Turbulent Re-acceleration of Cosmic Rays as a Mechanism of Radio Mega Halo in Galaxy Clusters

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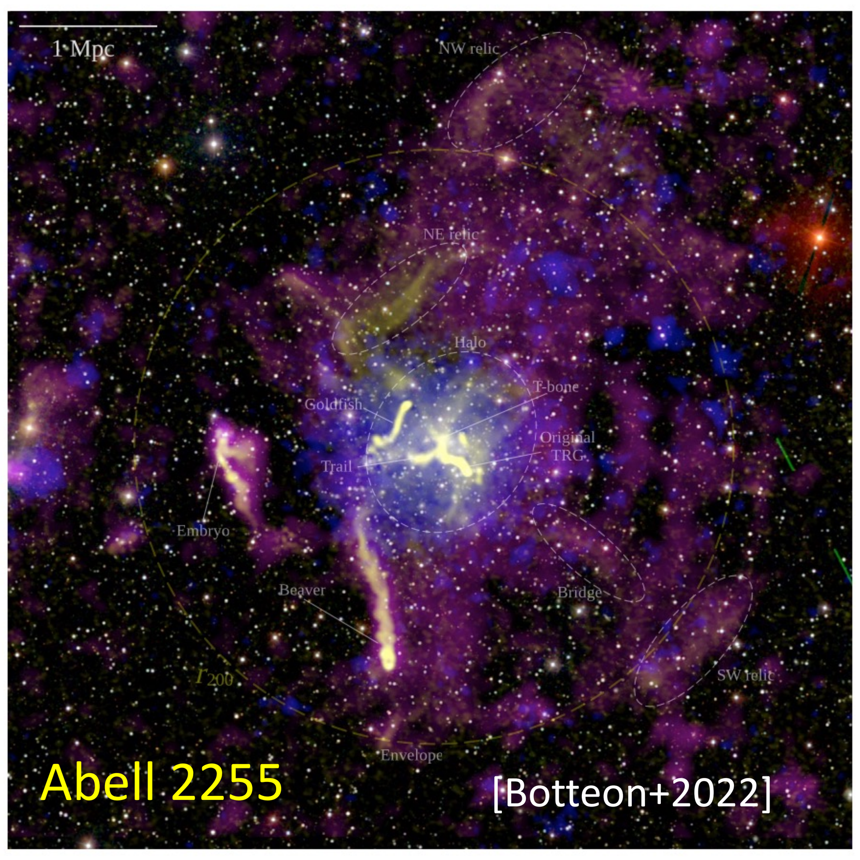
Radio "Mega" Halo

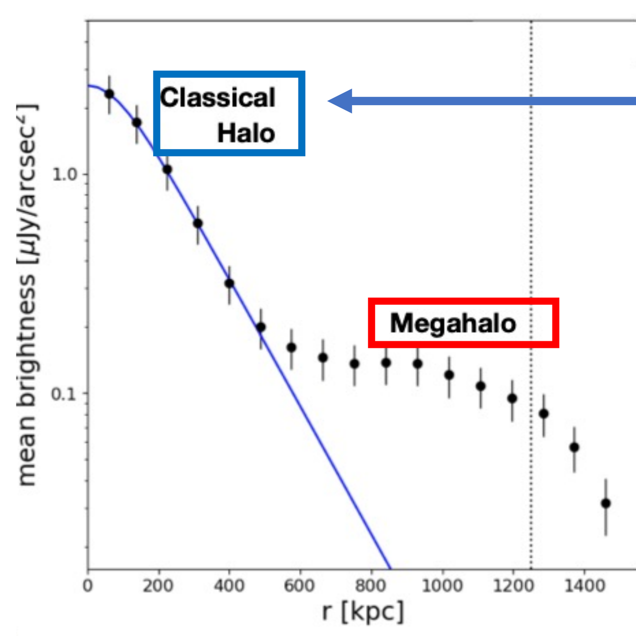
[Cuciti et al. 2022, Botteon et al.2022]

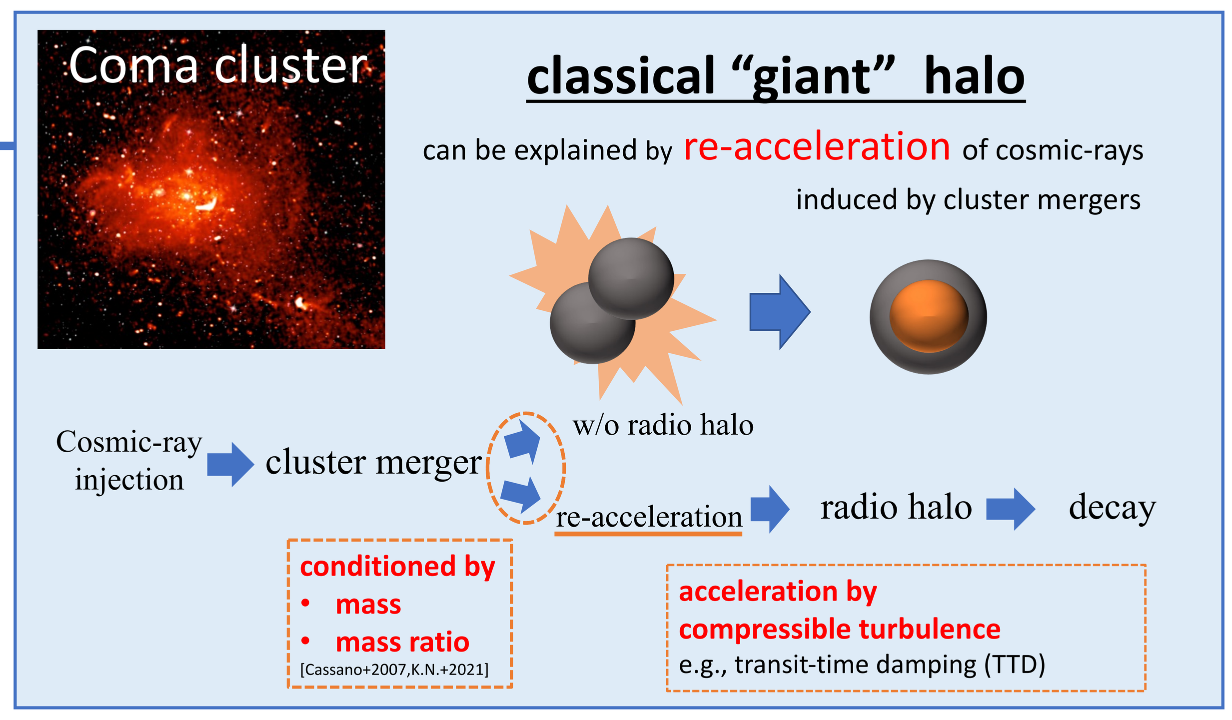
Recent **LOFAR** observation (~100 MHz) reports gigantic diffuse radio emission in galaxy clusters
(×30 lager than classical "giant" radio halo!)



- extending up to virial radius
- steep spectral index ($\alpha_{syn} \approx 1.6-1.8$)
- large filling factor
- considered to be synchrotron emission of electrons

galaxy cluster is filled with
magnetic field & relativistic electrons!





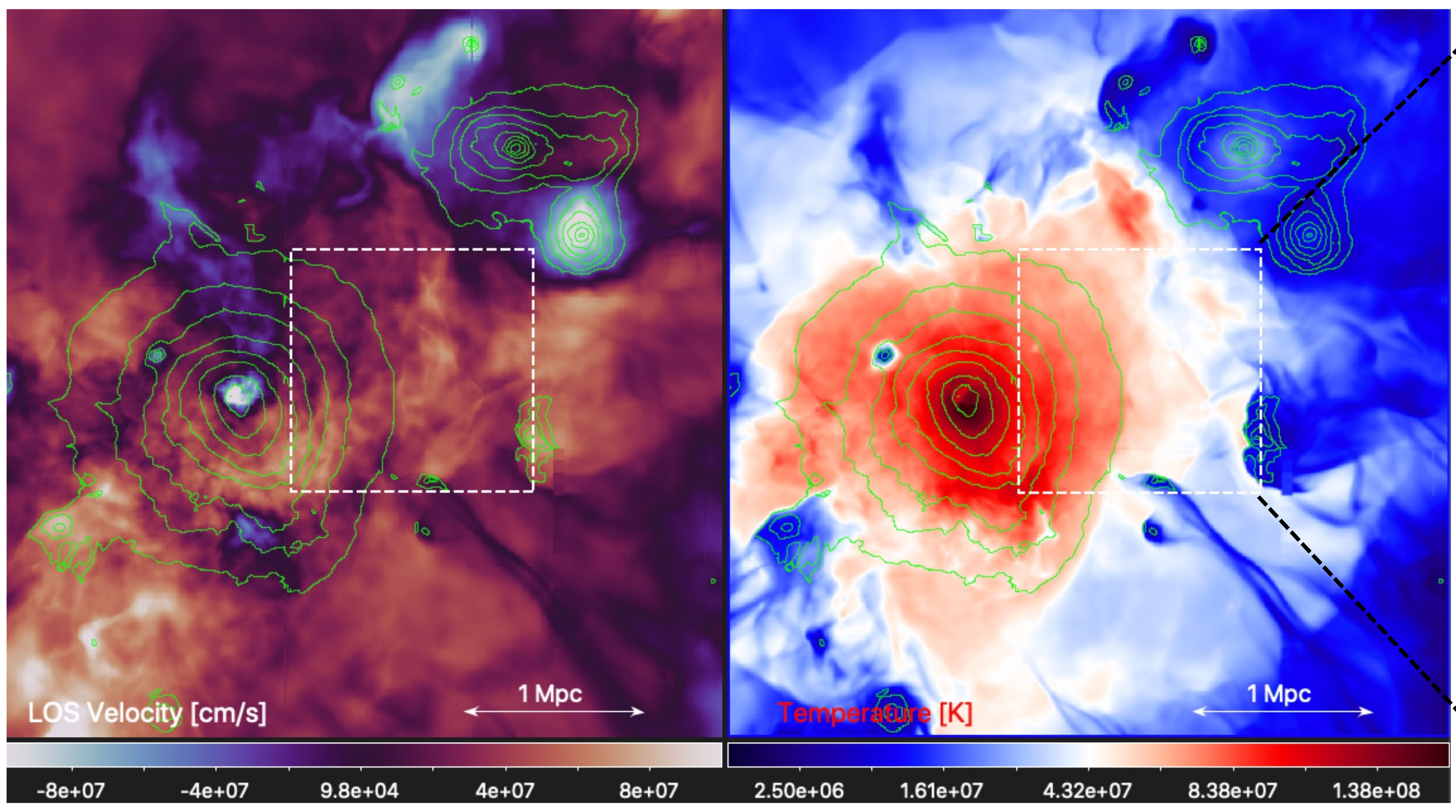
efficient mechanisms for
- amplification of the magnetic field
- particle acceleration working in the entire volume of the cluster

magnetic dynamo & Fermi II acceleration by turbulence?

Peripheral Region of the Cluster

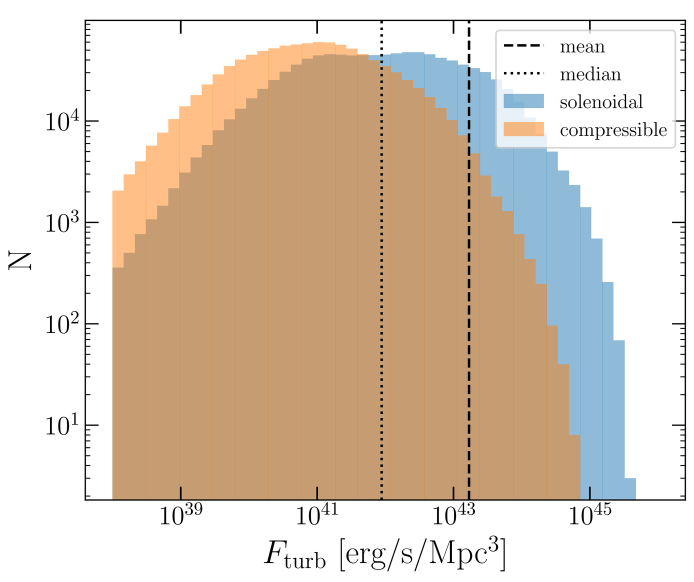
cosmological MHD simulation with *ENZO*

[Vazza+2007, 2011,2017]
- grid code
- 8 level of adaptive mesh refinement

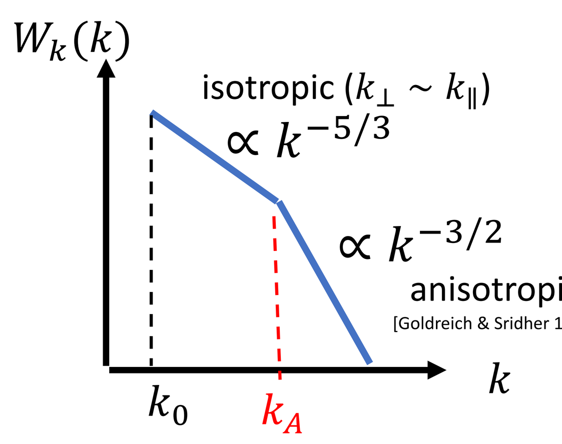


LOS projected fluid velocity — gas temperature
(green contour roughly shows the region seen with X-ray observation)

mass accretion from the large-scale structure continuously drives turbulence



the turbulence is dominated by
solenoidal ($\nabla \cdot v = 0$) mode



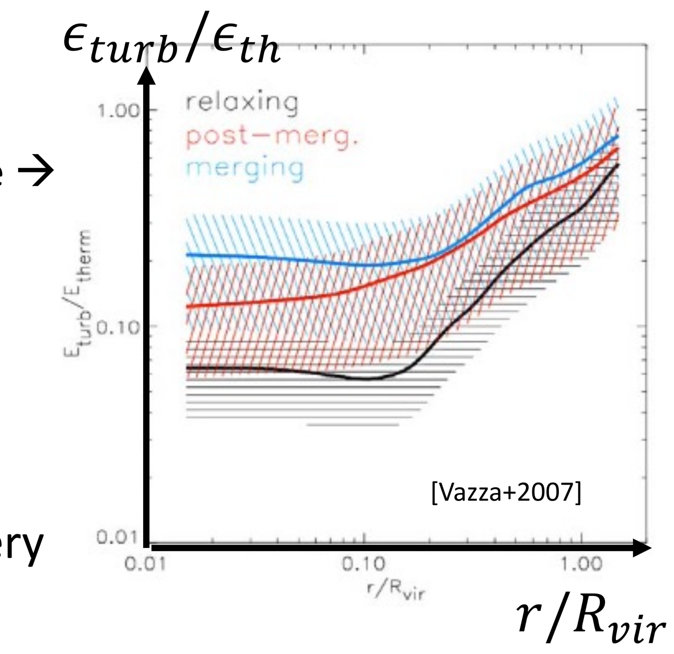
k_0: injection scale
- sub-sonic ($\delta V_0 < c_s$)
- super-Alfvenic ($\delta V_0 > v_A$)

k_A: **Alfven scale**
$\delta V_A(k_A) \sim v_A$

$\epsilon_{turb}/\epsilon_{th}$

radial profile →

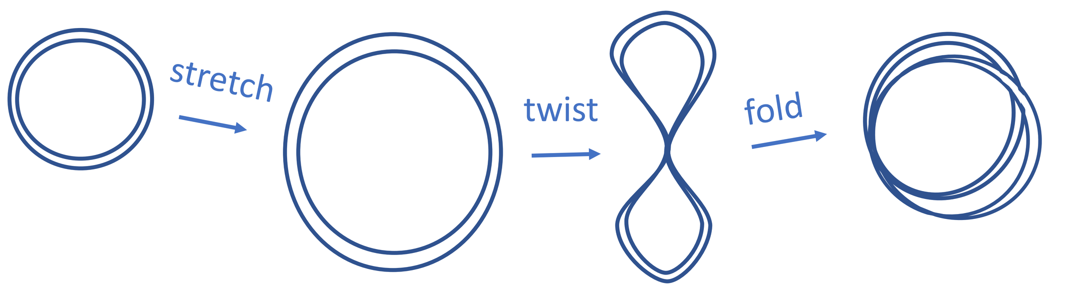
energetically important in cluster periphery



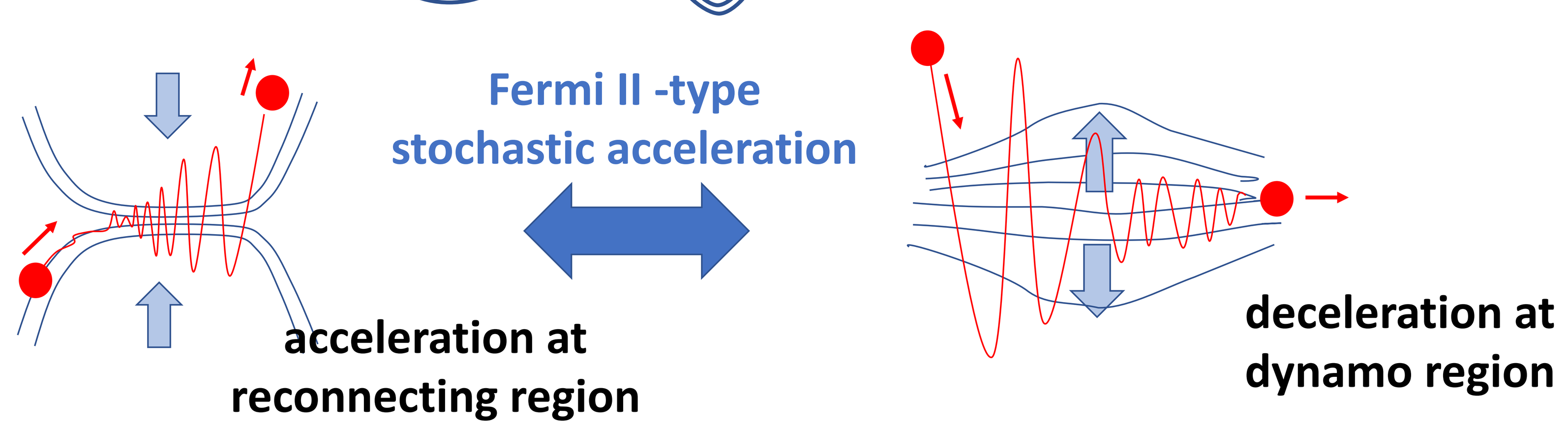
r/R_{vir}

Acceleration & Dynamo by solenoidal turbulence

turbulent reconnection & dynamo [Zeldovich+1960, Lazarian & Vishniac 1999]



working at the Alfven scale k_A



- **acceleration time** [Brunetti & Lazarian 2016]

$$t_{acc} = 3\left(\frac{l_A}{\lambda_{mfp}}\right)^2 \frac{v_A^2}{\lambda_{mfp} c} p^2 = \frac{\sqrt{6/5}}{12}\frac{c}{c_s}\frac{L_0}{\sqrt{\beta_{pl}}} M_s^{-3}\psi^3$$

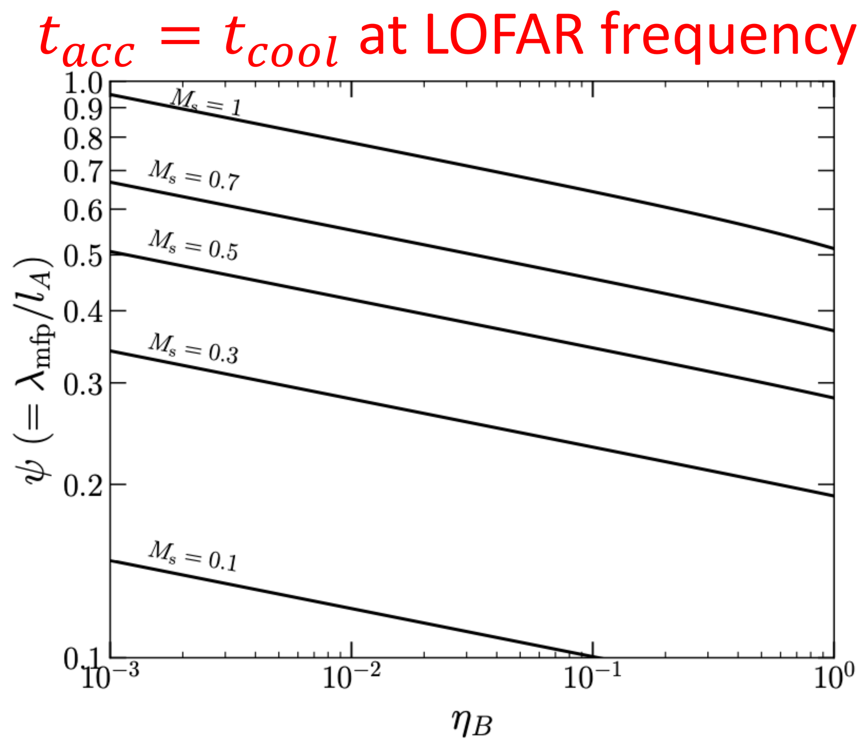
mean free path
$$\psi = \frac{\lambda_{mfp}}{l_A}$$

- **Cooling time of electrons**

$$t_{cool} = \frac{\sqrt{27\pi e m_e c}}{\sigma_T}\frac{B^{1/2}}{B^2 + B_{CMB}^2}\xi^{1/2}\nu_s^{-\frac{1}{2}}$$

model parameters: η_B & ψ

$t_{acc} = t_{cool}$ at LOFAR frequency



- **Dynamo efficiency**

$$\frac{B_{dynamo}^2}{8\pi} = \frac{1}{2}\eta_B F_{turb}^{sol} t_{eddy}$$
$$\sim 0.1\mu G\left(\frac{\eta_B}{0.05}\right)\left(\frac{F_{turb}^{sol}}{10^{44} erg/s/Mpc^3}\right)\left(\frac{t_{eddy}}{Gyr}\right)$$

Fokker-Planck calculation in 10^6 cells

for electrons

carried out on **PLEIADI** at IRA http://www.pleiadi.inaf.it

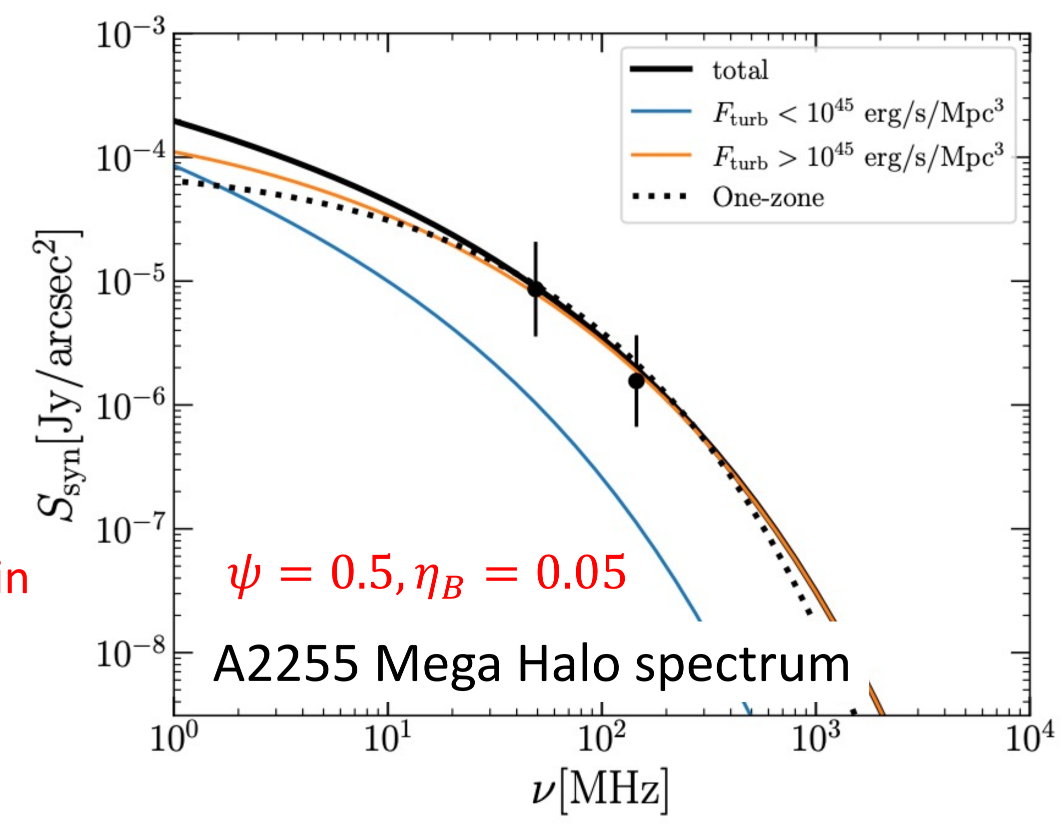
$$\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial p}[\dot{p}N_e] + \frac{\partial}{\partial p}\left[D_{pp}\frac{\partial N_e}{\partial p} - \frac{2}{p}N_e D_{pp}\right] + Q_e$$

cooling — acceleration by turbulence — injection

☆ **mean free path** of relativistic electron is comparable to the Alfven scale (~0.1 kpc)

☆ $\eta_{acc} \approx 0.1$ of the turbulent energy should be consumed for particle acceleration

☆ observed emission is produced in most turbulent regions, which fills only ~1% of the volume



Conclusions

the first theoretical model for mega halo

- mega halo: diffuse radio emission extending up to the virial radius of galaxy clusters
- there should be efficient mechanisms of magnetic field amplification and particle acceleration
- turbulence in the cluster periphery is dominated by solenoidal mode
- relativistic particle can be accelerated by Fermi II process associated with turbulent reconnection & dynamo
- we confirmed the above scenario with high-resolution MHD simulation and an expensive Fokker-Planck calculation