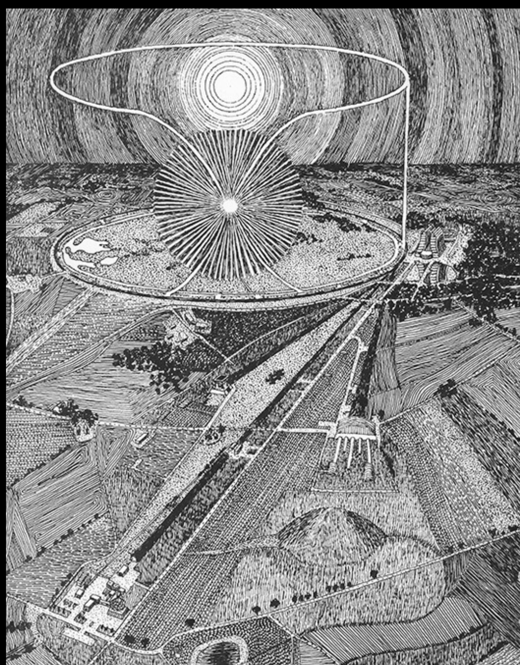
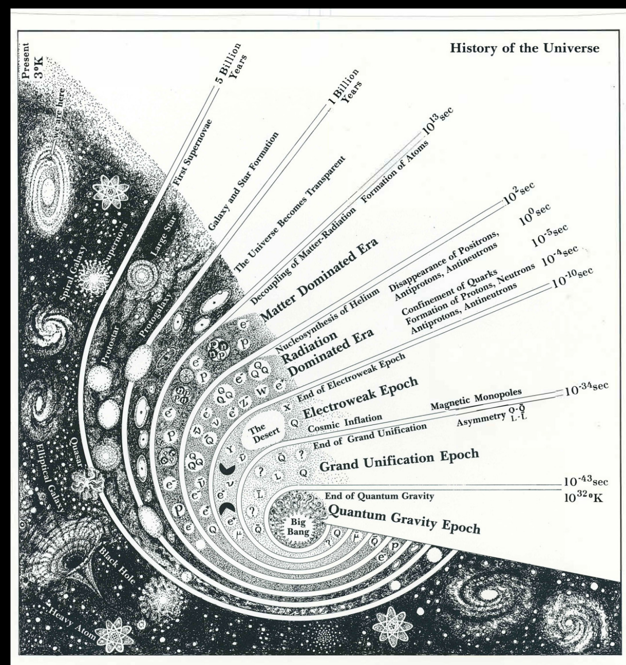
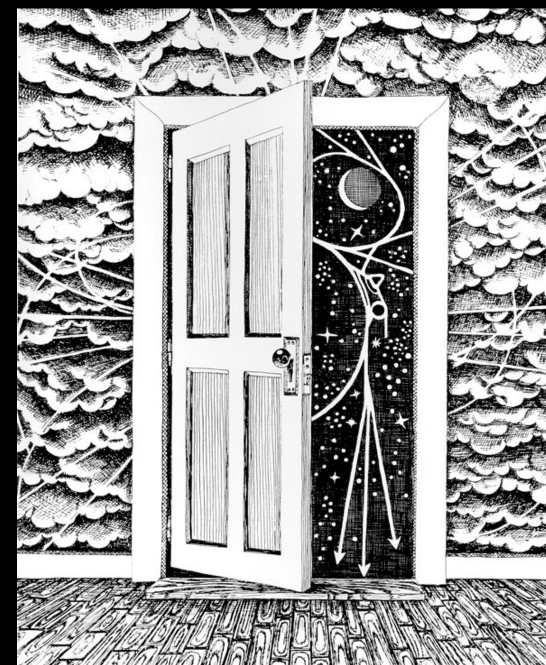
High-Energy Neutrino Astrophysics: Frontiers

John Beacom, The Ohio State University







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

CCAPP

NSF

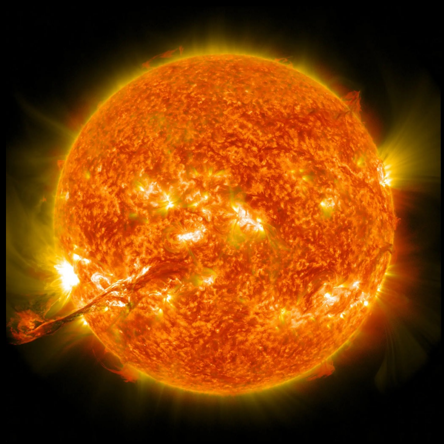
Neutrino Astronomy – Unique Impact

To understand astrophysics,
only neutrinos can reveal these extreme conditions

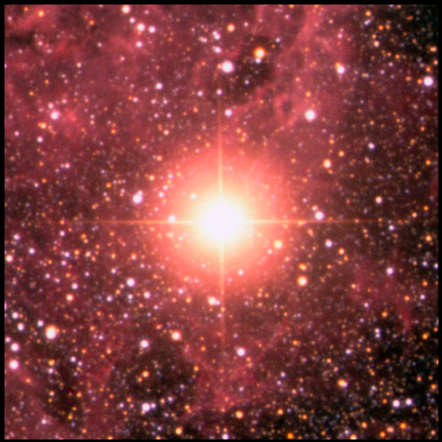
To understand neutrinos,
only these extreme conditions can reveal particle properties

Is Neutrino Astronomy Real?

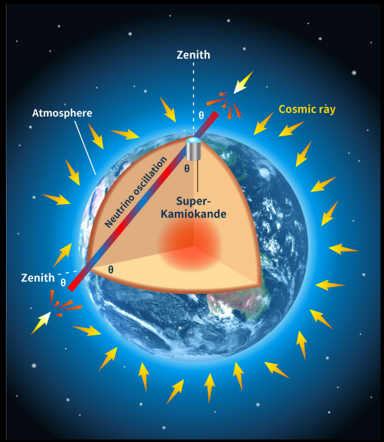
Sun



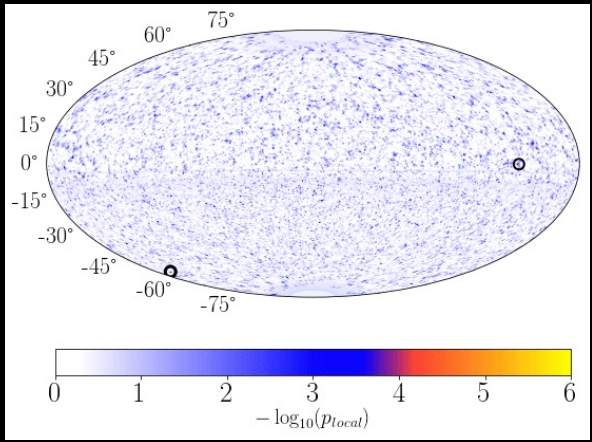
SN 1987A



Atmosphere



Extragalactic Sources



How do we make this list bigger and better?

Outline

Opening
Neutrino astrophysics

Towards …
better measurements
better astrophysics
better particle physics

broader neutrino science

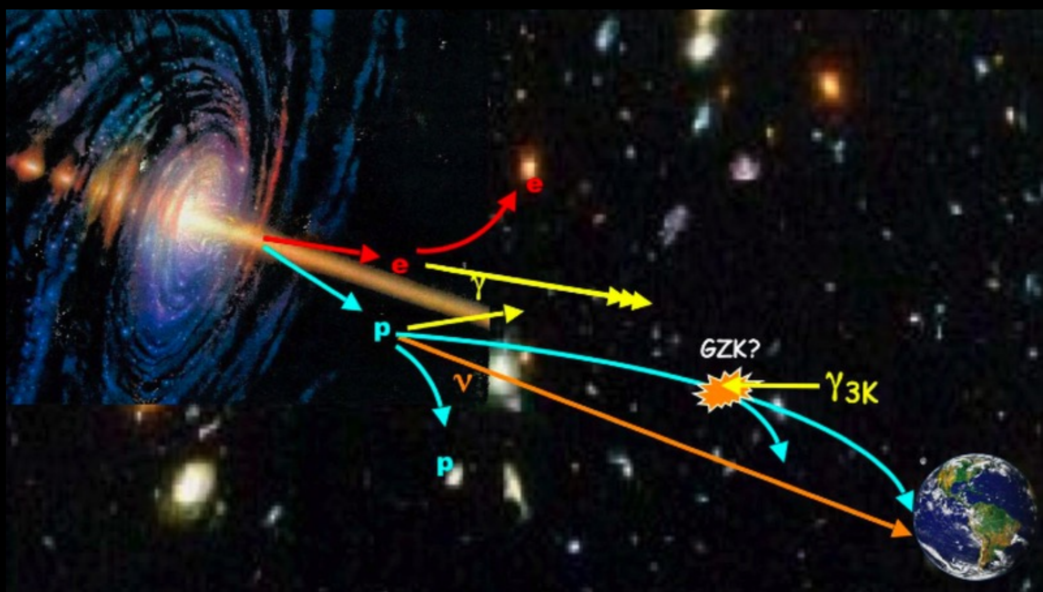
Towards Better Measurements

Example of higher energies

UHE Fluxes: Initial Motivations

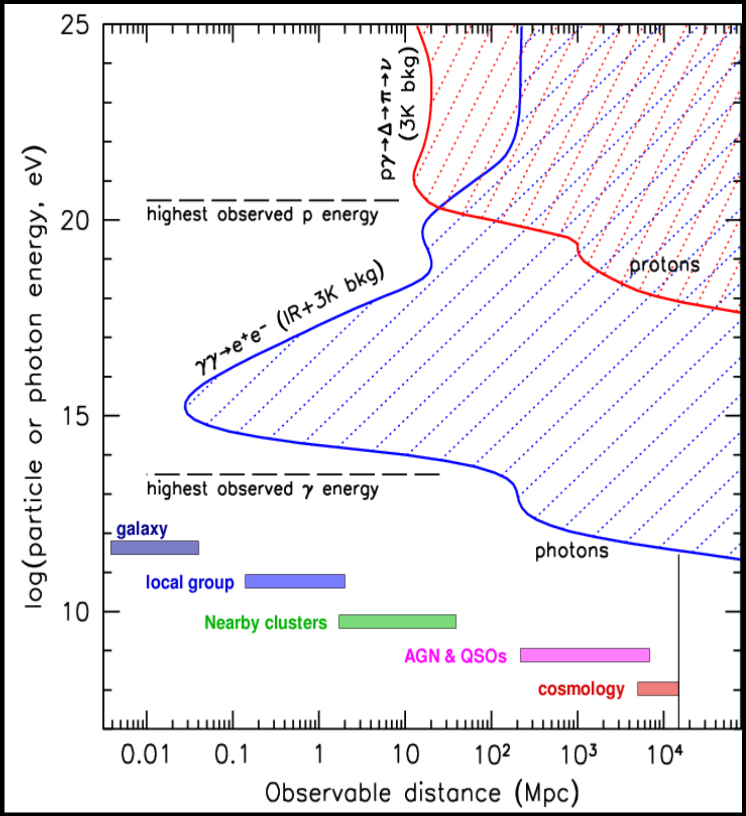
The neutrino spectrum produced by protons on microwave photons is calculated. A spectrum of extensive air shower primaries can have no cut-off at an energy $E > 3 \times 10^{19}$ eV, if the neutrino-nucleon total cross-section rises up to the geometrical one of a nucleon.

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

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

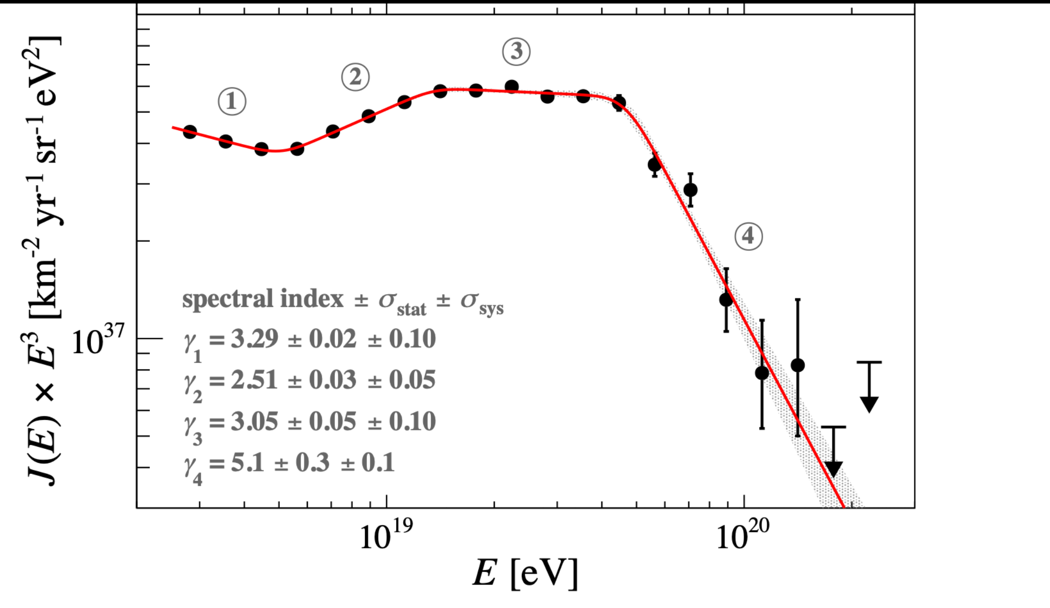
Highest-energy CRs all die

Neutrinos are their ghosts

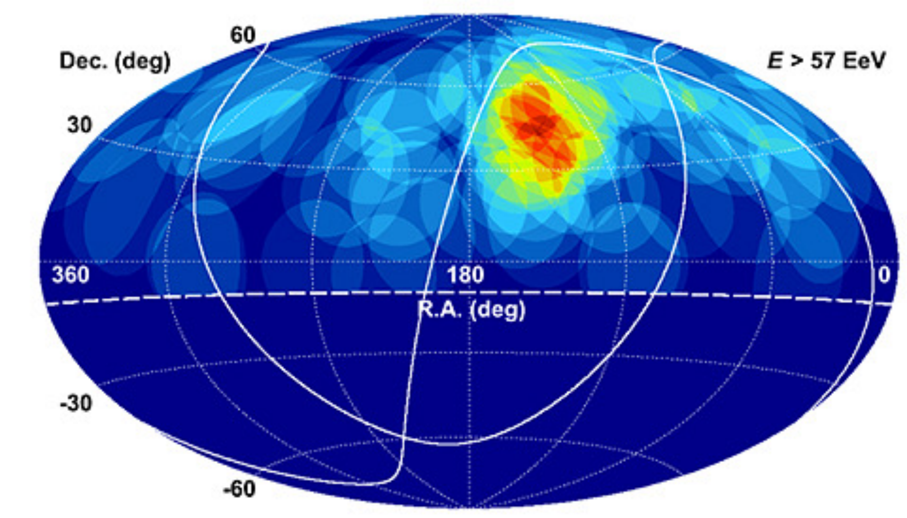
Offline homework:

Threshold energy for this?

UHE Cosmic Ray Discoveries

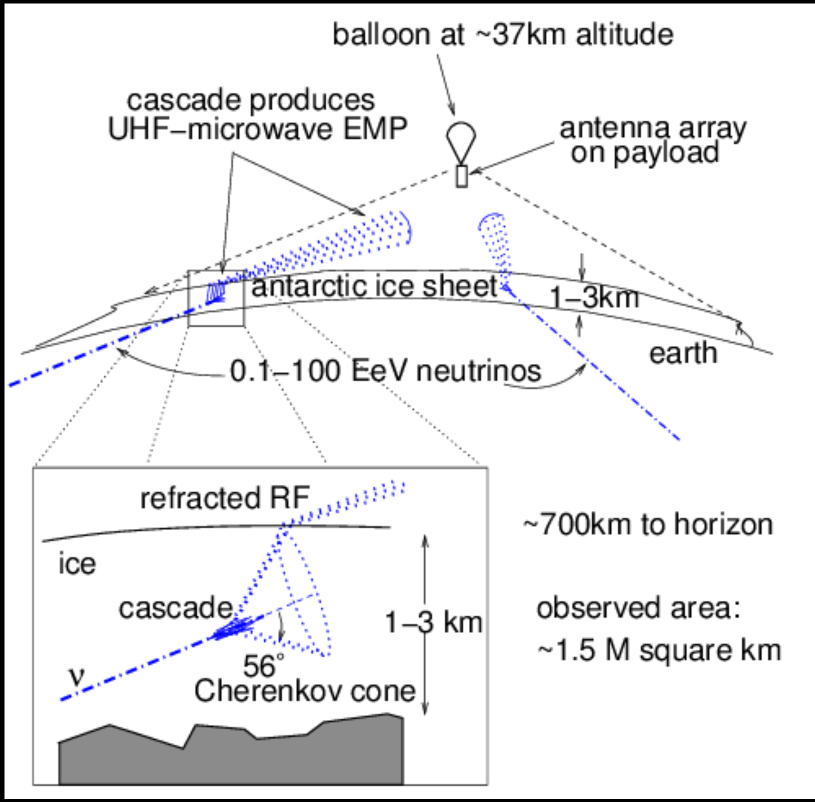


Auger (2020)

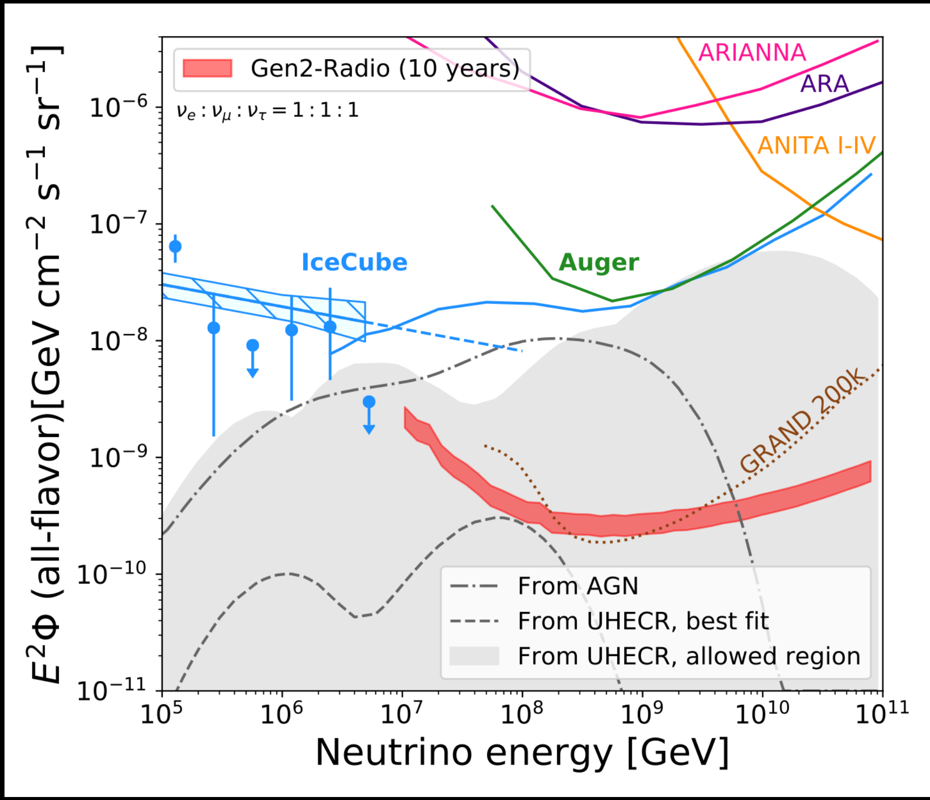


Telescope Array (2019)

UHE Neutrino Limits



ANITA (2019)



IceCube (2020)

New Questions

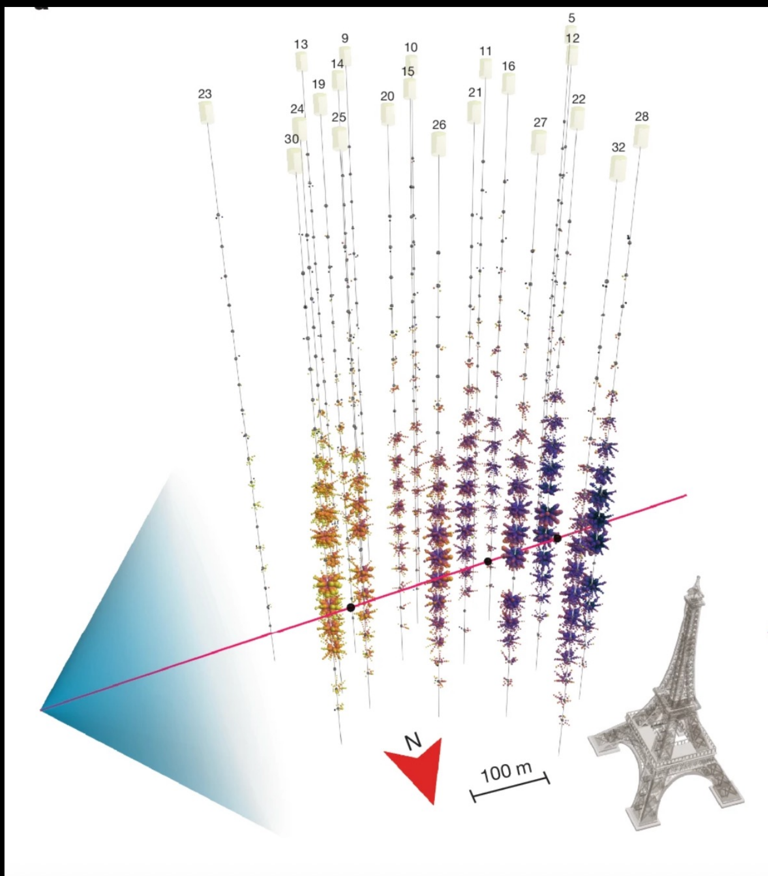
1. What sources accelerate cosmic rays to ultrahigh energies?

2. What is the cosmic ray composition?

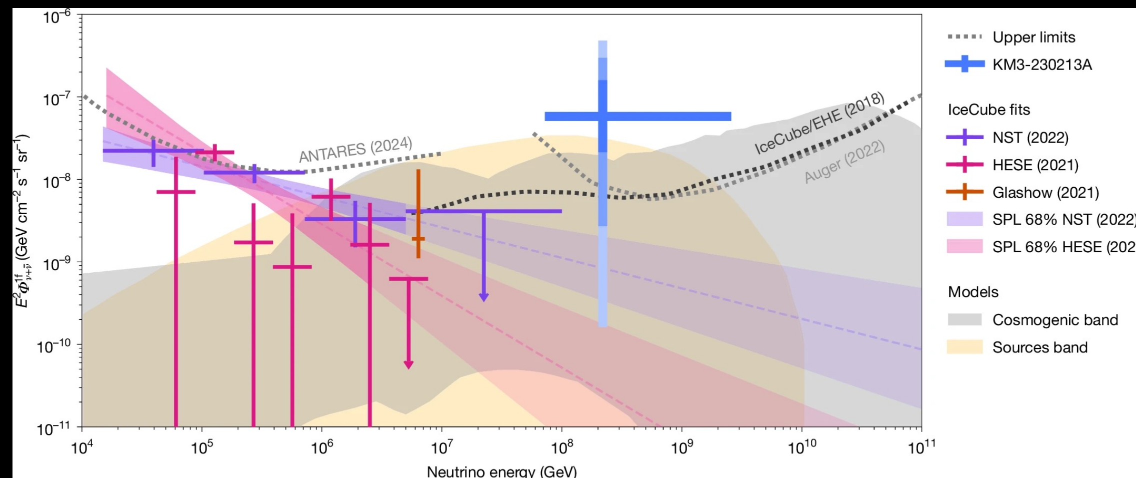
3. What is the cosmic ray sky distribution?

4. What are the properties of neutrinos?

KM3NeT Event



KM3NeT (2024)

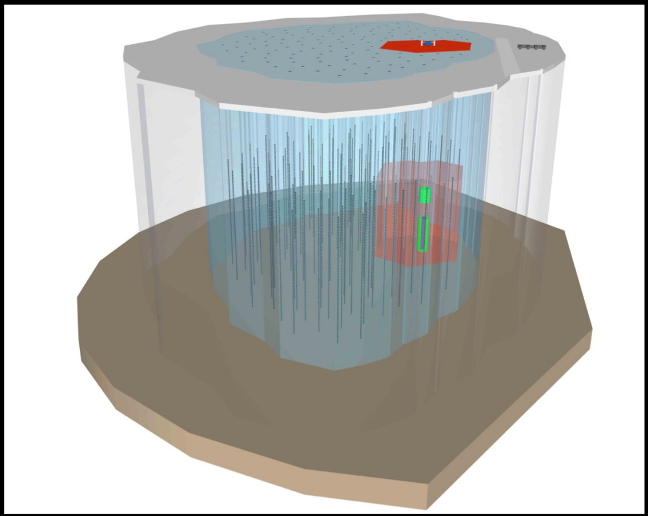


Before: IceCube found events up to several PeV
After: KM3NeT found one event at 120 PeV with *much less exposure*

Puzzling but exciting, and would be very lucky

Proposed Multi-Gton Neutrino Detectors

IceCube-Gen2



~10 Gton optical array
+ huge surface radio array

Several others:

KM3NeT (Europe, ~1 Gton)

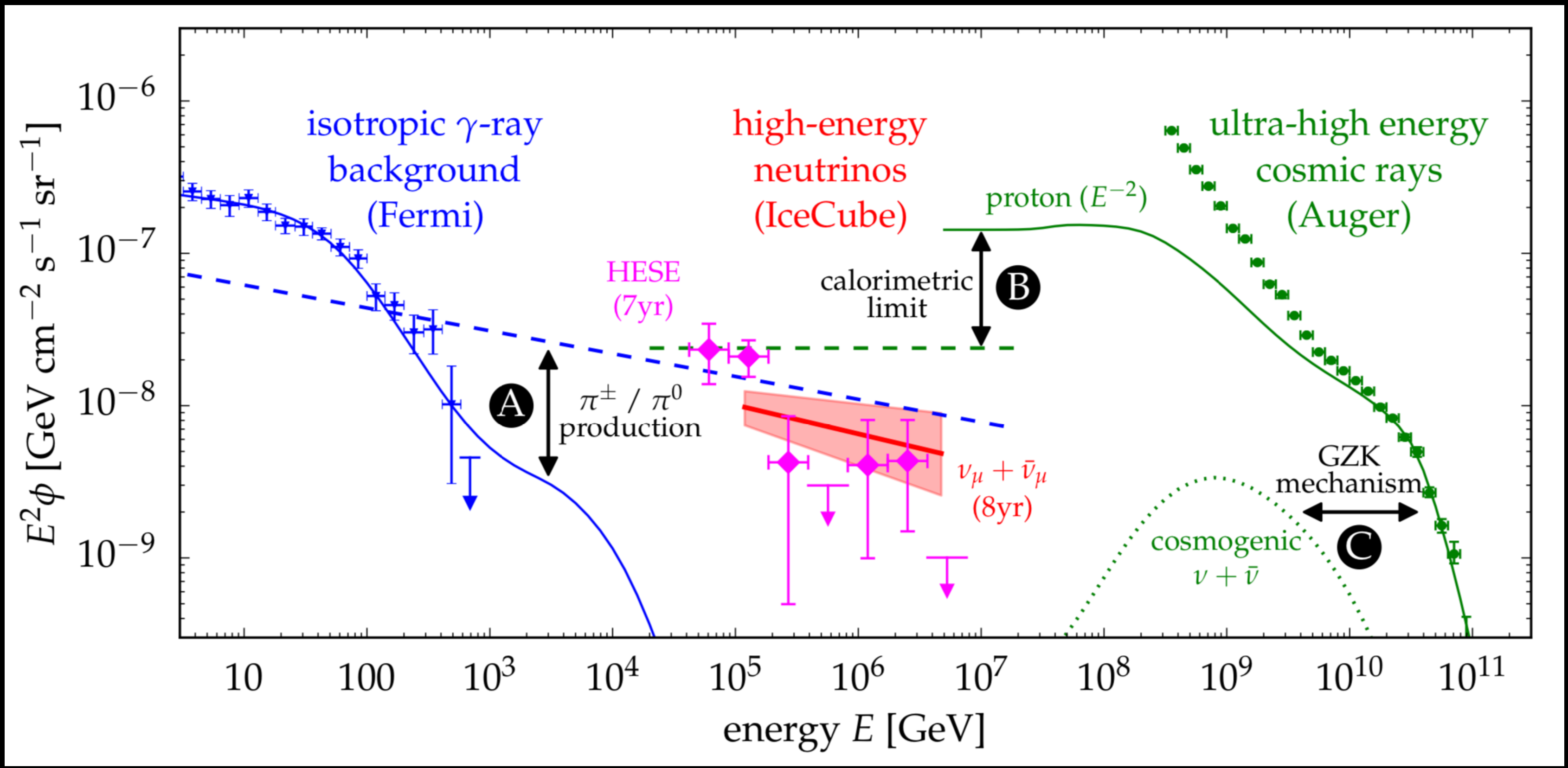
Baikal-GVD (Europe, ~1 Gton)

P-ONE (Canada, ~1 Gton)

TRIDENT (China, ~8 Gton)

HUNT (China, ~30 Gton)

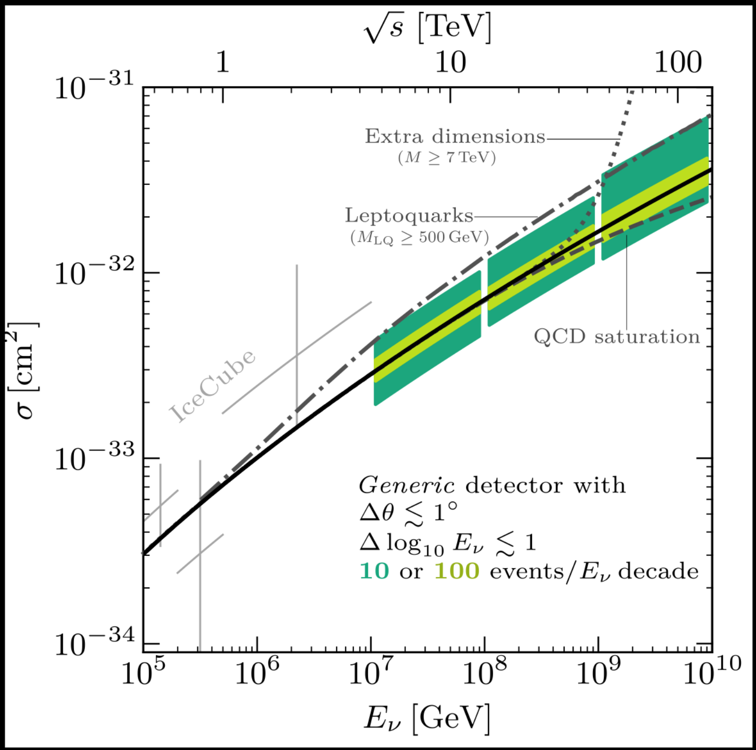
Example: Multi-Messenger Astronomy



Ahlers (2018)

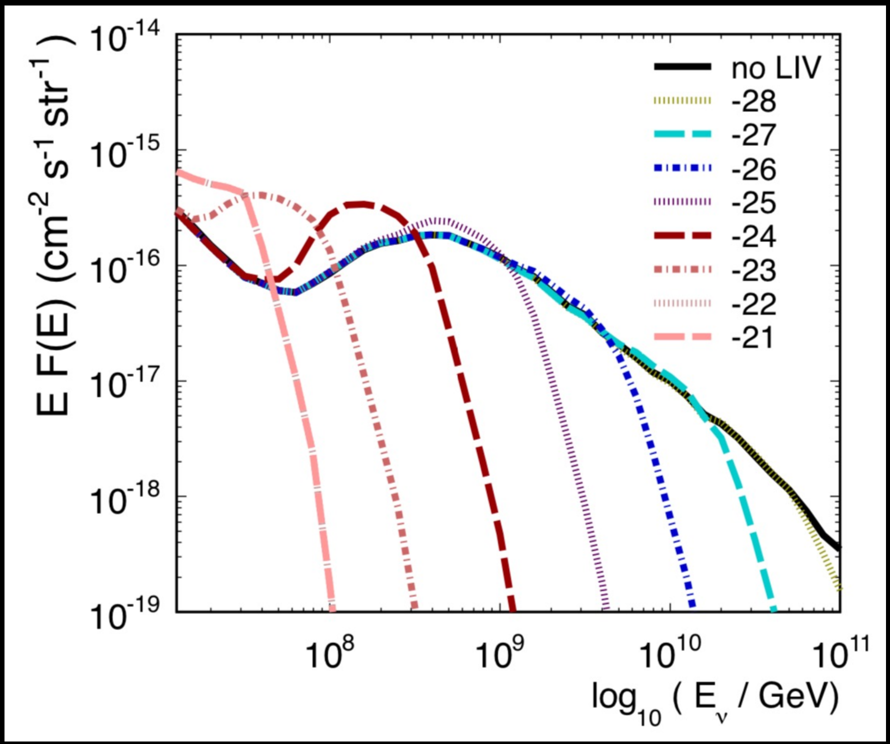
Examples: Testing Neutrino Properties

Cross Section



Esteban, Prohira, Beacom (2022)

Lorentz Invariance Violation

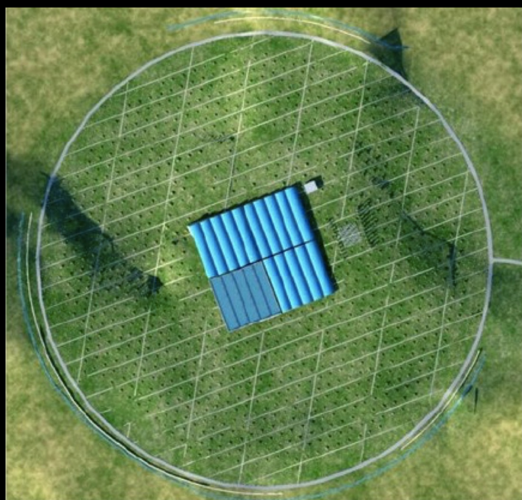


Gorham et al. (2012)

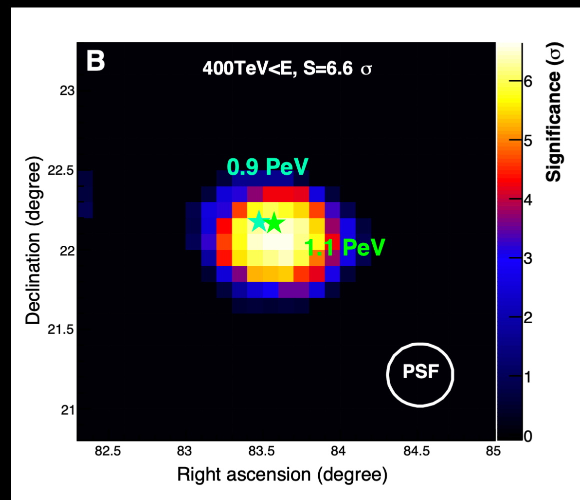
Towards Better Astrophysics

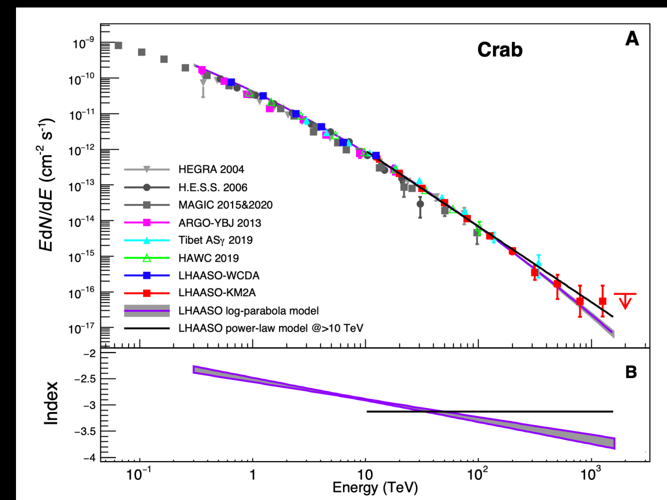
Example of Milky Way sources

LHAASO Discovers MW Sources to PeV+



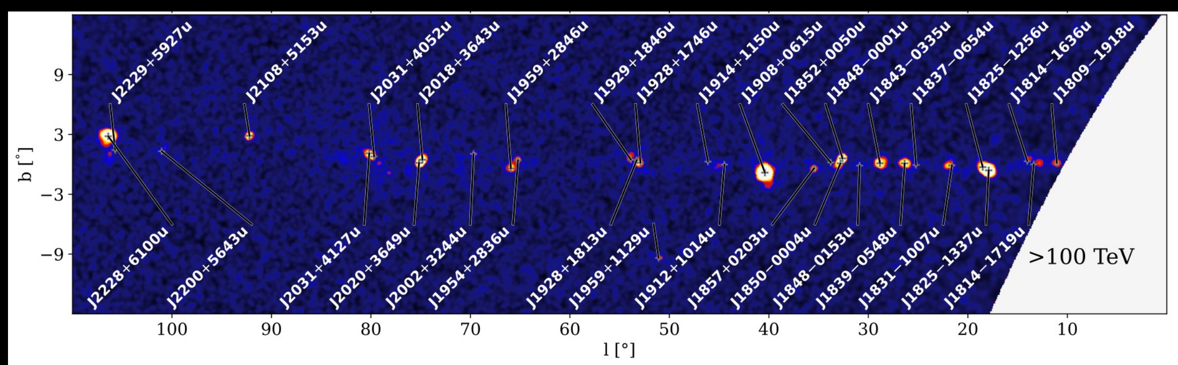
~1 km^2 array



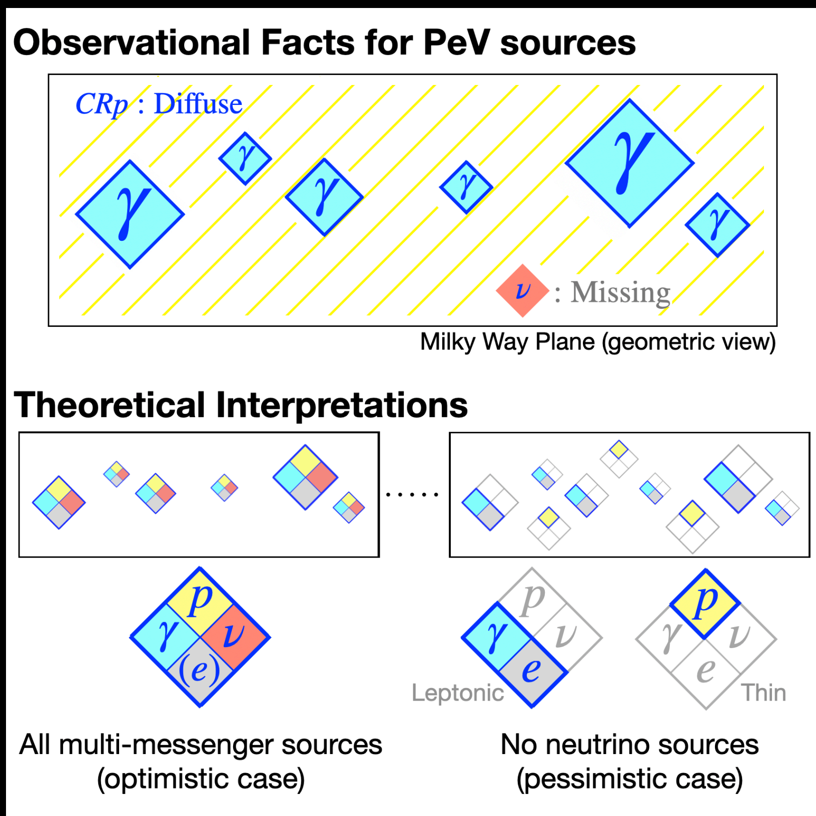


LHAASO (2021)

LHAASO (2024)



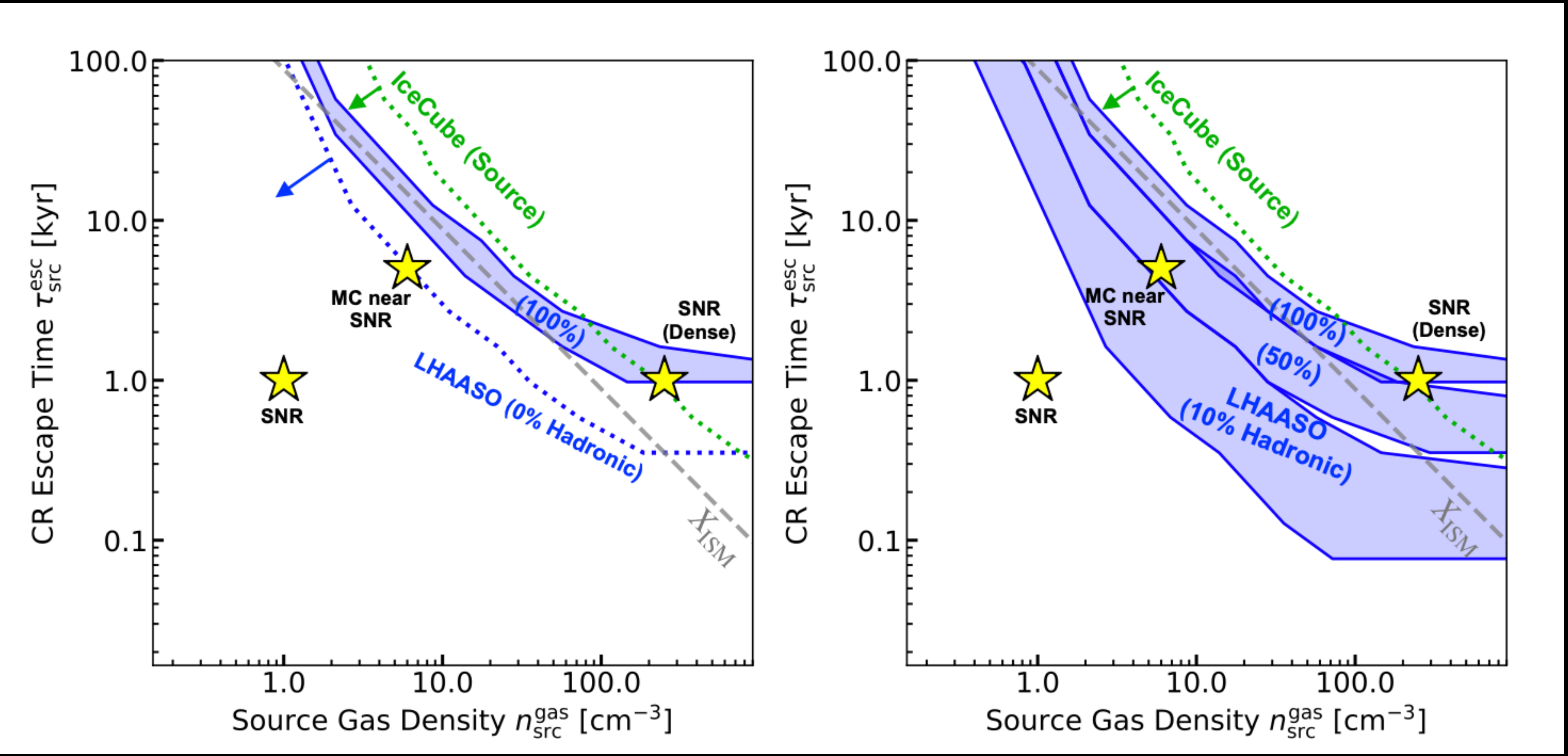
Where Are the Milky Way PeVatrons?



Sudoh and Beacom (2022)

This paper outlines a systematic new approach to connect multi-messenger observations in cosmic-rays, gamma-ray, and neutrinos. What do those joint data tell us about possible PeVatron hadonic cosmic ray accelerators in the Milky Way?

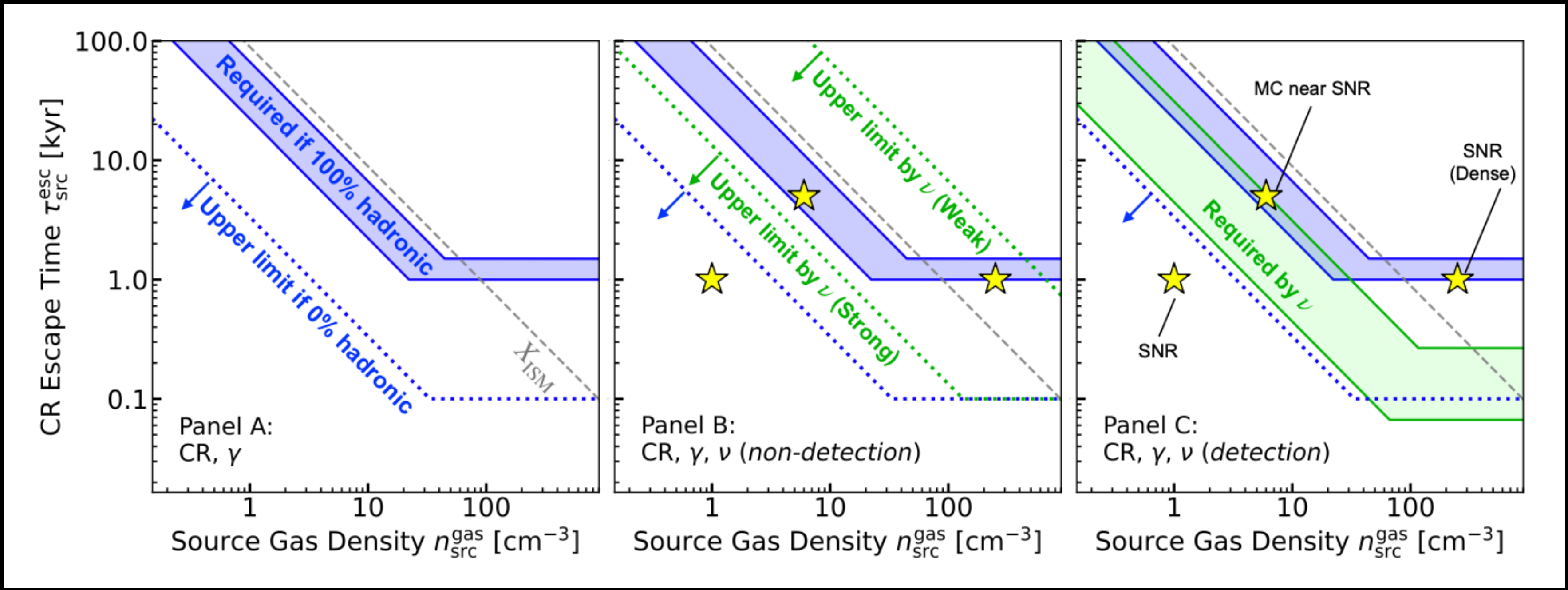
Example of Present Constraints



Sudoh and Beacom (2022)

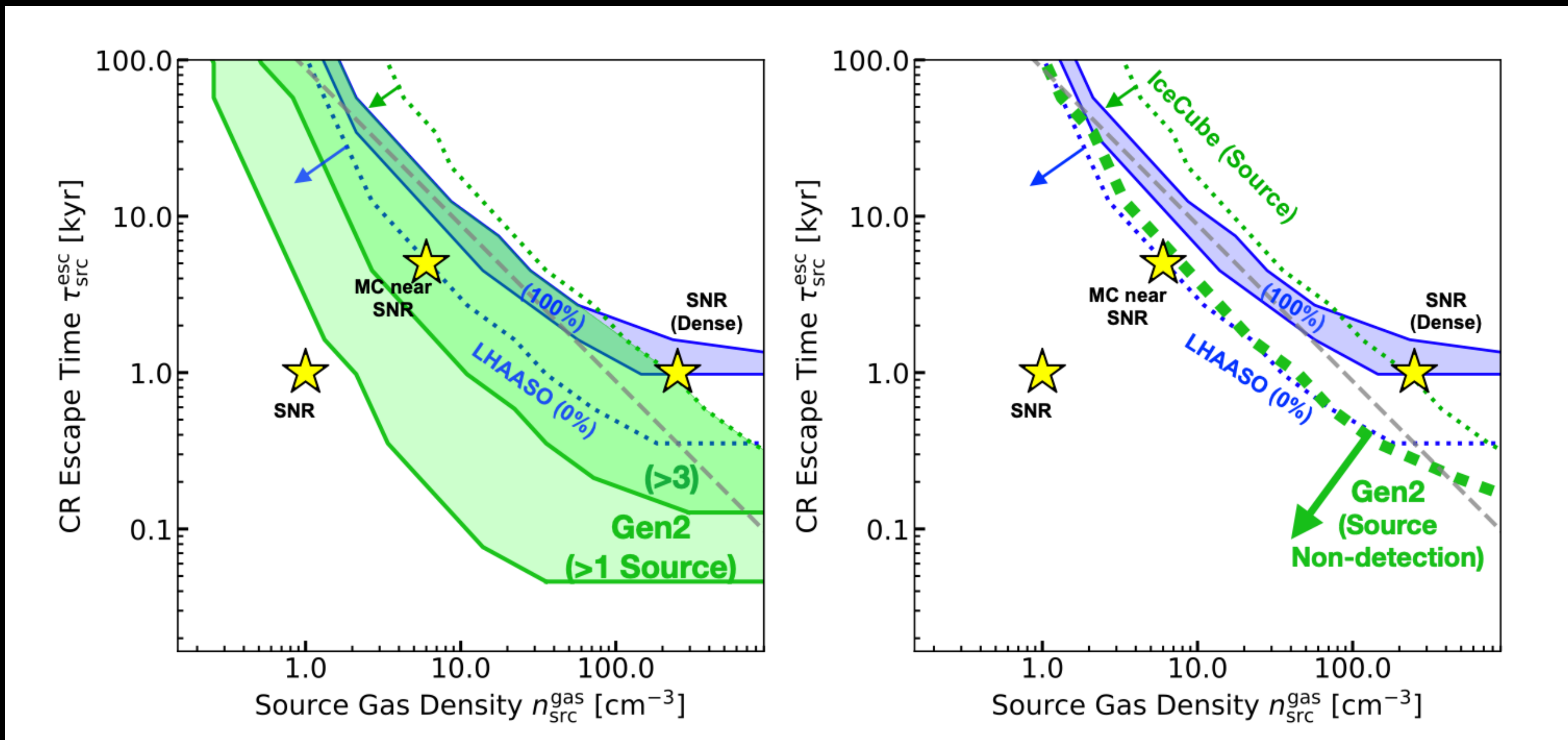
What Types of Sources Are Allowed?

We generically characterize sources by their gas density and CR escape time



Sudoh and Beacom (2022)

Example of Future Sensitivity



Sudoh and Beacom (2022)

Towards Better Particle Physics

Example of neutrino self-interactions

Neutrino Self Interactions (nuSI)

Neutrino interactions with matter are weak …

… but could neutrino interactions with neutrinos be strong?

Supernova SN 1987a and the Secret Interactions of Neutrinos #45

Edward W. Kolb (Rome Observ. and Fermilab and Chicago U., Astron. Astrophys. Ctr.), Michael S. Turner (Fermilab and Chicago U., Astron. Astrophys. Ctr. and Chicago U. and Chicago U., EFI) (Jul, 1987)

Published in: *Phys.Rev.D* 36 (1987) 2895

pdf links DOI cite claim reference search 159 citations

Do Neutrinos Interact between Themselves? #11

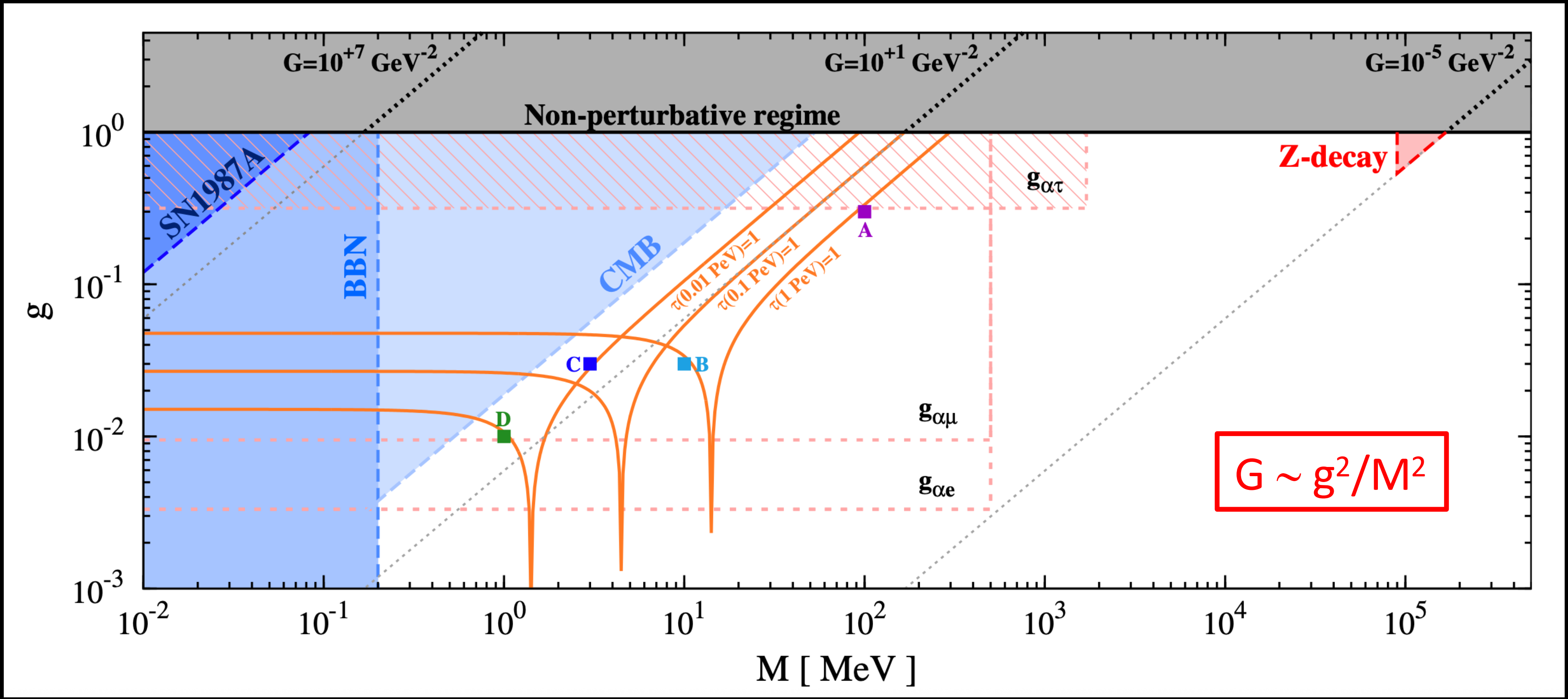
Z. Bialynicka-Birula (Warsaw, Inst. Phys.) (Sep, 1964)

Published in: *Nuovo Cim.* 33 (1964) 1484-1487

DOI cite claim reference search 30 citations

* Ignore worries about $SU(2)_L$ invariance requiring strong self interactions among *electrons* :)

Step One: Organize the Parameter Space



Ng and Beacom (2014)

Step Two: Choose a Setup

To probe new parameter space, we need:

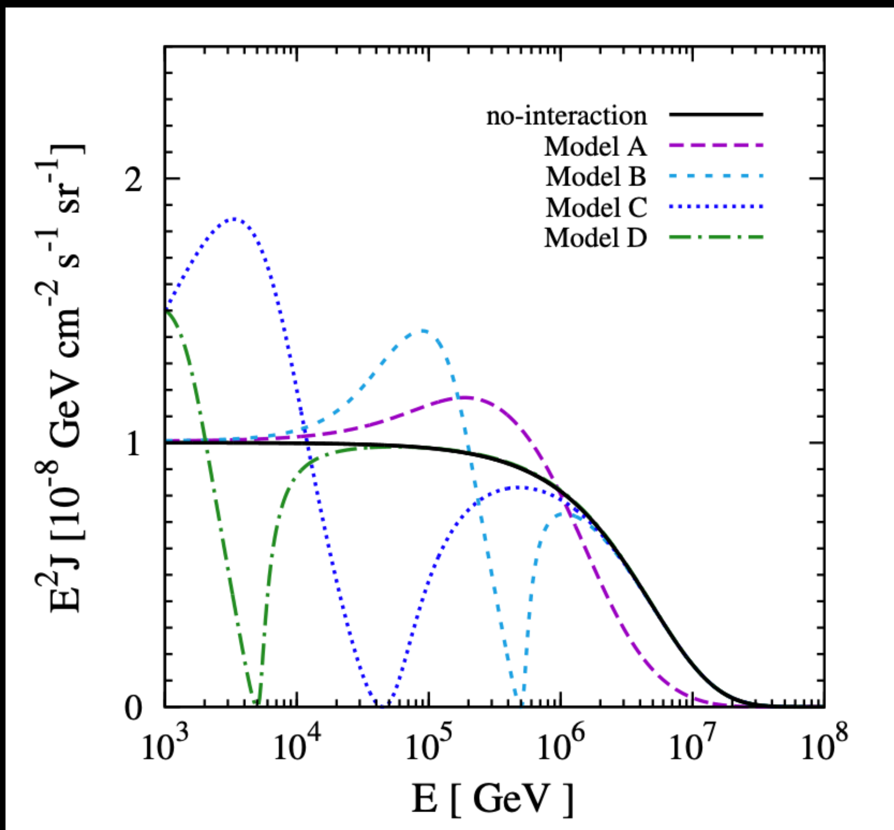
Large column density of neutrino targets
High energy neutrino beam to probe large mediator masses
Distinctive observables for nuSI effects on beam

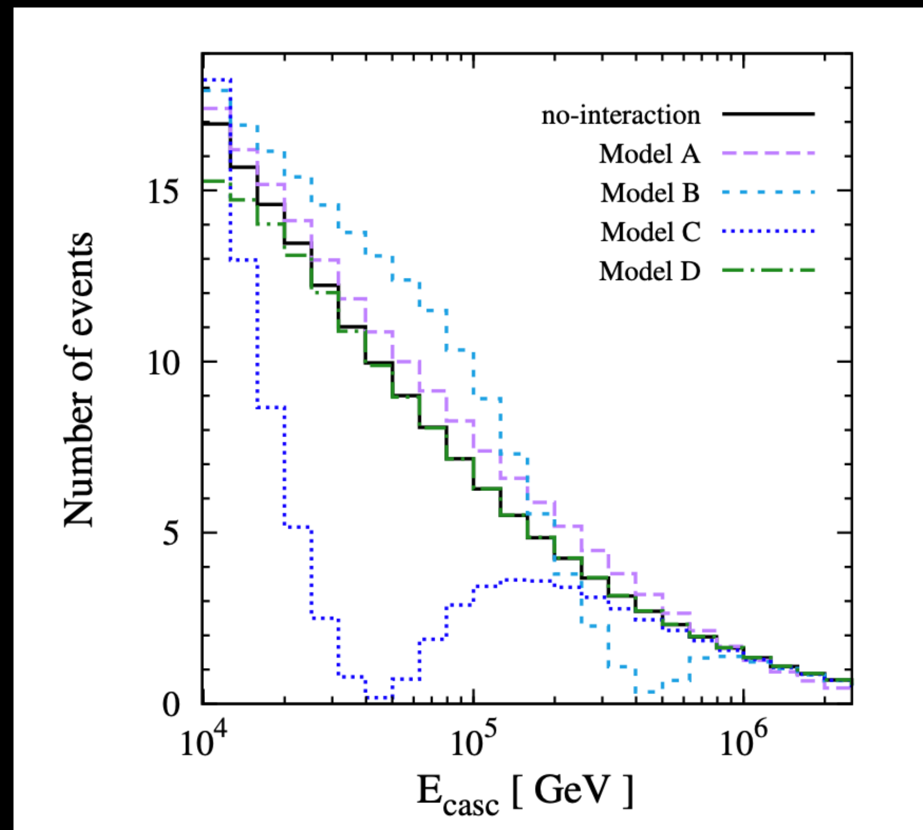
So how about this?

Targets are relic neutrinos
Beam is IceCube diffuse flux
Effects are dips in spectrum

Ng and Beacom (2014)
Ioka and Murase (2014)
Cherry, Friedland, Shoemaker (2014)

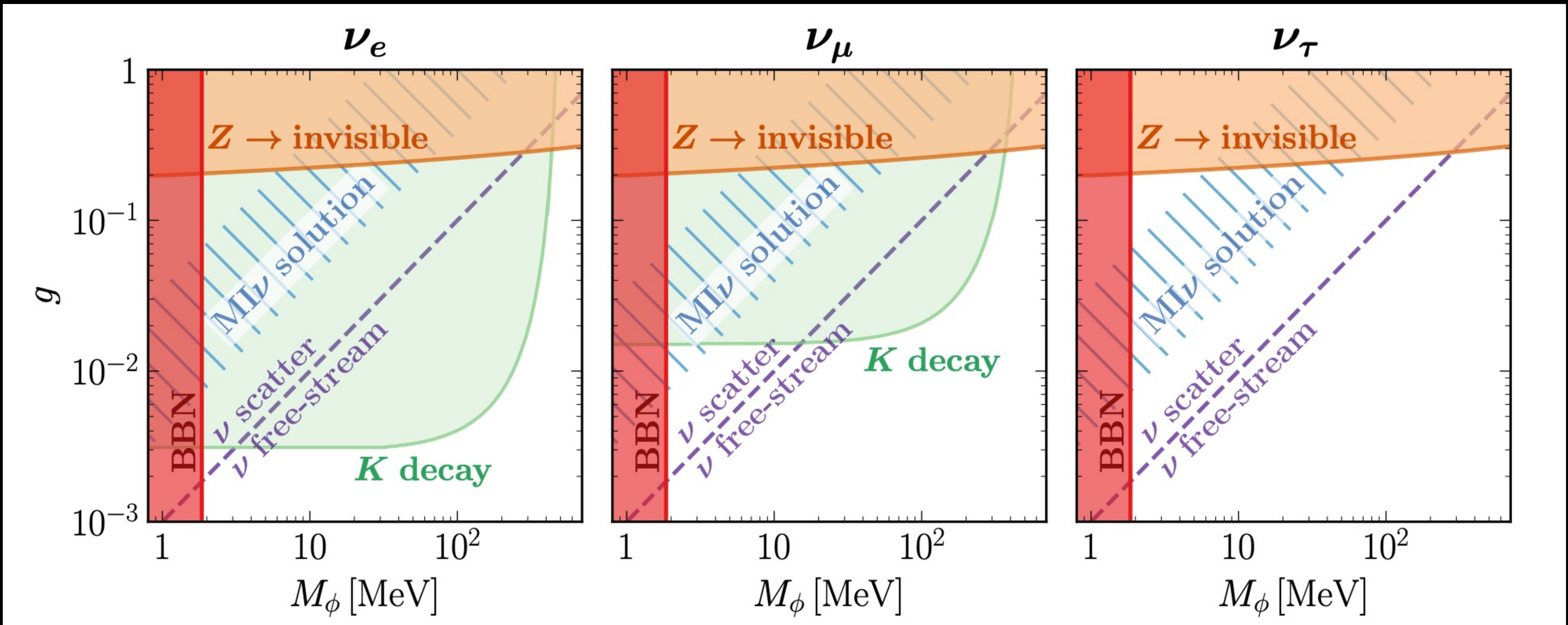
Possible Effects On the Spectrum





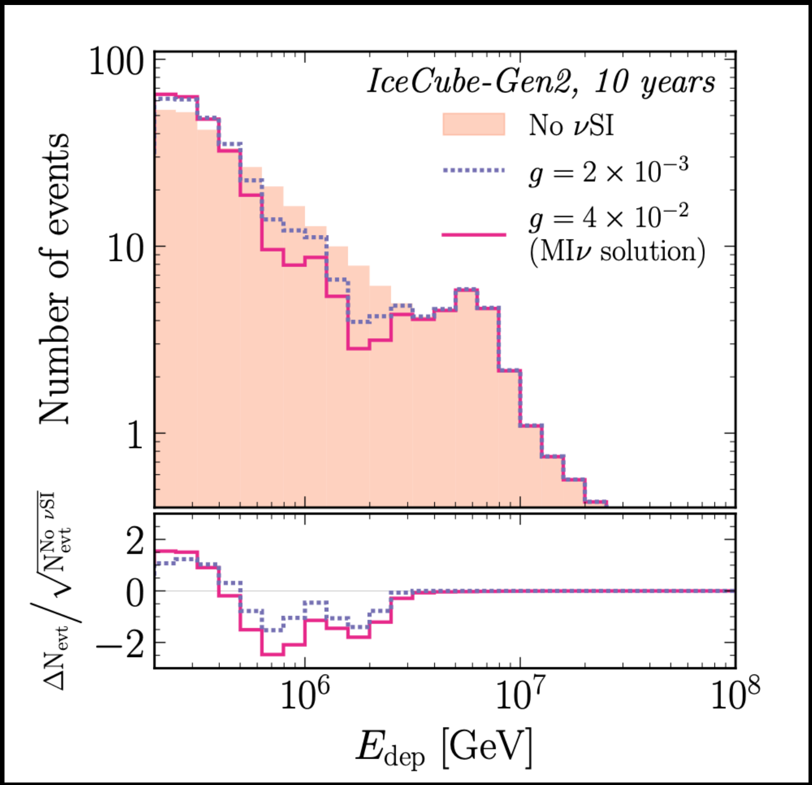
Ng and Beacom (2014)

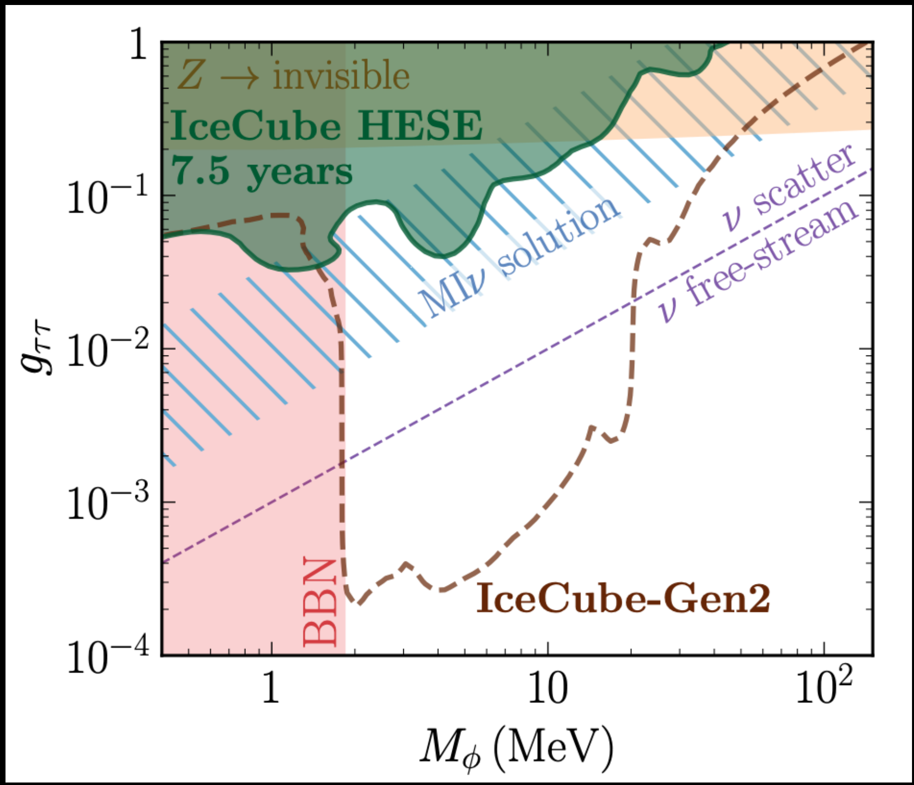
New Examination of Parameter Space



Esteban, Pandey, Brdar, Beacom (2021)

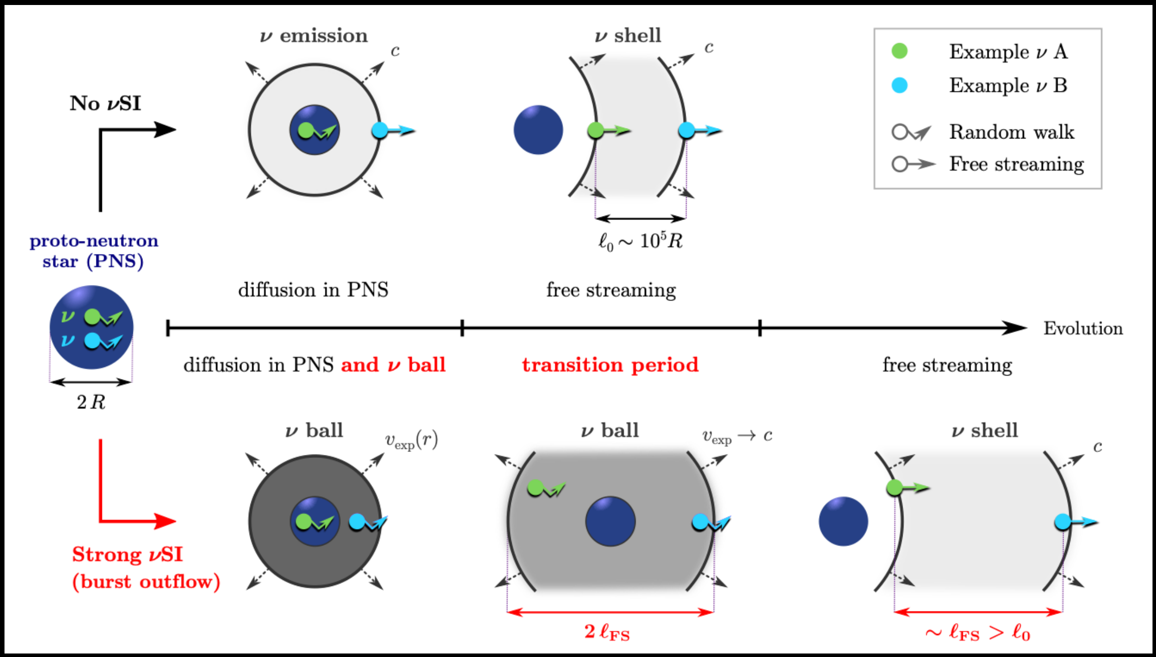
New Reach With IceCube-Gen2





Esteban, Pandey, Brdar, Beacom (2021)

Maybe There's Another Way?

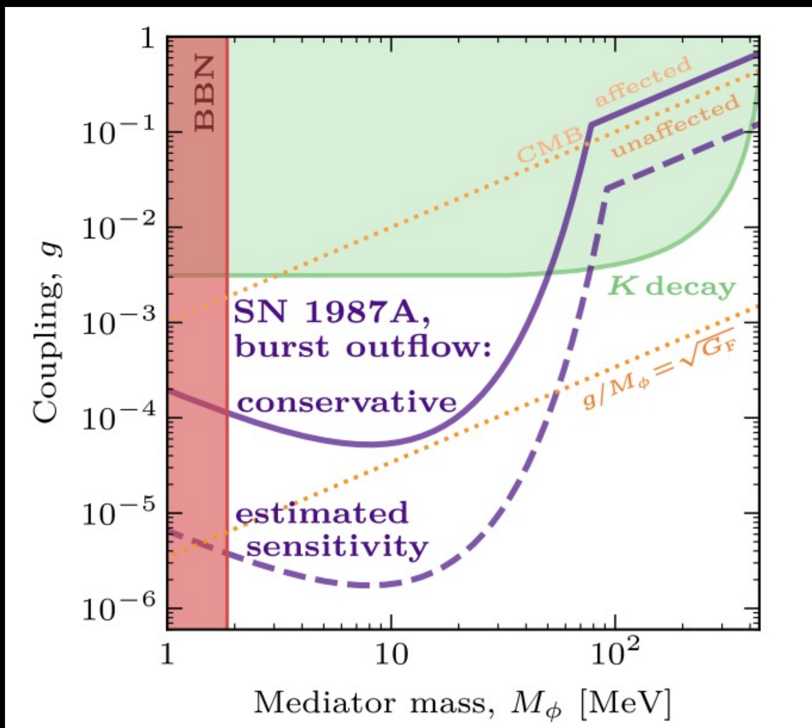


Chang, Esteban, Beacom, Thompson, Hirata (2022)

In a core-collapse supernova:

1. High column density of neutrino targets
2. Can reach large mediator masses directly
3. May have distinctive effects

Promising Sensitivity to nuSI



Chang, Esteban, Beacom, Thompson, Hirata (2022)

In the presence of nuSI, the supernova neutrinos form a tightly coupled fluid that expands under relativistic hydrodynamics

- If it expands as a *burst,* then sensitivity as in the figure
- If it expands as a *wind,* then the observables would be different but seem promising

Towards a Broader Neutrino Science

Details of Directions for Progress

Laboratory Nu:

Superpowers:
Window to BSM physics at low mass scales;
to feeble interactions

Kryptonite:
Can’t reach extremes needed

Cosmology Nu:

Superpowers:
Windows to dark radiation and dark matter;
possibly to the matter asymmetry

Kryptonite:
Can’t isolate particles

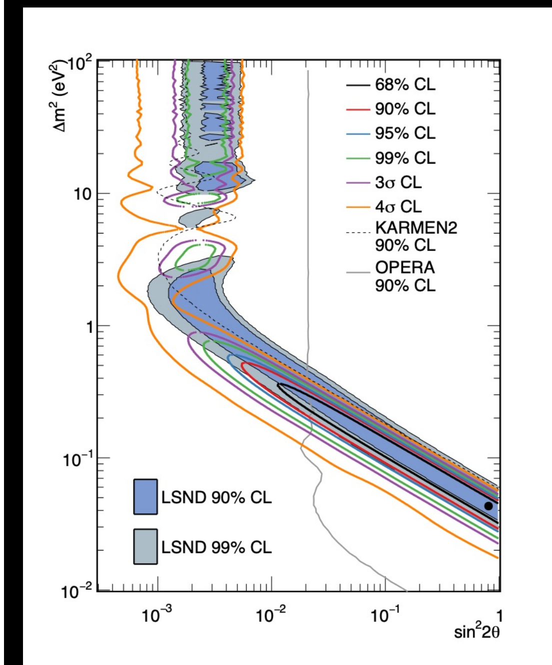
Astrophysics Nu:

Superpowers:
Windows to the interiors of sources;
to the largest energies and distances

Kryptonite:
Can’t control conditions

Overlapping unknowns are liability … but also an opportunity

Example: Are Sterile Neutrinos Real?



MiniBooNE (2021)

Laboratory

Could have large dm², large sin² sterile neutrino mixing

This would reveal new particle physics

BUT

Cosmology

This would violate neutrino number, mass bounds

Evading requires new early universe physics

BUT

Astronomy

But this could change supernova neutrino signals

Evading could require new astrophysics

How to Advance our Goals?

We're going to need a bigger boat

The Time for Neutrino Astronomy is Now

Neutrino Astronomy

MeV—GeV ν	TeV—PeV ν	EeV—ZeV ν
Efforts: SK, HK and more	Efforts: IceCube and more	Efforts: ANITA and more
Targets: Solar, SN, more Surprises	Targets: GRBs, AGN, more Surprises	Targets: GZK process Surprises

Neutrino astronomy must be broad

The Time for Neutrino Science is Now

Neutrino Science

Laboratory ν	Cosmology ν	Astronomy ν
Efforts: Fermilab and more	Efforts: CMB and more	Efforts: IceCube and more
Context: Precision Physics, BSM reach	Context: Precision Cosmology, BSM reach	Context: Transient Astronomy, Multi-messenger

Neutrinos are multi-frontier science

Closing Message

Neutrinos take patience, but they reward it richly