Black Hole Jets in Galaxy Clusters as Common Origins of High-energy Cosmic Particles

Ke Fang
Stanford University
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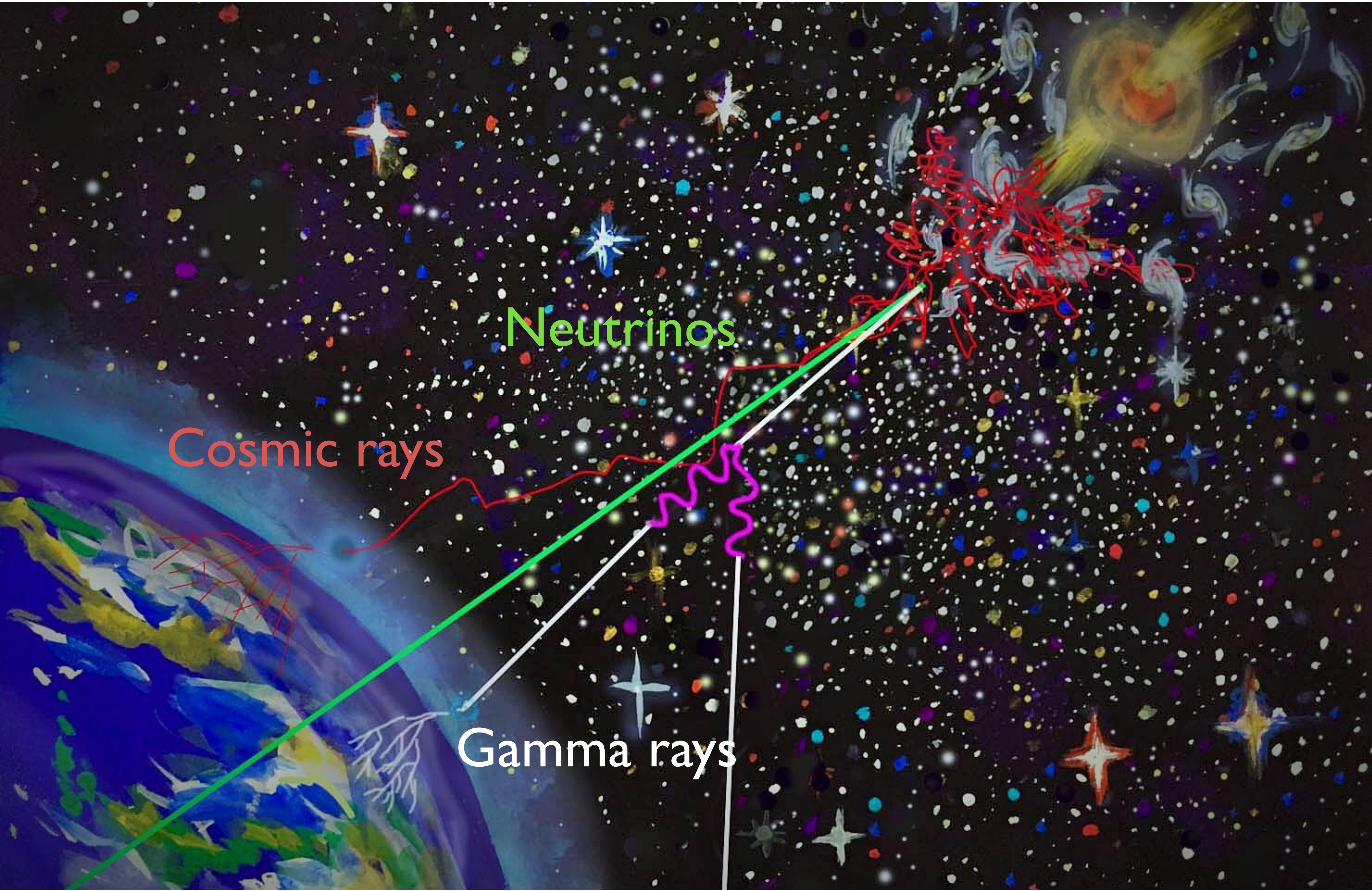
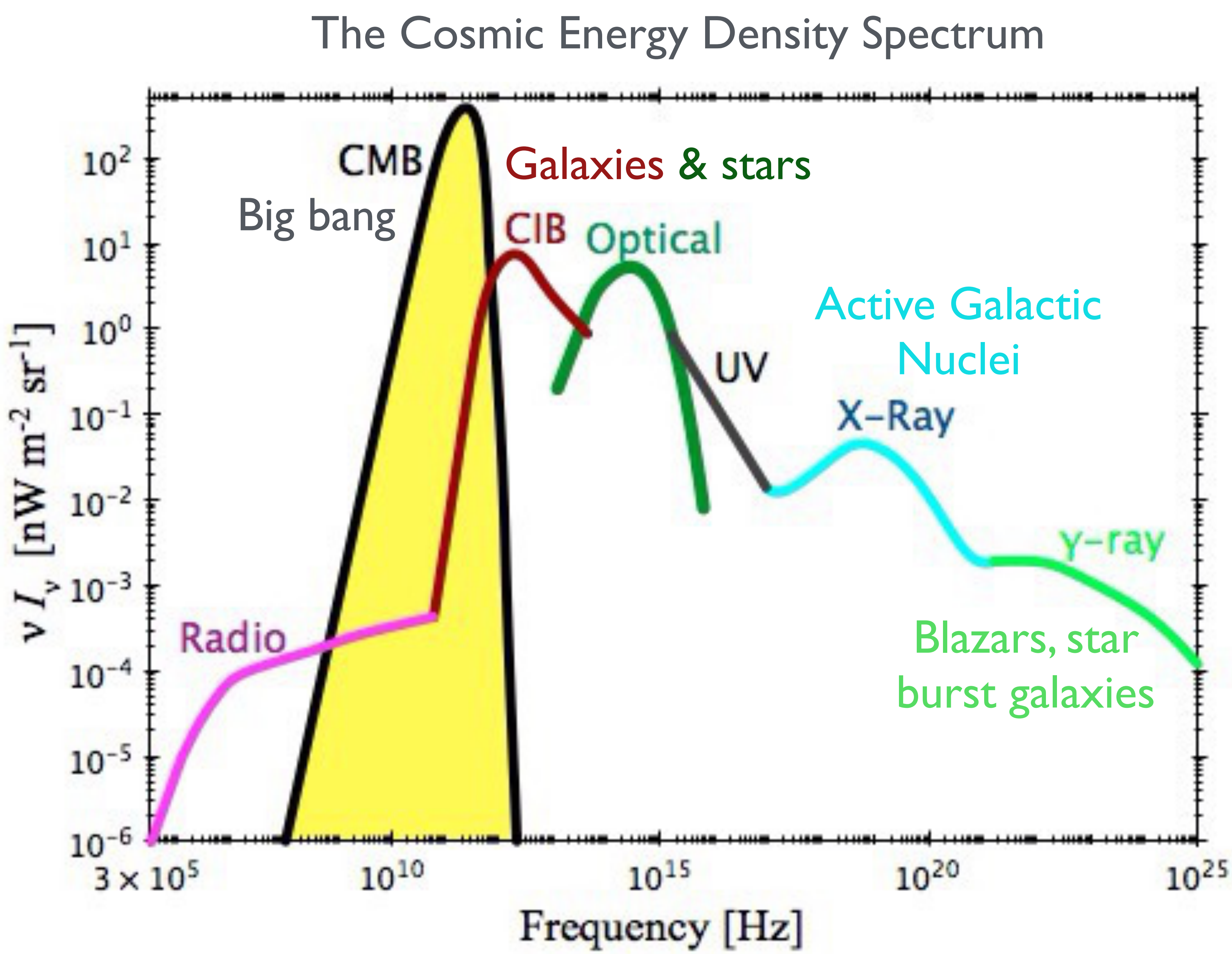
Astroparticles



Comparing to Cosmic Lights In Other Wavelengths

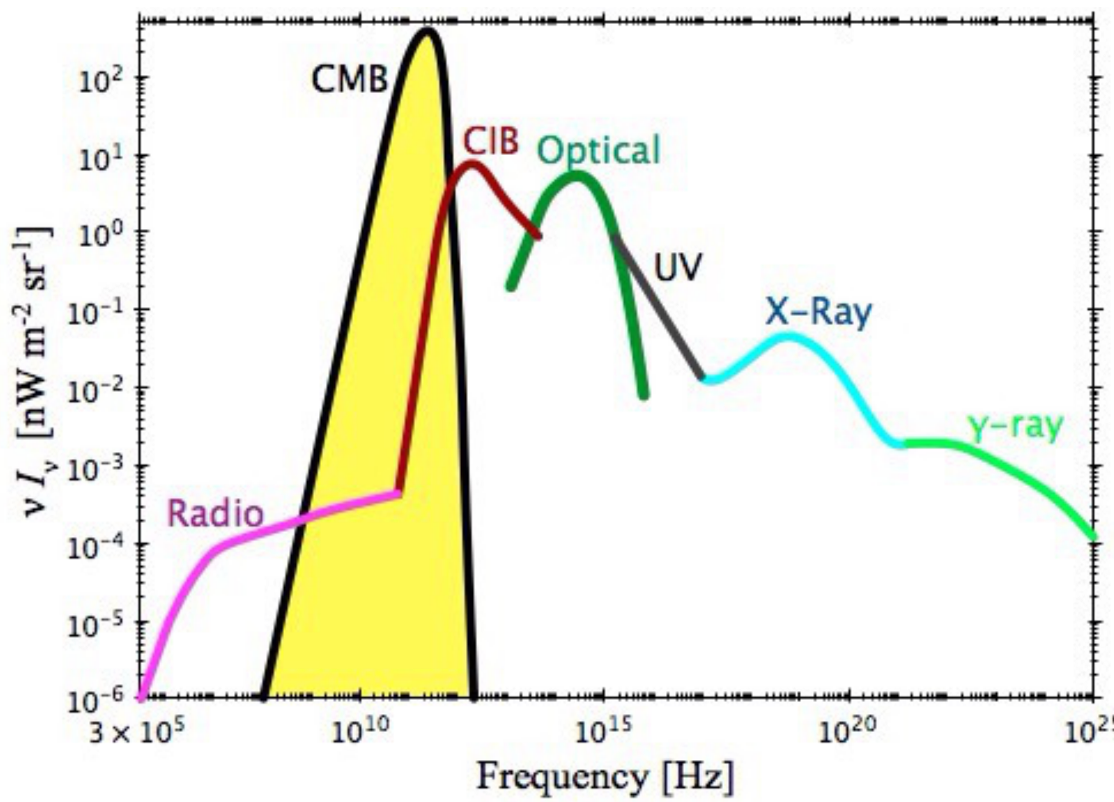


Energy Fraction: 0.0003% 94.8% 2.9% 2.2% 0.03% 0.001%

Plot credit: Lacasa (2014)

Comparing to Cosmic Lights In Other Wavelengths

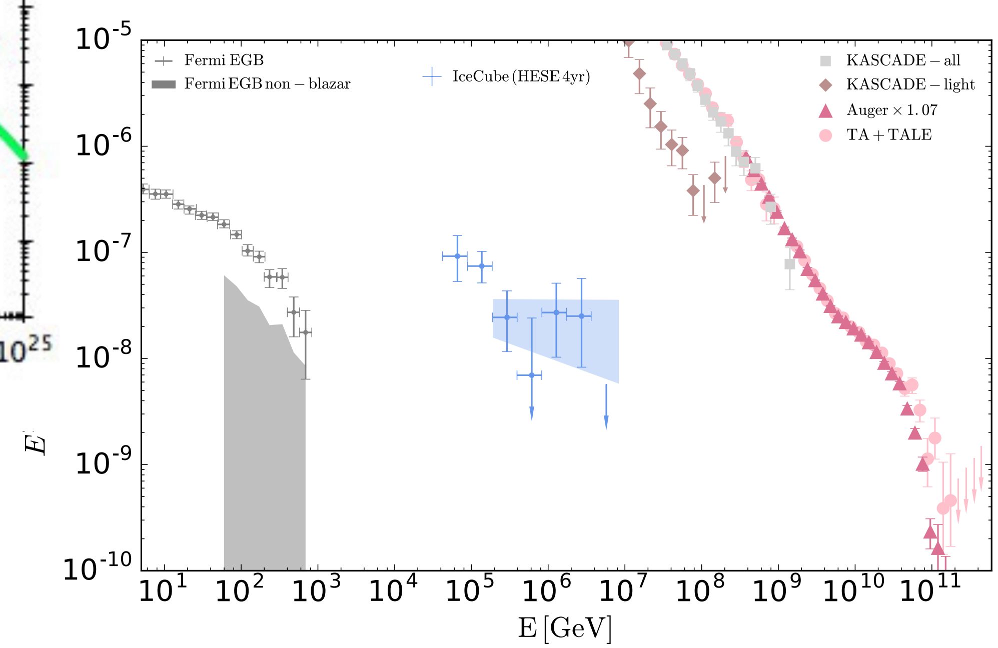
The Cosmic Energy Density



Gamma rays

Neutrinos

Ultrahigh Energy Cosmic Rays



A tip of the cosmic energy …

...with the Highest Individual Particle Energy in the Universe!

How energetic?

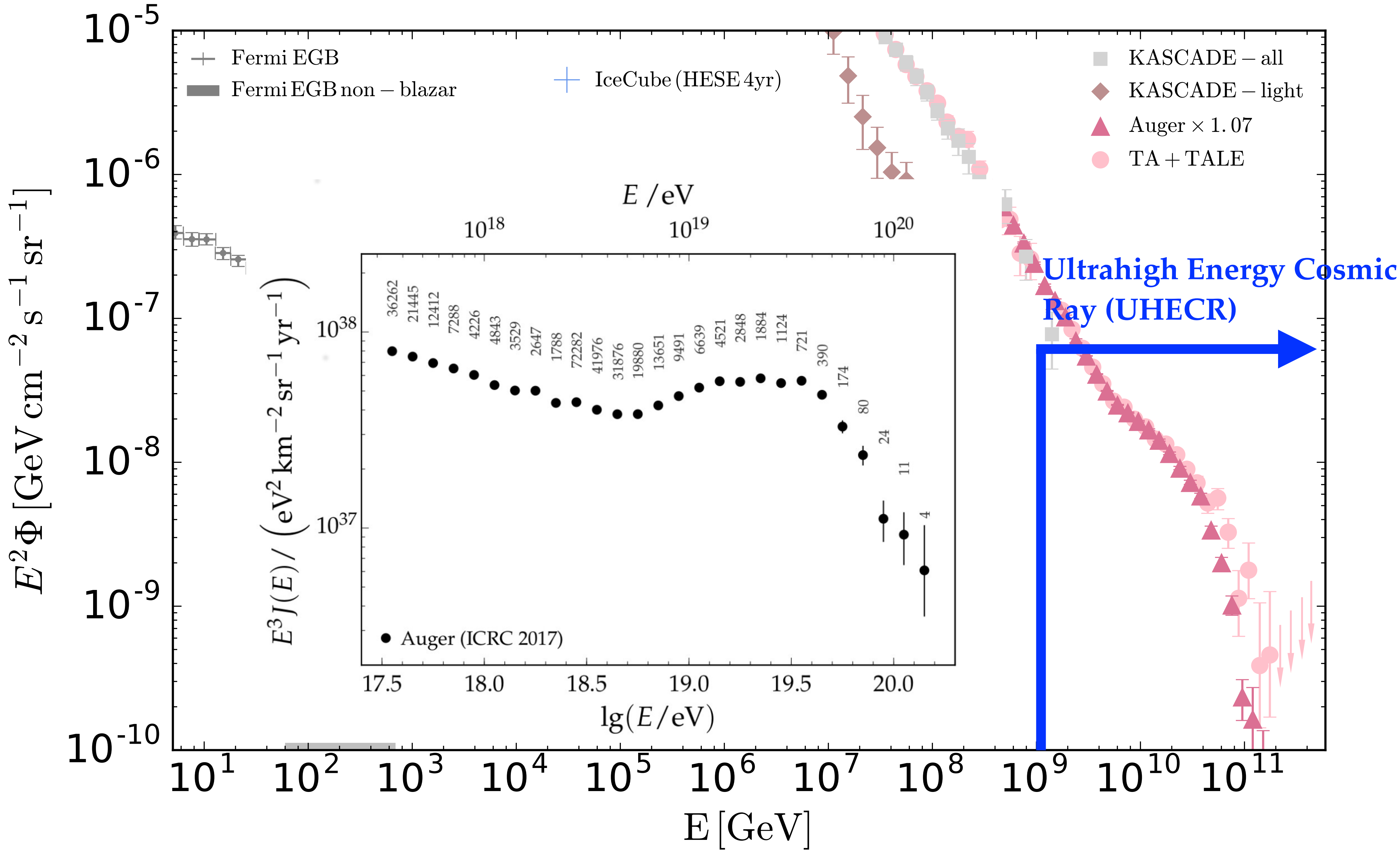
up to 10^{20} eV

Large Hadron Collider

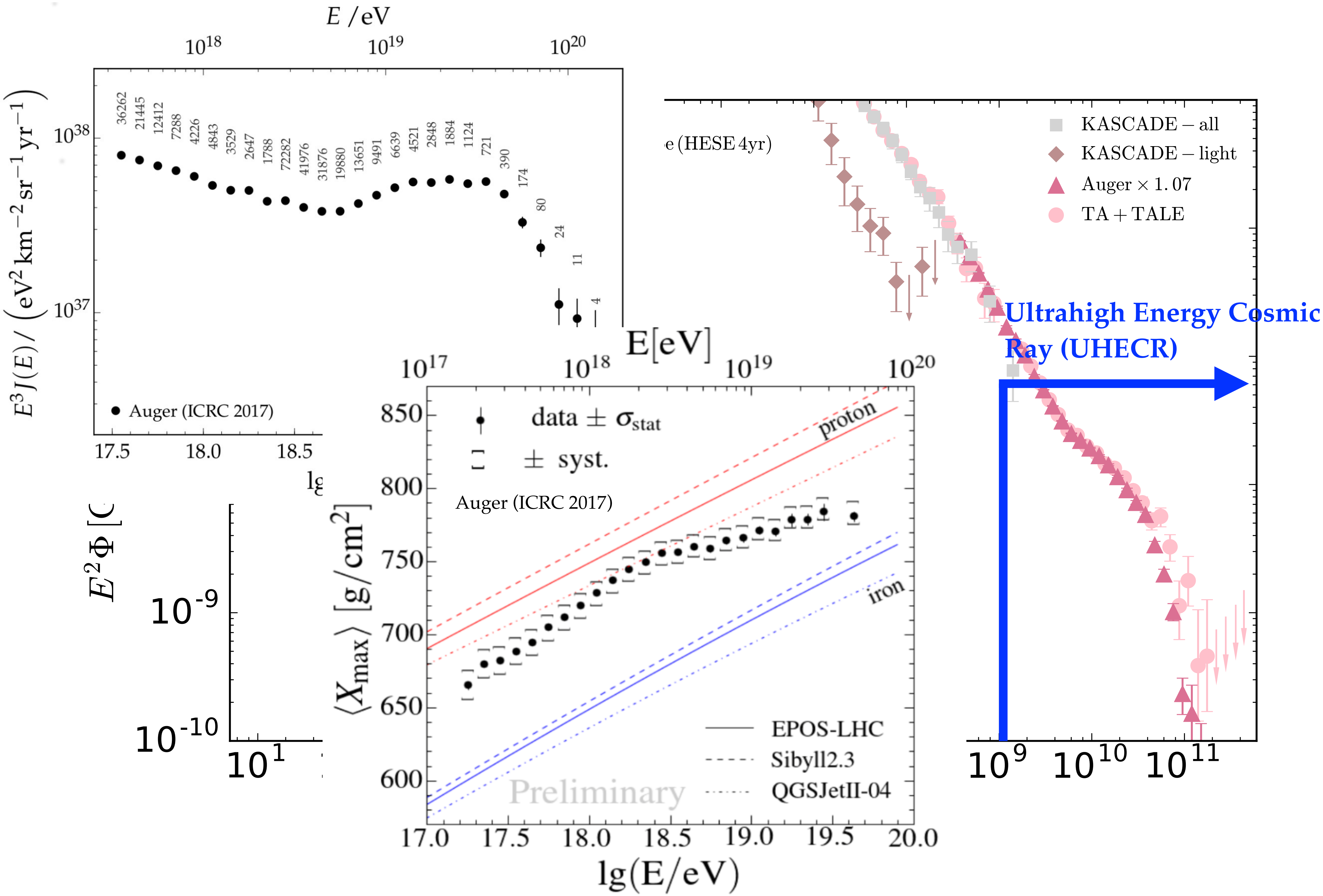
14×10^{12} eV

Kinetic energy of a speeding bullet ~ 10^{20} eV

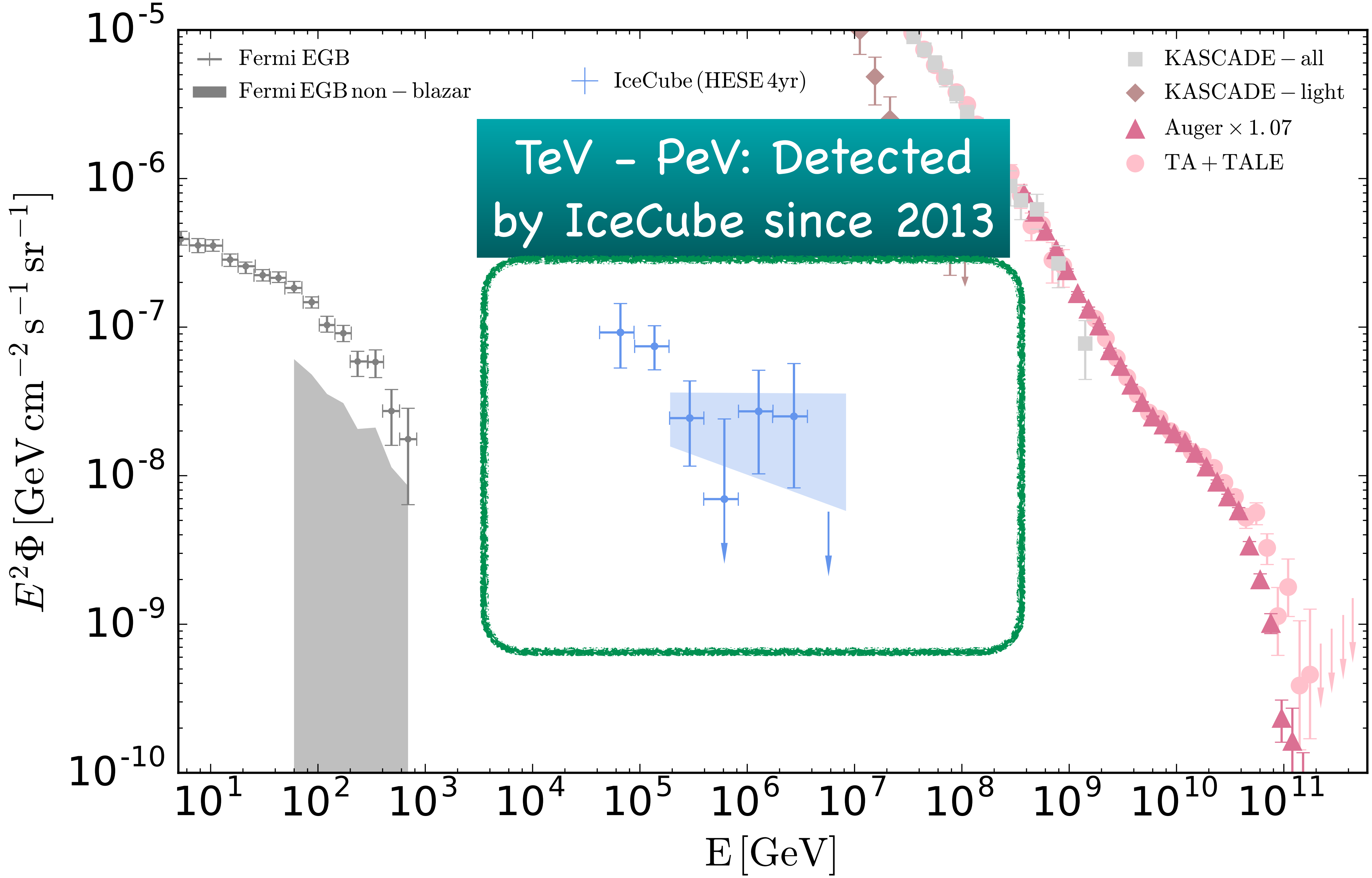
UHECRs, High-energy Neutrinos & Gamma Rays



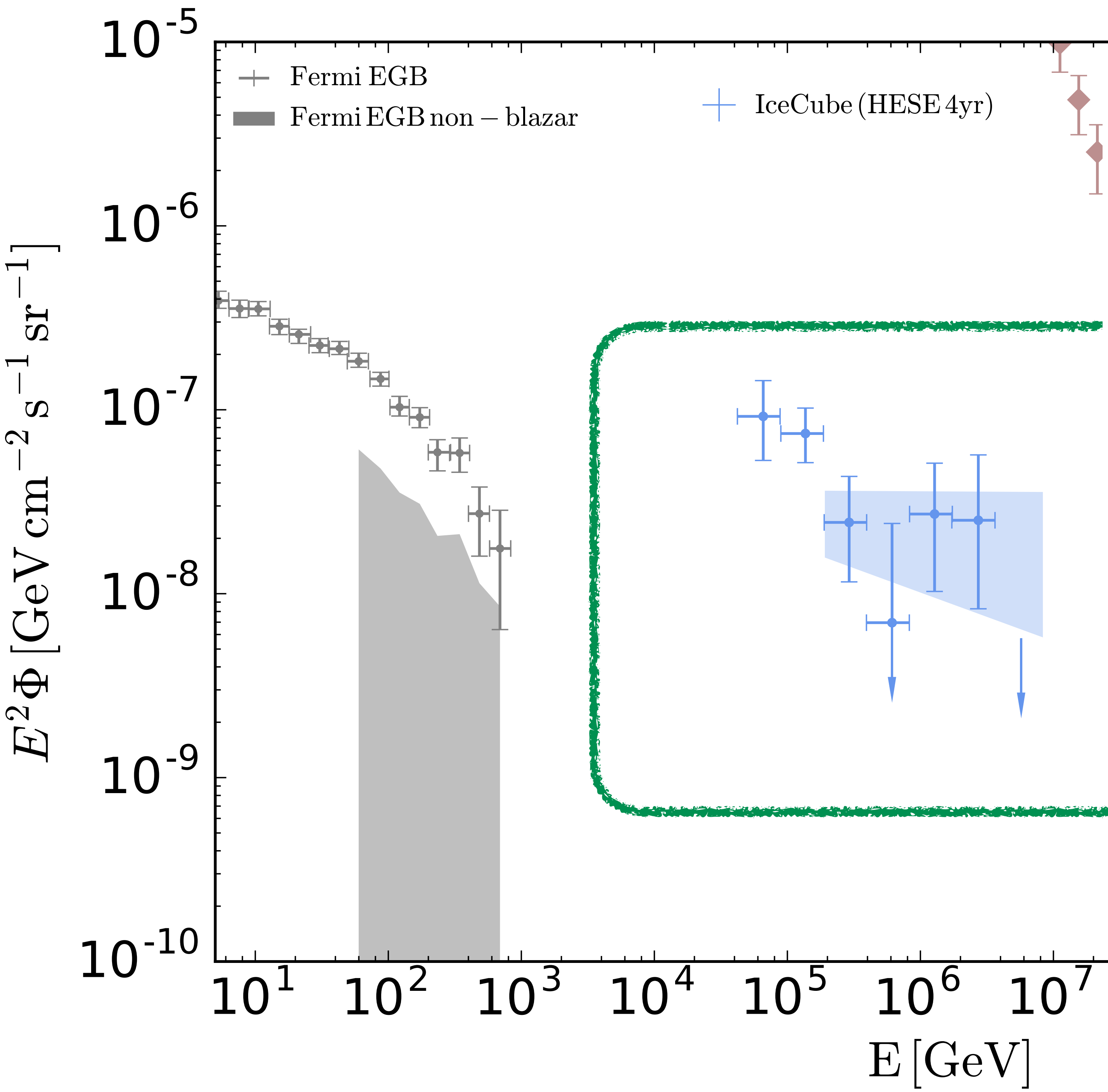
UHECRs, High-energy Neutrinos & Gamma Rays

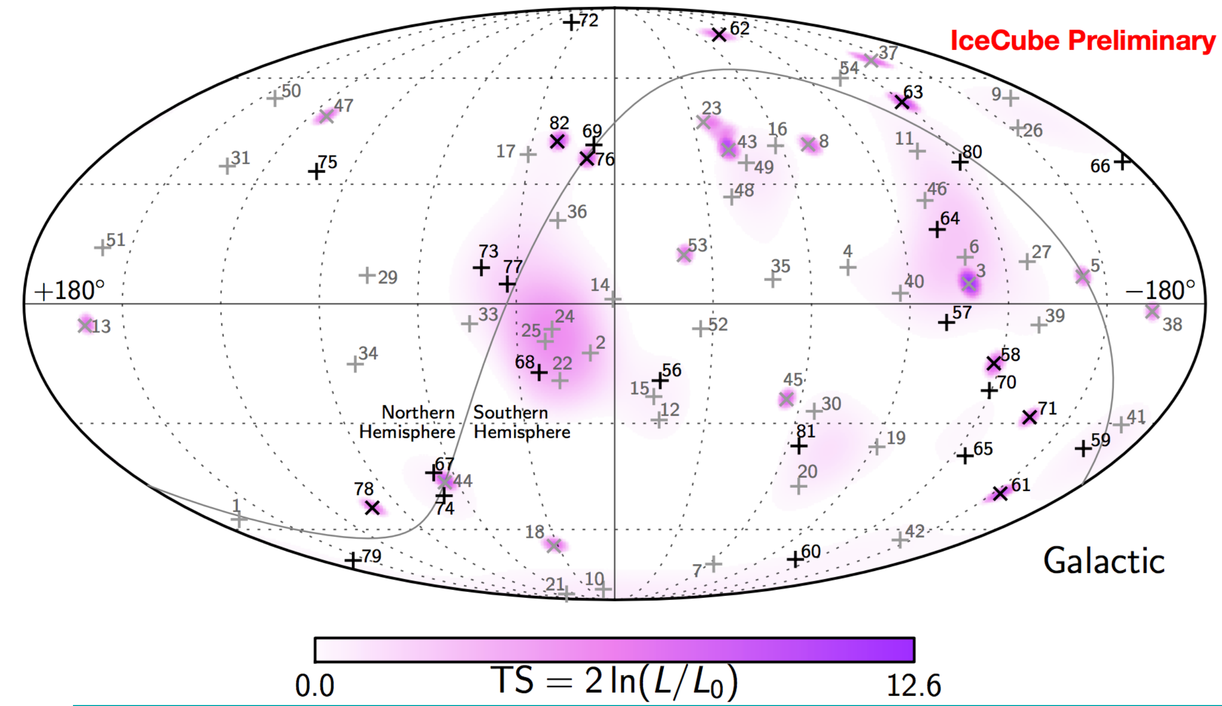


UHECRs, High-energy Nu, & Gamma Rays



UHECRs, High-energy Nu, & Gamma Rays



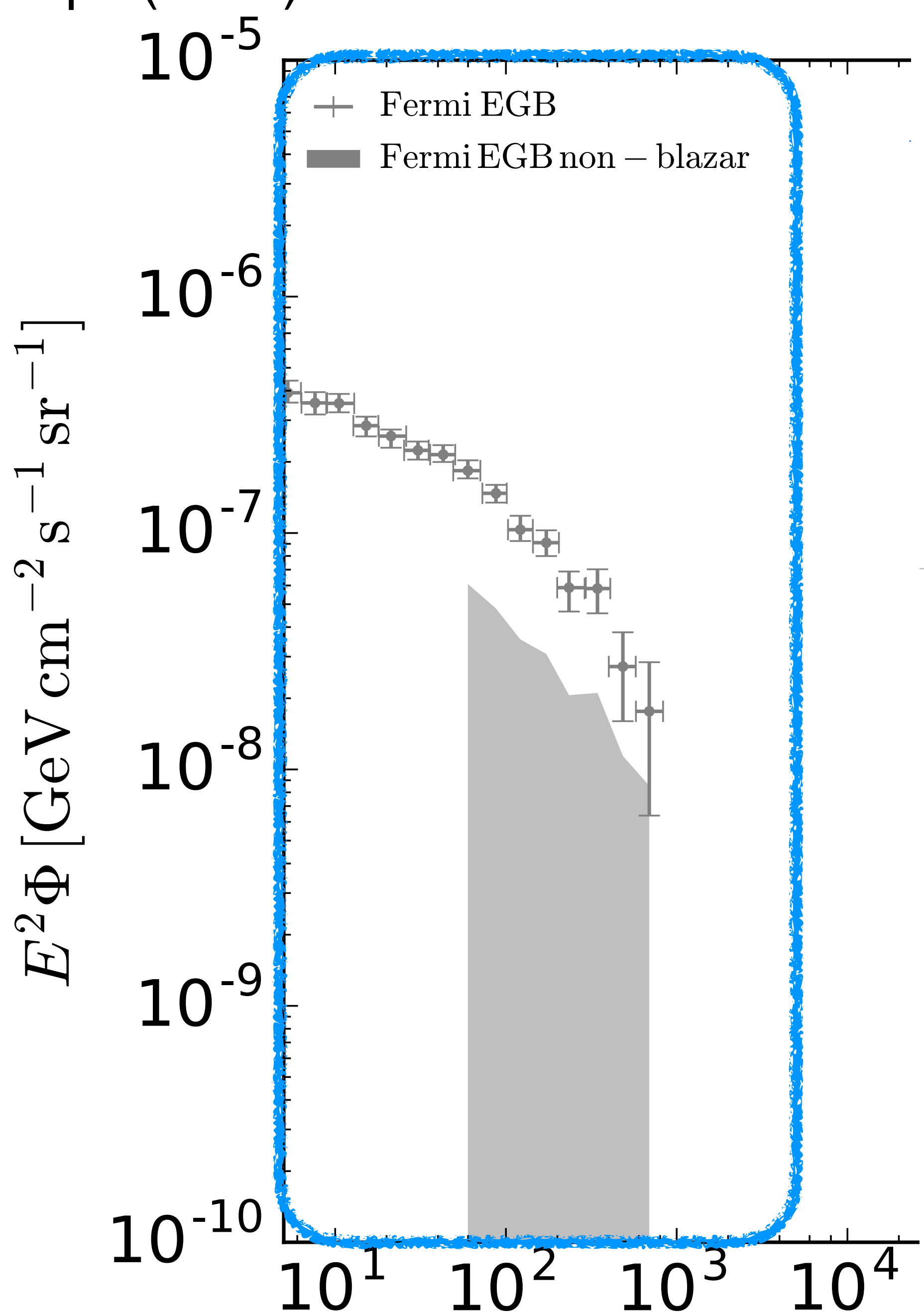


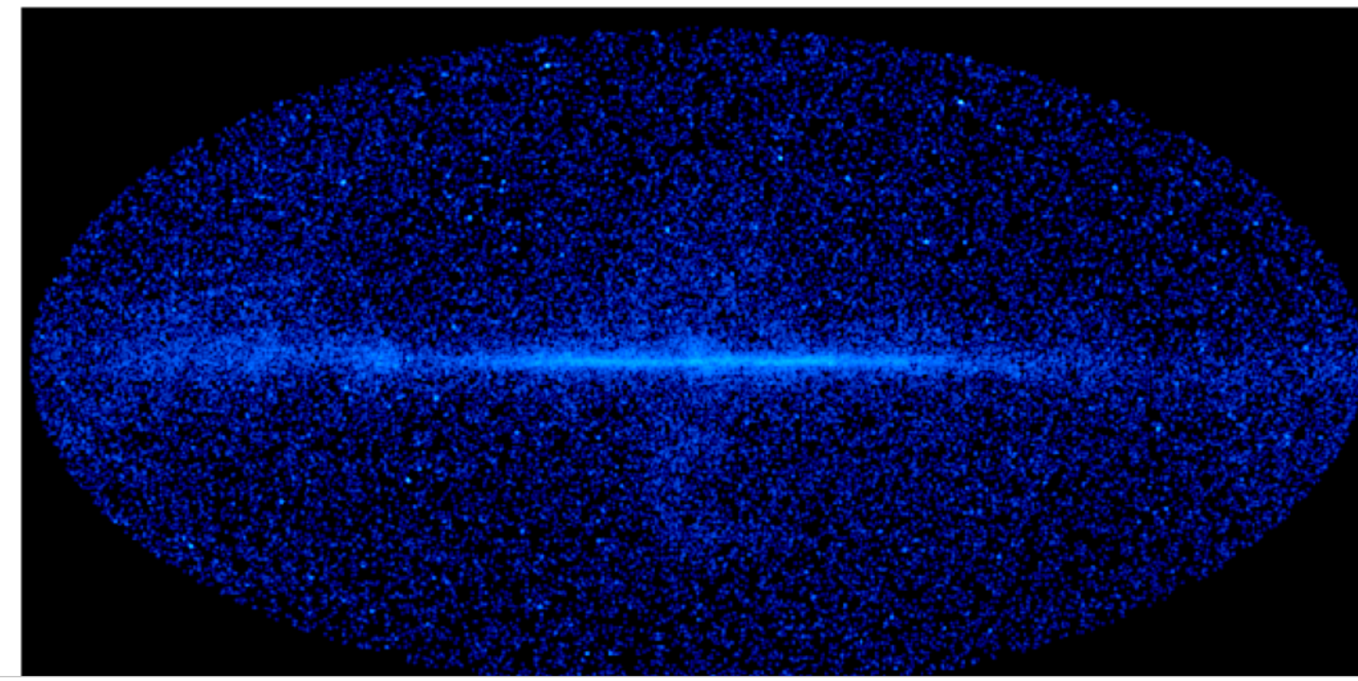
Fermi Blazars ? (IceCube 16, Kun+17, Muller+17, IceCube 18ab)
Not GRBs (within 100 seconds; IceCube 12, 15)
Not TDEs (Wang & Liu 16, Dai & KF 16, Zhang+17, Guepin,.. KF+17, Daniel+17)
Your call..

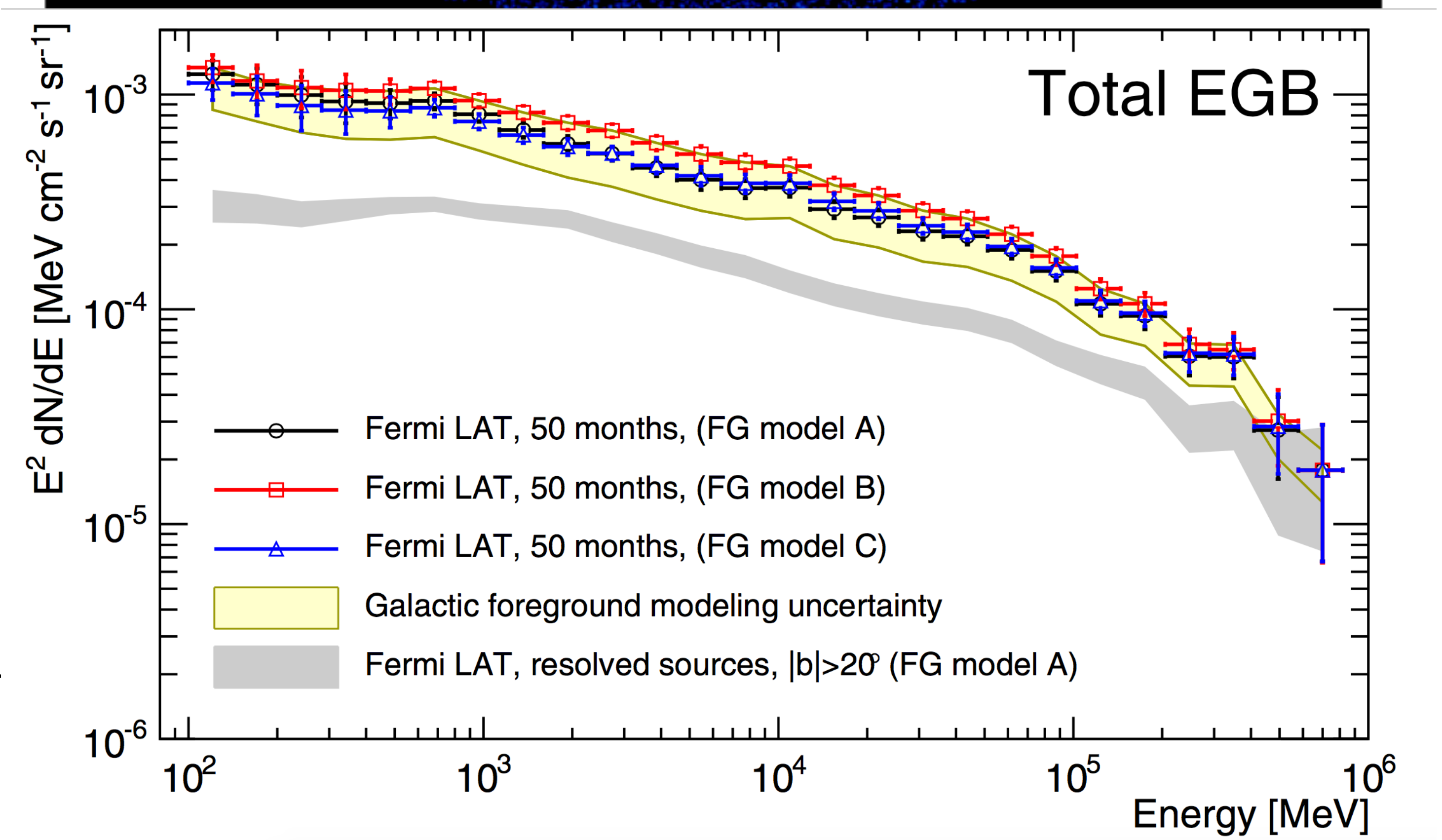
See Halzen 2016 review

UHECRs, High-energy Nu, & Gamma Rays

Fermi Collaboration, PRL (2016)
Lisanti + ApJ (2016)

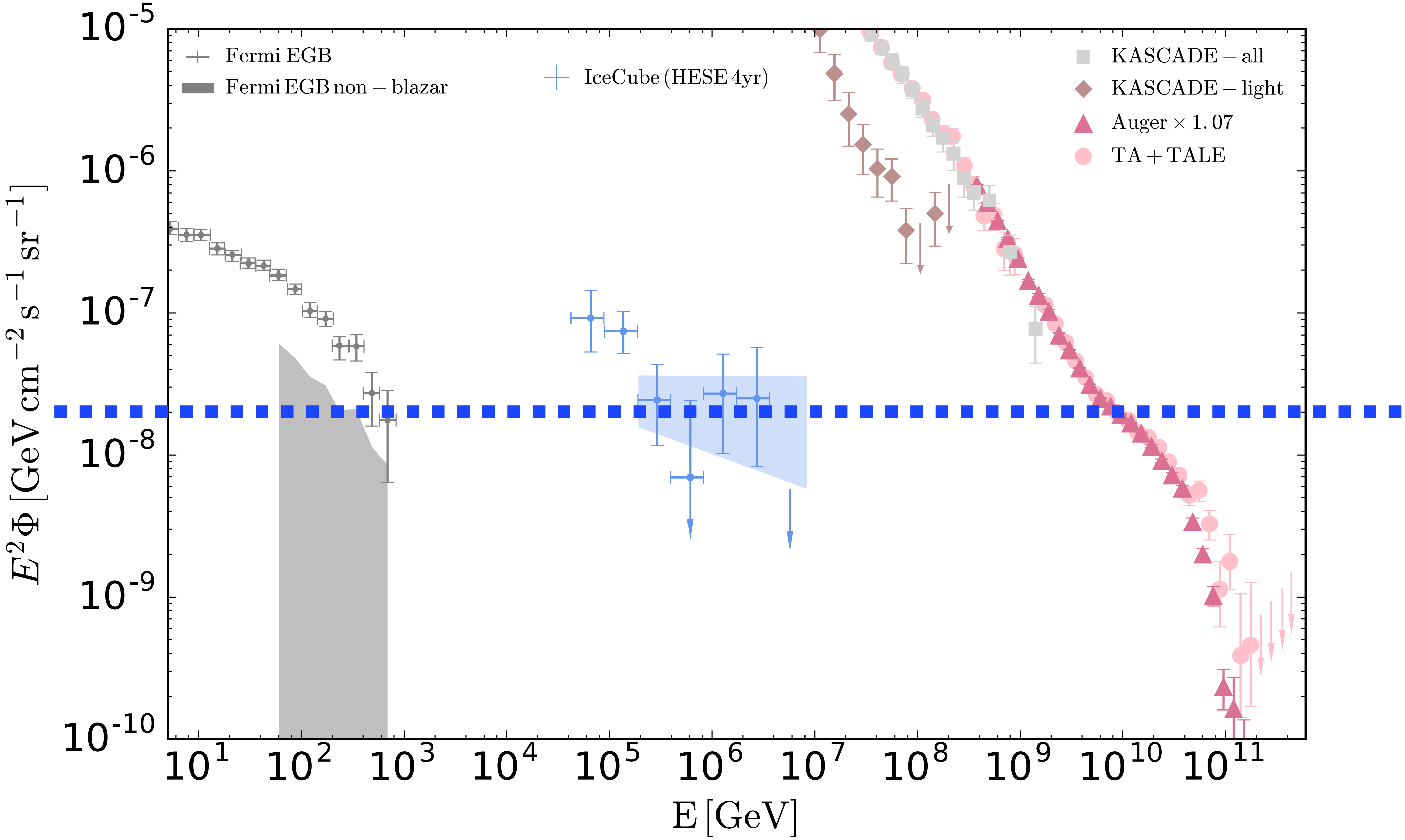






~14% of the Fermi extragalactic gamma-ray background is contributed by unknown sources.

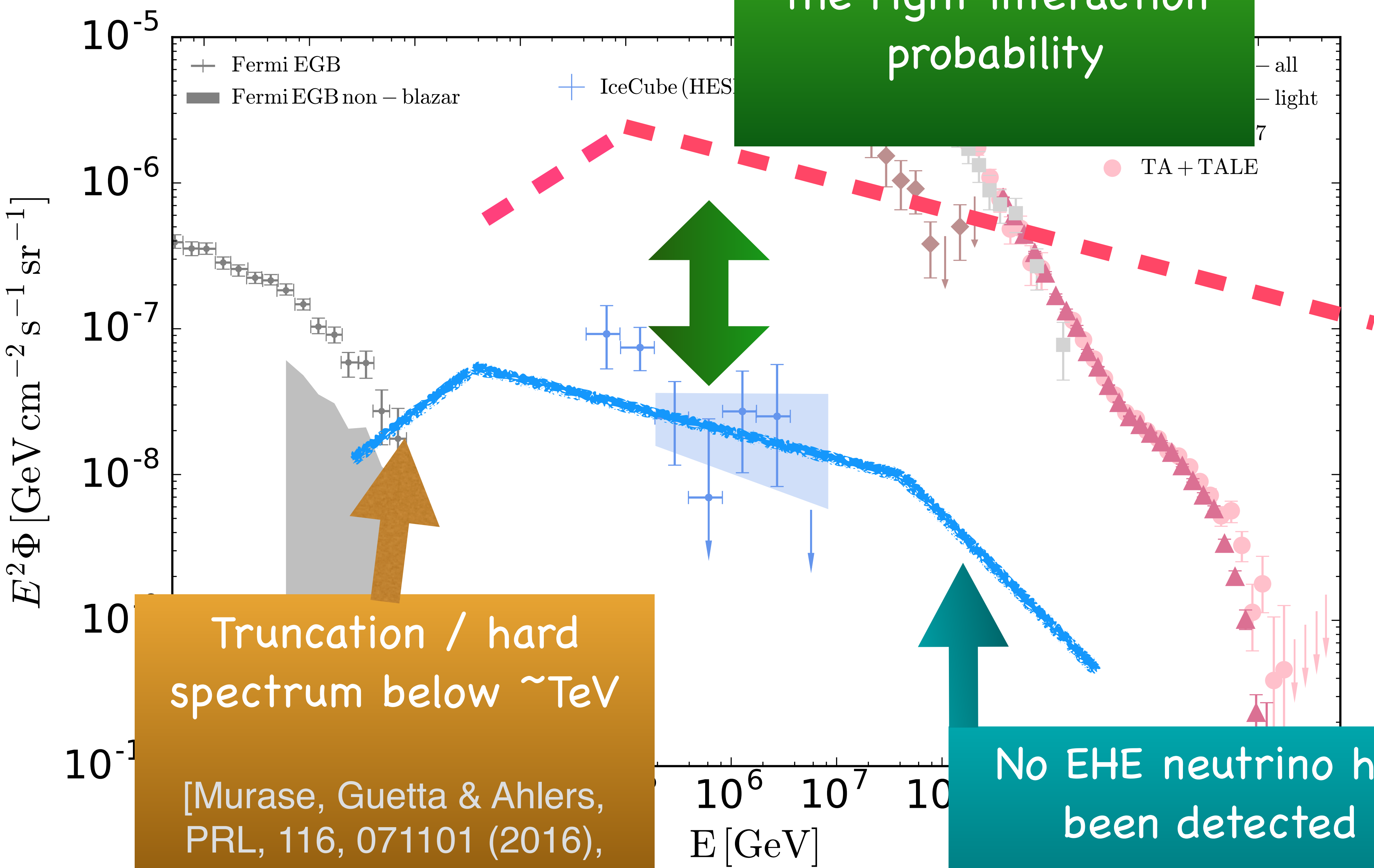
When putting them together..



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

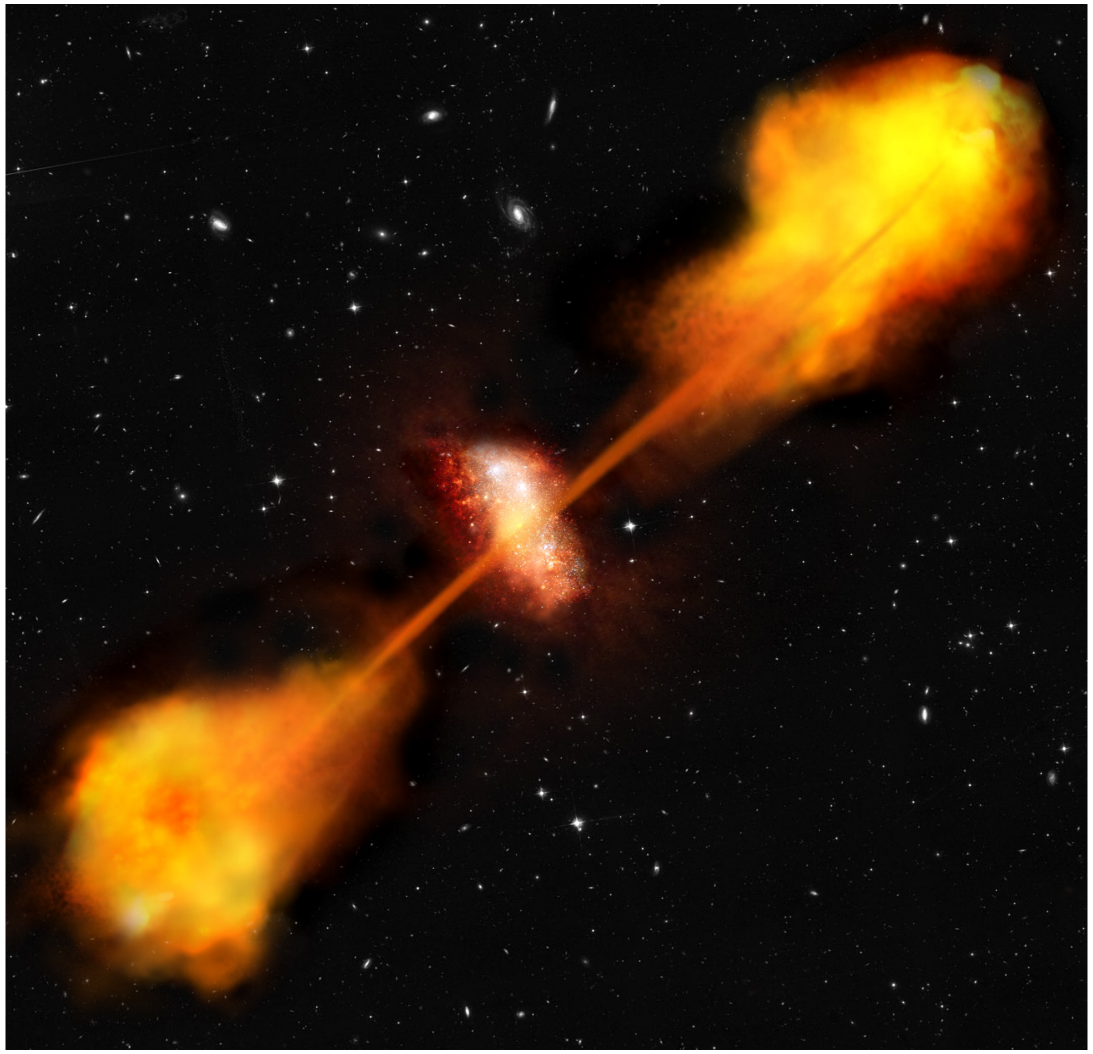
Truncation / hard spectrum below ~TeV

[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

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

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

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.

Cluster Environment

ICM gas

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

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

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

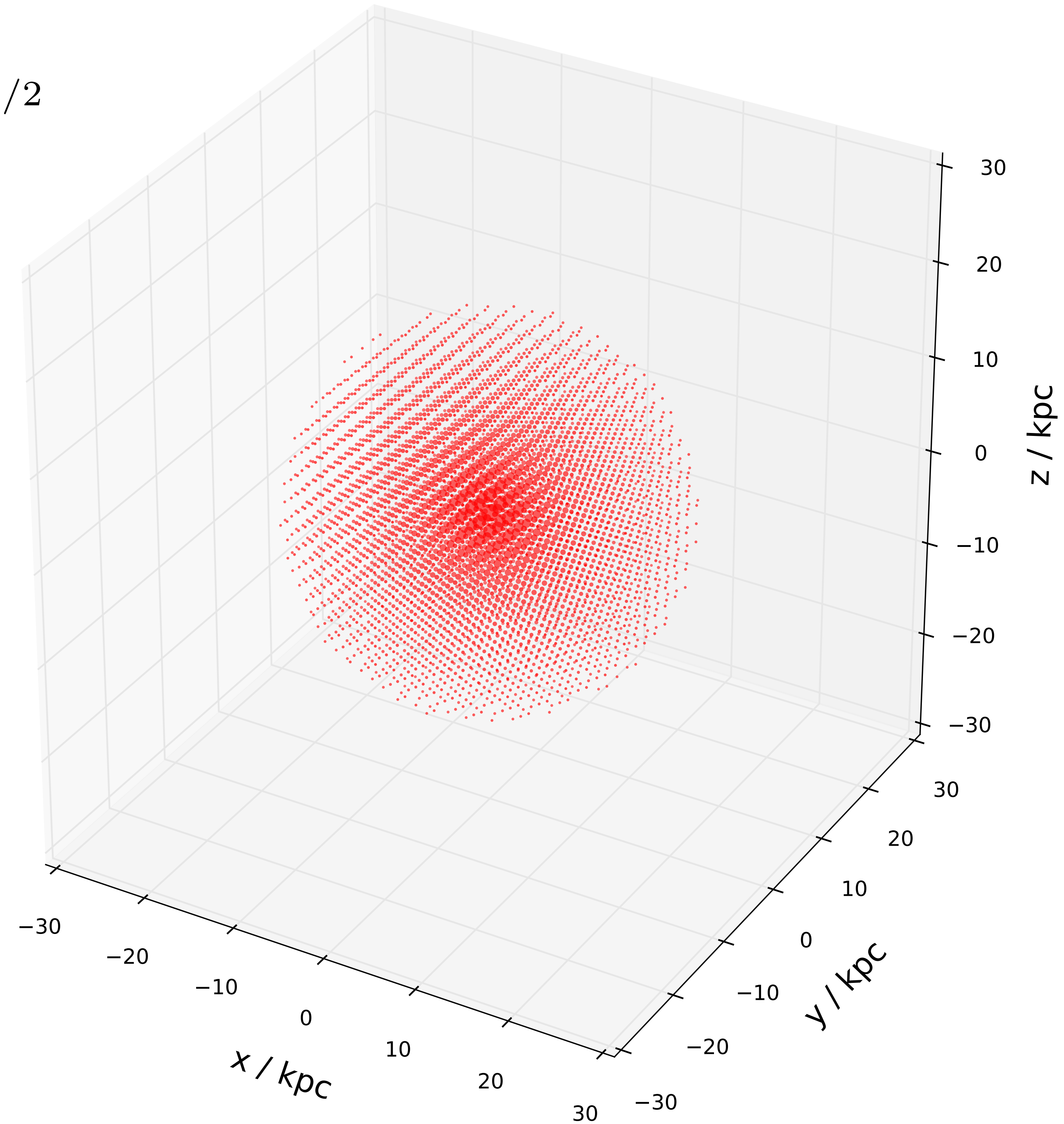
Infrared background from galaxies
[Takami & Murase ApJ 2012]

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

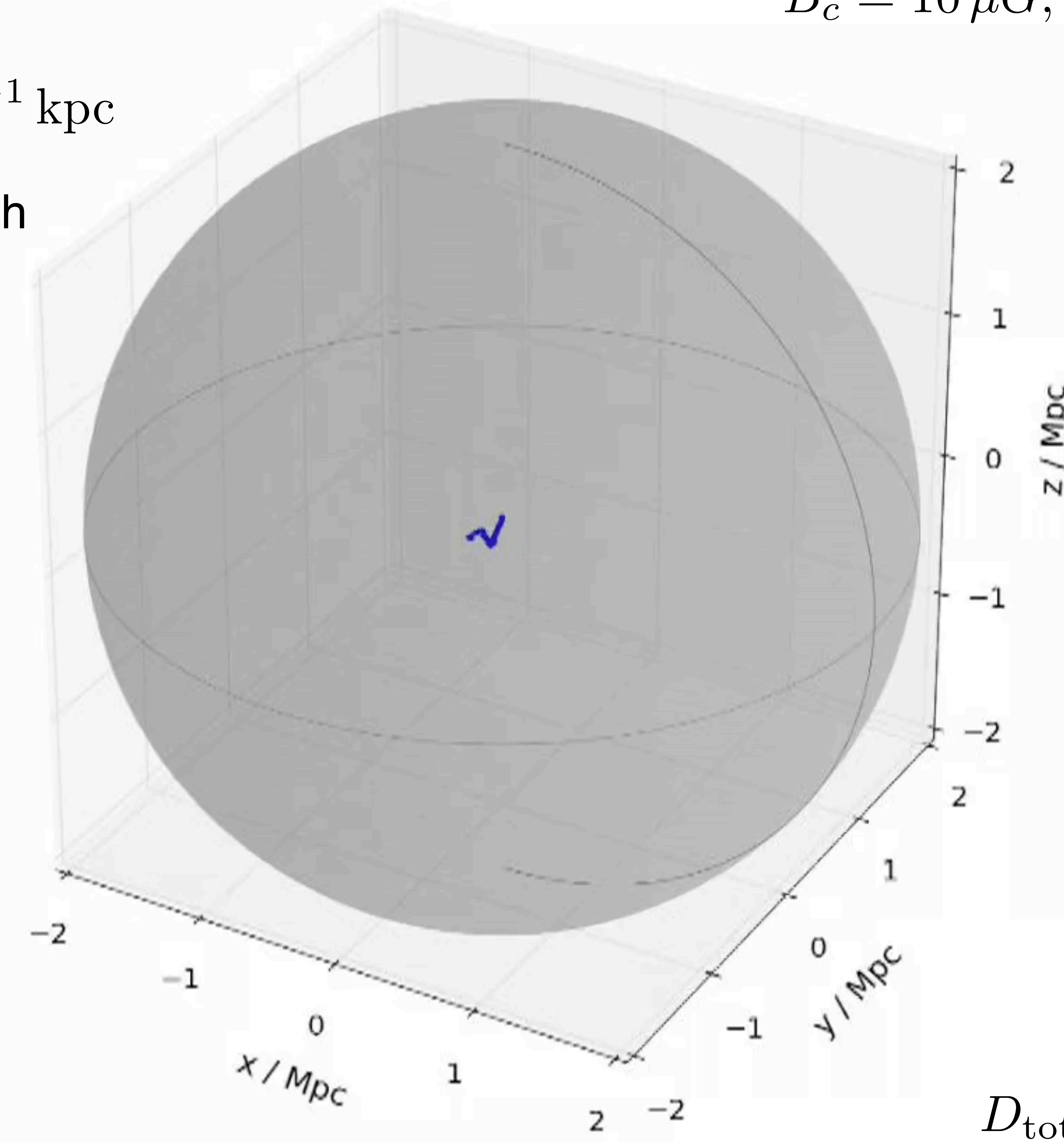
$B_c = 10\,\mu G, M = 10^{15}\,M_\odot$

Particle Larmor Radius

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

Field Coherence Length

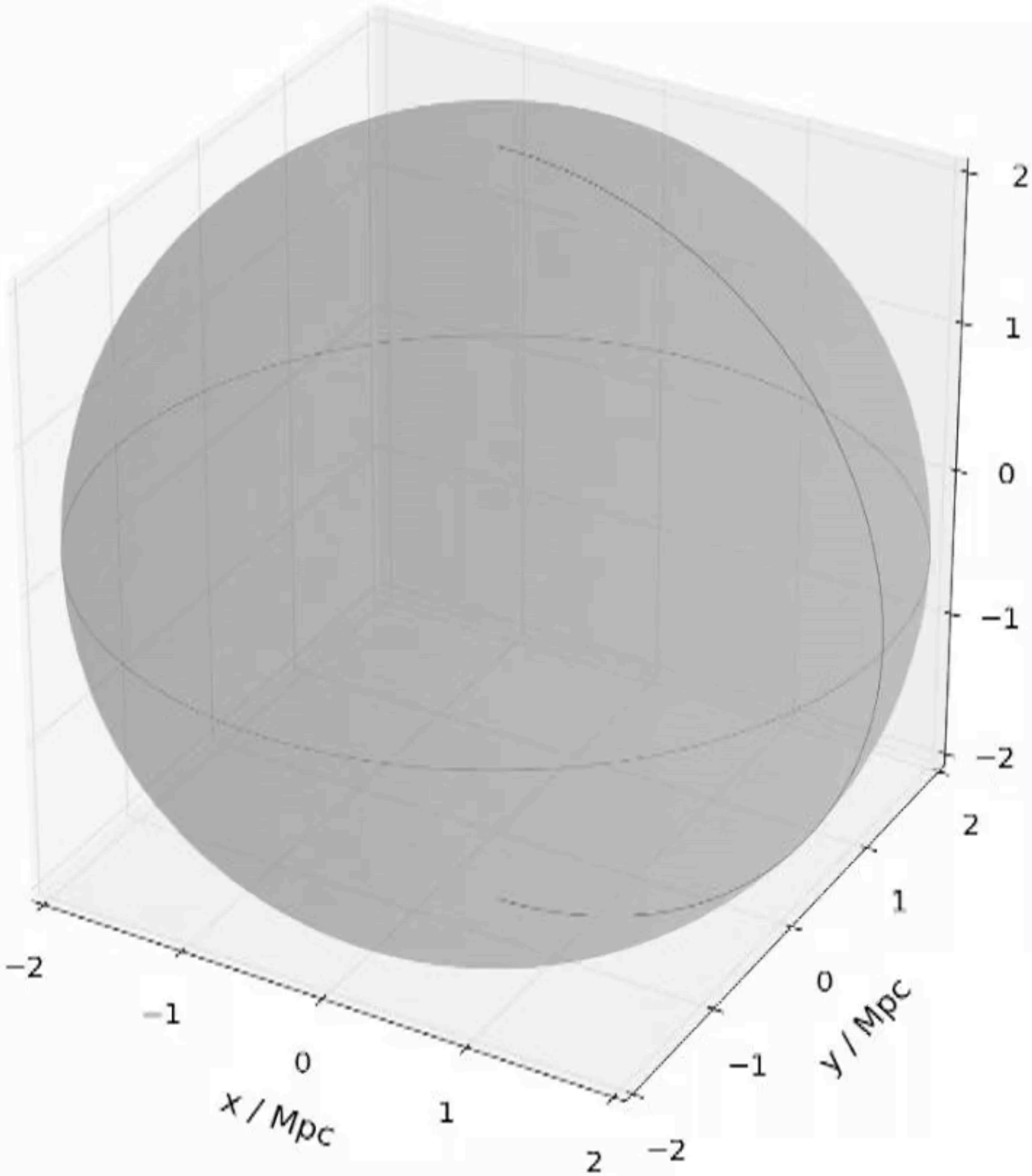
$$l_0 \sim 20\,\mathrm{kpc}$$

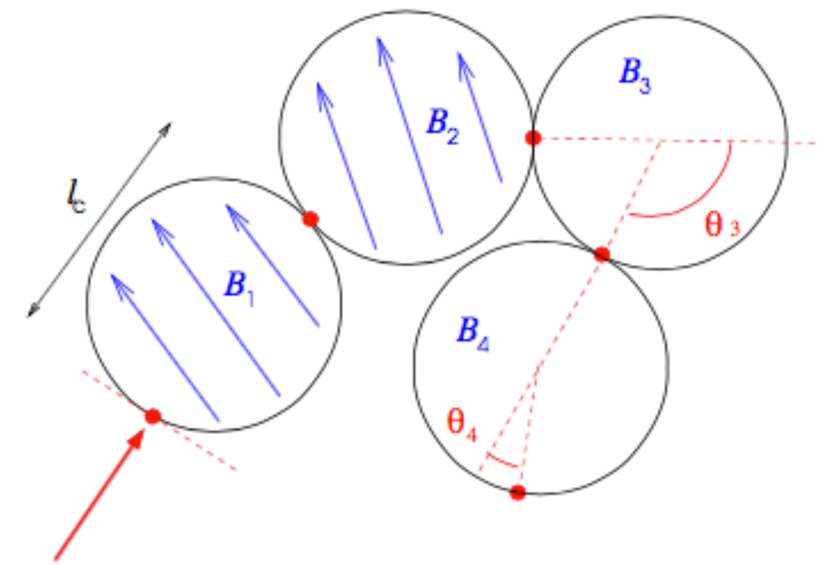


$D_{\mathrm{total}} = 46\,\mathrm{Mpc}$

Particle Trajectory - 0.1 EeV

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



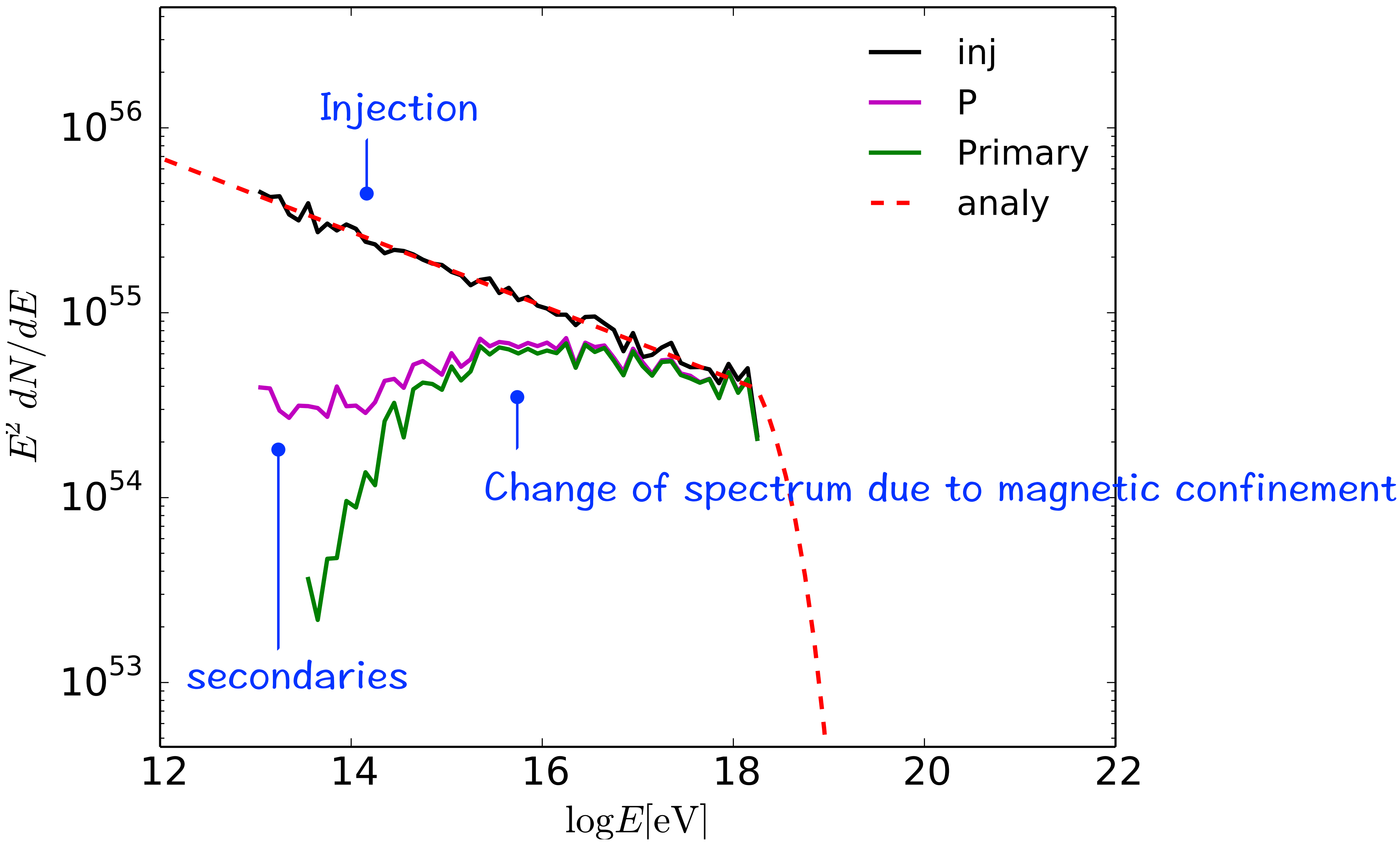


Approximation for diffusion computation

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

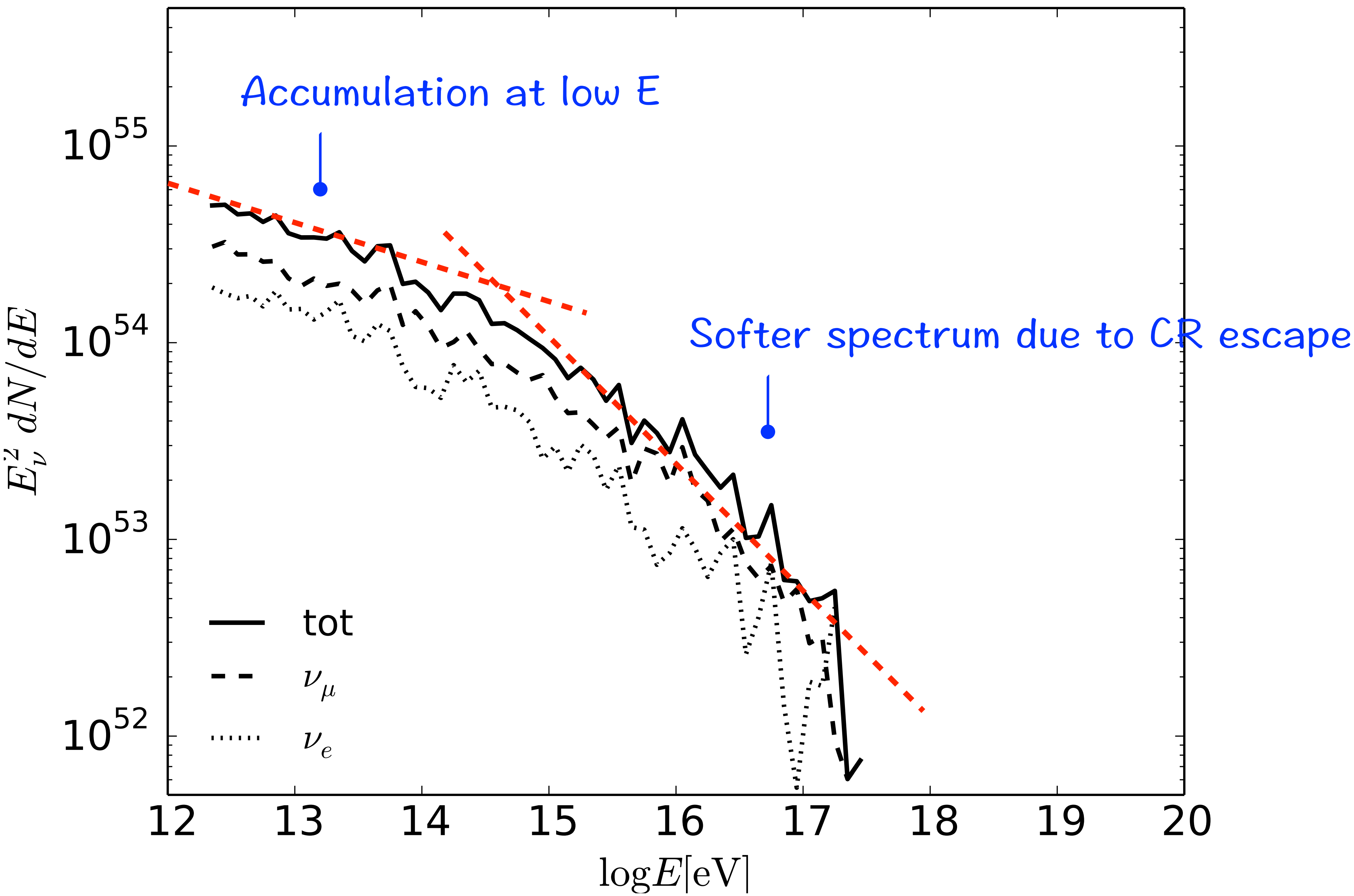
Cosmic Ray Flux from One Single Cluster

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



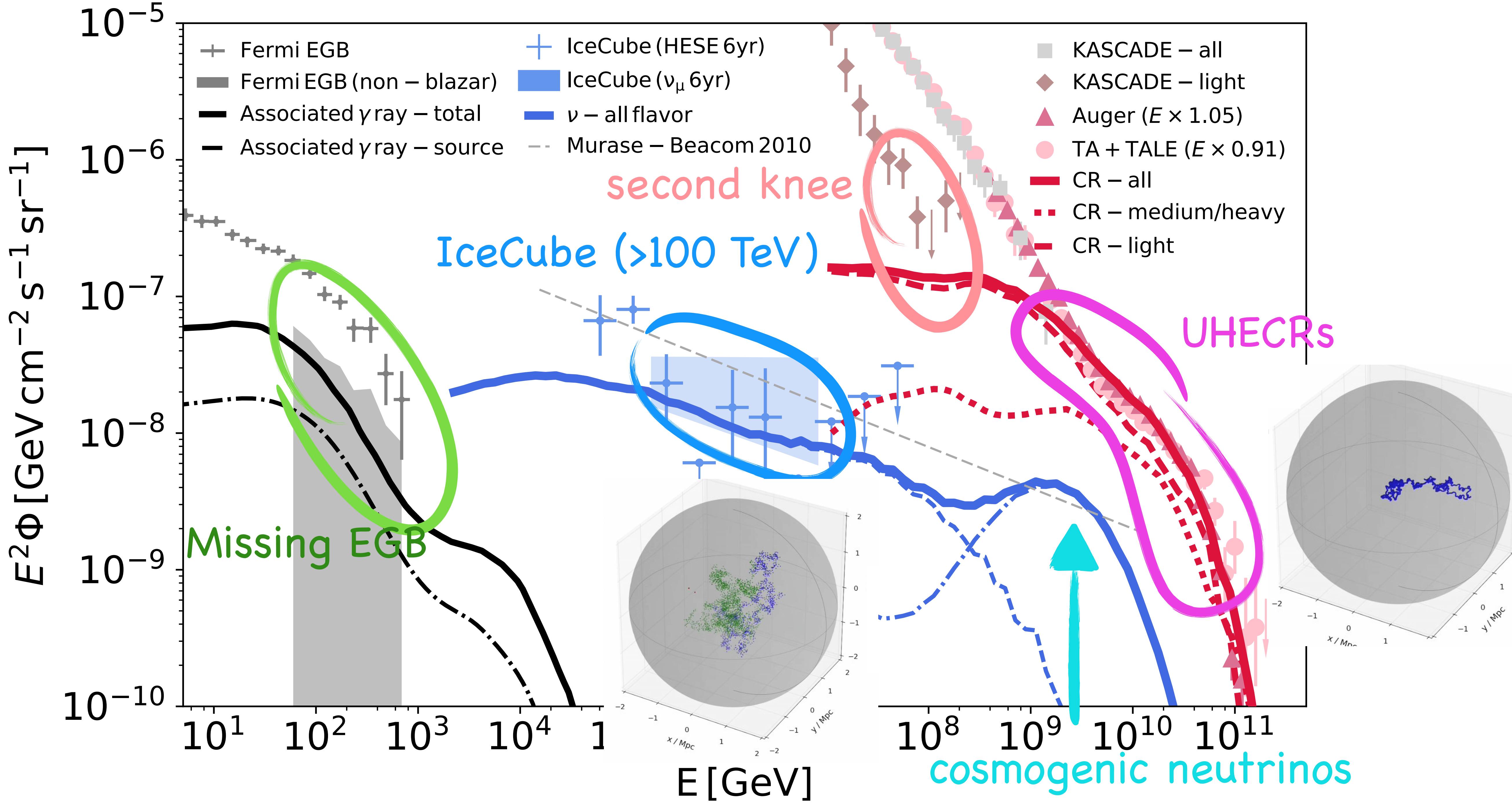
Neutrino Flux from One Single Cluster

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



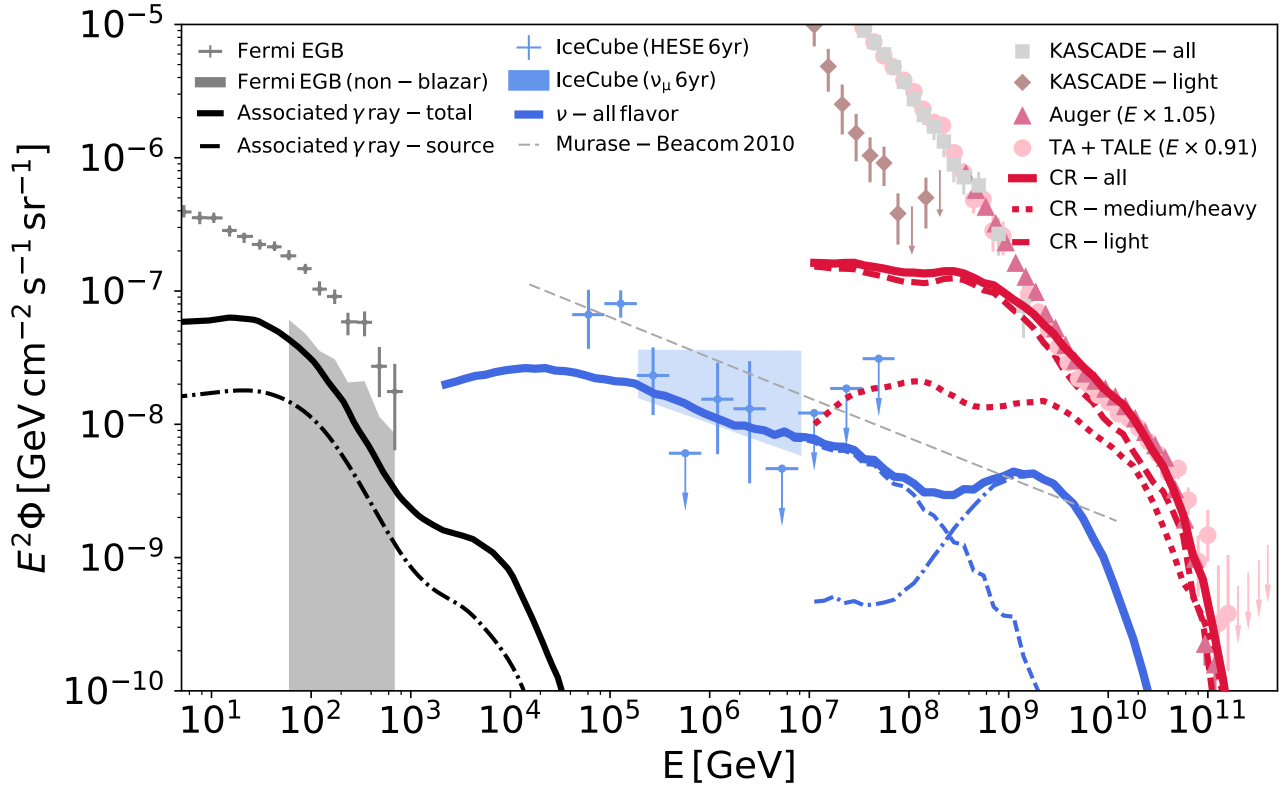
A Unified Picture of Multi-messengers

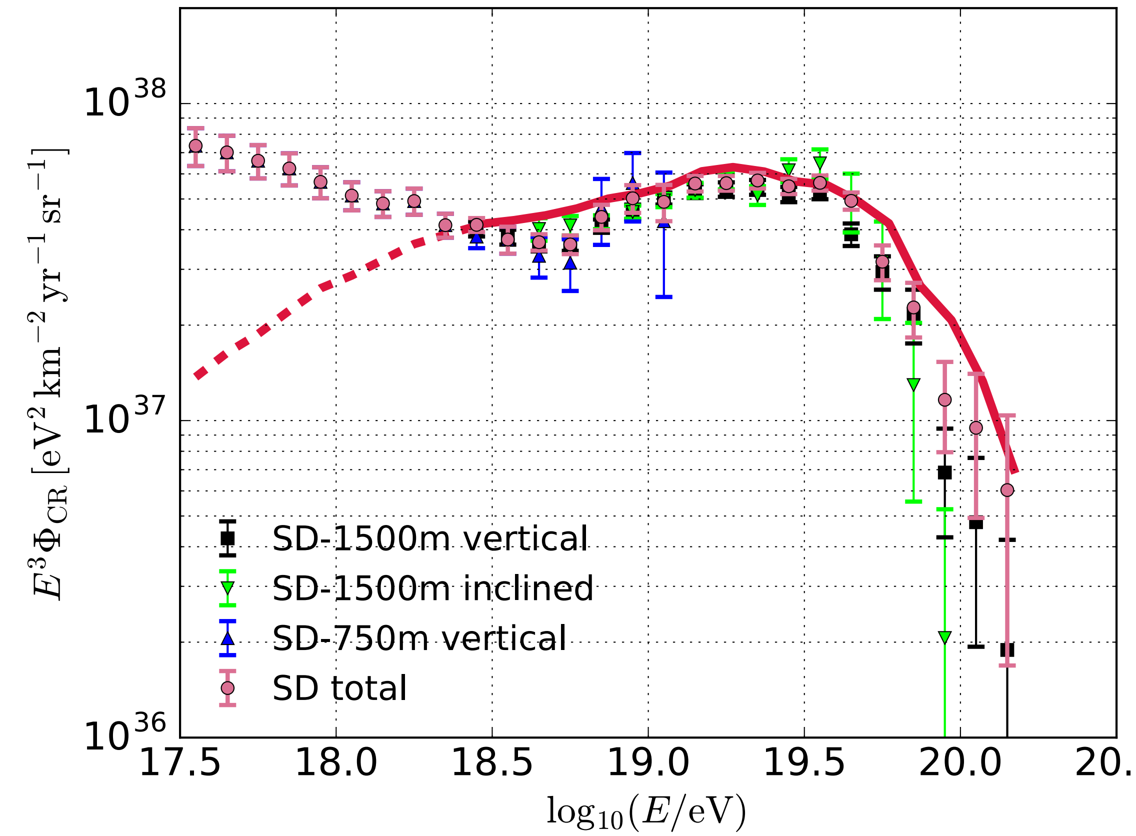
KF & Murase, Nature Physics (2018)



Injection Composition = Galactic CR abundance

Fitting to Data



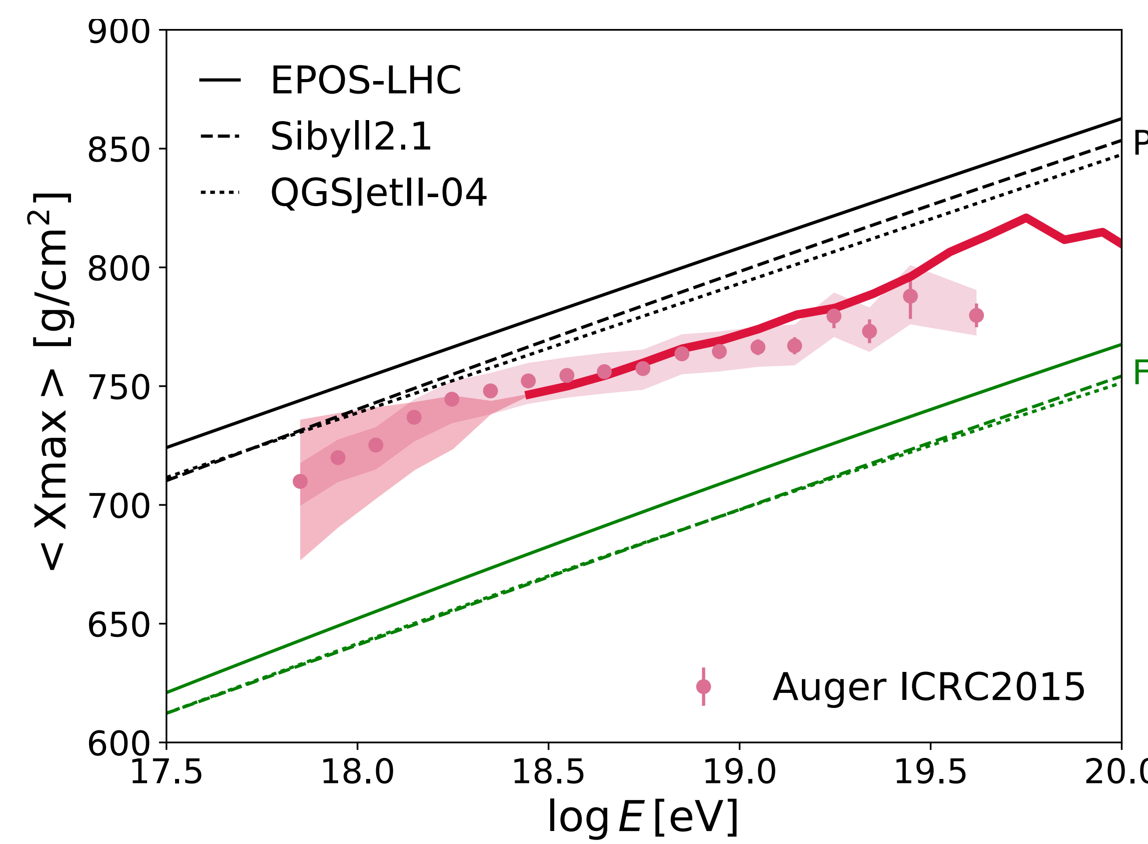


$$\chi^2_{\mathrm{CR}/\nu,\,\mathrm{spec}} = \sum_i \left(\frac{\Phi_{\mathrm{CR}/\nu}(E'_i, C_{\mathrm{norm}}) - \left(\Phi_{\mathrm{CR}/\nu}\right)_i^{\mathrm{obs}}}{\left[\Delta\left(\Phi_{\mathrm{CR}/\nu}\right)\right]_i^{\mathrm{obs}}} \right)^2 + \left(\frac{\delta_E^{\mathrm{CR}/\nu}}{\Delta_E^{\mathrm{CR}/\nu}}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

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

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

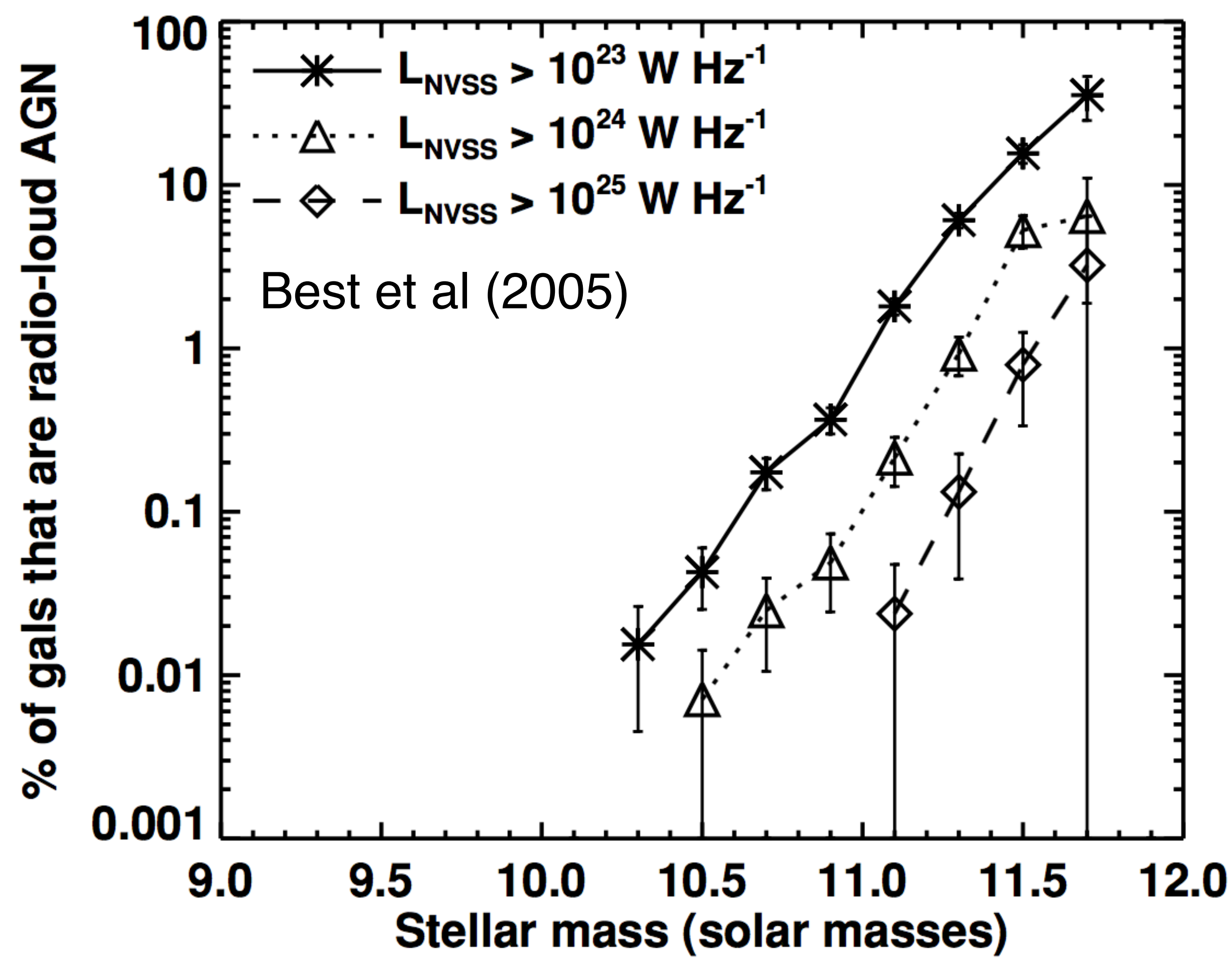
$$\rightarrow \chi^2_{\mathrm{dof}} = 1.5$$



KF & Murase, Nature Physics (2018)

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.



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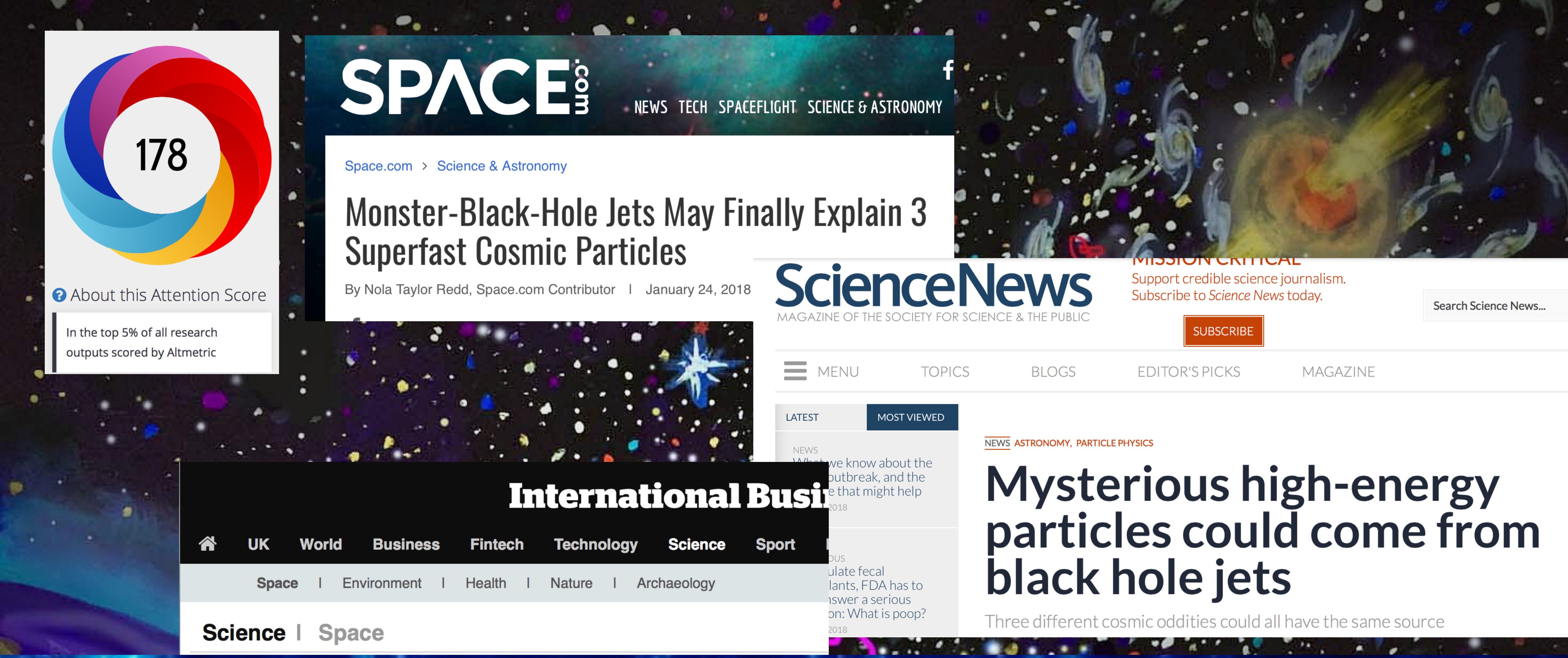

Black hole jets embedded in galaxy clusters can simultaneously explain UHECRs, high-energy neutrinos, and the non-blazar component of isotropic gamma-ray background.