Black Hole Jets in Clusters of Galaxies as Sources of High-energy Cosmic Particles

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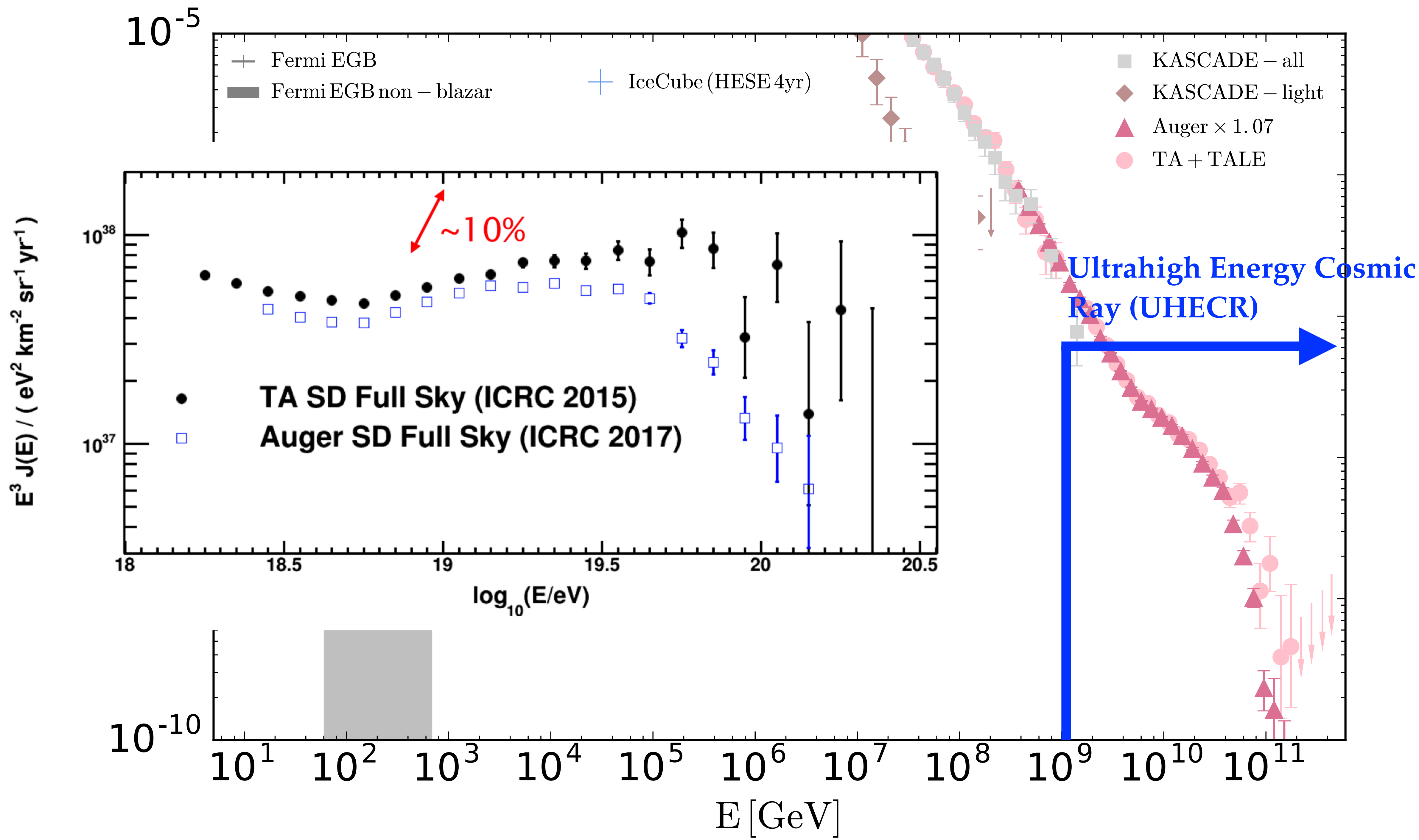
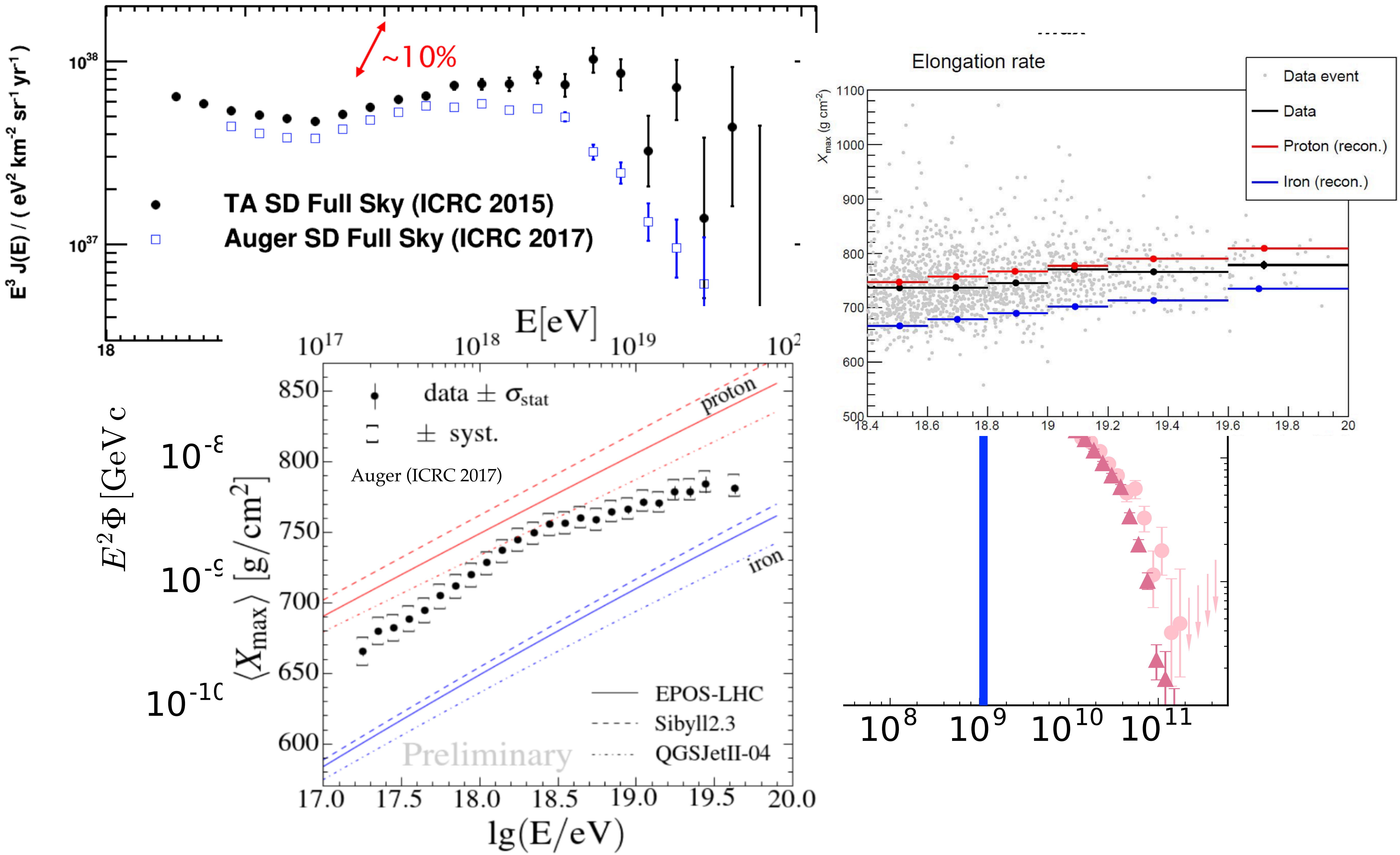
Oct 10, 2018

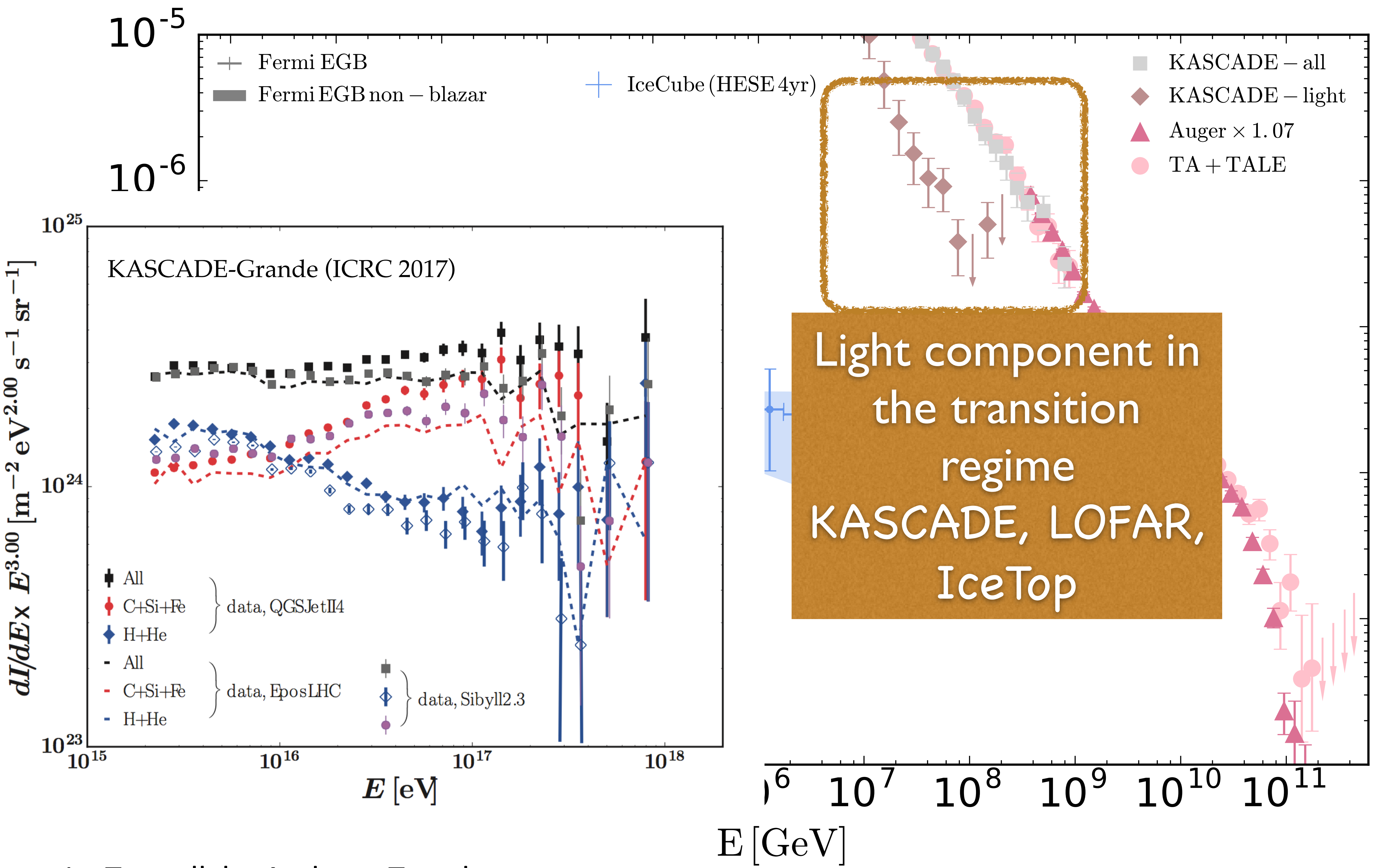
UHECRs, High-energy Neutrinos, & Gamma Rays



UHECRs, High-energy Neutrinos, & Gamma Rays

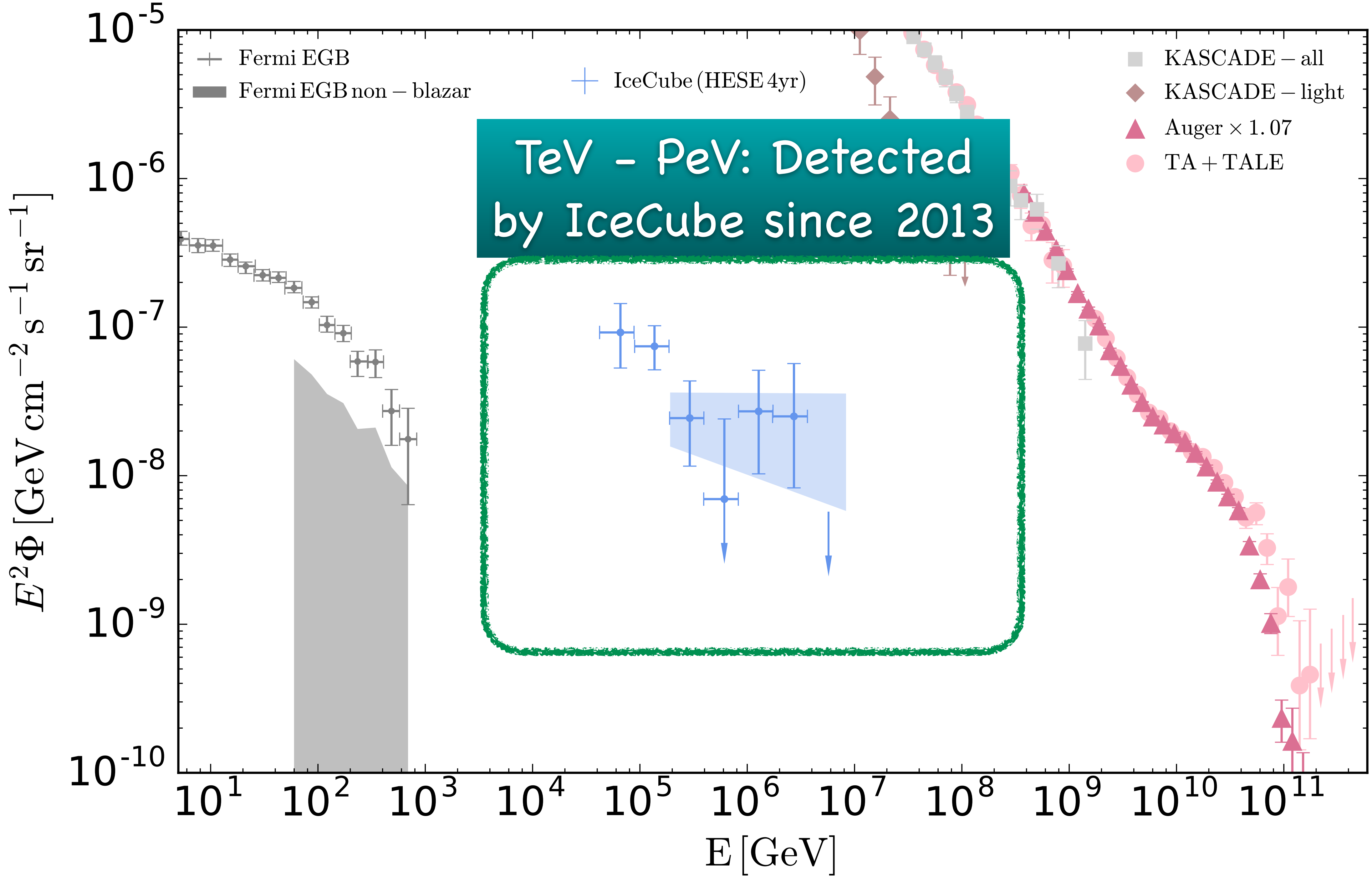


UHECRs, High-energy Nu, & Gamma Rays

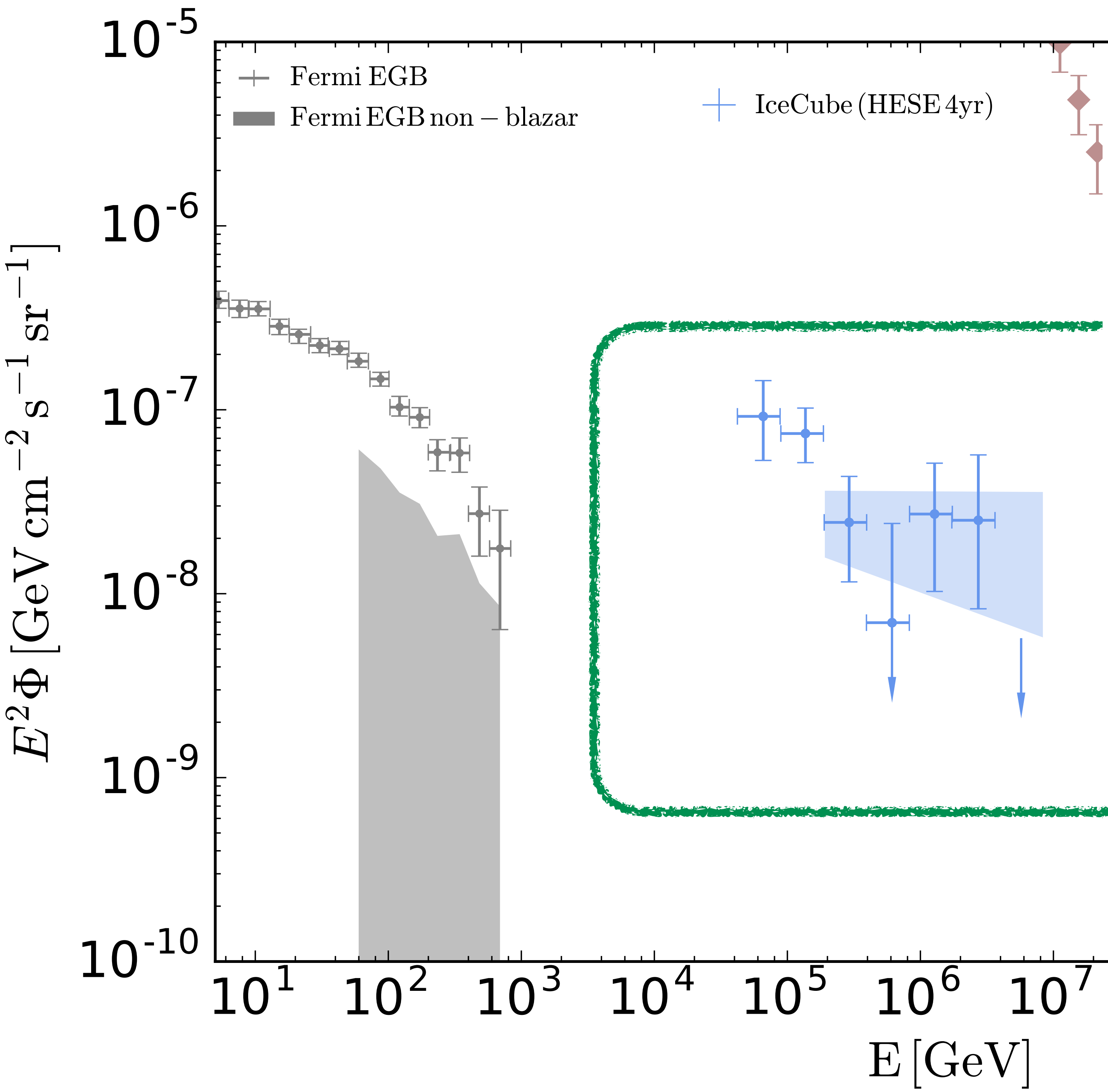


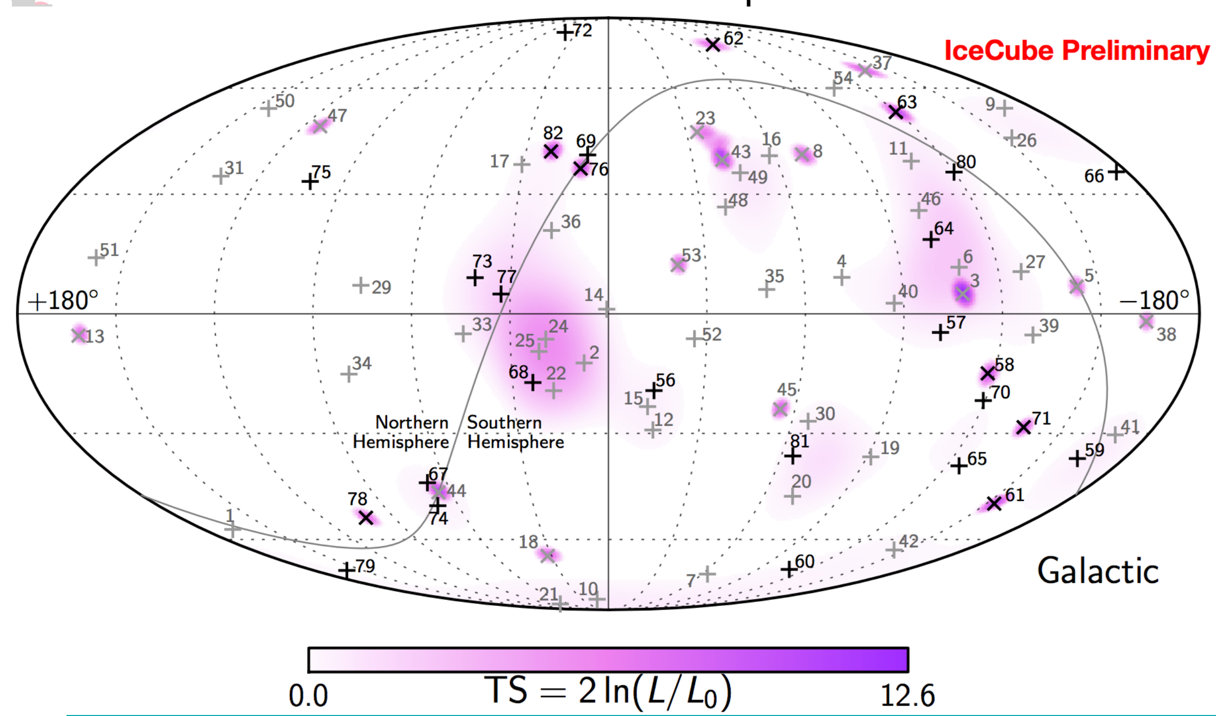
Also see IceTop talk by Andeen, Tuesday

UHECRs, High-energy Nu, & Gamma Rays



UHECRs, High-energy Nu, & Gamma Rays





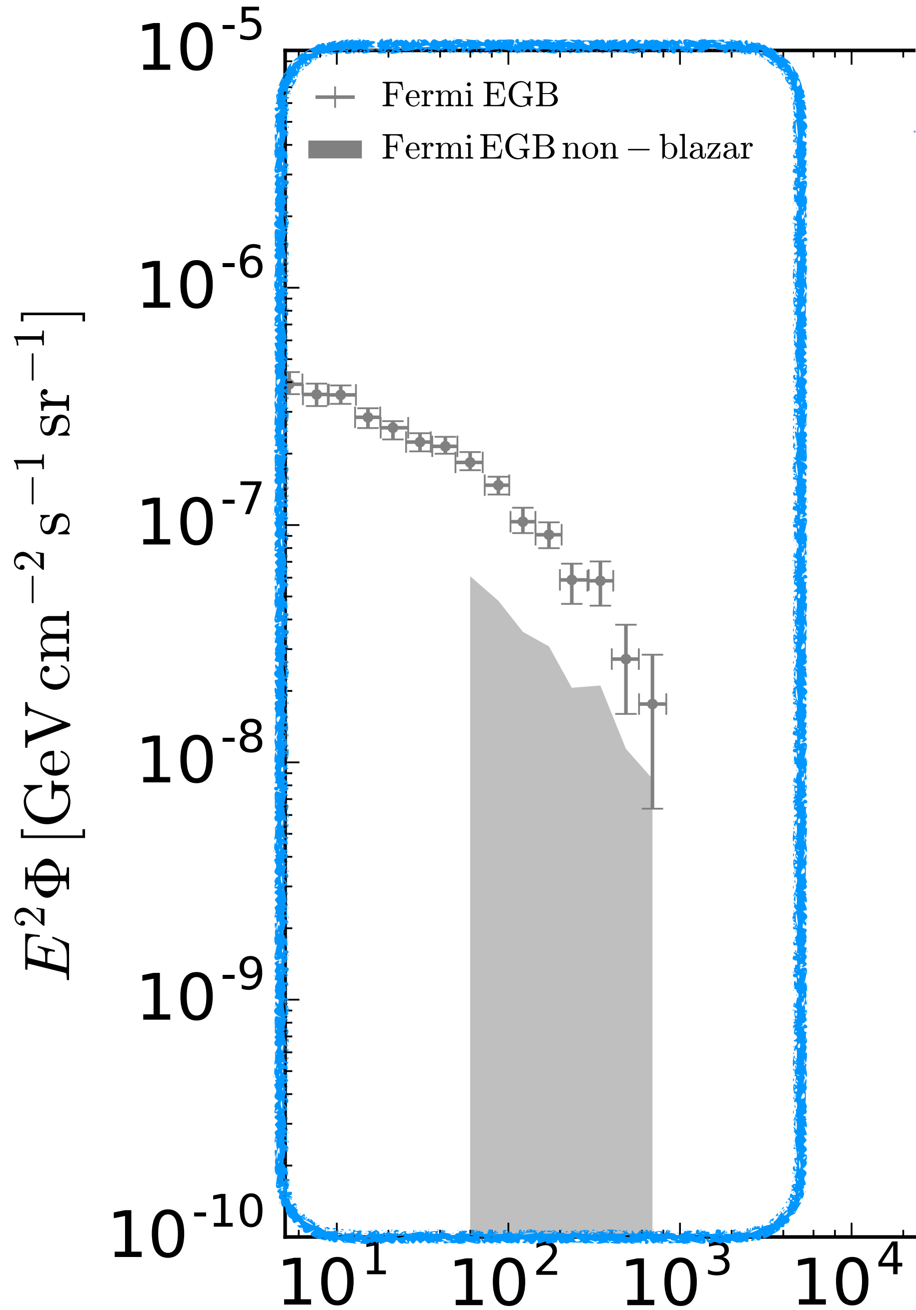
Fermi Blazars? (IceCube 16, Kun+17, Muller+17, IceCube 18ab)
GRBs (not within 100 seconds; IceCube 12, 15)
TDEs (cannot be jetted; Wang & Liu 16, Dai & KF 16, Zhang+17, Guepin,.. KF+17, Daniel+17)
Your call..

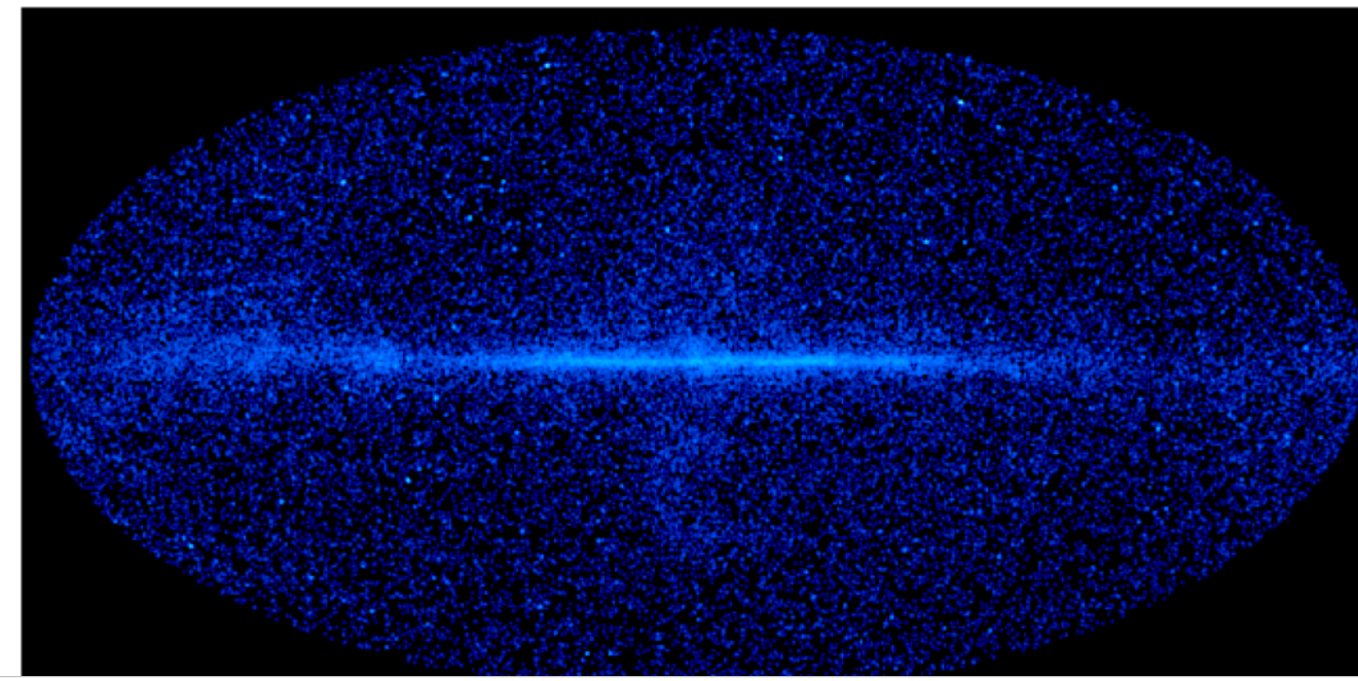
See Halzen 2016 review

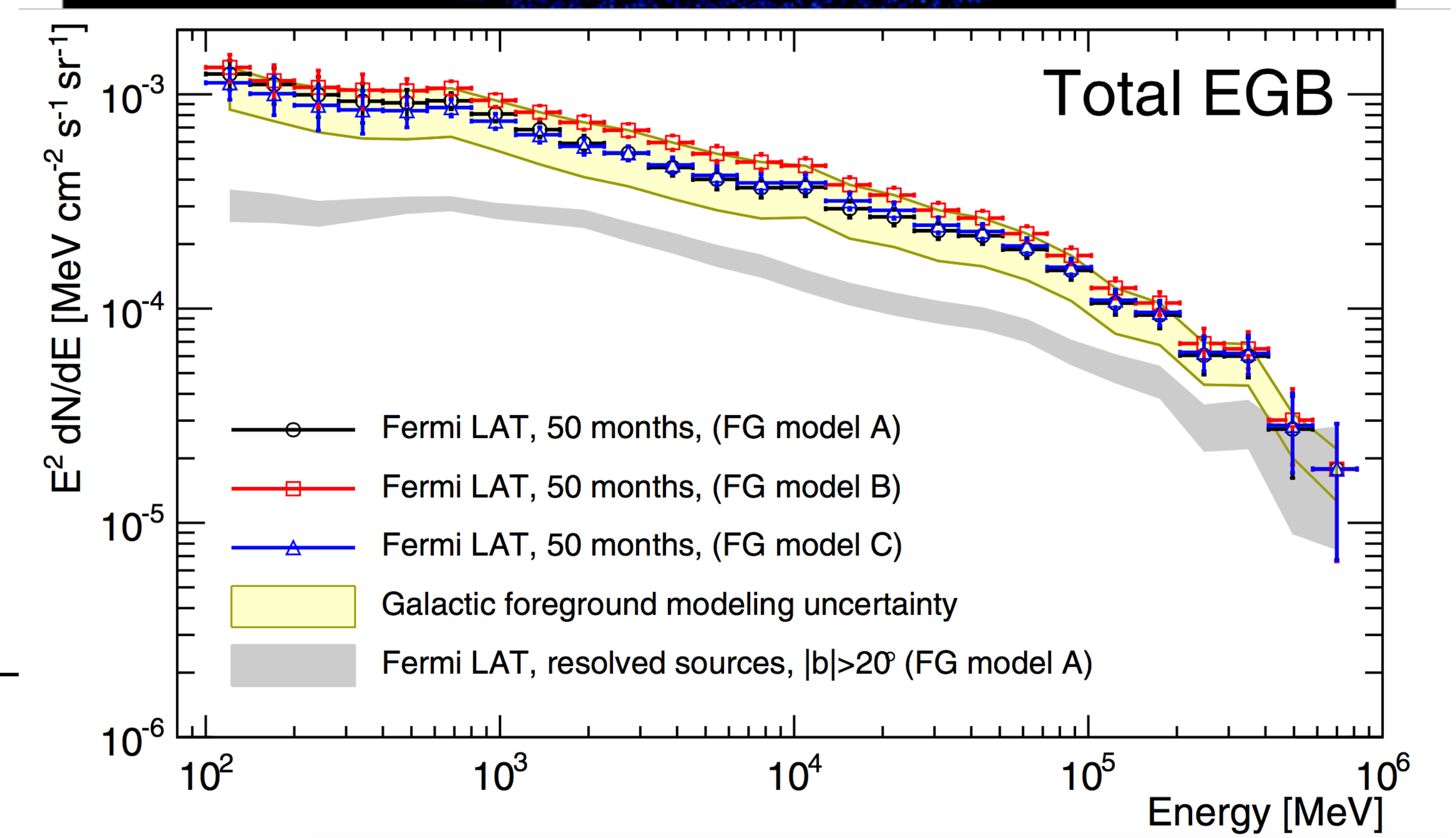
UHECRs, High-energy Nu, & Gamma Rays

Fermi Collaboration, PRL (2016)

Lisanti + ApJ (2016)

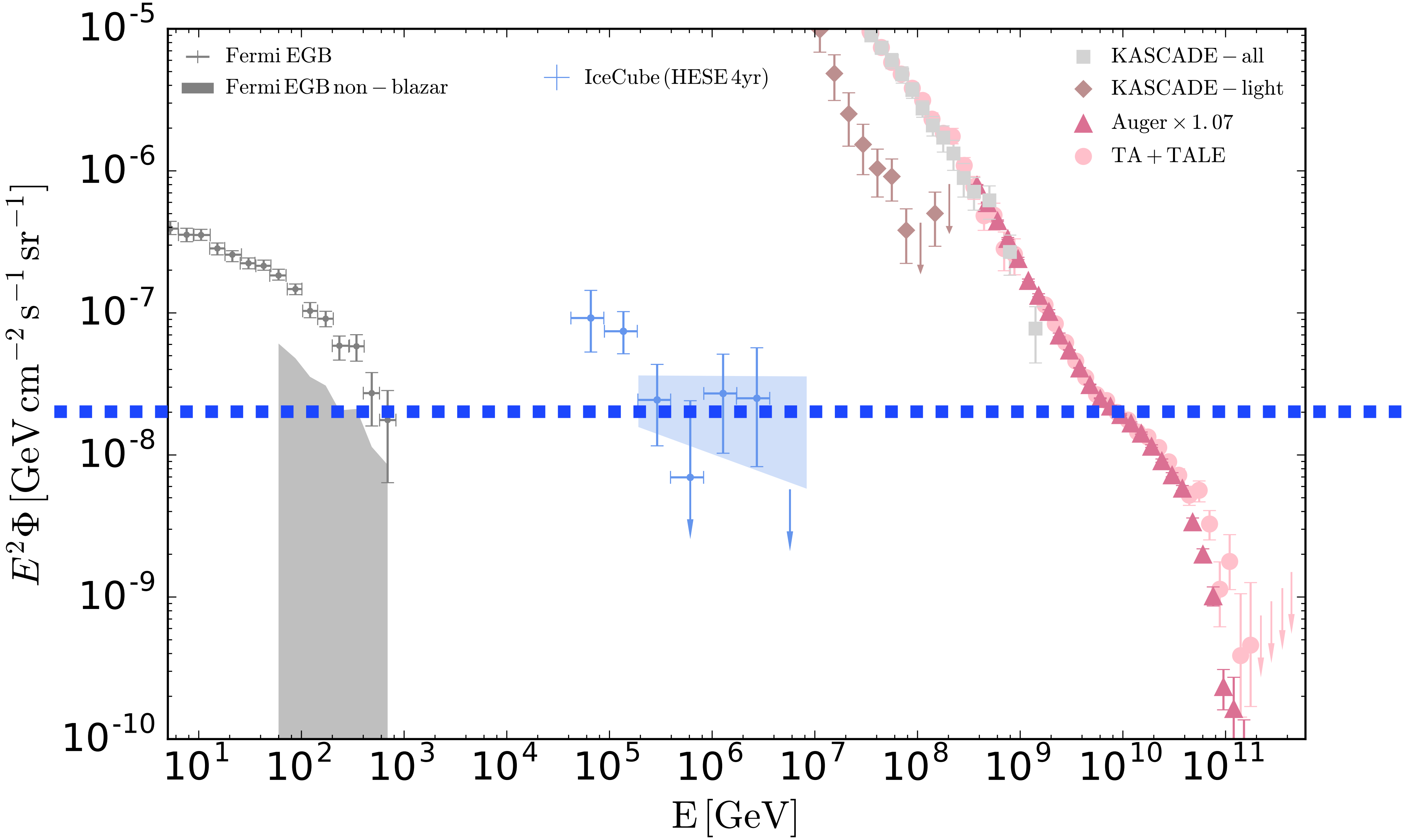






~14% of the Fermi extragalactic gamma-ray background is contributed by unknown sources.

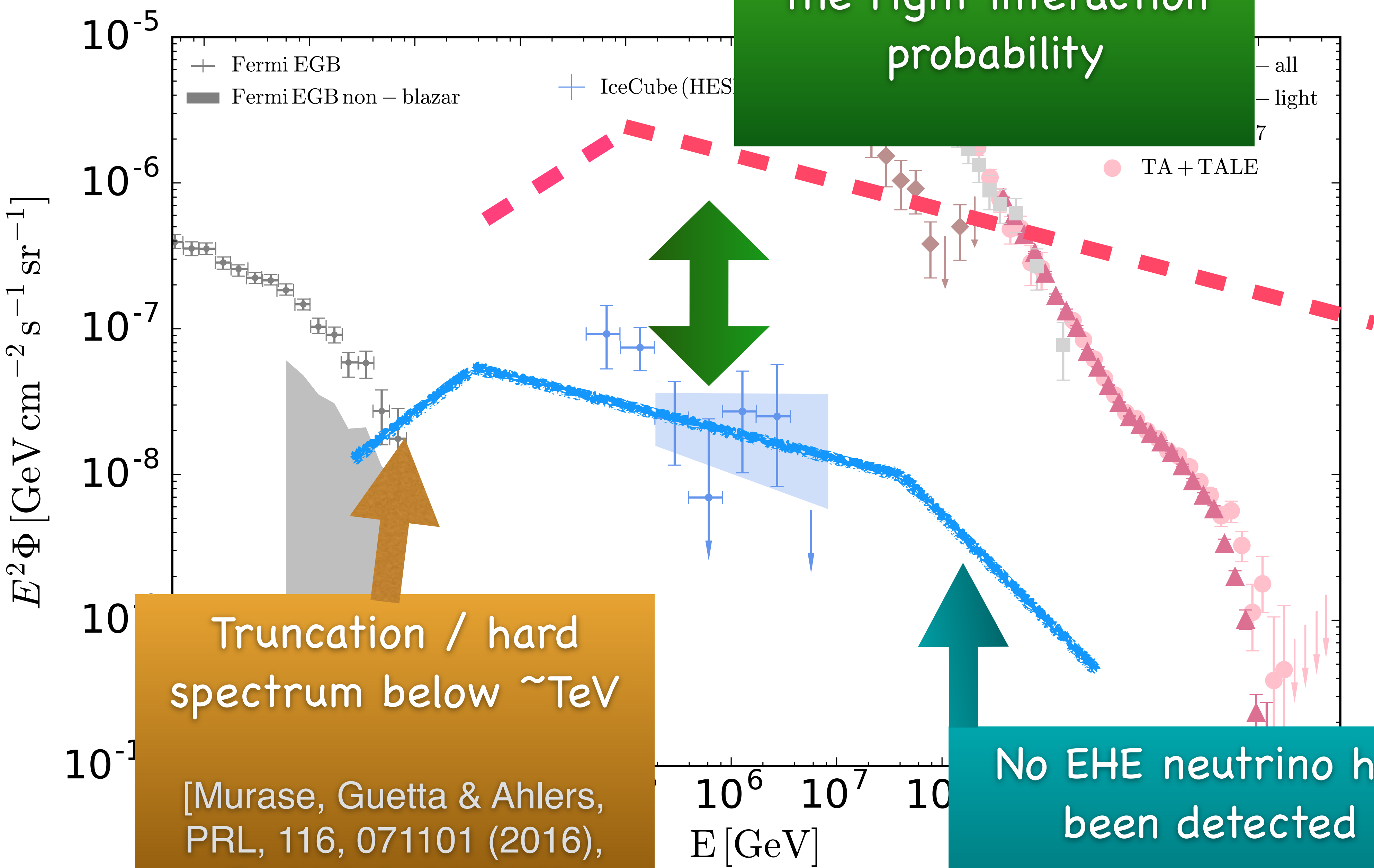
When putting them together..



Despite ten orders of magnitudes difference in energy, UHECRs, IceCube neutrinos, Fermi non-blazar EGB share similar energy injection rate.

Murase, Ahlers & Lacki, PRD (2013)
Waxman 1312.0558
Giacinti et al (2015)
Murase & Waxman PRD (2016)
Wang & Loeb PRD (2017) …

A common origin is not trivial



Source should provide the right interaction probability

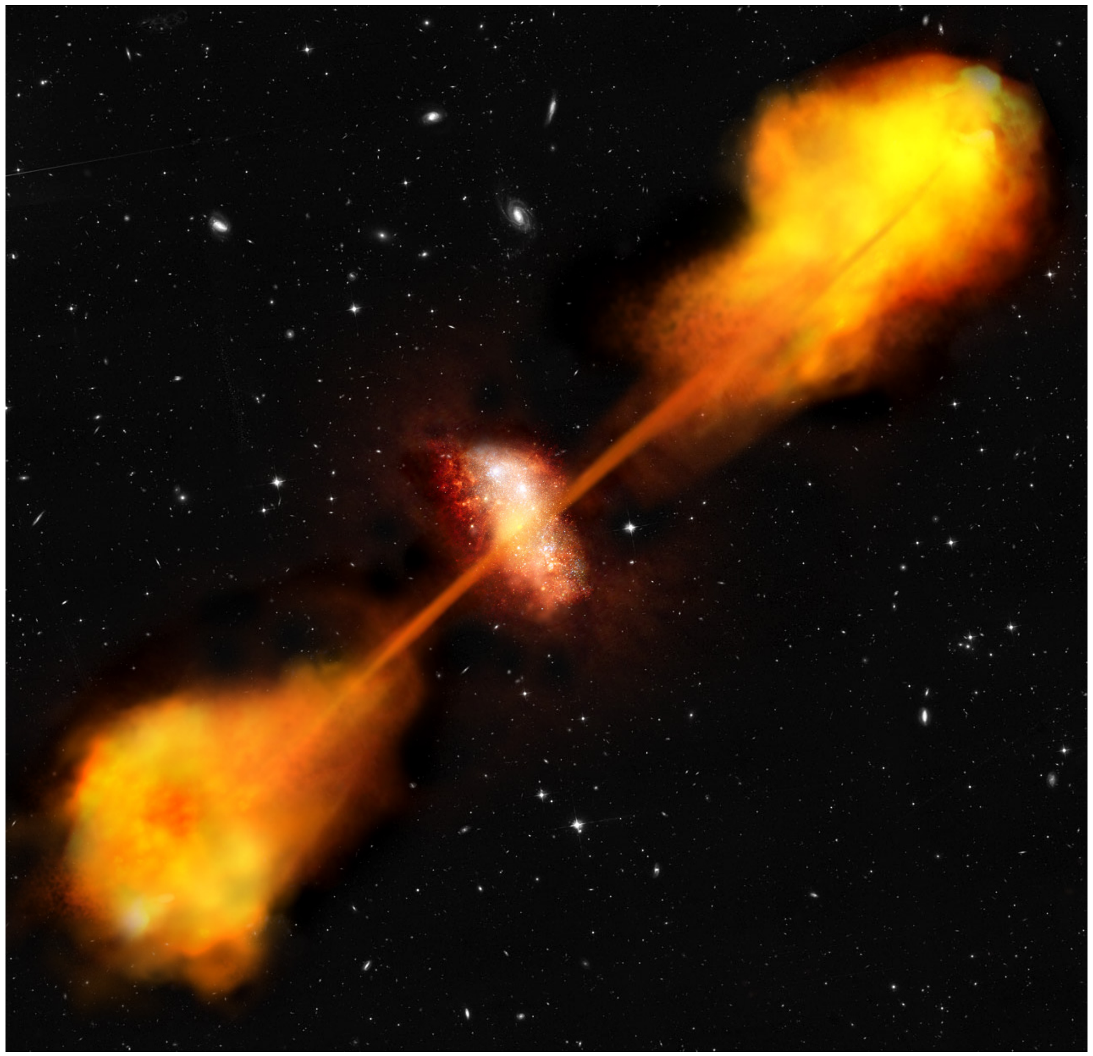
Truncation / hard spectrum below ~TeV

[Murase, Guetta & Ahlers, PRL, 116, 071101 (2016), Bechtol+ApJ (2017)]

No EHE neutrino has been detected

[IceCube, PRL 117, 241101, 2016]

Cosmic Ray Production by the Jet



$$E \sim Z\,10^{19}\left(\frac{B}{1\,\mu G}\right)\left(\frac{R}{10\,\mathrm{kpc}}\right)\,\mathrm{eV}$$

Cosmic rays that are confined by the radio lobes cool adiabatically

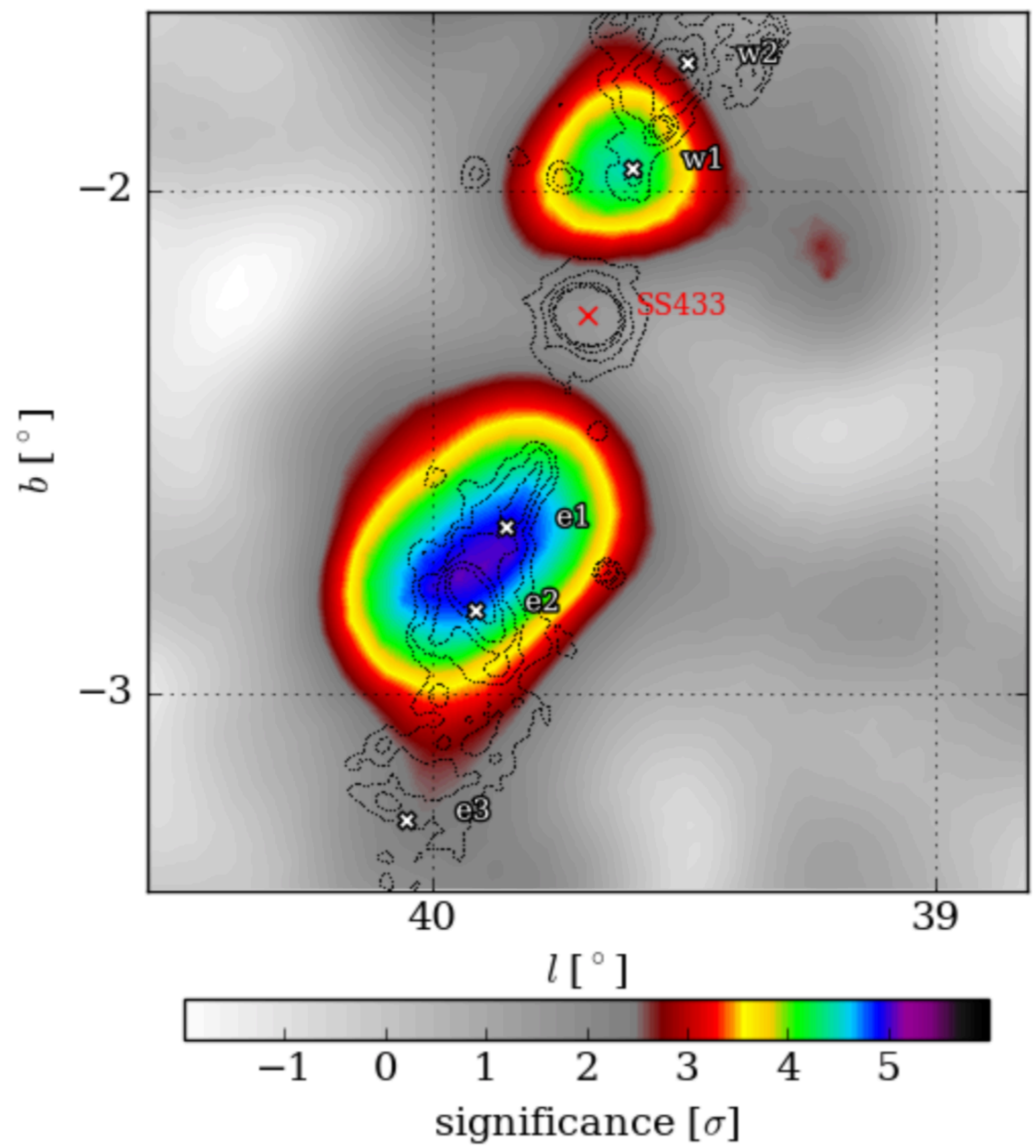
$$t_{\mathrm{diff}}^{\mathrm{lobe}} \sim 6.1\left(\frac{E/Z}{1\,\mathrm{PeV}}\right)^{-1/3}\,\mathrm{Myr}\ *$$

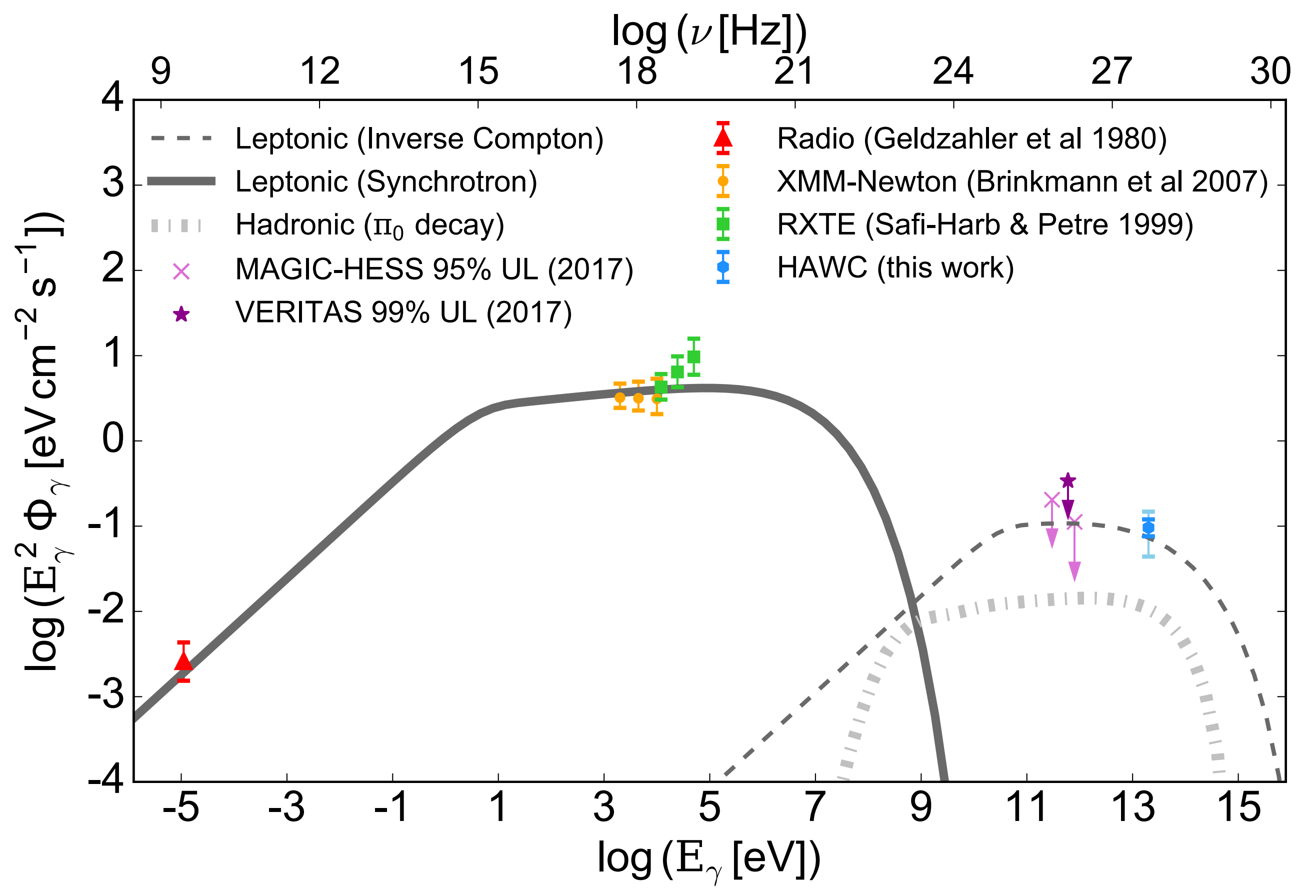
$$t_{\mathrm{cool}} \sim 5\,\mathrm{Myr}$$

Only particles above ~PeV leave the source

*taking a typical lobe size 10 kpc, coherence length 0.3 kpc, magnetic field strength 5 muG, and expansion velocity 2000 km/s.

Jets Are Great Astroparticle Accelerators!





Very-high-energy gamma rays are observed from the lobes of SS 433, showing that jets of compact objects provide promising sites for particle acceleration to highest energies

HAWC Collaboration, Nature (2018)
Main authors: BenZvi, Brenda, KF, Rho, Zhang, Zhou

Cluster Environment

ICM gas

$$n_{\rm ICM}(r) = n_{\rm ICM,0}\left[1+\left(\frac{r}{r_c}\right)^2\right]^{-3\beta/2}$$

$$B(M,r) \propto n(M,r)^\eta$$

[Cavaliere & Fusco-Femiano, A&A (1976)]

Infrared background from galaxies

[Takami & Murase ApJ 2012]

CMB, EBL

CRPropa3 + SOPHIA for turbulent field & $N\gamma$

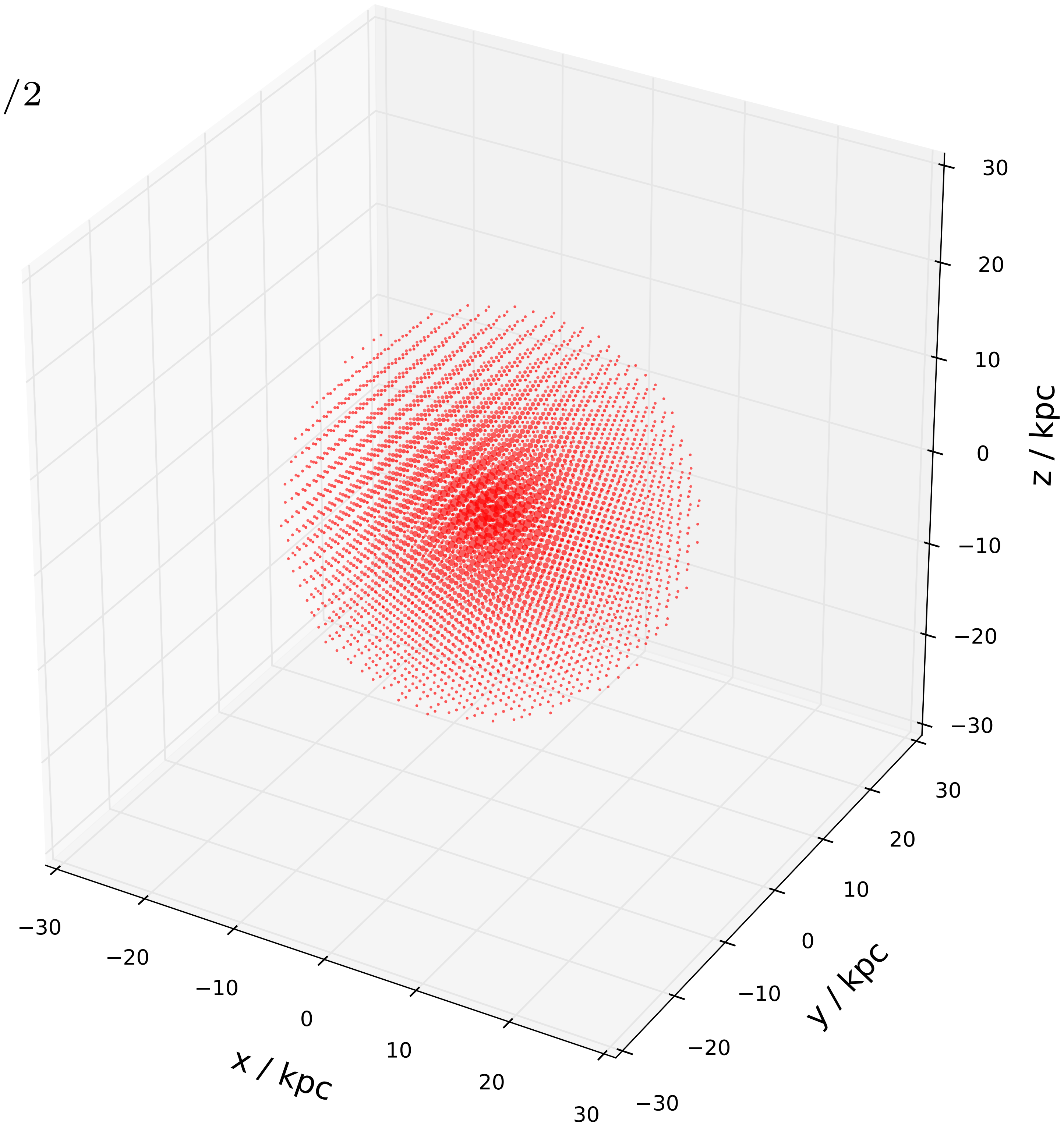
[Batista+ JCAP (2016)]

EPOS for Np

[KF, Kotera & Olinto ApJ (2012)]

Diffuse propagation

[Kotera & Lemoine PRD (2007), KF & Olinto ApJ (2016)]



Particle Trajectory - 10 EeV

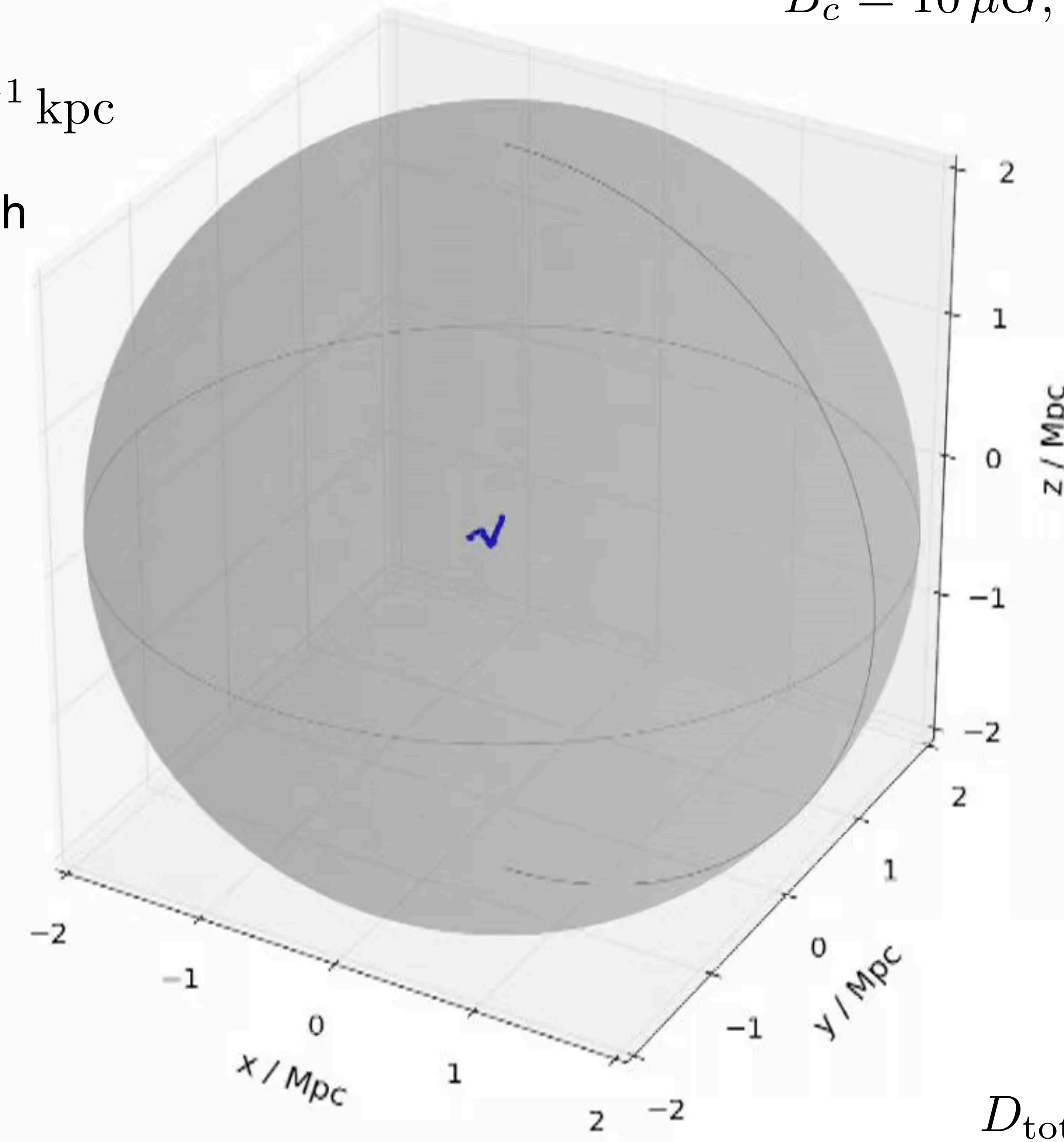
Particle Larmor Radius

$$r_L = 10\,E_{19}\,B_{-6}^{-1}\,Z^{-1}\,\mathrm{kpc}$$

Field Coherence Length

$$l_0 \sim 20\,\mathrm{kpc}$$

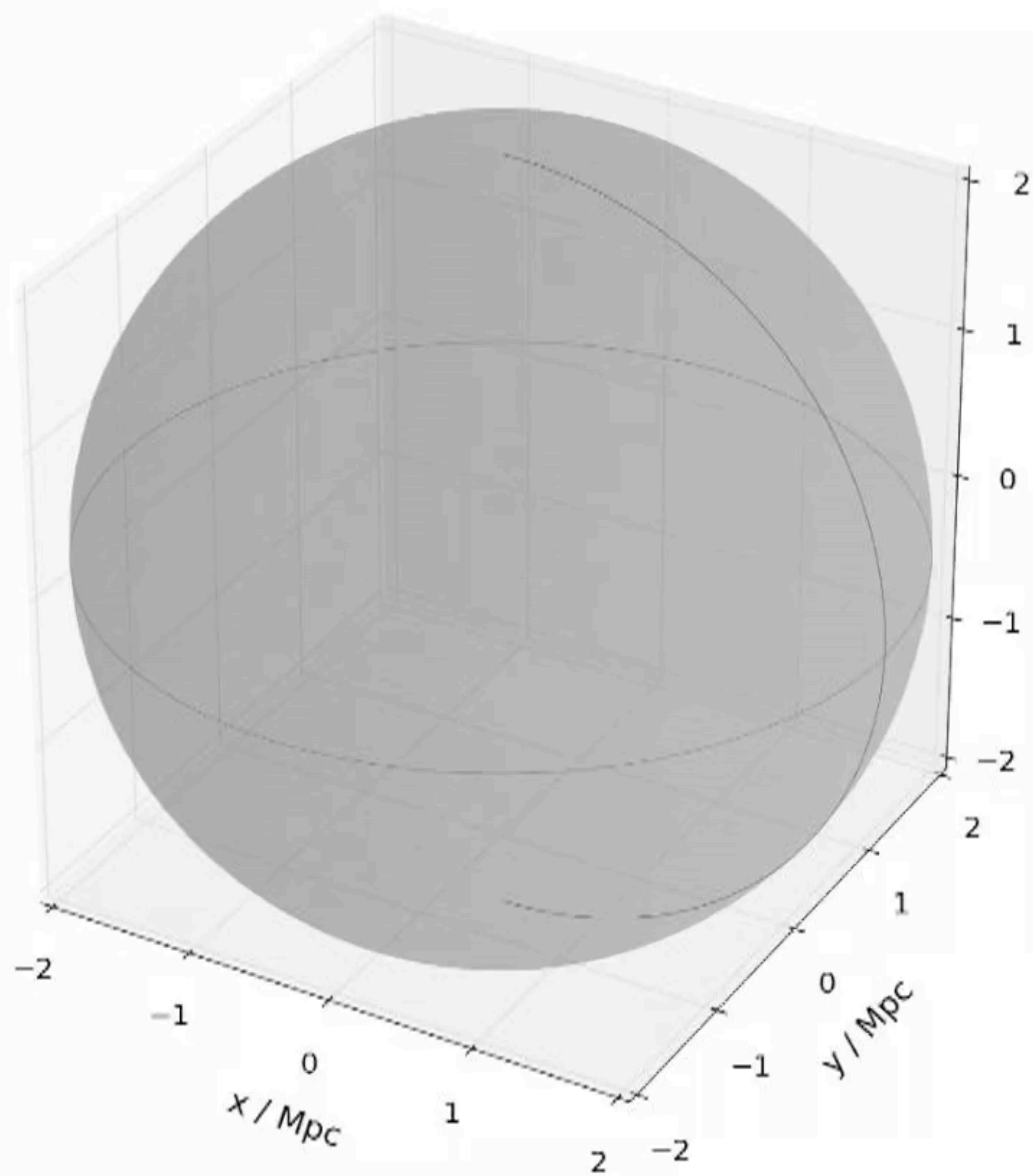
$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$

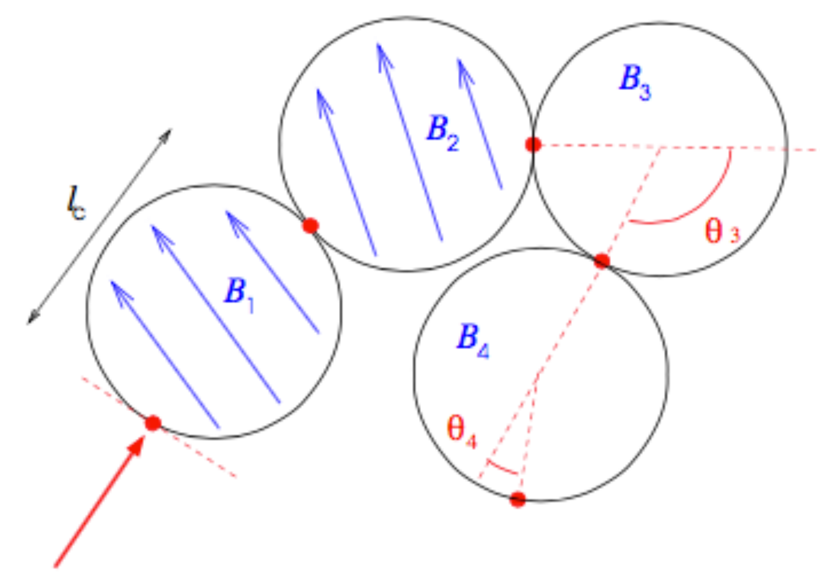


$D_{\mathrm{total}} = 46\,\mathrm{Mpc}$

Particle Trajectory - 0.1 EeV

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$



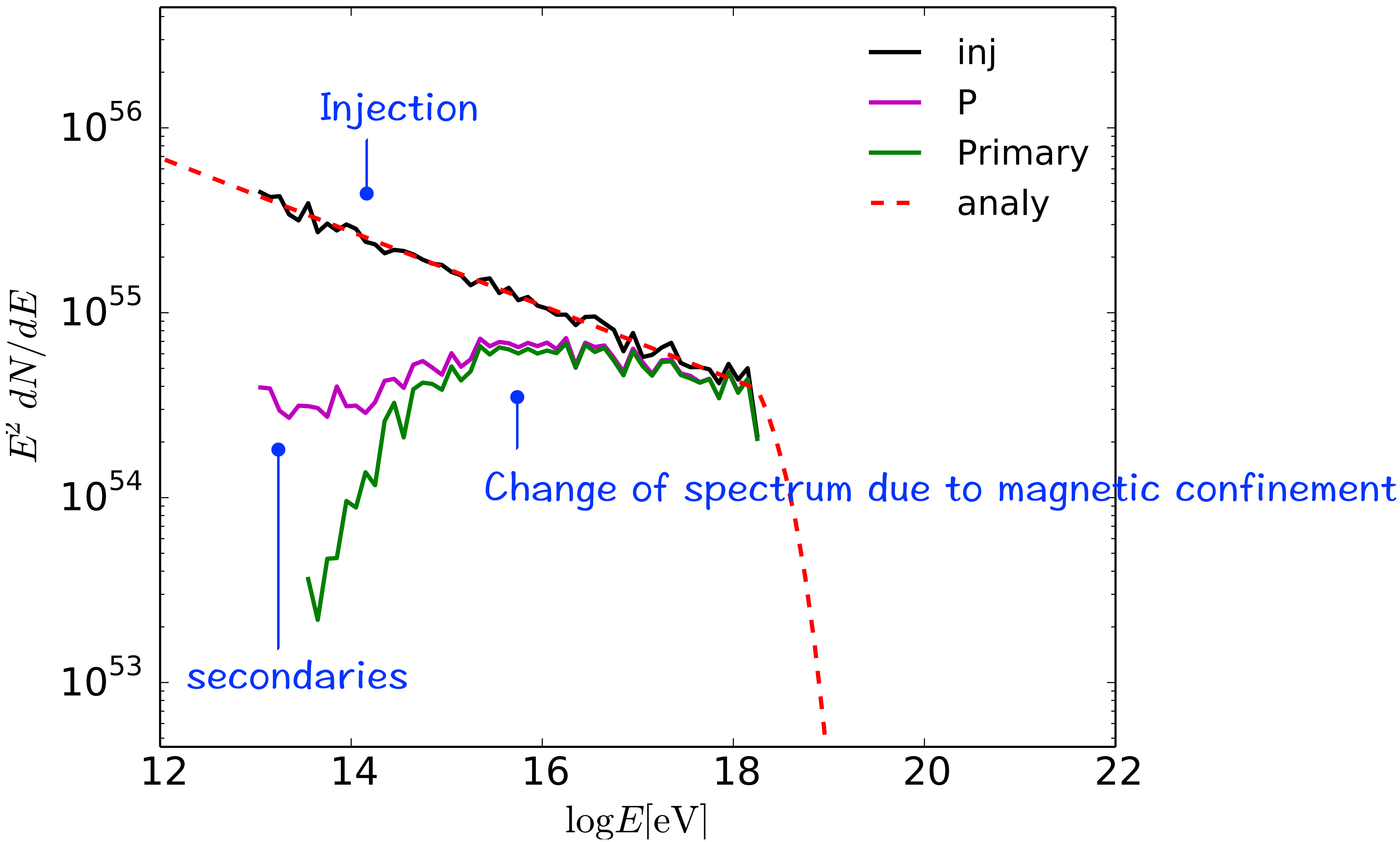


Approximation for diffusion computation

$D_{\text{total}} \sim t_{\text{Hubble}}$

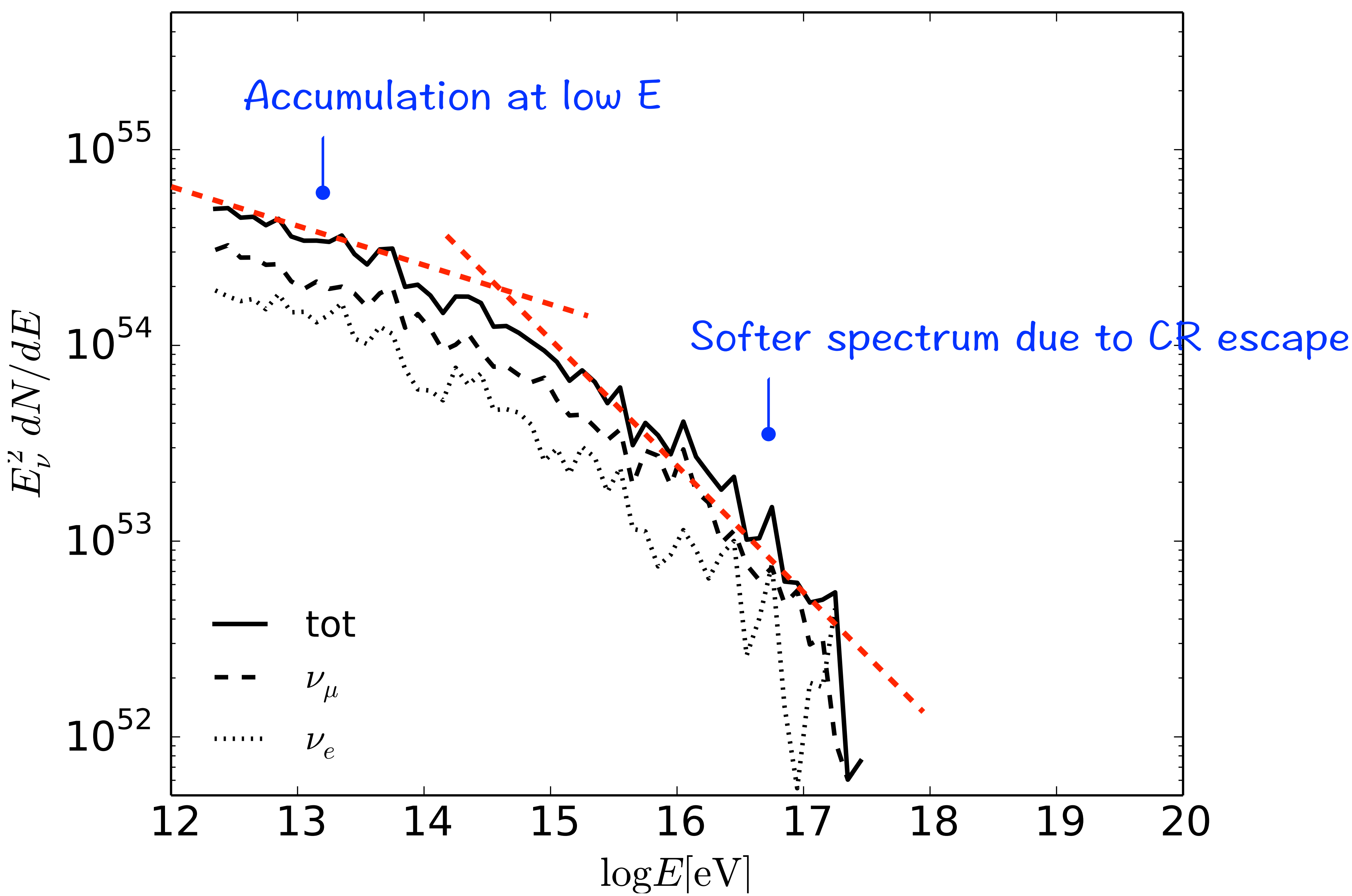
Cosmic Ray Flux from One Single Cluster

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$



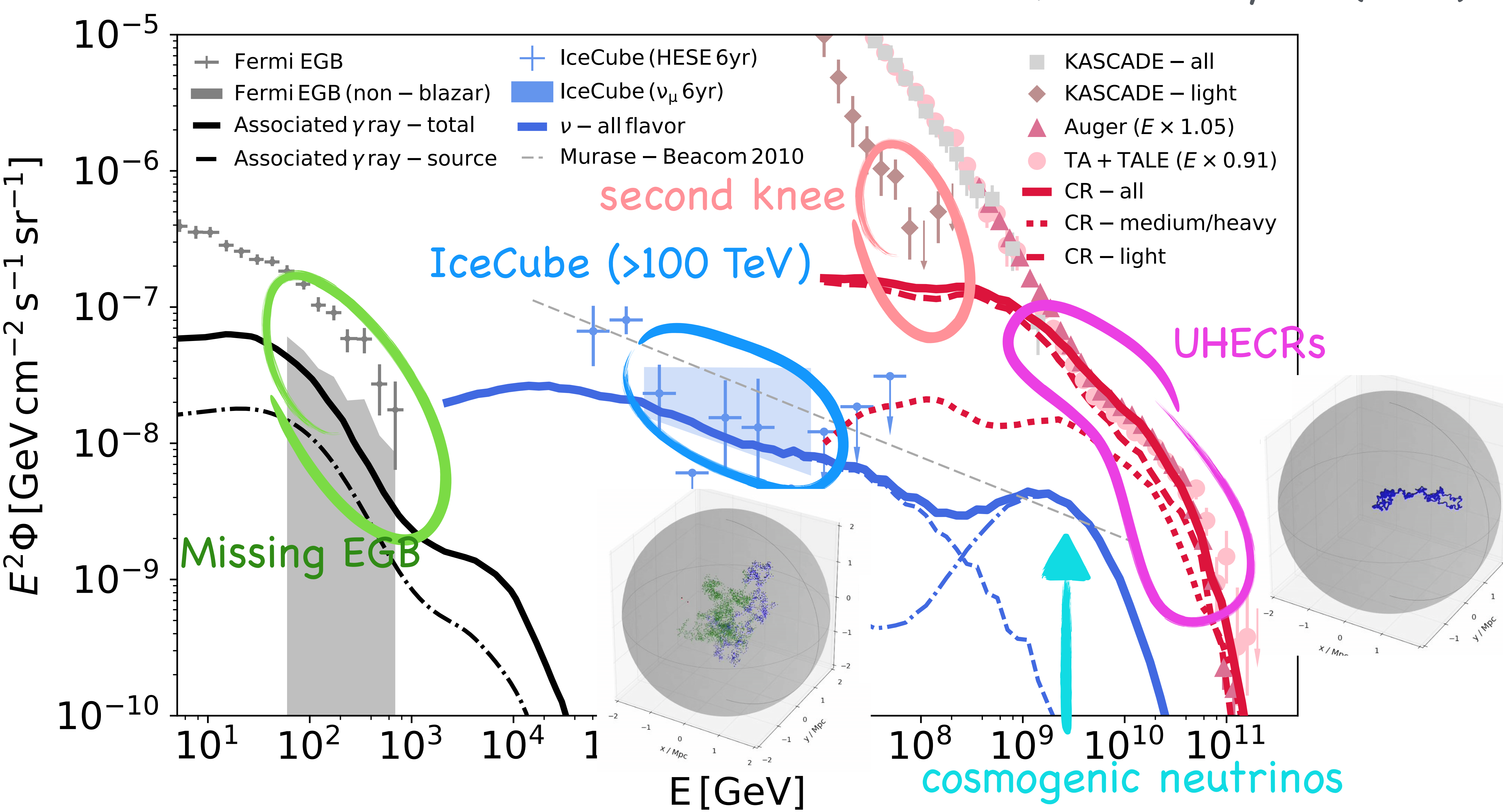
Neutrino Flux from One Single Cluster

$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$



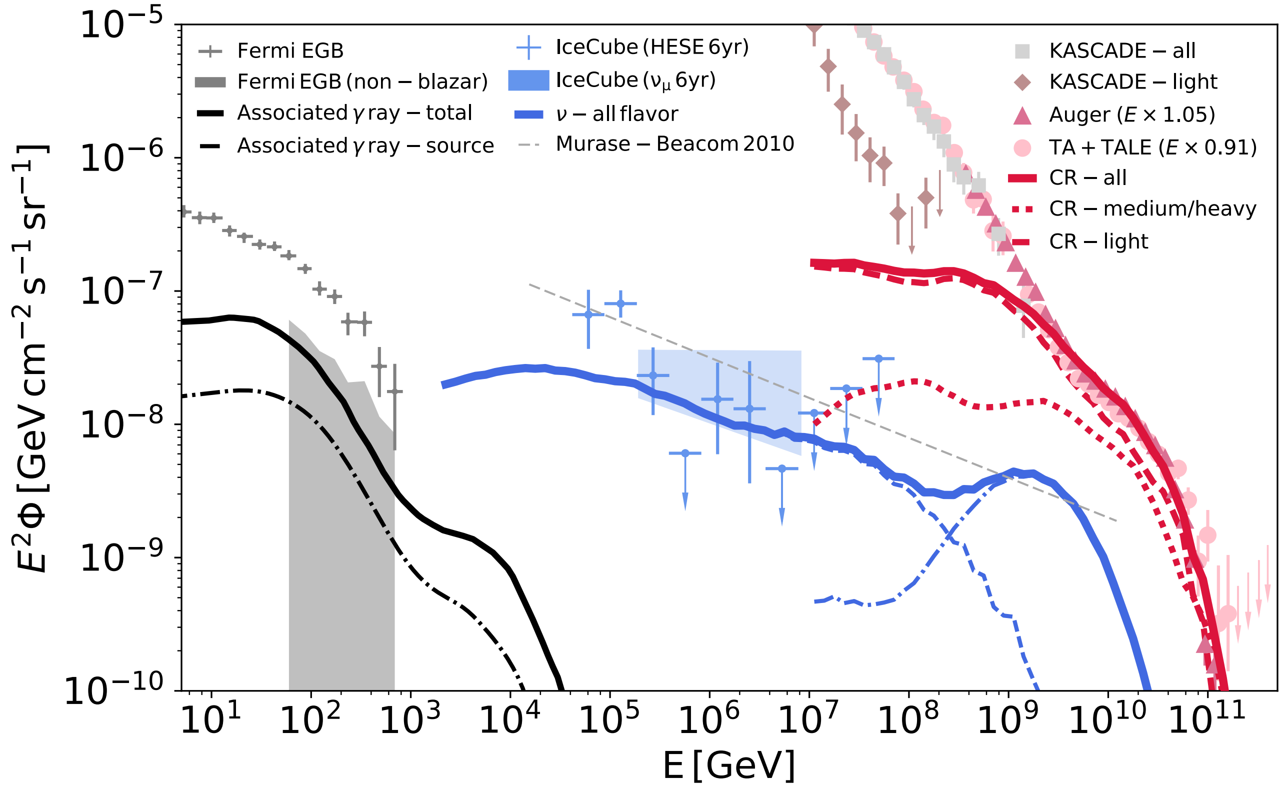
A Unified Picture of Multi-messengers

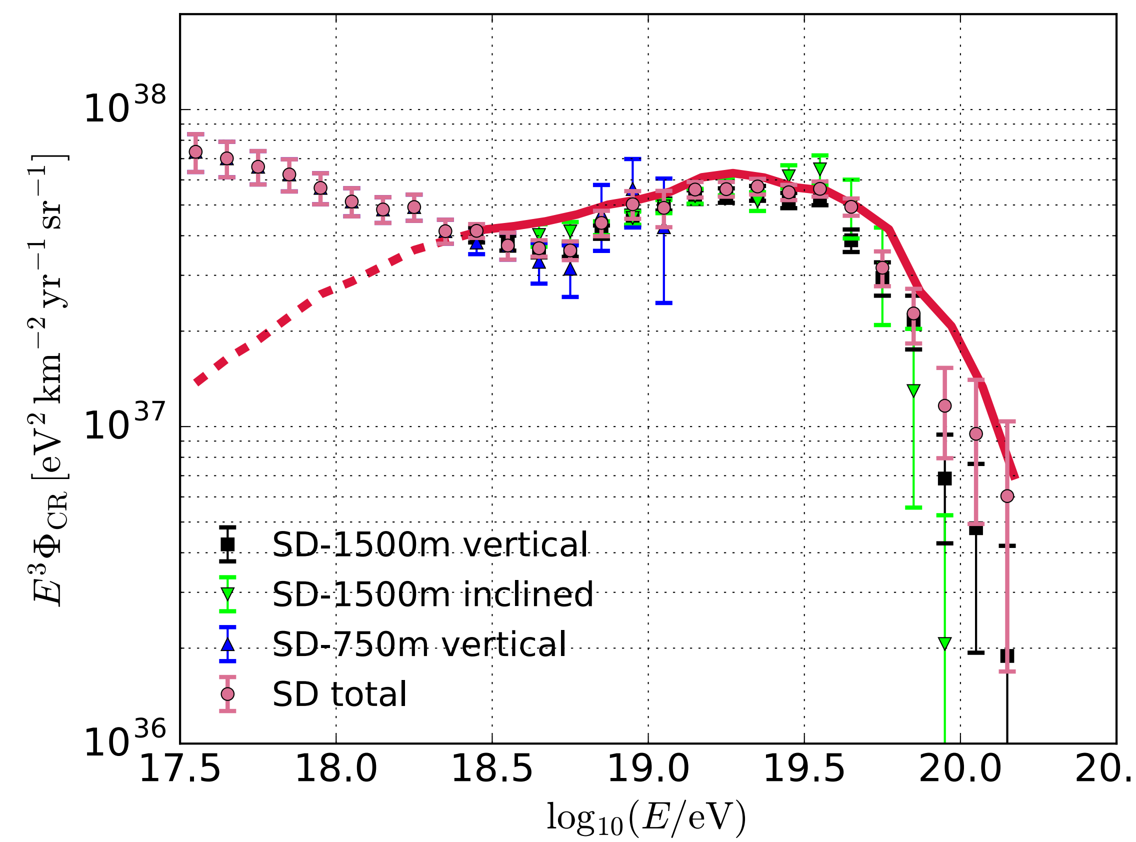
KF & Murase, Nature Physics (2018)



Injection Composition = Galactic CR abundance

Fitting to Data



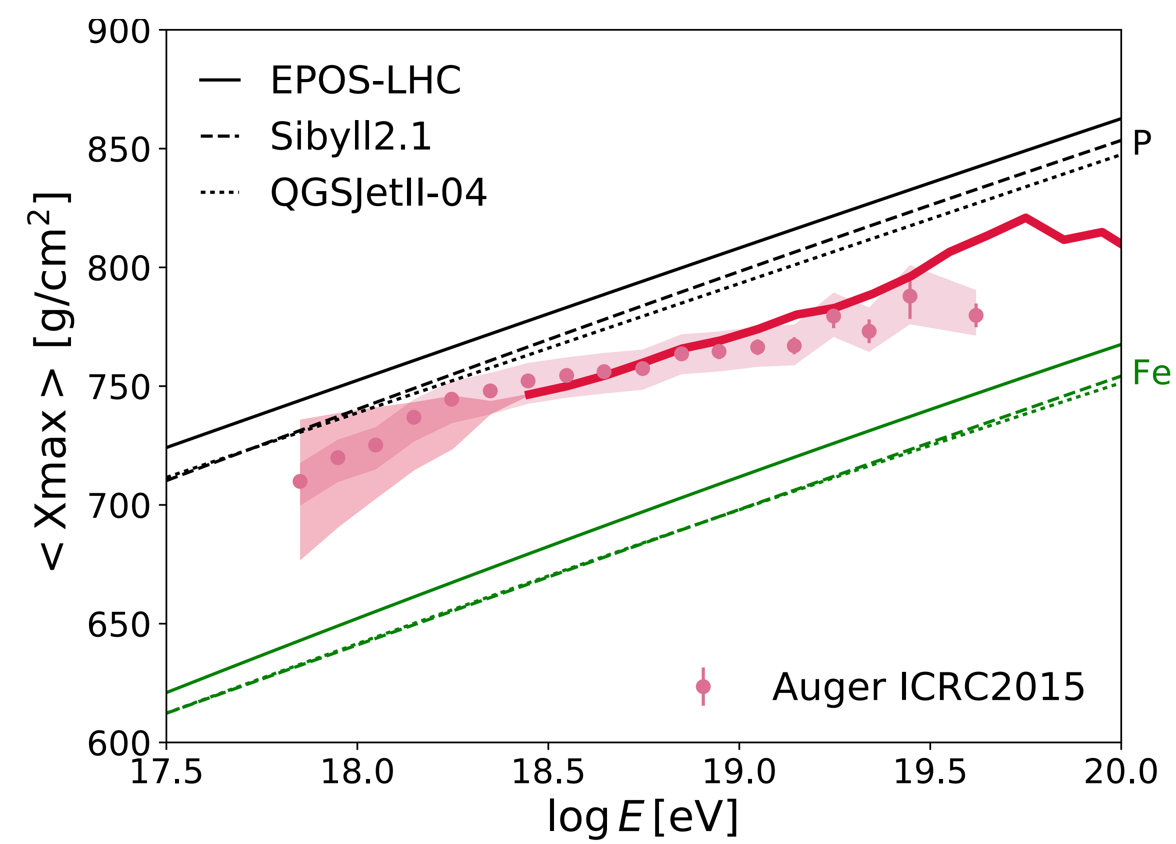


$$\chi^2_{\mathrm{CR}/\nu,\,\mathrm{spec}} = \sum_i \left(\frac{\Phi_{\mathrm{CR}/\nu}(E'_i, C_{\mathrm{norm}}) - \left(\Phi_{\mathrm{CR}/\nu}\right)_i^{\mathrm{obs}}}{\left[\Delta\left(\Phi_{\mathrm{CR}/\nu}\right)\right]_i^{\mathrm{obs}}}\right)^2 + \left(\frac{\delta_E^{\mathrm{CR}/\nu}}{\Delta_E^{\mathrm{CR}/\nu}}\right)^2$$

$$E_{\max} = 2\times 10^{21}/Z\,\mathrm{eV}$$

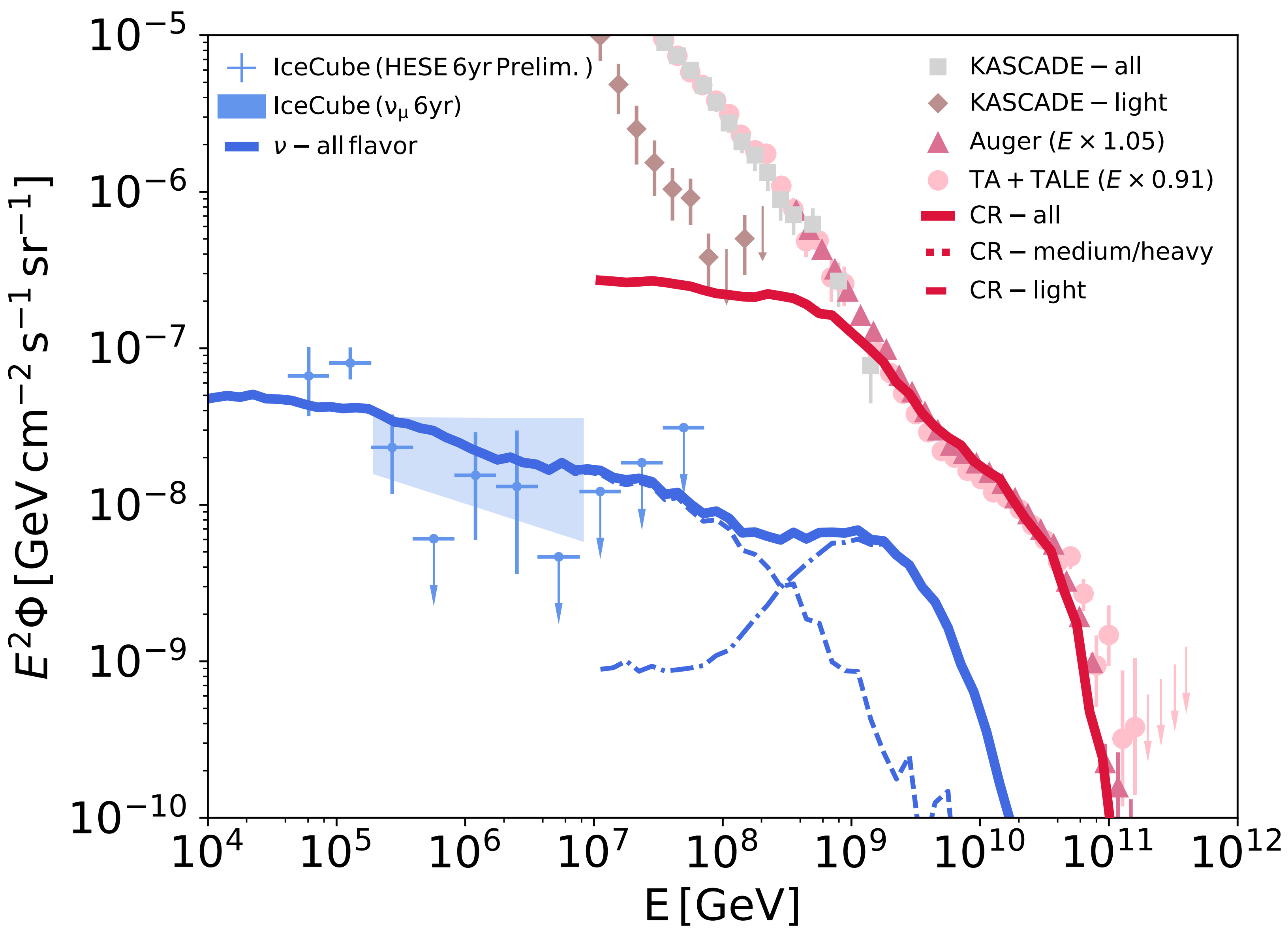
$$s_{\mathrm{acc}} = 2.3$$

$$\rightarrow \chi^2_{\mathrm{dof}} = 1.5$$



KF & Murase, Nature Physics (2018)

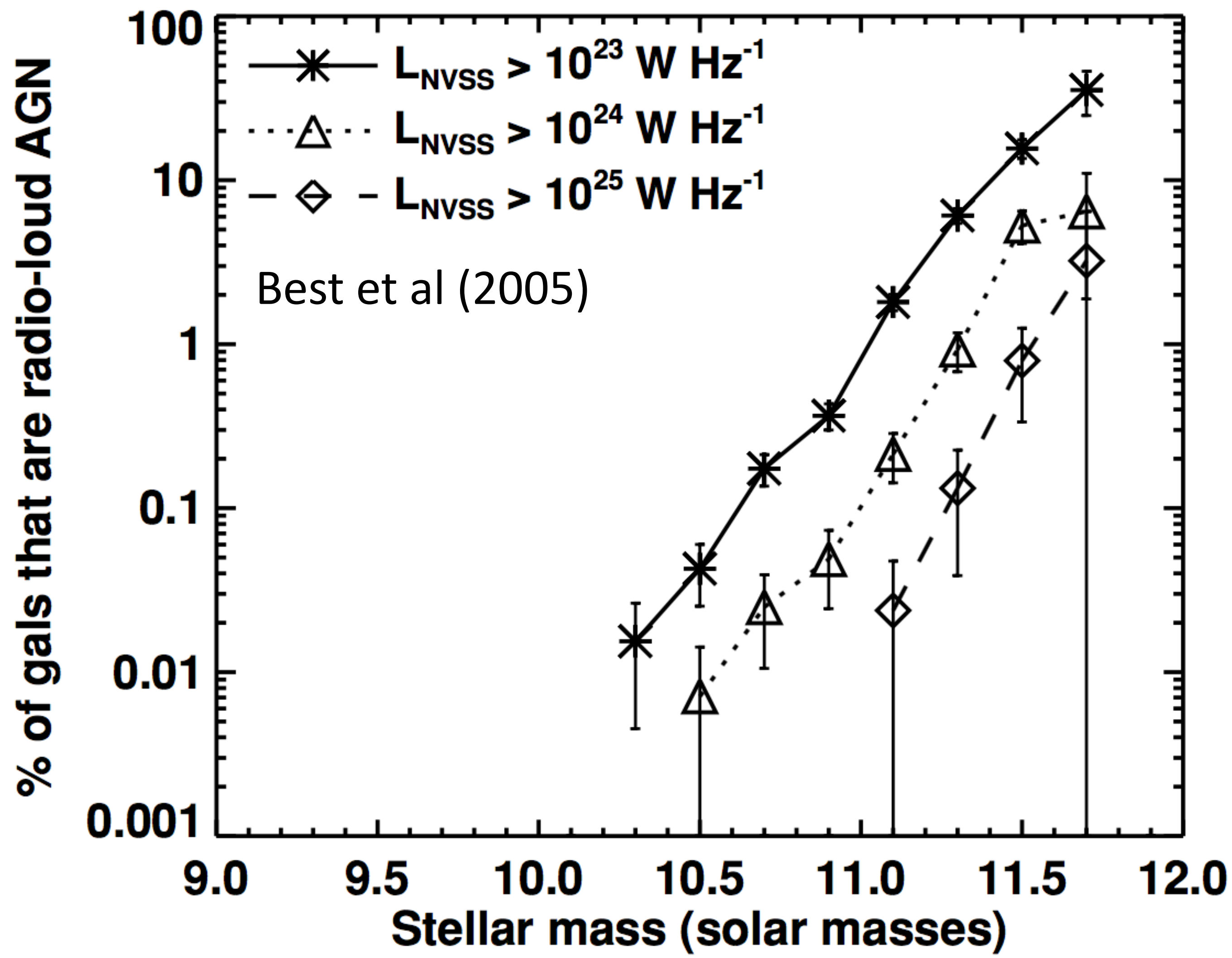
Fitting to Data (pure proton)



KF & Murase, Nature Physics (2018)

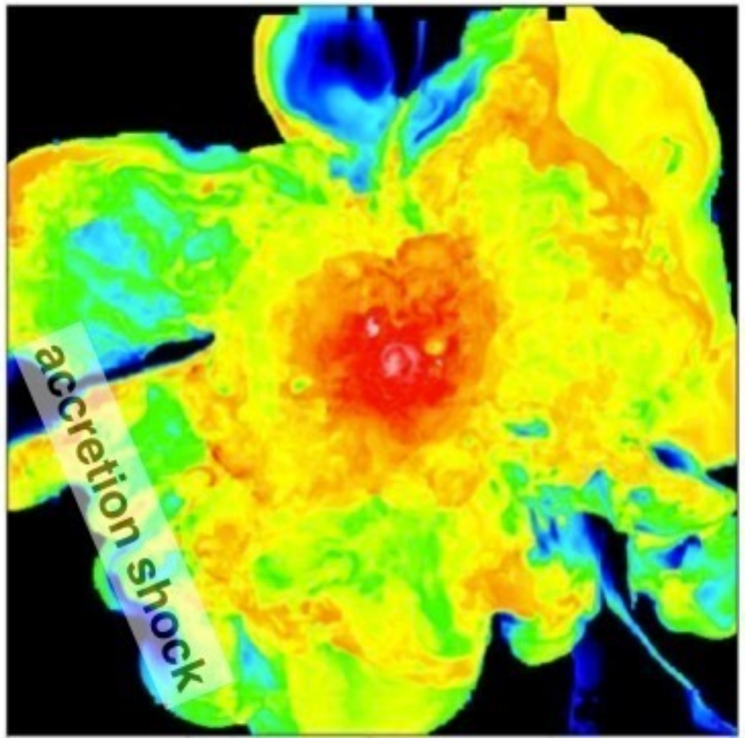
Energy Budget

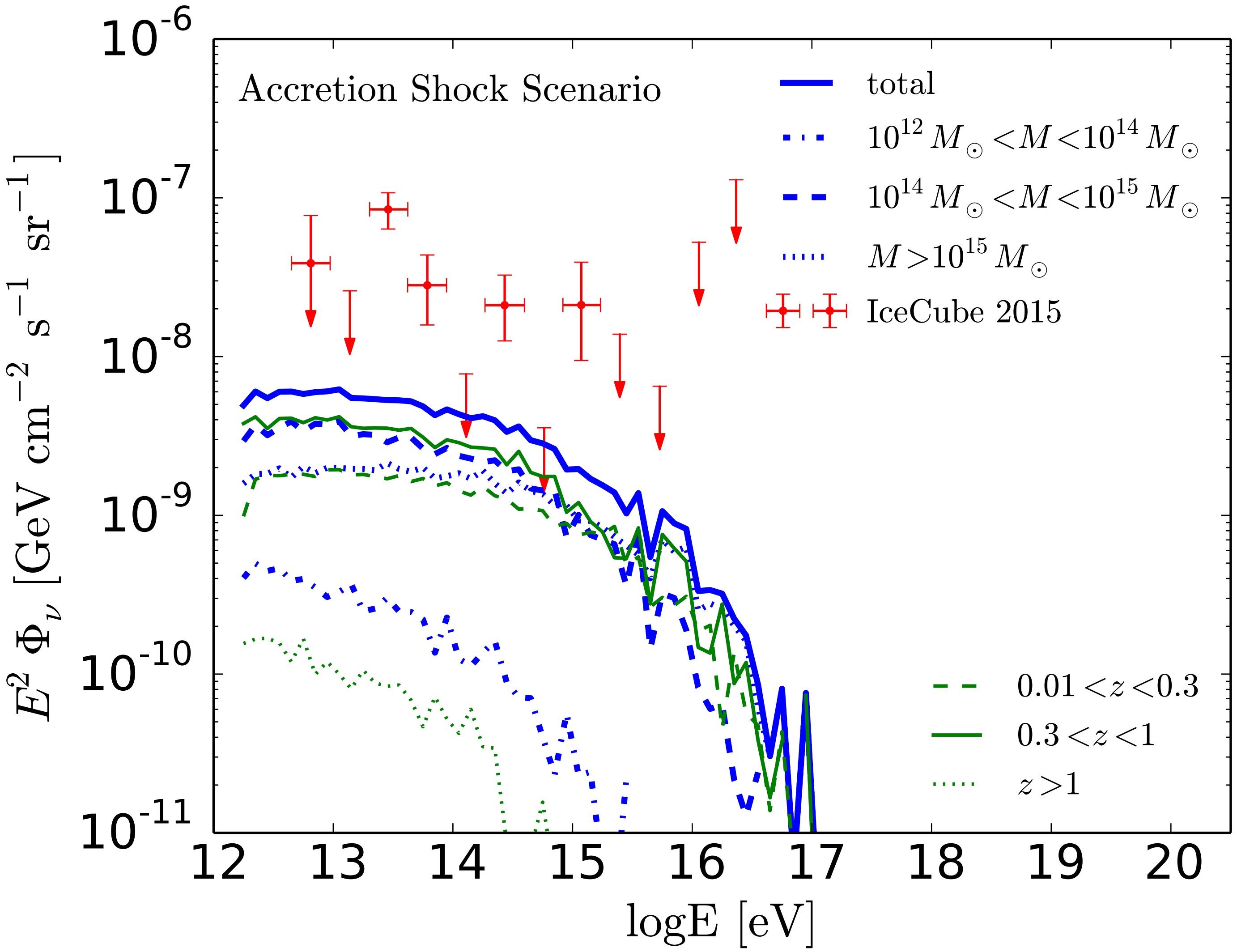
Fits to data require that about 10% of galaxy clusters hosted or are hosting active black hole jets. This is consistent with observations of radio-load active galactic nuclei.



KF & Murase, Nature Physics (2018)

Accretion Shocks





Due to low baryon density at the outskirts of clusters, particle interaction near accretion shocks is too weak to explain observed high-energy neutrinos.

KF & Olinto, ApJ (2016)

also see talk by Kim, Wednesday

Black hole jets embedded in galaxy clusters can simultaneously explain UHECRs, high-energy neutrinos, and the non-blazar component of isotropic gamma-ray background.