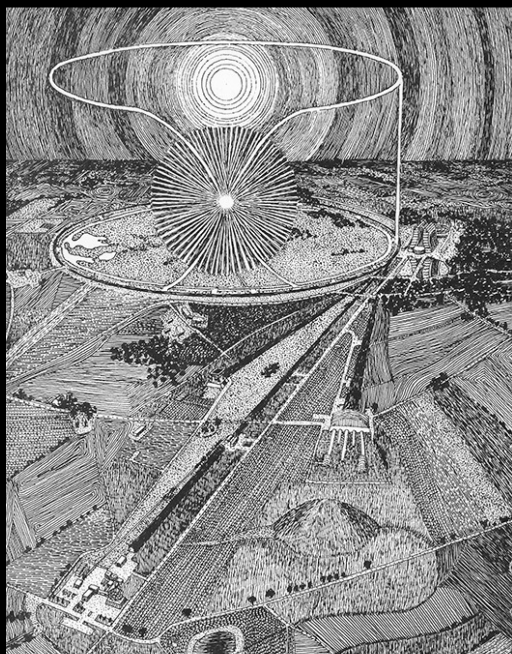
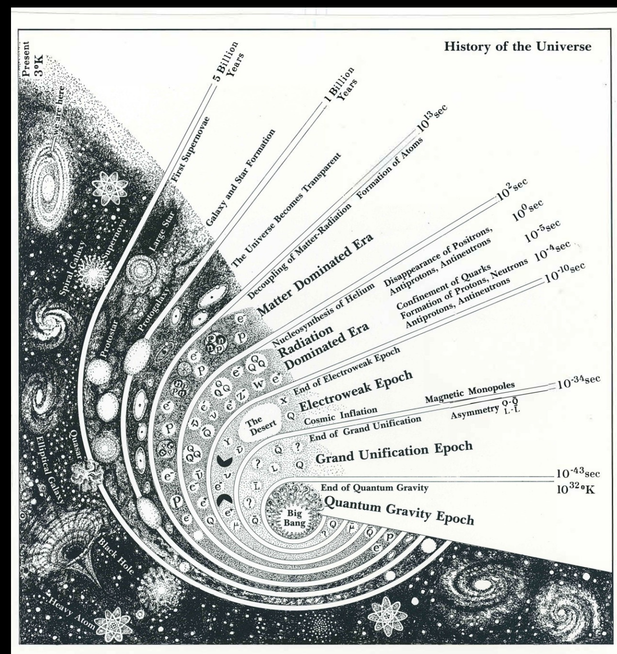
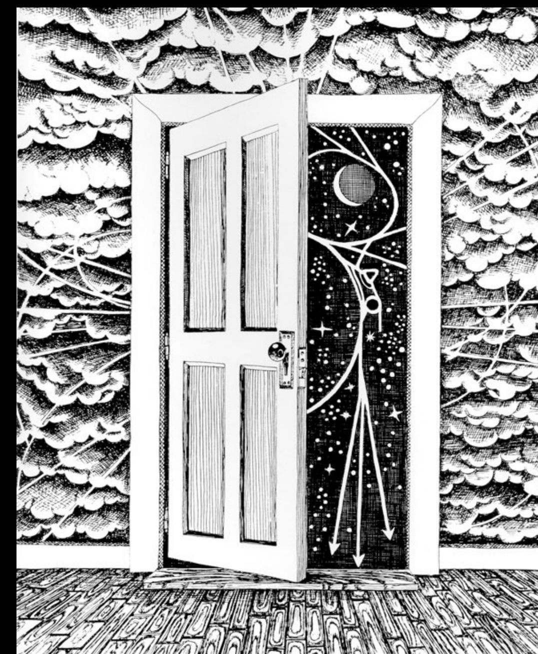
What is the Future of Neutrino Astronomy?

John Beacom, The Ohio State University







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

Unique Impacts of Neutrino Astronomy

To understand astrophysics,
only neutrinos can reveal extreme conditions

To understand neutrinos,
only extreme conditions can reveal particle properties

Talk Outline

Introductory Remarks

MeV–GeV Frontier (HE range)

TeV–PeV Frontier (VHE range)

EeV–ZeV Frontier (UHE range)

Concluding Remarks

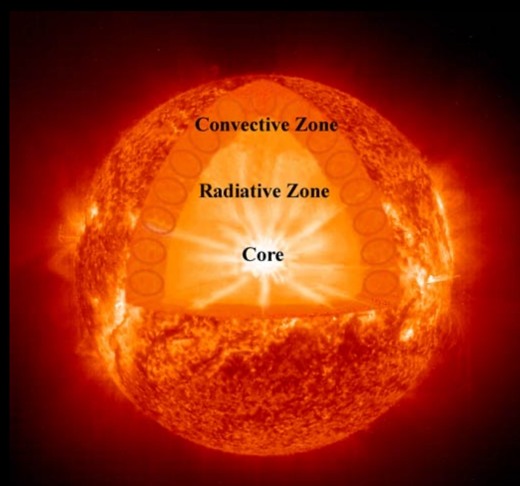
MeV–GeV Frontier

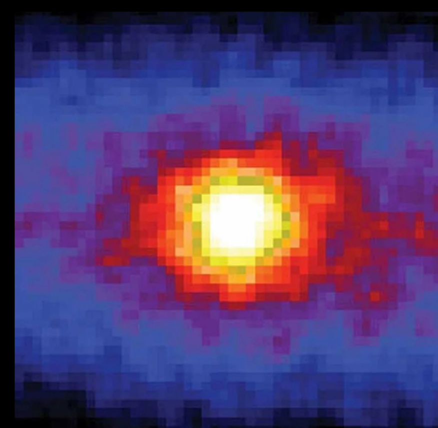
Sun
Supernovae, NS-NS mergers
NS common-envelope evolution
atmospheric neutrinos
dark matter annihilation or decay
surprises

Solar Fluxes: Initial Motivations

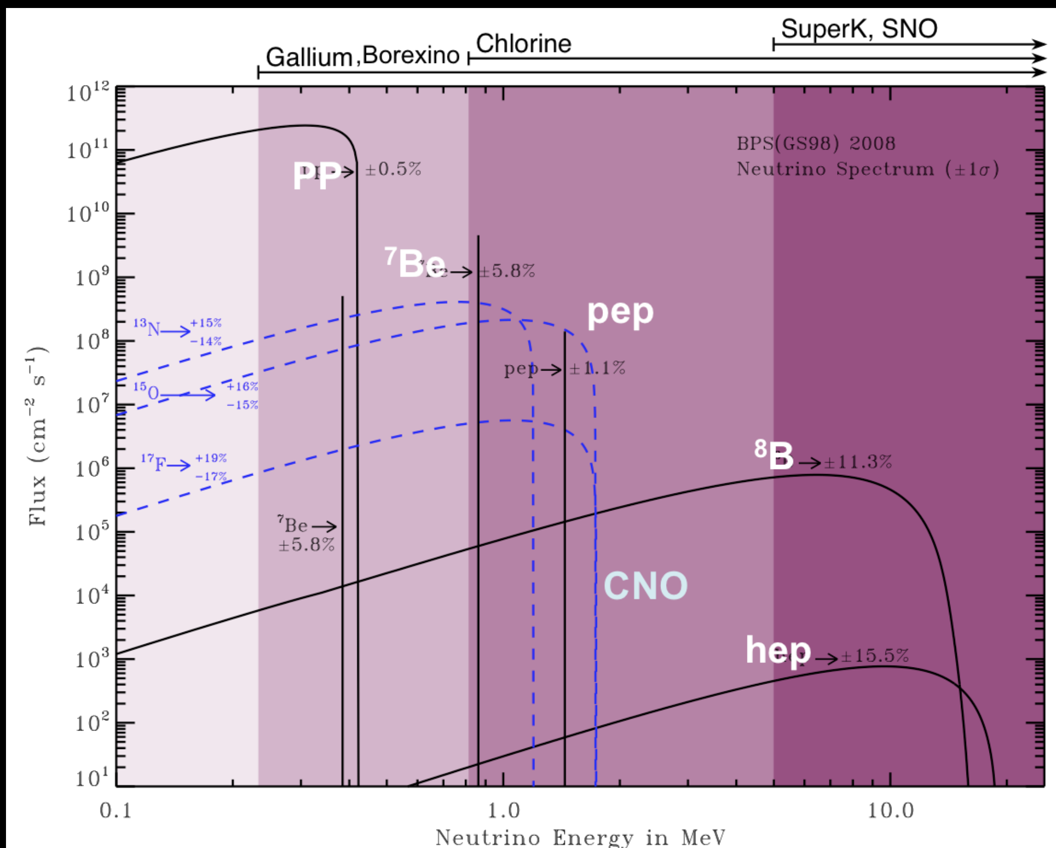
the star. Only neutrinos, with their extremely small interaction cross sections, can enable us to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars.

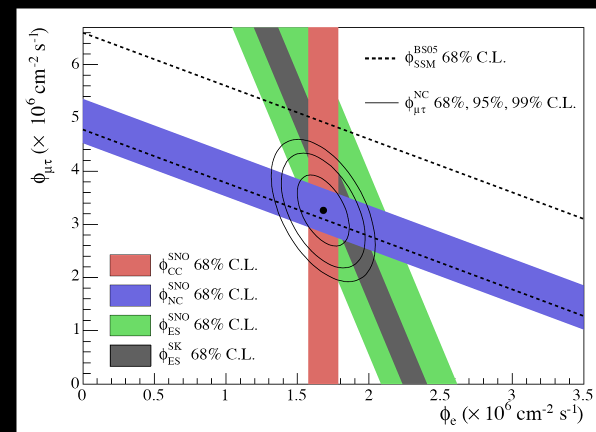
John Bahcall (1964)



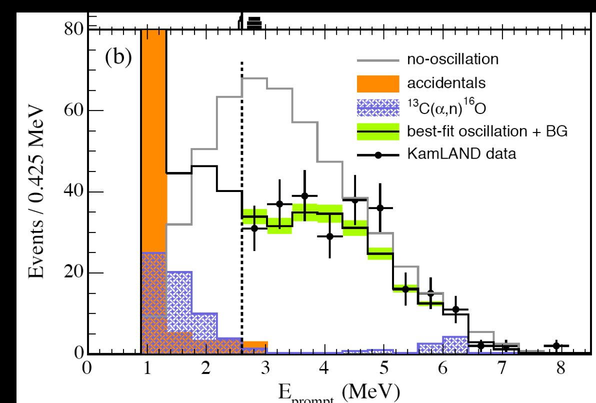


Diversion — The Solar Neutrino Problem



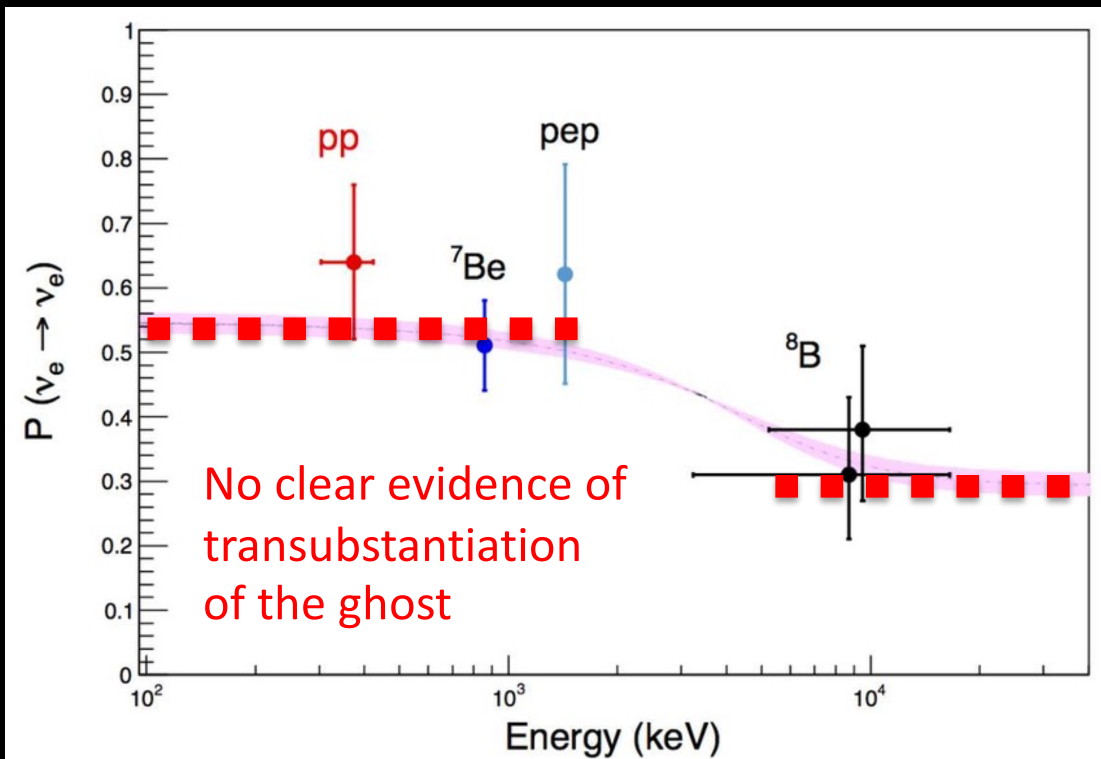


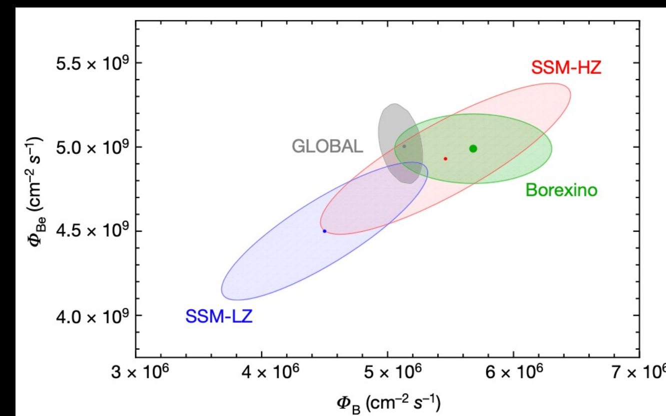
SNO



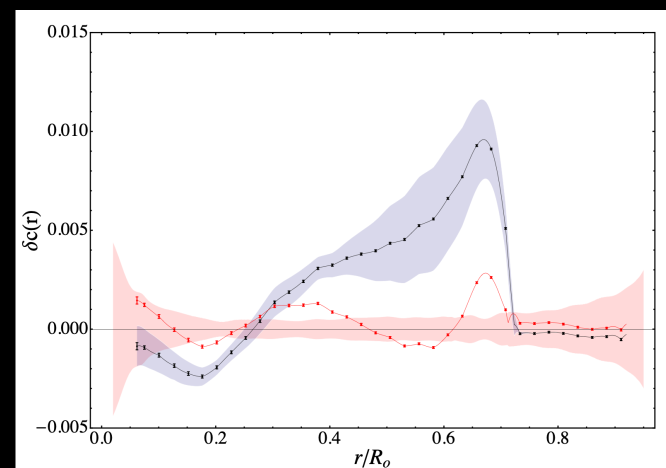
KamLAND

New Questions





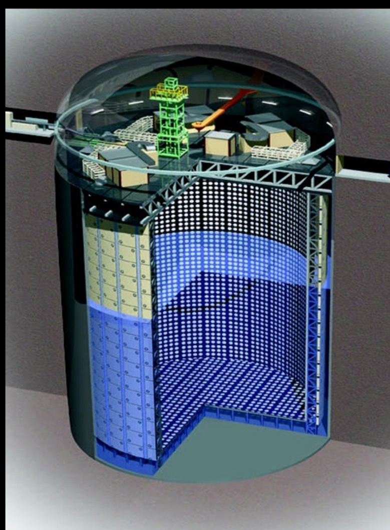
Borexino



Villante et al. (2013)

New Multi-kton Neutrino Detectors

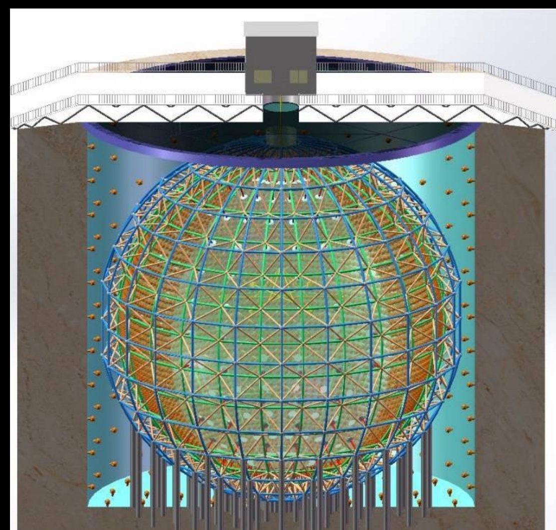
Super-K Gd



32 kton water+Gd
running (Japan)

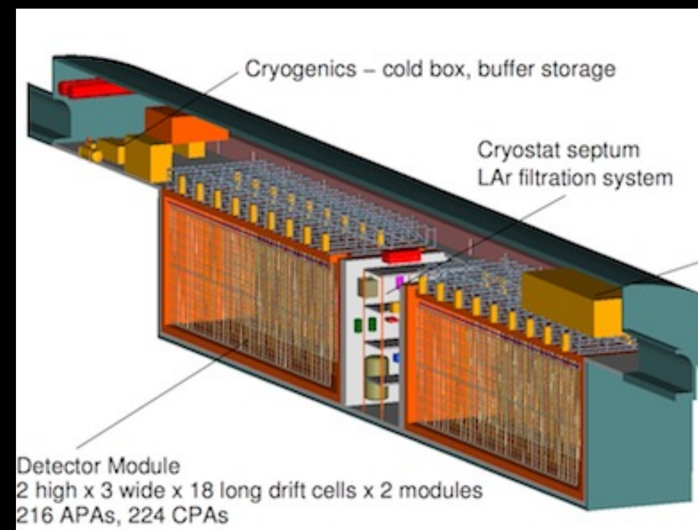
+
Hyper-K (260 kton) starts 2027

JUNO



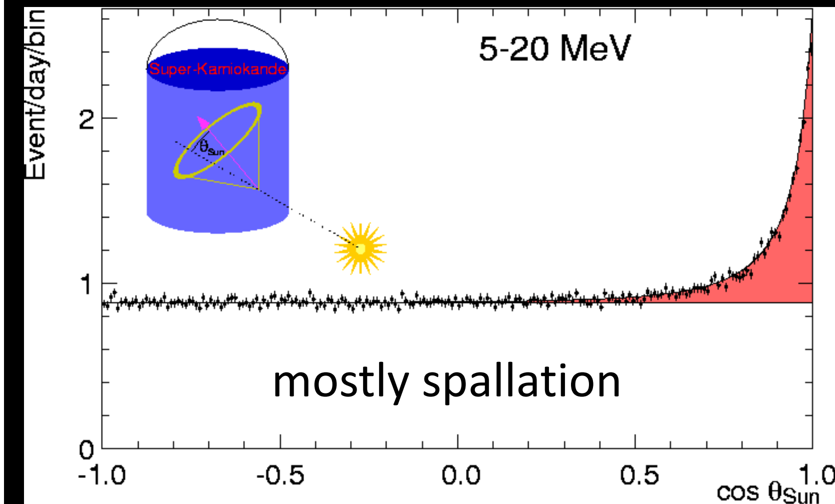
20 kton scintillator
starts 2025 (China)

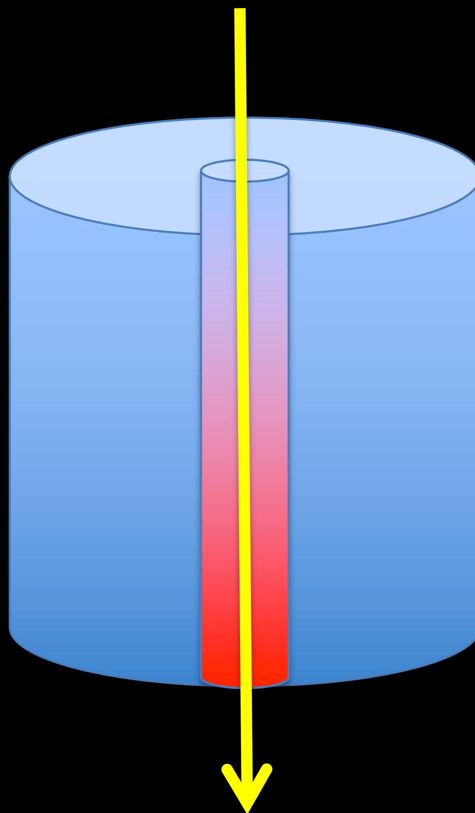
DUNE

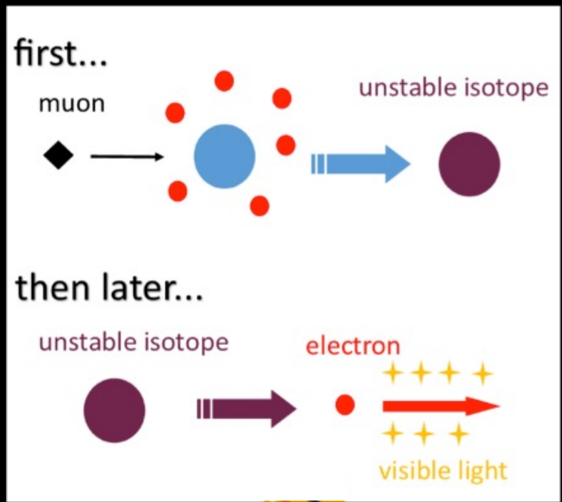


34 kton liquid argon
starts ~2029 (United States)

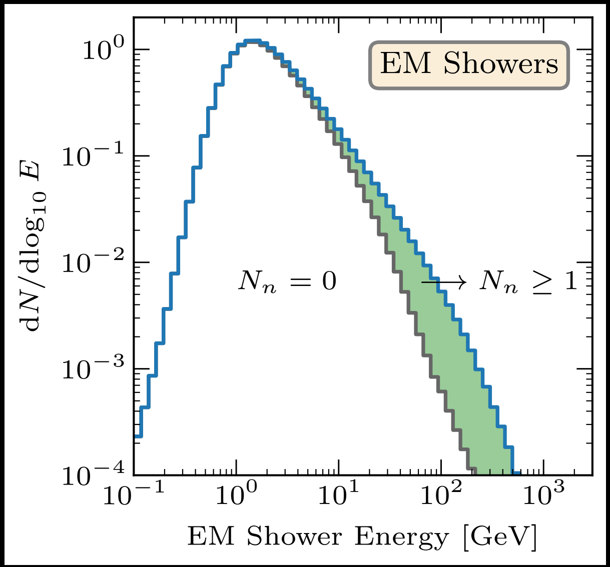
Problem of Spallation Backgrounds

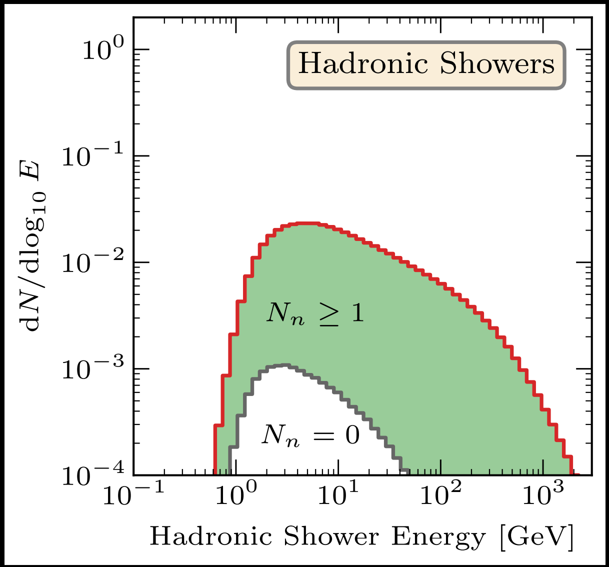




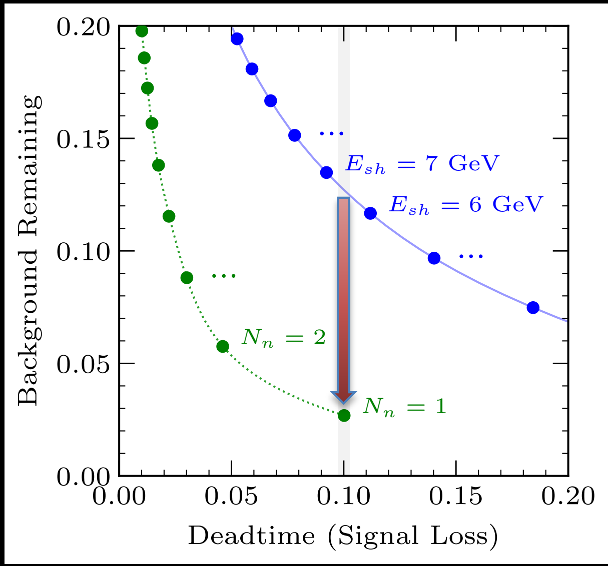


New Spallation Reduction Technique





Nairat, Beacom, Li (2024)



Hadronic showers are *rare*

But they produce *almost all* the isotopes and neutrons

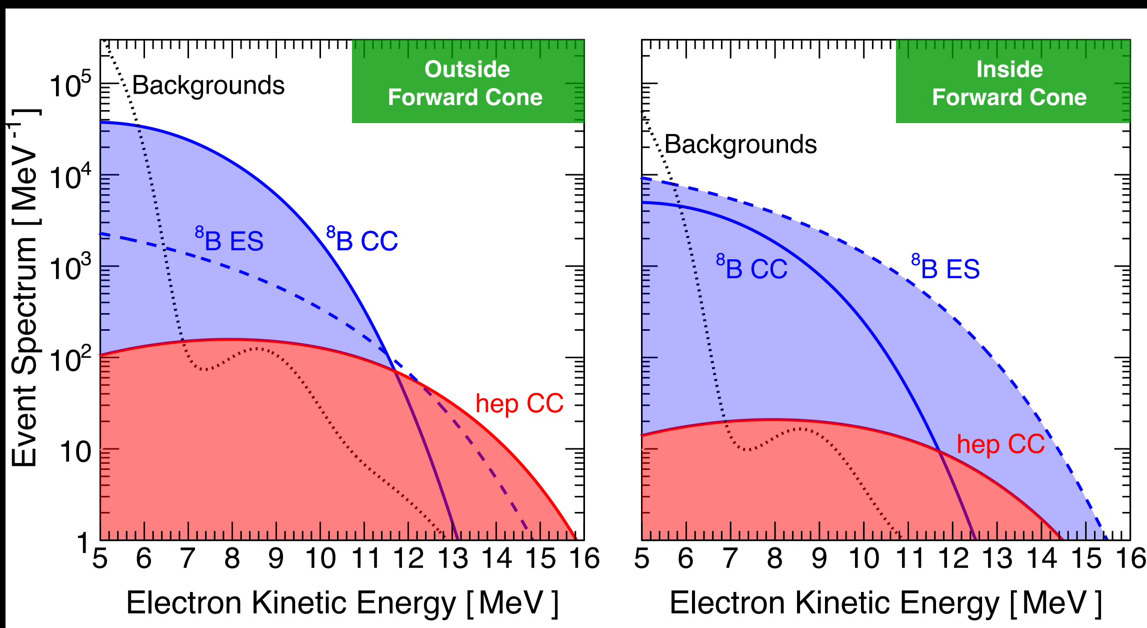
Neutron tagging enabled by gadolinium loading

DUNE Solar Concept

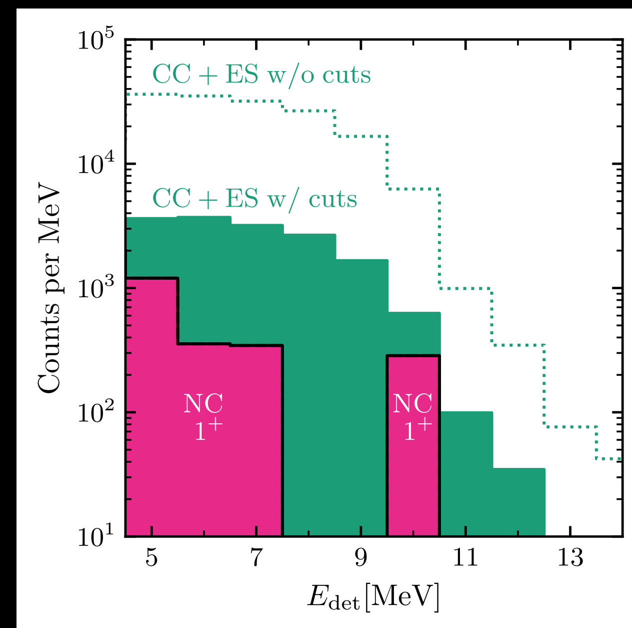
CC: $\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$

ES: $\nu + e^- \rightarrow \nu + e^-$

NC: $\nu + {}^{40}\text{Ar} \rightarrow \nu + {}^{40}\text{Ar}^*$

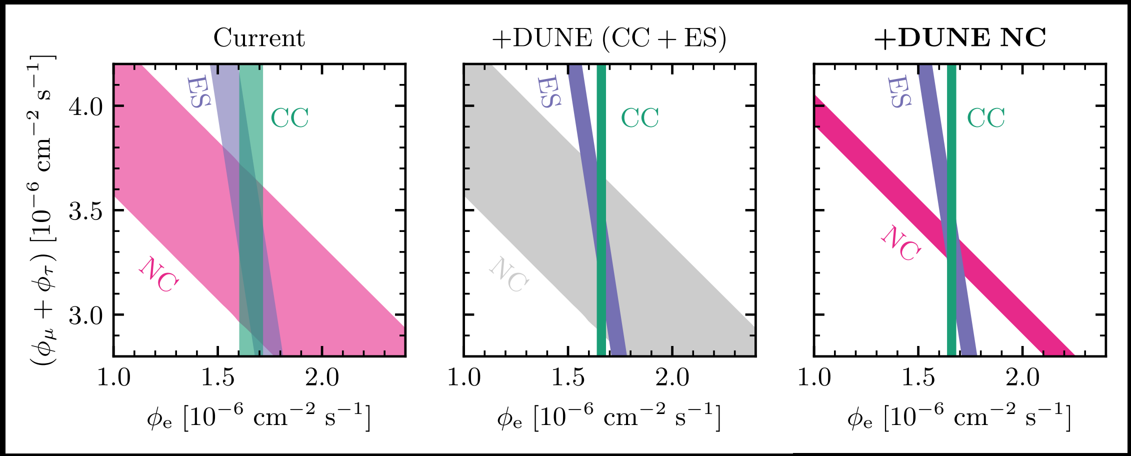


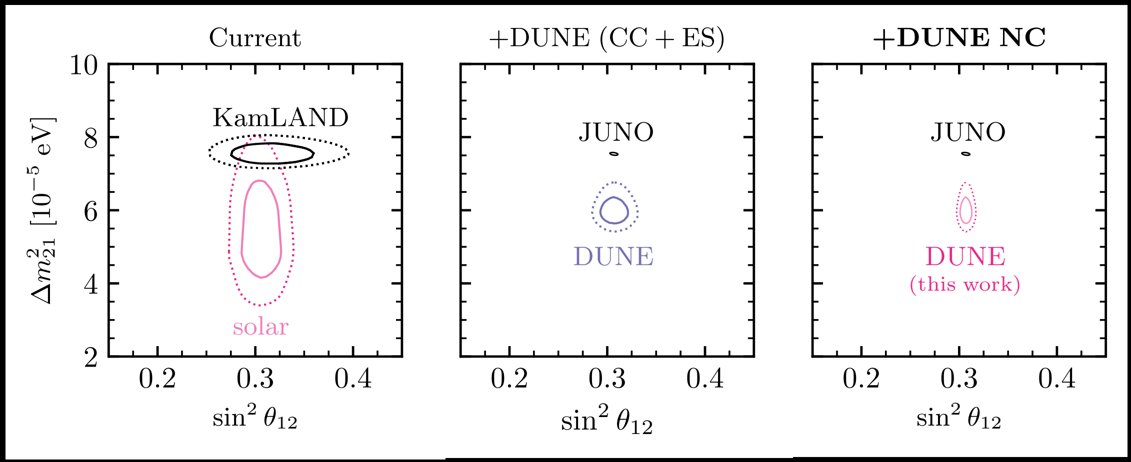
Capozzi, Li, Zhu, Beacom (2018)
Zhu, Li, Beacom (2018)



Meighen-Berger, Newstead, Beacom, Bell, Dolan (2024)

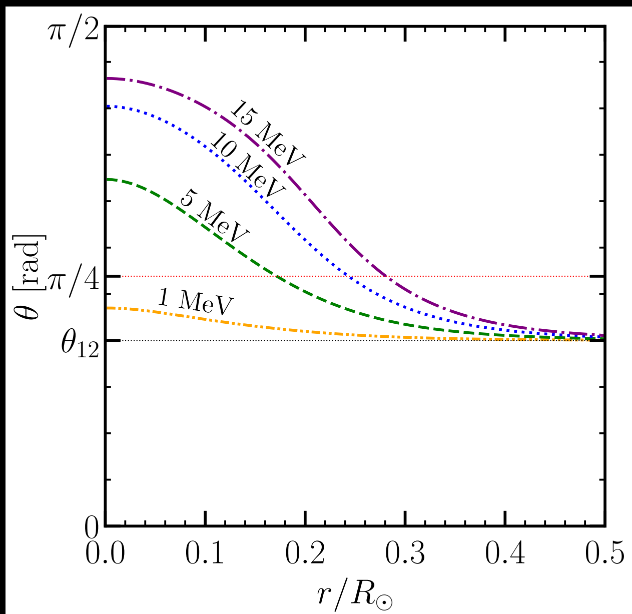
DUNE Solar Prospects



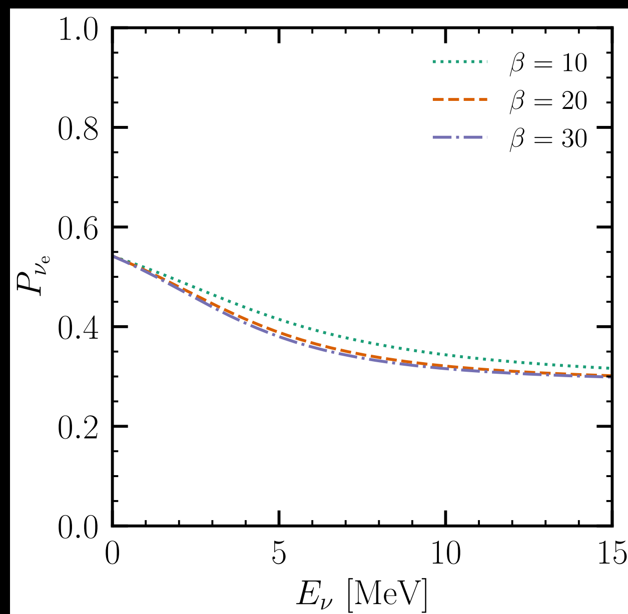


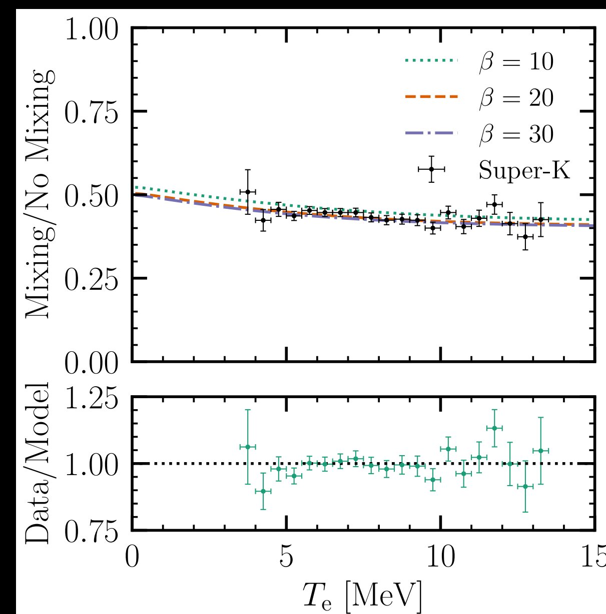
Meighen-Berger et al. (2024)

Using MSW to Probe the Solar Core

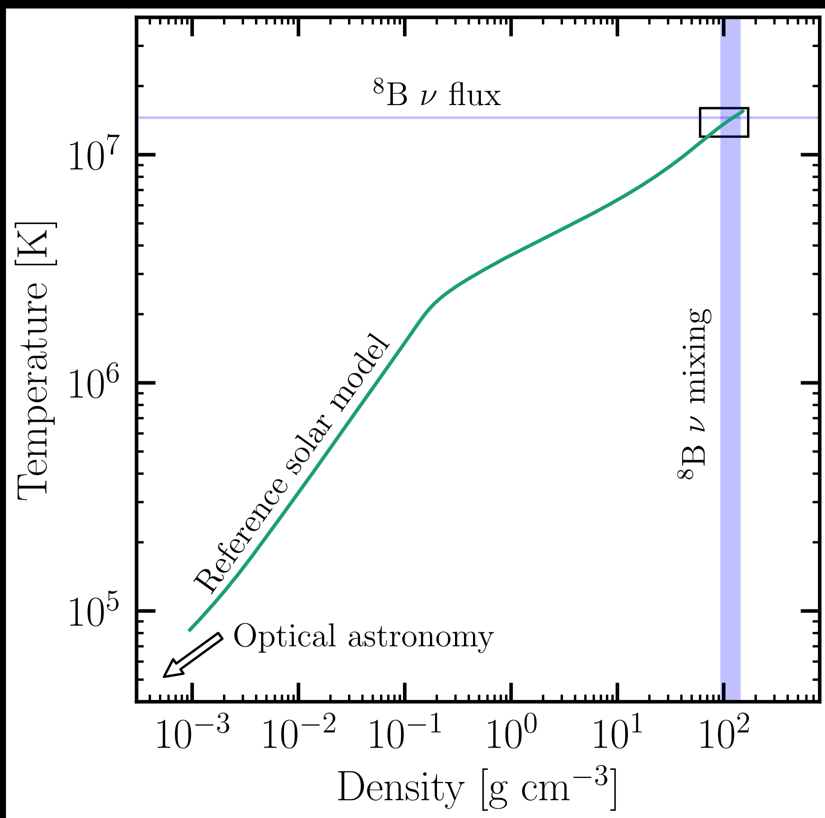


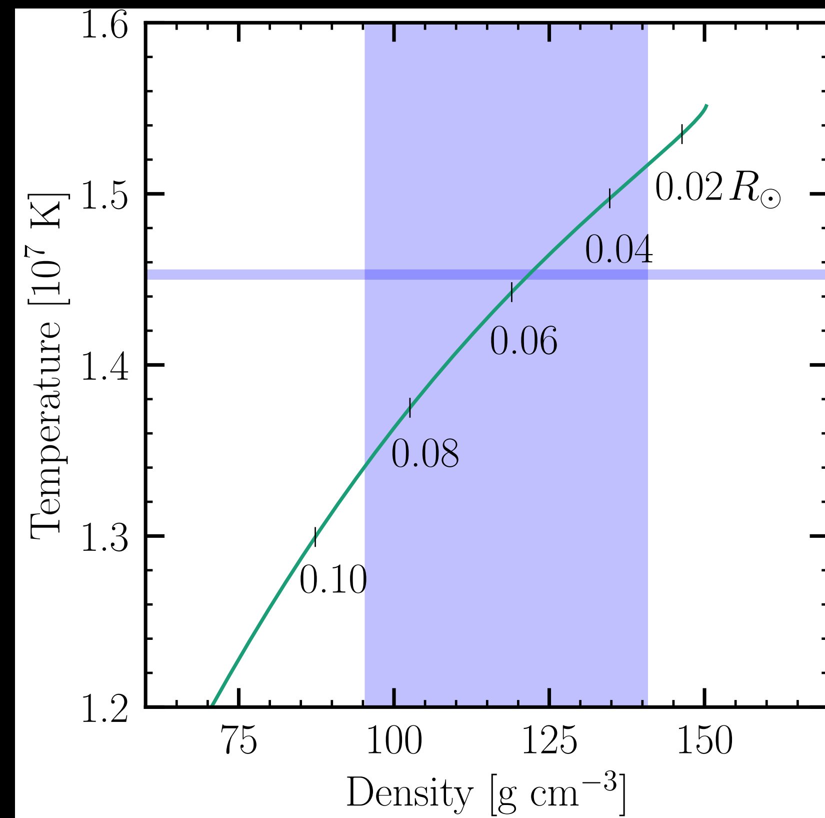
Zaidel, Beacom (2025)





Projected Sensitivity for ρ and T





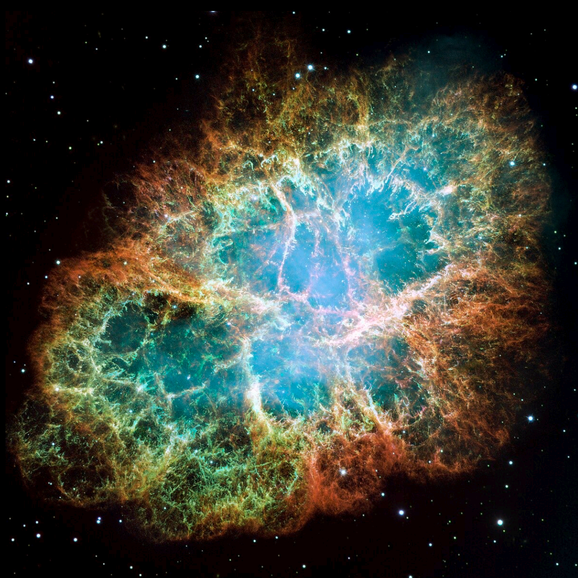
TeV–PeV Frontier

IceCube signals
SNRs, etc.
GRBs, AGN, etc.
cosmic-ray collisions with Sun
dark matter annihilation or decay
surprises

VHE Fluxes: Initial Motivations

(c) The spectacular quasi-stellar radio sources, radio galaxies, and galactic optical synchrotron radiators such as the Crab nebula will be considered as possible candidates for detectable neutrino sources (as well as x ray, γ ray, etc.) as long as their origin remains uncertain. The observed synchrotron radiation suggests the

Malvin Ruderman (1965)



1. *Where are cosmic rays accelerated?*
2. *What are the high-energy sources?*

Key Production Processes

Hadronic mechanism:

$$p + p \rightarrow p + p + \pi^0 \qquad \pi^0 \rightarrow 2\gamma$$

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

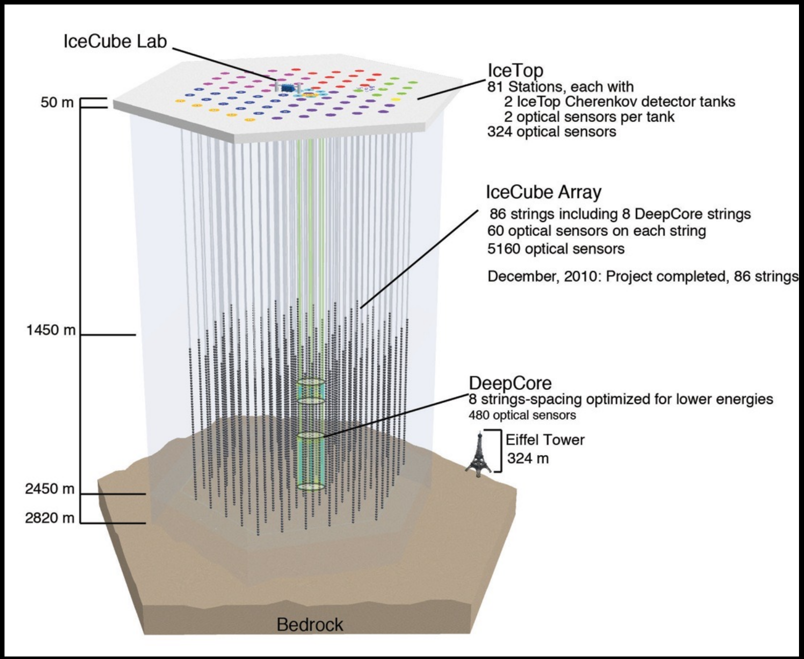
Leptonic mechanism:

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

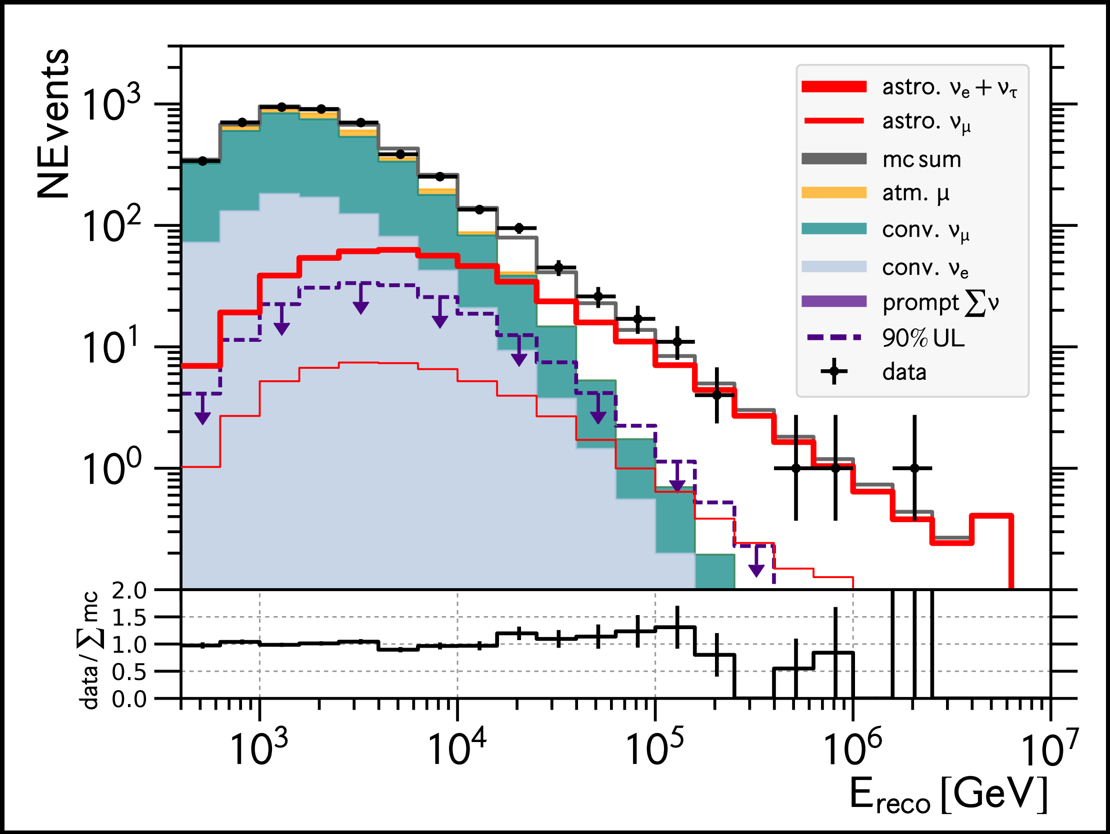
no neutrinos!

Production always makes a mess; propagation makes more

IceCube Discovers Diffuse Neutrino Flux to PeV+

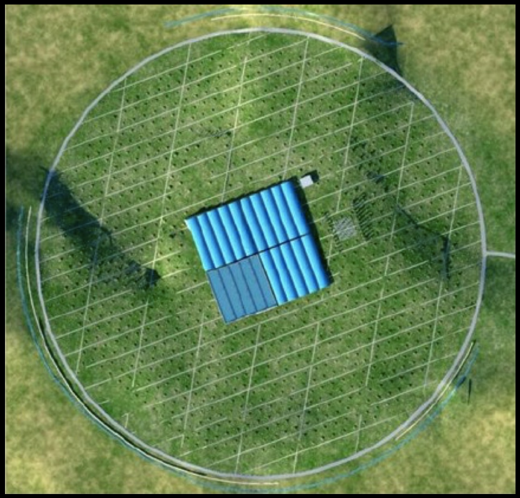


1 km^3 ~ 1 Gton optical array

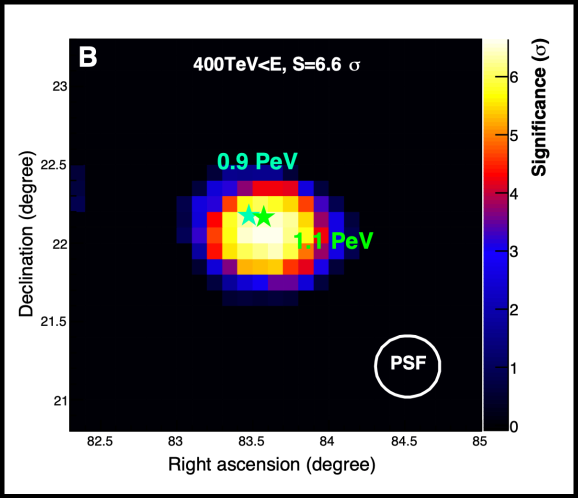


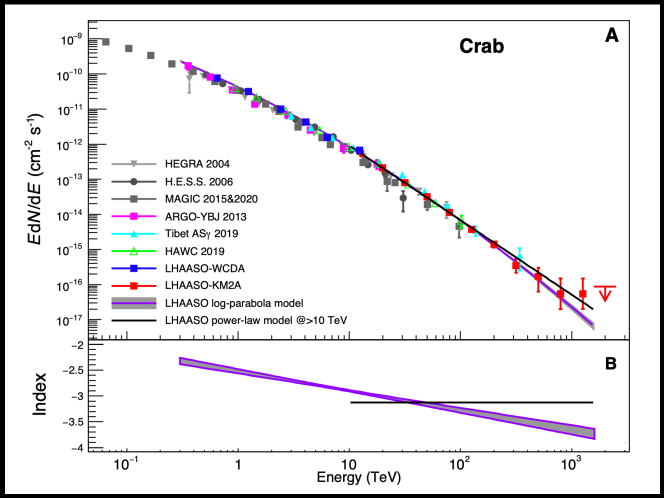
IceCube (2020)

LHAASO Discovers MW Sources to PeV+

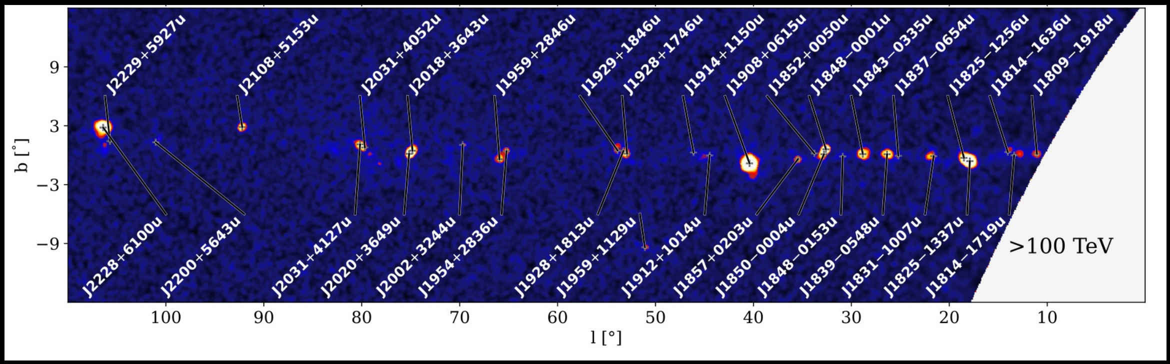


~1 km^2 array





LHAASO (2021)



LHAASO (2024)

New Questions

1. What are the high-energy sources?

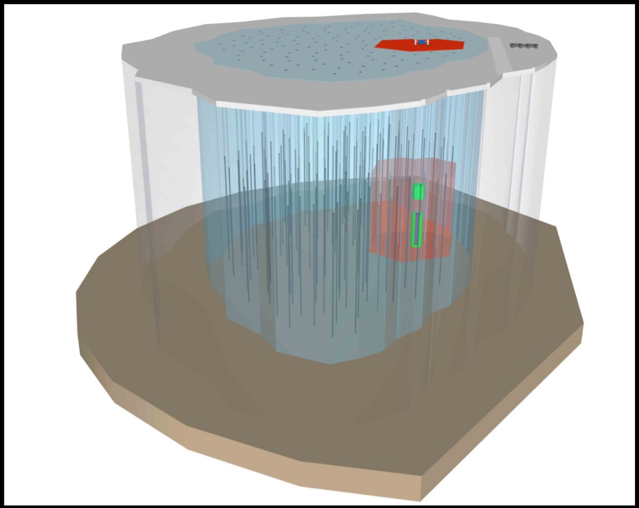
2. Where are cosmic rays accelerated?

x 2 (Galactic and Extragalactic)

3. What are the properties of neutrinos?

Proposed Multi-Gton Neutrino Detectors

IceCube-Gen2



~10 Gton optical array
+ huge surface radio array

Several others:

KM3NeT (Europe, ~1 Gton)

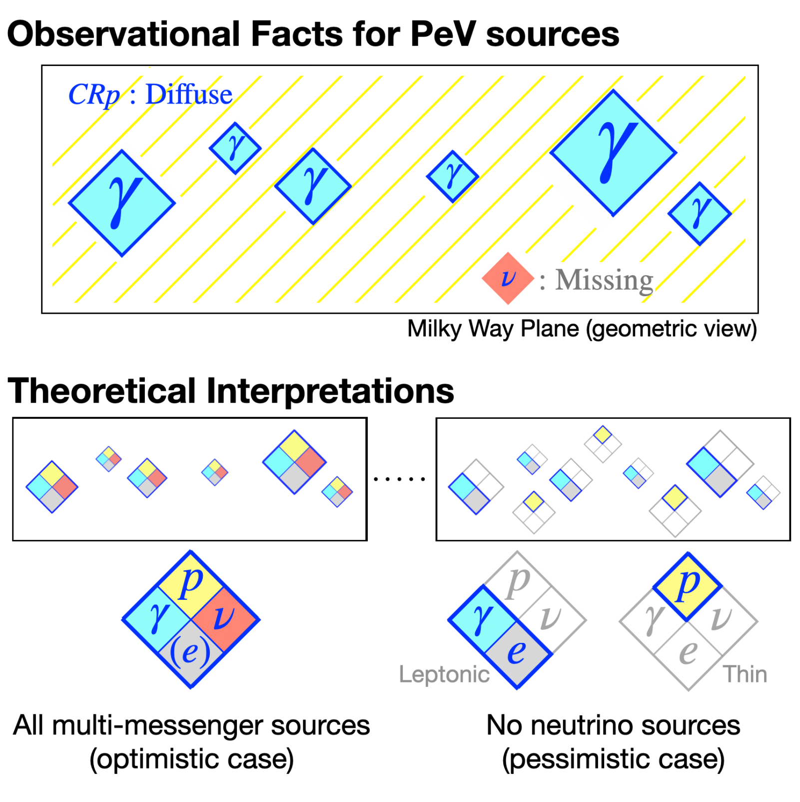
Baikal-GVD (Europe, ~1 Gton)

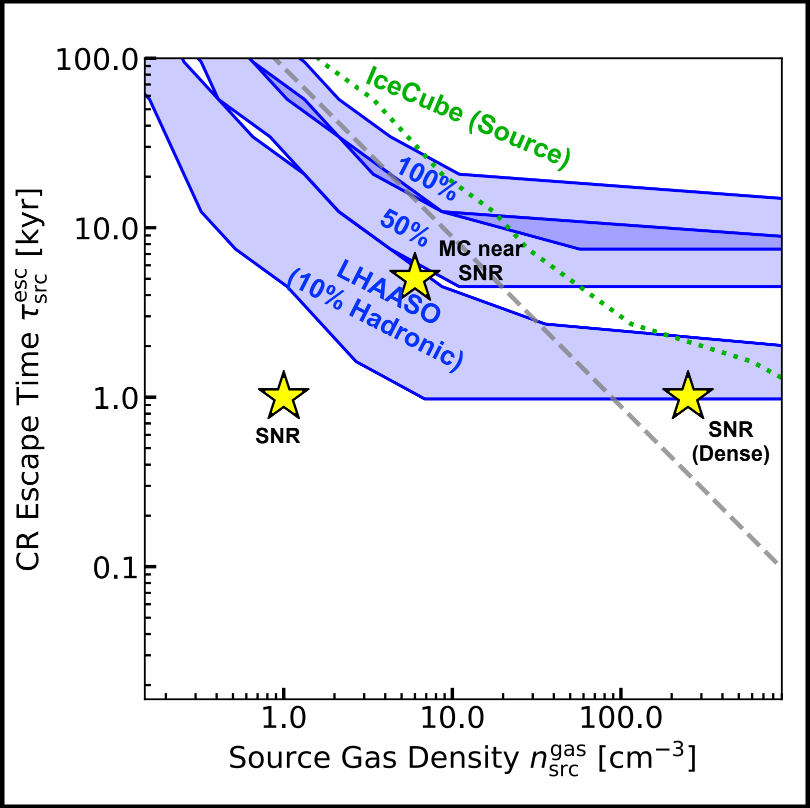
P-ONE (Canada, ~1 Gton)

TRIDENT (China, ~8 Gton)

HUNT (China, ~30 Gton)

Example: Where are the MW PeVatrons?

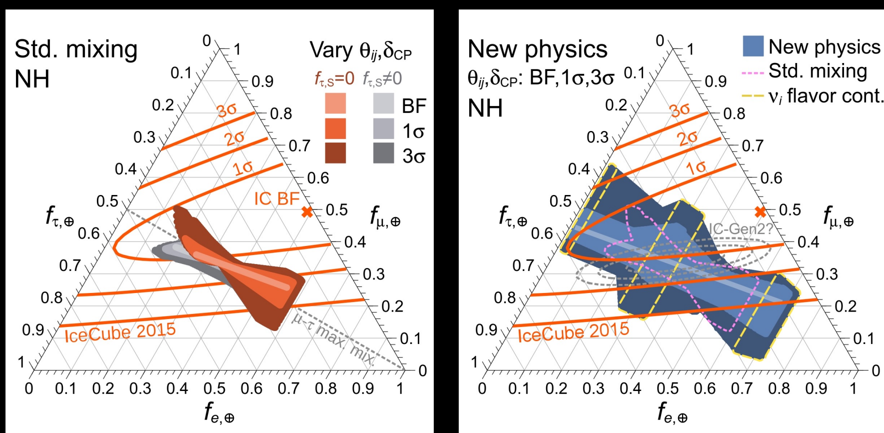




Sudoh and Beacom (2022)

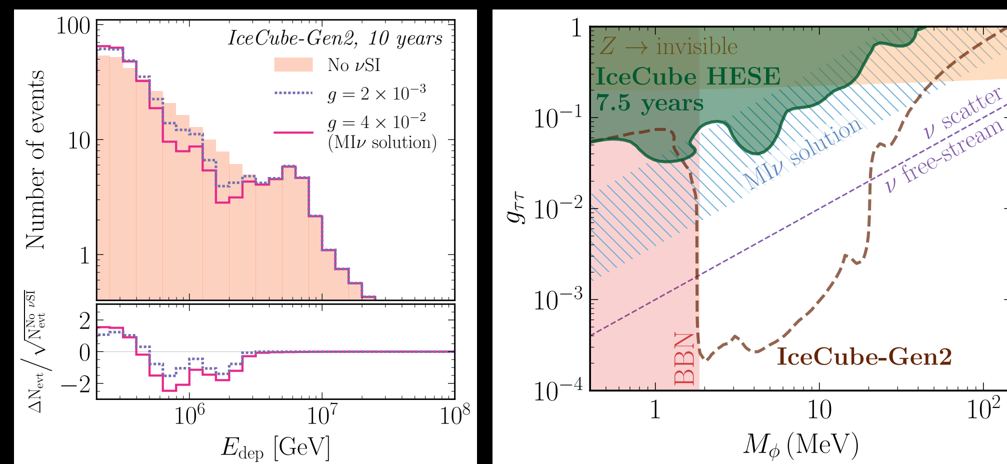
Examples: Testing Neutrino Properties

Neutrino Flavor Probes



Bustamante, Beacom, Winter (2015)

Neutrino Secret Interactions



Esteban, Pandey, Brdar, Beacom (2021)

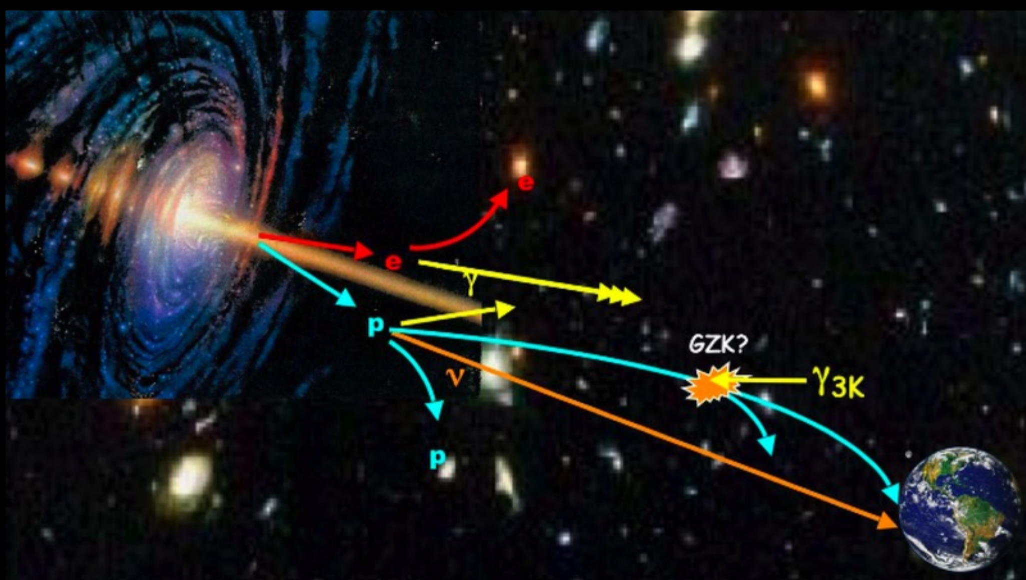
EeV–ZeV Frontier

GZK process
sources of UHE cosmic rays
supermassive dark matter decay
surprises

UHE Fluxes: Initial Motivations

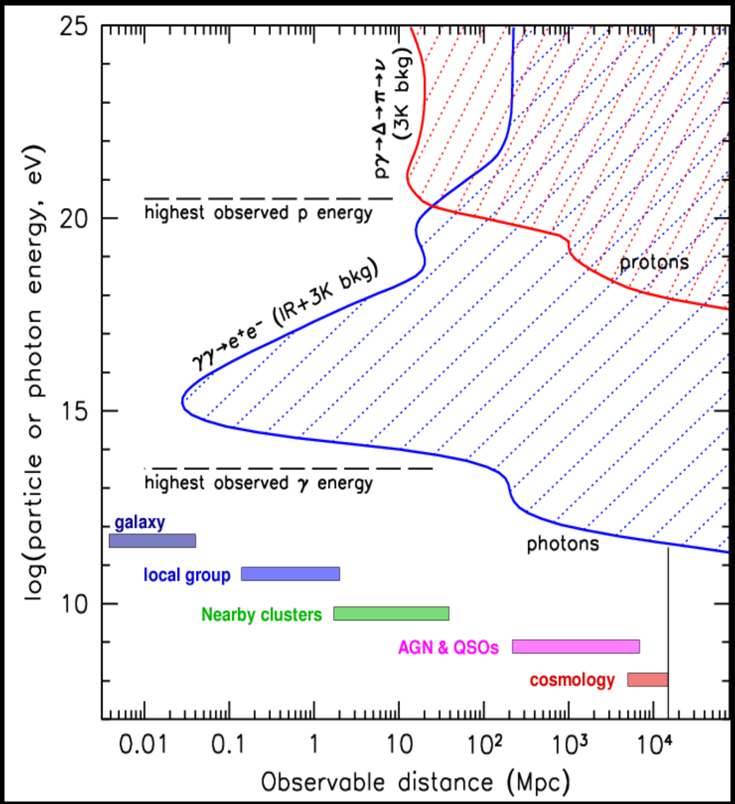
The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

Venya Beresinsky and Georgiy Zatsepin (1969)



1. What accelerates cosmic rays to beyond 10^{20} eV?

Key Production Processes



Gorham (2005)

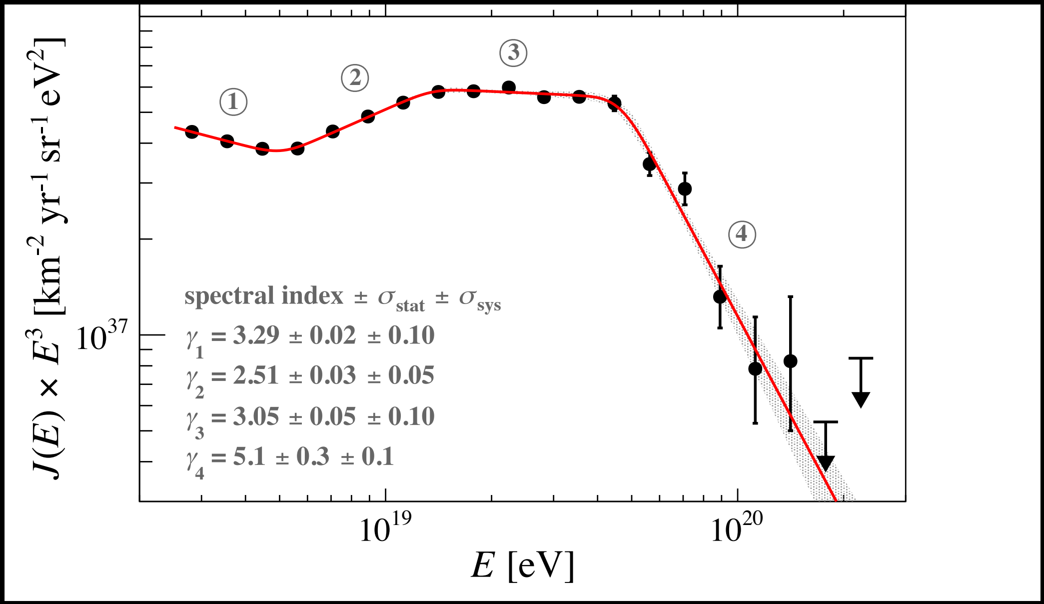
Greisen-Zatsepin-Kuzmin process

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

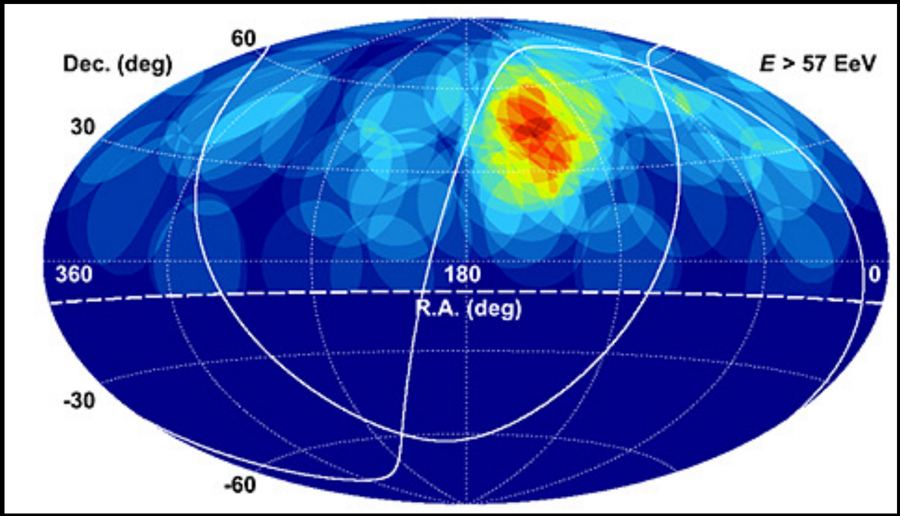
Highest-energy CRs all die

Neutrinos are their ghosts

UHE Cosmic Ray Discoveries

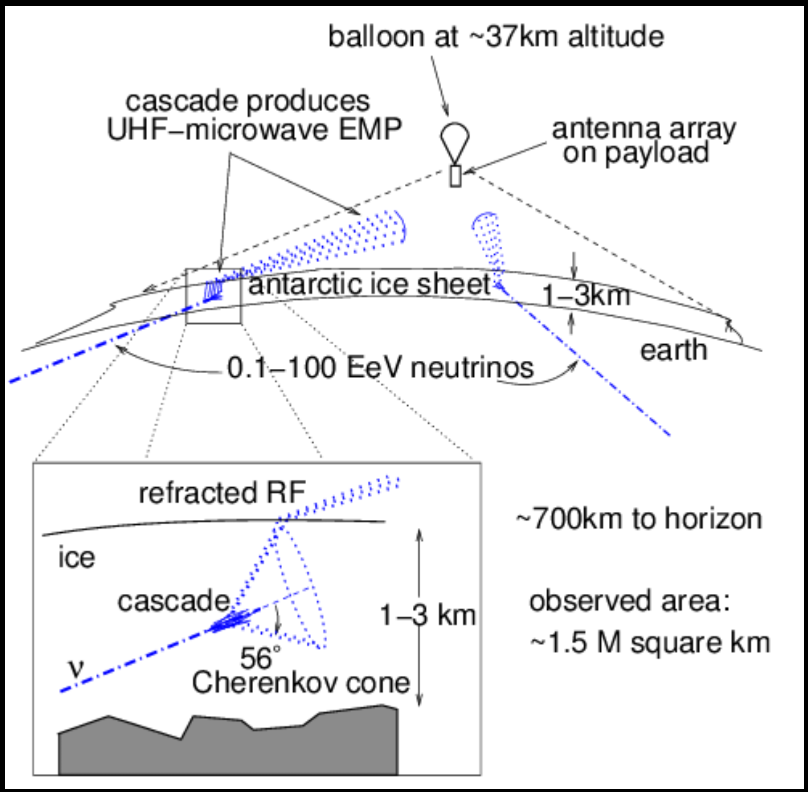


Auger (2020)

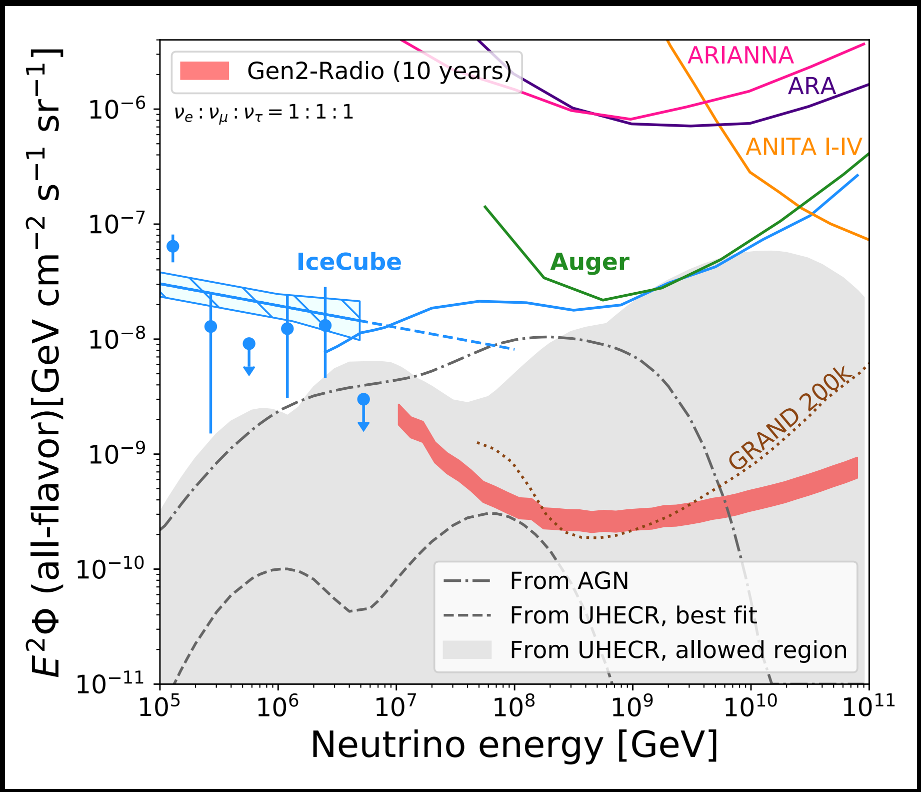


Telescope Array (2019)

UHE Neutrino Limits



ANITA (2019)



IceCube (2020)

New Questions

1. What sources accelerate cosmic rays to ultrahigh energies?

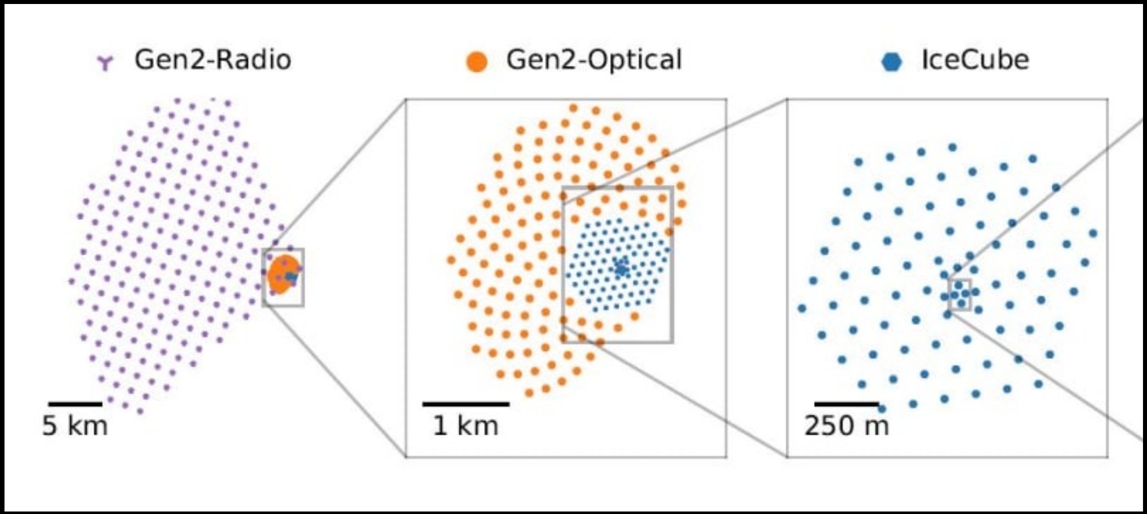
2. What is the cosmic ray composition?

3. What is the cosmic ray sky distribution?

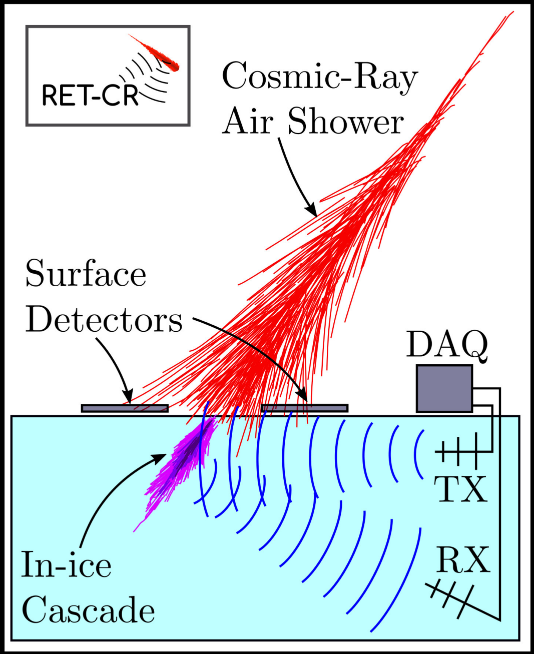
4. What are the properties of neutrinos?

Proposed New Detectors

IceCube-Gen2 Radio

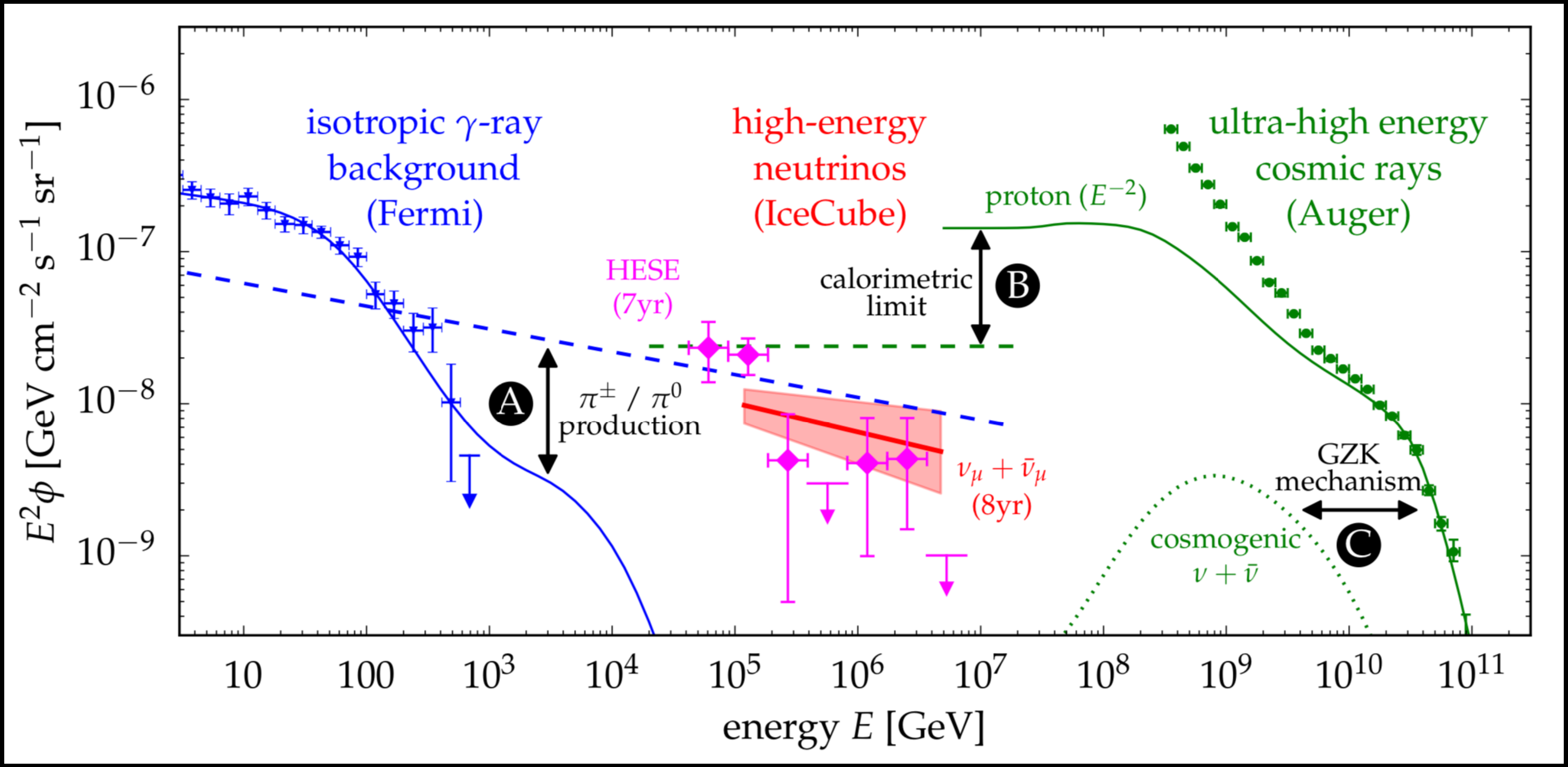


Radar Echo Telescope



And many others!

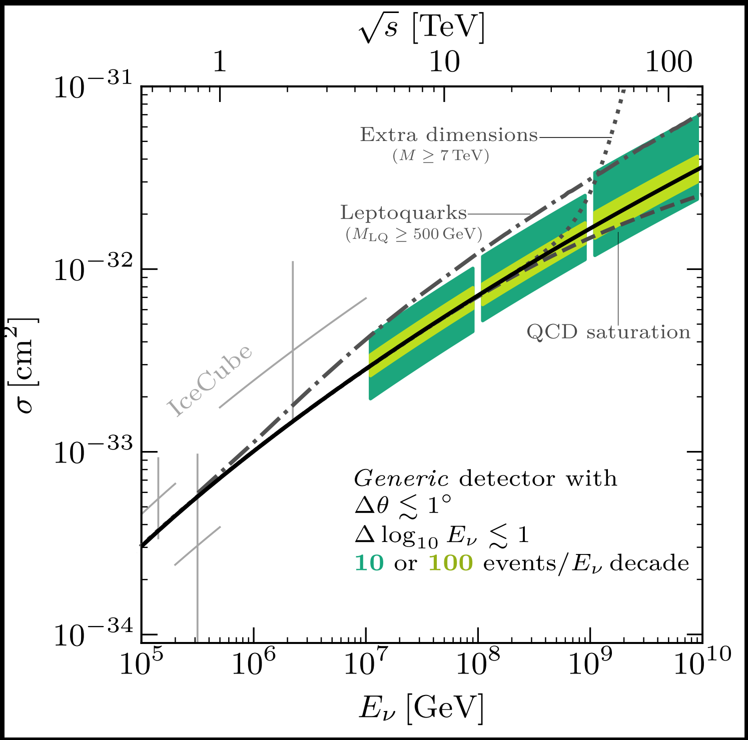
Example: Multi-Messenger Astronomy



Ahlers (2018)

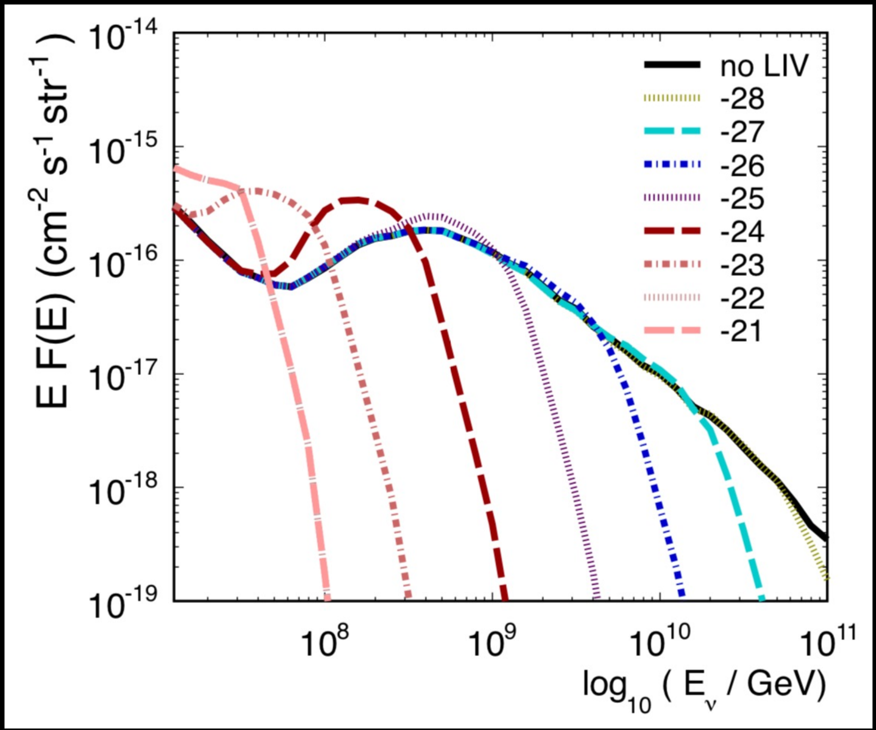
Examples: Testing Neutrino Properties

Cross Section



Esteban, Prohira, Beacom (2022)

Lorentz Invariance Violation



Gorham et al. (2012)

Concluding Remarks

The Good News

- We have a variety of sources and great prospects for more
- Key problems in astronomy can only be solved with neutrinos
- Key problems in physics can only be solved with neutrinos
- Future observations may easily yield surprises

The Challenging News

Four eras of neutrino astronomy, with different areas of focus:

1. Heroic past: astronomy
2. Recent past: neutrino mixing
3. Present: neutrino mixing, astronomy, and new physics
4. Near future: *maybe only astronomy and new physics*

Our chance to detect a Milky Way supernova may end with the completion of the laboratory-neutrino missions of JUNO, Hyper-K, and DUNE. We must build a case for the future based on solar, DSNB, and tests of new physics.

Closing Message

Neutrinos take patience, but they reward it richly

Center for Cosmology and AstroParticle Physics

CCAPP

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

Columbus, Ohio: 1 million people (city), 2 million people (metro area)
Ohio State University: 60,000 students
CCAPP: 30 faculty, 20 postdocs, 45 students
Recent/incoming faculty: Tyler Gorda, Ryan Plestid, Yuan-Sen Ting, Zoya Vallari
Placements: CCAPP postdoc and student alumni are in top jobs worldwide
Culture: Highly interactive, connected, and supportive

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