Cosmic rays in galaxy clusters: physics & gamma-ray observations

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OUTLINE :

(1) Introduction

- Galaxy Clusters & nonthermal components

(2) CRp in GClusters

- sources & dynamics of Cosmic Rays in GClusters
- gamma-ray limits & CRp accel efficiency

(3) Synchrotron cluster-scale radio emission & CRp

- Turbulent acceleration of CRp & secondaries
- constraints from new gamma-ray limits

Clusters of galaxies:

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

≈30-300 galaxies

Galaxy cluster matter :

Barions

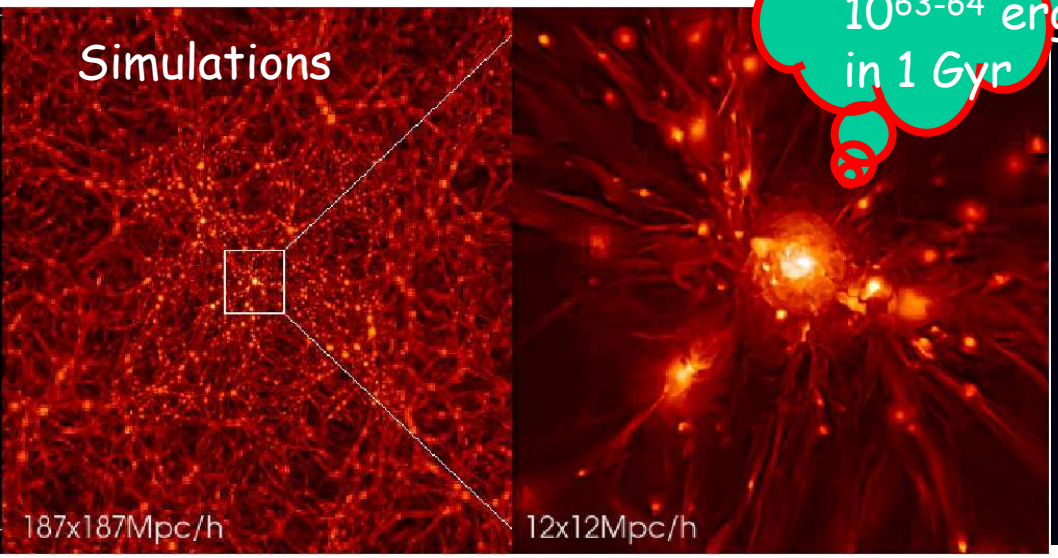
- 10% of stars in galaxies
- 15-20% of hot diffuse gas

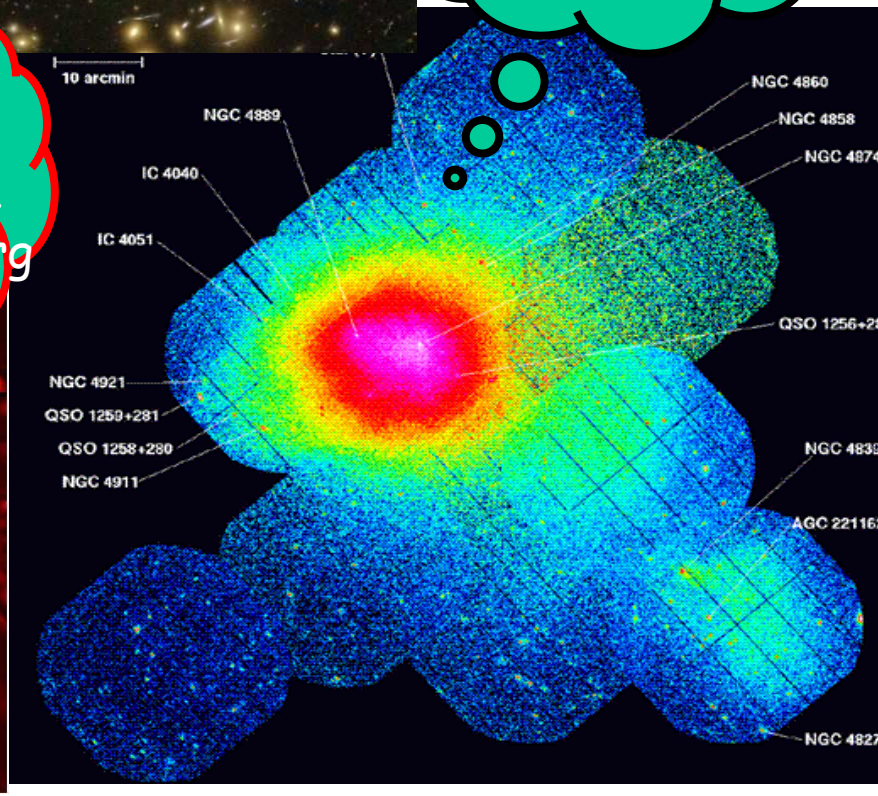
Dark Matter 70%

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

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

Mergers dissipate 10^{63-64} erg in 1 Gyr



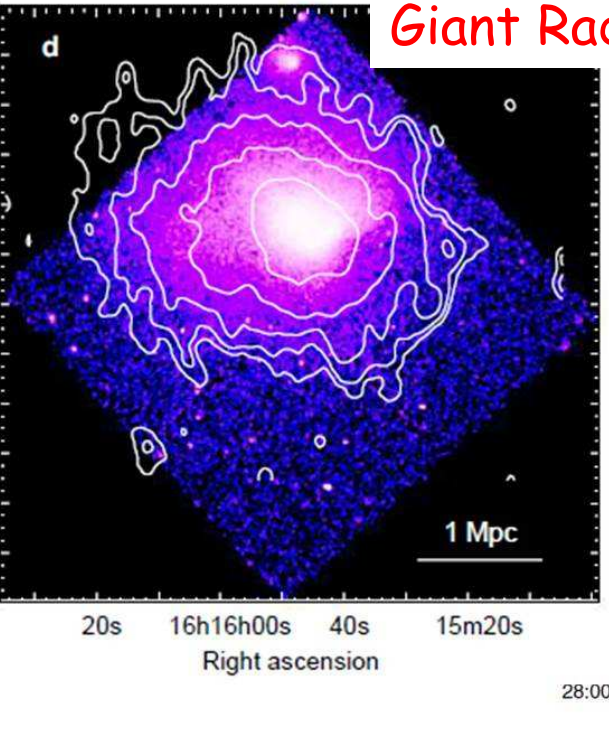


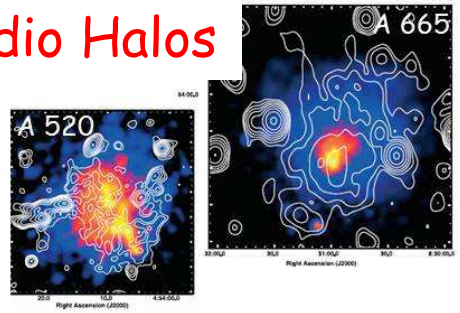
Cluster-scale radio emission

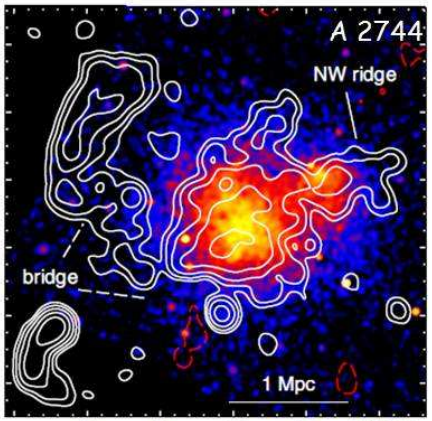
- GeV+ CR electrons
- μG+ level magnetic fields
- Connected with cluster mergers

[rev Brunetti & Jones 14, Feretti et al 12]

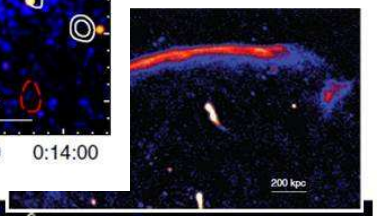
Giant Radio Halos

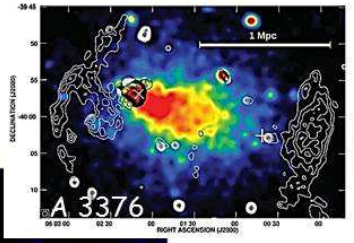


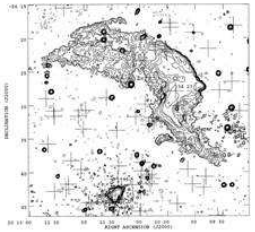


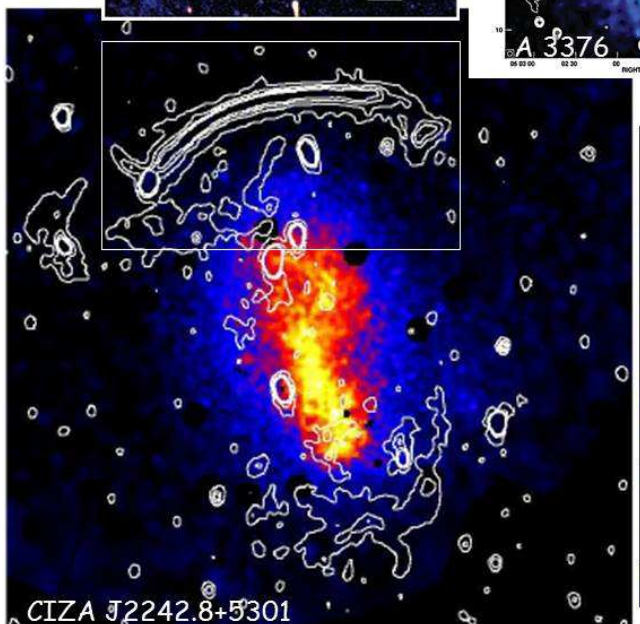


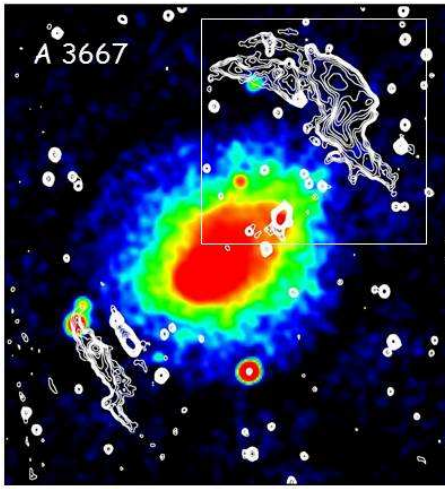
Giant Radio Relics









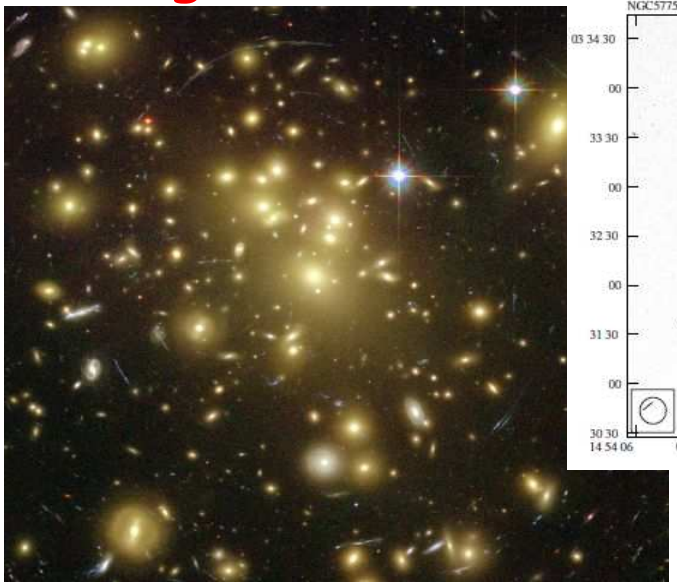


What about CRp ??

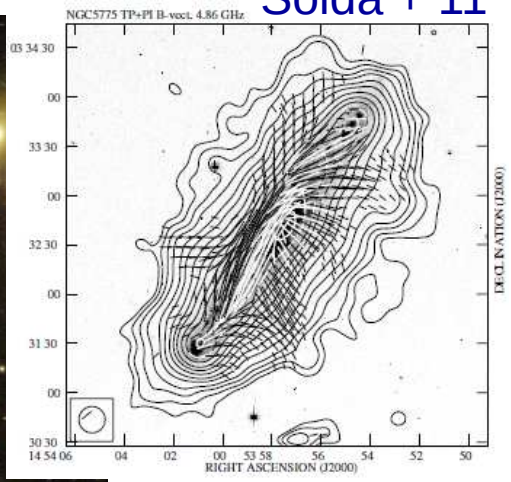
CRs in galaxy clusters: sources

Plenty of CR sources :

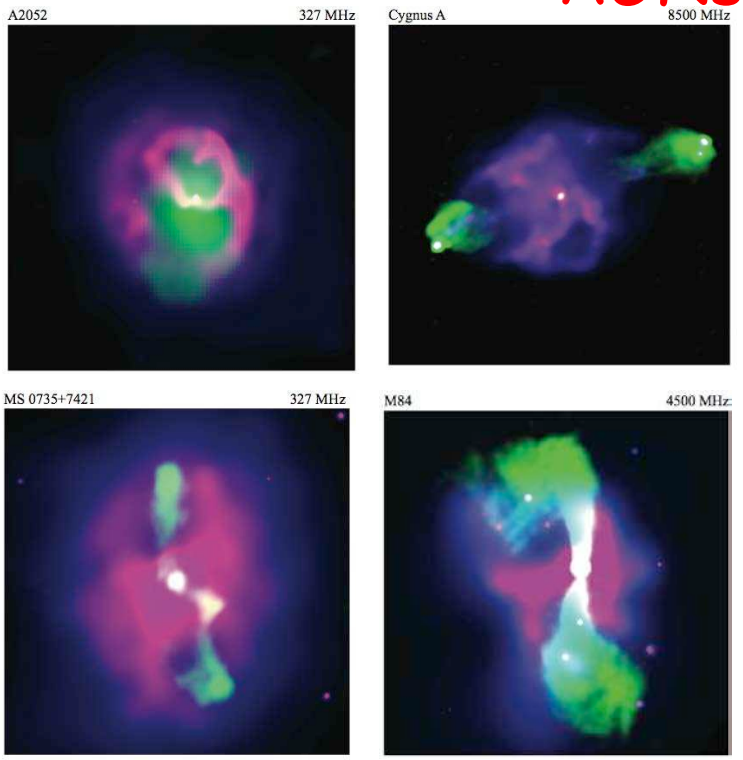
100+ galaxies



Soida + 11



AGNs



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

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

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

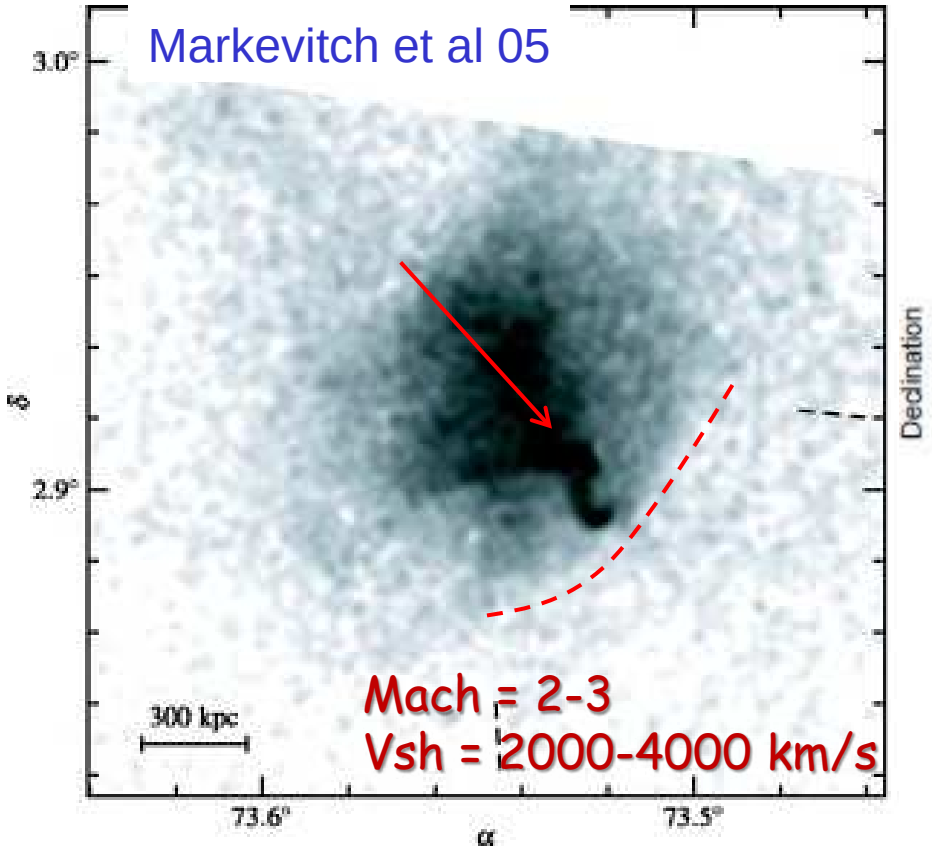
E_{CR} = 0.001-0.01 of E_{ICM} [CRprotons]

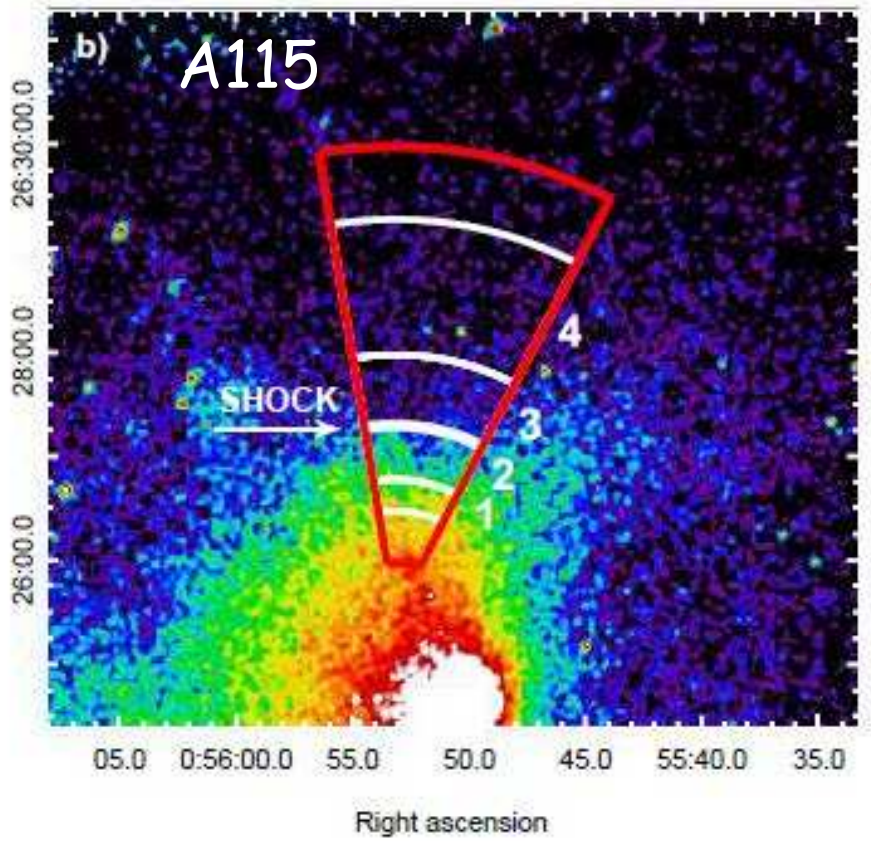
Estimate of number of AGNs, life-time and injection rate :

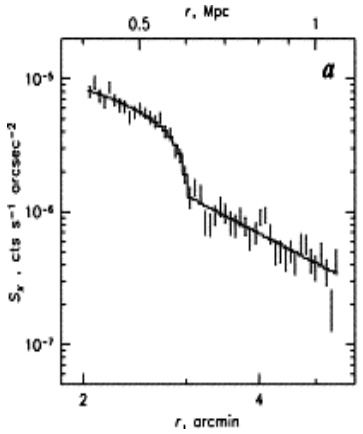
E_{CR} = 0.001 - 0.1 of E_{ICM} (??)

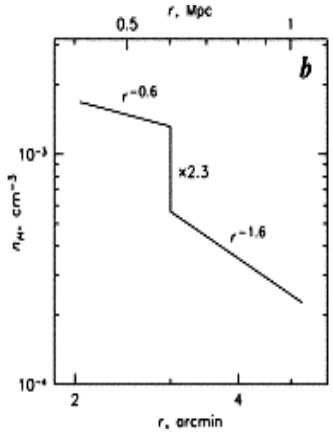
- Thermal plasma in the bubbles
- Poynting/leptonic/hadronic
  (rev: McNamara & Nulsen 07)

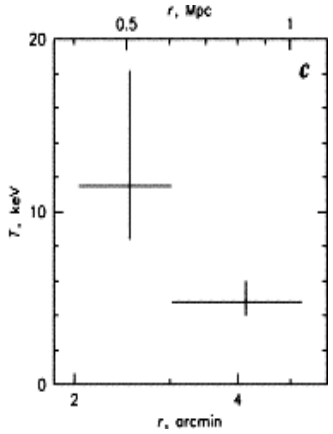
CRs sources: Shocks in Galaxy Clusters

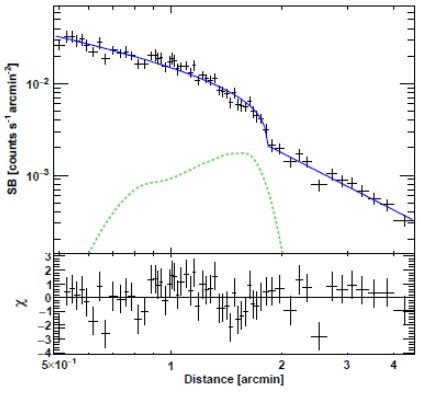


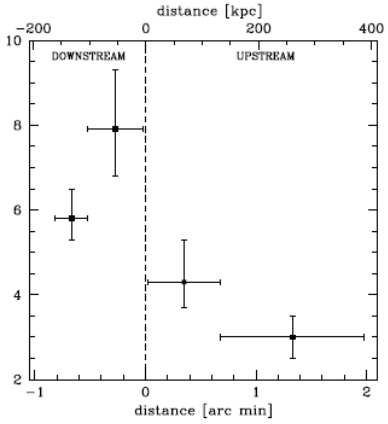








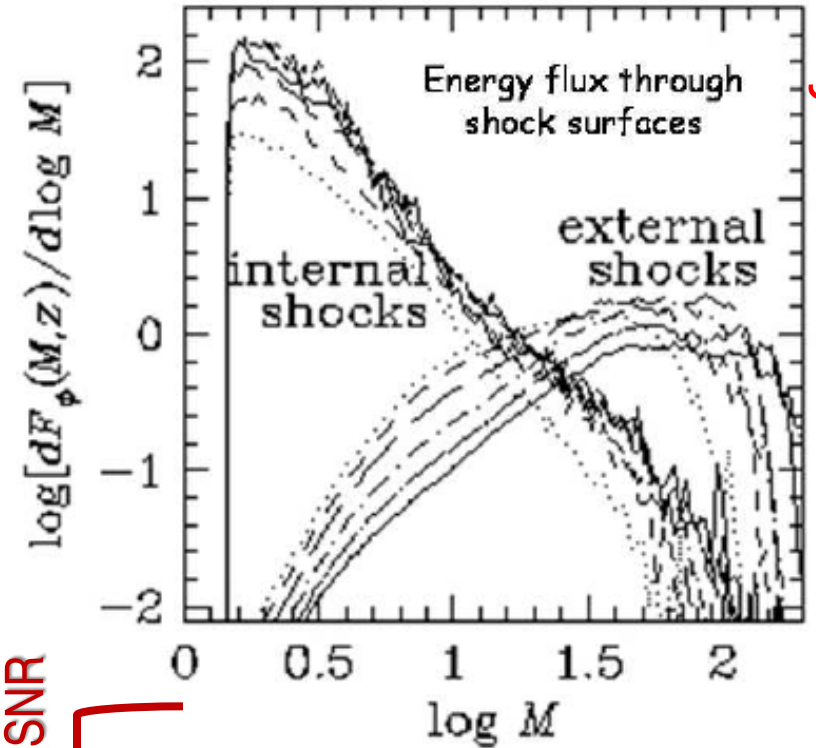




Cosmological Shocks as CRs accelerators

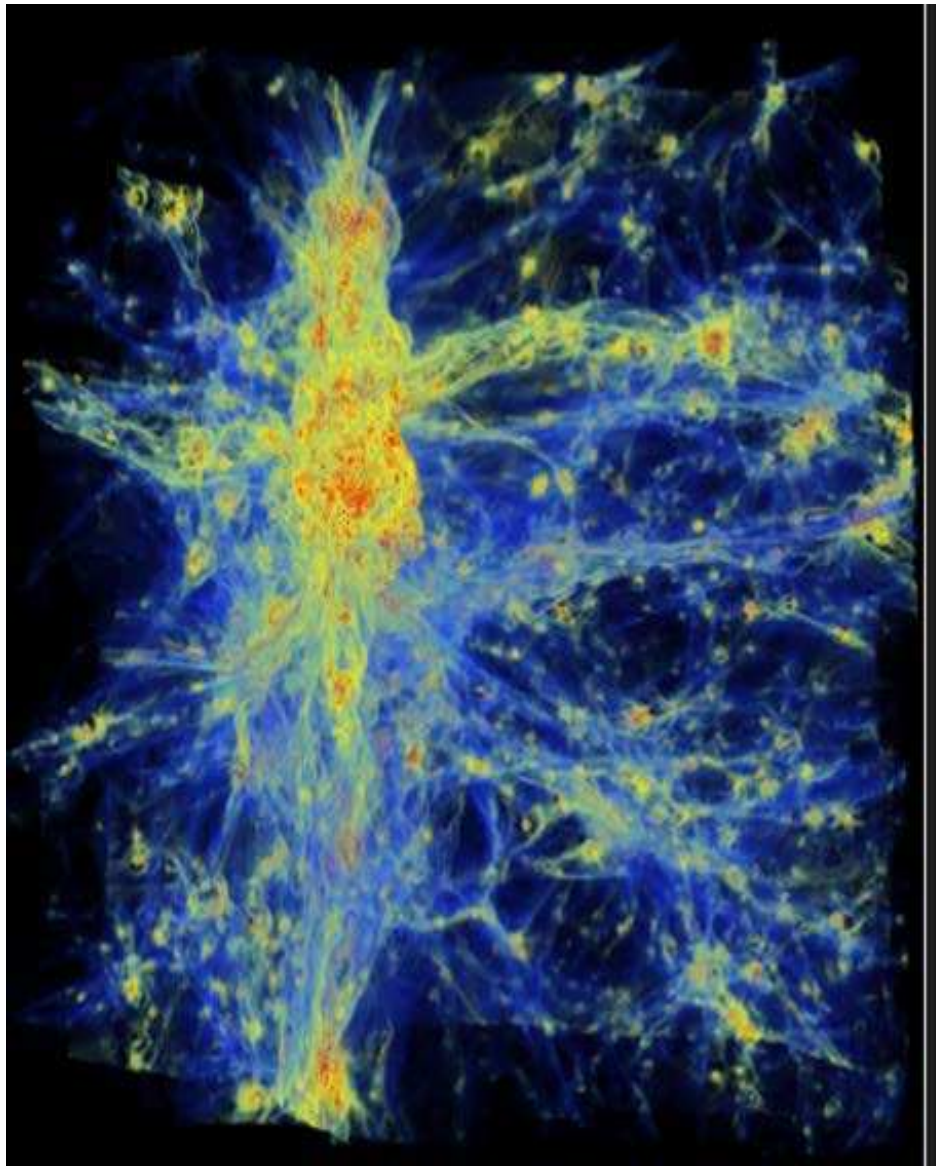
(Bruggen et al 12, Brunetti & Jones 14 for revs)

Most popular in the last 10+ yrs



Ryu et al 03

Vazza, Brunetti, Gheller 09

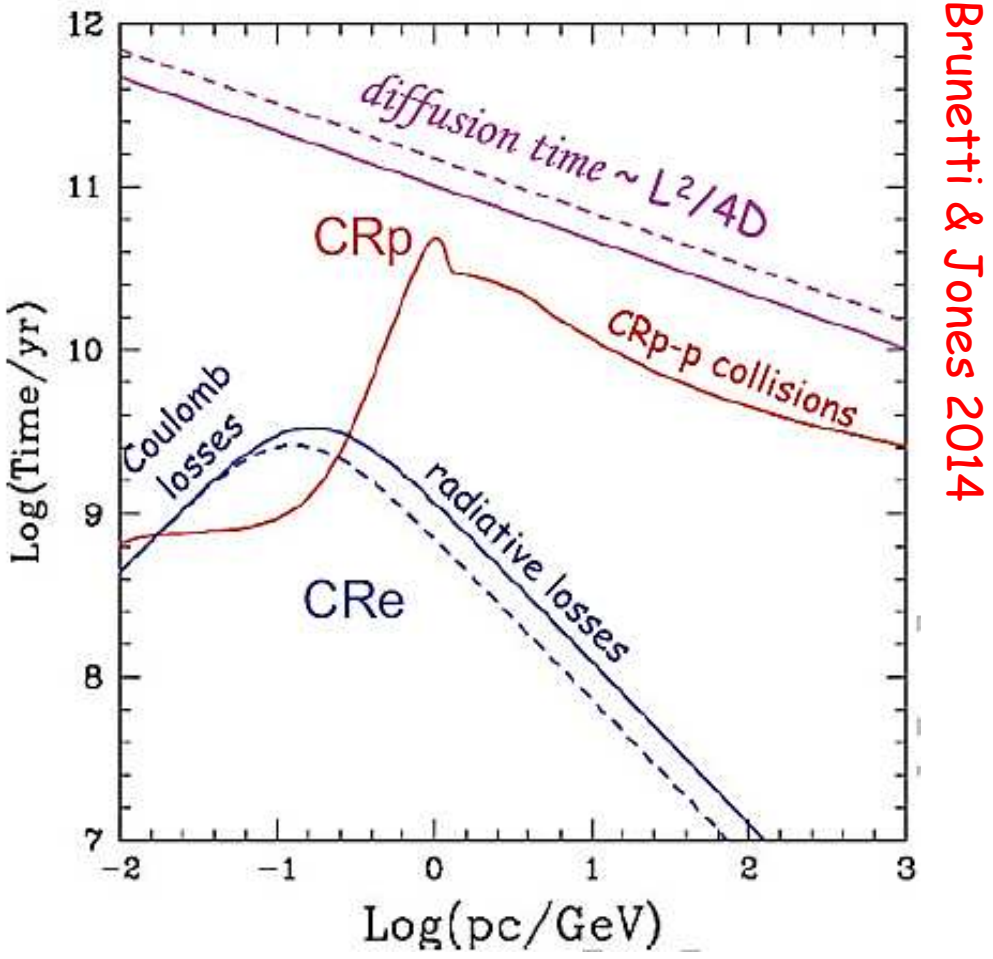


extrapolation from SNR

The bulk of ICM heating is due to internal shocks.
If shock acceleration efficiency in the ICM is 10% the resulting CRs (CRp) would store up to. 0.1 E_{TH}

CRp confinement

(Voelk et al. 96, Kang et al 96, Berezinsky et al 97,.. etc) …

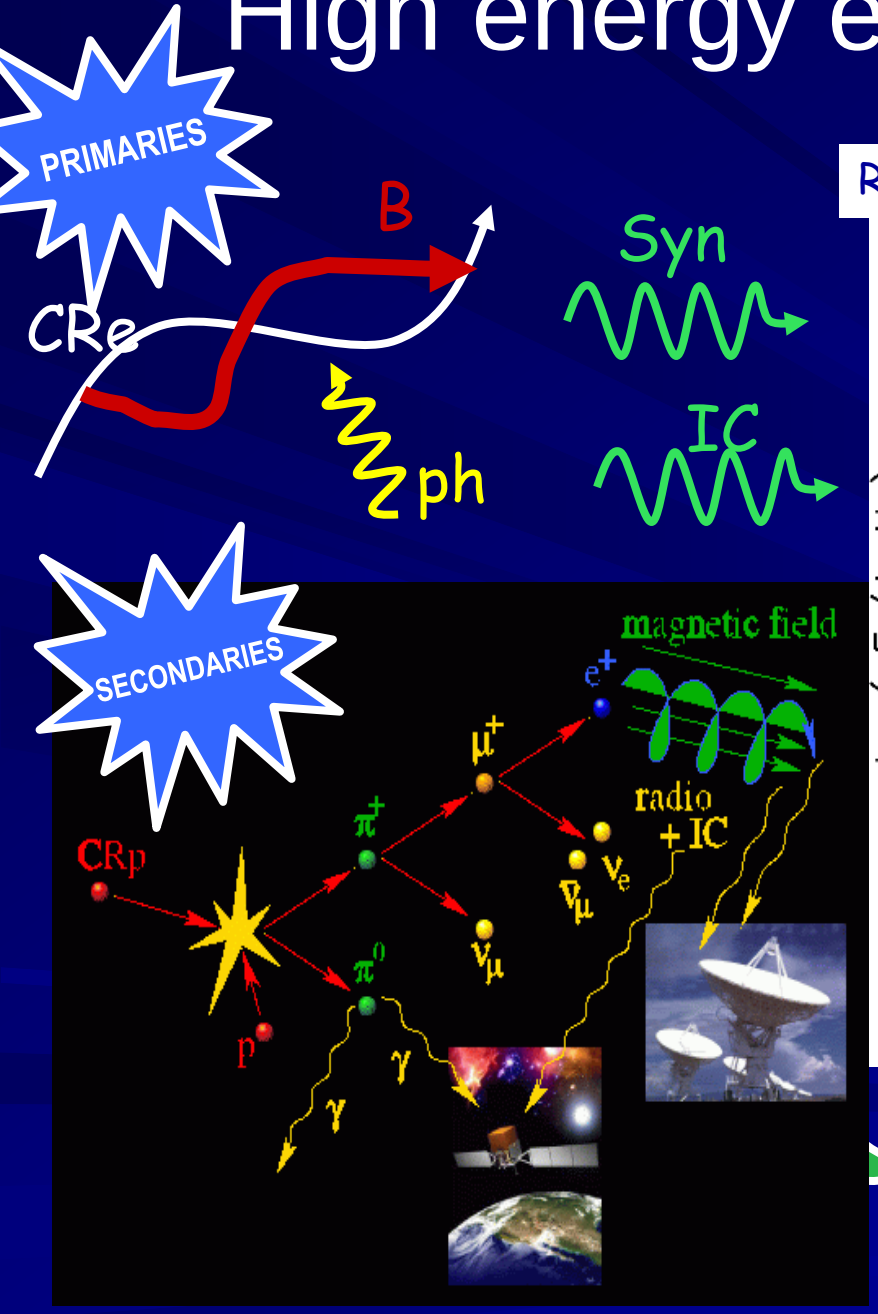


Brunetti & Jones 2014

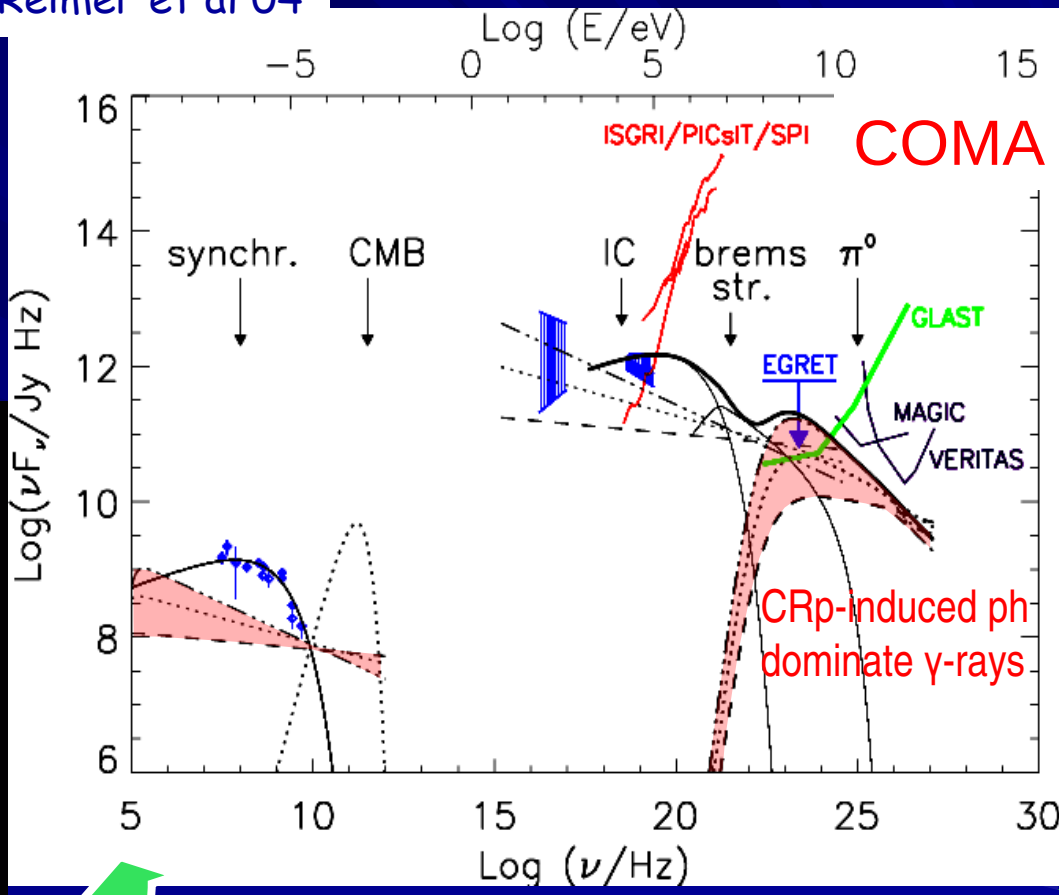
- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

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

High energy emission from GC



Reimer et al 04

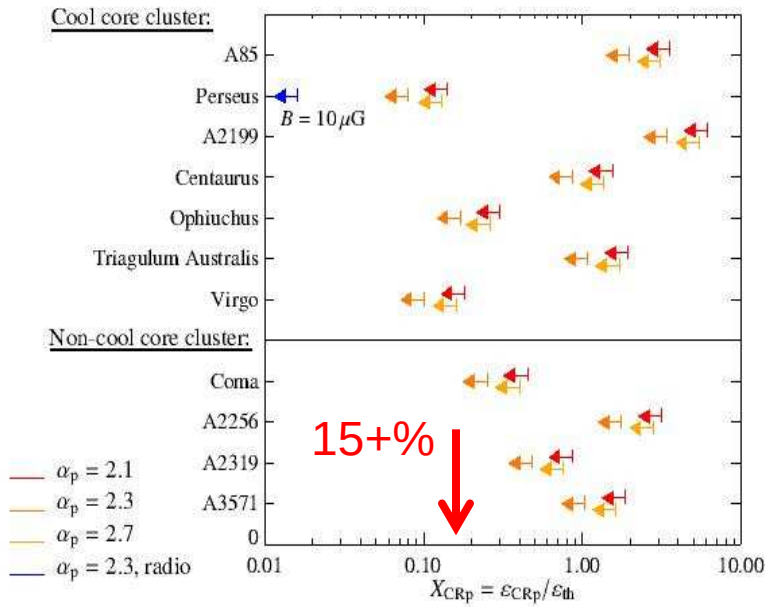


Miniati et al 01, Brunetti & Blasi 05, Blasi et al 07, Pfrommer et al 08, Brunetti & Lazarian 11

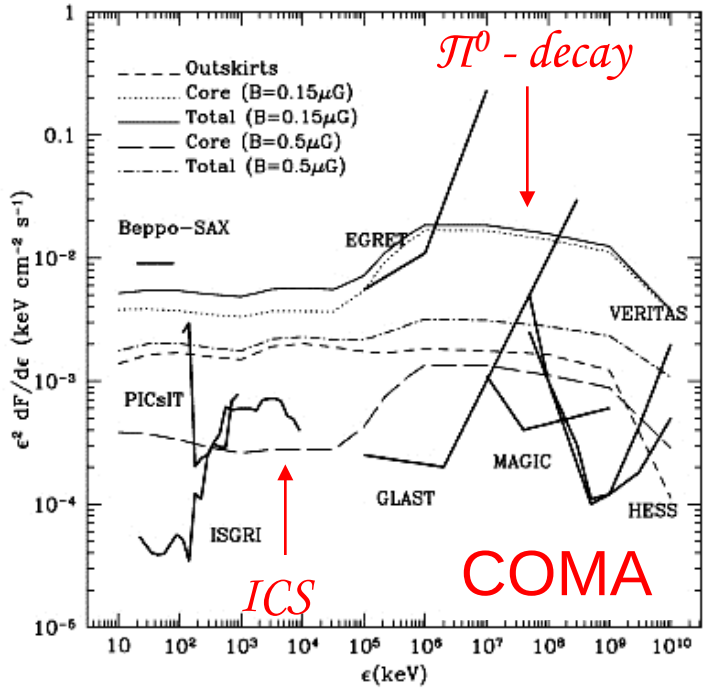
Limits & predictions in the "pre"- FERMI era

EGRET

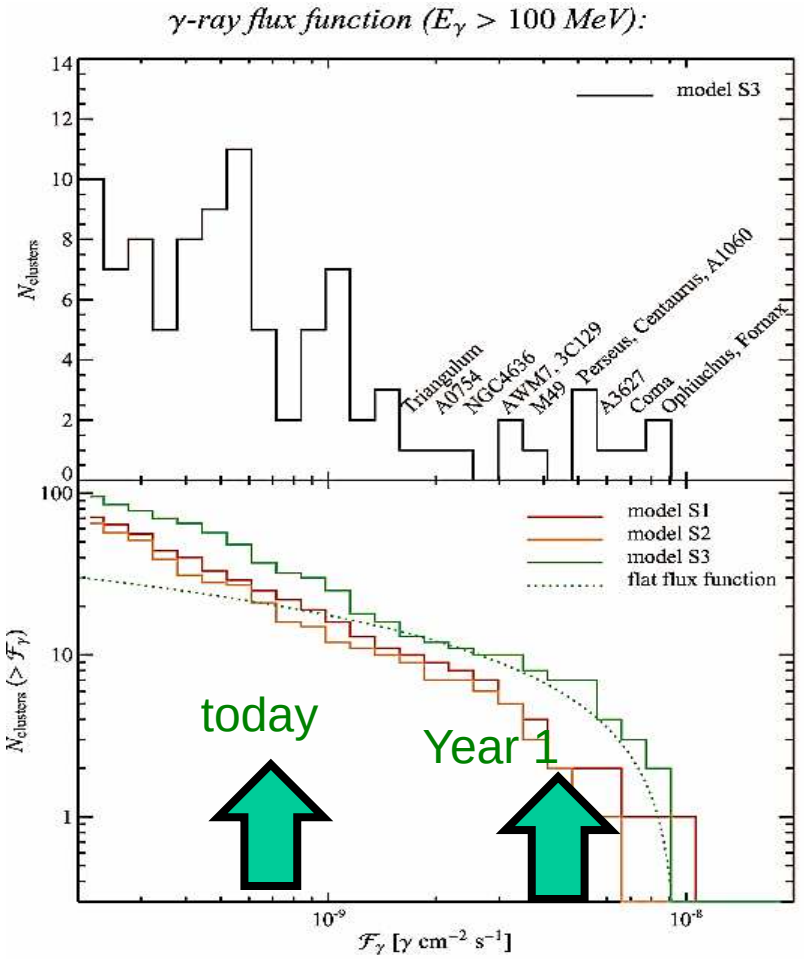
Reimer et al. 03, Pfrommer & Ensslin 04



Miniati 03



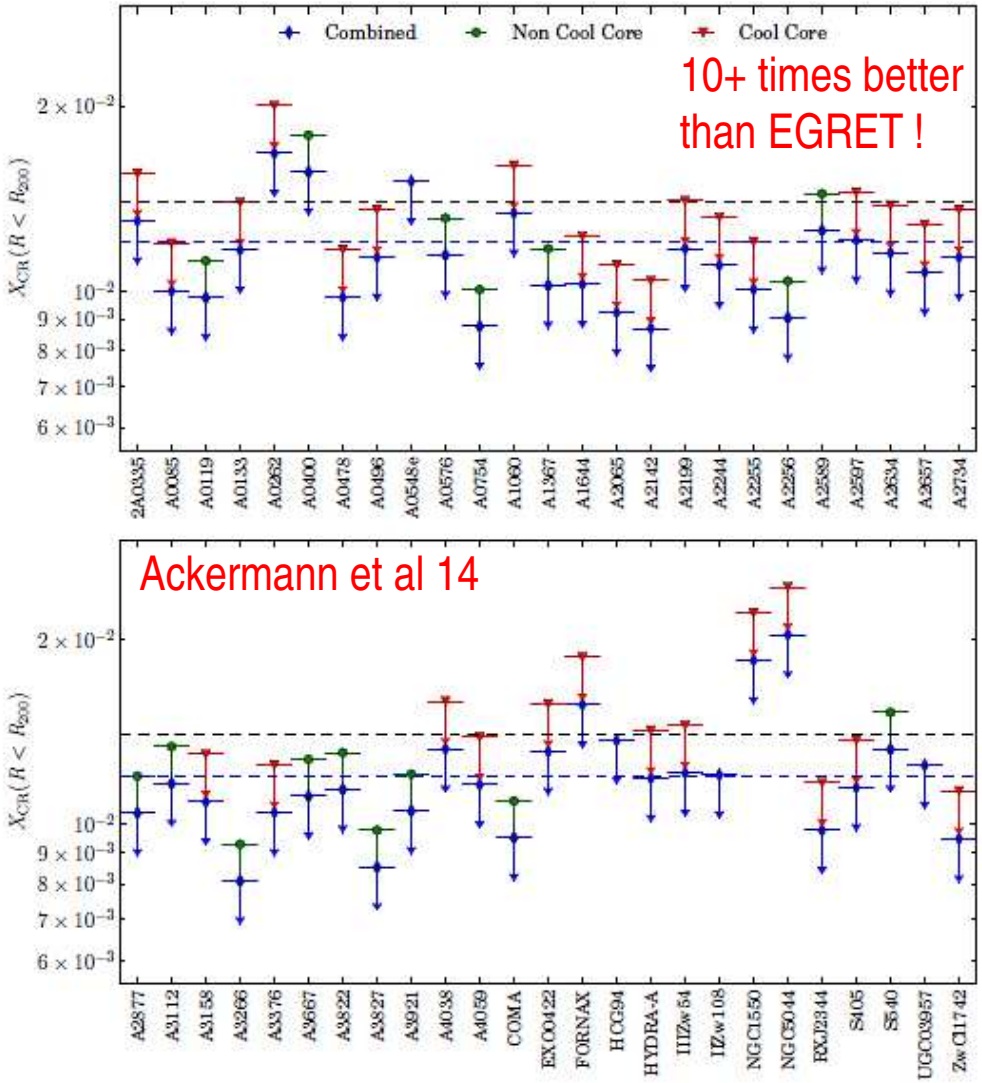
Predictions for Fermi-LAT based on "optimistic" extrapolation of SNR-shock physics

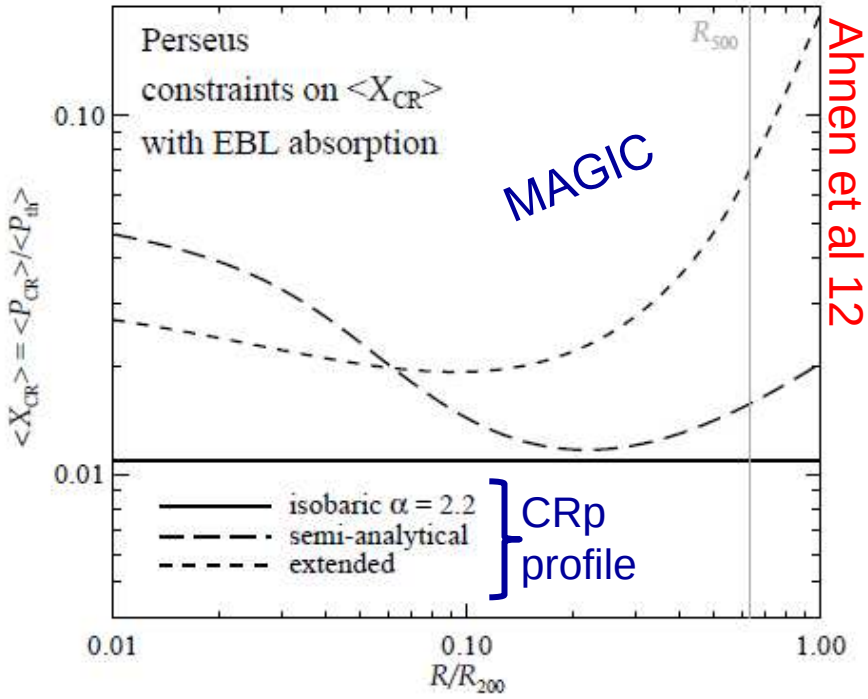


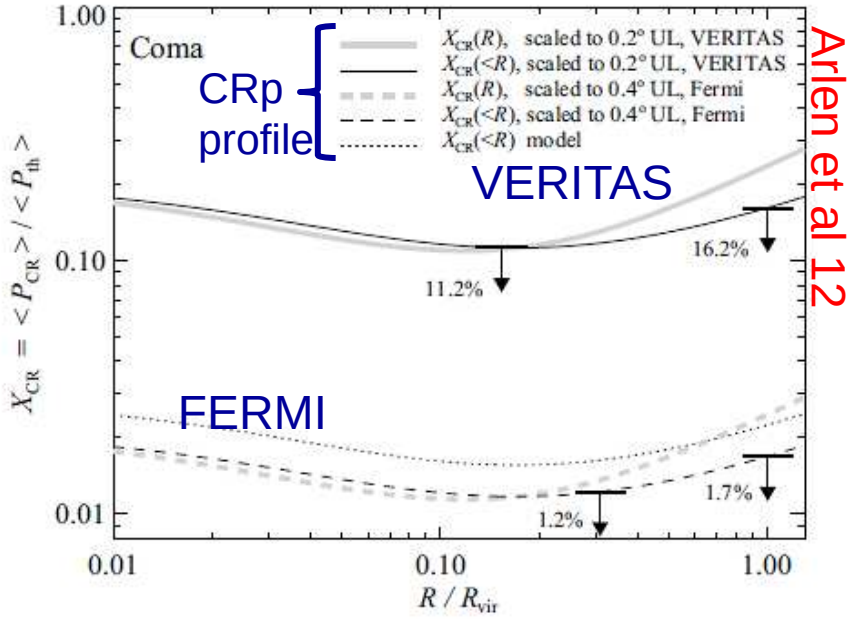
Pfrommer 08

Limits to the CRp energy budget

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

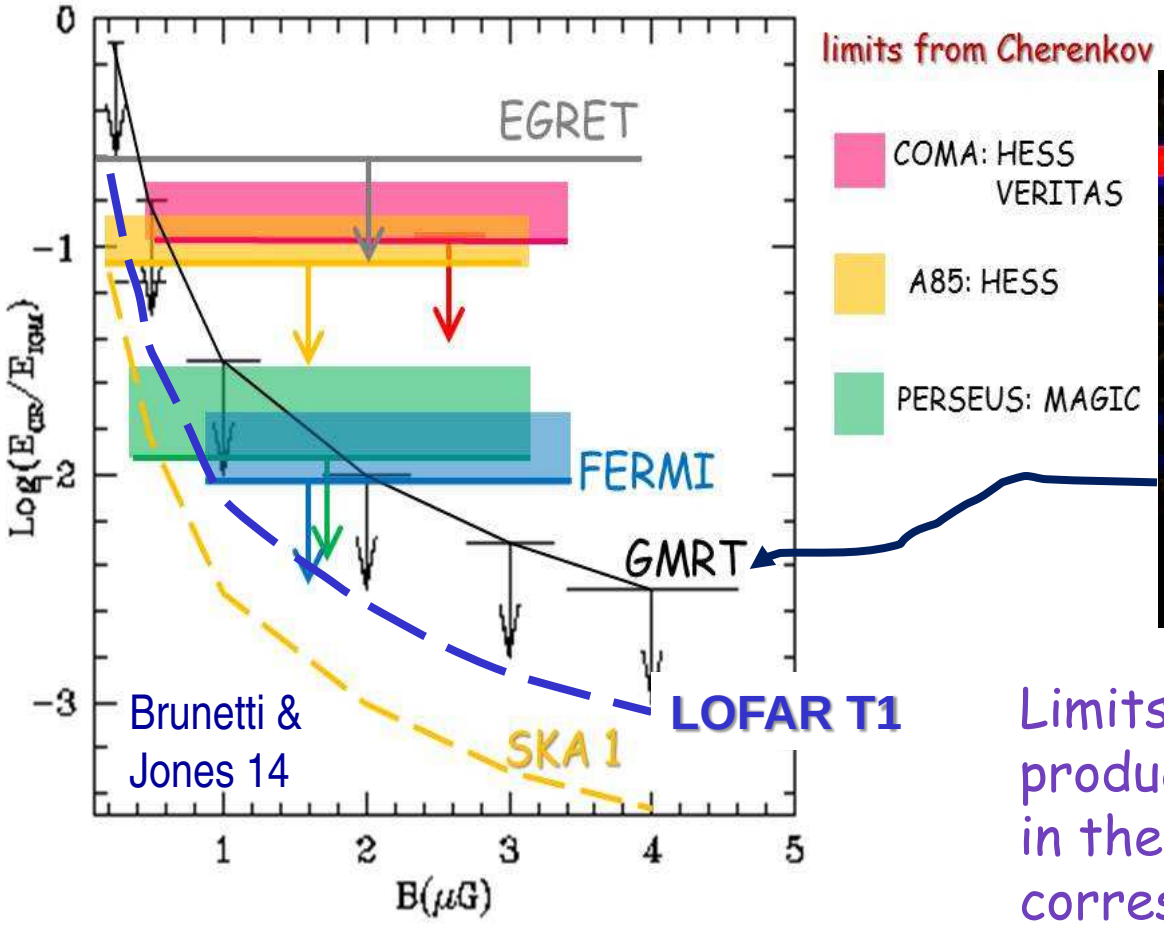




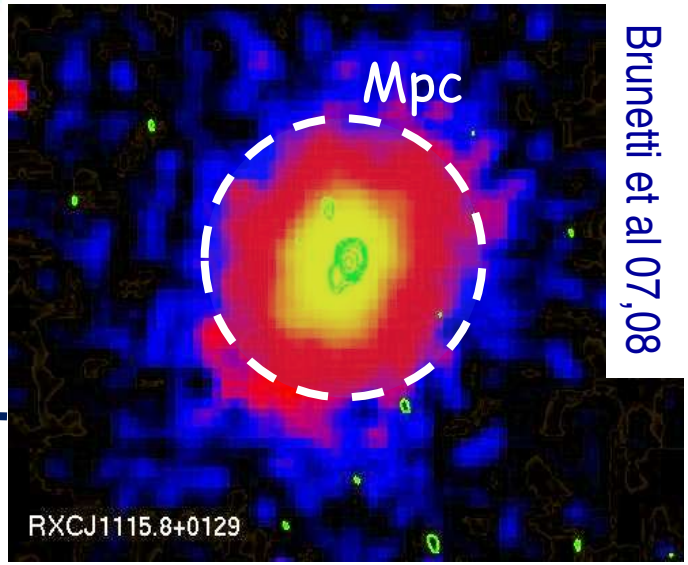


Limits to the CRp energy budget

Wrap up….



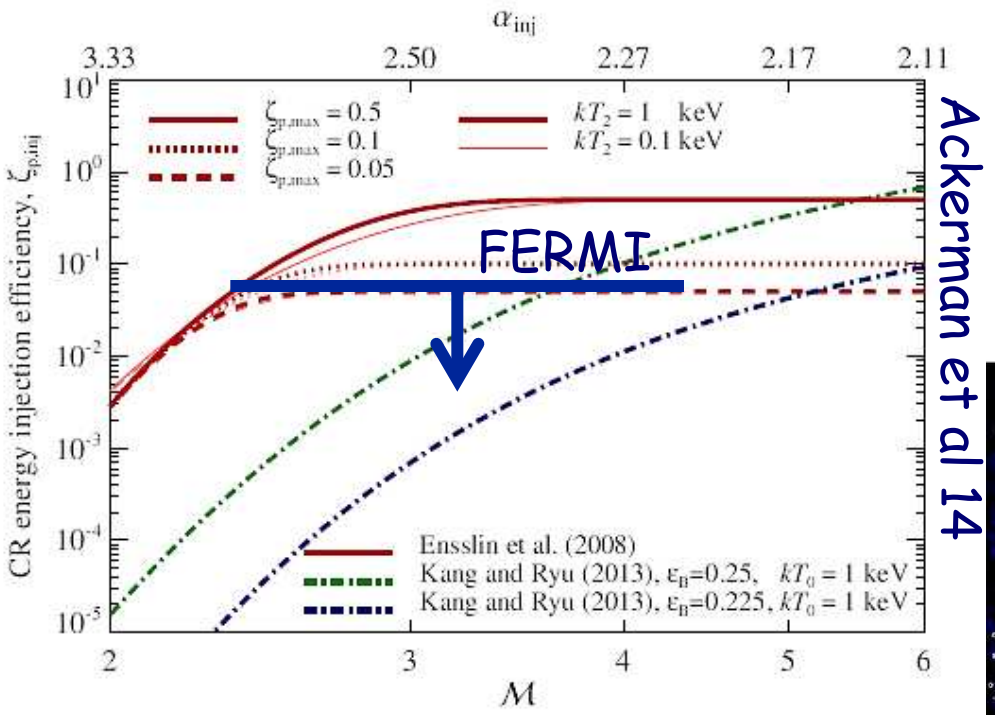
Syn radio limits :



Limits on the synchrotron flux produced by secondary electrons in the ICM allow to calculate corresponding limits on (B, ECRp).

Reimer et al. 04, Pfrommer & Ensslin 04,Perkins et al. 06, 08, Brunetti et al. 07,08, Perkins et al. 08, Aharonian et al. 08, Aleksic et al. 09,12, Ackermann et al 10,14, Arlen et al 12, Griffin et al 14, Zandanel+Ando 14, …

Constraining CRp acc efficiency

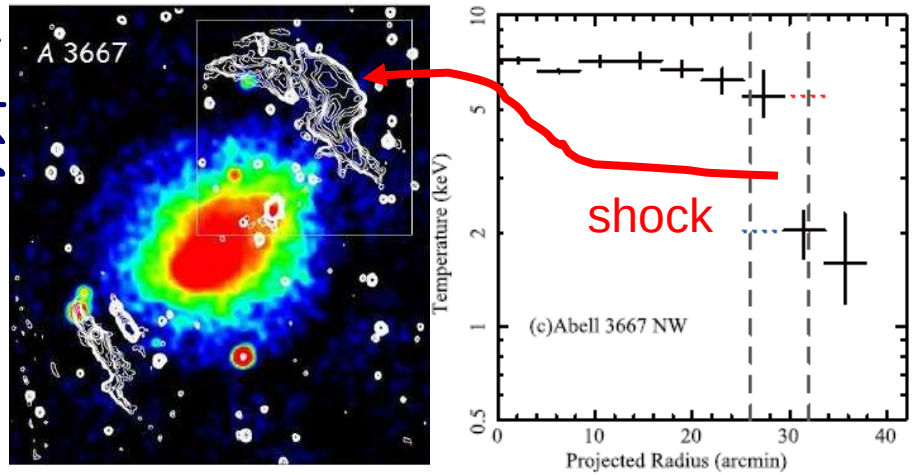


Ackerman et al 14

Limits on the CRp energy density allow to put corresponding limits on the acceleration efficiency assuming shock acceleration and CRp confinement.

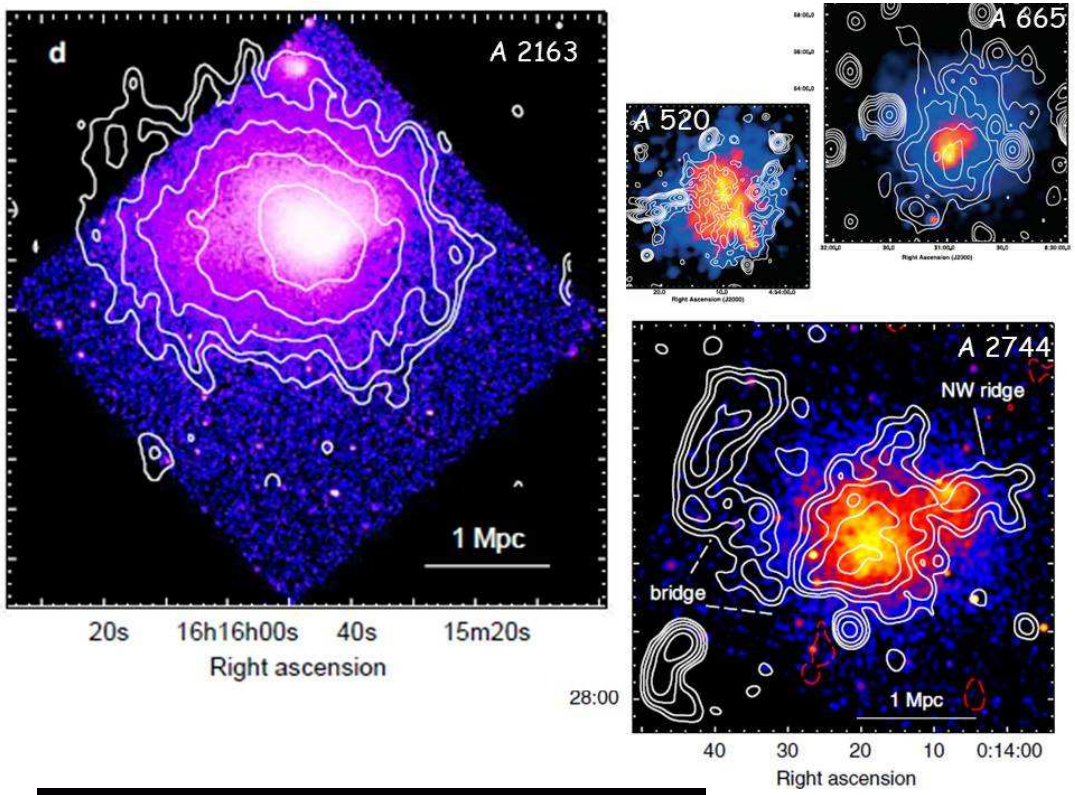
"optimistic" extrapolation based on SNR shocks is ruled out …

BUT clusters shocks are efficient to (re)accelerate CRe (to GeV+) as demonstrated by Radio Relics
(Ensslin et al 98, Markevitch et al 05, van Weeren et al 10, Kang et al 12…)



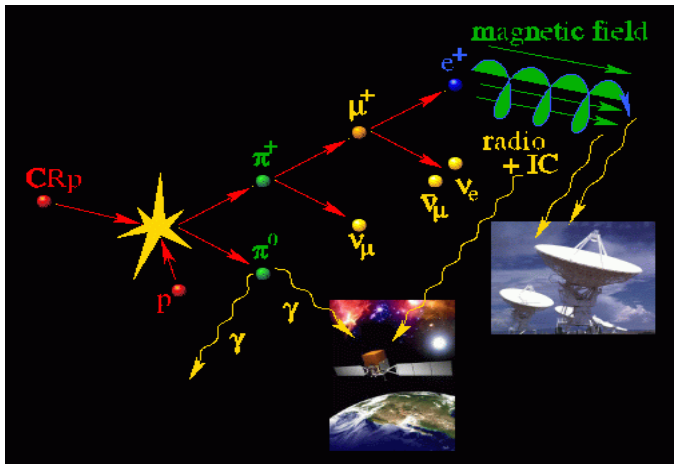
Combination of γ-ray limits and Syn power of radio relics implies
CRp/CRe < 10 at cluster shocks.
(Vazza & Bruggen 14, Brunetti & Jones 14)
CR physics at cluster shocks different from SNR.

Giant Radio Halos & CRp



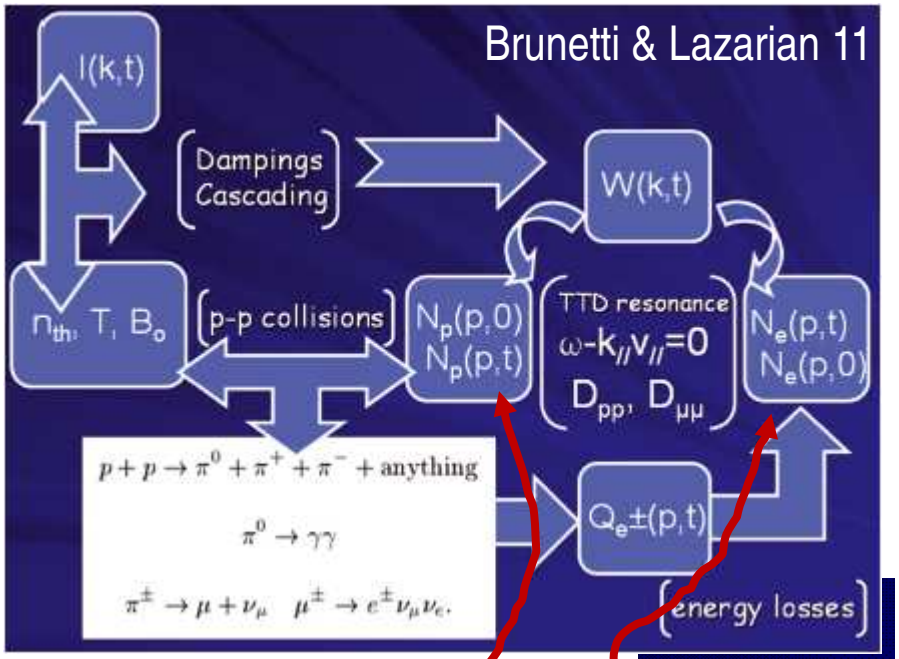
Interpretation is that Radio Halos trace gigantic turbulent regions where **seeds** CRe are (re)accelerated to GeV+ during cluster-cluster merger events

(Brunetti et al 01, Petrosian 01, Brunetti & Lazarian 07, etc …).



- Can CRp play a role for the origin of Giant Radio Halos ?
- Can CRp-p collisions provide the seeds to reaccelerate ?

Reacceleration of CRp & secondaries



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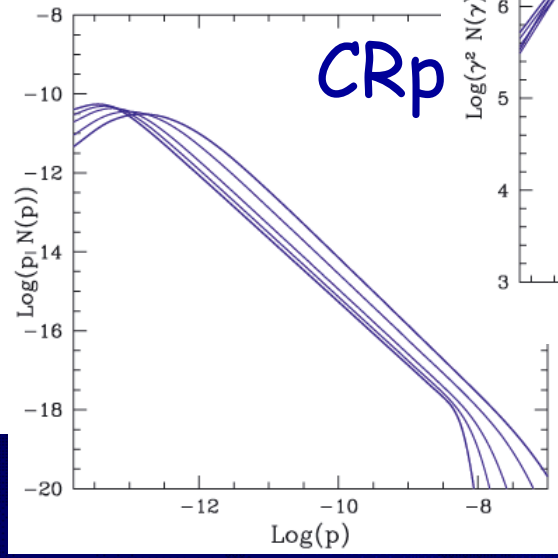
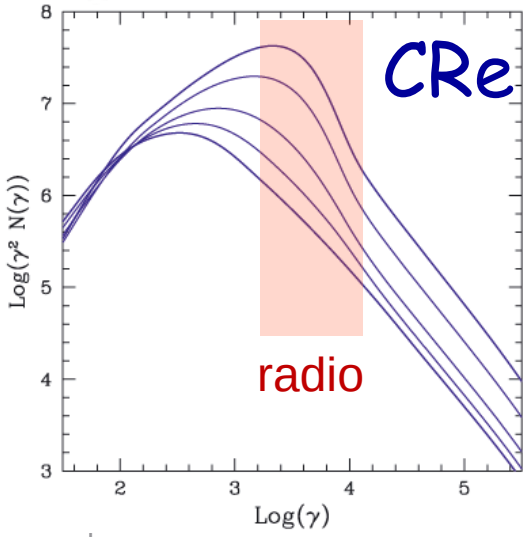




sources of CRp

sources of CRe

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

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

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

Turbulent models : Radio & high energies

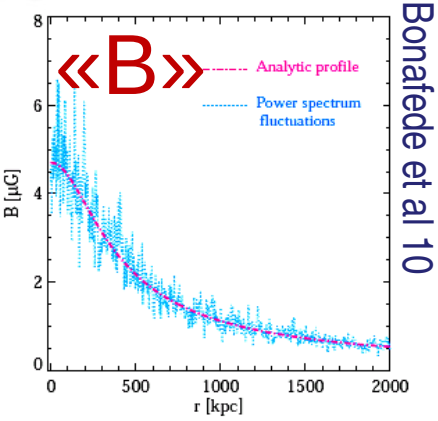
Reacceleration of CRp, secondaries and primary CRe

(Brunetti, Blasi et al 05,09, Brunetti & Lazarian 11, Brunetti et al 12, Pinzke, Oh, Pfrommer 15)

assumptions

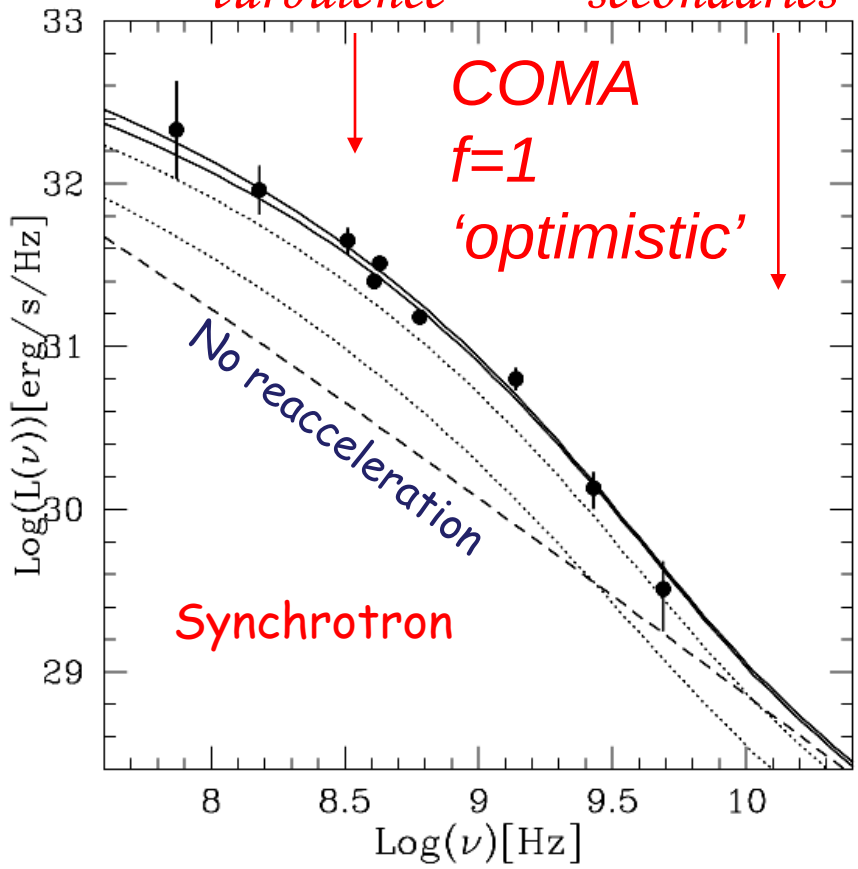
$E_{tur} \approx 10\ \% E_{th}$

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

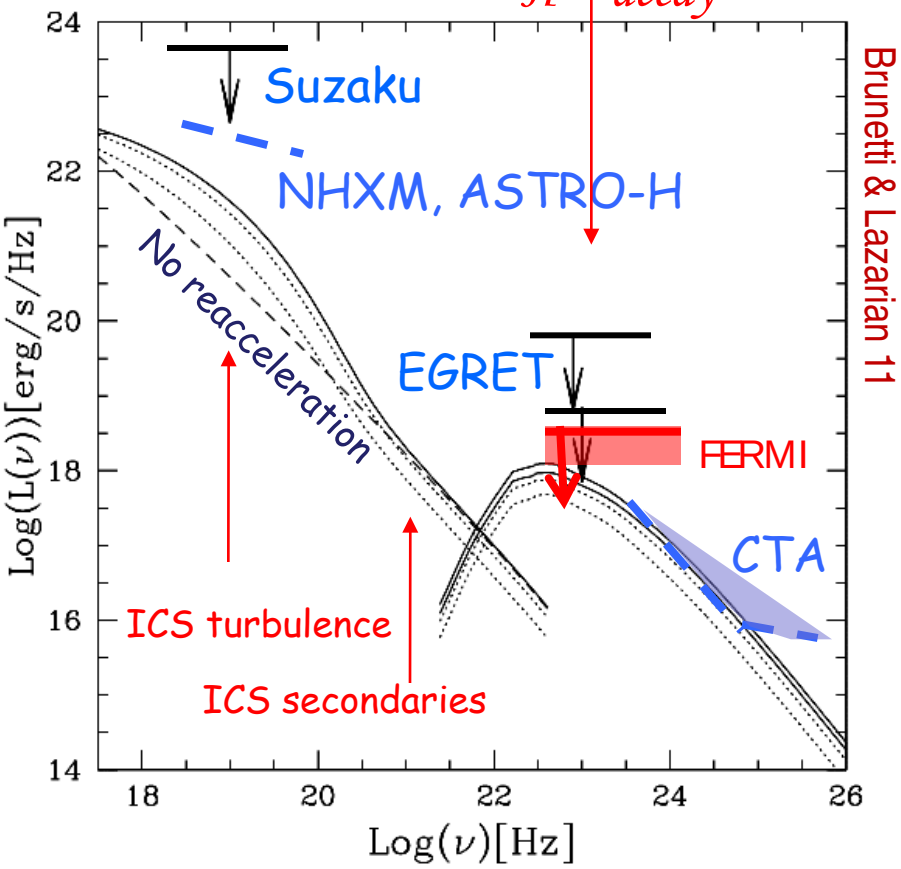


$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

turbulence *secondaries*



π^0 decay



Turbulent models : Radio & high energies

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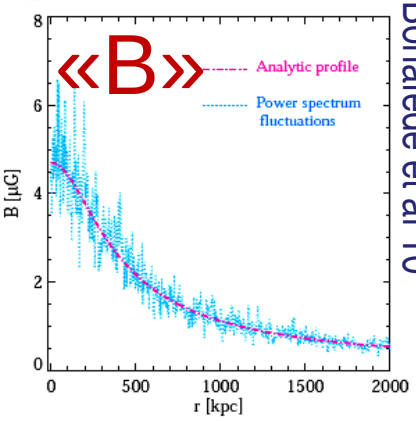
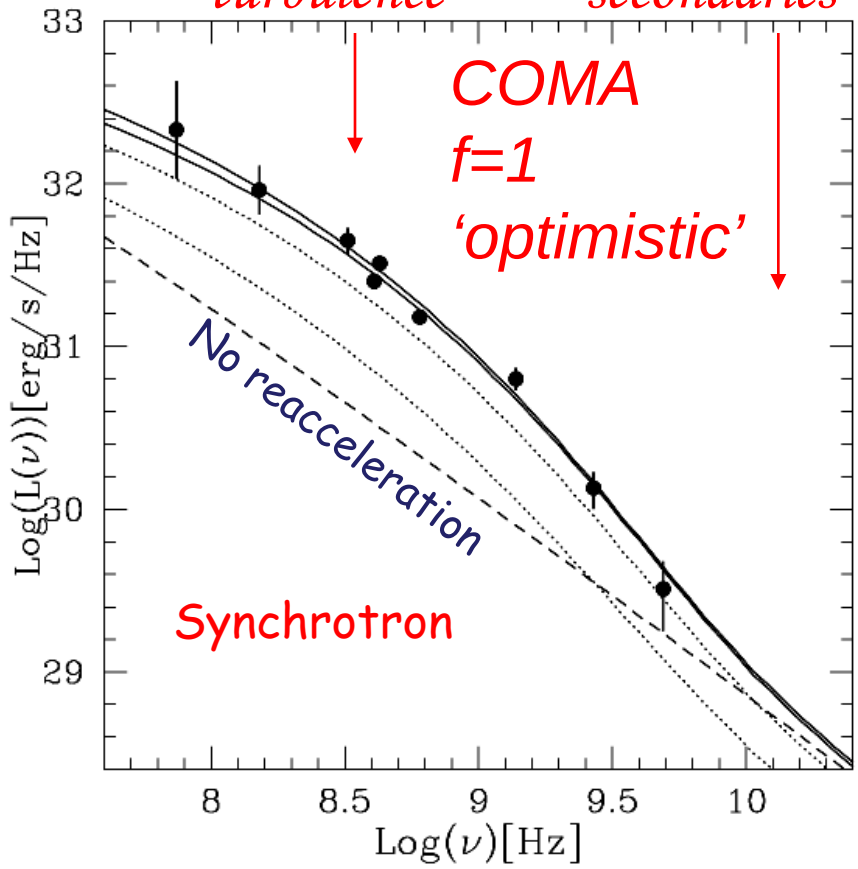


$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

turbulence *secondaries*



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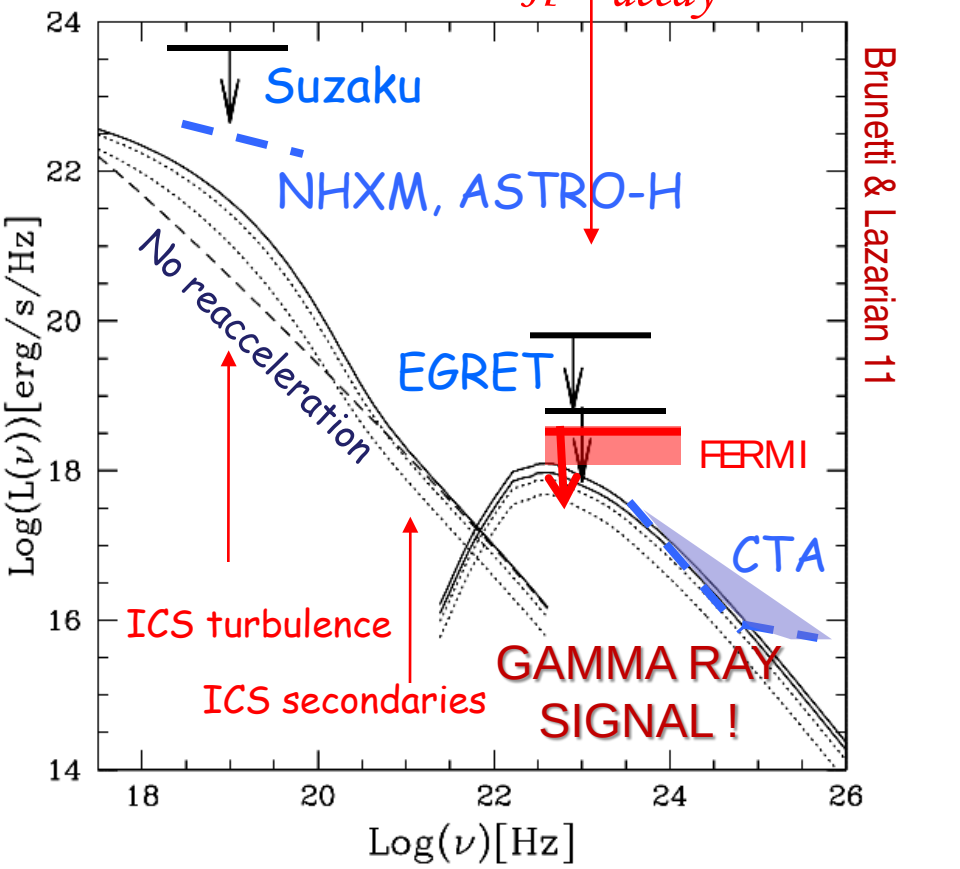
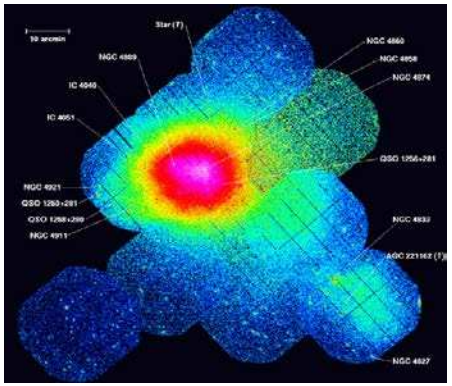


COMA RADIO HALO

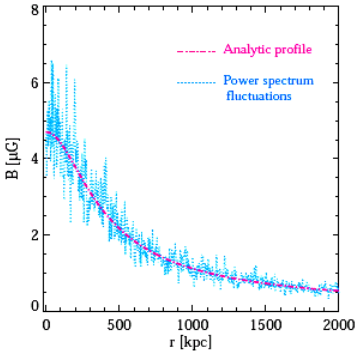
New FERMI limits for the Coma cluster (Ackermann et al 2016)

ASSUMPTIONS

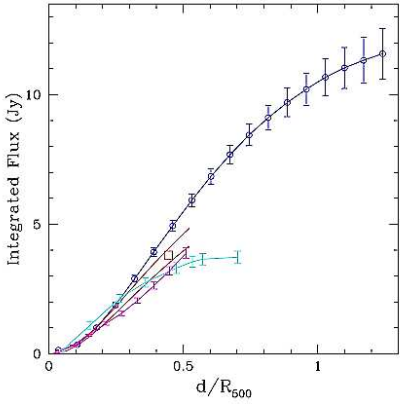
Thermal model



B model



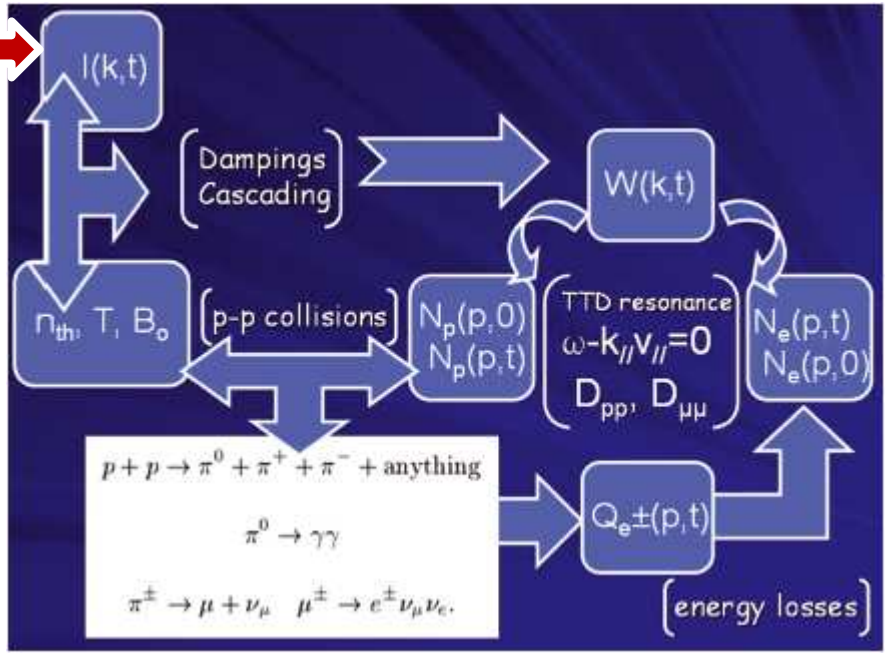
Spatial profile of the radio flux



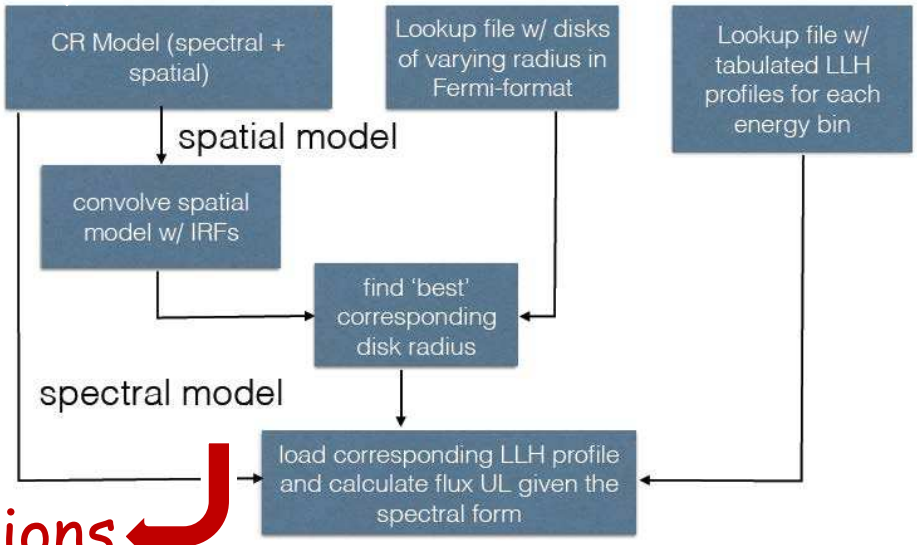
turbulence

$I(k)$

Δt_{acc}

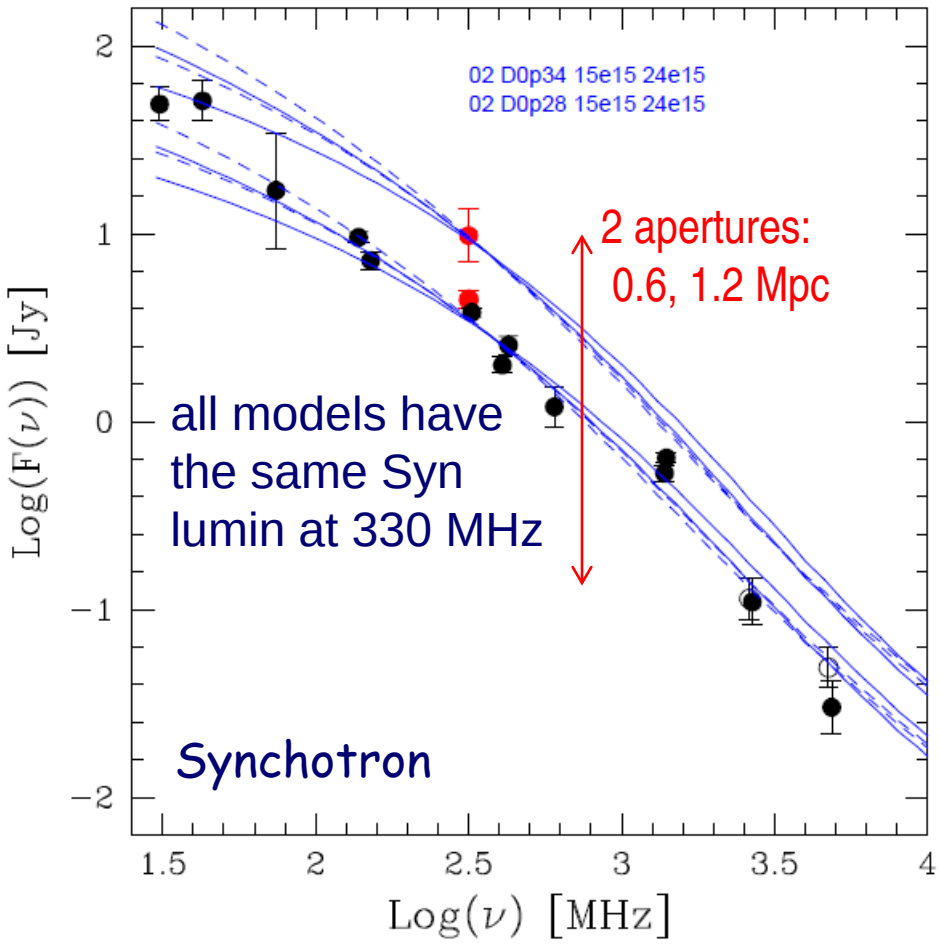


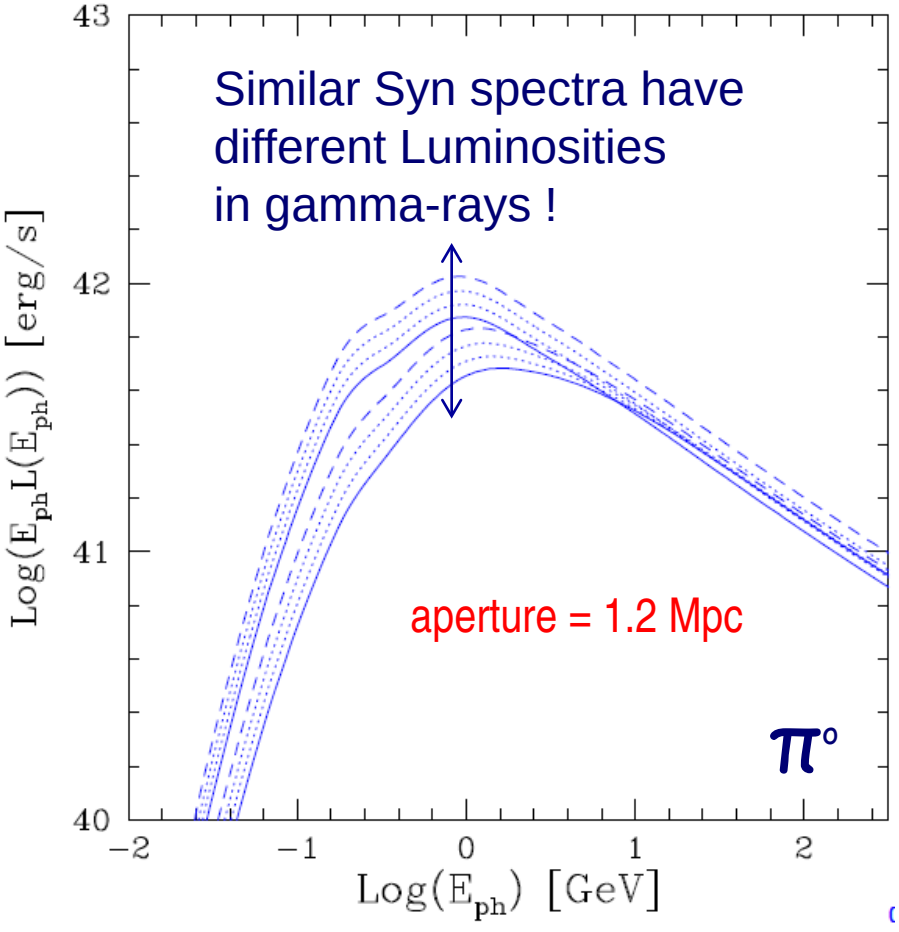
Method



Limits vs expectations

Preliminary results (Brunetti, Zandanel, Zimmer..)





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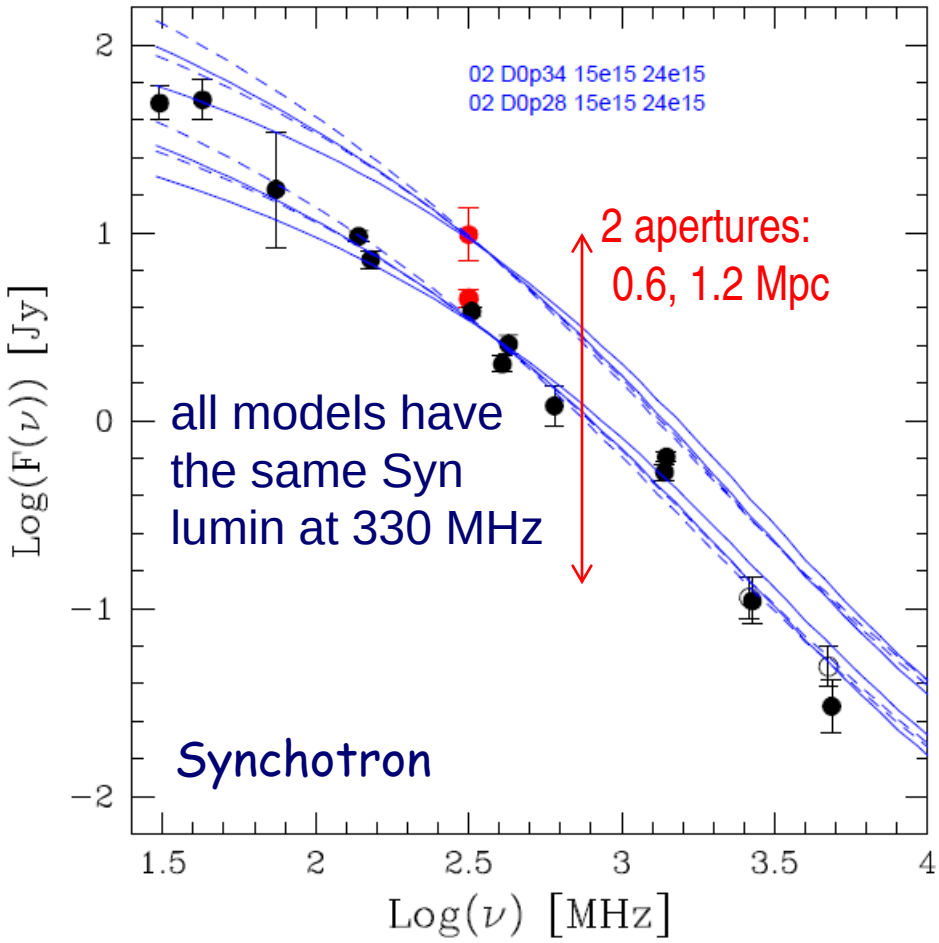
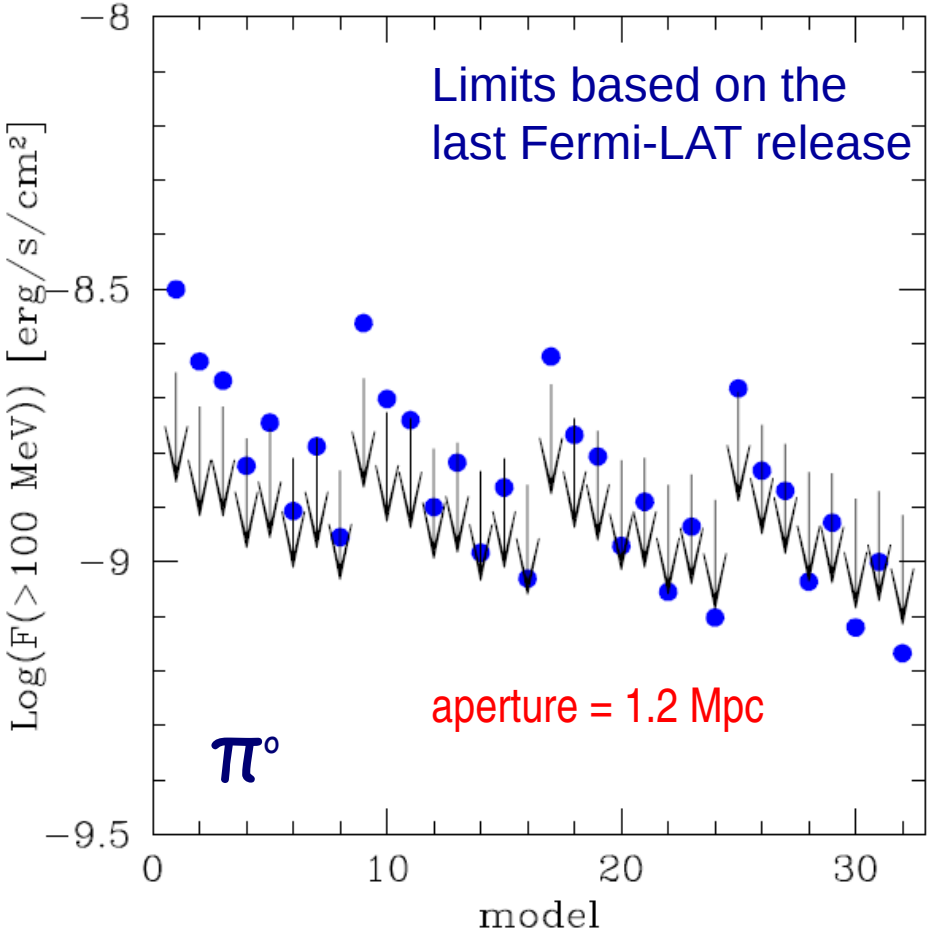




$T_{acc} \sim p^2/4D_{pp} < 200$ Myrs

$\Delta t_{acc} > 600$ Myrs

FERMI starts constraining the role of CRp also in reacceleration models (optimistic f=1 case)

TAKE HOME MESSAGES :

(1) Expected mix of CRp & CRe (primary+secondary)

- SED of GClustes: from radio to gamma-rays

(2) CRp energy budget & accel efficiency

- γ-rays : <0.01 x thermal energy (Mpc scale)
- LOFAR and … SKA will improve constraints
- Radio Relics & γ-ray limits constrain CRp/CRe<10

(3) CRp & Giant Radio Halos: do CRp play a role ??

- turbulent accel of CRp+secondaries: gamma-rays
- important constraints from new Fermi-LAT data

Turbulent models : Radio & high energies

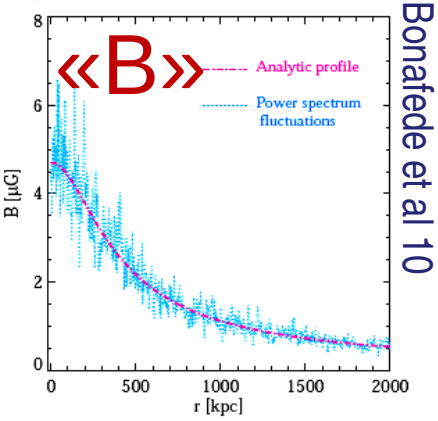
Reacceleration of CRp, secondaries and primary CRe

(Brunetti, Blasi et al 05,09, Brunetti & Lazarian 11, Brunetti et al 12, Pinzke, Oh, Pfrommer 15)

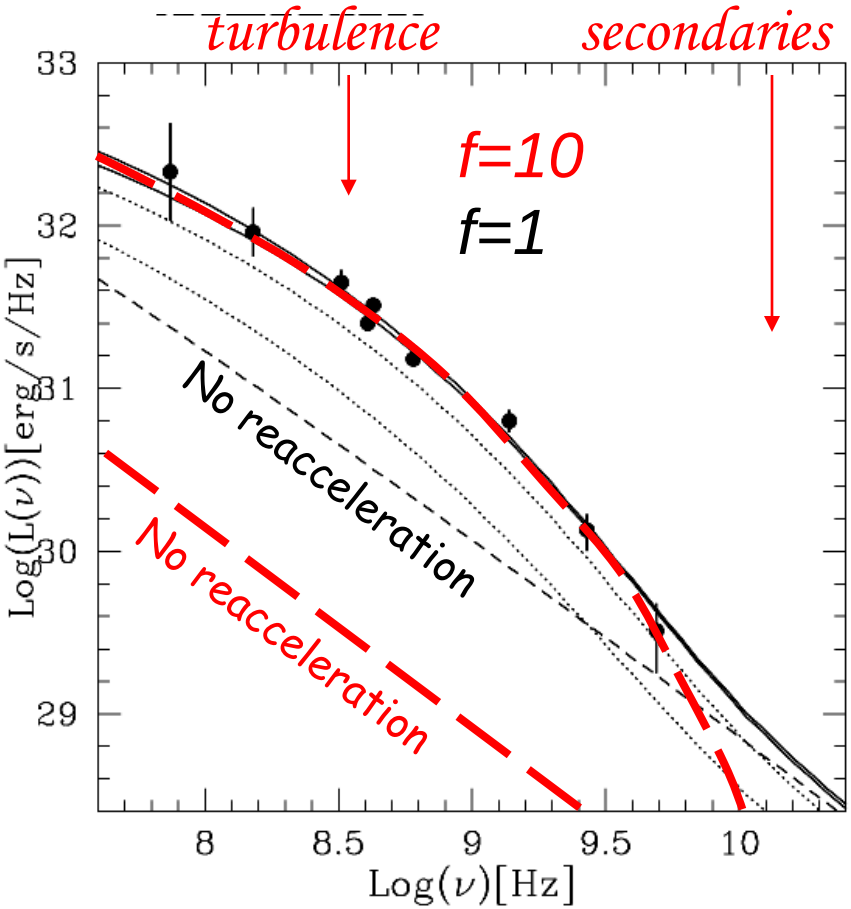
assumptions

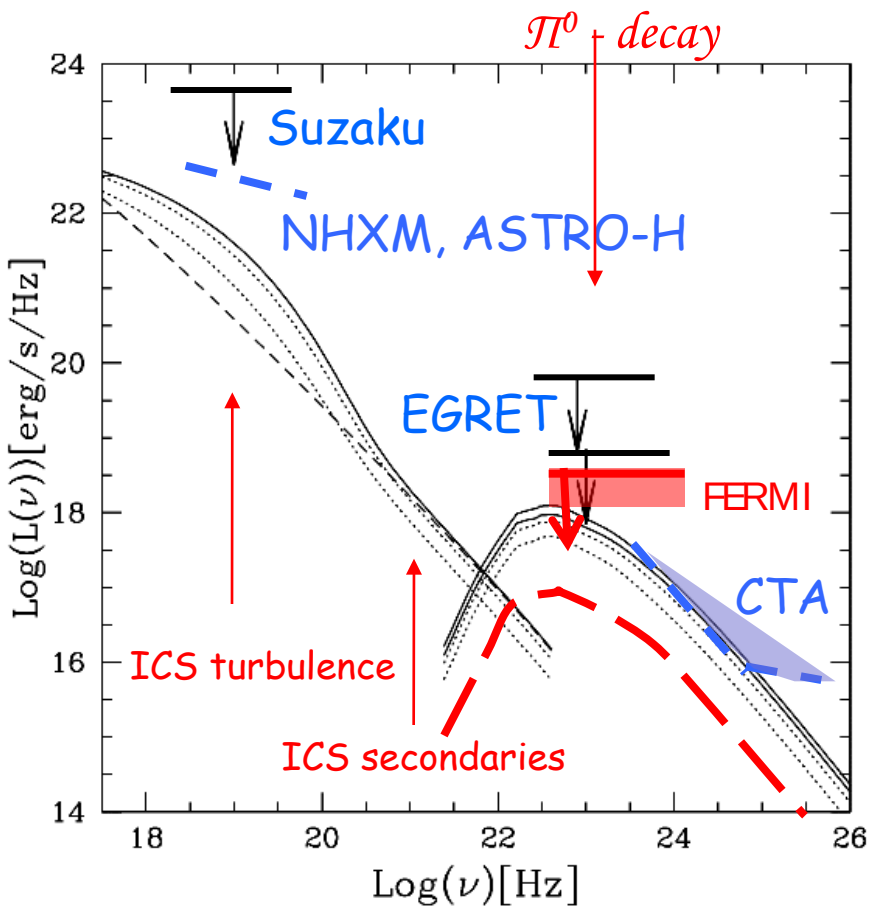
$E_{tur} \approx 10\ \% E_{th}$

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



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





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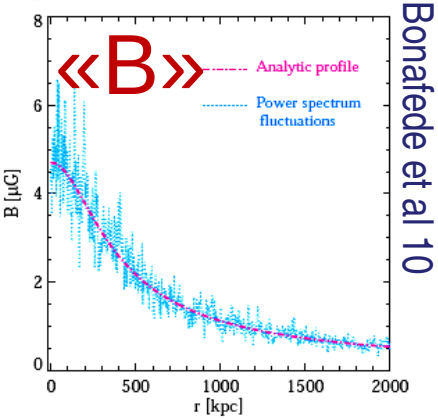
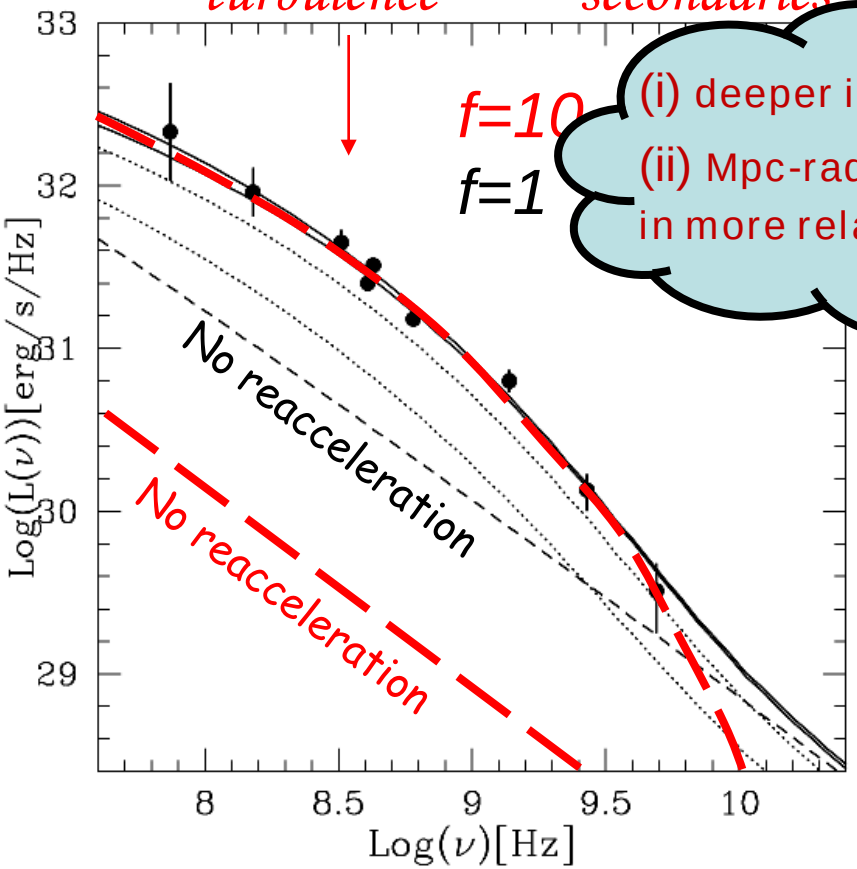


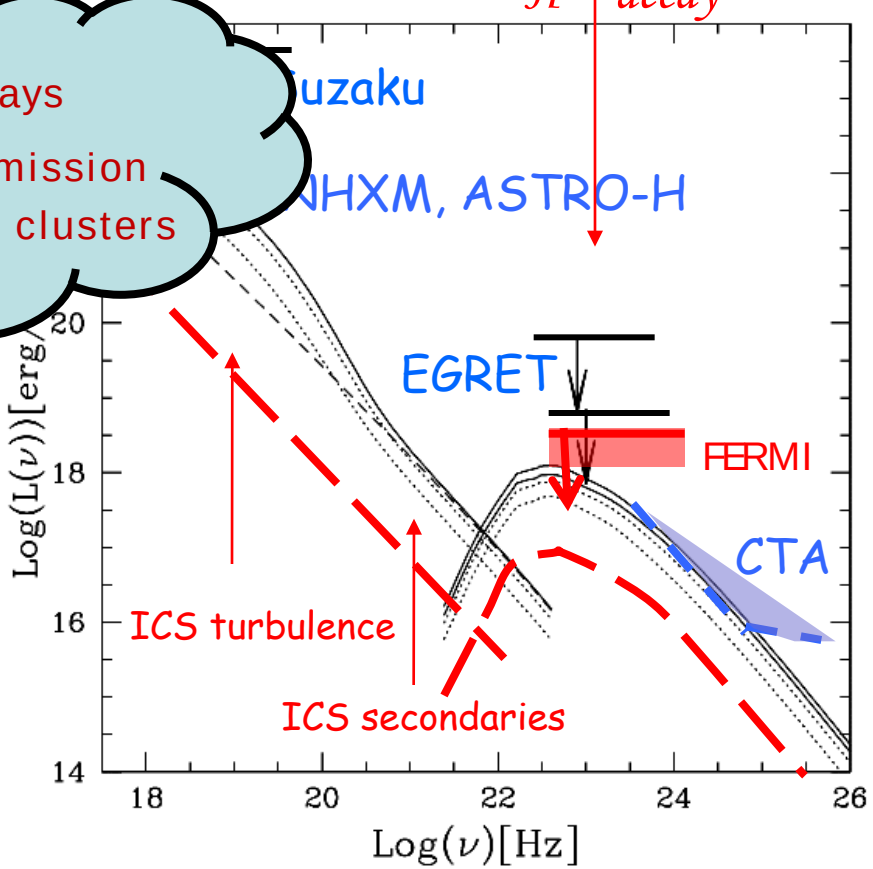
$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

turbulence *secondaries* π^0 *decay*



(i) deeper in γ-rays

(ii) Mpc-radio emission in more relaxed clusters



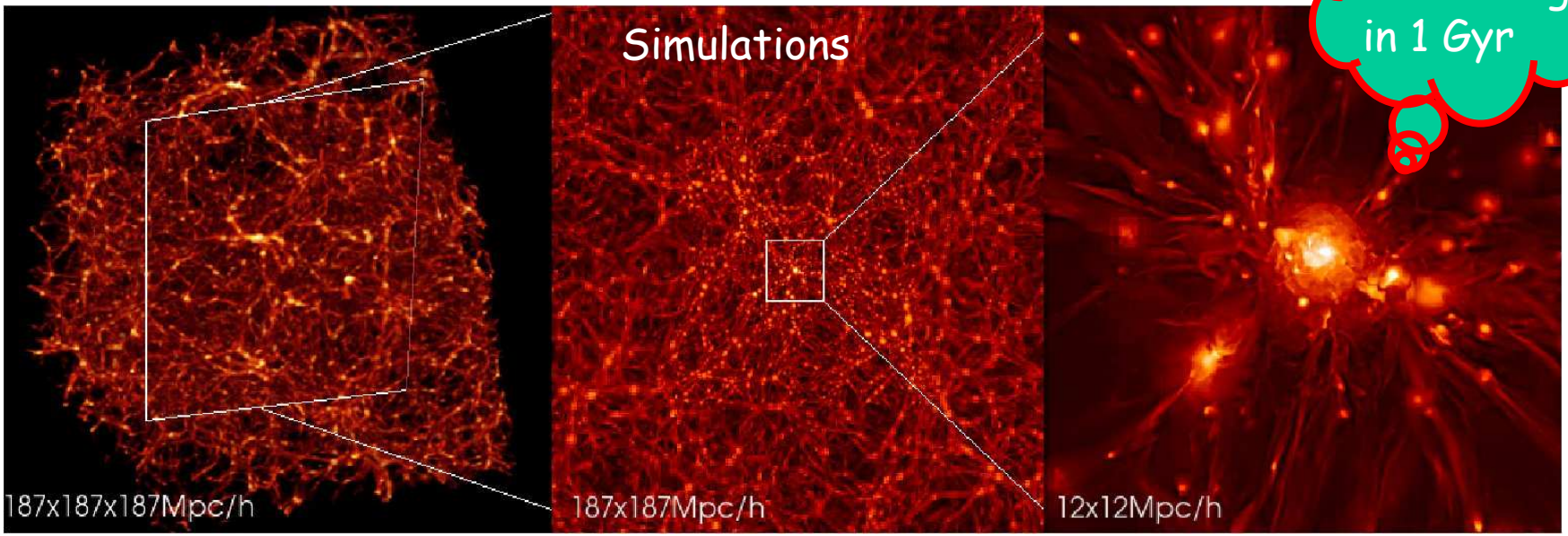
Clusters of galaxies:

Galaxy cluster matter :

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

Dark Matter **70%**

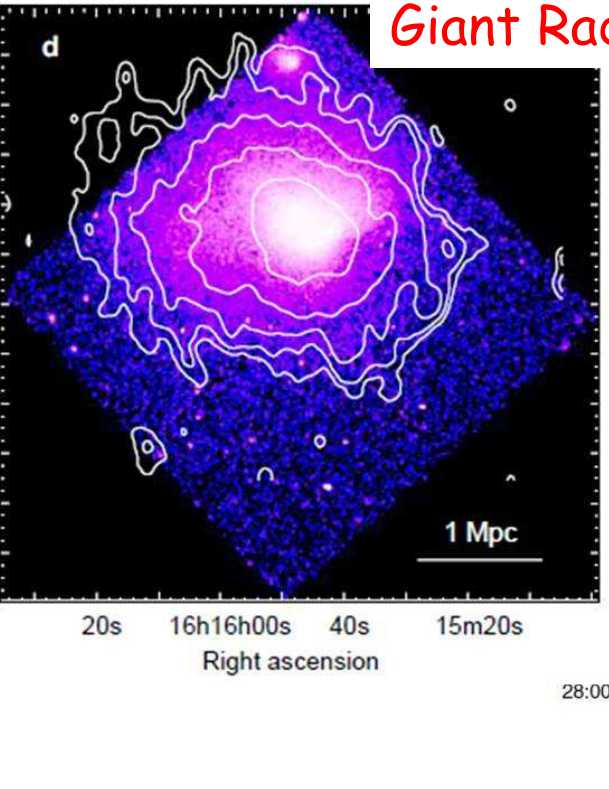
Mergers dissipate 10^{63-64} erg in 1 Gyr

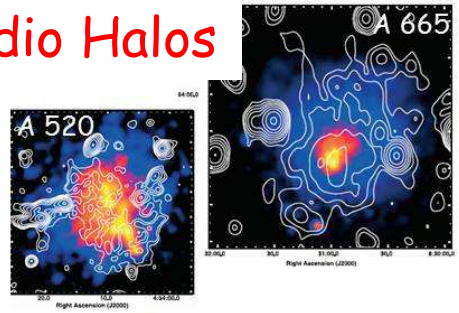


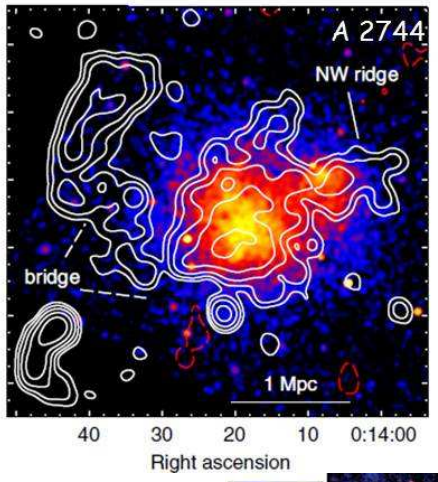
Cluster-scale radio emission

- GeV+ CR electrons
- μG+ level magnetic fields
- Connected with cluster mergers

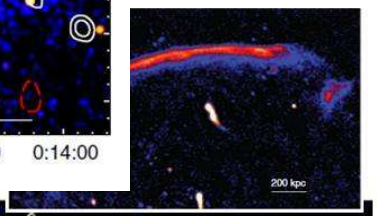
Giant Radio Halos

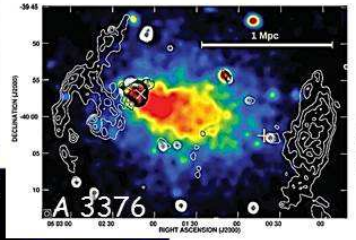


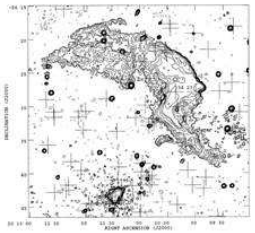




Giant Radio Relics



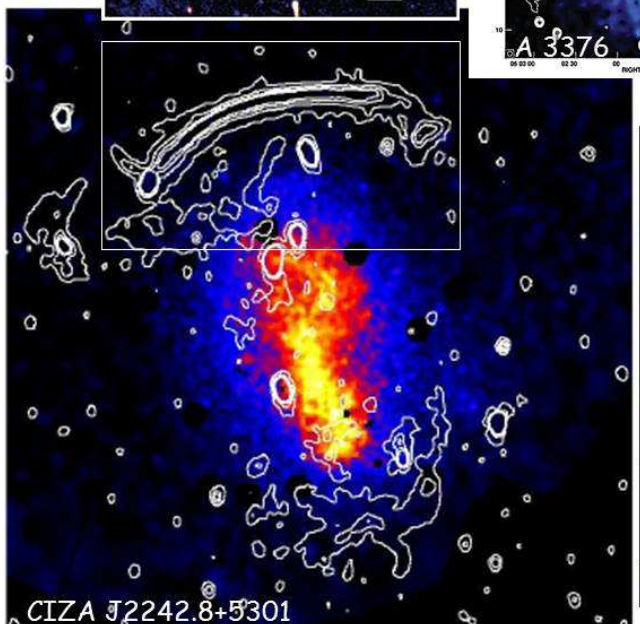


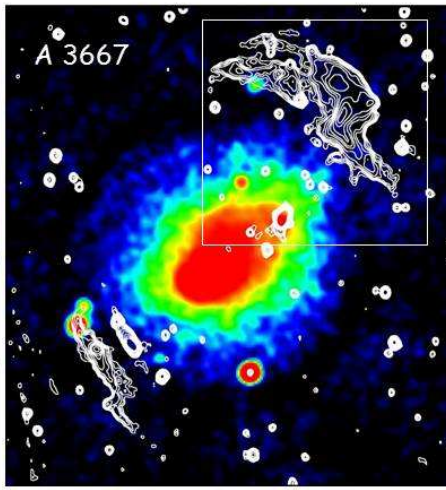


GeV+ electrons in the ICM are short living particles, 100 Myrs, do to Syn and ICS losses

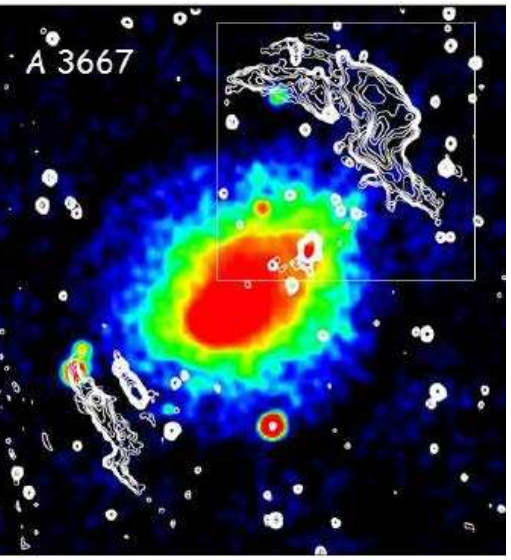
Need for "in situ" particle (re)acceleration mechanisms

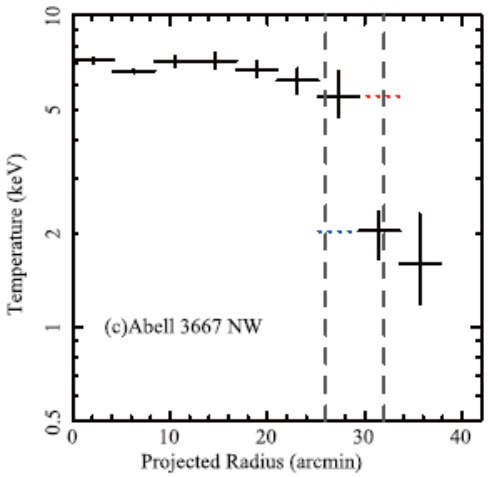
[rev Brunetti & Jones 14
obs rev by Feretti et al 12]

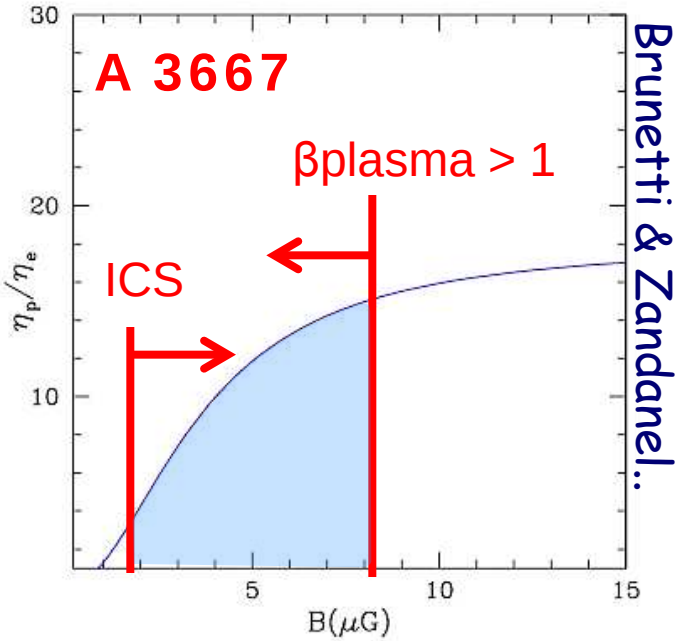




CRp/CRe efficiency







The combination of γ-ray limits and Syn power of radio relics allows to constrain CRp/CRe acc efficiencies at shocks

$$0.5\eta_e\rho_1 v_s^3\left(1-\frac{1}{C^2}\right)=\epsilon_e v_2$$

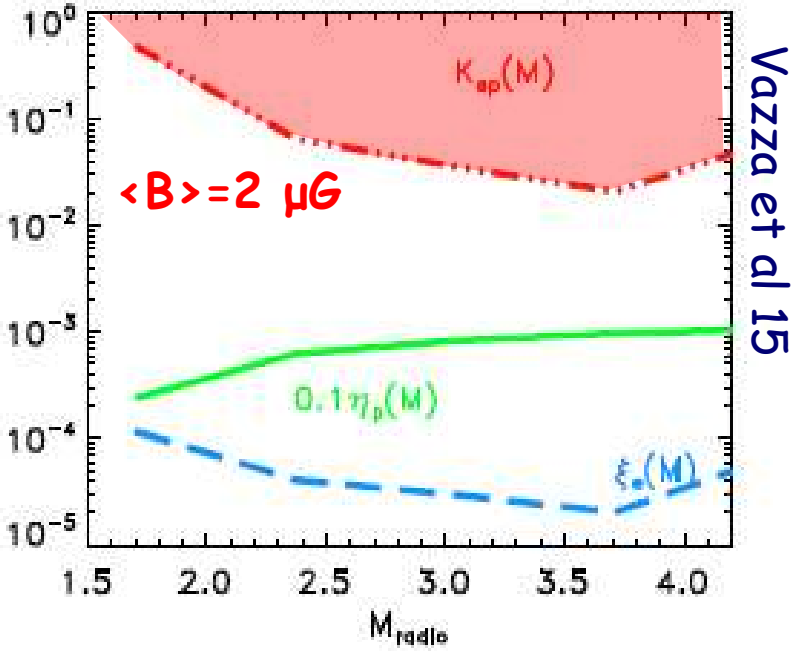
density upstream · shock speed · shock compression · downstream speed

CRp -- π^o → Gamma

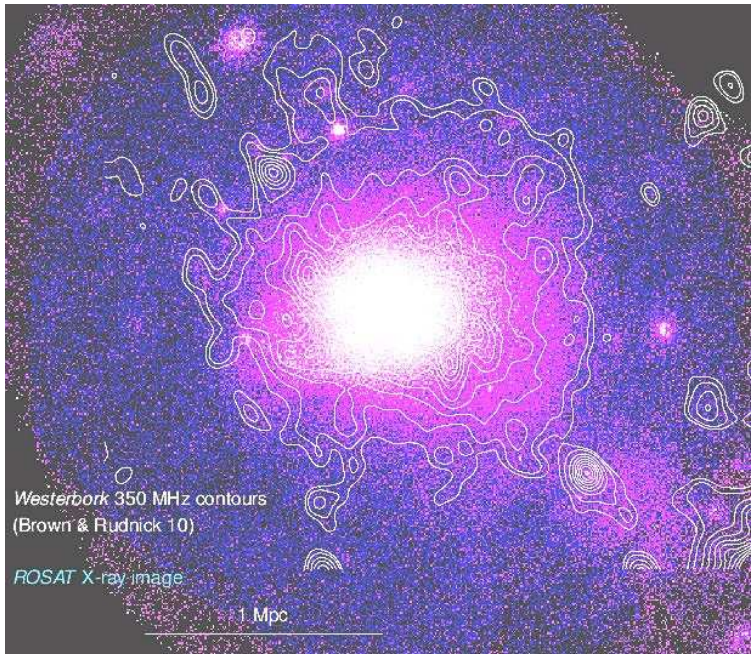
CRe -- Syn → RRelics

CRp/CRe < 10 or so …

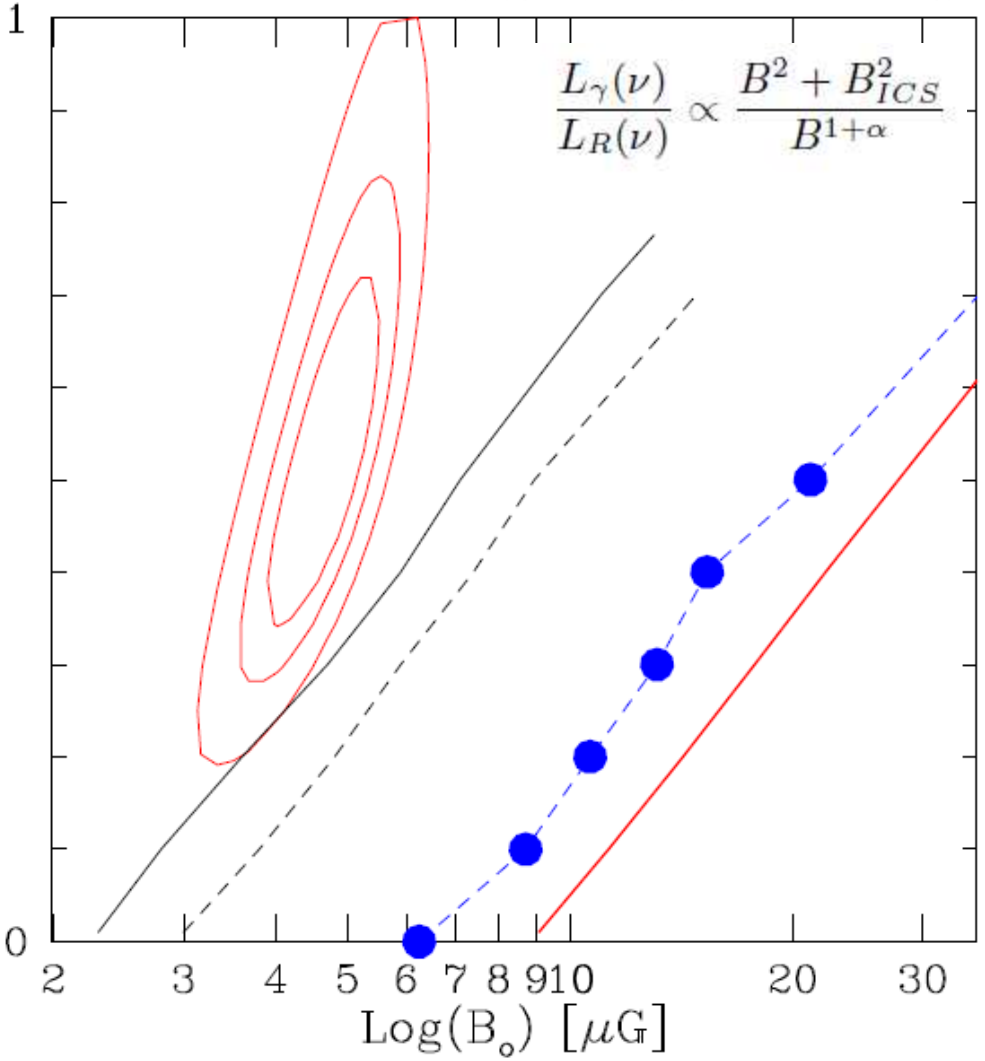
(see Brunetti & Jones 14 for discussion)



Based on a sample of GC scaling relations + simulations

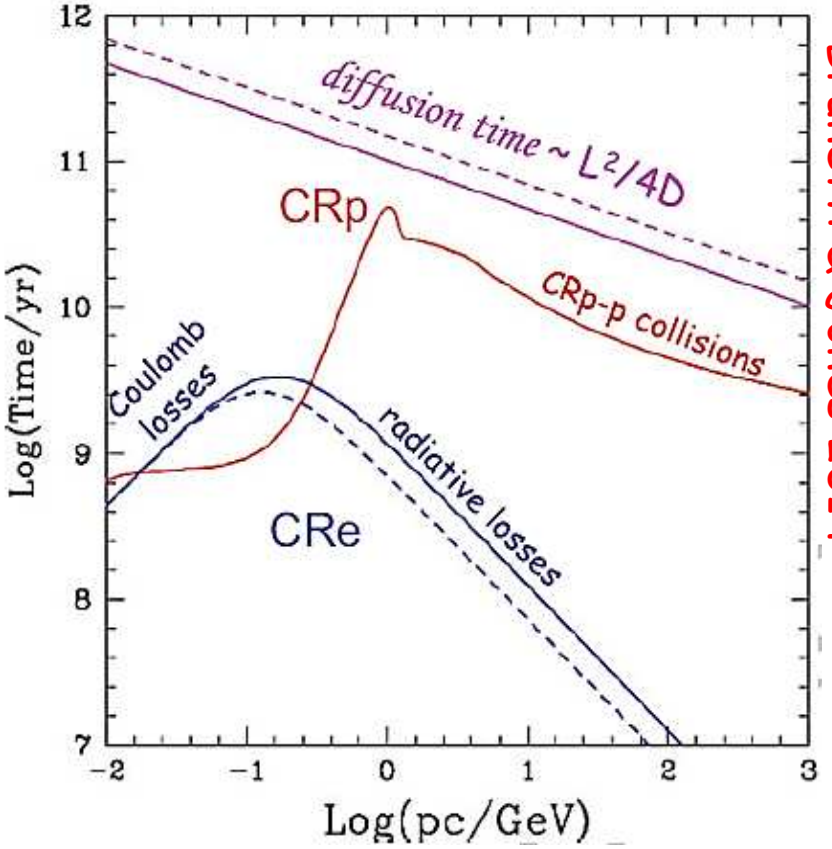


$B(r)=B_o(\varepsilon_{ICM}/\varepsilon_o)^n$

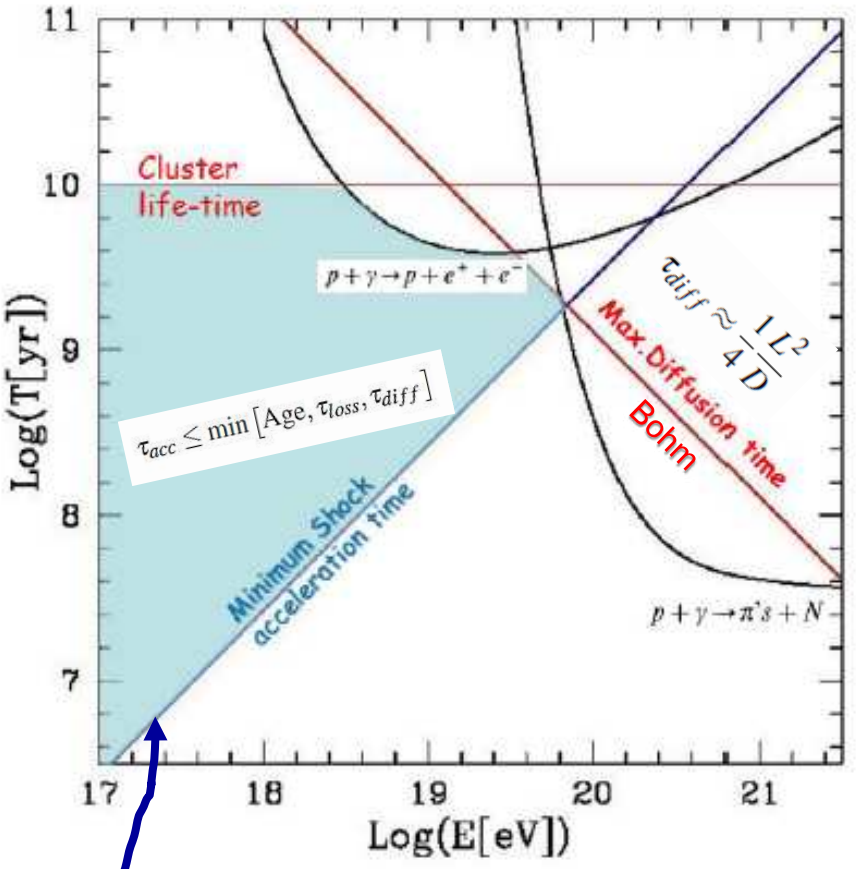


CRp confinement & max E

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



Brunetti & Jones 2014



Brunetti & Jones 2014

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

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

''optimistic'' shock acc efficiency & ''minimum'' CR diffusion (DSA Bohm)

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