The challenge of turbulence in galaxy clusters: physics and particle acceleration

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microphysics of ICM: basic considerations

mfp (Coulomb coll) : 1-100 kpc

$$l_{Coul} = \frac{m_e^2 v^4}{8\pi n Z^2 e^4 ln\Lambda} \approx 1.4 \times 10^4 (\frac{T}{K})^2 (\frac{n}{cm^{-3}})^{-1} cm$$

Larmor radius (TH)

$r_{L,th} \approx 10^{10} B_\mu T_8^{1/2}$ cm ~ 1000-10000 km

beta-plasma :

$\beta = P_g/P_B = (2/\gamma)c_s^2/V_A^2$ ~ 100

plasma frequency & collisional parameter:

$$\omega_{p,j} = \sqrt{\frac{4\pi n_j Z_j^2 e^2}{m_j}}$$

$$R_C = \nu_C/\omega_{p,j} \sim 5 \times 10^{-14} \frac{n_e^{1/2}}{T_{\rm keV}^{3/2}}$$

ratio of Coulomb coll freq and plasma freq

$R_c = \nu_C/\omega_p$ ~ 10^{-16}

ν_C^{-1} > Myr

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weakly collisional

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Plasma Collective effects

 # plasma frequency & collisional paramet

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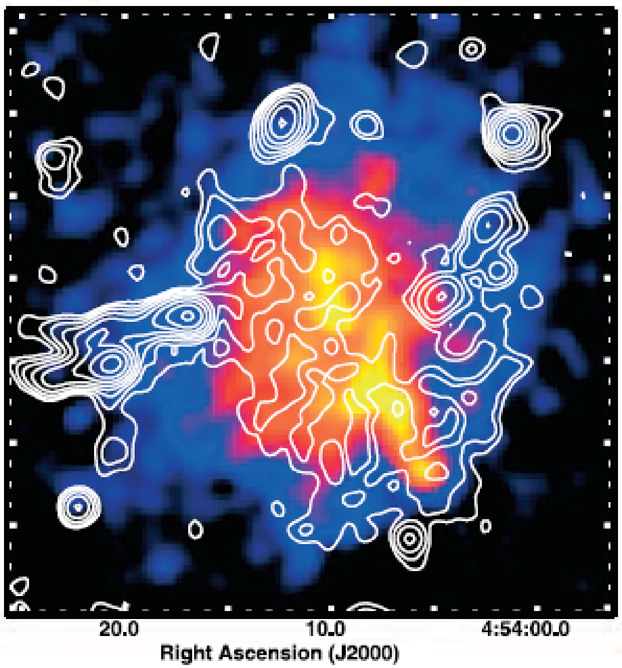
Radio Halos as tracers of turbulent regions in clueters

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

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



COMBINATION OF FACTS:

- **Diffusion Problem**

  Diffusion scale of relativistic electrons in a lifetime is << RH sale [Jaffe 77, … Berezynsky et al 97, …]

- **Lack of CR protons**

  Gamma-ray limits suggest that number of CRp is not enough to generate RH via pure CRp--p collisions [Fermi Coll 2010,14, Jeltema+Profumo 10, Brunetti et al 12]

- **Steep Spectrum of RH**

  Acceleration mechanisms for RH should be inefficient (Fermi-II ?) [Schlickeiser et al 87, … Brunetti et al 08…]

- **Connection with Mergers**

  Robust statistical evidences that RH are generated in discturbed clusters [Cassano et al 2010, … Cuciti et al 15, ..]

Cluster-scale non-thermal emission probes that energy generated on LS (100+ kpc) is channeled into electromagnetic fluctuations and CR acceleration at smaller scales.

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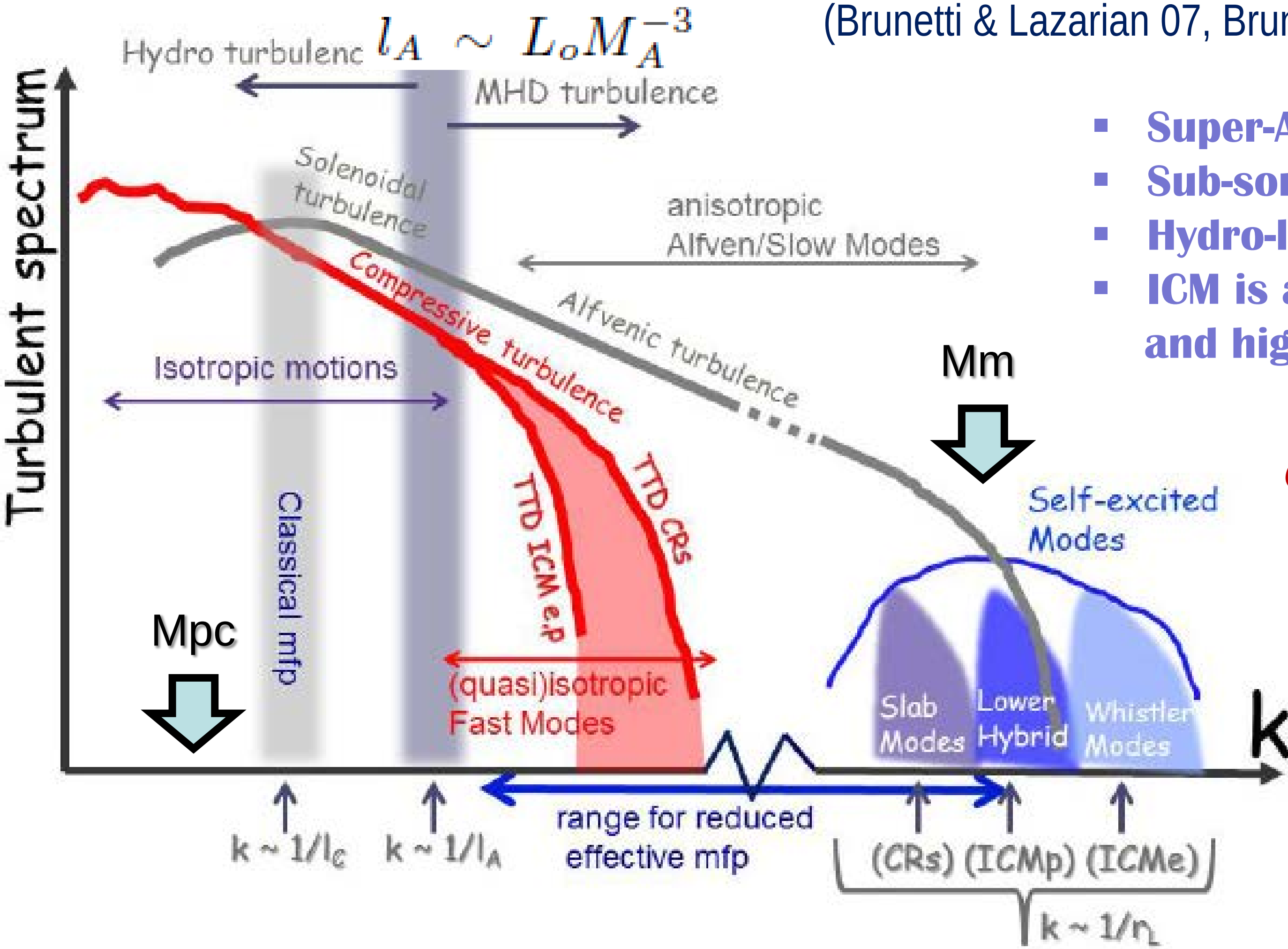
RH are probes of ICM microphysics

ICM Turbulence & acceleration

(Brunetti & Lazarian 07, Brunetti & Jones 14)



- **Super-Alfvenic : MA=3-10**
- **Sub-sonic : Ms=0.1-0.5**
- **Hydro-like > kpc, MHD < kpc**
- **ICM is a "weakly collisional" and high-beta plasma**

CR acceleration :

- **Fast Modes**
- **Slow Modes**
- **Modes driven at small scales**

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

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

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

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

Focus on LS Compressive turbulence …

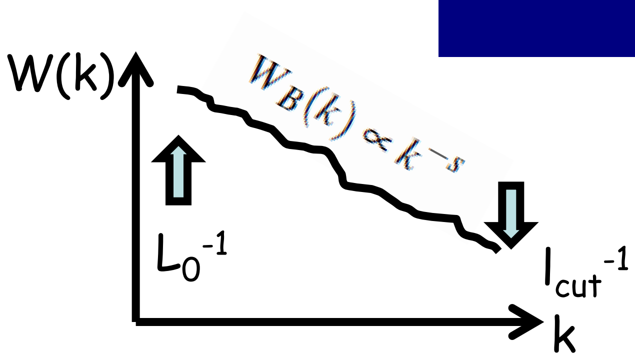
TTD acceleration

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

Transit Time Damping (TTD)

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

Interaction between magnetic momentum of particles and parallel gradient of B



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

$$D_{pp} = \mathscr{A}(s,..)\frac{\delta B^2}{B_0^2}\left(\frac{L_0}{l_{cut}}\right)^{1-s}\left(\frac{c_s^2}{c\, l_{cut}} p^2\right)$$

fraction of energy available at small scales

l_{cut} is the dominant scale for acceleration

TTD acceleration

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Cut-off is generated at scales where damping is faster than cascading.

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

$$\tau_{kk} \approx \frac{k^2}{(\partial/\partial k)(k^2 D_{kk})} \sim \frac{2}{9} \frac{c_s}{\delta V^2} (k k_0)^{-1/2}$$

MHD model?

MACROPHYSICS

microphysics

$$k_{\mathrm{cut,K}} \simeq \frac{81}{4} \left(\frac{\delta V^2}{c_s} \right)^2 \frac{k_0}{\left(\sum_\alpha \langle \Gamma_\alpha \rangle k^{-1} \right)^2}$$ Kraichnan

$$k_{\mathrm{cut},s} = \left[\frac{2}{7} (5-s) k_{\mathrm{cut,K}}^{1/2} k_0^{s-3/2} \right]^{\frac{1}{s-1}}$$ general

The spectrum affects also the cut-off scale

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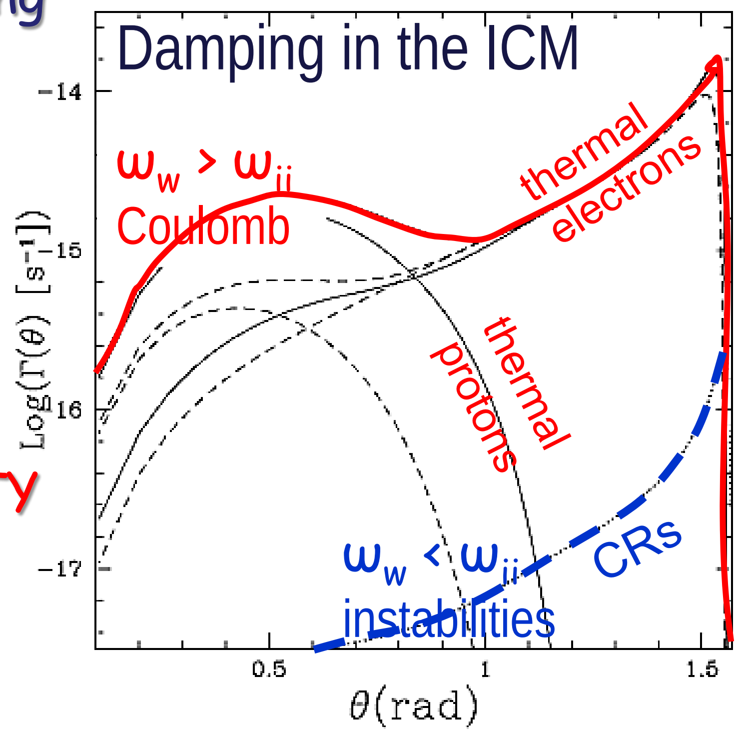

Acceleration depends on COLLISIONALITY and on the SPECTRUM of electromagnetic fluctuations in the ICM
(Brunetti & Lazarian 11, Miniati 15, Brunetti 16)

TTD acceleration

(Miller et al 96, Schlickeiser & Miller 98
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Transit Time Damping (TTD)

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Interaction between magnetic momentum of particles and parallel gradient of B

$\omega_w > \omega_{ii}$
Coulomb

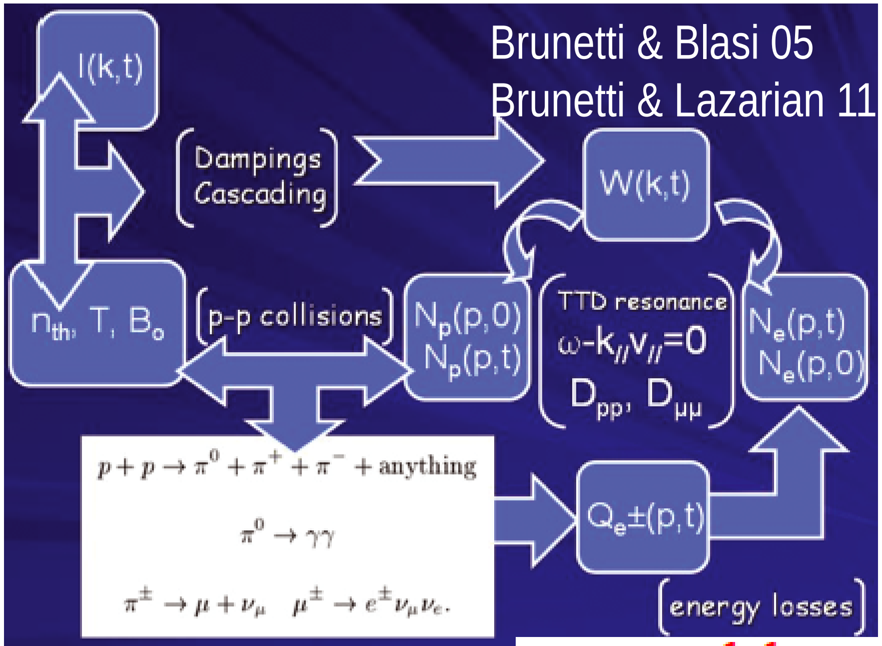
$$\tau_{acc} = \frac{p^2}{4D_{pp}} \simeq 125\left(\frac{M_o}{1/2}\right)^{-4} \left(\frac{L_o/300\,\mathrm{kpc}}{c_s/1500\,\mathrm{km\,s^{-1}}} \right) \ (\mathrm{Myr})$$

$\omega_w < \omega_{ii}$
instabilities

$$\tau_{acc} = \frac{p^2}{4D_{pp}} \simeq 10\left(\frac{M_o}{1/2}\right)^{-4} \left(\frac{L_o/300\,\mathrm{kpc}}{c_s/1500\,\mathrm{km\,s^{-1}}} \right) \left(\left[\frac{c \int p^4 dp \frac{\partial f}{\partial p}}{\rho c_s^2} \right] /0.04 \right) \ (\mathrm{Myr})$$

Acceleration efficiency is larger if plasma effects increase ICM effective collisionality because the bulk of turbulent energy flux is channeled into CR acceleration [Brunetti & Lazarian 11, Miniati 15, Brunetti 16]

Reacceleration of CRe, CRp & secondaries

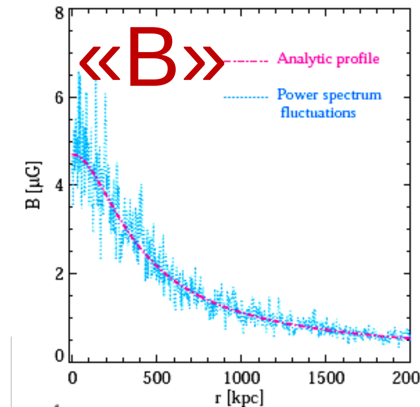


assumptions

$\omega_w > \omega_{ii}$
Coulomb

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

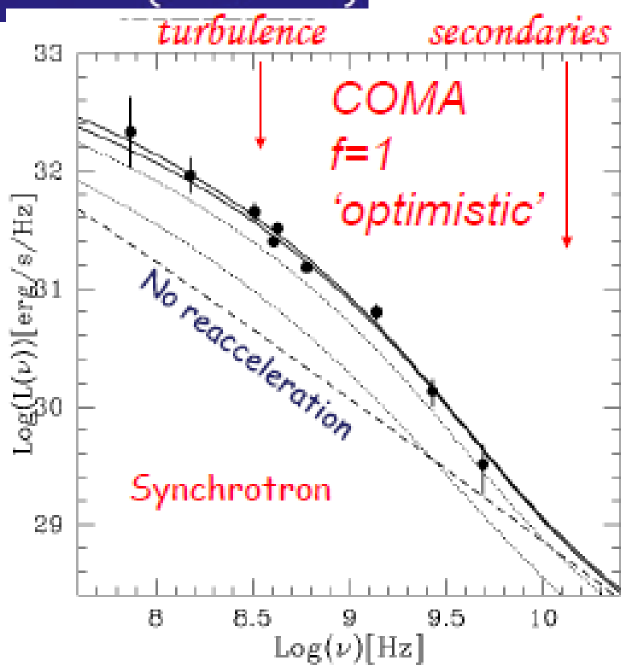
$$f = \frac{PRIMARY\ e^{\pm}}{SECONDARY\ e^{\pm}} + 1$$

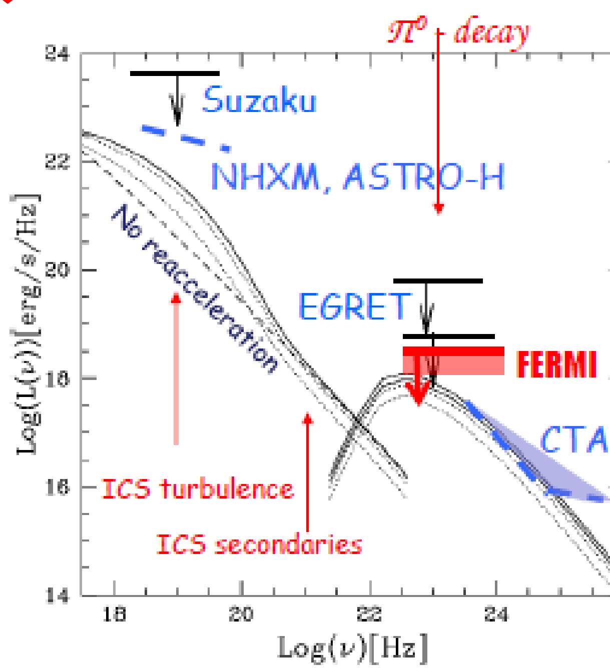


Bonafede et al 10

if the compressive turbulence is much smaller

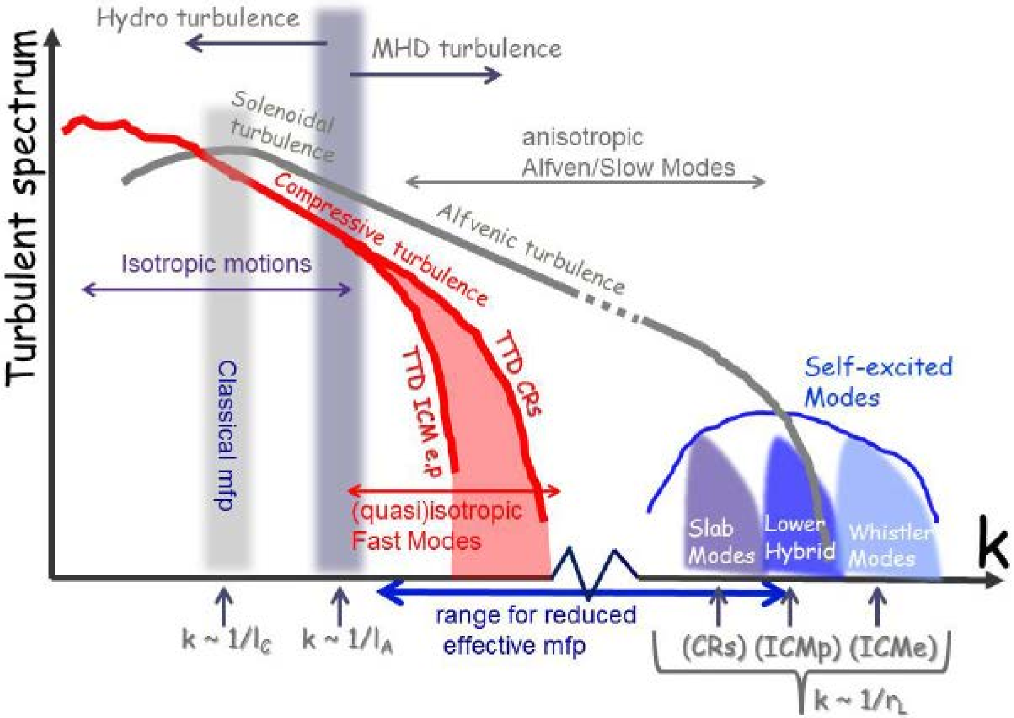
$\omega_w < \omega_{ii}$
instabilities

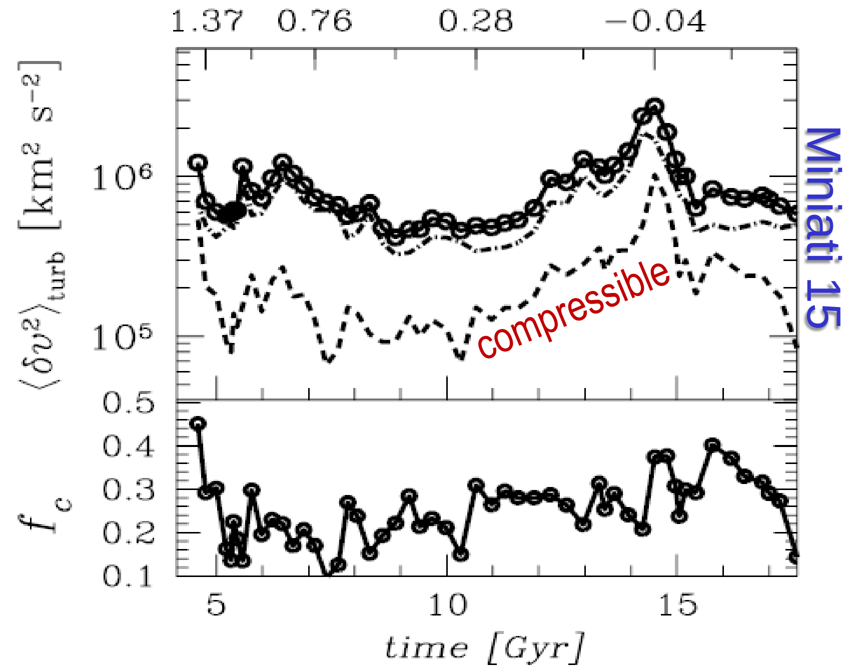


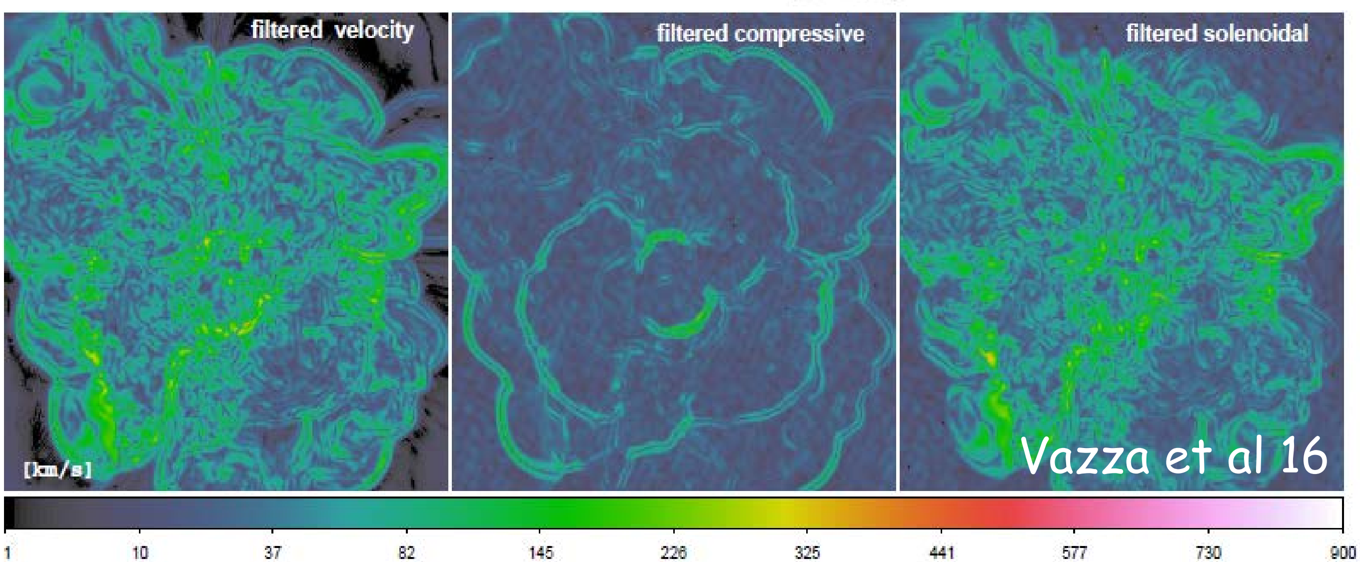


Brunetti & Lazarian 11

Turbulence acceleration: can we use solenoidal ?



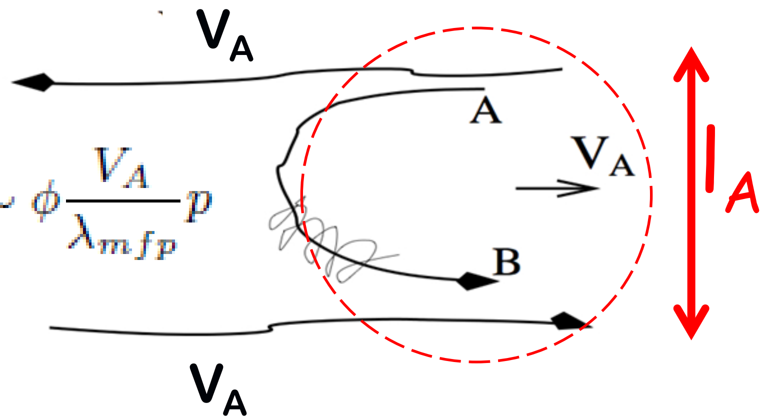




Simulations suggest that most of the large scale turbulence in the ICM is solenoidal

Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

[Brunetti & Lazarian 2016, MNRAS 458, 2584]



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

Starting point: turbulent reconnection and acceleration (Lazarian+Vishniac 99, deGouveia dal Pino+ Lazarian 05,..). Acceleration works even without compression as motions of scattering centers is provided by Richardson-like diffusion of field lines :

$$\Delta_B \sim \left(\frac{\delta V^3}{L_0}\right)^{\frac{1}{2}} \tau^{\frac{3}{2}}$$

(2) CRe diffuse faster than eddy turnover time

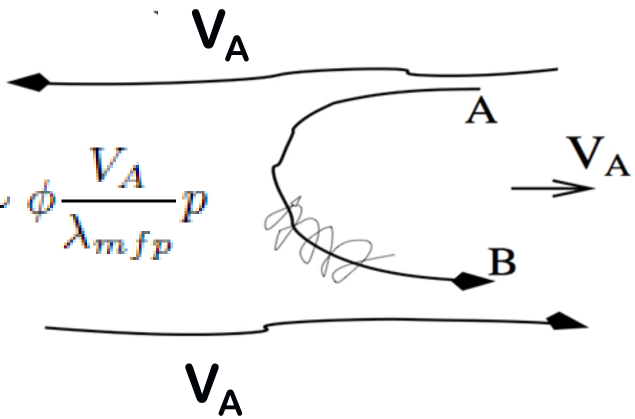
(3) Case : $p >> \Delta p$

$$\Delta p = p\phi \frac{V_A}{\lambda_{mfp}} \quad \mathrm{X} \quad \frac{l_A^2}{D}$$

} per cycle

Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

CRe diffuse in reconnecting ('collapsing') and dynamo ('stretching') regions



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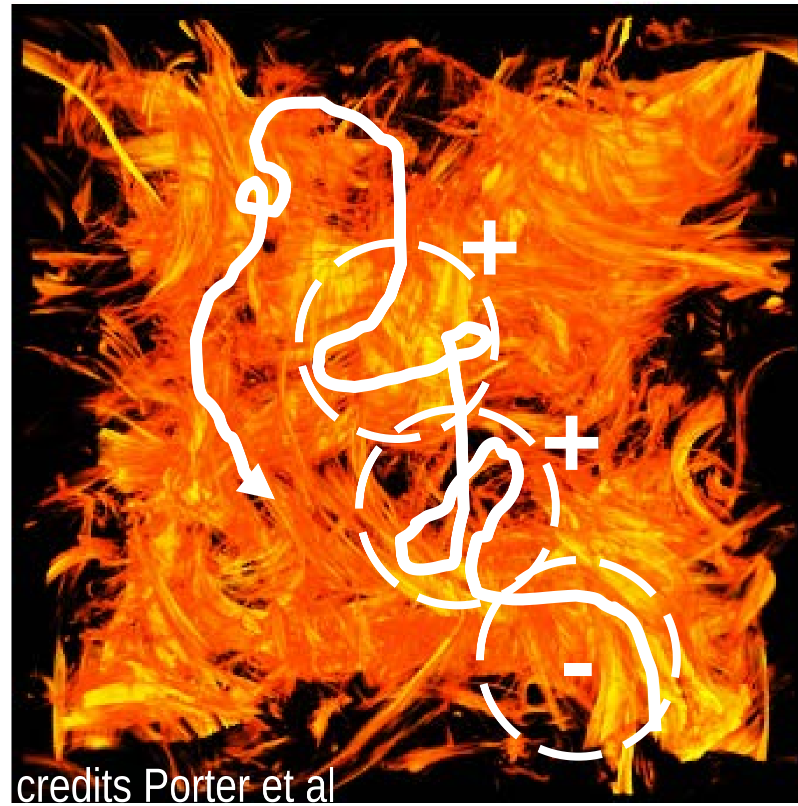


Several +/- cycles result is a random walk in space and momentum : Fermi II

Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM

[Brunetti & Lazarian 2016]

$$D_{pp} \equiv \lim_{t\to\infty} \frac{1}{2t}\langle \Delta p(t)\Delta p^*(t+\tau)\rangle = \Re\int_0^\infty d\tau \langle \dot{p}(t)\dot{p}^*(t+\tau)\rangle = \langle \frac{\Delta p \Delta p}{2\Delta t}\rangle \sim 3\sqrt{\frac{5}{6}}\frac{c_s^2}{c}\frac{\sqrt{\beta_{pl}}}{L_o}M_t^3\psi^{-3}p^2$$

where $\lambda_{mfp} = \psi l_A$

Lo=300 kpc
β=60-120
Ψ=0.5

acceleration time

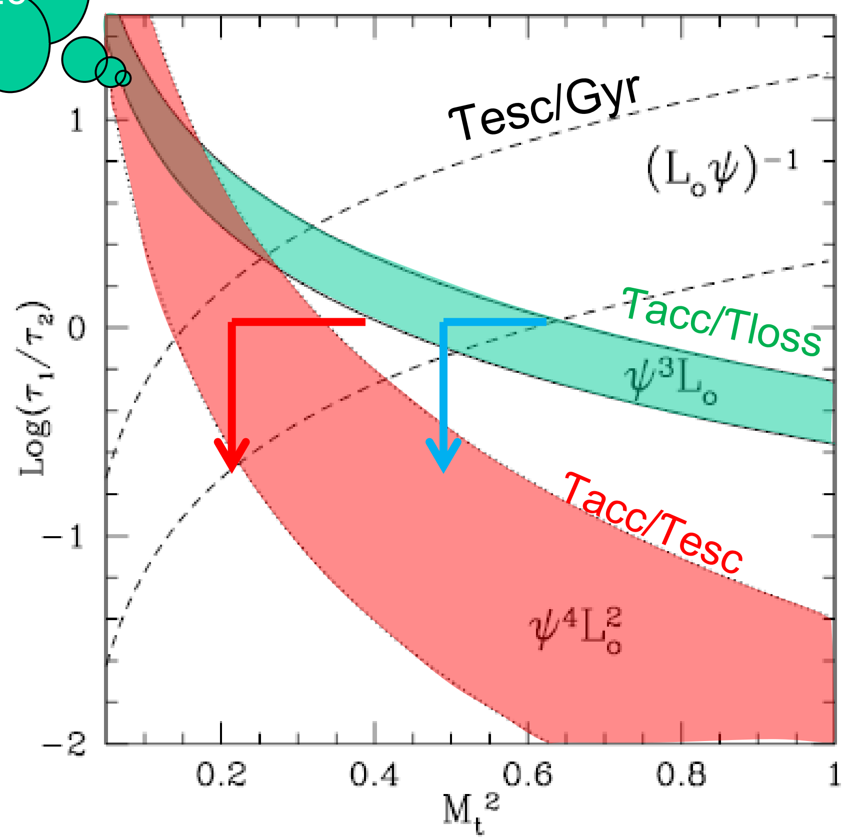
$$\tau_{acc} = \frac{p^2}{4D_{pp}} \simeq \frac{\sqrt{2}}{12}\frac{c}{c_s^2}\frac{L_o}{\sqrt{\beta_{pl}}}M_t^{-3}\psi^3$$

Losses of CRe in the ICM

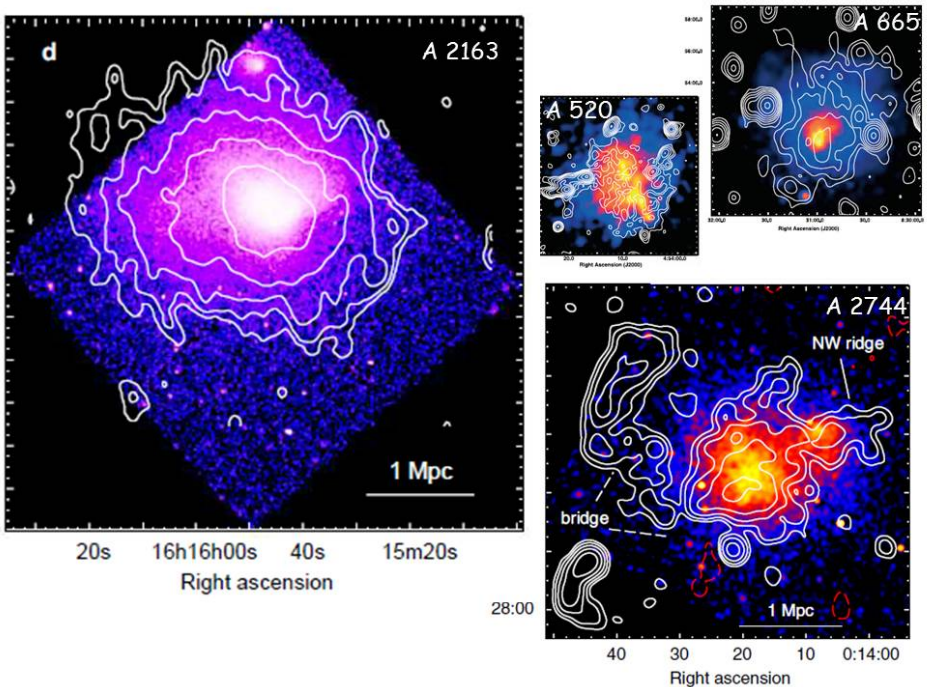
$$\tau_{loss}(Gyrs) = 4\left\{\frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 + (1+z)^4\right] + \left(\frac{n_{th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{th}/10^{-3}}\right)\right]\right\}^{-1}$$

escape

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



Reacceleration mediated by turbulent reconnection in super-Alfvenic ICM



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"magic" formula :

Syn observed frequency

$$M_t \simeq 0.8\frac{10^3 \mathrm{km\,s^{-1}}}{c_s}\left(\frac{\nu_o(\mathrm{GHz})}{35}\frac{7}{\xi}\right)^{1/6} \times \left(\frac{L_o}{10^2\mathrm{kpc}}\right)^{1/3}\frac{(1+z)^{11/6}\frac{\psi}{0.5}}{\left(\frac{n_{ICM}}{10^{-3}}\right)^{1/6}}$$

request : $\delta V_o \sim 100+$ km/s

using the min value of Ψ that is allowed in test-particle calculations (Brunetti+Lazarian 16)

Take home messages

(1) The ICM is an unique envionment for plasma astrophysics : stirred , unstable and very small $R_c = \nu_C/\omega_p$

Most of the microphysics is likely driven by plasma effects….

(2) Nonthermal phenomena in GC (radio to gamma) probe the interplay between ICM microphysics and particle acceleration physics.
Hard to explain Radio Halos without consideriing plasma effects that reduce viscosity in the ICM

(3) Favoured scenario for Radio Halos is acceleration by LS turbulence driven by cluster mergers :

- Compressive case : successful but several unknowns: damping, spectrum, collisionality and mfp
- Incompressive case : possible if turbulent reconnection is considered. The big unknown here is the role of kinetic effects