Non thermal emission in Galaxy Clusters & impact of low frequency observing

- A review -

Gianfranco Brunetti

INAF ira ISTITUTO DI RADIOASTRONOMIA

ISTITUTO NAZIONALE DI ASTROFISICA
INAF
NATIONAL INSTITUTE FOR ASTROPHYSICS

Alexander von Humboldt Stiftung/Foundation

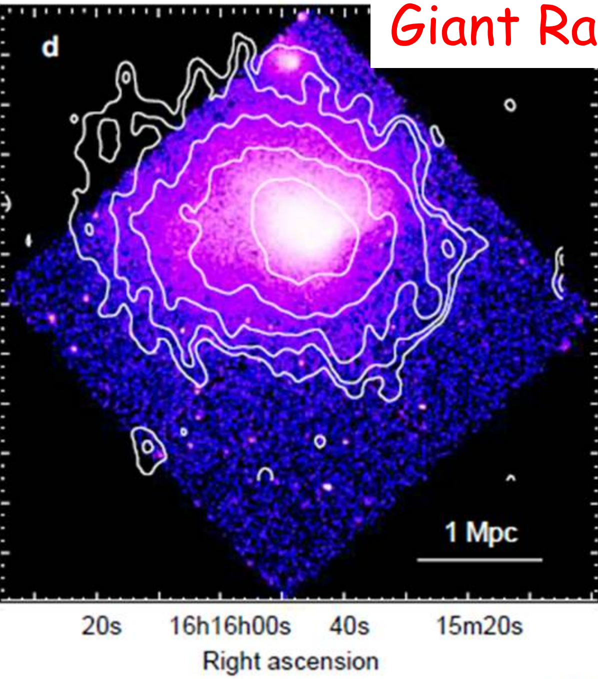
European Commission

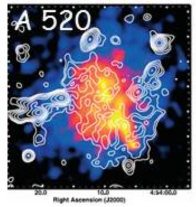
Cluster-scale radio emission

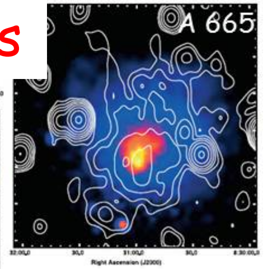
- ❑ Steep spectrum sources
- ❑ Low brightness

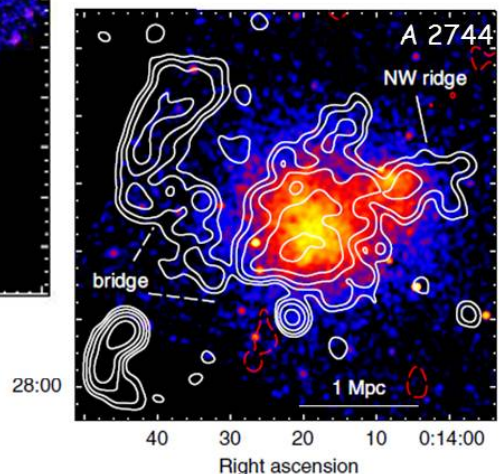
- ✓ Synchrotron radiation FROM the ICM
- ✓ Relativistic GeV+ electrons (protons?) and B distributed on Mpc-scales…

Giant Radio Halos



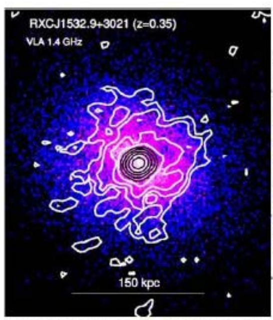


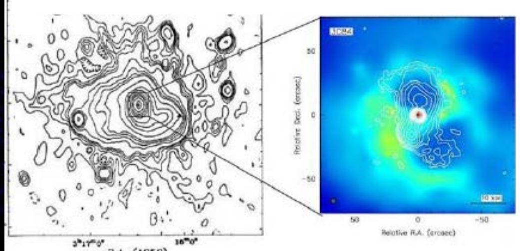


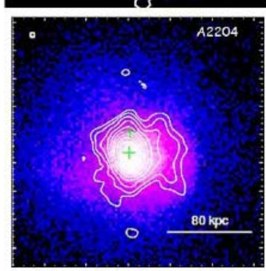


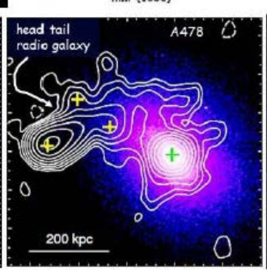
Feretti+ 12
Brunetti+Jones 14

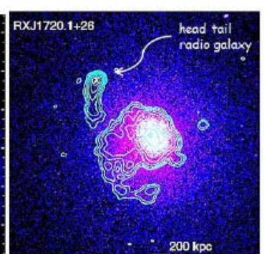
MINI- Radio Halos



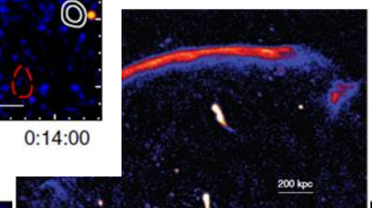


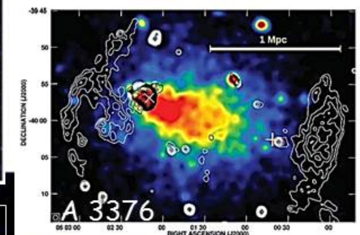


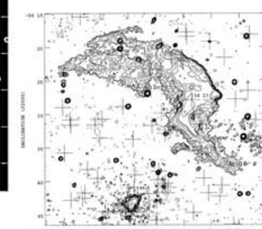


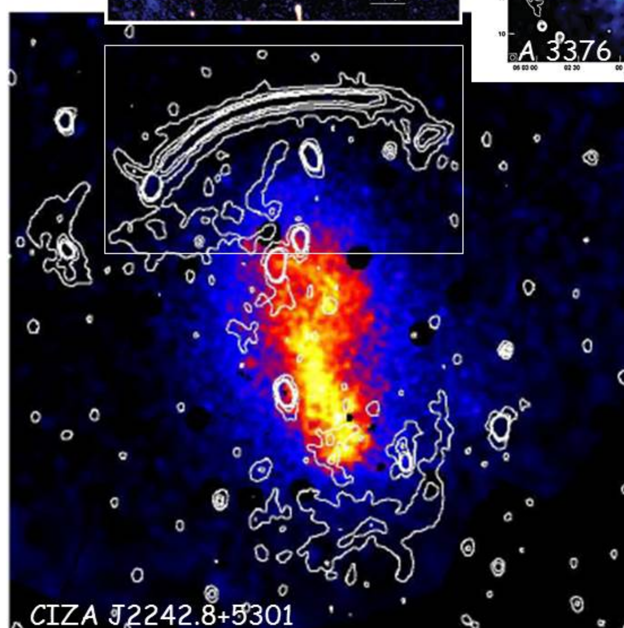


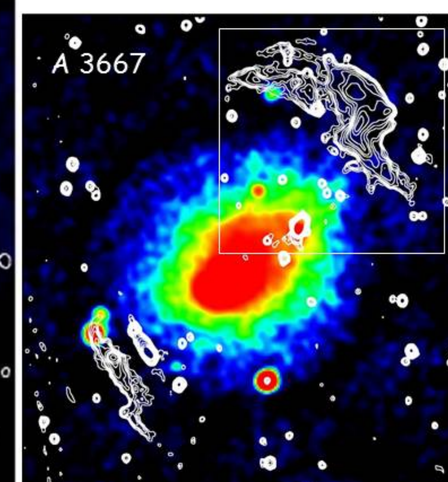
Giant Radio Relics











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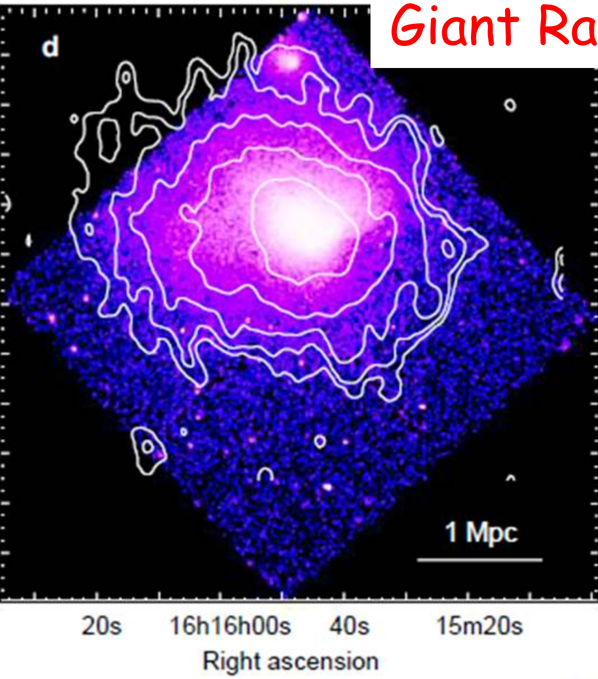

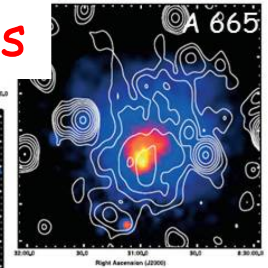

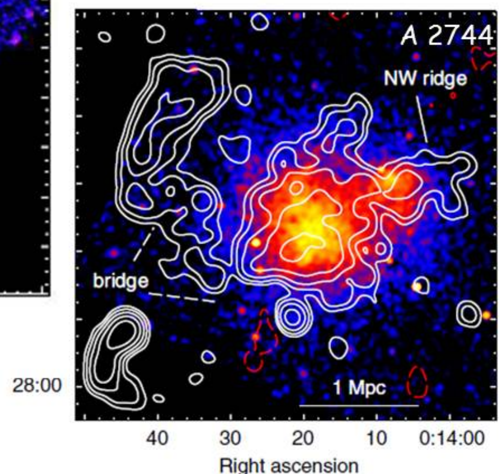

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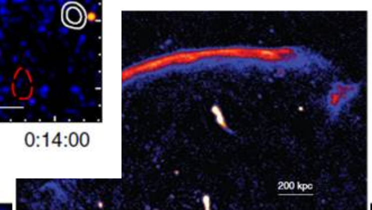
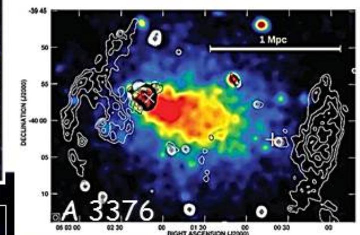
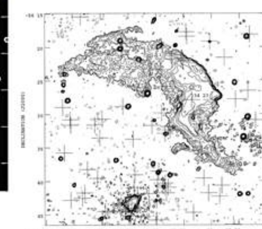
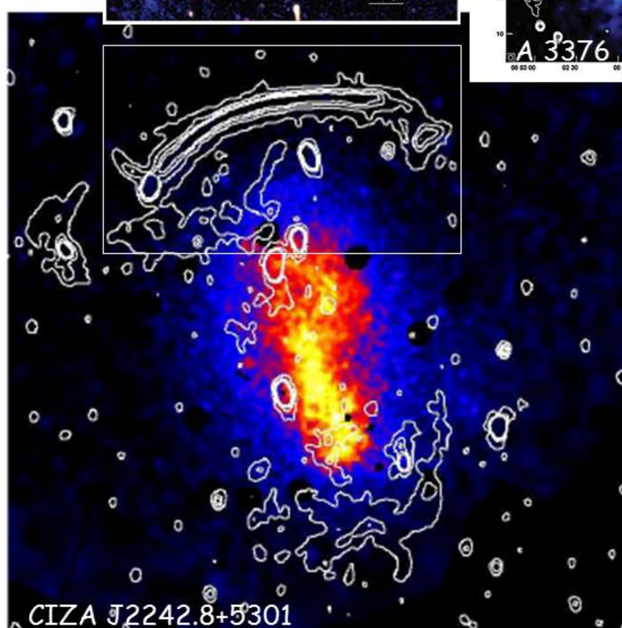
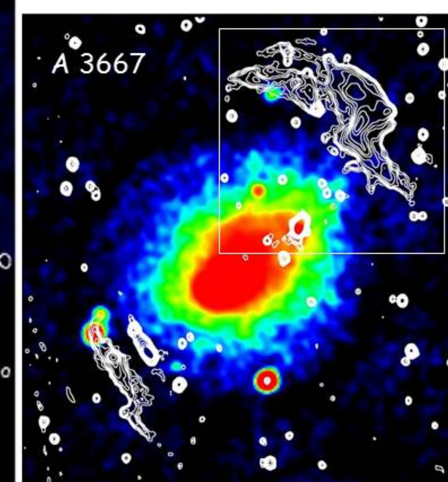










Syn+IC lifetime of radio electrons

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

ICM acceleration site !

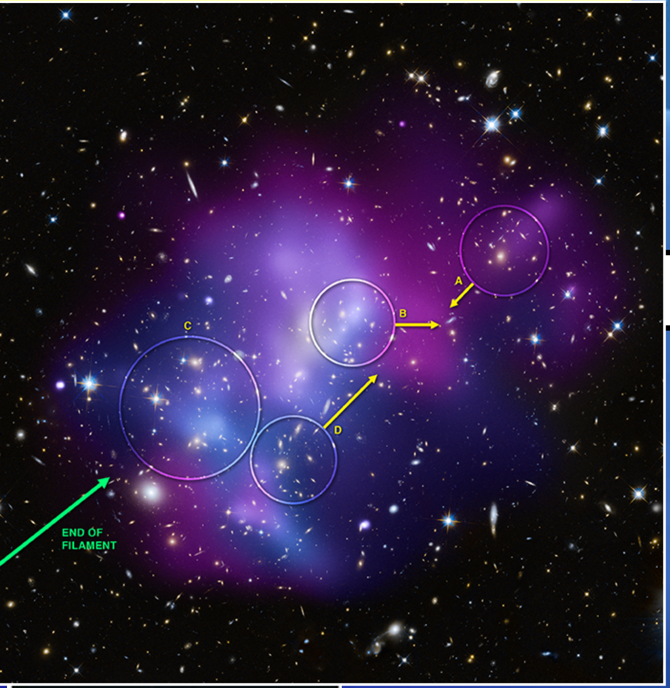
- ➢ ORIGIN & Physics ??
- ➢ IMPACT on thermal ICM ?? (microphysics & dynamics)

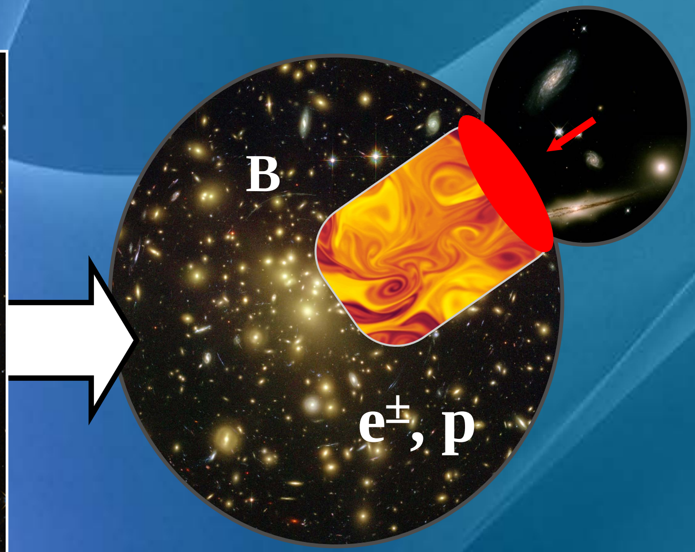
[Brunetti & Jones 14 for rev]

CR-acceleration

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B





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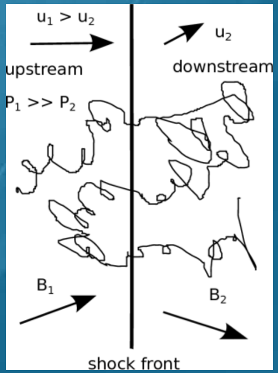
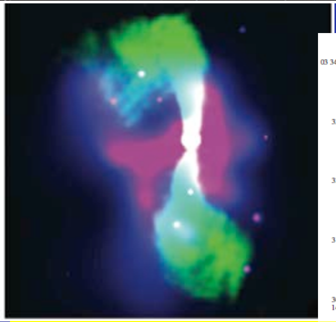
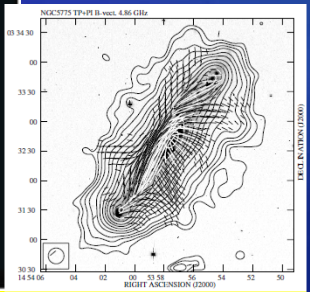


SHOCKS

accelerate CRe$^{\pm}$,CRp





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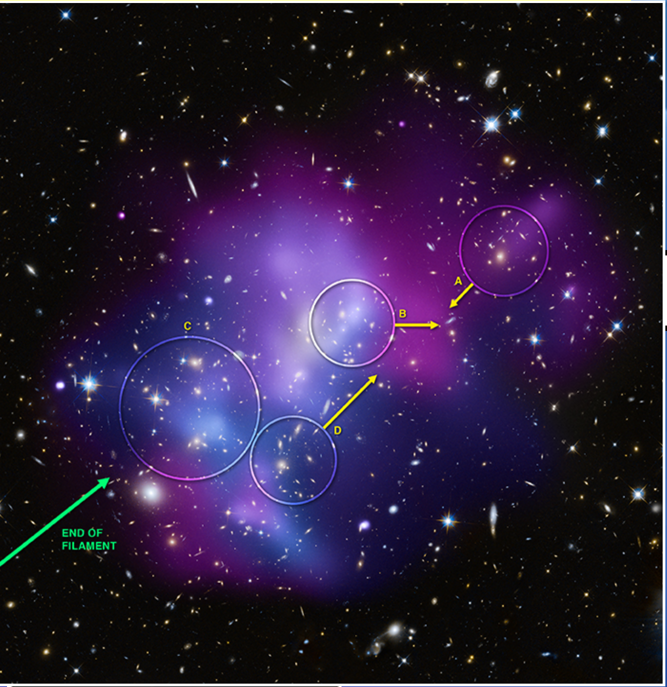

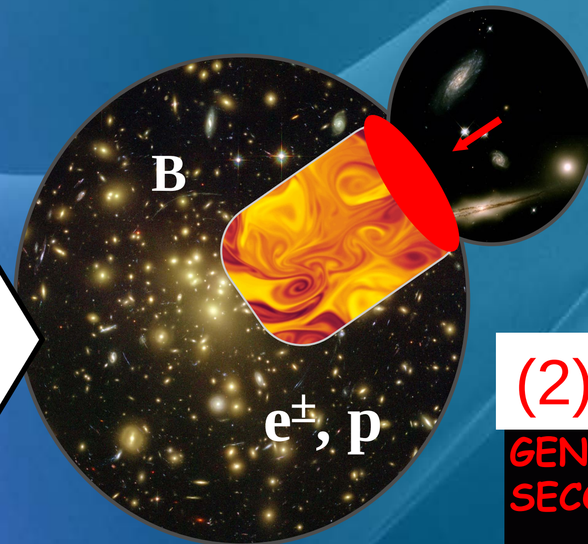

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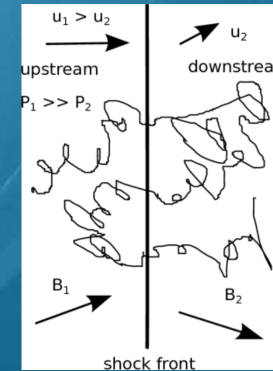

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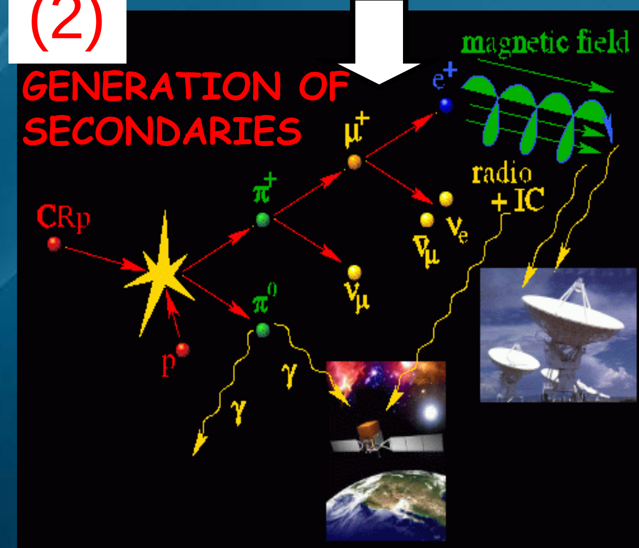
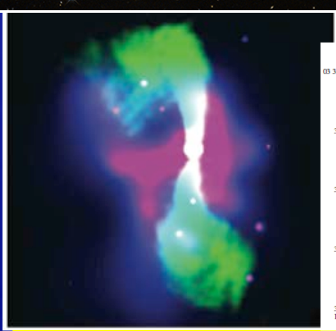
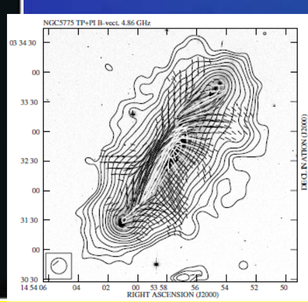
accelerate CRe±,CRp

(2)







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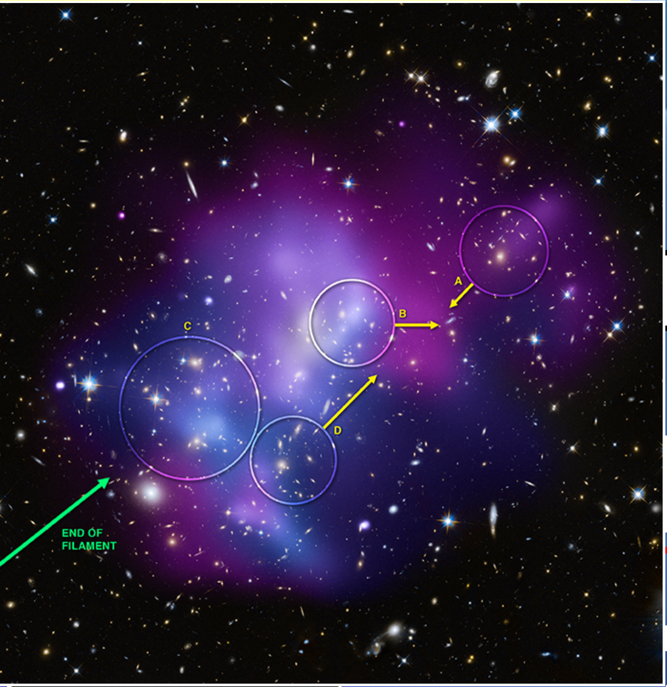

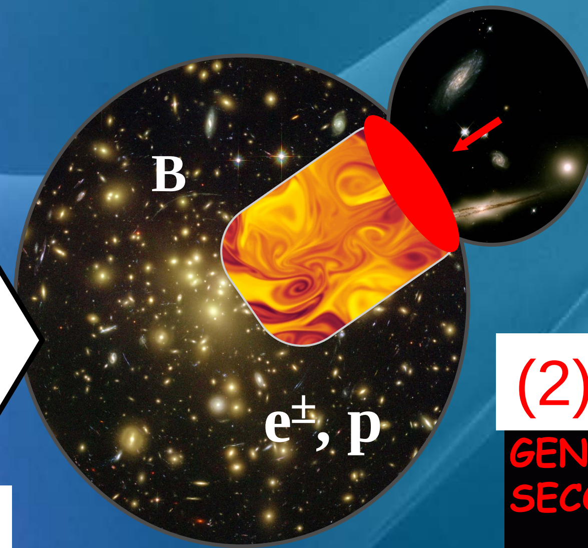

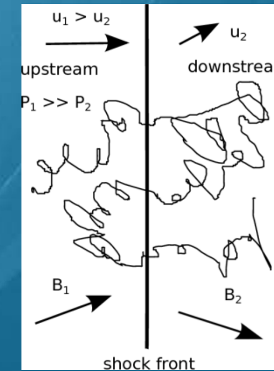

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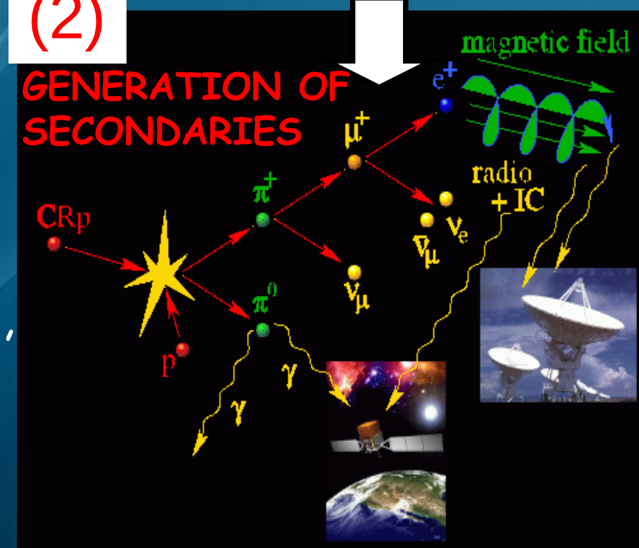
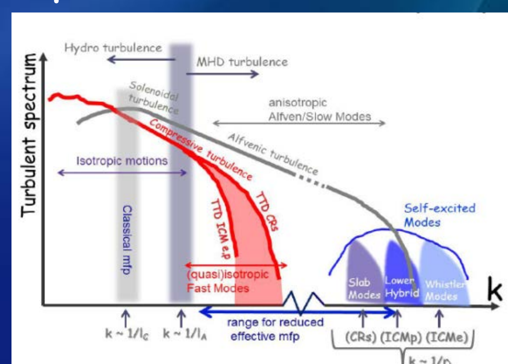
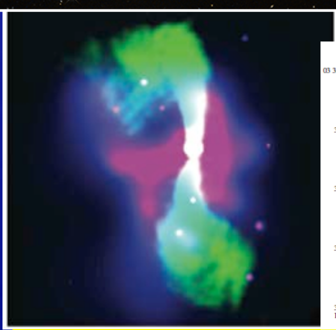


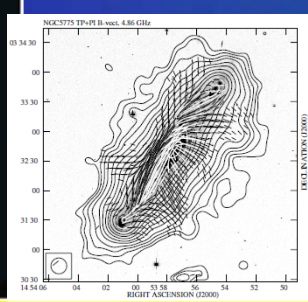
(3)

TURBULENCE

reaccelerates fossil CRe± , CRp and secondaries CRe±







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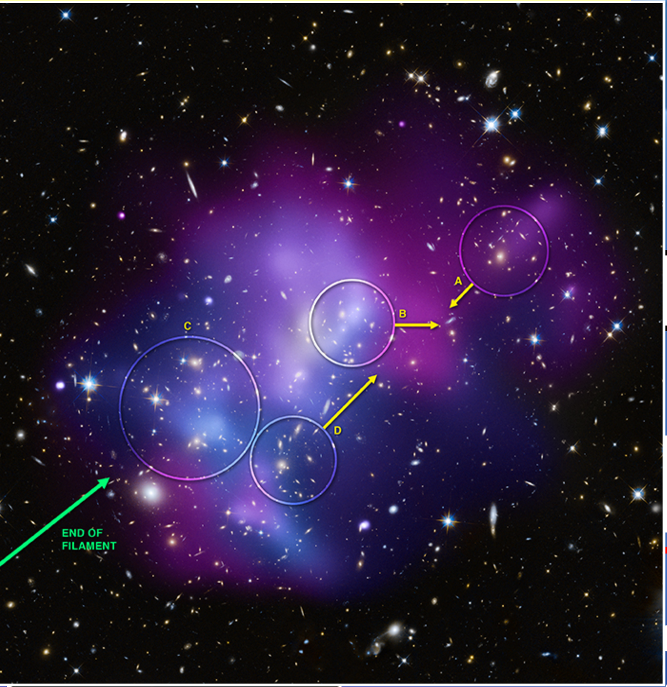

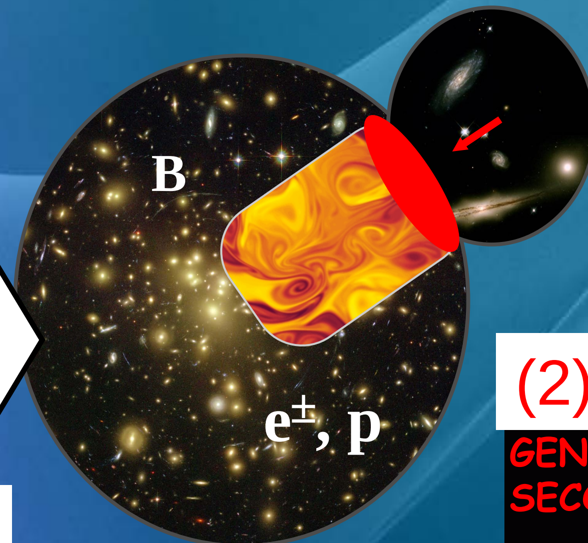

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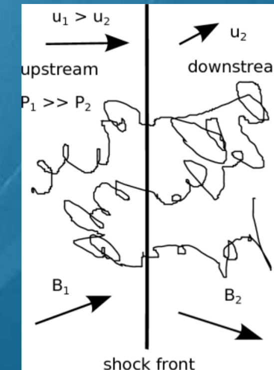

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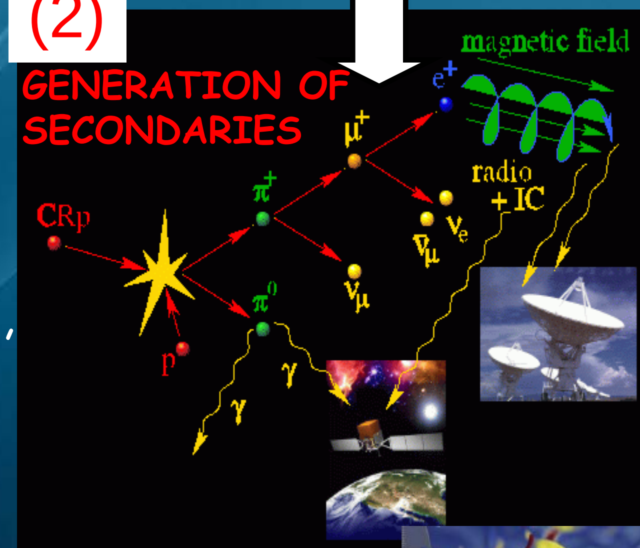

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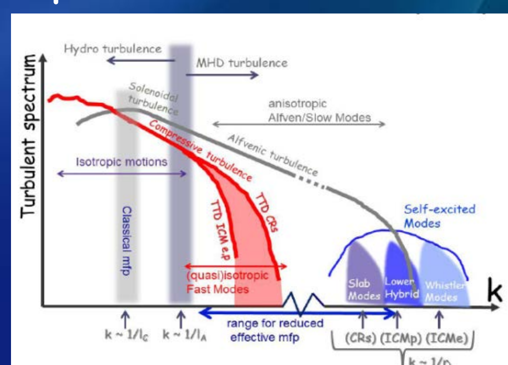

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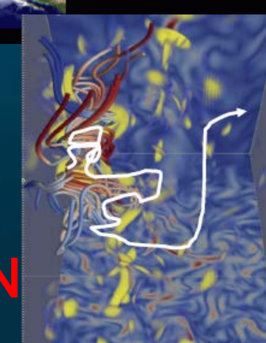
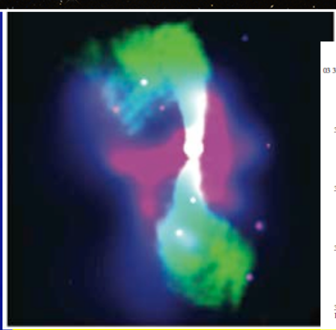
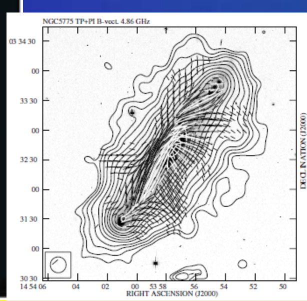
MAGNETIC RECONNECTION







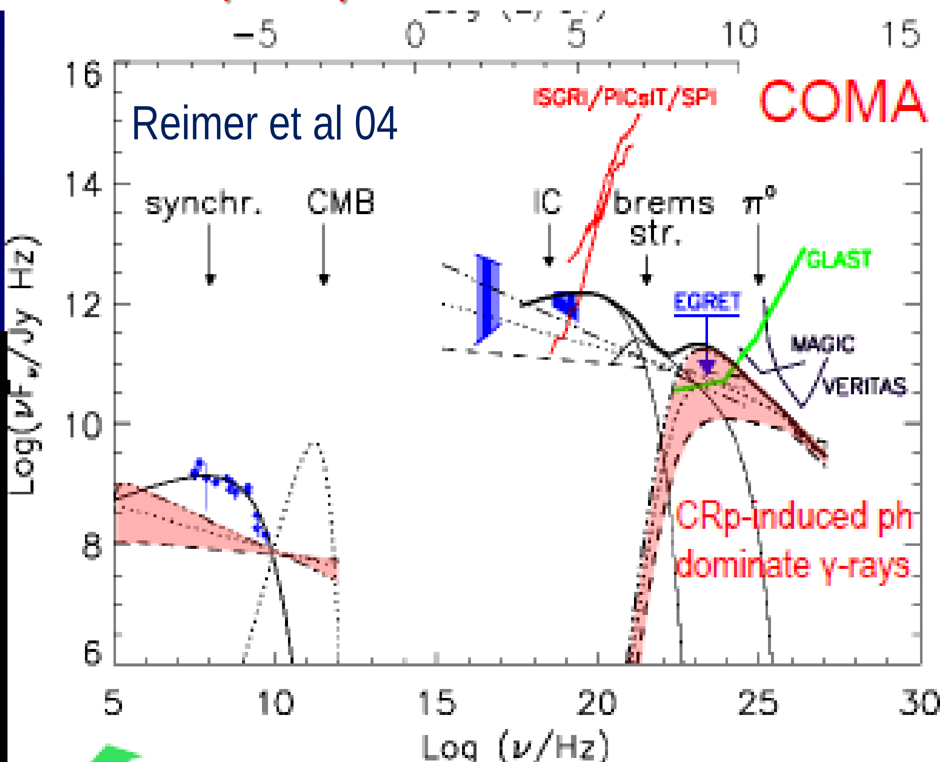
Astrophysical sources Galaxies (SN), AGN..

CR-acceleration

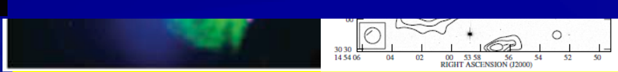
(eg. Brunetti + Jones 14)

Mergers guide CRe

Multifrequency emission + neutrino



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



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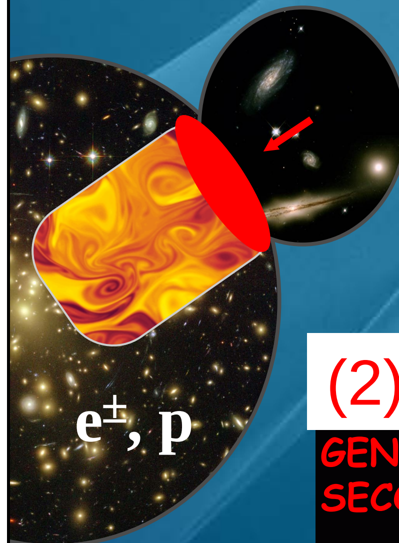

NCE

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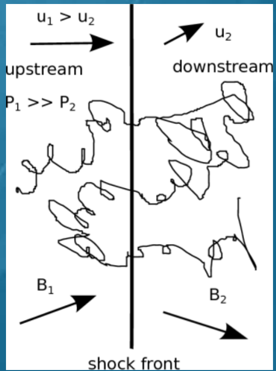

SHOCKS

accelerate CRe±,CRp

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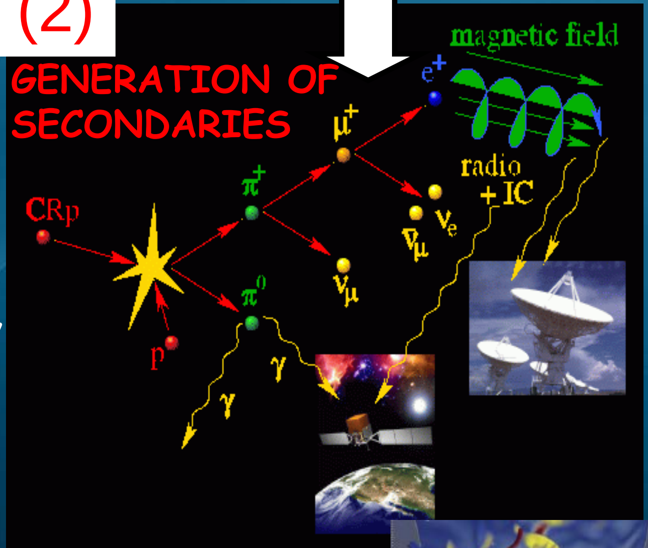

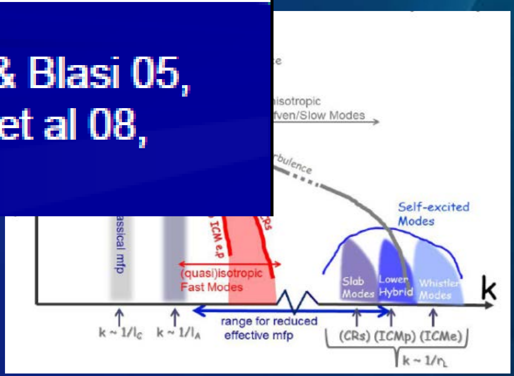

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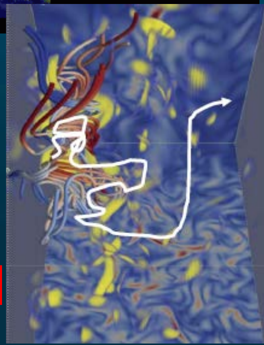

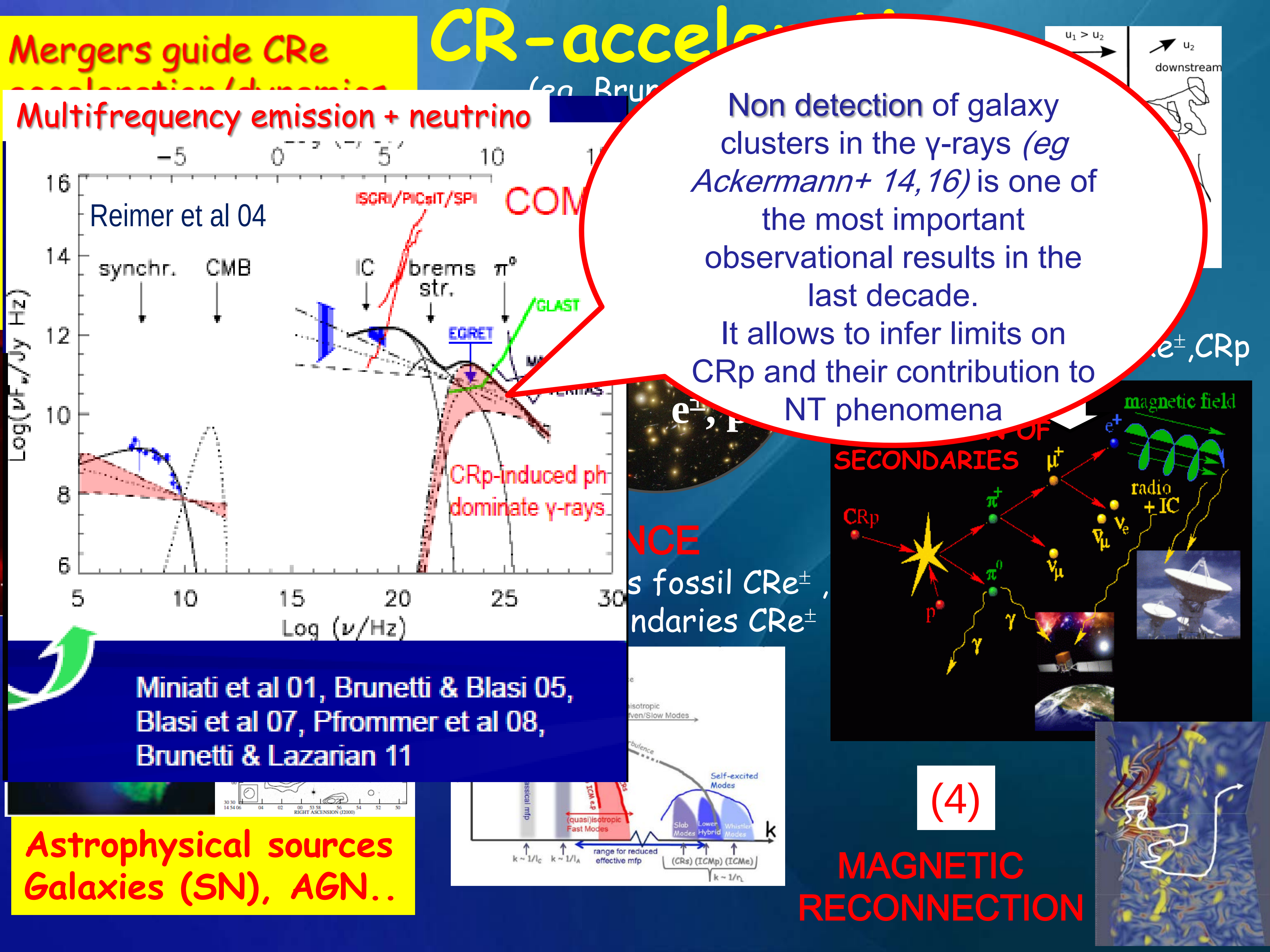

Mergers guide CRe
Multifrequency emission + neutrino
Reimer et al 04
synchr.
CMB
IC
brems str.
π°
ISGRI/PICsIT/SPI
GLAST
EGRET
COM
CRp-induced ph
dominate γ-rays
Log(νF_ν/Jy Hz)
Log (ν/Hz)
Miniati et al 01, Brunetti & Blasi 05, Blasi et al 07, Pfrommer et al 08, Brunetti & Lazarian 11
Non detection of galaxy clusters in the γ-rays (eg Ackermann+ 14,16) is one of the most important observational results in the last decade.
It allows to infer limits on CRp and their contribution to NT phenomena
CR-accele
e±,CRp
s fossil CRe± ,
ndaries CRe±
NCE
SECONDARIES
CRp
magnetic field
radio + IC
u₁ > u₂
u₂
downstream
Self-excited Modes
(quasi)isotropic Fast Modes
range for reduced effective mfp
k
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(eg Brunetti + Jones 14

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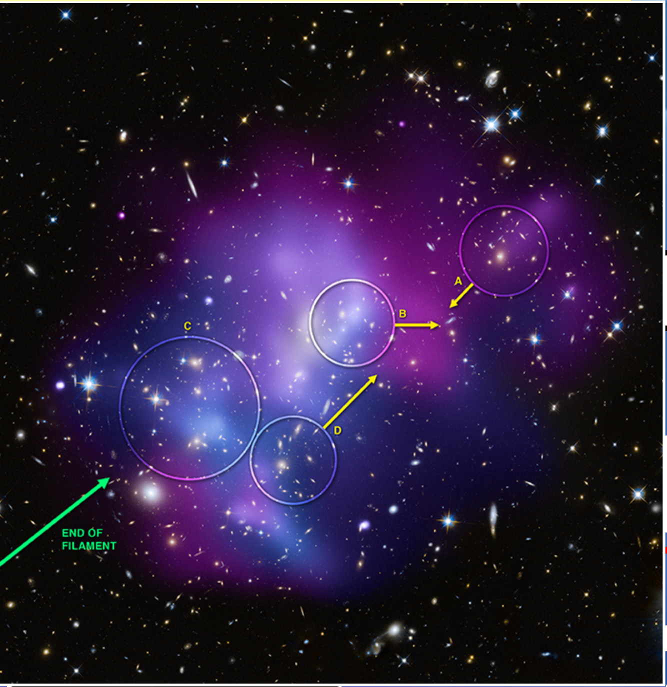

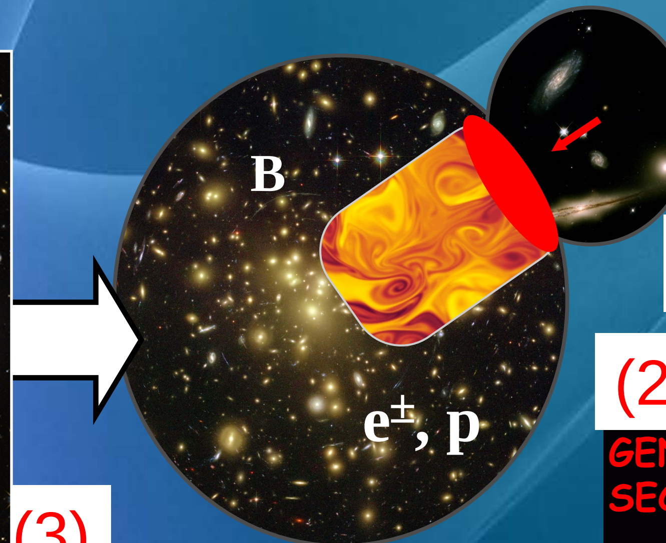

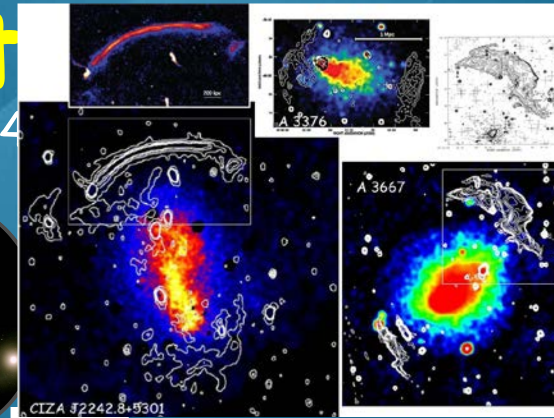

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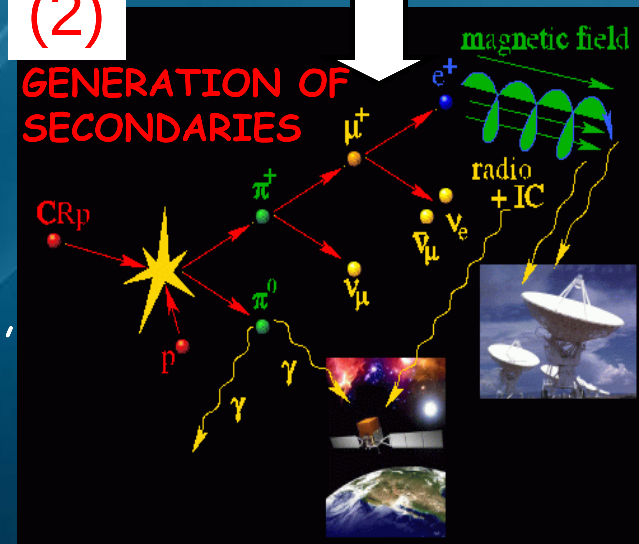
(2)



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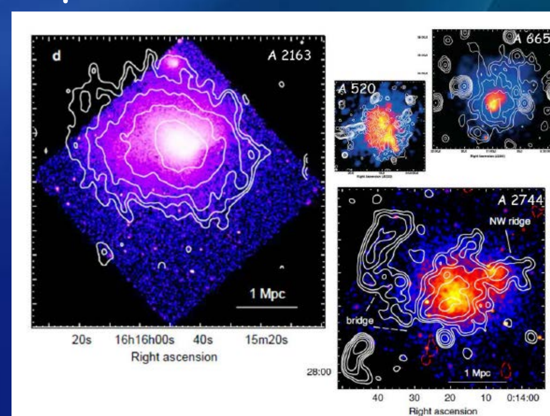

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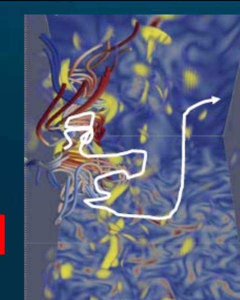

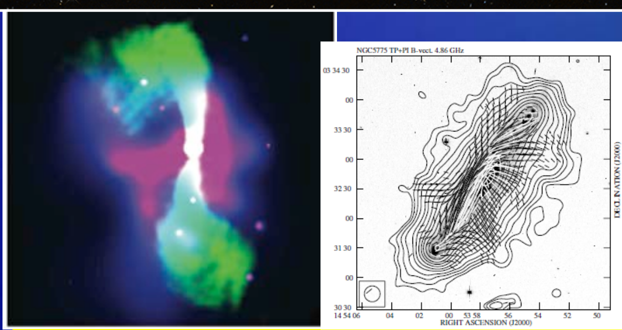

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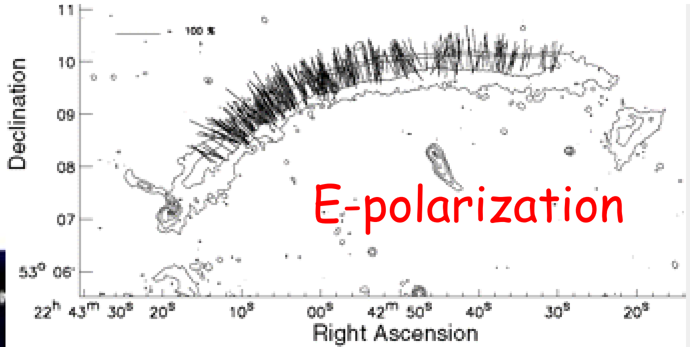
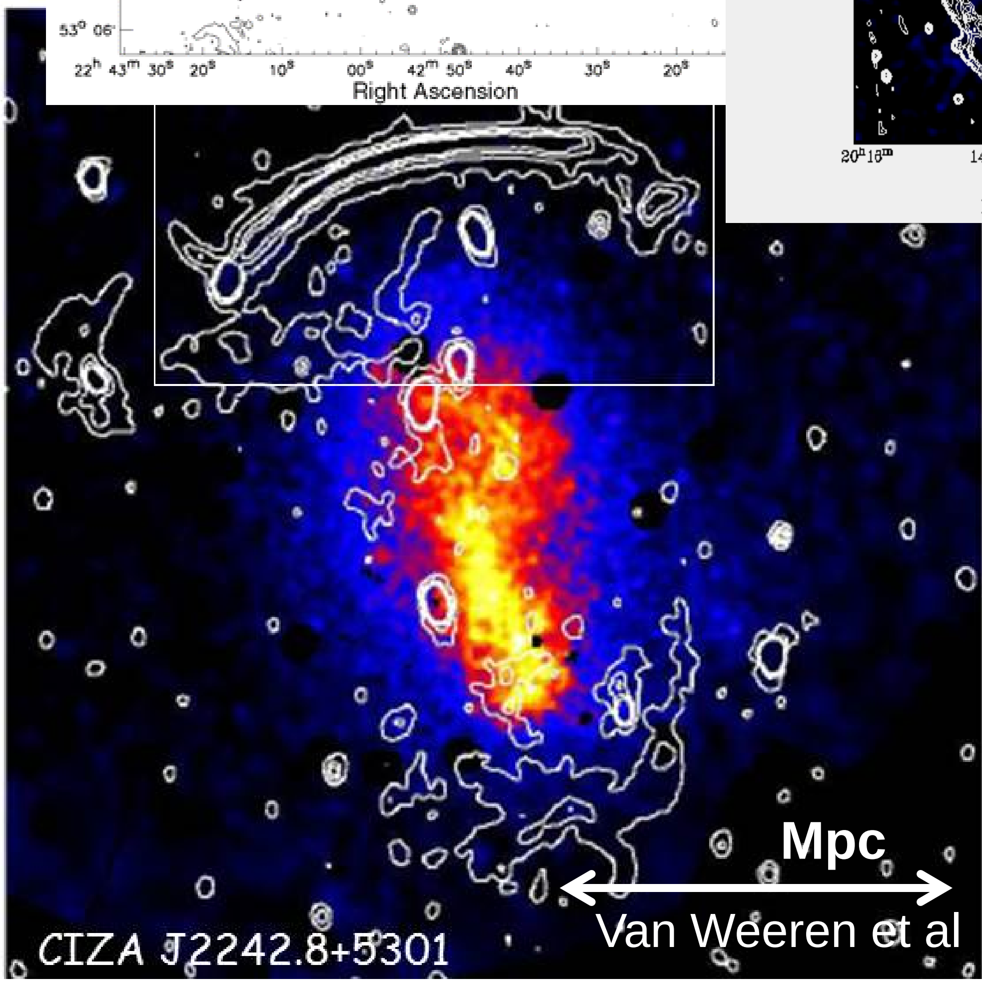
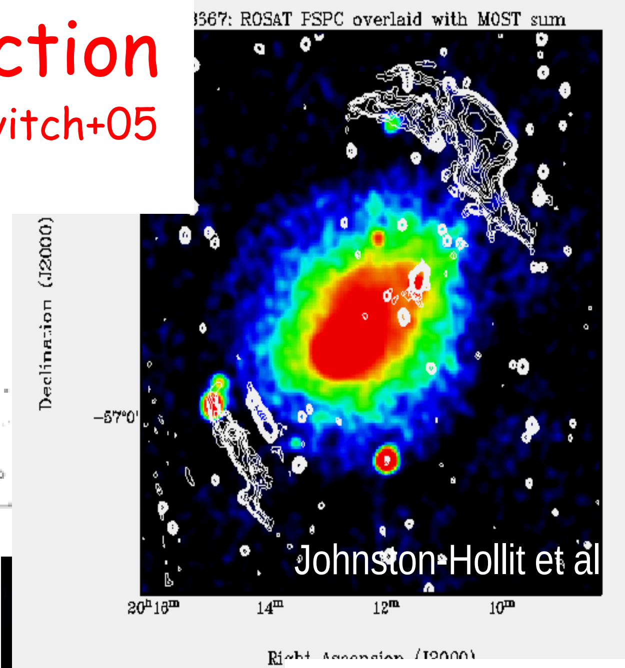
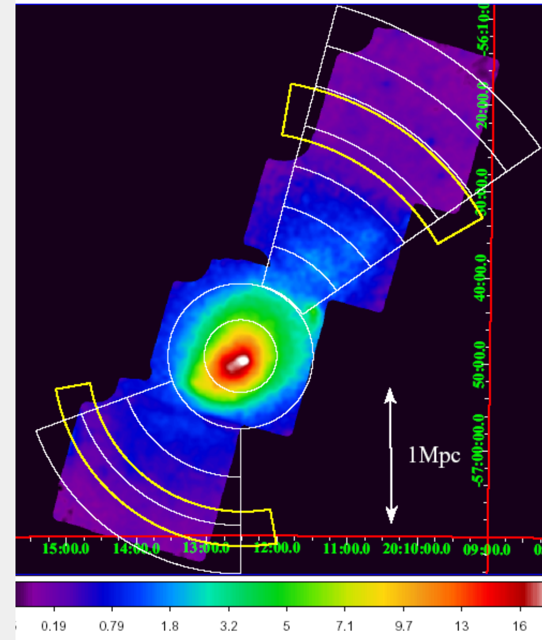
Relics - shock connection

Ensslin+98,Roettiger+99, Markevitch+05
Hoeft+Bruggen 07, Kang+ 12,17, ...

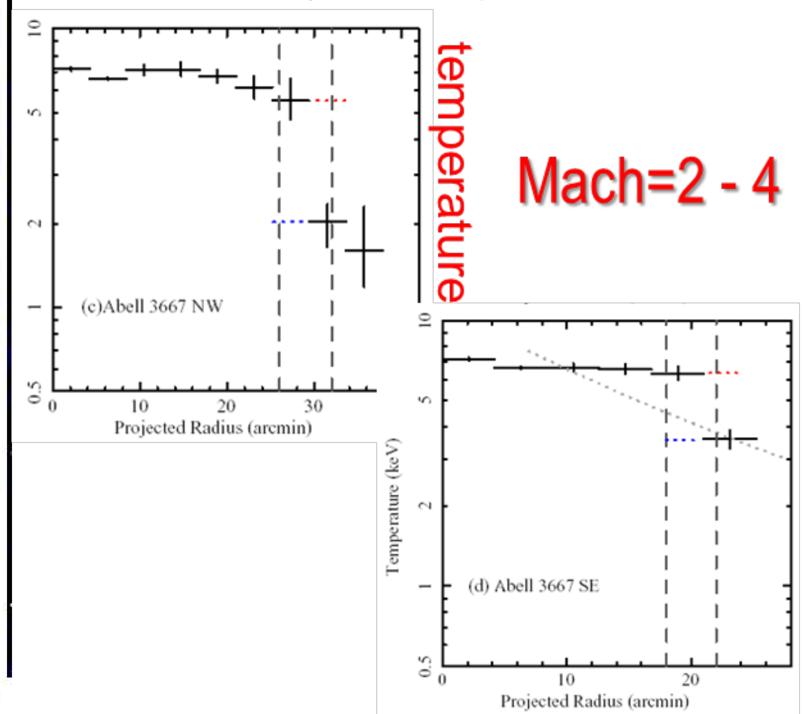






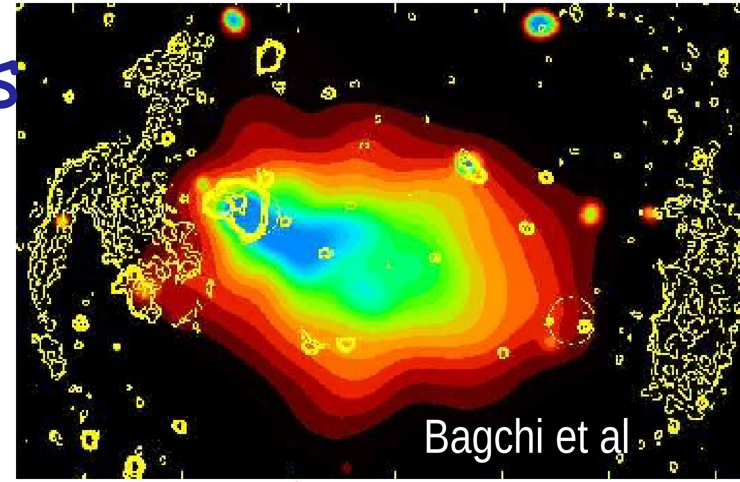


Akamatsu & Kawahara 12



Mach=2 - 4

OQuestions in Shock Models

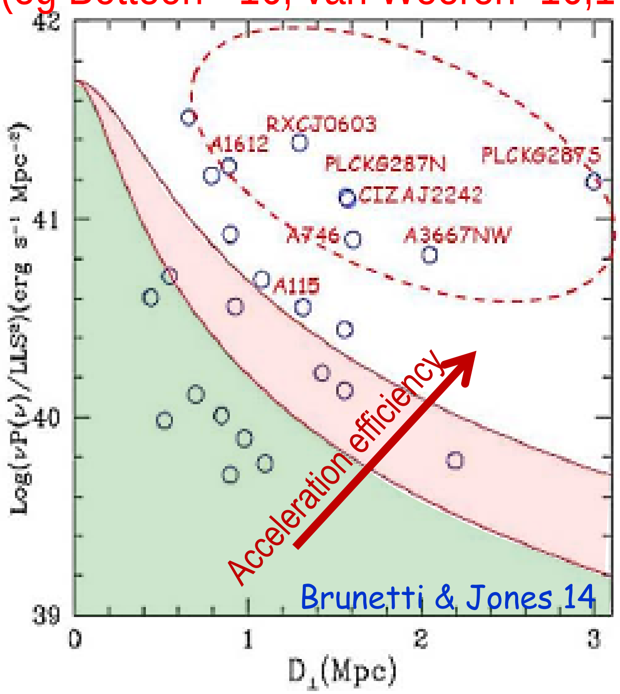


- Acceleration OR reacceleration ?
  (eg Markevitch et al 05, Kang et al 11,16, Pinzke & Pfrommer 13, Nuza+ 17, ..)

- Anomalous (high) ratio CRe/CRp ? … CRp escape ??!
  (Vazza et al 14,16, Brunetti & Jones 14, Guo et al 14, …)

- Efficiency is too big -

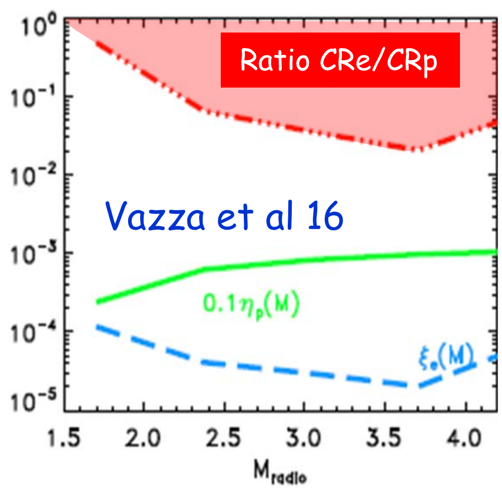
(eg Botteon+ 16, van Weeren+16,17)



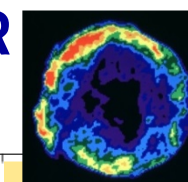
In combination with gamma-ray limits :

-Too many electrons

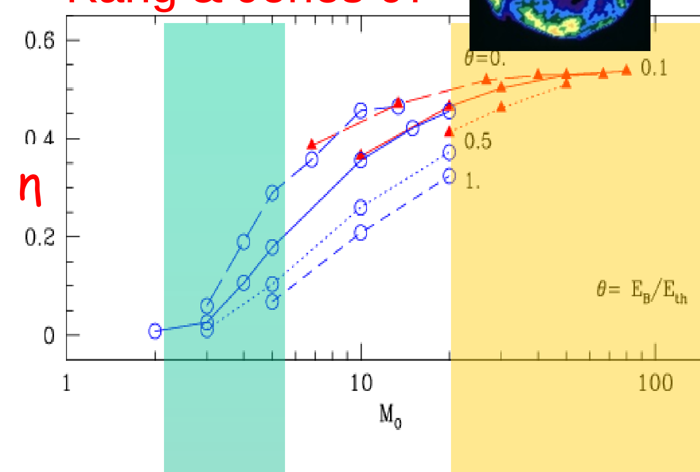
-Too few protons



Constraints in a regime different from SNR



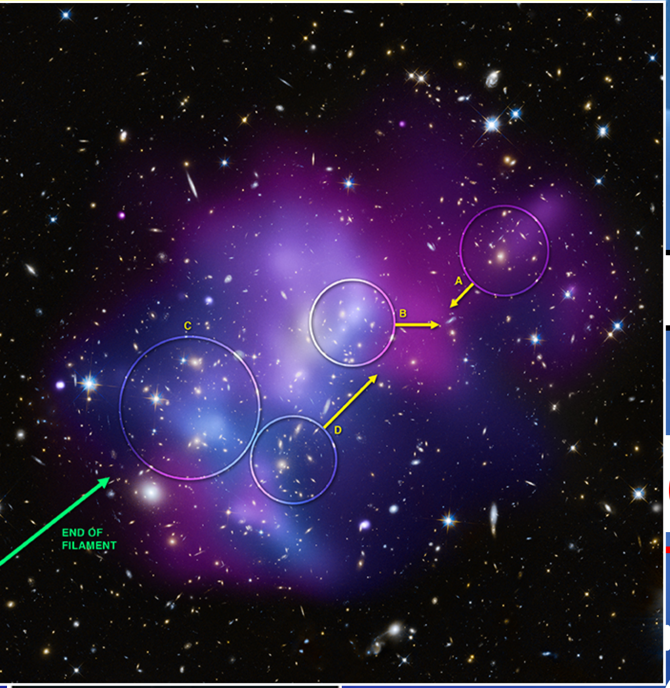
Kang & Jones 07

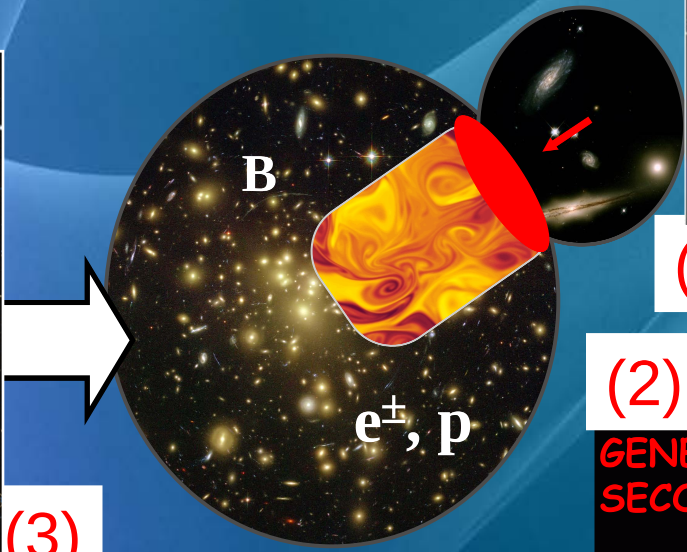


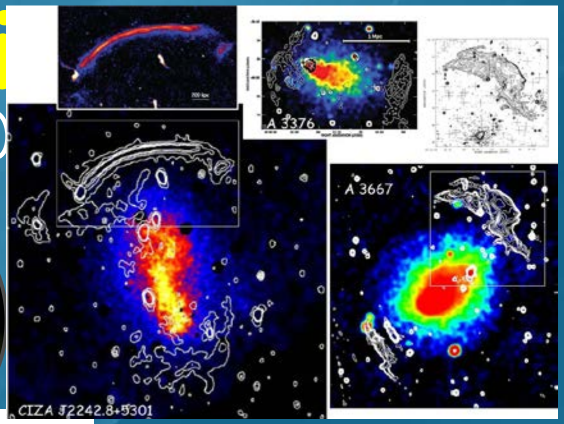
CR-accelerati

(eg Brunetti + Jones 14)

Mergers guide CRe acceleration/dynamics and/or amplify B





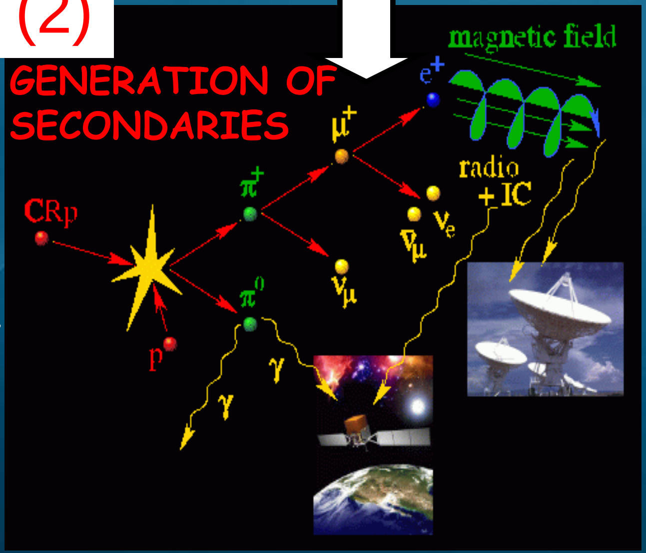


(1) SHOCKS

accelerate $CRe^{\pm}$,CRp

(2)

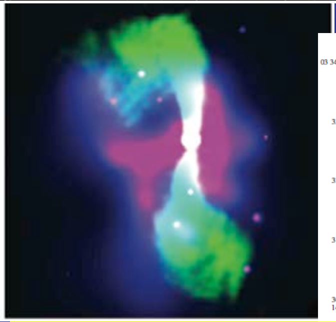
GENERATION OF SECONDARIES

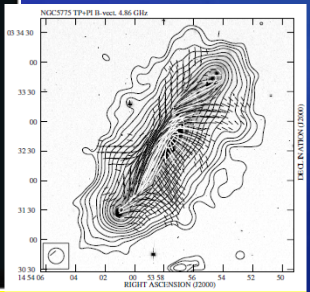


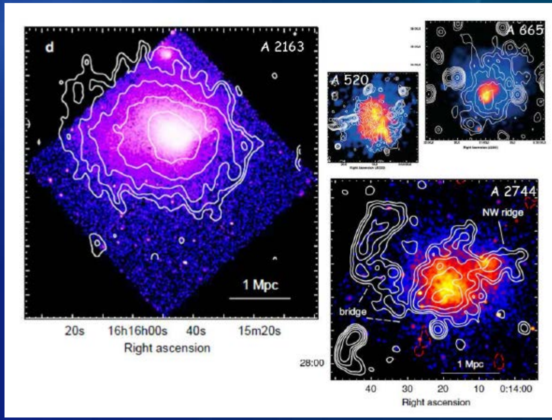
(3)

TURBULENCE

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

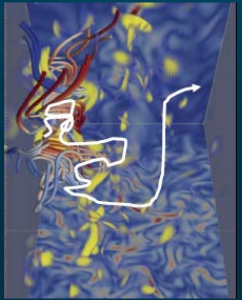






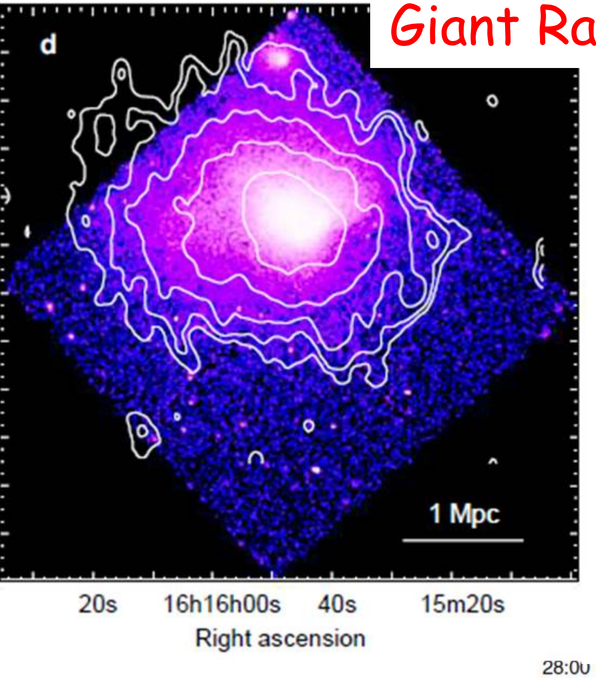
(4)

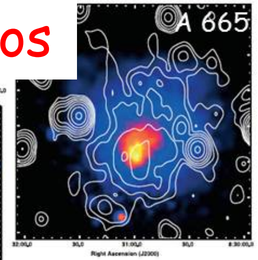
MAGNETIC RECONNECTION



Astrophysical sources Galaxies (SN), AGN..

Giant Radio Halos





Turbulent acceleration scenario

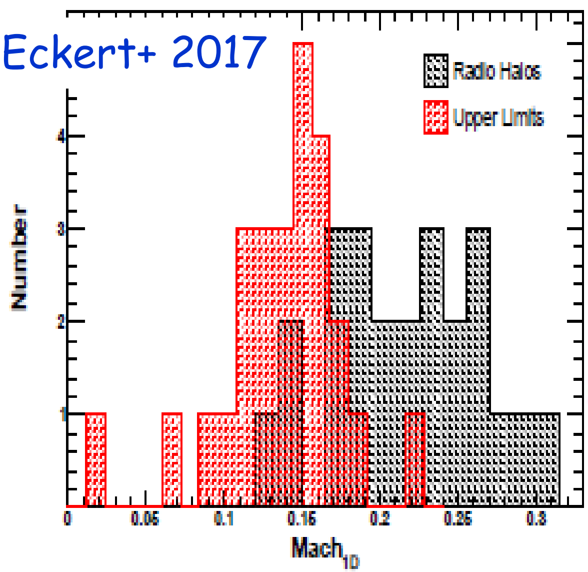
Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on second-order Fermi

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

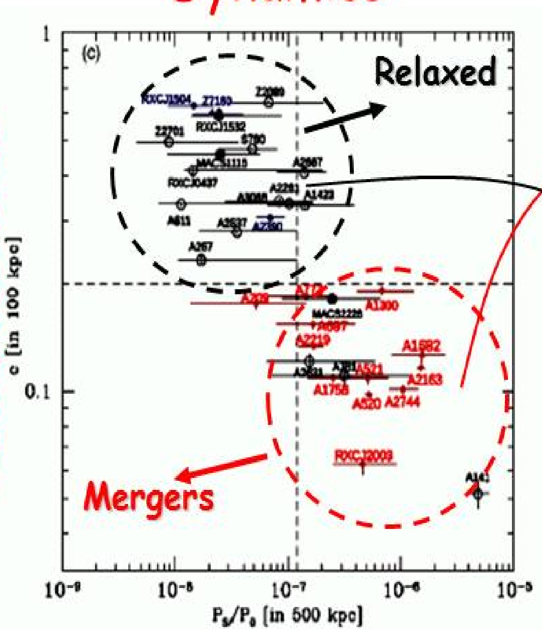
Halos – LS turbulece

Eckert+ 2017



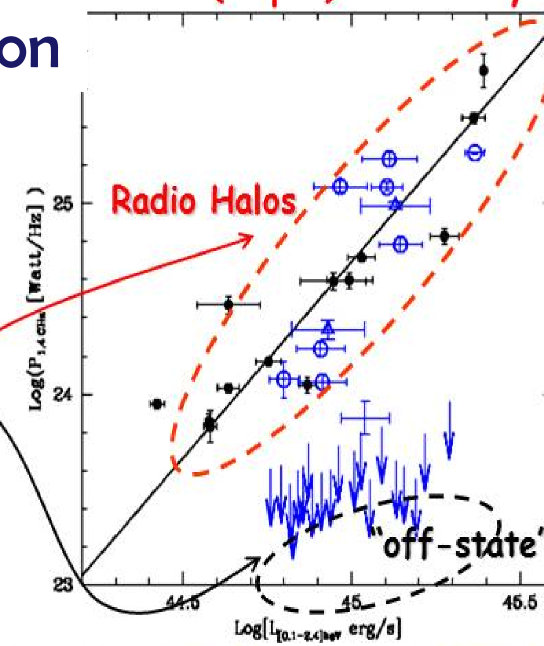
Dynamics

Cassano et al 10

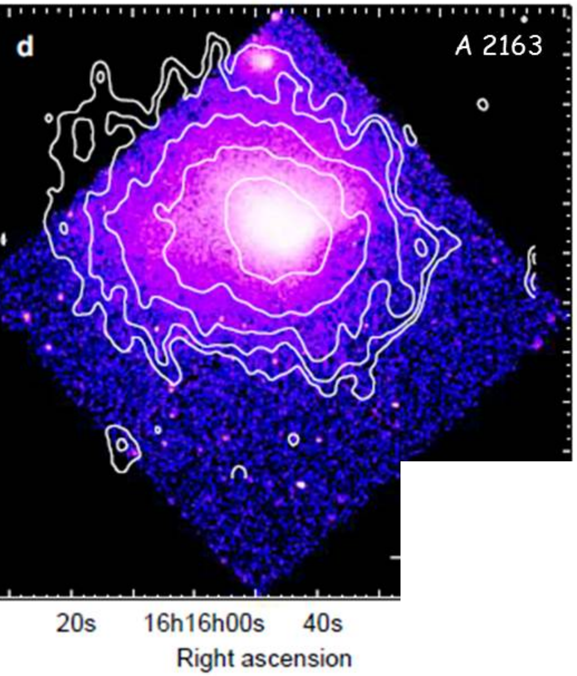


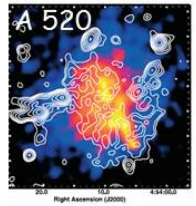
Radio(Mpc) - X-rays

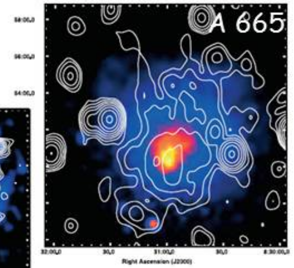
Brunetti et al 07,09



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







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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…]

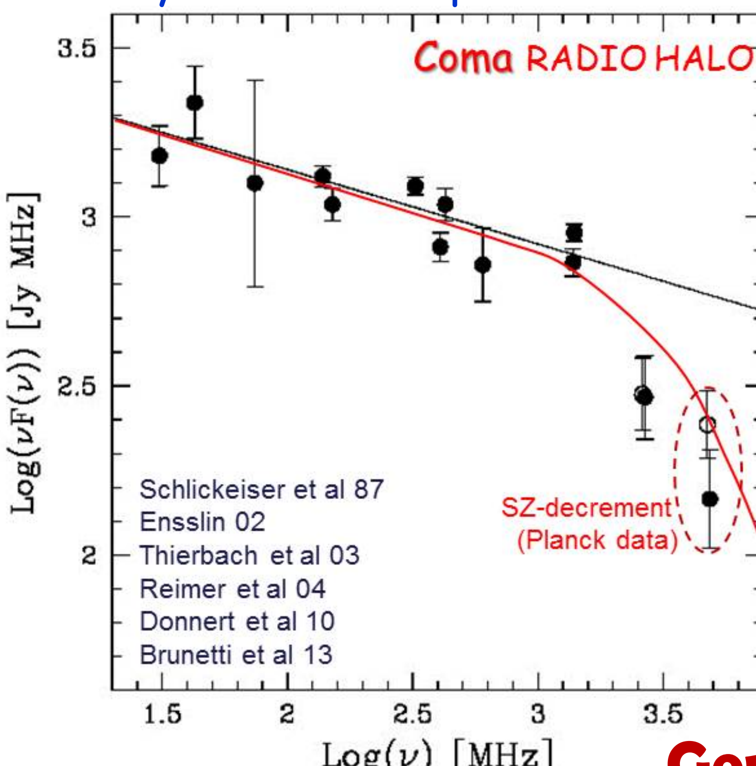
Manifestation of complex microphysics in the ICM:

Energy is transported From Mpc to Mm scales into non-thermal particles.

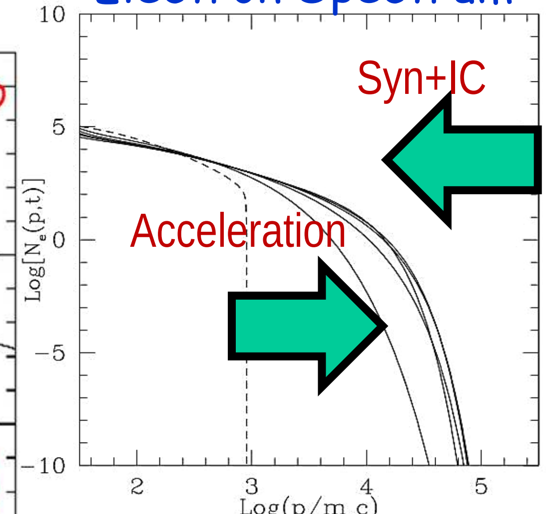
This requires a hierarchy of complex mechanisms and plasma/kinetic effects!

[eg Brunetti+Jones 14 rev]

Synchrotron Spectrum



Electron Spectrum



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

Gentle reacceleration

OQuestions in turbulent Models

❑ Details of mergers-halos connection

Not all merging systems have RHs *(Cassano+10, Russell+ 11, Bonafede+ 17, Johnston-Hollitt+Pratley 17)* and a few less disturbed systems also host RHs *(Sommer+ 17, Venturi+ 17)*. Additional ingredients (energetics, microphysics, seeds,…).

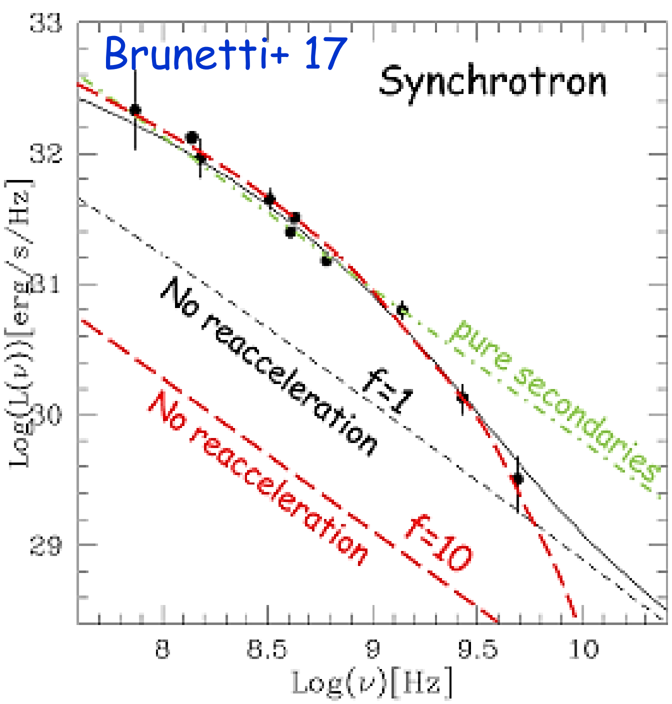
OQuestions in turbulent Models

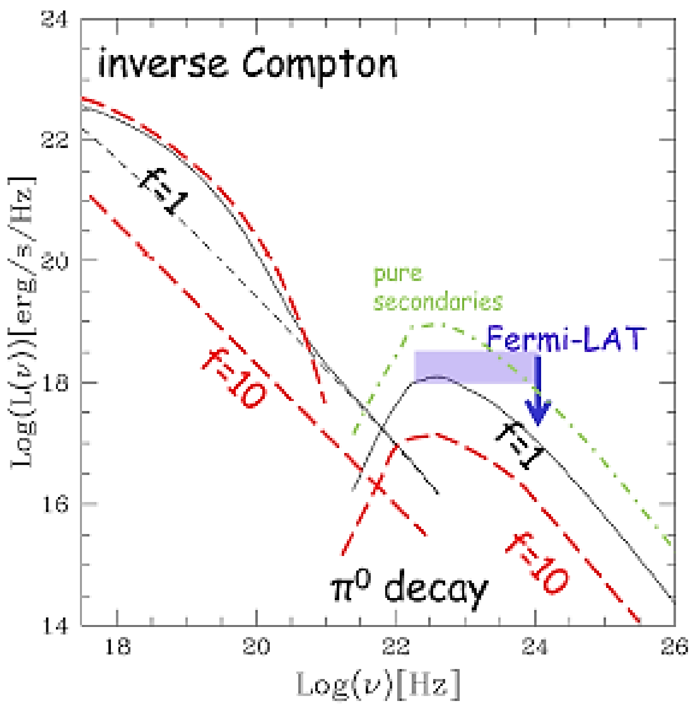
- **Details of mergers-halos connection**

Not all merging systems have RHs and a few less disturbed systems also host RHs: additional players (energetics, timescales, microphyics, seeds..)

Do CRp play a role ?

- Pure hadronic models are ruled out by Fermi-LAT limits *(eg, Brunetti+ 12,17, Ackermann+ 14,16, Zandanel+ 15, Pinzke+ 17)*
- New theoretical framework: CRp and secondaries may be reaccelerated by turbulence (??) *(Brunetti+Blasi 05, Brunetti+Lazarian 11, Pinzke+ 17)*



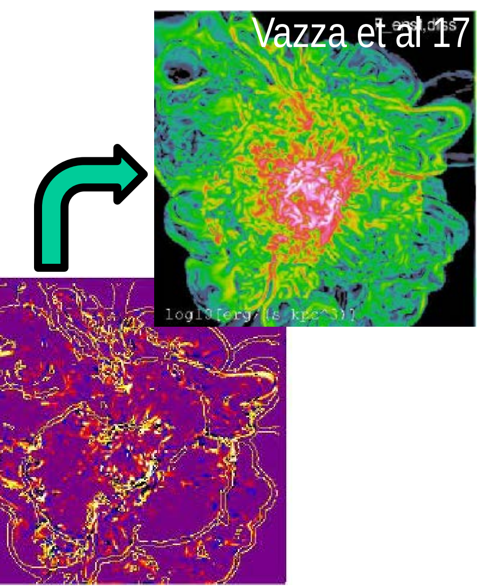


A signal at 3σ+ level can be detected in 10 yrs with Fermi-LAT for Coma (Brunetti+ 17)

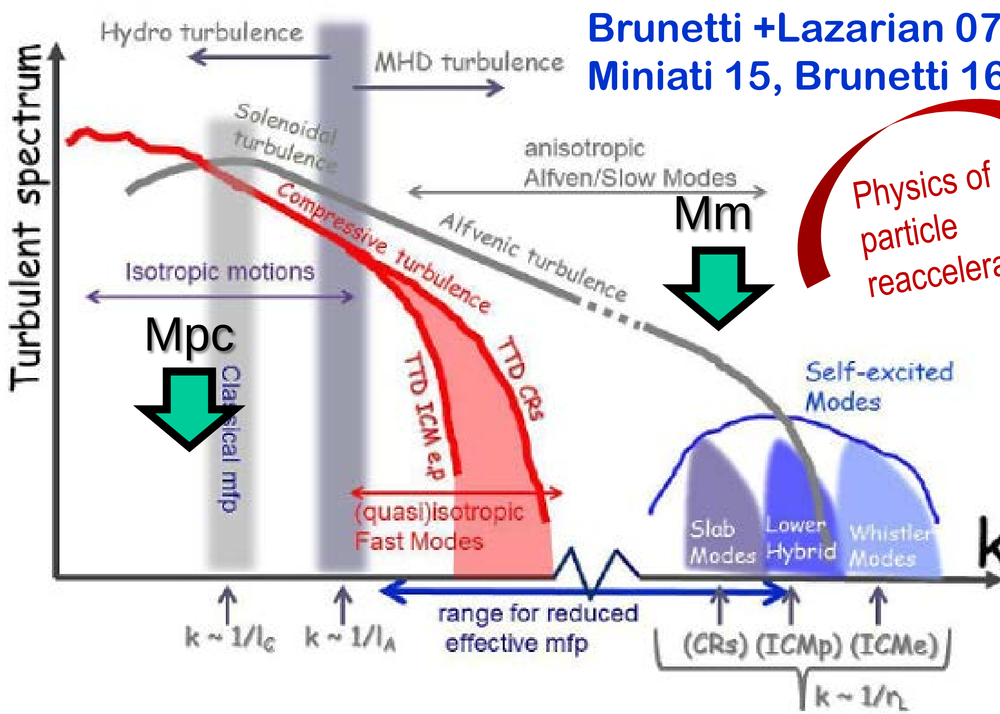
Detection of a large population of underluminous giant radio halos 'in less dynamically disturbed systems (Brown+ 11, Cassano+ 12, Bonafede+ 15, Cuciti's talk)

OQuestions in turbulent Models

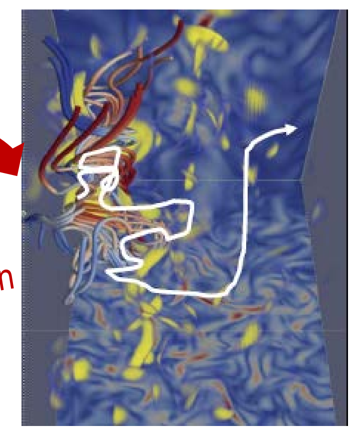
- **Details of mergers-halos connection**
  - *Additional ingredients (energetics, timescales,microphysics, seeds,…).*
- **Do CRp play a role ?**
  - Pure hadronic models are ruled out from Fermi-LAT limits
  - Still… CRp and secondaries may be reaccelerated by turbulence
- **How energy is transported from LS into particle acceleration ?**



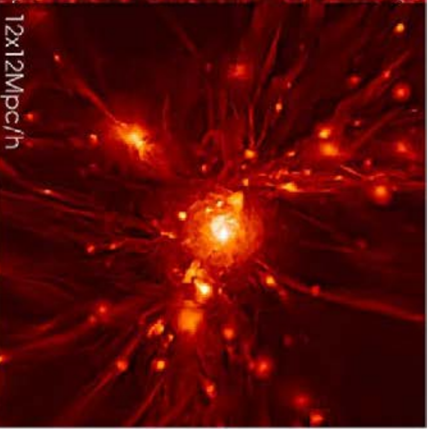
Brunetti +Lazarian 07
Miniati 15, Brunetti 16

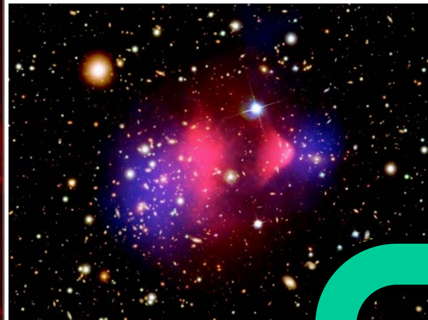


Physics of particle reacceleration



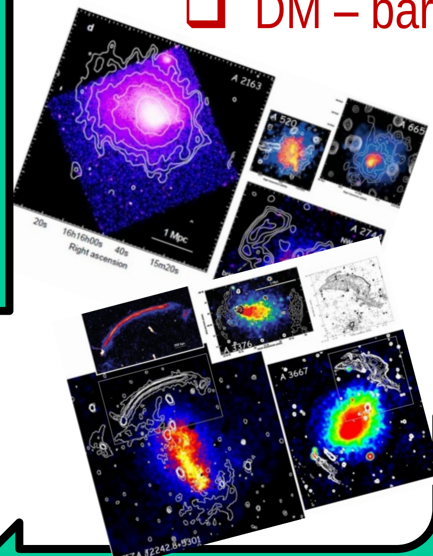
Collective effects
& plasma instabilites
more important than
Coulomb collisions





COSMOLOGY

- ❑ Structure formation
- ❑ DM – barions interplay

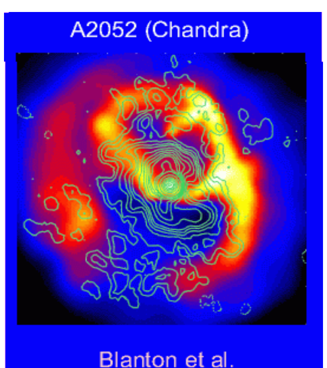


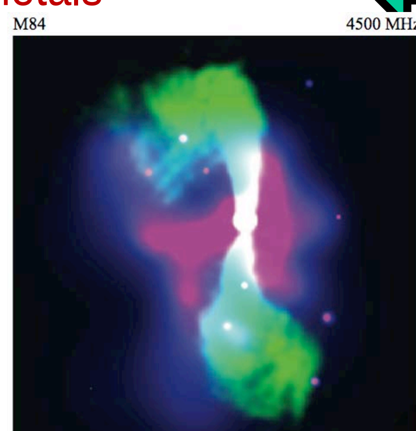
PLASMA ASTROPHYSICS

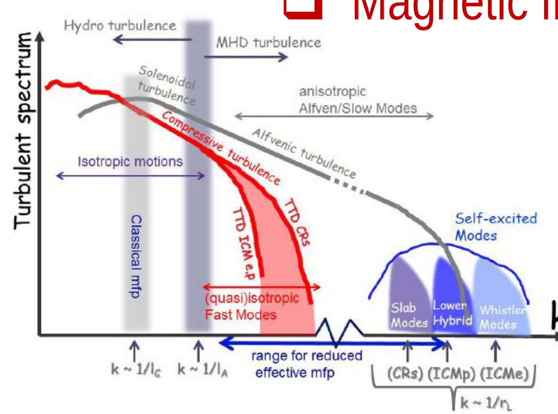
- ❑ How energy is transported from large to small scales ?
- ❑ Particle energy distrbution & transport
- ❑ Particle acceleration
- ❑ Magnetic fields

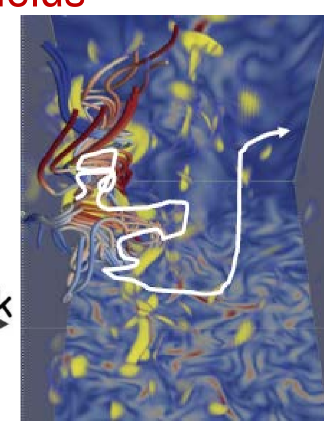
ASTROPHYSICS

- ❑ AGN & galaxies as CR sources
- ❑ Heating of the thermal gas
- ❑ Transport of metals
- ❑ Feedback









THE ROLE OF LOW FREQUENCY OBSERVING

- ❑ Much better sensitivity to steep spectra *(statistics & serendipity)*
- ❑ Observing "gentle" acceleration mechanims in the ICM *(halos, RGs, plasma)*
- ❑ Targeting longer-living CRe : life-cycle of non-thermal plasma in the ICM *(astrophysics, transport, … …surprises?)*

COSMOLOGY

- ❑ Structure formation
- ❑ DM – barions interplay

PLASMA ASTROPHYSICS

- ❑ How energy is transported from large to small scales ?
- ❑ Particle energy distrbution & transport
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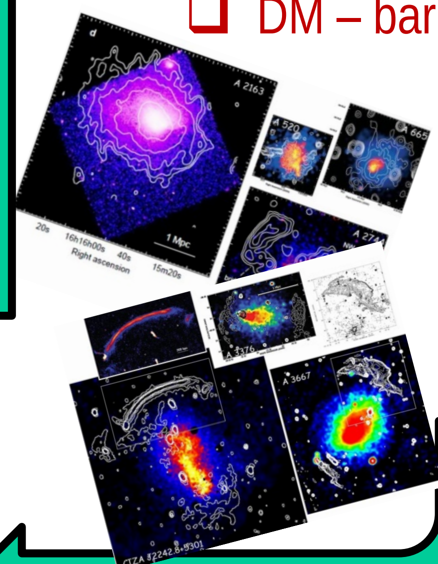
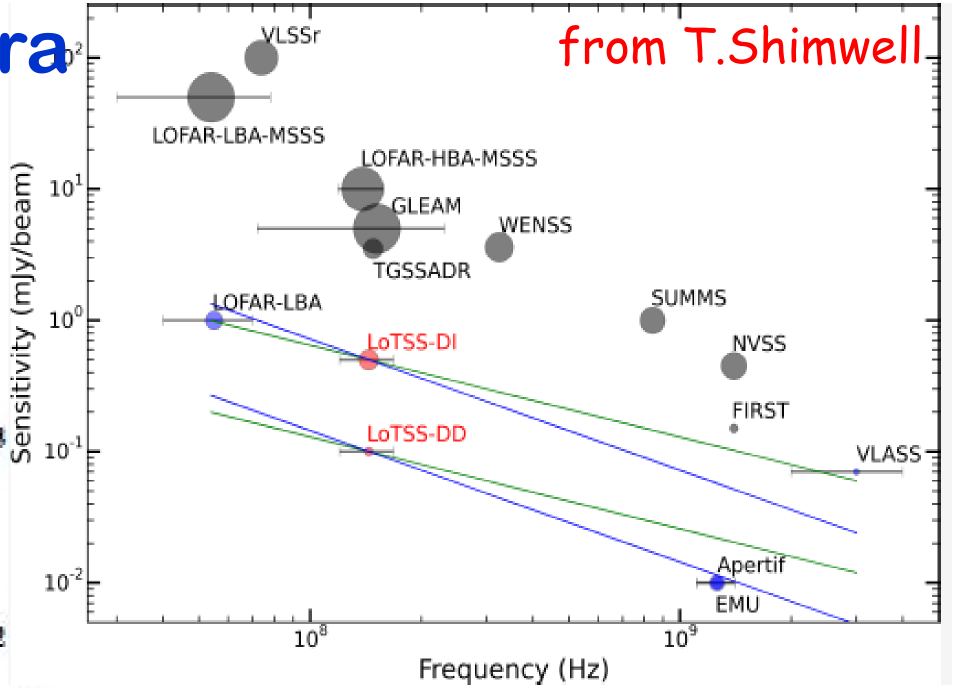


ASTROPHYSICS

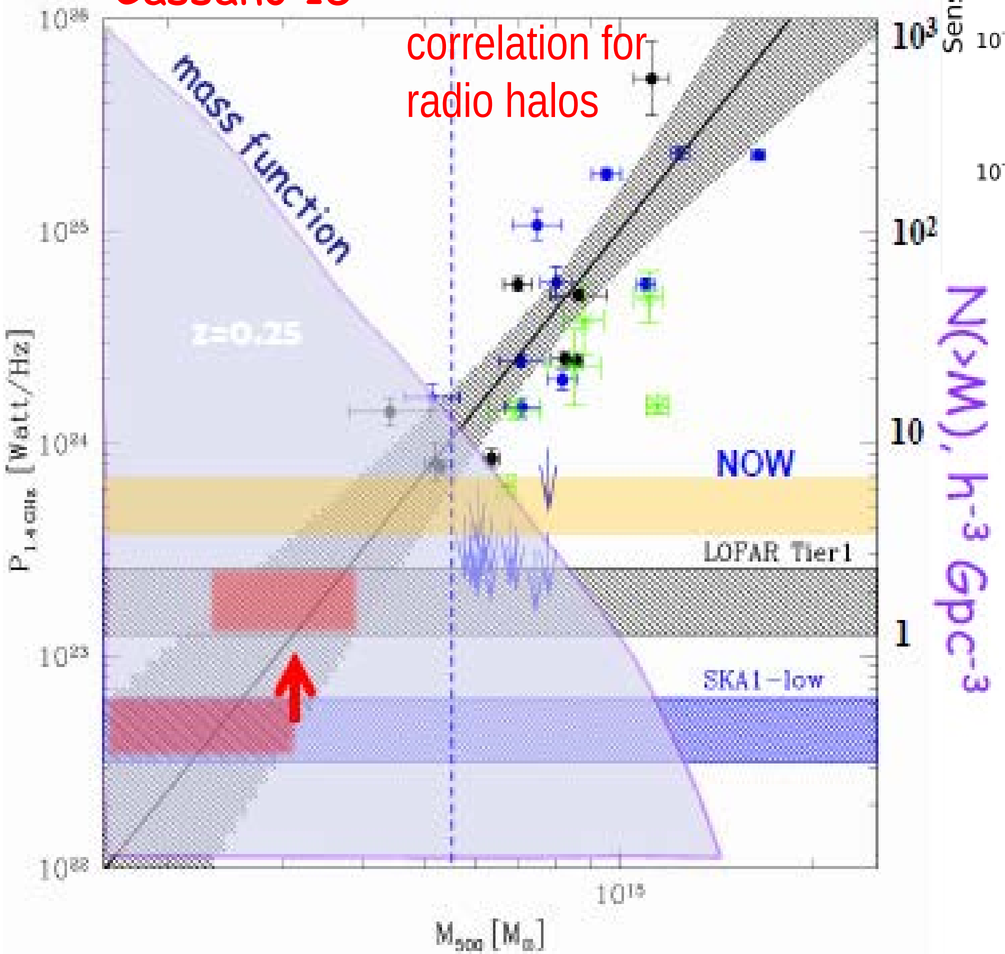
- ❑ AGN & galaxies as CR sources
- ❑ Heating of the thermal gas
- ❑ Transport of metals
- ❑ Feedback

Sensitivity to steep spectra

(eg, Ensslin+Rottgering 02, ...)



Cassano 15



LOFAR T1 obsevrations have the sensitivity to detect radio halos in 2+ times less massive systems than current targets increasing x10 times the numer of potential targets

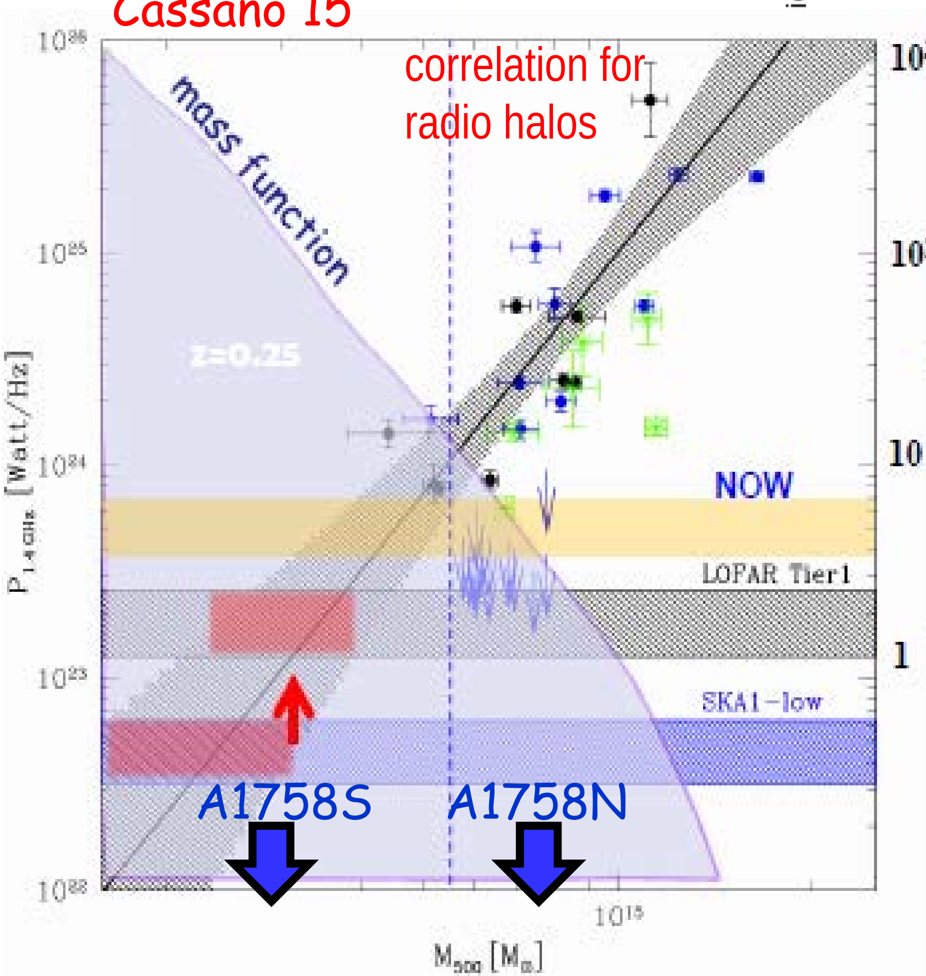
(with respect to a north sky survey with the GMRT !)

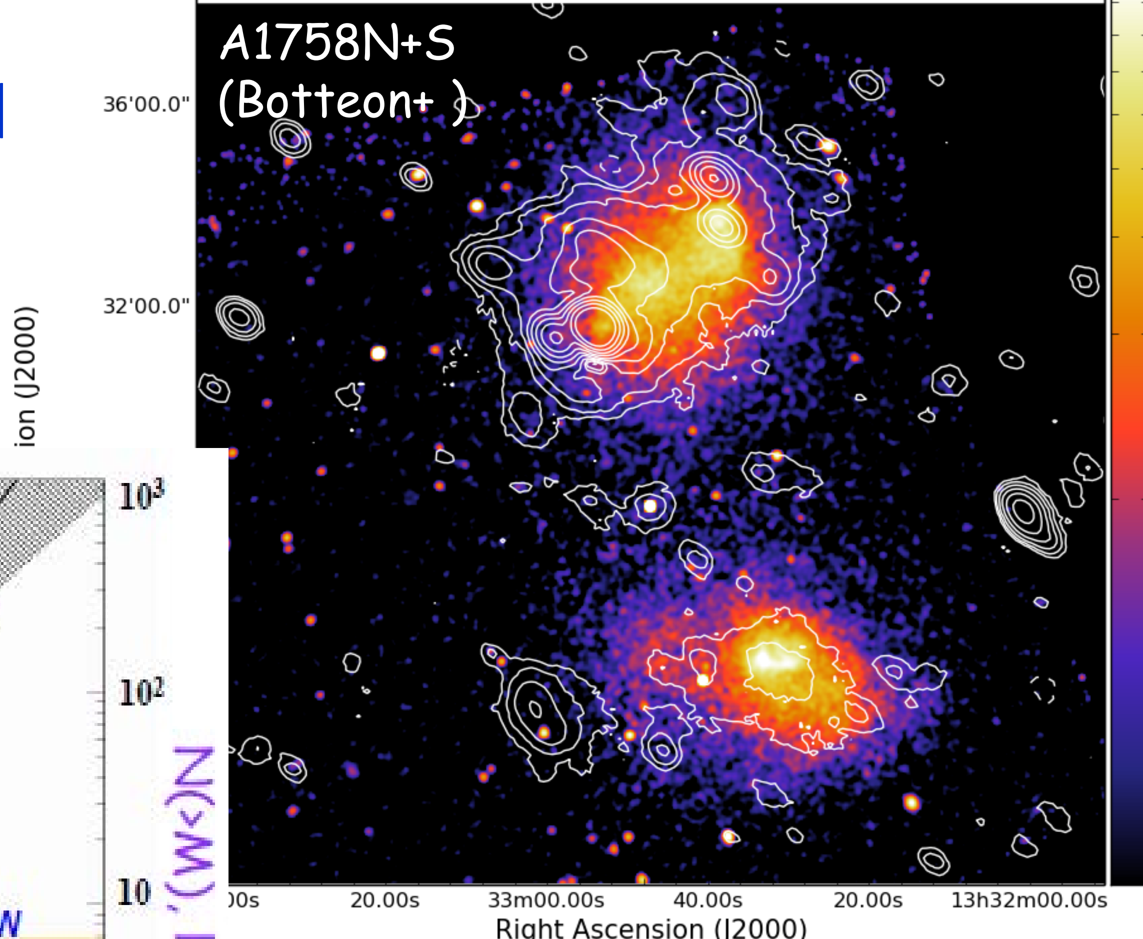
[caveat:assuming the P-M correlation]

Sensitivity to steep s|

(eg, Ensslin+Rottgering 02, ...)

Cassano 15





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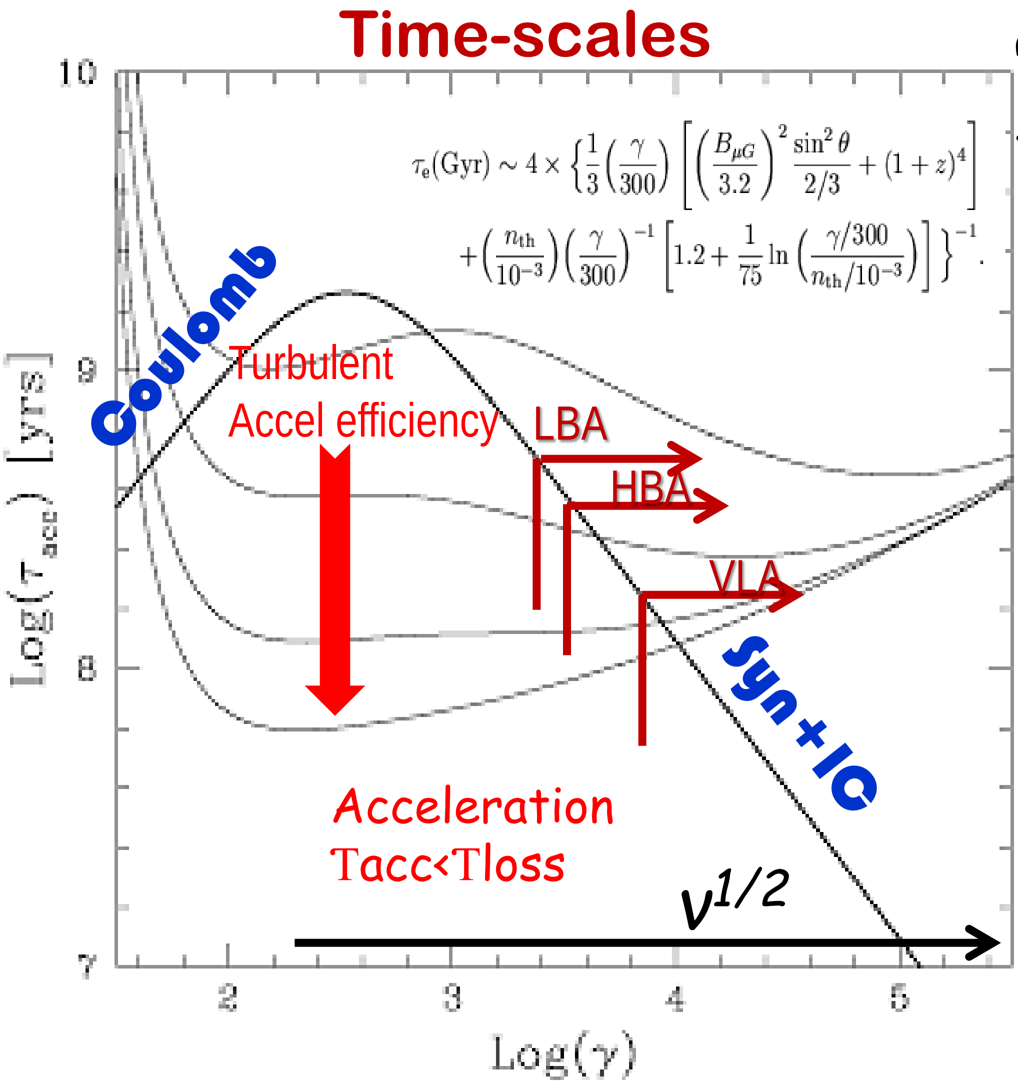
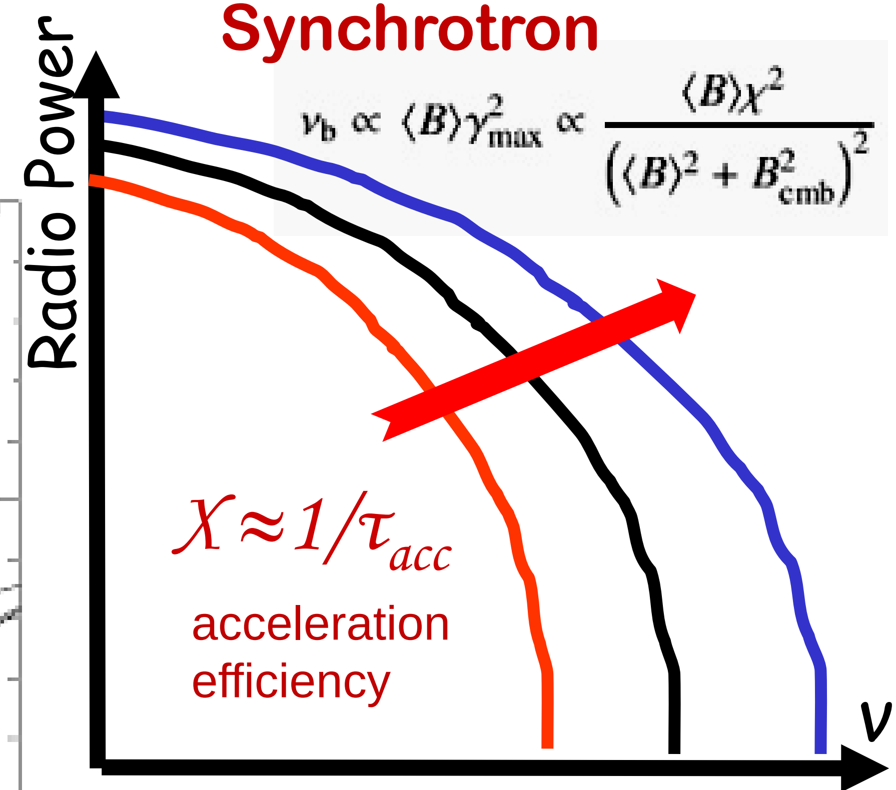
[caveat:assuming the P-M correlation]

Gentle reacceleration: Turbulent reacceleration and ultra-steep spectrum halos

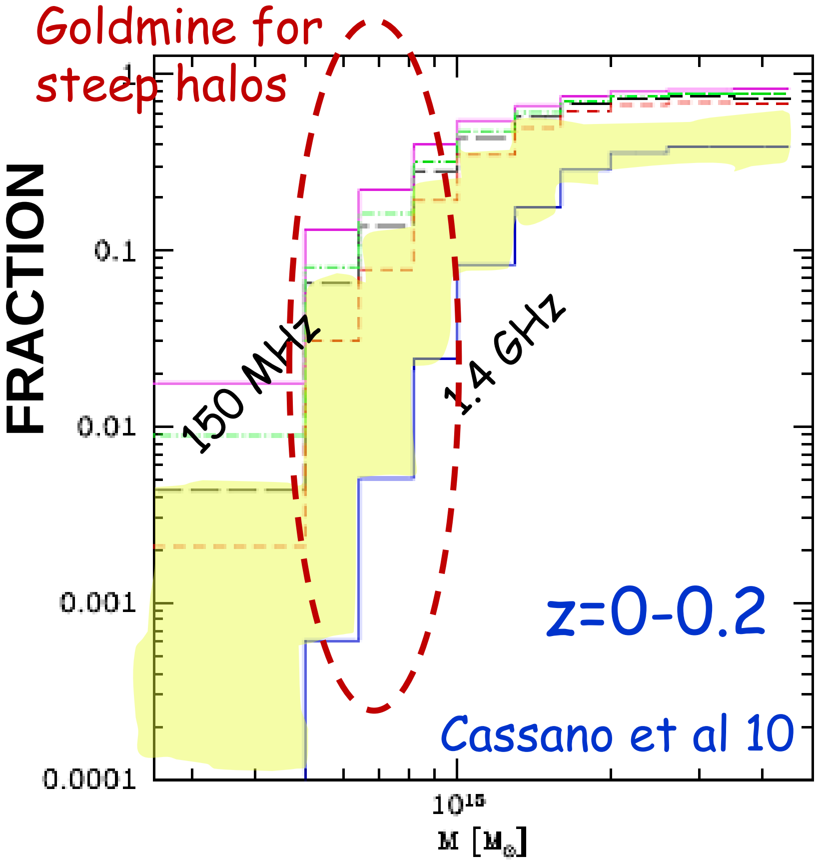


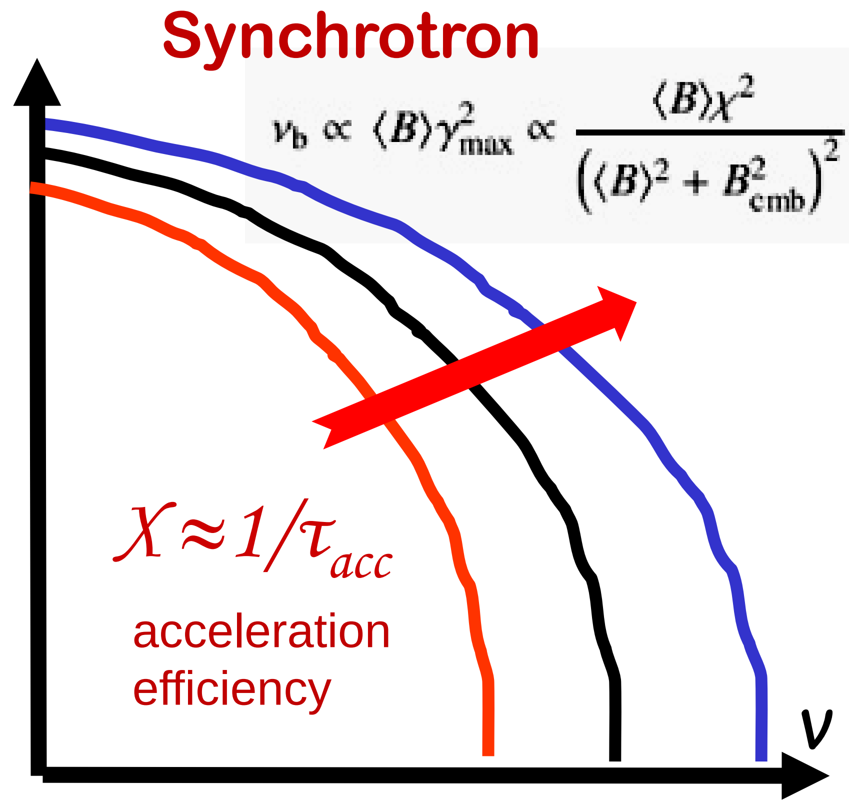


Radio Halos predicted to be a mix of different populations including with very steep spectrum sources "invisible" at high frequencies

(Cassano+ 06, Brunetti+ 08)

Turbulent reacceleration and ultra-steep spectrum halos





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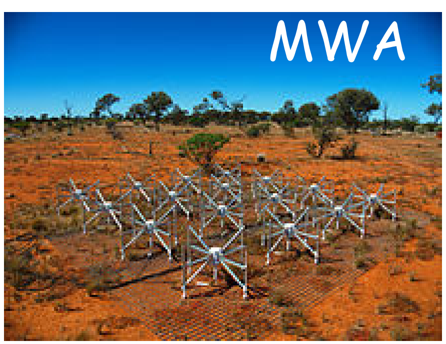
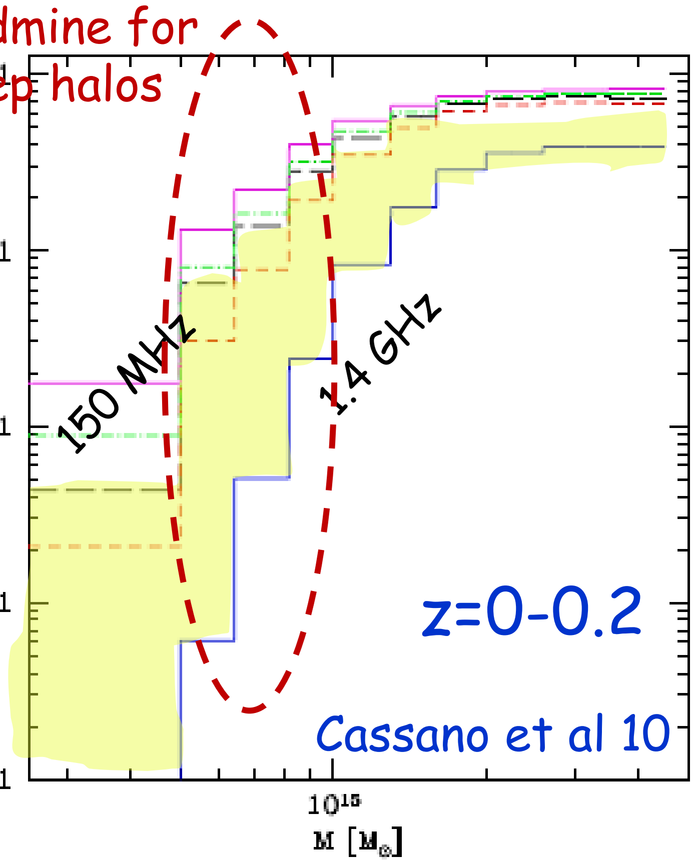
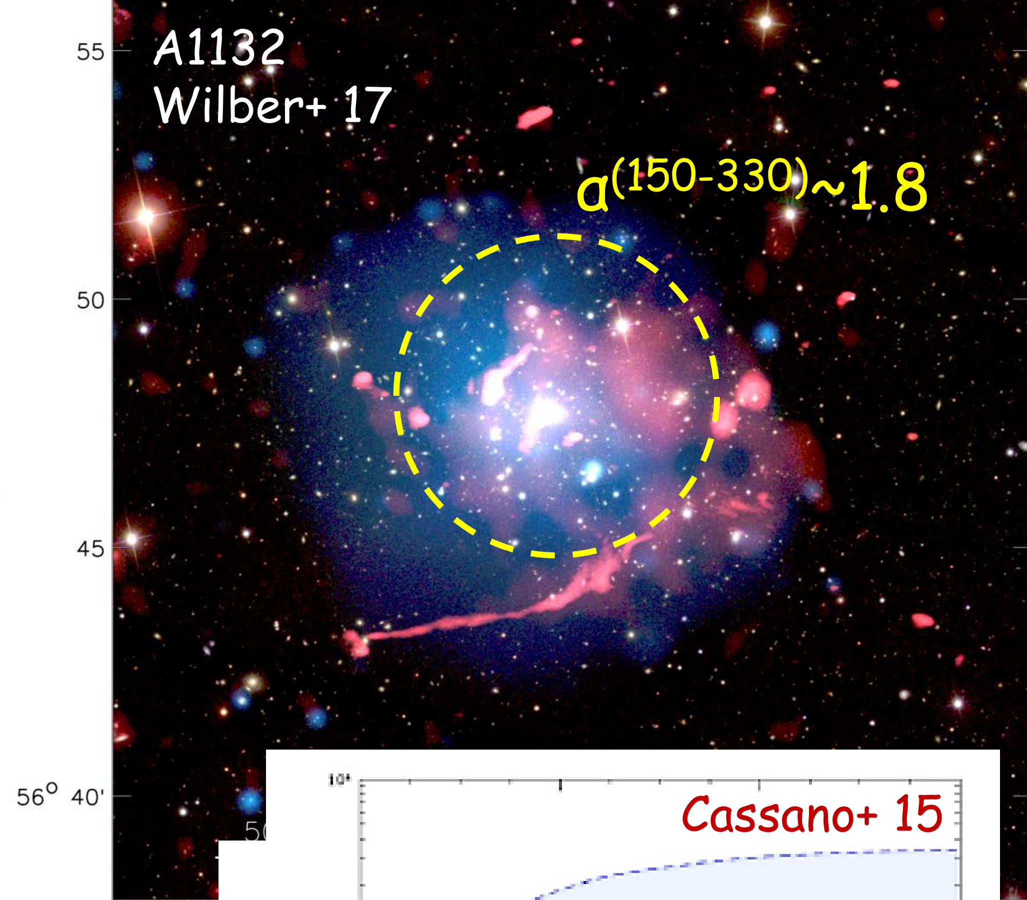
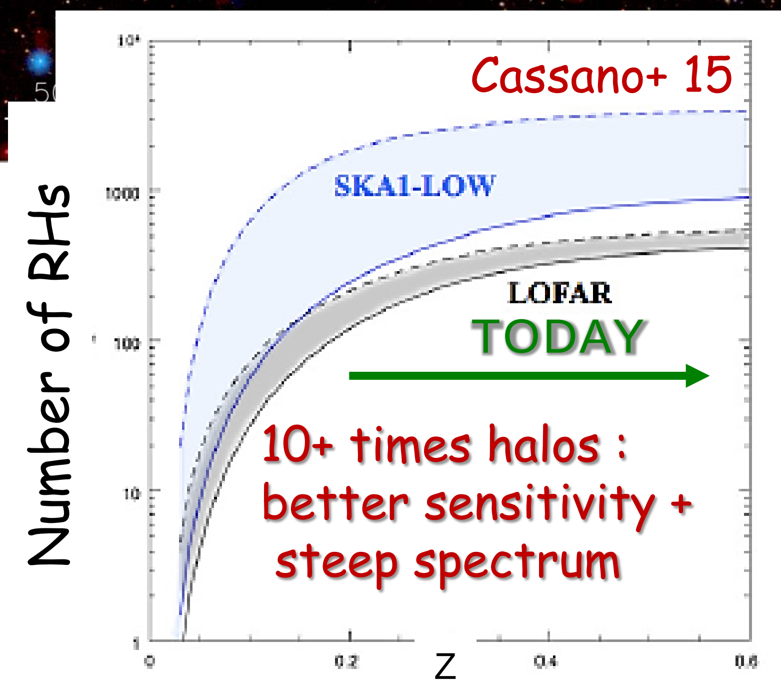


Turbulent reacceleratio
ultra-steep spectrum h



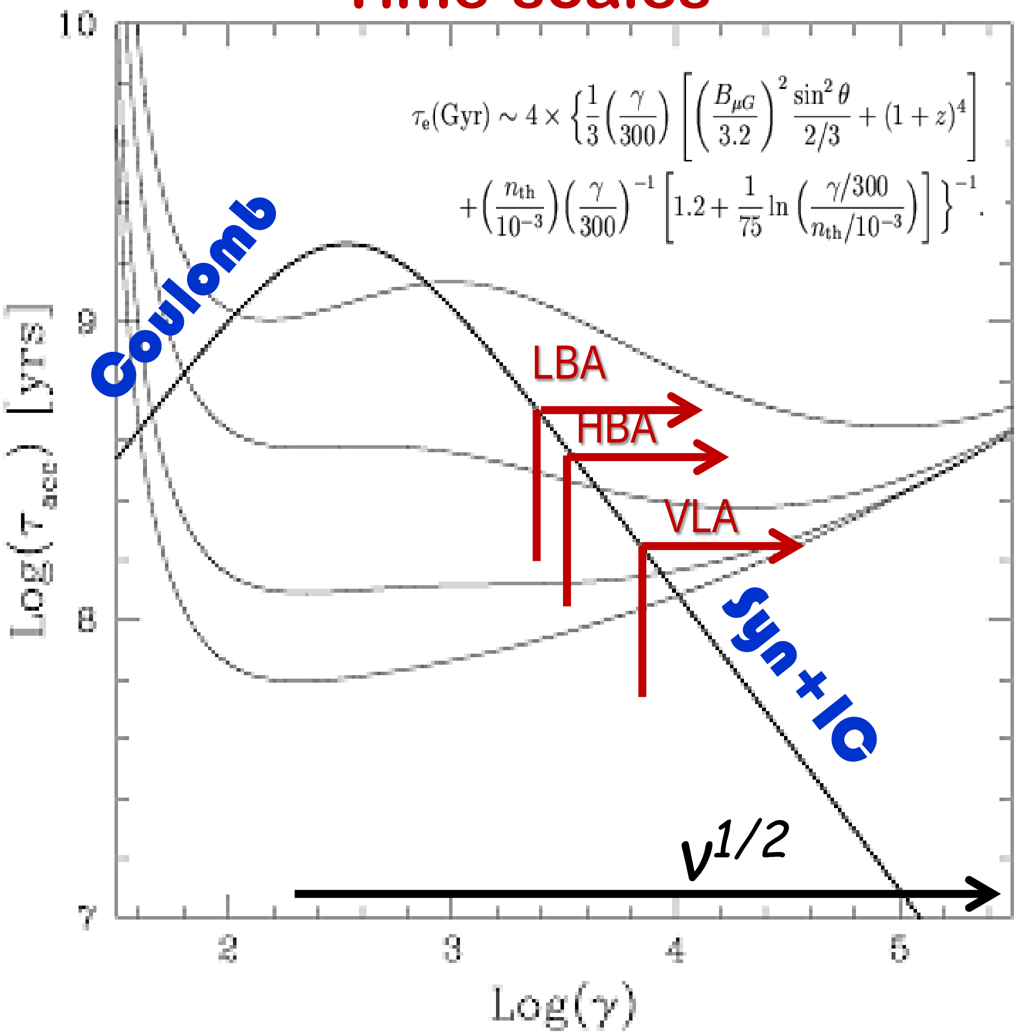




The discovery of a large number of ultra-steep spectrum radio halos is a fundamental task to probe ICM plasma physics : energy goes from Mpc to Mm scales into particle reacceleration !

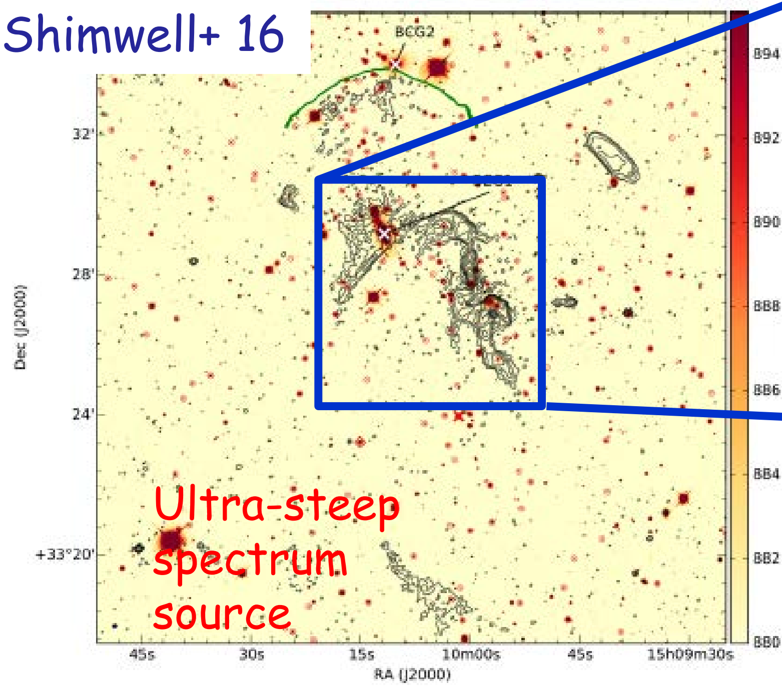
life-cycle of non-thermal plasma in the ICM

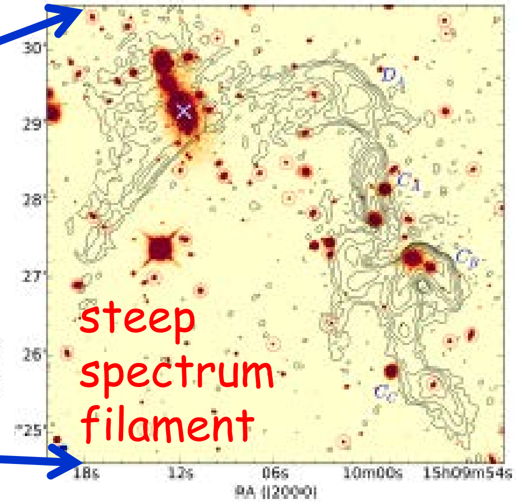
Time-scales



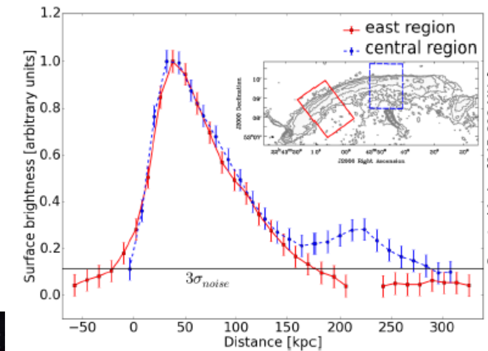
- ❑ Targeting long-living electrons in the ICM
- ❑ Following mixing and dynamics of relativistic plasma on timescales of several x100 Myr
- ❑ If Gentle reacceleration processes operate in the ICM and in RGs they may become visible at very low frequencies generating radio emission in excess of that expected from simple cooling

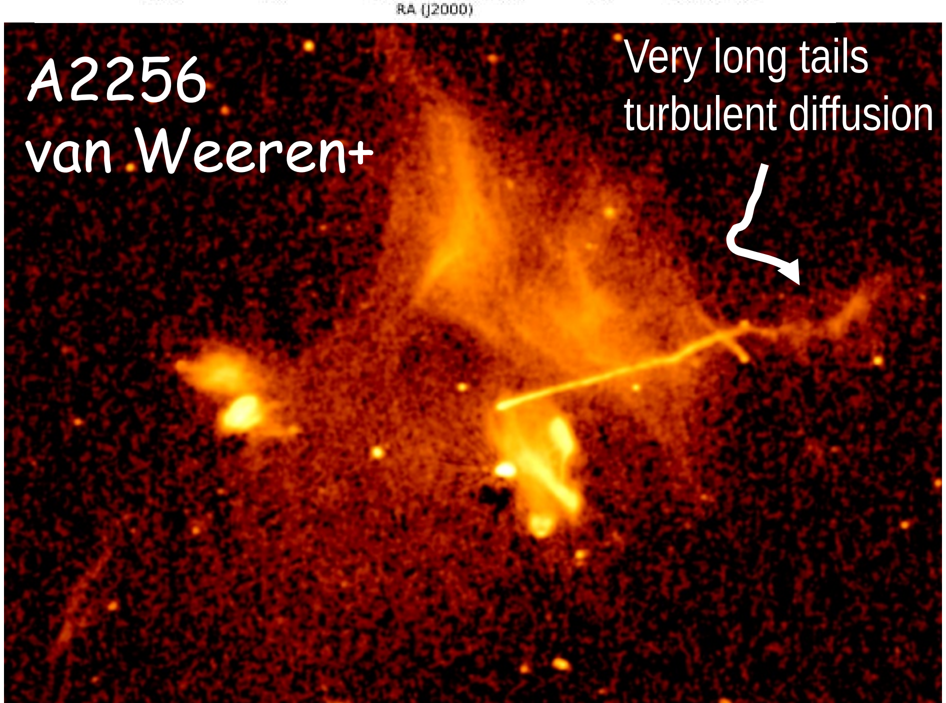
A2034
Shimwell+ 16

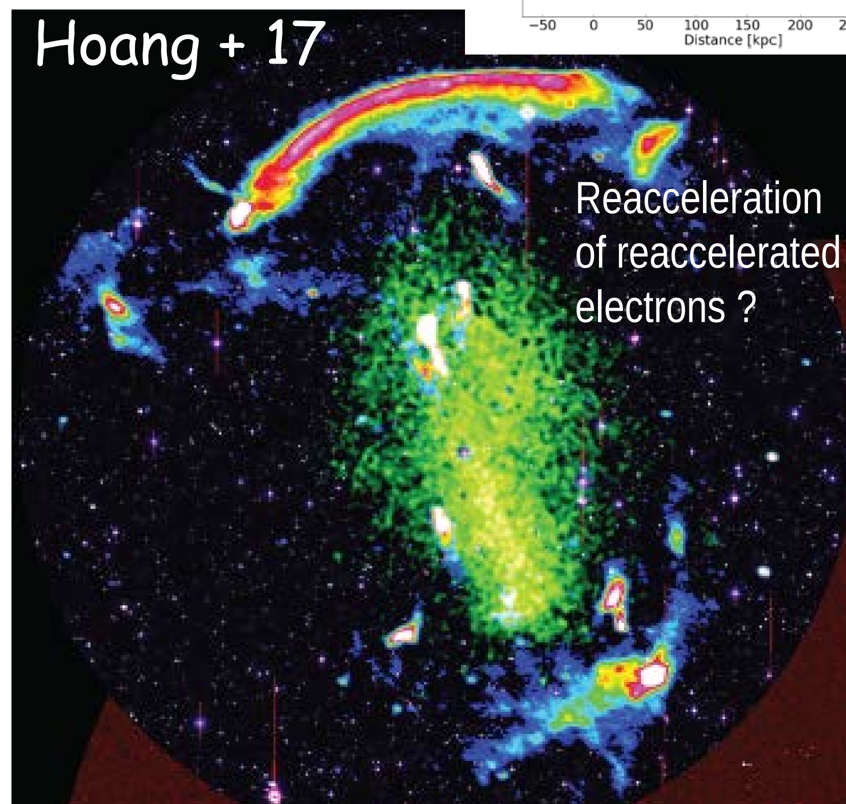




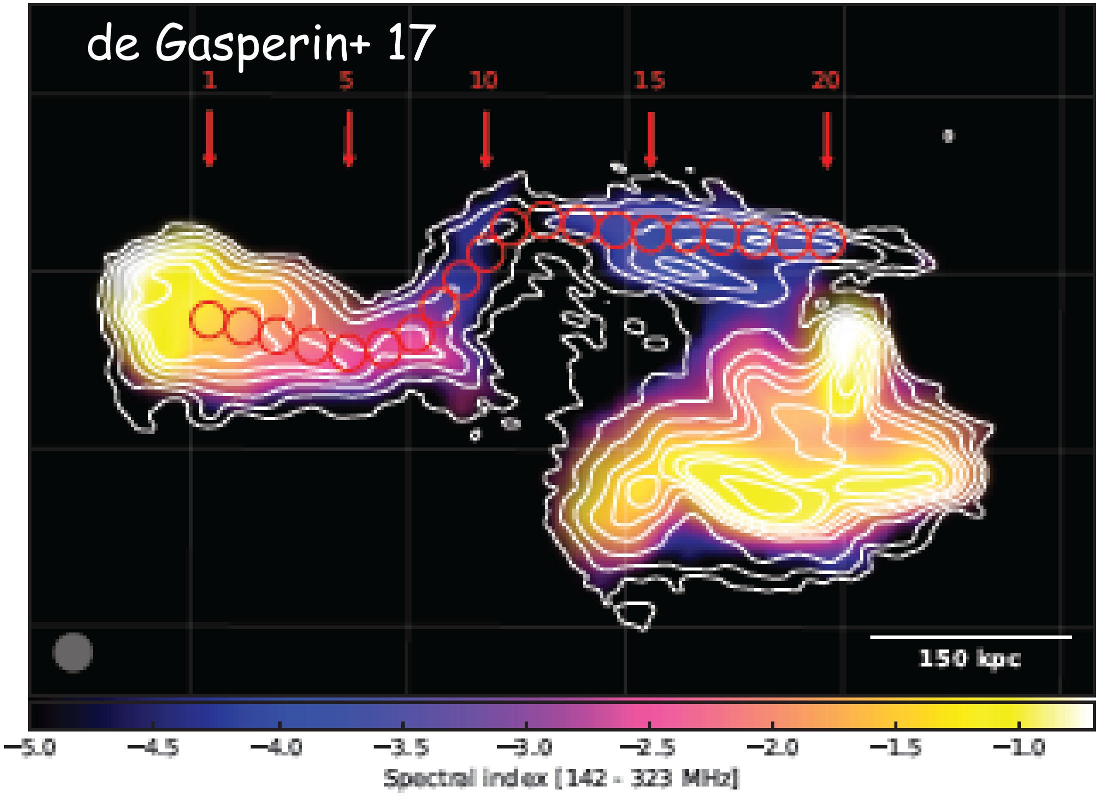
OQ:
how old/steep plasma
can be (still) confined ?
Interaction with very
weak shocks/compression ?

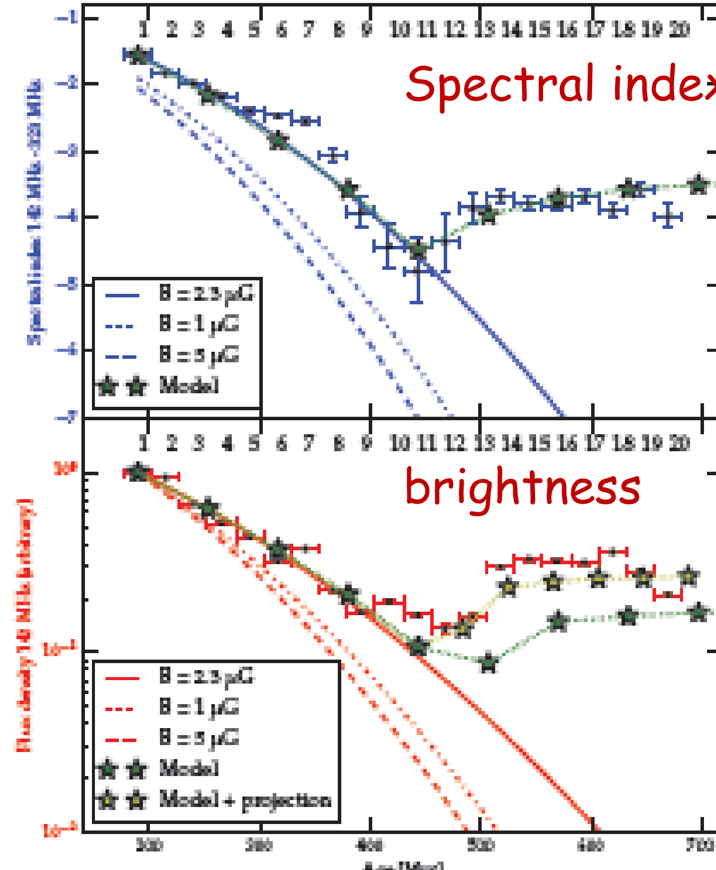






Very gentle acceleration mechanism in RS tails ?





$$\frac{\partial N_e(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[N_e(p,t)\left(\left|\frac{dp}{dt}\right|_r \overbrace{- \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{pp})\right)\right] + \frac{\partial^2}{\partial p^2}\left[D_{pp}N_e(p,t)\right]}^{\text{adding physics}}$$

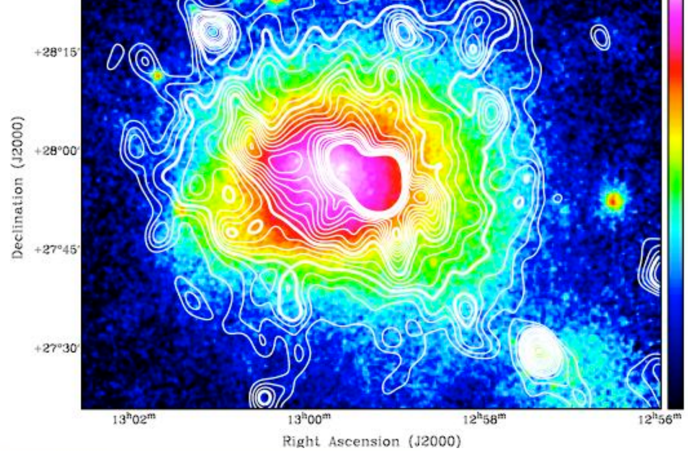
$$\tau_{acc} = p\left(\langle\frac{dp}{dt}\rangle\right)^{-1} = p^3\left(\frac{\partial p^2 D_{pp}}{\partial p}\right)^{-1} \sim 500\text{-}700 \text{ Myr}$$

Take home messages :

- ✓ Galaxy clusters are unique environments for CR acceleration & plasma astrophysics: energy generated on Mpc scales is dissipated on smaller (Mm??) scales into CRs and B .
- ✓ Observed Mpc-scale Syn emission results from several players (**shocks**, **turbulence**, CRp-p, reconnection?) .
  Good reasons to believe that these sources are unique probes of "hidden" & complex mechanisms governing the ICM microphysics.
- ✓ Important advances have been achieved in the last decade.
  Still open questions remain, including details of acceleration mechanisms and of the co-evolution of thermal (dynamics) and nonthermal (Mpc-halos/relics) properties of clusters.
- ✓ Importance of low frequencies (LOFAR, MWA, SKA-low):
  (i) Discovery of numerous ultra-steep spectrum Mpc-scale halos is a test of models and allows fundamental constraints on ICM microphysics
  (ii) Probing/unveiling "gentle" acceleration mechanims in the ICM+RS
  (iii) Life-cycle of non-thermal plasma in the ICM via targeting longer living electrons

OQuestions in turbulent Models

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



❑ Do CRp play a role ?

- Pure hadronic models are ruled out by Fermi-LAT limits

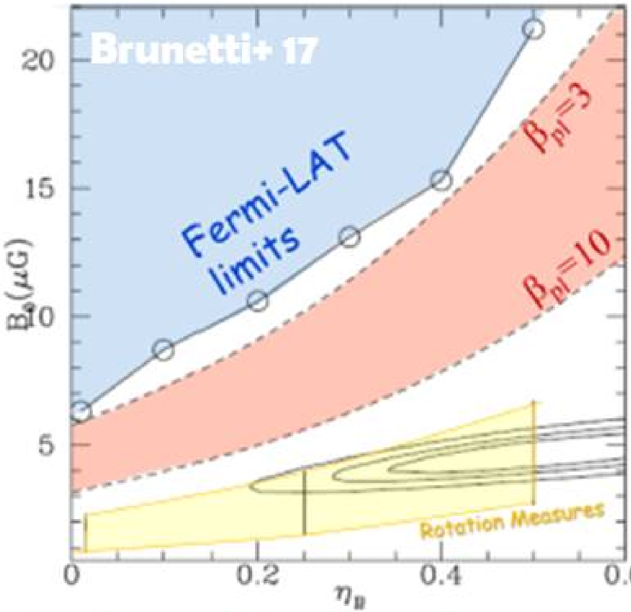
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$

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

Gamma-ray limits + Syn Flux constrain the magnetic field

$$B(r) = B_0 \left(\frac{n_{ICM}(r)}{n_{ICM}(0)} \right)^{\eta_B}$$ (Bonafede+ 10)

- ➢ Radio Halo spectrum
- ➢ Radio Halo brightness distribution

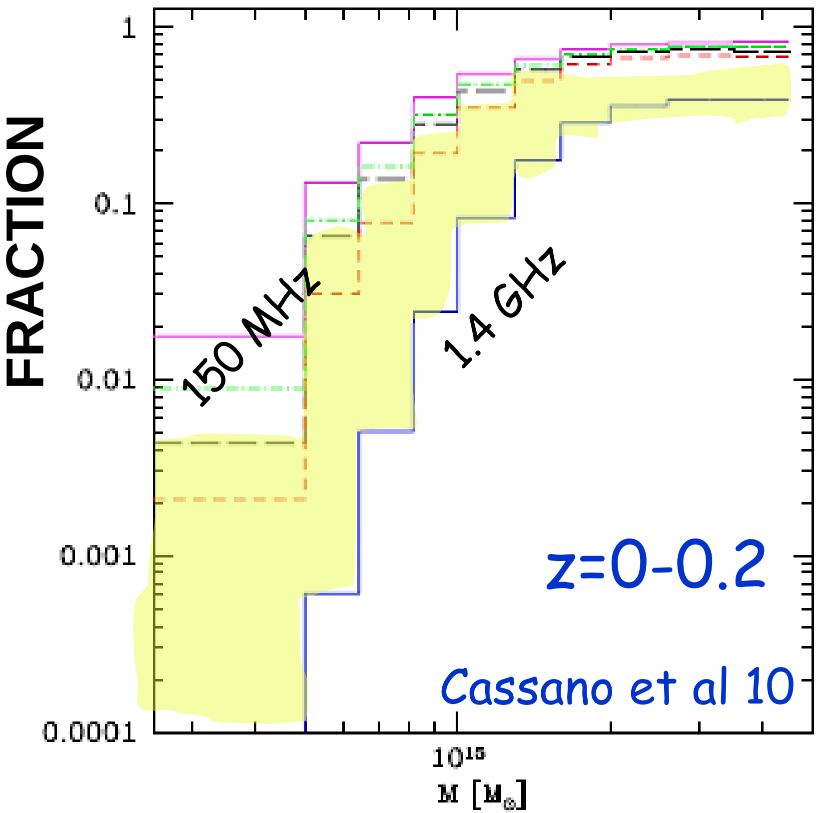


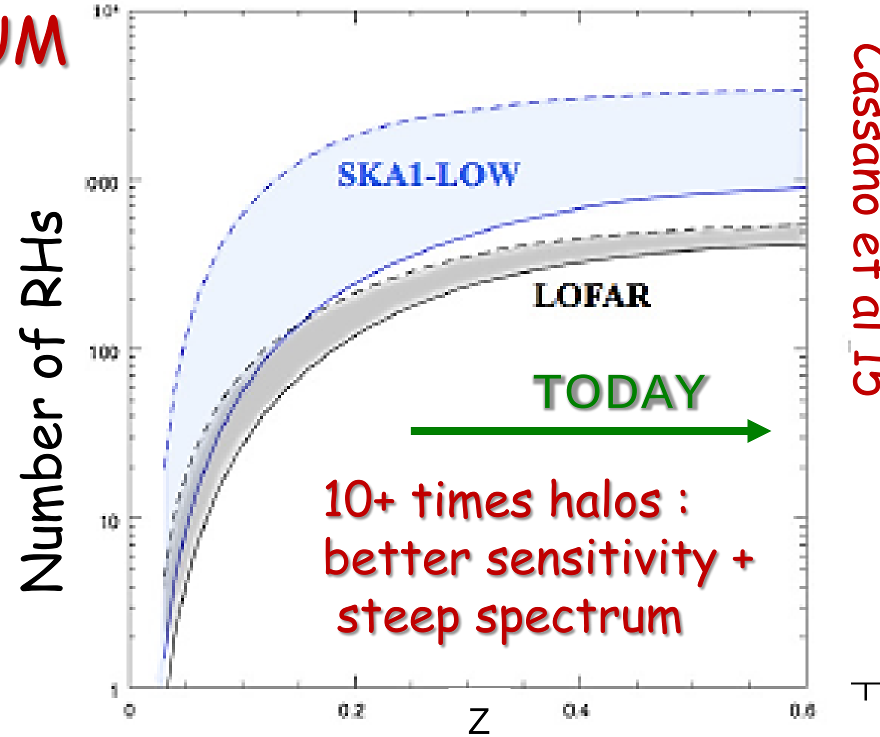
- ➢ B much higher than RM
- ➢ B dynamically important

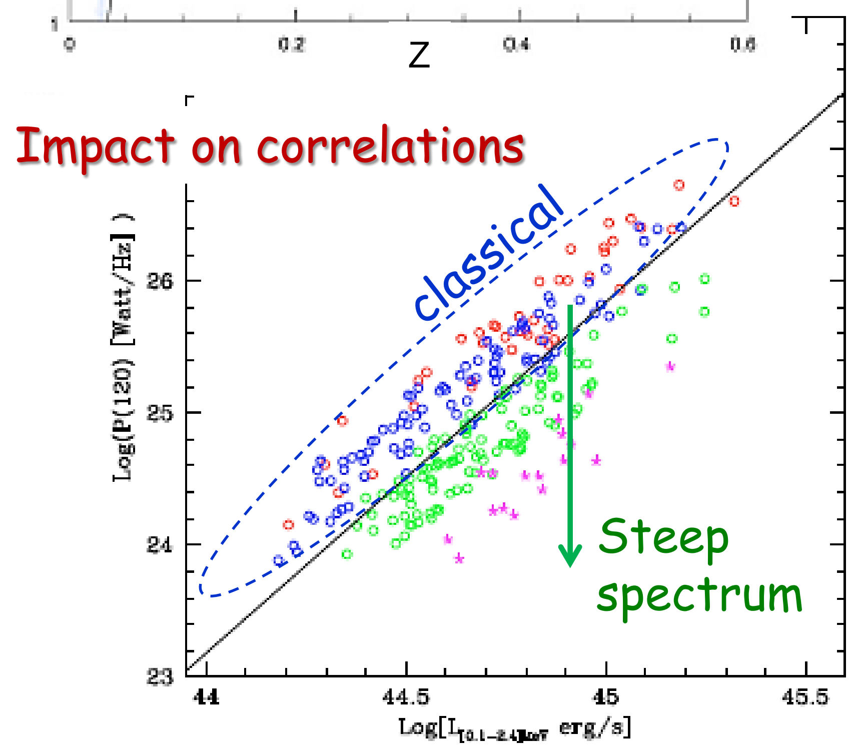
Jeltema+Profumo 11, Brunetti+12, Zandanel+Ando 14, Ackermann+16

Too many CRp are necessary to contribute significantly

HOW MANY STEEP-SPECTRUM HALOS ARE PREDICTED ??

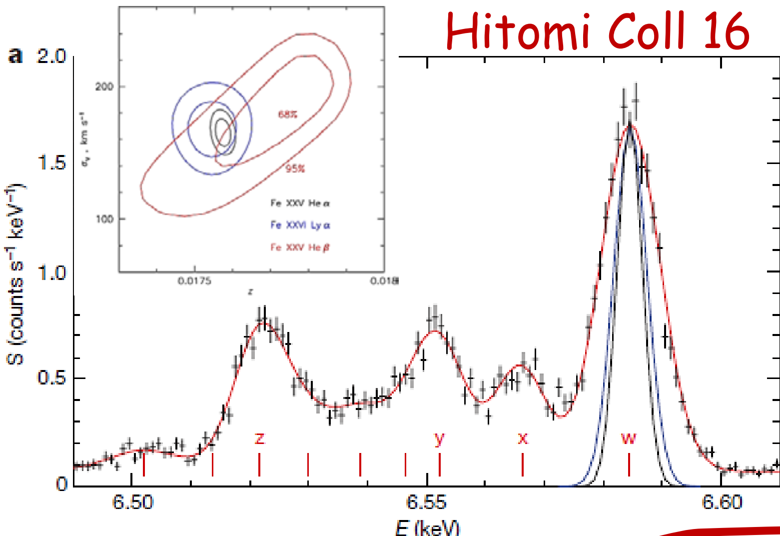




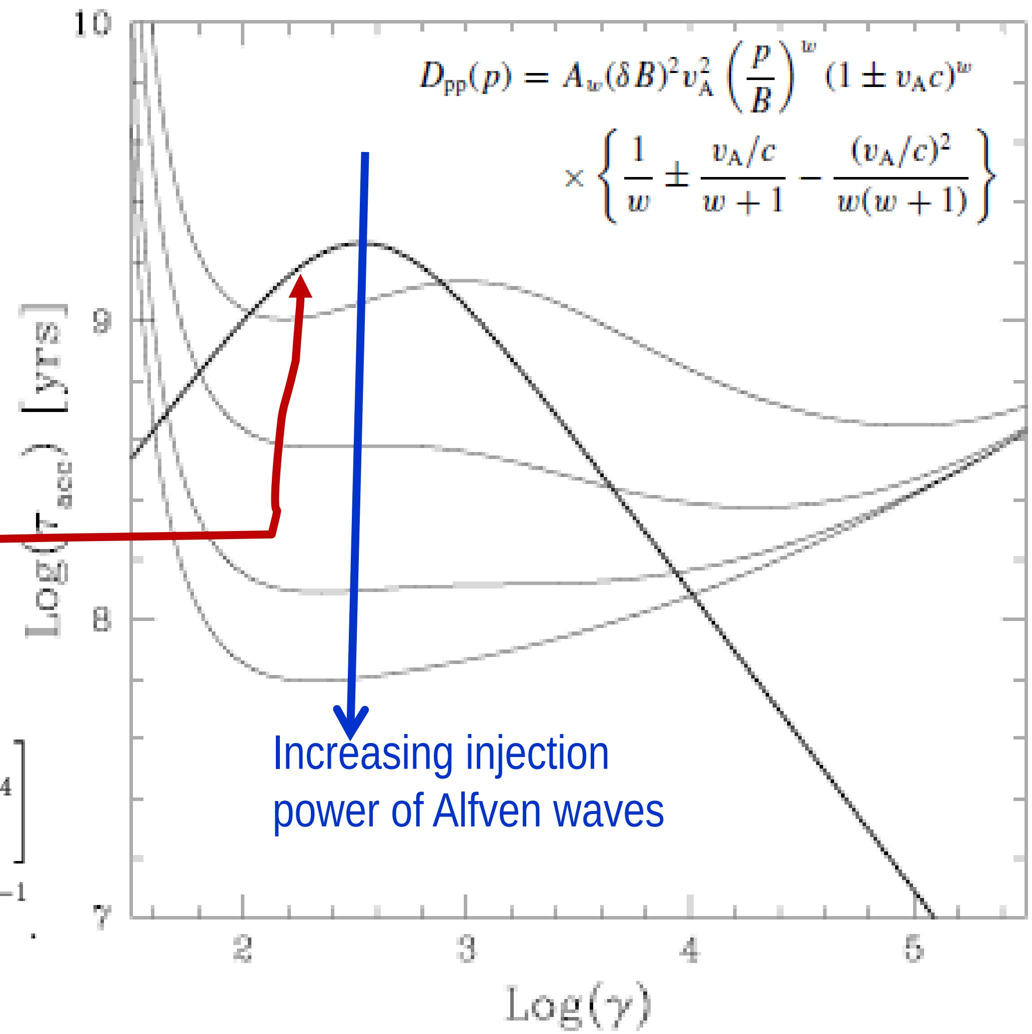


THE QUEST FOR ULTRA-STEEP-SPECTRUM CLUSTER SCALE EMISSION

$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2} \sim 10 - 1000 \text{ Myr}$$



Hitomi Coll 16

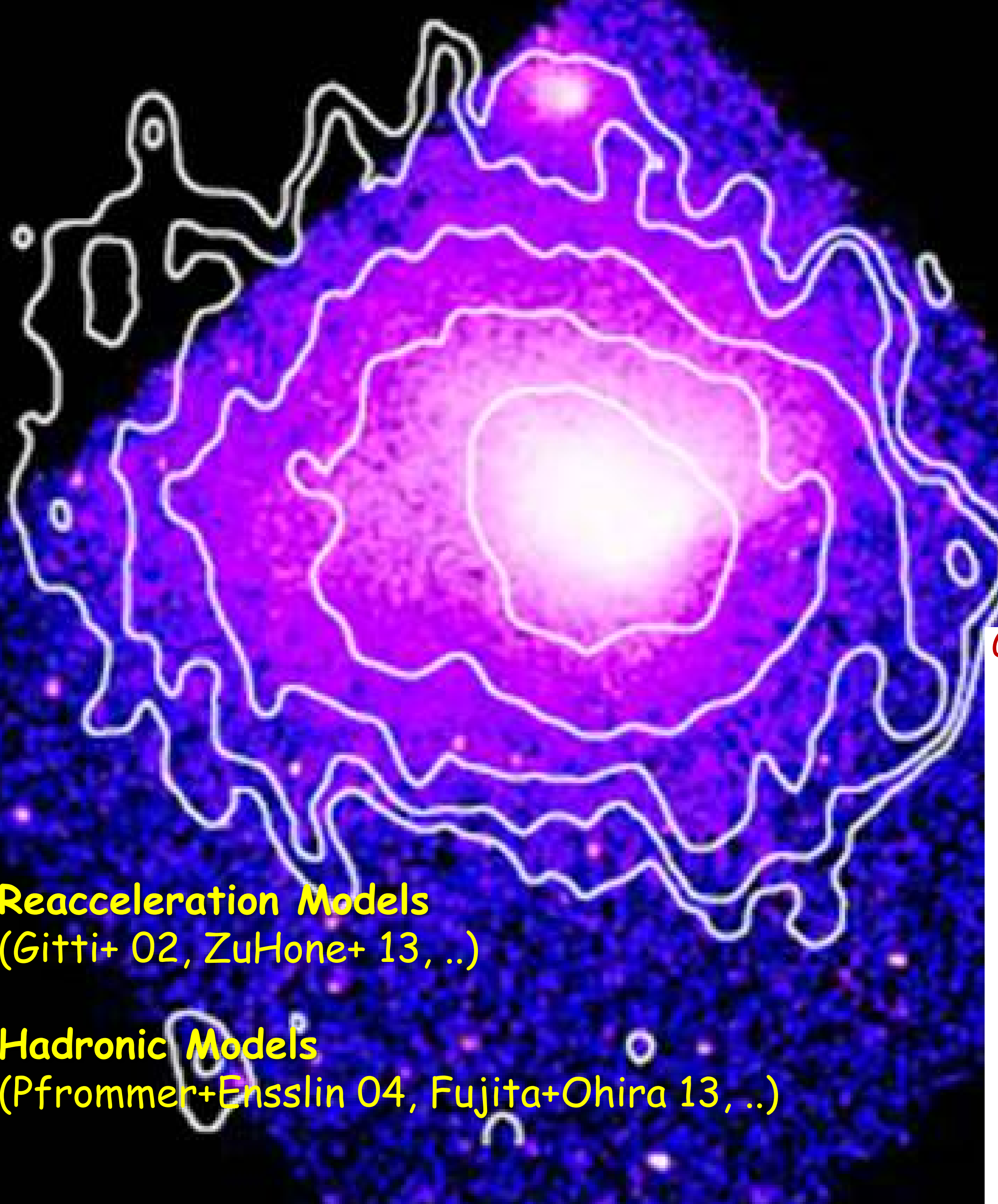


$$D_{\rm pp}(p) = A_w (\delta B)^2 v_{\rm A}^2 \left(\frac{p}{B}\right)^w (1 \pm v_{\rm A} c)^w \times \left\{ \frac{1}{w} \pm \frac{v_{\rm A}/c}{w+1} - \frac{(v_{\rm A}/c)^2}{w(w+1)} \right\}$$

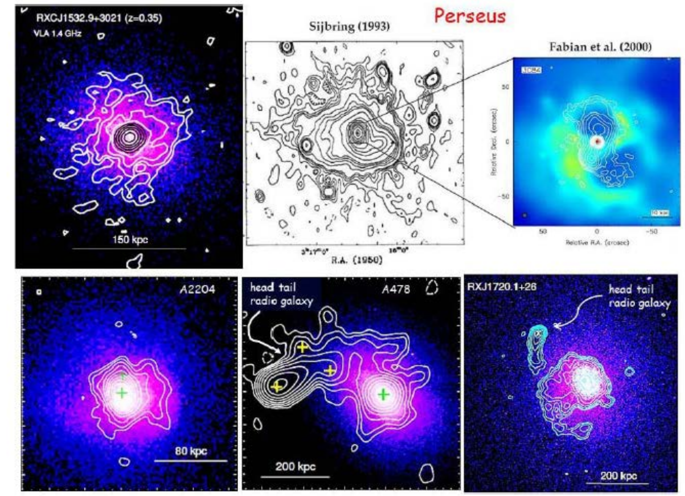
Brunetti et al 04

electrons life-time

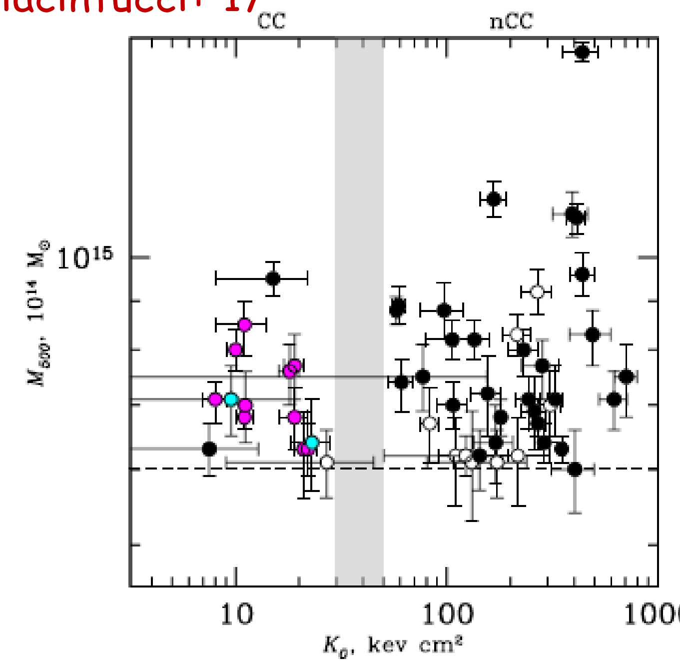
$$\tau_{\rm e}({\rm Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right) \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4 \right] + \left(\frac{n_{\rm th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1} \left[1.2 + \frac{1}{75} \ln\left(\frac{\gamma/300}{n_{\rm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



ORIGIN OF MINI-HALOS ?



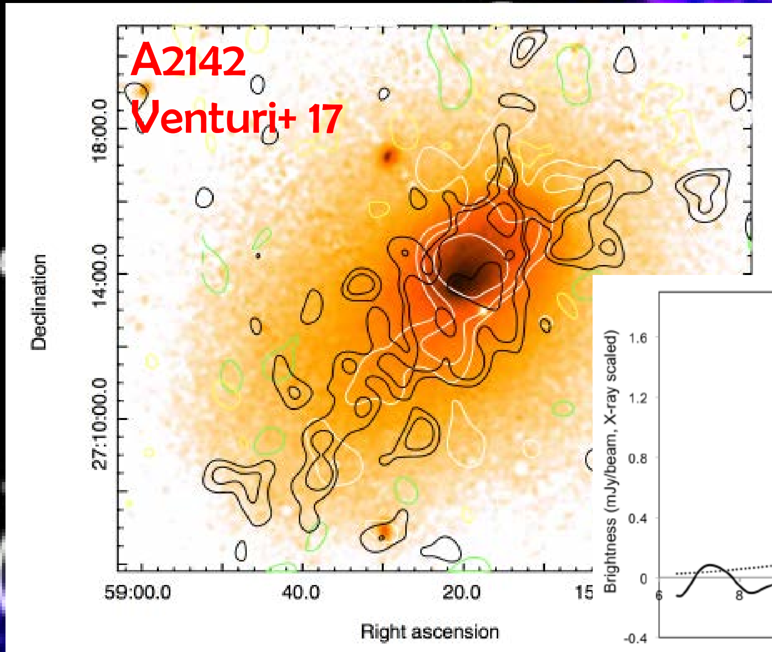
Giacintucci+ 17

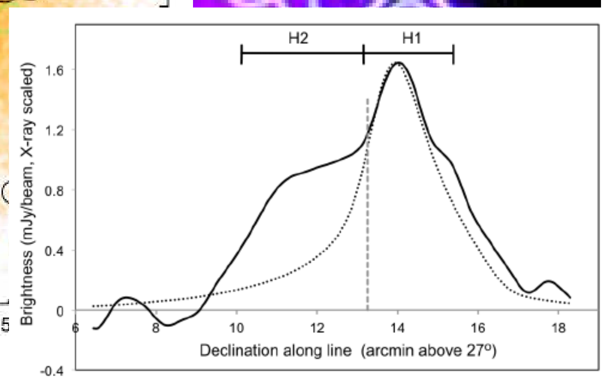


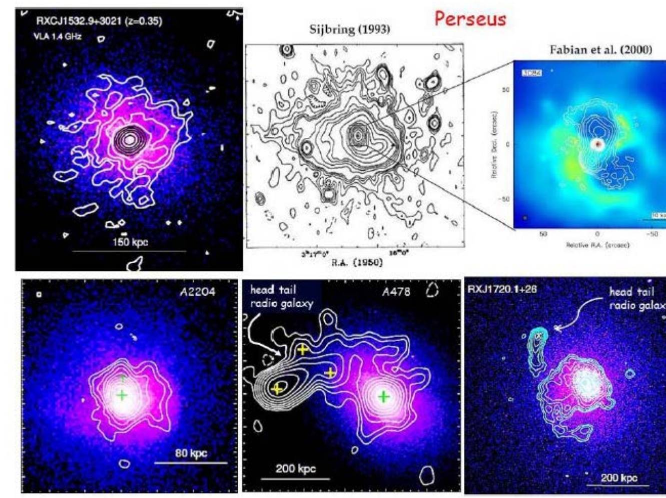
Reacceleration Models
(Gitti+ 02, ZuHone+ 13, ..)

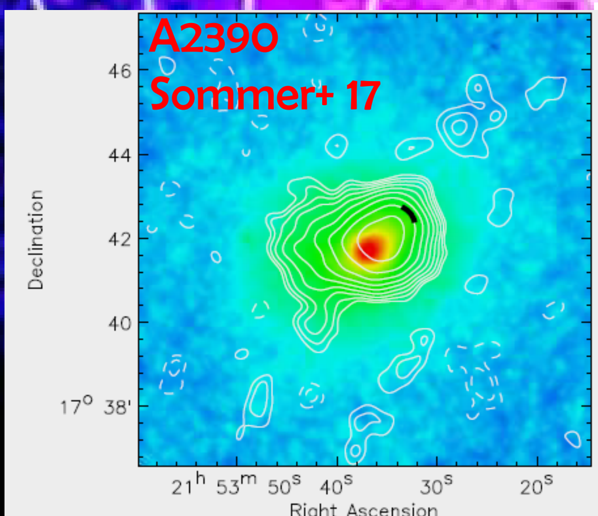
Hadronic Models
(Pfrommer+Ensslin 04, Fujita+Ohira 13, ..)

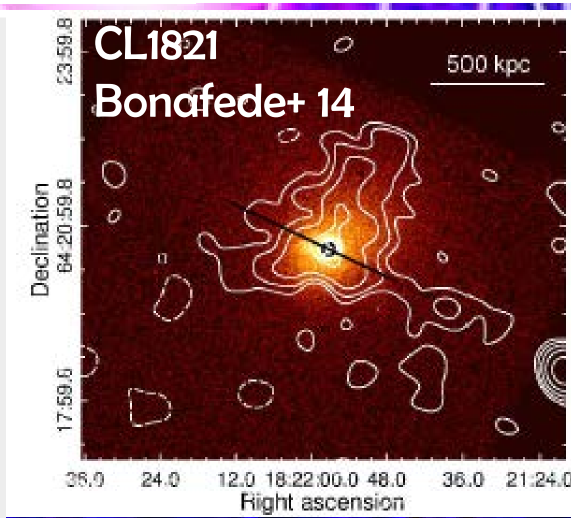
CONNECTION WITH Giant-HALOS ?



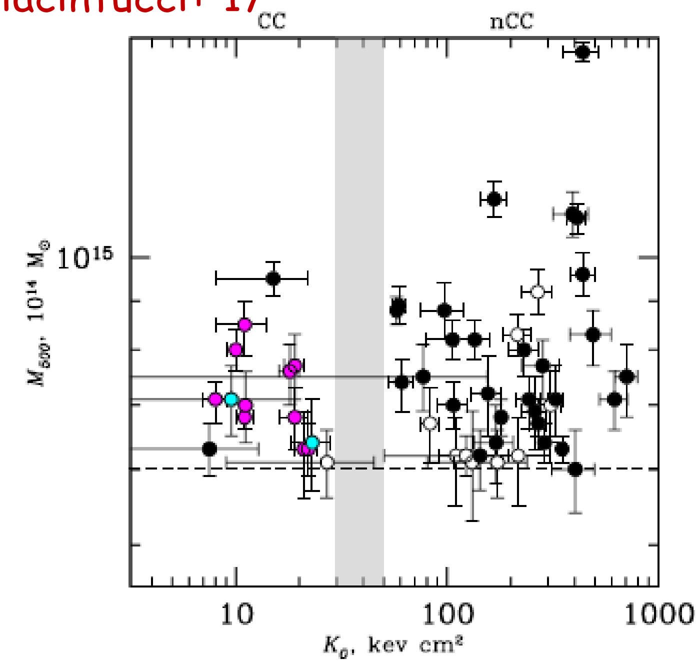








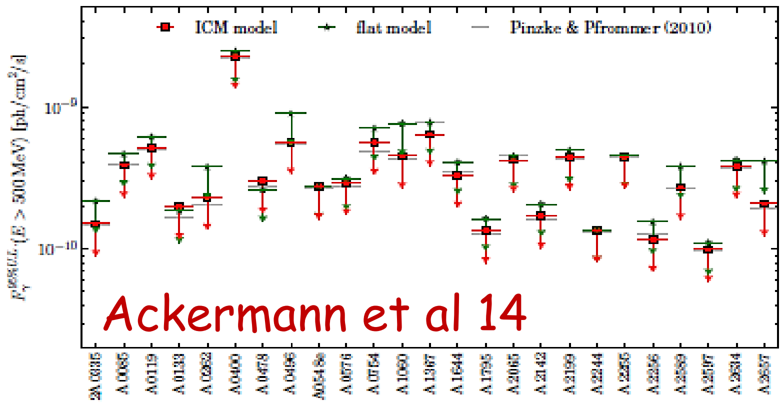
Giacintucci+ 17

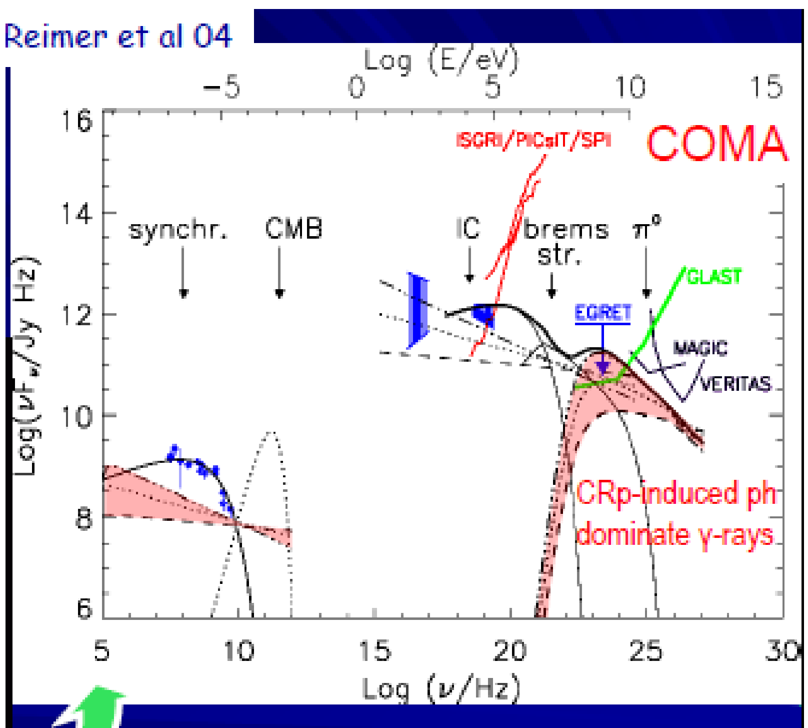


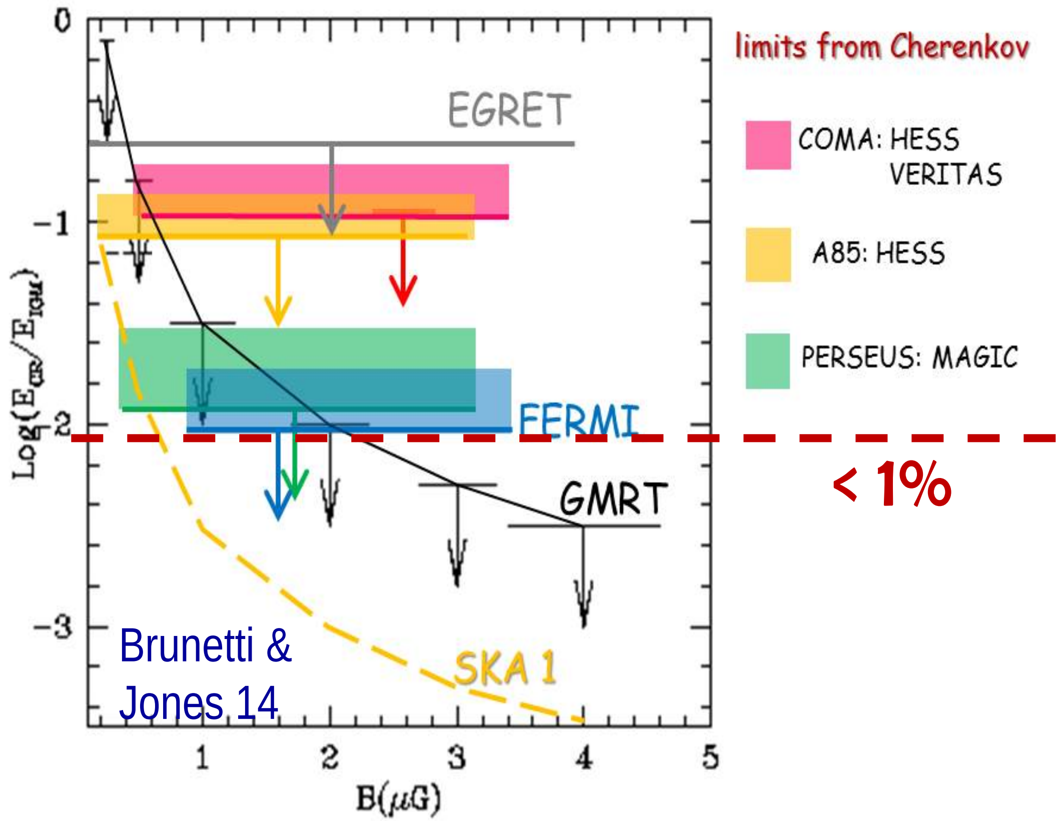
Role of CR dynamics ? Evolutionary stage ?
(Ensslin+ 11, Brunetti+Jones 14, Zandanel+ 14, ..)

No gamma-rays : Where are the CRp ?
Limits to their energy budget

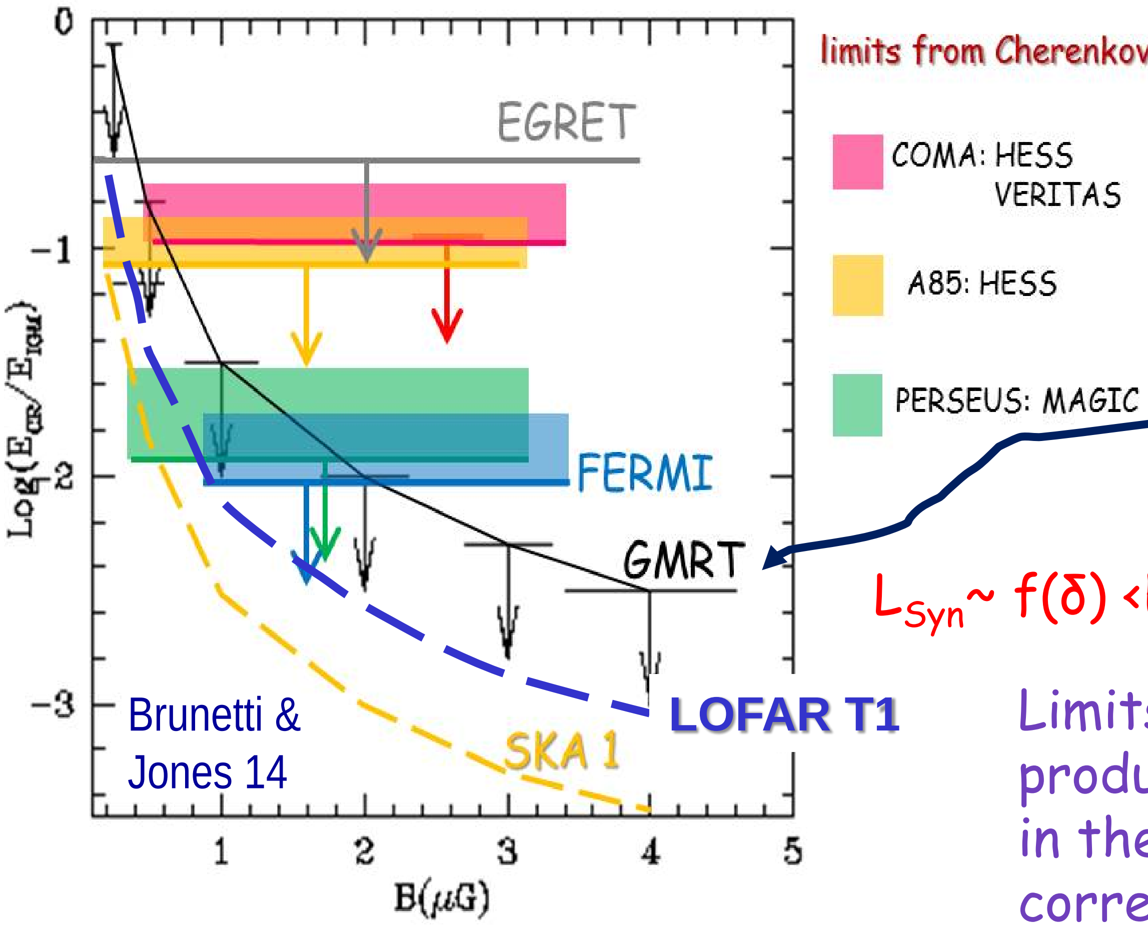
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$
$$\pi^0 \rightarrow \gamma\gamma$$
$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$



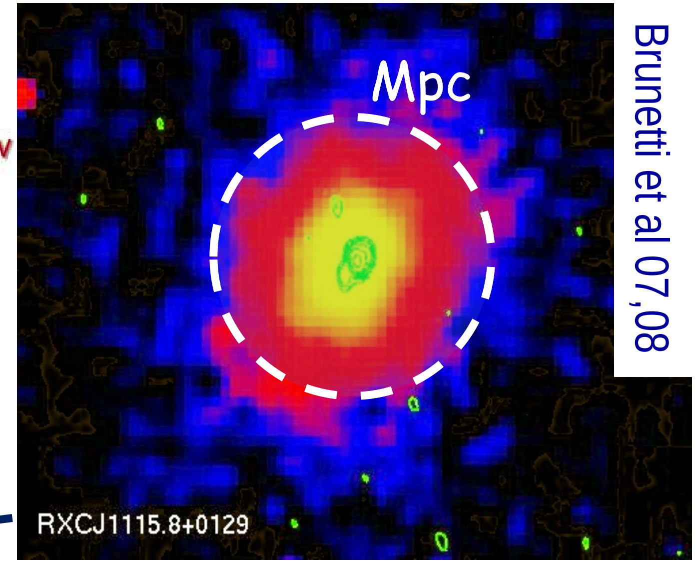




Where are the CRp ?
Limits to their energy budget



Syn radio limits :



Brunetti et al 07,08

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

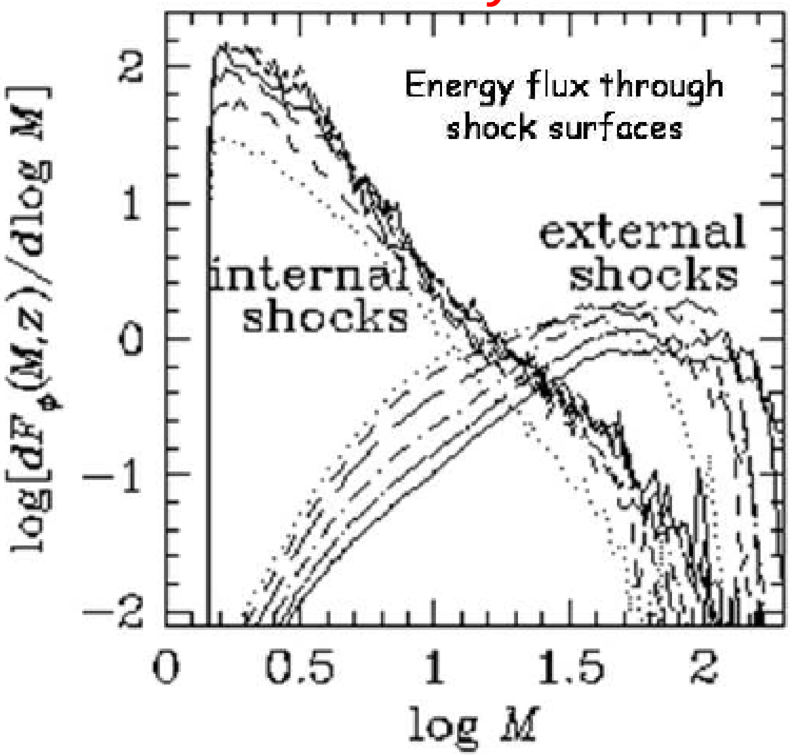
Limits on the synchrotron flux produced by secondary electrons in the ICM allow to calculate corresponding limits on (B, ECRp).

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, …

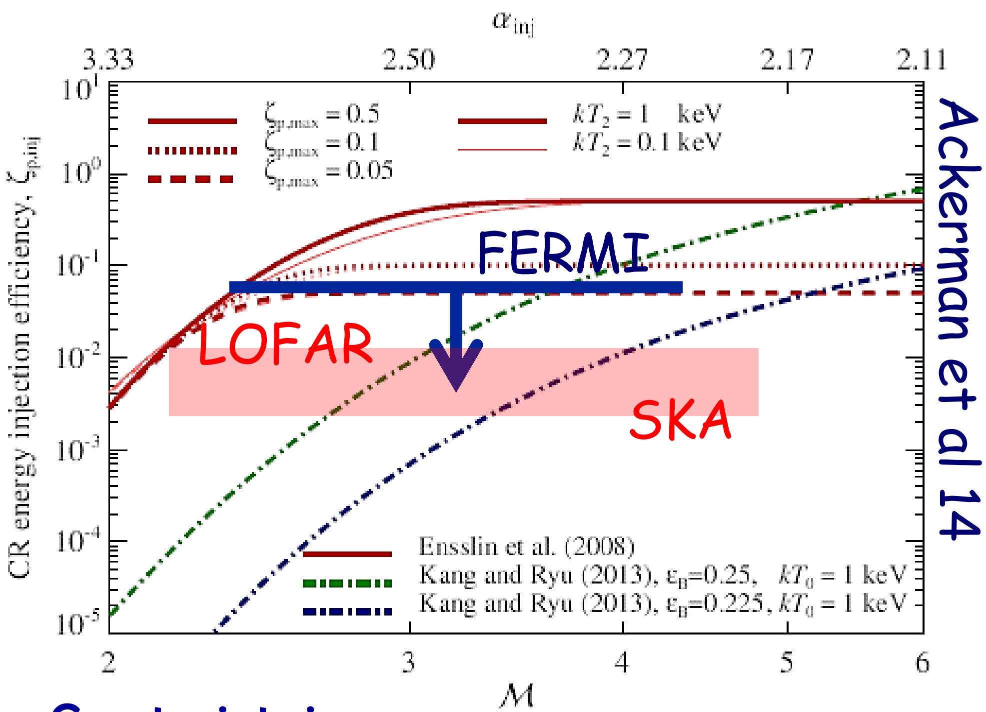
Constraining CRp acc efficiency +dynamics

Acceleration efficiency + confinemnet set the level of energy accumulated in CRp

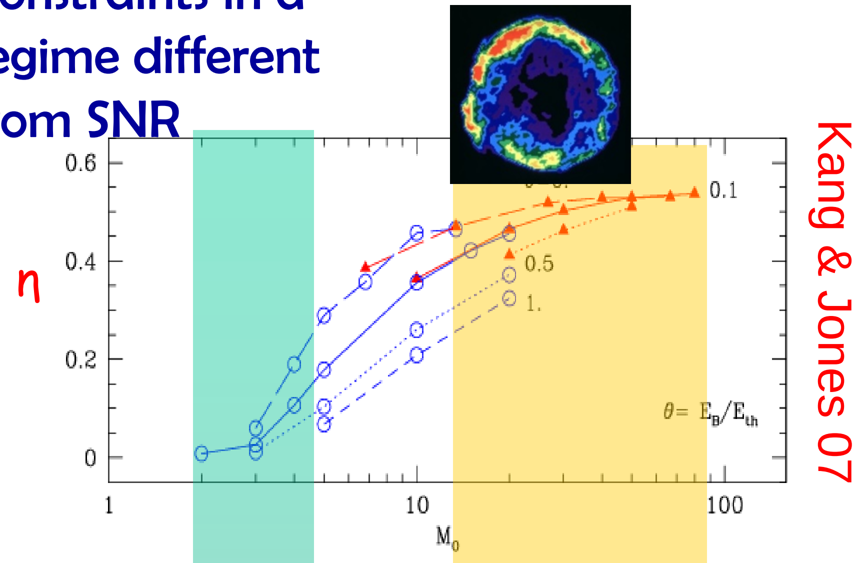
Ryu et al 03



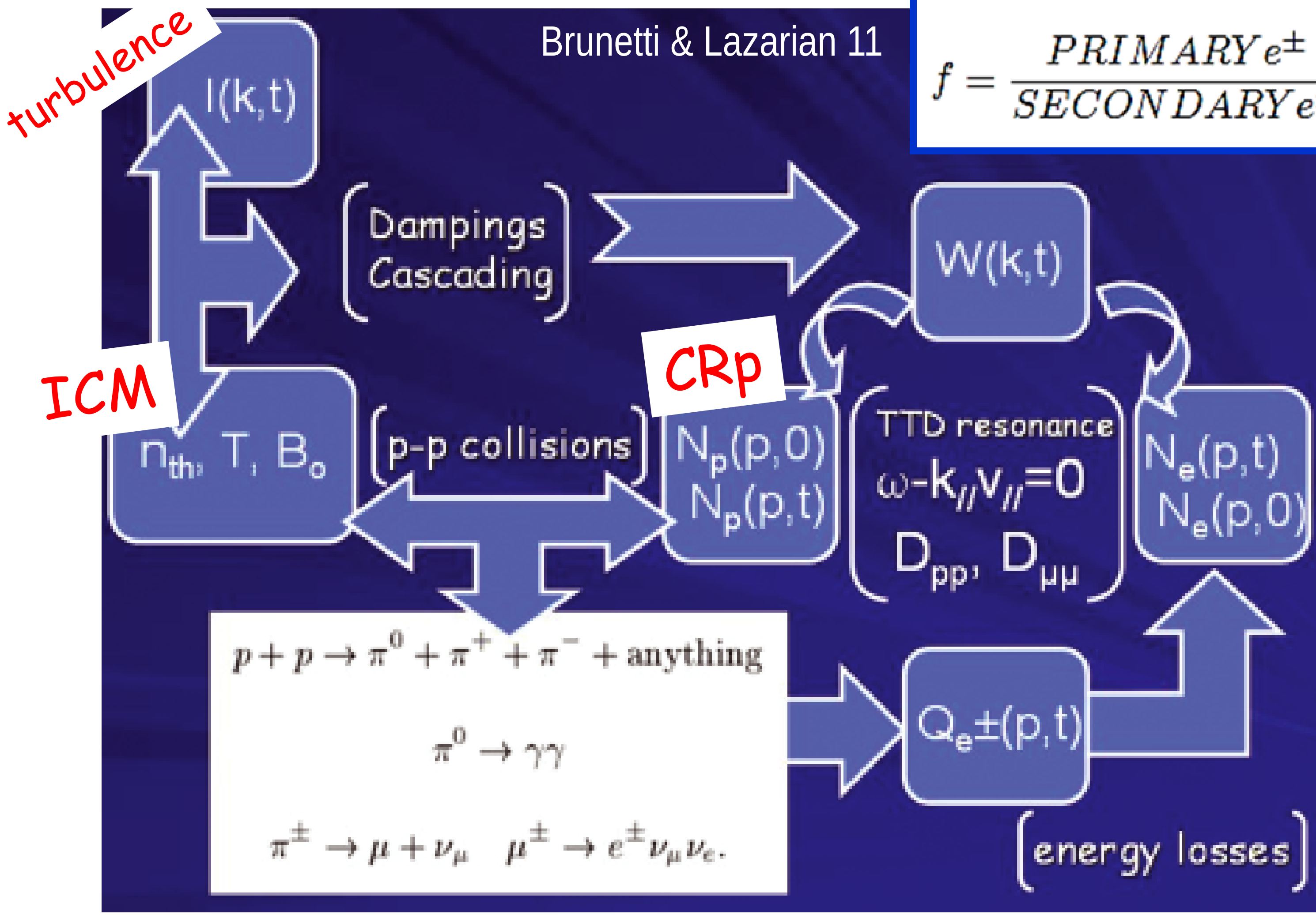
The bulk of ICM heating is due to shocks, so current limits imply an efficiency of CRp acceleration at shocks << 0.1.



Constraints in a regime different from SNR

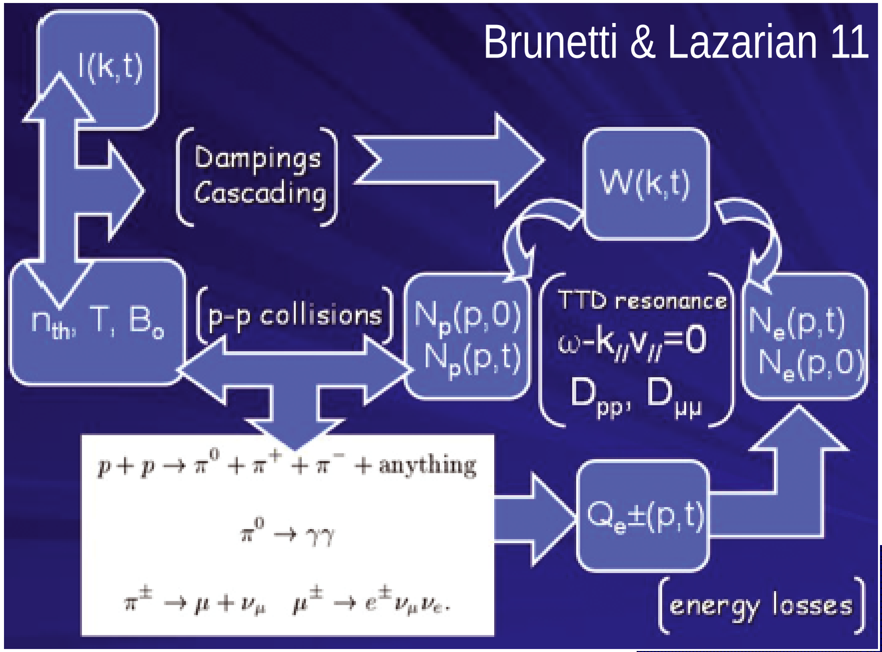


Can CRp play a role in reacceleration models ?
- Reacceleration of CRp & secondaries -



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

Reacceleration of CRp & secondaries



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

Q_e: secondaries from CRp-p collisions

Electrons/Positrons

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

losses + sys acceleration   p-diffusion

Protons

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

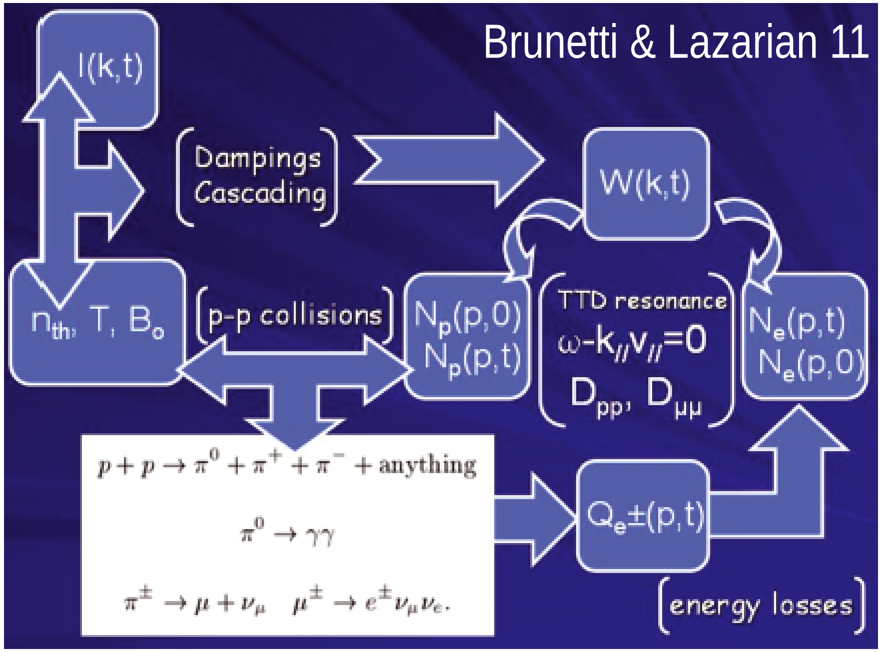
losses + sys acceleration   p-diffusion   injection

Turb. Modes

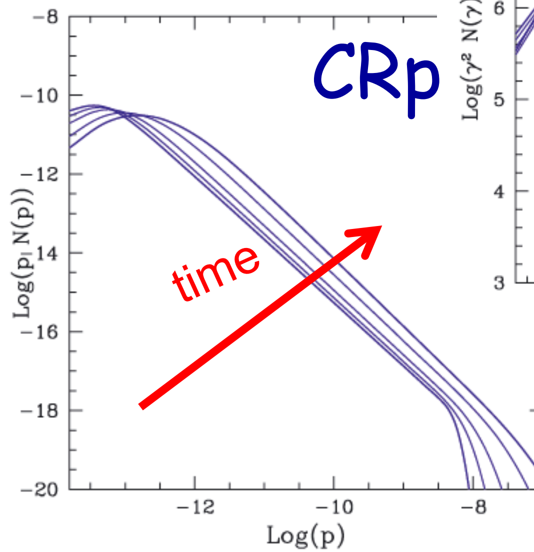
$$\frac{\partial \mathcal{W}(k,t)}{\partial t} = \frac{\partial}{\partial k}\left(k^2 D_{kk}\frac{\partial}{\partial k}\left(\frac{\mathcal{W}(k,t)}{k^2}\right)\right) - \sum_i \Gamma_i(k,t)\mathcal{W}(k,t) + I(k,t)$$

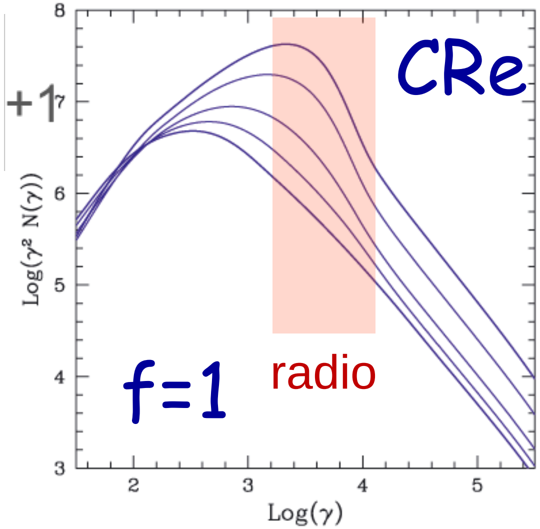
mode coupling   collisionless dampings   injection

Reacceleration of CRp & secondaries



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





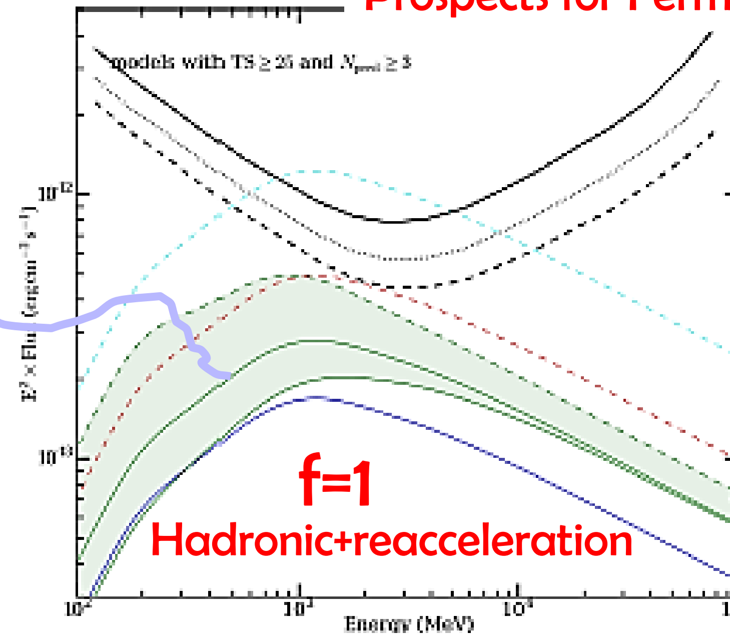
- ❑ The Syn/gamma ratio is much higher
- ❑ Less CRp are necessary to generate the observed radio emission

Weaker magnetic field are constrained by current gamma-ray limits

Relativistic protons in the Coma galaxy cluster: first gamma-ray constraints ever on turbulent reacceleration

G. Brunetti,[1*] S. Zimmer,[2†] F. Zandanel,[3‡]
[1] INAF-IRA, Via Gobetti 101, I-40129 Bologna, Italy
[2] DPNC, University of Geneva, 24 Quai Ernest-Ansermet, CH-1211 Geneva,
[3] GRAPPA, University of Amsterdam, Science Park 904, 1098XH, Amsterda

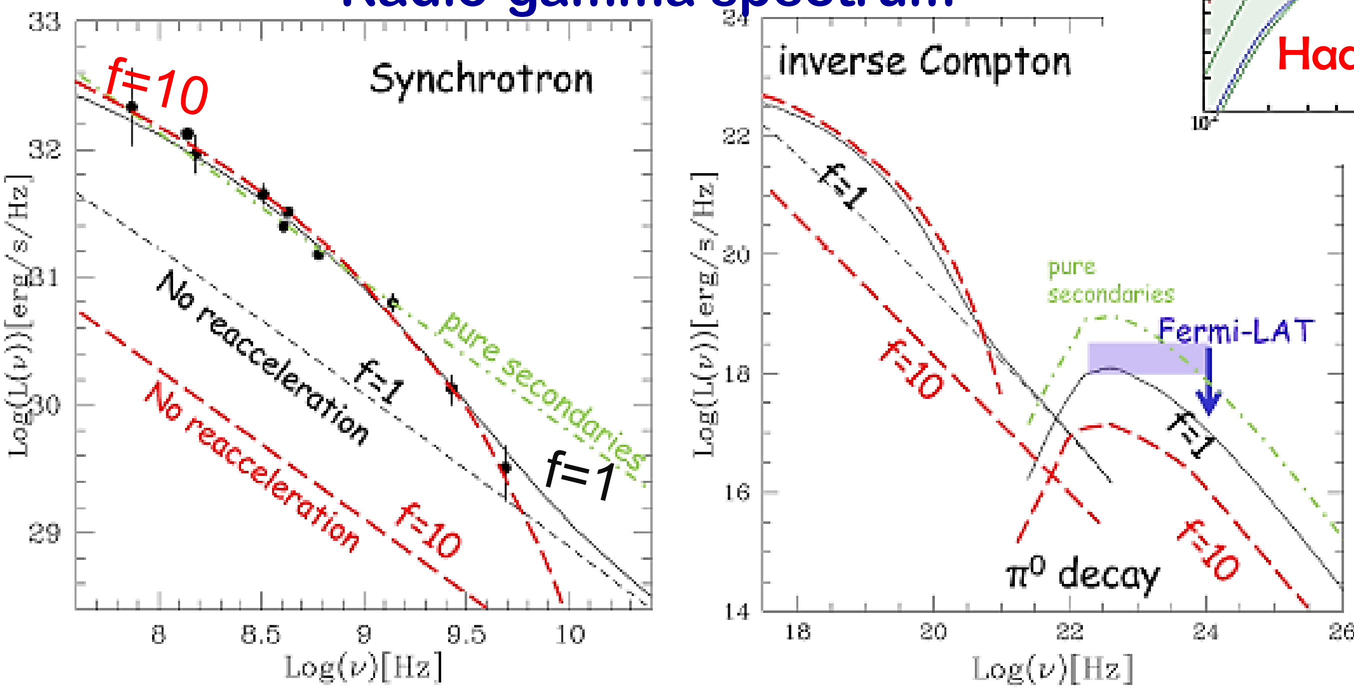
Prospects for Fermi



Models with
B consistent
with Faraday RM

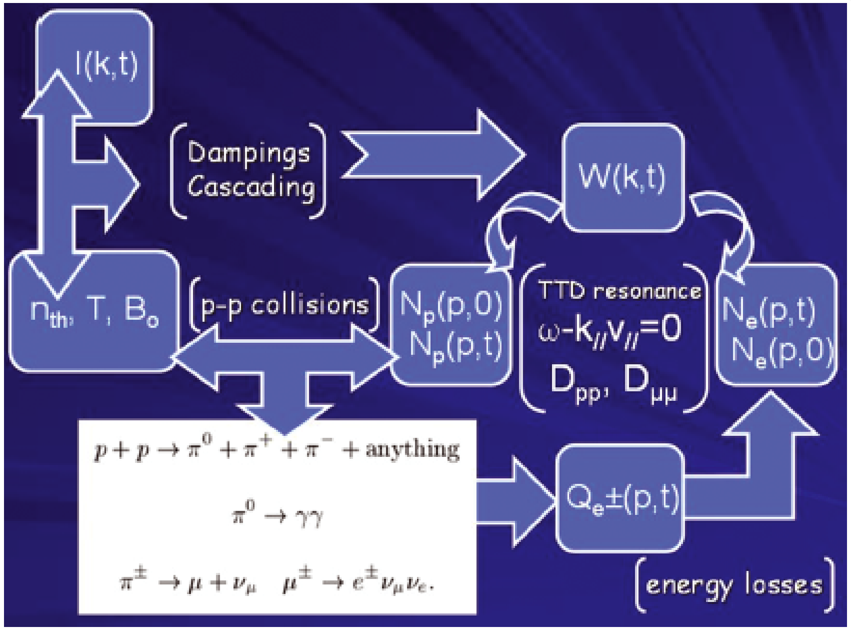
$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

Radio-gamma spectrum



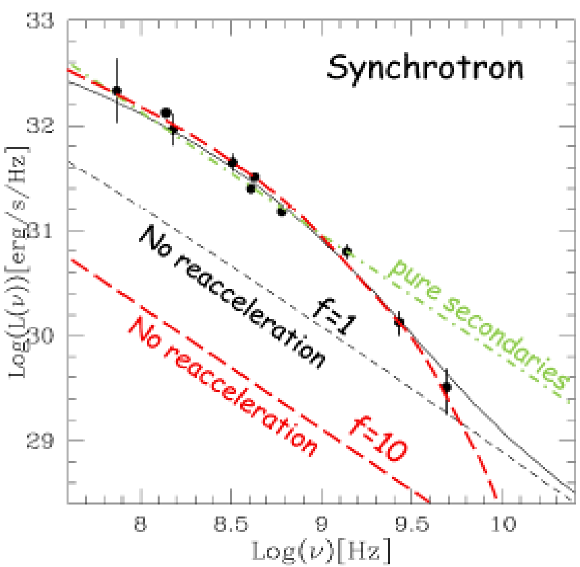
A signal at 3σ level can be detected in 15 yrs of observations if CRp play a role

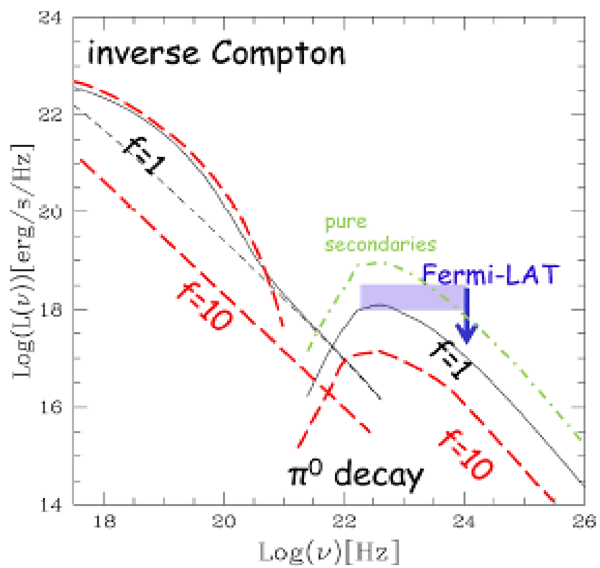
Reacceleration of CRp & secondaries



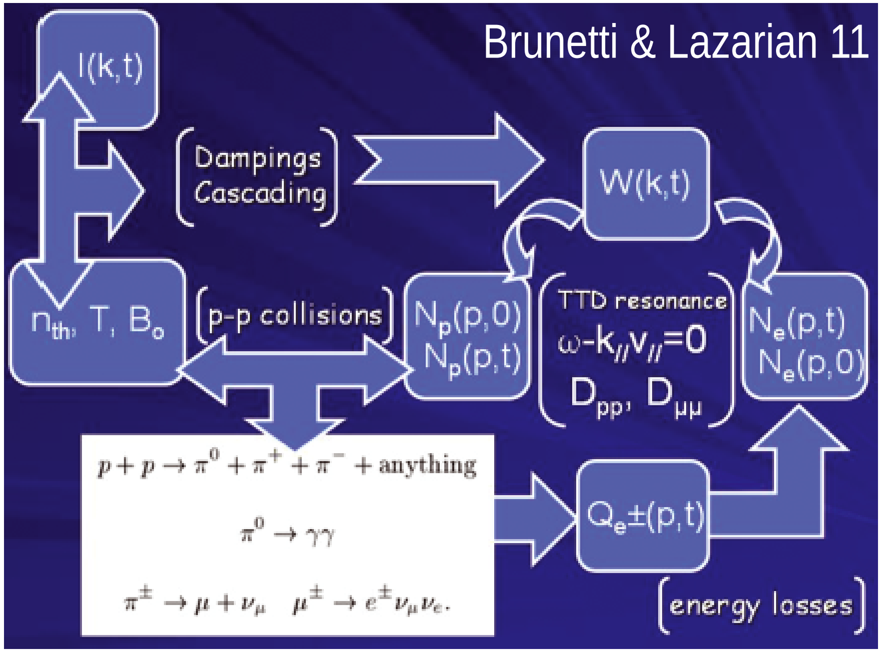
$$f = \frac{PRIMARY\,e^{\pm}}{SECONDARY\,e^{\pm}} + 1$$

CRp

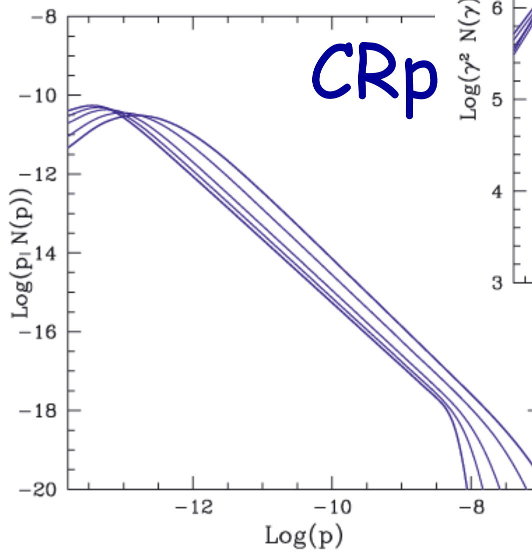


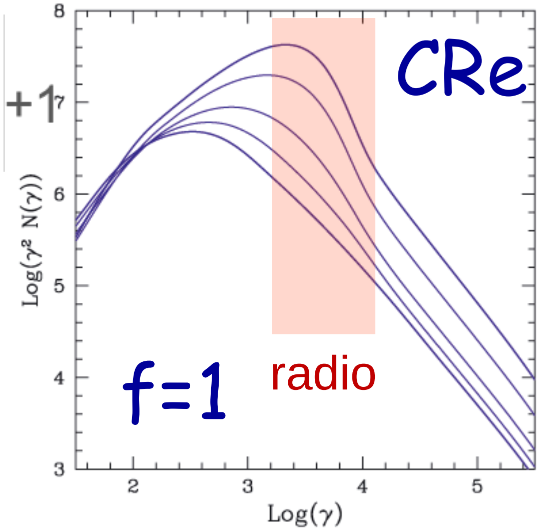


Reacceleration of CRp & secondaries



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





Weaker magnetic field are constrained by current gamma-ray limits

Are these magnetic fields consistent with values from Faraday RM ?

Relativistic protons in the Coma galaxy cluster: first gamma-ray constraints ever on turbulent reacceleration

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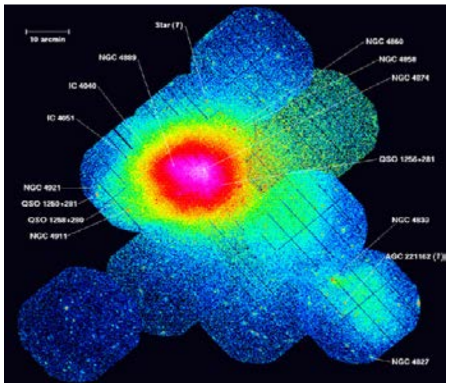
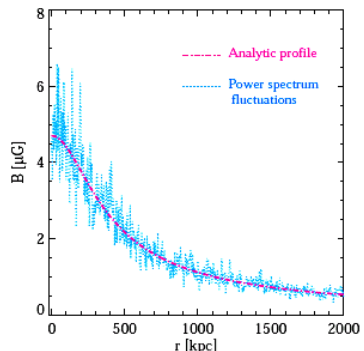
[2]DPNC, University of Geneva, 24 Quai Ernest-Ansermet, CH-1211 Geneva, Switzerland
[3]GRAPPA, University of Amsterdam, Science Park 904, 1098XH, Amsterdam, Netherlands

ASSUMPTIONS

Thermal model

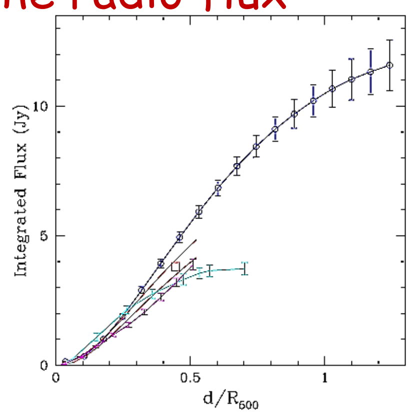


B model



(Bonafede+ 10)

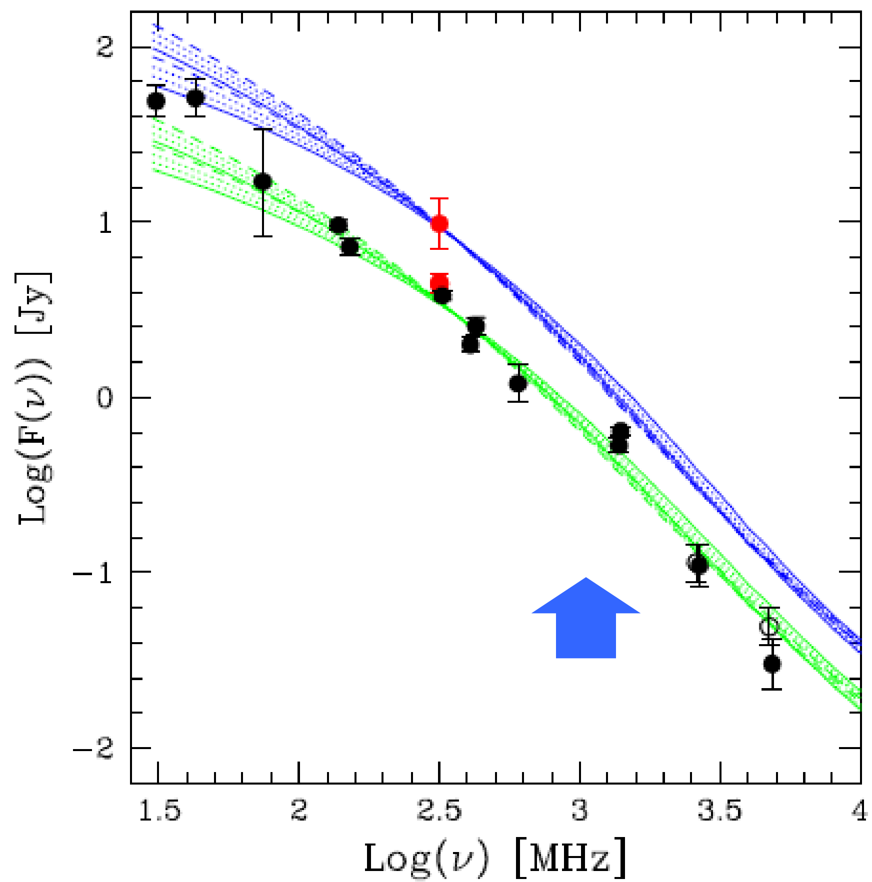
Spatial profile of the radio flux



- T_{acc}
- Δt_{acc}

Acceleration time/rate can be constrained from the spectrum

$$\nu_s/\mathrm{GHz} \sim (\tau_{acc}/400\mathrm{Myr})^{-2}$$



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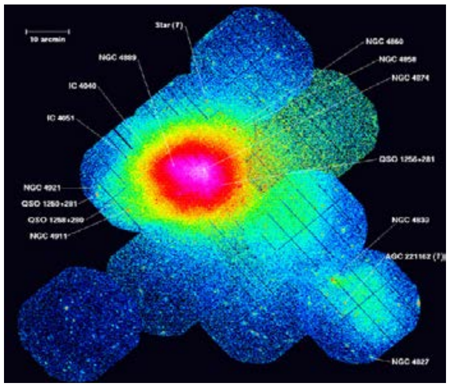
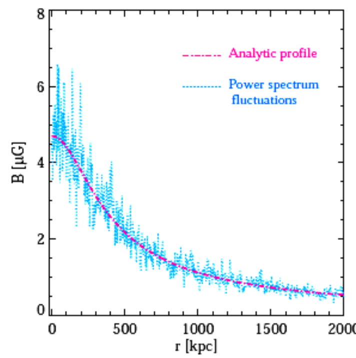
ASSUMPTIONS

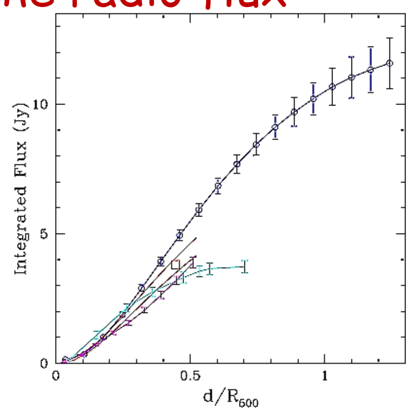
Thermal model



B model

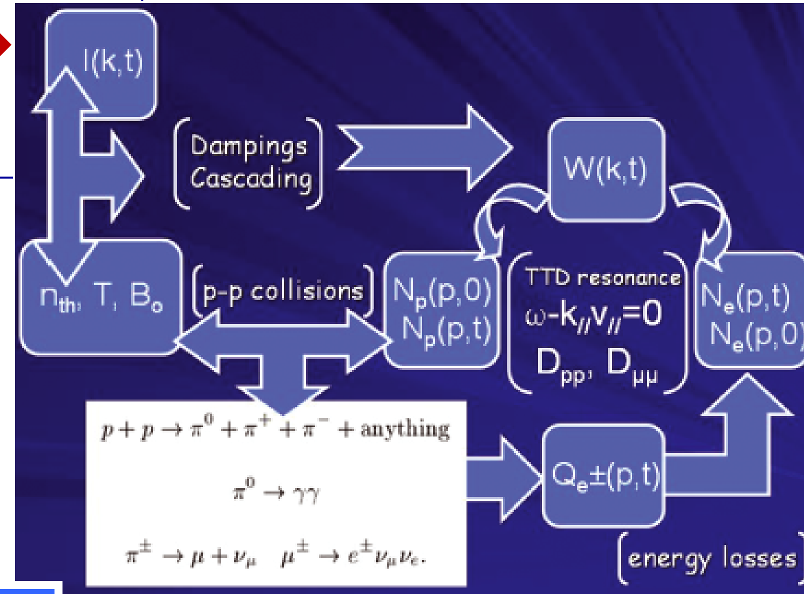


Spatial profile of the radio flux

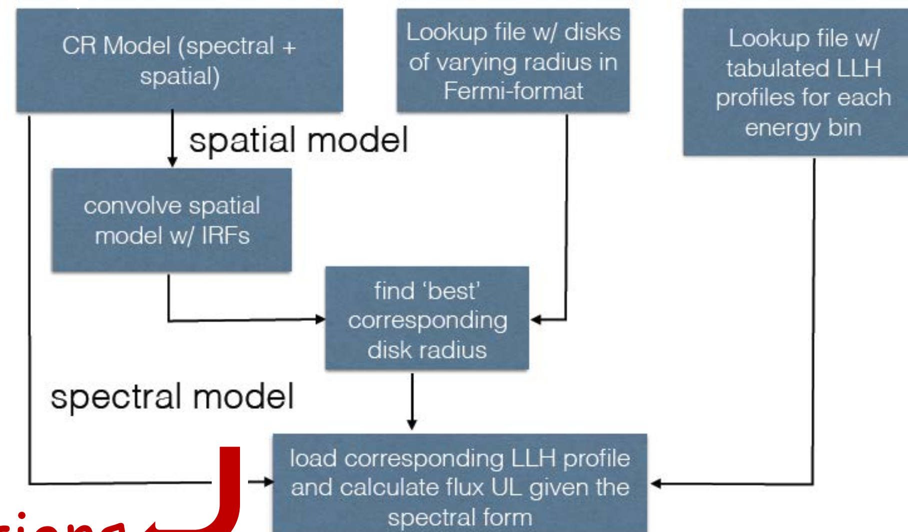


➤ T_{acc}

➤ Δt_{acc}



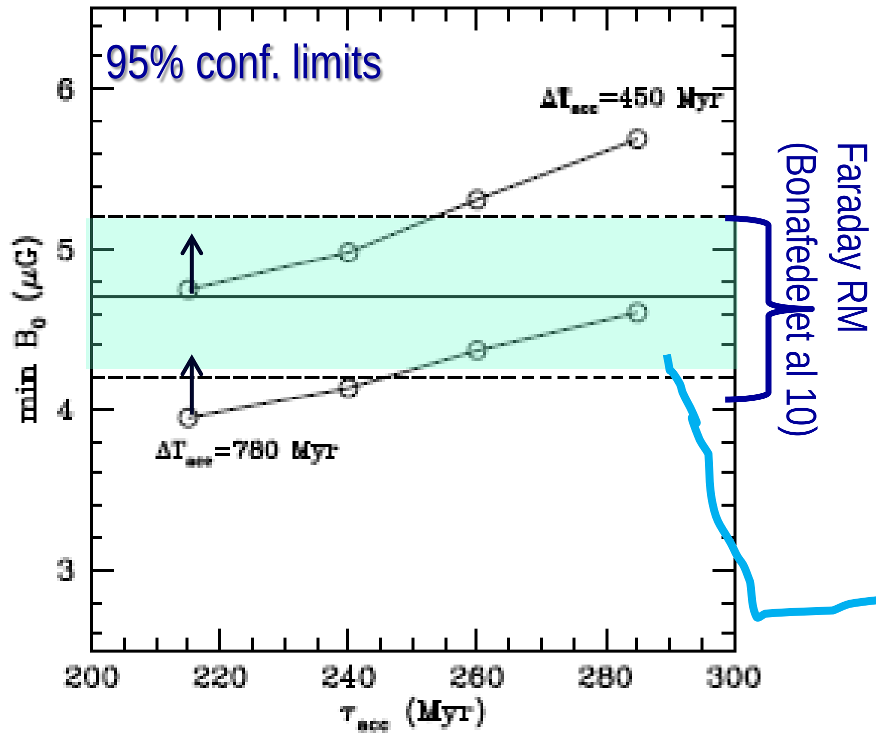
Method

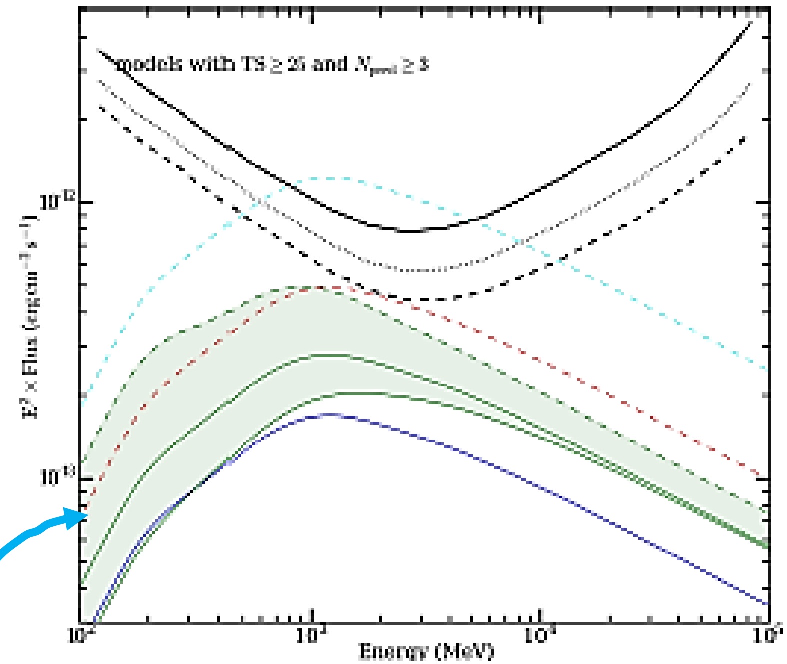


Limits vs expectations

Relativistic protons in the Coma galaxy cluster: first gamma-ray constraints ever on turbulent reacceleration

G. Brunetti,[1⋆] S. Zimmer,[2†] F. Zandanel,[3‡]
[1] INAF-IRA, Via Gobetti 101, I-40129 Bologna, Italy
[2] DPNC, University of Geneva, 24 Quai Ernest-Ansermet, CH-1211 Geneva, Switzerland
[3] GRAPPA, University of Amsterdam, Science Park 904, 1098XH, Amsterdam, Netherlands





Accel. efficiency

Short reacceleration periods are in tension with current limits

A signal at 3σ level can be detected in 15 yrs of observations if CRp play a role

SED & main dependences

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

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

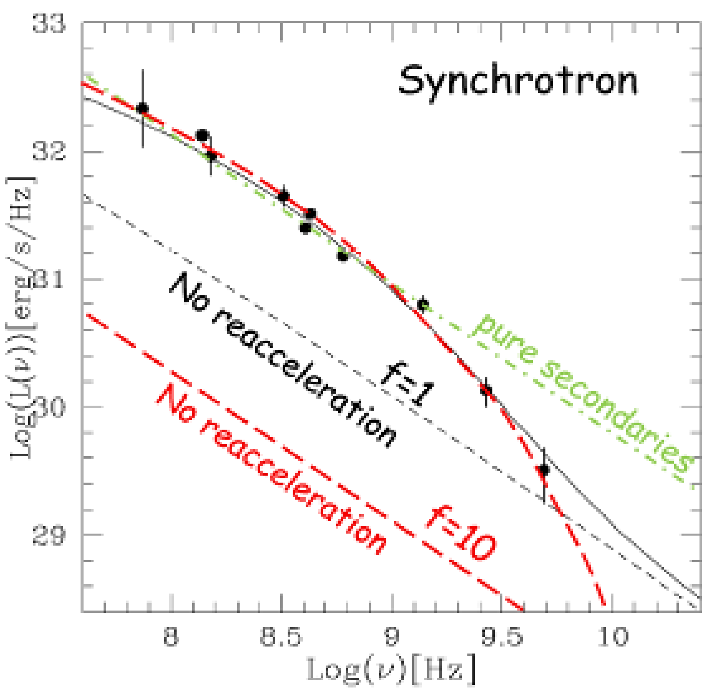
$$L_{SYN} \propto \underbrace{I_{tu}\Gamma_{CRe}}_{\text{Turb energy flux}}\frac{B^2}{B^2+B^2_{IC}}V_{SYN}$$

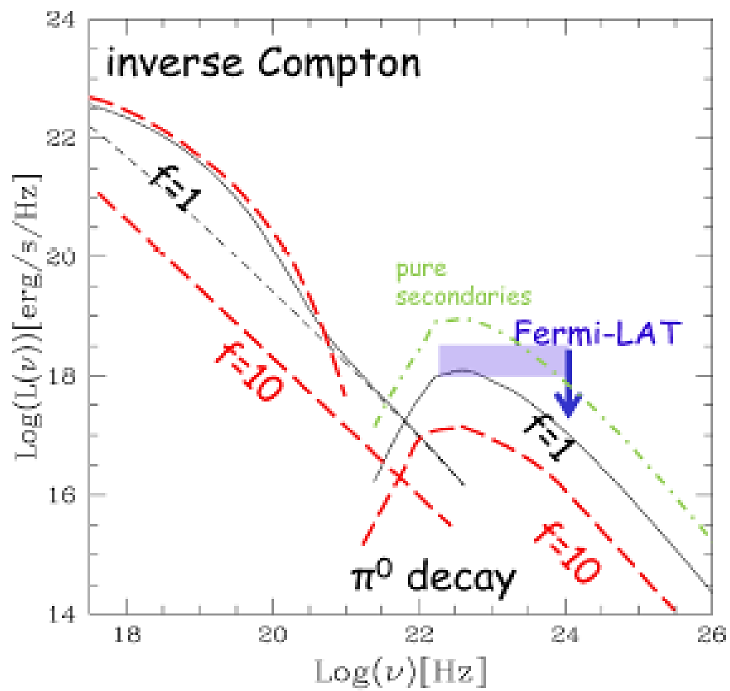
$$L_{ICS} \propto I_{tu}\Gamma_{CRe}\frac{B^2_{IC}}{B^2+B^2_{IC}}V_{ICS}$$

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

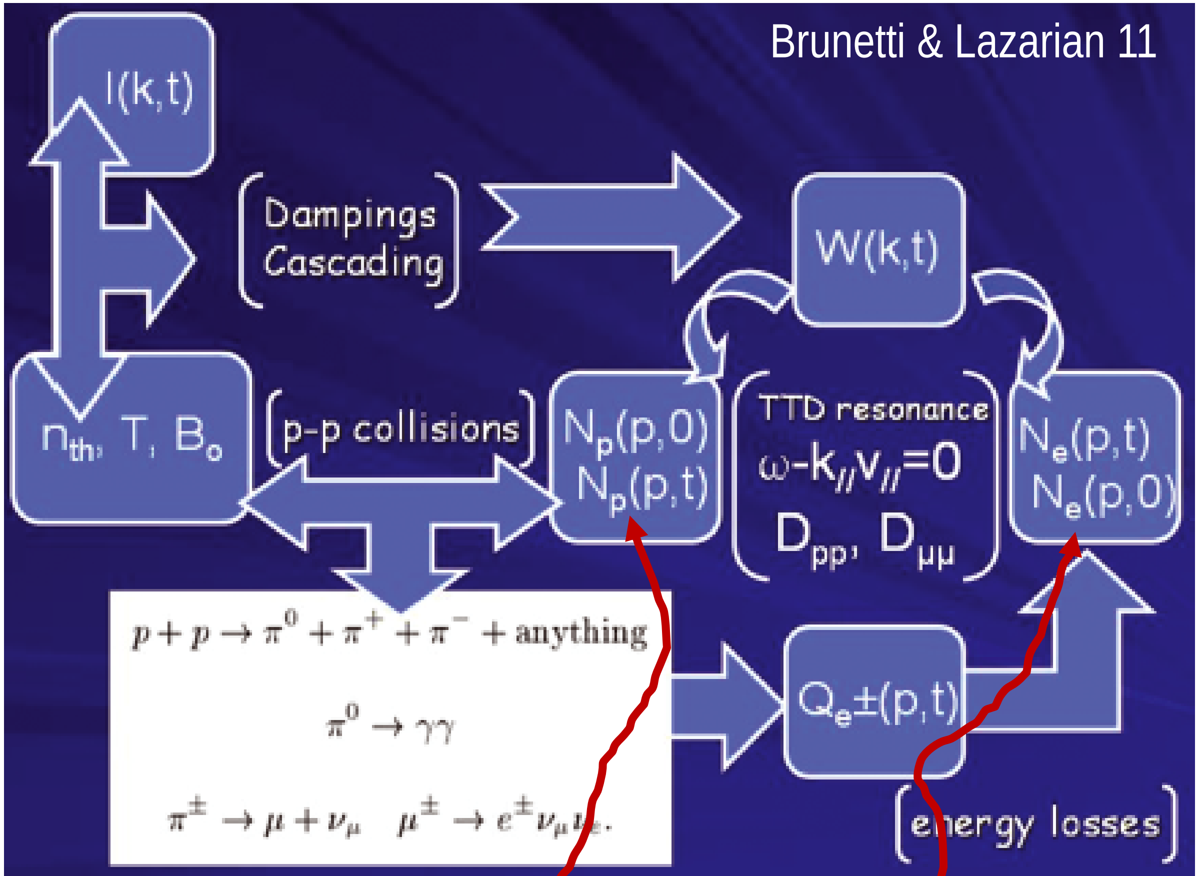
$$\frac{L_{SYN}}{L_{ICS}} \propto \frac{B^2}{B^2_{IC}}$$

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



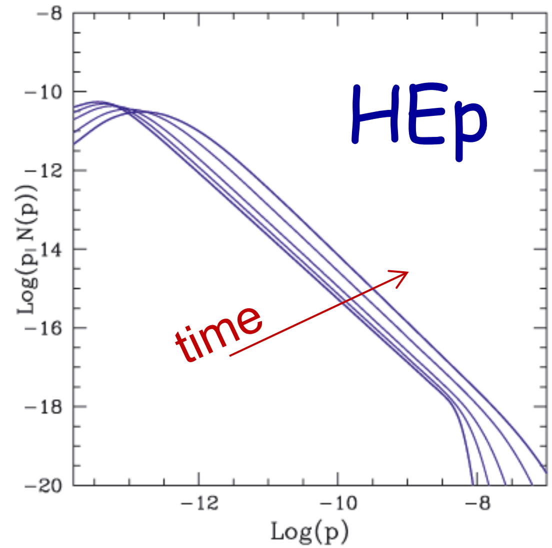


Reacceleration of CRp & secondaries



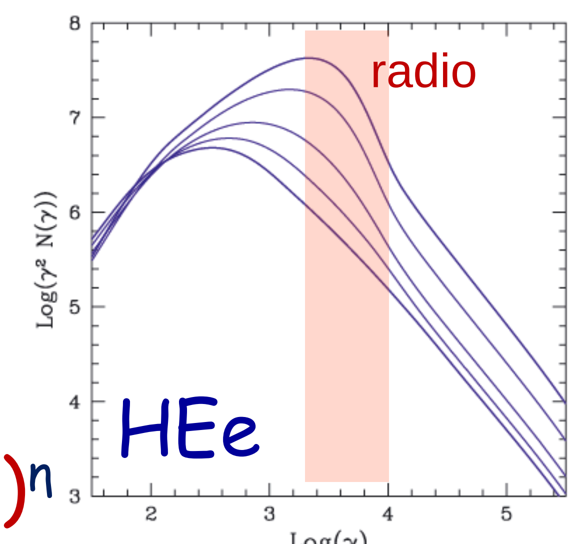
sources of HEp

sources of HEe



f=1

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

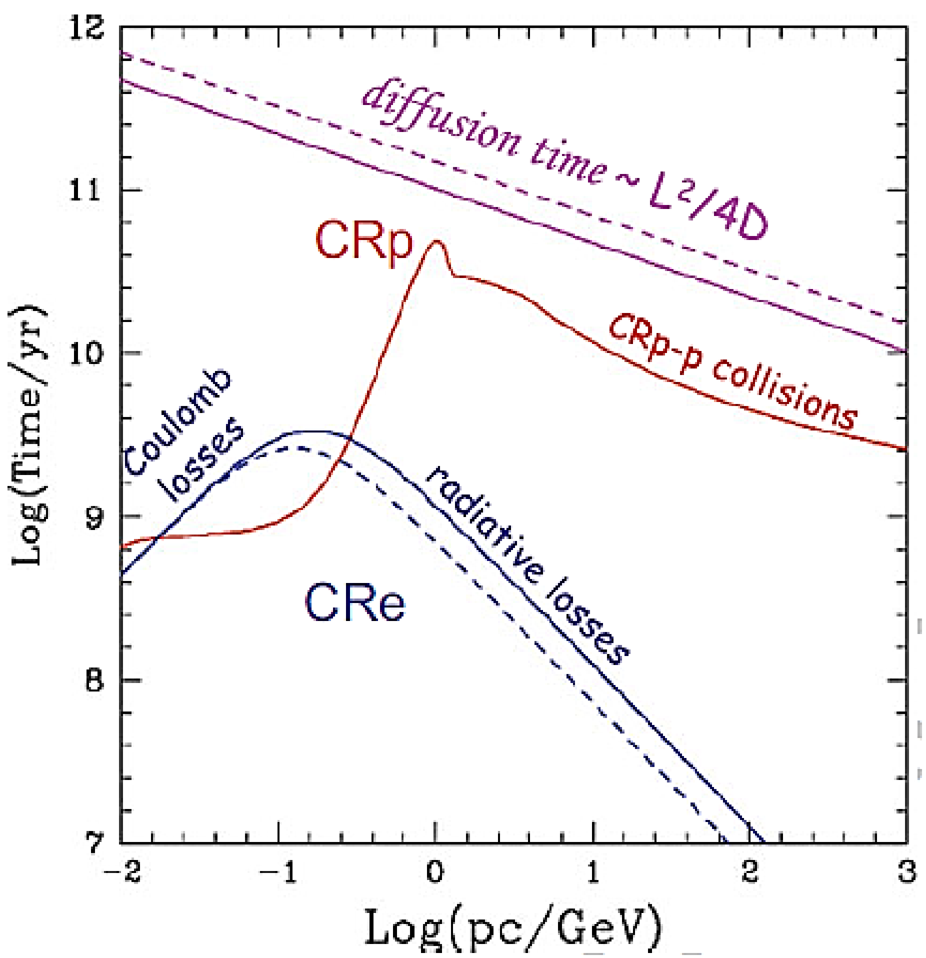


Main parameters :

$T_{acc} \sim p^2/4D_{pp}$, Δt_{acc}, $B(r)=B_o(\varepsilon_{ICM}/\varepsilon_o)^n$

HEp confinement

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

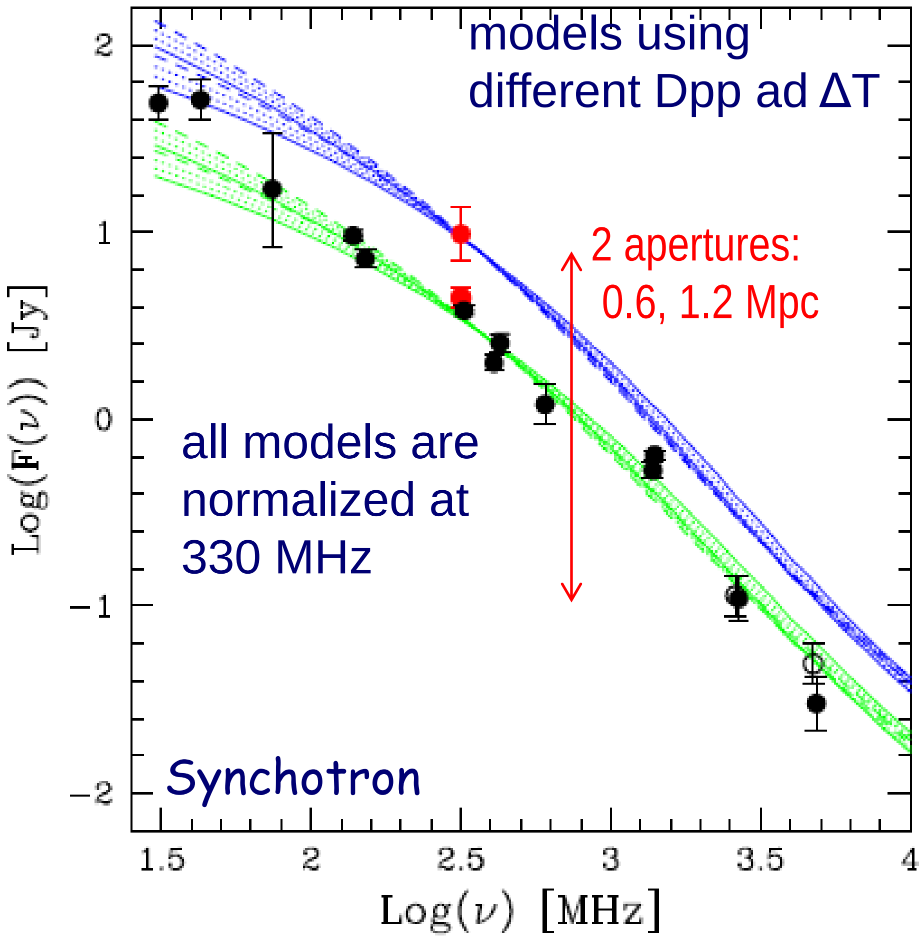


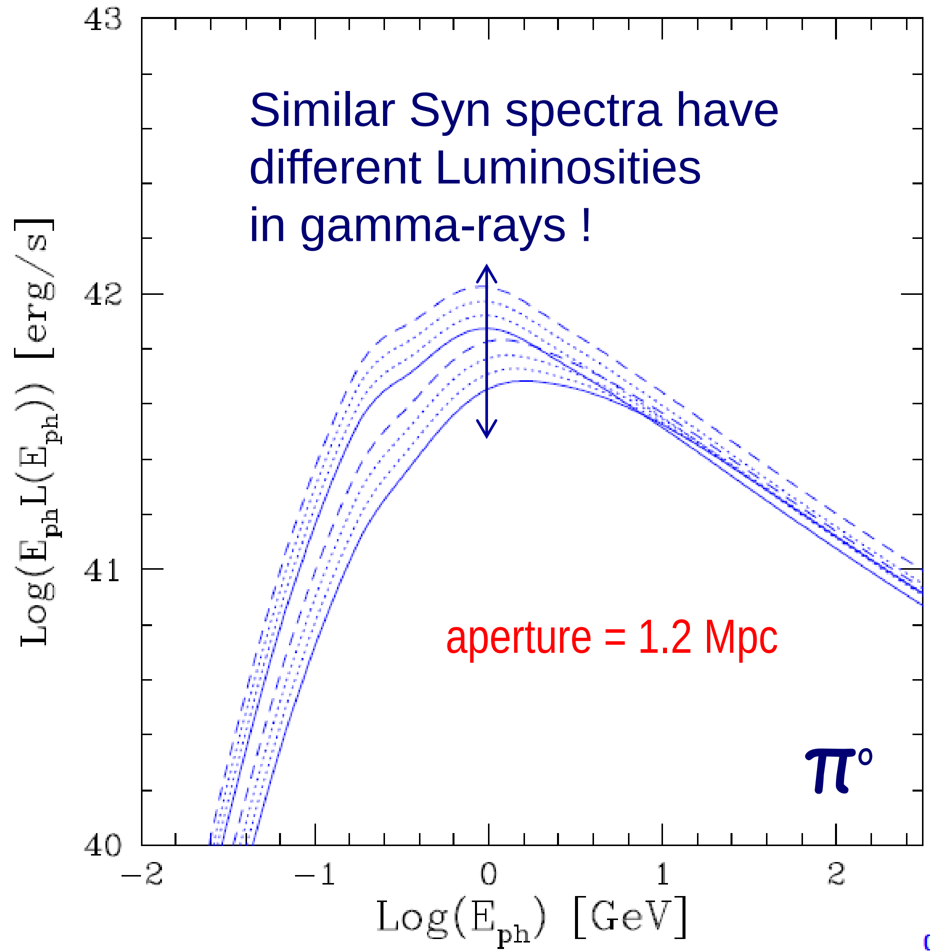
Brunetti & Jones 2014

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

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times

Radio & gamma-rays results: Coma cluster





$$B(r)=B_o(\varepsilon_{ICM}/\varepsilon_o)^{\eta}$$
$$\eta=0.5$$
$$B_o=4.7\ \mu G$$

Faraday Rotation Measure
Coma cluster
(Bonafede et al 10)

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

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

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

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

Turb. Modes

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

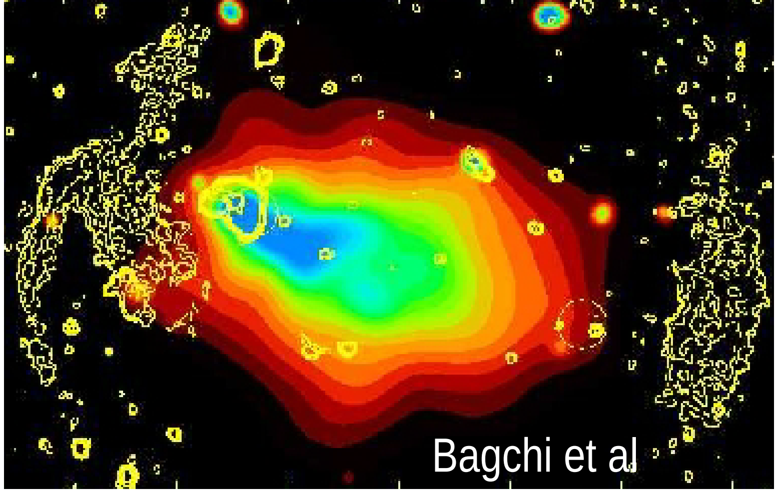
mode coupling — collisionless dampings — injection

dampings

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

Shock Acceleration Model

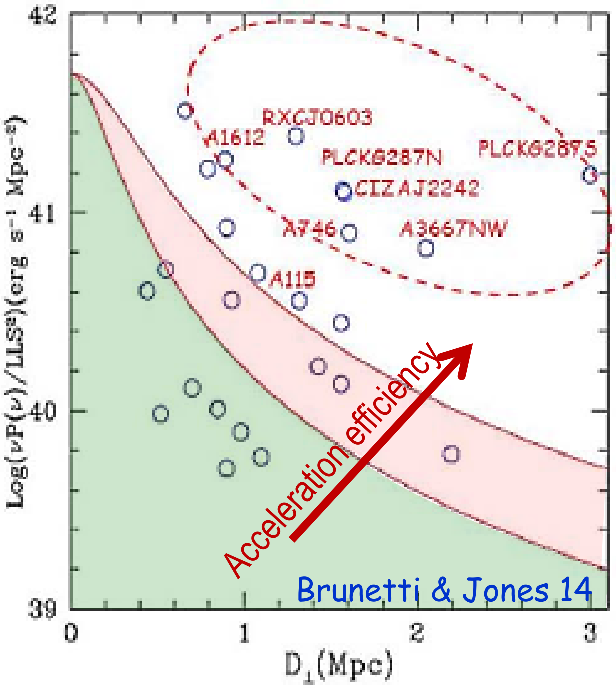
(Ensslin et al 98, Roettiger et al 99, …++)



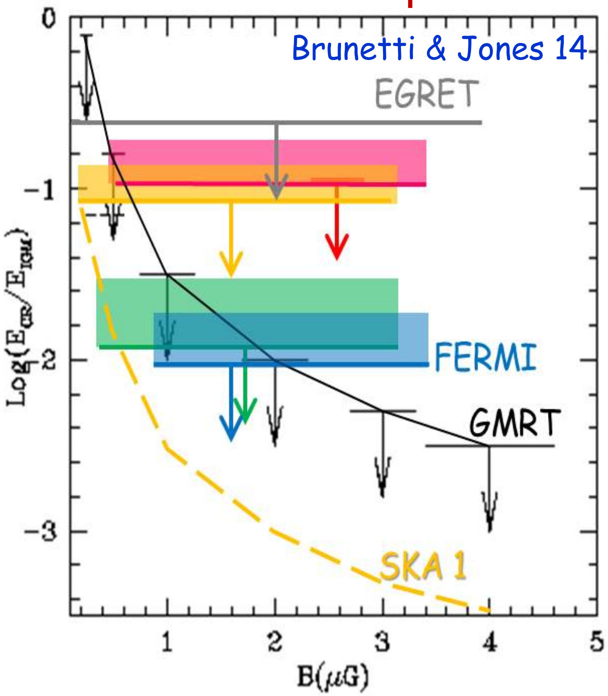
- Acceleration OR reacceleration ?
  (eg Markevitch et al 05, Kang et al 11,16, Pinzke & Pfrommer 13, … Botteon's talk)

- Anomalous (high) ratio CRe/CRp ? … CRp escape ??!
  (Vazza et al 14,16, Brunetti & Jones 14, Guo et al 14, …)

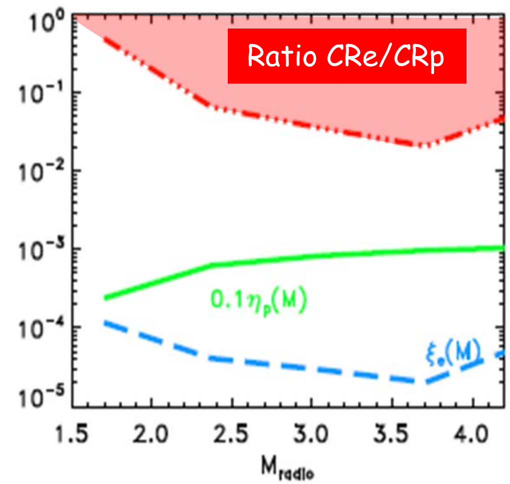
- Efficiency is too big -



- Limits on CRp/ICM -

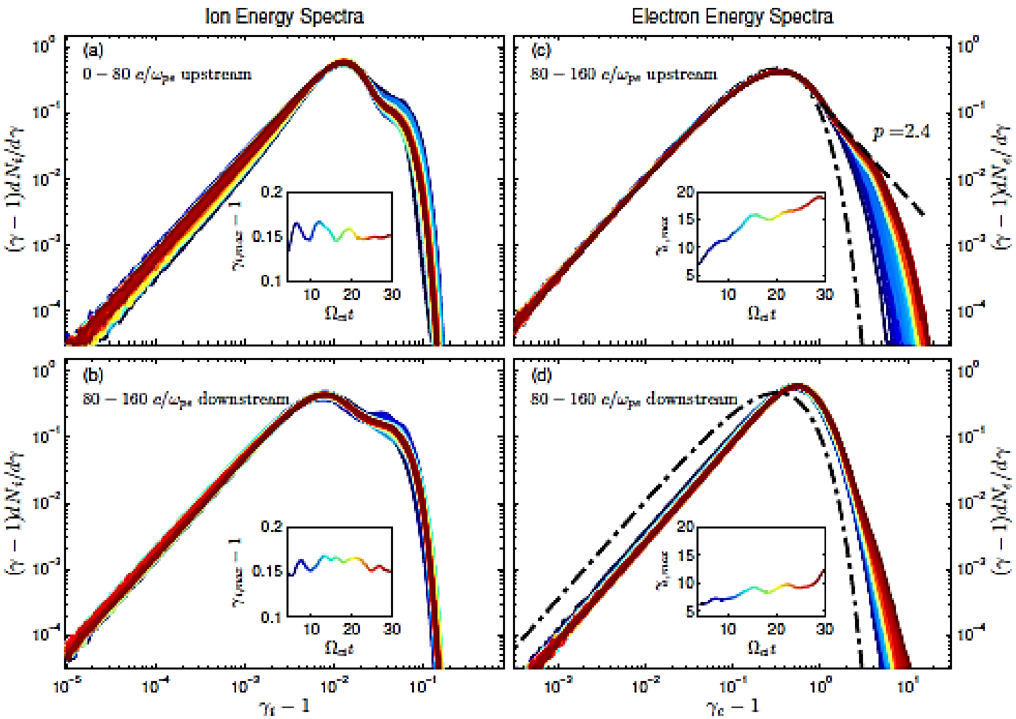


Too many electrons
Too few protons



Vazza & Bruggen 14
Vazza et al 16

CRe 'pre-heating': role of drift acceleration?

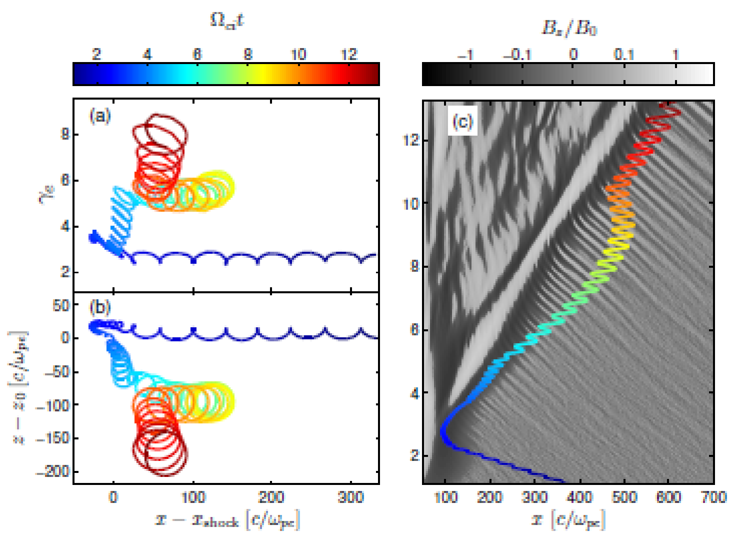


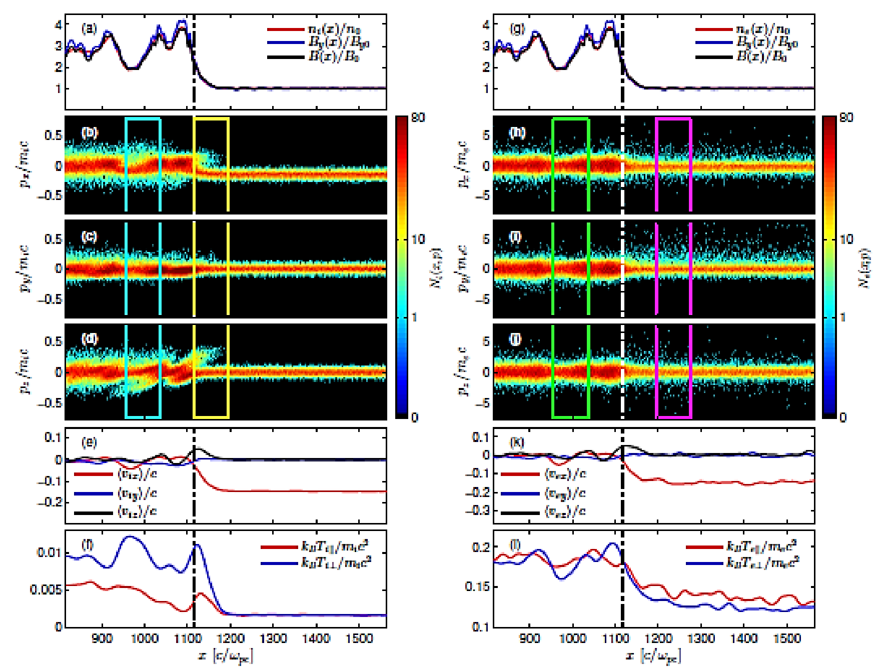
Low Mach number perpendicular shock in high-beta plasma

(Guo, Sironi, Narayan 14a,b, Caprioli et al)

Efficient CRe acceleration.

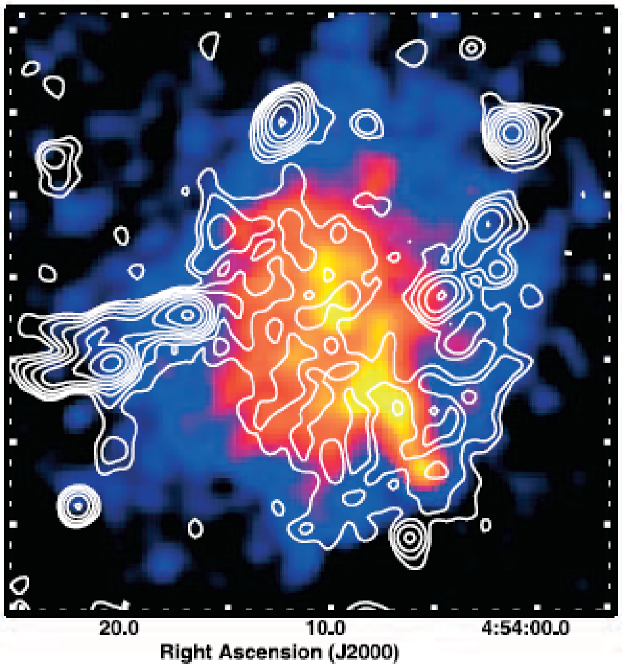
shock drift acceleration + Fermi-like via scattering upstream-downstream mediated by self-generated waves .

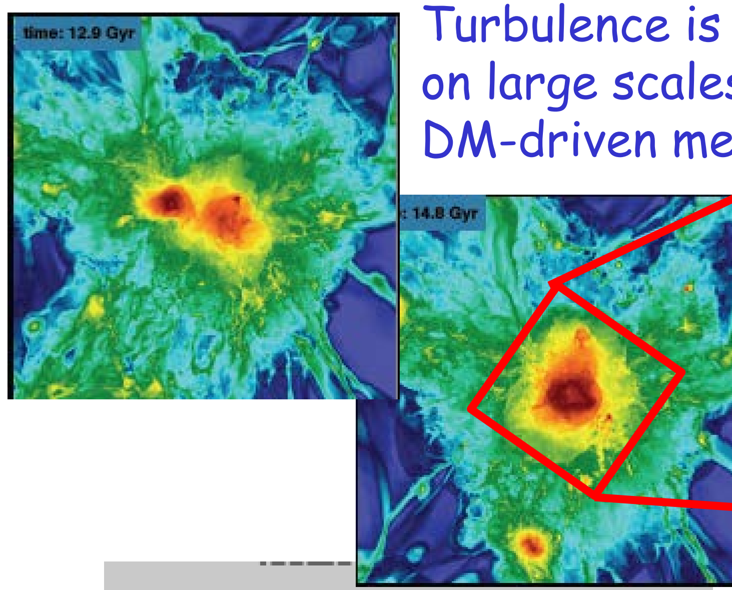




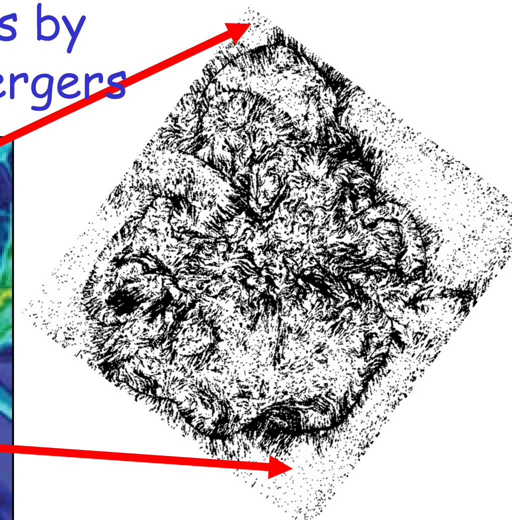
Radio Halos as tracers of turbulent regions in galaxy clueters

(Brunetti et al. 01,04, Petrosian 01, Ohno et al 02, Fujita et al. 03, Cassano & Brunetti 05, Brunetti & Blasi 05, Brunetti & Lazarian 07,11 Donnert et al 13, Beresnyak et al 13, Donnert & Brunetti 14, Miniati 15, Brunetti 16, Pinzke et al 15, Fujita et al 16.)



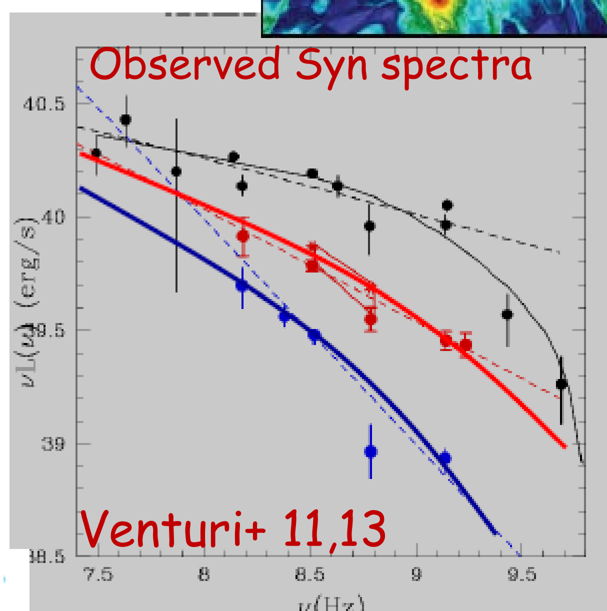


Turbulence is injected on large scales by DM-driven mergers



Merger-driven turbulence traps particles in Mpc volumes and (re)accelerates them.

Radio halos probes physics of the ICM at dissipation scales.



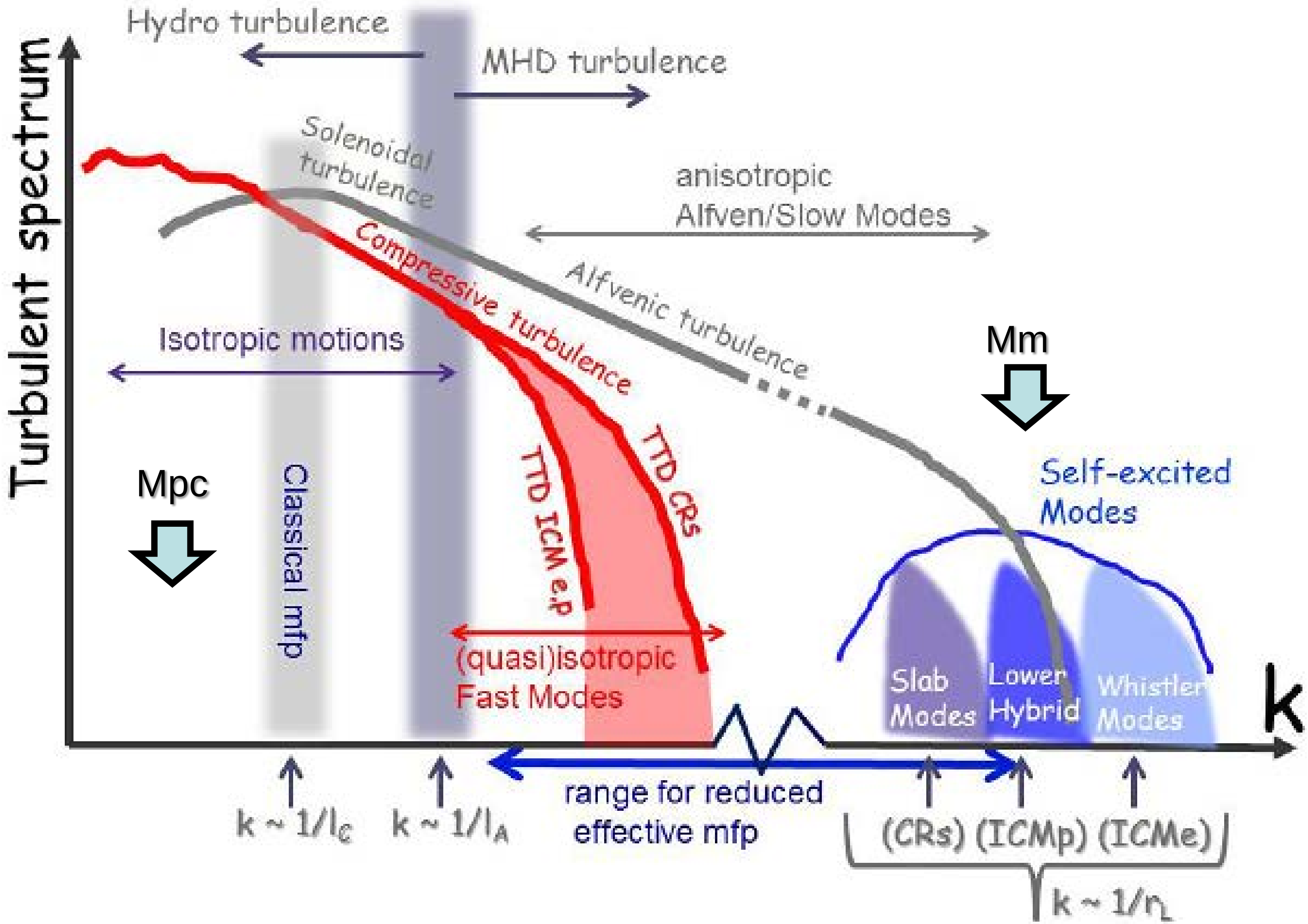
Comparison between Syn spectrum and CRe lifetime allows to estimate acceleration time :

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

(Schlickeiser+ 87, Brunetti+ 01,08)

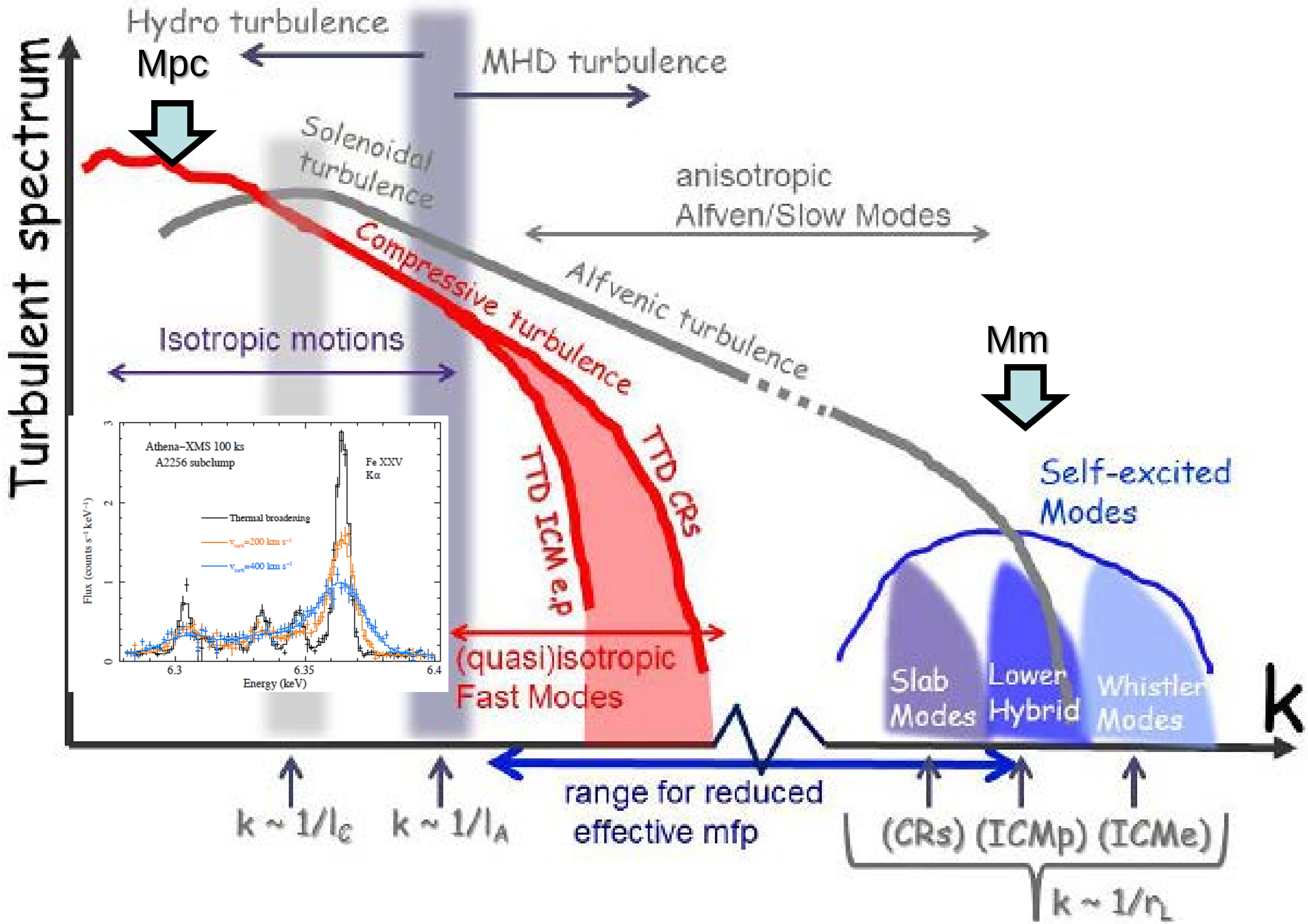
Probing physics of ICM Turbulence

- via synchrotron RH & line broadening -

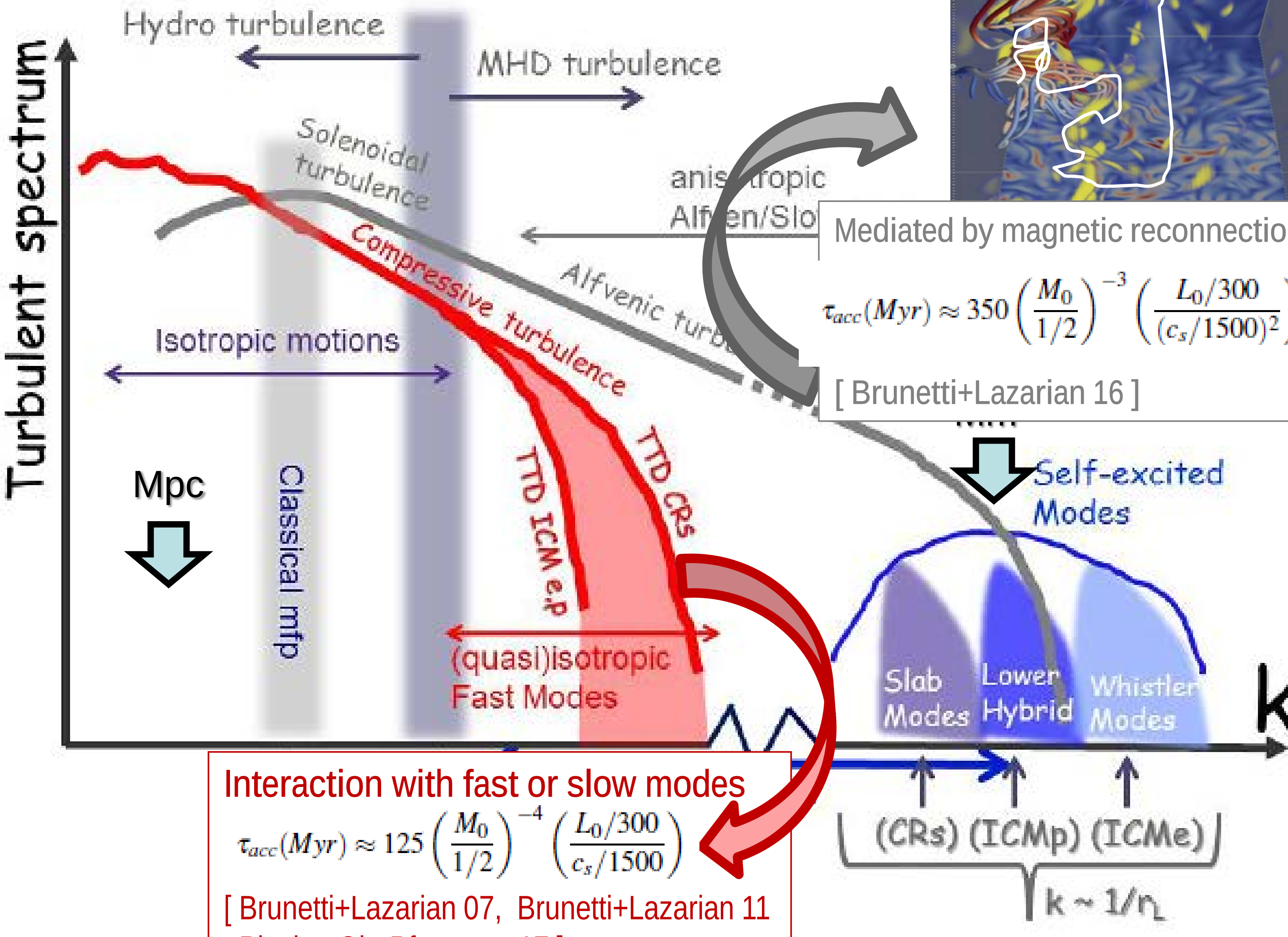


Probing physics of ICM Turbulence

- 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]

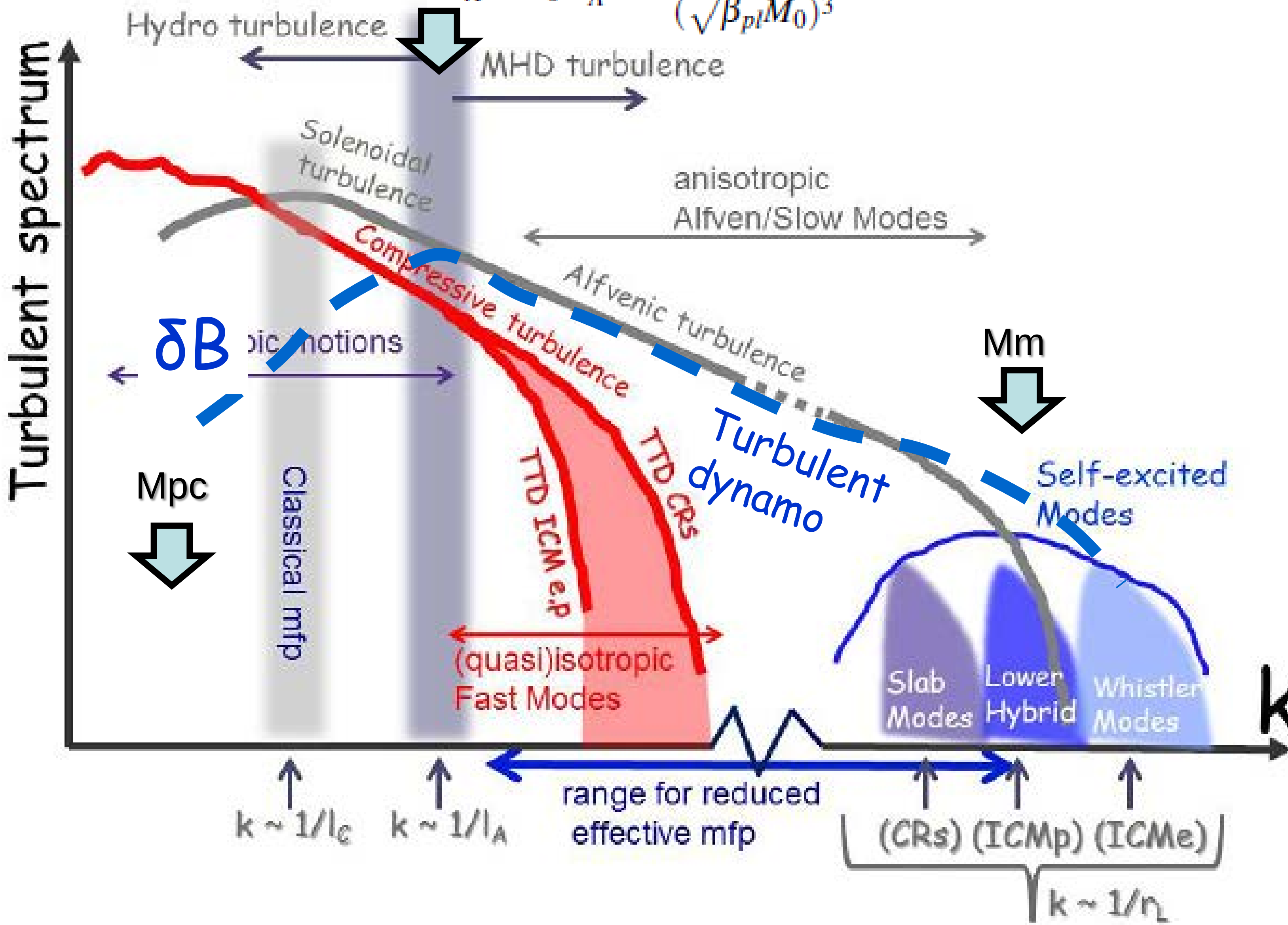
Interaction with fast or slow modes

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

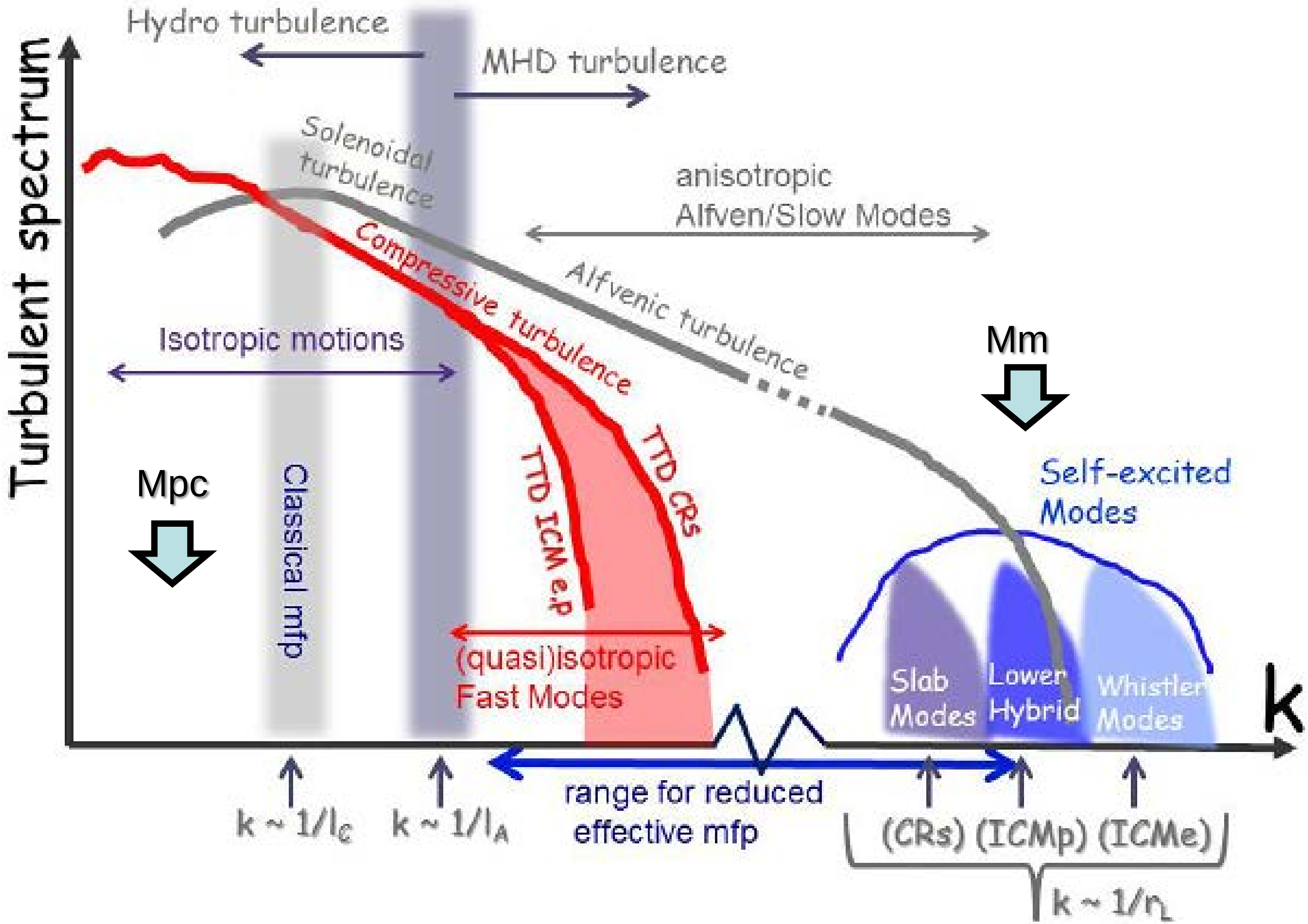
[Brunetti+Lazarian 07, Brunetti+Lazarian 11
Pinzke, Oh, Pfrommer 17]

Probing physics of ICM Turbulence

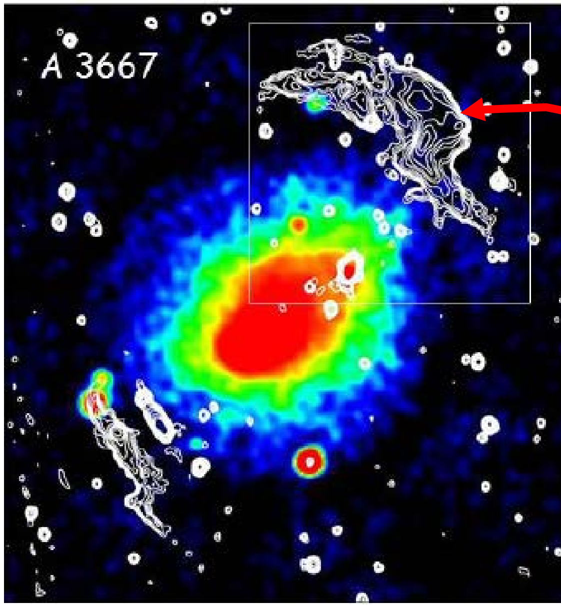
$$l_A = L_0 M_A^{-3} = \frac{(6/5)^3 L_0}{(\sqrt{\beta_{pl}} M_0)^3}$$

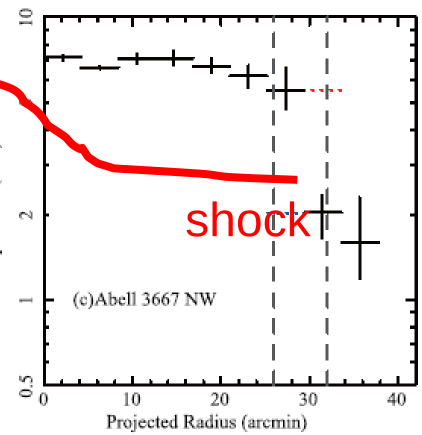


Probing physics of ICM Turbulence
- via synchrotron RH & line broadening -



HEp/HEe acceleration efficiency





BUT clusters shocks are efficient to accelerate HEe (to GeV+) as demonstrated by Giant Radio Relics
(Ensslin et al 98, Markevitch et al 05, van Weeren et al 10, Kang et al 12, Pinzke et al 13, …)

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

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

CRp -- π^o → Gamma

CRe -- SynRelics

density upstream

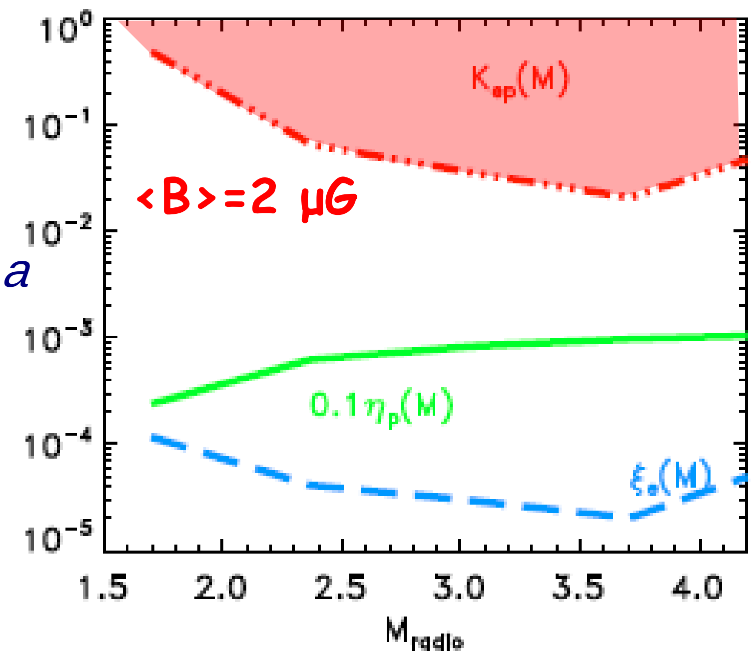
shock speed

shock compression

downstream speed

CRp/CRe < 10 or so …

(see Brunetti & Jones 14 for discussion)



Vazza et al 15

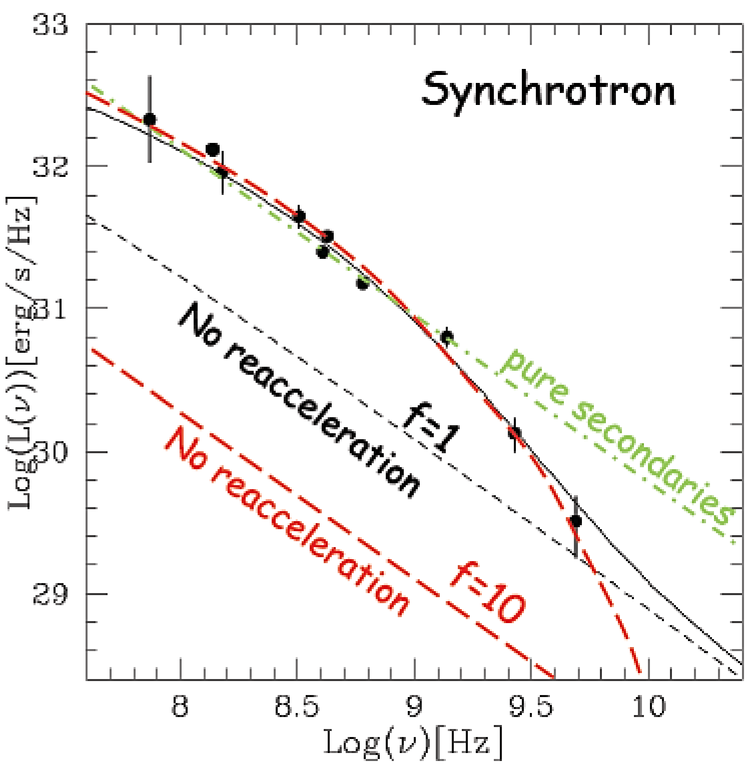
Based on a sample of GC scaling relations + simulations

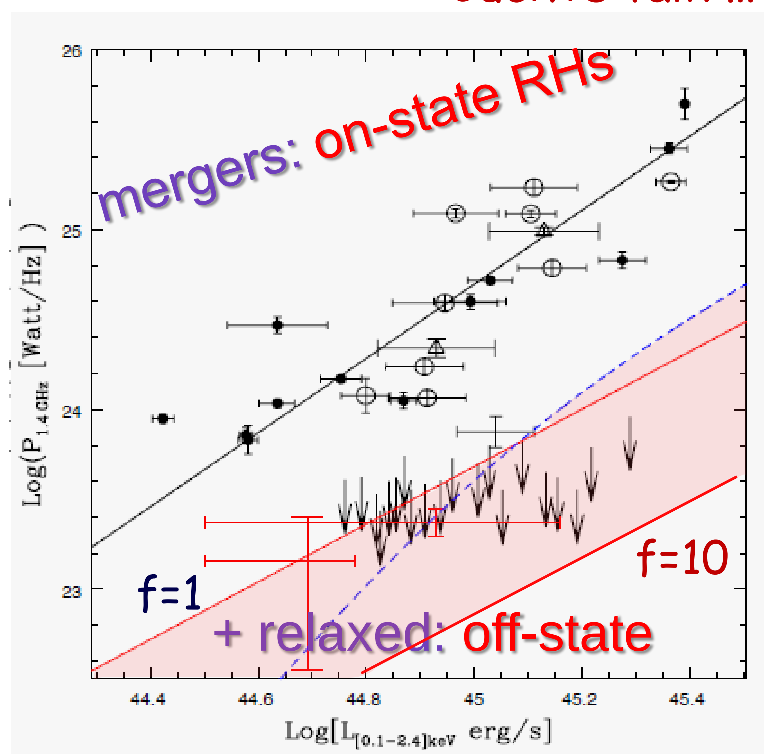
CRp & off-state RADIO HALOS

IF CRp play a role.. merging (turbulent) clusters evolve into relaxed (less turbulent) clusters whose radio emission depends on the injection rate of secondary electrons .

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

Brunetti & Lazarian 11
Brown et al 11
Cassano et al 12
Pinzke et al 16
Sommer et al 17
Cuciti's talk …





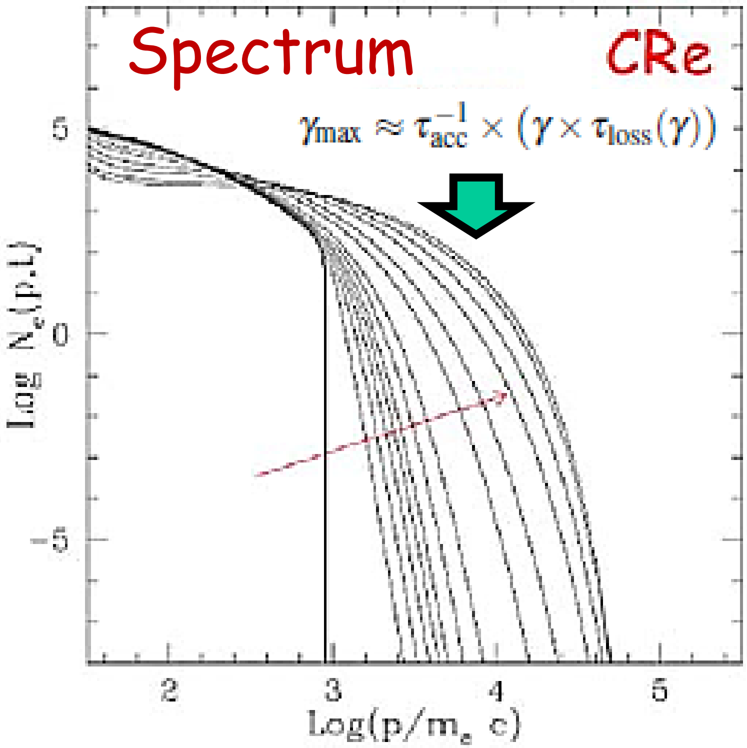
High-state (turbulent)

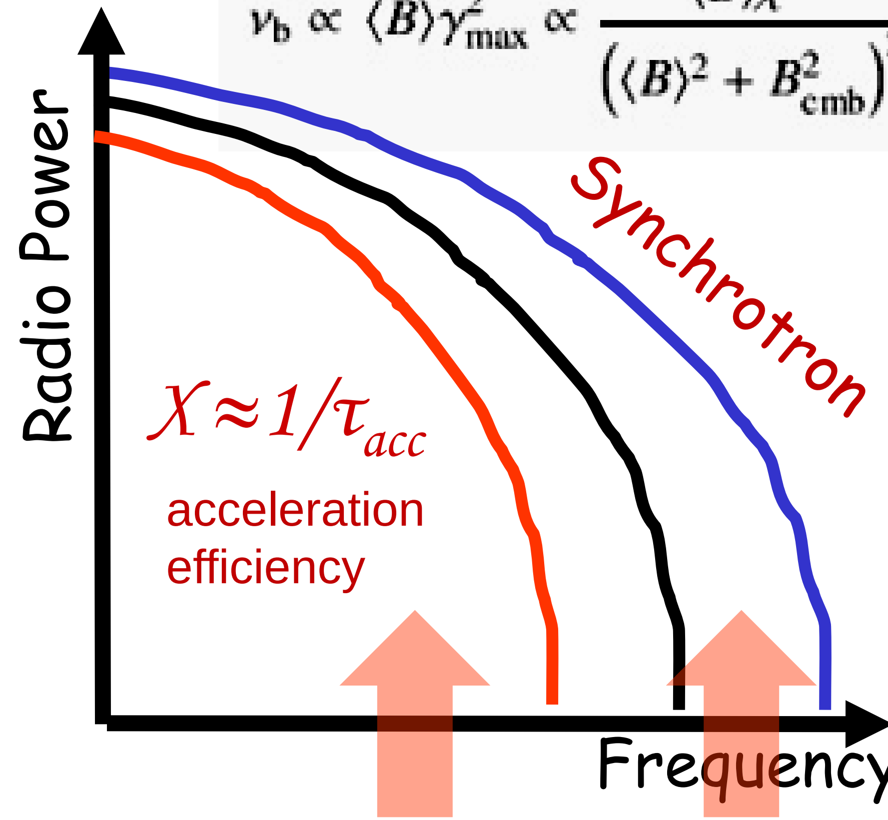
Low-state (secondaries)

DISCOVERY WINDOW AT LOW RADIO FREQUENCIES

$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2} \sim 10 - 1000 \text{ Myr}$$

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



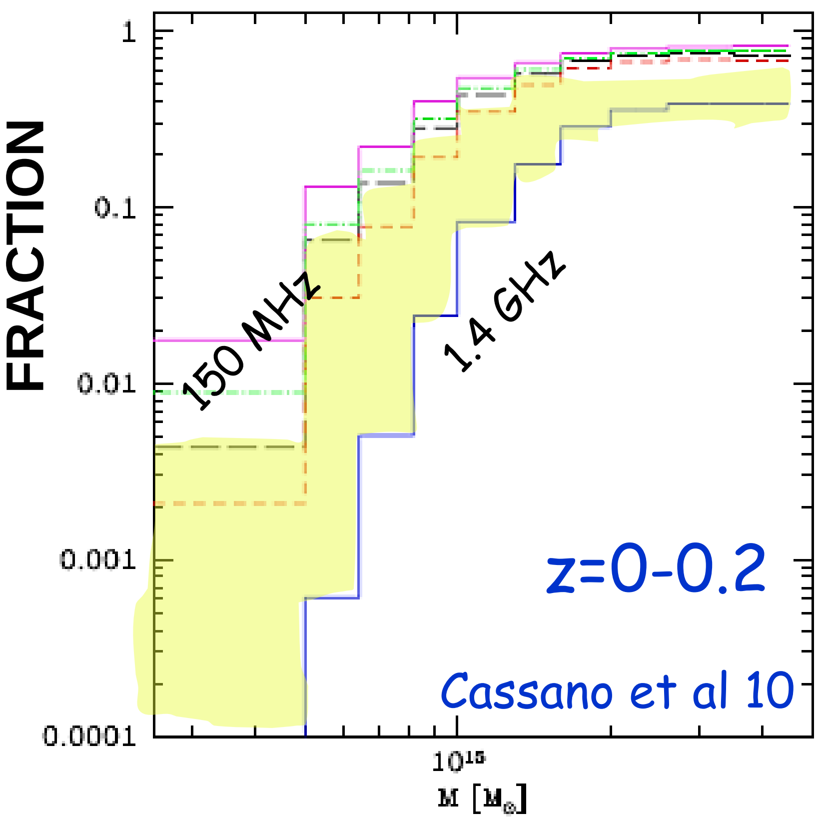


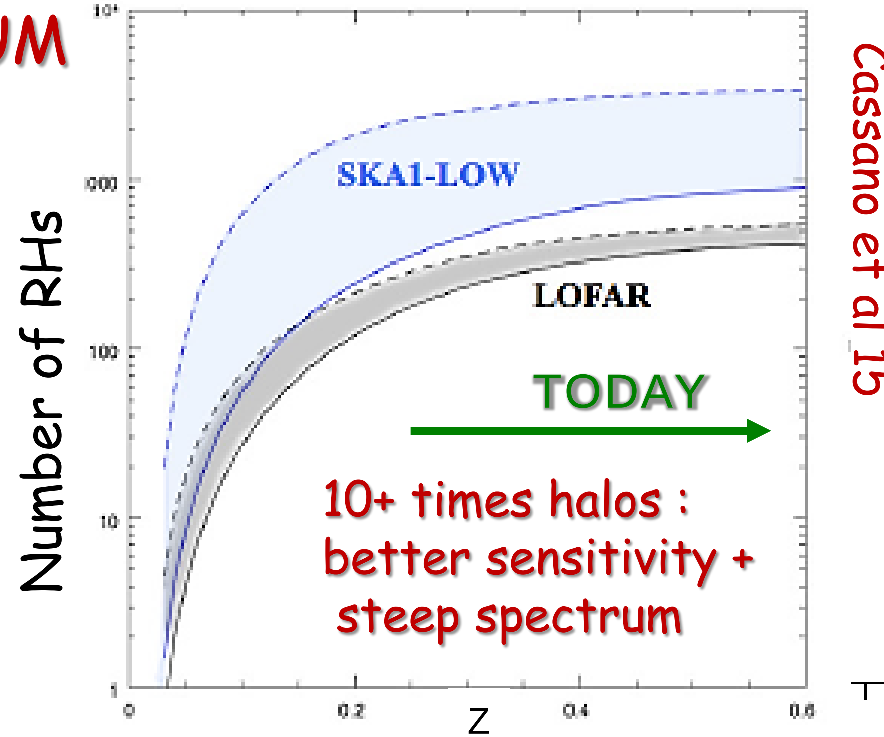
$$\tau_{loss}(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right) \left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4 \right] + \left(\frac{n_{th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1} \left[1.2 + \frac{1}{75} \ln\left(\frac{\gamma/300}{n_{th}/10^{-3}}\right)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

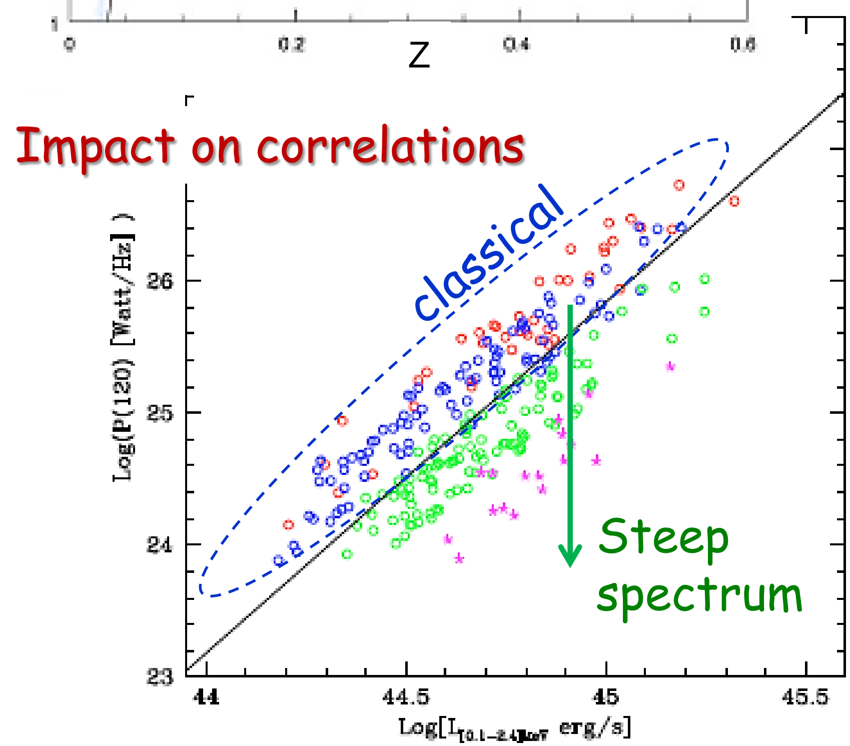
Radio Halos predicted to be a mix of different populations including with very steep spectrum sources «invisible» at classical frequencies.

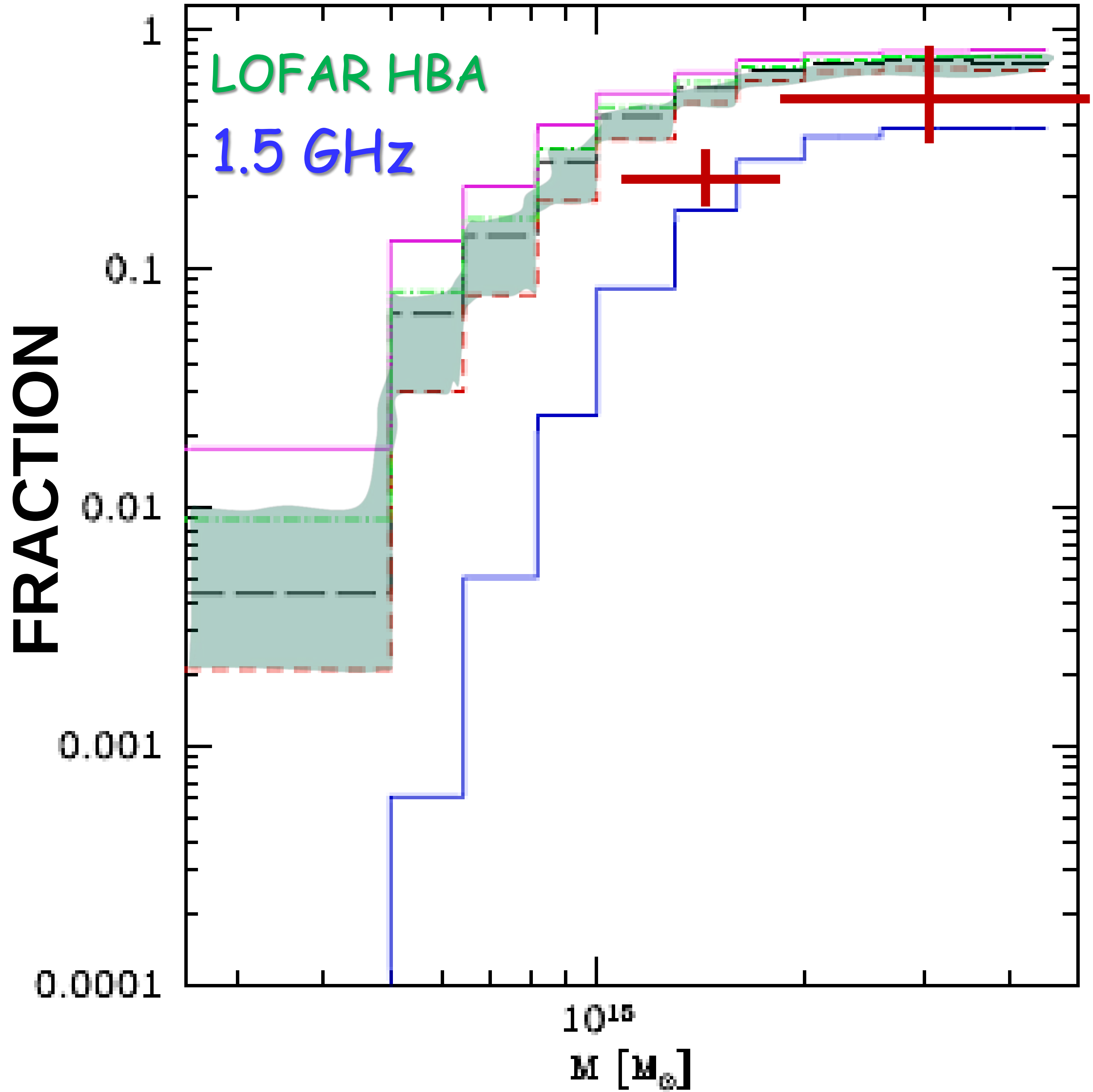
(Cassano, Brunetti, Setti 06)

HOW MANY STEEP-SPECTRUM HALOS ARE PREDICTED ??



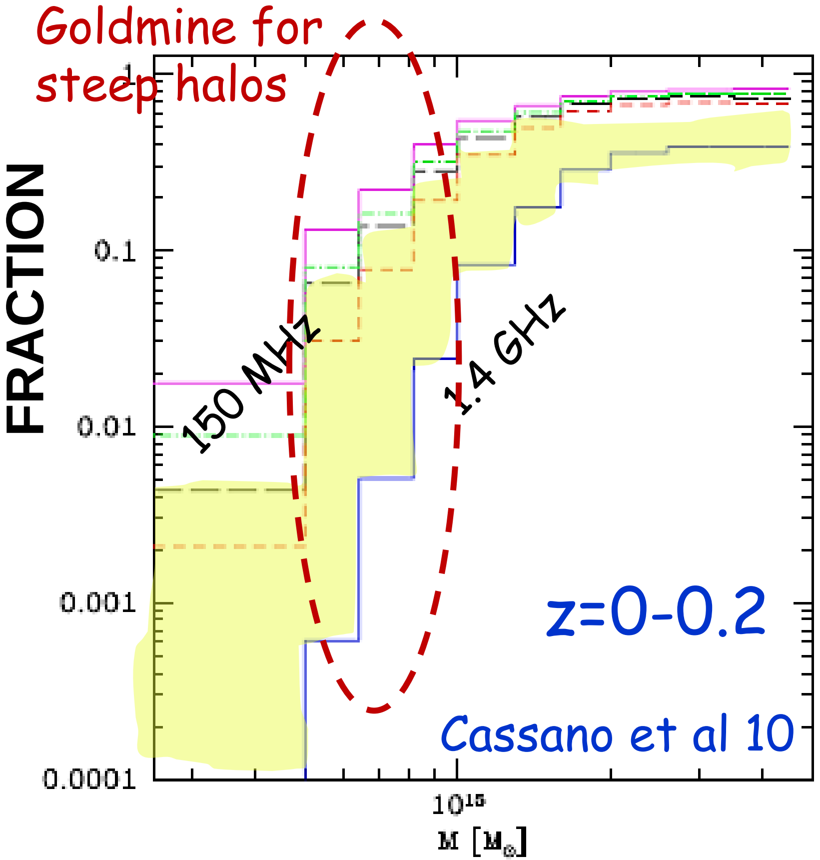


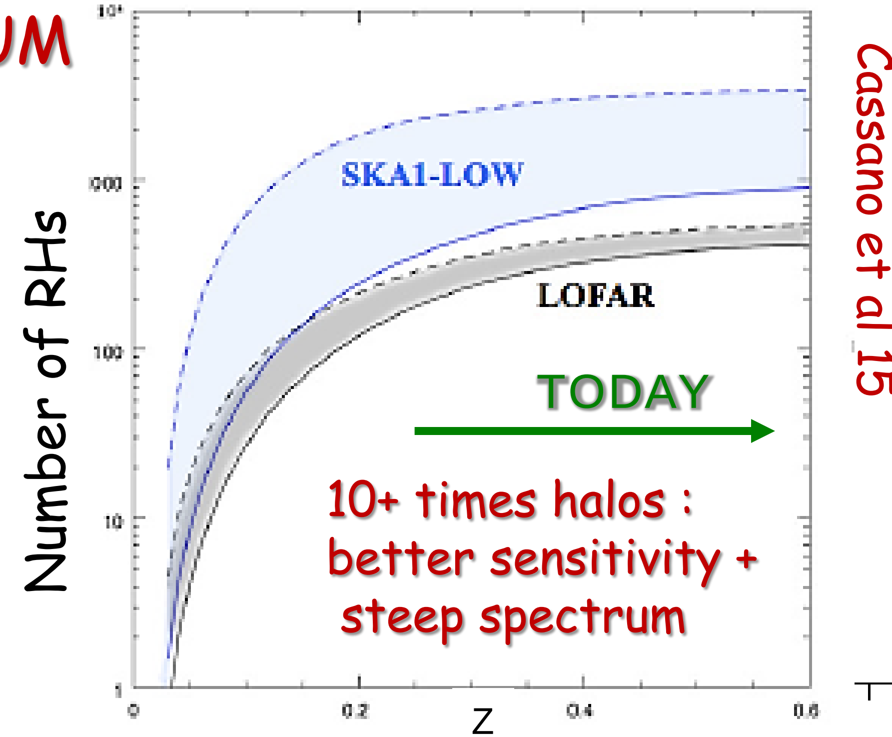


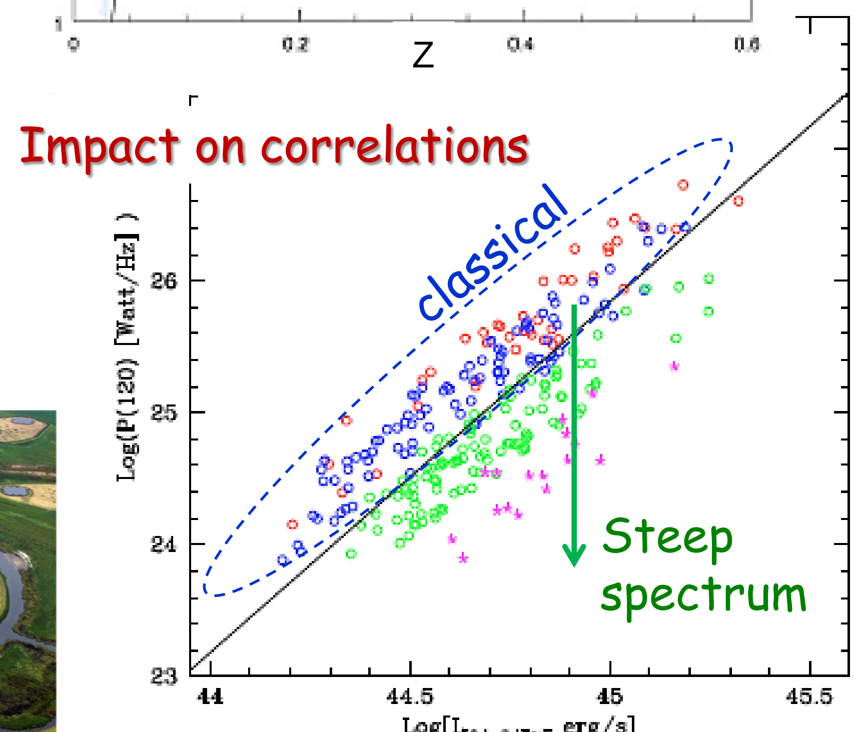


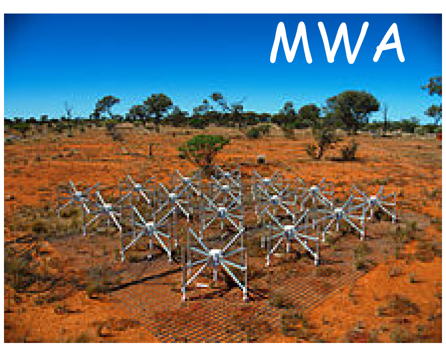
LOFAR HBA
1.5 GHz
FRACTION
1
0.1
0.01
0.001
0.0001
10^{15}
$M\ [M_\odot]$

HOW MANY STEEP-SPECTRUM HALOS ARE PREDICTED ??









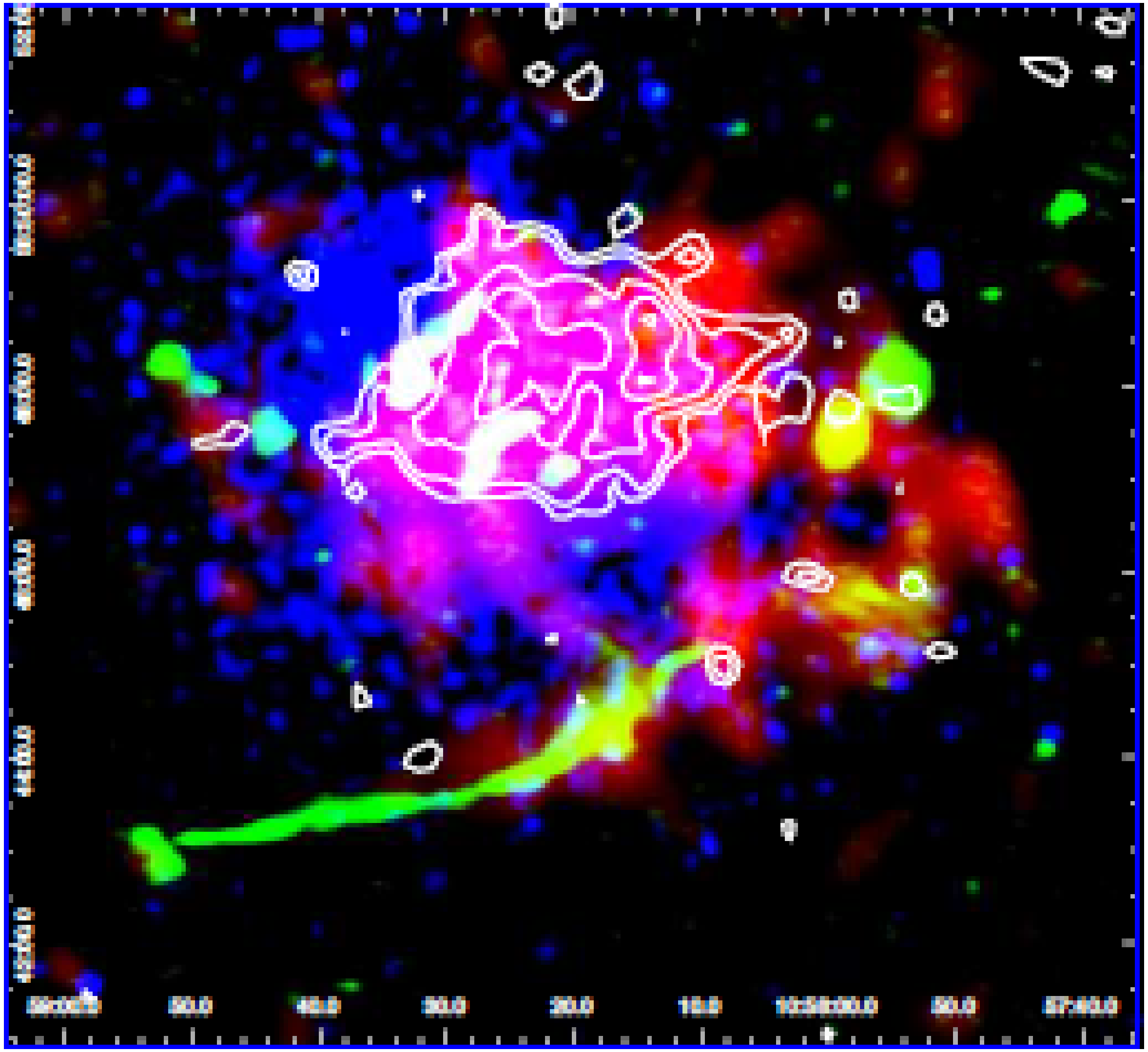
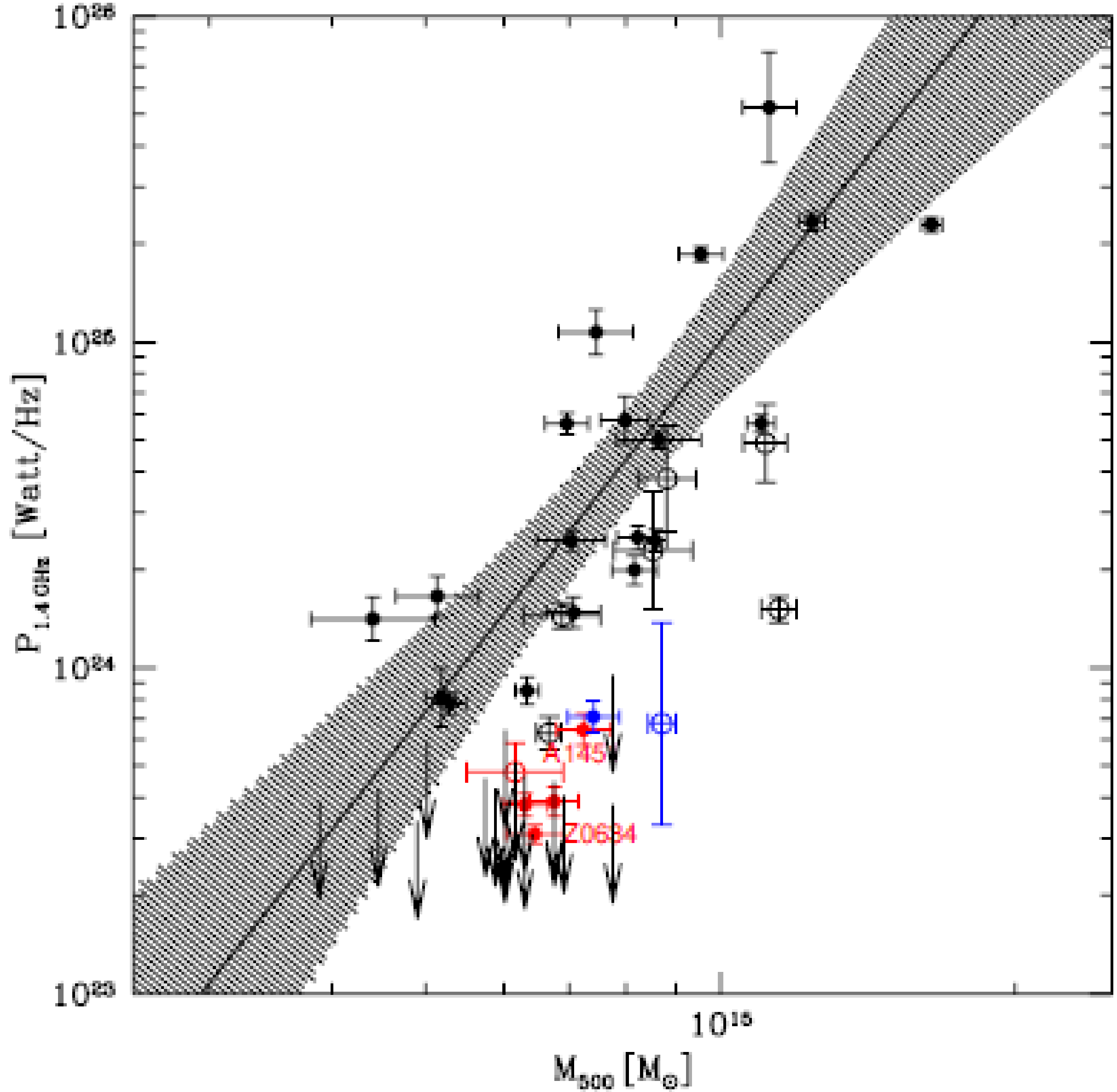


Figure 6. Chandra X-ray emission in blue, LOFAR high-resolution emission in green, LOFAR diffuse emission (after compact-source-subtraction) in red, and GMRT 325 MHz diffuse emission (after compact-source-subtraction) contours in white. Diffuse halo emission (LOFAR & GMRT) is imaged after subtracting compact sources imaged above a uv-range of 1000λ (corresponding to a 500 kpc scale at Abell 1132's redshift). Diffuse emission is im-

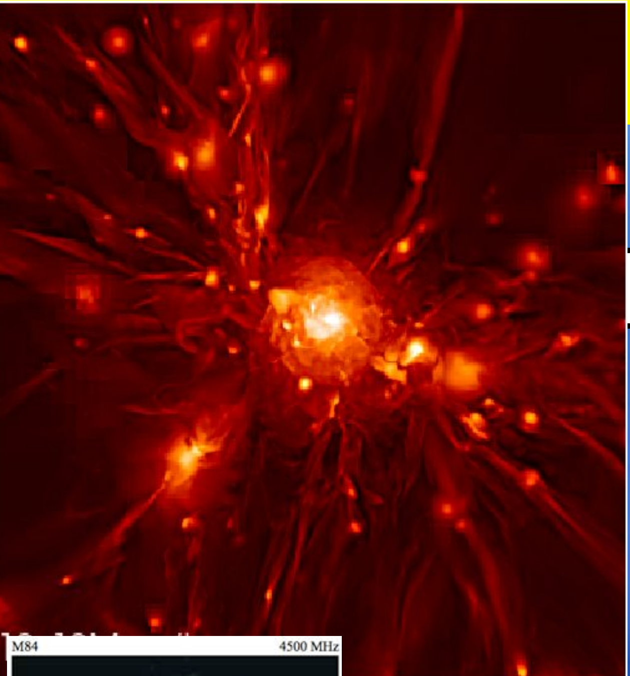


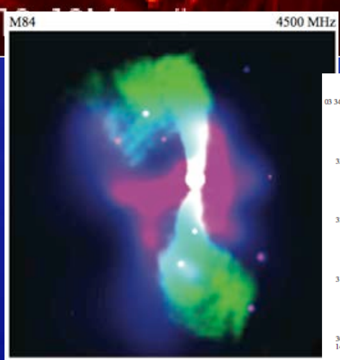
10^{26}
10^{25}
10^{24}
10^{23}
10^{15}
$P_{1.4GHz}$ [Watt/Hz]
M_{500} [$M_{\odot}$]
A1451
Z0634

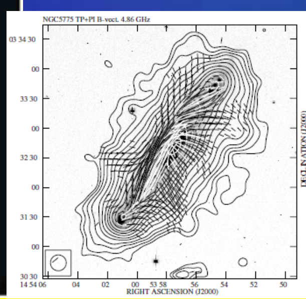
CR-acceleration

(eg Brunetti + Jones 14)

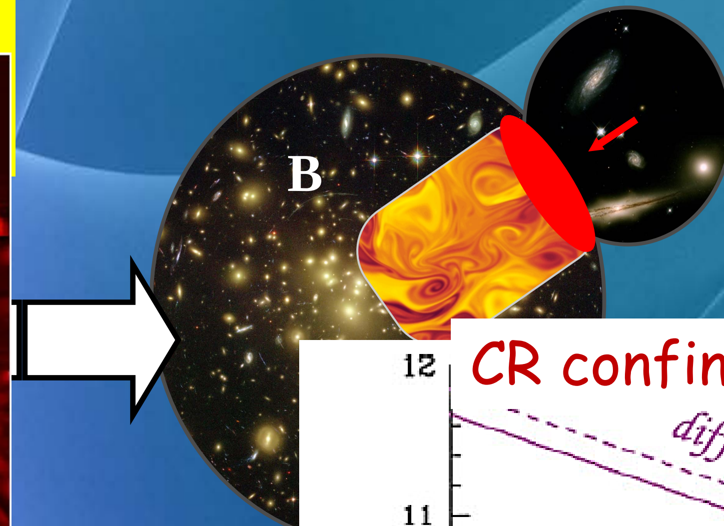
Mergers guide CRe acceleration/dynamics and/or amplify B



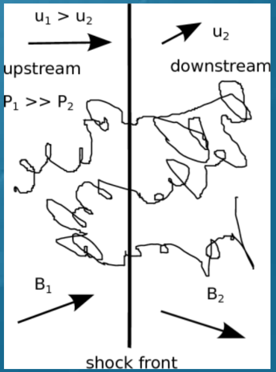




Astrophysical sources Galaxies (SN), AGN..



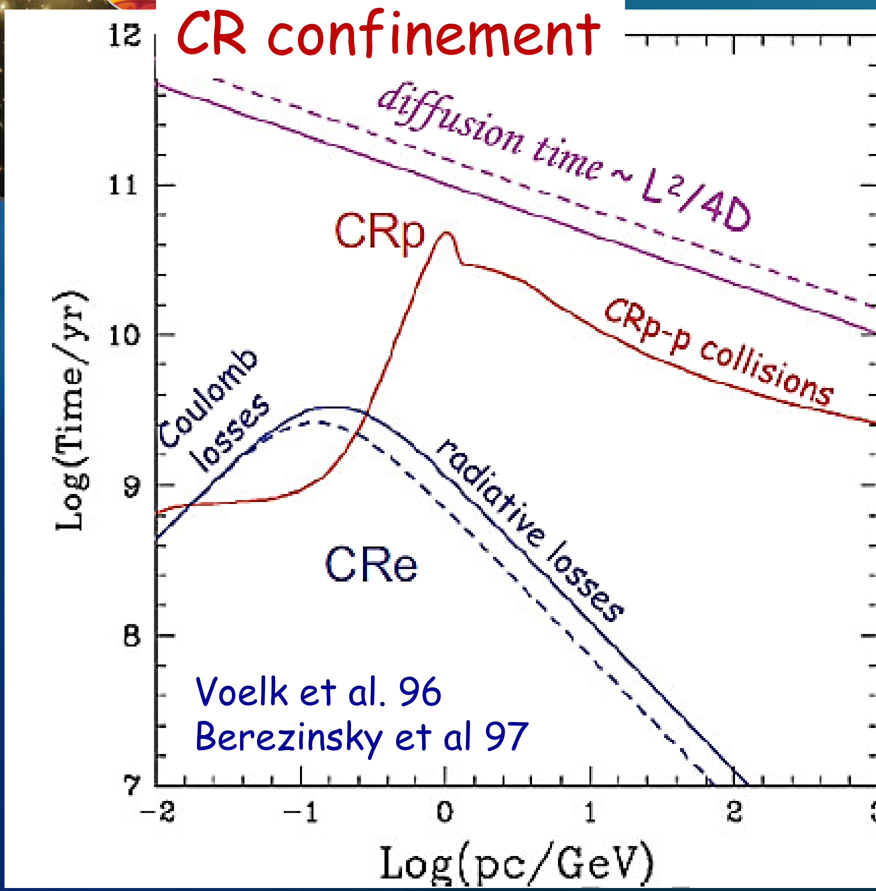
(1)



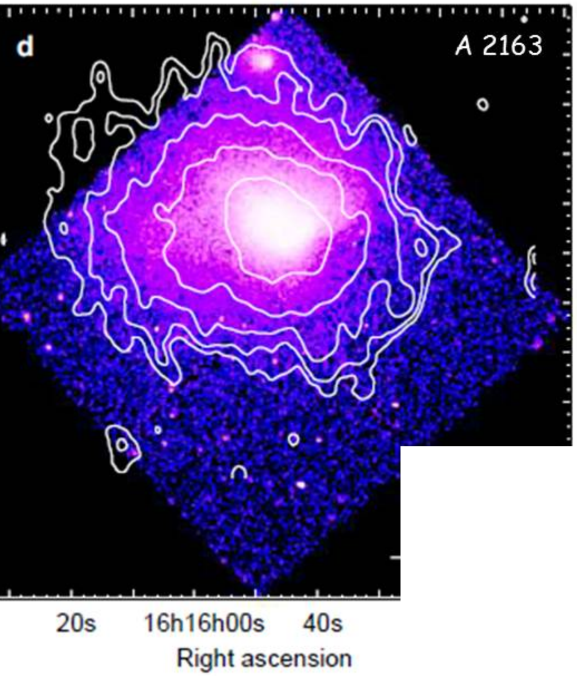
SHOCKS

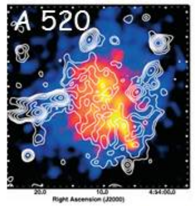
accelerate CRe$^{\pm}$,CRp

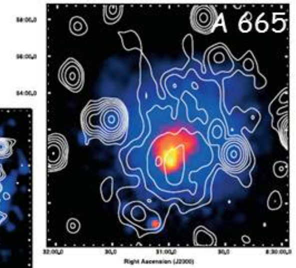
CR confinement



Brunetti & Jones 2014





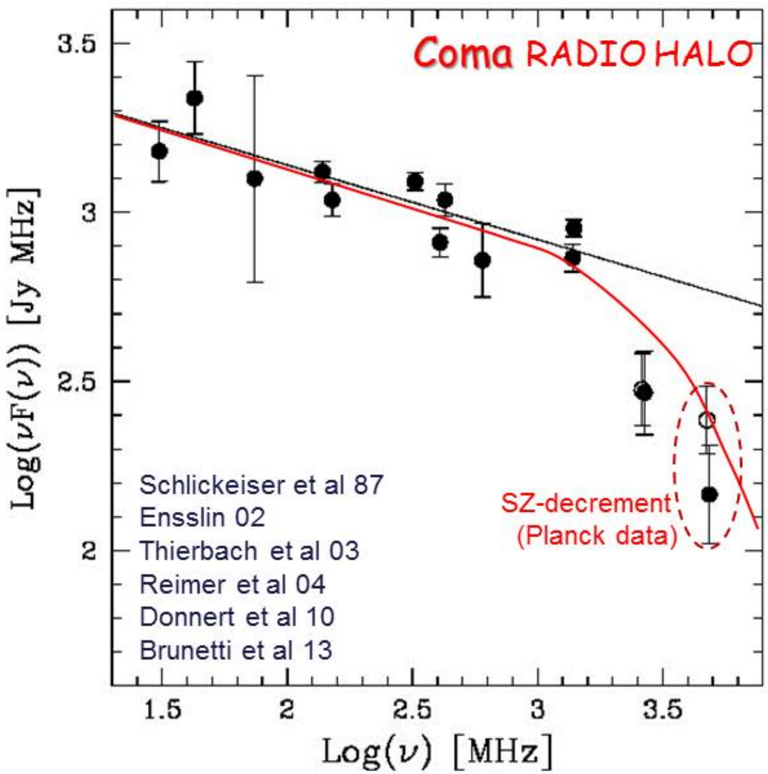


Turbulent acceleration scenario:

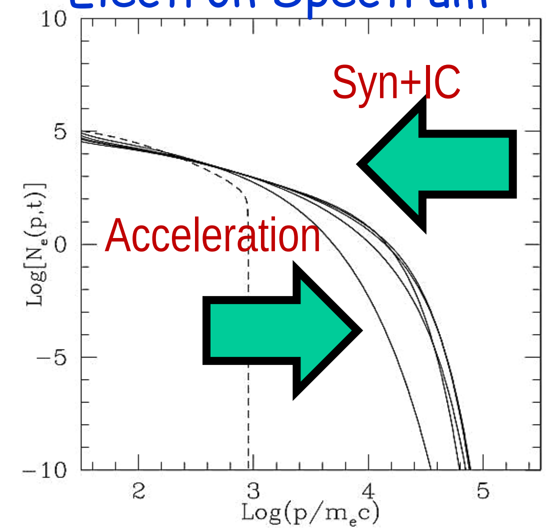
Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on second-order Fermi

Brunetti+01, Petrosian 01, Ohno+02, 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



Manifestation of complex microphysics in the ICM:

Energy is transported From Mpc to Mm scales into non-thermal particles.

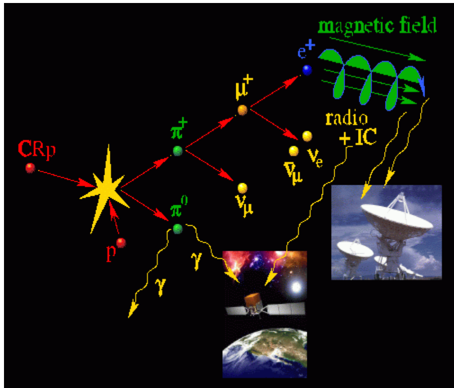
This requires a hierarchy of complex mechanisms and plasma/kinetic effects!

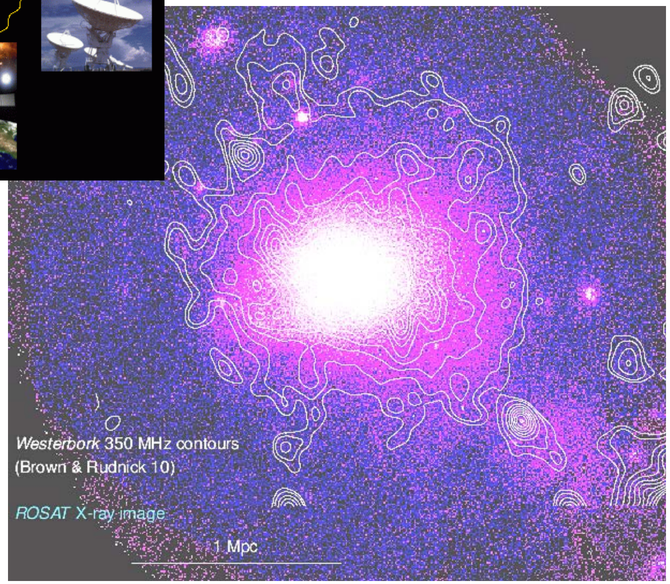
[eg Brunetti+Jones 14 rev]

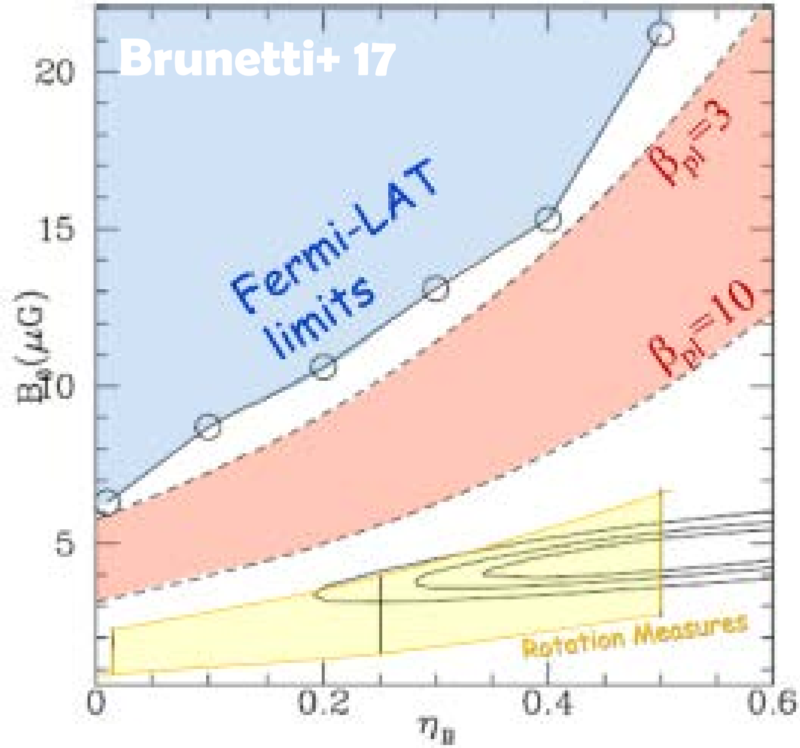
$T_{acc} \sim T_{rad}$(GeV+) =100-300 Myr

LOFAR + MWA are unveiling many examples of gentle reacceleration in the ICM

Giant Radio Halos: How much is contributed by secondaries ?







$$\frac{L_{radio}}{L_\gamma} \propto \left(\frac{B^{\alpha+1}}{B^2 + B^2_{cmb}}\right)$$

Gamma-ray limits + Syn Flux constrain the magnetic field

$$B(r) = B_0 \left(\frac{n_{ICM}(r)}{n_{ICM}(0)}\right)^{\eta_B}$$ (Bonafede+ 10)

- Radio Halo spectrum
- Radio Halo brightness distribution

- B much higher than RM
- B dynamically important

Jeltema+Profumo 11, Brunetti+12, Zandanel+Ando 14, Ackermann+16

Too many CRp are necessary to contribute significantly

$$p + p \to \pi^0 + \pi^+ + \pi^- + \text{anything}$$
$$\pi^0 \to \gamma\gamma$$
$$\pi^\pm \to \mu^\pm + \nu_\mu(\bar{\nu}_\mu), \quad \mu^\pm \to e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e).$$

$$\frac{L_{radio}}{L_\gamma} \propto \left(\frac{B^{\alpha+1}}{B^2 + B^2_{cmb}}\right)$$

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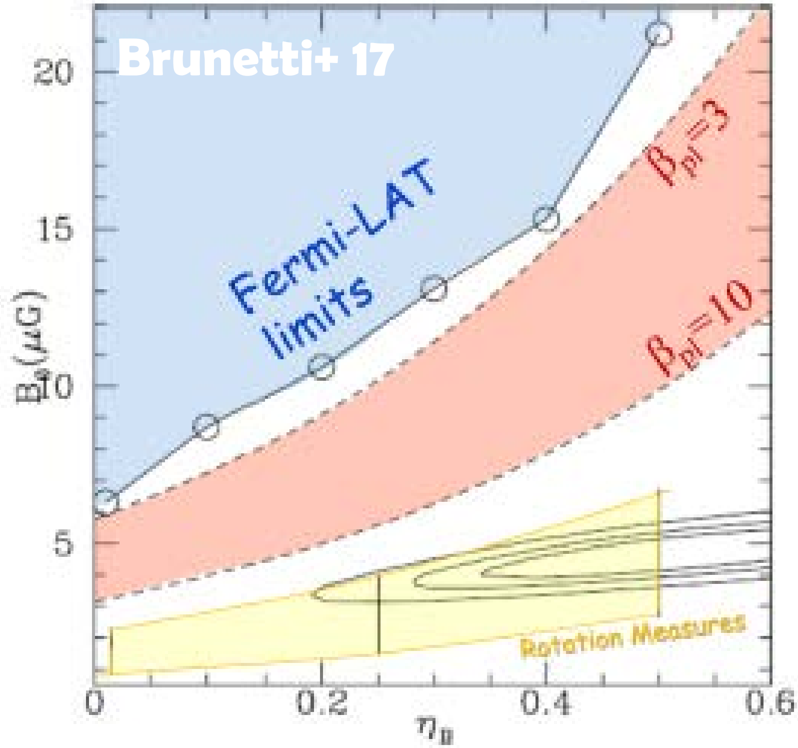

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