

High-energy cosmic neutrinos for particle physics and astrophysics

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

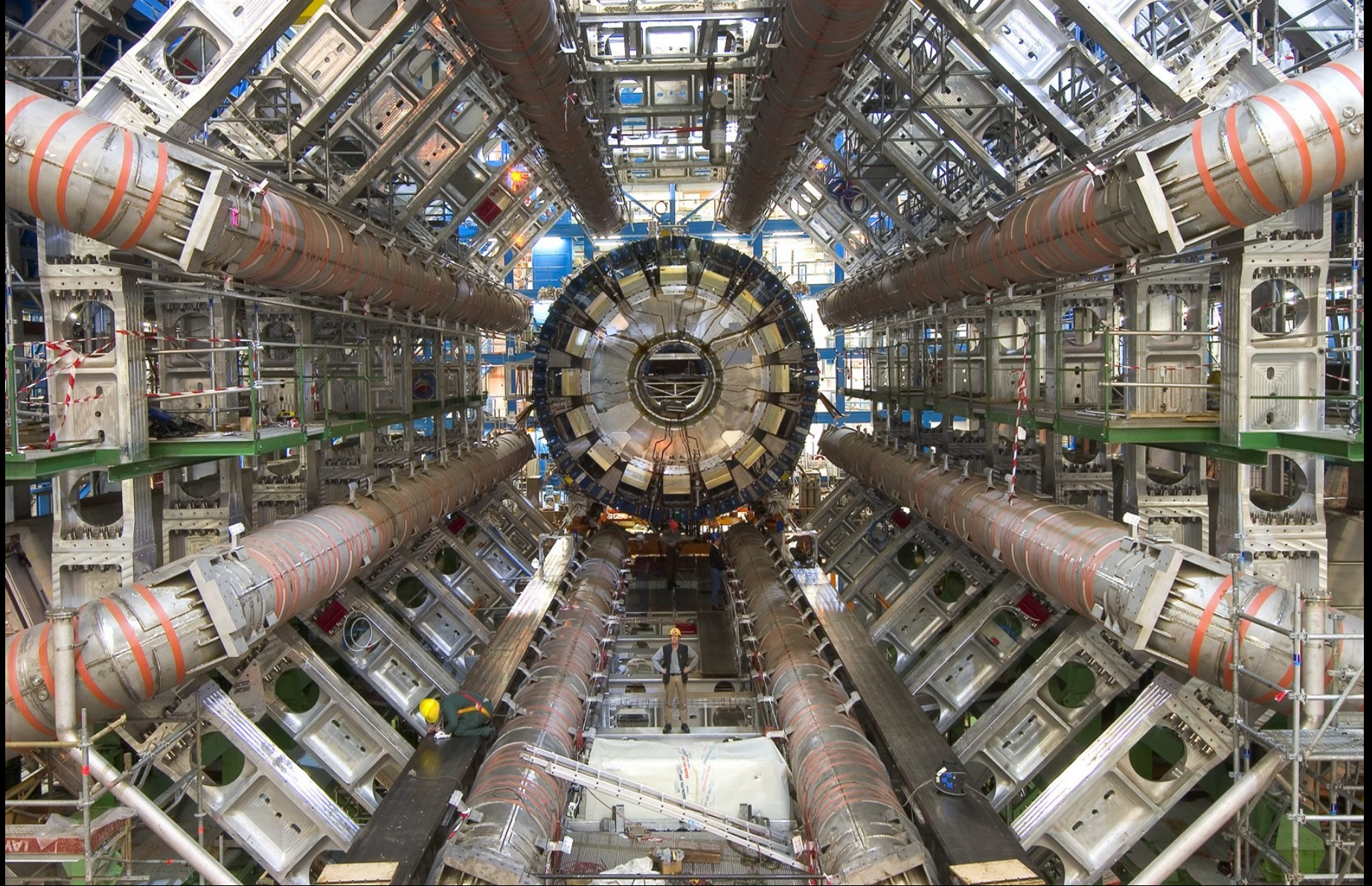
FestiGago
PUCP, March 10, 2025

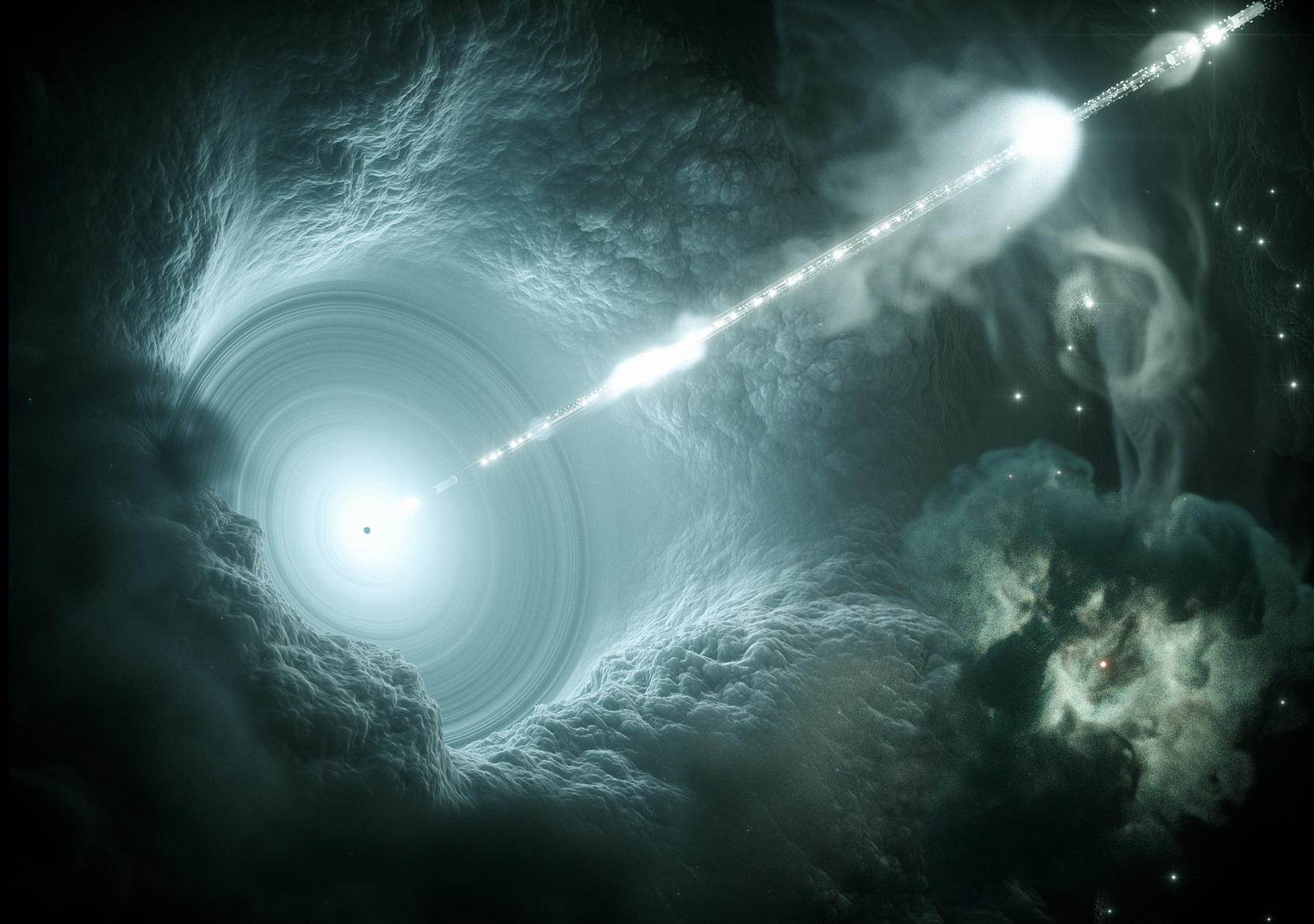
UNIVERSITY OF
COPENHAGEN

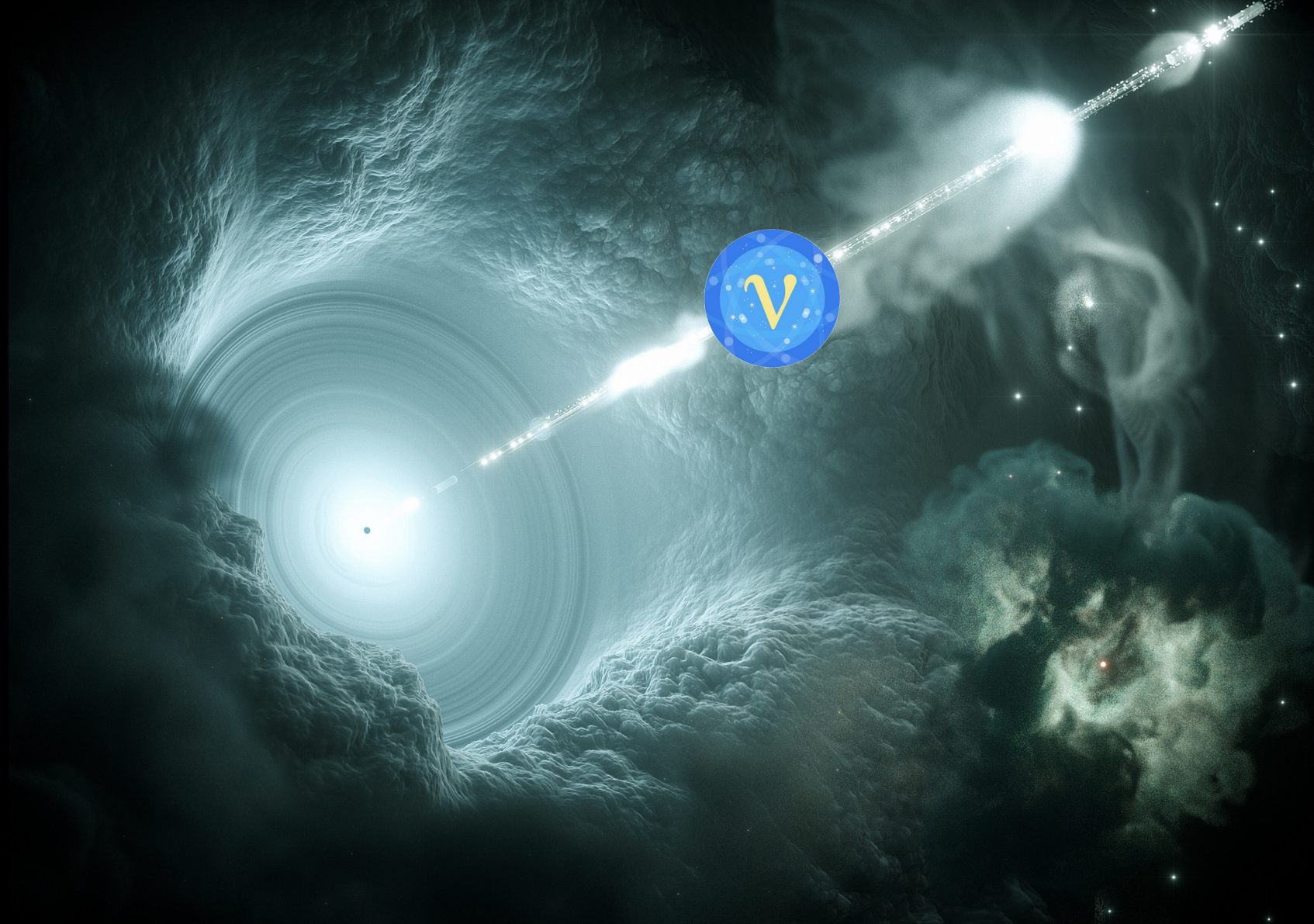


VILLUM FONDEN









How it
started

How it's
going

10–20 years
from now



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First predictions
of high-energy
cosmic ν



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PeV ν
discovered

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Hints of sources
First tests of ν physics

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EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν

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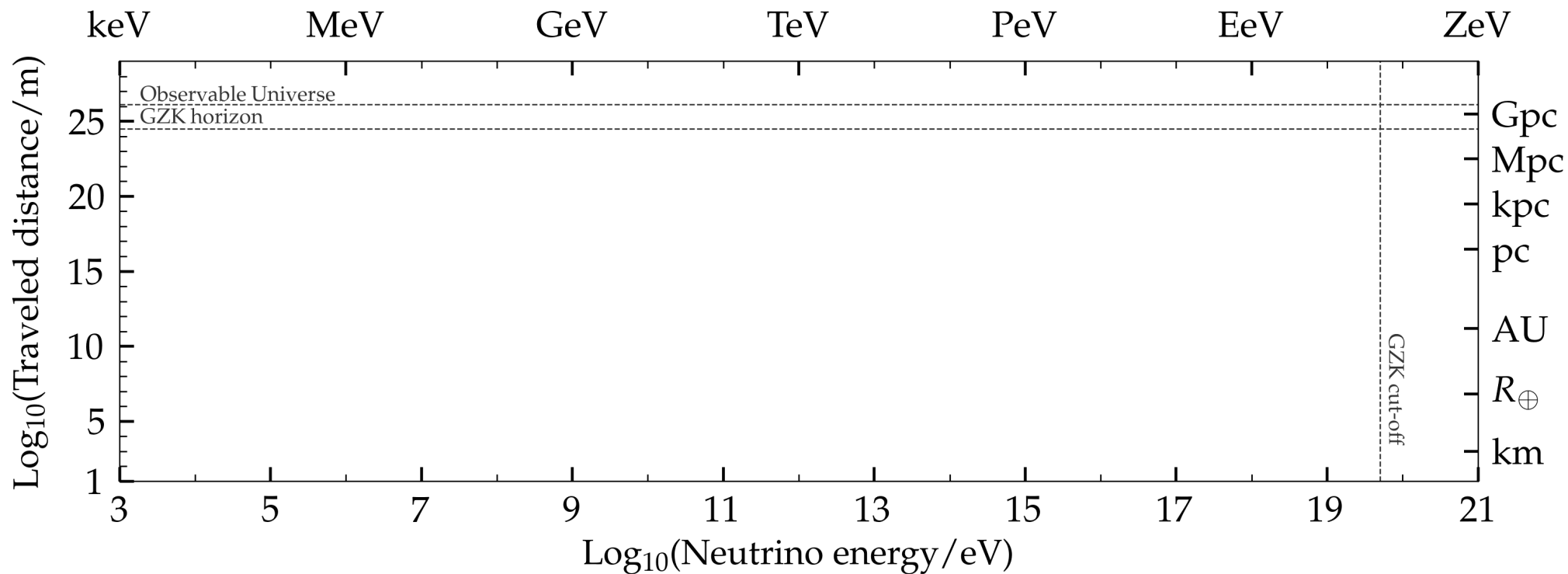
First predictions
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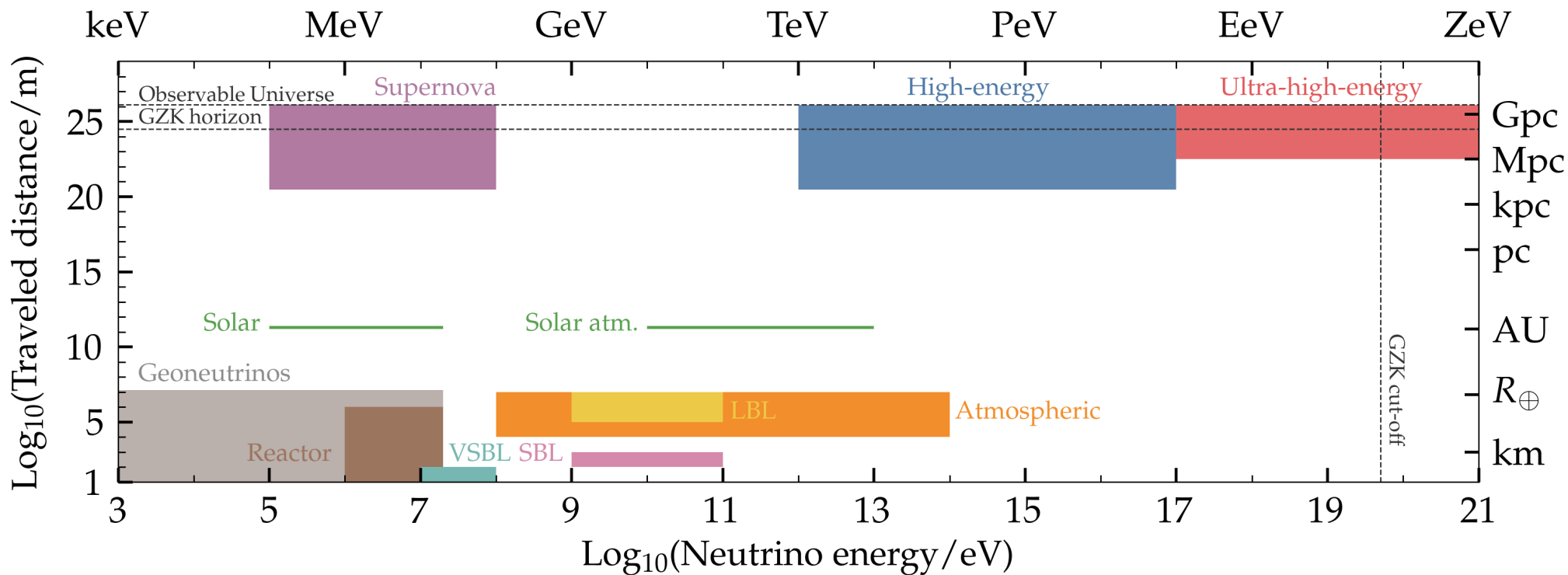
PeV ν
discovered

Hints of sources
First tests of ν physics

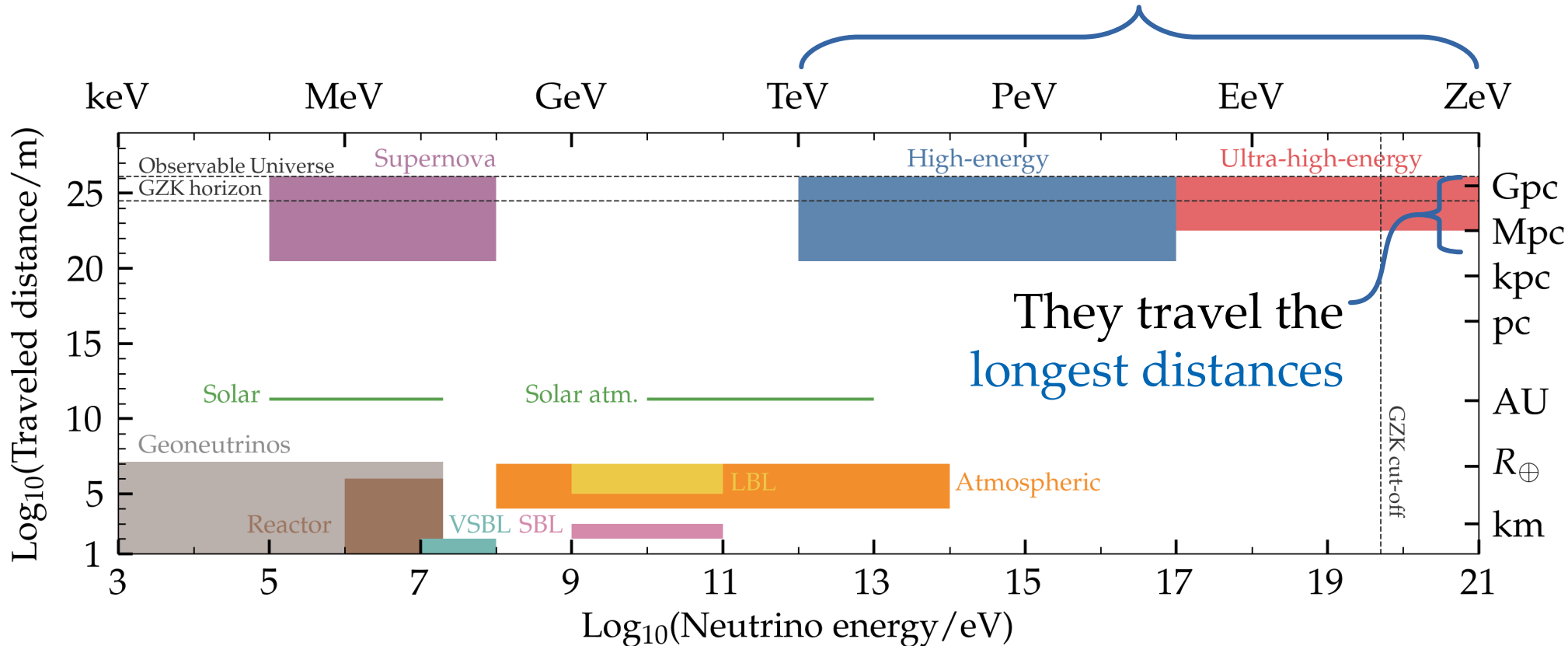
How do we get there?

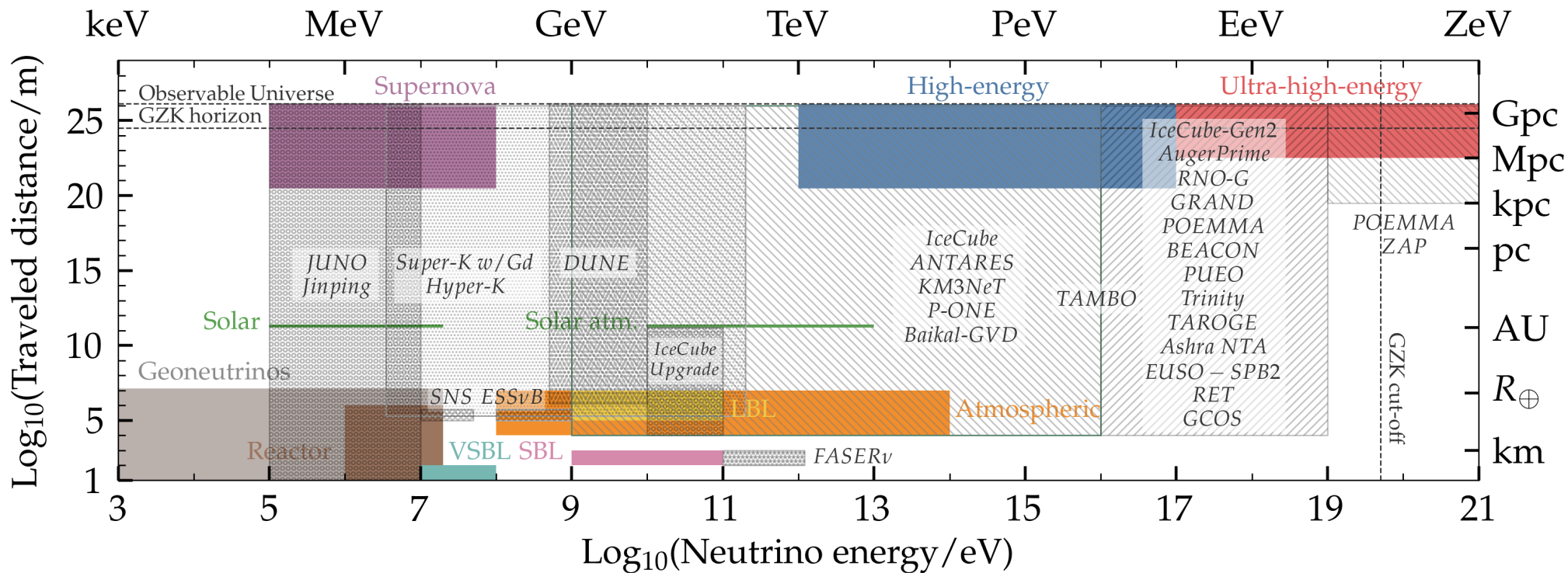
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν

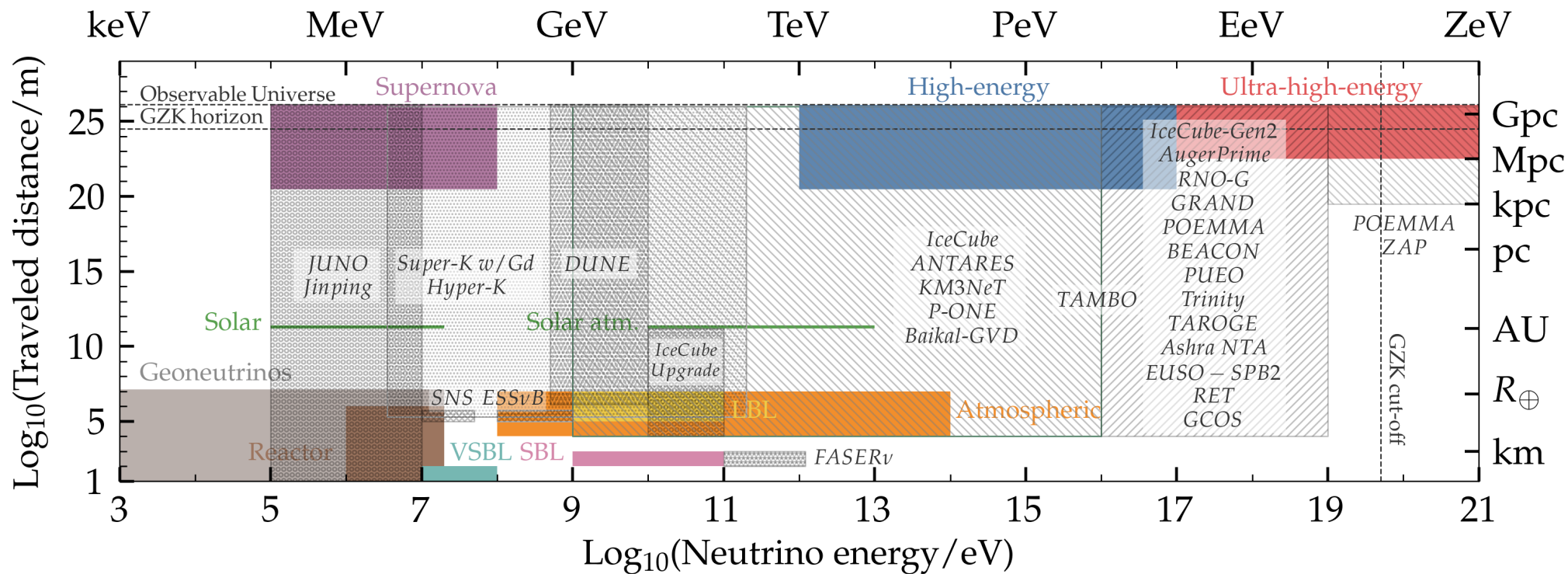




They have the **highest energies**

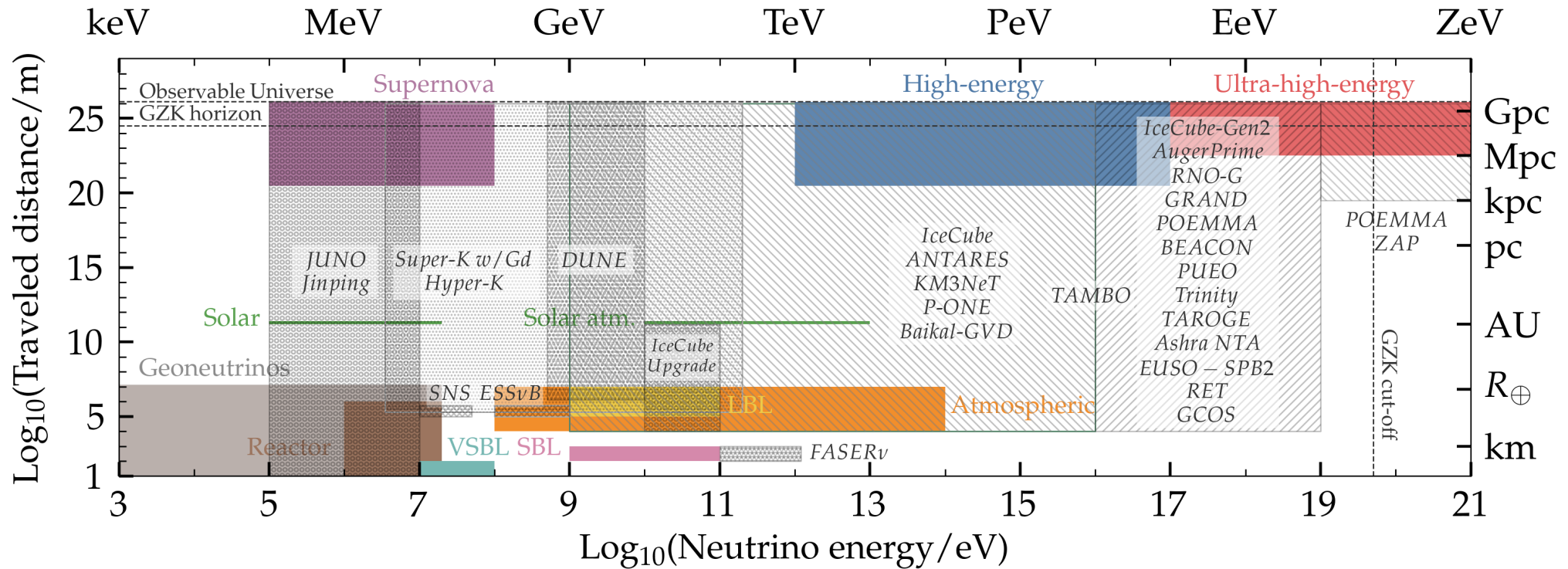






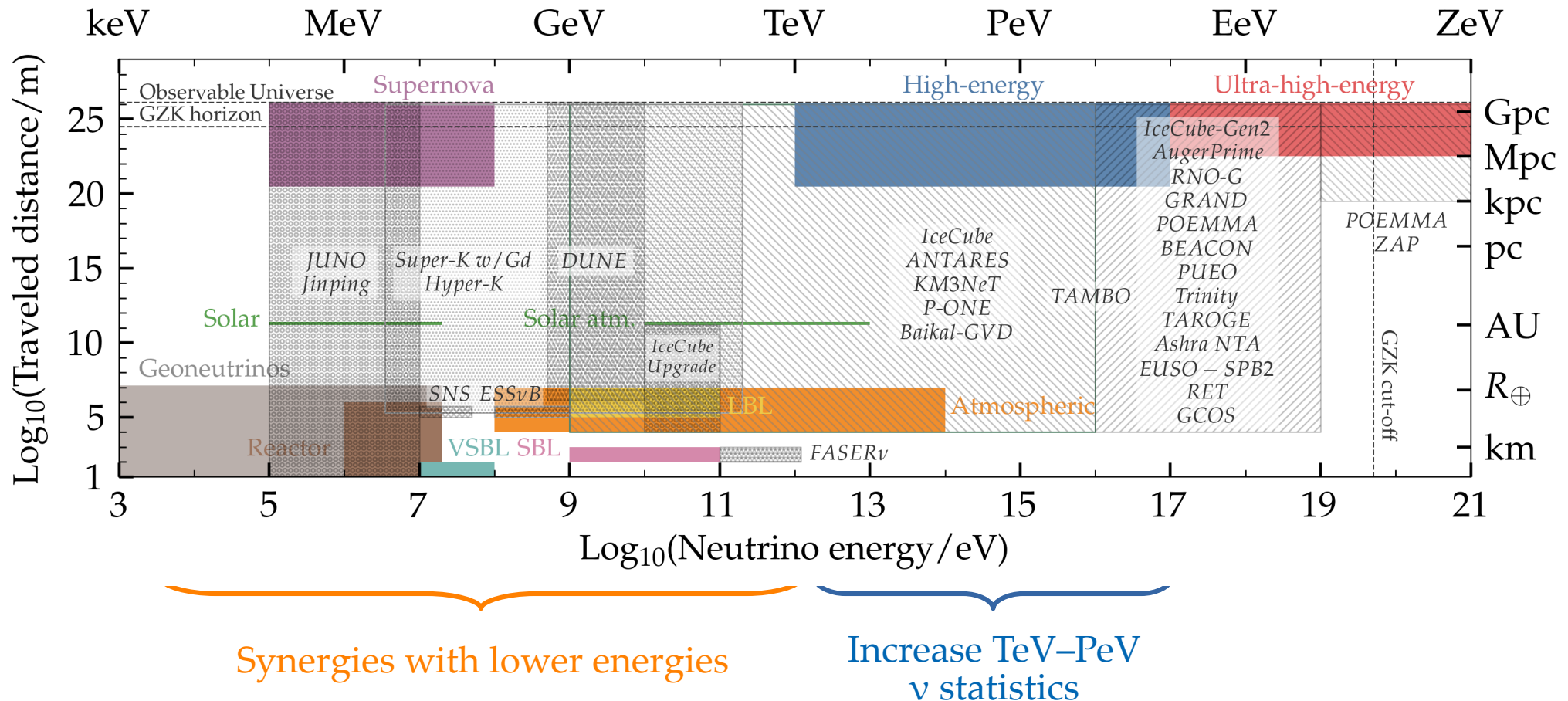
Synergies with lower energies

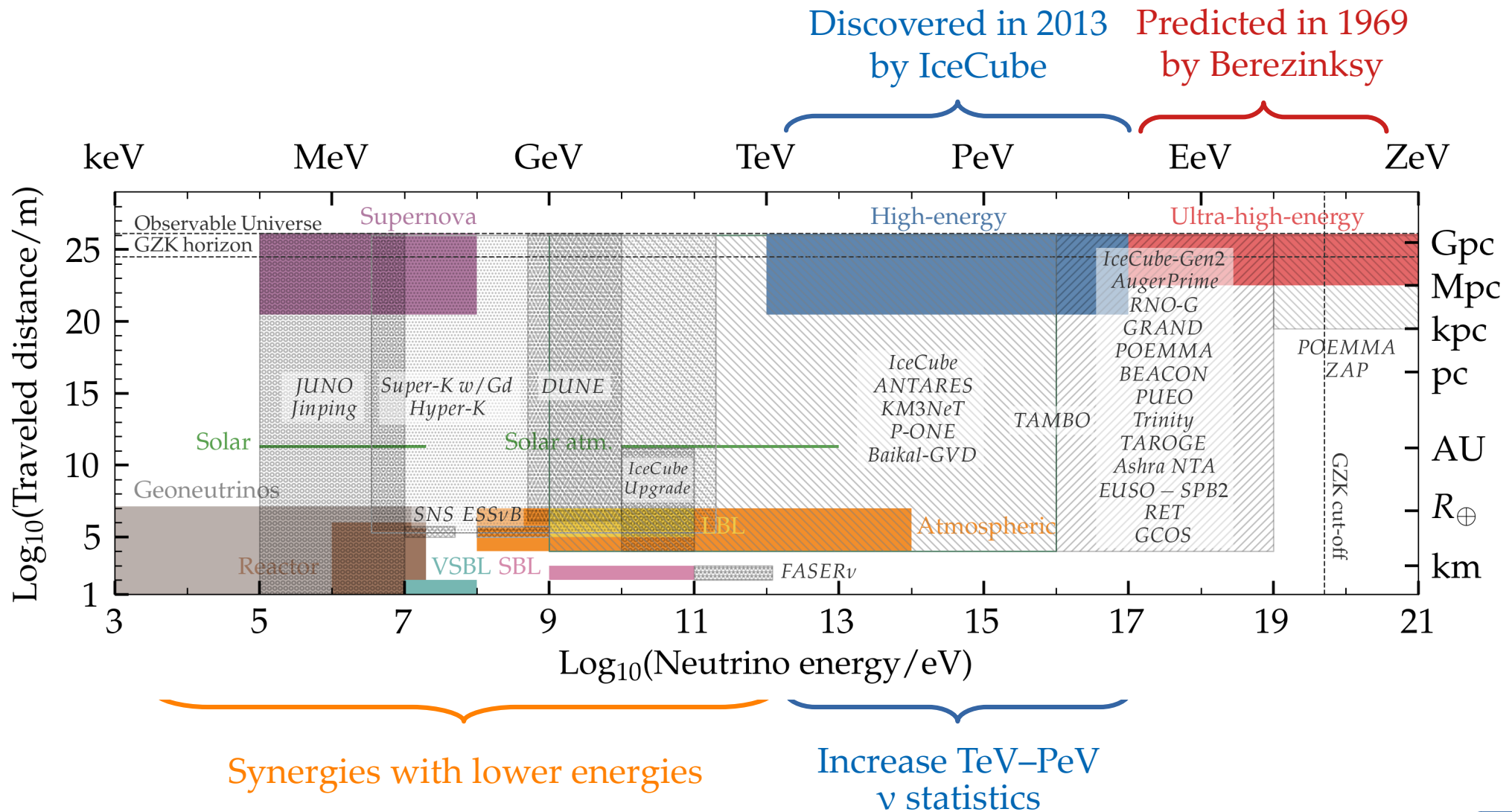
Discovered in 2013
by IceCube

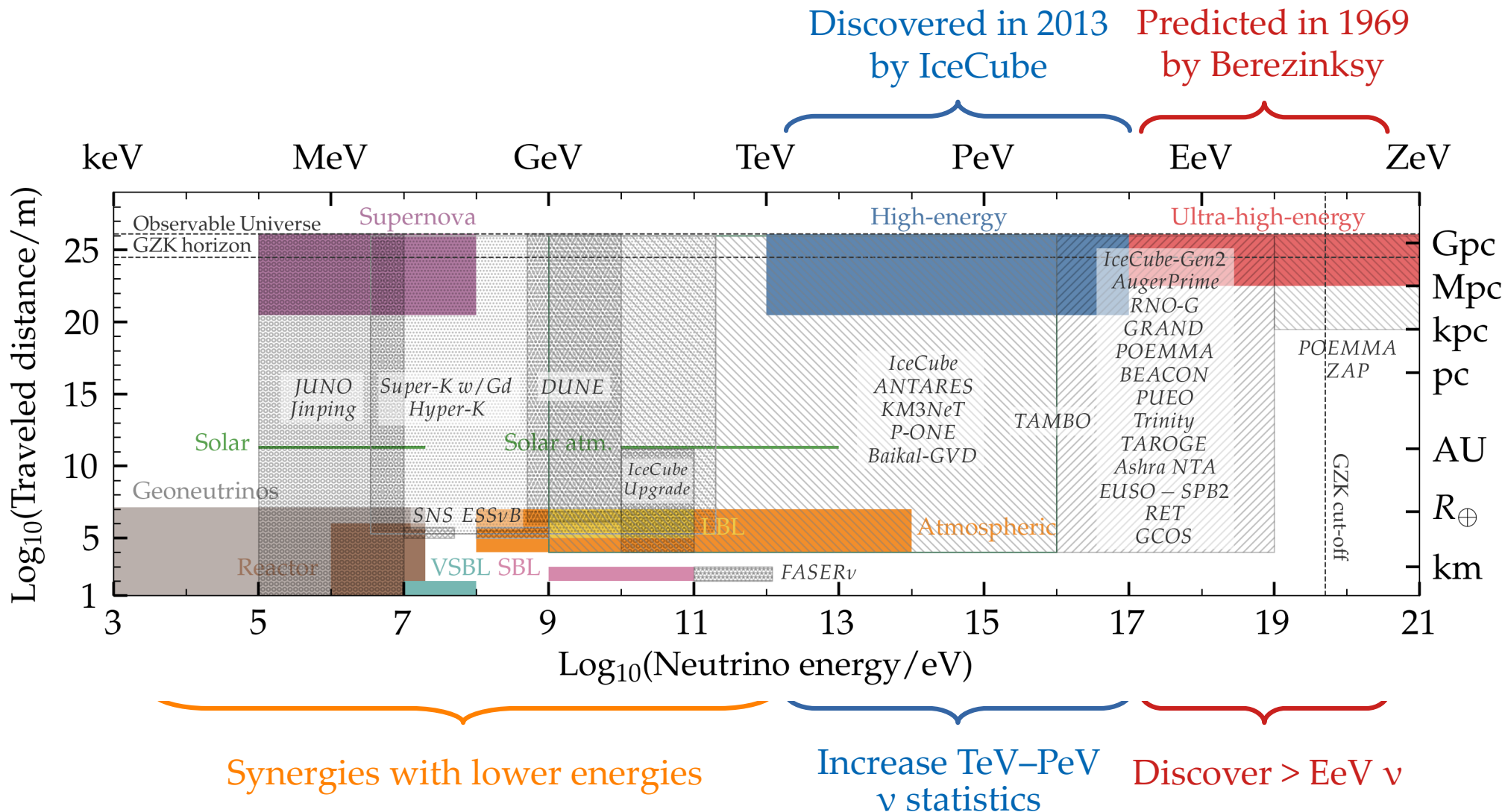


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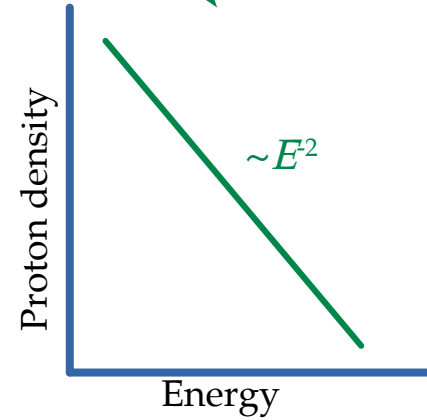
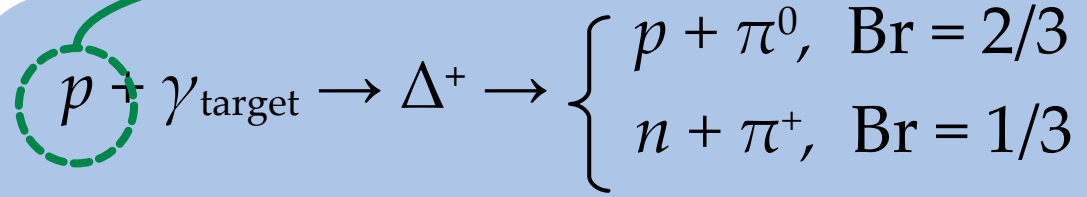
The multi-messenger connection: a simple picture

(or $p + p$)

$$p + \gamma_{\text{target}} \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

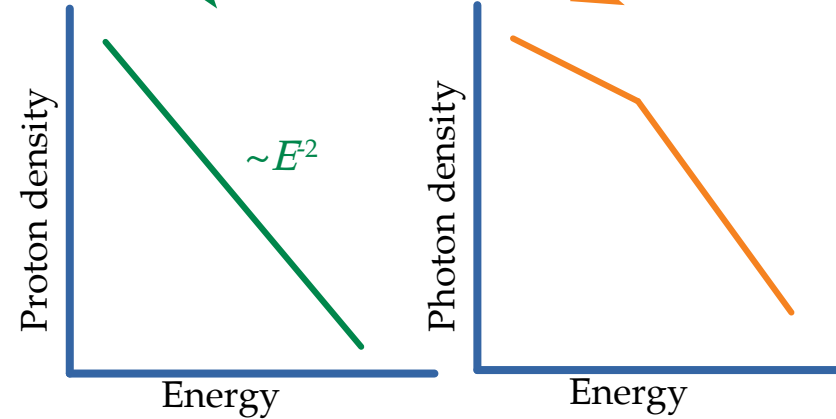
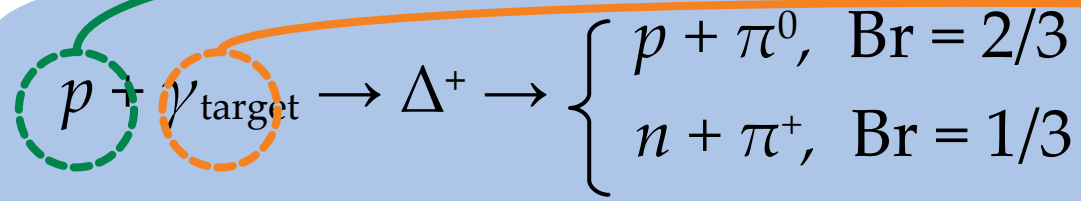
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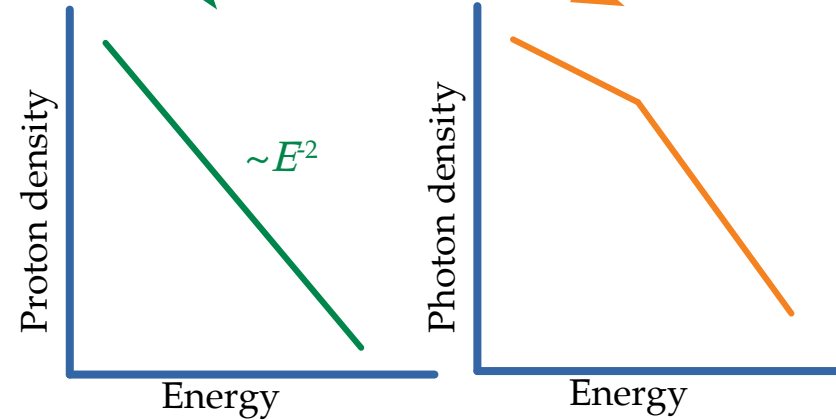
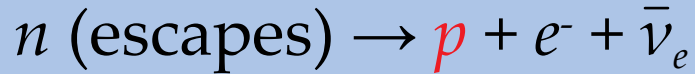
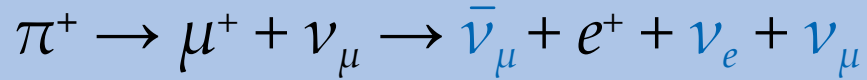
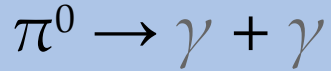
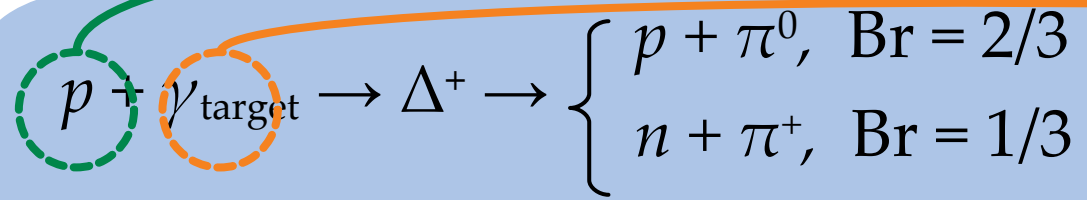
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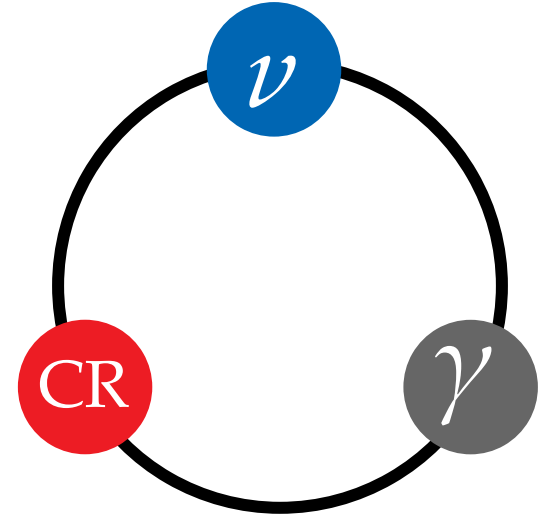
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$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow \bar{\nu}_\mu + e^+ + \nu_e + \nu_\mu$$

$$n \text{ (escapes)} \rightarrow \textcolor{red}{p} + e^- + \bar{\nu}_e$$



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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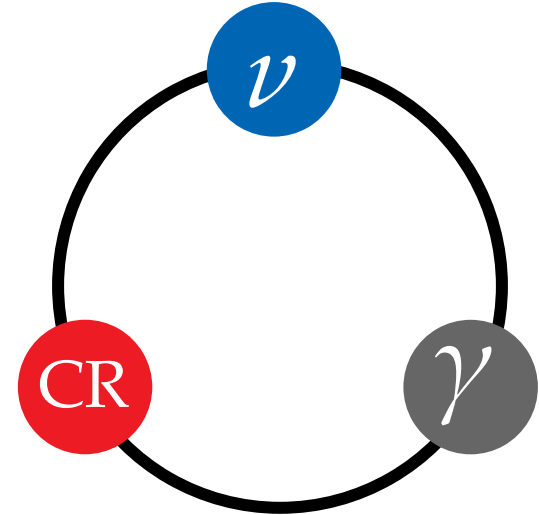
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20 PeV

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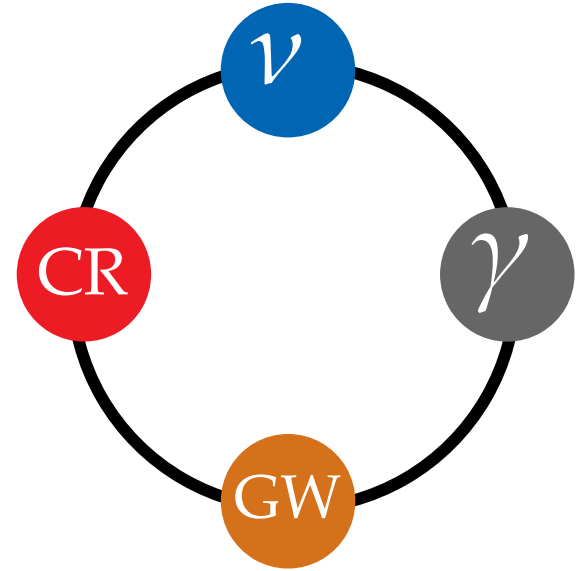
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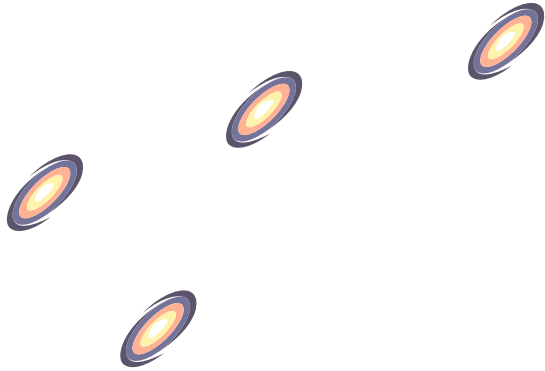
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Redshift



$z = 0$

Note: ν sources can be steady-state or transient



Redshift

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Note: ν sources can be steady-state or transient

MeV γ

Discovered

TeV–PeV ν

“High-energy”

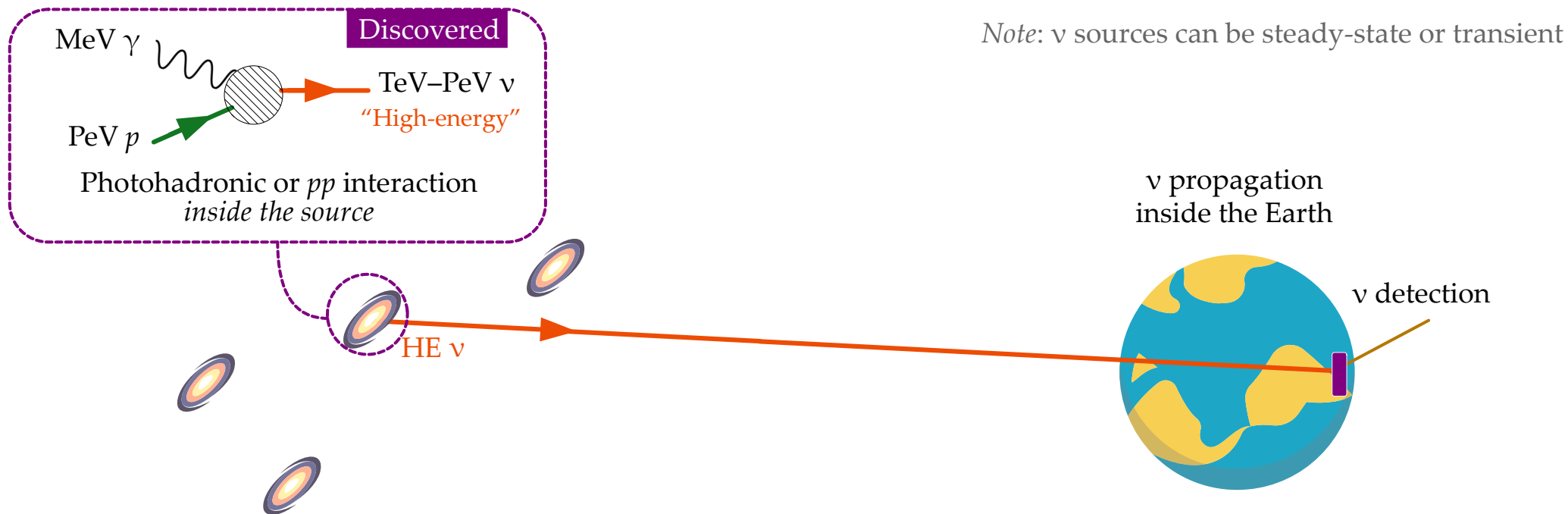
PeV p

Photohadronic or pp interaction
inside the source

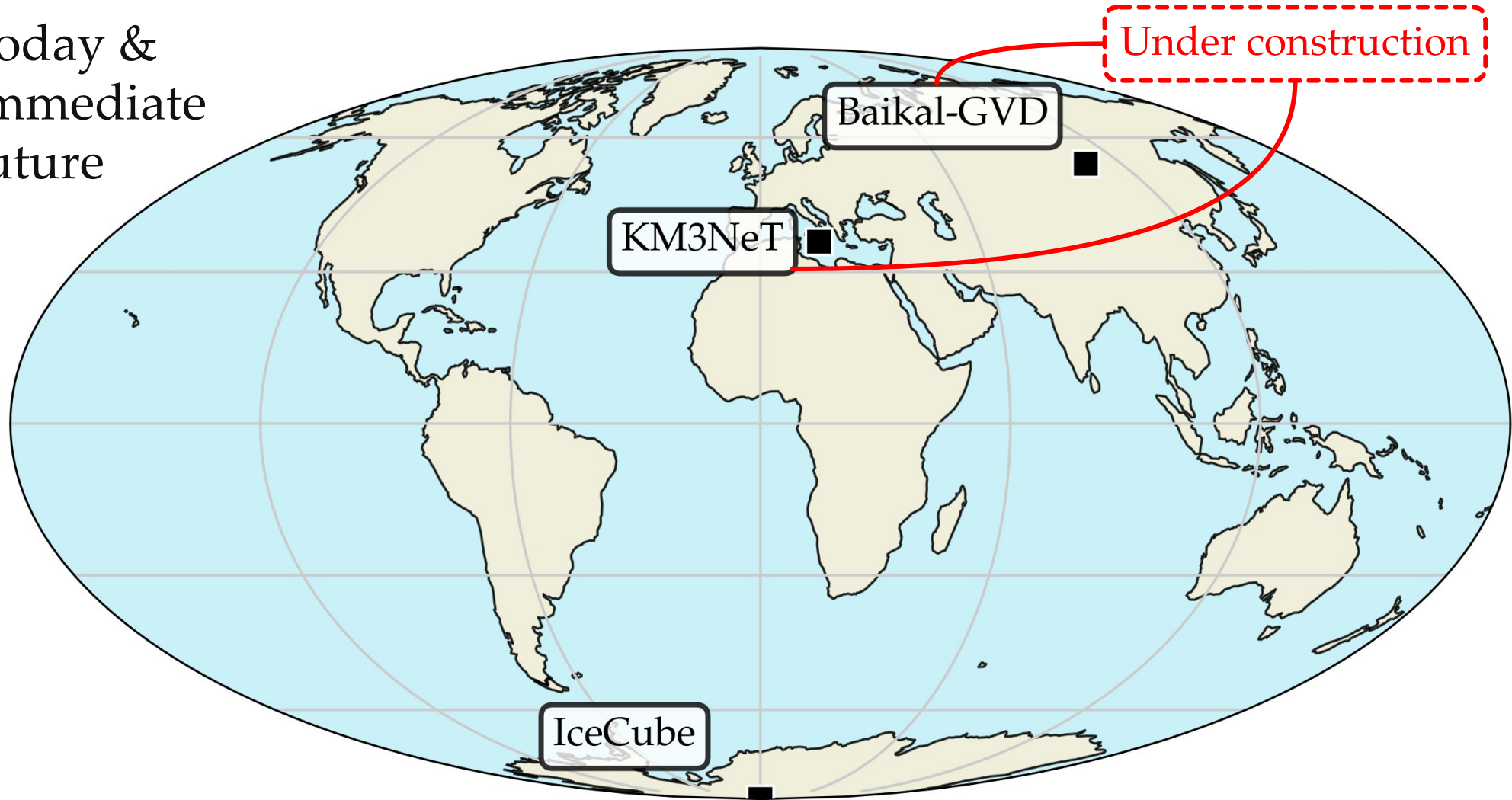
HE ν

ν propagation
inside the Earth

ν detection

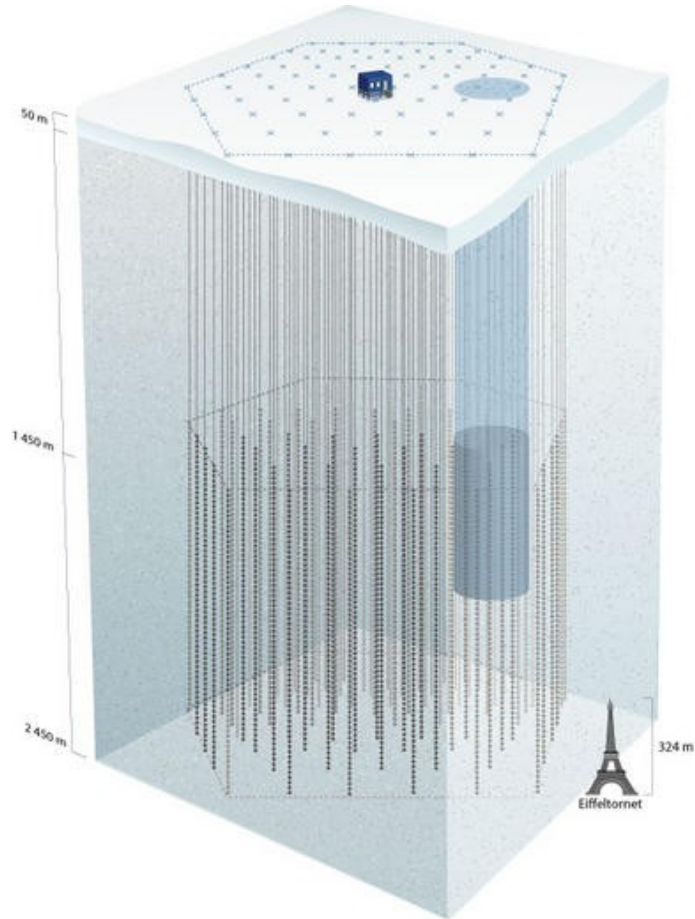


Today &
immediate
future

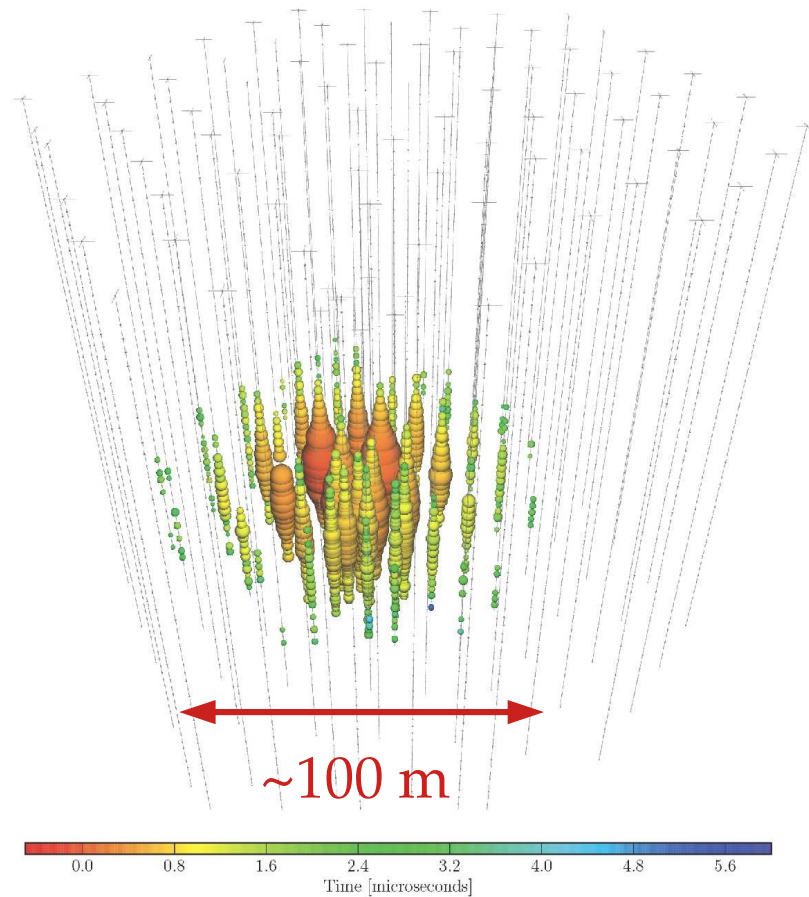


IceCube – What is it?

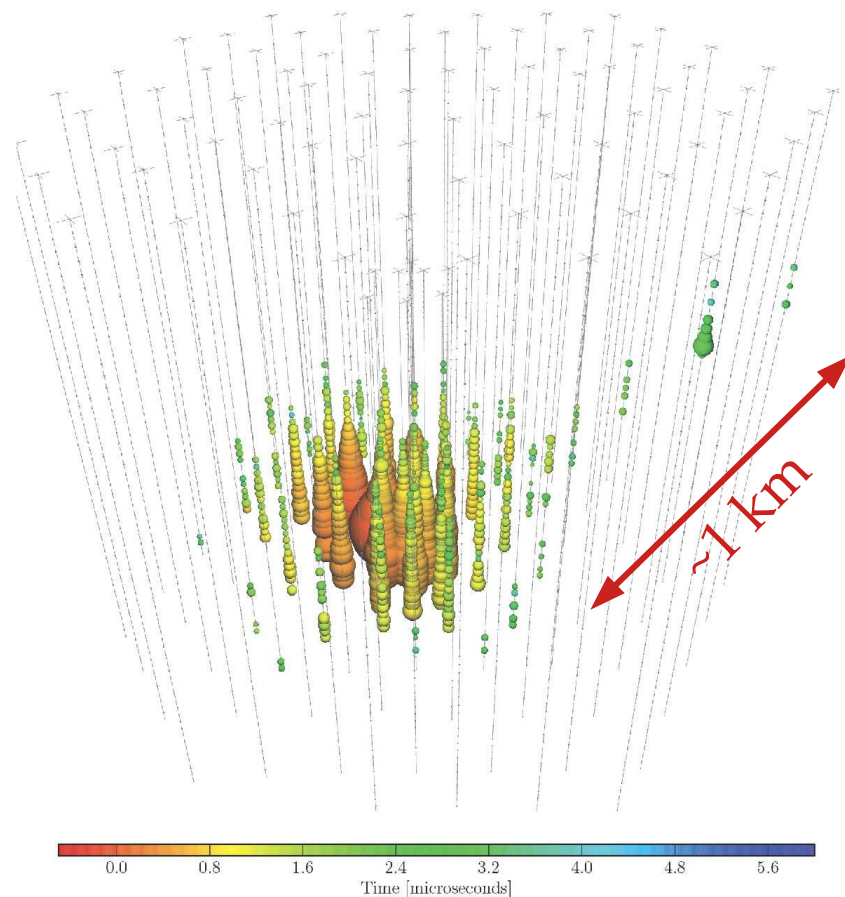
- ▶ Km^3 in-ice Cherenkov detector in Antarctica
- ▶ > 5000 PMTs at 1.5–2.5 km of depth
- ▶ Sensitive to neutrino energies > 10 GeV



Shower
(mainly from ν_e and ν_τ)

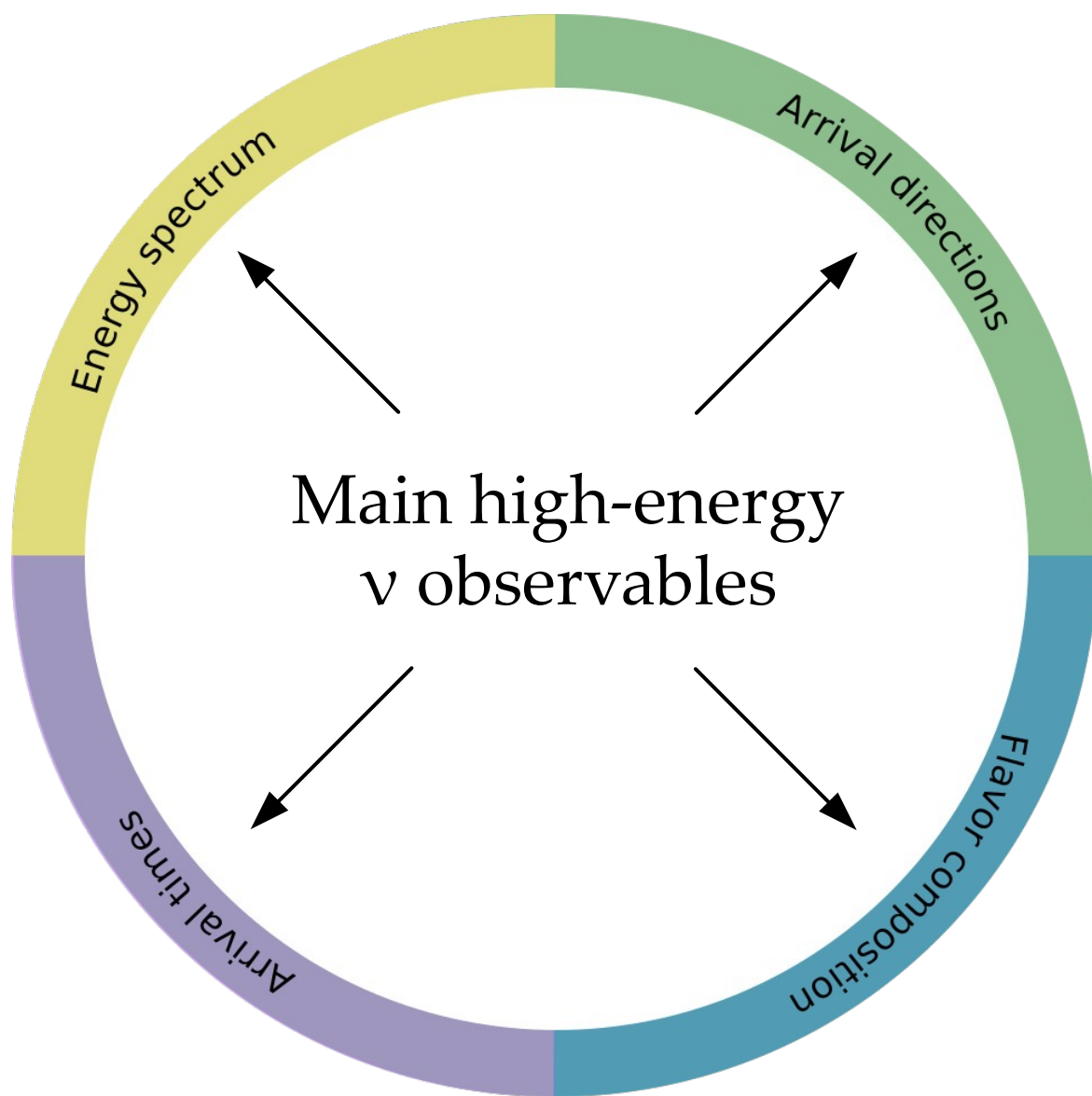


Track
(mainly from ν_μ)



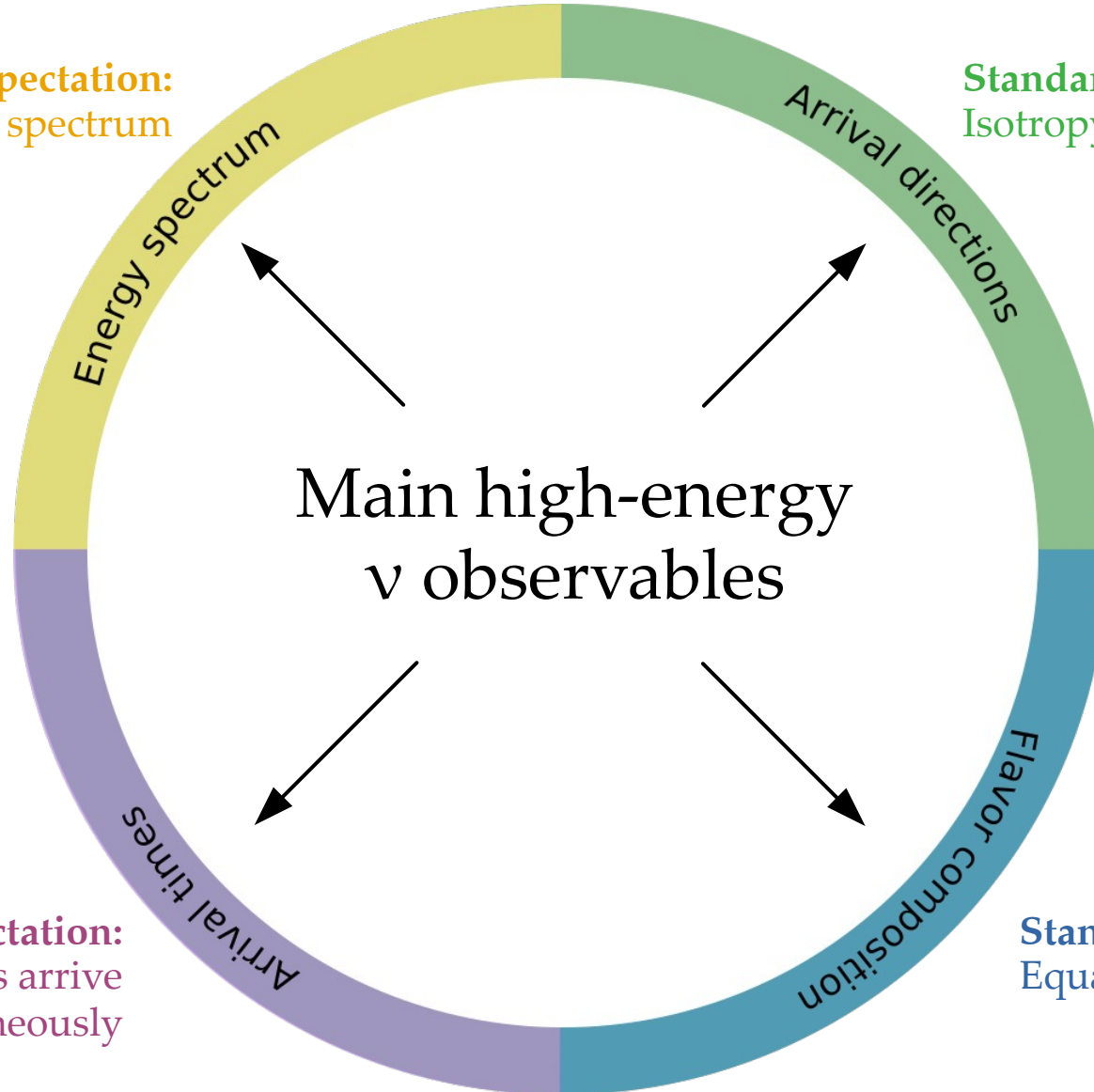
Poor angular resolution: $< 5^\circ$

Angular resolution: $< 1^\circ$



Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

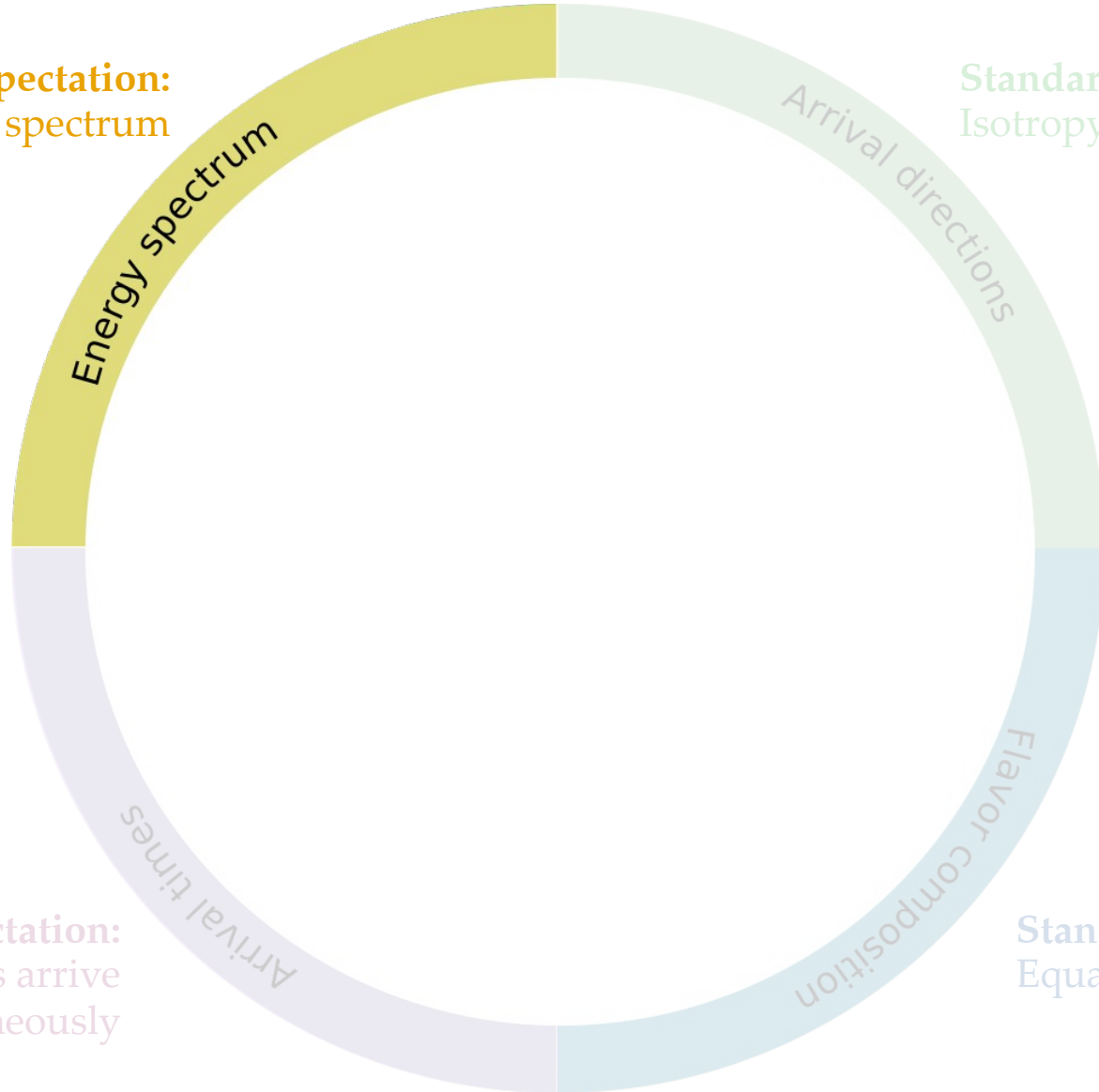


Standard expectation:
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Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

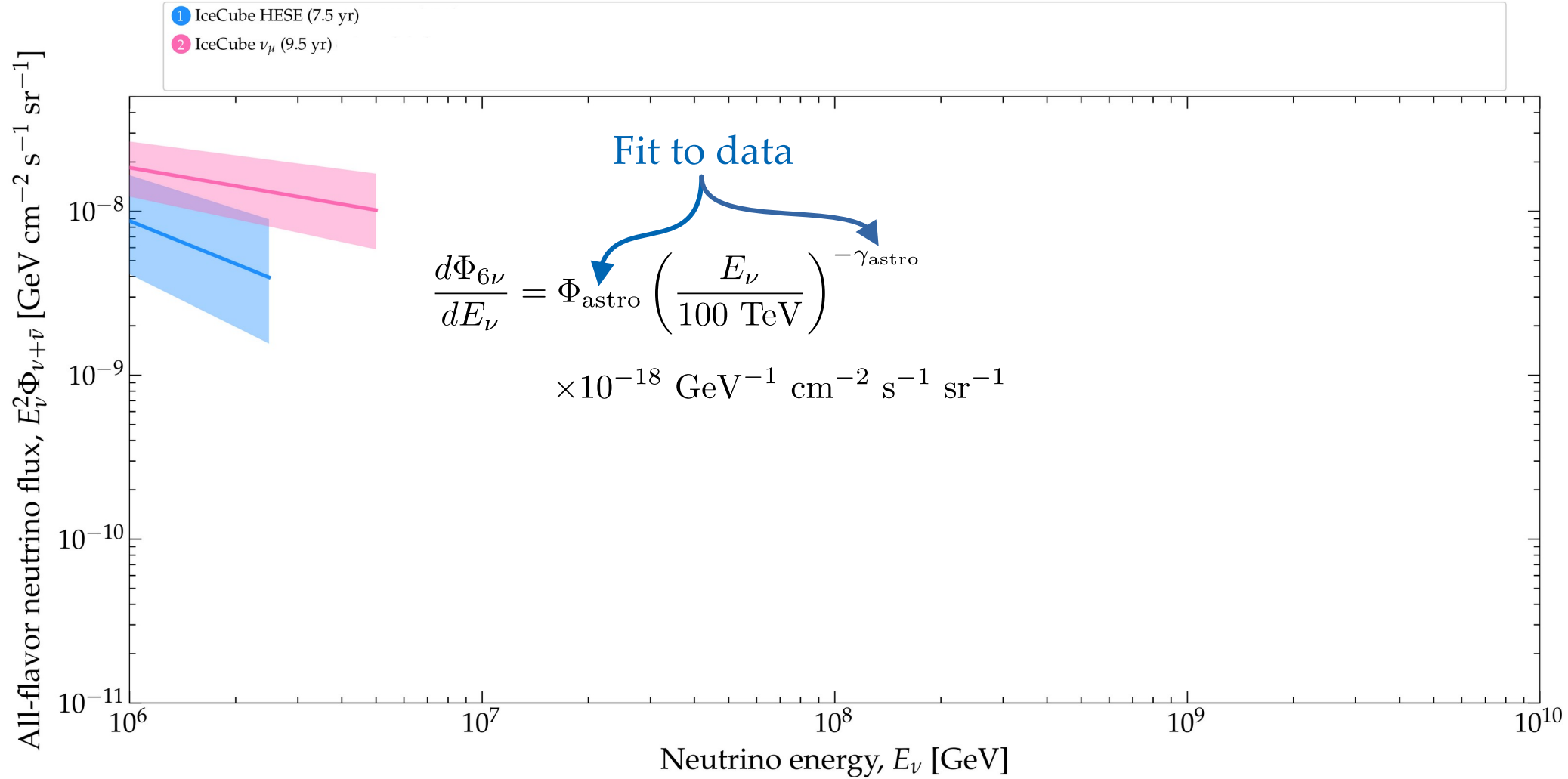
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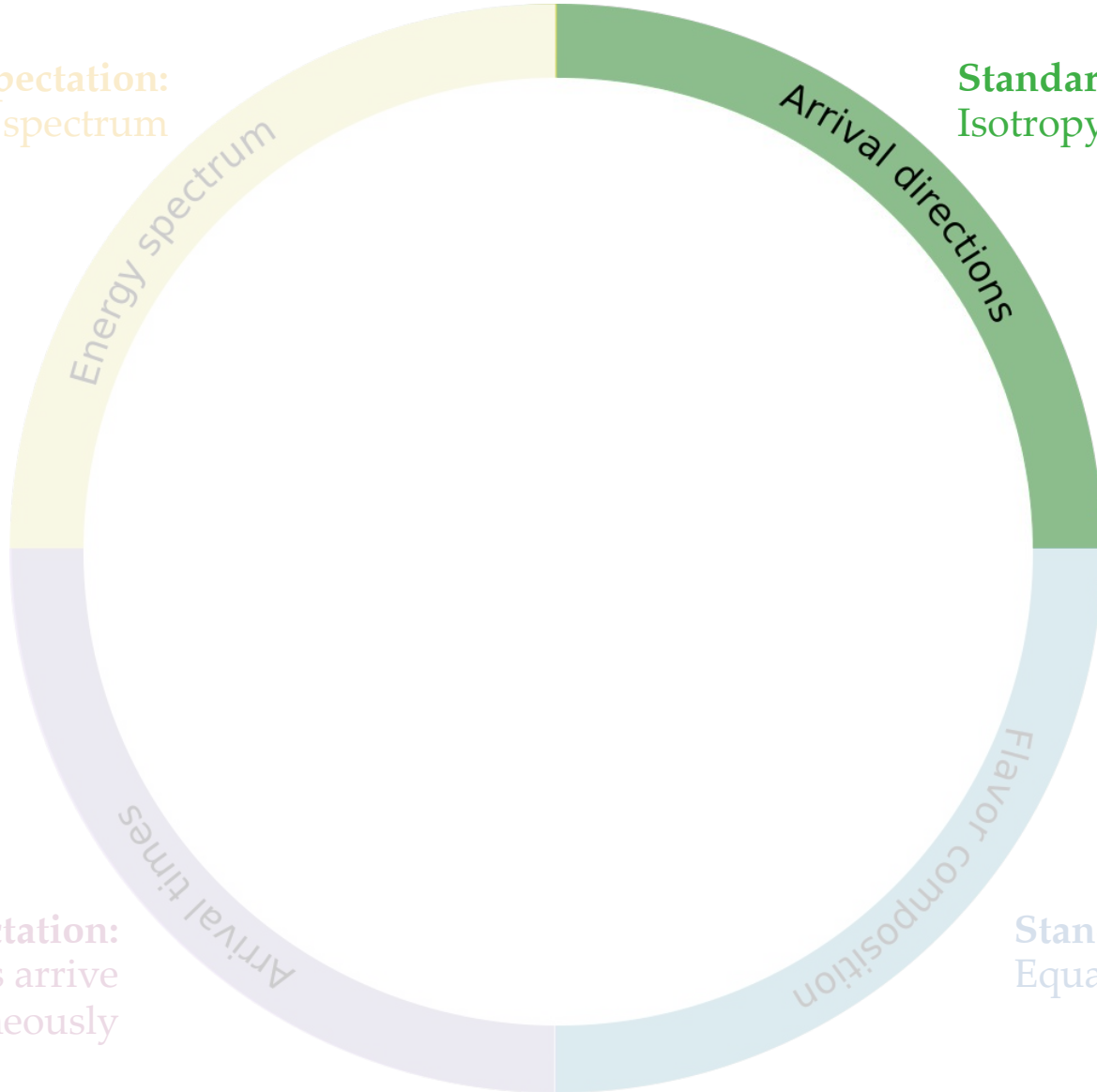


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Arrival directions

Flavor composition

Standard expectation:
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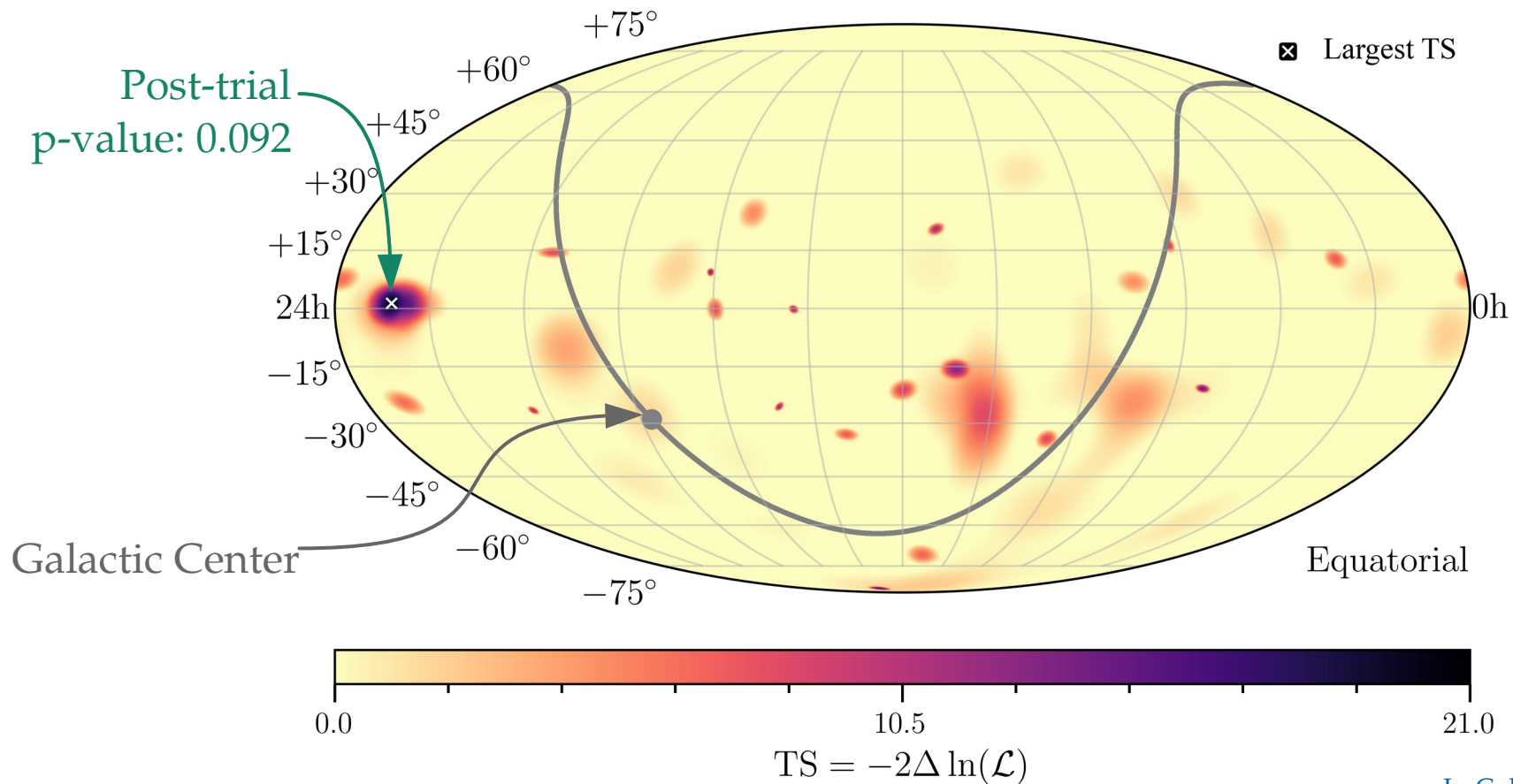
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Arrival times

Energy spectrum

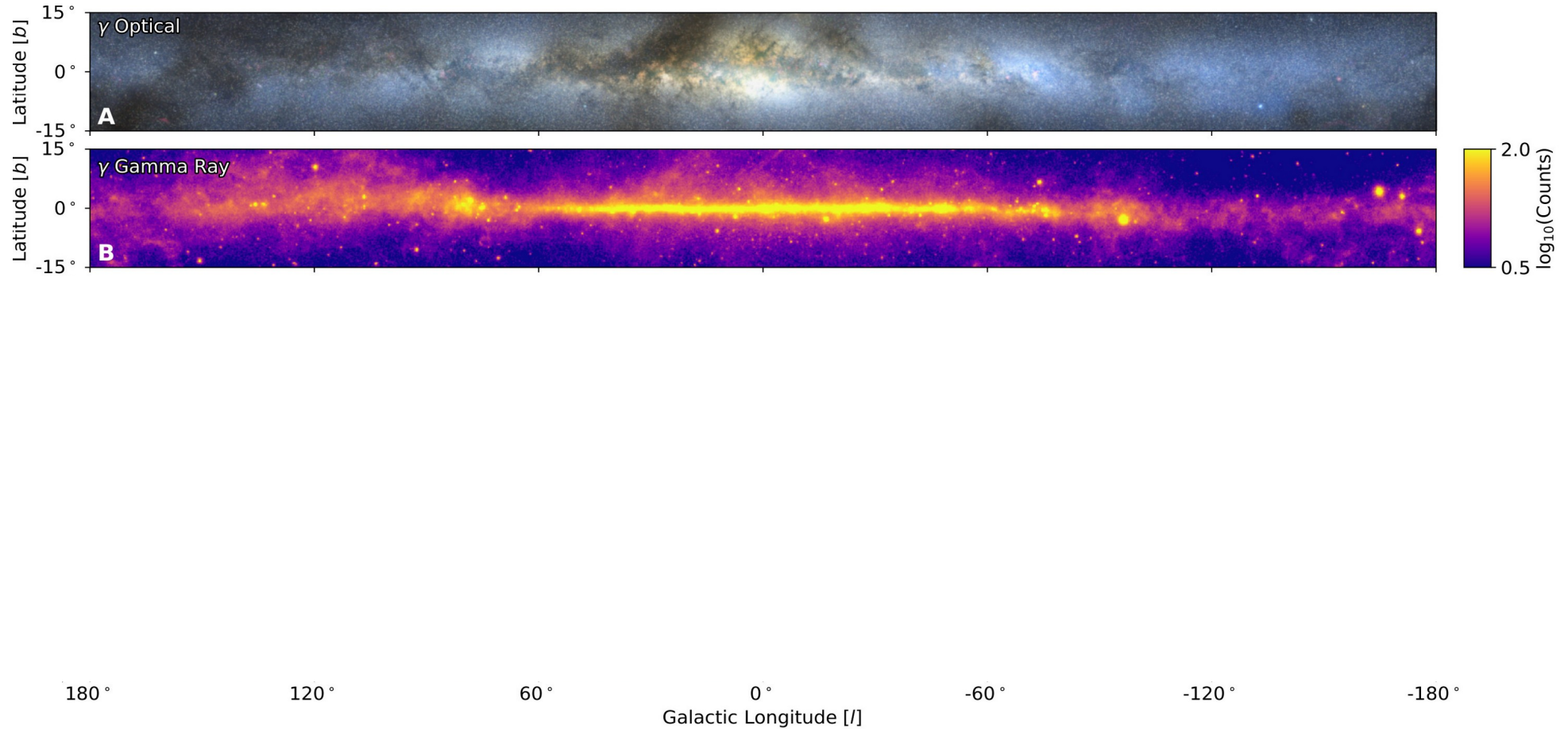
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:

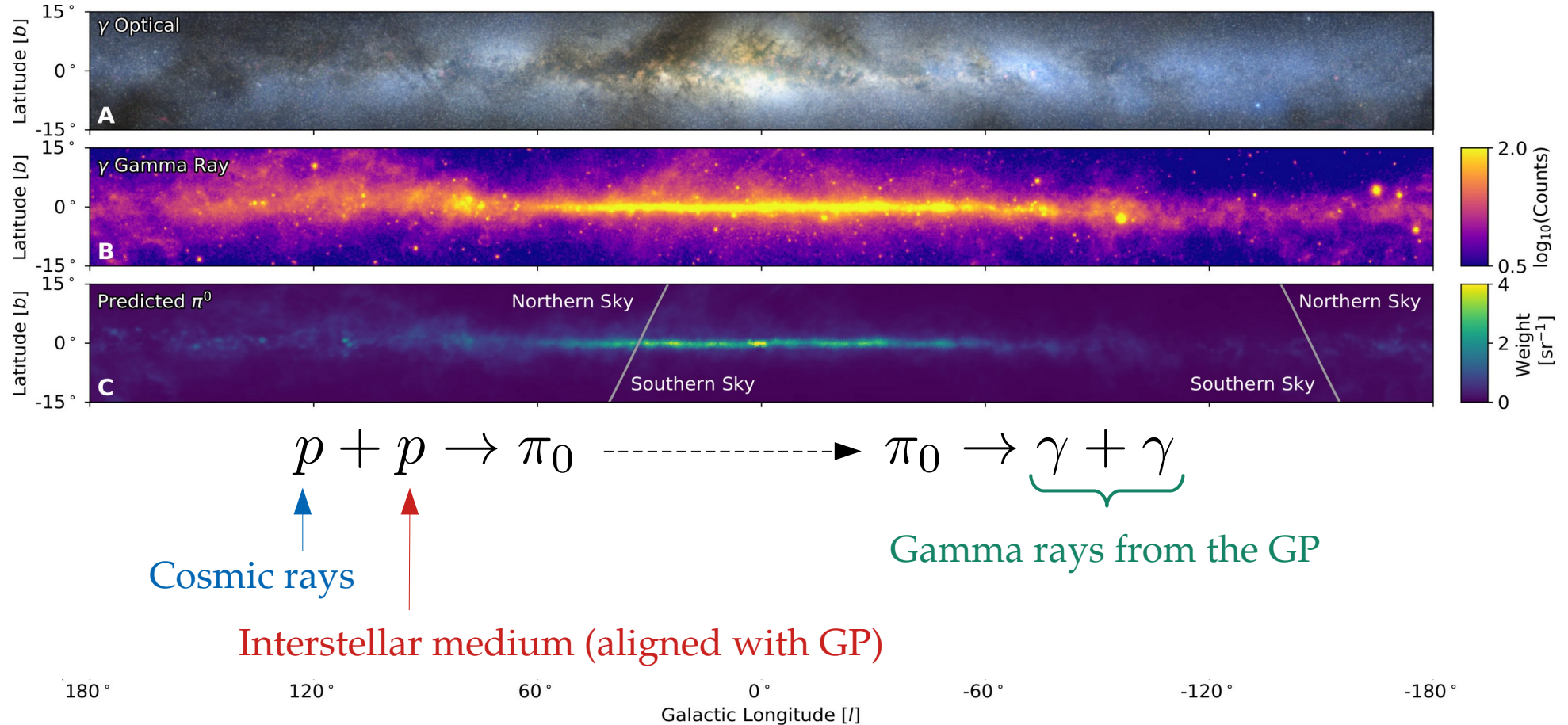


IceCube, PRD 2021

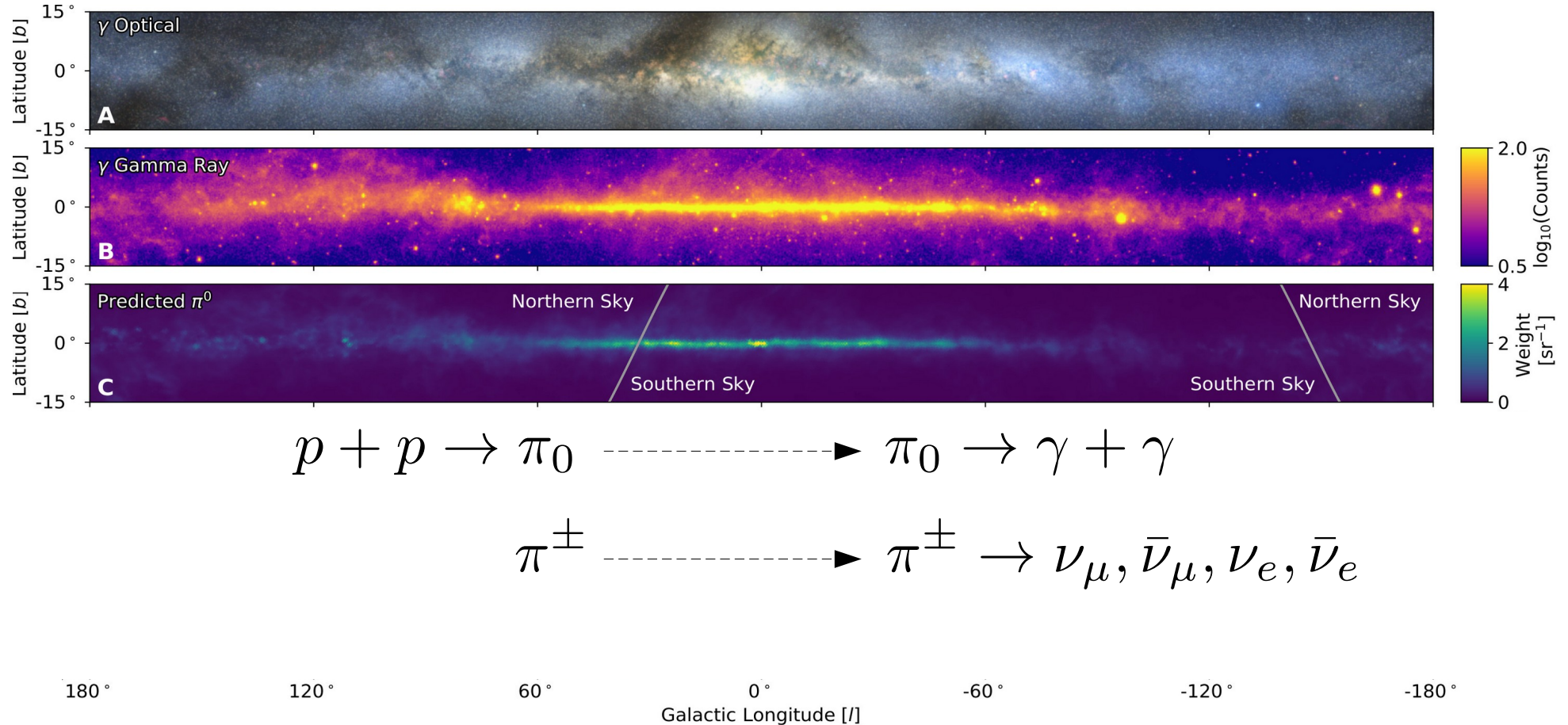
High-energy neutrinos from the Galactic Plane



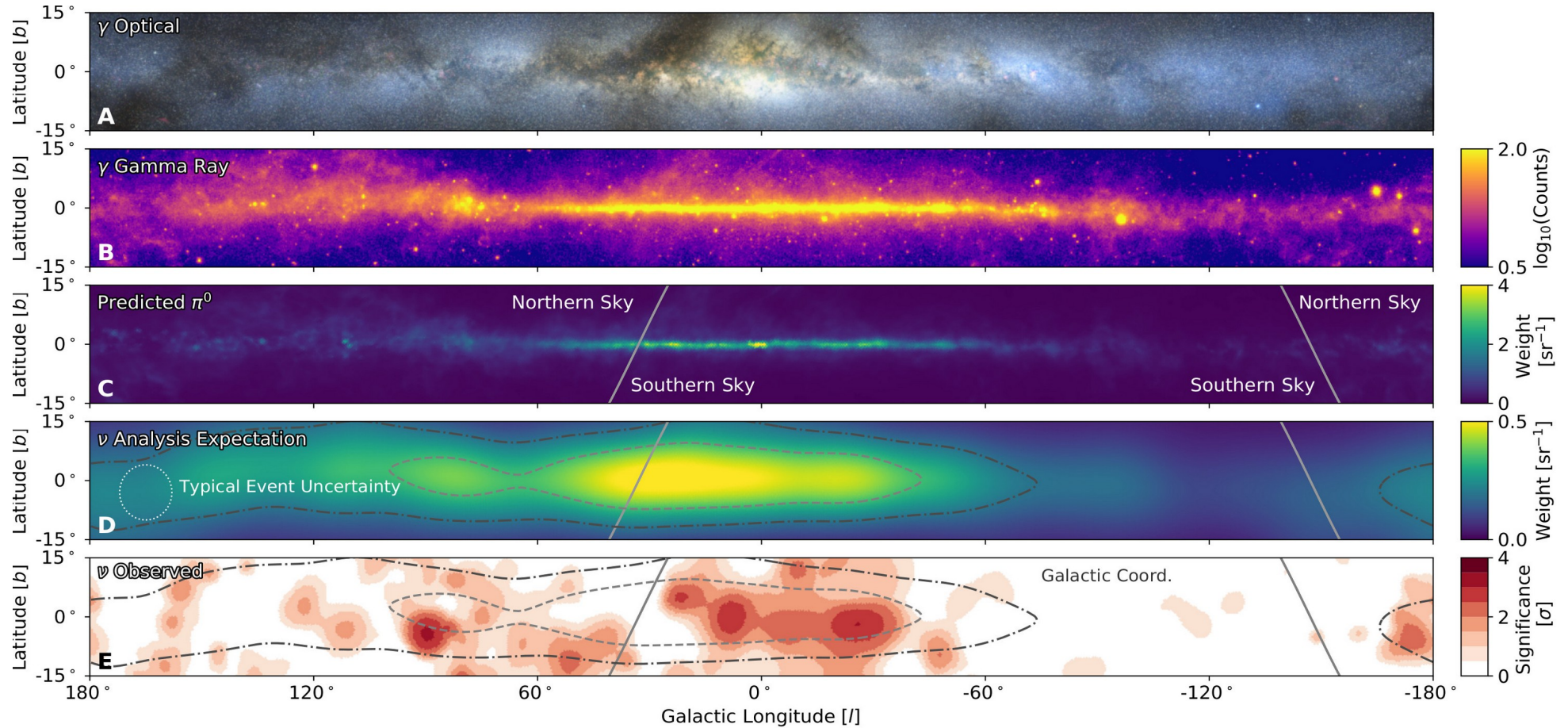
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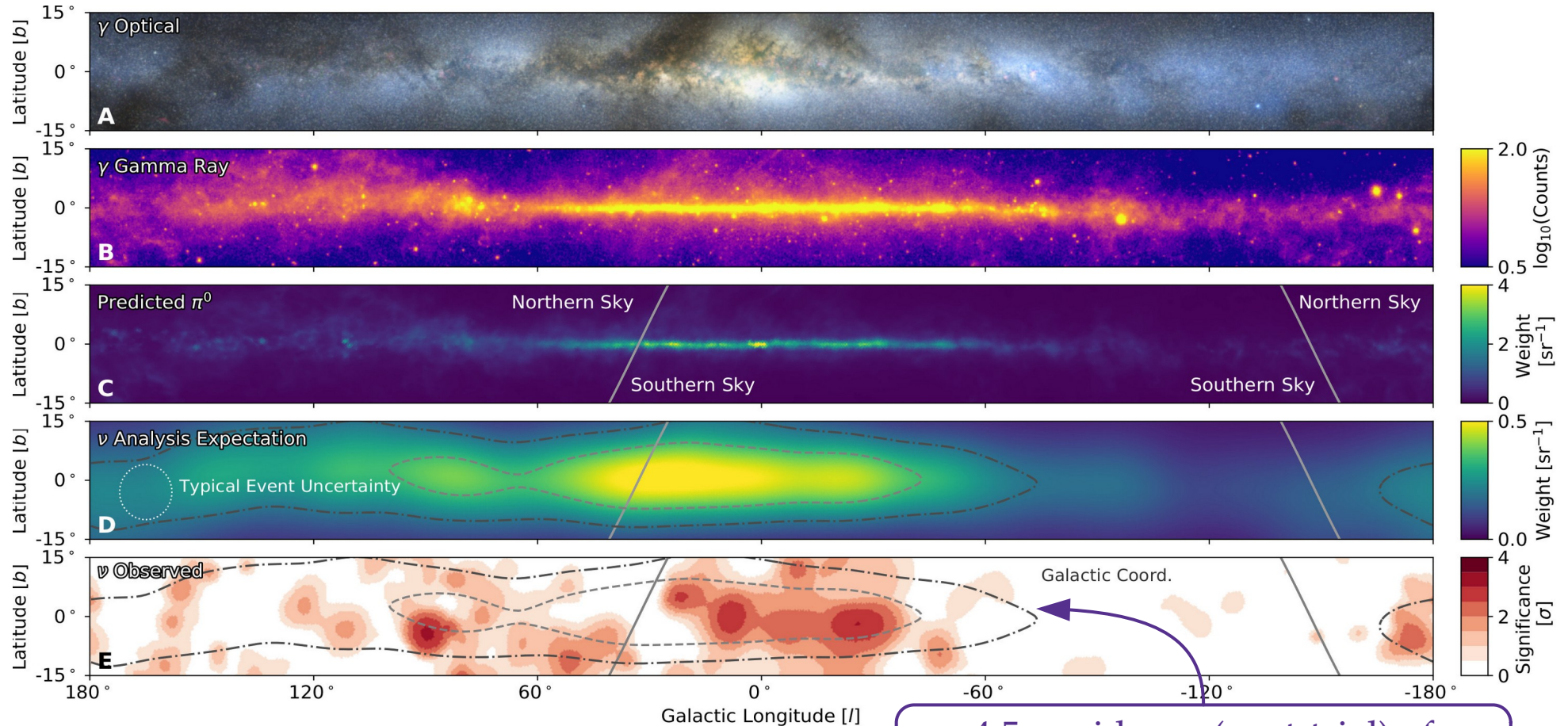
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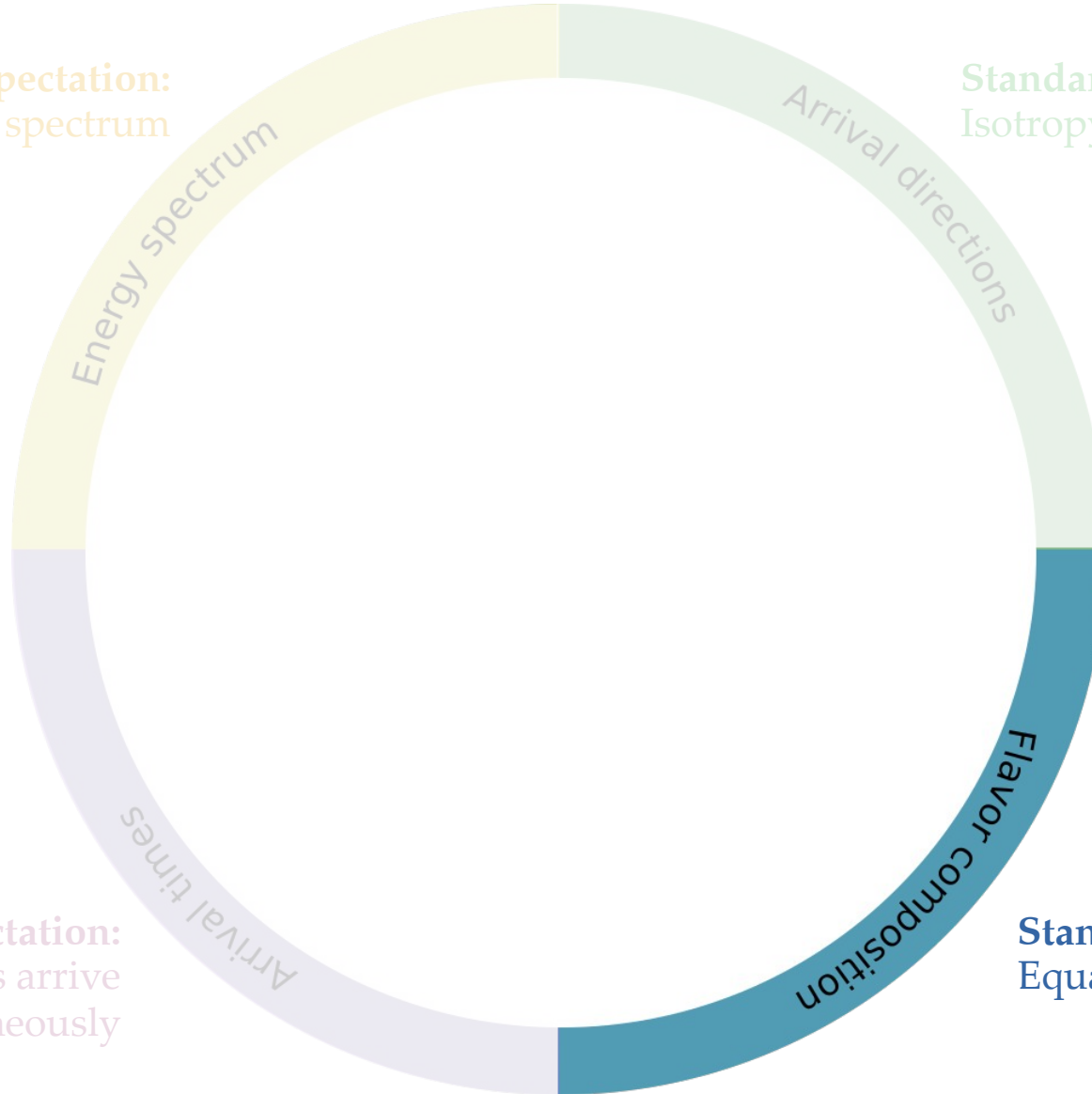
High-energy neutrinos from the Galactic Plane



4.5 σ evidence (post-trial) of
diffuse flux of $> \text{TeV}$ ν from the GP

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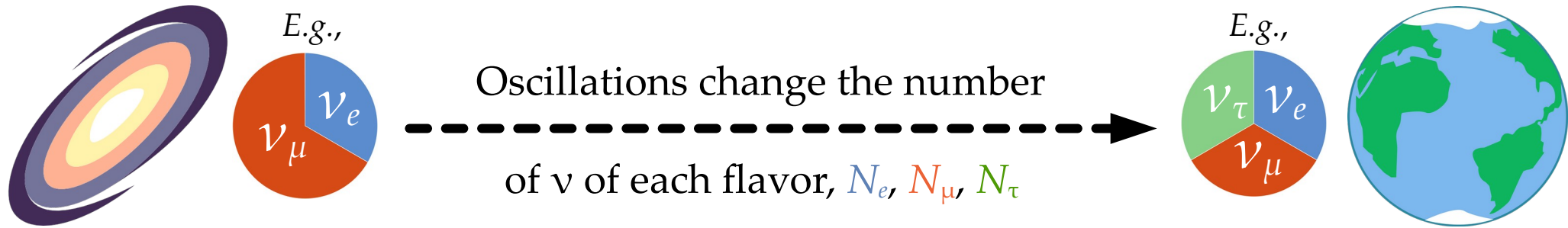
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Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{\text{tot}}$$

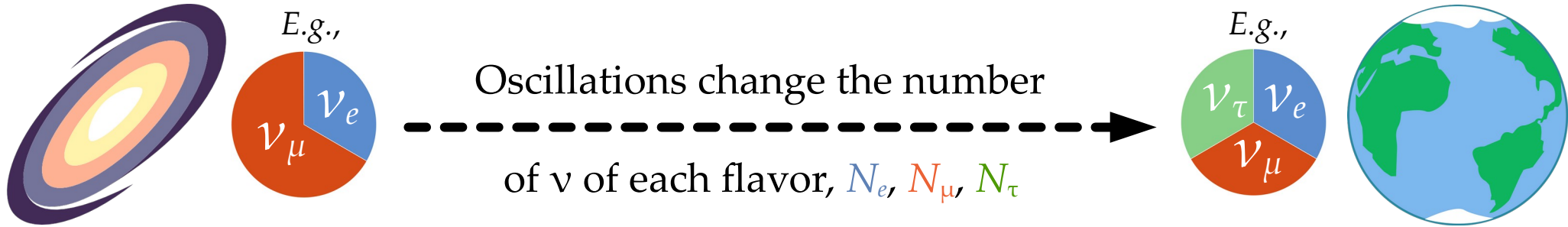
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \rightarrow \nu_\alpha} f_{\beta,S}$$

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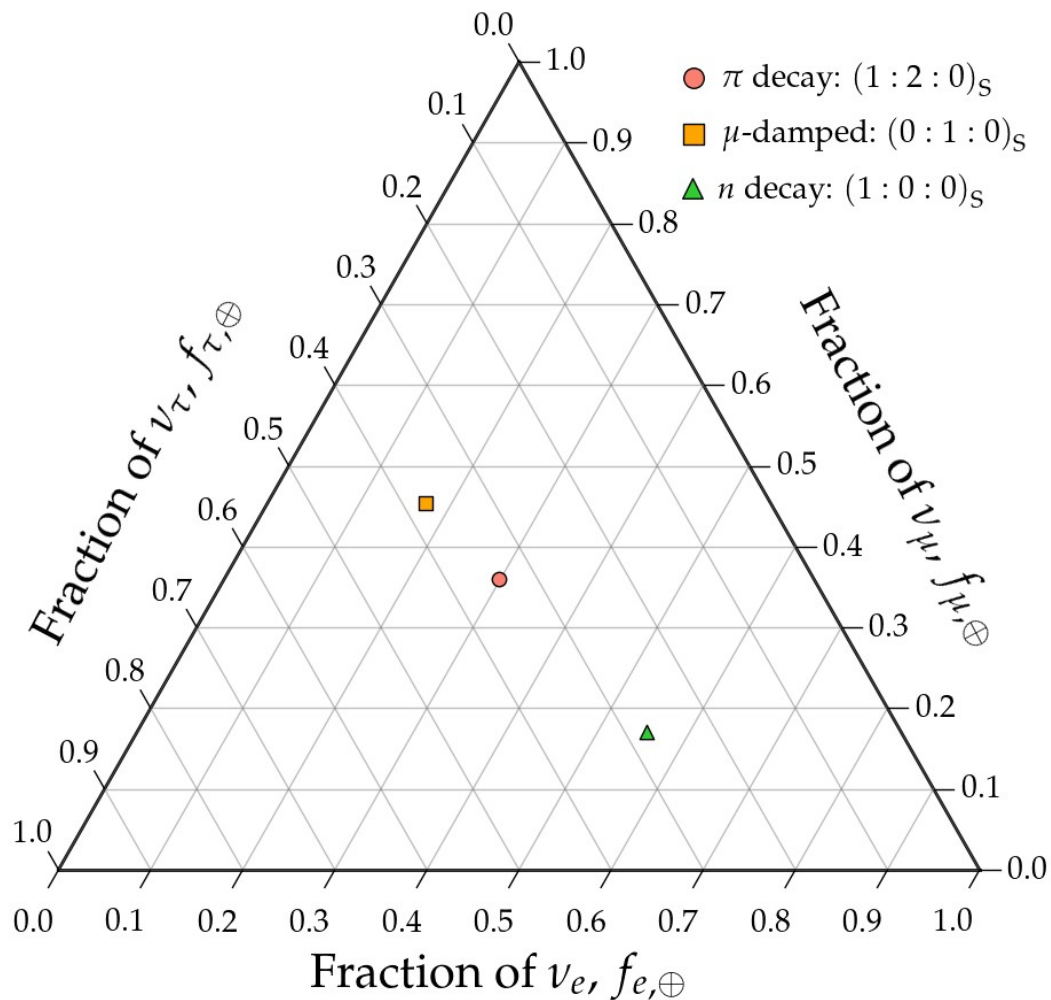
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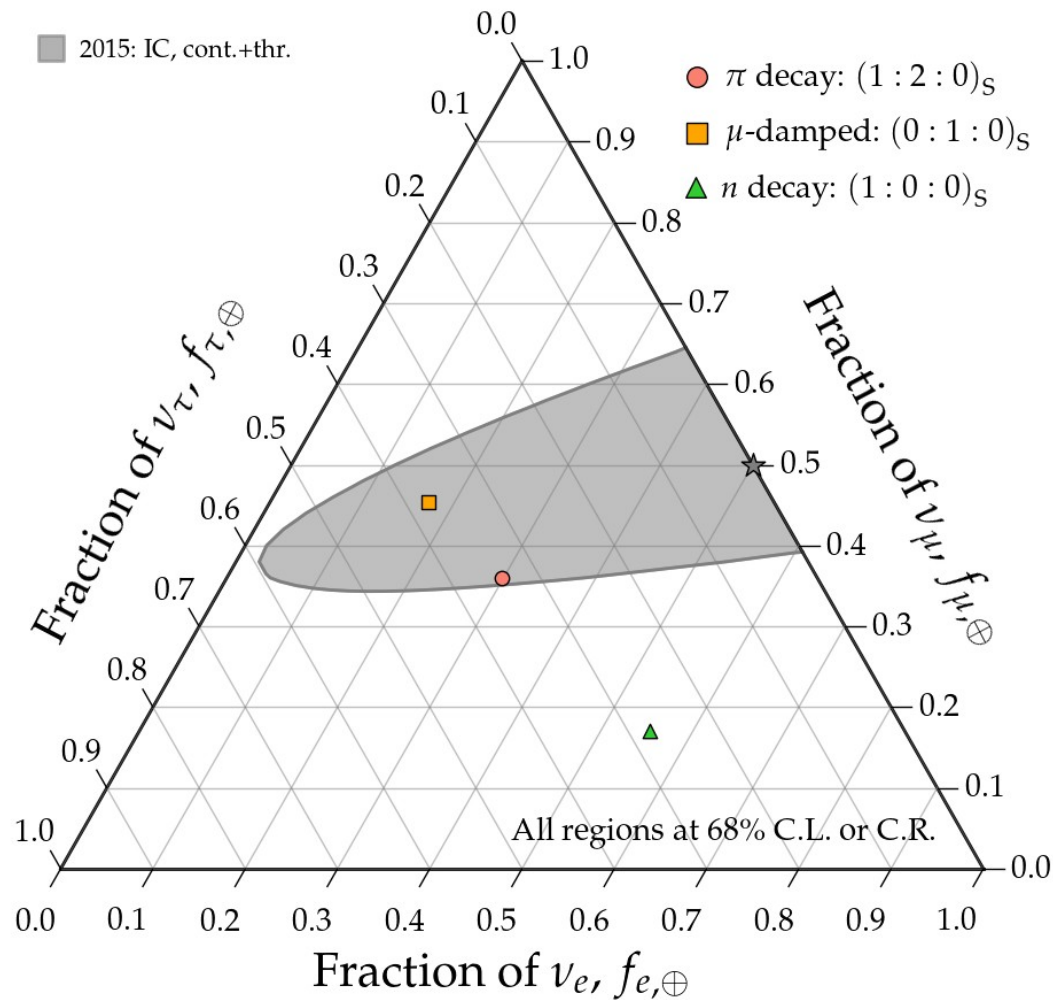
Standard
oscillations
or
new physics

Measuring flavor composition

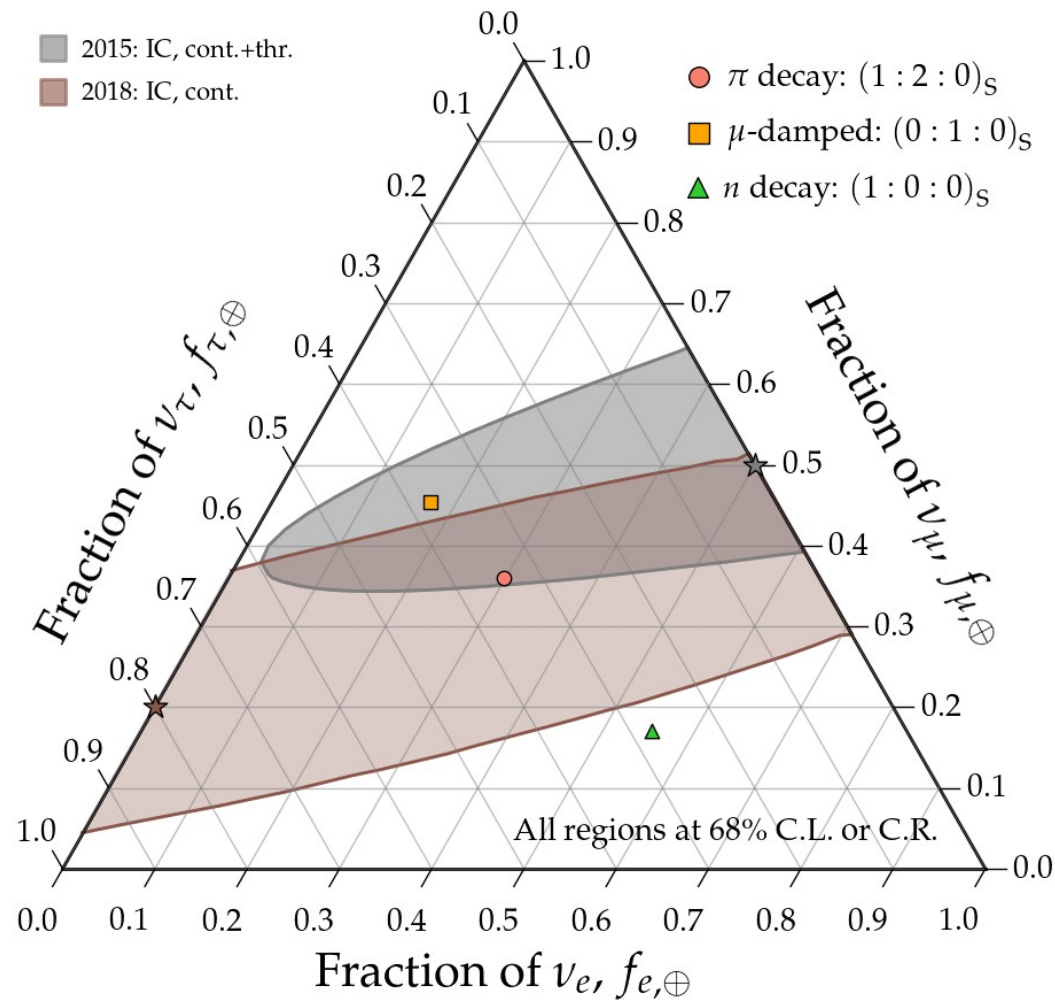
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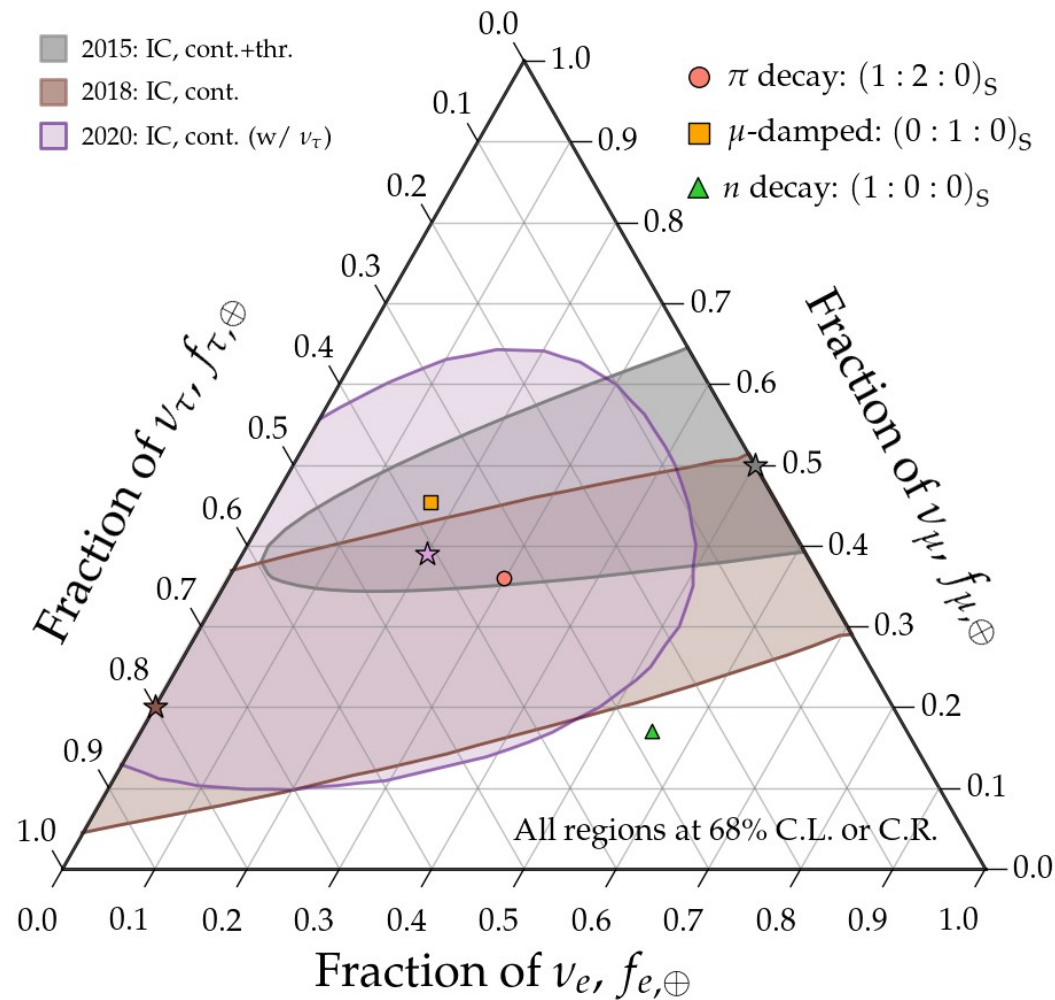
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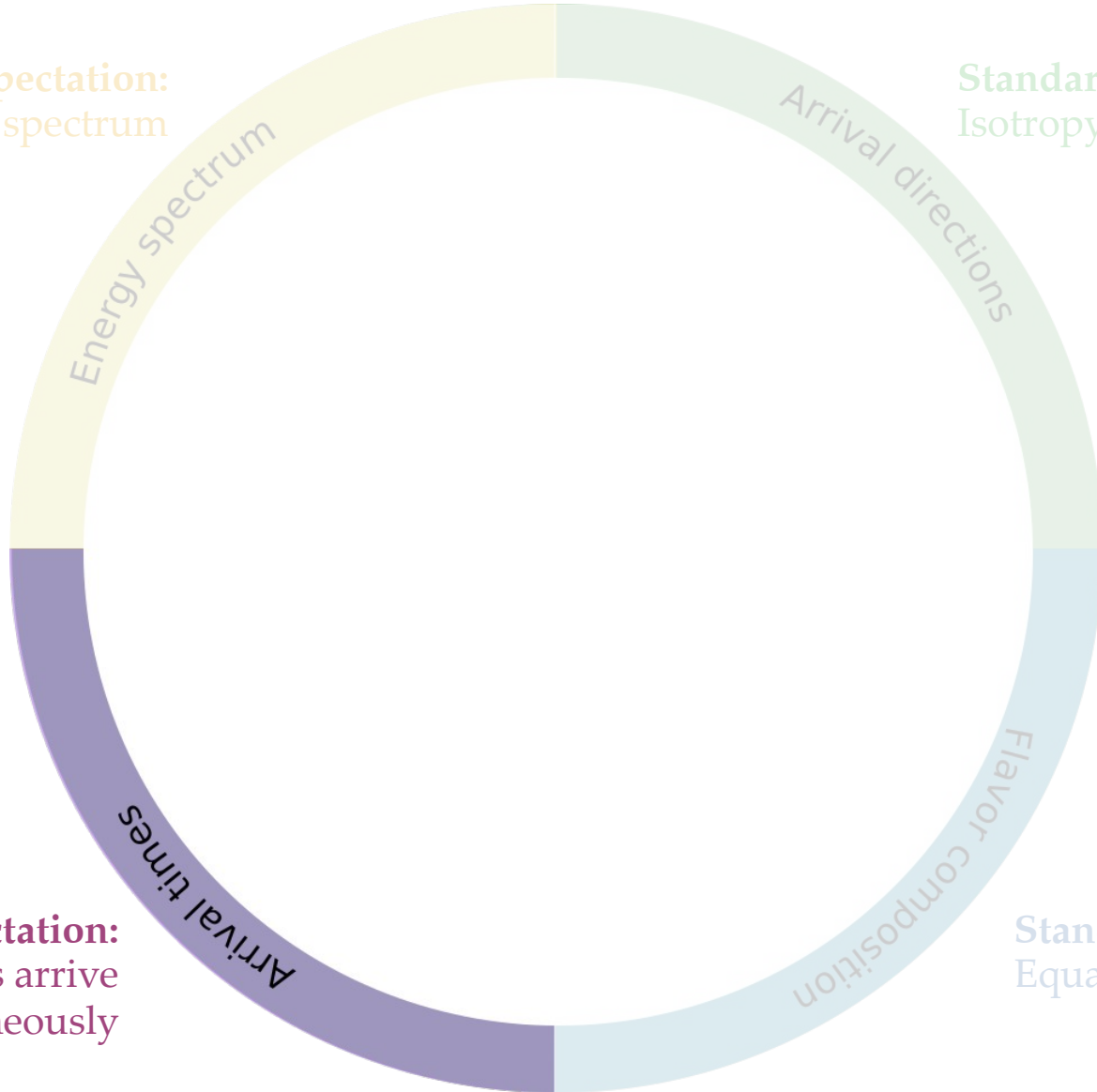


Measuring flavor composition



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Standard expectation:
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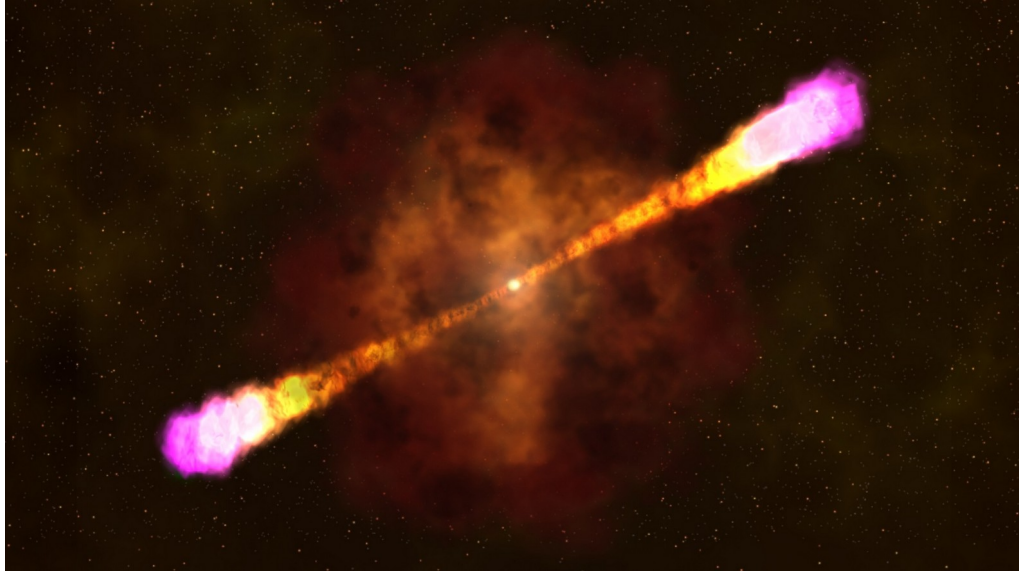
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What have we learned
about astrophysics?

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

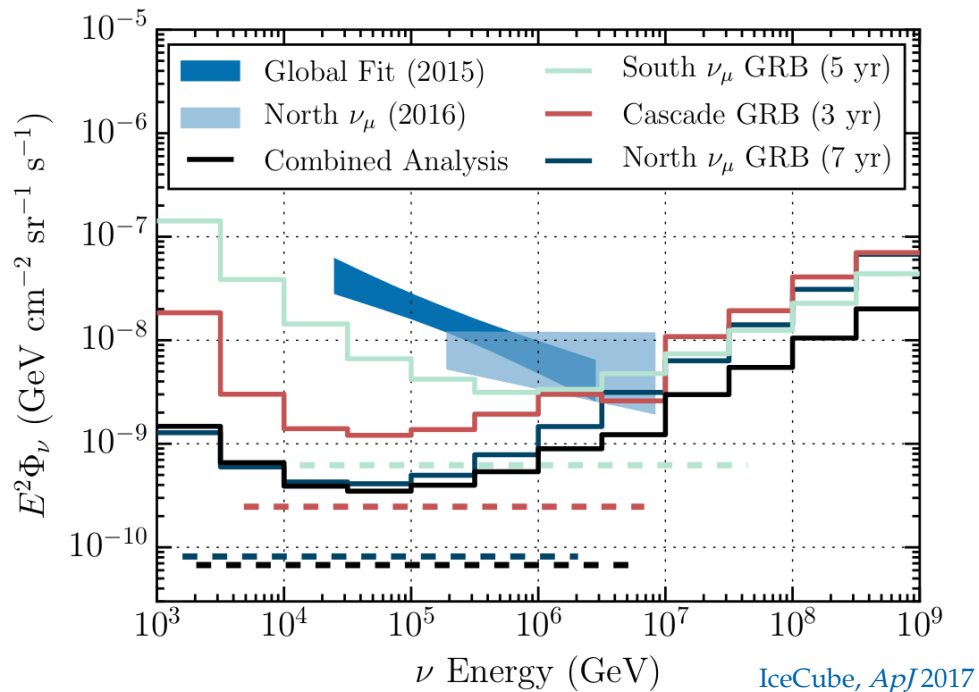


Blazars



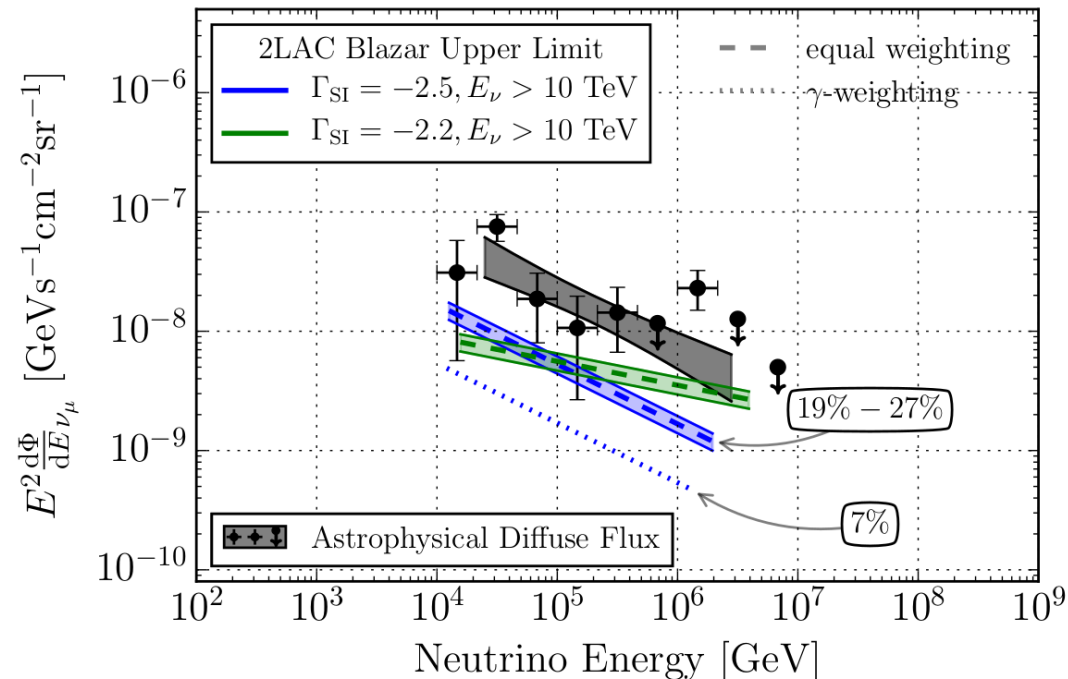
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Gamma-ray bursts



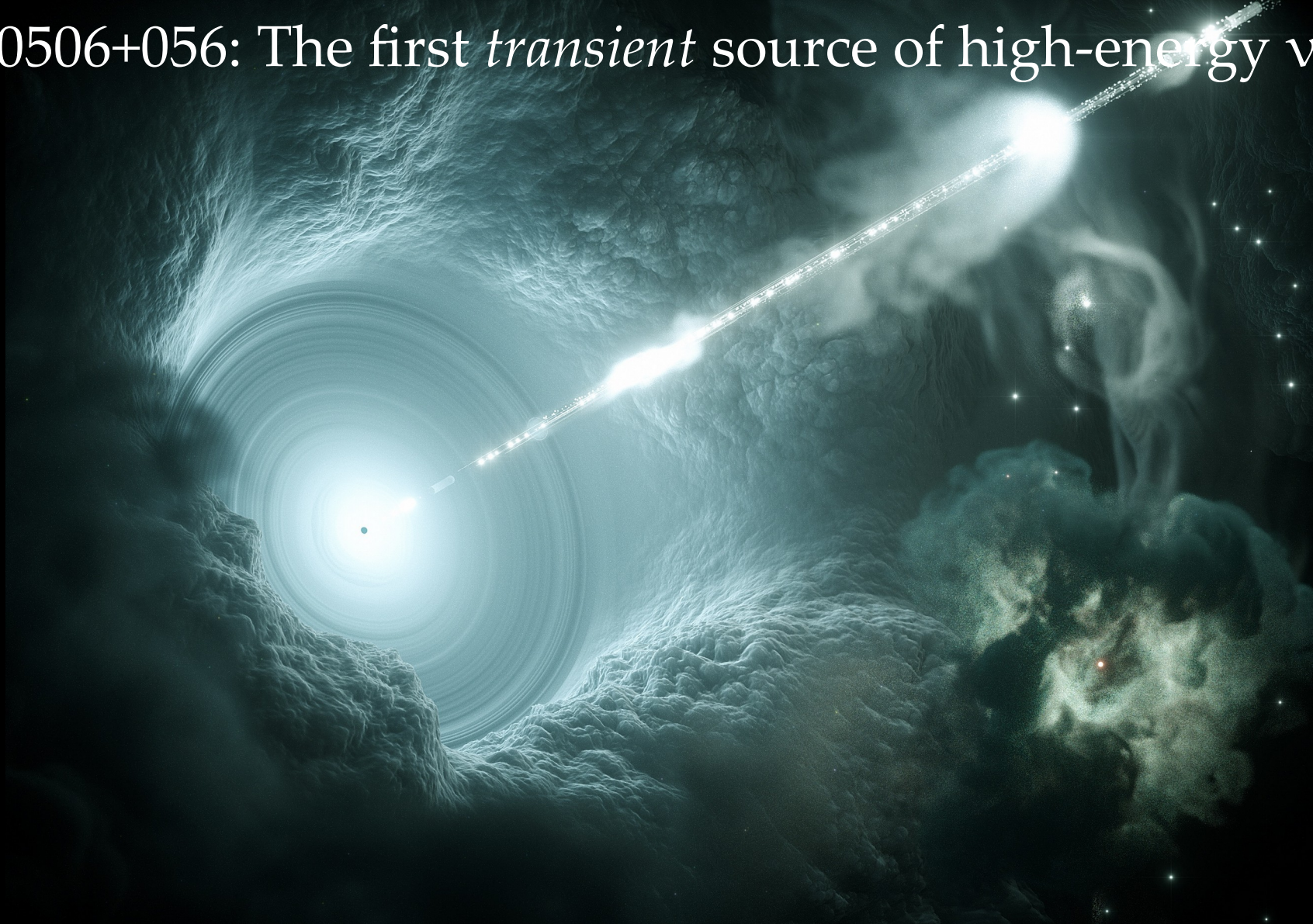
1172 GRBs inspected, no correlation found
< 1% contribution to diffuse flux

Blazars



862 blazars inspected, no correlation found
< 27% contribution to diffuse flux

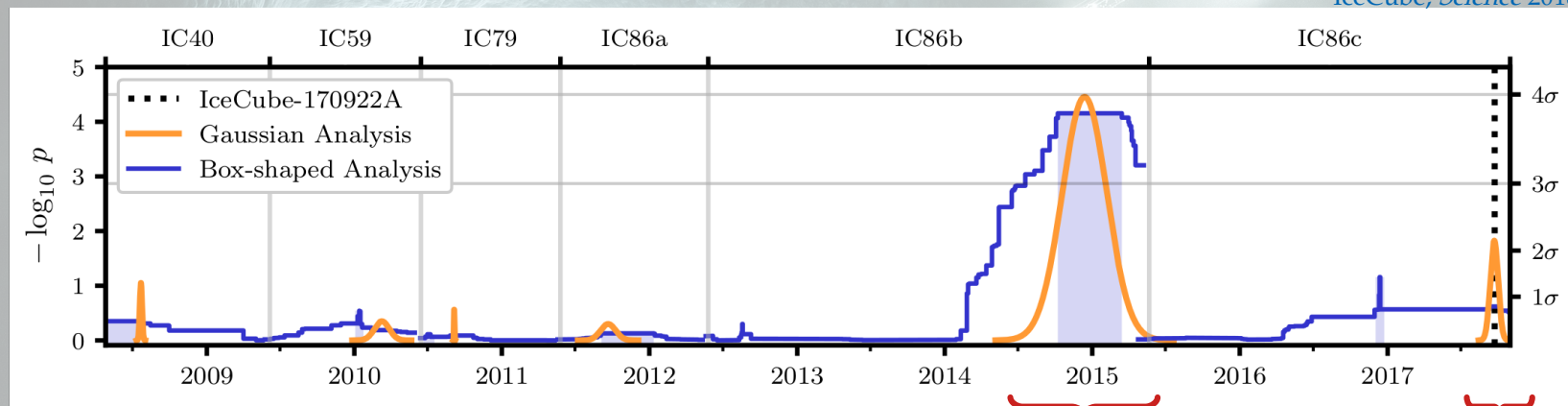
TXS 0506+056: The first *transient* source of high-energy ν



TXS 0506+056: The first *transient* source of high-energy ν

Blazar TXS 0506+056:

IceCube, *Science* 2018



After re-analysis (2101.09836),
significance dropped
from $p=7 \times 10^{-5}$ to $p=8 \times 10^{-3}$

2014–2015: 13 ± 5 ν flare, no X-ray flare
 3.5σ significance of correlation (post-trial)

2017: one 290-TeV ν + X-ray flare
 1.4σ significance of correlation

Combined (pre-trial): 4.1σ

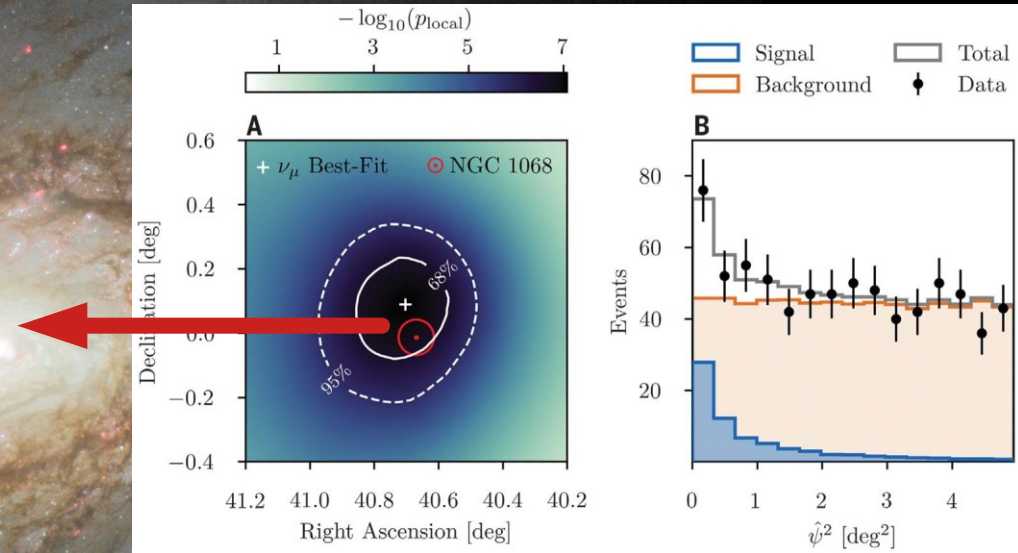
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



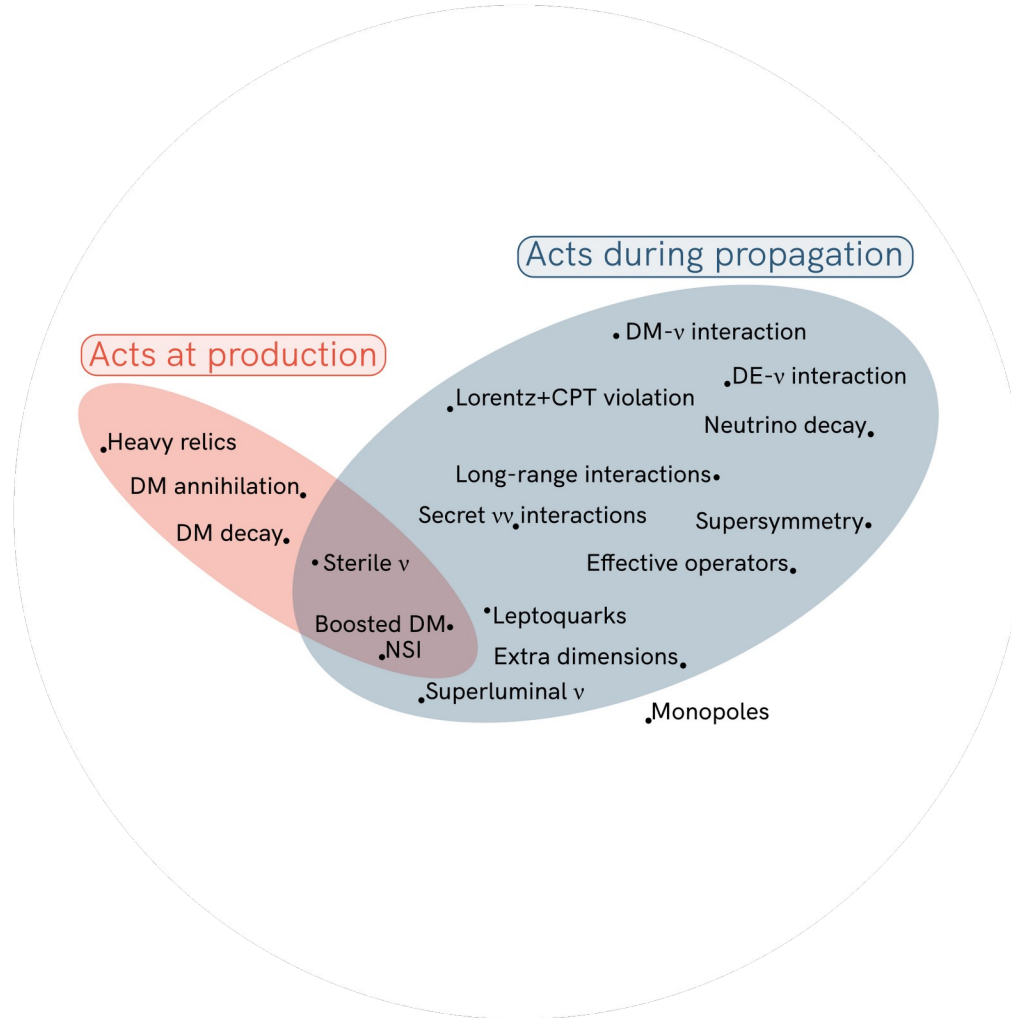
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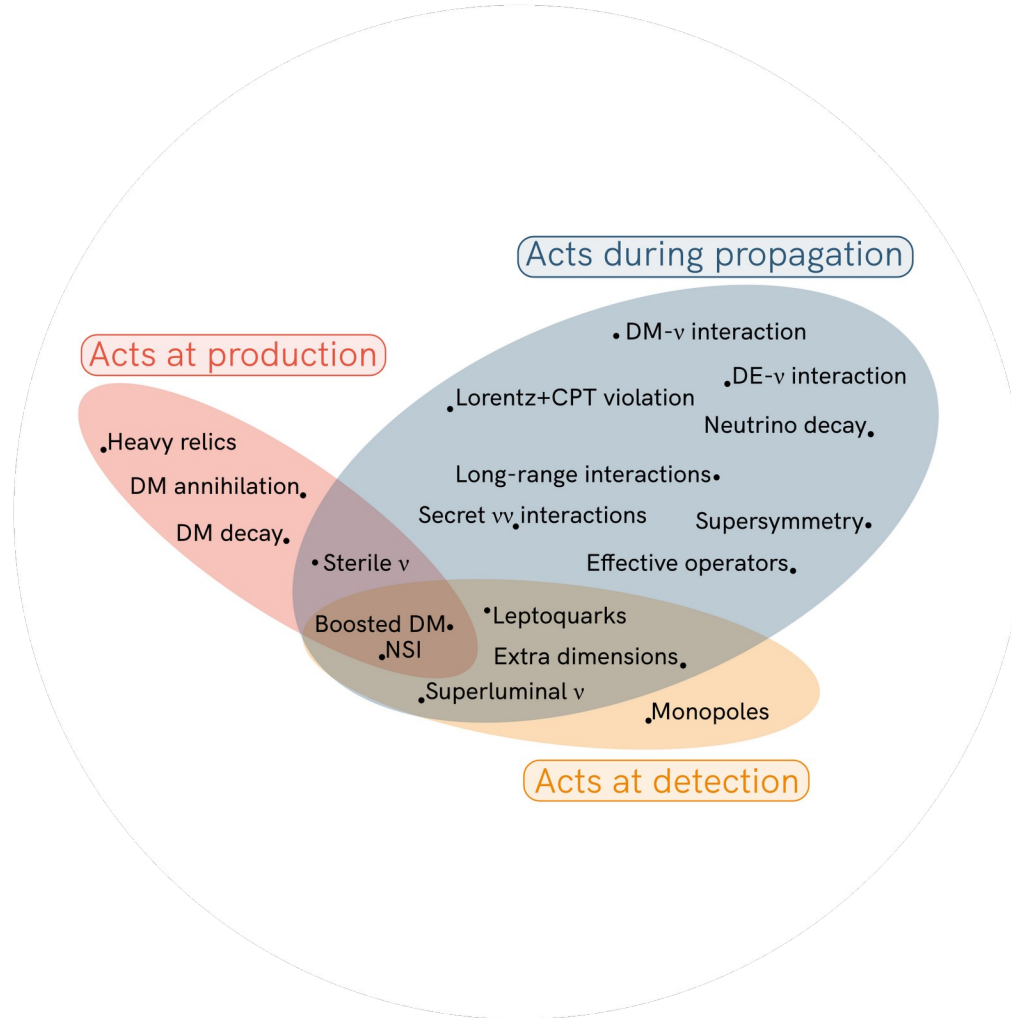
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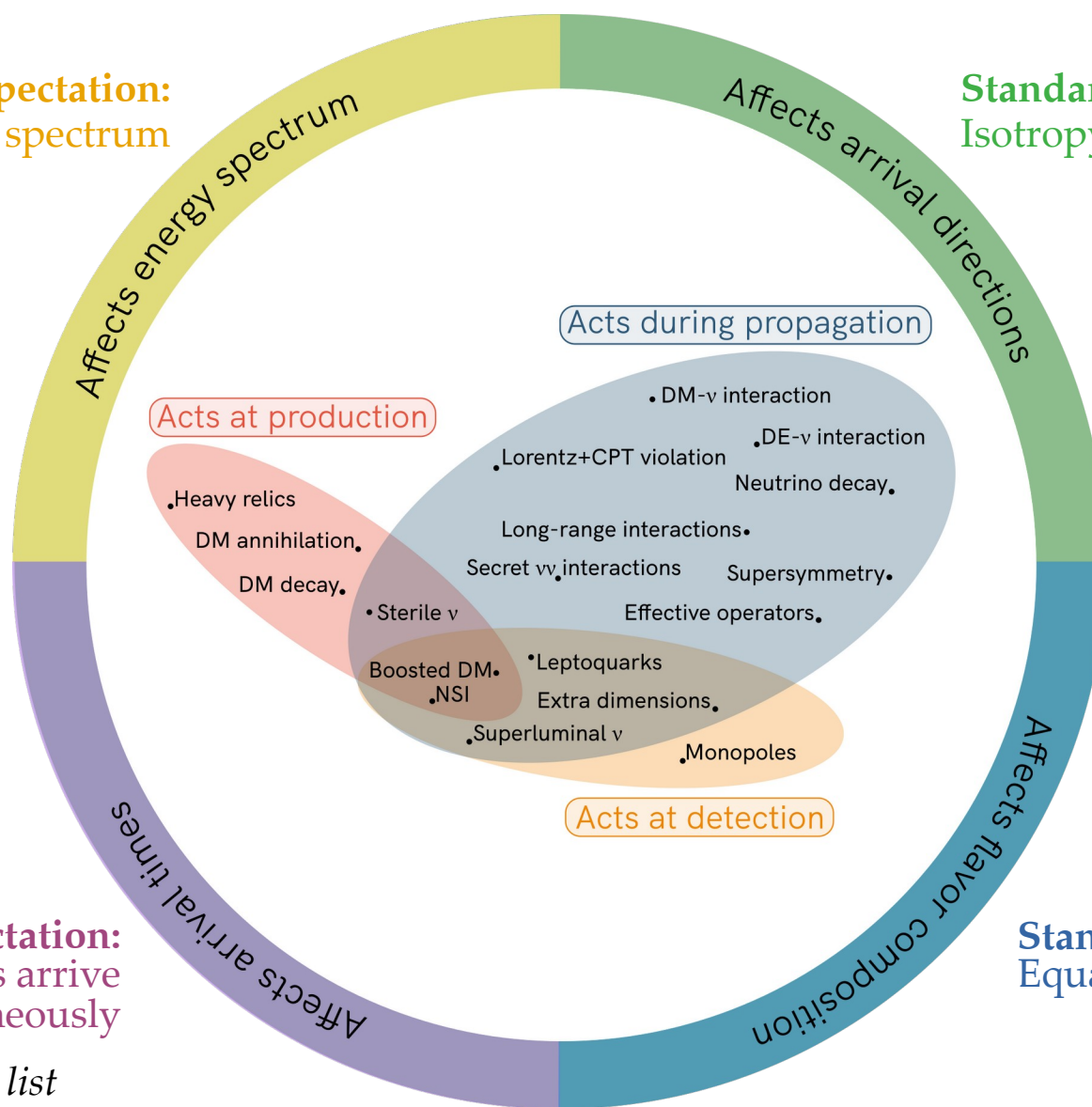
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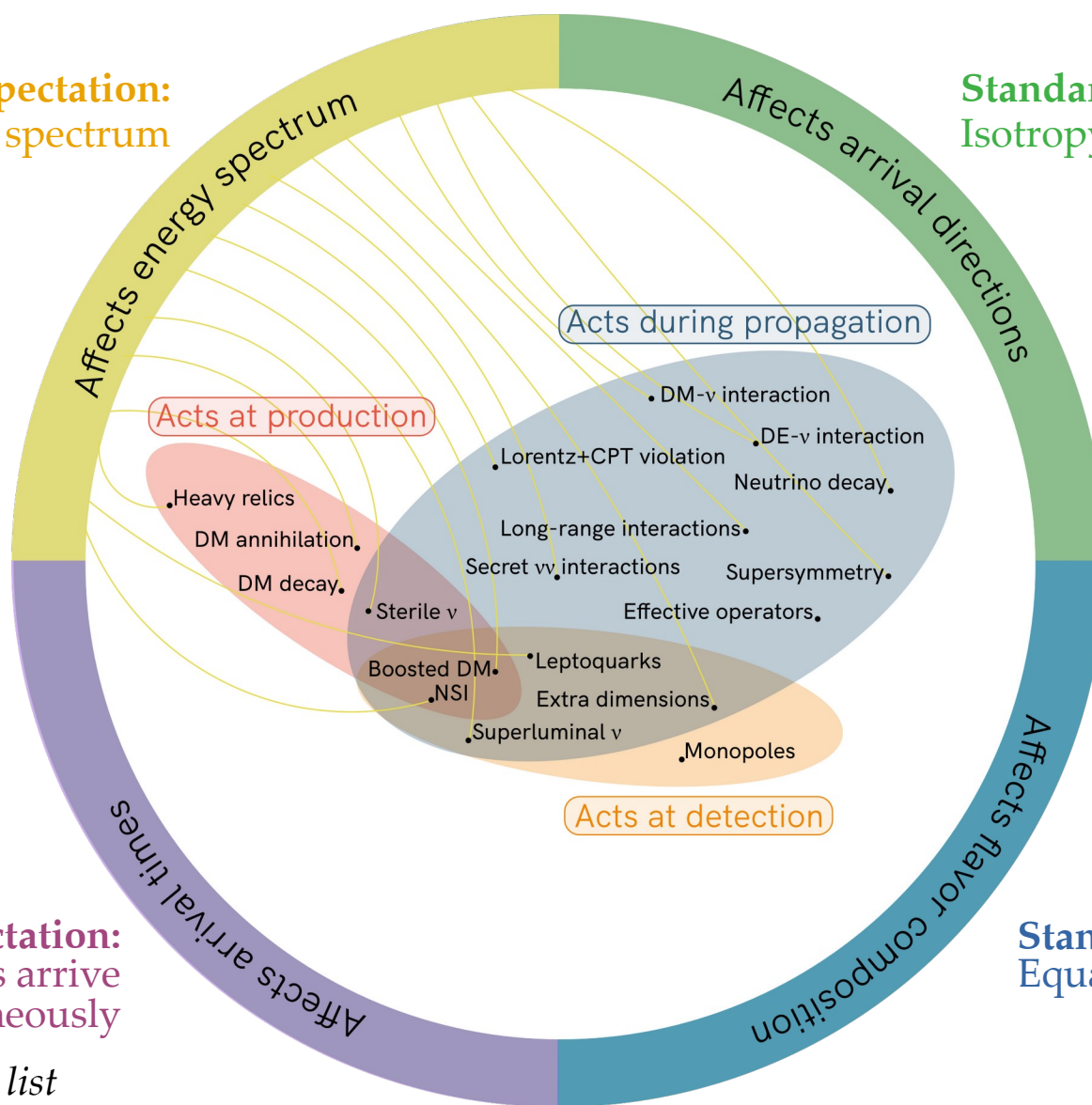
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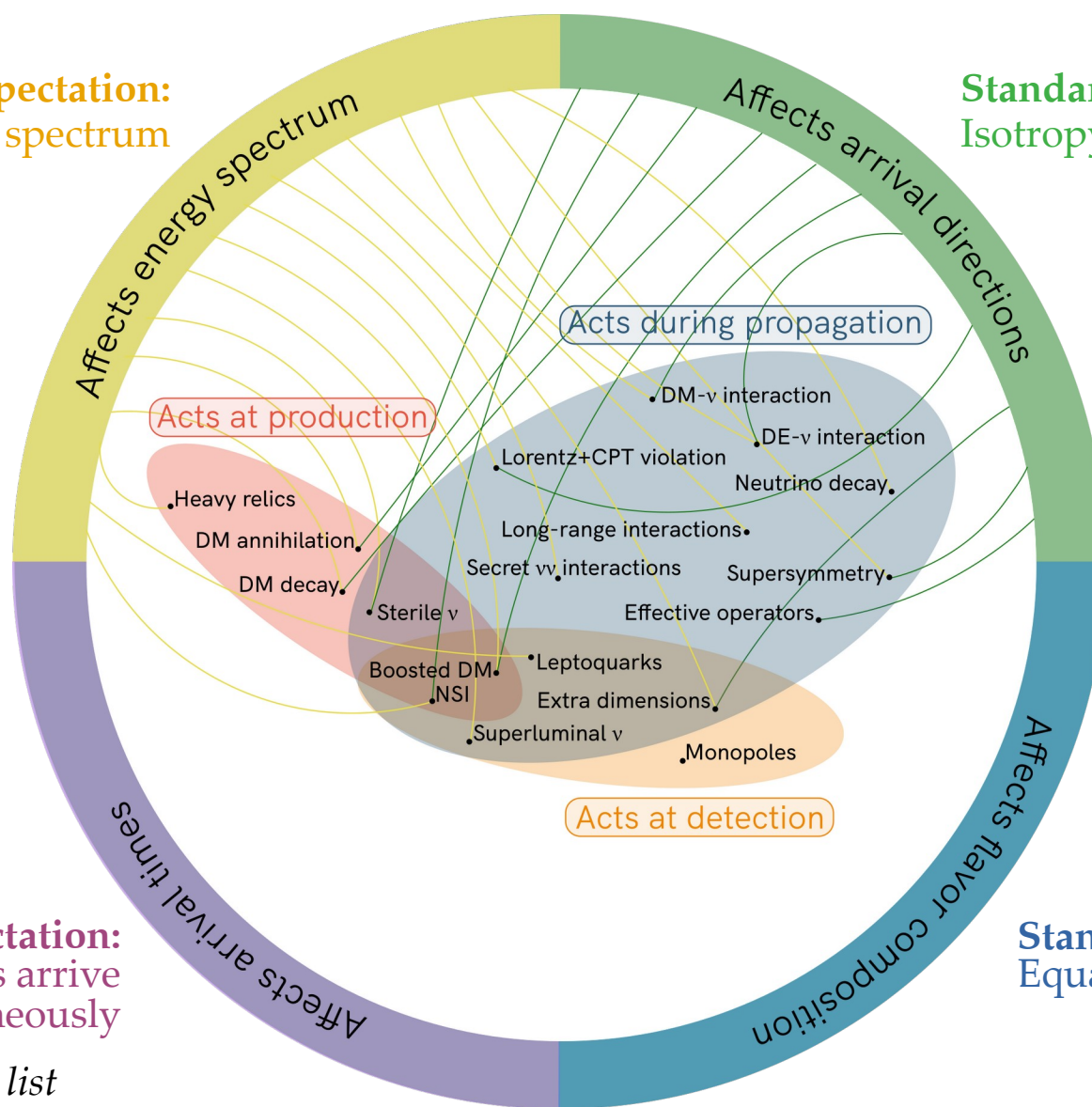
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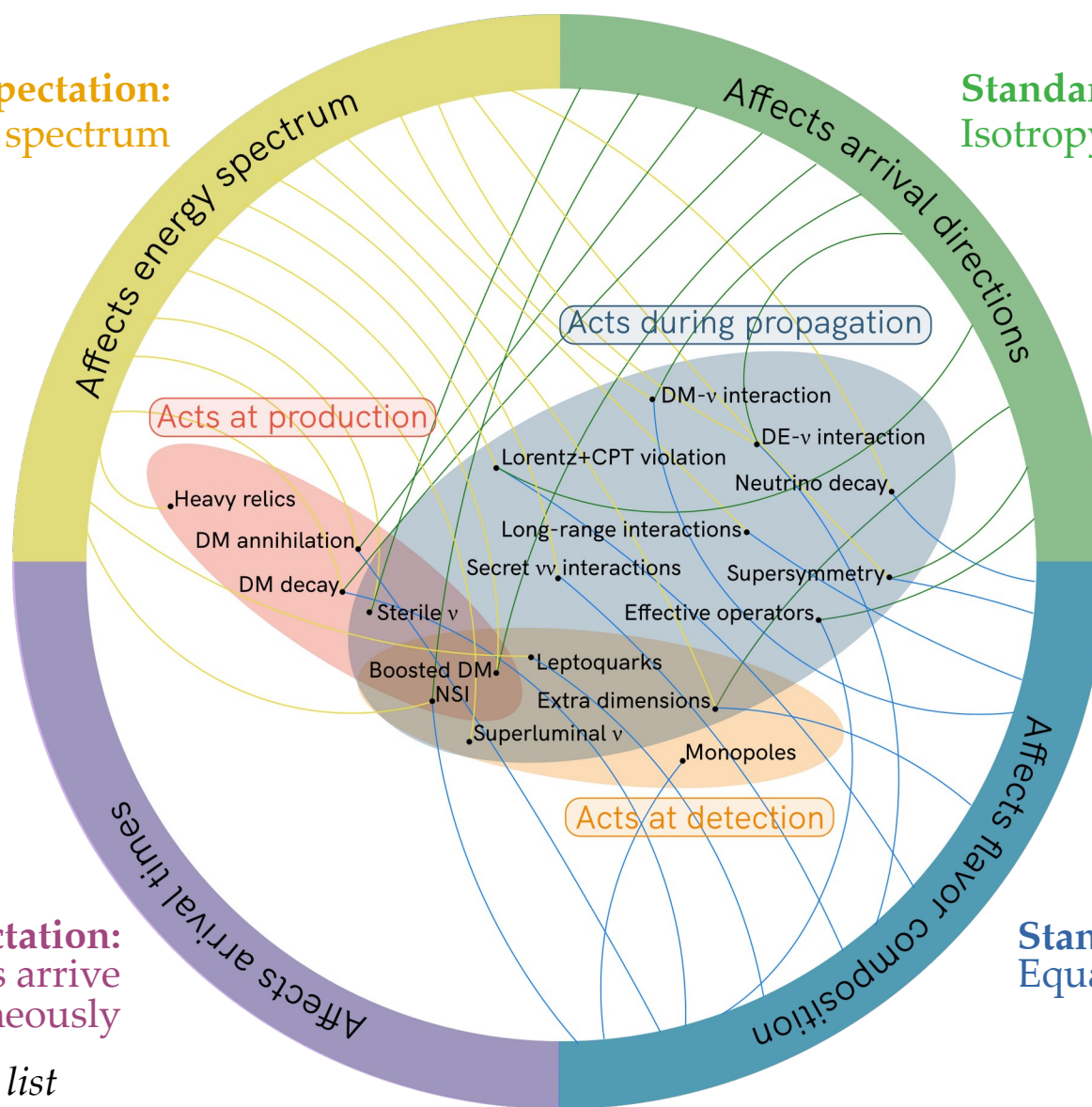
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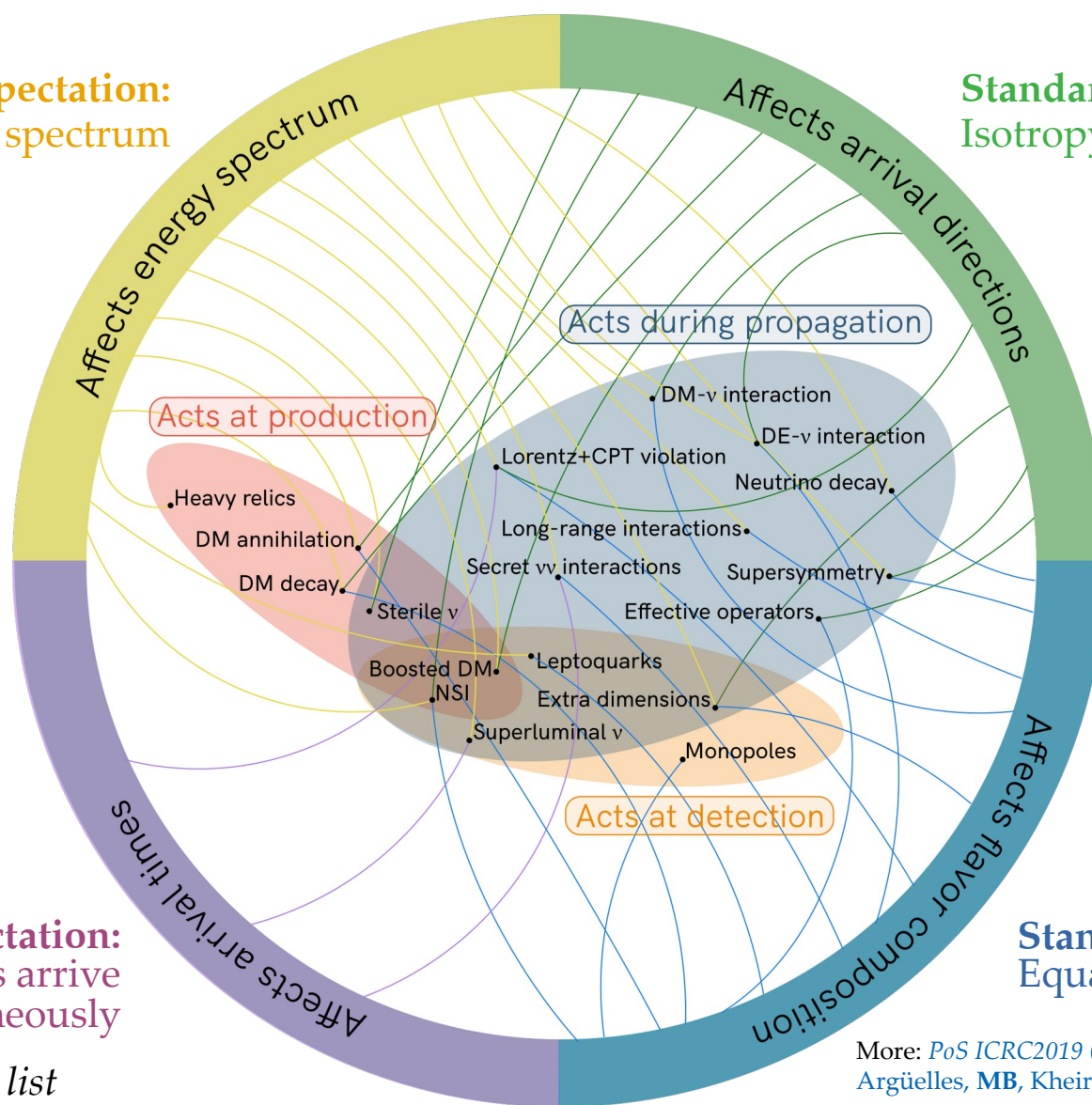
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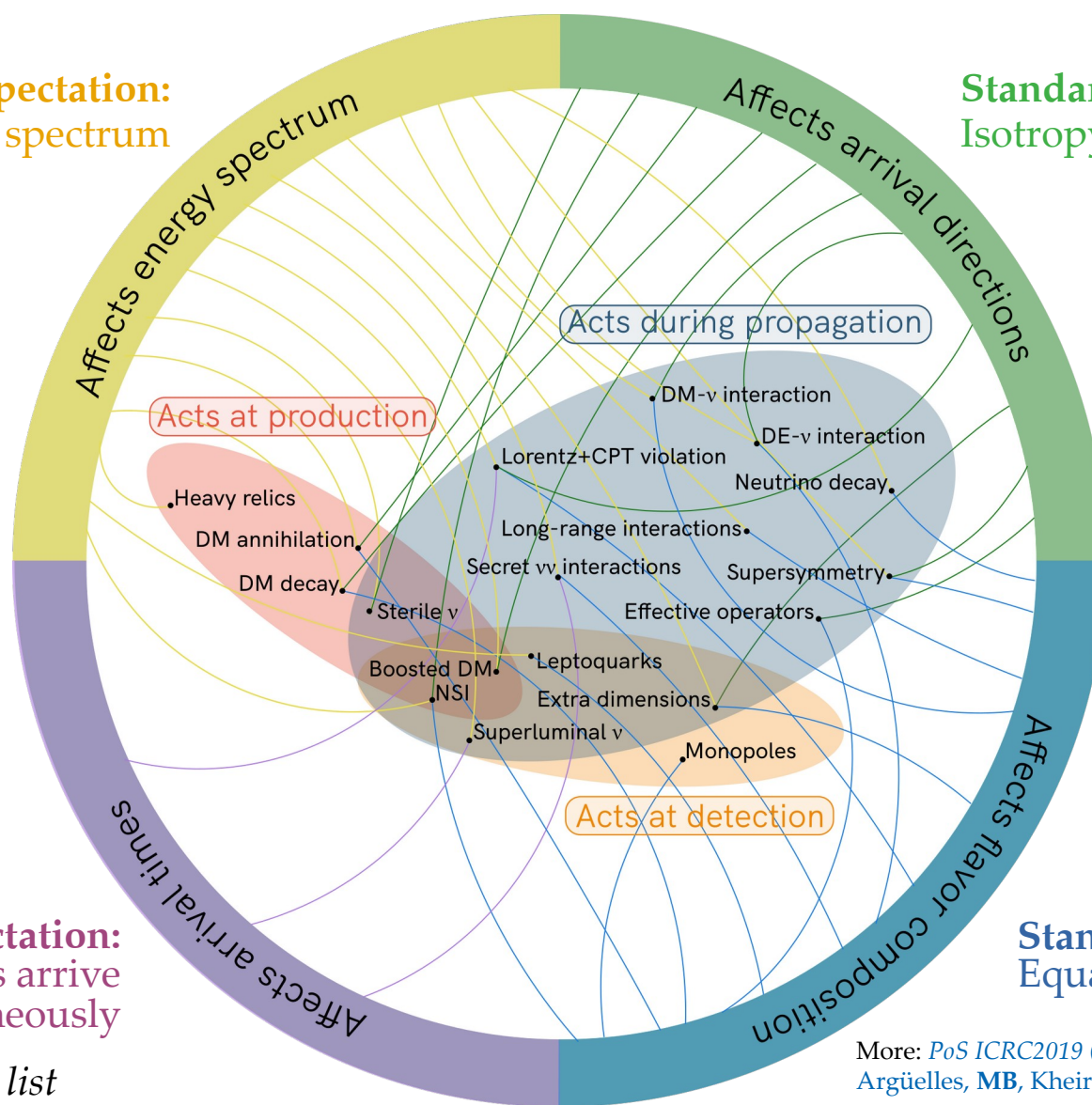
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More: *PoS ICRC2019* (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

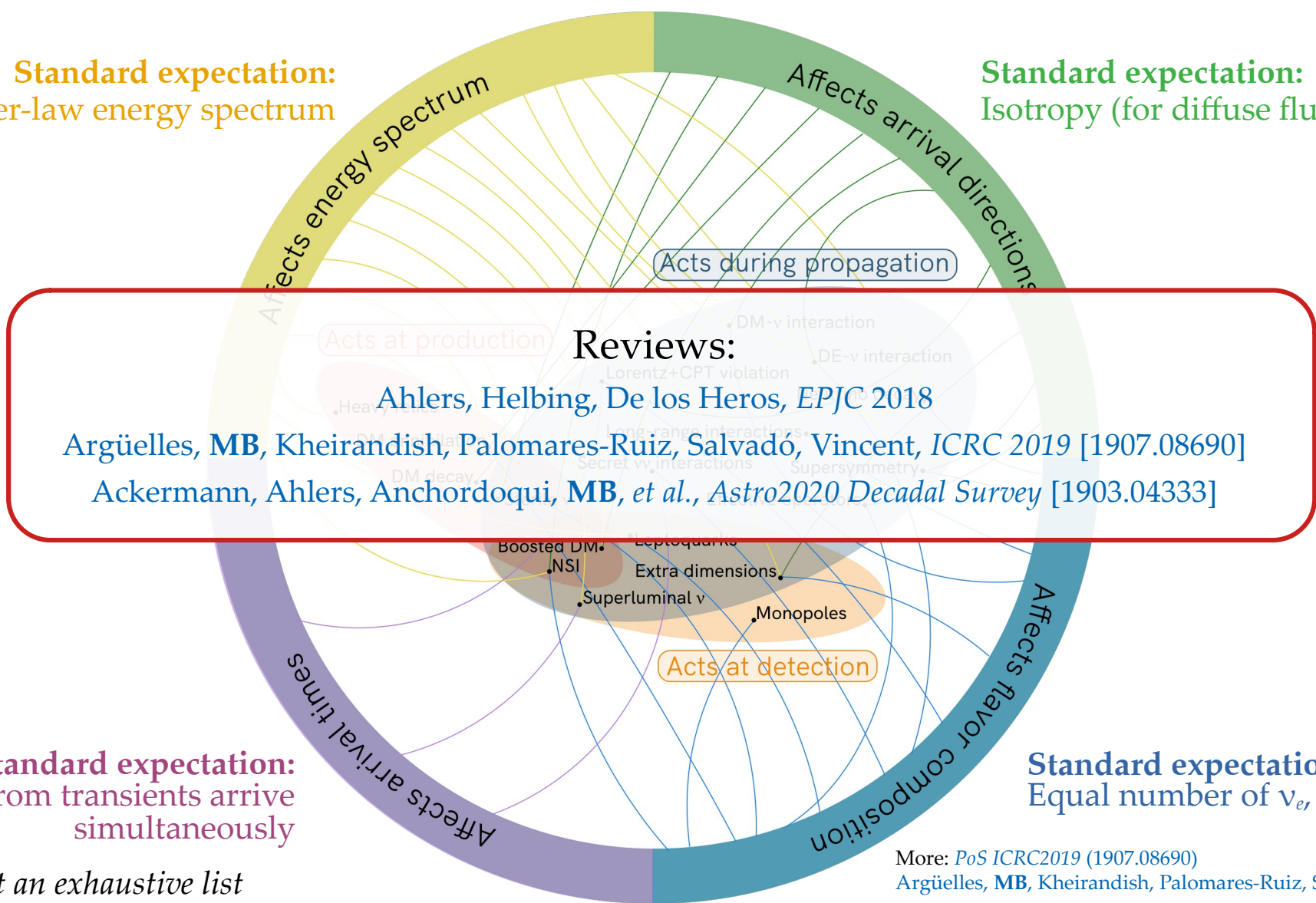
Note: Not an exhaustive list

More: *PoS ICRC2019* (1907.08690)

Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Reviews:

Ahlers, Helbing, De los Heros, *EPJC* 2018

Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC* 2019 [1907.08690]

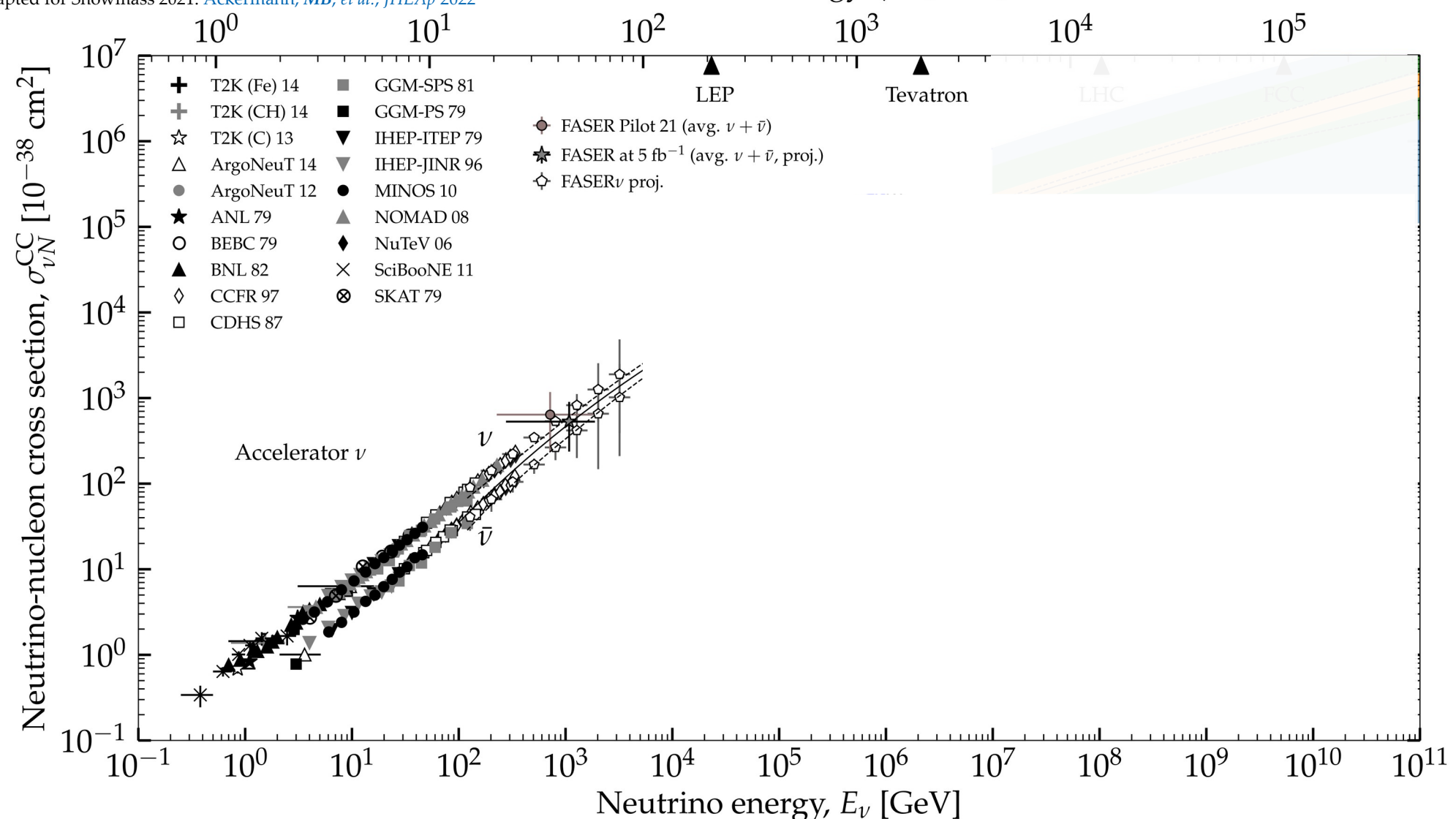
Ackermann, Ahlers, Anchordoqui, **MB**, *et al.*, *Astro2020 Decadal Survey* [1903.04333]

Standard expectation:
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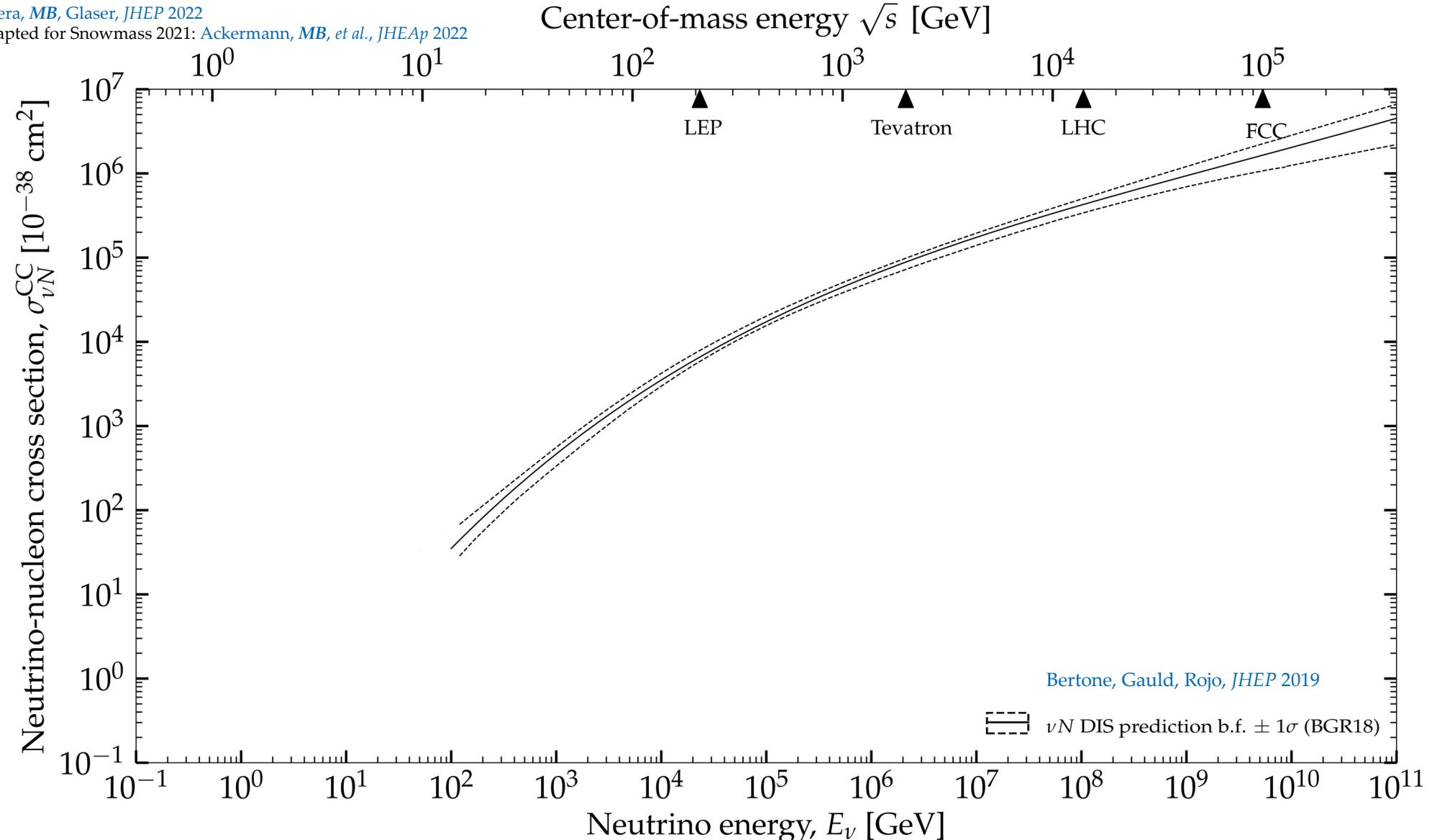
More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

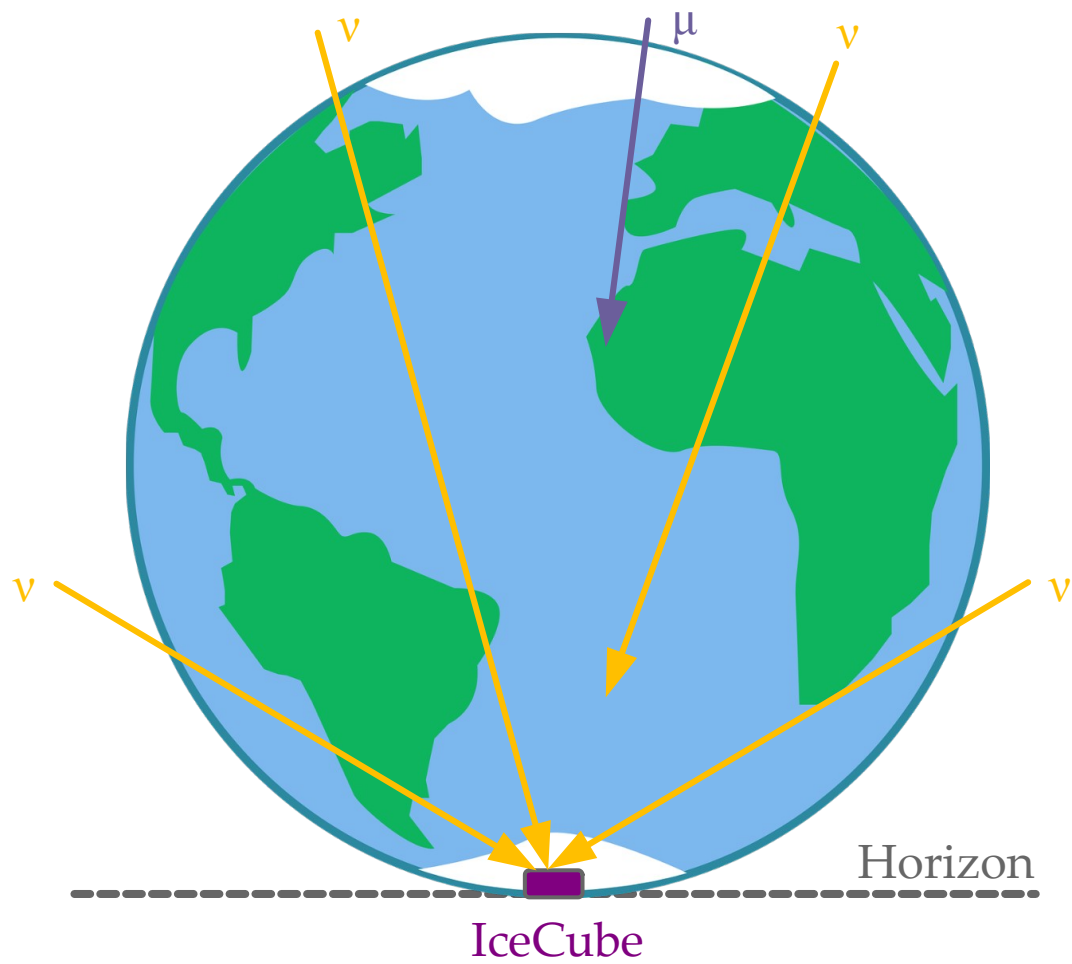
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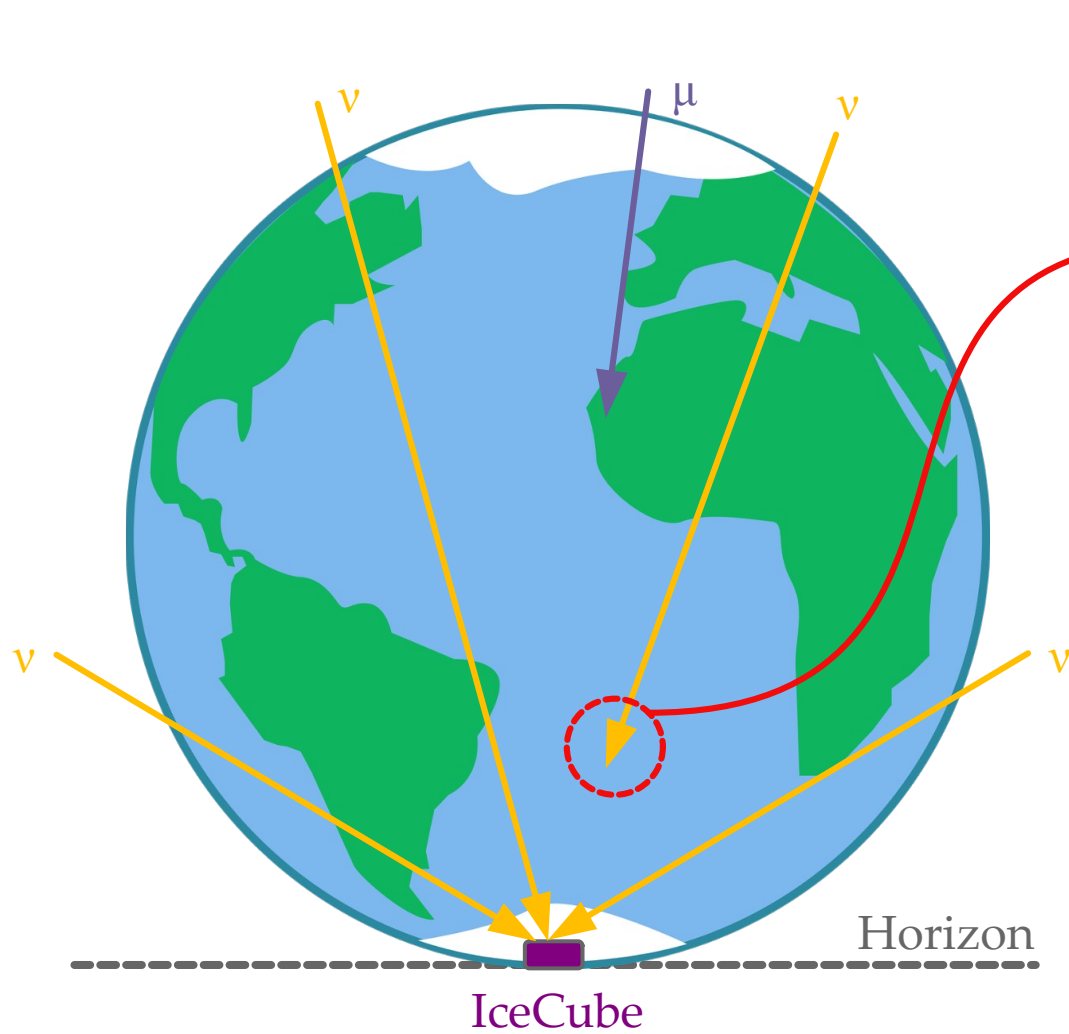
Center-of-mass energy $\sqrt{s}$ [GeV]



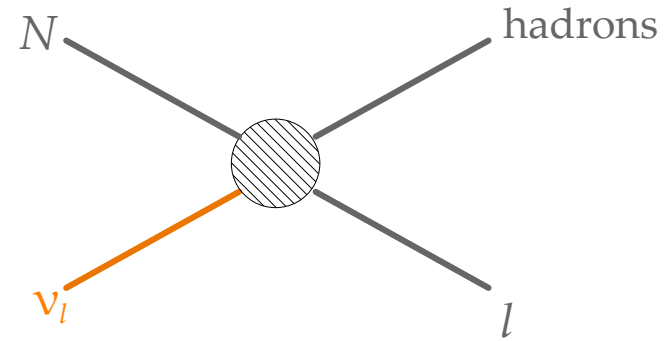
Center-of-mass energy $\sqrt{s}$ [GeV]

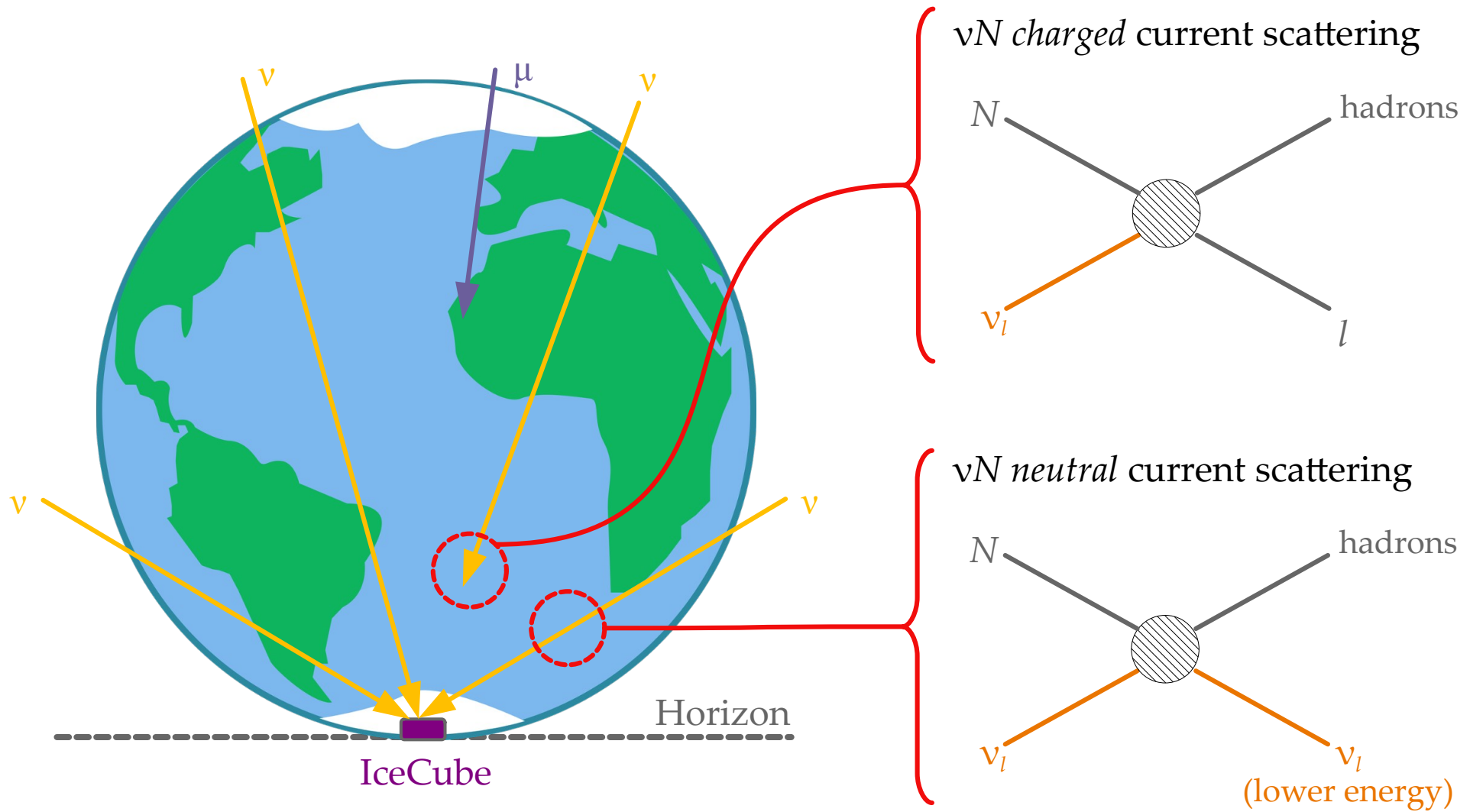


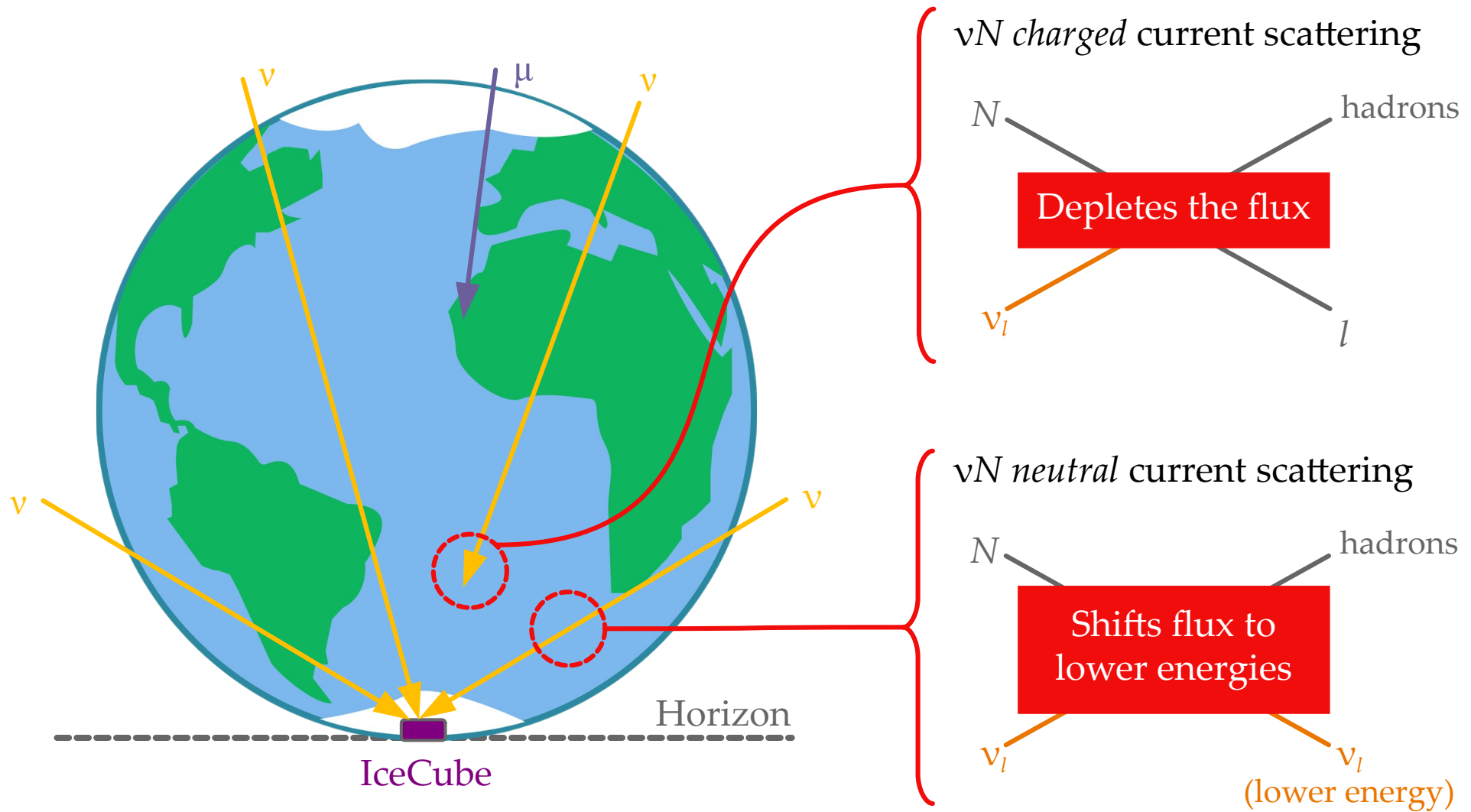




νN charged current scattering

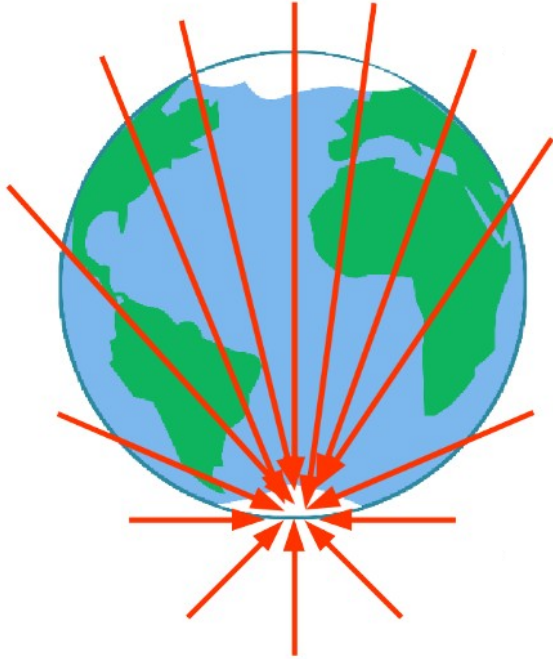




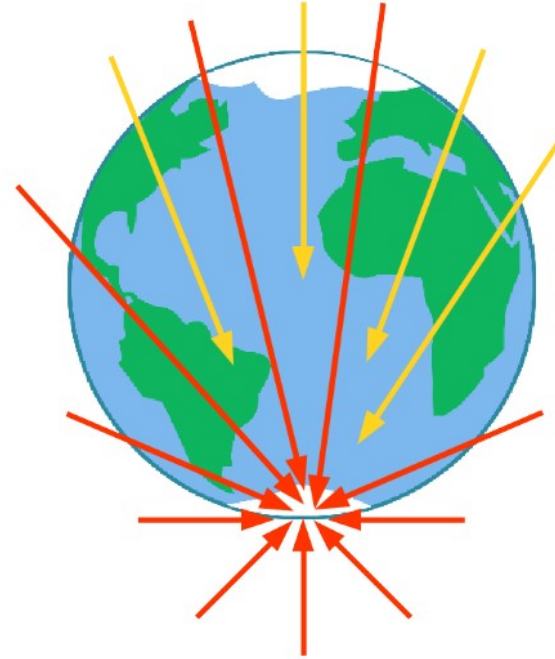


Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

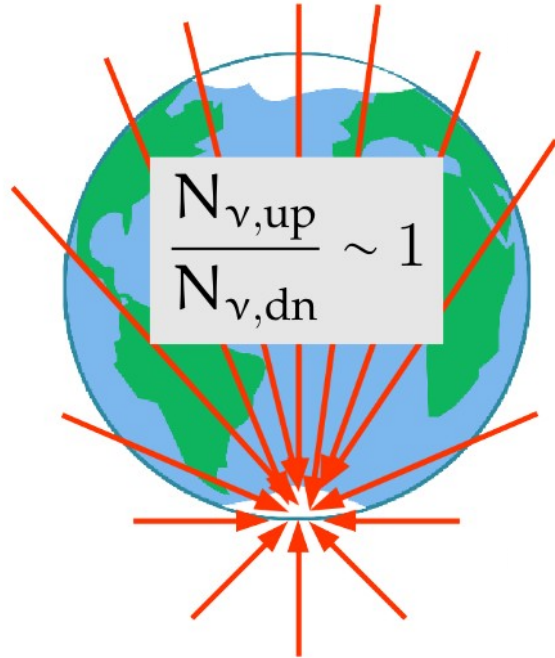


Above ~ 10 TeV: Earth is opaque

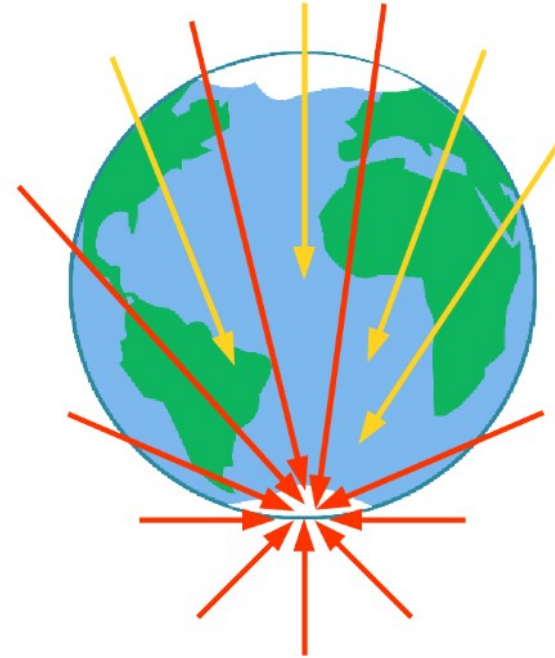


Measuring the high-energy νN cross section

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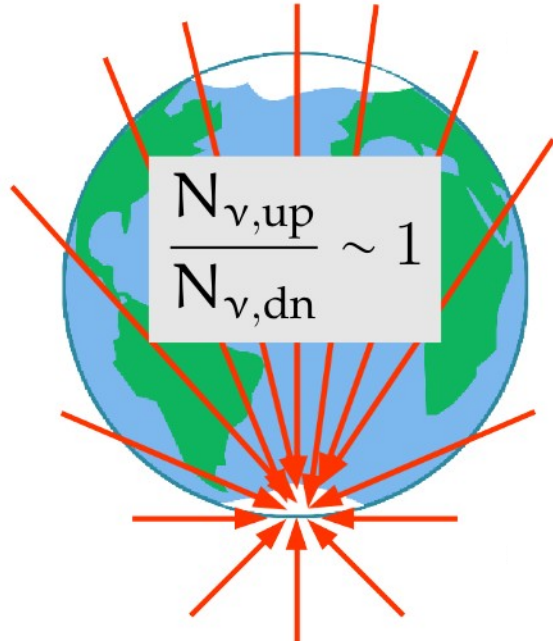


Above ~ 10 TeV: Earth is opaque

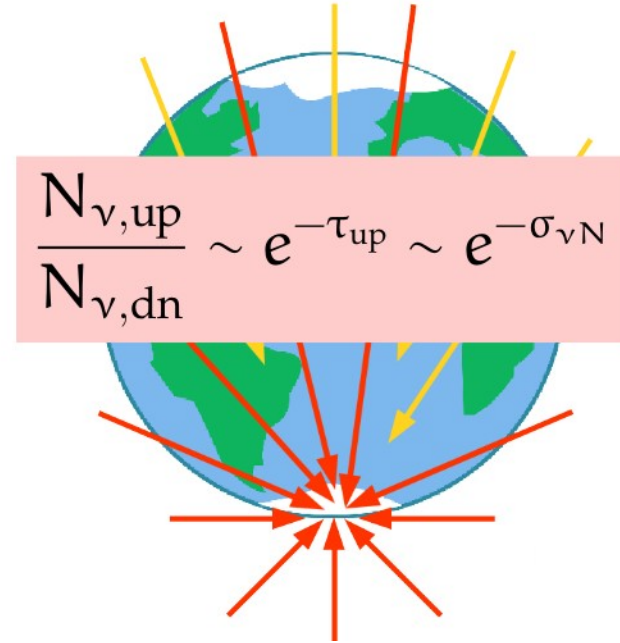


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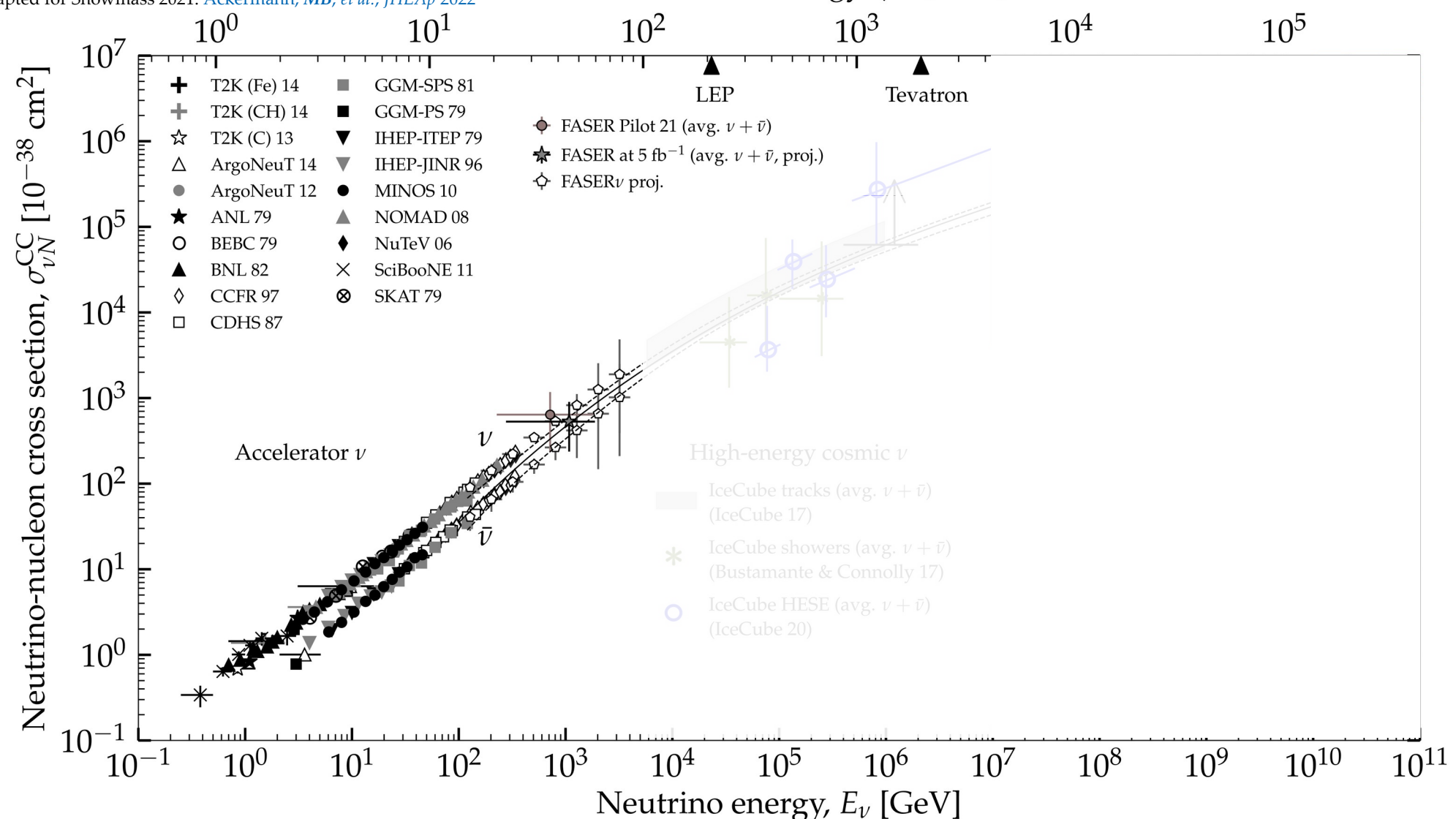
Below ~ 10 TeV: Earth is transparent



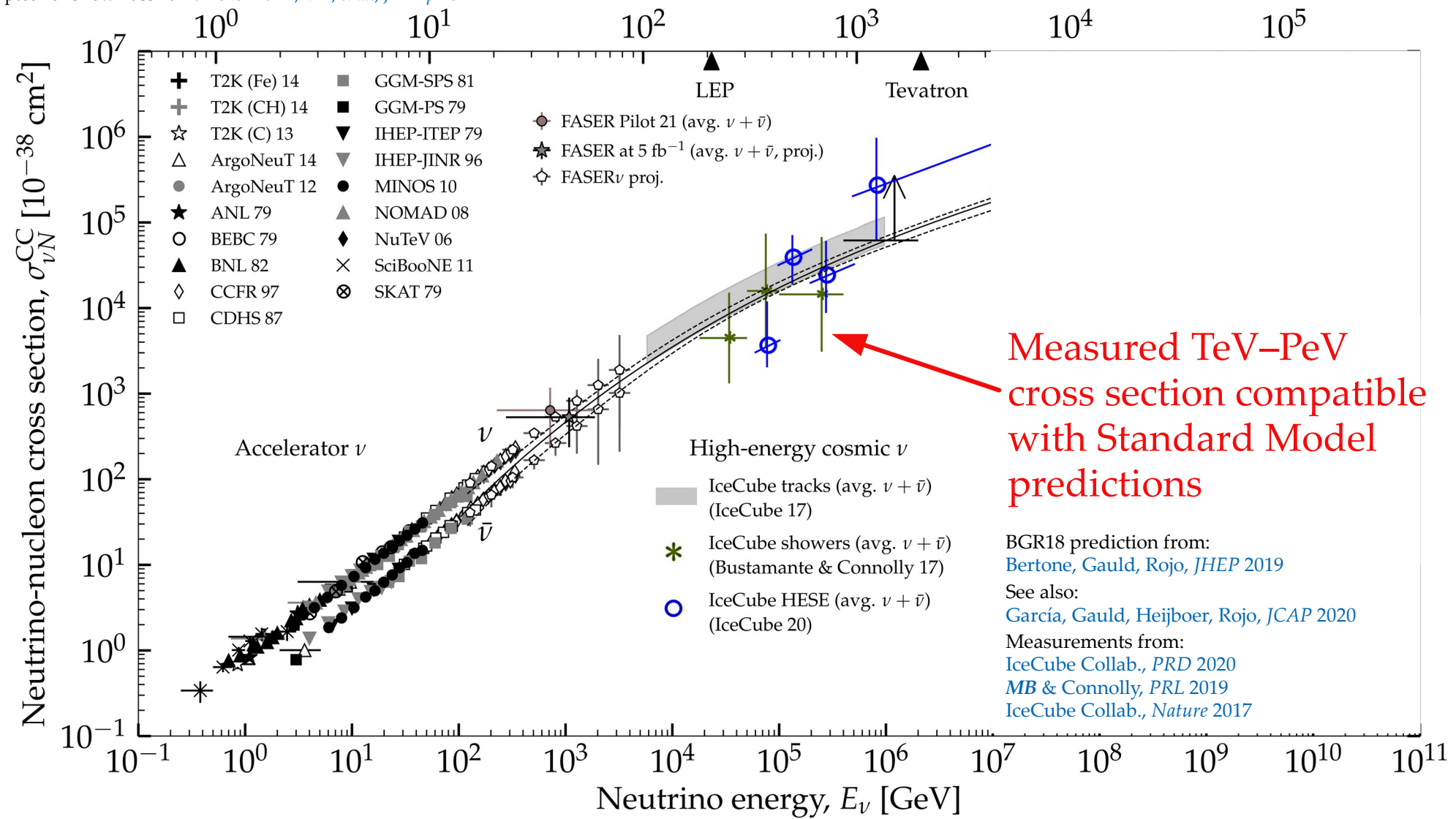
Above ~ 10 TeV: Earth is opaque



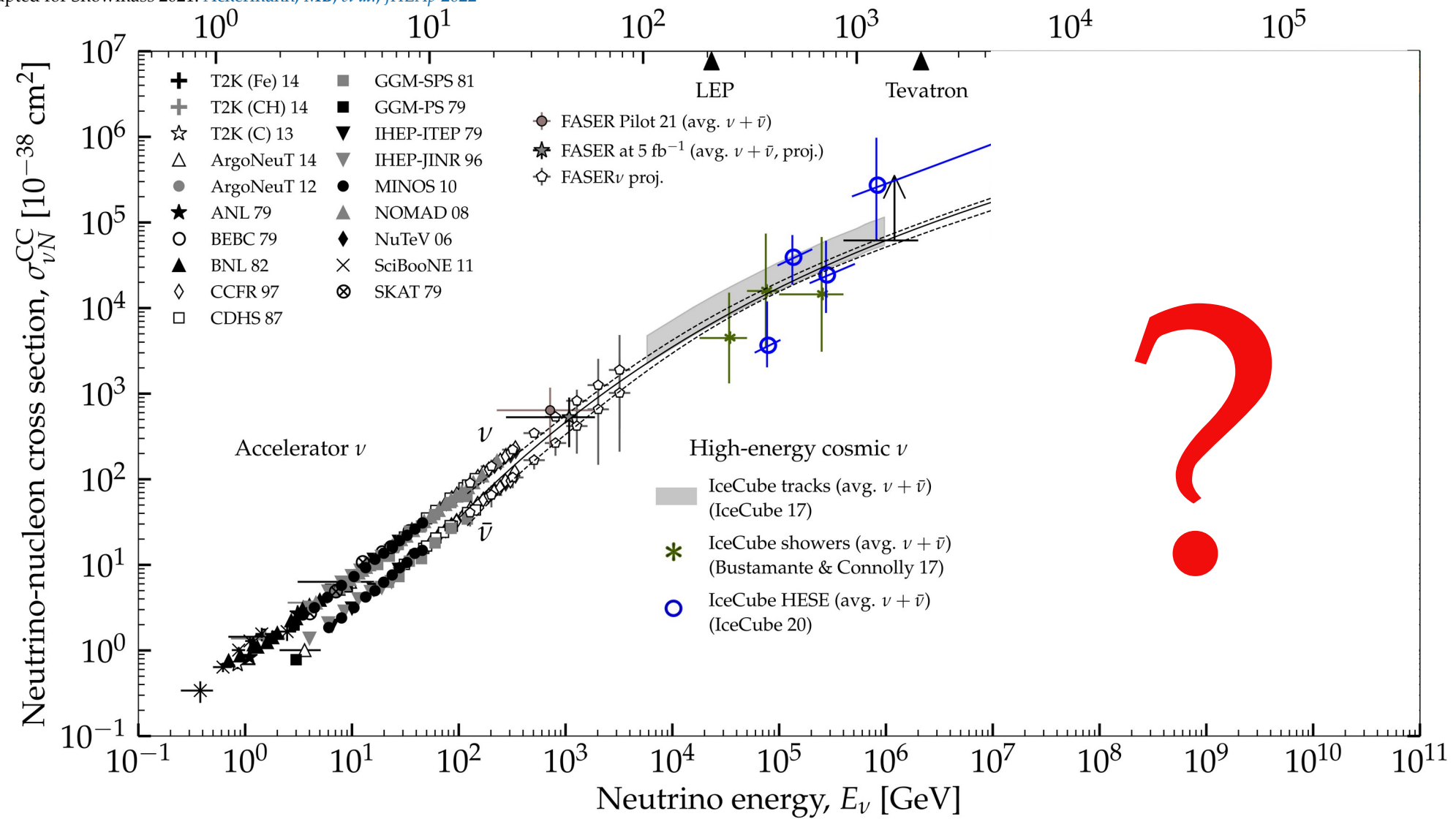
Center-of-mass energy $\sqrt{s}$ [GeV]



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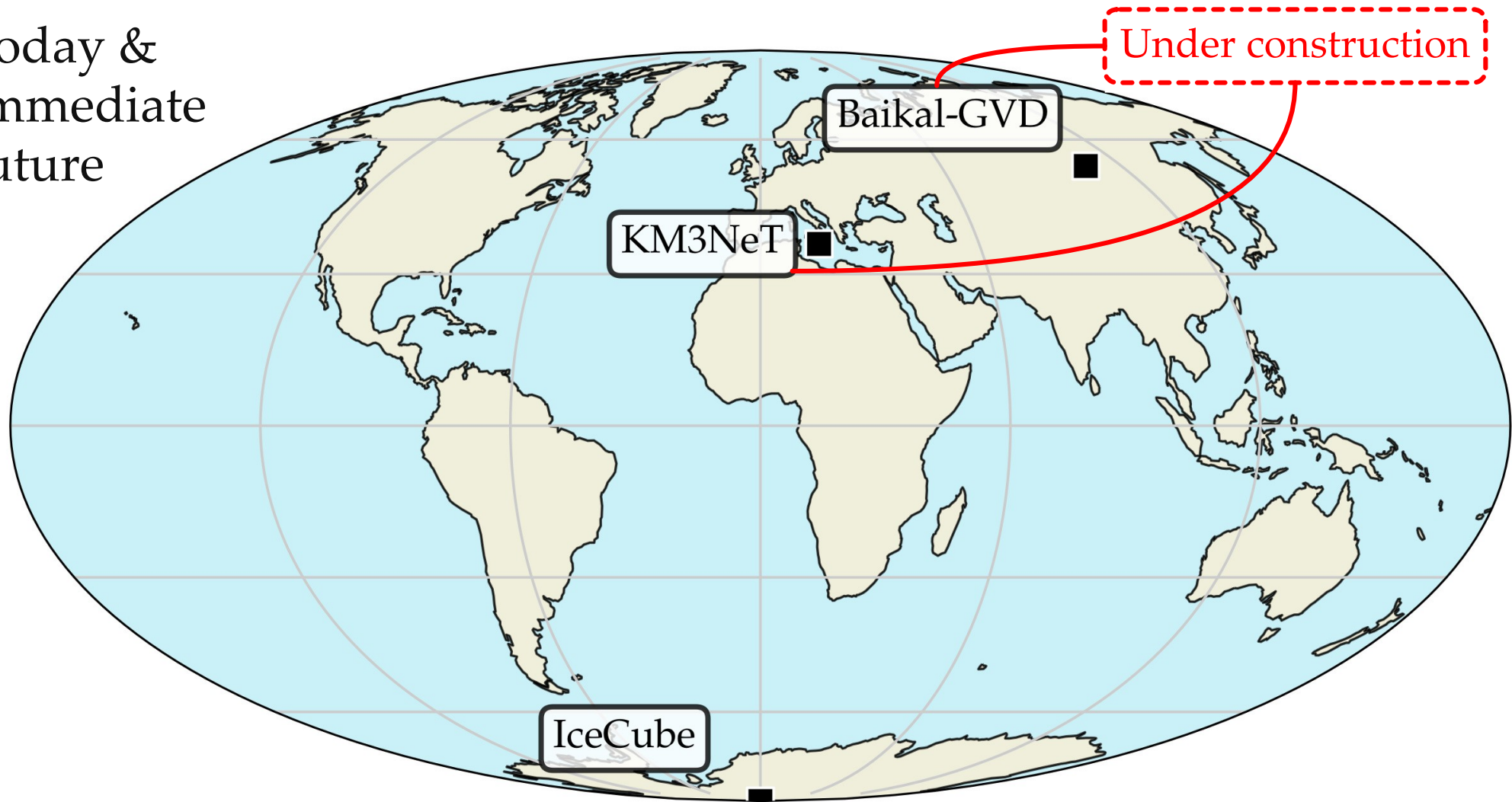


Center-of-mass energy $\sqrt{s}$ [GeV]

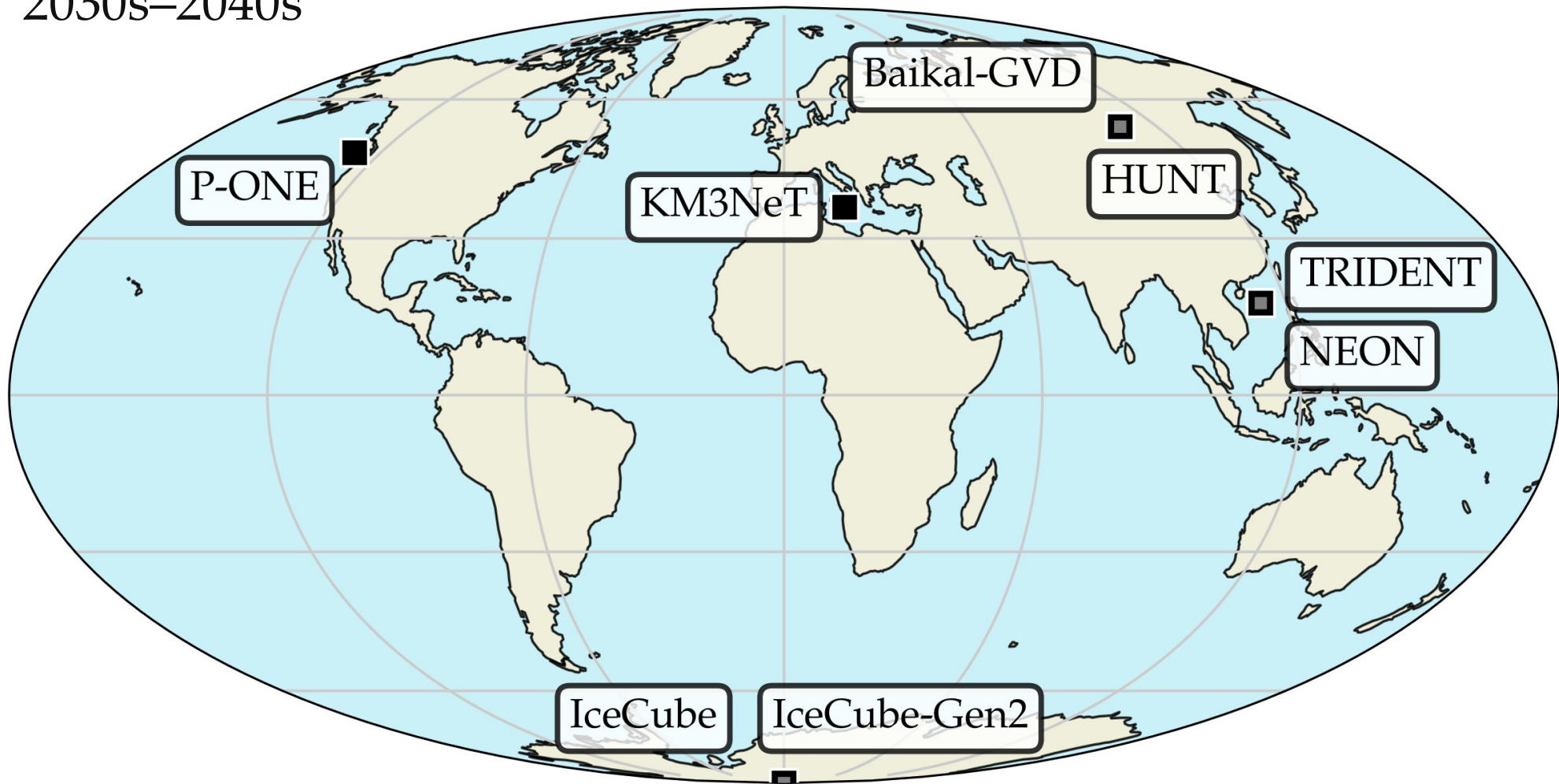


Quo vadis?

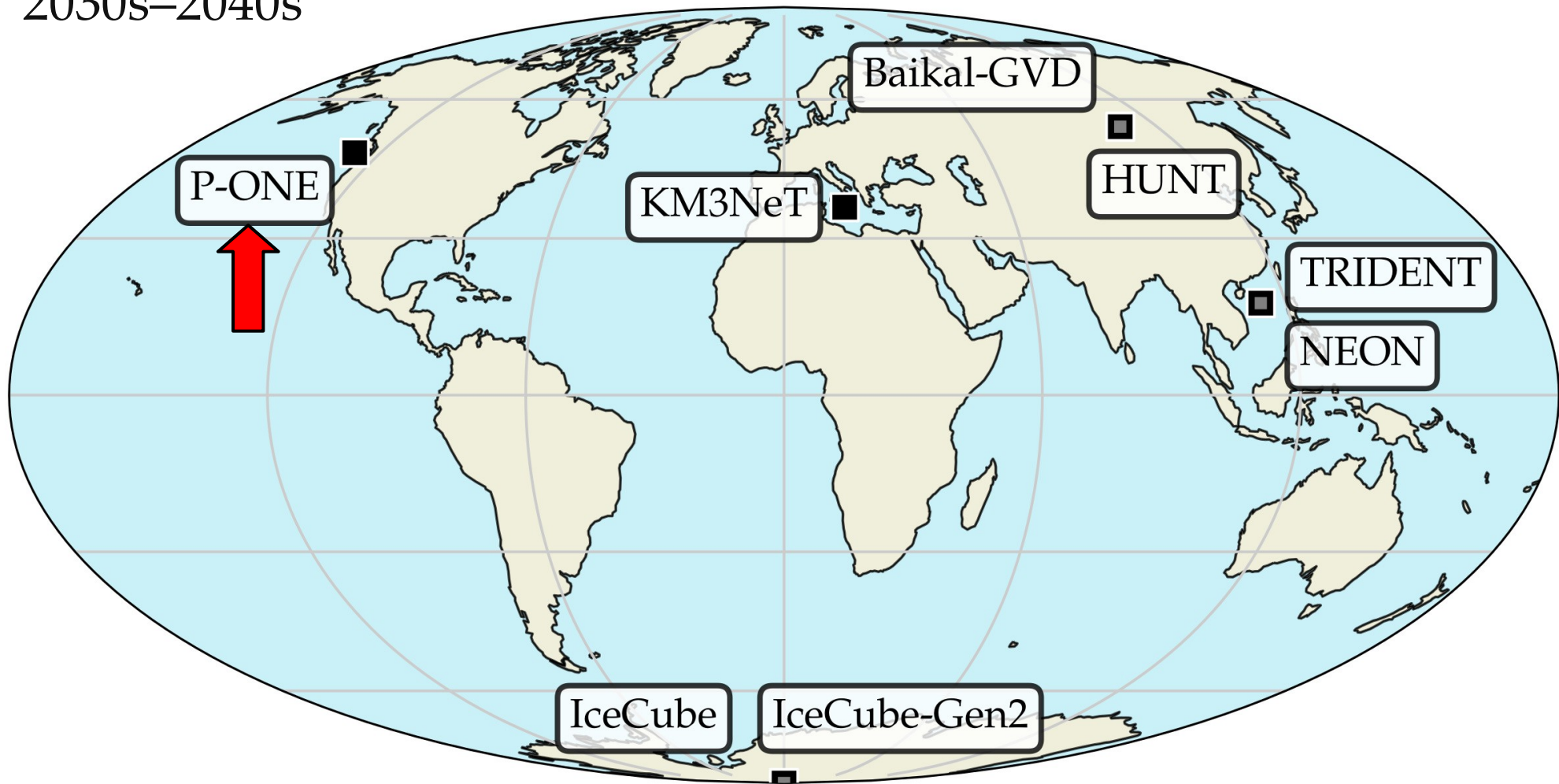
Today &
immediate
future



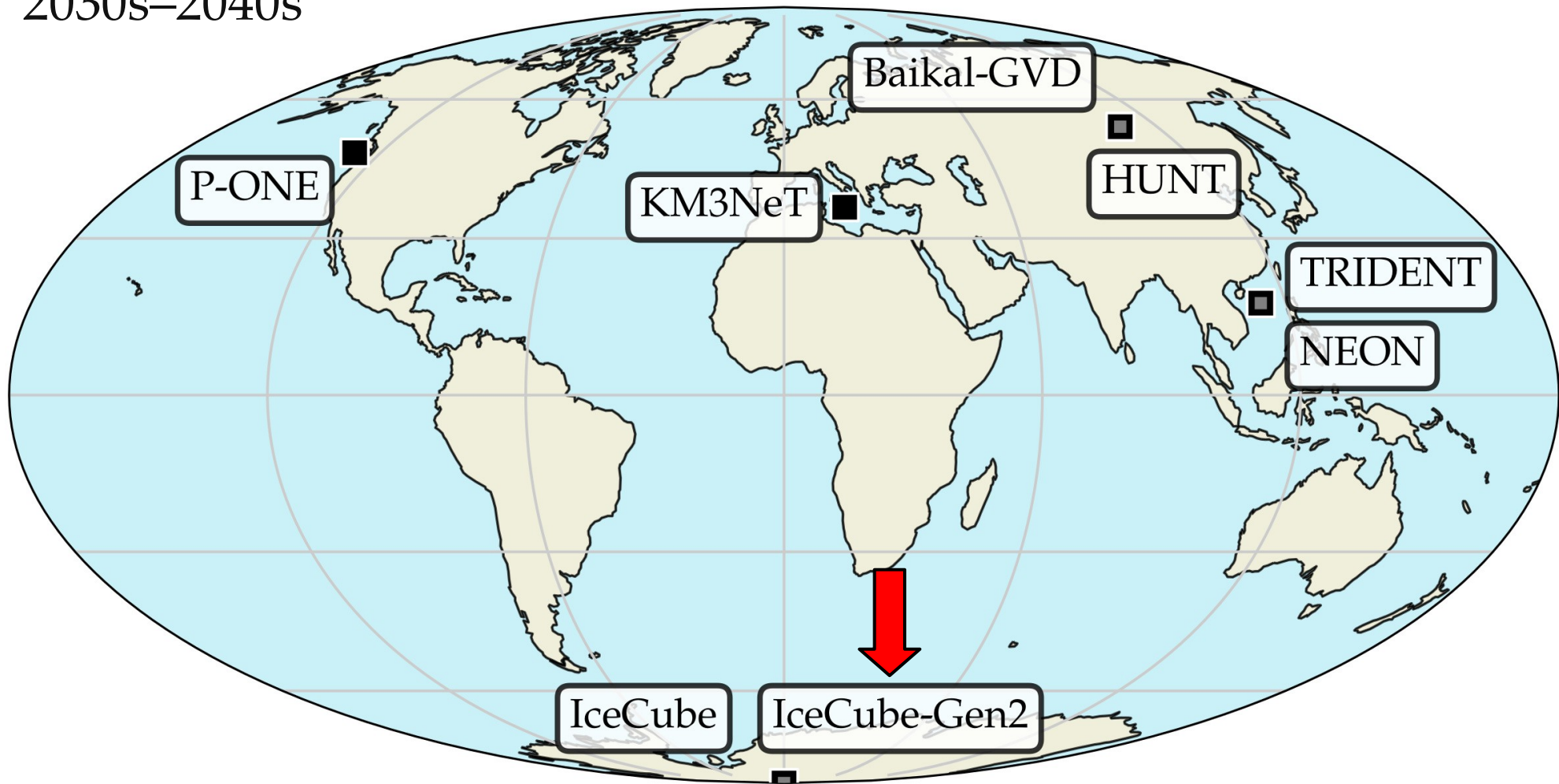
2030s–2040s



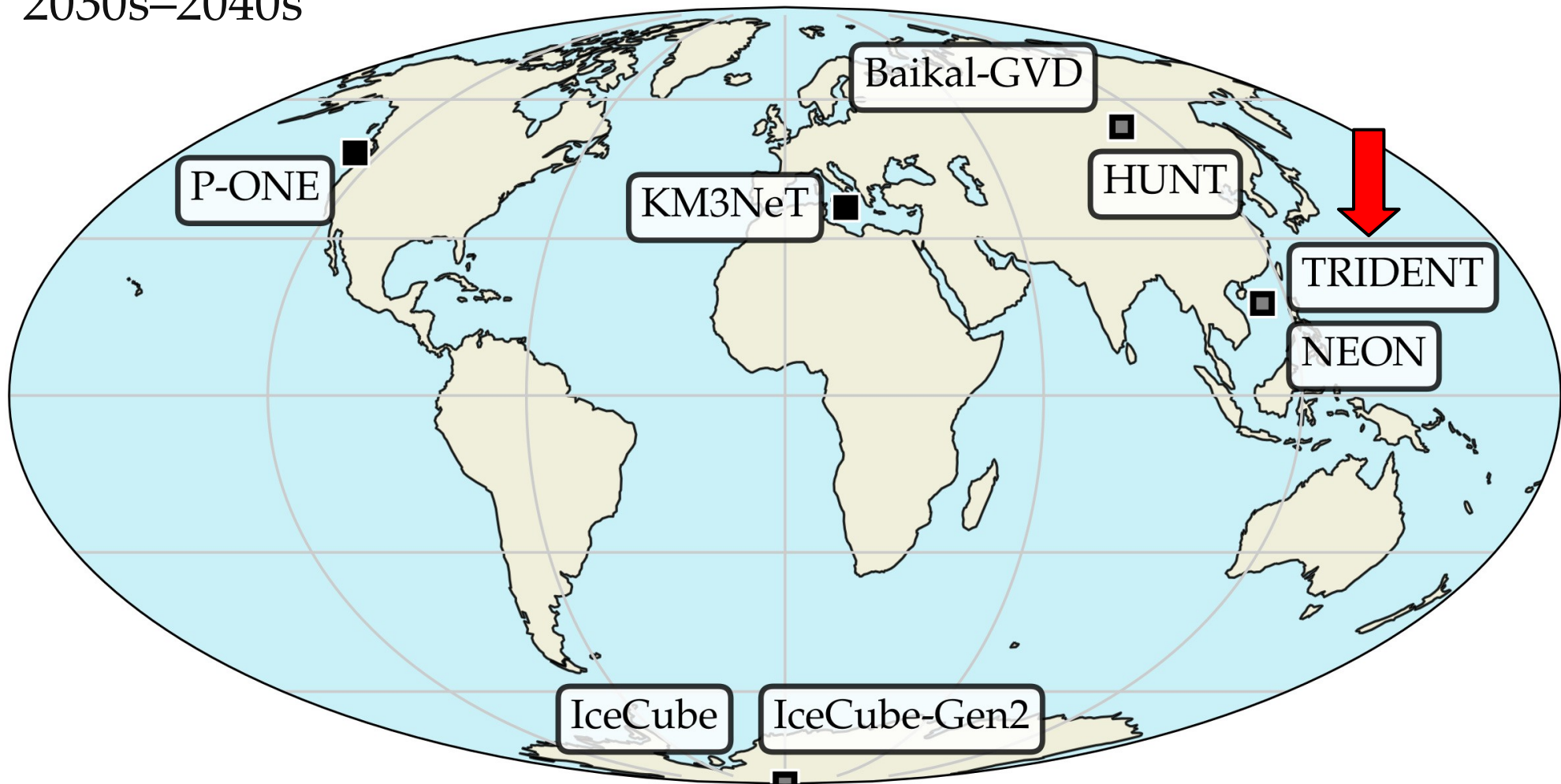
2030s–2040s



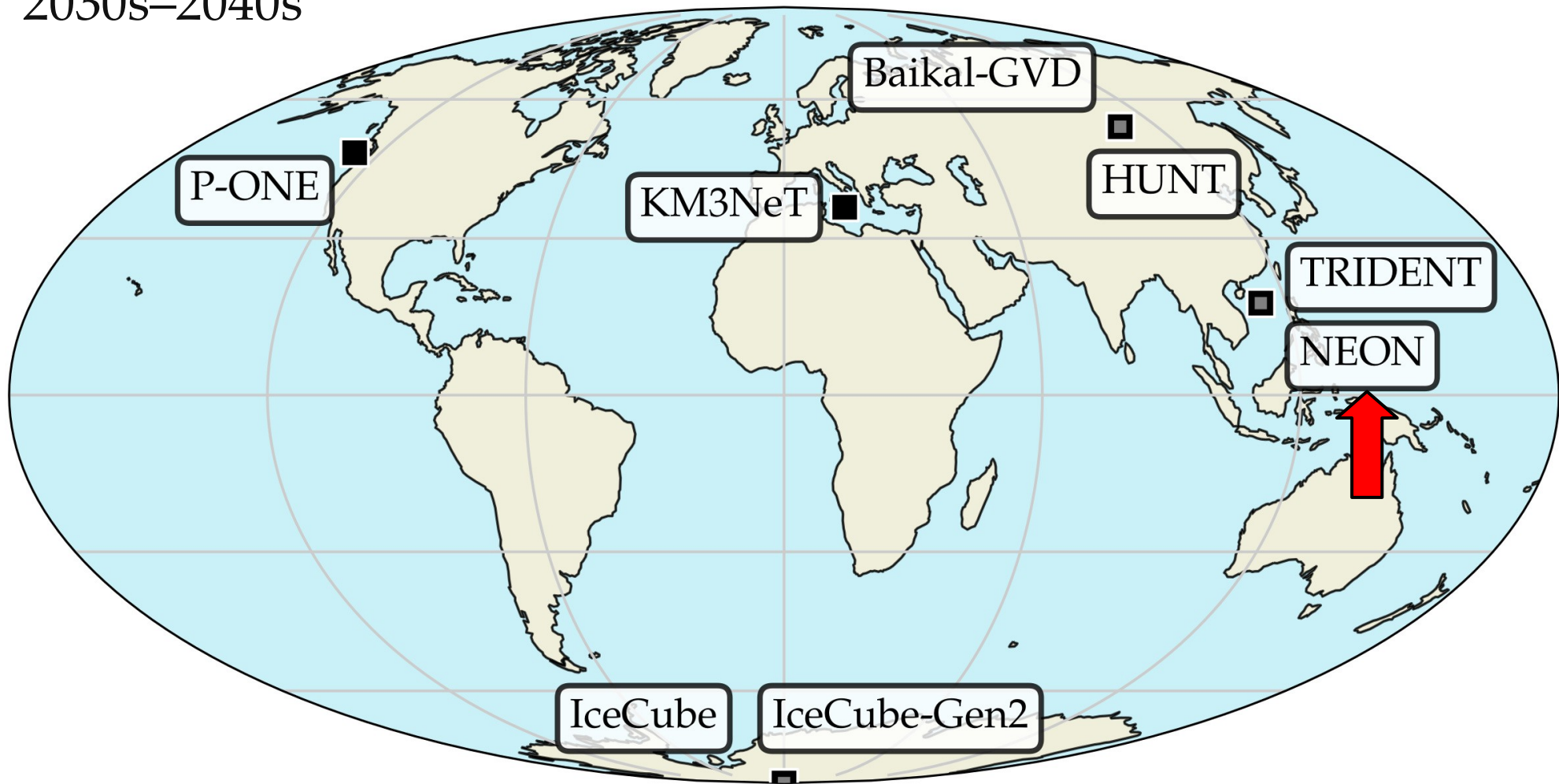
2030s–2040s



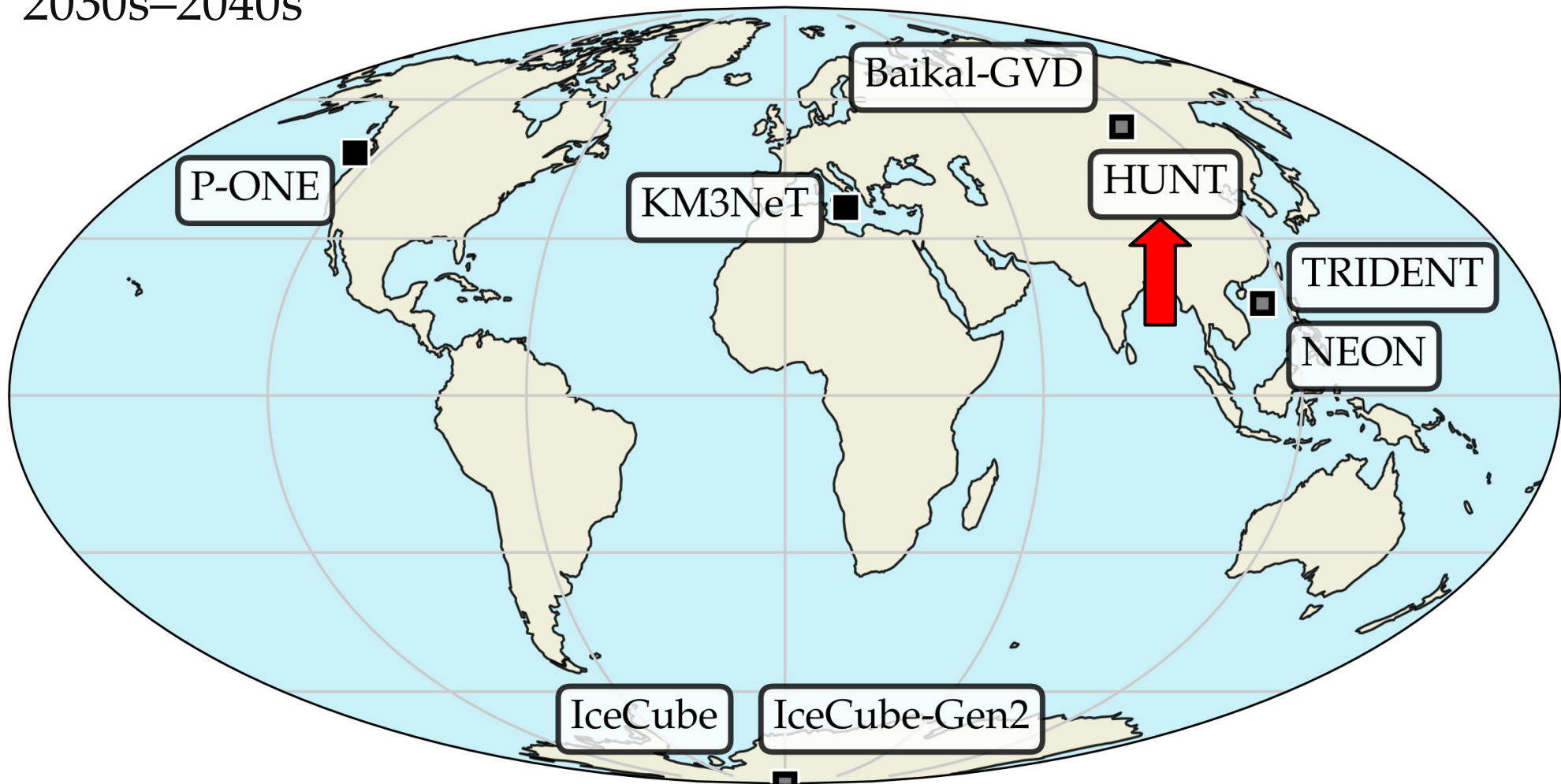
2030s–2040s

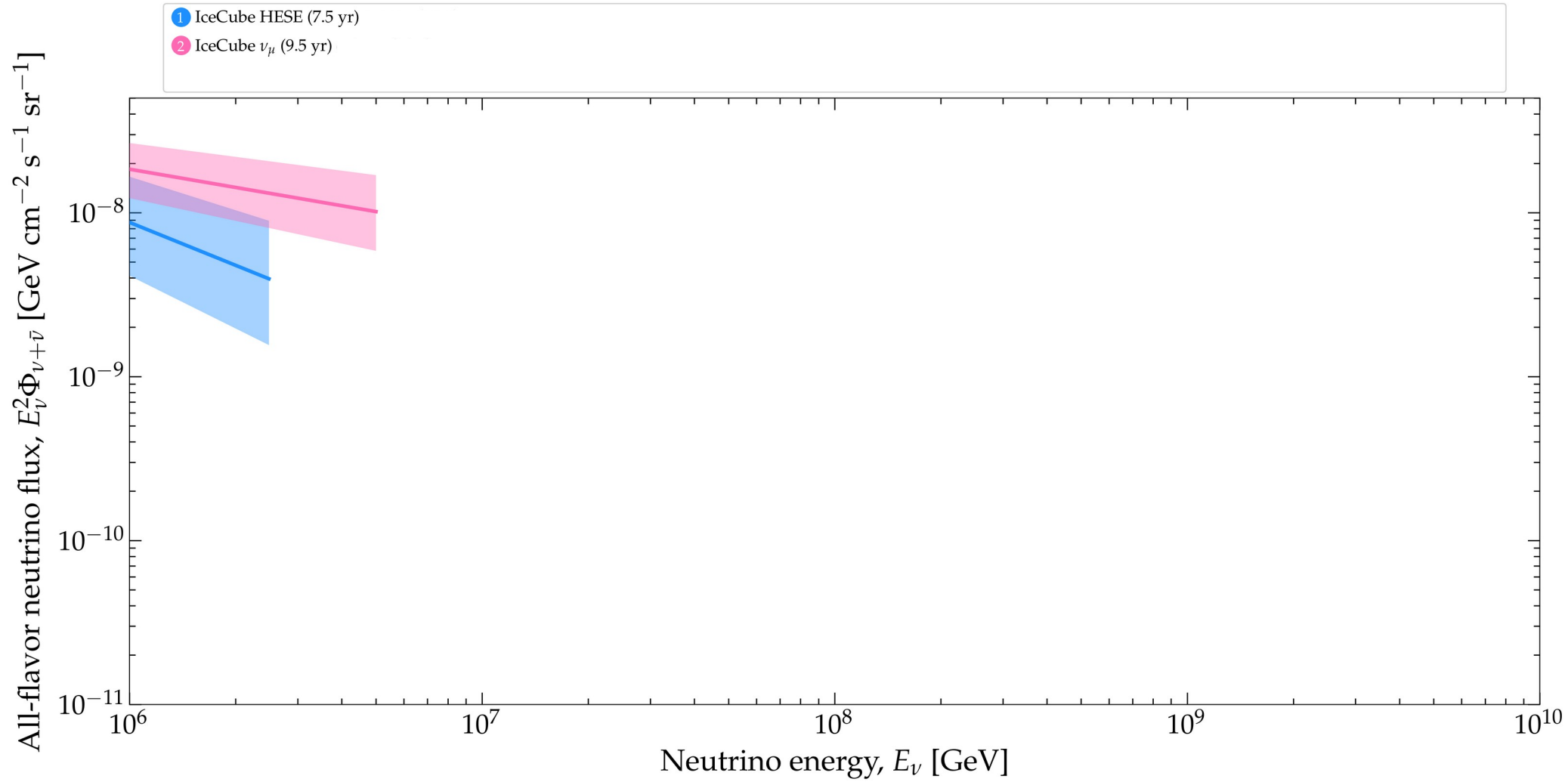


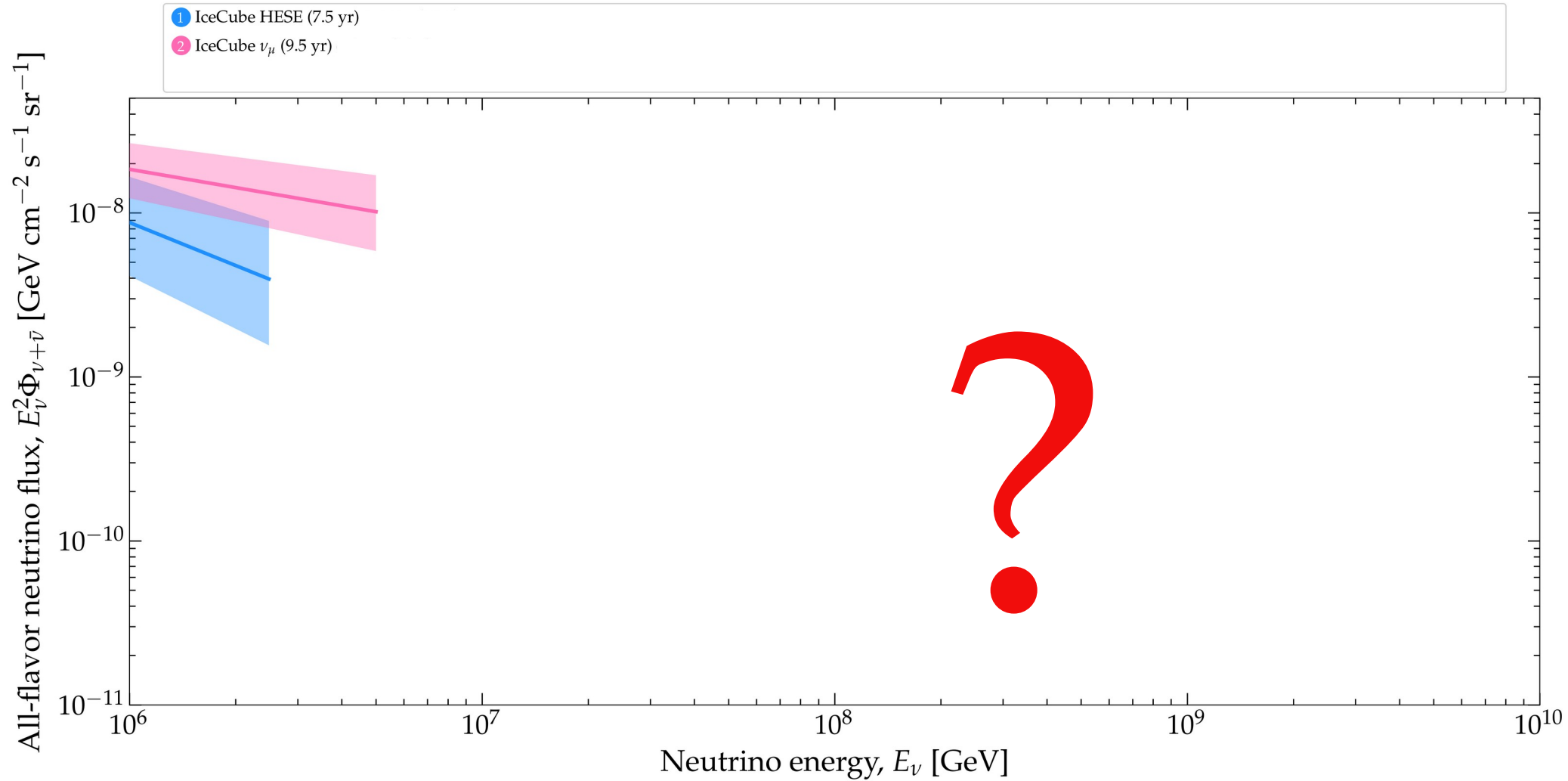
2030s–2040s

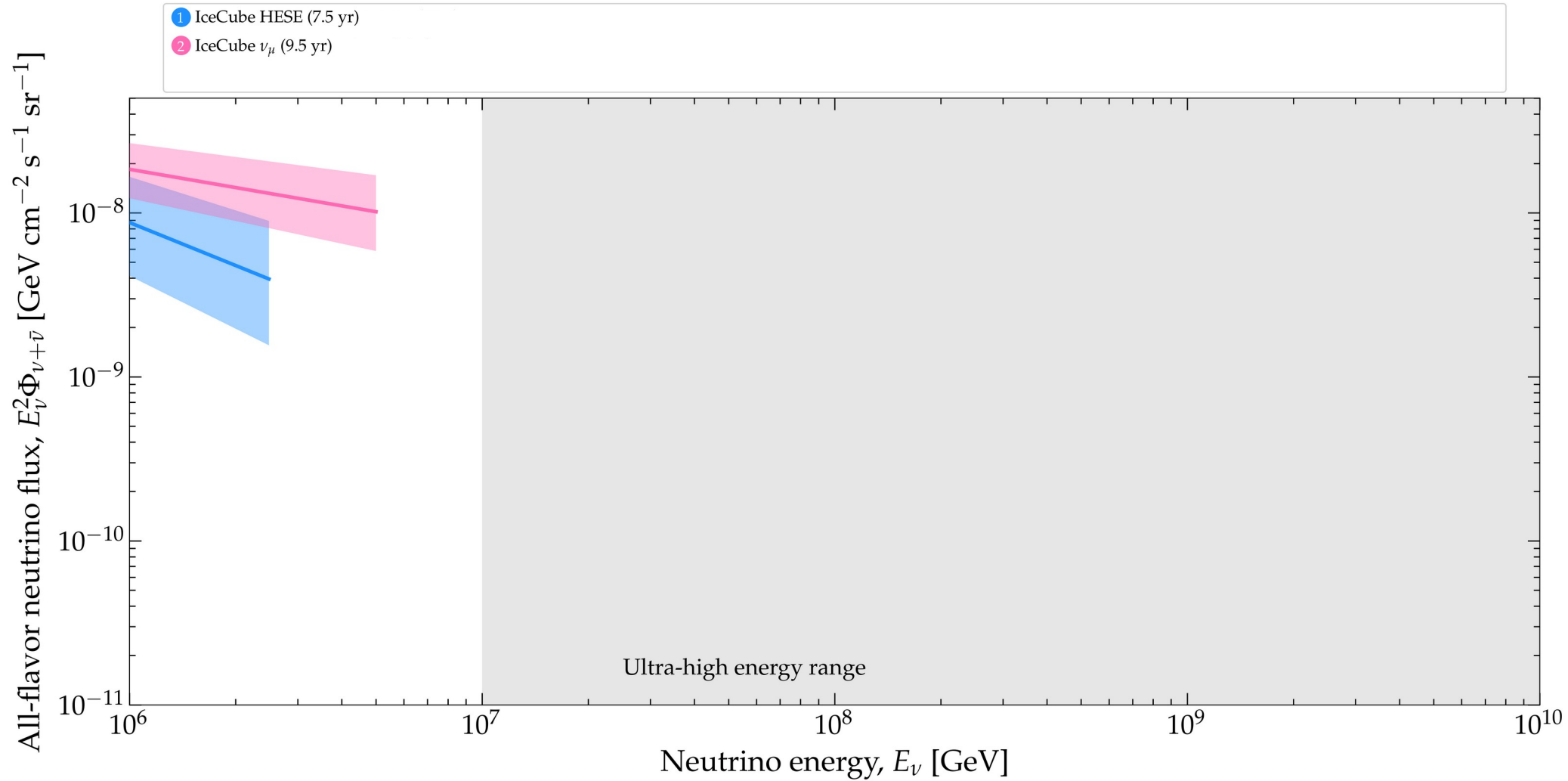


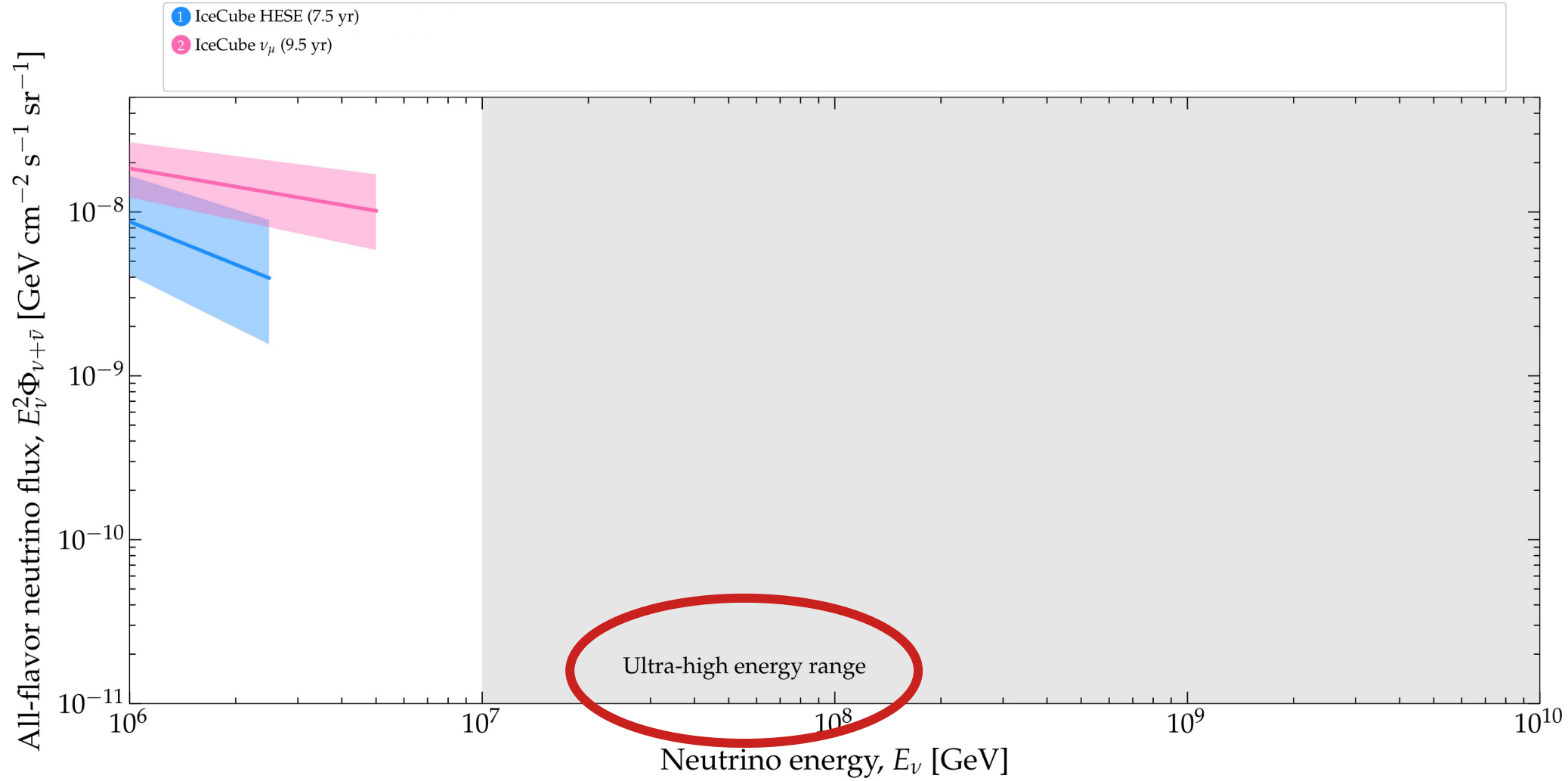
2030s–2040s





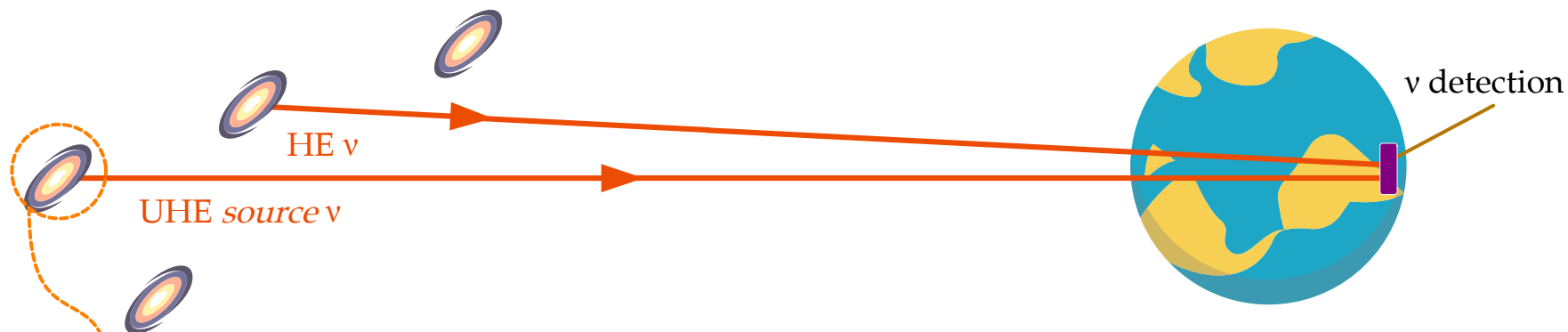






Redshift

$z = 0$



Undiscovered

meV γ

EeV p

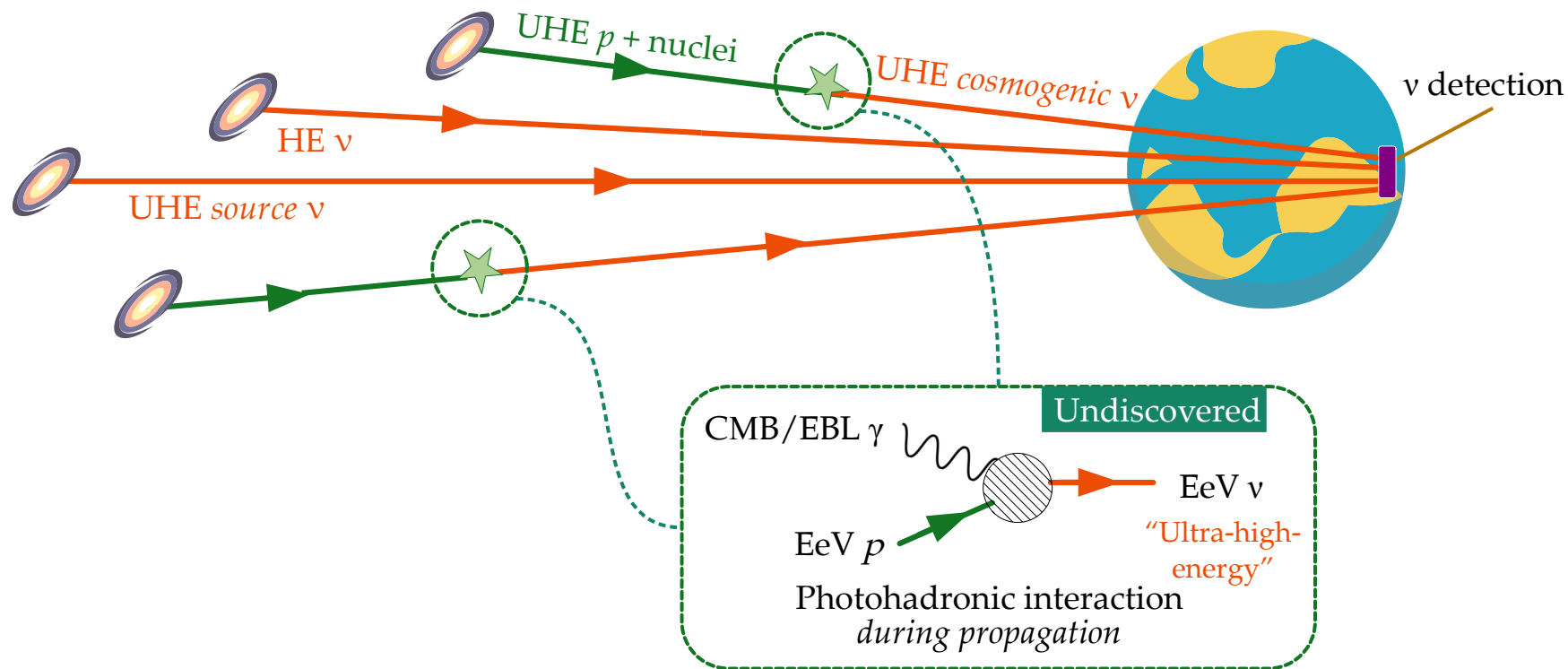
EeV ν

"Ultra-high-energy"

Photohadronic or pp interaction
inside the source

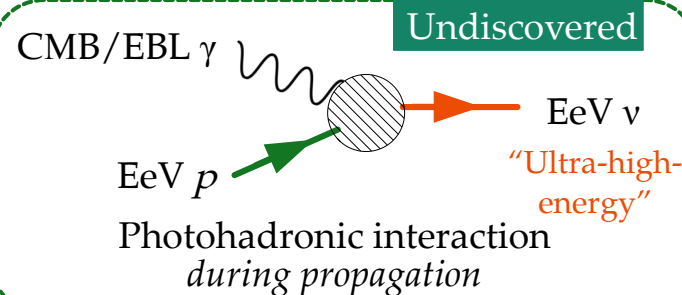
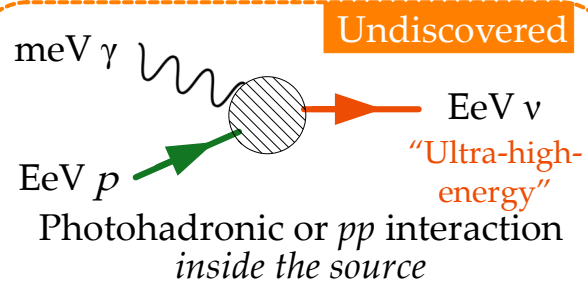
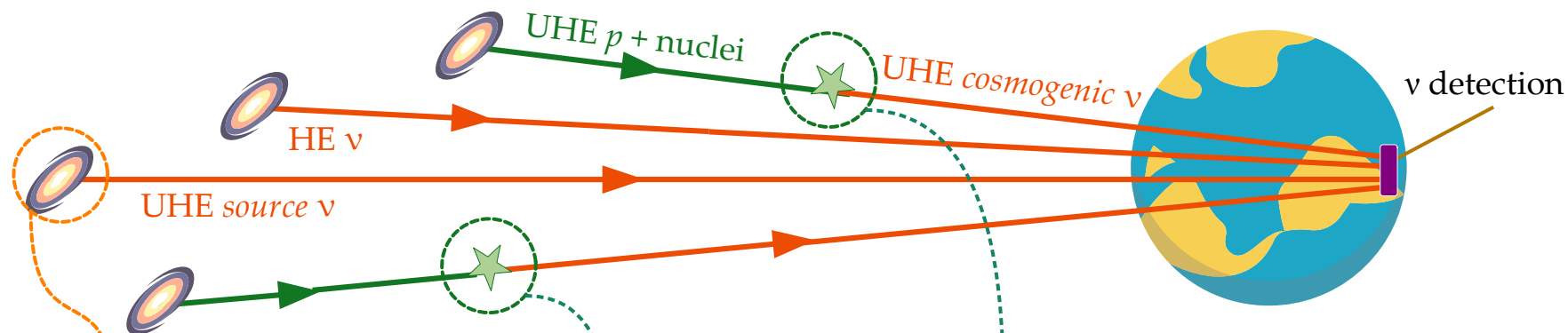
Redshift

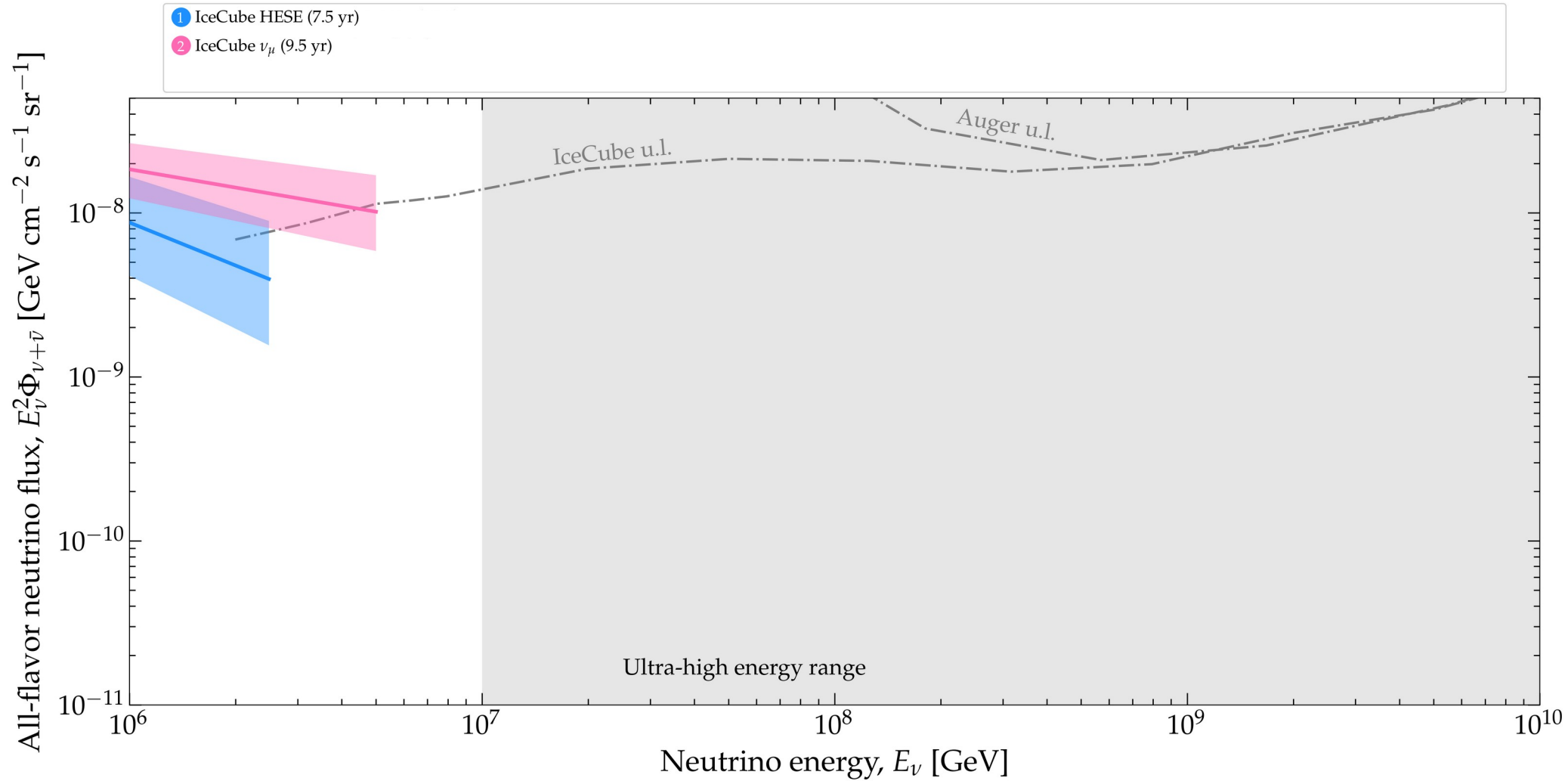
$z = 0$



Redshift

$z = 0$





The international journal of science / 13 February 2025

nature

COSMIC CATCHER

Deep-sea telescope detects
neutrino with highest
energy ever recorded

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

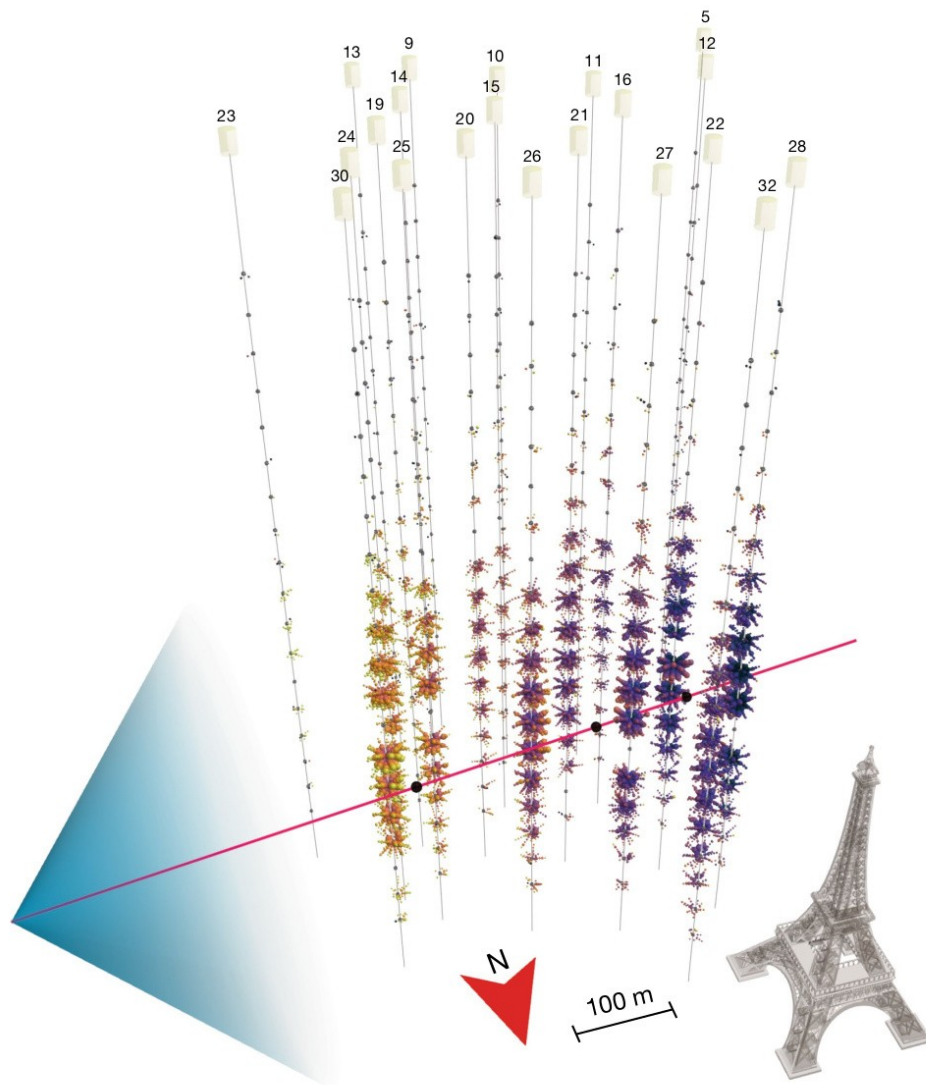
One muon detected with 120^{+110}_{-60} PeV

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But is it due to a neutrino?

Yes! Direction points underground,
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Inferred neutrino energy: 220^{+570}_{-110} PeV

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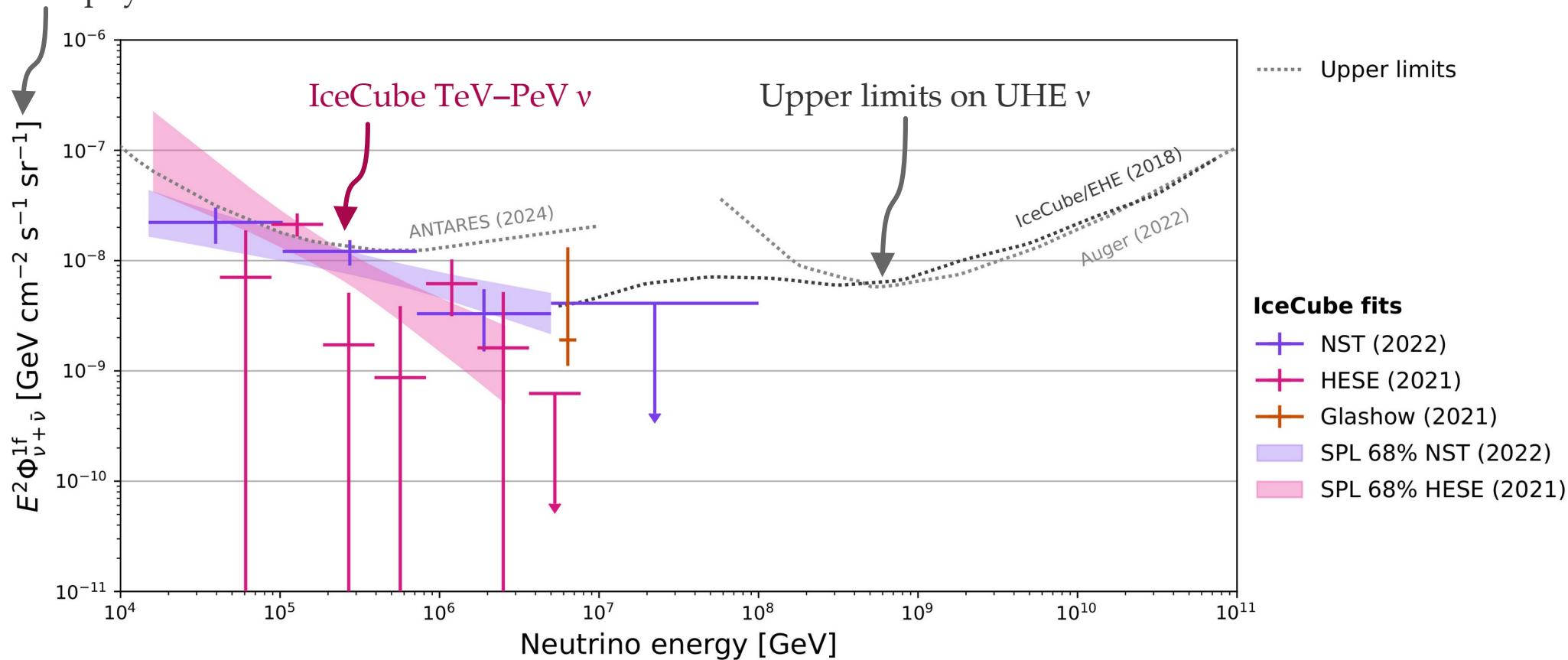
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**RECORD
BREAKER**

Was it a *cosmogenic* neutrino? KM3NeT vs. IceCube

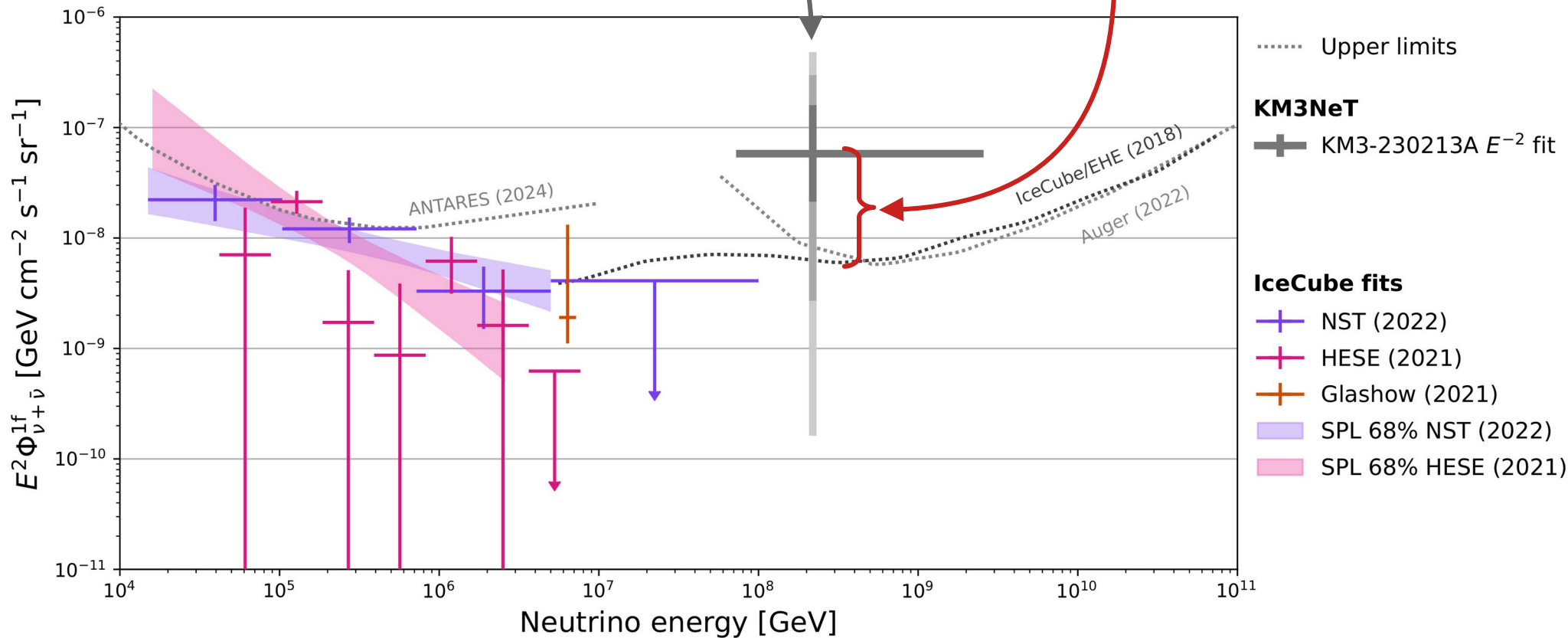
Diffuse flux of high-energy
astrophysical ν



Was it a *cosmogenic* neutrino? KM3NeT vs. IceCube

UHE ν flux inferred from KM3NeT event

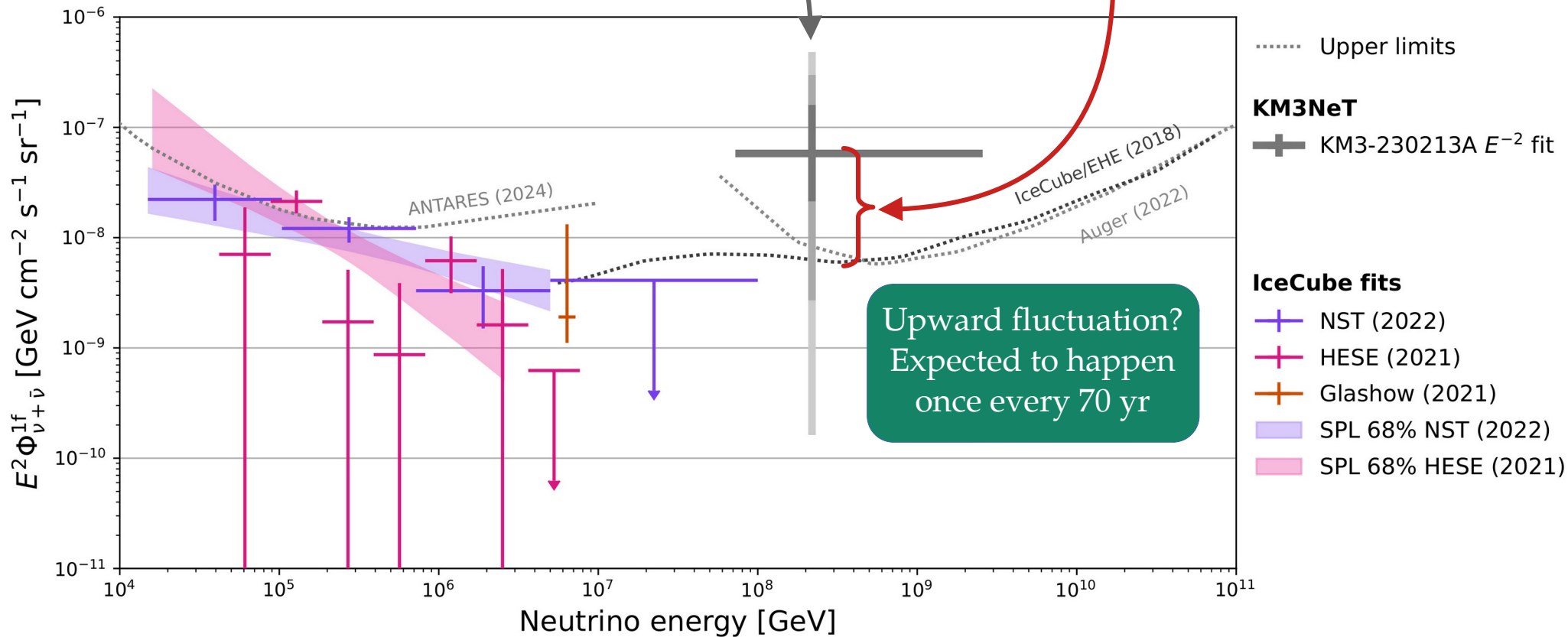
Flux is above upper limits! 2.5σ – 3σ tension



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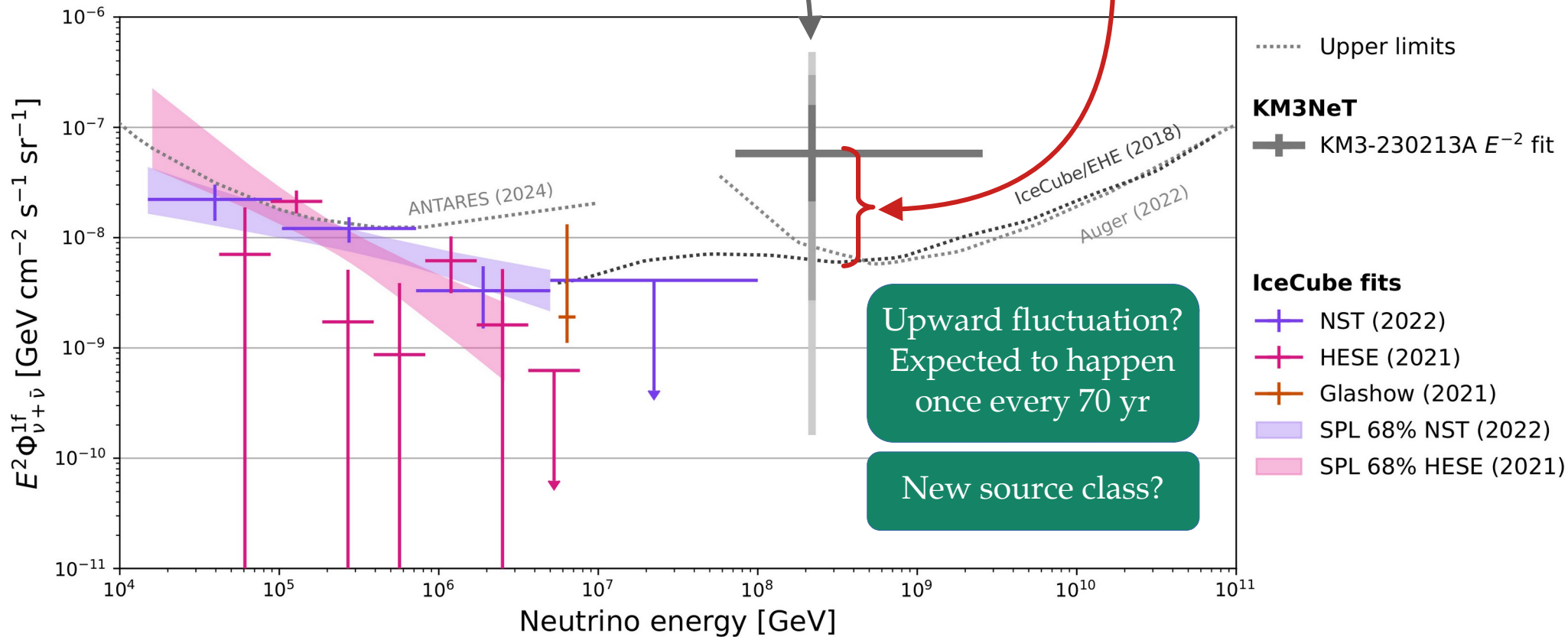
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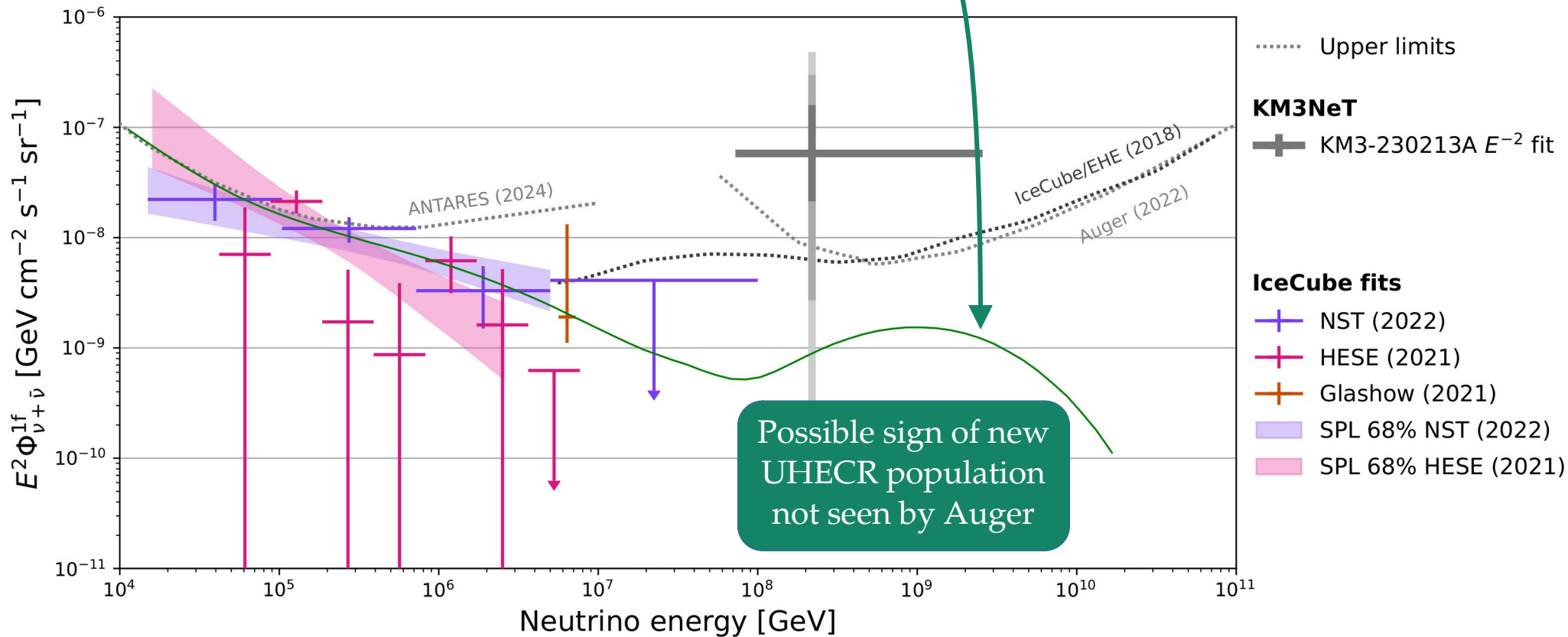
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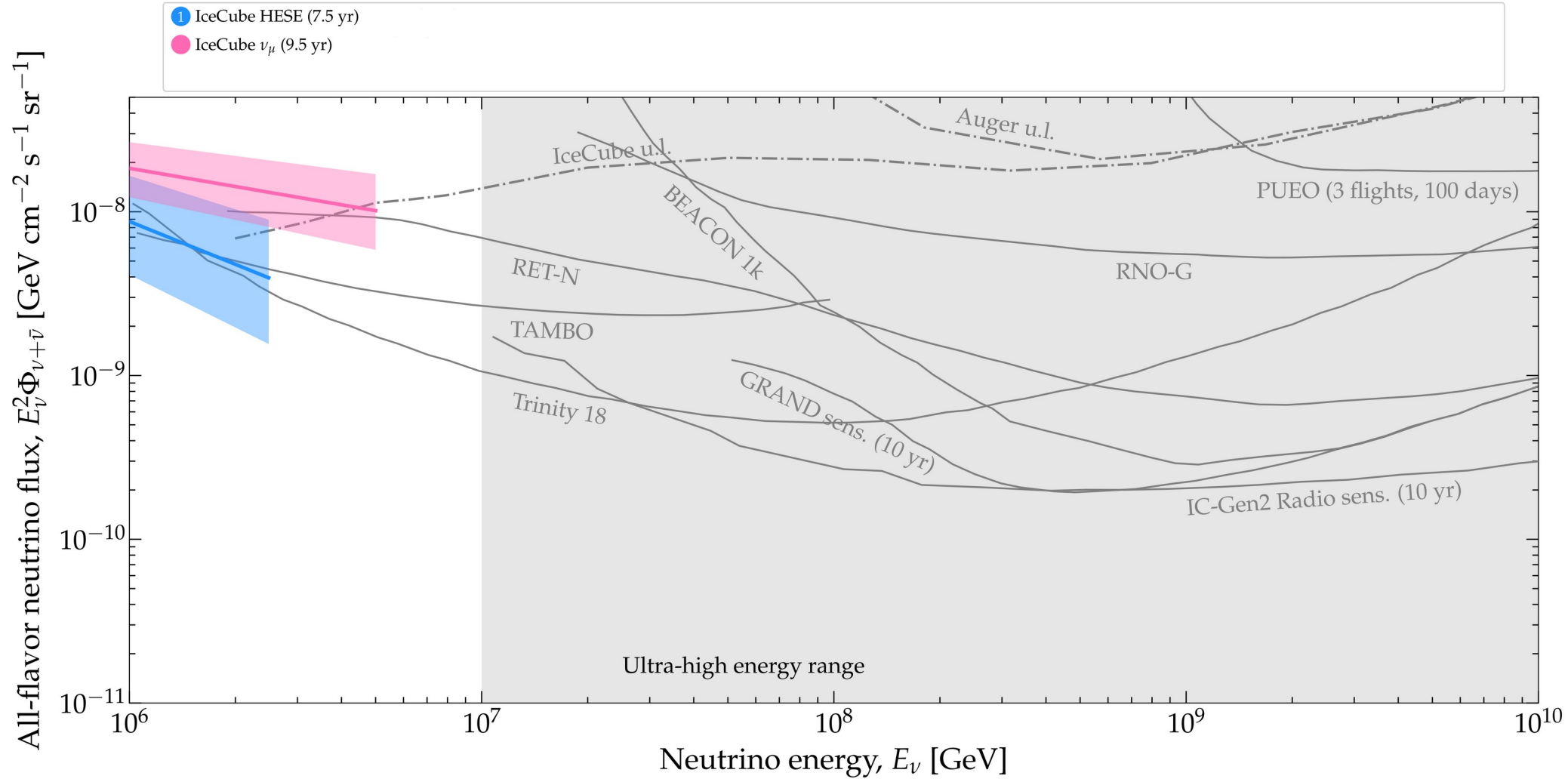


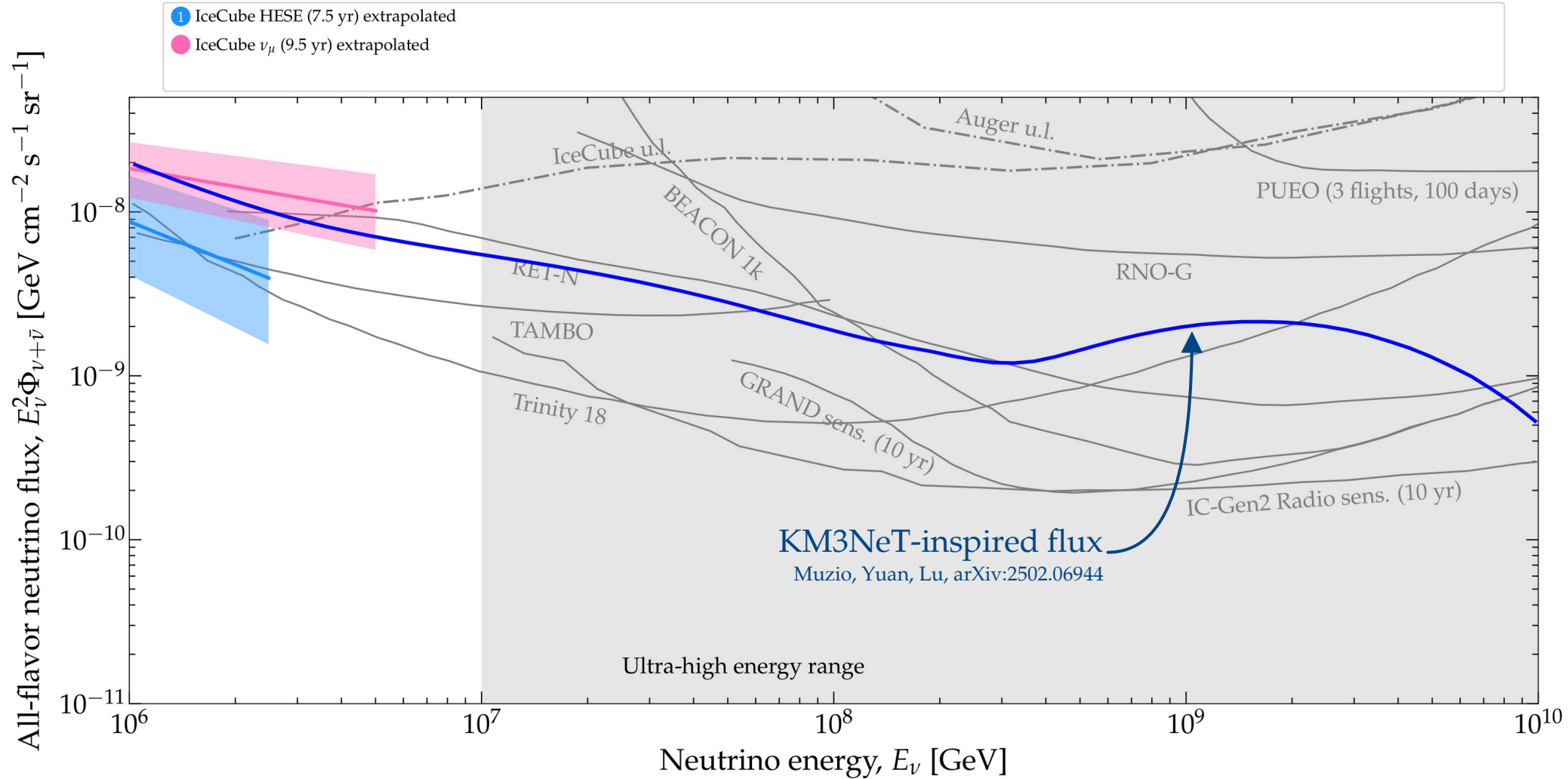
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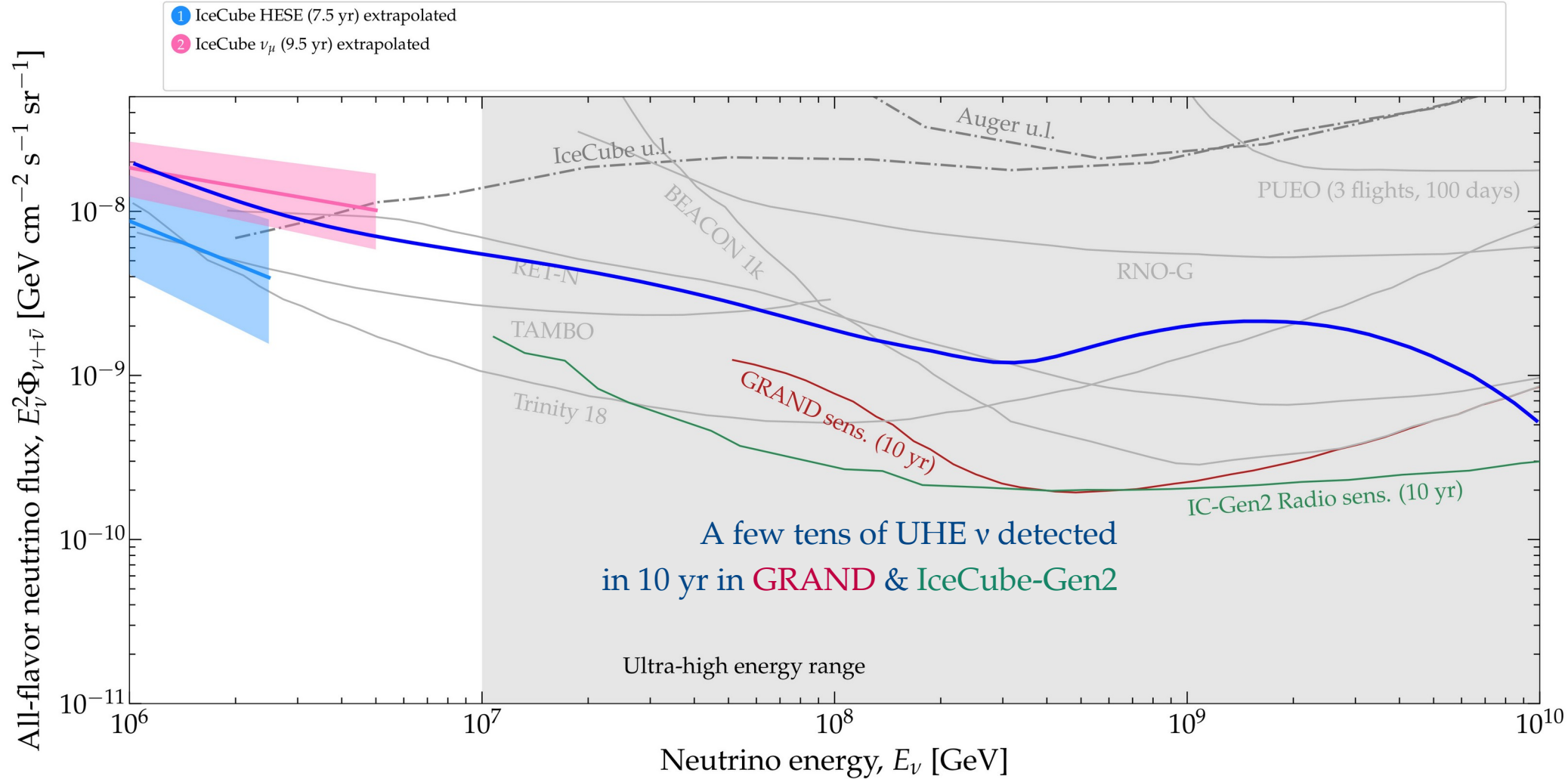
Joint fit to IceCube and KM3NeT ν data + Auger UHECR data

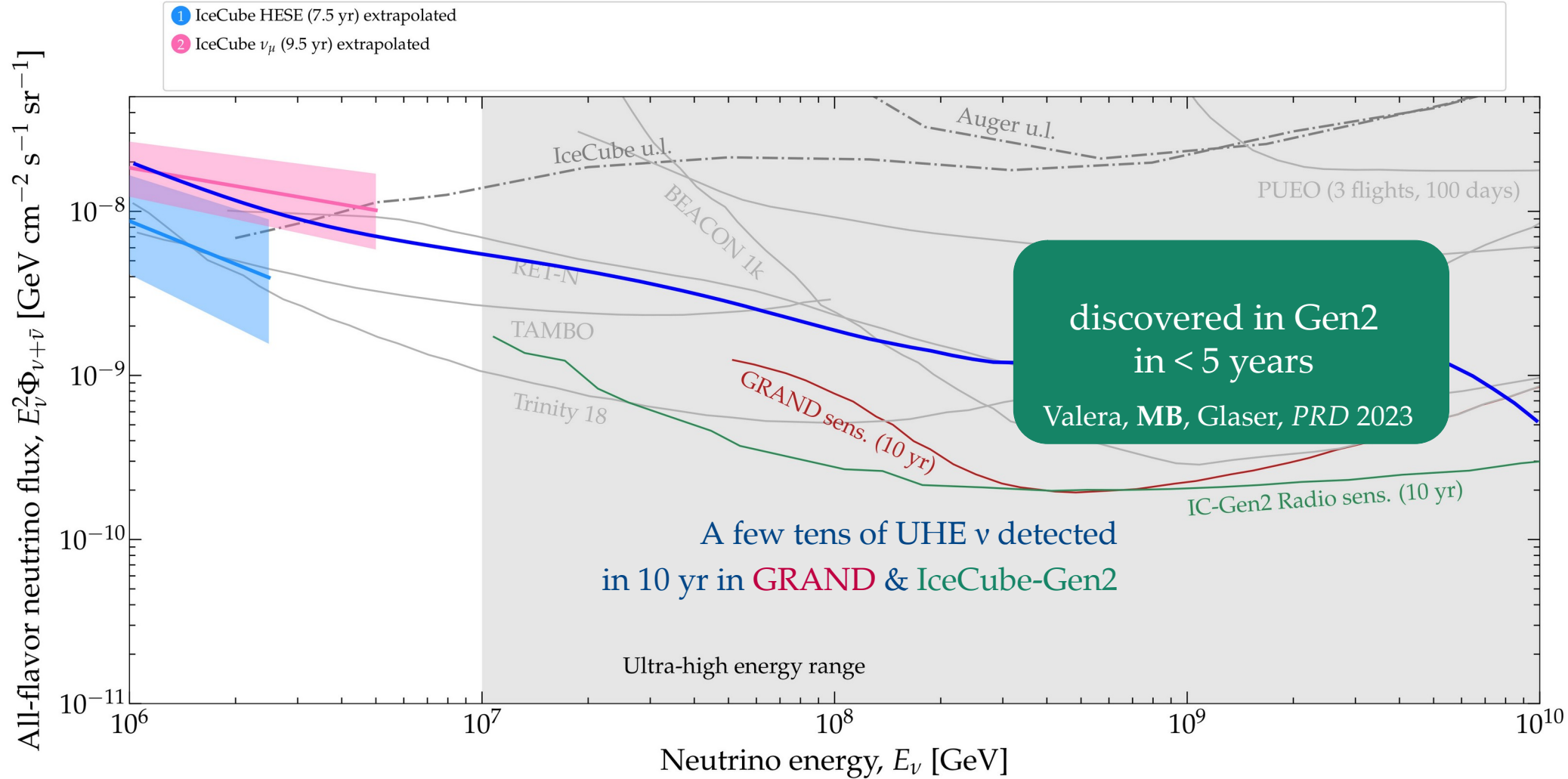
Muzio, Yuan, Lu, arXiv:2502.06944





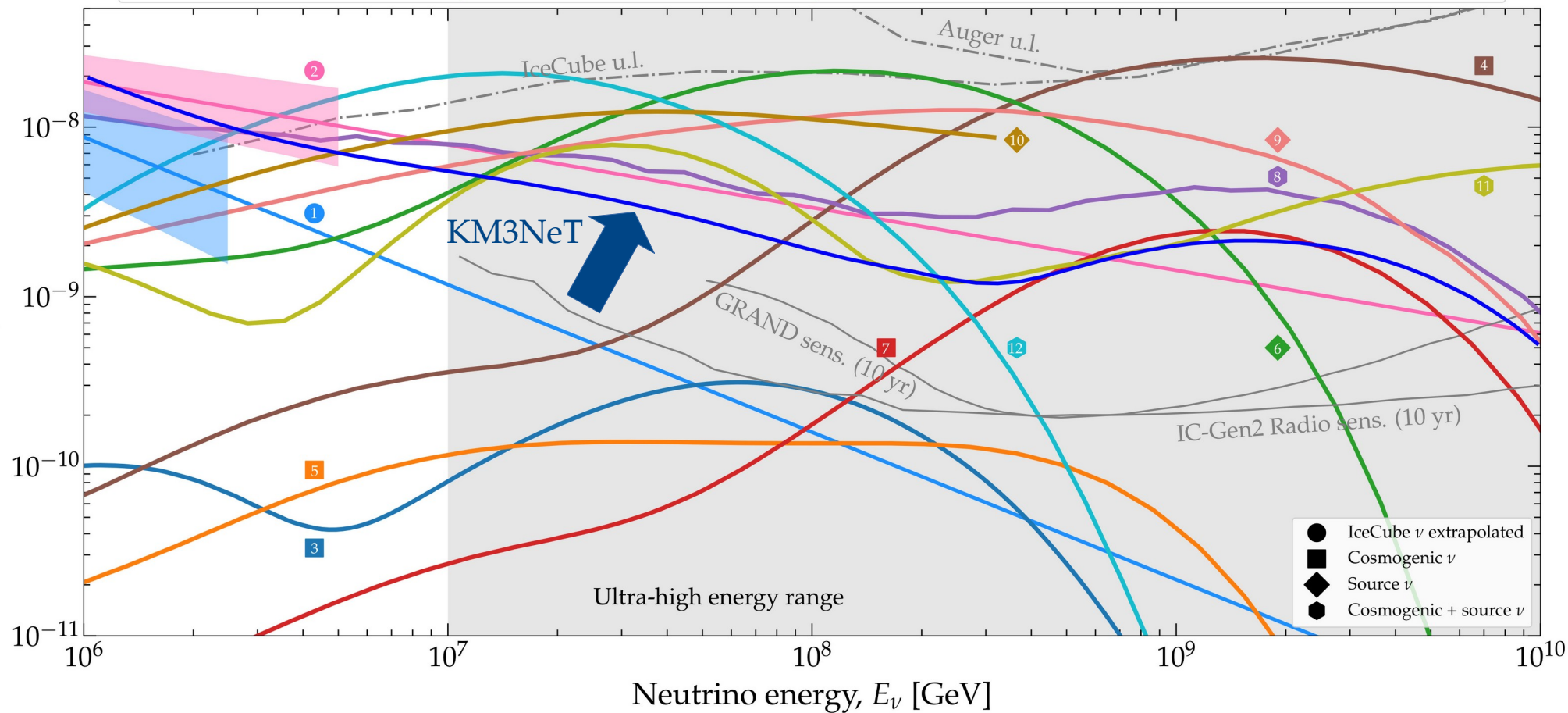






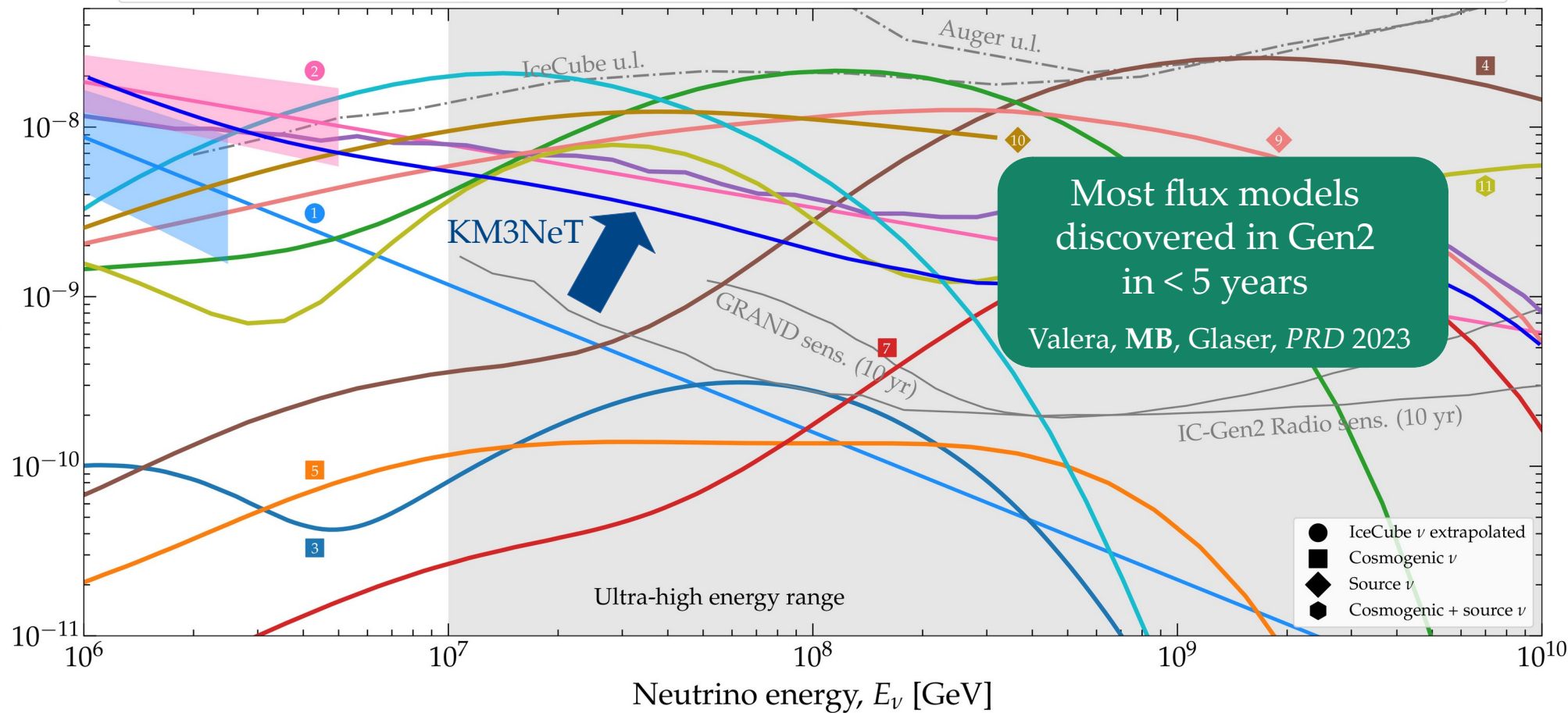
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

- | | | | |
|--|---|--|--|
| 1 IceCube HESE (7.5 yr) extrapolated | 4 Bergman & van Vliet, fit to TA UHECRs | 7 Rodrigues <i>et al.</i> , HL BL Lacs | 10 Padovani <i>et al.</i> , BL Lacs |
| 2 IceCube ν_μ (9.5 yr) extrapolated | 5 Rodrigues <i>et al.</i> , all AGN | 8 Fang & Murase, cosmic-ray reservoirs | 11 Muzio <i>et al.</i> , maximum extra p component |
| 3 Heinze <i>et al.</i> , fit to Auger UHECRs | 6 Rodrigues <i>et al.</i> , all AGN | 9 Fang <i>et al.</i> , newborn pulsars | 12 Muzio <i>et al.</i> , fit to Auger & IceCube |



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How it
started

How it's
going

10–20 years
from now

First predictions
of high-energy
cosmic ν

PeV ν
discovered

Hints of sources
First tests of ν physics

How do we get there?

EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν

Energy-independent new physics in the flavour ratios of high-energy astrophysical neutrinos

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ABSTRACT: We have studied the consequences of breaking the CPT symmetry in the neutrino sector, using the expected high-energy neutrino flux from distant cosmological

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DOI: 10.1142/S0217732315501461

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Searching for cavities of various densities in the Earth's crust with a low-energy $\bar{\nu}_e$ β -beam

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HIGH ENERGY ASTROPHYSICAL NEUTRINO FLUX AND MODIFIED DISPERSION RELATIONS

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SUSY renormalization group effects in ultra high energy neutrinos

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JHEP05(2011)

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Keywords:
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1. Introduc

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IceCube expectations for two high-energy neutrino production models at active galactic nuclei

C.A. Argüelles,^a M. Bustamante^{a,b} and A.M. Gago^a

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Accepted November 25, 2010

Published December 7, 2010

s of the parameter spaces of tw
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the AMANDA upper bound o
nd given by the half-complete
of the proposed power-law fluxe
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and another in which it evolve
upper bound, we have found th
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obtained from fits to cosmic-ra
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discriminate between the mode
them give testable predictions
is guaranteed.

ctive galactic nuclei, ultra hig

doi:10.1088/1475-7516/2010/12/00

Energy-independent new physics in the flavour ratios of high-energy astrophysical neutrinos

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SUSY renormalization group effects in ultra high energy neutrinos

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IceCube expectations for two high-energy neutrino production models at active galactic nuclei

C.A. Argüelles,^a M. Bustamante^{a,b} and A.M. Gago^a

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PACS num

1. Introduc

Experimental former so-cal dence was pr accelerators : responsible fc a flavor trans

Energy-independent new physics in the flavour ratios of high-energy astrophysical neutrinos

M. Bustamante,^a A.M. Gago^a and C. Peña-Garay^b

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ABSTRACT: We have studied the consequences of breaking the CPT symmetry in the neutrino sector, using the expected high-energy neutrino flux from distant cosmological

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HIGH ENERGY ASTROPHYSICAL NEUTRINO FLUX AND MODIFIED DISPERSION RELATIONS

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Searching for cavities of various densities in the Earth's crust with a low-energy $\bar{\nu}_e$ β -beam

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Searching for cavities of various densities in the Earth's crust with a low-energy $\bar{\nu}_e$ β -beam

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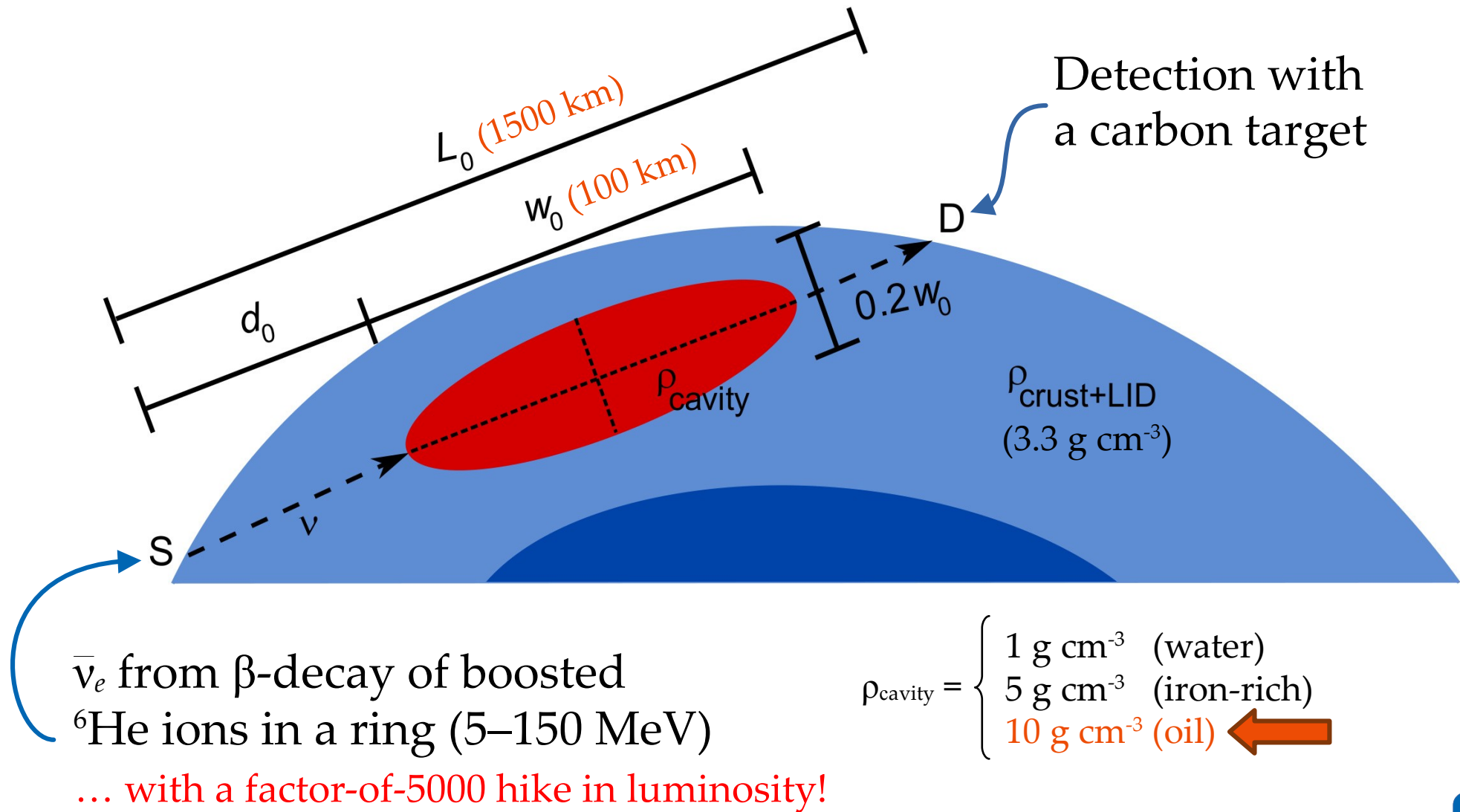
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active galactic nuclei, ultra high

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How Neutrino Beams Could Reveal Cavities Inside Earth

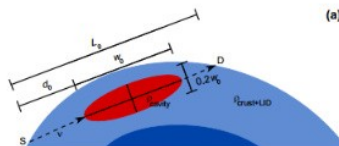
Geophysicists want to use neutrinos to 'x-ray' the Earth, a technique that could reveal undiscovered oil fields. But how practical is such a scheme?

By Emerging Technology from the arXiv

February 1, 2012

Neutrinos are peculiar particles. They have little mass, no charge and come in three flavours. These flavours are not fixed. The strange thing about neutrinos is that once created, they change from one flavour to another as they travel.

For a long time, that puzzled physicists. A neutrino's variety determines how it interacts with matter. Physicists built experiments to detect the flavour coming out of the Sun only to find far fewer than they expected.



POPULAR

How a top Chinese AI model overcame US sanctions

Caiwei Chen

OpenAI has created an AI model for longevity science

Antonio Regalado

**sheasie** · 13y ago

would these "neutrino beams" be harmful to underground organisms at all ? (sorry, i don't know anything about the intensity of these beams. just curious if they would be blanketing vast areas of land/seabed with rays that would kill bacteria and/or fungal ecosystems.)



1



Award



Share

**mbustamante** · 13y ago

Neutrinos interact very weakly with matter. In order for neutrinos to be harmful to an organism, one would expect that their energy and/or flux (i.e., number of neutrinos per interval of energy, per second, per area of impact) would have to be tremendously large (e.g., *perhaps* the neutrino flux from a very close supernova; please note that this is speculative at best). The energies and luminosities involved in the low-energy beta-beam of our proposal are very, very far from that.



1



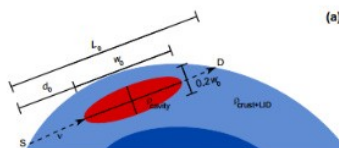
Award



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How a top Chinese AI model overcame US sanctions

Caiwei Chen

OpenAI has created an AI model for longevity science

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From [redacted]
 To c.arguelles@pucp.edu.pe <c.arguelles@pucp.edu.pe> @
 Cc mbustamante@pucp.edu.pe <mbustamante@pucp.edu.pe> @
 Subject **Monetizing Oil & Gas Fields**

2/6/12, 15:13

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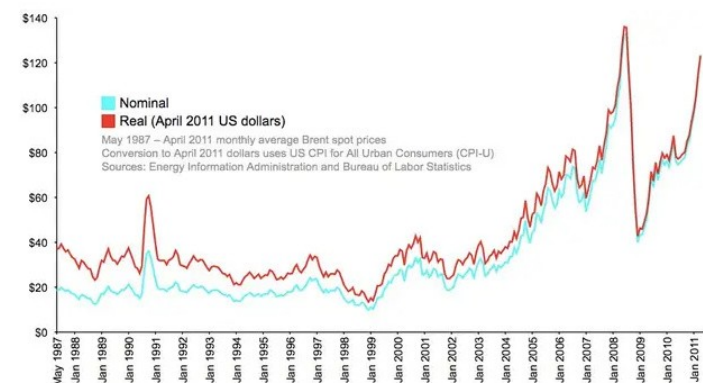
Dear Prof. Arguelles,

There is a great interest in discovering large new oil & gas fields - that including in Arctics and deep ocean,

www.nature.com/news/the-great-arctic-oil-race-begins-1.9932

however also other deposits such as iron ore, coal, etc. Hence, I did recently note your rather intriguing (attached) publication describing a hypothetical - yet not inconceivable, method to help discover them one day especially in difficult to access such remote areas. I thought however that given a need to discover natural resources - that including fossil fuels, it would be interesting to verify its practical viability. The key question is probably whether your described low energy beam neutrino based method would provide sufficient degree of detectability for relevant natural resources of interest - that especially relevant geological oil & gas configurations.

If that hypothetical method would turn out to be viable to discover and 'precision estimate' natural resources existing and finds, it would allow their upfront monetization to fund accelerated economic development. I did share several years ago with several folks my note on the creation of potentially as large as \$100Trillion liquid still-in-the-ground natural resources asset backed securities market. Realistically, that could be \$10-\$20Trillion large, however that would be already a non trivial addition to the wealth creation. The idea was to monetize known natural resources still in the ground even if untapped so as to create wealth for relevant countries. To be sure given a strong rebound in energy commodities, that was also a good timing to float such a concept.



"If that hypothetical method would turn out to be viable [...] creation of potentially as large as **\$100Trillion** liquid still-in-the-ground natural resources asset backed securities market."

Since the idea was also for relevant central banks in their 'market making' capacity to help scale that market, it would have had made money for them too, and allowed today to stimulate target economies. As you might recall that idea was also intended at that time to help anchor 'Gulf Union' common central bank platform since for example Saudi Arabia or Iraq have reportedly as much as 50% of population less than 24 years old which - as anywhere else, aspires to ever better education, jobs, etc. Assuming for example \$5Trillion of such assets today on those central banks balance sheet, Gulf States would have been provided with incremental financing capability for its own as well as MENA (Middle East North Africa) states economic development.

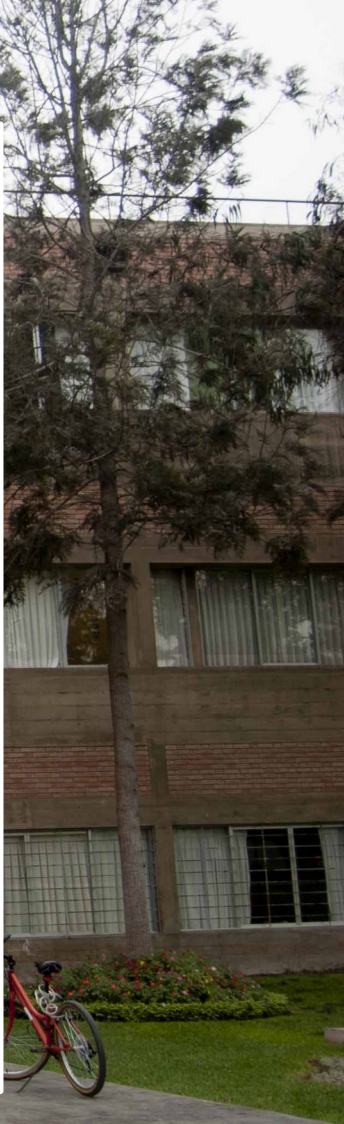
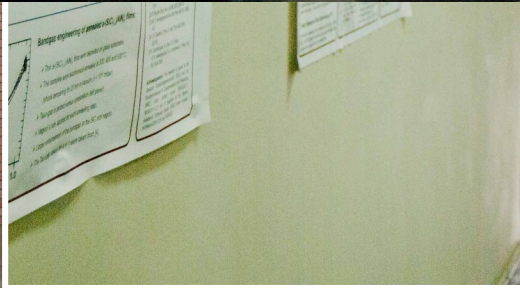
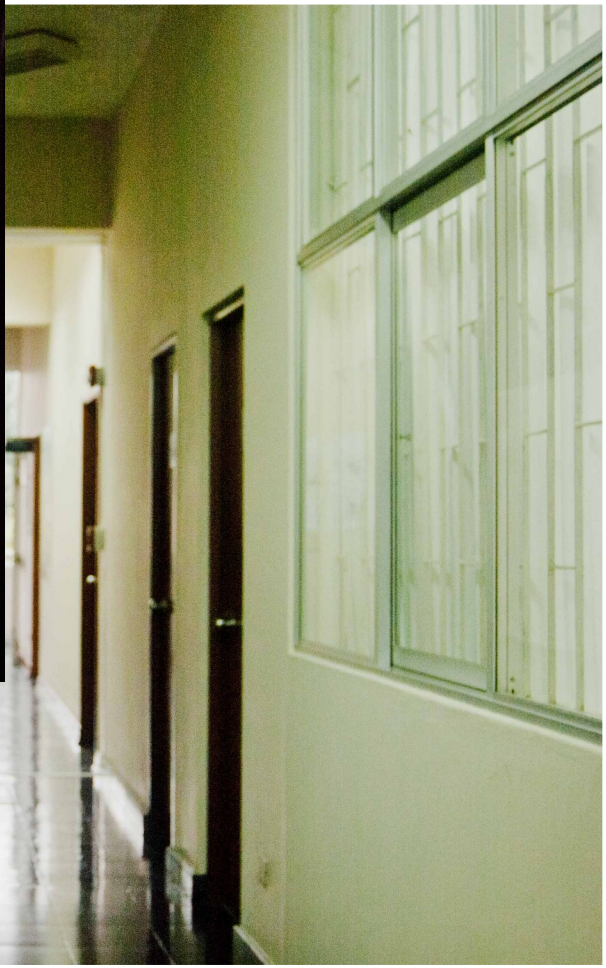
Having said that, clearly there are many other energy commodities, futures, etc. public and private securities structures, both liquid and illiquid. Yet, since there are \$100Trillion in such energy assets still-in-the-ground - that including also in the US, Canada, or Brasil, it was an intriguing conceptually idea at the time.

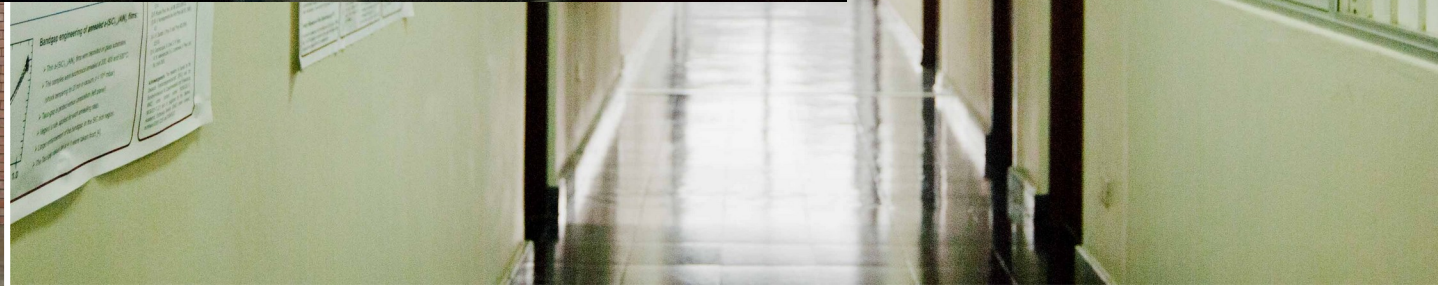
I had also thought that you can actually also do it for the farm land - that including folding the so designed public exchange listed securities it into ETFs. Some investors from for example Saudi Arabia, etc. could have wanted to swap their oil & gas still-in-the-ground securities for US or Brazilian farmland securities so as to ensure 'food security'. That is certainly viable today in private transactions however not tradeable ones.

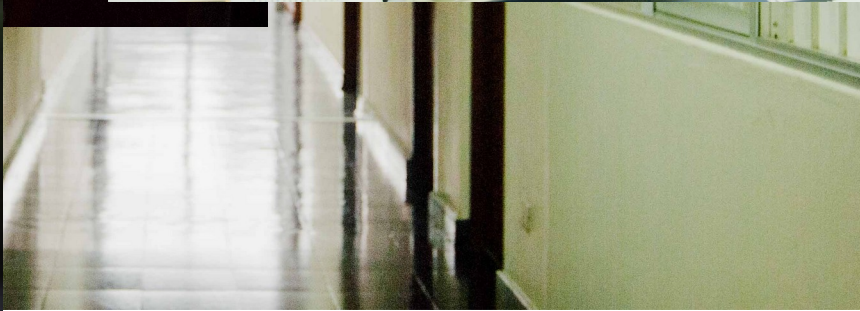


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¡Feliz cumpleaños!

Thanks!

IV PHD SUMMER SCHOOL ON NEUTRINOS HERE, THERE & EVERYWHERE

Lectures:

Mariam Tórtola (U. Valencia) • Neutrino phenomenology
Maria Petropoulou (U. Athens) • Neutrino astrophysics
Vivian Poulin (U. Montpellier) • Neutrino cosmology

Registration:

nbia.dk/neutrino2025

Deadline:

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For PhD and advanced MSc students • Organizers: Markus Ahlers & Mauricio Bustamante

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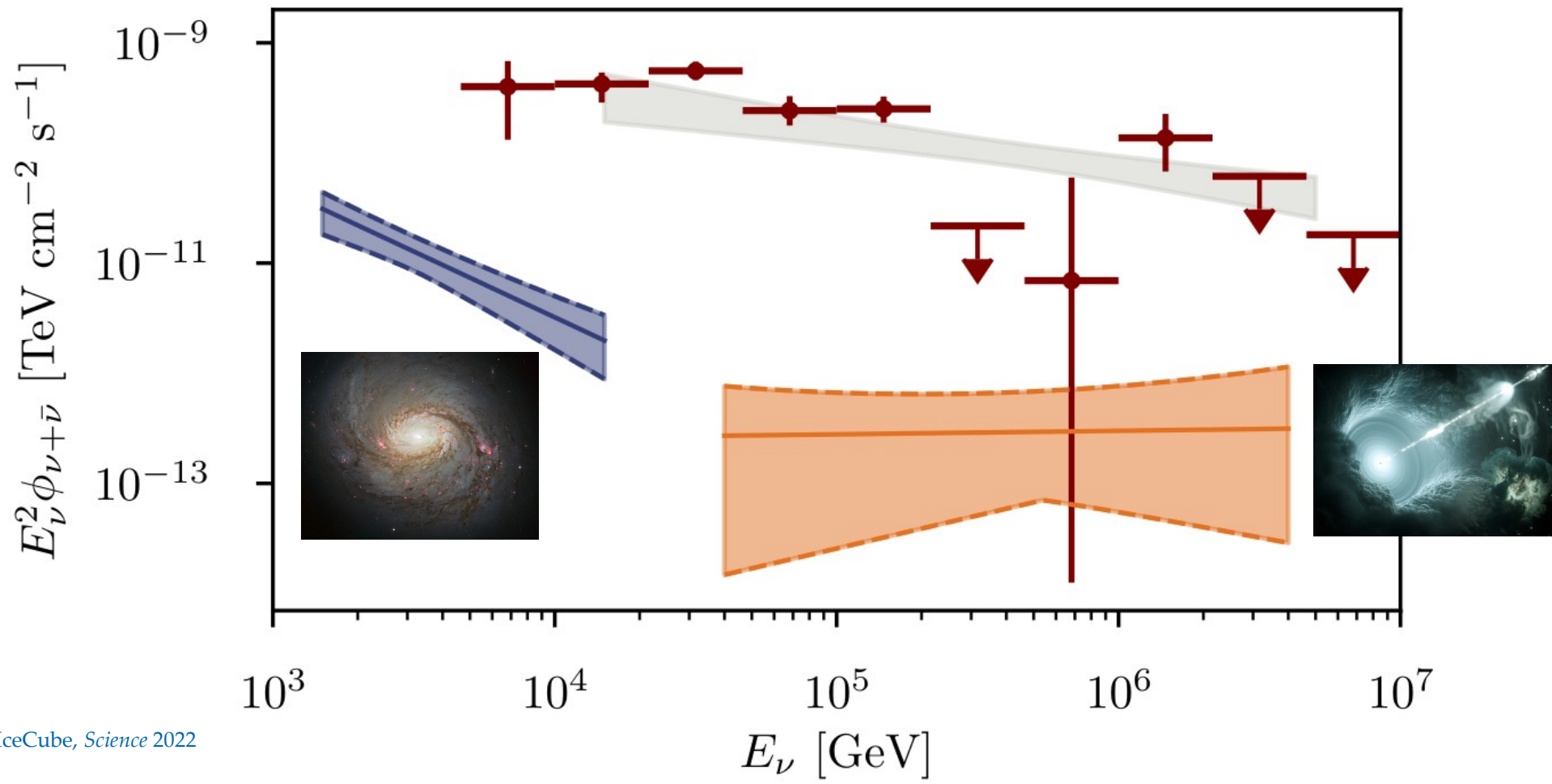


- ▶ Three tracks:
 - ▶ Neutrino **phenomenology**:
Mariam Tórtola (Valencia)
 - ▶ Neutrino **astrophysics**:
Maria Petropoulou (Athens)
 - ▶ Neutrino **cosmology**:
Vivian Poulin (Montpellier)
- ▶ Plus topical seminars & student talks
- ▶ Registration open (**deadline: March 31**)

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Thanks!

Backup slides



TAMBO

AIR SHOWER:
3 – 10 KM LENGTH
200 M DIAMETER

DECAY

τ

RANGE:
50 M – 5 KM

ROCK

> 4 KM SHIELDING FROM
BACKGROUND MUONS

ν_{τ}

CHARGED-CURRENT
INTERACTION

~100 M
SEPARATION

AIR-SHOWER
DETECTOR ARRAY
~M³ EACH

DEEP VALLEY

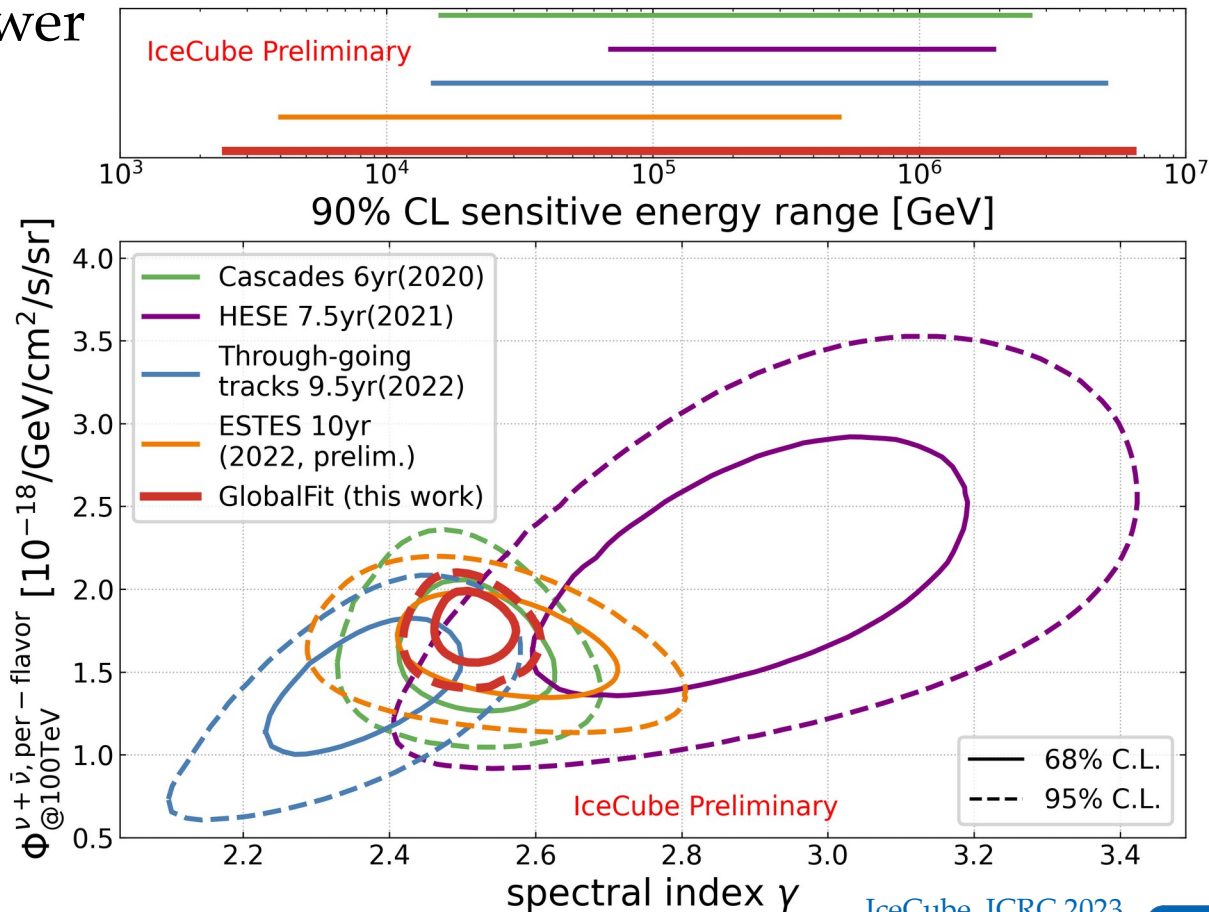
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) • COLCA VALLEY, PERU

Neutrino energy spectrum

IceCube data is fit well by a power law in neutrino energy:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \times 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

The power law is inherited from the parent protons



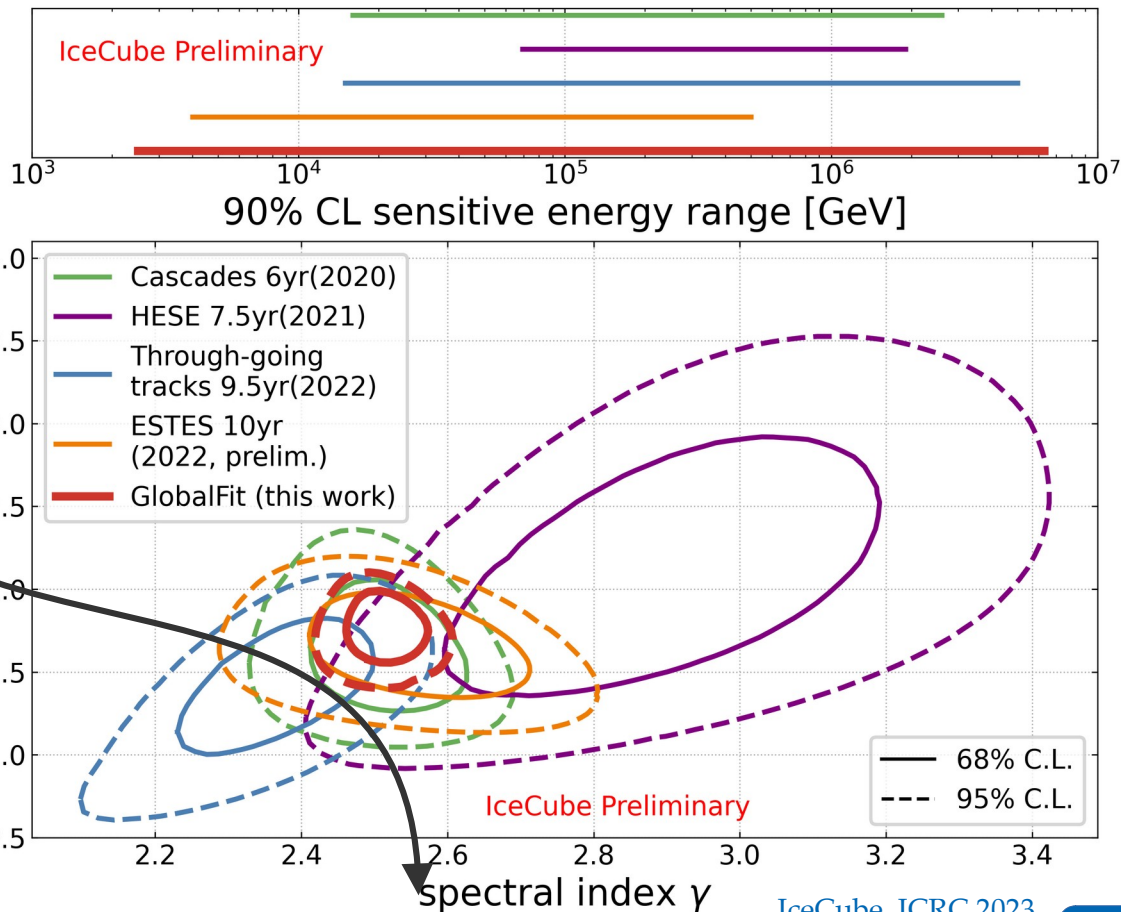
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The power law is inherited from the parent protons

$\Phi_{\nu + \bar{\nu}, \text{ per-flavor}} [10^{-18} / \text{GeV/cm}^2/\text{s/sr}]$



One likely TeV–PeV ν production scenario:

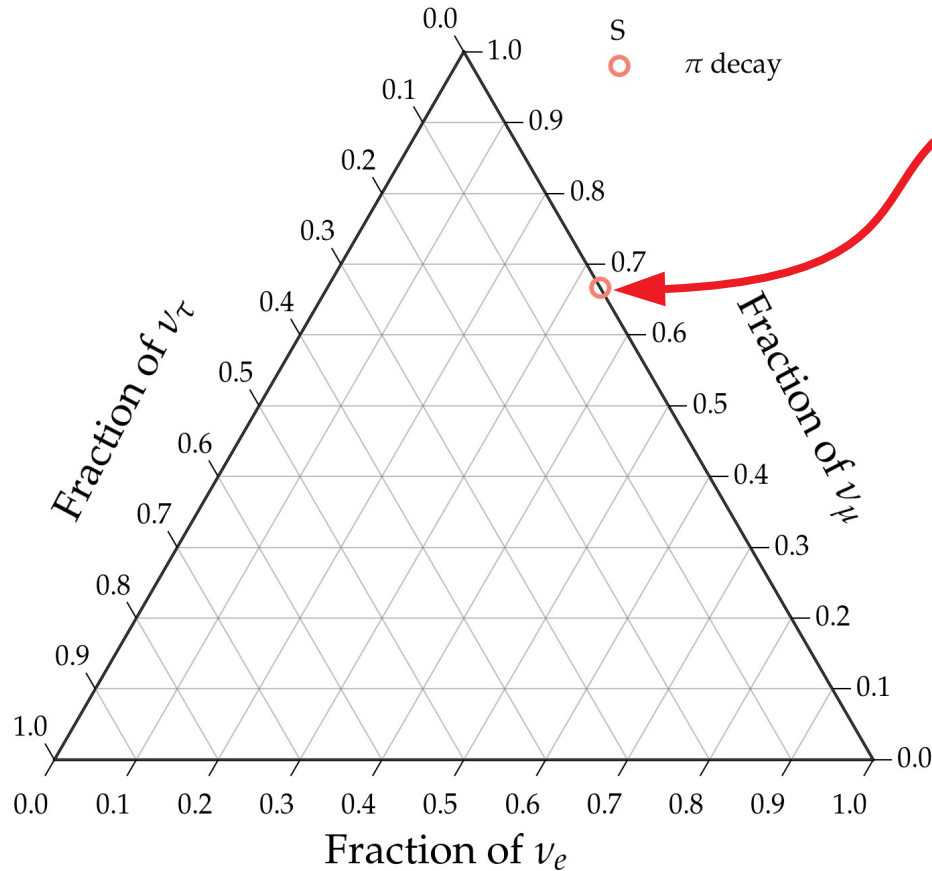
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

$$(1/3:2/3:0)_S$$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable
in neutrino telescopes

One likely TeV–PeV ν production scenario:

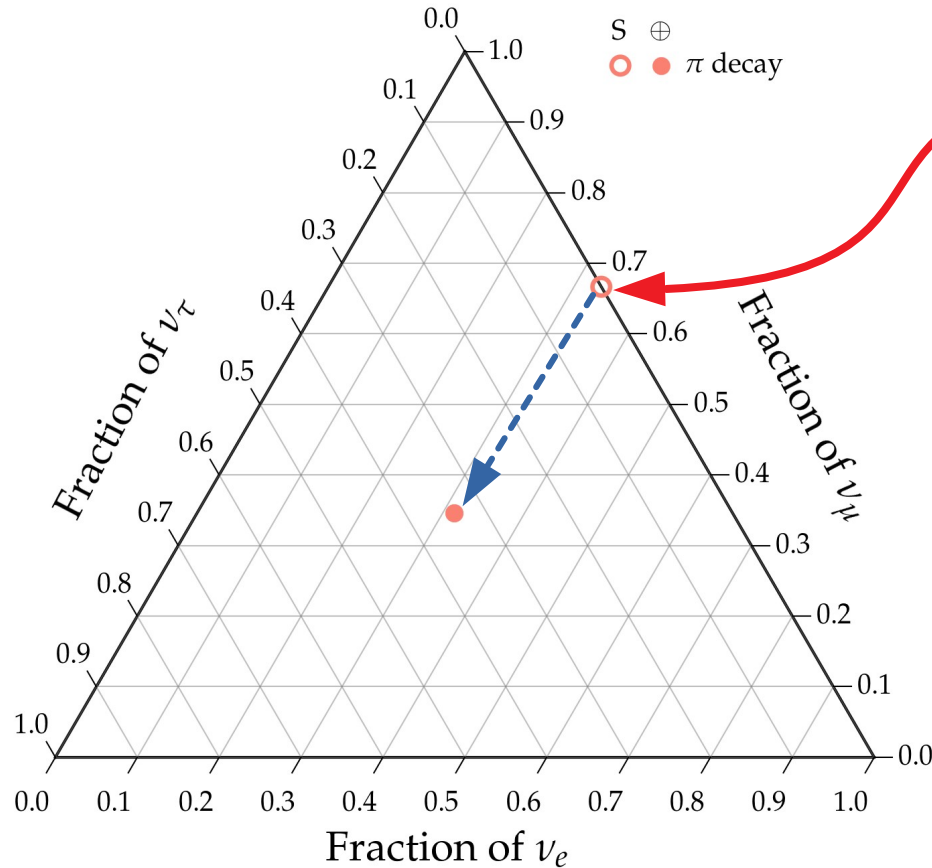


Full π decay chain

$(1/3:2/3:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:

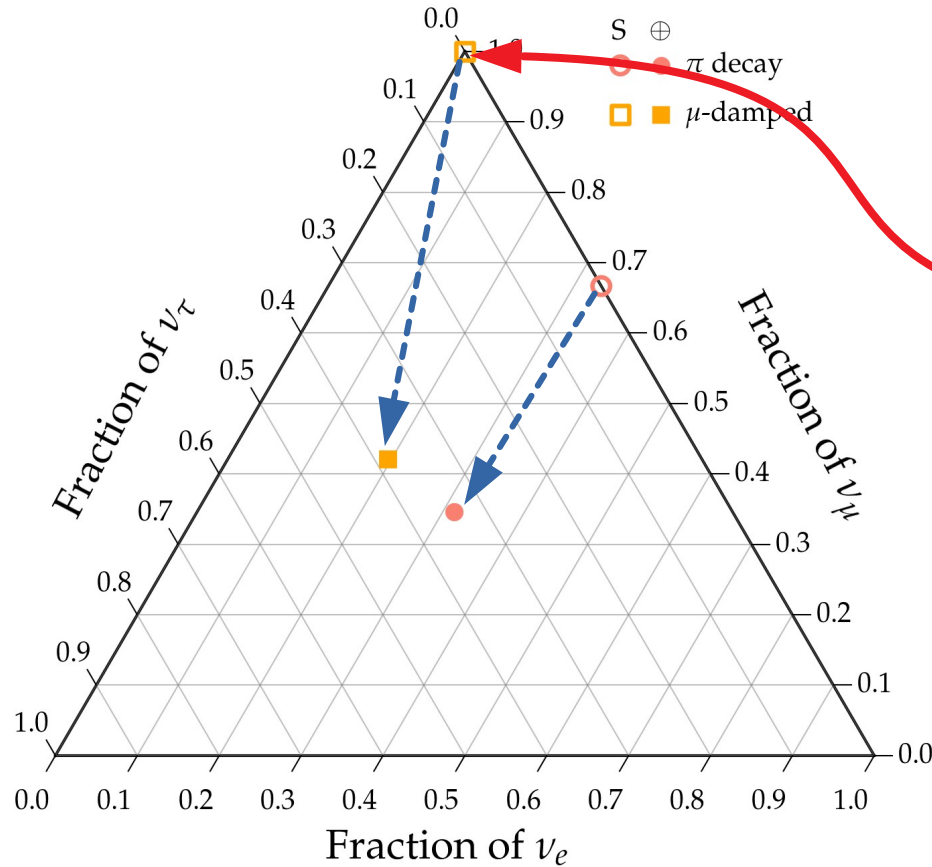


Full π decay chain

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One likely TeV–PeV ν production scenario:



Full π decay chain

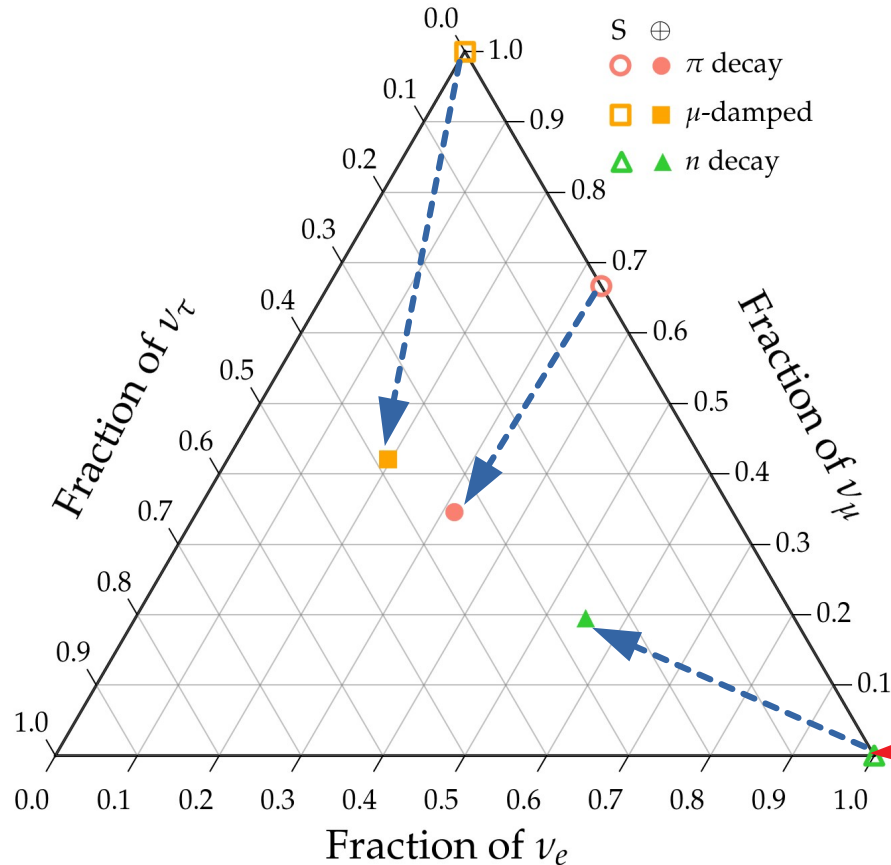
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

One likely TeV–PeV ν production scenario:



Full π decay chain

$(1/3:2/3:0)_S$

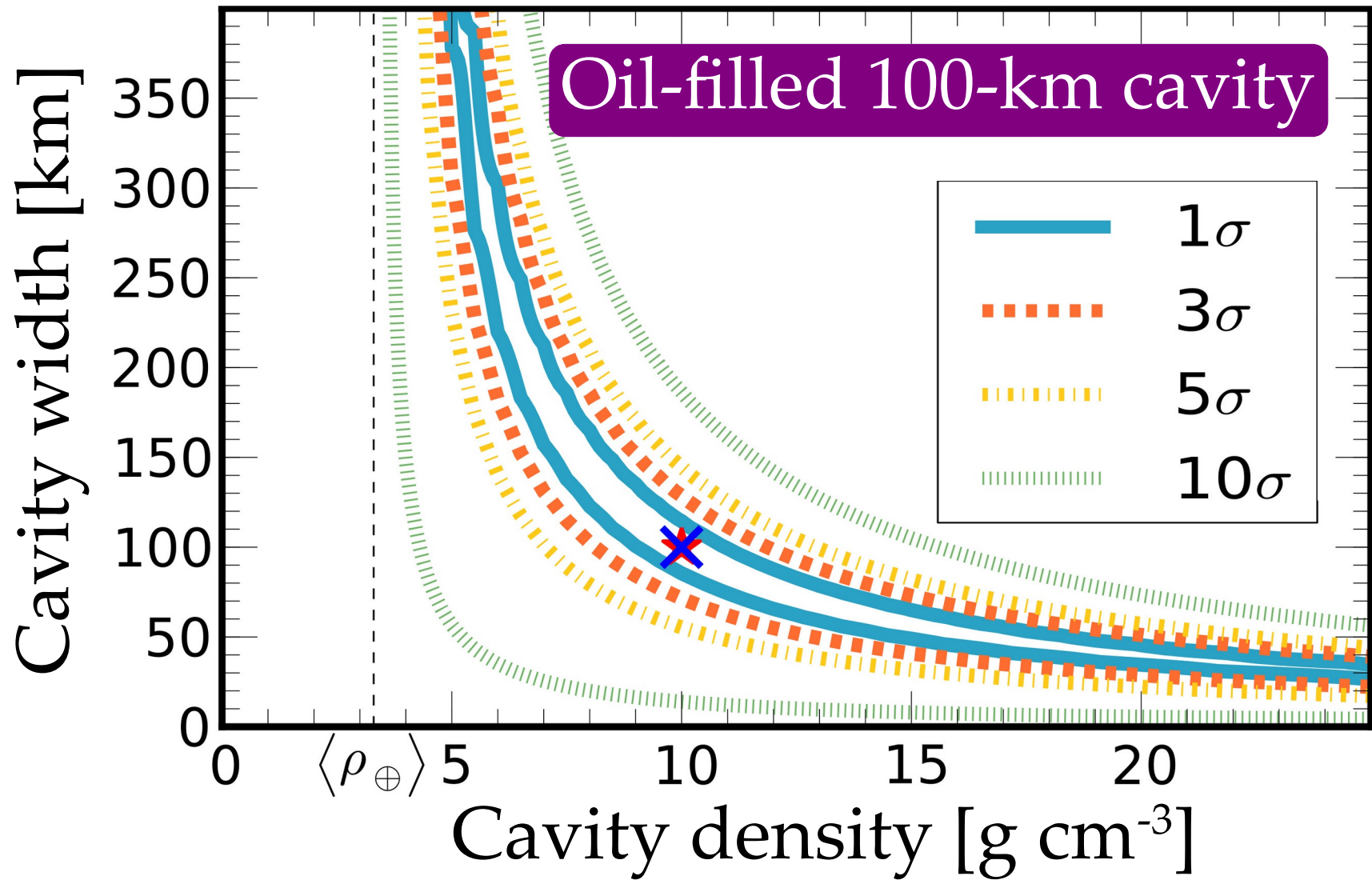
Muon damped

$(0:1:0)_S$

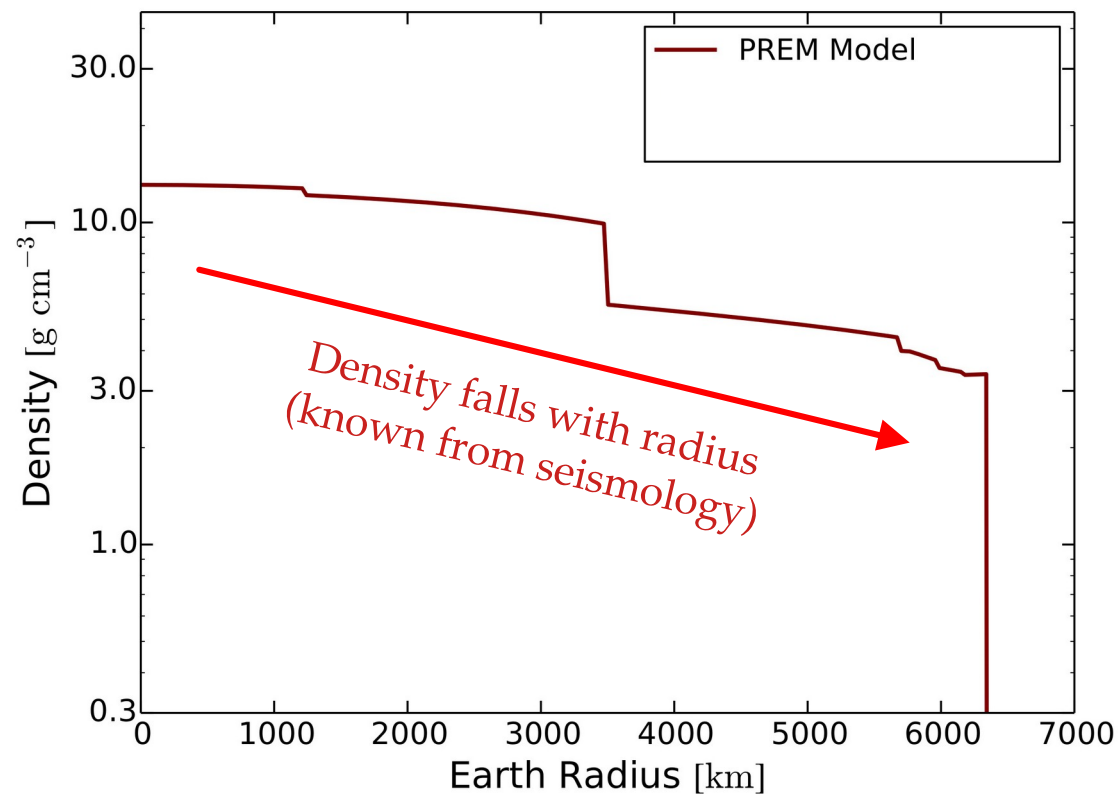
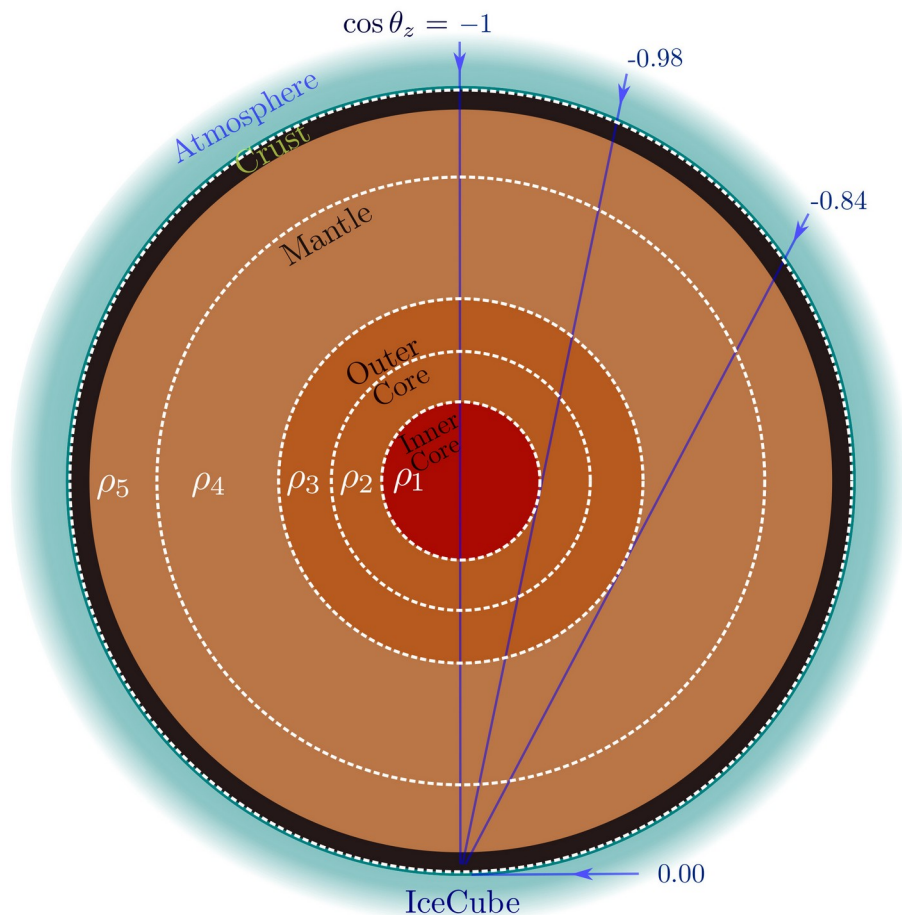
Neutron decay

$(1:0:0)_S$

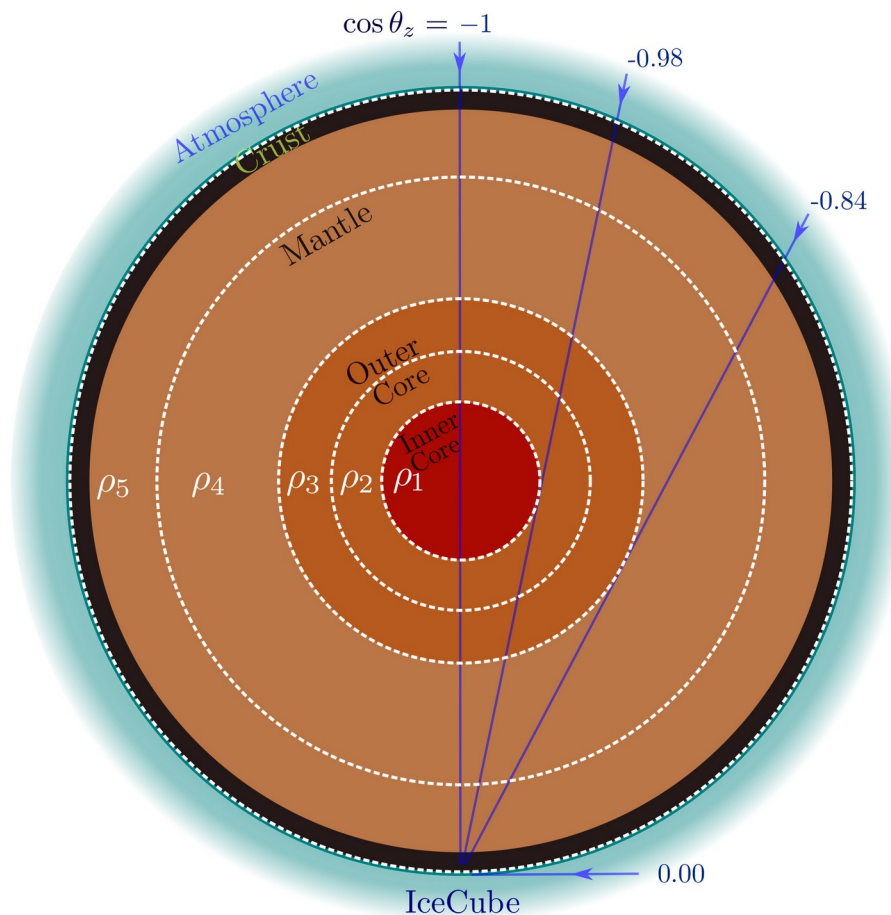
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes



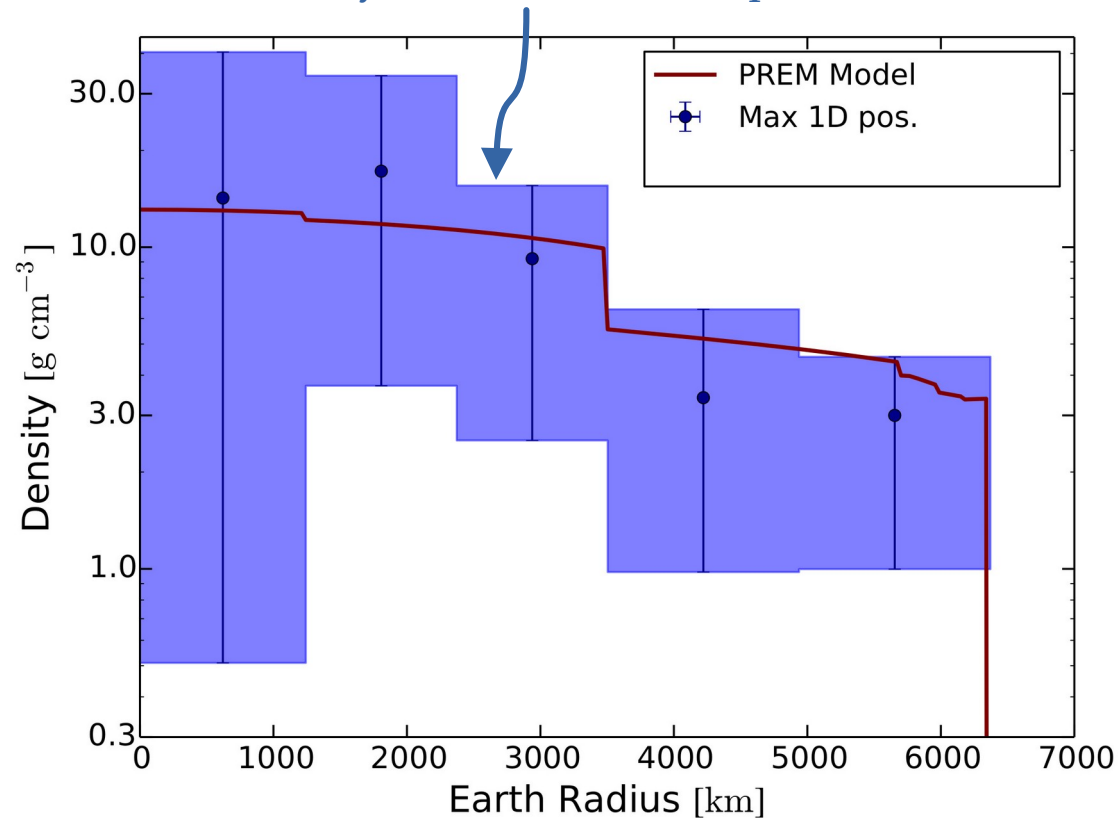
Weighing the Earth with neutrinos



Weighing the Earth with neutrinos



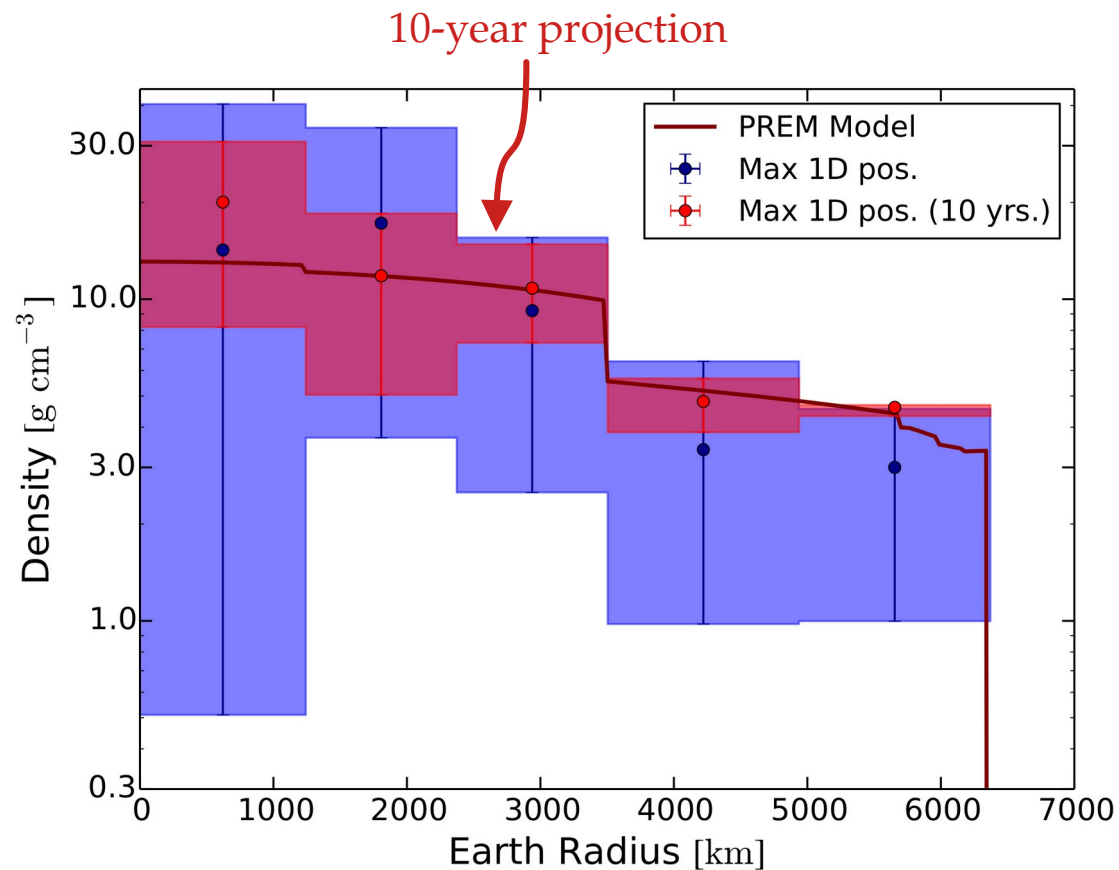
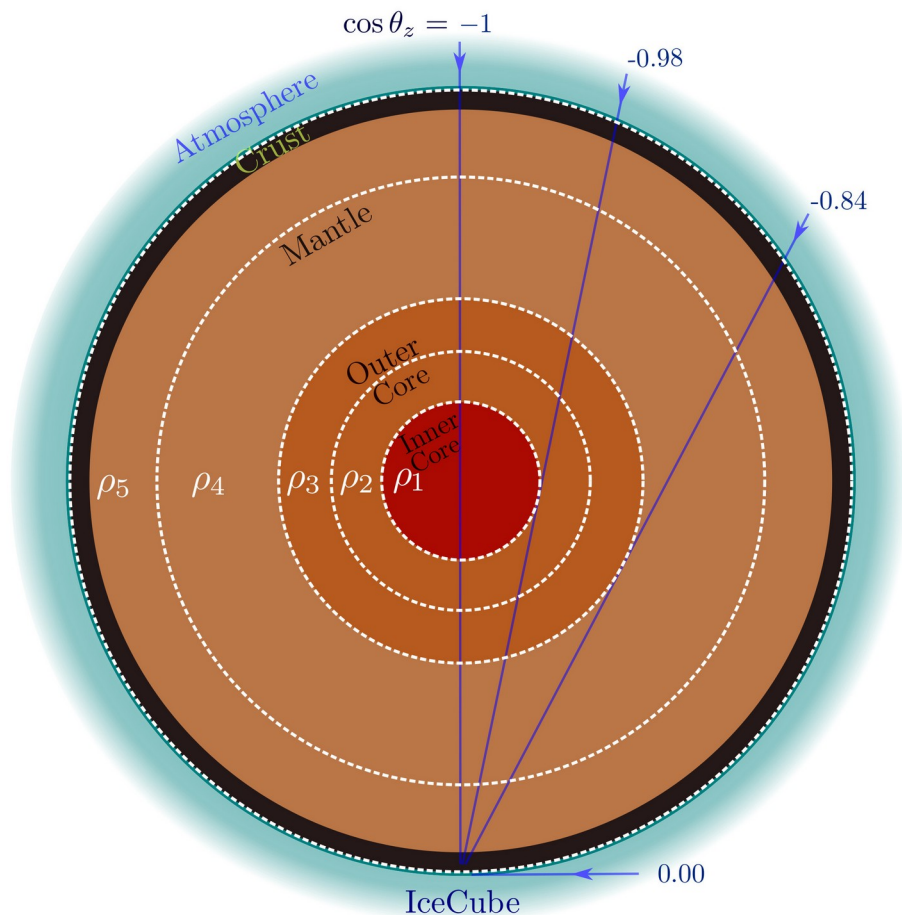
With 1 yr of IceCube (atmospheric) TeV ν



Mass of the Earth using ν : $6.0^{+1.6}_{-1.3} \times 10^{24} \text{ kg}$

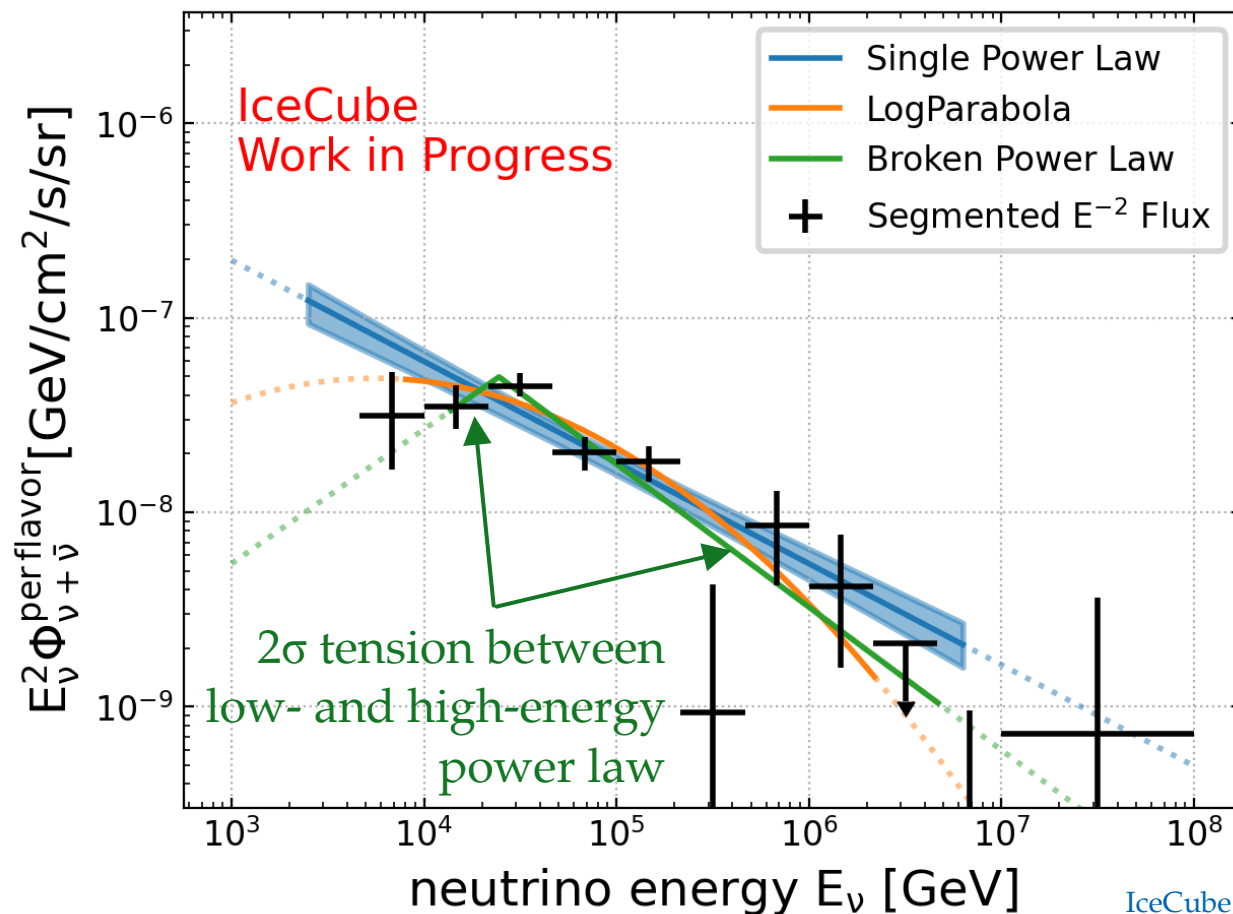
From gravitational measurements: $(5.9722 \pm 0.0006) \times 10^{24}$

Weighing the Earth with neutrinos



Neutrino energy spectrum

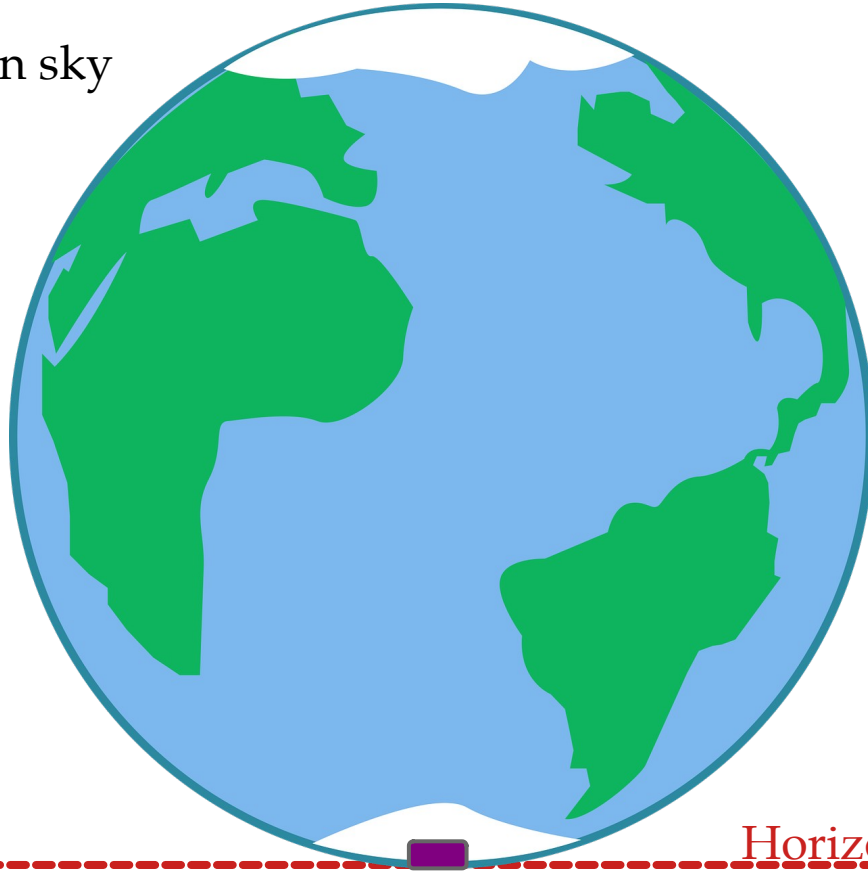
With > 10 years of data, deviations from a power law start to be testable:



Different spectra might reflect different source populations

Upgoing vs. downgoing neutrinos

Northern sky



Horizon

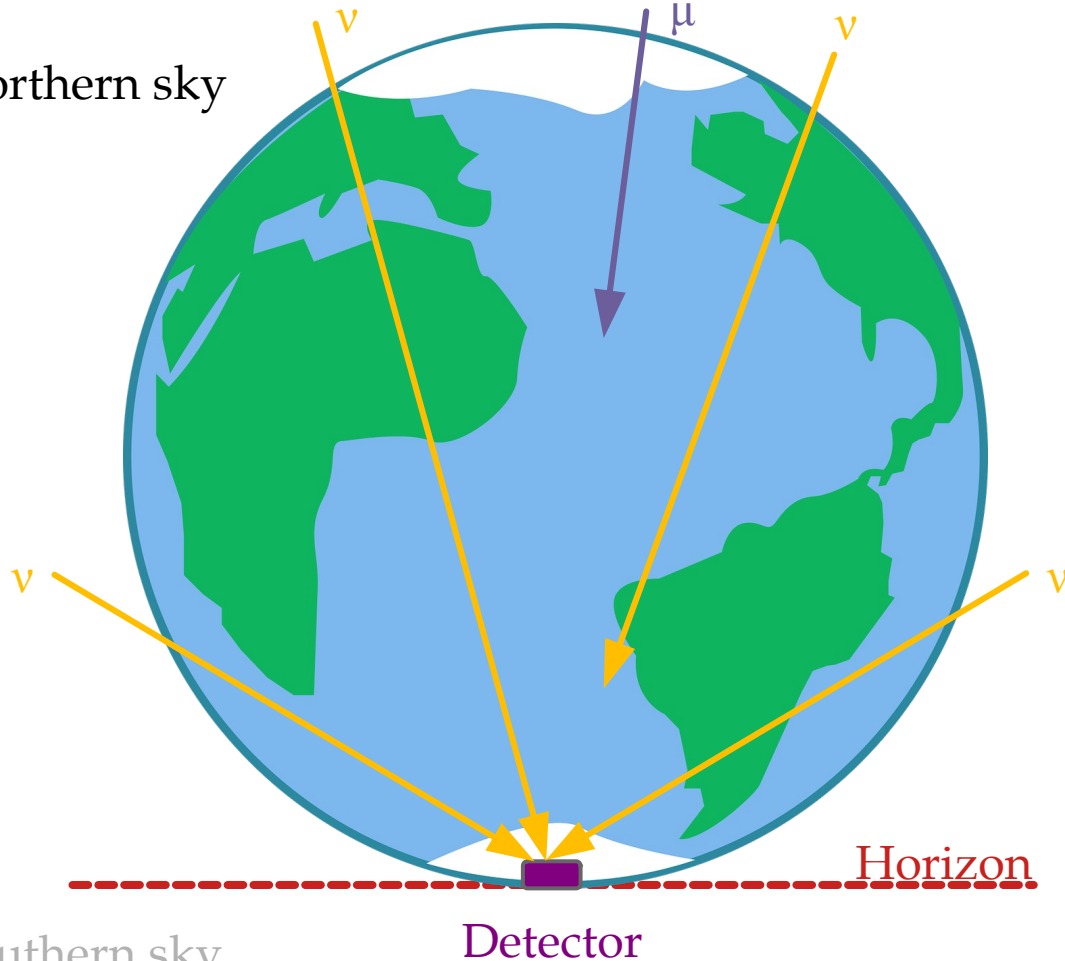
Detector

Southern sky

(Galactic Center is here)

Upgoing vs. downgoing neutrinos

Northern sky



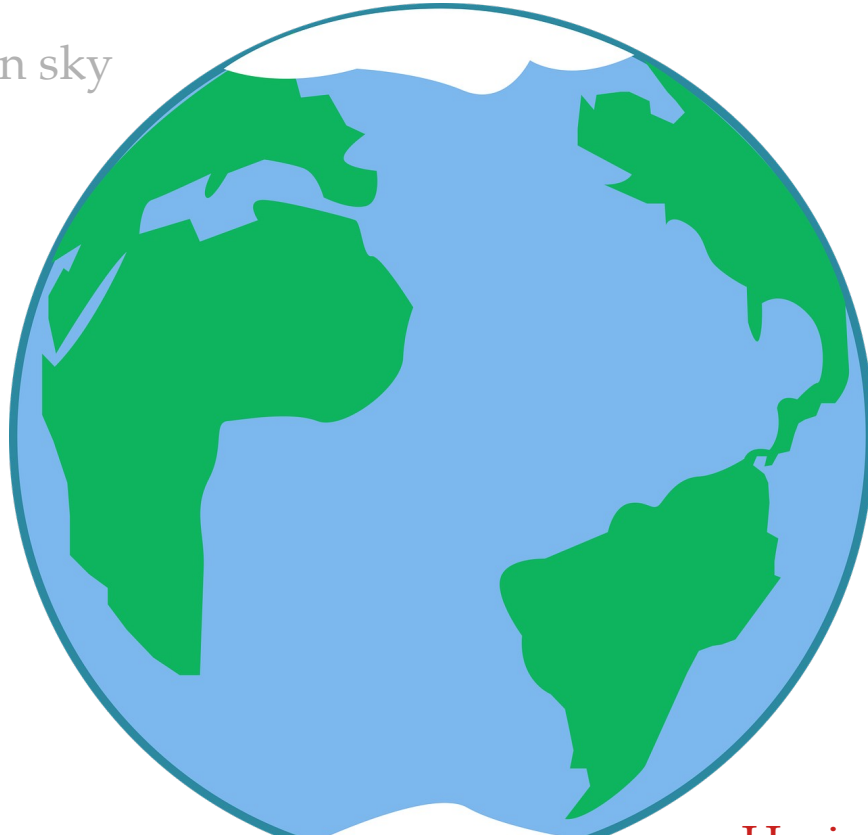
Southern sky
(Galactic Center is here)

Neutrinos from the Northern sky
 $\equiv$
Upgoing neutrinos

- ▶ Atmospheric μ ons stopped
- ▶ Dominated by atmospheric ν
- ▶ High-energy ν flux attenuated
- ▶ High statistics
- ▶ Good for finding sources with through-going muon tracks

Upgoing vs. downgoing neutrinos

Northern sky



Southern sky
(Galactic Center is here)

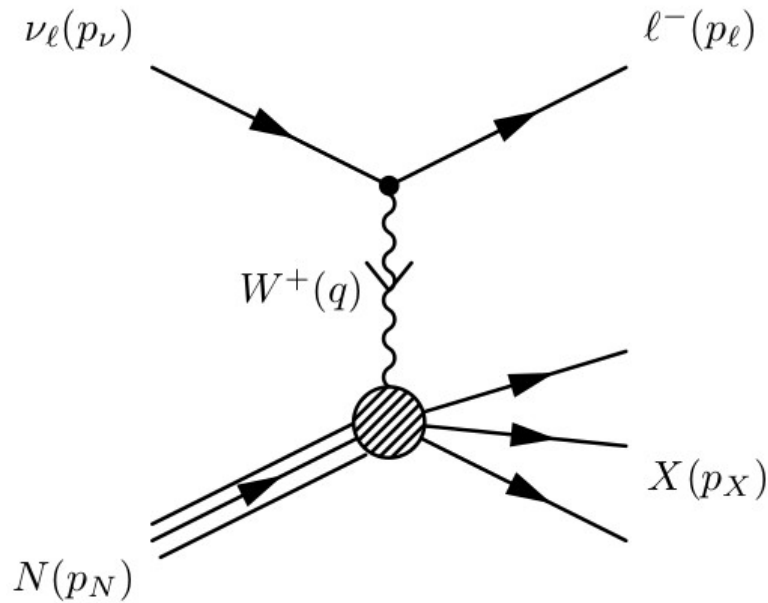
Neutrinos from the Southern sky
≡

Downgoing neutrinos

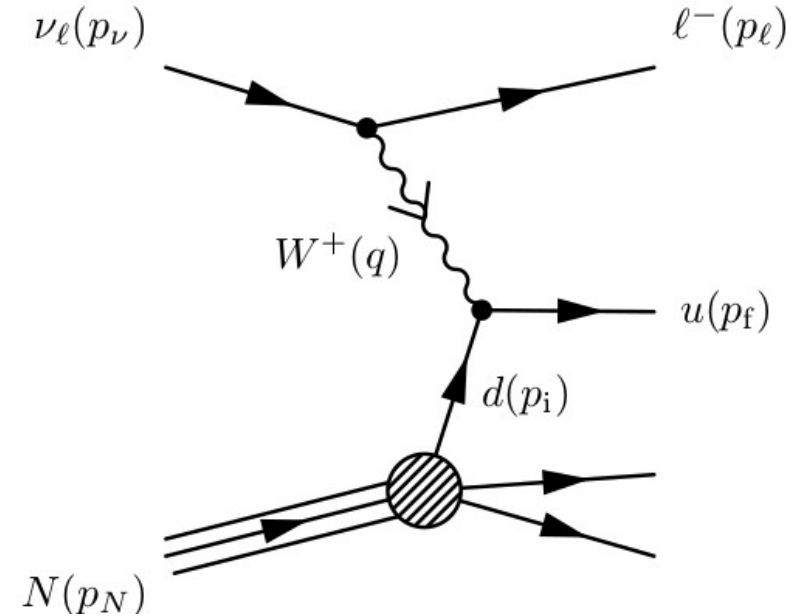
- ▶ Need to mitigate atmospheric **muons** and **ν** :
 - ▶ Use higher-energy events
 - ▶ Use starting a self-veto
- ▶ Dominated by astrophysical **ν** (*after* event selection)
- ▶ Low statistics
- ▶ Good for measuring the diffuse flux of astrophysical **ν**

Deep inelastic scattering

What you see

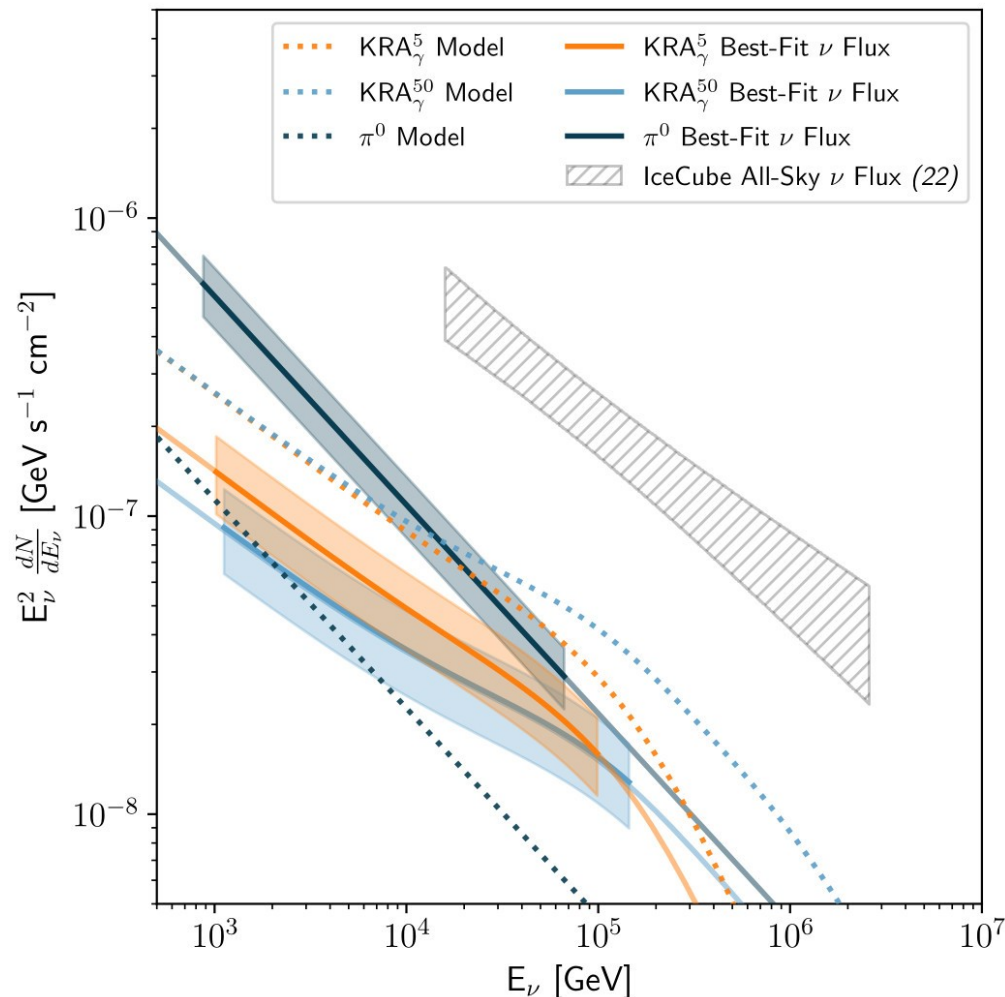


Beneath the hood



(Plus the equivalent neutral-current process (Z-exchange))

High-energy neutrinos from the Galactic Plane



Three models of Galactic diffuse ν :

π^0 : MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA_γ^5 : Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

KRA_γ^{50} : Cut-off at 50 PeV in CR energy

None of the models matched data

(*caveat: there are relatively simple models*)

No Galactic ν source identified

(*likely diffuse + source: Fang & Murase, 2307.02905*)

GP flux is 6–13% of all-sky at 30 TeV

Fundamental physics with high-energy cosmic neutrinos

- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$

Fundamental physics with high-energy cosmic neutrinos

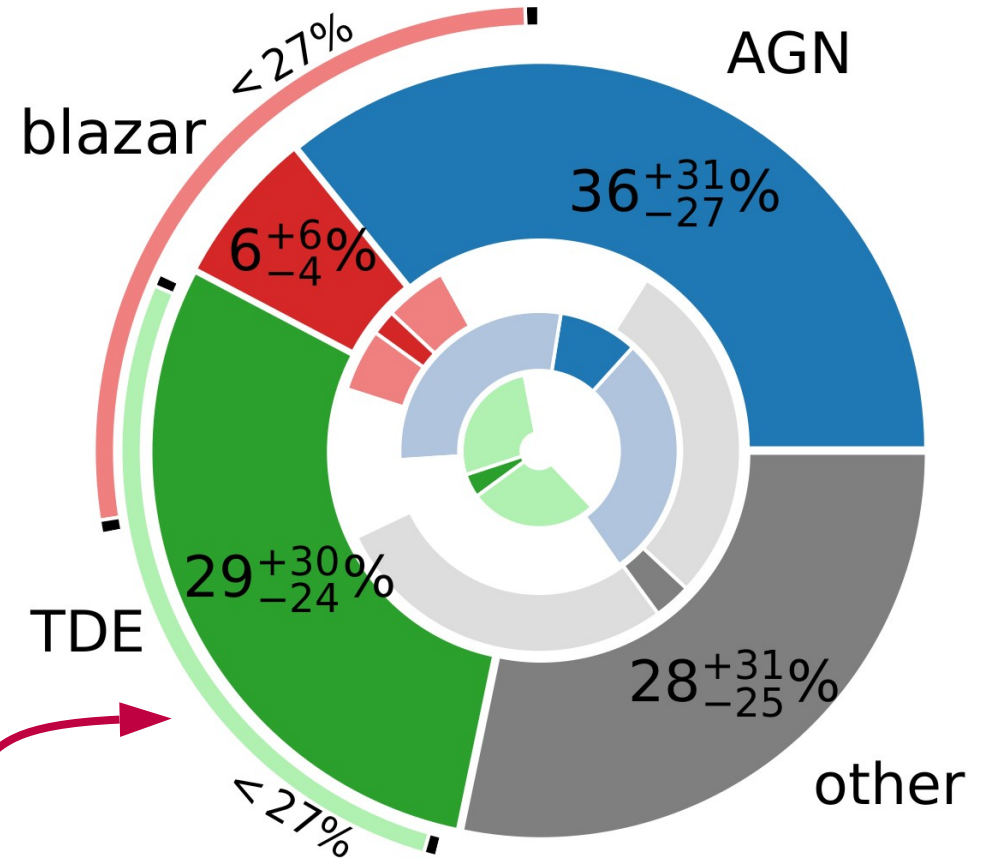
- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left. \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right\}$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$

The IceCube pie chart

Sources with associated ν emission:

Name	Type	p
NGC 1068	AGN	0.008
TXS 0506+056	blazar	0.001
PKS 1502+106	blazar	0.01
PKS 1424-41	blazar	0.05
AT2019dsg	TDE	0.002

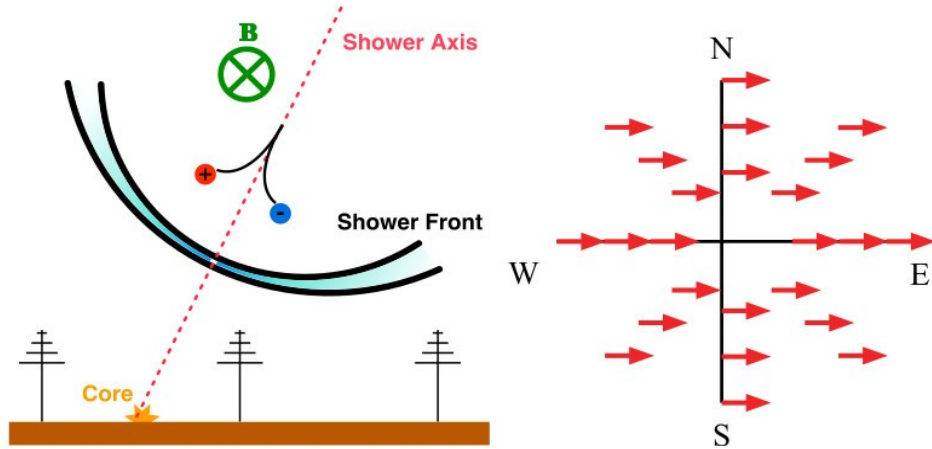
Fractional contribution
of each source population
to total diffuse flux
(Bayesian analysis)



Note: Outer rings are from separate stacking analyses

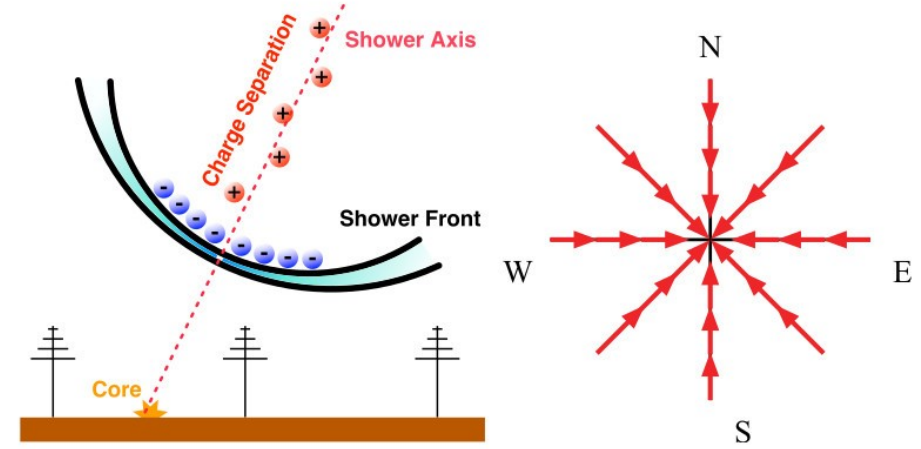
Radio emission: geomagnetic and Askaryan

Geomagnetic



- ▶ Time-varying transverse current
- ▶ Linearly polarized parallel to Lorentz force
- ▶ Dominant in air showers

Askaryan



- ▶ Time-varying negative-charge $\sim 20\%$ excess
- ▶ Linearly polarized towards axis
- ▶ Sub-dominant in air showers

Figures by H. Schoorlemmer and K. D. de Vries

Radio emission: geomagnetic and Askaryan

Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

But likely **not** of Milky-Way origin

[KM3NeT Collab. arXiv:2502.08387](#)

Likely extragalactic origin

Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

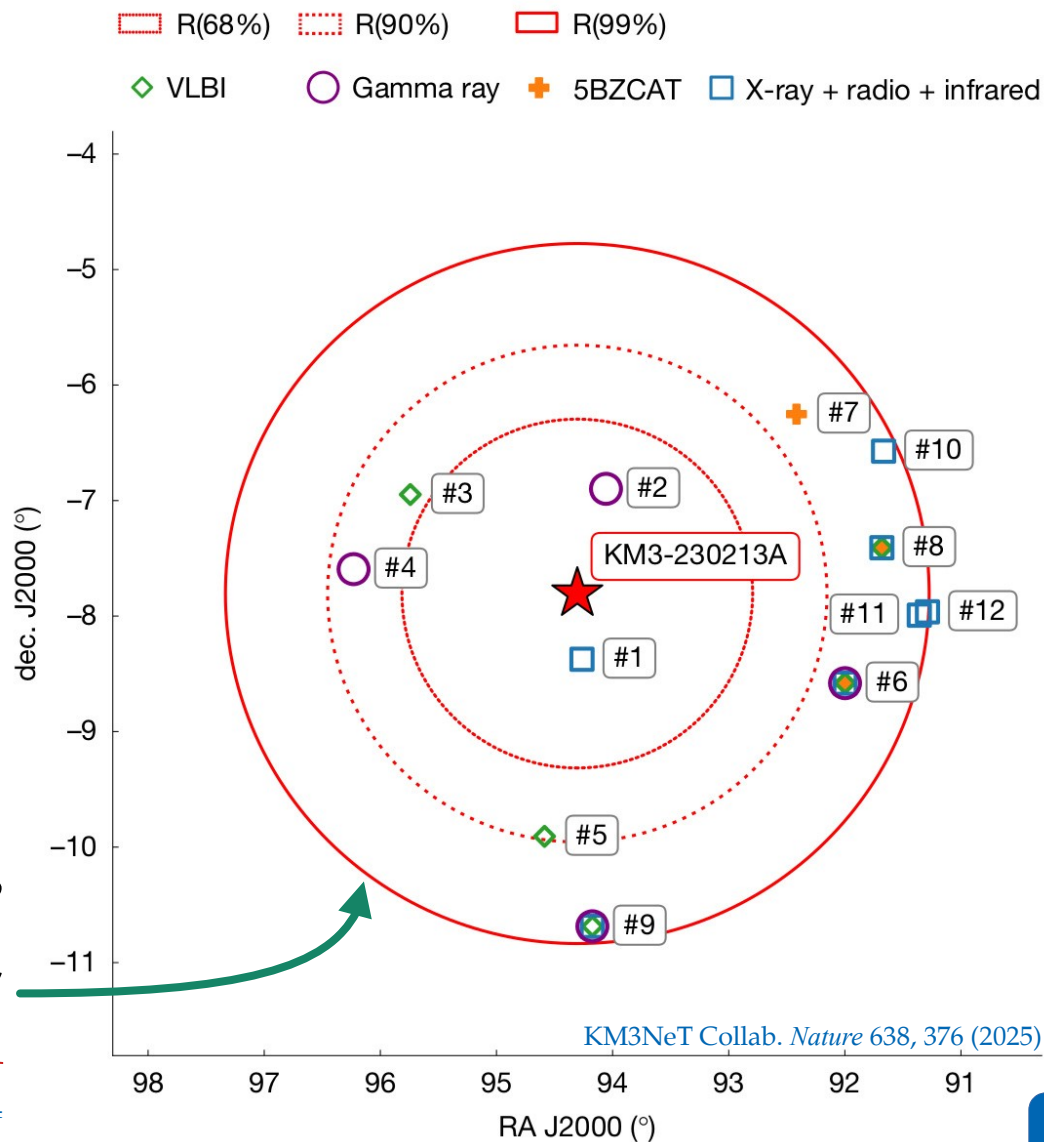
But likely **not** of Milky-Way origin

KM3NeT Collab. [arXiv:2502.08387](#)

Likely extragalactic origin

Few extragalactic sources
(blazars) near event position,
but no strong association

KM3NeT Collab. [arXiv:2502.08484](#)



Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

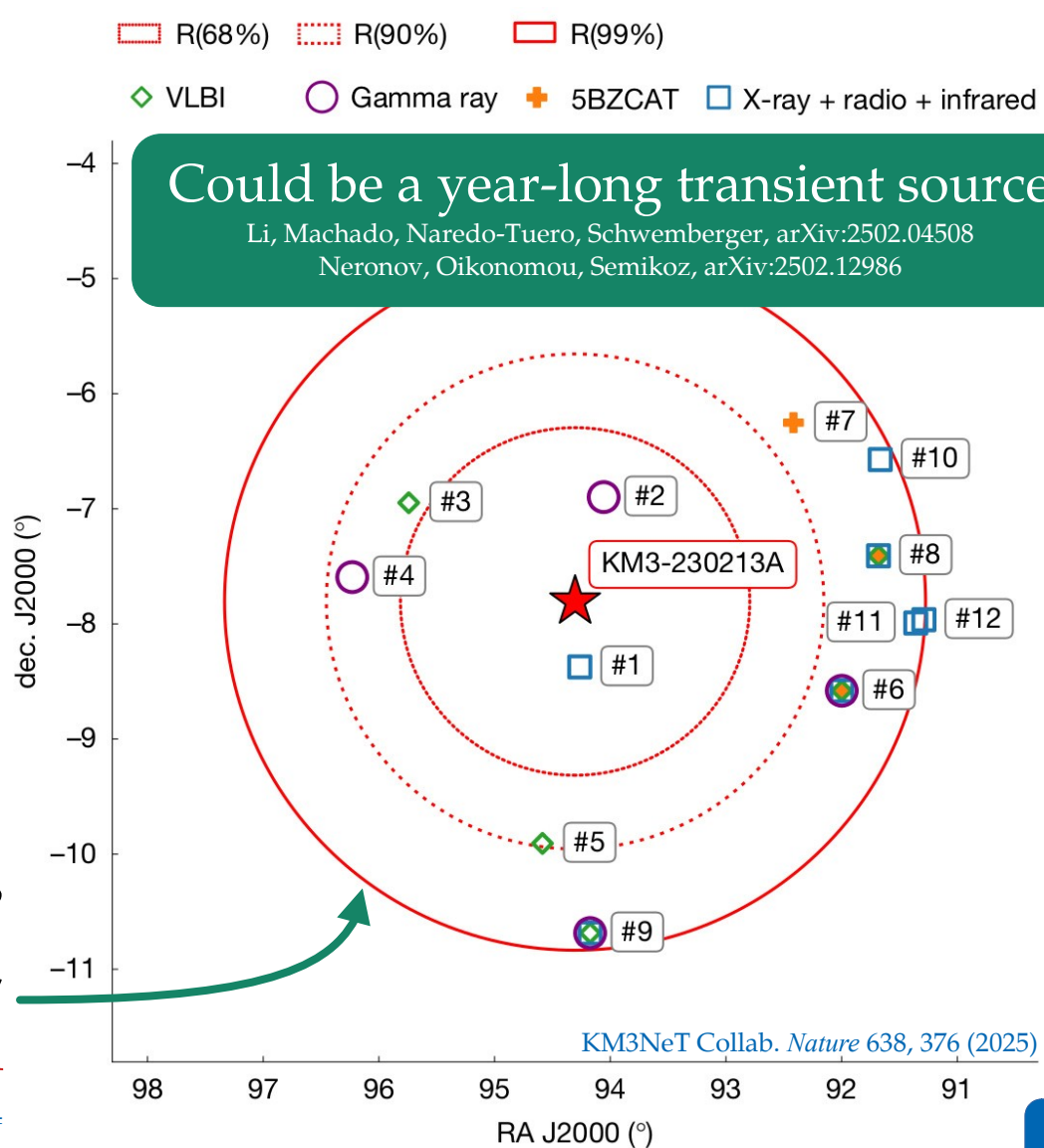
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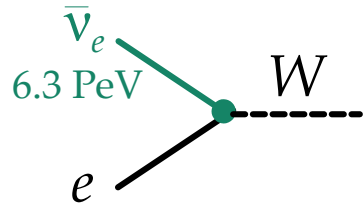
Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

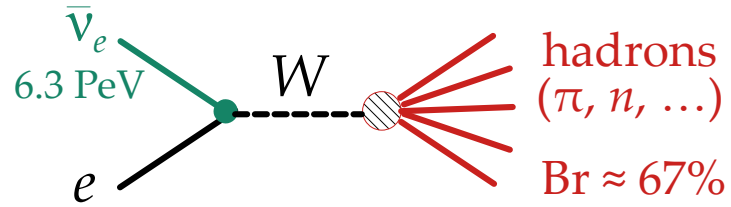
First observation of a Glashow resonance

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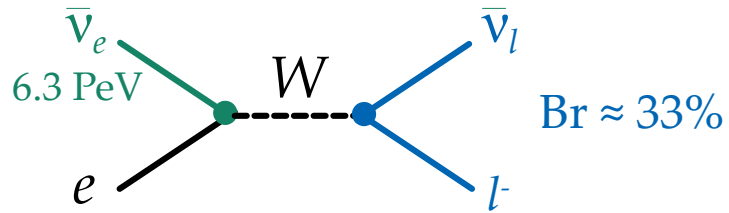
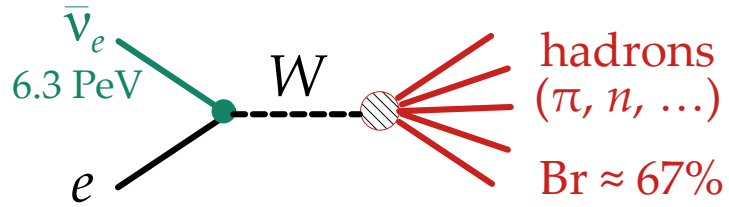
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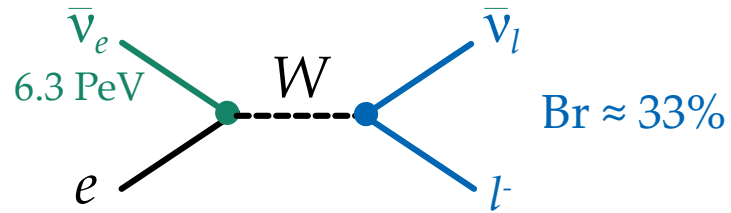
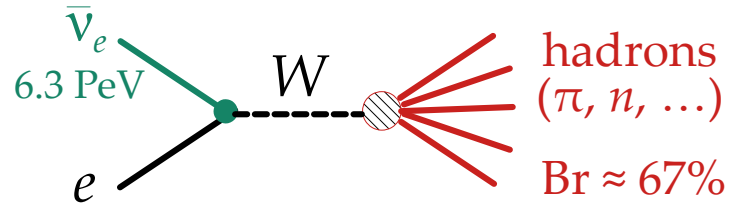
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Predicted in 1960:

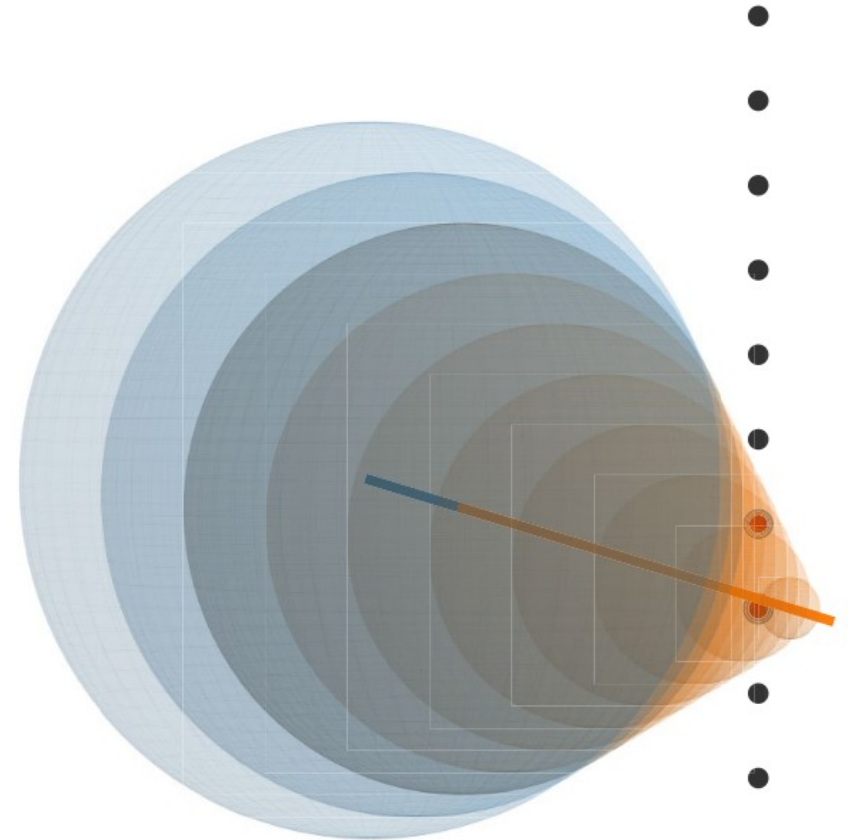


First observation of a Glashow resonance

Predicted in 1960:

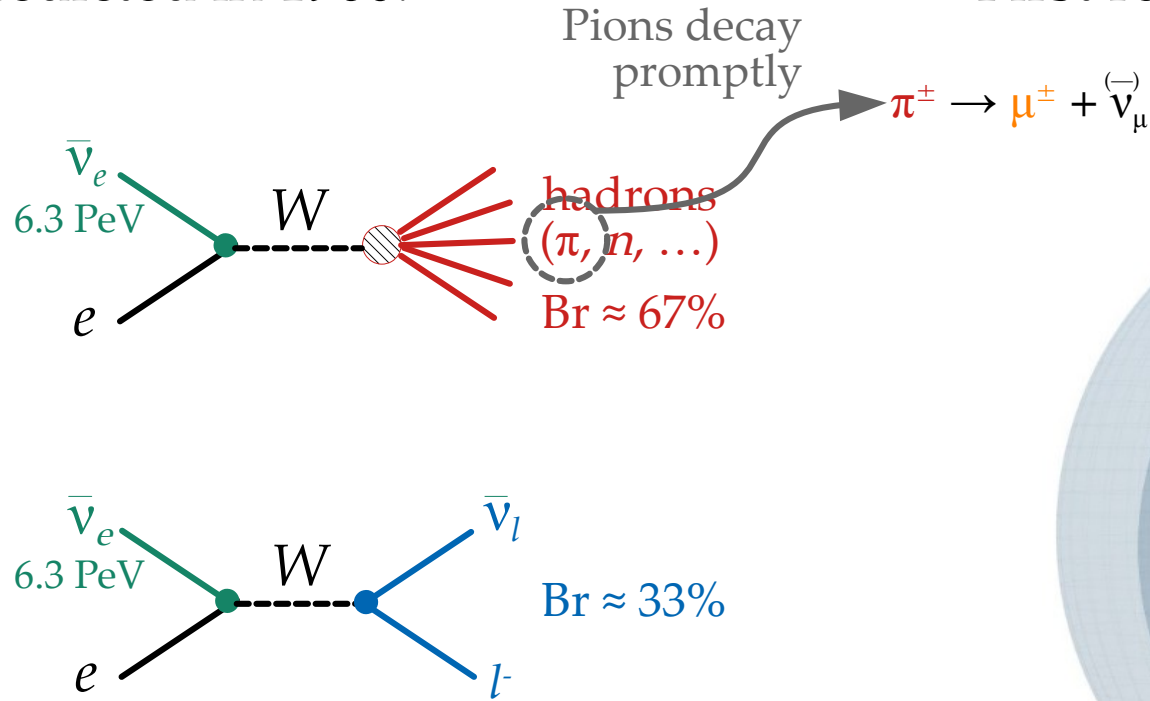


First reported by IceCube in 2021:

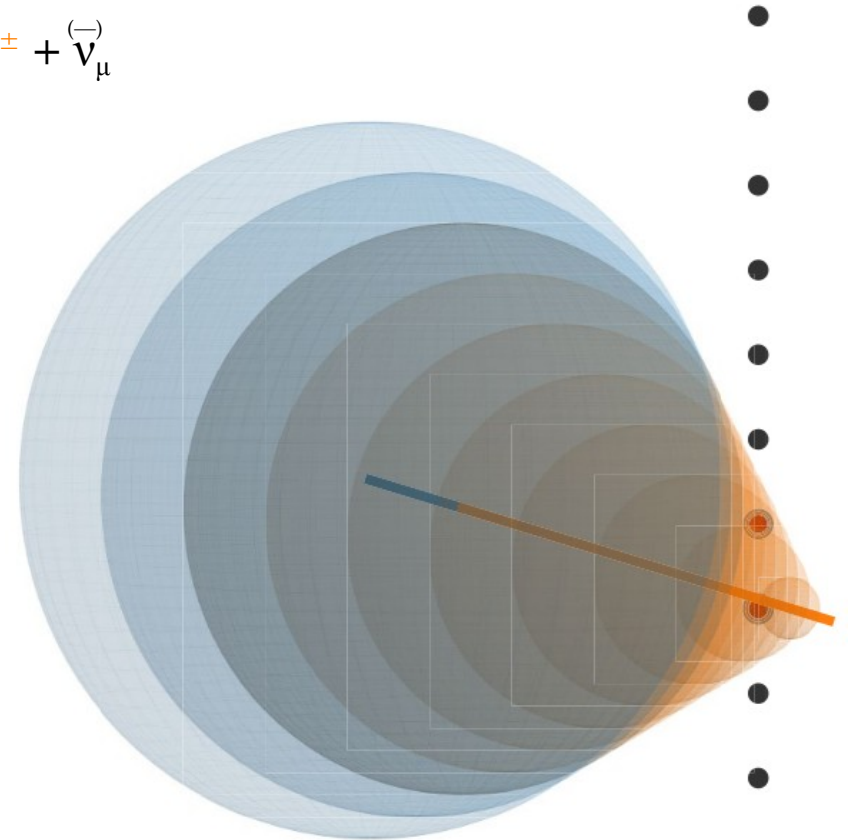


First observation of a Glashow resonance

Predicted in 1960:

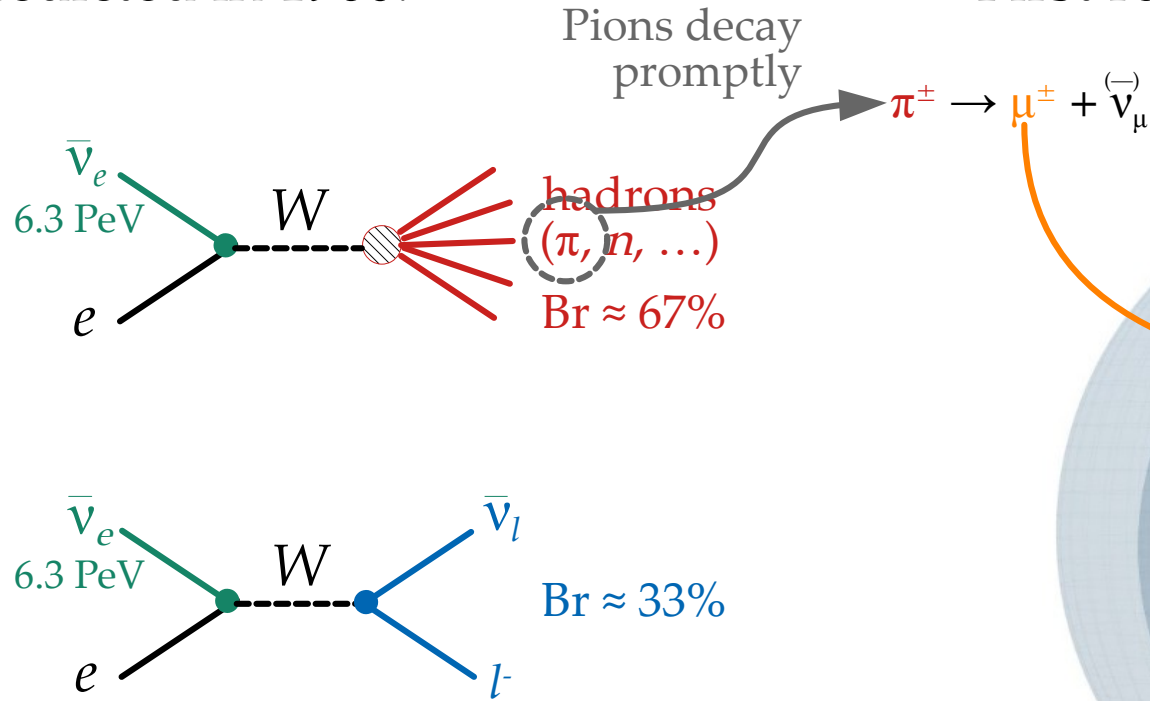


First reported by IceCube in 2021:

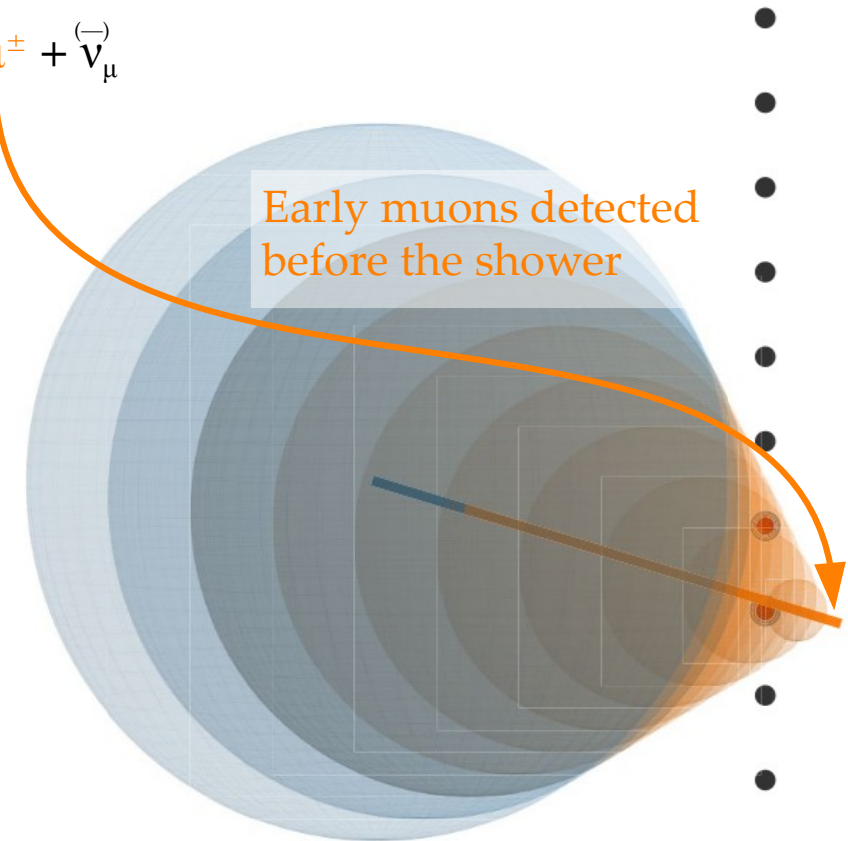


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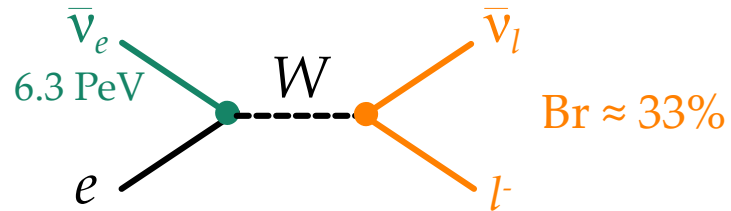
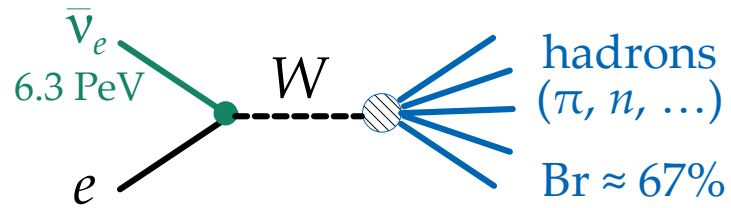


First reported by IceCube in 2021:

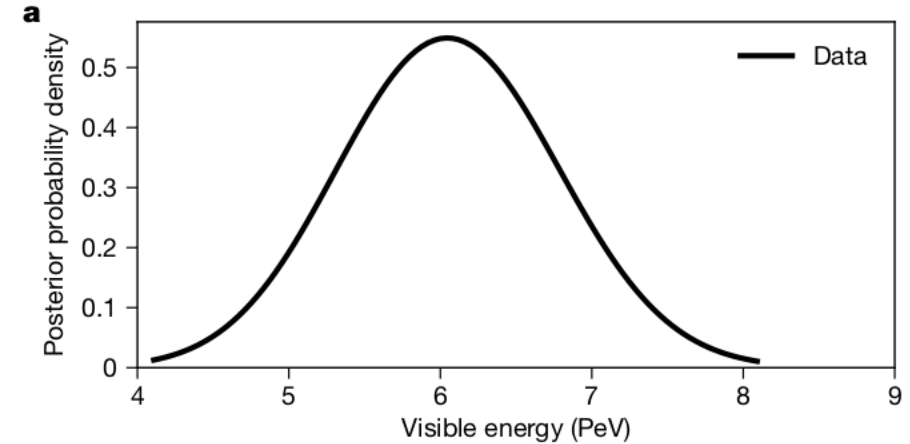


First observation of a Glashow resonance

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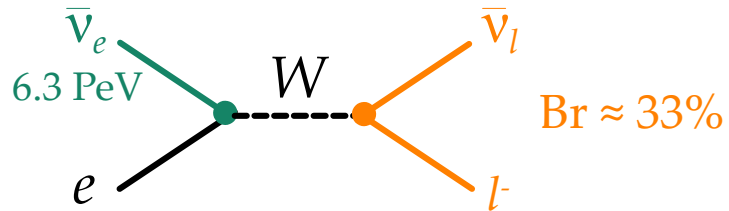
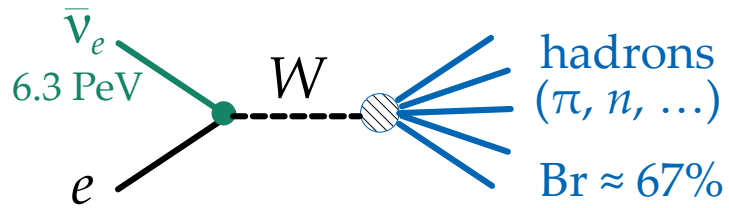


First reported by IceCube in 2021:

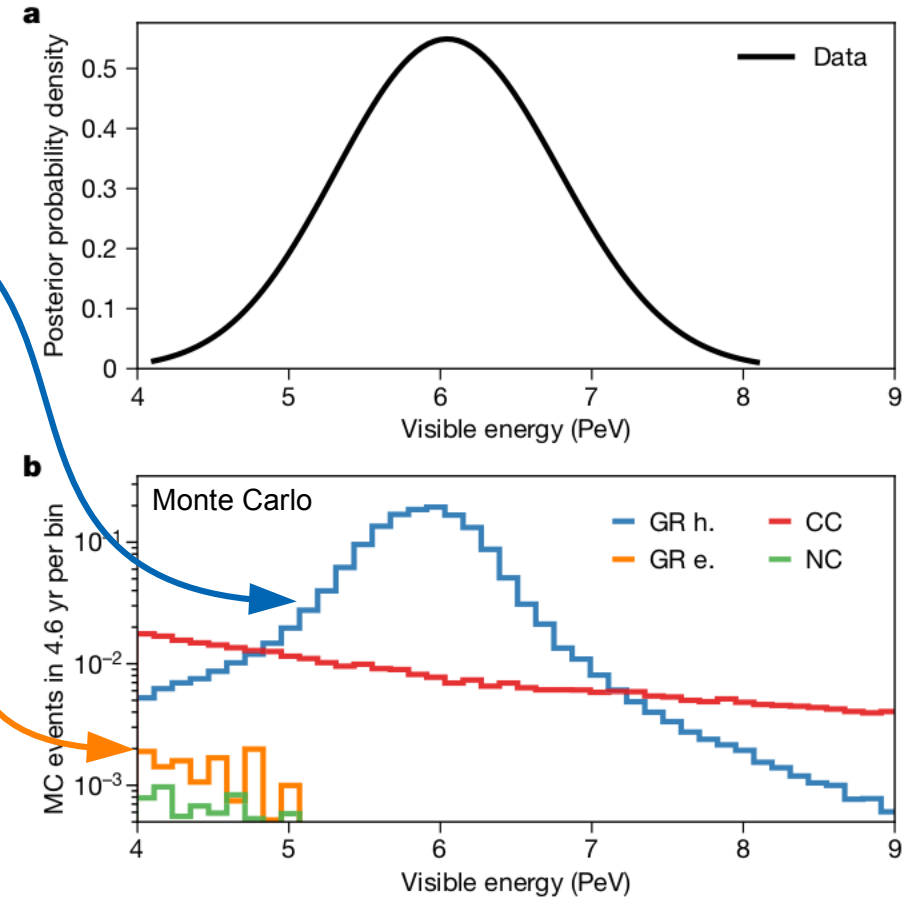


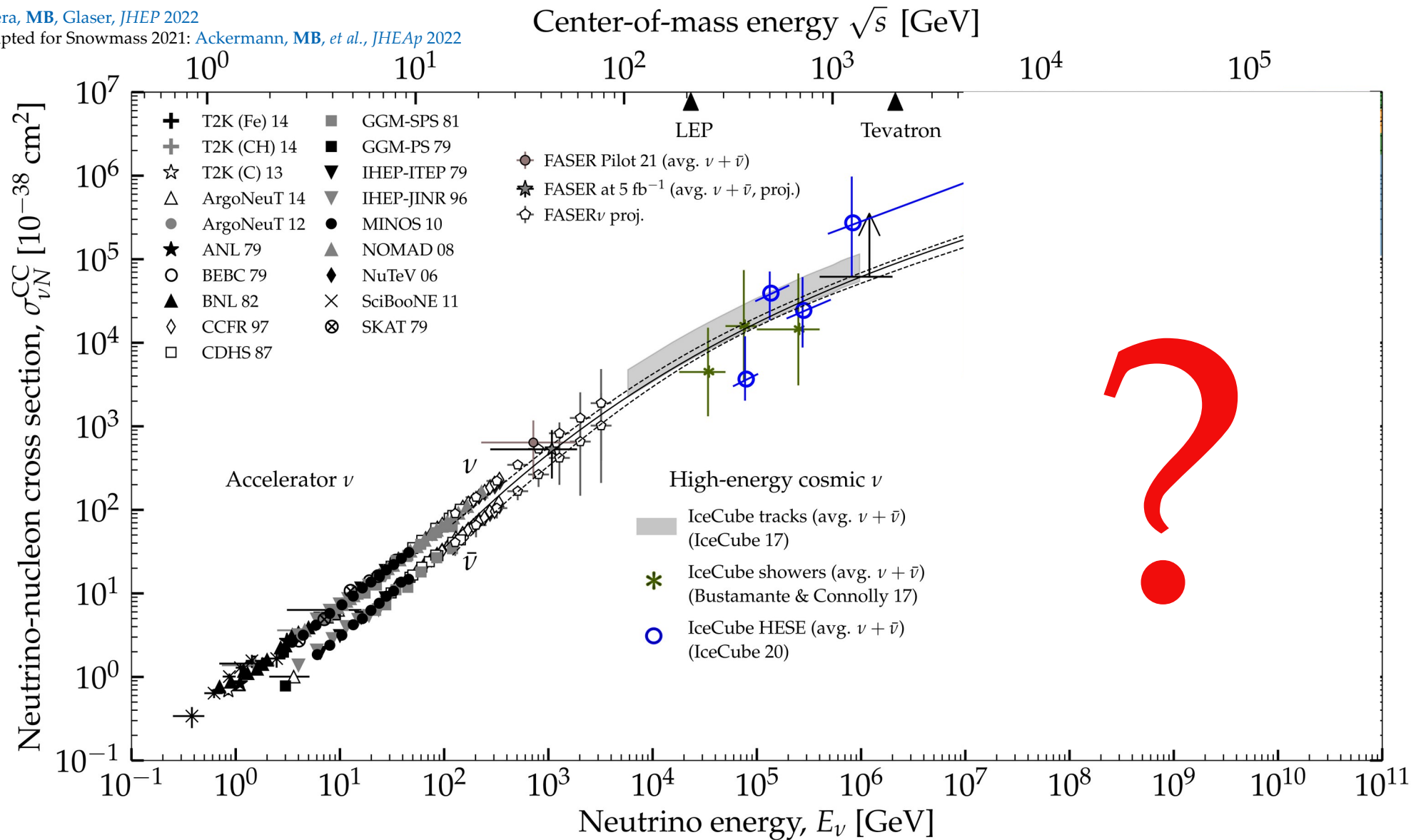
First observation of a Glashow resonance

Predicted in 1960:

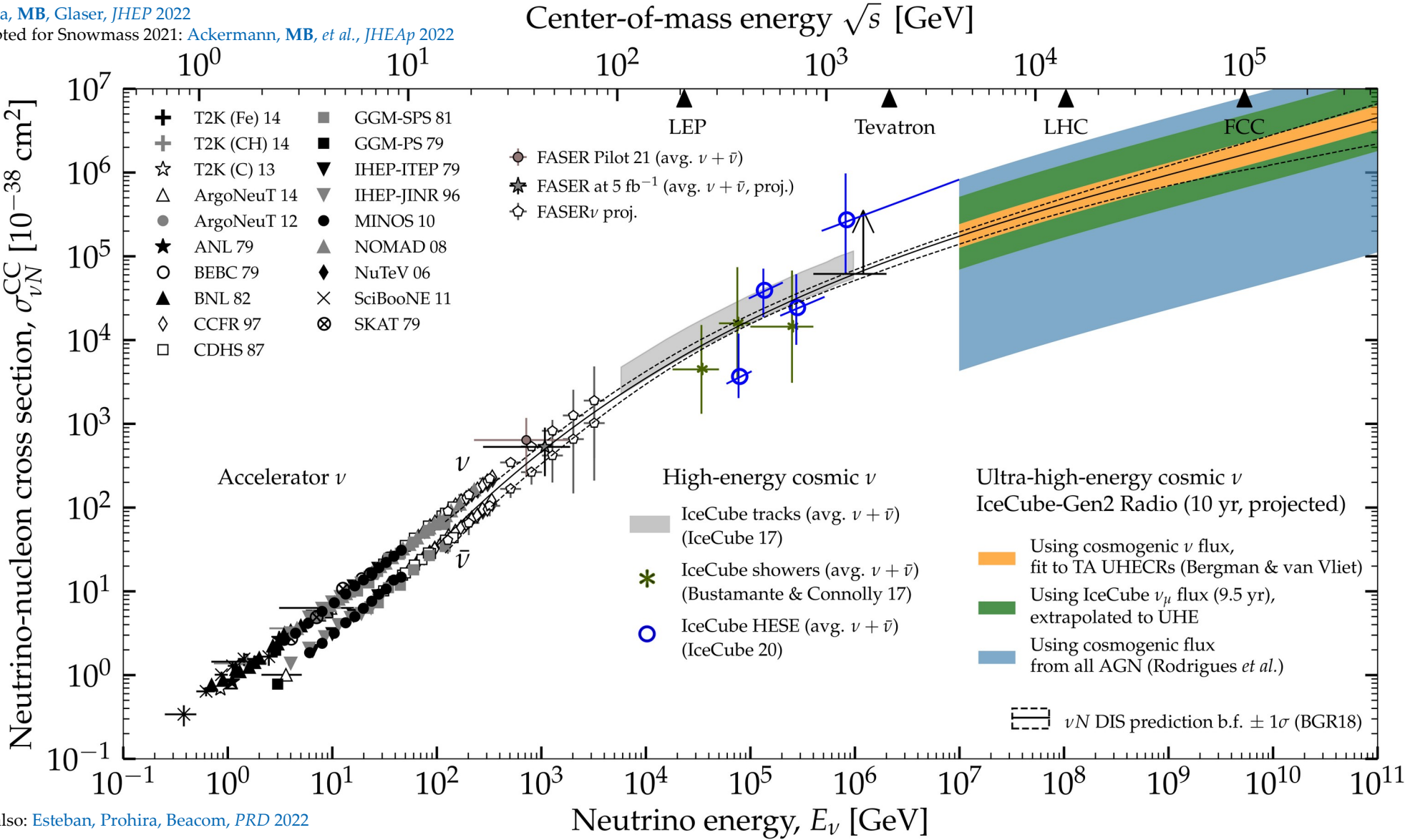


First reported by IceCube in 2021:

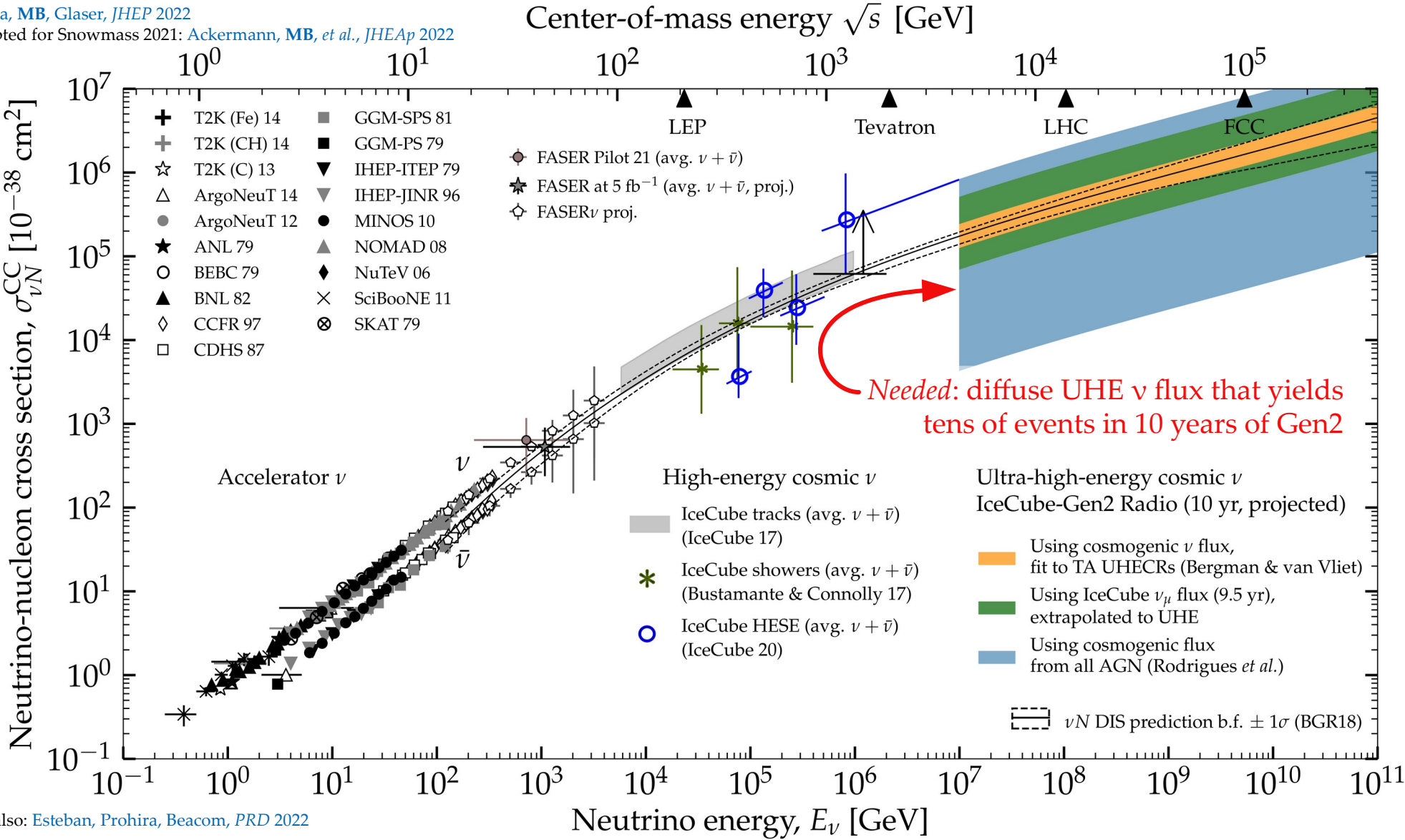




Center-of-mass energy $\sqrt{s}$ [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]



4. Dark matter:

Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$$\chi + \chi \rightarrow \nu + \bar{\nu}$$

$$\chi + \chi \rightarrow \dots \rightarrow \nu + \bar{\nu} + \dots$$

$$E_{\max} = m_{\chi}$$

Dark matter decay:

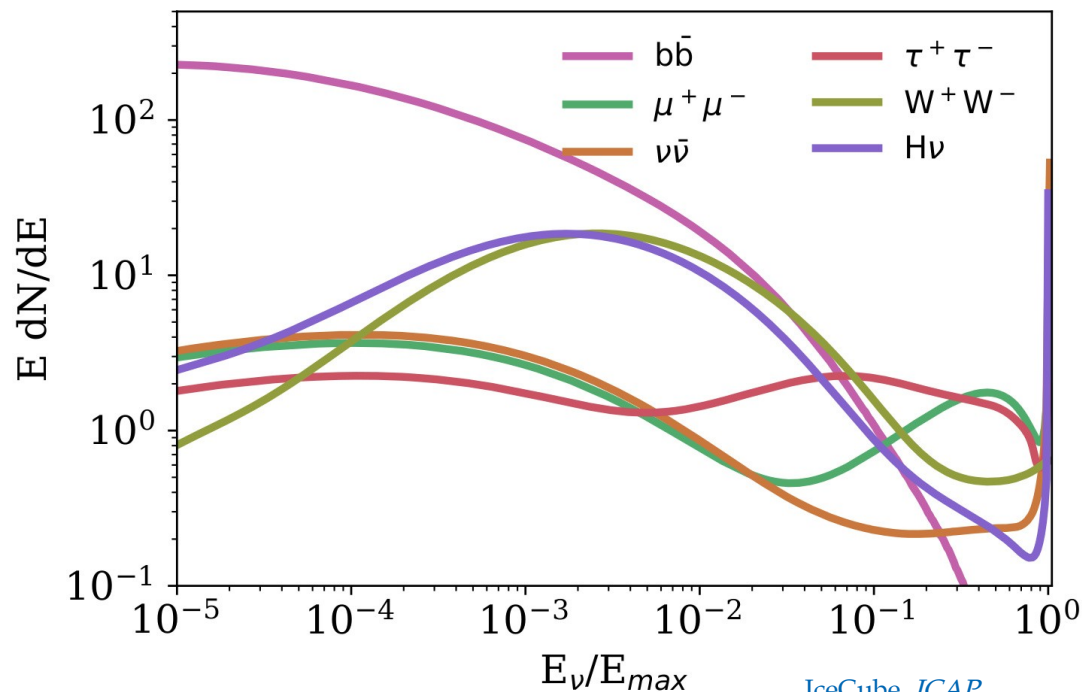
$$\chi \rightarrow \nu + \bar{\nu}$$

$$\chi \rightarrow \dots \rightarrow \nu + \bar{\nu} + \dots$$

$$E_{\max} = m_{\chi}/2$$

Electroweak corrections (off-shell W and Z emission) broaden the ν spectrum

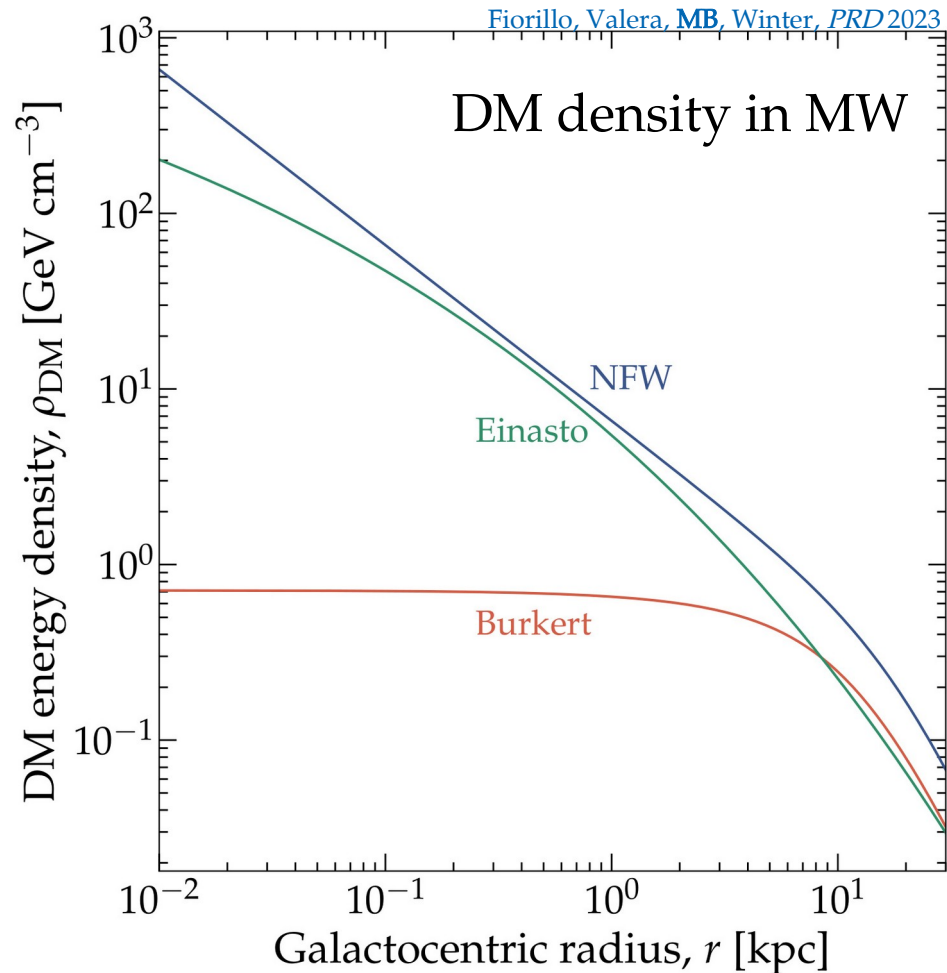
$\nu + \bar{\nu}$ yield from DM (at source)



IceCube, JCAP
2023

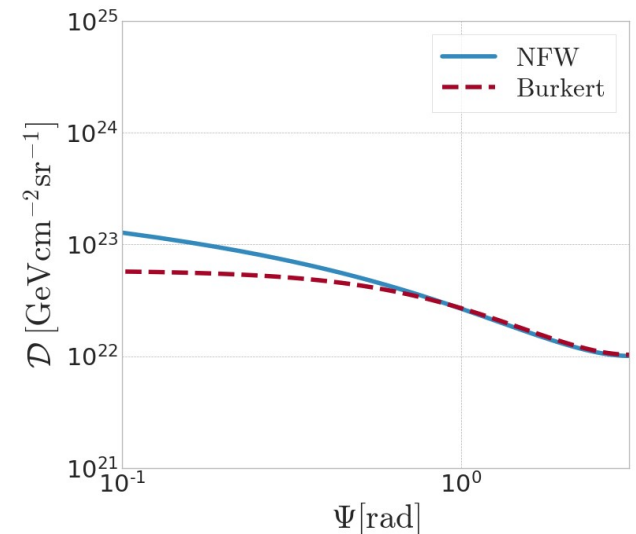
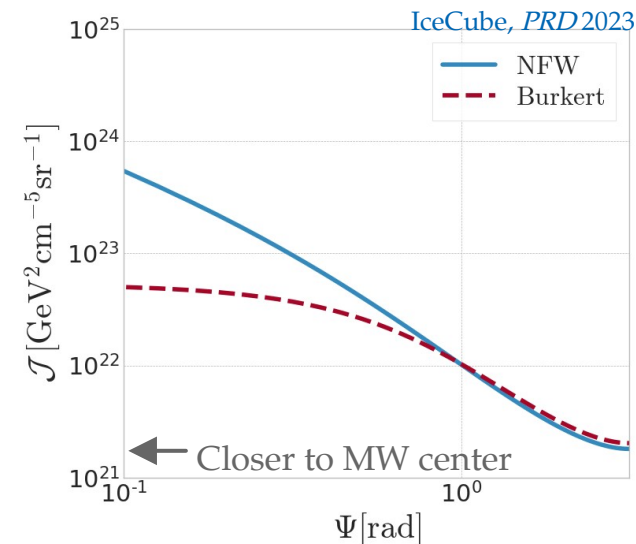
Approximate independence on m_{χ}
valid for $m_{\chi} \approx 100 \text{ TeV} - 10 \text{ PeV}$

Dark matter in the Milky Way



DM annihilation
 $\Phi_\nu \propto \mathcal{I} \propto \rho_{\text{DM}}^2$

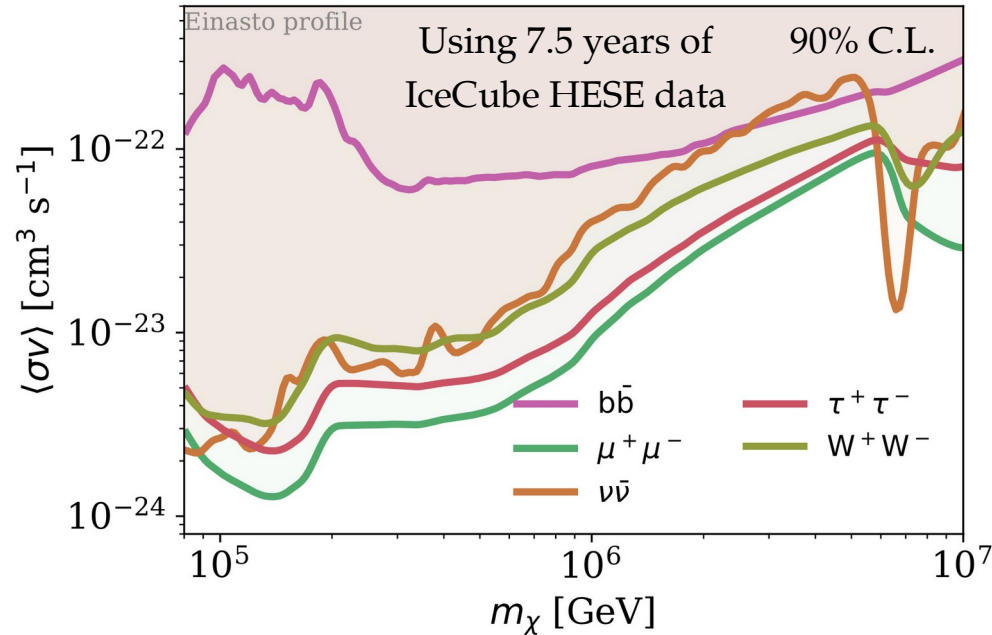
DM decay
 $\Phi_\nu \propto \mathcal{D} \propto \rho_{\text{DM}}$



Limits on dark matter annihilation

Per annihilation channel

(assuming 100% branching ratio)



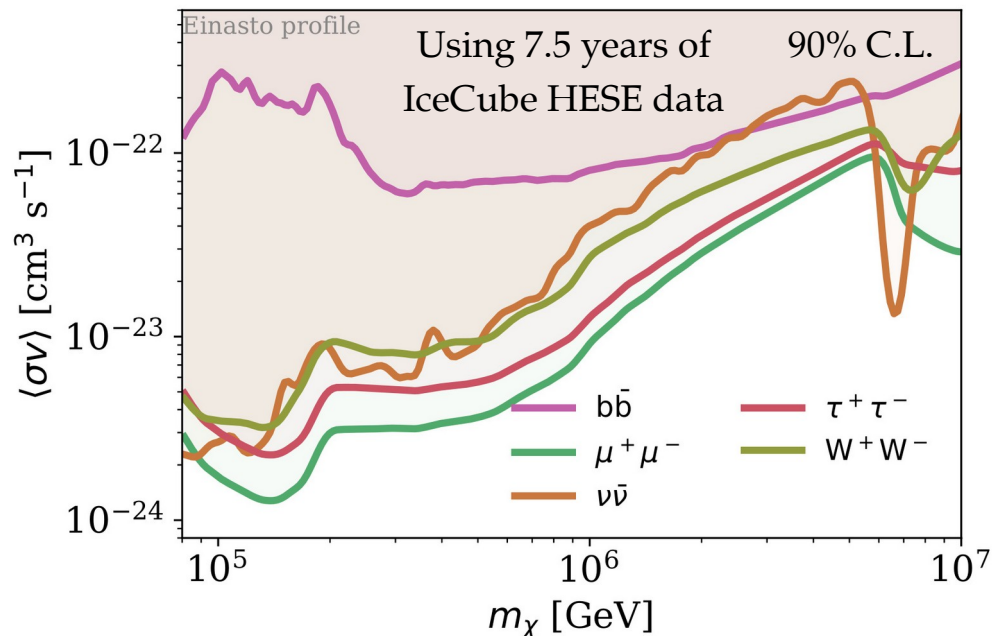
Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

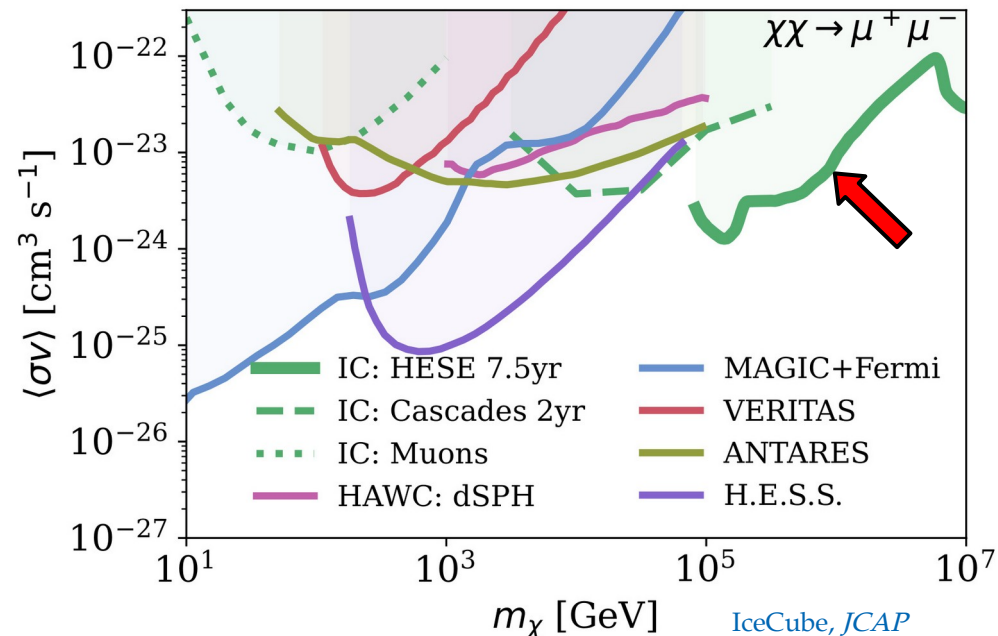
Per annihilation channel

(assuming 100% branching ratio)



Compared to other limits

(assuming annihilation to muons)



IceCube, JCAP
2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

5. New neutrino interactions:
Are there secret $\nu\nu$ interactions?

Astrophysical neutrino sources

Earth

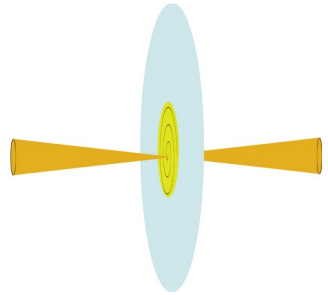


Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

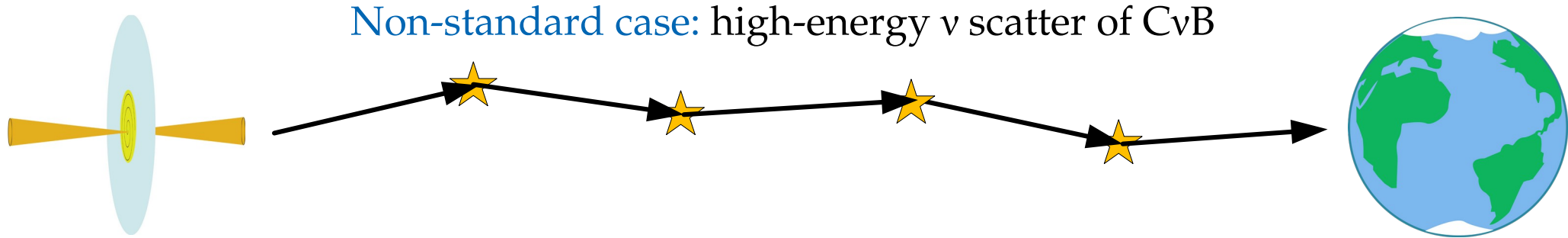
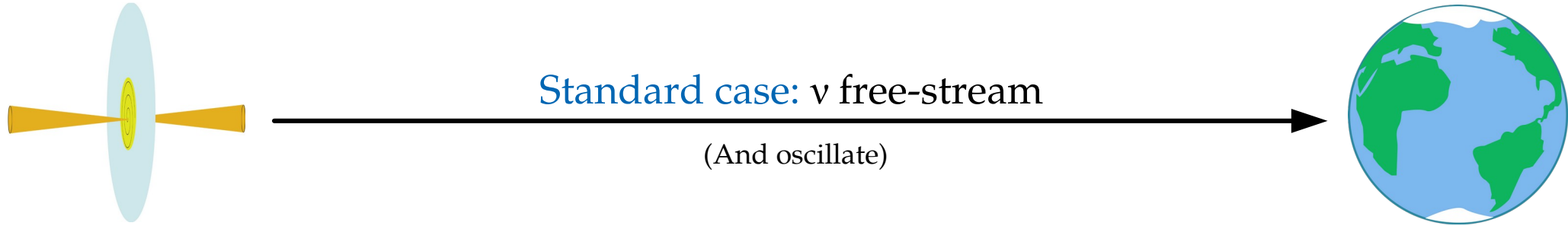
(And oscillate)



Astrophysical neutrino sources

Earth

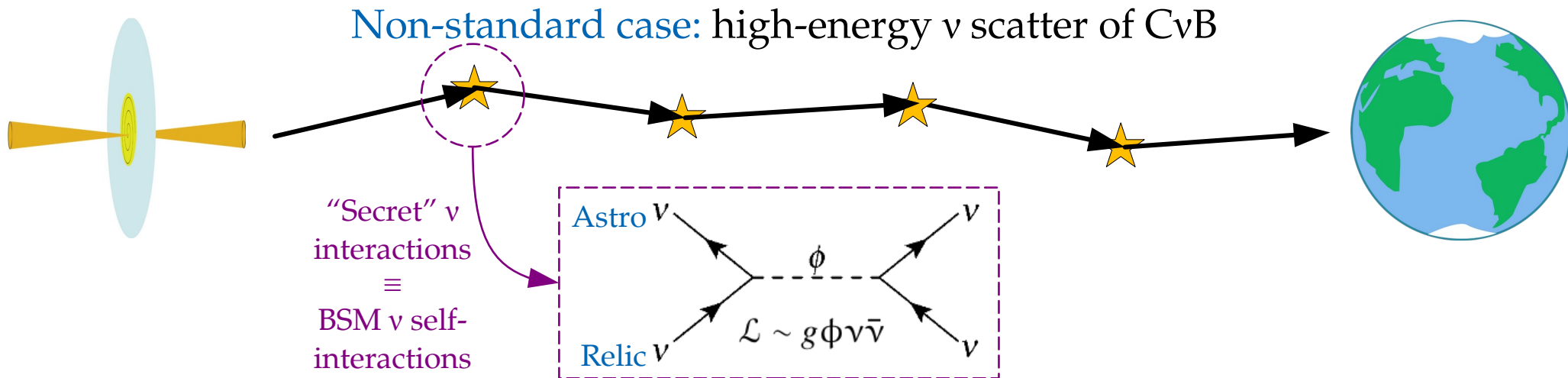
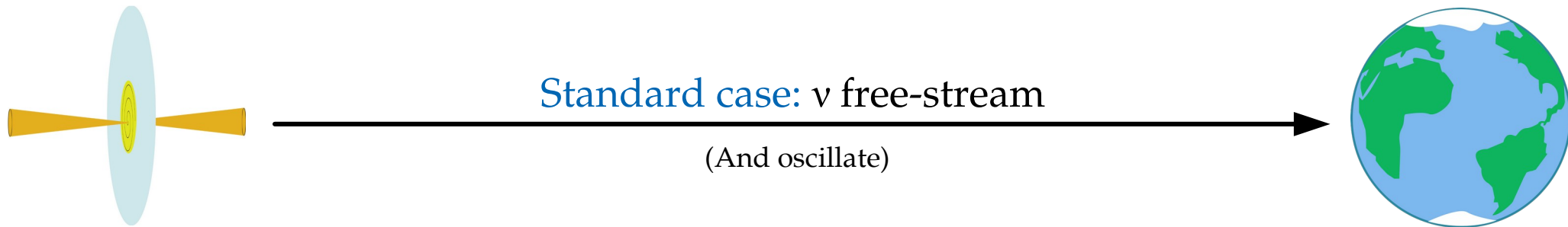
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Astrophysical neutrino sources

Earth

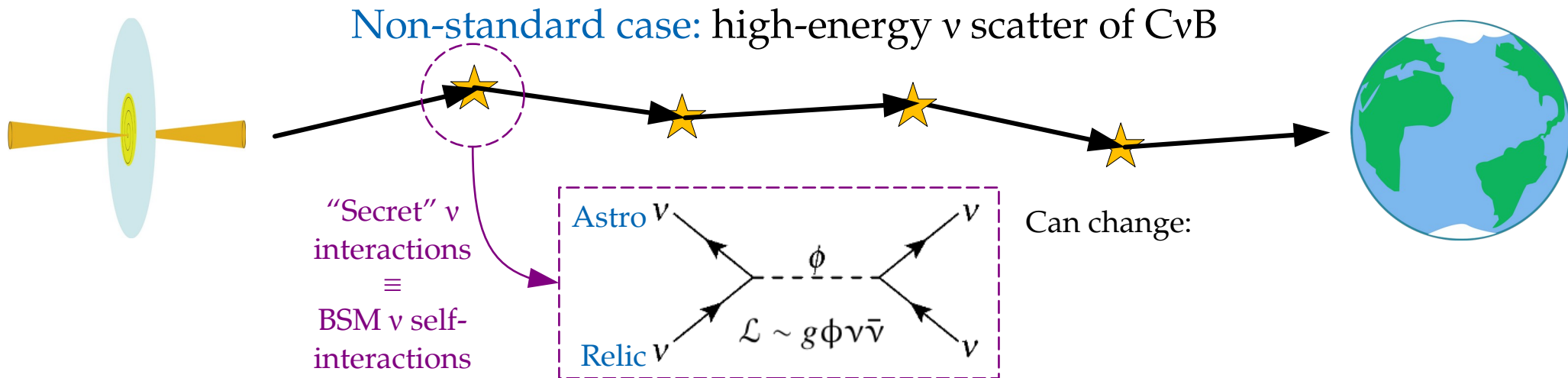
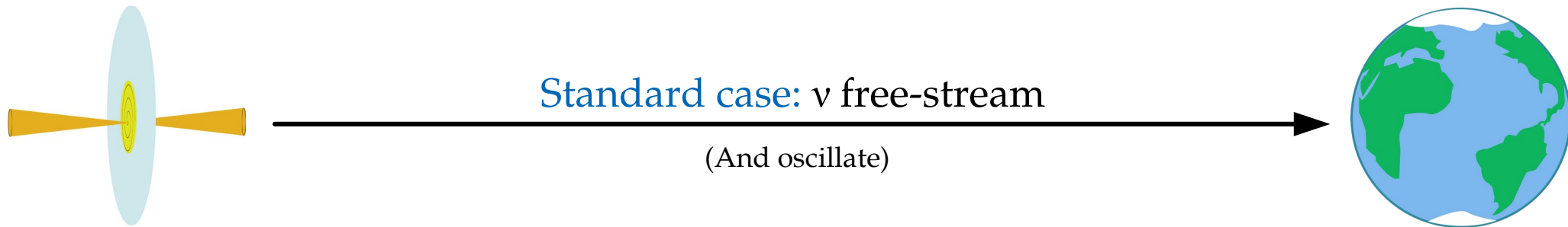
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Astrophysical neutrino sources

Earth

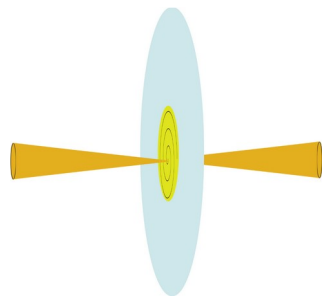
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Astrophysical neutrino sources

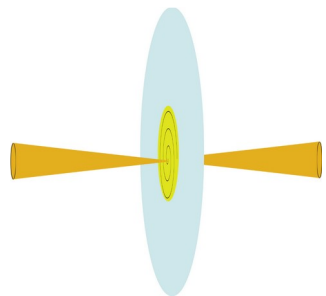
Earth

Galactic (kpc) or extragalactic (Mpc – Gpc) distance

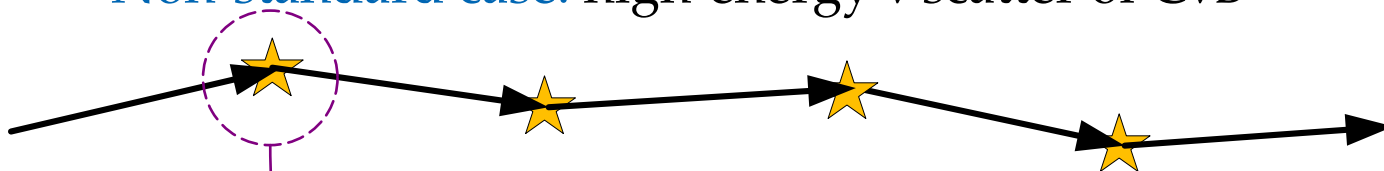


Standard case: ν free-stream

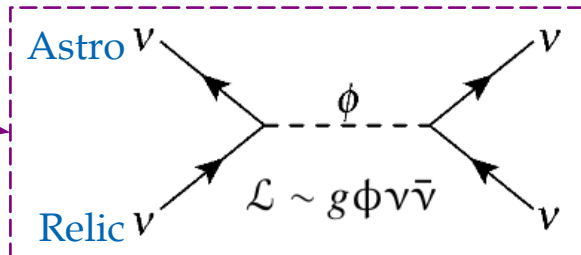
(And oscillate)



Non-standard case: high-energy ν scatter of CvB



“Secret” ν
interactions
 $\equiv$
BSM ν self-
interactions



Can change:

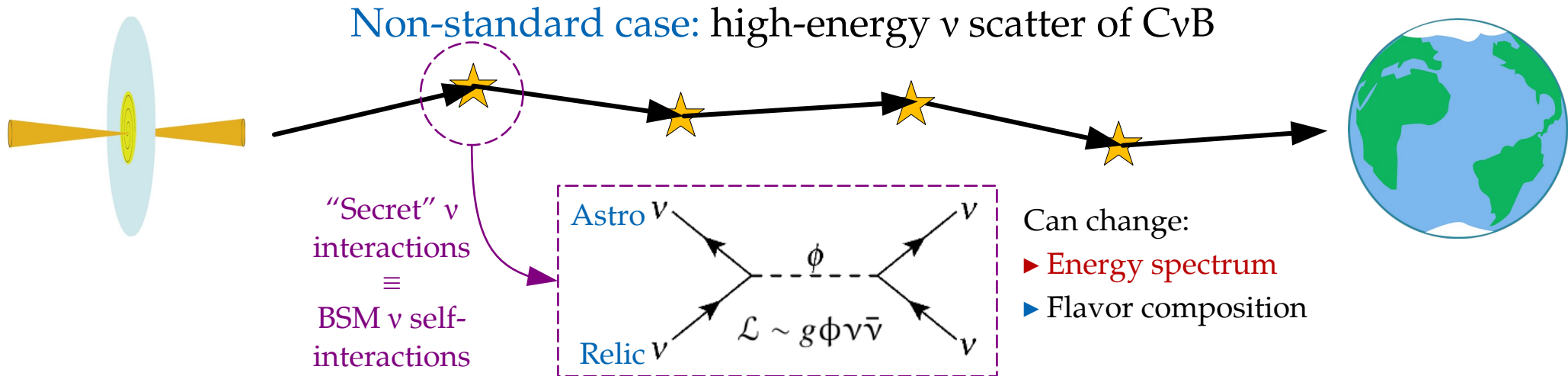
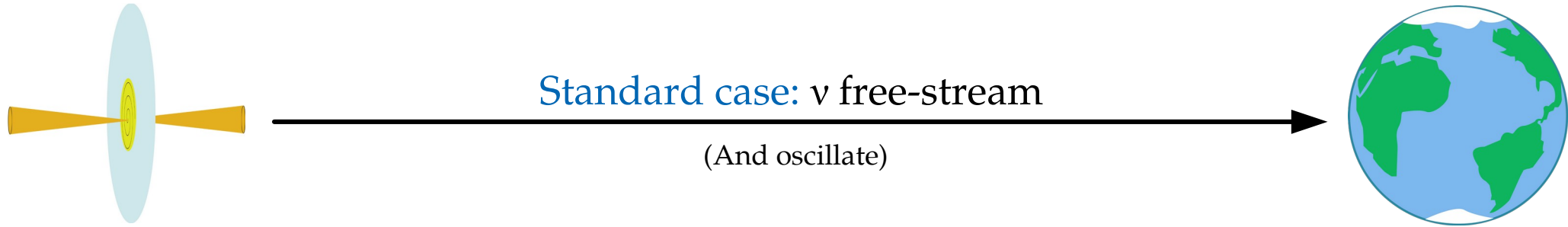
► Energy spectrum



Astrophysical neutrino sources

Earth

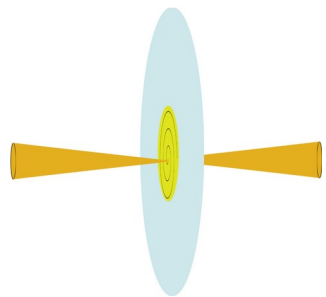
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Astrophysical neutrino sources

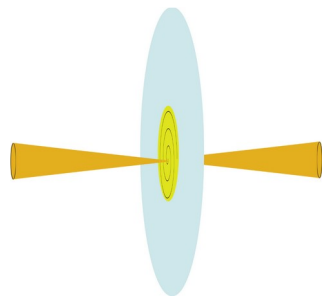
Earth

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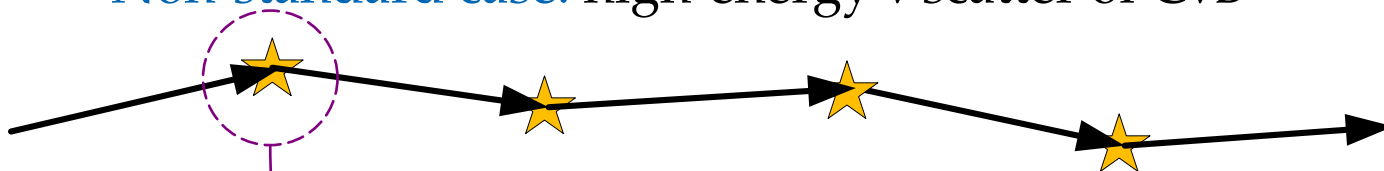


Standard case: ν free-stream

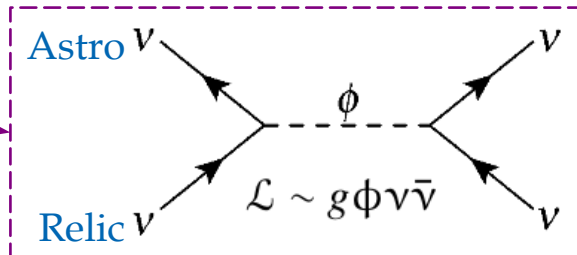
(And oscillate)



Non-standard case: high-energy ν scatter of CvB



“Secret” ν
interactions
 $\equiv$
BSM ν self-
interactions



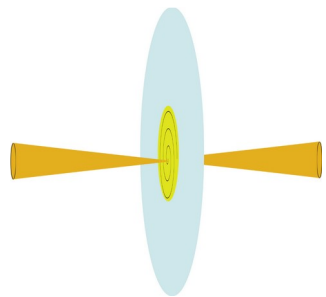
Can change:

- Energy spectrum
- Flavor composition
- Direction

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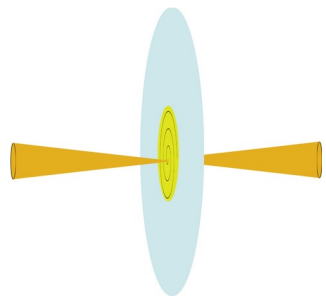
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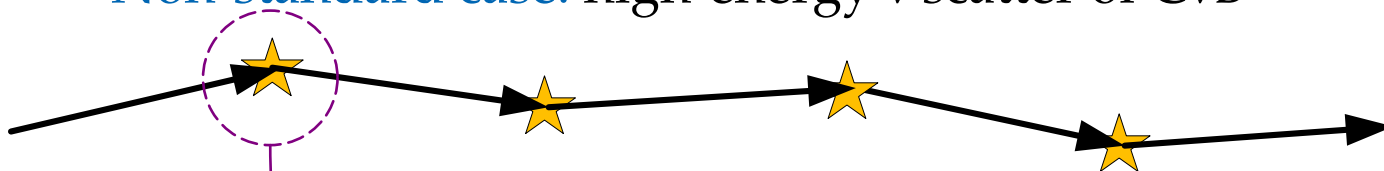


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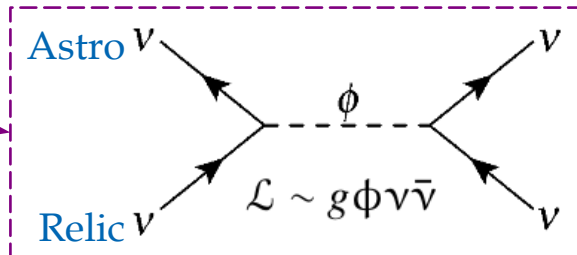
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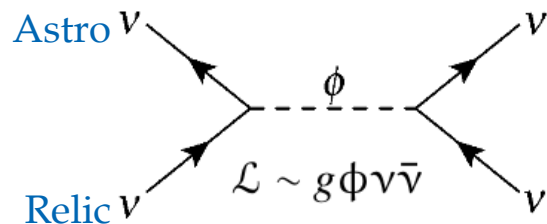


Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

Secret interactions of high-energy astrophysical neutrinos

“Secret” neutrino interactions between
astrophysical ν (PeV) and relic ν (0.1 meV):



Cross section:
$$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

[MB, Rosenstroem, Shalgar, Tamborra, PRD 2020](#)

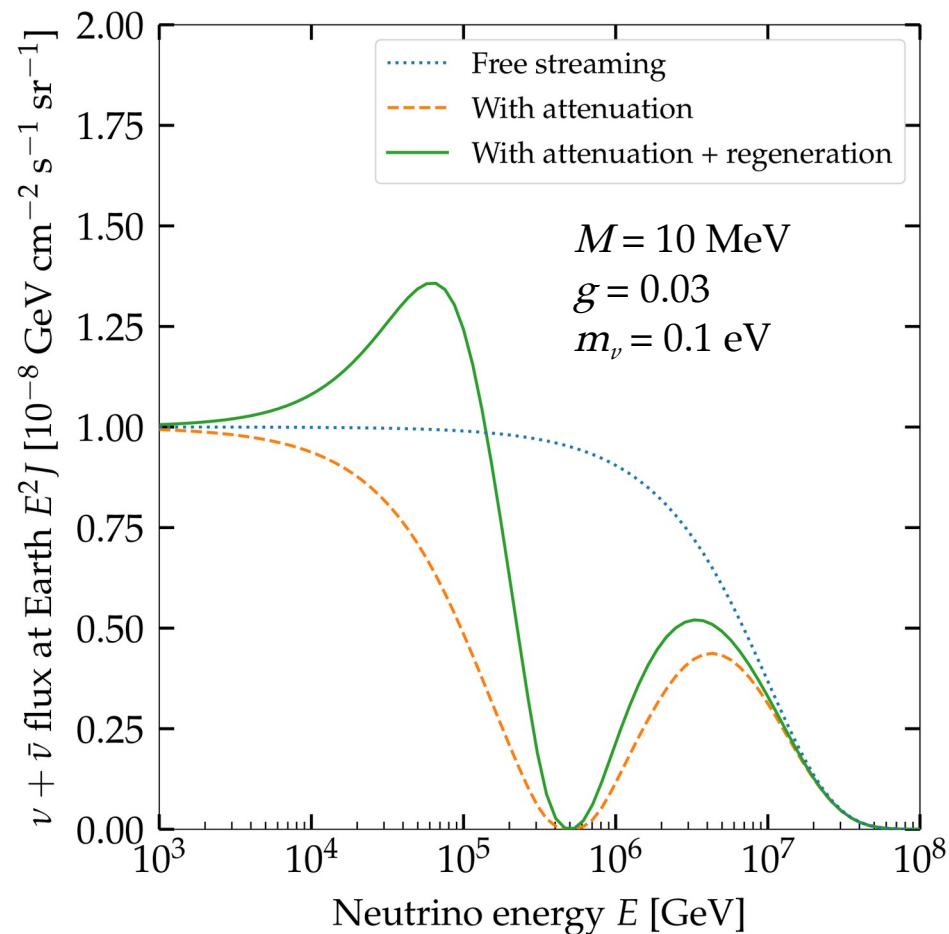
See also: [Esteban, Pandey, Brdar, Beacom, PRD 2021](#)

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[Ng & Beacom, PRD 2014](#)

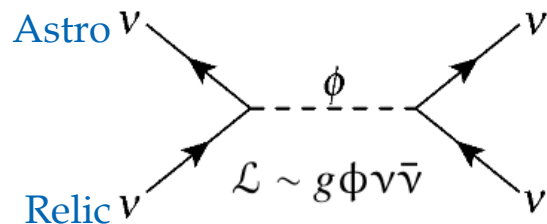
[Cherry, Friedland, Shoemaker, 1411.1071](#)

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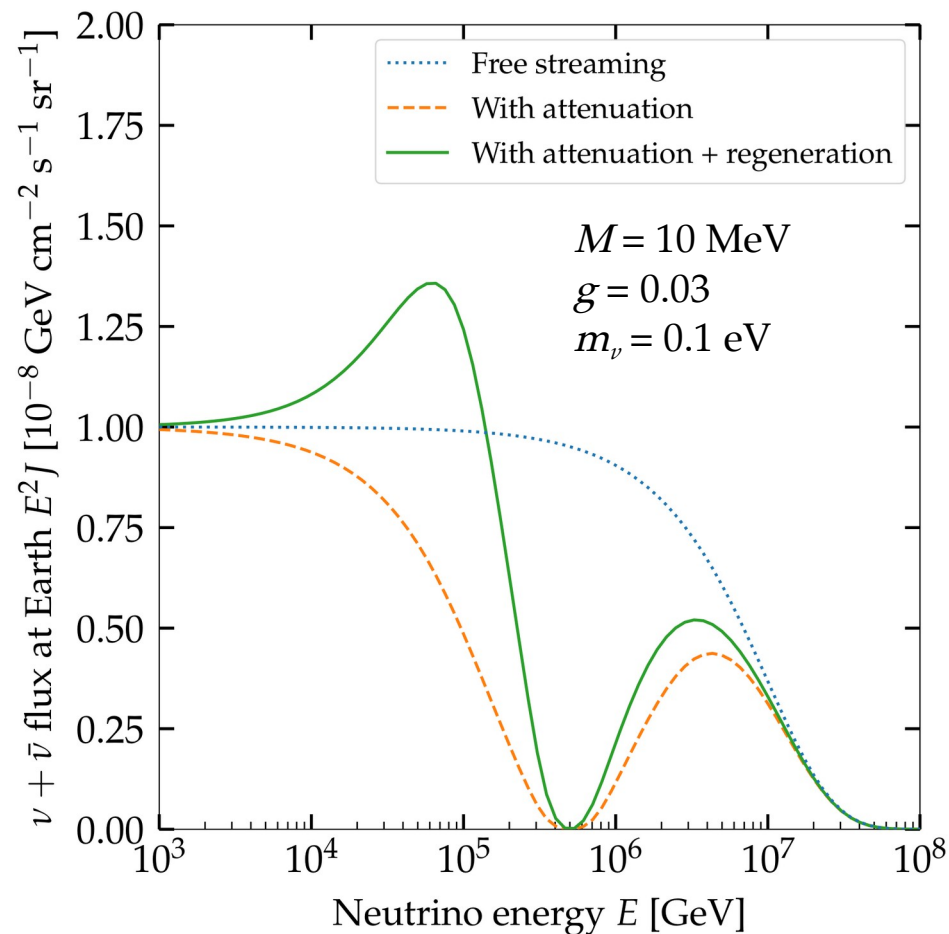
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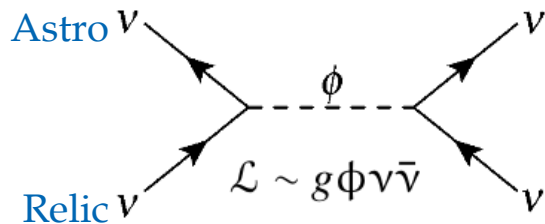
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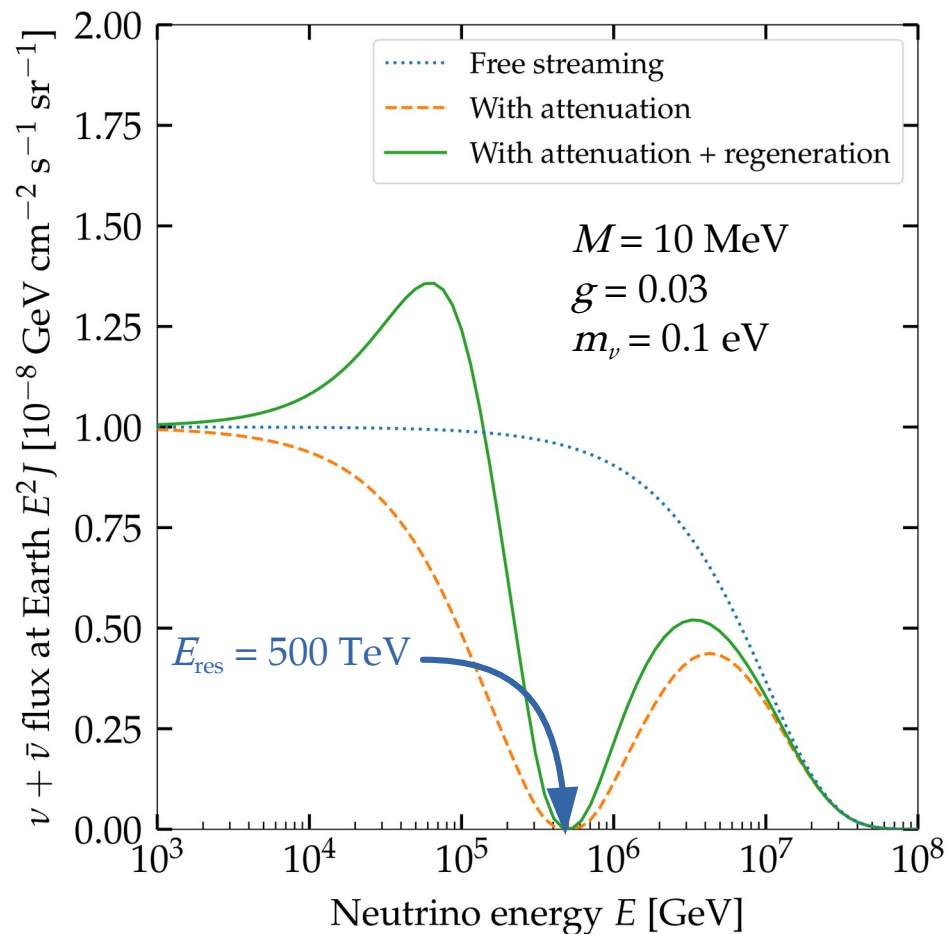
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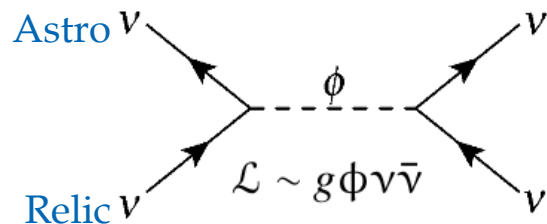
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New coupling g^4 Mediator mass M^2

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MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

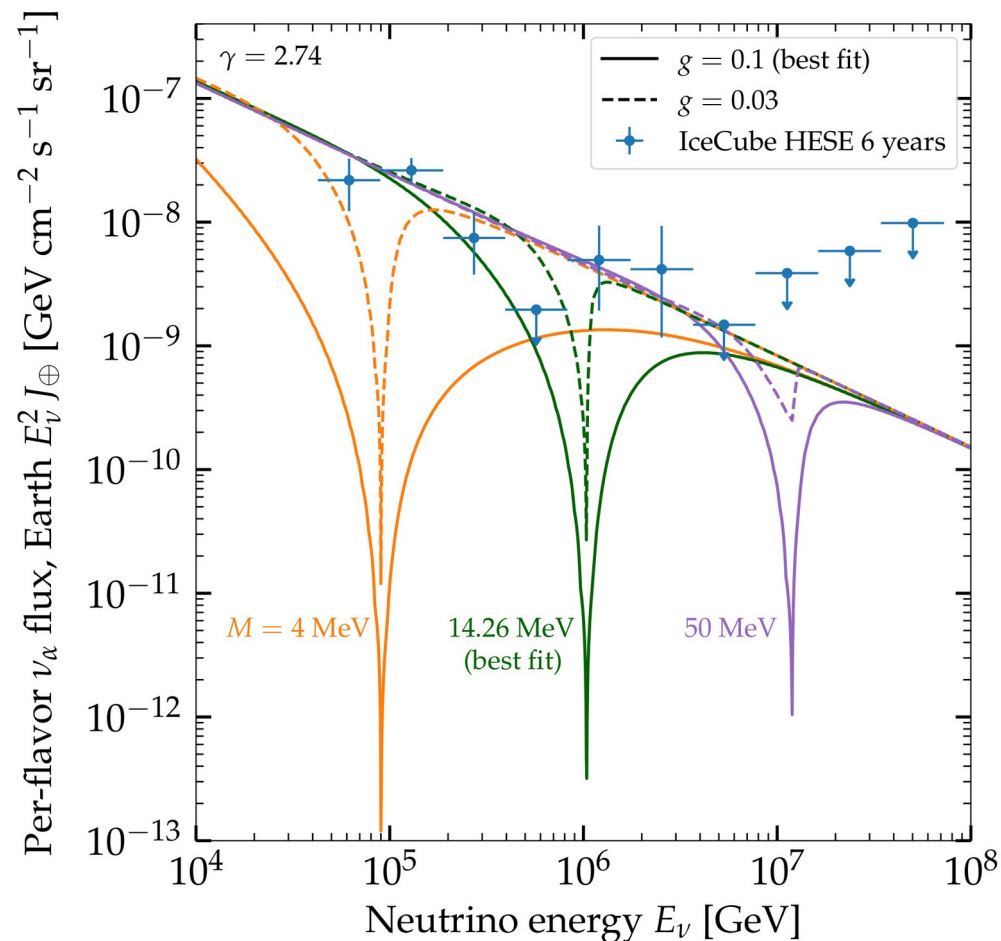
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021

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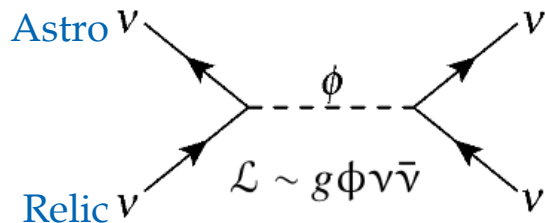
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The term g^4 is circled in red and labeled "New coupling". The term M^2 is circled in green and labeled "Mediator mass".

Resonance energy:
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MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

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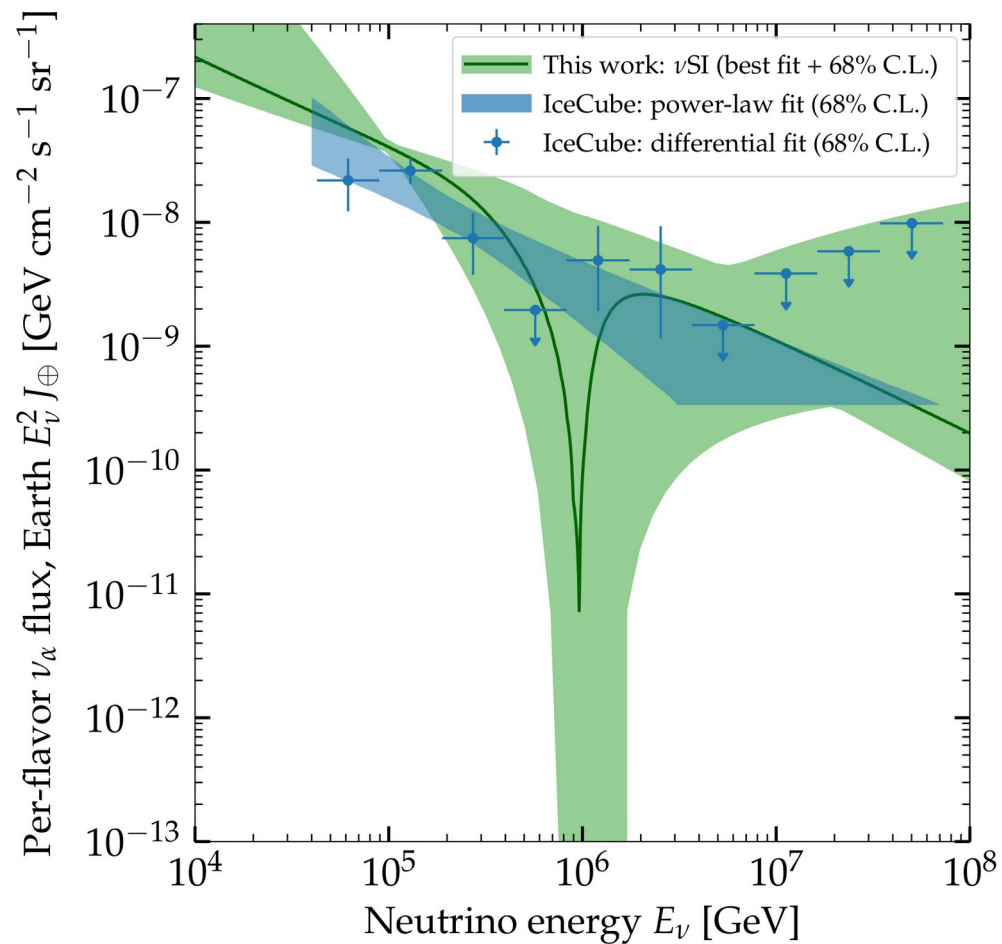
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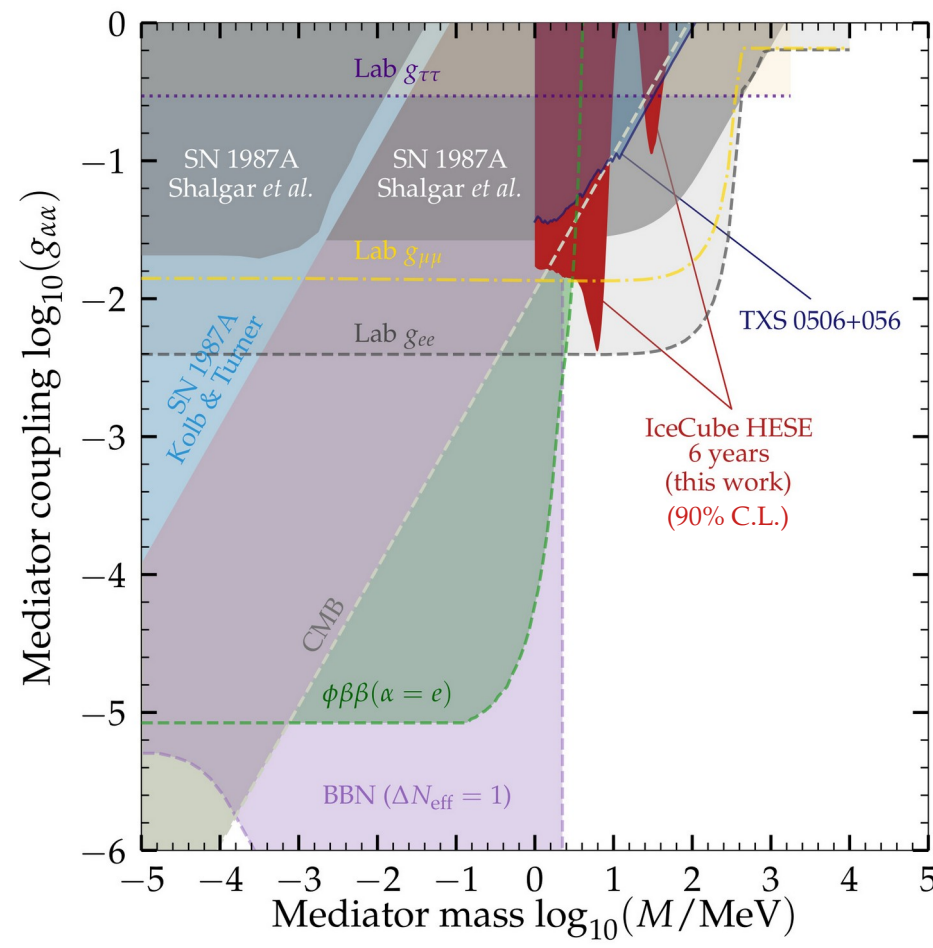
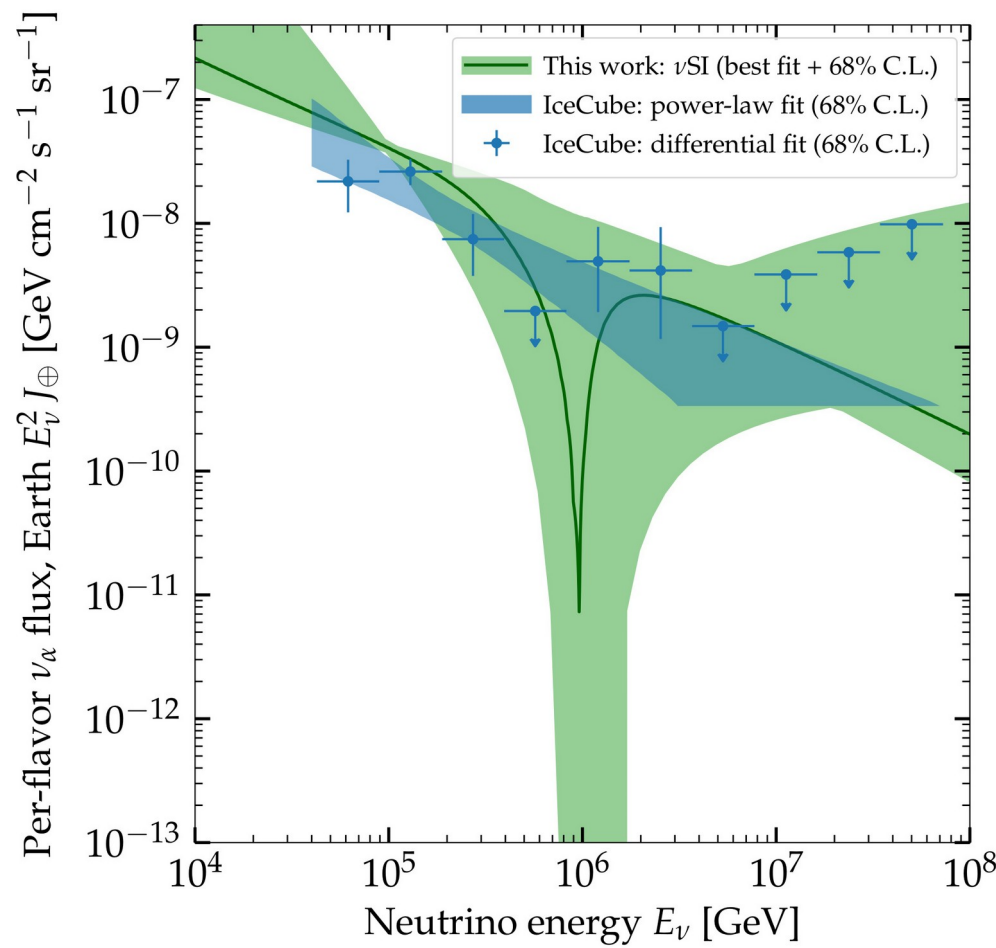
Looking for evidence of ν SI

- ▶ Look for dips in 6 years of public IceCube data (HESE)
- ▶ 80 events, 18 TeV–2 PeV
- ▶ Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g \delta_{\alpha\alpha}$
- ▶ Bayesian analysis varying M , g , shape of emitted flux (γ)
- ▶ Account for atmospheric ν , in-Earth propagation, detector uncertainties

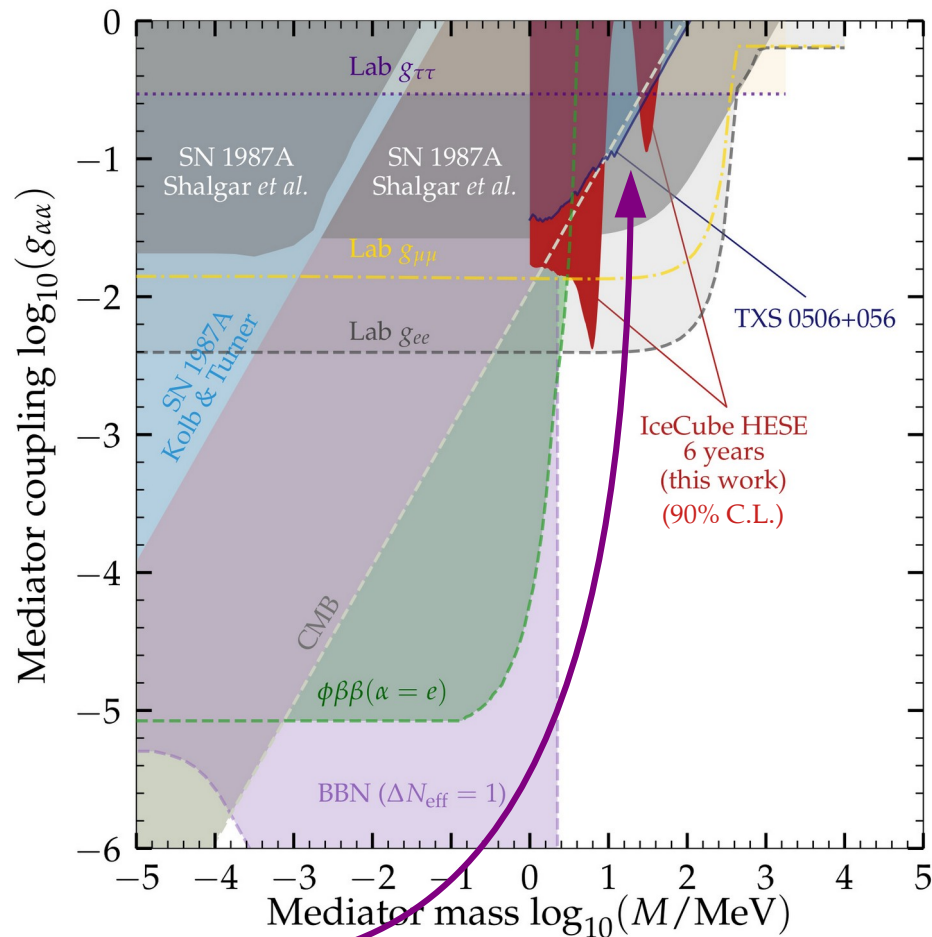
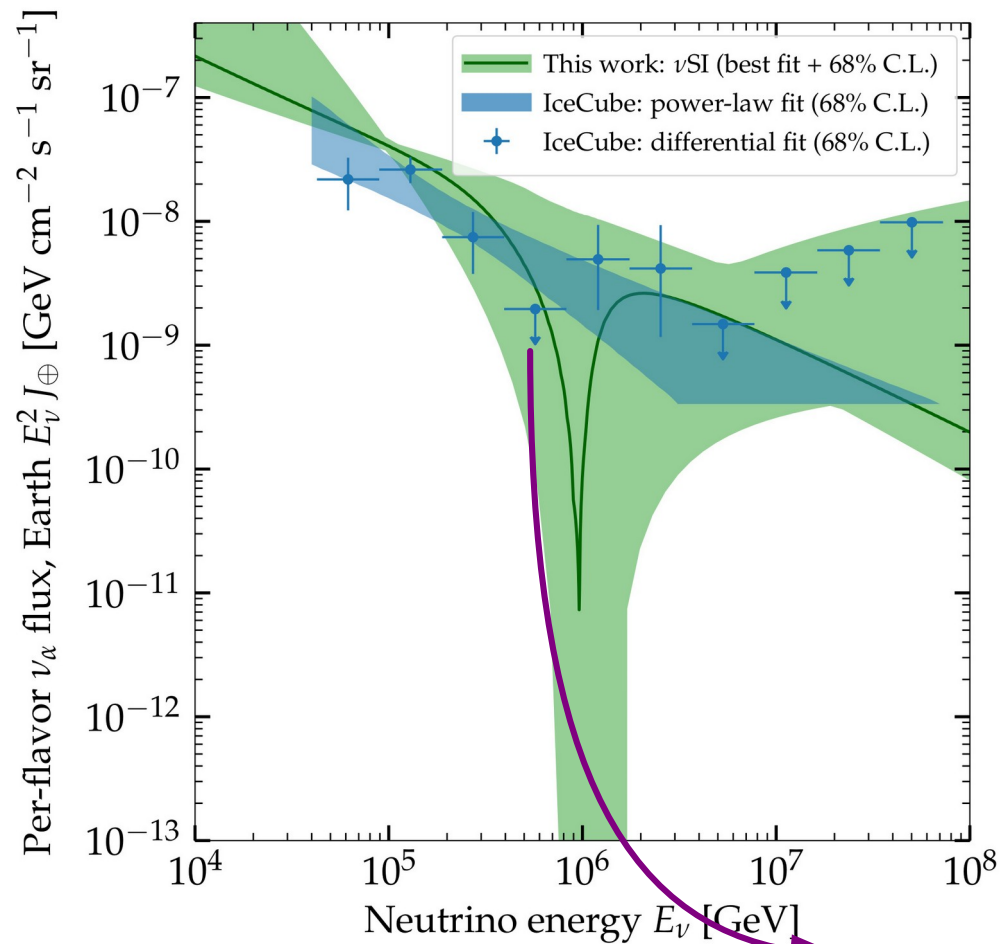
No significant ($> 3\sigma$) evidence for a spectral dip ...



No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



The 300 TeV–1 PeV “gap”
degrades the limit at ~ 10 MeV

6. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

- ▶ In the Standard Model (vSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
 - ▶ One-photon decay ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36} (m_i/\text{eV})^{-5}$ yr
 - ▶ Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57} (m_i/\text{eV})^{-9}$ yr
 - ▶ Three-neutrino decay ($\nu_i \rightarrow \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55} (m_i/\text{eV})^{-5}$ yr

» Age of Universe (~ 14.5 Gyr)
- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j + \varphi$
- ▶ We work in a model-independent way:
the nature of φ is unimportant if it is invisible to neutrino detectors

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Nambu-Goldstone
boson of a broken
symmetry

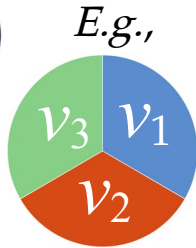
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Astrophysical sources

Earth

$L \sim$ up to a few Gpc



Decay changes the number
of each ν mass eigenstate, N_1, N_2, N_3

?



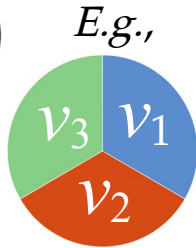
The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (m_i/\tau_i)]$

$\underbrace{m_i}_{\text{Mass of } \nu_i} \underbrace{\tau_i}_{\text{Lifetime of } \nu_i}$

Astrophysical sources

Earth

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Decay changes the number
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Only sensitive to their ratio

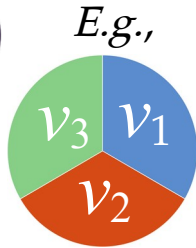
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Mass of ν_i Lifetime of ν_i

Astrophysical sources

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Decay changes the number
of each ν mass eigenstate, N_1, N_2, N_3

?



Lower- E ν are longer-lived...

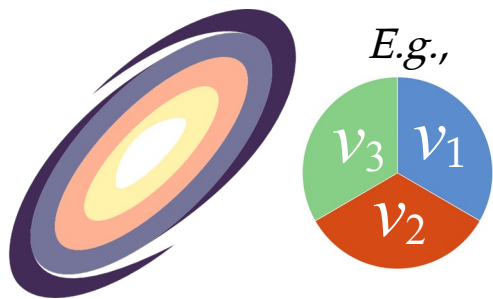
The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (m_i/\tau_i)]$

... but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



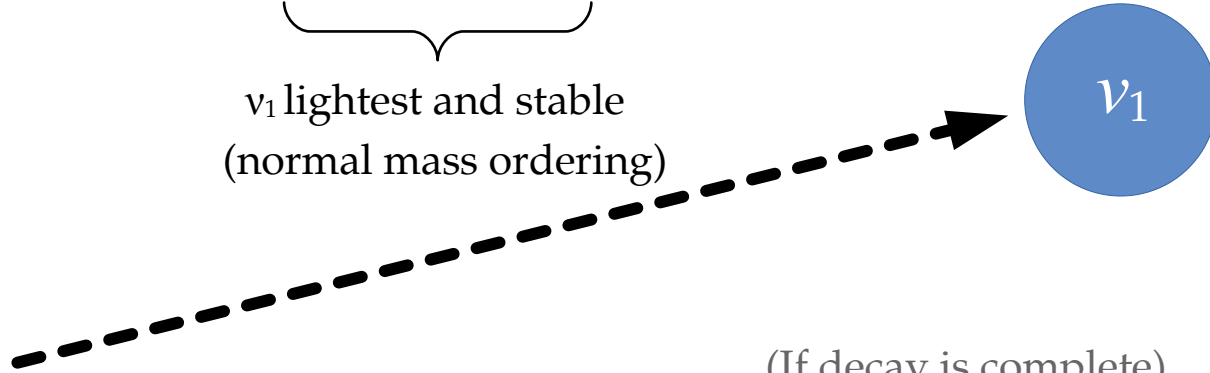
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

$$\nu_2, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)



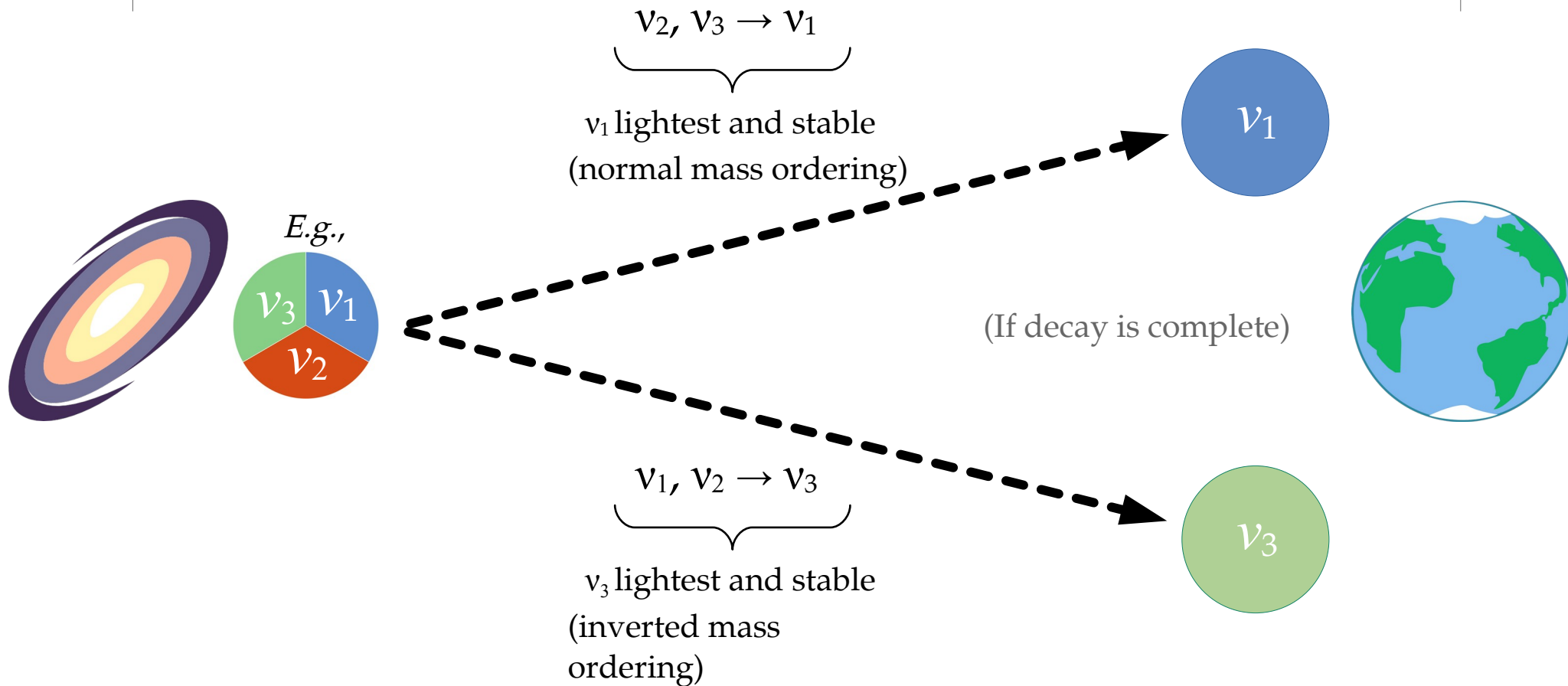
(If decay is complete)



Astrophysical sources

Earth

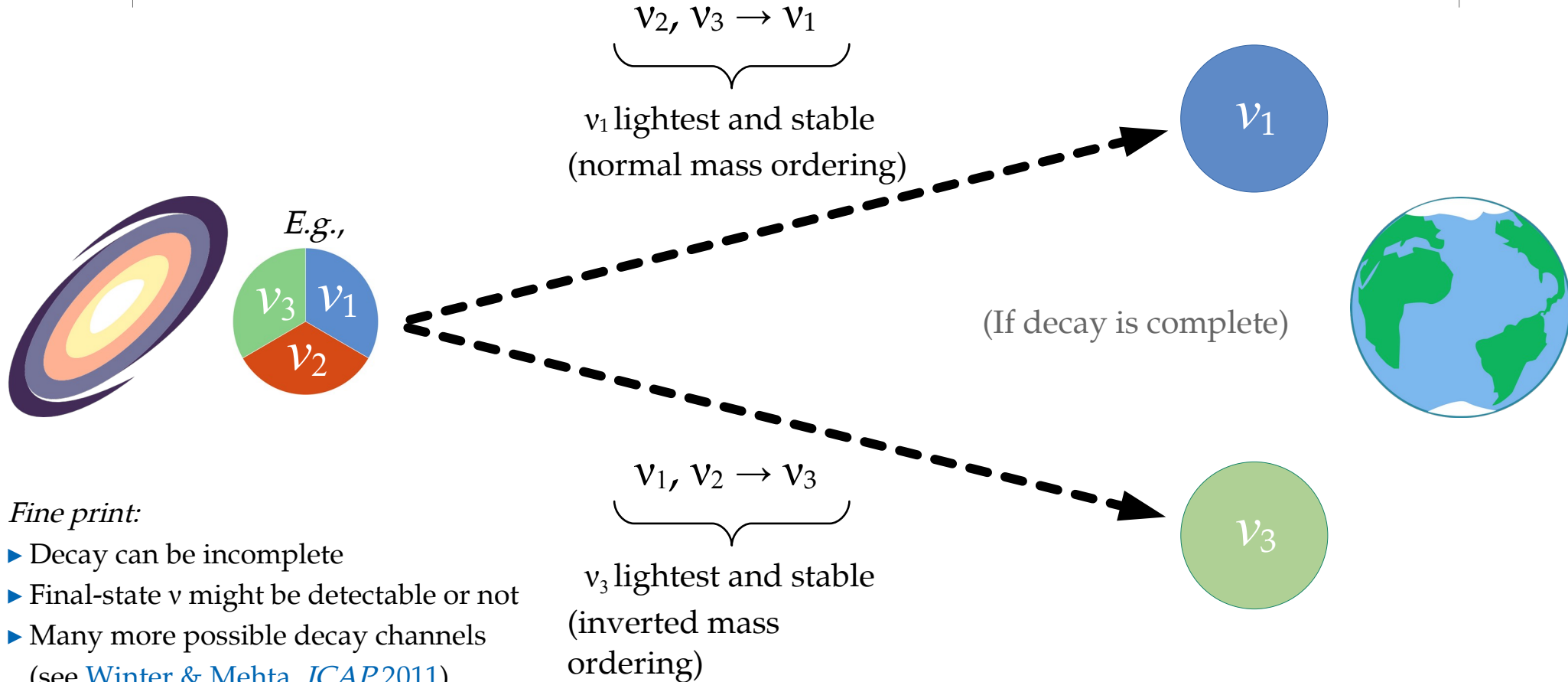
$L \sim$ up to a few Gpc



Astrophysical sources

Earth

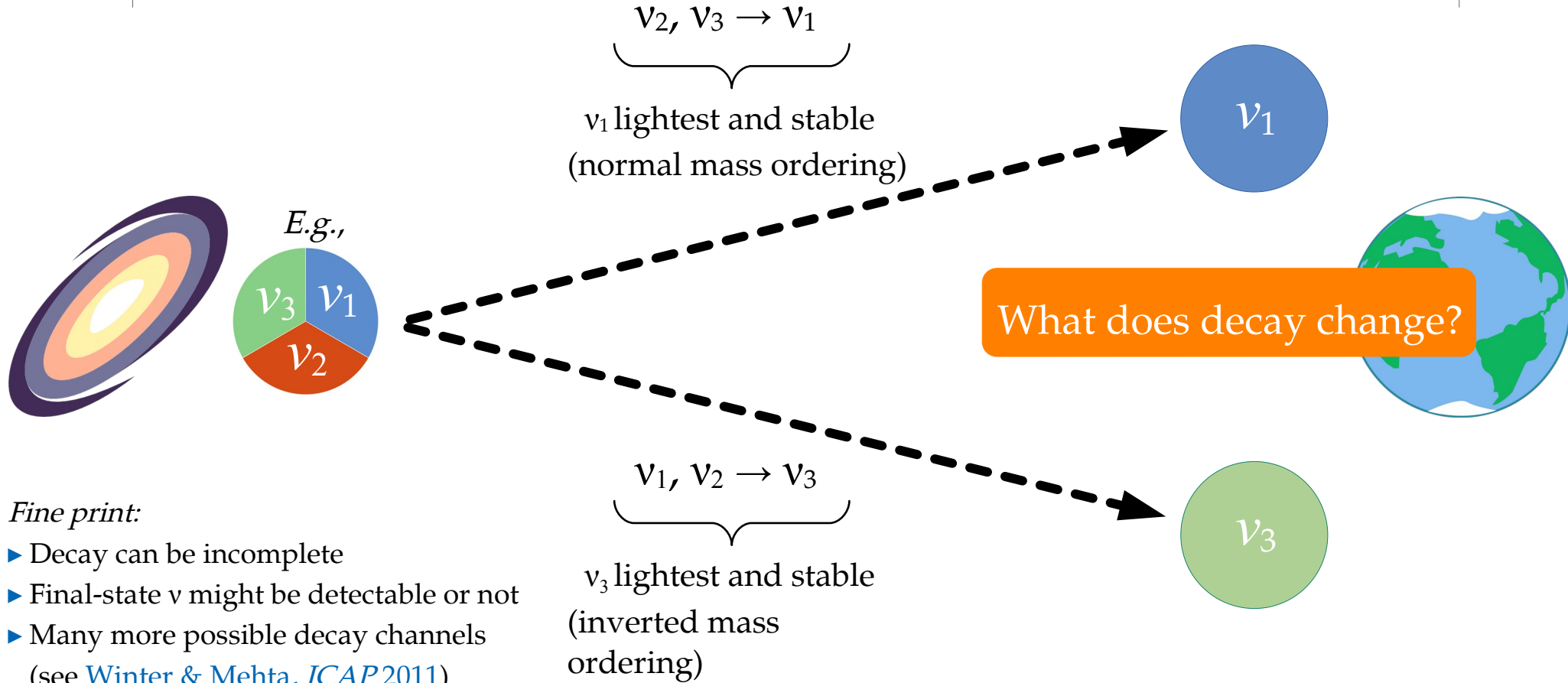
$L \sim$ up to a few Gpc



Astrophysical sources

Earth

$L \sim$ up to a few Gpc



What does neutrino decay change?

Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate

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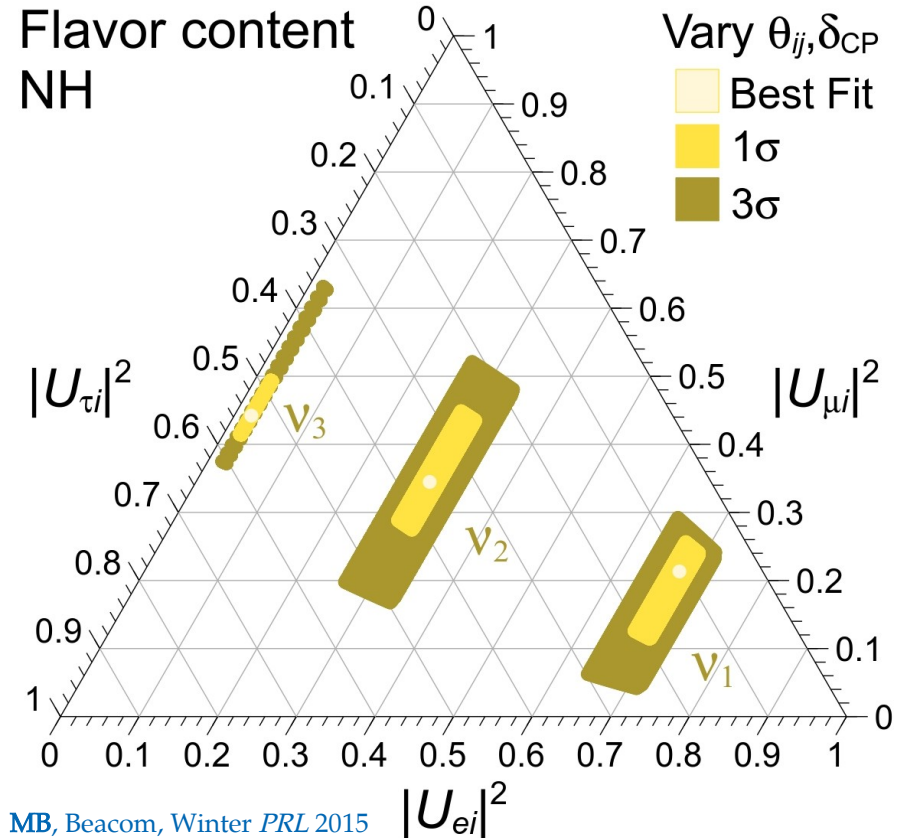
Flavor content of mass eigenstates:

Known to within 2%

$$|U_{ai}|^2 = |U_{ai}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

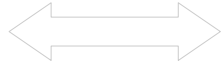
Known to within 8%

Known to within 20% (or worse)

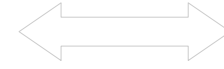


What does neutrino decay change?

Flavor composition



Spectrum shape

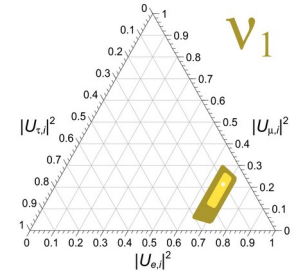


Event rate



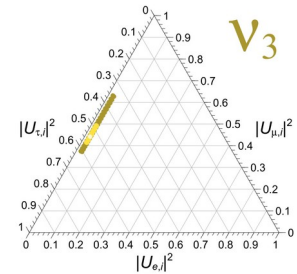
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ν_1 lightest and stable
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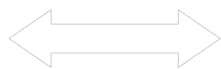
ν_3 lightest and stable
(inverted mass ordering)



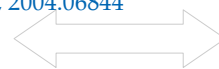
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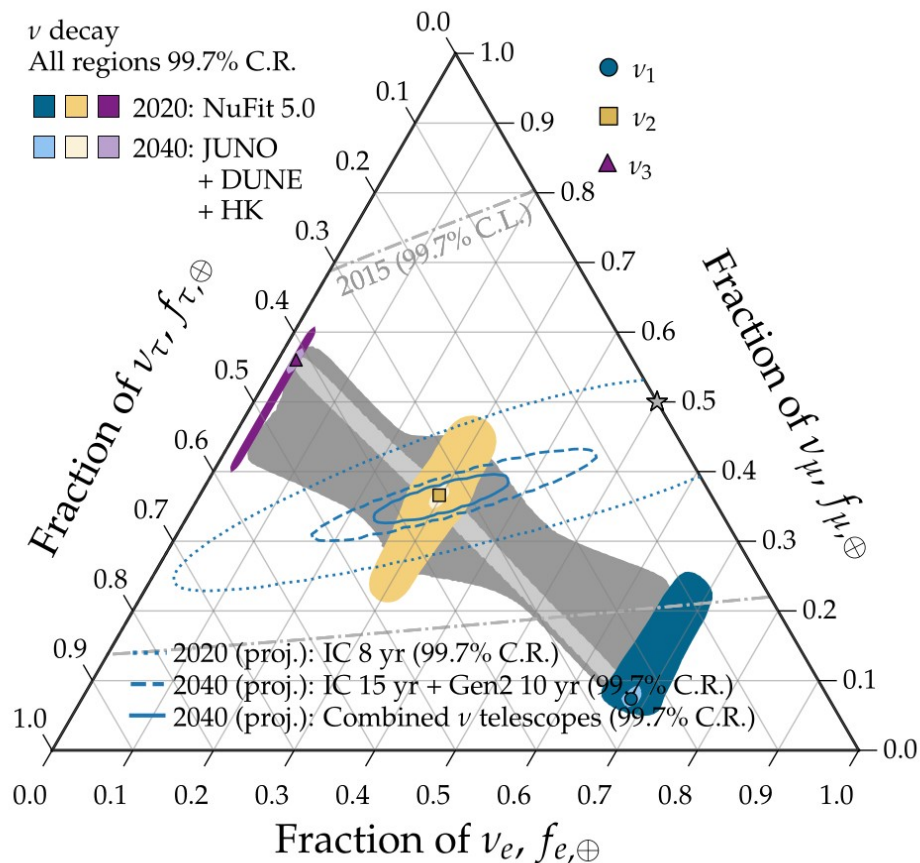
Flavor composition



Spectrum shape



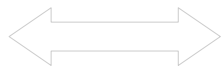
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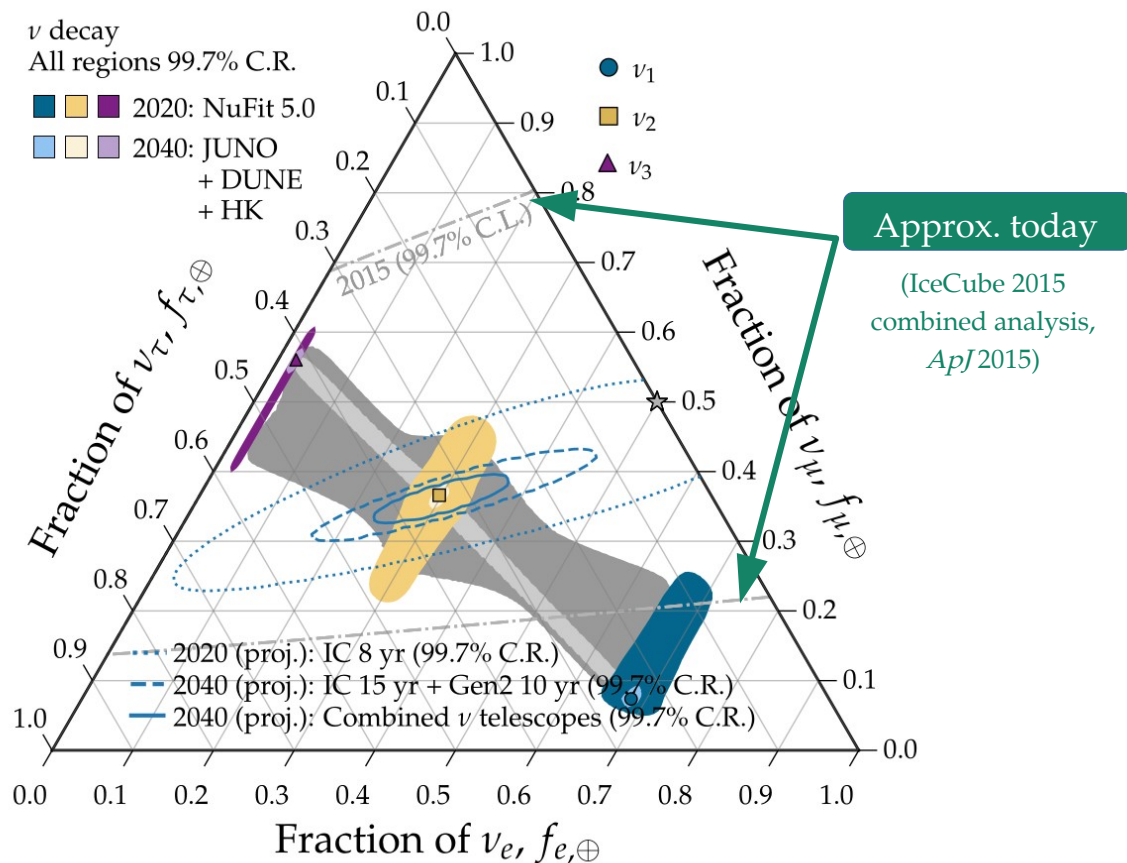
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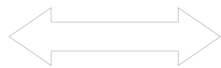
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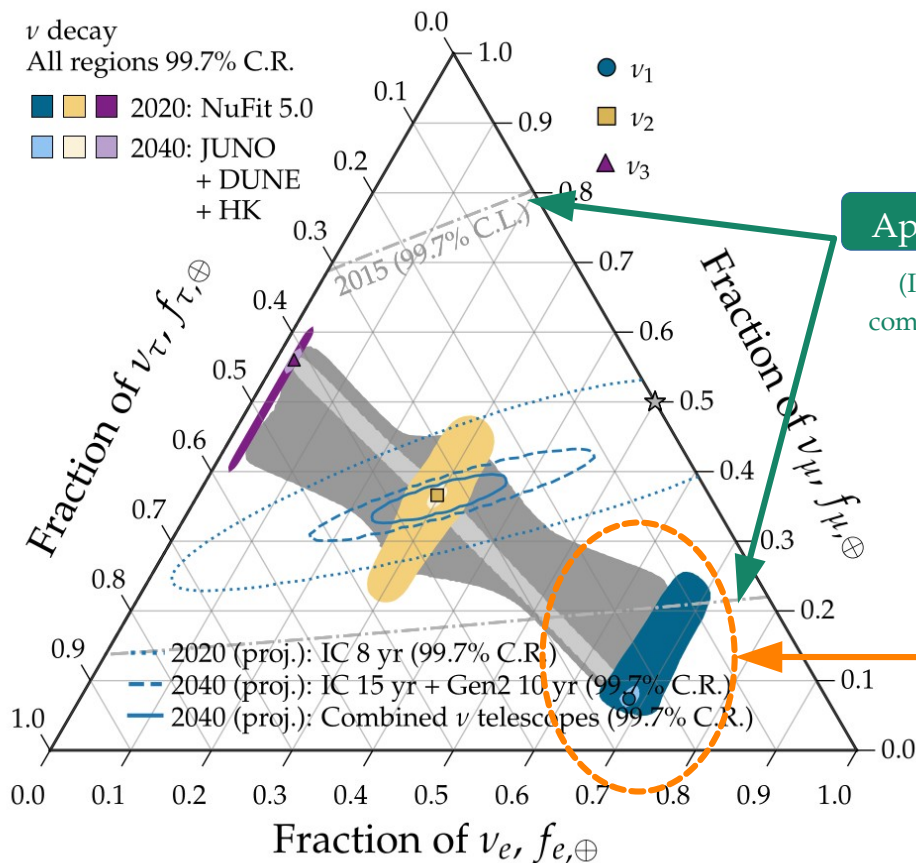
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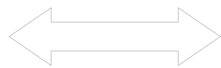
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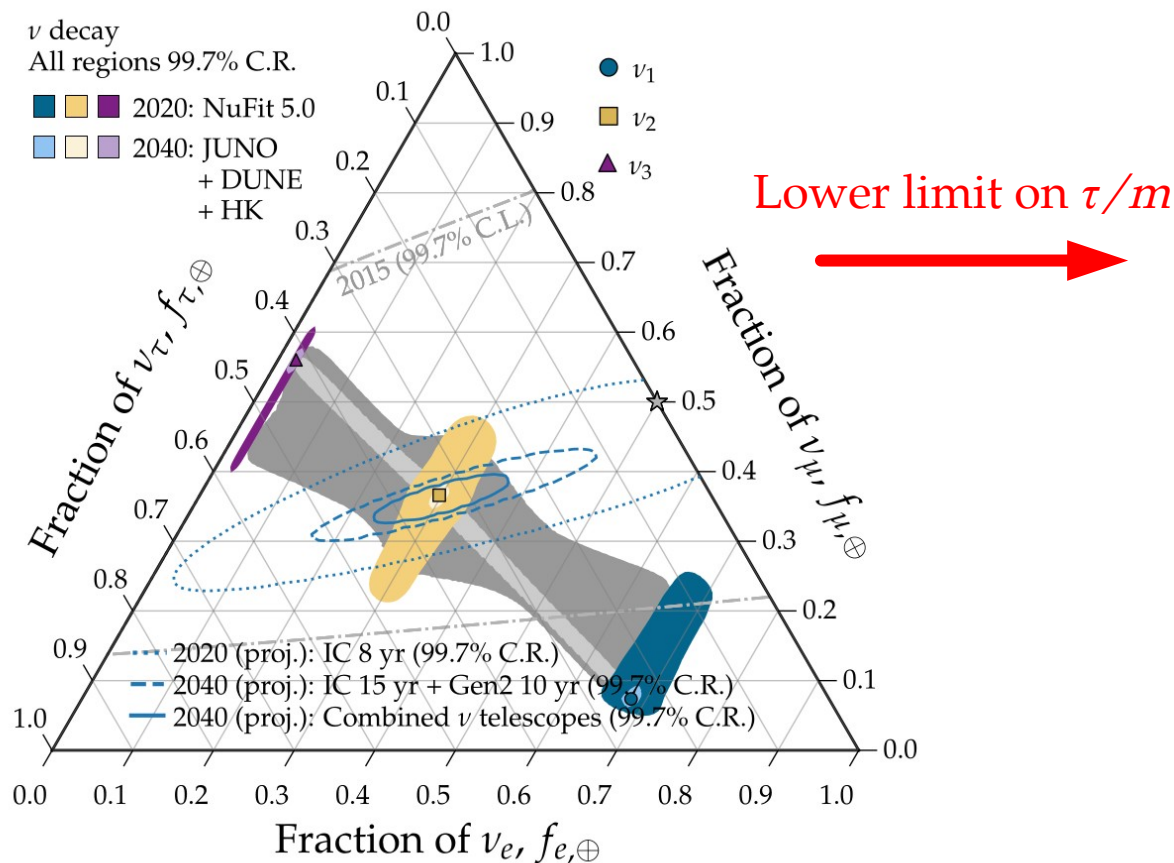
Flavor composition



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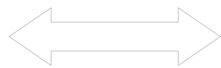
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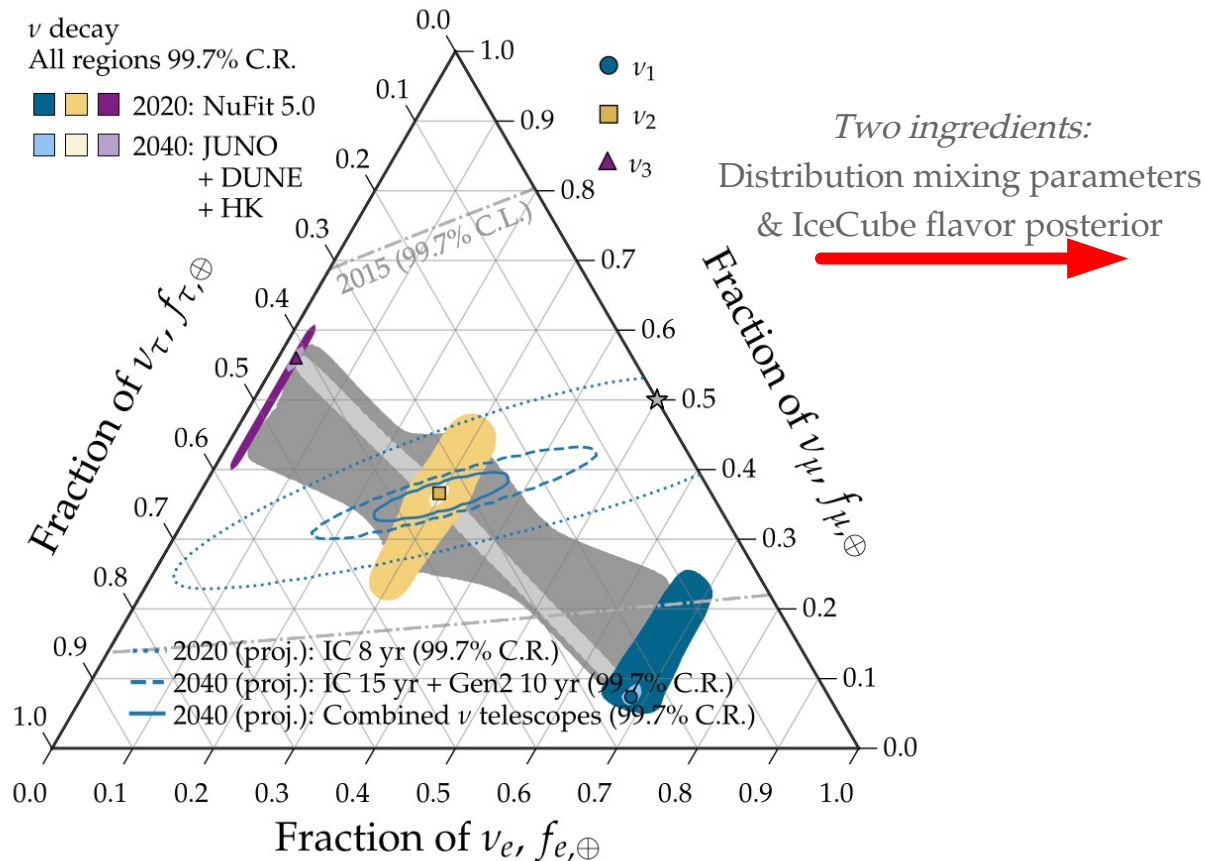
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Spectrum shape



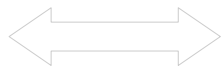
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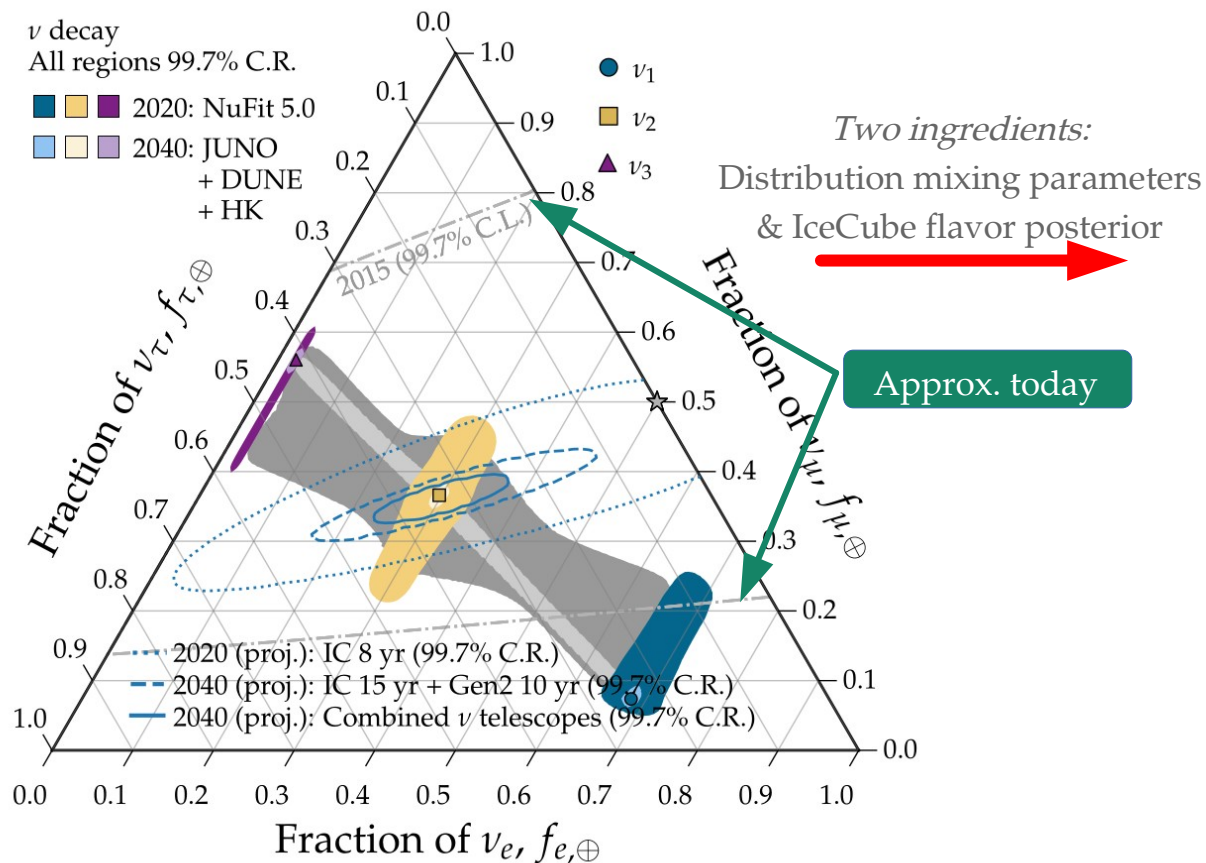
Flavor composition



Spectrum shape



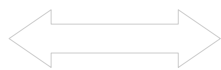
Event rate



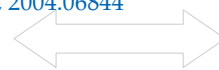
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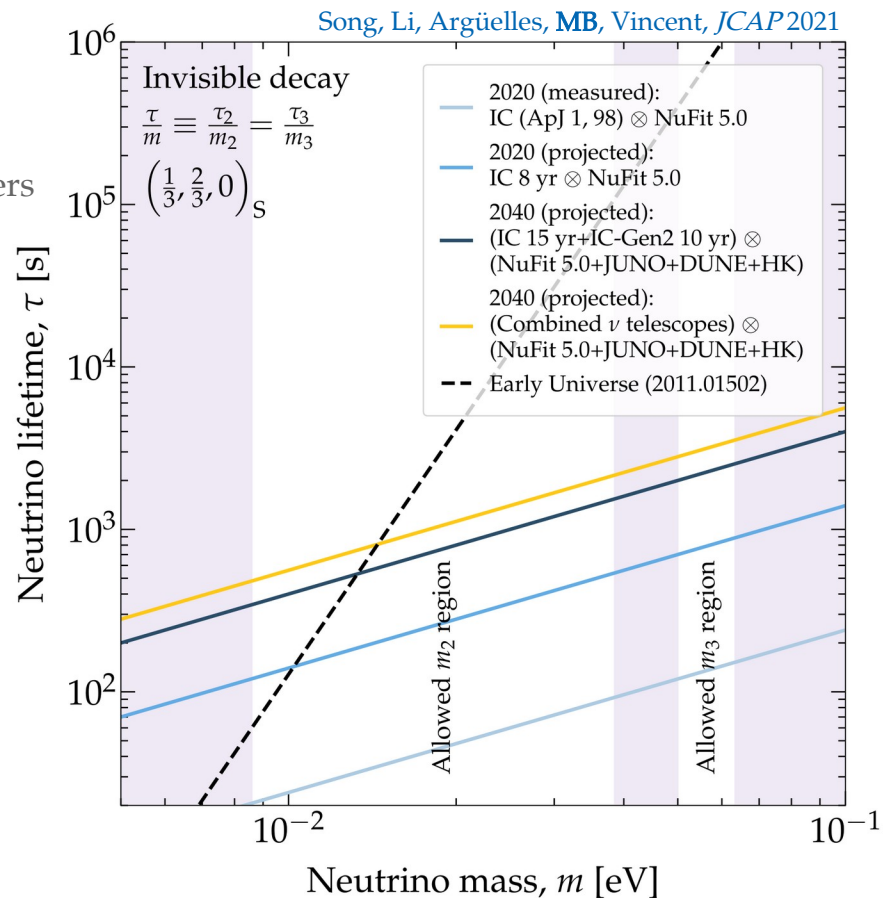
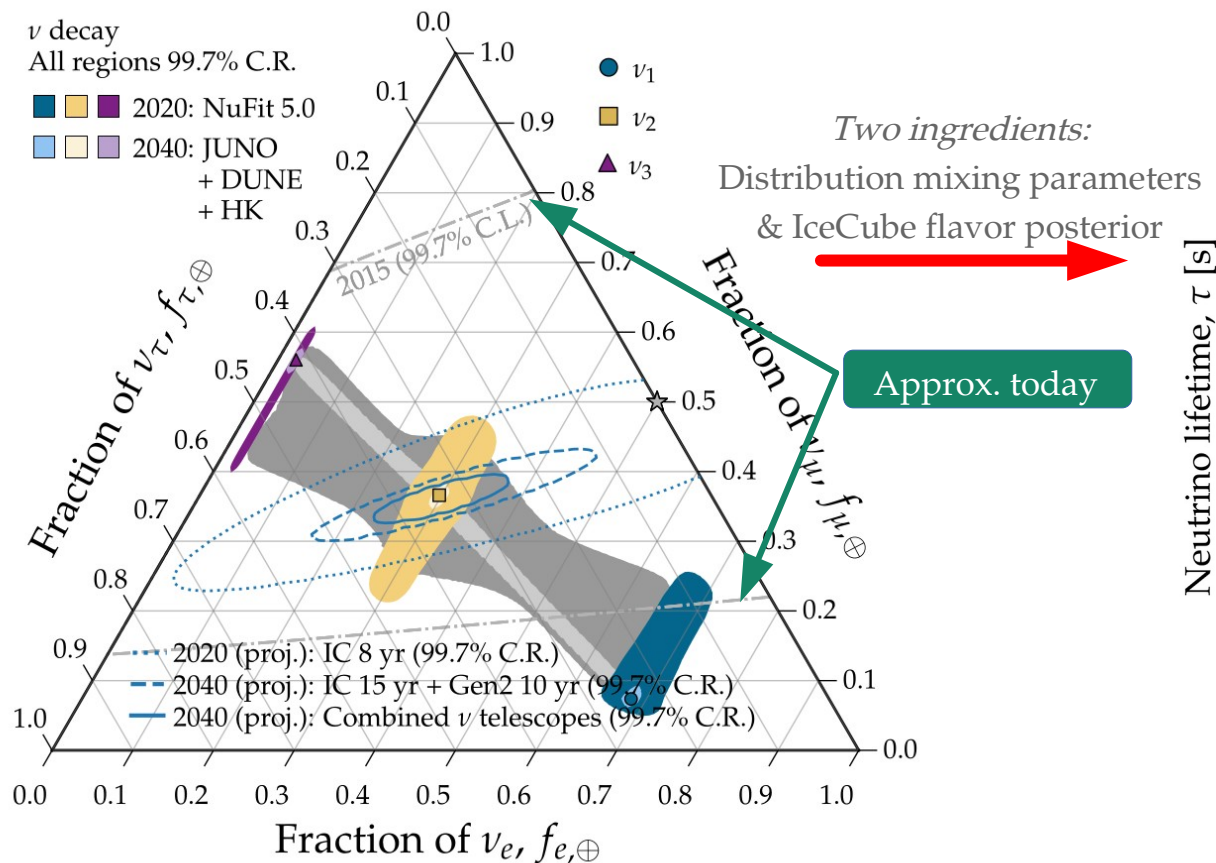
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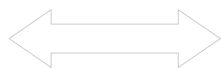
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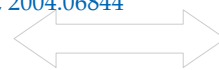
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See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

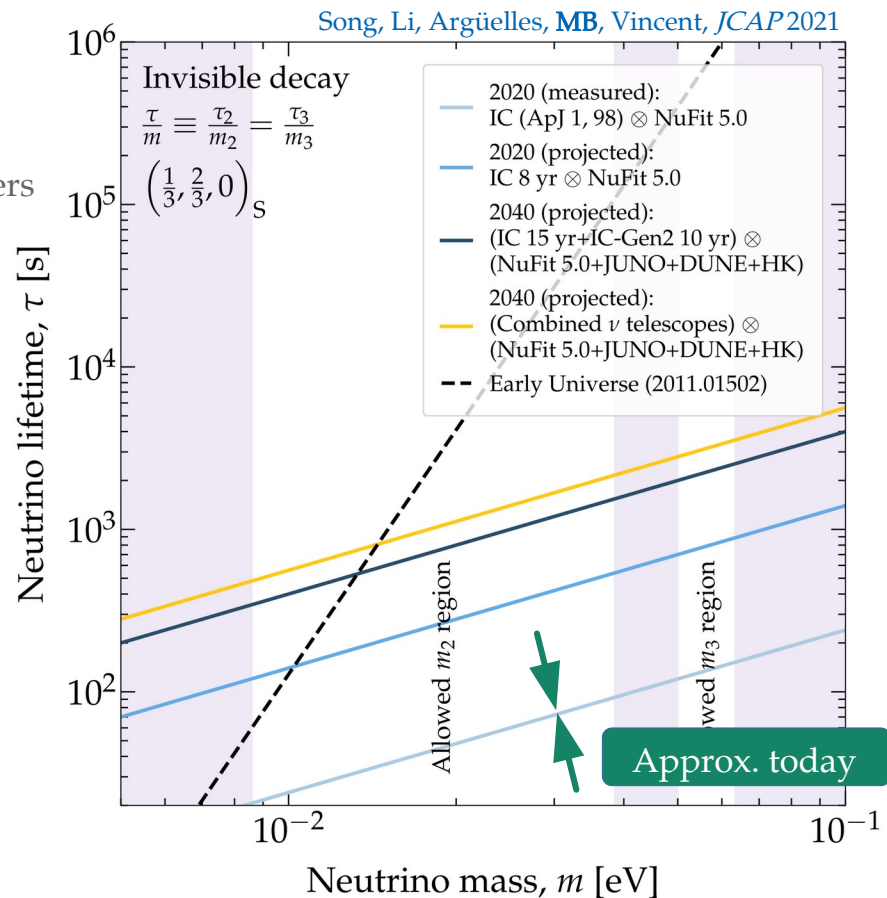
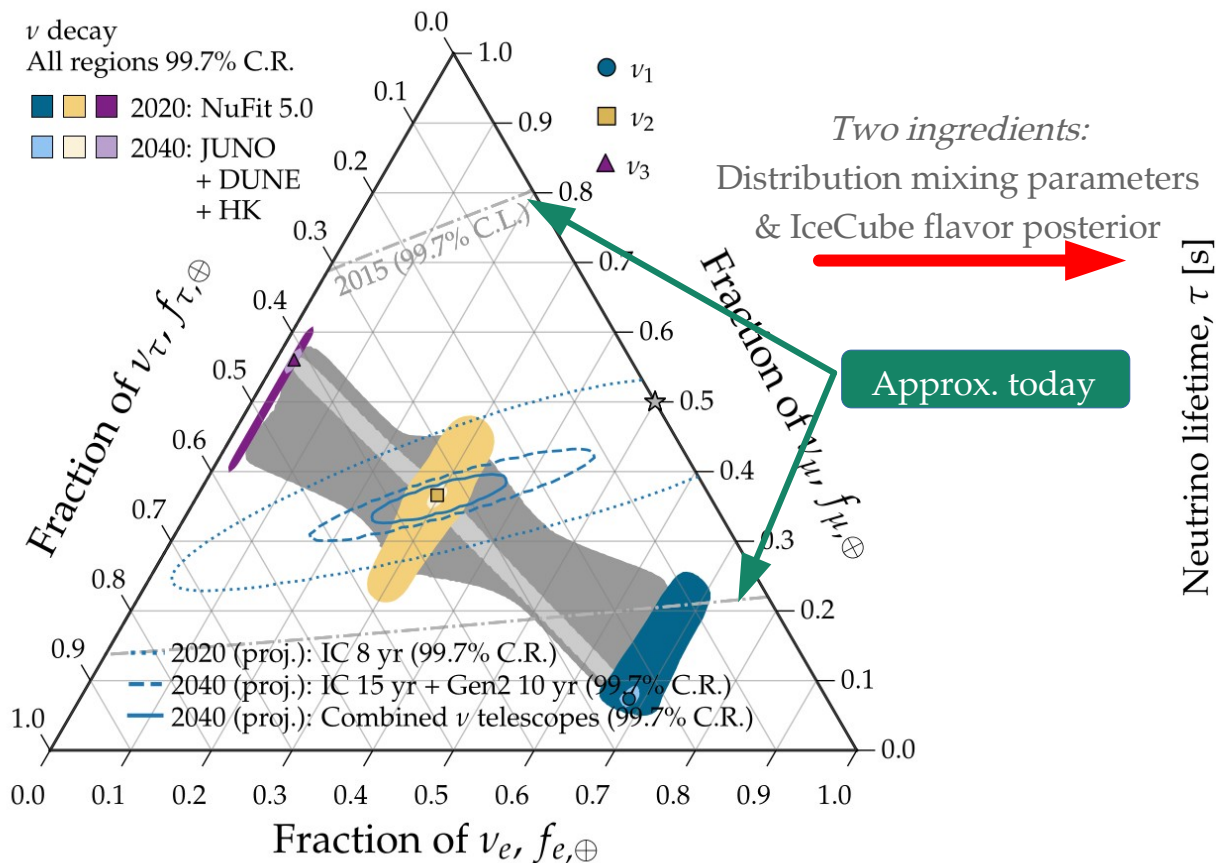
Flavor composition



Spectrum shape



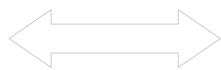
Event rate



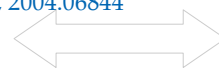
What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, MB, Winter, *JCAP* 2012 / MB, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / MB, 2004.06844

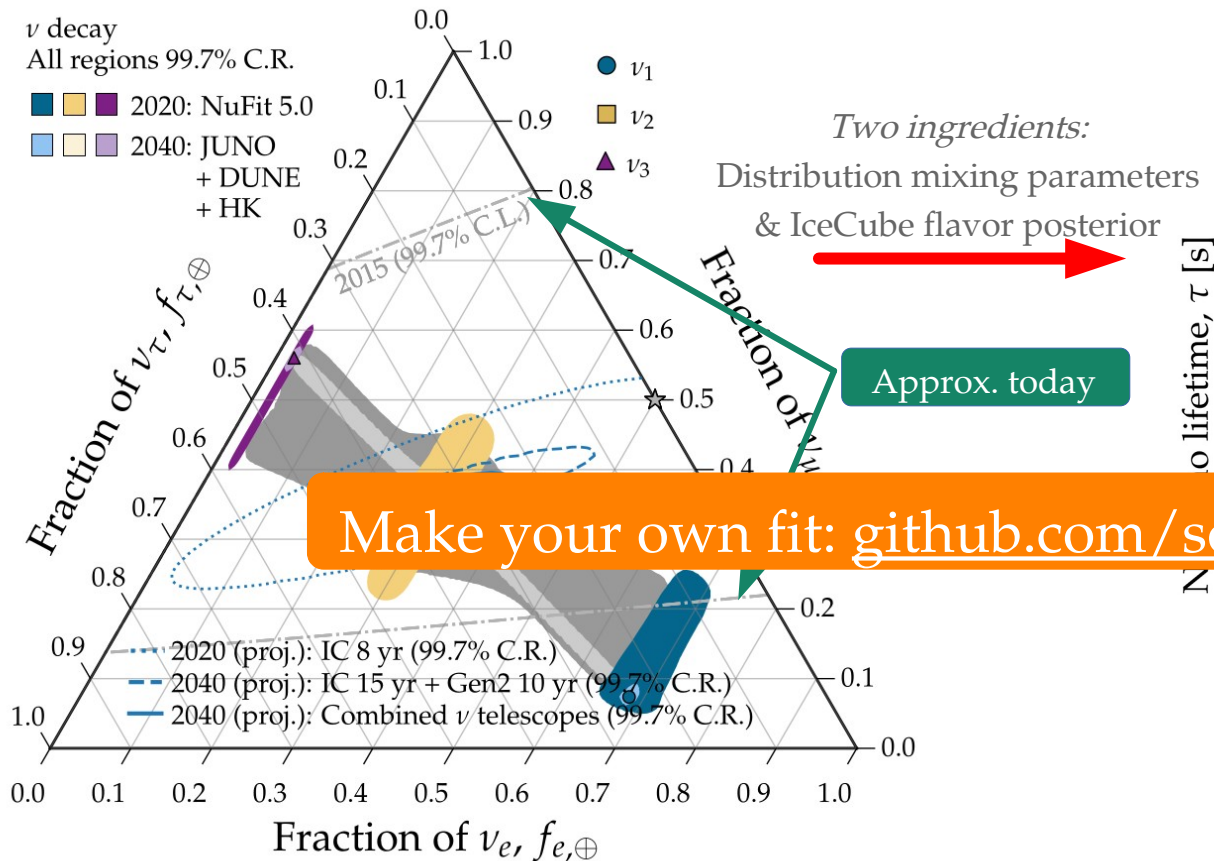
Flavor composition



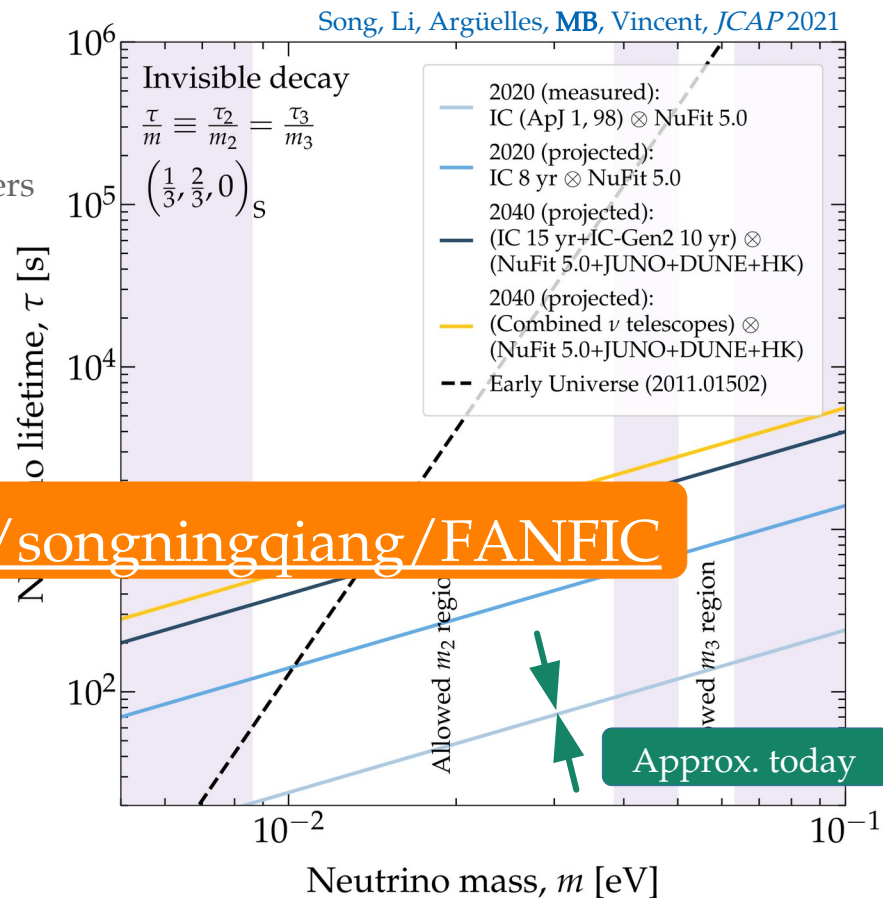
Spectrum shape



Event rate



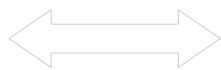
Make your own fit: github.com/songningqiang/FANFIC



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 /
Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 /
Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844 /
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

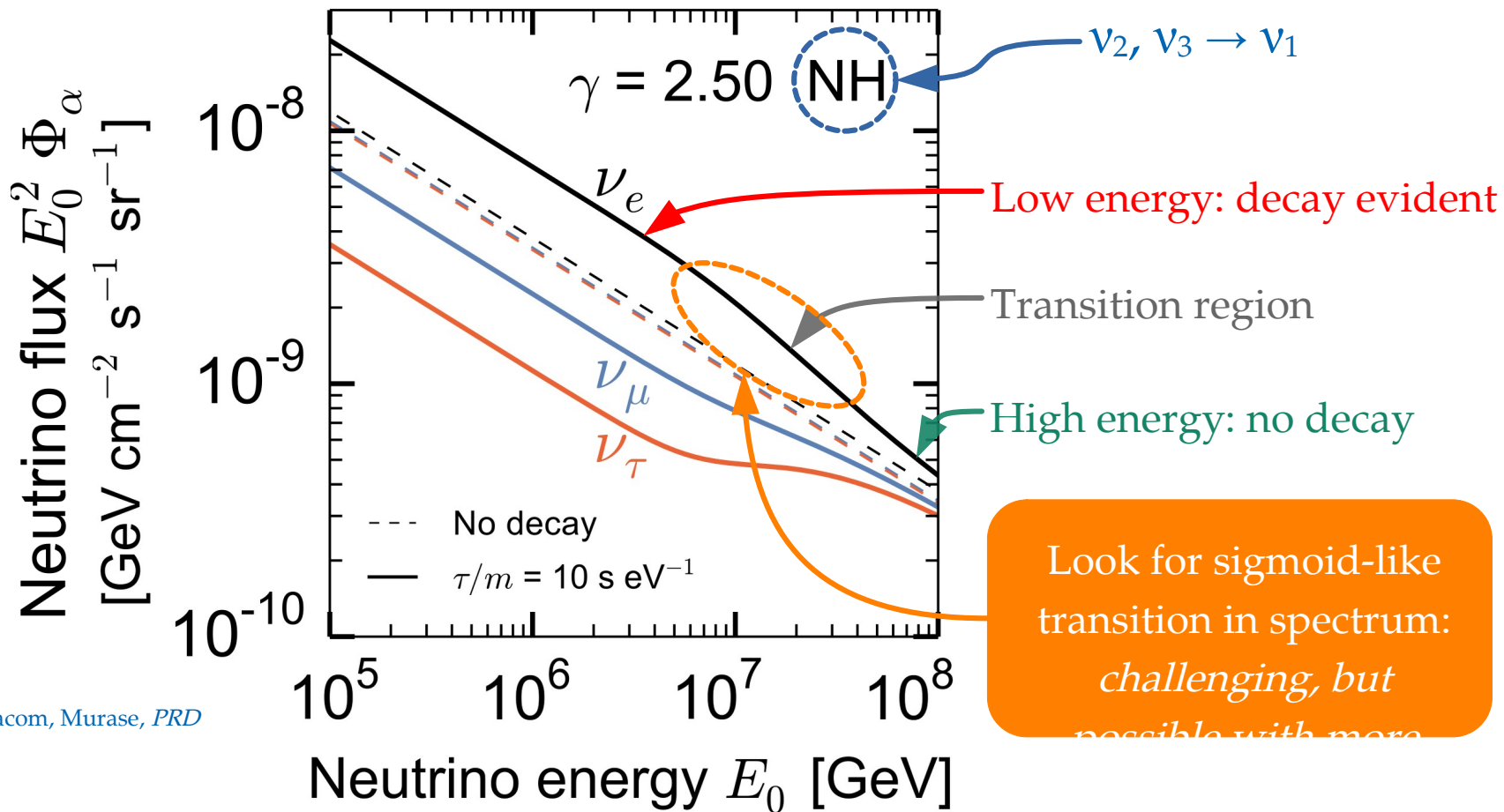
Flavor composition



Spectrum shape



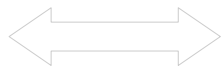
Event rate



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

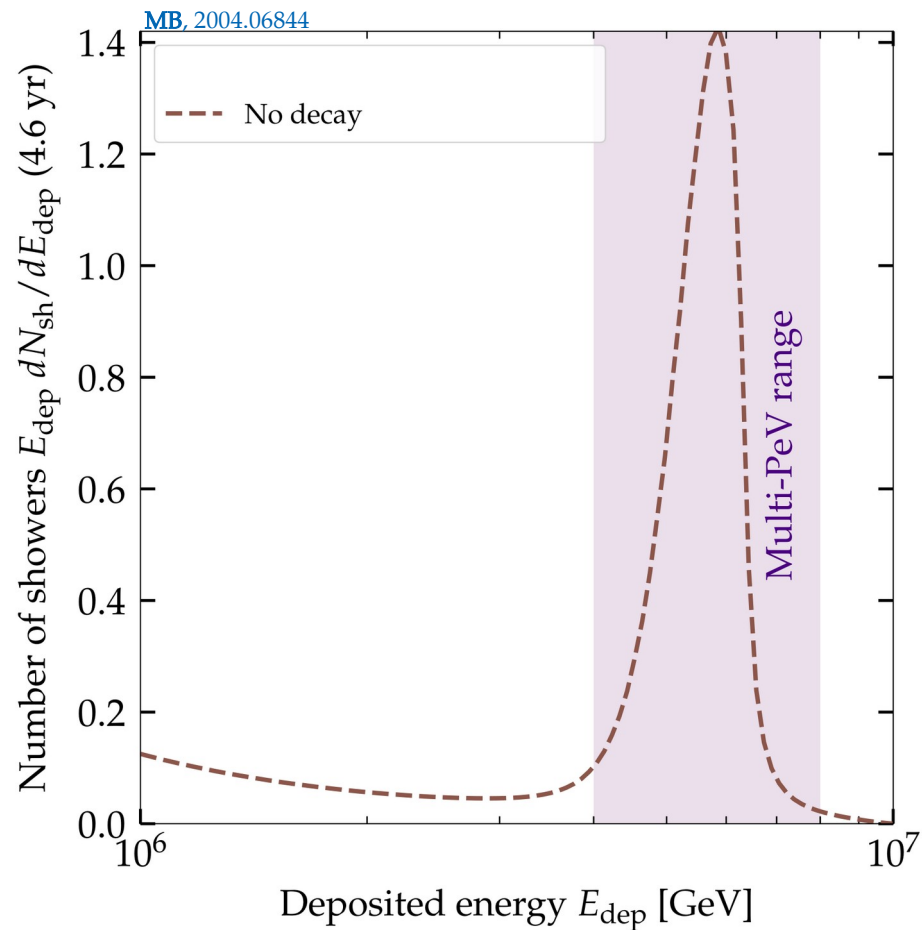
Flavor composition



Spectrum shape



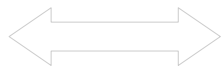
Event rate



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

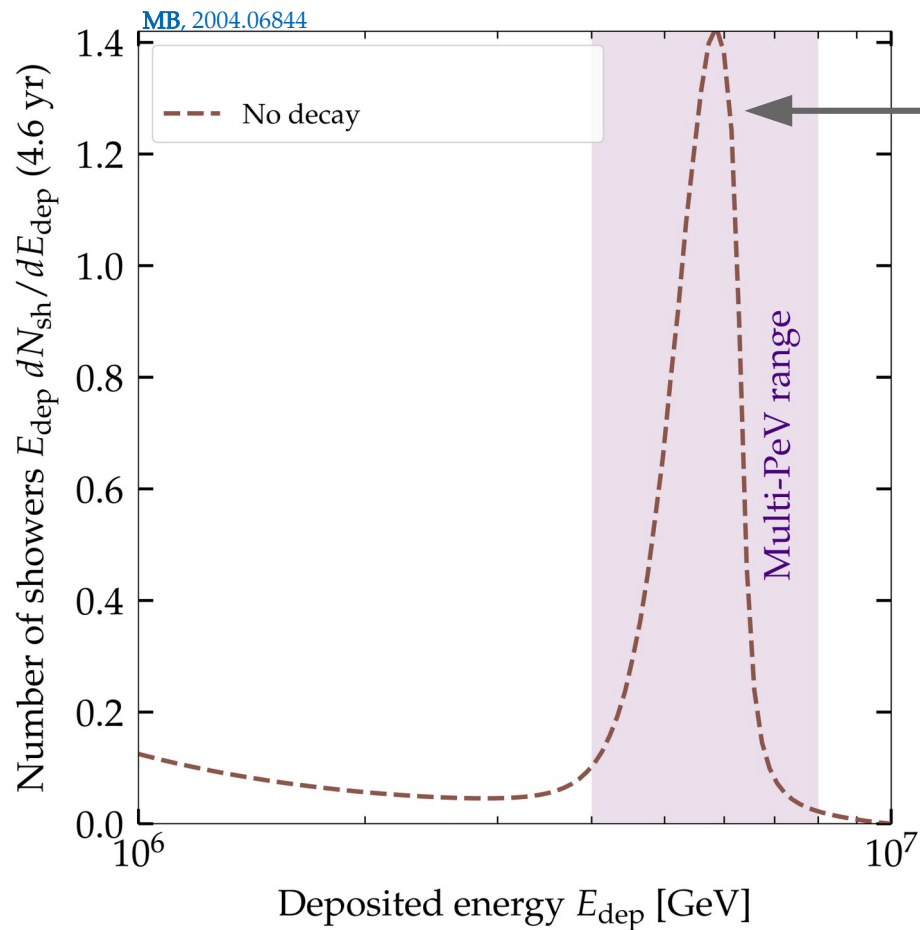
Flavor composition



Spectrum shape



Event rate

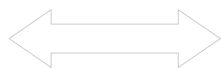


Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

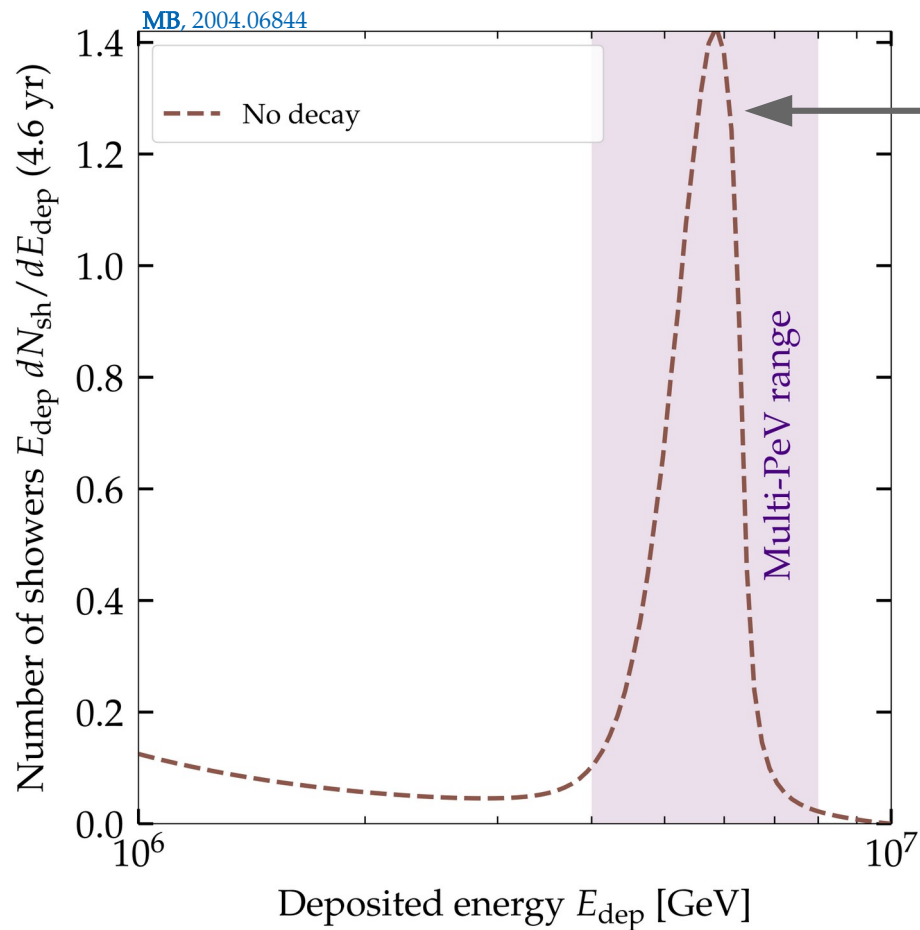
Flavor composition



Spectrum shape

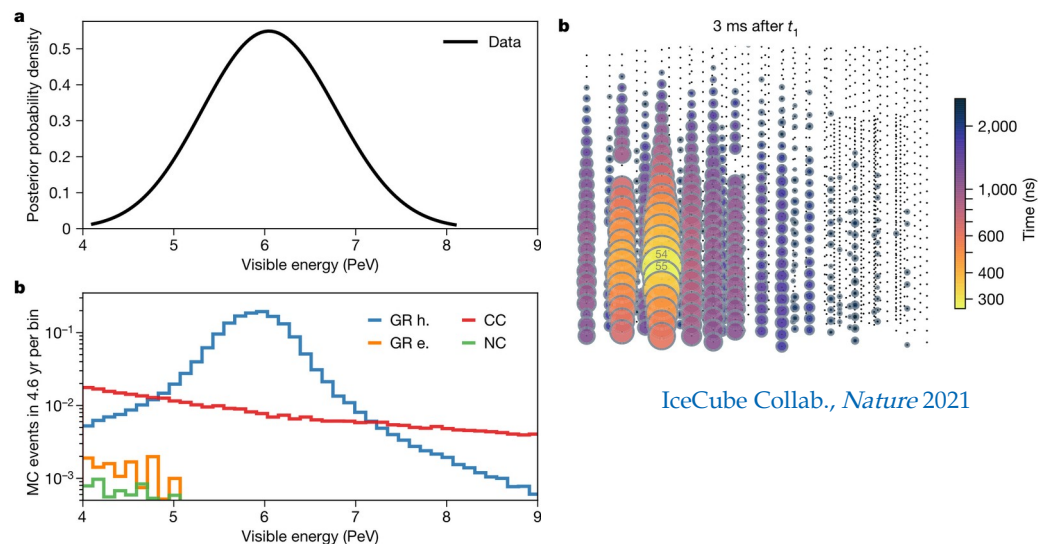


Event rate



Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow$
 shower

IceCube has seen one GR candidate in 4.6 years:



IceCube Collab., *Nature* 2021

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, MB, Winter, *JCAP* 2012 / MB, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, MB, Vincent, *JCAP* 2020

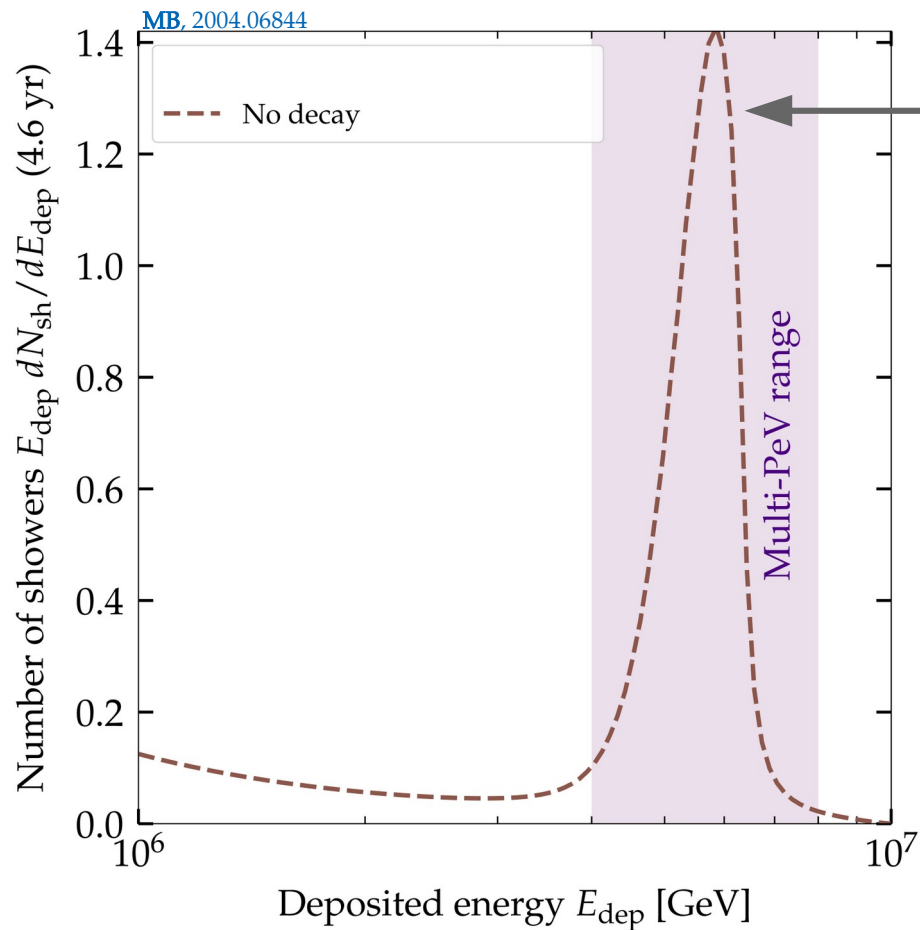
Flavor composition



Spectrum shape



Event rate

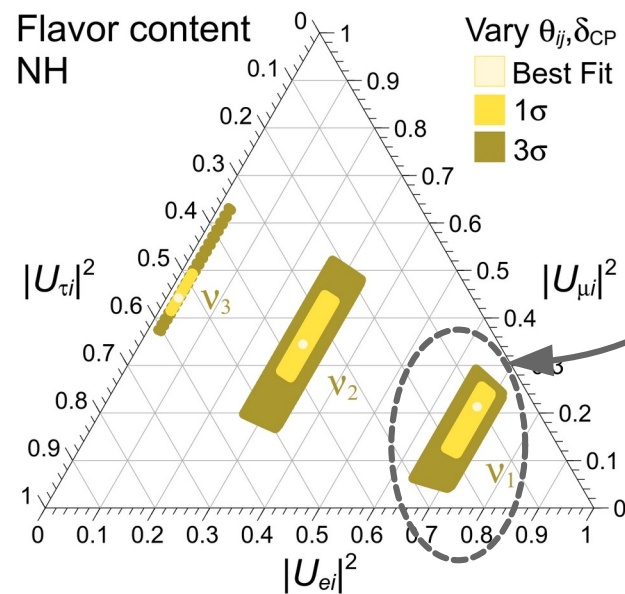


Glashow resonance (GR):

$\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow$

shower

ν_1 is the mass eigenstate with the most e flavor



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, MB, Winter, *JCAP* 2012 / MB, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, MB, Vincent, *JCAP* 2020

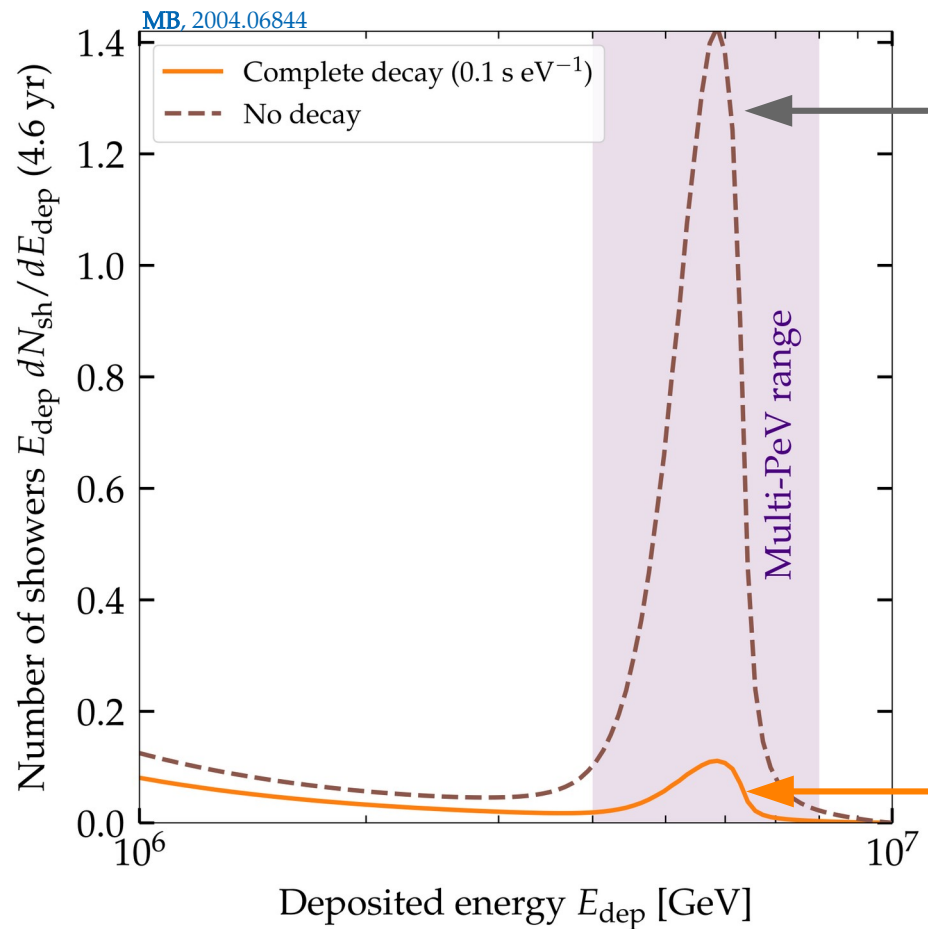
Flavor composition



Spectrum shape



Event rate



Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, MB, Winter, *JCAP* 2012 / MB, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, MB, Vincent, *JCAP* 2020

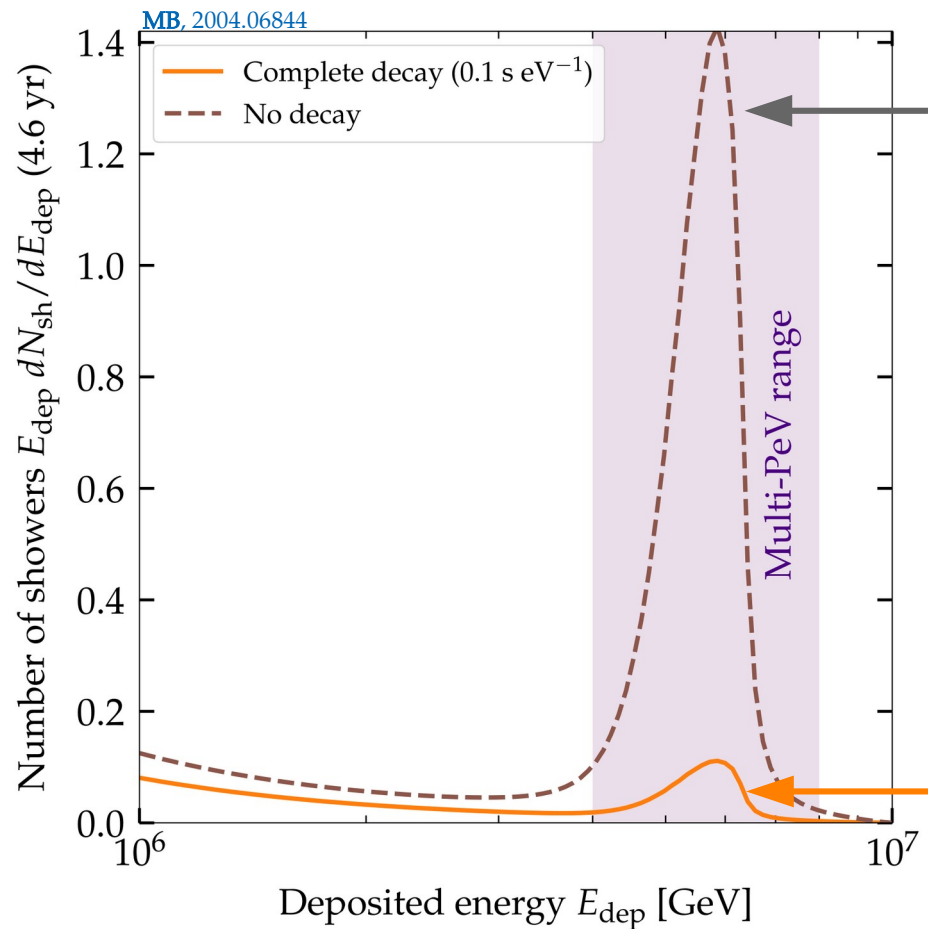
Flavor composition



Spectrum shape



Event rate



Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ ($= \nu_1$)

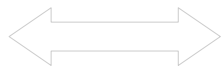


If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition

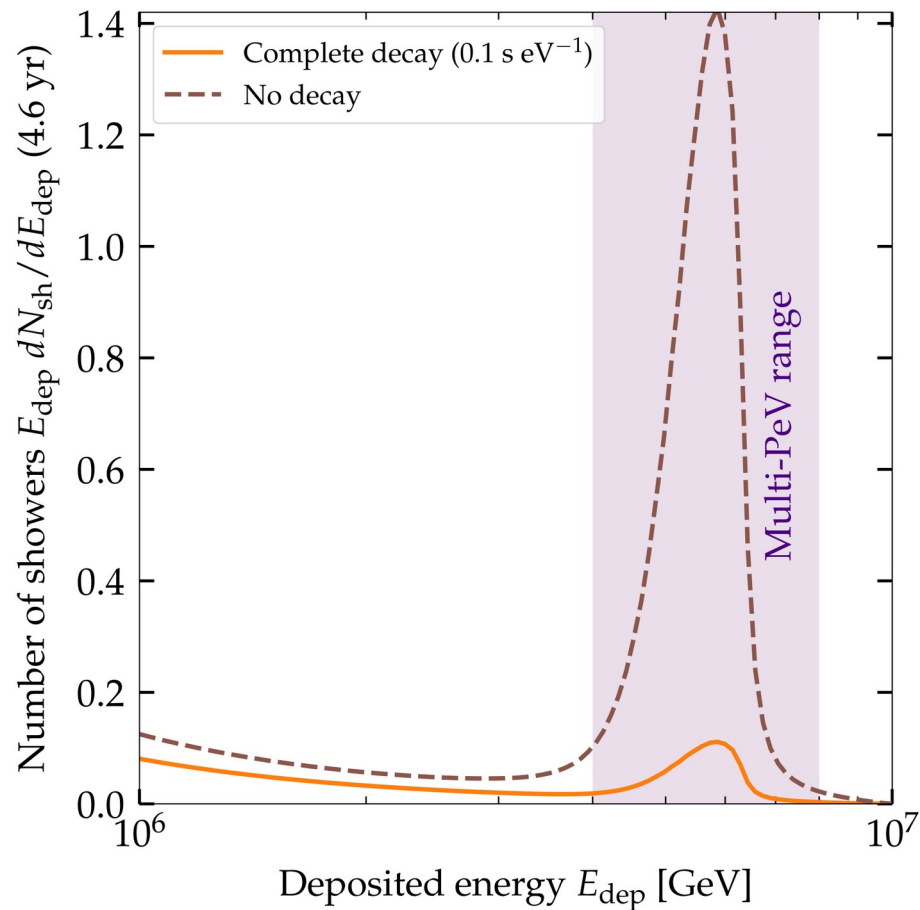


Spectrum shape



Event rate

MB, 2004.06844



What does neutrino decay change?

See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition

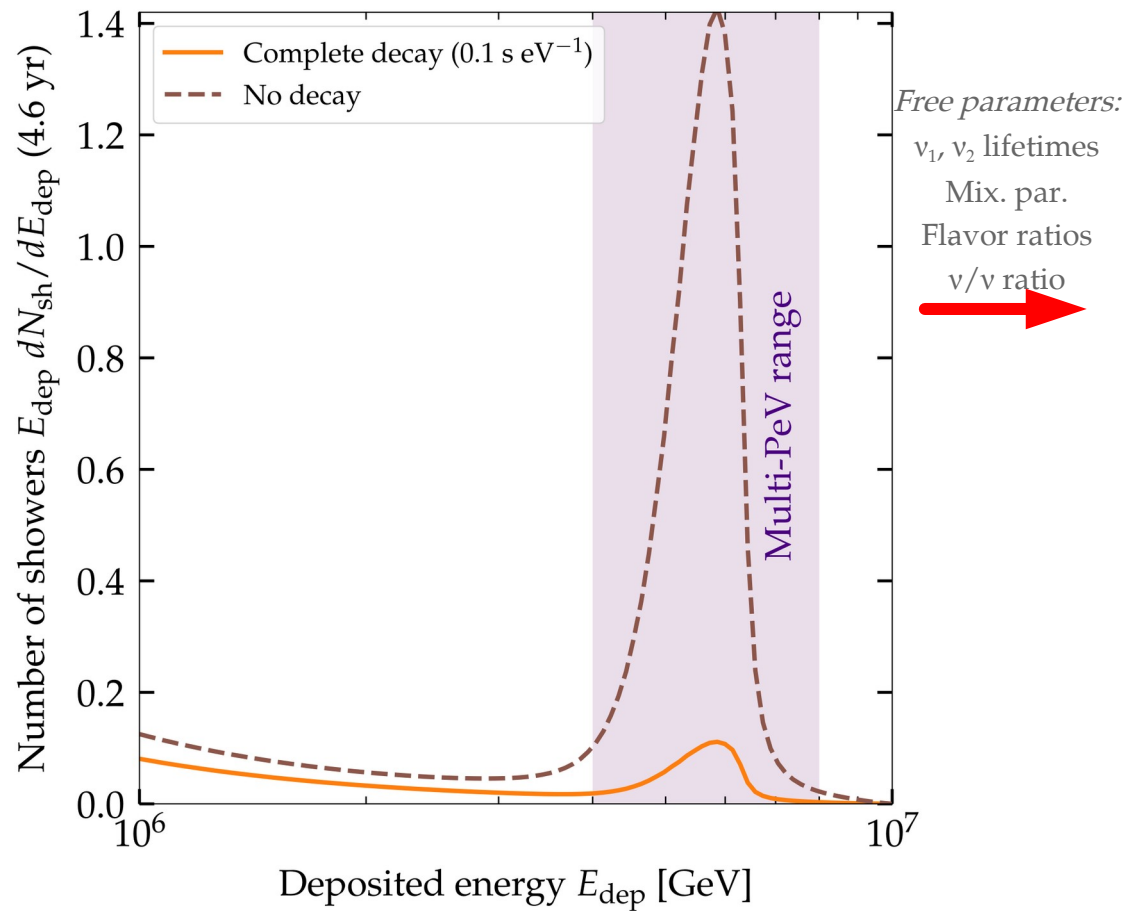


Spectrum shape



Event rate

MB, 2004.06844



What does neutrino decay change?

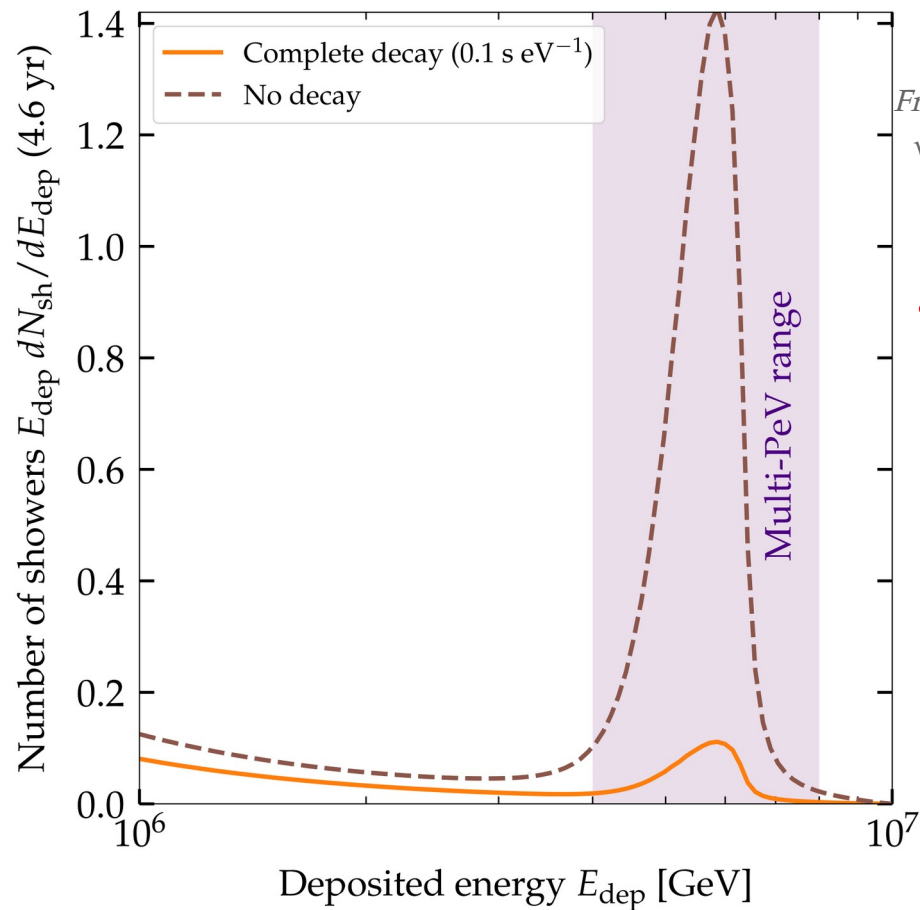
Flavor composition



Spectrum shape



Event rate



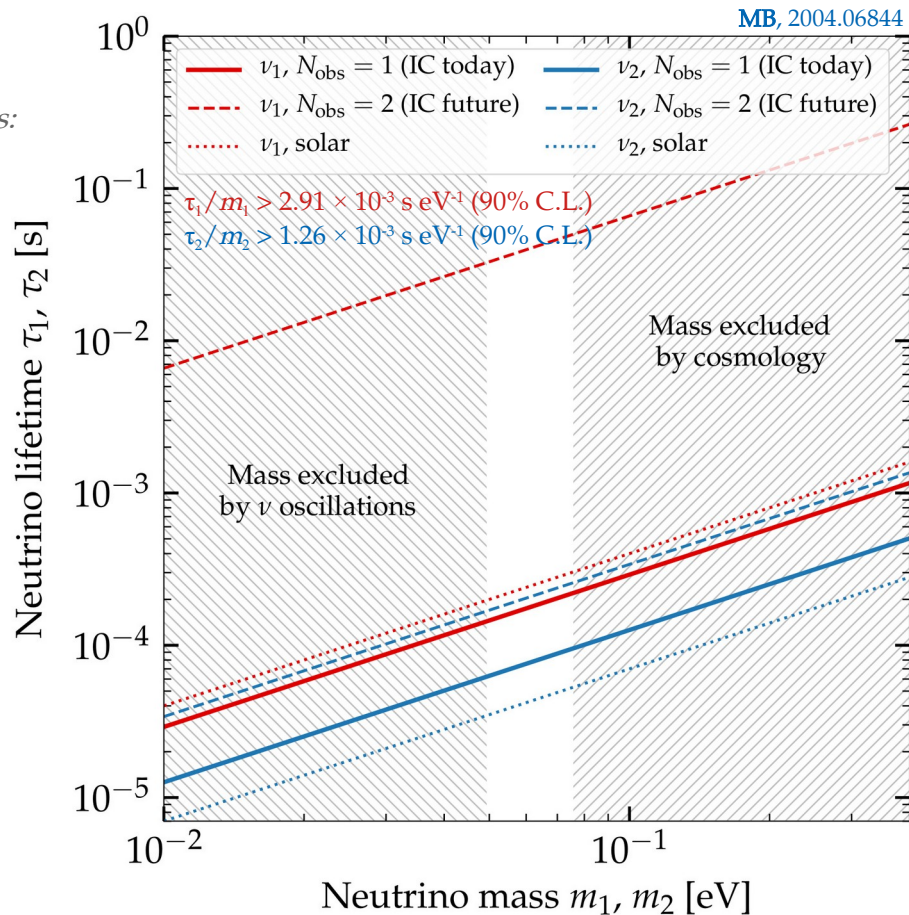
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

ν/ν ratio



See also: Beacom *et al.*, *PRL* 2002 / Baerwald, MB, Winter, *JCAP* 2012 / MB, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, MB, Vincent, *JCAP* 2020

What does neutrino decay change?

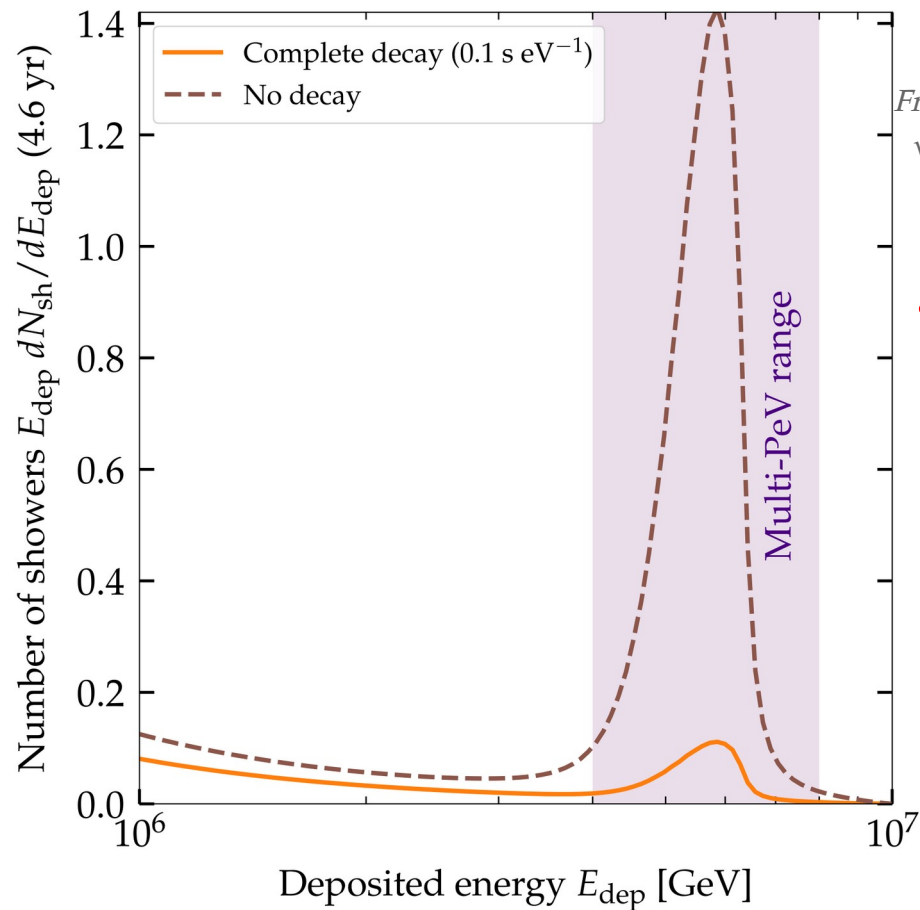
Flavor composition



Spectrum shape



Event rate



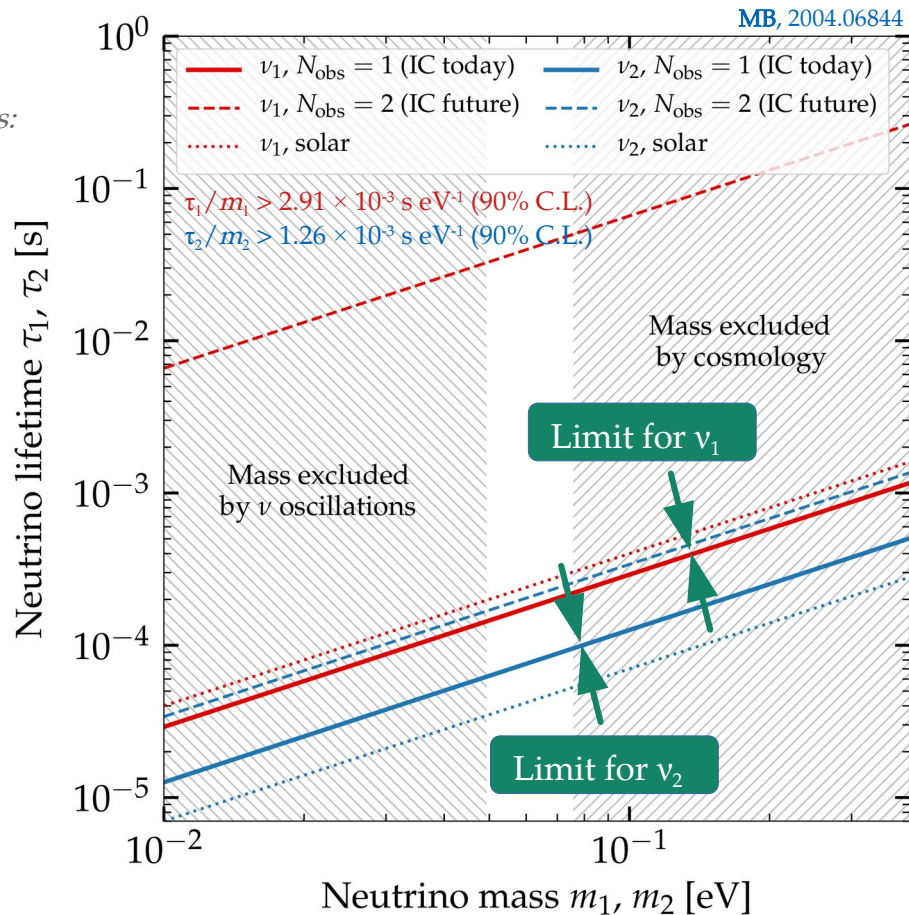
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

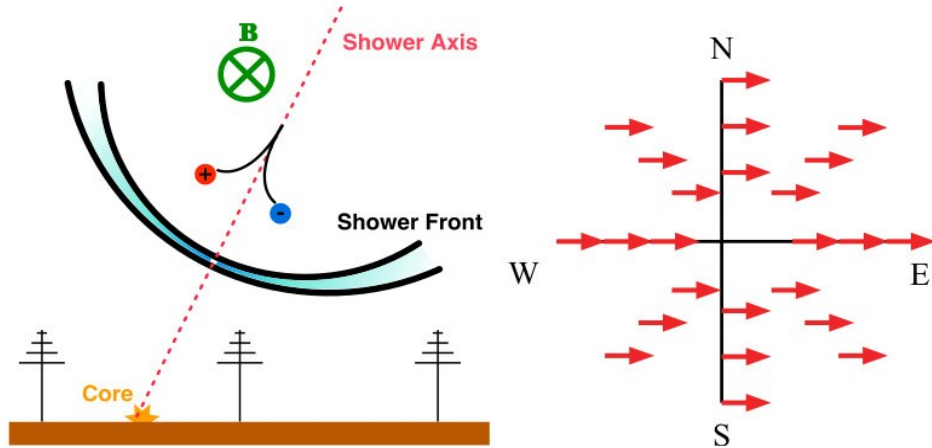
ν/ν ratio



Neutrino radio-detection

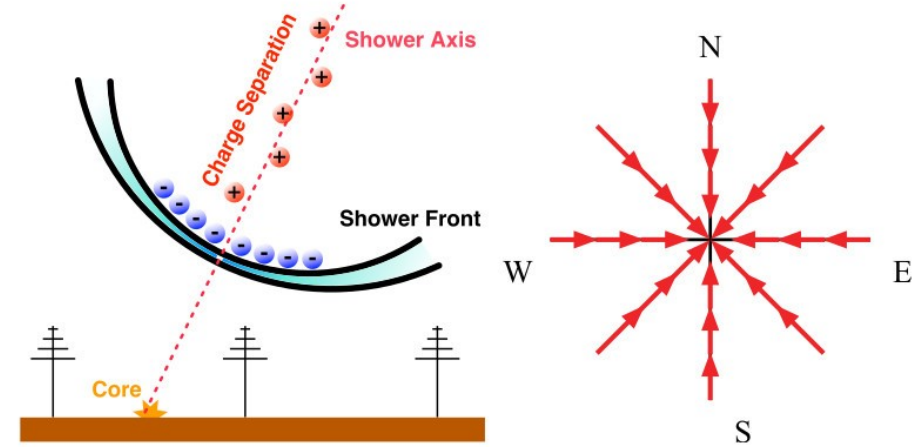
Radio emission: geomagnetic and Askaryan

Geomagnetic



- ▶ Time-varying transverse current
- ▶ Linearly polarized parallel to Lorentz force
- ▶ Dominant in air showers

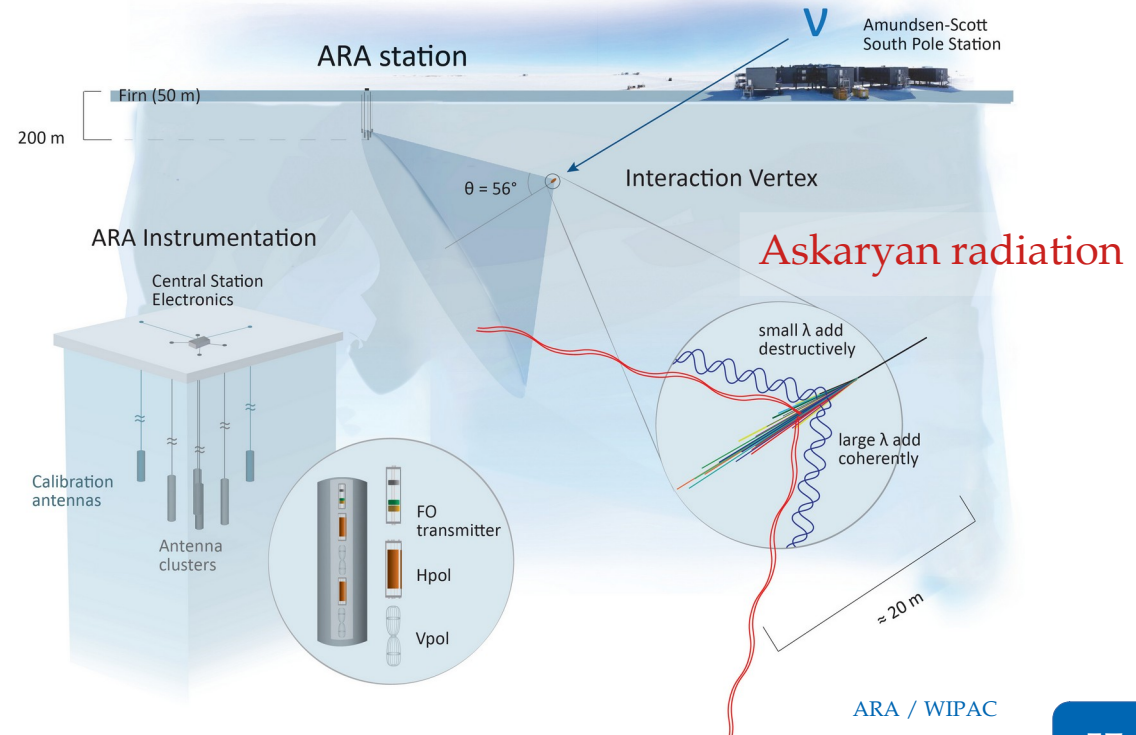
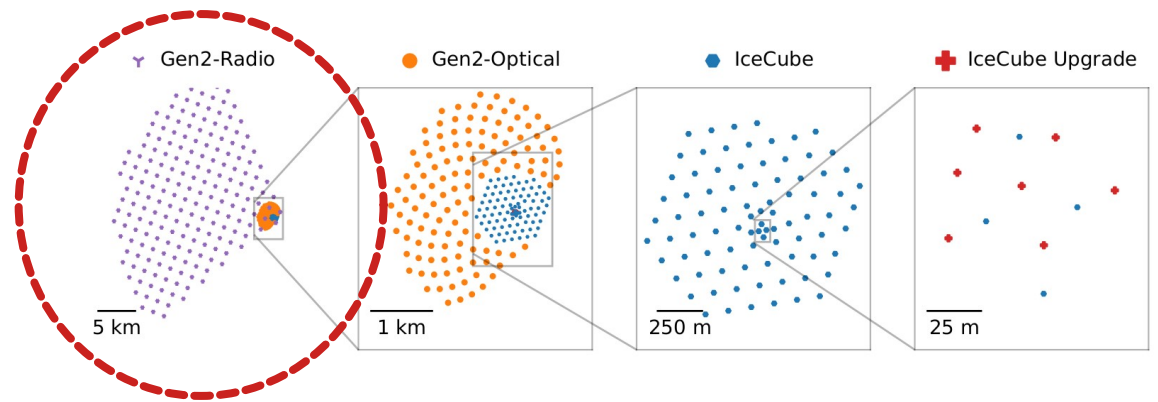
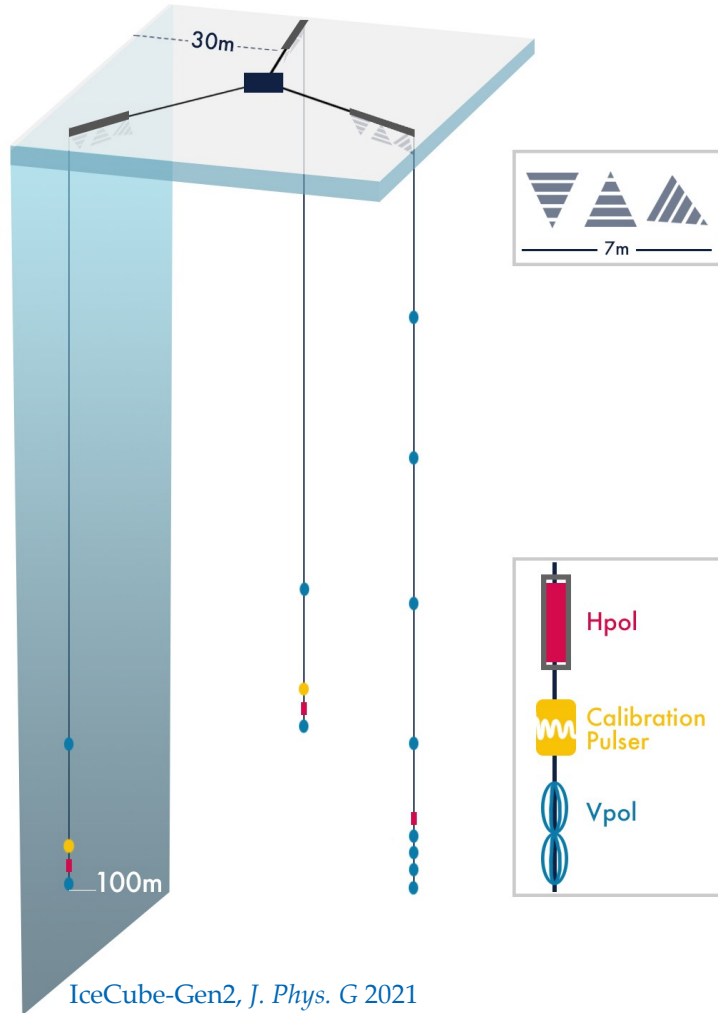
Askaryan



- ▶ Time-varying negative-charge $\sim 20\%$ excess
- ▶ Linearly polarized towards axis
- ▶ Sub-dominant in air showers

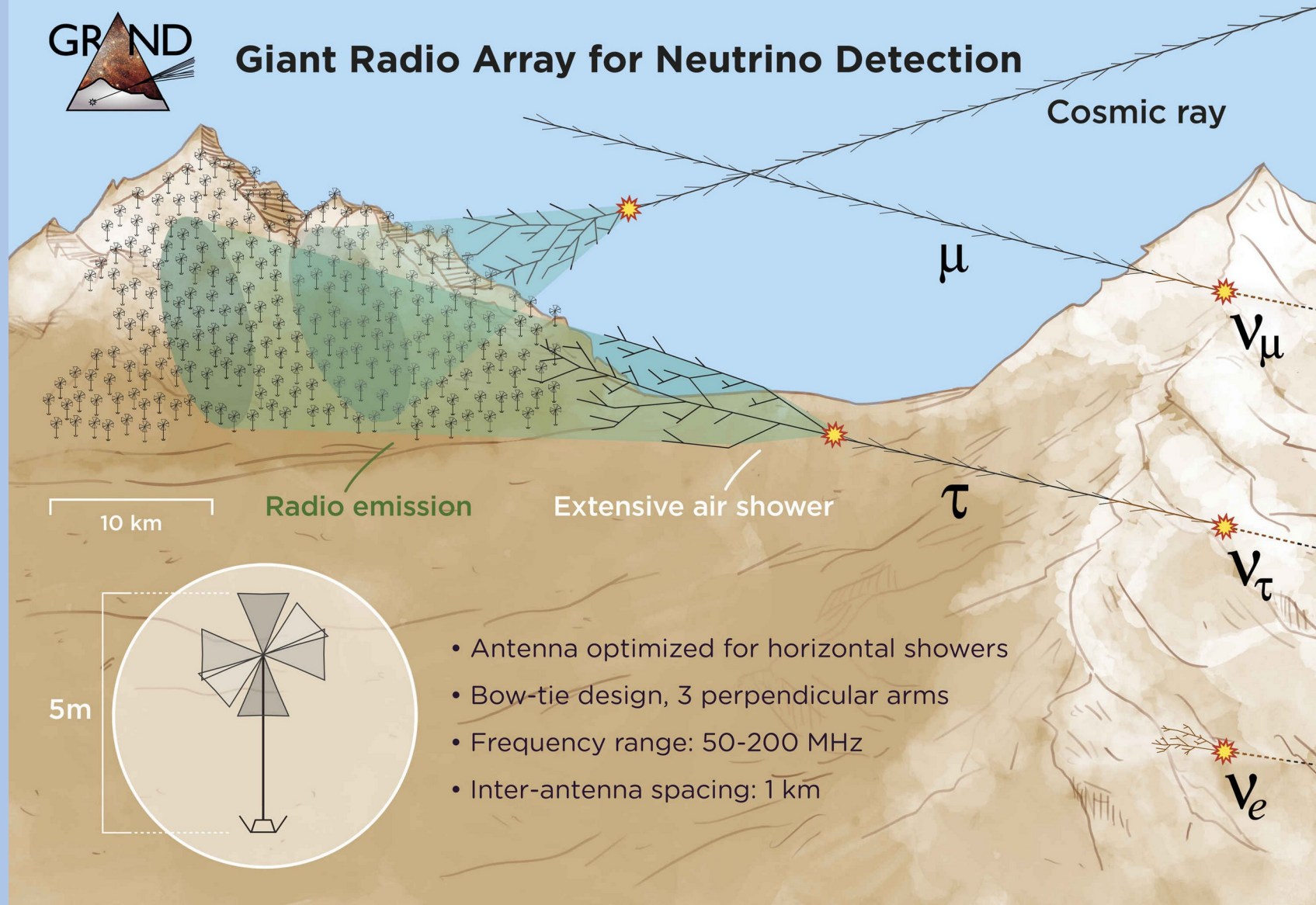
Radio emission: geomagnetic and Askaryan

IceCube-Gen2 Radio



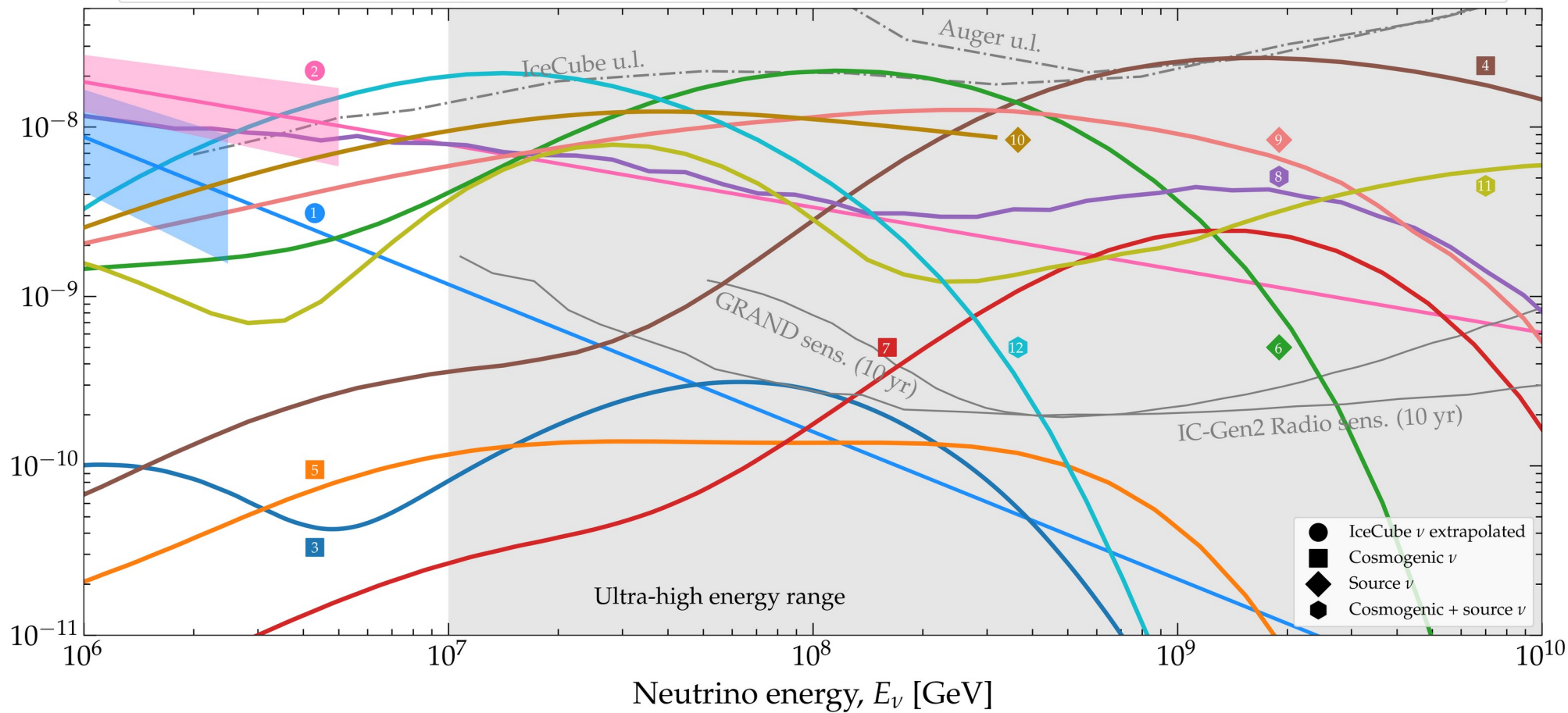


Giant Radio Array for Neutrino Detection

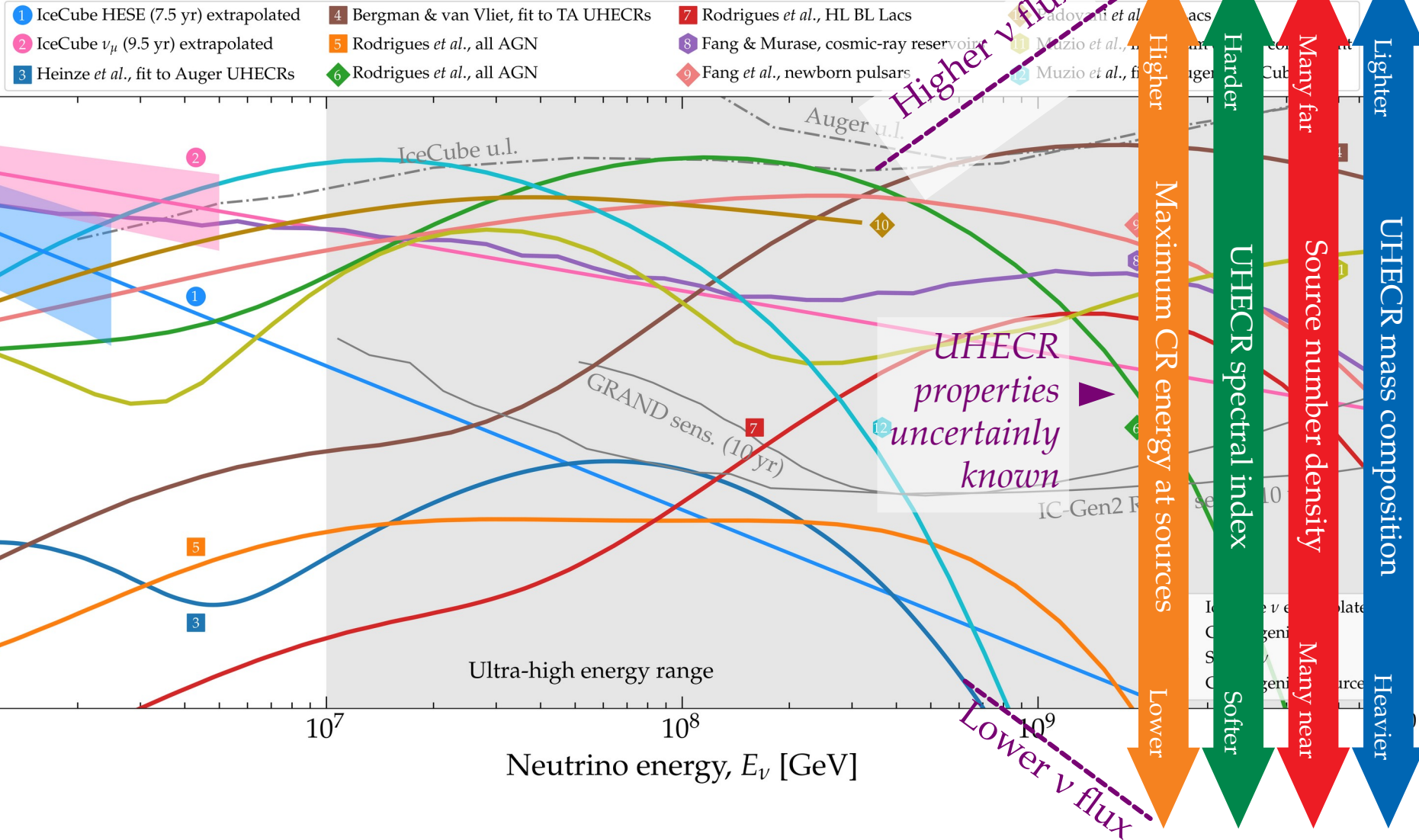


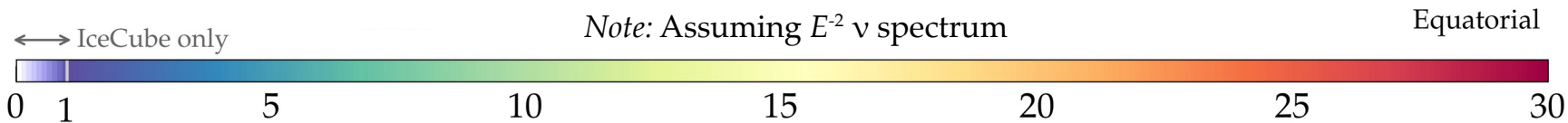
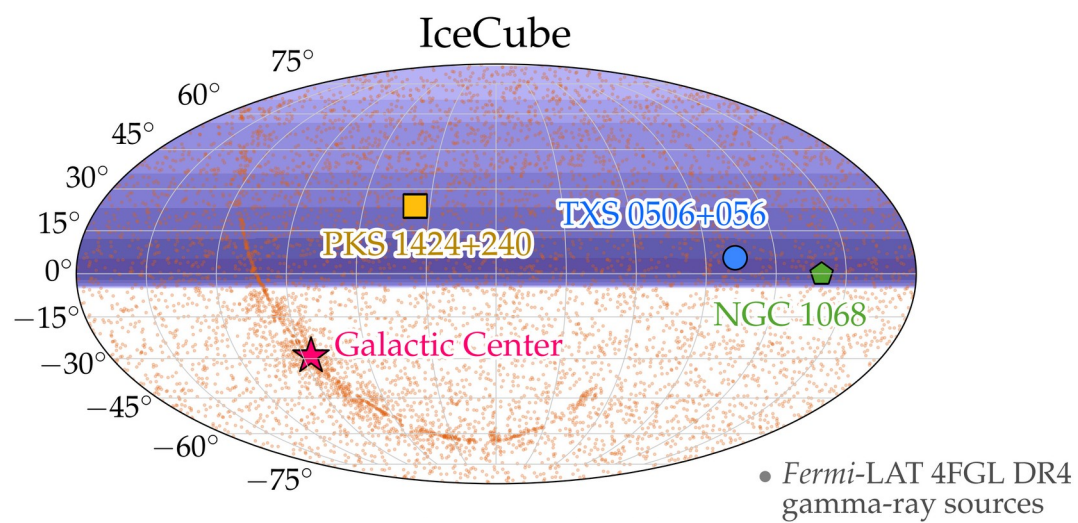
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]

- | | | | |
|--|---|--|--|
| 1 IceCube HESE (7.5 yr) extrapolated | 4 Bergman & van Vliet, fit to TA UHECRs | 7 Rodrigues <i>et al.</i> , HL BL Lacs | 10 Padovani <i>et al.</i> , BL Lacs |
| 2 IceCube ν_μ (9.5 yr) extrapolated | 5 Rodrigues <i>et al.</i> , all AGN | 8 Fang & Murase, cosmic-ray reservoirs | 11 Muzio <i>et al.</i> , maximum extra p component |
| 3 Heinze <i>et al.</i> , fit to Auger UHECRs | 6 Rodrigues <i>et al.</i> , all AGN | 9 Fang <i>et al.</i> , newborn pulsars | 12 Muzio <i>et al.</i> , fit to Auger & IceCube |



All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [$\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$]





Rate of detected muon tracks relative to IceCube maximum

