Gamma rays from galaxy clusters

- and the contribution from CTA-

Gianfranco Brunetti

INAF ira ISTITUTO DI RADIOASTRONOMIA

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%

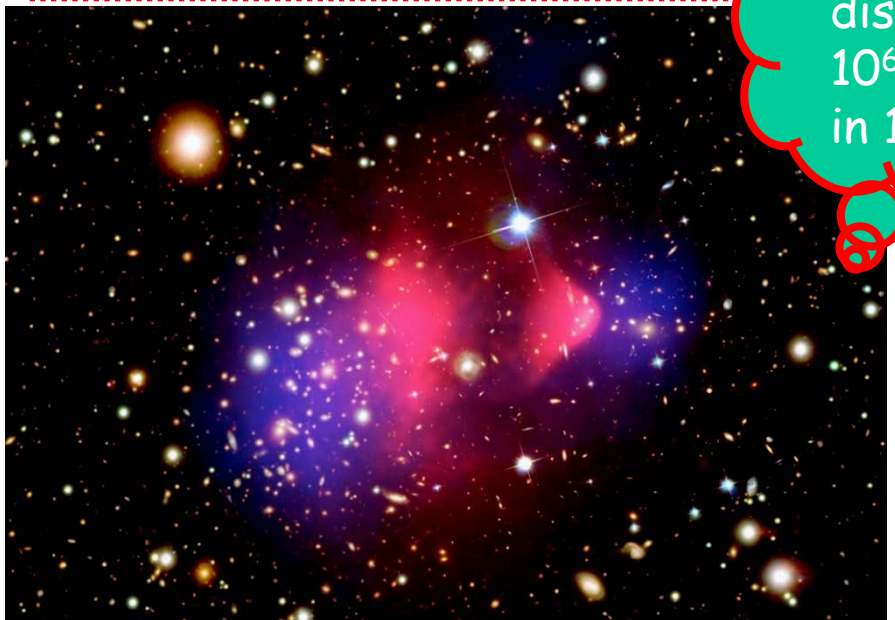
$n \approx 10^{-3} cm^{-3}$

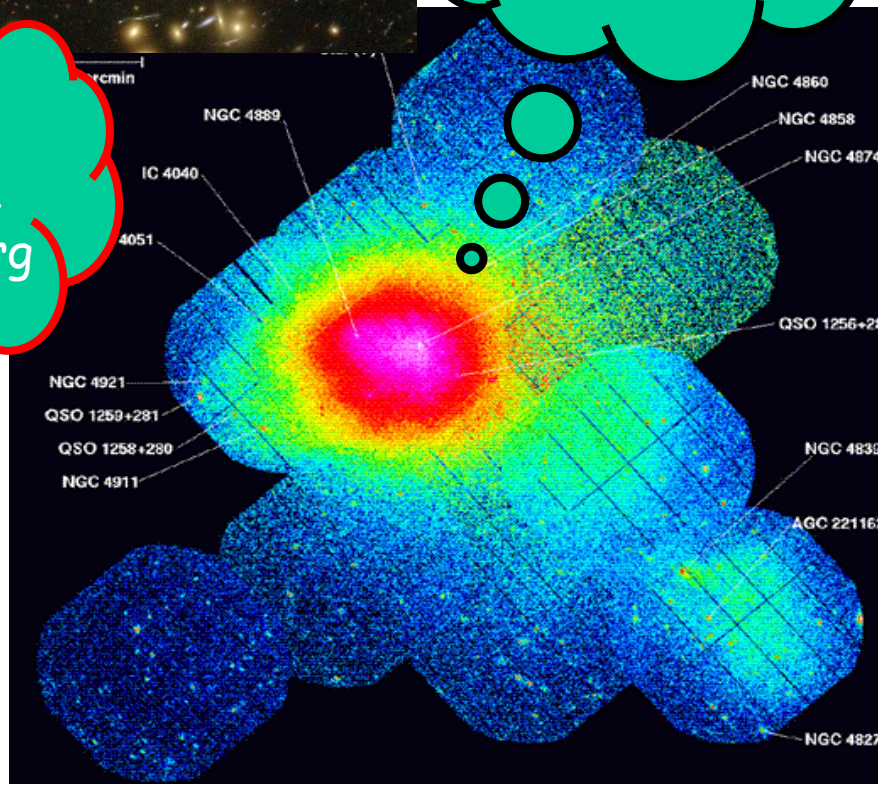
$T \approx 10^{7}$-$10^{8} K$

High beta

Weakly coll.

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



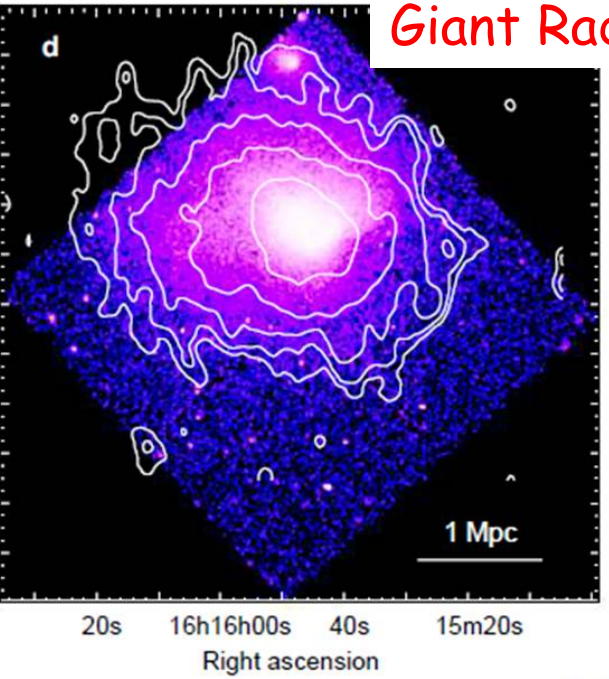


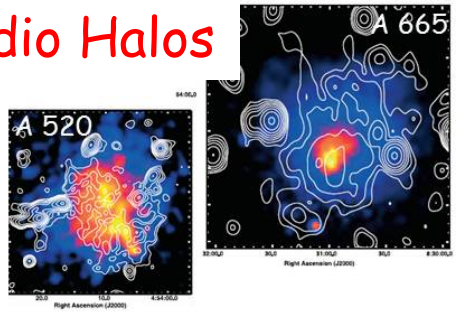
Cluster-scale radio emission

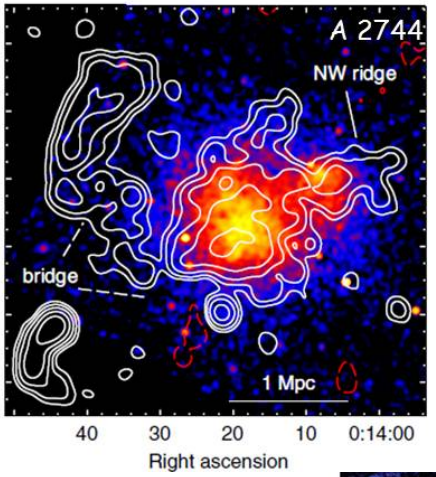
- Steep spectrum sources
- Low brightness

- ✓ Synchrotron radiation FROM the ICM
- ✓ Relativistic GeV+ electrons (protons?) and B distributed on Mpc-scales…

Giant Radio Halos



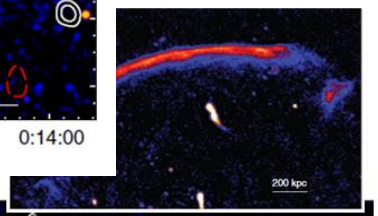


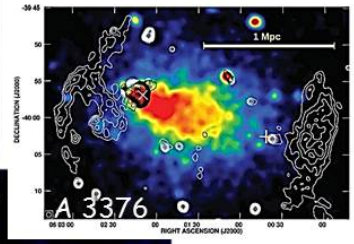


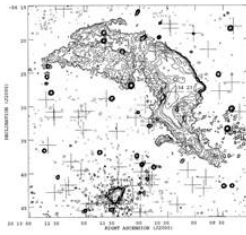
Feretti+ 12

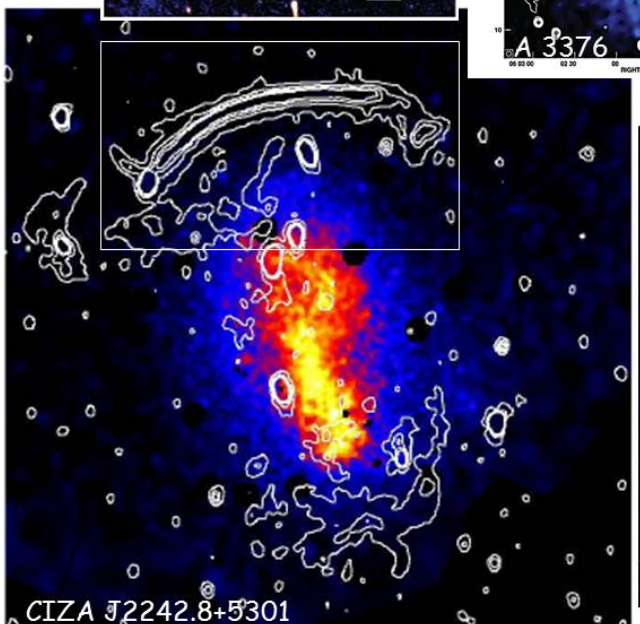
Brunetti+Jones 14

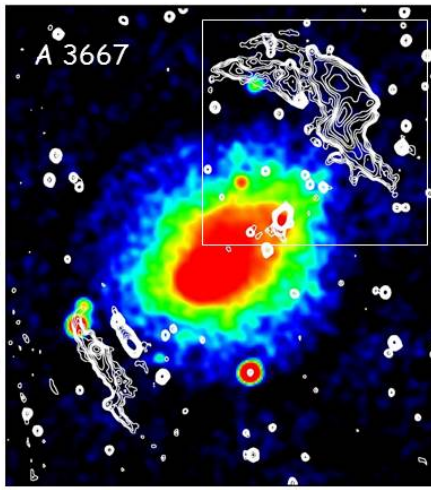
Giant Radio Relics



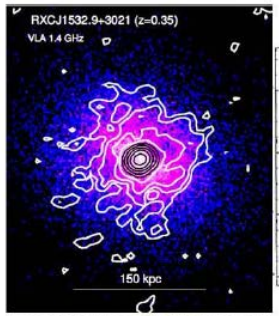


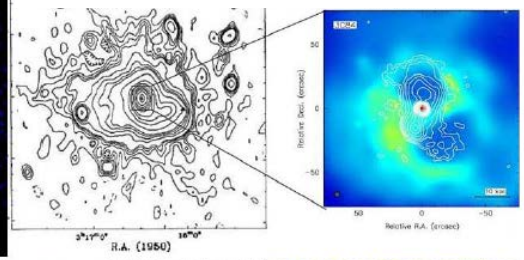


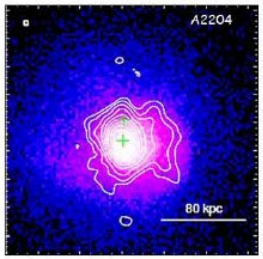


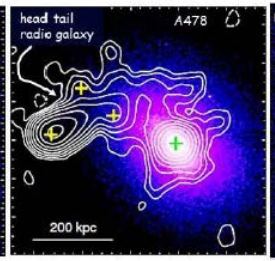


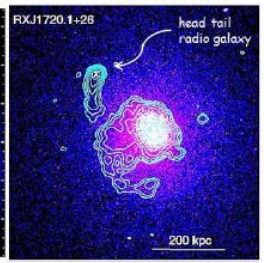
MINI- Radio Halos









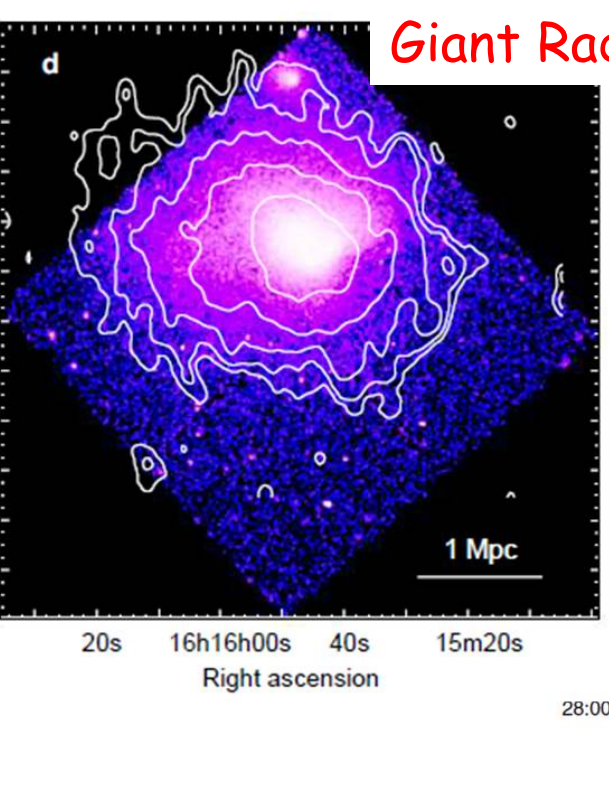


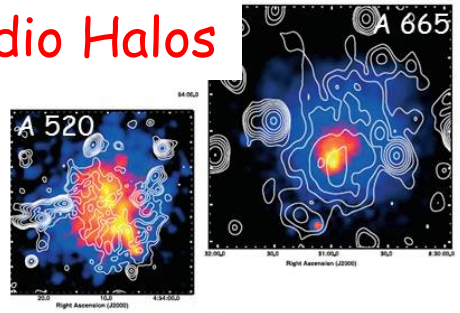
Cluster-scale radio emission

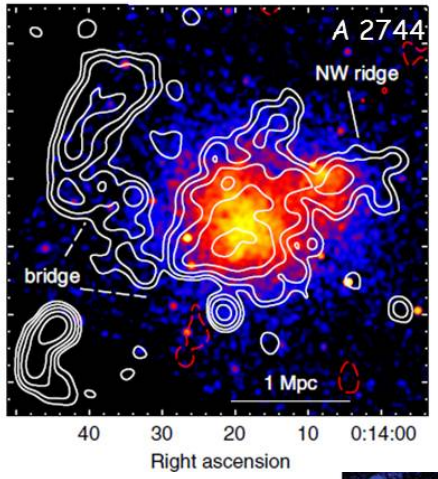
- Steep spectrum sources
- Low brightness

- ✓ Synchrotron radiation FROM the ICM
- ✓ Relativistic GeV+ electrons (protons?) and B distributed on Mpc-scales…

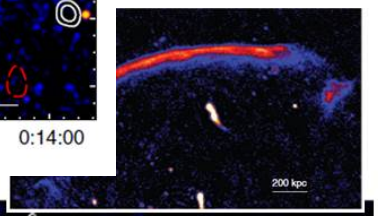
Giant Radio Halos

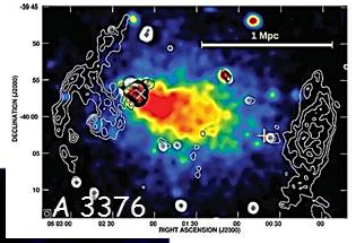


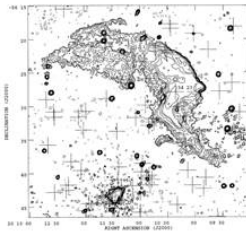


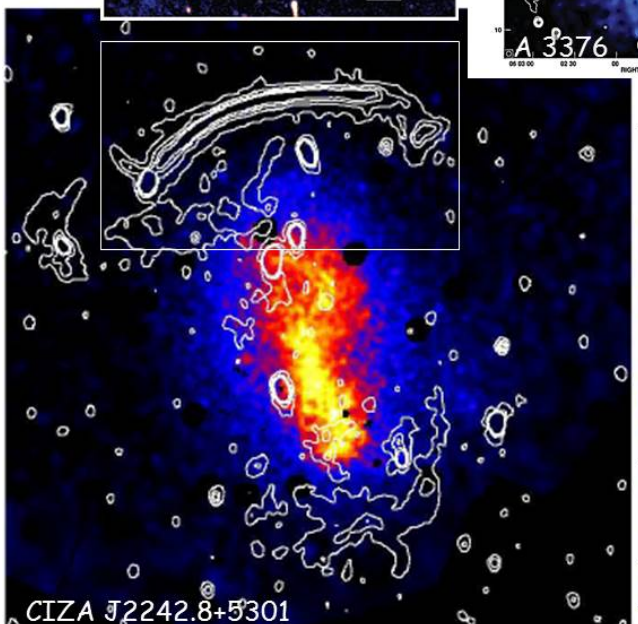


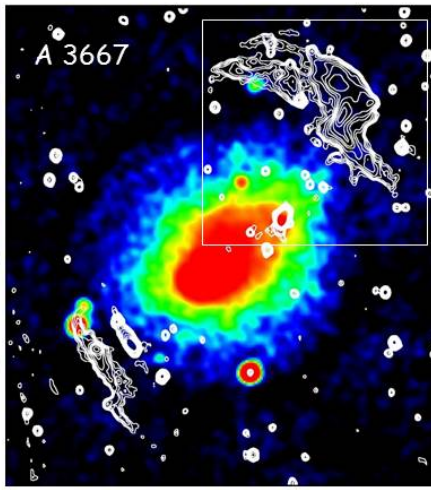
Giant Radio Relics











Syn+IC lifetime of radio electrons

T_{rad}~100-300 Myr << diffusion time

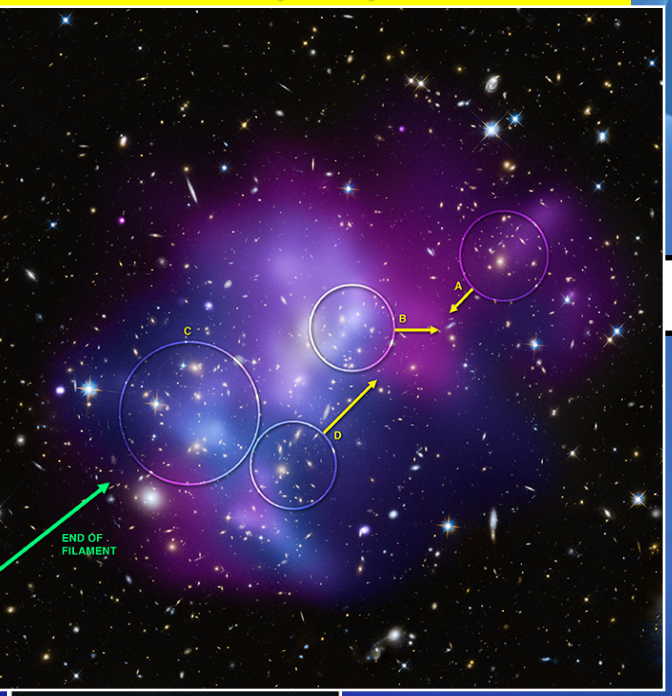
ICM acceleration site !

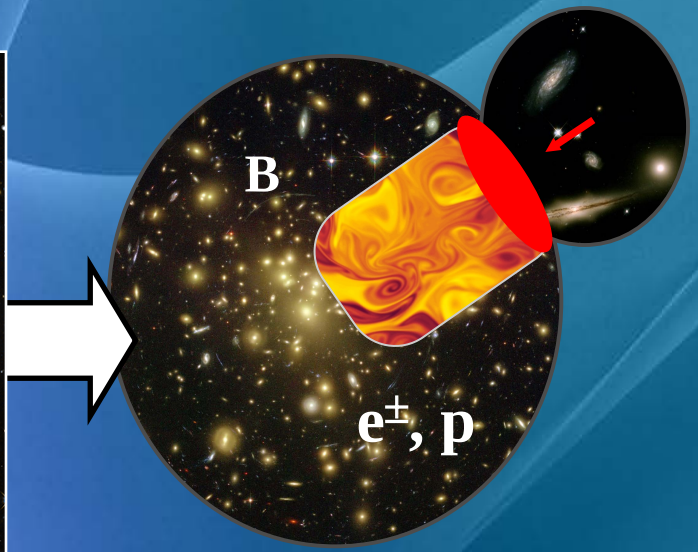
- ➢ ORIGIN & Physics ??
- ➢ IMPACT on thermal ICM ?? (microphysics & dynamics)

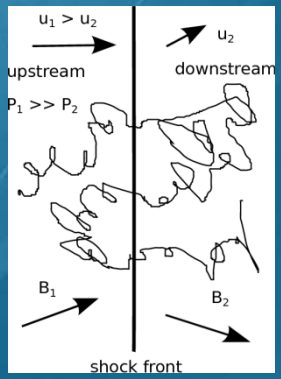
[Brunetti & Jones 14 for rev]

CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B



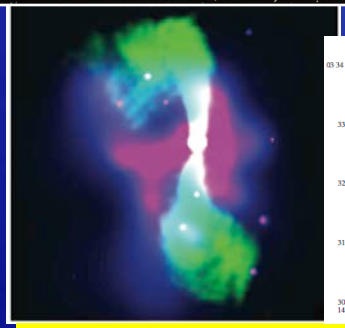


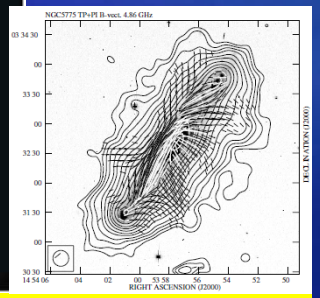


(1)

SHOCKS

accelerate CRe±,CRp

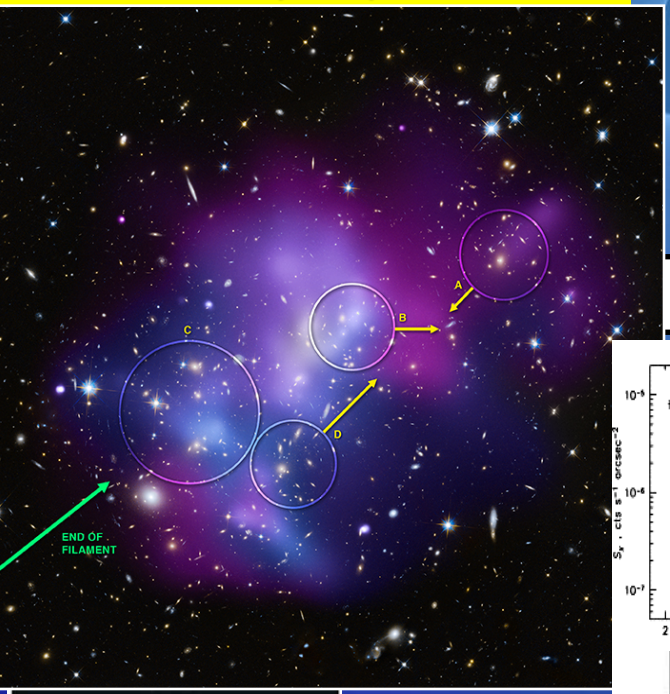


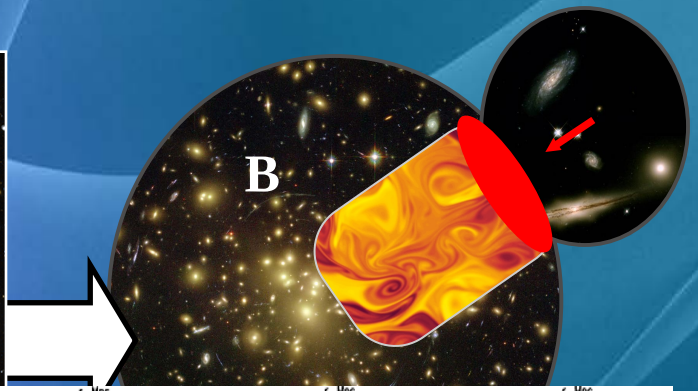


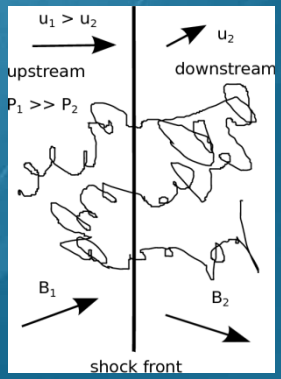
Astrophysical sources
Galaxies (SN), AGN..

CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B



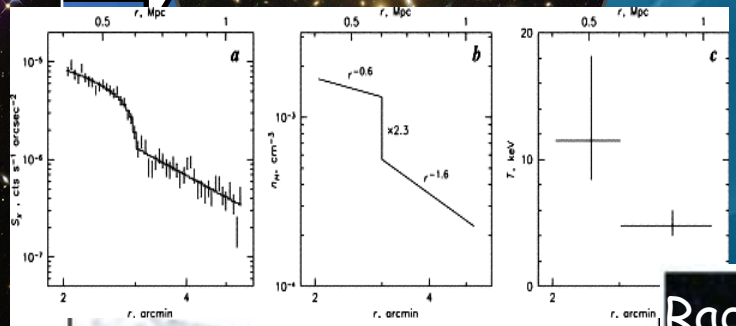


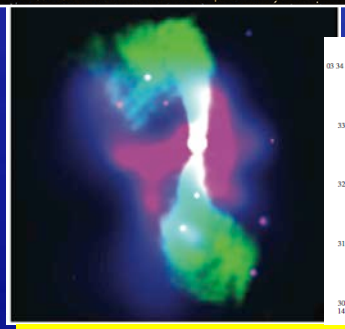


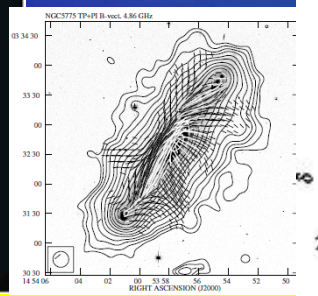
(1)

SHOCKS

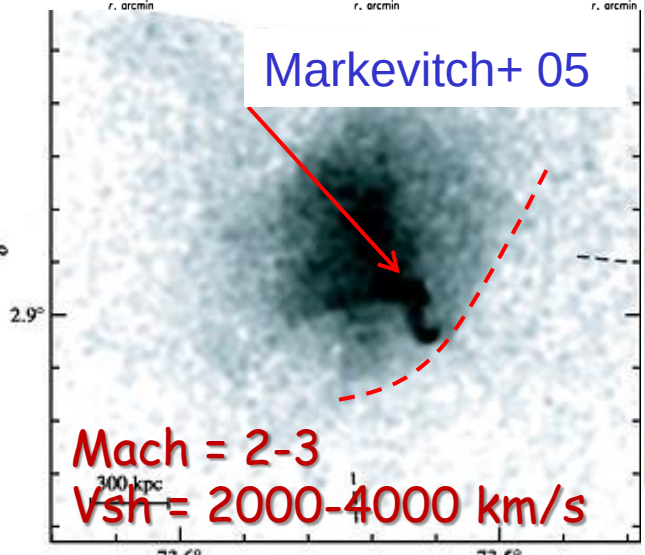
accelerate CRe$^{\pm}$,CRp



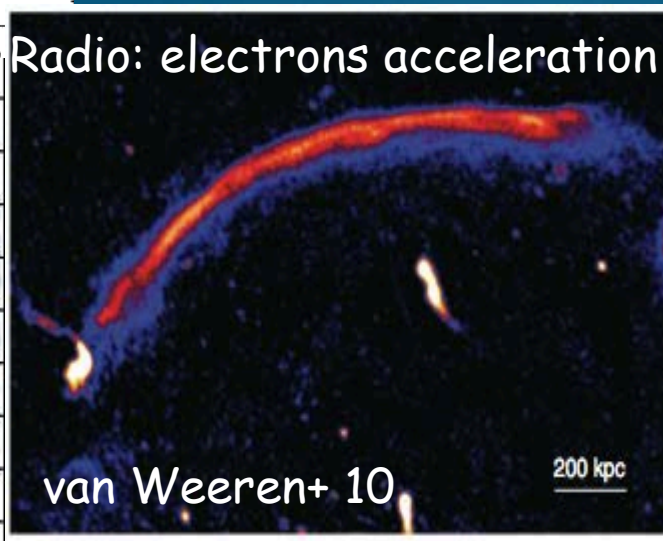




Markevitch+ 05



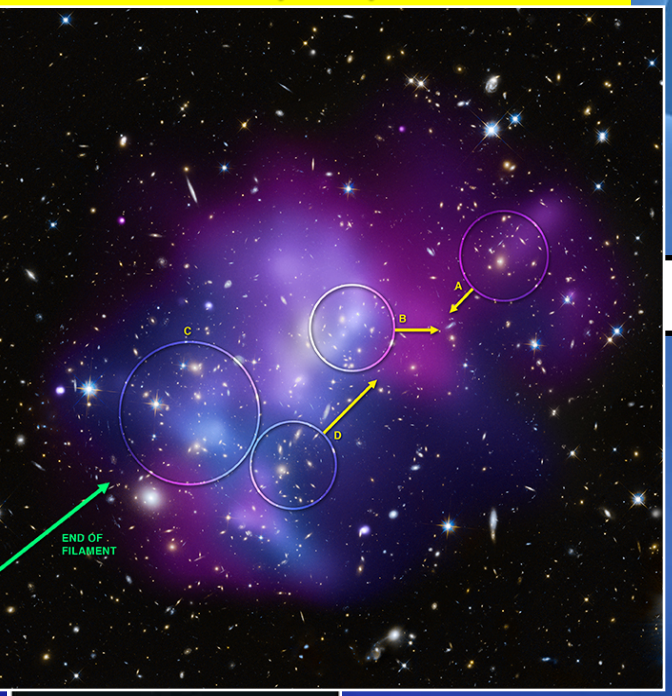
Radio: electrons acceleration

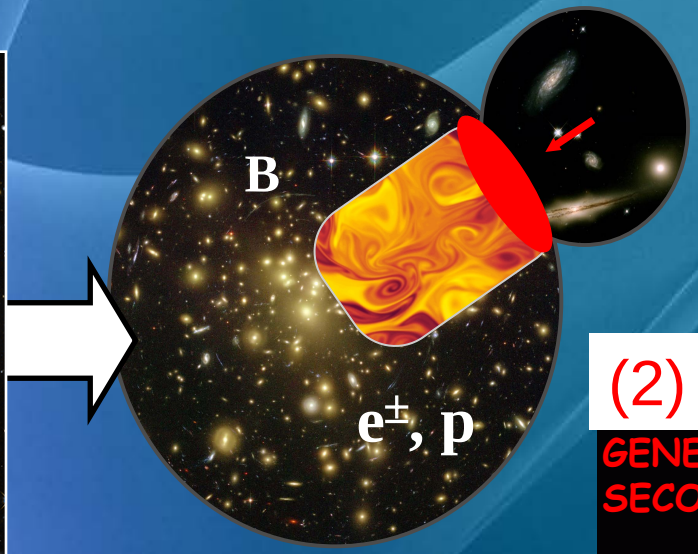


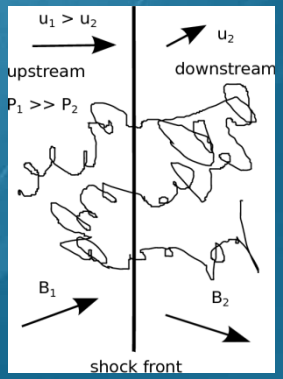
Astrophysical sources
Galaxies (SN), AGN..

CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B





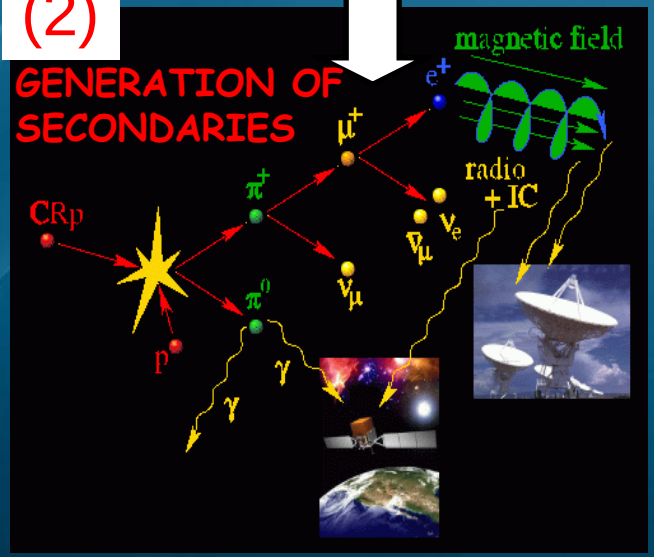


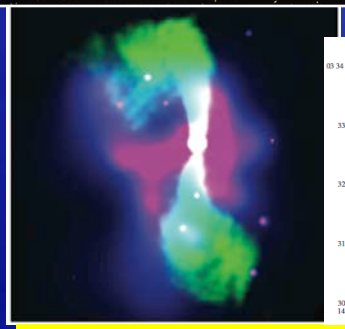
(1)

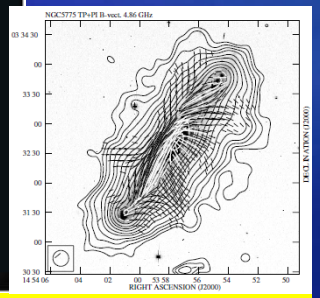
SHOCKS

accelerate CRe±,CRp

(2)



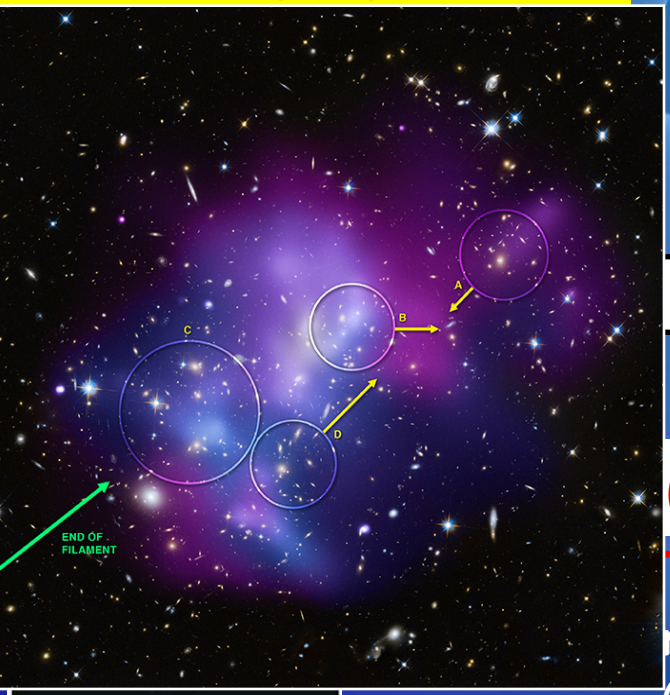


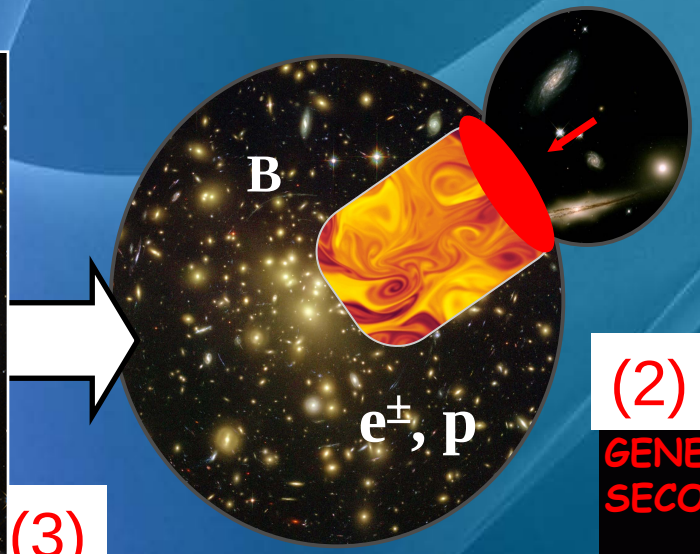


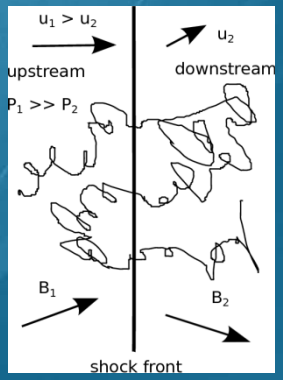
Astrophysical sources
Galaxies (SN), AGN..

CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B





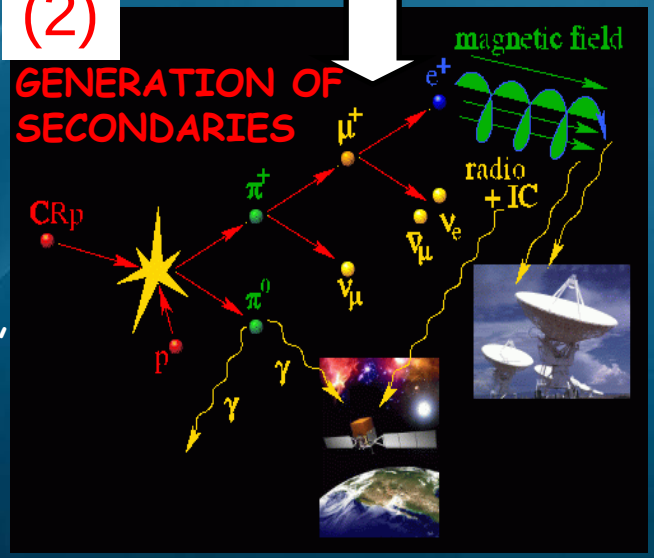


(1)

SHOCKS

accelerate CRe±,CRp

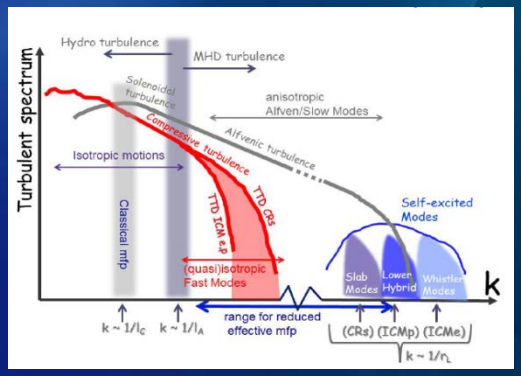
(2)

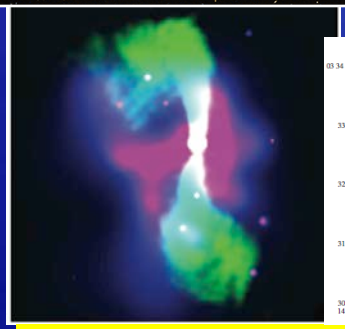


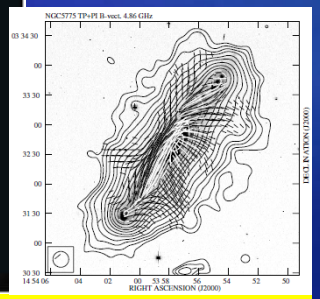
(3)

TURBULENCE

reaccelerates fossil CRe± , CRp and secondaries CRe±



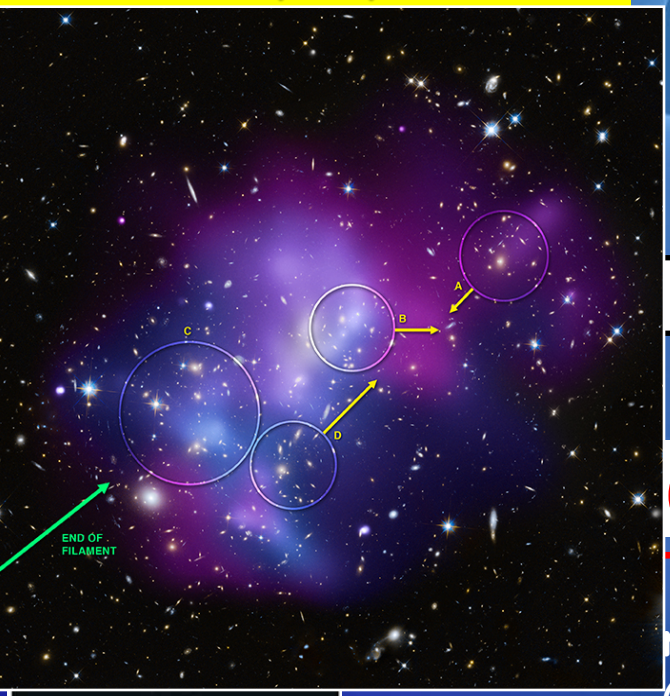


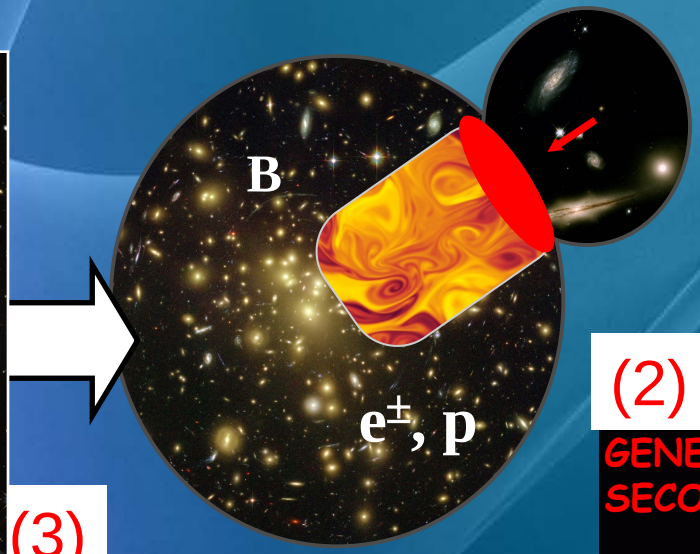


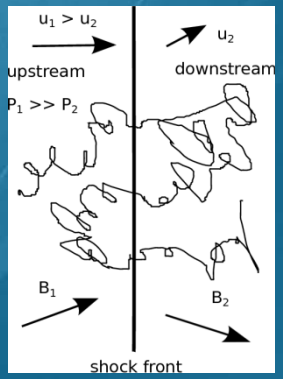
Astrophysical sources Galaxies (SN), AGN..

CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B





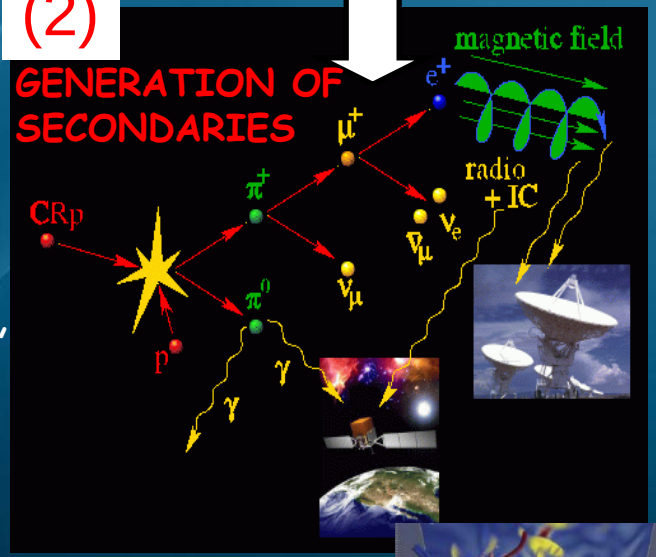


(1)

SHOCKS

accelerate CRe±,CRp

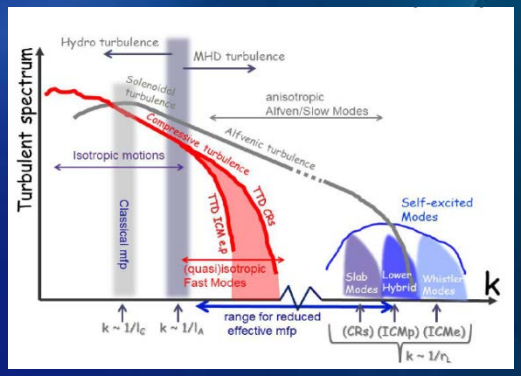
(2)

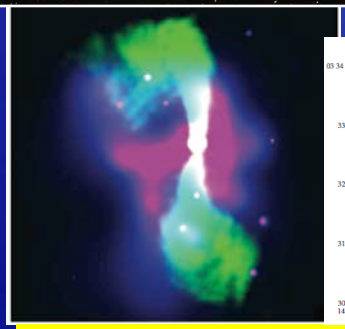


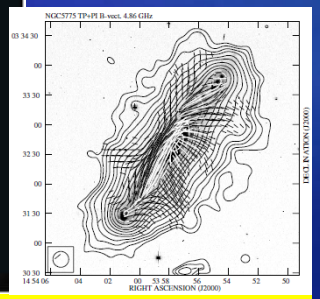
(3)

TURBULENCE

reaccelerates fossil CRe± , CRp and secondaries CRe±



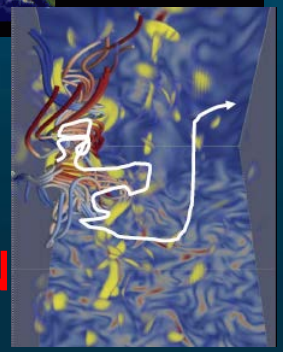




Astrophysical sources Galaxies (SN), AGN..

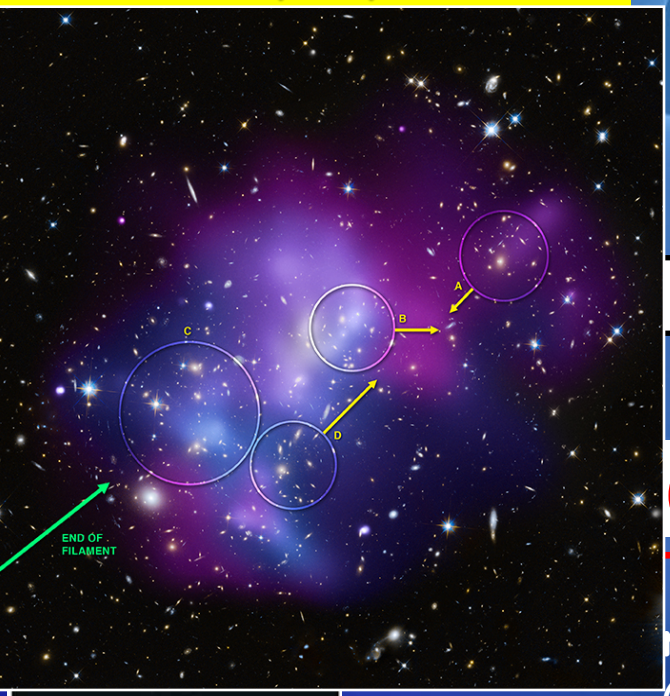
(4)

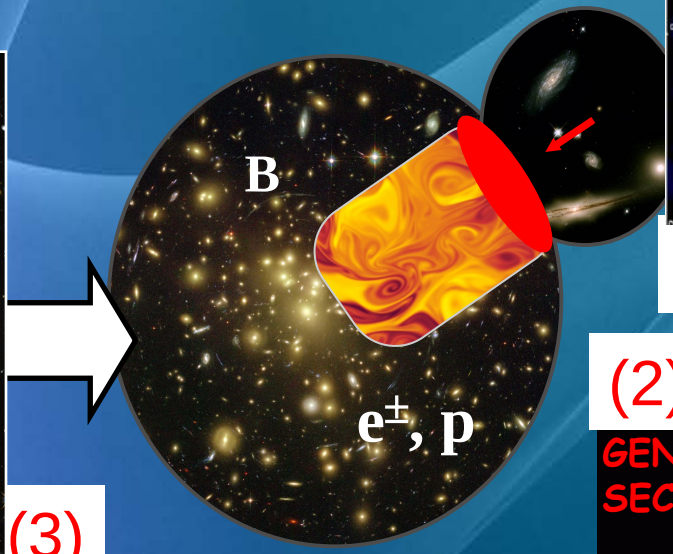
MAGNETIC RECONNECTION

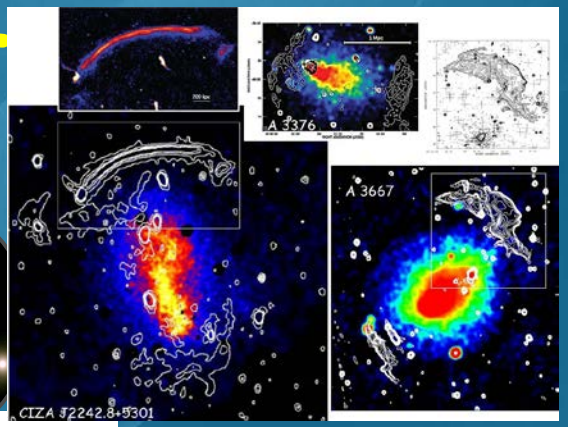


CR-accelerat

Mergers guide CRe acceleration/dynamics and/or amplify B



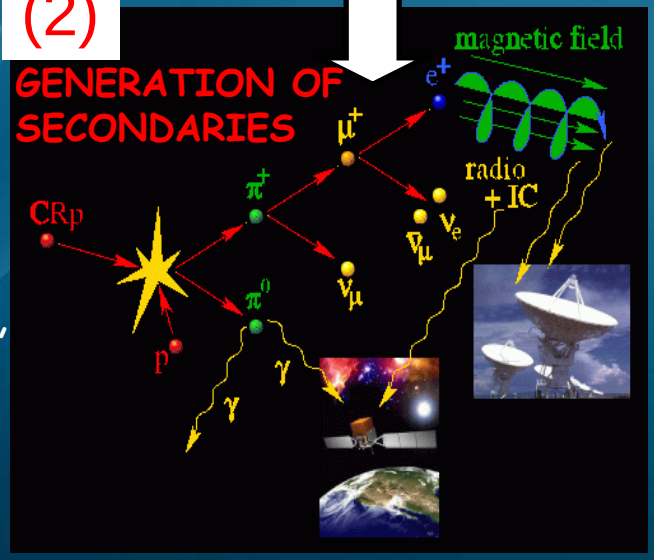




(1) SHOCKS

accelerate CRe±,CRp

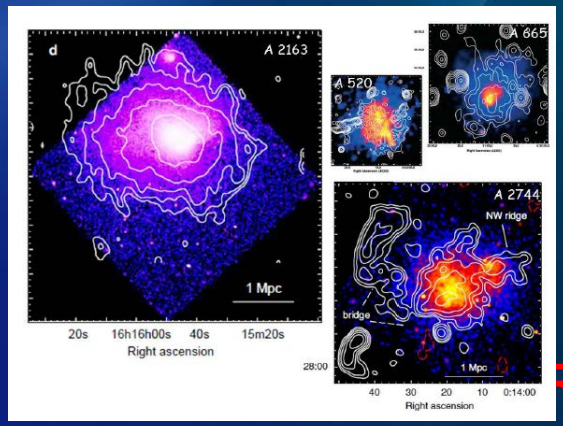
(2)

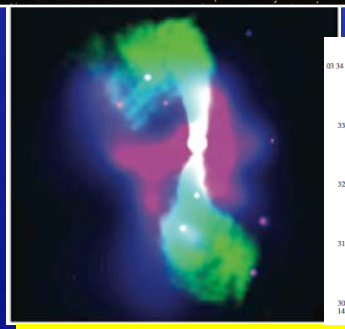


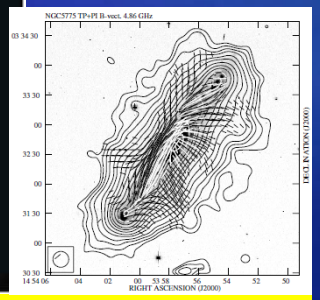
(3)

TURBULENCE

reaccelerates fossil CRe± , CRp and secondaries CRe±



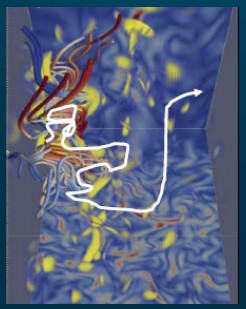




Astrophysical sources Galaxies (SN), AGN..

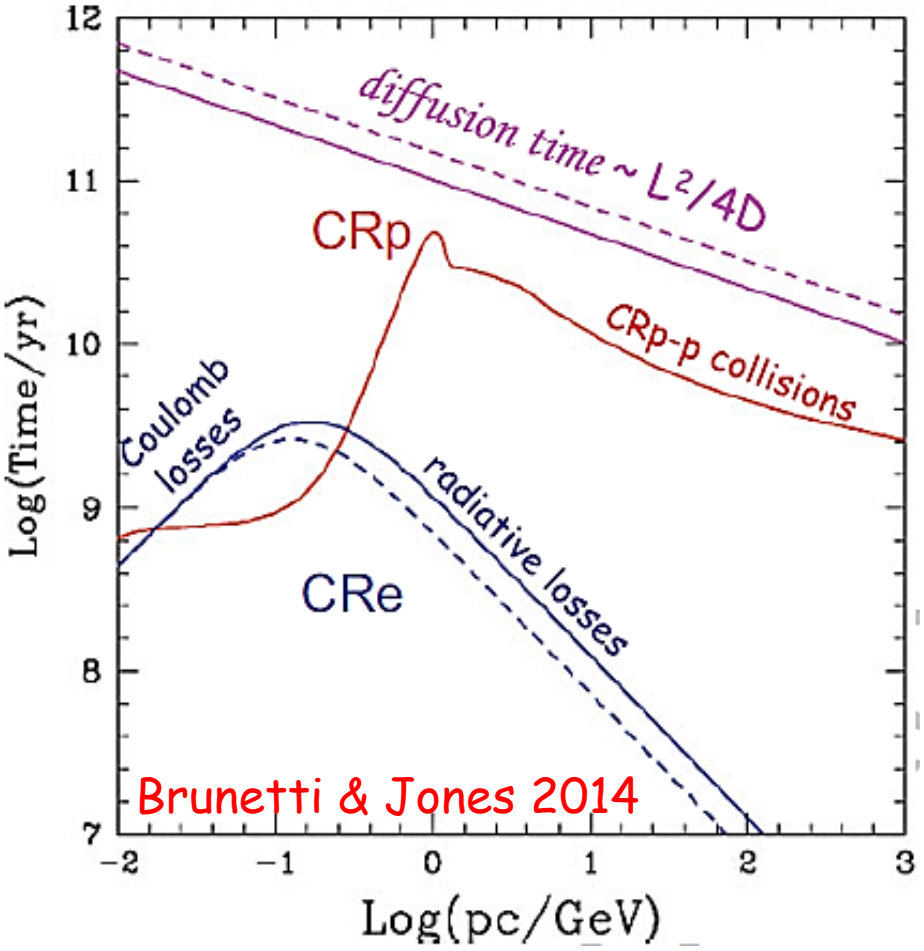
(4)

MAGNETIC RECONNECTION



Why gamma-rays ? : CR confinement

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

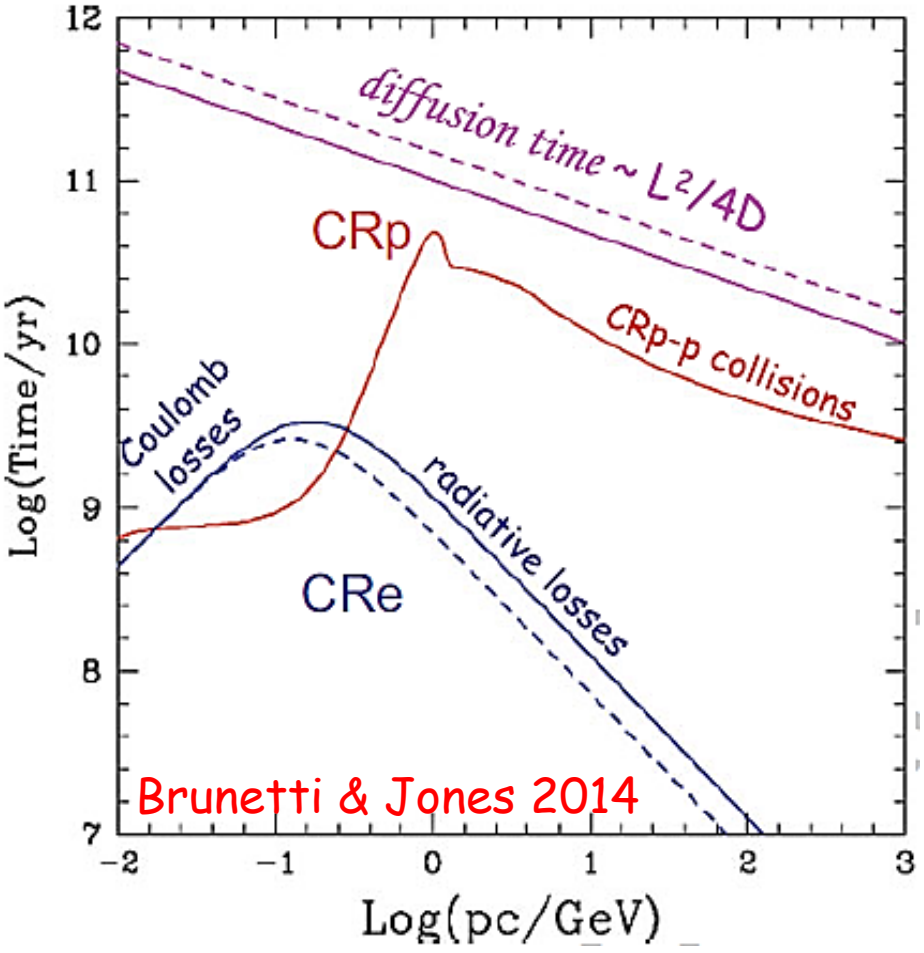


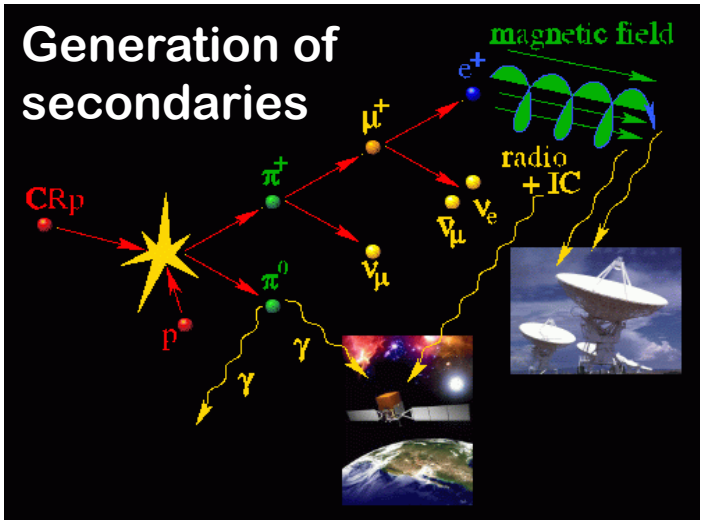
- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

Why gamma-rays ? : CR confinement

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





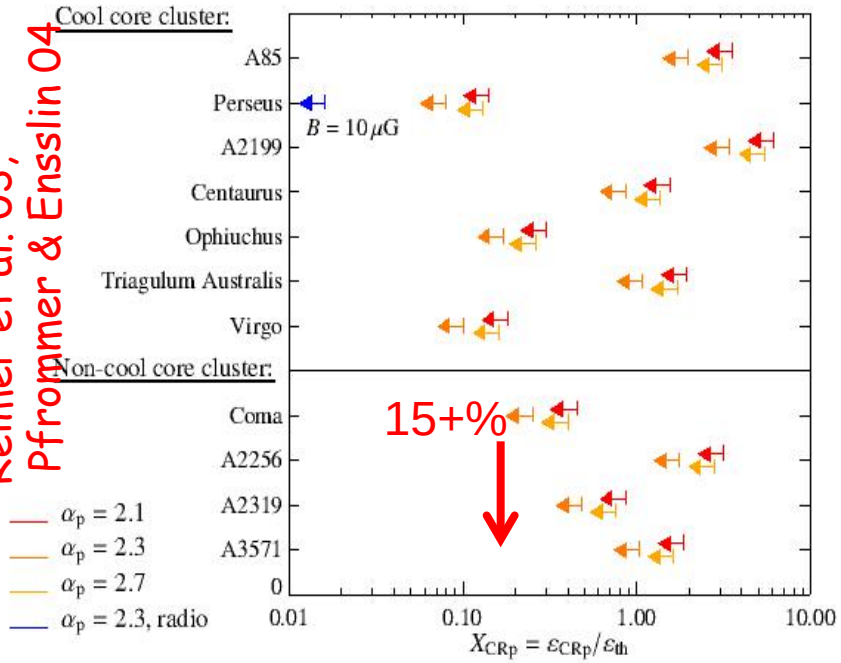
We should see gamma-rays due to neutral pion decay. Luminosity depends on the energy budget in CRp which in turns constrains efficiency of CRp acceleration.

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

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

EGRET

Reimer et al. 03, Pfrommer & Ensslin 04



Limits before FERMI

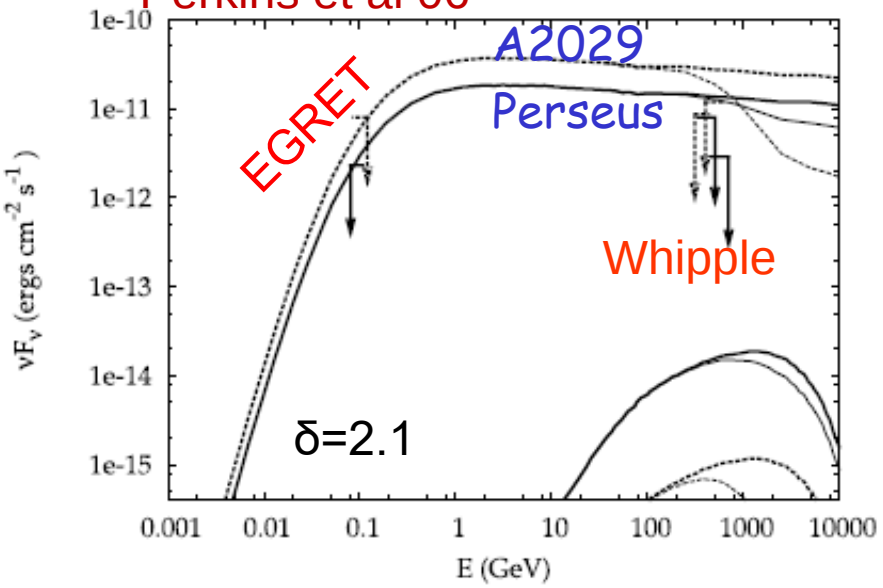
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

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

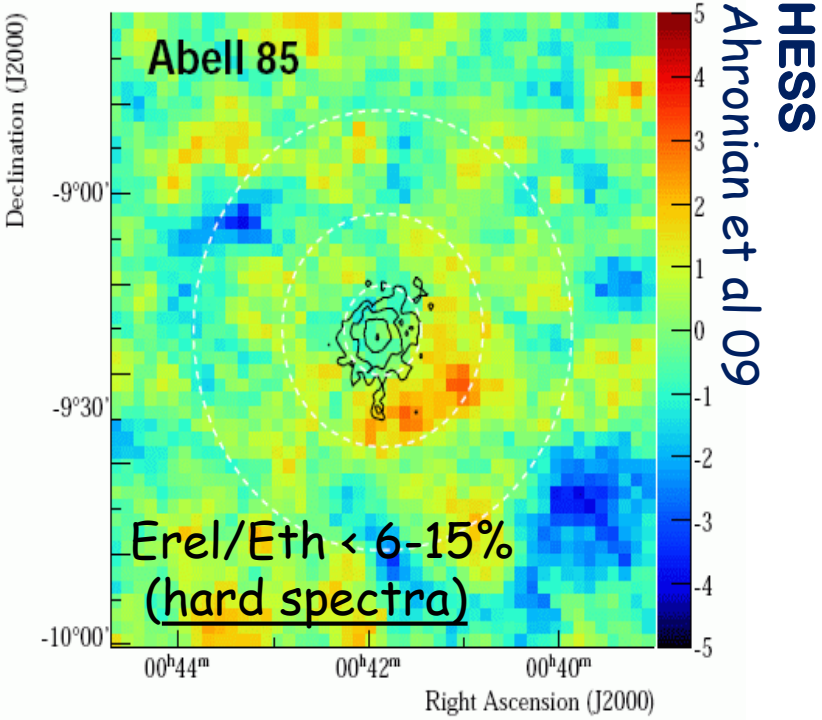
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu), \quad \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$

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

Perkins et al 06



HESS Aharonian et al 09

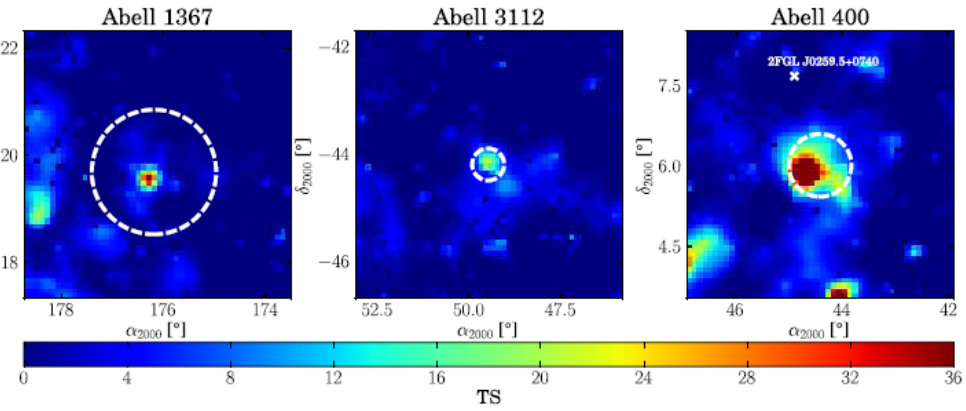


Population analysis of about 50 nearby clusters, including CC and mergers and clusters with diffuse radio emission :

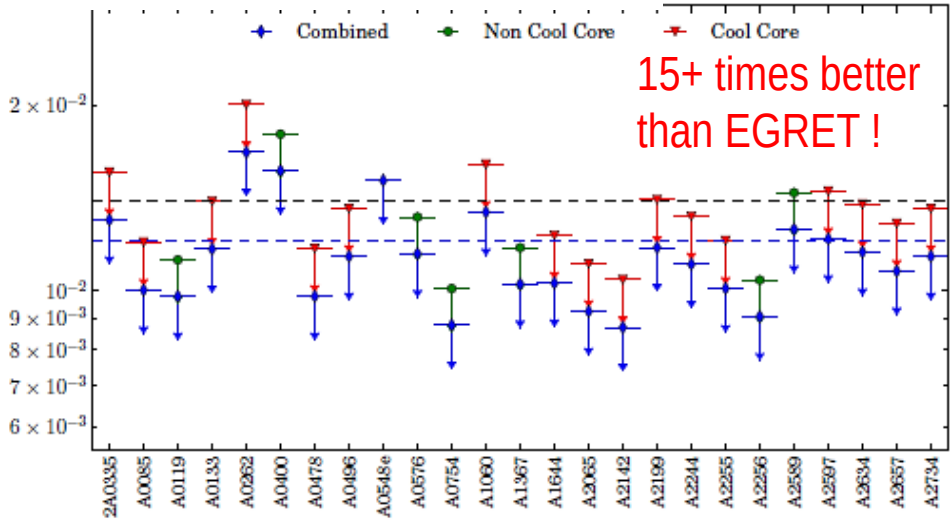
NO DETECTIONS...

Fermi-LAT limits

(LAT-Coll: Ackermann+ 10, 14)

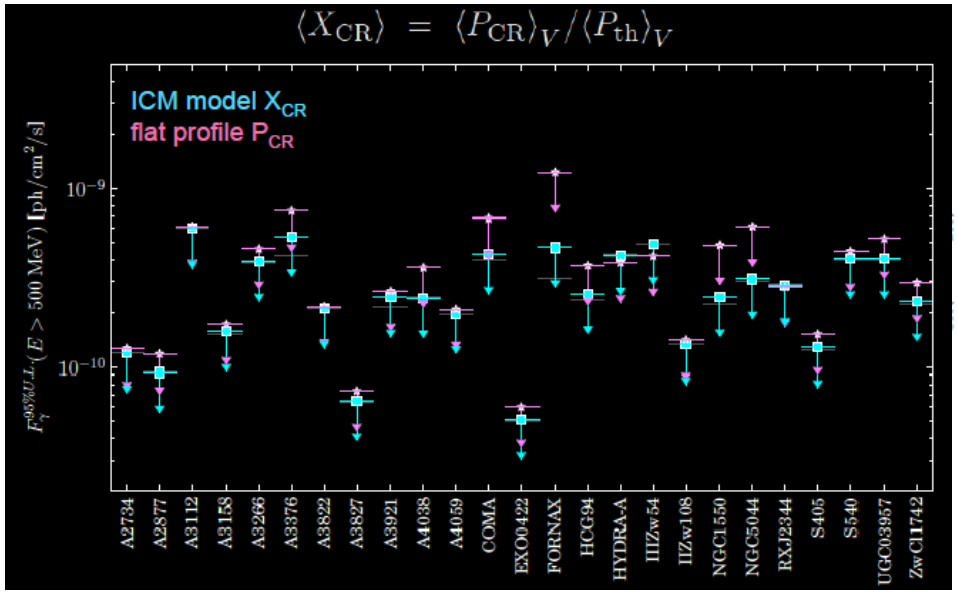


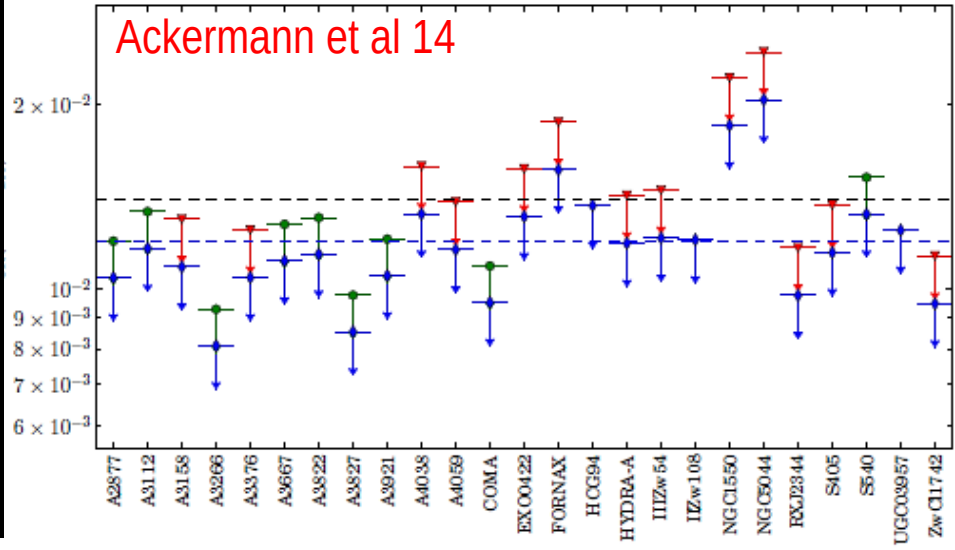
$$\langle X_{\rm CR}\rangle = \langle P_{\rm CR}\rangle_V / \langle P_{\rm th}\rangle_V$$



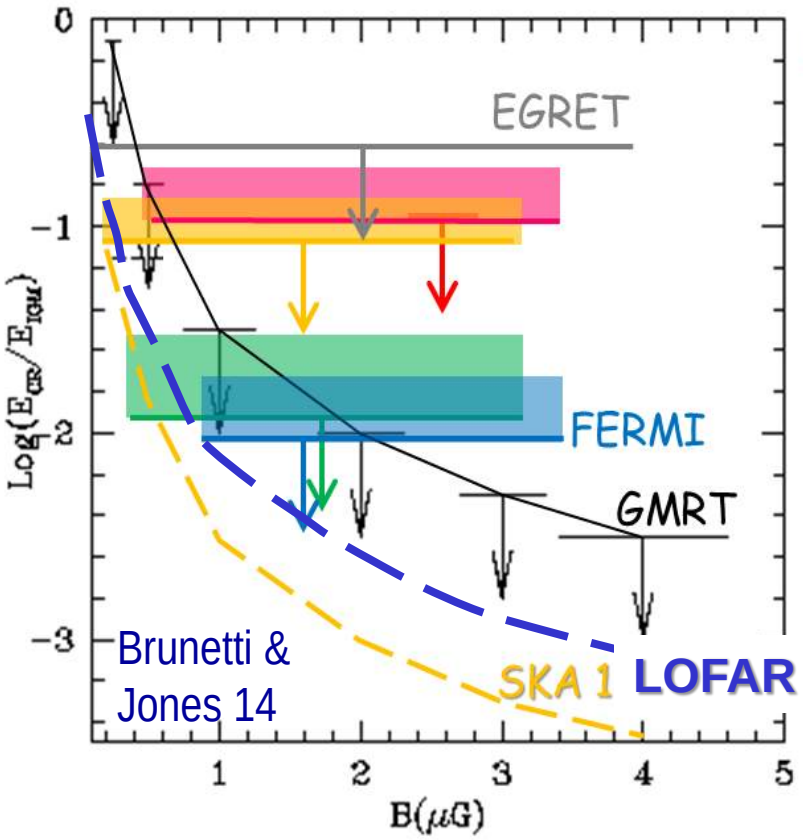
Spatial distribution of CRp

$$\langle X_{\rm CR}\rangle = \langle P_{\rm CR}\rangle_V / \langle P_{\rm th}\rangle_V$$

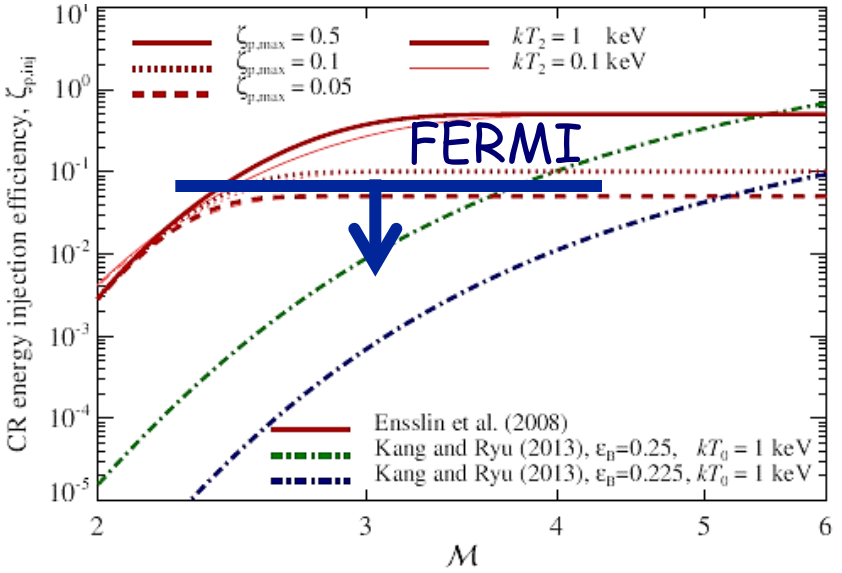




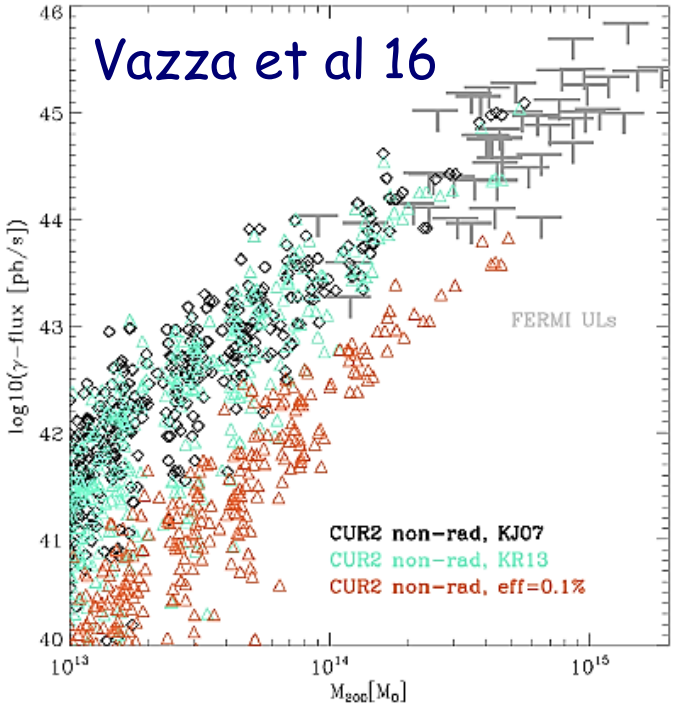
Where are CRp ?



Strong constraints on CRp acceleration efficiency at shock in galaxy clusters



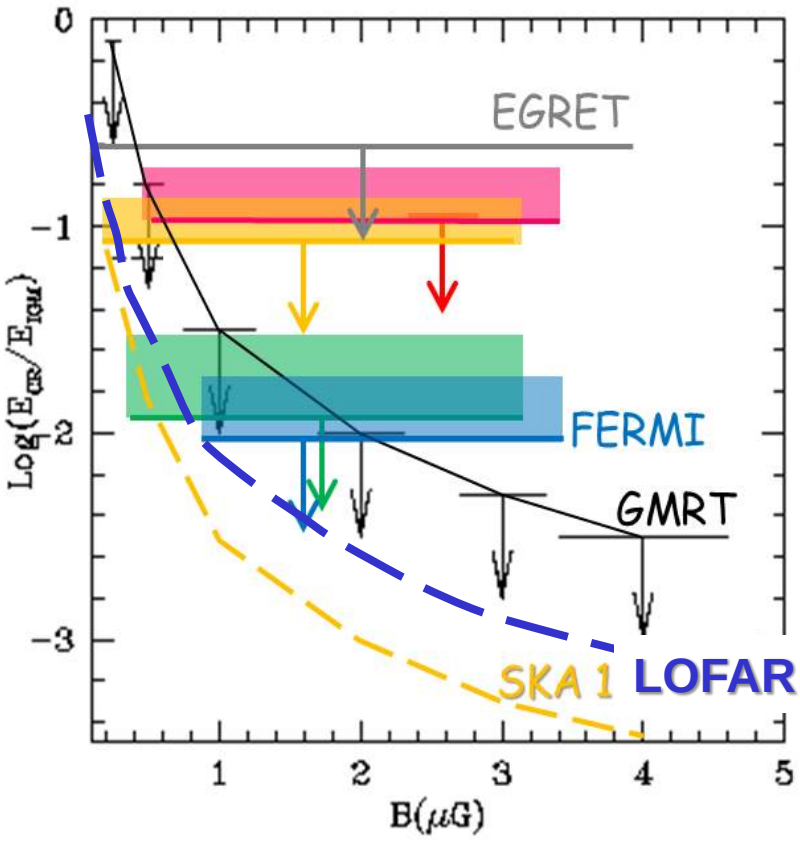
Ackerman et al 14



Big Questions *[Brunetti+Jones 14]*

- Inefficient CRp acceleration ??
- Complex CRp spectra ??
- Is confinement true ??

Where are CRp ?

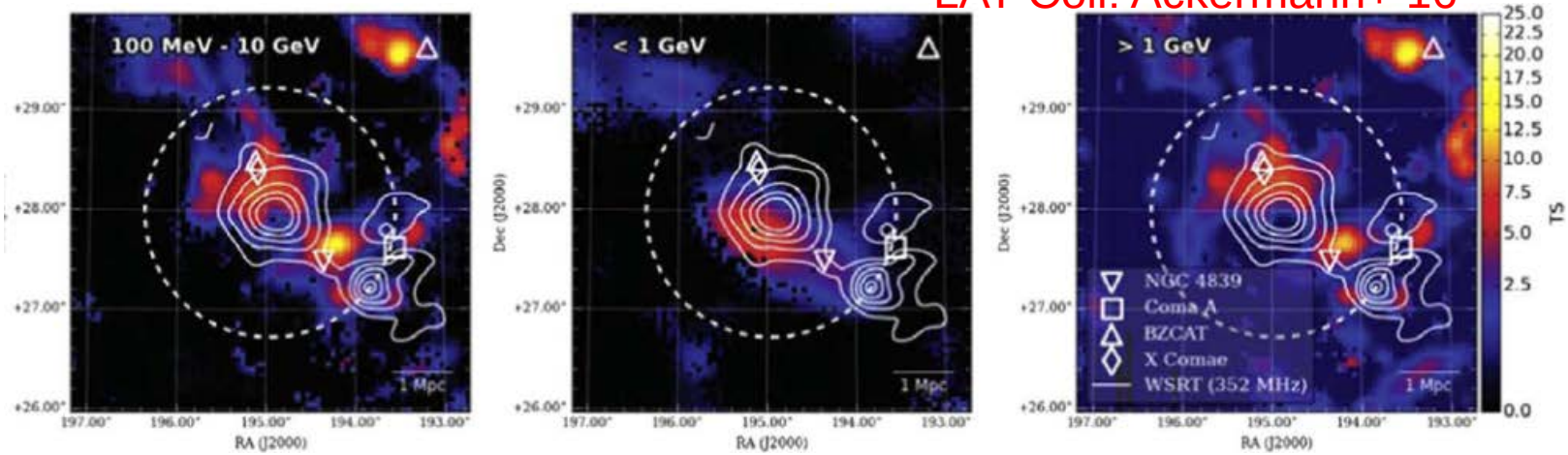


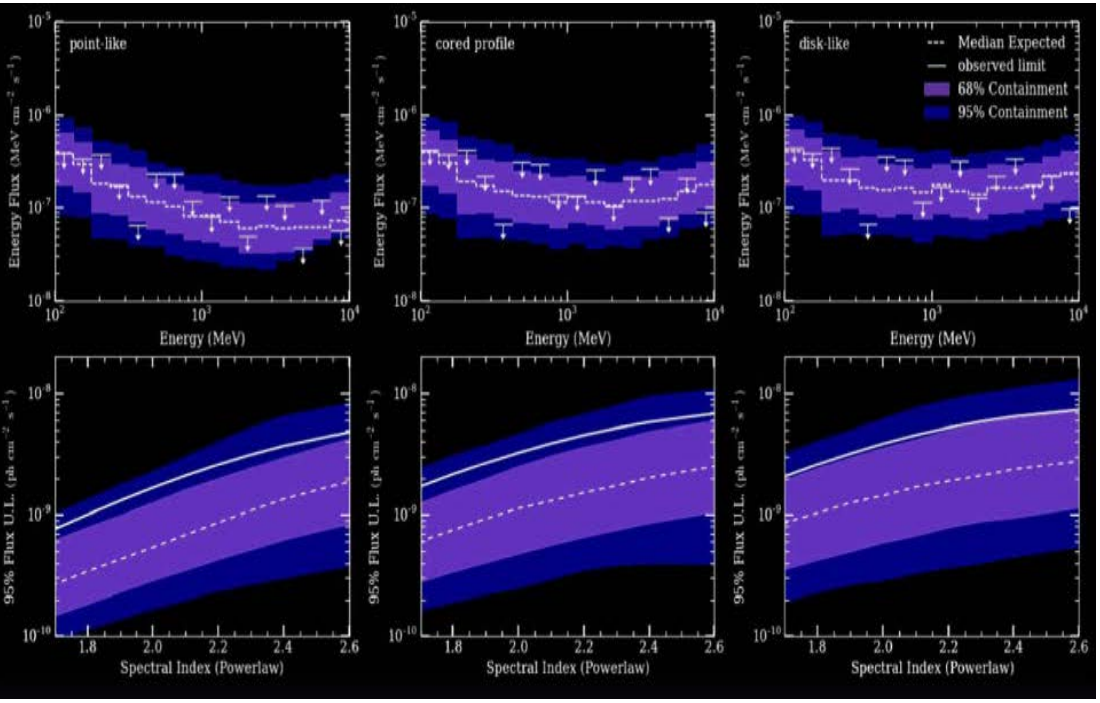
Big Questions *[Brunetti+Jo*

- Inefficient CRp acceleration ??
- Complex CRp spectra ??
- Is confinement true ??

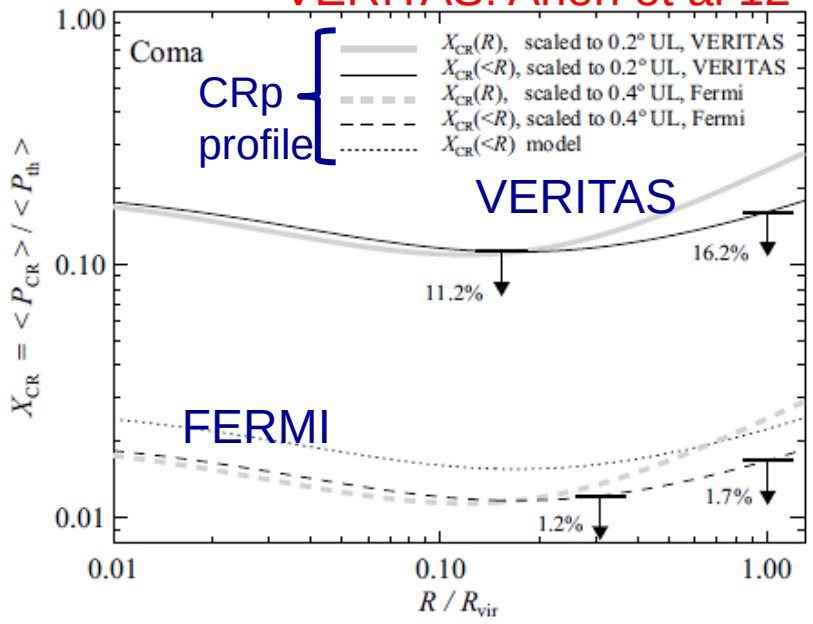
Limits for the Coma cluster

LAT Coll: Ackermann+ 16





VERITAS: Arlen et al 12



Consequences : origin of radio halos

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

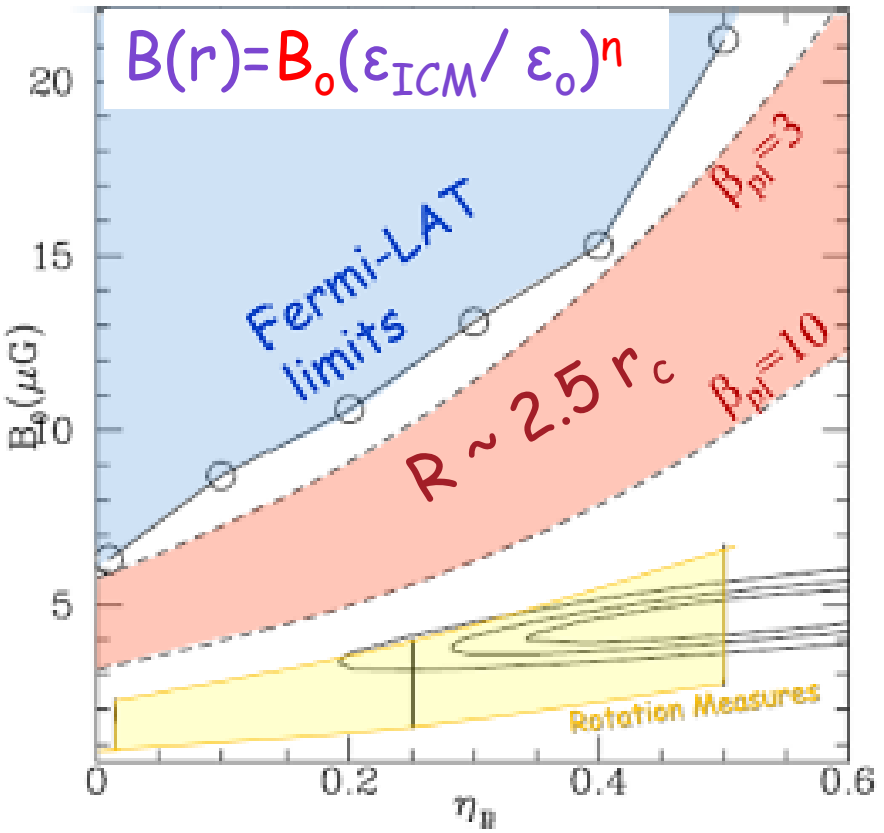
$$\pi^0 \rightarrow \gamma\gamma$$

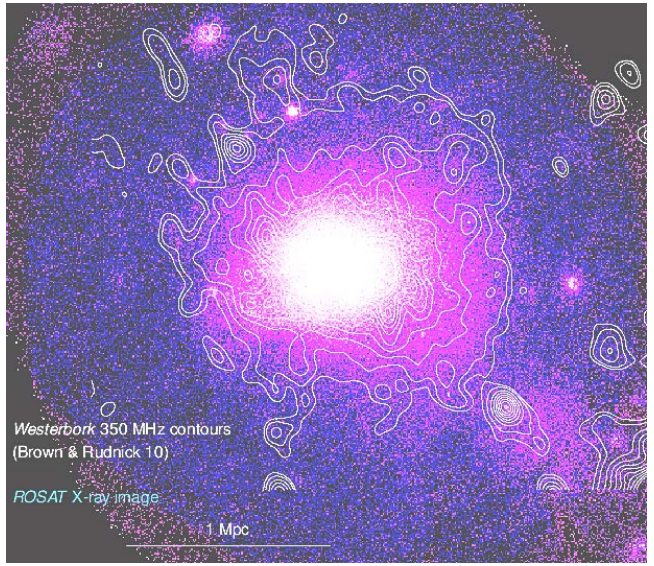
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu}), \quad \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_e(\bar{\nu}_e).$$

$$\frac{L_{radio}}{L_{\gamma}} \propto \langle \frac{B^{\alpha+1}}{B^2 + B_{cmb}^2} \rangle$$

Radio to gamma-ray ratio depends on B

Brunetti et al 17

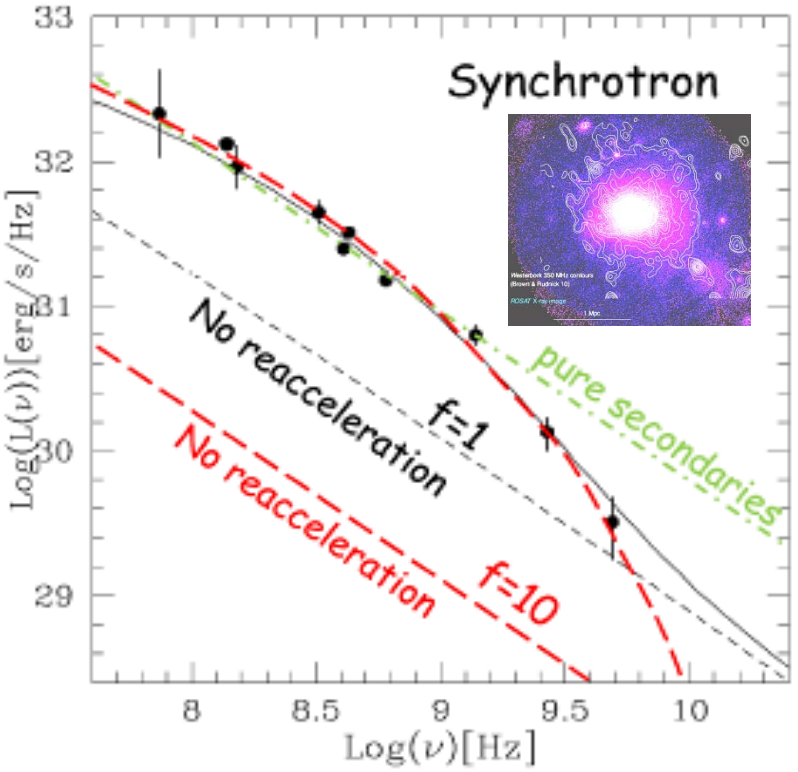


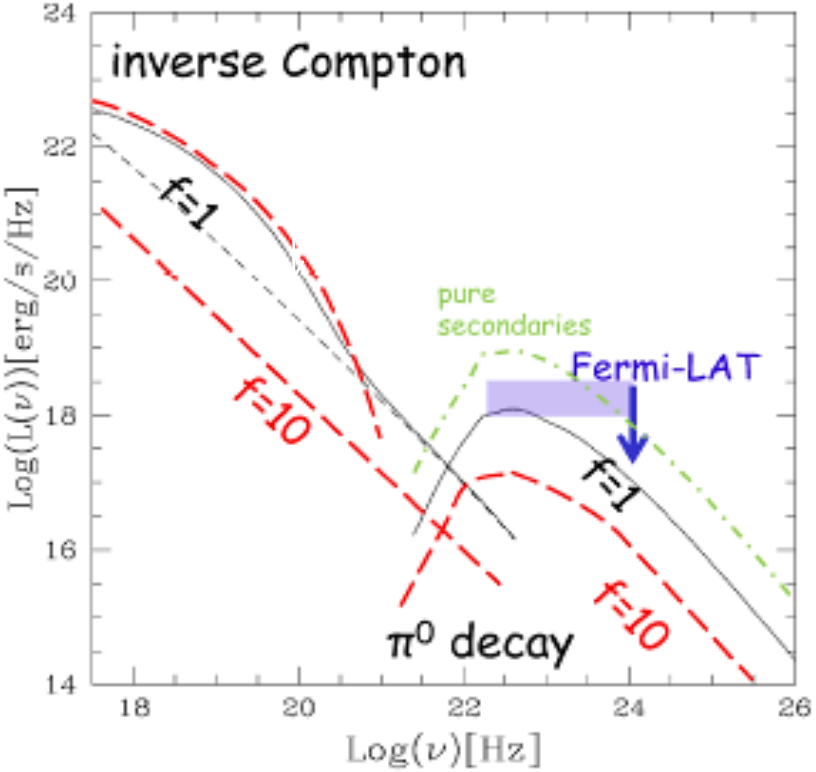


- B much higher than RM
- B dynamically important

Not hadronic origin: too many CRp are necessary to contribute significantly to the observed RH

Radio halo: consequences for gamma





Full calculations of turbulent reacceleration of
(i) CRp,
(ii) secondaries,
(iii) primary CRe
(iv) turbulent damping
(eg Brunetti+Lazarian 11, Pinzke+ 17, Brunetti+ 17)

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

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

Turb energy flux

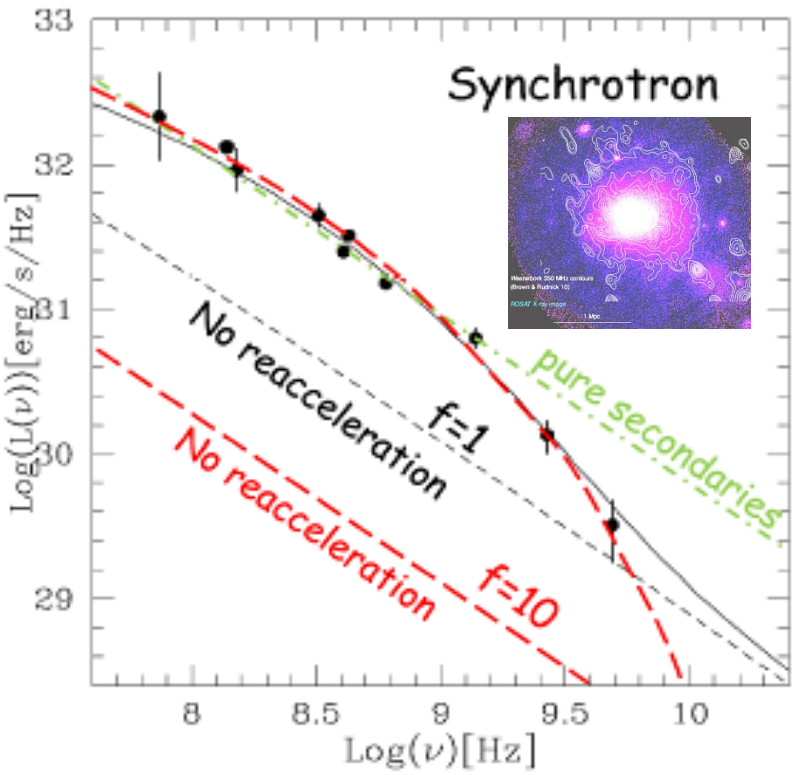
$$L_{ICS} \propto I_{tu} \Gamma_{CRe} \frac{B_{IC}^2}{B^2 + B_{IC}^2} V_{ICS}$$

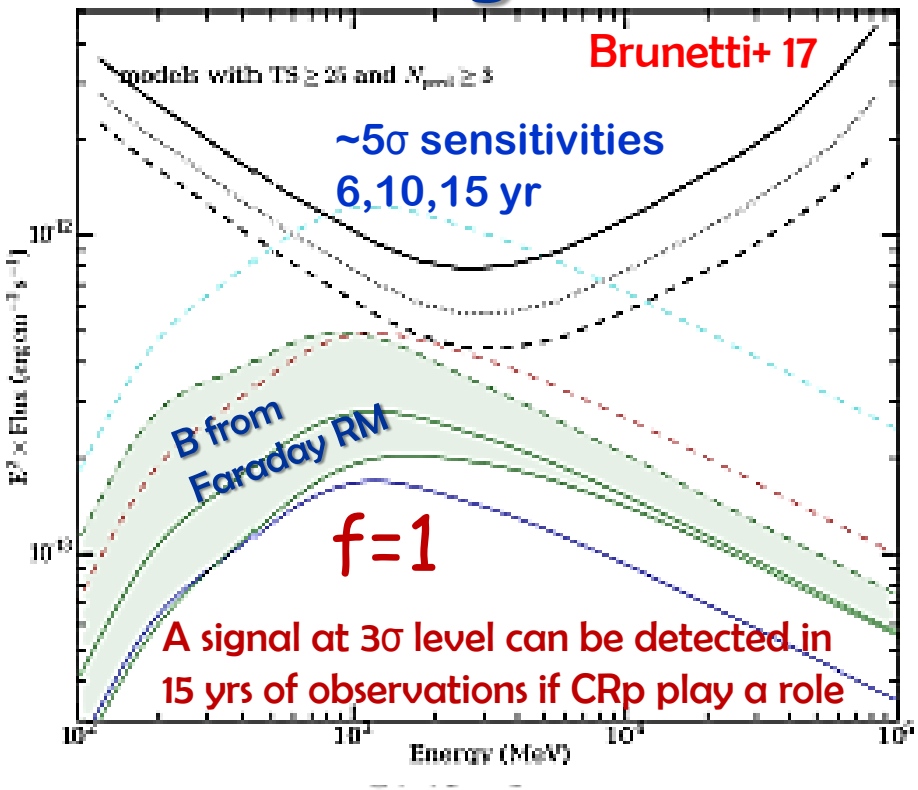
$$\frac{L_{SYN}}{L_\gamma} \propto F(\delta) \frac{I_{tu} B^2}{B^2 + B_{IC}^2} f$$

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

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

Radio halo: consequences for gamma





Full calculations of turbulent reacceleration of
(i) CRp,
(ii) secondaries,
(iii) primary CRe
(iv) turbulent damping
(eg Brunetti+Lazarian 11, Pinzke+ 17, Brunetti+ 17)

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

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

Turb energy flux

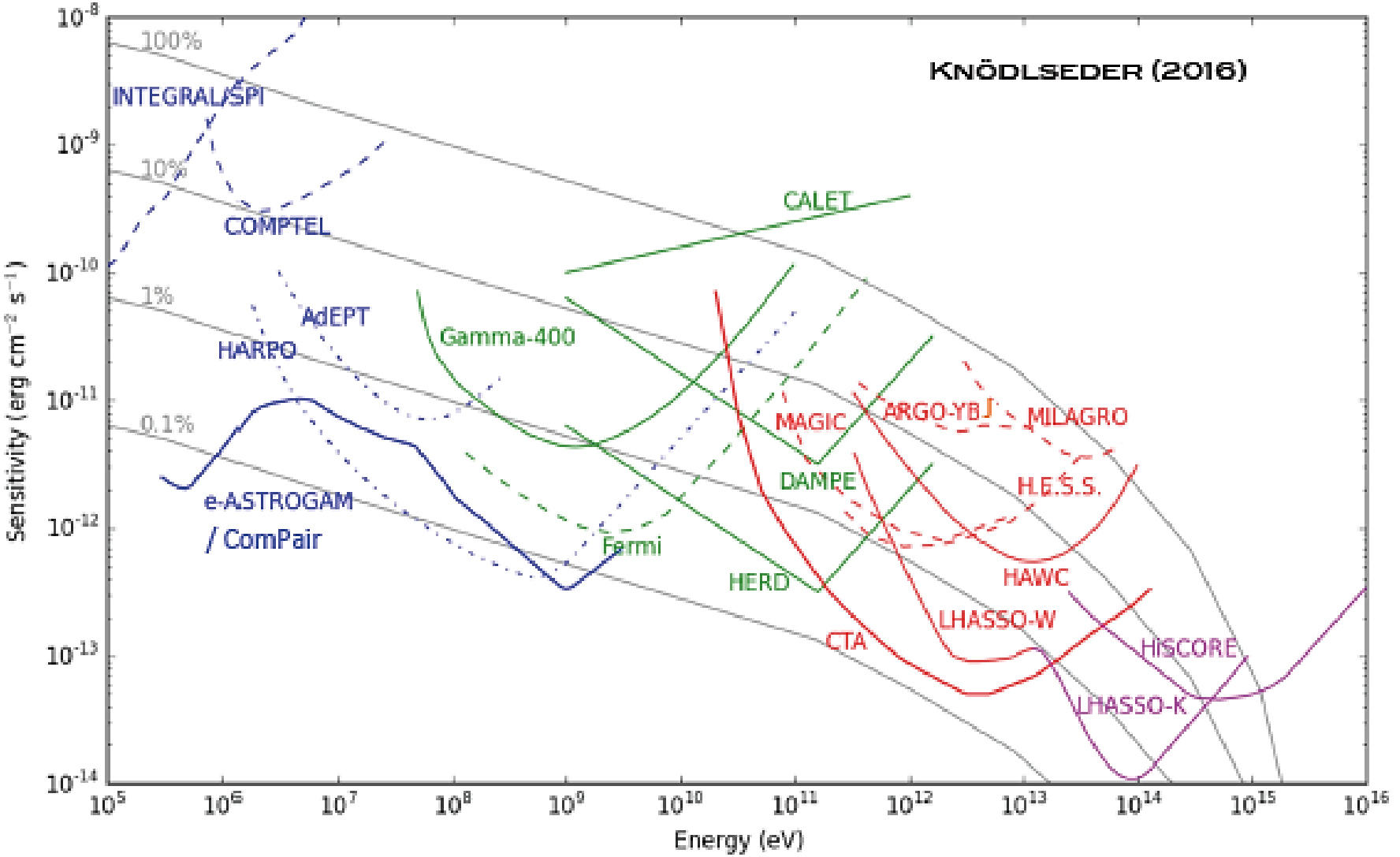
$$L_{ICS} \propto I_{tu} \Gamma_{CRe} \frac{B_{IC}^2}{B^2 + B_{IC}^2} V_{ICS}$$

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

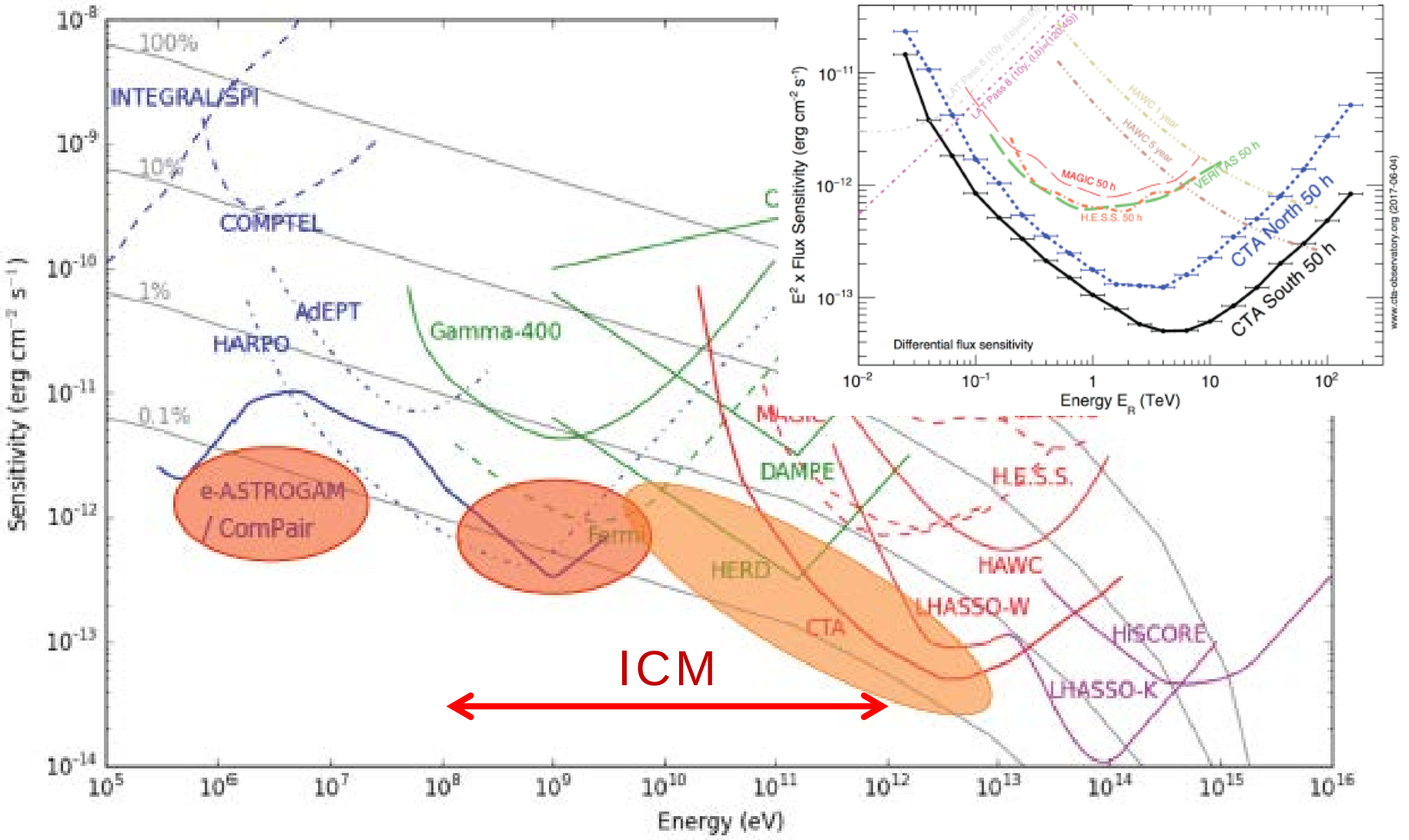
$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B_{IC}^2}$$

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

What's next ?


KNÖDLSEDER (2016)
100%
10%
1%
0.1%
INTEGRAL/SPI
COMPTEL
AdEPT
HARPO
e-ASTROGAM
/ ComPair
CALET
Gamma-400
Fermi
MAGIC
ARGO-YBJ
MILAGRO
DAMPE
H.E.S.S.
HERD
HAWC
LHASSO-W
CTA
HISCORE
LHASSO-K
Sensitivity (erg cm^{-2} s^{-1})
Energy (eV)
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
10^{16}

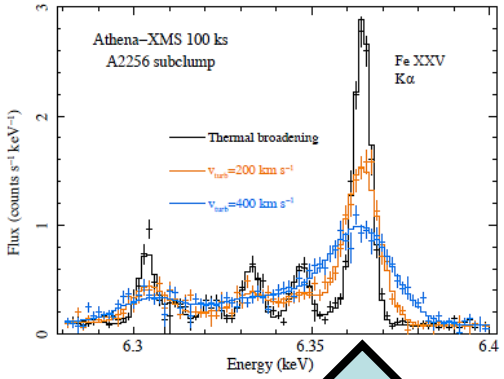
What's next ?


Sensitivity (erg cm^{-2} s^{-1})
Energy (eV)
100%
10%
1%
0.1%
INTEGRAL/SPI
COMPTEL
AdEPT
HARPO
Gamma-400
e-ASTROGAM
/ ComPair
Fermi
DAMPE
HERD
CTA
H.E.S.S.
HAWC
LHASSO-W
HISCORE
LHASSO-K
ICM
E^2 x Flux Sensitivity (erg cm^{-2} s^{-1})
Energy E$_R$ (TeV)
Differential flux sensitivity
HAWC 1 year
HAWC 5 year
MAGIC 50 h
H.E.S.S. 50 h
VERITAS 50 h
CTA North 50 h
CTA South 50 h
www.cta-observatory.org (2017-06-04)

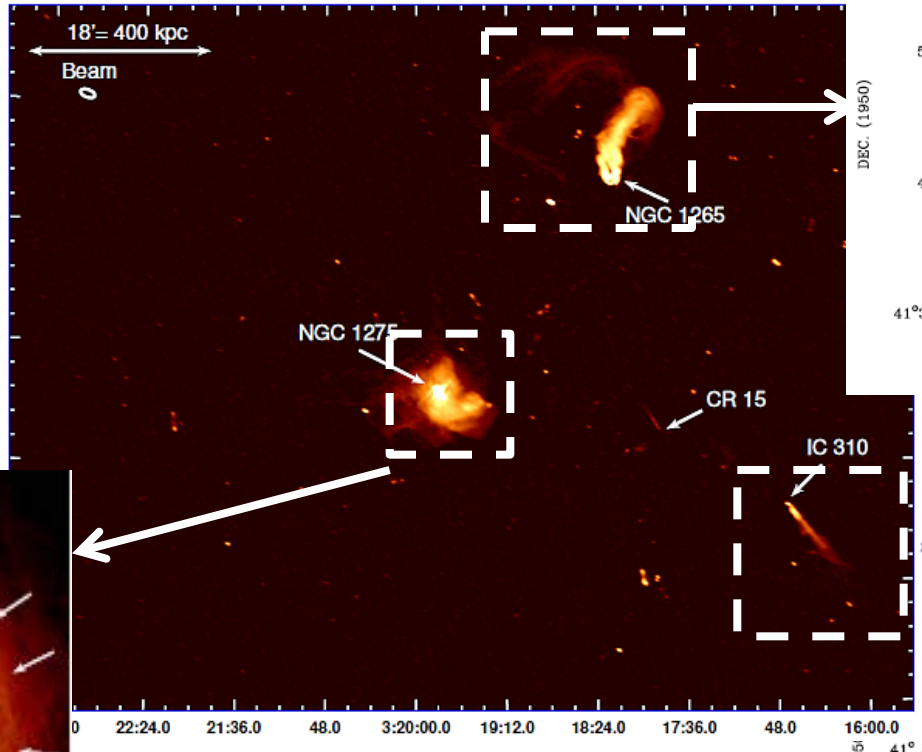
CTA KP on Perseus : by far the brightest one (expected) in the gamma-rays

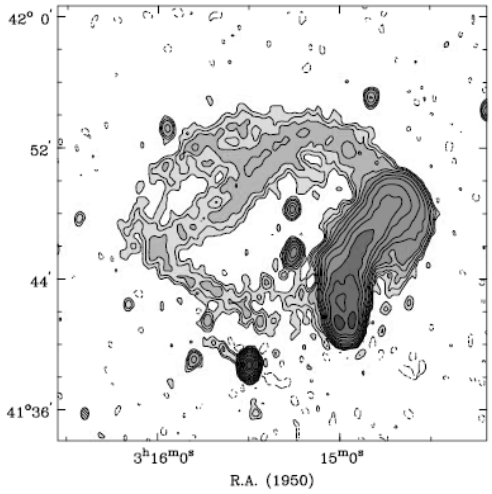
F Zandanel, A Brown, G Brunetti, M Doro, C Farnier, M Fornasa, S Gabici, S Inoue, J Palacio, D Prokhorov, J Rico, M- Sanchez-Conde, CTA coll...

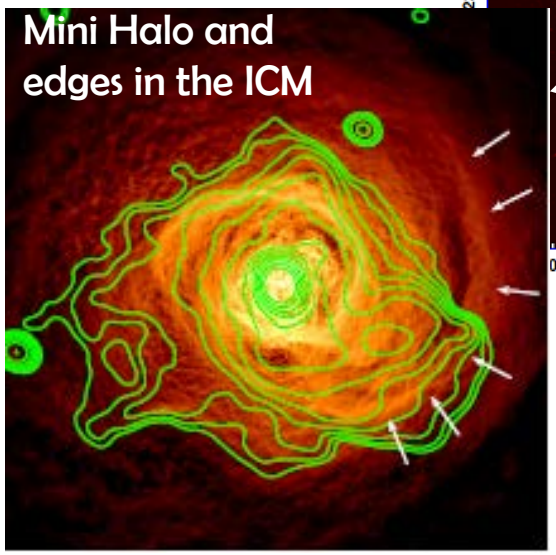
Hitomi Coll, 16

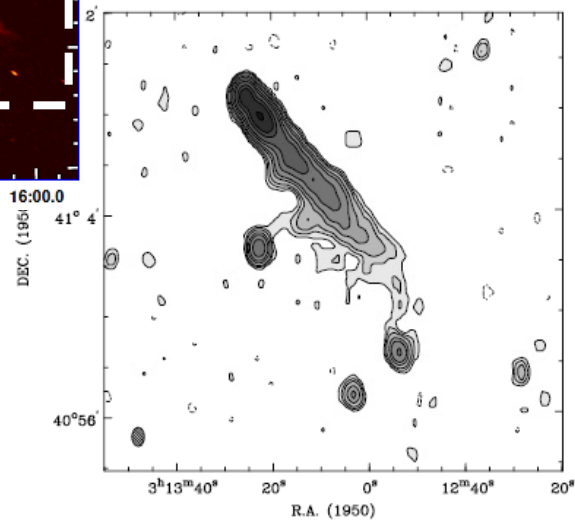


turbulence



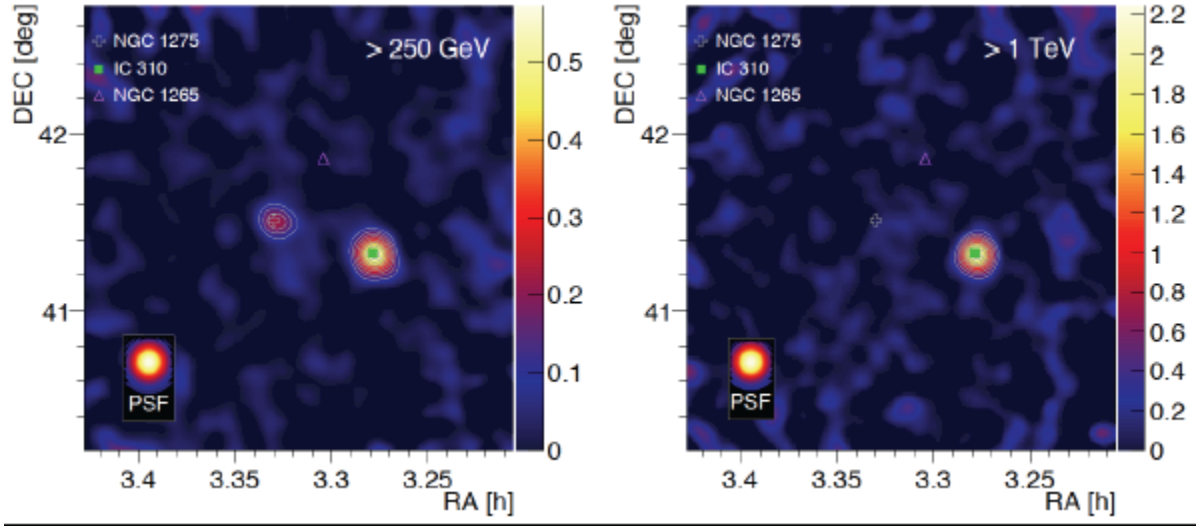




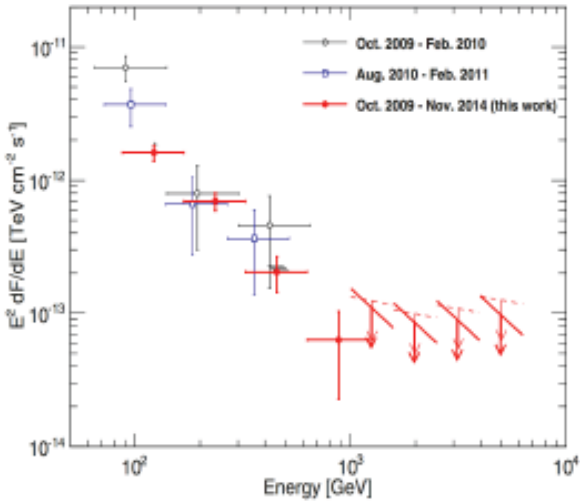


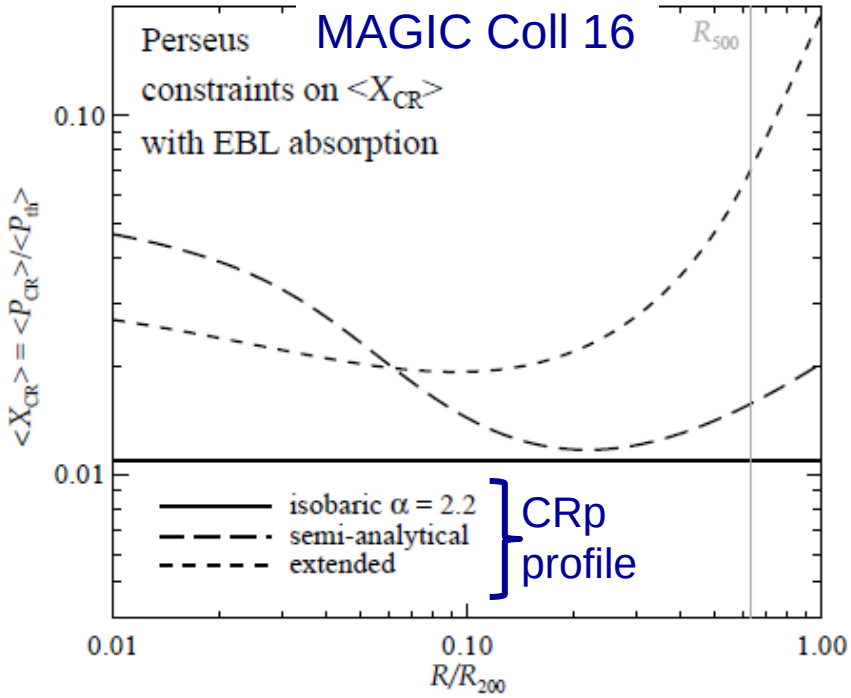
- +Nearby massive
- Brightest (ICM targets)
- AGNs sources of CRs
- Turbulence : CR transport

Current limits for Perseus



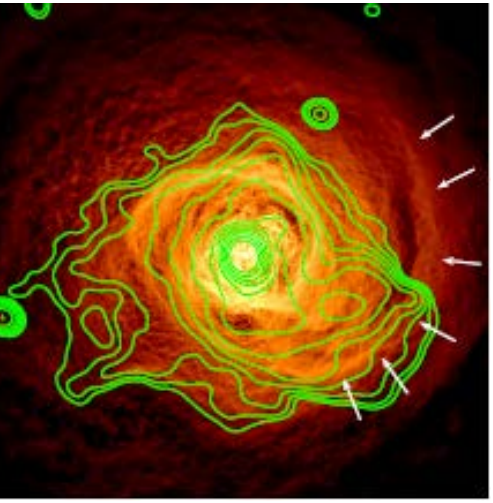
MAGIC Coll: Ahnen et al 16

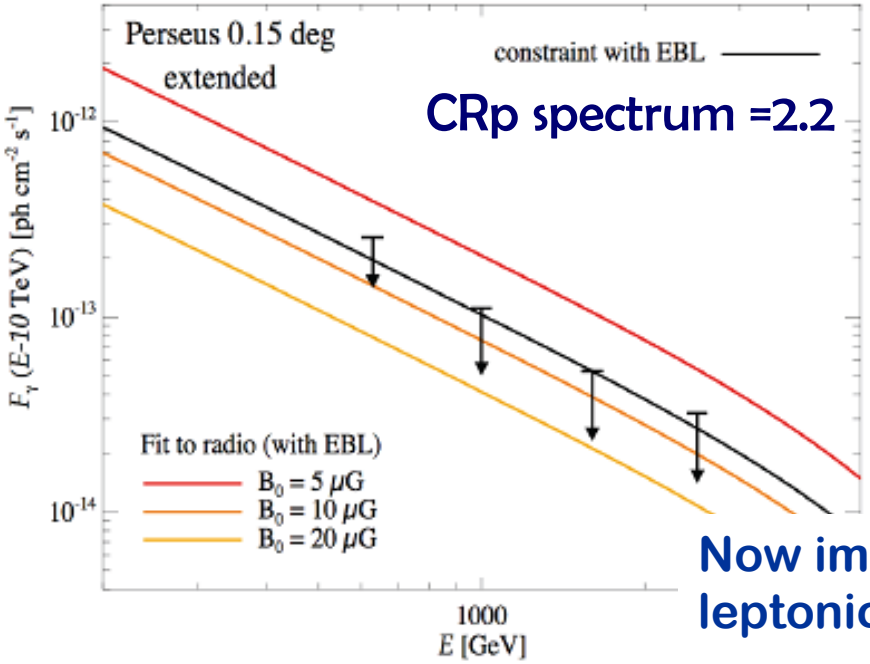




- Fermi-LAT blinded by NGC1265
- Limits on CRp from MAGIC similar to LAT limits for nearby/pop clusters

Origin of radio mini-halos



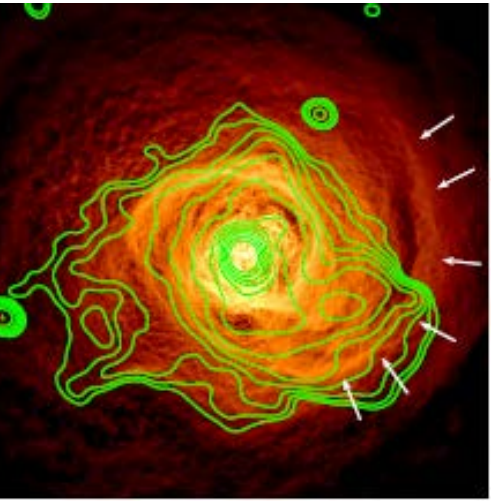


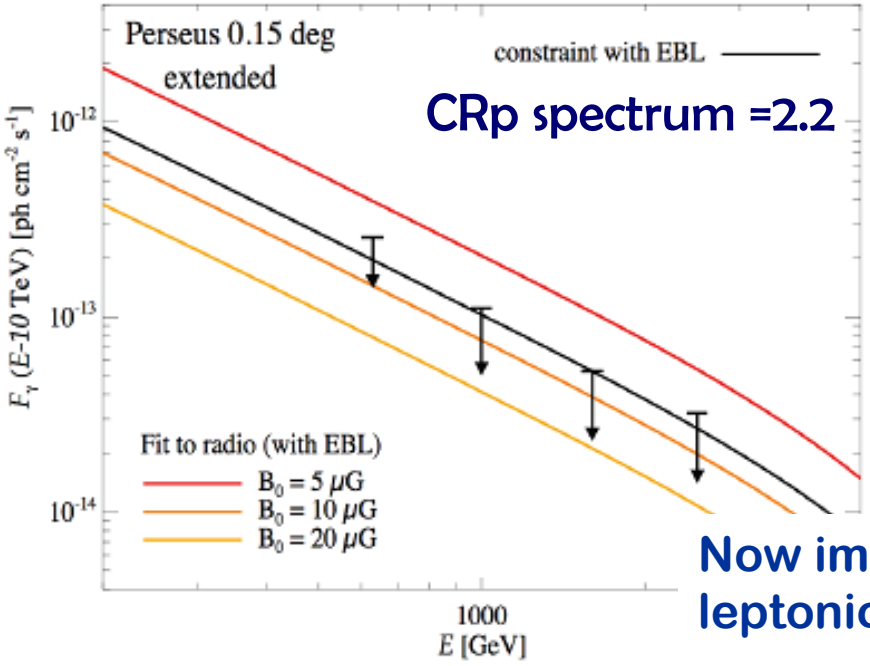
$$B(R) = B_0 \left(\frac{\rho_{\rm gas}(R)}{\rho_{\rm gas,0}} \right)^{\alpha_B}$$

Assuming an contribution from CRp (secondaries) B_0 > 5-8 μG

Now impossible to discriminate leptonic vs hadronic origin

Origin of radio mini-halos





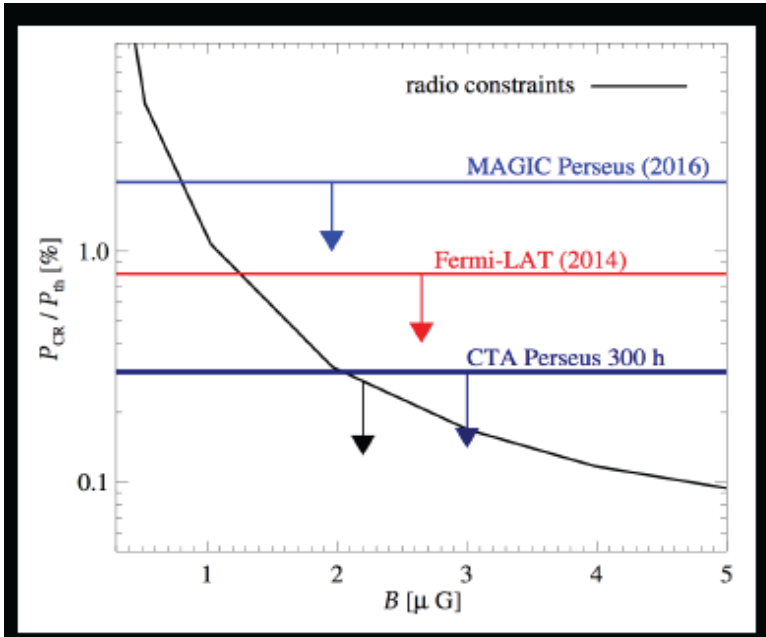
$$B(R) = B_0 \left(\frac{\rho_{\rm gas}(R)}{\rho_{\rm gas,0}} \right)^{\alpha_B}$$

Assuming an contribution from CRp (secondaries) B_0 > 5-8 μG

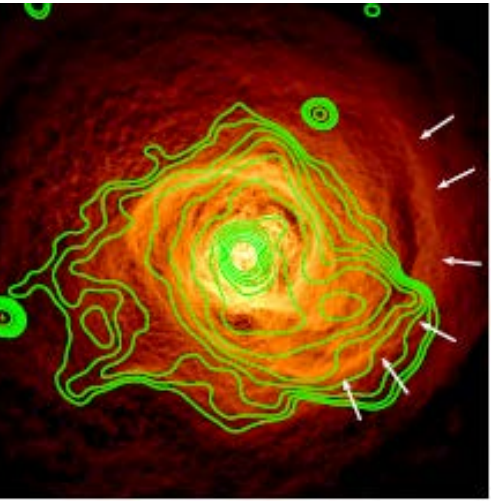
Now impossible to discriminate leptonic vs hadronic origin

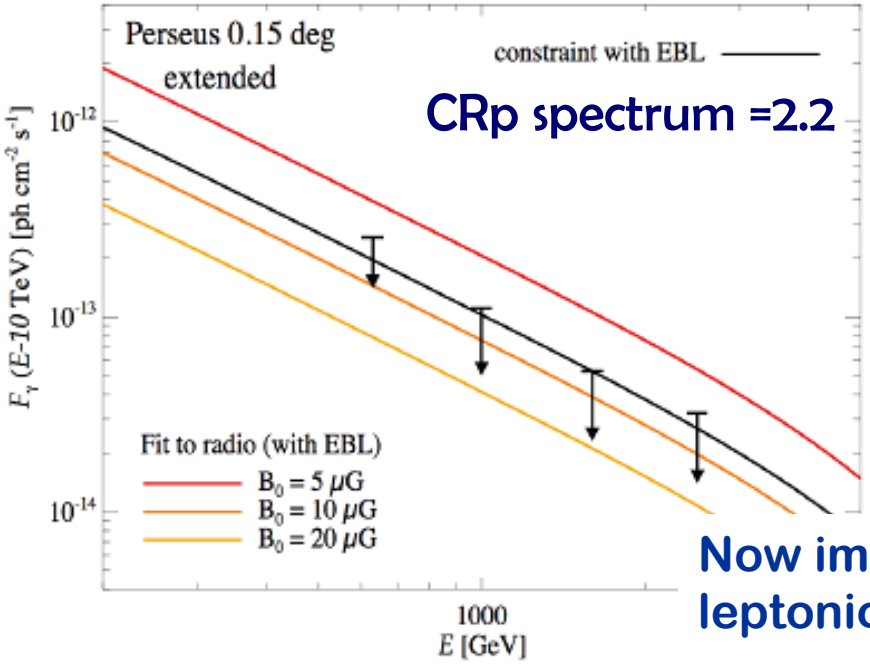
Clusters science

- Deepest limits on CRp
- Strongest constraints on CRp acceleration
- Origin of radio mini-halos



Origin of radio mini-halos





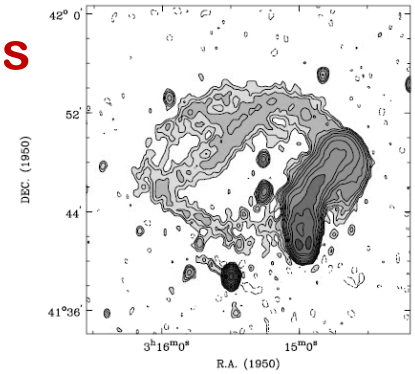
$$B(R) = B_0 \left(\frac{\rho_{\rm gas}(R)}{\rho_{\rm gas,0}} \right)^{\alpha_B}$$

Assuming an contribution from CRp (secondaries) B_0 > 5-8 μG

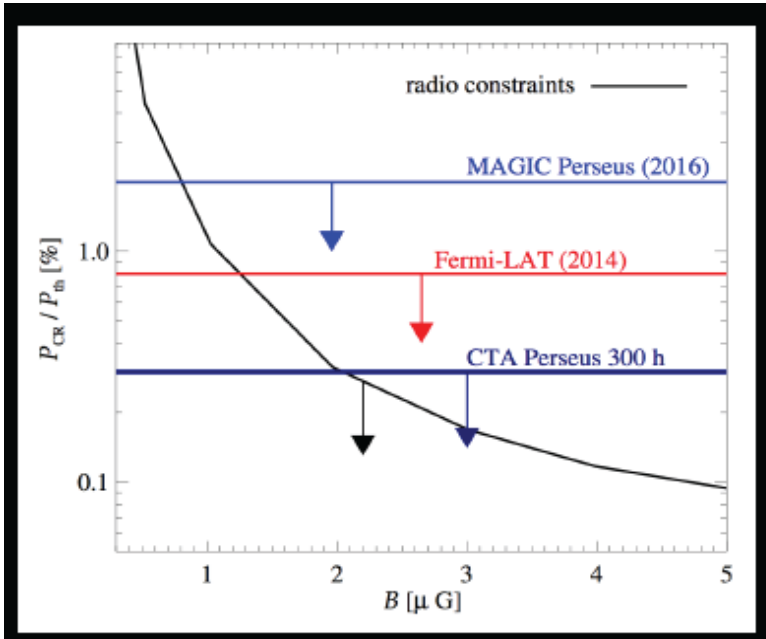
Now impossible to discriminate leptonic vs hadronic origin

Beyond clusters science

- CRp in RSs
- Transport of CRp



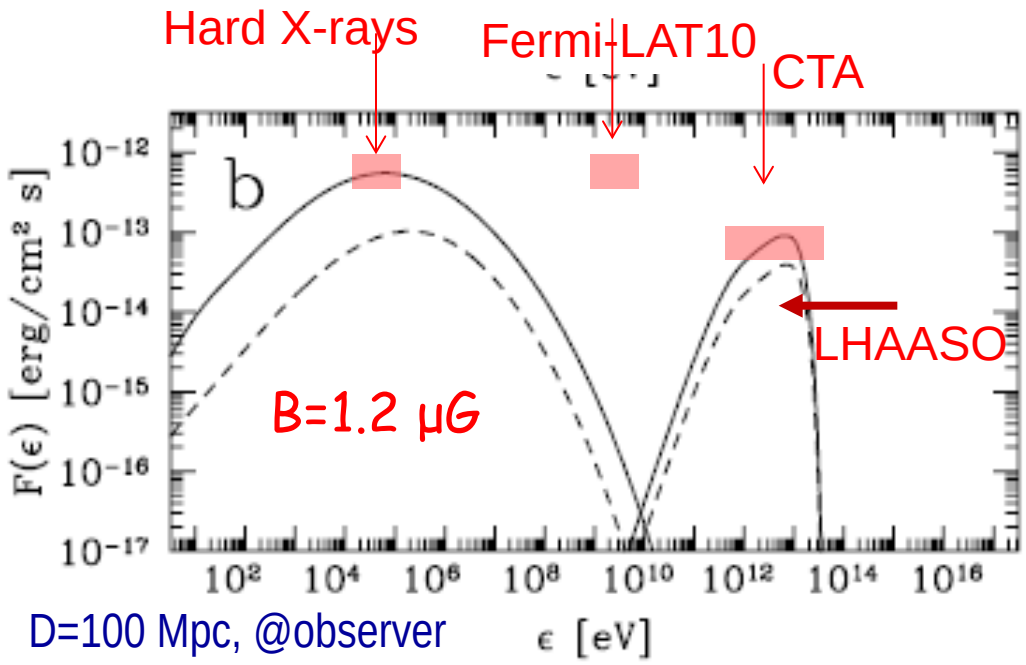
Synergies with (LOFAR)SKA (Hitomi2)Athena



Exotic CTA science: Max energy of CR

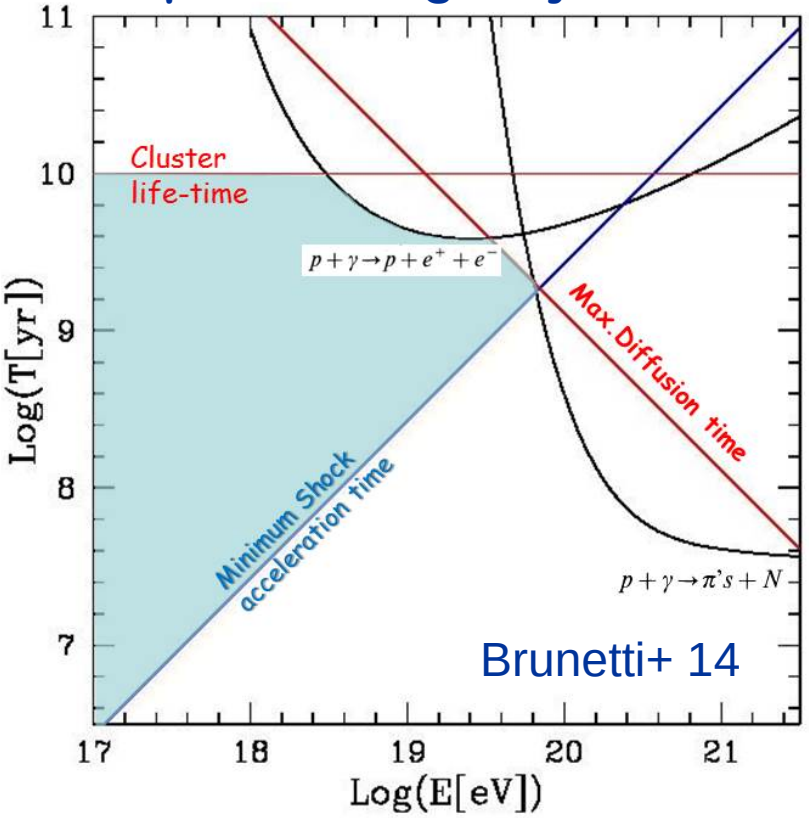
Acceleration of EeV CRp @accretion shocks ?

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



D=100 Mpc, @observer

In principle…
acceleration of EeV CRp is possible in galaxy clusters



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

TAKE HOME MESSAGES :

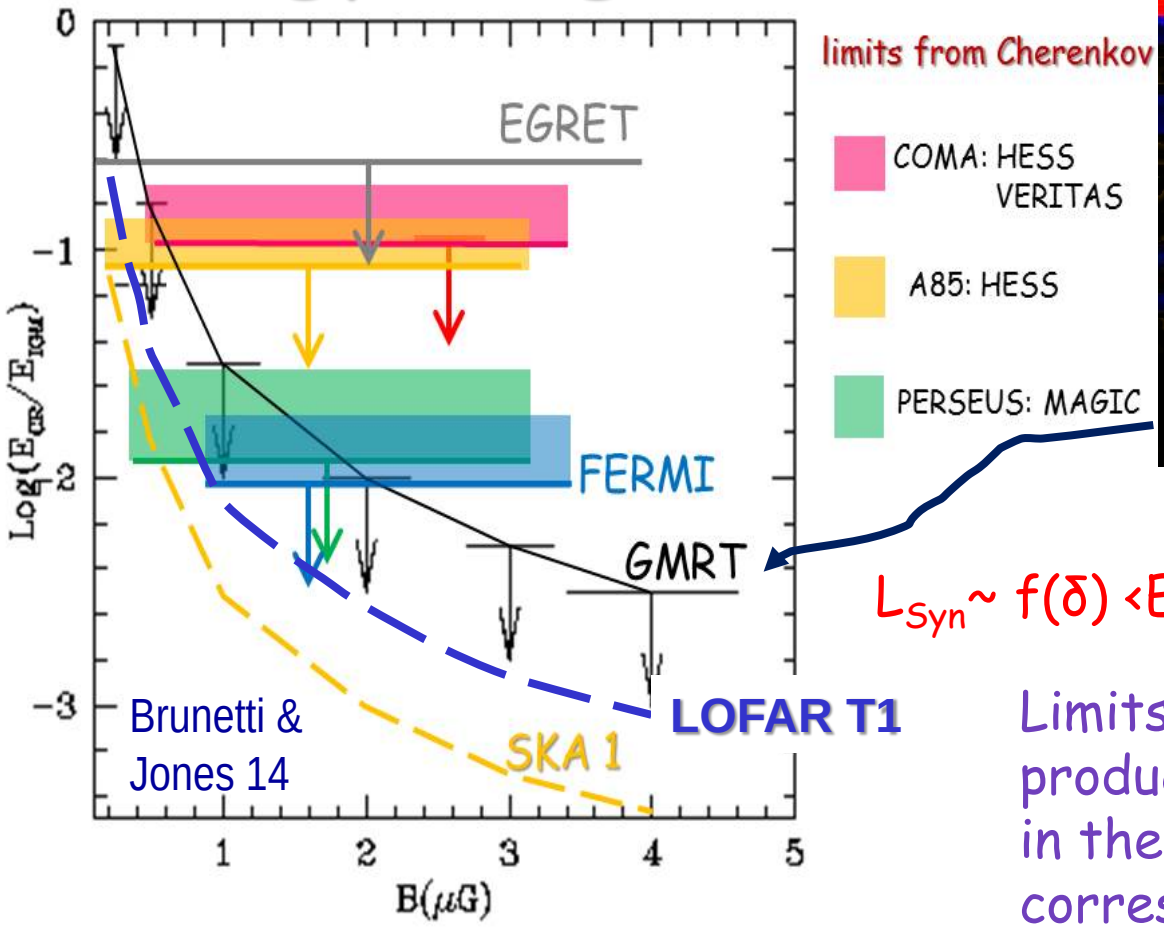
(1) Expected mix of CRp & CRe (primary+secondary)
- SED of GClustes: from radio (well observed) to gamma-rays. CRp should contain most of the energy budget

(2) CRp energy budget, accel efficiency & transport
- γ-rays : <0.01 x thermal energy (Mpc scale)
- This is a potential problem for current theories

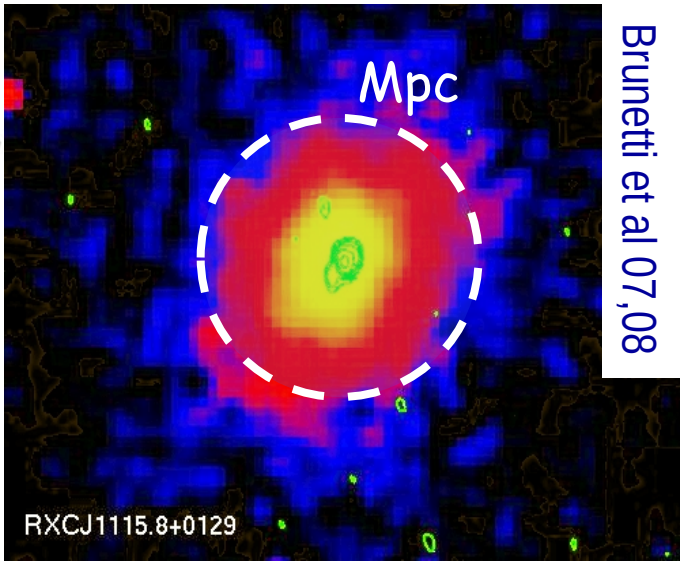
(3) Do CRp play a role for Giant Radio Halos ??
- turbulent accel of CRp+secondaries: gamma-rays. Constraints from Fermi-LAT

(4) CTA KP : Perseus cluster (mini-halo, AGNs,..)
- Detection/best limit (factor 3-6) on CRp
- Origin of mini-halos
- Constraints on AGN composition & transport
- More exotic science : max energy of CRp in GC

Limits to the CRp energy budget



Syn radio limits :



$L_{Syn} \sim f(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{Syn} B^2/(B^2+B_{IC}^2)$

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, Aharonian et al. 09, Aleksic et al. 09,12, Ackermann et al 10,14, Arlen et al 12, Griffin et al 14, Zandanel & Ando 14, Prokhorov & Churazov 14, Vazza et al 15, Ahnen et al 16, ...

Consequences : origin of radio halos

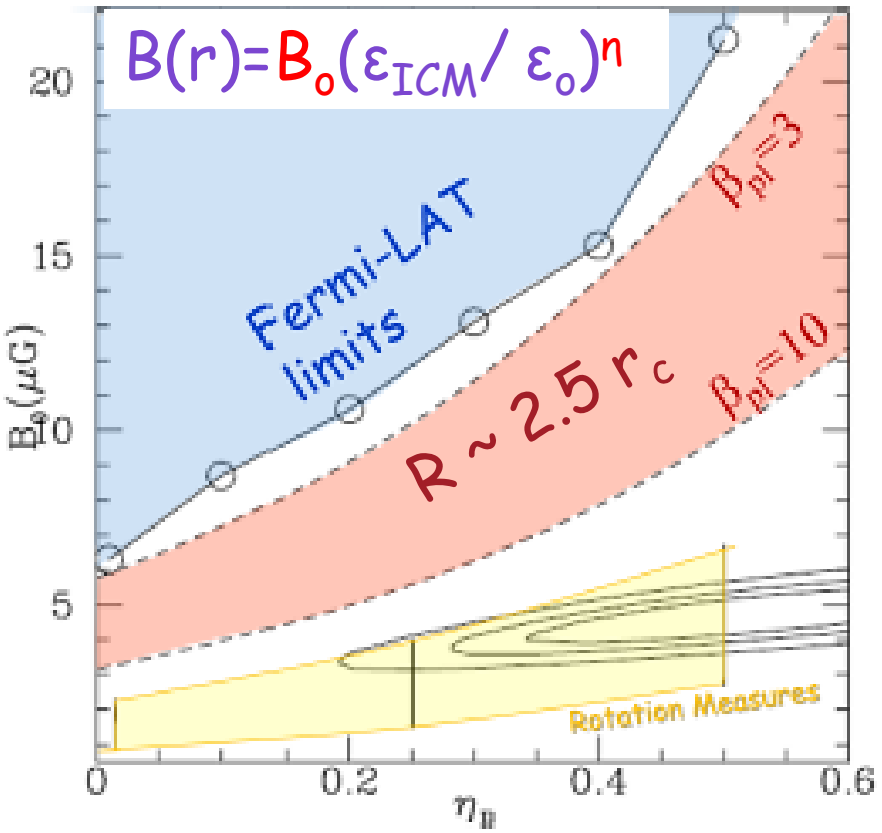
$L_{\gamma,\pi} \sim f_{\gamma}(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{\gamma}$

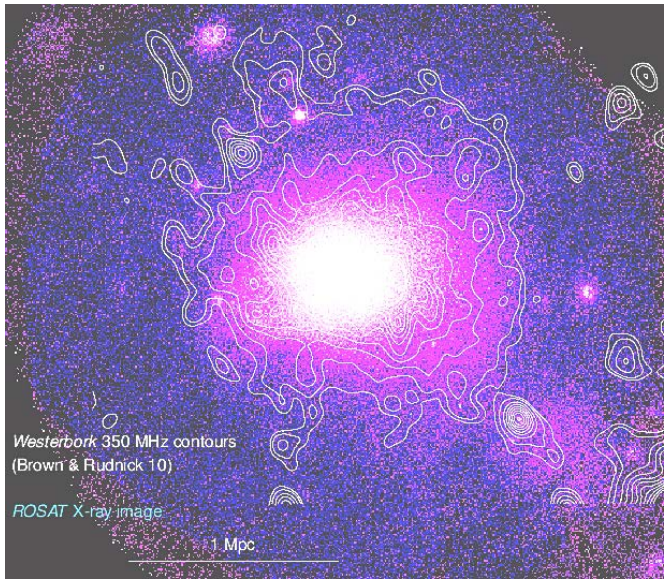
$L_{syn} \sim f_1(\delta) \langle E_{CR} \rangle \langle E_{th}/T \rangle V_{syn} B^{(1+\delta/2)}(B^2+B_{cmb}^2)^{-1}$

$$\frac{L_{radio}}{L_{\gamma}} \propto \left\langle \frac{B^{\alpha+1}}{B^2 + B_{cmb}^2} \right\rangle$$

Radio to gamma-ray ratio depends on B

Brunetti et al 17

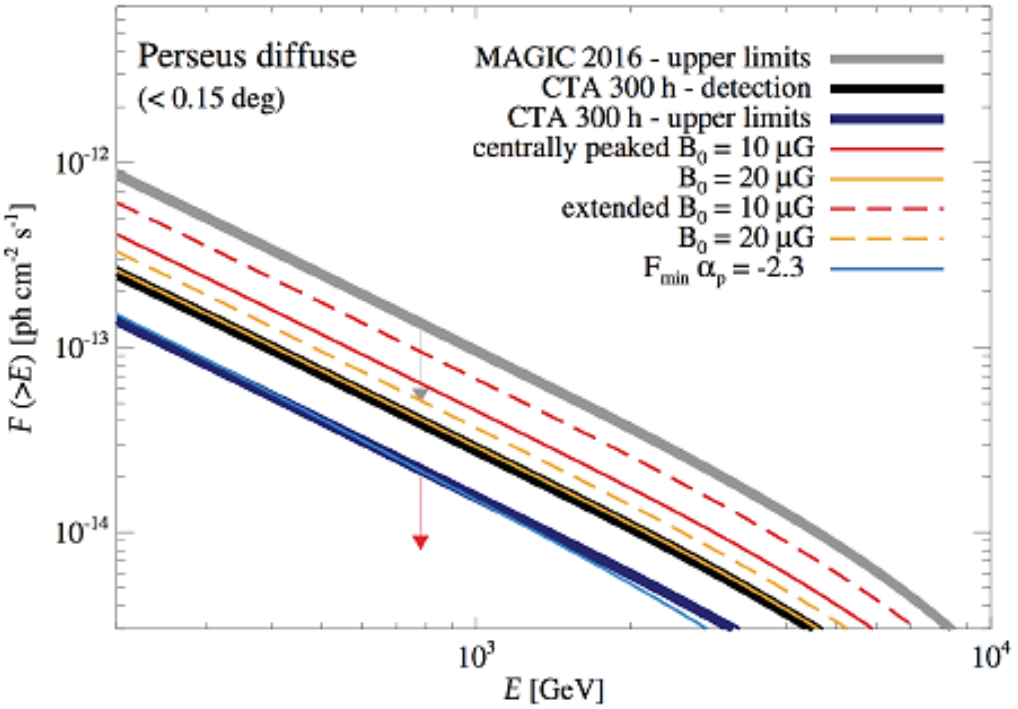




- B much higher than RM
- B dynamically important

Not hadronic origin: too many CRp are necessary to contribute significantly to the observed RH

CTA vs MAGIC

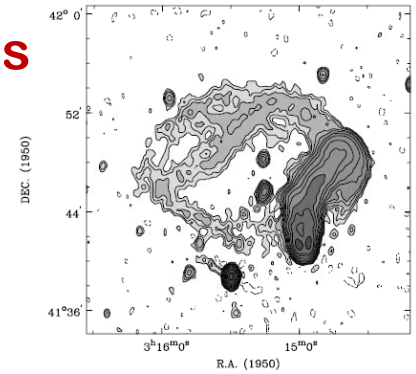


Clusters science

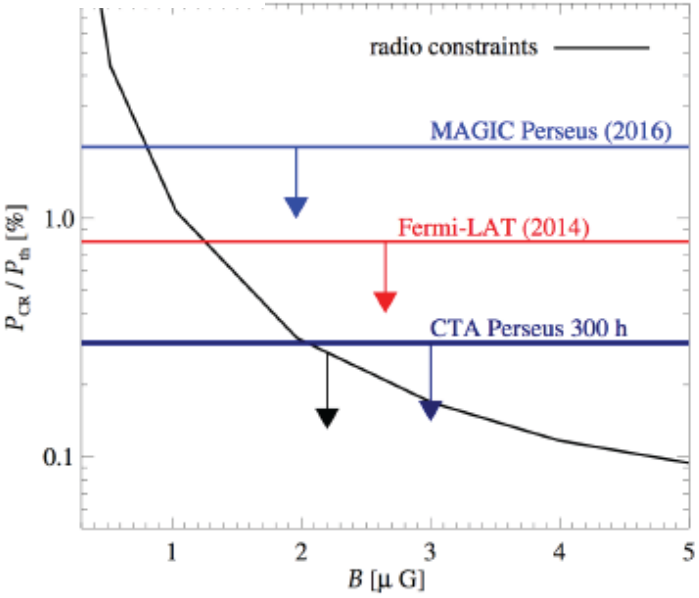
- Deepest limits on CRp
- Strongest constraints on CRp acceleration
- Origin of radio mini-halos

Beyond clusters science

- CRp in RSs
- Transport of CRp



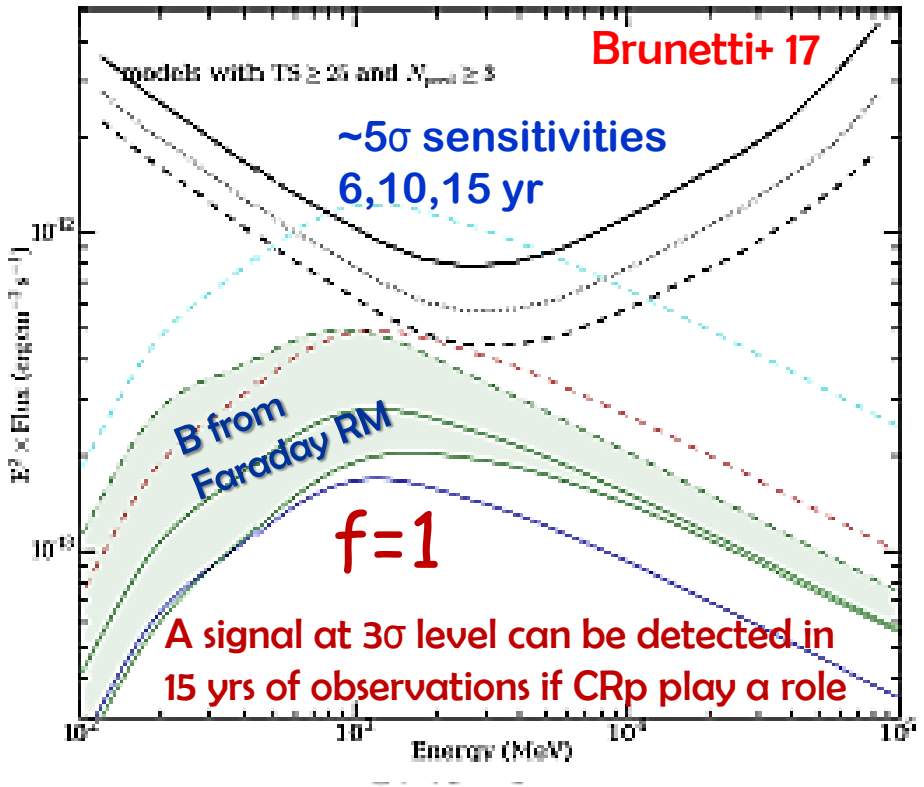
Synergies with (LOFAR)SKA (Hitomi2)Athena

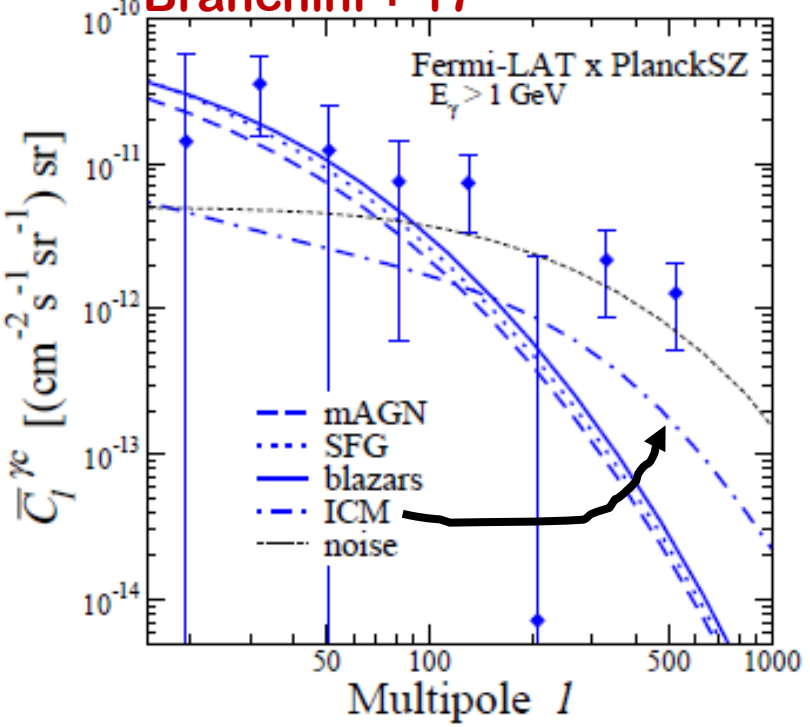


A FACTOR OF 6 IMPROVEMENT ON CURRENT MAGIC CONSTRAINTS ON PERSEUS

FOR $\alpha_p \sim$ 2.2, WE WILL TEST $B_0 >$ 20 μG

Possible evidence of gamma rays from ICM from stacked analysis of Planck clusters ?





Full calculations of turbulent reacceleration of
(i) CRp,
(ii) secondaries,
(iii) primary CRe
(iv) turbulent damping
(eg Brunetti+Lazarian 11, Pinzke+ 17, Brunetti+ 17)

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

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

Turb energy flux

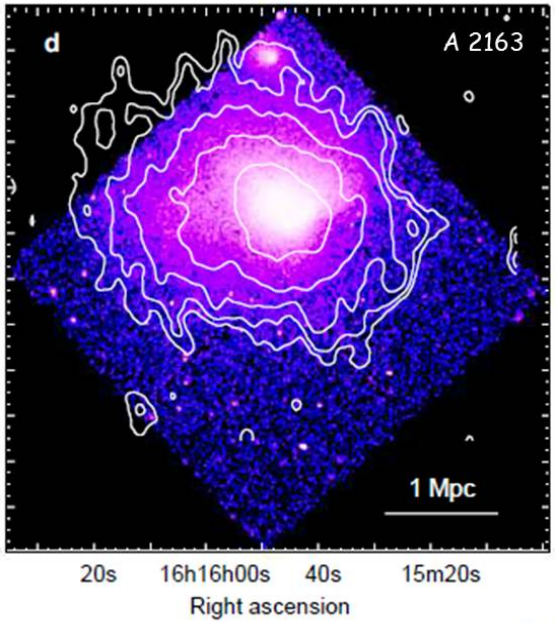
$$L_{ICS} \propto I_{tu} \Gamma_{CRe} \frac{B_{IC}^2}{B^2 + B_{IC}^2} V_{ICS}$$

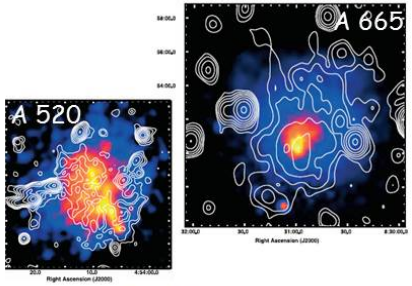
$$\frac{L_{SYN}}{L_\gamma} \propto F(\delta) \frac{I_{tu} B^2}{B^2 + B_{IC}^2} f$$

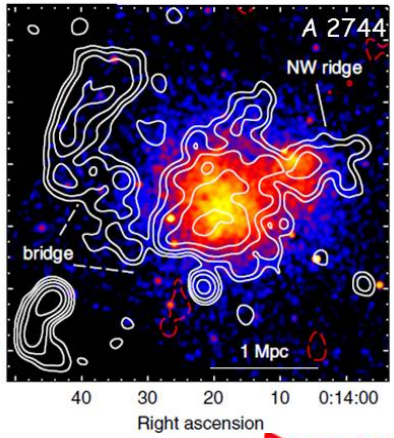
$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B_{IC}^2}$$

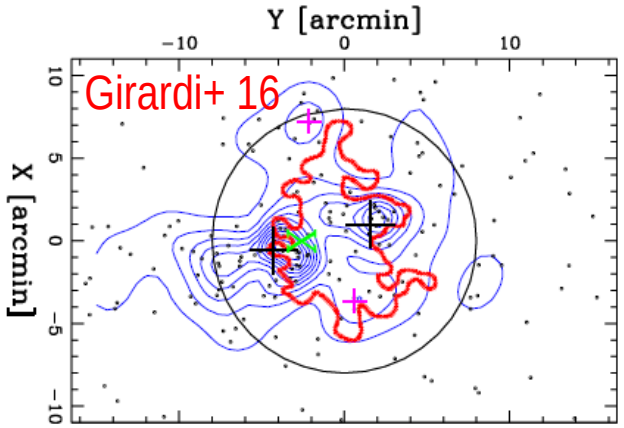
$$f = \frac{PRIMARY e^\pm}{SECONDARY e^\pm} + 1$$

Halos – Mergers connection





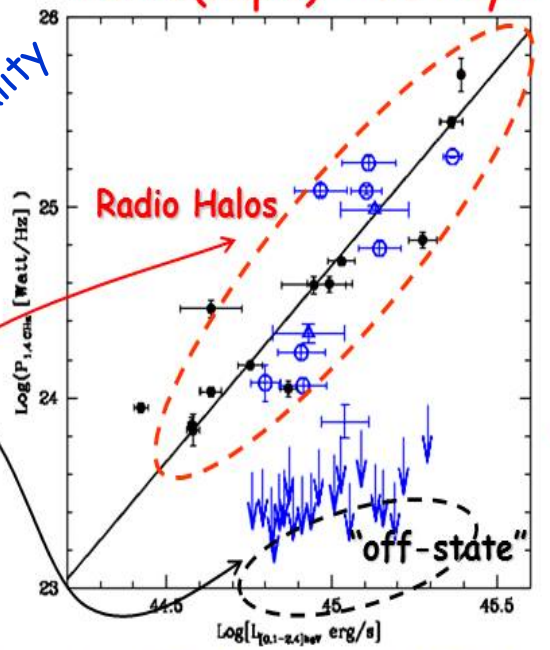




radio halo galaxies

Radio(Mpc) - X-rays

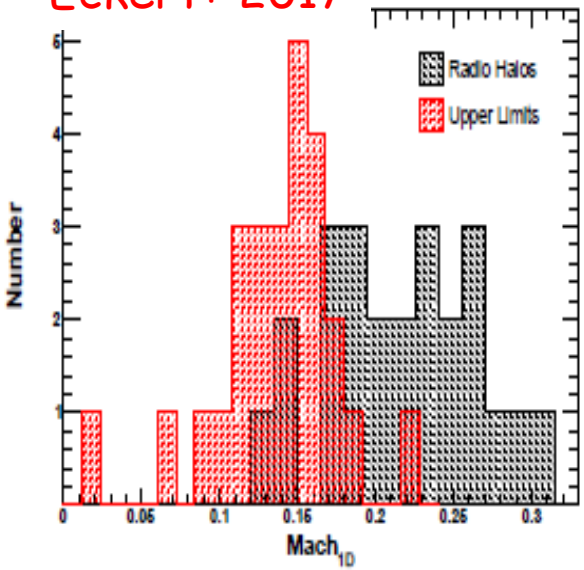
Radio bimodality



Brunetti et al 07,09

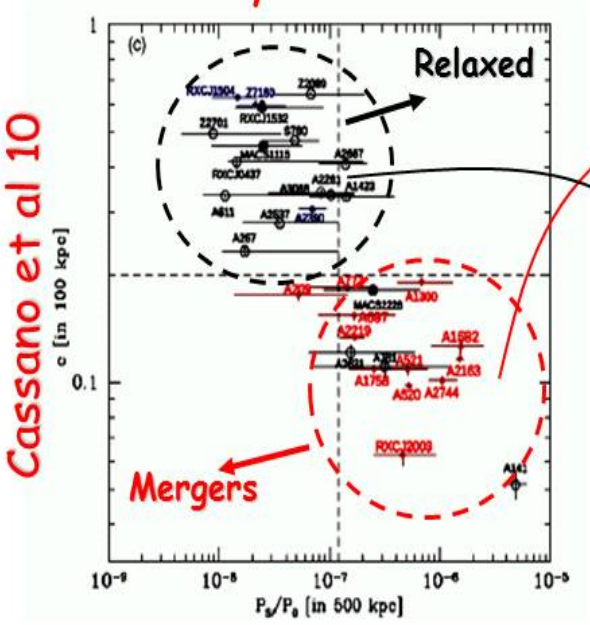
Halos – LS turbulece

Eckert+ 2017



Dynamics

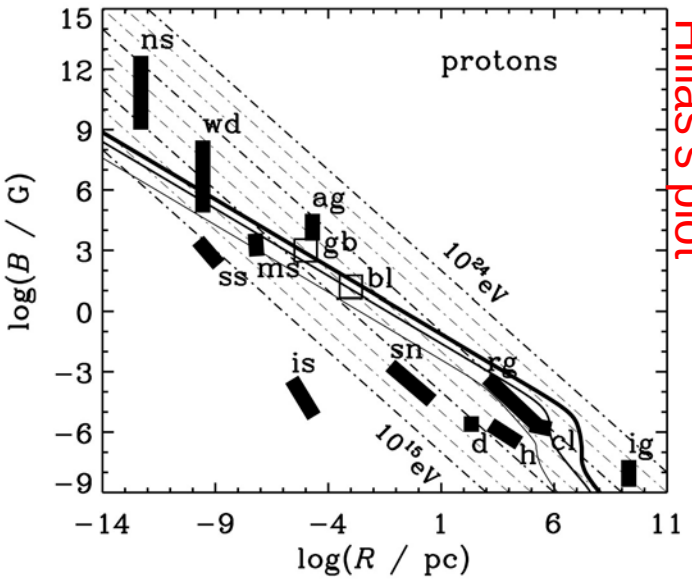
Cassano et al 10



Venturi et al 08, Cassano et al 10,13,16, Brown et al 11, Rossetti et al 11, Basu 12, Sommer+Basu 14, Kale et al 15, Yuan et al 15, Cuciti et al 15, Sommer+17

Exotic CTA science: Max energy of CR

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



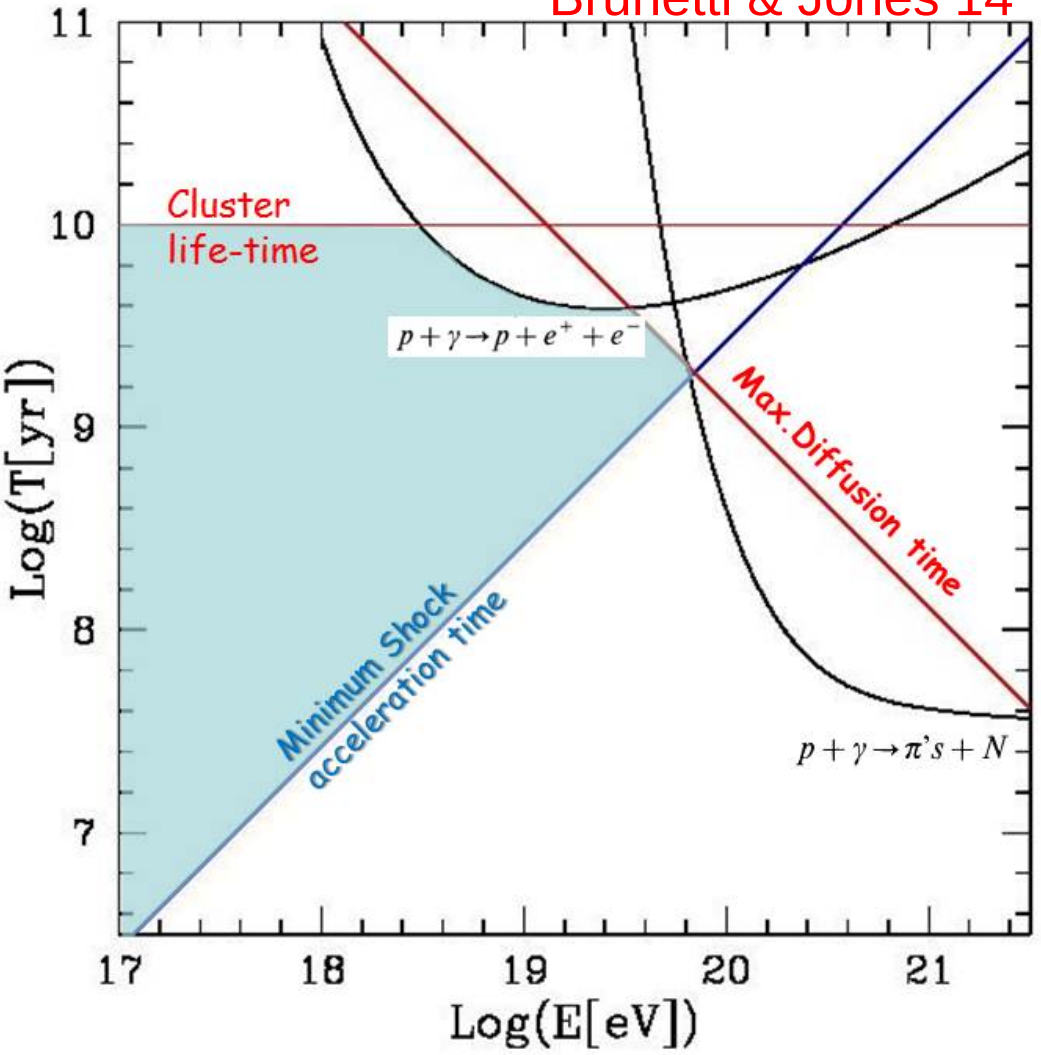
Hillas's plot

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

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

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

Brunetti & Jones 14



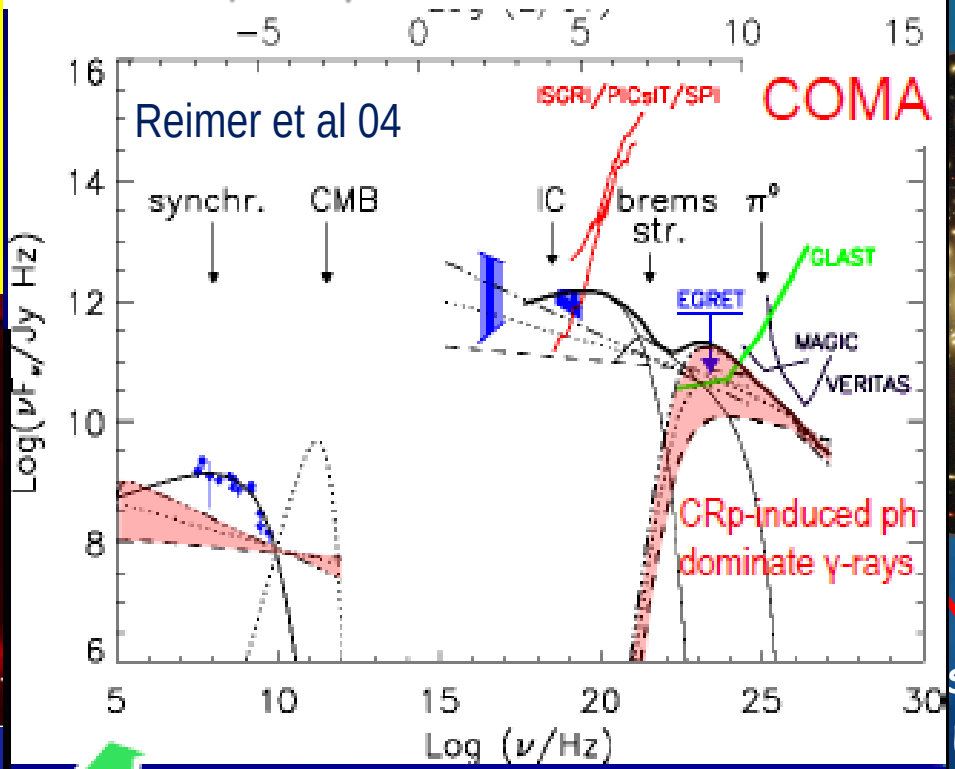
$E_{max} \approx 10+..$ EeV

CR-acceleration

(eg. Brunetti + Jones 14)

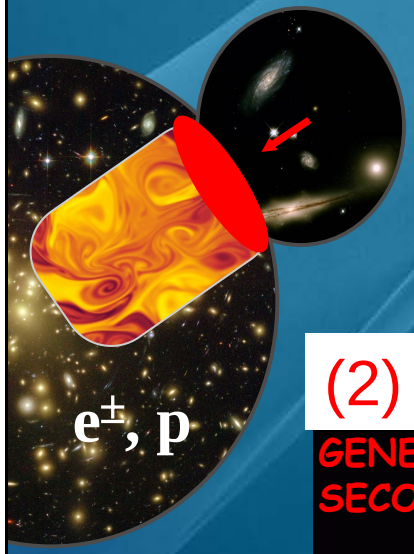
Mergers guide CRe

Multifrequency emission + neutrino



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

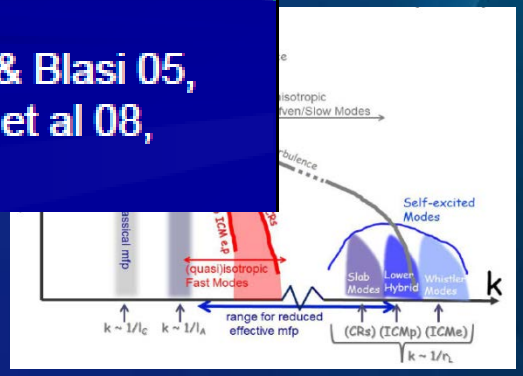
Astrophysical sources
Galaxies (SN), AGN..

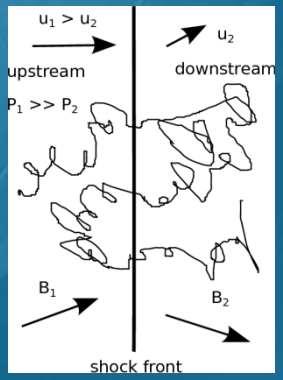


NCE

s fossil CRe±,

ndaries CRe±



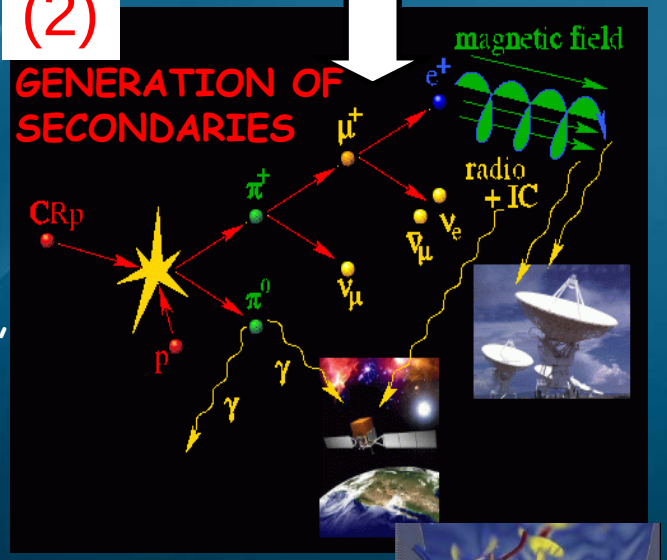


(1)

SHOCKS

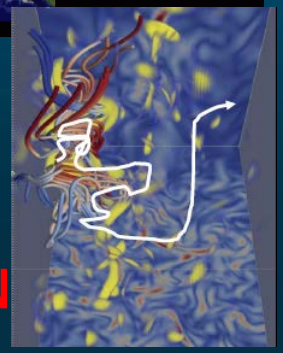
accelerate CRe±,CRp

(2)

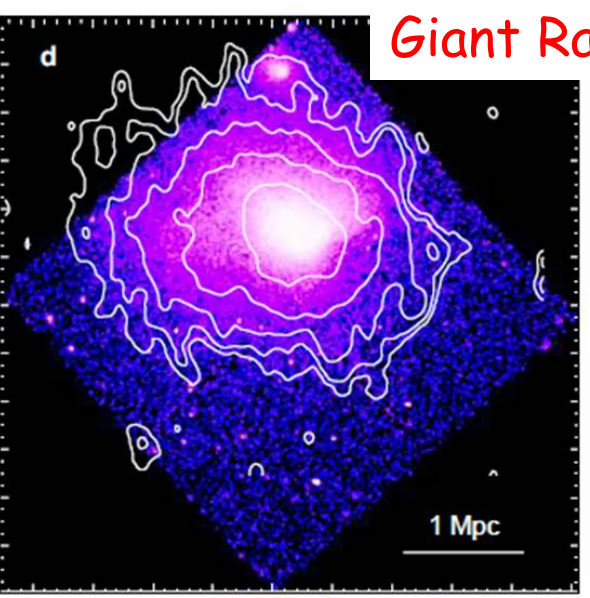


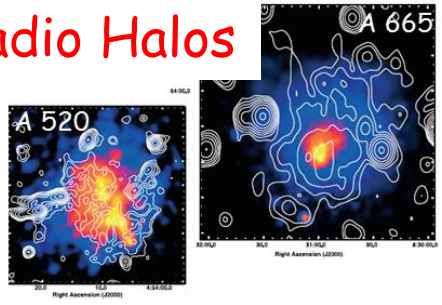
(4)

MAGNETIC RECONNECTION



Giant Radio Halos





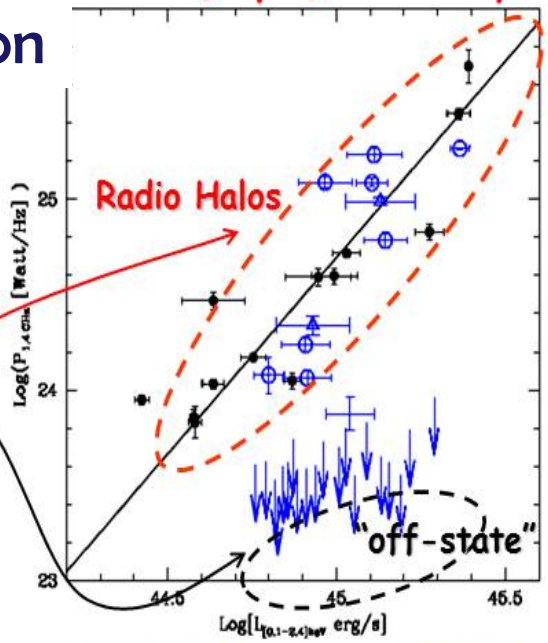
Turbulent acceleration scenario

Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on second-order Fermi

Brunetti+01, Petrosian 01, Fujita+03, Cassano+Brunetti 05, Brunetti+Lazarian 07,Brunetti+Lazarian 11, Beresnyak+al 13, Miniati 15, Brunetti+Lazarian 16, Pinzke+al 17…]

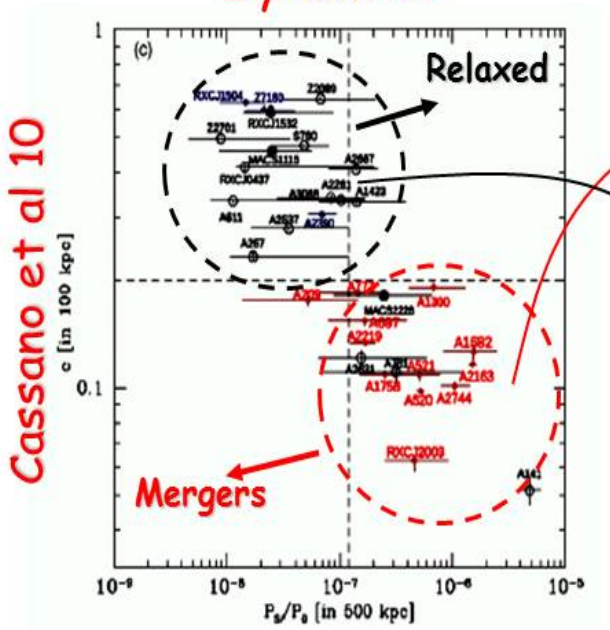
Halos – Mergers connection

Radio(Mpc) - X-rays



Brunetti et al 07,09

Dynamics

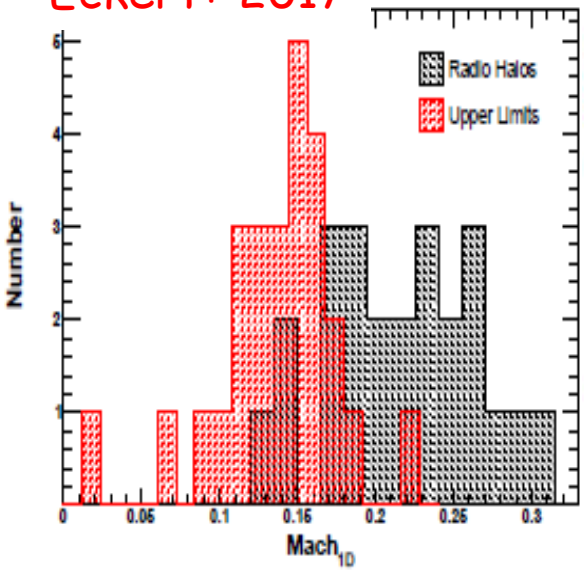


Cassano et al 10

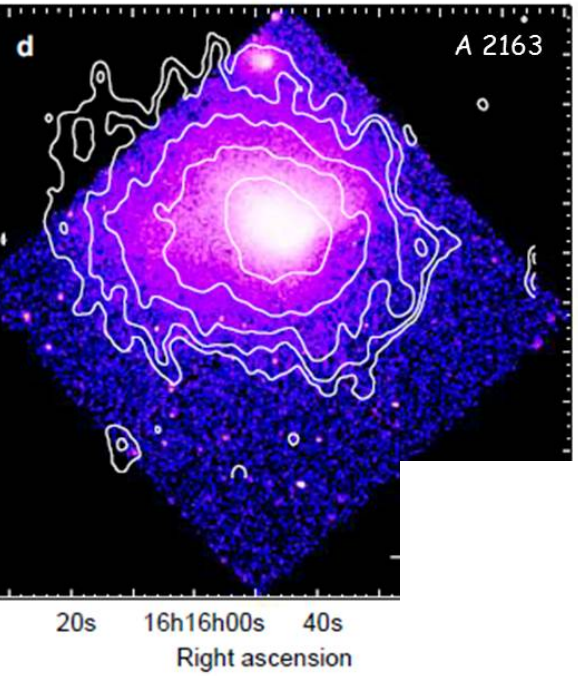
Venturi et al 08, Cassano et al 10,13,16, Brown et al 11, Rossetti et al 11, Basu 12, Sommer+Basu 14, Kale et al 15, Yuan et al 15, Cuciti et al 15, Sommer+17

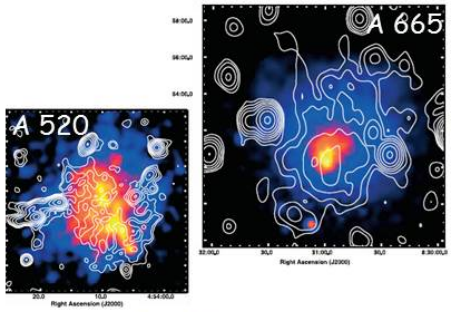
Halos – LS turbulece

Eckert+ 2017



Turbulent acceleration scenario:

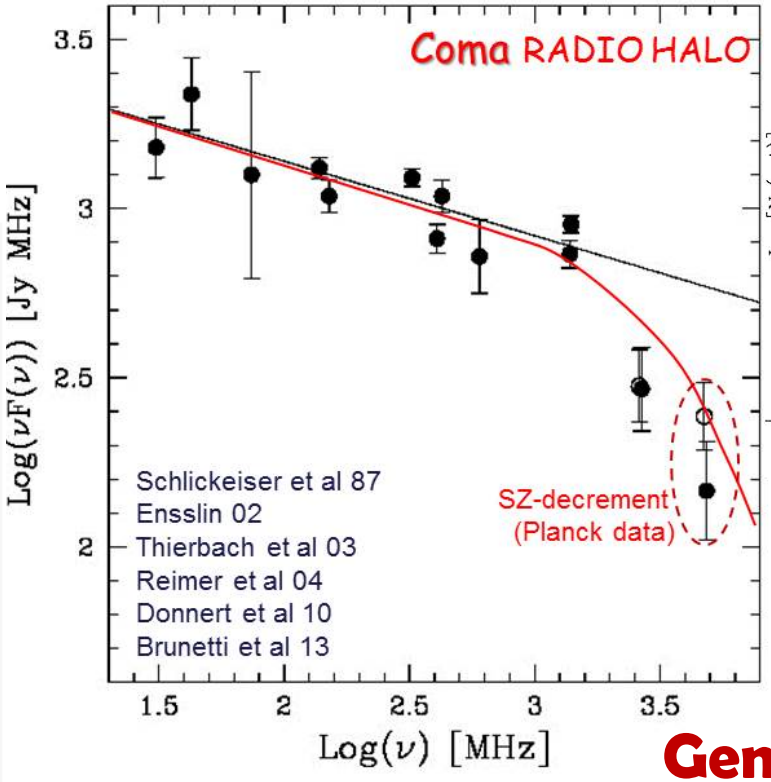




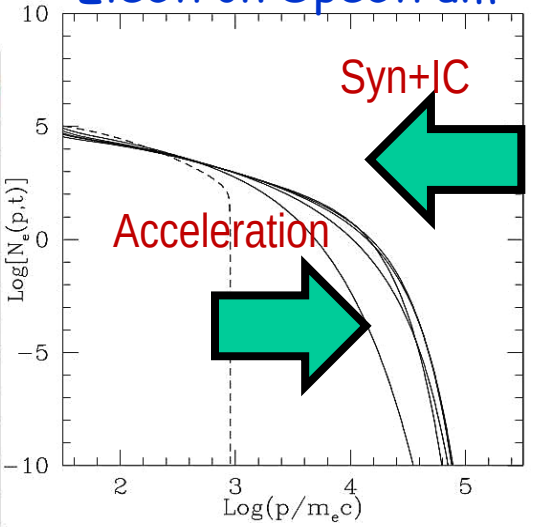
Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on second-order Fermi

Brunetti+01, Petrosian 01, Fujita+03, Cassano+Brunetti 05, Brunetti+Lazarian 07,Brunetti+Lazarian 11, Beresnyak+al 13, Miniati 15, Brunetti+Lazarian 16, Pinzke+al 17…]

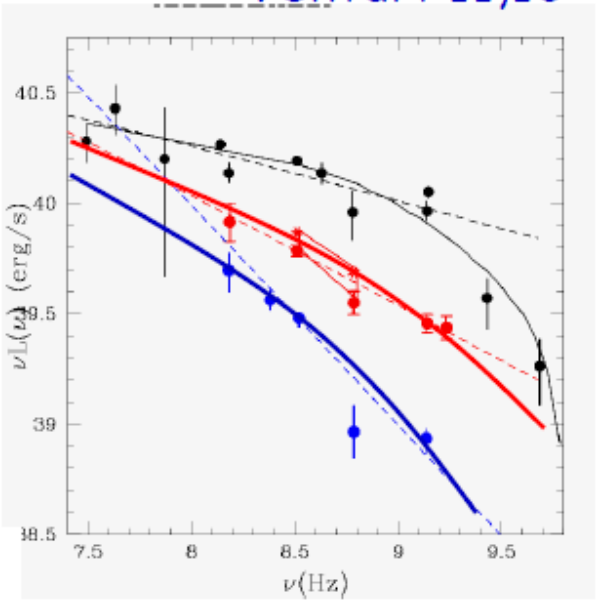
Synchrotron Spectrum



Electron Spectrum



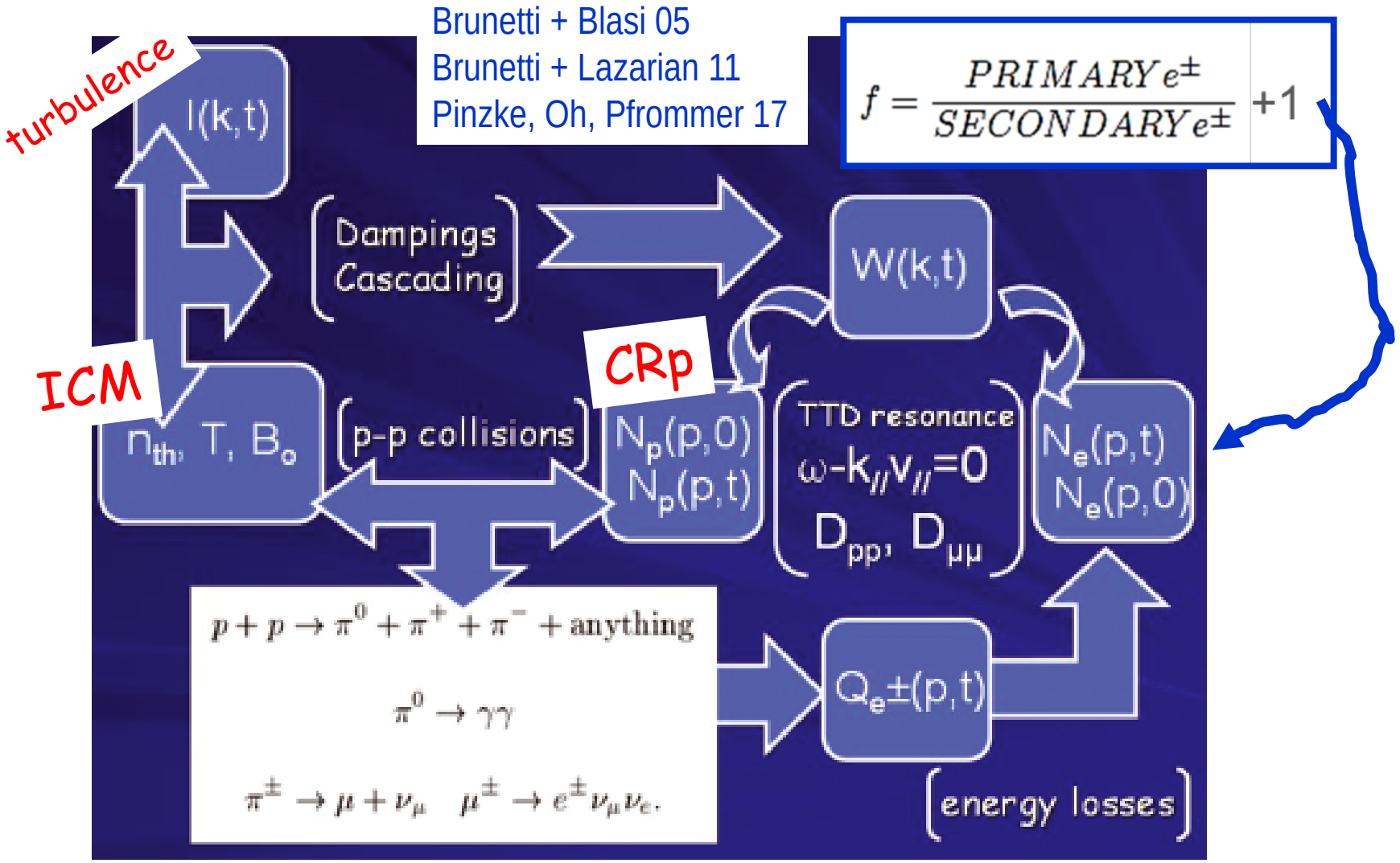
Venturi 11,13



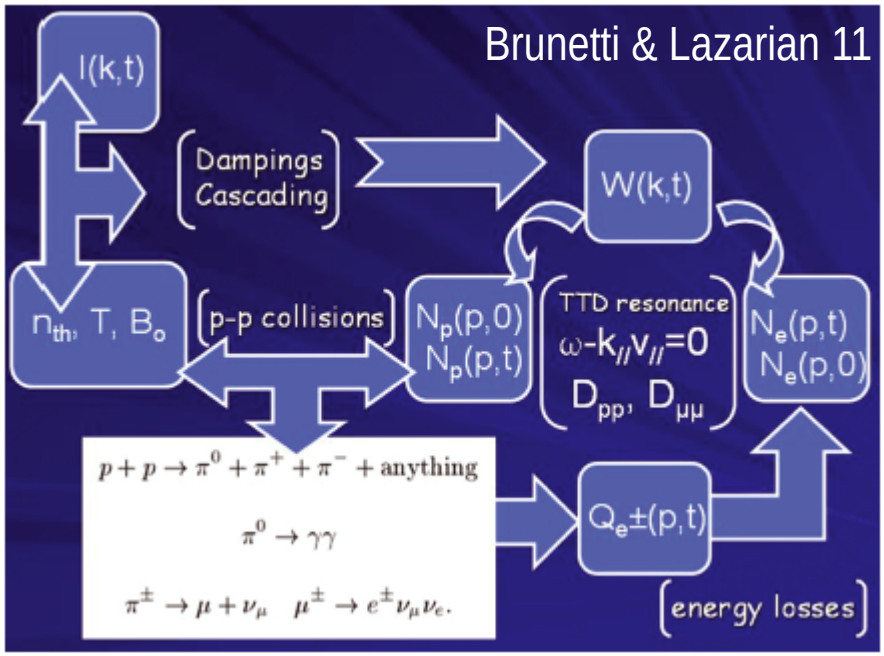
$T_{acc} \sim T_{rad}$(GeV+) =100-300 Myr

Gentle reacceleration

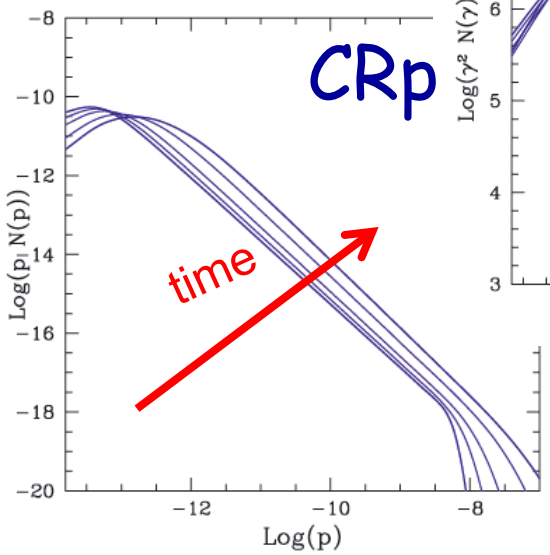
Can CRp play a role in reacceleration models ?
- Reacceleration of CRp & secondaries -

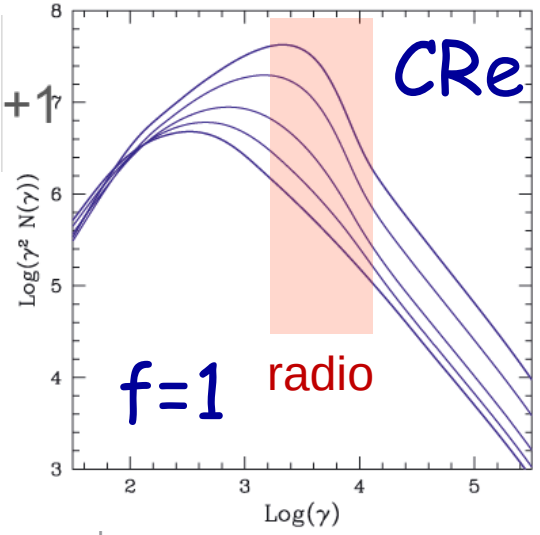


Reacceleration of CRp & secondaries



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



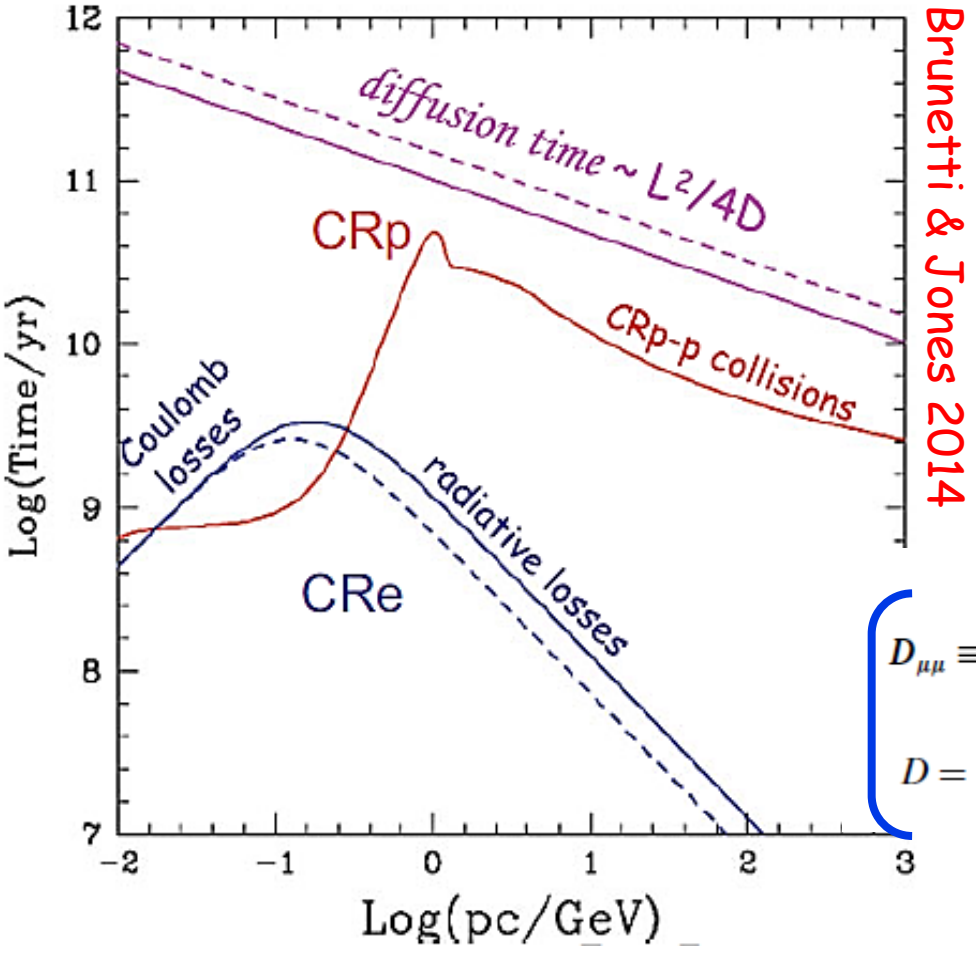


- The Syn/gamma ratio is much higher
- Less CRp are necessary to generate the observed radio emission

Weaker magnetic field are constrained by current gamma-ray limits

CRp confinement

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



Brunetti & Jones 2014

Obvious consequence of the fact that clusters ar BIG :

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

And that the diffusion coefficient is not ''huge'' because CRs are scattered by microturbulence :

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

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

gyroresonance

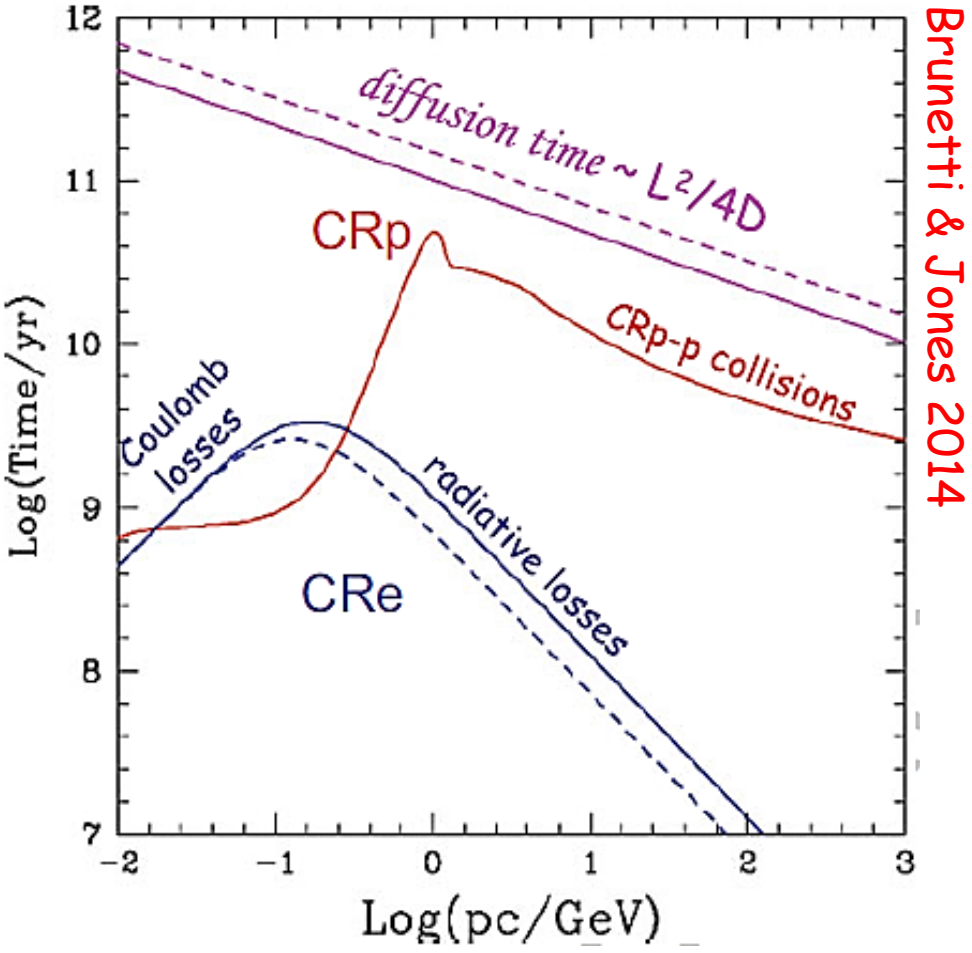
$$D(E_p) = \frac{1}{3} r_L c \frac{B^2}{\int_{1/r_L}^{\infty} dk P(k)}$$

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

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

CRp confinement

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

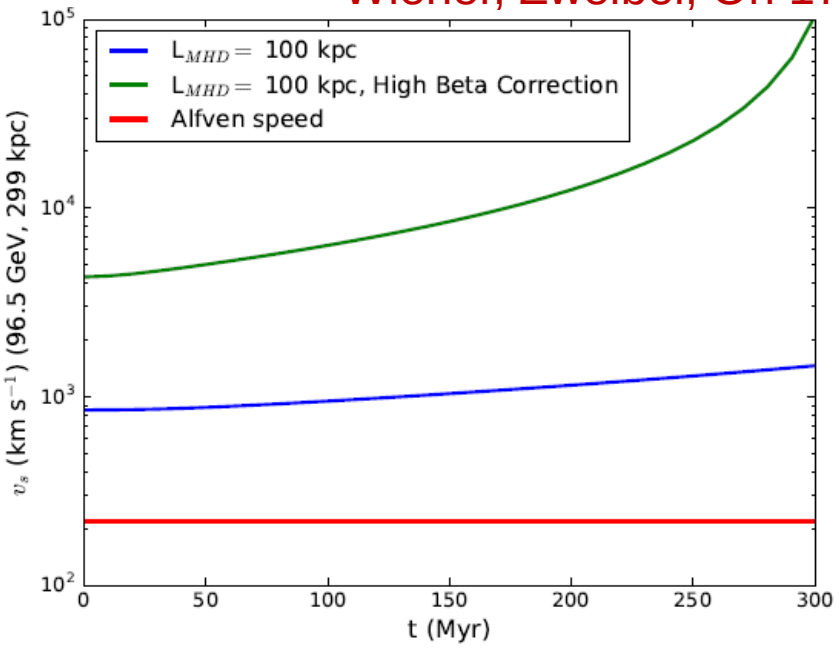


Brunetti & Jones 2014

Are CRs scattered efficiently by croturbulence ?

For example, streaming along field lines (Wiener + 13,17, Lazarian 17)

Wiener, Zweibel, Oh 17

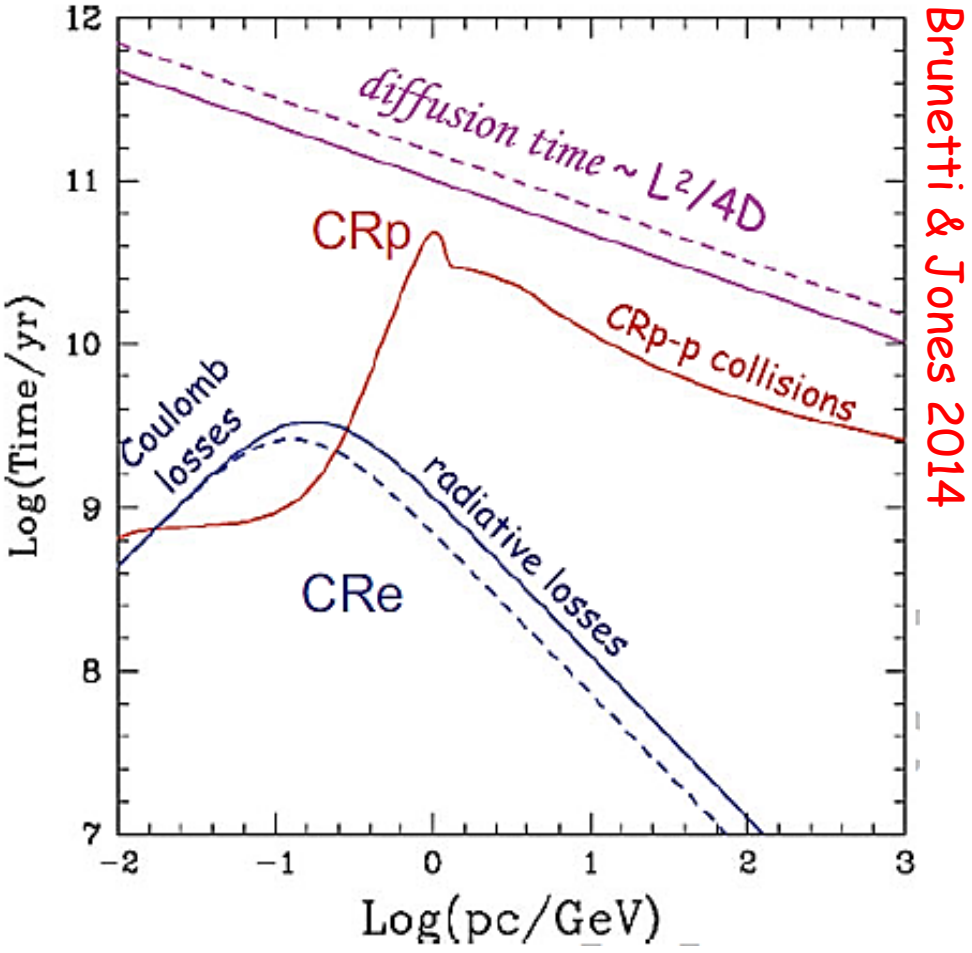


- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

CRp confinement

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

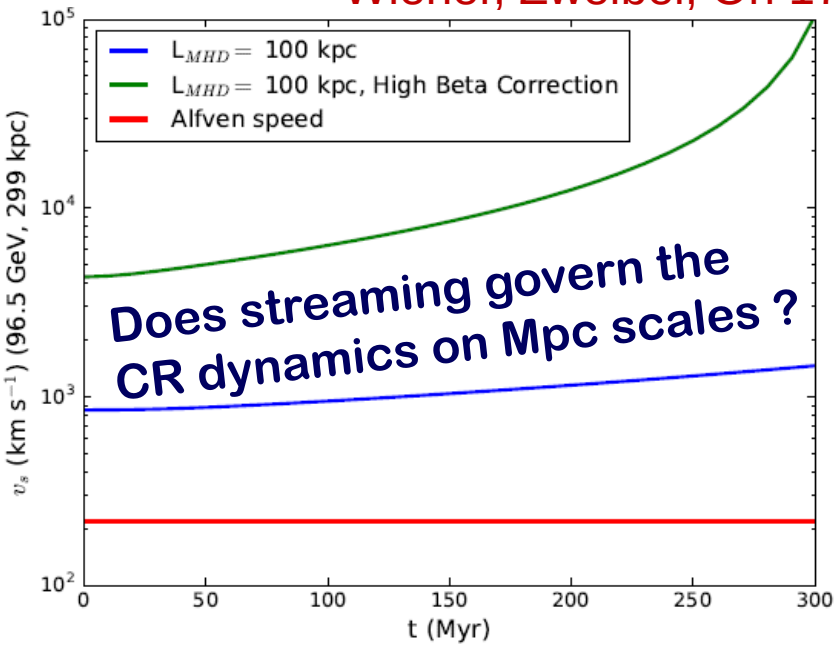


Brunetti & Jones 2014

Are CRs scattered efficiently by croturbulence ?

For example, streaming along field lines (Wiener + 13,17, Lazarian 17)

Wiener, Zweibel, Oh 17



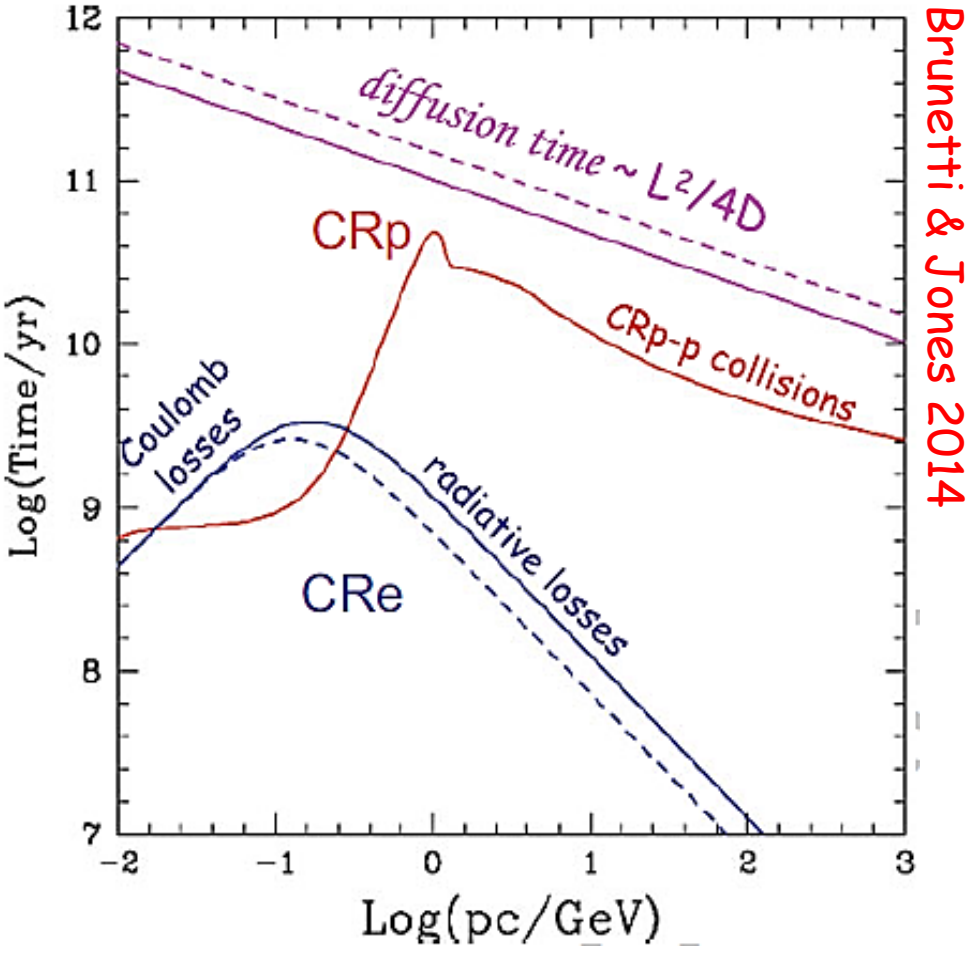
Does streaming govern the CR dynamics on Mpc scales ?

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

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

CRp confinement

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

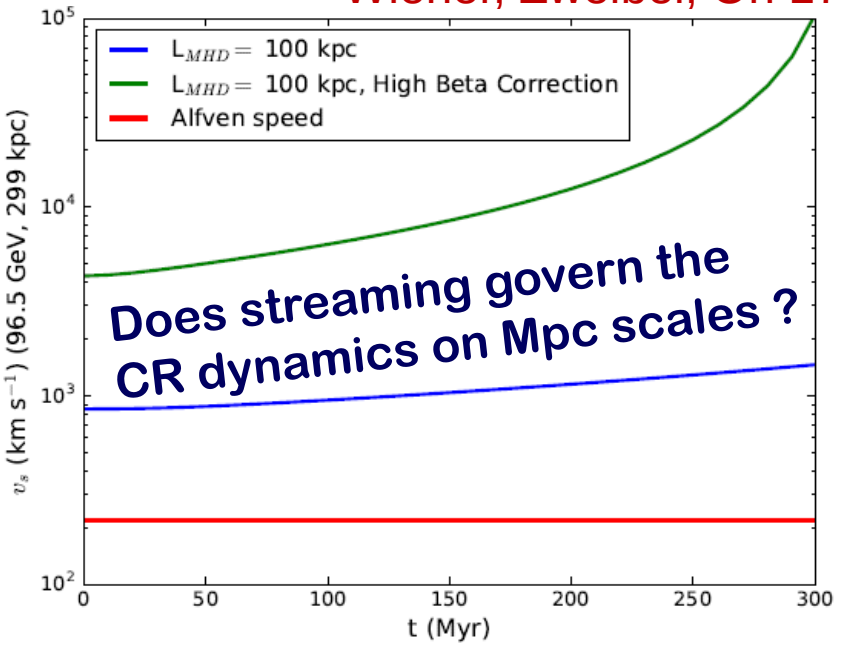


Brunetti & Jones 2014

Mgnetic *field lines in the ICM are TANGLED (RM, theory) thus CRs will still DIFFUSE :*

$$D \sim 1/3\ V_{drift}\ l_B$$

Wiener, Zweibel, Oh 17

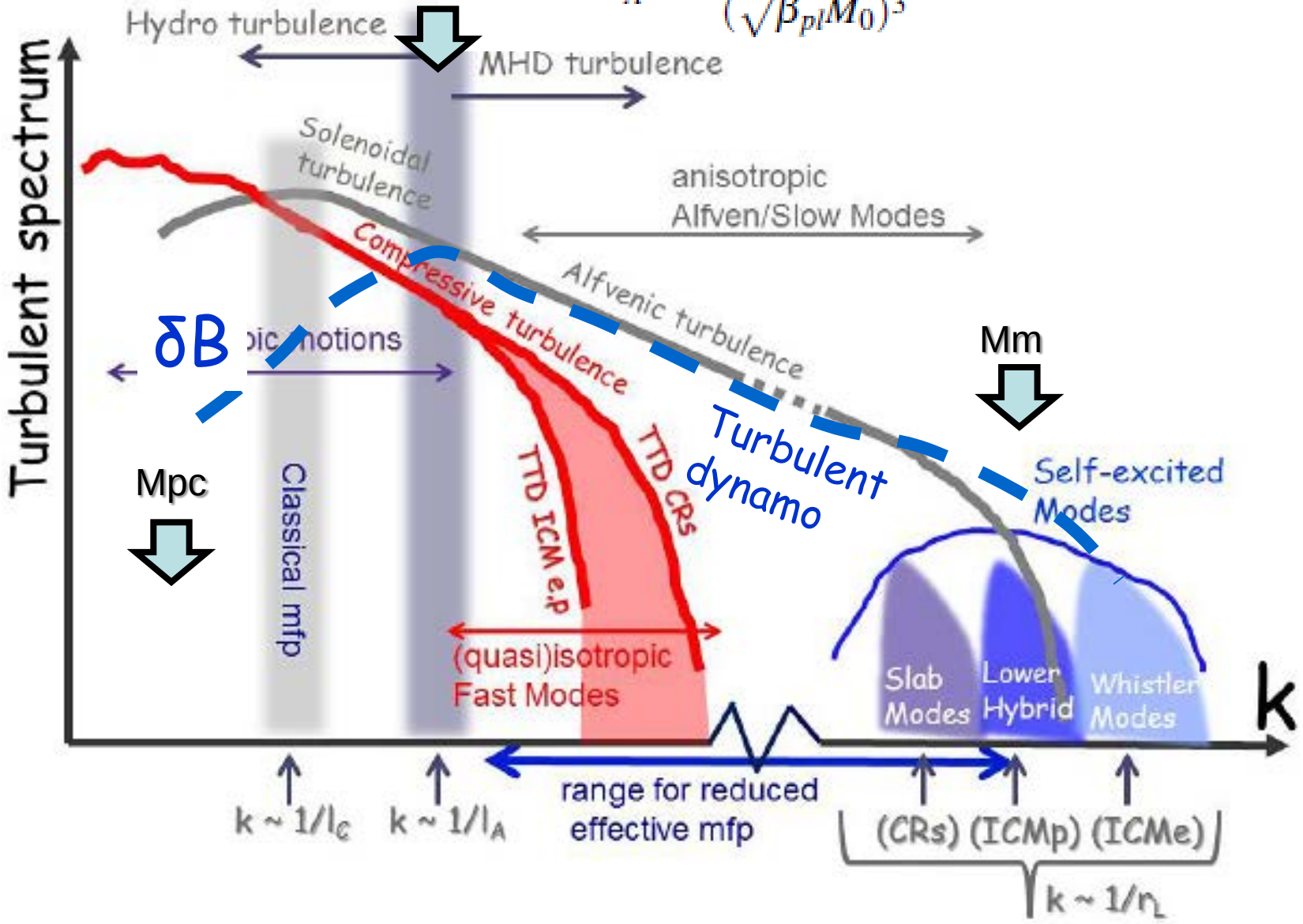


- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : this is why we expect gamma-rays !

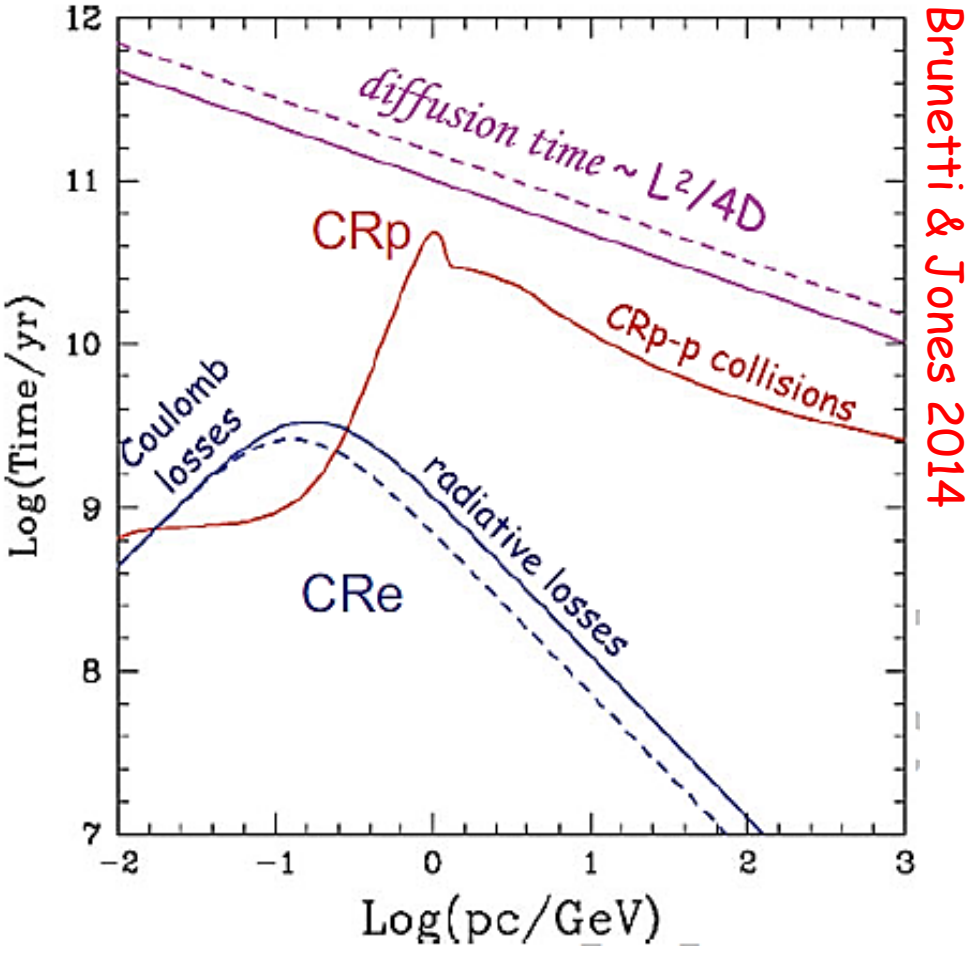
THE MHD SCALE IN THE ICM

$$l_A = L_0 M_A^{-3} = \frac{(6/5)^3 L_0}{(\sqrt{\beta_{pl}} M_0)^3}$$



CRp confinement

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



Brunetti & Jones 2014

Mgnetic *field lines in the ICM are TANGLED (RM, theory) thus CRs will still DIFFUSE :*

D ~ 1/3 Vdrift l_B

$$l_A = L_0 M_A^{-3} = \frac{(6/5)^3 L_0}{(\sqrt{\beta_{pl}} M_0)^3}$$

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

Vdrift ~ few 10^3 km/s

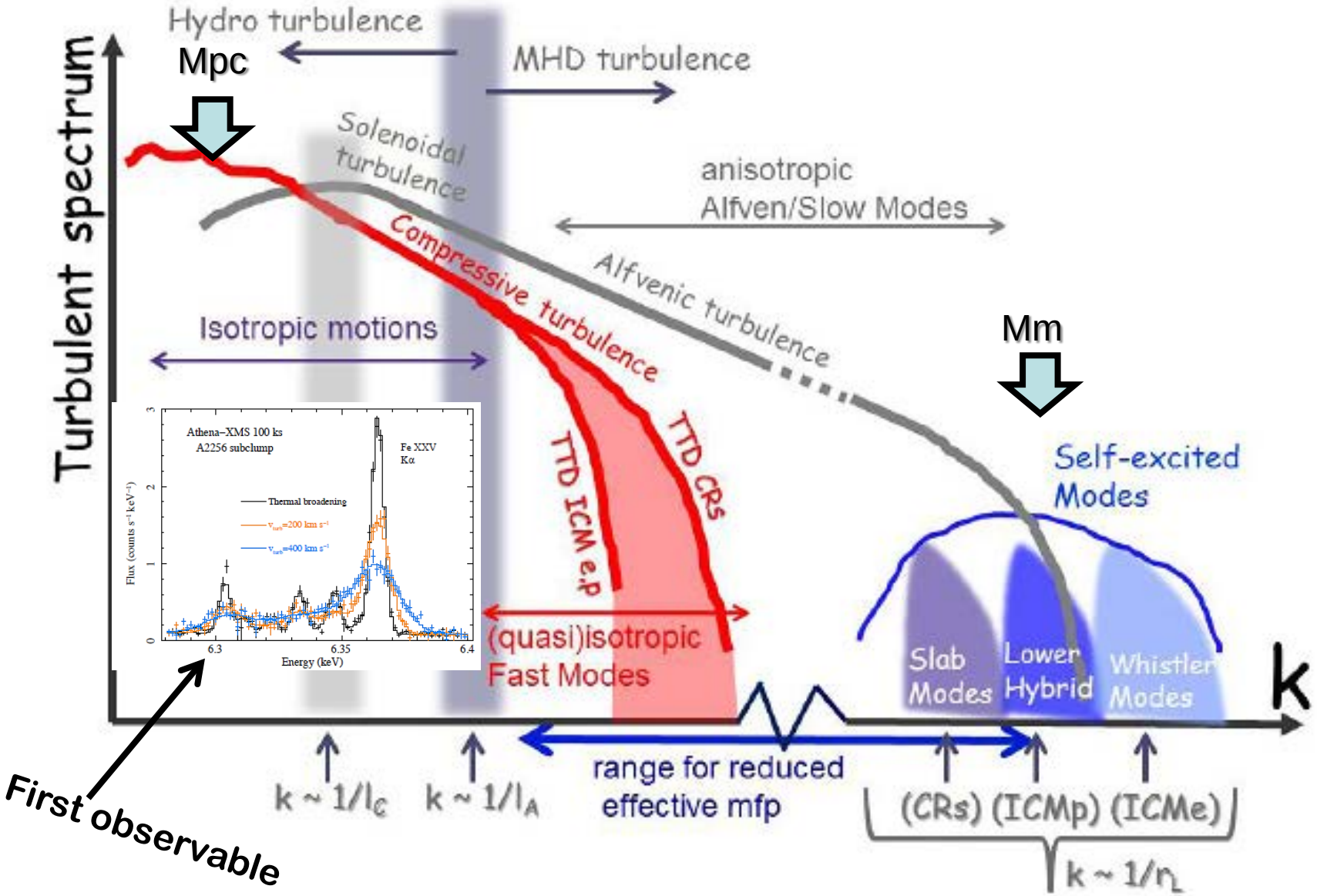
l_B < kpc

D < 10^{29} cm^2 /s

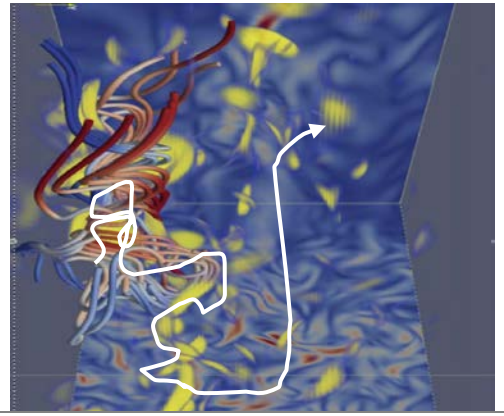
A slow diffusion process is guaranteed by magnetic field tangling
Streaming/drift etc do not play a role on CRs propagation on Mpc scales

Probing physics of ICM Turbulence

- via synchrotron RH & line broadening -



Probing physics of ICM Turbulence
- acceleration by LS turbulence-



Mediated by magnetic reconnection

$$\tau_{acc}(Myr) \approx 350 \left(\frac{M_0}{1/2}\right)^{-3} \left(\frac{L_0/300}{(c_s/1500)^2}\right) \frac{(\frac{\Phi}{1/2})^3}{\sqrt{\beta_{pl}/100}}$$

[Brunetti+Lazarian 16]

Turbulent spectrum

Hydro turbulence

MHD turbulence

Solenoidal turbulence

anisotropic Alfvén/Slo

Alfvenic turb

Compressive turbulence

Isotropic motions

Mpc

Classical mfp

TTD ICM e.p

TTD CRs

(quasi)isotropic Fast Modes

Self-excited Modes

Slab Modes

Lower Hybrid

Whistler Modes

k

(CRs) (ICMp) (ICMe)

k ~ 1/r_L

Second observable

Interaction with fast or slow modes

$$\tau_{acc}(Myr) \approx 125 \left(\frac{M_0}{1/2}\right)^{-4} \left(\frac{L_0/300}{c_s/1500}\right)$$

[Brunetti+Lazarian 07, Brunetti+Lazarian 11
Miniati 15, Pinzke, Oh, Pfrommer 17]

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

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