


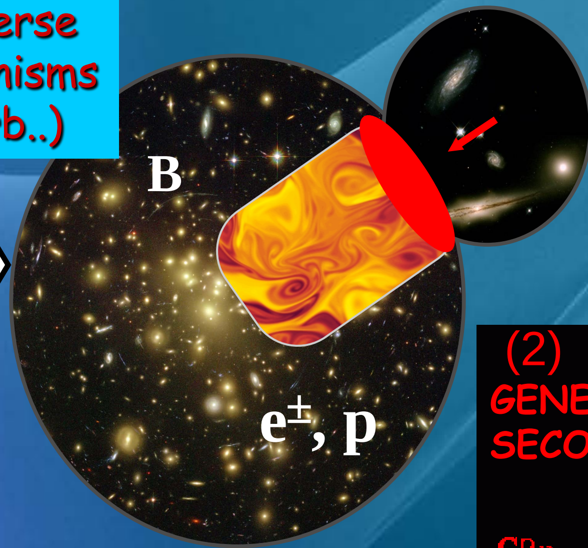
Mergers accelerate CRe and/or amplify B

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

Mergers & CR-acceleration

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

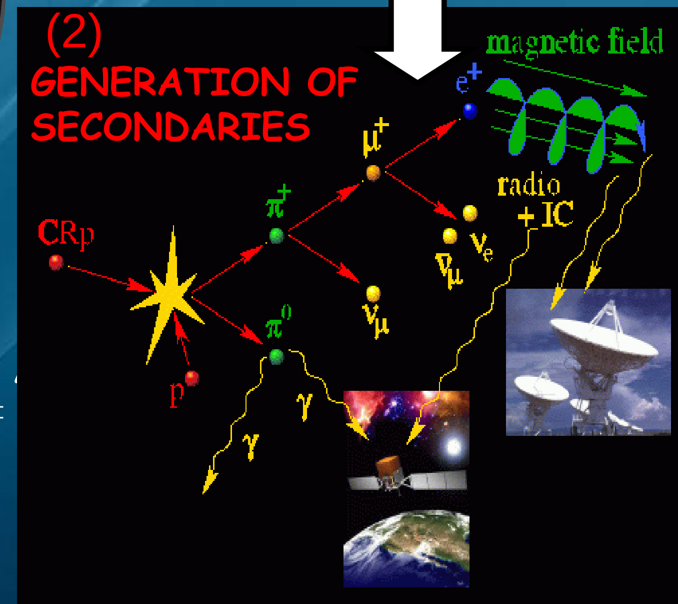




(1) SHOCKS

accelerate CRe$^{\pm}$,CRp

(2) GENERATION OF SECONDARIES



(3) TURBULENCE

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

Mergers & CR-acceleration

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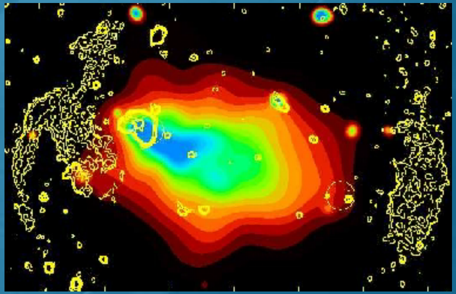
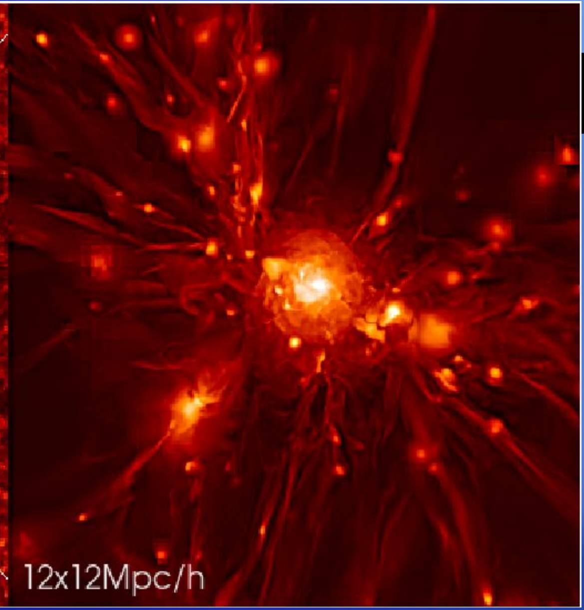
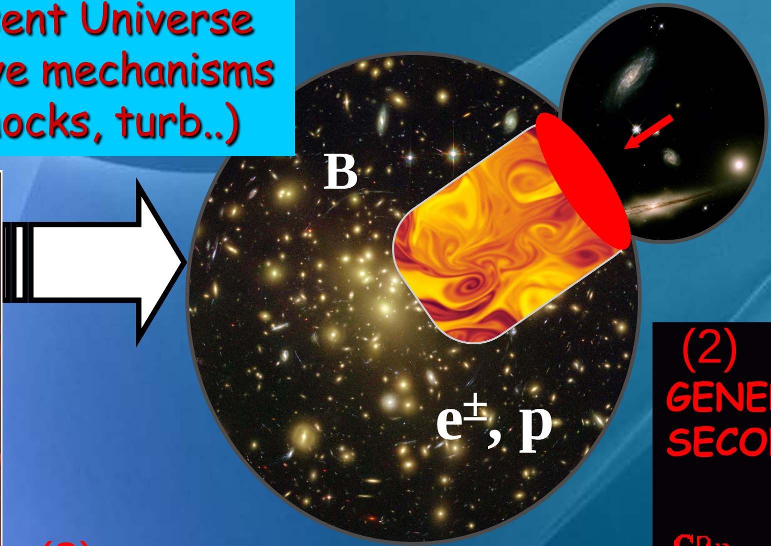
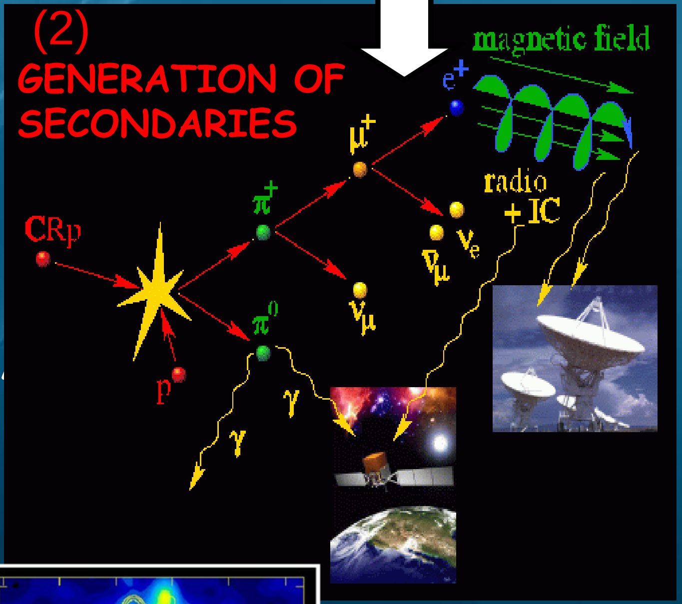






(1) **SHOCKS**

accelerate CRe$^{\pm}$,CRp



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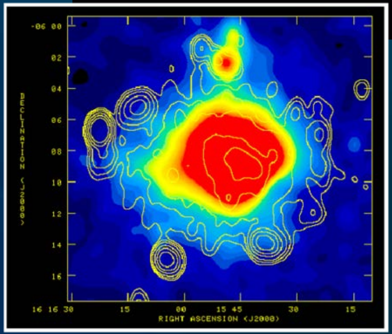

Mergers & CR-acceleration

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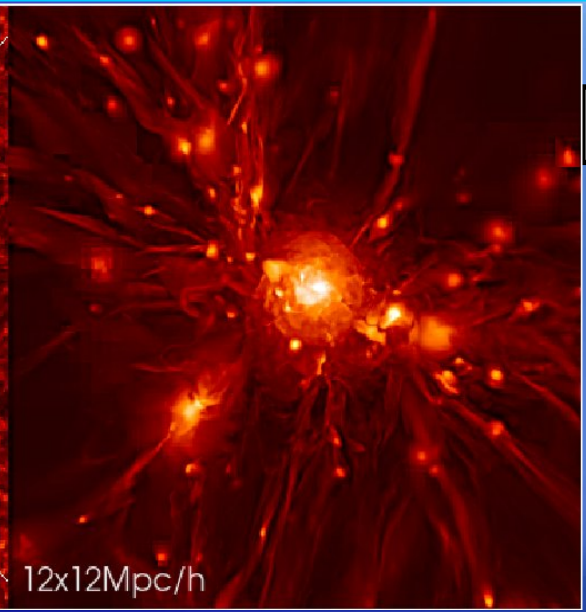
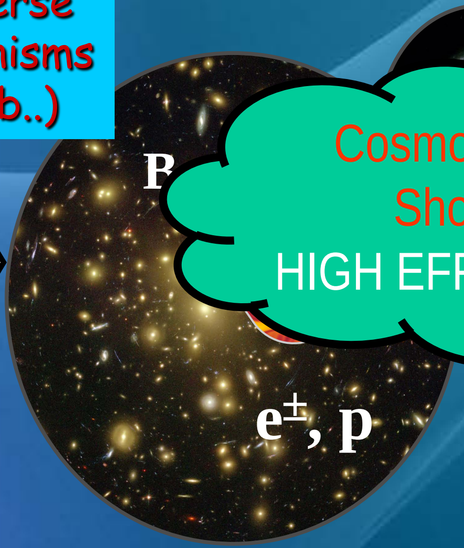
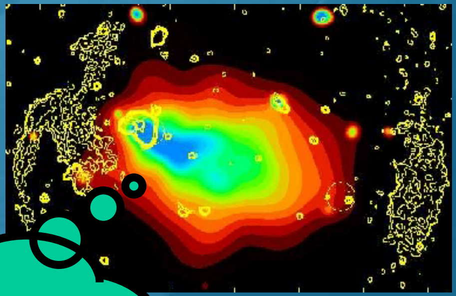


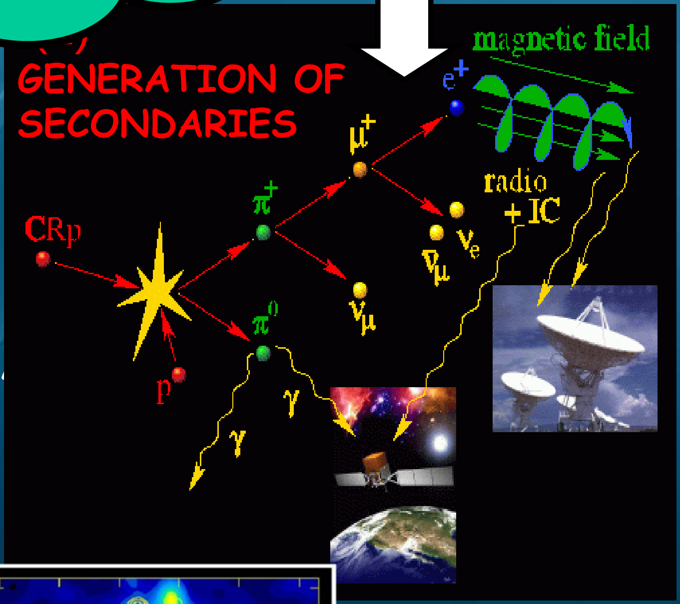




Cosmological Shocks
HIGH EFFICIENCY

…CKS

…erate $CRe^{\pm}$,CRp

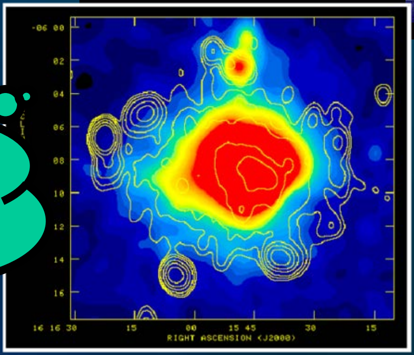


(3) TURBULENCE

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

REV: **Brunetti & Jones (2014)**

"Cosmic Rays in galaxy clusters and their nonthermal emission", IJMPD, 23, 1430007; arXiv: 1401.7519



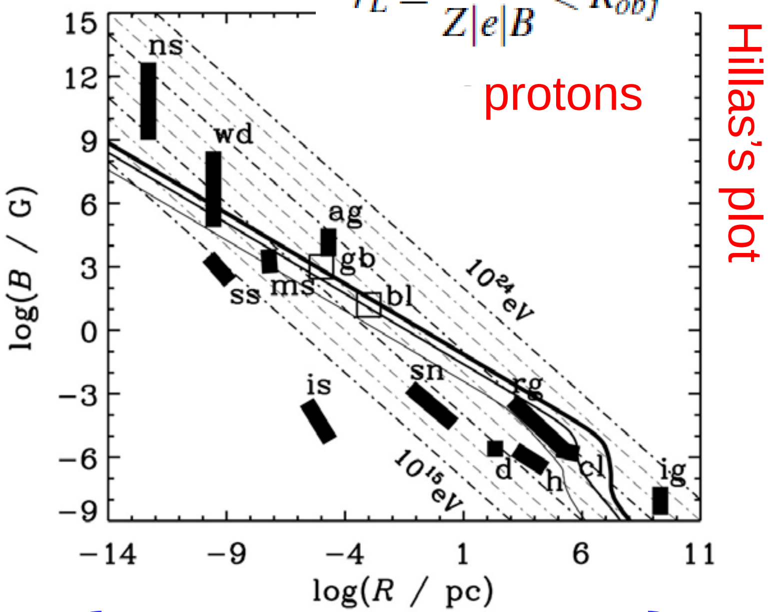
Giant Turbulent Regions
LOW EFFICIENCY

Max energy of CRp accelerated by shocks

(Kang et al 96, Blasi 01, Jones 04, ..)

Brunetti & Jones 14

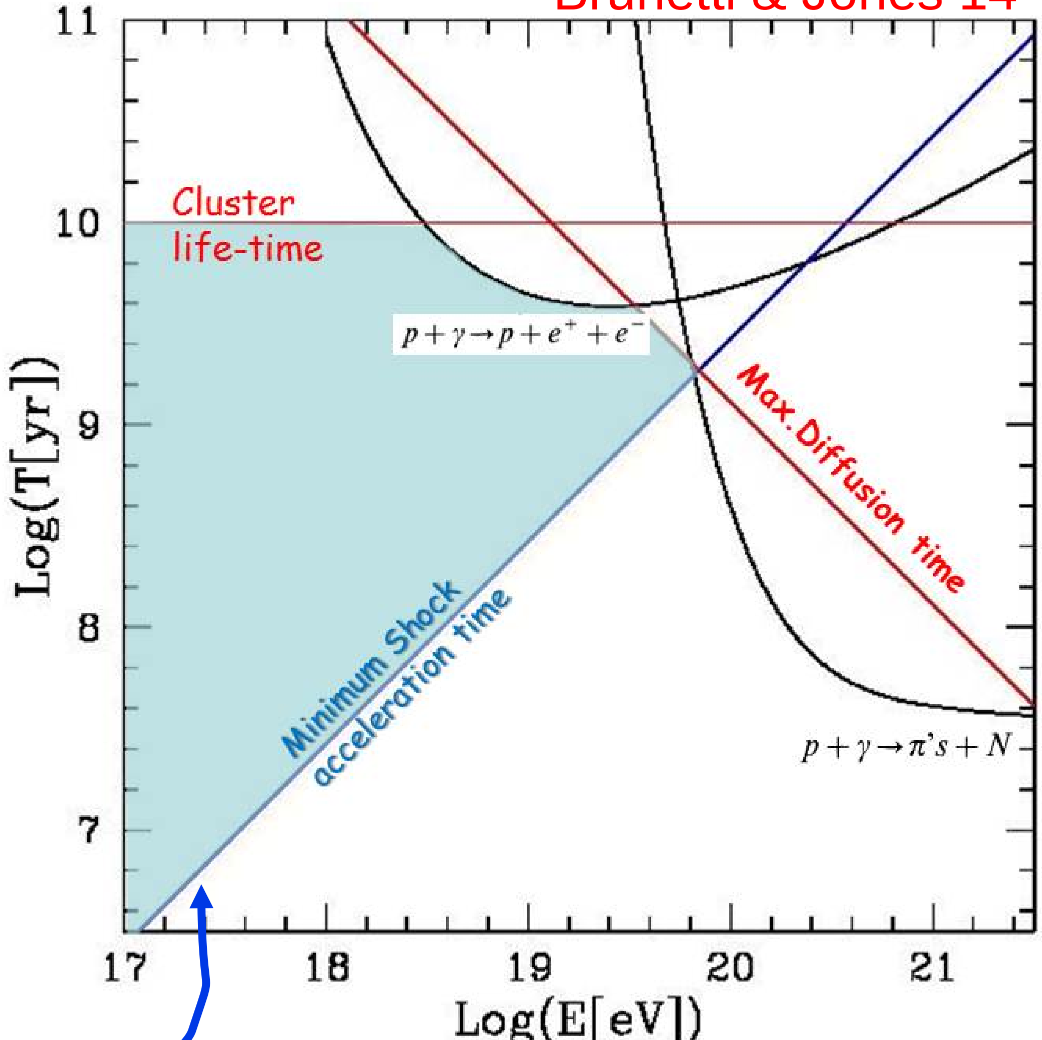
$$r_L = \frac{E/c}{Z|e|B} < R_{obj}$$



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

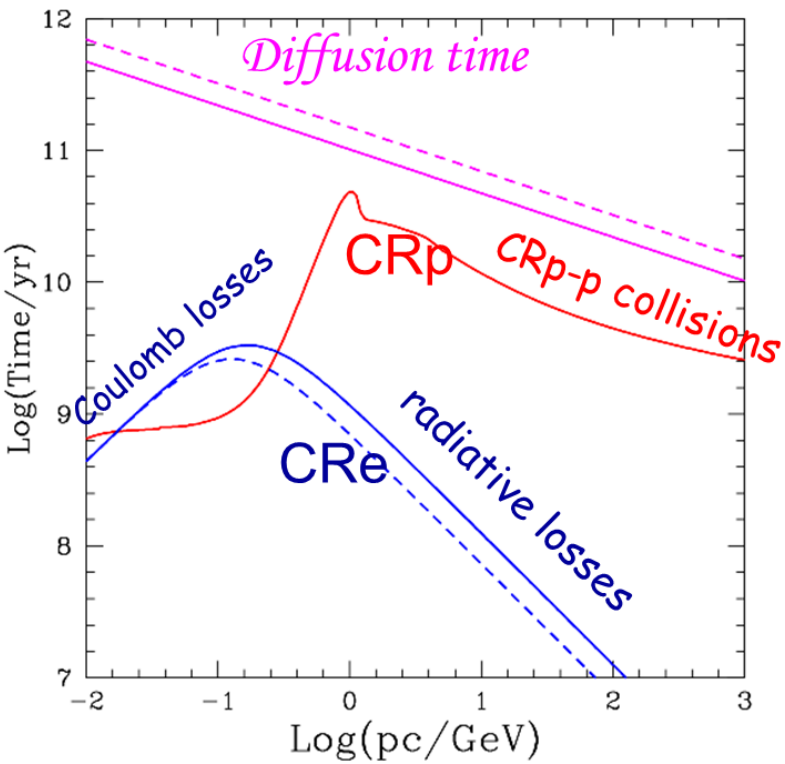
$$D(p) \sim 3 \times 10^{22} \frac{(cp/\mathrm{GeV})}{(B/\mu G)} \ \mathrm{cm}^2\mathrm{s}^{-1}.$$

$$\tau_{acc} \approx 2 \times 10^8 \left(\frac{cp/EeV}{B/\mu G}\right) \left(\frac{V_{sh}}{3000}\right)^{-2} yr$$



$E_{max} \approx$ 10+.. EeV

Quest for CRp in GC



Blasi, Gabici, Brunetti 07

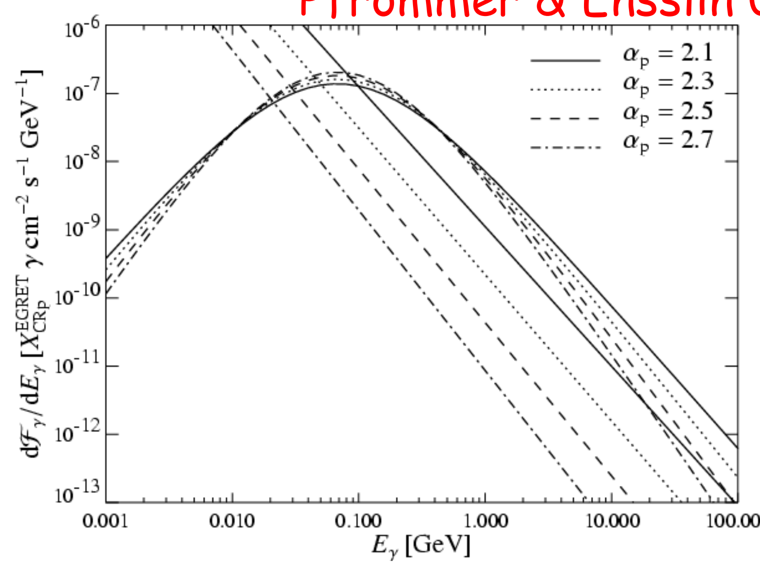
$$X_g \sim n_{ICM} m_p c \tau \sim 1.6 \times \frac{n_{ICM}}{10^{-3}} \times \frac{\tau}{\mathrm{Gyr}} \mathrm{g\ cm}^{-2}$$

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

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

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

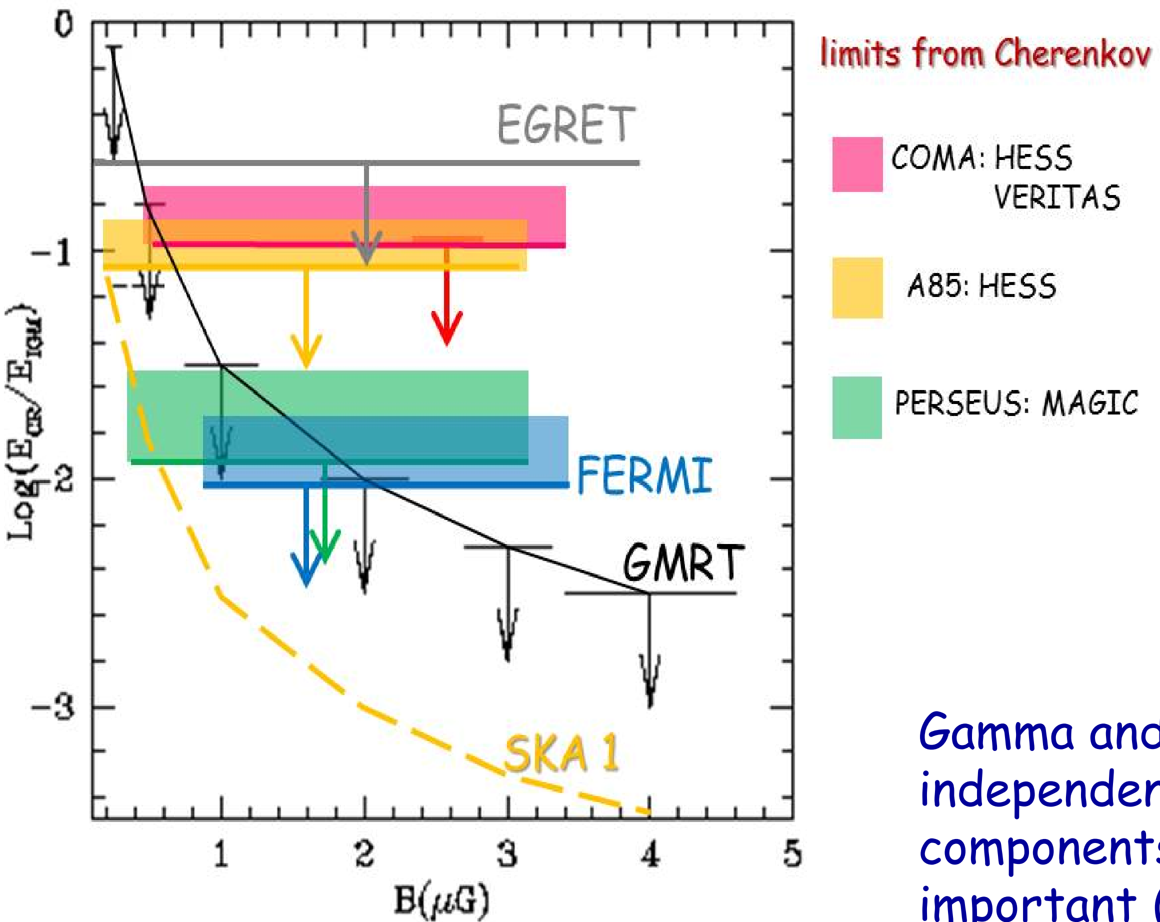
Pfrommer & Ensslin 04



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

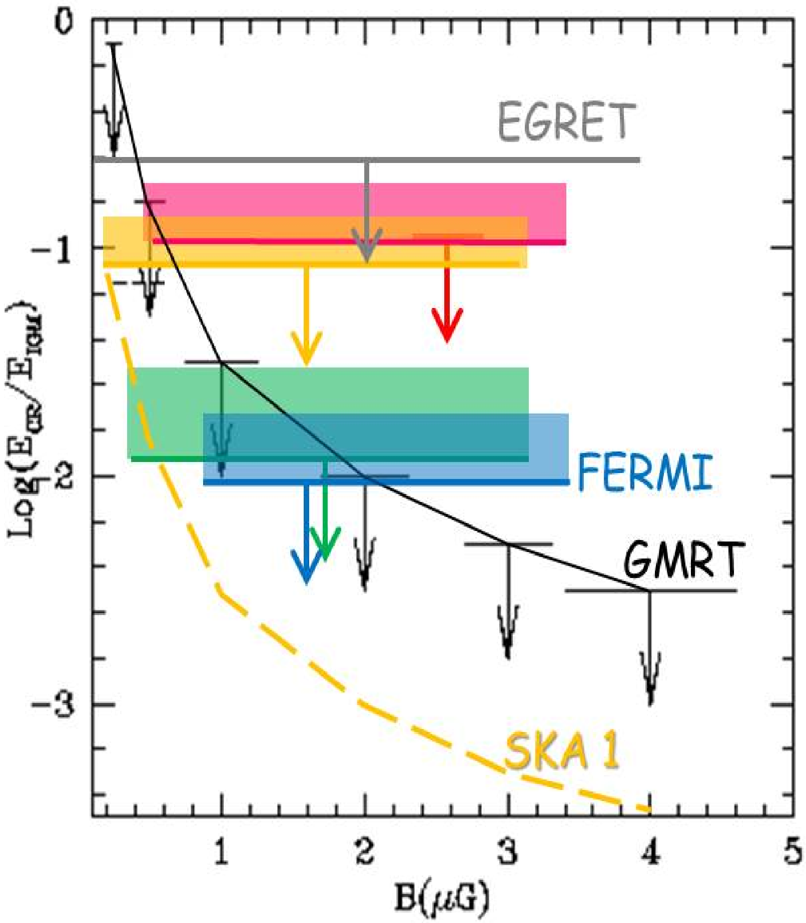
No gamma-rays from GC: limits on CRp

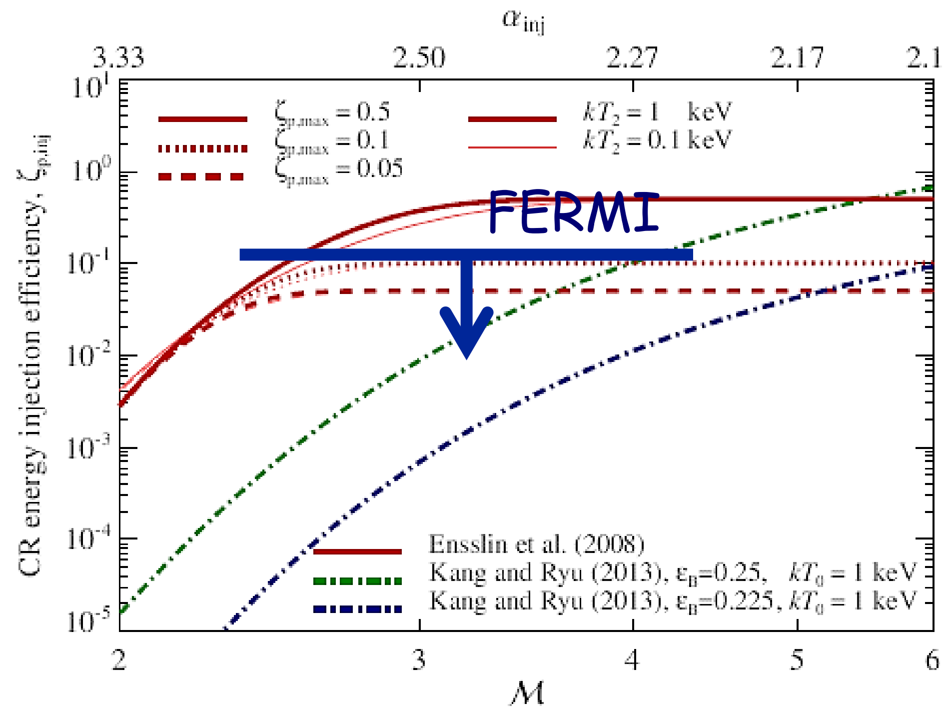


Reimer et al. 03
Reimer et al. 04
Pfrommer & Ensslin 04
Perkins et al. 06, 08
Brunetti et al. 07
Brunetti et al. 08
Aharonian et al. 08 a,b
Aleksic et al. 09,12
Ackermann et al 10,13
Arlen et al 12
Huber et al 13
Prokorov & Churazov 13

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

CRp acc efficiency… @ LS shocks



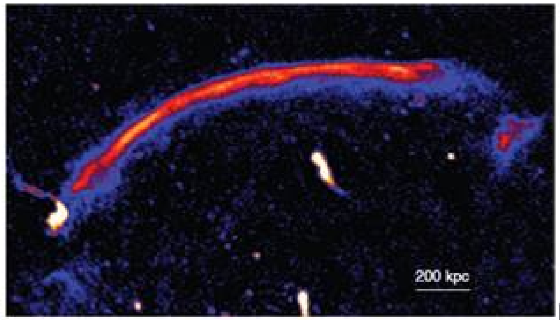


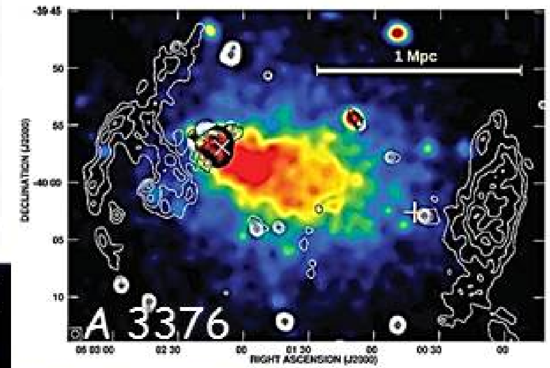
Ackerman et al 13

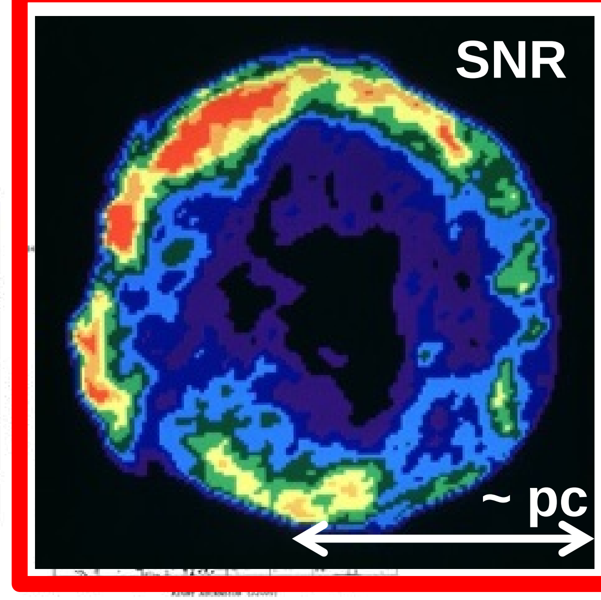
The max acceleration efficiency that is constrained by current Fermi-LAT limits is 3x smaller than that «expected» by «optimistic» models and «boarder line» with more «pessimistic» models.

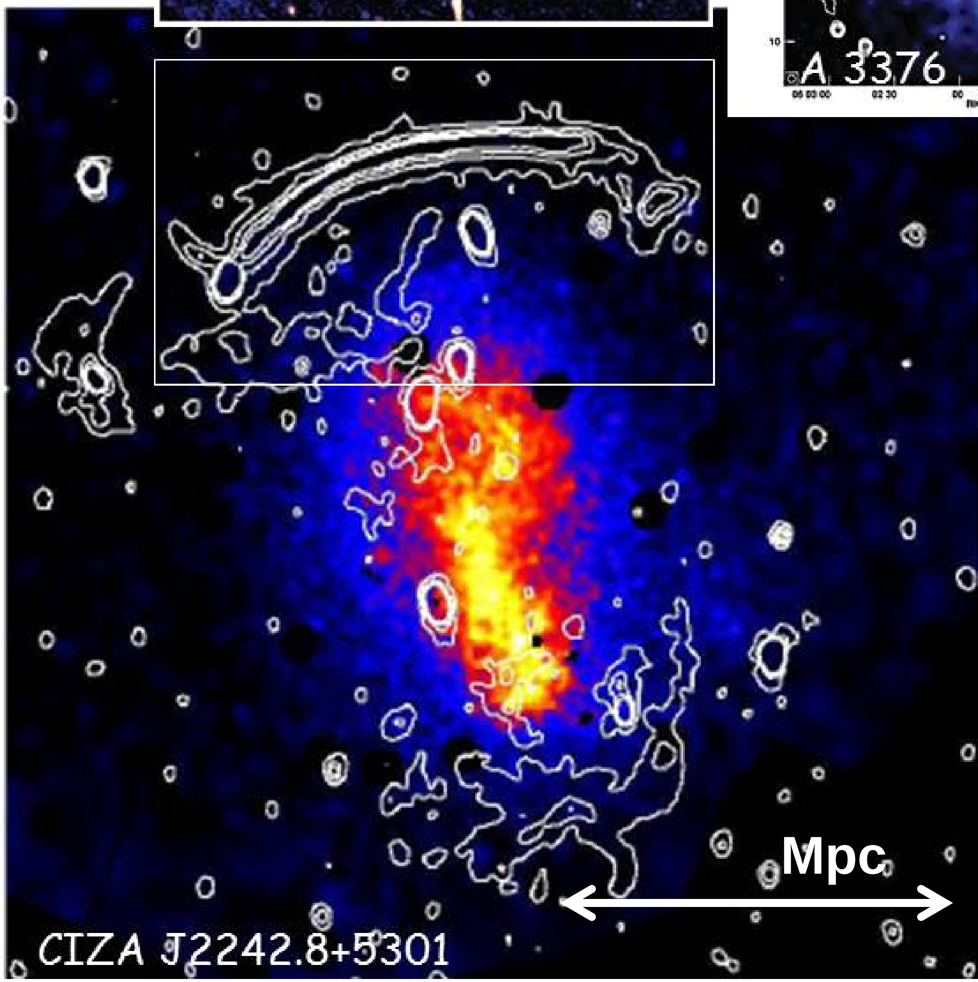
It means that ** if CRs are confined in galaxy clusters ** we are probably close to detecting galaxy clusters in gamma-rays. FERMI10 AND CTA …

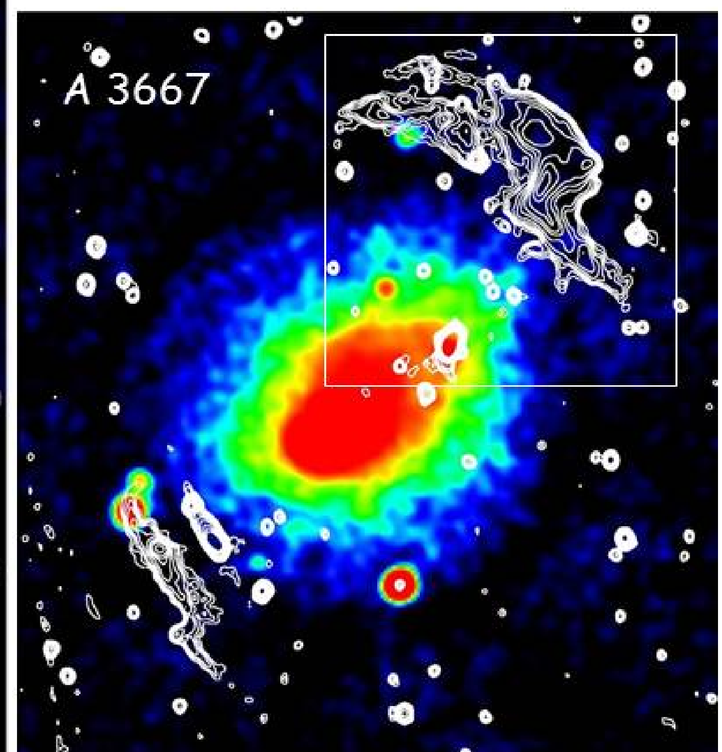
CRe: Giant Radio Relics





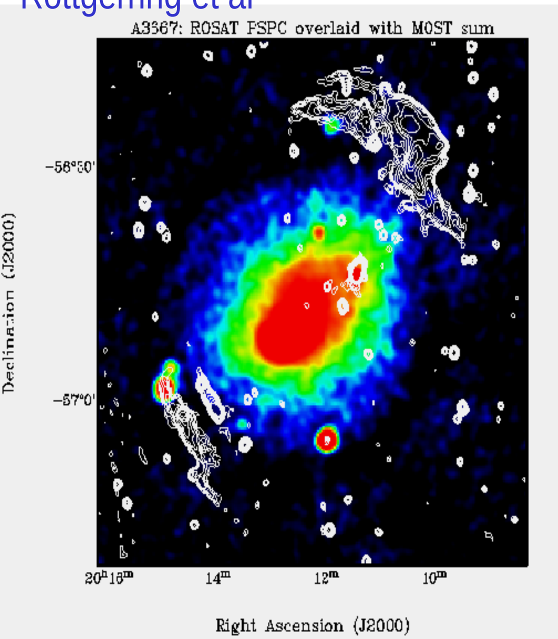


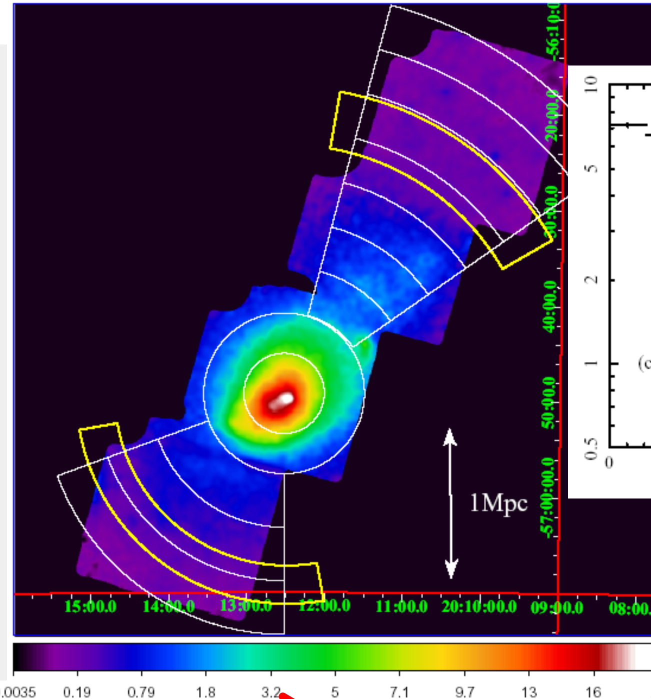




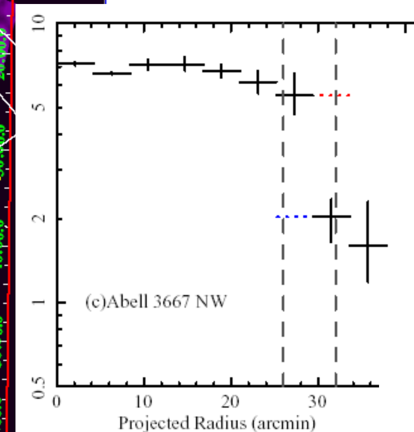
Radio Relics -- Shocks connection

Rottgerring et al



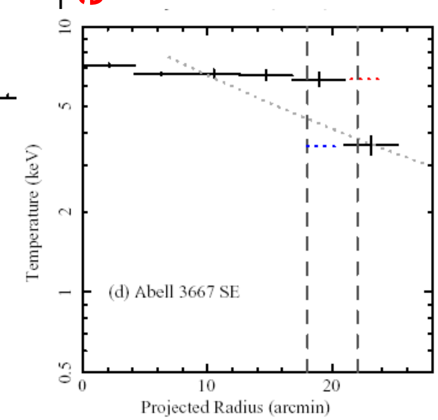


Akamatsu & Kawahara 12

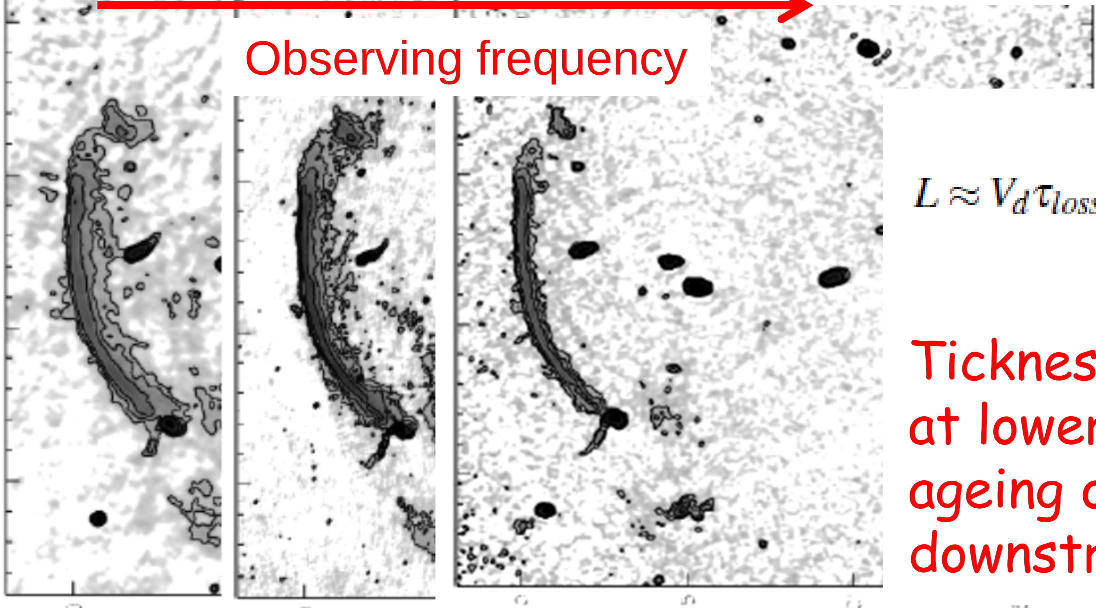


temperature

Mach=2 - 4



Observing frequency



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

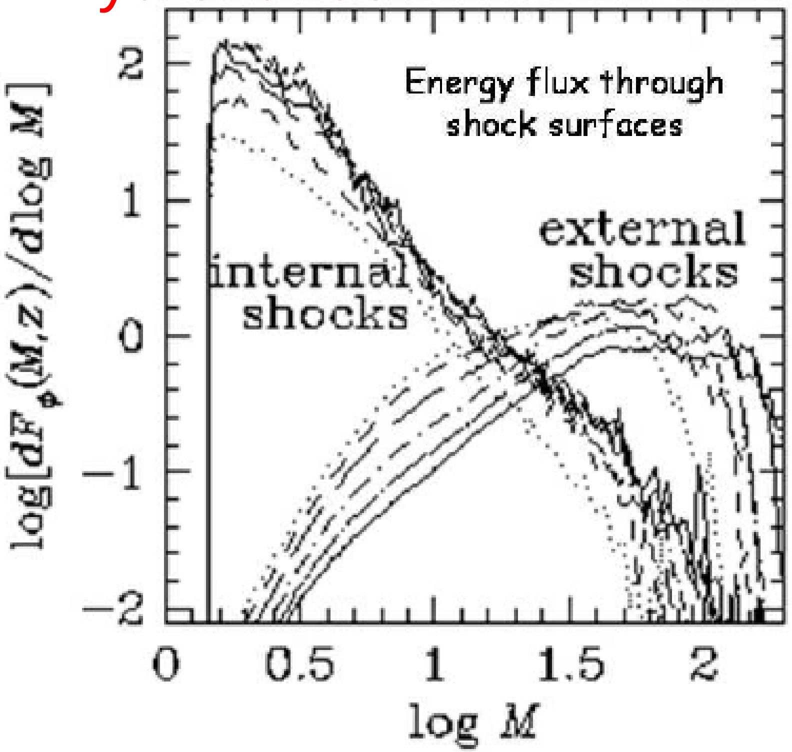
$$\tau_{loss} \approx \frac{4\pi}{\sigma_T} \frac{m^2 c^3}{B_\perp^2 + B_{IC}^2} \frac{1}{E}$$

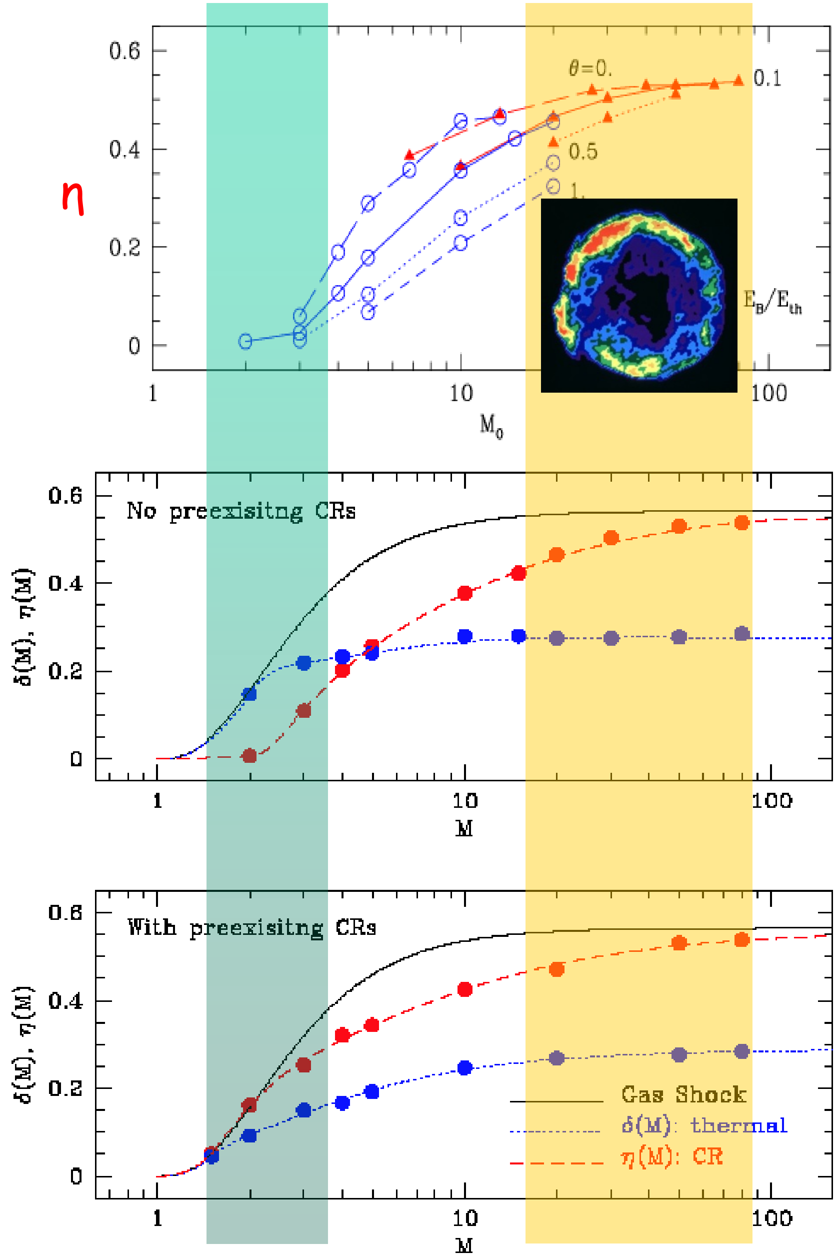
Tickness increases at lower frequencies: ageing of CRe downstream

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

CRs acceleration at weak shocks

Ryu et al 03





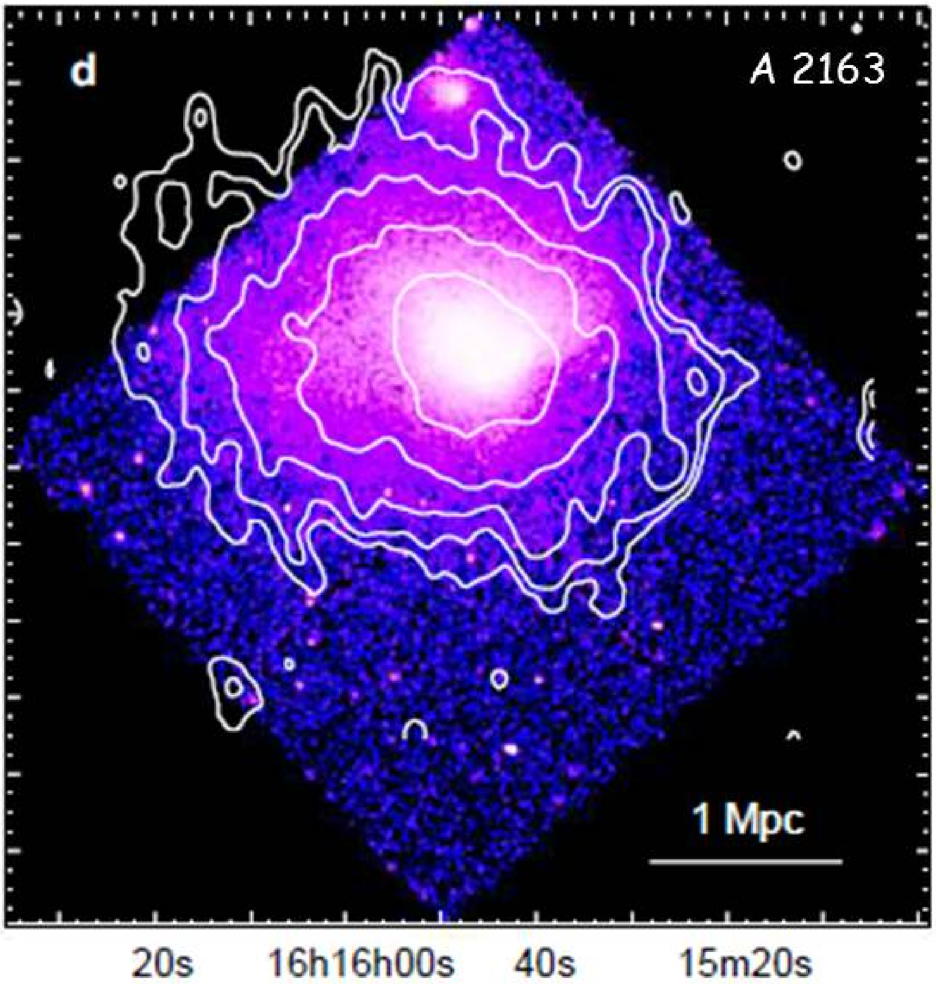
Kang & Jones 07

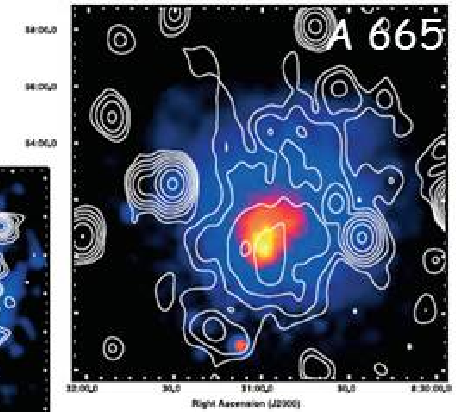
Kang et al 07, 12

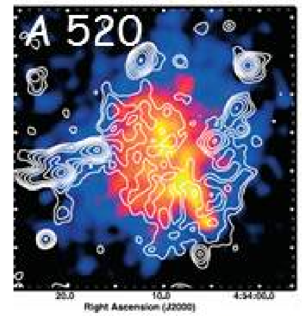
Miniati et al. 01 Gabici & Blasi 03 Ryu et al 03
Pfrommer et al 06,08 Hoeft et al 07,09
Skillman et al 08,11,13 Vazza et al 09,11,12

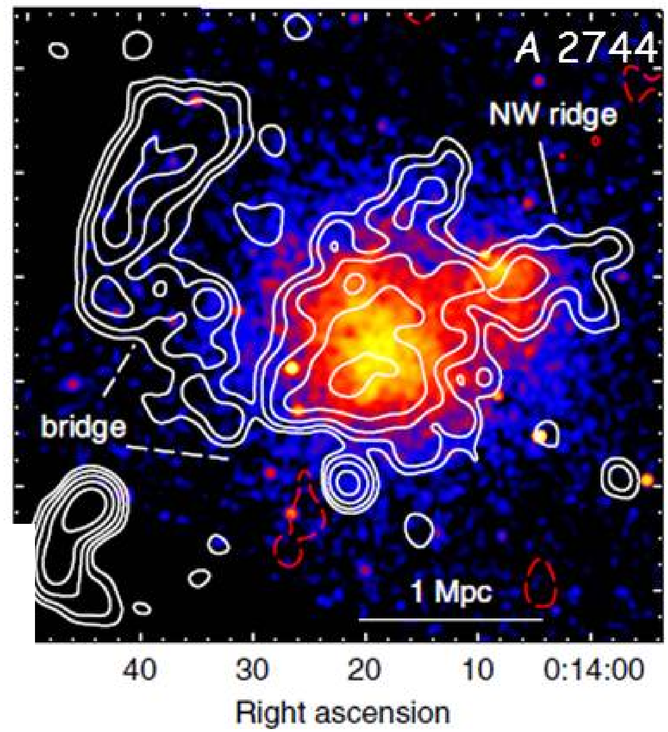
- Efficiency of CRs (RE)acceleration ?
- Ratio CRp/CRe ?
- B-amplification ?

RADIO HALOS



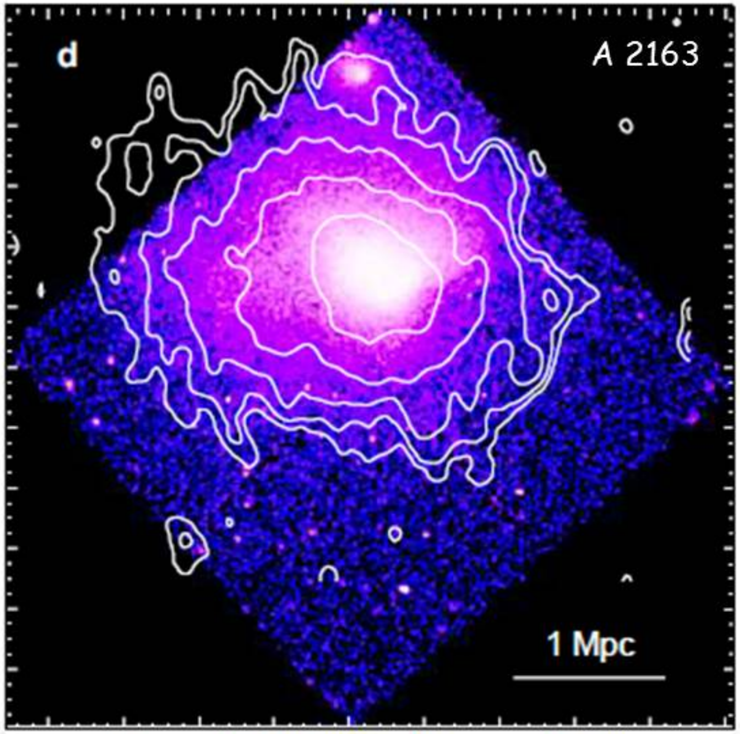


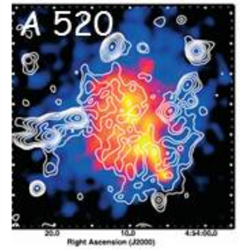


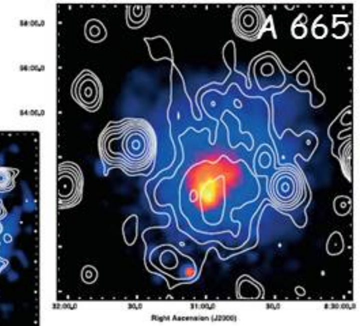


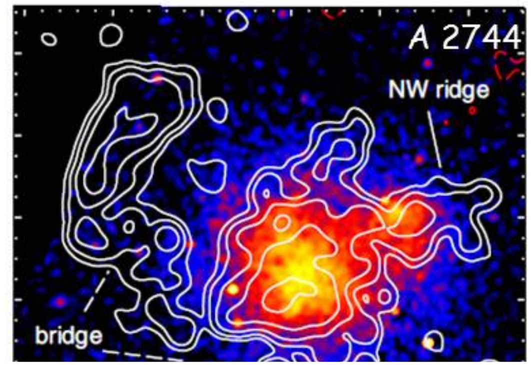
The time necessary to CRe to diffuse on a sizeable fraction of Radio Halos (i.e. about Hubble time) is much larger than the radiative life-time of CRe (e.g., Jaffe 1977).

RADIO HALOS



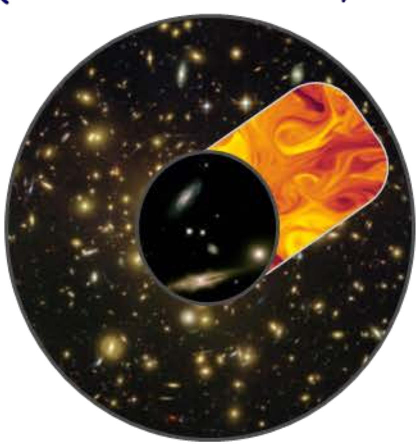




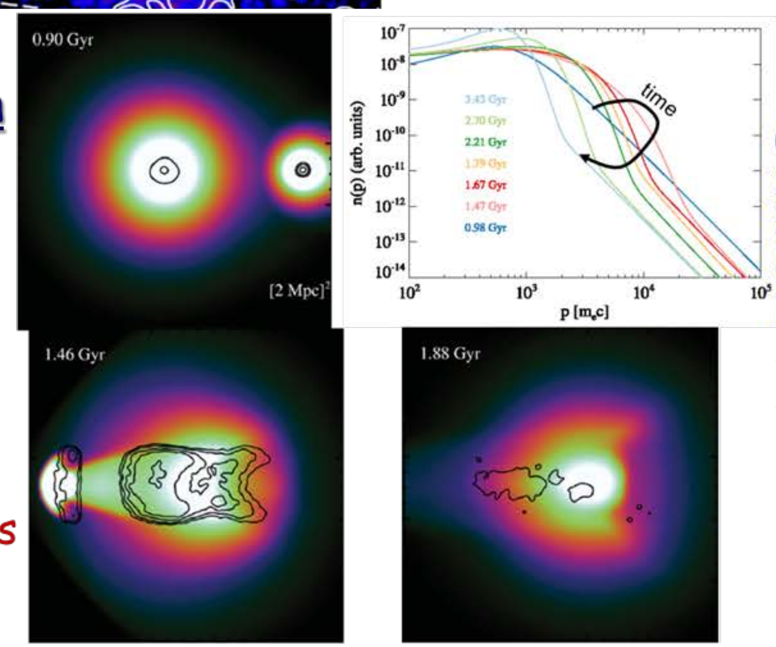


Turbulence and stochastic (re)acceleration

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

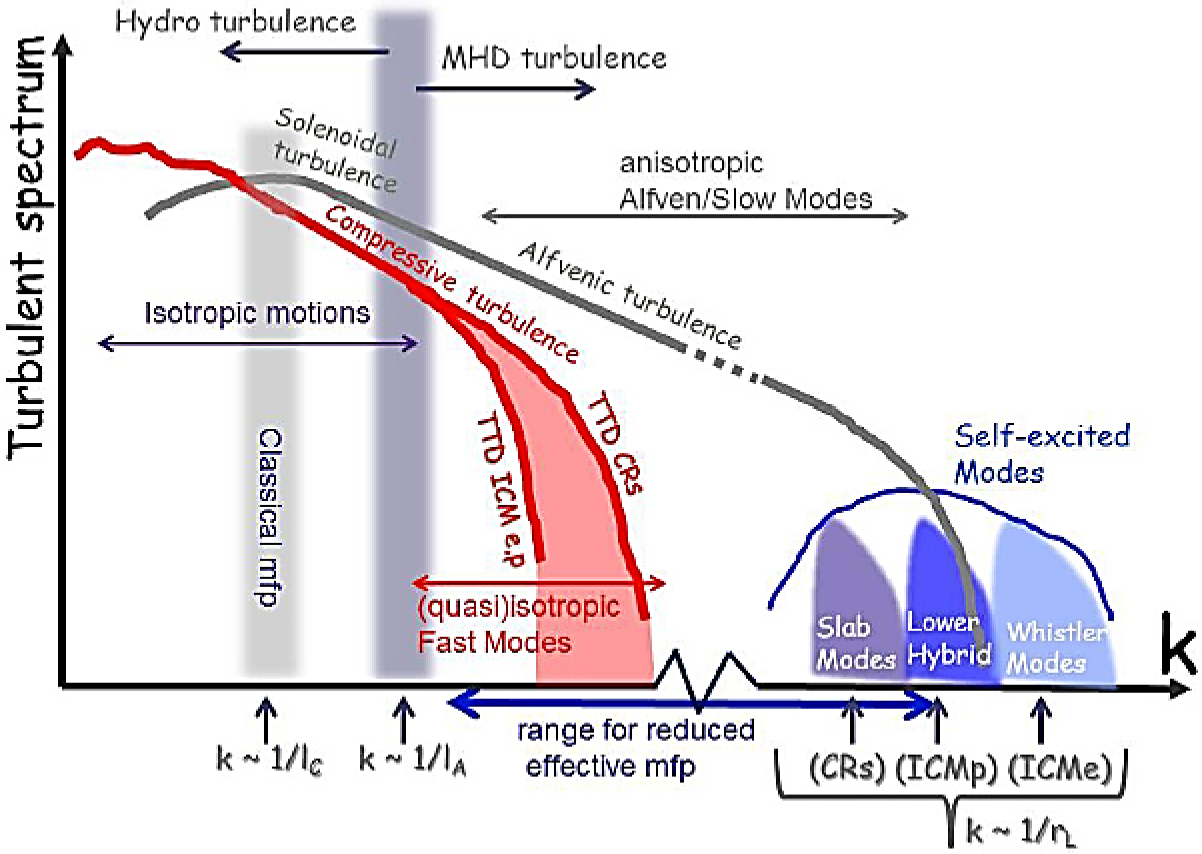


Radio halos probe the dissipation of energy in dark-matter driven collisions between clusters



Donnert et al 13

RADIO HALOS : probes of plasma physics in the ICM



- The ICM is a «weakly collisional», high-beta medium: complex & poorly understood
- Gravitational energy goes into EM fluctuations and into heating+CRs+B
- Electromagnetic fluctuations (eg turbulent-B) affect particle diffusion/transport
- CRs+B back-react on ICM dynamics (thermal & turbulence)

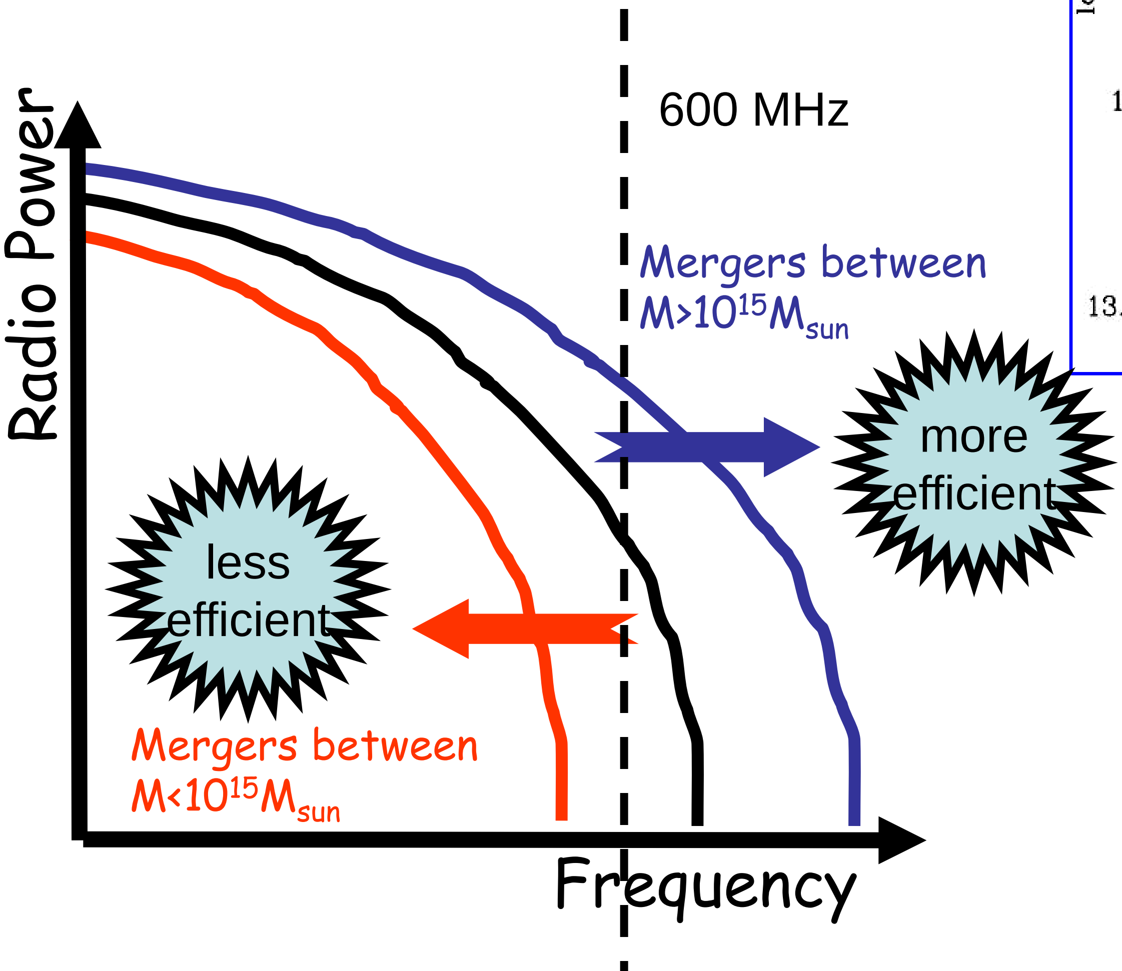
Expectations for Radio Halos

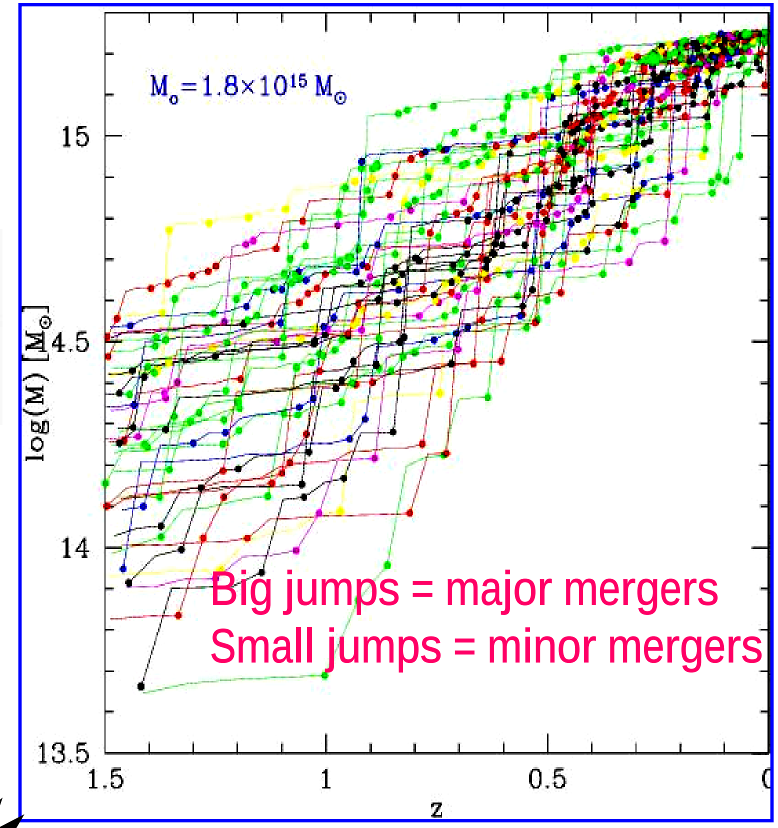
Acceleration efficiency

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

Steepening frequency

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



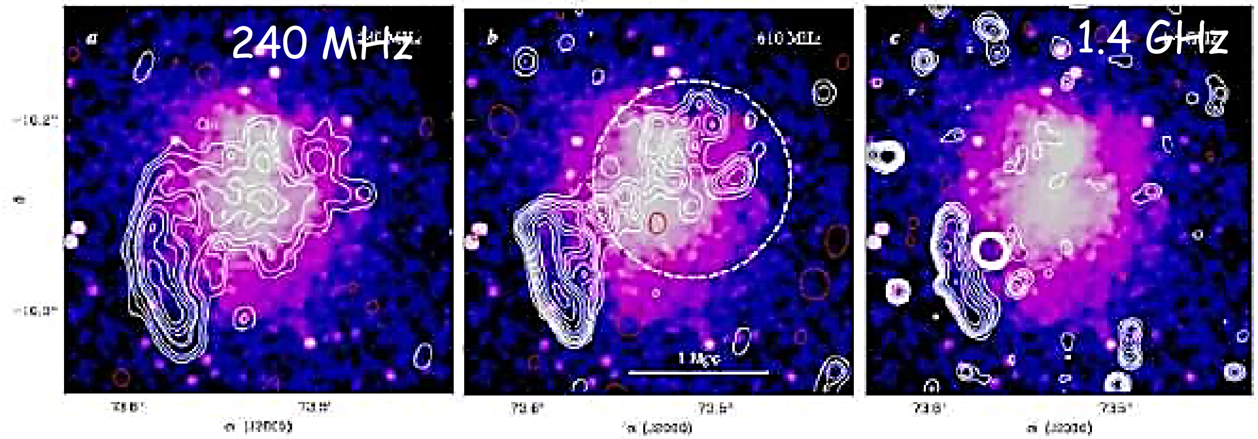


Radio Halos with very steep spectrum in the classical radio band must exist

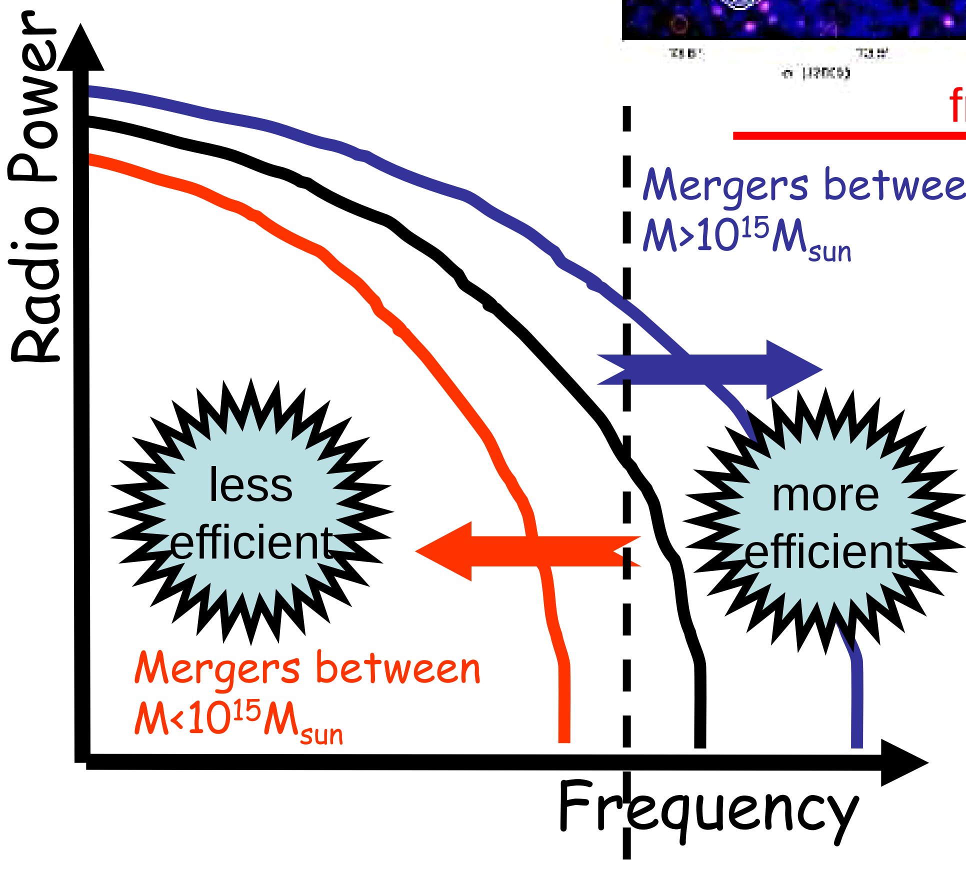
(Cassano, Brunetti, Setti 06)

OBS: Syn spectra of Radio Halos

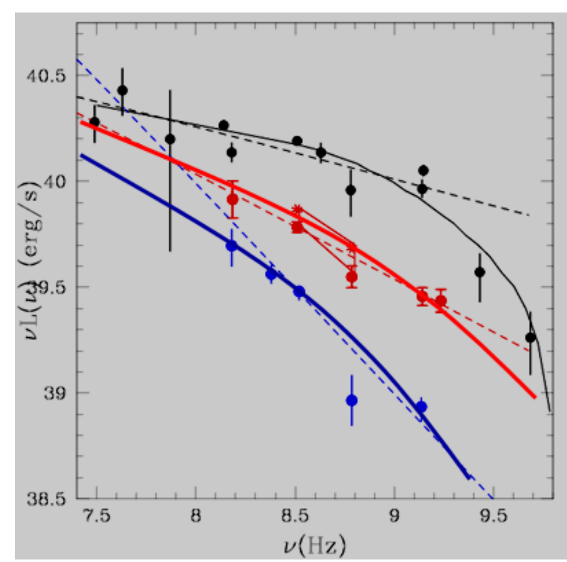
Brunetti et al 08 Nature 455, 944



frequency



Venturi 11,13, Macario 13



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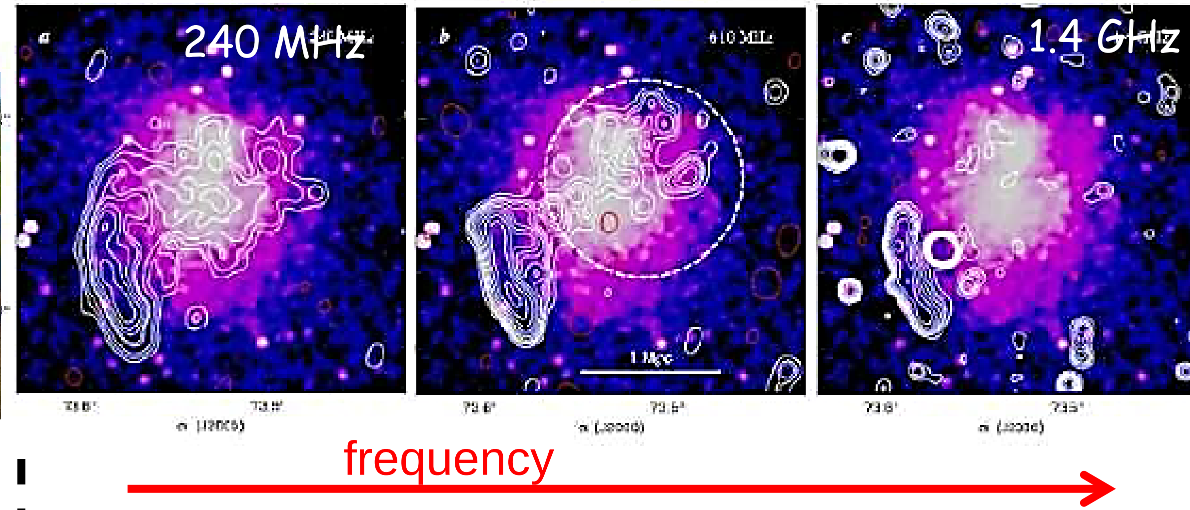

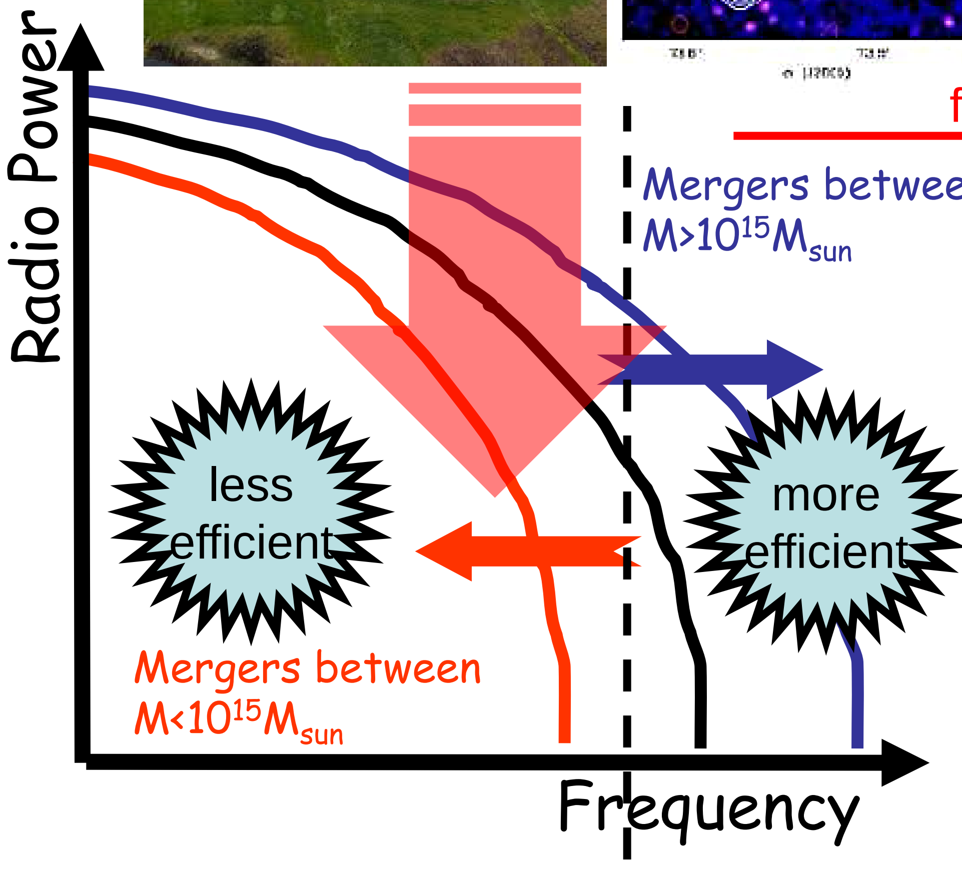

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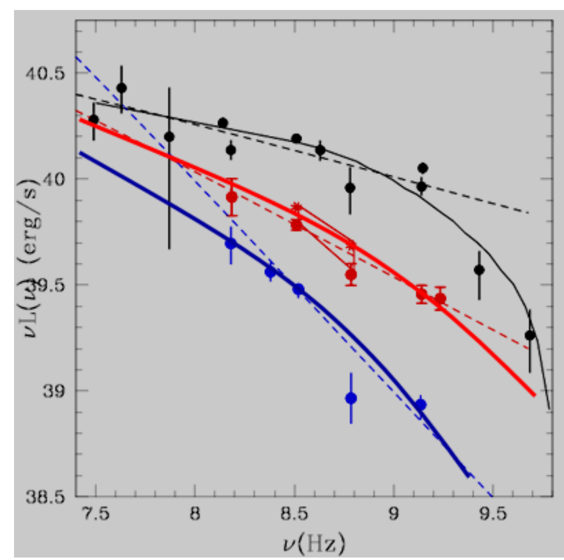
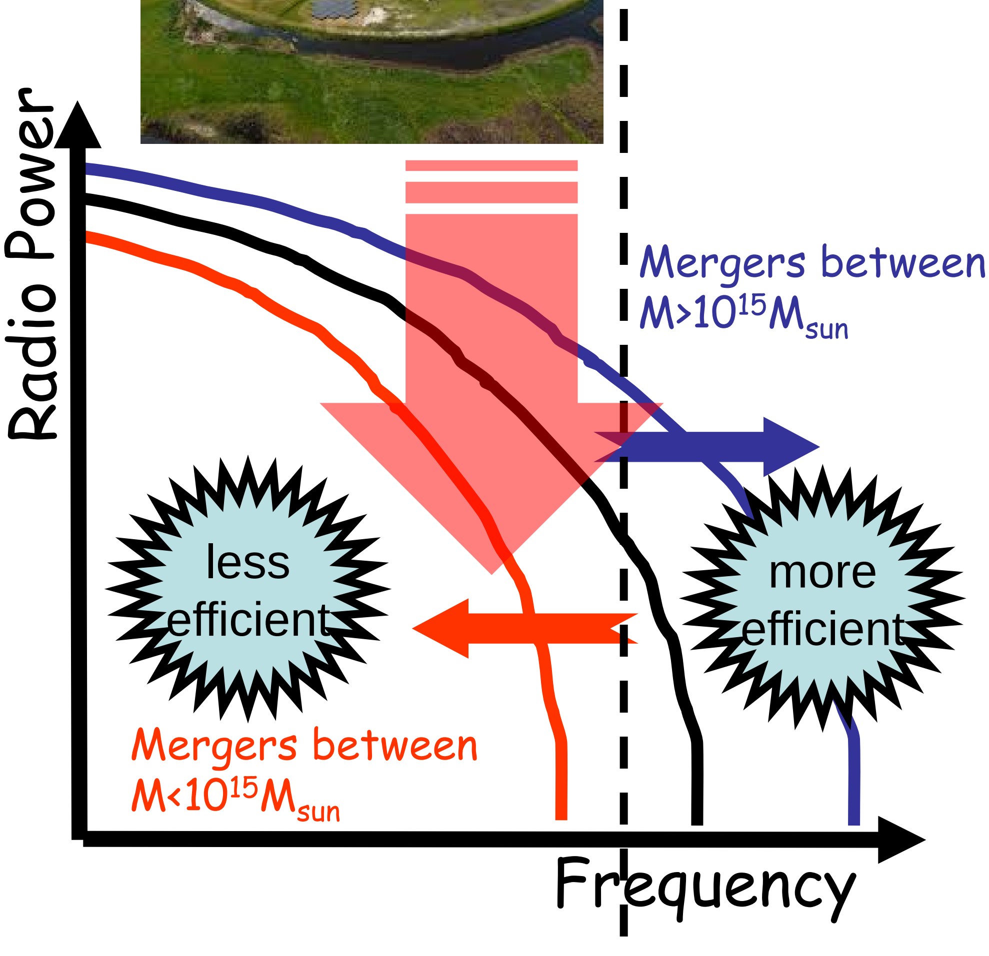
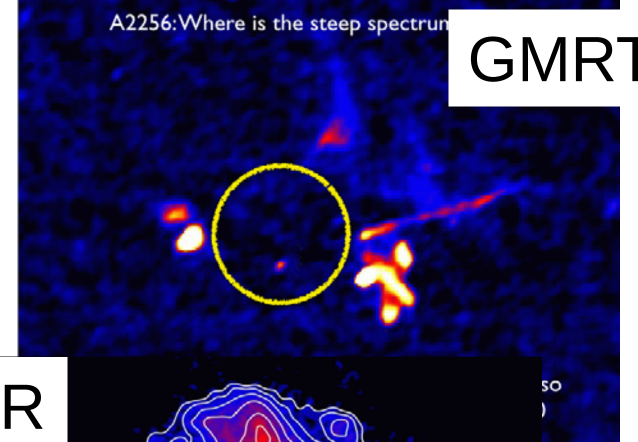
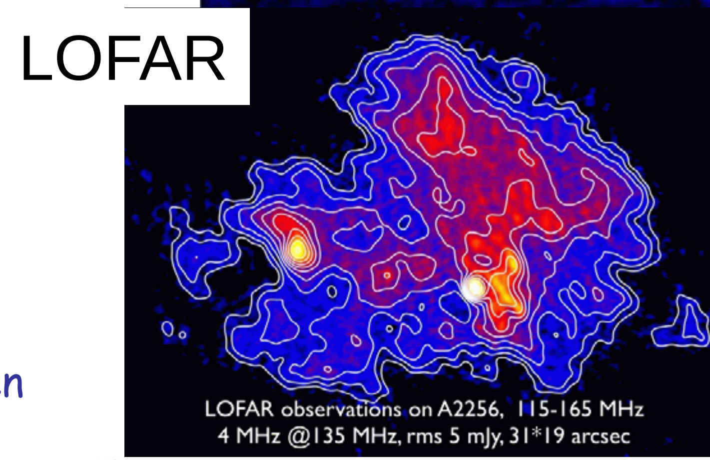
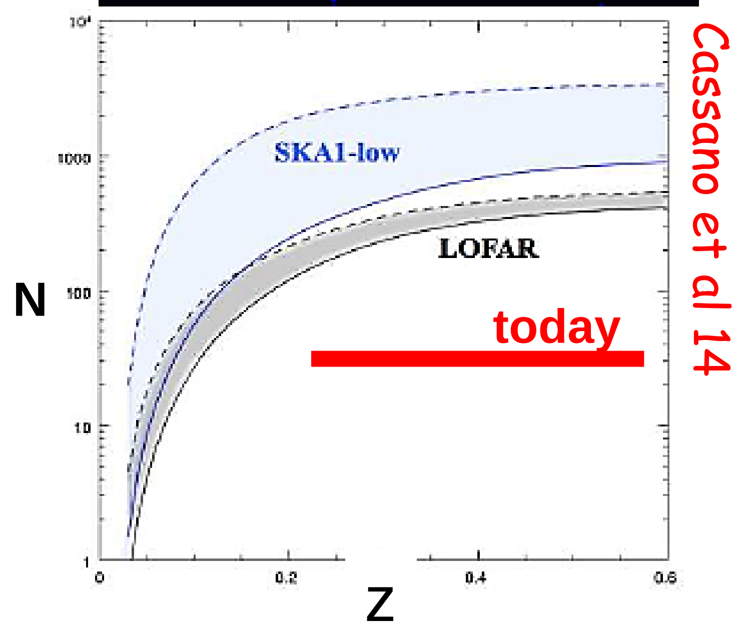


Radio Halos: LOFAR & SKA









From radio to high energies

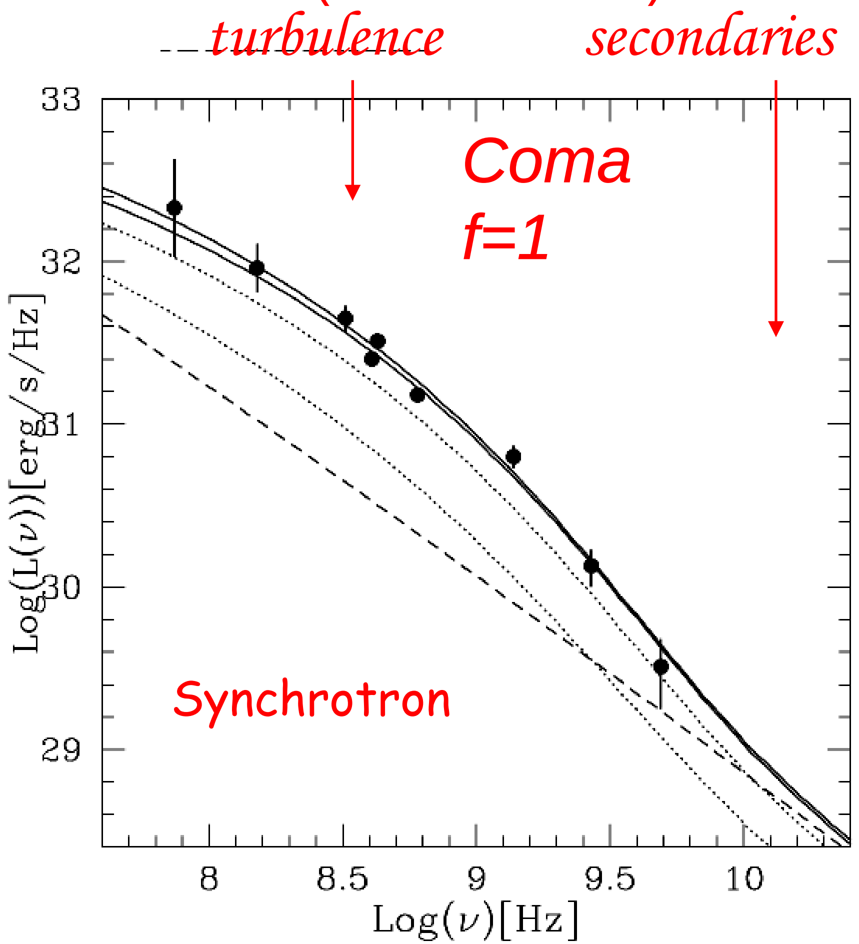
(Brunetti & Lazarian 11)

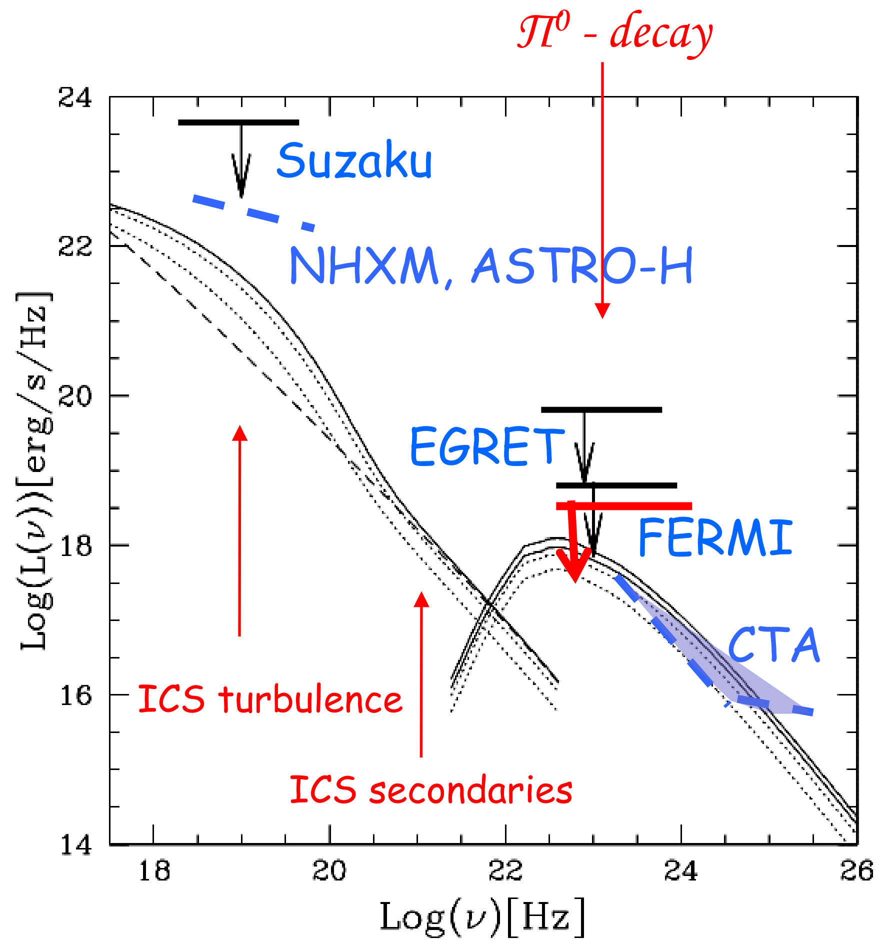
Calculations that consider the general case where both primaries (CRp,CRe) and secondaries (CRe) interact with Turbulence (reaccelerated)

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

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

E_{CRp} = ~ % E_{th}





Importance of high-energy observations

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

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

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

Turb energy flux

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

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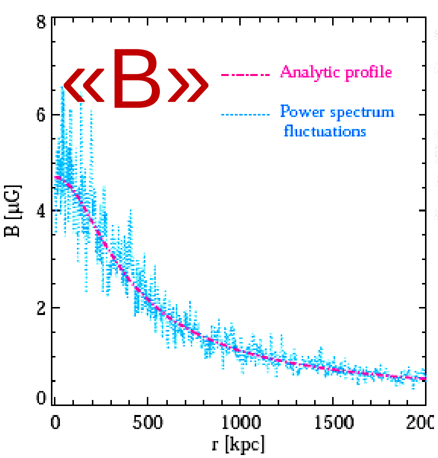
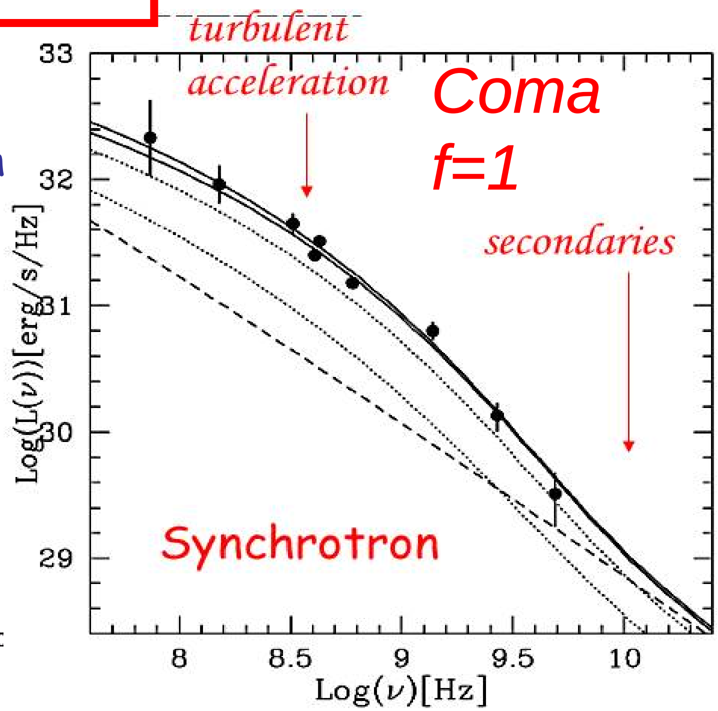
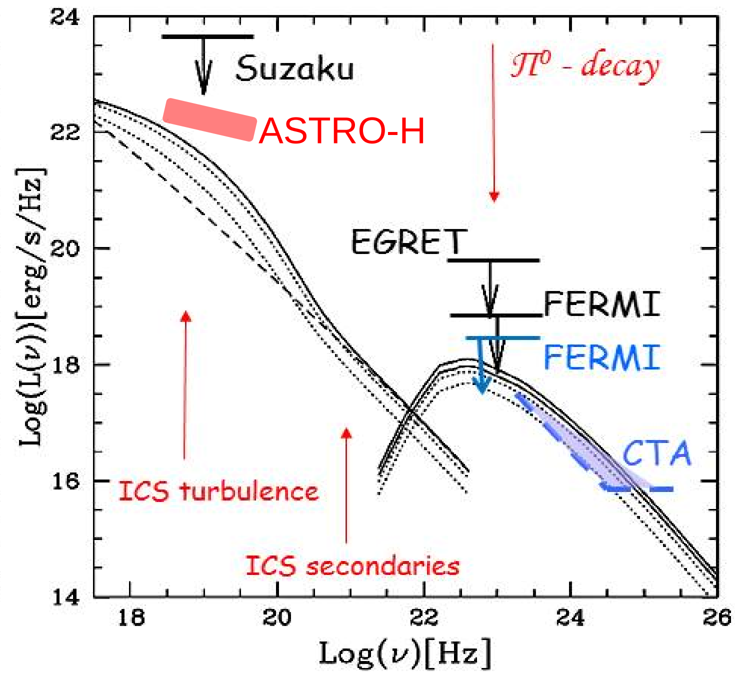
$$f = \frac{PRIMARY\, e^\pm}{SECONDARY\, e^\pm} + 1$$

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

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







Constraining phys parameters

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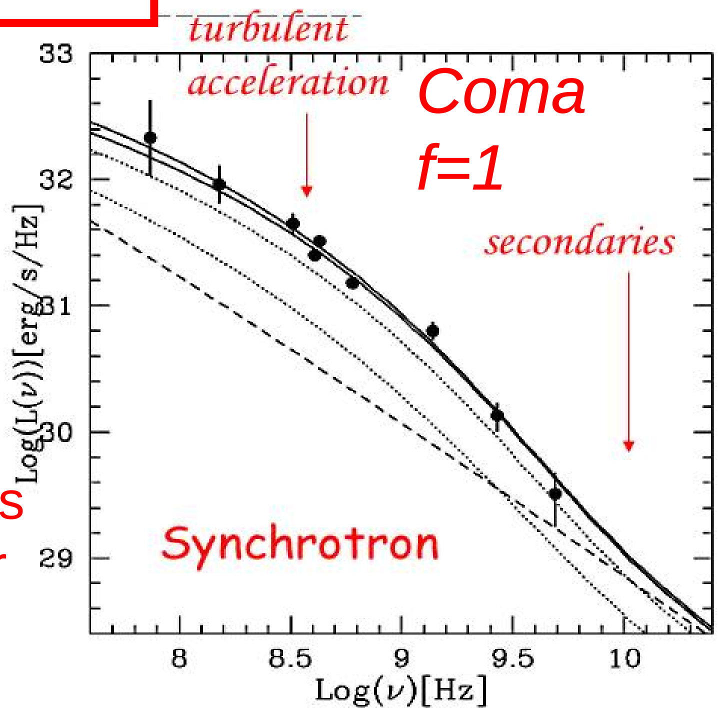
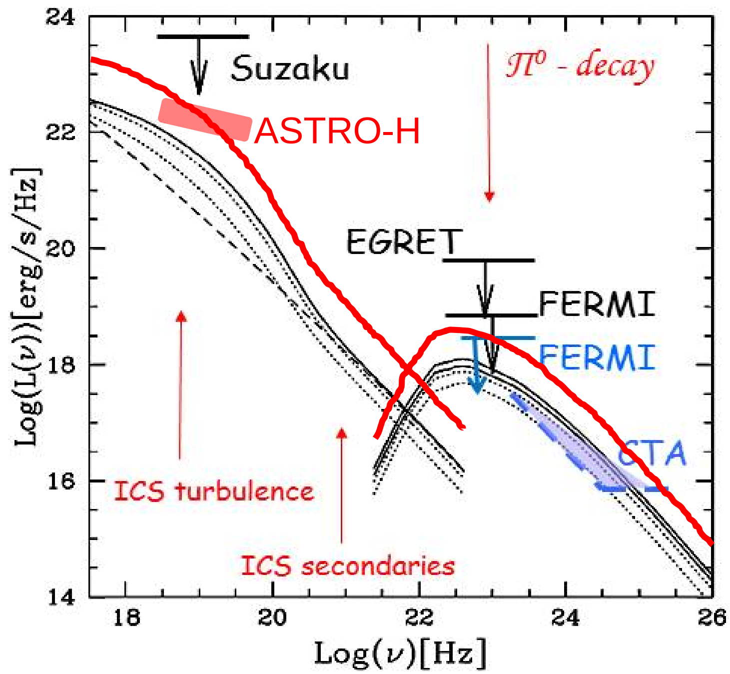
0.4xB

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





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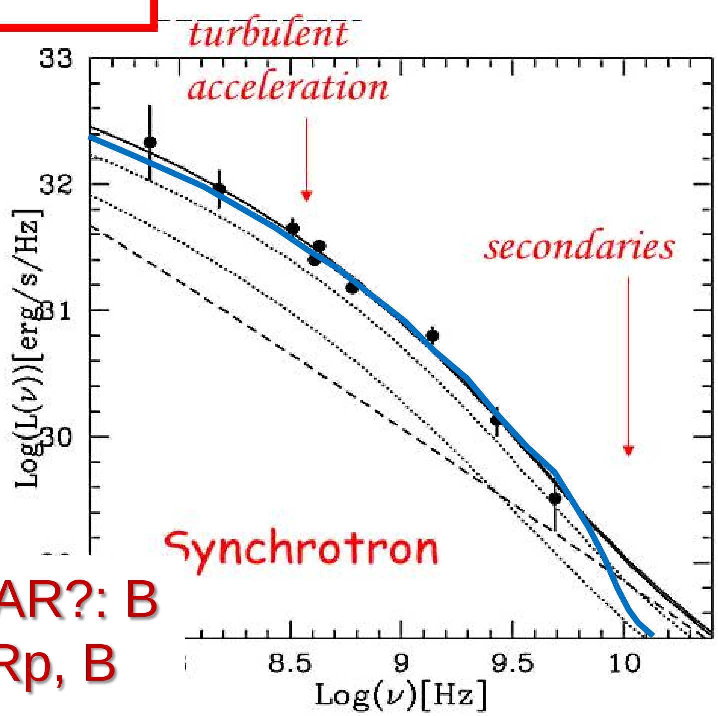
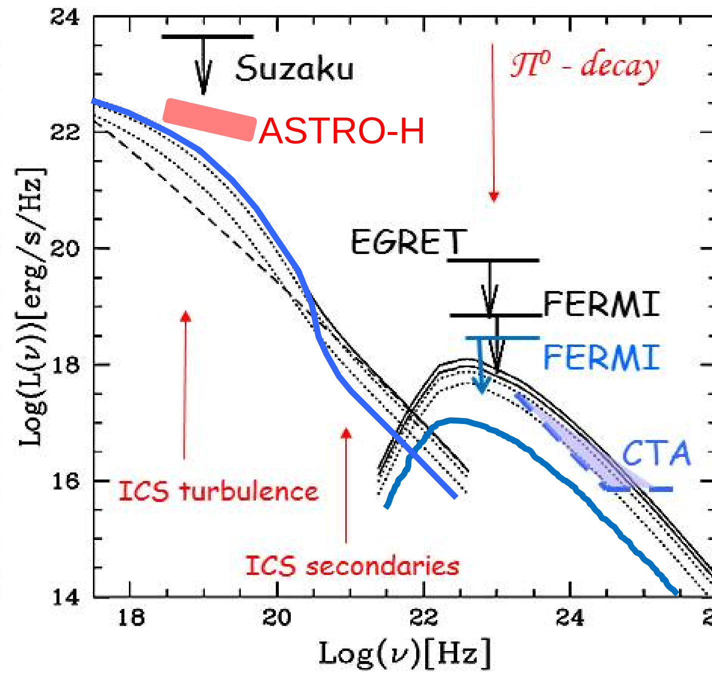
f=10





ASTRO-H, NuSTAR?: B

CTA, Fermi10: CRp, B

Summary

- ✓ A fraction of the gravitational energy of LSS is dissipated into SHOCKS, TURBULENCE and non-thermal components (CRs, B).
  All these components play a crucial role for the physics of the ICM.

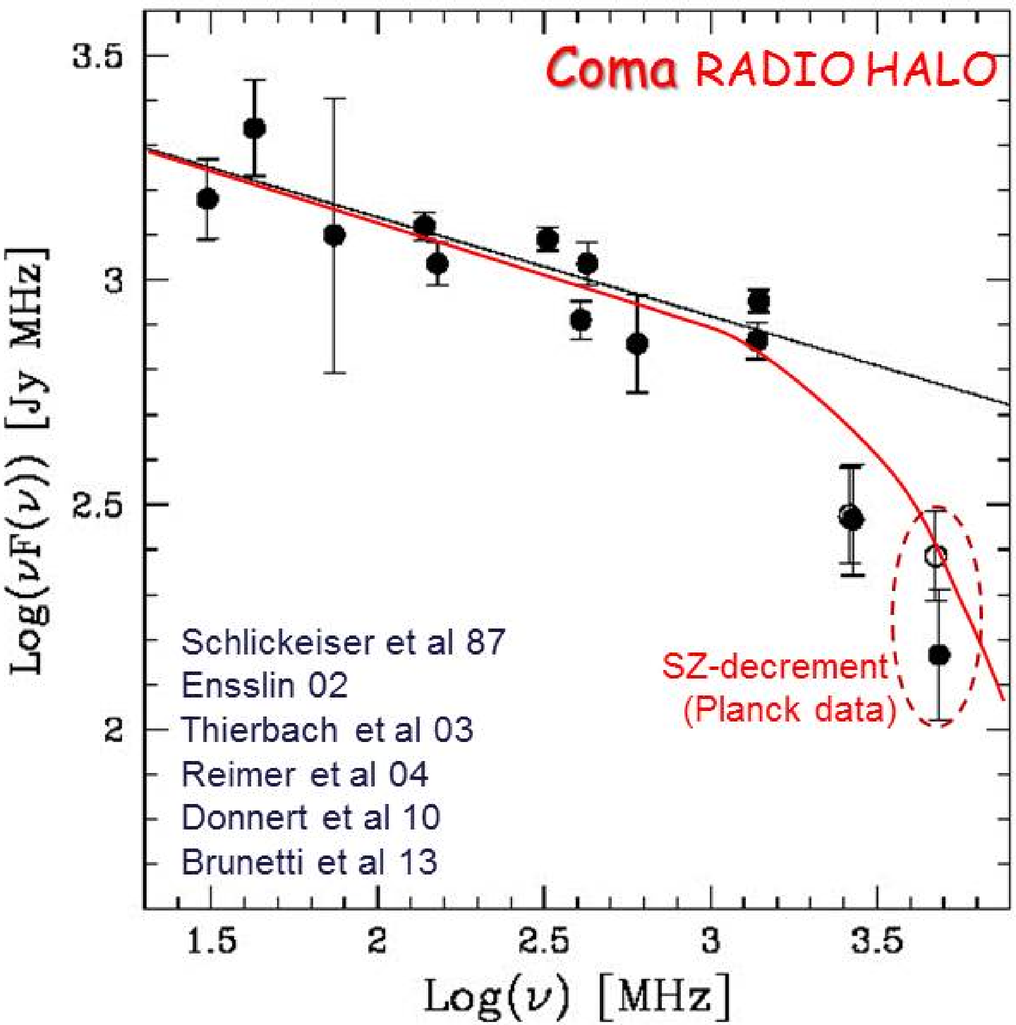
- ✓ Extraordinary conditions for particle acceleration materialize in galaxy clusters.
  CRe+B are traced by current radio observations: RADIO RELICS & HALOS.
  Only limits exist for CRp, yet we believe that they are the dominant non-thermal (particle) component in the ICM.

- ✓ RADIO RELICS probe shock acceleration at LS weak shocks.
  RADIO HALOS probe turbulence in the ICM and its interplay with CRs.

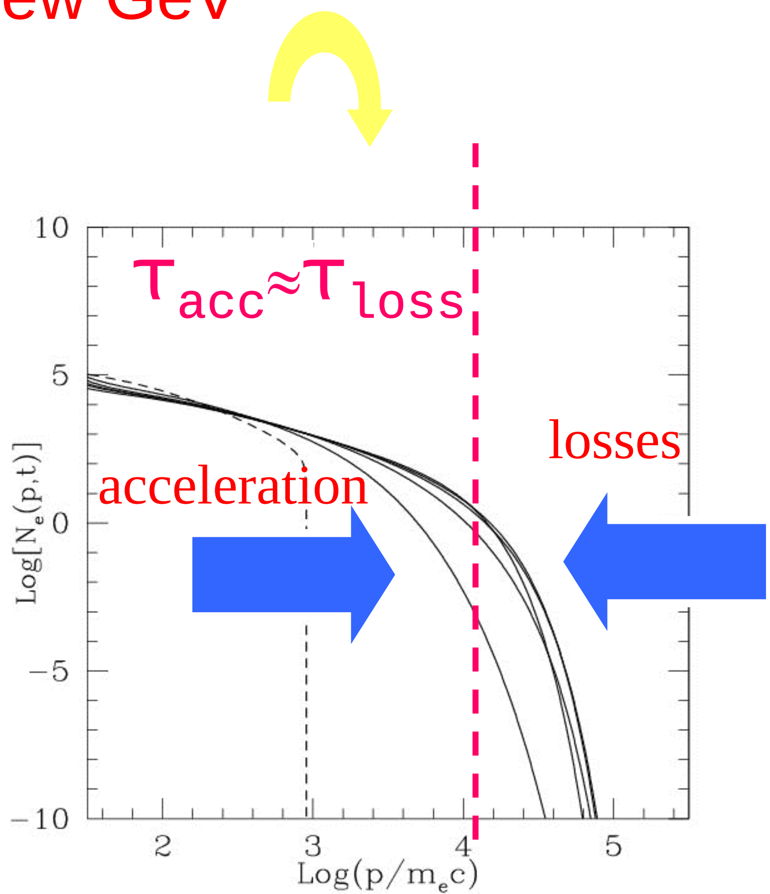
- ✓ The next generation of RADIO telescopes (LOFAR,.. SKA) will step into an unexplored territory probing CRs acceleration in the ICM.

- ✓ The FERMI10 and CTA and the ASTRO-H have the potential to obtain first detections of galaxy clusters at high energies OR unprecedented contrsints on the CRs and B physics in the ICM.

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

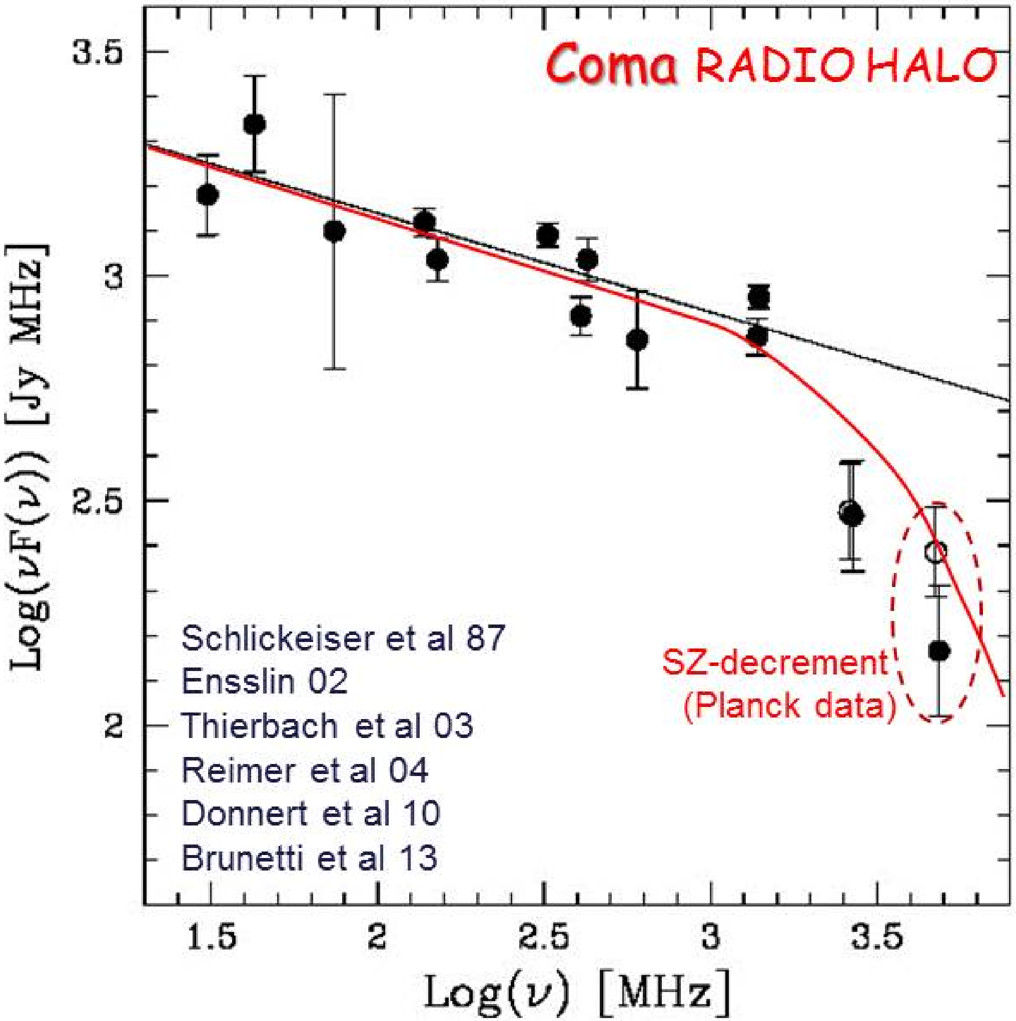


Evidence of break in the spectrum of the emitting electrons at energies of few GeV

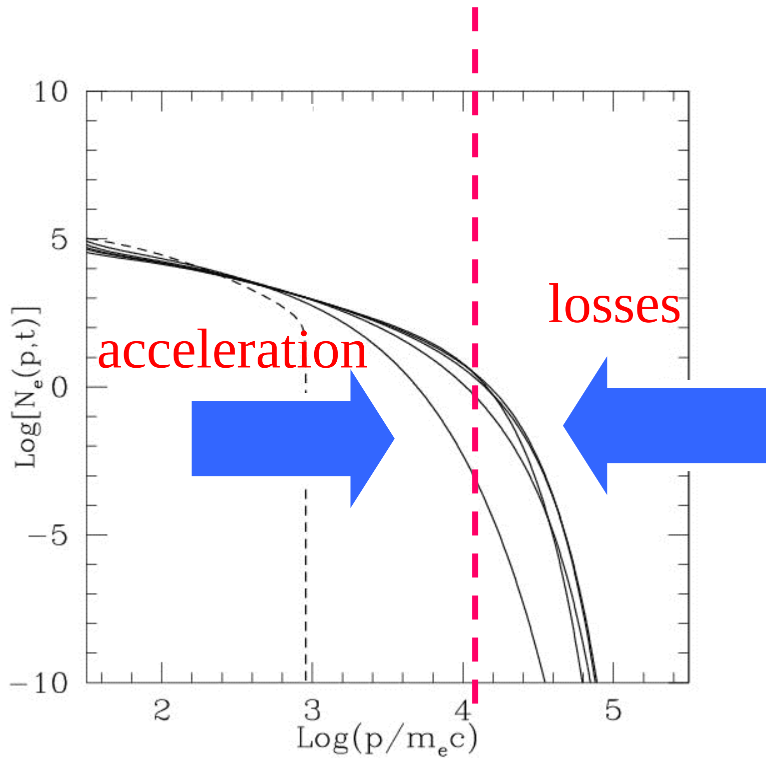


Radio Halos : are they generated by "inefficient" mechanism of CRe acceleration ?

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



Acceleration time-scale ≈10^8 years



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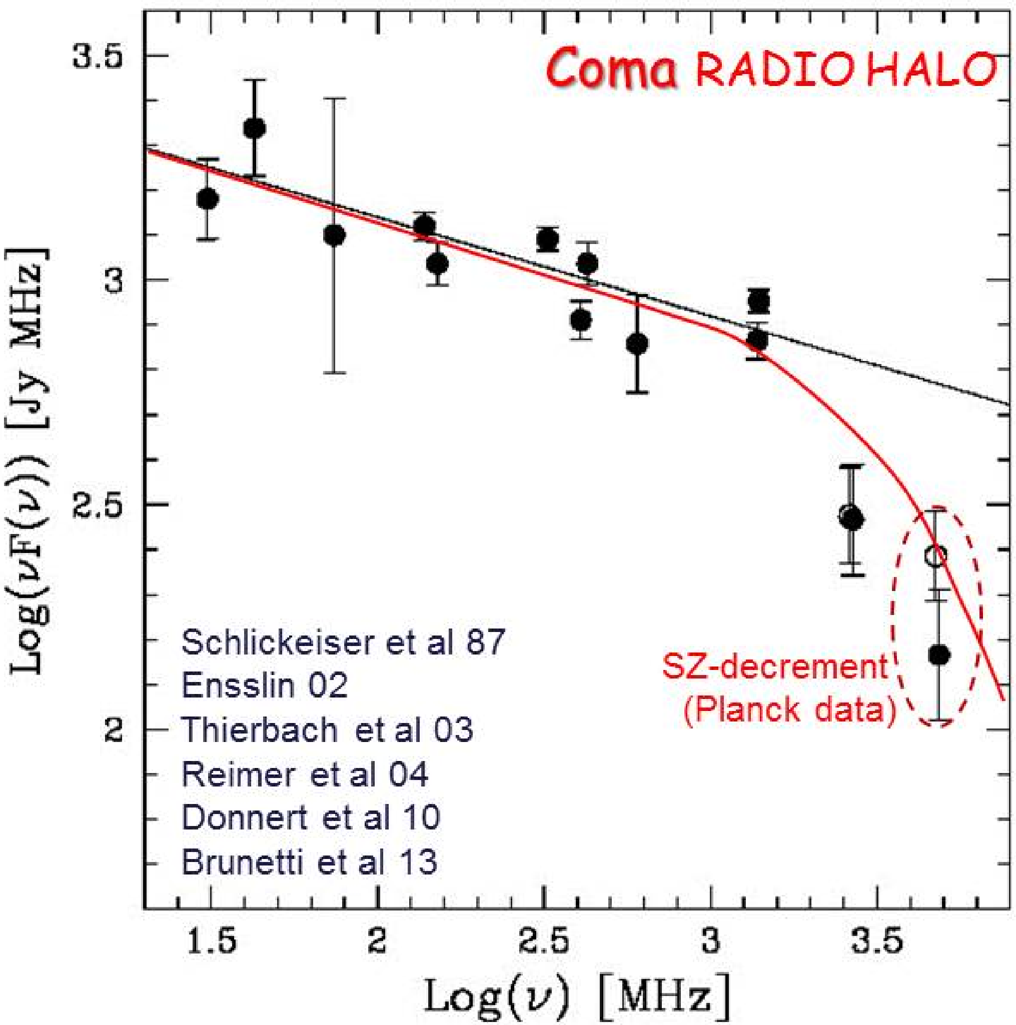
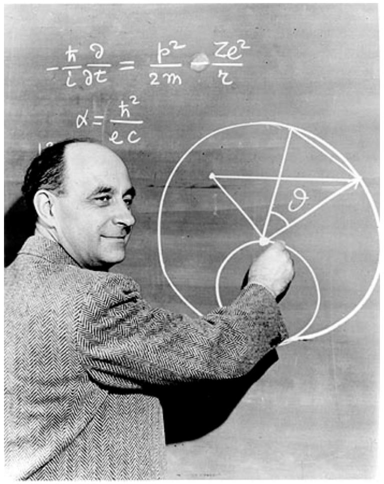


Acceleration time-scale $\approx 10^8$ years

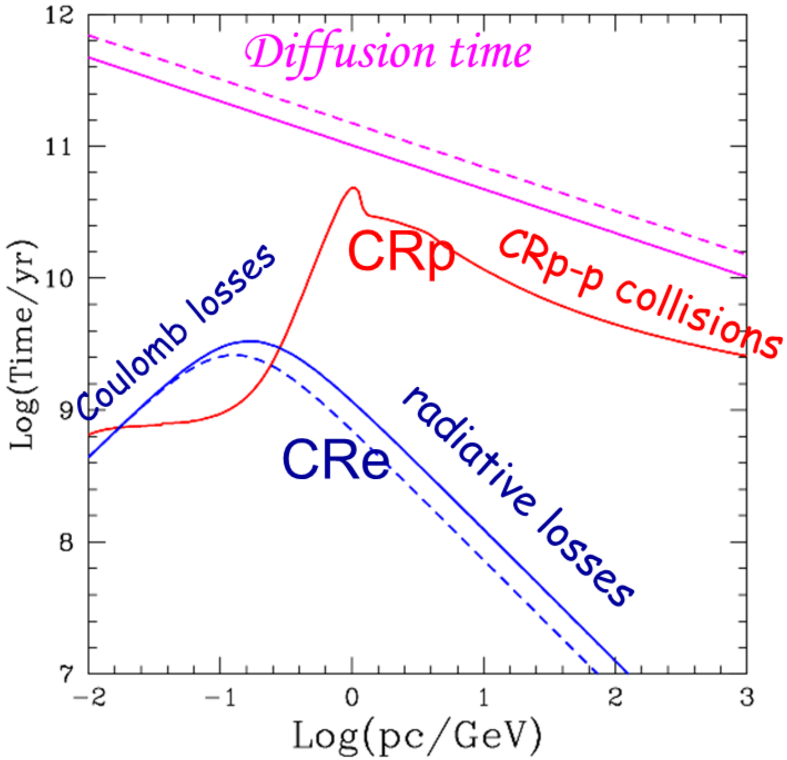
eg., "classical" Fermi II

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

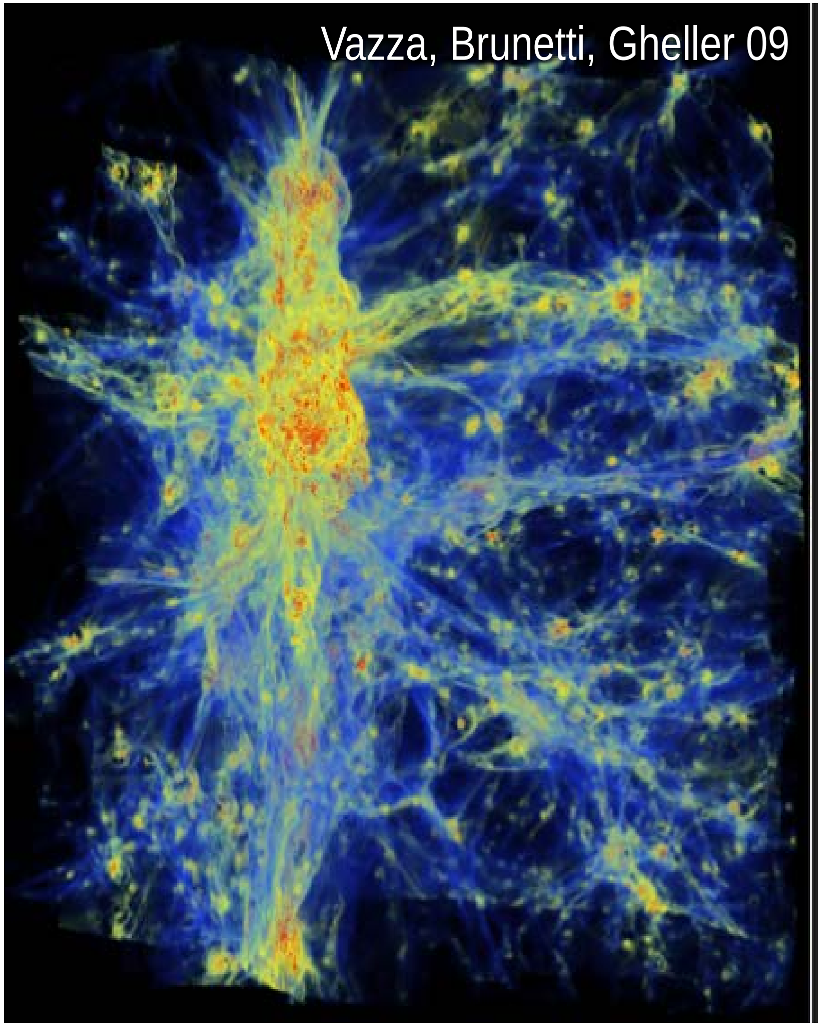
$> 10^7$yrs



Quest for CRp in GC



Blasi, Gabici, Brunetti 07

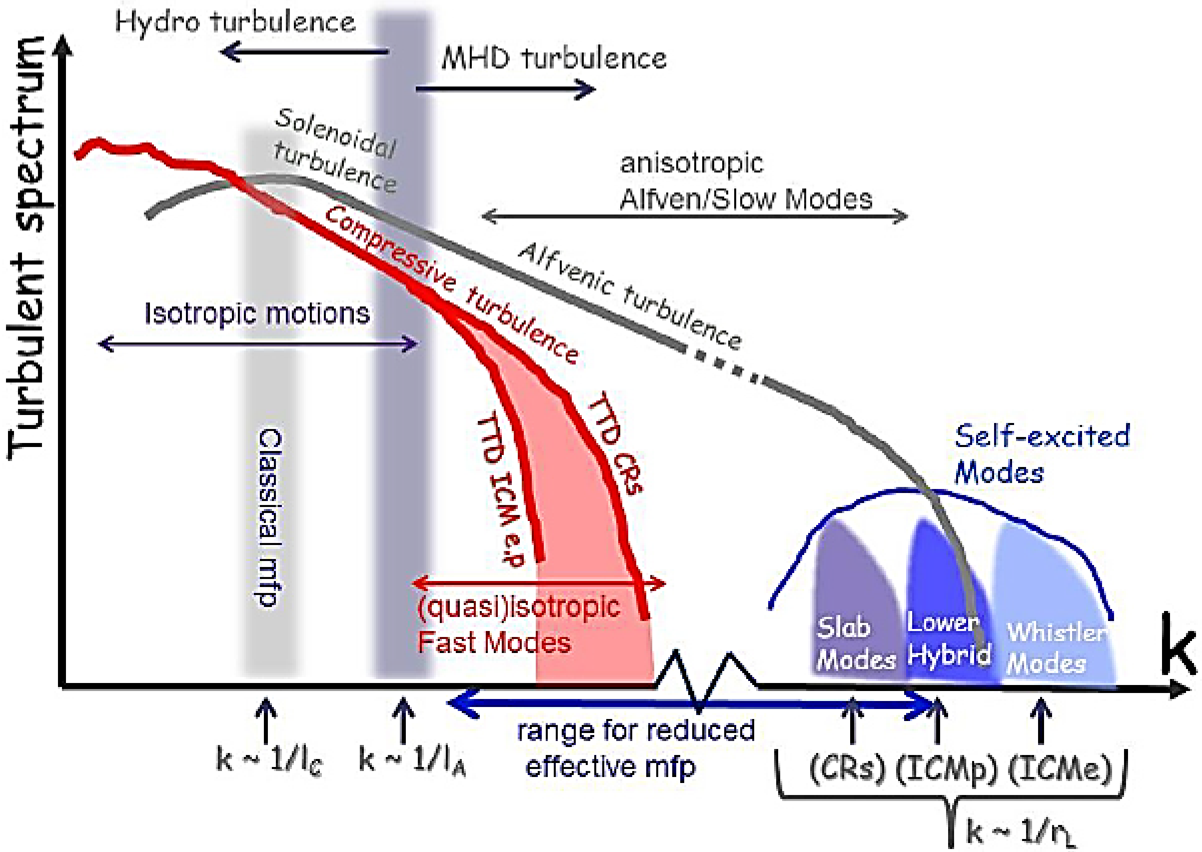


- ❑ CRp have LONG life-times in the ICM
- ❑ CRp need Hubble+ time to diffuse on Mpc

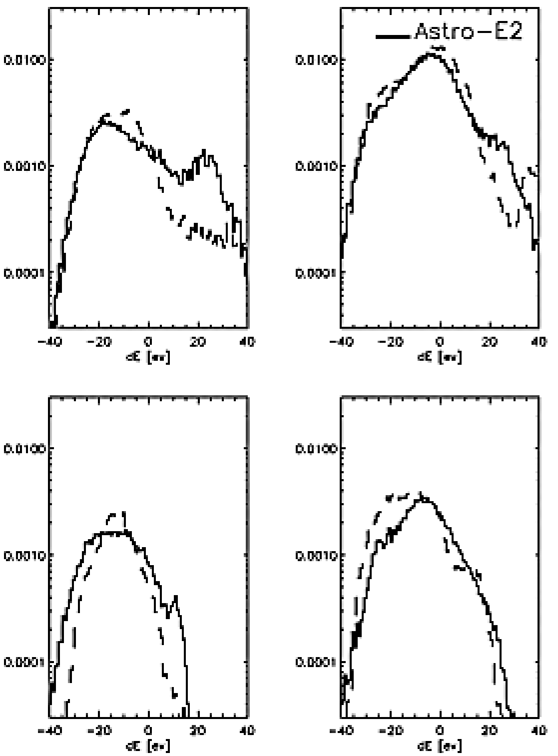
Cosmic ray protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times
(Voelk et al 96, Berezinsky et al.97)

How much energy in CRp? :
.. the bulk of ICM heating is due to shocks, so if shock accelerate like In SNR the resulting CRs would have ..up to.. 0.1 E_{TH}

RADIO HALOS : probes of plasma physics in the ICM



Dolag, Vazza, GB, Tormen 05



ICM-line broadening
ASTRO-E, Athena+

- The ICM is a «weakly collisional», high-beta medium: complex & poorly understood
- Electromagnetic fluctuations (eg turbulent-B) affect particle diffusion/transport
- Gravitational energy goes into EM fluctuations and into heating+CRs+B
- CRs+B back-react on ICM dynamics (thermal & turbulence)

Constraining phys parameters

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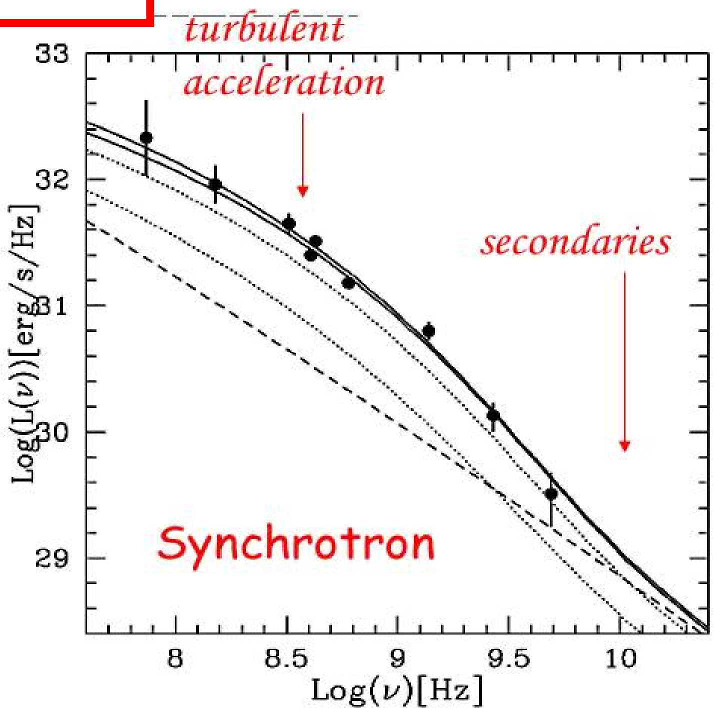
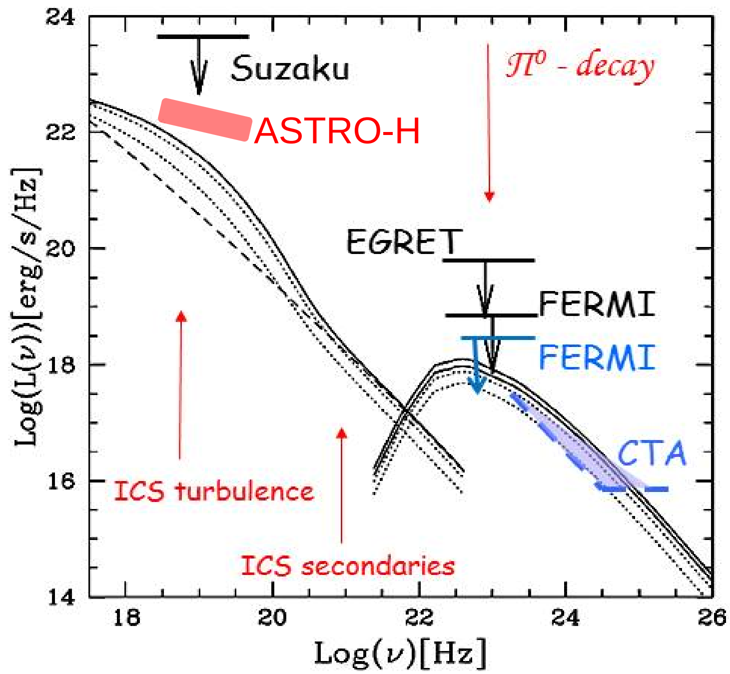
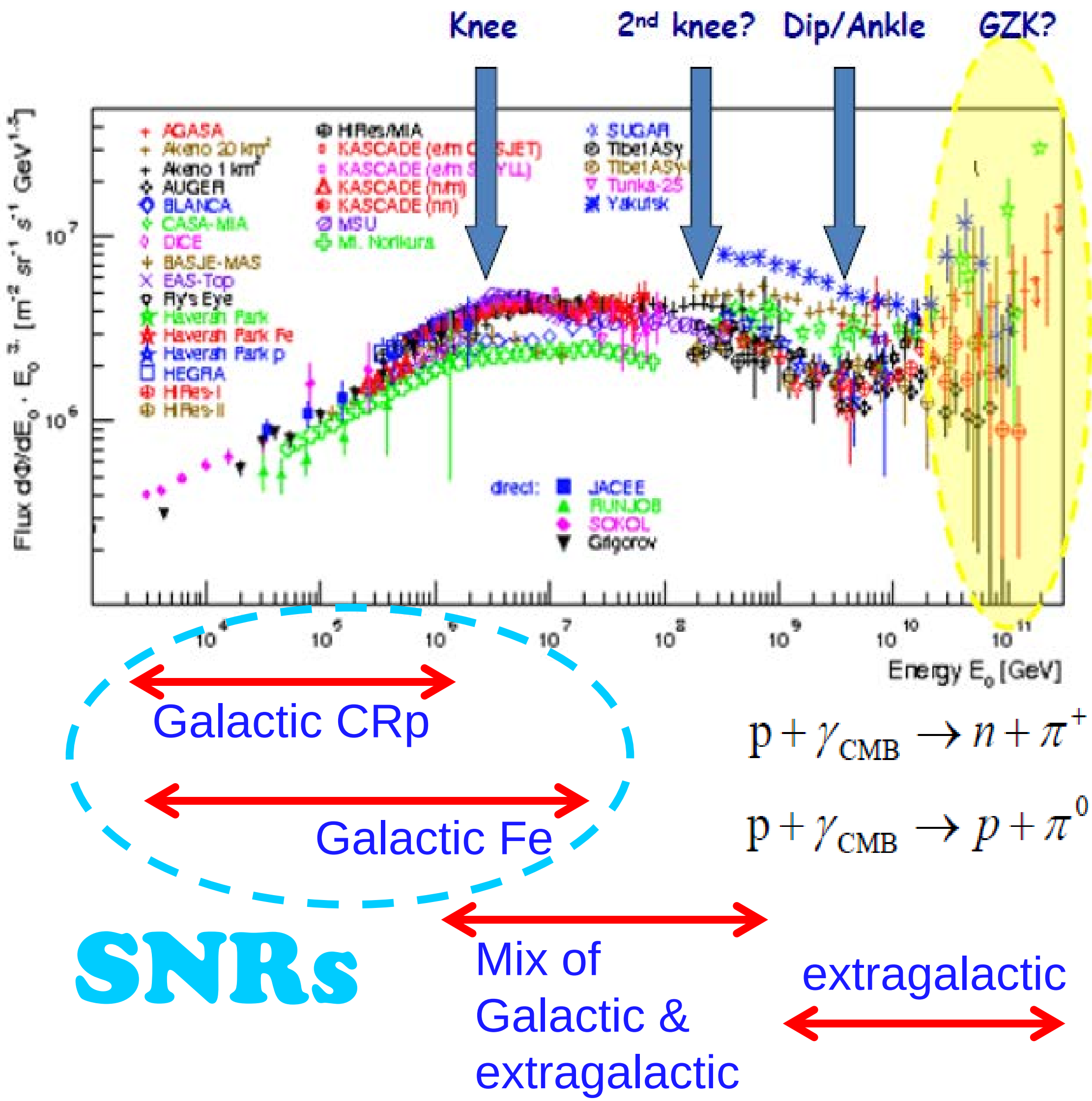




The spectrum of Cosmic Rays

(recent rev. : Blasi, RA&A 2013 ..)

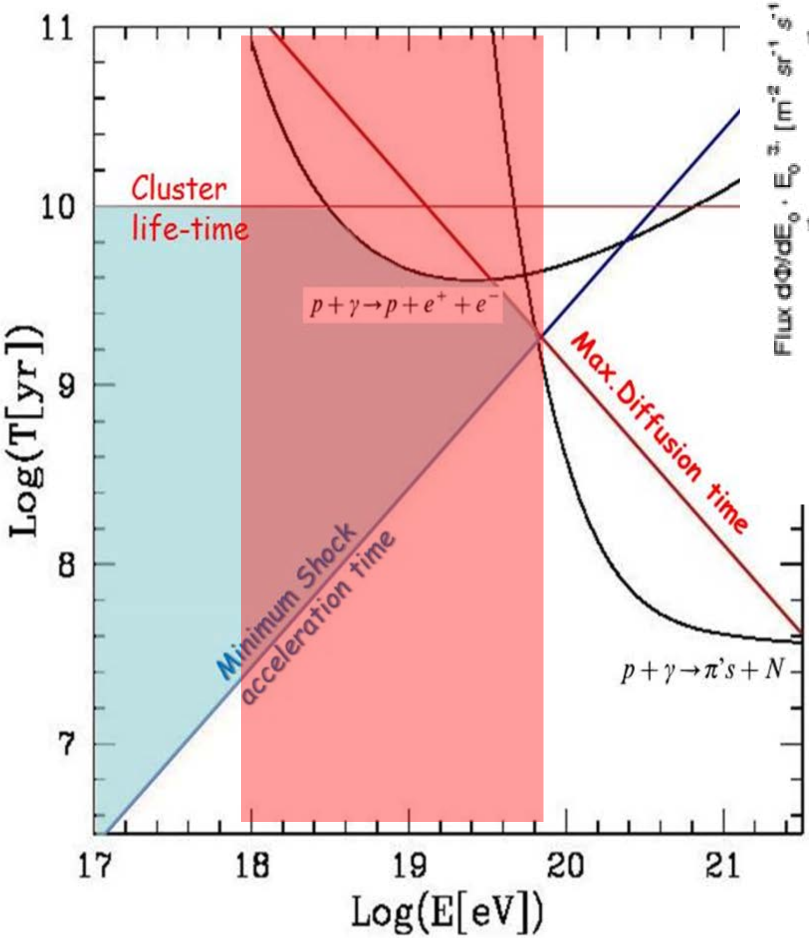


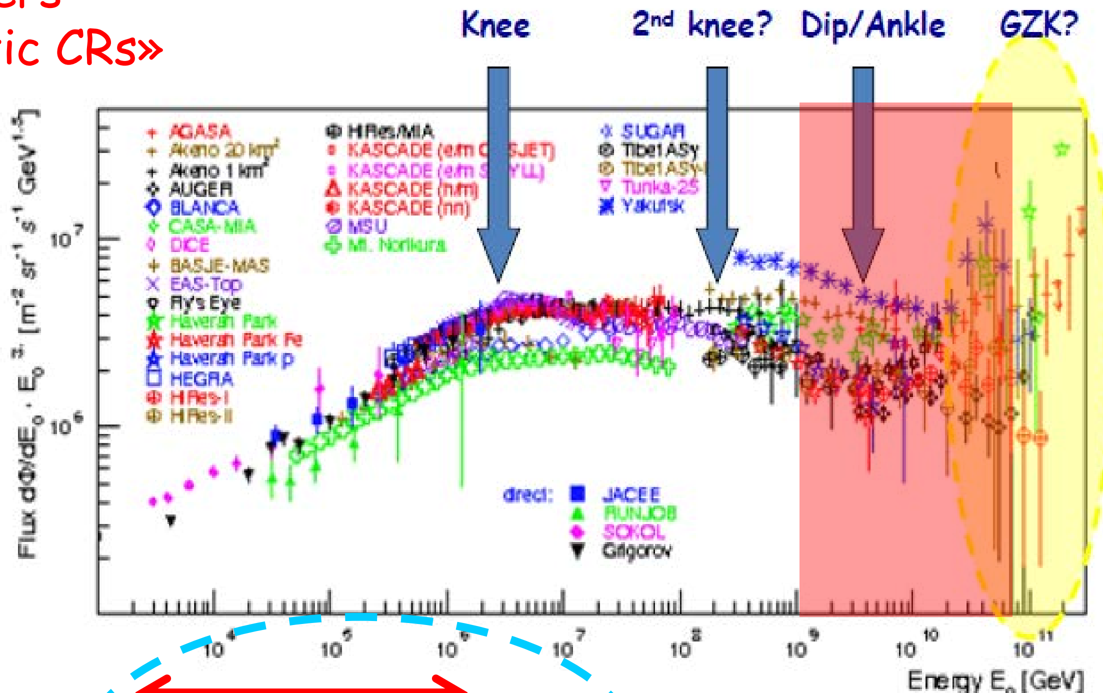
The spectrum of Cosmic Rays

(recent rev. : Blasi, RA&A 2013 ..)

Galaxy clusters are potential players for the origin of the «extragalactic CRs»

Brunetti & Jones 14





Galactic CRp

Galactic Fe

SNRs

Mix of Galactic & extragalactic

extragalactic

$$p+\gamma_{CMB} \rightarrow n+\pi^{+}$$

$$p+\gamma_{CMB} \rightarrow p+\pi^{0}$$

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 matter :

Barions **10%** of stars in galaxies

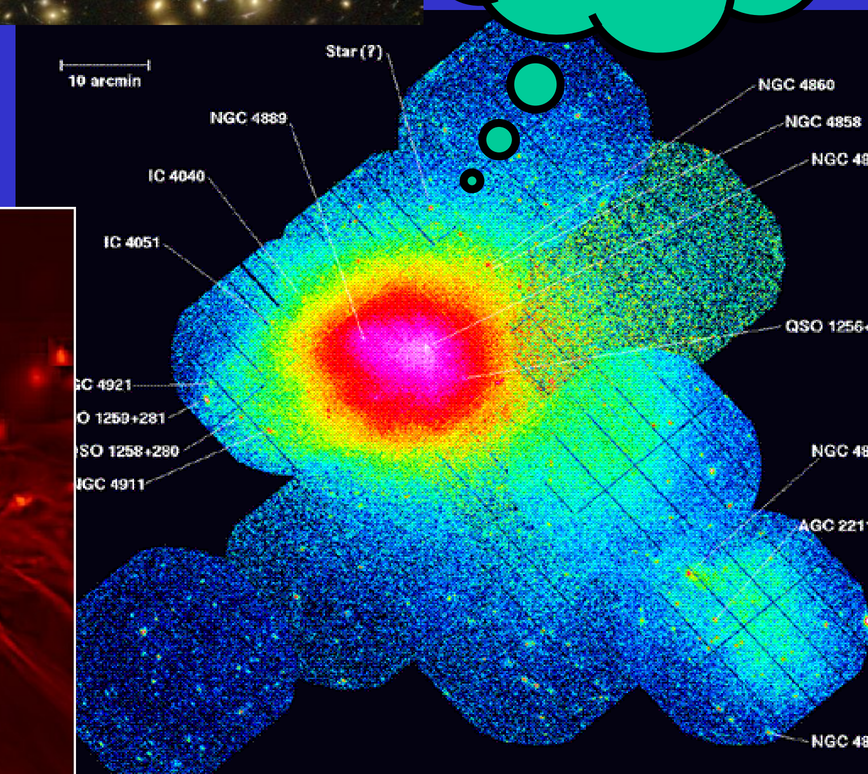
15-20% of hot diffuse gas

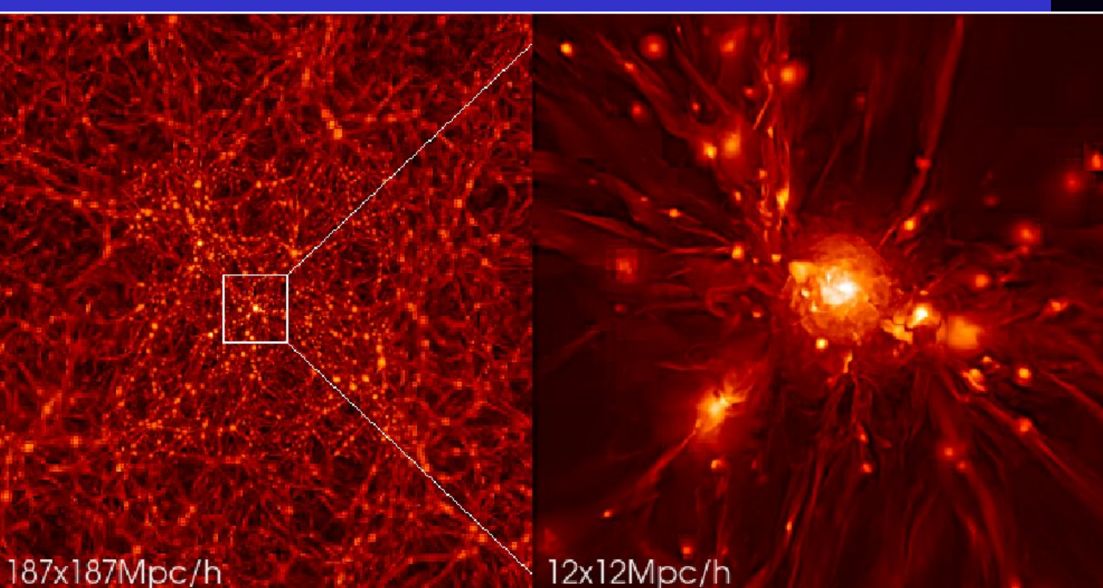
Dark Matter **70%**

≈30-300 galaxies

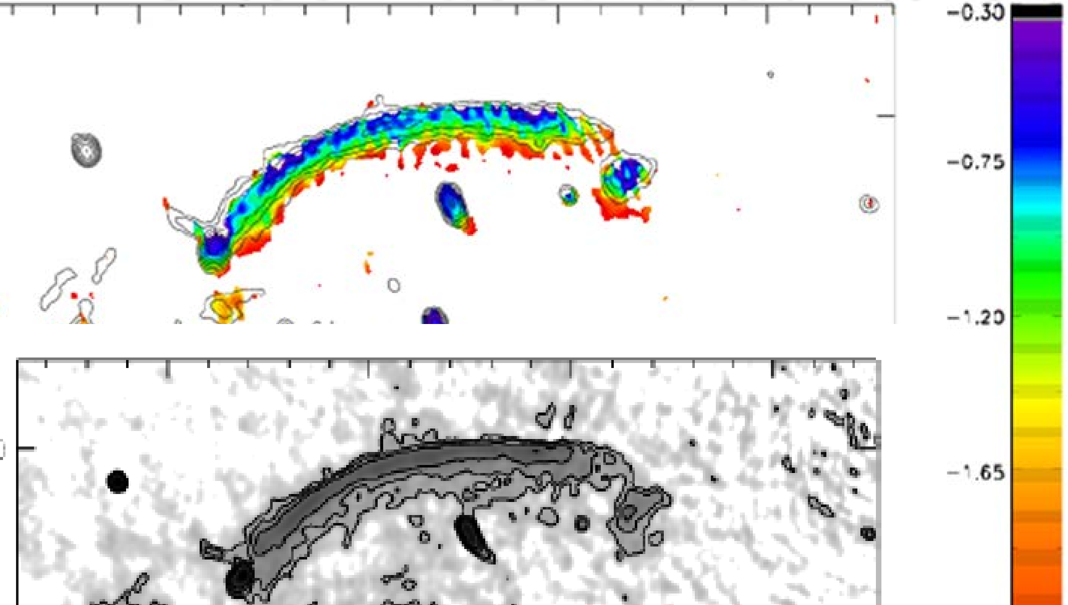
$n \approx 10^{-3} cm^{-3}$

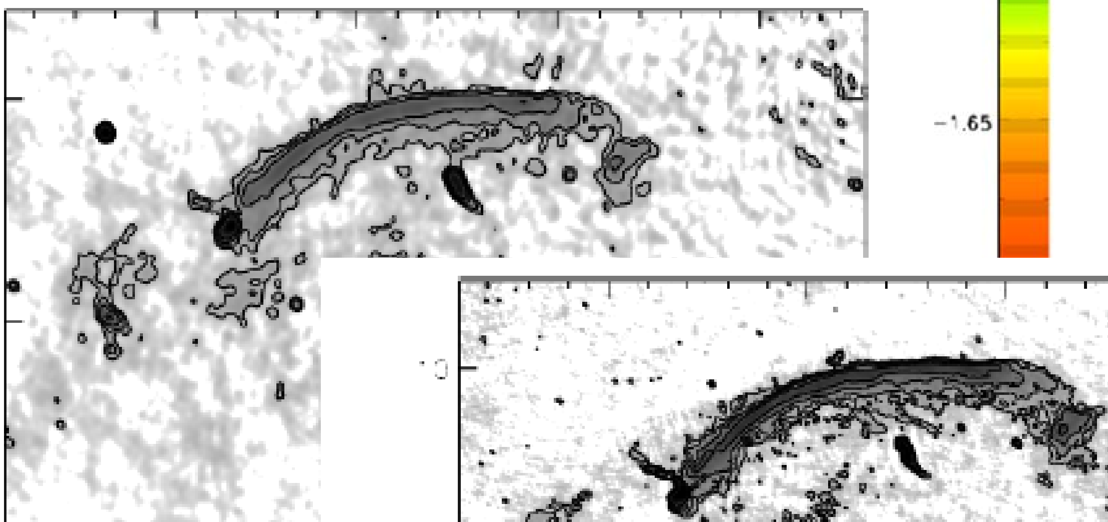
$T \approx 10^7$-10^8K





Shock acceleration OR reacceleration ?





(Brunetti & Jones 14 for REV)

SPECTRUM:
The DSA of thermal electrons predicts that the Syn spectrum depends on the Mach number :

$$\alpha_{inj} = \frac{1}{2}\frac{M^2+3}{M^2-1}$$

Reacceleration of seed relativistic particles may produce a flatter Spectrum. REacceleration ?

ACCELERATION EFFICIENCY :

$$\nu_o L(\nu_o) \approx \frac{1}{2}\rho_u V_{sh}^3 \xi \eta_{(>\gamma_o)} S \left[1 + \left(\frac{B_{IC}}{B}\right)^2\right]^{-1}$$

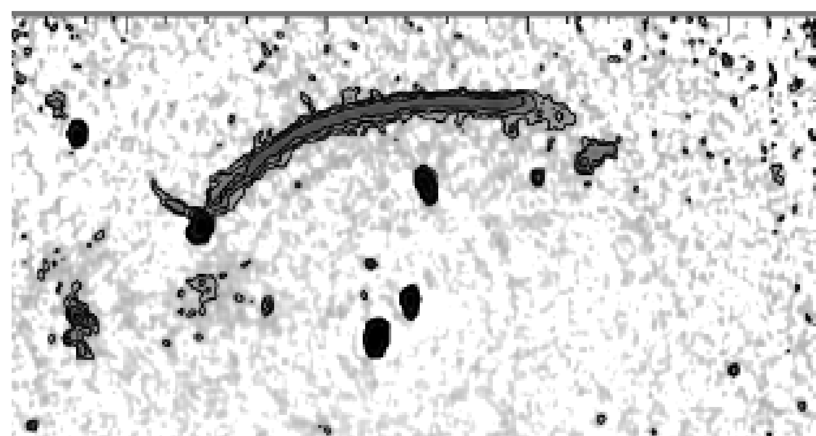
anomalous CRe/CRp ratio (~0.1) ?
REacceleration ?

DOWNSTREAM PHYSICS :

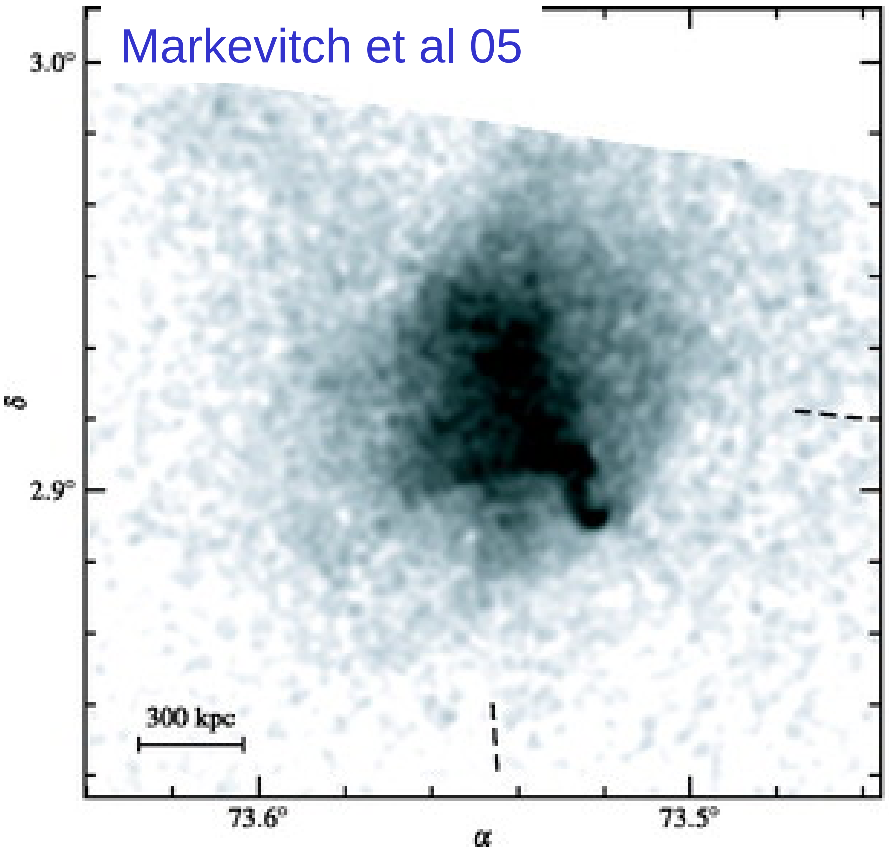
$$L \approx V_d \tau_{loss} \approx \frac{M^2+3}{4M^2} V_{sh} \tau_{loss}(E \rightarrow \nu_{ph})$$

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

Increase of relic's tickness at lower frequencies constrains Mach number and B



Shocks in Galaxy Clusters



$$\frac{dW}{dVdtd\nu} = \frac{2^5 \pi e^6}{3mc^3}\left(\frac{2\pi}{3km}\right)^{1/2} T^{-1/2} Z^2 n_e n_i \, e^{-h\nu/kT} \bar{g}_{ff}$$

Issues/caveats

... integrated along line-of-sight

... deprojection

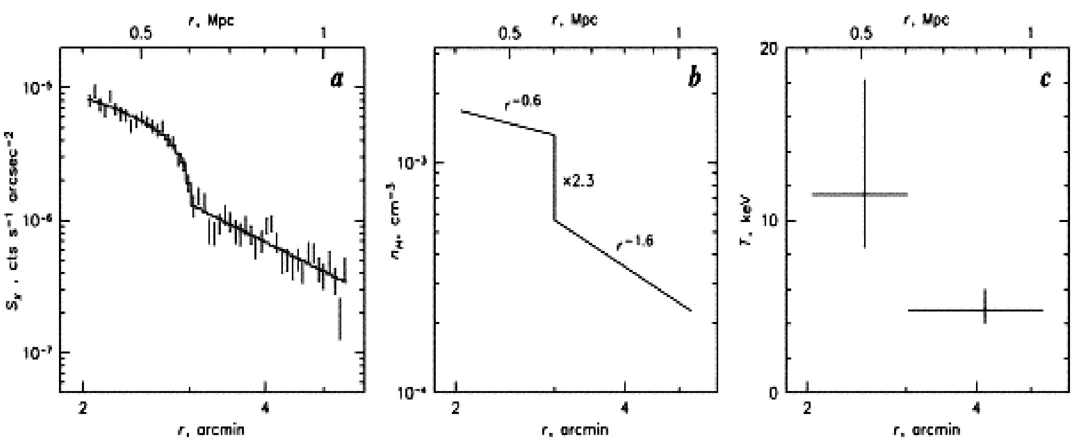
... multi-temperature

... electrons – ions thermal equilibrium

T_u, T_d, ρ_u, ρ_d

$$\frac{\rho_d}{\rho_u} = \frac{V_u}{V_d} = r = \frac{4M^2}{M^2+3}$$

$$\frac{T_d}{T_u} = \frac{(5M^2-1)(M^2+3)}{16M^2}$$

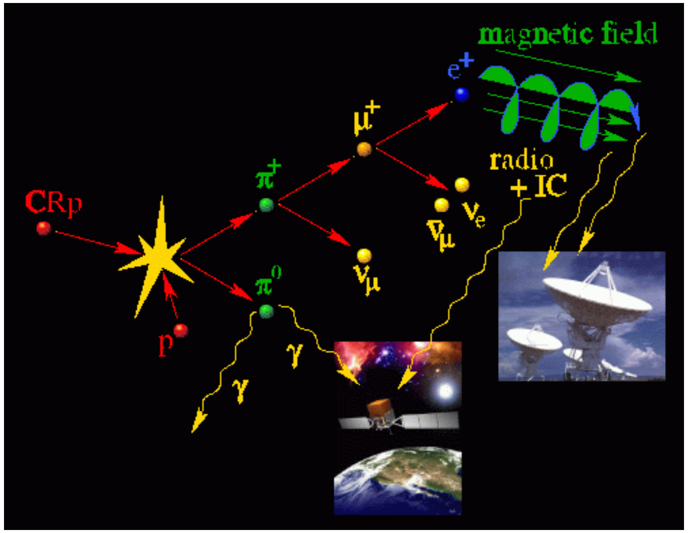


Mach 2-3+ are measured

The two leading mechanisms

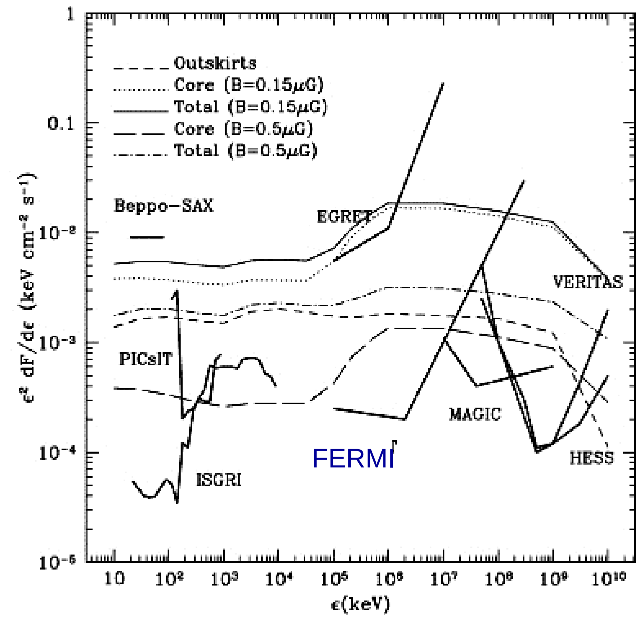
Hadronic interactions

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



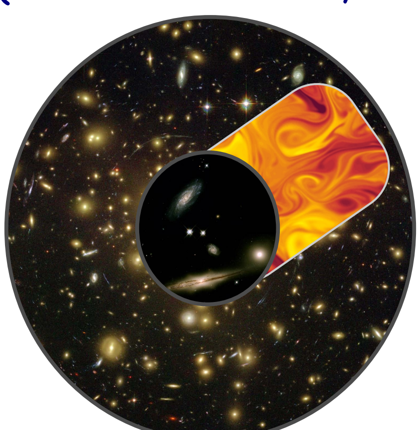
High energy and neutrino emission from galaxy clusters

Miniati 2003

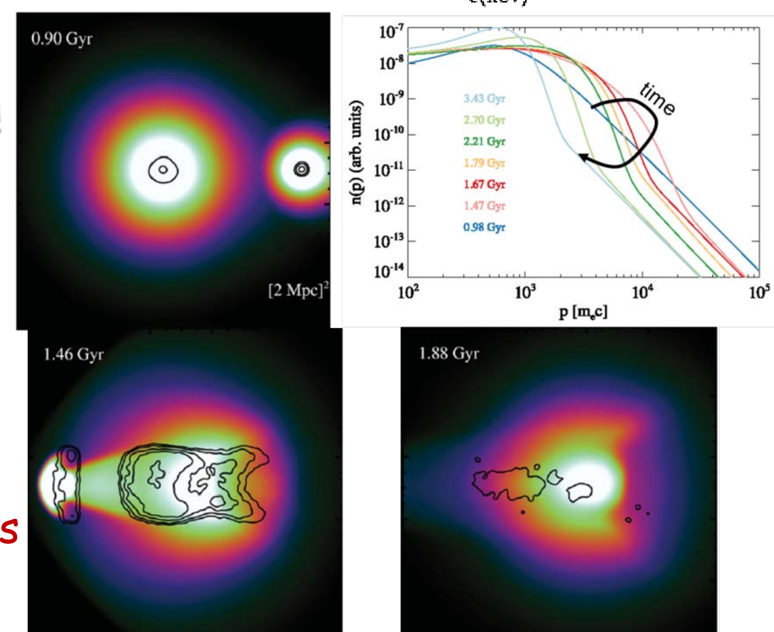


Turbulence and stochastic (re)acceleration

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



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



Donnert et al 13

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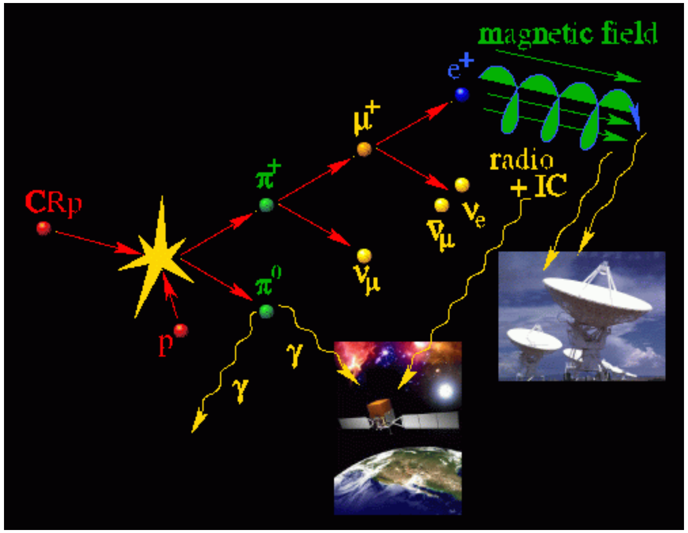
Hadronic interactions

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

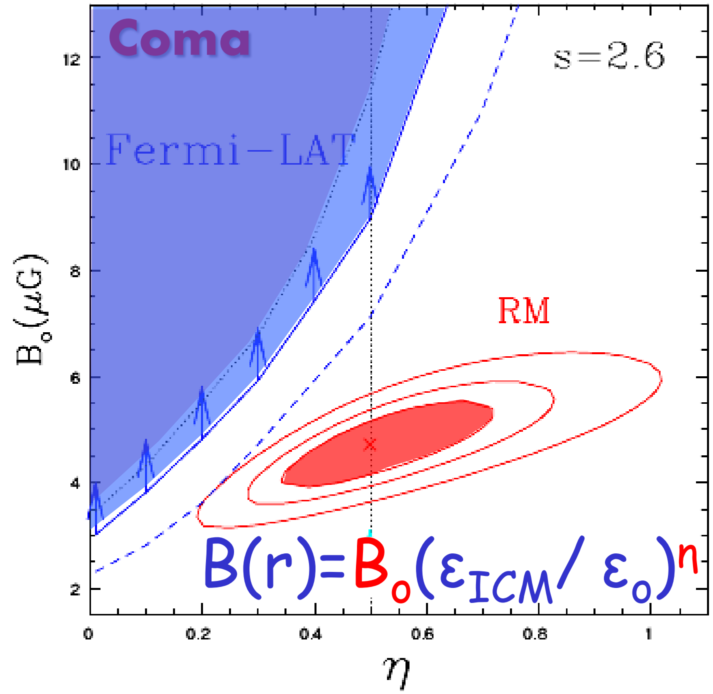


Challenged by gamma-ray u.l.

ratio Fradio/Fgamma depends on «B»

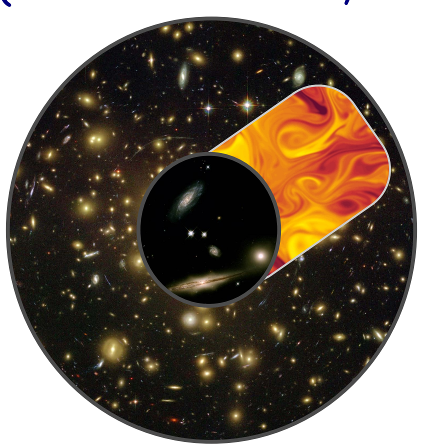
High energy and neutrino emission from galaxy clusters

Brunetti et al 12

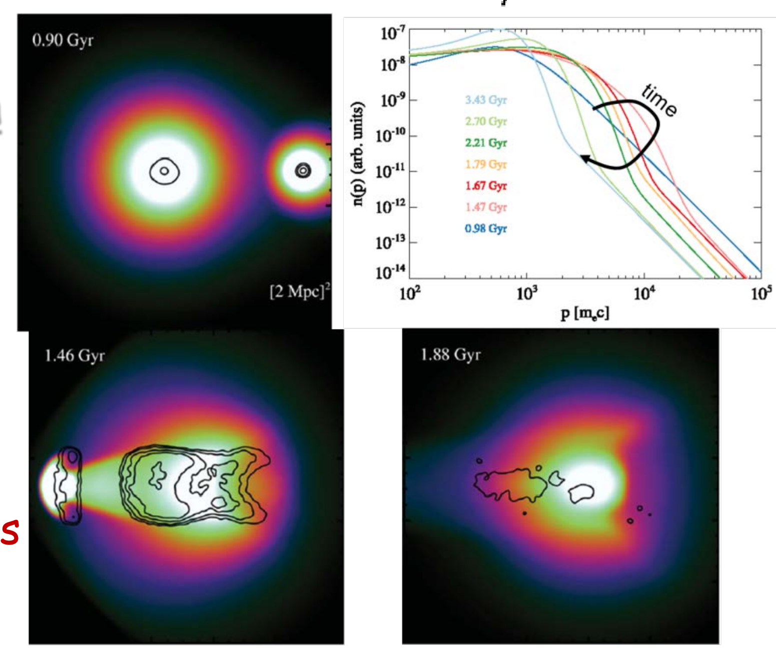


Turbulence and stochastic (re)acceleration

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

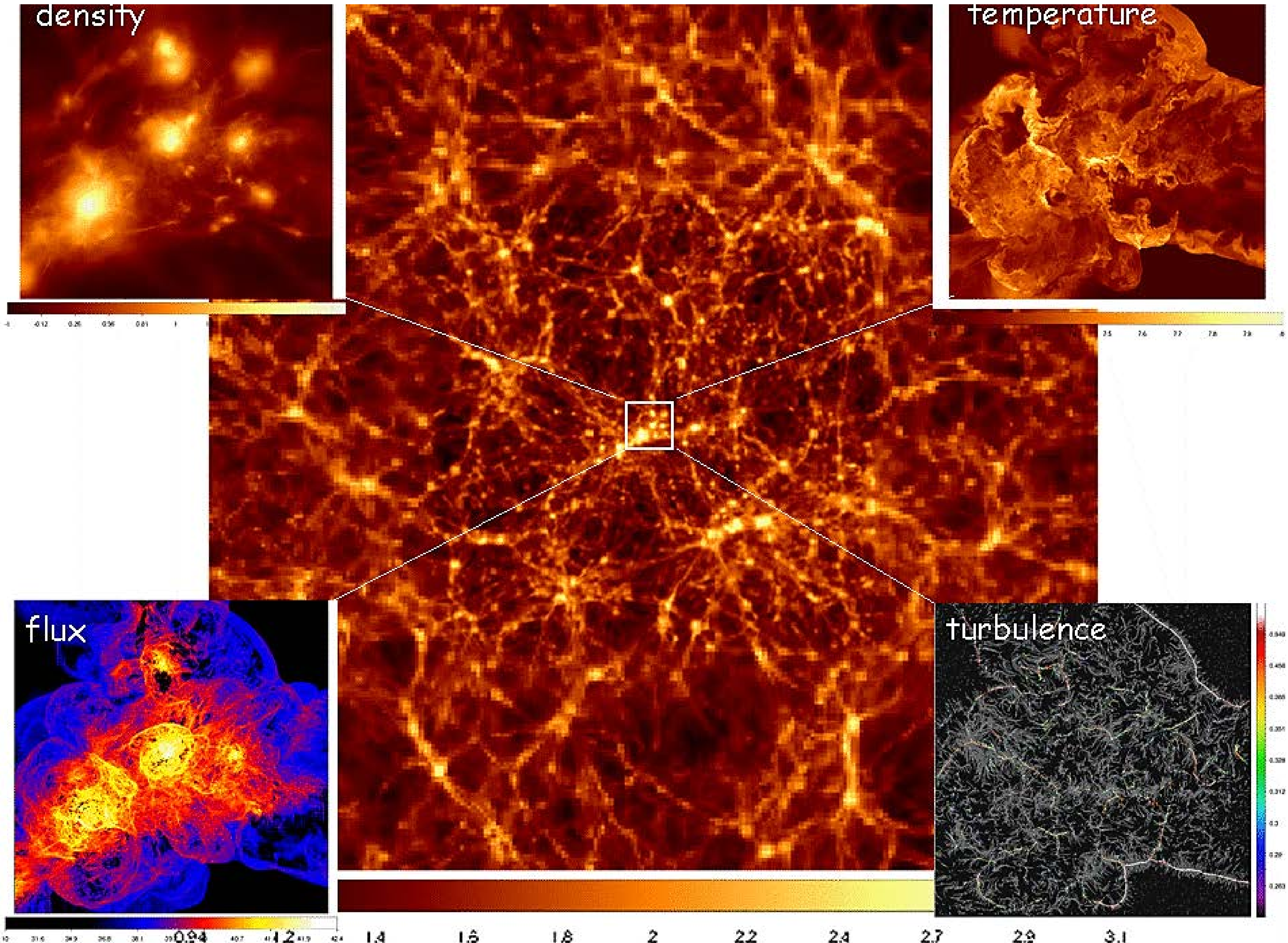


Radio halos probe the dissipation of energy in dark-matter driven collisions between clusters



Donnert et al 13

Dissipation of gravitational energy & CR acceleration



Max energy of CRe

Condition for acceleration :

(term n.3 is Hillas ++)

$$\tau_{acc} \leq \min\left[\mathrm{Age}, \tau_{loss}, \tau_{diff}\right]$$

Age ~ Gyr+

Shock : yesterday Lecture

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

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

Bohm diffusion

$$D \sim \frac{1}{3}c\lambda_{mfp} \qquad D \approx \frac{1}{3}\frac{E}{eB}$$

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

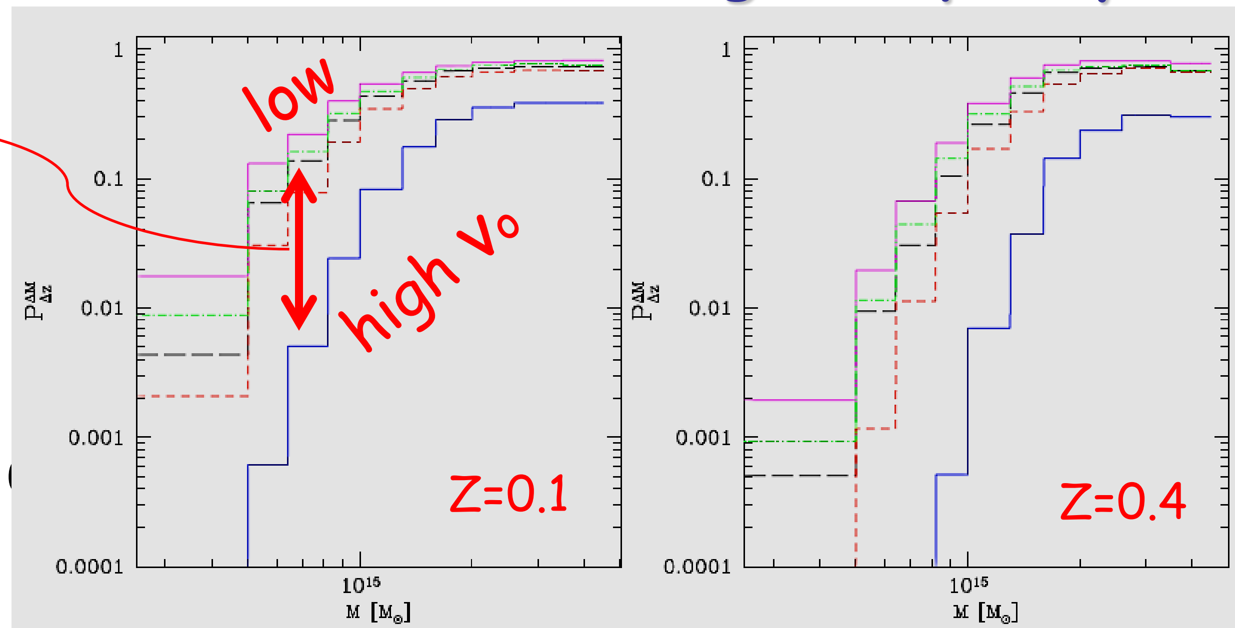
Huge

$$D(p) \sim 3\times10^{22}\frac{(cp/\mathrm{GeV})}{(B/\mu G)}\ \mathrm{cm^2s^{-1}}$$

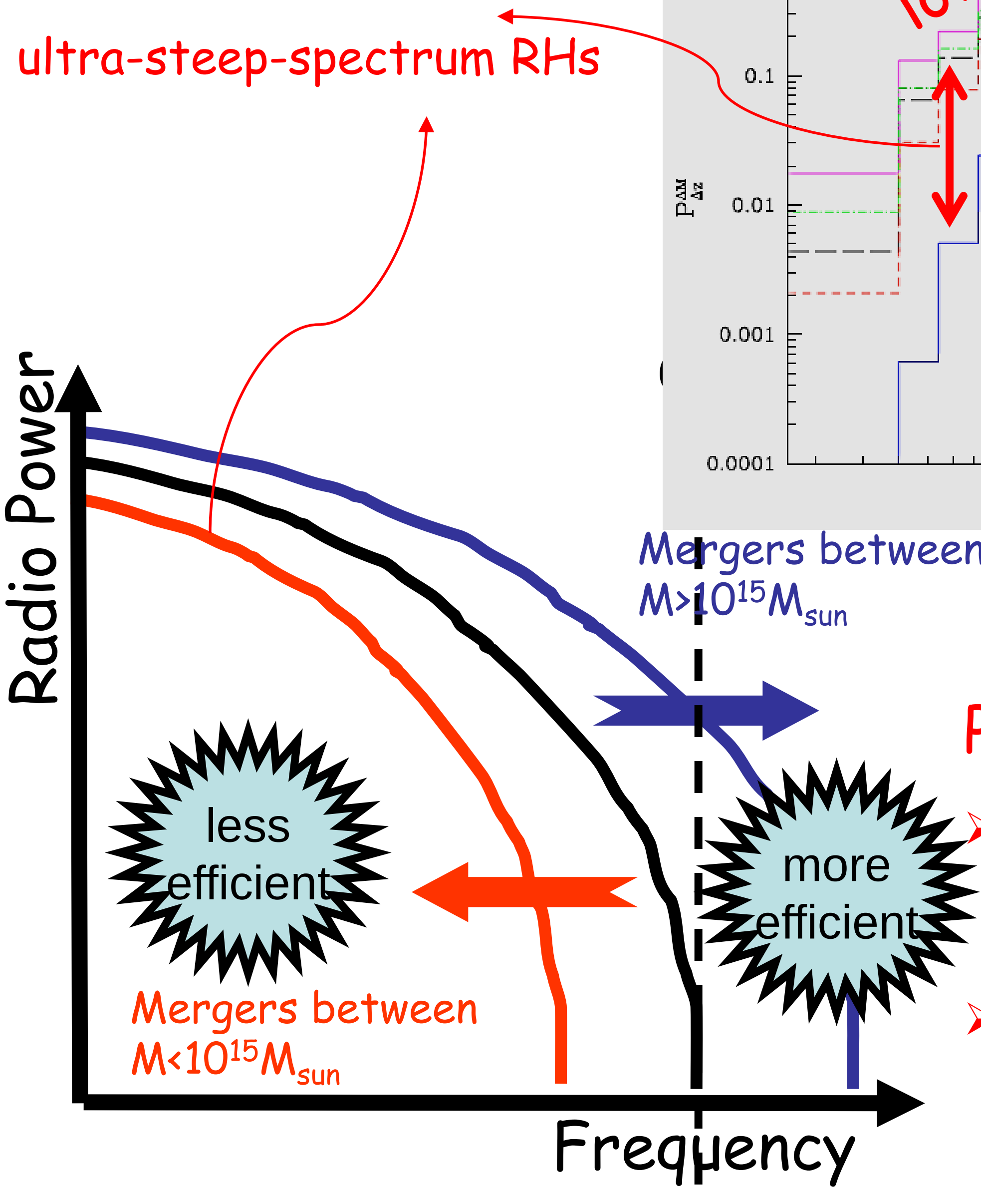
$$E^e_{max} \approx 6.3\times10^4 B_\mu^{1/2} v_8 g(r)^{-1/2}\ GeV$$

where $g = r(r+1)/(r-1)$

Syn spectra of RHs & occurrence @low/high frequency



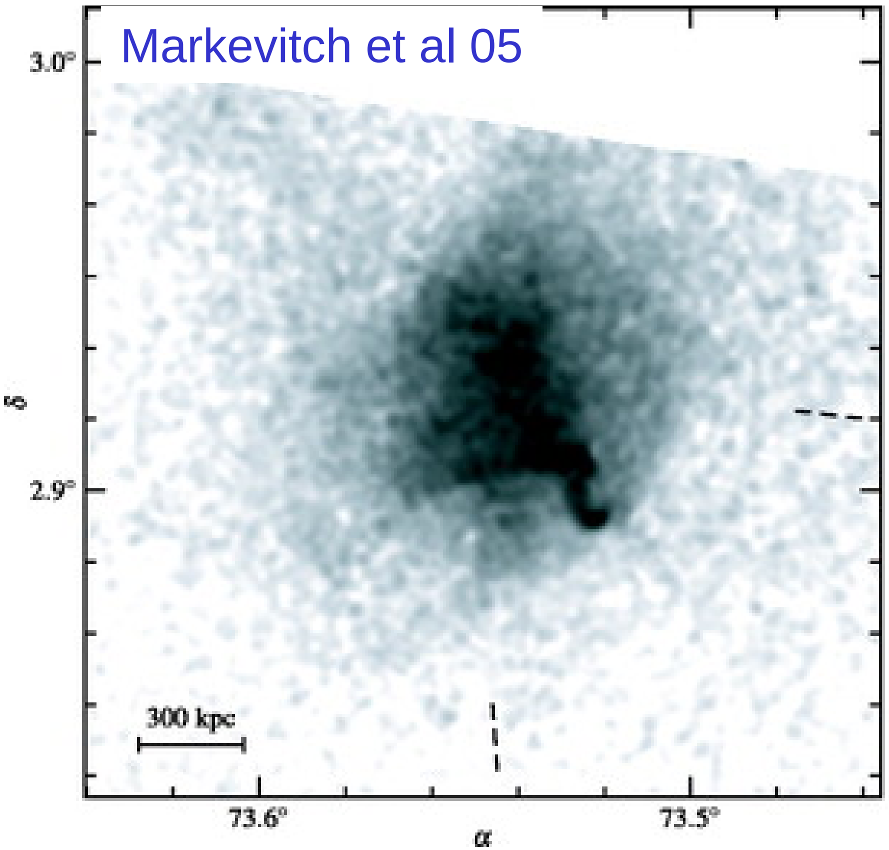
Cassano, GB, Rottgering, Bruggen 10



Predictions Summary

- drop of fraction of RHs at lower masses «mass sets the energy available»
- increase of fraction of RHs at lower ν_o «different spectra» & «ultra-steep»

Shocks in Galaxy Clusters



$$\frac{dW}{dVdtd\nu} = \frac{2^5 \pi e^6}{3mc^3}\left(\frac{2\pi}{3km}\right)^{1/2} T^{-1/2} Z^2 n_e n_i \, e^{-h\nu/kT} \bar{g}_{ff}$$

Issues/caveats

… integrated along line-of-sight

… deprojection

… multi-temperature

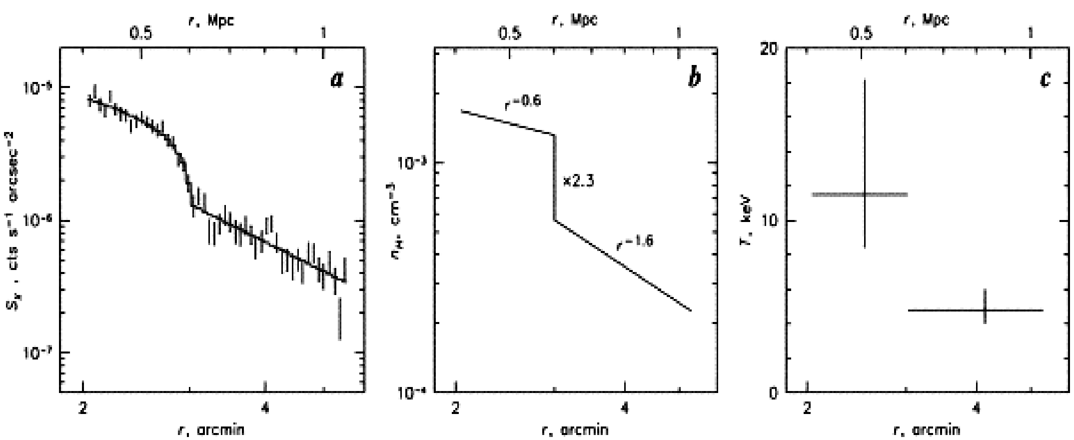
… electrons – ions thermal equilibrium

T_u, T_d, ρ_u, ρ_d

$$\frac{\rho_d}{\rho_u} = \frac{V_u}{V_d} = r = \frac{4M^2}{M^2+3}$$

$$\frac{T_d}{T_u} = \frac{(5M^2-1)(M^2+3)}{16M^2}$$

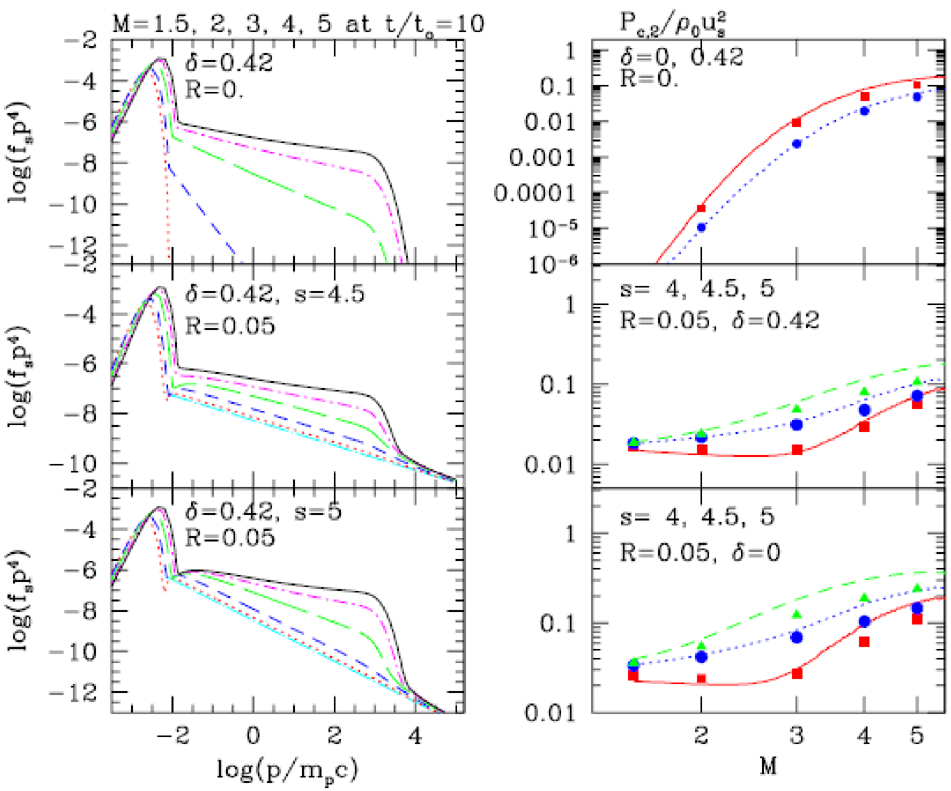
Mach 2-3+ are measured



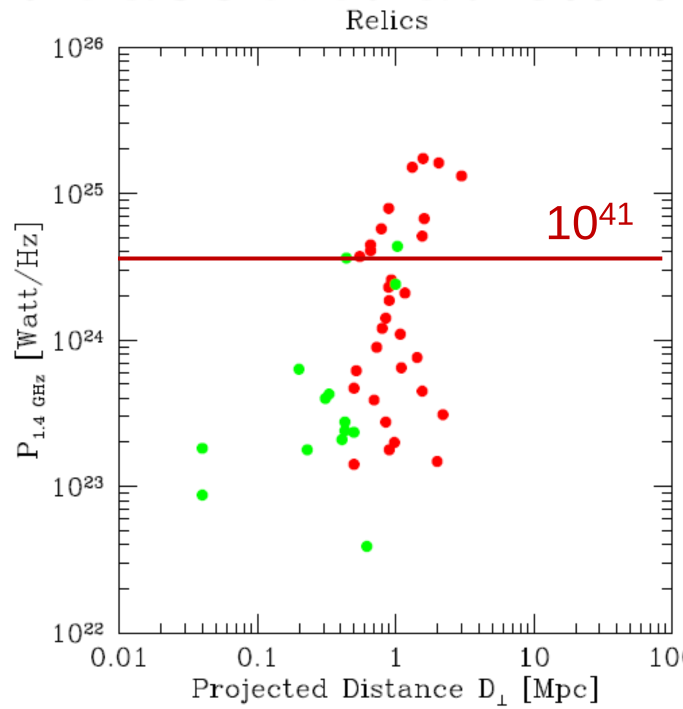
Shock acceleration OR reacceleration ?

$$\nu_o L(\nu_o) \approx \frac{1}{2}\rho_u V_{sh}^3 \xi \eta_{(>\nu_o)} S \left[1+\left(\frac{B_{IC}}{B}\right)^2\right]^{-1}$$

$$\eta_e > 10^{-5}\left(\frac{S}{10^{48}}\right)^{-1}\left(\frac{V_{sh}}{3000}\right)^{-3}\left(\frac{n}{5/10^4}\right)^{-1}\left(\frac{\nu L(\nu)}{10^{41}}\right)$$



Kang & Ryu 11

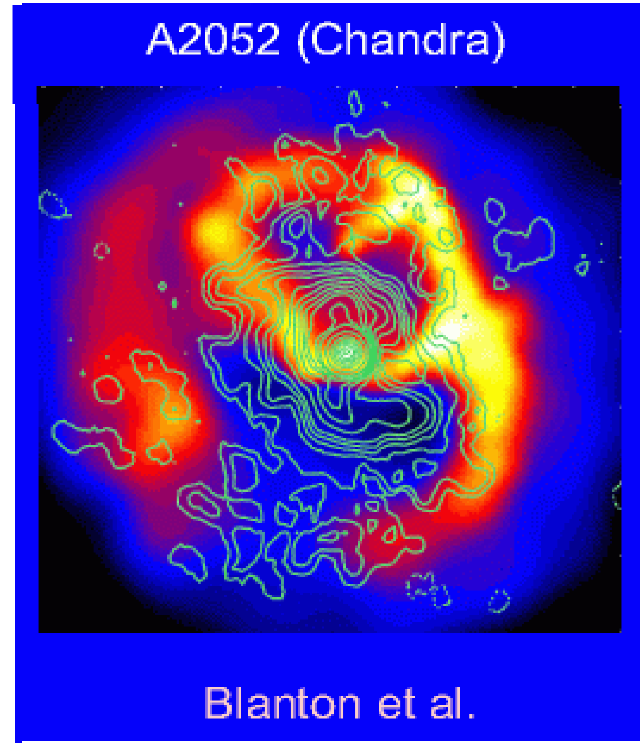


$$\alpha_{inj} = \frac{1}{2}\frac{M^2+3}{M^2-1}$$

In some cases there are appreciable discrepancies between the «measured» synchrotron spectral index and that «expected» from the Mach number.

Ensslin & Gopal-Krishna 01, Markevitch et al 05, Macario et al 11, Kang et al 11,12, Pinzke & Pfrommer 13

Galaxies and Starbursts



$P_{NT} \approx P_{TH}$

- About 100 massive galaxies per cluster
  (Berezinsky et al.97, ..)

- Fe abundance in the ICM (Voelk et al 96)

$$E_{CR}^{SN} = N_{SN}\eta_{CR}^{SN}E_{SN} \leq \frac{[Fe]_{\odot}X_{cl}M_{cl,gas}}{\delta M_{Fe}}E_{SN}\eta_{CR}^{SN}$$

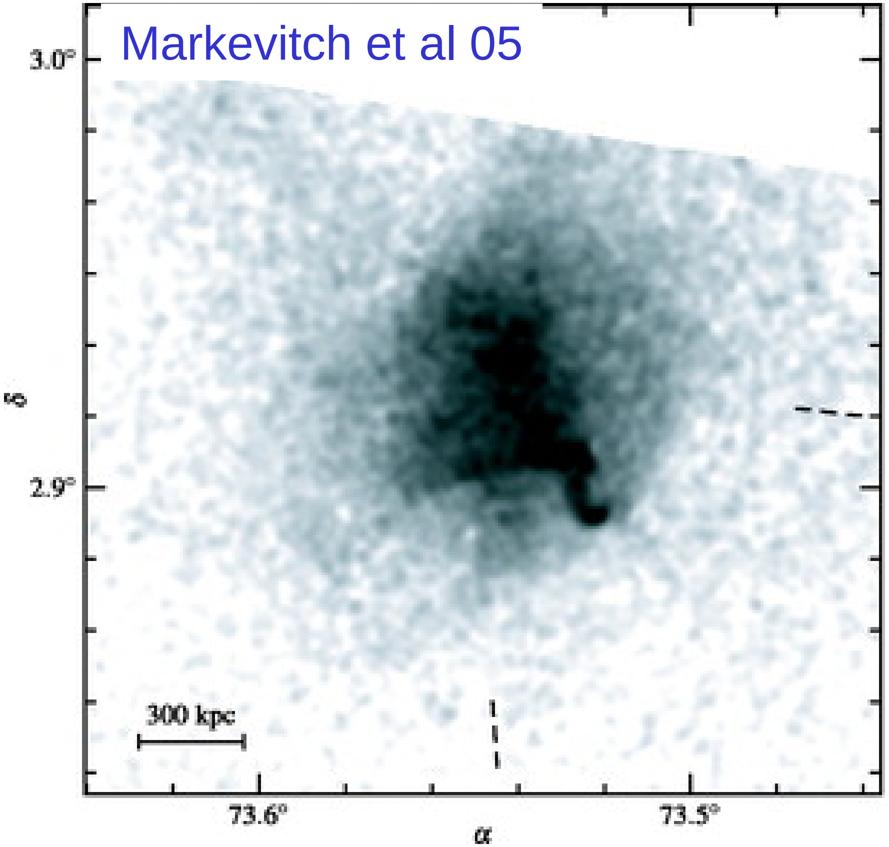
E_{CR} = 0.001 of E_{ICM} (??)

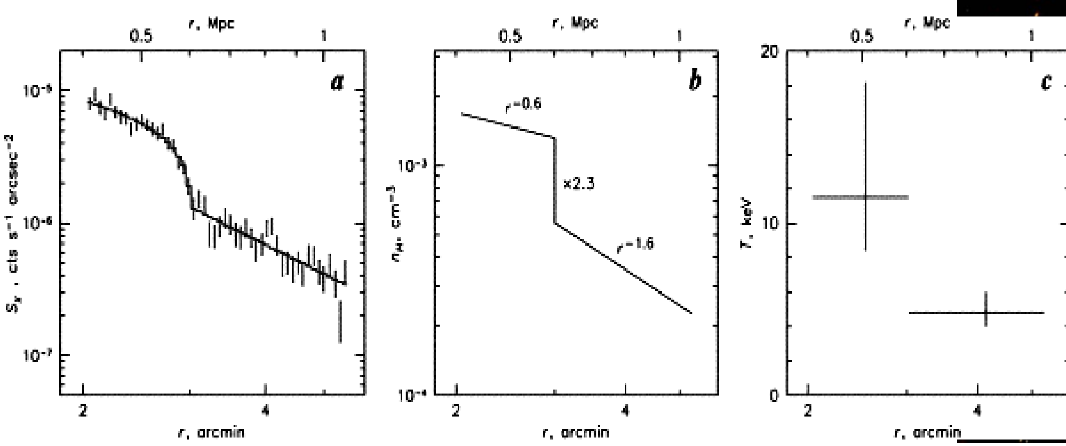
Estimate of number of AGNs, life-time and injection rate :

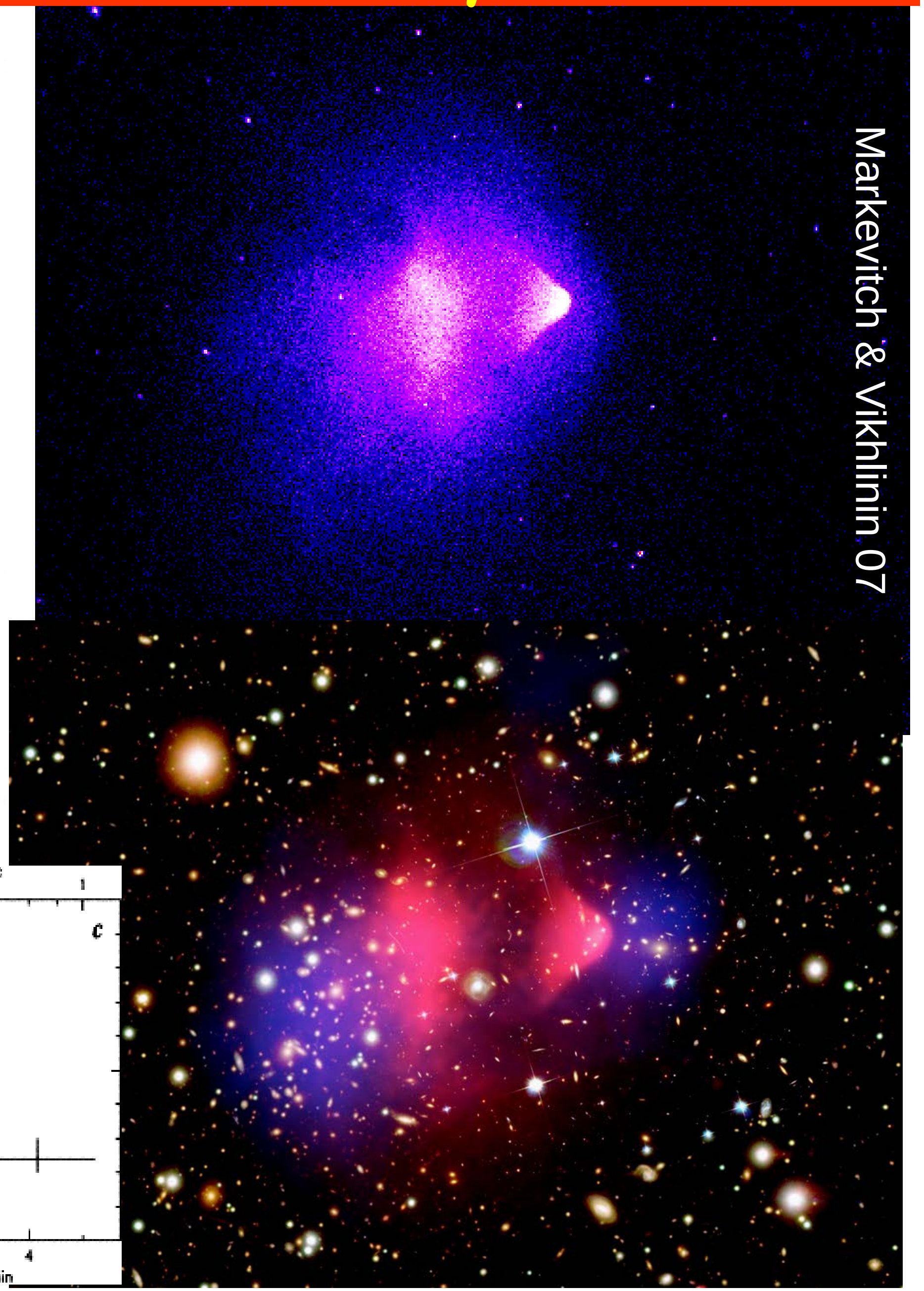
E_{CR} = 0.001 - 0.1 of E_{ICM} (??)

- Thermal plasma in the bubbles
- Poynting/leptonic/hadronic
  (Ensslin et al 97, ..
  rev: McNamara & Nulsen 07)

Shocks “are observed” in Galaxy Clusters

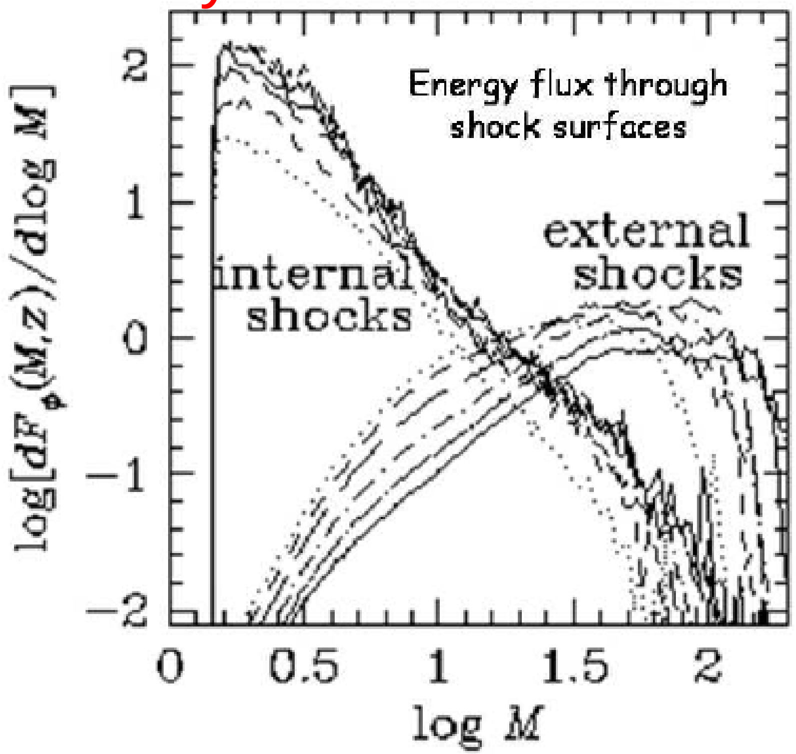


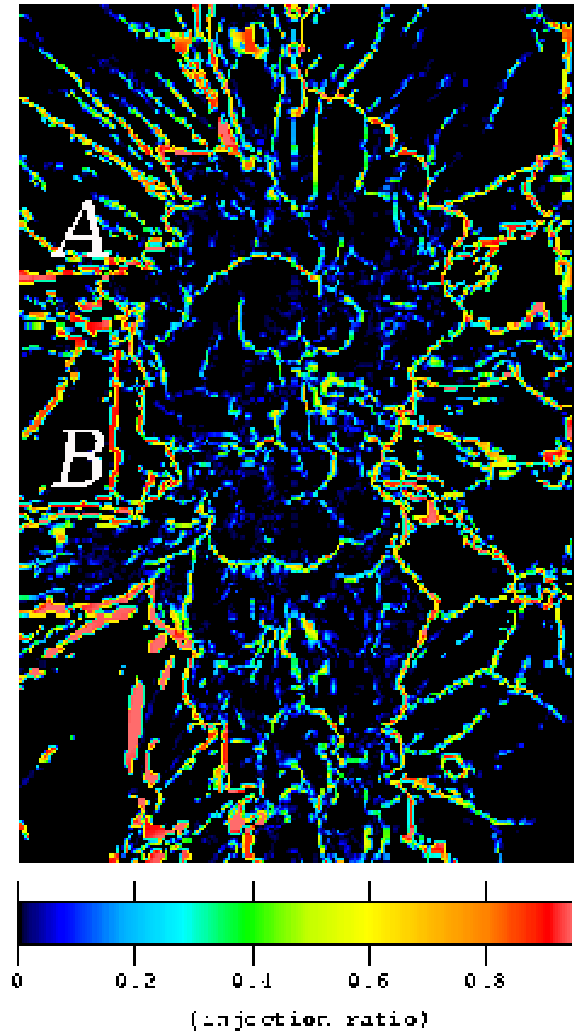




Cosmological Shocks & CRs accelerators

Ryu et al 03





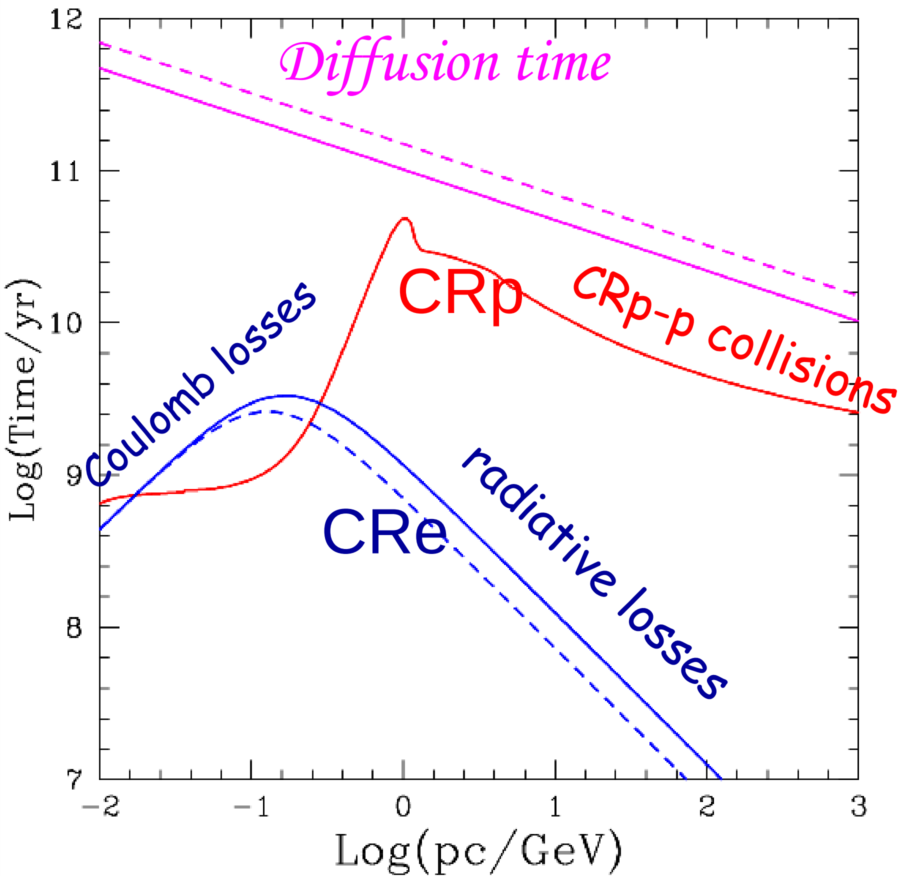
Vazza, GB, Gheller 09

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, Ensslin et al 97,..) ...

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



$$\left[\frac{dp}{dt}\right]_i = -3.3\times10^{-29} n_{th}\left[1+\frac{\ln(\gamma/n_{th})}{75}\right]$$

$$\left[\frac{dp}{dt}\right]_{rad} = -4.8\times10^{-4} p^2\left[\left(\frac{B_{\mu G}}{3.2}\right)^2+(1+z)^4\right]$$

$$\left(\frac{dp}{dt}\right)_i \simeq -1.7\times10^{-29}\left(\frac{n_{th}}{10^{-3}}\right)\frac{\beta_p}{\frac{3}{4}\sqrt{\pi}\beta_e^3+\beta_p^3} \quad \text{(cgs)}$$

$$\tau_{pp}(p) \simeq \frac{1}{c\, n_{th}\sigma_{pp}}$$

$$p+\gamma\rightarrow p+e^+ + e^- \qquad p+\gamma\rightarrow \pi\text{'s}+N$$

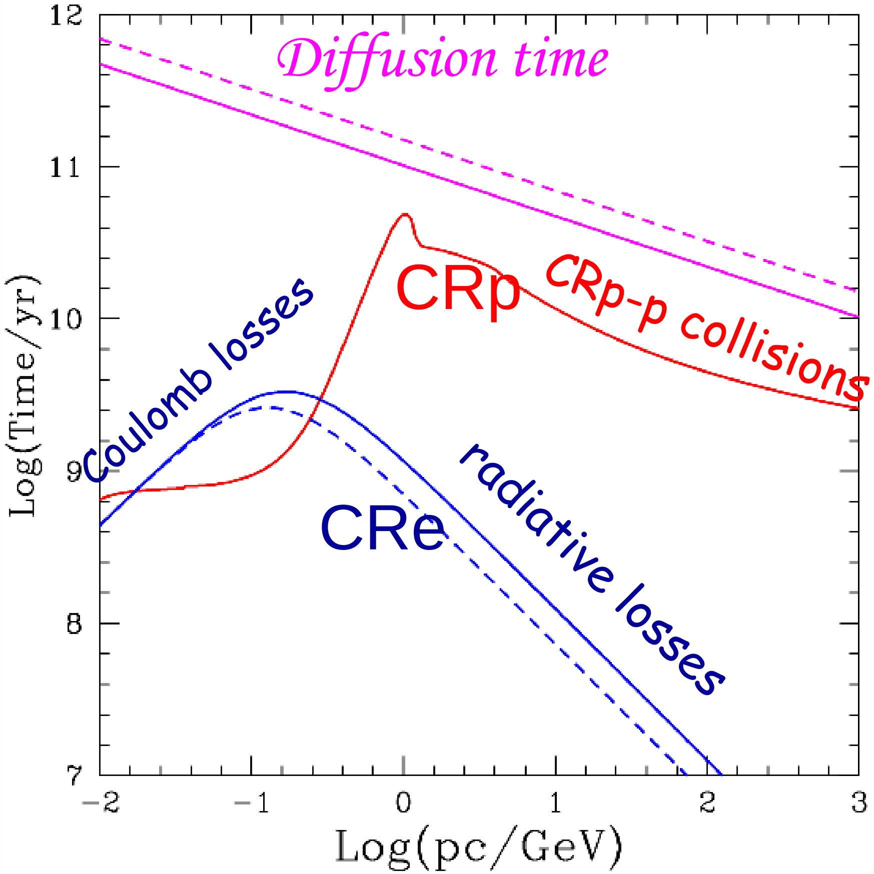
review: Blasi, Gabici, Brunetti 07
Brunetti & Jones 13

Cosmic rays confinement

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

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

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



D(GeV) ≈10^{27}-10^{28} cm^2/s

<< $10^{32} cm^2/s$

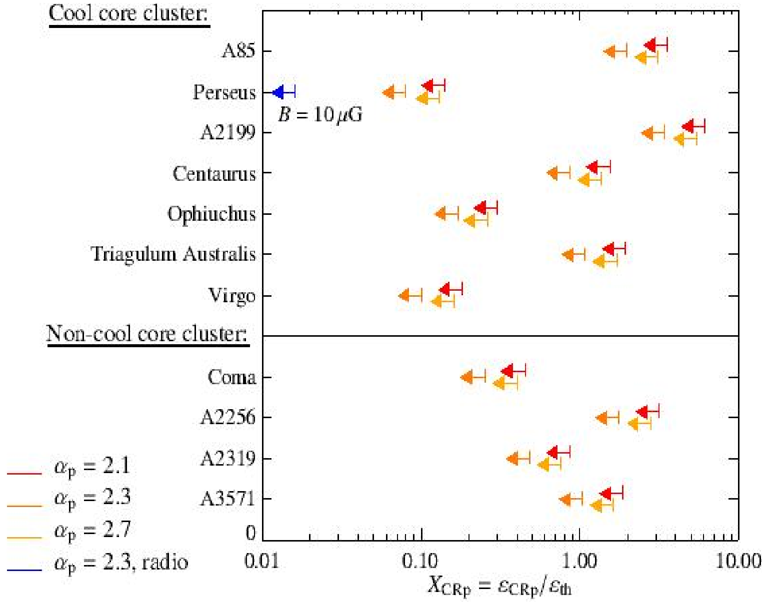
Generation of small scales B-perturbations/waves in the ICM

(rev: Brunetti & Jones 13)

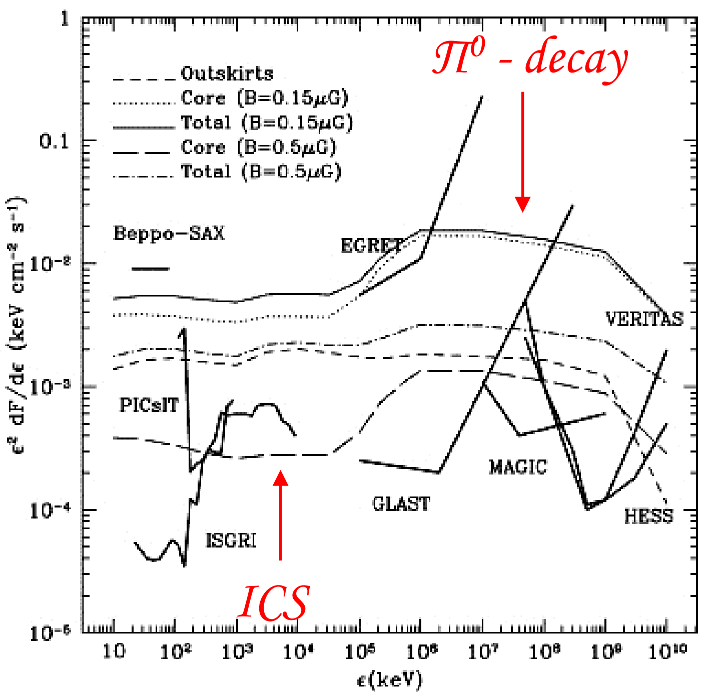
- Streaming instability
  (.. Wiener et al 13)
- Firehose instability
  (.. Brunetti & Lazarian 11, Kunz et al 11)
- Gyrokin instability
  (.. Yan & Lazarian 11)

Limits & expectations in the "pre"-Fermi era

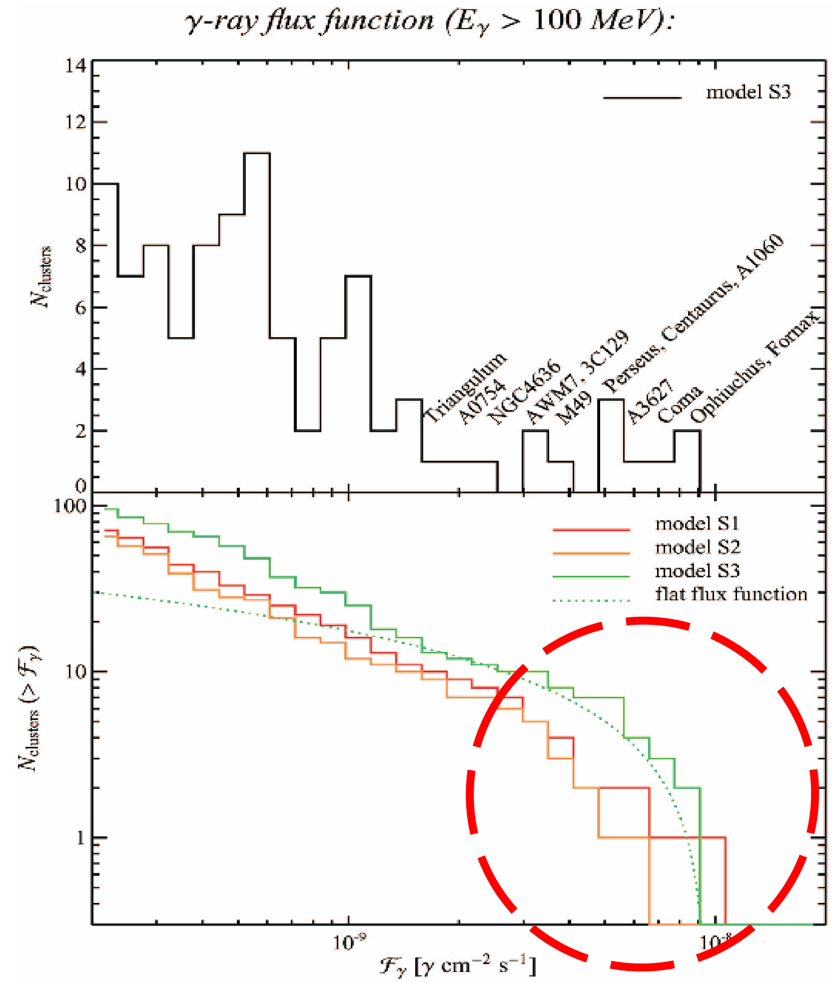
EGRET



Reimer et al. 03, Pfrommer & Ensslin 04



Miniati 03



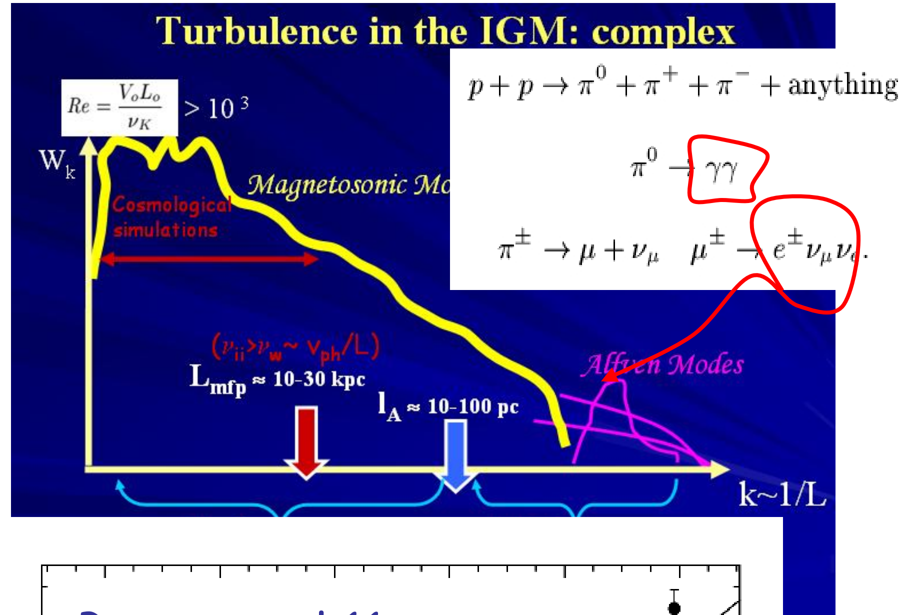
Pfrommer 08

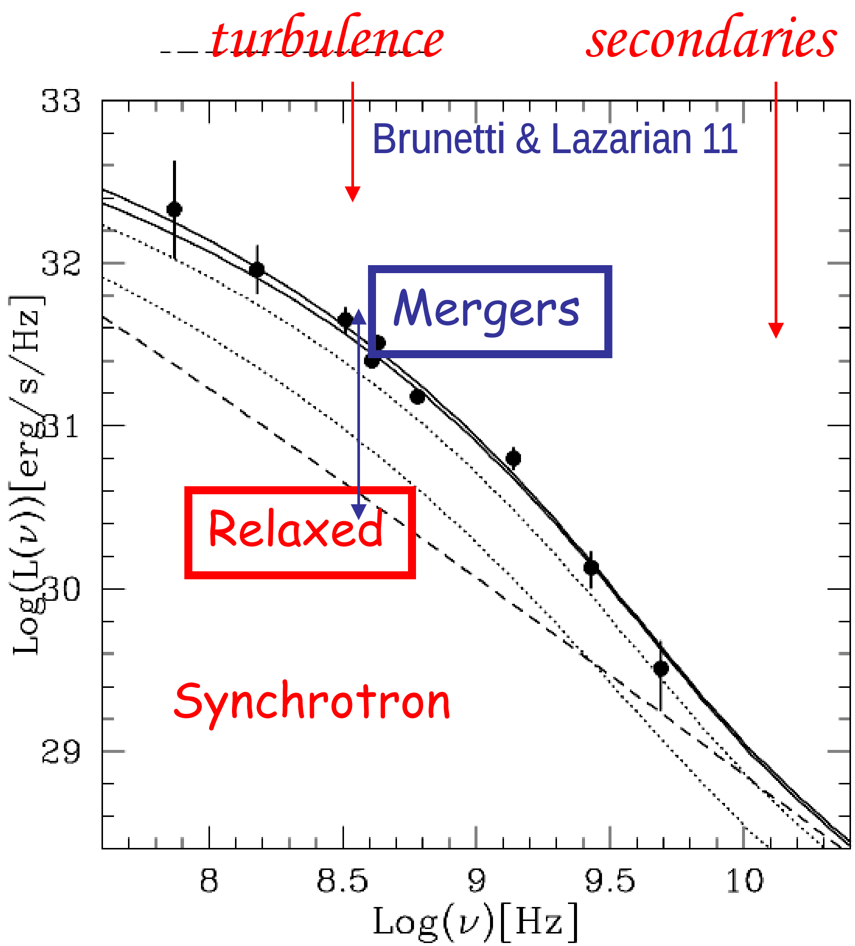
These expectations depend on the «assumed efficiency» of acceleration of CRs at cosmological shocks

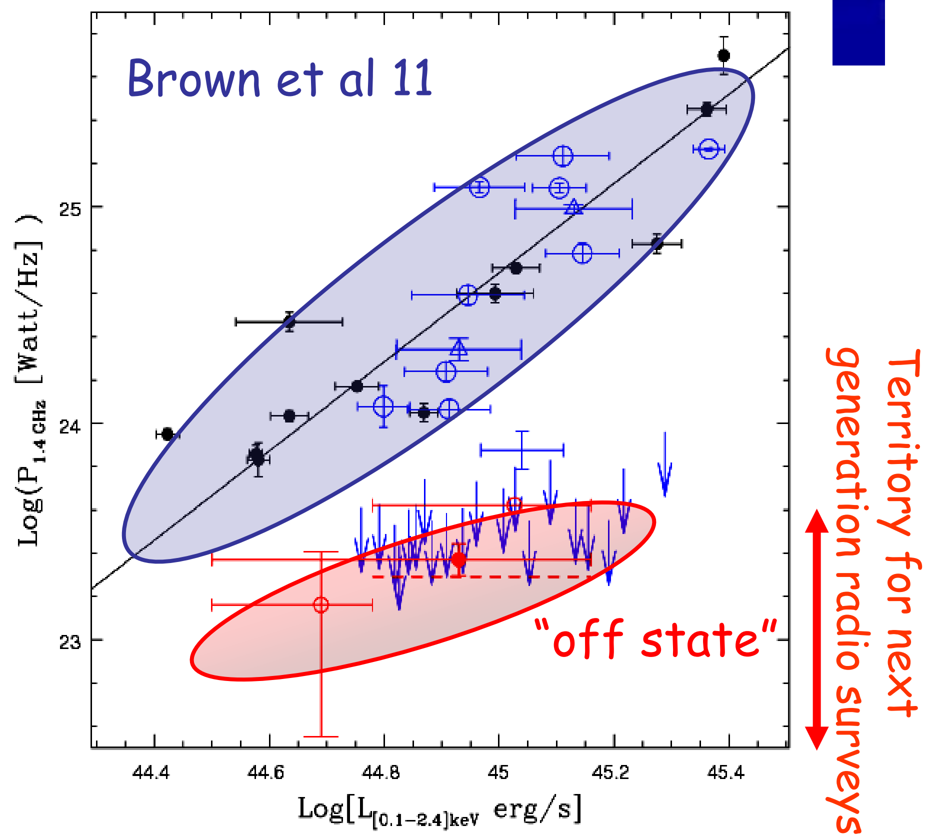
Radio Halos & high energies

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

E_{CRp} = ~ % E_{th}







Stochastic REacceleration of primaries & secondaries

(Brunetti & Lazarian 11)

ICM, B, CRp ⟺ Transit Time Damping (TTD)

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

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

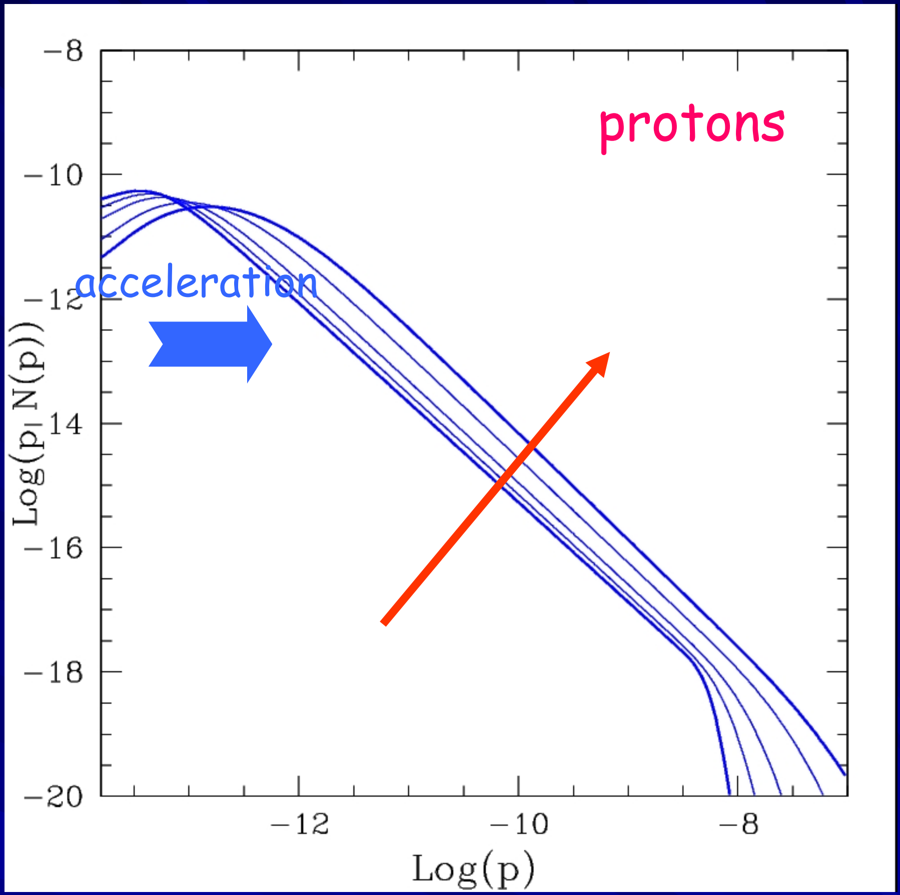
dampings

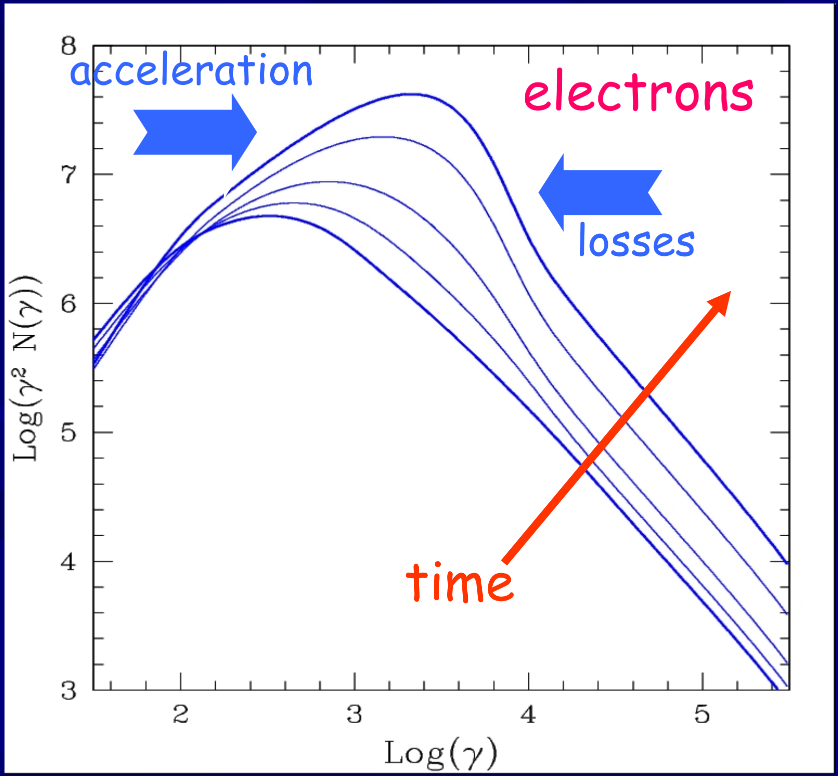
$$\Gamma = -i\left(\frac{E_i^* K_{ij}^a E_j}{16\pi W}\right)_{\omega_i=0}\omega_r$$

Transit Time Damping (TTD)

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

(from Brunetti & Lazarian 11, MNRAS 410, 127)

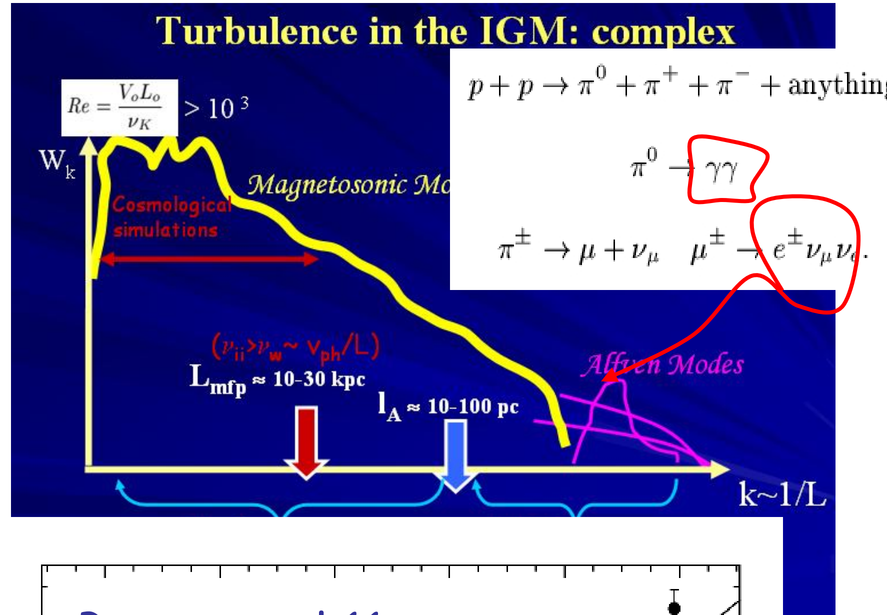


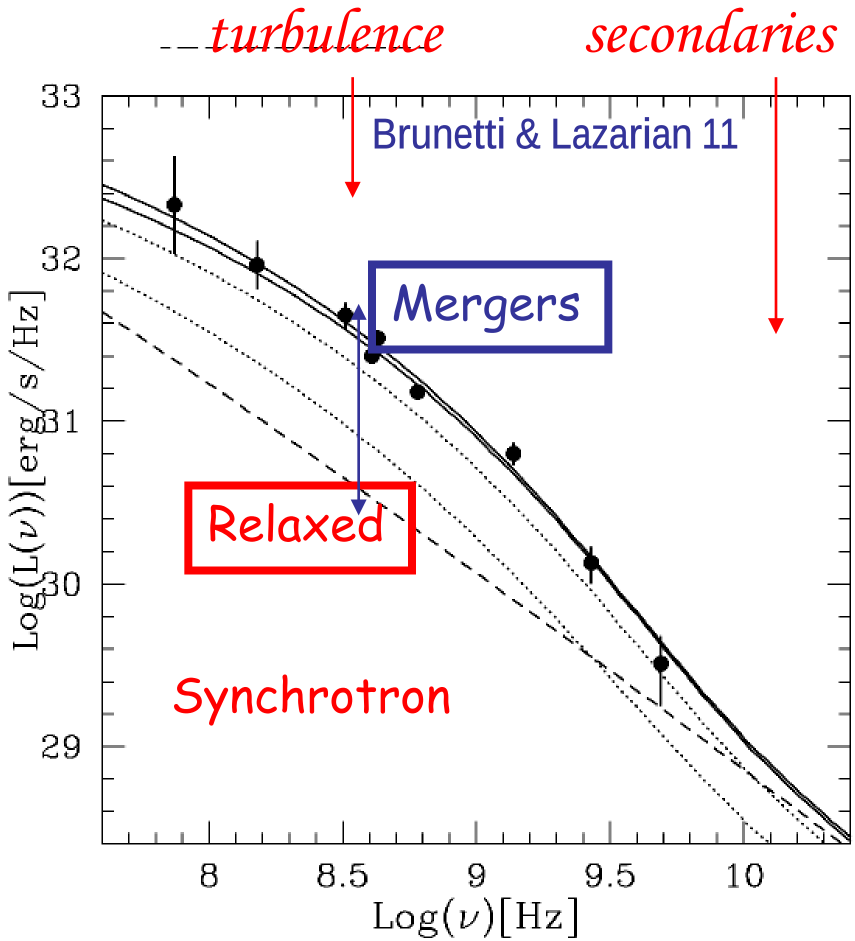


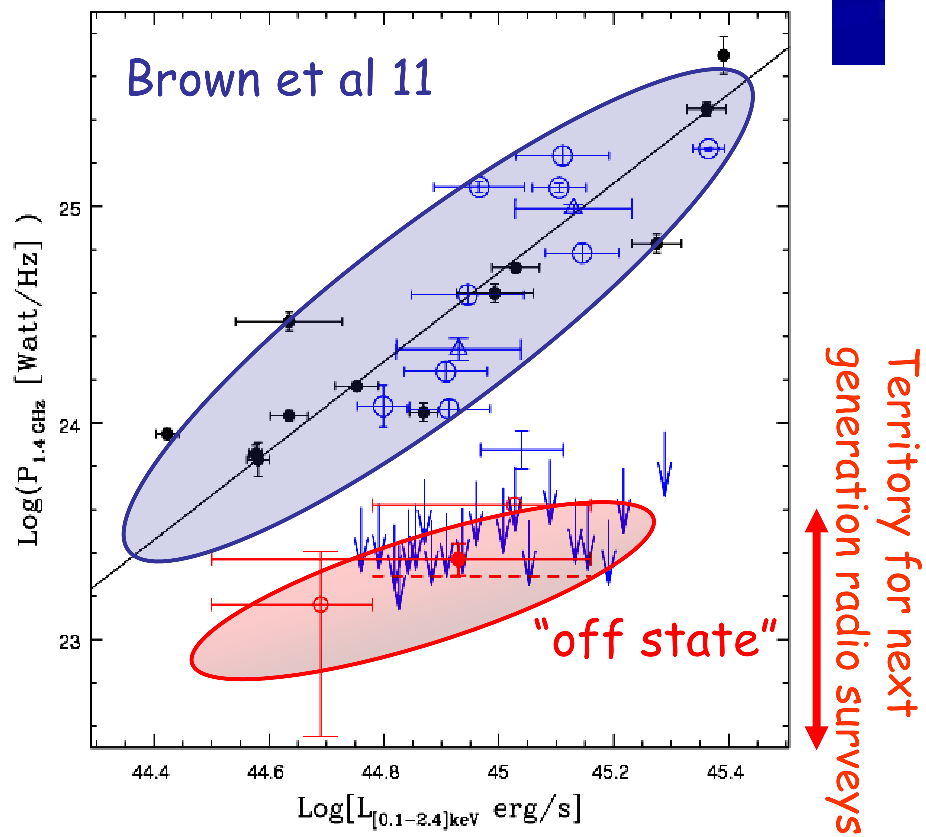
The modification of the electrons spectrum at energies of few GeV
(i) increases the ratio Syn/gamma and
(ii) is reflected in a curvature in the Syn spectrum at higher radio frequencies

Radio Halos & high energies

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





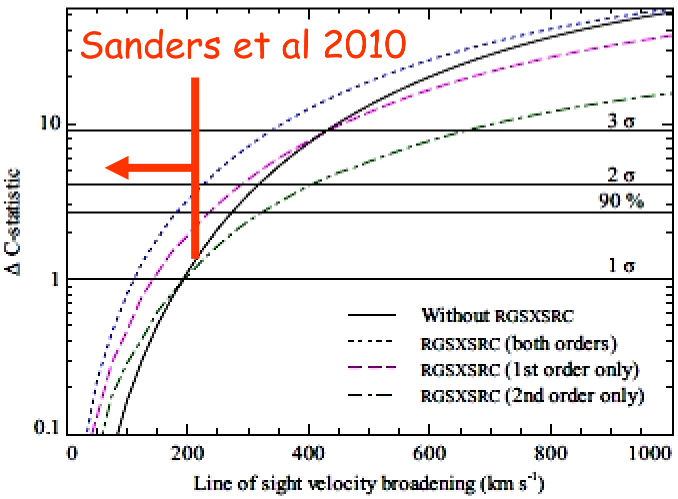


Turbulence in clusters & ASTRO-H

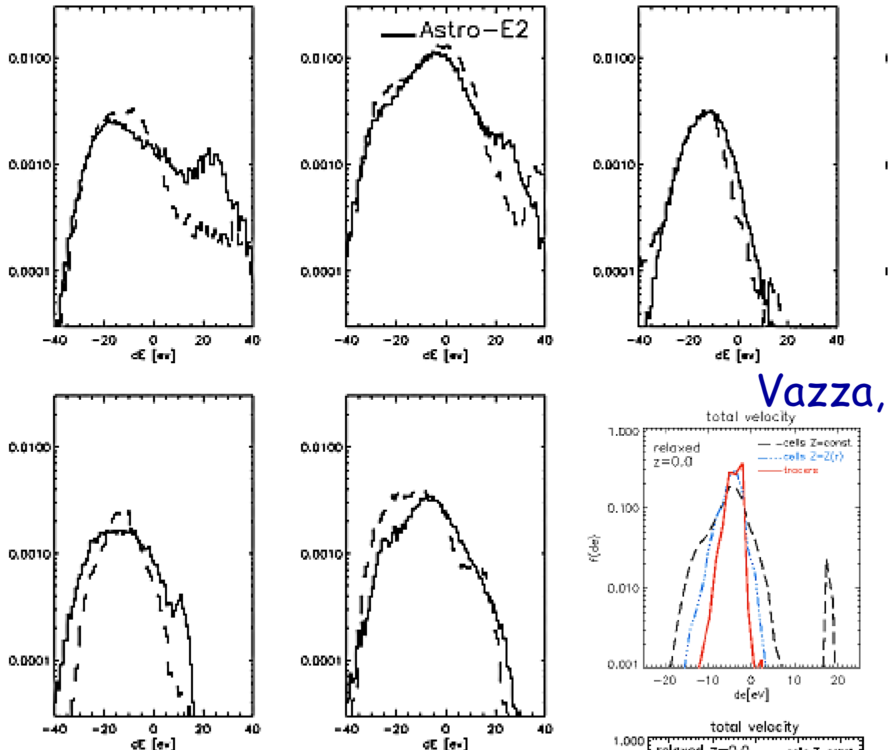
$$\Delta v^2=(2k_B T/m)+\delta v^2$$

(eg., Sunyaev, Norman,Bryan 2003…)

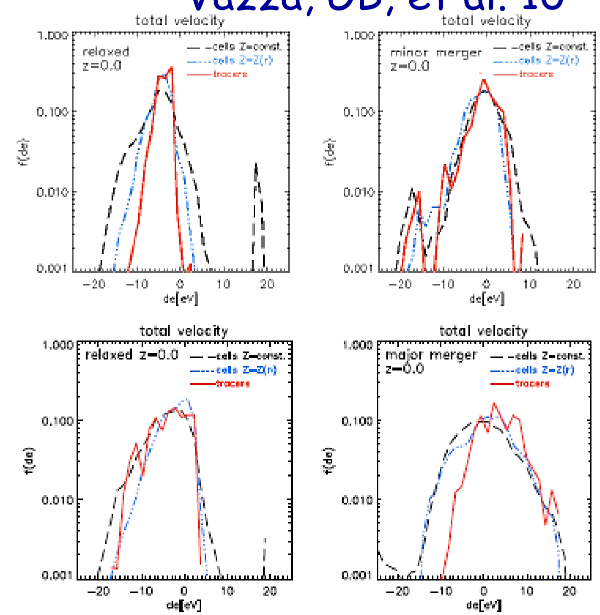
Current limits (XMM)
(cool-core clusters, A1835..)



Dolag, Vazza, GB, Tormen 05



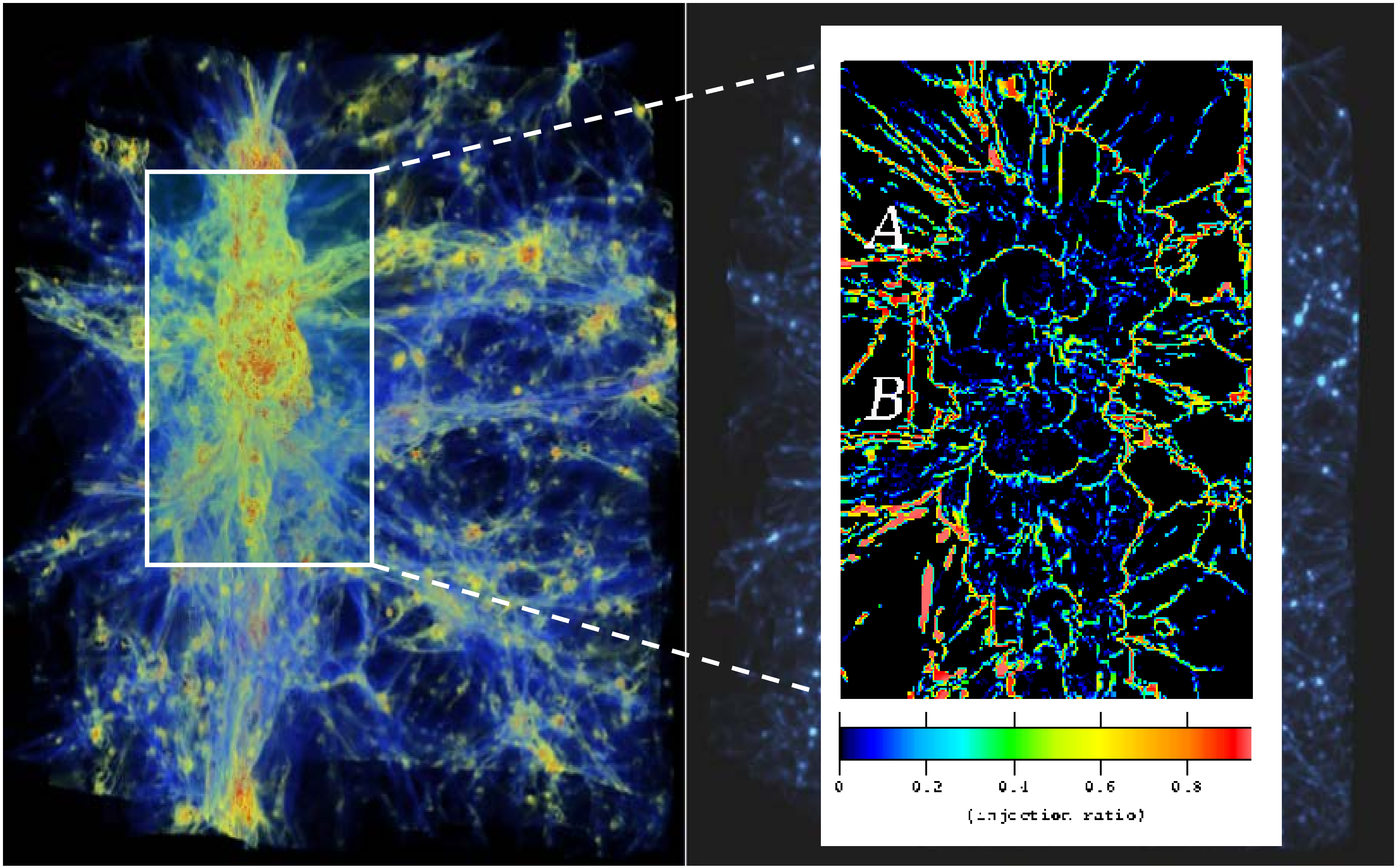
Vazza, GB, et al. 10



Warning :

- Line broadening is also produced by laminar motions of substructures along the line of sight

Some speculations on accretion shocks ?

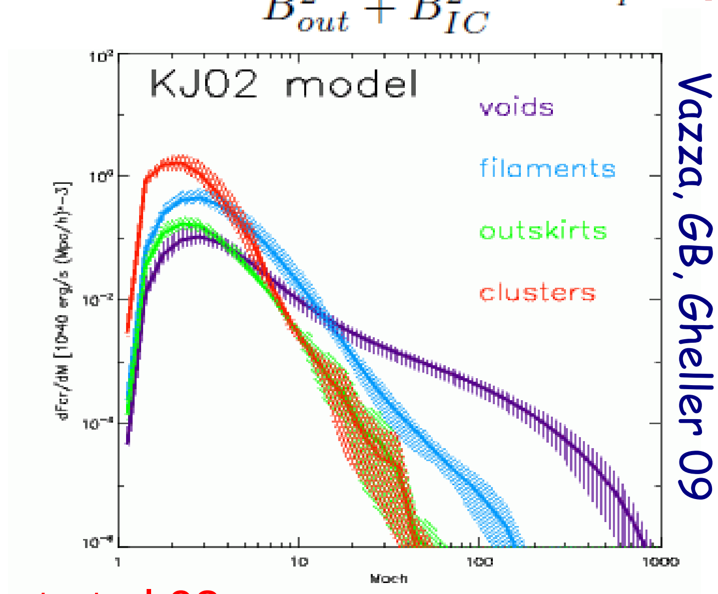


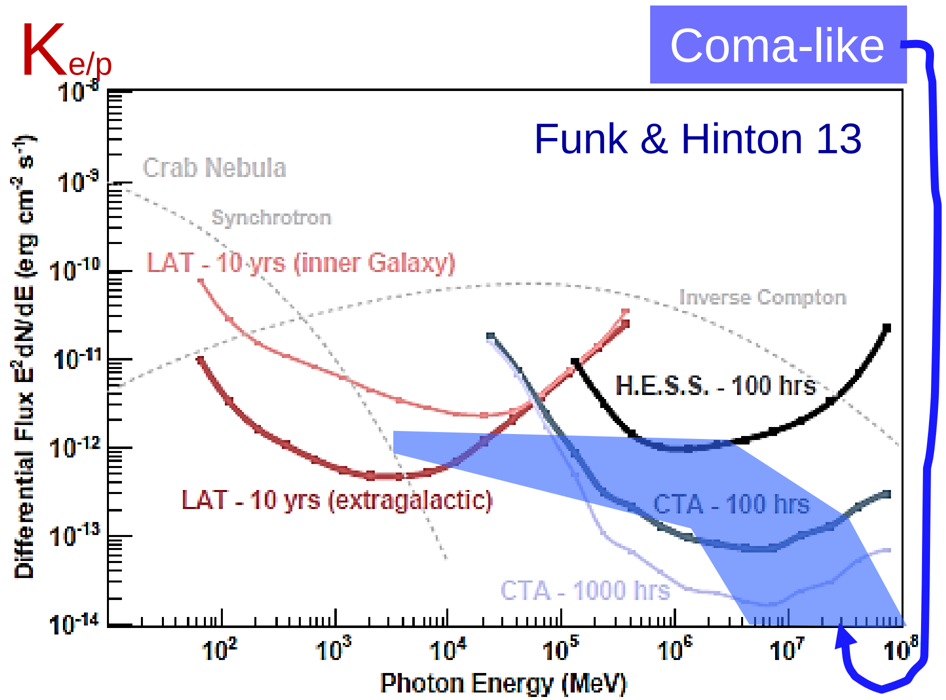
Detection of ICS from primaries ?

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

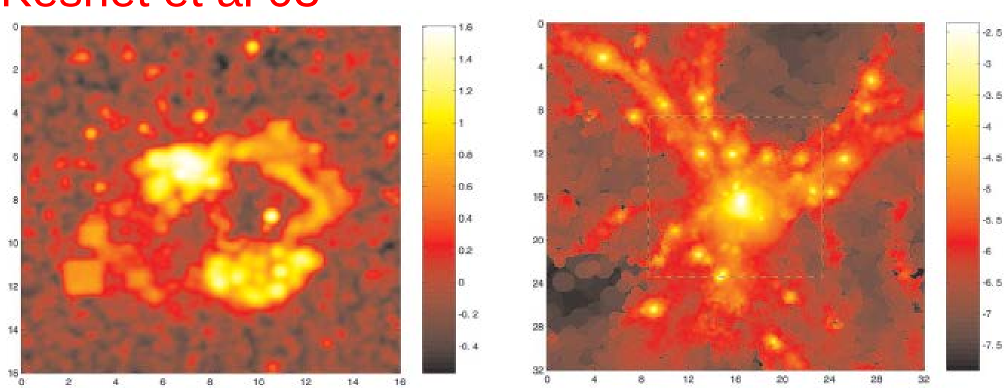
$$E^e_{max} \approx 6.3 \times 10^4 B_\mu^{1/2} v_8 g(r)^{-1/2}\ GeV,$$

$$L_{\gamma,ICS} \propto S\rho V_{sh}^3 \frac{B_{IC}^2}{B_{out}^2+B_{IC}^2}\eta_{CR}K_p^e \approx 10^{42}\ K_{e/p}$$





Keshet et al 03



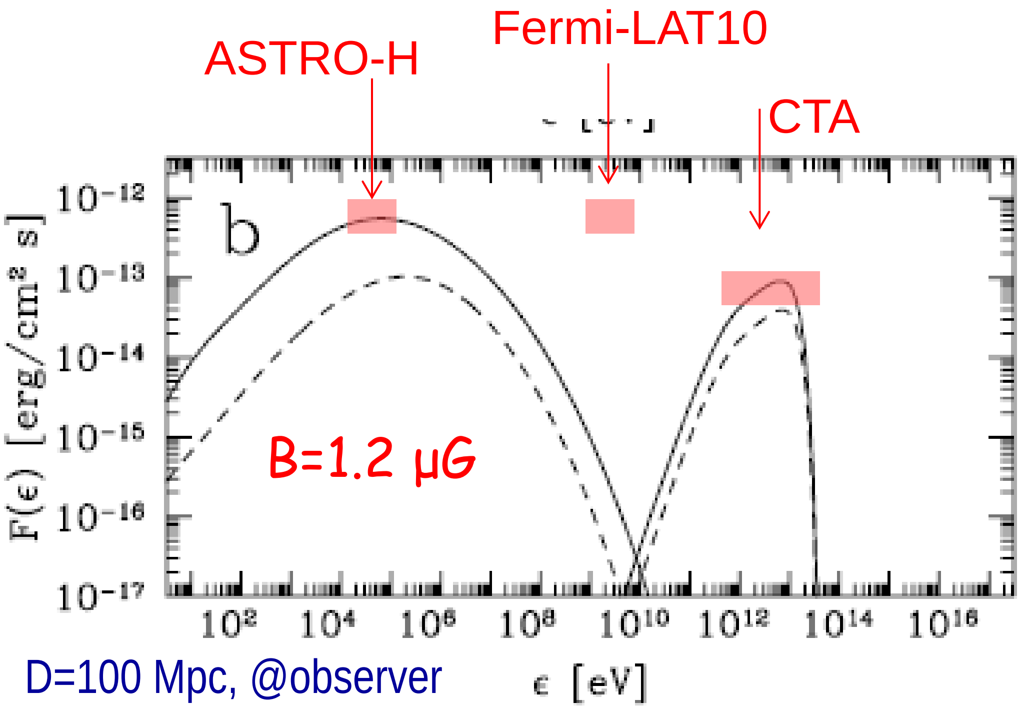
Efficiency of CRe acceleration at (strong) peripheral shocks > 0.01 would imply a detection by Fermi-LAT.

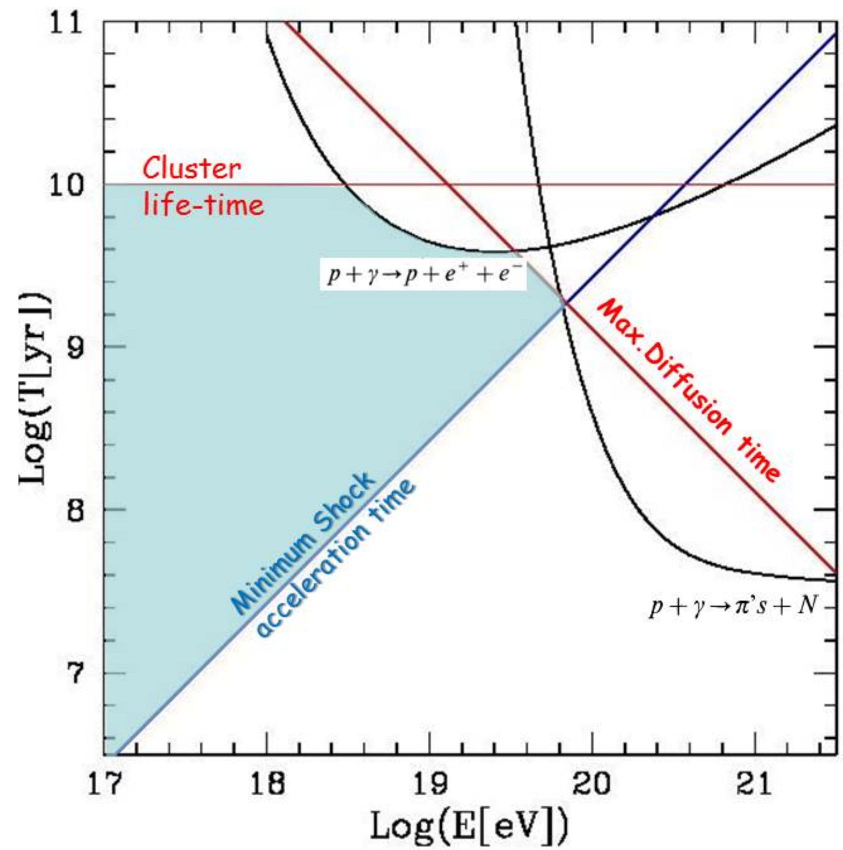
CTA may constrain CRe efficiencies in the range «0.001-0.01» … (again)

over-resolving is a potential caveat ..

Acceleration of EeV CRp @accretion shocks ?

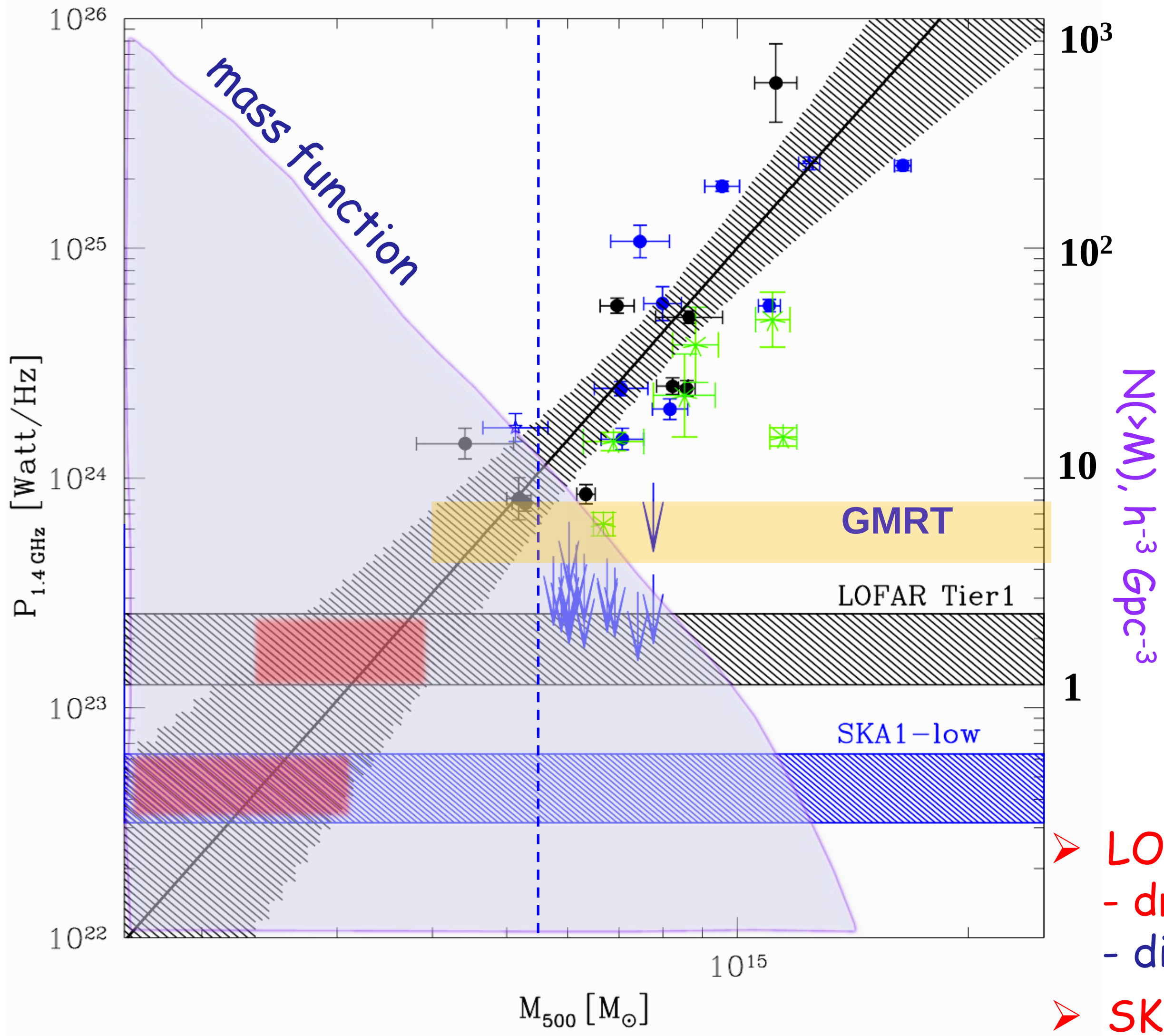
(Inoue et al 05, Vannoni et al 11..)

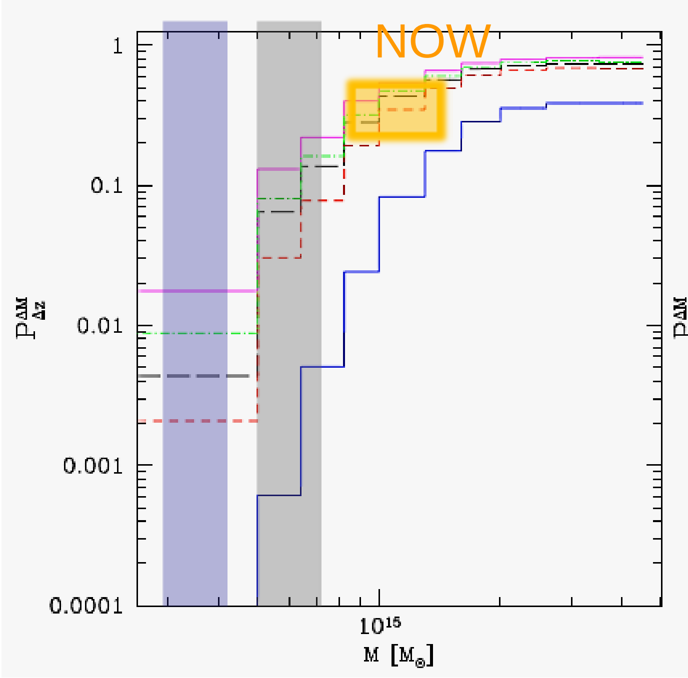




CRp with energy 1-10 EeV interact with the cosmic microwave background and efficiently very high energy electron-positron pairs, which radiate synchrotron and inverse Compton emission, peaking at hard X-rays and TeV

GOING TO SMALLER MASSES : FUTURE SURVEYS





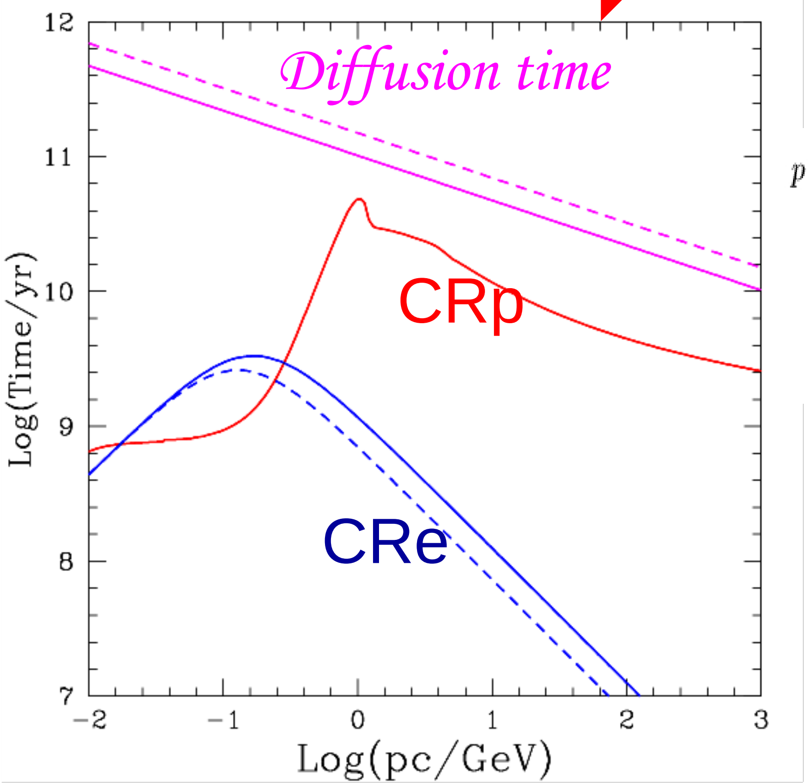
- LOFAR :
  - drop of radio halo fraction
  - discovery of ultra-steep RHs
- SKA : population dominated by other physical processes

Going to smaller masses does not necessarily imply that more (much more) RHs will be found !

See… next slides ….

How to reconcile CRp confinement & RHs with Fermi u.l.?

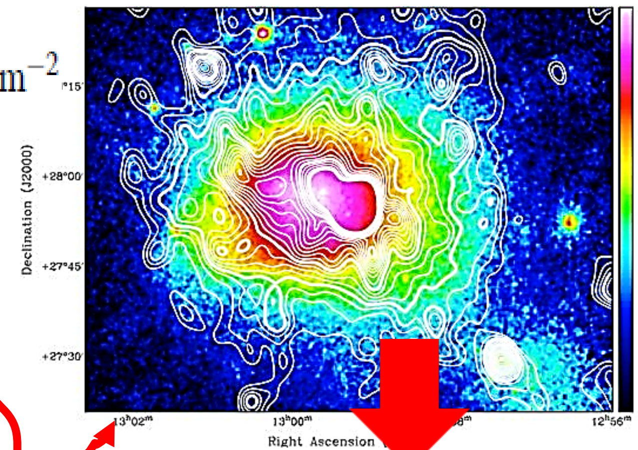
Confinement → $X_g \sim n_{ICM} m_p c \tau \sim 1.6 \times \frac{n_{ICM}}{10^{-3}} \times \frac{\tau}{\mathrm{Gyr}} \mathrm{g\ cm}^{-2}$



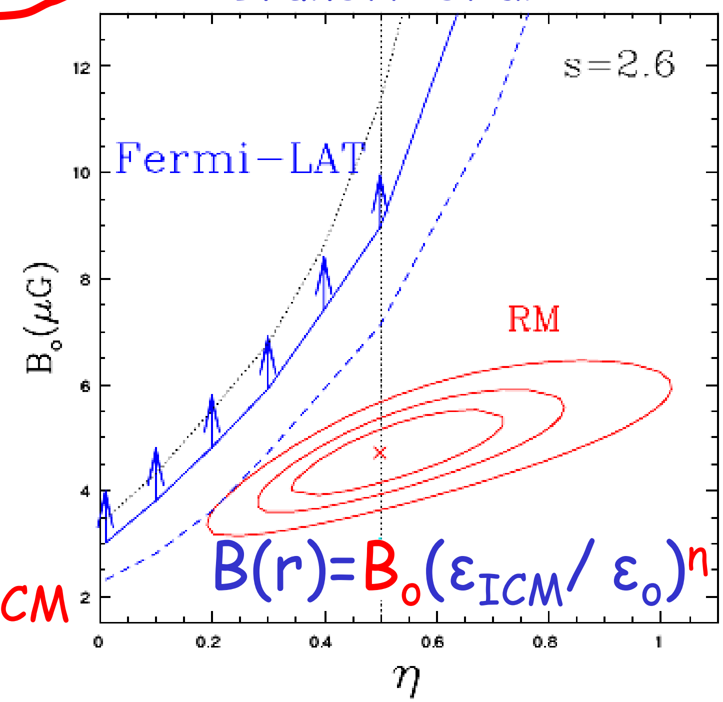
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

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

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



Brunetti et al 12



$B(r)=B_o(\varepsilon_{ICM}/\varepsilon_o)^\eta$

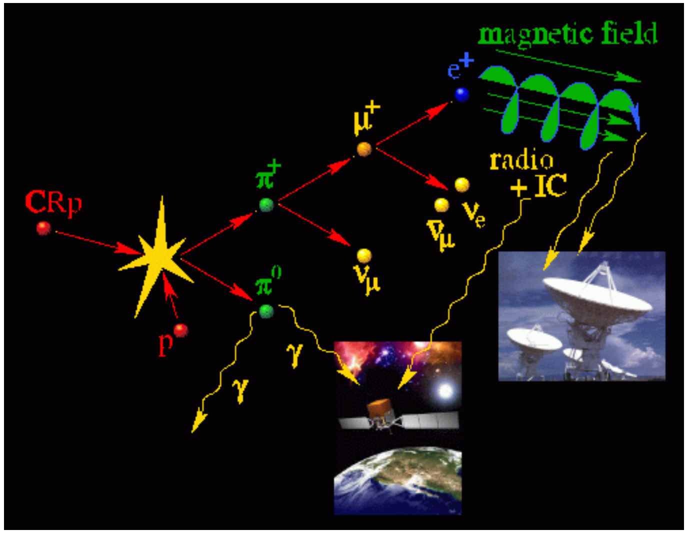
Purely leptonic models (Brunetti 01, Petrosian 01, Ohno et al 02, Fujita et al 03,....)

Hybrid models : hadronic models in turbulent ICM (Brunetti & Blasi 05, Brunetti & Lazarian 11)

The two leading mechanis...

Hadronic interactions

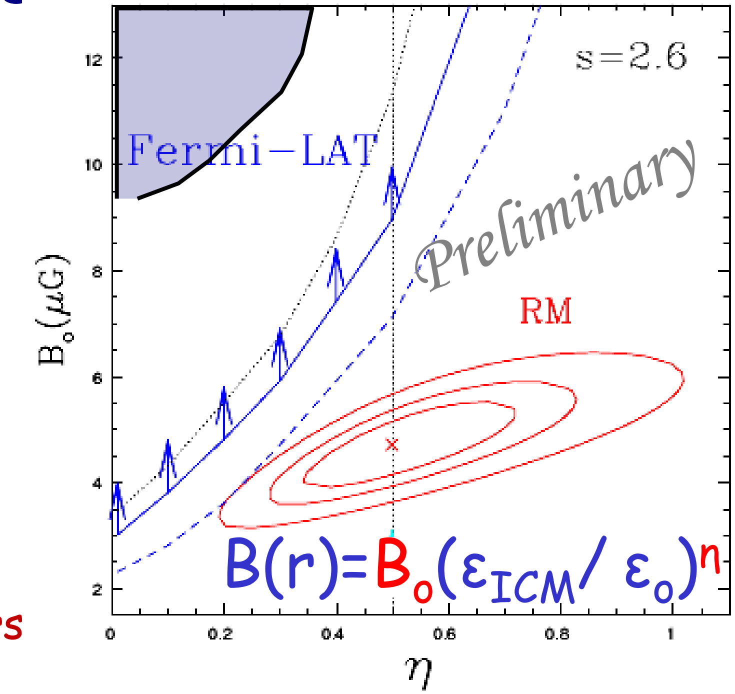
(Dennison 1980, Blasi & Colafrancesco 99, ...)



Challenged by gamma-ray u.l.

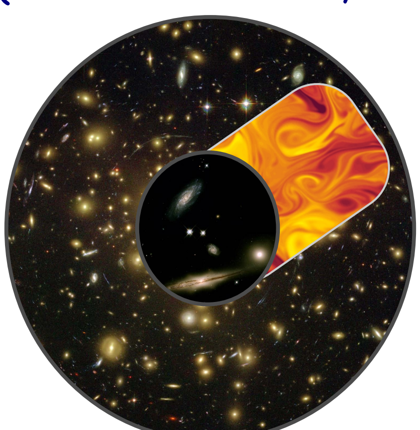
High energy and neutrino emission from galaxy clusters

Brunetti et al 12

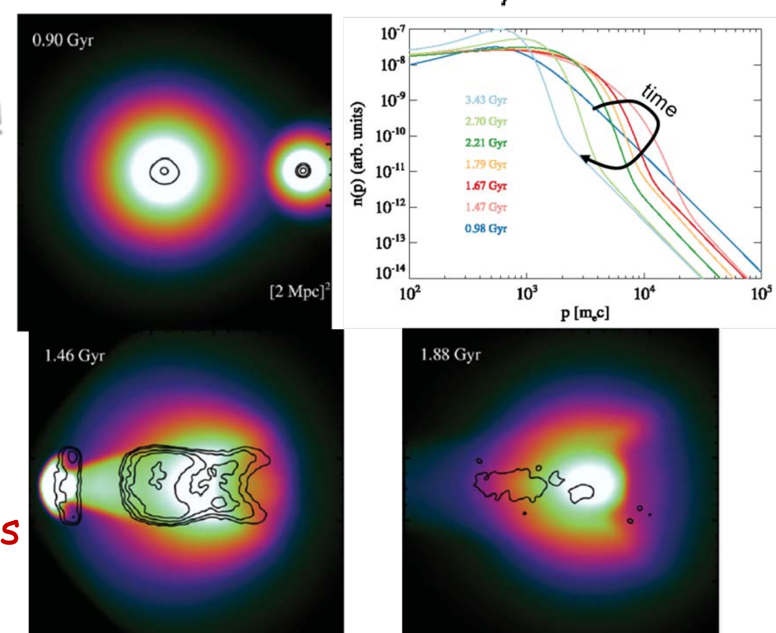


Turbulence and stochastic (re)acceleration

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



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



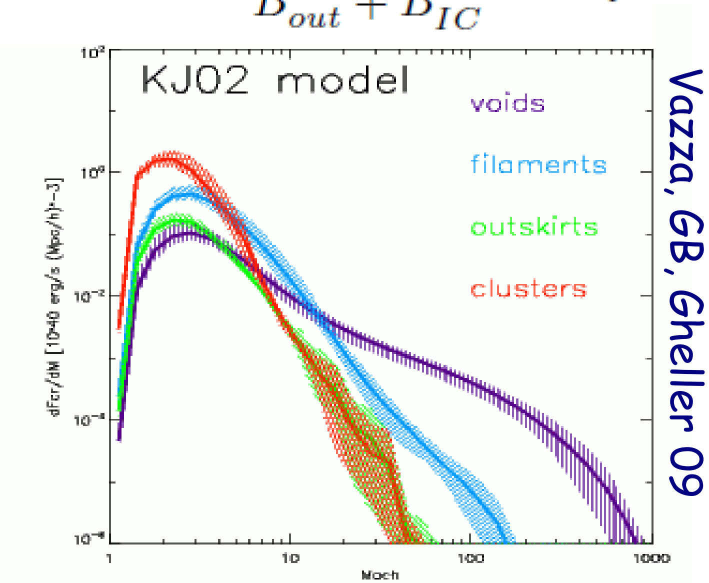
Donnert et al 13

Detection of ICS from primaries ?

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

$$E^{e}_{max} \approx 6.3 \times 10^{4} B_{\mu}^{1/2} v_{8} g(r)^{-1/2}\ GeV,$$

$$L_{\gamma,ICS} \propto S \rho V_{sh}^{3} \frac{B_{IC}^{2}}{B_{out}^{2} + B_{IC}^{2}} \eta_{CR} K_{p}^{e} \approx 10^{42}\ K_{e/p}$$



Vazza, GB, Gheller 09

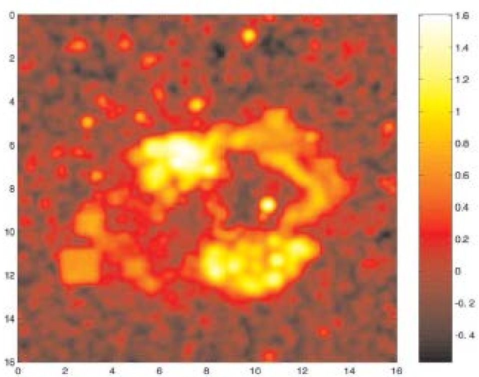
$$L\gamma, \pi^{0} \propto L^{ul}_{SYN} \frac{B^{2} + B_{IC}^{2}}{B^{2}}$$

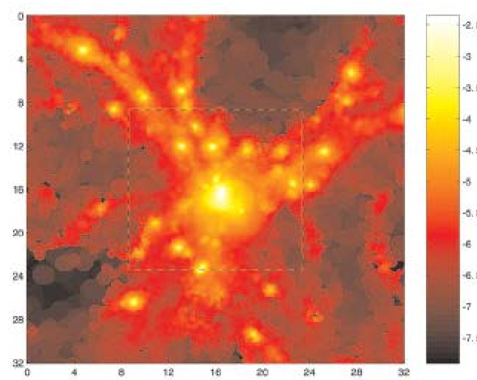
$$\frac{L_{\gamma,ICS}}{L\gamma,\pi^{0}} \propto S \rho V_{sh}^{3} \frac{(B_{IC} B)^{2}}{(B^{2} + B_{IC}^{2})(B_{out}^{2} + B_{IC}^{2})} \eta_{CR} K_{p}^{e}$$

«IF» $K_{e/p}$ > 0.1 «ICS dominated»

(eg Waxman & Loeb 00, Keshet et al 09)

Keshet et al 03





Efficiency of CRe acceleration at (strong) peripheral shocks > 0.01 would imply a detection by Fermi-LAT.

CTA may constrain CRe efficiencies in the range «0.0005-0.01» … (again) over-resolving is a potential caveat ..

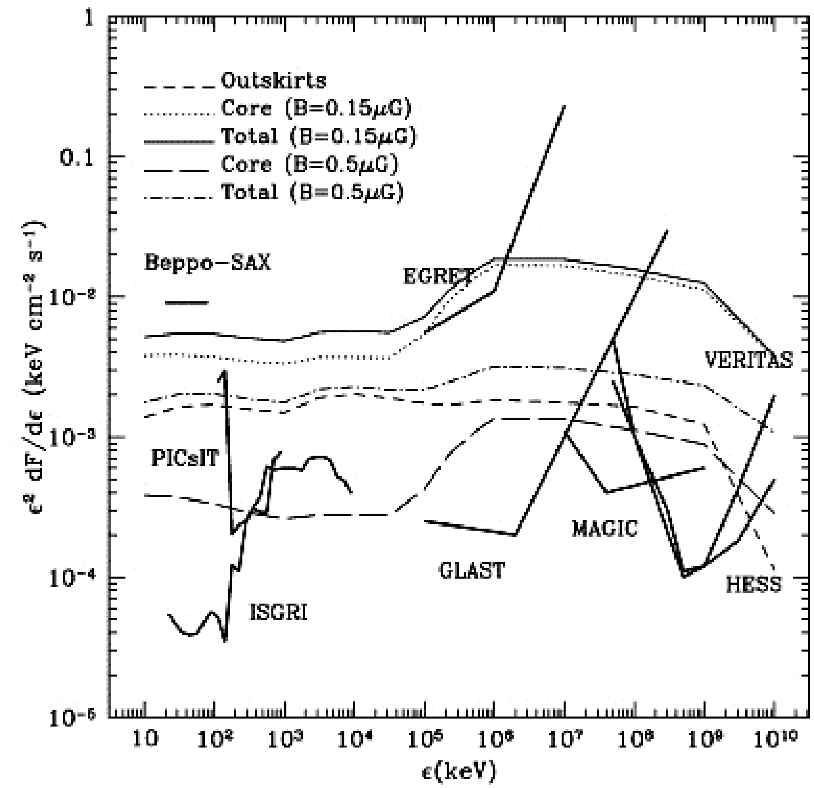
Detection of ICS from primaries ?

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

$$L_{\gamma,ICS} \propto S\rho V_{sh}^3 \frac{B_{IC}^2}{B_{out}^2 + B_{IC}^2} \eta_{CR} K_p^e$$

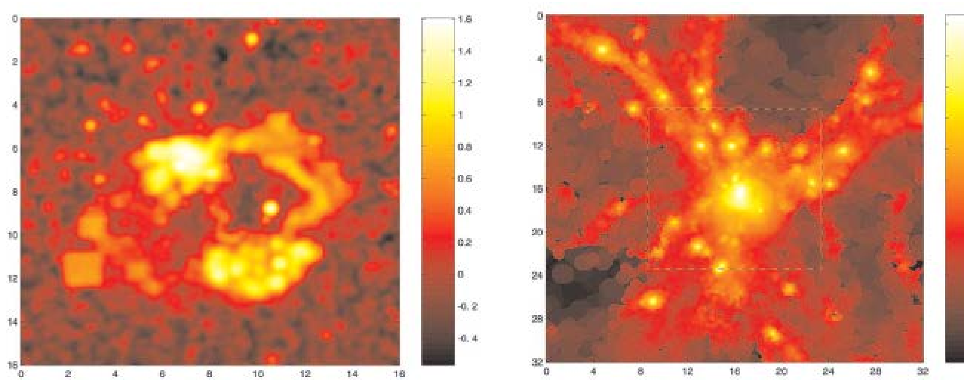
$$L\gamma,\pi^0 \propto L_{SYN}^{ul} \frac{B^2 + B_{IC}^2}{B^2}$$

$$\frac{L_{\gamma,ICS}}{L\gamma,\pi^0} \propto S\rho V_{sh}^3 \frac{(B_{IC}B)^2}{(B^2 + B_{IC}^2)(B_{out}^2 + B_{IC}^2)} \eta_{CR} K_p^e$$



IF $K_{e/p}$ > 0.1 «ICS dominated» !

Keshet et al 03



Efficiency of CRe acceleration at (stro
peripheral shocks > 0.01 would imply a detection by Fermi-LAT.
CTA may constrain CRe efficiencies in the range 0.0005-0.01... (again)
over-resolving is a potential caveat ..

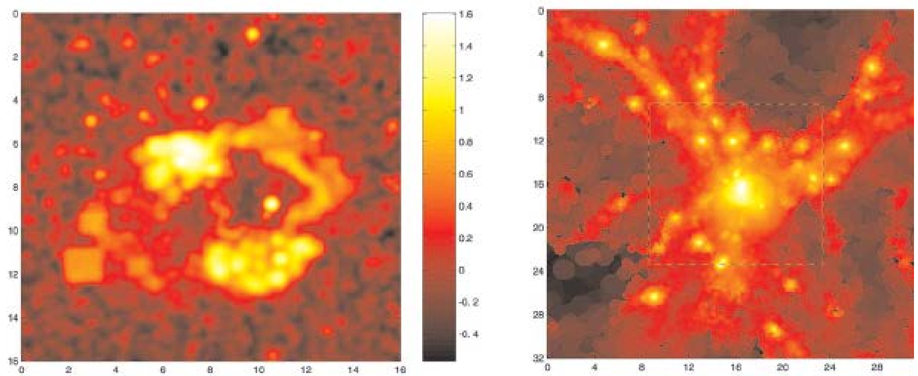
Shock Acceleration CRe : ICS

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

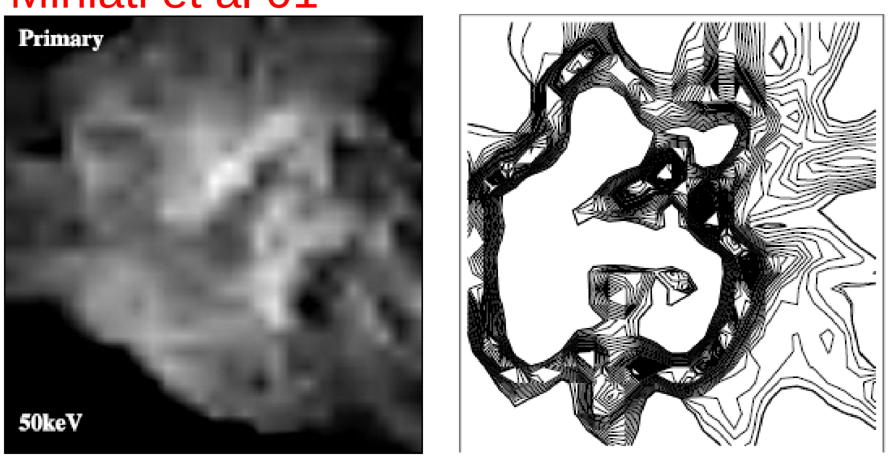
$$E^{e}_{max} \approx 6.3 \times 10^{4} B_{\mu}^{1/2} v_{8} g(r)^{-1/2}\ GeV,$$

$$\nu_o L(\nu_o) \approx \frac{1}{2}\rho_u V_{sh}^{3} \xi \eta_{(>\gamma_o)} S \left[1 + \left(\frac{B_{IC}}{B}\right)^{-2}\right]^{-1}$$

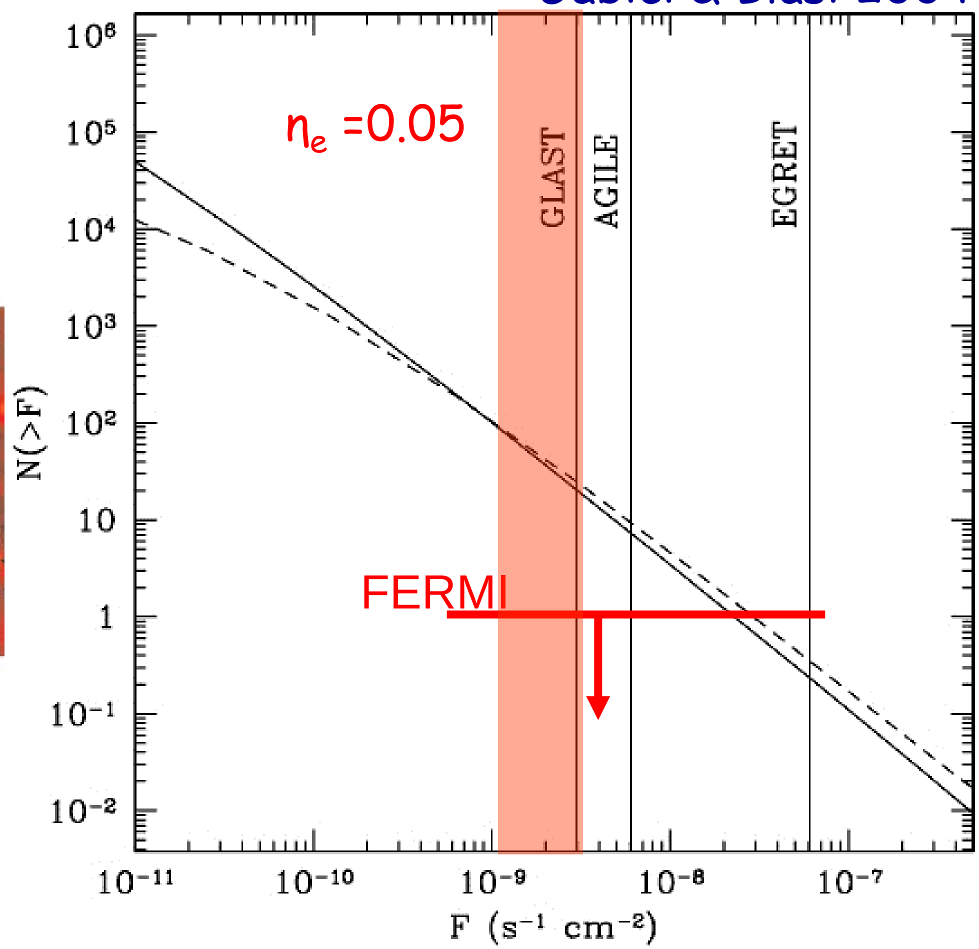
Keshet et al 03



Miniati et al 01



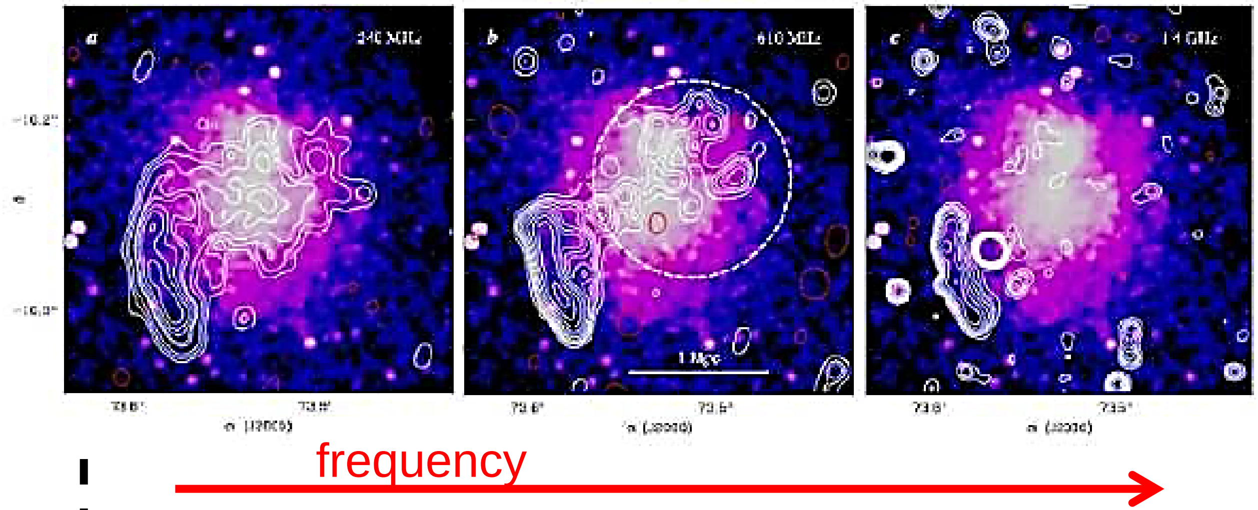
Gabici & Blasi 2004

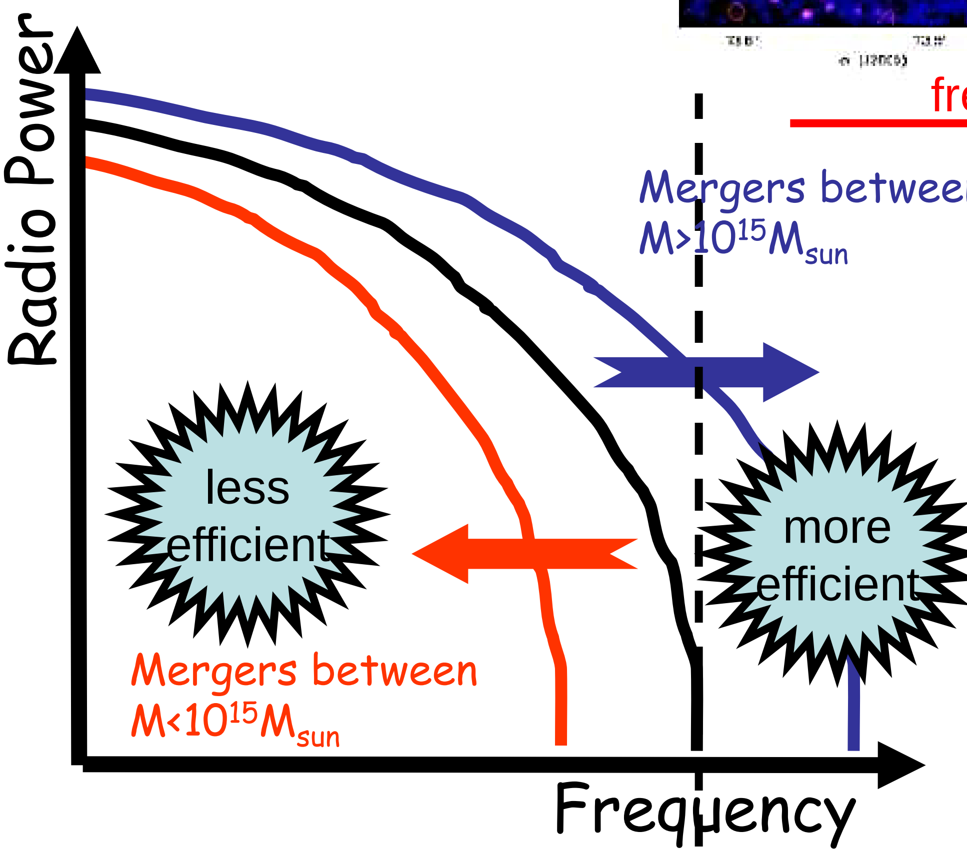


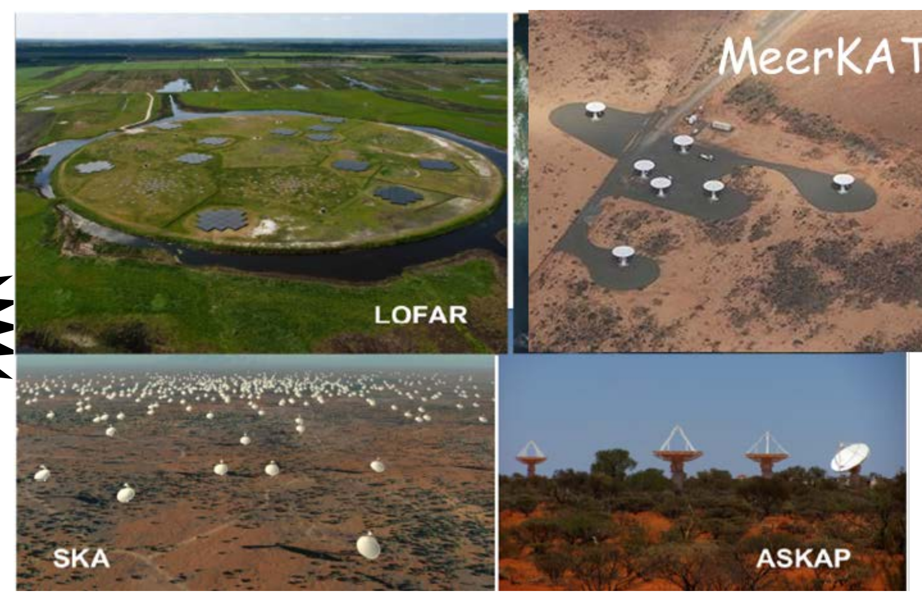
FERMI upper limits constrain the efficiency of electrons acceleration at shocks in galaxy clusters $\eta_e < 10^{-4}$

Syn spectra of Radio Halos

Brunetti et al 08 Nature 455, 944



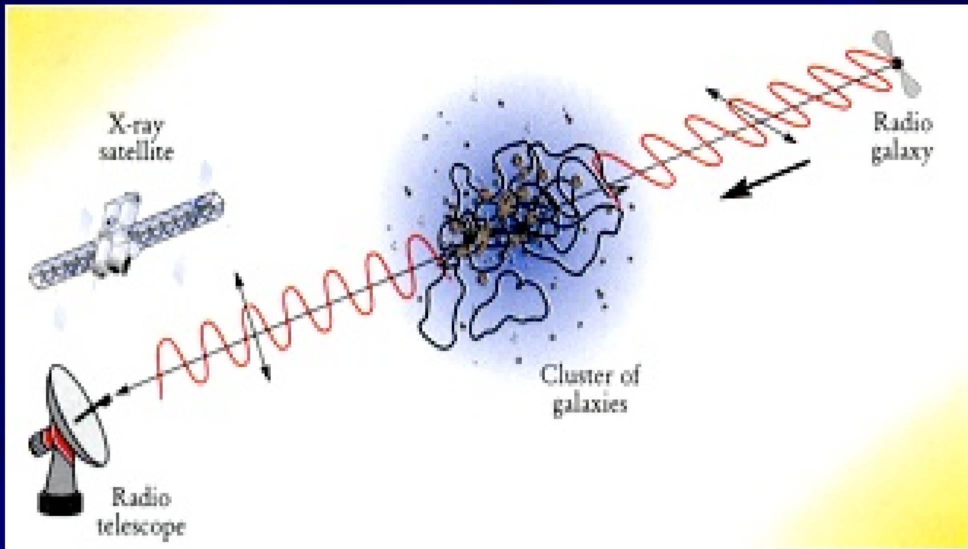




The ICM is magnetised

B ≈ few μG

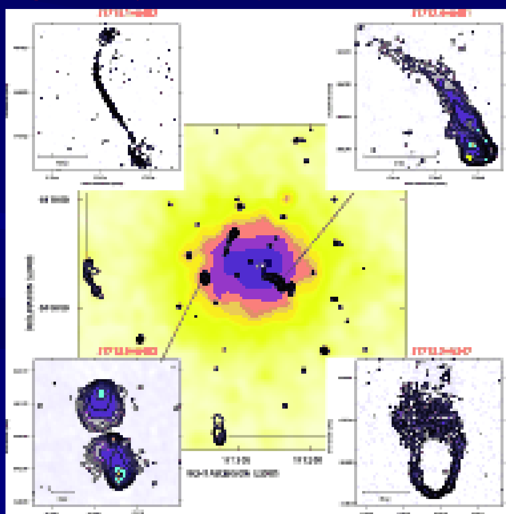
Coher. scale ≈ few-50 kpc

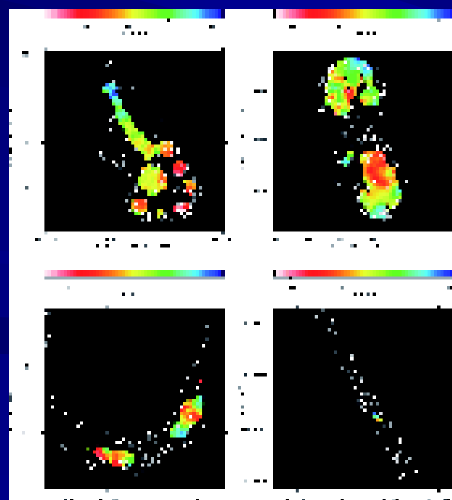


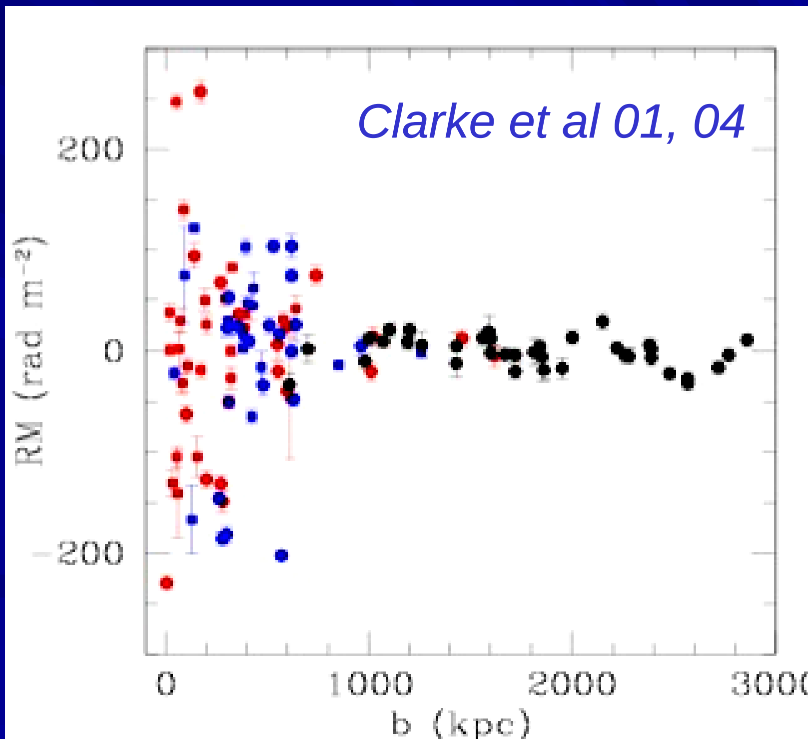
RM probe turbulent motions & mixing in the ICM (Clarke et al, Murgia et al 04, Govoni et al.10, Bonafede et al 10, Guidetti et al 11, Pizzo et al 11, Vacca et al 12 ..)

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

Govoni et 05







(impact parameter)

CR+B : important not only for NT-physics ....

Thermal conduction, kin. Viscosity, "collisionality" in the ICM
(Schekochihin et al 05,08, Lazarian & Brunetti 11, Brunetti & Lazarian 11)

Diffusion and transport of metals in the ICM
(Voigt & Fabian 04, Rebusco et al. 05, Cho et al. 06, Vazza et al 10..)

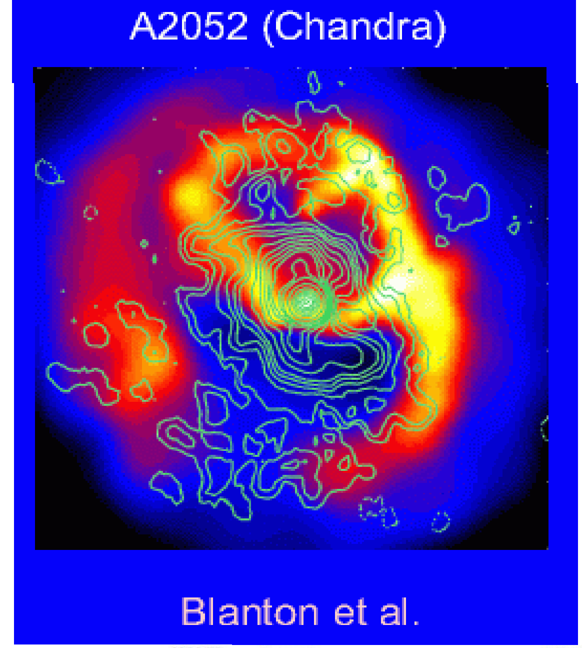
Impact on clusters dynamics, scalings and evolution
(Ryu et al 04, Colafrancesco et al., …)

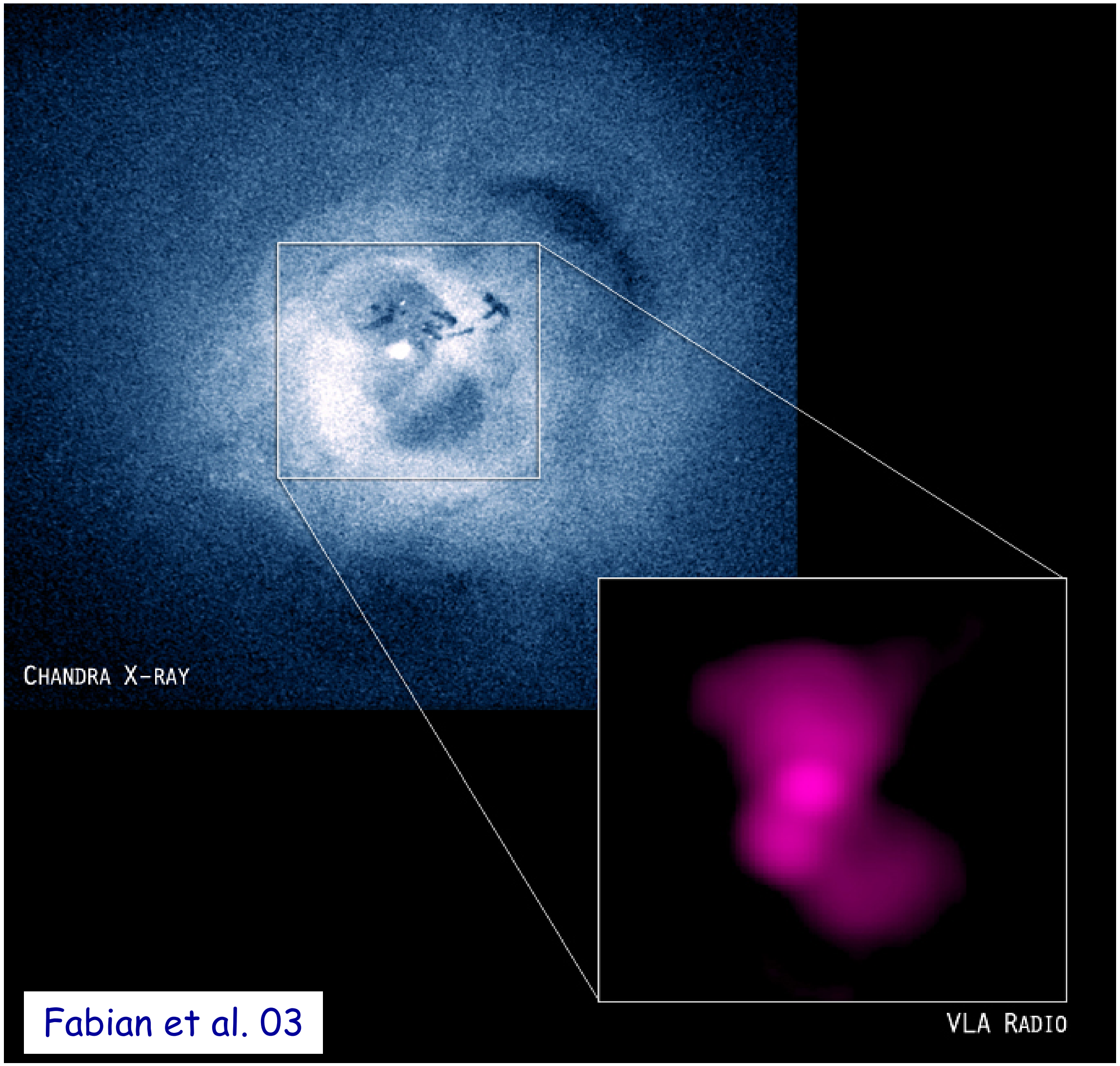
Heating of the ICM and "cooling flow" problem
(Fujita, Matsumoto, Weda 04, Guo & Oh 08, Fujita et al 11,12)

Diffusion and scattering of HE & UHECR in the Universe
(Sigl et al. 05, Dolag et al. 05, Wiener et al 13)

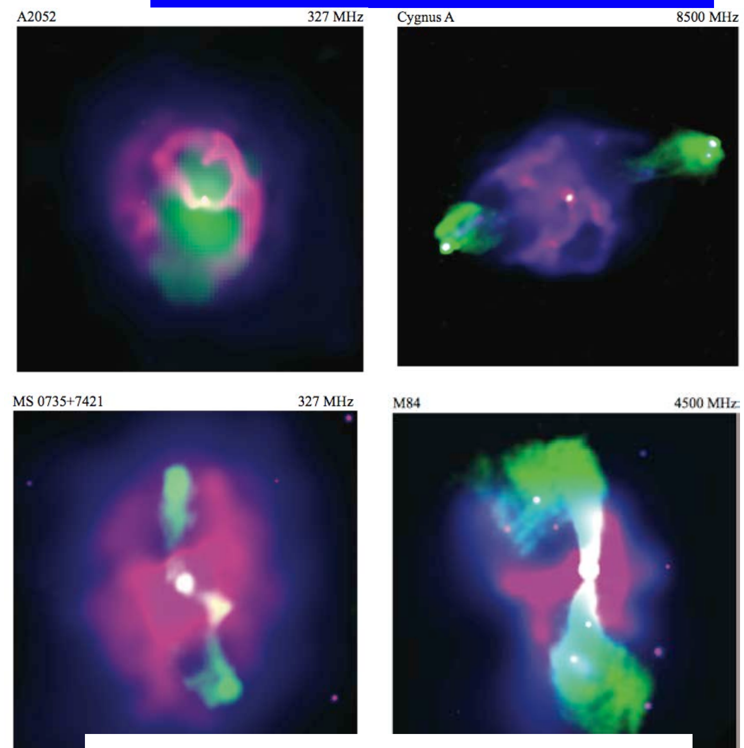
Cavities on small scales (~ 100 kpc):

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





Fabian et al. 03



Raferty et al 06, Birzan et al. 07

Cavities on small scales (~ 100 kpc):

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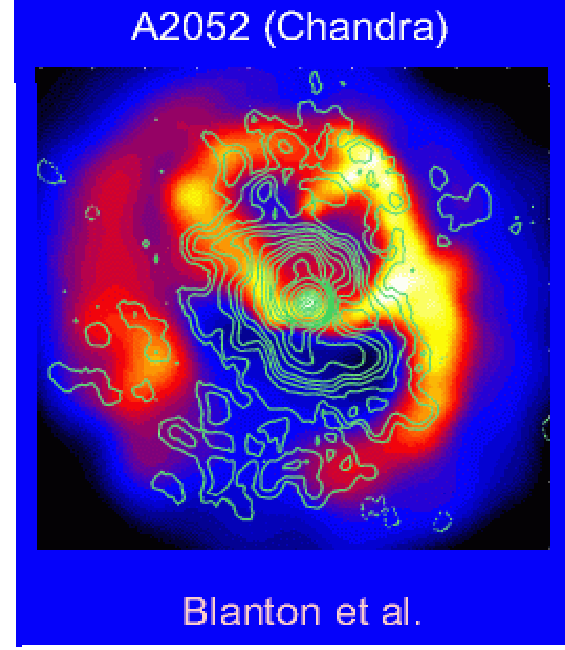
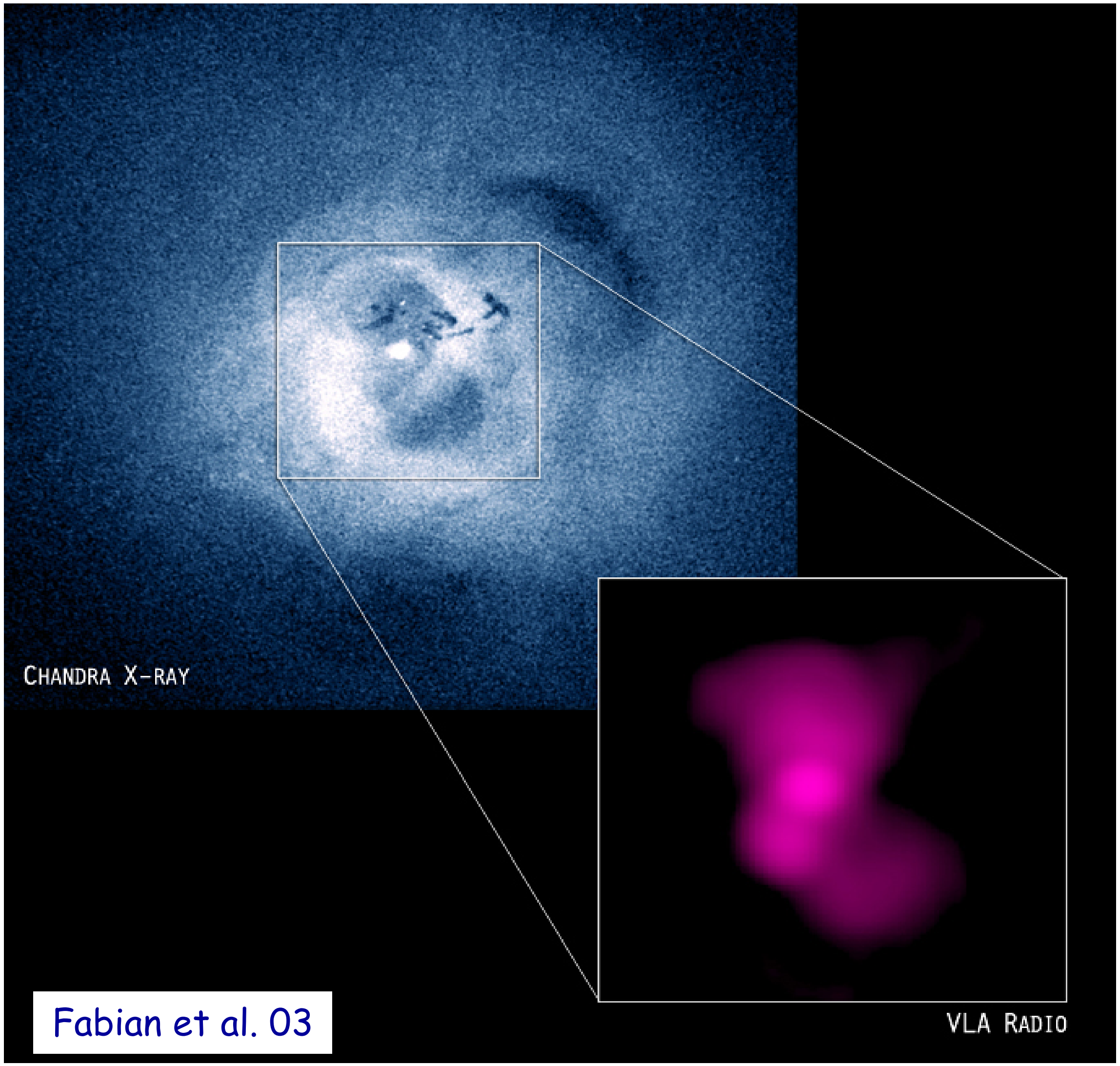




$P_{NT} \approx P_{TH}$

Estimate of number of AGNs, life-time and injection rate :

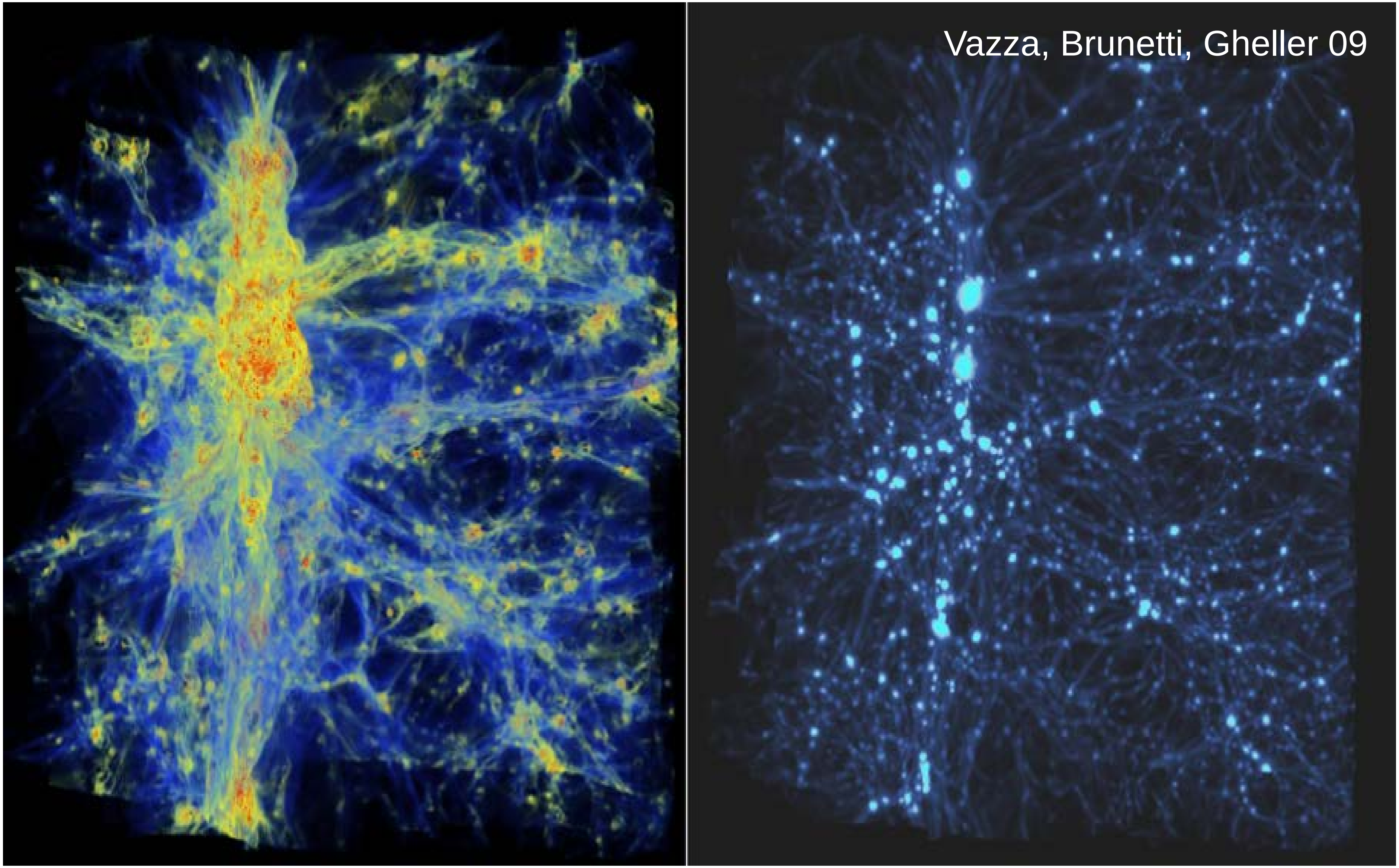
E_{CR} = 0.01- 0.1 of E_{ICM} (??)

- Thermal plasma in the bubbles
- Poynting/leptonic/hadronic

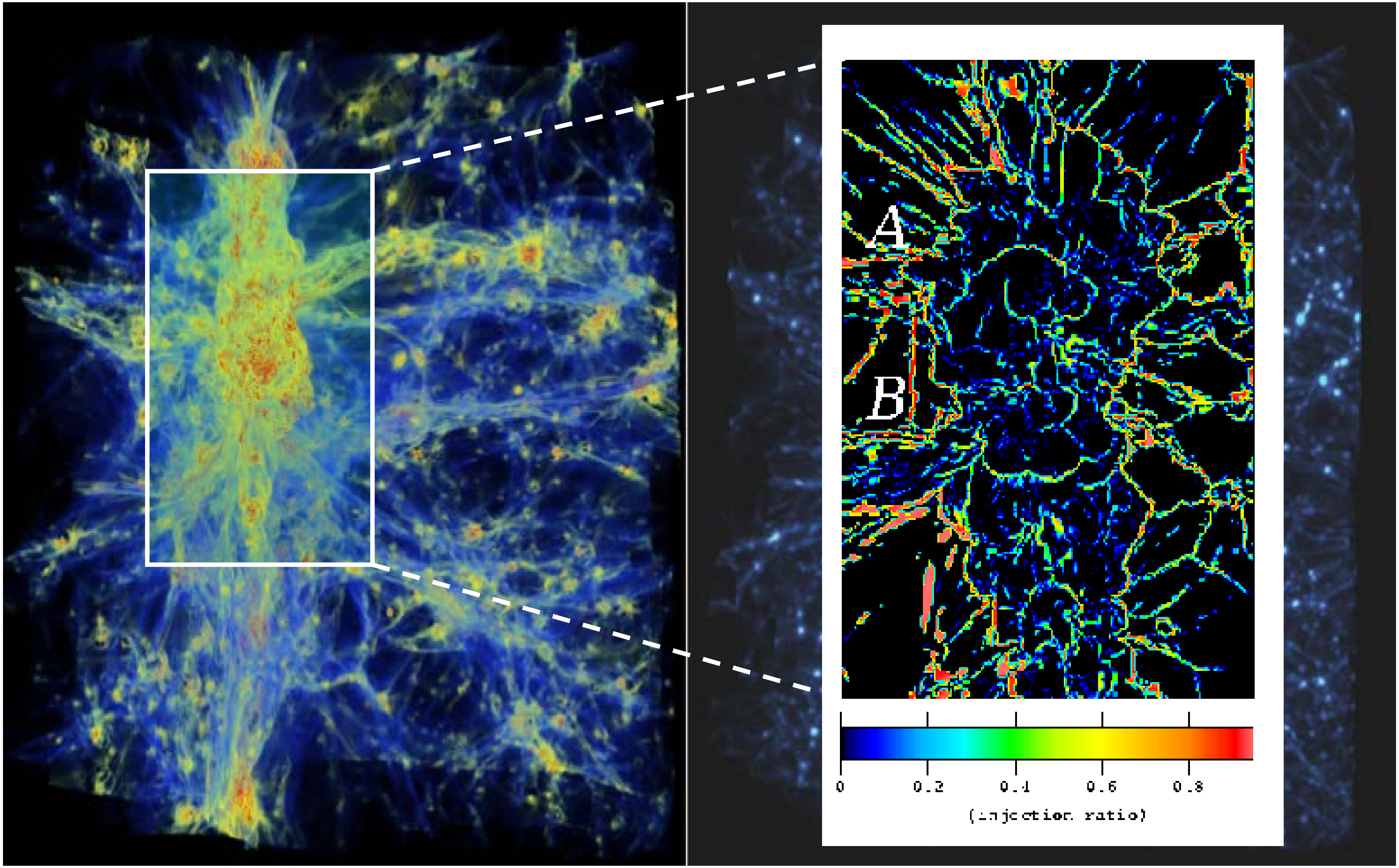
(Ensslin et al 97, ..
rev: McNamara & Nulsen 07)

Cosmological Shocks as CRs accelerators

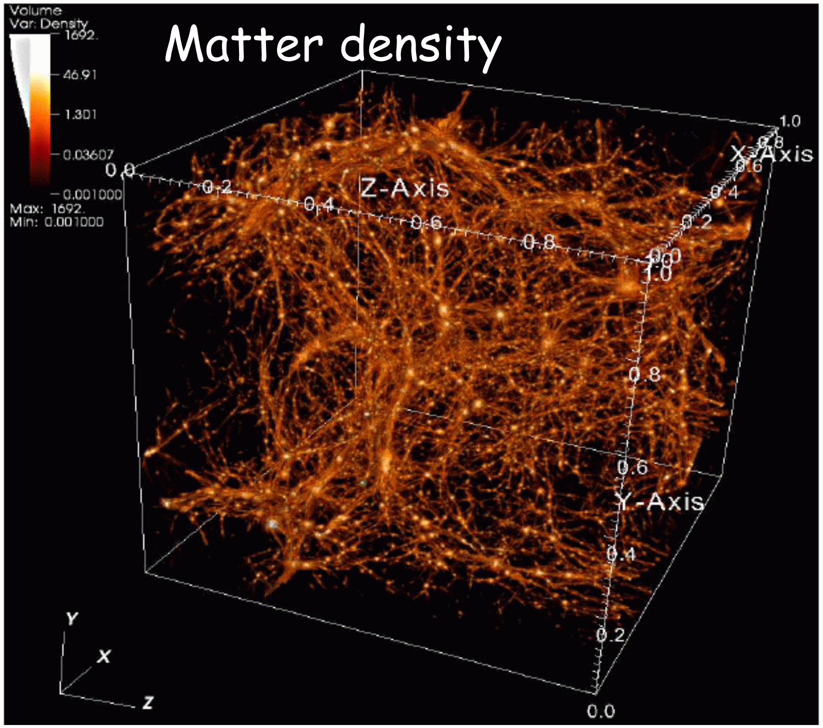
Kang et al. 96, Miniati et al. 01, Ryu et al. 03, Gabici & Blasi 03, Pfrommer et al. 06,08, Hoeft & Bruggen 07,08, Skillman 08,11,12, Vazza et al. 09, 11, 12

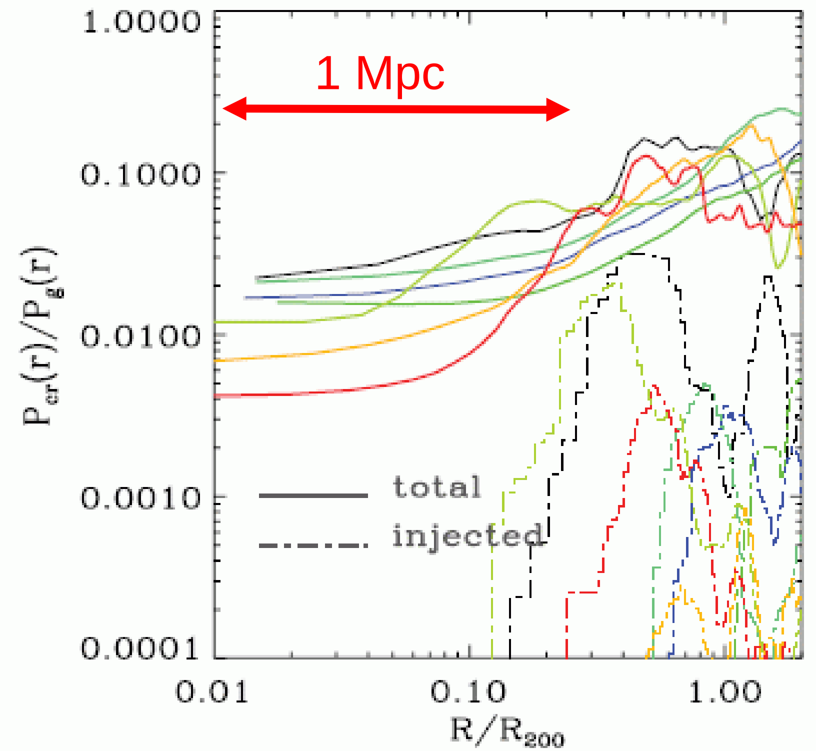


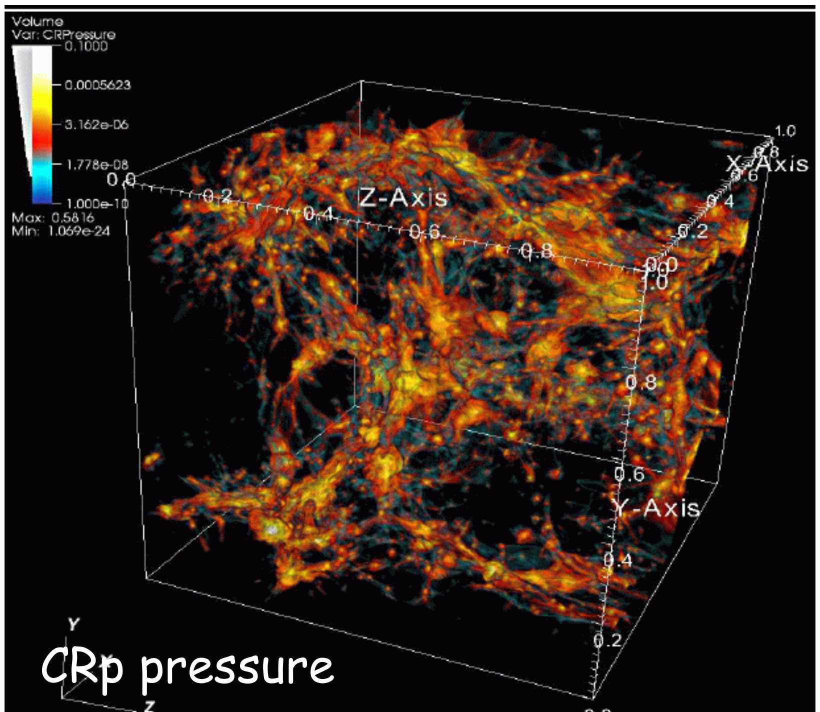
Cosmological Shocks as CRs accelerators



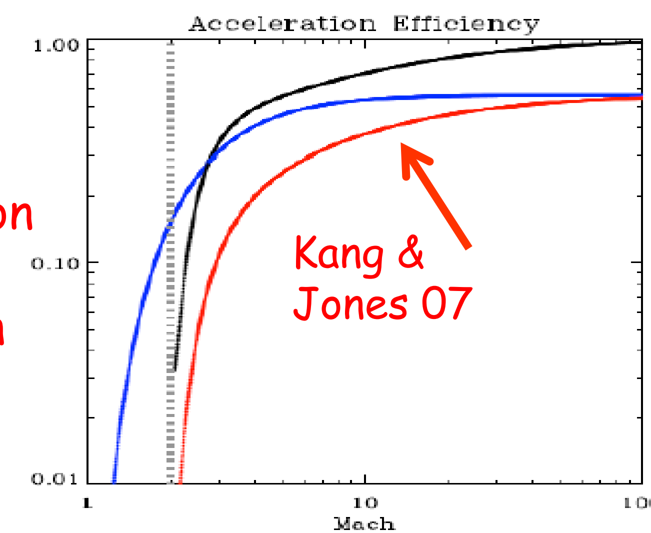
Vazza, Bruggen, Gheller, Brunetti 12





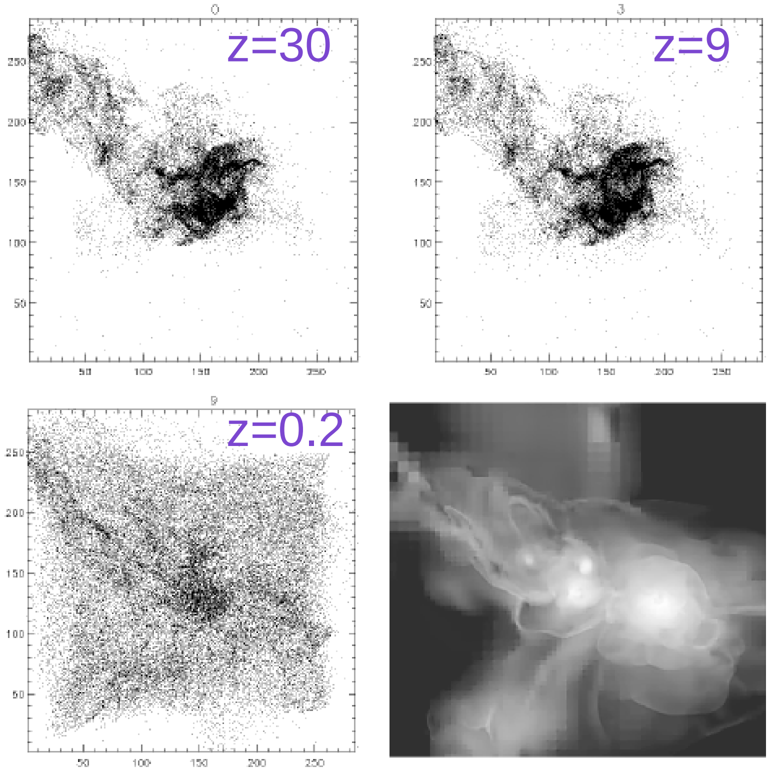


Results depend on the acceleration efficiency and on its dependence on Mach number

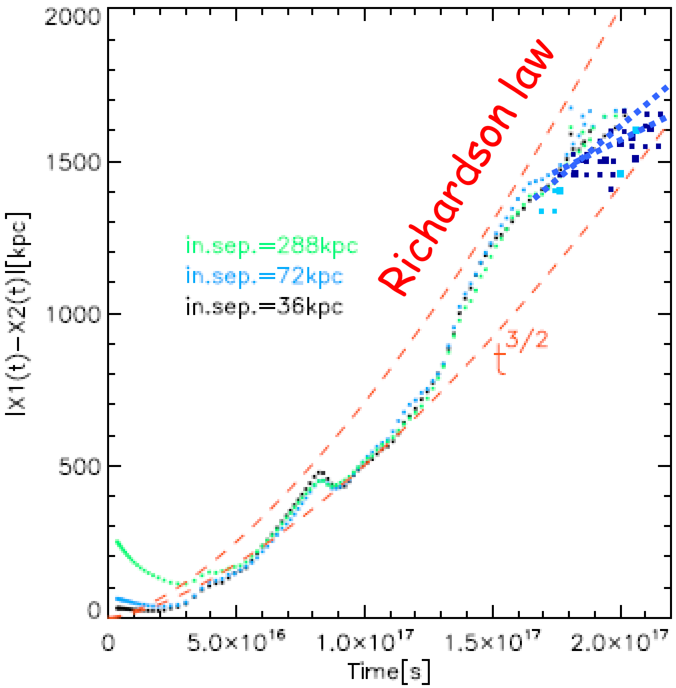


Cosmic rays confinement

In a turbulent (super-Alfvenic) ICM CRs are transported on LS by turbulent eddies.



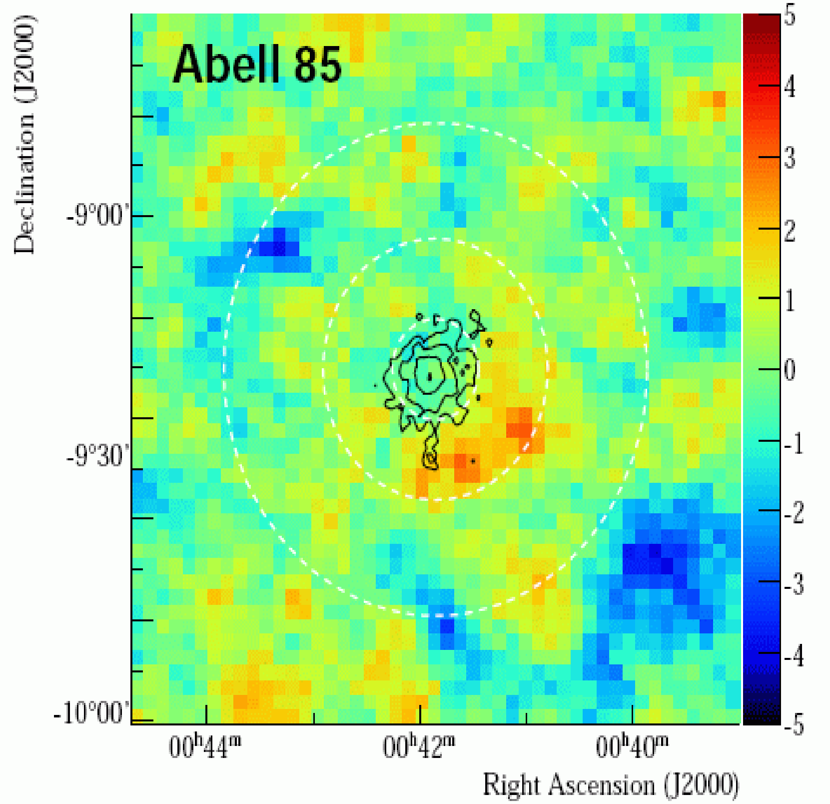
Vazza, Gheller, Brunetti 10



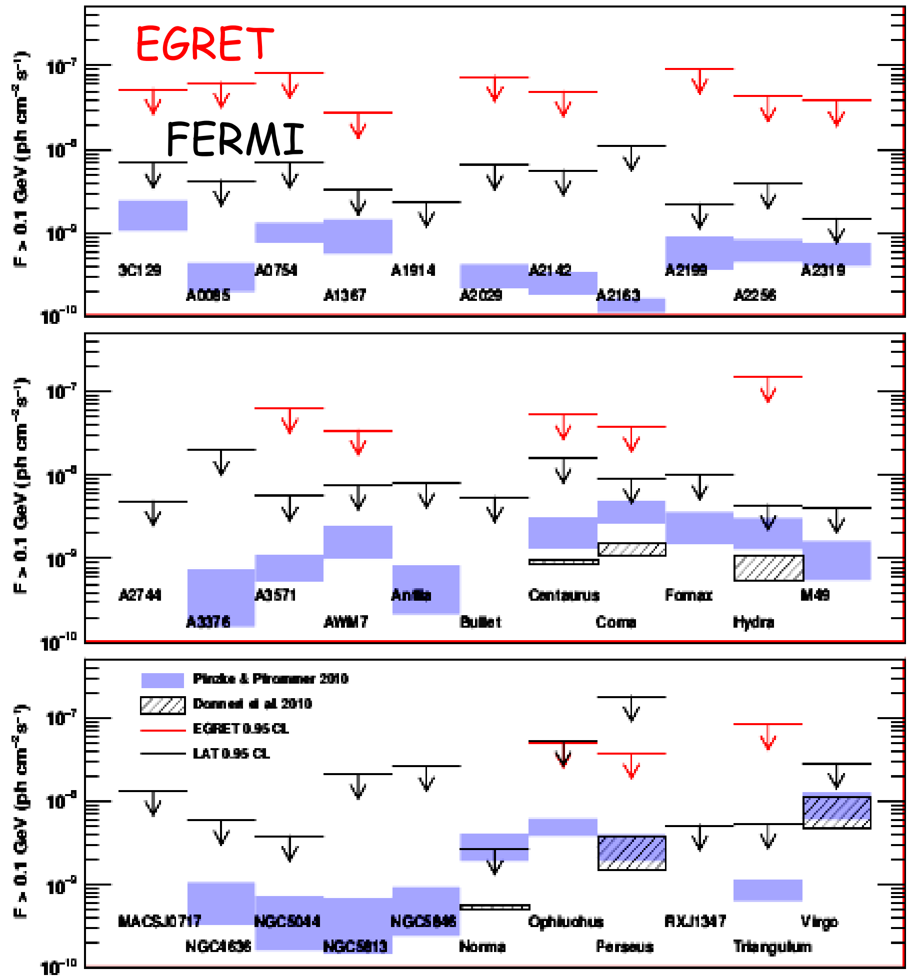
On scales smaller than the injection scale the transport is super-diffusive, $L^2 \propto \tau_{diff}^{3/2}$, and diffusive on larger scales, $L^2 = 4D\tau_{diff}$, with $D \approx L_{tur}\, V_{tur}$

Limits & CRp content

Aharonian et al. 2009



Ackermann et al 2010



H.E.S.S.

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

Coma : Ecr/Eth < 12%

VERITAS (Perkins +al. 2008)

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

MAGIC (Aleksic +al. 10, 12)

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

After 18 months of operations
FERMI-LAT u.l. imply Ecr/Eth < 5%
(assuming Ecr~Eth)

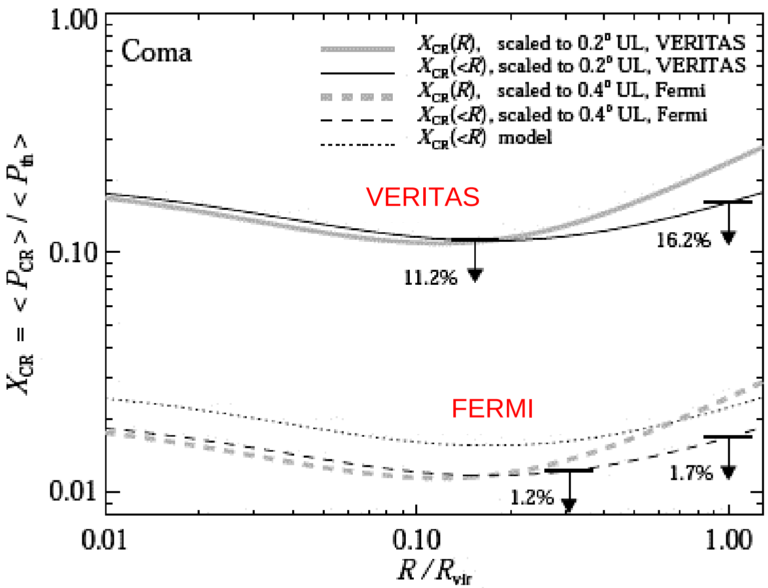
Gamma rays : energy content of CRp

Gamma ray lum from π^0 decay

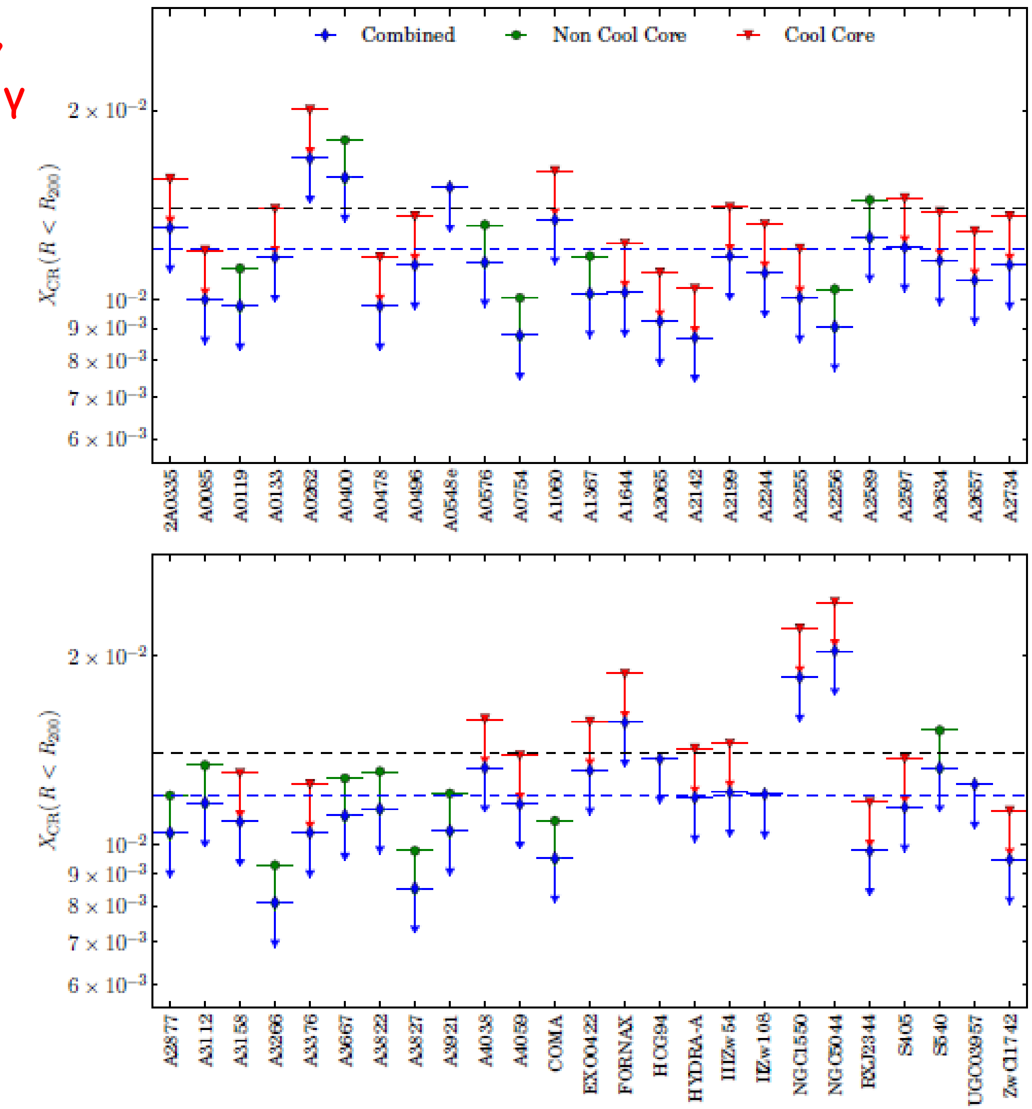
$$L_{\gamma,\pi} \sim f(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_\gamma$$

$$X_{CR} = \langle E_{CR} \rangle / \langle E_{th} \rangle$$

Arlen et al 12



Ackermann et al 13

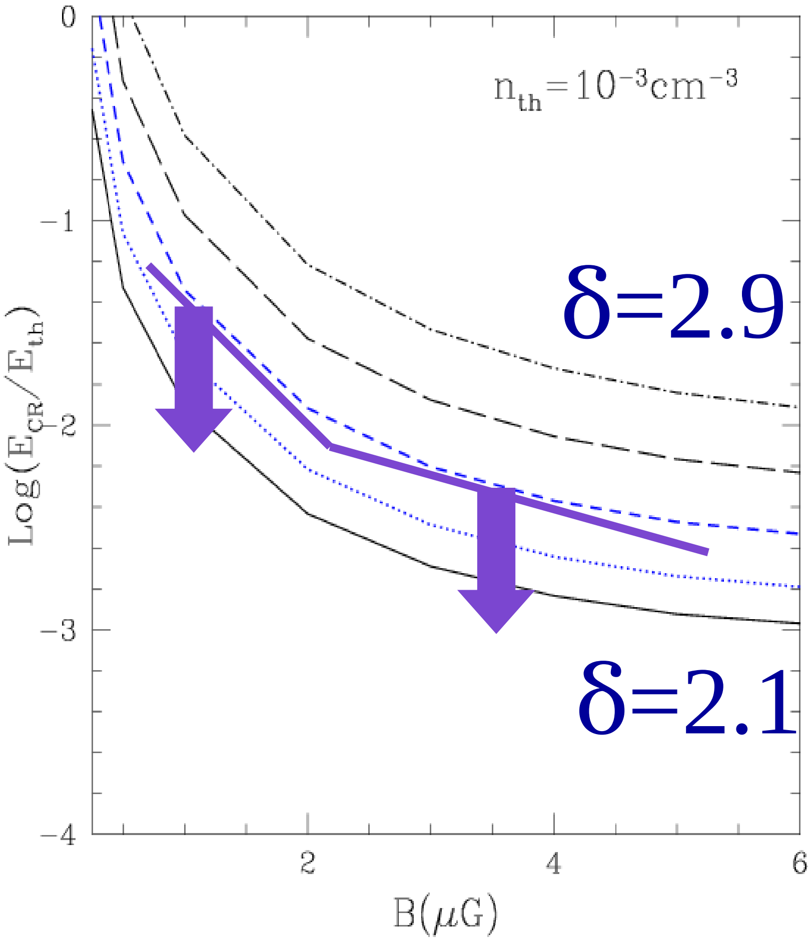


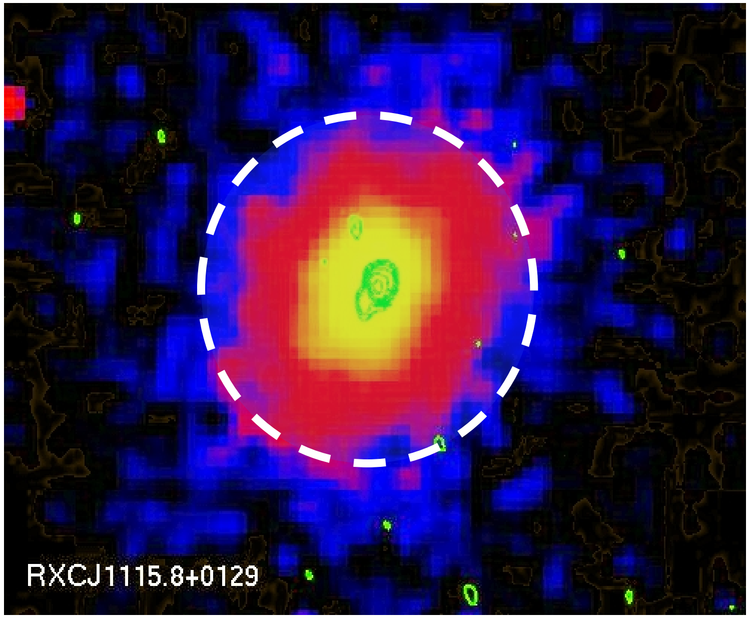
CRp: limits from Radio (Reimer et al 04, Brunetti et al. 07,08)

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

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

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





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

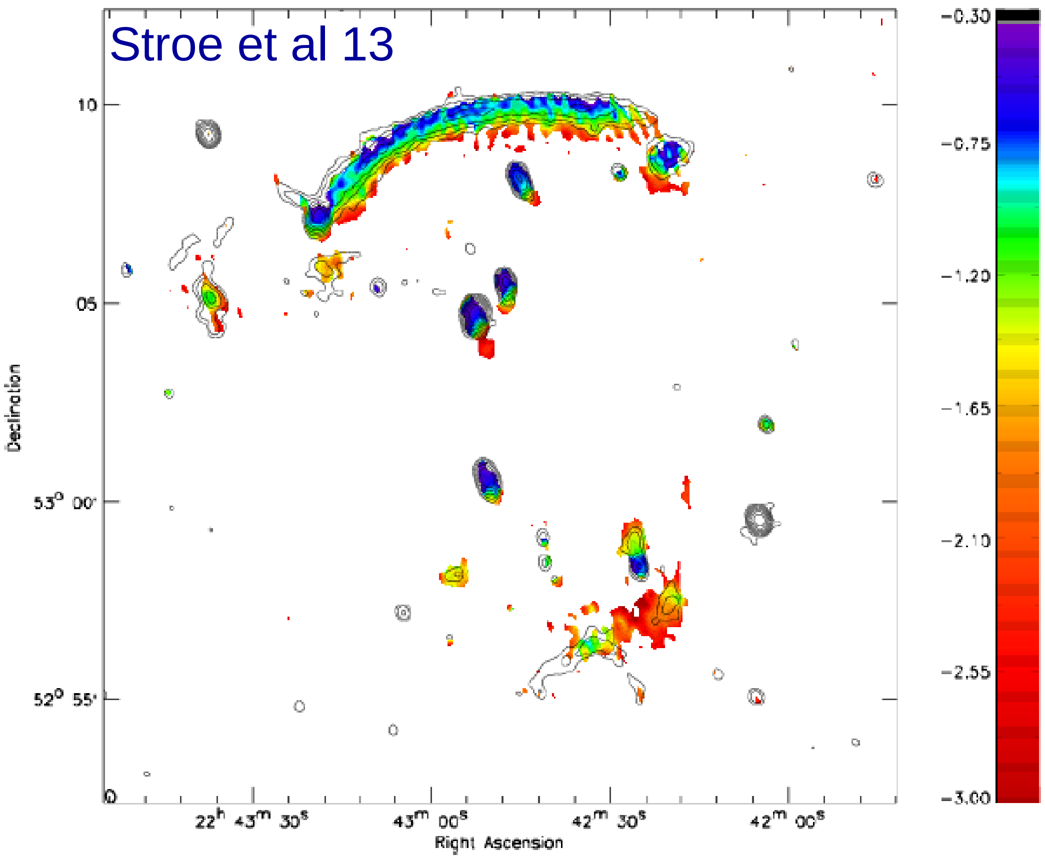
limits on : $(B\ ,\ E_{CRp})$, δ

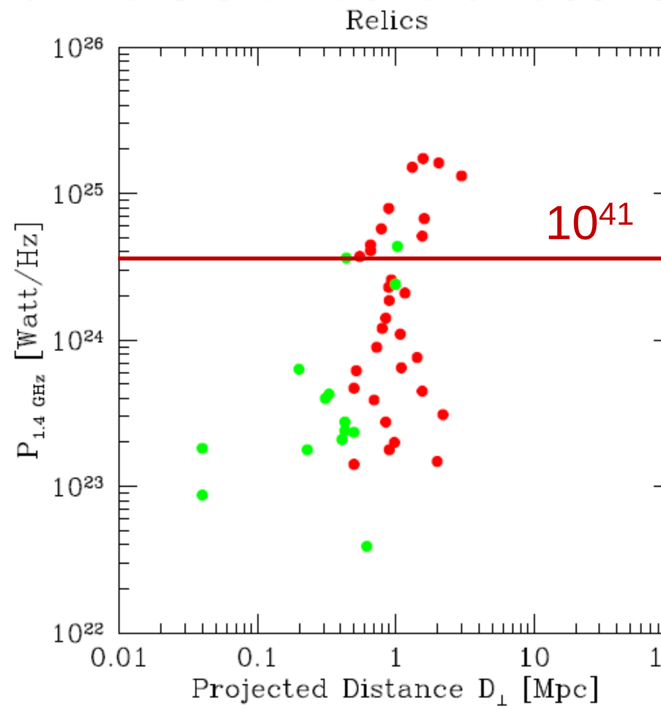
$N(p)=K\ p^{-\delta}$

Shock acceleration OR reacceleration ?

$$\nu_o L(\nu_o) \approx \frac{1}{2}\rho_u V_{sh}^3 \xi \eta_{(>\gamma_o)} S \left[1 + \left(\frac{B_{IC}}{B}\right)^2\right]^{-1}$$

$$\eta_e > 10^{-5} \left(\frac{S}{10^{48}}\right)^{-1} \left(\frac{V_{sh}}{3000}\right)^{-3} \left(\frac{n}{5/10^4}\right)^{-1} \left(\frac{\nu L(\nu)}{10^{41}}\right)$$





Feretti et al 12

$$\alpha_{inj} = \frac{1}{2}\frac{M^2+3}{M^2-1}$$

In some cases there are appreciable discrepancies between the «measured» synchrotron spectral index and that «expected» from the Mach number.

Shock acceleration OR reacceleration ?

$$\nu_o L(\nu_o) \approx \frac{1}{2}\rho_u V_{sh}^3 \xi \eta_{(>\nu_o)} S \left[1 + \left(\frac{B_{IC}}{B}\right)^2\right]^{-1}$$

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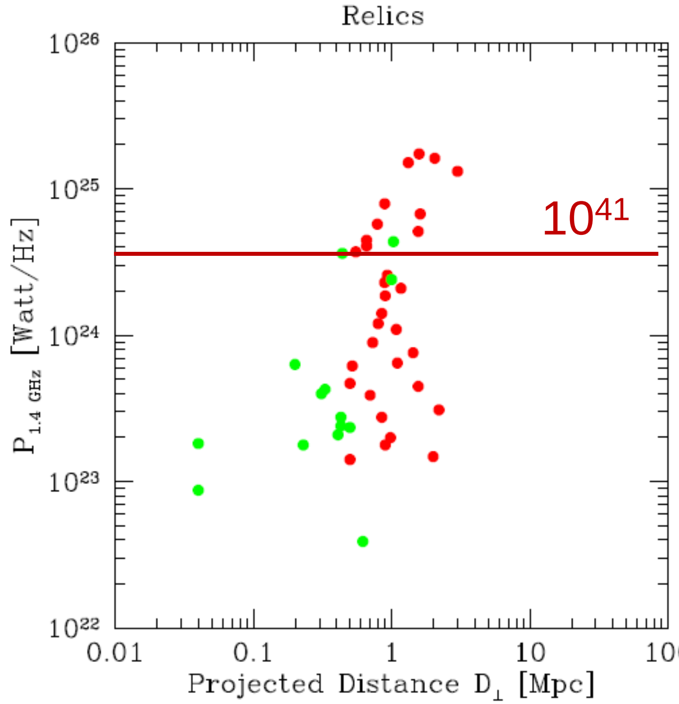
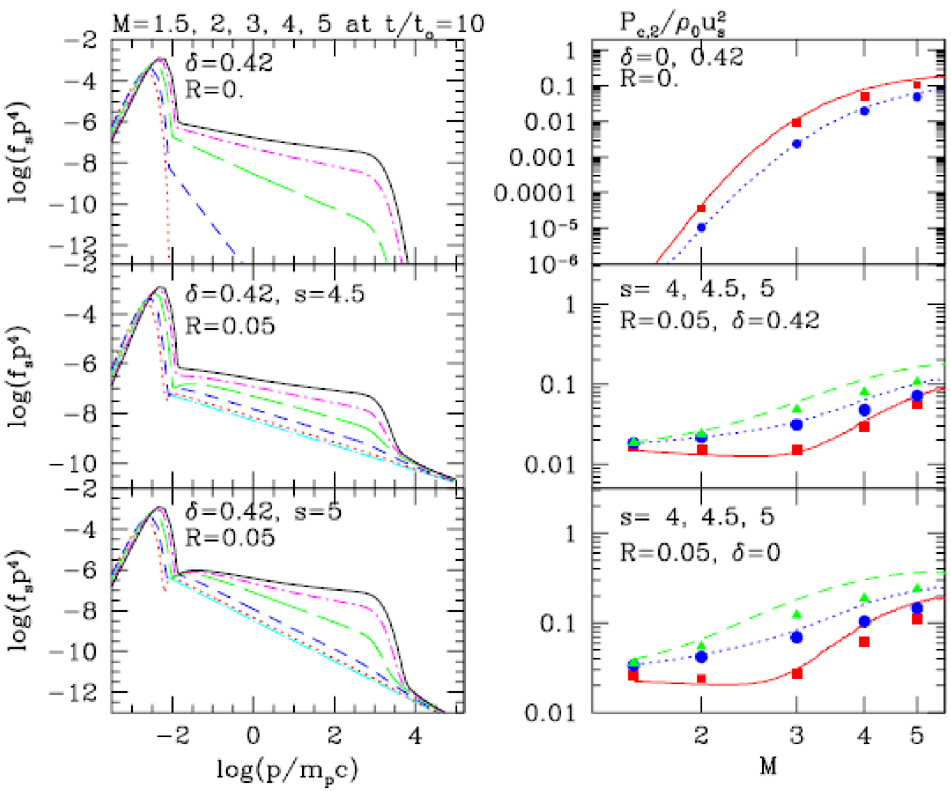




Kang & Ryu 11

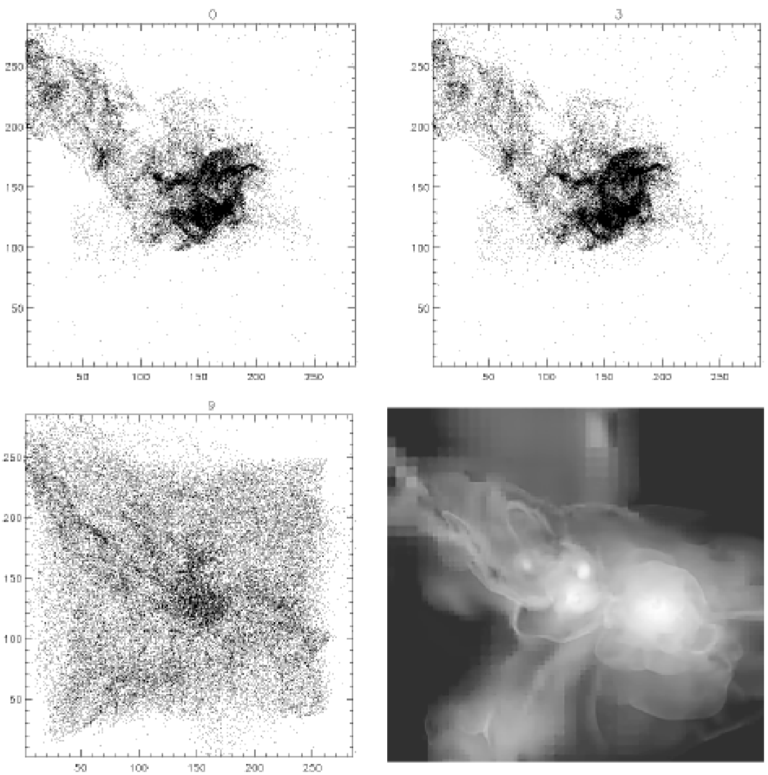
$$\alpha_{inj} = \frac{1}{2}\frac{M^2+3}{M^2-1}$$

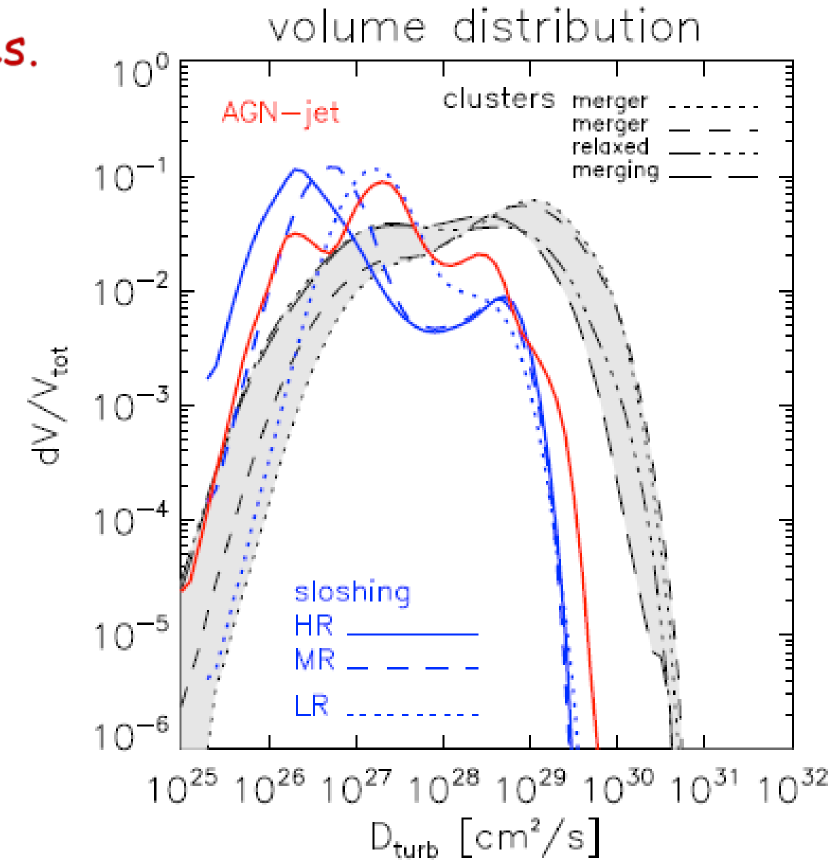
In some cases there are appreciable discrepancies between the «measured» synchrotron spectral index and that «expected» from the Mach number.

Ensslin & Gopal-Krishna 01, Markevitch et al 05, Macario et al 11, Kang et al 11,12, Pinzke & Pfrommer 13

Cosmic rays confinement

In a turbulent (super-Alfvenic) ICM CRs are transported on LS by turbulent eddies.



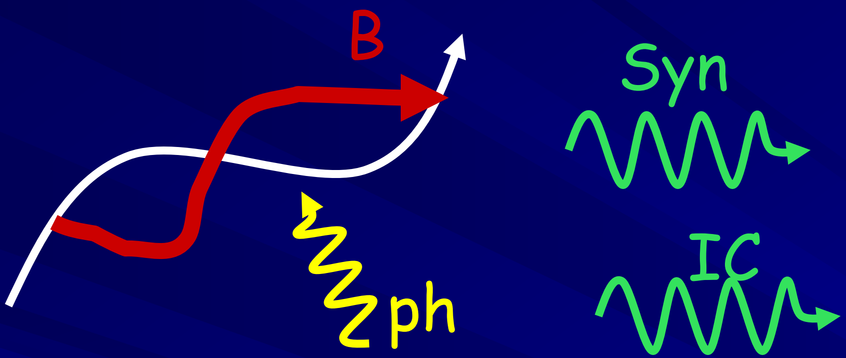


On scales smaller than the injection scale the transport is super-diffusive, $L^2 \propto \tau_{diff}^{3/2}$, and diffusive on larger scales, $L^2 = 4D\tau_{diff}$, with $D \approx L_{tur} V_{tur}$

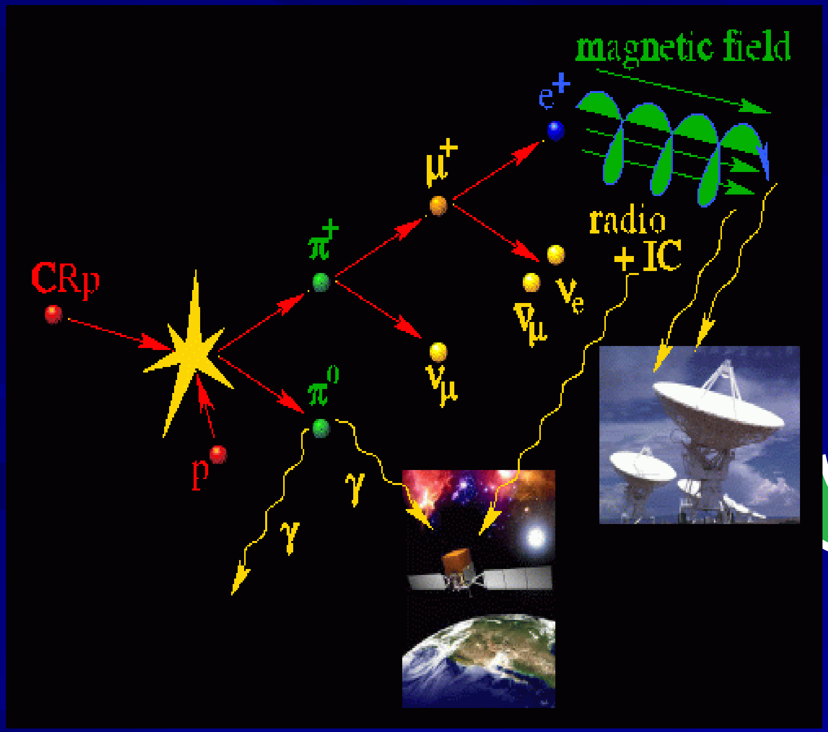
$$D \ll 10^{32} cm^2/s$$

Radiation from Cosmic Rays in GC

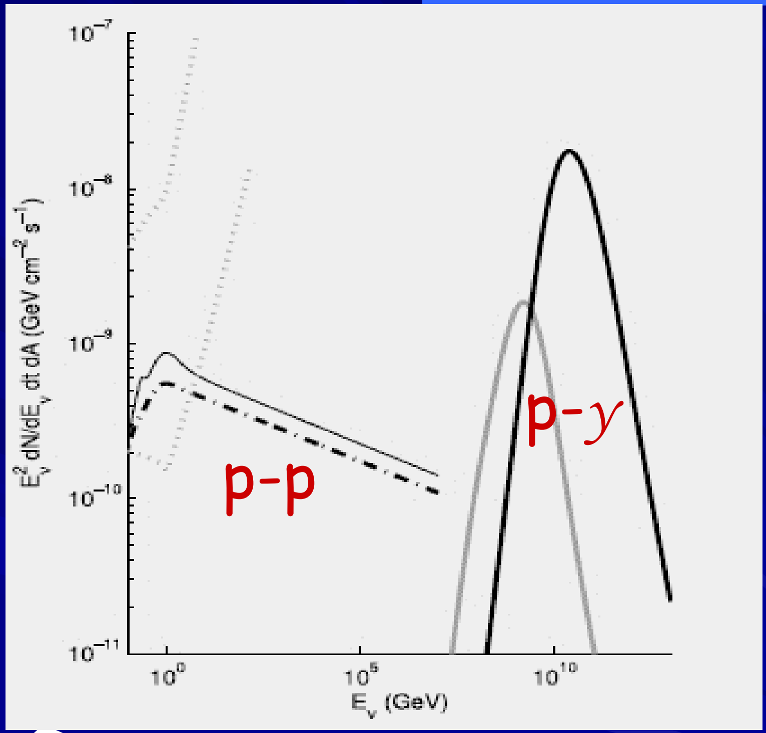
CRe



CRp

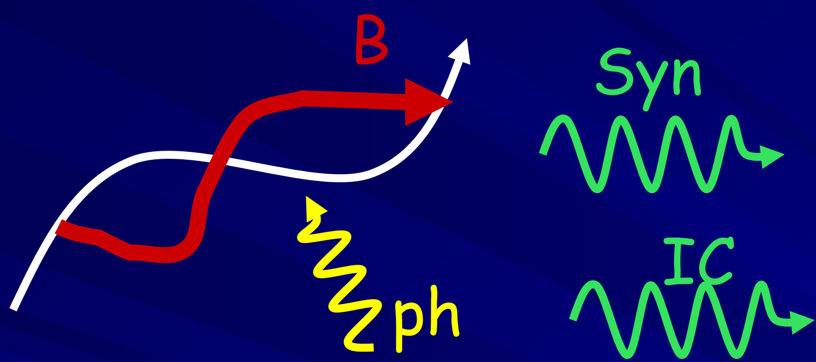


Wolfe +al 2008

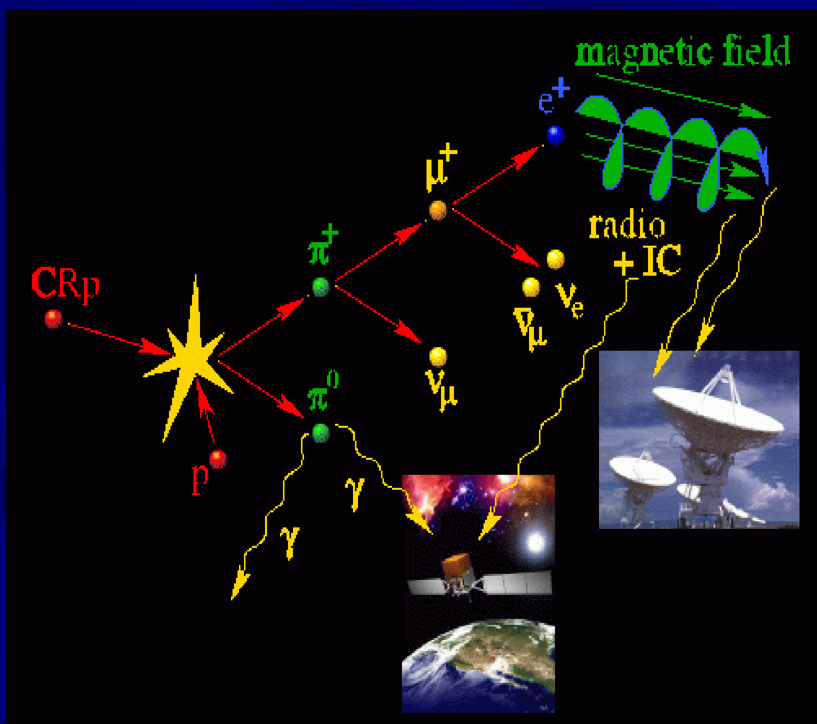


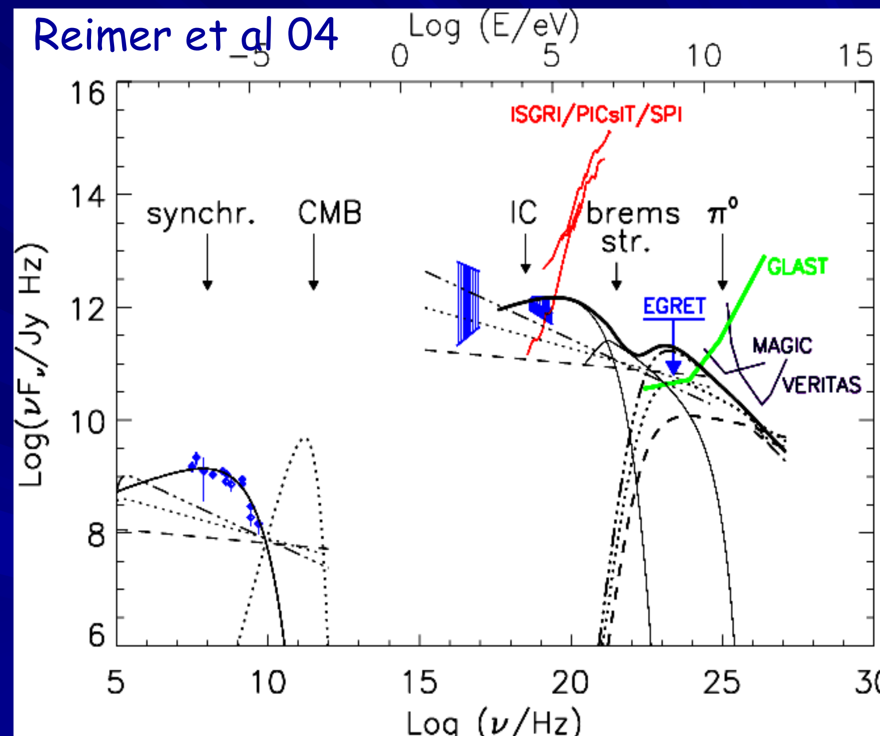
High energy emission from GC

CRe



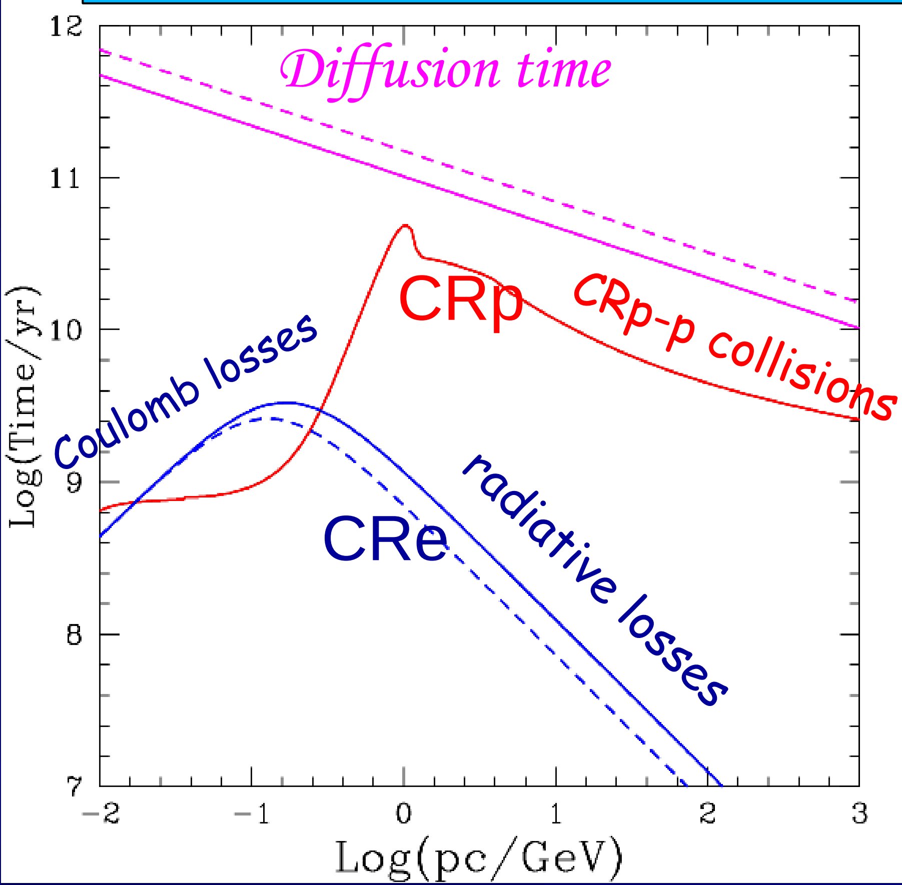
CRp





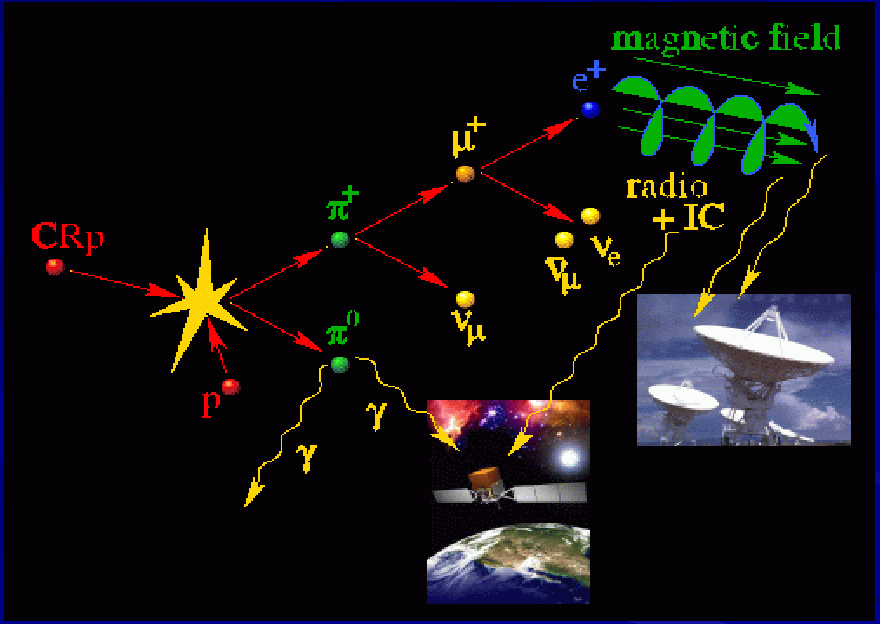
Cosmic rays confinement

review: Blasi, Gabici, Brunetti 07



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

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

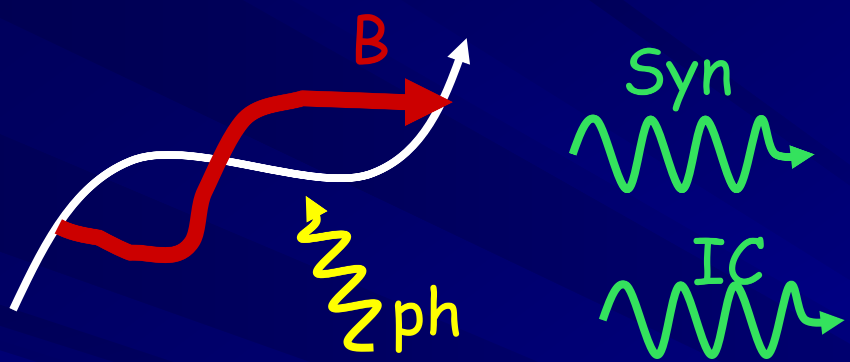


Voelk et al. 96, Berezinsky et al 97, Ensslin et al 97, Sarazin 99, …

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

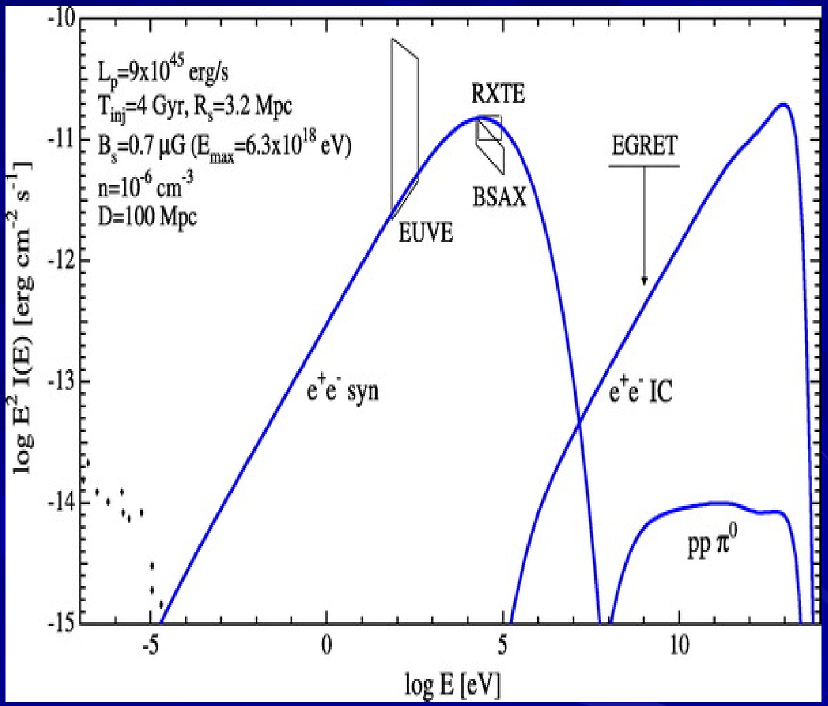
Radiation from Cosmic Rays in GC

CRe

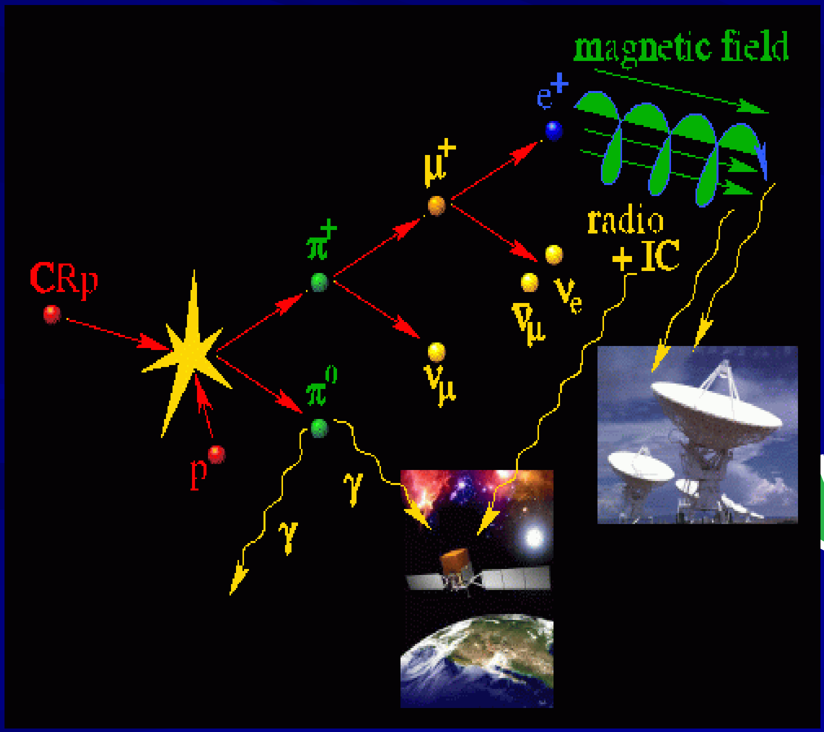


UHEp-γ

Inoue et al 05

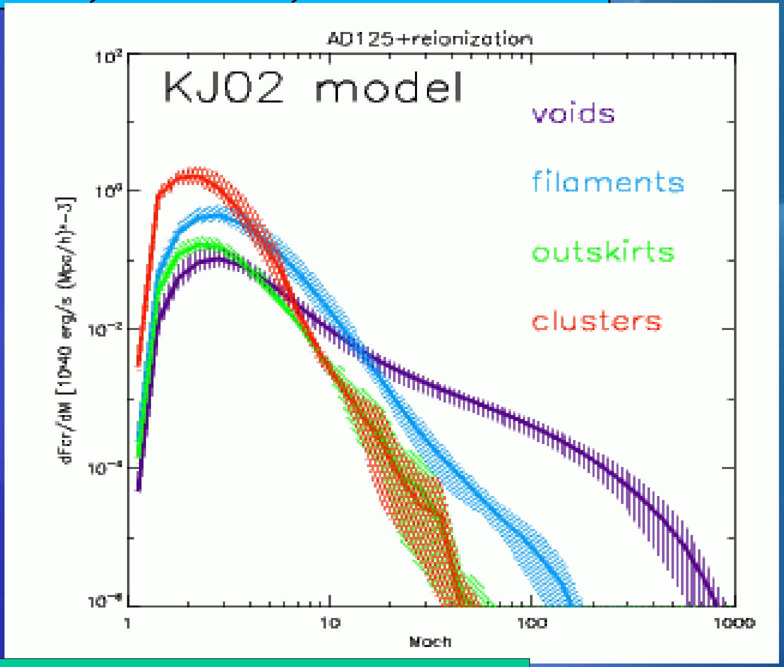


CRp



Shocks Mach numbers in galaxy clusters

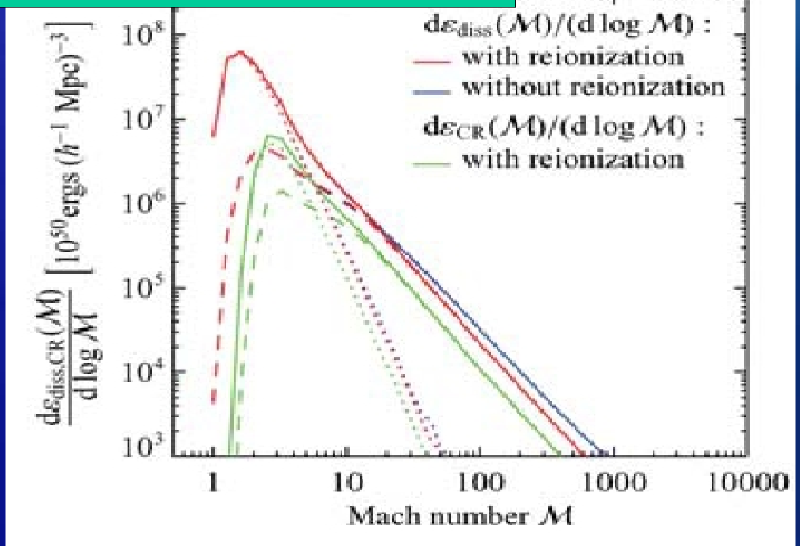
Vazza, Brunetti, Gheller 2009

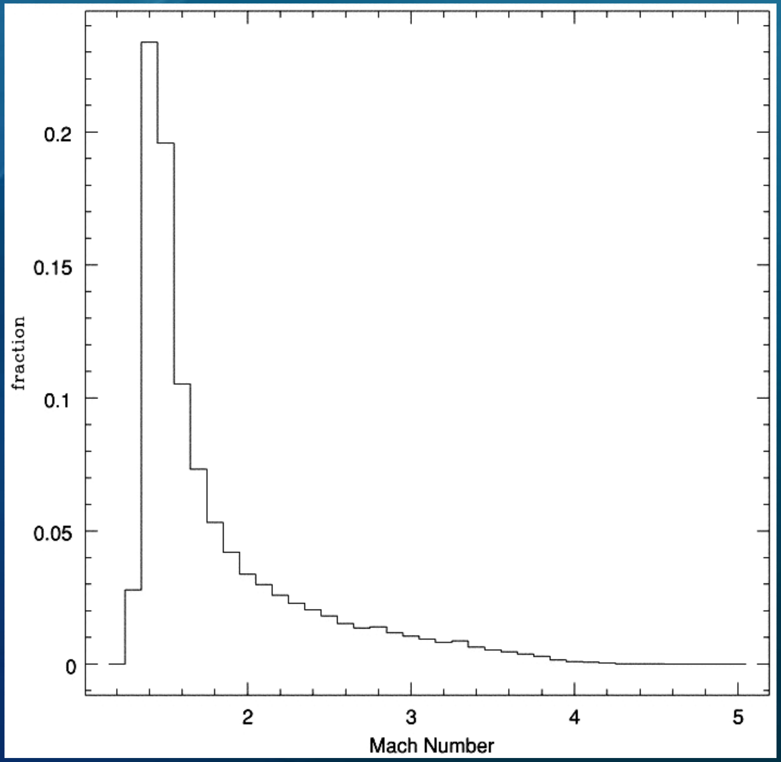


Semi-analytics :
Gabici & Blasi 2003
Berrington & Dermer 2003

some agreement…

Pfrommer et al. 2008

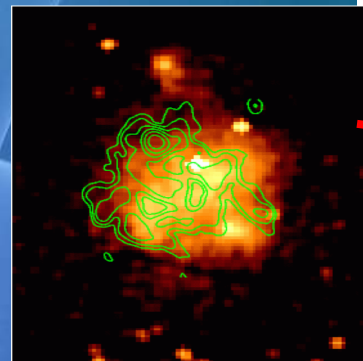


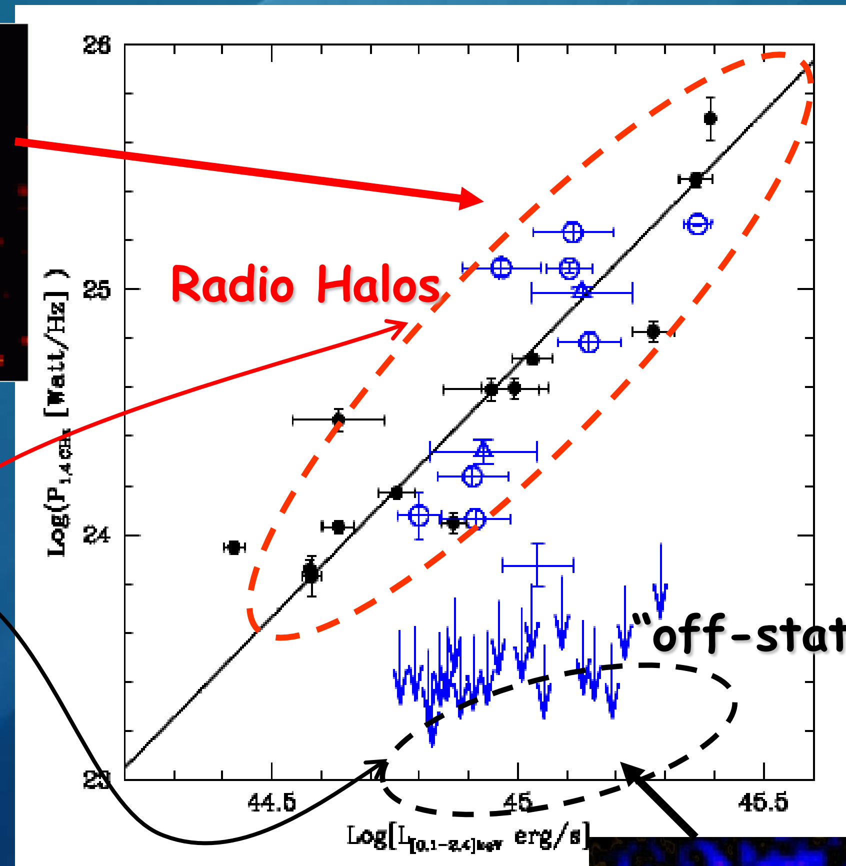


Cluster mergers – NT connection

Venturi et al 08, Brown et al 11
Rossetti et al 11, Basu 12

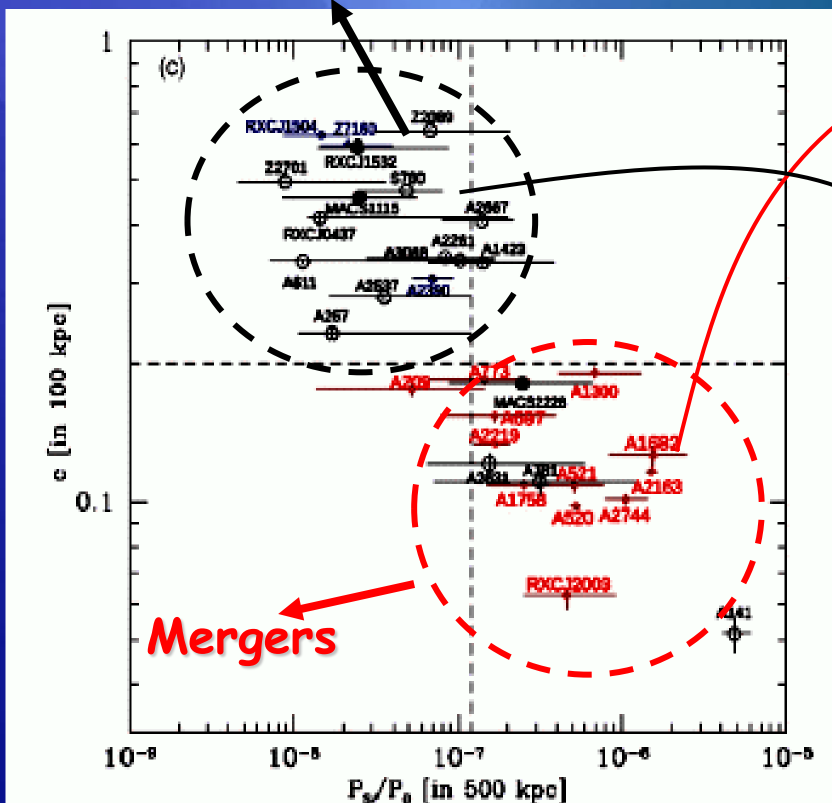
Radio halos probe the dissipation of kin energy in the DM-driven merger events into CRs and B





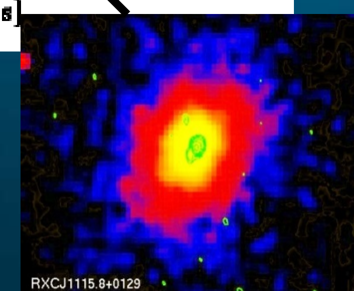
Brunetti et al 09

Relaxed

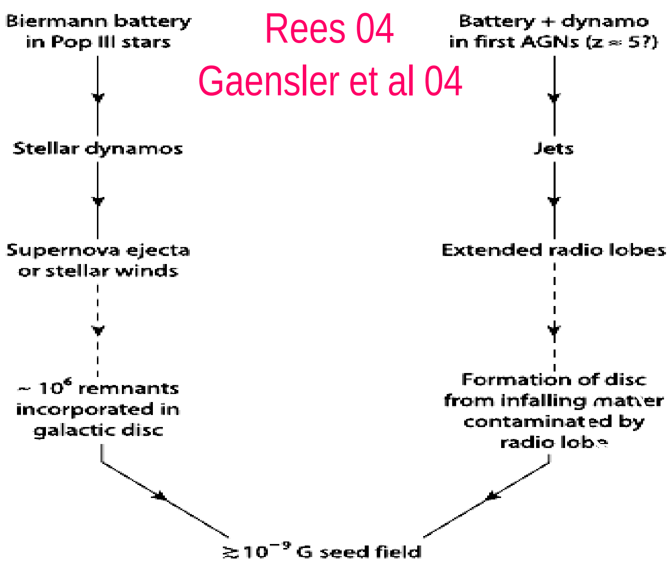


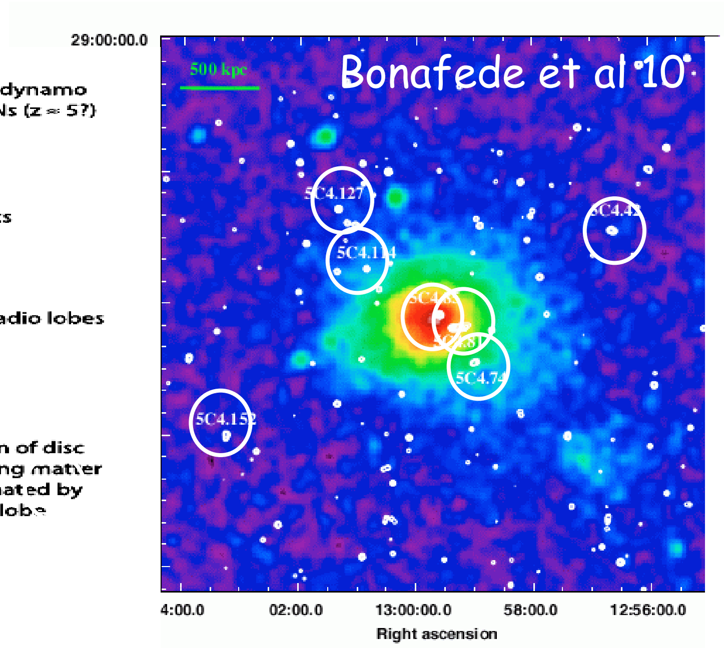
Cassano et al 10

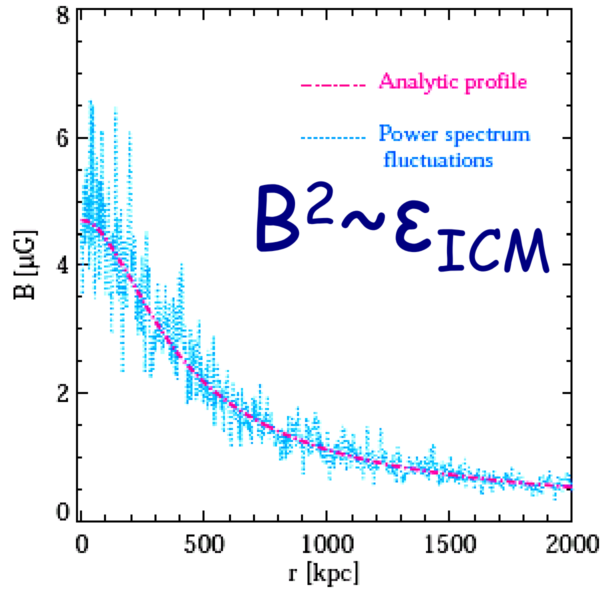
Mergers accelerate CRe and/or amplify B
Brunetti 07, 09
Kushnir et al 09
Ensslin et al 11
Wiener et al 13

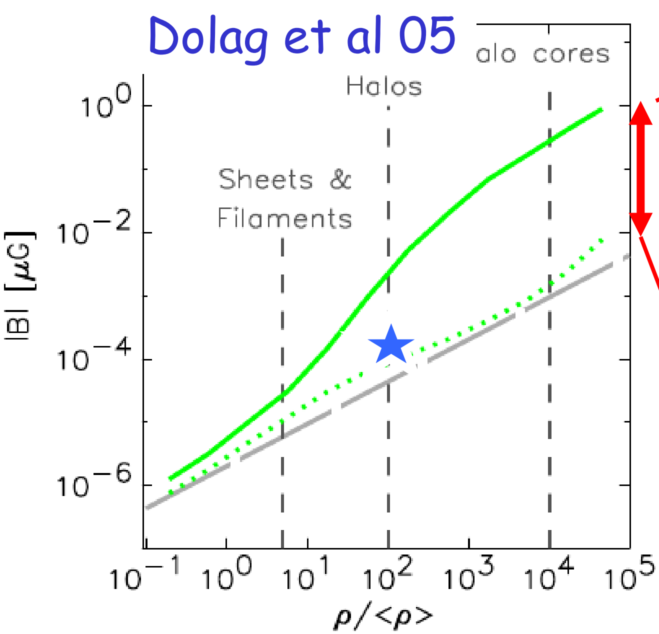


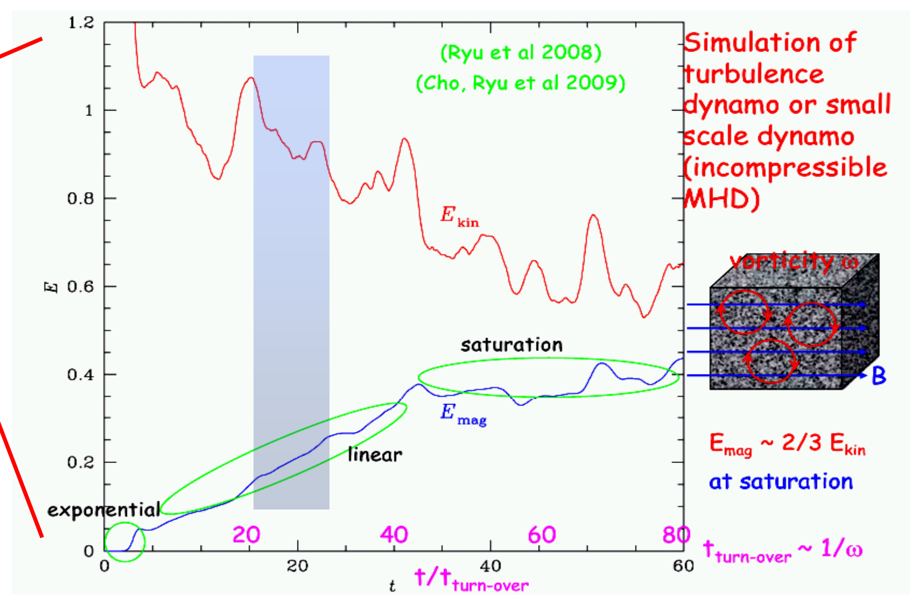
Origin of magnetic fields in galaxy clusters











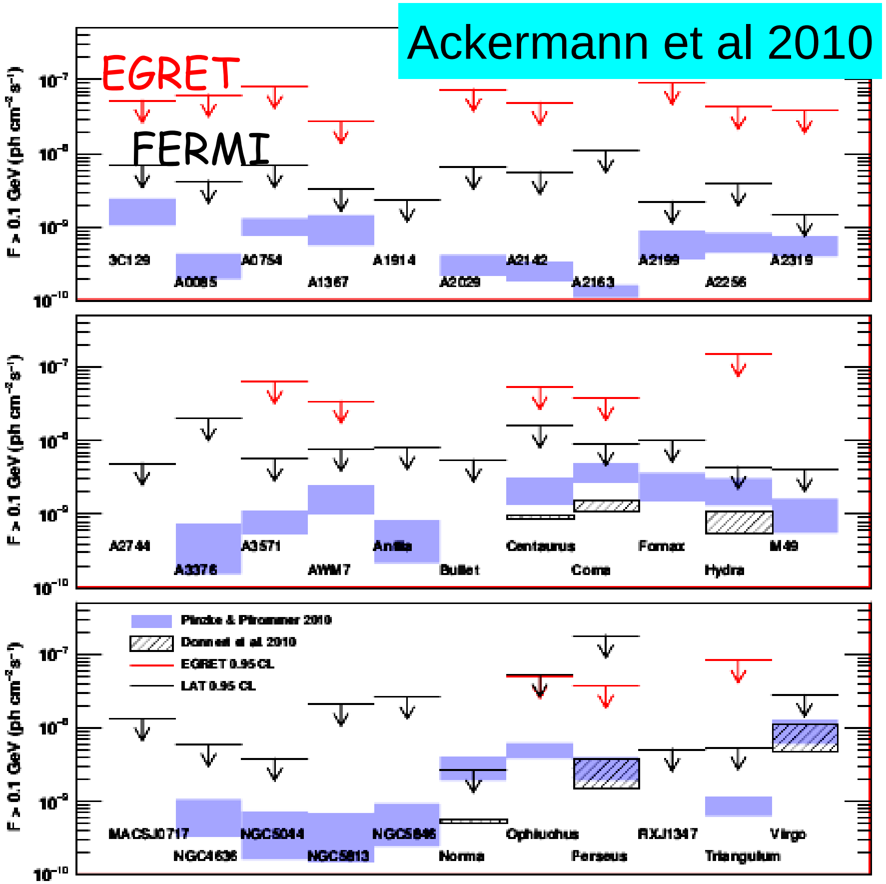
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

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

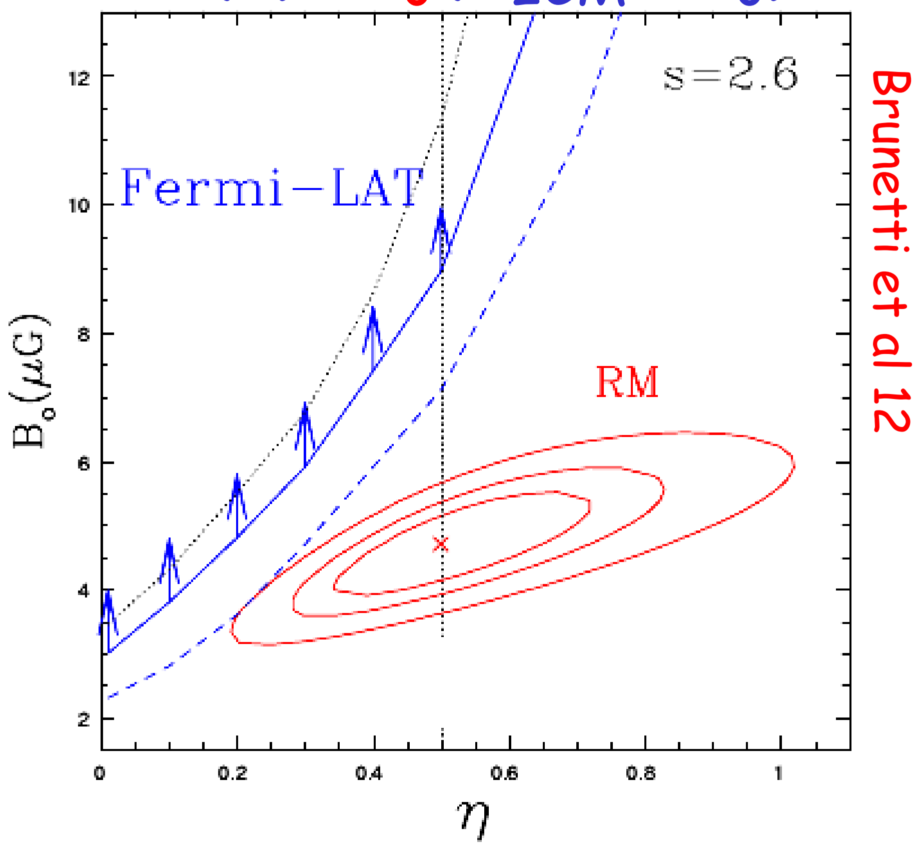
$$\pi^\pm \rightarrow \mu + \nu_\mu \quad \mu^\pm \rightarrow e^\pm \nu_\mu \nu_e .$$

The non detection of gamma-rays from galaxy clusters a allows us to constrain the role played by secondary particles for the non-thermal emission from galaxy clusters

Secondaries cannot play an important role if we assume clusters magnetic fields derived from Faraday Rotation Measures (Jeltema & Profumo 11, .. Brunetti et al 12).

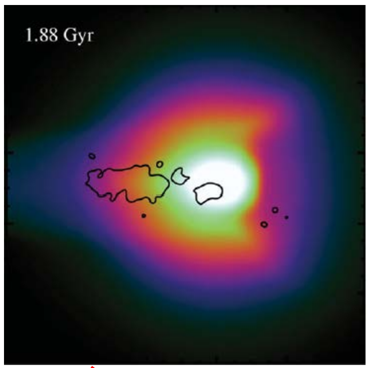


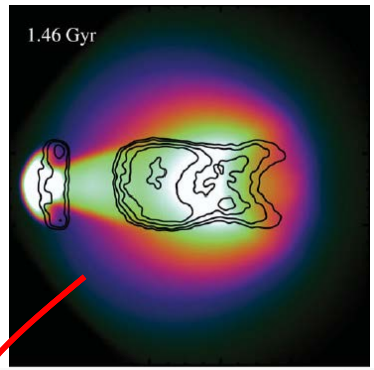
$$B(r) = B_o(\varepsilon_{ICM} / \varepsilon_o)^n$$



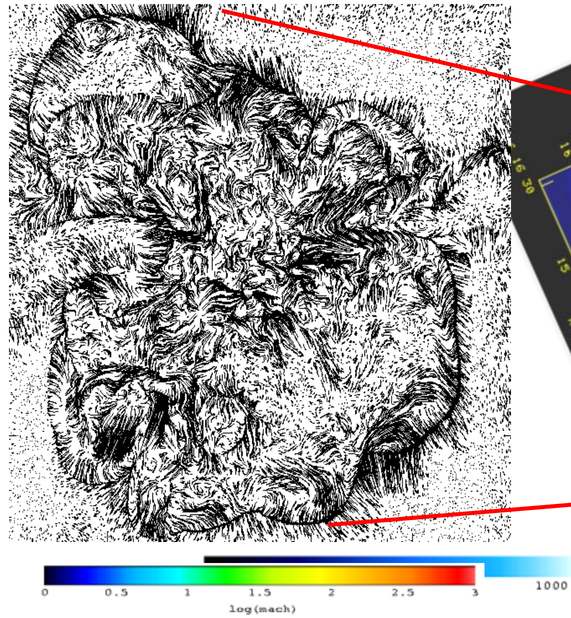
Radio Halos as tracers of turbulent regions in galaxy clueters

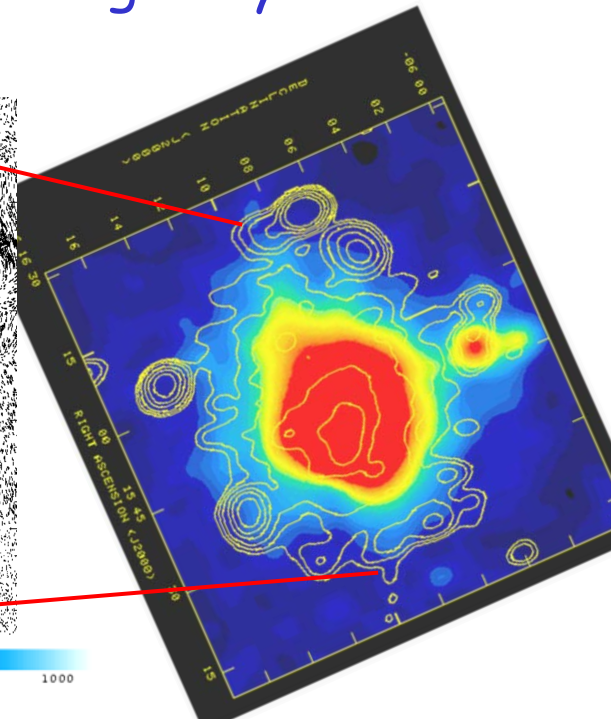
(Brunetti et al. 01, 04, Petrosian 01, Liang et al 02, Kuo et al 02, Fujita et al. 03, Cassano & Brunetti 05, Brunetti & Lazarian 07,11, ZuHone et al 12, Donnert et al 13, Beresnyak et al 13)

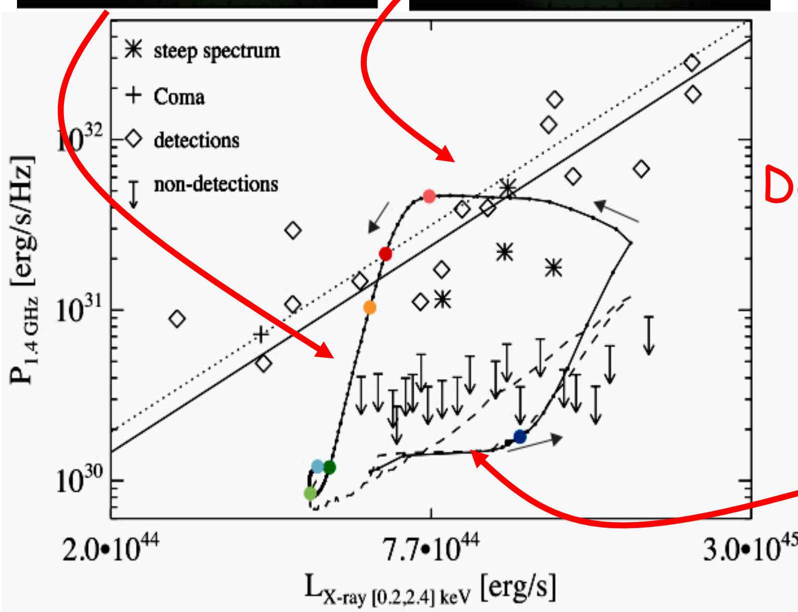




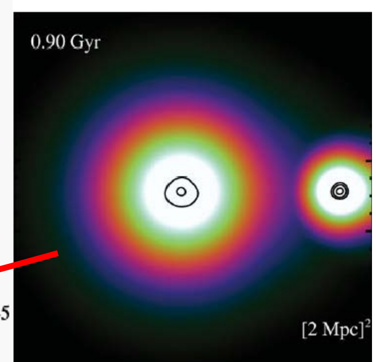
Turbulence/Shocks







Donnert et al 13



Turbulence plays a role for the spatial diffusion of CRs, for their (re)acceleration and for the amplification (and reconnection!) of magnetic fields.

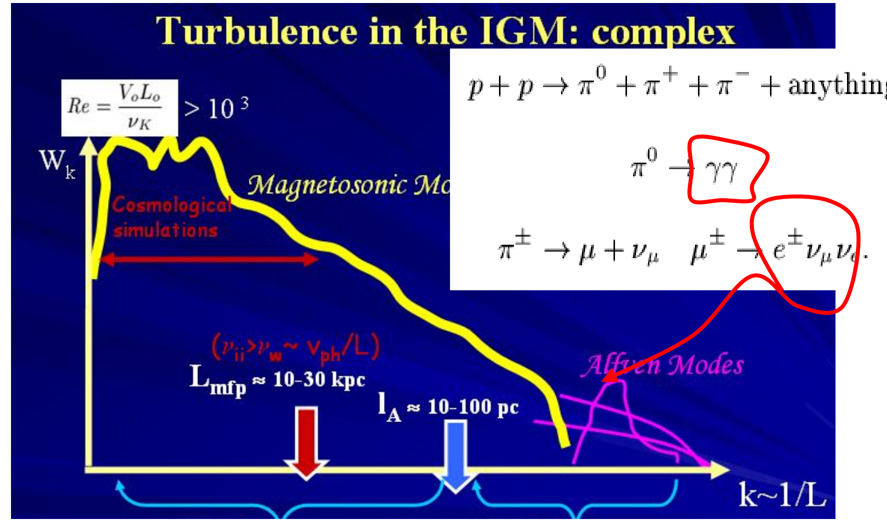
Energy is injected on large scales by DM-driven mergers.

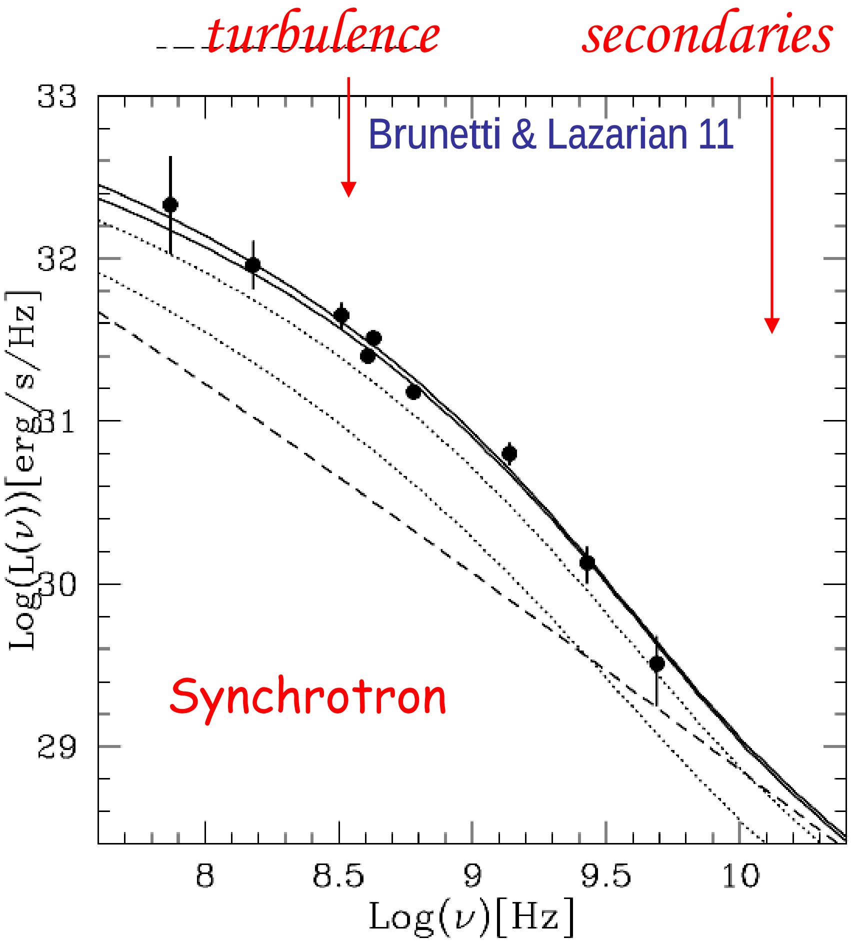
Radio halos probes physics of the ICM at dissipation scales.

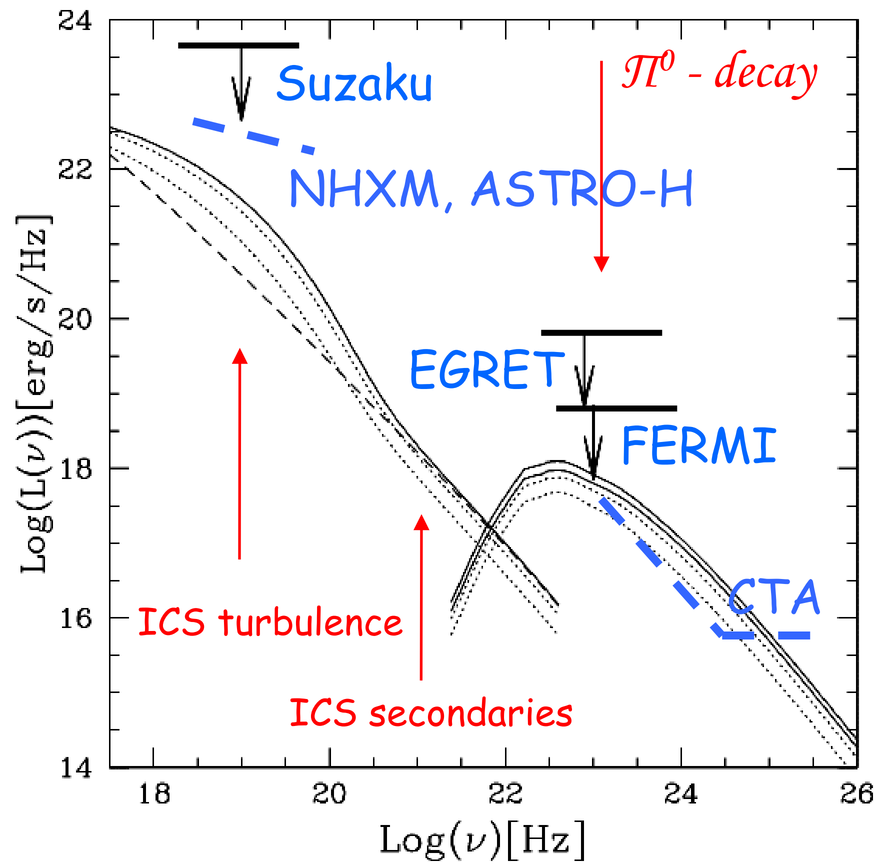
Radio Halos & high energies

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

E_{CRp} = ~ % E_{th}







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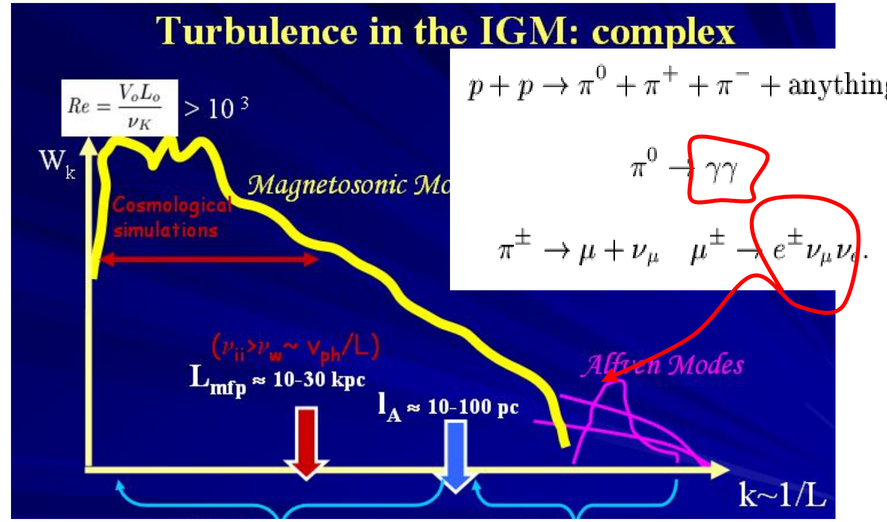
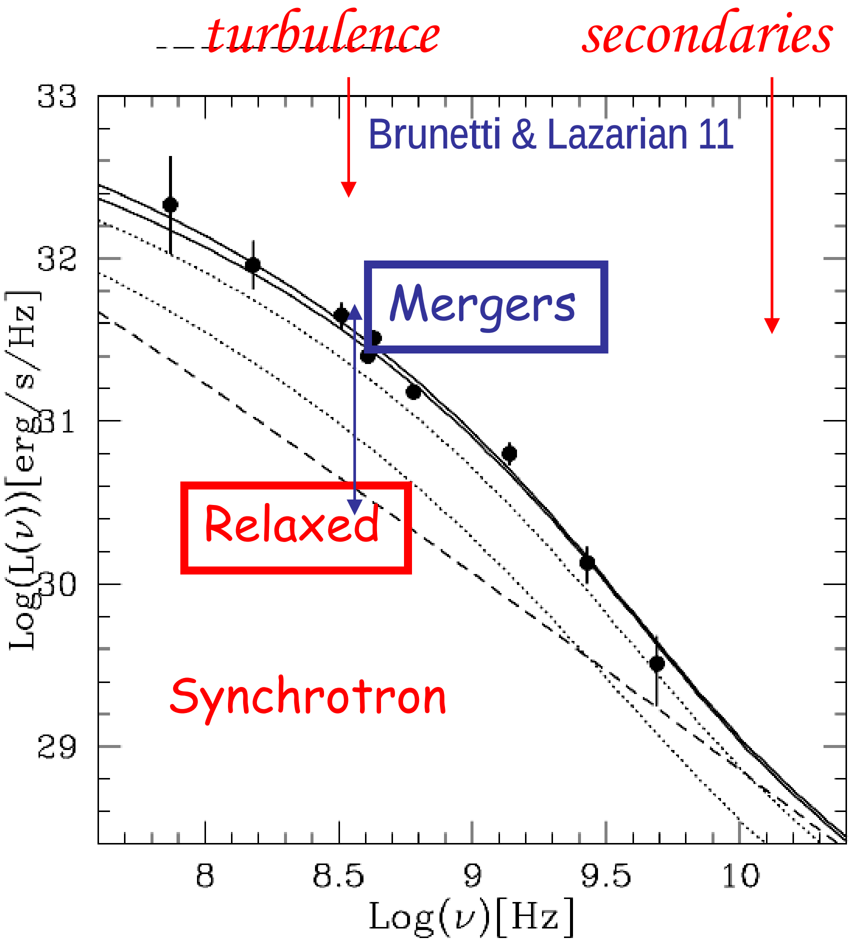
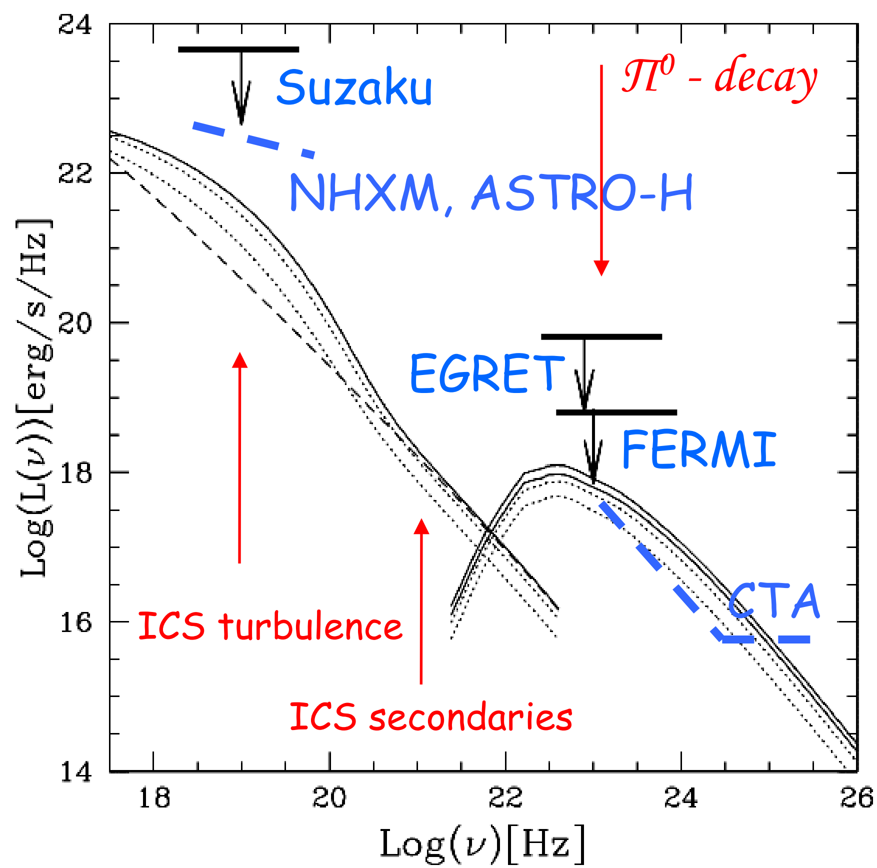
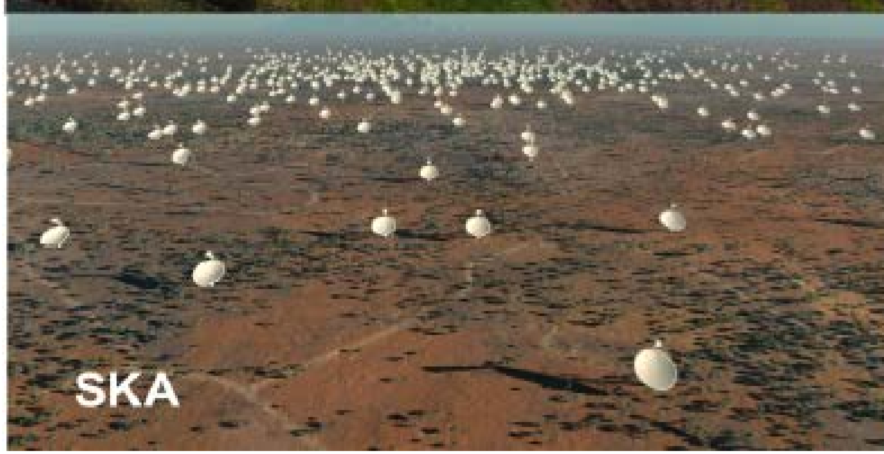






The "radio clusters" roadmap of the SKA



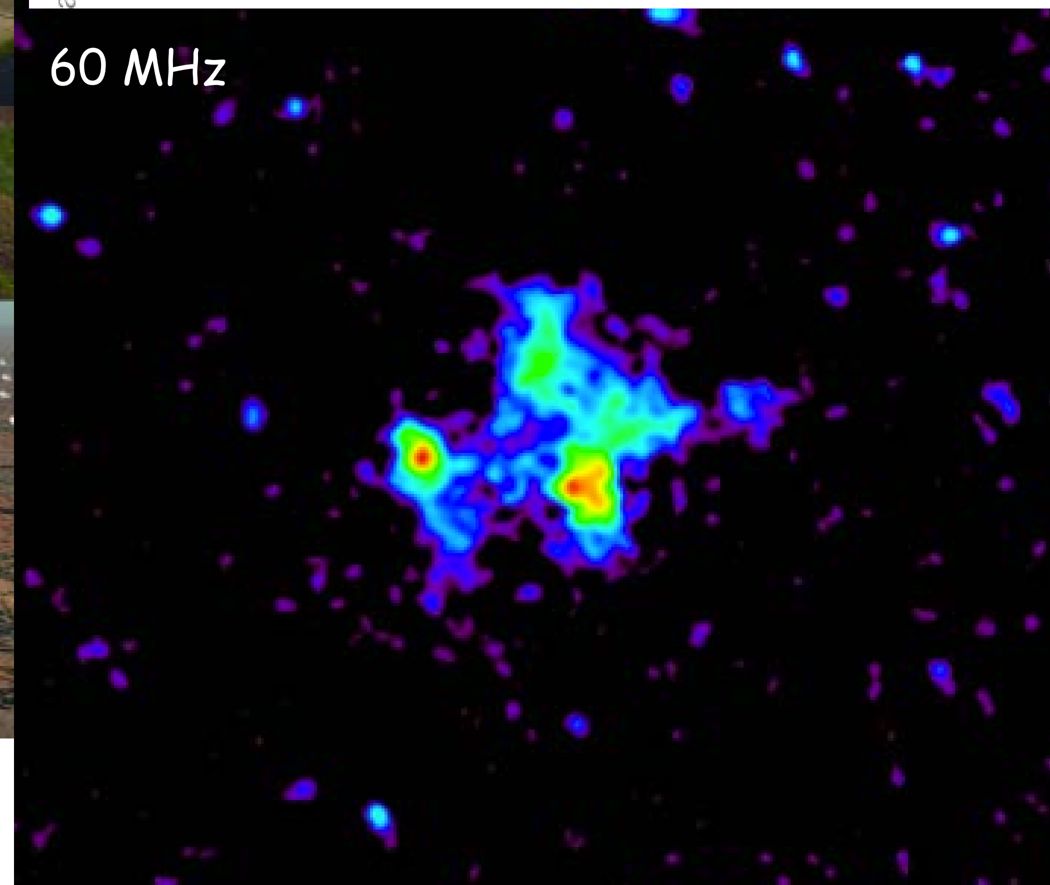
Clusters science : M. Johnston-Hollitt talk

The "radio clusters" roadmap of the SKA

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

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

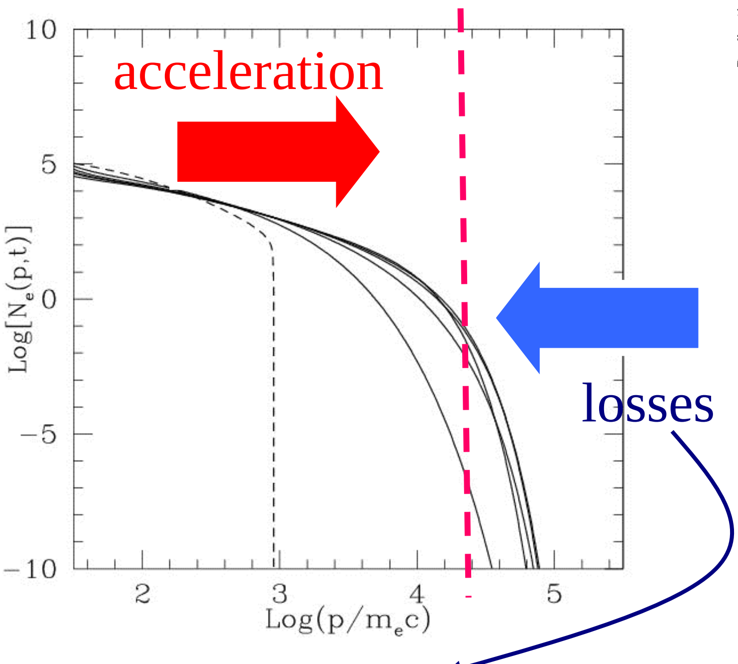
ay 2012



Radio Halos : are they generated by "inefficient" mechanism of CRe acceleration ? – low frequencies important !

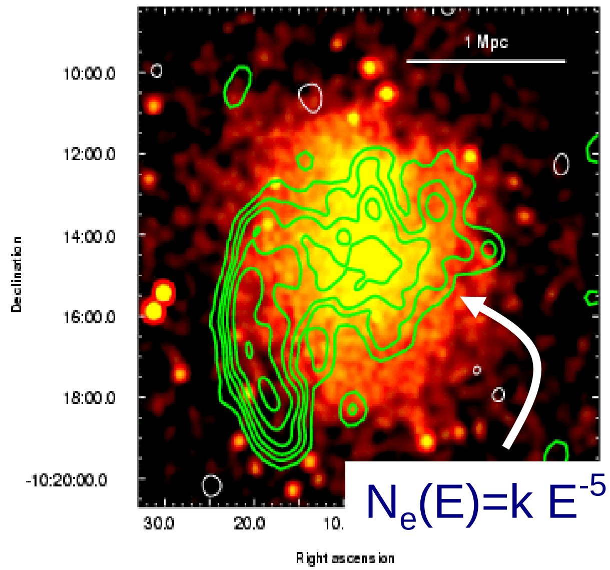
Acceleration time-scale

$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2} \quad \approx 10^{7\text{-}9} \text{ years}$$



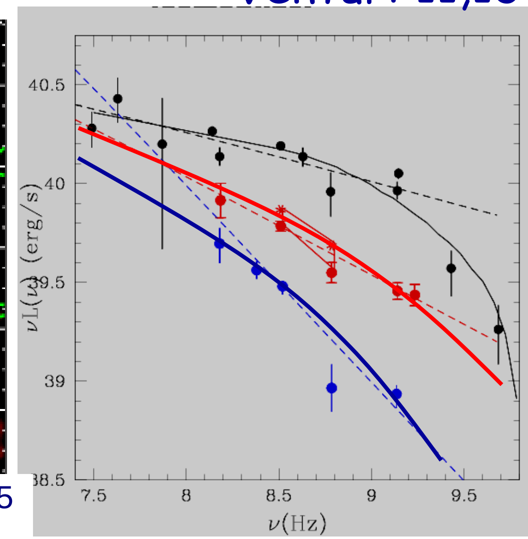
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right) \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4 \right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1} \left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\rm th}/10^{-3}}\right)\right] \right\}^{-1} \approx 10^8 \text{ yrs}$$

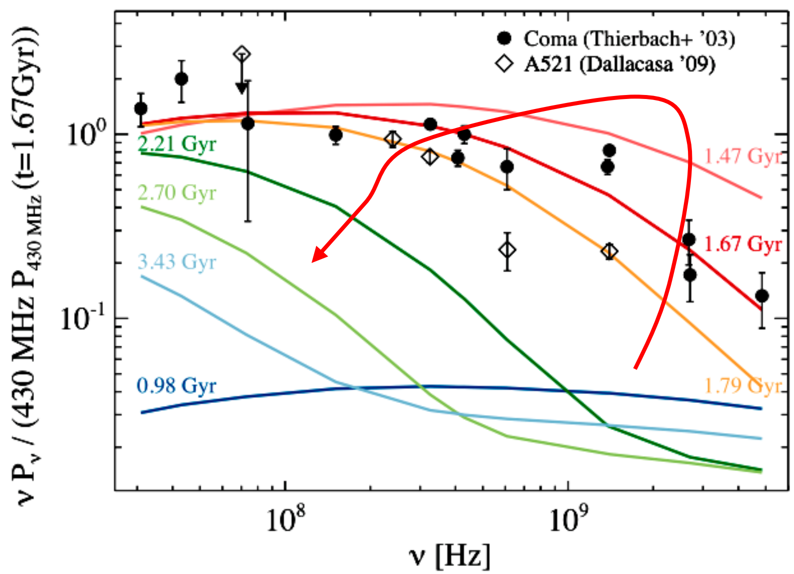
GB et al 08 Nature 455, 944



$N_e(E)=k\,E^{-5}$

Venturi 11,13





Donnert et al 13

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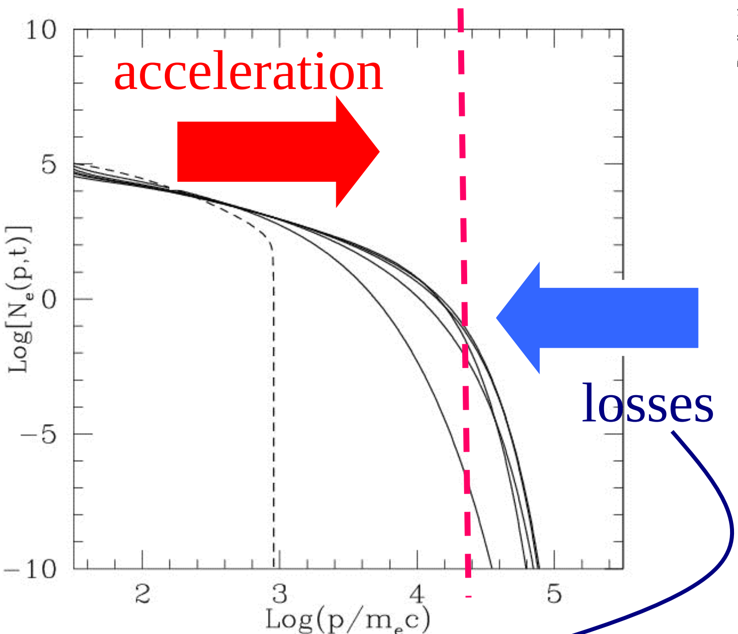

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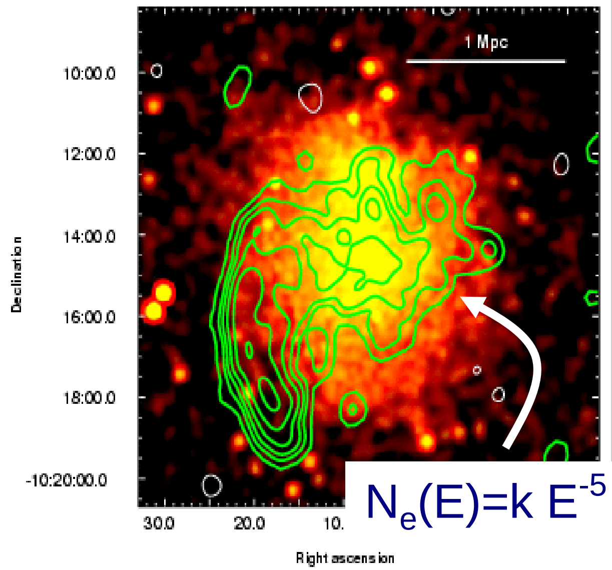
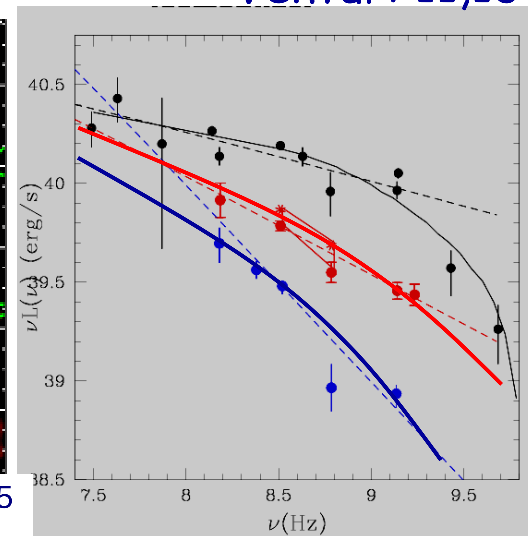
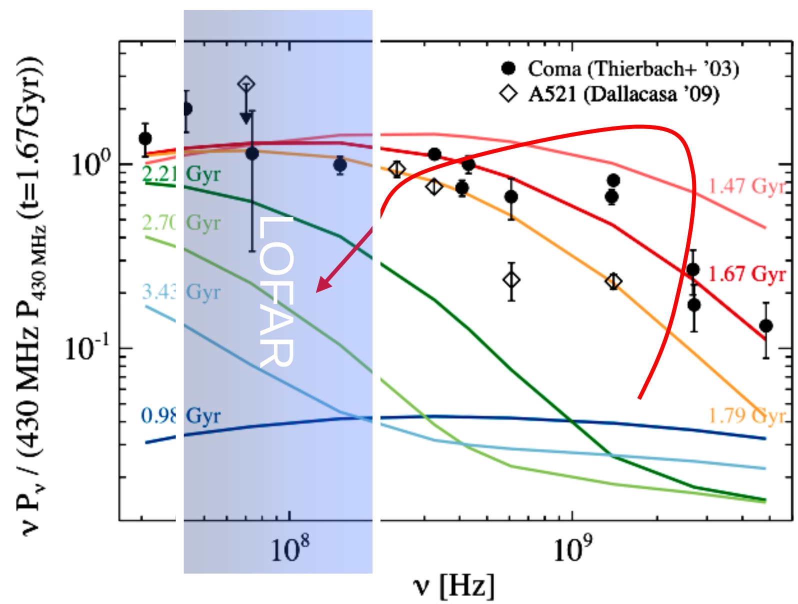
GB et al 08 Nature 455, 944



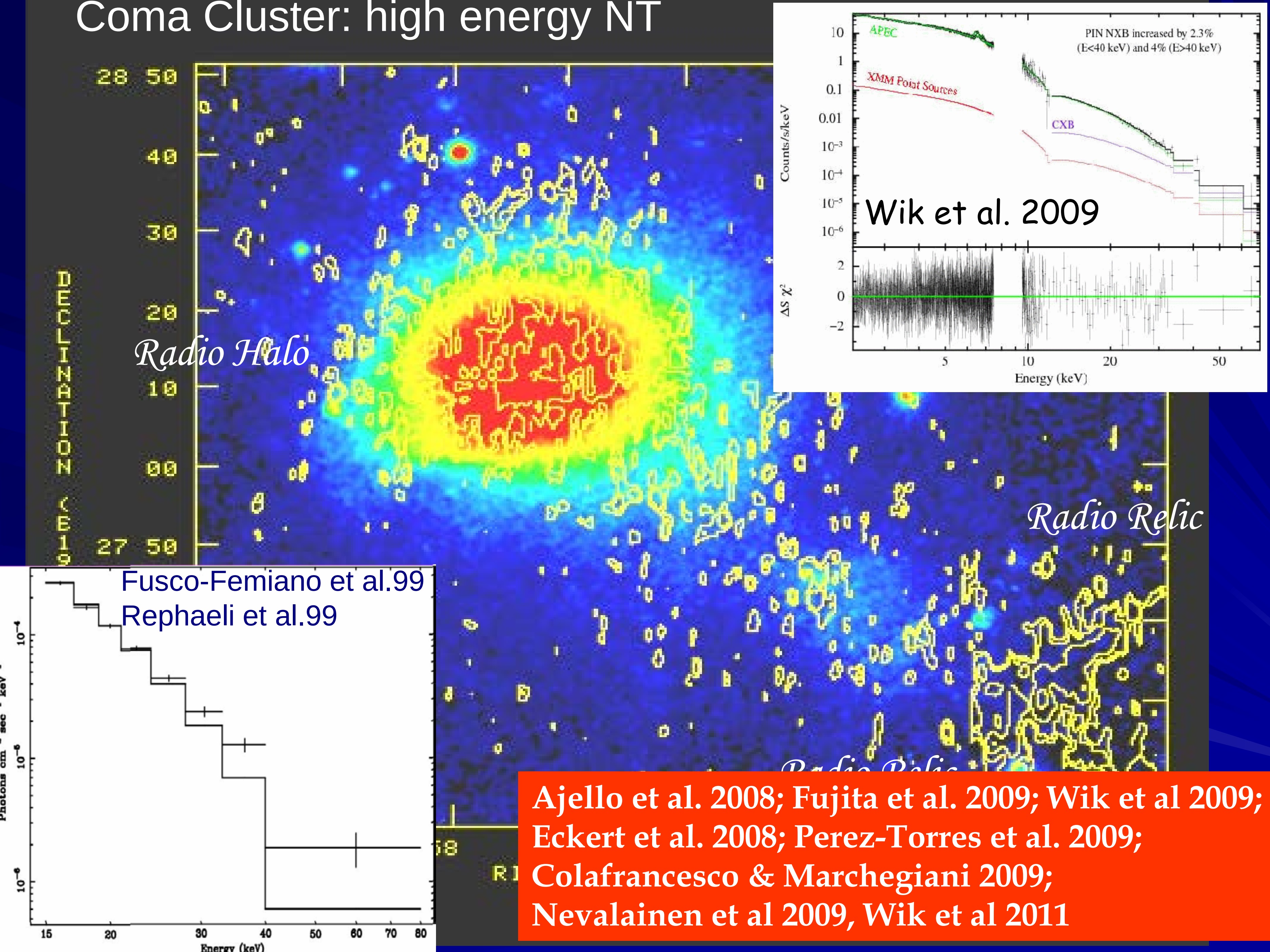
Venturi 11,13





Donnert et al 13

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

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

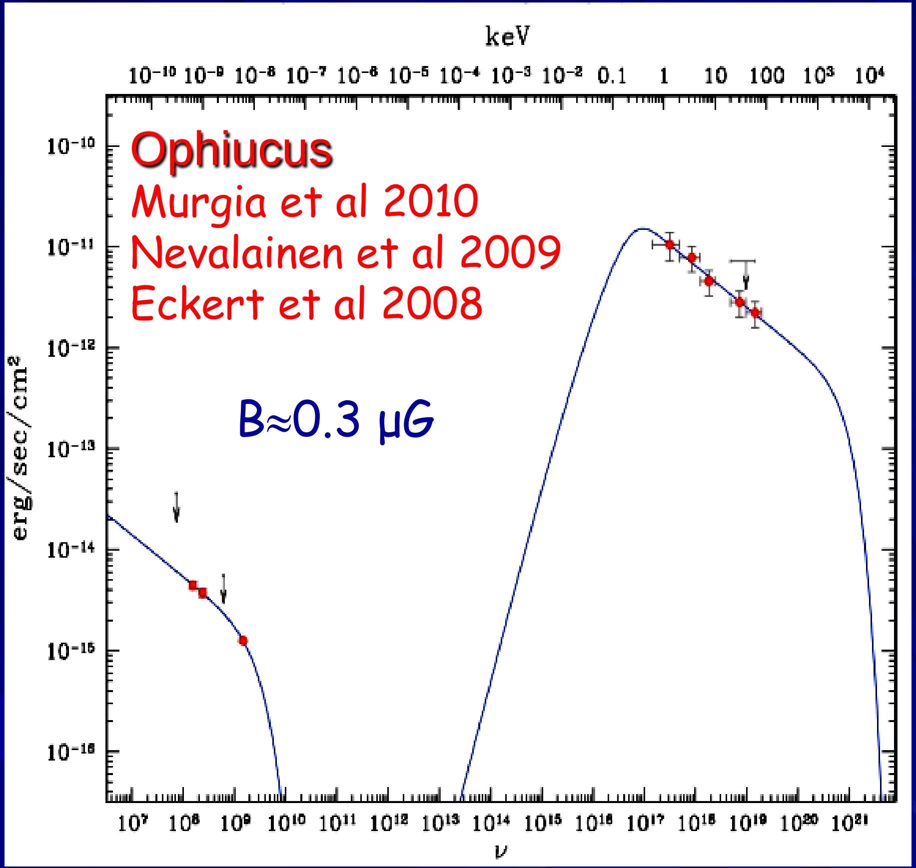
$L_{rad} / L_{HE} \approx U_B / U_{ph}$ -> B

Ajello et al 2010

om Combined *XMM-Newton* and BAT Data

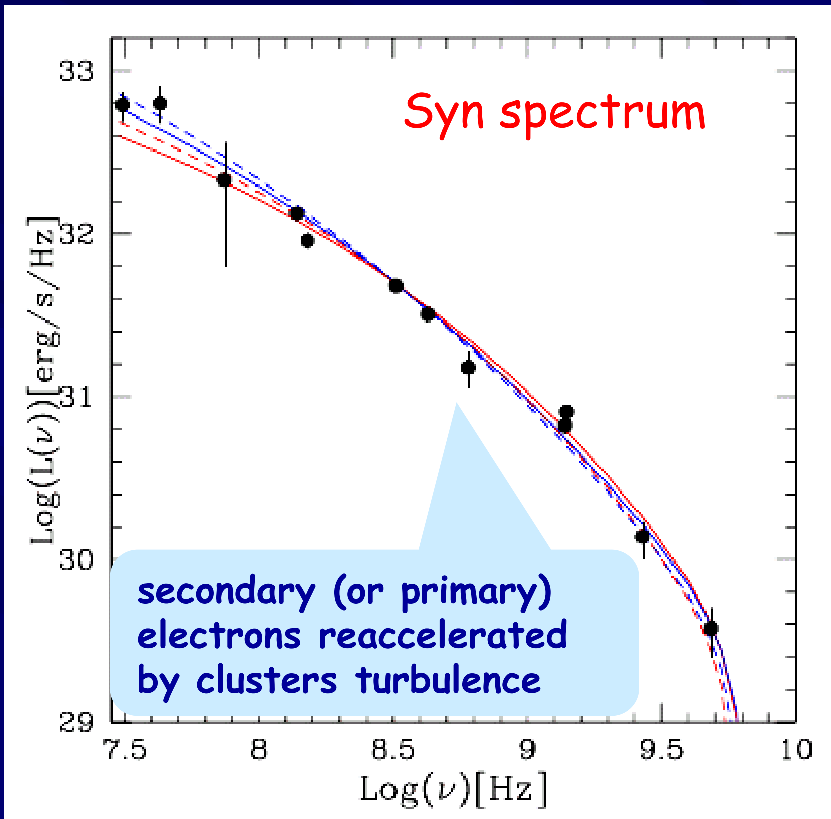
Name	$F_{50-100\,keV}$[a] (10^{-12} erg cm^2 s^{-1})	B[b] (μG)
A85	<2.51	~0.6
A401	<0.22	~0.4
Bullet	$1.58^{+0.43}_{-0.47}$	~0.16
PKS 0745-19	<1.6	~0.5
A1795	<1.38	/
A1914	<1.08	~0.3
A2256	<0.19	~0.6
A3667	$2.98^{+4.17}_{-0.73}$	/
A2390	<0.25	~0.8

B > 0.3-0.5 μG

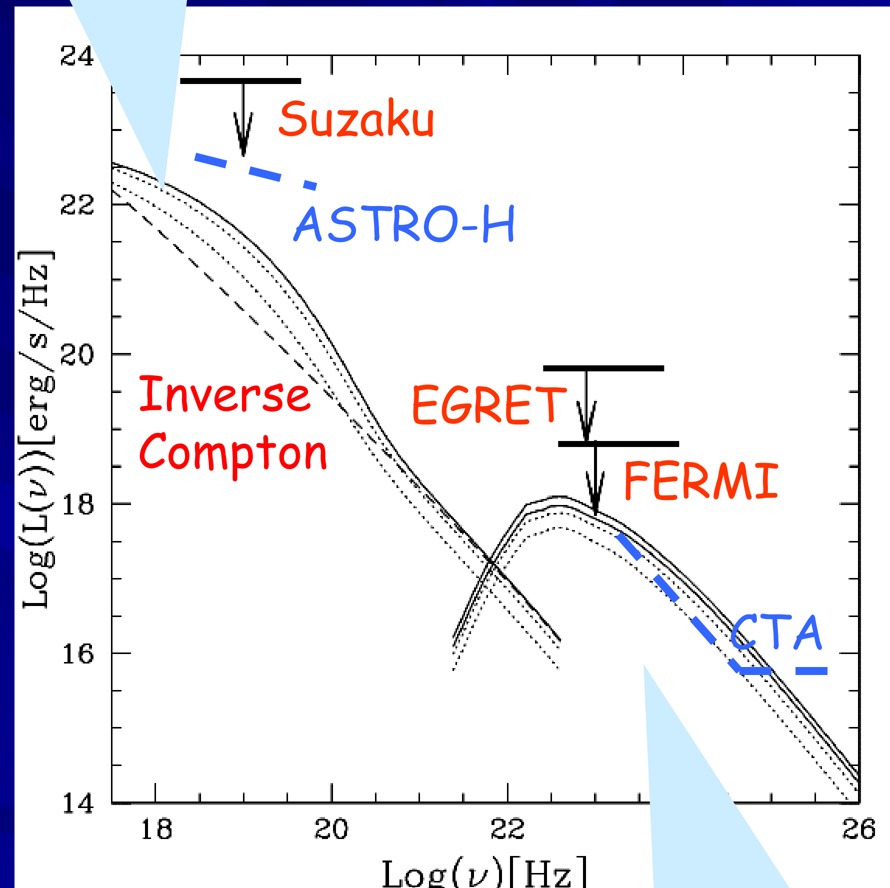


$E_B \approx E_{tur} \approx 0.1\, E_{th}$ … B≈5-10 μG
B ≈ 0.1-0.3 μG would indicate magnetic field dissipation on time scale « clusters life-time (few Gyrs) : reconnection ??

Radiation from CR in clusters (Brunetti & Lazarian 11)



secondary (or primary) electrons reaccelerated by clusters turbulence

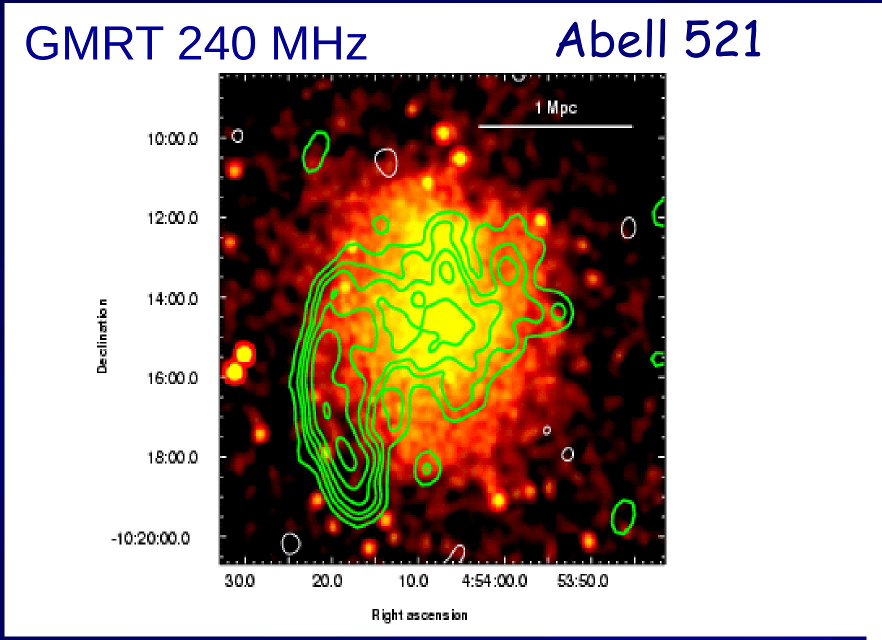


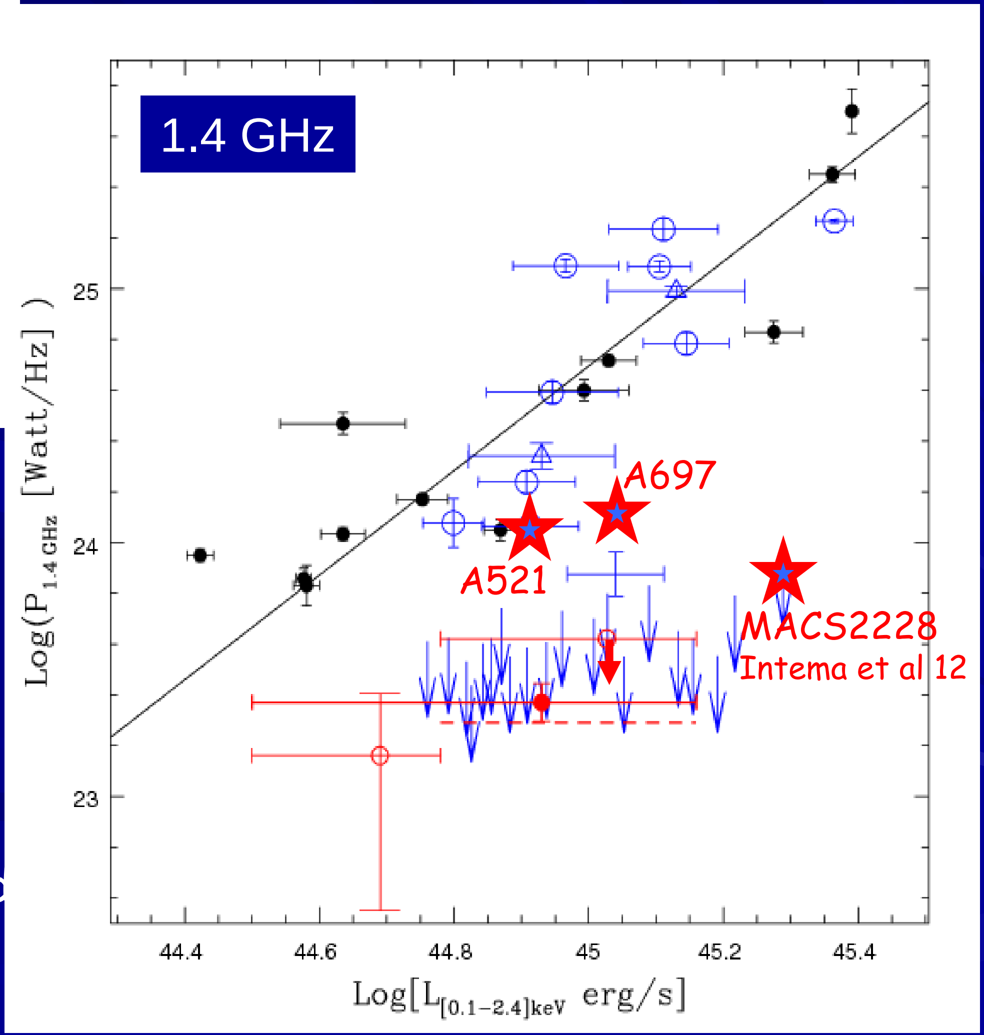
Gamma rays from decay of π^0 from CRp-p collisions

Observations in different bands provide constraints on different processes …

Turbulent acceleration?

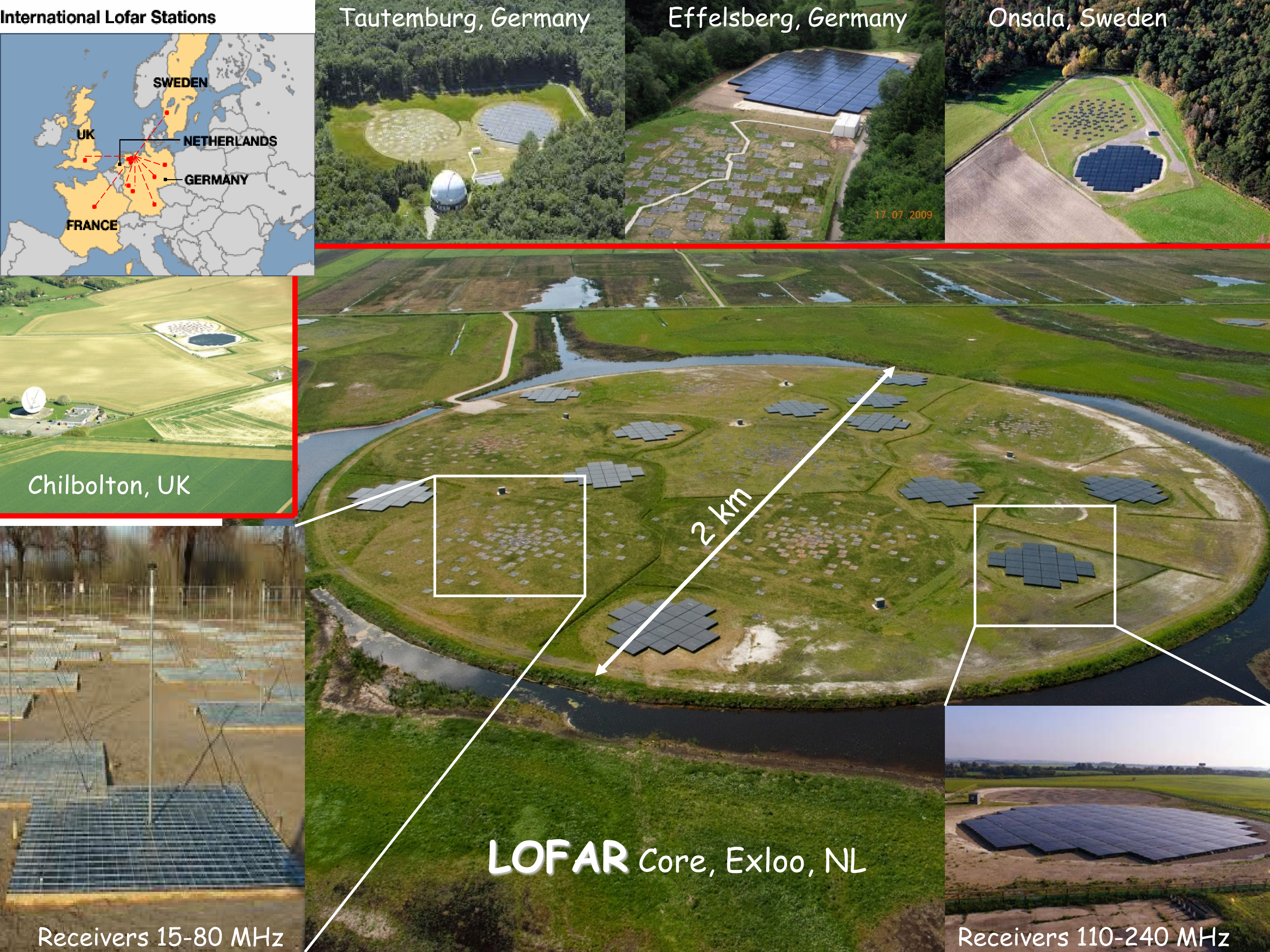
Brunetti +al 2008, *Nature 455, 944*

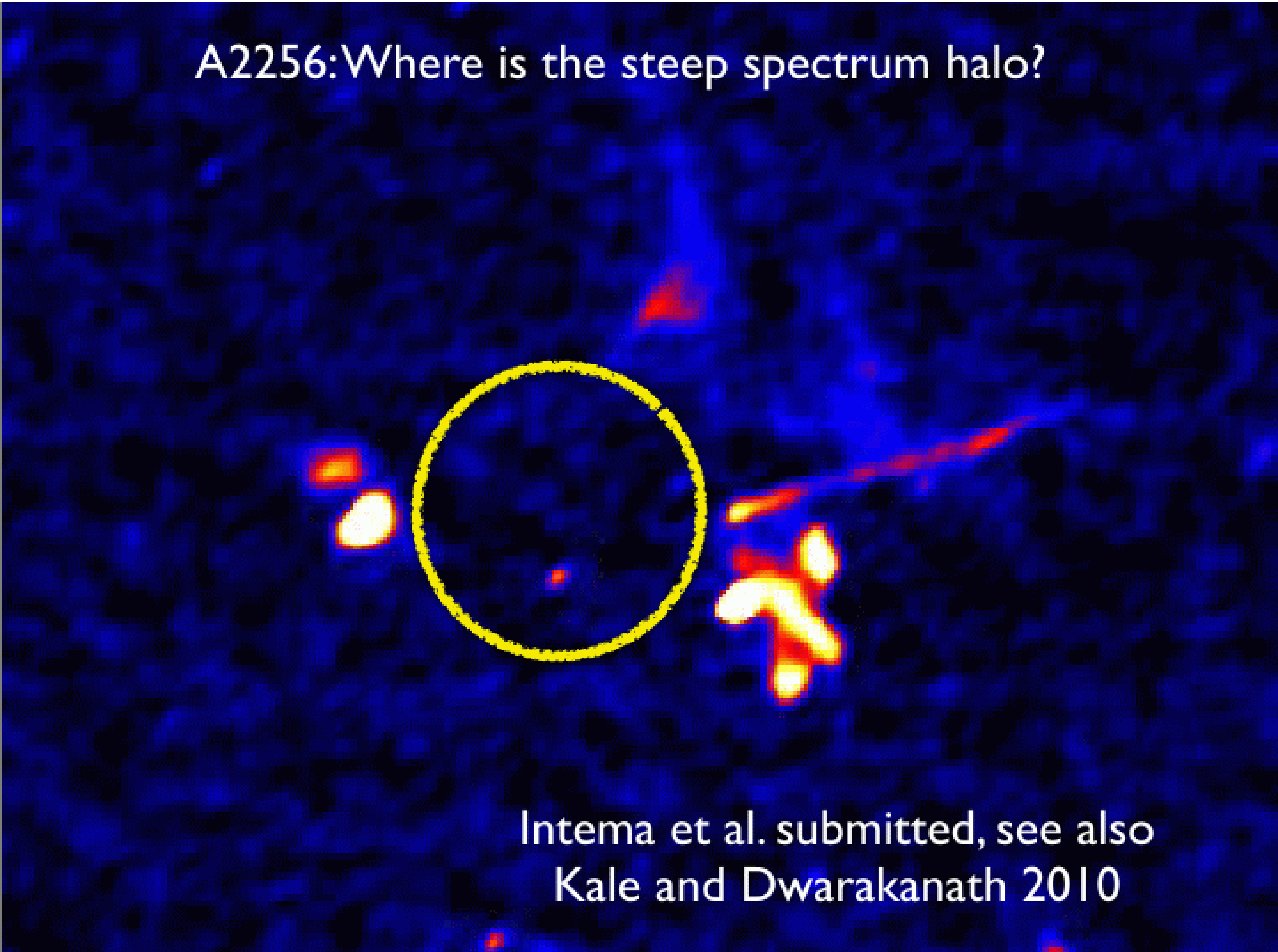


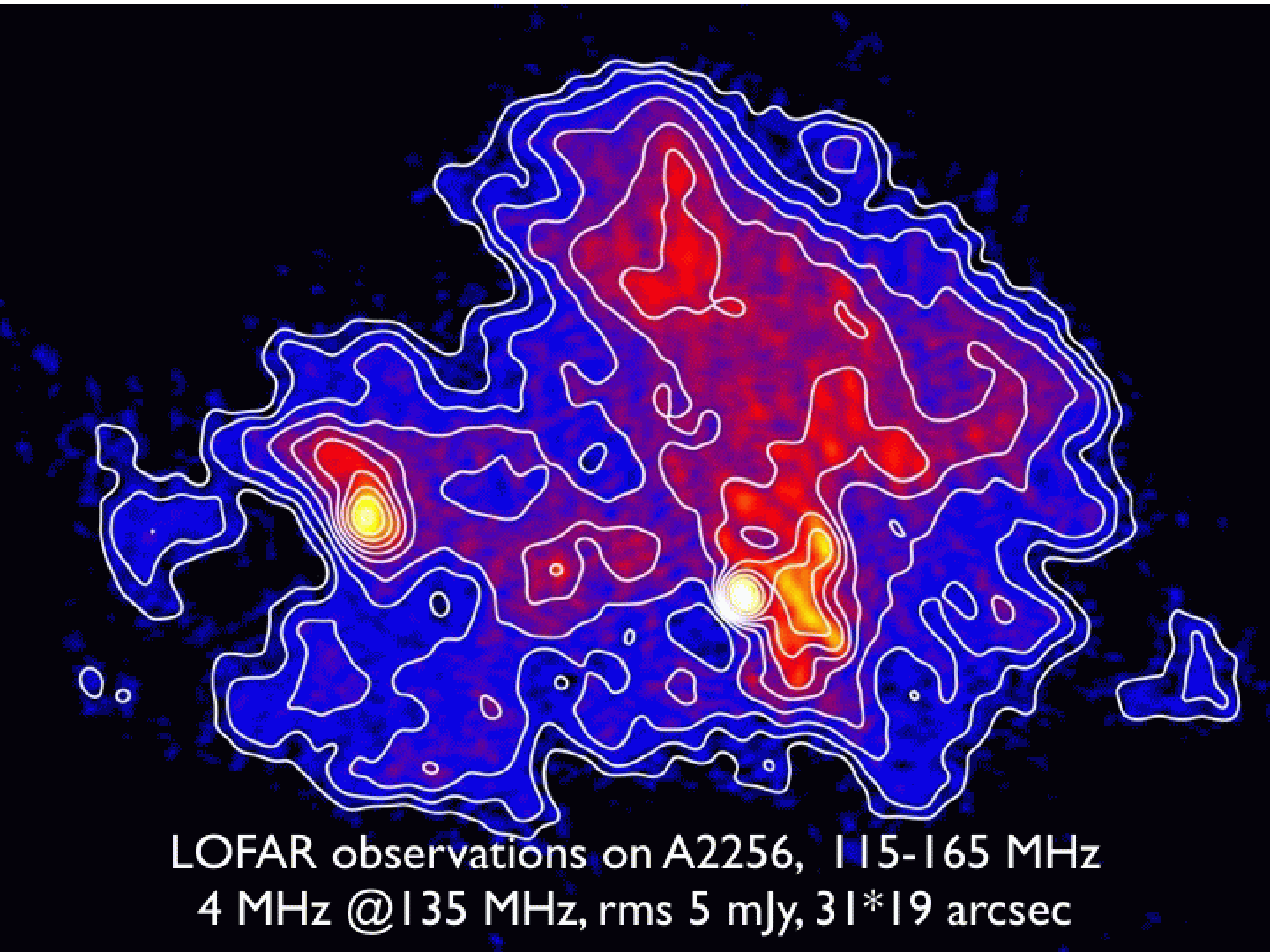


Several giant radio halos with ultra-steep spectrum have been discovered so far, they fill the transition region in the Psyn-Px diagram as expected by the reacceleration model .

Radio observations/surveys at low radio frequencies with unprecedented sensitivity are required to unveil the majority of halos in the Universe…


International Lofar Stations
SWEDEN
UK
NETHERLANDS
GERMANY
FRANCE
Tautemburg, Germany
Effelsberg, Germany
17.07.2009
Onsala, Sweden
Chilbolton, UK
2 km
Receivers 15-80 MHz
LOFAR Core, Exloo, NL
Receivers 110-240 MHz


A2256: Where is the steep spectrum halo?
Intema et al. submitted, see also
Kale and Dwarakanath 2010

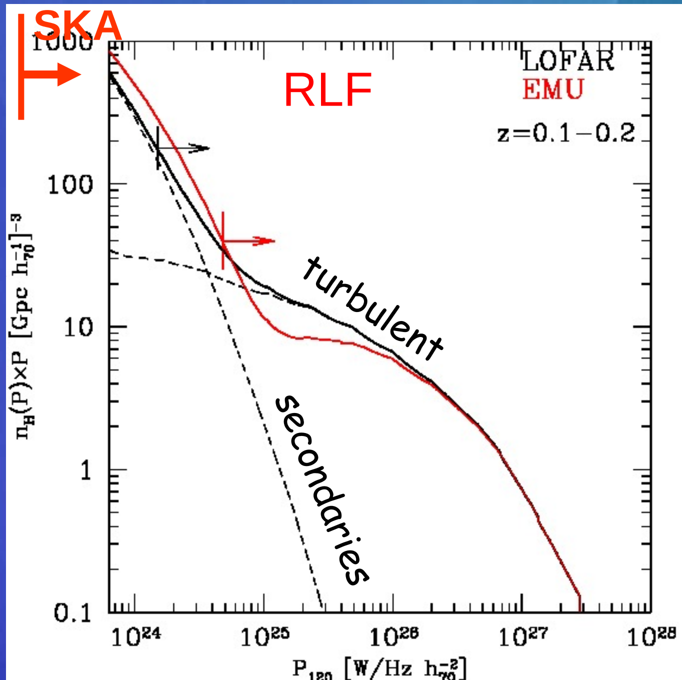

LOFAR observations on A2256, 115-165 MHz
4 MHz @135 MHz, rms 5 mJy, 31*19 arcsec

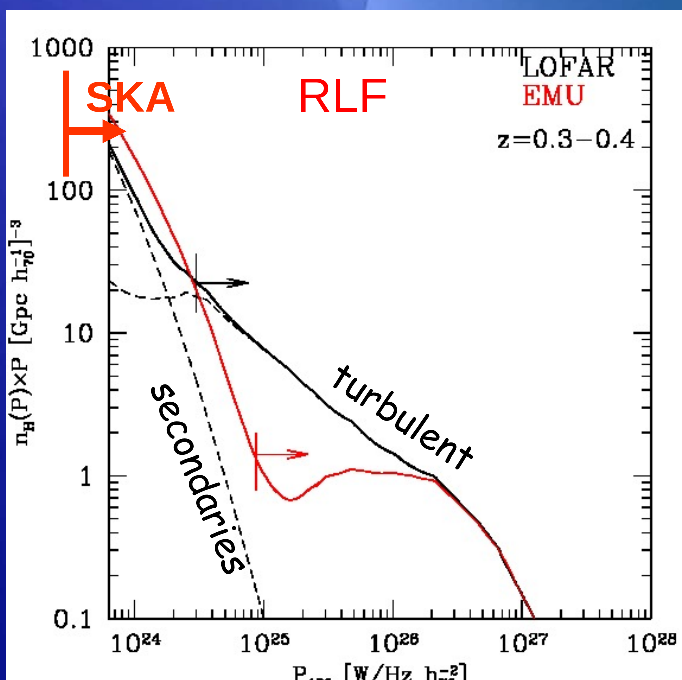
How many radio halos can be discovered ??

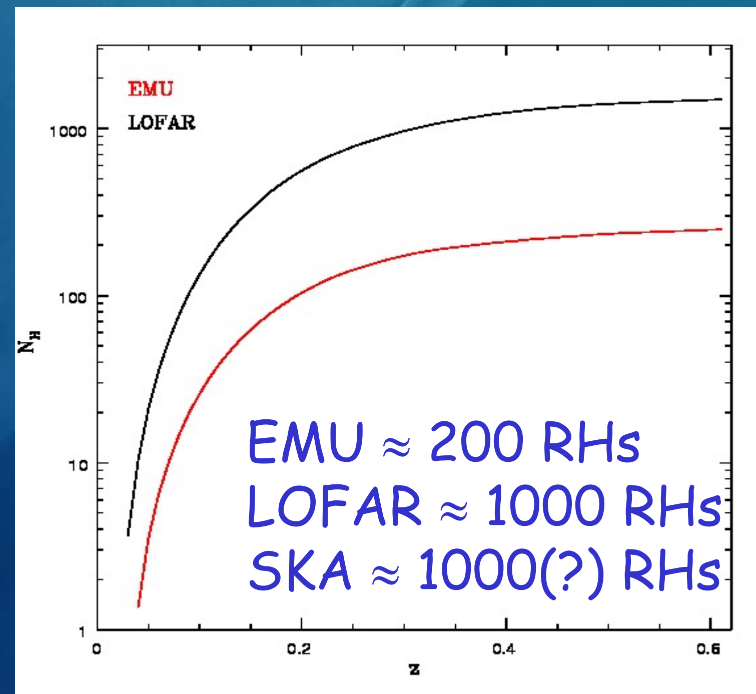
Results from MonteCarlo calculations including (turbulence) reaccelerated and secondary electrons

(Cassano,GB, Johnston-Hollit, Norris, Rottgering, Trasatti 12)

LF at 1.4 GHz (EMU,SKA) are shifted at 120 MHz assuming α=1.2



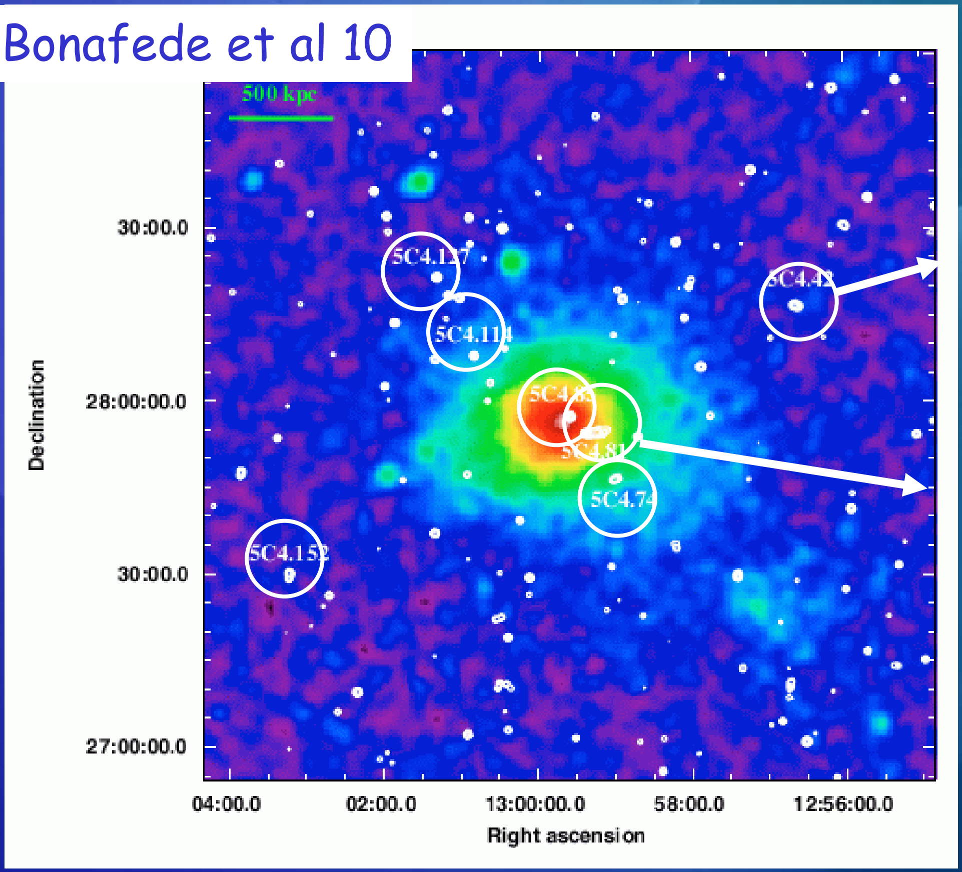


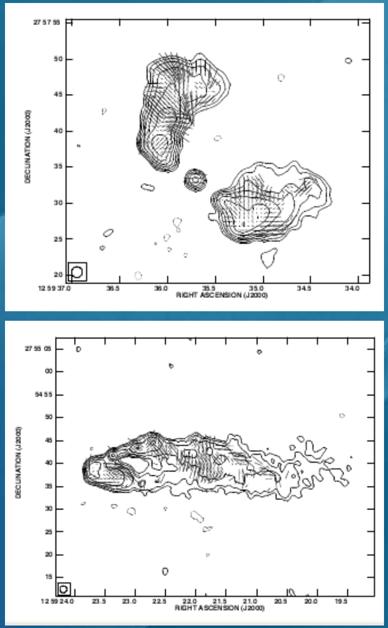


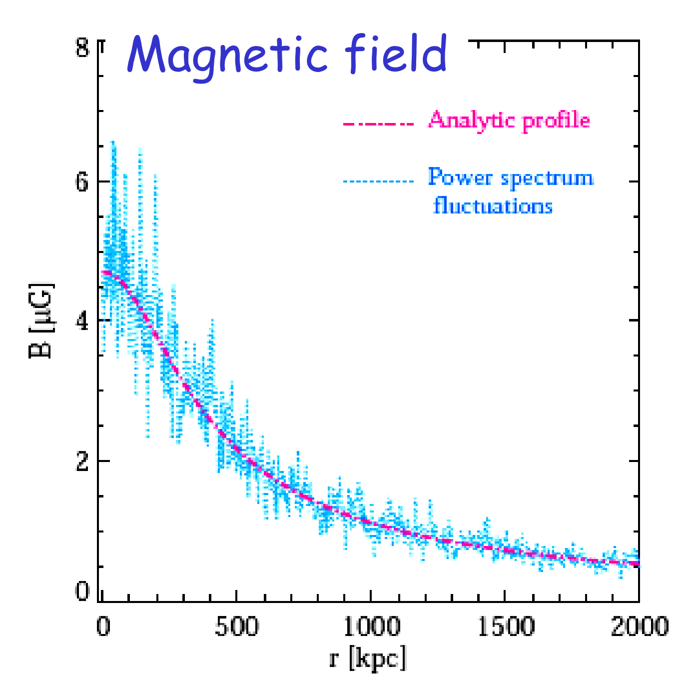
Constrain B amplification and CR acceleration up to z=1, with impact on Cosmology …

Leap forward in RM-science with SKA

Bonafede et al 10



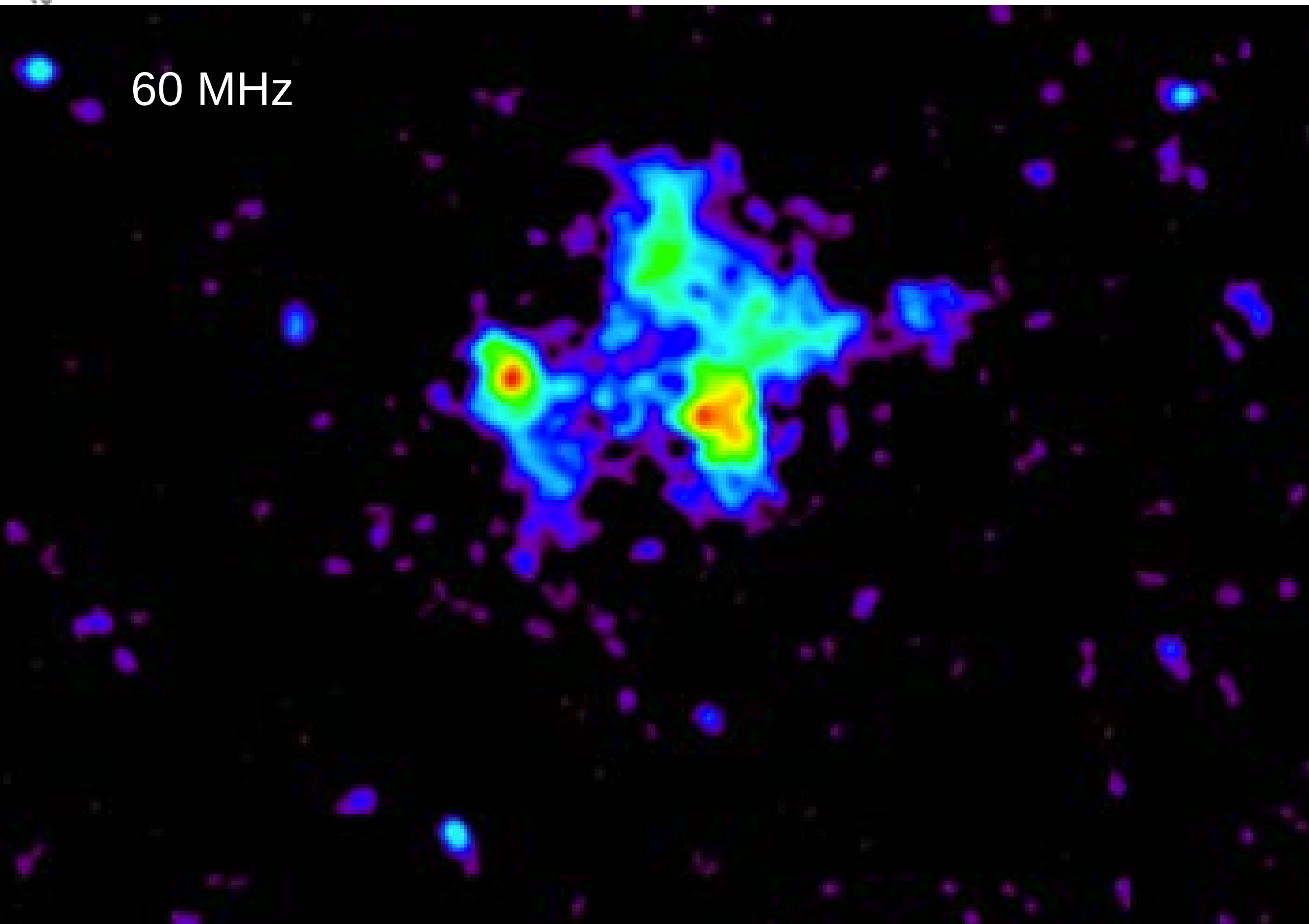


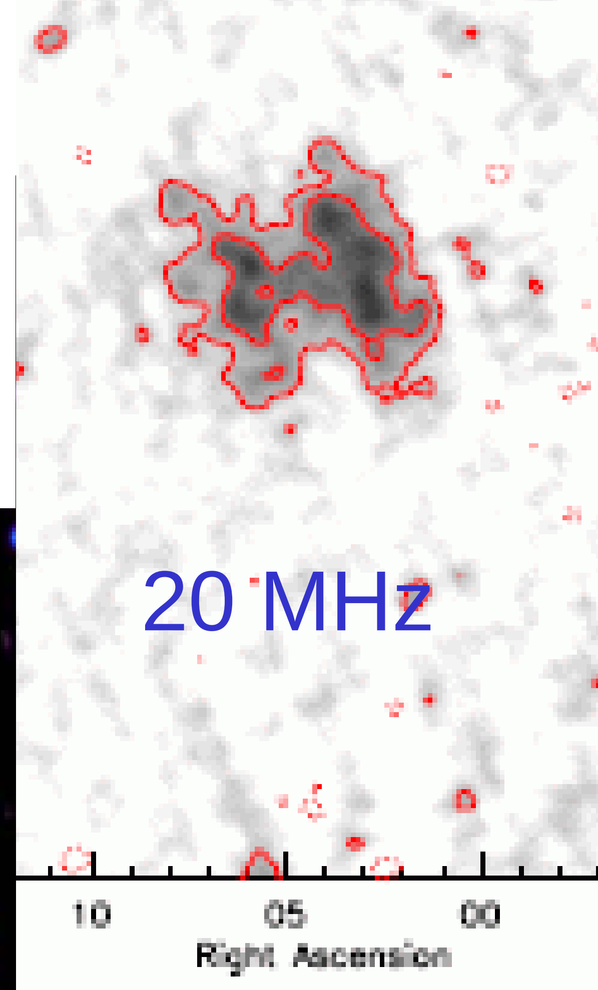


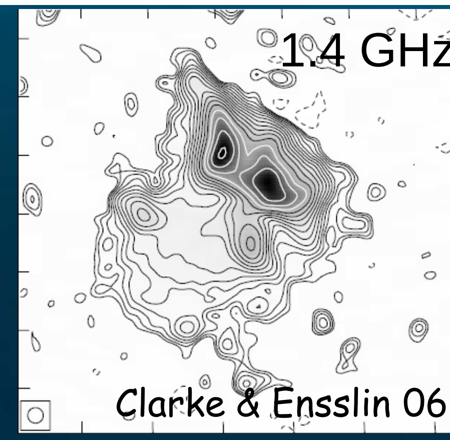
"State of the Art" results are based on few (3-8) backgroud sources/line of sight.
Variance and assumptions (geometry) are major problems for a reliable measure of B and its spatial profile.
Limitations are due to the poor sensitivity of radiotel… few sources "available" per deg2

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

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

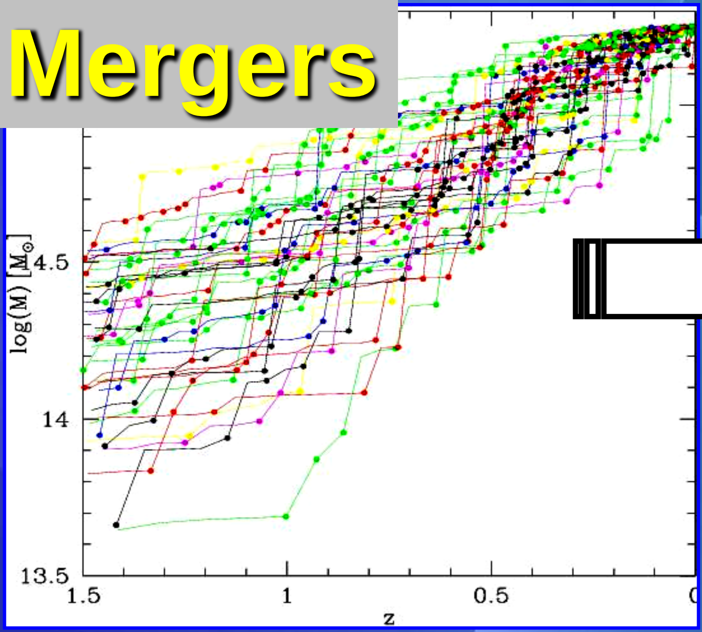


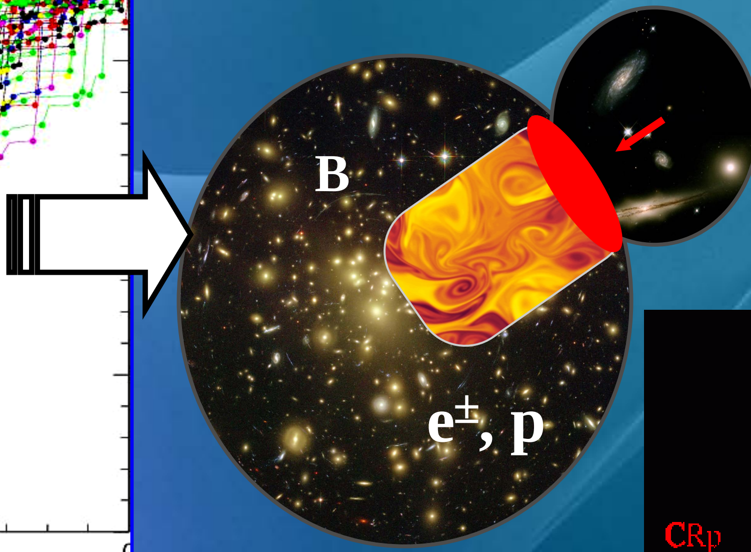


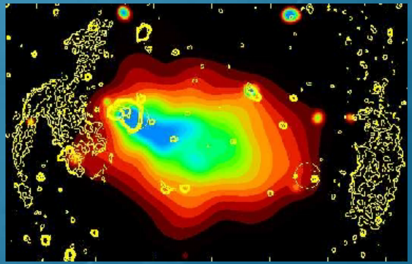


Mergers & CR-acceleration

Mergers

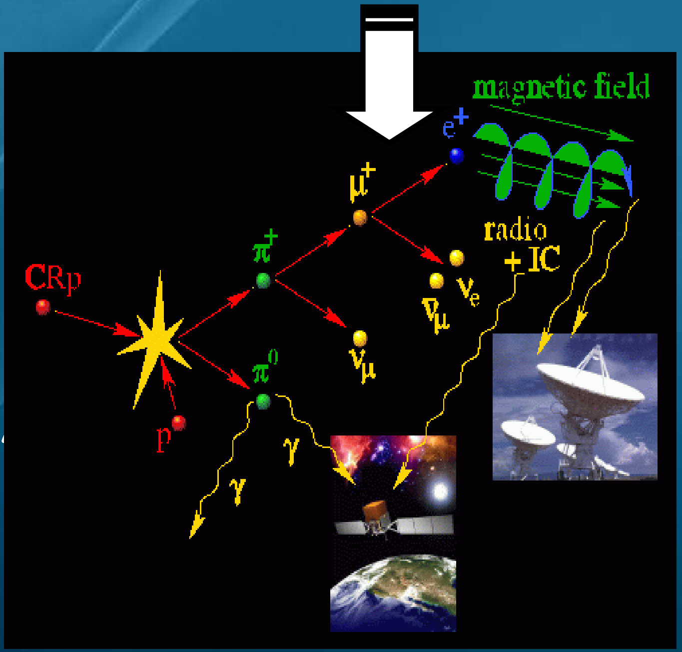






SHOCKS

accelerate $CRe^{\pm}$,CRp

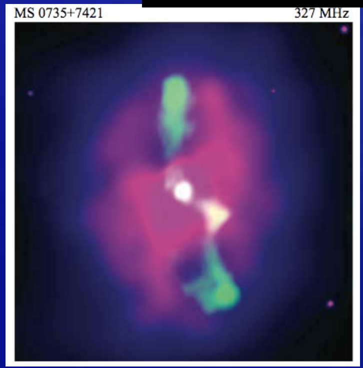


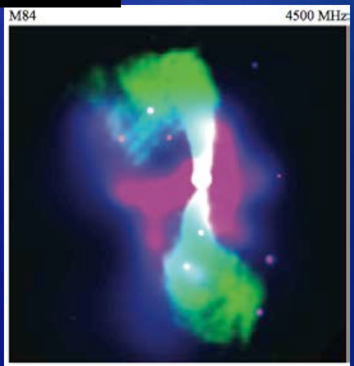
TURBULENCE

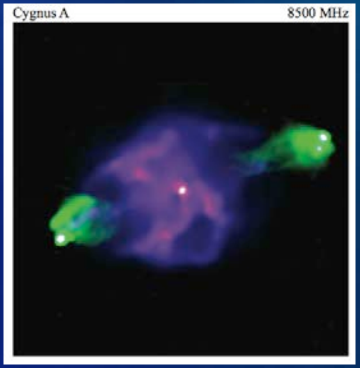
reaccelerates fossil $CRe^{\pm}$,
CRp and secondaries $CRe^{\pm}$

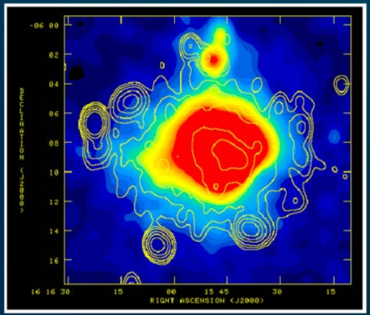
AGN/GW

Voelk et al 96, 99



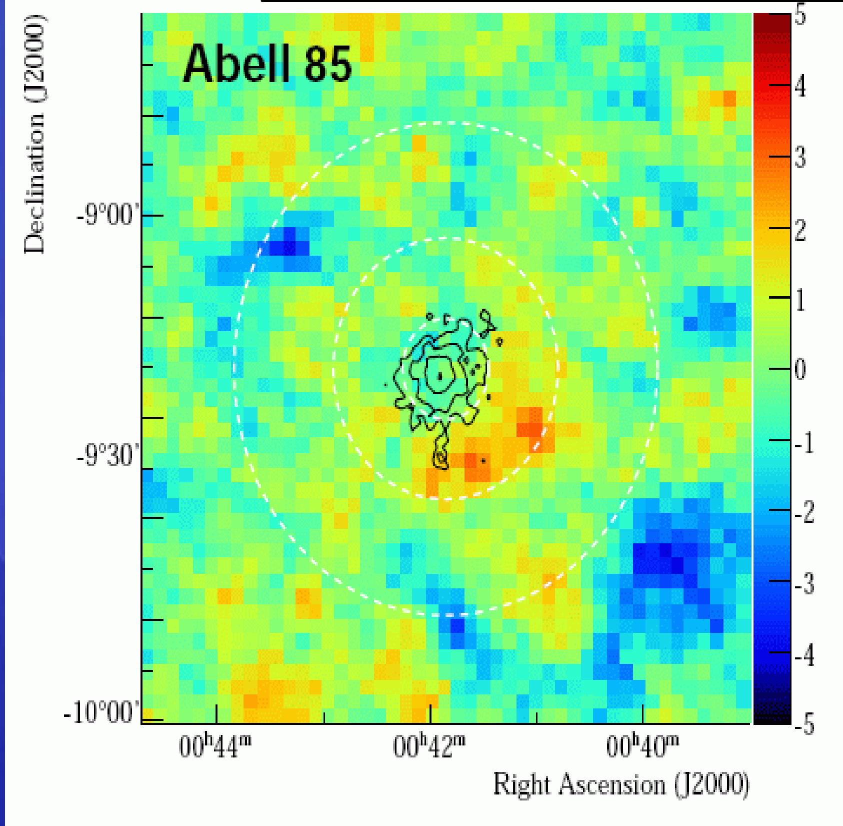




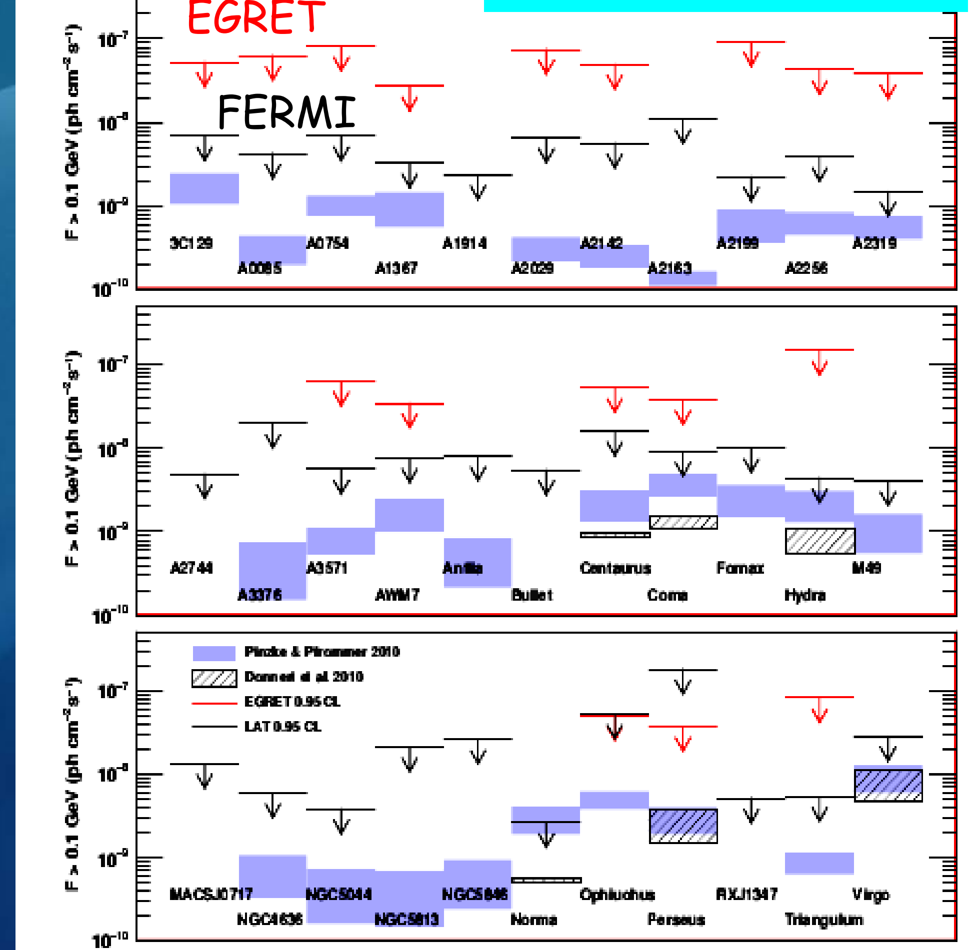


Limits & CRp content

Aharonian et al. 2009



Ackermann et al 2010



H.E.S.S.

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

Coma : Ecr/Eth < 12%

VERITAS (Perkins +al. 2008)

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

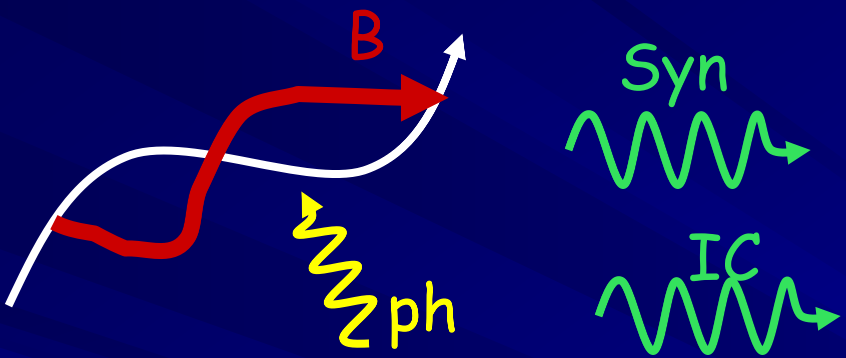
MAGIC (Aleksic +al. 10, 12)

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

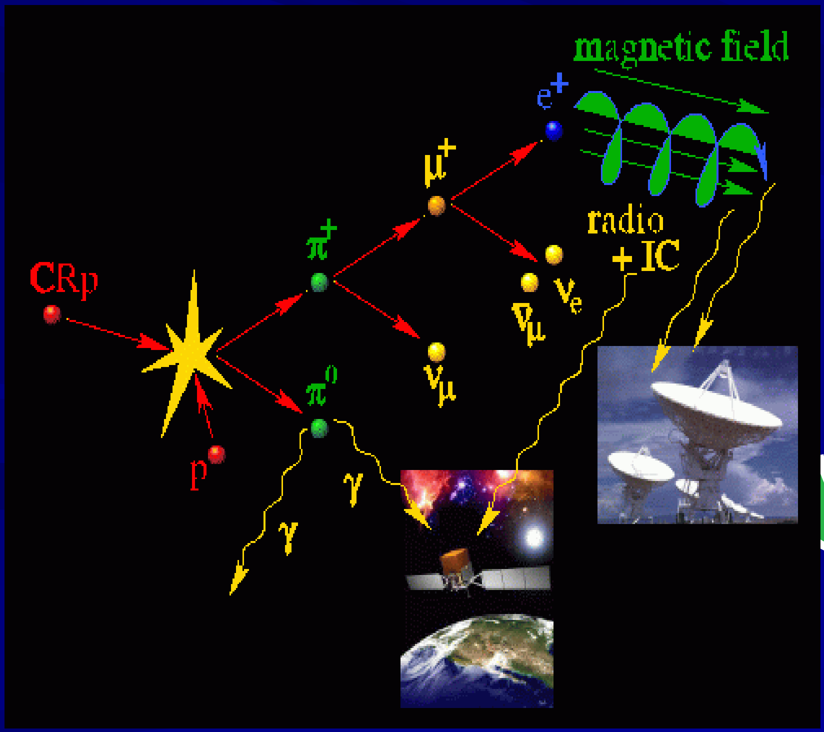
FERMI-LAT u.l. imply Ecr/Eth < 5%
(assuming Ecr~Eth)

High energy emission from GC

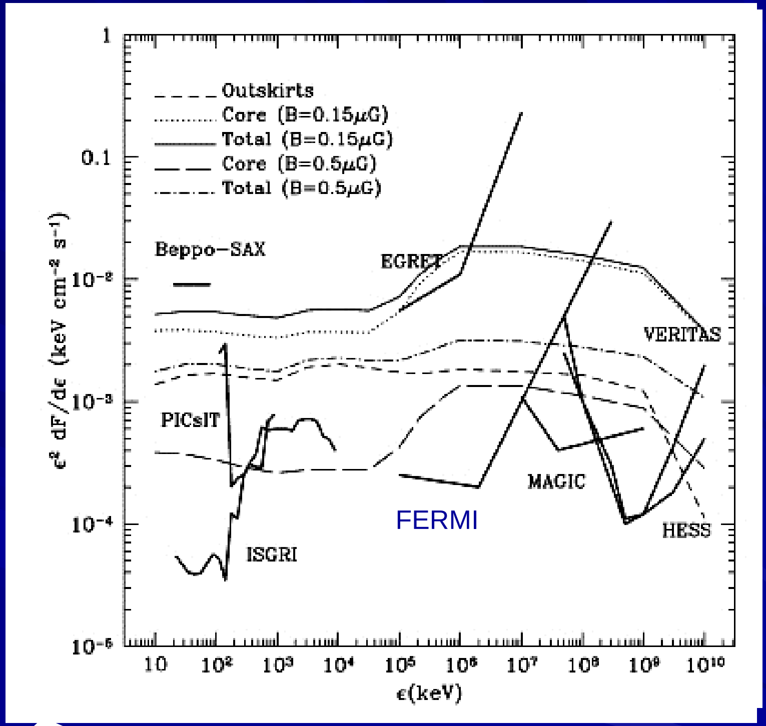
CRe



CRp



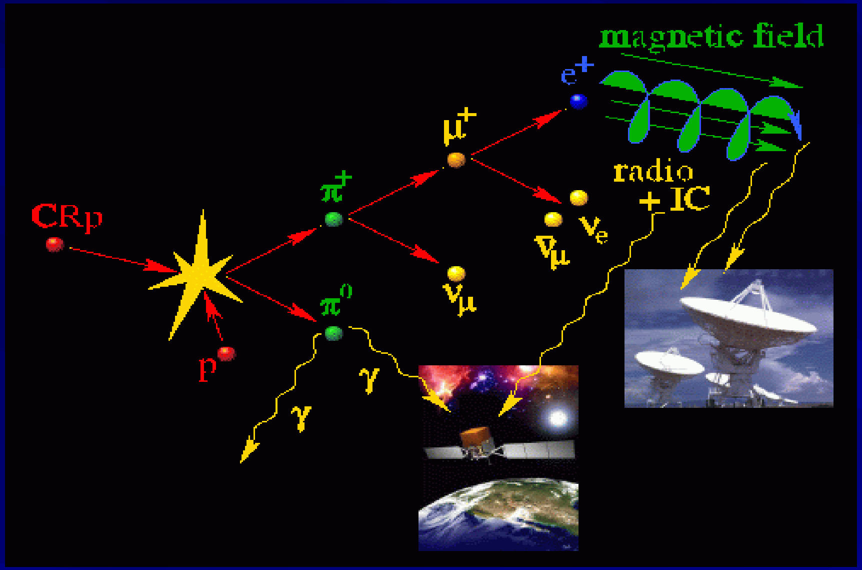
Miniati 2003

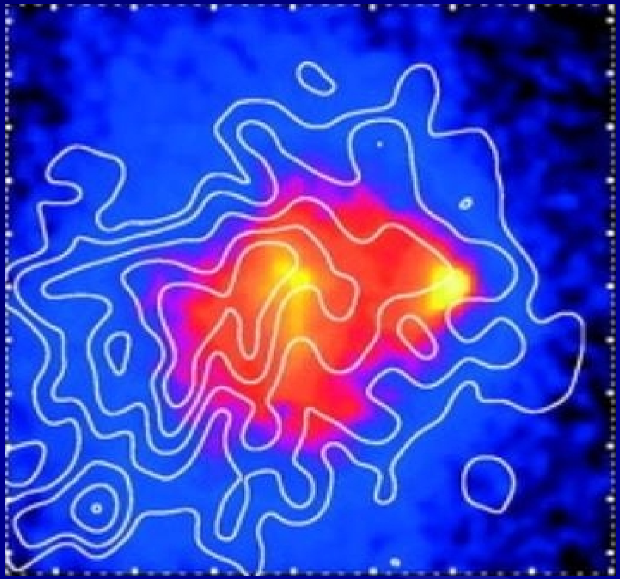


Do CRp generate Radio Halos ?

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

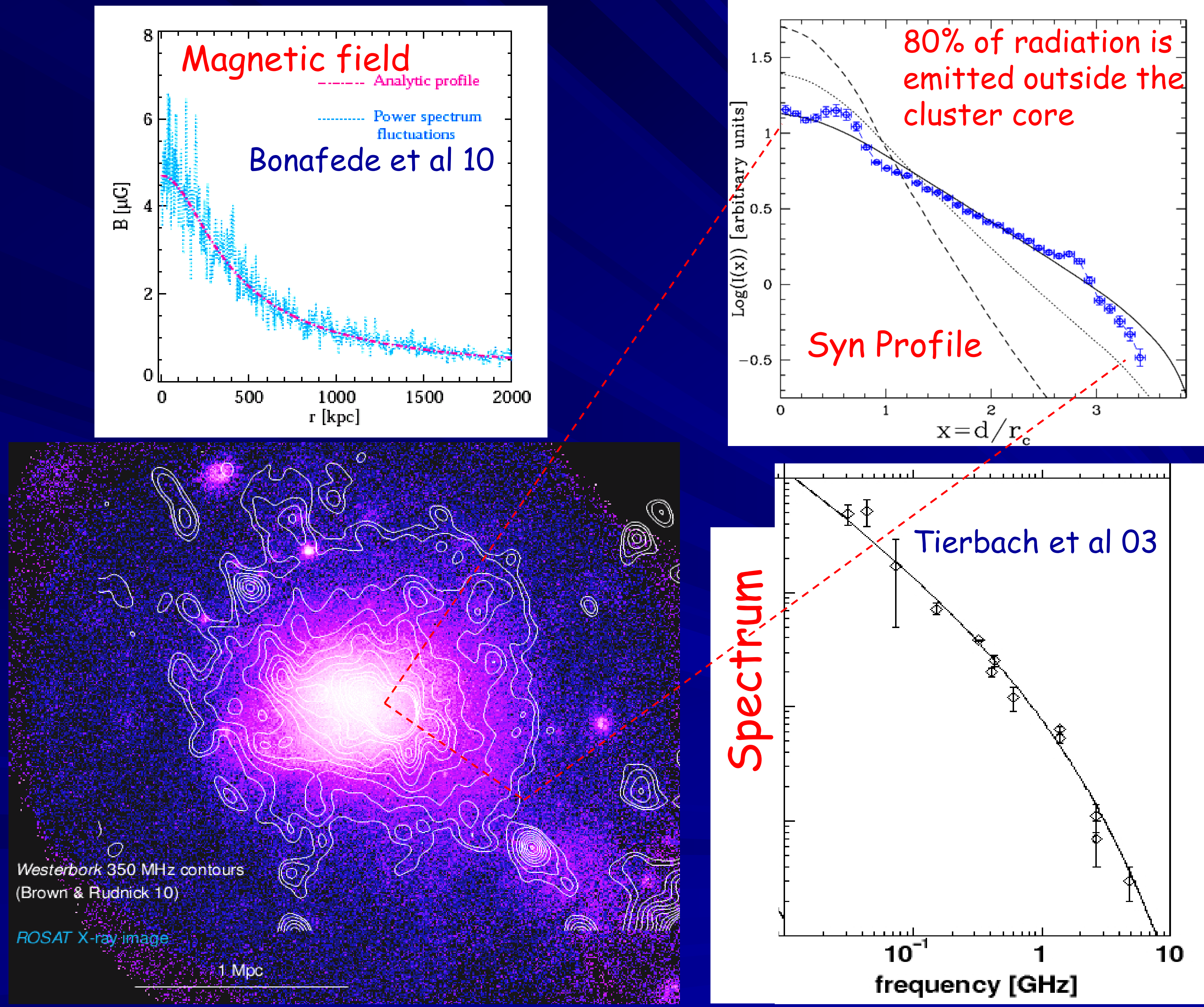
$L_{\gamma,\pi} \sim f_{\gamma}(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{\gamma}$





$L_{syn} \sim f_1(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{syn} B^{(1+\delta/2)}(B^2+B_{cmb}{}^2)^{-1}$

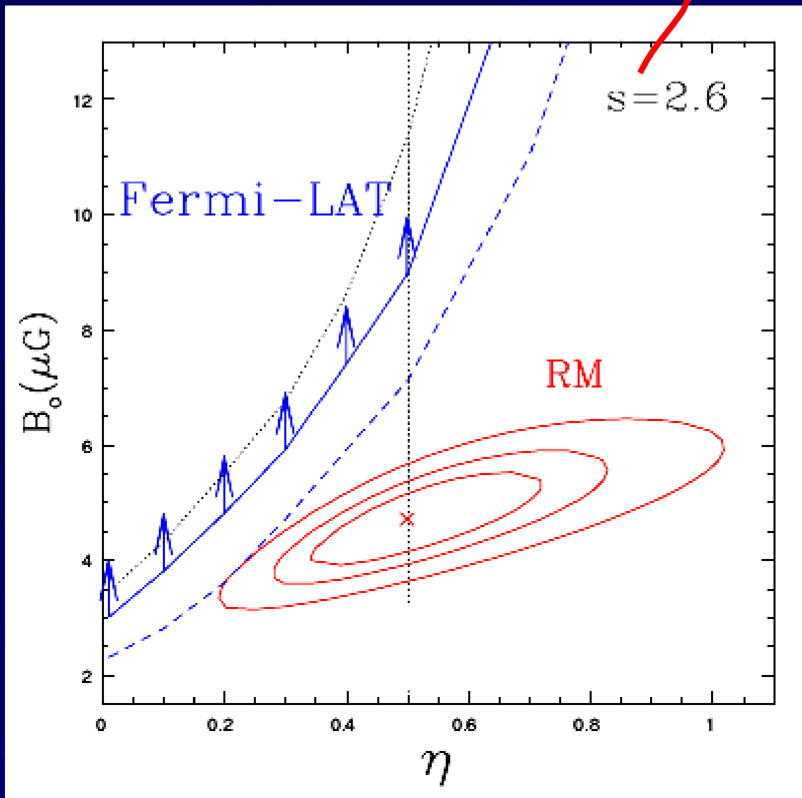
$L_{Syn}/ L_{\gamma,\pi} \dashrightarrow \langle B^{\delta/2+1}/(B^2+B_{cmb}{}^2) \rangle$ _(emission weighted)


Magnetic field
Analytic profile
Power spectrum fluctuations
Bonafede et al 10
B [μG]
r [kpc]
0
500
1000
1500
2000
8
6
4
2
0
80% of radiation is emitted outside the cluster core
Syn Profile
Log(I(x)) [arbitrary units]
x=d/r_c
1.5
1
0.5
0
−0.5
0
1
2
3
Westerbork 350 MHz contours
(Brown & Rudnick 10)
ROSAT X-ray image
1 Mpc
Tierbach et al 03
Spectrum
frequency [GHz]
10^-1
1
10

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

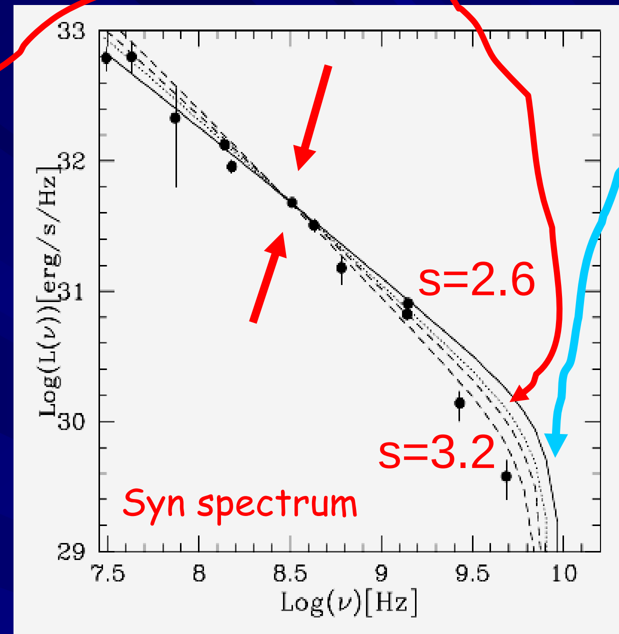
$N_{cr}(p,r)=K(r)\, p^{-s}$

$B(r)=B_o(\varepsilon_{TH}/\varepsilon_o)^{\eta}$



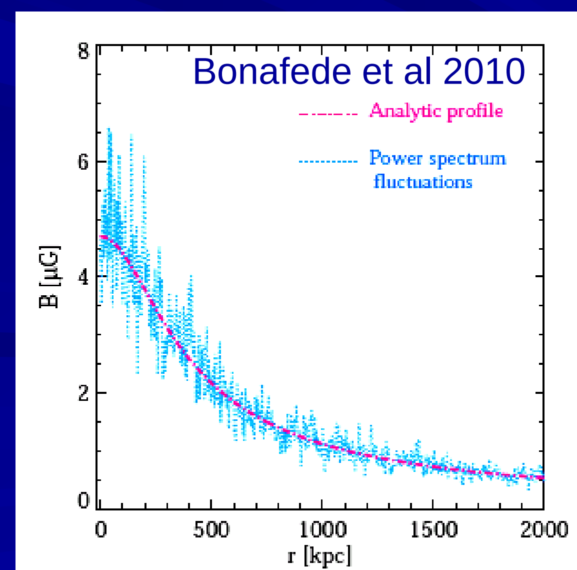
$$\sigma^2_{RM} = \langle RM^2 \rangle = 812^2 \Lambda_c \int (n_e B_{\|})^2 dl.$$

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



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

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



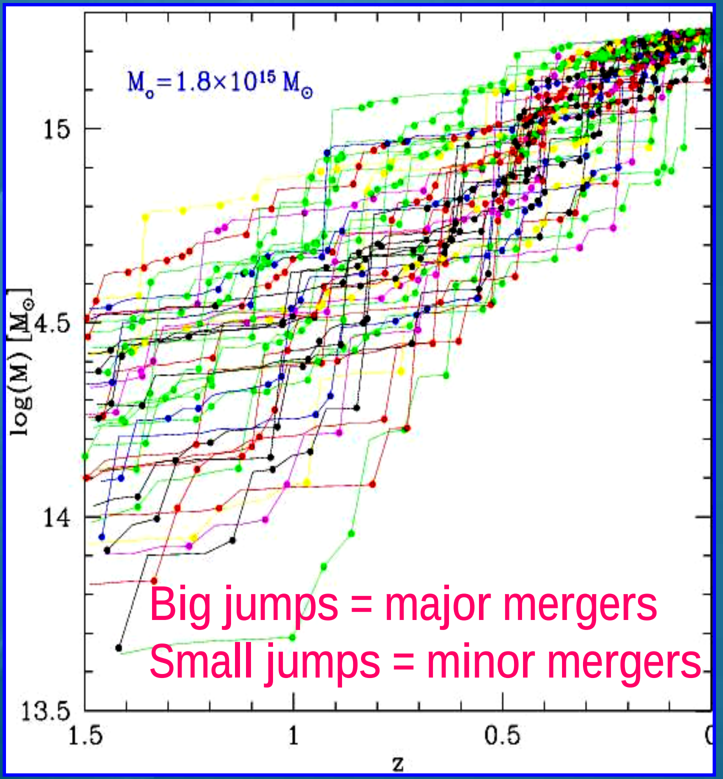
Testing turbulent models ??

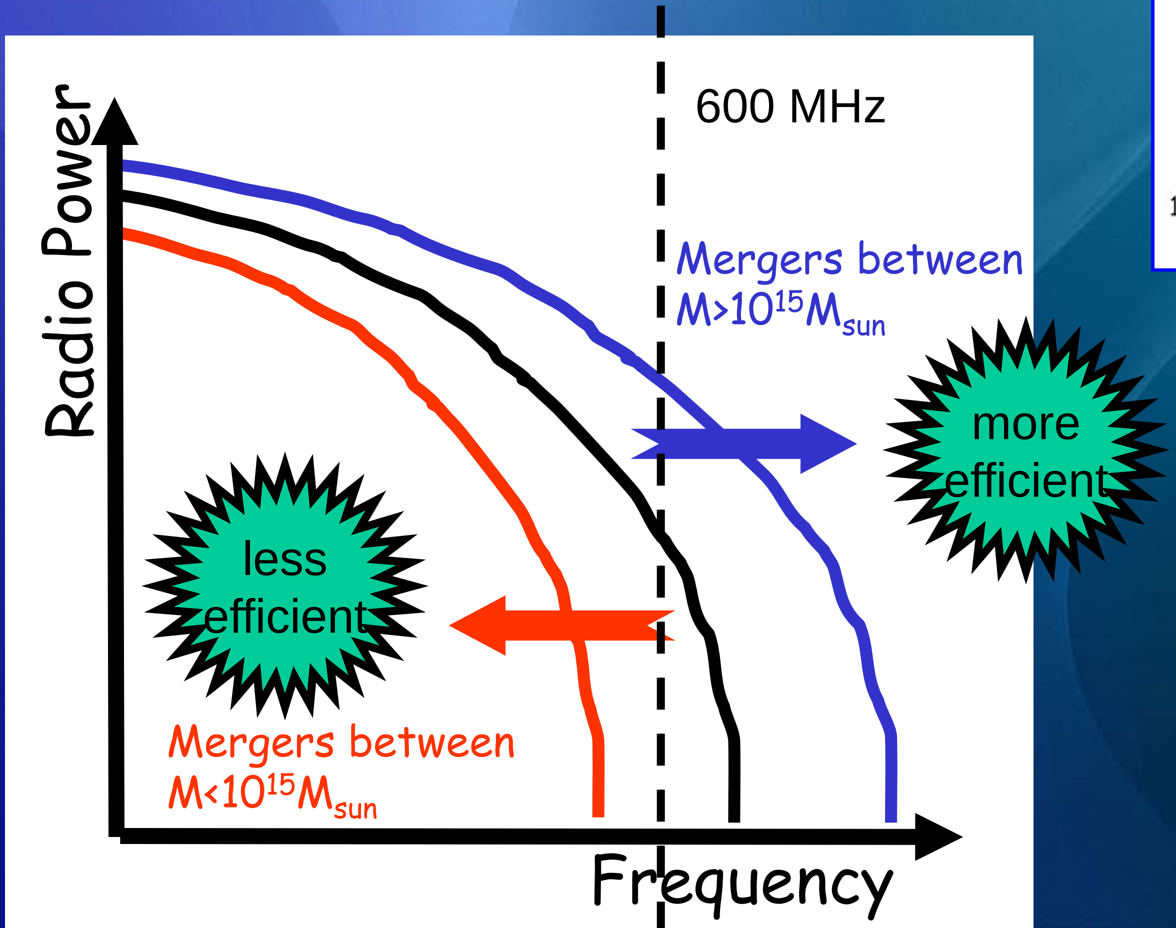
Acceleration efficiency

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

Steepening frequency

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





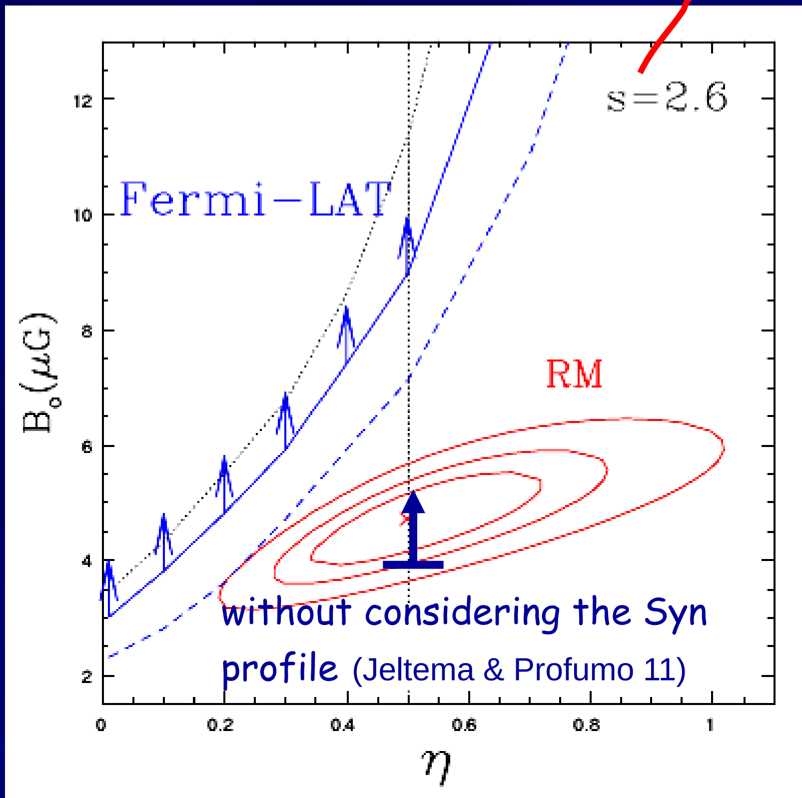
Radio Halos with very steep spectrum in the classical radio band must exist

(Cassano, GB, Setti 06)

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

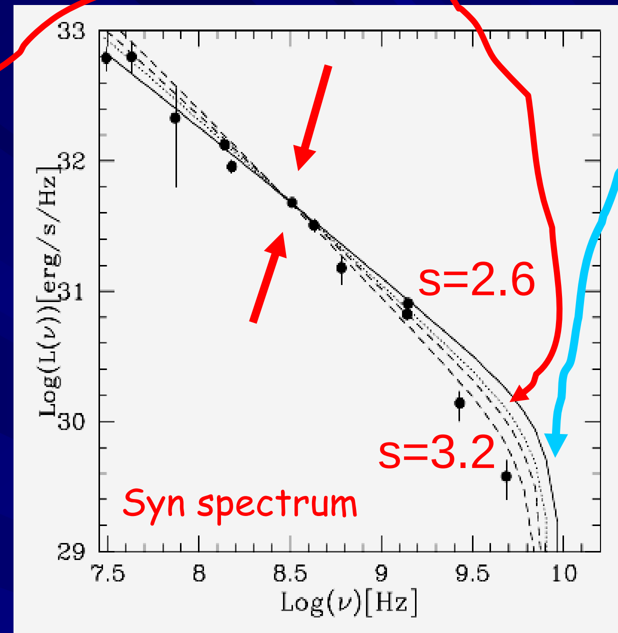
$N_{cr}(p,r)=K(r)\,p^{-s}$

$B(r)=B_o(\varepsilon_{TH}/\varepsilon_o)^{\eta}$



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

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



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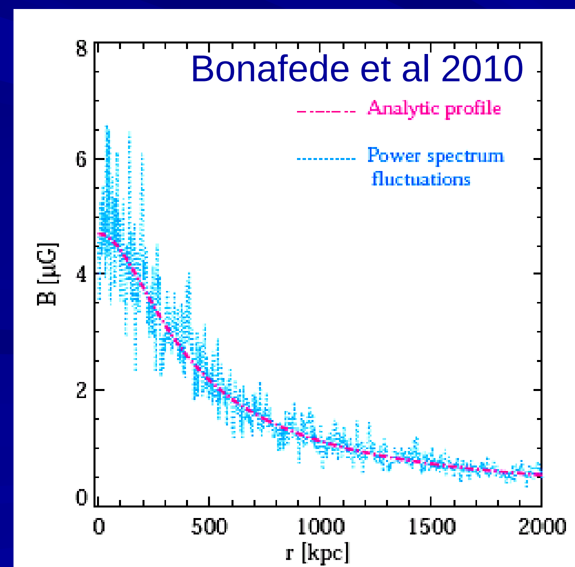


Does turbulence alleviate problems with γ-rays in a "hadronic-based" scenario ?

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

see also GB+Blasi 2005 MNRAS 363 1173

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

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

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

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

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

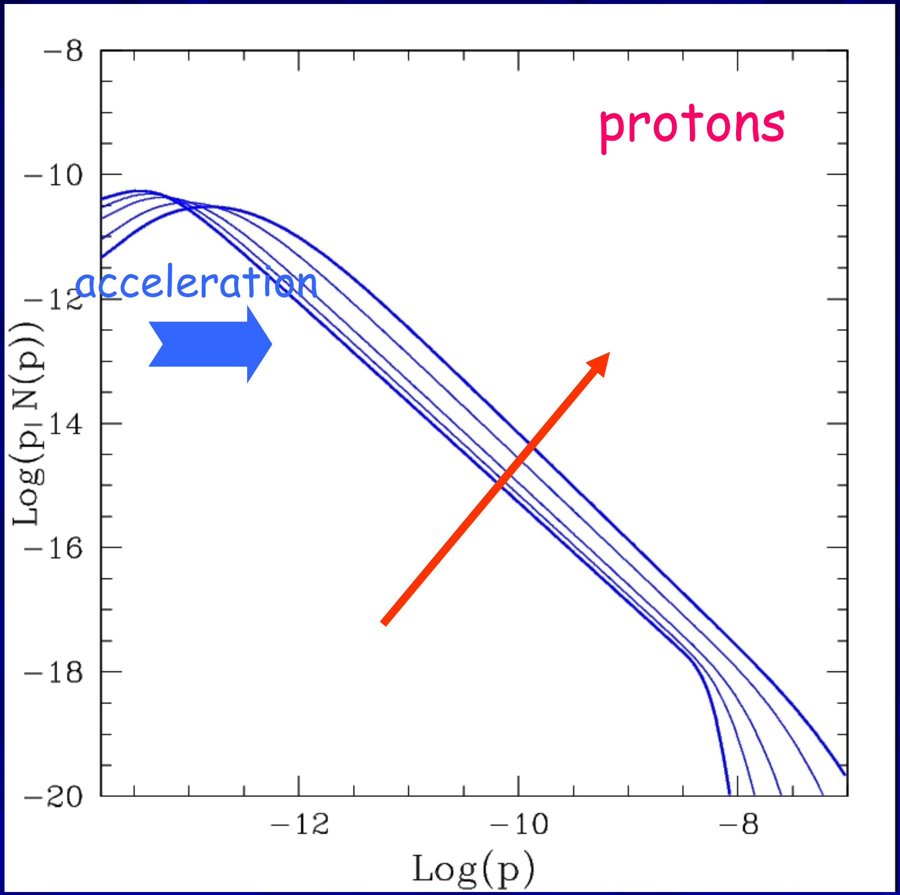
For I(k)=0 this is a "pure" secondary model.

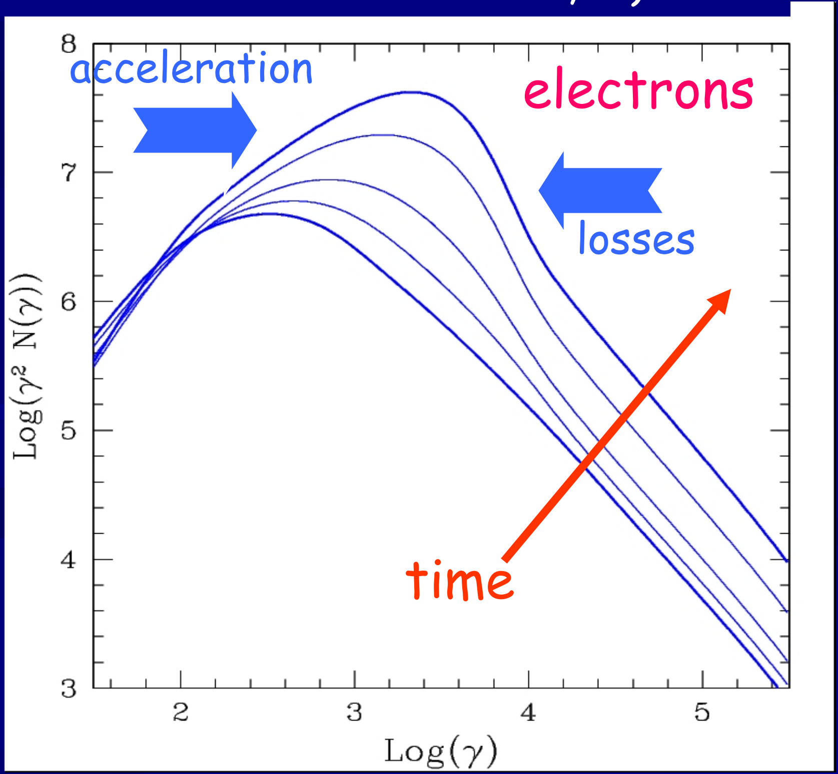
Transit Time Damping (TTD)

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

Interaction btw magnetic moment of particle and parallel gradient of B

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

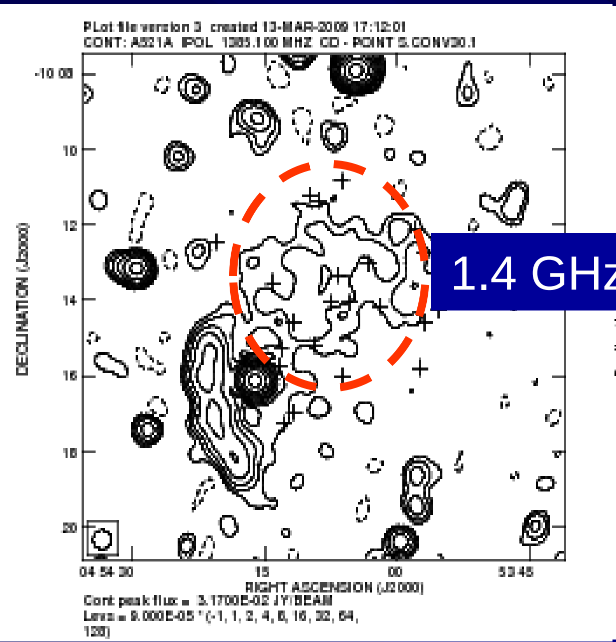


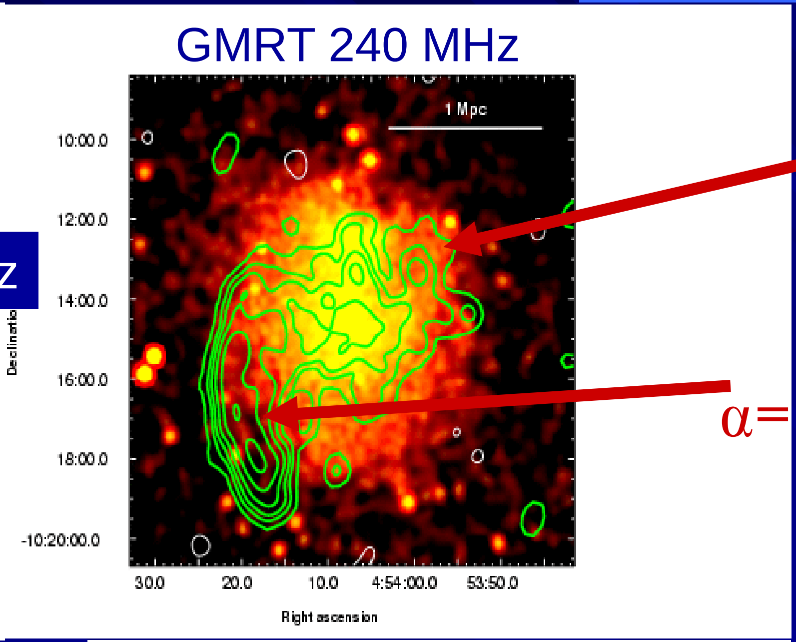


The modification of the electrons spectrum at energies of few GeV increases the ratio Syn/gamma and creates a curvature in the Syn spectrum at higher radio frequencies

Turbulent acceleration?

Brunetti +al 2008, *Nature 455, 944*

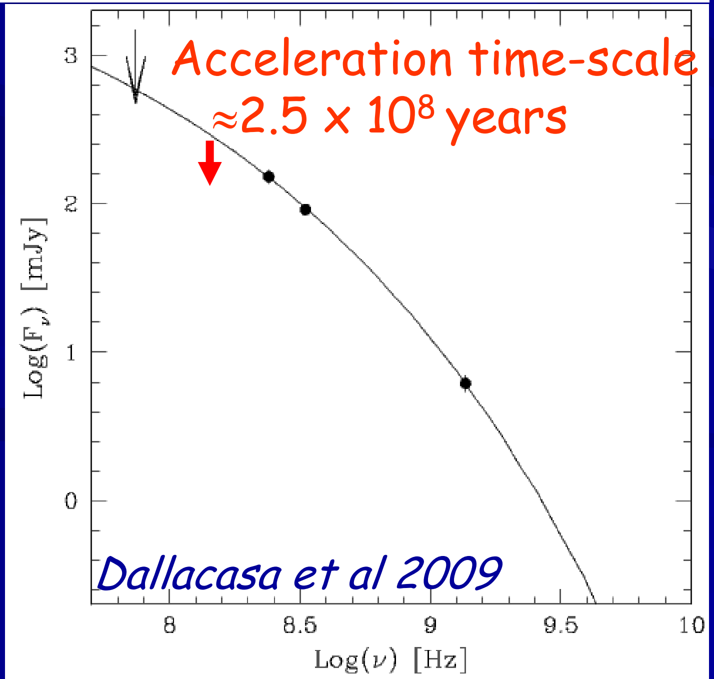




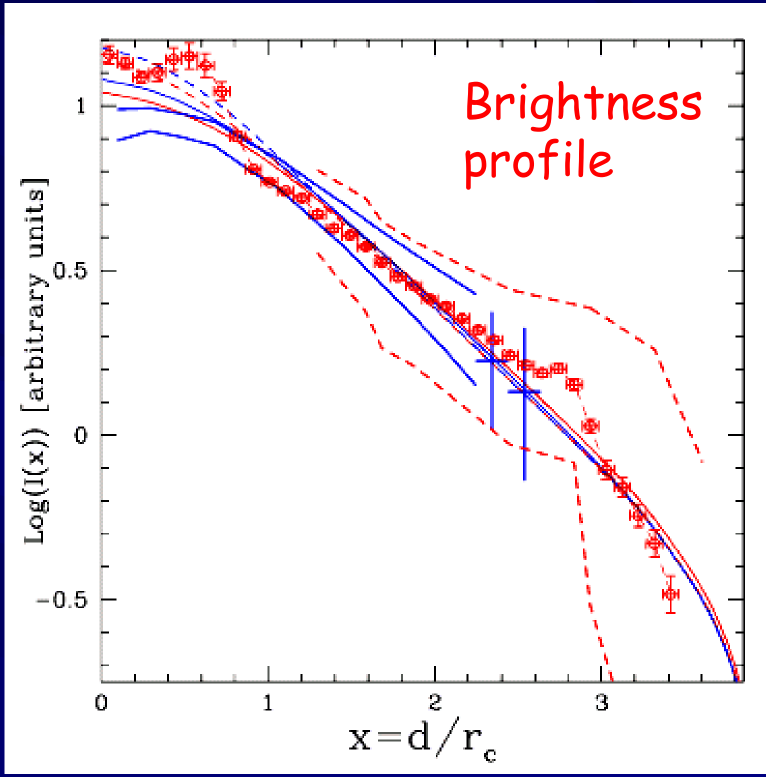
α=1.9

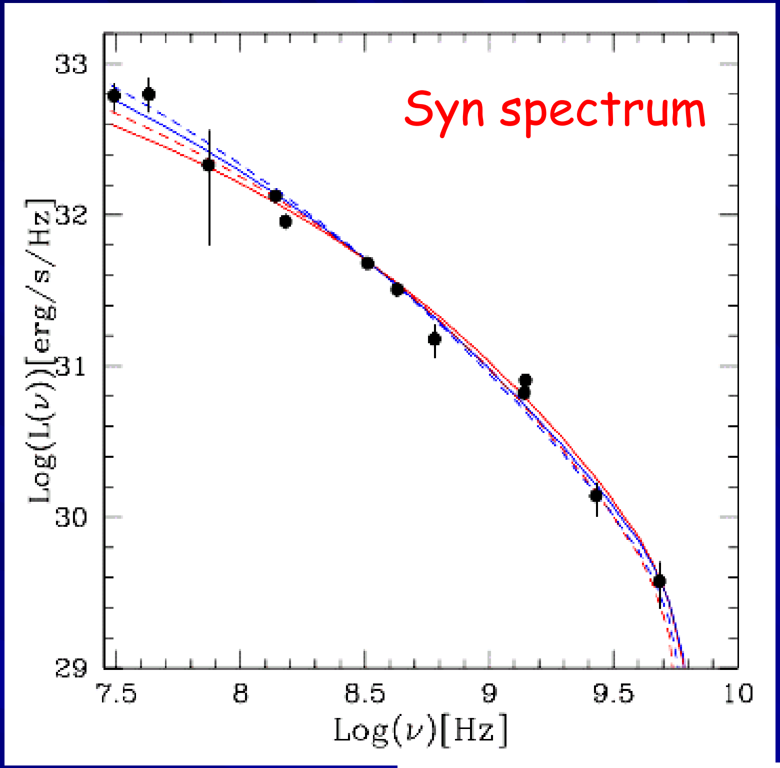
$N(E)=k\,E^{-4.8}$

α=1.4



Results from reacceleration (GB +al 2012, sub)



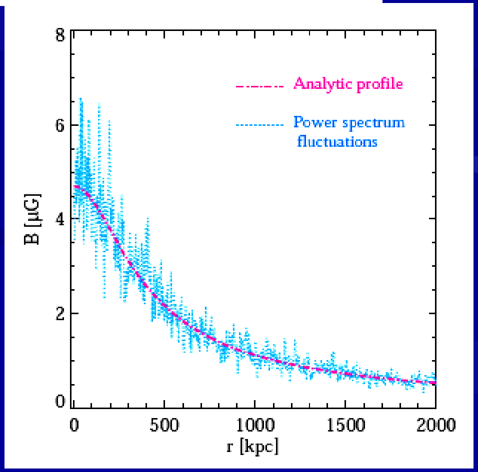


$\varepsilon_{CRp}/\varepsilon_{TH} \approx 0.05$

(flat CRp profile on RH-scale)

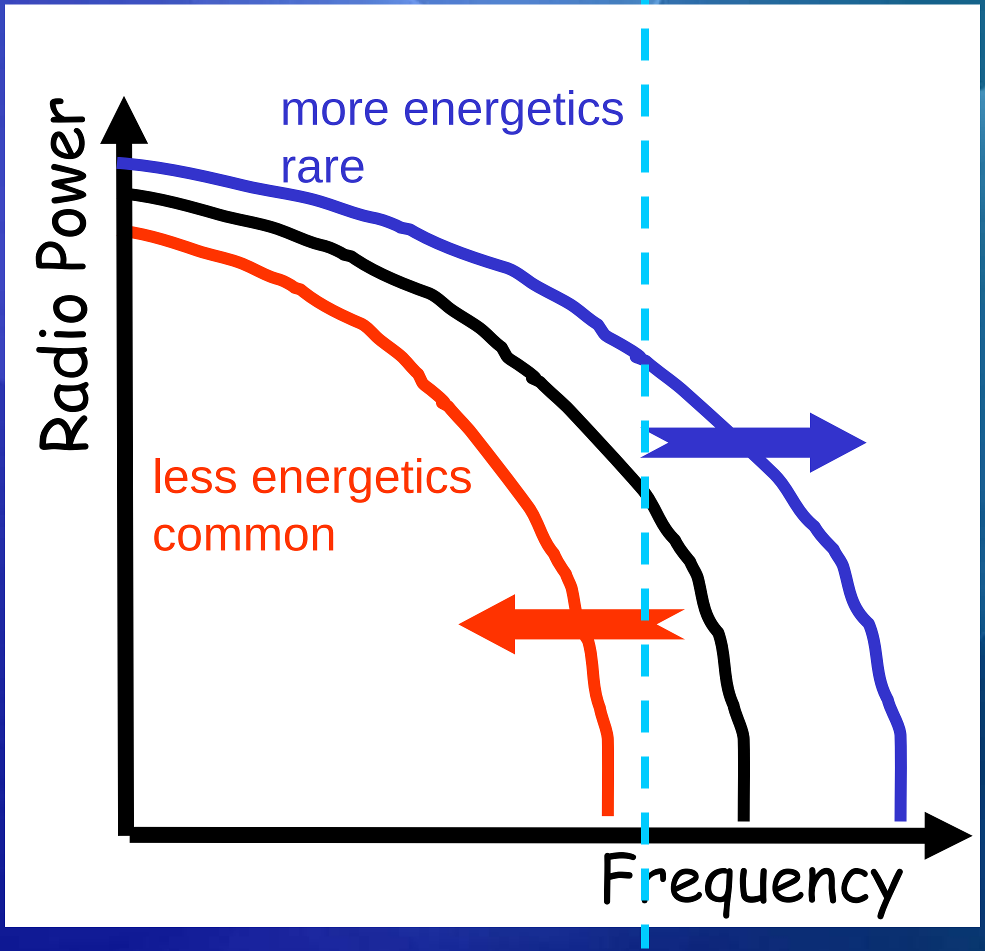
$(\delta V_l)^2/ c_s^2 \approx 0.05$

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

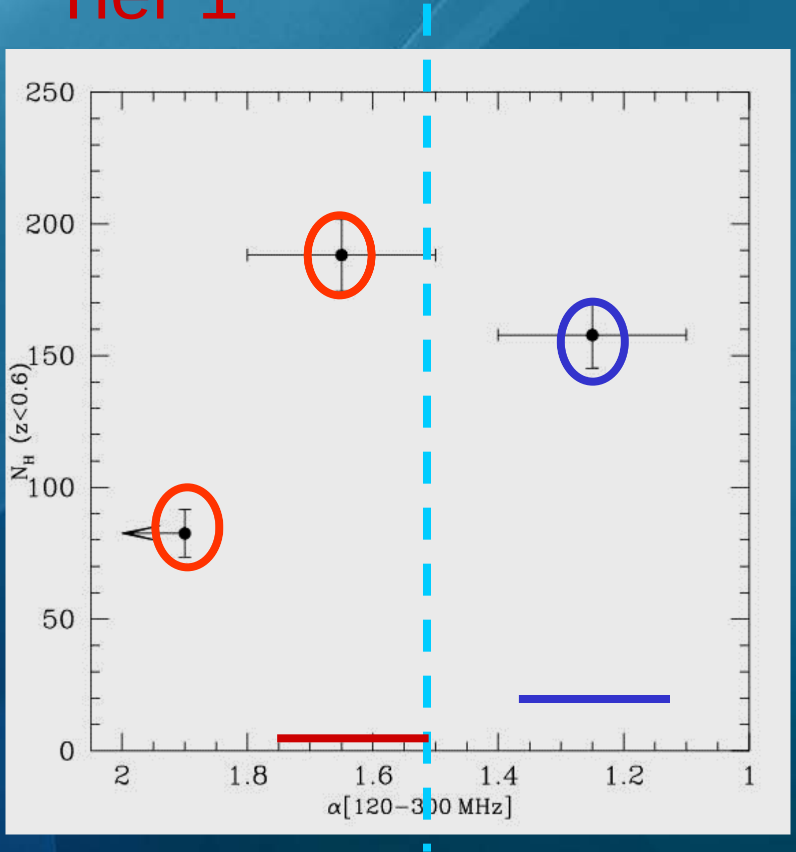


Spectral properties of Radio Halos

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



Tier 1



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