

# neutrinos and gamma rays from clusters of galaxies

Rafael Alves Batista

Instituto de Física Teórica (IFT UAM-CSIC)

Universidad Autónoma de Madrid

In collaboration with

Elisabete de Gouveia Dal Pino

Klaus Dolag

Saqib Hussain

Judit Pérez-Romero

✉ [rafael.alvesbatista@uam.es](mailto:rafael.alvesbatista@uam.es)

↑ [www.8rafael.com](http://www.8rafael.com)

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FM6: Dynamics of the ICM  
Busan, South Korea  
11 August, 2022

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

> GeV-TeV gamma rays  
> TeV-PeV neutrinos

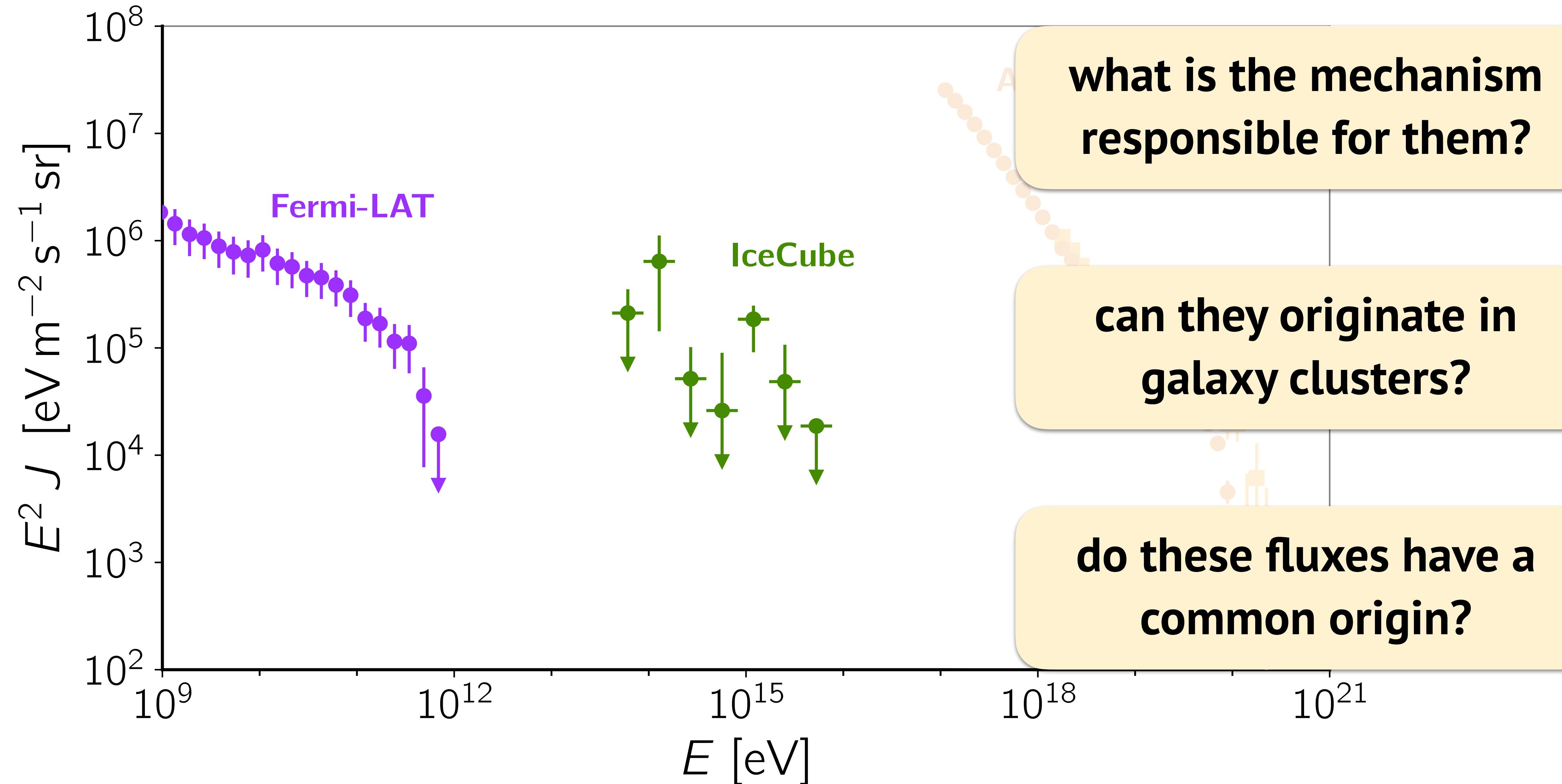
cosmic rays

electrons

dark matter

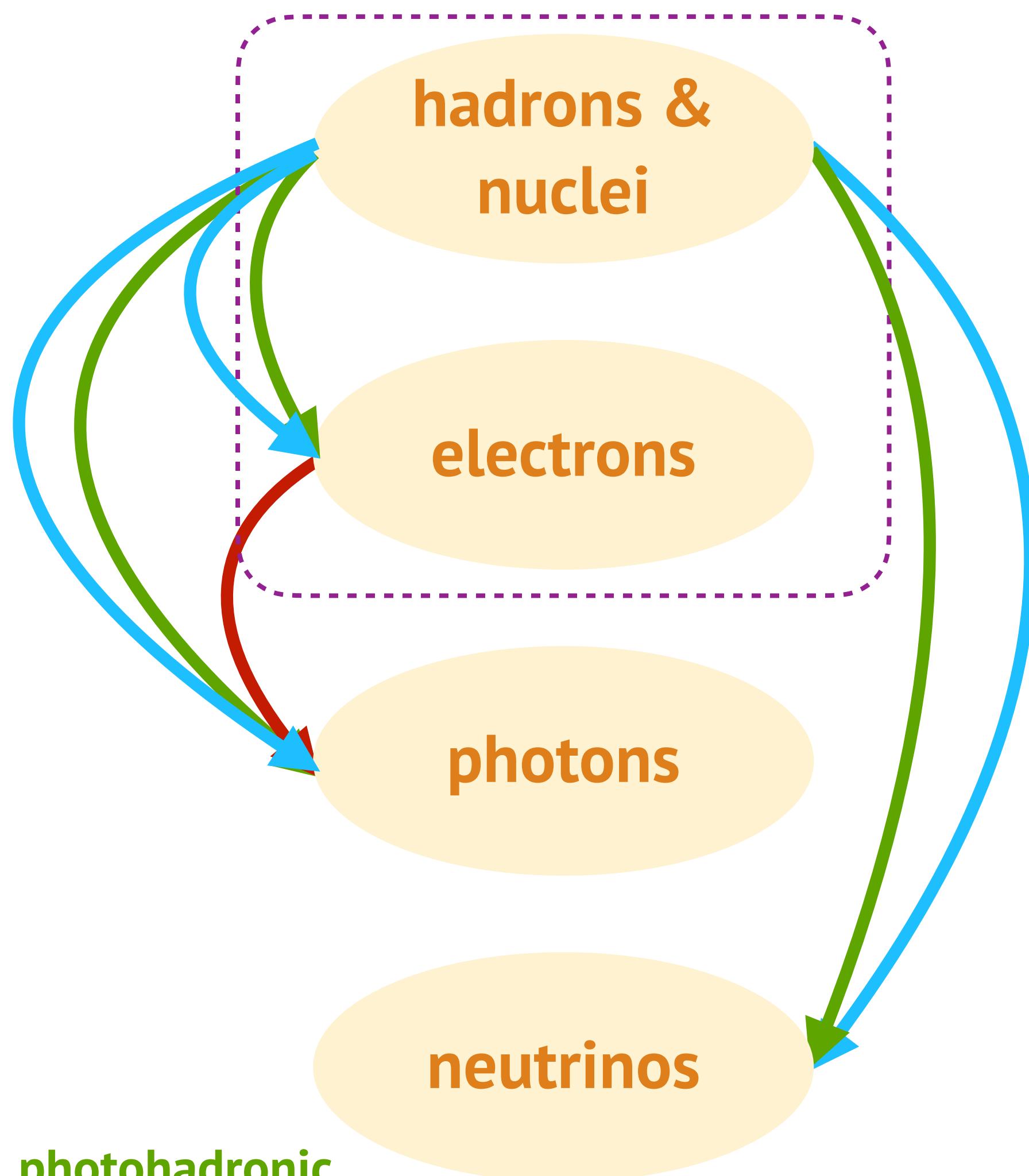
# high-energy multimessenger landscape

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



# the multimessenger link: particle interactions and acceleration

## particle acceleration

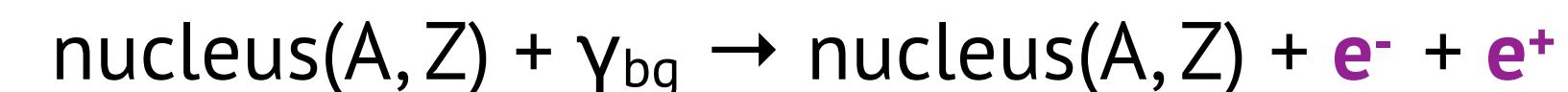


photohadronic  
photonuclear  
electromagnetic  
hadronuclear  
others (negligible)

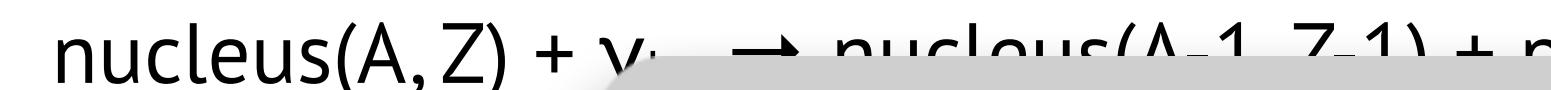
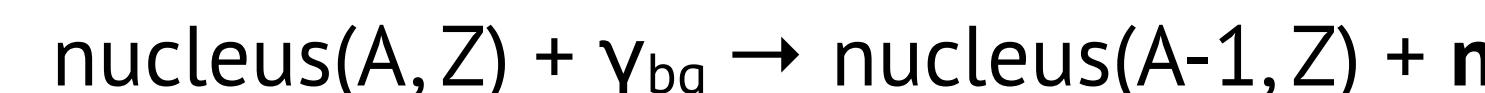
## photopion production



## Bethe-Heitler pair production



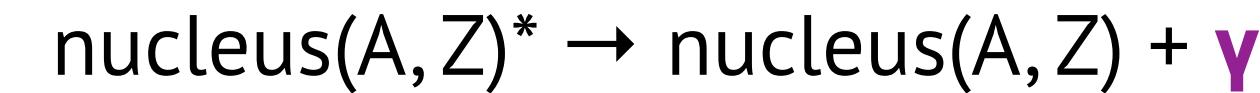
## photodisintegration



**cosmic rays  $\rightarrow \nu, \gamma$**

**electrons  $\rightarrow \gamma$**

## nuclear decay



## nucleus-nucleus interactions



## decays



...

duction  
 $e^- + e^+$

double pair production



inverse Compton scattering



triplet pair production



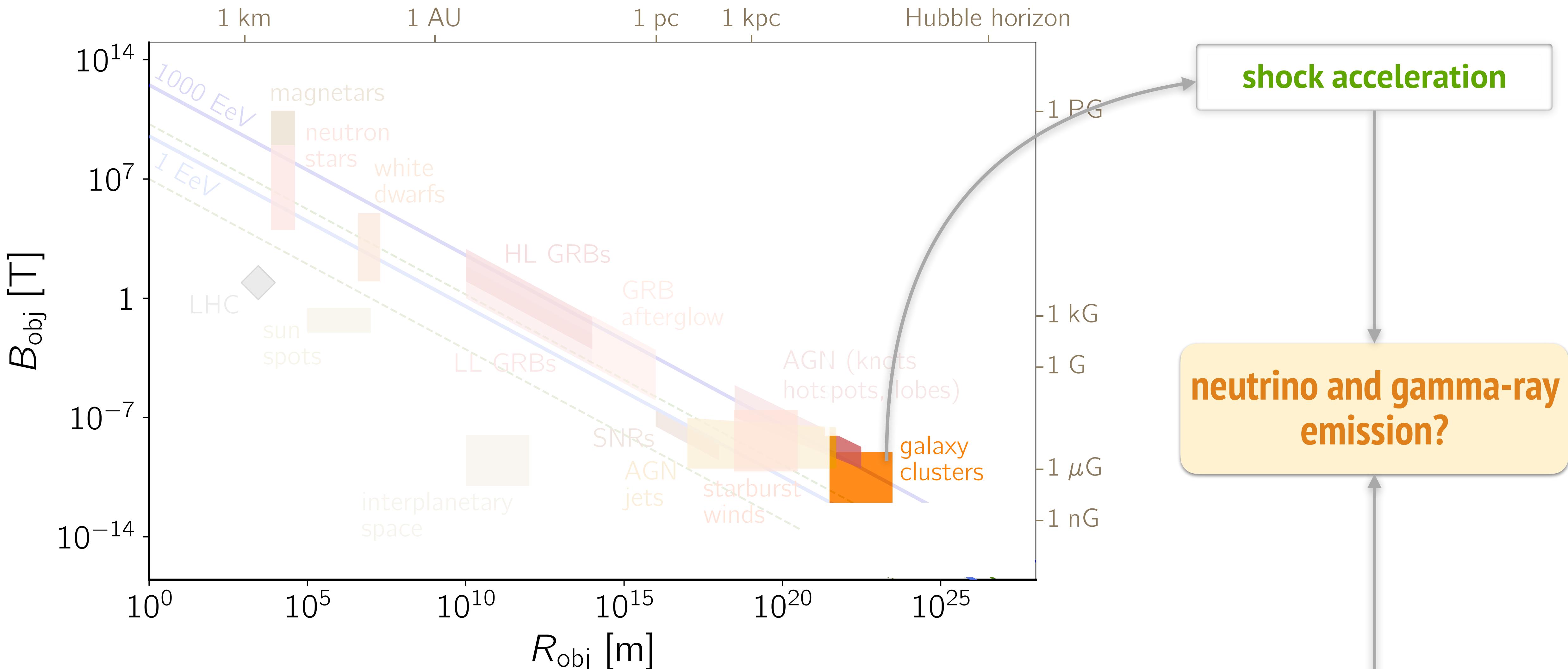
# **what is the origin of high-energy emission by galaxy clusters?**

**electrons**

**cosmic rays**

**dark matter**

# high-energy emission by galaxy clusters: particle acceleration



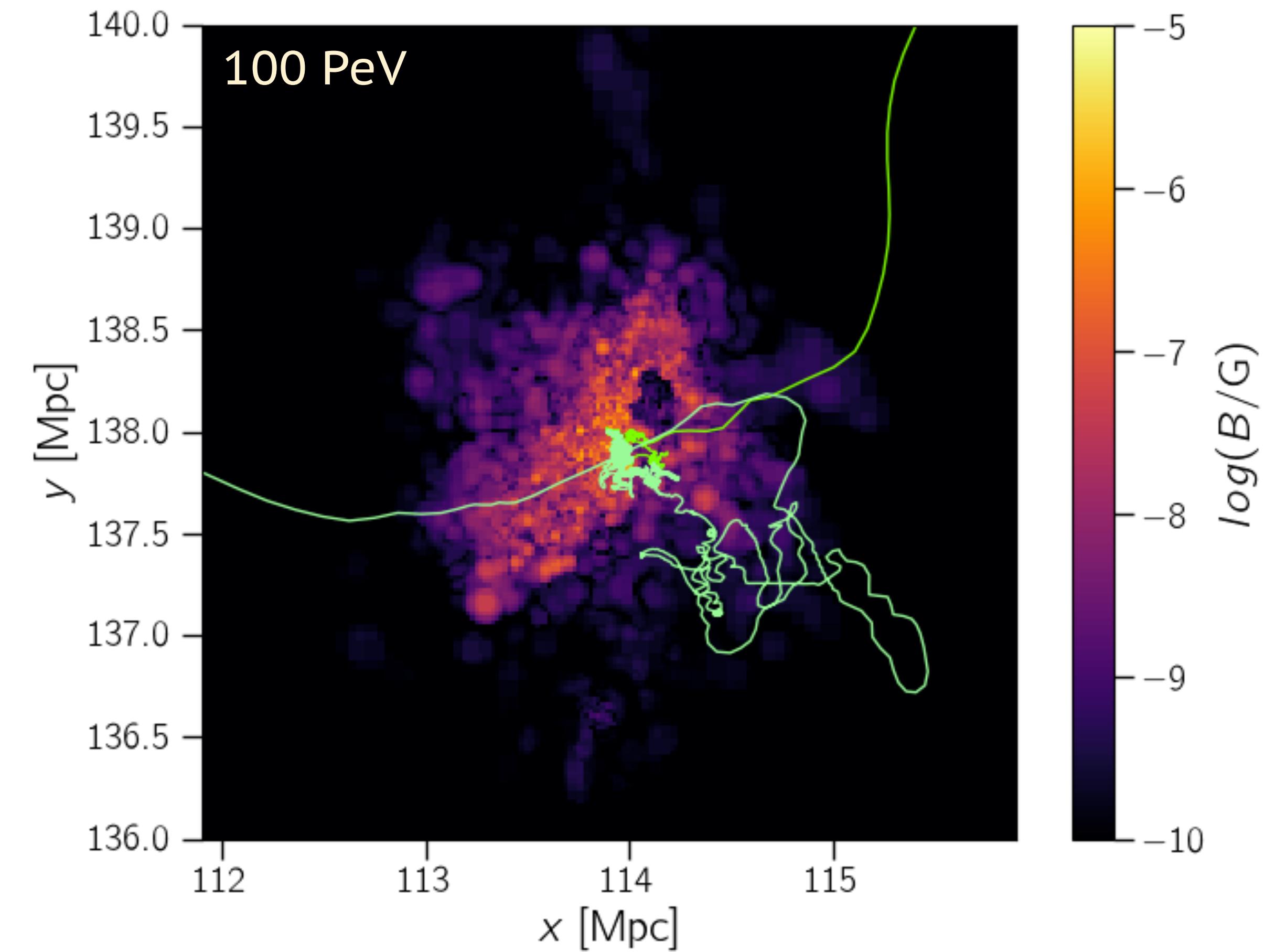
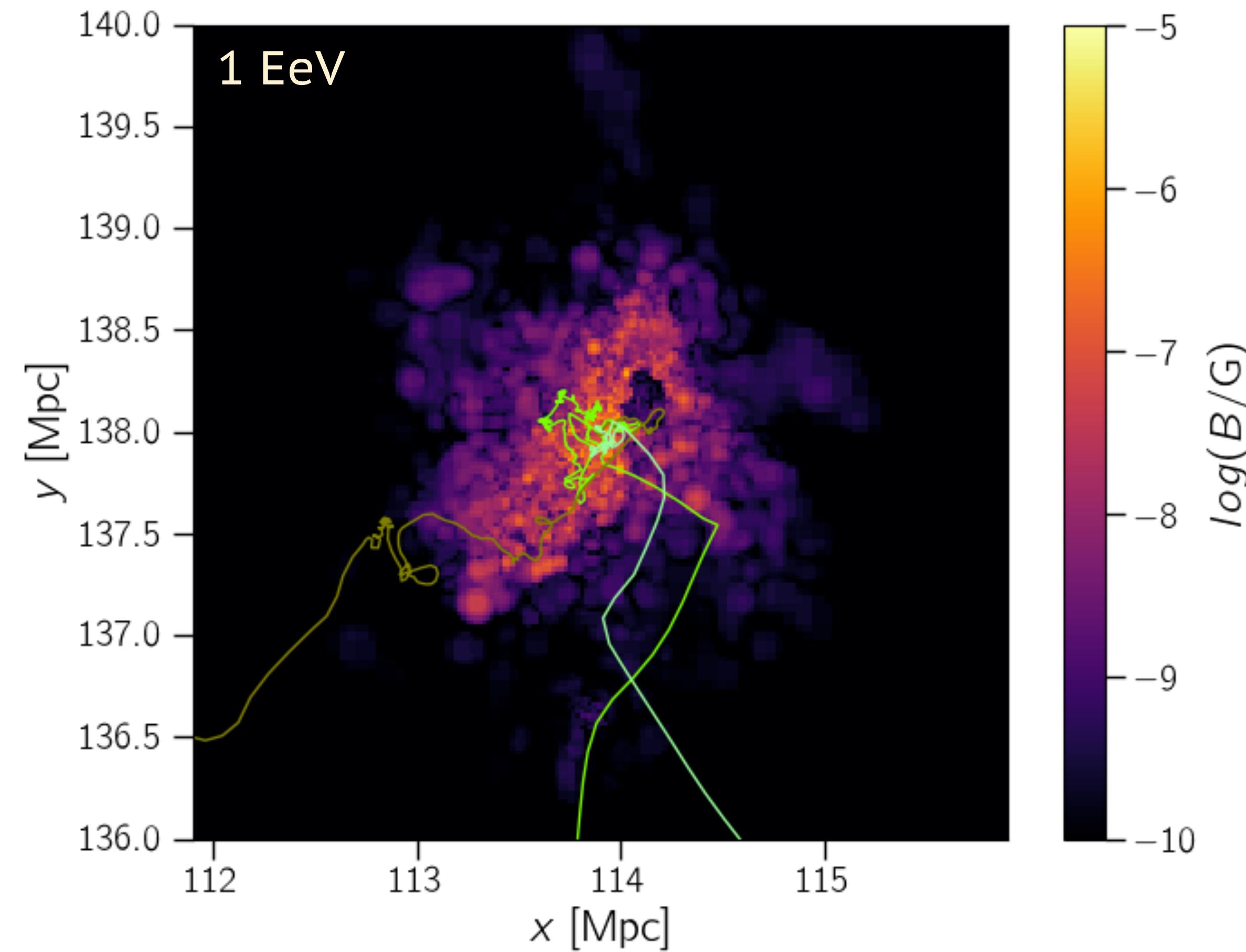
Hillas  
criterion

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

embedded cosmic  
accelerators

# propagation of CRs in the ICM

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



obtained with the CRPropa code

<https://crpropa.desy.de>

Alves Batista et al. JCAP 05 (2016) 038. arXiv:1603.07142

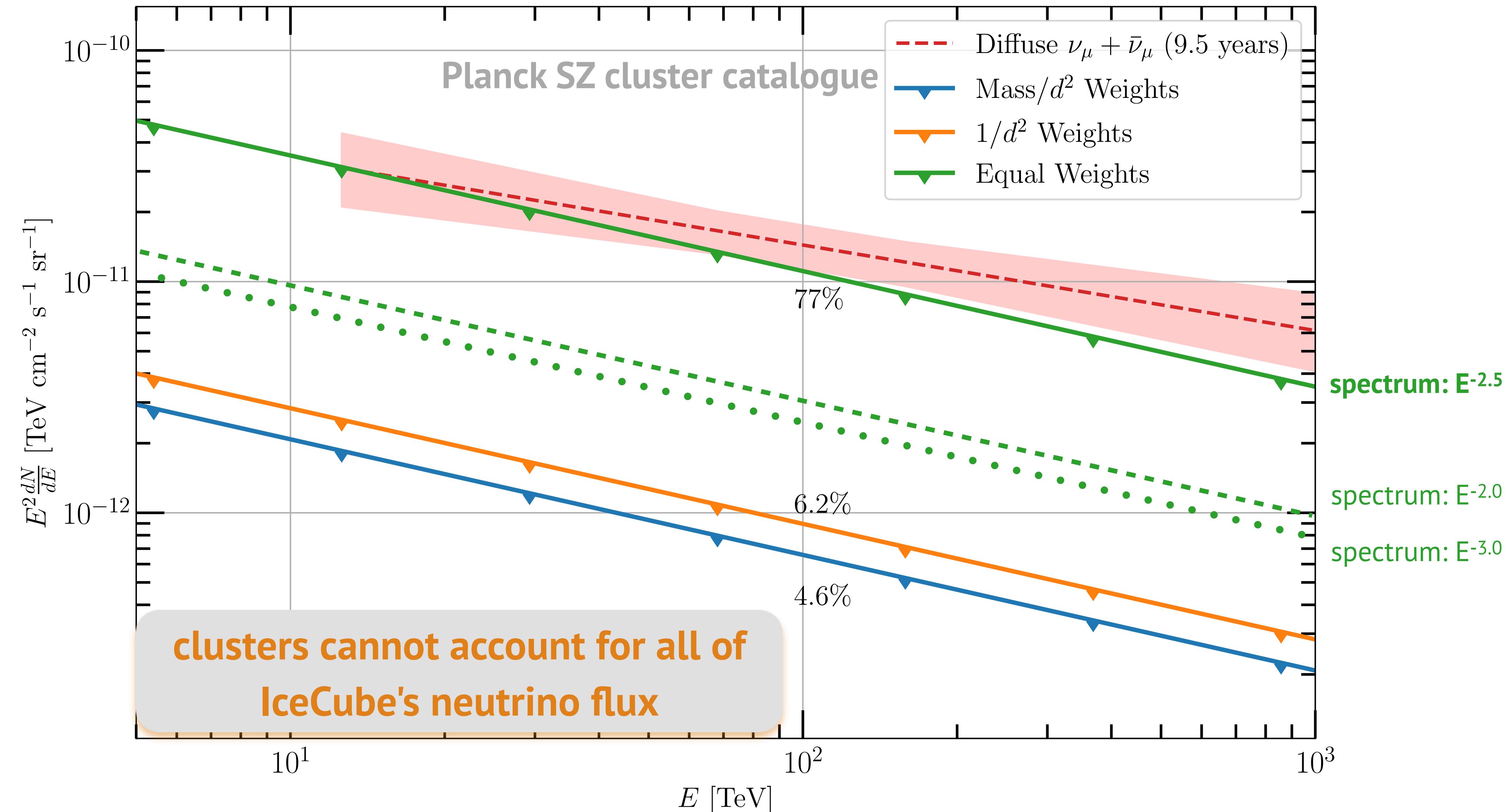
Alves Batista et al. arXiv:2208.00107



# neutrino emission

# high-energy neutrinos from galaxy clusters

IceCube Collaboration. arXiv:2206.02054



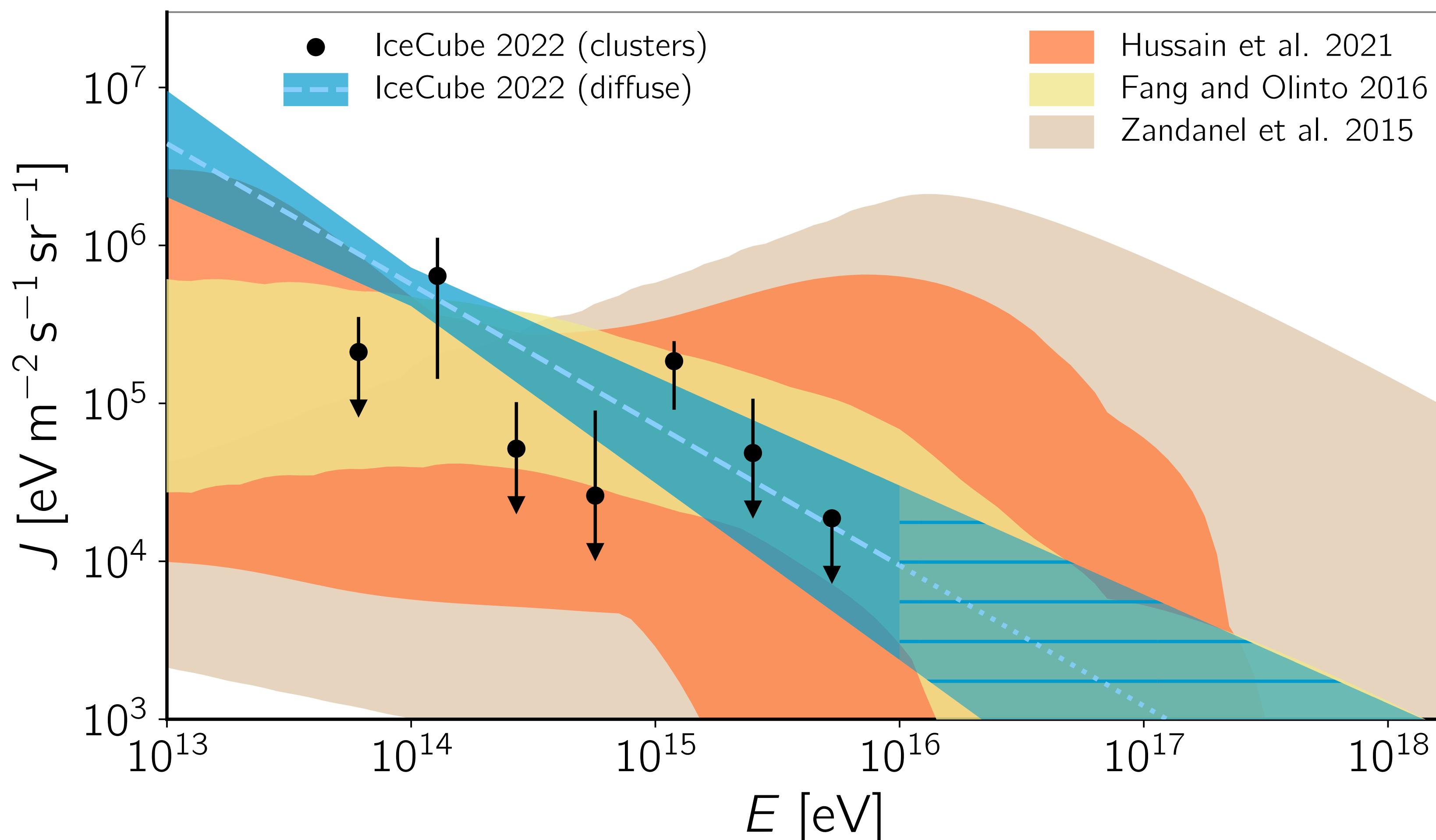
caveats: weighting scheme, distribution of CR sources, emission spectrum

# the diffuse flux of high-energy neutrinos

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

Fang and Olinto. Astrophys. J. 828 (2016) 37. arXiv:1607.00380

Zandanel, Tamborra, Gabici, Ando. Astron. Astrophys. 578 (2015) A32. arXiv:1410.8697



**clusters could account for up to 100% of the neutrino flux  
(depending on the choice of parameters)**

**Hussain et al. 2021**

embedded source

interactions: pp + p $\gamma$  + EM

$\alpha = [1.5, 2.7]$

$E_{\max} = [5, 500] \text{ PeV}$

source evolution = AGN, SFR, none

$L_{\text{CR}} = [0.005, 0.05] L_{\text{tot}}$

**Fang and Olinto 2016**

embedded source + accretion shocks

interactions: pp

$\alpha = [1.5, 2.0]$

$E_{\max} = 50 \text{ PeV}$

$L_{\text{CR}} = [0.005, 0.02] L_{\text{tot}}$

**Zandanel et al. 2015**

accretion shocks

interactions: pp

$\alpha = [1.5, 2.4]$

$B = 0.5 \mu\text{G}, 1.0 \mu\text{G}, \gg B_{\text{CMB}}$

$L_{\text{CR}} = [0.02 L_{\text{tot}}$

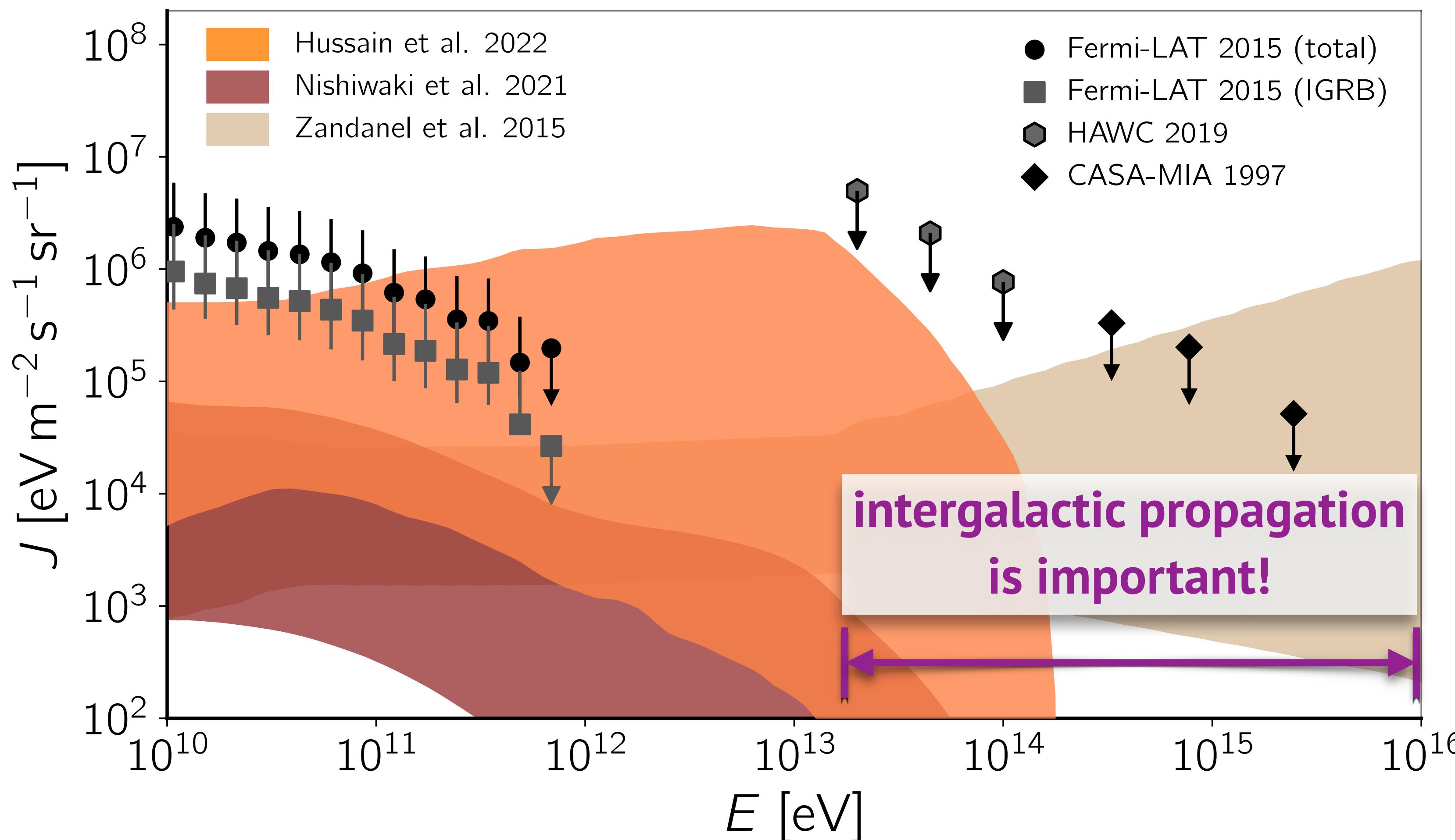
# gamma-ray emission

# the diffuse flux of high-energy gamma rays

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2203.01260

Nishiwaki, Sano, Murase. Astrophys. J. 992 (2021) 190.

Zandanel, Tamborra, Gabici, Ando. Astron. Astrophys. 578 (2015) A32. arXiv:1410.8697



clusters could account for up to 100% of the gamma-ray flux (depending on the choice of parameters)

**Hussain et al. 2021**

embedded source

interactions: pp + p $\gamma$  + EM

$\alpha = [1.5, 2.7]$

$E_{\max} = [5, 500] \text{ PeV}$

source evolution = AGN, SFR, none

$L_{\text{CR}} = [0.005, 0.05] L_{\text{tot}}$

**Zandanel et al. 2015**

accretion shocks

interactions: pp

$\alpha = [1.5, 2.4]$

$B = 0.5 \mu\text{G}, 1.0 \mu\text{G}, \gg B_{\text{CMB}}$

$L_{\text{CR}} = 0.02 L_{\text{tot}}$

no intergalactic propagation

**Nishiwaki et al. 2021**

accretion shocks (w/ re-acceleration)

interactions: pp + EM

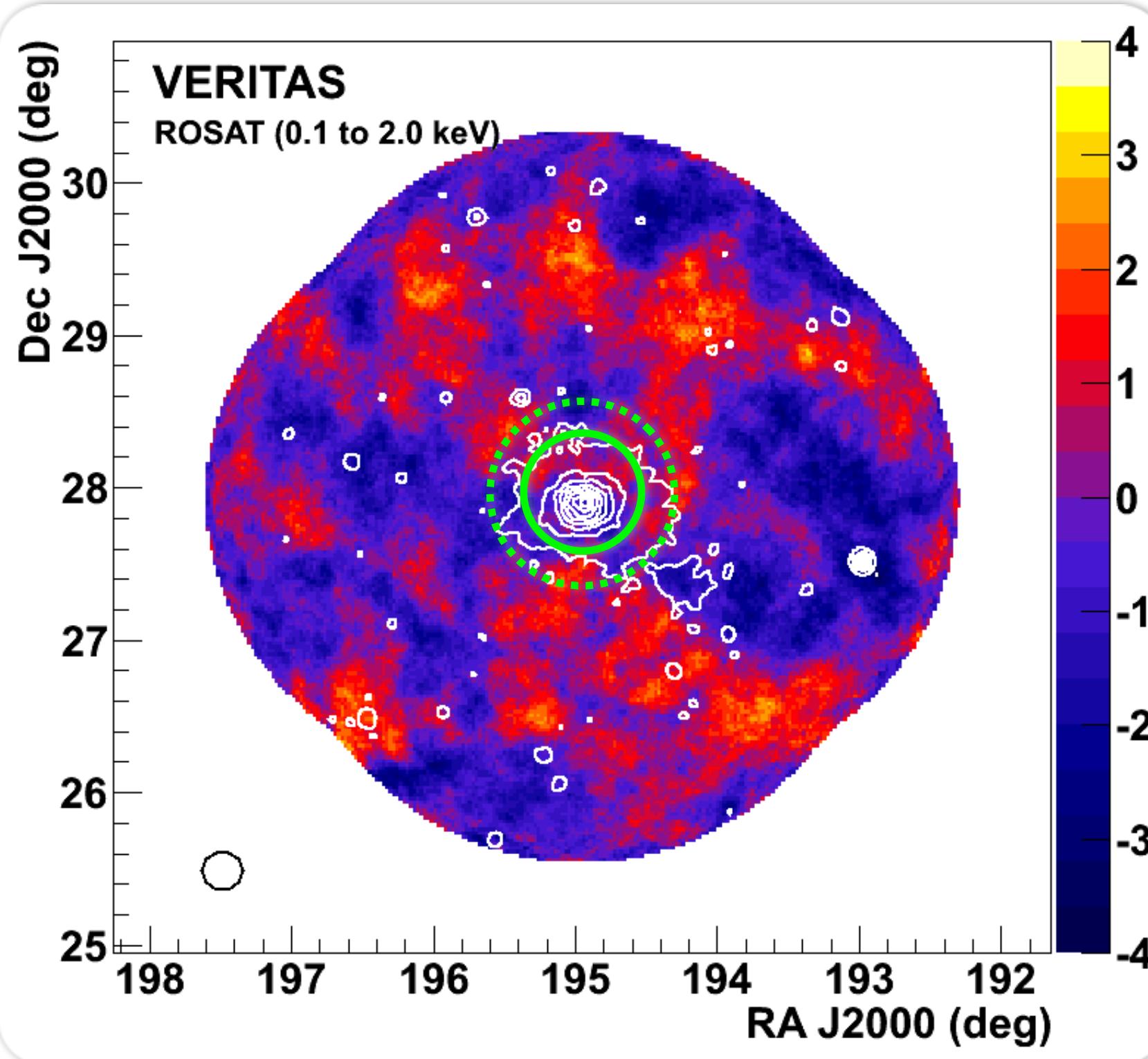
$\alpha = [2.00, 2.45]$

$f_{pe} = [0.00, 0.01]$  (primary electrons)

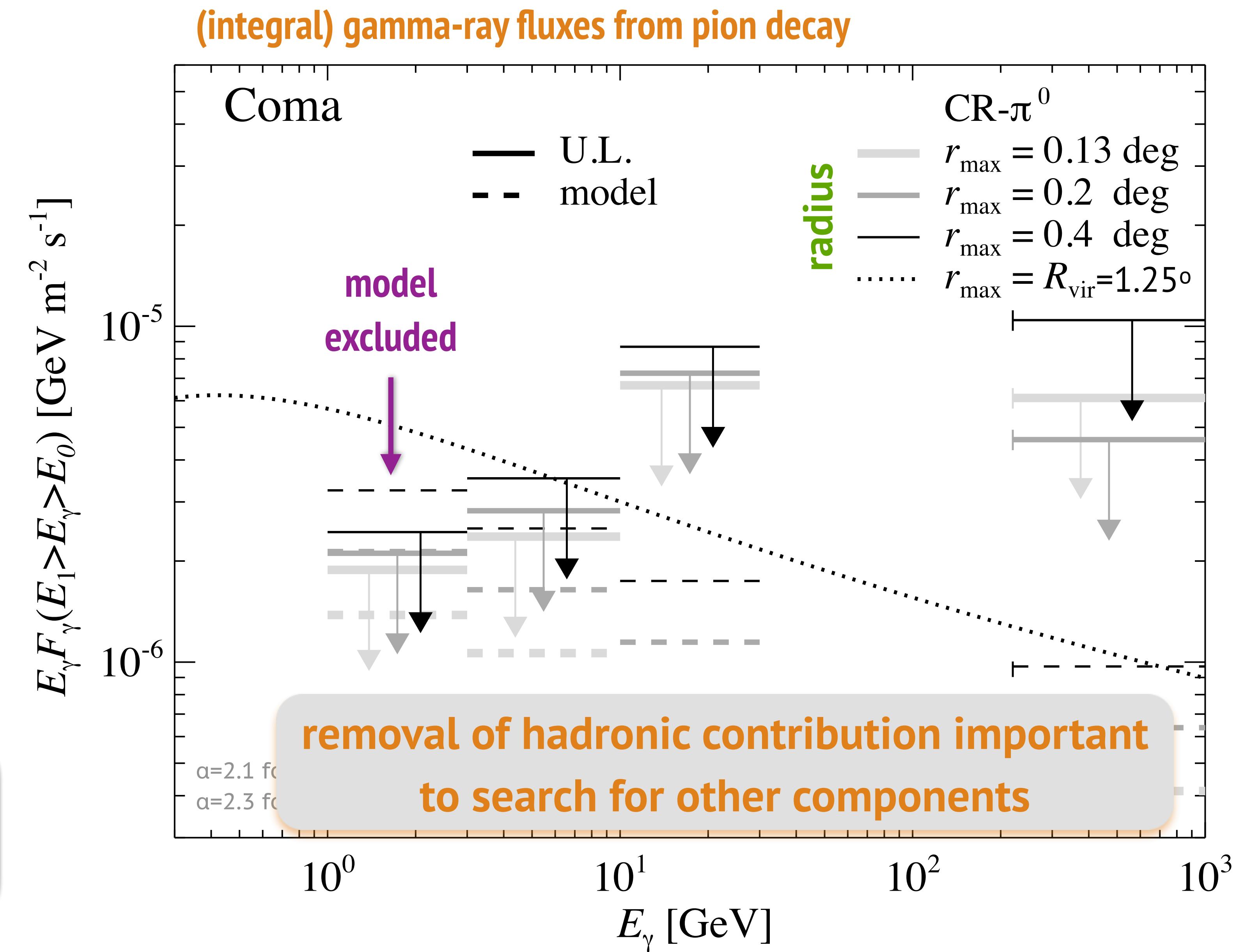
"hard-sphere" acceleration

# case study: gamma rays from the Coma cluster

VERITAS Collaboration. *Astrophys. J.* 757 (2012) 123. arXiv:1208.0676



is there room for gamma rays  
from dark matter?



# gamma rays from individual clusters

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

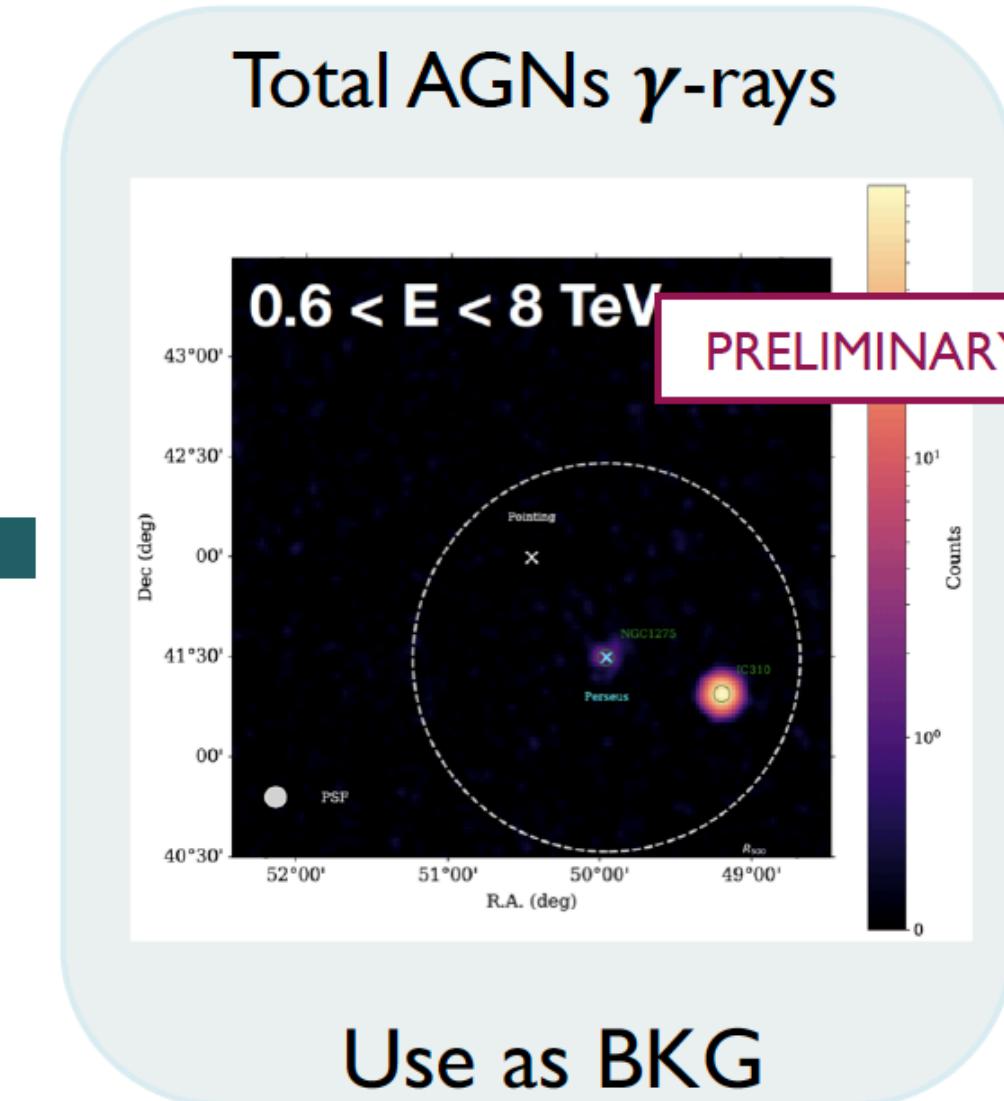
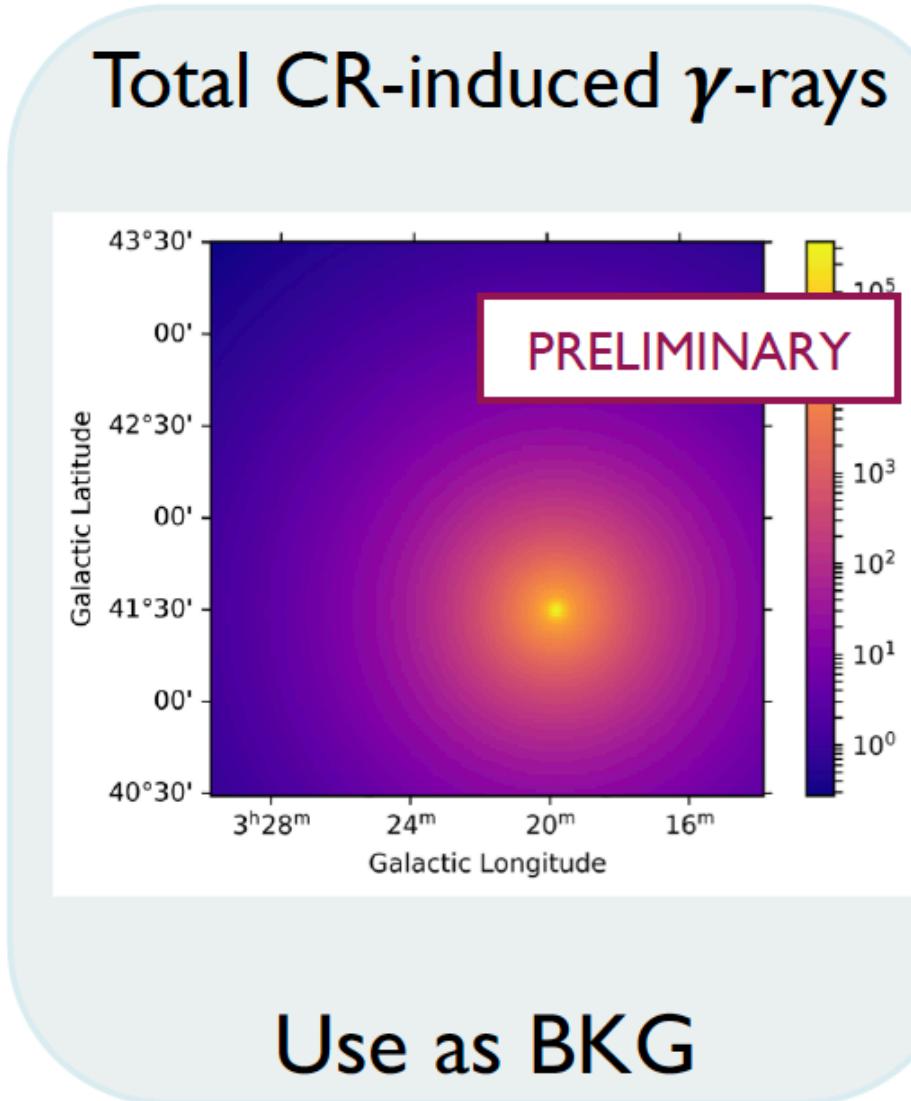
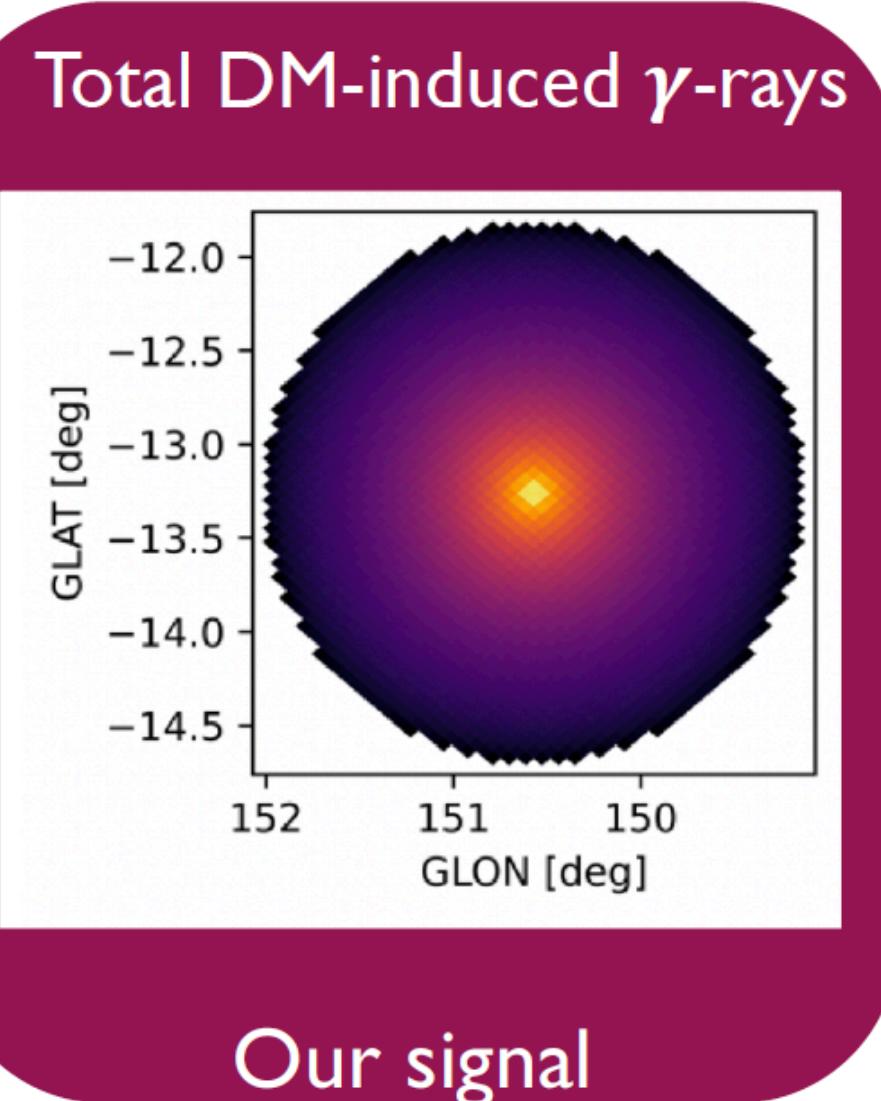
**electrons**

**cosmic rays**

**dark matter**

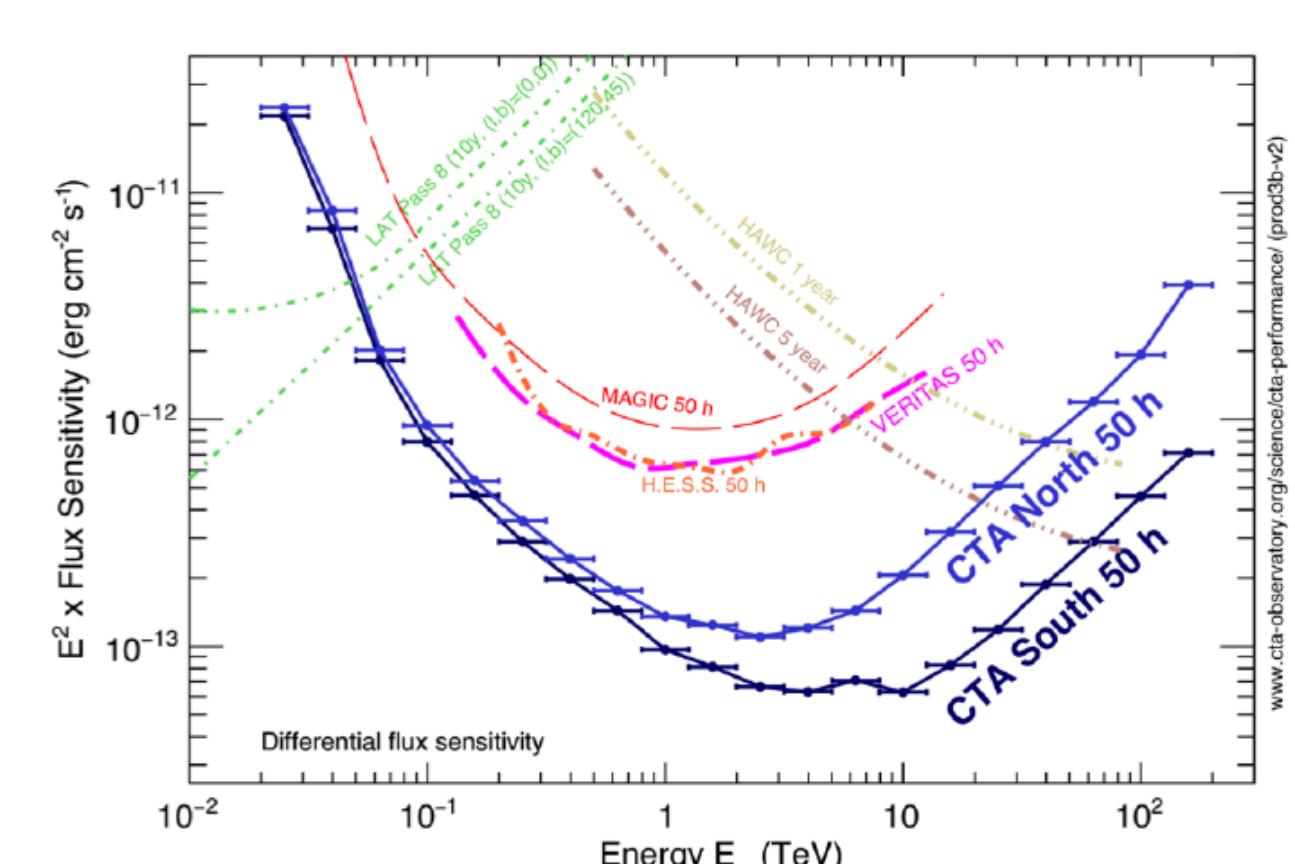
# studying galaxy clusters with the Cherenkov Telescope Array

Pérez-Romero for the CTA Consortium. PoS (ICRC2021) 546. arXiv:2108.05141



all components must be understood when searching for dark matter

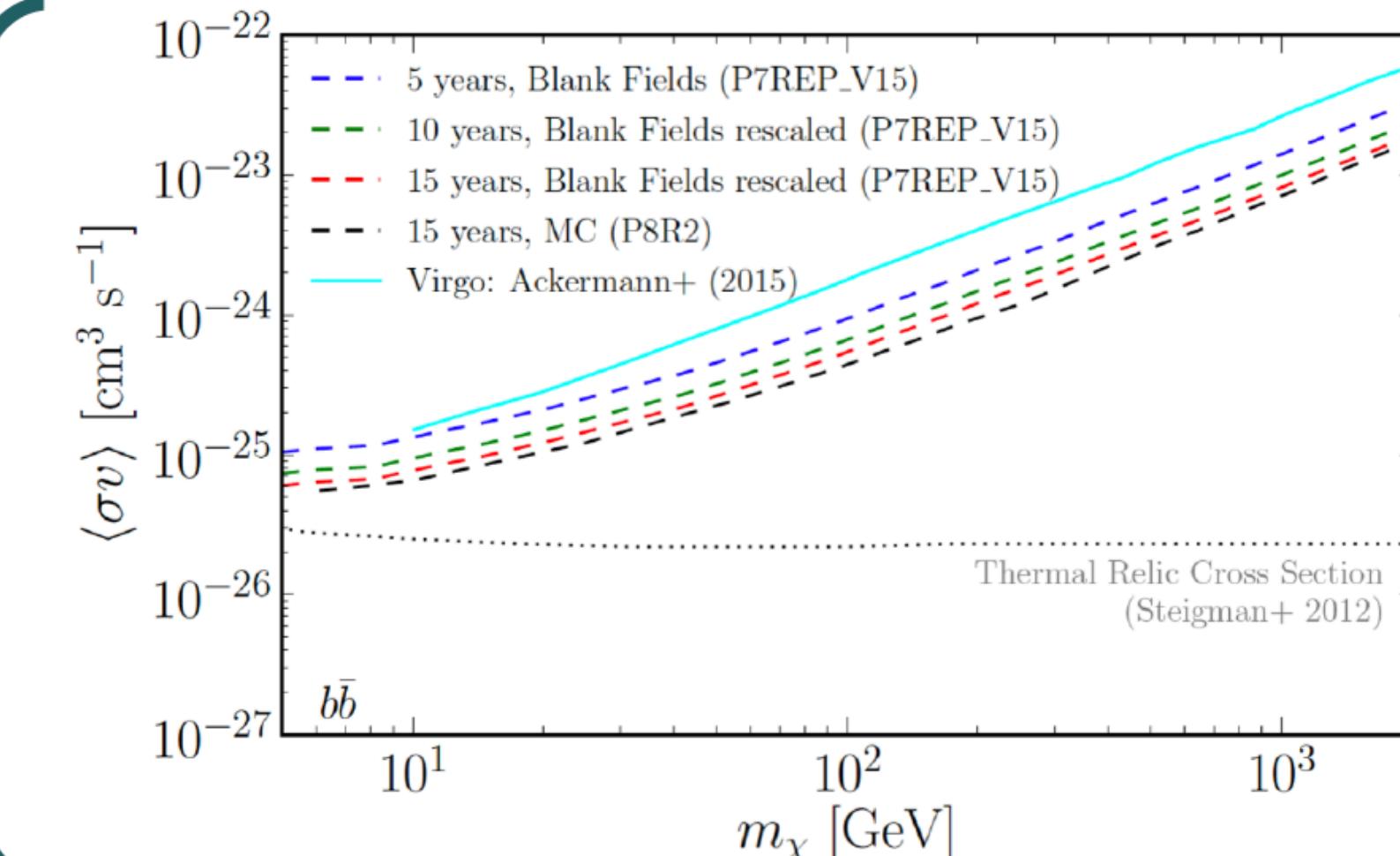
## CTA performance



## Observation Simulation

If no signal found

## Constraints on DM models

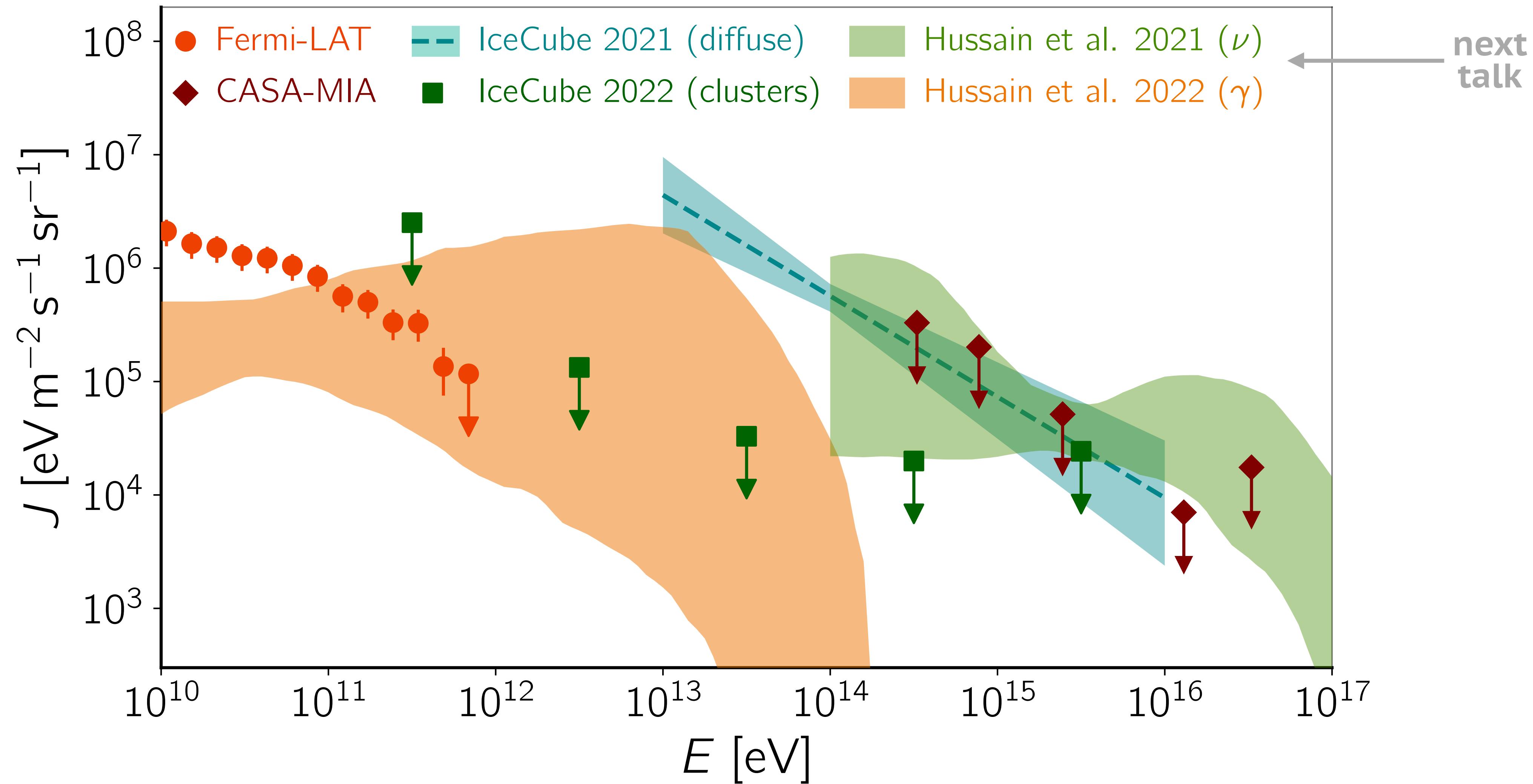


# summary & outlook

- ▶ **HE emission by galaxy clusters can be due to:**
  - ◆ CR nuclei
  - ◆ leptons
  - ◆ photons
  - ◆ other channels
- ▶ **processes responsible for high-energy emission:**
  - ◆ sources embedded in the ICM
  - ◆ accretion shocks
  - ◆ re-acceleration mechanisms
- ▶ **CR-related uncertainties**
  - ◆ spectral shape (depends on acceleration mechanism)
  - ◆ propagation regime in IGM
  - ◆ cosmological evolution of CR sources
- ▶ **uncertainties that affect gamma-ray fluxes**
  - ◆ electromagnetic interactions in the ICM
  - ◆ propagation effects during intergalactic propagation in the IGM
- ▶ **the contribution of galaxy clusters to the diffuse neutrino and gamma-ray backgrounds**
  - ◆ is *guaranteed*
  - ◆ could, in principle, account for up to 100% of the observed diffuse fluxes
- ▶ **better models are needed to separate each emission component:**
  - ◆ embedded source
  - ◆ intrinsic ICM emission
  - ◆ other contributions (e.g., dark matter)

# neutrinos and gamma rays from galaxy clusters: summary

contribution from clusters of galaxies to the DGRB and D $\nu$ B  
remain uncertain but may be sizeable



thank you 😊



"la Caixa" Foundation

# back-up

# where do the high-energy CRs come from?

## ► scenario 1. shocks in the ICM

- ◆ accretion shocks  $\sim$  virial radius of cluster
- ◆ shock velocity comparable to free-fall velocity
- ◆ acceleration vs. energy losses
- ◆ maximal CR energy
- ◆ accretion luminosity

$$R_{\text{sh}} \sim R_{\text{vir}}$$

$$\frac{1}{2}m v_{\text{sh}}^2 = G \frac{mM}{r_{\text{sh}}} \implies v_{\text{sh}} = 3 \times 10^3 \left( \frac{10}{10^{14} M_{\odot}} \right) \text{ km/s}$$

$$D = \frac{R_{\text{L}} c}{3} = \frac{E c}{q B}$$

$$E_{\text{max}} \sim 2 \times 10^{18} \left( \frac{M}{10^{15} M_{\odot}} \right) \left( \frac{B}{1 \mu\text{G}} \right) \text{ eV}$$

$$L = \mathcal{F}_b \frac{G M \dot{M}}{R_{\text{sh}}} \sim 4 \times 10^{39} \left( \frac{\eta_{\text{CR}}}{0.01} \right) \left( \frac{M}{10^{14} M_{\odot}} \right)^{\approx 2} \text{ W}$$

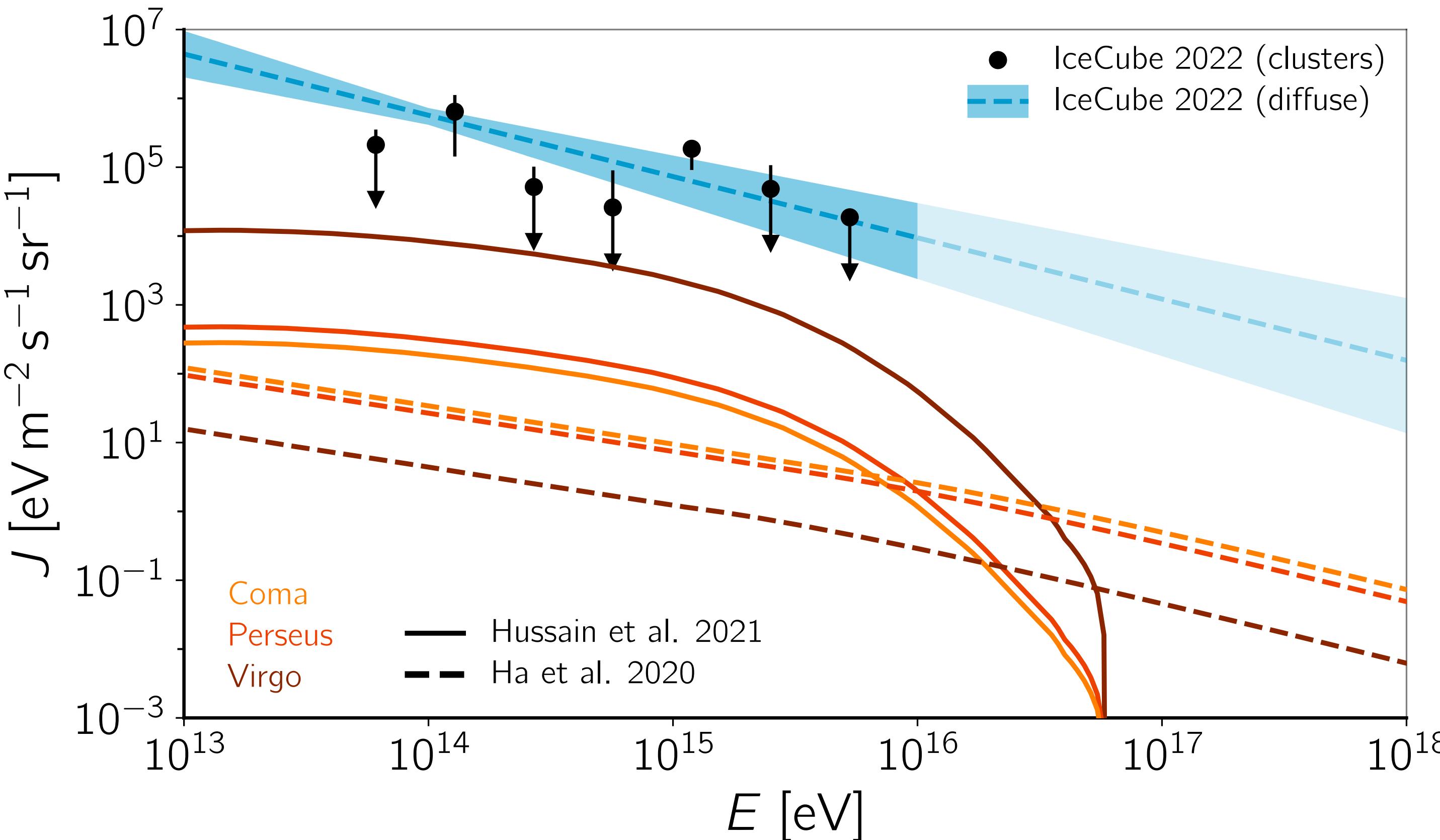
## ► scenario 2. embedded sources

- ◆ CRs with  $E < E_B$  magnetically confined

$$E_B \sim 10^{15} Z e \left( \frac{M}{10^{15} M_{\odot}} \right)^2 \left( \frac{B}{1 \mu\text{G}} \right) \left( \frac{L_B}{100 \text{ kpc}} \right)^{-2} \text{ eV}$$

# high-energy neutrinos from individual galaxy clusters

Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702  
Ha, Ryu, Kang. Astrophys. J. 892 (2020) 86. arXiv:1910.02429



individual clusters may produce  
sizeable fluxes of neutrinos

## embedded central source [Hussain et al. 2021]

- ▶ proton spectrum: power-law (index  $a$ ) with exponential cut-off at  $E_{\max}$
- ▶ interactions:  $\text{pp} + \text{p}\gamma + \text{EM}$
- ▶ this example:  $a=2.0$ ,  $E_{\max} = 50 \text{ PeV}$ ,  $L_{\text{CR}} = 0.02 L_{\text{tot}}$

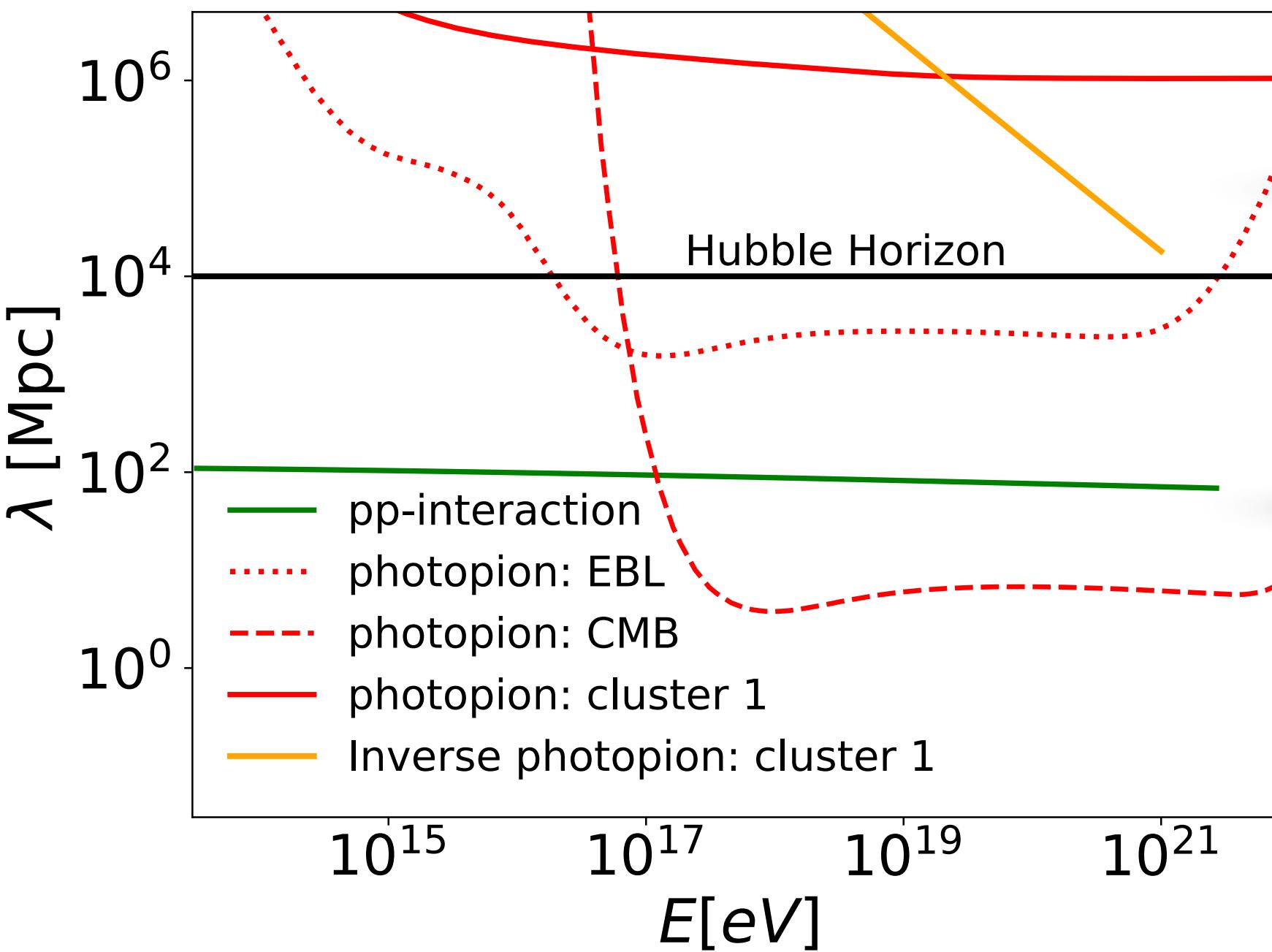
## accretion shocks [Ha et al. 2021]

- ▶ proton spectrum: power-law of index  $a$
- ▶ diffusive shock acceleration with re-acceleration
- ▶ CR distribution follows gas density to  $\delta$
- ▶ this example:  $a=2.4$ ,  $\delta=0.75$

embedded sources vs. accretion →  
very different results

# particle interactions

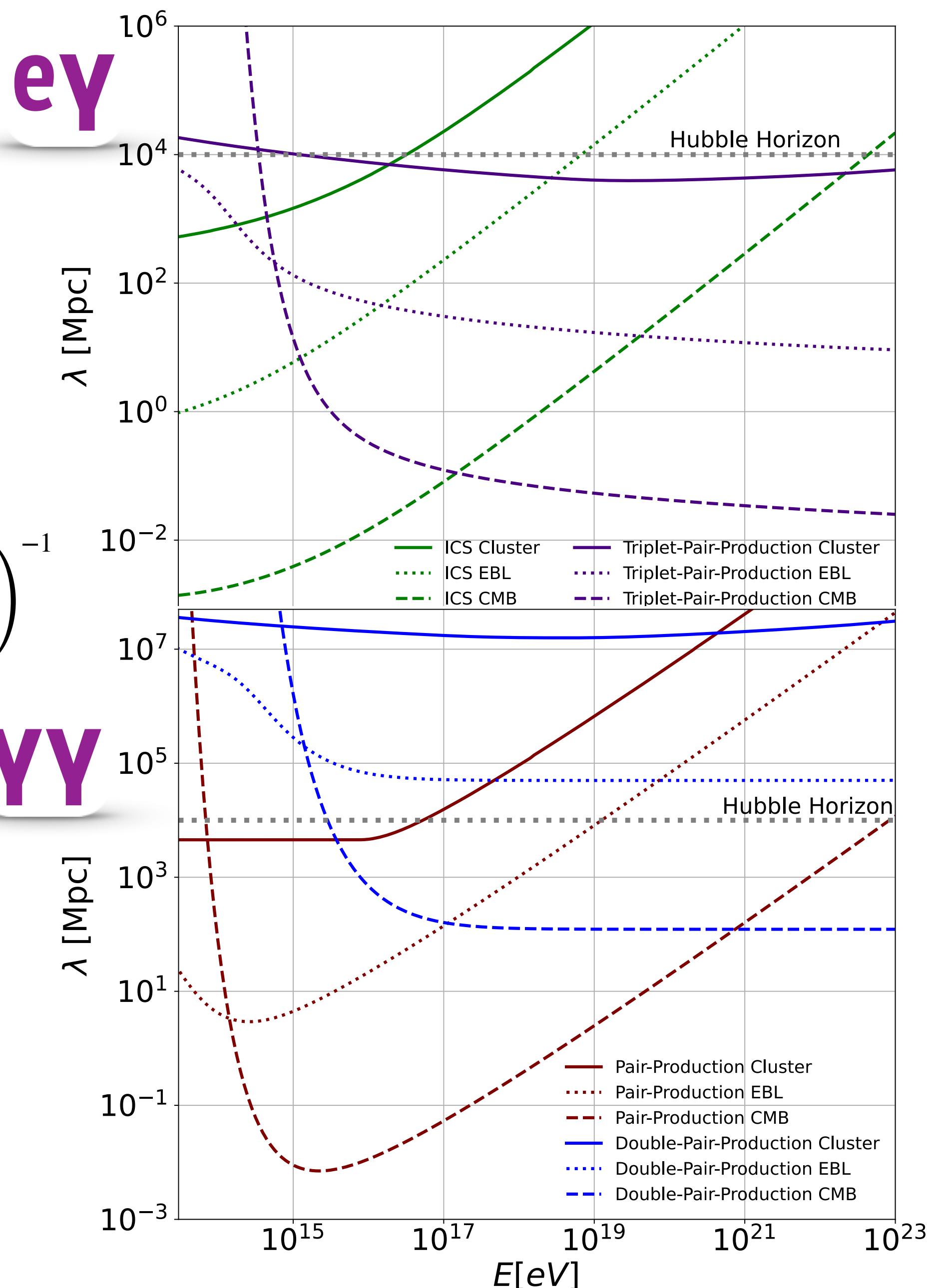
Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. MNRAS 507 (2021) 1762. arXiv:2101.07702  
 Hussain, Alves Batista, de Gouveia Dal Pino, Dolag. arXiv:2203.01260

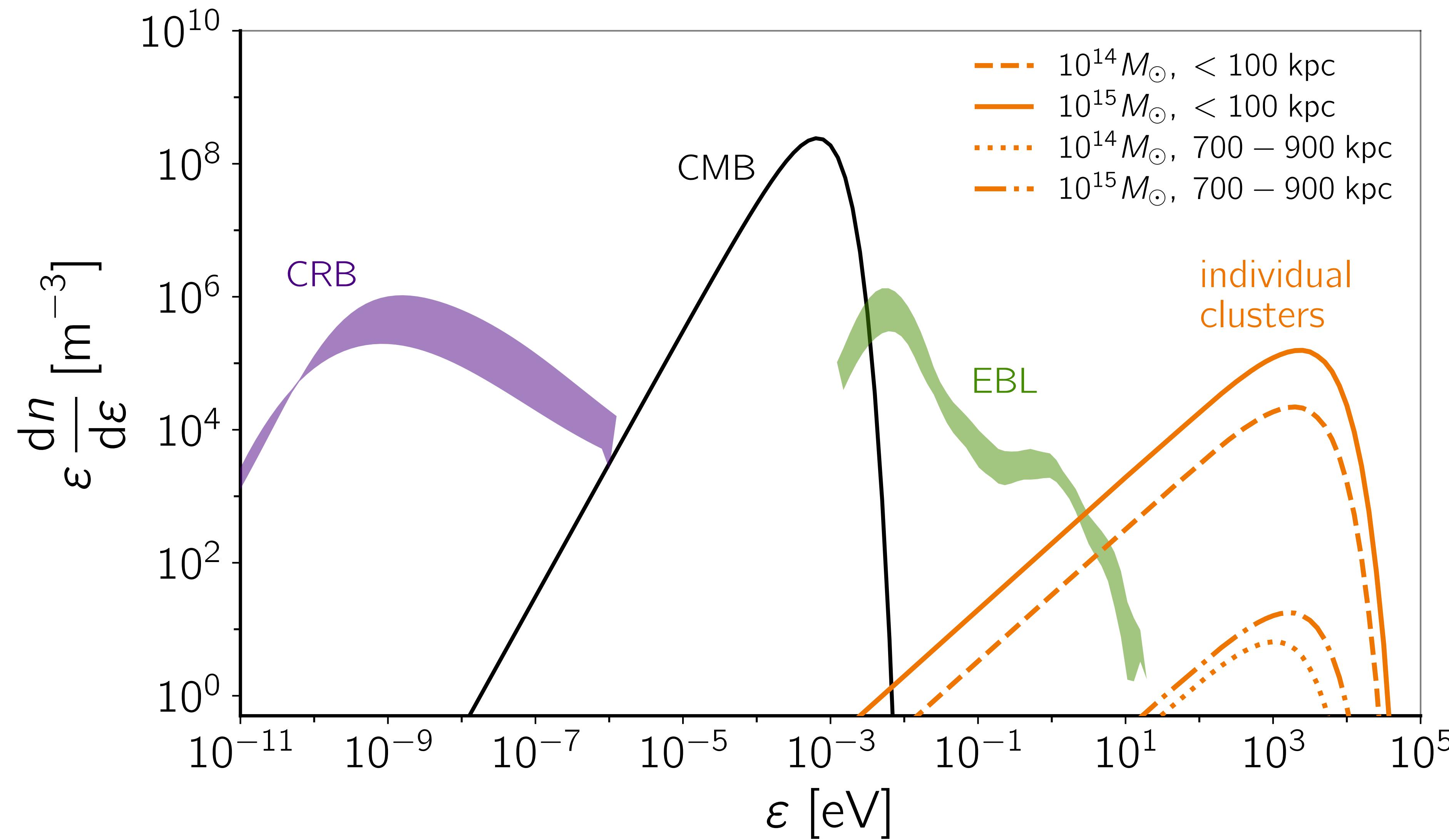


**pp**  
**py**

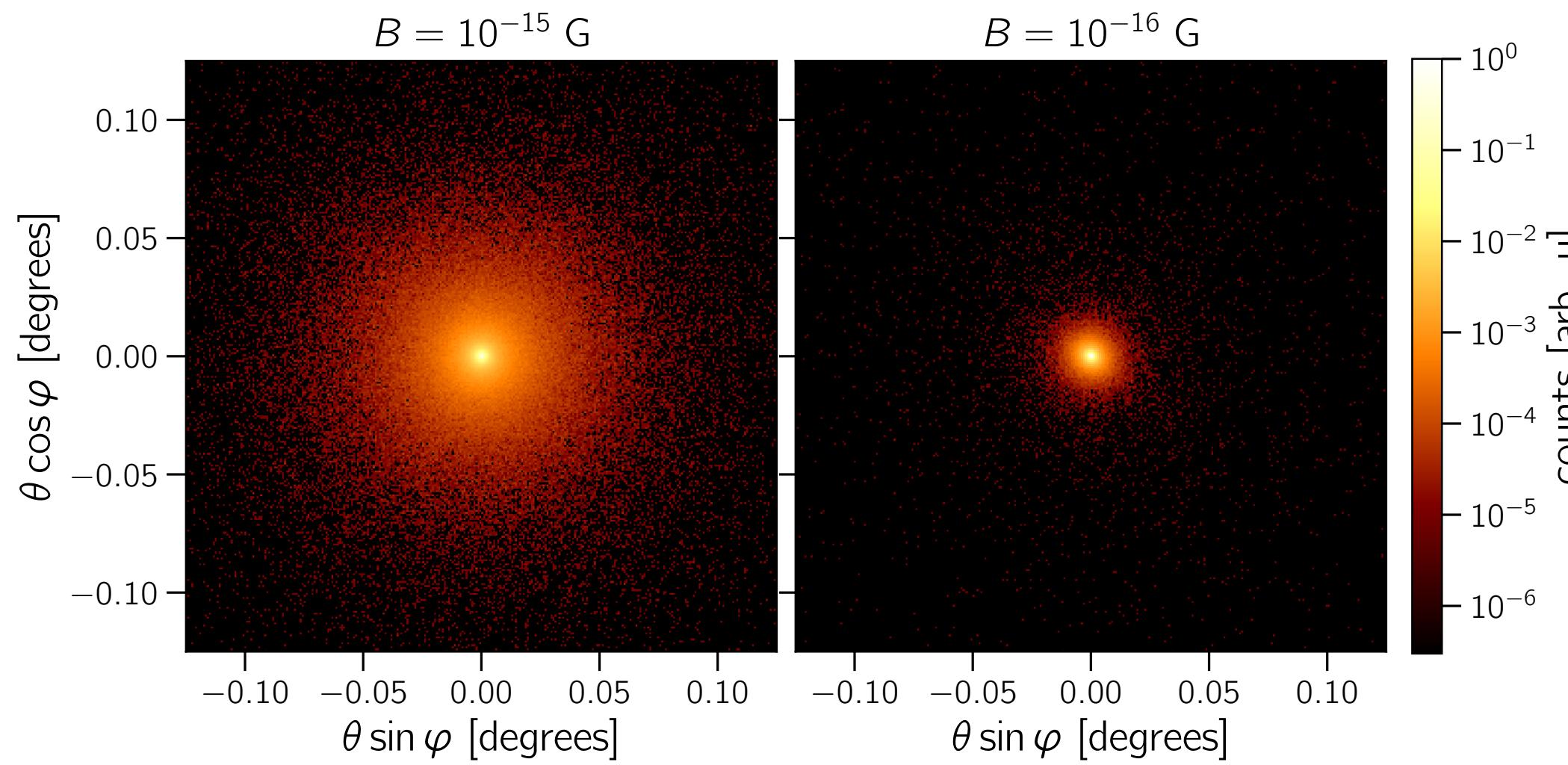
$$R_L = Z 10^{18} \text{ eV} \left( \frac{B}{1 \mu\text{G}} \right)^{-1} \left( \frac{R}{1 \text{ kpc}} \right)^{-1}$$

- ▶ **pp** in **ICM**: dominant for CRs with  $E < 100$  PeV
- ▶ **py** in **CMB**: dominant for CRs with  $E > 100$  PeV
- ▶ **py** in **ICM**: negligible at all energies
- ▶ **yp** in **ICM**: unimportant (photons with gas)
- ▶ **ey** in **CMB**: dominant at all energies *at cluster scales*
- ▶ **yy** in **CMB**: dominant for  $E > 100$  TeV *at cluster scales*
- ▶ **yy** in **EBL**: dominant for  $E < 100$  TeV





# high-energy gamma rays: intergalactic propagation



propagation effects must be taken into account when modelling gamma-ray emission by clusters