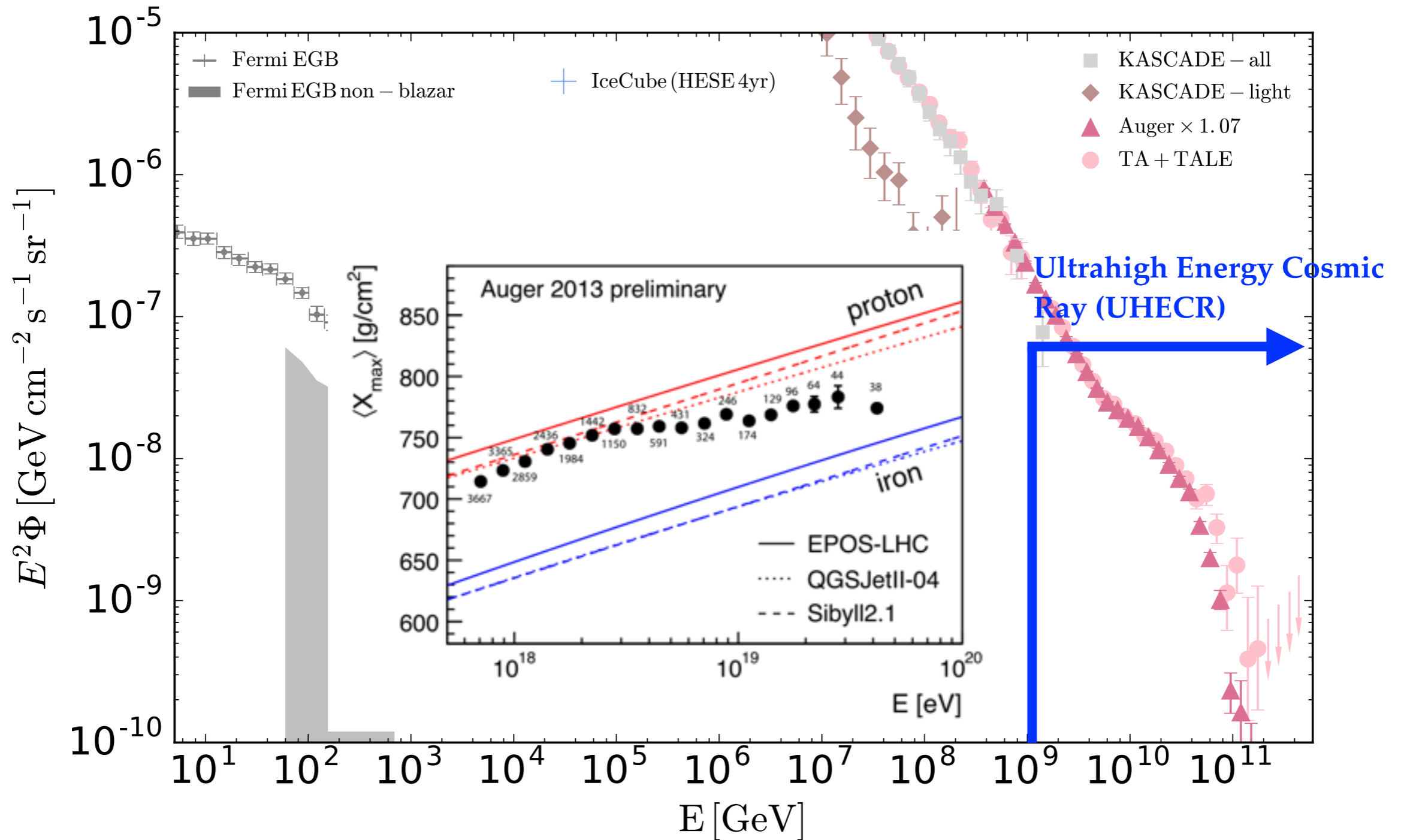


Black Hole Jets in Clusters of Galaxies as Sources of High-energy Cosmic Particles

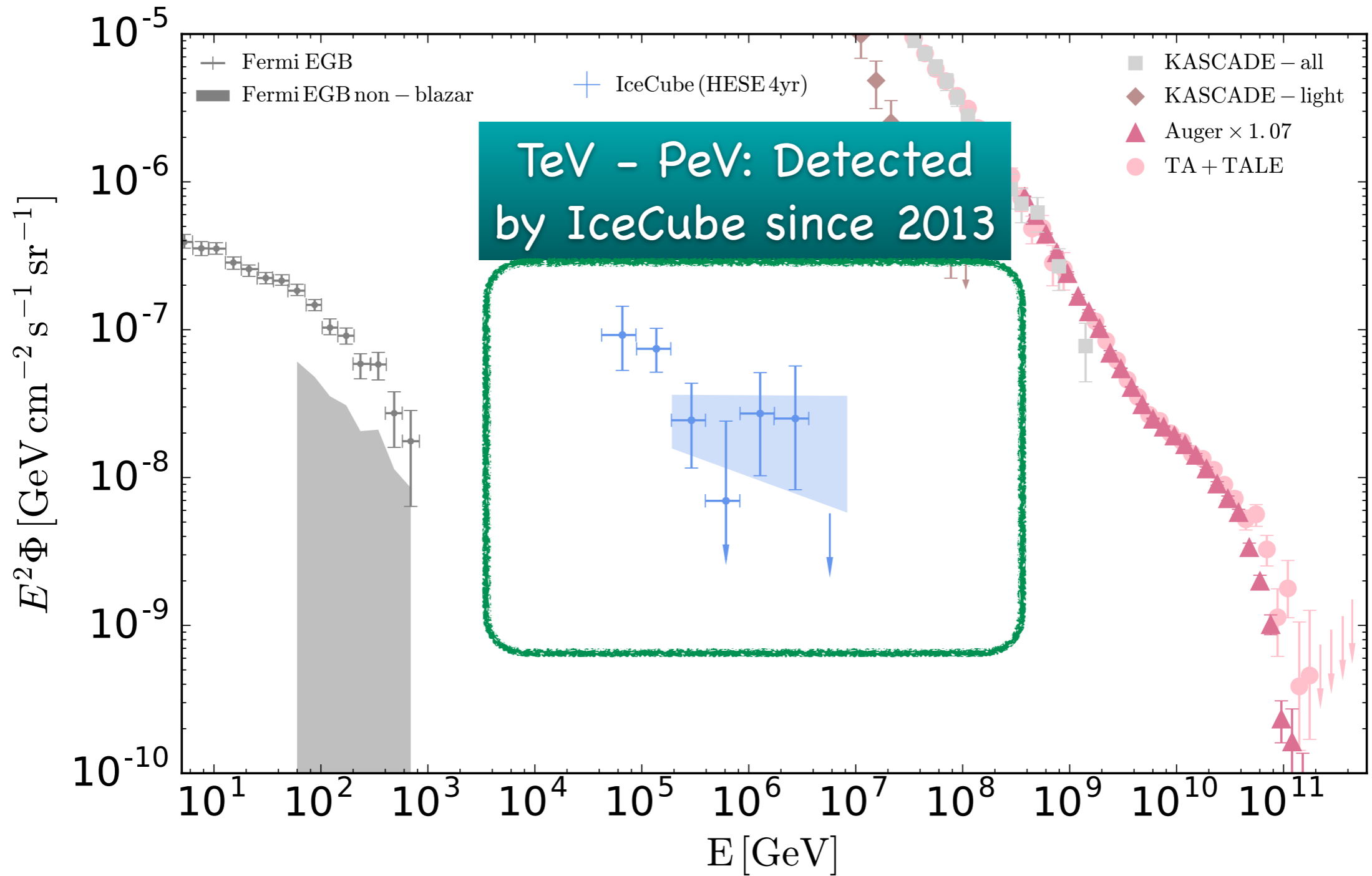


Ke Fang
JSI Fellow
University of Maryland
Aug 11, 2017

UHECRs, High-energy Nu, & Gamma Rays



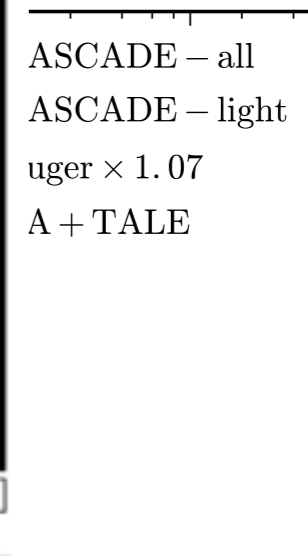
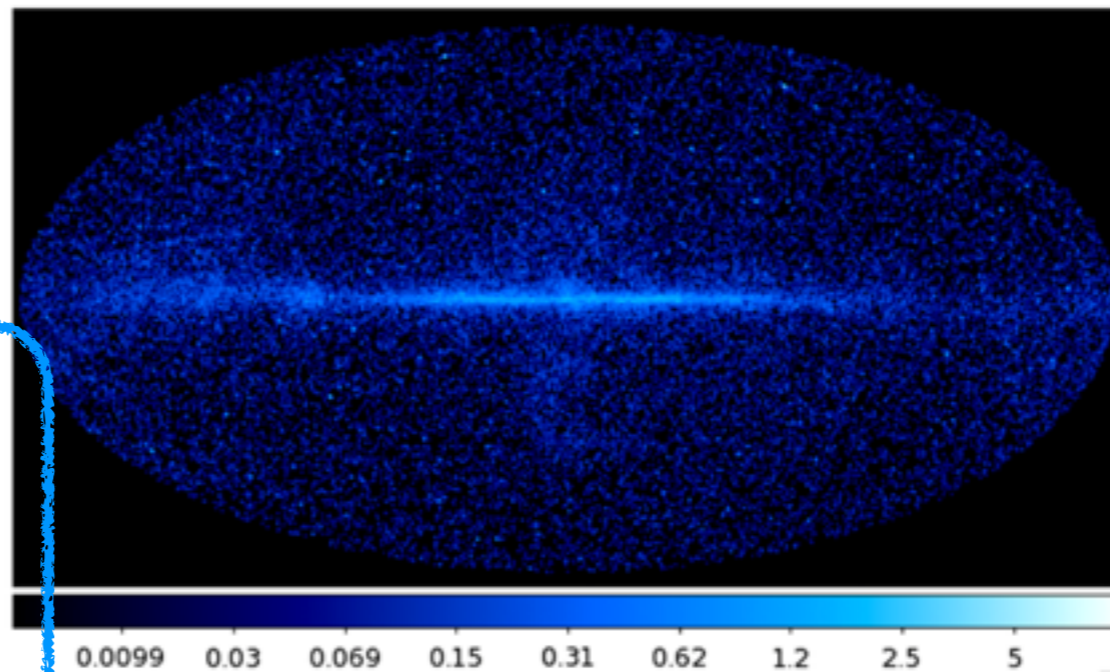
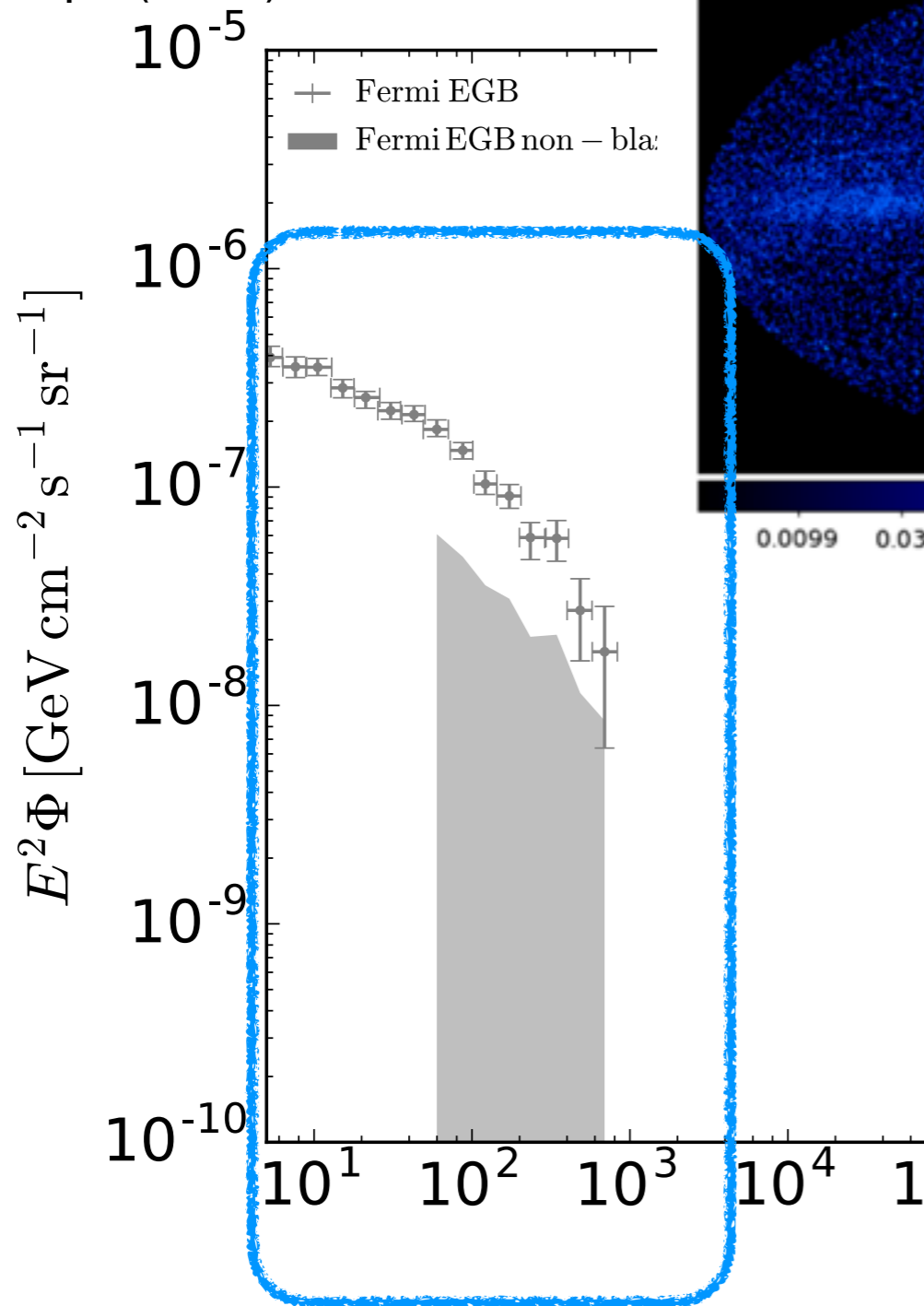
UHECRs, High-energy Nu, & Gamma Rays



UHECRs, High-energy Nu, & Gamma Rays

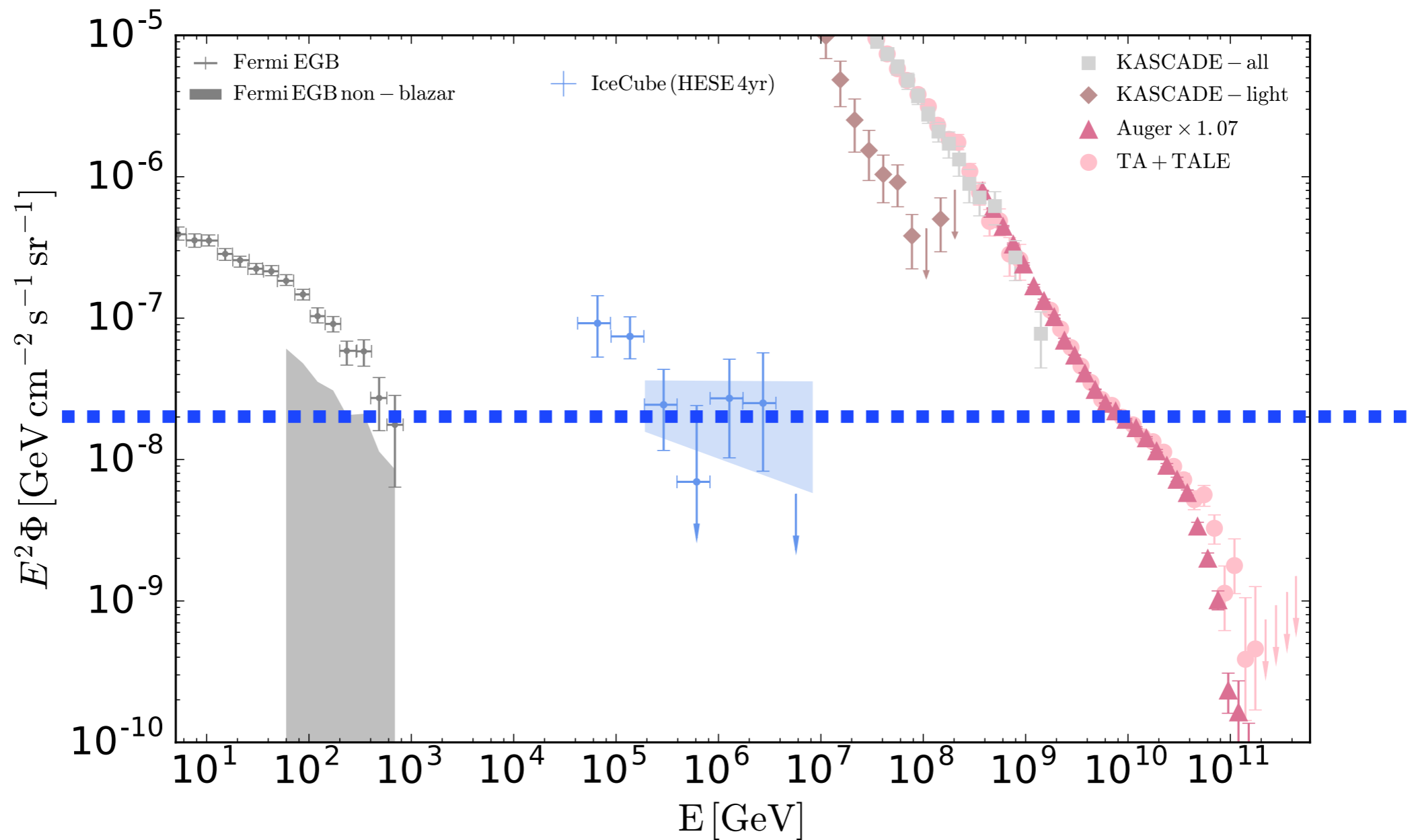
Fermi Collaboration, PRL (2016)

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)

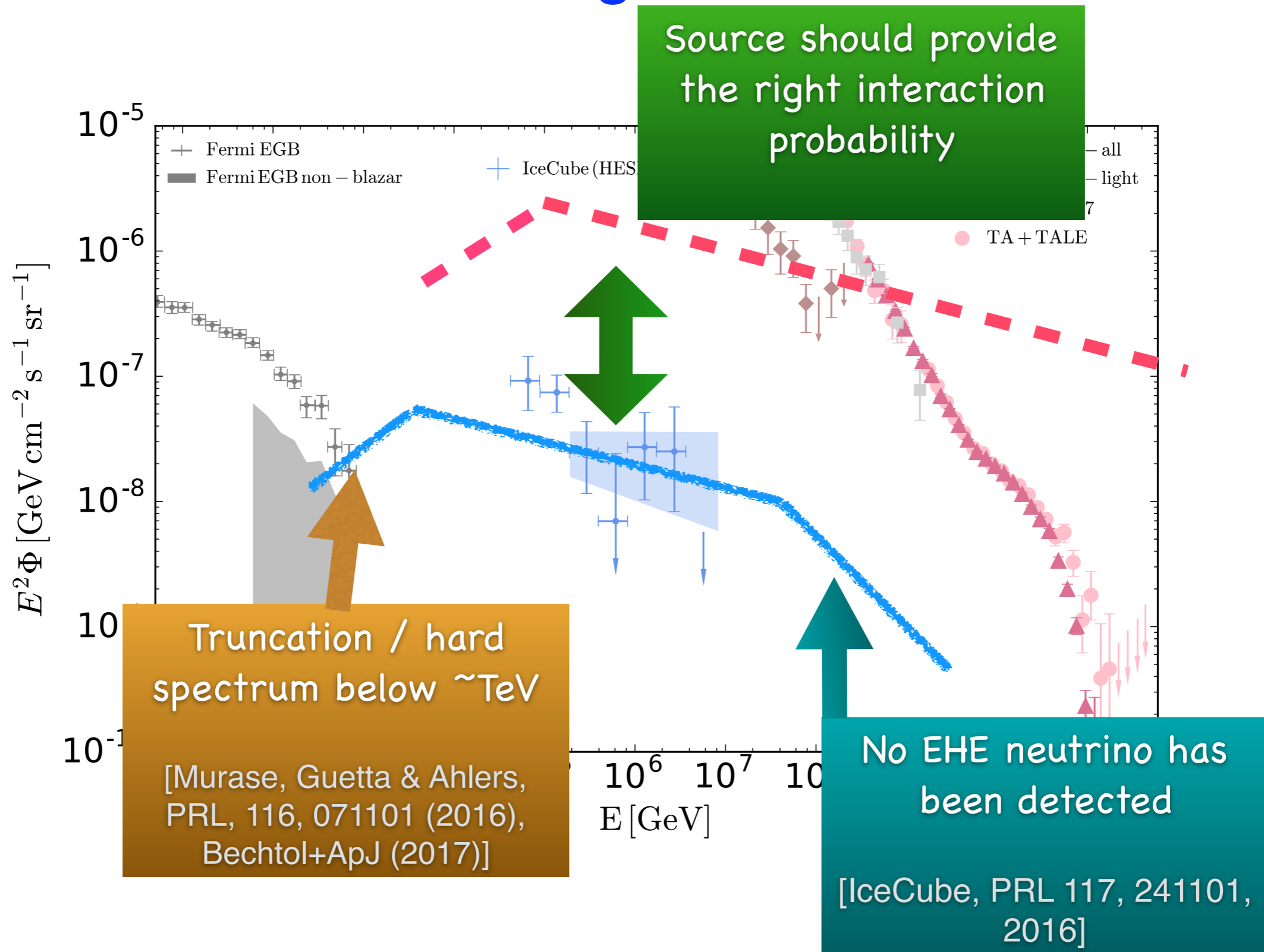
Waxman 1312.0558

Giacinti et al (2015)

Murase & Waxman PRD (2016)

Wang & Loeb PRD (2017) ...

A common origin is not trivial



Cosmic Ray Production by the Jet



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

Cosmic rays that are confined by the radio lobes cool adiabatically

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

$$t_{\text{cool}} \sim 5 \text{ Myr}$$

Only particles above \sim PeV leave the source

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

Cluster Environment

ICM gas

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

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

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

Infrared background from galaxies

[Takami & Murase ApJ 2012]

CMB, EBL

CRPropa3 + SOPHIA for turbulent field & N_γ

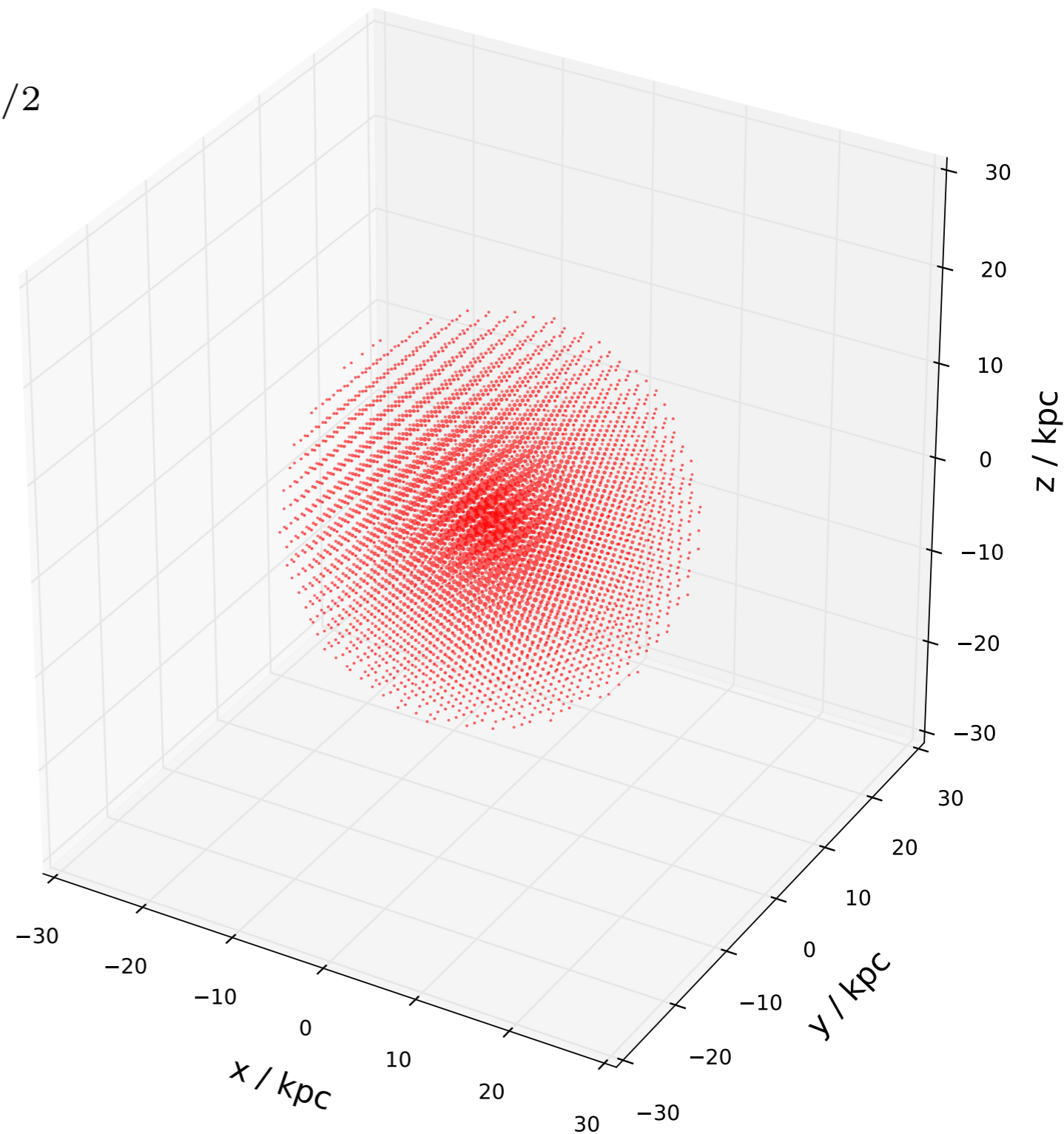
[Batista+ JCAP (2016)]

EPOS for N_p

[KF, Kotera & Olinto ApJ (2012)]

Diffuse propagation

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



Particle Trajectory - 10 EeV

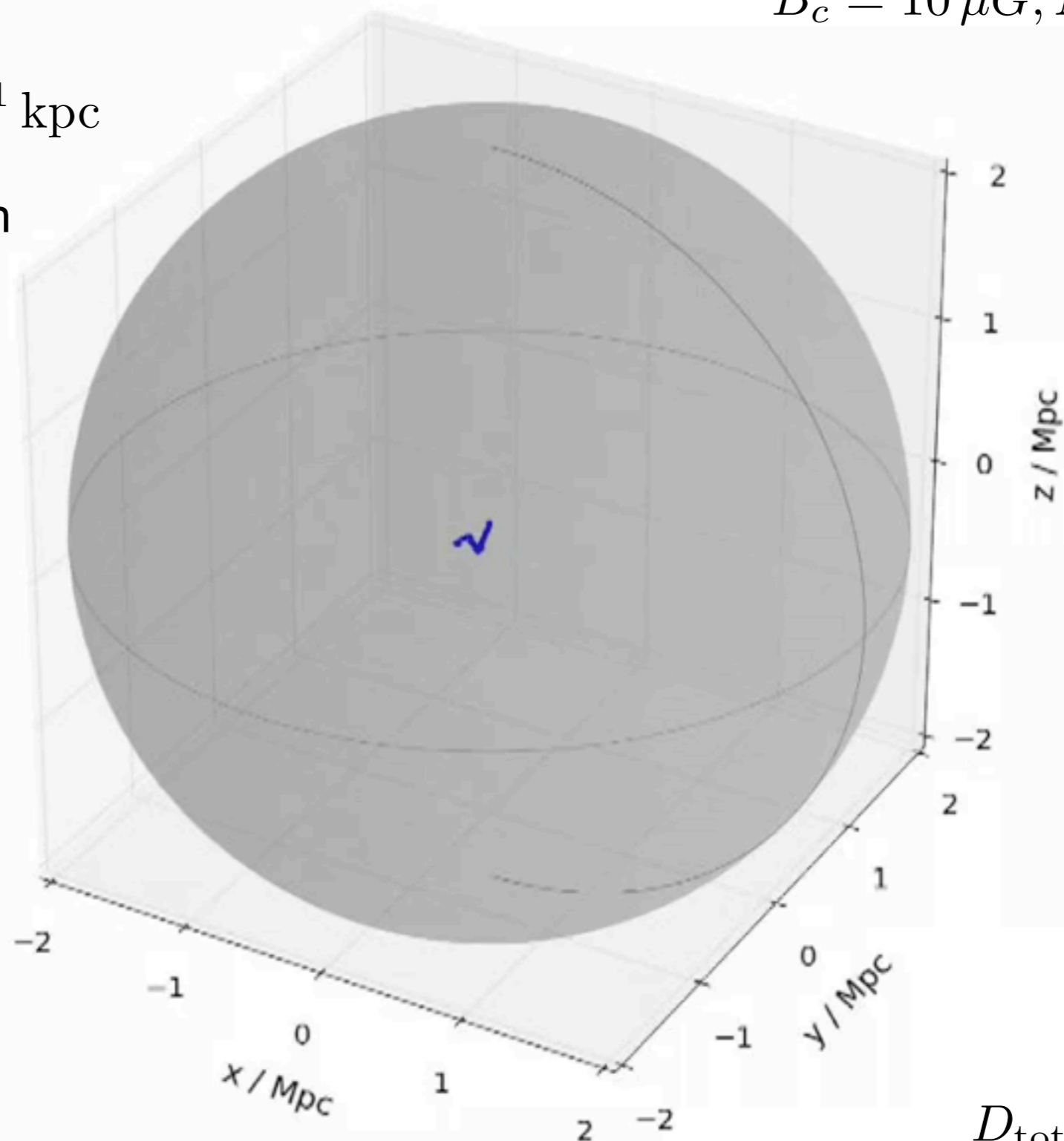
$$B_c = 10 \mu\text{G}, M = 10^{15} M_\odot$$

Particle Larmor Radius

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

Field Coherence Length

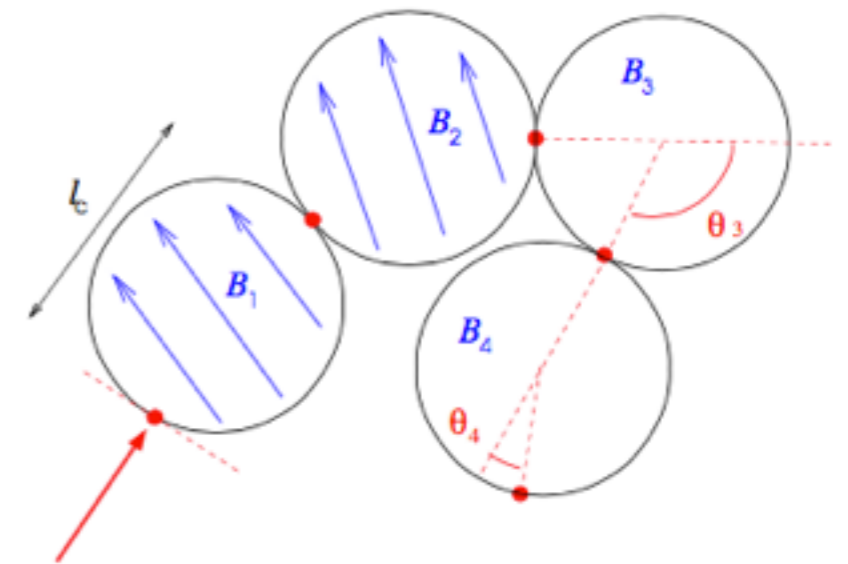
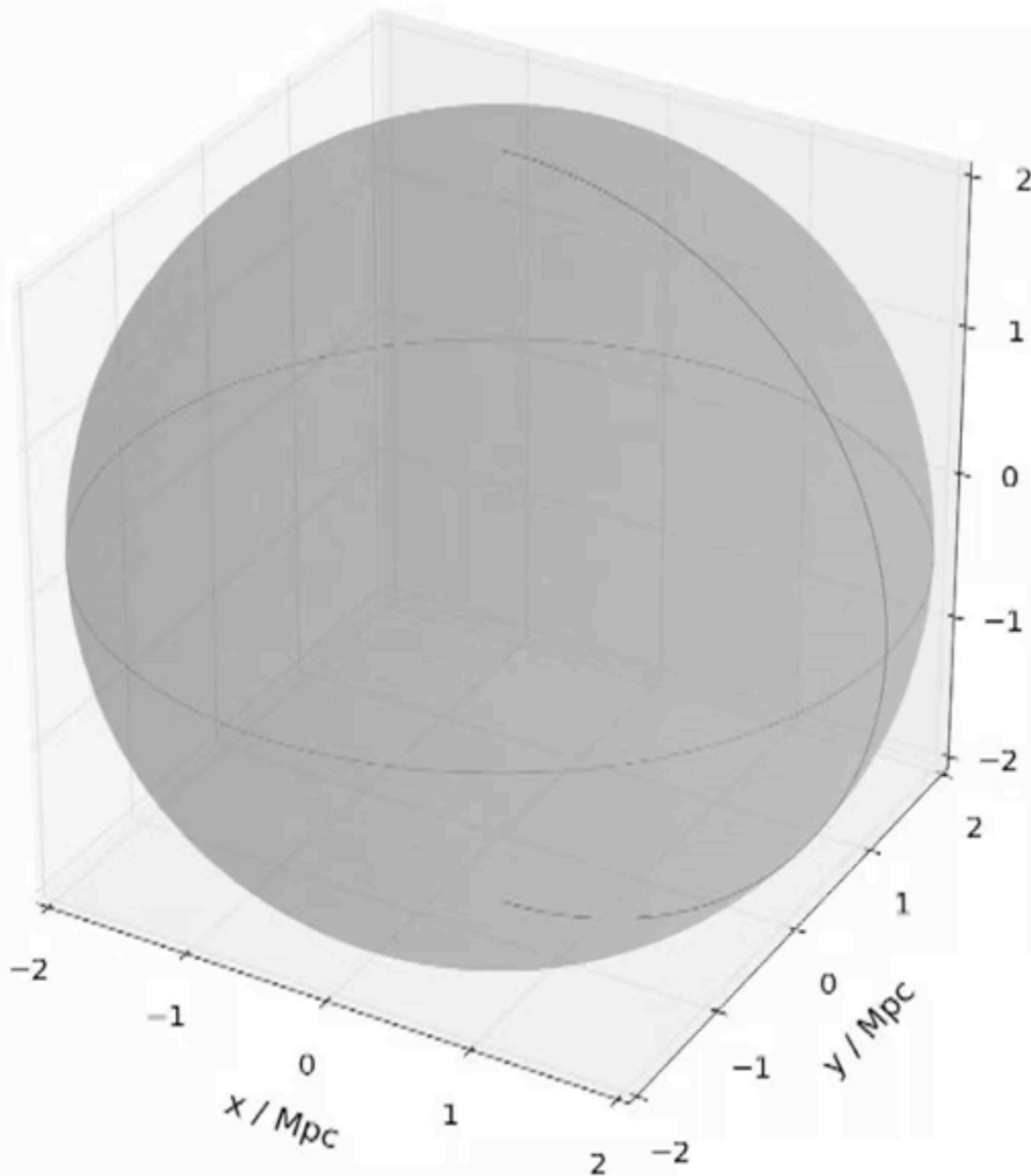
$$l_0 \sim 20 \text{ kpc}$$



$$D_{\text{total}} = 46 \text{ Mpc}$$

Particle Trajectory - 0.1 EeV

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

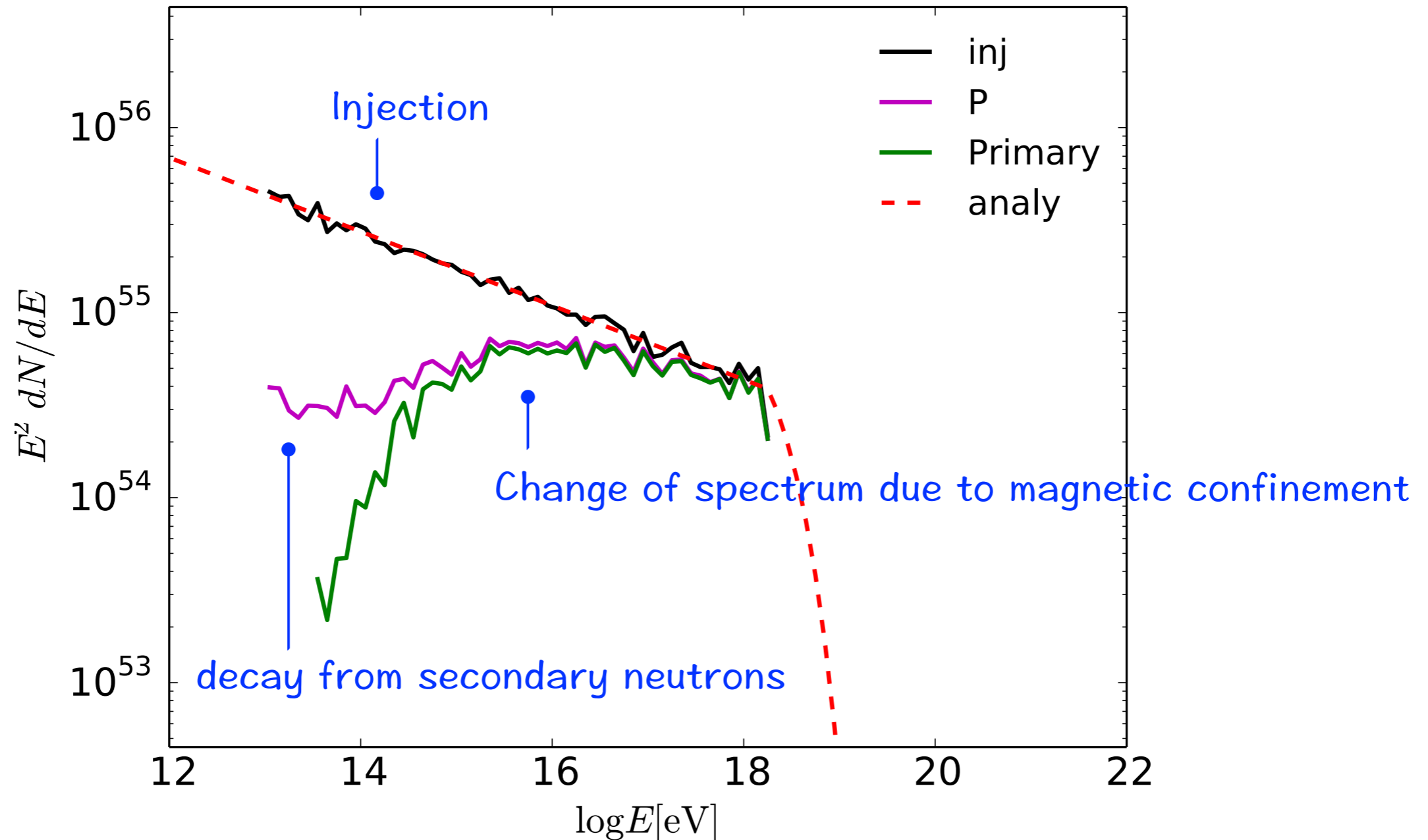


Approximation for diffusion computation

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

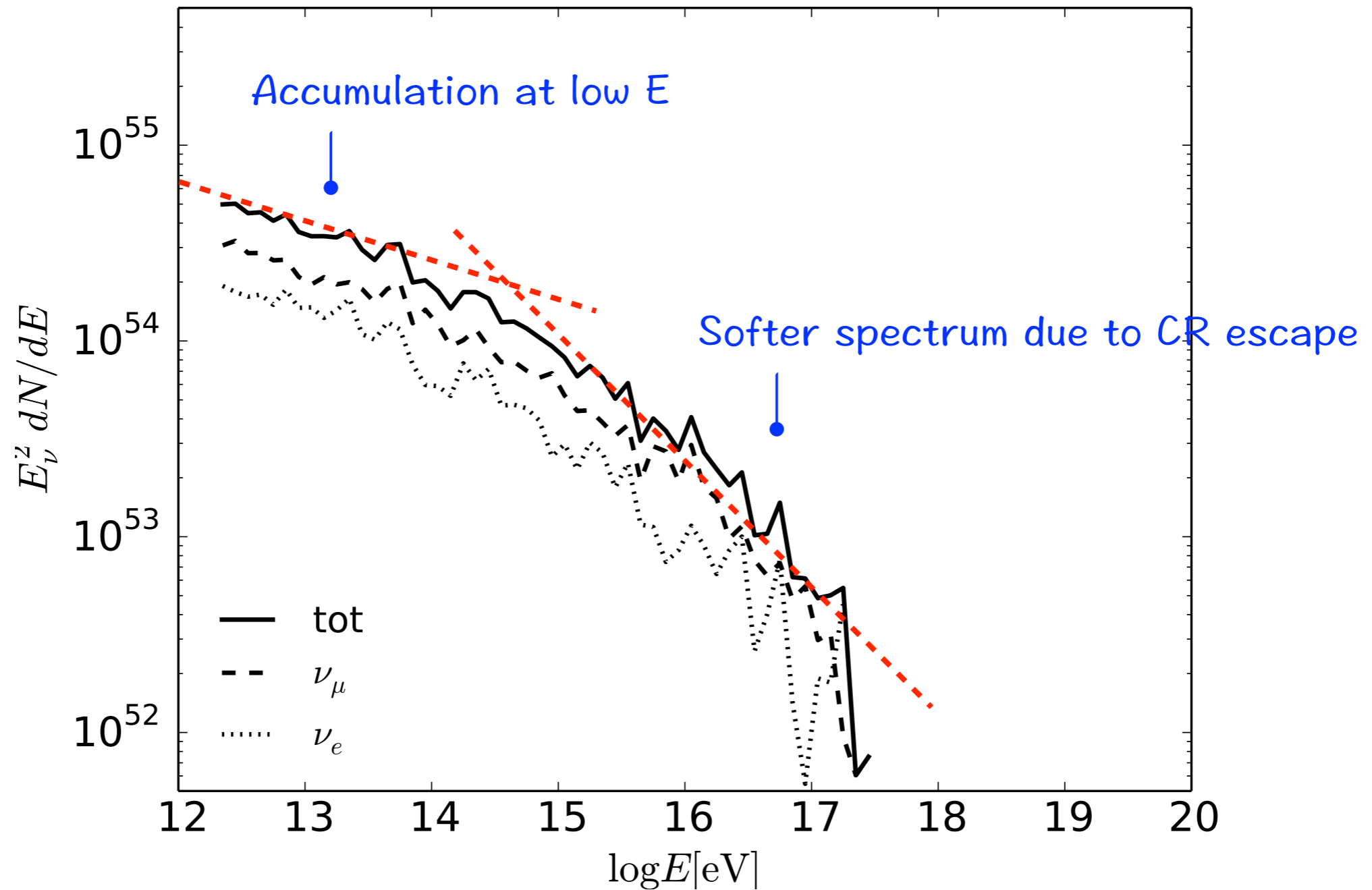
Cosmic Ray Flux from One Single Cluster

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



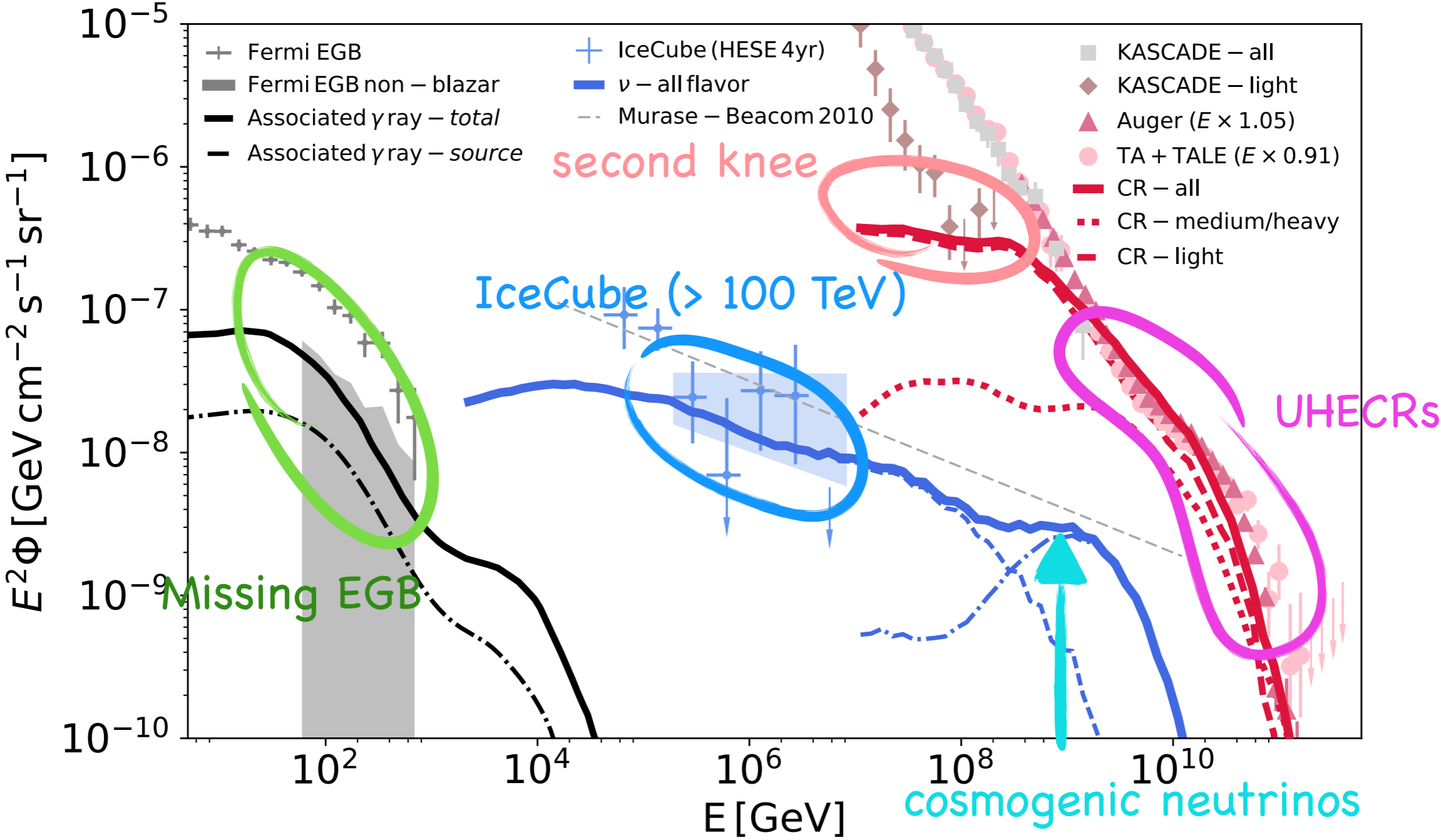
Neutrino Flux from One Single Cluster

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

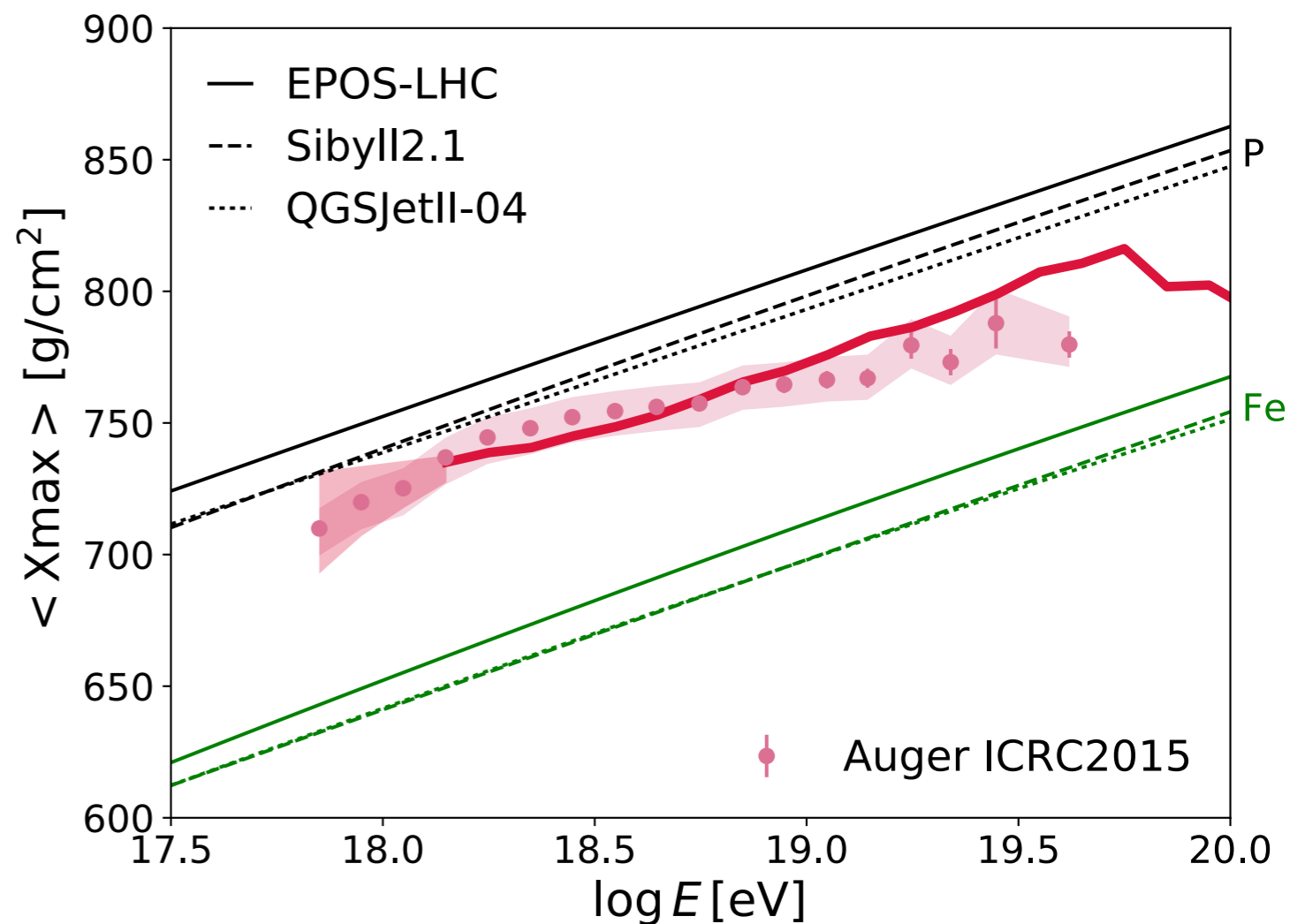
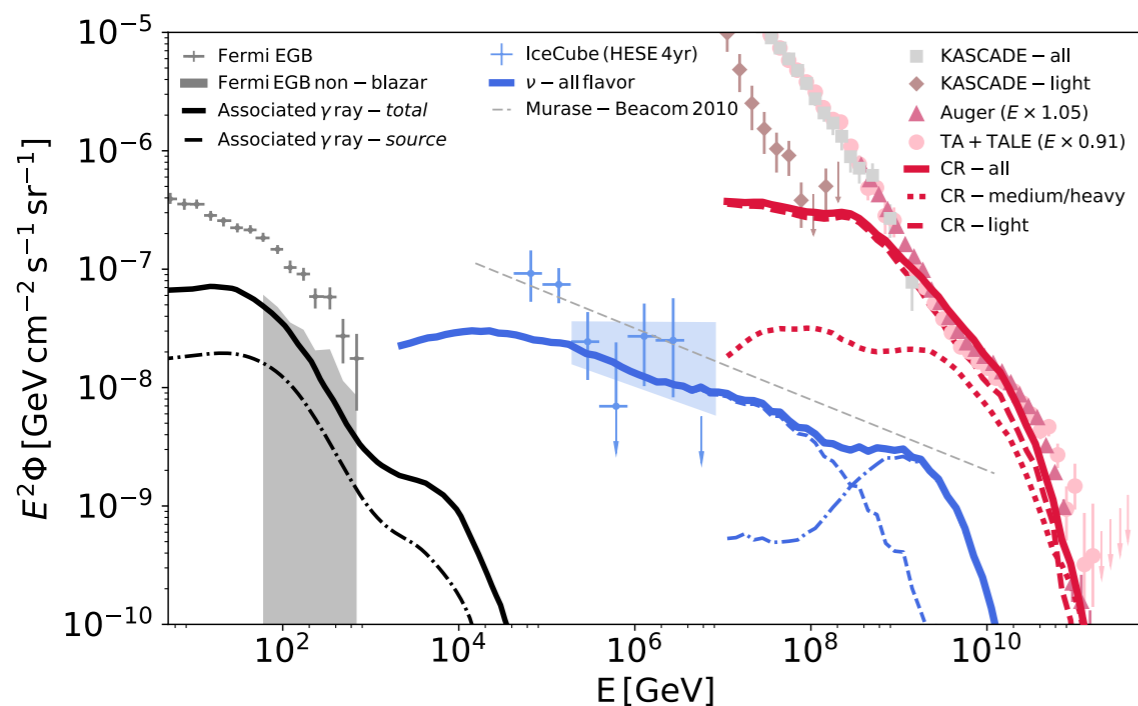


Cosmic Particles from Black Hole Jets in Clusters

Injection Composition = Galactic CR abundance



A Unification Picture of Multi-messengers



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