neutrinos and gamma rays from clusters of galaxies

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Klaus Dolag

Saqib Hussain

CRPropa Workshop on Astroparticle Propagation

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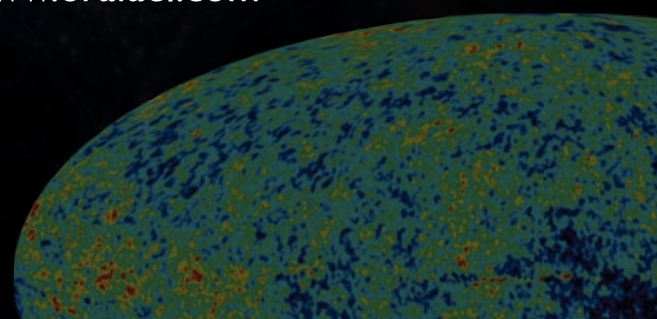

what is the origin of high-energy emission by galaxy clusters?

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> GeV-TeV gamma rays
> TeV-PeV neutrinos

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> *GeV-TeV gamma rays*
> *TeV-PeV neutrinos*

electrons

what is the origin of high-energy emission by galaxy clusters?

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> TeV-PeV neutrinos

cosmic rays

electrons

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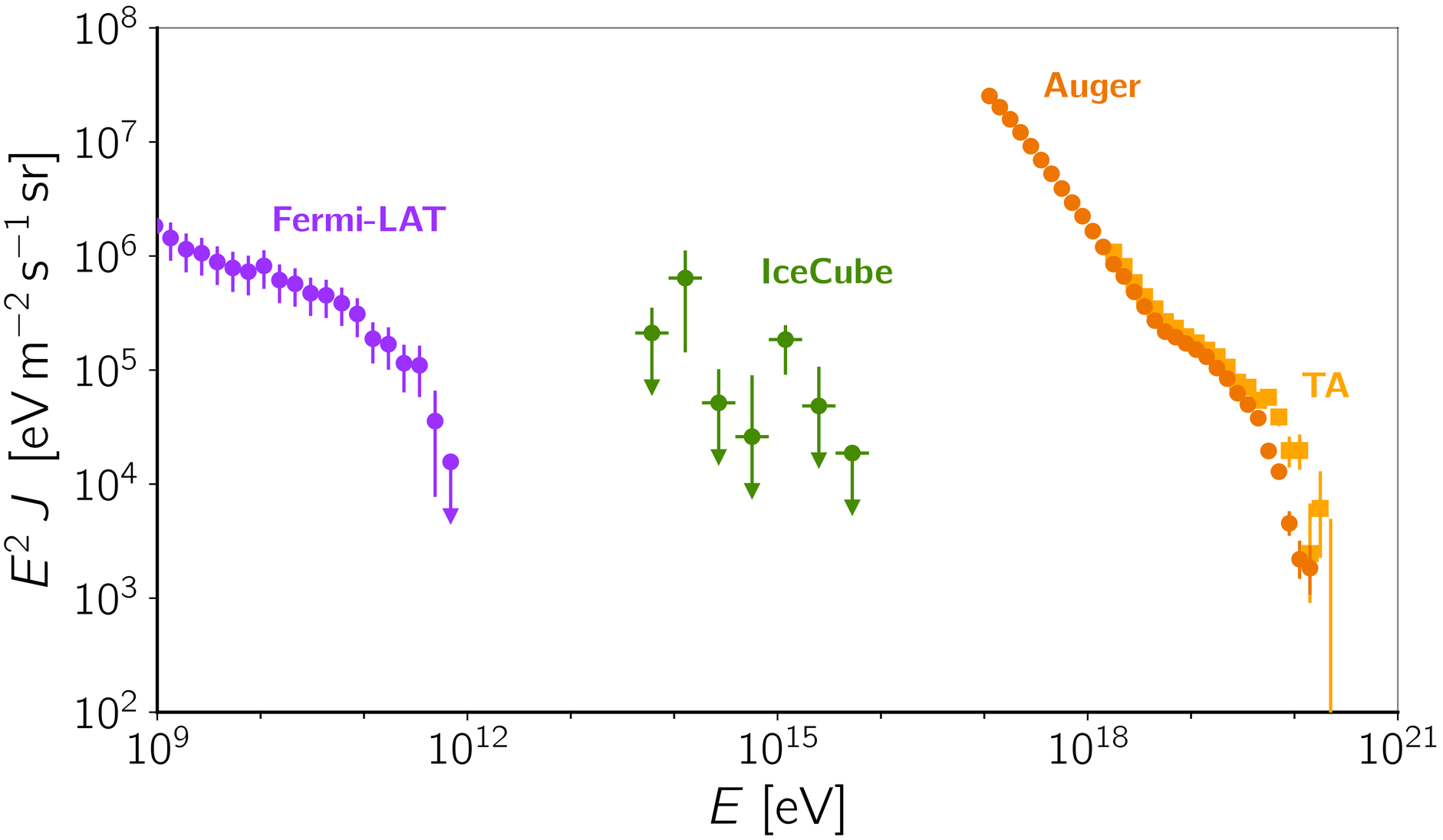
cosmic rays

electrons

dark matter

high-energy multimessenger landscape

Alves Batista et al. Front. Astron. Space. Sci. 6 (2019) 23. arXiv:1903.06714



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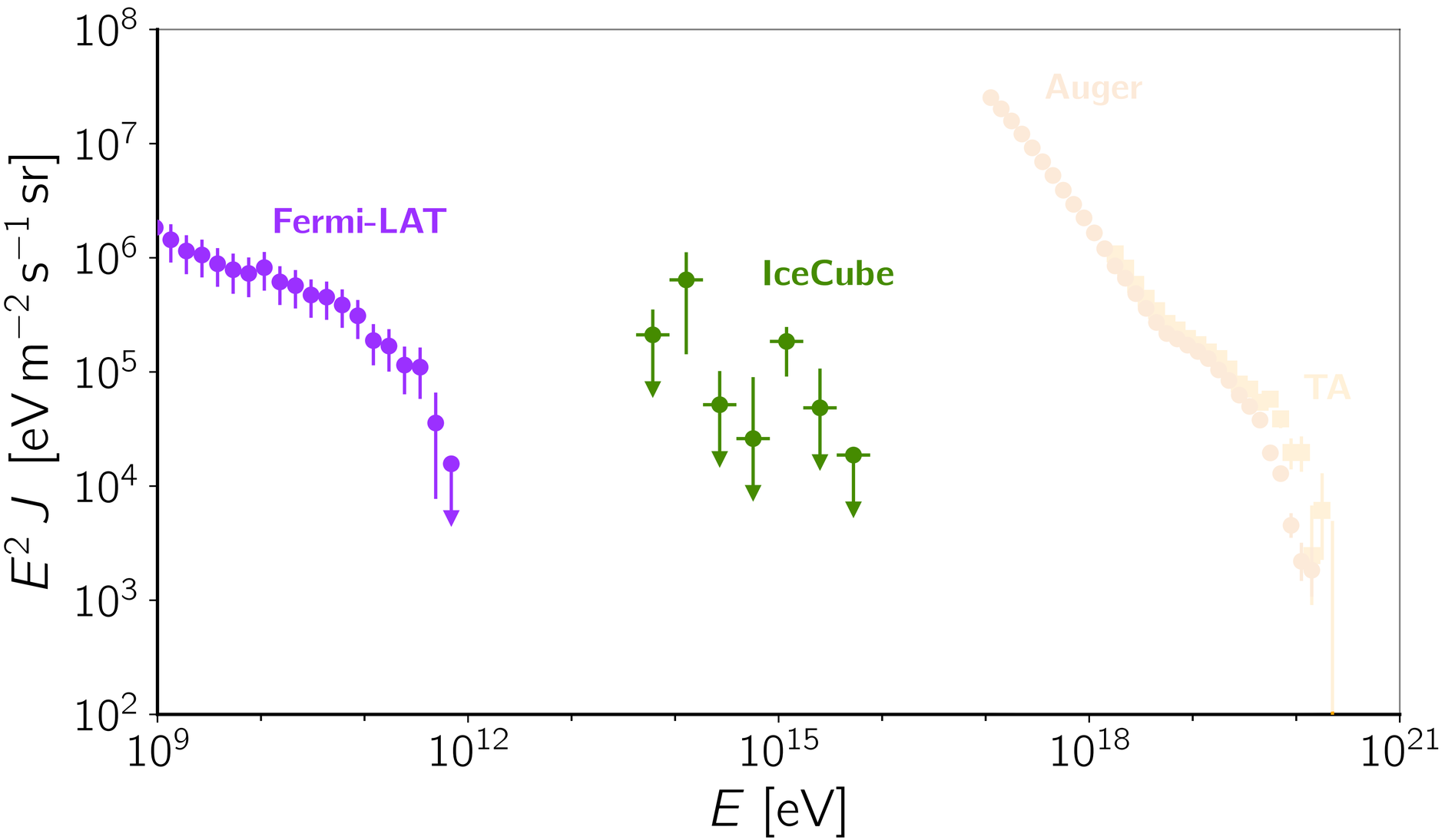

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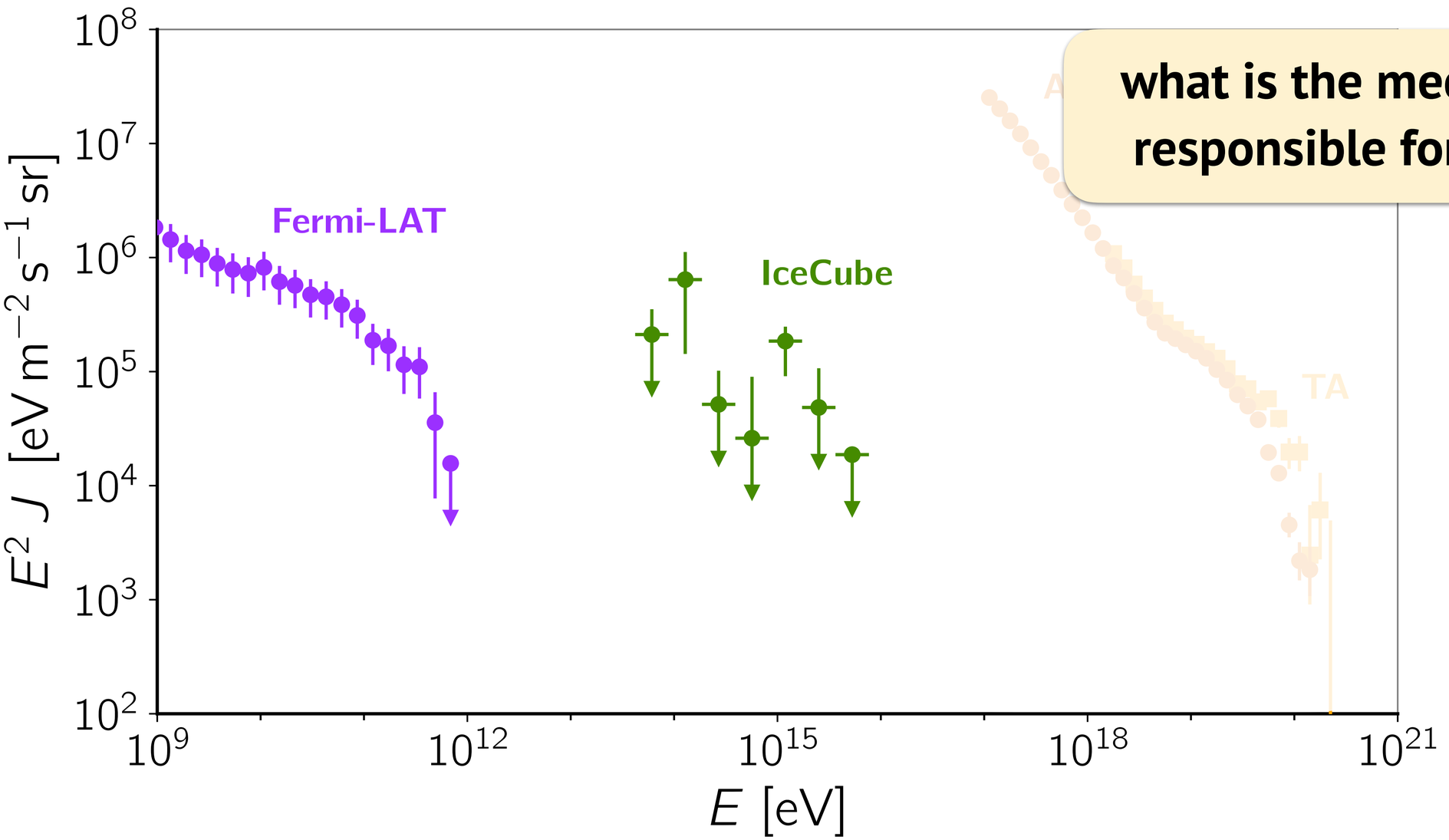

what is the mechanism responsible for them?

high-energy multimessenger landscape

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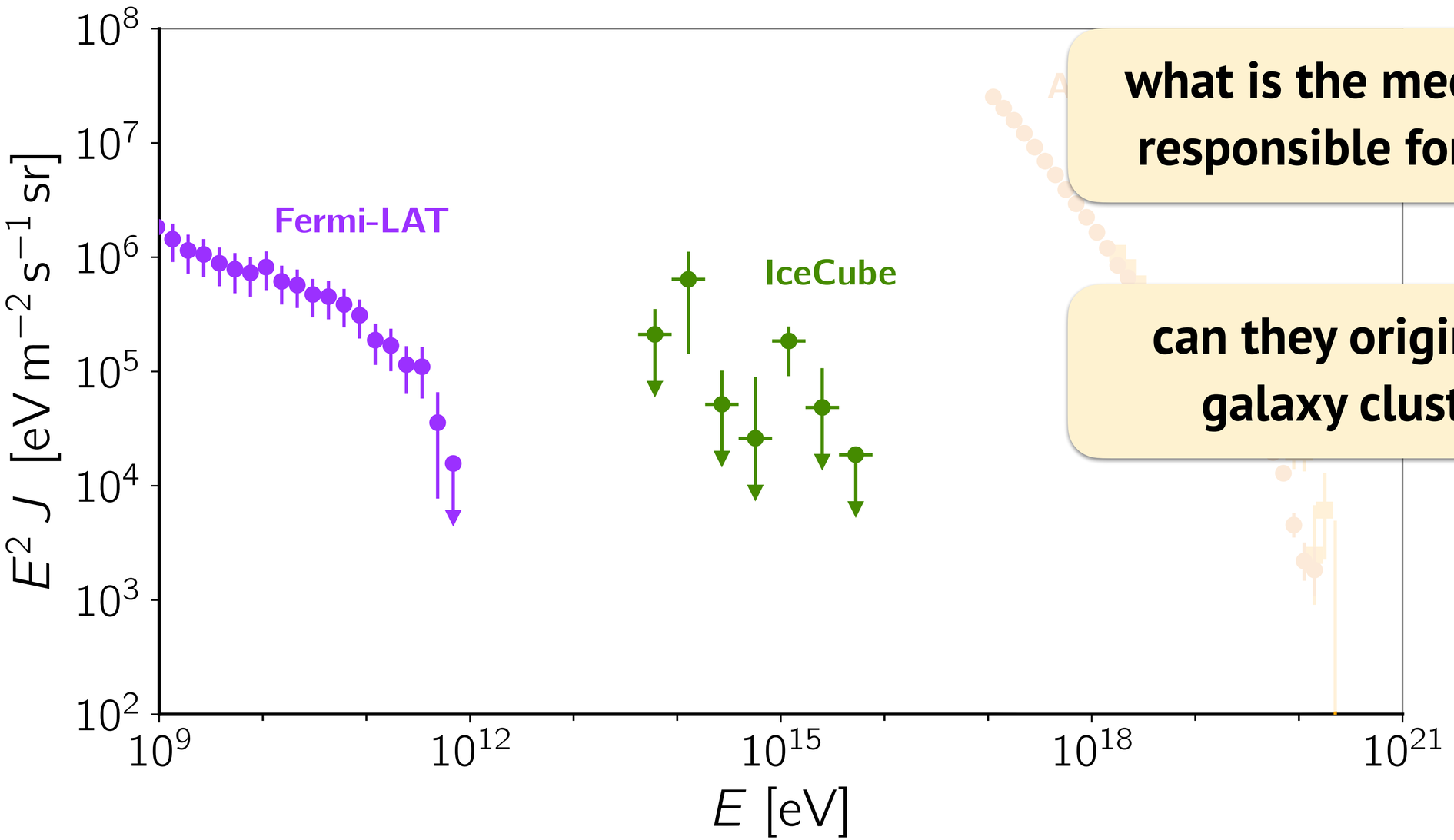

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can they originate in galaxy clusters?

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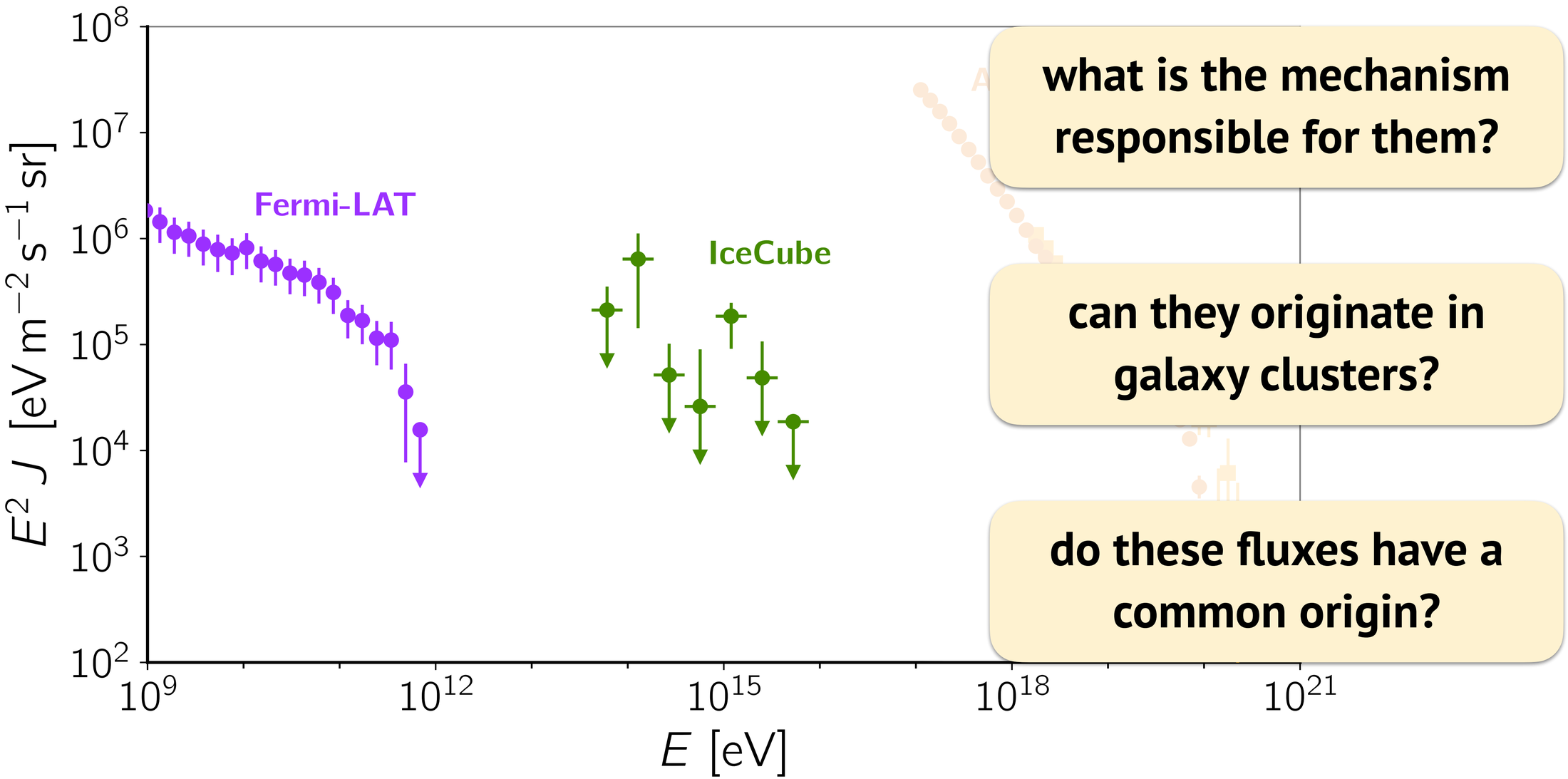

what is the mechanism responsible for them?

can they originate in galaxy clusters?

do these fluxes have a common origin?

the multimessenger link: particle interactions and acceleration

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hadrons & nuclei

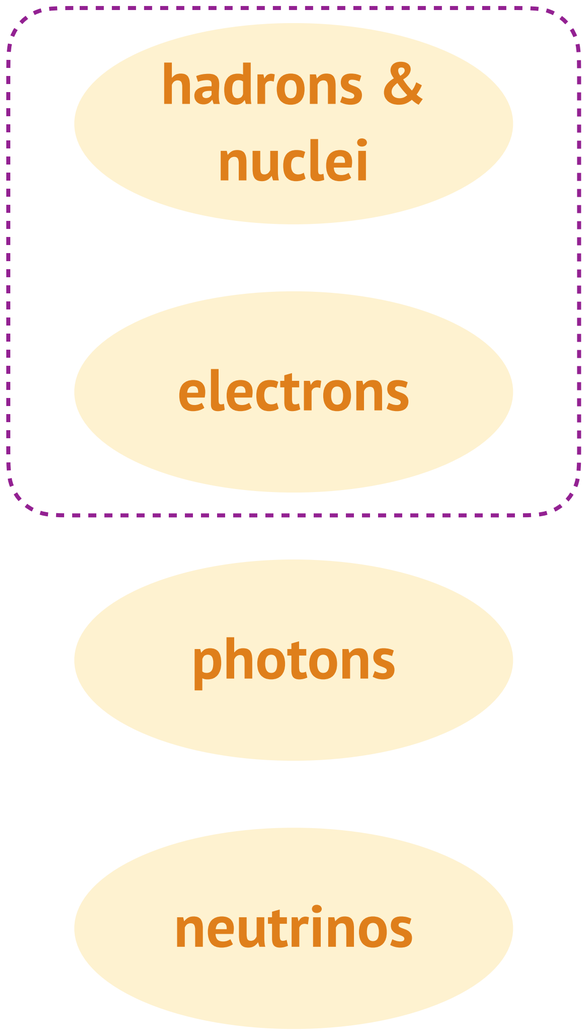
electrons

photons

neutrinos

the multimessenger link: particle interactions and acceleration

particle acceleration



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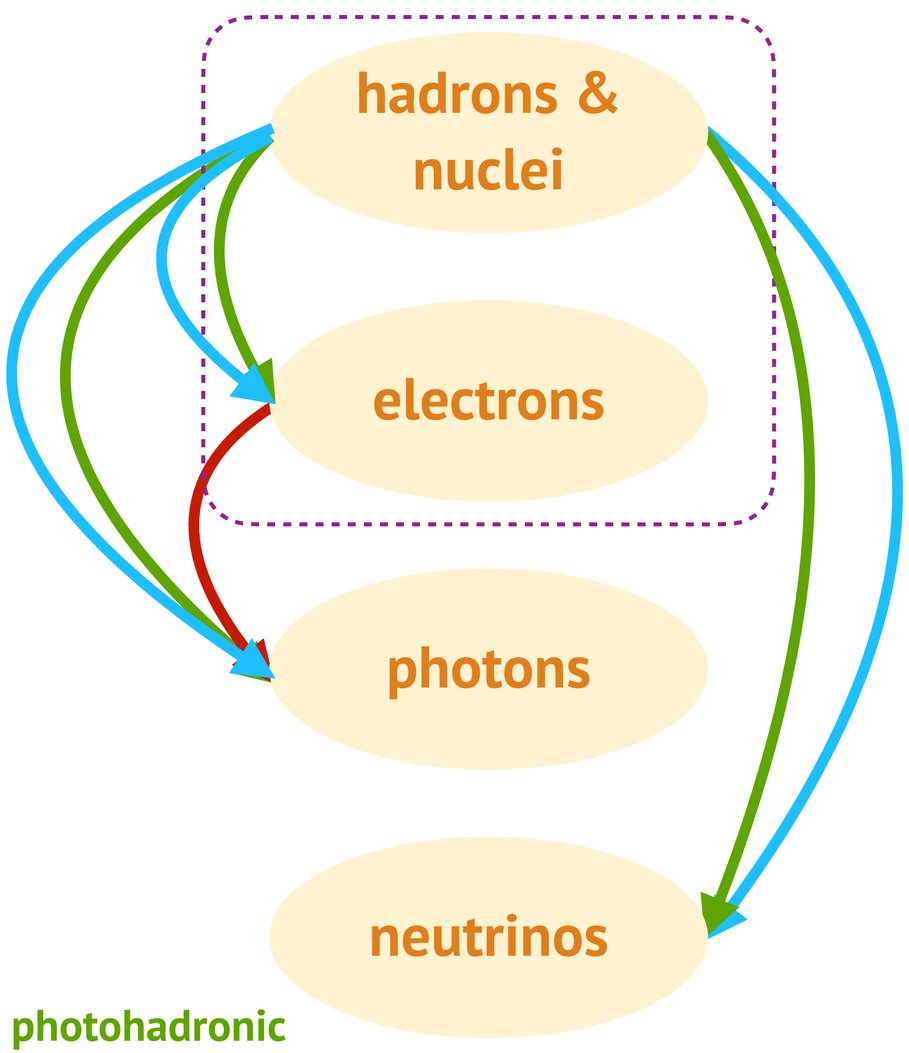
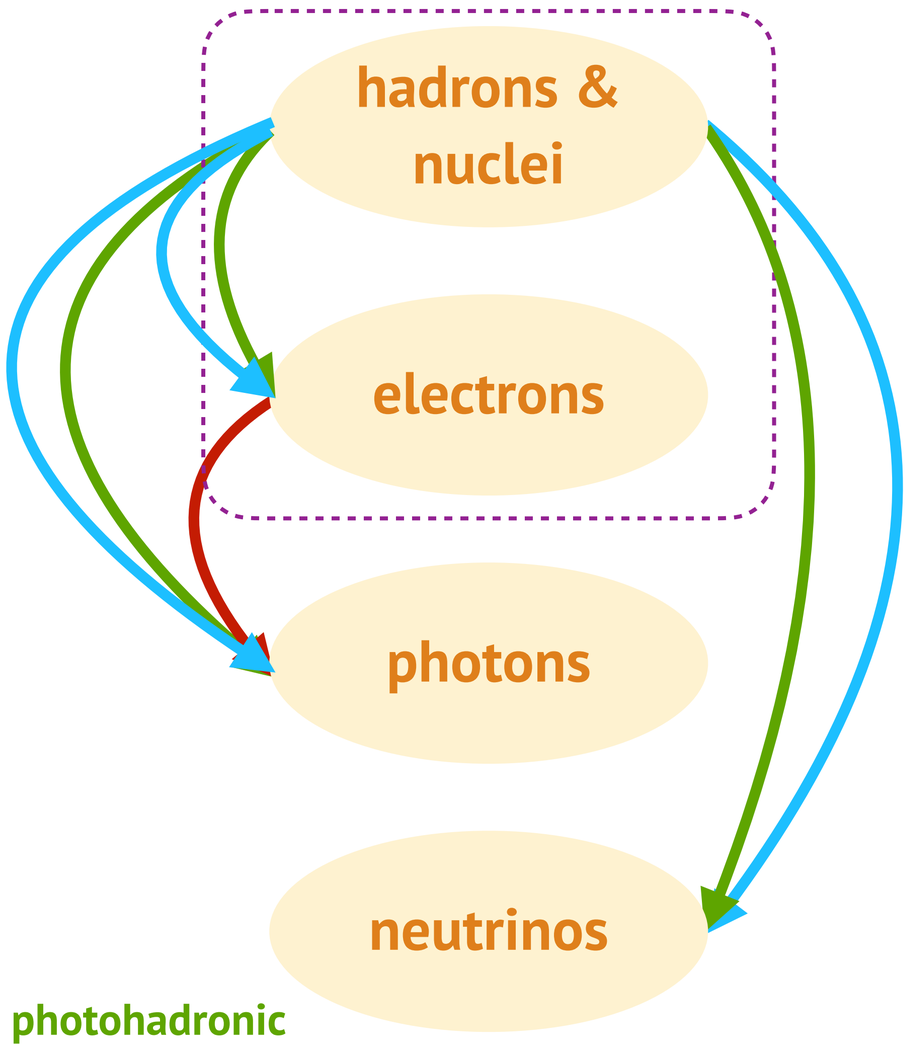


photohadronic
photonuclear
electromagnetic
hadronuclear
others (negligible)

the multimessenger link: particle interactions and acceleration

particle acceleration



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photopion production

$p + \gamma_{bg} \rightarrow p + \pi^0$

$p + \gamma_{bg} \rightarrow n + \pi^+$ *(similar for nuclei)*

Bethe-Heitler pair production

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A,Z) + e^- + e^+$

photodisintegration

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z) + \mathbf{n}$

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \text{nucleus}(A\text{-}1,Z\text{-}1) + p$

$\text{nucleus}(A,Z) + \gamma_{bg} \rightarrow \ldots$

nuclear decays

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A\text{-}4,Z\text{-}2) + \alpha$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{+}1) + e^- + \underline{\nu_e}$

$\text{nucleus}(A,Z) \rightarrow \text{nucleus}(A,Z\text{-}1) + e^{-+} + \nu_e$

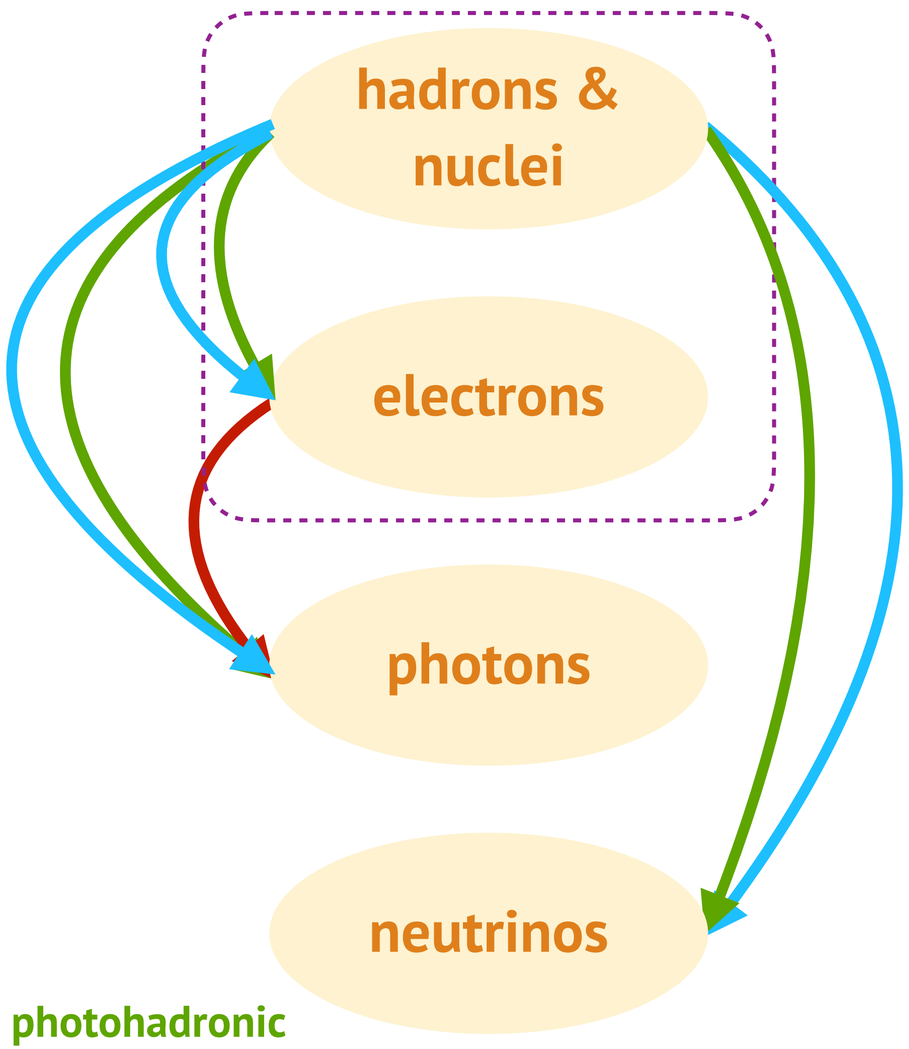
$\text{nucleus}(A,Z)^* \rightarrow \text{nucleus}(A,Z) + \gamma$

nucleus-nucleus interactions

$p + p \rightarrow \ldots + \pi^0 + \pi^- + \pi^+$

the multimessenger link: particle interactions and acceleration

particle acceleration



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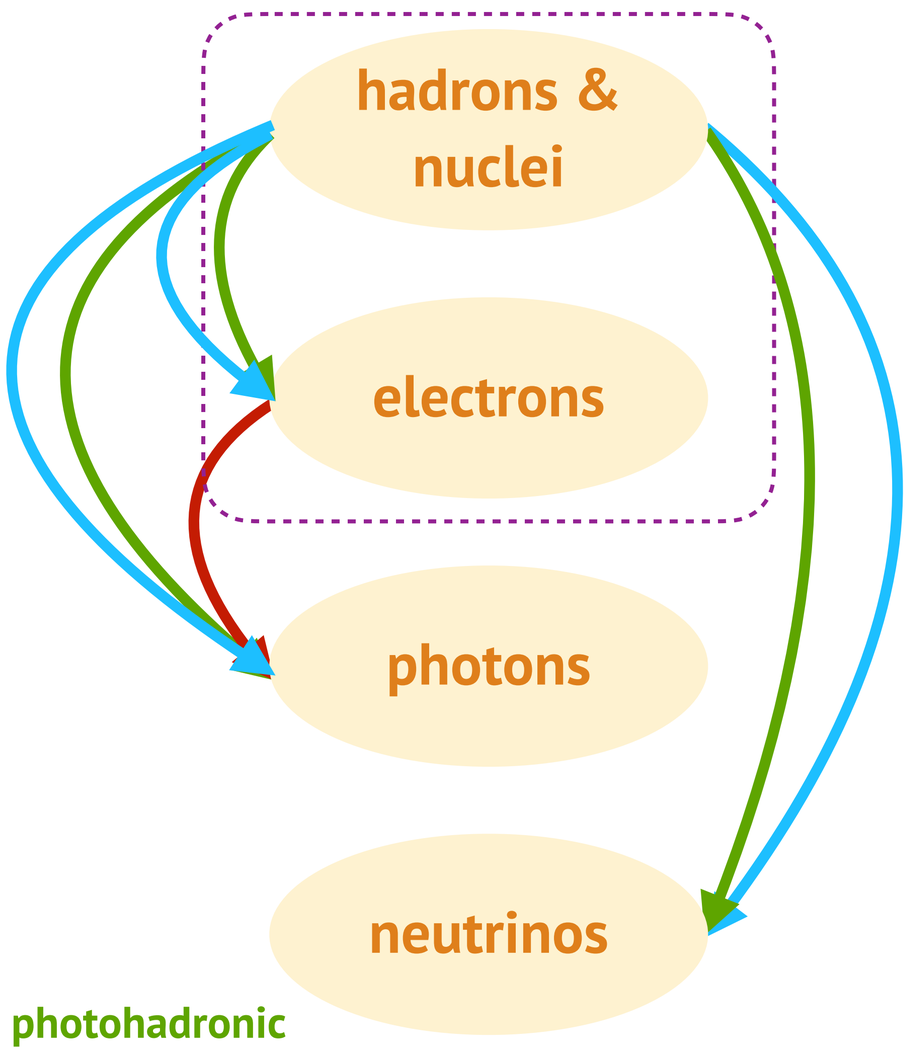

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decays

$\pi^0 \rightarrow \gamma + \gamma$

$\pi^+ \rightarrow \nu_\mu + \mu^+$

$\pi^- \rightarrow \underline{\nu_\mu} + \mu^-$

$\mu^+ \rightarrow e^+ + \nu_e + \underline{\nu_\mu}$

$\mu^- \rightarrow e^- + \underline{\nu_e} + \nu_\mu$

$n \rightarrow p + e^- + \underline{\nu_e}$

...

pair production

$\gamma + \gamma_{bg} \rightarrow e^- + e^+$

double pair production

$\gamma + \gamma_{bg} \rightarrow e^- + e^+ + e^- + e^+$

inverse Compton scattering

$e^\pm + \gamma_{bg} \rightarrow e^\pm + \gamma$

triplet pair production

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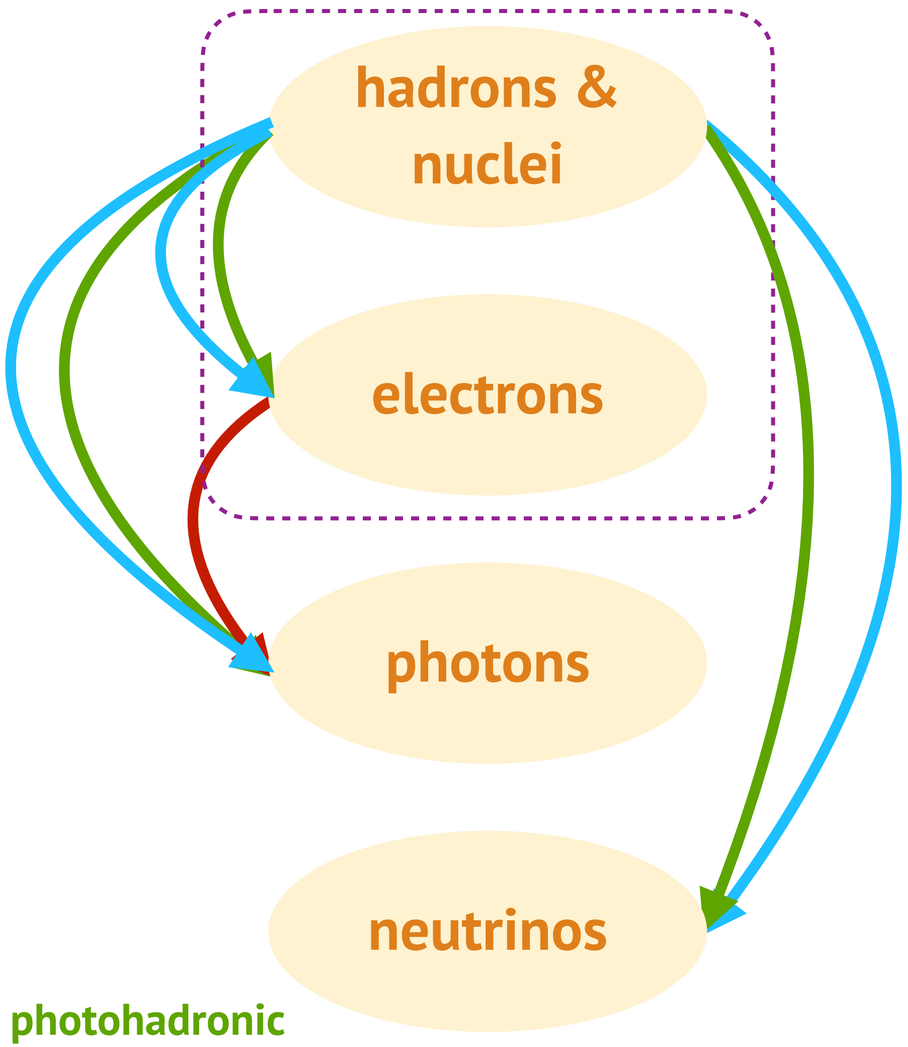
the multimessenger link: particle interactions and acceleration

particle acceleration



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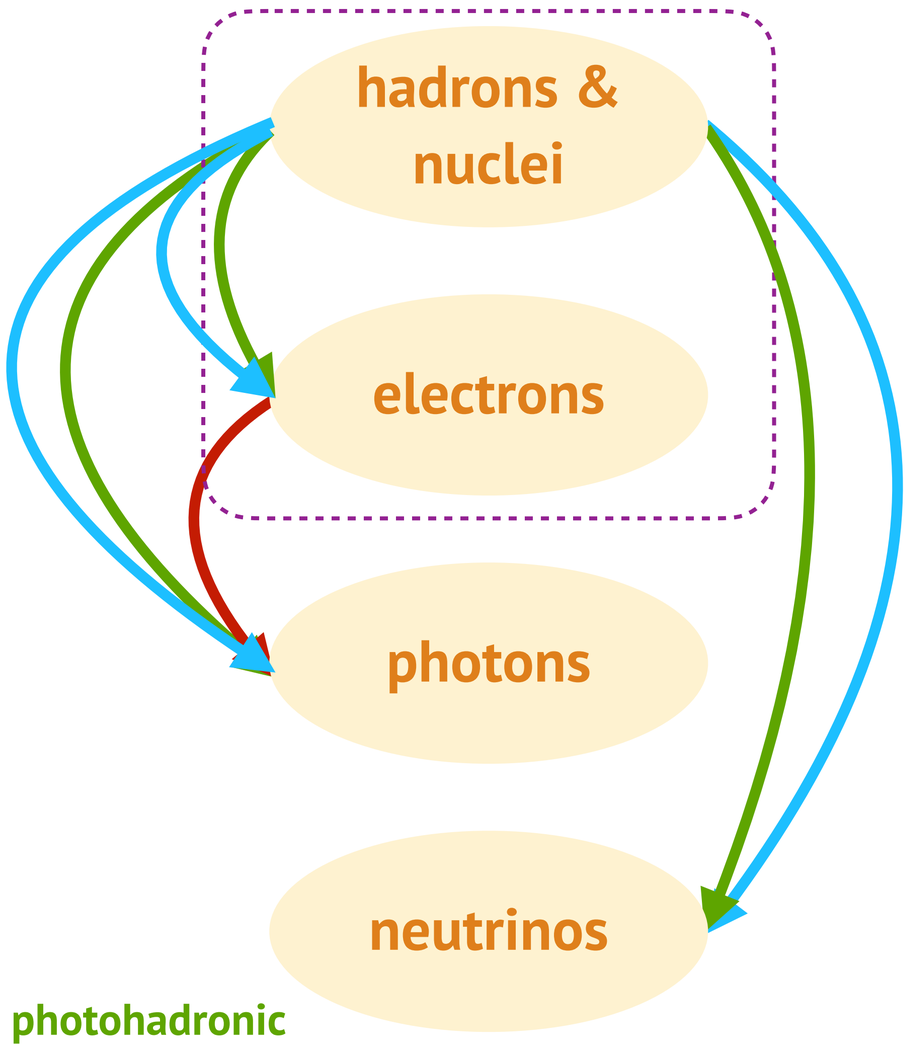

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$\text{nucleus}(A,Z) +$

cosmic rays → ν, γ

electrons → γ

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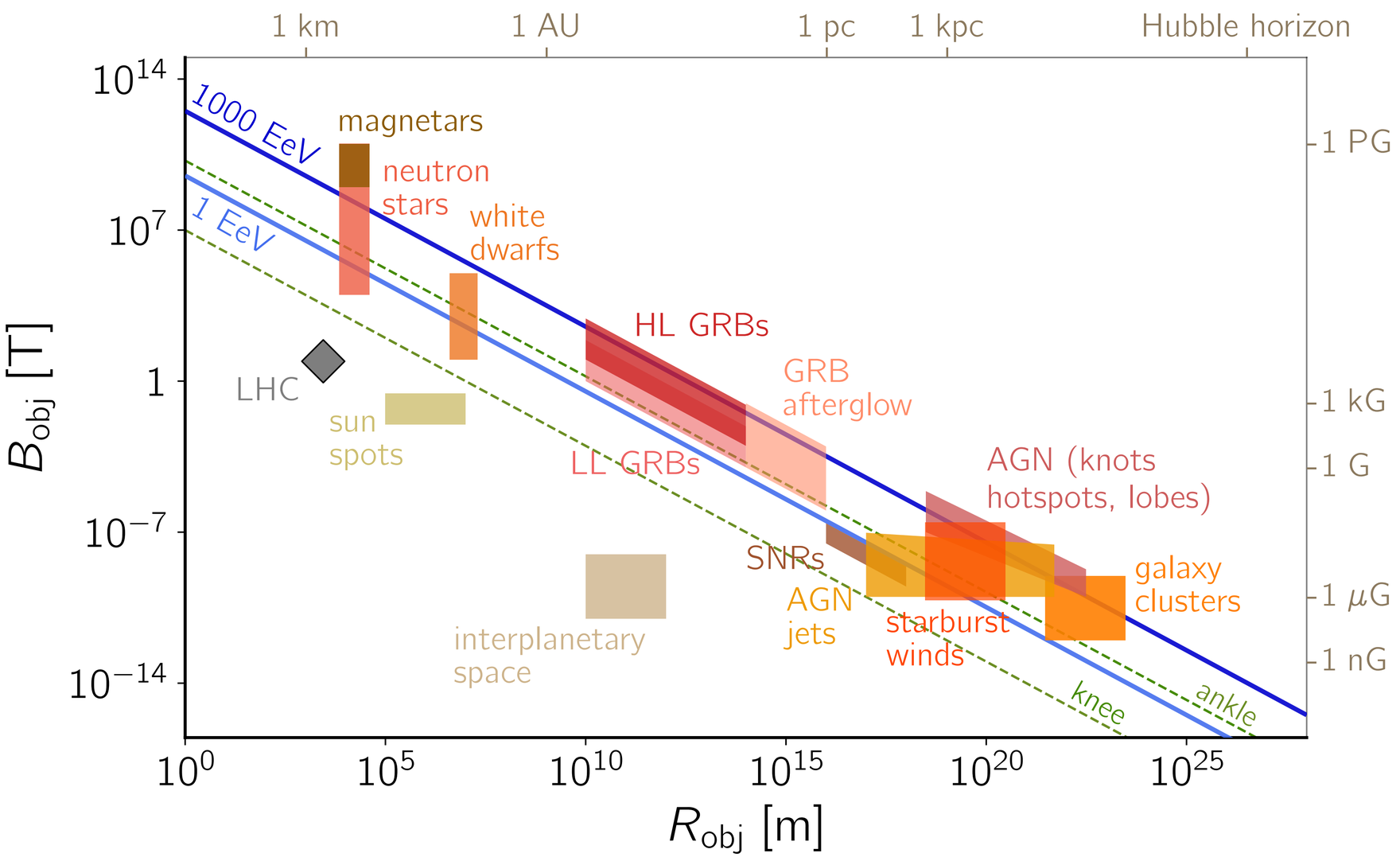
high-energy emission by galaxy clusters: particle acceleration



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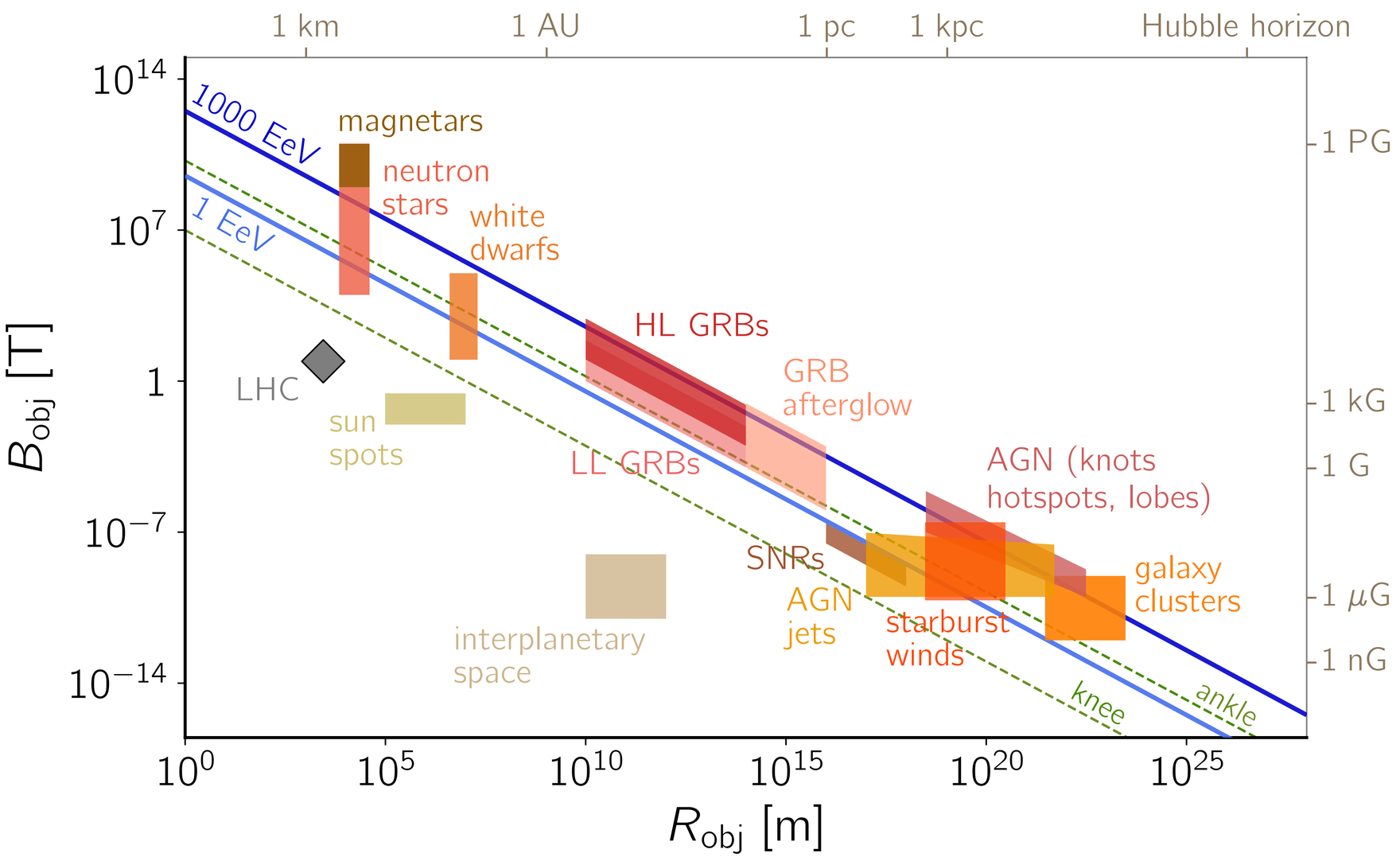

Hillas criterion

$$E_{\rm max} \sim 2qv_{\rm sh}BR_{\rm L} \sim 10^{18}Z\left(\frac{B}{\mu{\rm G}}\right)\left(\frac{R}{\rm kpc}\right)\ {\rm eV}$$

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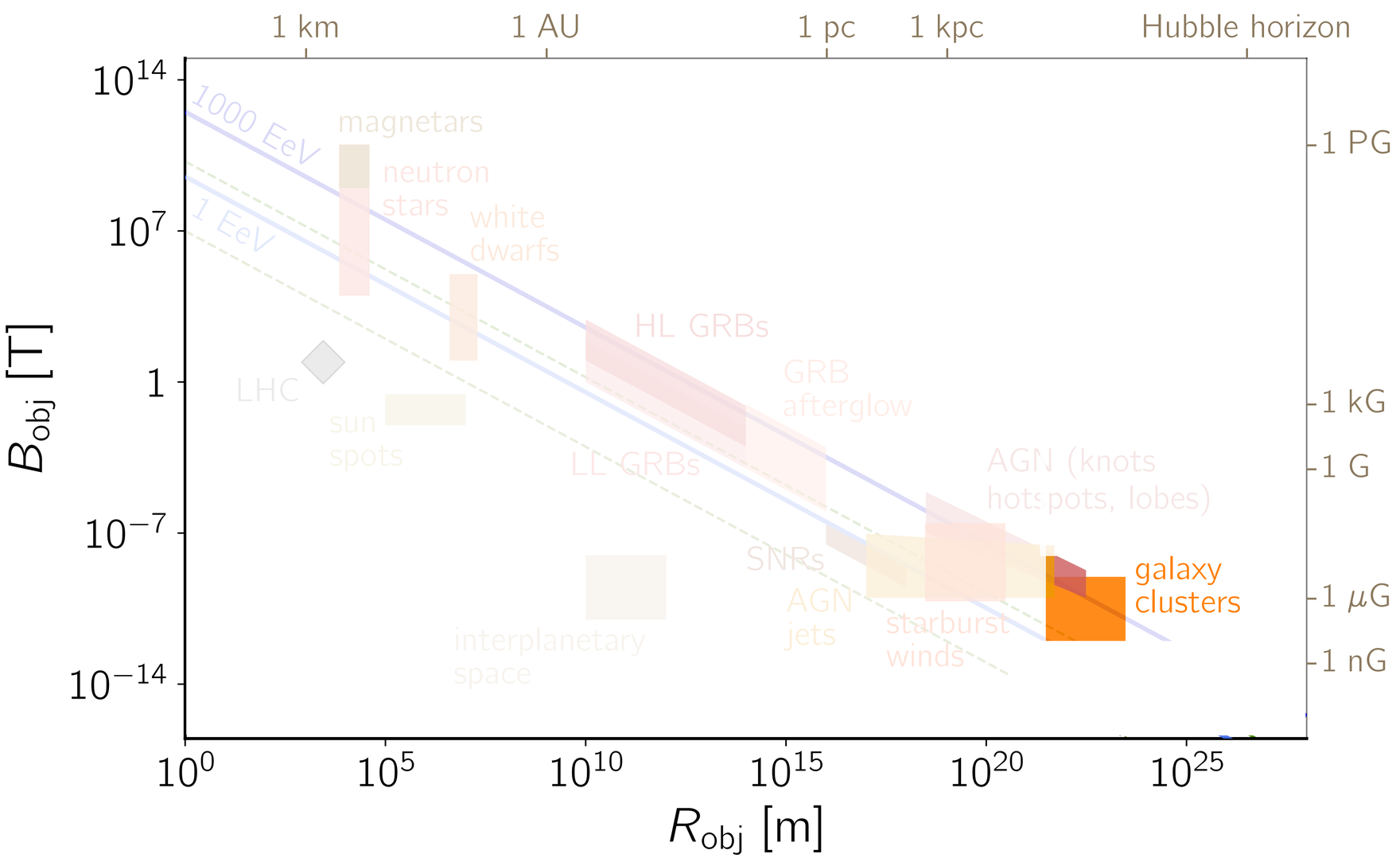

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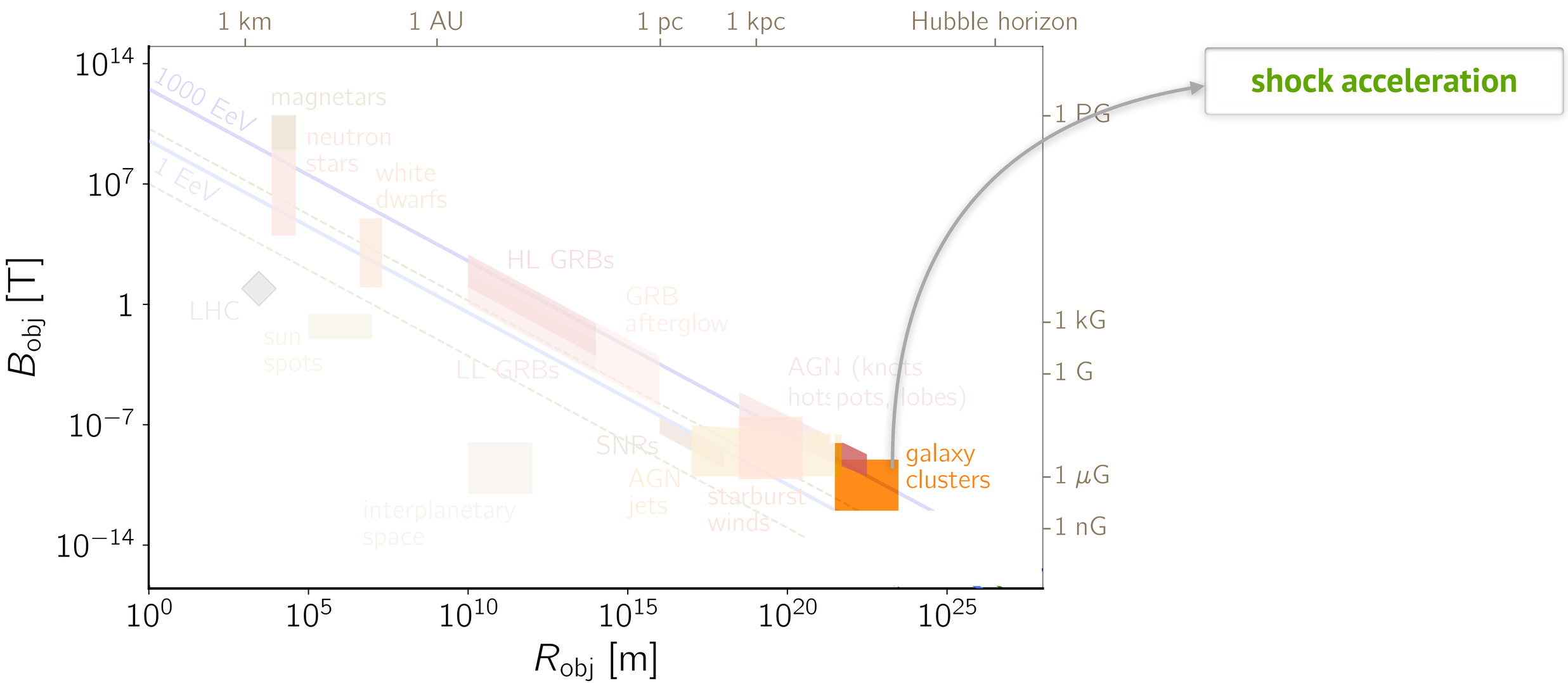

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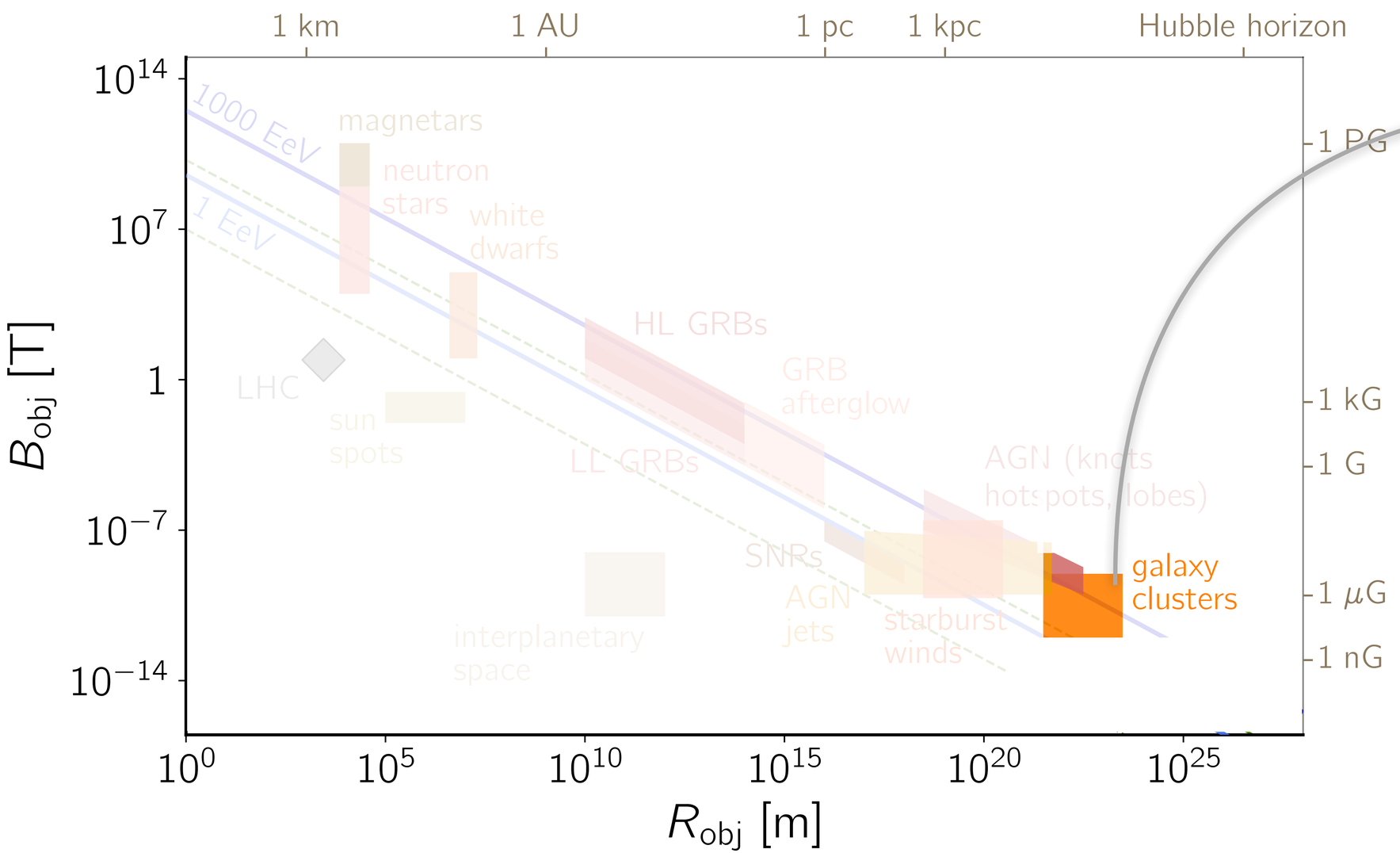

shock acceleration

neutrino and gamma-ray emission?

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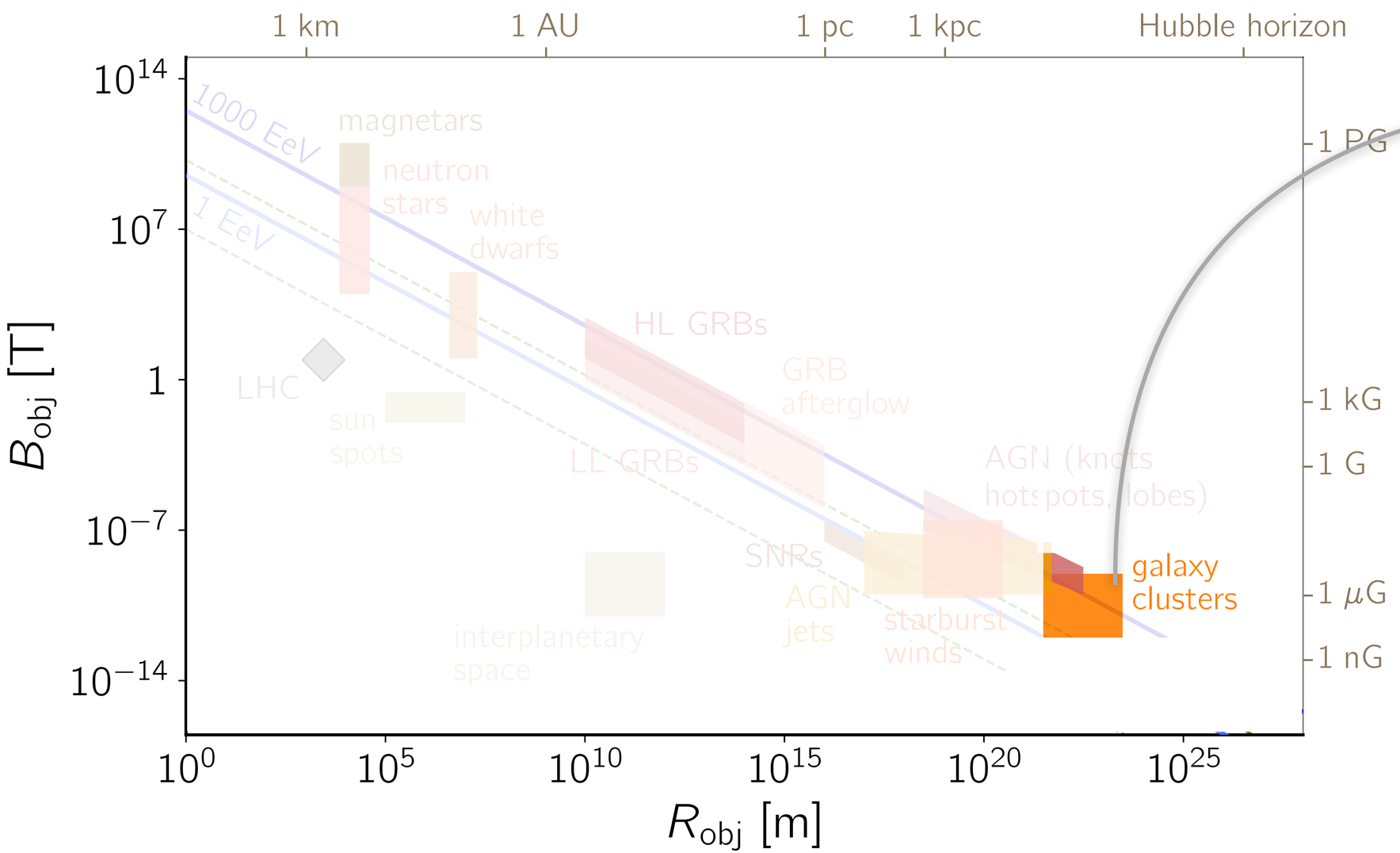

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shock acceleration

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embedded cosmic accelerators

propagation of CRs in the intracluster medium

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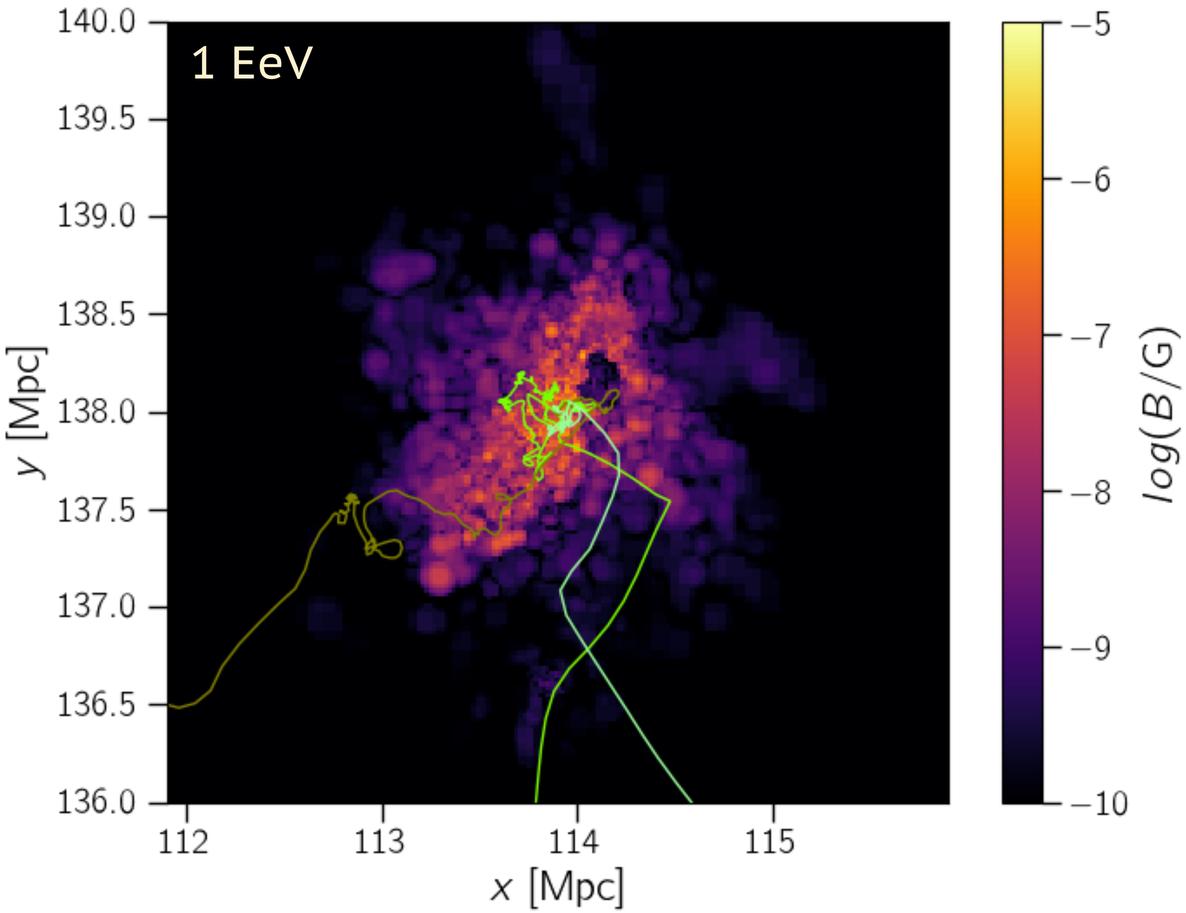
Alves Batista, de Gouveia Dal Pino, Dolag, Hussain. Proceedings IAU 2018 FM8. arXiv:1811.03062



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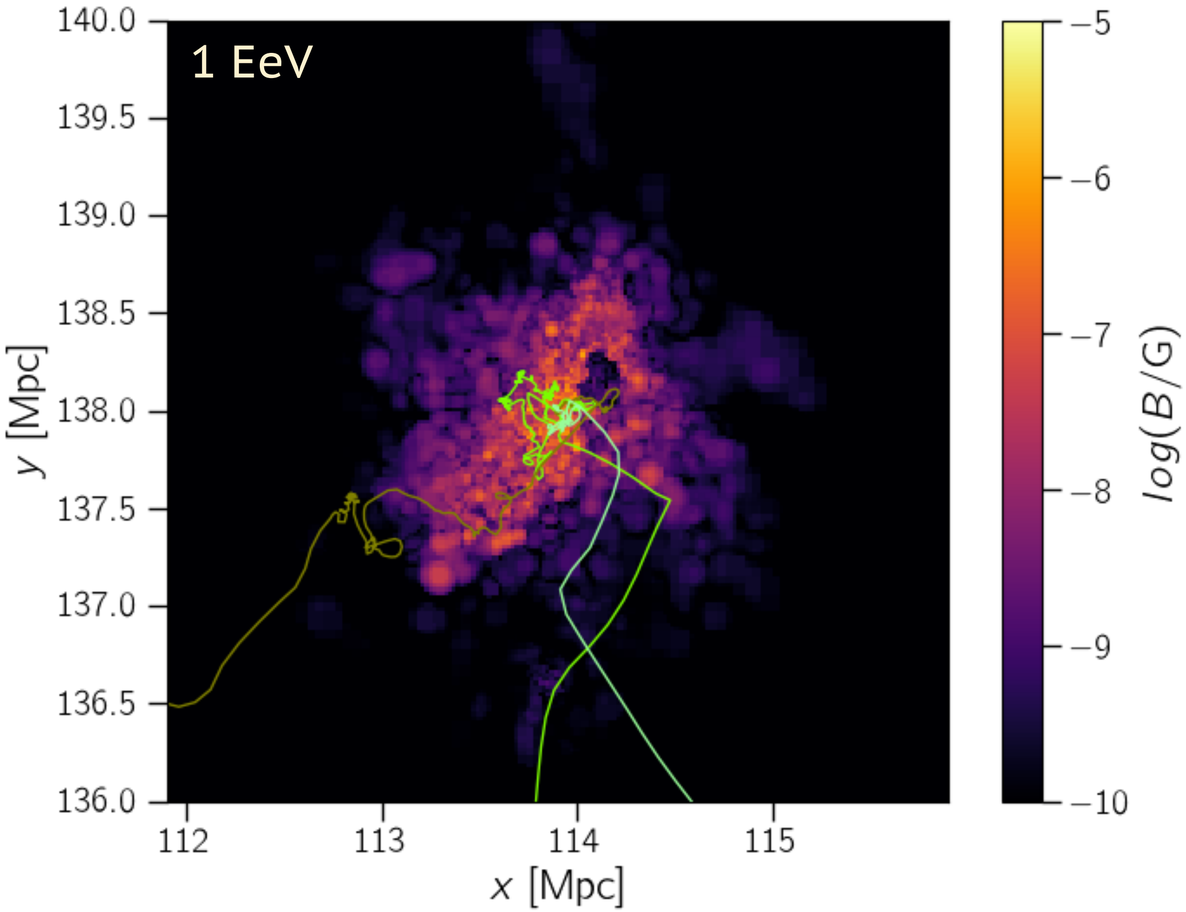

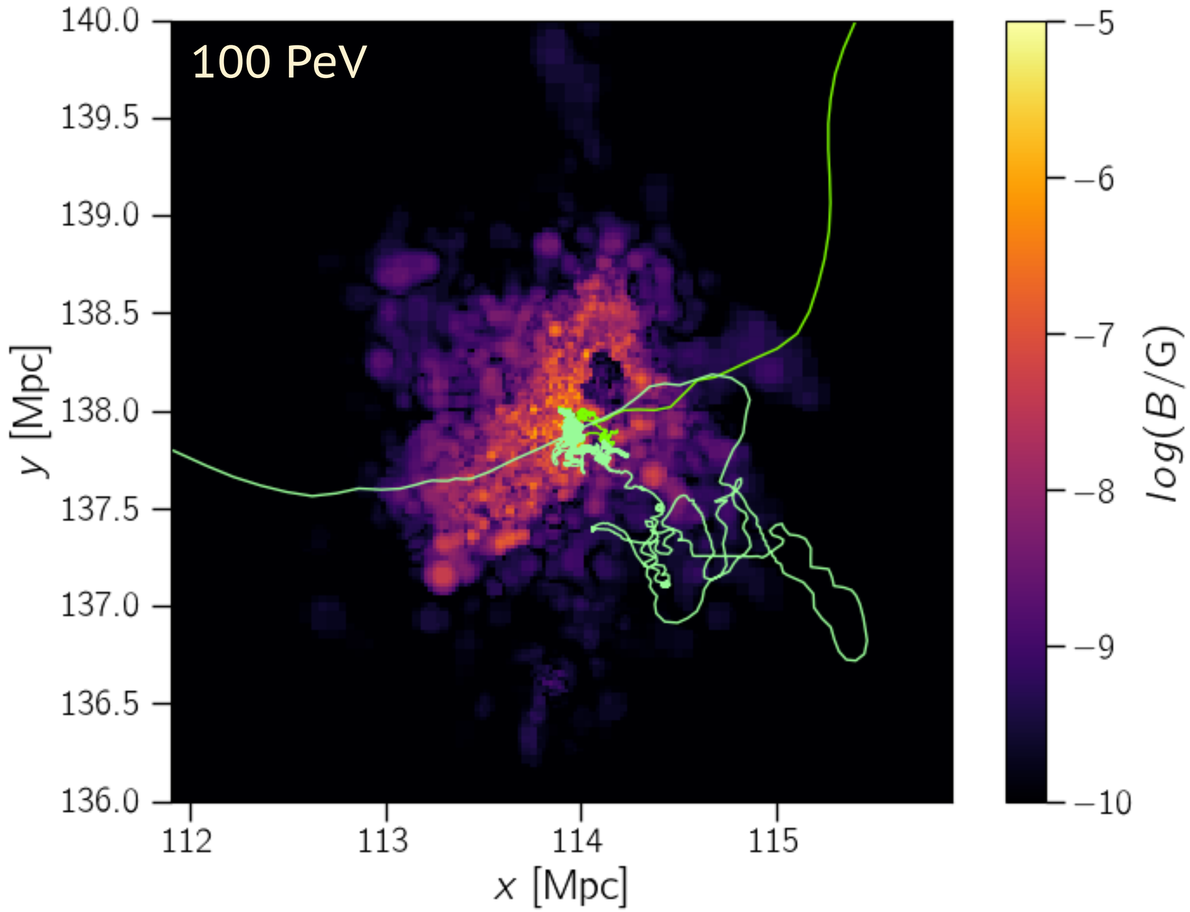

cosmological MHD simulations

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Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702

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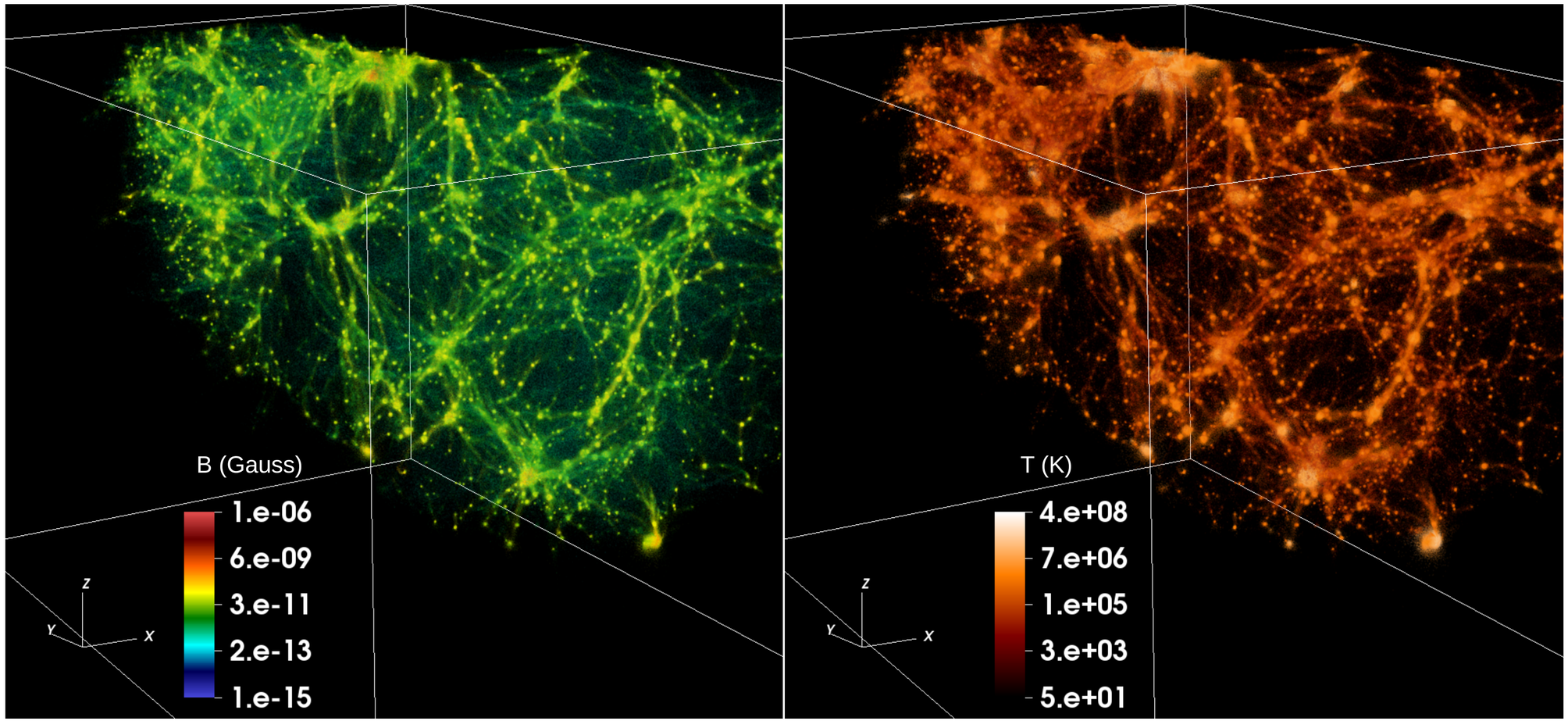
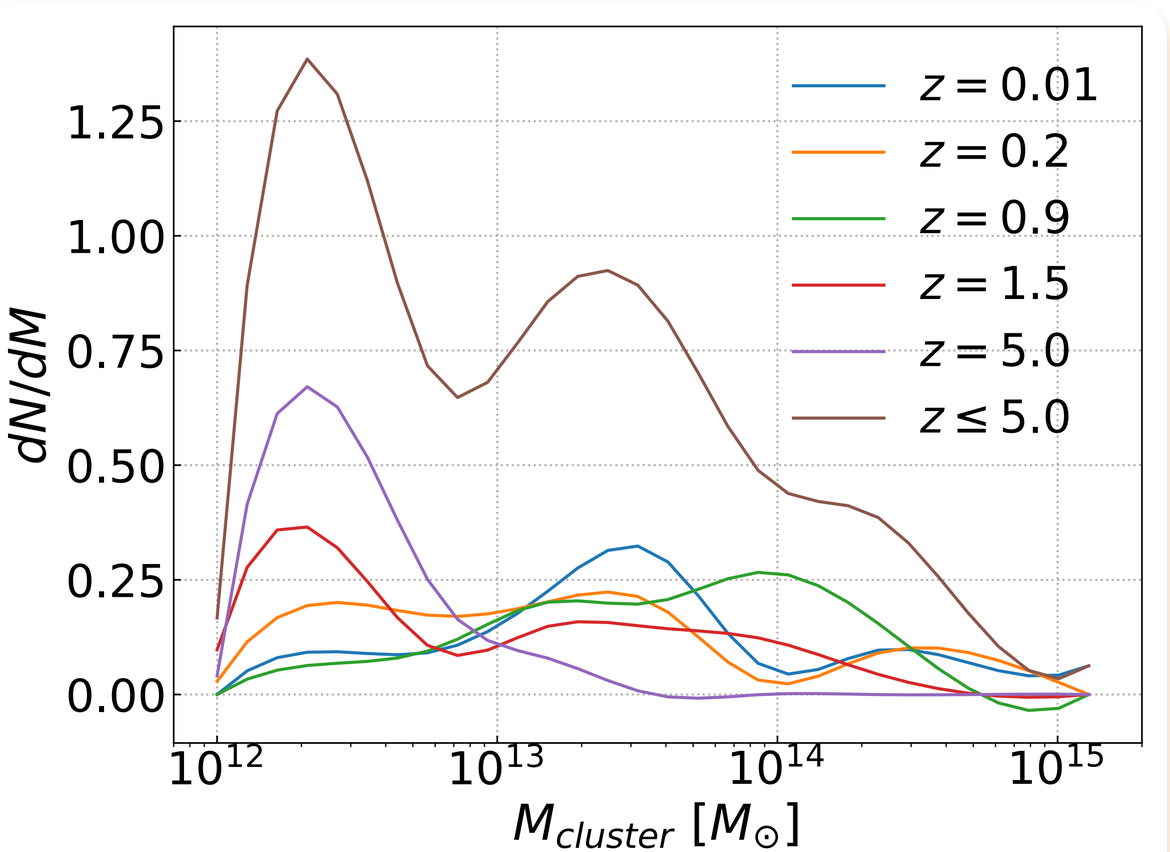
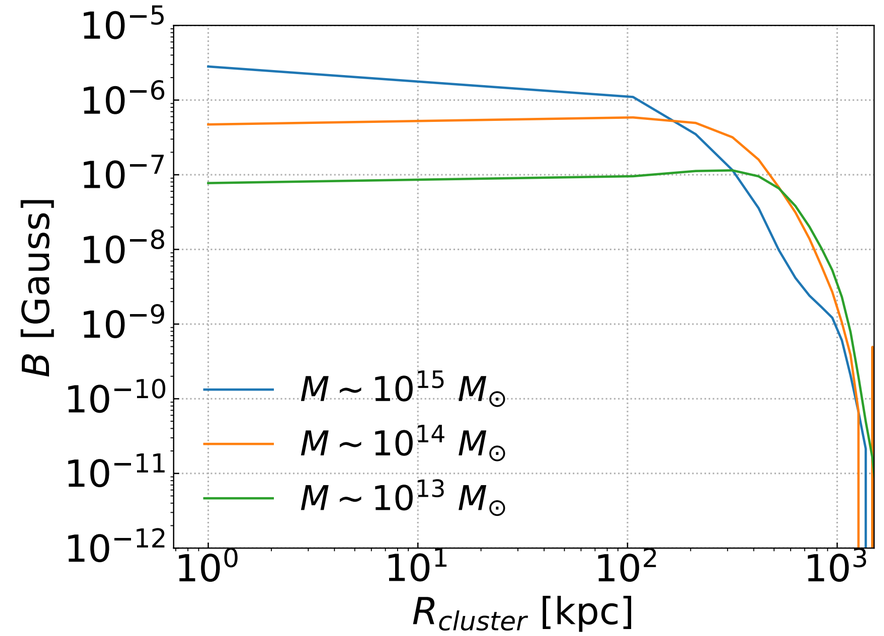
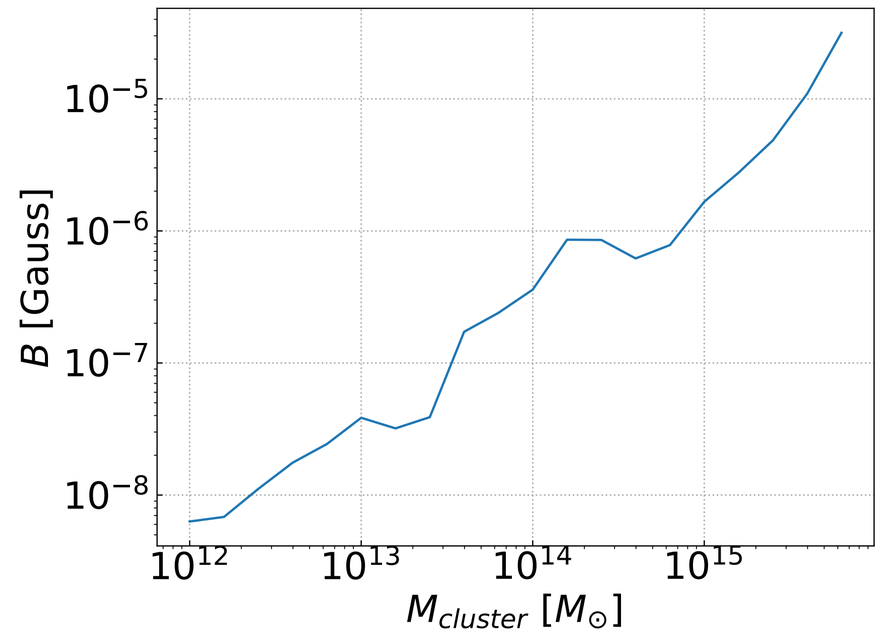


statistical properties of the galaxy clusters







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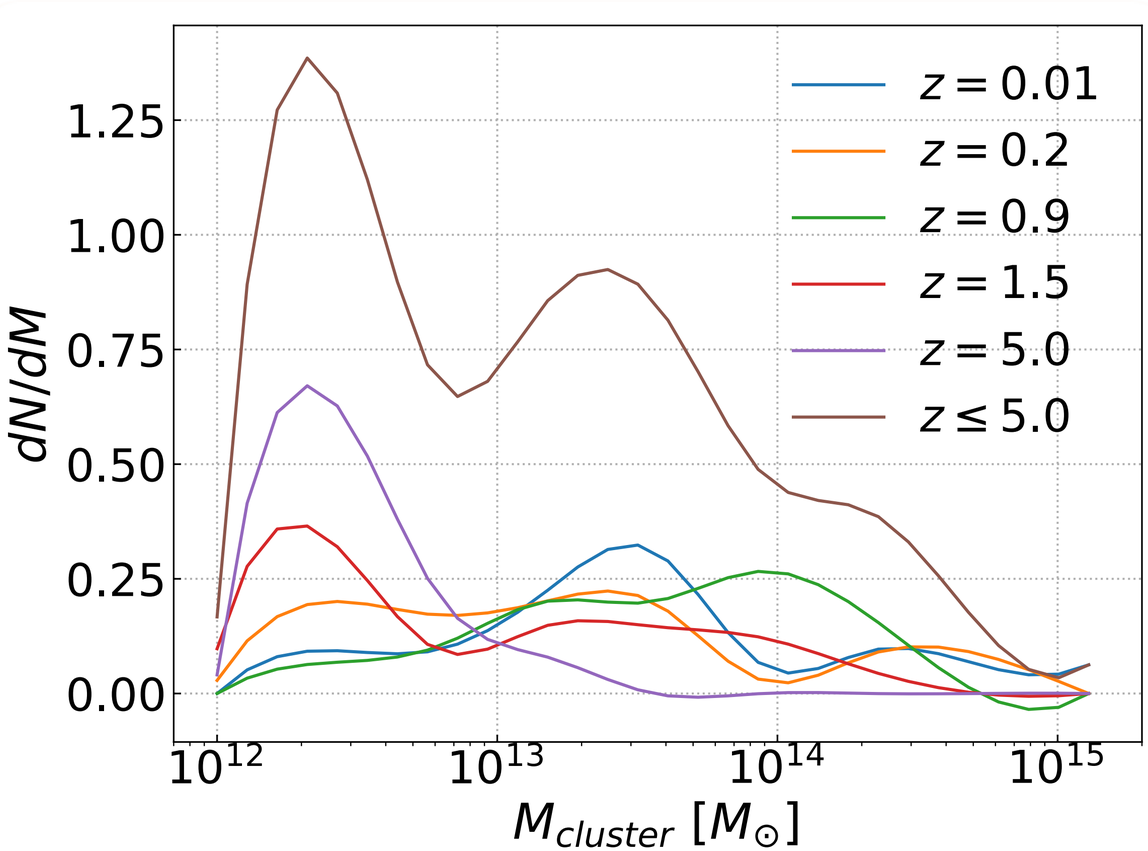
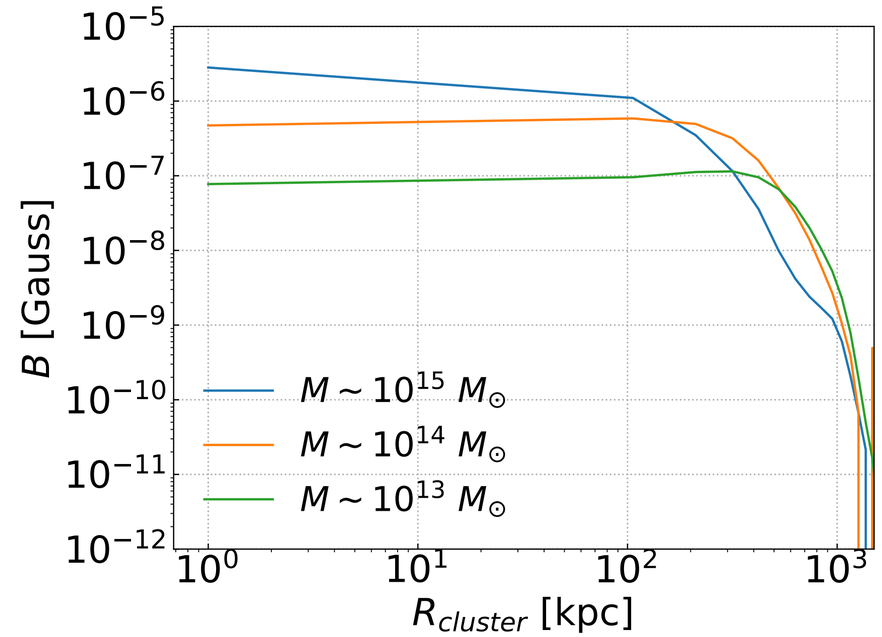
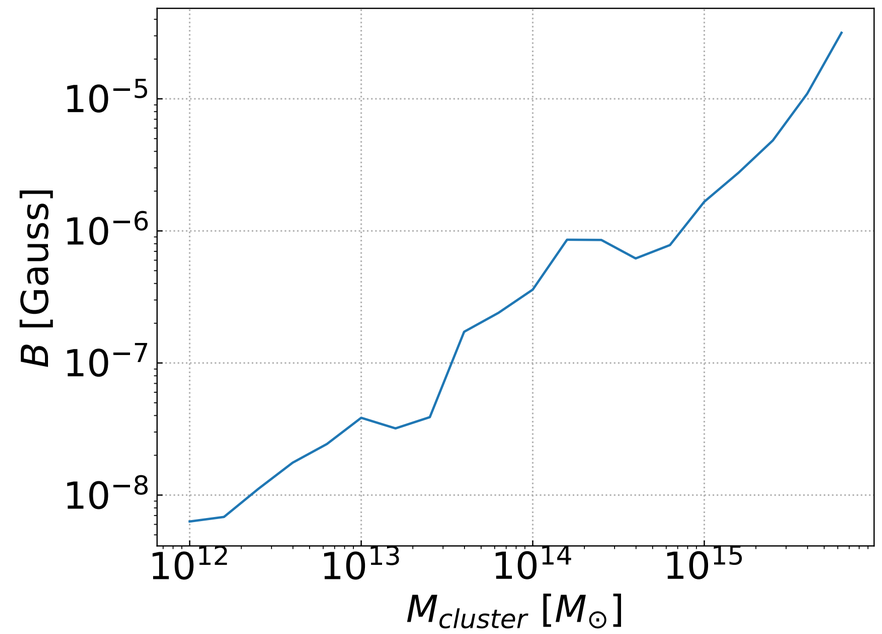
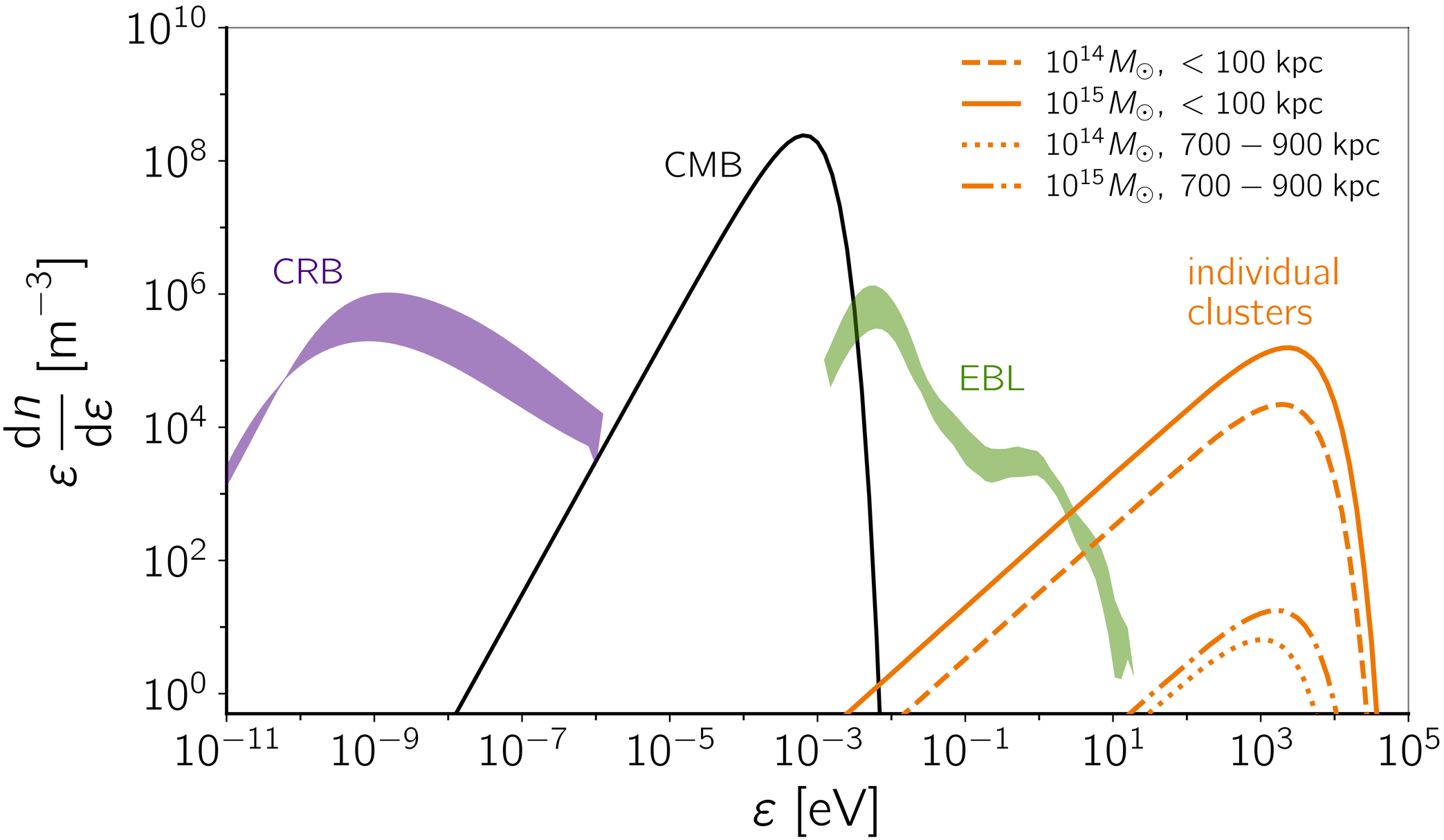


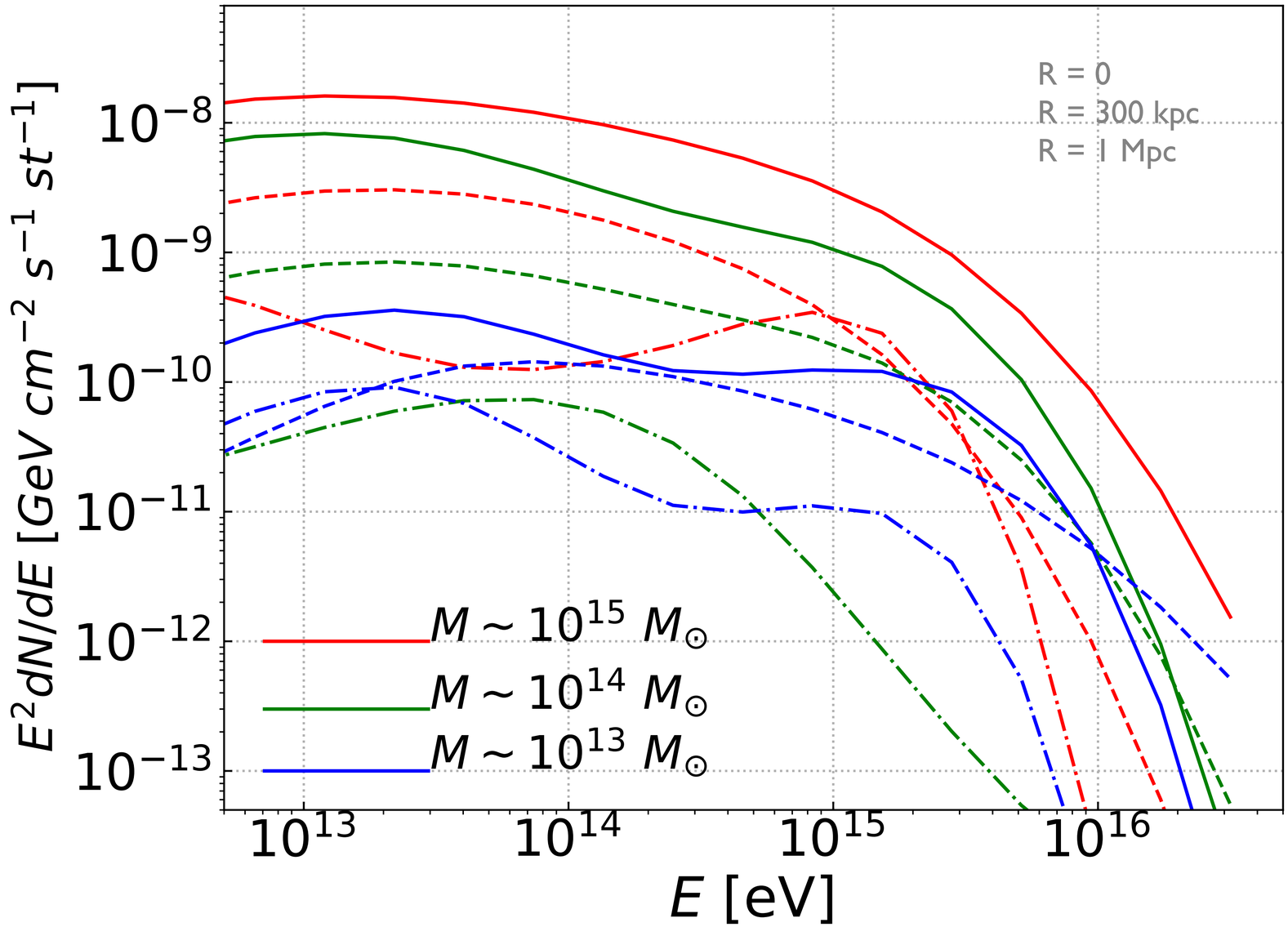




the photon field in clusters



neutrinos from individual clusters



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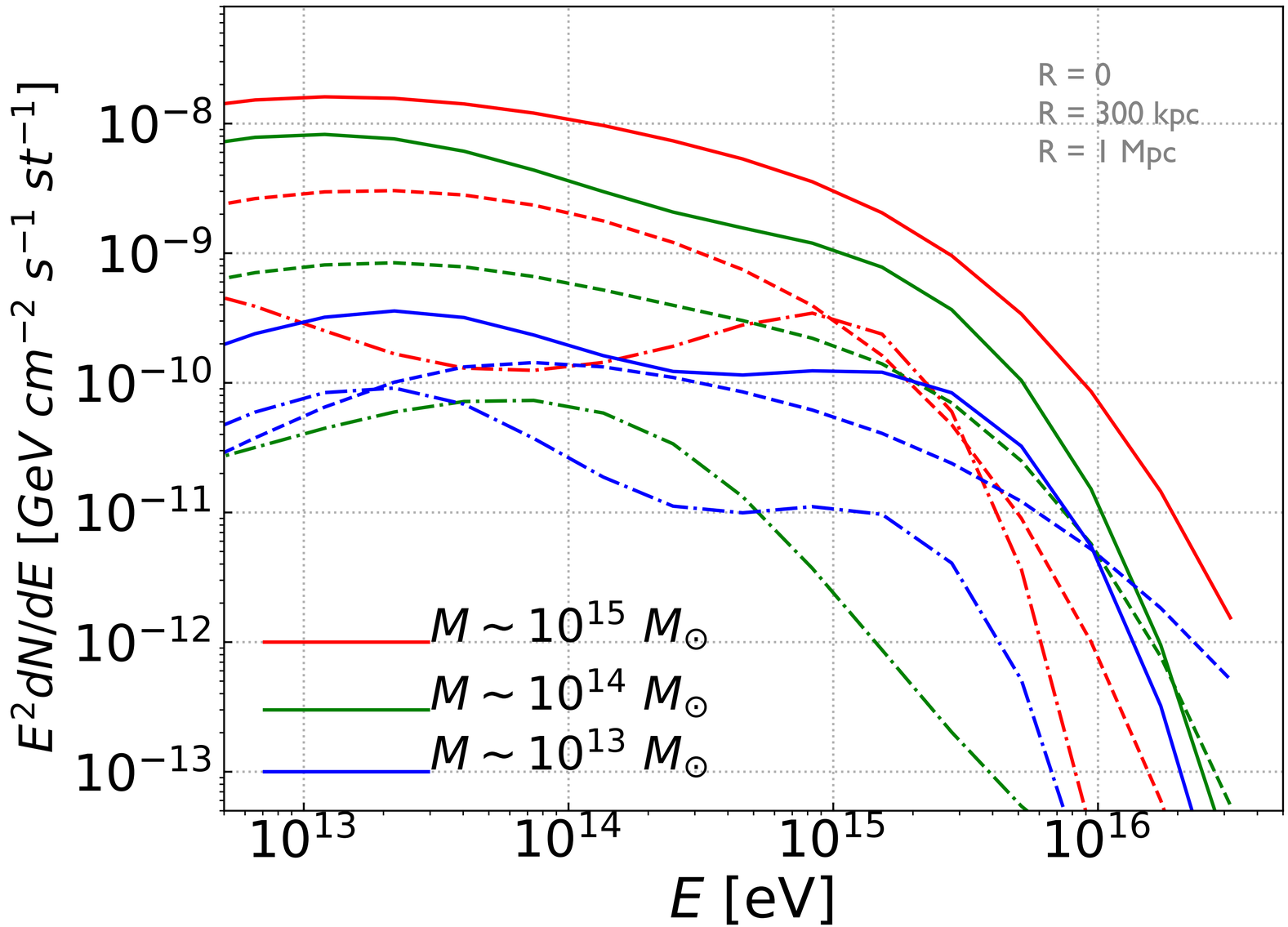
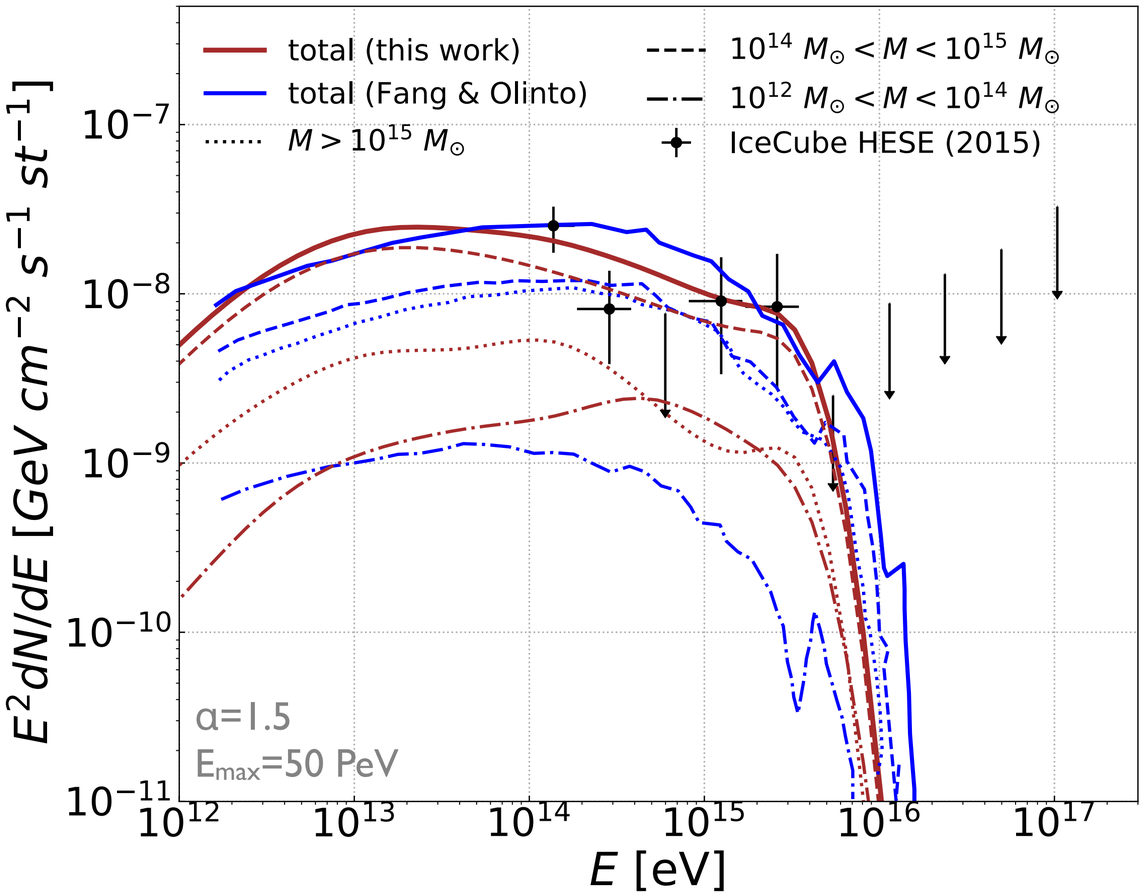
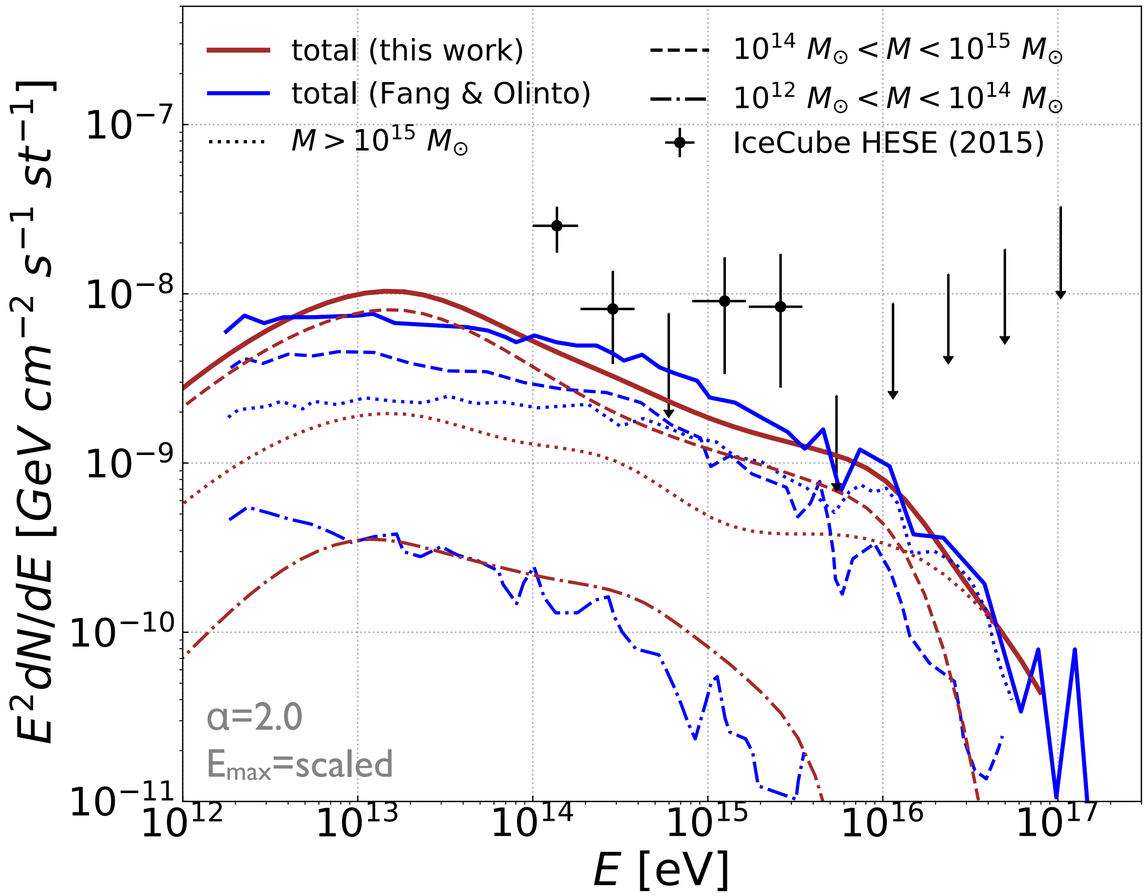


the diffuse neutrino flux due to galaxy clusters





$$E_{\text{max}} = 2.8 \times 10^{18} \left(\frac{M_{\text{cluster}}}{10^{15} M_\odot} \right)^{2/3} \left(\frac{B_{\text{cluster}}\ \text{G}}{10^{-6}\ \text{G}} \right)\ \text{eV}$$

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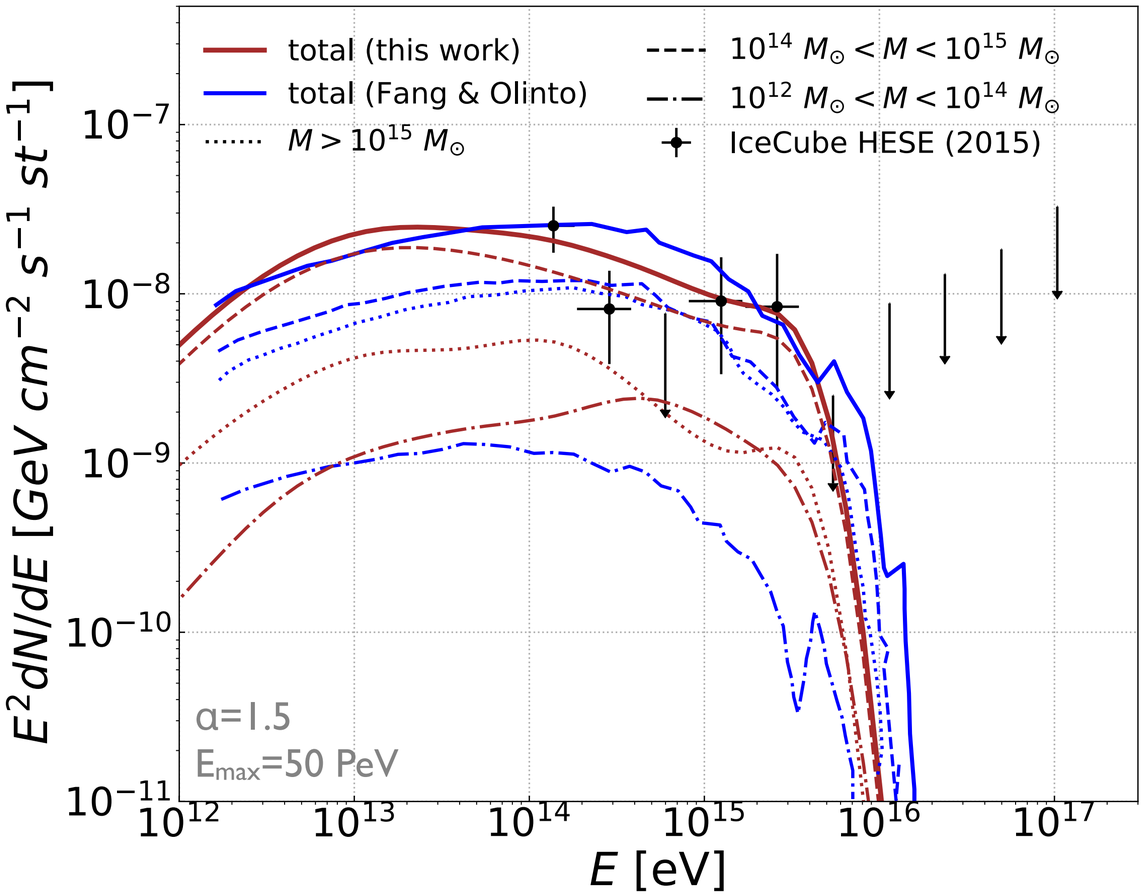

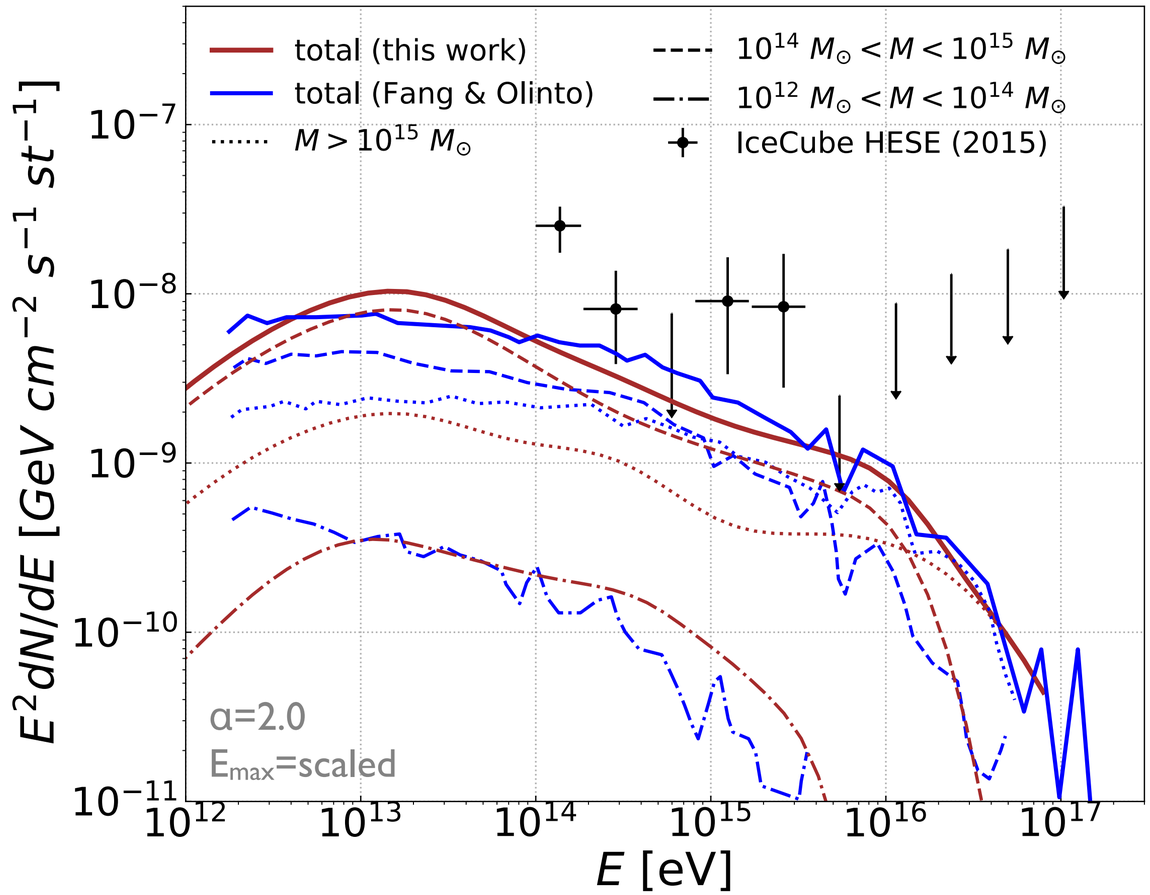

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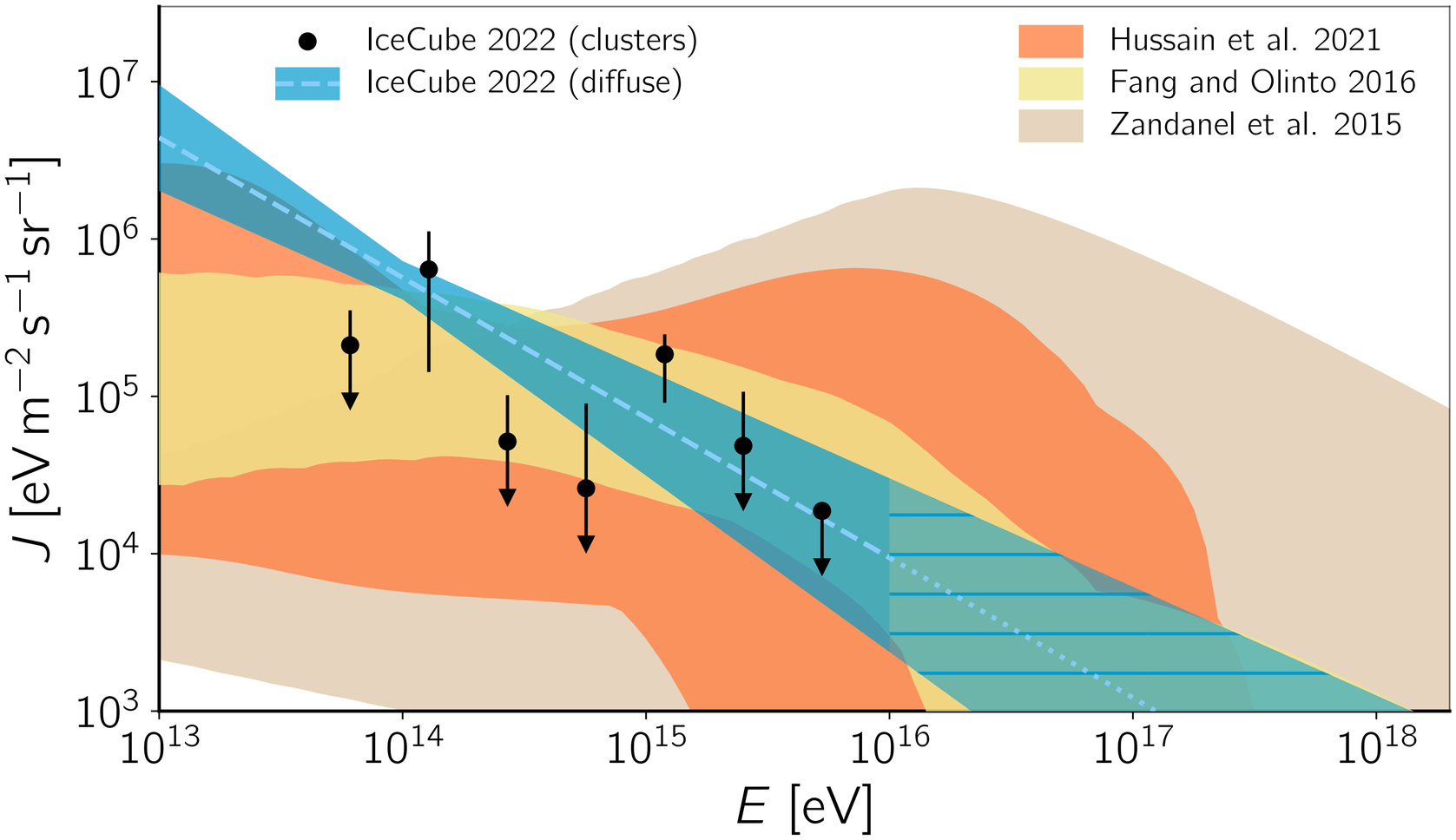

Hussain et al. 2021

embedded source
interactions: pp + pγ + EM
α = [1.5, 2.7]
E_{max} = [5, 500] PeV
source evolution = AGN, SFR, none
L_{CR} = [0.005, 0.05] L_{tot}

Fang and Olinto 2016

embedded source + accretion shocks
interactions: pp
α = [1.5, 2.0]
E_{max} = 50 PeV
L_{CR} = [0.005, 0.02] L_{tot}

Zandanel et al. 2015

accretion shocks
interactions: pp
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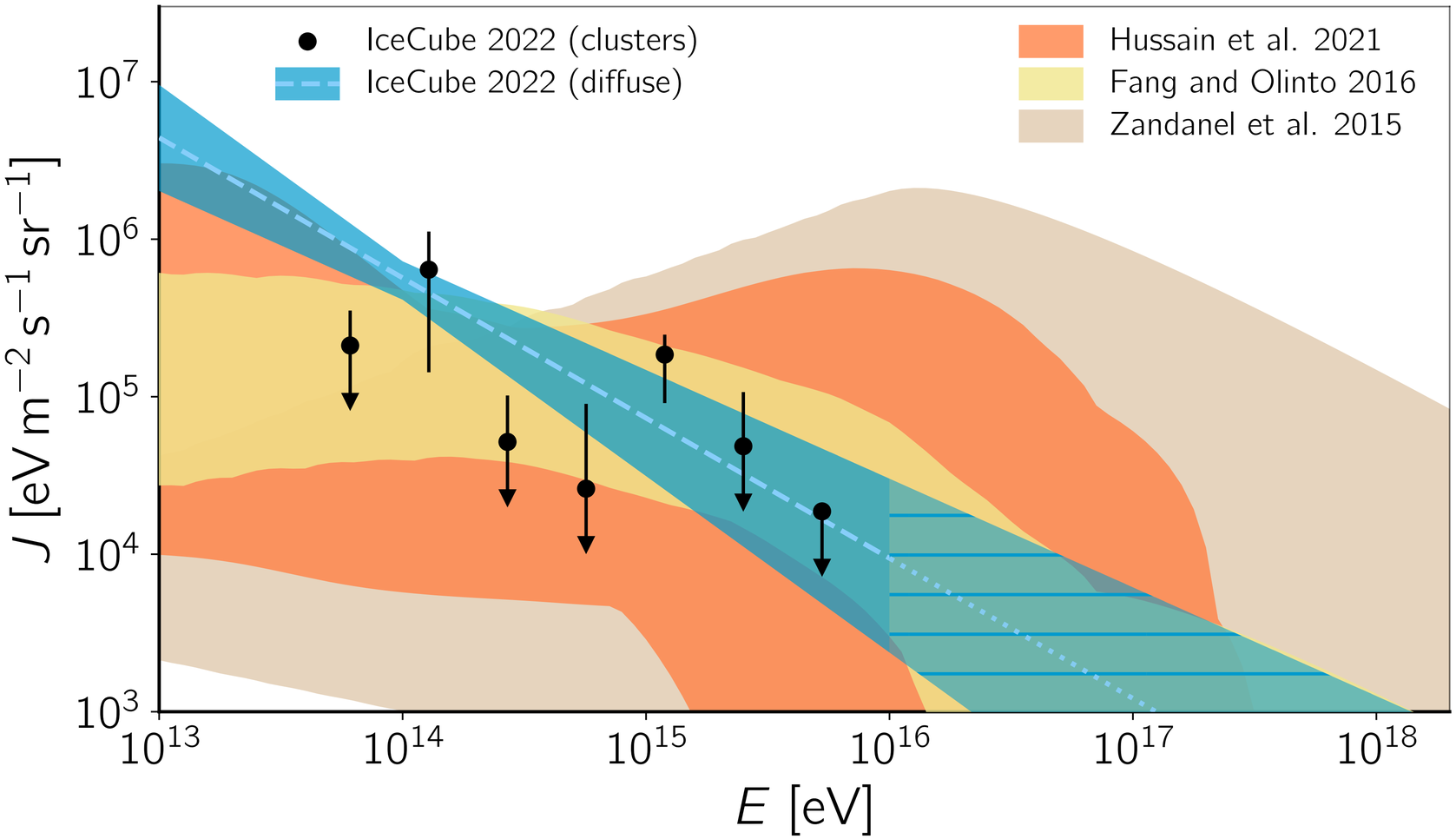

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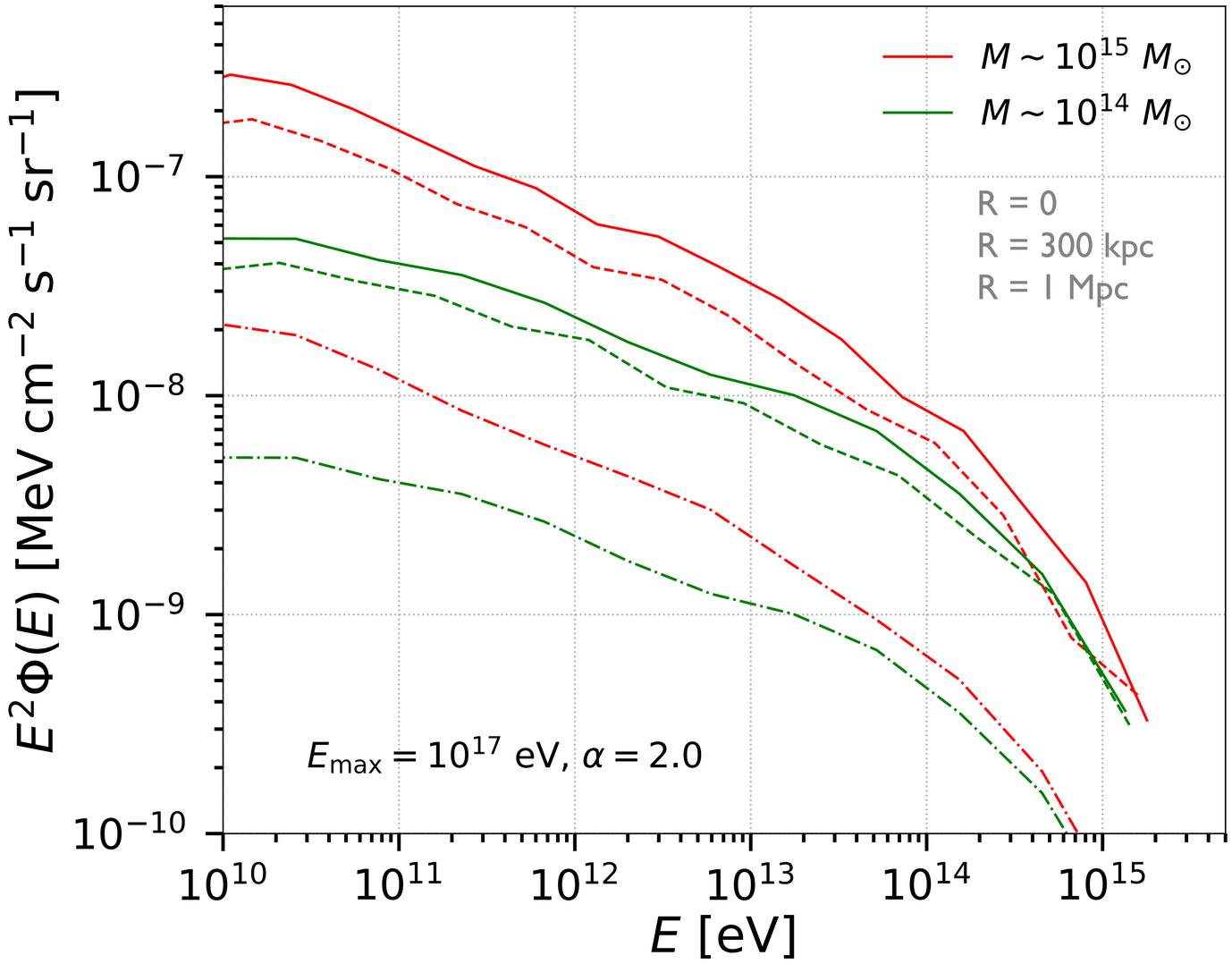

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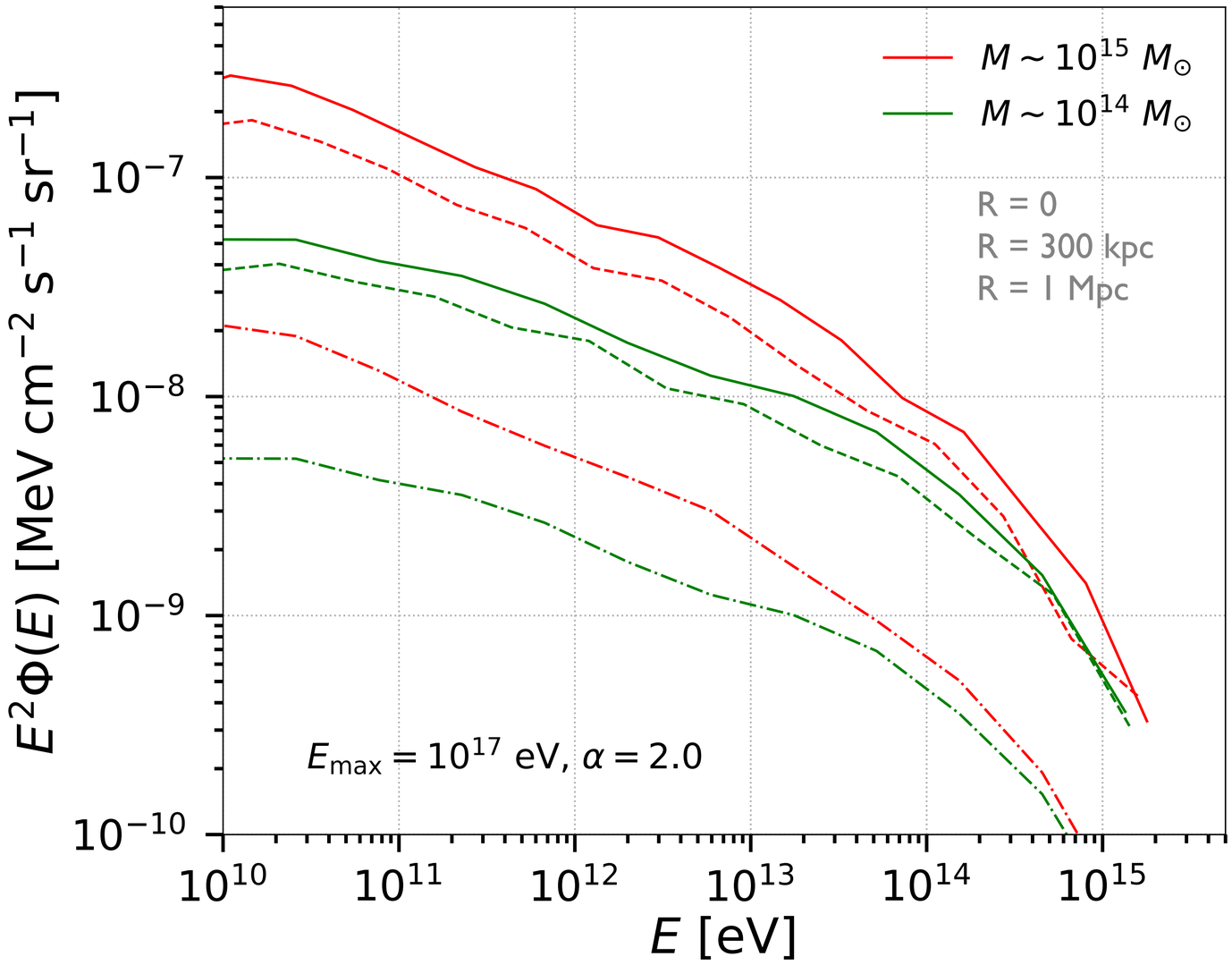

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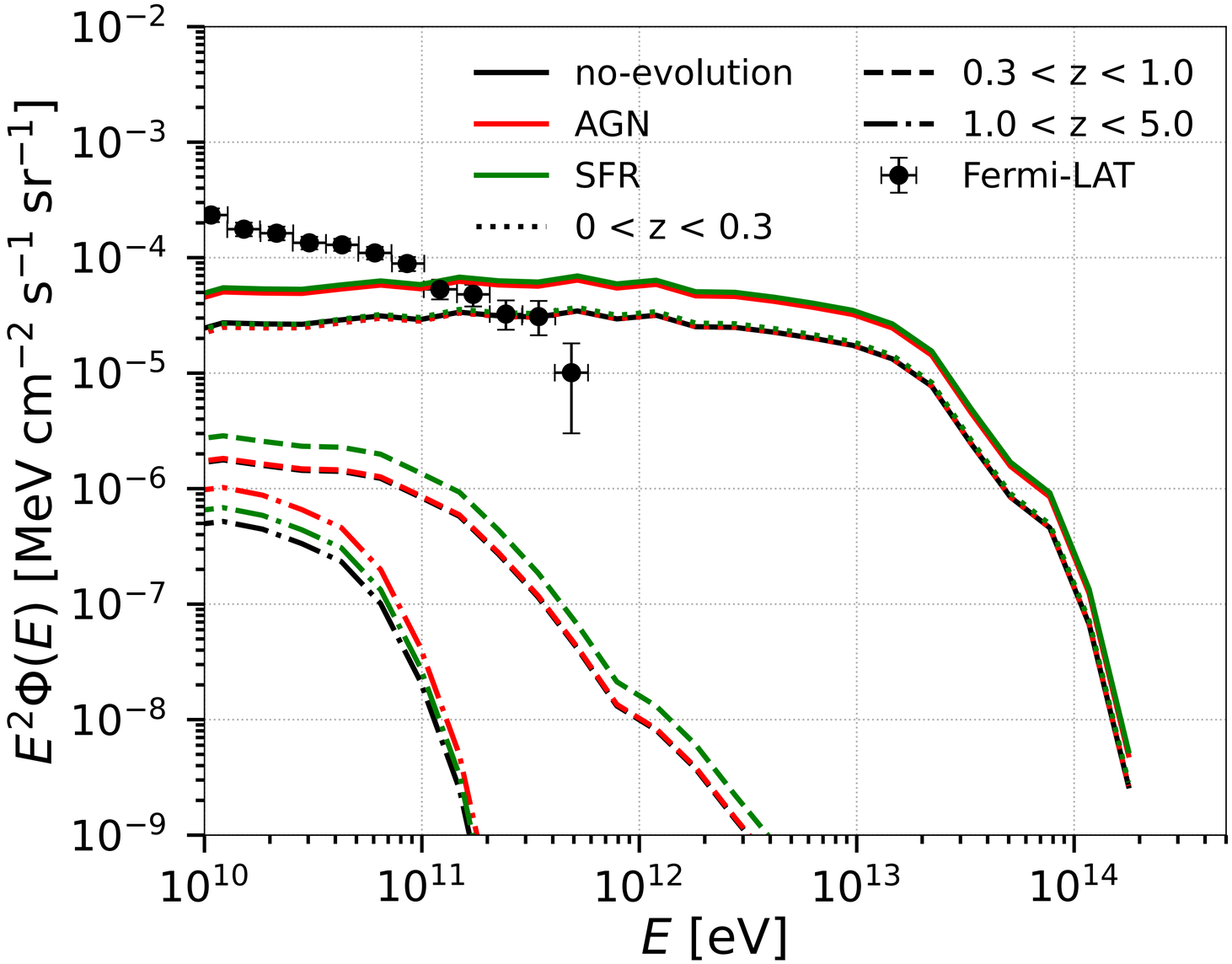

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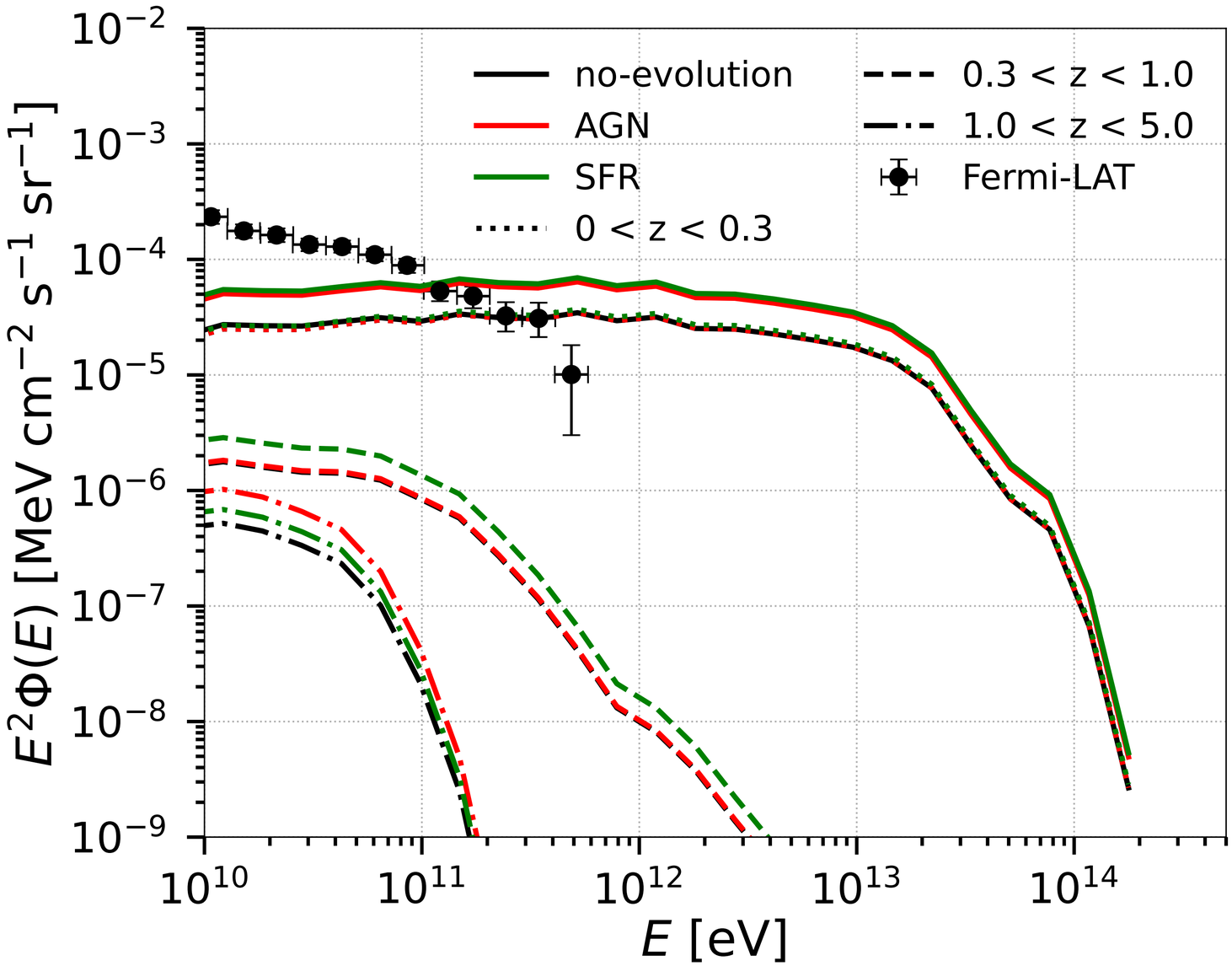

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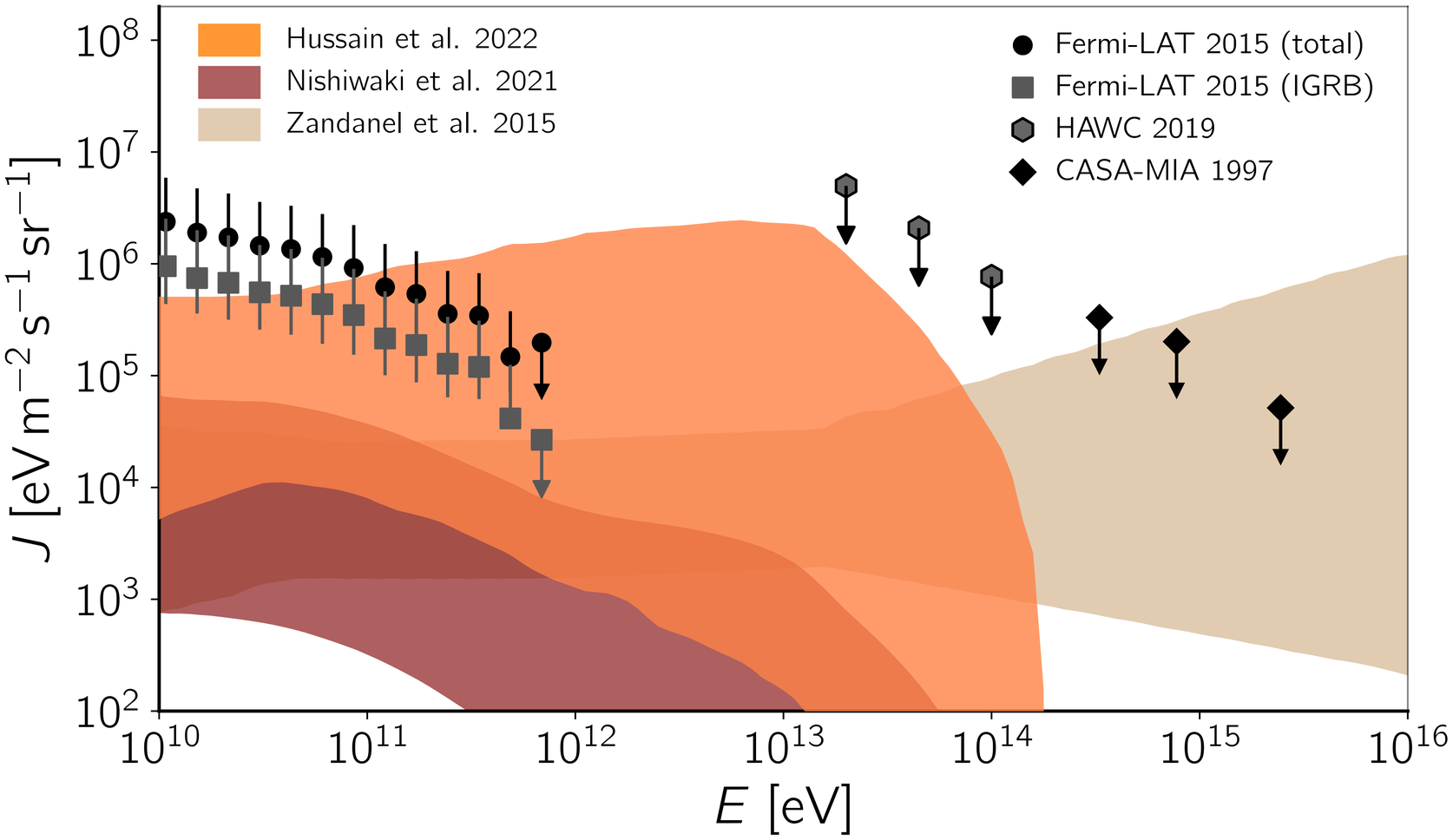

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Nishiwaki et al. 2021

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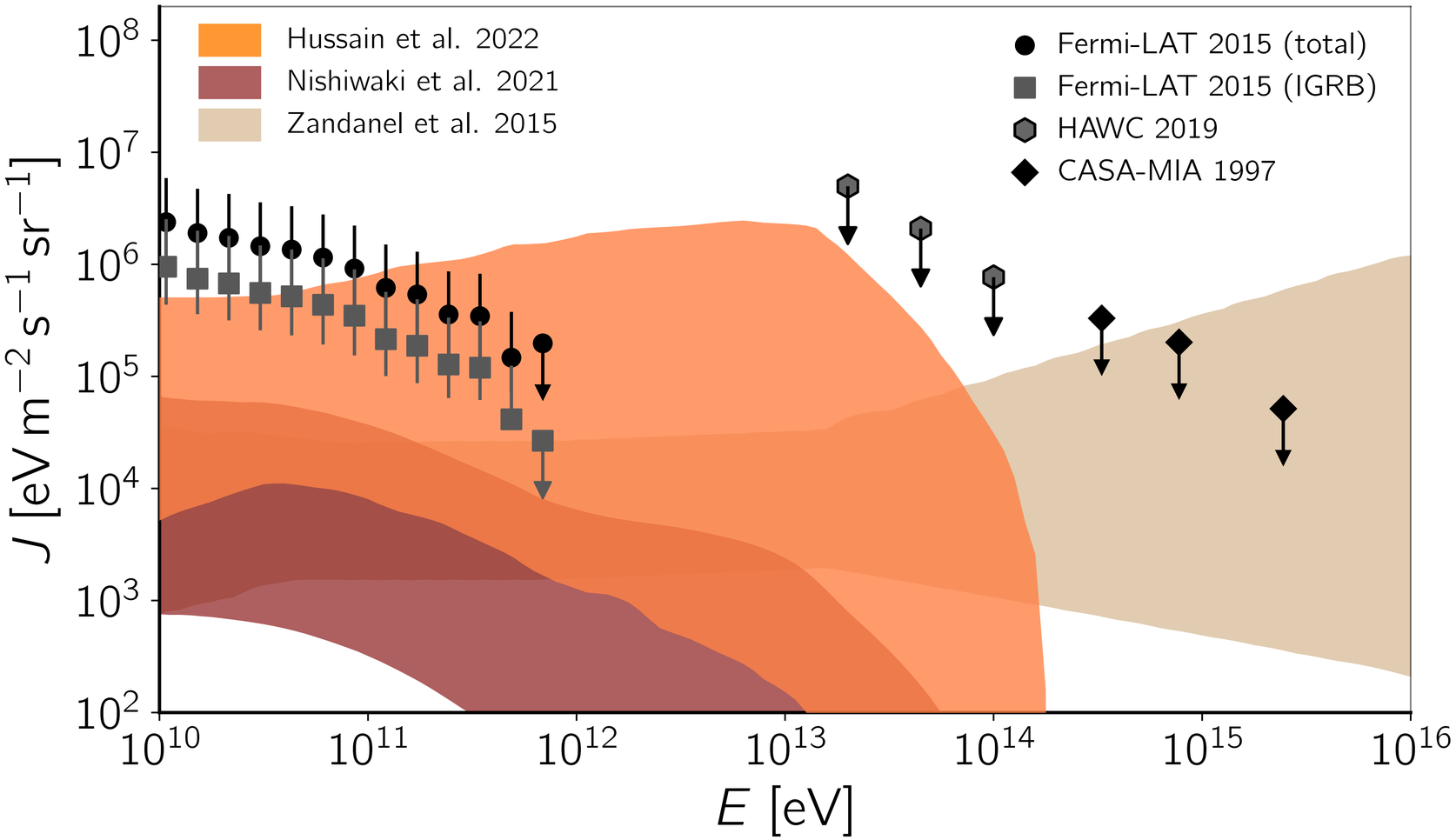

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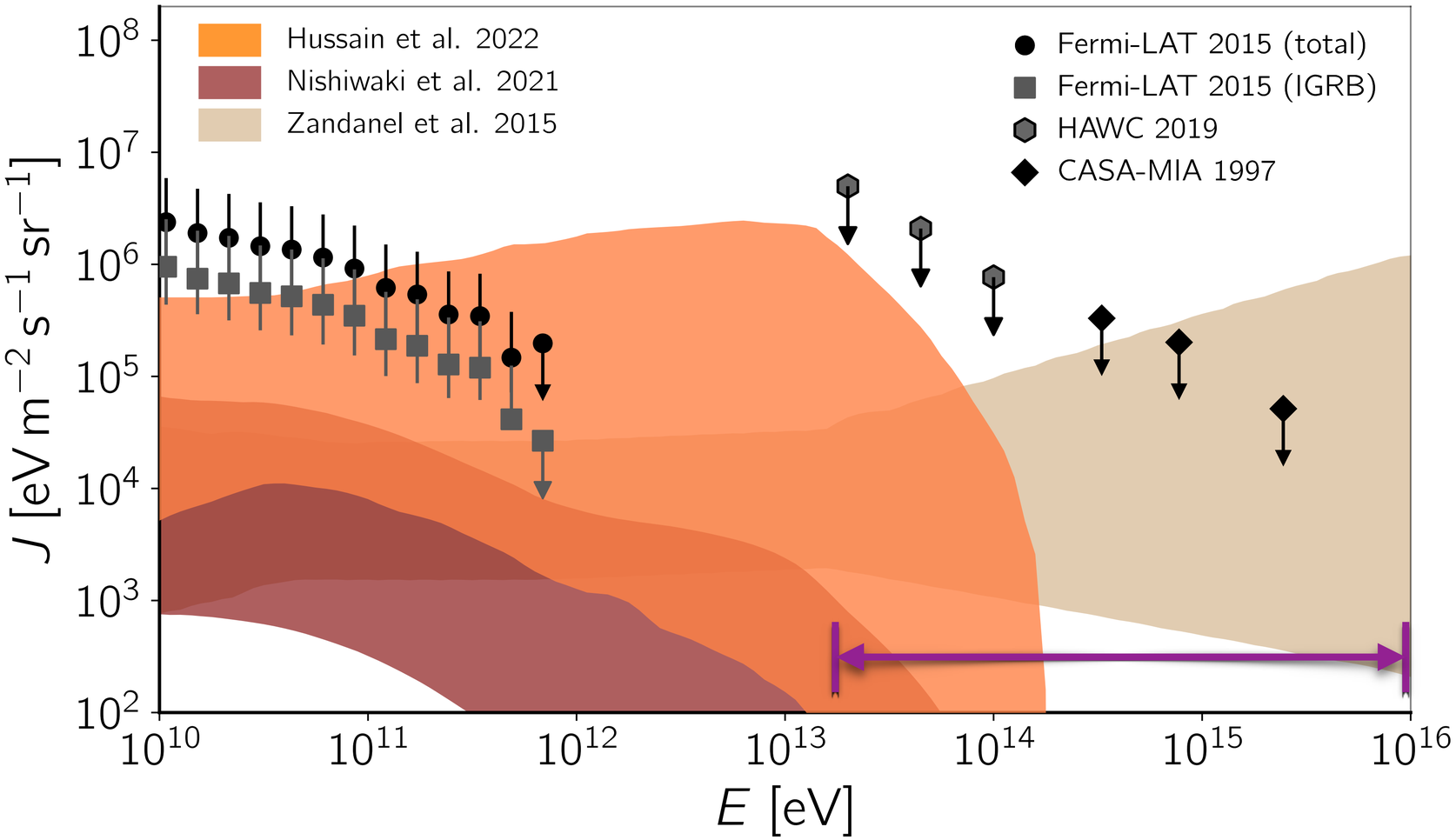

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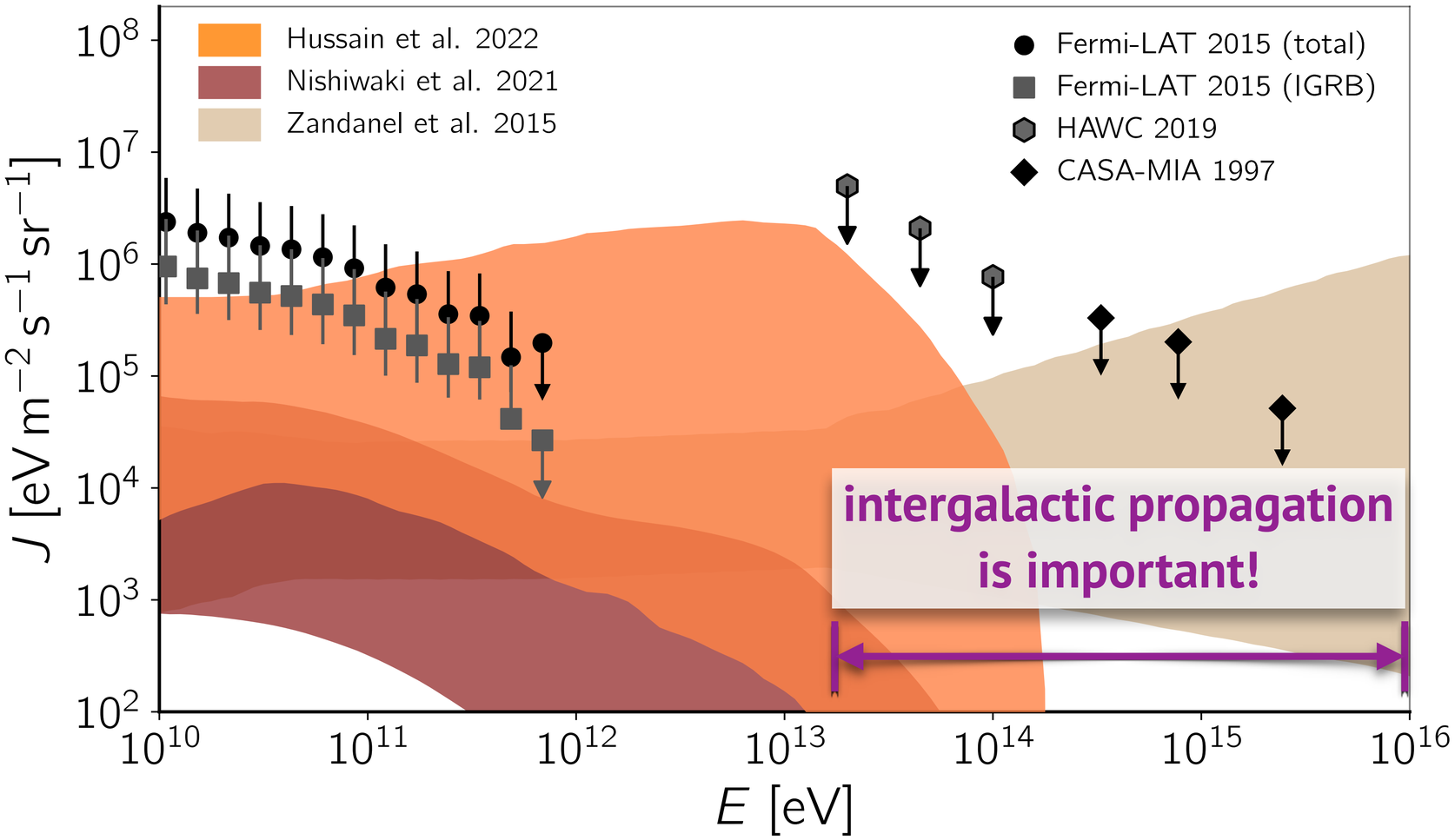

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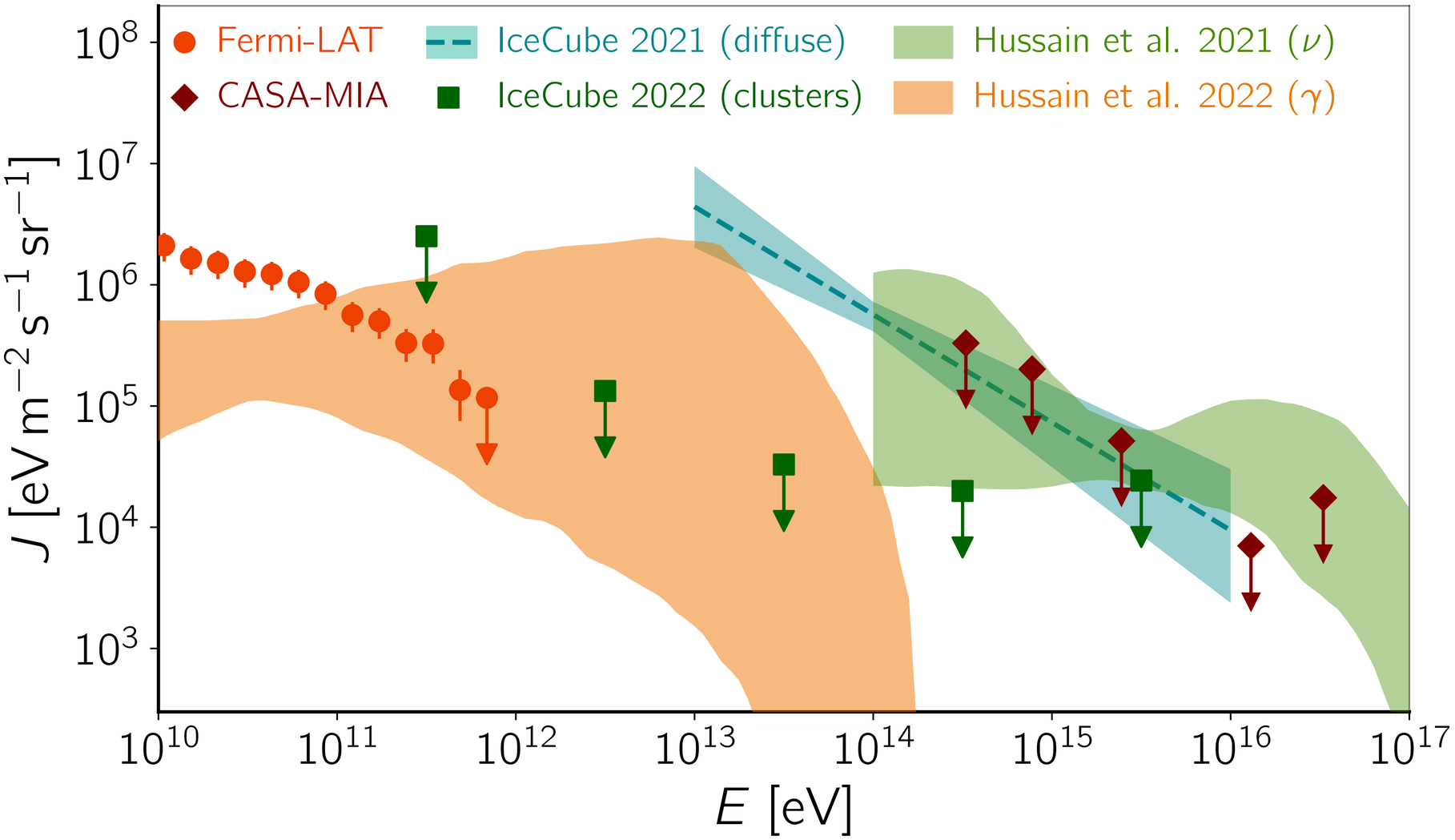

acknowledgements

thank you 😊

"la Caixa" Foundation