SECOND ORDER FERMI ACCELERATION IN GALAXY CLUSTERS

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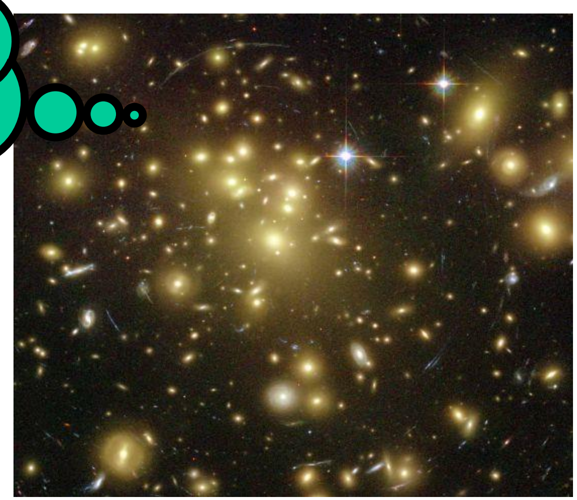
AIMS

- BRIEF OVERVIEW OF FERMI II AS SEEN IN GC
- TRIGGER INTEREST/FIND SYNERGIES WITH GALACTIC COMMUNITY

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

≈30-300 galaxies

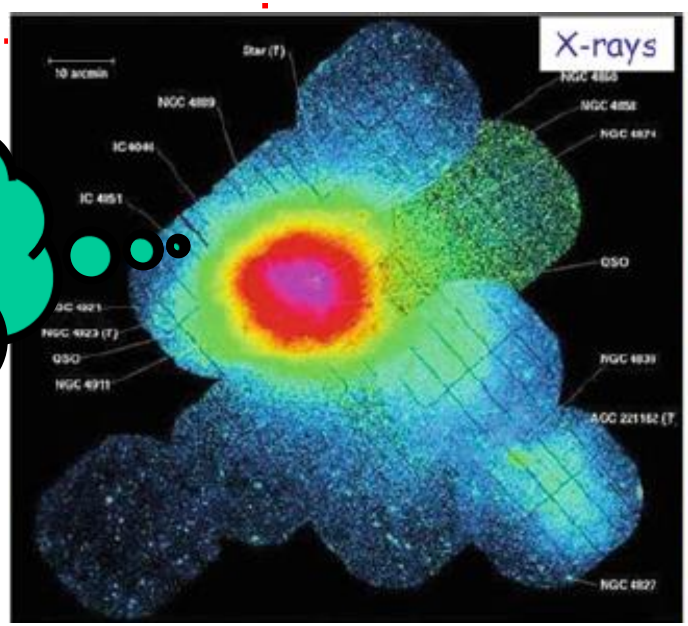


Galaxy cluster matter :

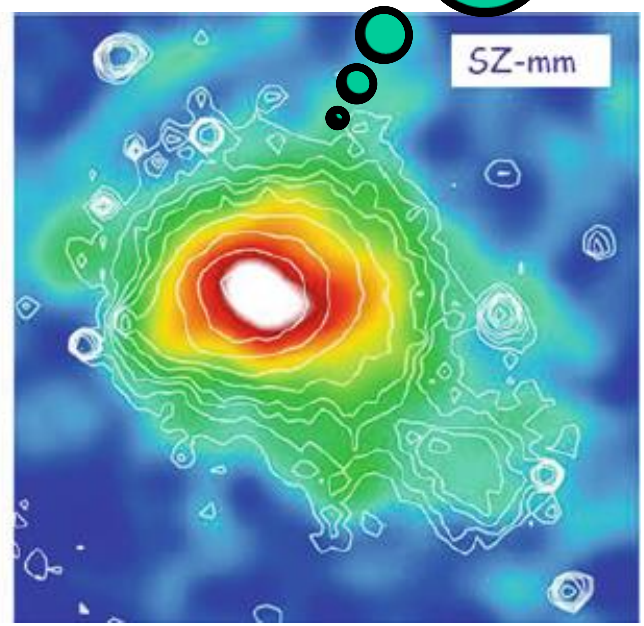
Barions
- 10% of stars in galaxies
- 15-20% of hot diffuse gas

Dark Matter 70%

$$\sim \int n_e^2 dl$$



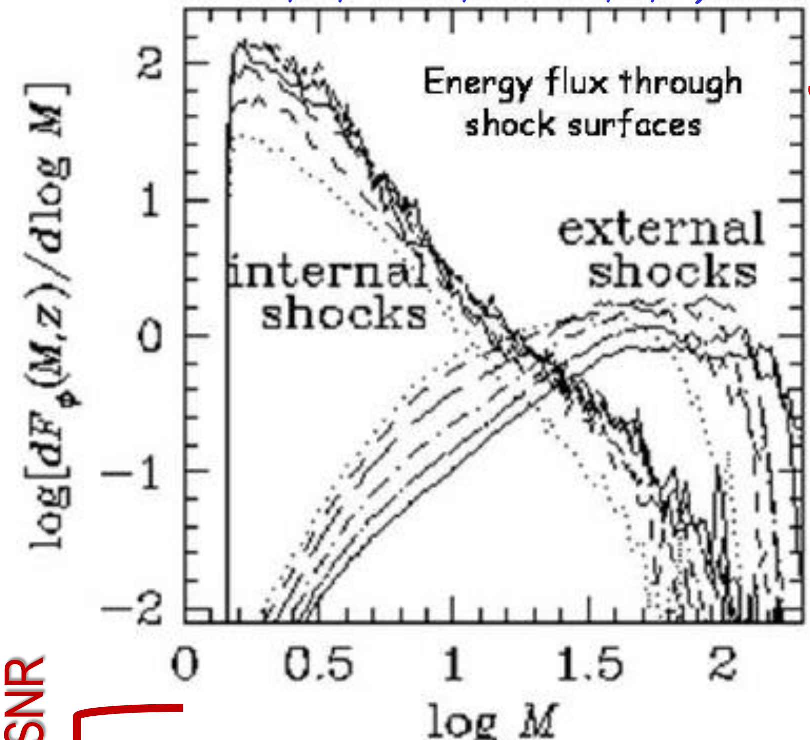
$$\sim \int n_e T dl$$



CRs sources in galaxy clusters

(Brunetti+Jones 14 for review)

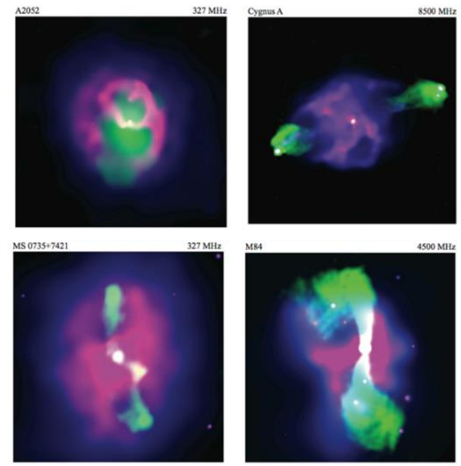
(Blasi +01, Miniati +01, Pfrommer +06,08, Skillman +08,12, Vazza, GB +09,11, …)



Ryu et al 03

extrapolation from SNR

The bulk of ICM heating is due to internal shocks.
If shock acceleration efficiency in the ICM is 10% the resulting CRs (CRp) would store up to. 0.1 E_{ICM}



AGNs

Estimate of number of AGNs, life-time :

E_{CR} = 0.001-0.1 x E_{ICM} (?)

- Thermal plasma in the bubbles
- Leptonic/hadronic

Galaxies

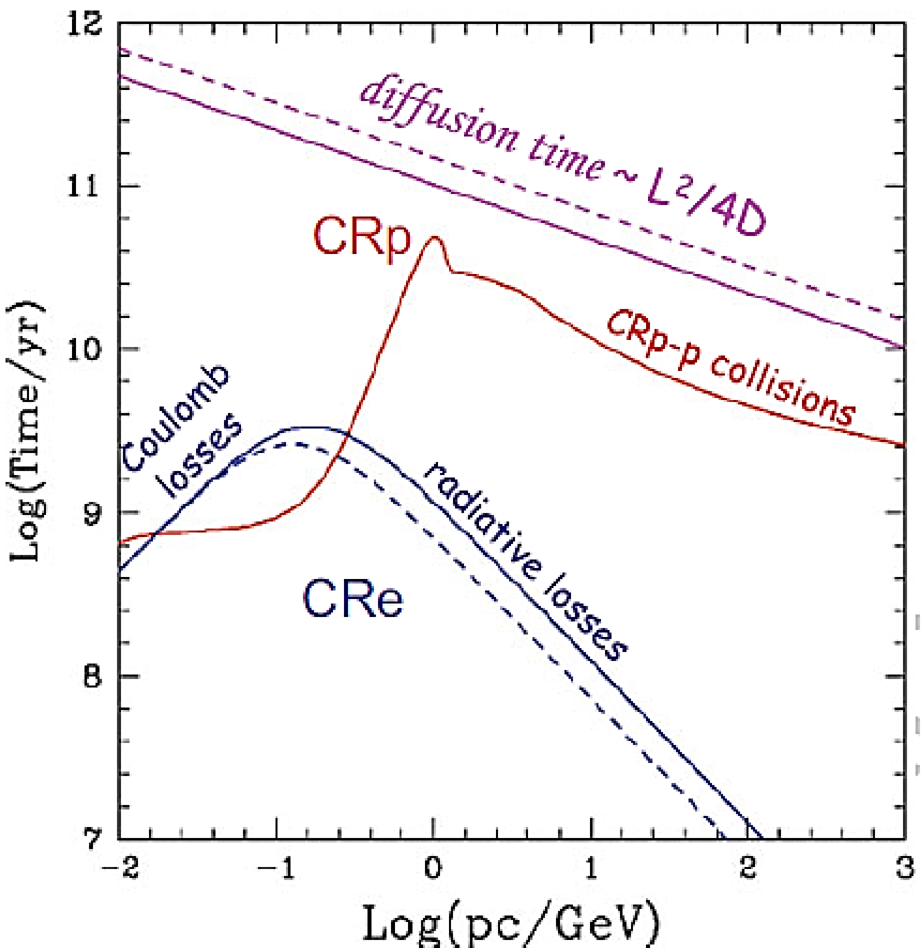
- About 100 massive galaxies per cluster (Berezinsky et al.97, ..)
- Fe abundance in the ICM (Voelk et al 96)

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

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

CR confinement

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



Brunetti & Jones 2014

Obvious consequence of the fact that clusters ar BIG :

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

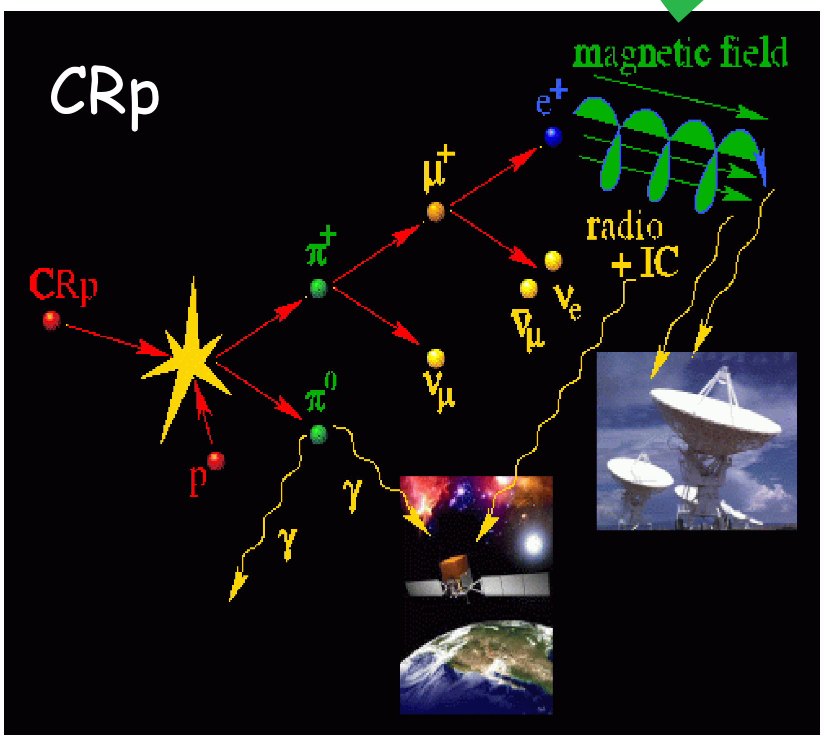
And that the diffusion coefficient is not ''huge'' because CRs are scattered by microturbulence :

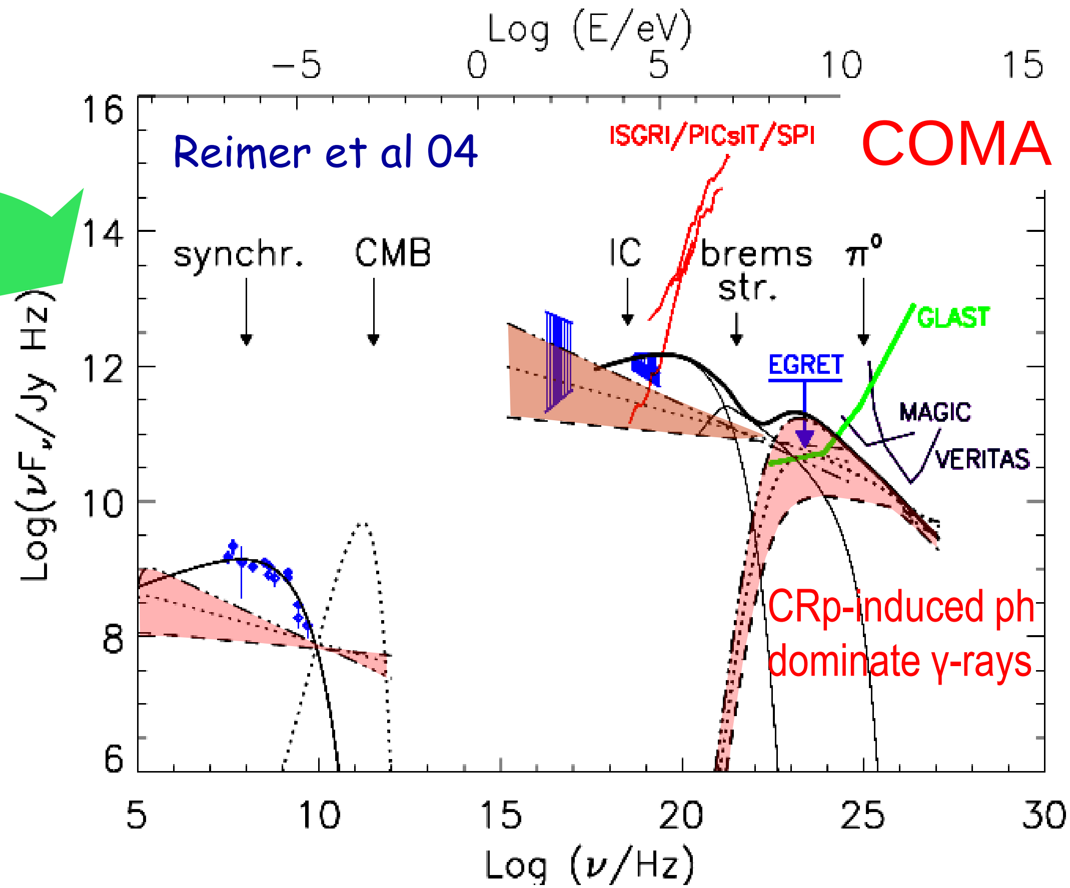
- CRp have LONG life-times in the ICM
- CRs take Hubble+ time to diffuse Mpc

High Energy protons are CONFINED and ACCUMULATED in galaxy clusters for cosmological times : CRp are the dominant component

Radiation from Cosmic Rays in GC

- Confinement
- Acceleration
- Reacceleration

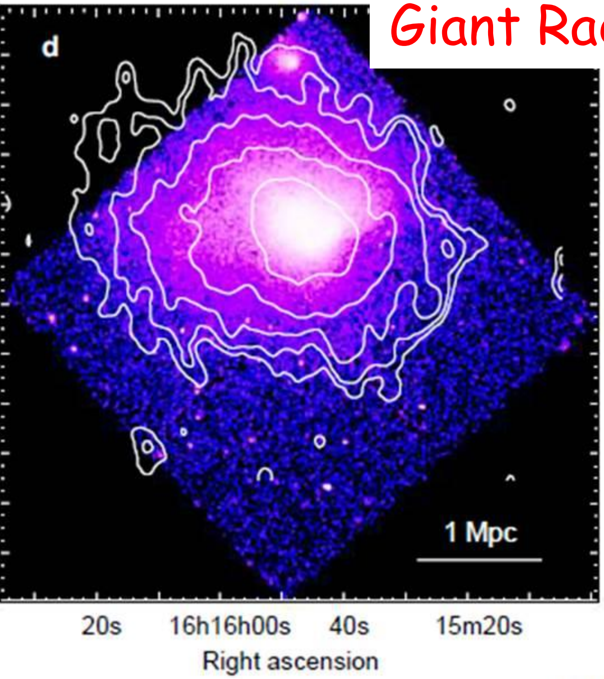


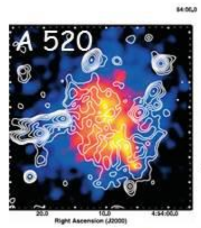


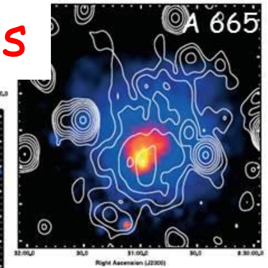
In principle non-thermal emission may range from radio to gamma-rays

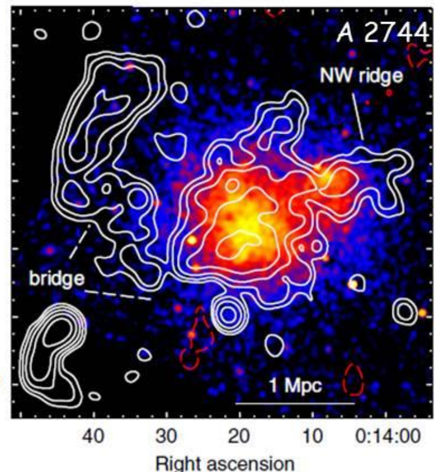
Cluster-scale radio emission

Giant Radio Halos









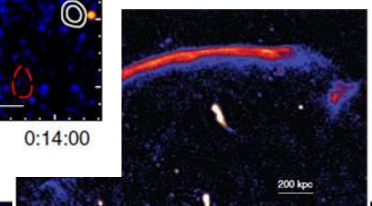
- ❑ Steep spectrum sources
- ❑ Low brightness

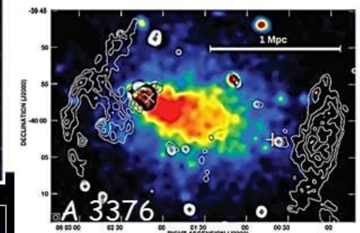
✓ Synchrotron radiation FROM the ICM

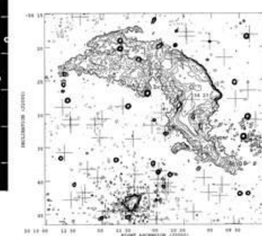
✓ Relativistic electrons (protons?) and B distributed on Mpc-scales…

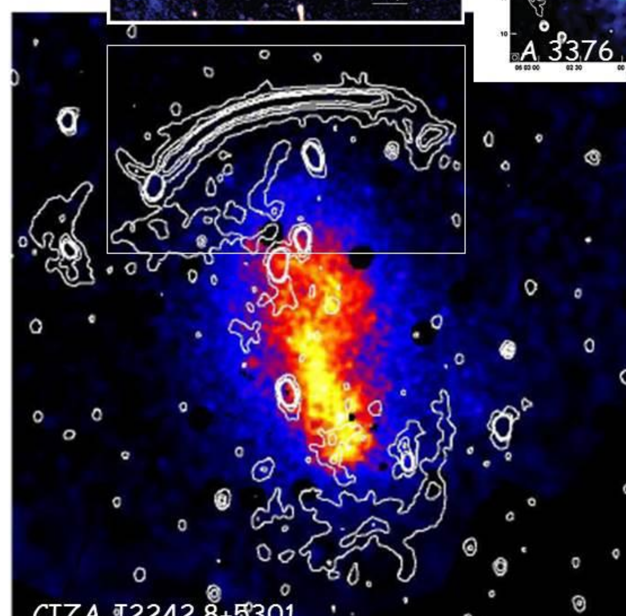
review
Brunetti+Jones 2014
van Weeren+ 2019

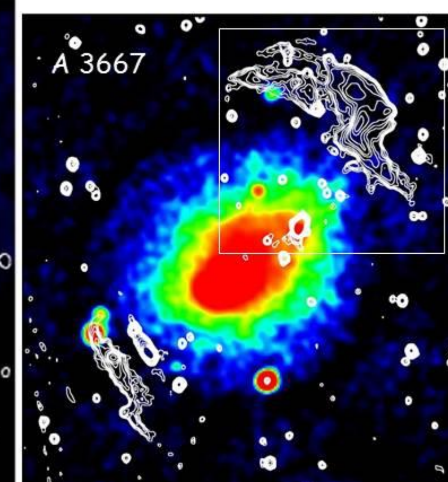
Giant Radio Relics











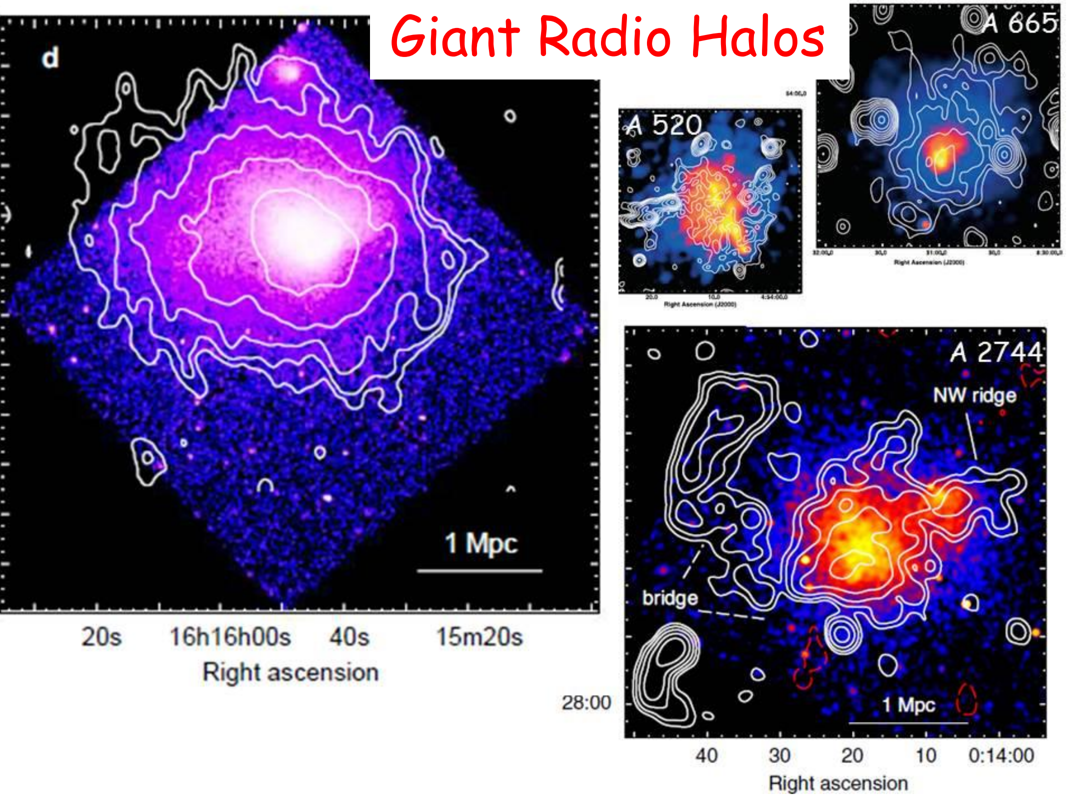
Syn frequency

$$\nu_{SYN} \simeq 4.6 \gamma^2 B_{\mu G} (1+z)^{-1}$$

few-10 GeV

Cluster-scale radio emission

Giant Radio Halos



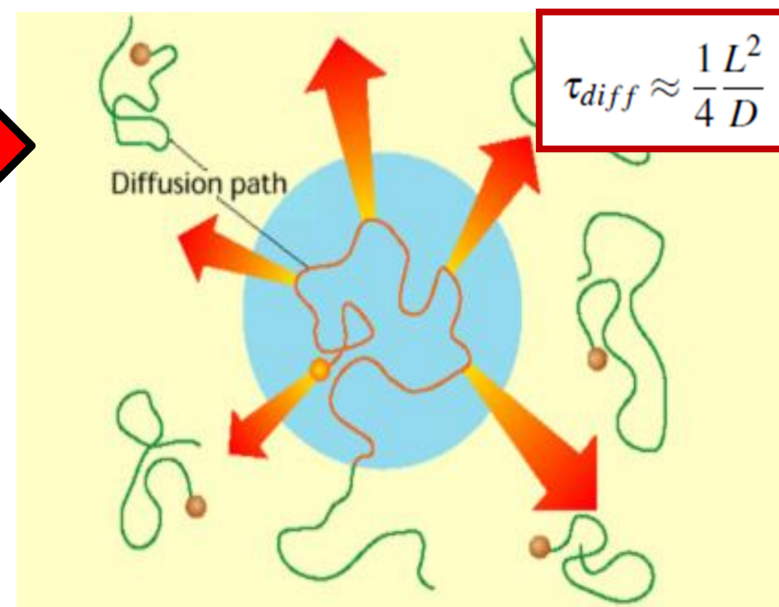
- ❑ Steep spectrum sources
- ❑ Low brightness

Synchrotron radiation FROM the ICM

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

Diffusion problem (Jaffe 1977)

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



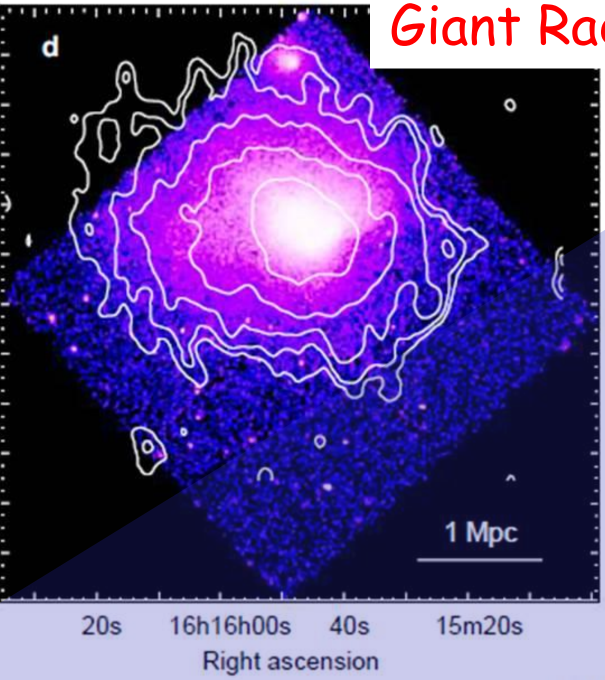
$$\tau_{diff} \approx \frac{1}{4}\frac{L^2}{D}$$

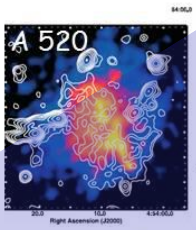
What we observe cannot be the "direct" result of CRs sources

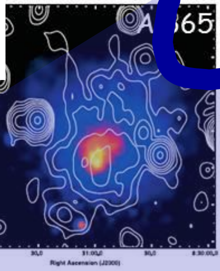
➤ ORIGIN & Physics ??

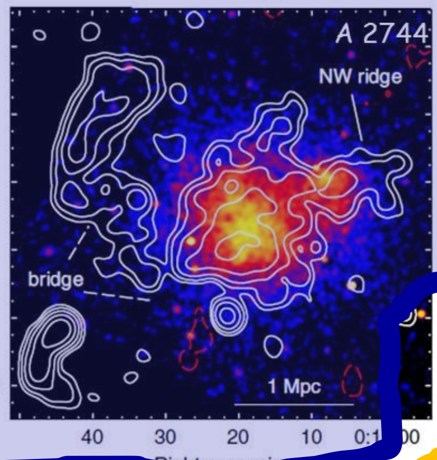
"in situ" mechanisms operating within clusters drain energy into relativistic particles and magnetic fields

Giant Radio Halos

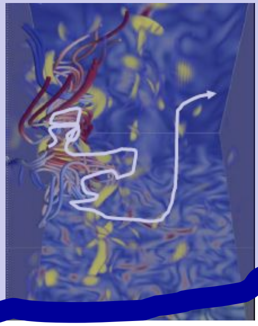


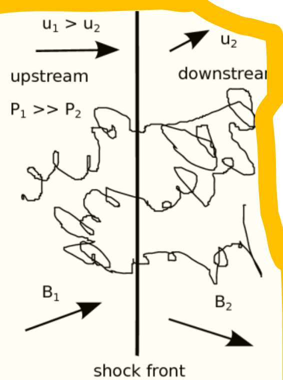






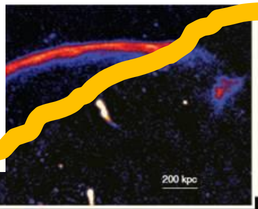
TURBULENT ACCELERATION FERMI II : NEW PHYS

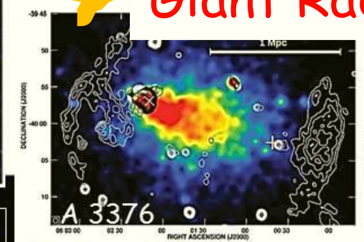


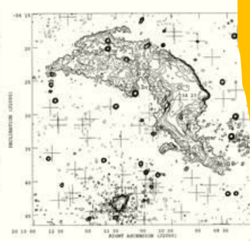


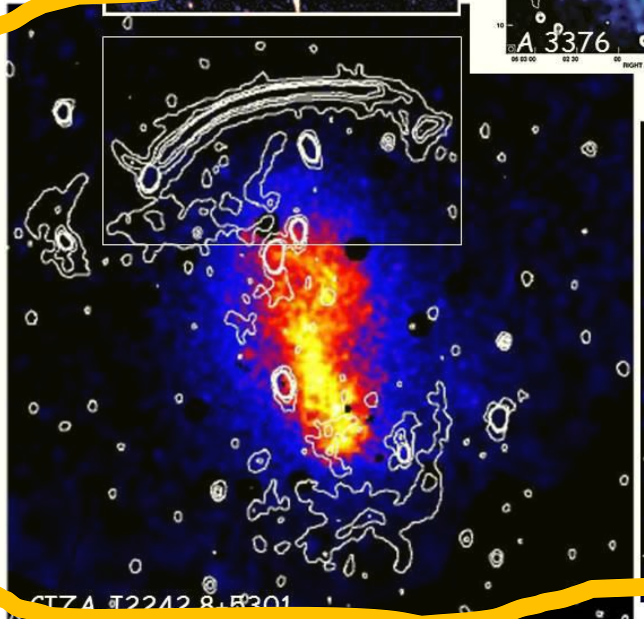
SHOCK ACCELERATION FERMI I

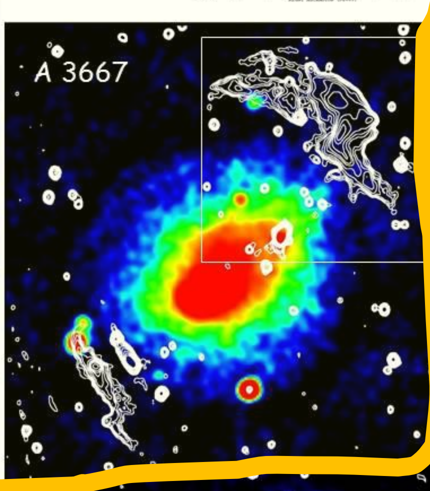
Giant Radio Relics









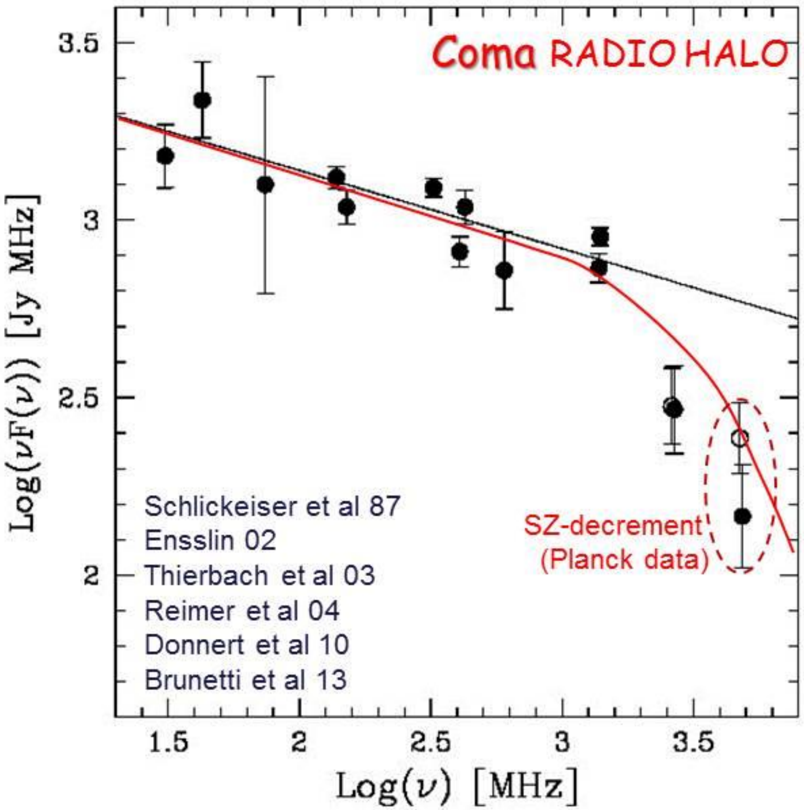


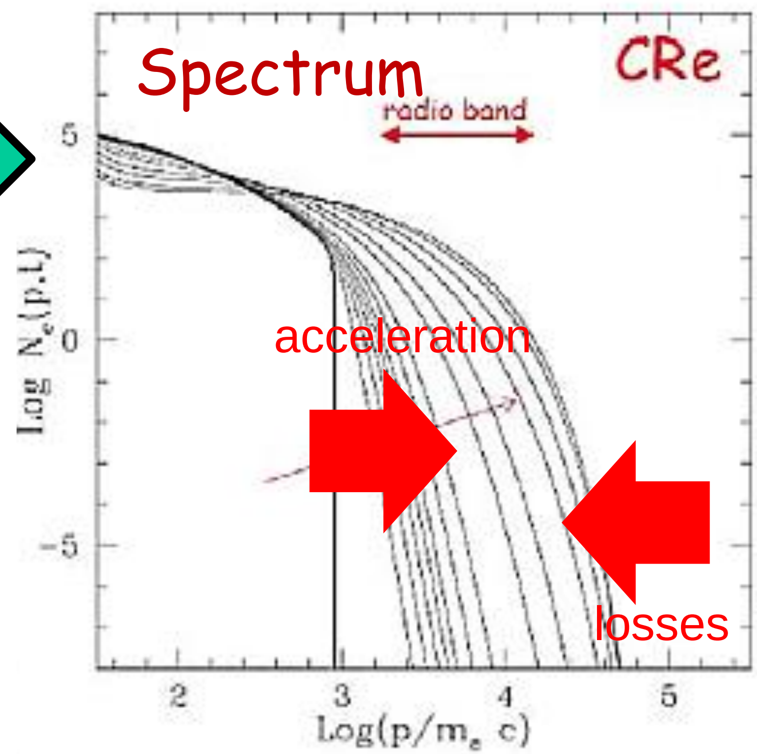
During the **hierarchical process of cluster formation** mergers and accretion of matter generate weak (M ~ 2-3) **shocks** and **turbulence** (M ~ 0.1-0.7).
Both ingredients can power mechanism of **particle acceleration** and **magnetic field amplification.**

[Brunetti & Jones 14 for rev]

WHY TURBULENT REACCELERATION ?

(Schlickeiser+87, Brunetti+01, Petrosian 01)



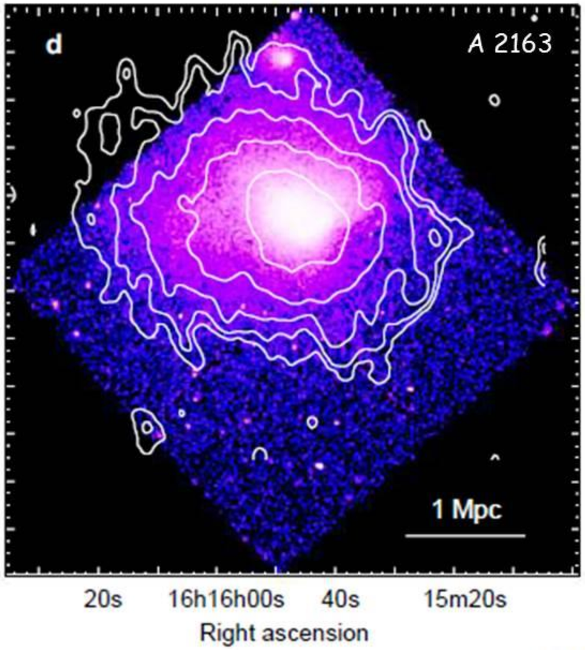


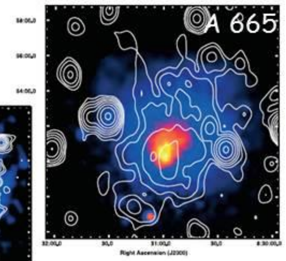
$$\tau_{loss}(\mathrm{Gyr}) \sim 4 \times \left\{ \frac{1}{3}\left(\frac{\gamma}{300}\right)\left[\left(\frac{B_{\mu G}}{3.2}\right)^2 \frac{\sin^2\theta}{2/3} + (1+z)^4\right] + \left(\frac{n_{th}}{10^{-3}}\right)\left(\frac{\gamma}{300}\right)^{-1}\left[1.2 + \frac{1}{75}\ln\left(\frac{\gamma/300}{n_{th}/10^{-3}}\right)\right]\right\}^{-1}.$$

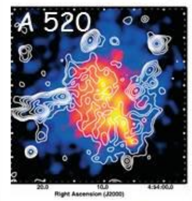
$\tau_{acc} \sim \tau_{rad}$(GeV+)

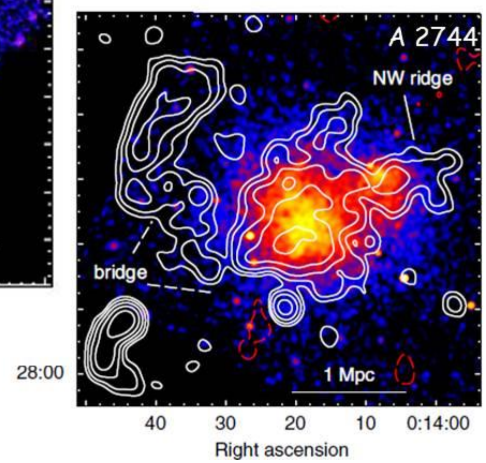
=100-300 Myr

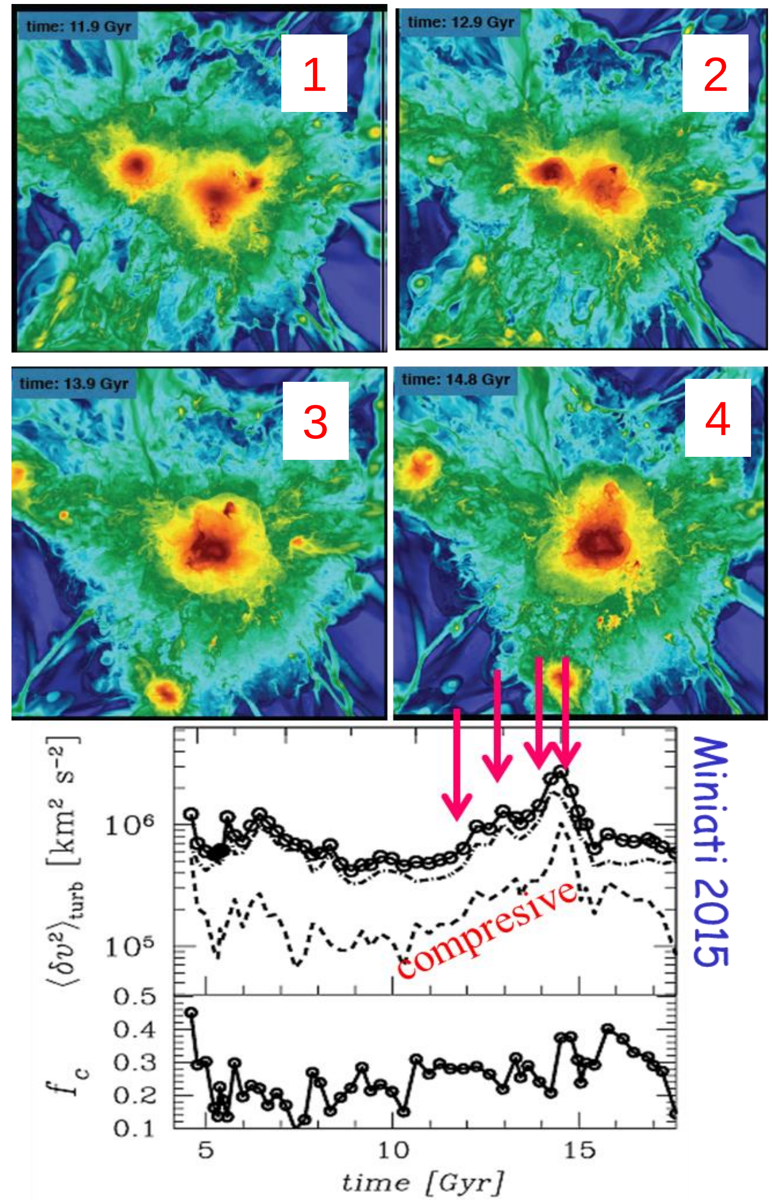
Gentle/inefficient mechanisms











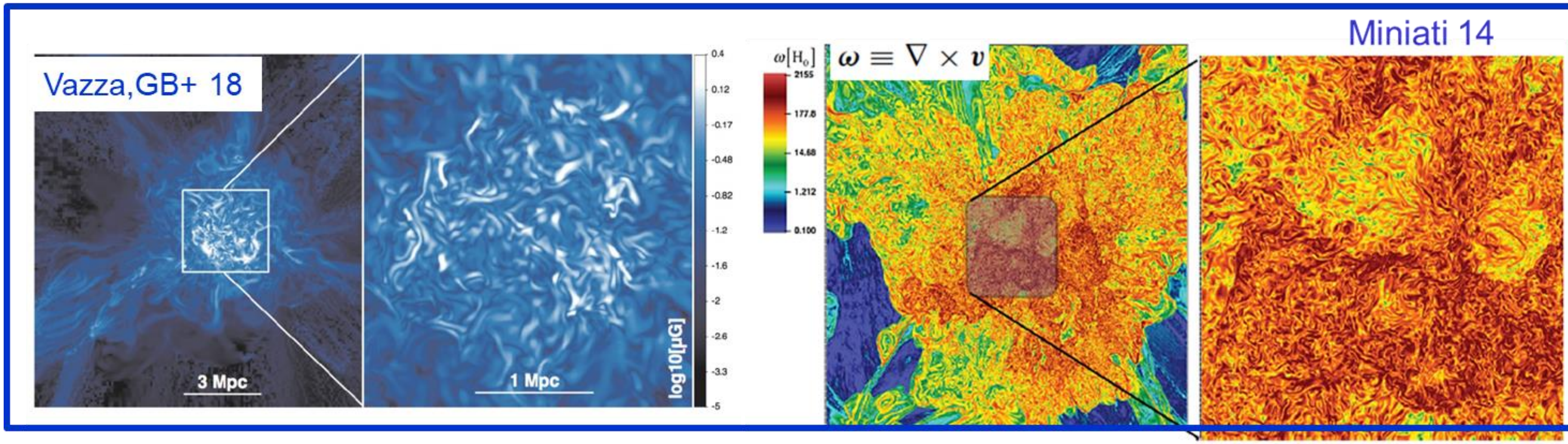
Turbulent acceleration scenario

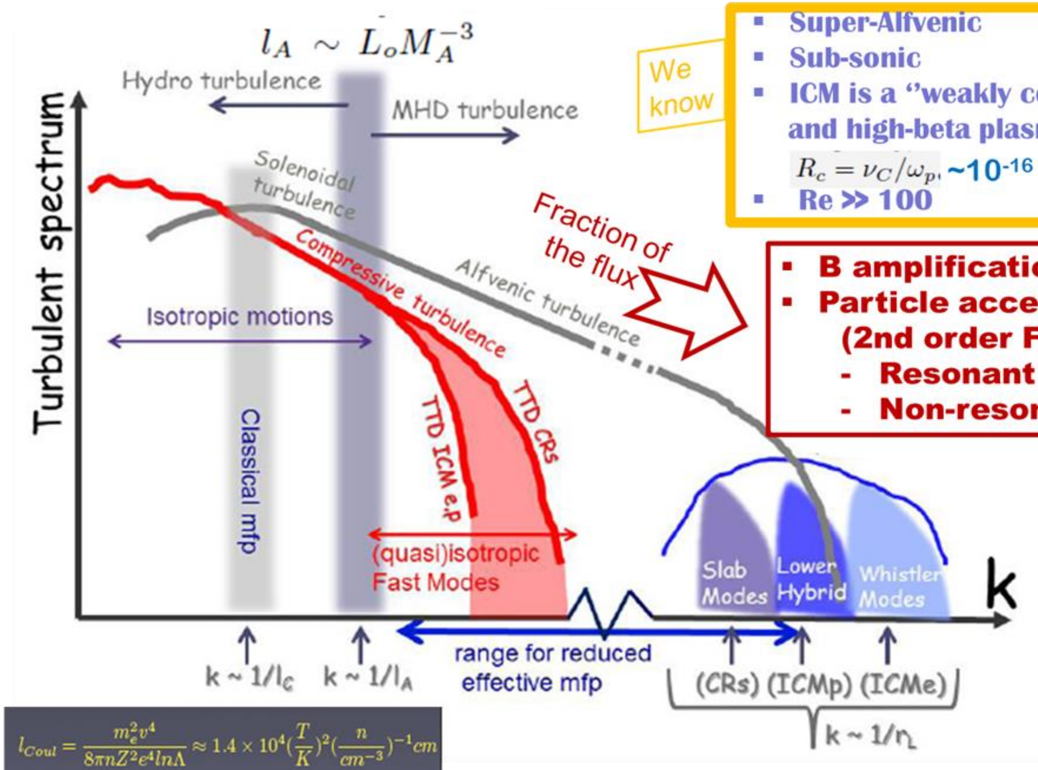
Turbulence is generated during mergers (shocks, DM sloshing, instabilities etc) and powers reacceleration mechanisms based on **second-order Fermi**

[Brunetti+01, Petrosian 01, Fujita+03, Cassano+Brunetti 05, Brunetti+Blasi 05, Brunetti+Lazarian 07,11,16, Beresnyak+al 13, Miniati 15, Pinzke+ 17, Marchegiani 19, Nishiwaki+Asano 21,22]

TURBULENT REACCELERATION PHYSICS IN THE ICM

High res Cosmological Simulations





We know

- Super-Alfvenic
- Sub-sonic
- ICM is a "weakly collisional" and high-beta plasma
  $R_c = \nu_C/\omega_{p,i}$ ~10^{-16}
- Re >> 100

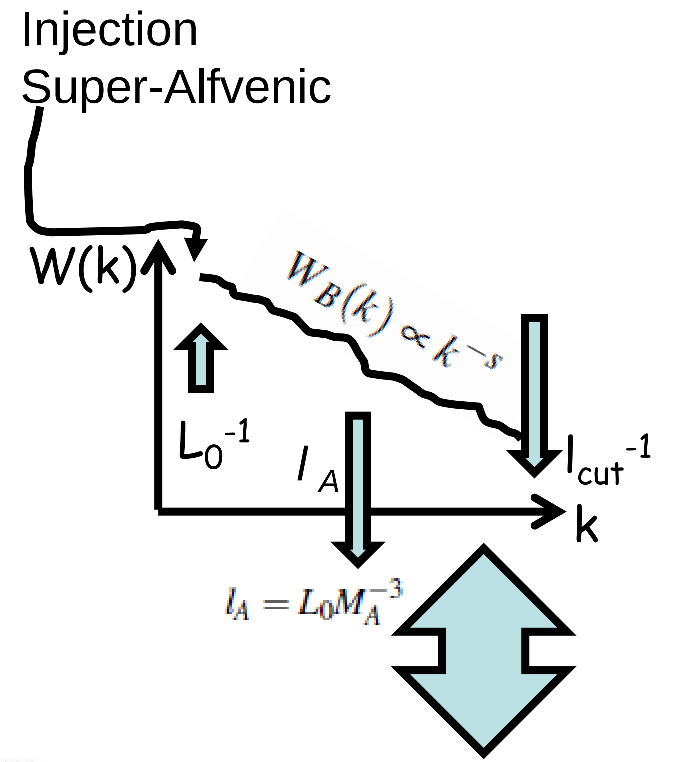
- **B amplification**
- **Particle acceleration (2nd order Fermi)**
  - **Resonant (..TTD)**
  - **Non-resonant**

Brunetti+Lazarian 07,11, Miniati 15, Brunetti 16, Pinzke+17, Brunetti+17, Nishiwaki+Asano 21

Brunetti+Lazarian 16, Brunetti+Vazza 20, Nishiwaki, GB+23

Ley+ 23

Turbulent accel physics : basic approach



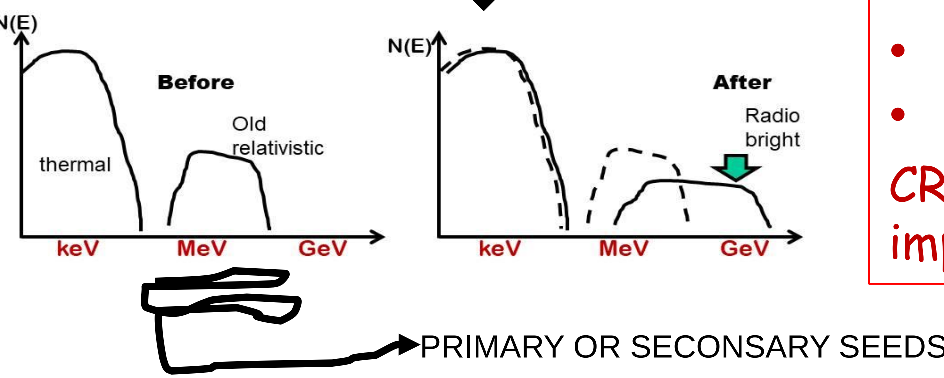
Turbulent energy flux

Particles heating/ acceleration rate

Turbulent collisionless damping

$$\rho_{ICM} V_A^3 l_A^{-1} \eta_{CRe} \sim \int d^3 p E \frac{\partial f_e}{\partial t} = \int d^3 k W(k) \Gamma_e(k)$$

- Second order mechanisms -



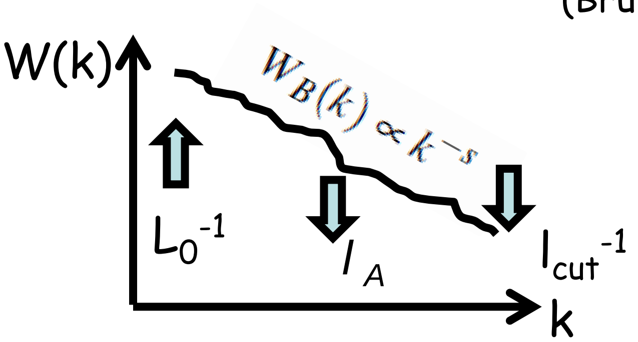
Energy flux can be channeled into

- ICM Protons+Electrons (heating)
- CRe,p (re-acceleration)

CRe acceleration efficiency depends on the importance of different dampings

Focus : compressive modes

(Brunetti+Lazarian 07,11, Beresnyak+ 13, Miniati 15, Brunetti 16, Pinzke+ 17)



TTD with Magnetosonic/fast Modes

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

eg Fisk 76, Miller 91, Schlickeiser+98, Yan+Lazarian 04, Xu+Lazarian 18,........

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

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

l_{cut} is the dominant scale for acceleration

Cut-off is generated at <u>scales where damping is faster than cascading</u> (Brunetti+Lazarian 07) :

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

ICM Protons+Electrons
CRe,p

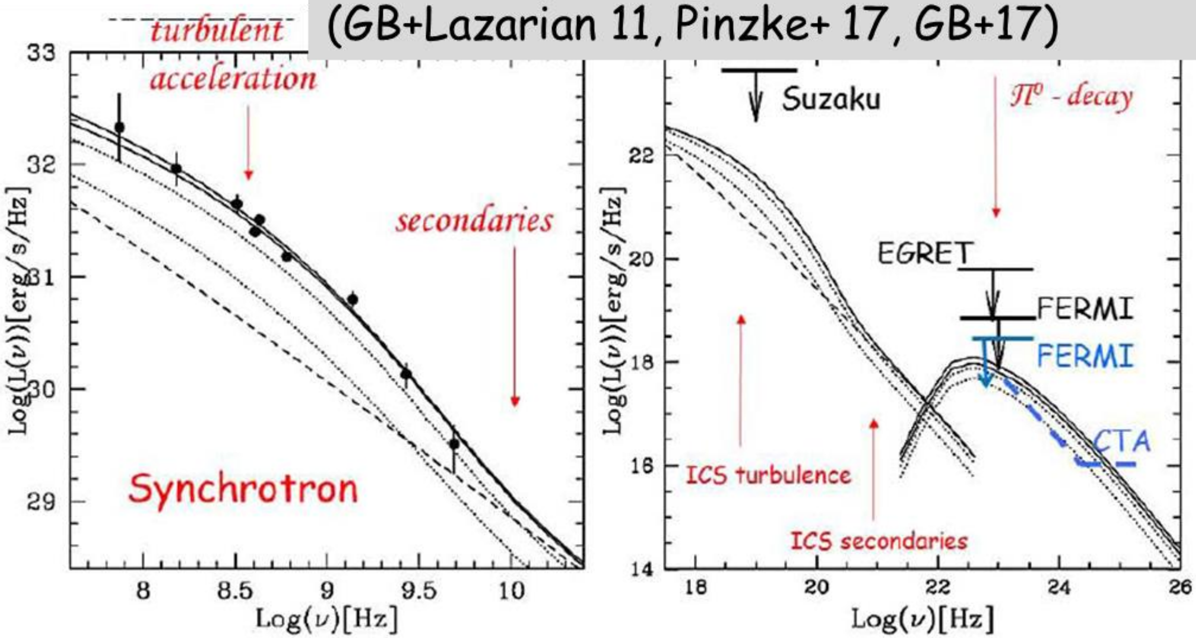
Classical formula used in many clusters papers

$$D_{pp} \propto p^2 \frac{\delta V_0{}^4}{L_0} c_S{}^{-2}$$

Fast dependence on turbulent velocity

Models are successful : reproduce current data

SED from primary+secondary electrons
(GB+Lazarian 11, Pinzke+ 17, GB+17)

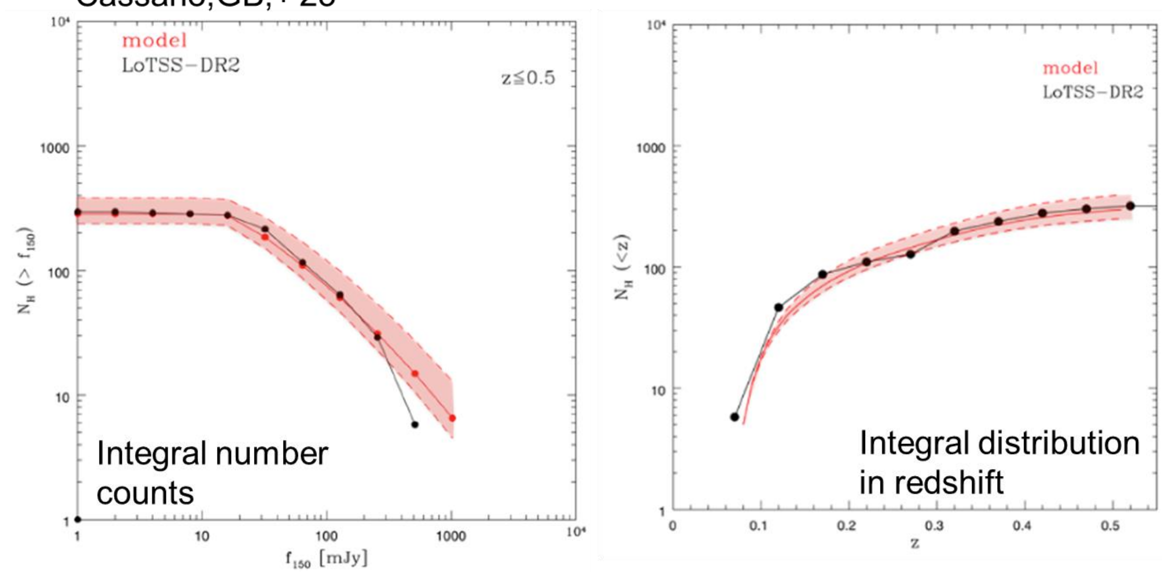


Spectral energy distribution and gamma-ray constraints

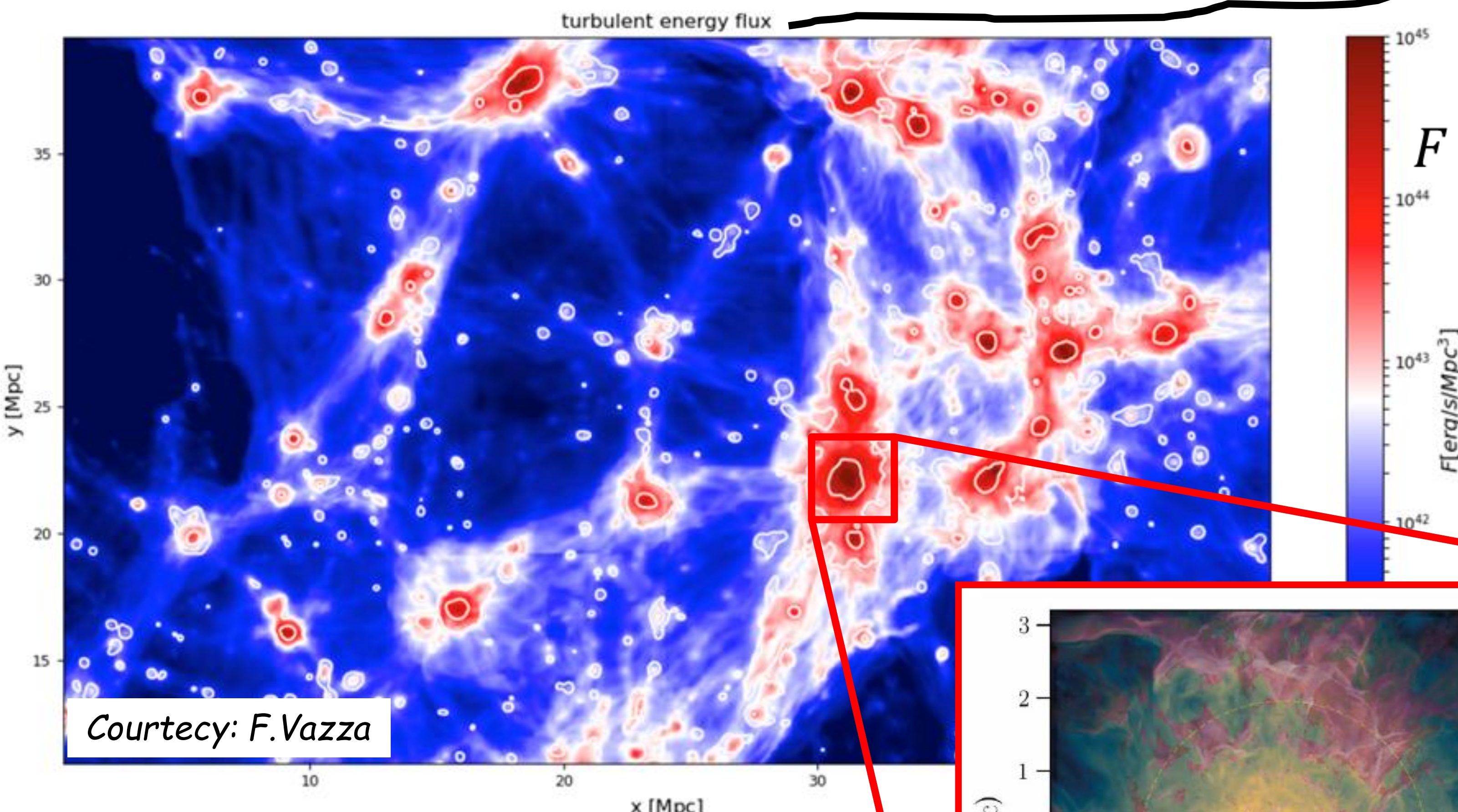
Connection between cluster dynamics and cluster-scale emission (radio and X-rays)

Statistics of radio halos in mass selected samples of galaxy clusters (GMRT, LOFAR)

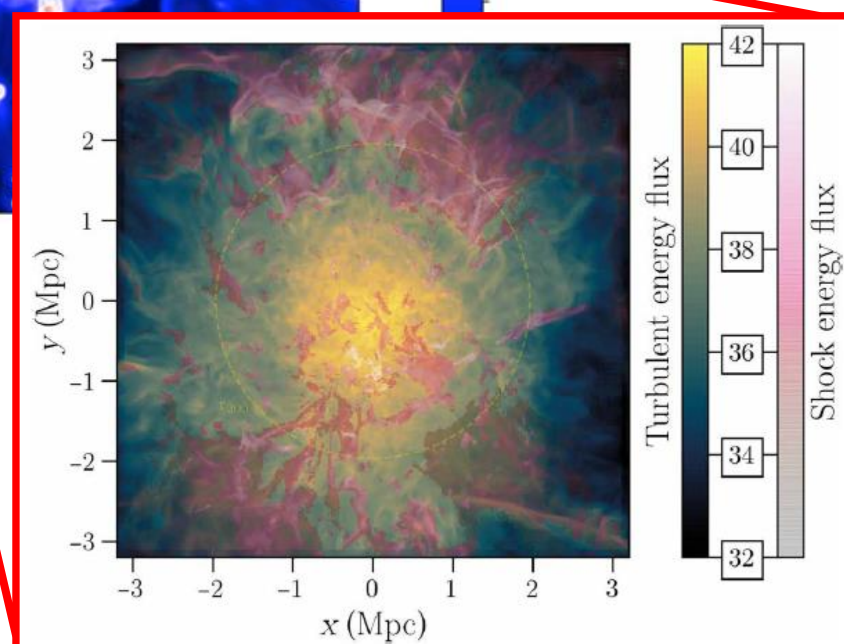
Cassano,GB,+ 23



TURBULENCE & SHOCKS IN LSS



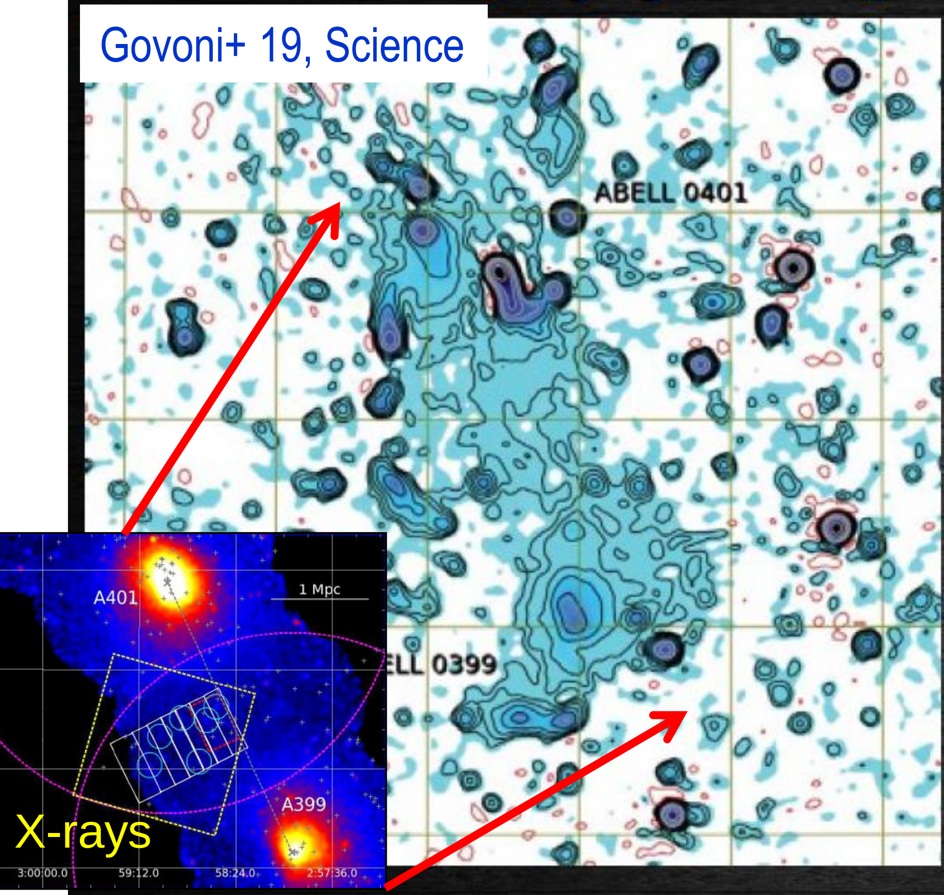
$$F = \frac{1}{2}\rho\frac{\delta V^3}{L}$$

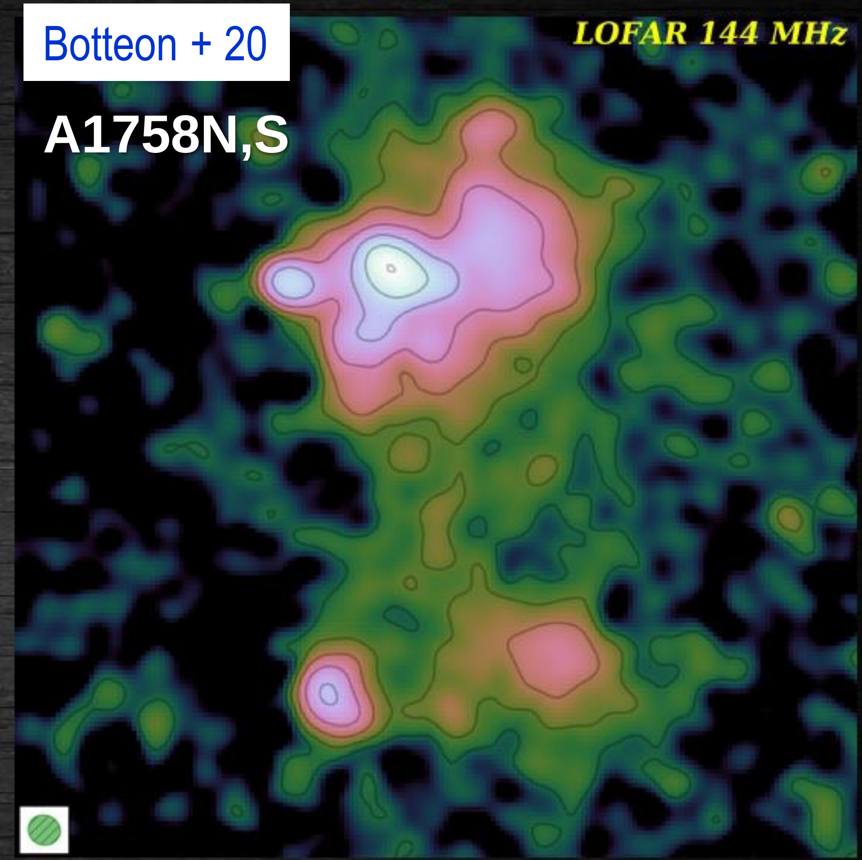


CAN WE DETECT STEEP SPECTRUM RADIO EMISSION FROM SCALES LARGER THAN HALOS ?

LOFAR ERA : THE MOST SENSITIVE RADIOTELESCOPE AT LOW FREQUENCIES

A399+A401 & A1758





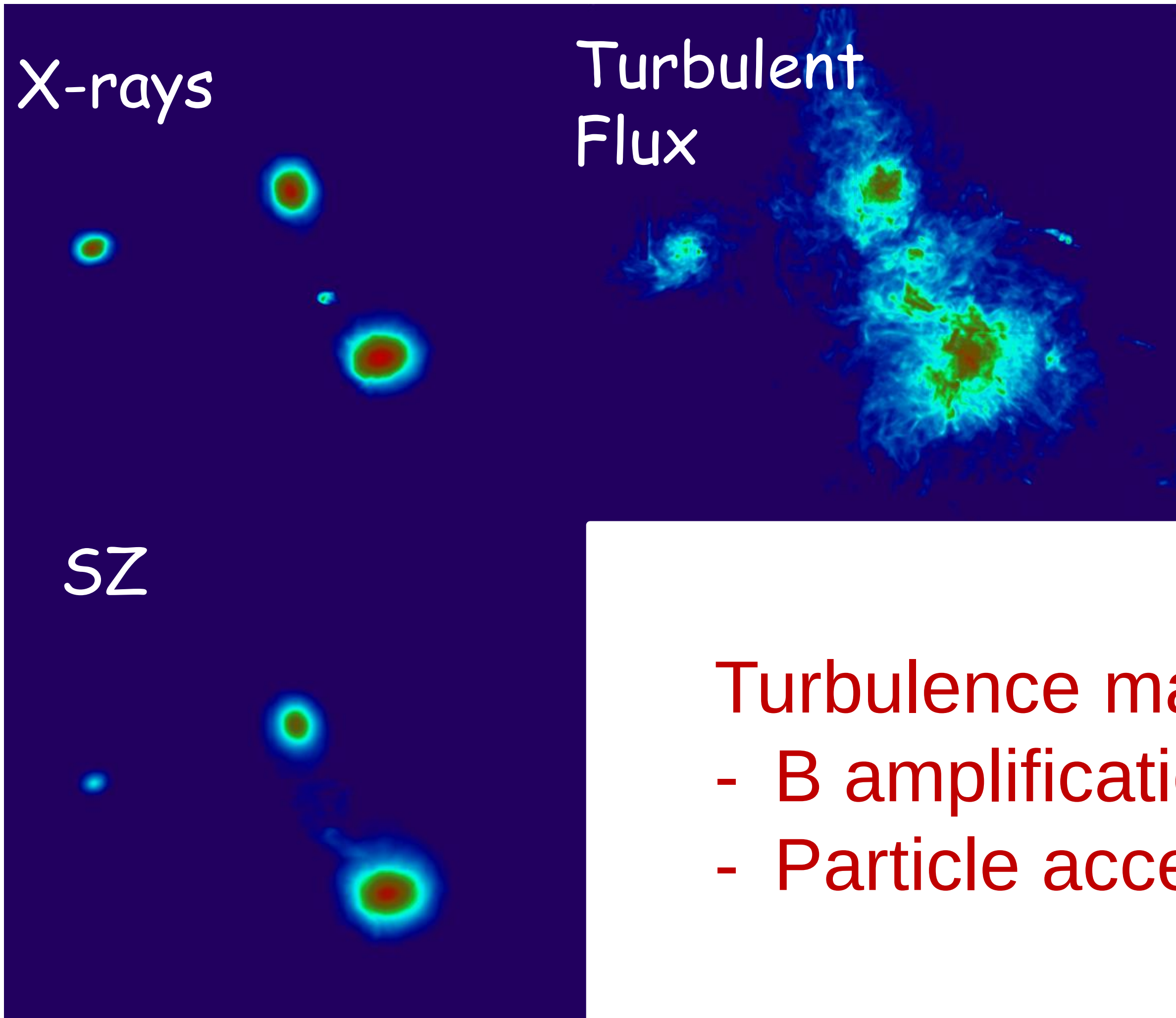
LOFAR has discovered *radio bridges* connecting *pre-merging* galaxy clusters

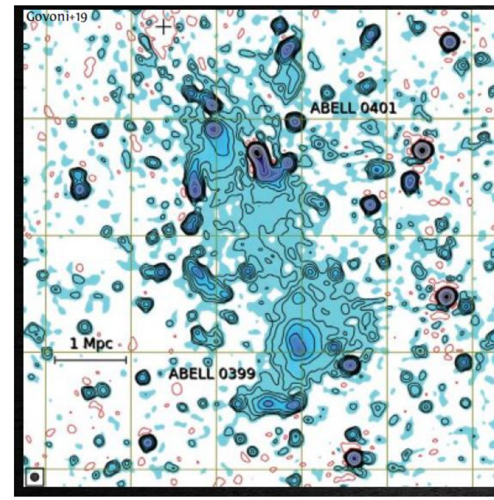
- ❑ ***Step toward the detection of cosmic filaments ?***
- ❑ **Magnetic field amplified on 3-5 Mpc**
- ❑ **GeV+ electrons (re?)accelerated**

Turbulent acceleration & B in LSS ??

(Brunetti+Vazza 2020, PRL..)

- Massive pairs of (pre-merging) clusters form in biased **high-density regions**
- Several **substructures** (DM+baryonic clumps) orbiting in the filament/bridge
- **Turbulence** (and shocks) driven by substructures





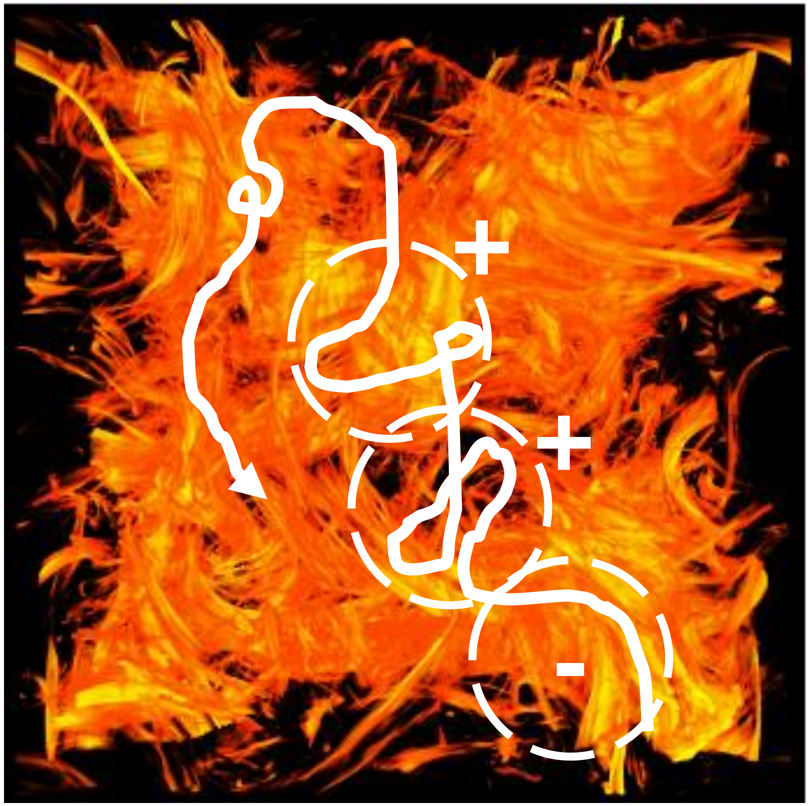
Turbulence may drive

- B amplification .. up to 0.3-1 μG
- Particle acceleration

Reacceleration in solenoidal super-Alfvenic turbulence

[Brunetti & Lazarian 16, ..Xu & Zhang 17, Xu+18, .. *Adiabatic Stochastic Acceleration*]

Particles diffusing in super-Alfvenic turbulence experience cycles of positive and negative acceleration via interaction with collapsing (in reconnection regions) and expanding (in dynamo regions) magnetic field lines.



$$D_{pp} \propto p^2 \psi^{-3} \eta_B^{-1/2} \delta V^2 / L$$

$$\left(\begin{array}{l} \lambda_{mfp} = \psi l_A \\ \frac{B^2}{8\pi} \sim \eta_B F \tau_{edd} \end{array} \right) \Updownarrow$$

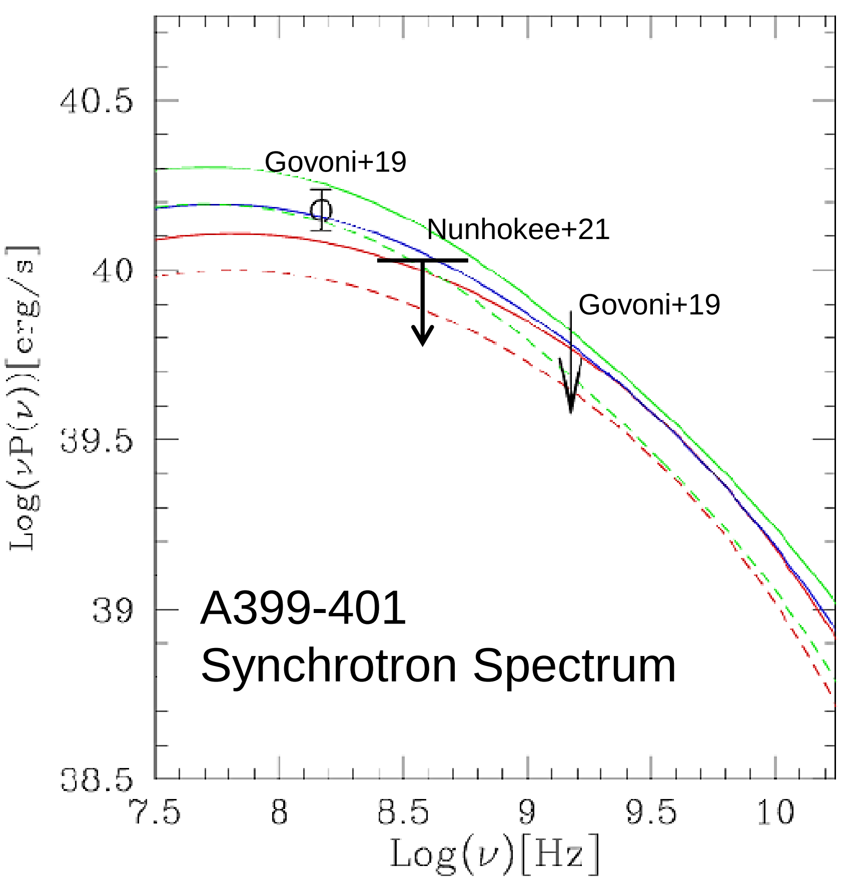
Although on much smaller scales/conditions, situations involving first order and second order-like Fermi acceleration are observed also in simulations of reconnection regions (Kowal et al 12, Dahlin et al 14, .. Guo et al 19, Comisso+Sironi 19, Lemoine+ 21)

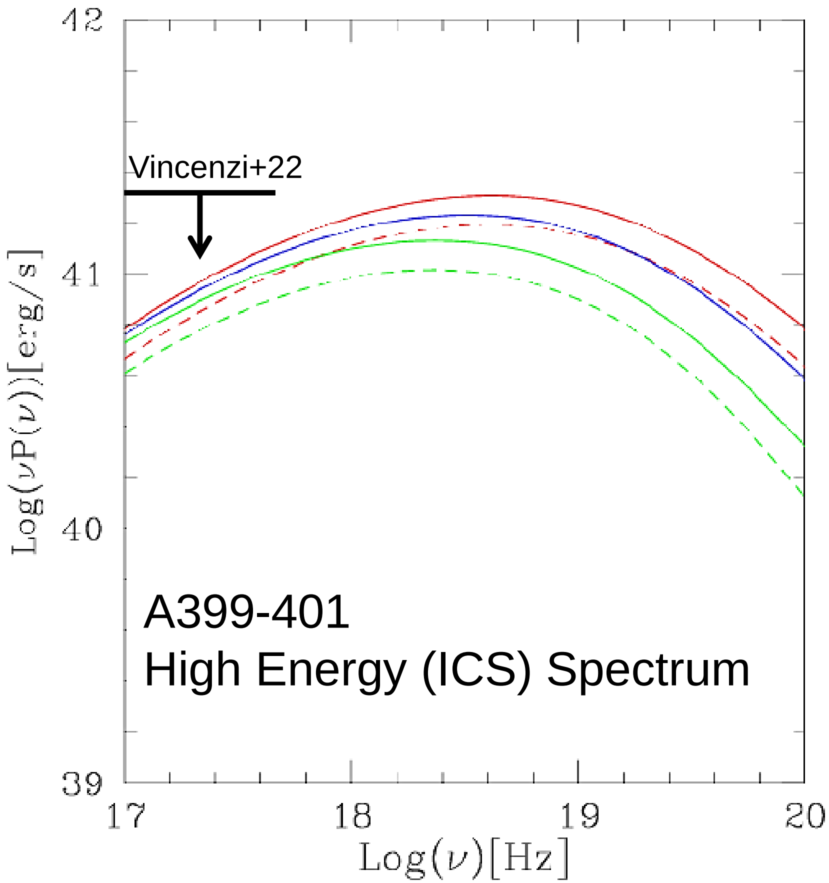
EXPECTATIONS & FIRST OBSERVATIONAL TESTS

(Brunetti+Vazza 20, PRL..)

Turbo reacceleration models predict :

- Steep spectrum emission, α >1.3-1.4, yet IC limit OK(!)
- Volume filling emission (increasing at lower frequencies)





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Cuciti+ 22

Article

Galaxy clusters enveloped by vast volumes of relativistic electrons

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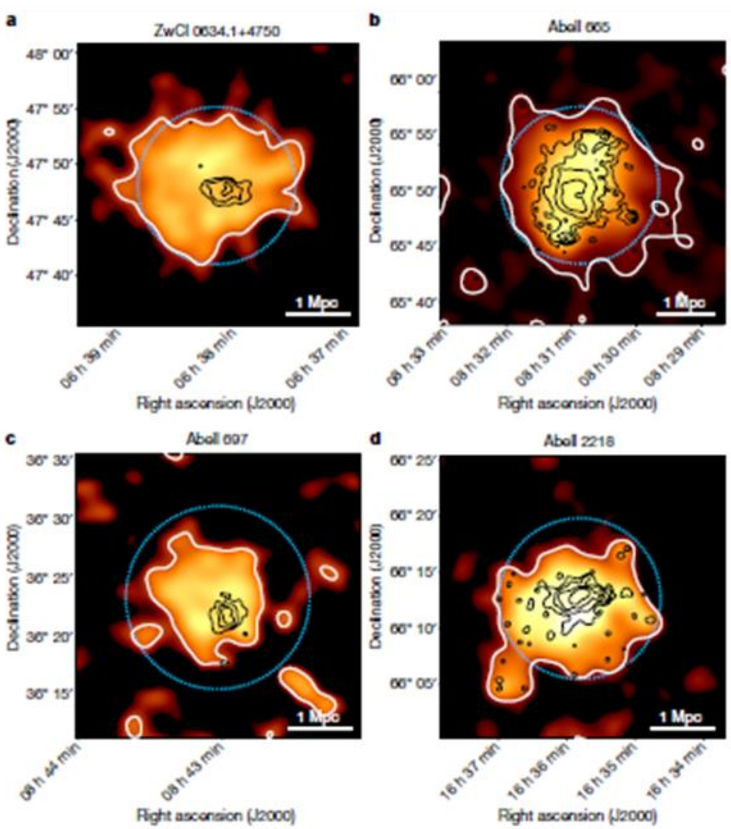


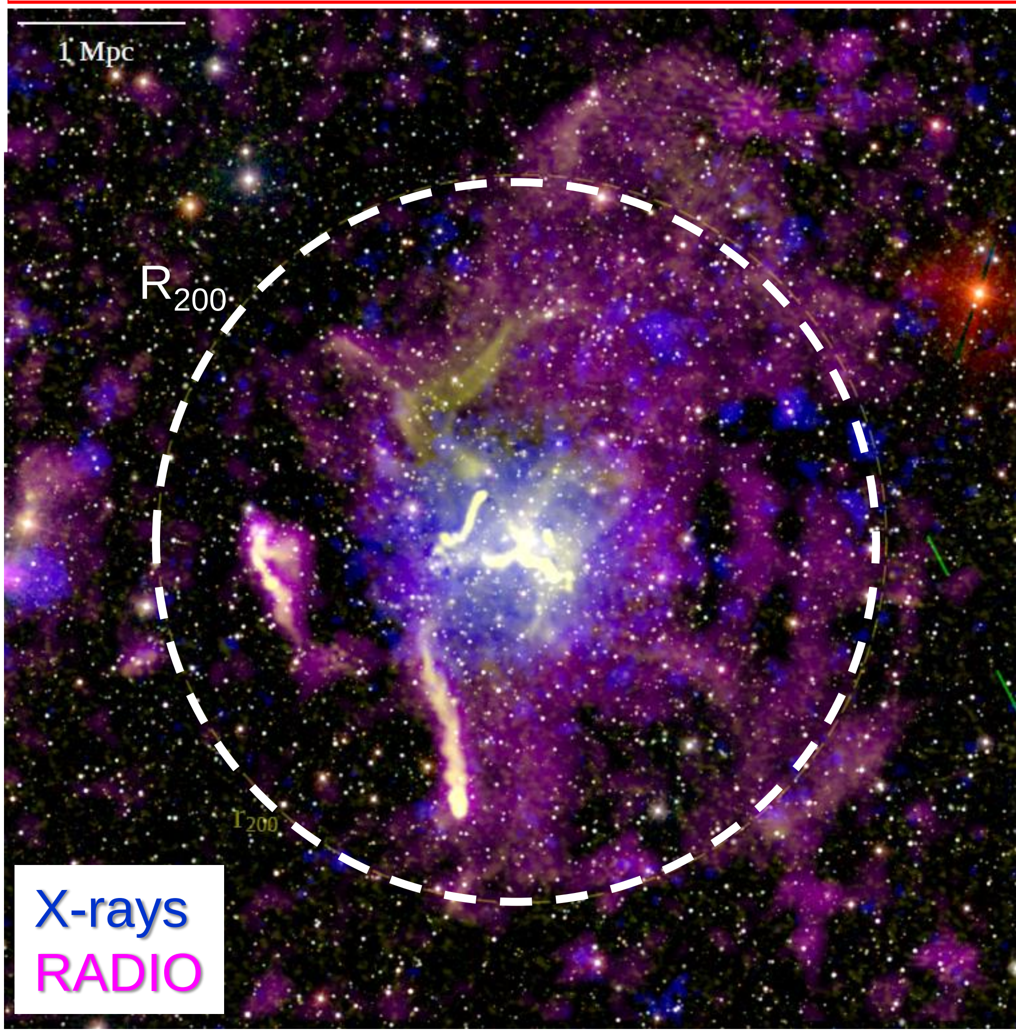
SCIENCE ADVANCES | RESEARCH ARTICLE

Science Advances AAAS

ASTRONOMY

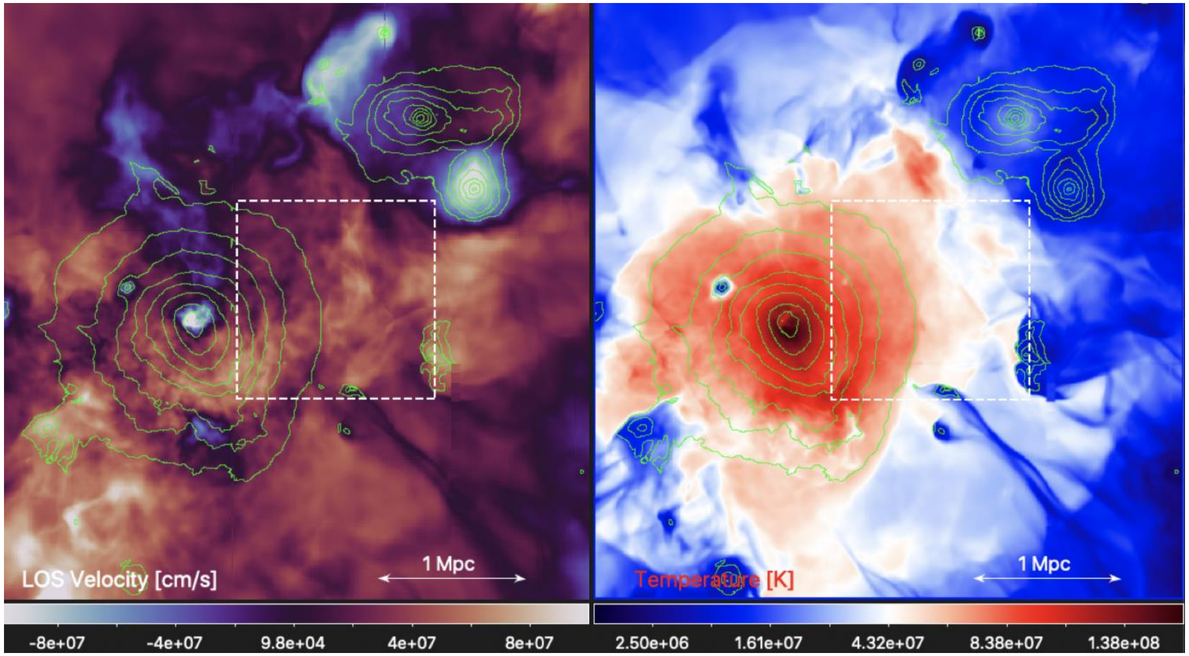
Magnetic fields and relativistic electrons fill entire galaxy cluster

Andrea Botteon[1,2,3]*, Reinout J. van Weeren[1], Gianfranco Brunetti[3], Franco Vazza[2,3], Timothy W. Shimwell[1,4], Marcus Brüggen[5], Huub J. A. Röttgering[1], Francesco de Gasperin[3,5], Hiroki Akamatsu[6], Annalisa Bonafede[2,3], Rossella Cassano[3], Virginia Cuciti[3,5], Daniele Dallacasa[2,3], Gabriella Di Gennaro[5], Fabio Gastaldello[7]



Second order acceleration in Mega Halos

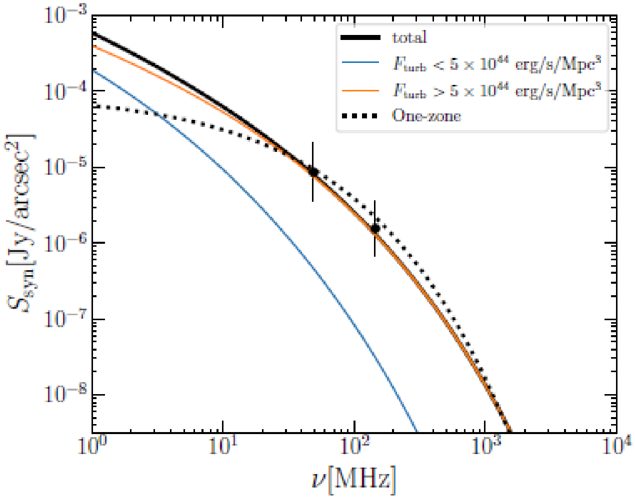
(Nishiwaki, GB, et al 2023+)



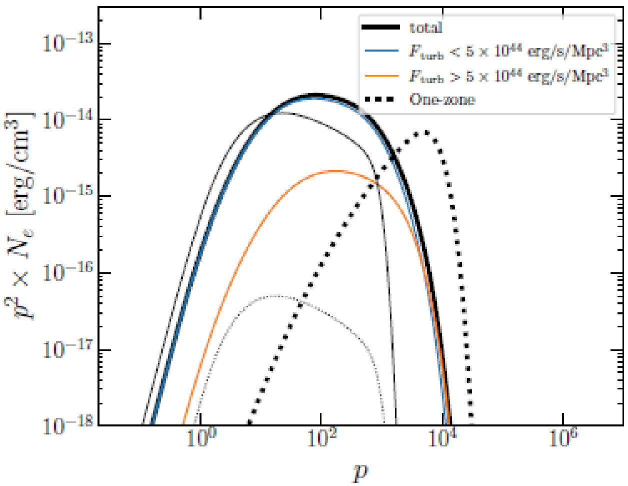
Similar to RADIO BRIDGES

- Turbulence (solenoidal) from high res Cosmological simulations
- B amplified by turbulent dynamo
- NL Turbulent reacceleration (GB+Lazarian 16)

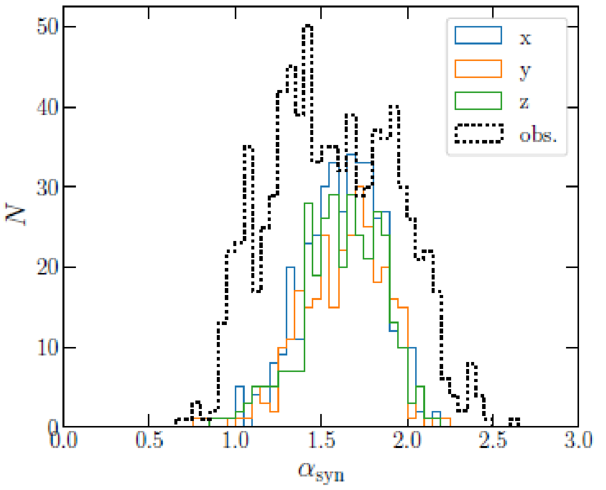
Syn Spectrum



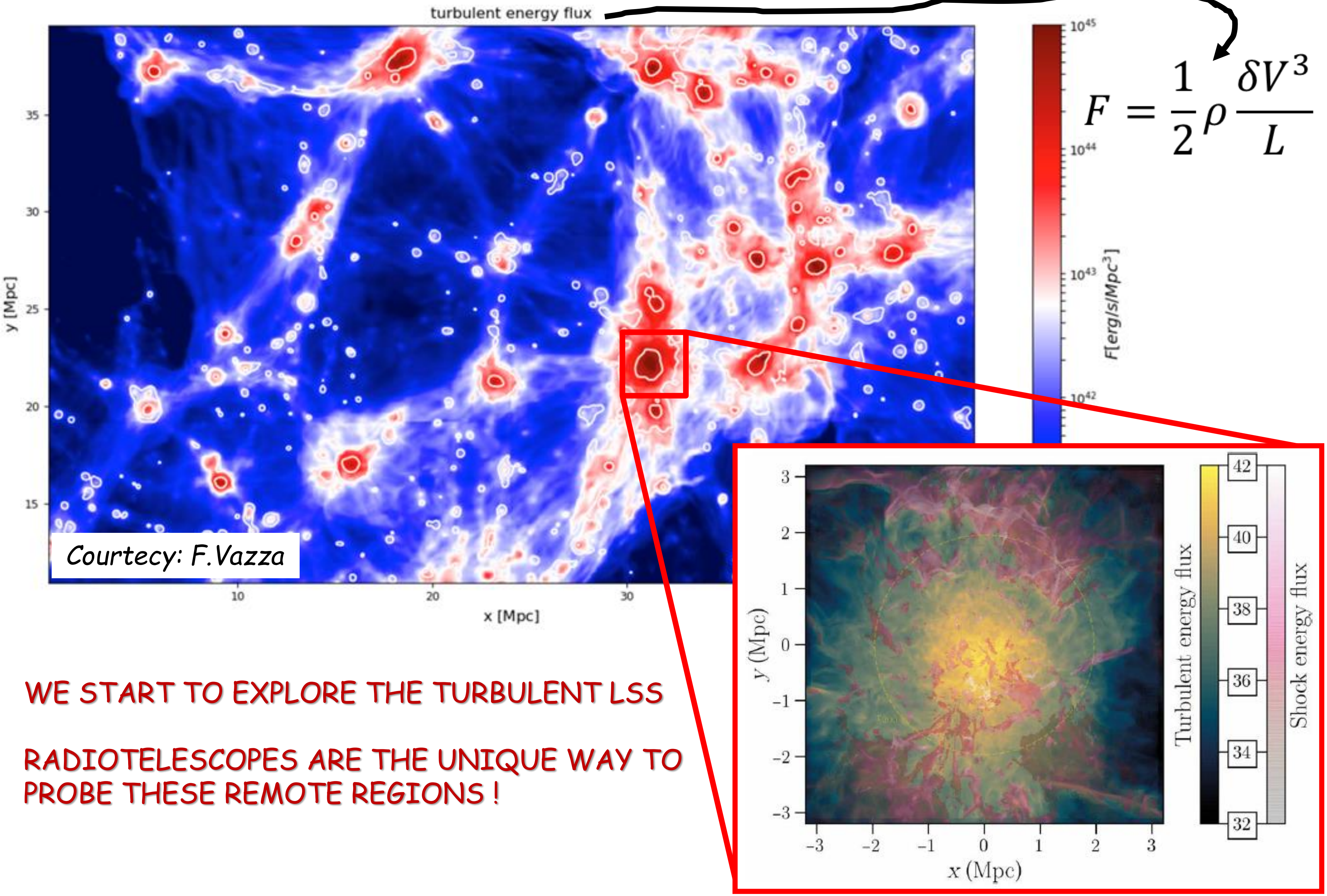
Electron Spectrum



Spectral index distribution



TURBULENCE & SHOCKS IN LSS



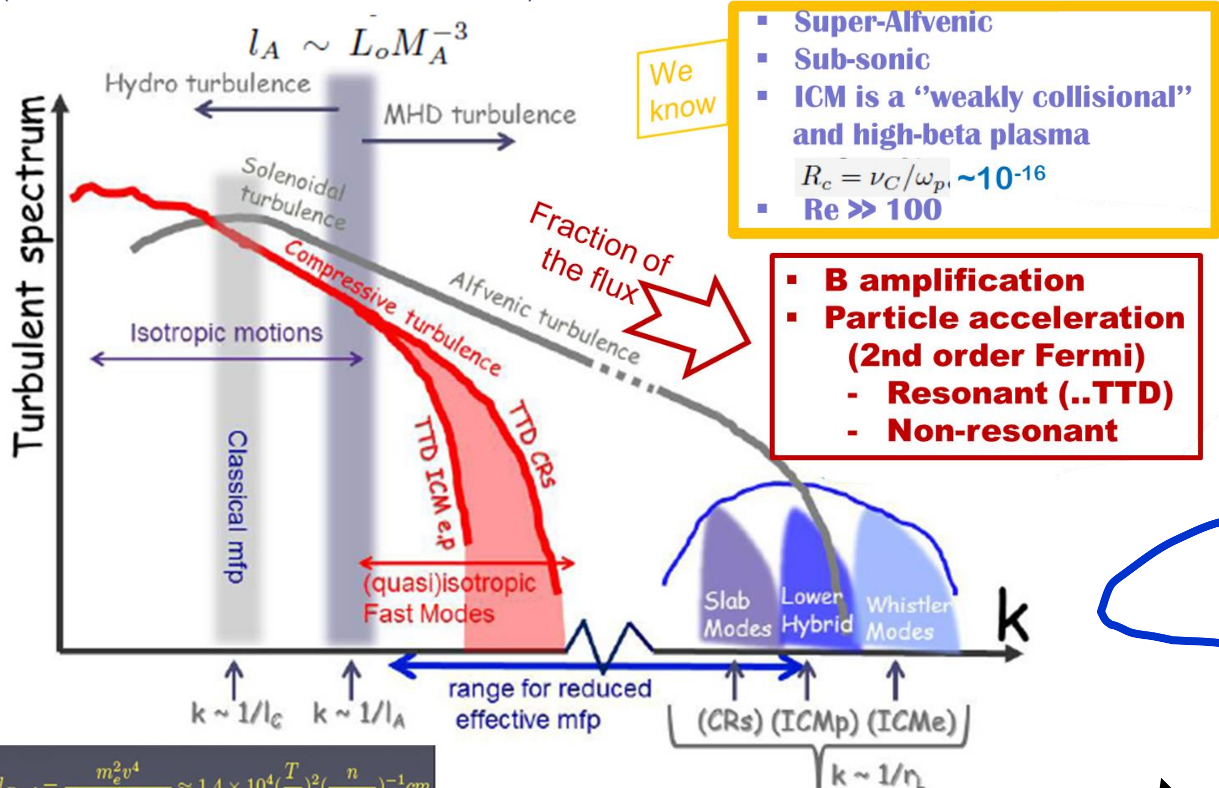
$$F = \frac{1}{2}\rho\frac{\delta V^3}{L}$$

WE START TO EXPLORE THE TURBULENT LSS

RADIOTELESCOPES ARE THE UNIQUE WAY TO PROBE THESE REMOTE REGIONS !

ICM/LSS Turbulence :Theoretical (incomplete..) picture

(Brunetti & Lazarian 07, Brunetti & Jones 14)



$$l_{Coul} = \frac{m_e^2 v^4}{8\pi n Z^2 e^4 ln\Lambda} \approx 1.4\times10^4 \left(\frac{T}{K}\right)^2 \left(\frac{n}{cm^{-3}}\right)^{-1} cm$$

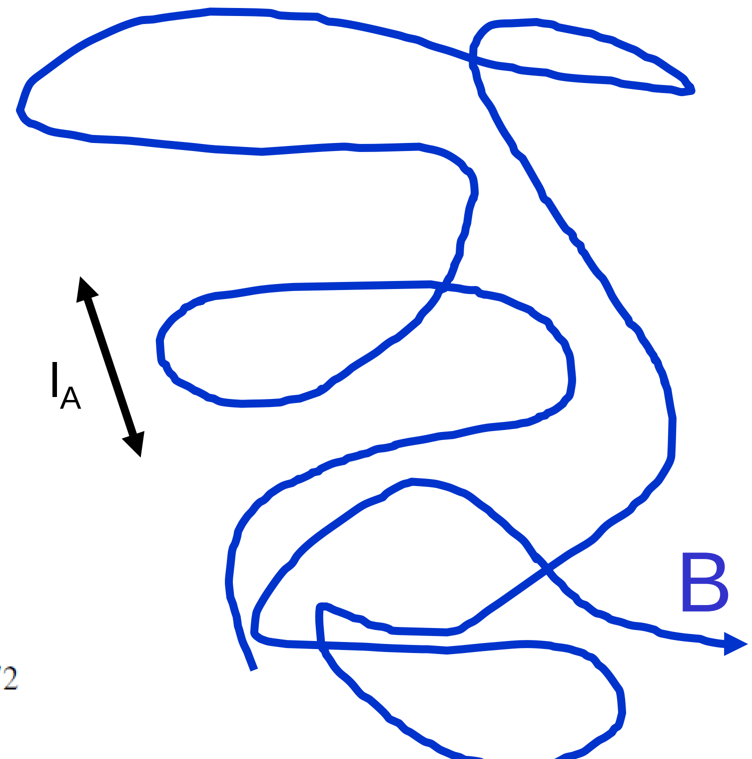
1. Super-Alfvenic
2. Large scale
3. High beta

If scattering is suppressed, particles will move ballistically along B lines

$$D \sim \frac{1}{3} l_A c \approx 3\times10^{30} \frac{L_0}{100kpc}\left(\frac{M_A}{10}\right)^{-3}$$

Diffusion scale in TIME

$$L \approx 70\mathrm{kpc}\left(\frac{L_0}{100kpc}\right)^{1/2}\left(\frac{\mathrm{TIME}}{100\mathrm{Myr}}\right)^{1/2}\left(\frac{M_A}{10}\right)^{-3/2}$$



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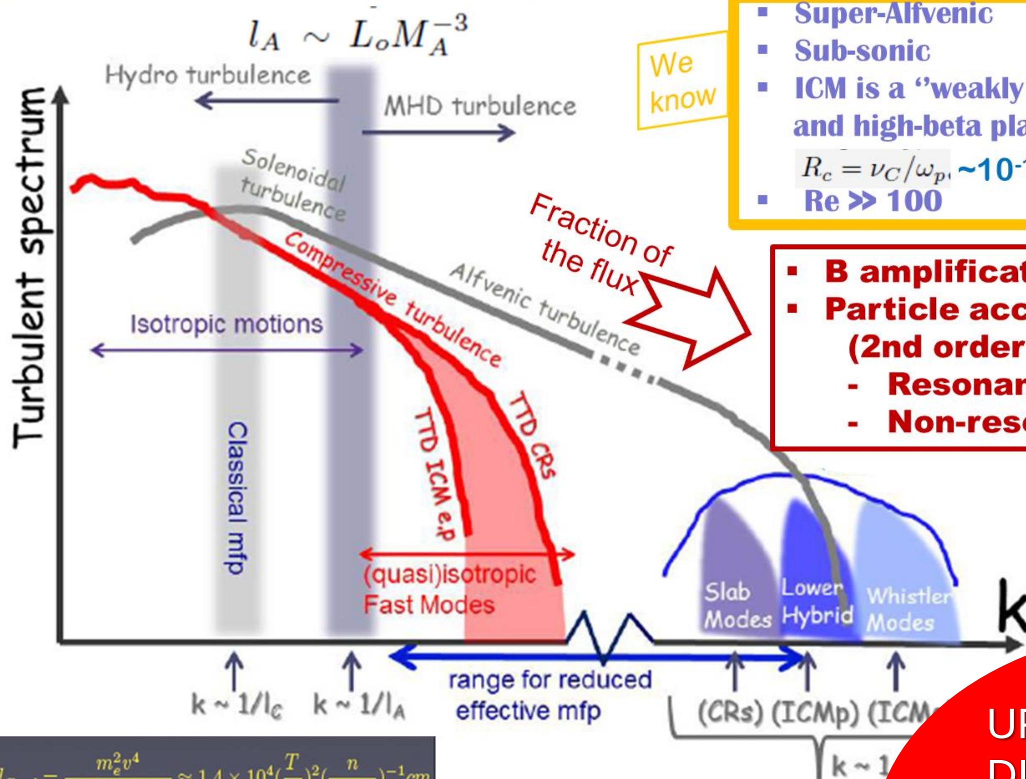
(Brunetti & Lazarian 07, Brunetti & Jones 14)

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



We know

- Super-Alfvenic
- Sub-sonic
- ICM is a "weakly collisional" and high-beta plasma
  $R_c = \nu_C/\omega_p$ ~10^{-16}
- Re >> 100

- **B amplification**
- **Particle acceleration (2nd order Fermi)**
  - **Resonant (..TTD)**
  - **Non-resonant**

$$l_{Coul} = \frac{m_e^2 v^4}{8\pi n Z^2 e^4 ln\Lambda} \approx 1.4\times10^4 (\frac{T}{K})^2 (\frac{n}{cm^{-3}})^{-1} cm$$

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UPPER LIMIT FOR DIFFUSION:
in case of lower Mach number CRs can diffuse across large regions

Diffusion scale in TIME

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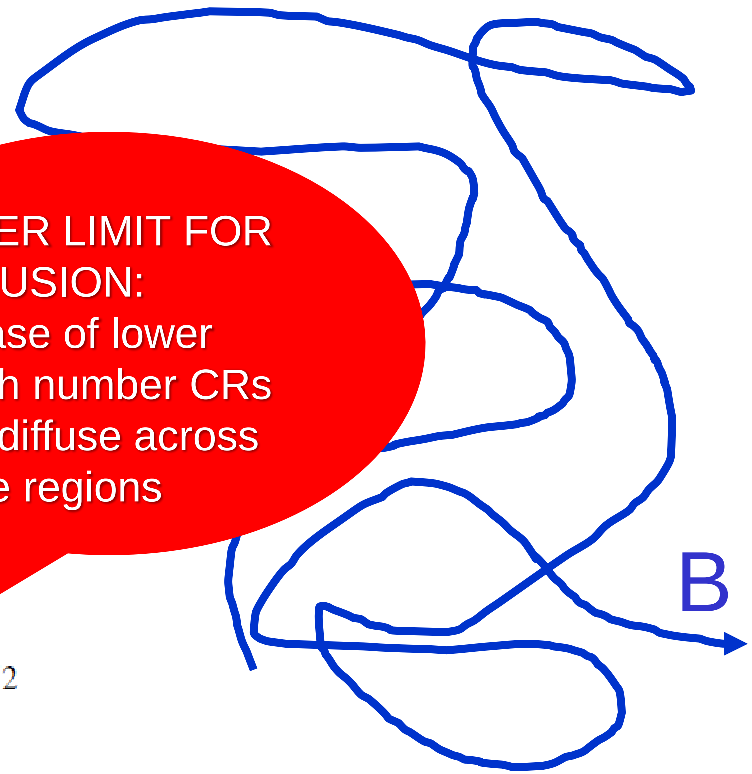

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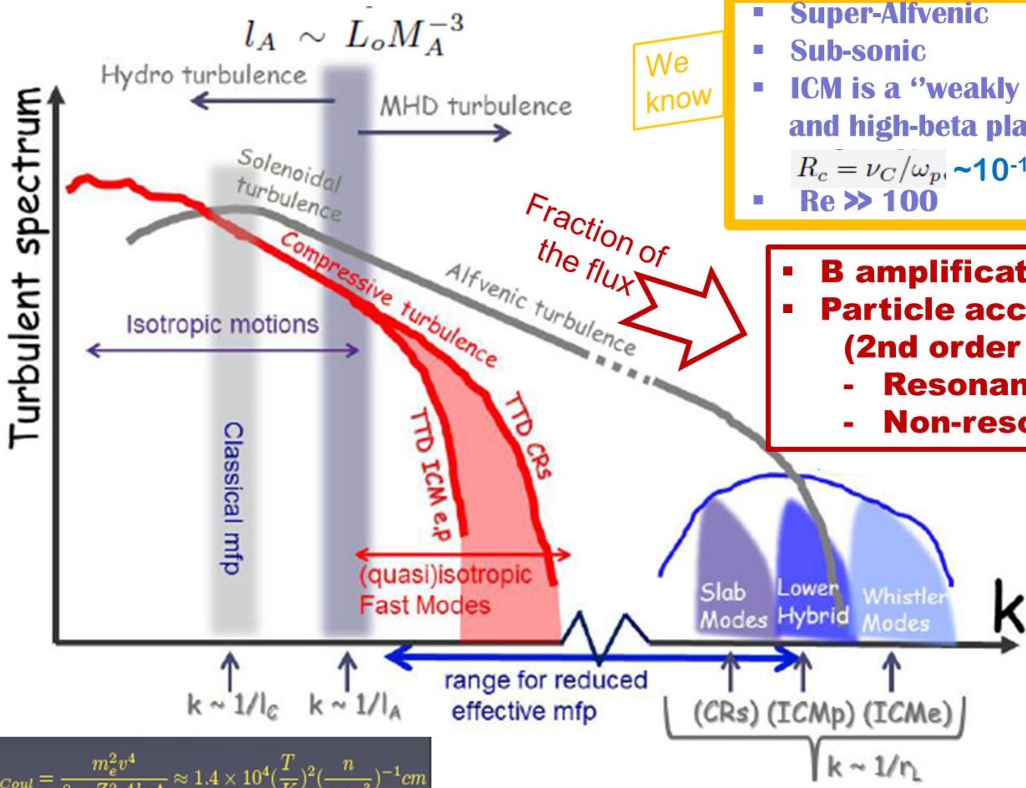
(Brunetti & Lazarian 07, Brunetti & Jones 14)



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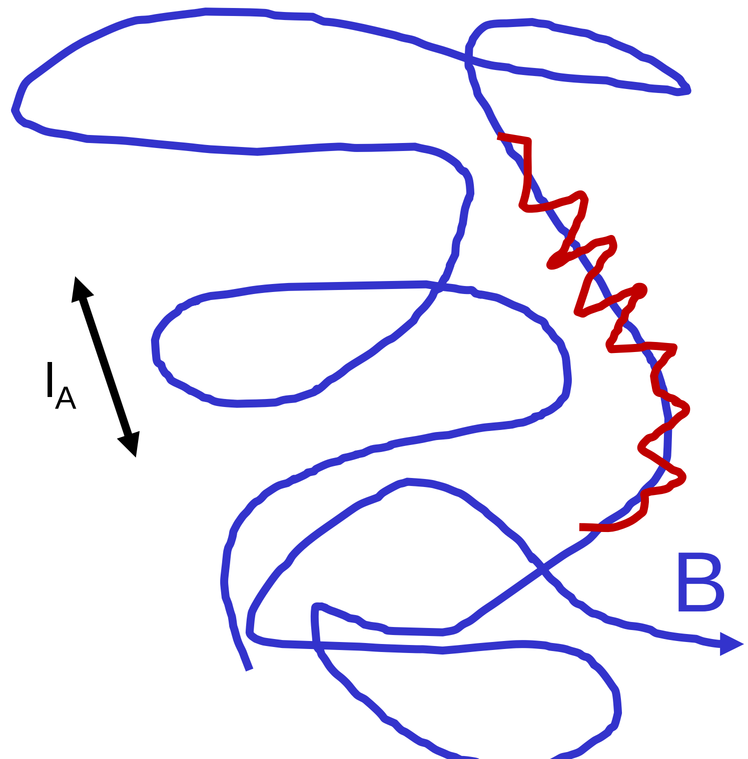
Scattering by self-generated modes, fast modes, mirrors, firehose turbulence, streaming+NL damping, etc (eg Kunz+14, Evoli+18, Wiener+18,19, Lazarian+Xu 21, Xu+Lazarian 22, Kempski+ 23..)



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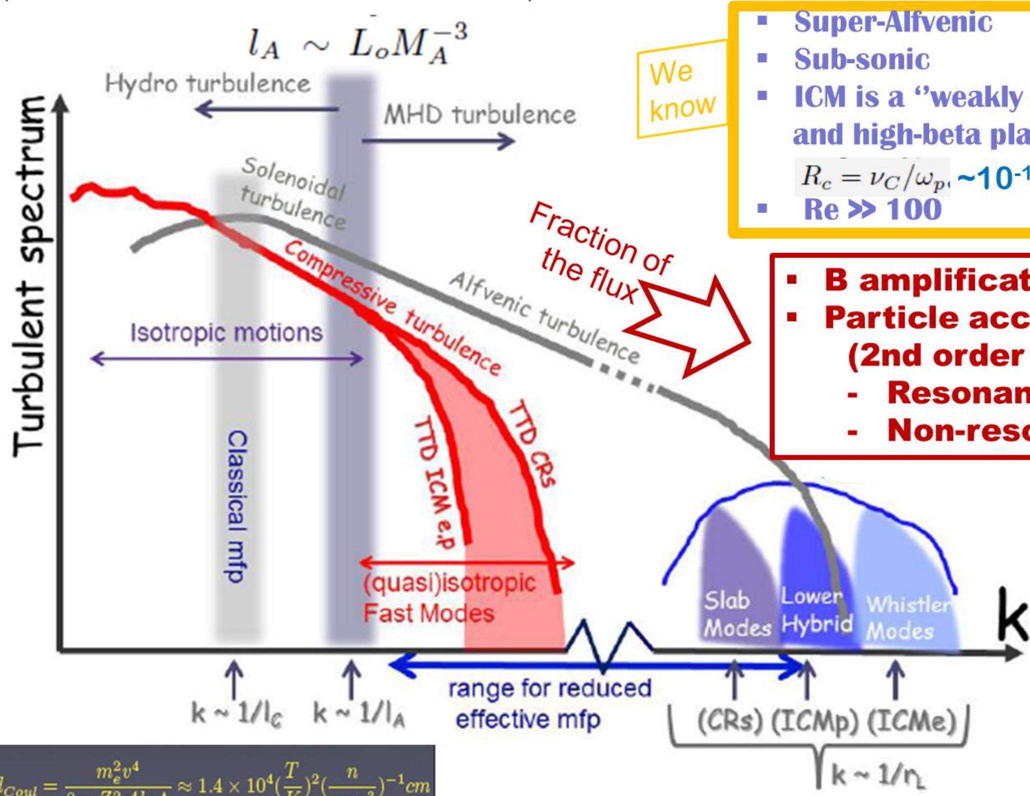

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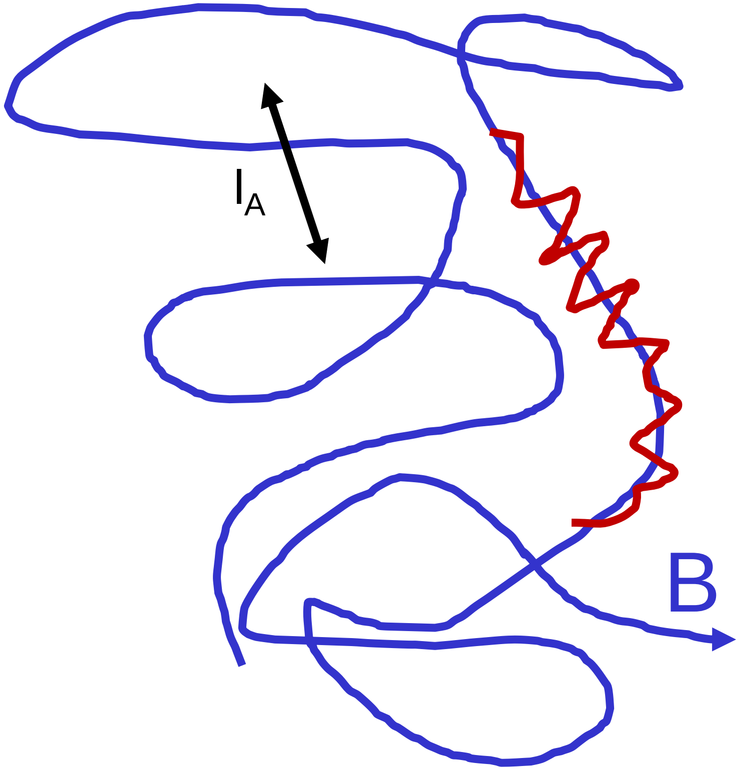
We can approximate the diffusion as random walk of step side l_e and frequency corresponding to decorrelation of field lines :

$$D \sim \frac{1}{3} l_e^2 \tau_c^{-1}$$

where

$$\tau_c \sim \tau_e \sim l_A V_A^{-1}$$



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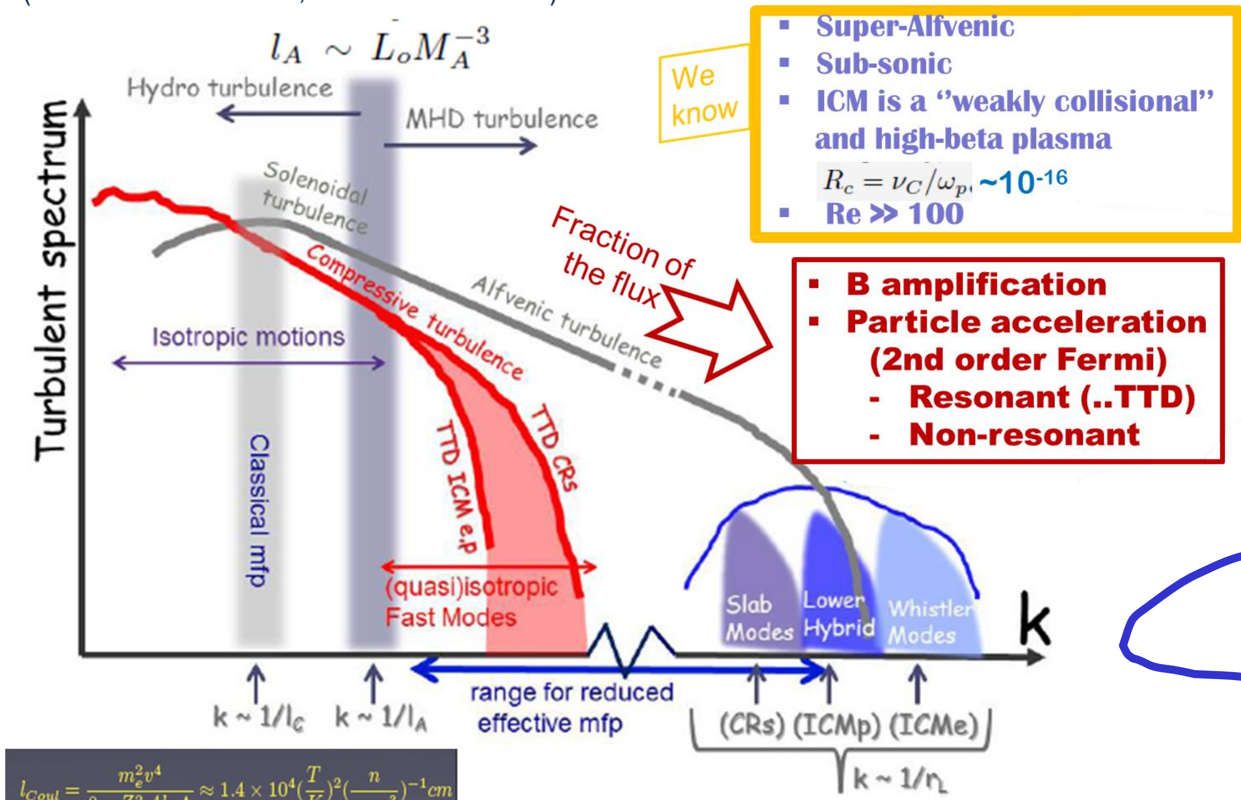

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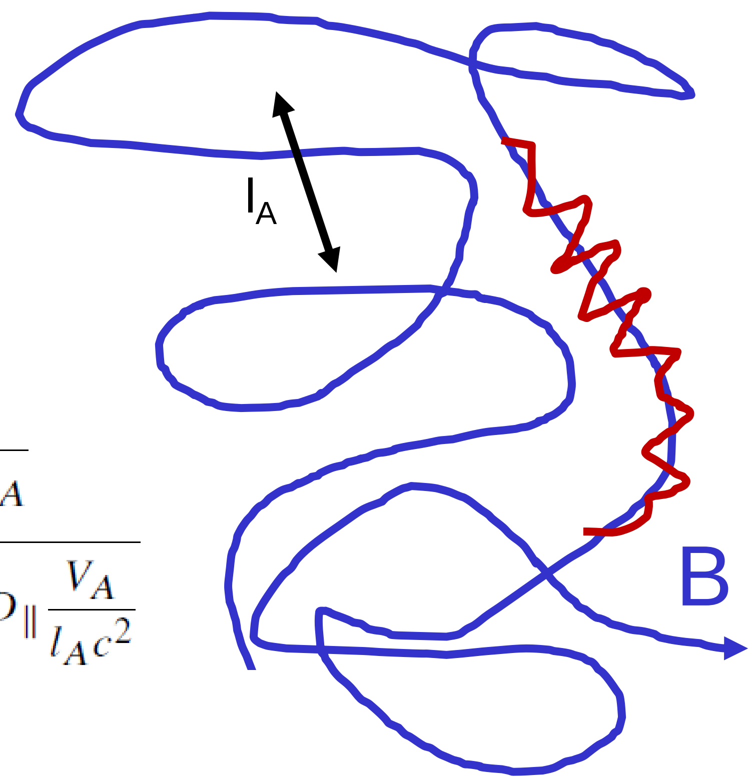

Distance covered in a correlation time :

$$\lambda_0 \sim \sqrt{D_{||} \tau_c} \sim \sqrt{D_{||} l_A V_A^{-1}}$$

IF ('fast' diffusion)

$$\lambda_0^2 \gg l_A^2 \iff D_{||} > l_A V_A$$

'fast' diffusion corresponds to situations of Alfvenic drift or faster

$$l_e \sim \sqrt{\lambda_0 l_A}$$

$$D \sim \frac{1}{3} l_A c \sqrt{D_{||} \frac{V_A}{l_A c^2}}$$

ICM/LSS Turbulence :Theoretical (incomplete..) picture

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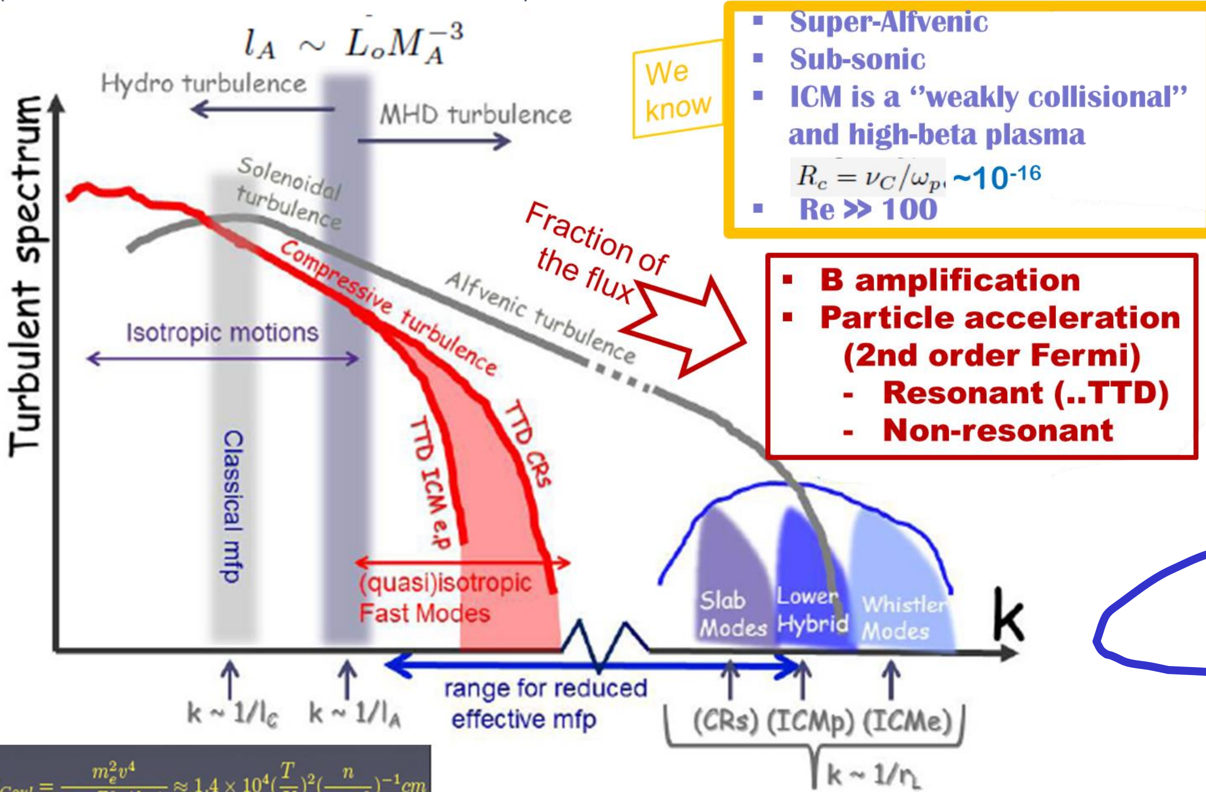

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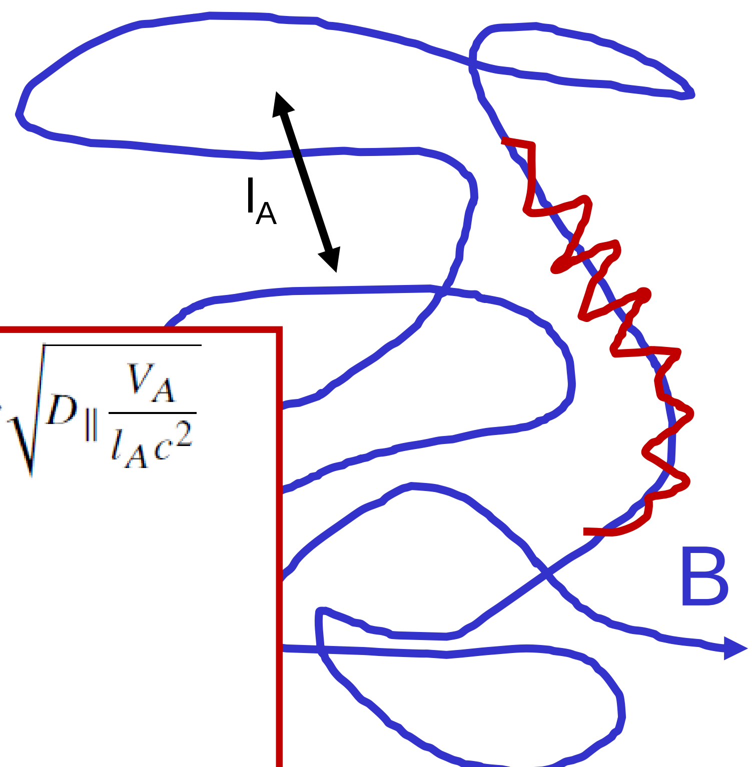
$$D_{\parallel} \propto p^{\alpha}$$

$$D \propto p^{\alpha/2}$$

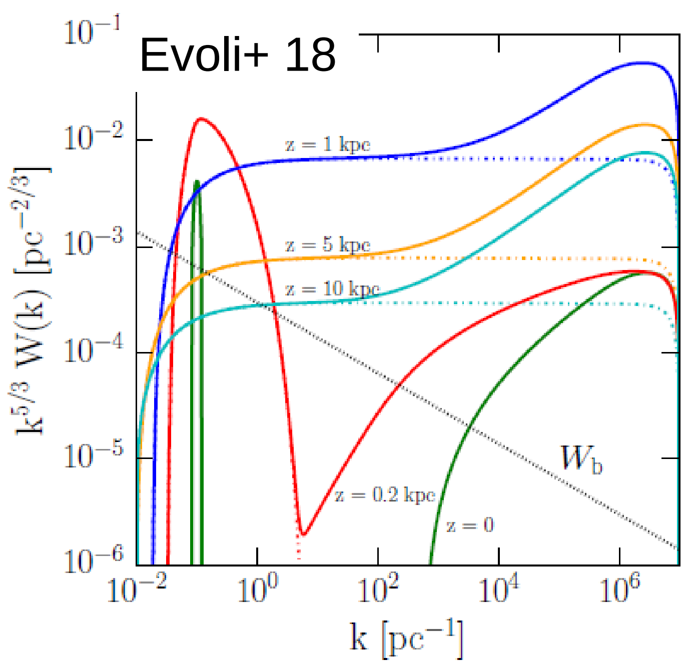


Connections with galactic turbulence & CR transport ?

Super-Alfvenic (GC, CC) — Sub-Alfvenic (Galactic halo, HIM, WIM, Sun)

	GC	CC	Galactic halo	HIM	WIM	Sun
T (K)	10^8	3×10^7	2×10^6	10^6	8×10^3	10^7
c_s (km s^{-1})	1650	900	130	90	8	360
n_{th} (cm^{-3})	10^{-3}	5×10^{-2}	10^{-3}	4×10^{-3}	0.1	10^{10}
l_{mfp} (cm)	5×10^{22}	10^{20}	4×10^{19}	2×10^{18}	6×10^{12}	10^8
L_o (pc)	1–5 $\times10^5$	1–5 $\times10^5$	100	100	50	3×10^{-10}
B (μG)	1	10	5	2	5	10^8
c_s^2/v_A^2	500	100	0.3	3.5	0.1	0.03
Damping	*Collisionless*[a]	*Collisionless?*	*Collisionless*	Collisional	Collisional	*Collisionless*[b]

[a] $V_L > 300\,\mathrm{km s^{-1}}$. [b] Alfvénic turbulent-Mach number $M_A \gtrsim 0.3$ is assumed.



- Self-generated waves
- Large scale turbulence

TAKE HOME

- GALAXY CLUSTERS ARE ENVIRONMENTS WHERE THE FERMI II OPERATES IN NEW REGIMES AND BECOMES VISIBLE .
- TURBULENT REACCELERATION IS THE GOLD STANARD FOR RADIO HALOS.

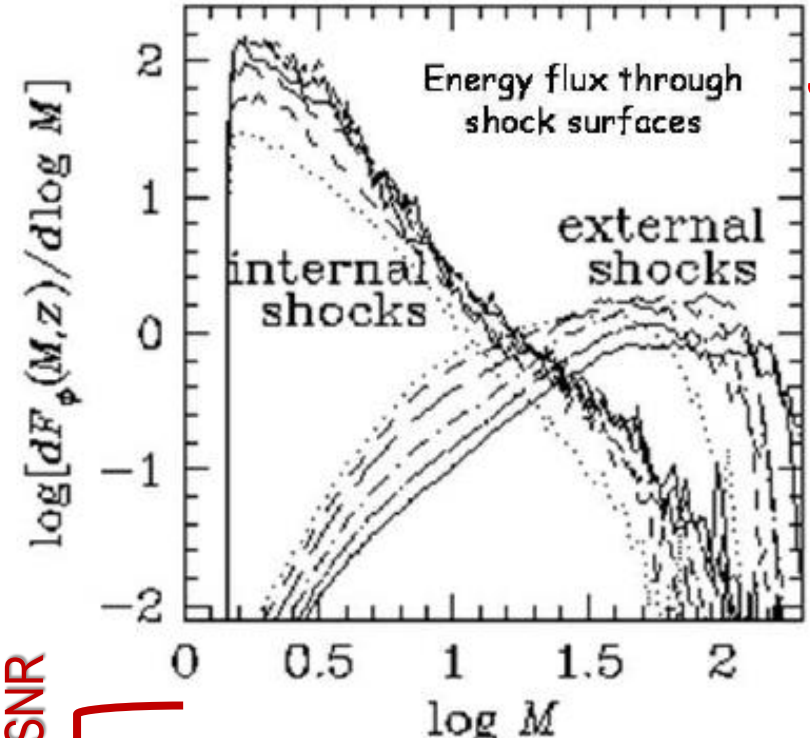
- THE NEW GENERATION OF RADIO TELESCOPES (es LOFAR) ALLOWS DETECTING STRUCTURES BEYOND GALAXY CLUSTERS.
- FERMI II ARE LIKELY THE KEY MECHANISMS ALSO ON THESE SCALES.

- THE SUPER-ALFVENIC NATURE OF ICM TURBULENCE HAS A KEY ROLE IN THE DIFFUSION/TRANSPORT OF CRs

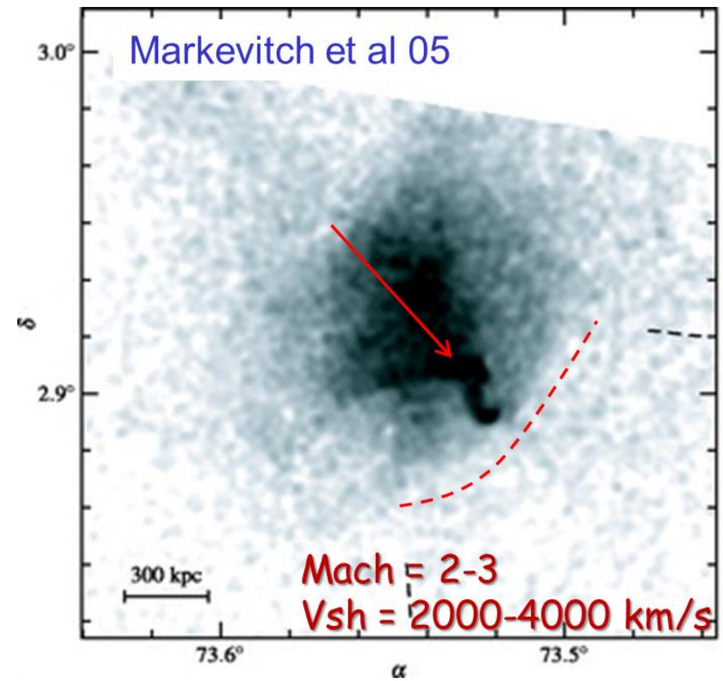
- OUR UNDERSTANDING OF TURBULENT ACCELERATION AND TRANSPORT IN THE ICM MAY HELP UNDERSTANDING RFFECTS OF LARGE SCALE TURBULENCE IN THE ISM/GAL.
- PHYSICS OF SELF-GENERATED TURBULENCE TRADITIONALLY STUDIED BY ISM/GAL COMMUNITY MAY HELP IMPROVING UNDERSTANDING OF CR DIFFUSION IN THE ICM.

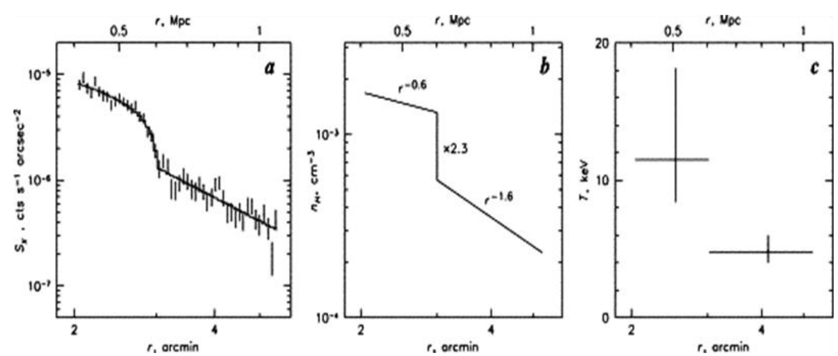
Cosmological Shocks and CRs in galaxy cluster

(Blasi +01, Miniati +01, Ryu +03, Pfrommer +06,08, Skillman +08,12, Vazza, GB +09,11, ...)



Ryu et al 03



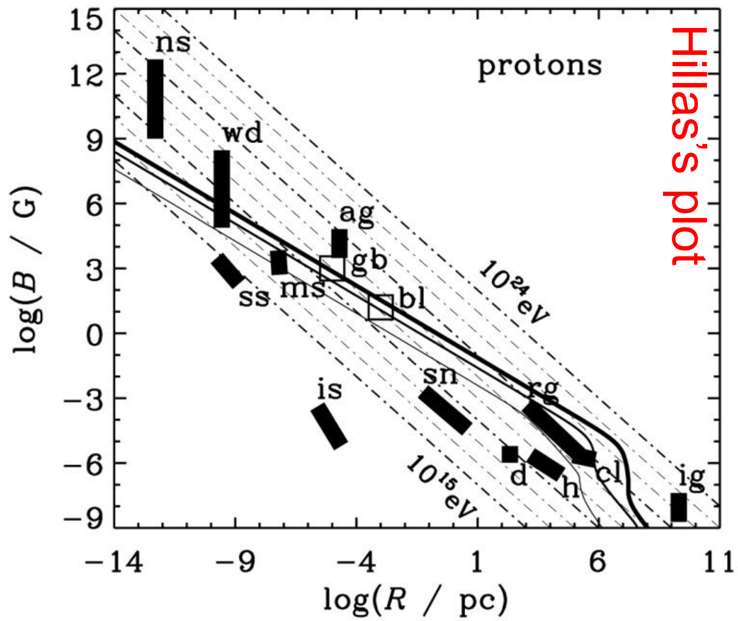


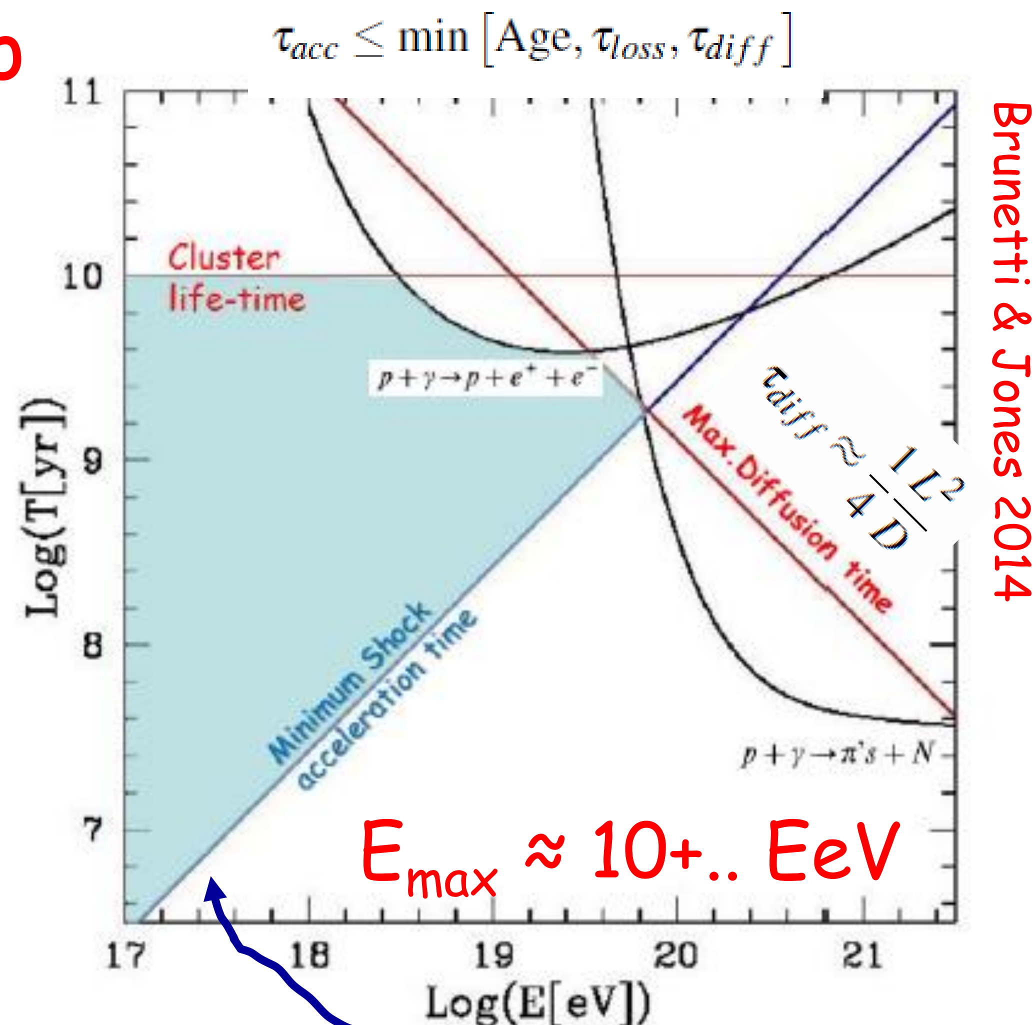
extrapolation from SNR

The bulk of ICM heating is due to internal shocks.
If shock acceleration efficiency in the ICM is 10% the resulting CRs (CRp) would store up to. 0.1 E_{TH}

Max energy of CRp

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





DSA Bohm

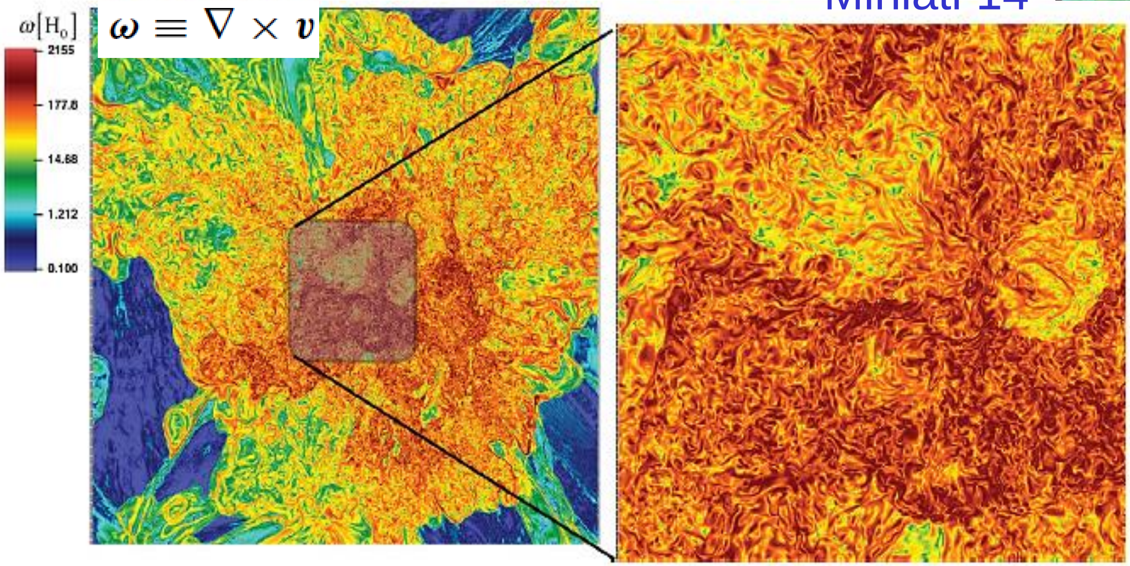
$$\tau_{acc}(p) \simeq \frac{4D(p)}{(c_s M)^2}\frac{M^2(5M^2+3)}{(M^2+3)(M^2-1)}$$

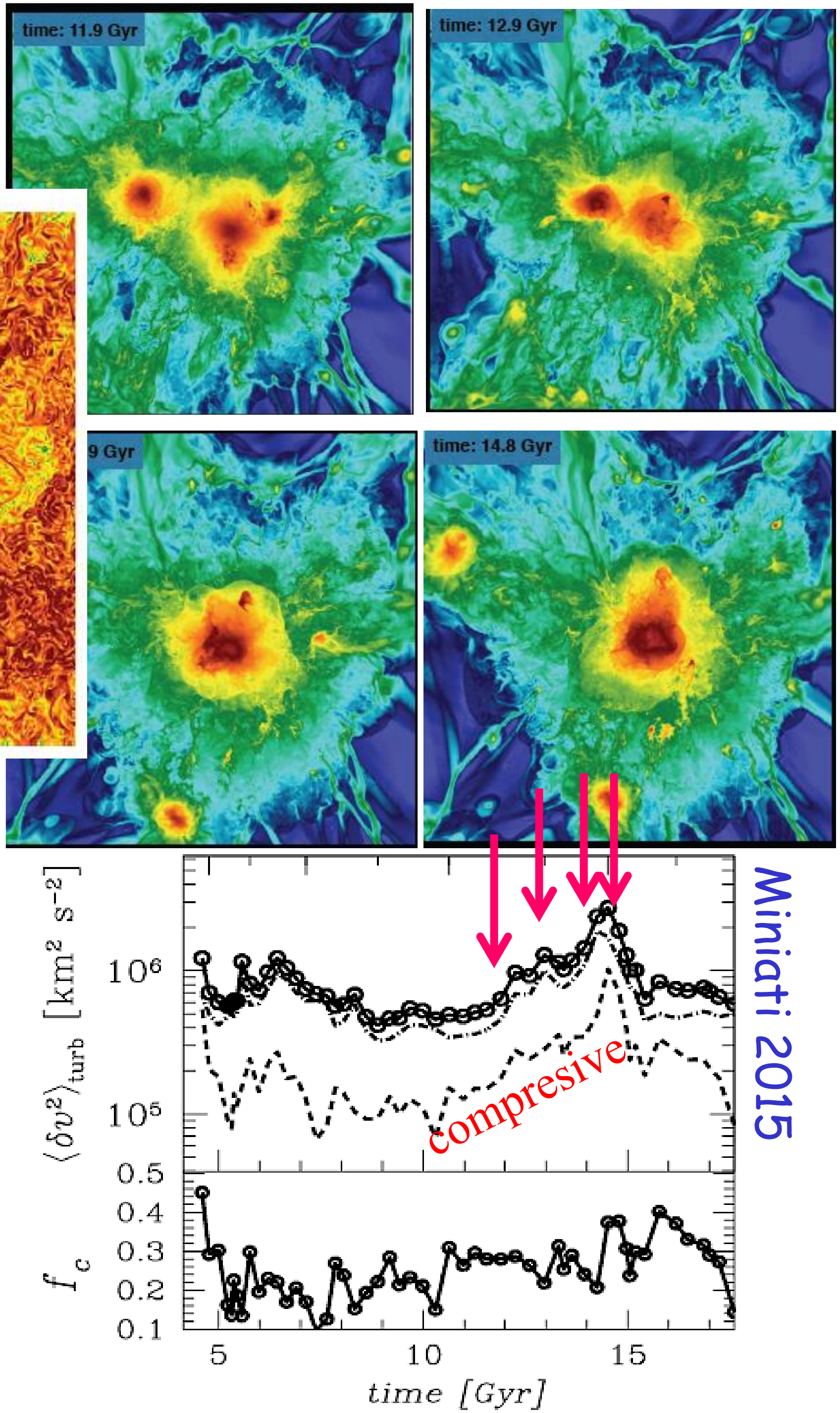
$$D(p) \sim 3\times 10^{22}\frac{(cp/\text{GeV})}{(B/\mu G)}\ \text{cm}^2\text{s}^{-1}.$$

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

TURBULENCE IN THE ICM

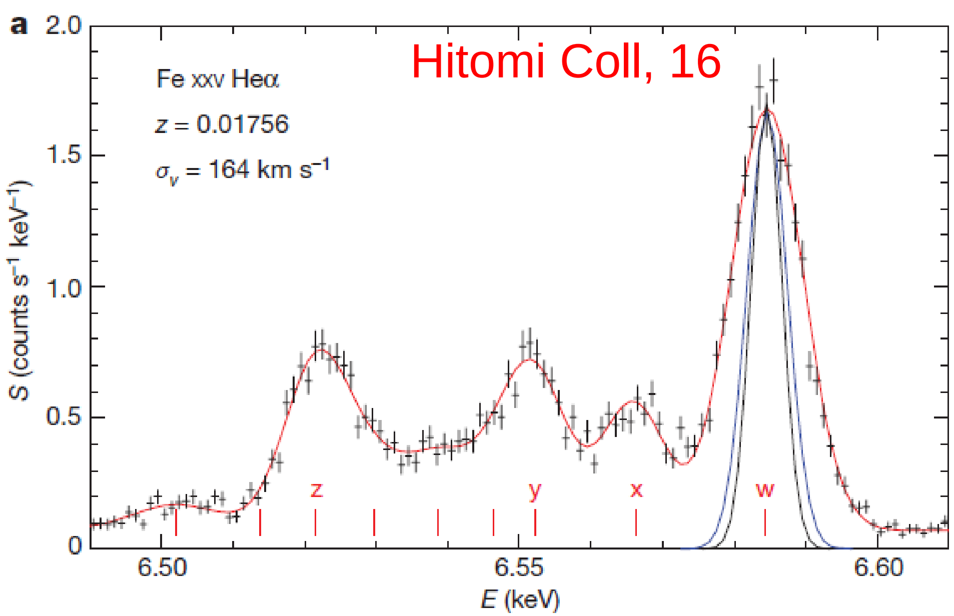
Miniati 14





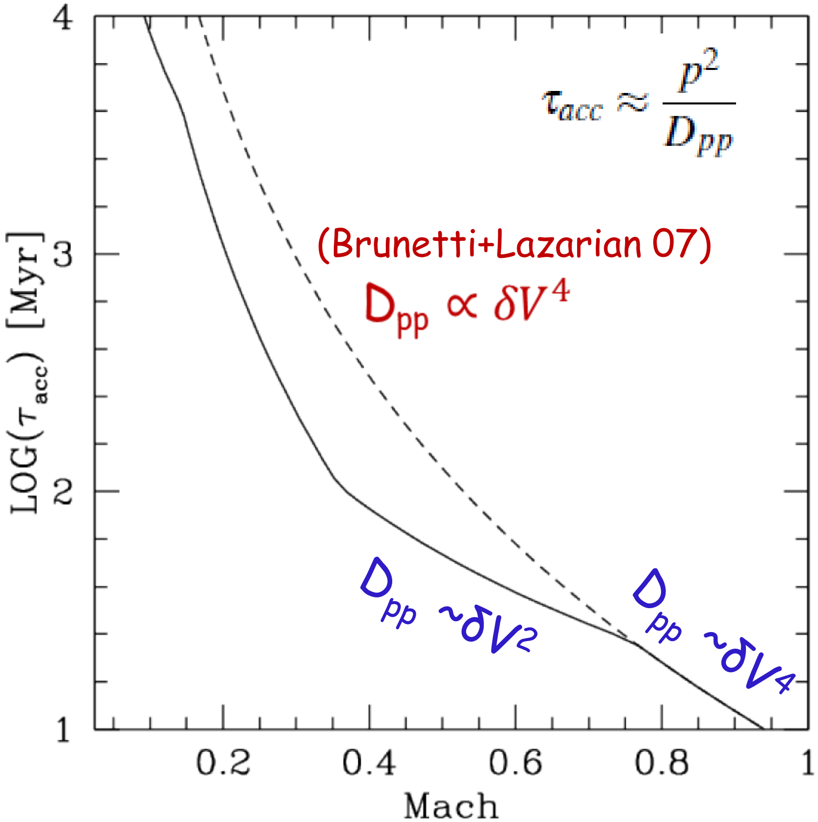
Miniati 2015

Hitomi Coll, 16



Effects of effective collisionality

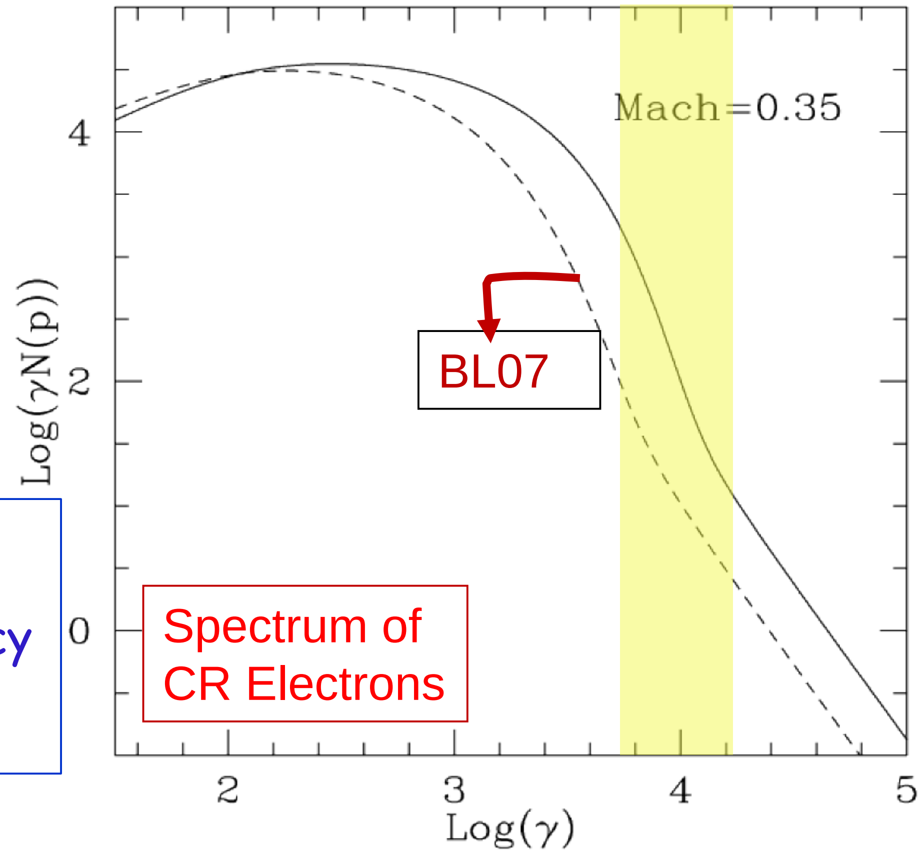
(GB+ in prep)



Include proton and electron collisionless dampings depending on collision frequency vs wave frequency ($\omega_w > \omega_{coll}$)

- ee, pp, ep Coulomb collisions
- pp scattering with firehose+mirror (Kunz+)

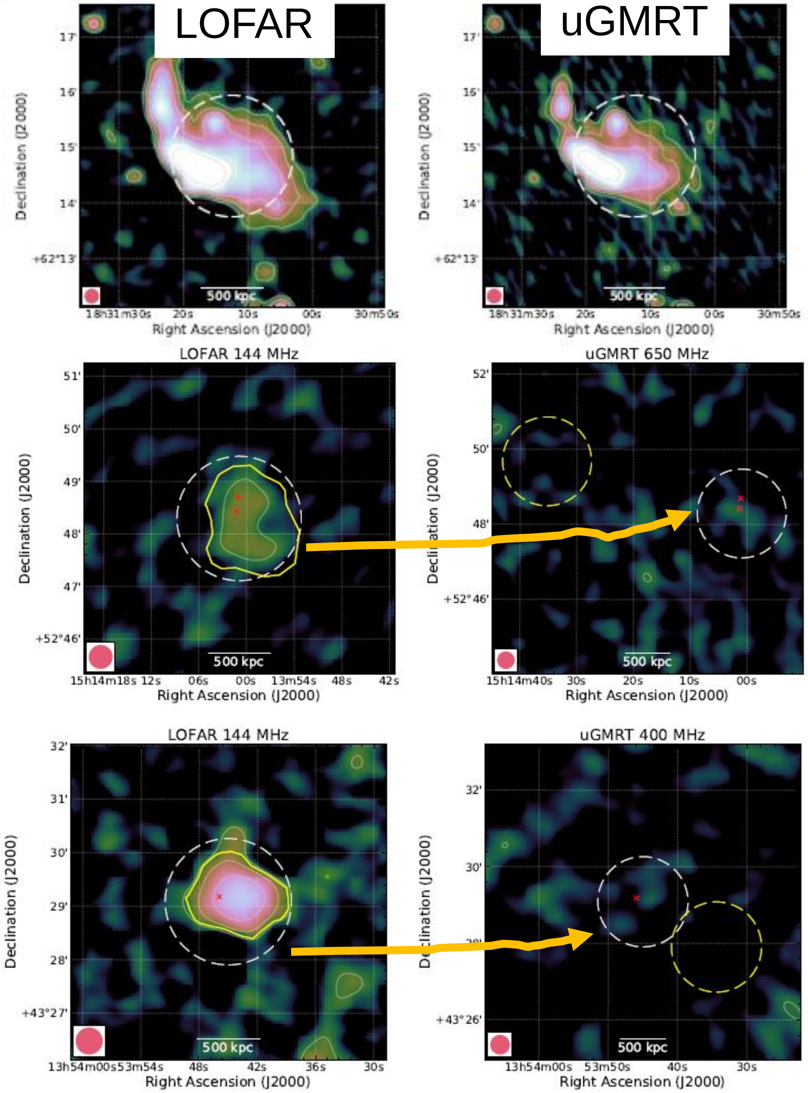
$$\nu \sim V_A \, \beta_{pl} / l_A$$



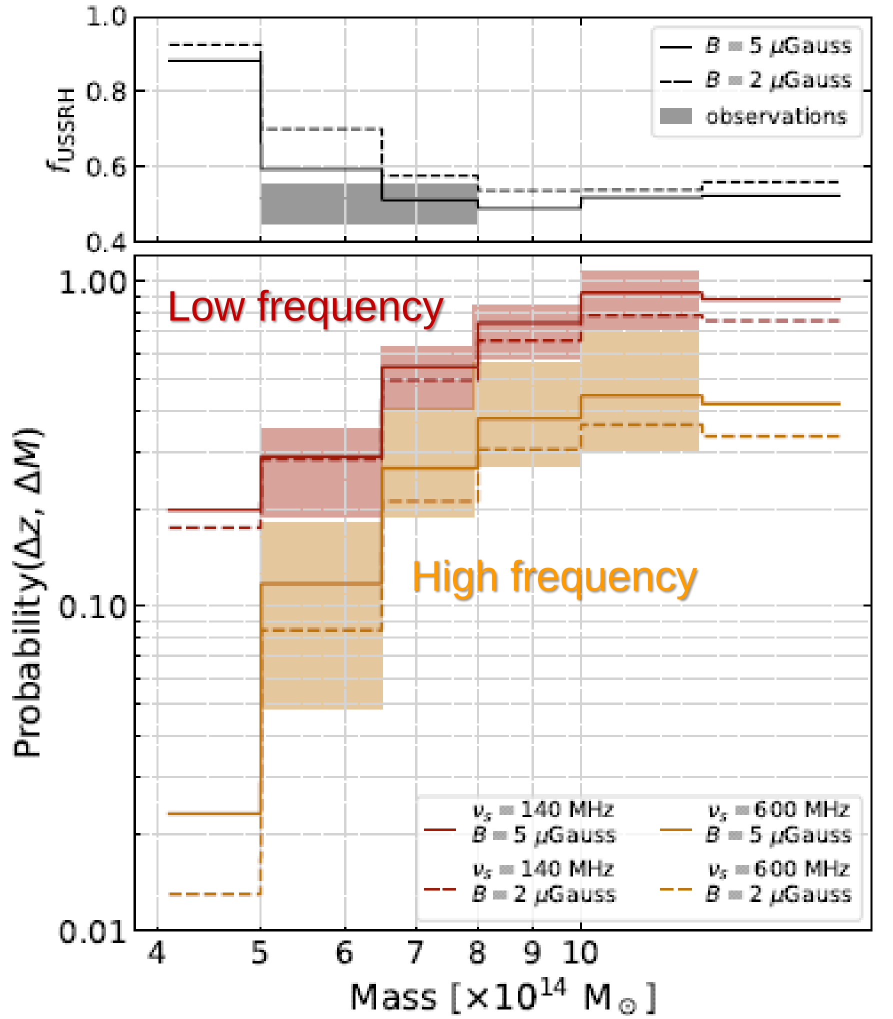
- ❑ Turbulence can **reach smaller scales**
- ❑ **Increase** of acceleration rate/efficiency
- ❑ New branch at intermediate Mach

High-z radio halos (z>0.6)

- Radio halos **discovered by LOFAR** + deep follow up at higher frequencies
- ~Half of the radio halos have **very steep spectrum (USS), $\alpha > 1.5$**
- Agreement with turbulent models



Di Gennaro, ..GB et al, 2021



Turbulent acceleration & B in LSS ??

(Brunetti+Vazza 2020, PRL..)

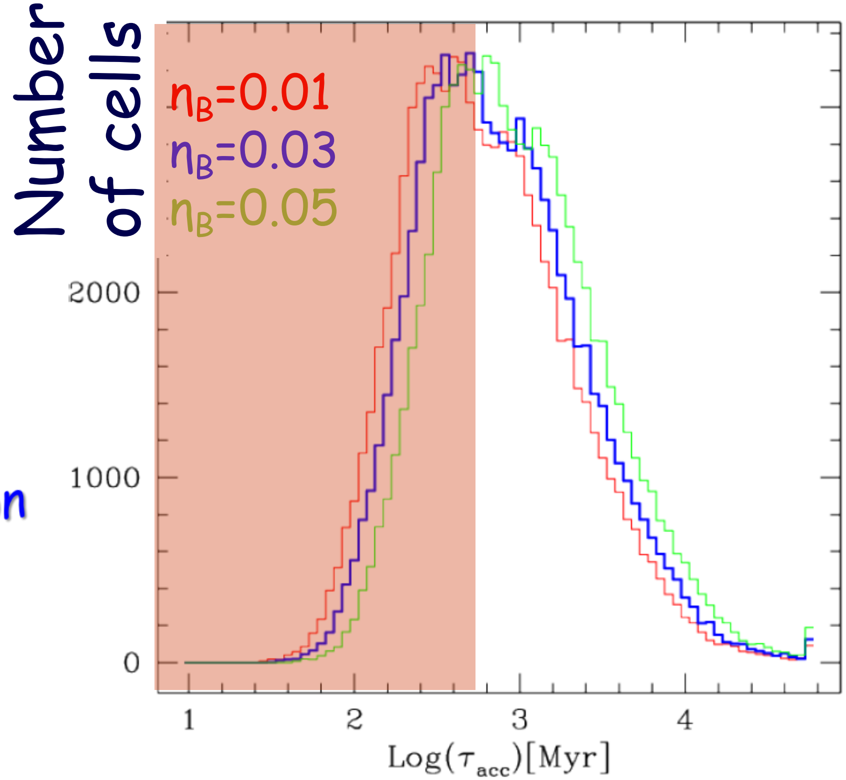
Acceleration

$$D_{pp} \propto p^2 \psi^{-3} \eta_B^{-1/2} \delta V^2 / L$$

$$\tau_{acc} = p^2 / (4 D_{pp})$$

Condition for generation of radio emission is Tacc < Tloss

Acc times PDF



Radiative losses:

$$\tau \sim 220 (B_{\mu G}/0.5)^{1/2} (\nu_{MHz}/150)^{-1/2} \ \mathrm{Myr}$$

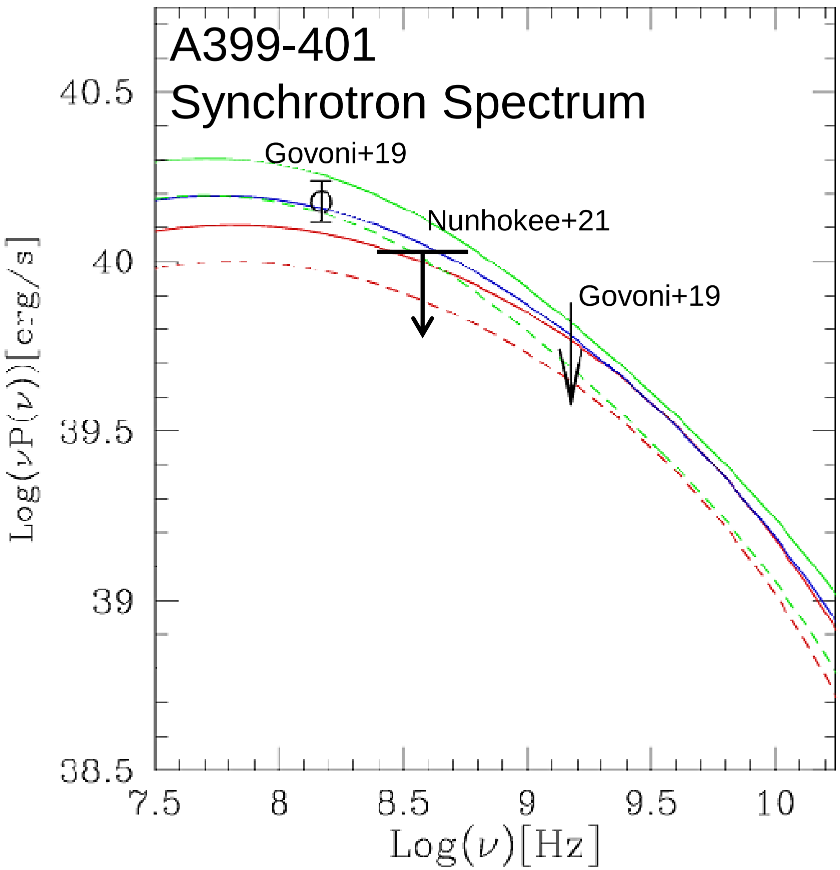
Up to 50% of the volume may produce Syn radiation at low frequencies

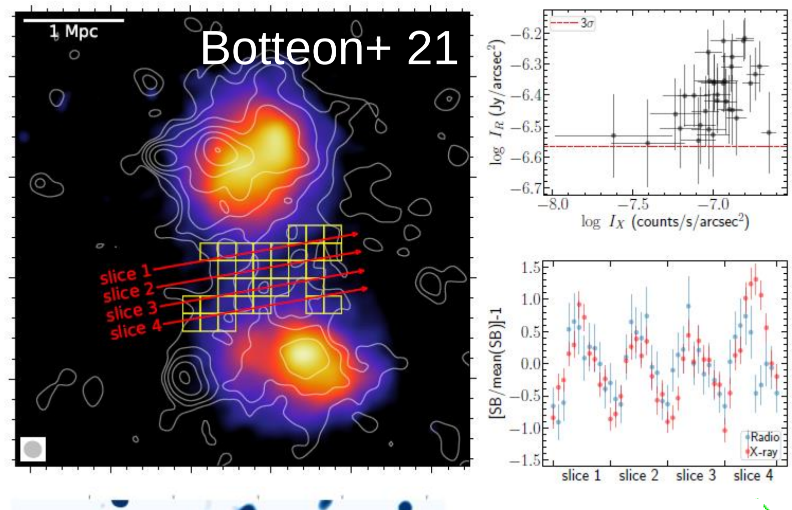
EXPECTATIONS & FIRST OBSERVATIONAL TESTS

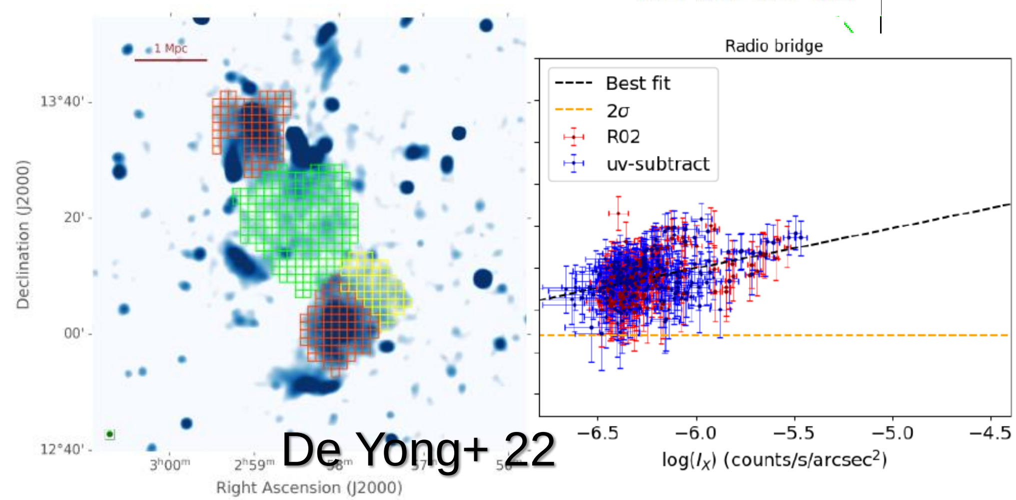
(Brunetti+Vazza 20, PRL..)

Turbo reacceleration models predict :

- Steep spectrum emission, α >1.3-1.4
- Volume filling emission (increasing at lower frequencies)

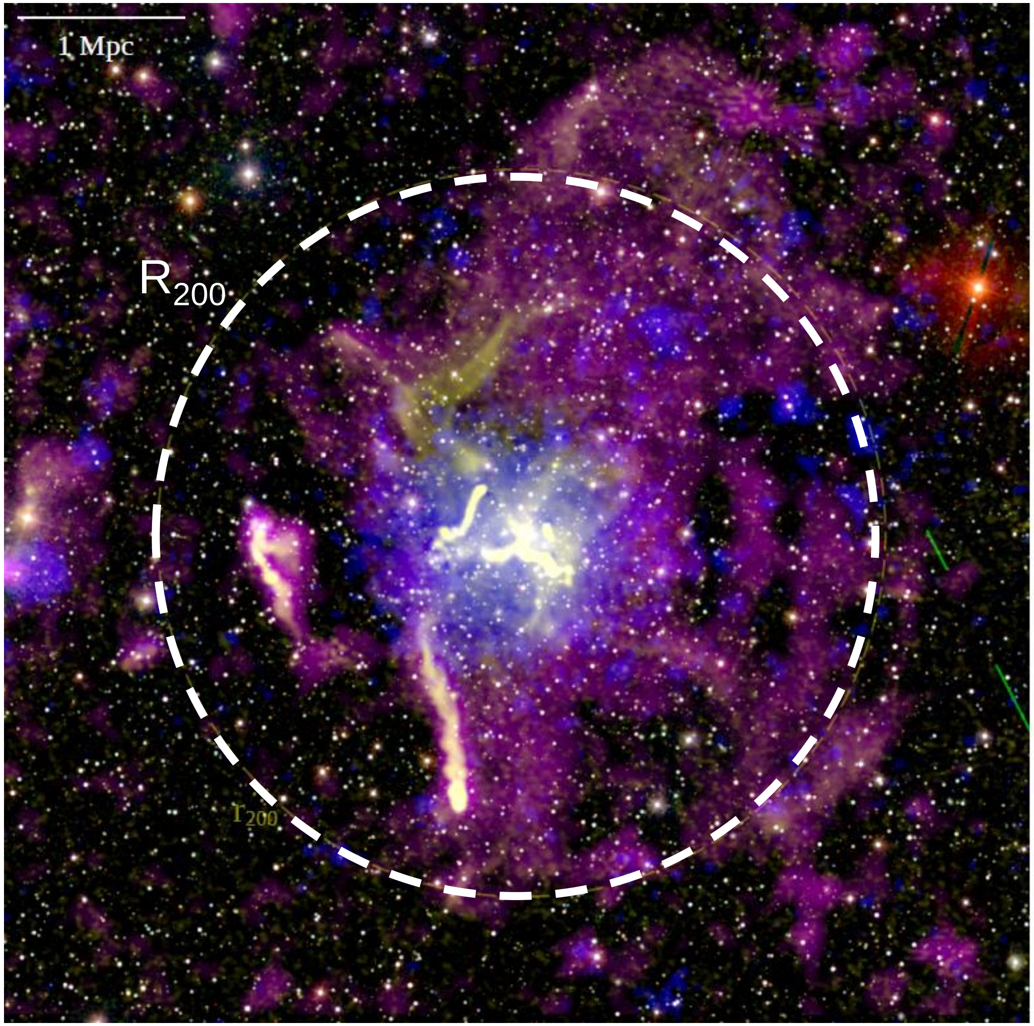






ABELL 2255

Botteon,vanW, GB, et al 23+



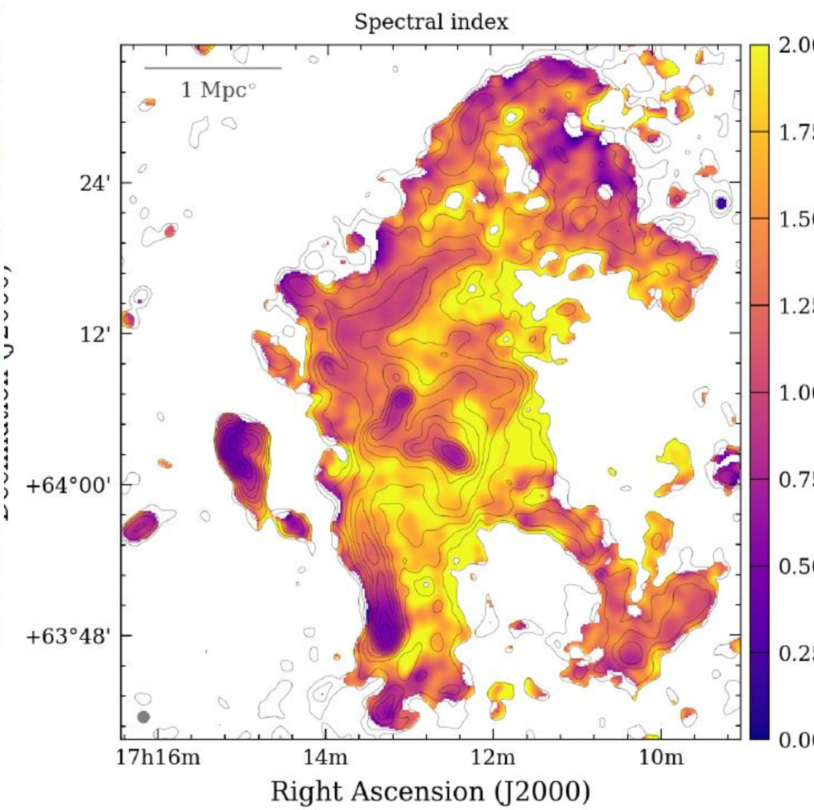
X-rays
RADIO

Emission on gigantic scale

Mix of components :

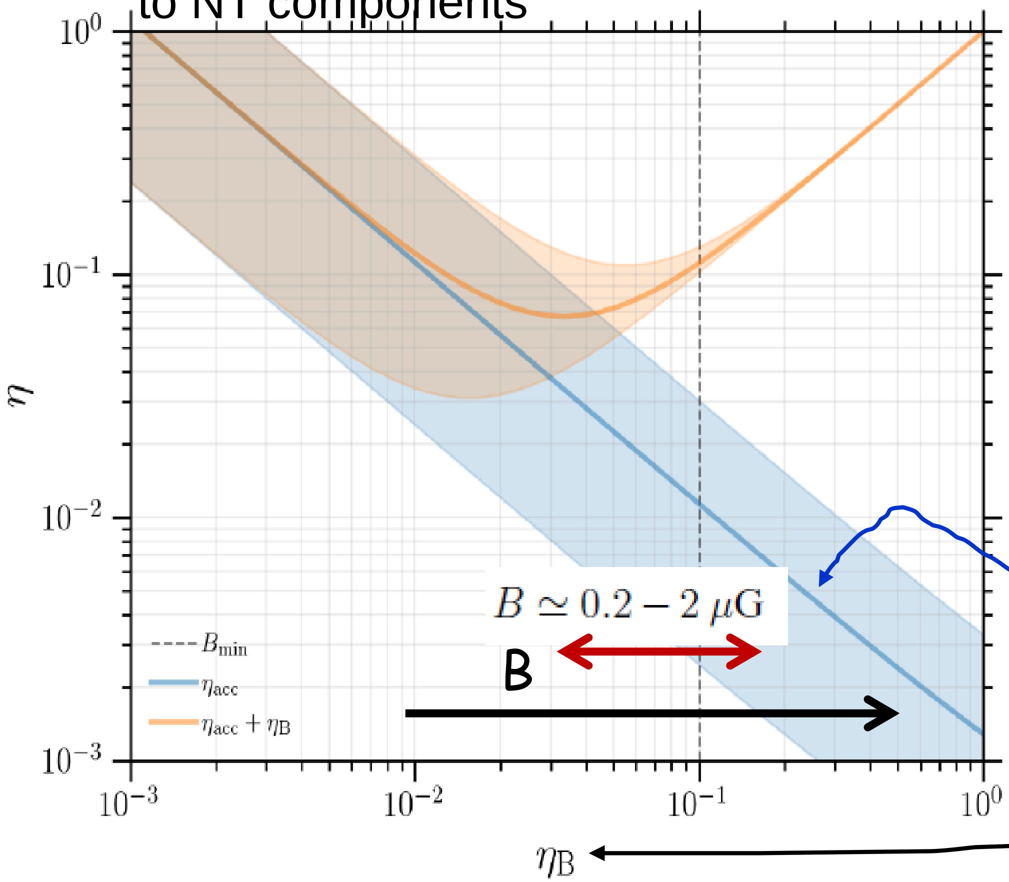
- Shock-like surfaces
- Volume filling (turb?) emission

Evidence that B is amplified (in addition to compression) and electrons are accelerated on very large scales.



First constraints on acceleration/amplification on LS

Efficiency of conversion from turbulence to NT components



Syn bolometric

SYN+ICS

$$L_{NT} = f L(\nu_{49}) \nu_{49} \left(1 + \frac{B_{cmb}^2}{B^2}\right)$$

Turbulence likely provides the source for particle (re)acceleration & B amplification

$$L_{NT} \sim \eta_{acc} F V = \frac{1}{2} \eta_{acc} \rho \frac{\delta V^3}{L} V \sim V \int dp \frac{\partial N}{\partial t} E$$

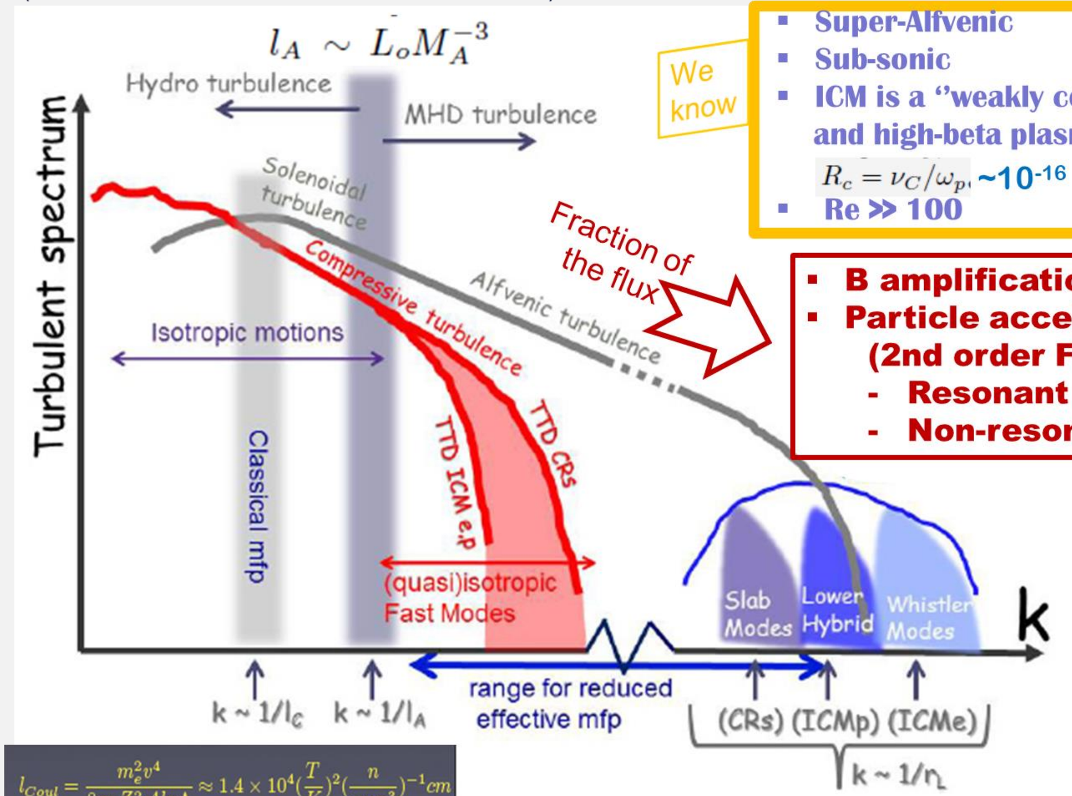
$$\frac{B^2}{8\pi} \sim \eta_B F \tau_{edd}$$

F= turb energy flux

- Non-thermal components are not negligible

ICM/LSS Turbulence : Theoretical (incomplete..) picture

(Brunetti & Lazarian 07, Brunetti & Jones 14)



- Super-Alfvenic
- Sub-sonic
- ICM is a "weakly collisional" and high-beta plasma $R_e = \nu_C/\omega_{p}$ ~10^{-16}
- Re >> 100

- **B amplification**
- **Particle acceleration (2nd order Fermi)**
  - **Resonant (..TTD)**
  - **Non-resonant**

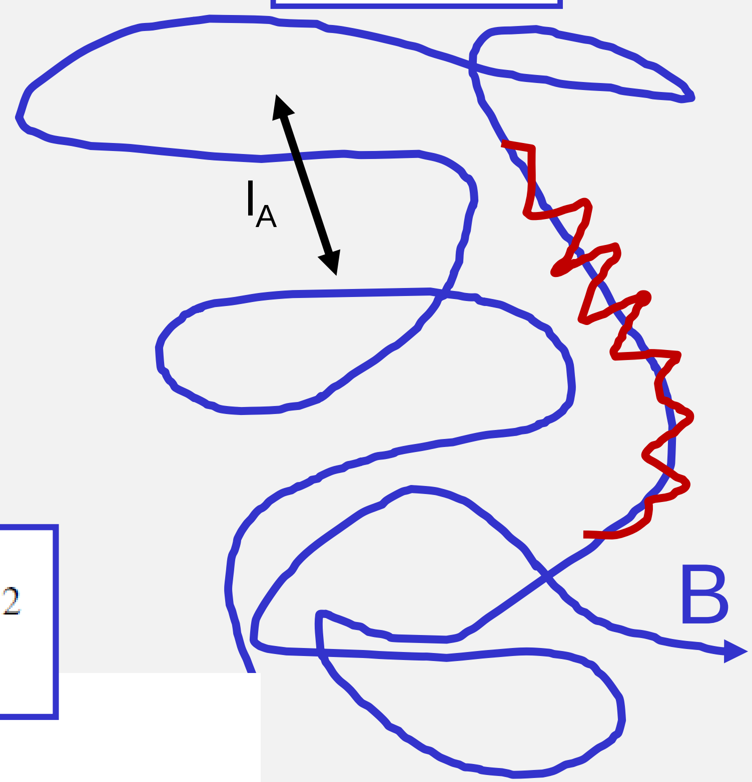
$$l_{Coul} = \frac{m_e^2 v^4}{8\pi n Z^2 e^4 ln\Lambda} \approx 1.4 \times 10^4 (\frac{T}{K})^2 (\frac{n}{cm^{-3}})^{-1} cm$$

We can approximate the diffusion as random walk of step side l_e and frequency corresponding to decorrelation of field lines :

$$D \sim \frac{1}{3} l_e^2 \tau_c^{-1}$$

where

$$\tau_c \sim \frac{L_0}{\delta V}$$

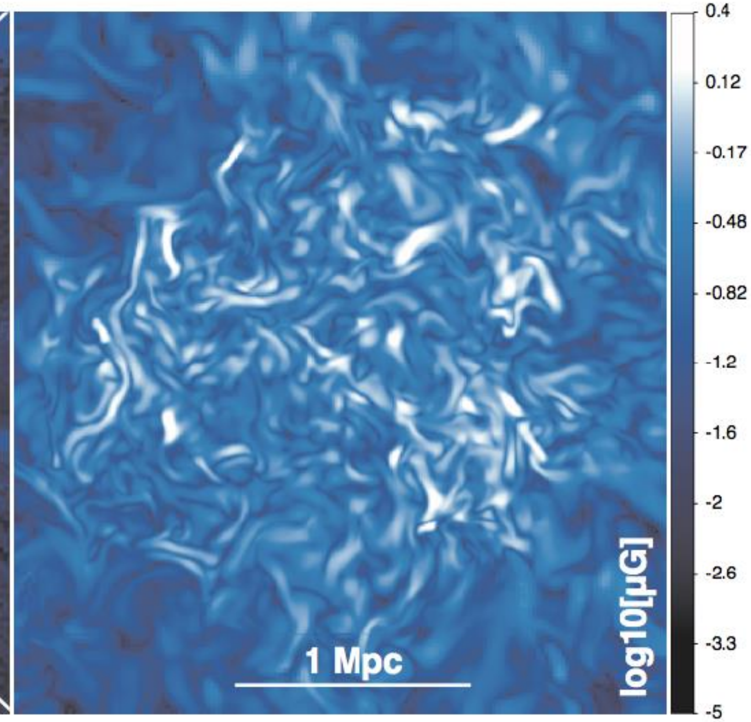


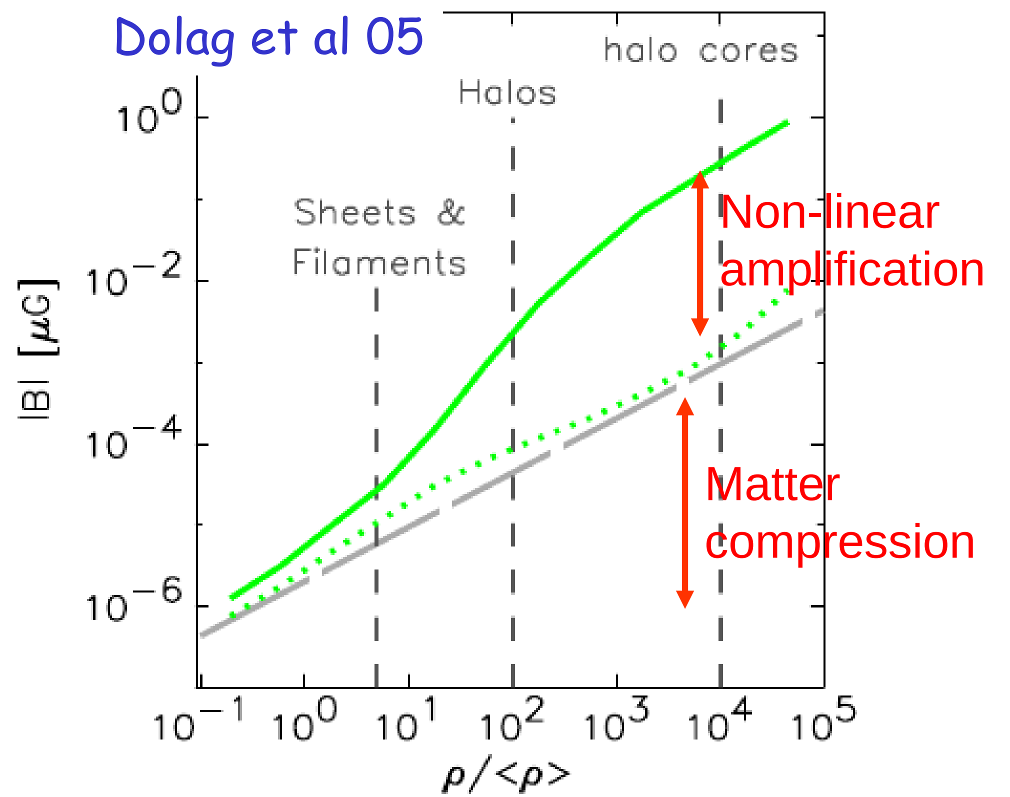
$$D \sim \frac{1}{3} l_A c \sqrt{D_{\|} \frac{V_A}{l_A c^2} \left(\frac{l_A}{L_0}\right)^{1/3}} \sim \frac{1}{3} l_A c \sqrt{D_{\|} \frac{V_A}{l_A c^2} M_A^{-1}}$$

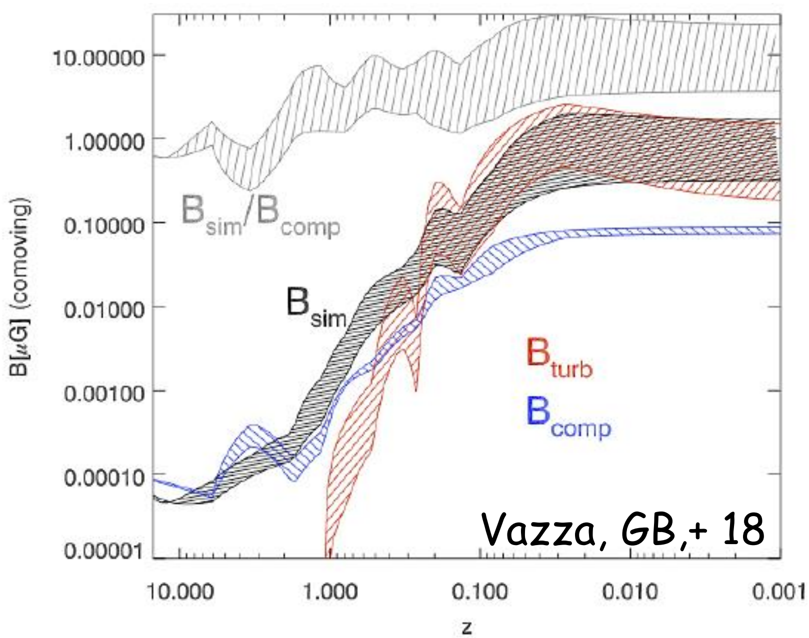
IF ('fast' diffusion)

$$\lambda_0^2 \gg l_A^2 \Leftrightarrow D_{\|} > l_A V_A \left(\frac{l_A}{L_0}\right)^{2/3} \sim l_A V_A M_A^{-2}$$

Origin of LS Magnetic Fields







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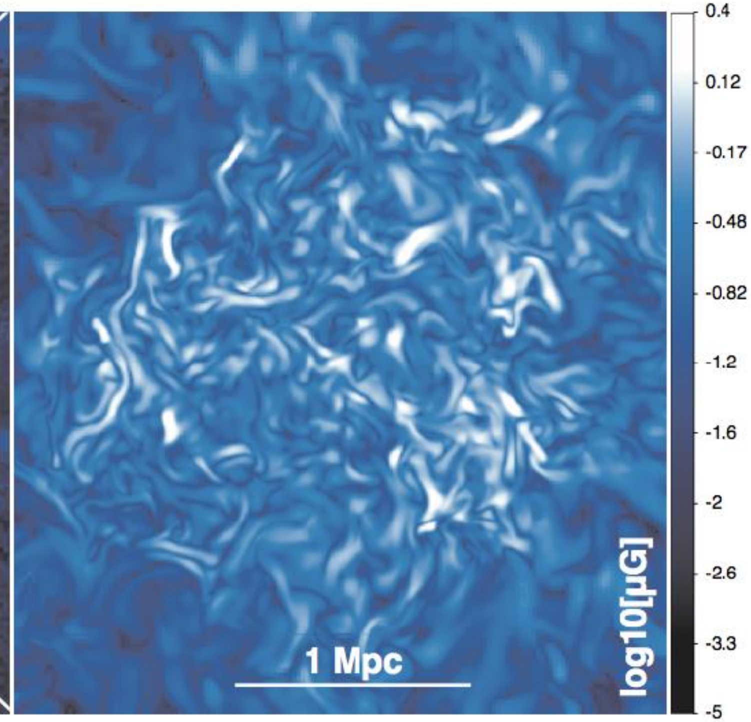
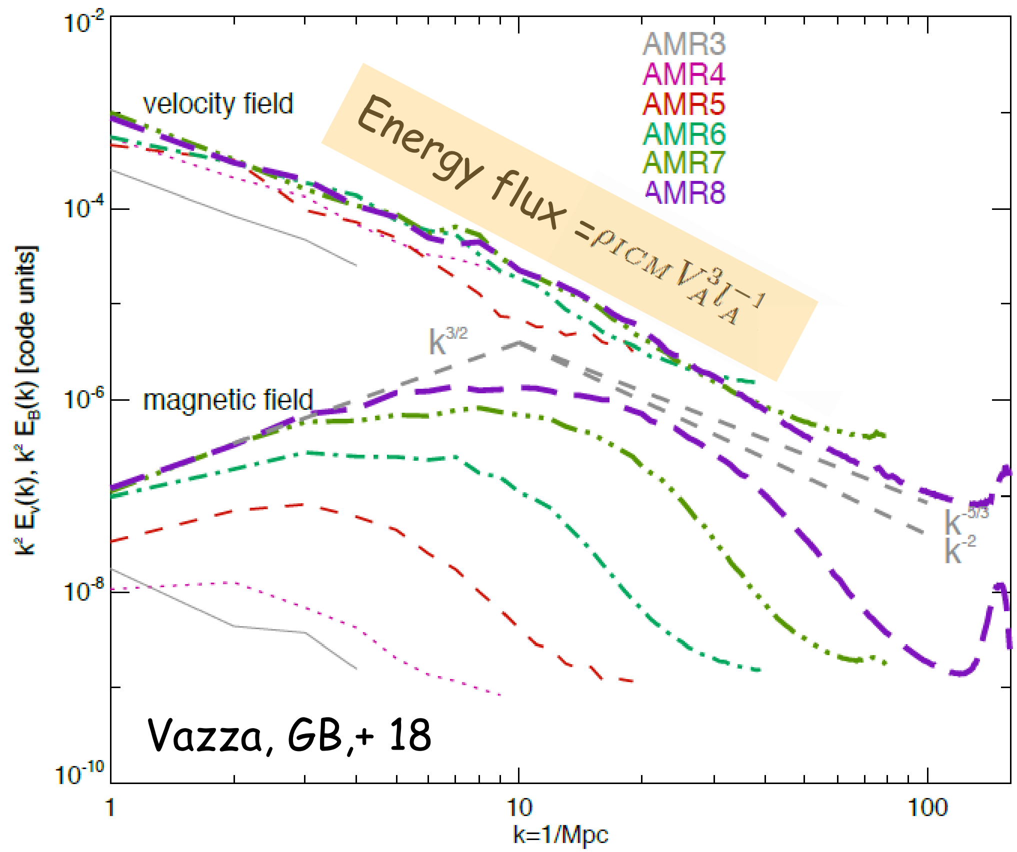
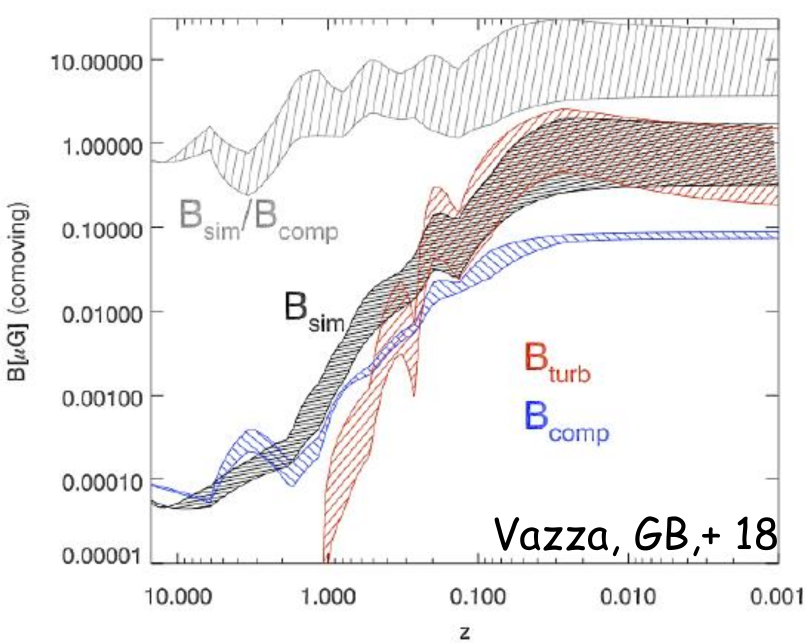
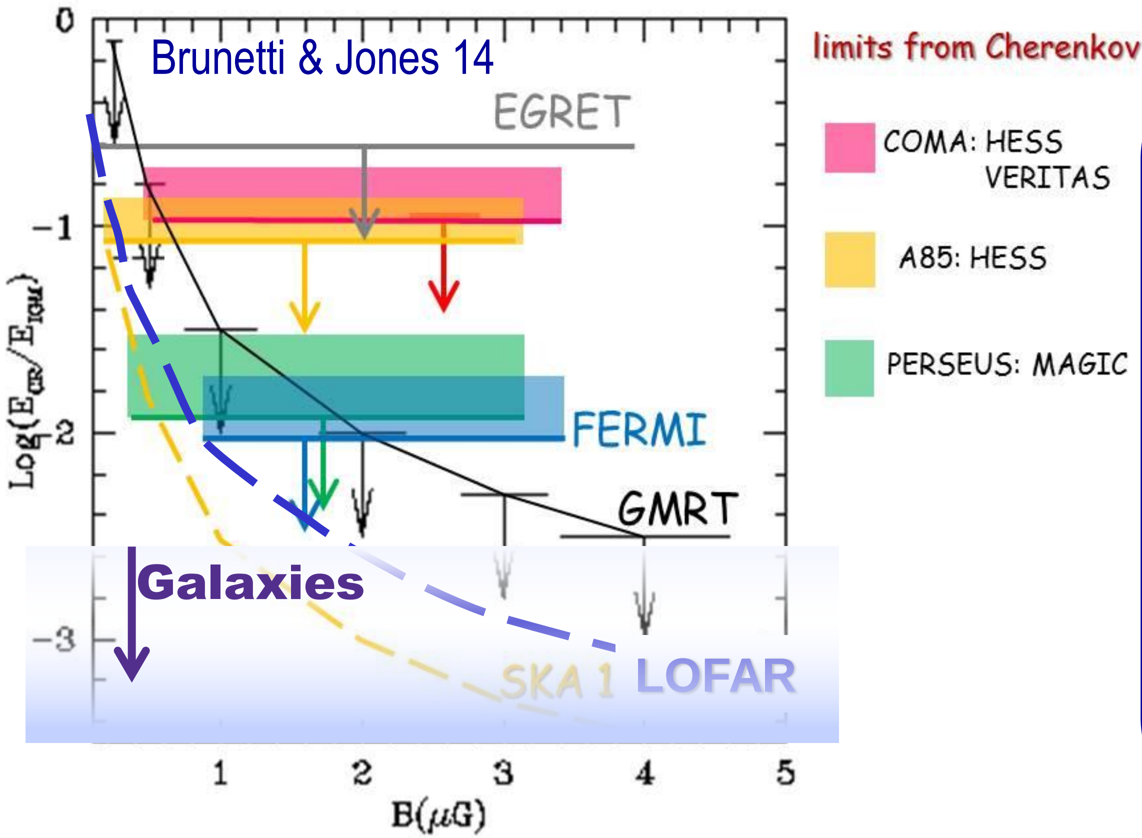






Shear flows and turbulent/kinetic dynamos amplify the magnetic field in the clusters internal regions. The amplification process increases B energy by 2+ orders of magnitude (with respect to matter compression).

Where are CRp ?



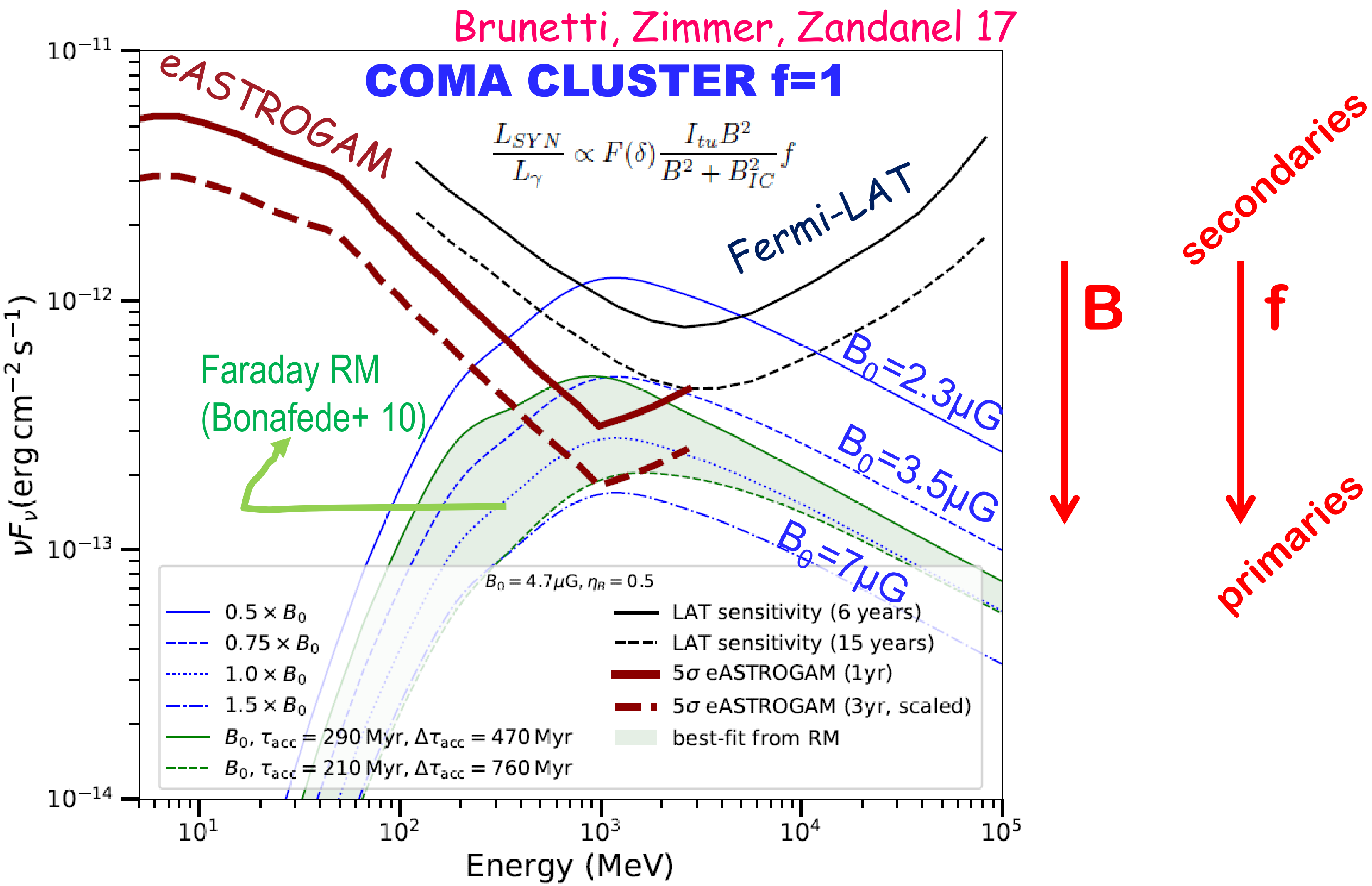
Reimer et al. 03
Reimer et al. 04
Pfrommer & Ensslin 04
Perkins et al. 06, 08
Brunetti et al. 07
Brunetti et al. 08
Aharonian et al. 08 a,b
Aleksic et al. 09,12
Ackermann et al 10,14,16
Arlen et al 12
Huber et al 13
Prokorov & Churazov 13

Gamma and radio observations independently suggest that non-thermal components are NOT dynamically important (% level) … at least in the central Mpc-scale regions

Reasons

- Acceleration efficiency ?
- Dynamics/escape of CRs ??
- CR spectrum ??

Reacceleration of CRp & secondaries

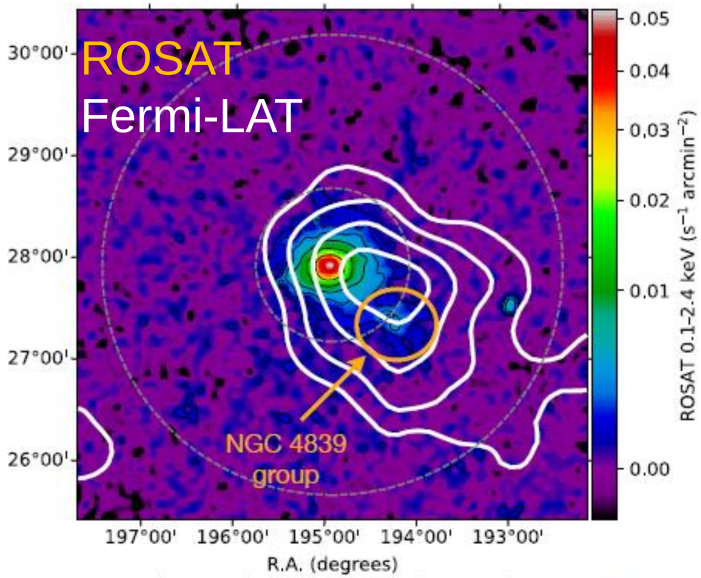


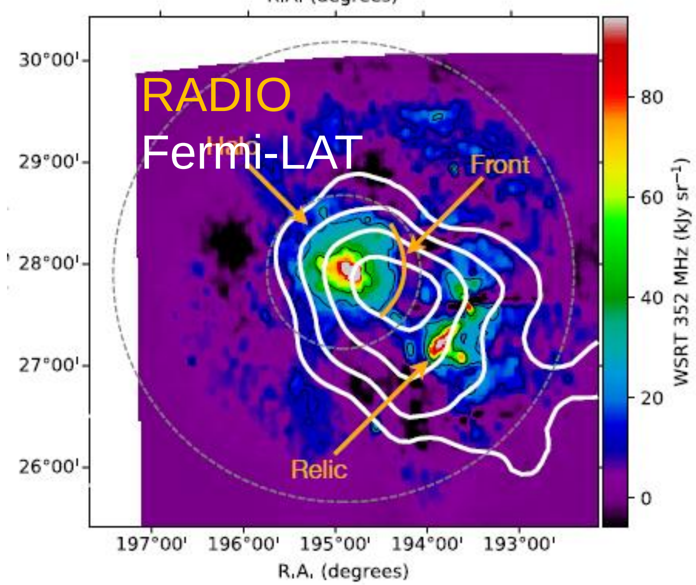
Non detection by Fermi-LAT assuming FaradayRM. Future detections in the case of weaker B or with eASTROGAM. IF f >>1 no detections !

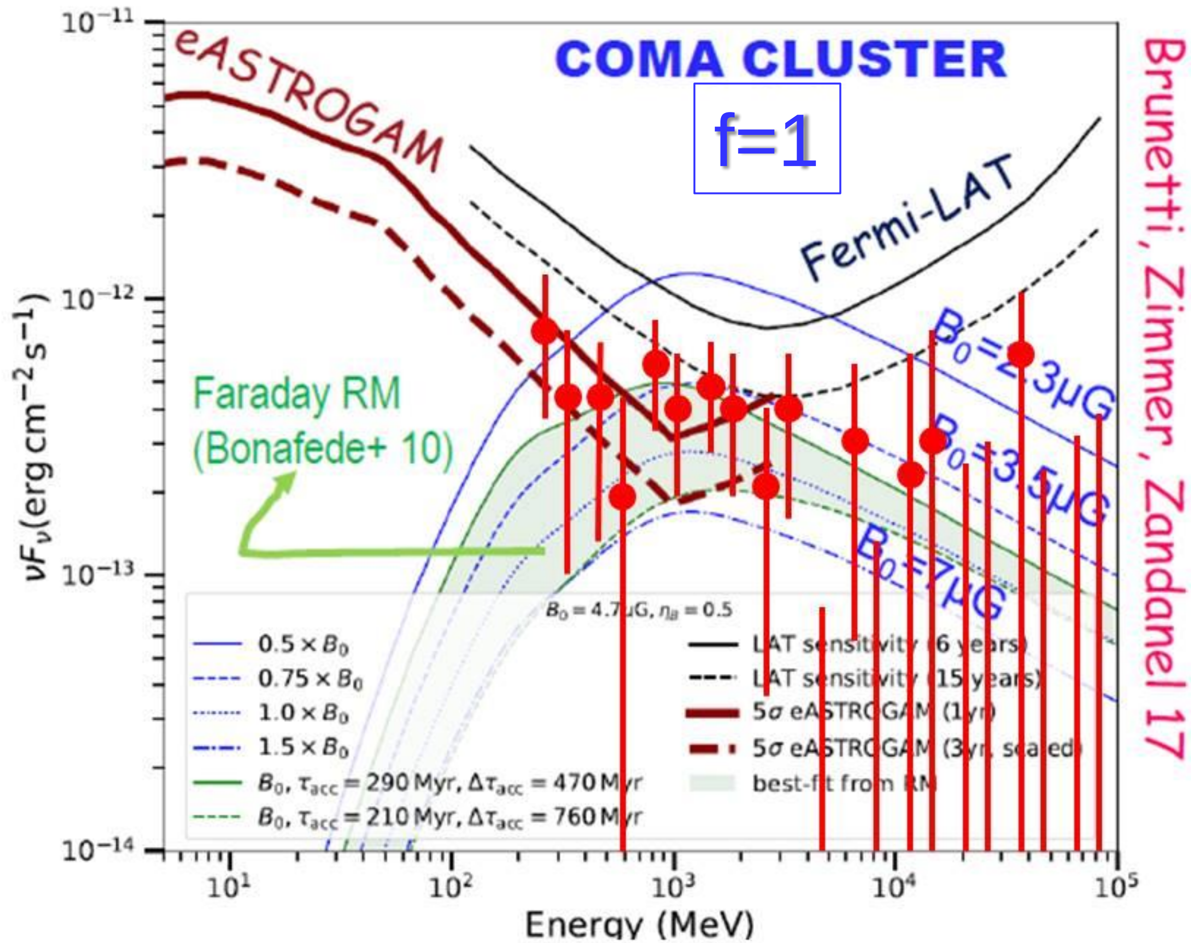
Constraints from gamma-rays

Xi+ 2018, Adam+ 21, Baghmanyan+ 22

- Detection implies an important role of CRp and their (reaccelerated) secondaries
- **Caveat** : contamination from discrete sources!







"astro-plasma" of ICM (complications!)

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

Debye sphere:

$$\lambda_D = (kT/(m_e \omega_{p,e}^2))^{1/2}$$ ~ 2-100 km

$$N_D = n_e \lambda_D^3 \sim 10^{13} T_{keV}^{3/2} n_e^{5/2}$$ ~ 10^{14} particles

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Plasma Collective effects

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"astro-plasma" of ICM (complications!)

Plasma effects & 'microphysics' (kinetic effects) are expected to affect CRs acceleration and transport !
(but also transport,.. ICM viscosity… B amplification etc)

weakly collisional

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