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Radio and Neutrino Constraints on Cosmic Ray Acceleration in Massive Galaxy Clusters

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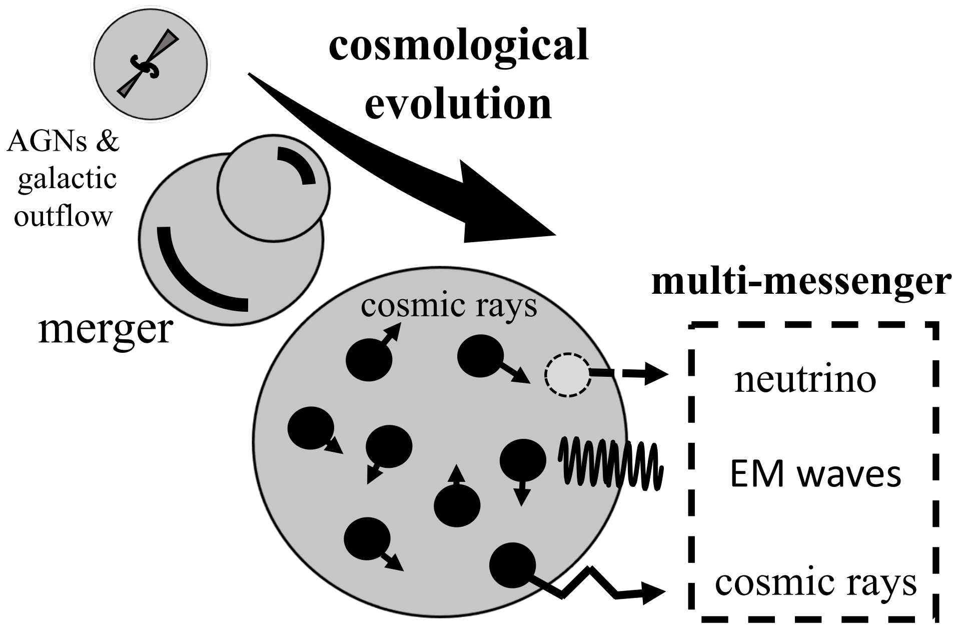
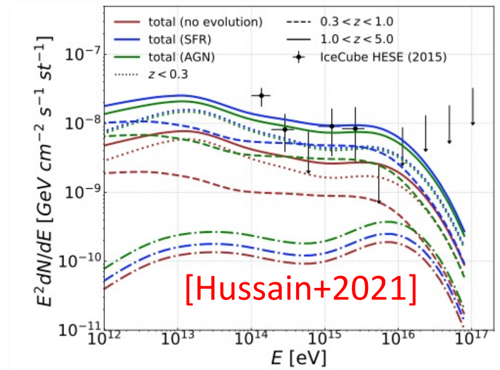
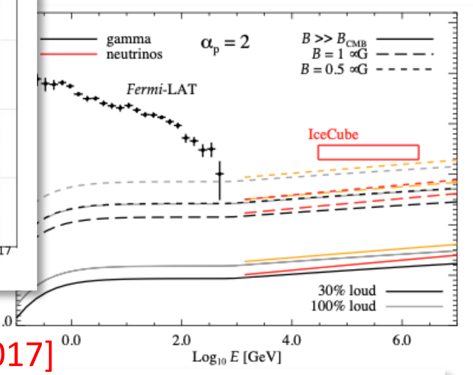
Galaxy Clusters as Cosmic ray "reservoirs"

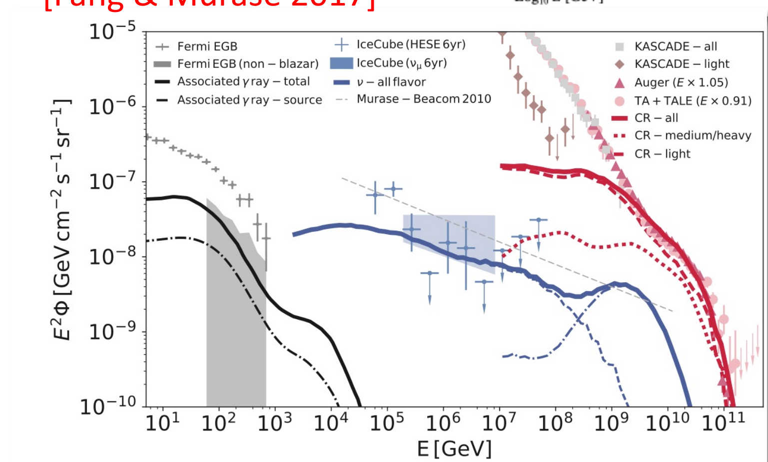




[Zandanel+2014]



[Fang & Murase 2017]



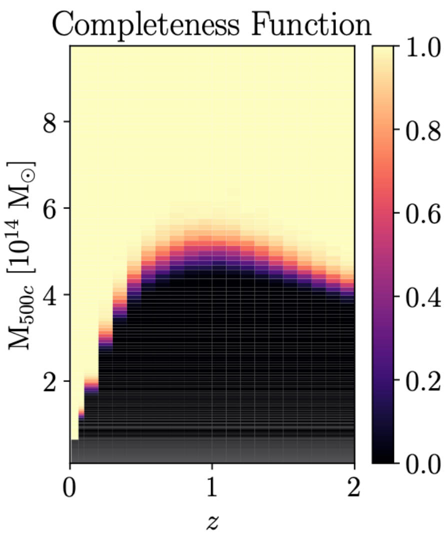
$$p + p \rightarrow \pi^0, \pi^\pm$$

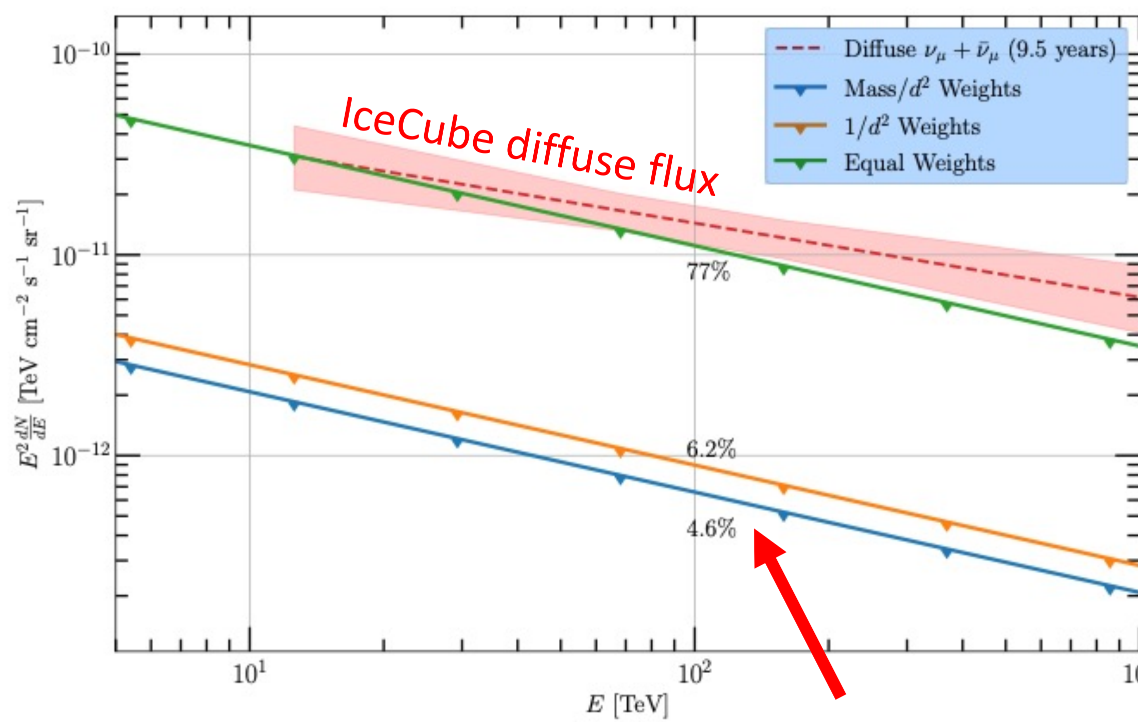
$$\pi^0 \rightarrow 2\gamma,$$
$$\pi^\pm \rightarrow \nu_\mu(\overline{\nu_\mu}) + \mu^\pm \rightarrow e^\pm + \nu_\mu(\overline{\nu_\mu}) + \nu_e(\nu_e)$$

optimistic (internal source) models explain ~100% of the diffuse neutrino background

Neutrino "Upper Limit"

[IceCube collaboration 2022]





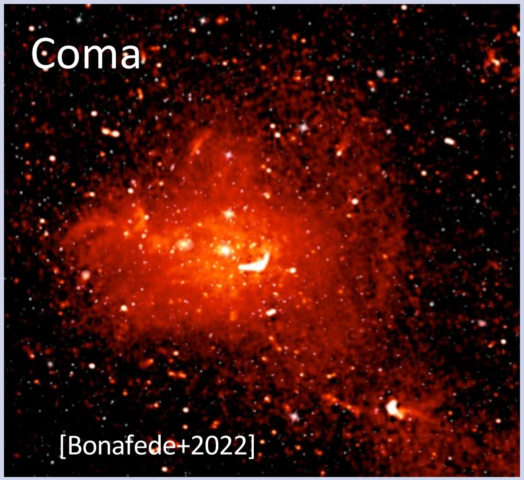
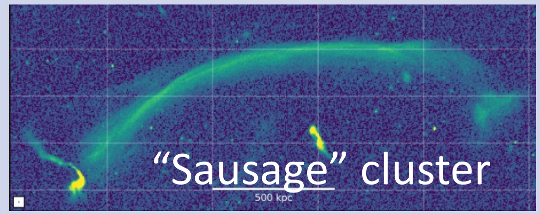
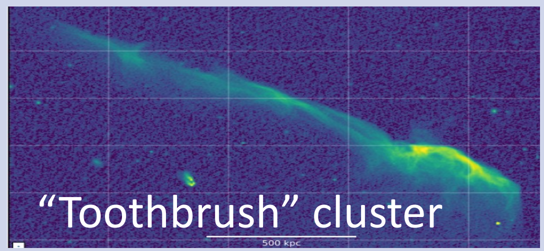
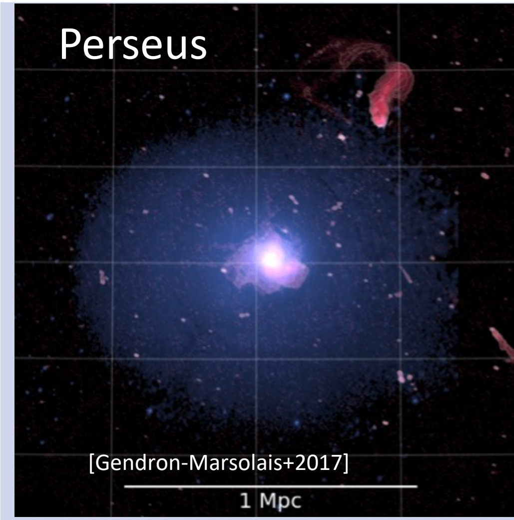
physically motivated limit

- *Planck*-SZ clusters
  &
- 9.5-yr data of muon track events

the contribution from massive ($M_{500} \gtrsim 3\times10^{14} M_\odot$) clusters is less than ~5%.

a very deep limit, **excludes some of the theoretical models**

Diffuse Radio Emission in Clusters

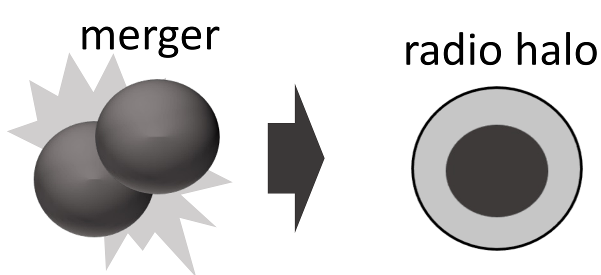
Giant Radio Halo	Radio Relic	Mini Halo
	 	
Spherical	elongated	Spherical
~ 1Mpc	~ 1Mpc	~ 300 kpc
Merging clusters	Merging clusters	Relaxed clusters

Correlate with dynamical state of clusters

mergers ・ mass accretion ⟷ **particle acceleration & magnetic field amplification**

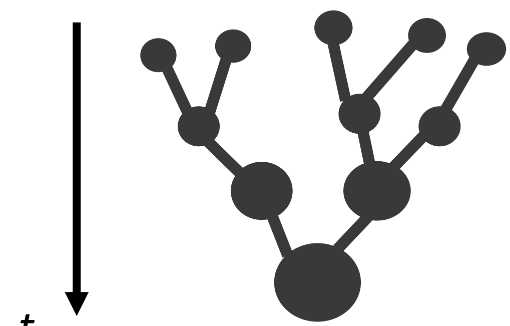
Overview

re-acceleration model



- merger-induced turbulence
- Fermi-II acceleration
- Fokker-Planck eq.

Merger tree



- number of mergers, mass ratio
- mass function

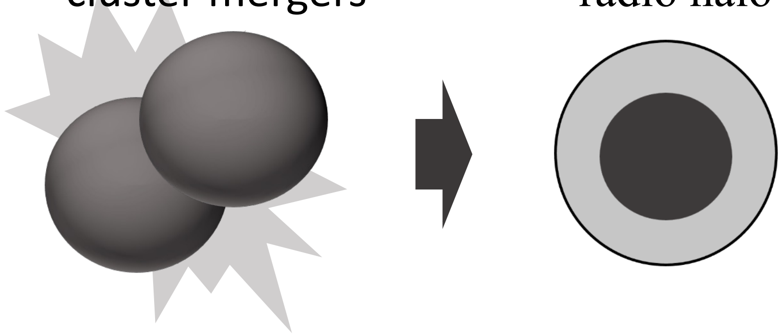
radio observations

diffuse neutrino background

IceCube upper limit

constraints on the re-acceleration model

Turbulent Re-acceleration Model



relativistic seed electrons
revived through the **Fermi-II acceleration**

[e.g., Brunetti+, Fujita+]

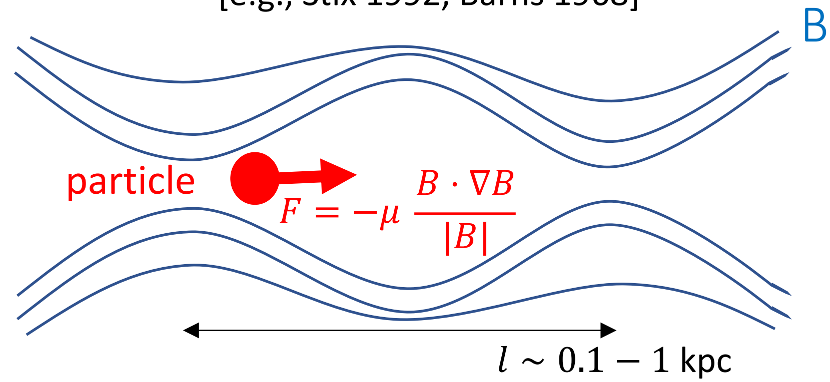
◆ Need of seed

- **primary electrons** : from AGNs shocks,...
- **secondary electrons** : from pp collision

both models are consistent with radio and gamma-ray observations [KN+21,KN+22]

Transit-time damping (TTD)

[e.g., Stix 1992, Barns 1968]



- acceleration timescale

$$t_{acc} \approx 200\ \mathrm{Myr} \left(\frac{M_s}{0.5}\right)^{-4} \left(\frac{L}{300\ \mathrm{kpc}}\right) \left(\frac{c_s}{1500\ \mathrm{kms}^{-1}}\right)$$

can explain various features of radio halos
[e.g., Brunetti & Jones 2014]

if, driven by major mergers

$$D_{pp} \propto M^{1/3}$$

acceleration efficiency scales with mass

Radio halo: Coma cluster

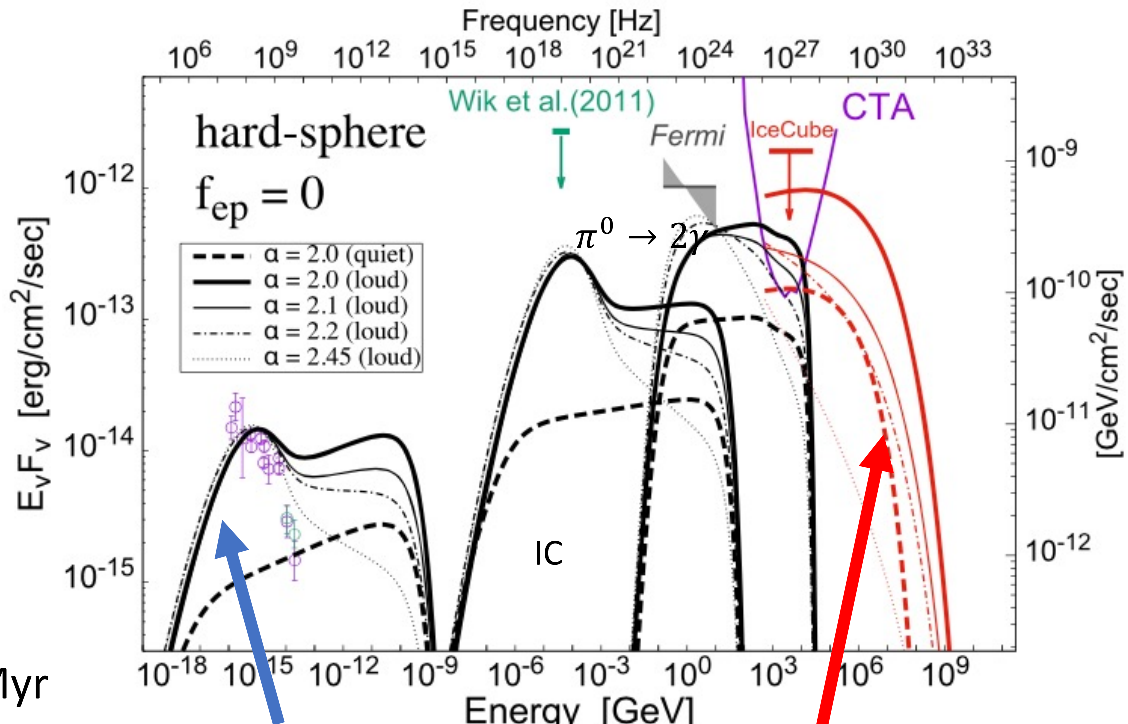
model normalized by the radio observation of Coma

- **Fokker-Planck eq. (CRe and CRp)**

$$\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial p}\left[\left(\dot{p} - \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\right)\right)N_e\right] + \frac{\partial^2}{\partial p^2}\left[D_{pp}N_e\right] + Q_e + (\text{diffusion})$$

cooling — re-acceleration — injection

seed: secondaries from *pp* collision
acceleration timescale: $t_{acc} \approx 300$ Myr
magnetic field: $B_0 = 4.7\ \mu\mathrm{G}$ [Bonafede+2010]



Synchrotron within $r < 0.5$ Mpc

[KN+21]

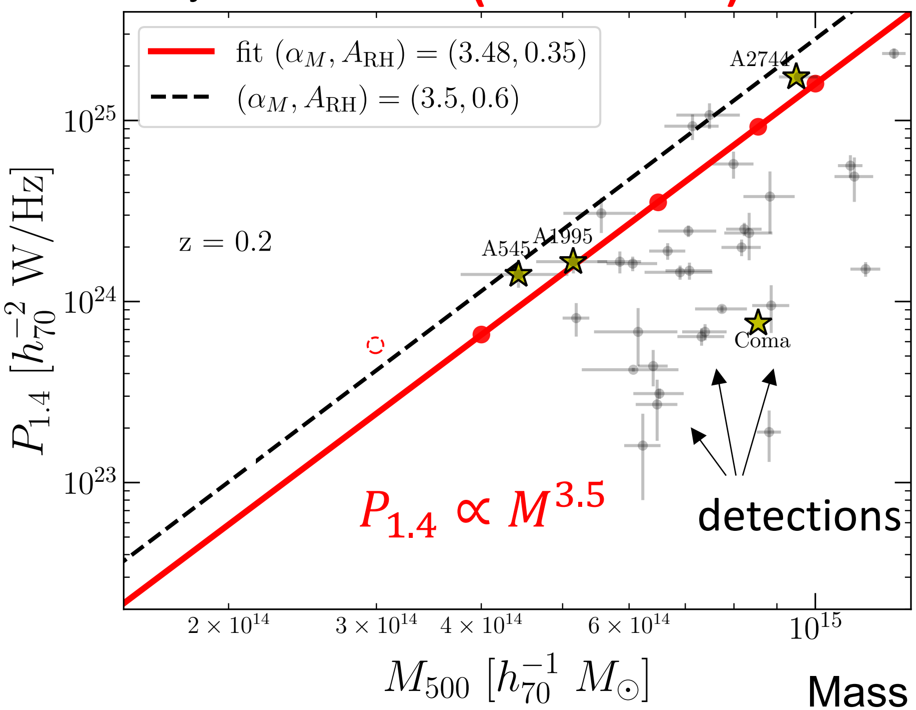
Neutrino within $r < 2.3$ Mpc

◆ gamma-ray upper limit (*Fermi*)
→ pure hadronic model without re-acceleration is excluded.
But, the re-acceleration of secondary *e* is possible.

Luminosity-Mass relation

luminosity

Radio (1.4 GHz)



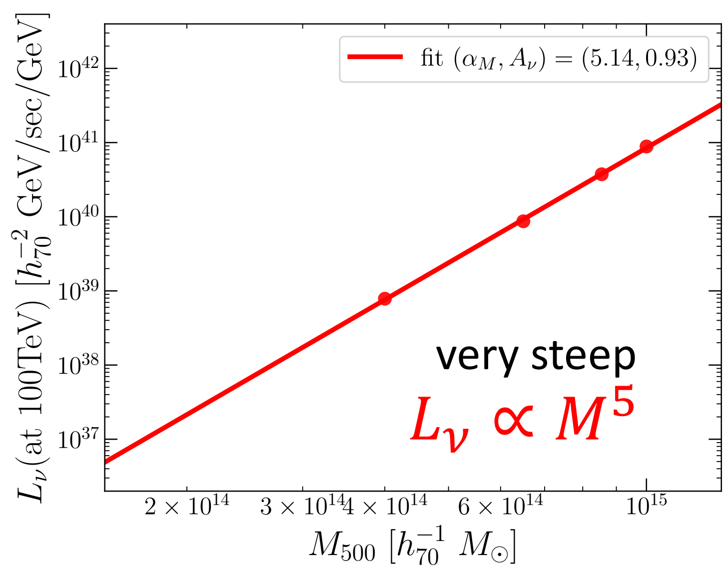
Mass

merger + TTD acceleration
for various M

$D_{pp} \propto M^{1/3}$

- magnetic field: $B \propto M^0$
- seed injection: $L_{CR}^{inj} \propto M^{5/3}$
- Fokker-Planck eq. (CRe and CRp)

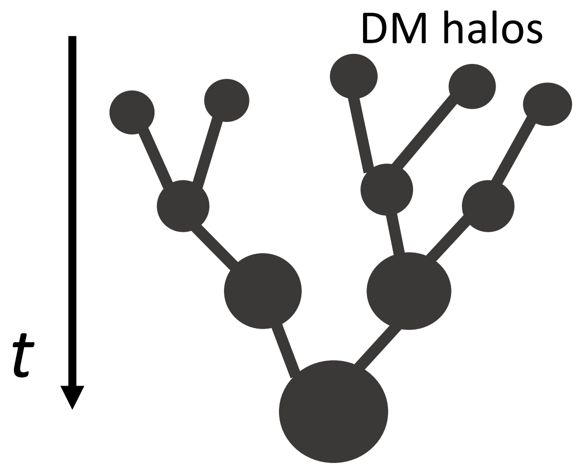
Neutrino (100 TeV)



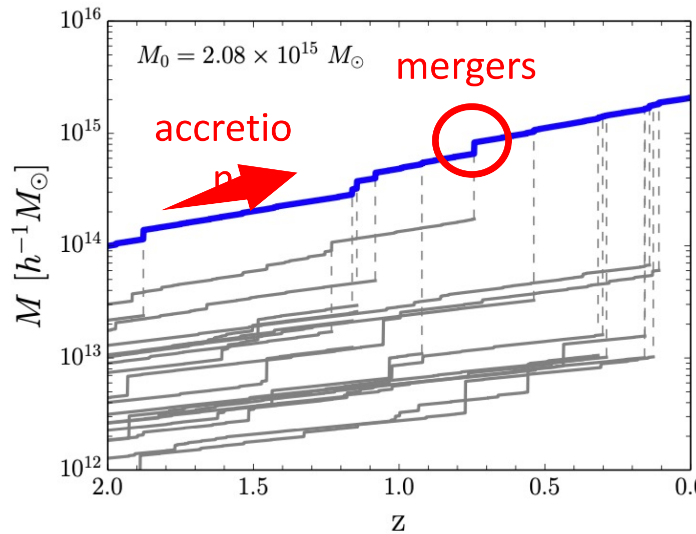
TTD model is consistent with the radio observation

observed radio halos are massive
$M_{500} > 3{\times}10^{14} M_\odot$

Monte Carlo Merger Tree

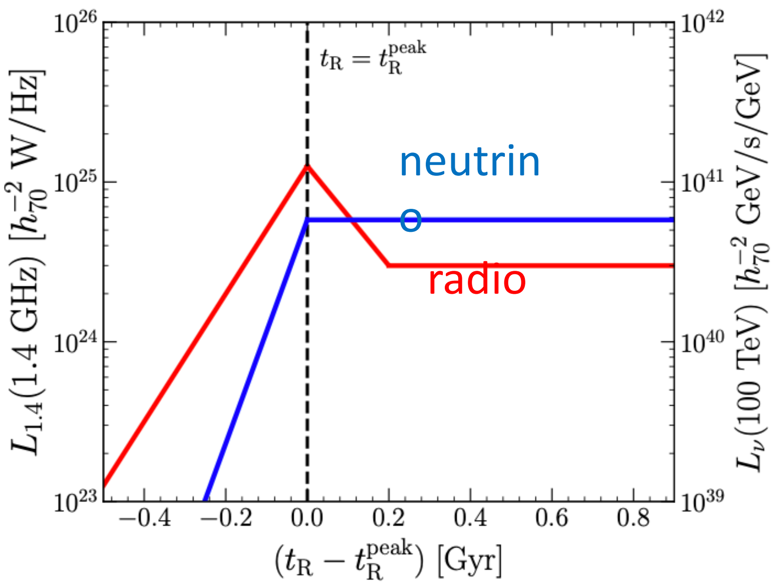


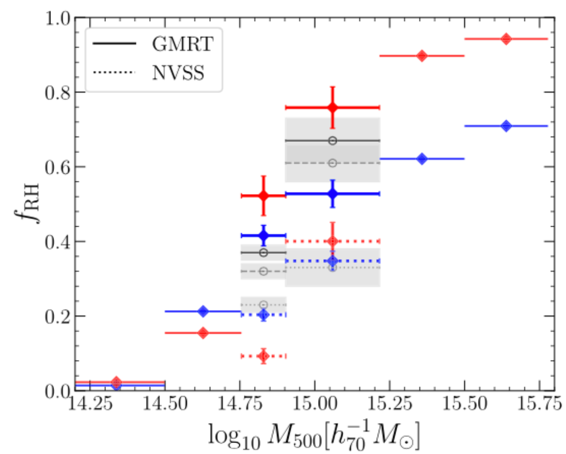
evolution of the mass



[KN+22]

- luminosity evolution after merger (re-acc. model)

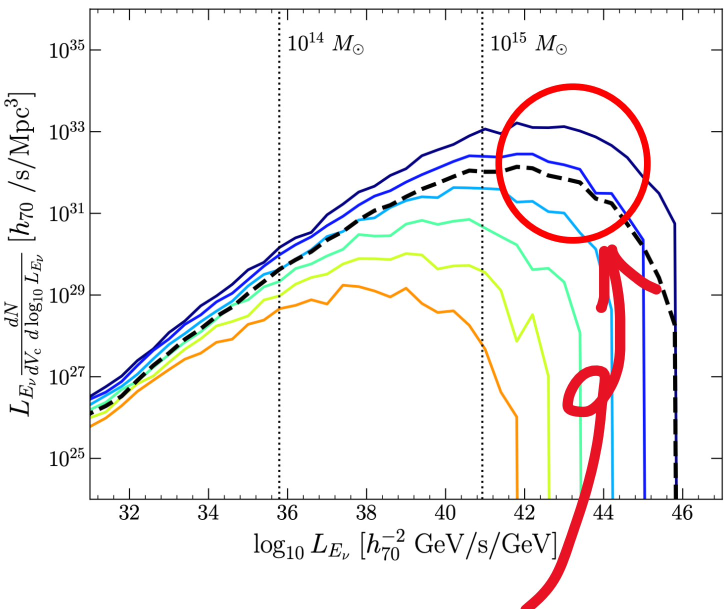




occurrence of RHs (~30-60%) can be explained with our model

Diffuse Neutrino Background

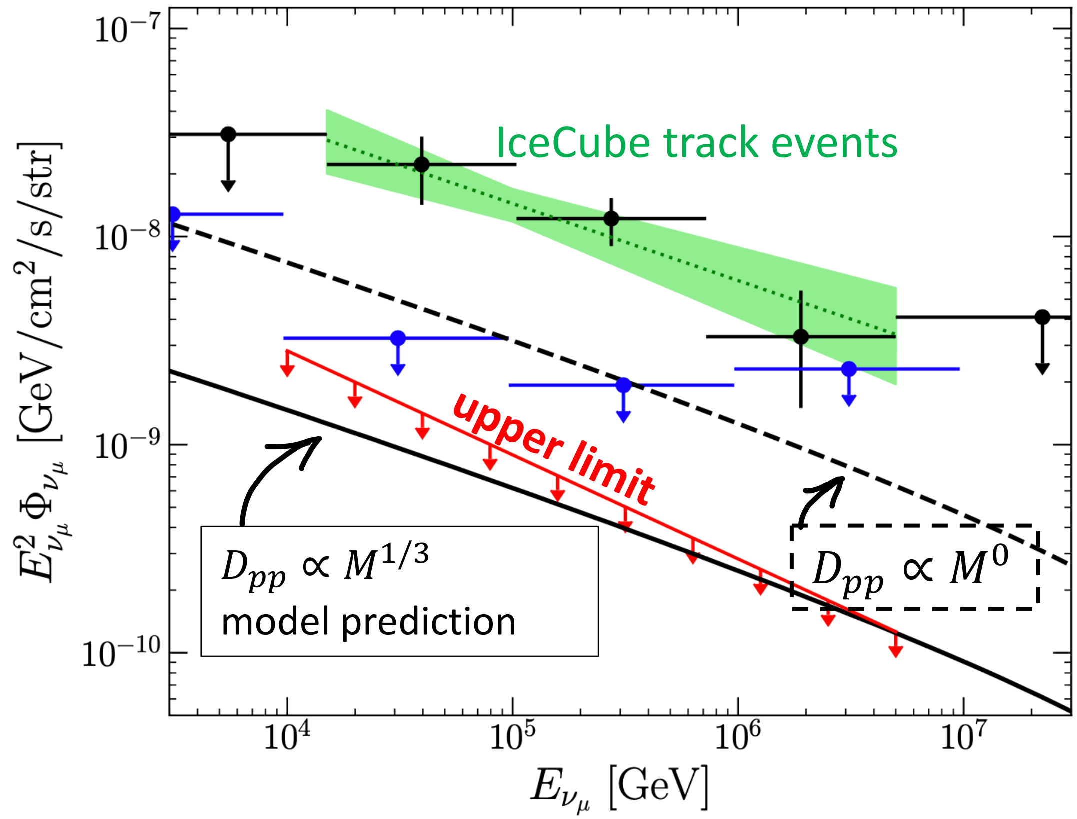
neutrino luminosity function
weighted by L_ν



dominated by
luminous & massive
$M_{500} \approx 2\times10^{15} M_\odot$ clusters

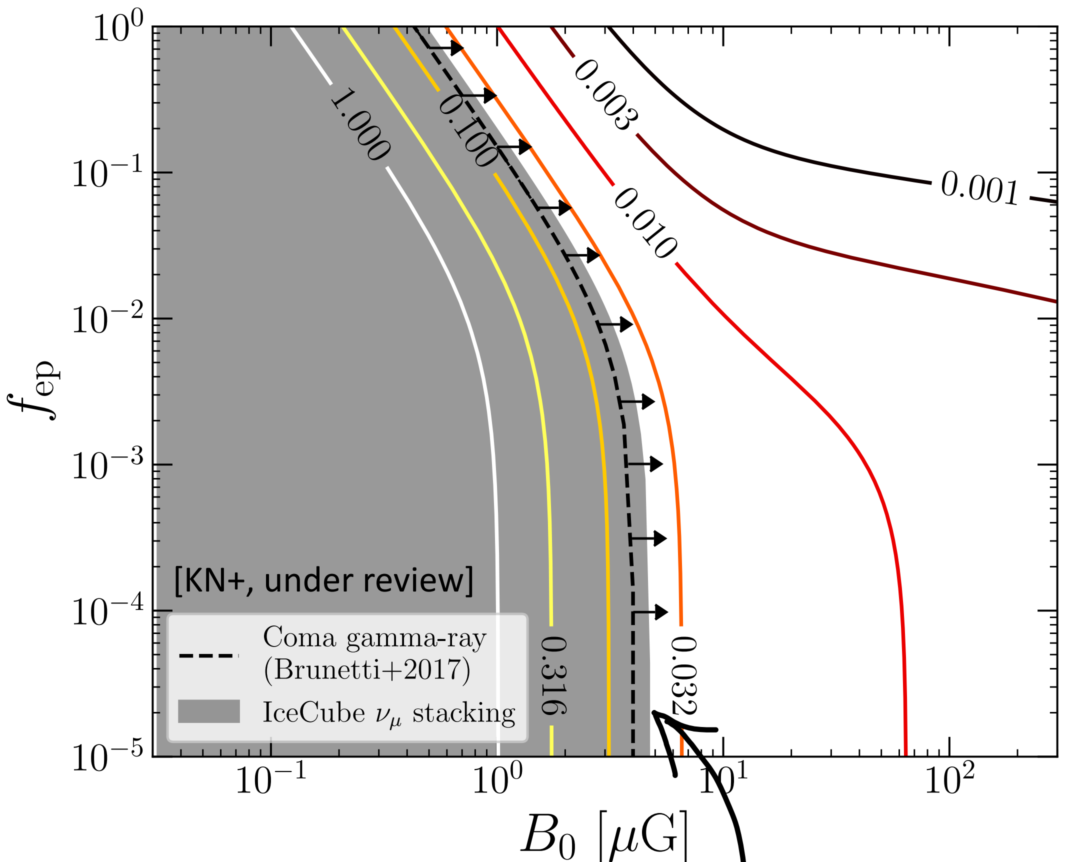
$$E_\nu^2 \Phi_\nu = \int dz \frac{dV_c}{dz} \int dL_{E_\nu} \frac{dN}{dL_{E_\nu} dV_c} L_{E_\nu} \frac{1+z}{4\pi D_L^2}$$

luminosity function



model prediction is comparable to the upper limit
→ more optimistic models are excluded

Constraints on the re-acceleration model



limit from the gamma-ray observation of Coma [Brunetti+]

Normalized by the radio luminosity

- ν flux is larger when B is smaller
- ν flux is smaller when there are "primary" electrons

$$\frac{L_\nu}{L_{\rm radio}} \propto \left(\frac{f_{ep}}{f_{ep} + f_{ep}^0}\right) B^{-\frac{q+1}{2}} \left[1 + \left(\frac{B}{B_{cmb}}\right)^2\right]$$

f_{ep}: electron-to-proton ratio of primary CRs

Radio & Neutrino combined limit

- **central magnetic field should be $B_0 > 4\ \mu\mathrm{G}$**

or

- **seed electrons are not from the *pp* collisions**

Summary

Multi-messenger (Radio & Neutrino) limit on the Turbulent Re-acceleration Model

◆ Radio halo and turbulent re-acceleration

- secondary electrons can be the *seed* electrons
- merger-induced TTD acceleration predicts $D_{pp} \propto M^{1/3}$
- $P_{1.4} \propto M^{3.5}$ is consistent with radio observations

◆ Neutrino upper limit

- massive ($M_{500} \sim 10^{15} M_{\odot}$) clusters dominate the neutrino background in re-acc. model
- however, massive clusters are constrained by the stacking analysis of ν_μ track events

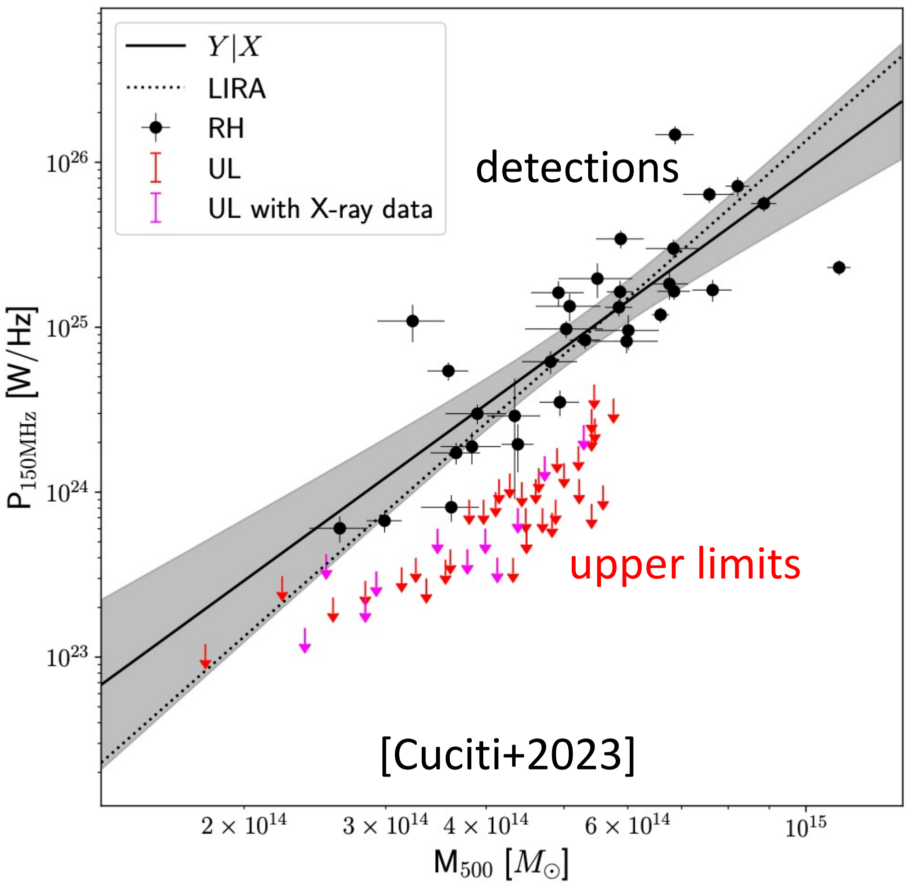
◆ Constraints on the re-acceleration model

- magnetic field $B < 1\mu$G is excluded, if seed originates from *pp*
- a deeper limit (~1% of IC level) would completely exclude the secondary model

Work II: Statistical properties of radio halos

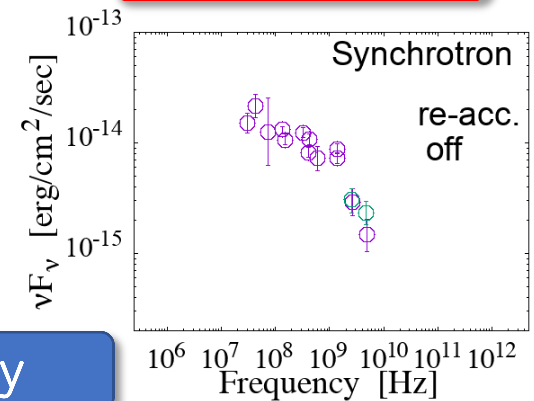
N.K. & Asano (2022)

radio halos appear in ~30% of galaxy clusters

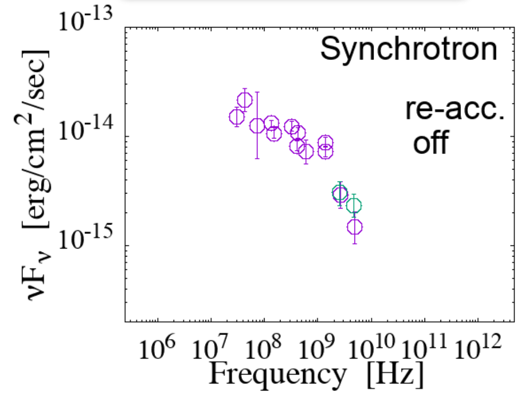


secondary

long lived! ←



primary



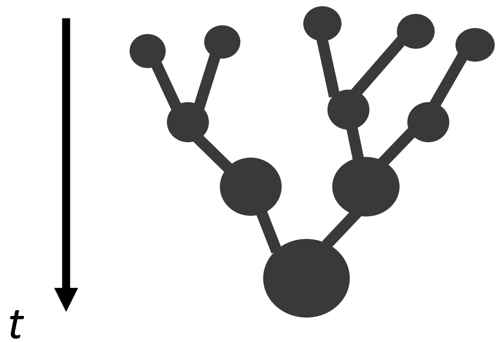
→ **short lived!**

Can we constrain the amount of CR protons???

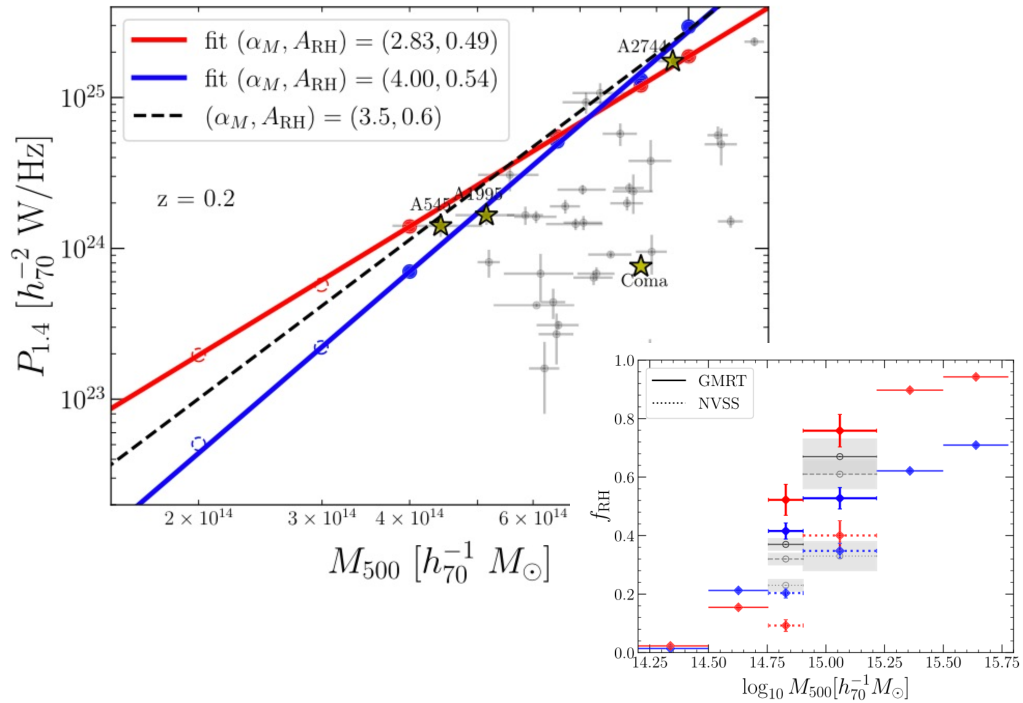
Work II: N.K. & Asano (2022)

Statistical properties of radio halos

Merger tree



- Monte Carlo simulation of cluster mergers. (cosmology)



◆ **Both primary & secondary electron models are consistent with the observation, but with different values of parameters.**

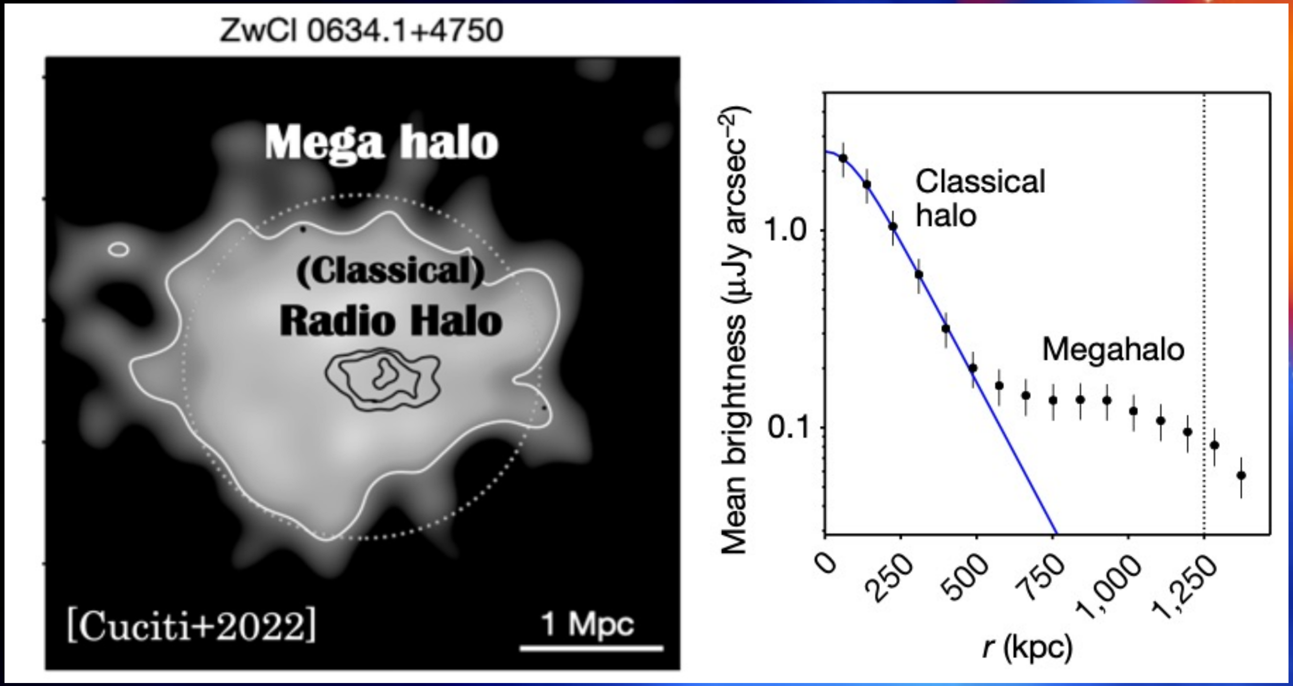
◆ **turbulent re-acceleration model can explain luminosity-mass relation**

◆ **future multi-frequency observation is important to test our model**

Work IV:

N.K., Brunetti, Vazza & Gheller, under review

Mega halos and solenoidal turbulence

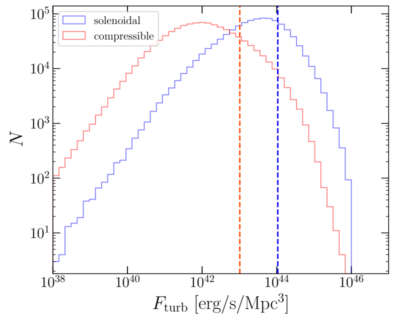


- $\times$ 30 larger than classical RH!
- extending up to the virial radius
- found at low frequency (~100MHz)

What is the origin of this "extended component" ??

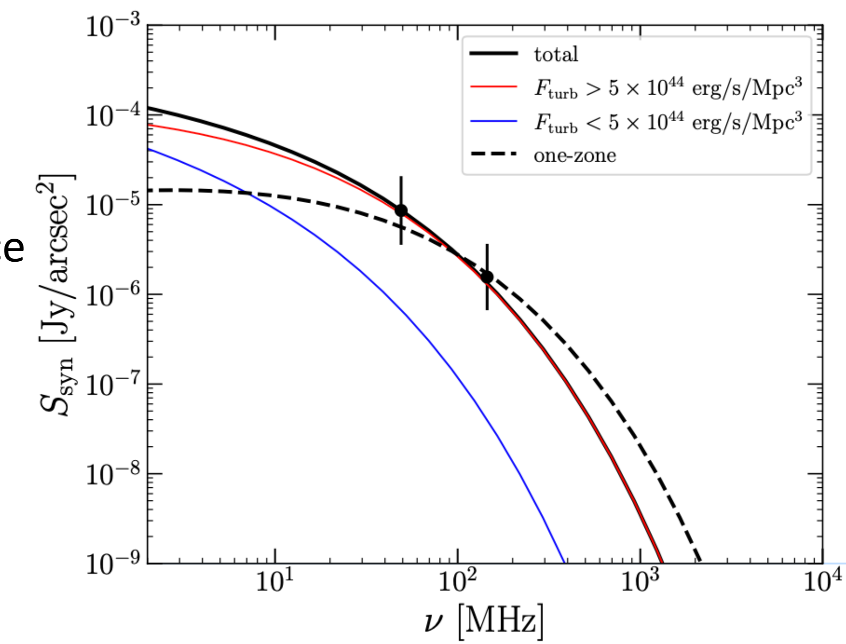
Work IV: Mega halos and solenoidal turbulence

N.K., Brunetti, Vazza & Gheller, under review



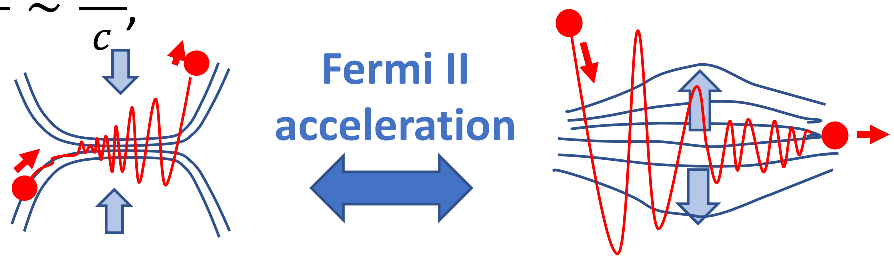
In cluster periphery, turbulence is dominated by **solenoidal (incompressible) mode!**

radio synchrotron spectrum



acceleration by solenoidal turbulence [Brunetti & Lazarian 2016]

$$\frac{\Delta p}{p} \sim \frac{v_A}{c},$$



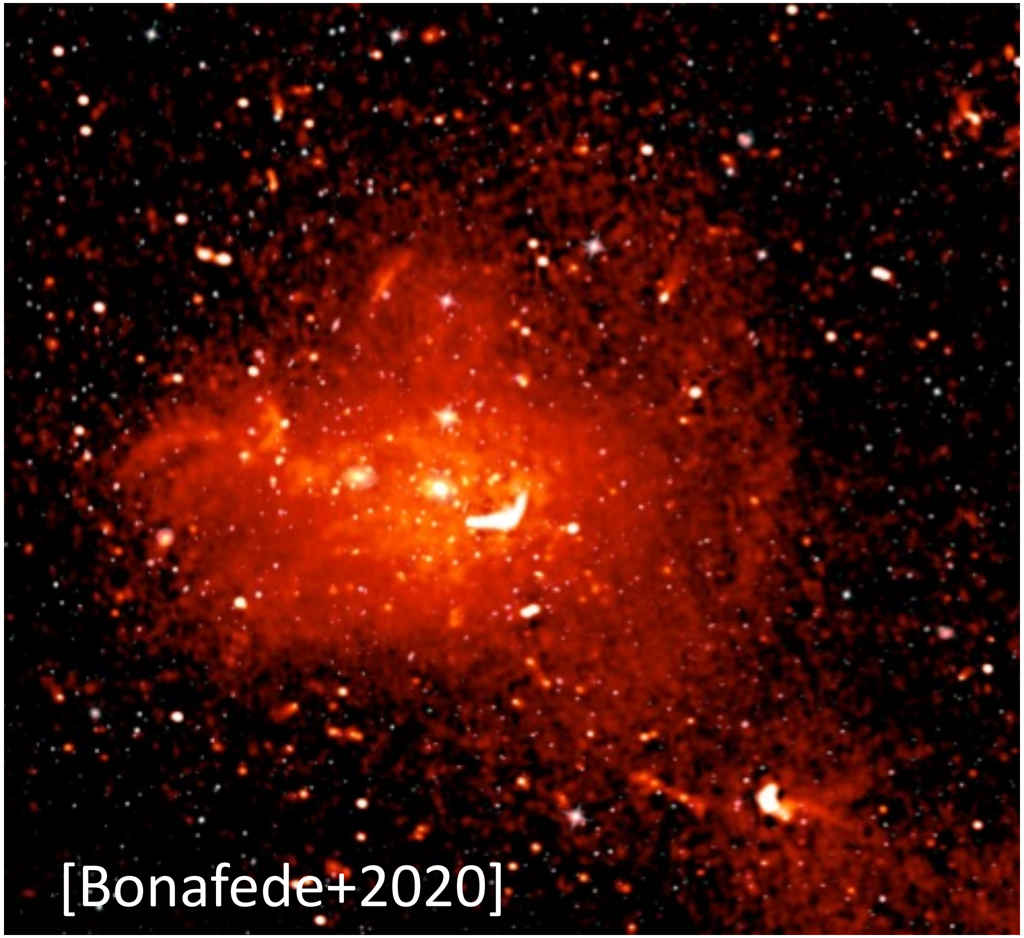
Turbulent kinetic energy → Thermal energy (ICM)

→ CR acceleration + B field

as much as 10% goes into non-thermal energy

Work I:
Radio halo of the Coma cluster

Nishiwaki, Asano & Murase (2021)



- Mpc scale radio (synchrotron) emission
- magnetic field by Faraday rotation ($\sim \mu G$)
- gamma ray upper limit by *Fermi*

Questions:

- **origin of CR electrons?**
  (primary or secondary?)
- **source of CRs?**
  (shocks? AGNs?)
- **neutrinos from clusters?**

develop 1D model, including re-acceleration and hadronic (pp) process!

Work I: Radio halo of the Coma cluster

N.K., Asano & Murase (2021)

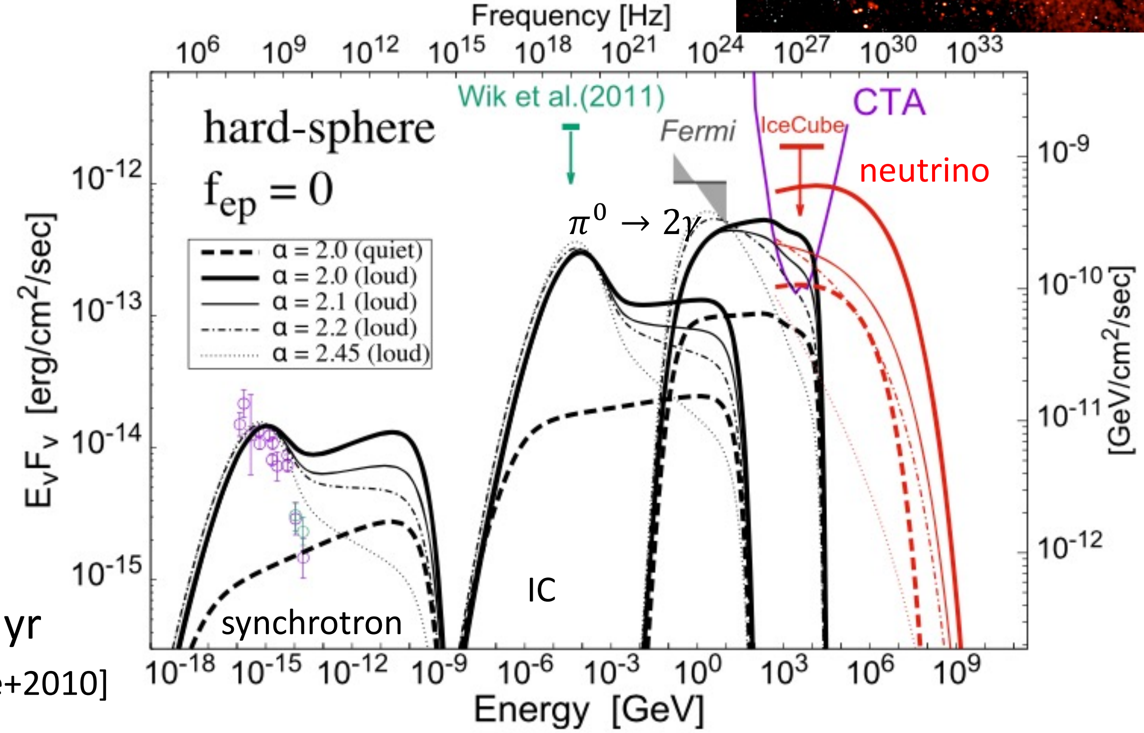
- **Fokker-Planck eq. (CRe and CRp)**

$$\frac{\partial N_e}{\partial t} = \frac{\partial}{\partial p}\left[\left(\dot{p} - \frac{1}{p^2}\frac{\partial}{\partial p}(p^2 D_{pp})\right)N_e\right] + \frac{\partial^2}{\partial p^2}[D_{pp}N_e] + Q_e + (\text{diffusion})$$

cooling   re-acceleration   injection

seed: secondaries from *pp* collision
acceleration timescale: $t_{acc} \approx 300$ Myr
magnetic field: $B_0 = 4.7\ \mu$G [Bonafede+2010]

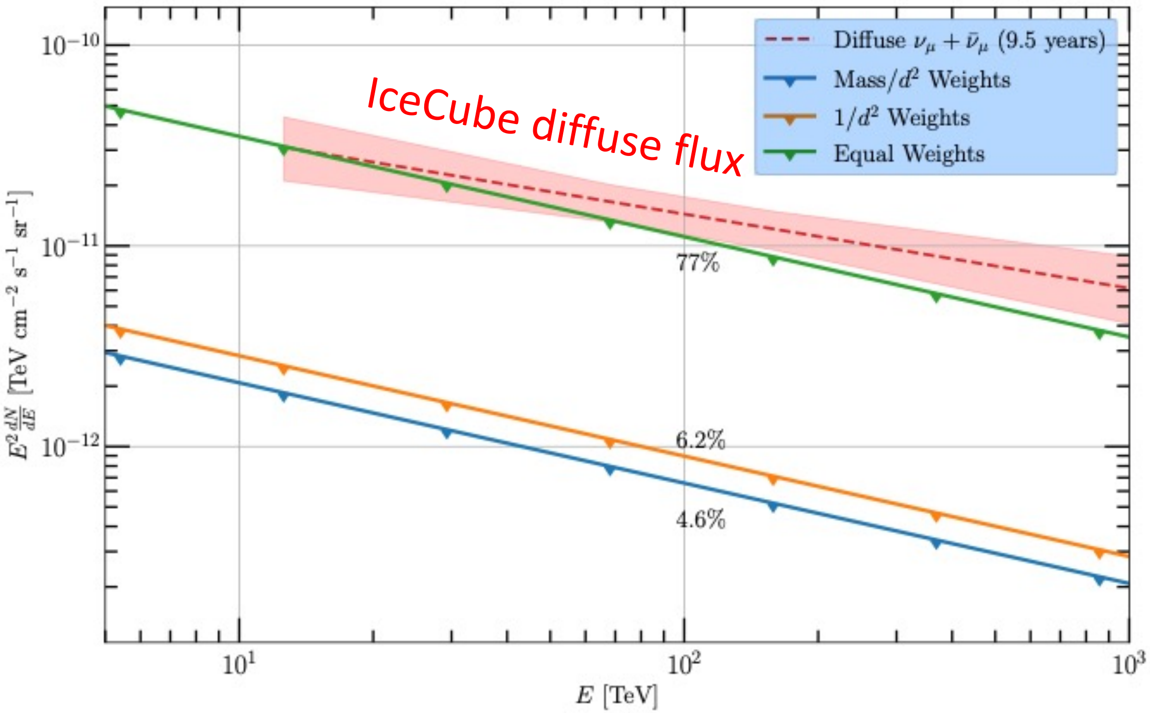
non-thermal emission



- **1D (radial) code to calculate multi-wavelength and multi-messenger emission from GCs.**
- **CR electrons can originate from *pp* collision of protons!**
- **the radial profiles of the CR injection and re-acceleration depend on electron-to-proton ratio of CRs.**

Work III: N.K., Asano & Murase (2023)
Neutrino upper-limit & constraints on the re-acceleration model

IceCube stacking analysis



[IceCube collaboration 2022]

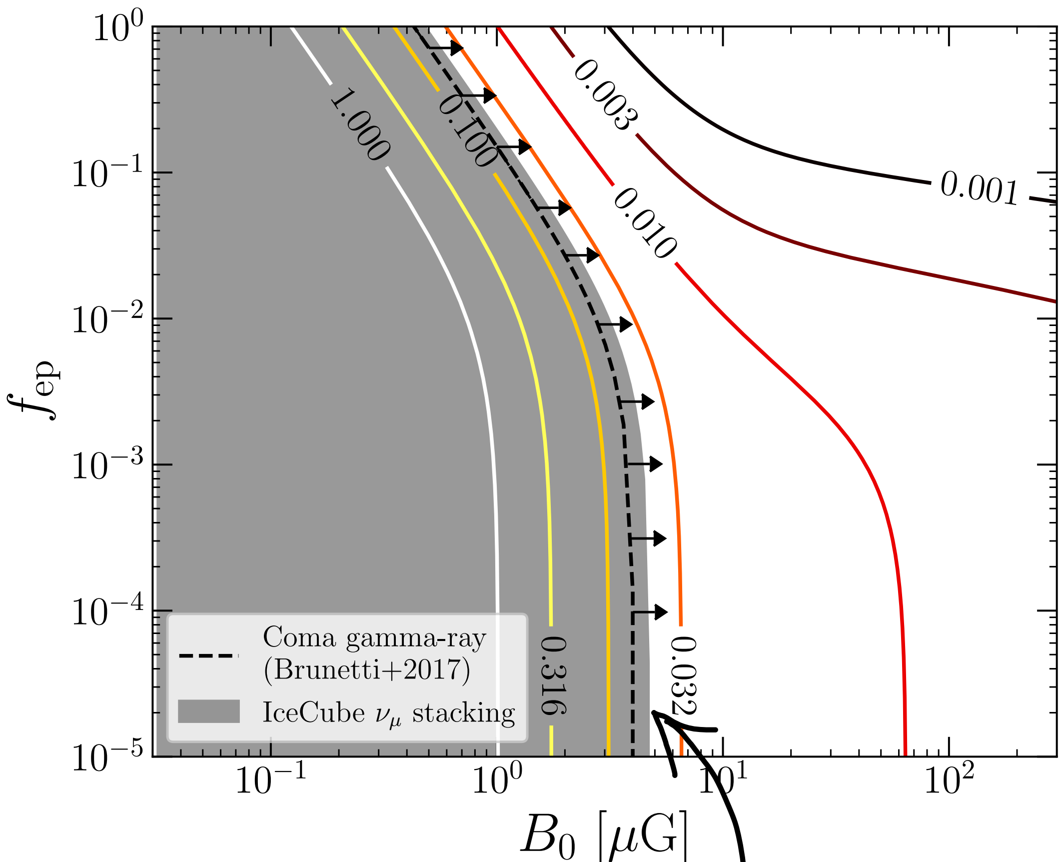
contribution to the diffuse neutrino background should be smaller than ~5%

constraints on re-acceleration model (e-p ratio, B field, mechanism…)

use **merger tree + FP equation** to calculate diffuse neutrino background

Work III: Neutrino upper-limit & constraints on the re-acceleration model

N.K., Asano & Murase (2023)



limit from the gamma-ray observation of Coma [Brunetti+]

Normalized by the radio luminosity

$$\frac{L_\nu}{L_{\rm radio}} \propto \left(\frac{f_{ep}}{f_{ep}+f_{ep}^0}\right) B^{-\frac{q+1}{2}}\left[1+\left(\frac{B}{B_{cmb}}\right)^2\right]$$

f_{ep}: electron-to-proton ratio of primary CRs

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