Cosmic rays in galaxy clusters: from losses to particle acceleration

Energy losses • confinement • CR sources • Fermi I & II

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From observations to physics: the key questions



Observed synchrotron emission from ≈ 100 kpc – Mpc scales



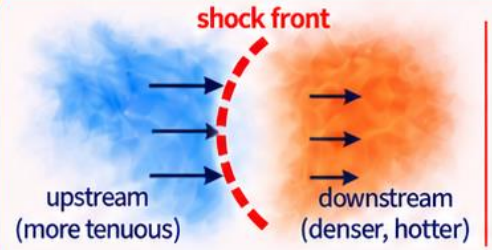
Can the electrons live long enough?

losses • lifetime • confinement



Where do the particles come from?

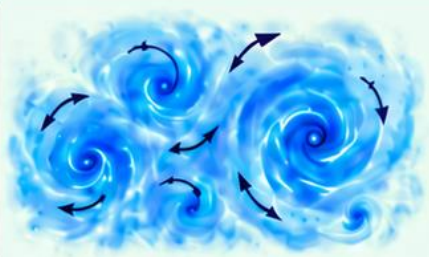
CR sources • seed electrons



SHOCKS

How are particles accelerated at shocks?

1st-order Fermi → **relics**

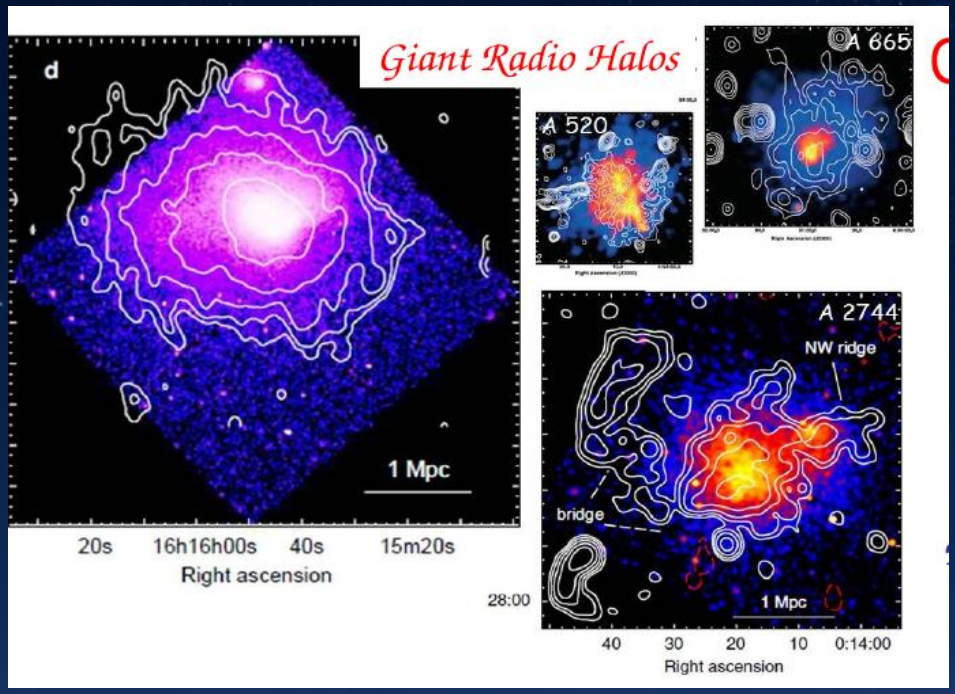


TURBULENCE

How are particles re-accelerated in the ICM?

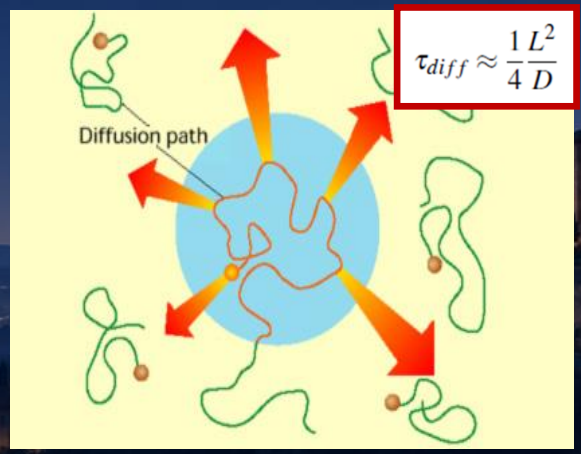
2nd-order Fermi → **halos**

Why do we need in-situ particle acceleration?



- Radio halos and relics require GeV electrons and μG magnetic fields over 100 kpc–Mpc scales
- Radiating electrons cool much faster than they can simply diffuse across a cluster
- The observed emission therefore requires acceleration or re-acceleration inside the ICM

the diffusion problem (*Jaffe 1977*)
$t_{diff} \gg t_{cool}$ for radio-emitting electrons.



Roadmap for this lecture

1. Energy losses / lifetime
How long do electrons and protons survive?

2. Confinement / escape
Can CRs remain inside the cluster?

3. Sources of CRs
Where do seed particles come from?

4. Fermi mechanisms
Shocks → relics; turbulence → halos

Goal: connect the observed diffuse radio emission to the plasma processes that can power them.

Useful quantities and notation

$\gamma = E / (m_e c^2)$

Lorentz factor of a relativistic elec.
Typical radio-emitting CRe: $\gamma \sim 10^4$

$t_{diff} \sim L^2 / D$

Diffusion timescale
D = spatial diffusion coefficient

$S_\nu \propto \nu^{-\alpha}$

Radio spectral index
Larger $\alpha \rightarrow$ steeper spectrum

$\mathcal{M} = v_{sh} / c_s$

Shock Mach number
v_{sh} = shock speed; c_s = sound speed

$t_{loss} = E / |dE/dt|$

Characteristic particle cooling time

$\beta = P_{th} / P_B$

Plasma beta
High $\beta \rightarrow$ thermal pressure $\gg$ magnetic pressure

Typical ICM: $T \sim 10^7$–10^8 K • $n_e \sim 10^{-4}$–10^{-2} cm^{-3} • B ~ 0.1–few μG • L ~ 100 kpc–1 Mpc

Energy losses of relativistic electrons in the ICM

(dE/dt) / $m_e c^2$ = b = rate of energy losses in units of $m_e c^2$

where $\gamma = \frac{E}{m_e c^2}, \qquad E \simeq pc \quad (\gamma \gg 1)$

$$b_{\rm IC}(\gamma) = \frac{4}{3}\frac{\sigma_{\rm T}}{m_e c}\gamma^2 U_{\rm CMB} = 1.37 \times 10^{-20}\gamma^2(1+z)^4 \ {\rm s}^{-1},$$

$$b_{\rm syn}(\gamma) = \frac{4}{3}\frac{\sigma_{\rm T}}{m_e c}\gamma^2 U_B = 1.30 \times 10^{-21}\gamma^2\left(\frac{B}{1\ \mu{\rm G}}\right)^2 {\rm s}^{-1},$$

radiative losses

$$U_B = \frac{B^2}{8\pi},$$

$$U_{\rm CMB} = \frac{B_{\rm CMB}^2}{8\pi},$$

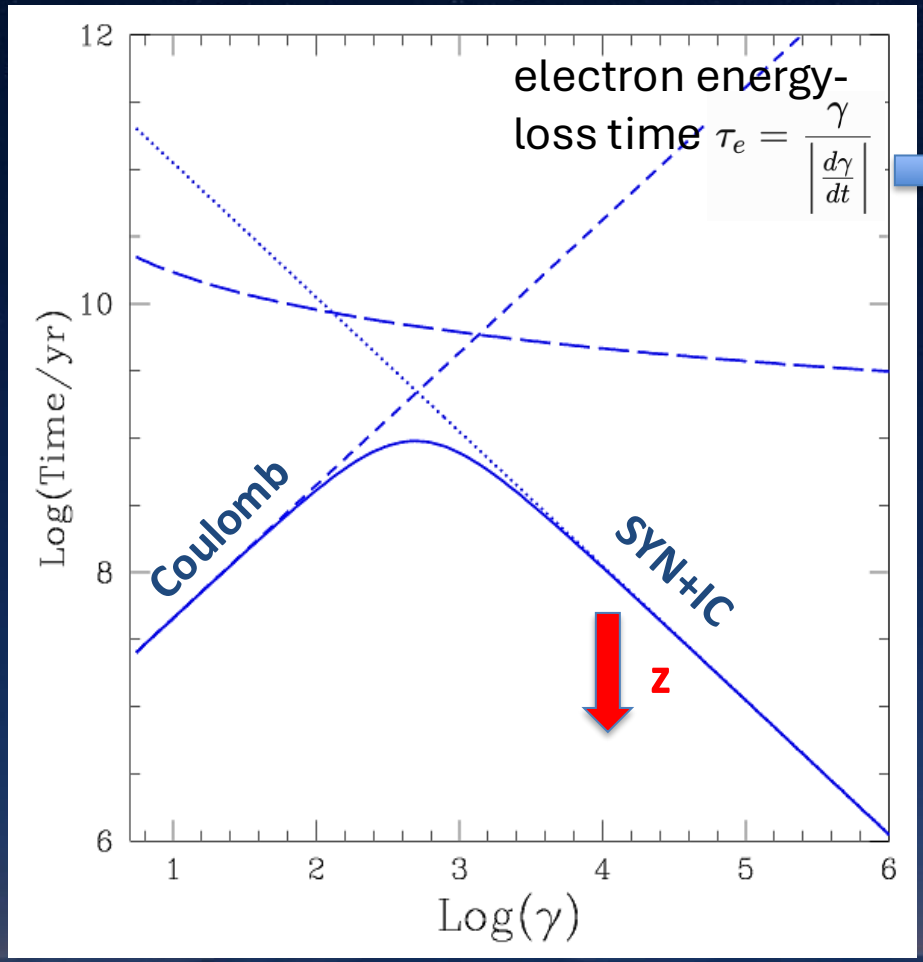
$$B_{\rm CMB} \simeq 3.25(1+z)^2\ \mu{\rm G}.$$

collisional losses

$$b_{\rm Coul}(\gamma) \approx 1.2 \times 10^{-12} n_e \left[1.0 + \frac{\ln(\gamma/n_e)}{75}\right] {\rm s}^{-1},$$

$$b_{\rm brem}(\gamma) \approx 1.51 \times 10^{-16} n_e \gamma[\ln(\gamma) + 0.36] \ {\rm s}^{-1},$$

Electron lifetime: the radio-emitting window is short



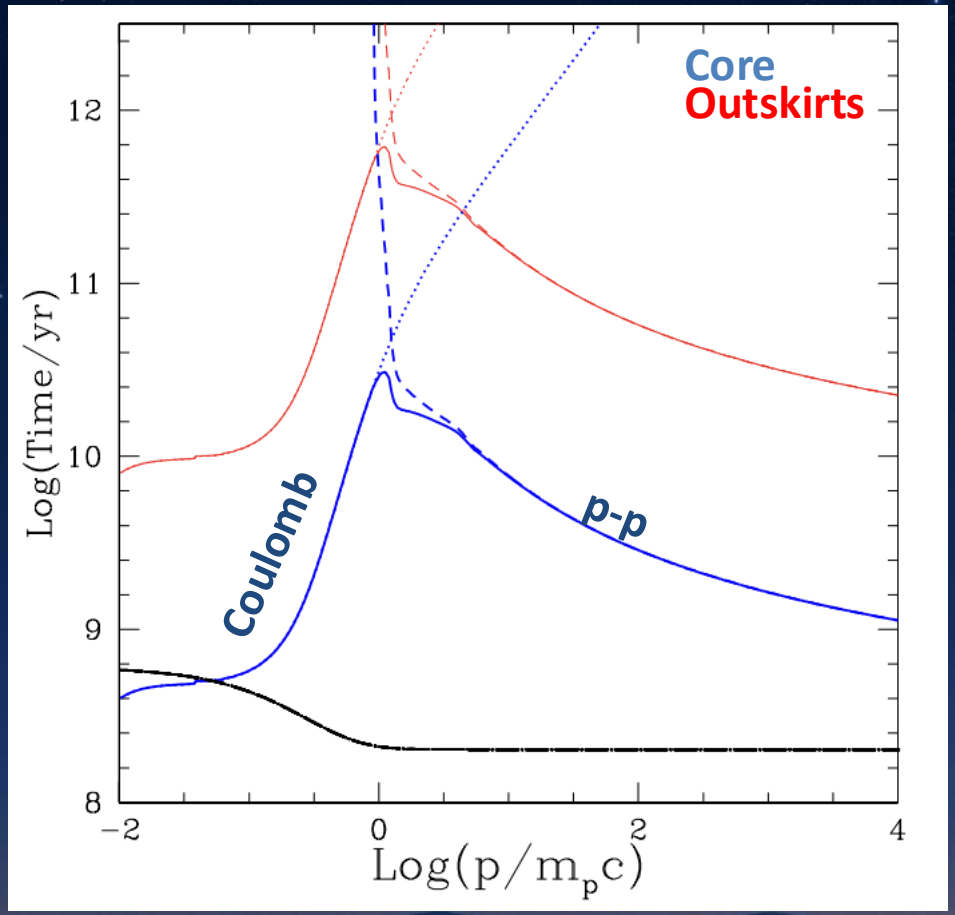
$$\tau_e(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{\mathrm{th}}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{\mathrm{th}}/10^{-3}}\right)\right]\right\}^{-1}.$$

$$\nu_{\mathrm{syn}} \sim 0.4 \left(\frac{B}{1\,\mu\mathrm{G}}\right)\left(\frac{\gamma}{10^4}\right)^2 \mathrm{GHz}.$$

- For GHz–MHz synchrotron-emitting electrons, typical lifetimes are only a few $\times 10^7$ – 10^8 yr
- Inverse-Compton losses increase rapidly with redshift through the CMB energy density
- This is much shorter than a cluster crossing time (~Gyr)

Radio emitting electrons (GeV electrons) have short radiative lifetime

Cosmic-ray protons are long-lived



Brunetti + Lazarian 07

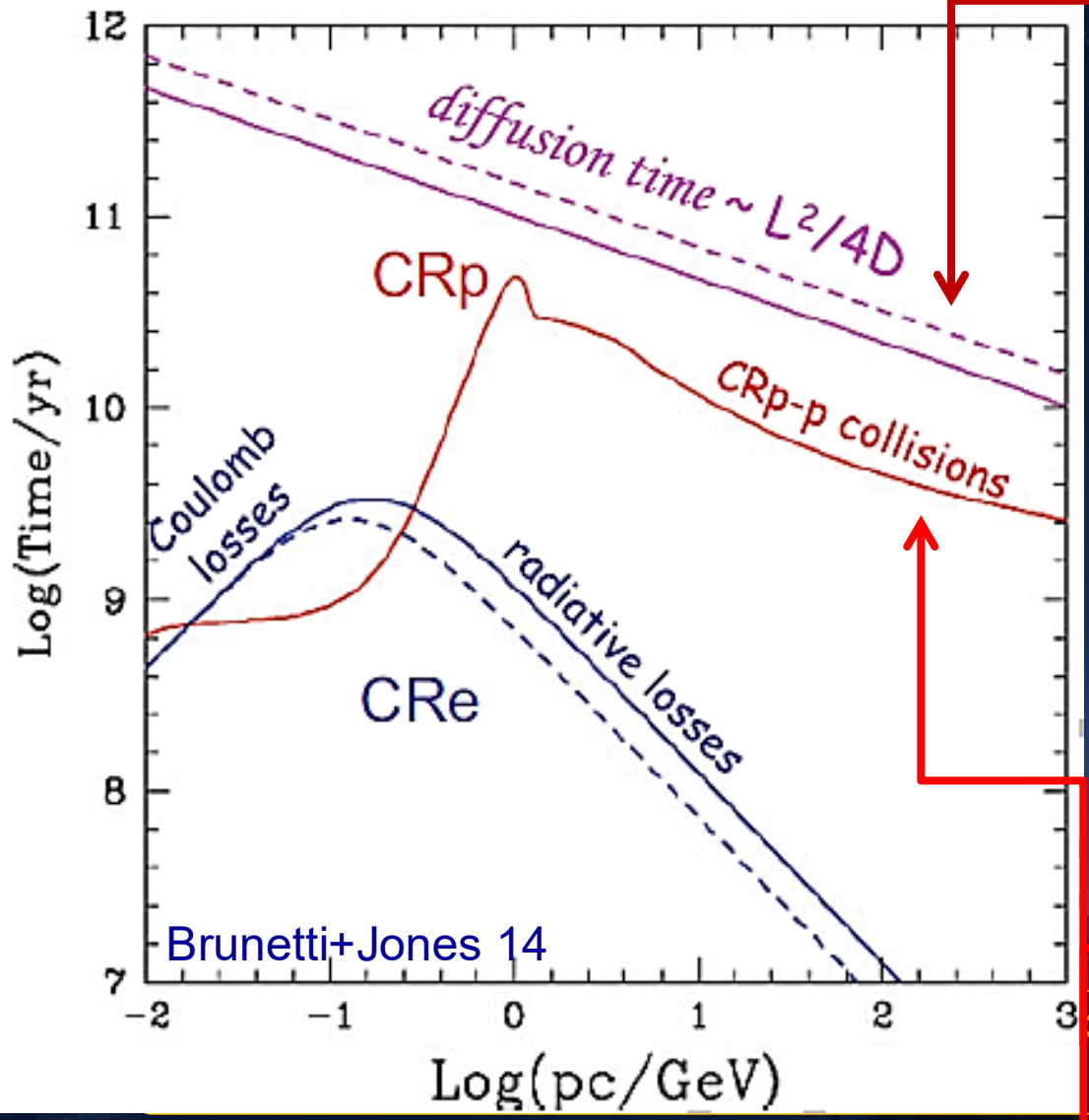
$$\tau_{pp} = \frac{1}{n_{\rm th}\sigma_{\rm pp}c} \sim 10^{18}\left(\frac{n_{\rm th}}{10^{-3}}\right)^{-1} s.$$

- Protons do not suffer synchrotron or inverse-Compton losses
- Inelastic p–p collisions are slow in the dilute ICM
- For typical cluster densities, t_{pp} is of order many Gyr
- CR protons can therefore accumulate over the cluster history

Inelastic collisions between CR & thermal protons ~10+ Gyrs

CRs IN GALAXY CLUSTERS

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



In summary:

$(-\frac{d\gamma}{dt})_{Ionis} \propto \ln(\gamma)$ Ionisation

$(-\frac{d\gamma}{dt})_{Brems} \propto \gamma$ Bremss./adiabatic

$(-\frac{d\gamma}{dt})_{Syn} \propto \gamma^2$ Synchrotron

$(-\frac{d\gamma}{dt})_{IC} \propto \gamma^2$ Inverse Compton

$$\tau_{pp} = \frac{1}{n_{\rm th}\sigma_{\rm pp}c} \sim 10^{18}\left(\frac{n_{\rm th}}{10^{-3}}\right)^{-1} s$$

Brunetti & Jones 2014 (review)

Losses + confinement: the first physical picture

CR protons

long-lived; can accumulate for Gyr

Radio electrons

short-lived; must be produced or re-energised recently

Cluster magnetic fields

confine particles and control transport

see Bonafede's lectures

Therefore the crucial question becomes: where do fresh or fossil relativistic particles come from?

Where do cluster cosmic rays come from?

Galaxies / SNe / winds

AGN jets and bubbles

Shocks in the ICM

Hadronic secondaries

The sources provide the CR energy budget and, crucially, the seed particles for re-acceleration.

Galaxies, supernovae and galactic winds

100+ galaxies



Galactic feedback and the ICM

- Supernovae produce metals and accelerate cosmic rays, while galactic winds can transport both into the surrounding medium.
- ICM metal enrichment traces the transport of stellar products throughout cluster assembly.

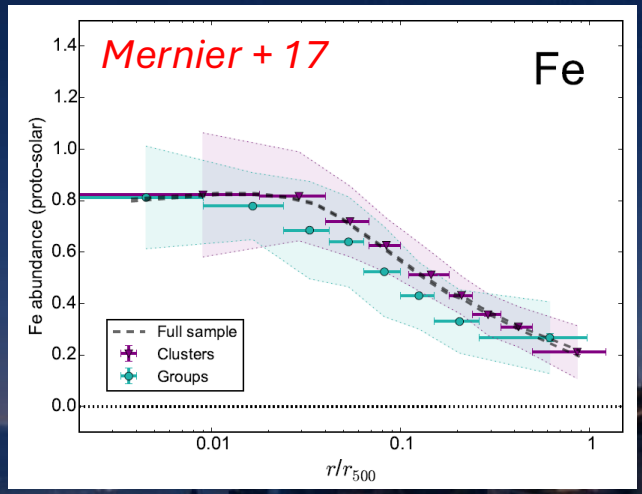
From iron enrichment to CR energetics

Fe abundance in the ICM (Voelk et al 96)

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

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

$E_{CR} \sim 0.1\% - 1\%$ of E_{ICM}

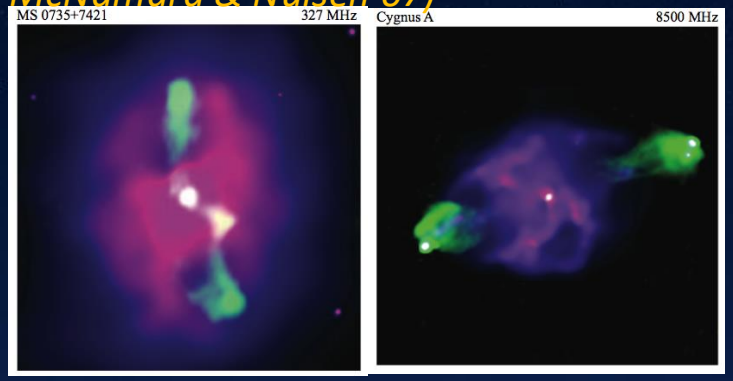


Fe abundance profile

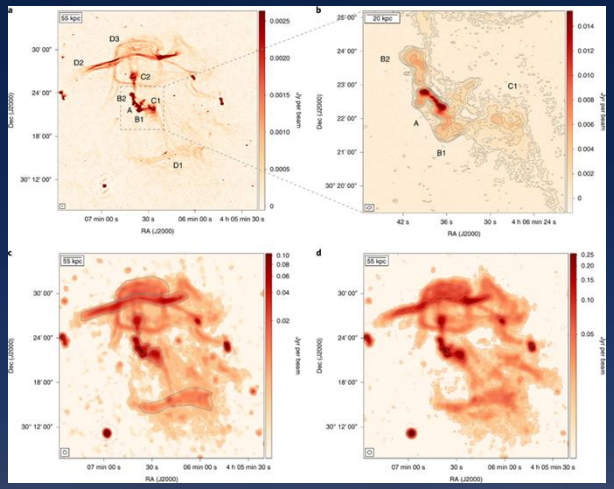
Galaxies can supply long-lived CR protons and seed electrons to the ICM.

AGN, radio bubbles and fossil plasma

McNamara & Nulsen 07)



Active radio galaxies and evolved plasma



Brienza+ 21

- Radio jets from galaxies inject relativistic plasma directly into the ICM
- After the AGN fades, low-frequency observations reveal complex fossil plasma structures (lower-energy electrons may persist as fossil plasma)
- Mixing and transport can distribute this seed population far from the parent AGN

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

E_{CR} = 0.001 - 0.1 of E_{ICM}

$E_{CR} = \mathbf{0.1\% - 10\%}$ of E_{ICM}

- AGN energy injection: highly uncertain
- total non-thermal energy partitioned among magnetic fields, relativistic electrons and protons.

shock and turbulent can re-accelerate these fossil electrons

Hadronic collisions: secondary electrons and gamma rays

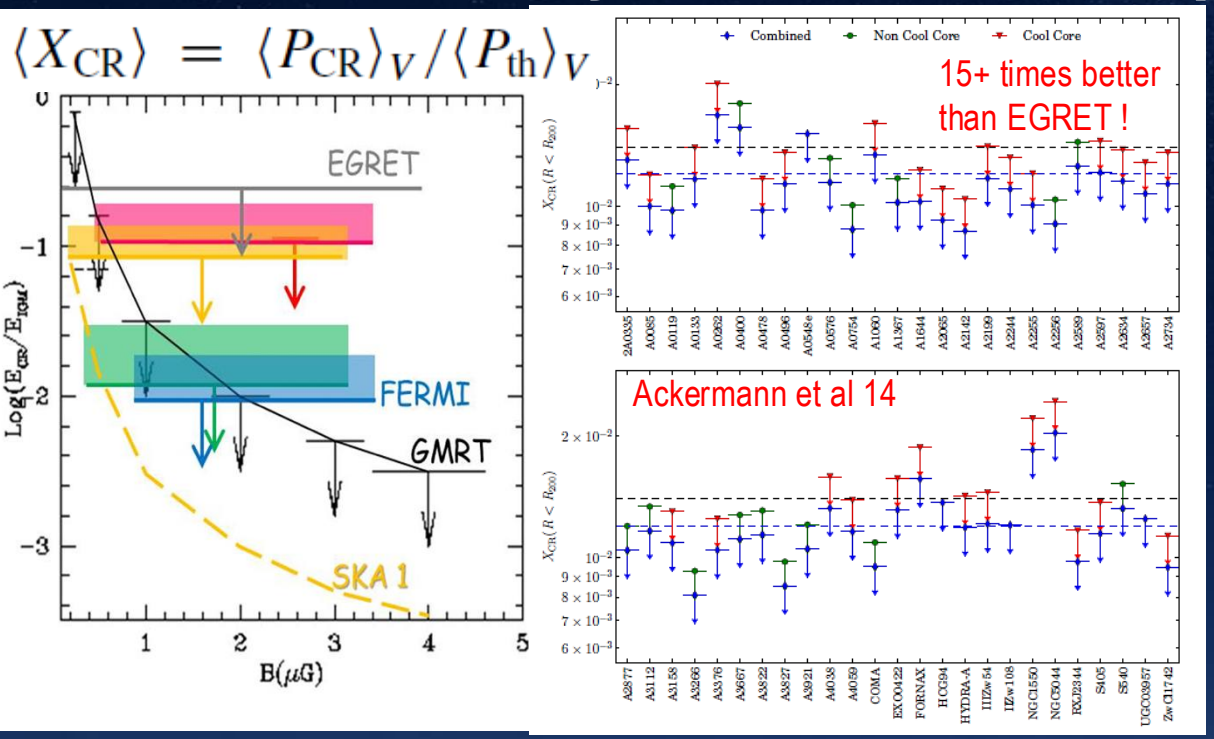
CR proton → p–p collision → $\pi^{\pm} \rightarrow e^{\pm}$, $\pi^{0} \rightarrow \gamma\gamma$

$$t_{pp} \sim \frac{1}{n\,\sigma_{pp} c}$$

- Secondary e± can contribute to synchrotron emission
- The same interactions unavoidably produce π^0-decay gamma rays
- Gamma-ray non-detections therefore constrain the CR proton energy density

Hadronic models are tightly linked to gamma-ray observations.

Gamma-ray limits on the CR proton content



Data suggest a ratio of energy budget **CR/TH < percent level.**

- Fermi-LAT searches of nearby clusters have yielded very stringent limits
- For standard assumptions, the CR-proton energy budget is constrained to the percent level in many systems
- This strongly limits pure hadronic explanations of giant radio halos
- A low-level hadronic component may still provide useful secondary seed electrons

Gamma rays tell us that CR protons are important — but cannot freely dominate the non-thermal energy budget.

Why seed electrons matter

- Direct acceleration from the thermal pool is inefficient in the ICM
- AGN fossil plasma supplies already-relativistic electrons
- Hadronic collisions continuously inject secondary electrons
- Previous shocks and turbulence can leave a low-energy CR reservoir
- Re-acceleration starts from this seed population and can strongly boost radio emissivity

The main question is not “how do we create GeV electrons from scratch?”, but “how do we re-energise the seeds already present?”

Fermi acceleration: 1st order vs 2nd order

1st-order Fermi

$\langle \Delta E/E \rangle \propto u/c$

Systematic gain at a shock → efficient acceleration

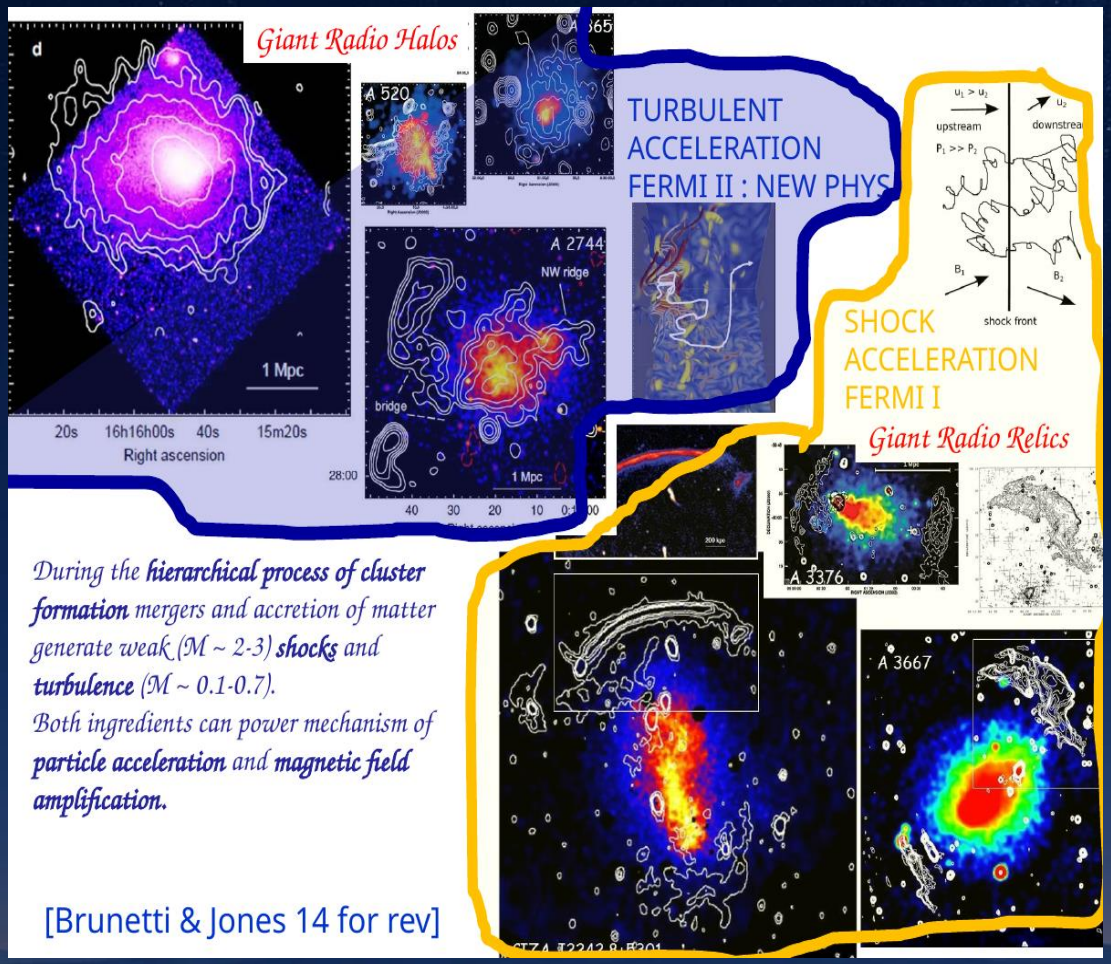
2nd-order Fermi

$\langle \Delta E/E \rangle \propto (u/c)^2$

Stochastic gain in turbulence → slower re-acceleration

Same basic idea — repeated scattering off moving magnetic structures — but very different efficiency and geometry.

Cluster formation supplies both shocks and turbulence

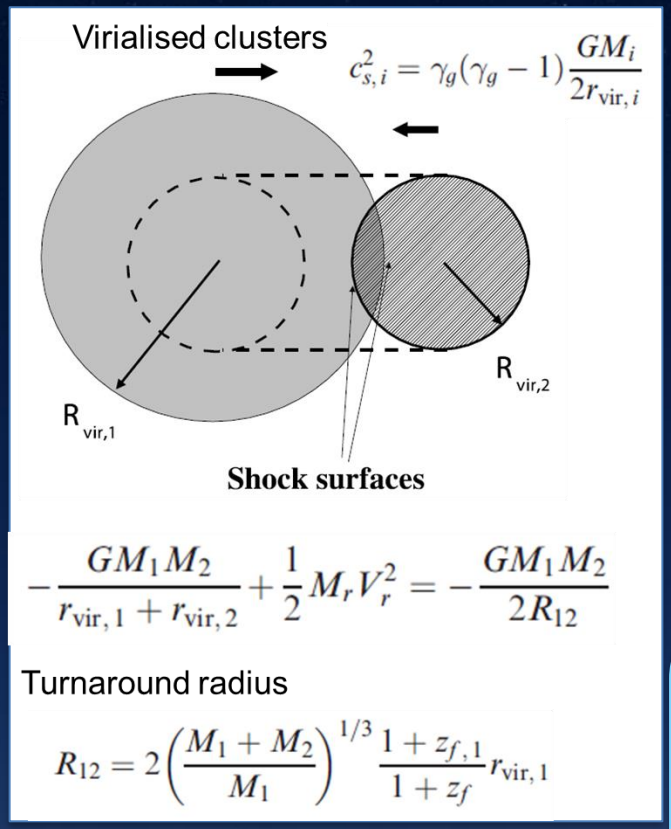


- Mergers and accretion dissipate huge gravitational energy
- weak **shocks** $\mathcal{M} \sim 2$–3 and subsonic **turbulence** $\mathcal{M} \sim 0.1$–0.7
- Both processes can amplify magnetic fields and transfer energy to CRs

This naturally maps onto the two main diffuse radio sources:

shocks → relics ? **turbulence → halos ?**

Shocks in galaxy clusters are weak

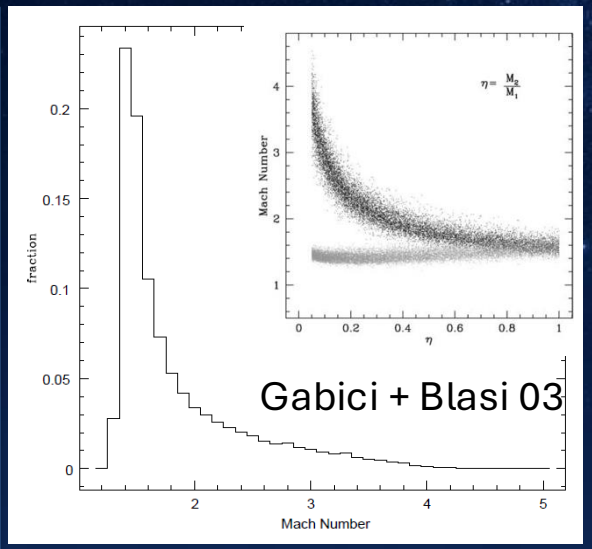


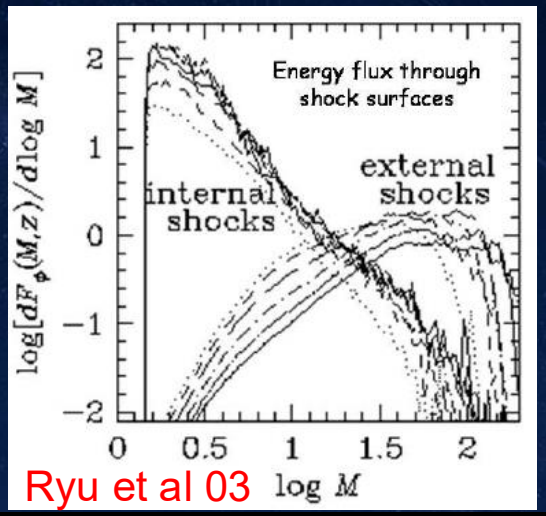
$$-\frac{GM_1M_2}{r_{\mathrm{vir},1}+r_{\mathrm{vir},2}}+\frac{1}{2}M_rV_r^2=-\frac{GM_1M_2}{2R_{12}}$$

Turnaround radius

$$R_{12}=2\left(\frac{M_1+M_2}{M_1}\right)^{1/3}\frac{1+z_{f,1}}{1+z_f}r_{\mathrm{vir},1}$$

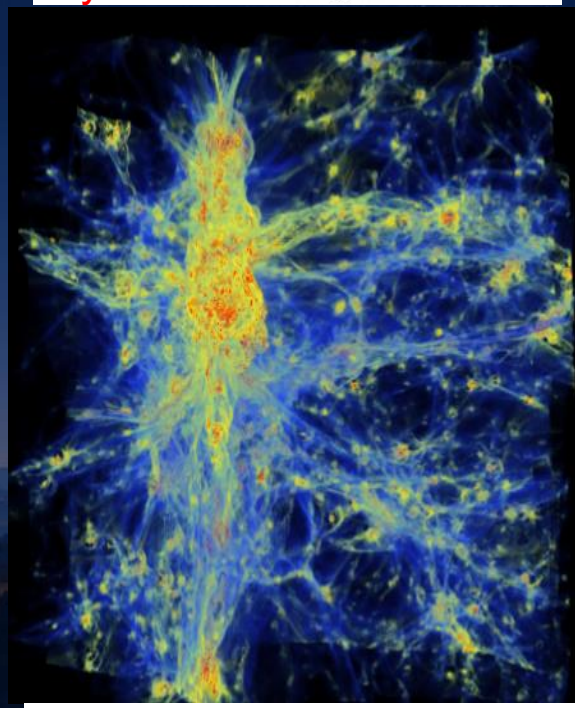
$$\mathcal{M}=\frac{v_{\mathrm{sh}}}{c_s},\qquad c_s\simeq\sqrt{\frac{\gamma_{\mathrm{gas}}kT}{\mu m_p}}.$$





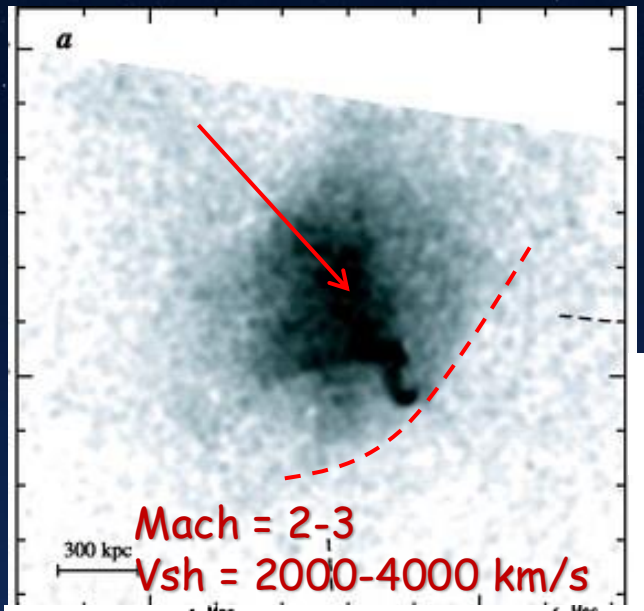
- shocks in galaxy cluster are expected to be weak: 1.5-2

The bulk of ICM heating comes from internal, relatively weak shocks



Radio relics test particle acceleration in weak, high-β collisionless shocks.

Observed shocks in galaxy clusters

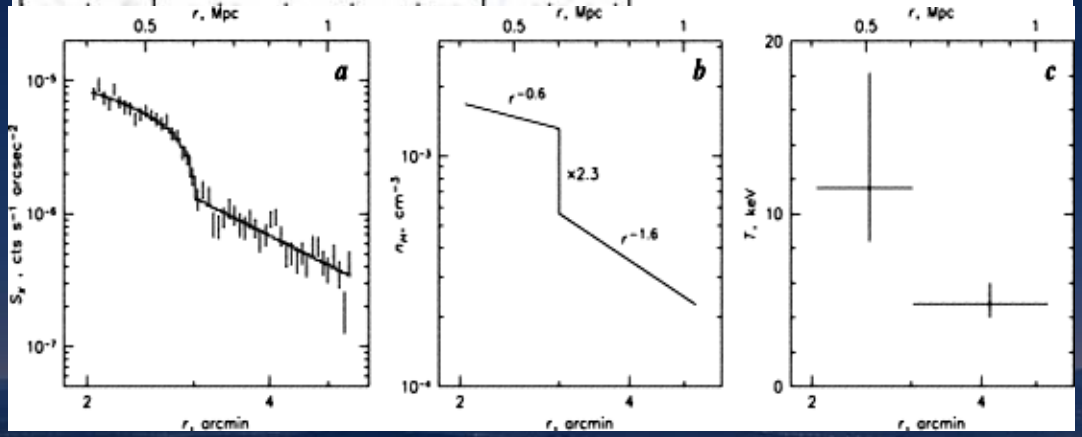


From X-rays we measure :

- density jump
- temperature jump
- surface-brightness edge

$$\frac{\rho_d}{\rho_u} = \frac{V_u}{V_d} = r = \frac{4M^2}{M^2+3}$$

$$\frac{T_d}{T_u} = \frac{(5M^2-1)(M^2+3)}{16M^2}$$



(Markevitch & Vikhlinin 01,07)



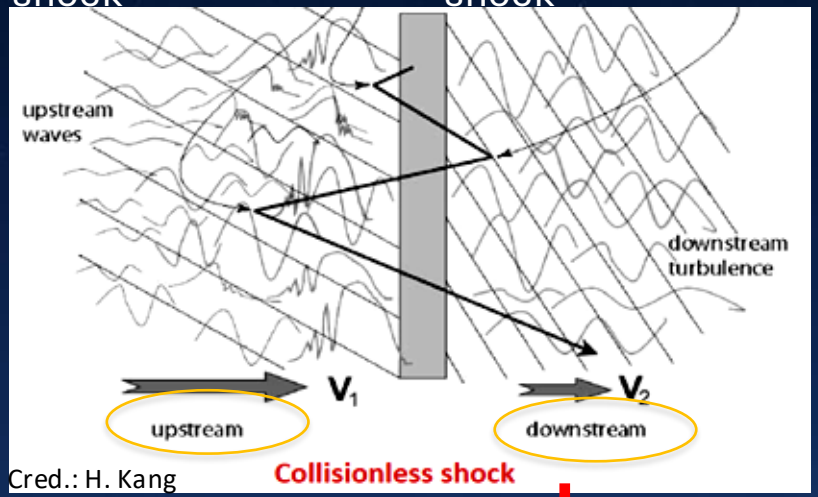
Key points

- X-ray shocks in clusters are usually weak: $\mathcal{M}$ ~ 1.5–3, occasionally up to ~4
- Most of the ICM heating is produced by internal, weak merger shocks
- Mach estimates are affected by projection and multi-temperature structure
- This is a very different acceleration regime from young SNR shocks

1st-order Fermi at shocks: diffusive shock acceleration (DSA)

upstream = gas not yet processed by the shock

downstream = gas that has crossed the shock



Cred.: H. Kang

- Particles scatter repeatedly across the shock front
- Each cycle gives a systematic energy gain because upstream and downstream flows converge
- Scattering is mediated by magnetic fluctuations generated by the particles and the shock
- The result is a non-thermal power-law tail

compression ratio

$$r = \frac{\rho_2}{\rho_1},$$

$$r = \frac{4\mathcal{M}^2}{\mathcal{M}^2 + 3}$$

Power-law spectra

$$N(p) \propto p^{-\delta_{inj}}$$

$$\delta_{inj} = 2\frac{\mathcal{M}^2+1}{\mathcal{M}^2-1}$$

Synchrotron spectra

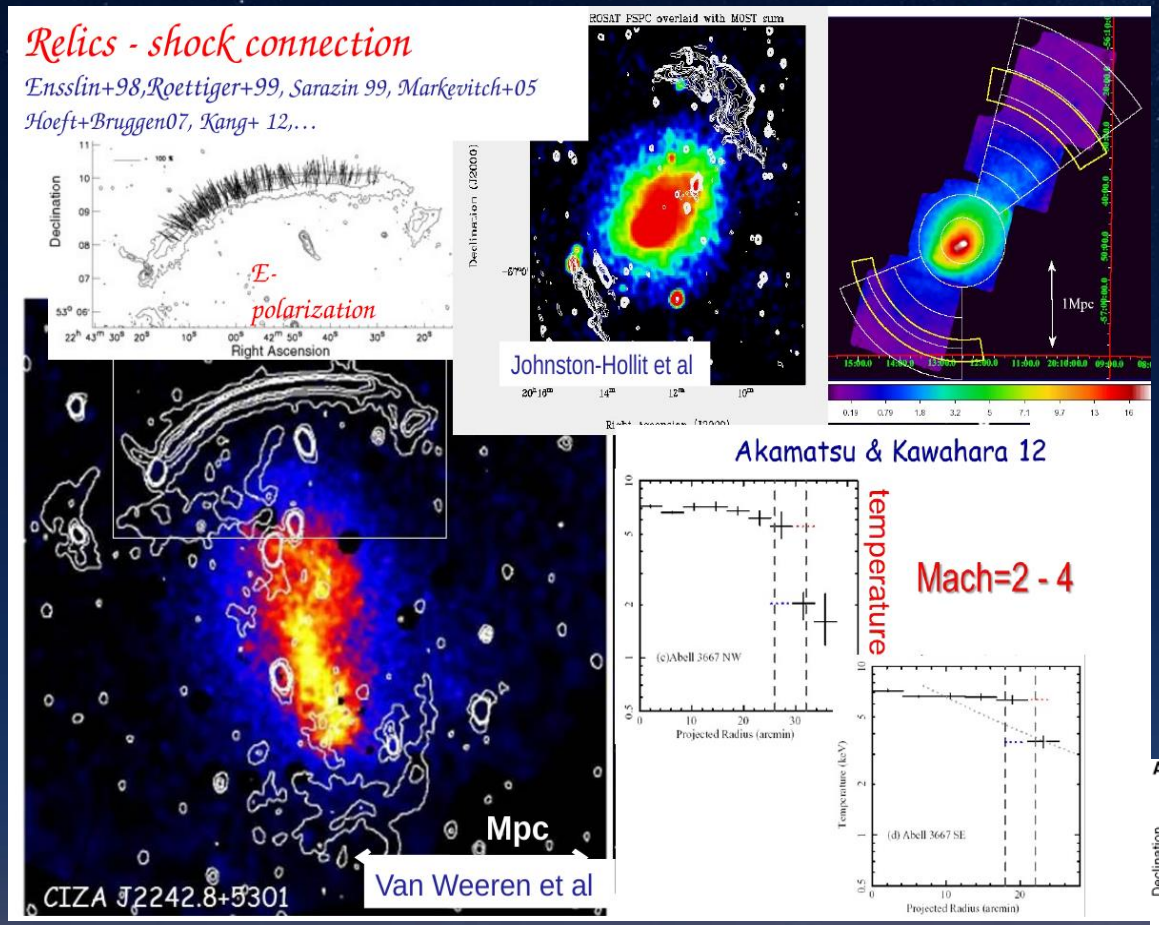
$$\alpha_{inj} = \frac{\delta_{inj}-1}{2}$$

DSA predicts

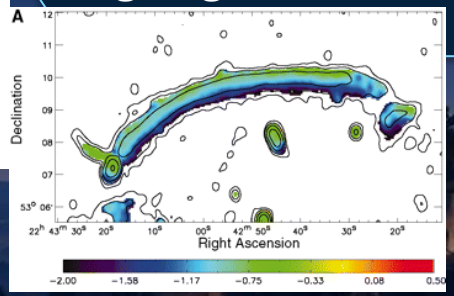
- <u>strong shocks</u> (M → ∞ and r=4) $\alpha \to 1$ ($\alpha_{inj} \to 0.5$)
- <u>weak shocks</u> (M ≥ 3–5) $\alpha > 1$ ($\alpha_{inj} > 0.5$).

DSA converts a fraction of the shock kinetic-energy flux into relativistic particles.

Radio relics: observational fingerprints of shocks



- Peripheral, elongated radio morphology
- High fractional polarization and ordered magnetic fields
- X-ray/SZ density and temperature jumps at the radio edge
- Spectral index steepens from the shock front downstream because of ageing

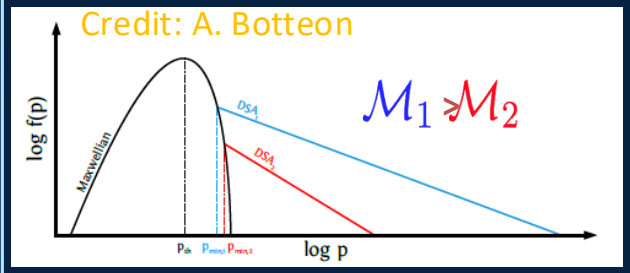


Relics provide the clearest cluster-scale laboratory for 1st-order Fermi acceleration.

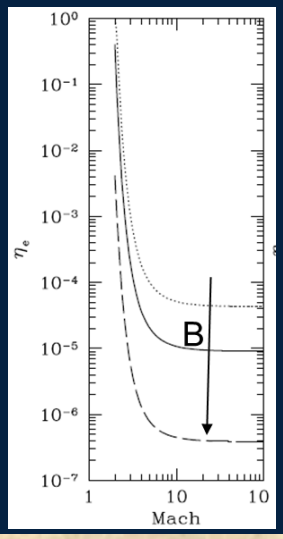
Why standard DSA is challenged in the ICM

Electron injection / efficiency

Merger shocks are weak: typically $\mathcal{M}$ ~ 1.5–3, in a high-β plasma. Injecting electrons directly from the thermal pool may be inefficient.



Botteon + 20



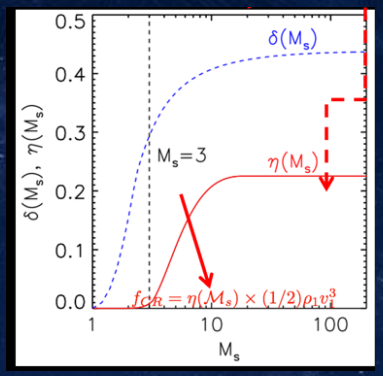
Strong increase of η_e for M < 3

Observed relic luminosities sometimes require a strong increase of the electron acceleration efficiency η_e at low Mach number (especially for M < 3).

This is difficult to reconcile with fresh acceleration from the thermal pool alone.

The proton / γ-ray problem

Standard DSA accelerates protons as well as electrons.
Too much proton acceleration can imply too much hadronic γ-ray emission.



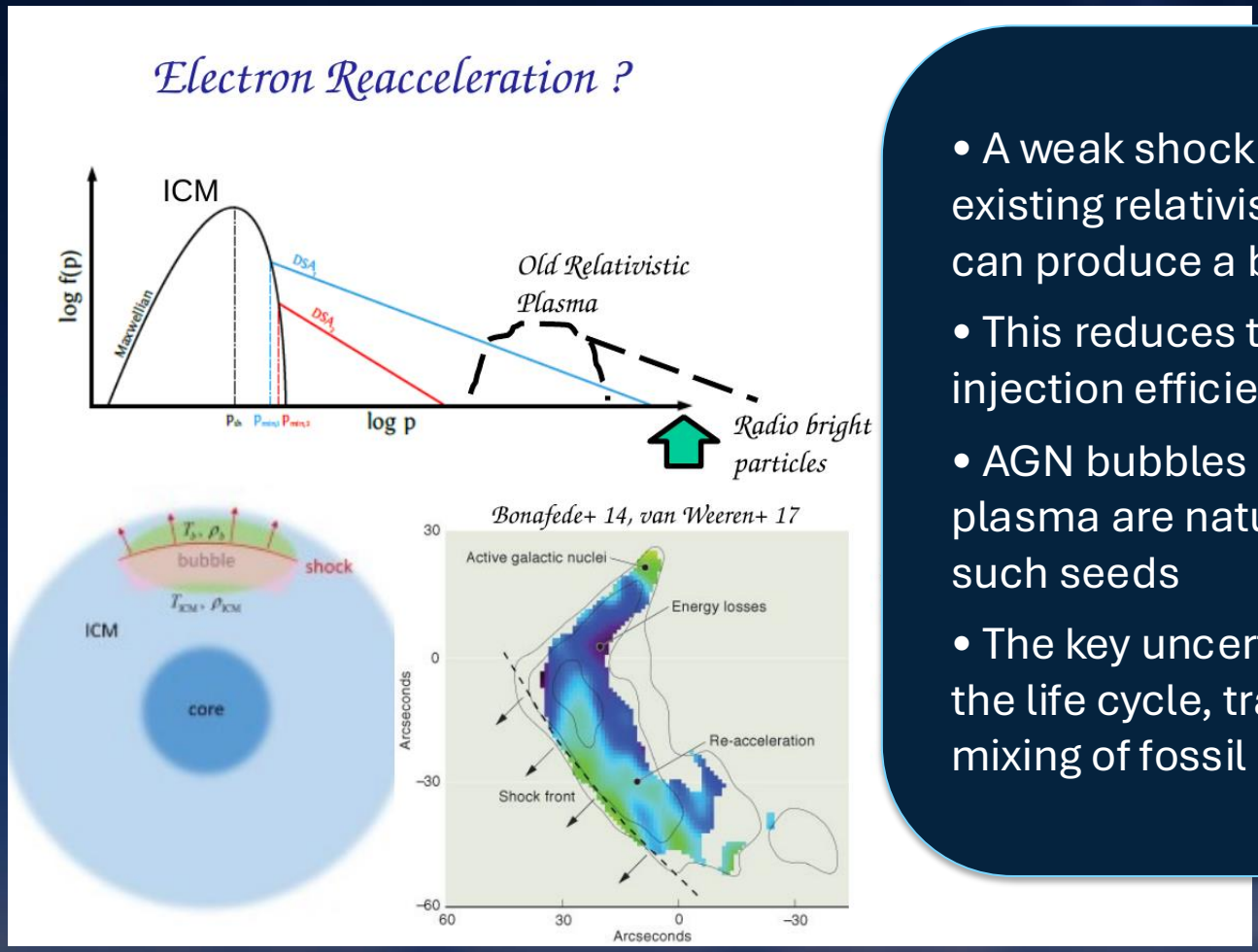
Kang & Ryu 13; Hong + 14

Radio vs X-ray Mach numbers

In several relics, $\mathcal{M}_{radio} > \mathcal{M}_{X}$.
radio emission preferentially traces high-Mach regions, while X-ray diagnostics are more sensitive to the bulk shock properties and projection effects. Complex shock surfaces and fossil electron populations may complicate the interpretation.

A key clue: many relics may re-accelerate fossil electrons rather than accelerate only from the thermal pool.

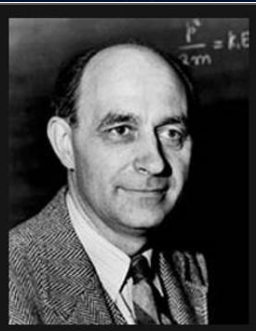
Shock re-acceleration of fossil electrons



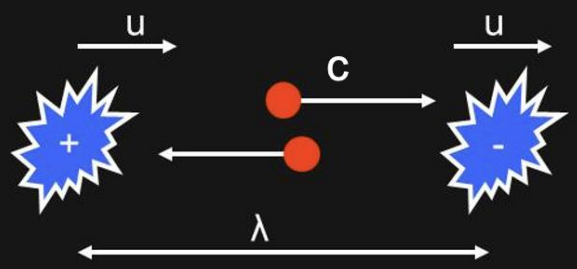
- A weak shock acting on a pre-existing relativistic population can produce a bright radio relic
- This reduces the required injection efficiency
- AGN bubbles and fossil plasma are natural sources of such seeds
- The key uncertainties become the life cycle, transport and mixing of fossil plasma

For many $M \lesssim 2.5$ shocks, re-acceleration is likely more plausible than fresh acceleration alone.

2nd-order Fermi: stochastic acceleration



Second order Fermi Mechanisms
(Fermi 1949)



Energy gain per collisions: $\Delta p_{\pm} \approx \pm 2 p \frac{u}{c}$

Frequency of collisions: $\nu_+ = \frac{u+c}{\lambda} \qquad \nu_- = \frac{c-u}{\lambda}$

$$\left\langle \frac{\Delta p}{\Delta t} \right\rangle = \nu_+ \Delta p_+ + \nu_- \Delta p_- \approx 2p \frac{u^2}{c^2} \frac{c}{\lambda}$$

$$\tau_{acc} \approx \frac{L_t\, c}{V_t^2}$$

100-1000 kpc

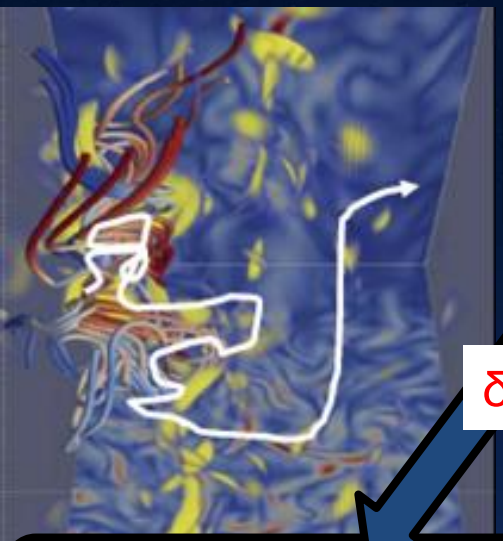
100-1000 km/s

~ 10-1000 Myrs ~ 10^7-10^9 yrs

- Particles scatter off moving magnetic irregularities in a turbulent medium
- Head-on encounters are slightly more frequent than overtaking encounters
- The net average gain is second order in the turbulent velocity: $\propto (u/c)^2$
- The process is therefore slower than shock acceleration

Fermi II is naturally suited to gentle, volume-filling re-acceleration over large regions.

Particles in a turbulent medium



Interaction between CRs & electromagnetic fluctuations

Faraday's law

$$\nabla \times \mathbf{E} + \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = 0$$

δB

δE

Spatial diffusion via pitch-angle scattering

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

Stochastic acceleration (diffusion in particles momentum space)

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

- A useful acceleration timescale is:

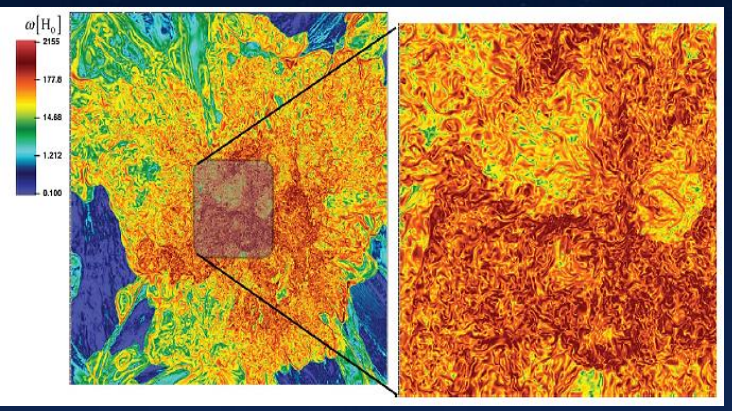
$$\tau_{acc} \approx \frac{p^2}{D_{pp}}$$

$$\tau_{acc} \sim \tau scatt \left(\frac{c}{V_{ph}}\right)^2$$

The microphysics enters through the momentum-diffusion coefficient D_{pp}.

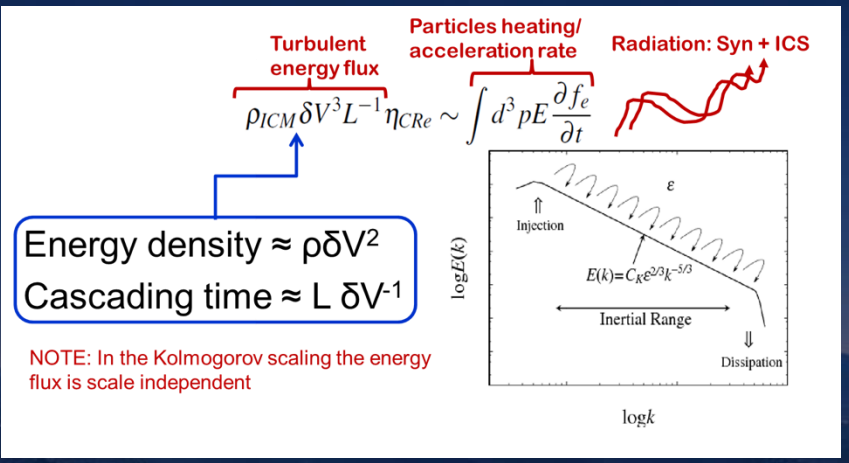
Turbulence in the intracluster medium

Turbulent Lum. ≈ 10^5 x Radio Lum.
energetically plausible mechanism



Miniati 14

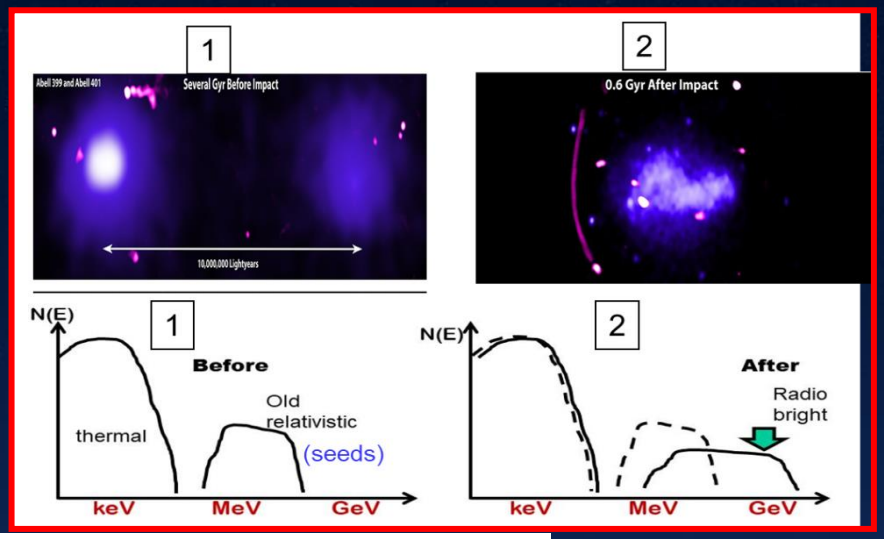
- Mergers inject motions on scales of hundreds of kpc
- The cascade develops compressive and solenoidal components
- Turbulence decays over ~0.1–1 Gyr timescales
- Only a fraction of the turbulent energy can reach CRs before being thermalised
- The partition depends on plasma microphysics and damping

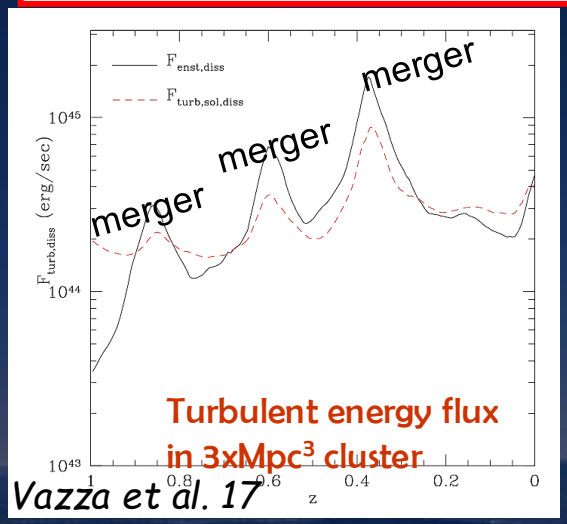


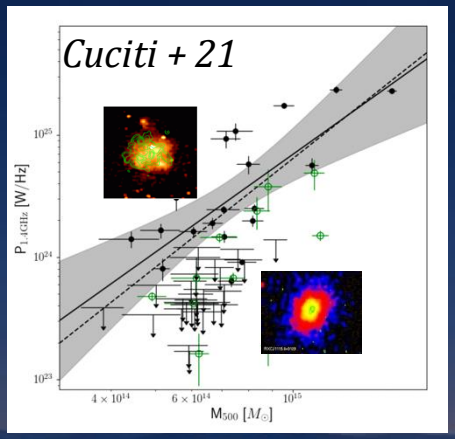
Challenge:
Energy is transported from Mpc injection scales down to kinetic/plasma scales into non-thermal particles through a hierarchy of complex mechanisms and kinetic effects !(Brunetti+Lazarian 07,11,16, Beresnyak+13, Pinzke+17,...)!

The central question is how efficiently turbulent energy is channelled into particle re-acceleration.

Turbulent re-acceleration scenario for giant radio halos





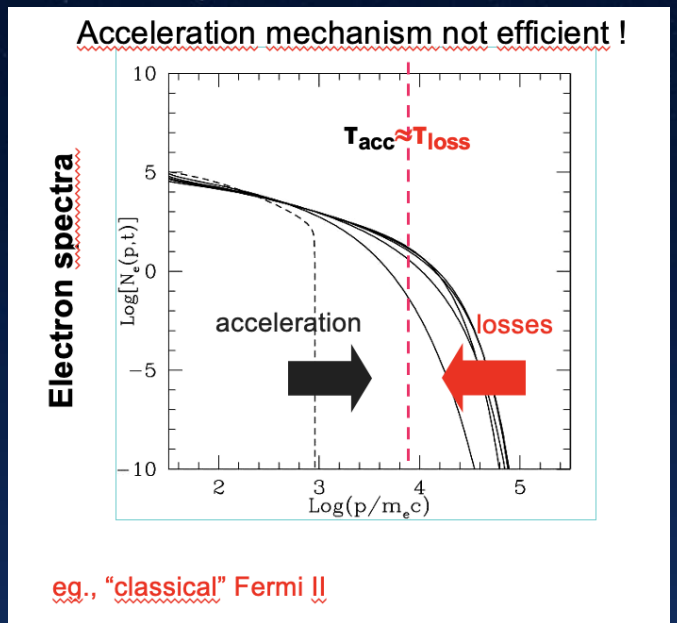


- Cluster mergers generate turbulence throughout a large fraction of the ICM
- Turbulence re-accelerates fossil and secondary electrons
- The process is **transient**: radio emission is bright only while acceleration competes successfully with losses
- This naturally links halos to merger dynamics

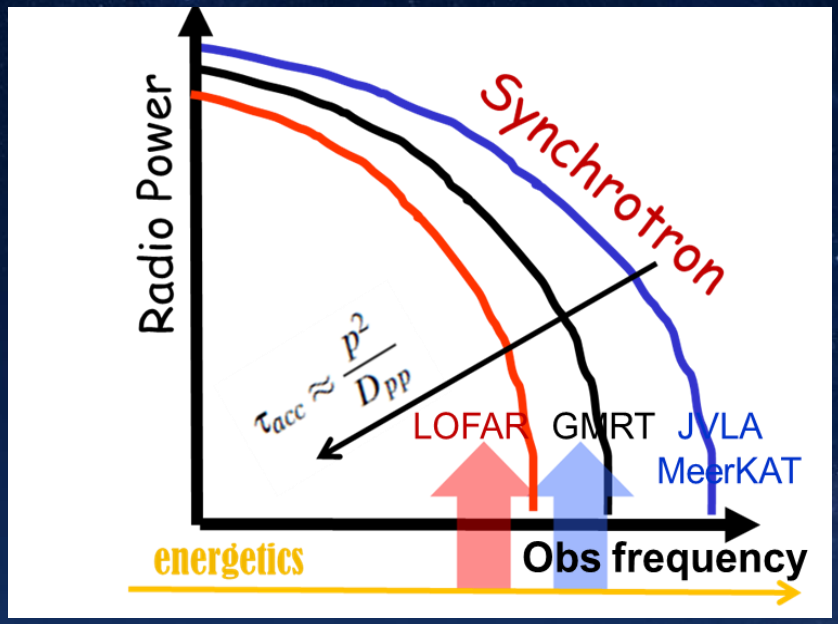
Radio halos are sustained by ongoing stochastic re-acceleration.

TURBULENT ACCELERATION IS A GENTLE MECHANISM

why steep-spectrum halos are expected



$$\nu_{syn} \propto B\gamma^2$$



$$\left(\frac{\tau_{ACC}}{\mathrm{Myr}}\right) \approx 400 \left(\frac{\delta V_t}{500\,\mathrm{km\,s^{-1}}}\right)^{-3} \left(\frac{L_t}{200\,\mathrm{kpc}}\right) \left(\frac{B}{\mu G}\right) \left(\frac{n_{ICM}}{10^{-3}\,\mathrm{cm^{-3}}}\right)^{-1/2}$$

1/specific turbulent energy flux

Max Syn frequency

Classical Fermi II

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

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

$\tau_{acc} \simeq \tau_{loss}$ set the max energy of the electrons emitting Syn radiation in the radio band !

- Less efficient acceleration produces lower spectral-break frequencies
- At GHz frequencies these halos may be faint or invisible
- Low-frequency surveys are therefore crucial for revealing the population

Very steep-spectrum halos are a direct observational test of inefficient stochastic re-acceleration.

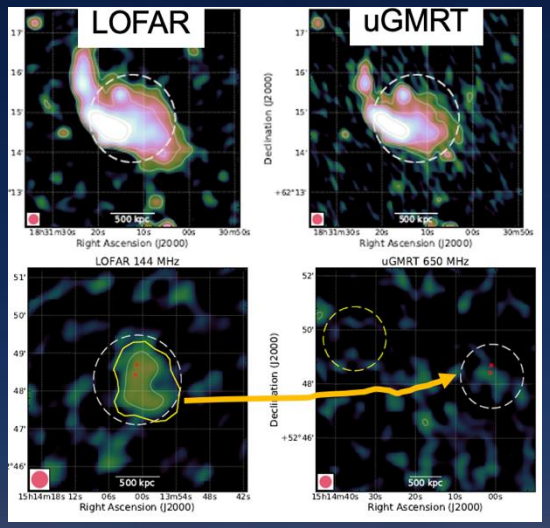
Observational tests with LOFAR

LOFAR: 67-70%

GMRT: 41-48%

The fraction of clusters hosting RH increases at low radio frequency (Cassano et al. 23).

Di Gennaro et al 21



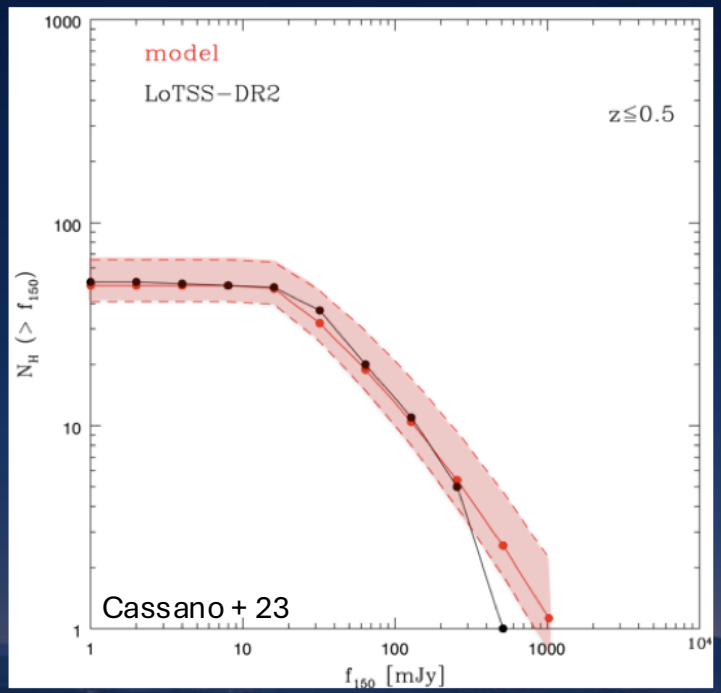
The follow-up at higher frequencies with the uGMRT reveals that 50% of these RHs are characterised by very steep radio spectra ($\alpha > 1.5$).

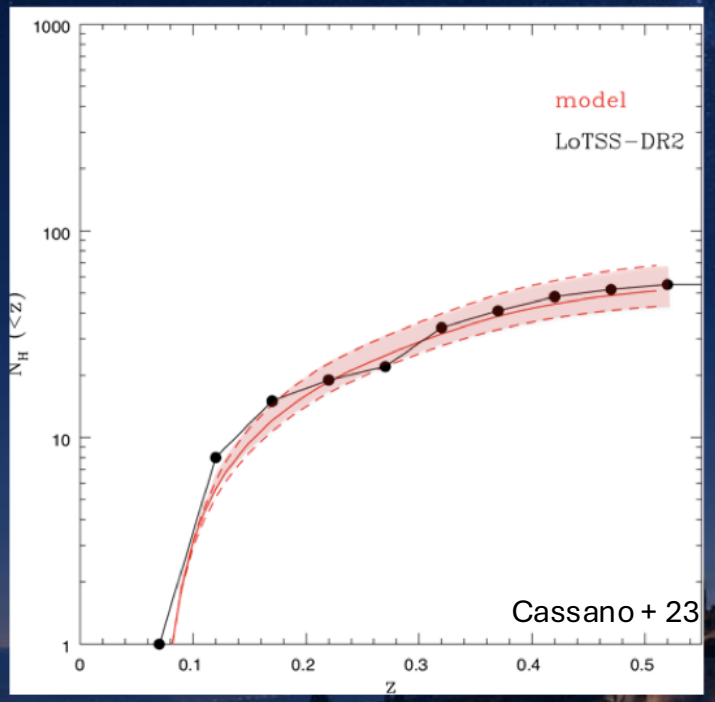
- LOFAR reveals many halos missed at GHz frequencies
- LOFAR found that a large fraction of high-redshift halo is carachterizeds by steep radio spectra
- LOFAR found radio halos also in less extreme mergers / less perturbed systems fraction

Statistical studies are providing important constraints to models.

Do turbulent re-acceleration models reproduce RH statistics?

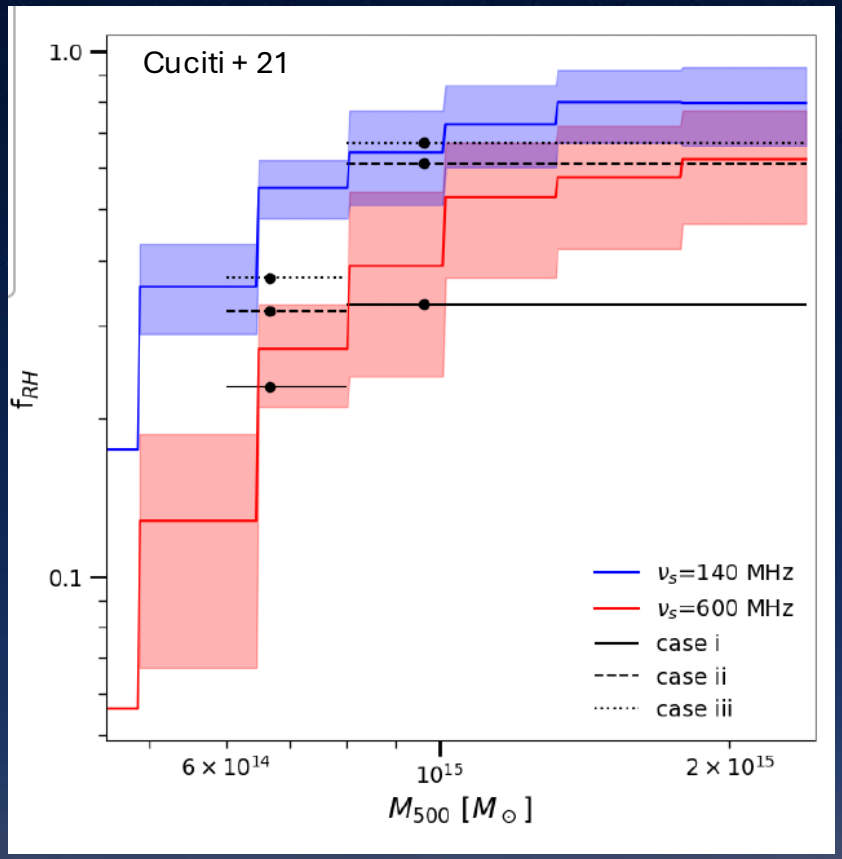
- semi-analytic models (statistical version of turbulent re-acceleration scenario; *Cassano & Brunetti 05,Cassano+06,Cassano+10*)
- mass and redshift limit of the observed sample
- normalise the theoretical cluster population to the observed sample



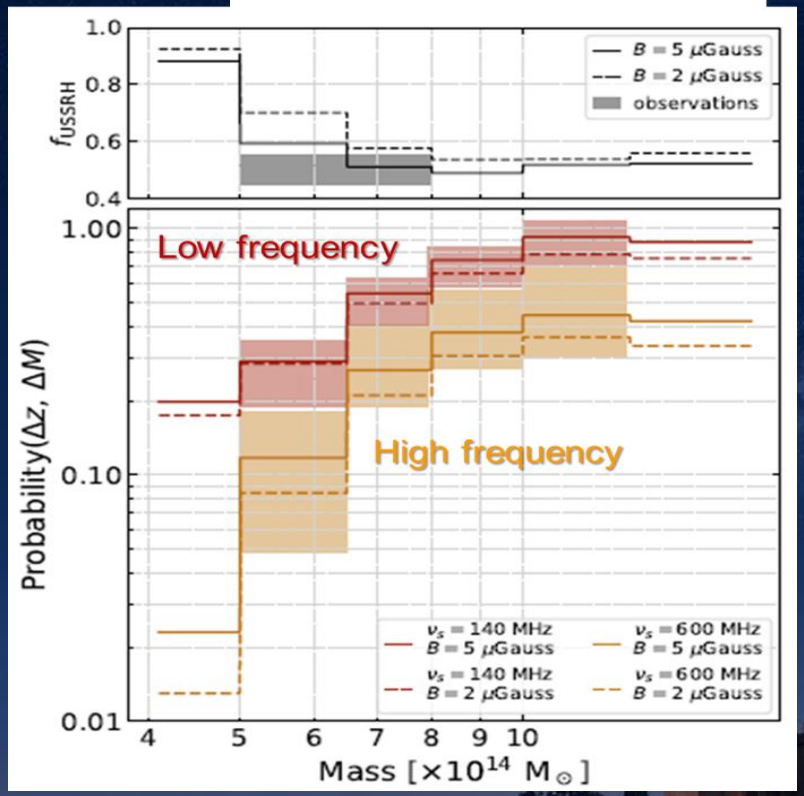


- we reproduce the cumulative number of RHs (40–70 expected), together with their flux-density and redshift distributions.
- predict that 100-200 RH could be detected in PSZ2 clusters by the **full LoTSS**

Do turbulent re-acceleration models reproduces RH statistics?

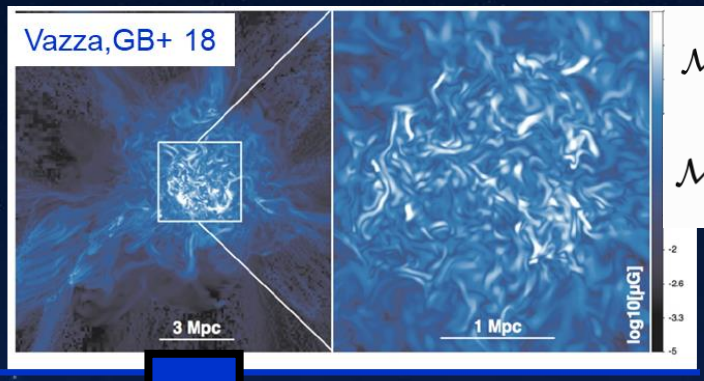


di Gennaro+ 21 (high z)



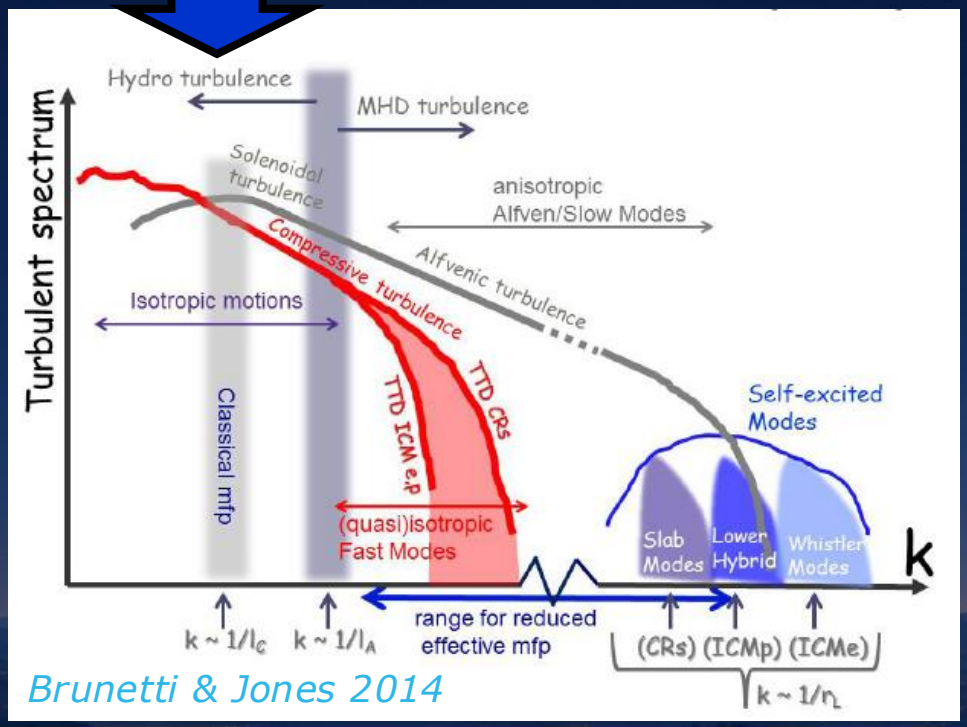
...with the same model and paramters we can produce the observed increase of the radio halo fraction with the cluster mass and how this fraction changes observning at different frequencies.

Open questions in turbulent re-acceleration physics



$$\mathcal{M}_s = \frac{V_t}{c_s} \sim 0.2 - 0.5,$$

$$\mathcal{M}_A = \frac{V_t}{v_A} \sim 5 - 10.$$



Brunetti & Jones 2014

- What fraction of turbulent energy is channelled into cosmic-ray acceleration rather than thermal heating?”
- Which turbulent modes dominate the acceleration?
- How do plasma microphysics and collisionless damping regulate the turbulent cascade?
- What is the spectrum and spatial distribution of seed particles?

How efficiently can merger-driven turbulence transfer its energy to relativistic particles?

Take-home physical picture

Losses: CRe cool rapidly; CRp are long-lived

Confinement: Clusters retain CRs efficiently

Seeds: AGN + galaxies + secondaries populate the ICM

Fermi I: Weak shocks accelerate/re-accelerate → radio relics

Fermi II: Turbulence re-accelerates seeds → radio halos

Observed diffuse radio emission is the macroscopic imprint of losses, transport and plasma acceleration physics in the ICM.