銀河団における宇宙線加速とマルチメッセンジャー放射
(Particle acceleration and Multi-messenger emission in galaxy clusters)

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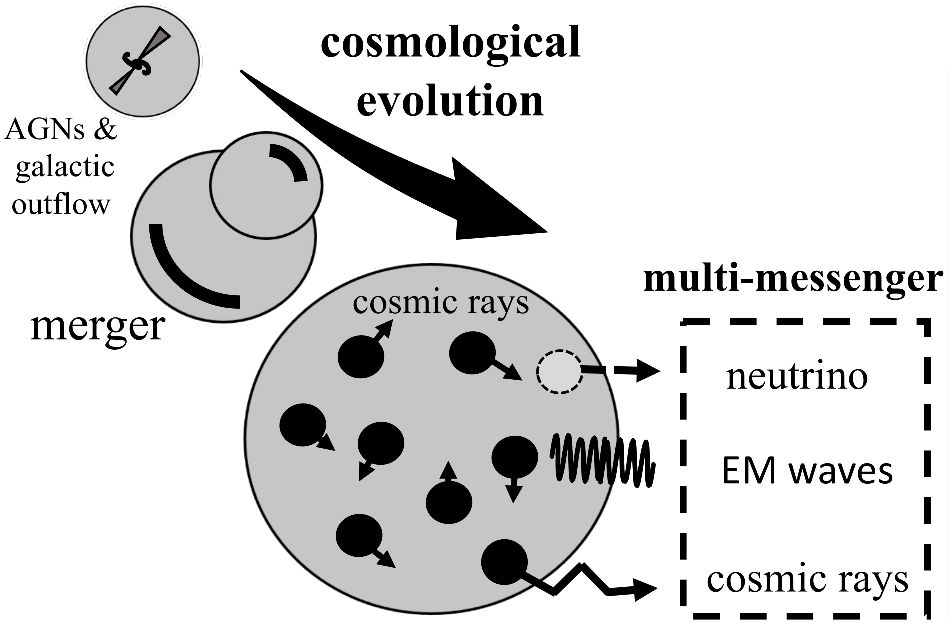
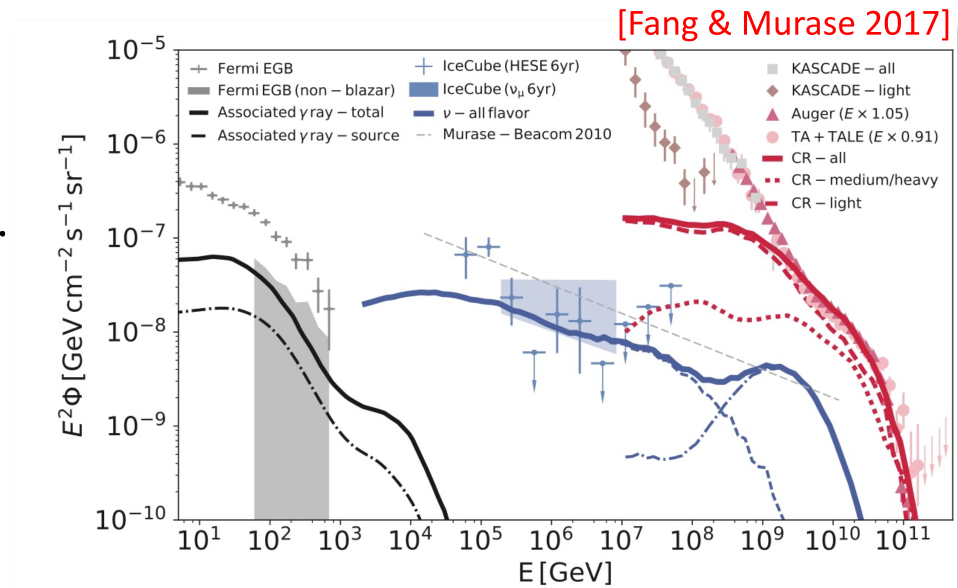
Galaxy Clusters as Cosmic ray “reservoirs”





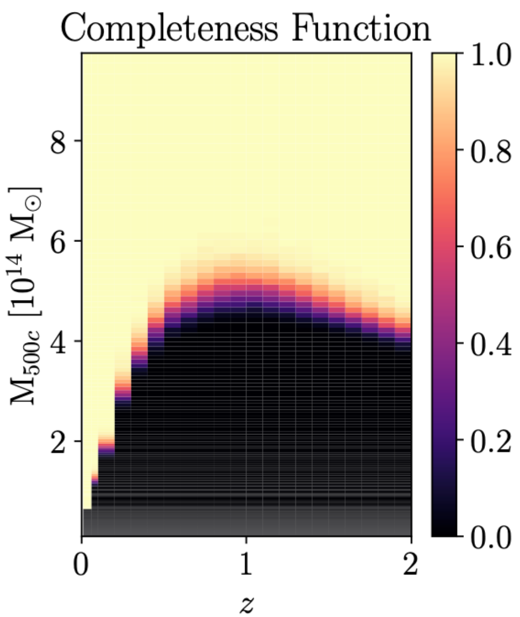
$$p + p \to \pi^0, \pi^{\pm}$$

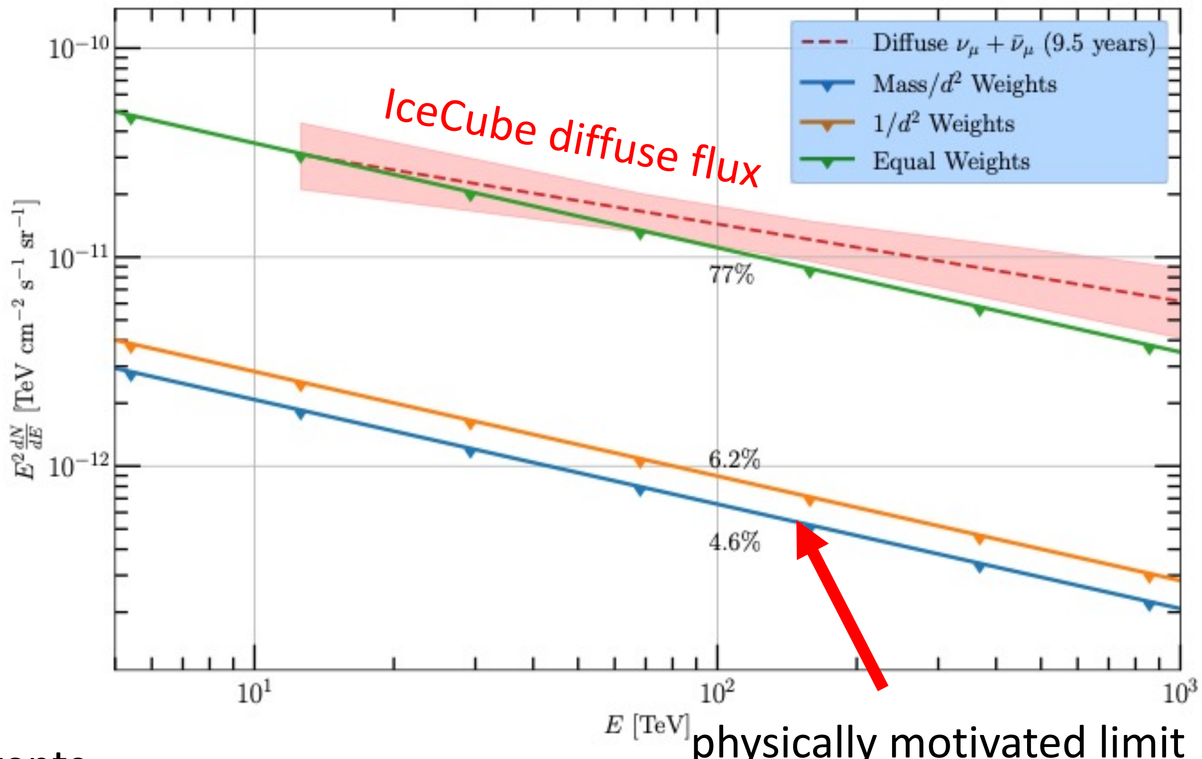
$$\pi^0 \to 2\gamma,$$
$$\pi^{\pm} \to \nu_\mu(\overline{\nu_\mu}) + \mu^{\pm} \to e^{\pm} + \nu_\mu(\overline{\nu_\mu}) + \nu_e(\nu_e)$$

Galaxy clusters as the sources of high-energy CR, gamma, and neutrino

Neutrino "Upper Limit"

[IceCube collaboration 2022]





- *Planck*-SZ clusters

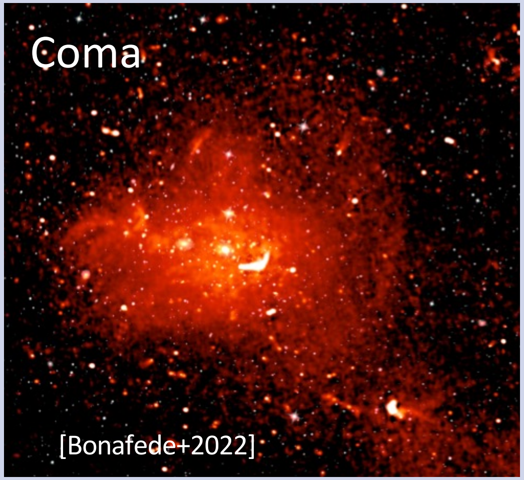
  &

- 9.5-yr data of muon track events

the contribution from massive ($M_{500} \gtrsim 3{\times}10^{14} M_\odot$) clusters is less than ~5%.

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

Diffuse Radio Emission in Clusters

<table>
<tr><th>Giant Radio Halo</th><th>Radio Relic</th><th>Mini Halo</th></tr>
<tr>
<td>
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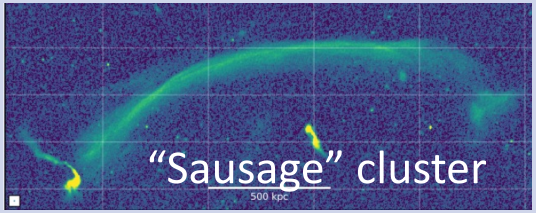
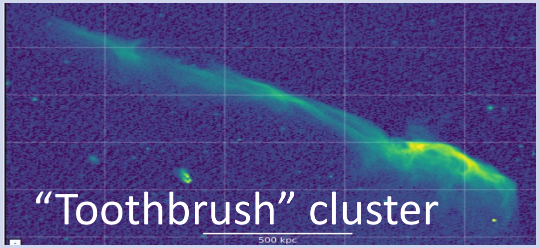
<td>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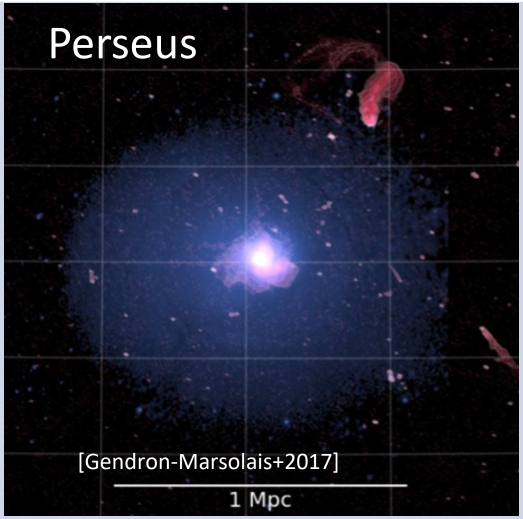
<td>
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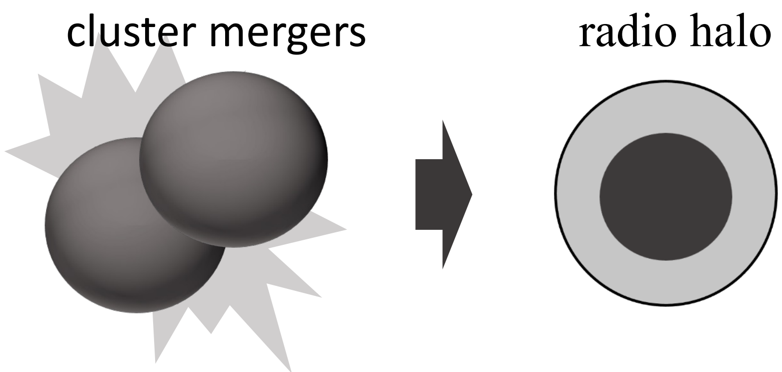
</tr>
<tr><td>Spherical</td><td>elongated</td><td>Spherical</td></tr>
<tr><td>~ 1Mpc</td><td>~ 1Mpc</td><td>~ 300 kpc</td></tr>
<tr><td>Merging clusters</td><td>Merging clusters</td><td>Relaxed clusters</td></tr>
</table>

Correlate with dynamical state of clusters

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

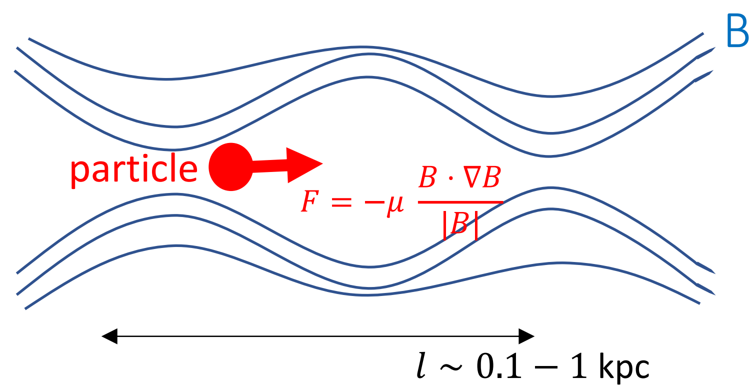
Turbulent Re-acceleration Model



relativistic seed electrons
revived through the **Fermi-II acceleration**
[e.g., Brunetti+, Petrosian+, Fujita+]

Transit-time damping (TTD)

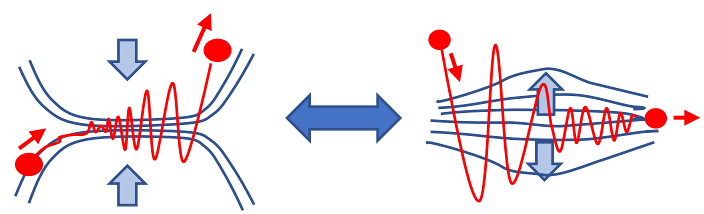
[e.g., Stix 1992, Barns 1968, Brunetti & Lazarian 2007]



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

Stochastic acceleration at turbulent reconnection/dynamo

[e.g., Brunetti & Lazarian 2016]

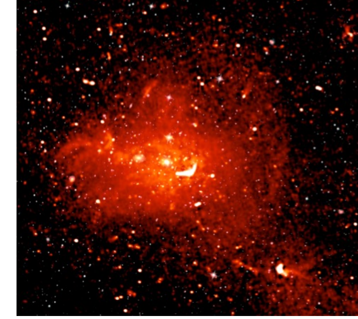


$$t_{acc} \approx 300\ \mathrm{Myr} \left(\frac{M_s}{0.5}\right)^{-3} \left(\frac{\psi_{mfp}}{0.5}\right)^{3} \left(\frac{L}{300\ \mathrm{kpc}}\right) \left(\frac{c_s}{1500\ \mathrm{kms^{-1}}}\right)^{-2} \left(\frac{\beta_{pl}}{100}\right)^{-\frac{1}{2}}$$

◆ Need of seed

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

Radio halo: Coma cluster



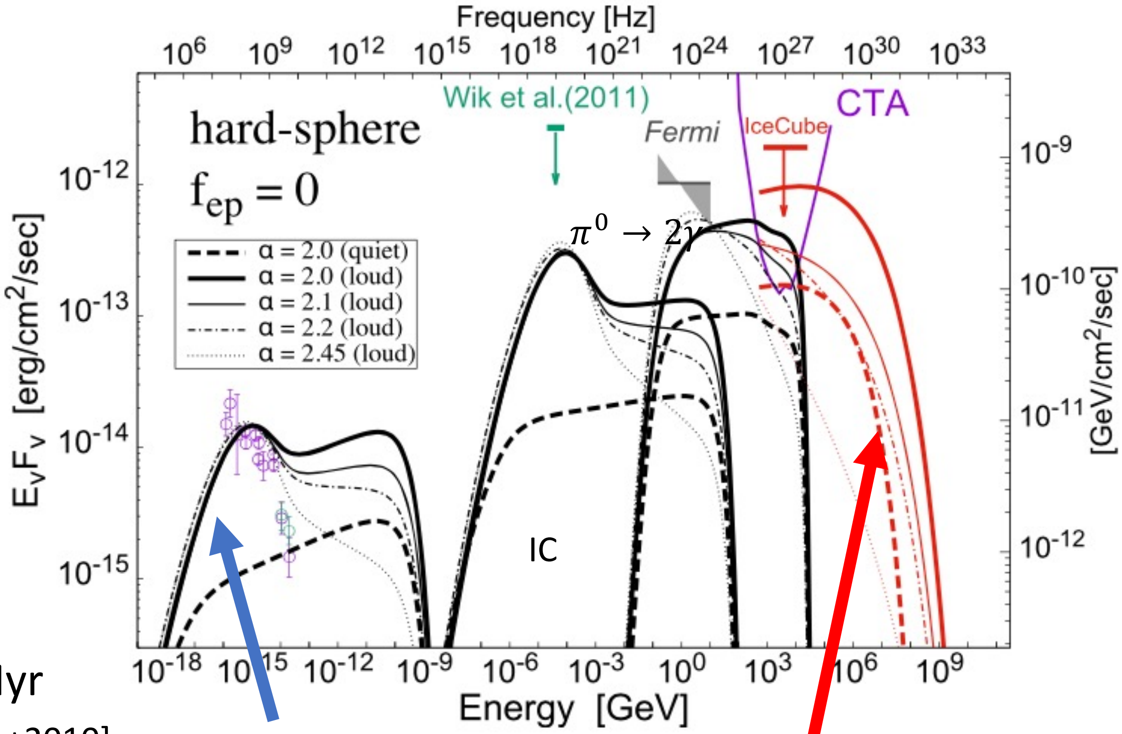
model normalized by the radio observation of Coma

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

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

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]



Synchrotron within $r < 0.5$ Mpc

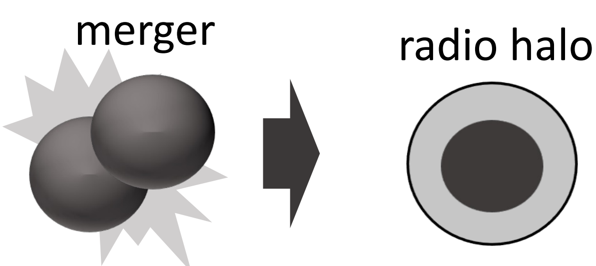
Neutrino within $r < 2.3$ Mpc

[KN+21]

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

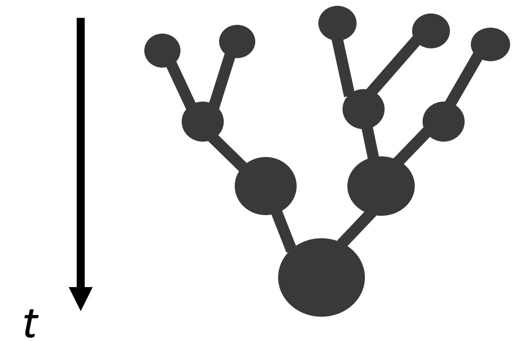
Overview

Re-acceleration model



- "secondary electron" + re-acceleration model
- injection from AGNs or accretion shocks

Merger tree



- number of mergers, mass ratio
- mass function

radio observation (Coma cluster)

diffuse neutrino background

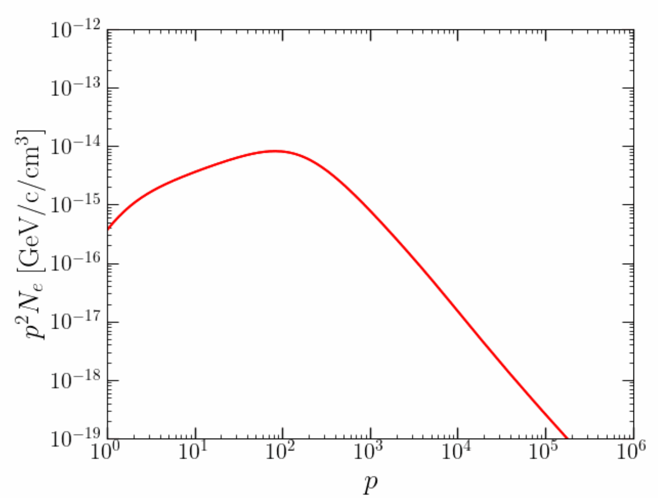
IceCube upper limit

constraints on the re-acceleration model

Re-acceleration of CRs

CR spectrum is significantly modified by re-acceleration

electron



short lifetime

due to efficient radiative cooling

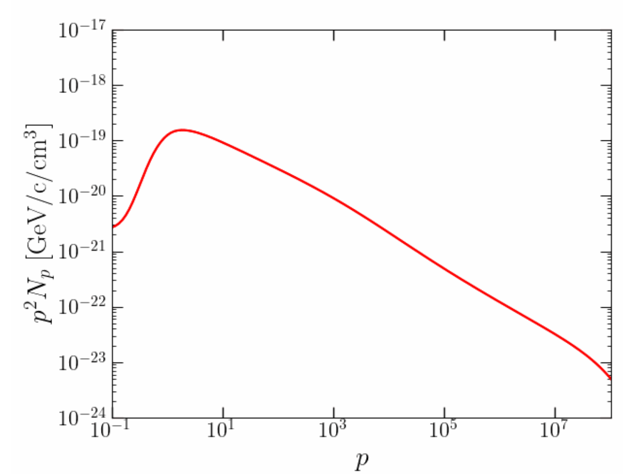
re-acceleration

on

↓

off

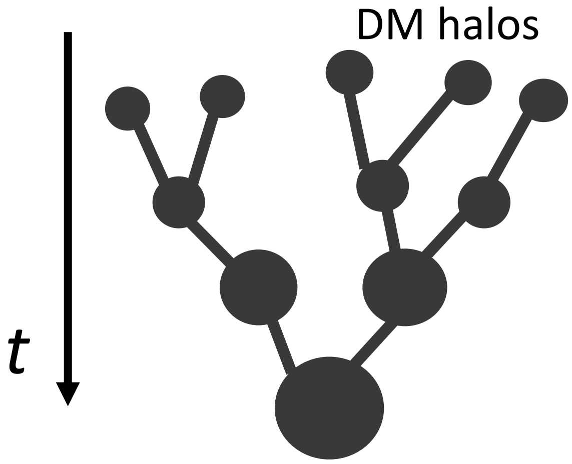
proton



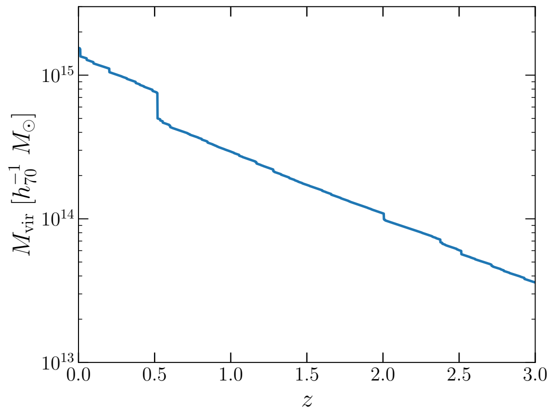
long lifetime
→ secondary electron also has long lifetime

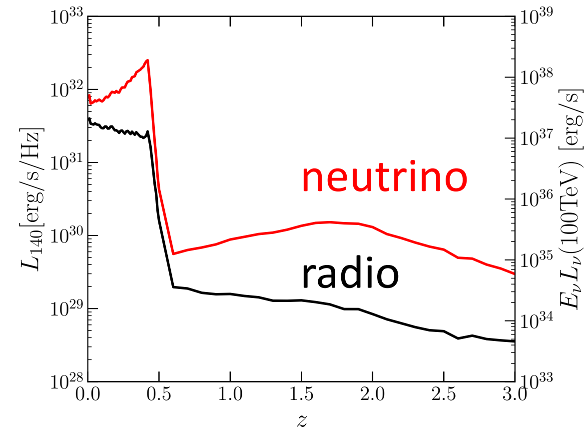
- **CR proton affects the \`\`lifetime" of emission after re-acceleration**
- **Amount of CR proton can be constrained from the *statistics* of the non-thermal emission (i.e., radio emission)**

Monte Carlo Merger Tree

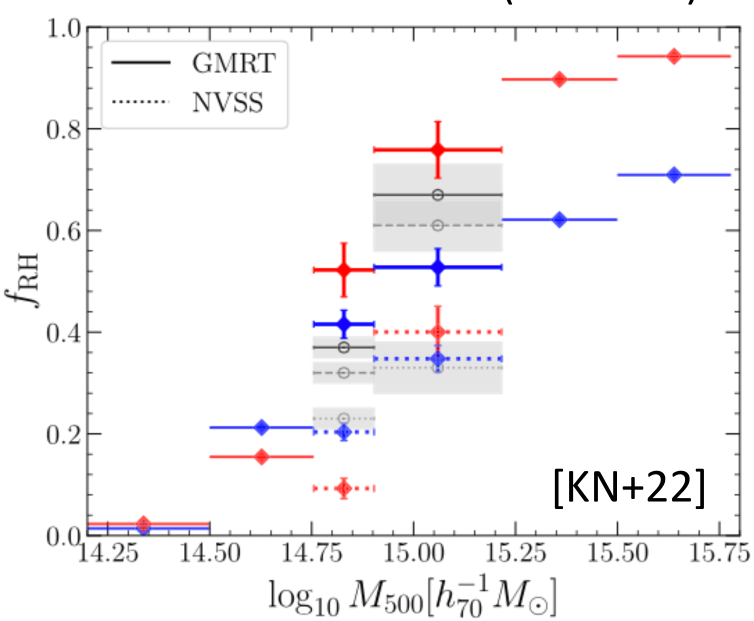


evolution of the mass & luminosity





- occurrence of RHs (~30-60%)



- **Secondary electrons from *pp* collision**

→ long lifetime (> 1 Gyr)

→ need (1: 3) mergers for re-acceleration

- **Primary electrons (without proton)**

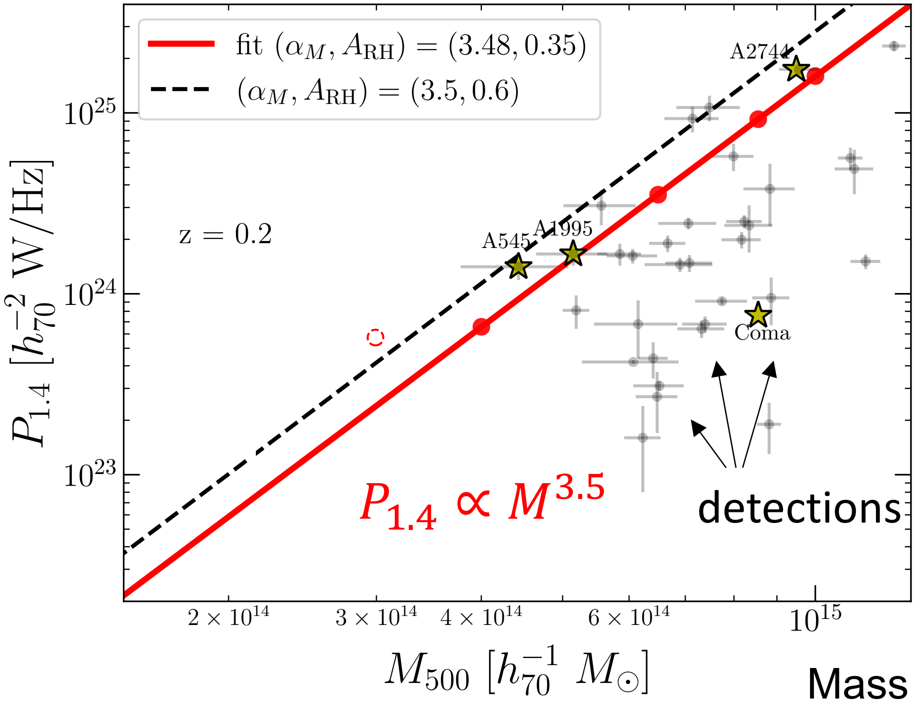
→ short lifetime (<1 Gyr)

→ need (1:10) mergers for re-acceleration

Luminosity-Mass relation

luminosity

Radio (1.4 GHz)



TTD model is consistent with the radio observation

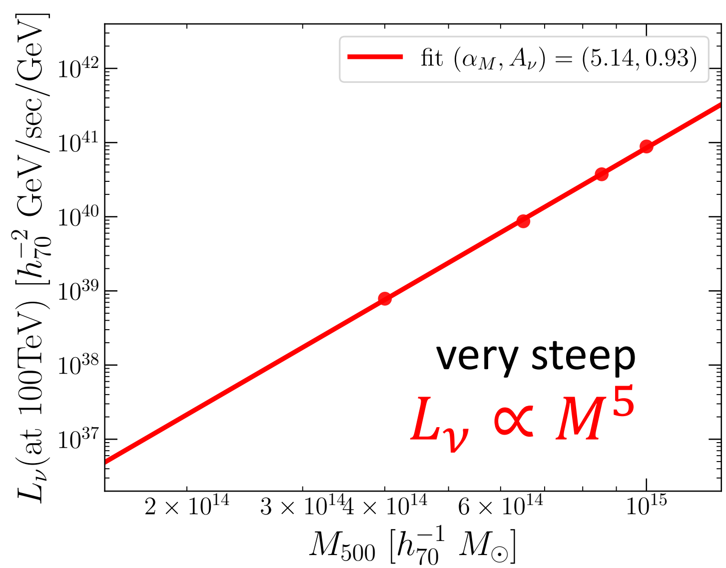
observed radio halos are massive
$M_{500} > 3\times10^{14} M_\odot$

merger + TTD acceleration for various *M*

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

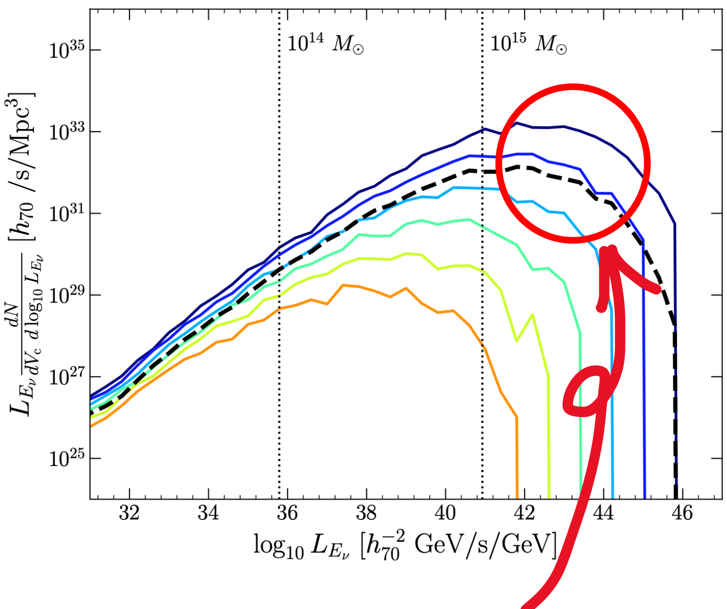
- magnetic field: $B \propto M^0$
- seed injection: $L_{CR}^{inj} \propto M^{5/3}$
- Fokker-Planck eq. (CRe and CRp)

Neutrino (100 TeV)



Diffuse Neutrino Background

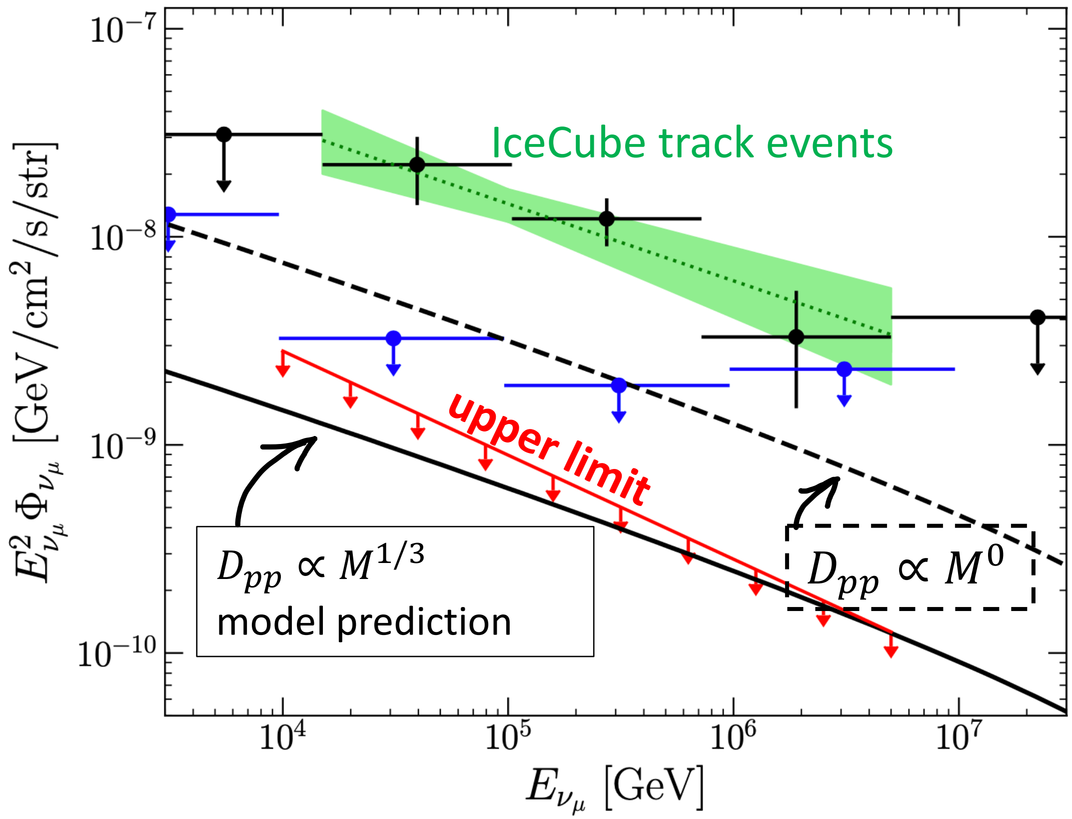
neutrino luminosity function
weighted by L_ν



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

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

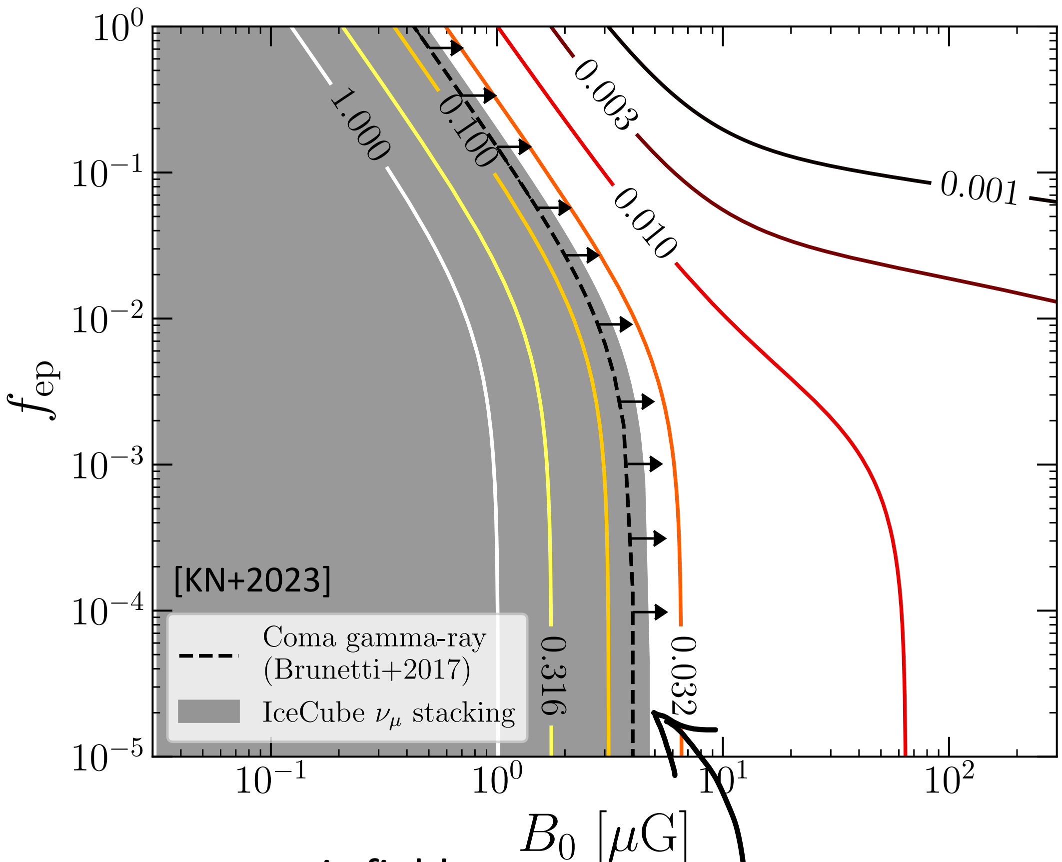
luminosity function



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

Constraints on the re-acceleration model

injection (pre- reacceleration)
e-p ratio



magnetic field

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 $B_0 > 4\ \mu G$**

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