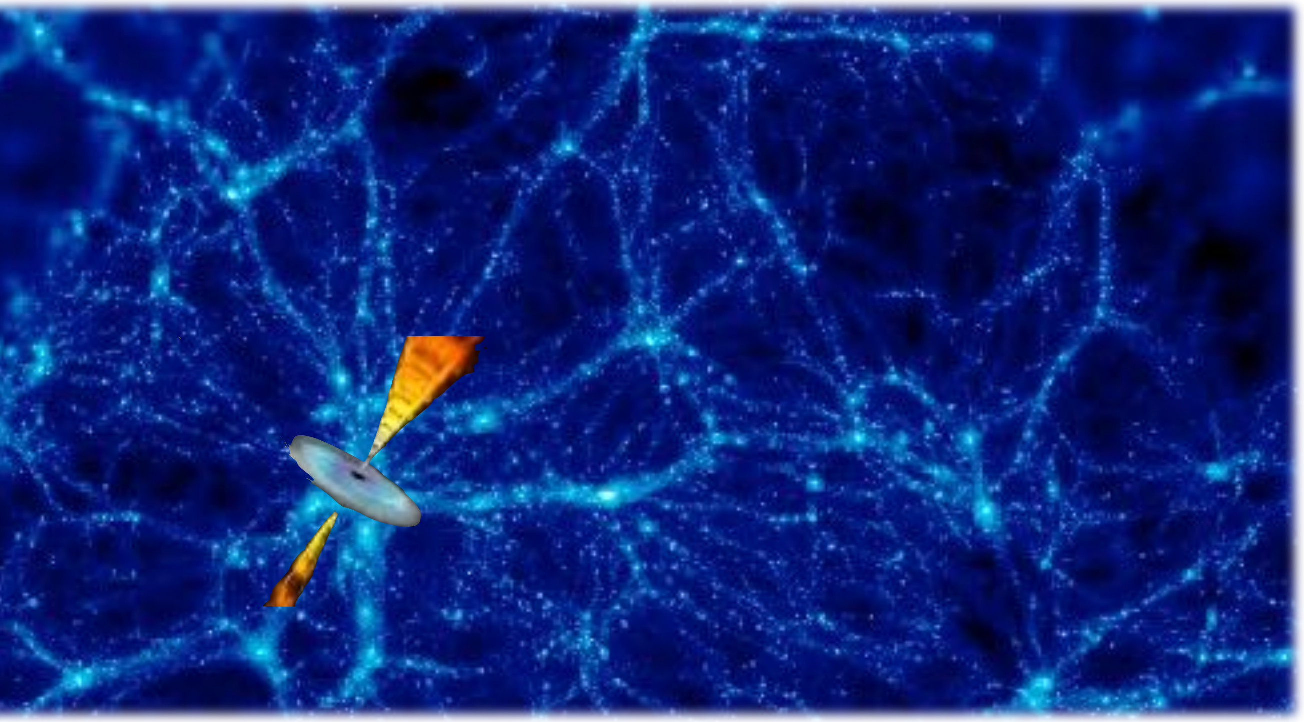

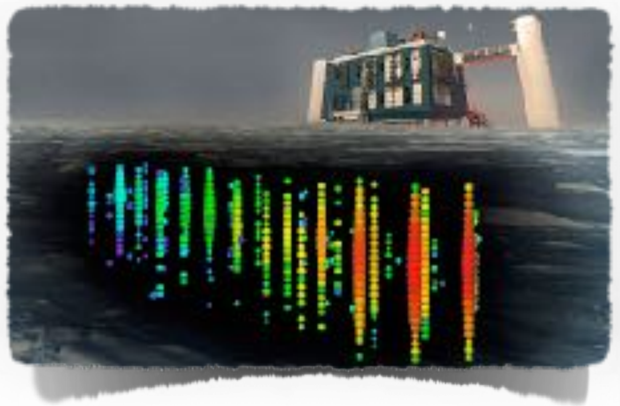

High-Energy Cosmic Particles by Black-hole Jets in Galaxy Clusters

Ke Fang

Einstein Fellow, Stanford University

YITP Workshop, Kyoto, Japan (virtual attendance)

Dec 10, 2020

- A “common origin” of cosmic particles?
- Cosmic-ray acceleration and confinement
- Astroparticles from galaxy clusters

- **A “common origin” of cosmic particles?**
- Cosmic-ray acceleration and confinement
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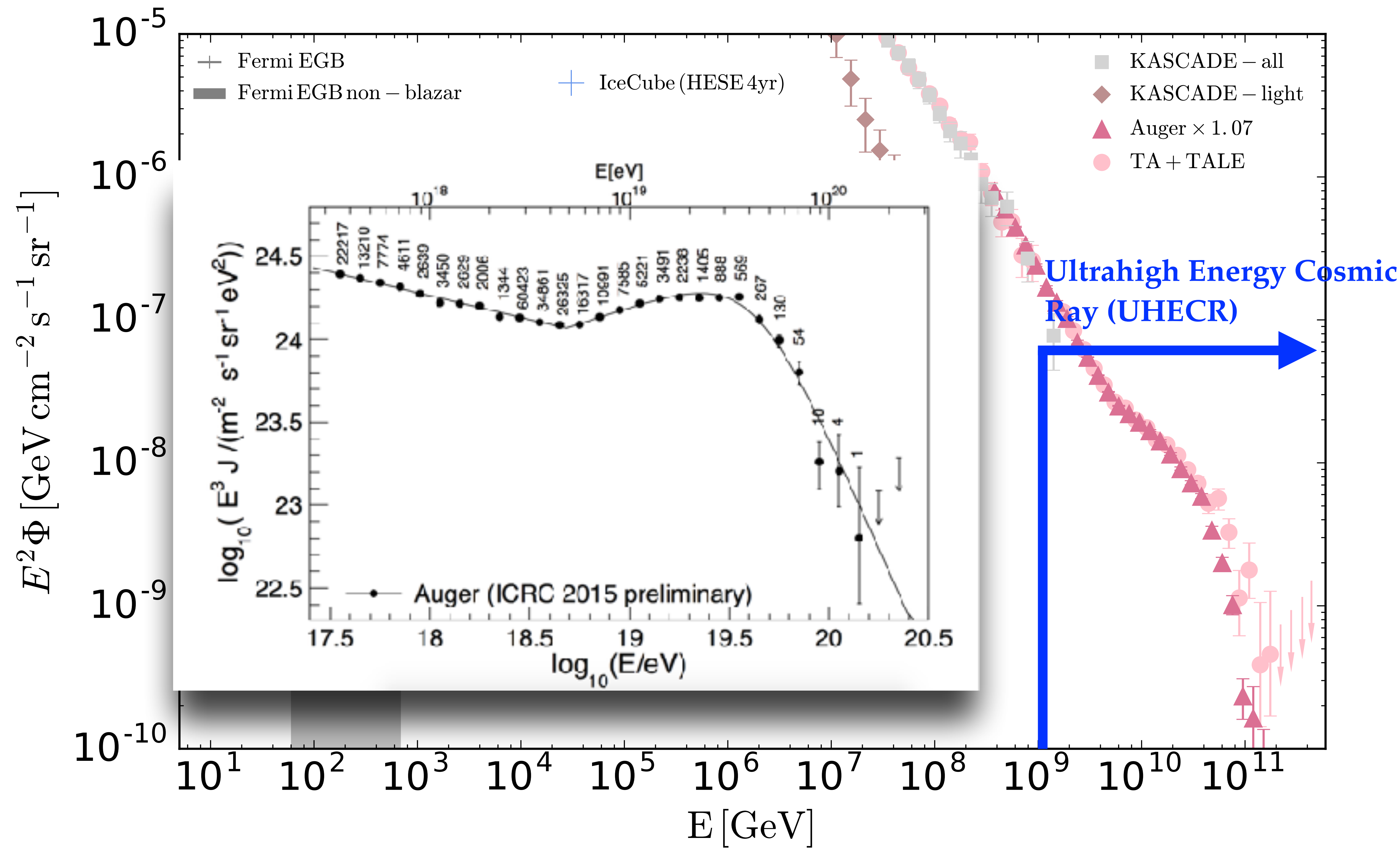
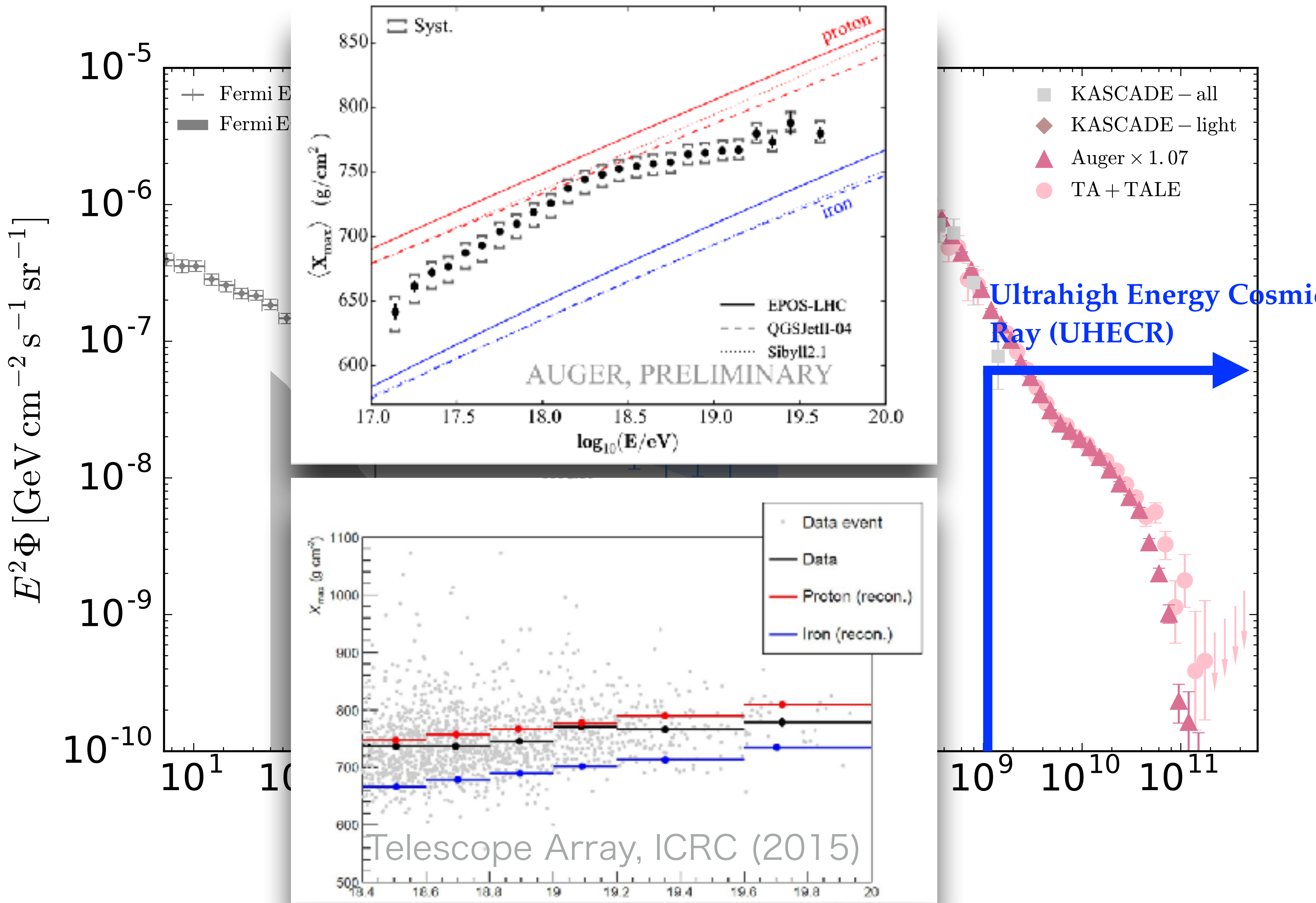
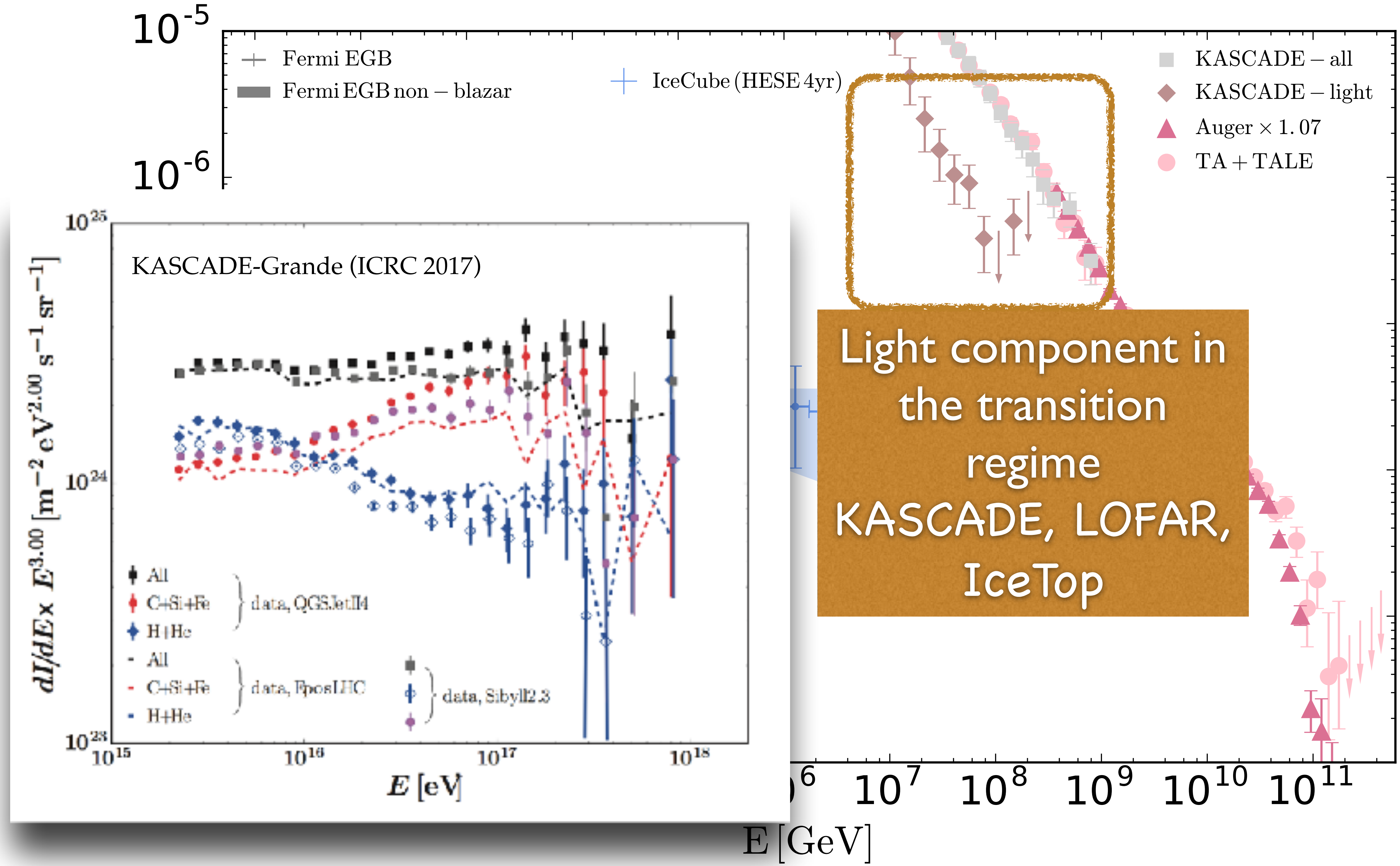
UHECRs, High-energy Neutrinos & Gamma Rays



UHECRs, High-energy Neutrinos & Gamma Rays

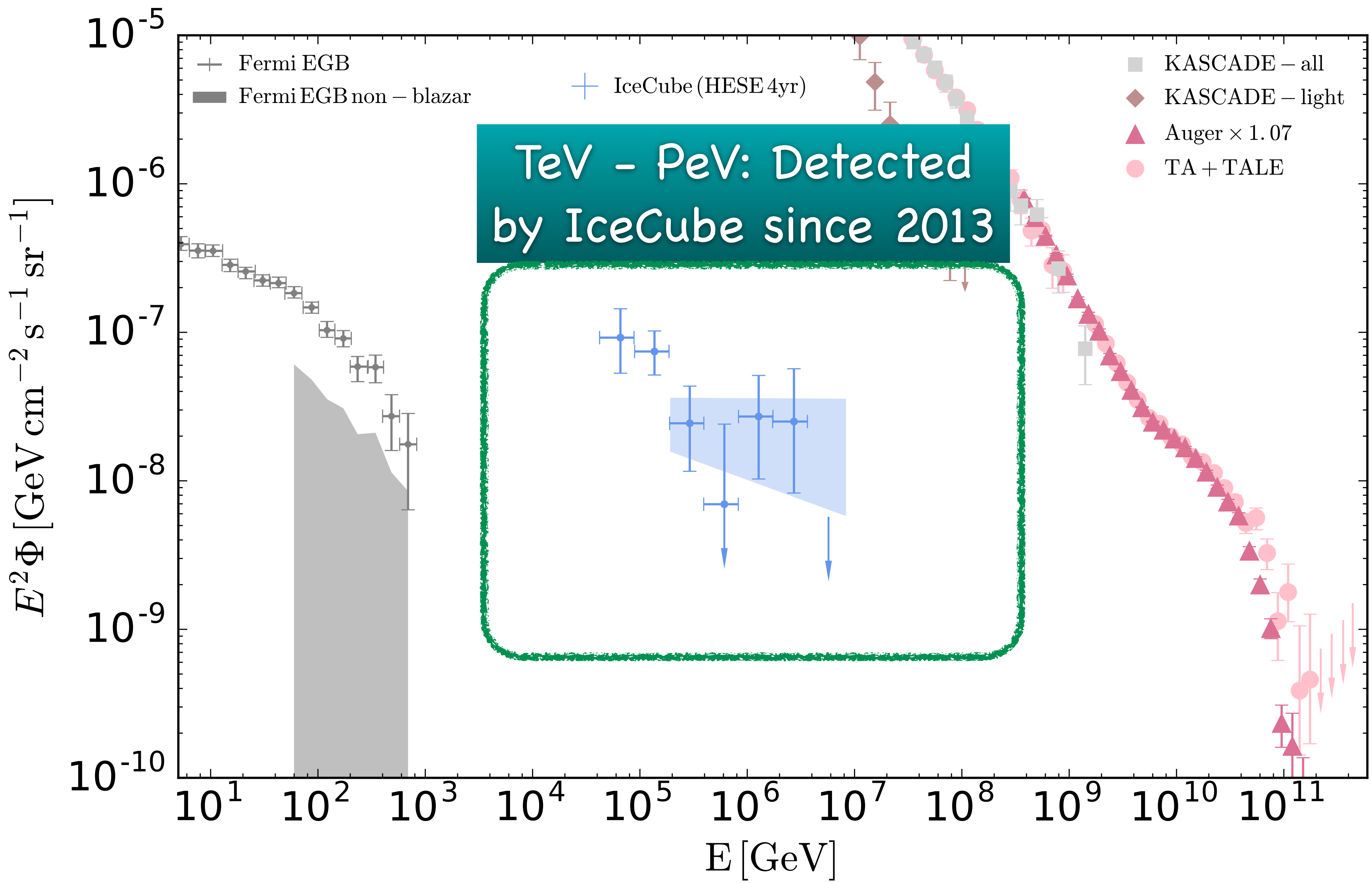


UHECRs, High-energy Neutrinos & Gamma Rays

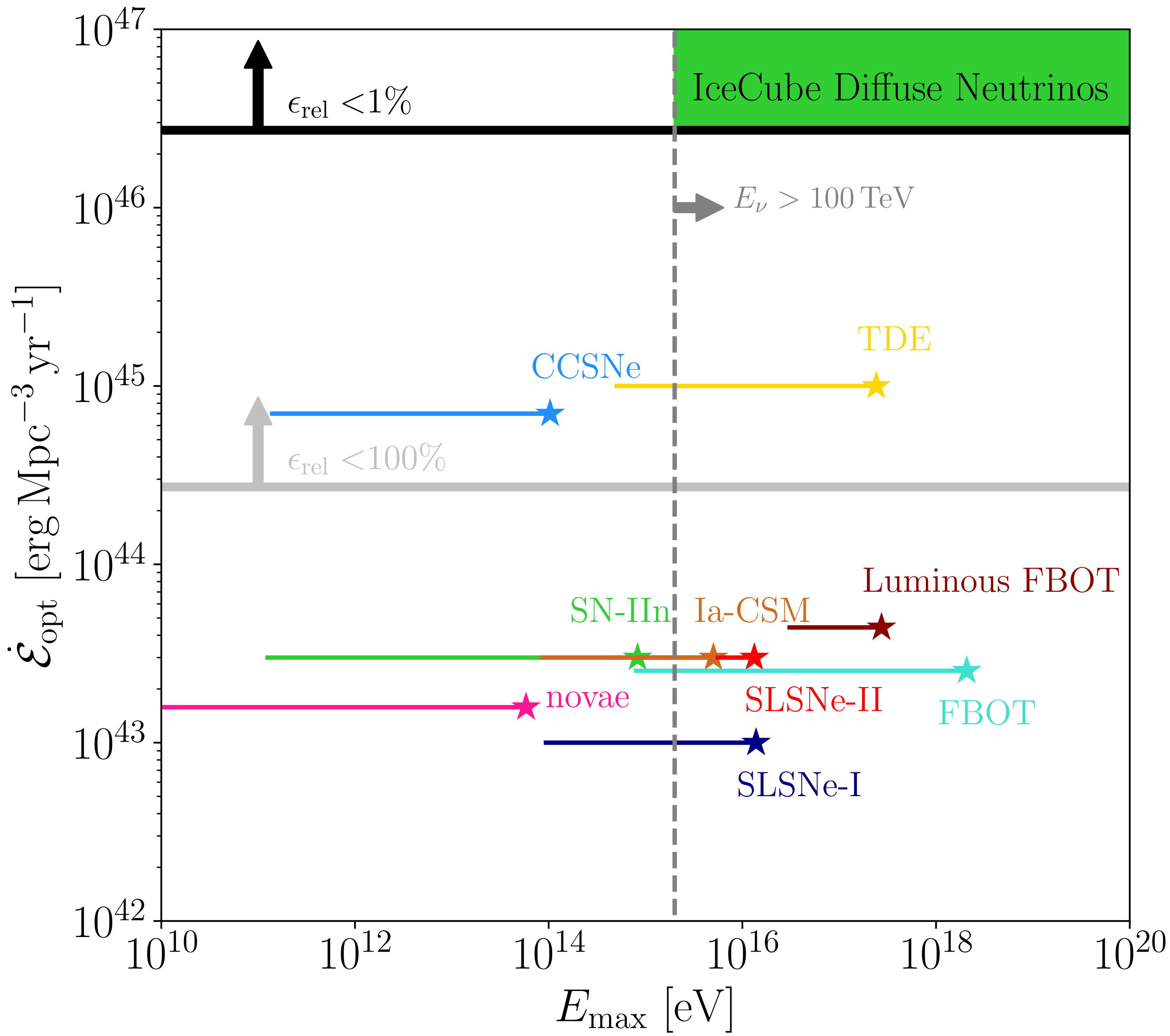


Light component in the transition regime
KASCADE, LOFAR, IceTop

UHECRs, High-energy Neutrinos & Gamma Rays



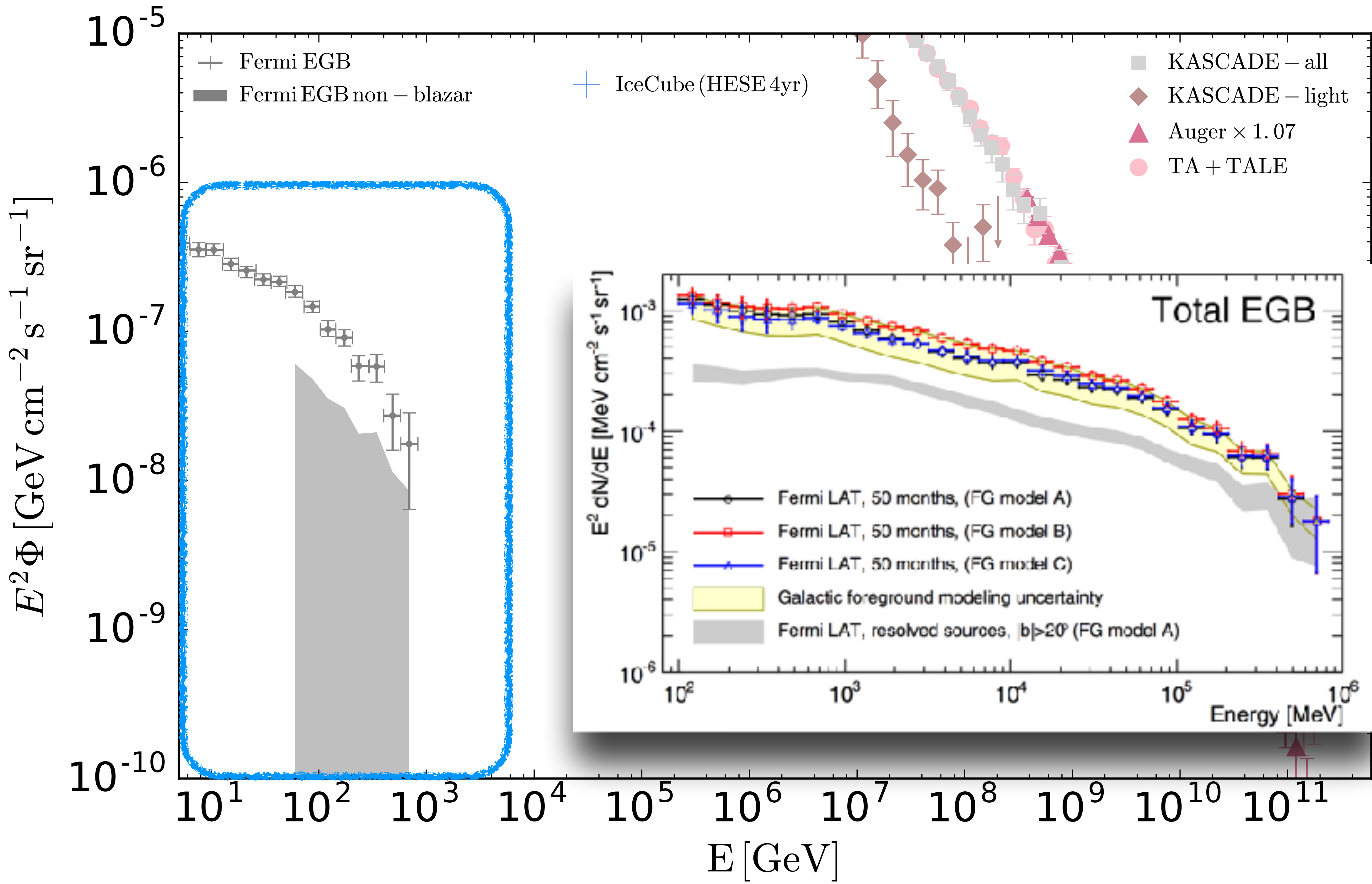
Neutrino Sources are Powerful and Abundant!



Transients powered by non-relativistic shocks can barely explain the IceCube diffuse neutrinos.

KF, Metzger, Vurm, Aydi, Chomiuk (2020)

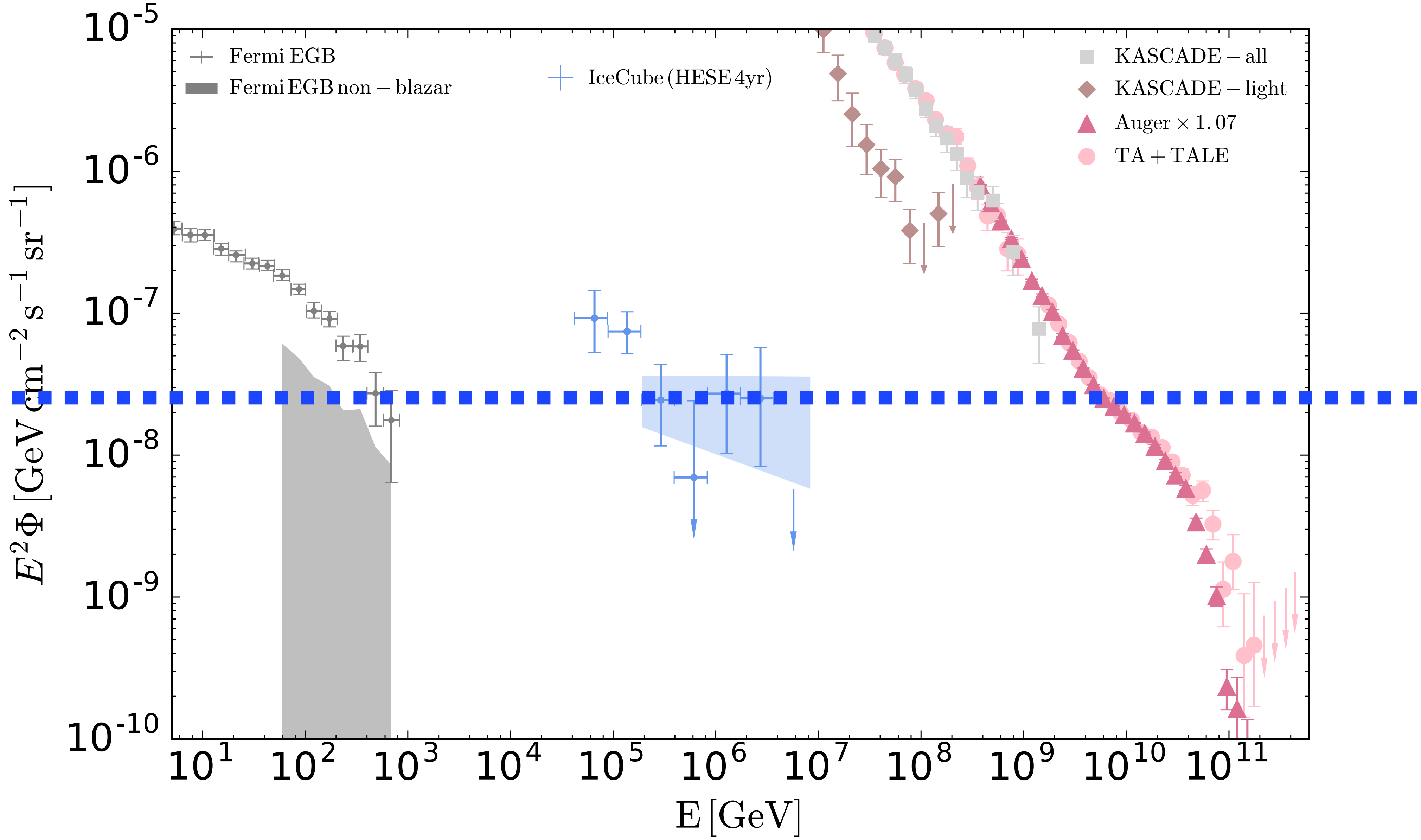
UHECRs, High-energy Neutrino & Gamma Rays



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

Fermi Collaboration (2016)
Lisanti et al (2016)

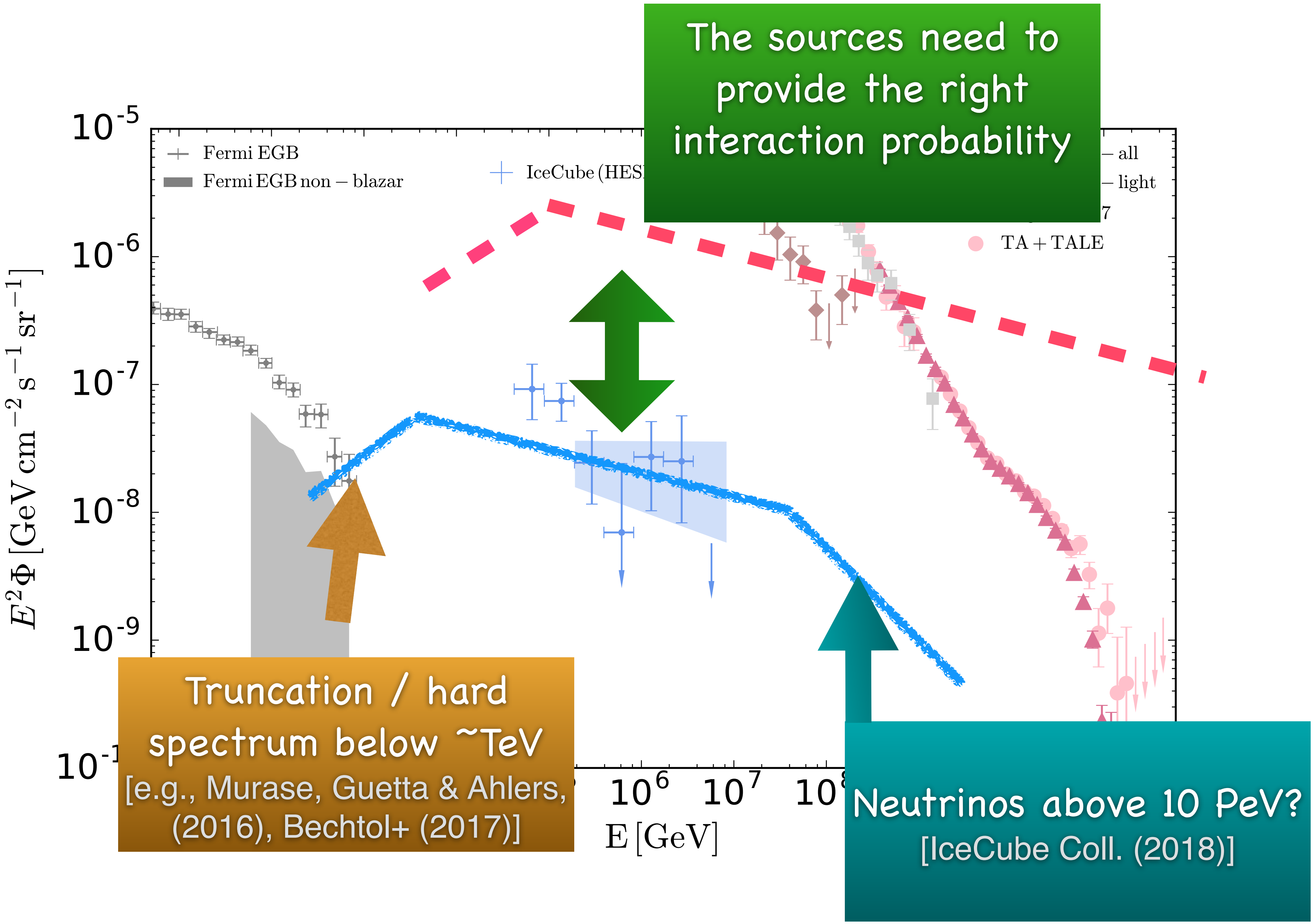
When putting them together..



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

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

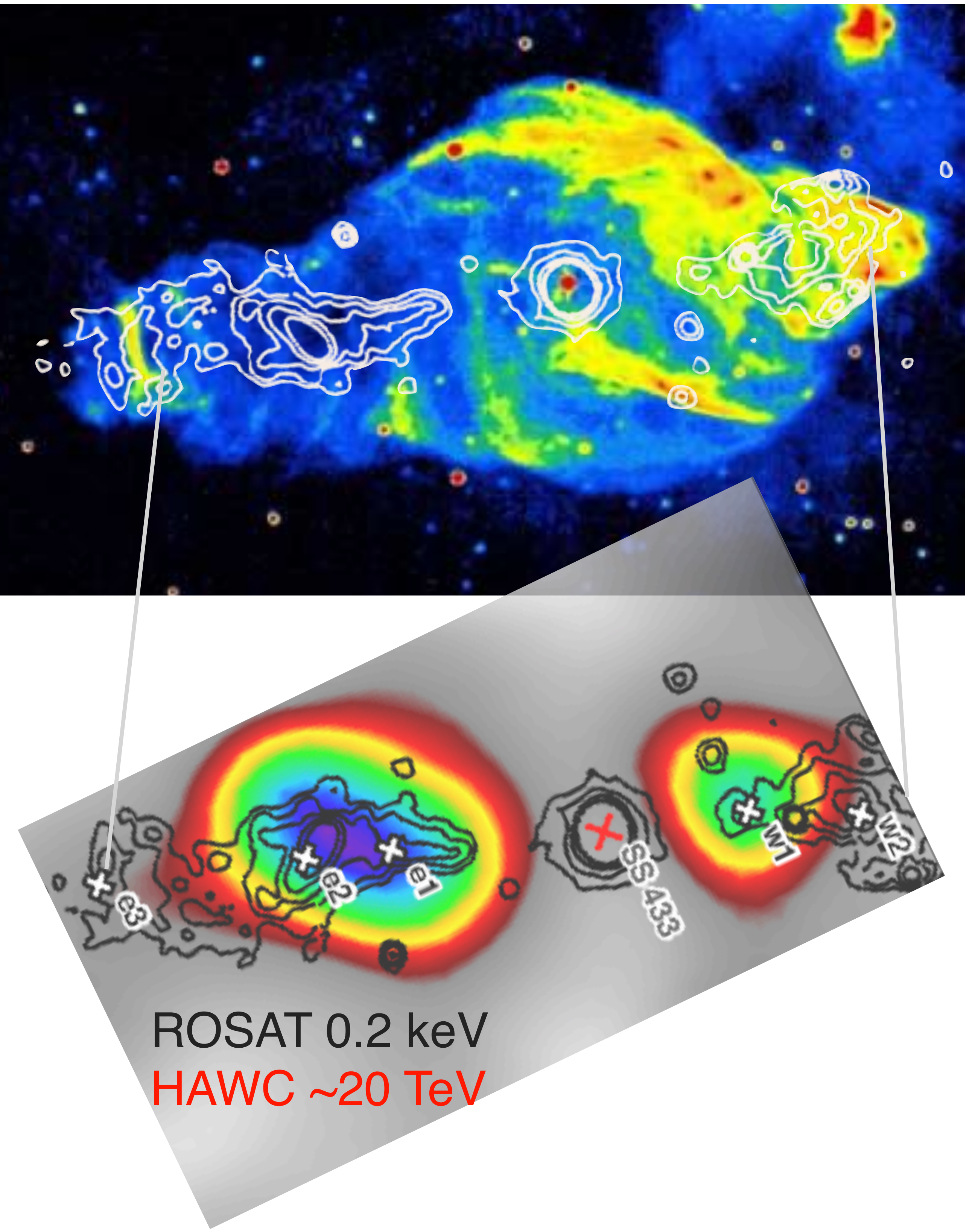
A common origin is nontrivial



- A “common origin” of cosmic particles?
- **Cosmic-ray acceleration and confinement**
- Astroparticles from galaxy clusters

Black Hole Jets as Cosmic Accelerators

Microquasar SS 433

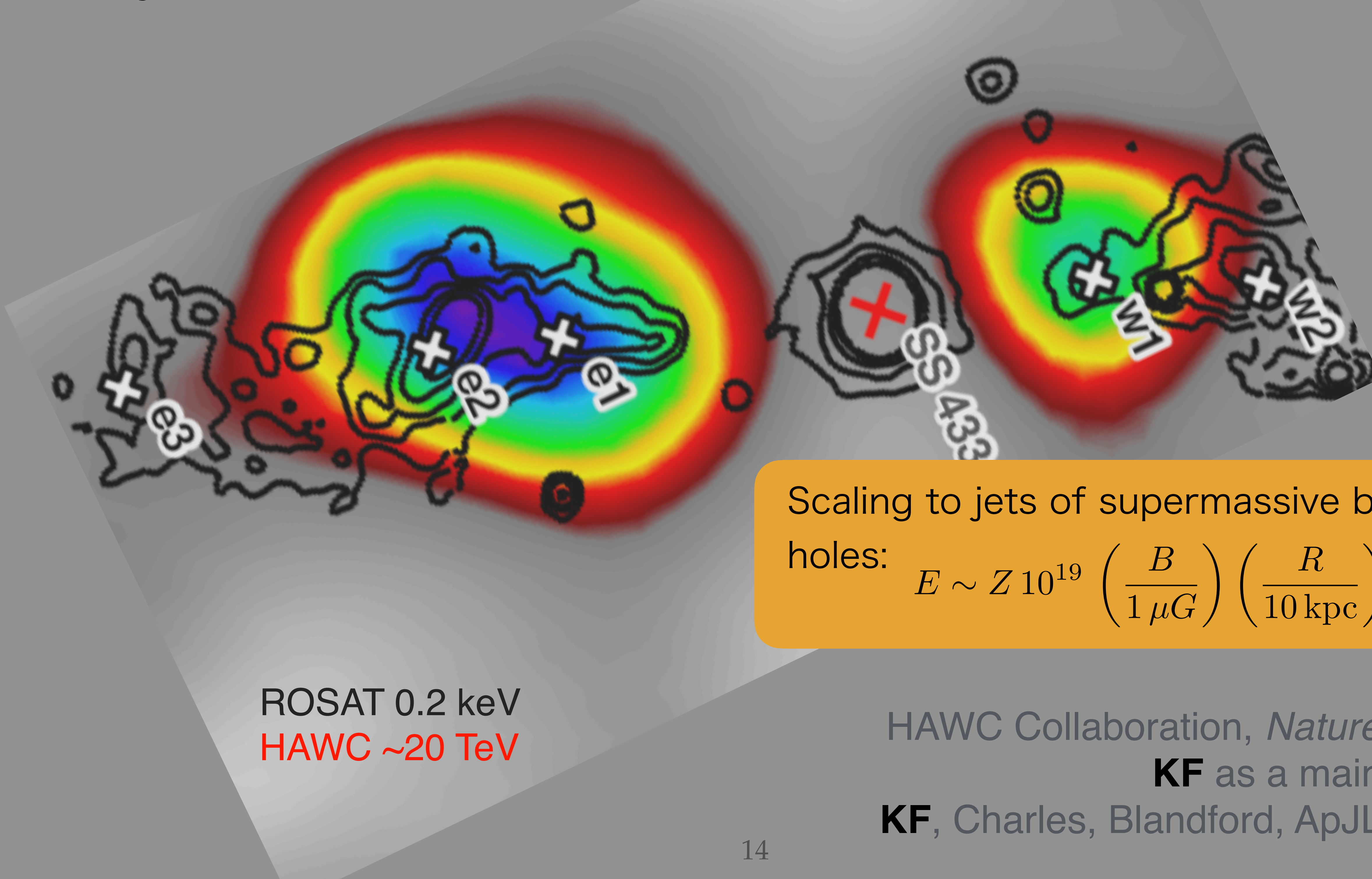


- “Mini AGN” in our own galaxy with extended X-ray jets
- **TeV gamma-rays in both lobes** detected by HAWC
- **GeV counterparts** identified in Fermi-LAT data

HAWC Collaboration, *Nature* (2018)
KF as a main author

KF, Charles, Blandford, ApJL (2020)

- **Electrons above 20 TeV** were accelerated
- Particle acceleration sites **~30 pc away from hole**

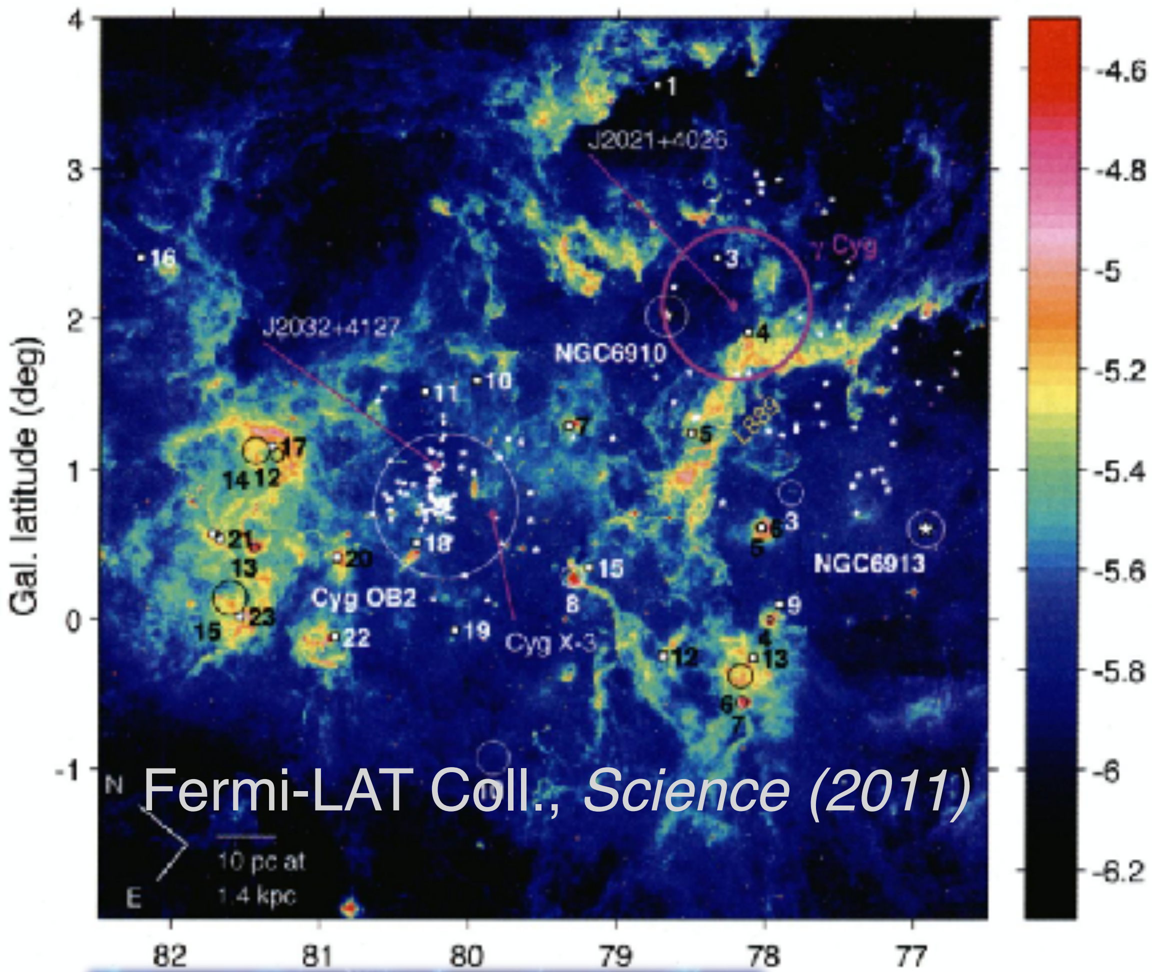


Scaling to jets of supermassive black holes: $E \sim Z\,10^{19} \left(\frac{B}{1\,\mu G}\right) \left(\frac{R}{10\,\mathrm{kpc}}\right) \mathrm{eV}$

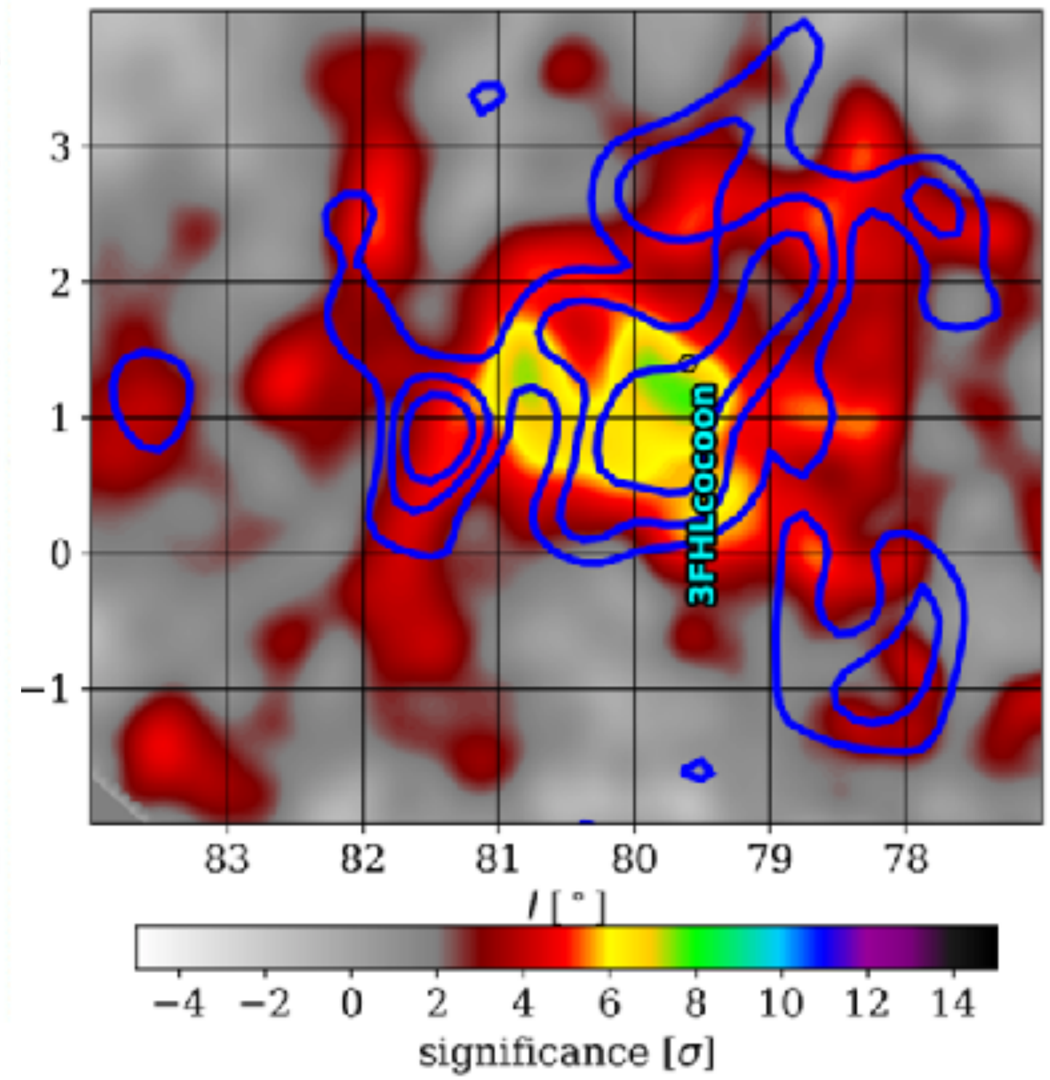
HAWC Collaboration, *Nature* (2018)
KF as a main author
KF, Charles, Blandford, ApJL (2020)

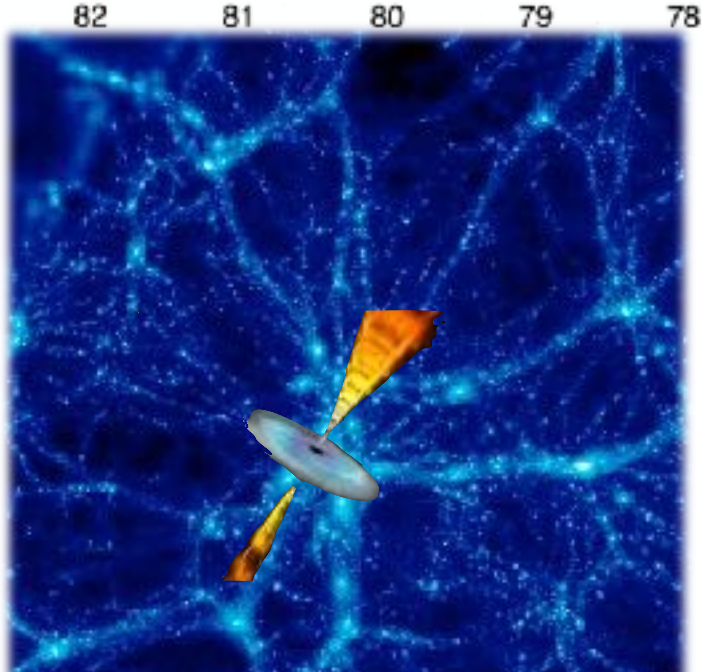
Confinement of Cosmic Rays in Local Environment

Cygnus Cocoon



Fermi-LAT Coll., *Science (2011)*





GeV to100 TeV gamma-rays trace infrared emission

HAWC Collaboration, *under review*
KF as a main author

- A “common origin” of cosmic particles?
- Cosmic-ray acceleration and confinement
- **Astroparticles from galaxy clusters**

The Intracluster Medium Environment for Interactions

ICM gas

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

Radiation backgrounds: Infrared background from galaxies, CMB, Extragalactic background lights

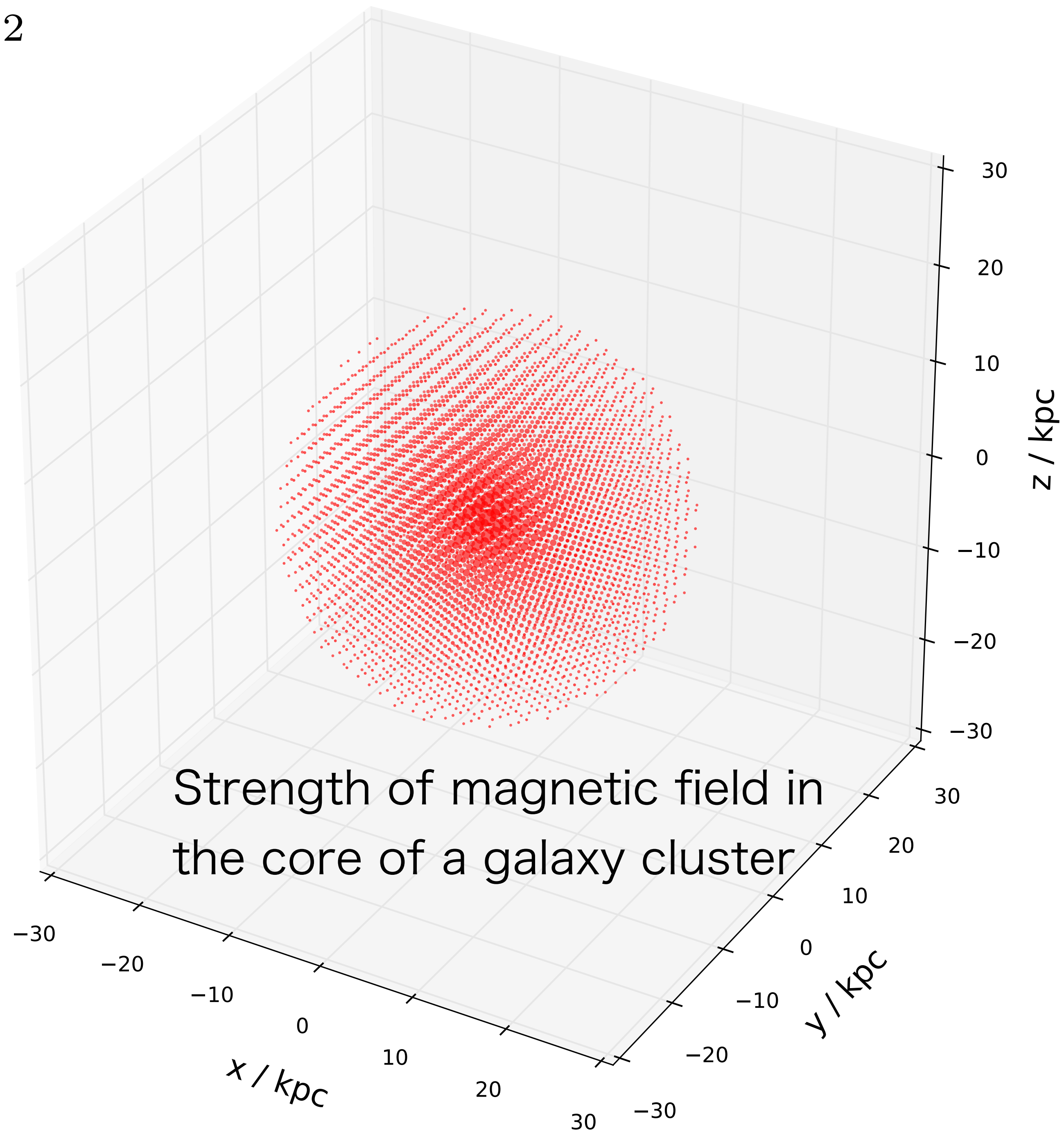
Magnetic field following Kolmogorov turbulence

$$B(M,r) \propto n(M,r)^{2/3}$$

CRPropa3 + SOPHIA for turbulent field & $N\gamma$
[Batista+ JCAP (2016)]

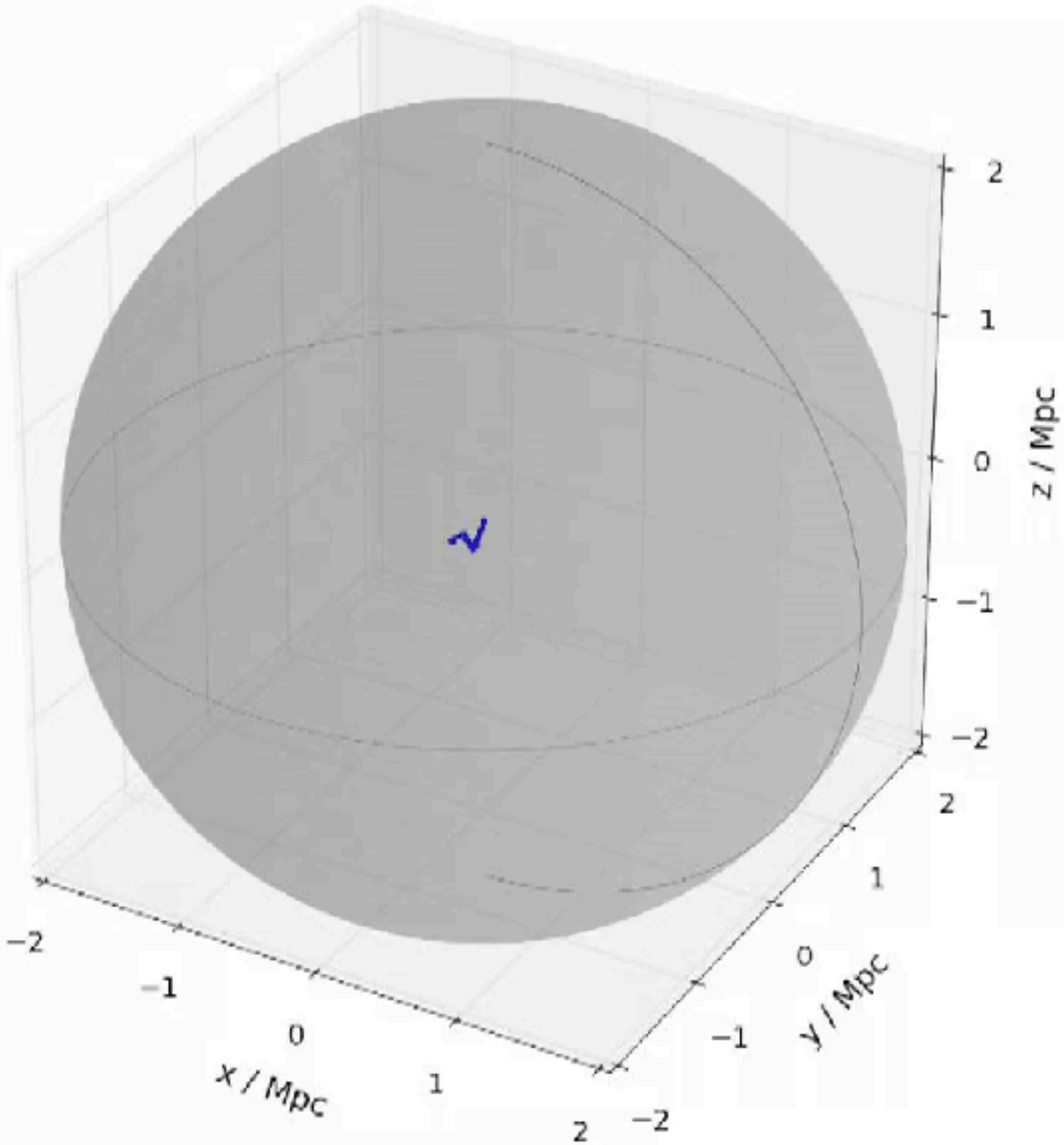
EPOS for Np
[KF, Kotera & Olinto ApJ (2012)]

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



KF & Olinto (2017)
KF & Murase *Nature Physics* (2018)

Particle Trajectory in the Intracluster Medium - 10 EeV



Particle Larmor Radius

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

Field Correlation Length

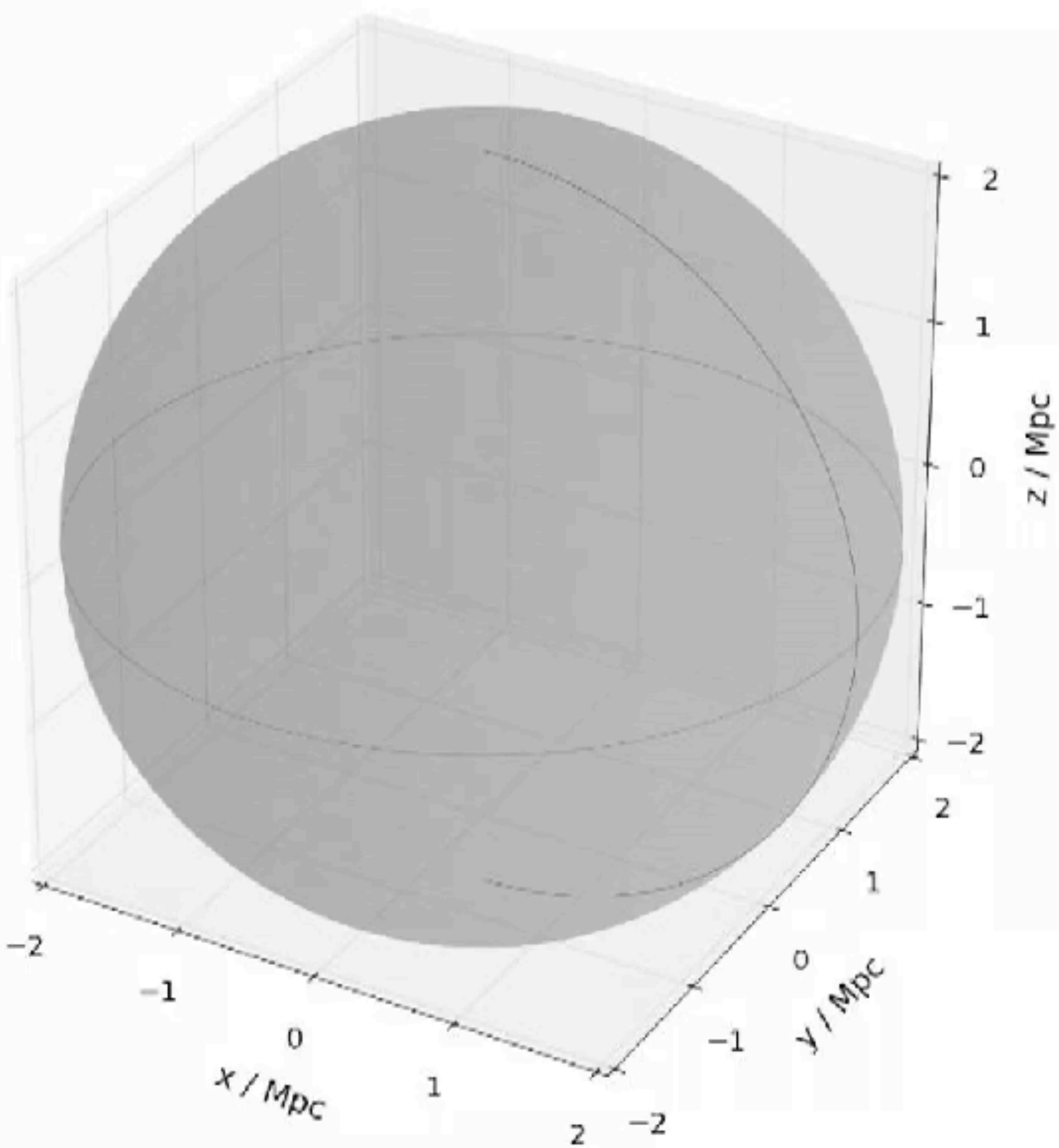
$$l_0 \sim 20\, \mathrm{kpc}$$

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

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

KF & Murase *Nature Physics* (2018)

Particle Trajectory in the Intracluster Medium - 0.1 EeV



Particle Larmor Radius

$$r_L = 0.1\, E_{17}\, B_{-6}^{-1}\, Z^{-1}\, \mathrm{kpc}$$

Field Correlation Length

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

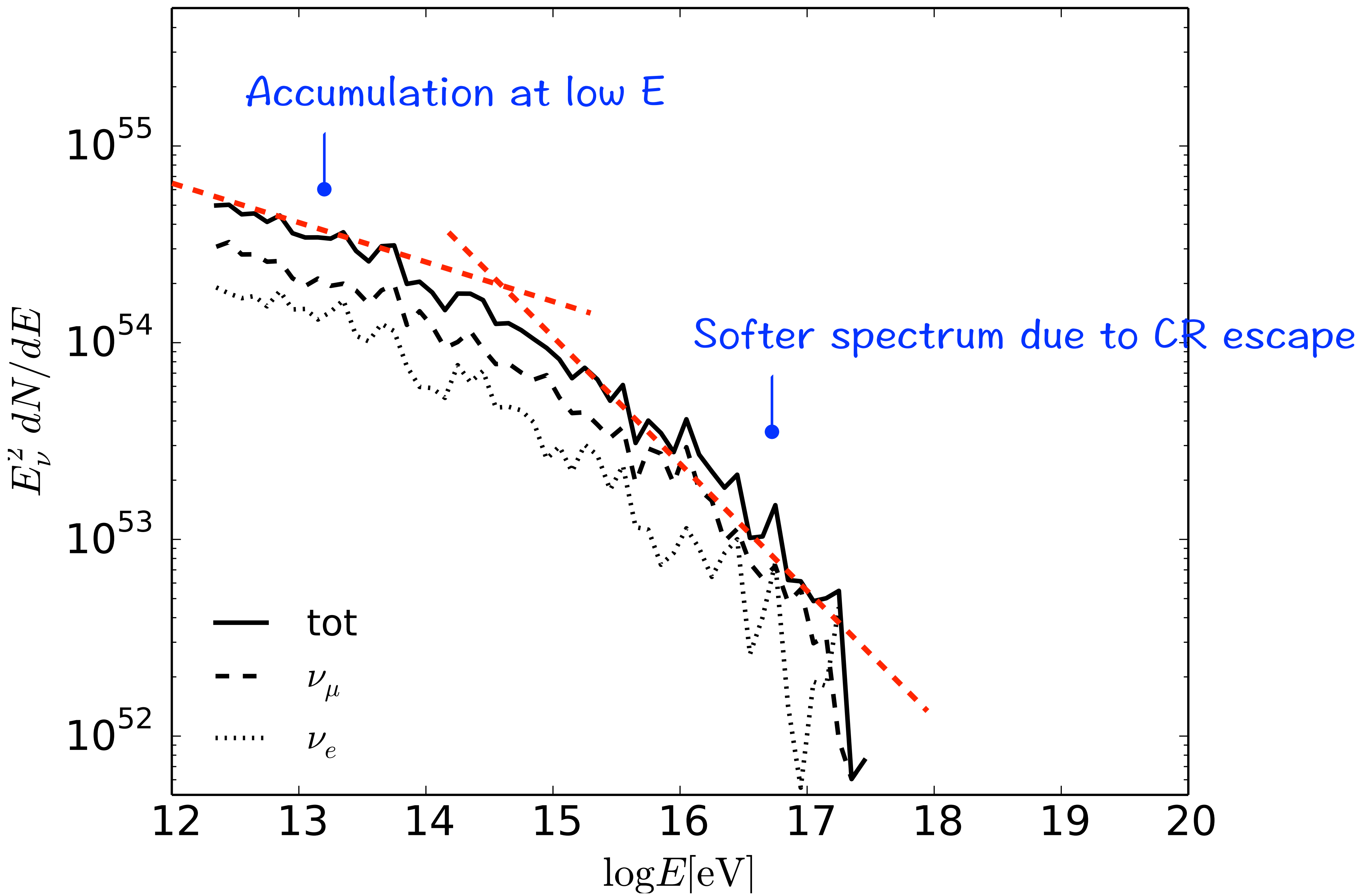
$$B_c = 10\, \mu G, M = 10^{15}\, M_\odot$$

$$D_{\rm total} \sim t_{\rm cluster}$$

KF & Murase *Nature Physics* (2018)

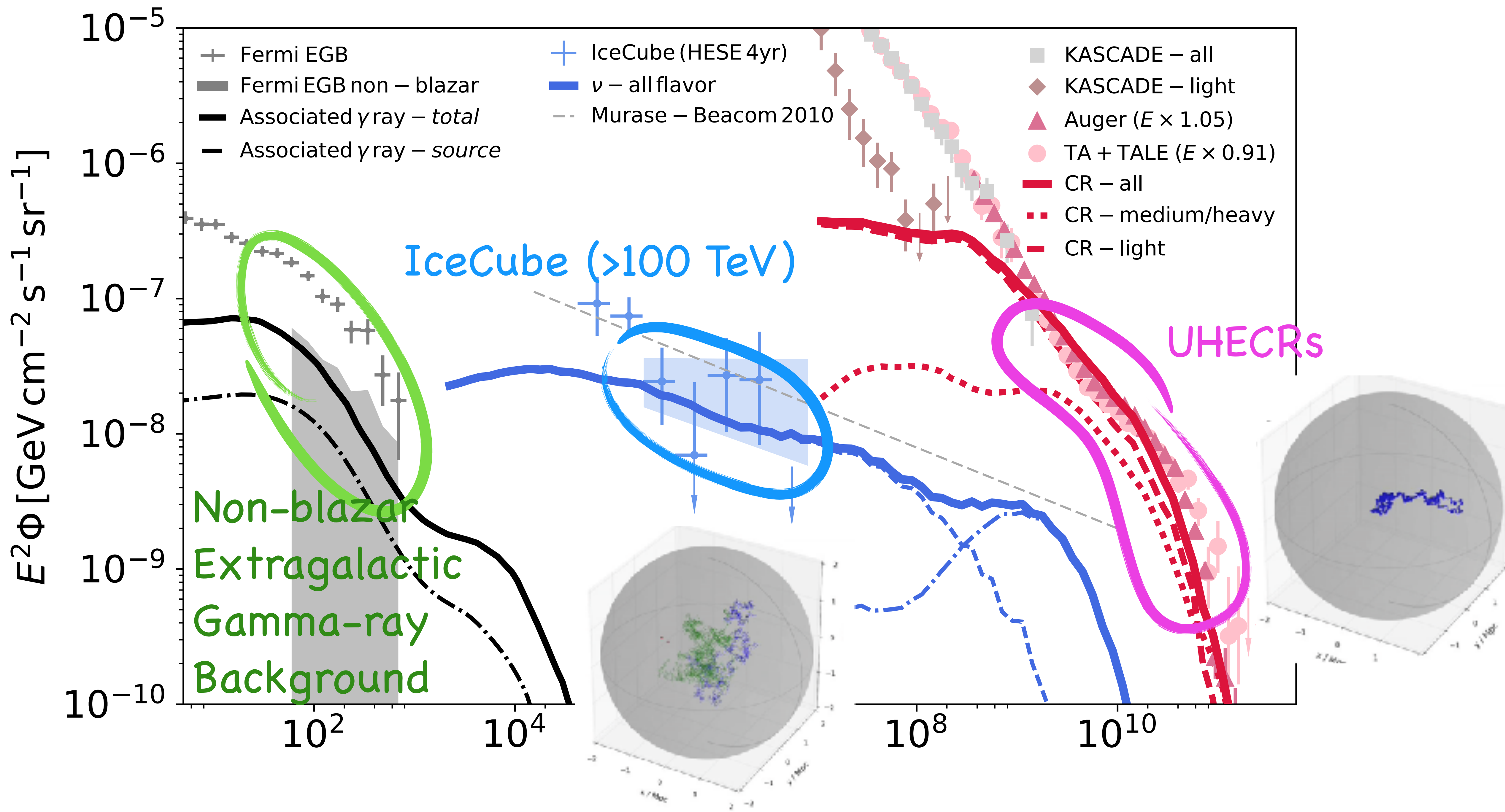
Neutrino Spectrum from One Cluster

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



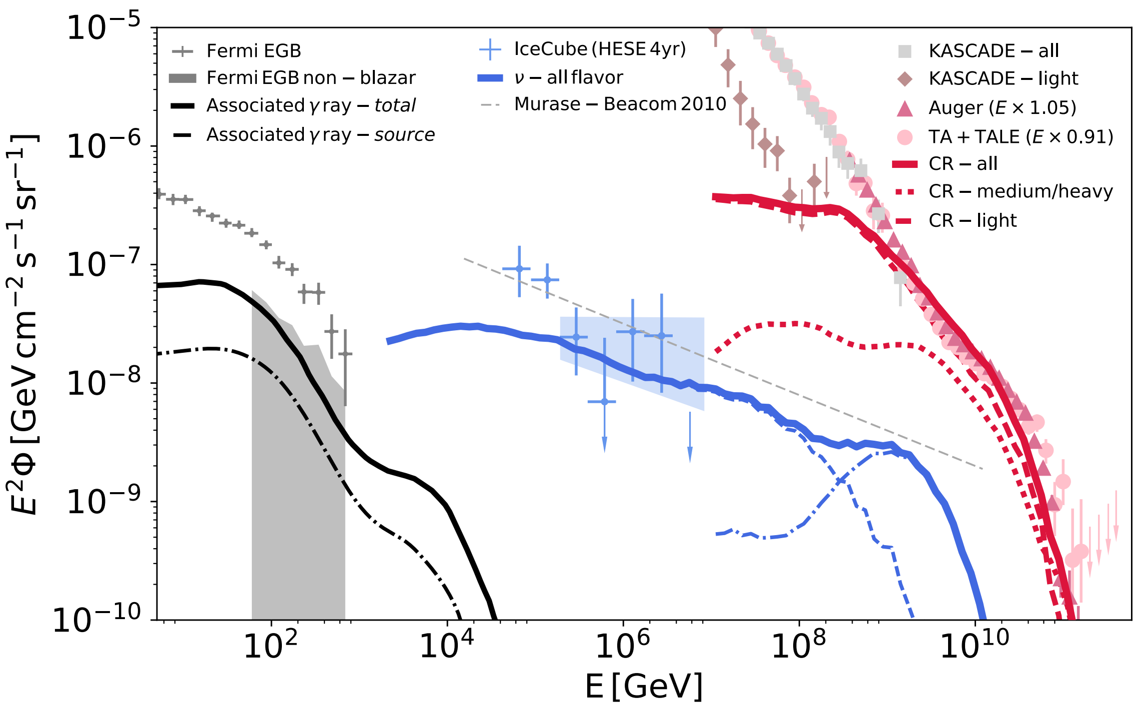
Cosmic Particles from Black Hole Jets in Galaxy Clusters

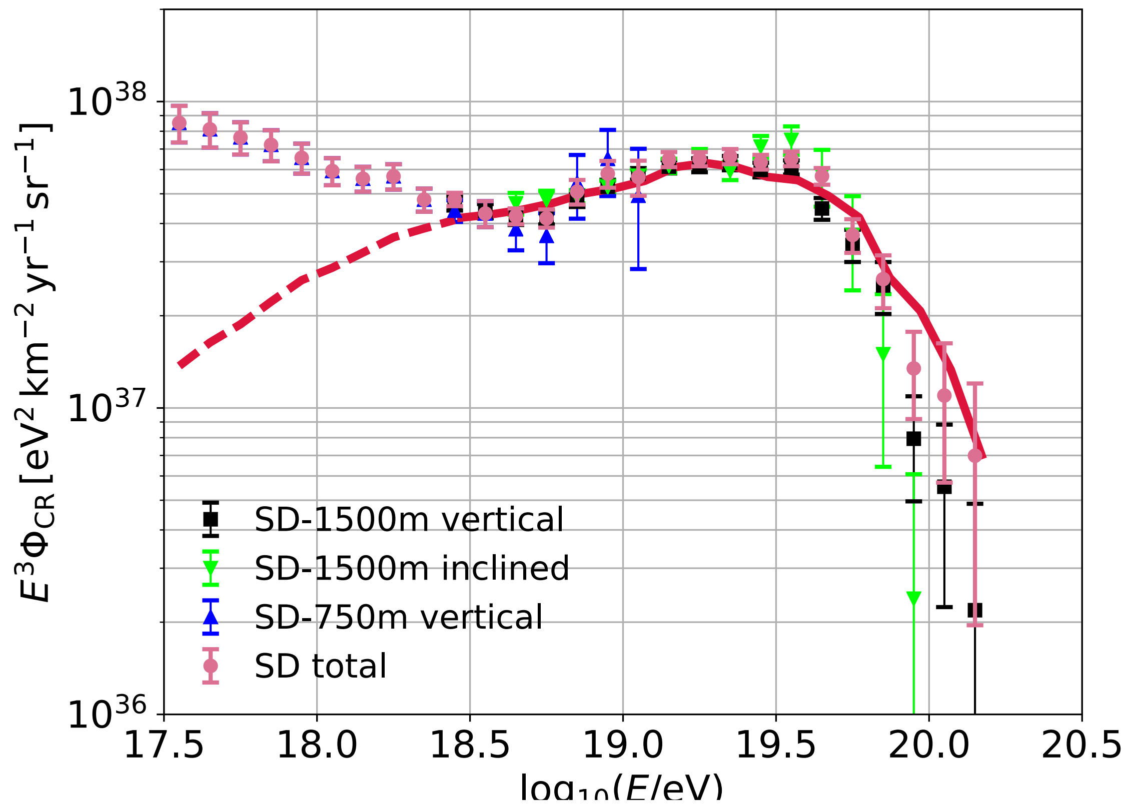
KF & Murase *Nature Physics* (2018)

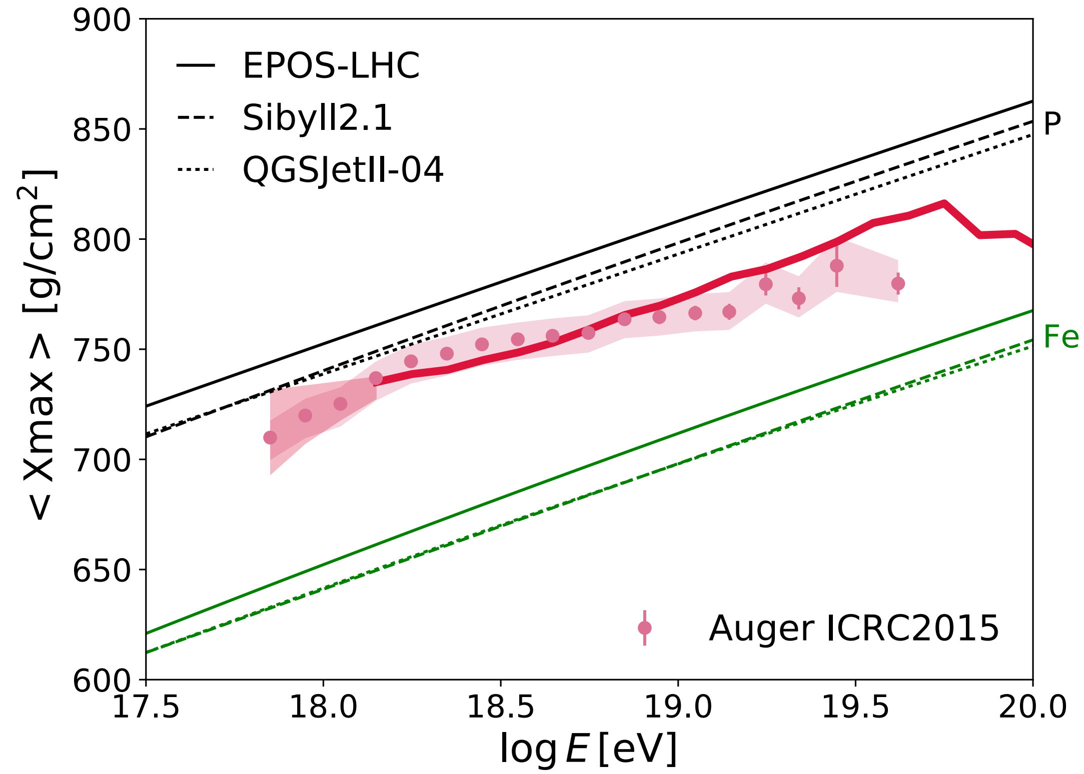


Injection Composition = Galactic CR abundance

Fits to UHECR data

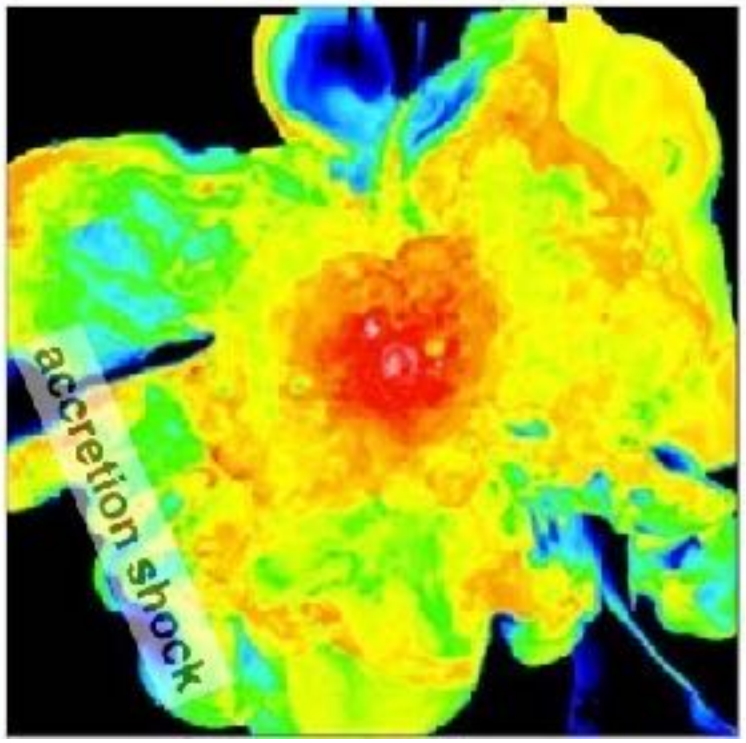


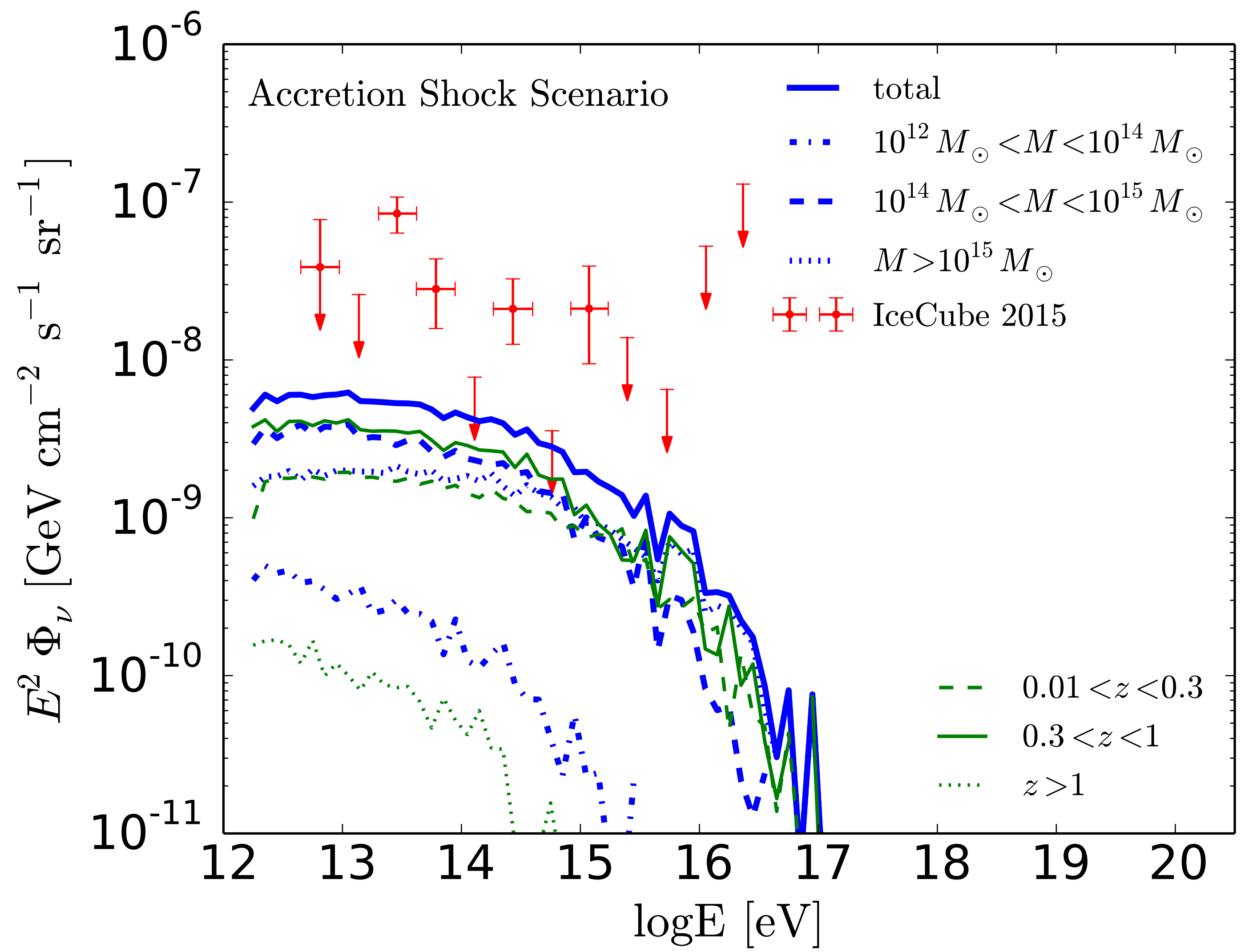




KF & Murase (2018)

Accretion Shocks around Galaxy Cluster





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 (2017)

Conclusion

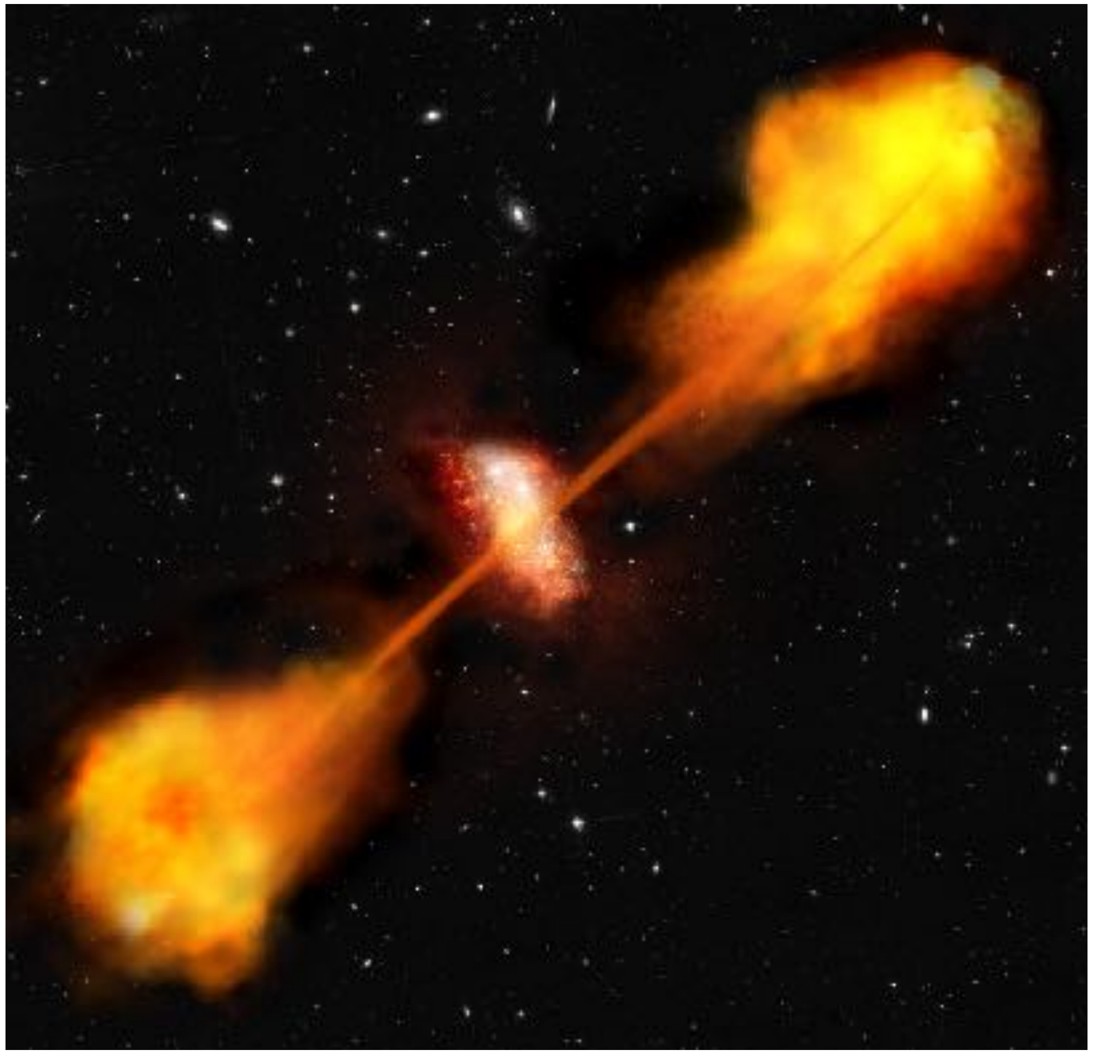
- Sources of high-energy neutrinos and ultrahigh energy cosmic rays are abundant and powerful
- Cosmic-ray acceleration and confinement commonly exist in astrophysical environments
- A “common origin” of cosmic particles may be explained by **black hole jets in galaxy clusters**

Conclusion

- **What's your targeted physics in next decade?**
  - ☆ Sources of high-energy neutrinos
  - ☆ High-energy messengers (gamma rays and neutrinos) from transients such as TDEs, binary mergers

- **What we need to accomplish?**
  - ☆ Design and planning of next-generation astroparticle experiments
  - ☆ Data analysis infrastructures that enable collaboration of different experiments

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

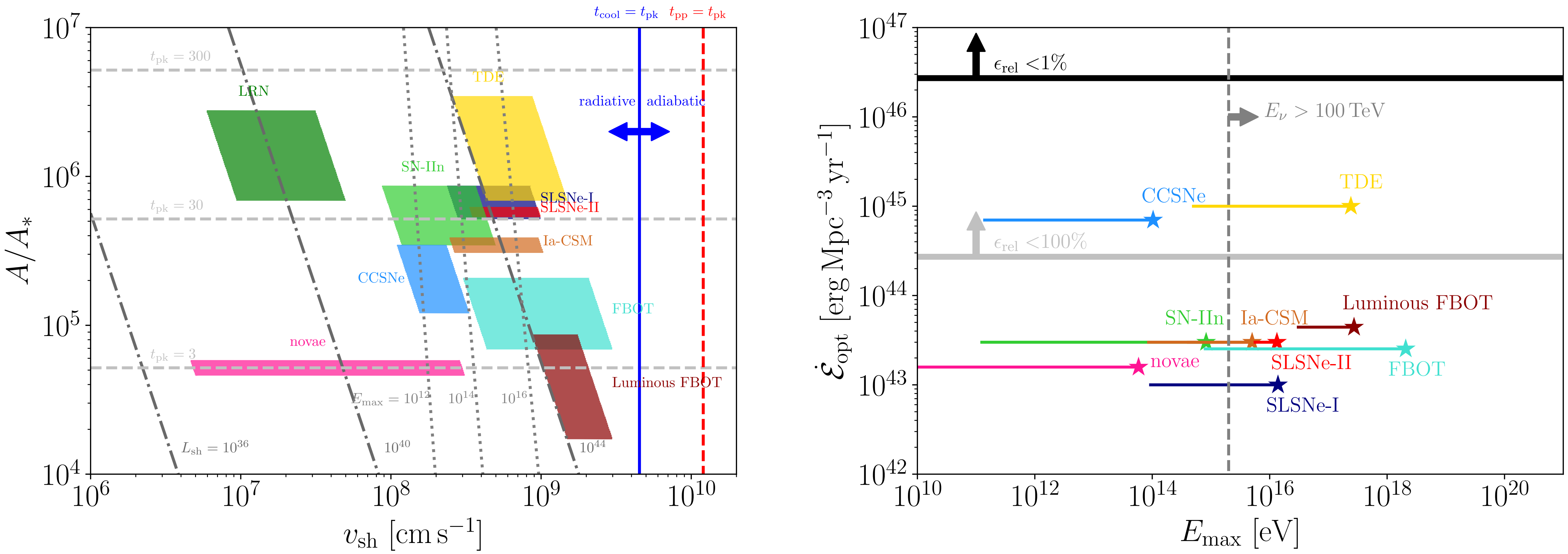
$$t_{\rm diff}^{\rm lobe} \sim 6.1 \left(\frac{E/Z}{1\,\mathrm{PeV}}\right)^{-1/3} \mathrm{Myr}\,*$$

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

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.

Neutrino Sources are Powerful and Abundant!



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