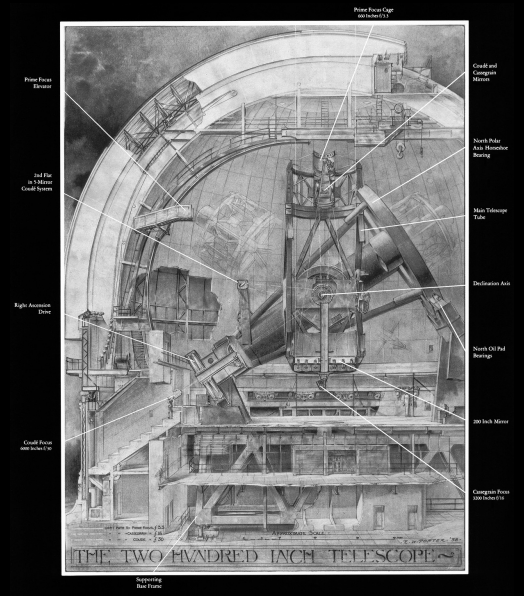
Big Questions in Particle Physics: Particle Astrophysics (Theory)

John Beacom, The Ohio State University
(Twitter: ProfJohnBeacom)



The Ohio State University's Center for Cosmology and AstroParticle Physics

CCAPP

NSF

What Are the Goals of Particle Physics?

Probe fundamental particles and forces

Explain emergent phenomena

Search for new physics

Three Ways of Making Progress

Laboratory

(Highest precision)

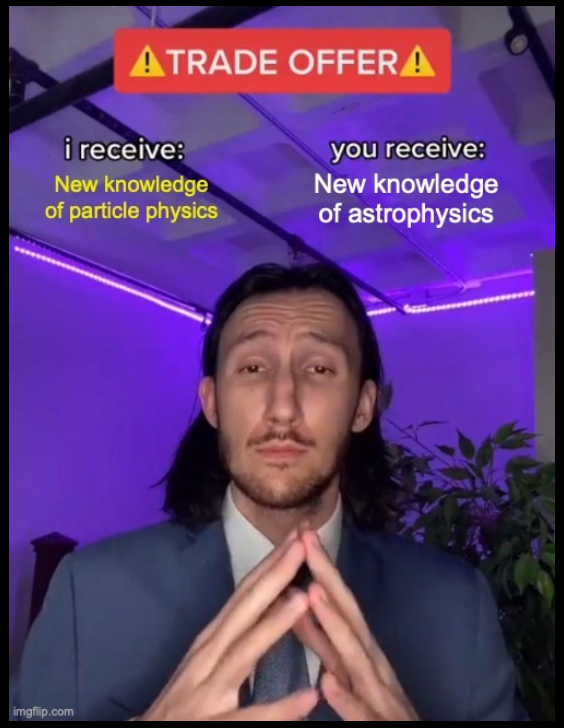
Cosmology

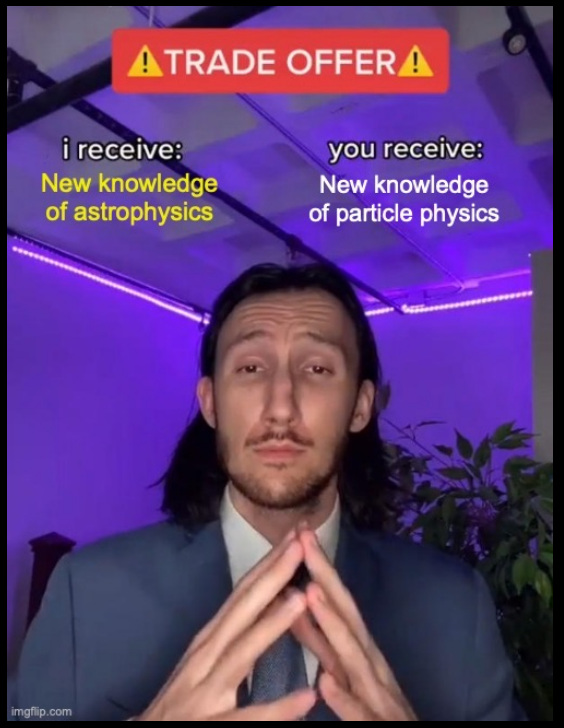
(Growing precision)

Astronomy

(Emerging precision)

What is Particle Astrophysics?





And must do both trades together

Choose Your MMA Fighter

Messenger	Best Probe of …	Weakness
photons (sub-MeV)	thermal sources	attenuates easily
cosmic rays	accelerators	deflects
gamma rays	nonthermal sources	attenuates
neutrinos	hidden sources	detection is hard
gravitational waves	dense dynamics	localization
dark matter	halo	not detected yet

Choose Your Arena

Stellar Scales:
stars
planets
supernovae
NS and BH
PBHs
…

Galaxy Scales:
SMBHs
jets
winds
bubbles
halos
subhalos
streams
…

Cosmic Scales:
large-scale structure
reionization
21-cm emission
CMB
BBN
DM freezeout
inflation
…

Talk Outline

Choosing to focus on high-energy multi-messenger astronomy

Introductory Remarks

- Extreme-Coverage Frontier
- Extreme-Luminosity Frontier
- Extreme-Energy Frontier

Concluding Remarks

Extreme-Coverage Frontier

Solar, HE range (MeV–GeV)

Solar: Motivations

How do cosmic rays interact in the Sun's magnetic environment?

(Nobody really knows)

How does this produce gamma rays and neutrinos?

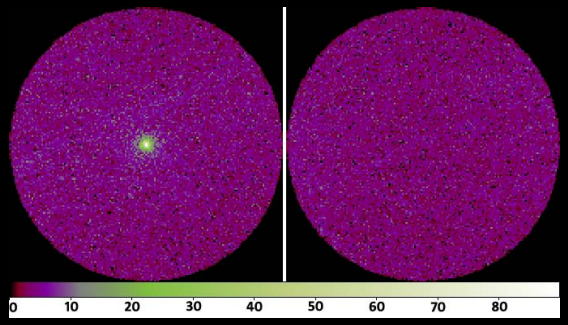
(Nobody really knows)

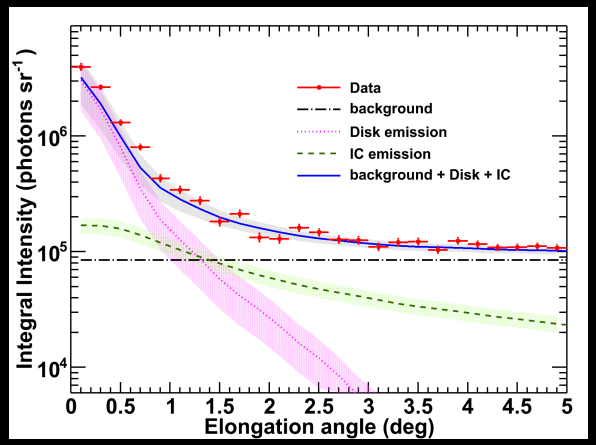
What other processes can do this?

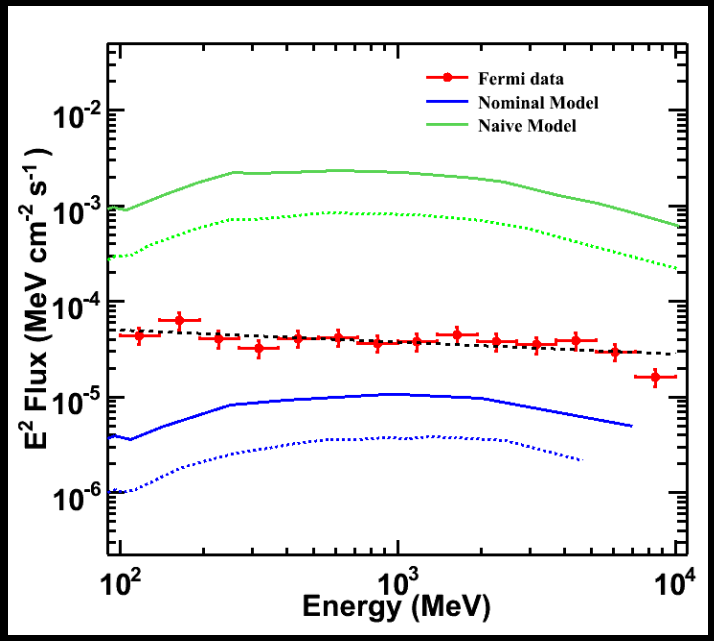
(Nobody really knows)

Solar: Orientation

Fermi–LAT OBSERVATIONS OF TWO GAMMA-RAY EMISSION COMPONENTS FROM THE QUIESCENT SUN (2011)

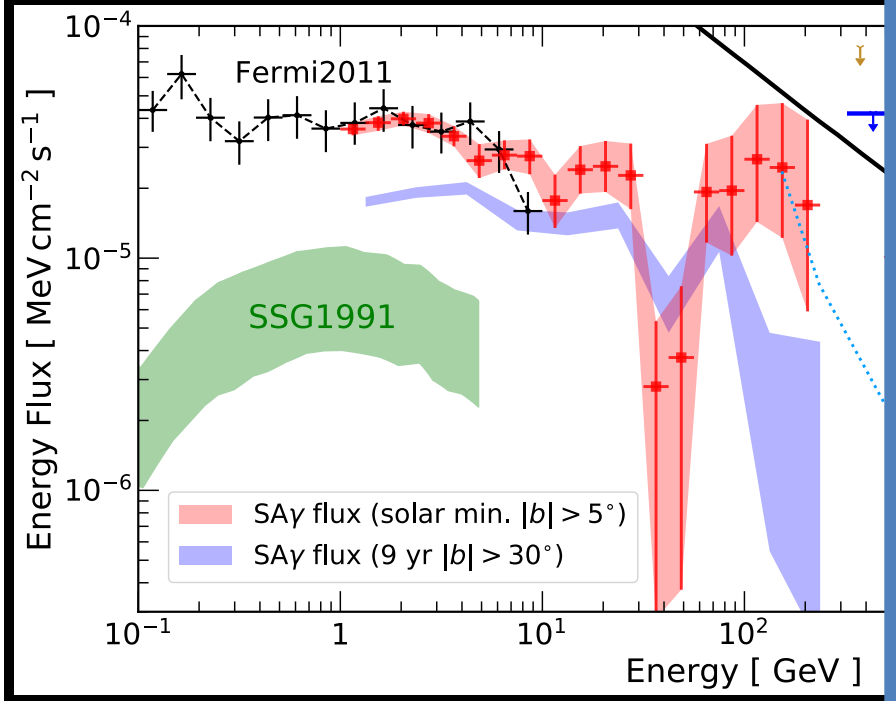


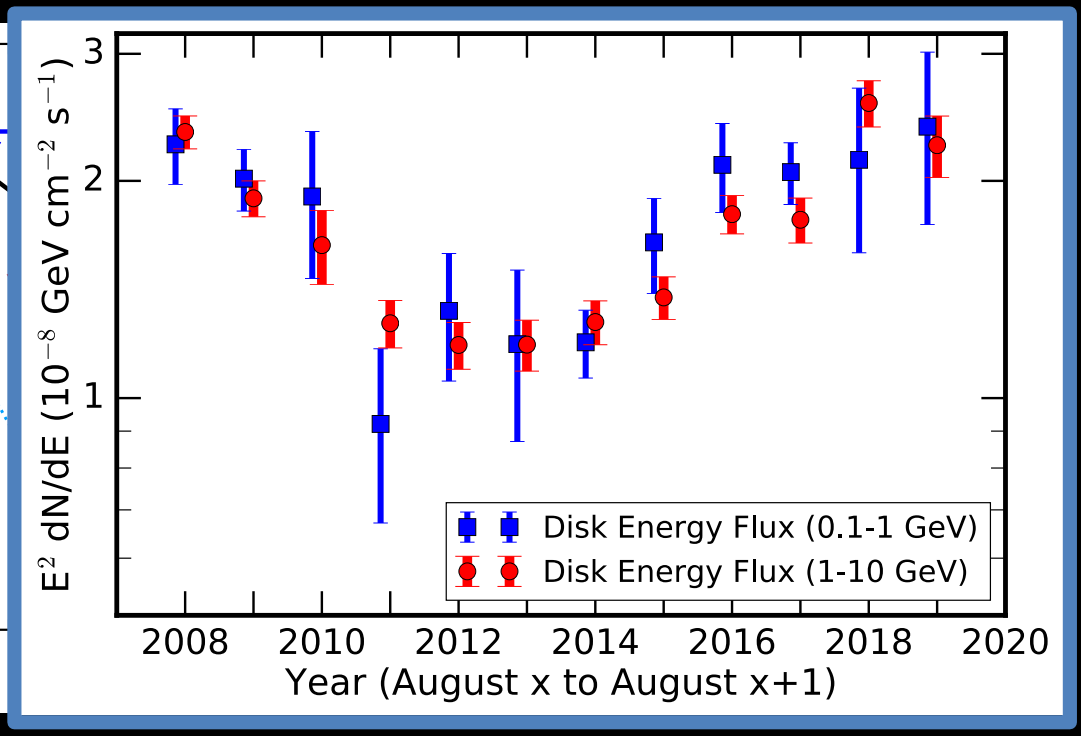




Predictions from Seckel, Stanev, Gaisser (1991)

Solar: Accomplishments



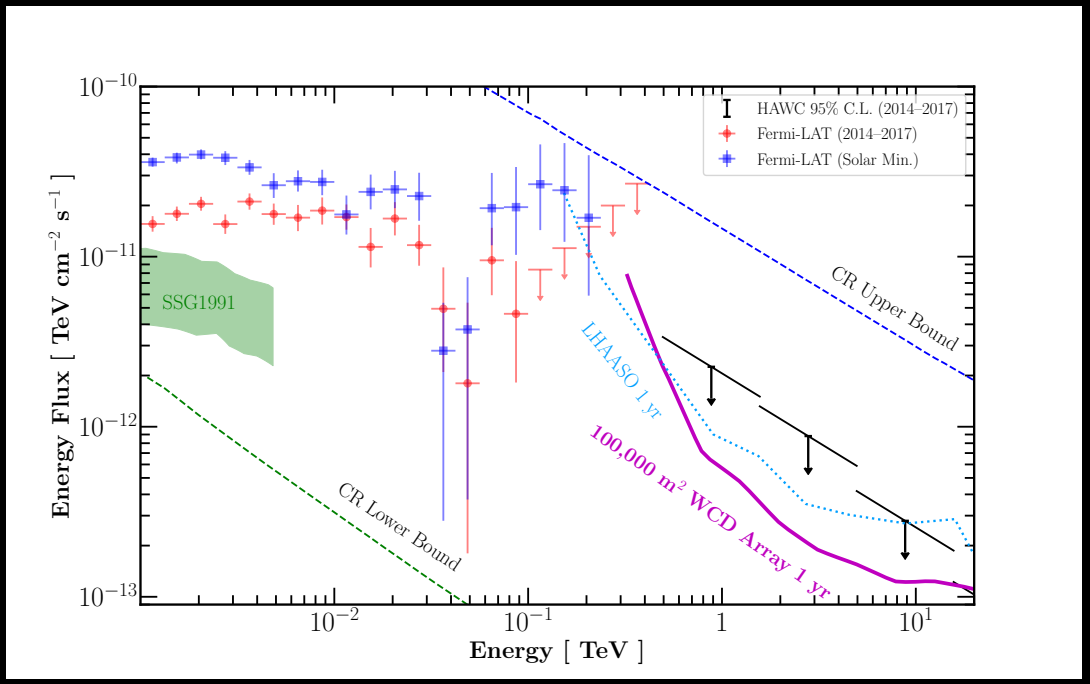


The solar disk gamma-ray emission is extremely weird!

(Ohio State group: Beacom, Linden, Ng, Peter, Tang, Zhou, Zhu, and friends)

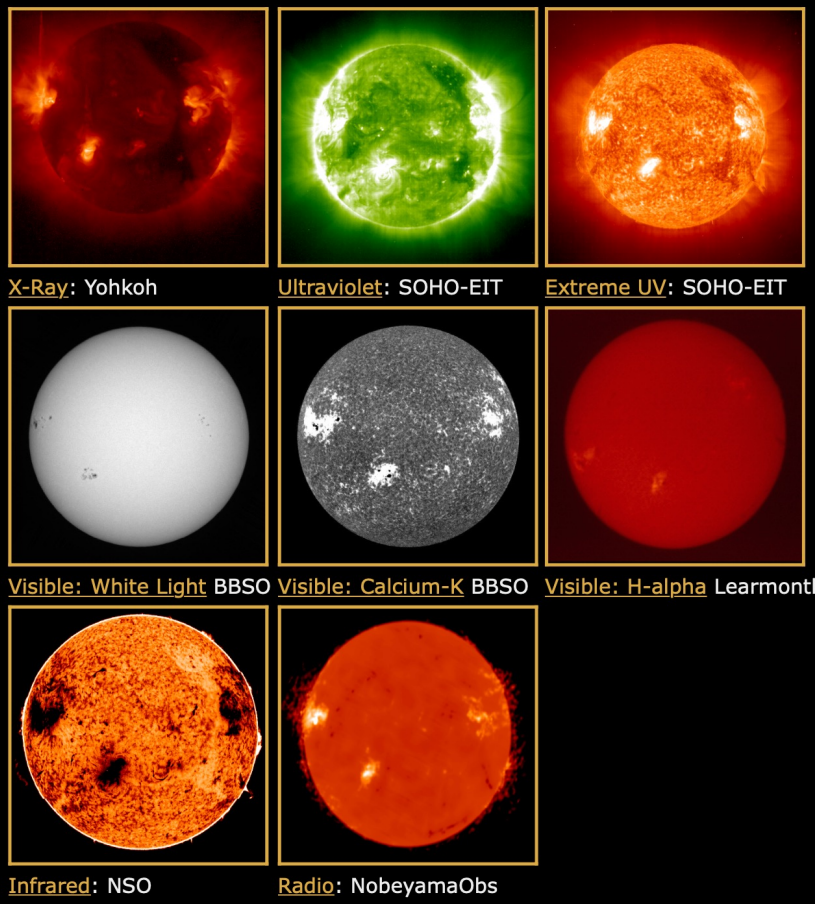
Solar: Hope

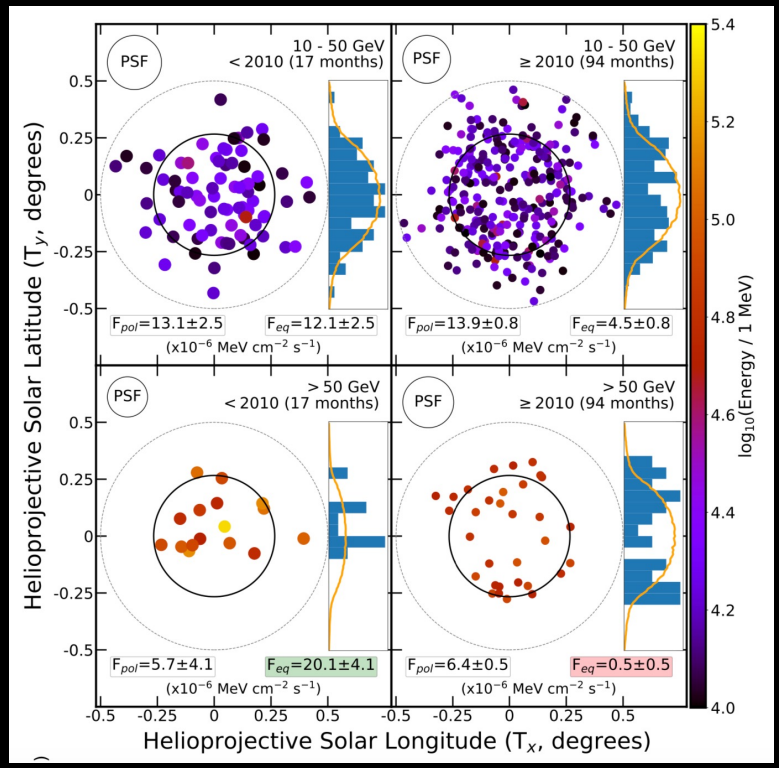
HAWC



Nisa et al. (2019)

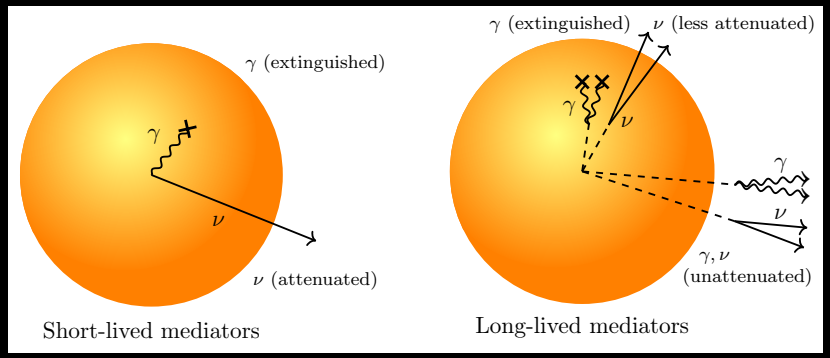
Solar: MMA

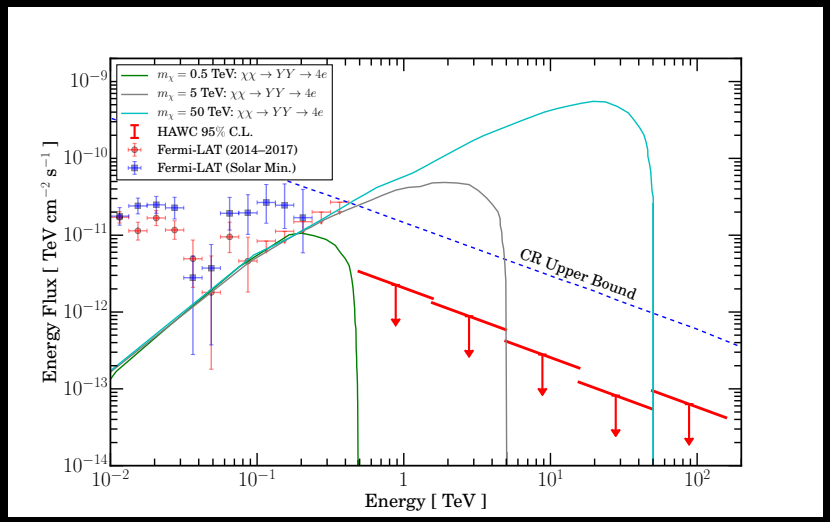


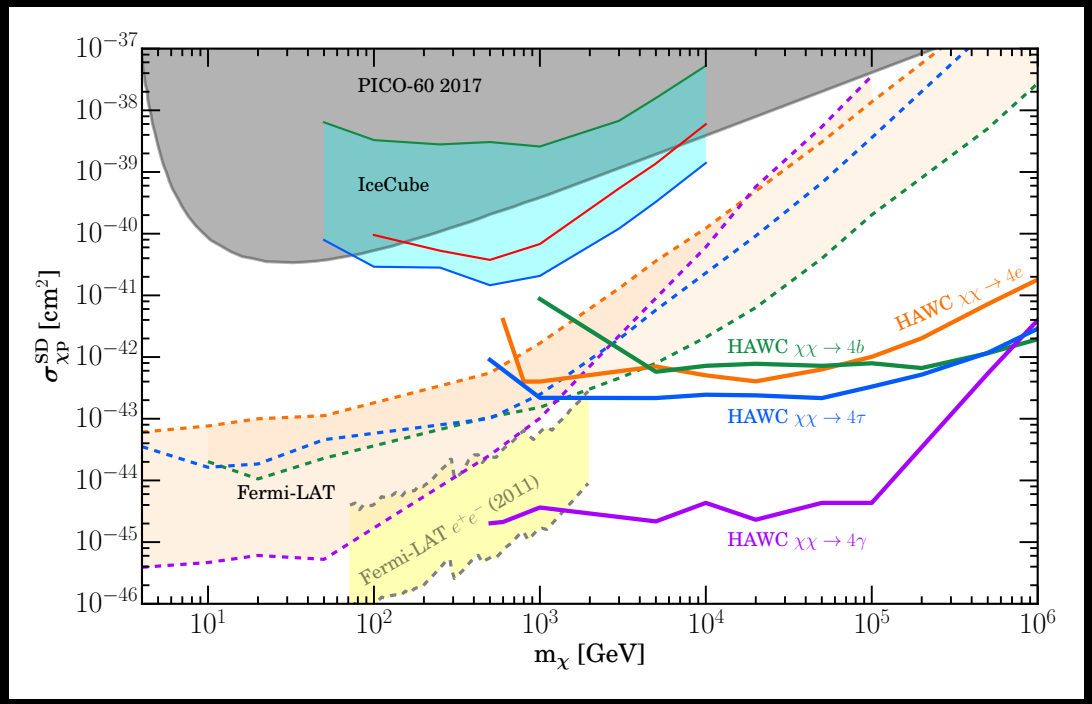


Linden et al. (2018) and related works for high-energy implications

Solar: BSM







HAWC, Beacom, Leane, Linden, Ng, Peter, Zhou (2018)

Extreme-Luminosity Frontier

VHE range (TeV–PeV)

VHE Fluxes: Motivations

Nature's most luminous accelerators?

(Yes, powering the cosmic rays that shape galaxies)

Evidence of dark matter annihilation or decay?

(Not yet, but we have not finished looking)

Probe new physics in neutrino sector?

(Yes, especially if we know the astrophysics better)

VHE Fluxes: Orientation (Co-Production)

Hadronic mechanism:

$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$
$$\rightarrow p + n + \pi^+ \qquad \pi^+ \rightarrow e^+ + 3\nu$$

Leptonic mechanism:

$$e + \gamma \rightarrow e + \gamma$$

Production always makes a mess; propagation makes more

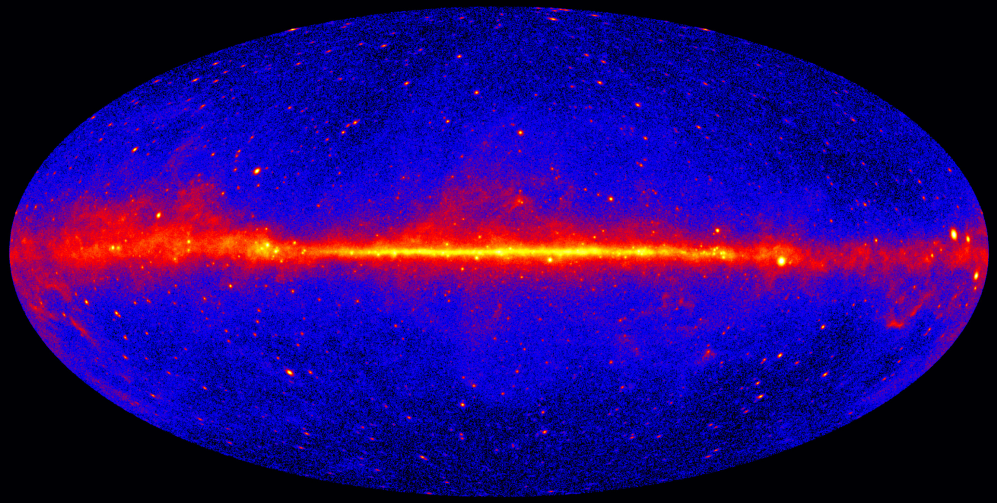
VHE Fluxes: Orientation (GeV–TeV Gamma Rays)

✓ Milky Way diffuse

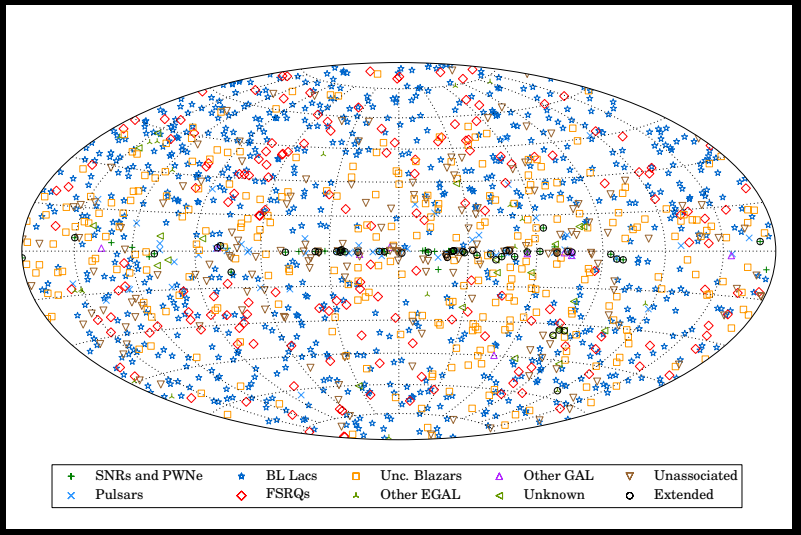
✓ Milky Way sources

✓ Extragalactic diffuse

✓ Extragalactic sources



Fermi



Fermi

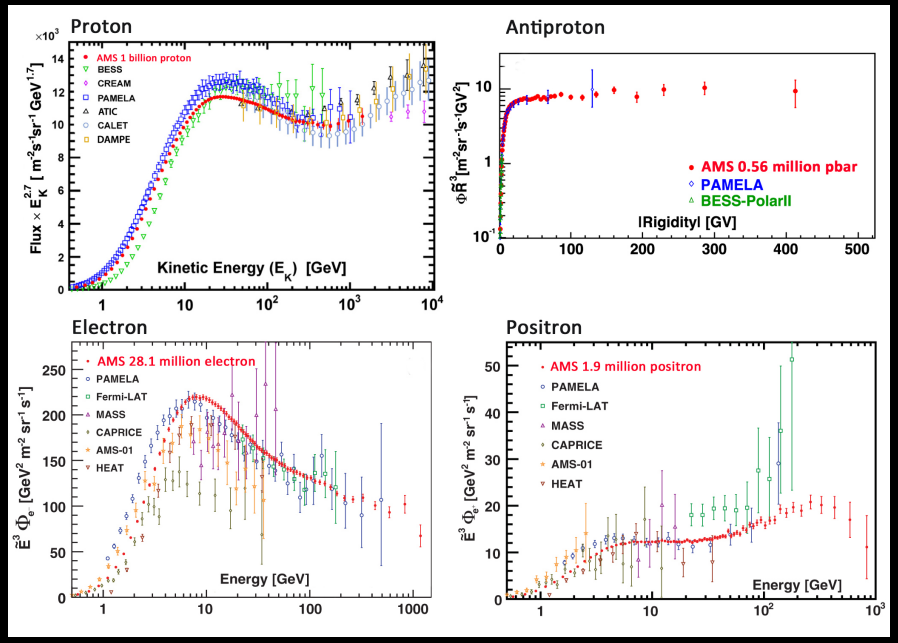
VHE Fluxes: Accomplishments (Cosmic Rays)

✓ Milky Way diffuse

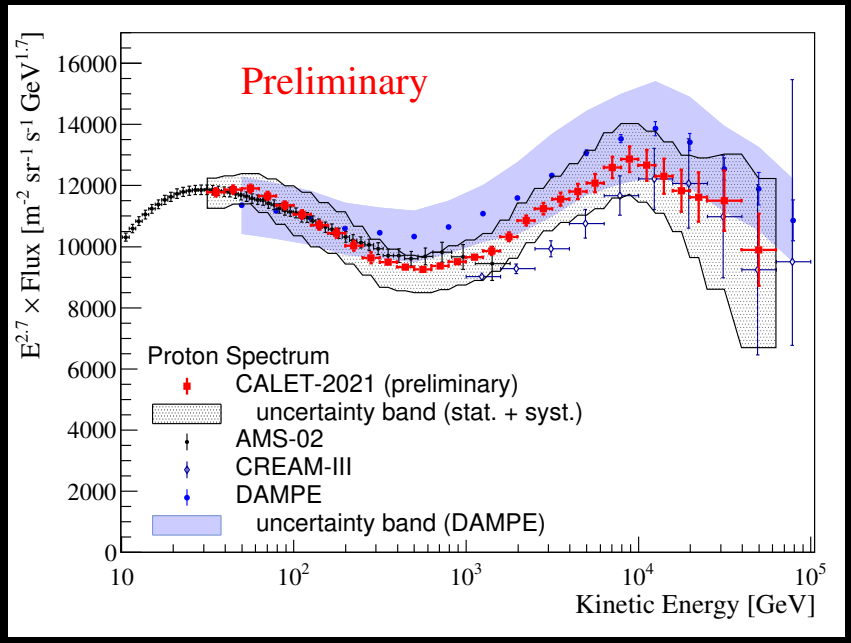
X Milky Way sources

X Extragalactic diffuse

X Extragalactic sources



AMS (2021)



CALET (2021)

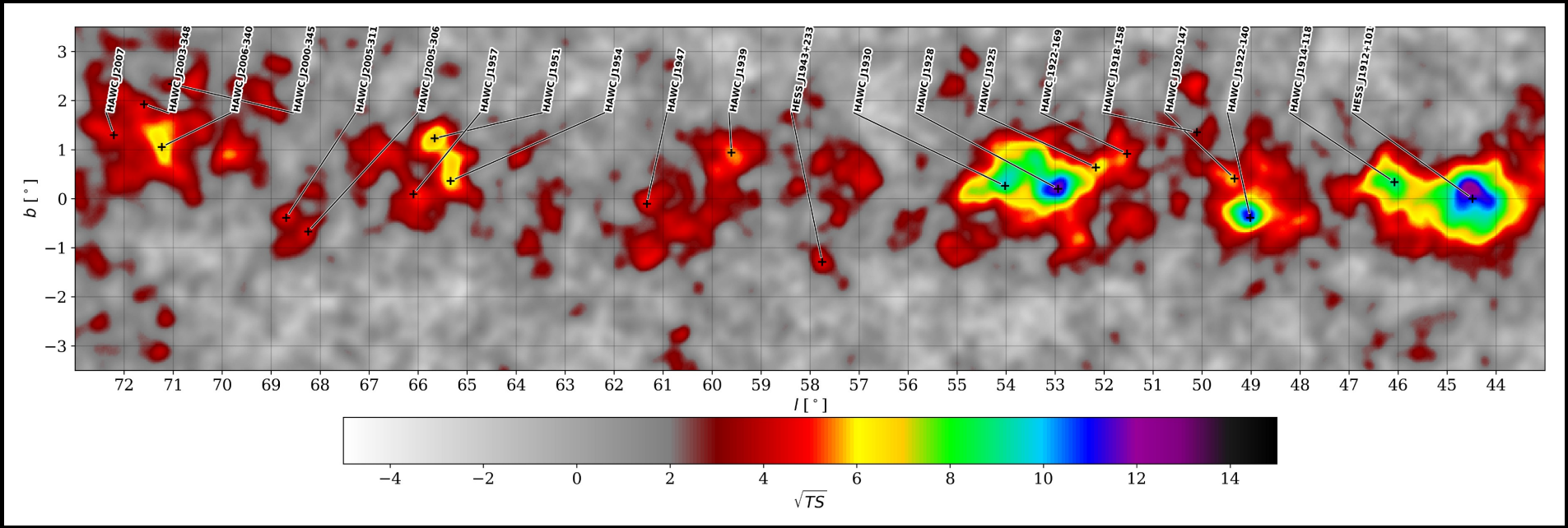
VHE Fluxes: Accomplishments (Gamma Rays)

✓ Milky Way diffuse

✓ Milky Way sources

X Extragalactic diffuse

✓ Extragalactic sources



HAWC (2021)

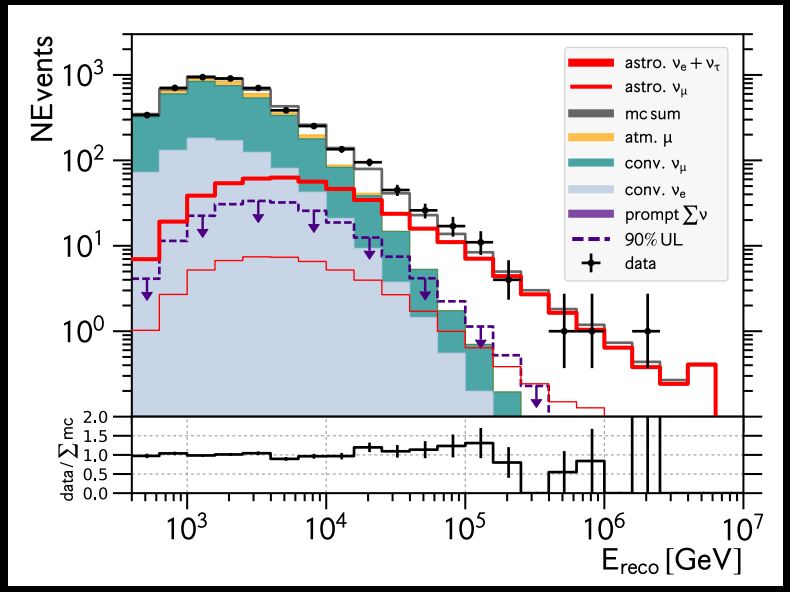
VHE Fluxes: Accomplishments (Neutrinos)

X Milky Way diffuse

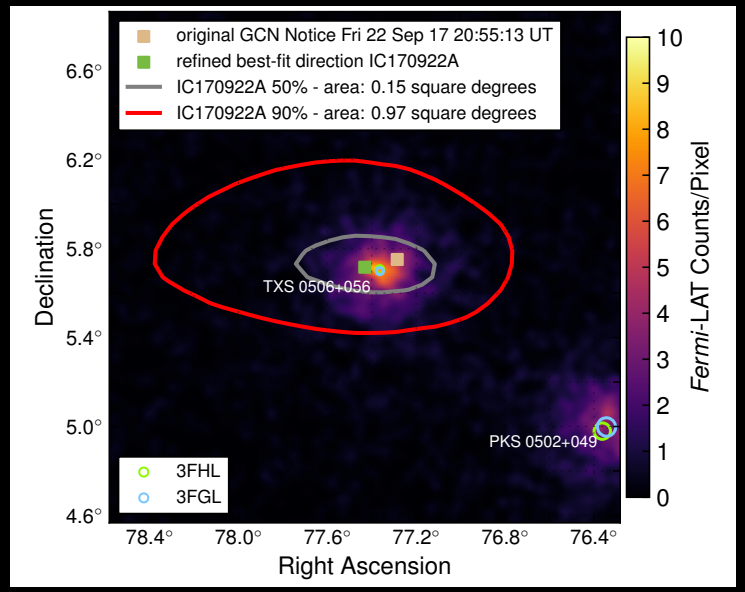
X Milky Way sources

✓ Extragalactic diffuse

~ Extragalactic sources



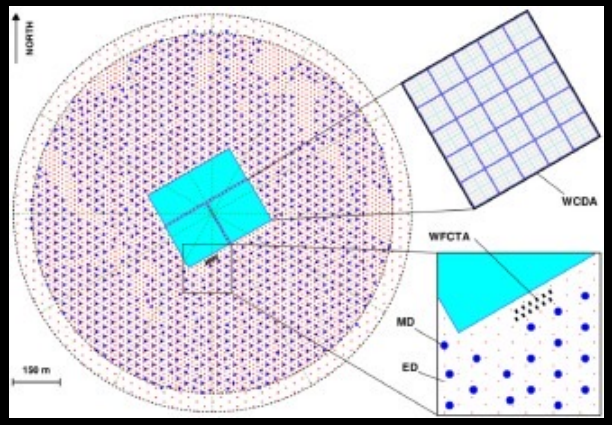
IceCube (2020)



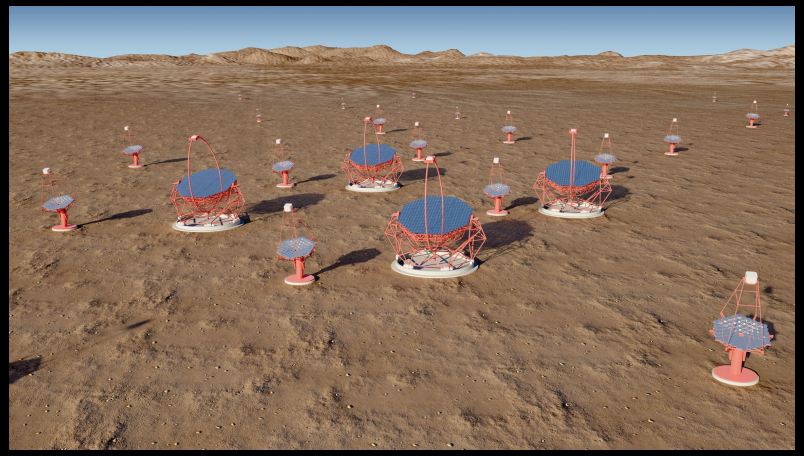
IceCube, Fermi, everyone (2017)

VHE Fluxes: Hope

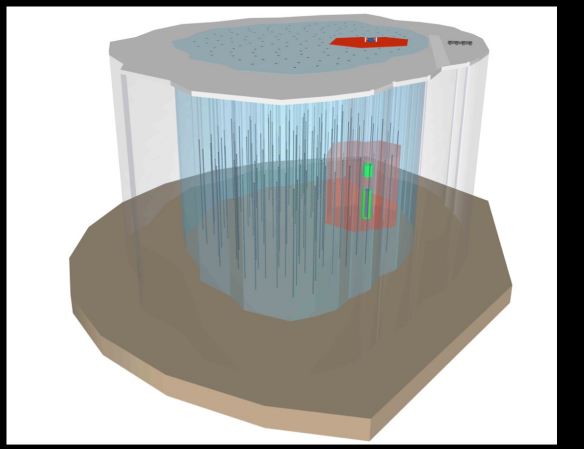
LHAASO
(cosmic rays, gamma rays)



Cherekov Telescope Array
precision gamma rays



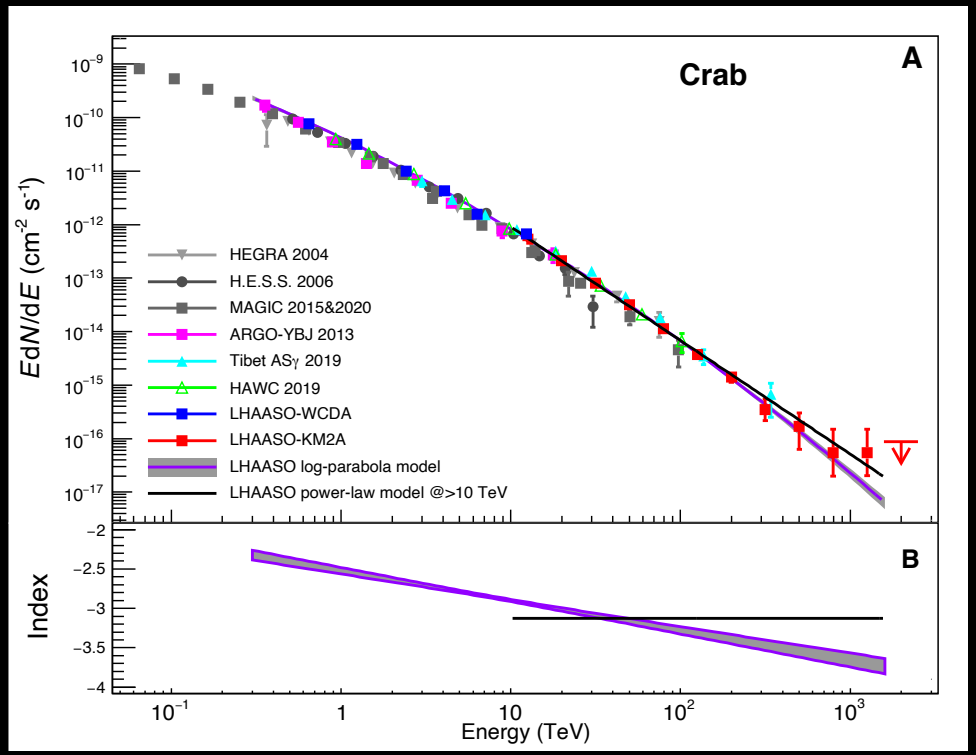
IceCube-Gen2
neutrinos



New neutrino detection channels:
B. Zhou and J.F. Beacom, three papers

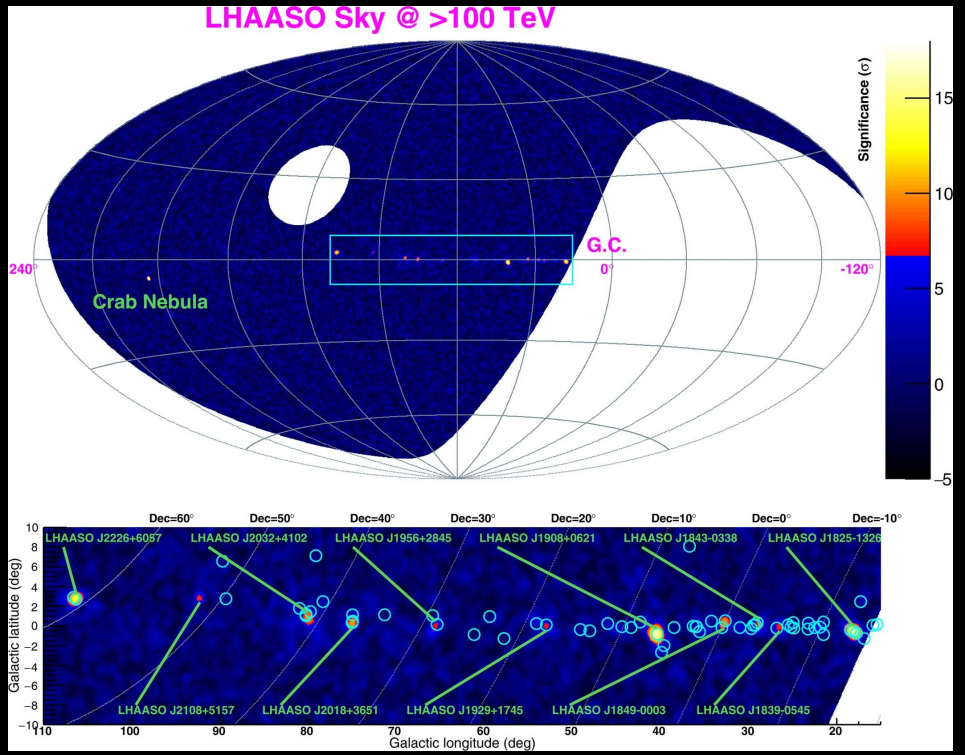
VHE Diffuse: MMA

Crab Nebula to 1 PeV!



LHAASO (2021)

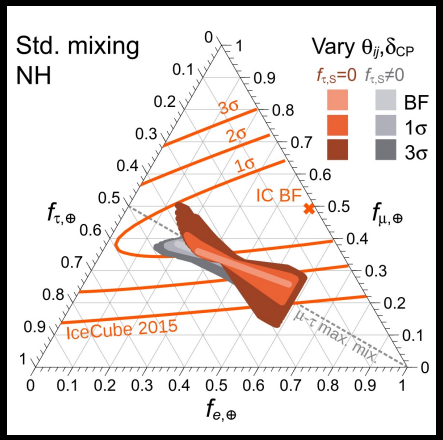
Many other sources!

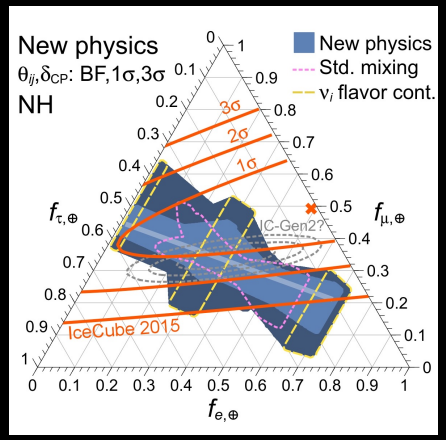


LHAASO (2021)

VHE Diffuse: BSM

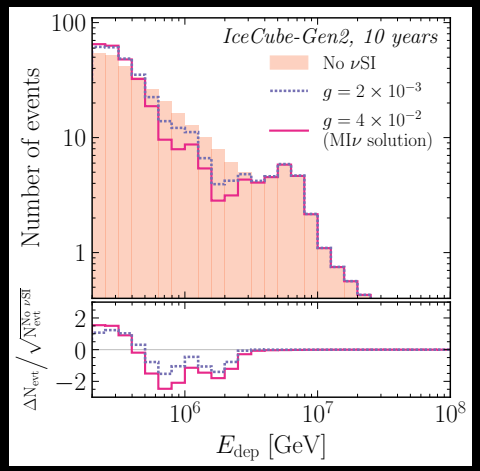
Neutrino Flavor Probes

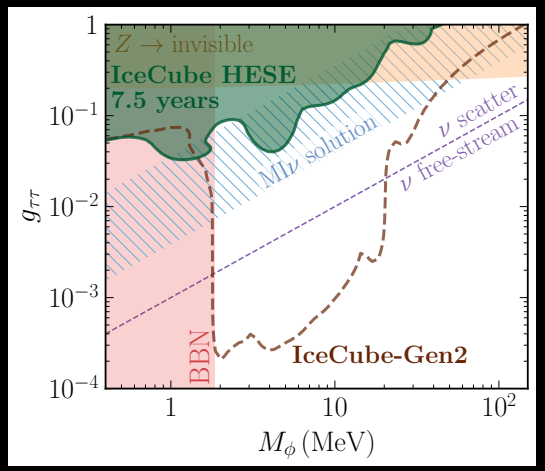




Bustamante, Beacom, Winter (2015)

Neutrino Secret Interactions





Esteban, Pandey, Brdar, Beacom (2021)

Extreme-Energy Frontier

UHE range (EeV–ZeV)

UHE (EeV–ZeV) Fluxes: Motivations

Nature's highest-energy accelerators?

(Yes, ~ 10^{20} eV and detectable across the universe)

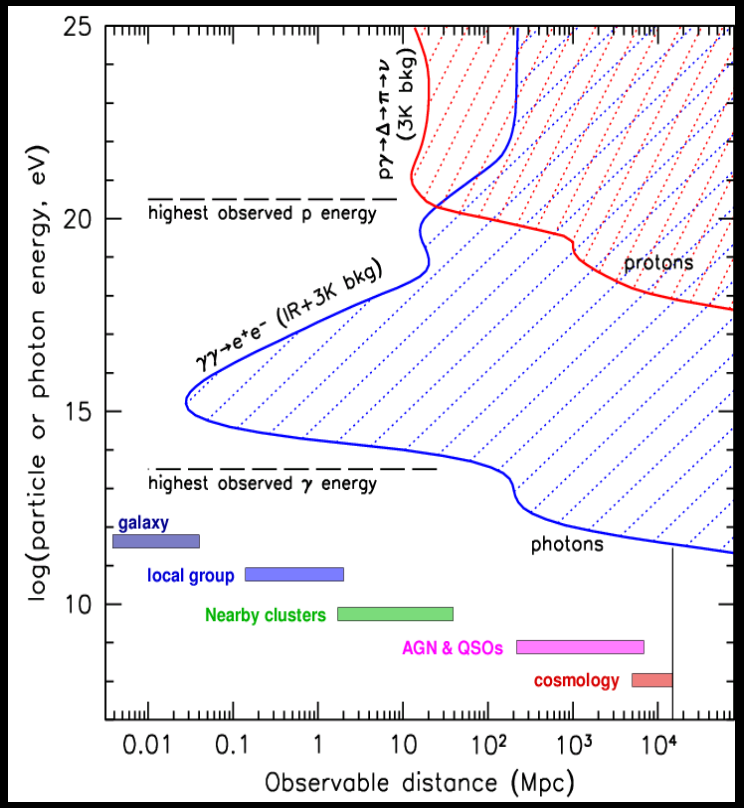
Evidence of super high mass scales?

(Not yet, but we have barely looked)

Probe new physics at extremes of energy and other variables?

(Yes, especially if we know the astrophysics better)

UHE Fluxes: Orientation (GZK Process)



Gorham (2005)

Greisen-Zatsepin-Kuzmin process

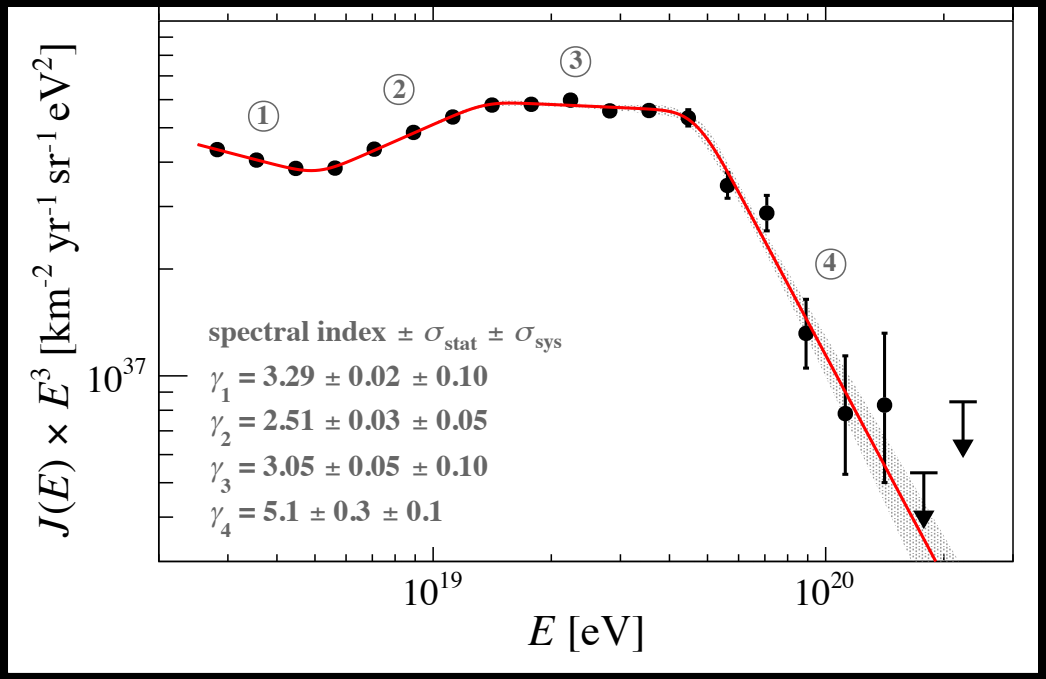
$$p + \gamma \to p + \pi^0$$
$$\to n + \pi^+$$

$$\pi^0 \to 2\gamma$$
$$\pi^+ \to e^+ + 3\nu$$

Highest-energy CRs all die

Neutrinos are their ghosts

UHE Fluxes: Accomplishments



Auger (2020)

CR Spectrum:
precise but mysterious

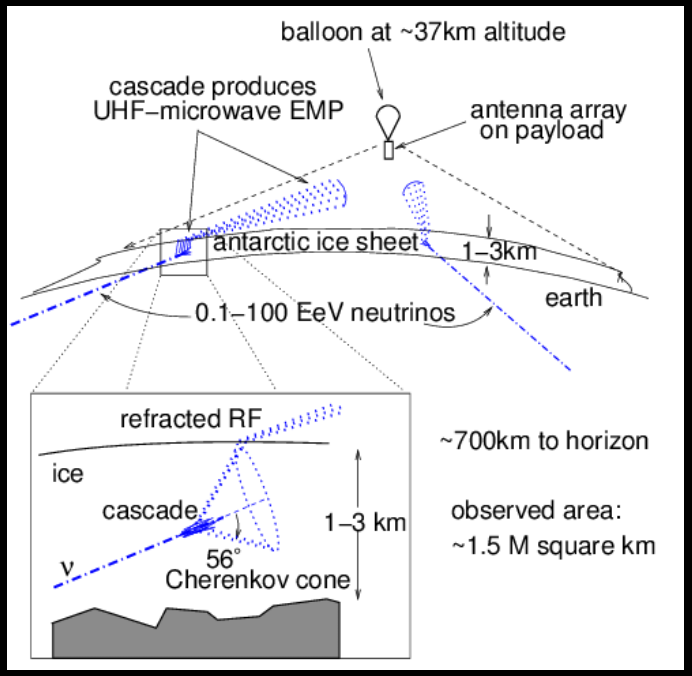
CR composition:
precise but limited by theory

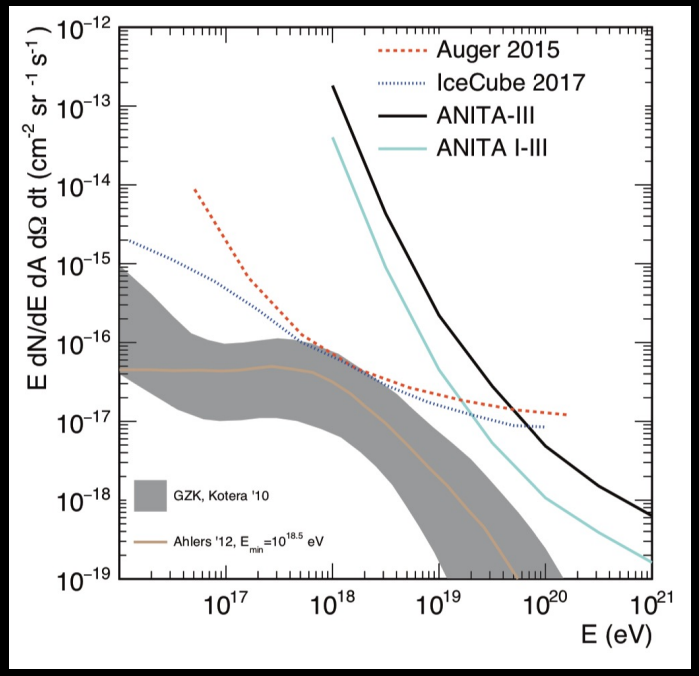
CR associations and anisotropies:
claimed but unconvincing

Gamma and neutrino fluxes:
only upper limits

UHE (Neutrino) Fluxes: Unsolved

Neutrinos probe *full line of sight*, are *very sensitive to composition*

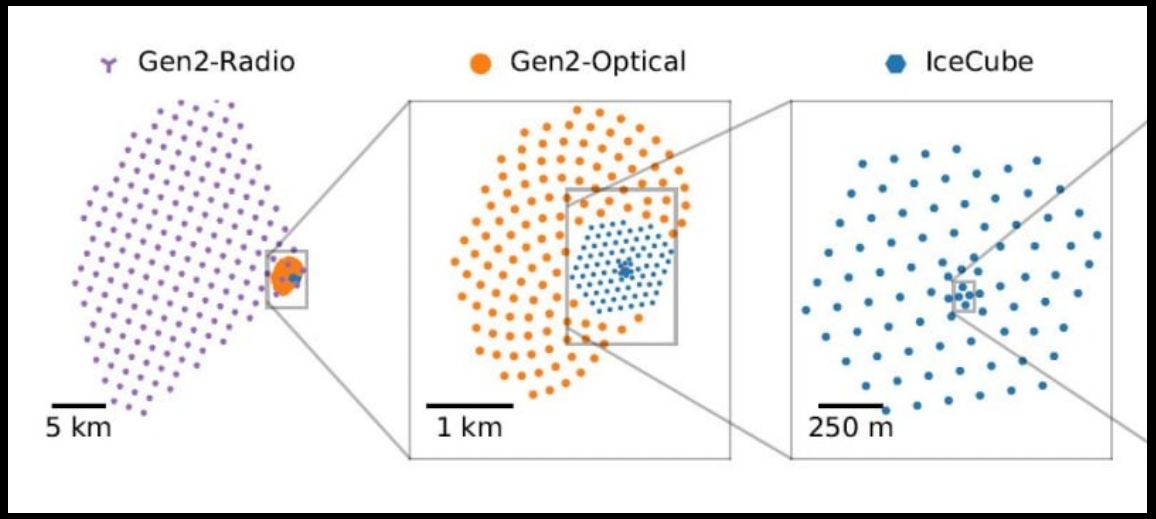




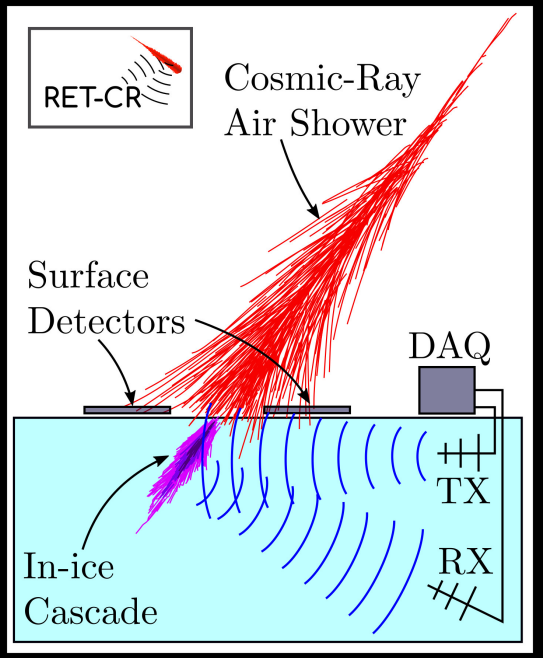
ANITA (2019)

UHE Fluxes: Hope

IceCube-Gen2 Radio

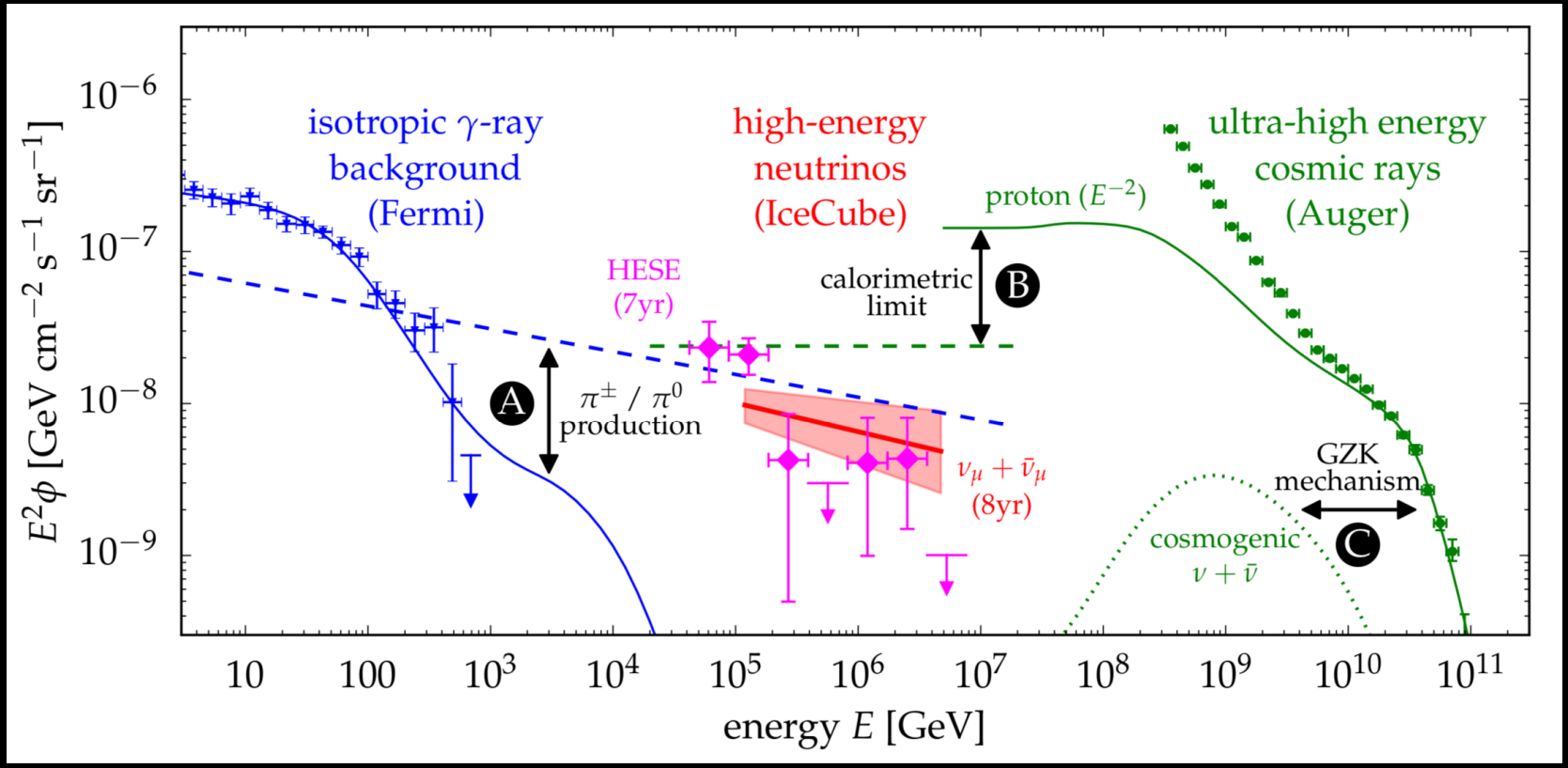


Radar Echo Telescope



And many other proposed experiments

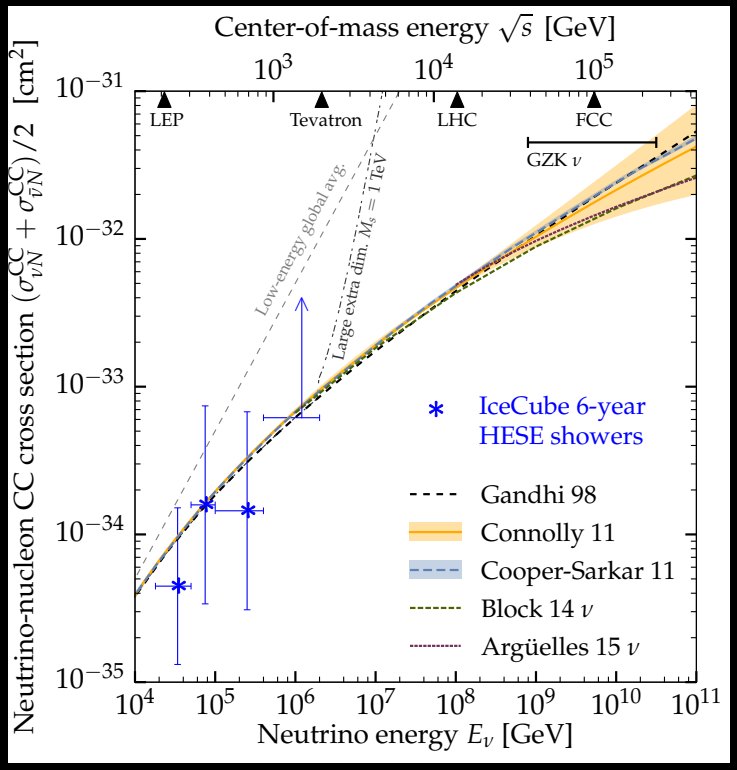
UHE Fluxes: MMA



Ahlers (2018)

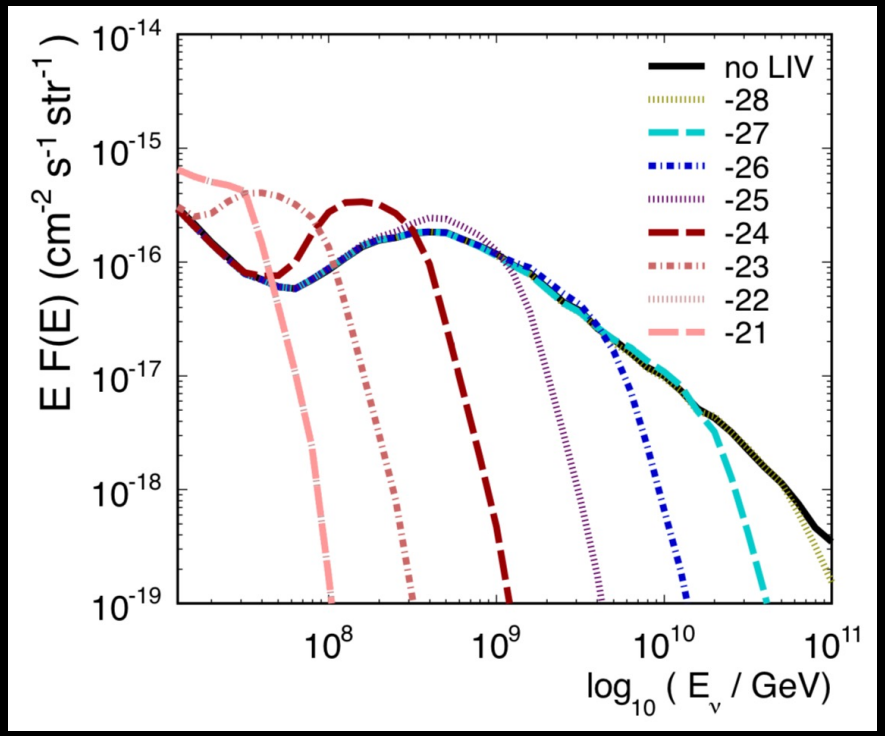
UHE Fluxes: BSM

Neutrino Cross Section



Bustamante and Connolly (2017)

Neutrino Lorentz Violation



Gorham et al. (2012)

Concluding Remarks

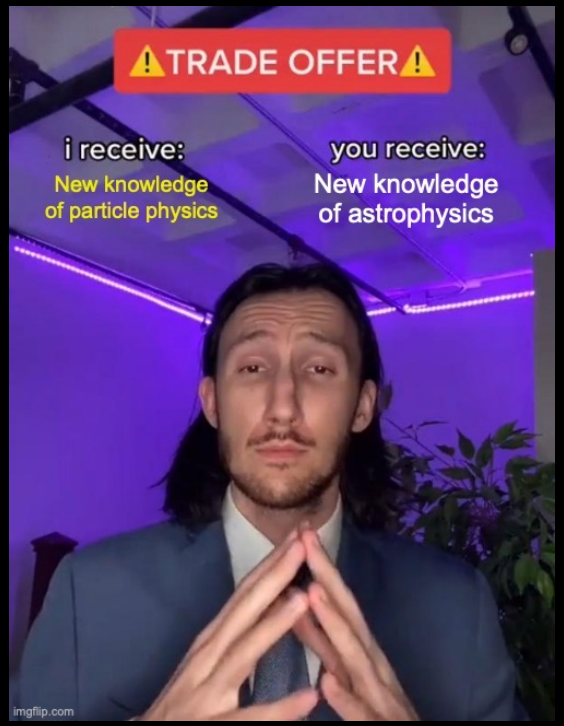
What Are the Goals of High-Energy Physics?

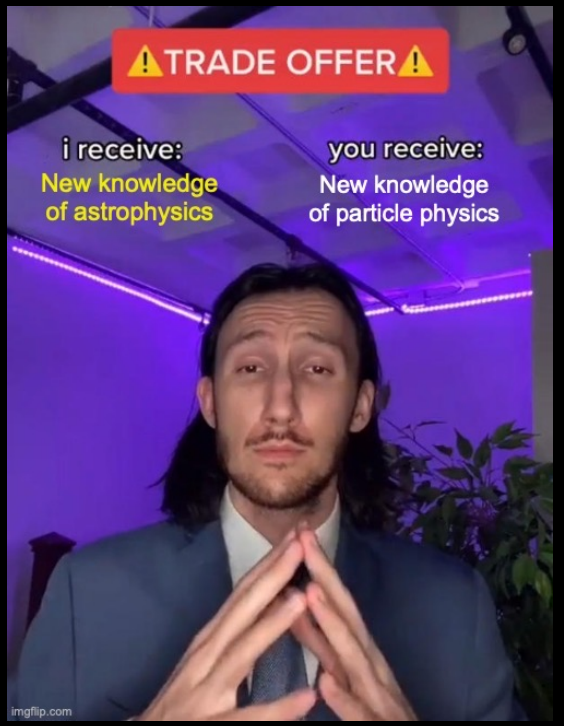
Probe fundamental particles and forces

Explain emergent phenomena

Search for new physics

So How Do We Do Particle Astrophysics?





Very carefully! But very profitably!

Key Messages

Multi-messenger observations are opening new vistas

A golden opportunity for astronomy

Astrophysics has physical conditions far beyond the lab

A golden opportunity for physics

Making the most of this requires working together

A golden opportunity for human understanding

Wait But How?

Please see report of the

Panel on Particle Astrophysics and Gravitation

John Beacom and Laura Cadonati, Co-Chairs

Wait But Who?

The success of the field of physics depends on:

- Broadening participation
  For example, AIP TEAM-UP, APS IDEA, etc.

- Good mentoring
  For example, YouTube: Mentoring Matters Beacom

- Sharing excitement with the public