Cosmic Rays & magnetic turbulence in galaxy clusters

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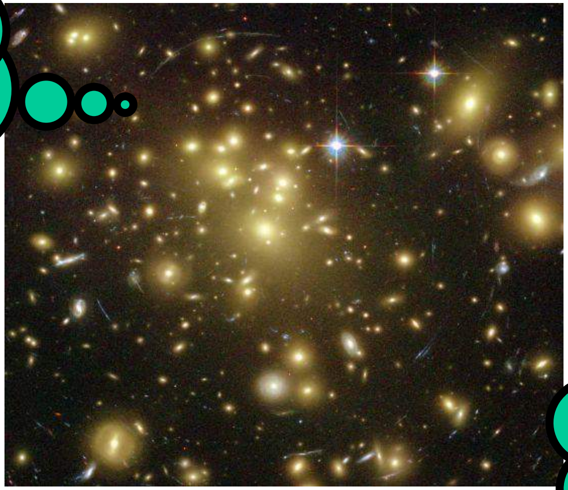
Clusters of Galaxies: the largest gravitational structures in the Universe ($M \approx 10^{14}$-$10^{15} M_{sun}$, $R_V \approx$ 2-3 Mpc)

≈30-300 galaxies



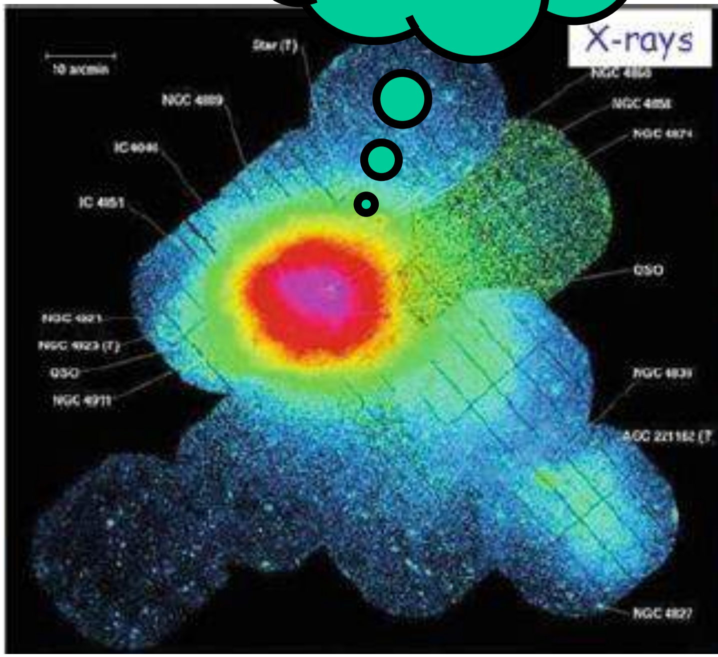
Galaxy cluster matter :

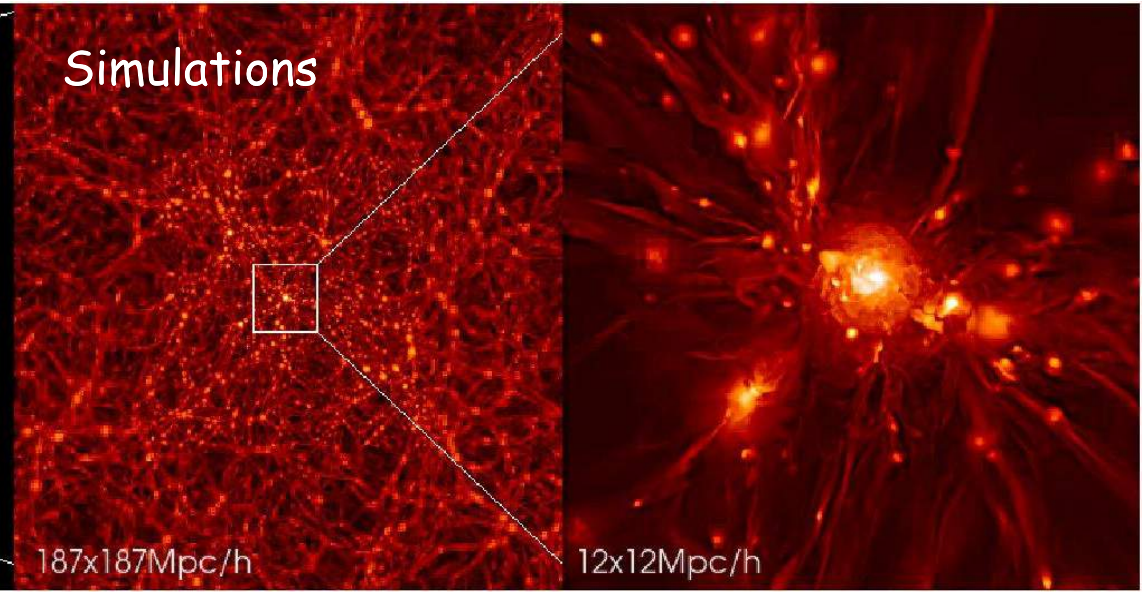
Barions
- 10% of stars in galaxies
- 15-20% of hot diffuse gas: **ICM**

Dark Matter 70%

$\approx 10^{-3}$ e/cm^3

T ≈ 10^8 K





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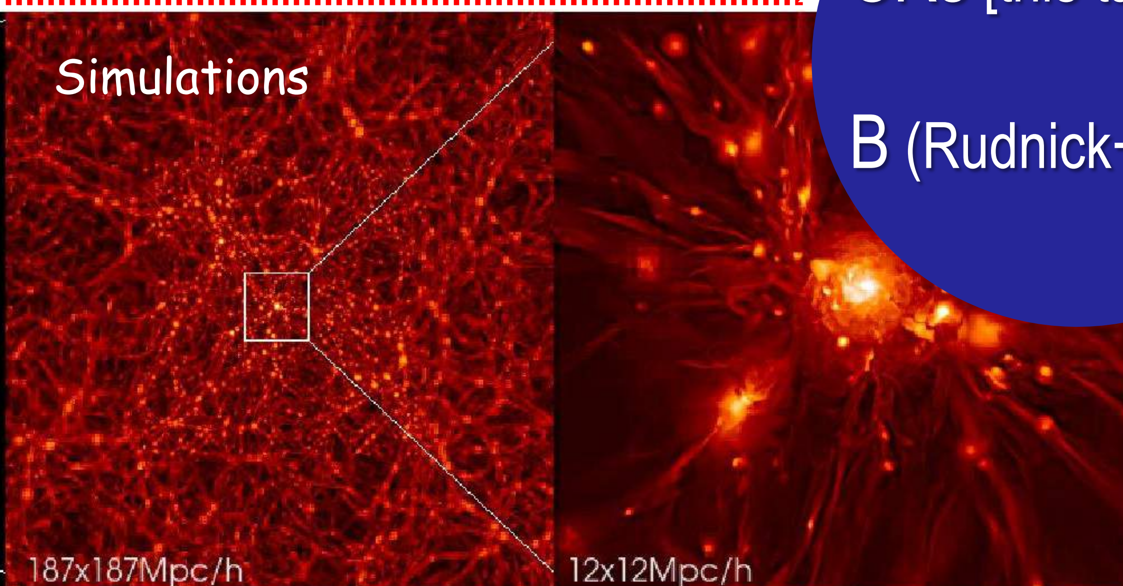
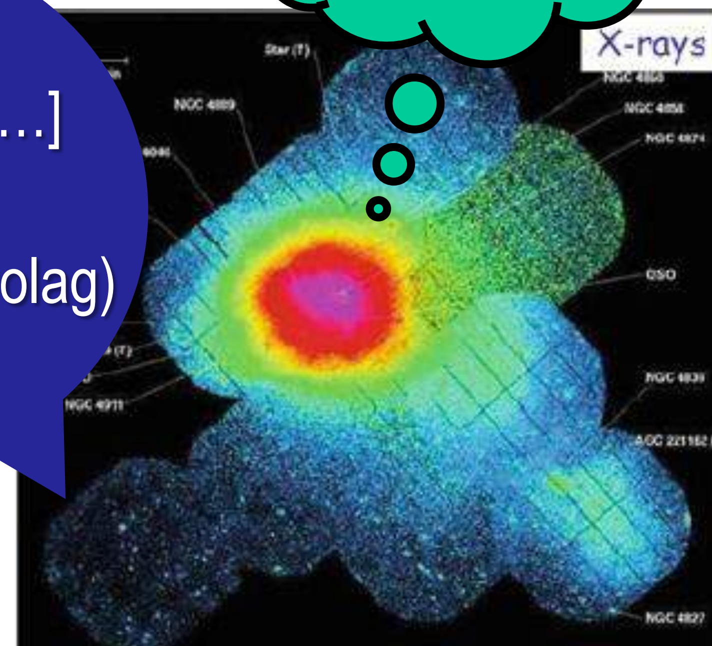


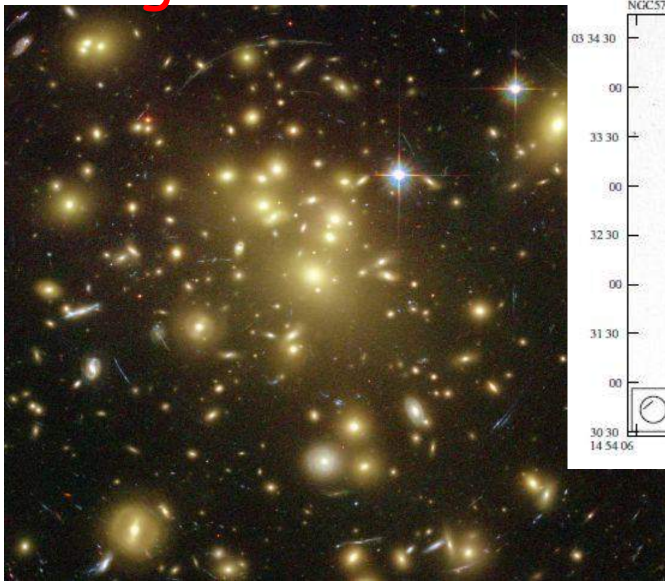
CRs [this talk…]

B (Rudnick+Dolag)

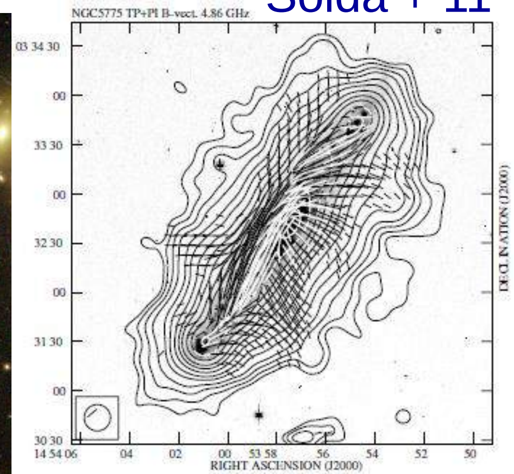


Sources of CRs in galaxy clusters

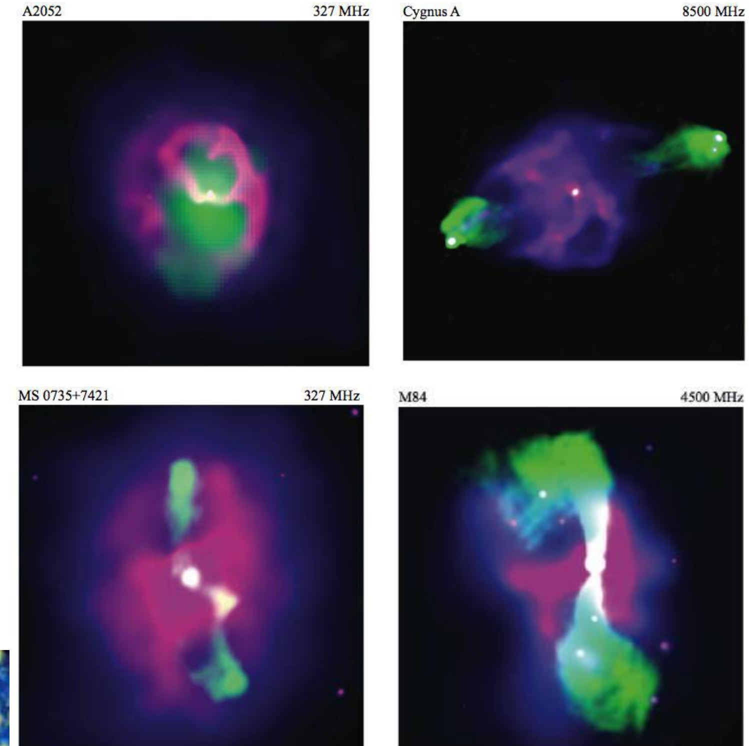
100 galaxies



Soida + 11

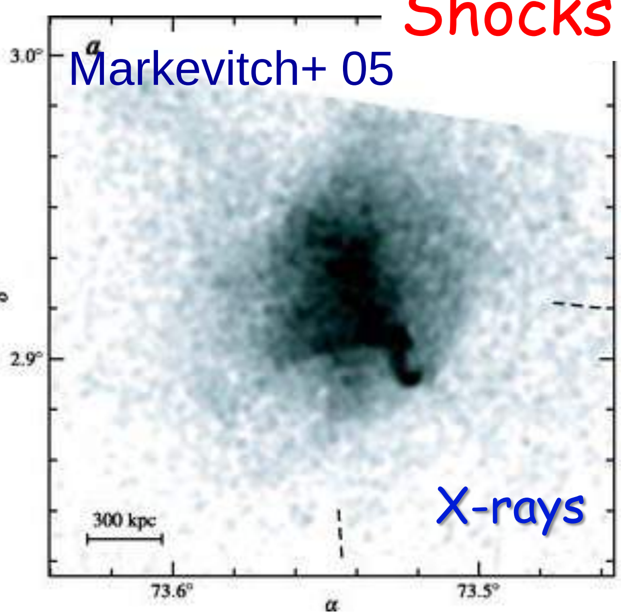


AGNs

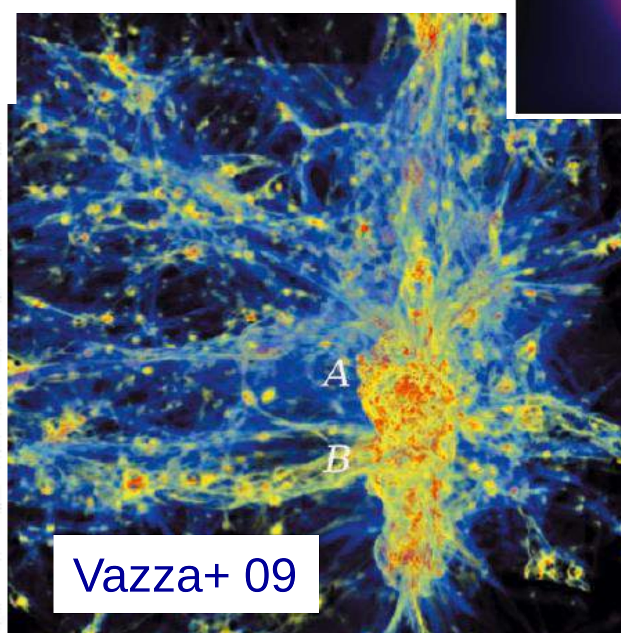


Shocks

Markevitch+ 05



X-rays



Vazza+ 09

Shocks are responsible for ICM heating.

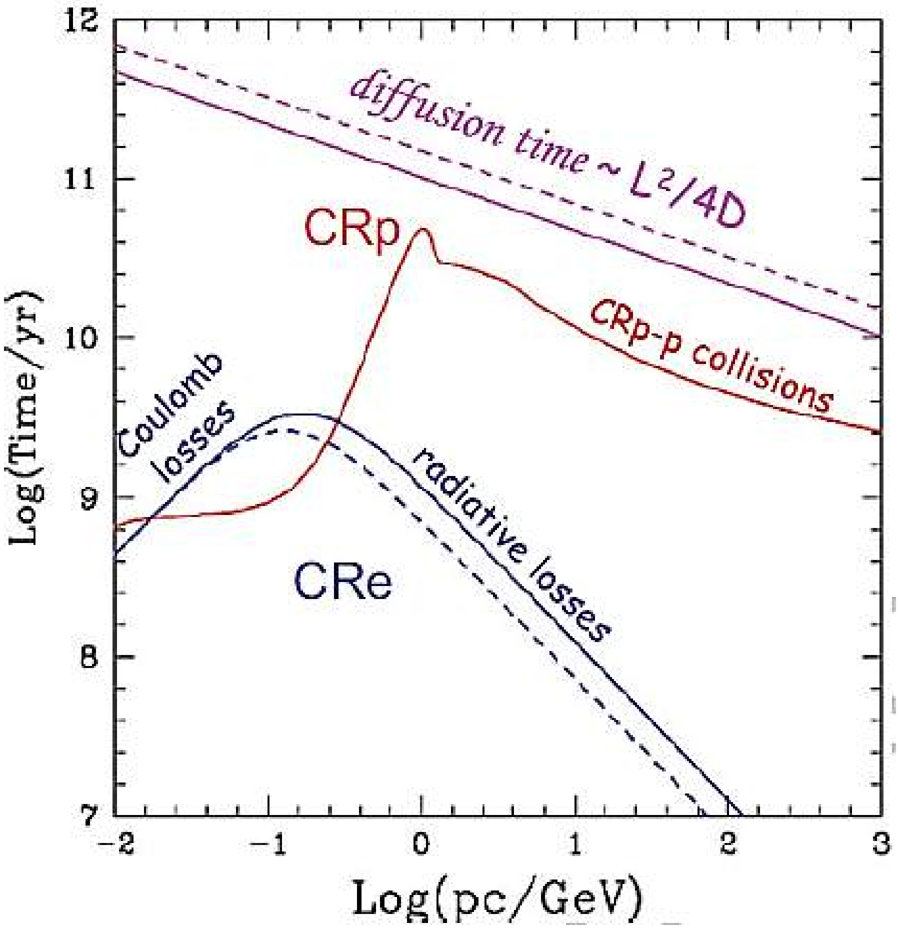
Substantial fraction of ICM energy is expected in CRs *IF* shocks works like in SNRs

[GB + Jones 14 rev]

CR confinement

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

Brunetti & Jones 14 for rev



- CRe short living and accumulated at E=100-300 MeV
- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

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

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

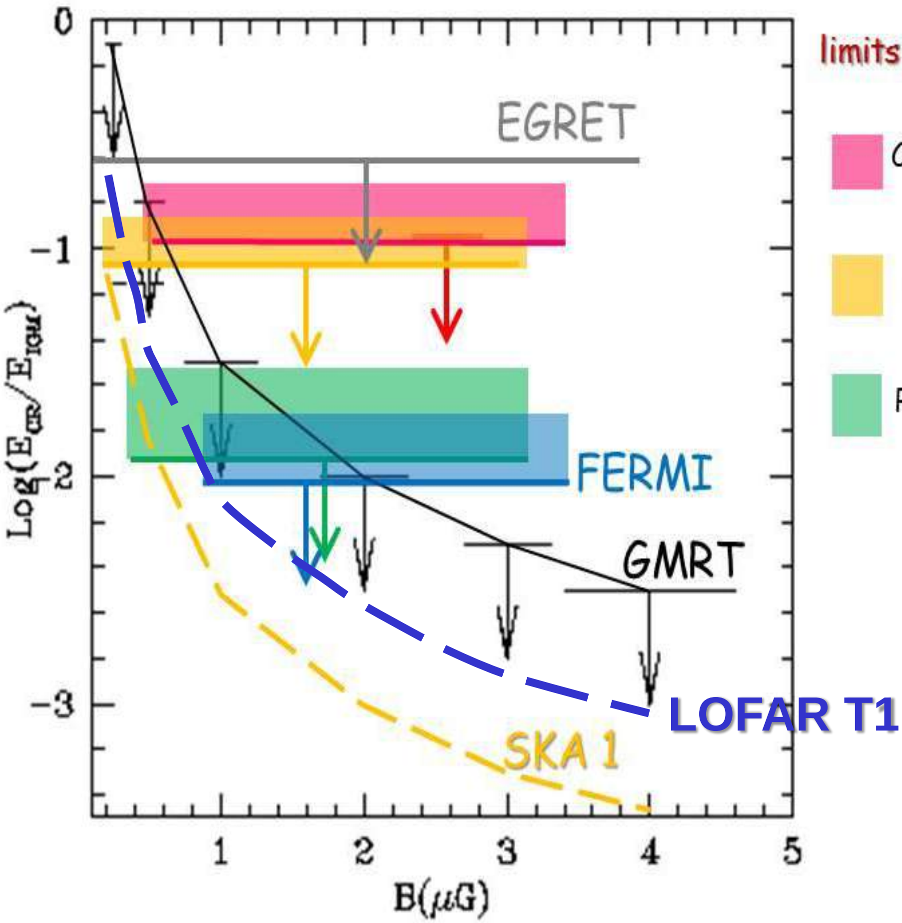
Generation of secondary particles

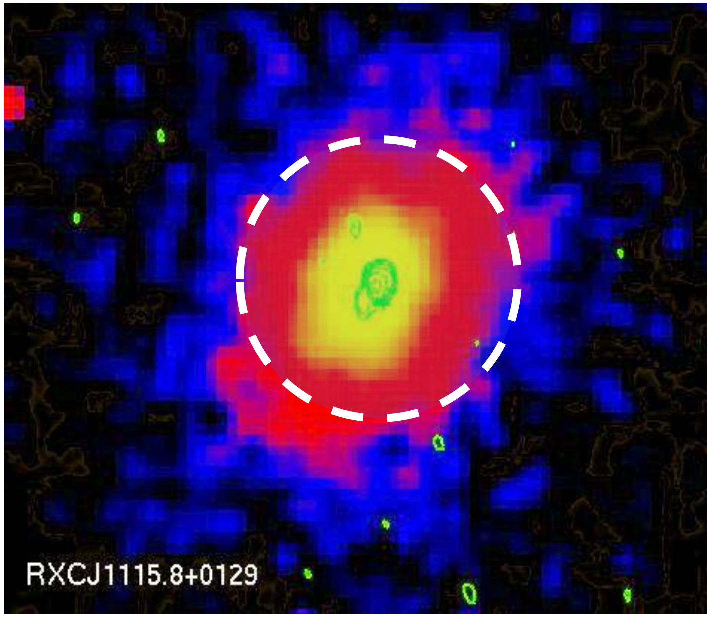
$$p + p \rightarrow \pi^0 + \pi^+ + \pi^- + \text{anything}$$

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

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

Limits to the CRp energy budget



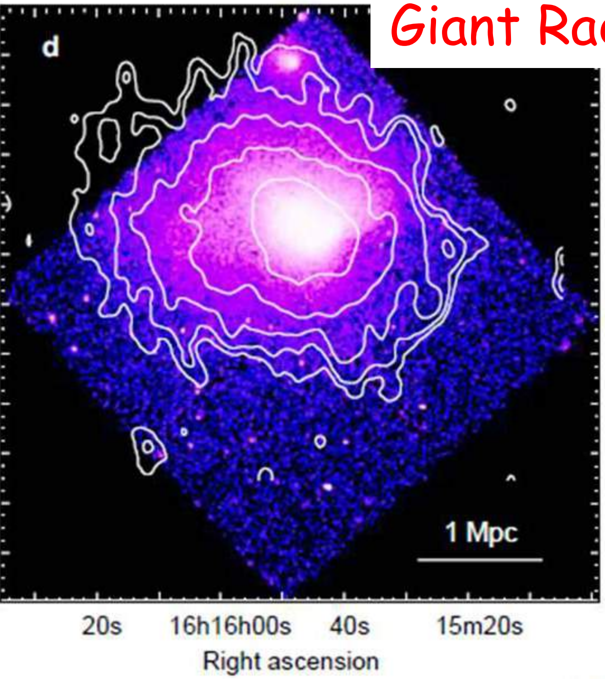


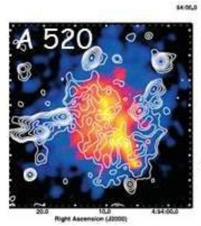
Limits on the synchrotron flux produced by secondary electrons in the ICM allow to calculate corresponding limits on (B, ECRp).

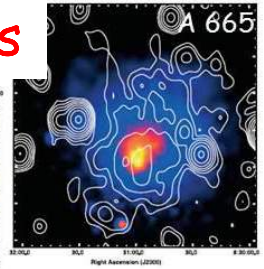
Reimer et al. 04, Pfrommer & Ensslin 04,Perkins et al. 06, 08, Brunetti et al. 07,08, Perkins et al. 08, Aharonian et al. 08, Aleksic et al. 09,12, Ackermann et al 10,14, Arlen et al 12, Griffin et al 14, Zandanel+Ando 14, …

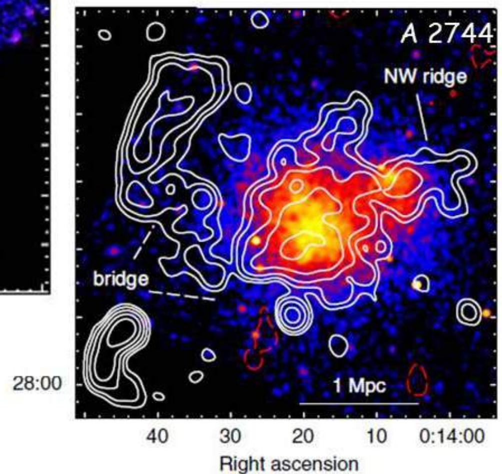
Cluster-scale radio emission

Giant Radio Halos







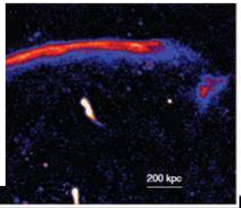


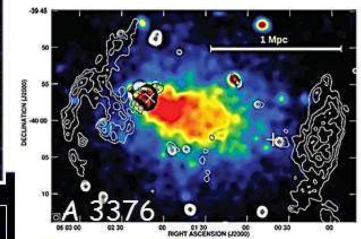
- Steep spectrum sources
- Low brightness

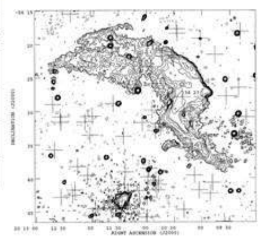
Synchrotron radiation FROM the ICM

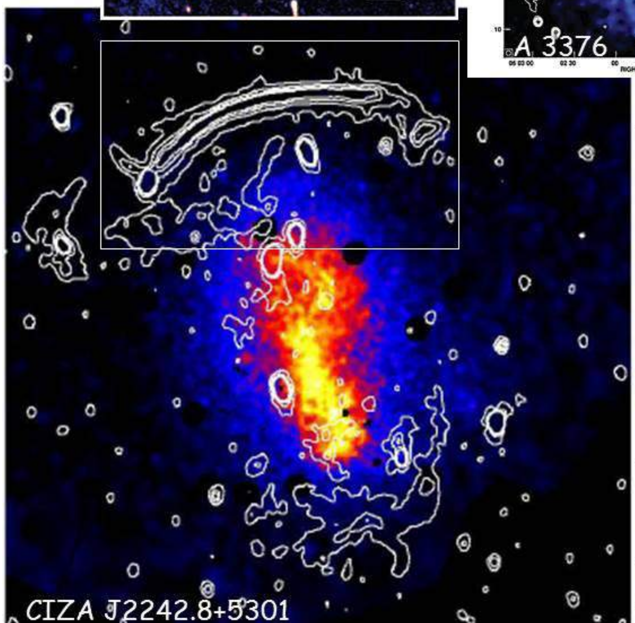
Relativistic GeV+ electrons (protons?) and B distributed on Mpc-scales…

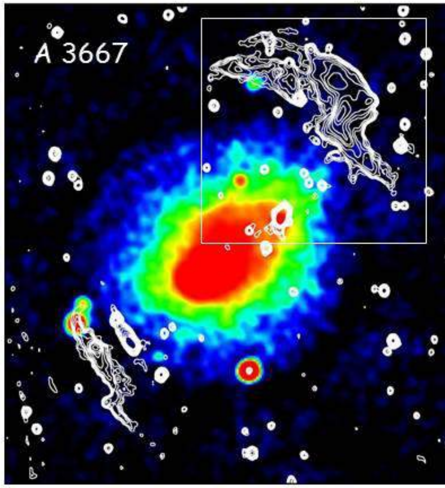
Giant Radio Relics









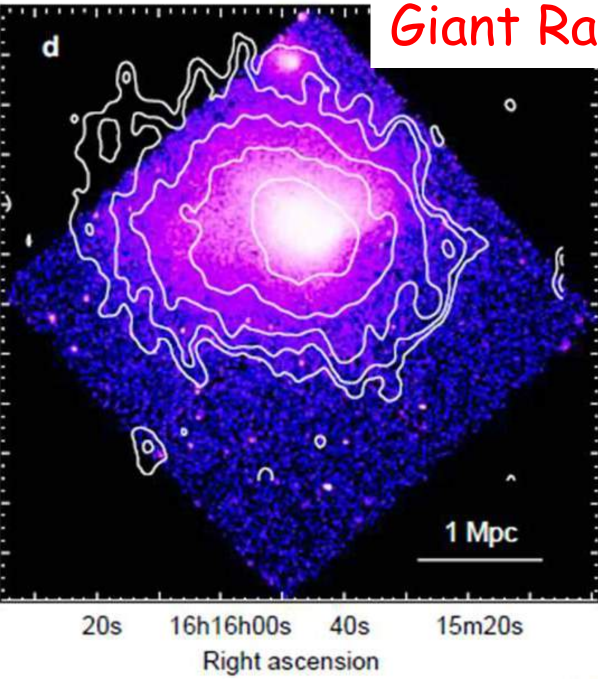


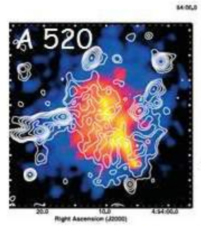
Diffuse Syn emission & CRe are "unique" probes of non-thermal activity in galaxy clusters

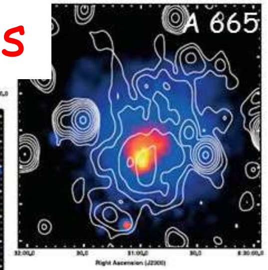
- ORIGIN & Physics ??
- IMPACT on thermal ICM ?? (microphysics & dynamics)

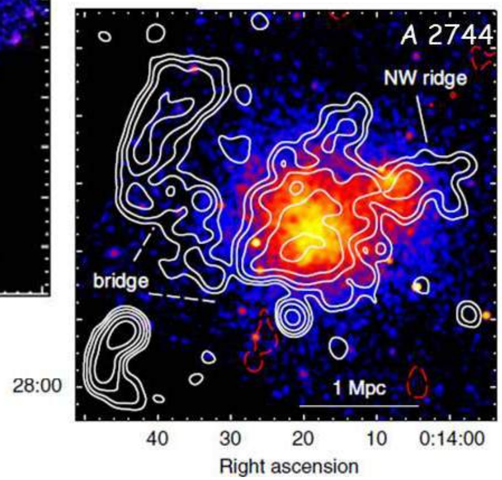
Cluster-scale radio emission

Giant Radio Halos









- ❑ Steep spectrum sources
- ❑ Low brightness

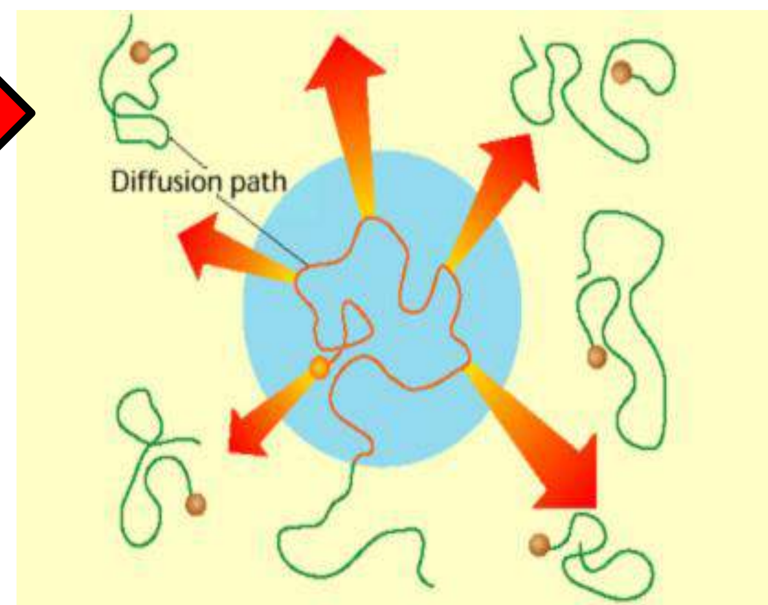
Synchrotron radiation FROM the ICM

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

Diffusion problem (Jaffe 1977)

$t_{diff} >> t_{cool}$

What we see is not produced "directly" by the CRs sources

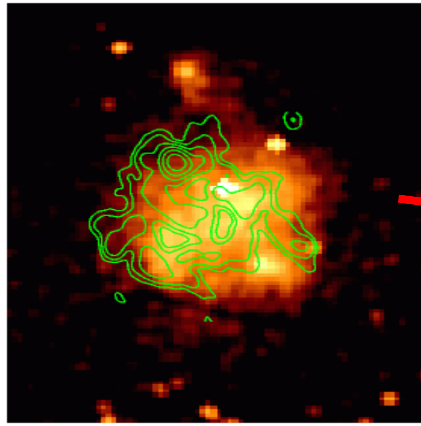


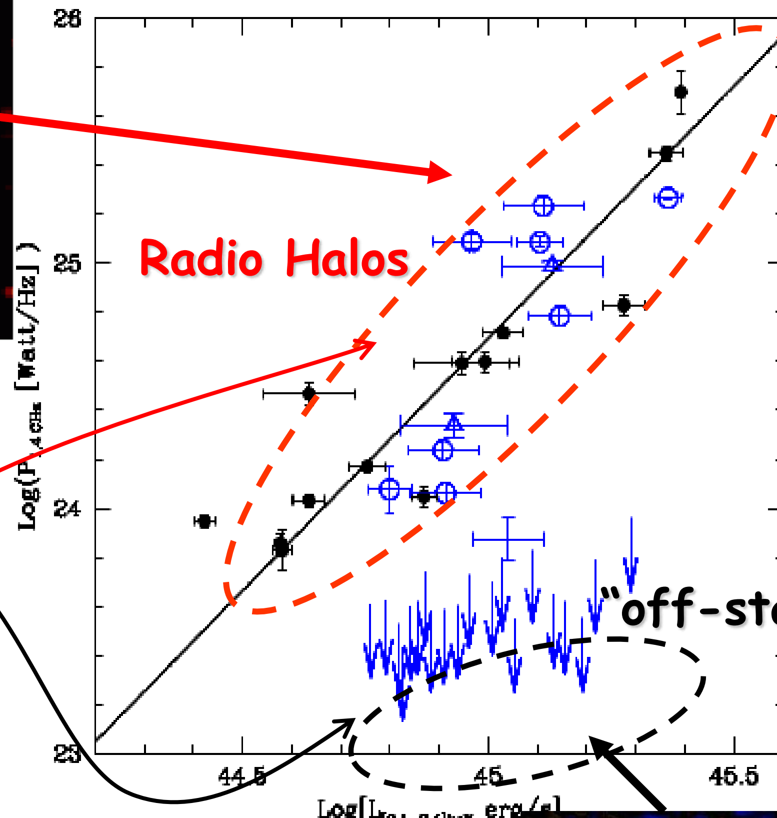
➢ ORIGIN & Physics ??

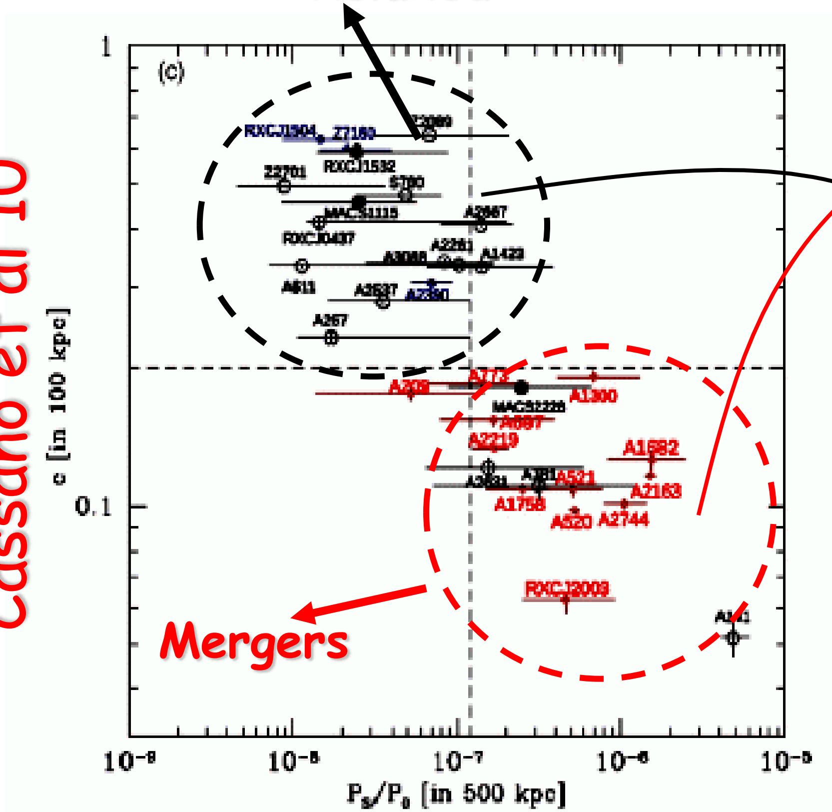
"in situ" mechanisms operating within clusters drain energy into relativistic particles and magnetic fields

Cluster mergers - NT connection

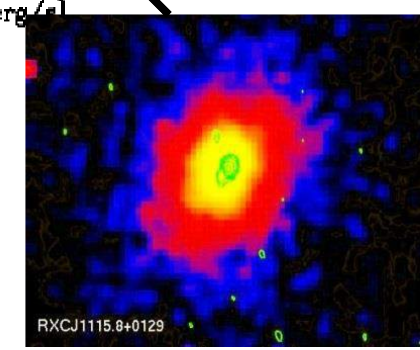
Venturi et al 08, Brown et al 11
Basu 12, Cassano et al 13, Sommer &
Basu 14, Kale et al 15, Cuciti et al 15





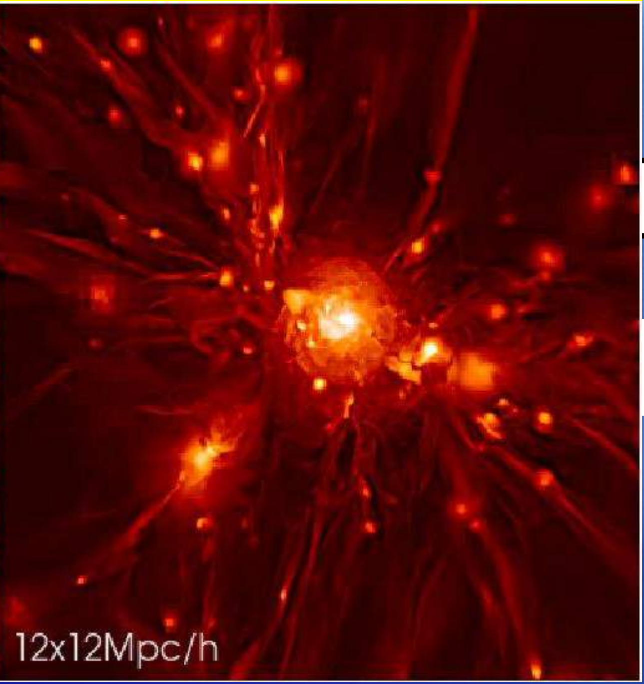


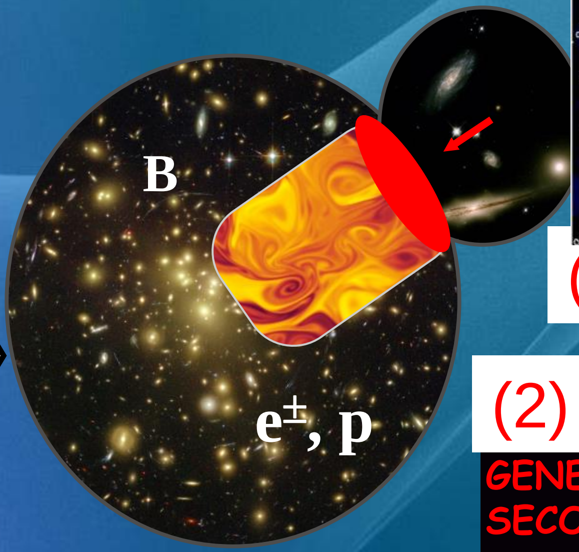
Radio halos probe the dissipation of kin energy in the DM-driven merger events into CRs and B

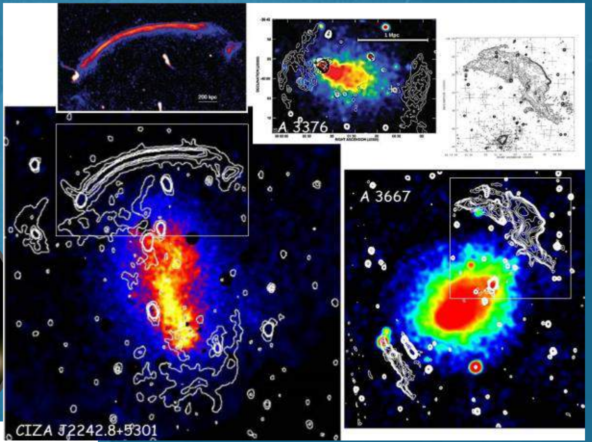


Mergers & CR-acceleration

Mergers guide CRe acceleration/dynamics and/or amplify B





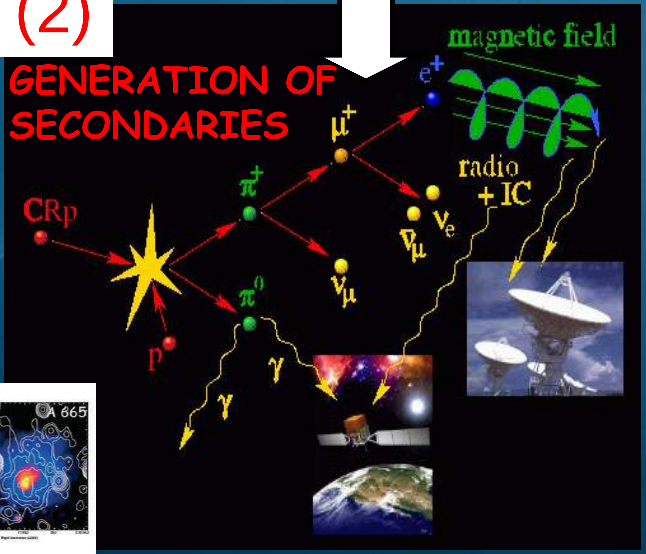


(1) SHOCKS

accelerate CRe$^{\pm}$,CRp

(2)

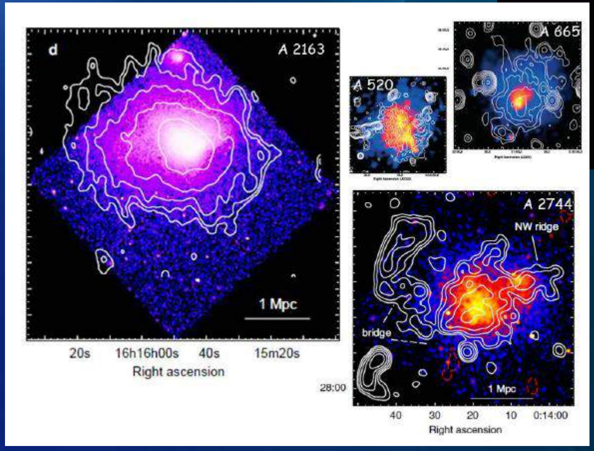
GENERATION OF SECONDARIES



(3)

TURBULENCE

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



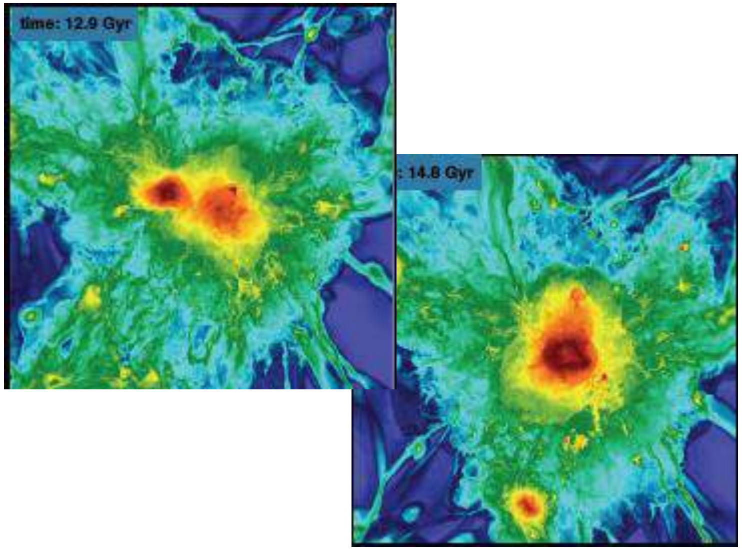
(4)

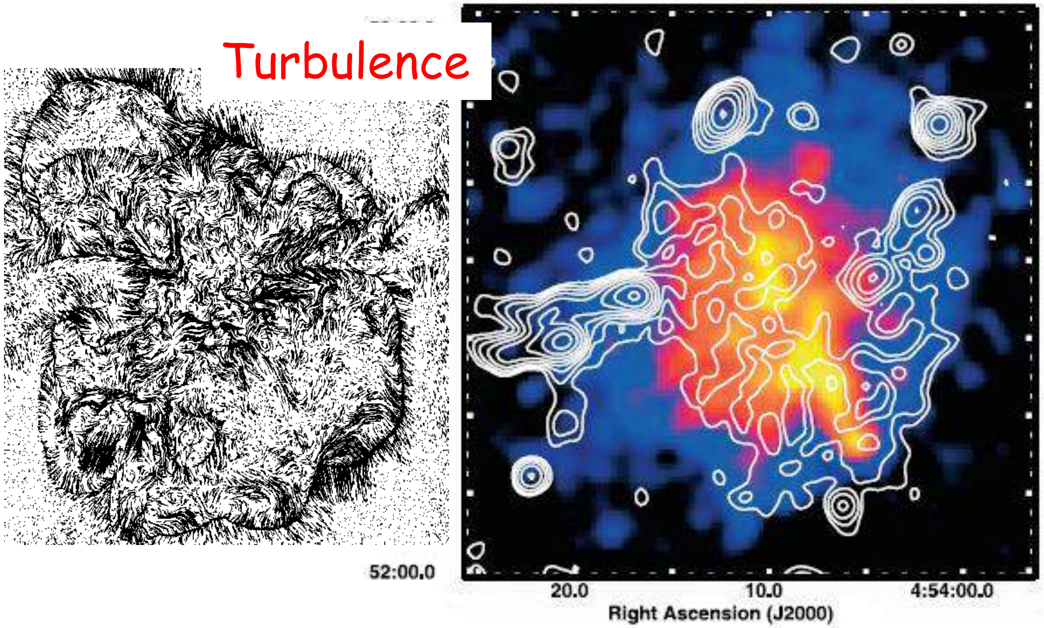
RECONNECTION

Brunetti & Jones 14
for recent review

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 15, Pinzke et al 15, … .)





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

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

Radio halos probes physics of the ICM at dissipation scales.

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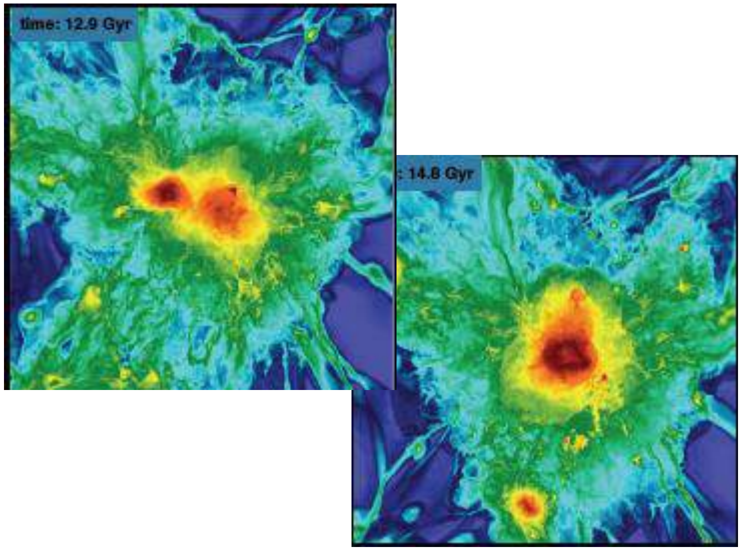
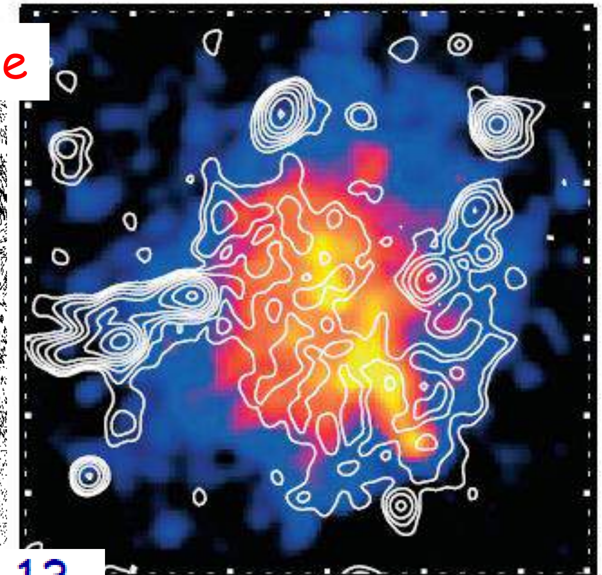
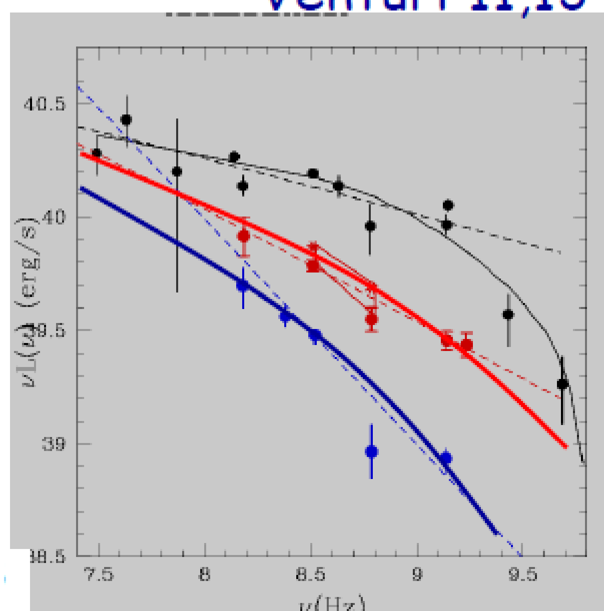


Turbulence



Venturi 11,13



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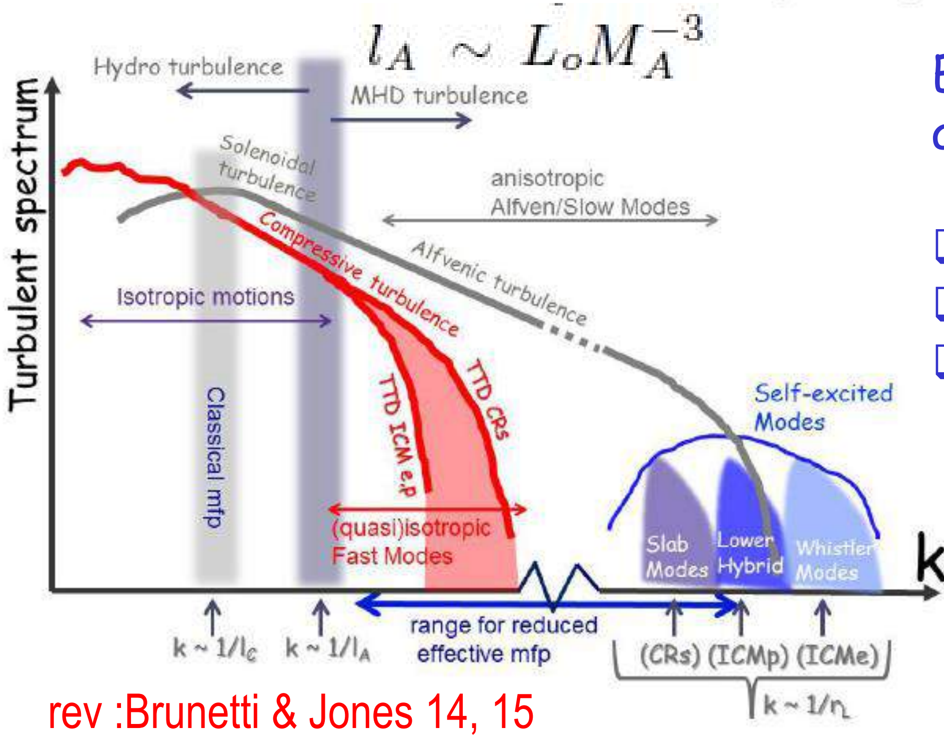
Radio halos probes physics of the ICM at dissipation scales.

Acceleration time-scale from Syn spectral breaks is 100 Myrs

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

Turbulence picture in the ICM



rev :Brunetti & Jones 14, 15
Bruggen & Vazza 15

Energy driven at large scale transported and channelled into CRs at smaller scales

- ❑ Sub-sonic
- ❑ Super-Alfvenic
- ❑ beta_pl = 100

In current reacceleration picture we use compressible modes that interact with particles via Transit-Time-Damping.

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

Interaction between magnetic momentm of particles and parallel gradient of B

[Fisk 76, Miller 91, Schlickeiser & Miller 98, Yan & Lazarian 04, Brunetti & Lazarian 07, ..]

Lepto-hadronic models : (re)acceleration of primary CRp+CRe and secondary CRe

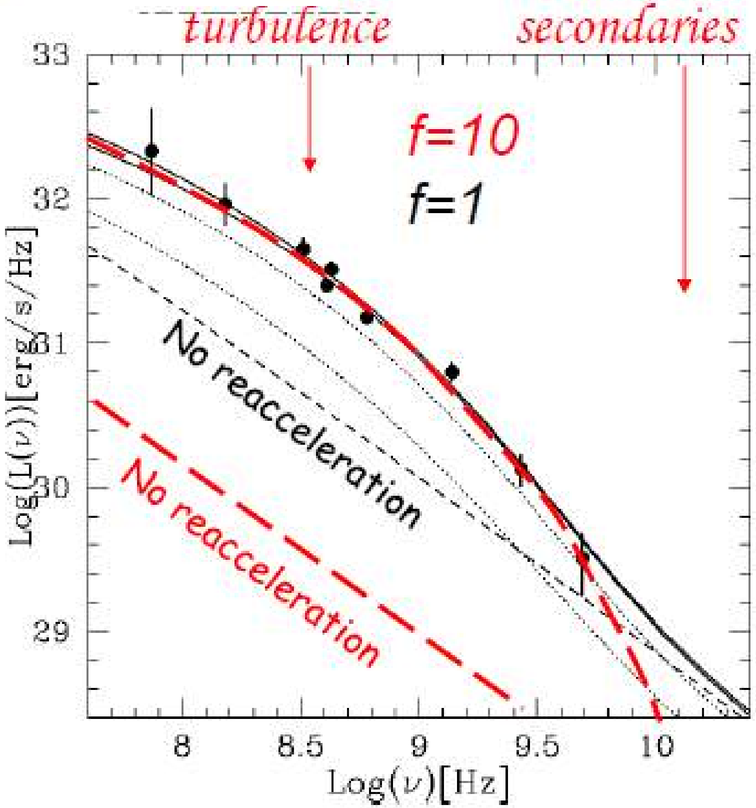
primary vs secondary particles

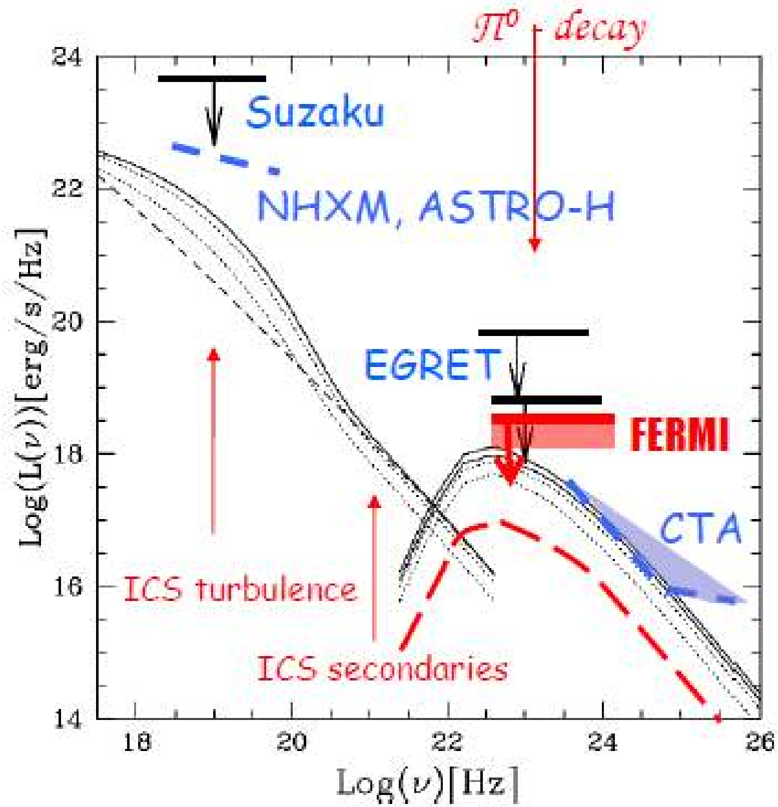
$$f = \frac{PRIMARY\, e^{\pm}}{SECONDARY\, e^{\pm}} + 1$$

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

Interaction between magnetic momentm of particles and parallel gradient of B

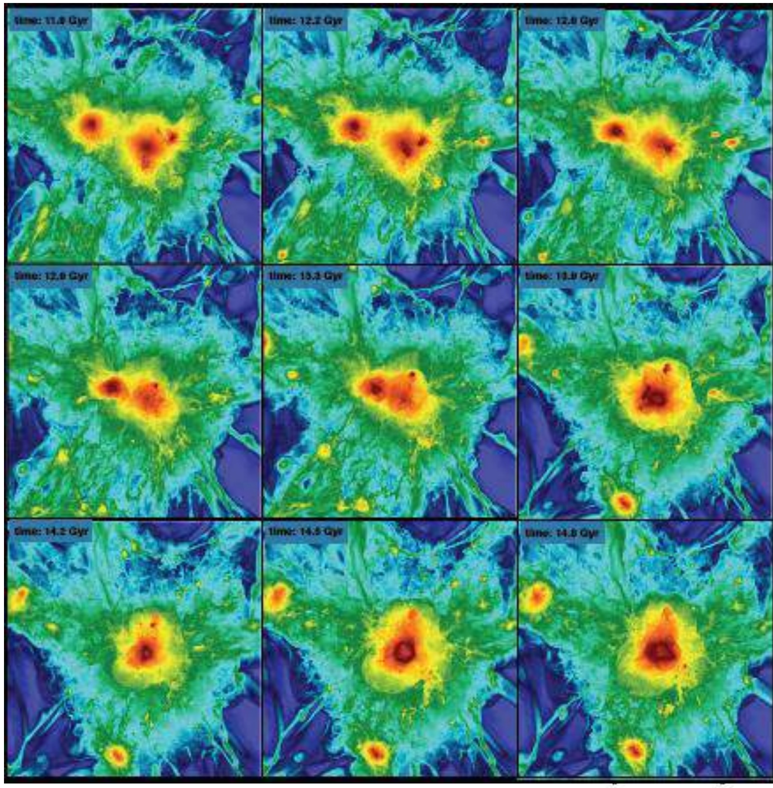
$E_{tur} \approx 10\ \%\ E_{th}$

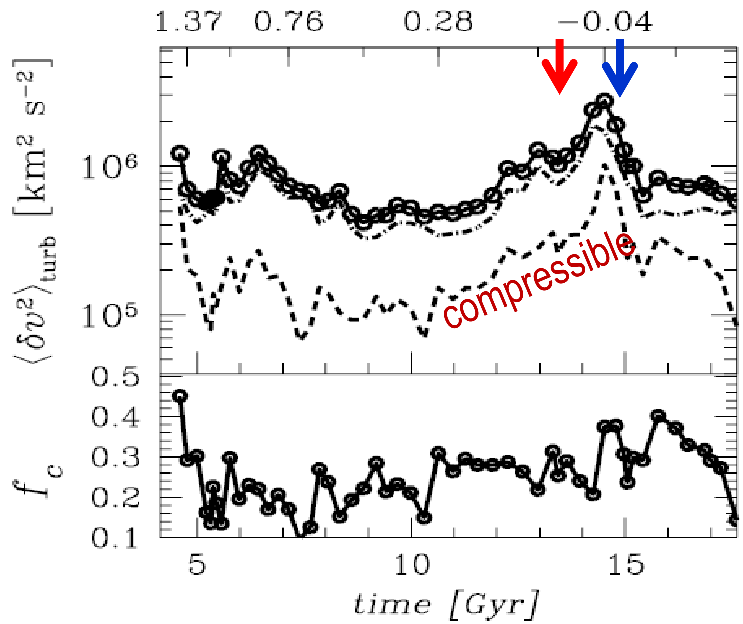




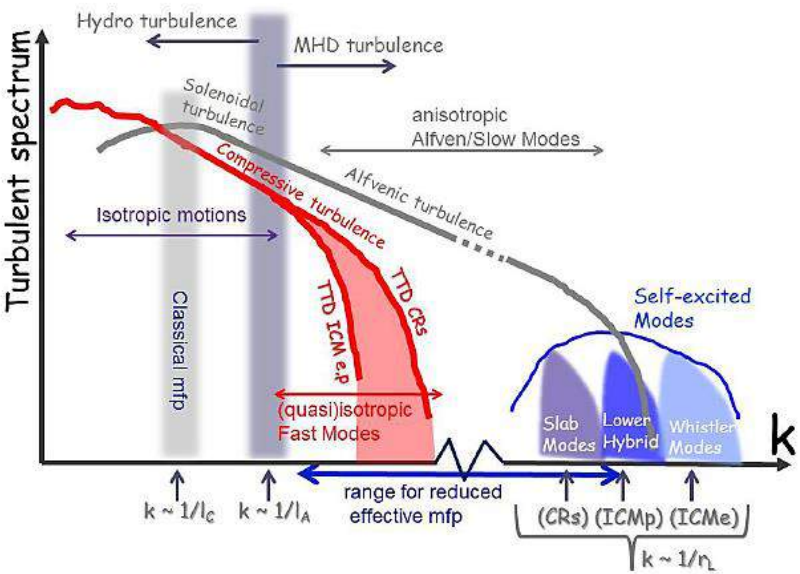
Brunetti, Blasi, Cassano, Gabici 09
Brunetti & Lazarian 11

Incompressible turbulence dominates

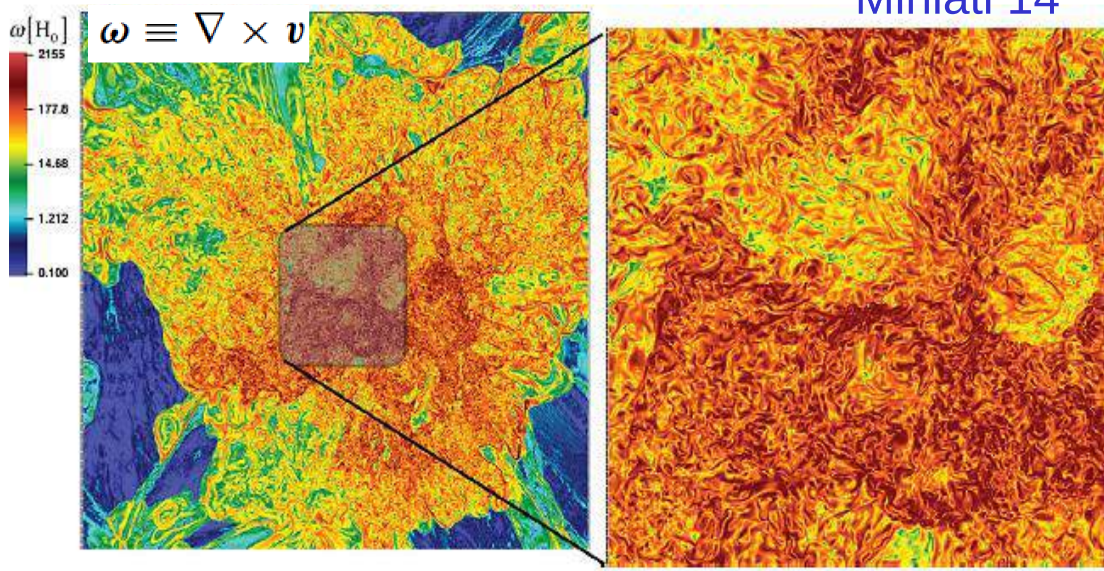




Miniati 15

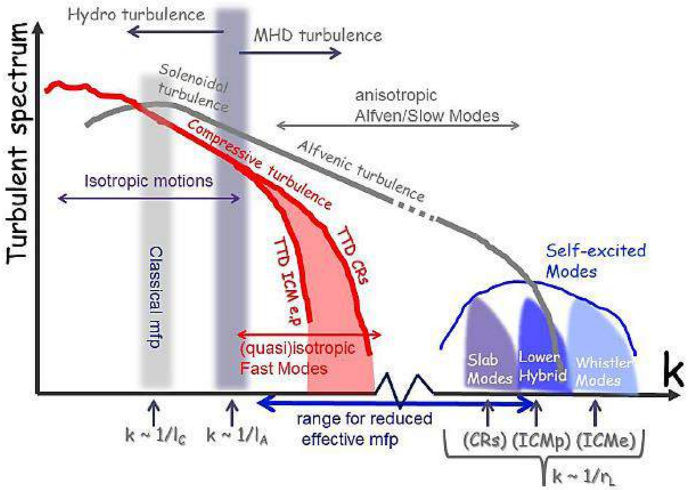


Miniati 14



Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

[Brunetti & Lazarian, submitted]



BASIC ASSUMPTIONS :

- Assume thermal ICM behaves a fluid (see Santos-Lima's talk)
  [Lazarian + Beresnyak 06, Schekochihin + 06, .. GB+Lazarian 11, Santos-Lima + 14, ..]

- Use MHD as a "guide"

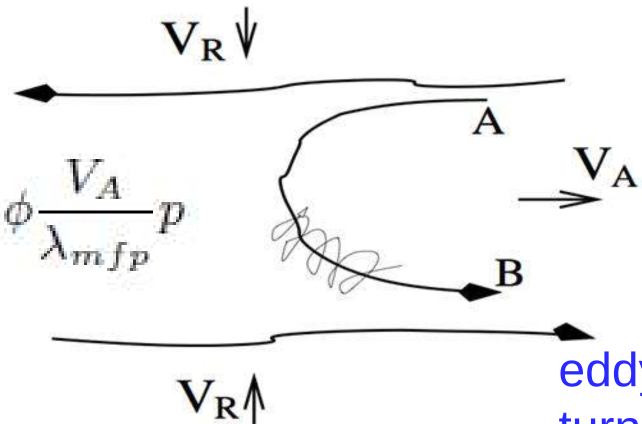
- CRs are the only collisionless component (diffusing)

- Use B-diffusion in turbulent reconnection :
  allows to scatter/accelerate particles without compressions
  [Lazarian+Vishniac 99, deGouveia dal Pino+Lazarian 03,05, ...]

Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

[Brunetti & Lazarian, submitted]

Fermi-I like (DG dal Pino & Lazarian 03,05, DG dal Pino's talk)



$$\frac{dp}{dt} \sim \phi \frac{V_A}{\lambda_{mfp}} p$$

reconnecting regions

$$l_A \sim L_o M_A^{-3}$$

$$\Delta p = p\phi \frac{V_A}{\lambda_{mfp}} \min\left\{ \frac{l_A}{V_A}, \frac{l_A^2}{D} \right\}$$

eddy turn-over (slow diffusion)

fast diffusion

Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

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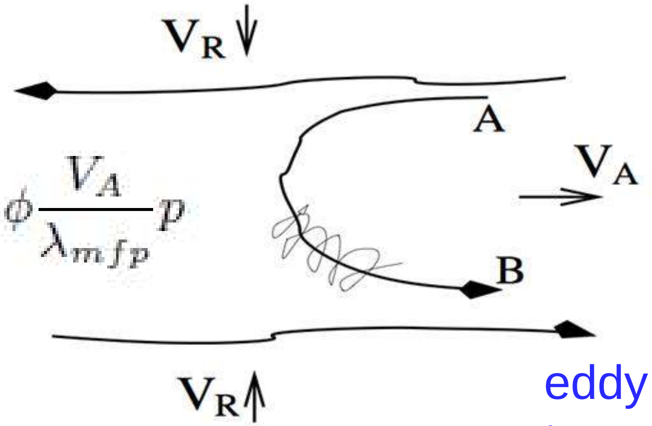

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fast diffusion

$$p >> \Delta p$$

fast diffusion regime

$$\lambda_{mfp} > l_A (3\phi V_A/c)^{1/2} \sim 0.05\, l_A$$

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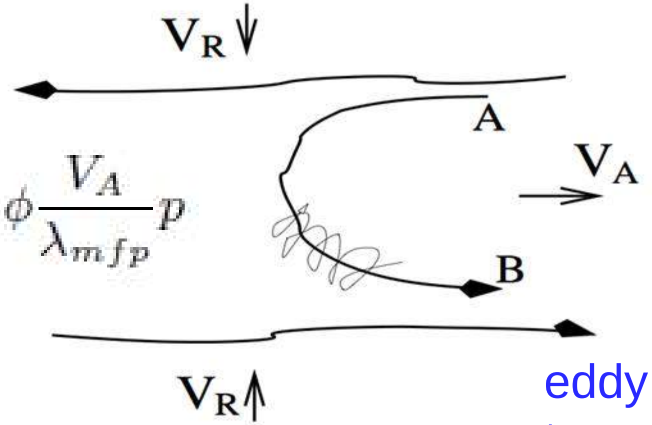

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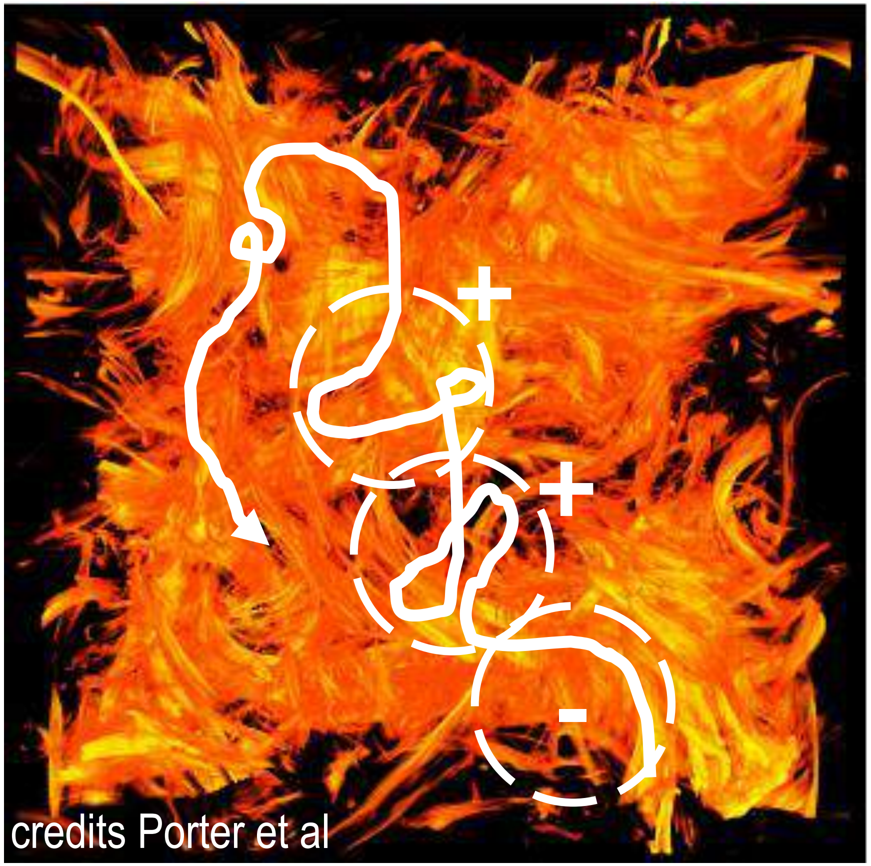
fast diffusion regime

$$\lambda_{mfp} > l_A (3\phi V_A / c)^{1/2} \sim 0.05\ l_A$$

Electrons diffusing through reconnecting ('collapsing') and dynamo ('stretching') regions



Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

[Brunetti & Lazarian, submitted]

$$D_{pp} \equiv \lim_{t\to\infty} \frac{1}{2t} \langle \Delta p(t) \Delta p^*(t+\tau) \rangle = \Re \int_0^\infty d\tau \langle \dot{p}(t) \dot{p}^*(t+\tau) \rangle = \langle \frac{\Delta p \Delta p}{2\Delta t} \rangle \sim 3 \left(\frac{l_A}{\lambda_{mfp}} \right)^2 \frac{V_A^2}{\lambda_{mfp} c} p^2$$

acceleration time

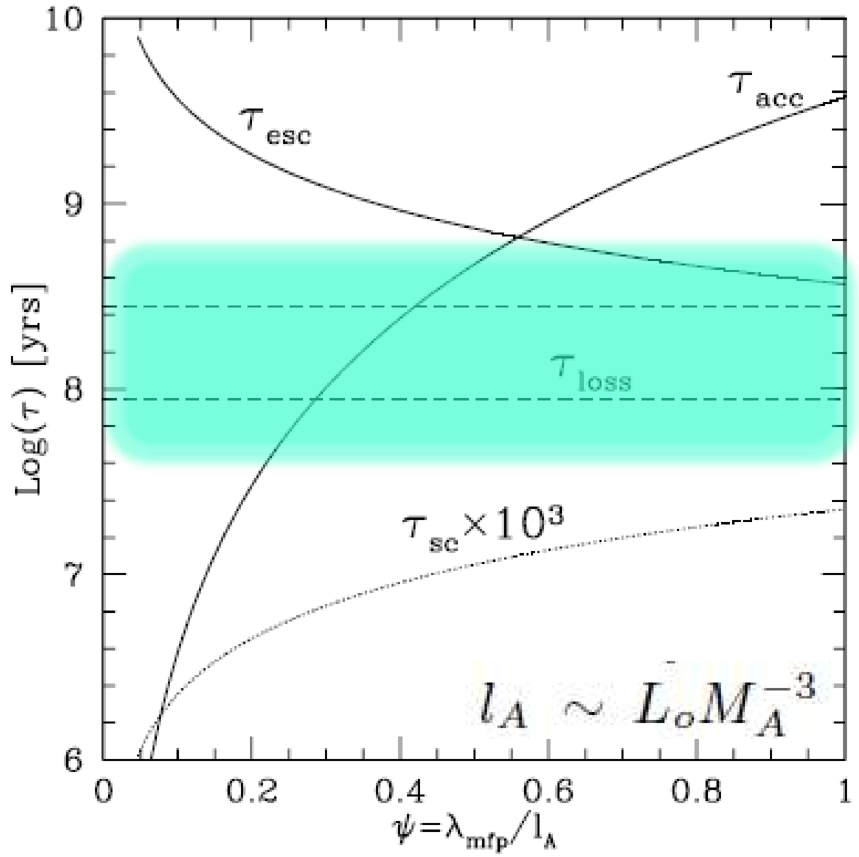
$$\tau_{acc} = \frac{p^2}{4 D_{pp}} \simeq \frac{\sqrt{2}}{12} \frac{c}{c_s^2} \frac{L_o}{\sqrt{\beta_{pl}}} M_t^{-3} \psi^3$$

losses

$$\tau_{loss}(Gyrs) = 4 \Big\{ \frac{1}{3} \left(\frac{\gamma}{300} \right) \left[\left(\frac{B_{\mu G}}{3.2} \right)^2 + (1+z)^4 \right] + \left(\frac{n_{th}}{10^{-3}} \right) \left(\frac{\gamma}{300} \right)^{-1} \left[1.2 + \frac{1}{75} \ln \left(\frac{\gamma/300}{n_{th}/10^{-3}} \right) \right] \Big\}^{-1}$$

escape

$$\tau_{esc} \sim \frac{L_{RH}^2}{4D} \sim \frac{3}{8\sqrt{2}c} \left(\sqrt{\beta_{pl}} M_t \right)^3 \frac{L_{RH}^2}{L_o} \psi^{-1}$$



RHs--cosmology : Populations .. of Radio Halos

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

Microphysics

$$D_{pp} \equiv \lim_{t \to \infty} \frac{1}{2t} \langle \Delta p(t) \Delta p^*(t+\tau) \rangle \Longleftrightarrow \delta E^2$$

Macrophysics

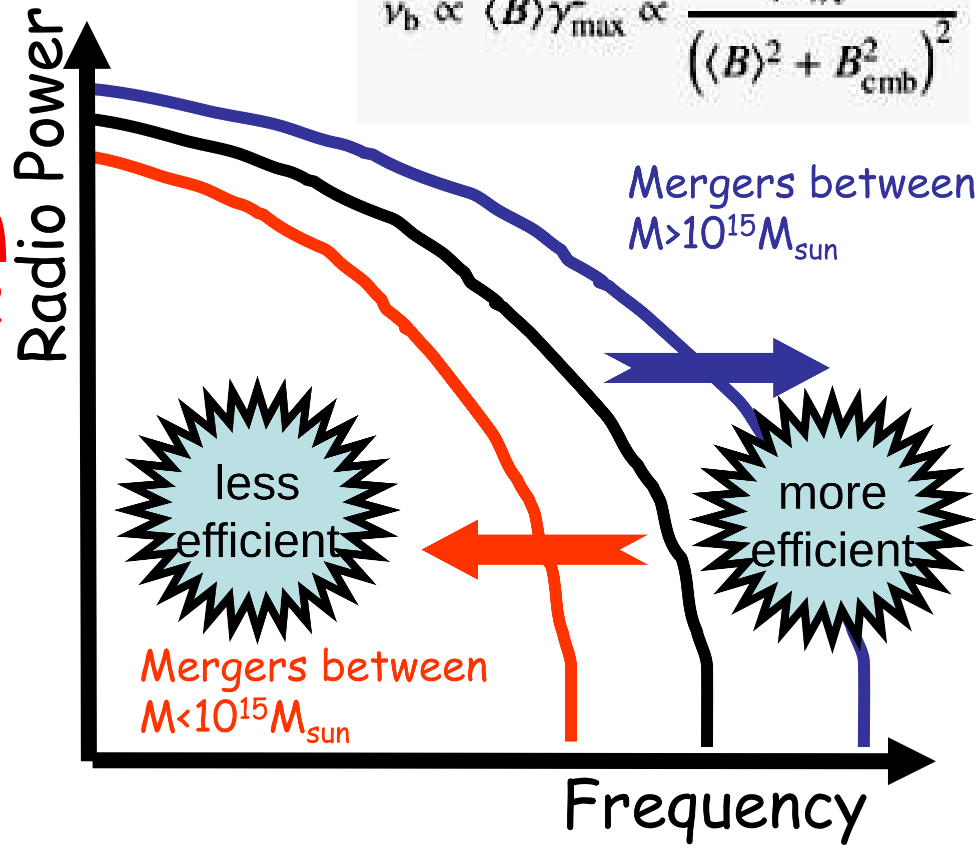
$$I_o \approx \rho_{cl} v_i^3 \frac{\sigma_{cl}}{V_{RH}}$$

Cosmology

$$v_i \simeq \left[2G \frac{(M_{max} + M_{min})}{R_{max}} \left(1 - \frac{1}{\eta_v} \right) \right]^{1/2}$$

$$R_{max} = \left[\frac{3 M_{max}}{4\pi \Delta_c(z) \rho_{crit}(z)} \right]^{1/3}$$

$$\eta_v \simeq 4 \left(\frac{M_{max} + M_{min}}{M_{max}} \right)^{1/3}$$



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

(Cassano, Brunetti, Setti 06)

RHs--cosmology : Populations .. of Radio Halos

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

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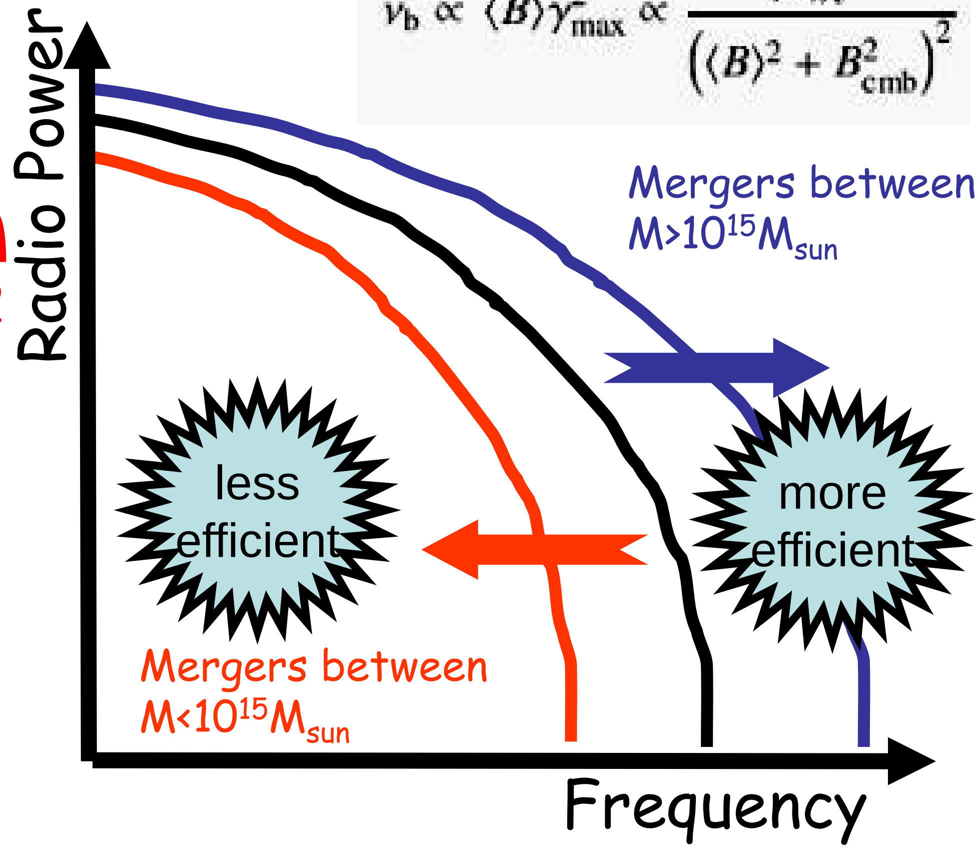
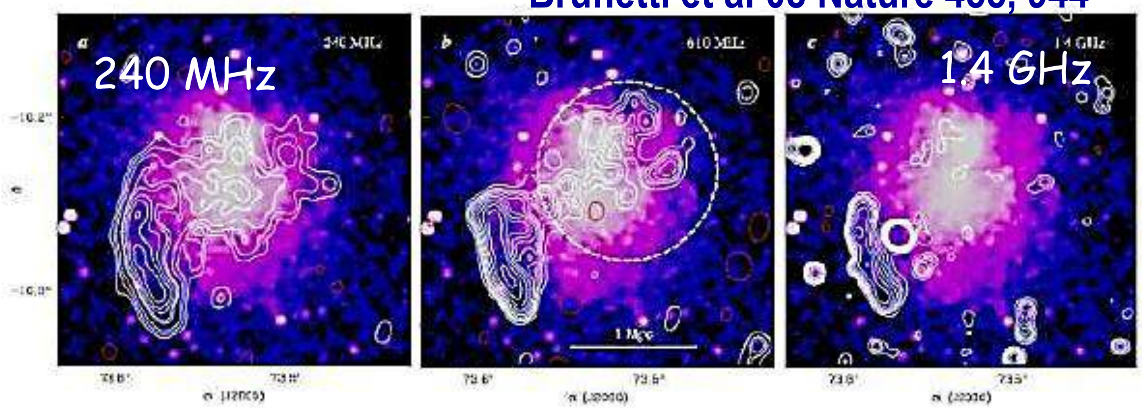
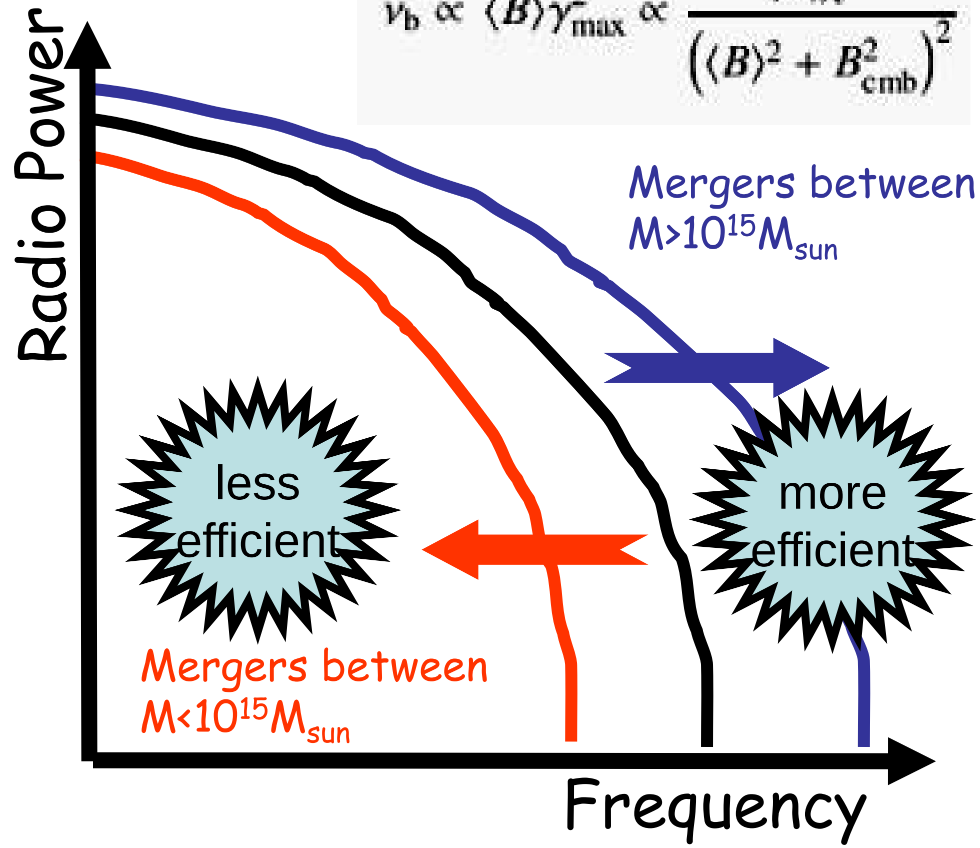


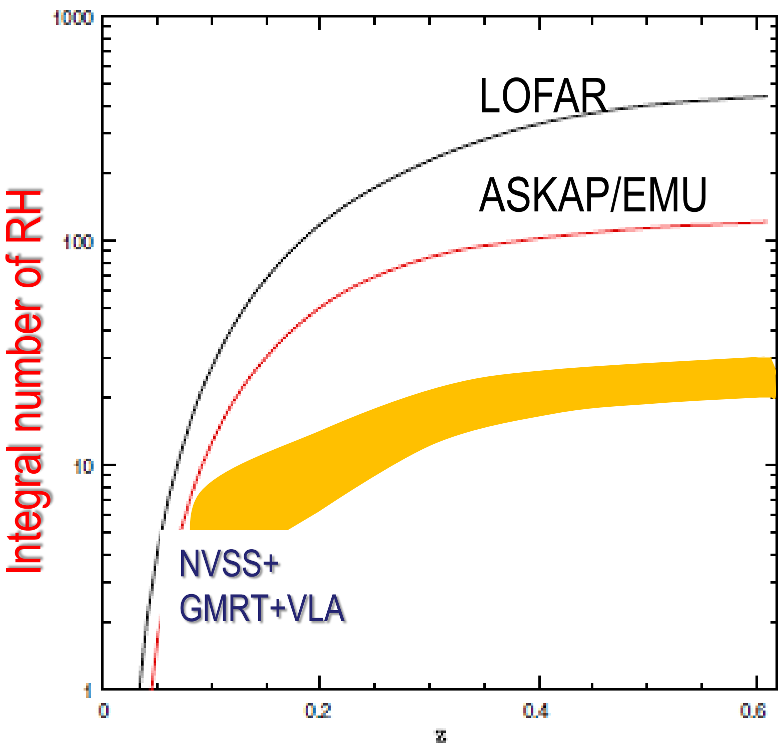
Brunetti et al 08 Nature 455, 944



LOFAR

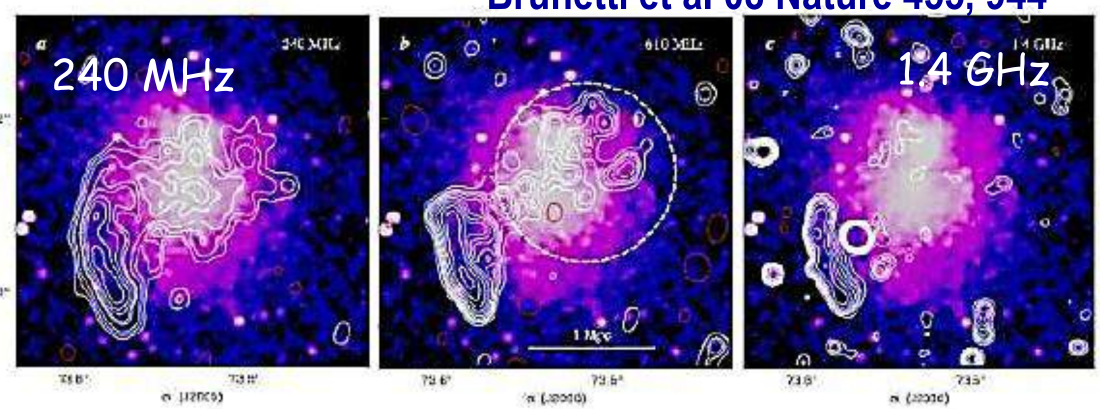
$$\nu_b \propto \langle B\rangle \gamma_{max}^2 \propto \frac{\langle B\rangle \chi^2}{\left(\langle B\rangle^2 + B_{cmb}^2\right)^2}$$





Cassano et al 12

Brunetti et al 08 Nature 455, 944



TAKE HOME MESSAGEs

1) Galaxy clusters are "unique" systems to study particle acceleration in astrophysics.
They confine high-energy (multi-TeV) particles for Hubble time !

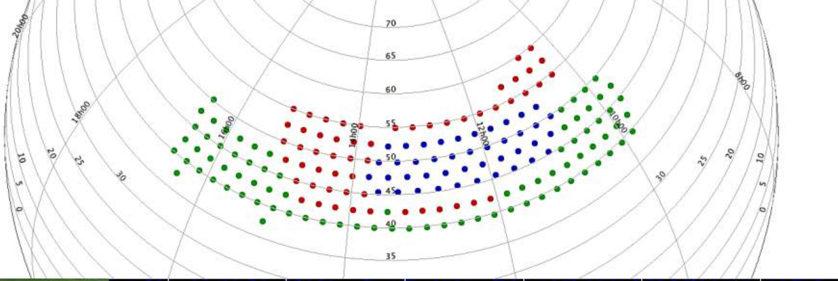
2) **Gamma-rays** put limits to the energy density of CR protons.

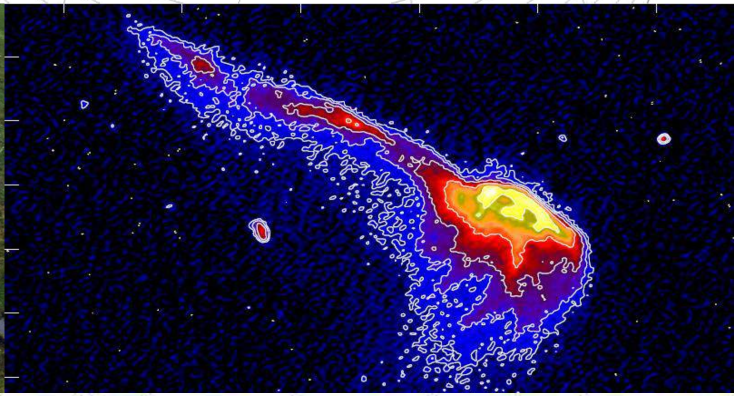
3) **Synchrotron radio** emission on Mpc scales suggests a role of SHOCKS & TURBULENT (re)acceleration in the ICM.
Energy is driven at Mpc scales (mergers) and dissipated at small scales via particle-wave coupling.

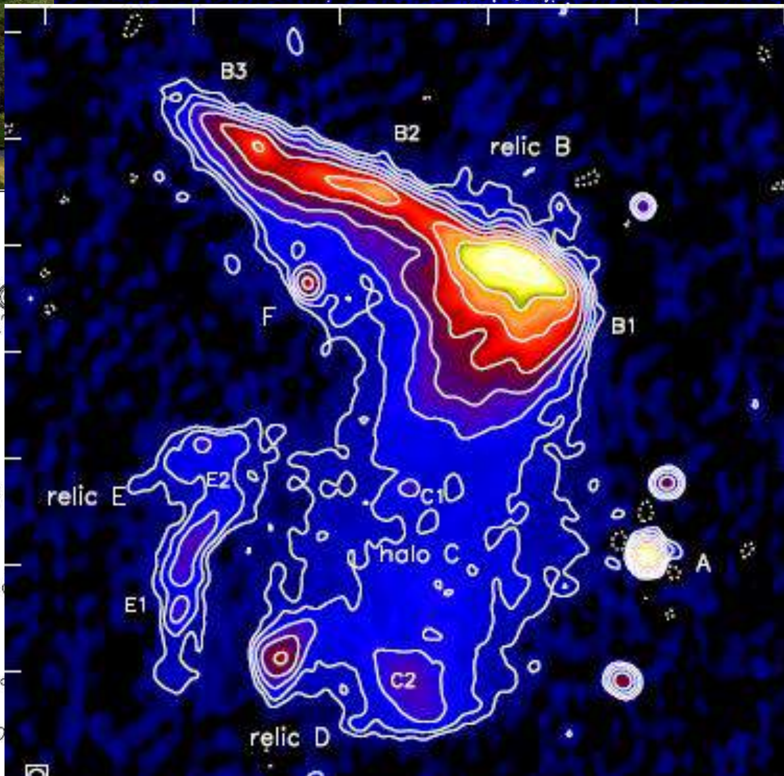
4) TURBULENT and TURBULENT RECONNECTION may couple to drain energy from incompressive turbulence to CRs.
This adds to the classical reacceleration scenario that is based on compressible turbulence

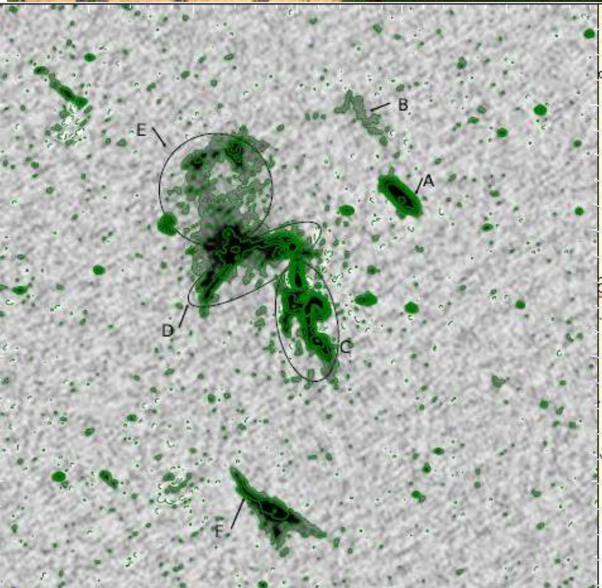
5) Future/ongoing observations :
RADIO : **LOFAR and SKA-low** : radio halos as "cosmological probes" of the interplay between MICRO and MACRO physics
GAMMA rays : **FERMI-10 and CTA** : role of HADRONS

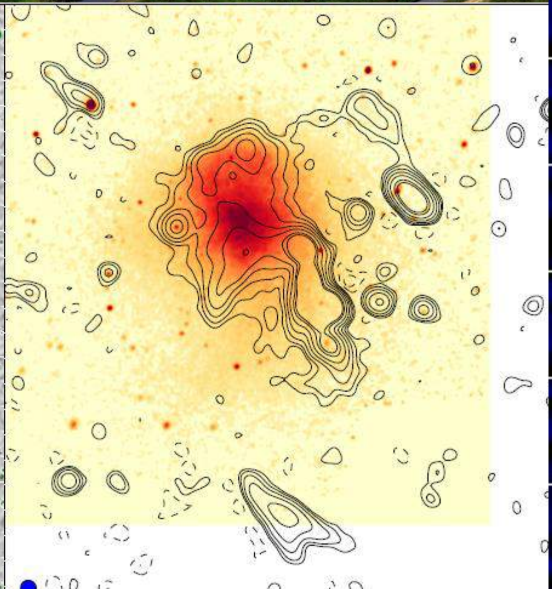
LOFAR Survey KP











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$$\frac{\partial f(p,t)}{\partial t} = \frac{1}{p^2} \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial f}{\partial p} - p^2 \sum \left| \frac{dp}{dt} \right|_{loss} f(p,t) \right) + Q(p,t) - \frac{f(p,t)}{T_{esc}}$$

Standard Fokker-Planck equation

Test particle approach :

$$\rho V_A^3 l_A^{-1} >> c \int d^3p \frac{1}{p} \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial f}{\partial p} \right)$$

available flux

energy flux in CR

$\Leftrightarrow$

$$\psi >> \left(\frac{3}{2} \beta_{pl} \frac{V_A}{c} \frac{\epsilon_{CR} \mathcal{S}}{\rho_{ICM} c_s^2} \right)^{1/3} \sim 0.02$$

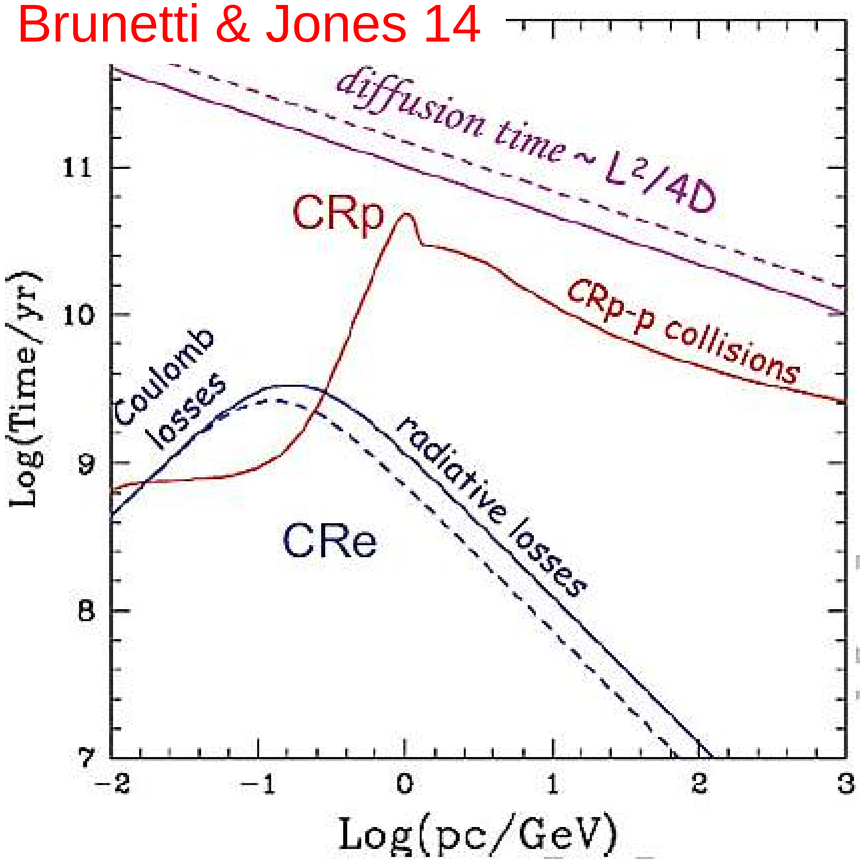
where we define :

$$\mathcal{S} = \frac{c \int d^3p \frac{1}{p} \frac{\partial}{\partial p} (p^4 \frac{\partial f}{\partial p})}{\int d^3p f p}$$

CR confinement

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

Brunetti & Jones 14



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

Time necessary to diffuse on scale = L

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

Spatial diffusion coefficient

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

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

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

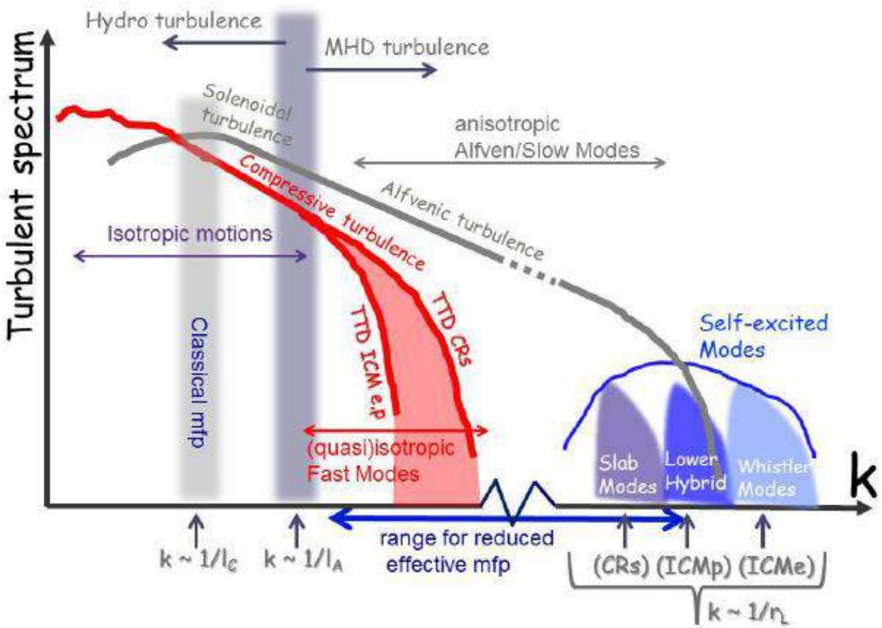
- CRe short living and accumulated at E=100-300 MeV

Generation of secondary particles

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

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

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



- **Fast Modes**
  (Cassano & Brunetti 05, Brunetti & Lazarian 07,11, Beresnyak et al 13, Donnert & Brunetti 14, Miniati 15)
- **Slow Modes**
- **Modes driven at small scales**
  (Ohno et al 02, Fujita et al 03, Brunetti et al 04)
- **Reconnection & Alfvenic…**

TTD acceleration

(Miller et al 96, Schlickeiser & Miller 98
ICM: Brunetti & Lazarian 07, 11)

Transit Time Damping (TTD)

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

Interaction between magnetic momentm of particles and parallel gradient of B

NOTE
we use E/B fluctuations
NOT velocity
…
Prandtl Number

$$\tau_{acc} \approx \frac{p^2}{D_{pp}}$$

$$D_{pp}(p) = \frac{\pi^2}{2c} p^2 \frac{1}{B_o^2} \int_0^{\pi/2} d\theta \, V_{ph}^2 \frac{\sin^3(\theta)}{|\cos(\theta)|} \mathcal{H}\left(1 - \frac{V_{ph}/c}{\cos\theta}\right) \left[1 - \left(\frac{V_{ph}/c}{\cos\theta}\right)^2\right]^2 \int^{k_{cut}} dk \mathcal{W}_B(k) k$$

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DAMPING

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

$1/\Gamma$ = damping time-scale

$$\Gamma_\alpha(k) = -\frac{\pi^2}{8} \frac{|B_k|^2}{B_o^2} \frac{\omega}{W} \left(\frac{k_\perp}{k}\right)^2 \frac{k_\|}{|k_\||} \frac{\mathcal{H}(1 - |\frac{\omega}{k_\| c}|) N_\alpha / m_\alpha}{\sqrt{1 - [\omega/(k_\| c)]^2}} \int_0^\infty {\rm d}p_\perp \frac{p_\perp^5}{\sqrt{1 + \left(\frac{p_\perp}{m_\alpha c}\right)^2}} \left(\frac{\partial \hat{f}_\alpha(p)}{\partial p_\|}\right)_{p_\|({\rm res})}$$

CASCADING

$$\tau_{kk} \approx \frac{k^3}{(\partial/\partial k)(k^2 D_{kk})}$$

MHD model?

TTD acceleration

(Miller et al 96, Schlickeiser & Miller 98
ICM: Brunetti & Lazarian 07, 11)

Transit Time Damping (TTD)

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

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MACROPHYSICS

microphysics

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

$$\tau_{kk} \approx \frac{k^3}{(\partial/\partial k)(k^2 D_{kk})}$$

MHD model?

$$k_{cut} \approx \frac{81}{14} \frac{I_o}{\rho \langle V_{ph} \rangle} \left[\frac{\langle \Gamma(k) \rangle}{k}\right]^{-2}$$

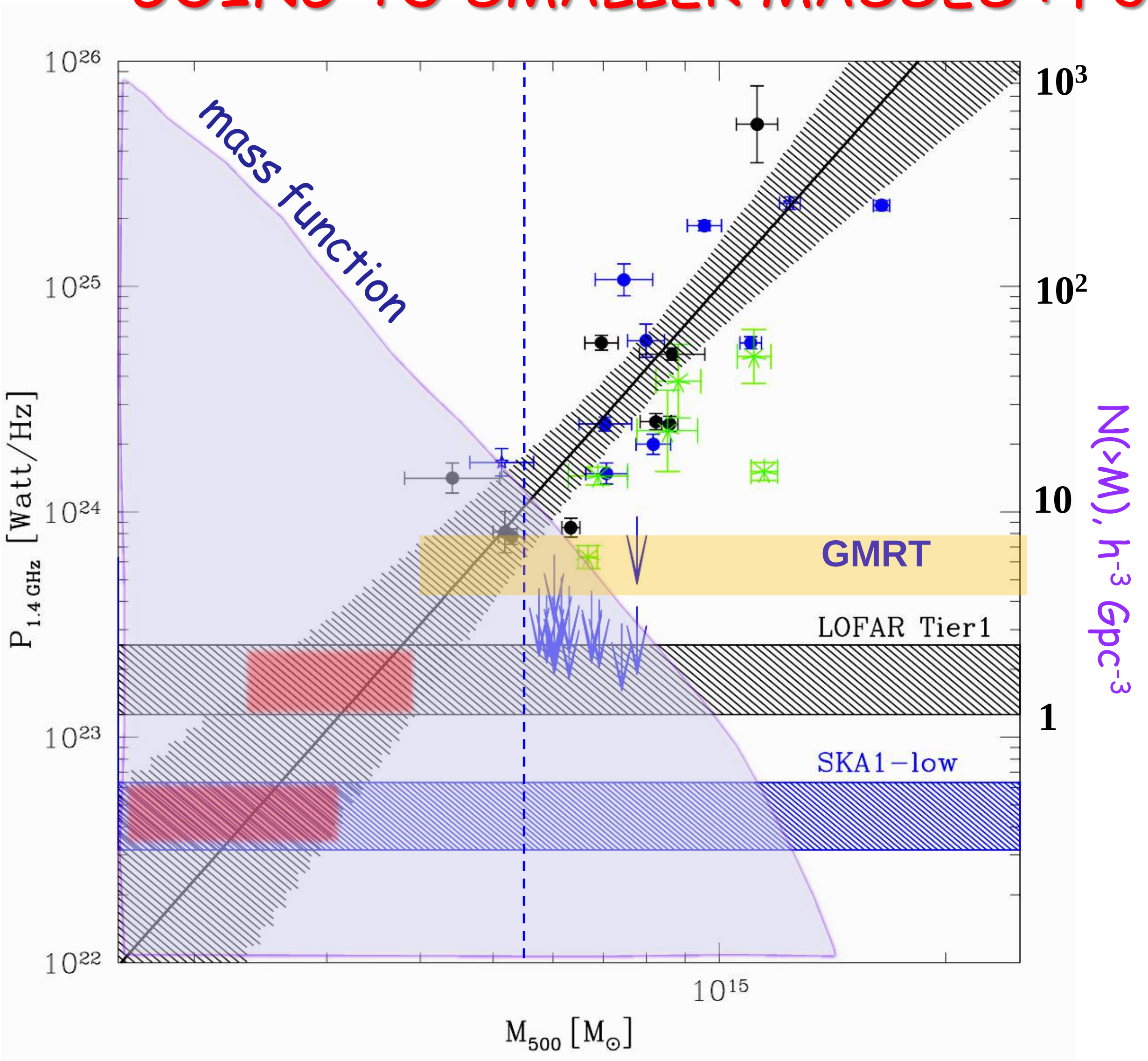
Cut-off is generated at scales where damping is faster than cascading.
Acceleration ultimately depends on damping…

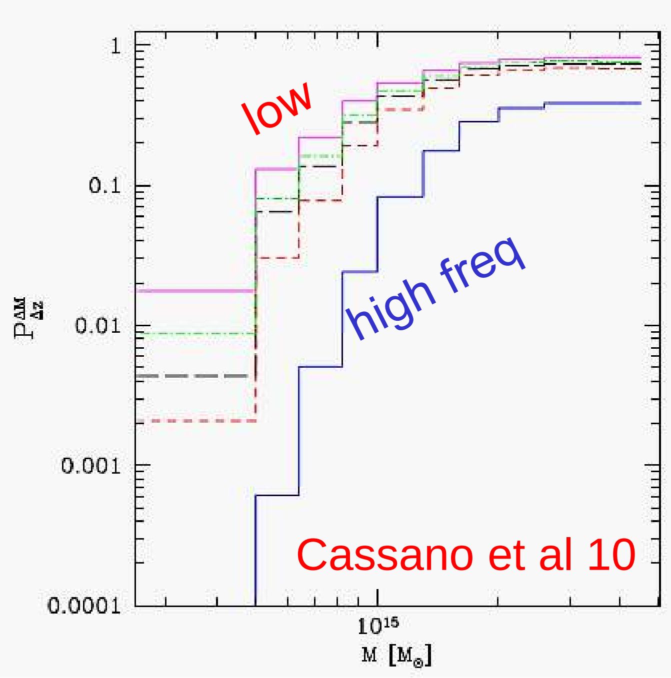
- Turbulent energy
- Turbulent (spectrum)
- Prandtl/Reynold numbers
- Plasma collision frequency
- effective mfp/diffusion

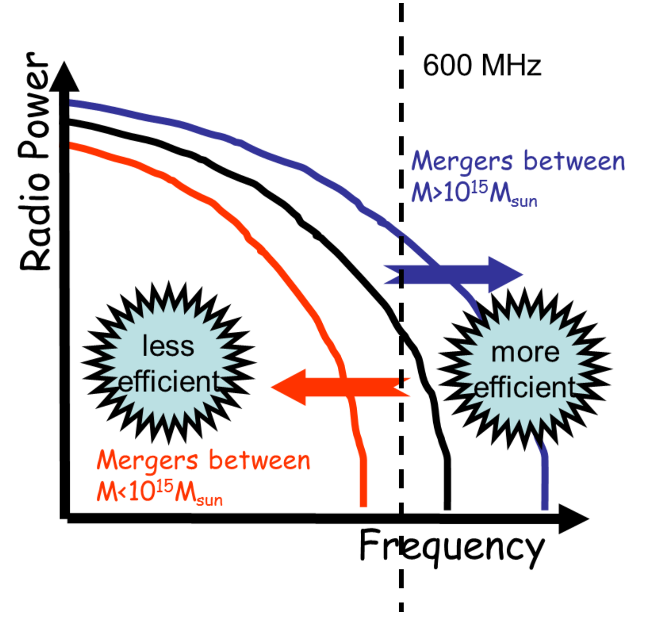
$\omega_w > \omega_{ii}$ standard Coulomb
$\omega_w < \omega_{ii}$ plasma instabilities

(Brunetti & Lazarian 07, 11, Miniati 15)

GOING TO SMALLER MASSES : FUTURE SURVEYS

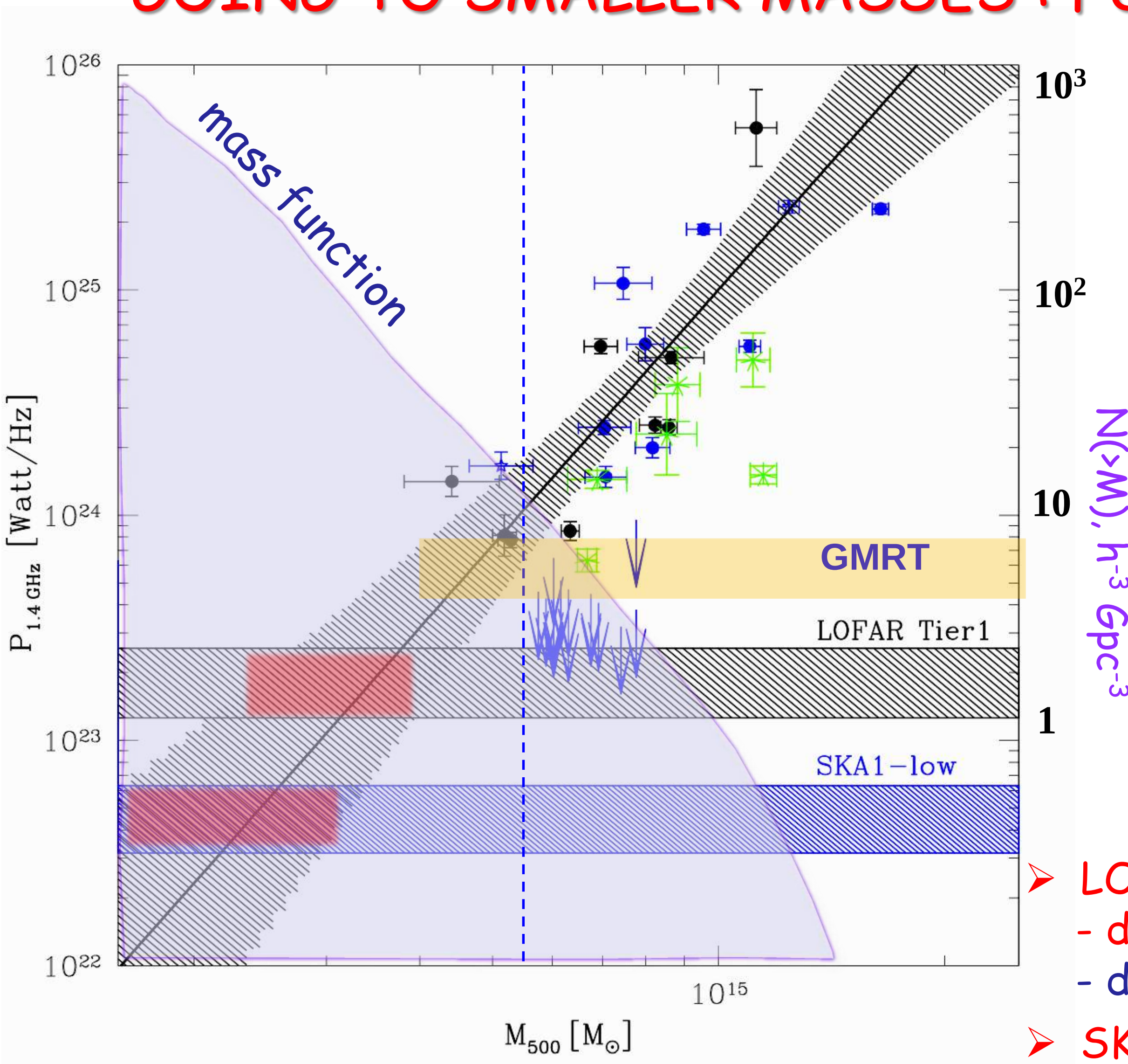


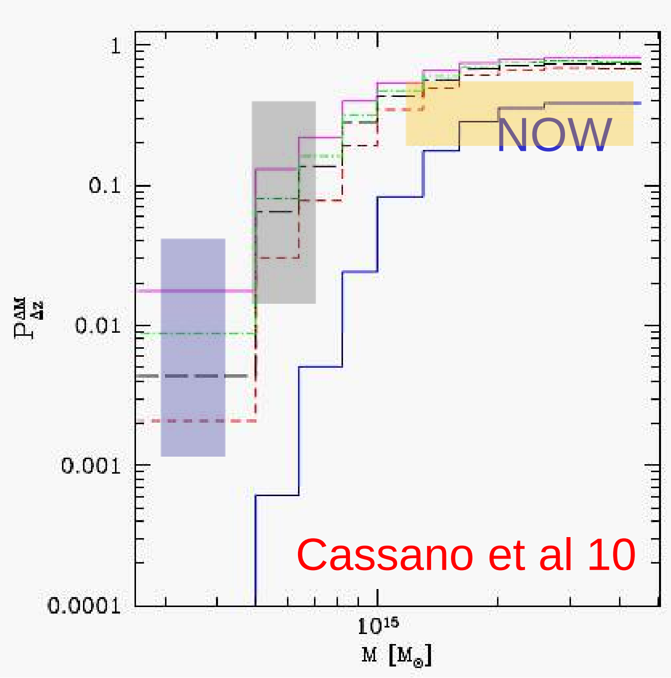




Going to smaller masses does not necessarily imply that more (much more) RHs will be found !

GOING TO SMALLER MASSES : FUTURE SURVEYS

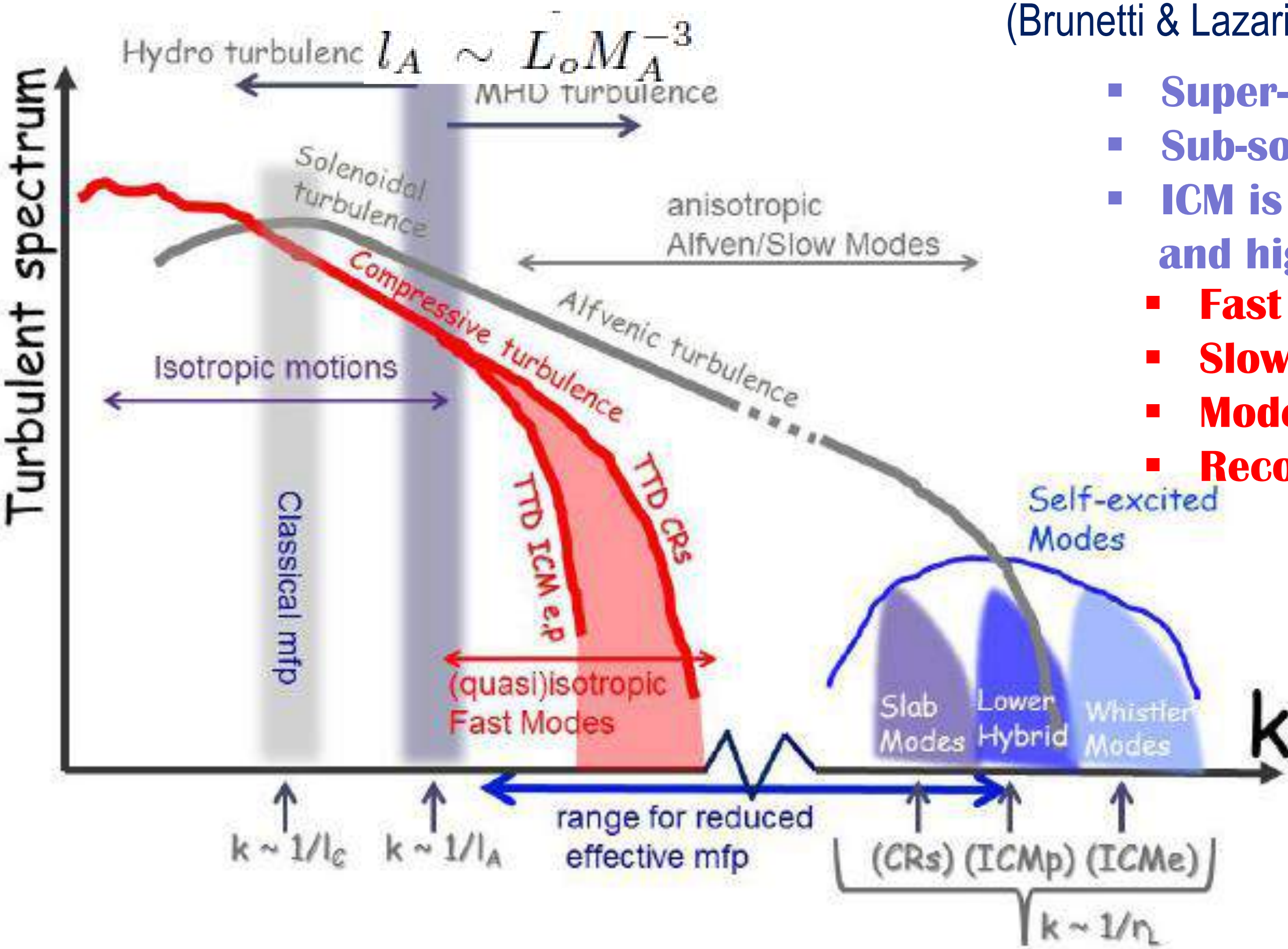




- LOFAR :
  - drop of radio halo fraction
  - discovery of ultra-steep RHs
- SKA : population dominated by other physical processes

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

Open problem : ICM Turbulence & acceleration



(Brunetti & Lazarian 07, Brunetti & Jones 14)

- **Super-Alfvenic**
- **Sub-sonic**
- **ICM is a "weakly collisional" and high-beta plasma**
  - **Fast Modes**
  - **Slow Modes**
  - **Modes driven at small scales**
  - **Reconnection & Alfvenic**

(i) How merger-driven turbulence is transported to small scales ??

(ii) How EM/kin turbulent spectrum evolves with scales ??

(iii)Which is the min scale of EM fluctuations ??

Inputs on Physics : Pm, compressive/solenoidal, …. collisionality, effective mfp

Cosmic rays confinement

Resonant scattering with B-fluctuations

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

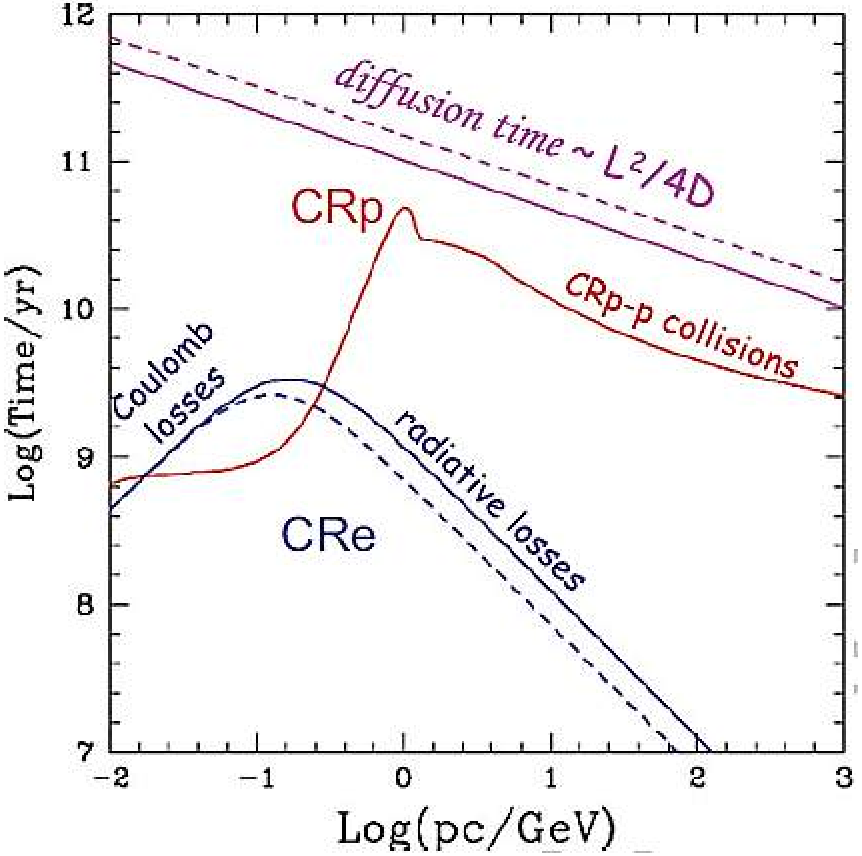
$$D = \frac{V_{CR}^2}{8}\int_{-1}^{1} d\mu \frac{(1-\mu^2)^2}{D_{\mu\mu}}$$

gyroresonance

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

$D(\mathrm{GeV}) \approx 10^{27}$-$10^{28}$ $\mathrm{cm^2/s}$

Brunetti & Jones 14



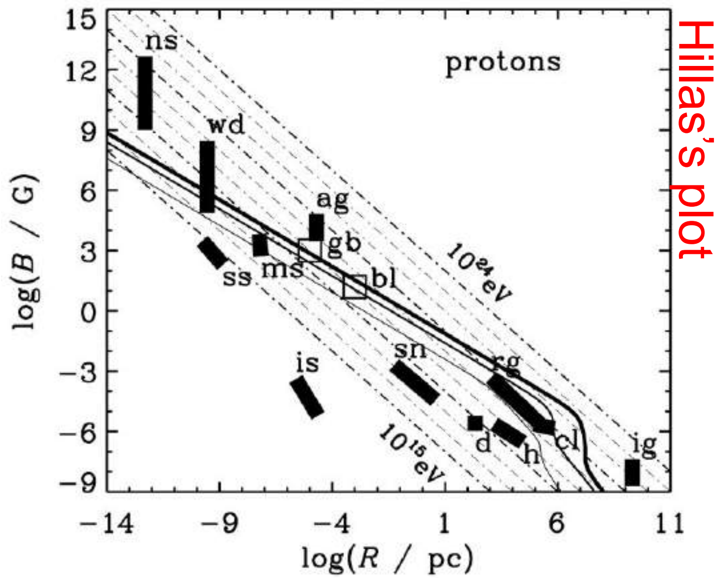
Generation of small scales B-perturbations/waves in the ICM
(rev: Brunetti & Jones 14)

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

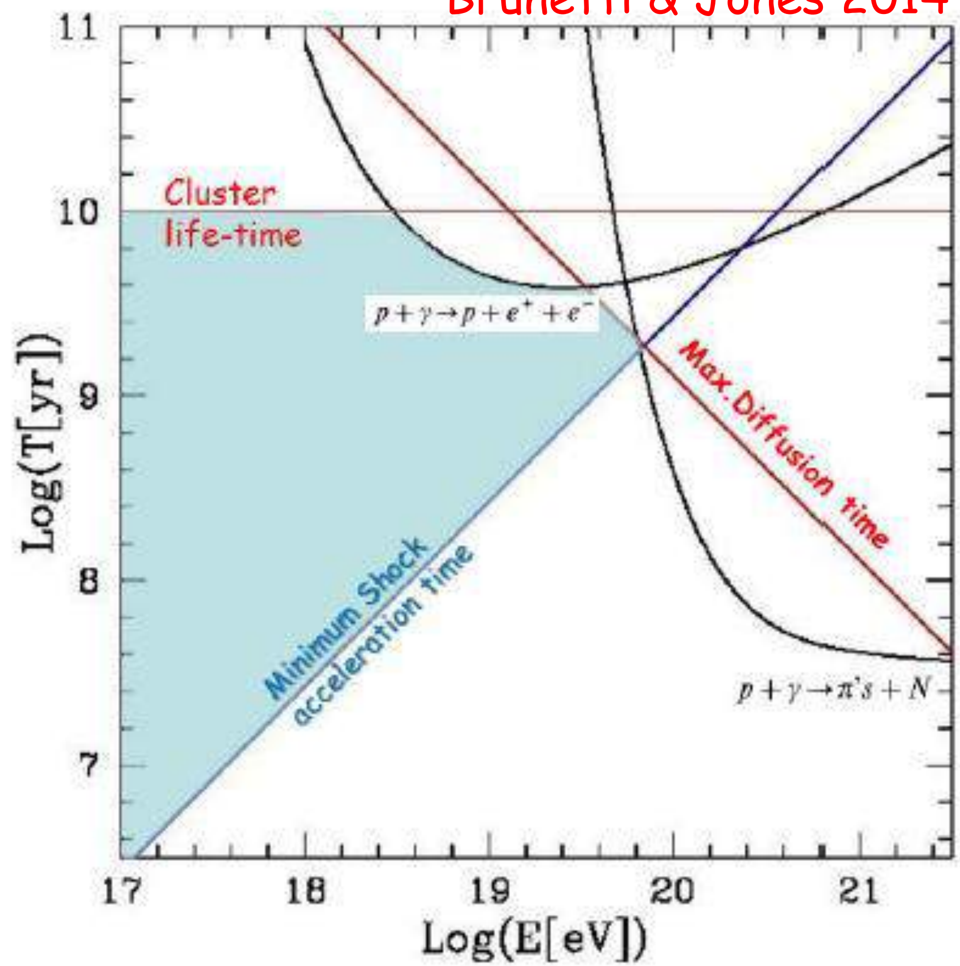
Shock acceleration : max energy of CRp (Kang et al 96, Blasi 01, Jones 04, ..)

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

diffusion time on scale L $\quad \tau_{diff} \approx \frac{1}{4}\frac{L^2}{D}$



Brunetti & Jones 2014



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

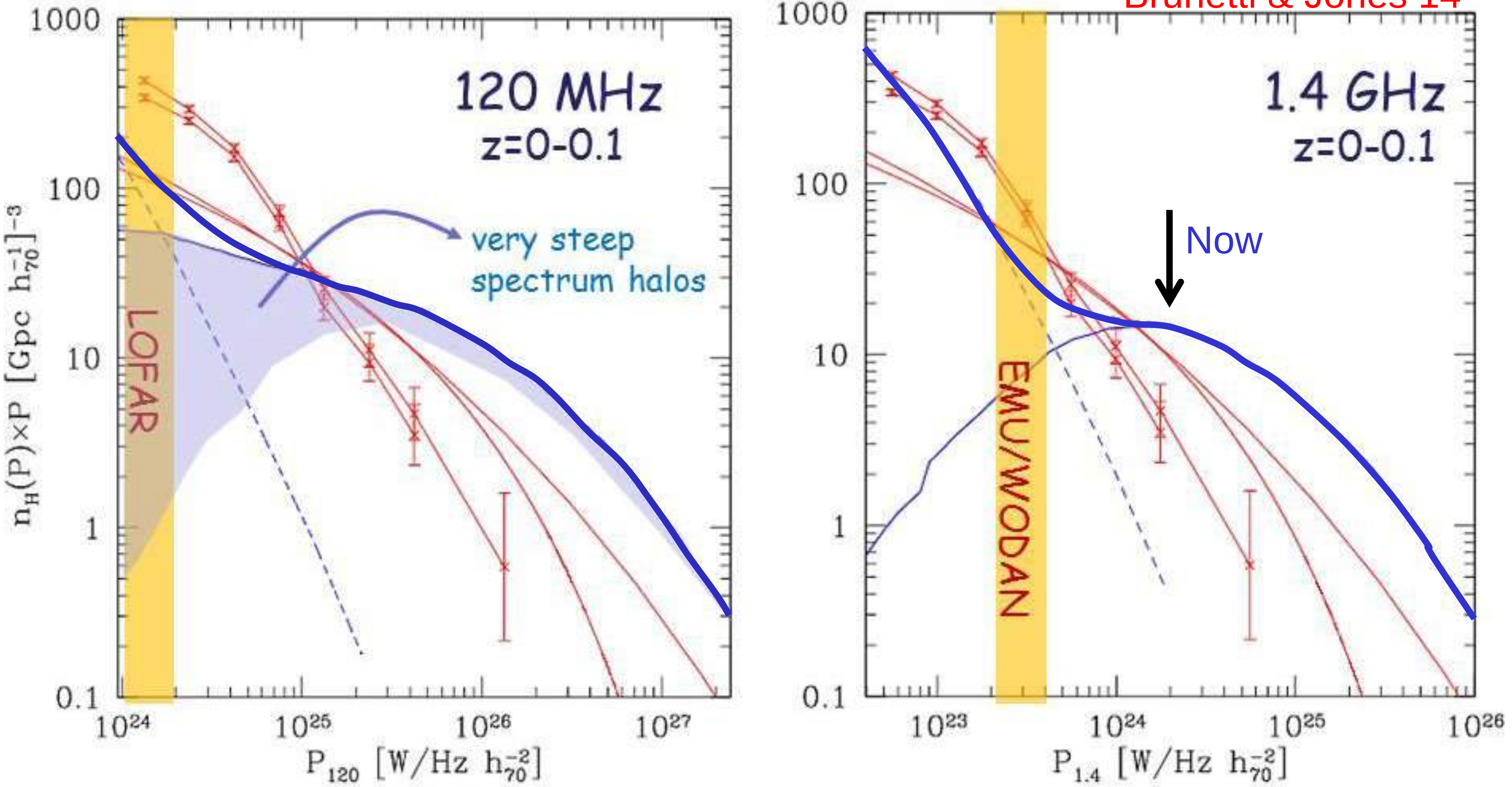
$$D(p) \sim 3\times10^{22}\frac{(cp/\mathrm{GeV})}{(B/\mu G)}\ \mathrm{cm^2 s^{-1}}.$$

$$\tau_{acc} \approx 2\times10^8\left(\frac{cp/EeV}{B/\mu G}\right)\left(\frac{V_{sh}}{3000}\right)^{-2} yr$$

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

FUTURE RADIO SURVEYS

Brunetti & Jones 14



- LOFAR & ASKAP/EMU are expected to start exploration of «off-state»
- Combination of LOFAR & EMU/WODAN efficient for discovery of ultra-steep spectrum : with ½ of RHs in LOFAR ultra-steep

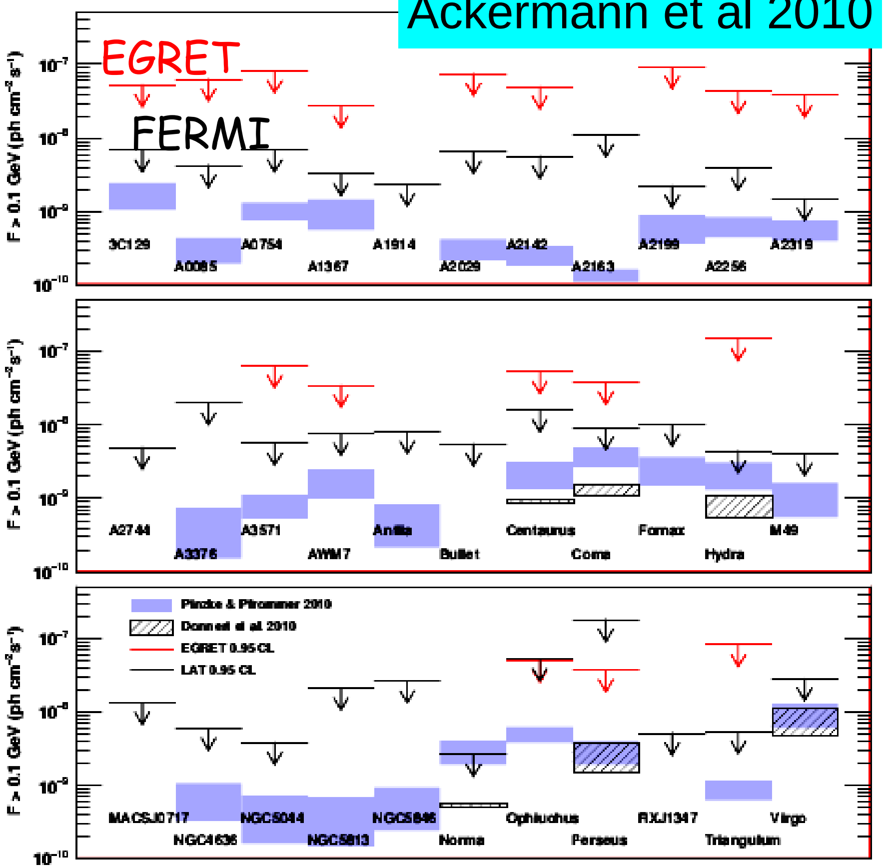
The non detection of gamma-rays from galaxy clusters is in tension with Faraday Rotation Measure of clusters magnetic fields (Jeltema & Profumo 11, .. Brunetti et al 12). New results on Coma cluster further challenge a pure hadronic model for the halo.

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

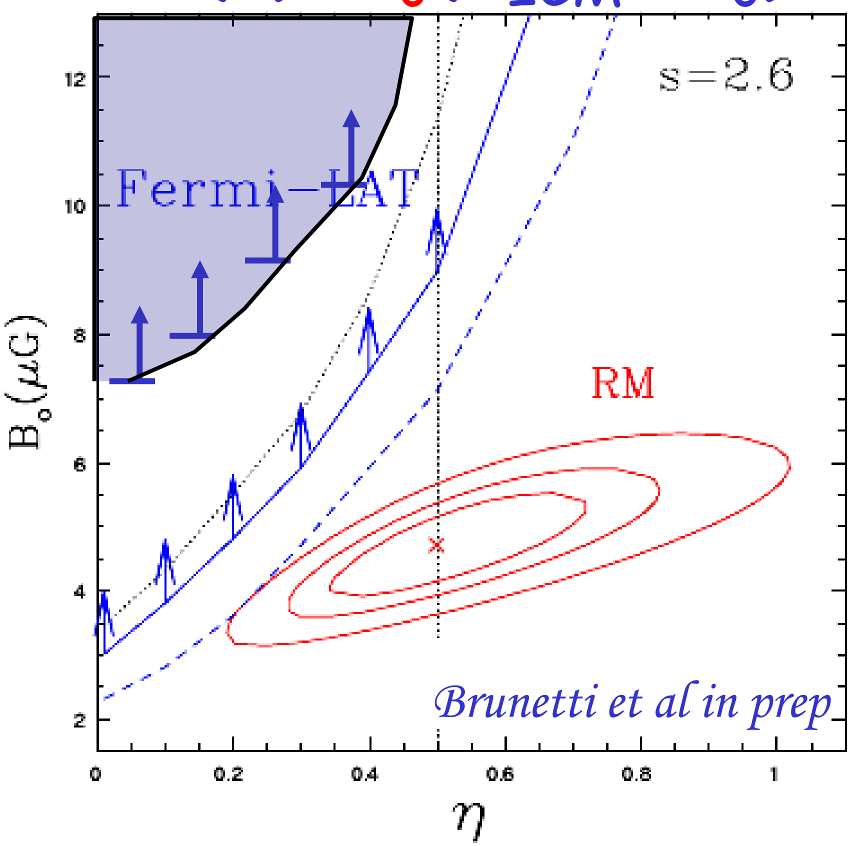
$$\pi^0 \rightarrow \gamma\gamma$$

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

Ackermann et al 2010

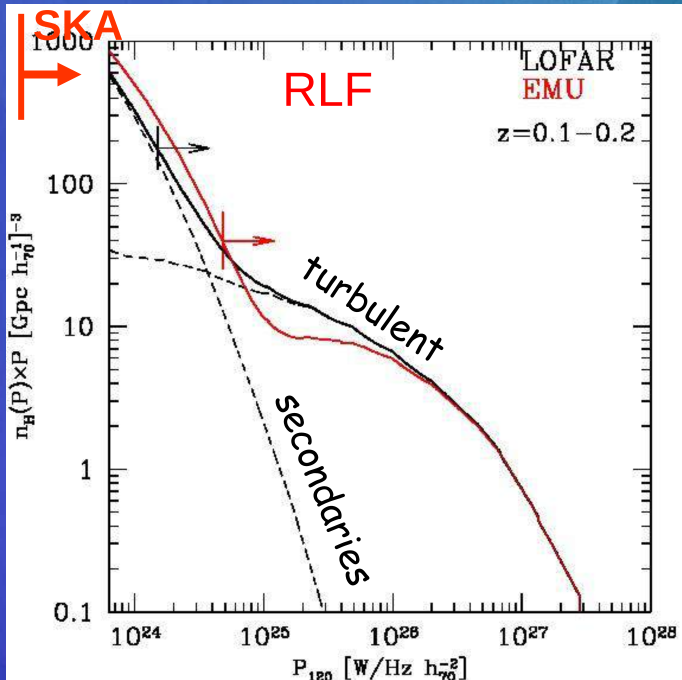


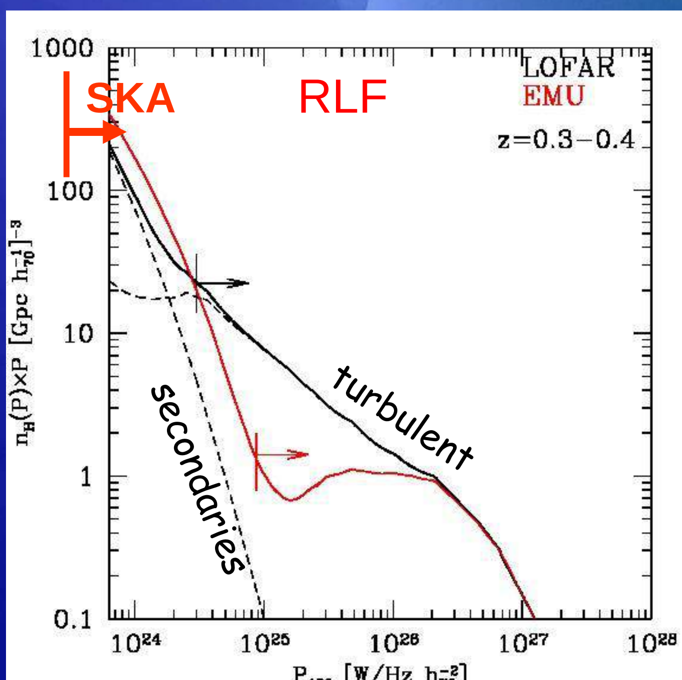
$$B(r)=B_o(\varepsilon_{ICM}/\varepsilon_o)^n$$



Brunetti et al 12

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

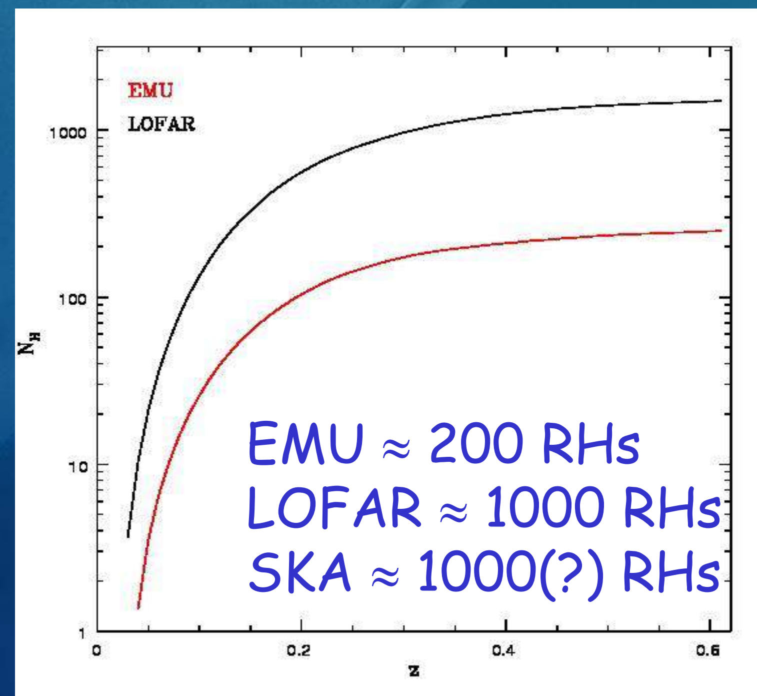




How many radio halos can be discovered ??

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

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



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

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

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Acceleration of primary and secondary particles in galaxy clusters by compressible MHD turbulence: from radio haloes to gamma-rays

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see also GB+Blasi 2005 MNRAS 363 1173

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

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

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

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

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

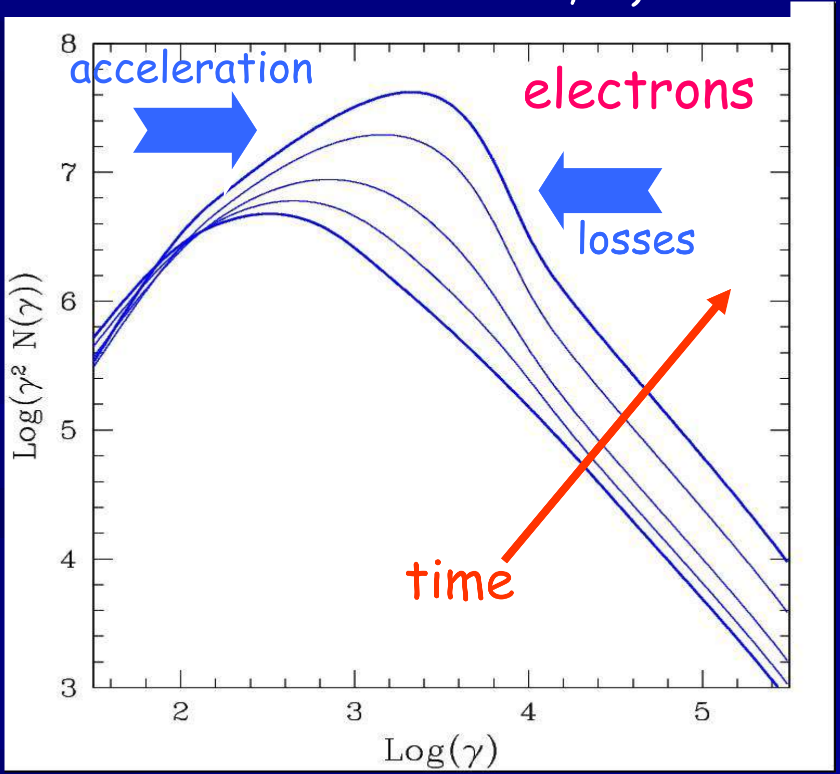
For I(k)=0 this is a "pure" secondary model.

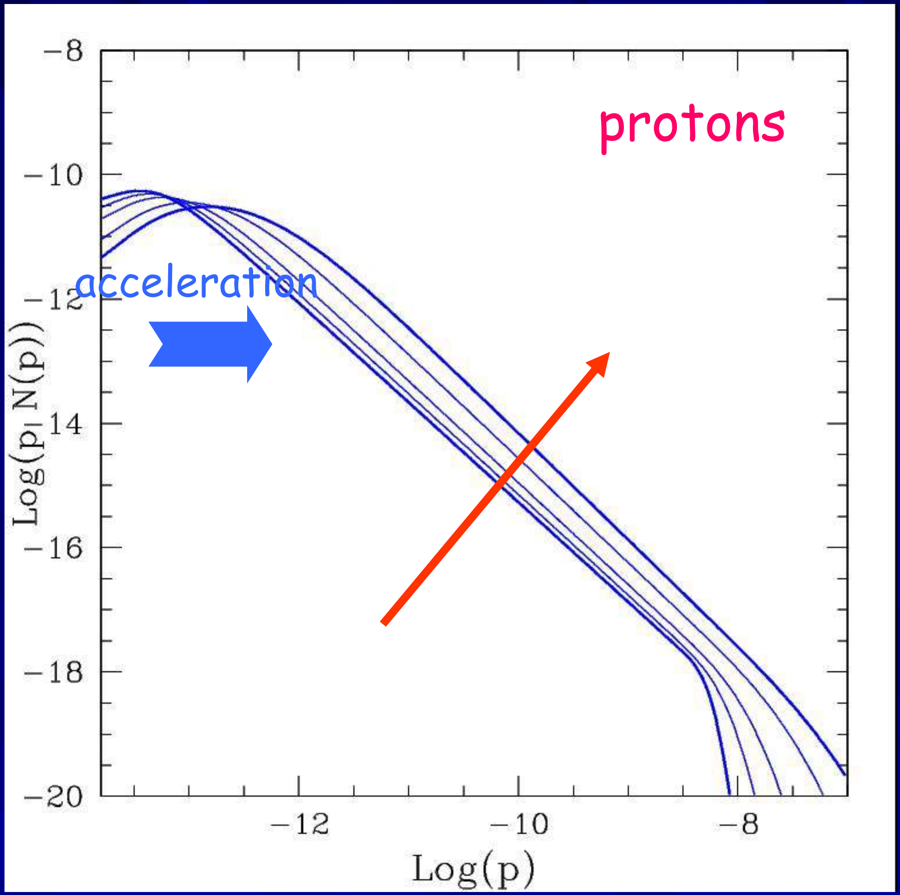
Transit Time Damping (TTD)

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

Interaction btw magnetic moment of particle and parallel gradient of B

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





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

Effects of the NL interaction of particles-waves on CR evolution

(Book reviews : Melrose 1980, Berezinskii et al 1990, Schlickeiser 2002)

The diffusion coefficients define characteristics of particle propagation and acceleration

Propagation $\nu = 2D_{\mu\mu}/(1-\mu^2)$ $\lambda_{\parallel} = \frac{3}{4}\int d\mu \frac{v(1-\mu^2)^2}{D_{\mu\mu}}$

Stochastic Acceleration $A(E) = \frac{\partial[vp^2 D(p)]}{4p^2\partial p}$, $D(p) = \frac{1}{2}\int_{-1}^{1} D_{pp} d\mu$

$D_{\mu\mu} \leftrightarrow \delta B$,

$D_{pp} \leftrightarrow \delta E = \delta v \times B_0/c$

Acceleration is sensitive to our model of turbulence

Where do δB, δv come from? MHD turbulence!

The diffusion coeffecients are determined by the statistical properties of turbulence

Stochastic acceleration of fast particles diffusing in turbulence (Fermi 1949, … Ptuskin 1988)

$$D_{pp} \simeq \frac{2}{9} D p^2 \frac{V_o^2}{L_o^{2/3}} \int_{1/L_o}^{1/l_{cut}} \frac{dy\, y^{1/3}}{c_s^2 + D^2 y^2}$$

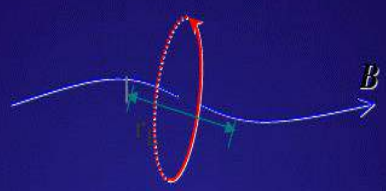
Gyroresonance scattering depends on the properties of turbulence

Gyroresonance

$\omega - k_{\parallel}v_{\parallel} = n\Omega$, $(n = \pm 1, \pm 2 \ldots)$,

Which states that the MHD wave frequency (Doppler shifted) is a multiple of gyrofrequency of particles ($v_{\parallel}$ is particle speed parallel to **B**).

So, $k_{\parallel,res} \sim \Omega/v = 1/r_L$



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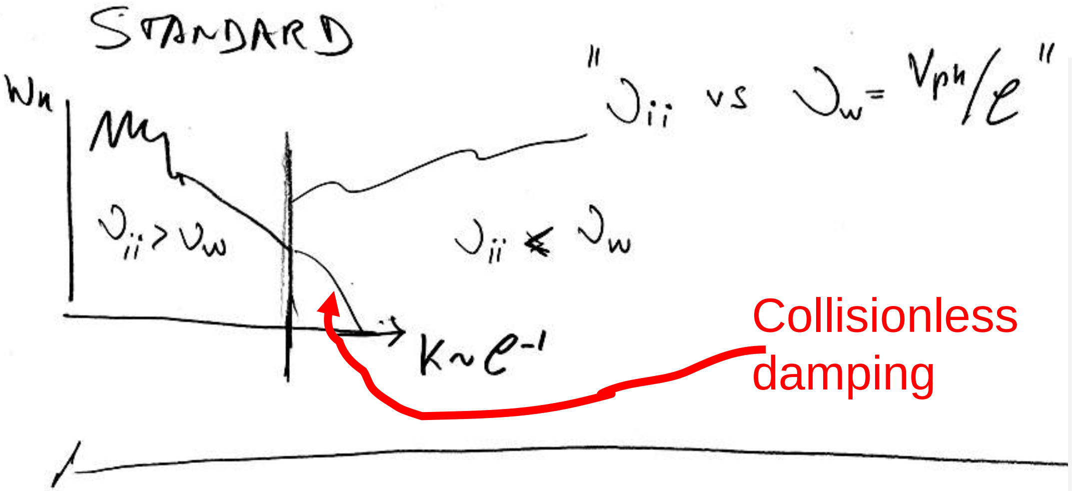
Comment on turbulent acceleration efficiency in ICM



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Particle reacceleration by compressible turbulence in galaxy clusters: effects of reduced mean free path

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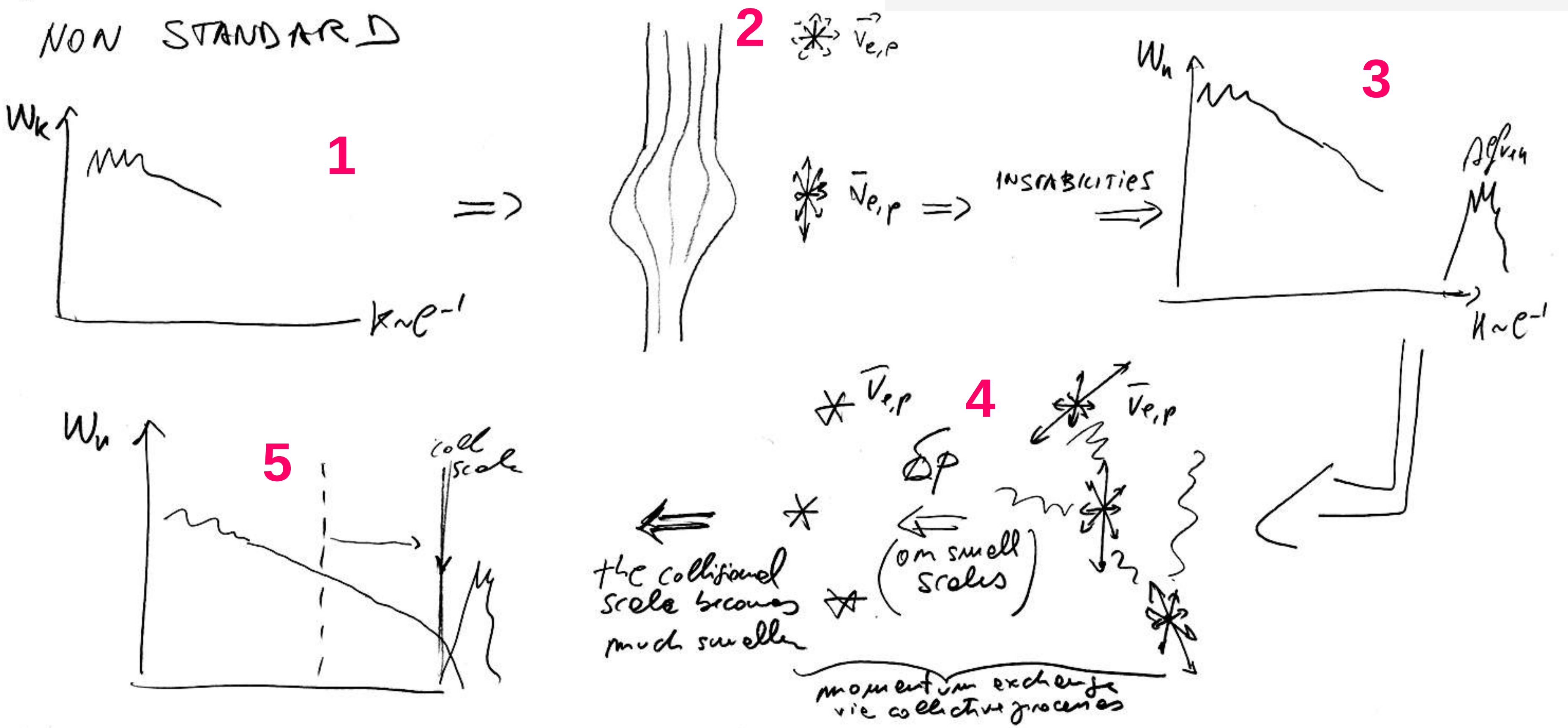
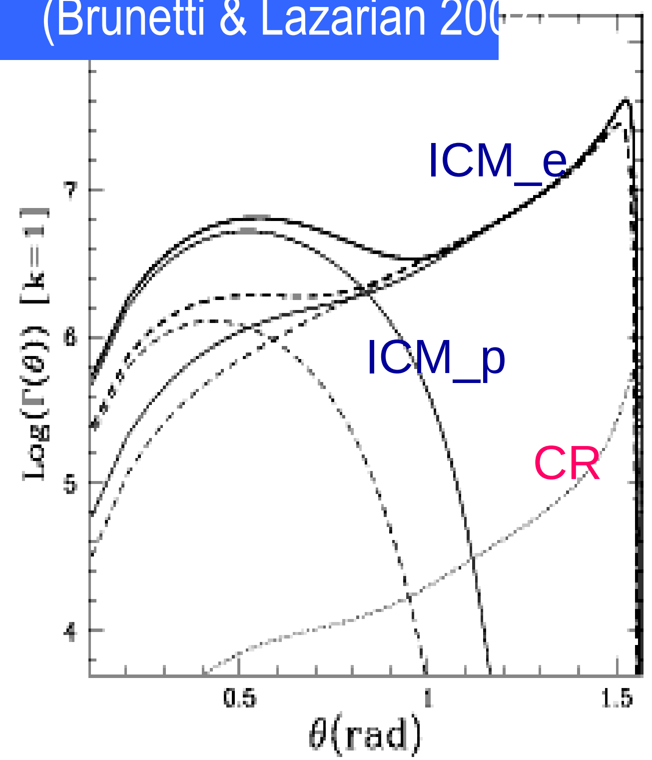


Heating of ICM & CR-acceleration by compressible turbulence in the ICM

QLTheory

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

(Brunetti & Lazarian 200



The most important damping of compressive (fast) modes in the ICM is via "magnetic Landau" damping (n=0 resonance, Transit Time Damping) with **thermal electrons and protons (CR contribute for < 10%).**

Thermal ICM back-reacts on the turbulence, modifies its spectrum and affects CR acceleration…

Line-bending *efficiency* >> *damping efficiency*

$\tau_{bb}(k)^{-1} \sim V_{lA} / l_A$ $\tau_d^{-1} = \Gamma(k)$

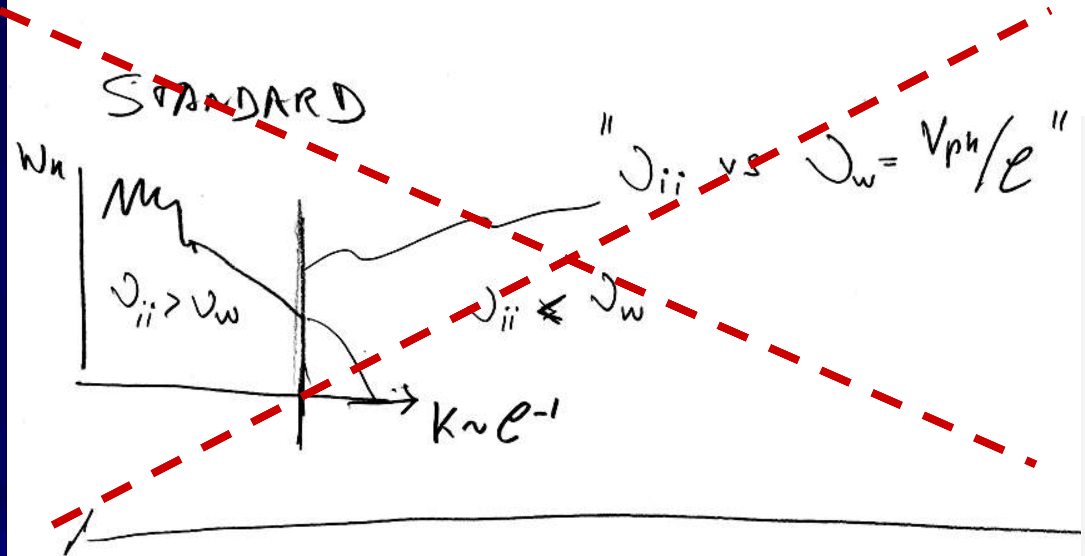
Isotropic Effective Damping

$l_{diss} \approx 100$ pc

CRp/e

$D_{pp} \sim V_L^4 L^{-1}$

+ observables



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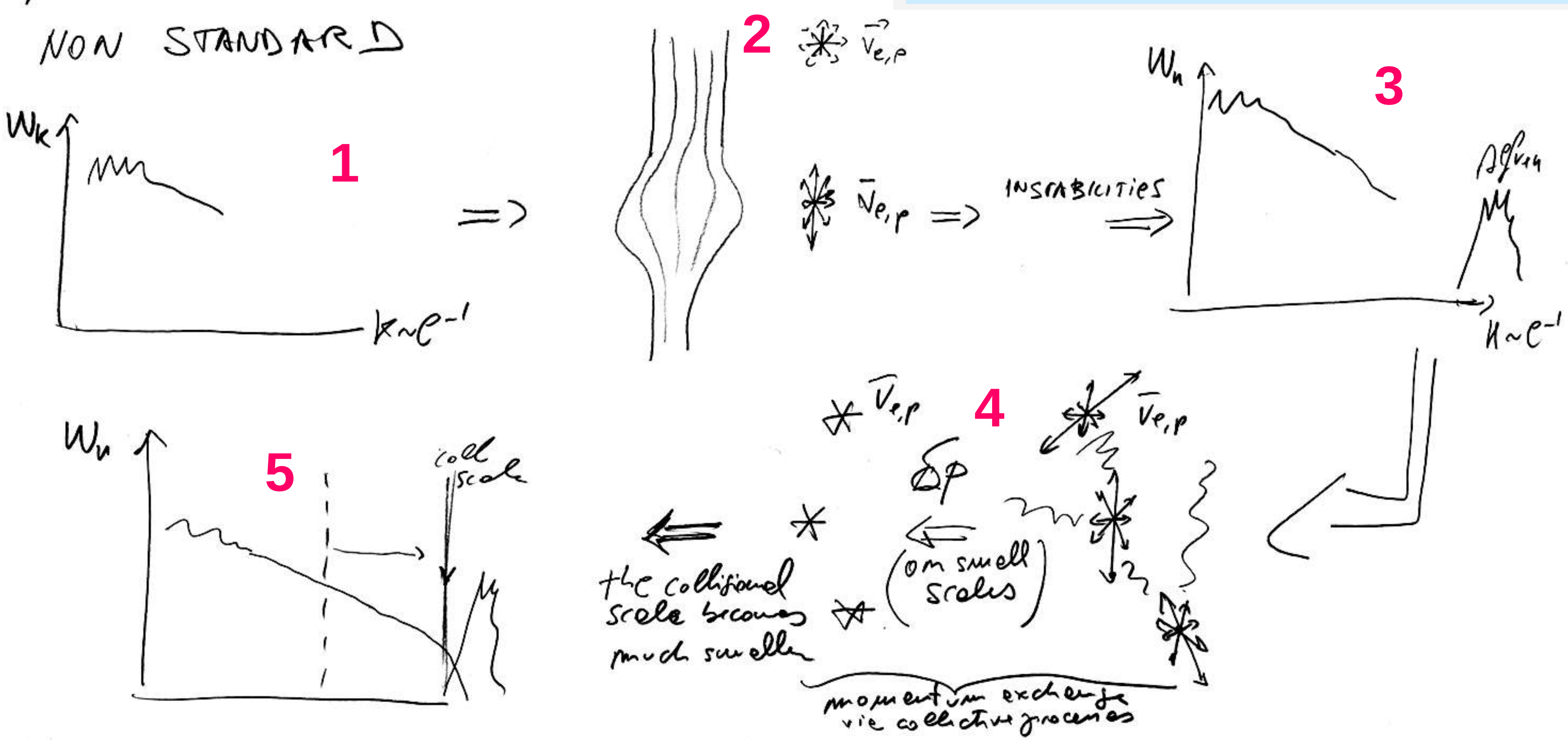

Damping of turbulence is dominated by CR that back react on turbulence as their energy density increases

$$D_{pp} \simeq 2 c_w c_k^{1/2} \frac{p^2 I_o^f}{\sum_{e,p} \int dp p^2 c \left| \frac{\partial N}{\partial p} - 2\frac{N}{p} \right|} \sim I_o E_{cr}^{-1}$$

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