

Multi-Messenger Astronomy: An Overview for Particle Physicists

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



What Are the Goals of High-Energy 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

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

Talk Outline

Introductory Remarks

Extreme-Coverage Frontier

Extreme-Luminosity Frontier

Extreme-Energy Frontier

Concluding Remarks

Extreme-Coverage Frontier

Solar, HE range (MeV–GeV)

Solar: Motivations

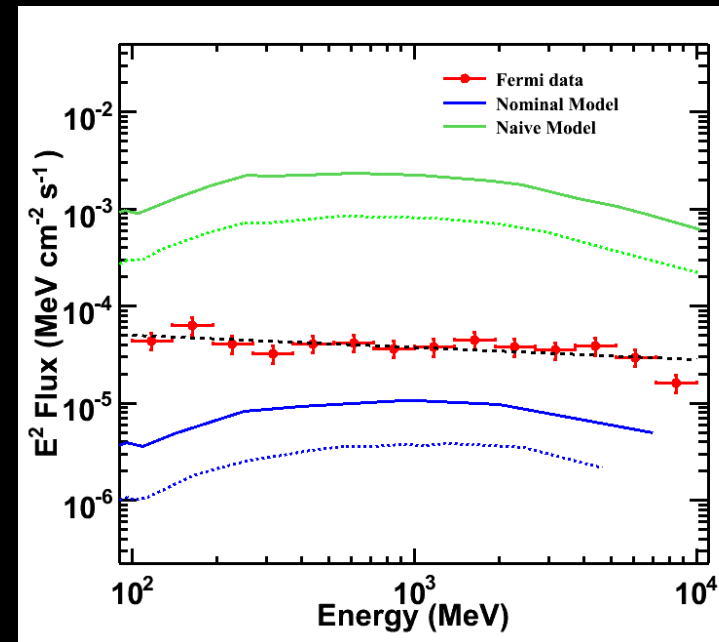
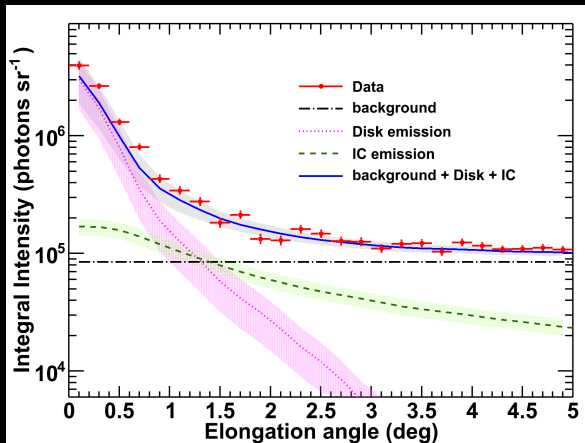
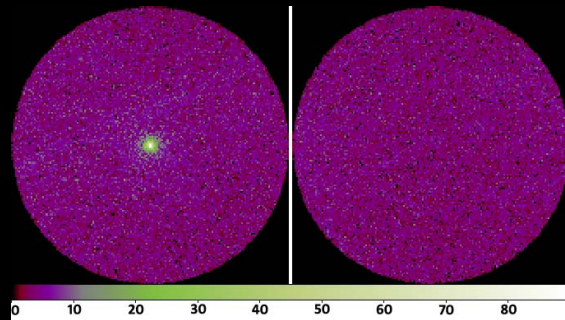
How do cosmic rays interact in the Sun's magnetic environment?
(Nobody really knows)

How does this produce gamma rays and neutrinos?
(Nobody really knows)

What other processes can do this?
(Nobody really knows)

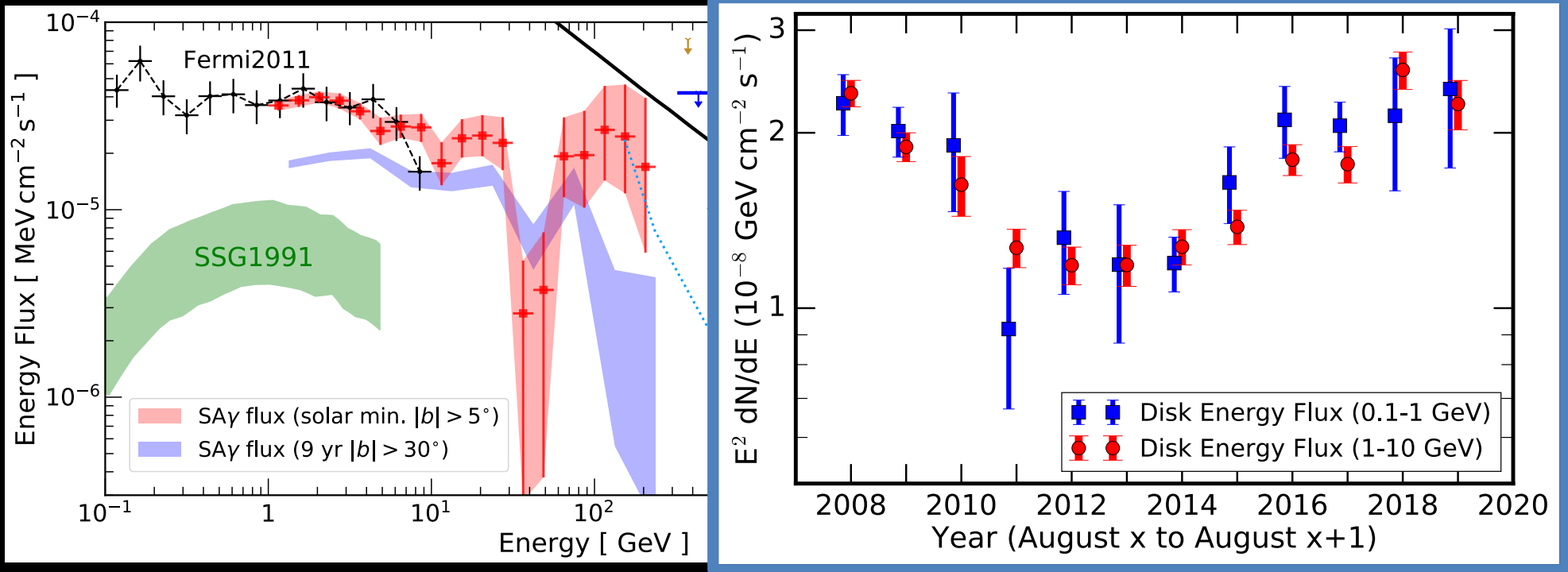
Solar: Orientation

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



Predictions from Seckel, Stanev, Gaisser (1991)

Solar: Accomplishments



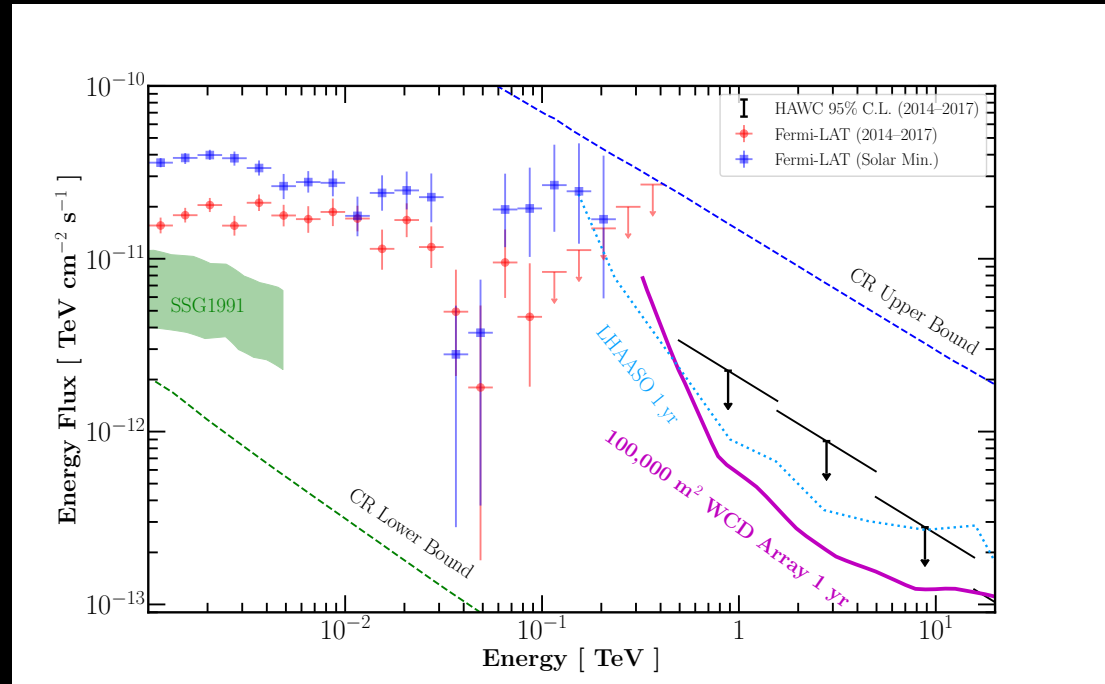
The solar disk gamma-ray emission is extremely weird!

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

Solar: Hope

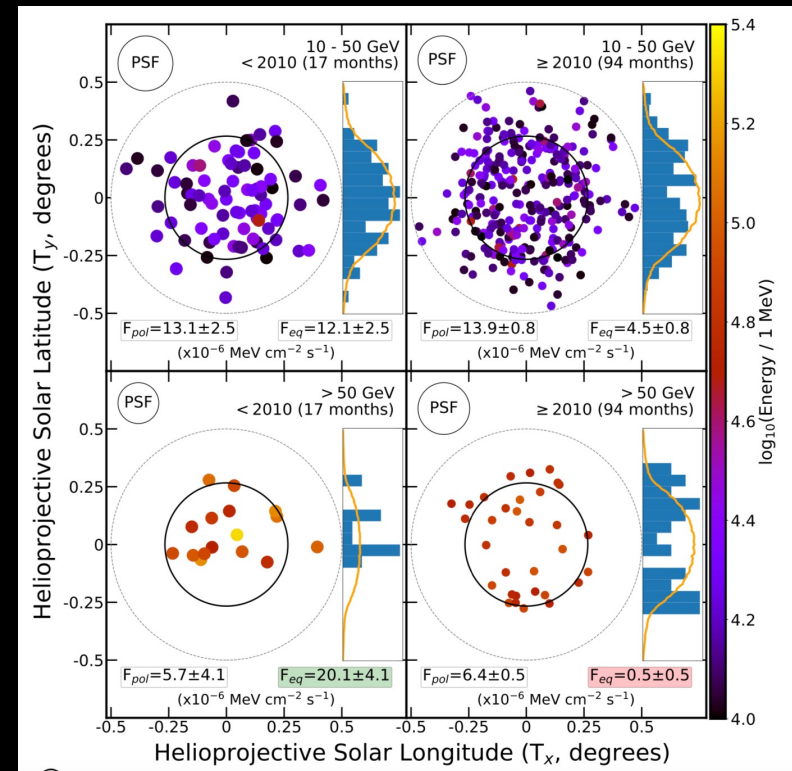
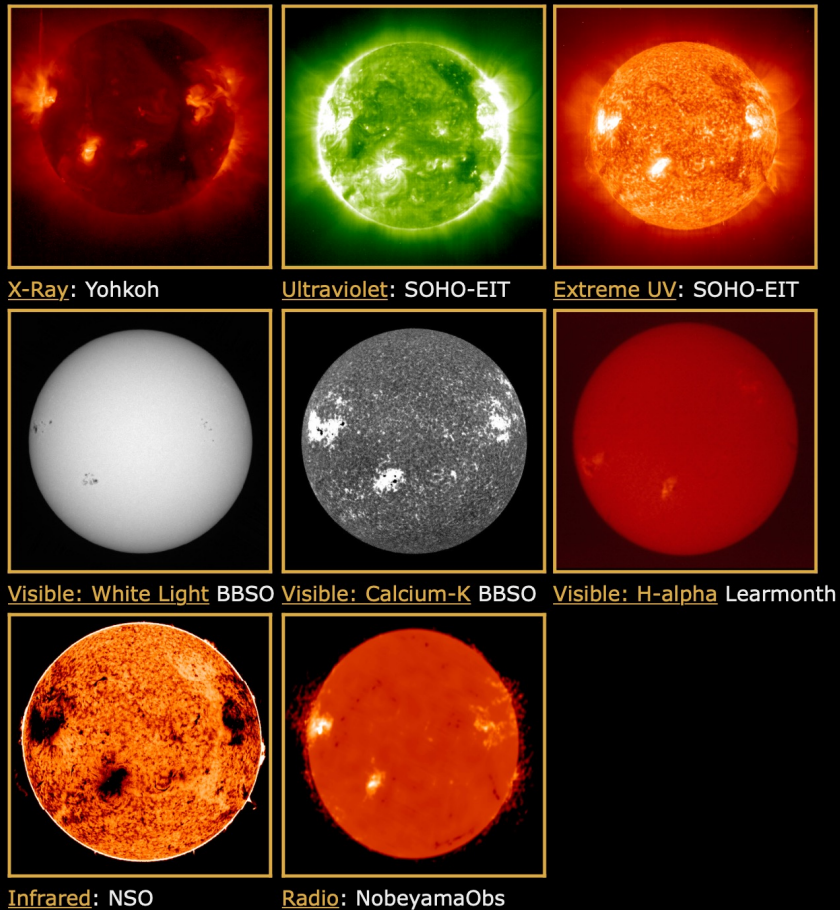


HAWC



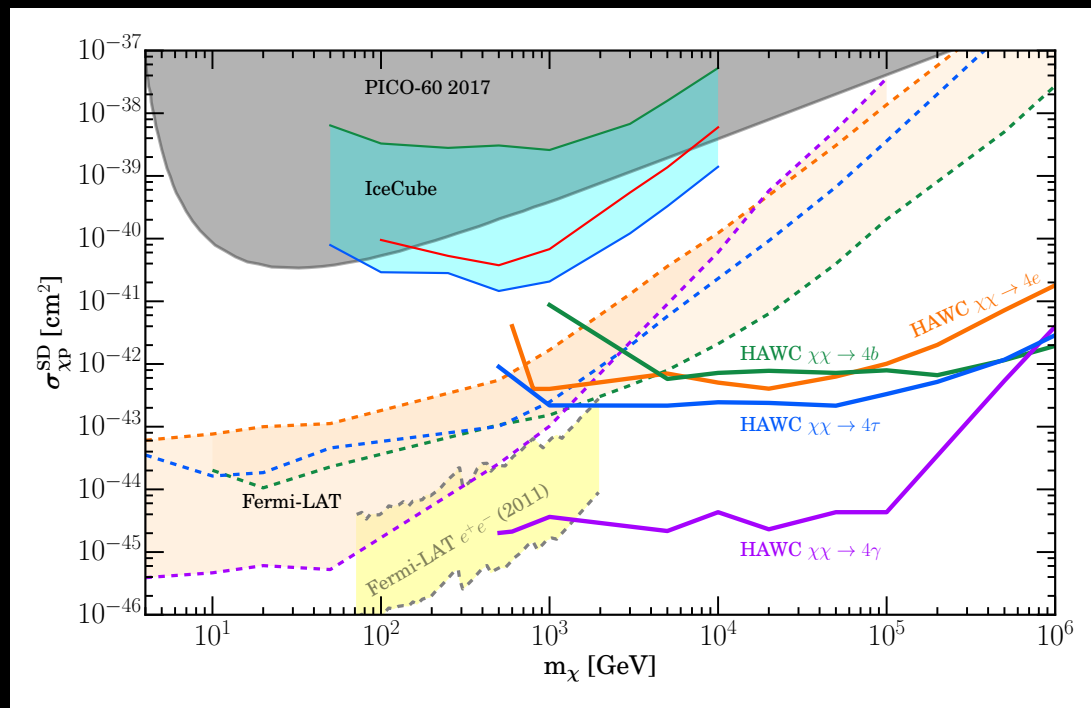
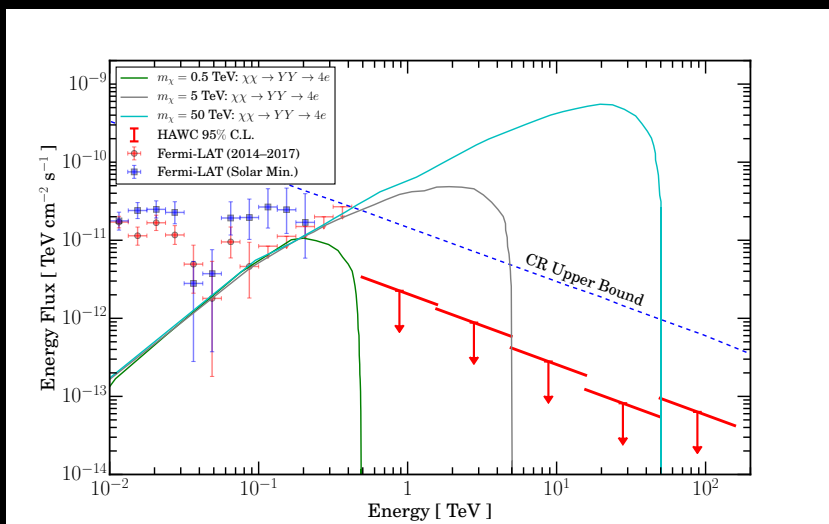
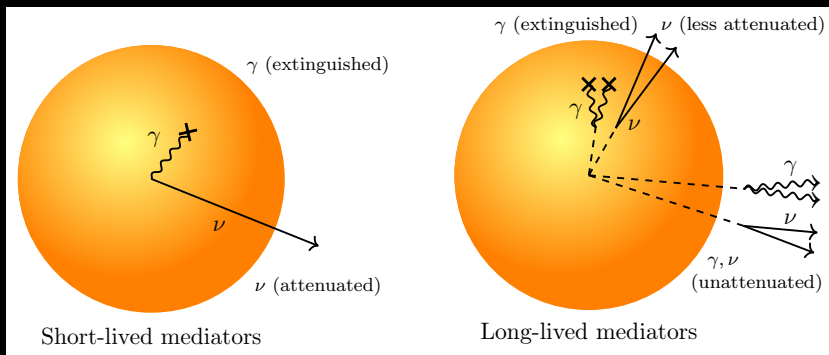
Nisa et al. (2019)

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?

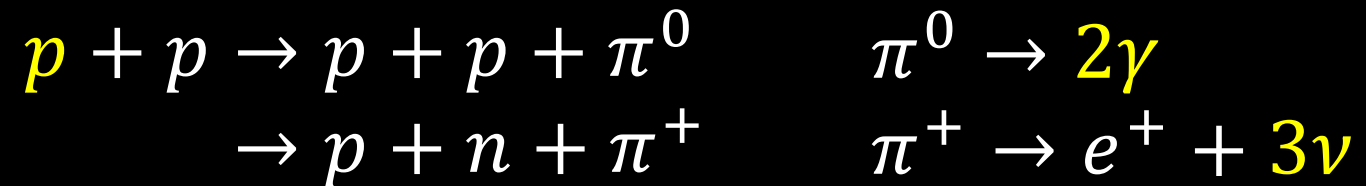
(Not yet, but we have not finished looking)

Probe new physics in neutrino sector?

(Yes, especially if we know the astrophysics better)

VHE Fluxes: Orientation (Co-Production)

Hadronic mechanism:



Leptonic mechanism:

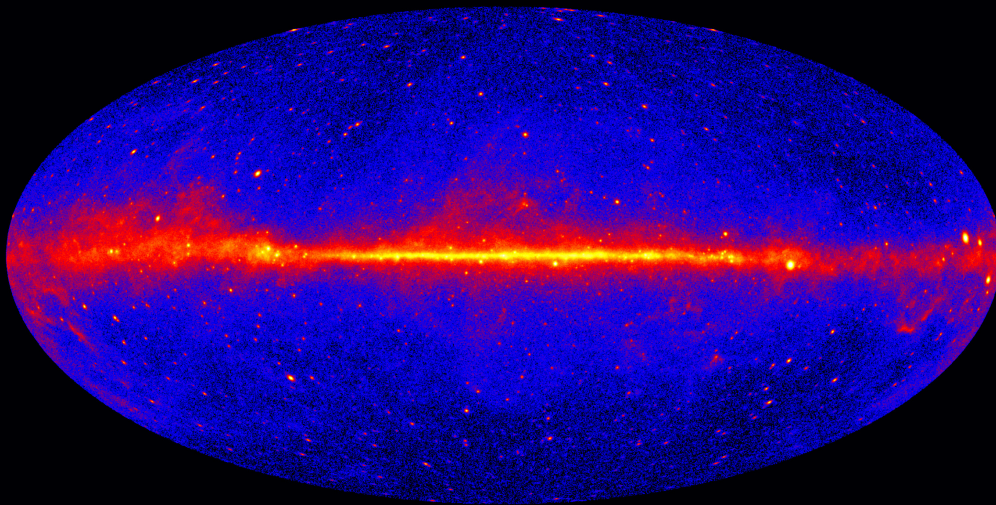


Production always **makes a mess**; propagation **makes more**

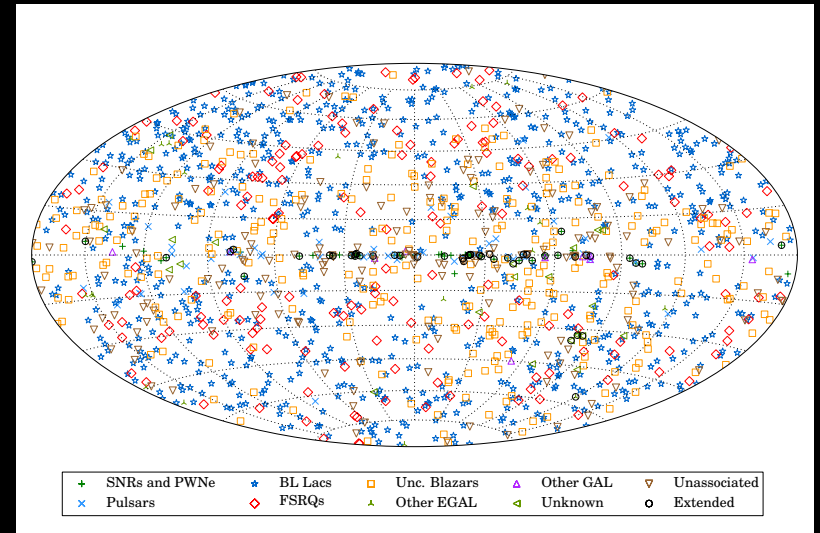
VHE Fluxes: Orientation (GeV–TeV Gamma Rays)

- ✓ Milky Way diffuse
- ✓ Milky Way sources

- ✓ Extragalactic diffuse
- ✓ Extragalactic sources



Fermi

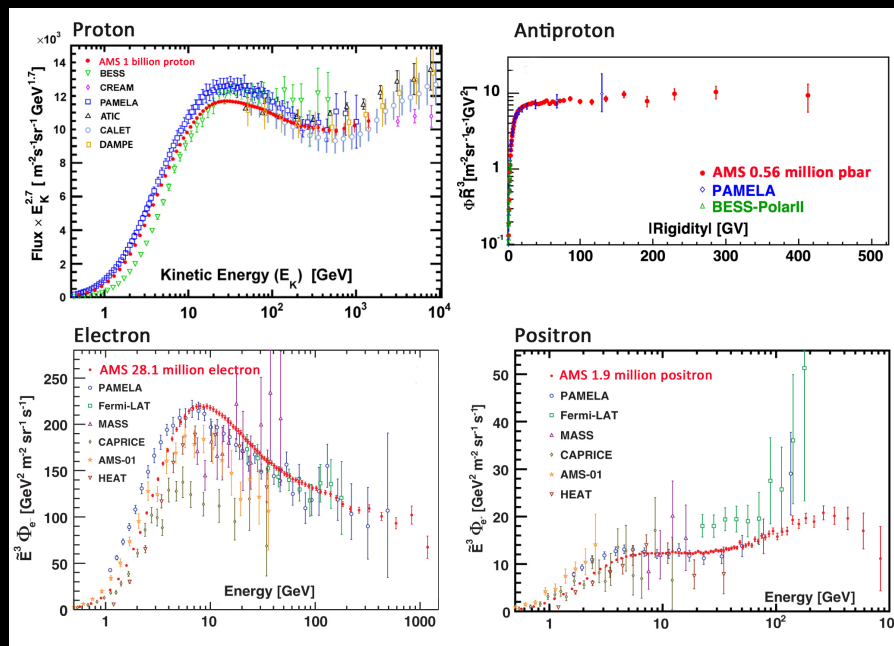


Fermi

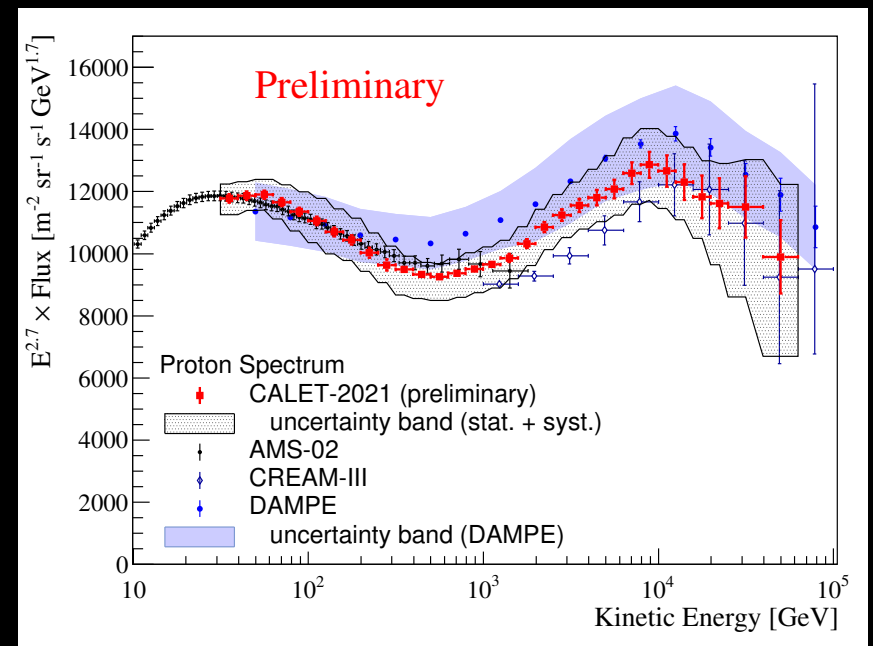
VHE Fluxes: Accomplishments (Cosmic Rays)

- ✓ Milky Way diffuse
- ✗ Milky Way sources

- ✗ Extragalactic diffuse
- ✗ Extragalactic sources



AMS (2021)

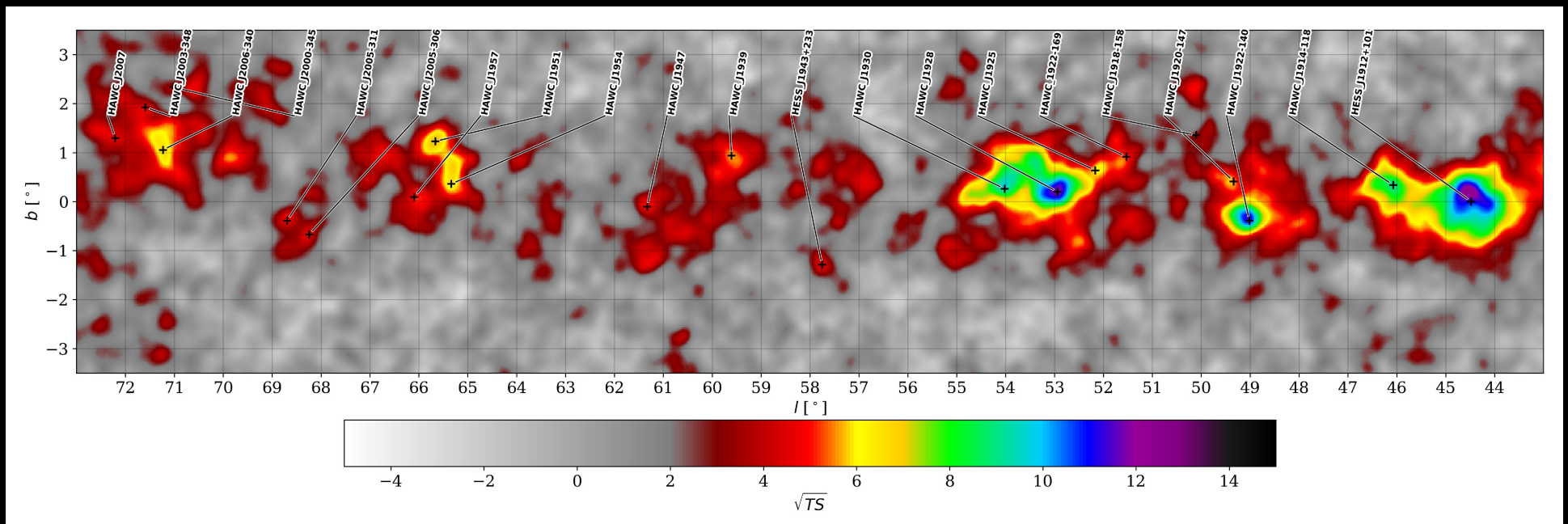


CALET (2021)

VHE Fluxes: Accomplishments (Gamma Rays)

- ✓ Milky Way diffuse
- ✓ Milky Way sources

- ✗ Extragalactic diffuse
- ✓ Extragalactic sources

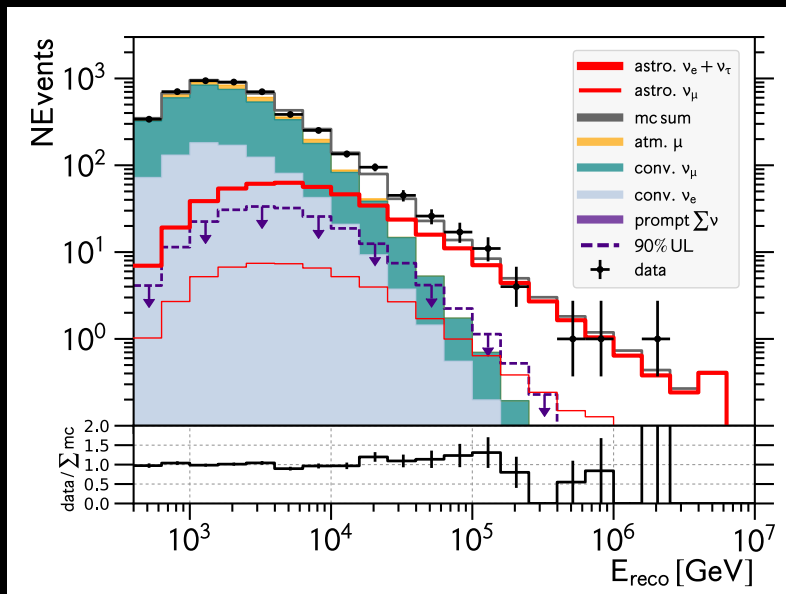


HAWC (2021)

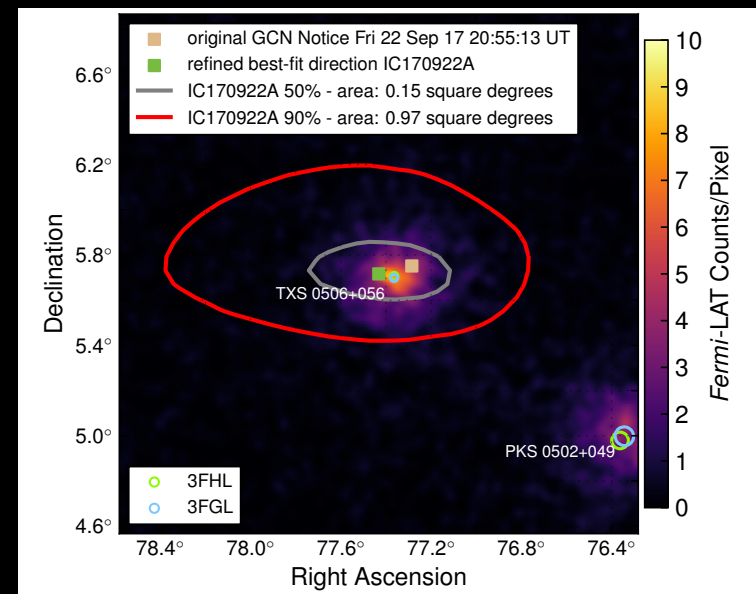
VHE Fluxes: Accomplishments (Neutrinos)

- ✗ Milky Way diffuse
- ✗ Milky Way sources

- ✓ Extragalactic diffuse
- ~ Extragalactic sources



IceCube (2020)

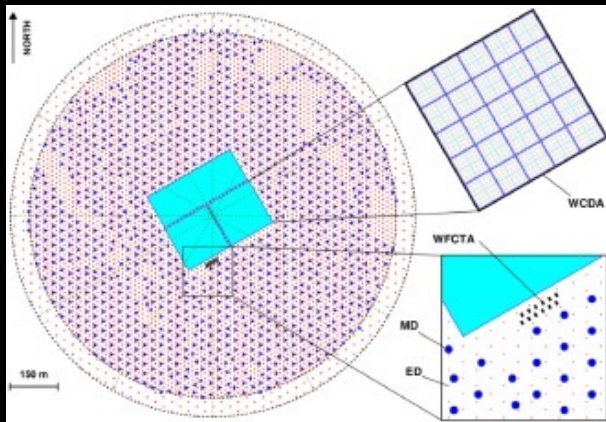


IceCube, Fermi, everyone (2017)

VHE Fluxes: Hope

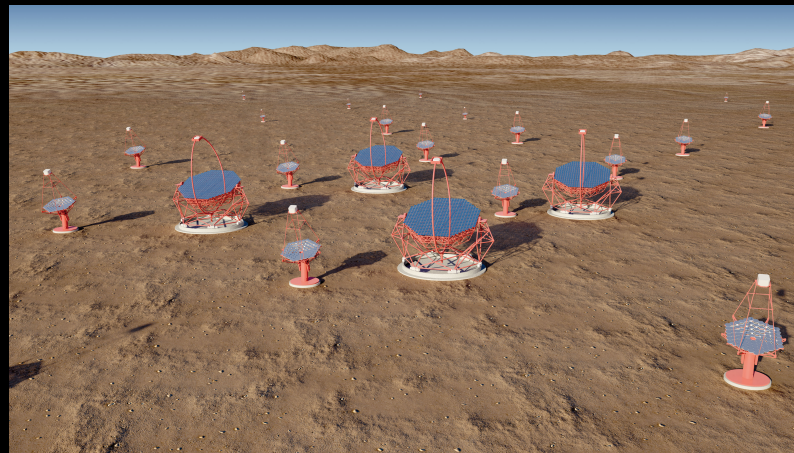
LHAASO

(cosmic rays, gamma rays)



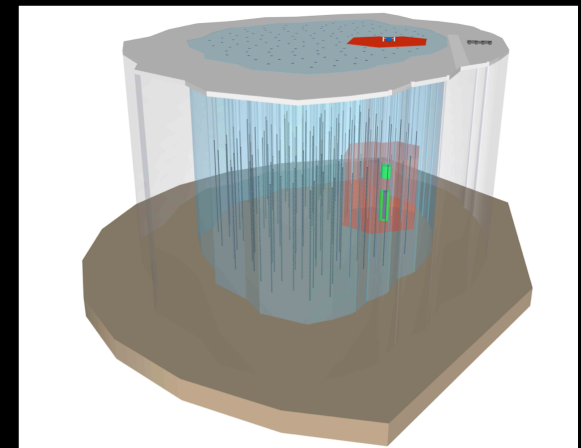
Cherokov Telescope Array

precision gamma rays



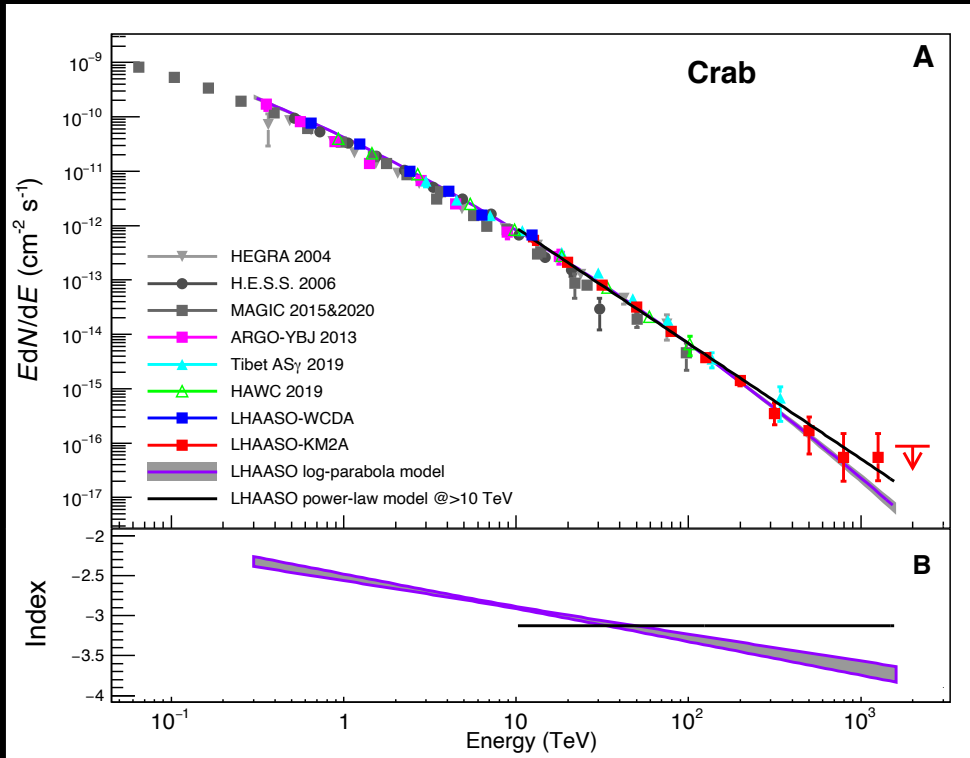
IceCube-Gen2

neutrinos



VHE Diffuse: MMA

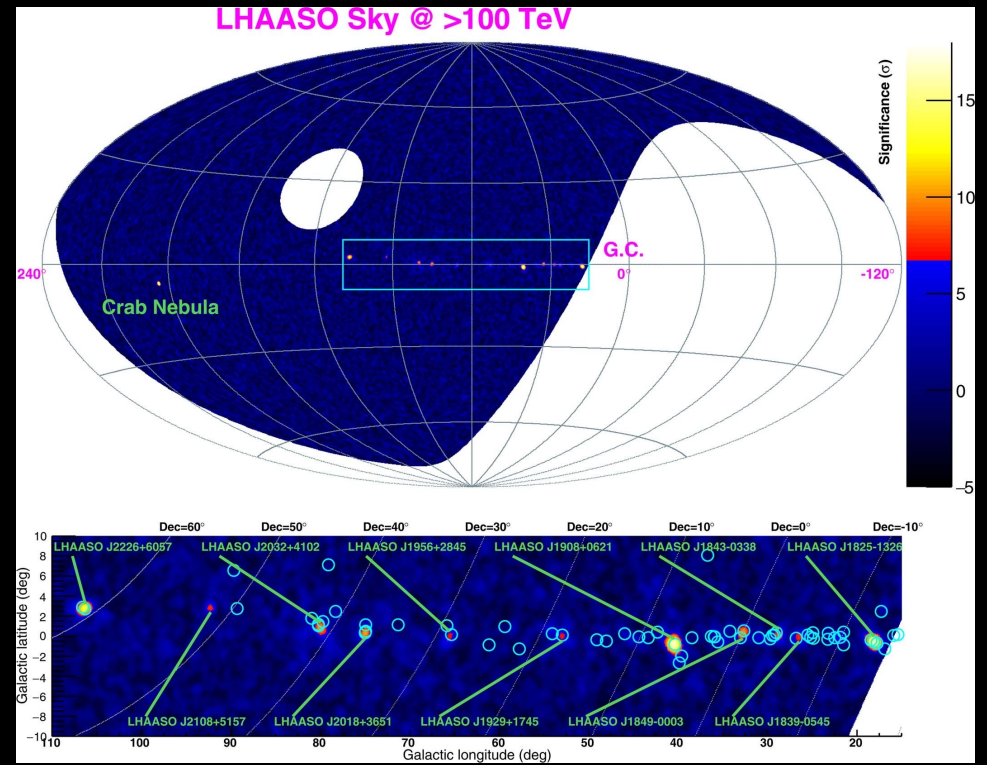
Crab Nebula to 1 PeV!



LHAASO (2021)

John Beacom, The Ohio State University

Many other sources!



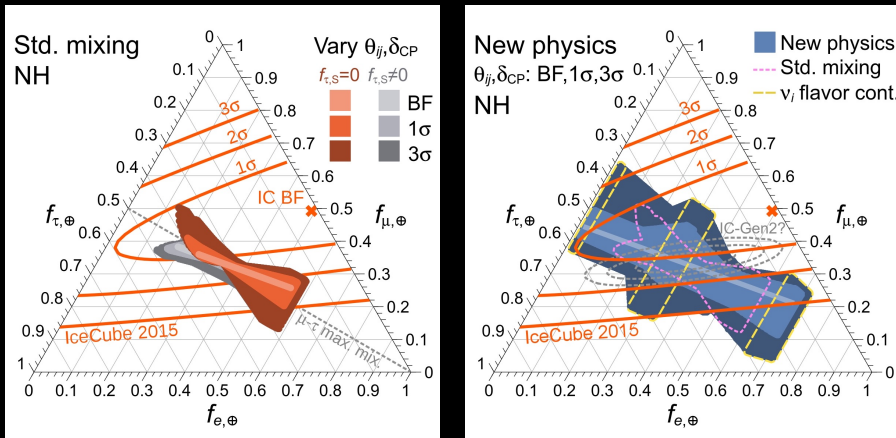
LHAASO (2021)

HEP 2022, Virtual Hong Kong, January 2022

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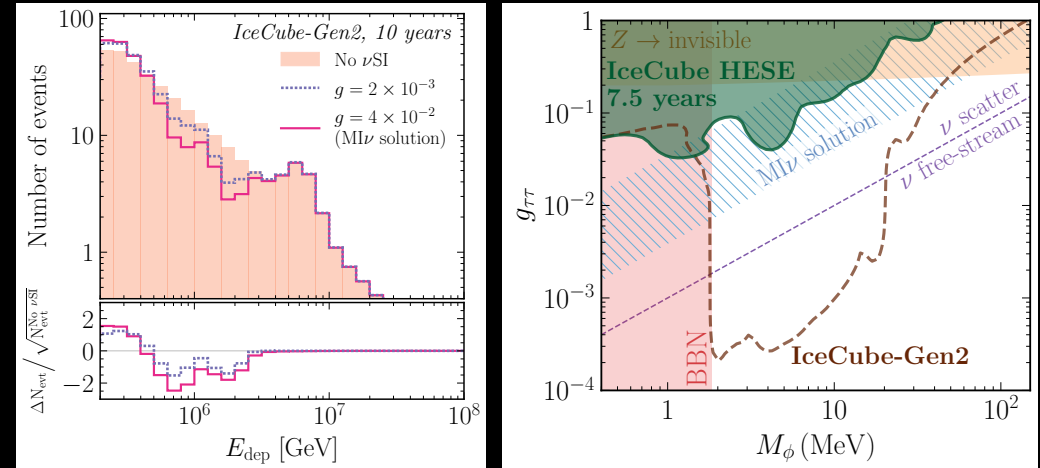
VHE Diffuse: BSM

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, $\sim 10^{20}$ eV and detectable across the universe)

Evidence of super high mass scales?

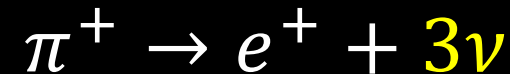
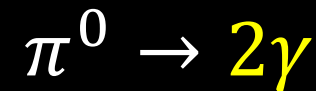
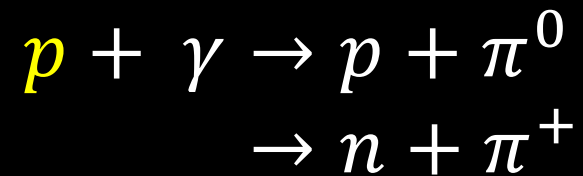
(Not yet, but we have barely looked)

Probe new physics at extremes of energy and other variables?

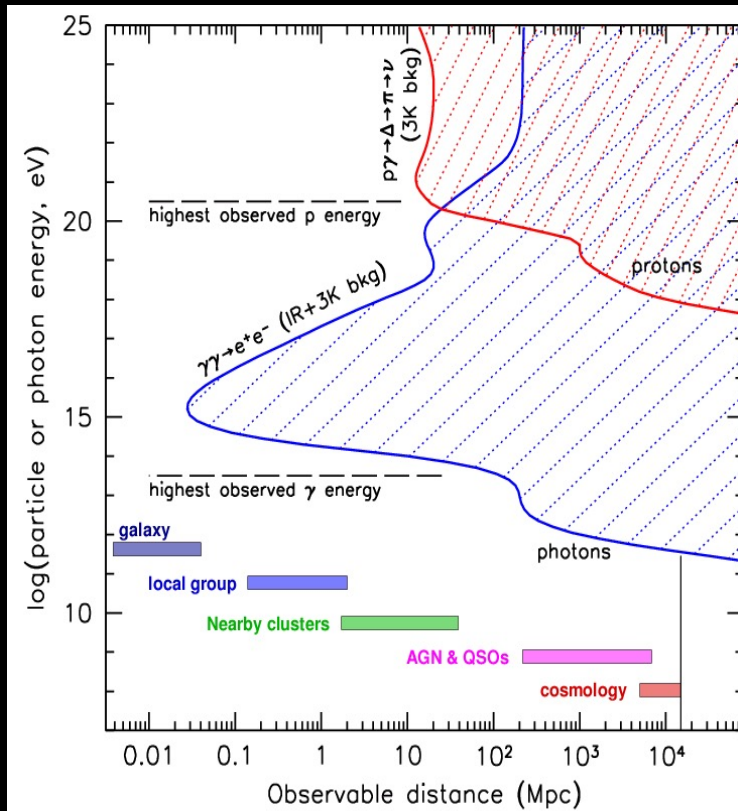
(Yes, especially if we know the astrophysics better)

UHE Fluxes: Orientation (GZK Process)

Greisen-Zatsepin-Kuzmin process

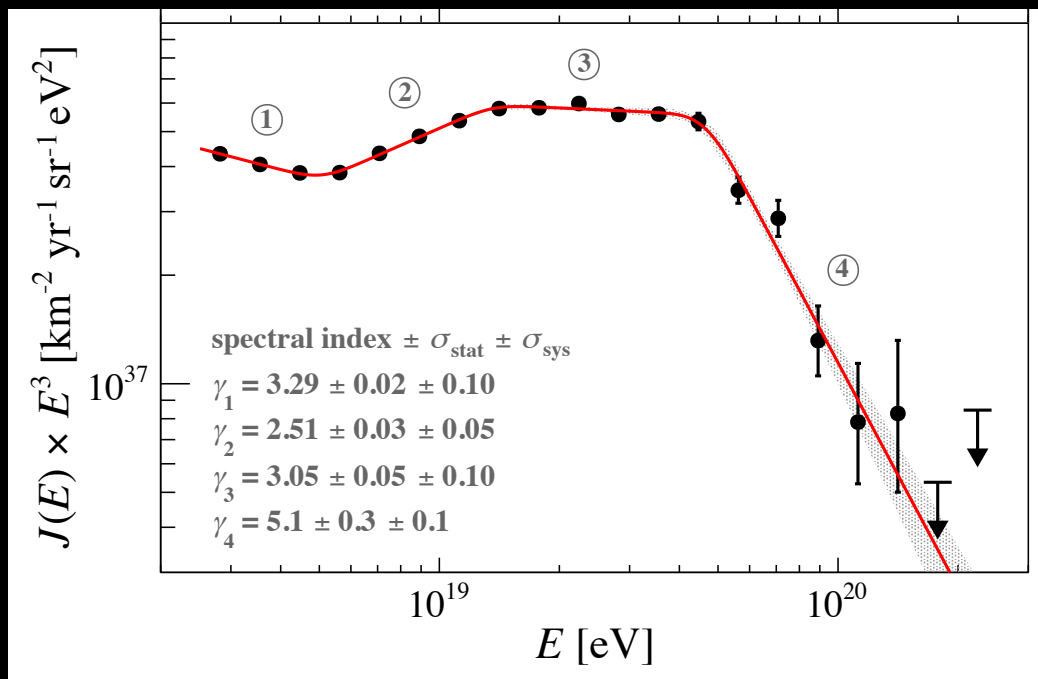


Highest-energy CRs all die
Neutrinos are their ghosts



Gorham (2005)

UHE Fluxes: Accomplishments



Auger (2020)

CR Spectrum:

precise but mysterious

CR composition:

precise but limited by theory

CR associations and anisotropies:

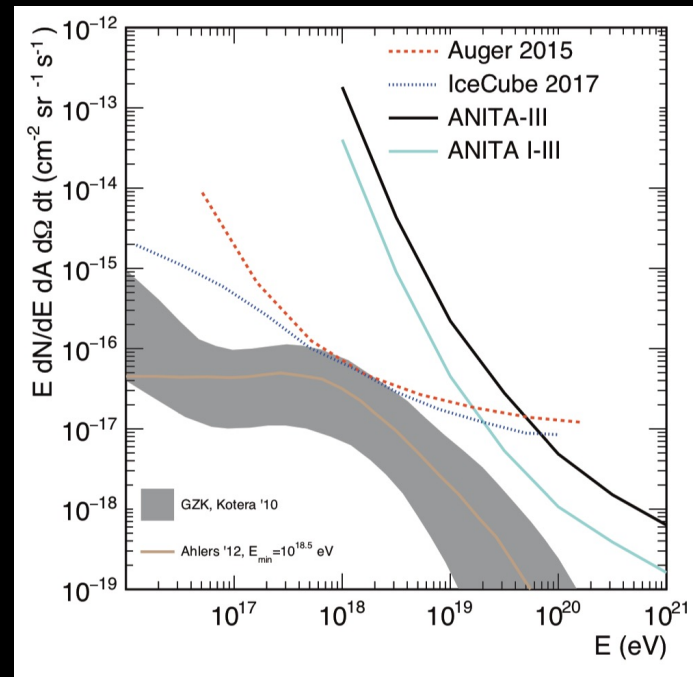
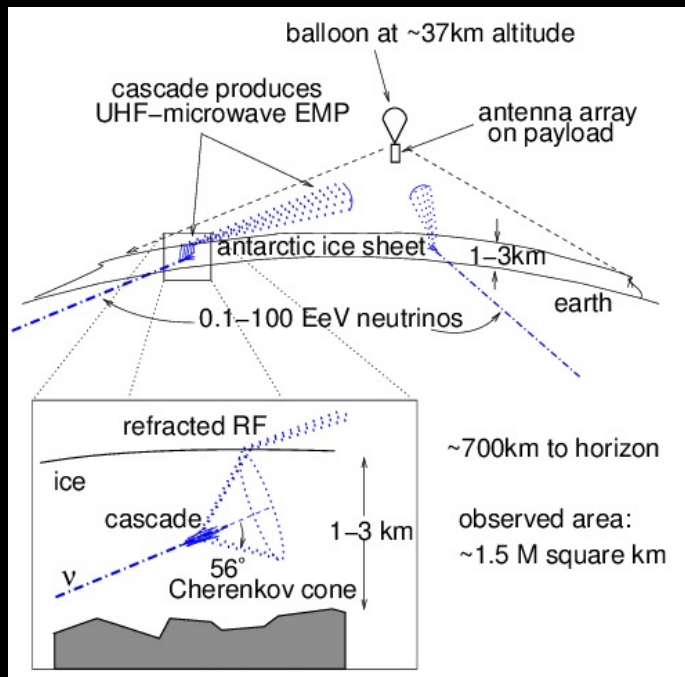
claimed but unconvincing

Gamma and neutrino fluxes:

only upper limits

UHE (Neutrino) Fluxes: Unsolved

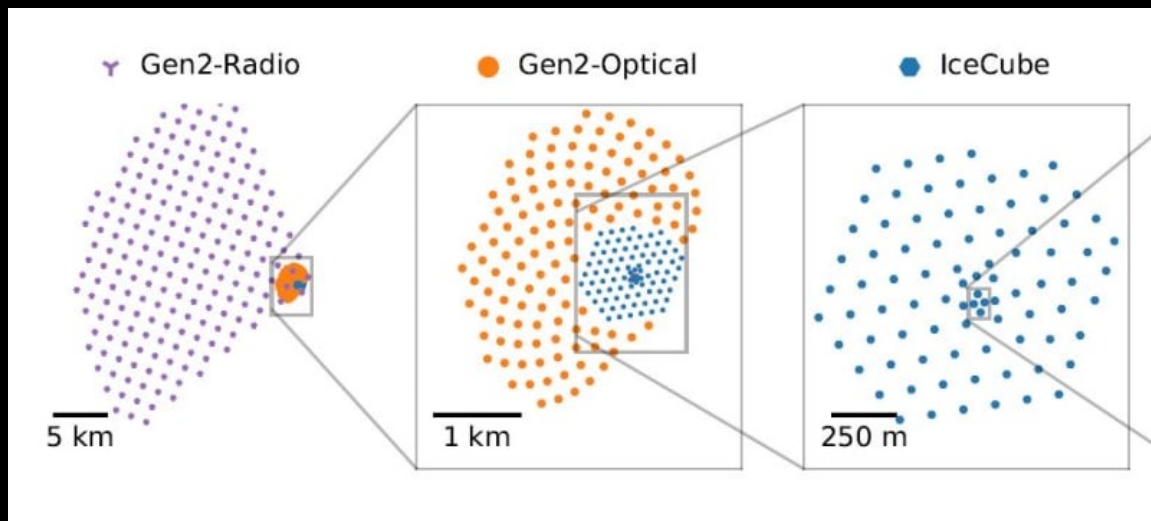
Neutrinos probe *full line of sight*, are *very sensitive to composition*



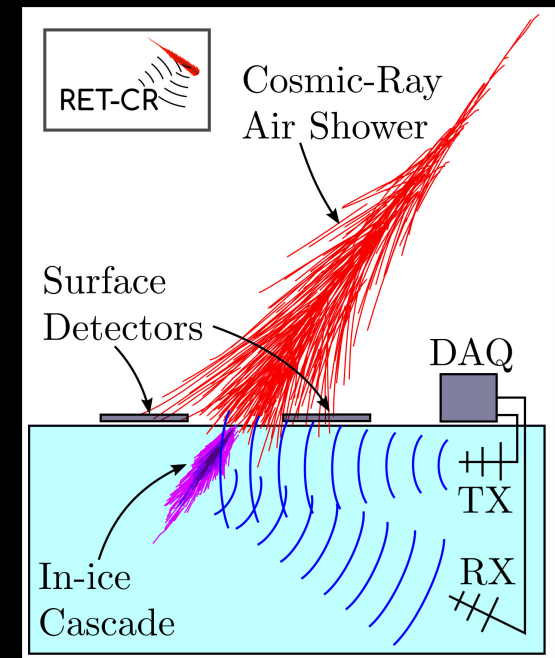
ANITA (2019)

UHE Fluxes: Hope

IceCube-Gen2 Radio

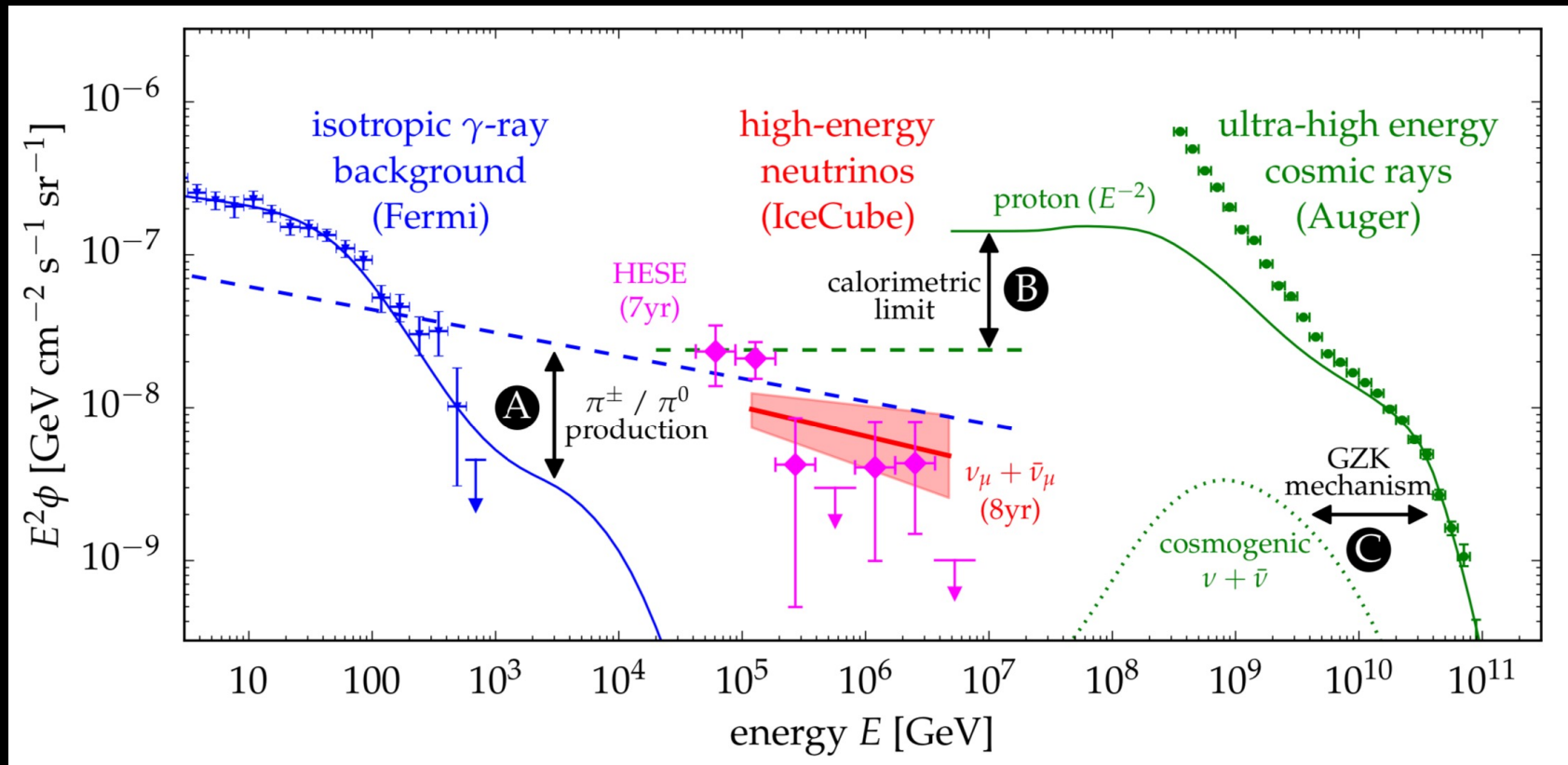


Radar Echo Telescope



And many other proposed experiments

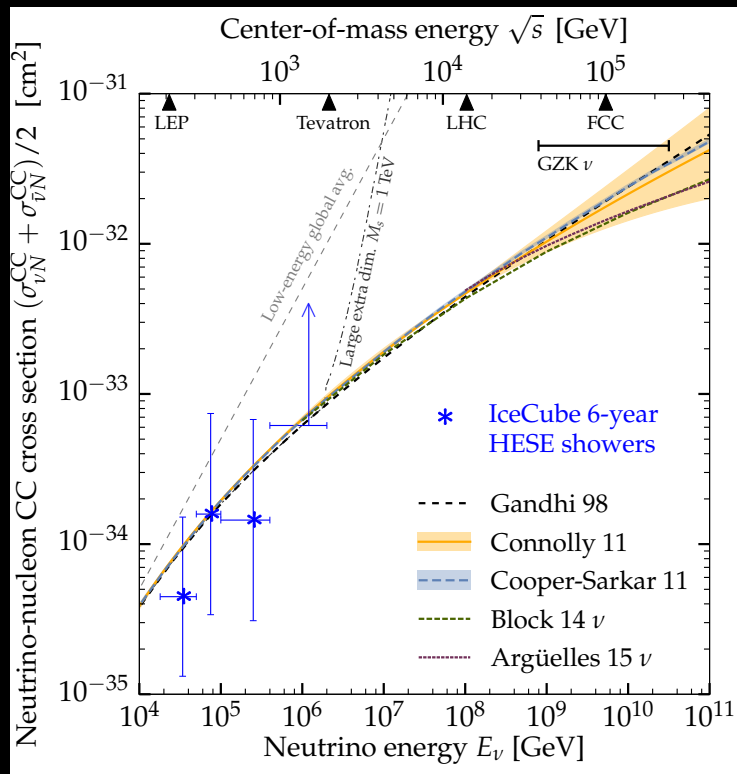
UHE Fluxes: MMA



Ahlers (2018)

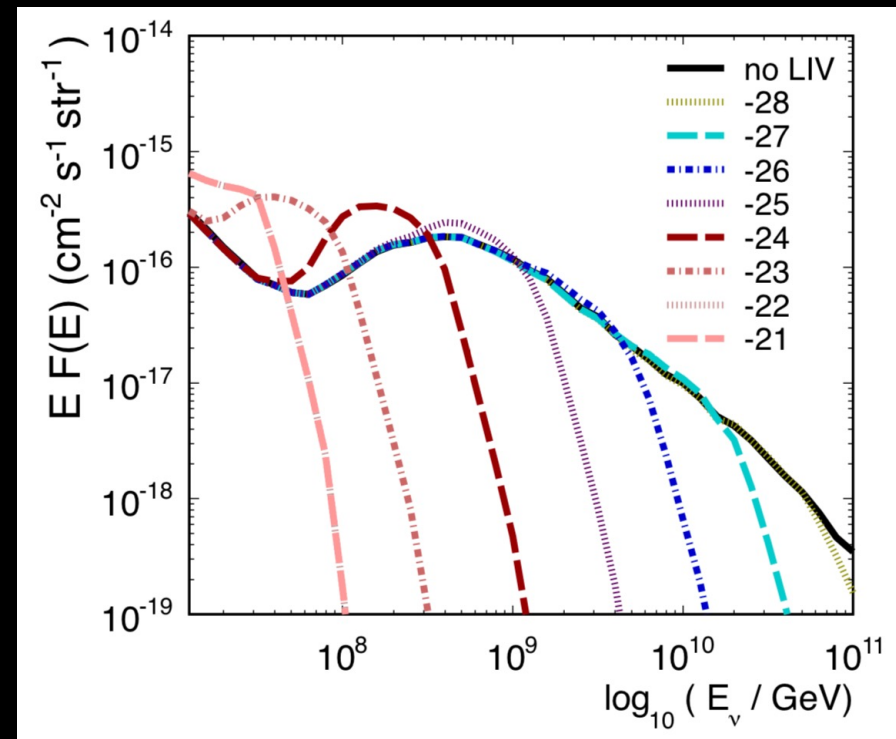
UHE Fluxes: BSM

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

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

Please see [Decadal Survey on Astronomy and Astrophysics 2020 \(Astro2020\)](#)