The future of (high-energy) neutrino astronomy

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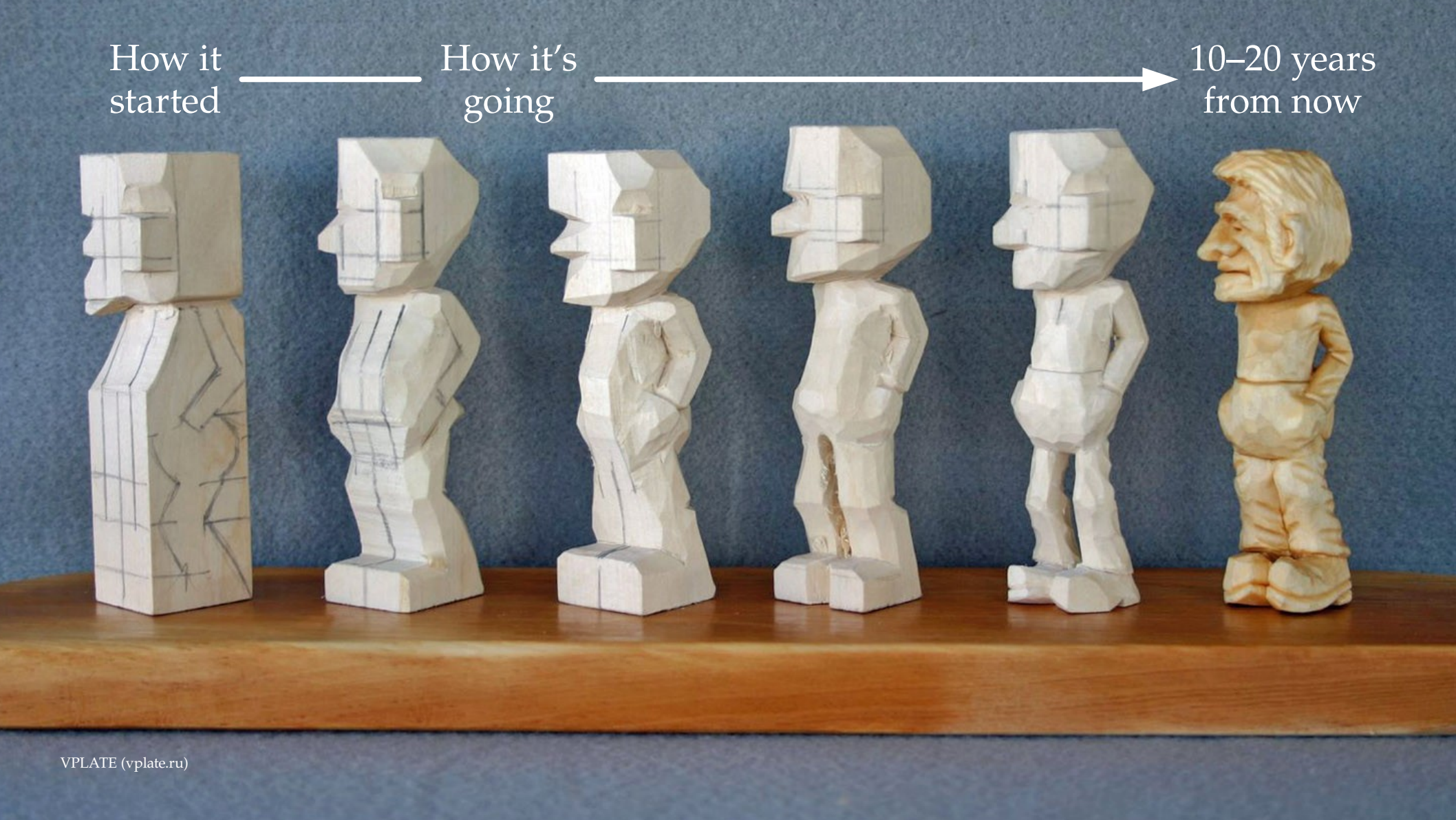
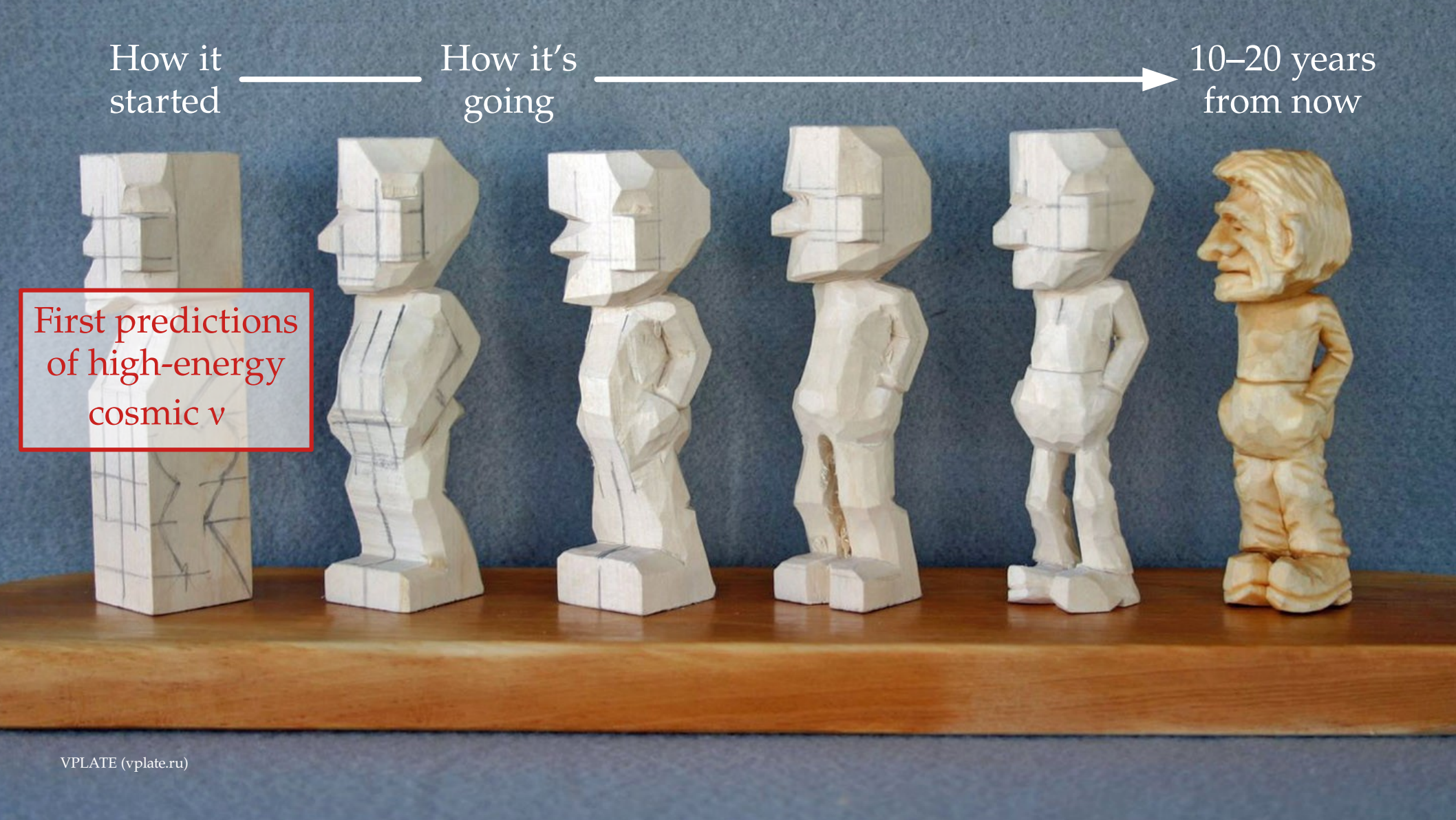
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

1st Nordic Meeting on Neutrino and Radio Astronomy
Chalmers U., May 30, 2024


How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)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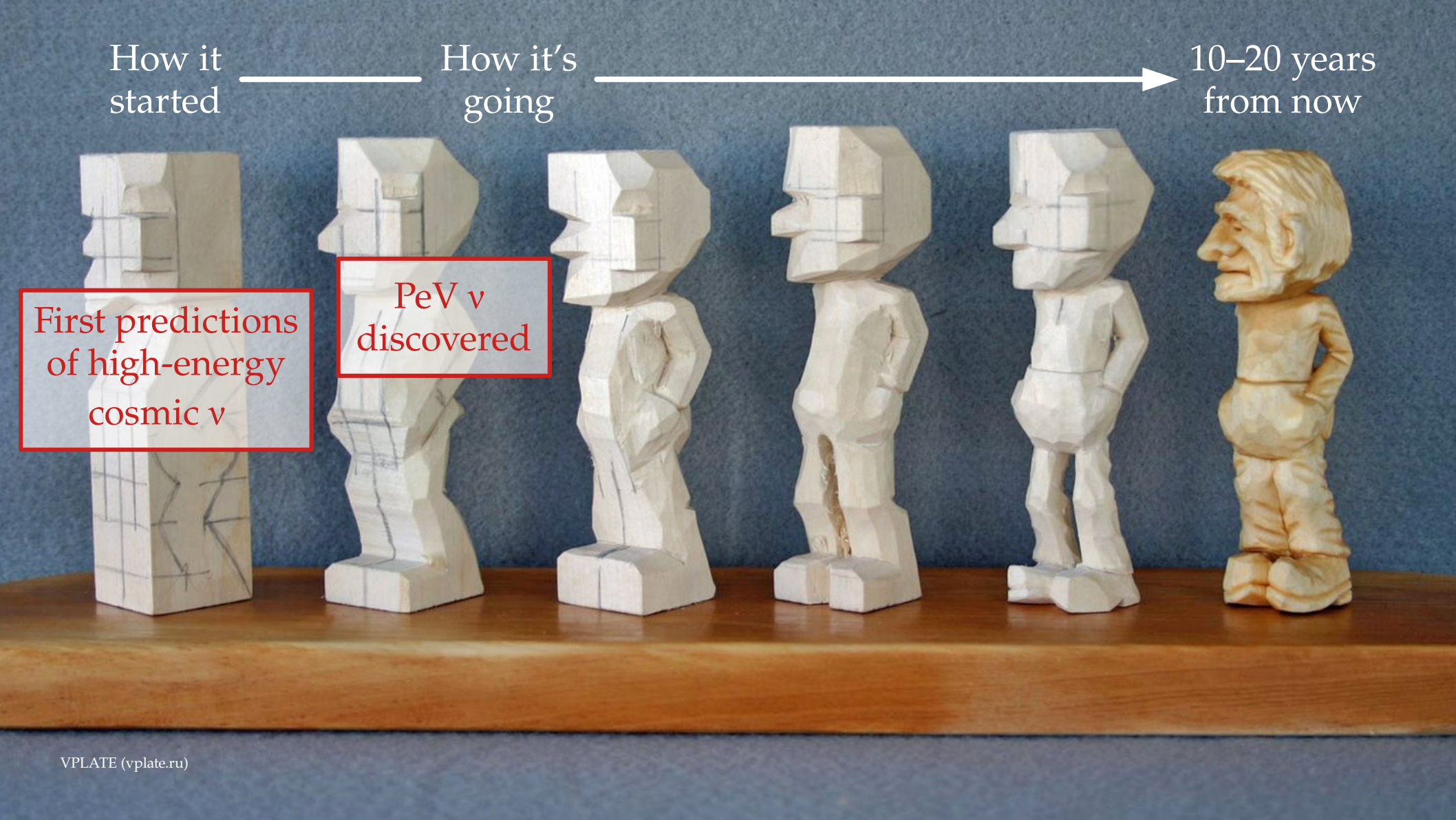
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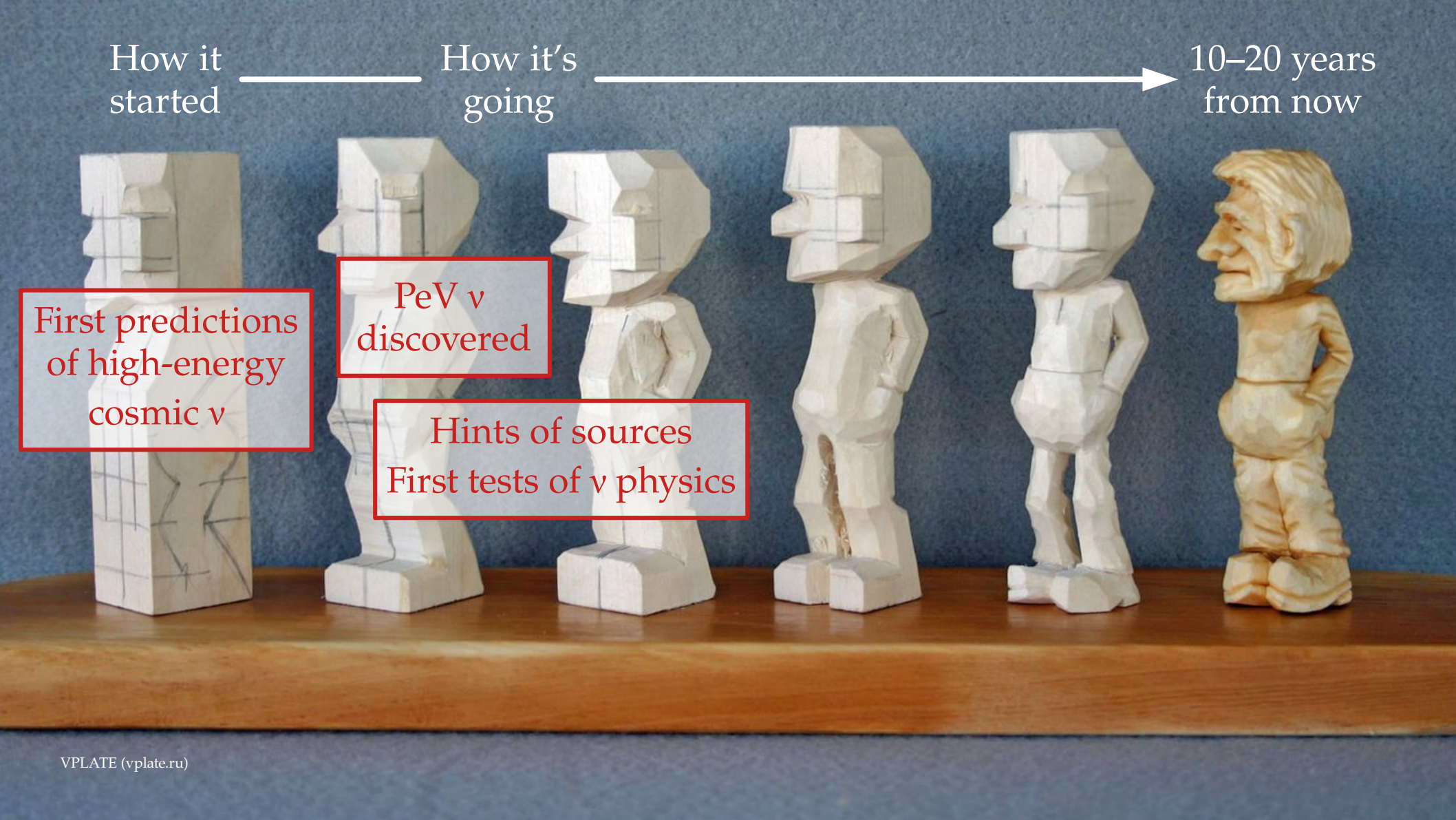
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First tests of ν physics
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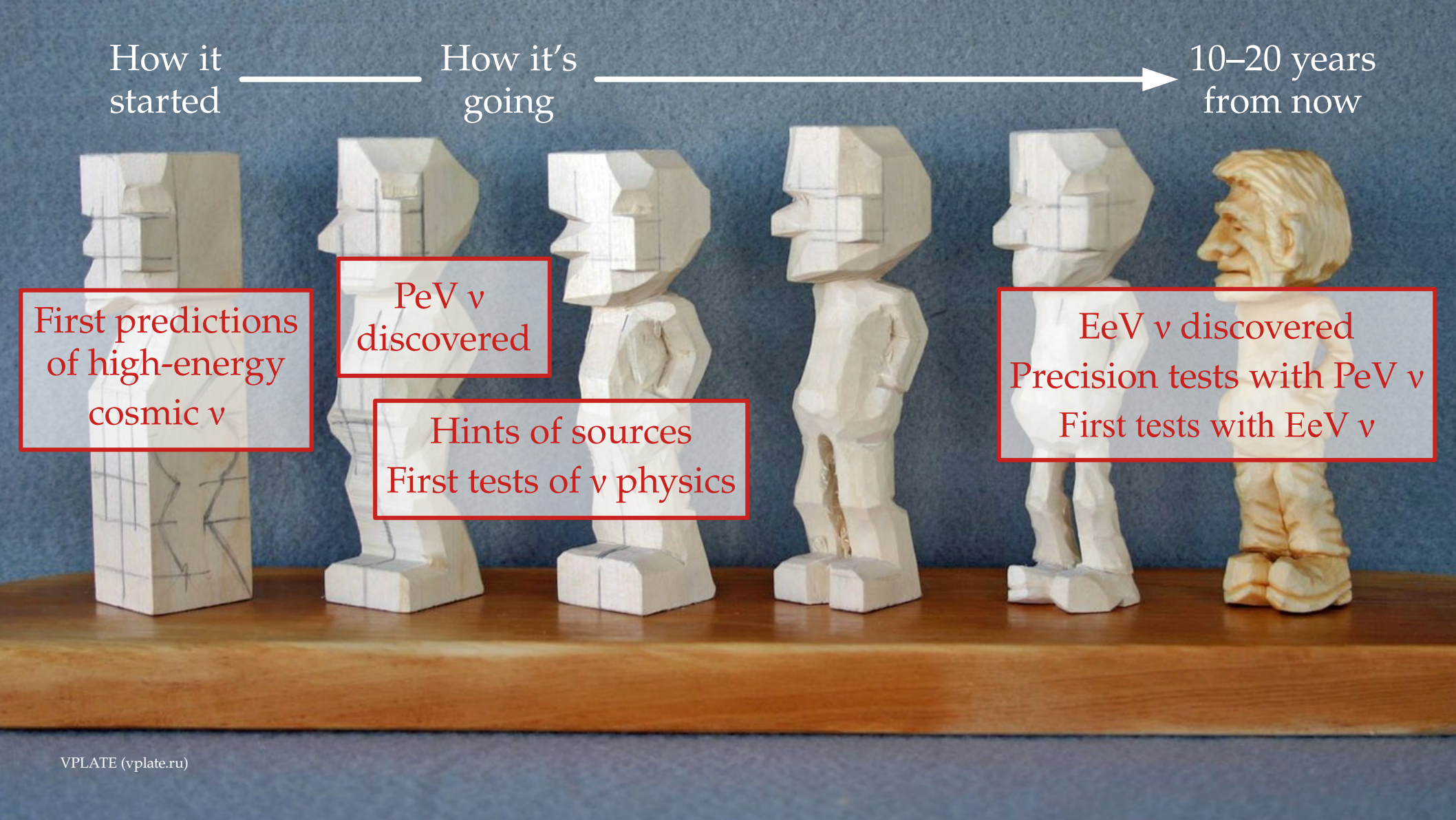
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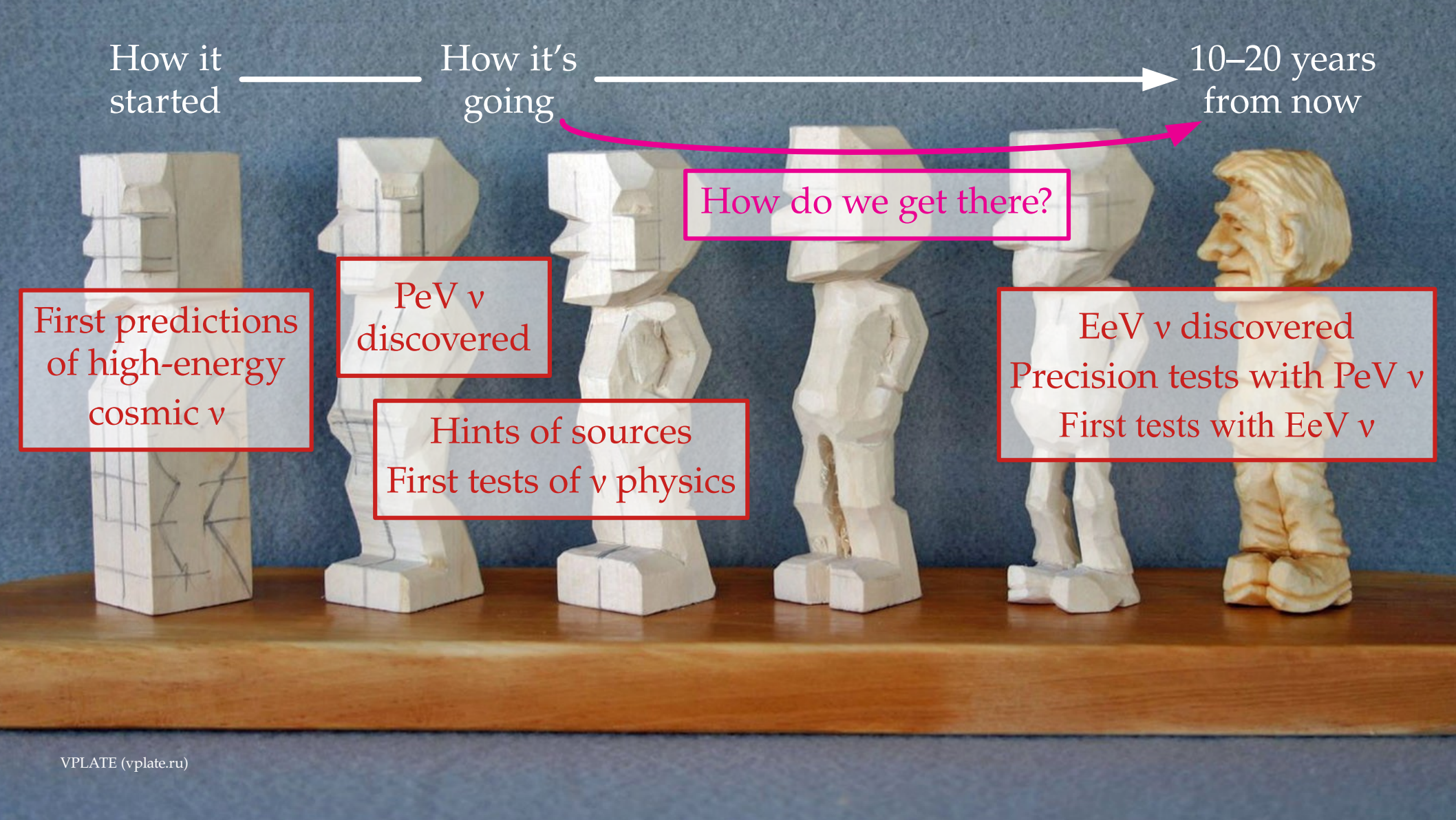
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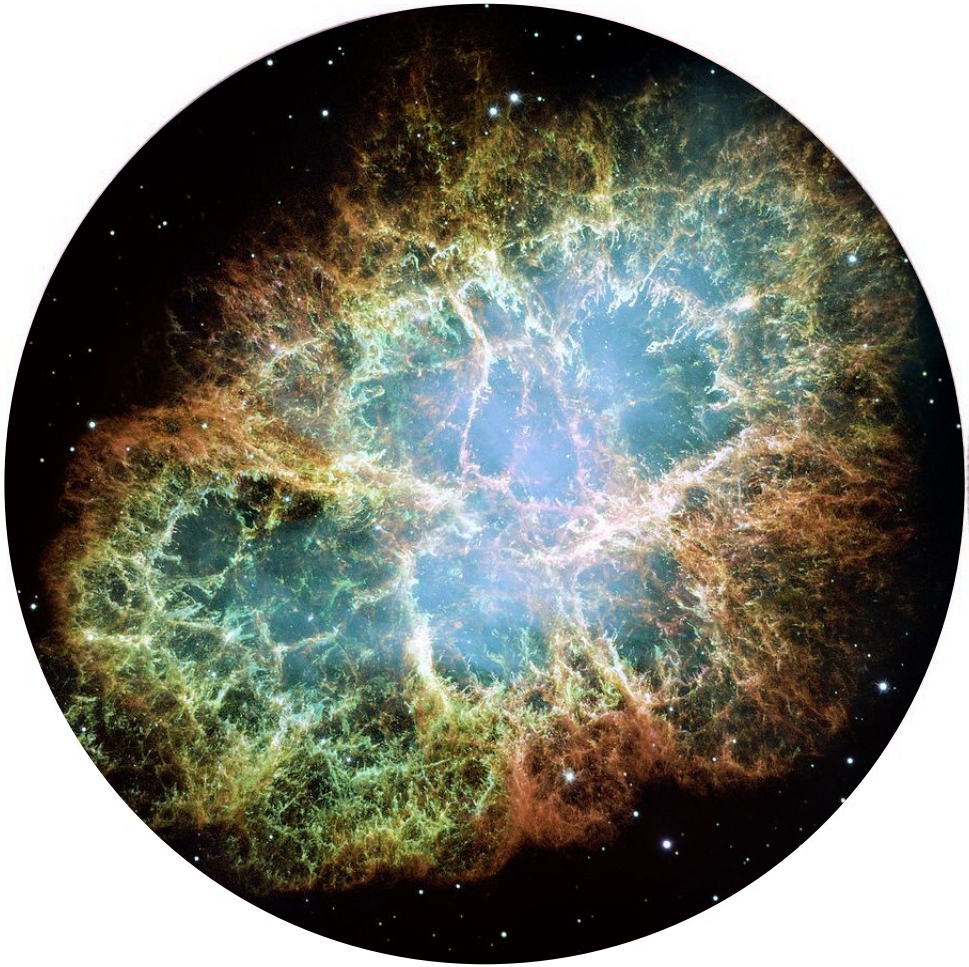

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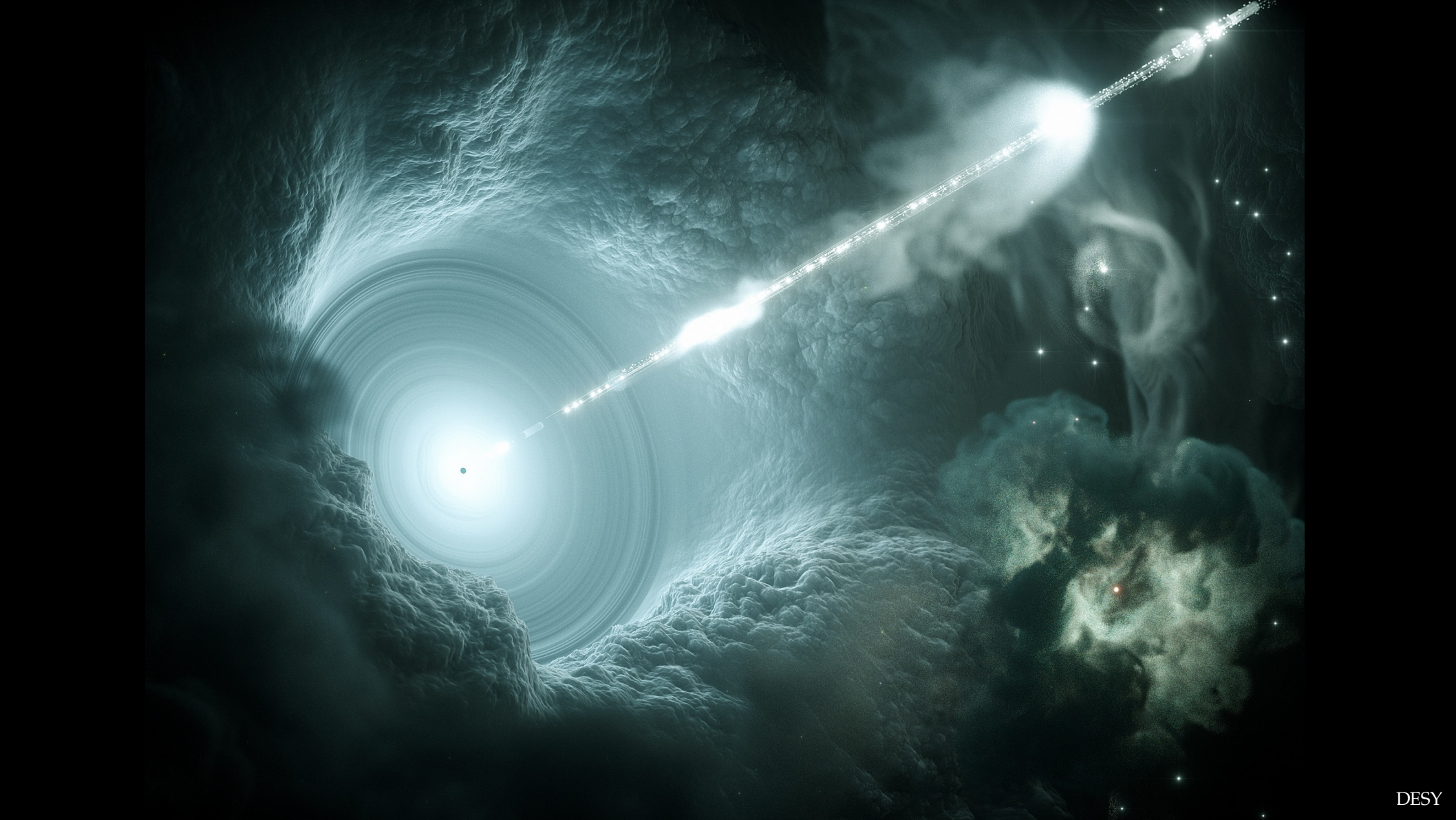

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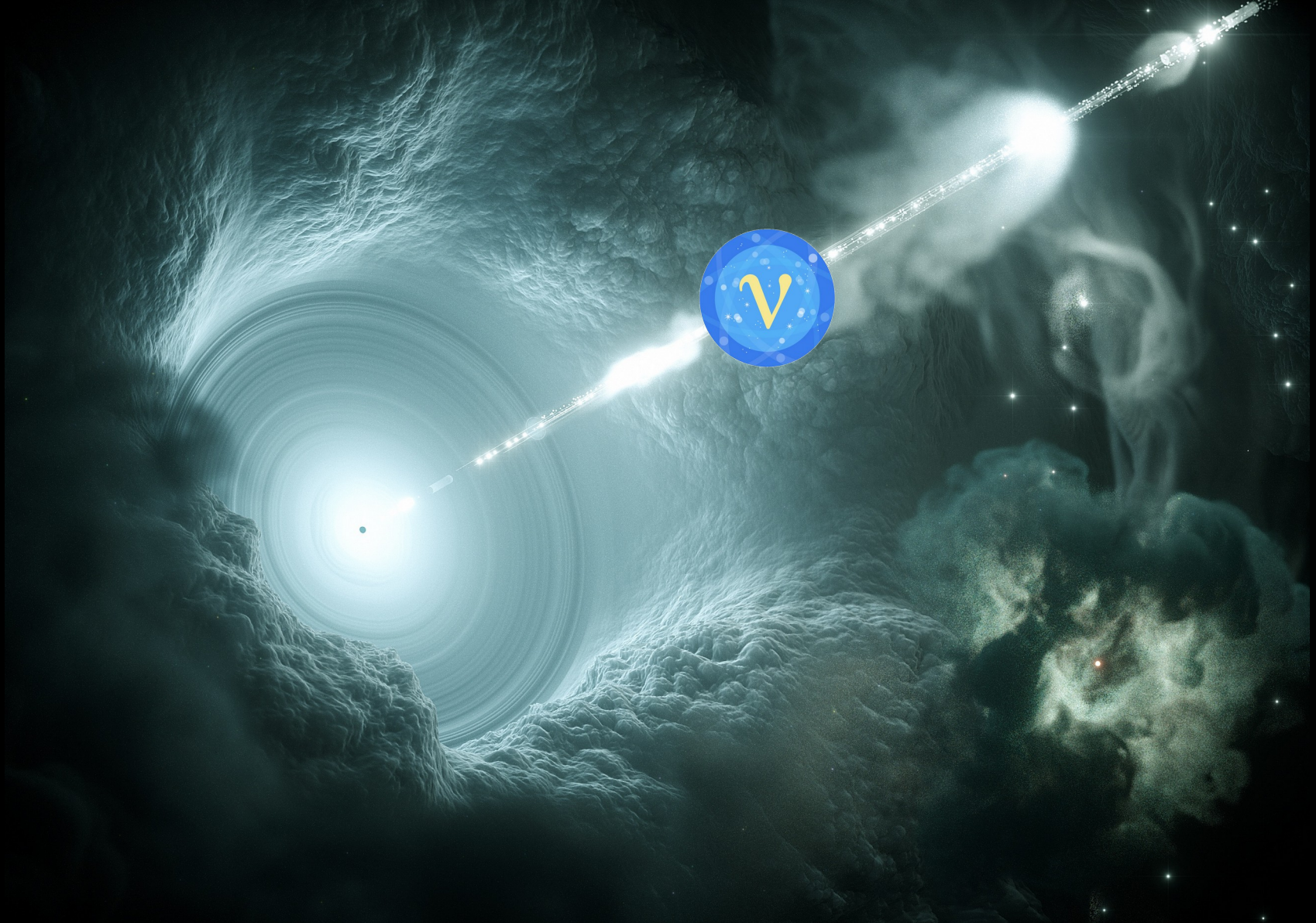

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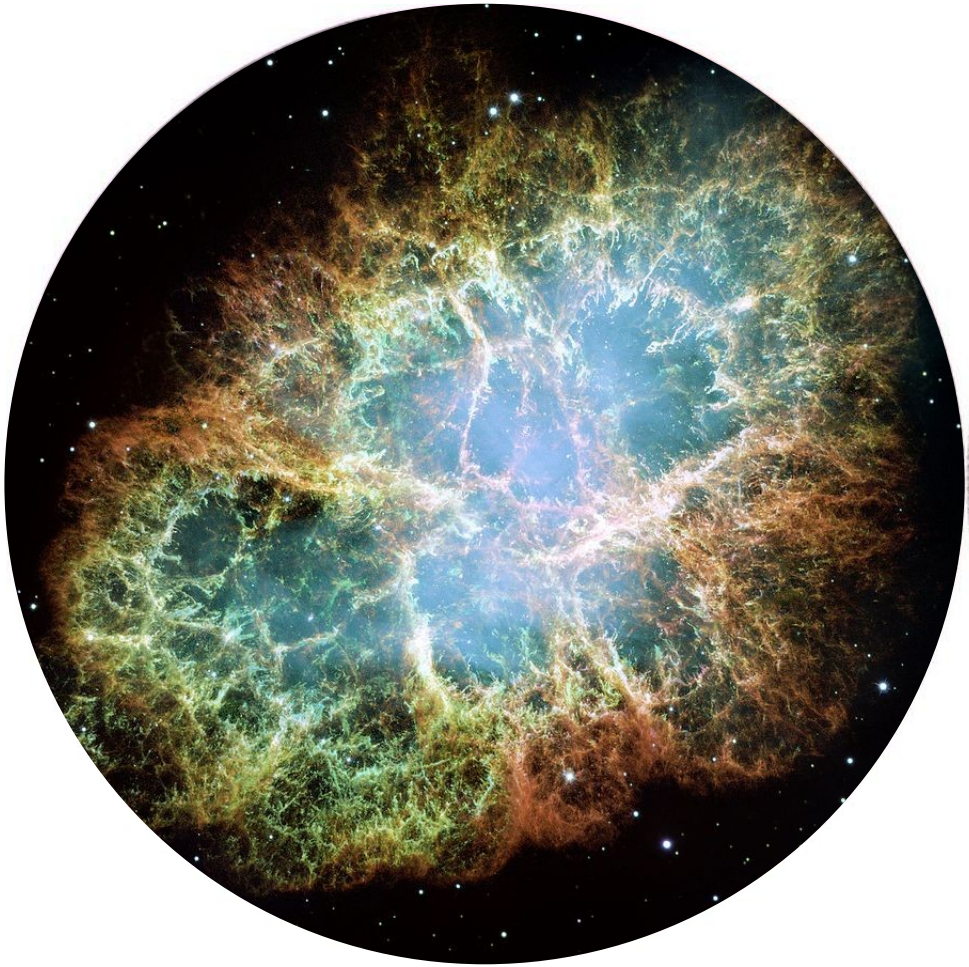

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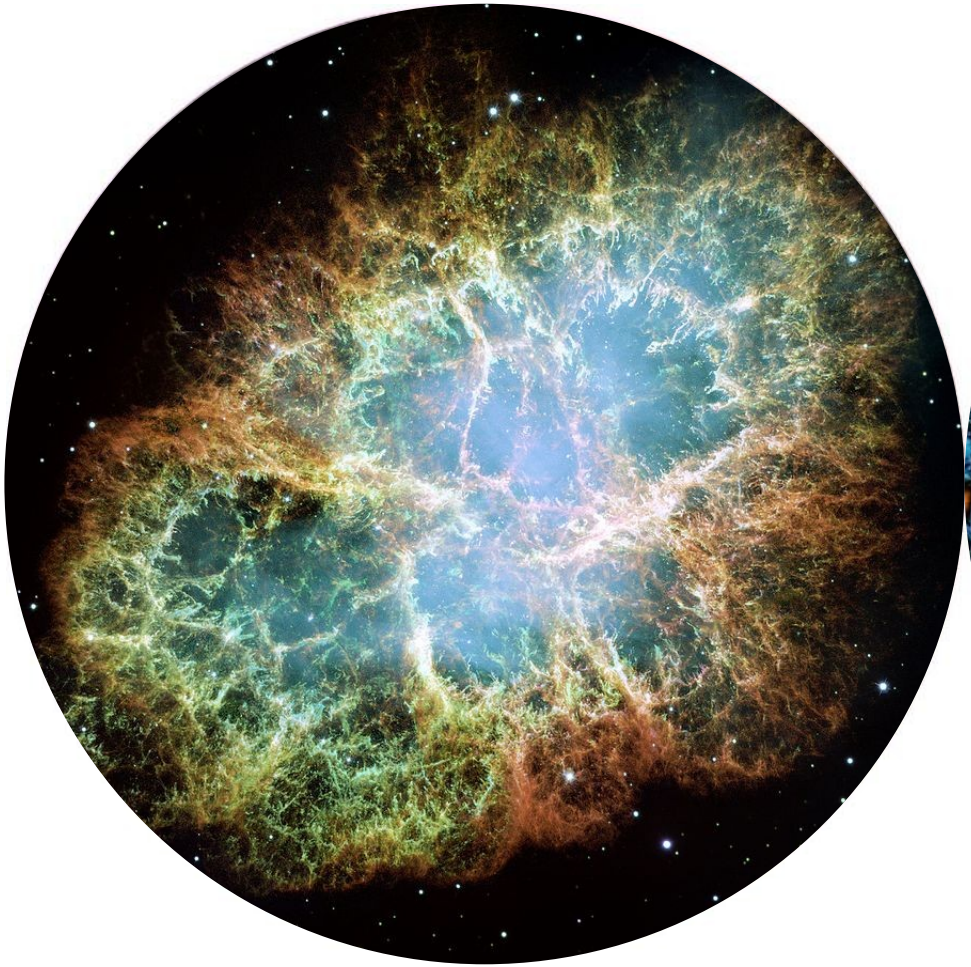

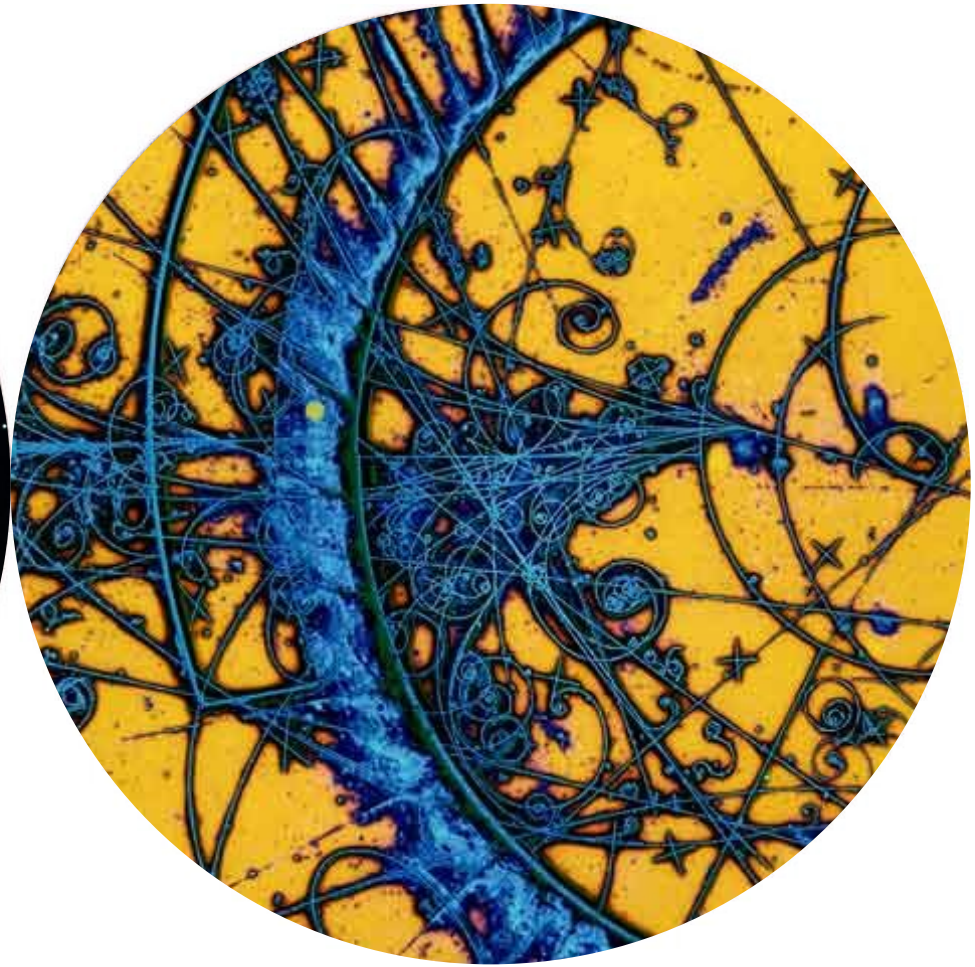

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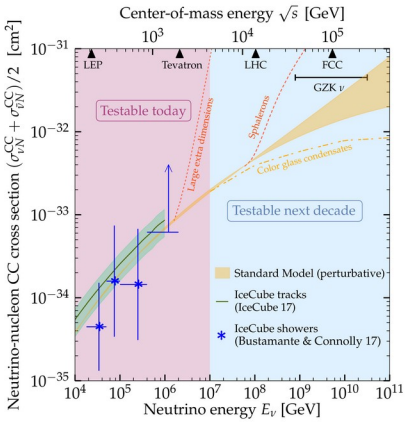
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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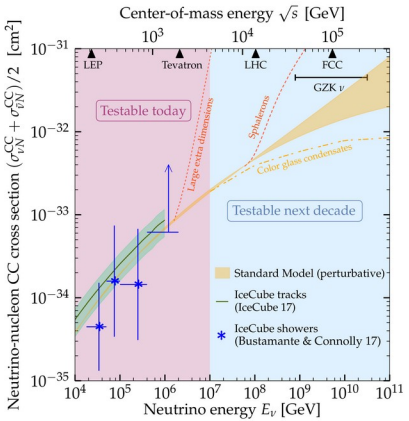
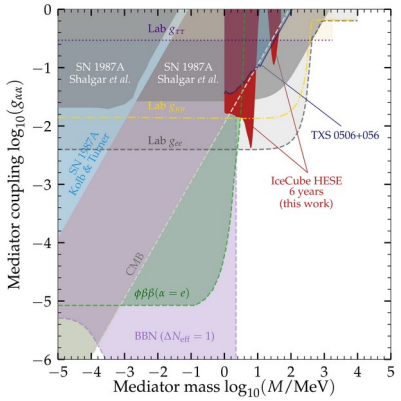


MB & Connolly, *PRL* 2019

ν self-interactions



MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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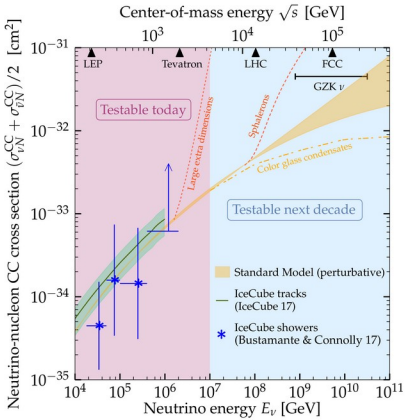

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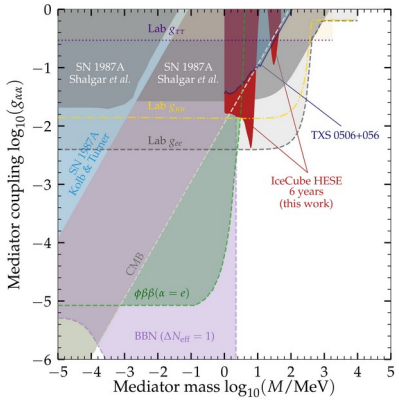

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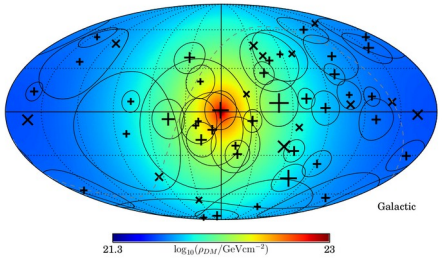
ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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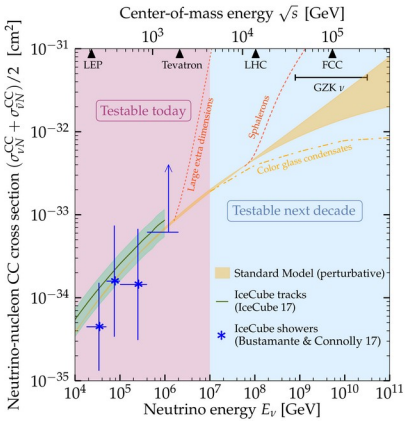

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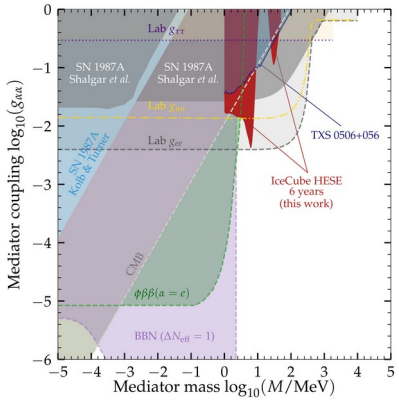

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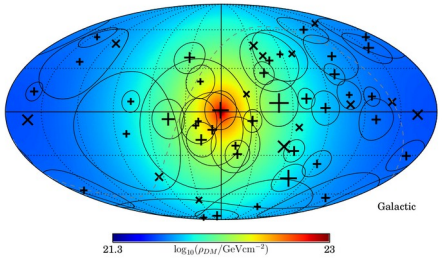

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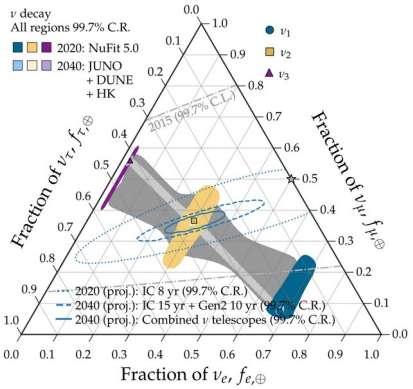
ν decay



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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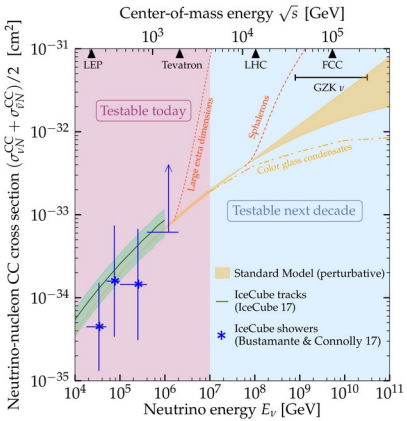

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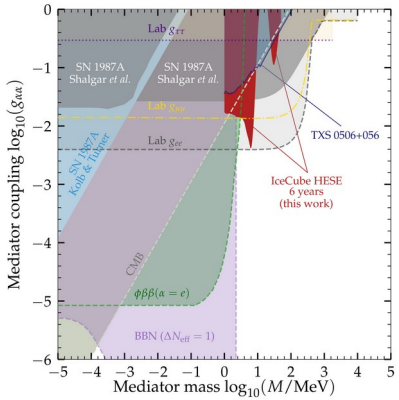

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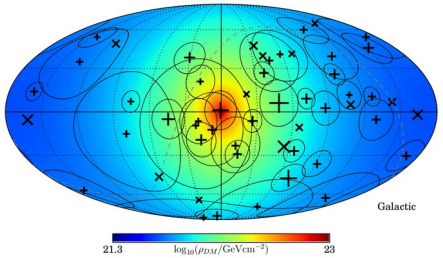

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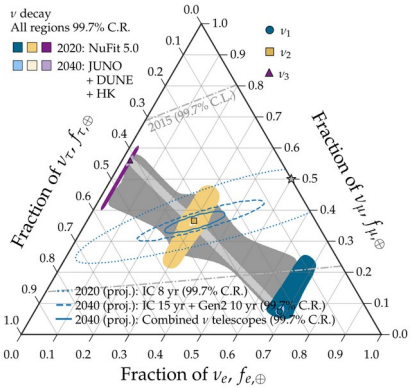

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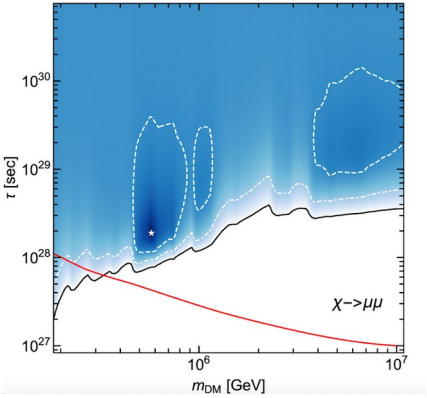
Dark matter decay



Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

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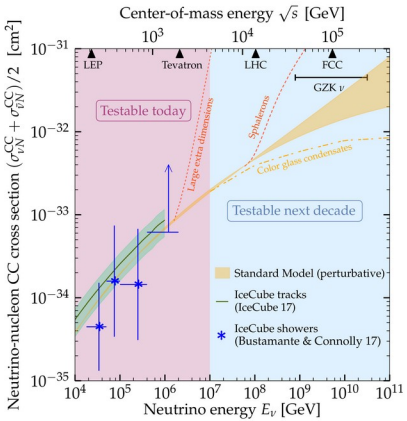

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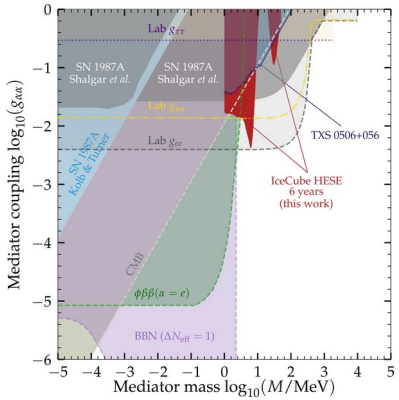

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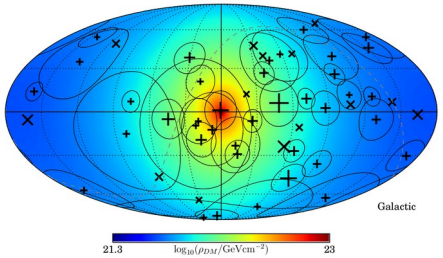

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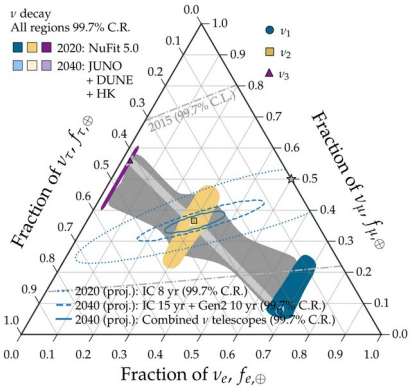

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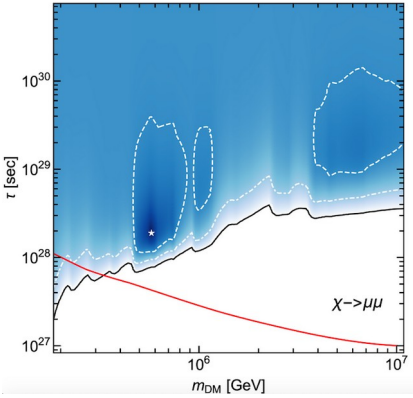

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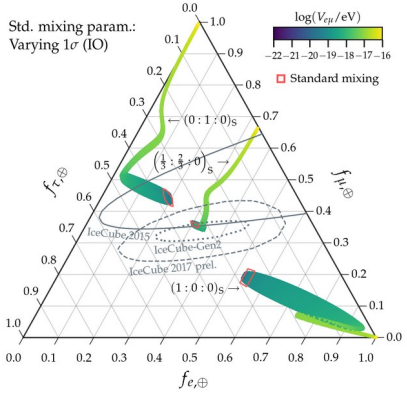

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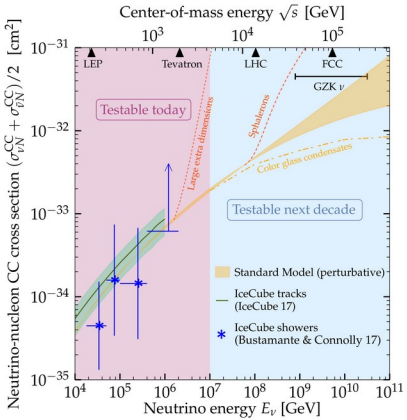

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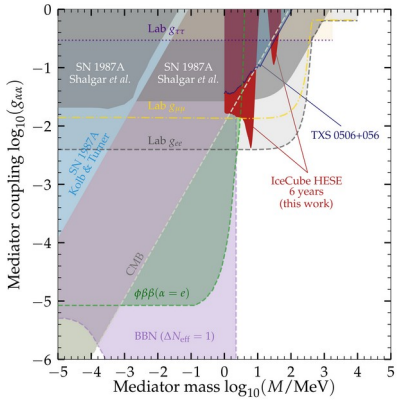

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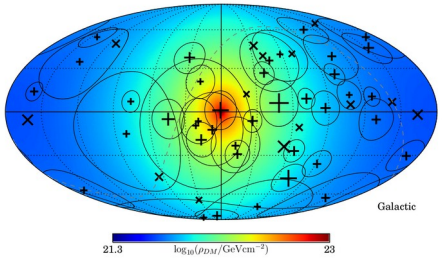

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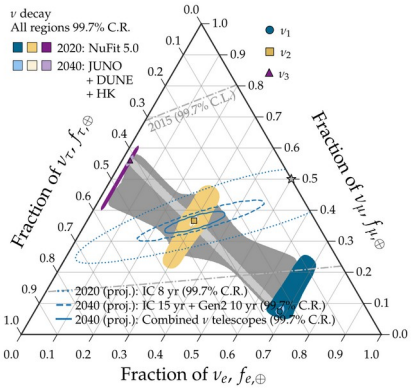

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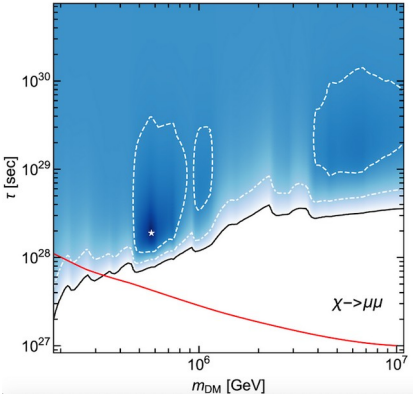

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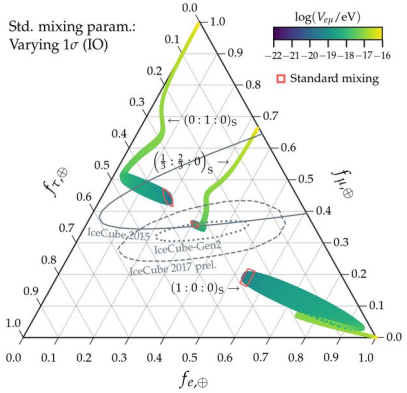

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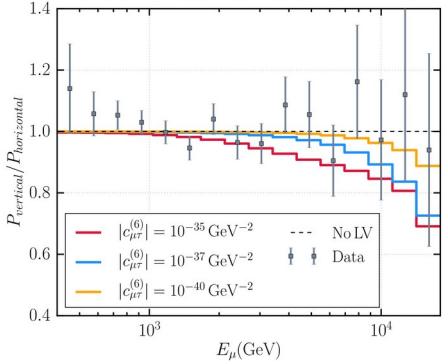
Lorentz-invariance violation



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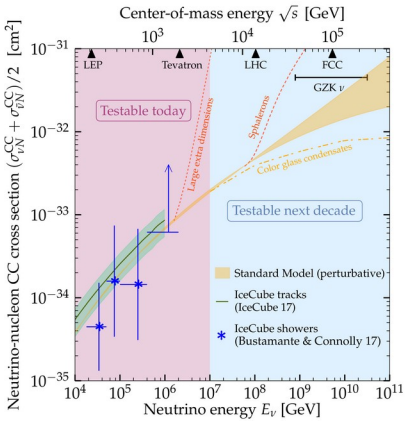

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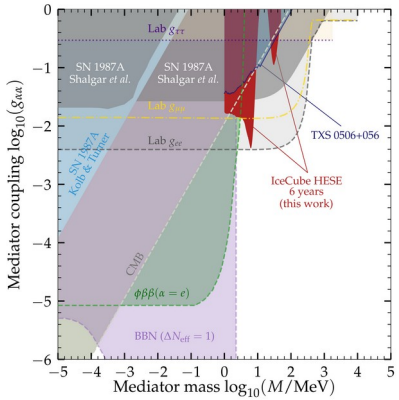

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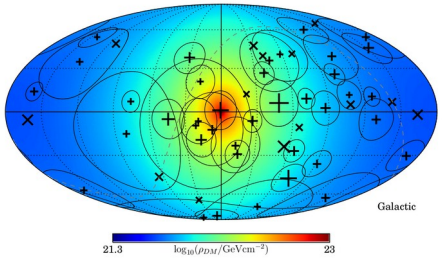

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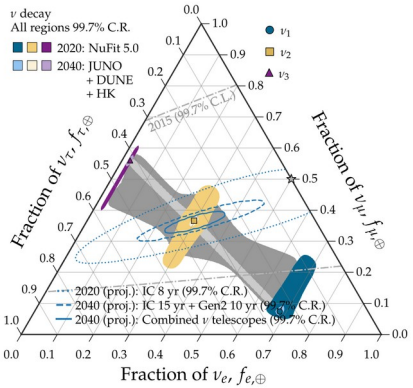

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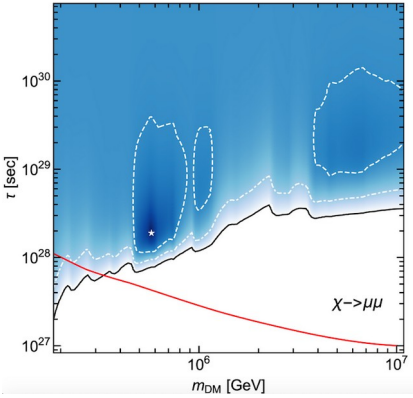

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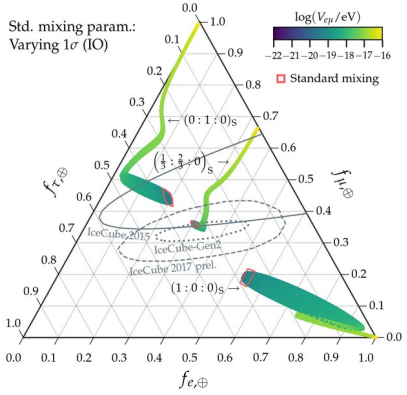

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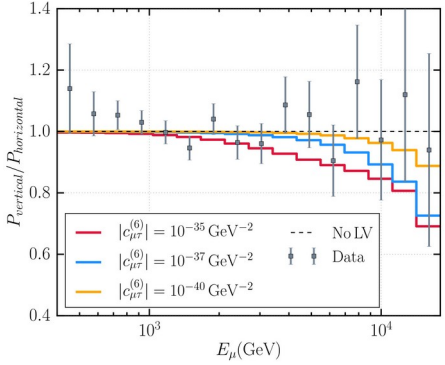
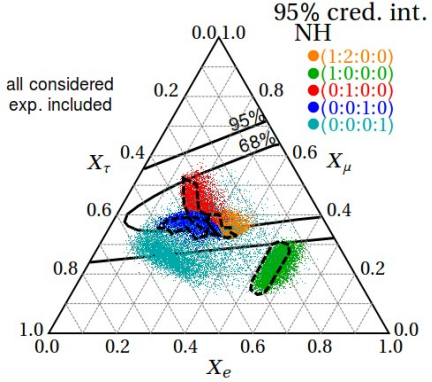
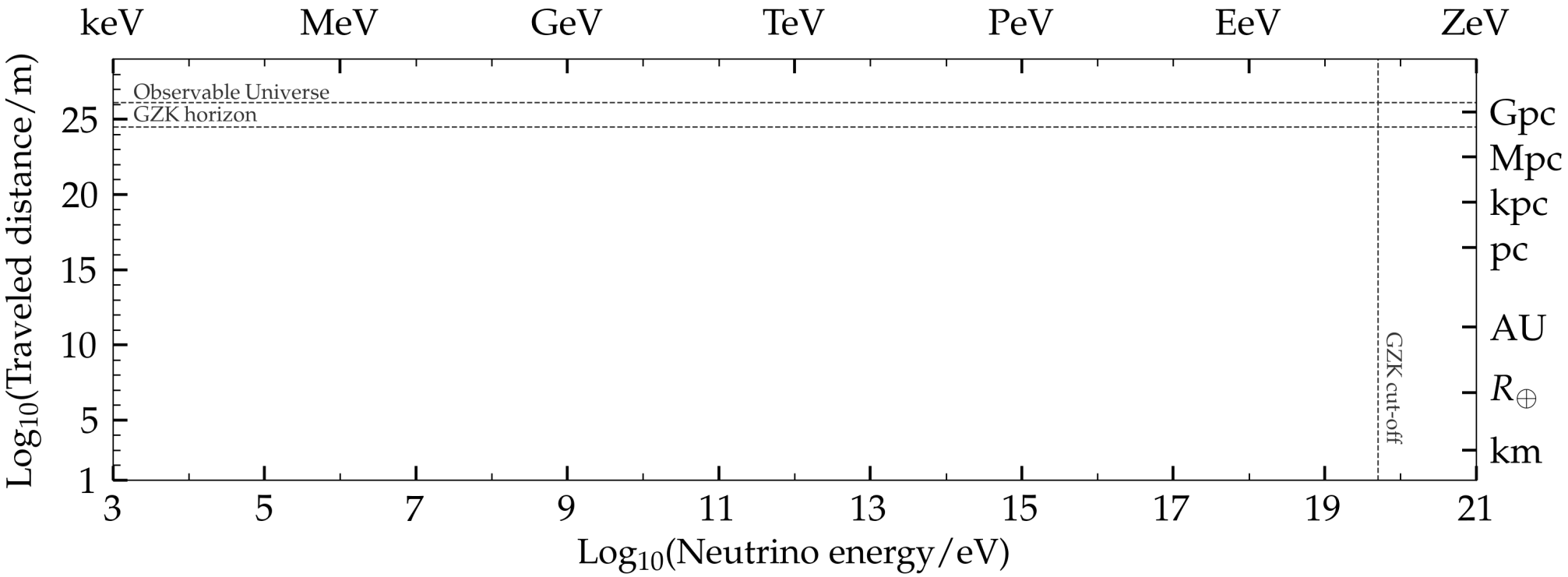


IceCube, *Nature Phys.* 2018

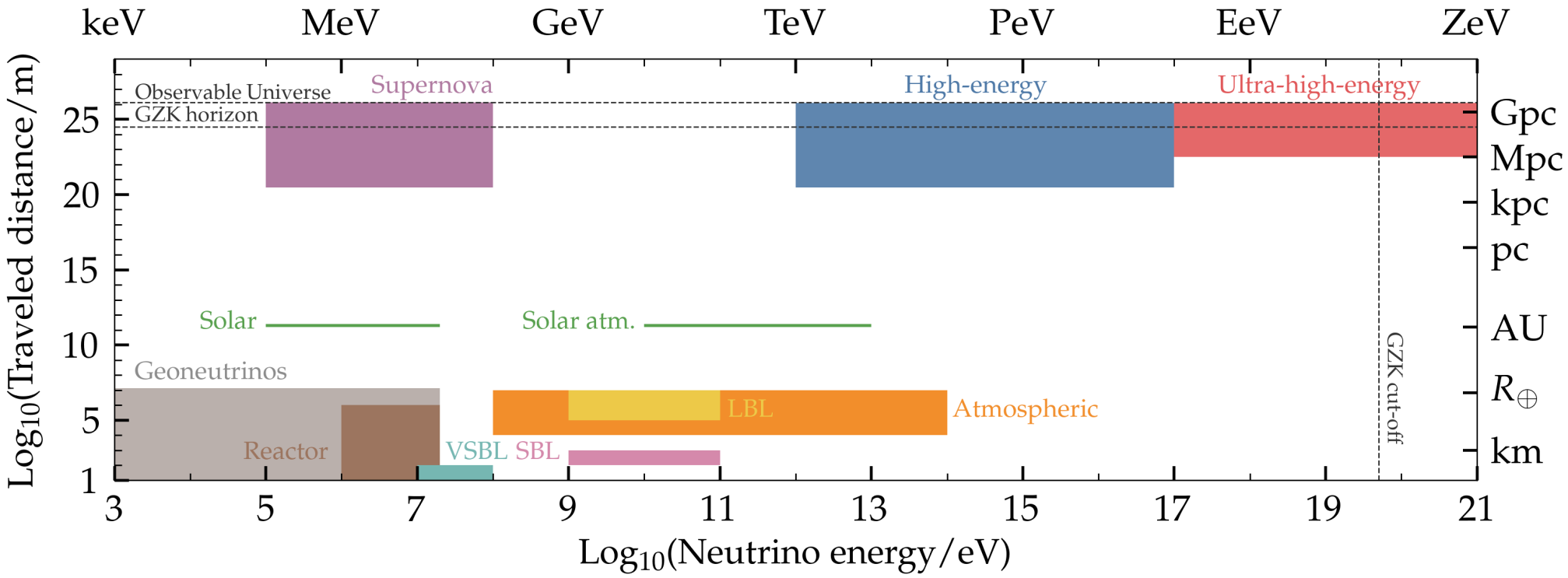
Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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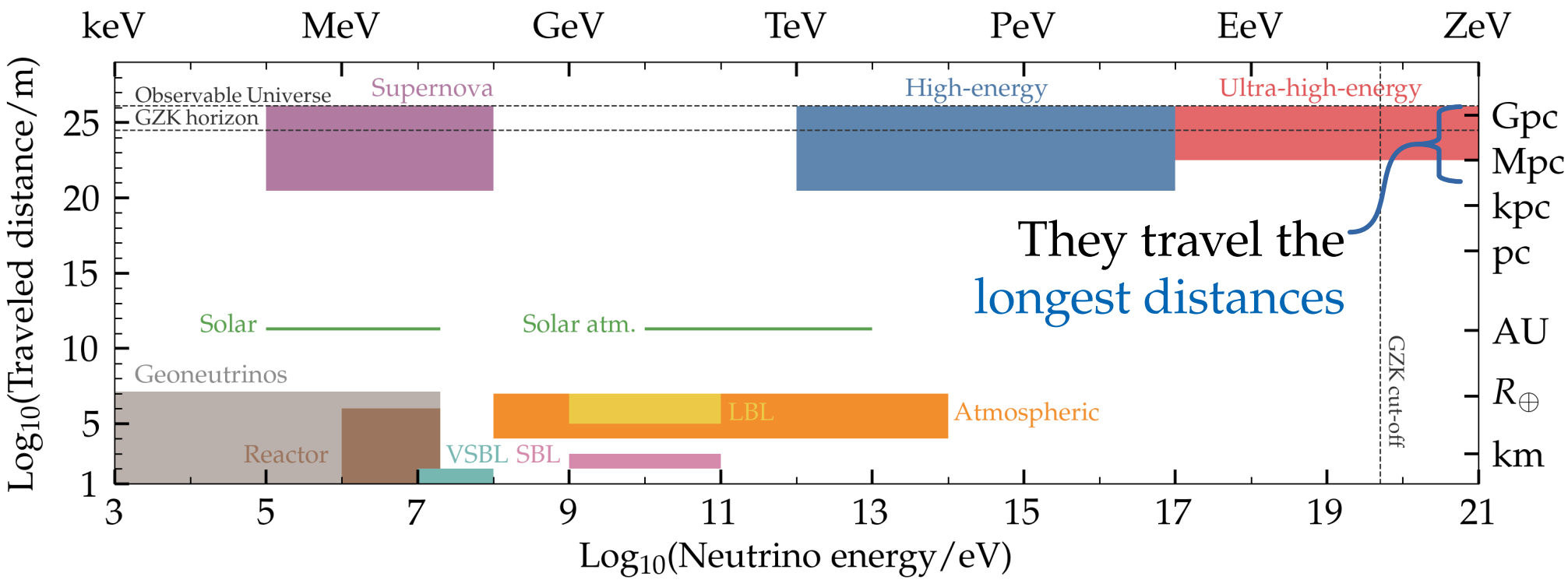
They have the highest energies



They travel the longest distances

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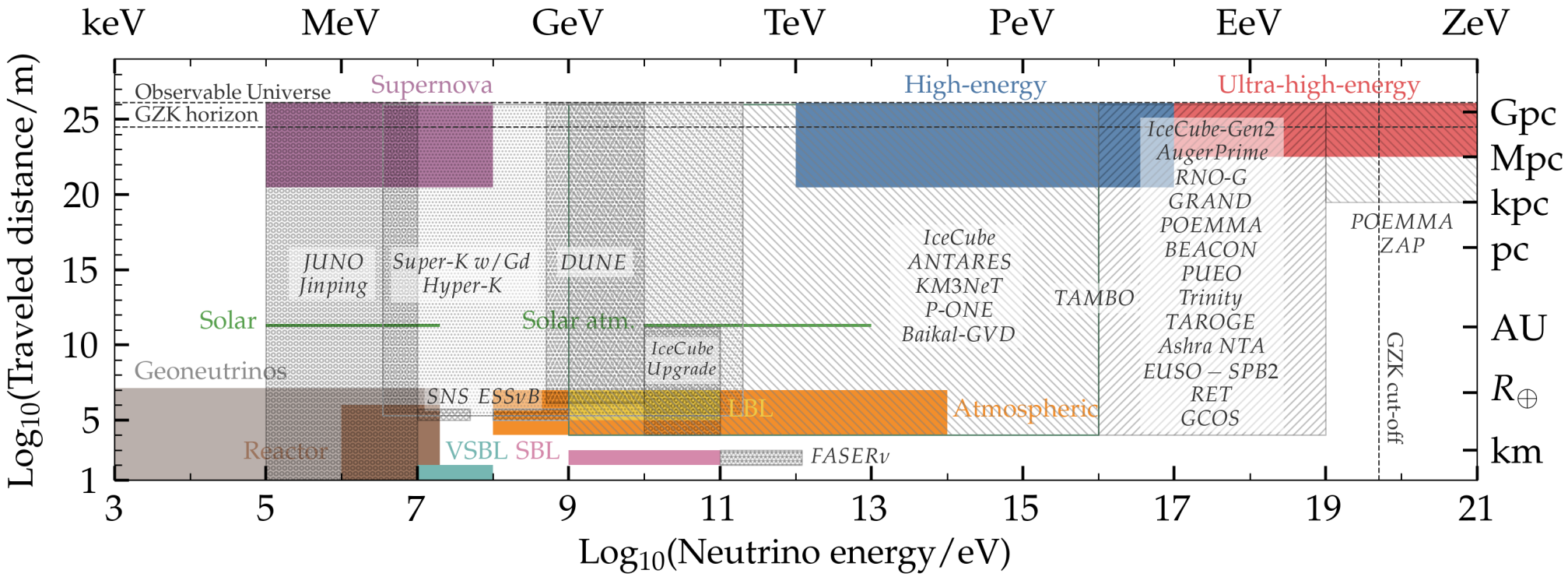

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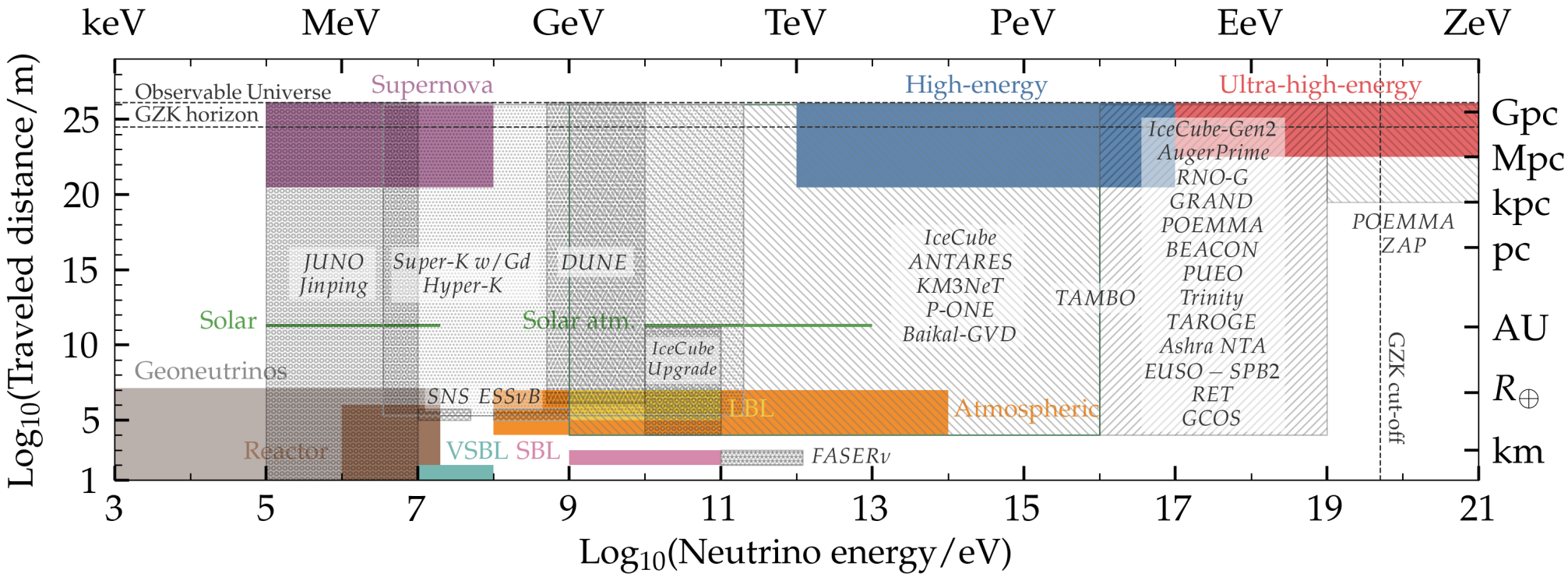
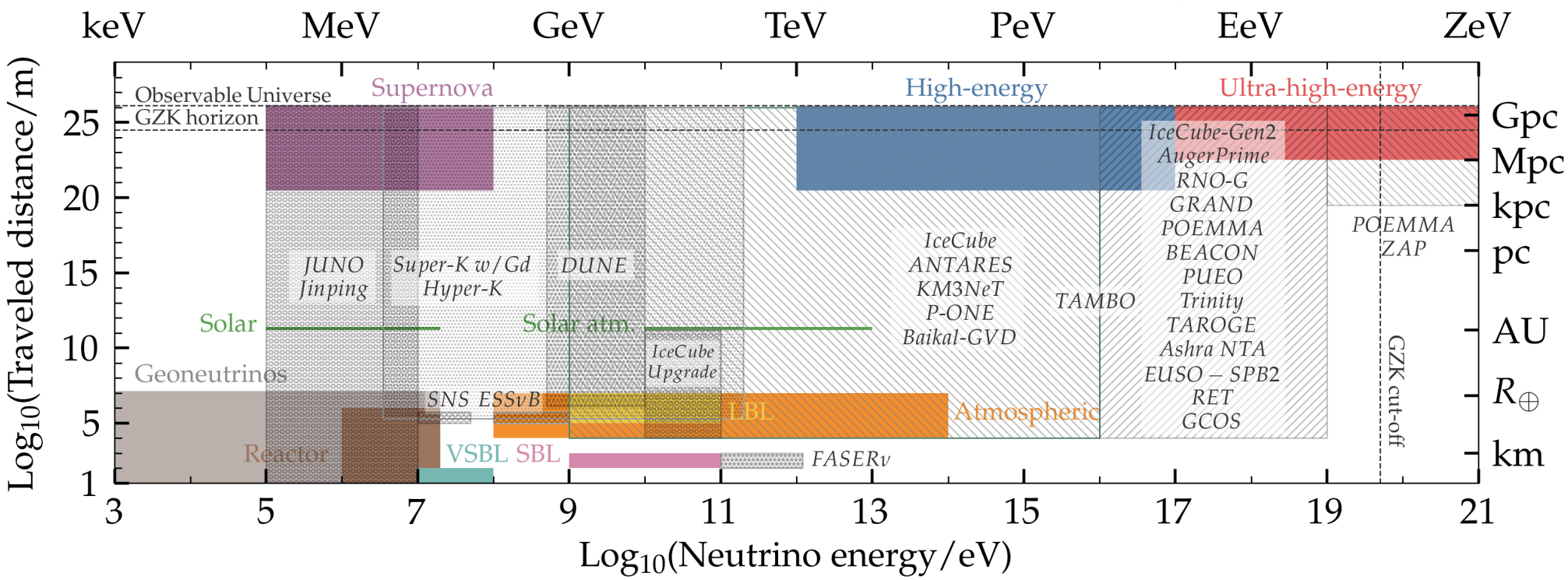


Synergies with lower energies

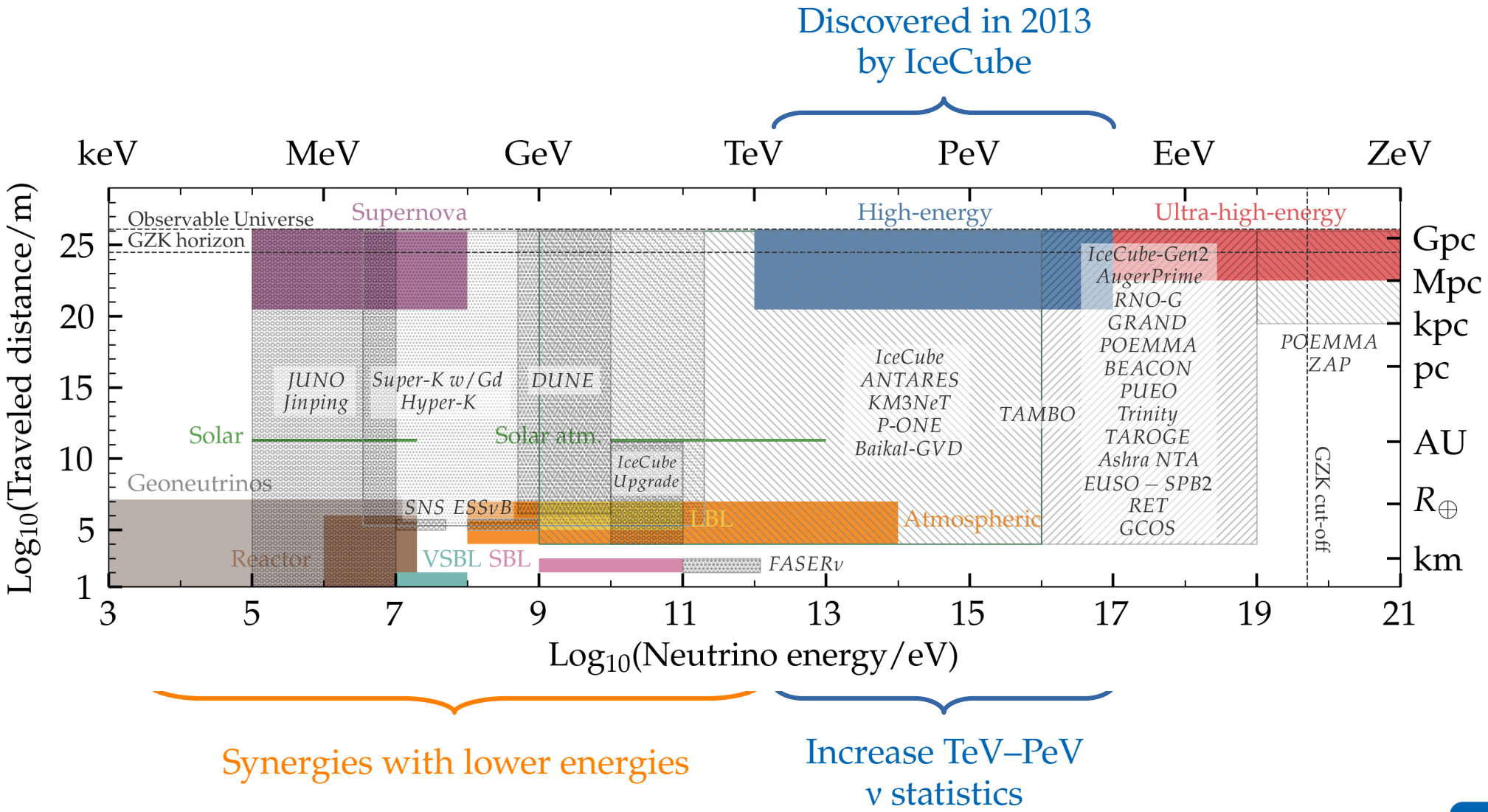
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Discovered in 2013
by IceCube

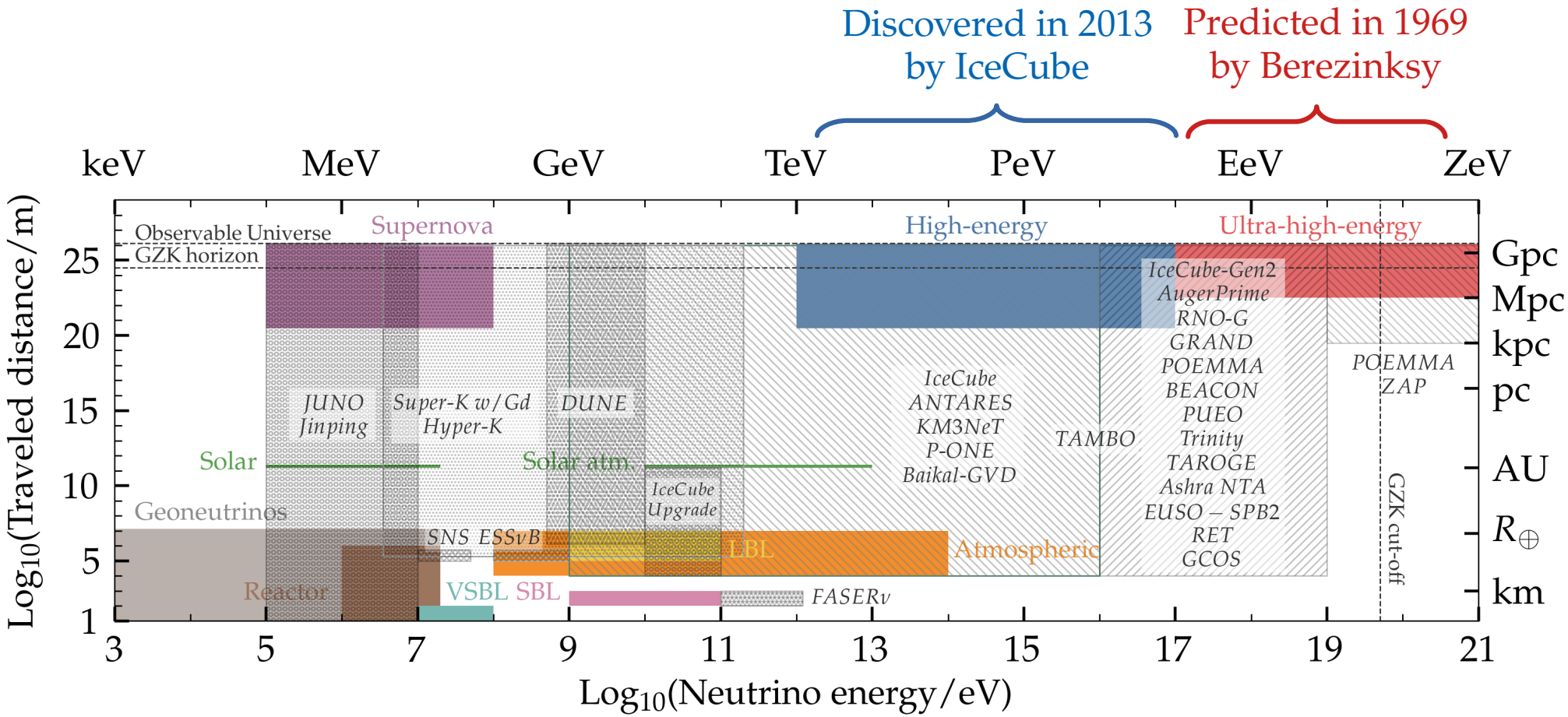


Synergies with lower energies

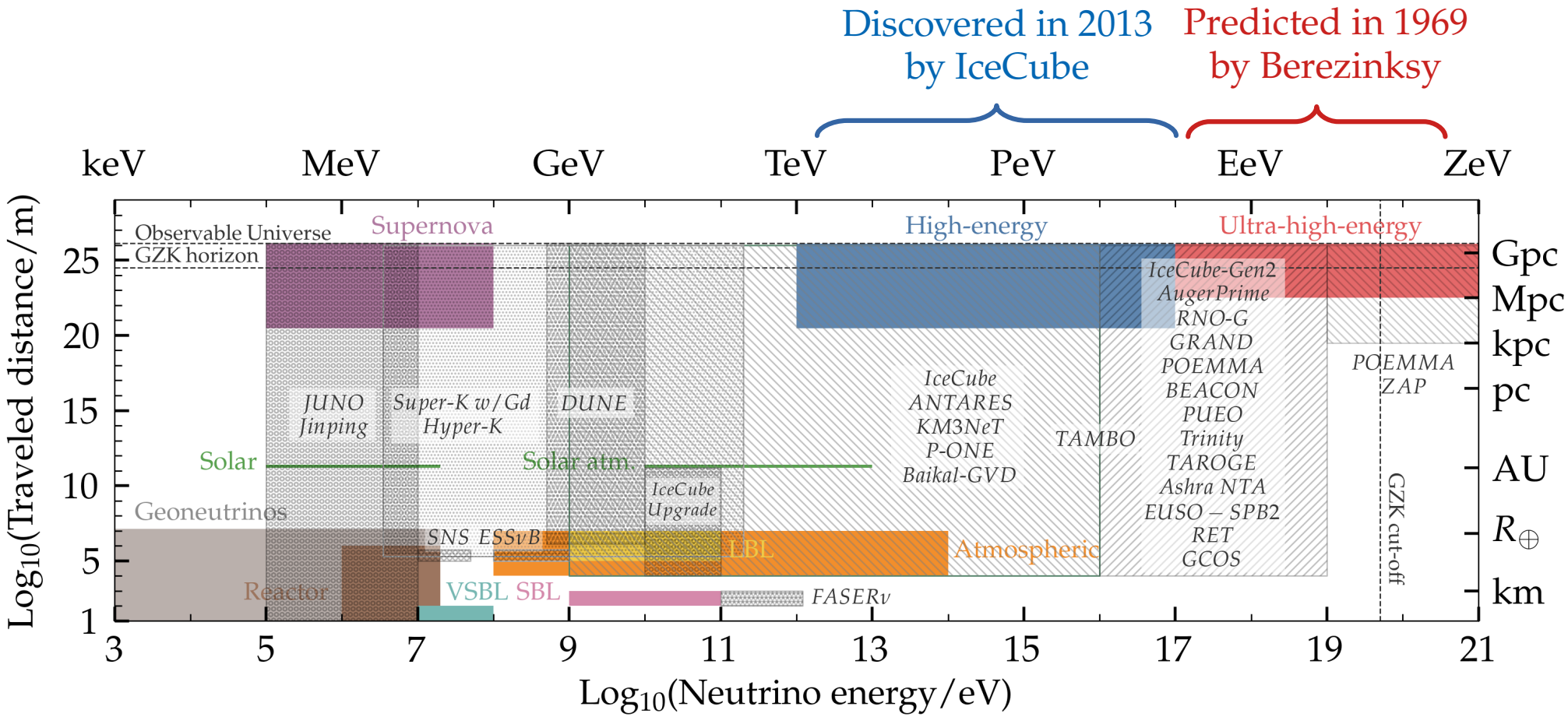
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

Today

TeV–PeV ν

Next decade

> 100-PeV ν

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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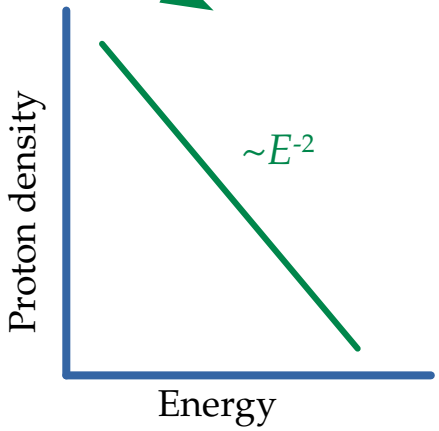

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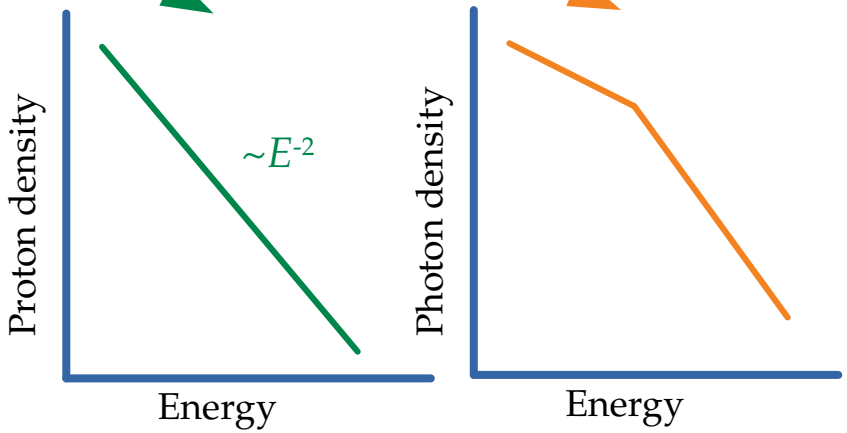

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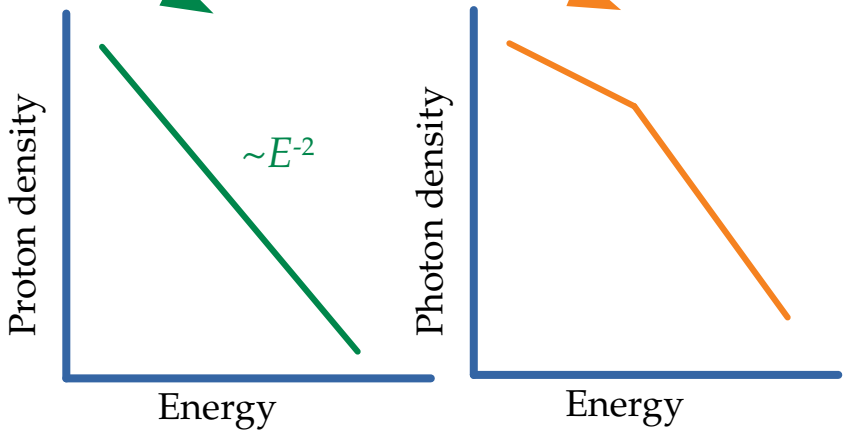
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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



Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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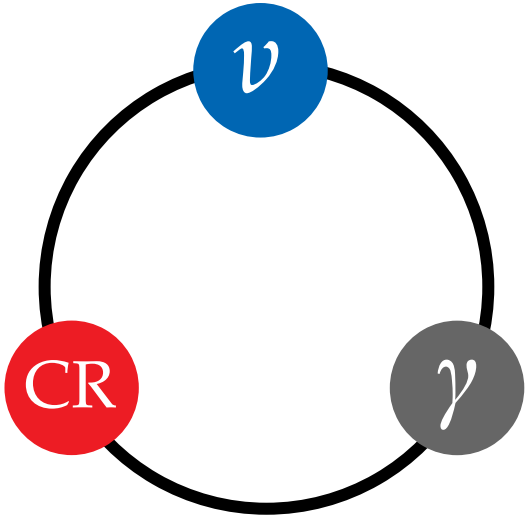
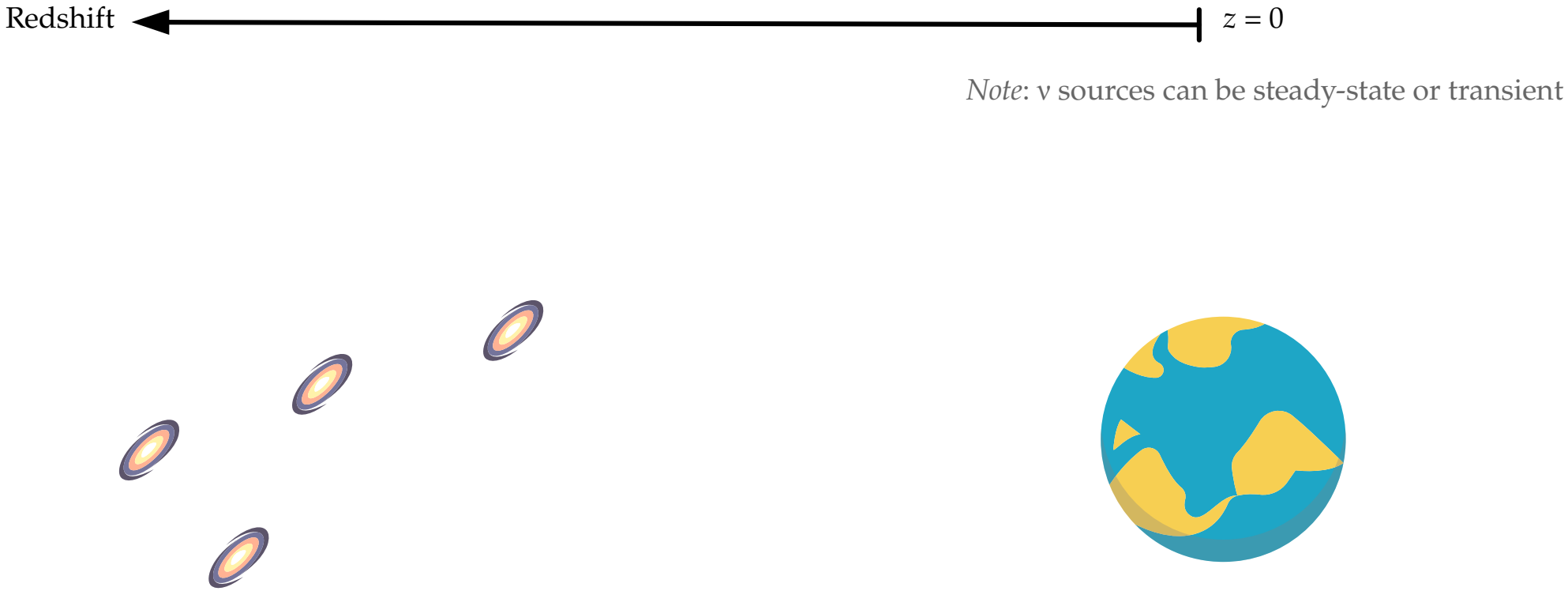
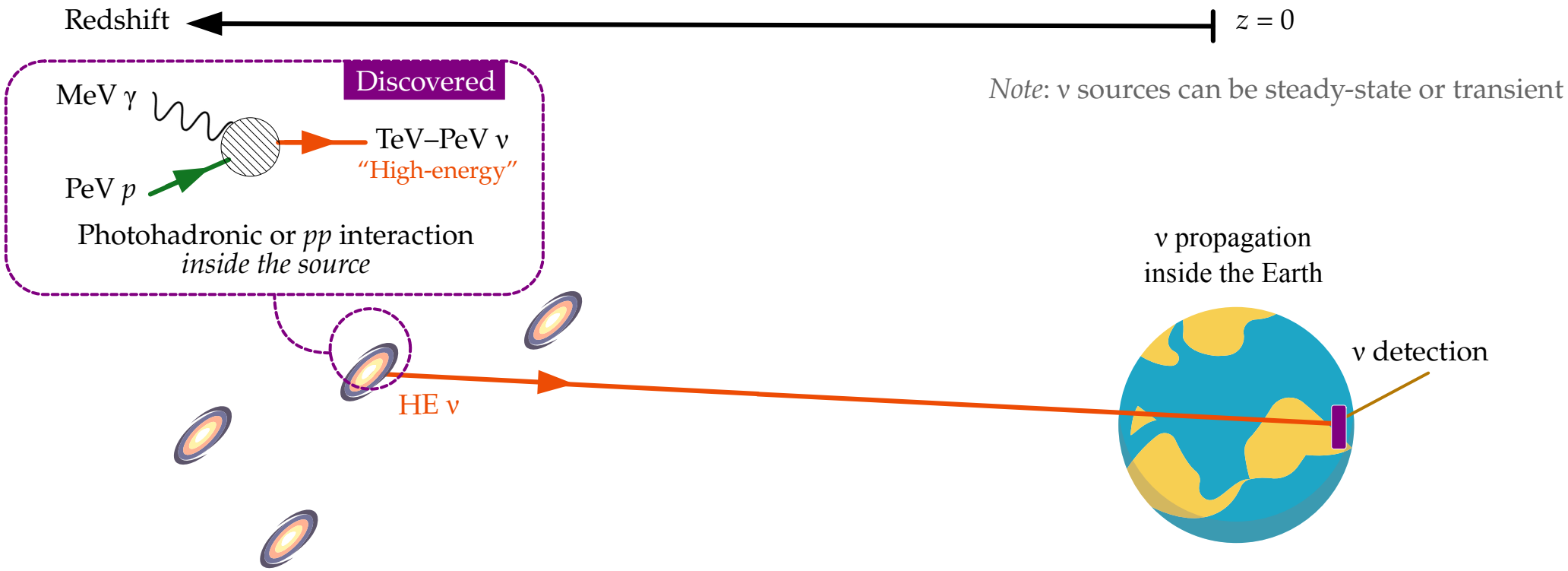


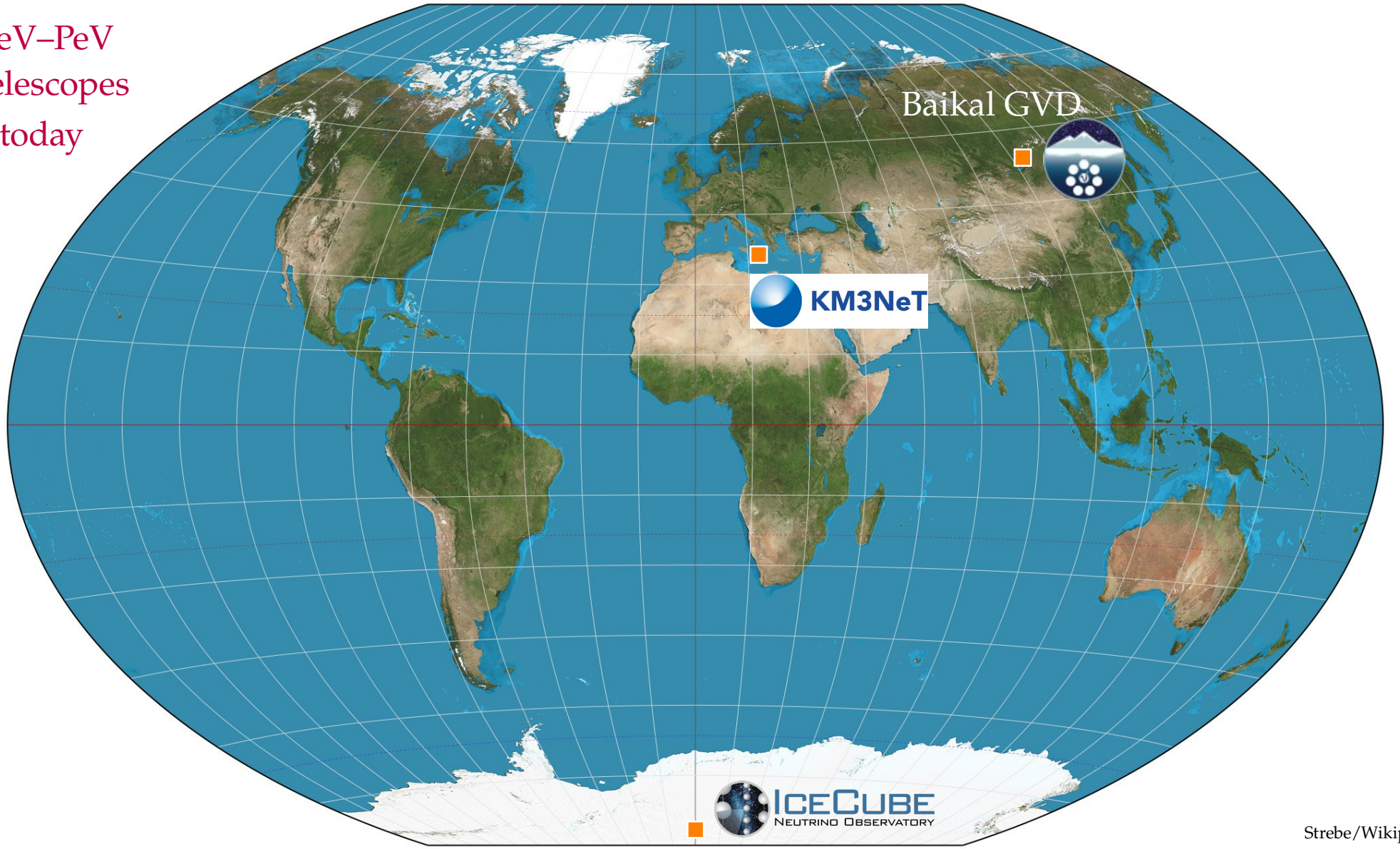
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

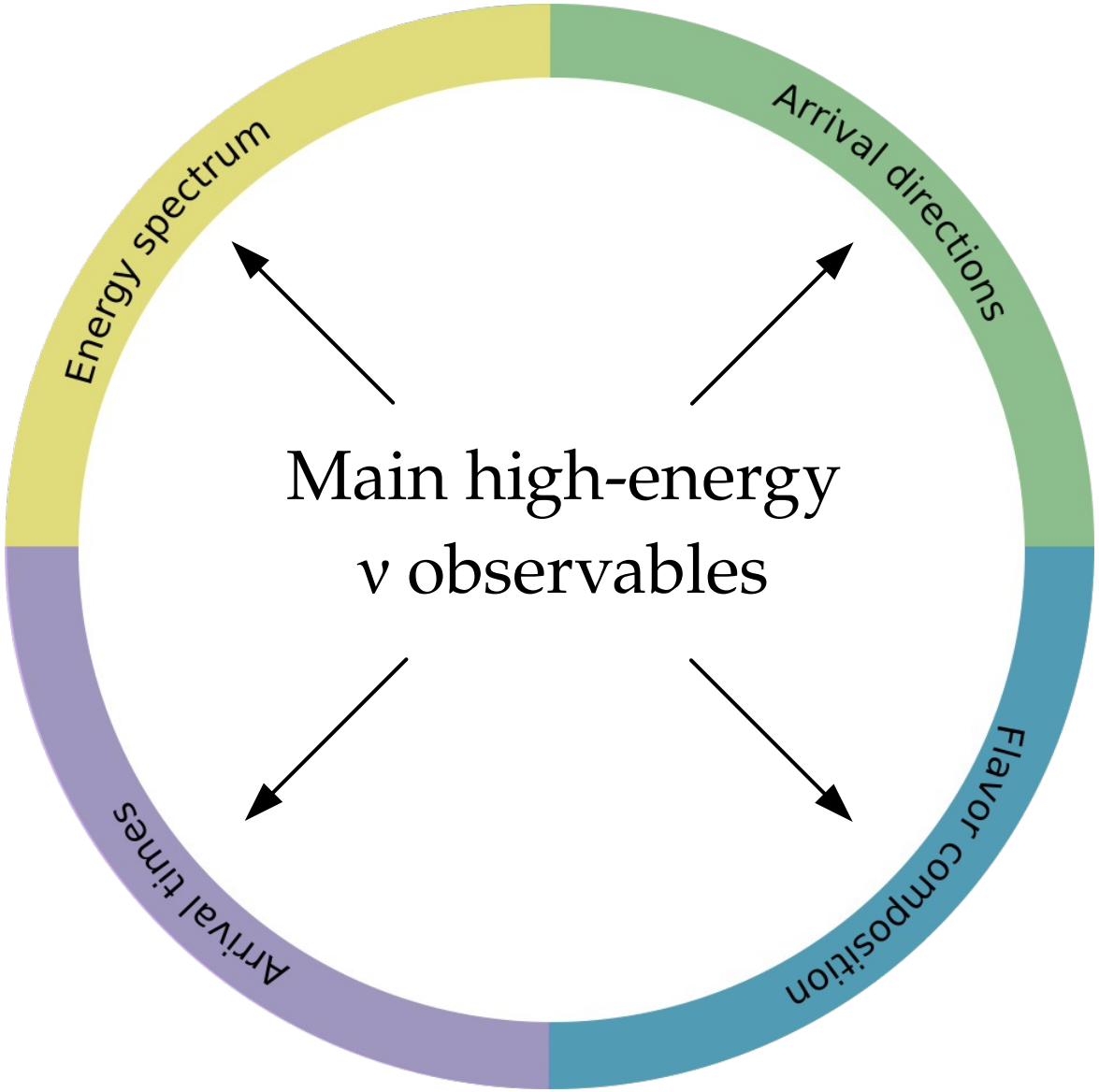

Redshift
$z = 0$
Note: ν sources can be steady-state or transient


Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

TeV–PeV ν telescopes today

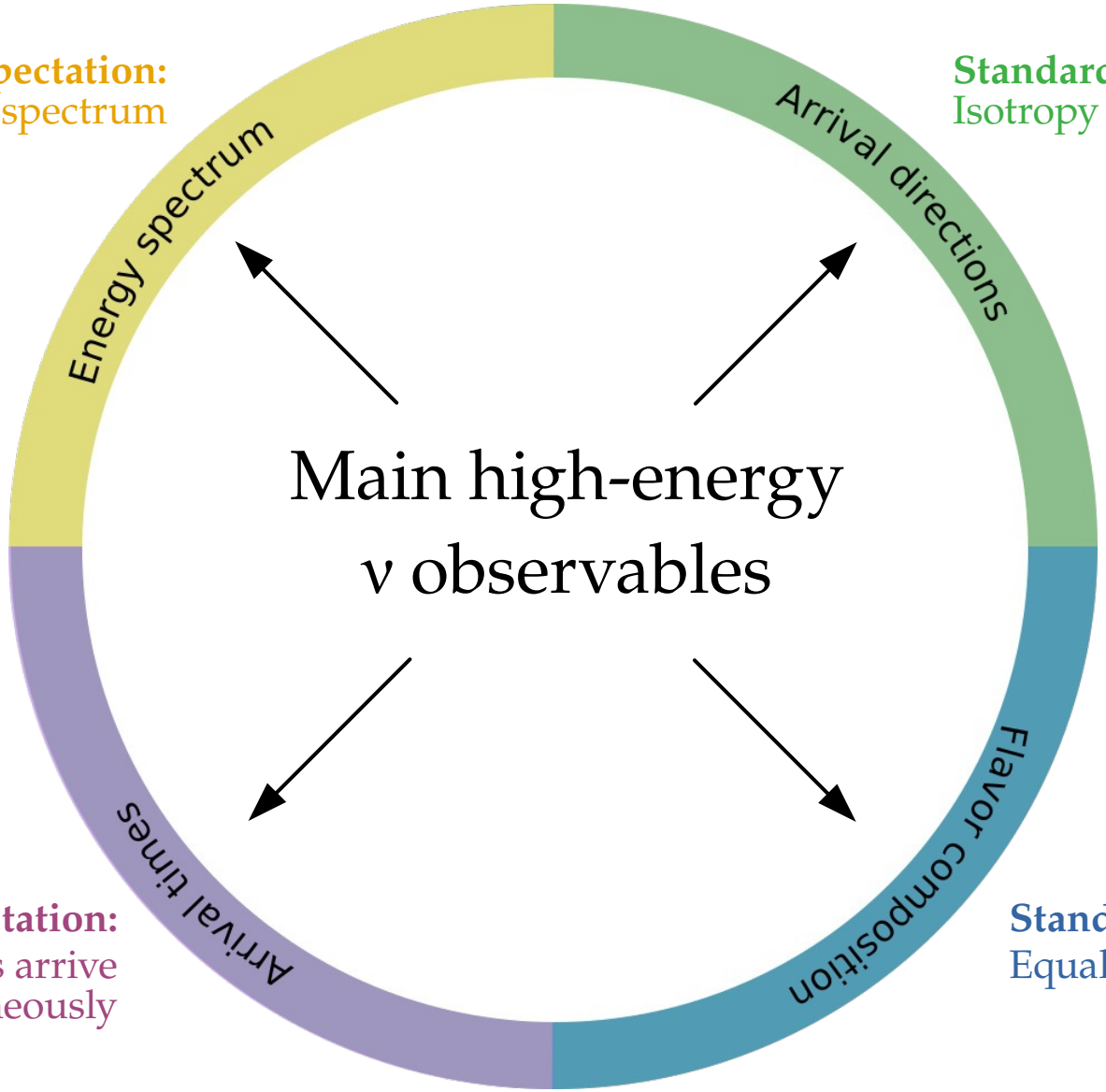


Strebe/Wikipedia


Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition

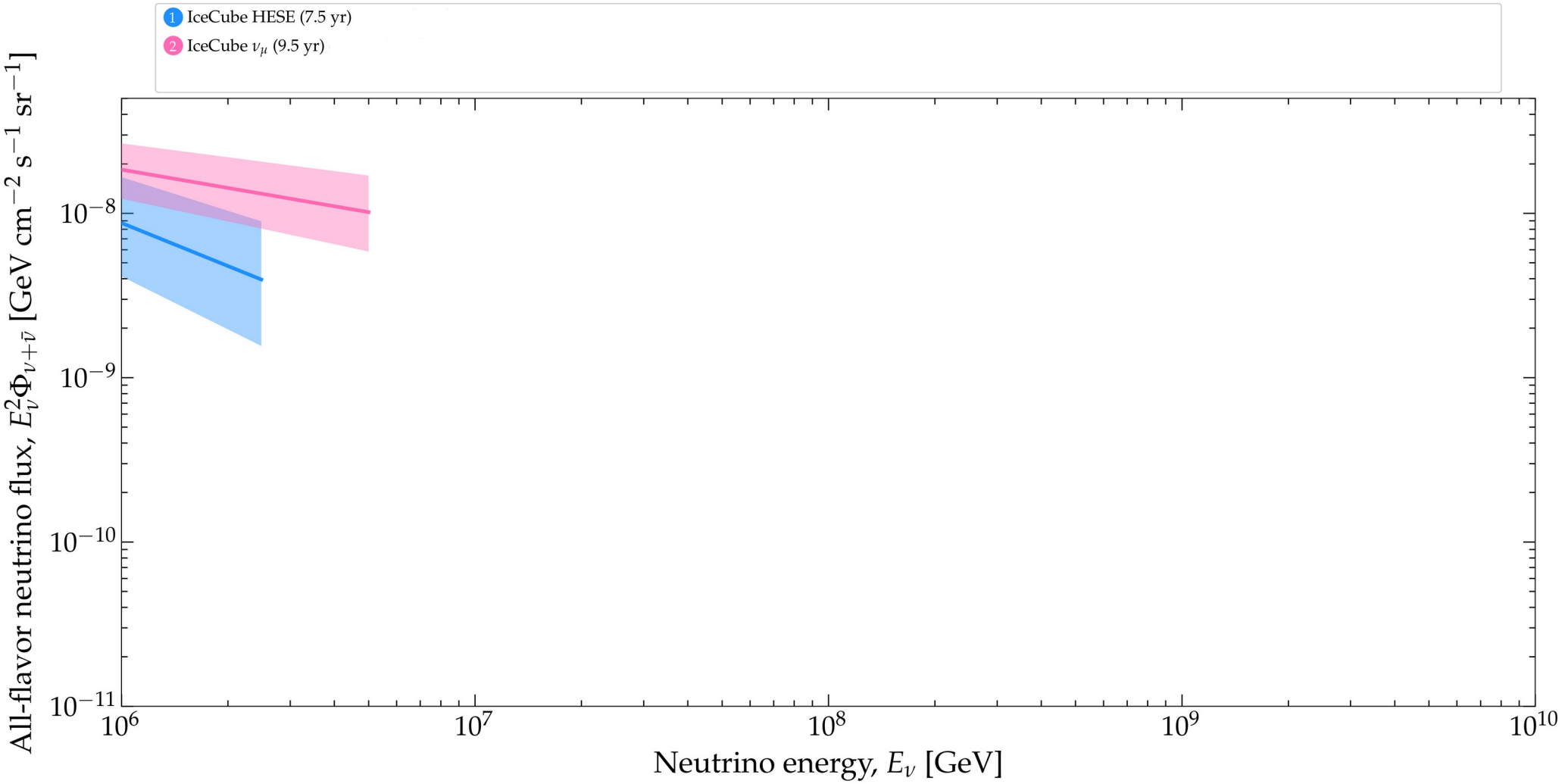
Standard expectation:
Power-law energy spectrum

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


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

Today

TeV–PeV ν

Today

TeV–PeV ν

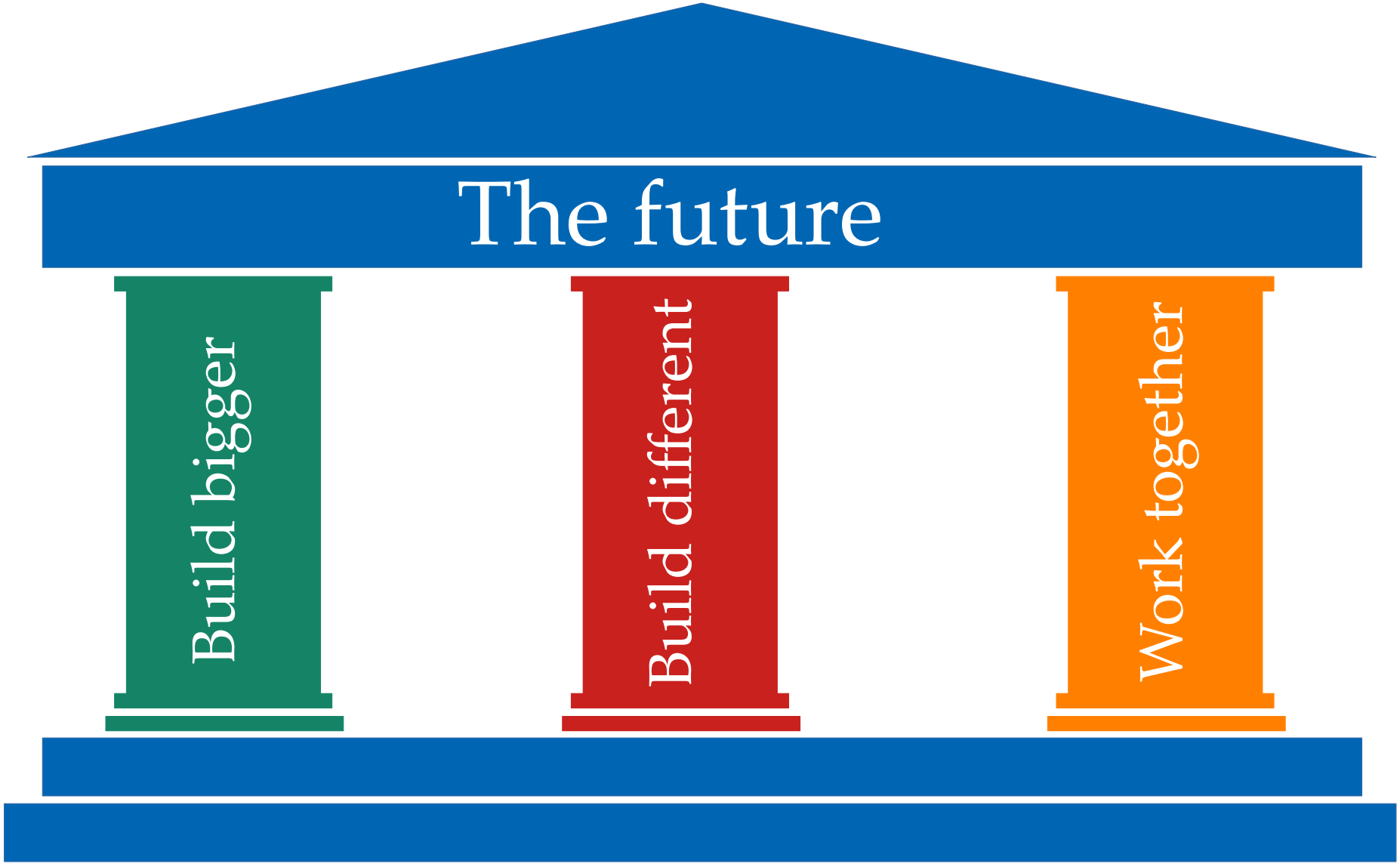
Turn predictions
into data-driven tests

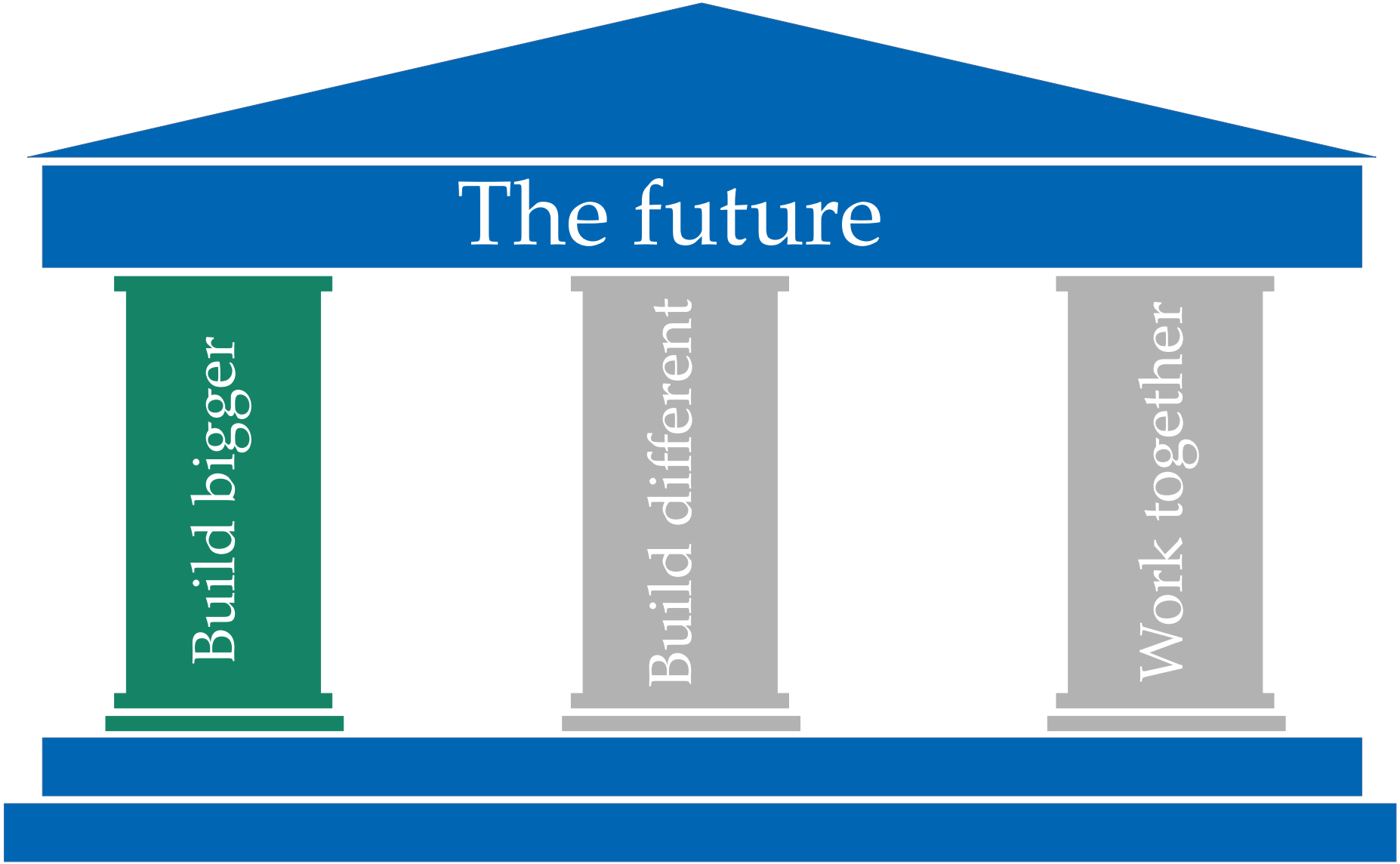
Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties


The future
Build bigger
Build different
Work together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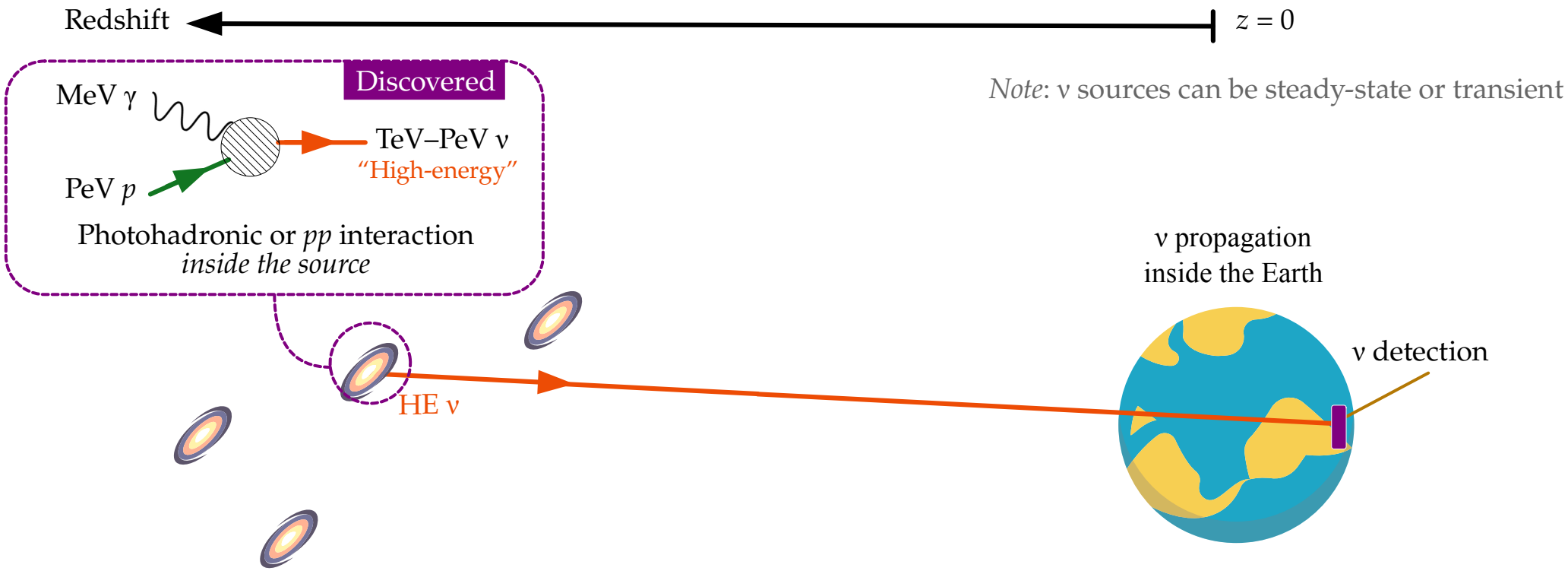
Redshift
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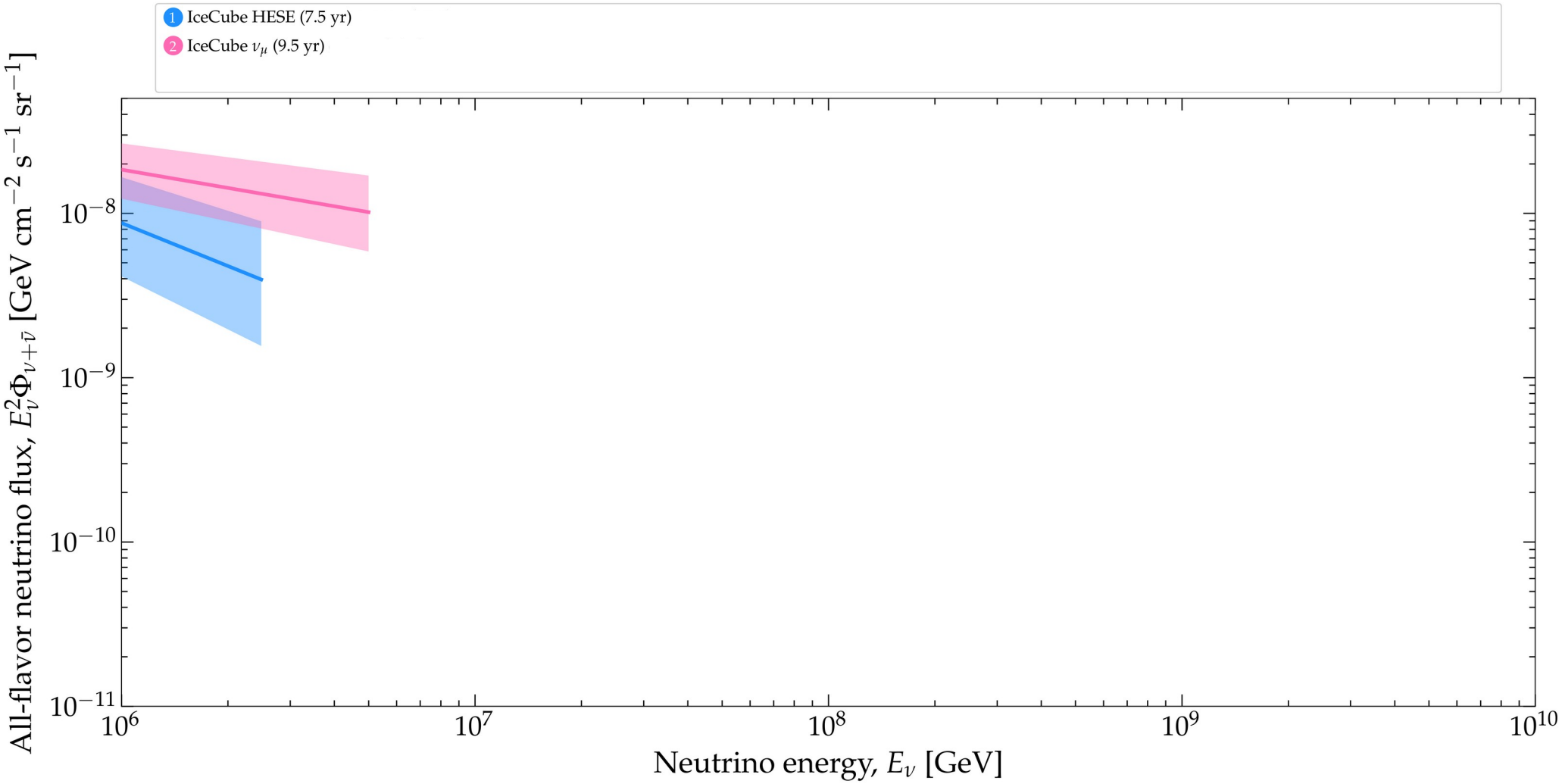
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10^{-8}
10^{-9}
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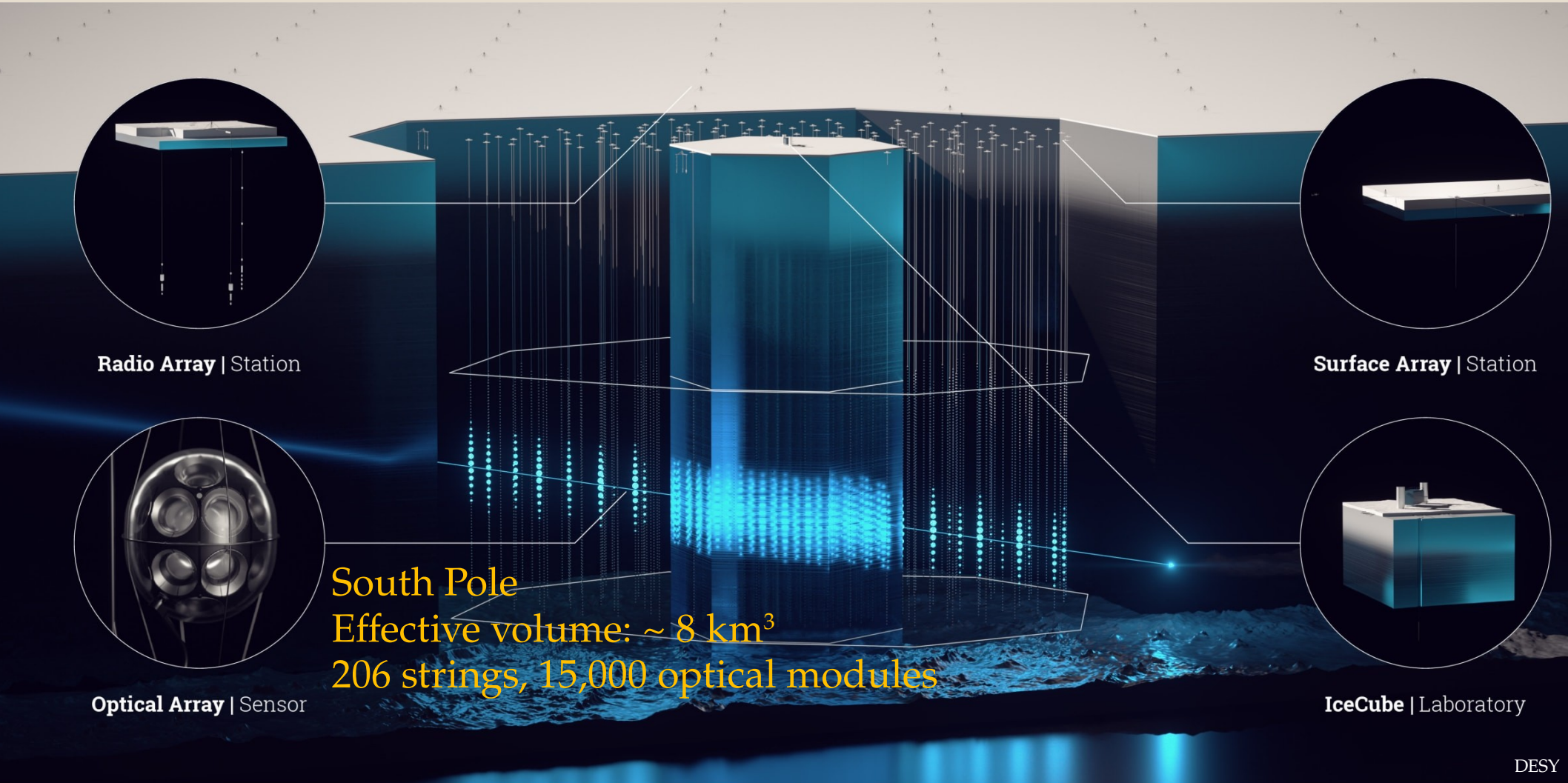
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

TeV–PeV ν telescopes 2030s

Strebe/Wikipedia

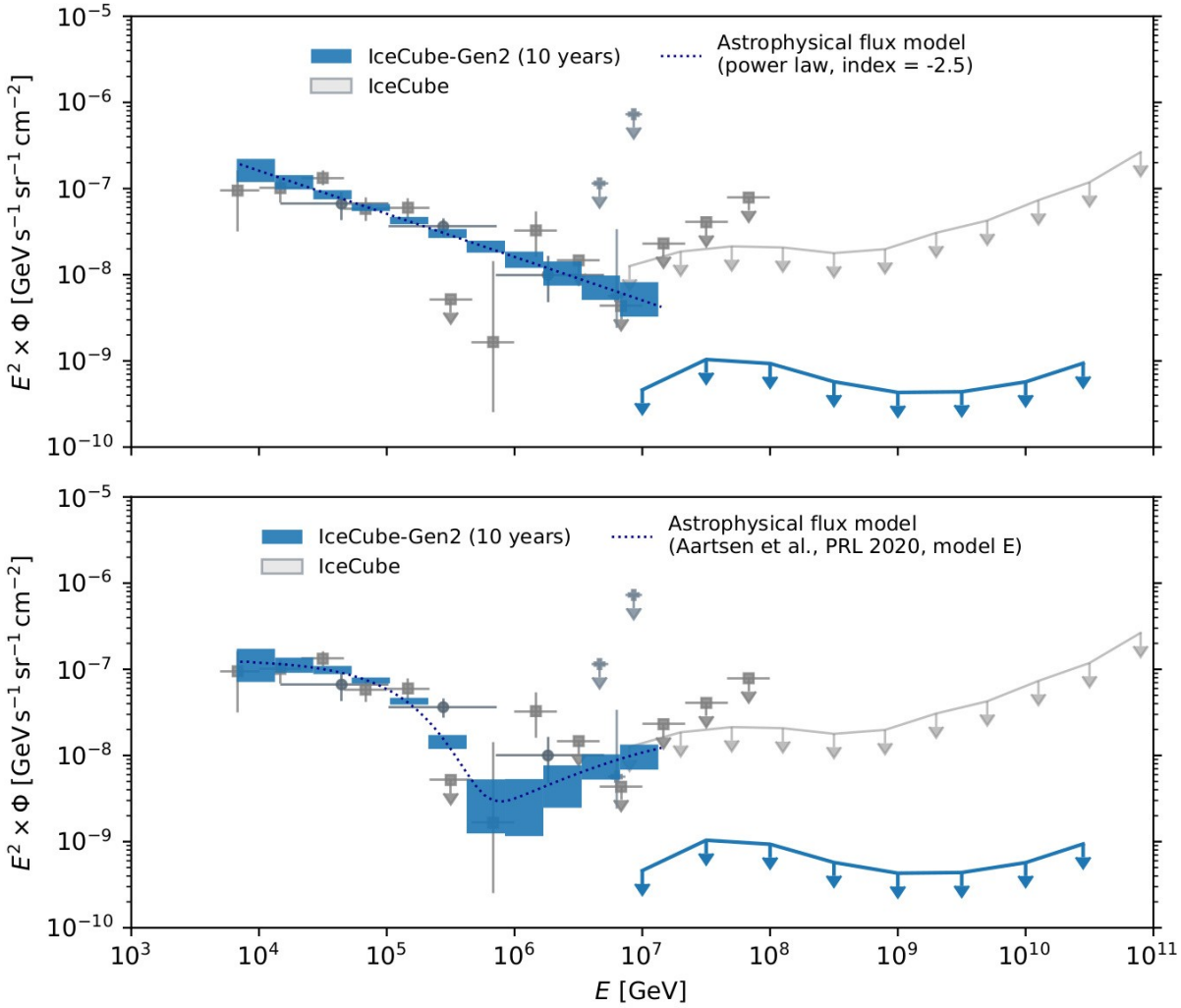
IceCube-Gen2



South Pole
Effective volume: ~ 8 km^3
206 strings, 15,000 optical modules

DESY

Measuring the diffuse flux *precisely*



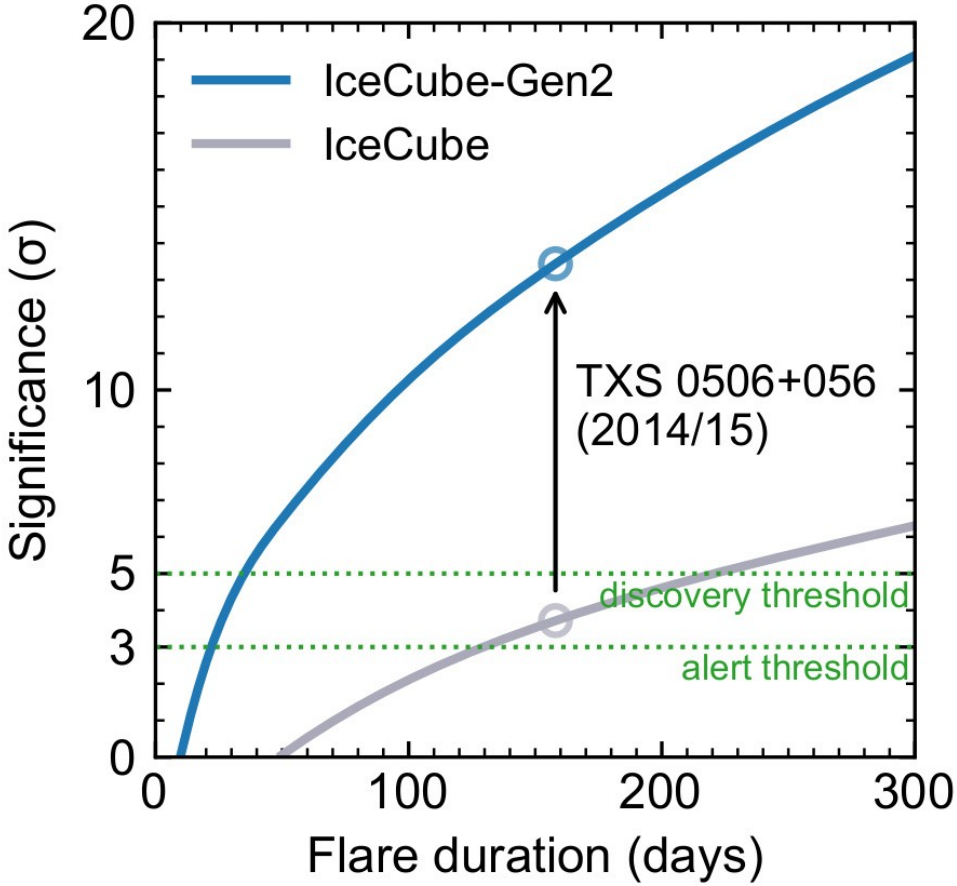
Assuming a power-law ν flux ∝ $E^{-2.5}$

Assuming a power-law ν flux with 100-TeV cut-off + $p\gamma$ bump at tens of TeV

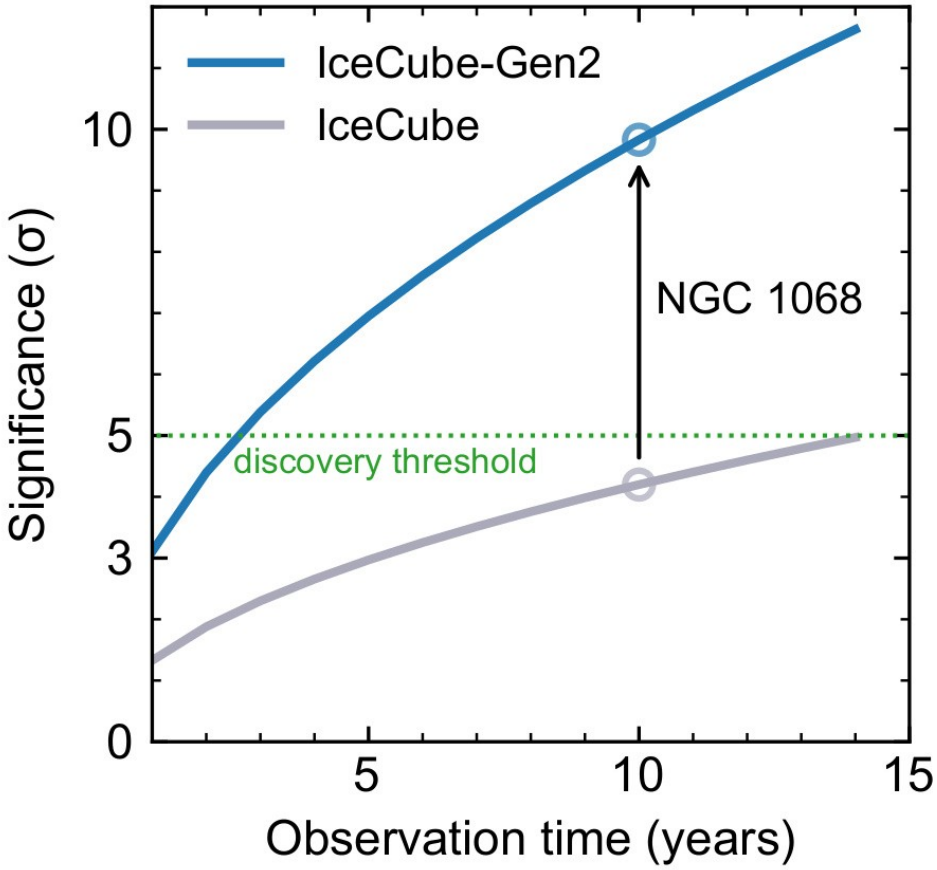
Ackermann, **MB** *et al.*, *JHEAp* 2022

Discovering sources fast, with high significance

TXS 0506+056



NGC 1068

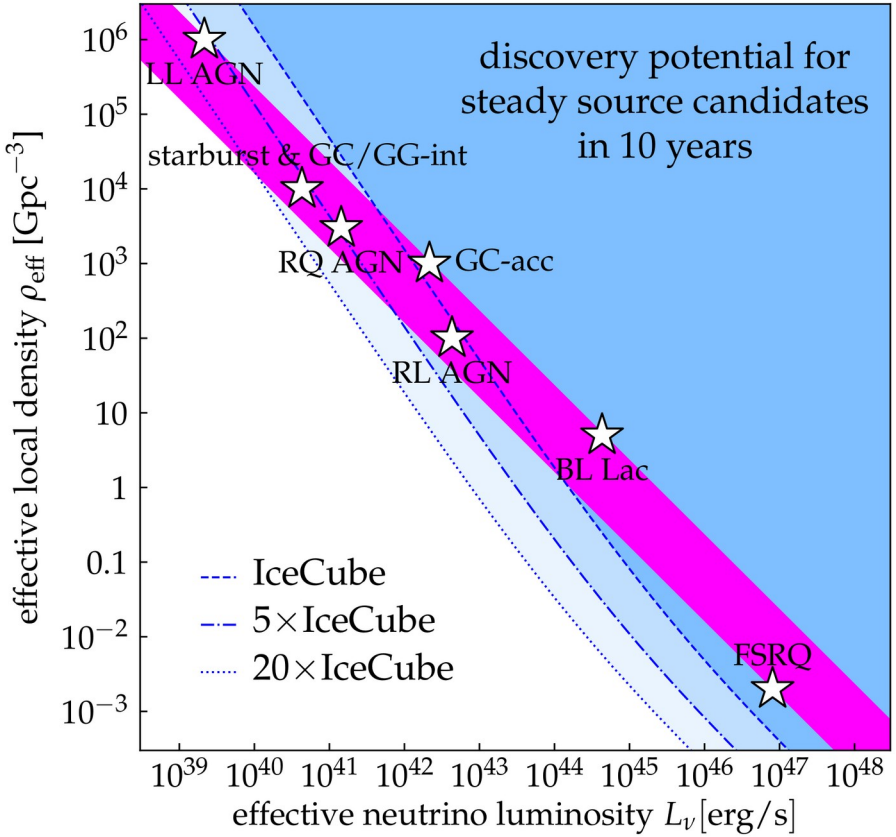


IceCube-Gen2 Collab. Technical Design Report Part I

Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

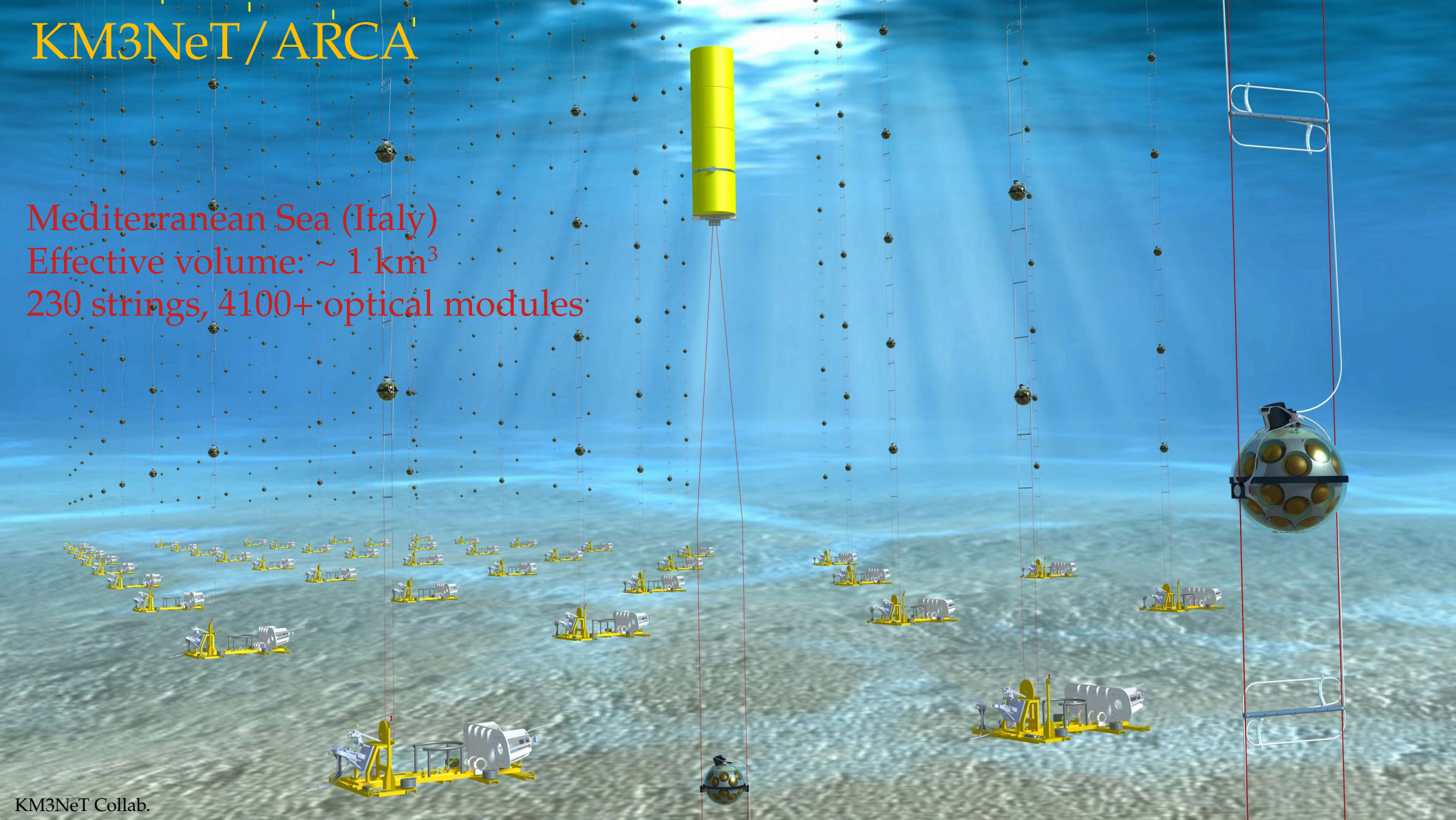
Closest source with $E^2\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

KM3NeT/ARCA

Mediterranean Sea (Italy)
Effective volume: ~ 1 km^3
230 strings, 4100+ optical modules

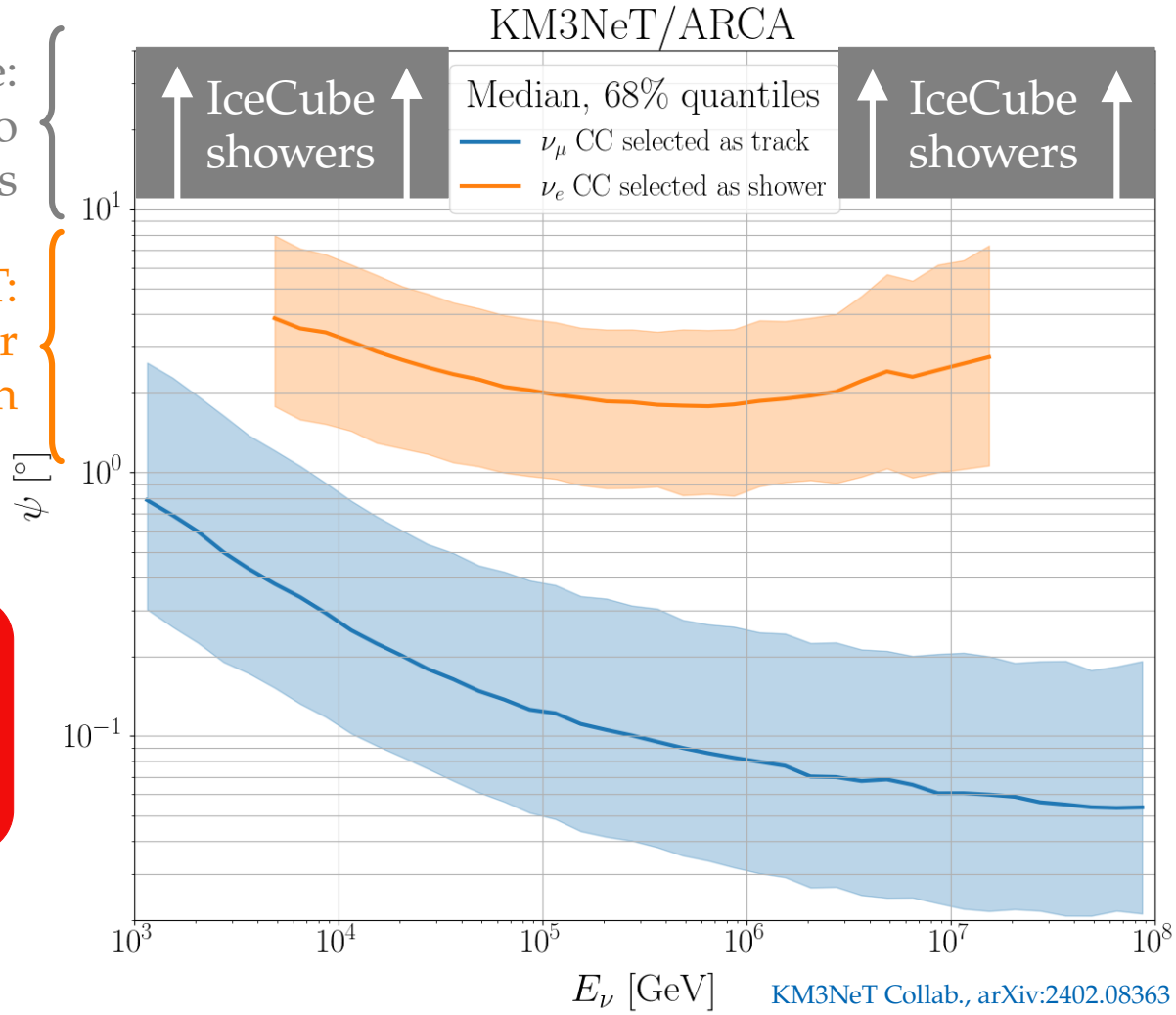


KM3NeT Collab.

Boosting source searches with showers

IceCube:
Hard to use showers to find point sources

KM3NeT:
Degree-scale shower Angular resolution



Light scattering length in water > in ice (100–300 m *vs.* 4–40 m)

IceCube Collab., *NIM* 2013
ANTARES Collab., *Astropart. Phys.* 2005

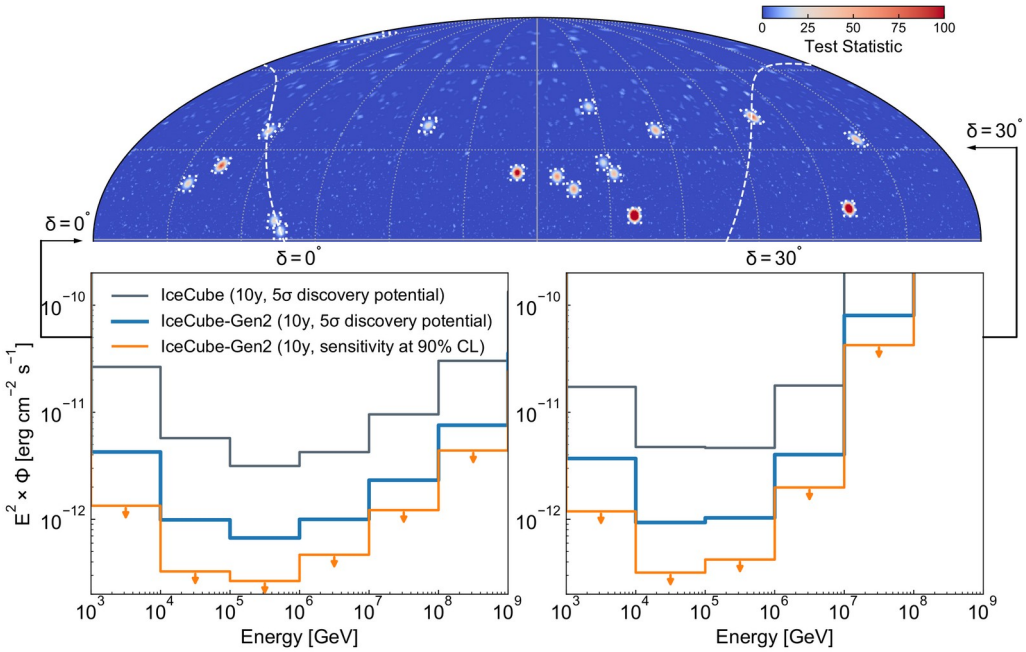
KM3NeT Collab., arXiv:2402.08363

Monitoring the full sky

Monitoring the full sky

IceCube-Gen2 (optical)

Northern sky

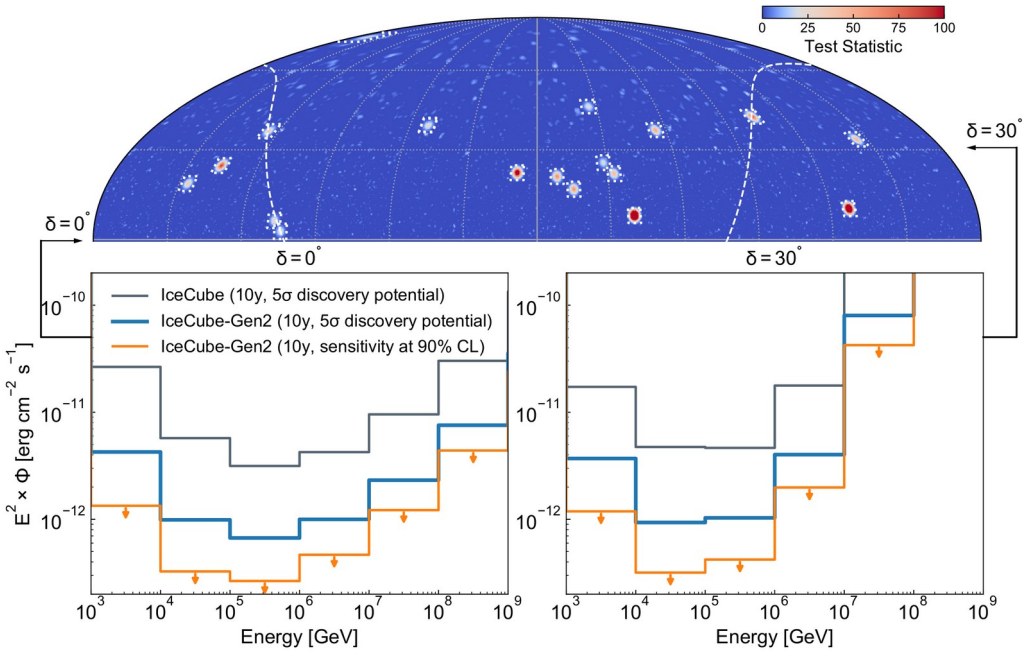


IceCube-Gen2, *J. Phys. G* 2021

Monitoring the full sky

IceCube-Gen2 (optical)

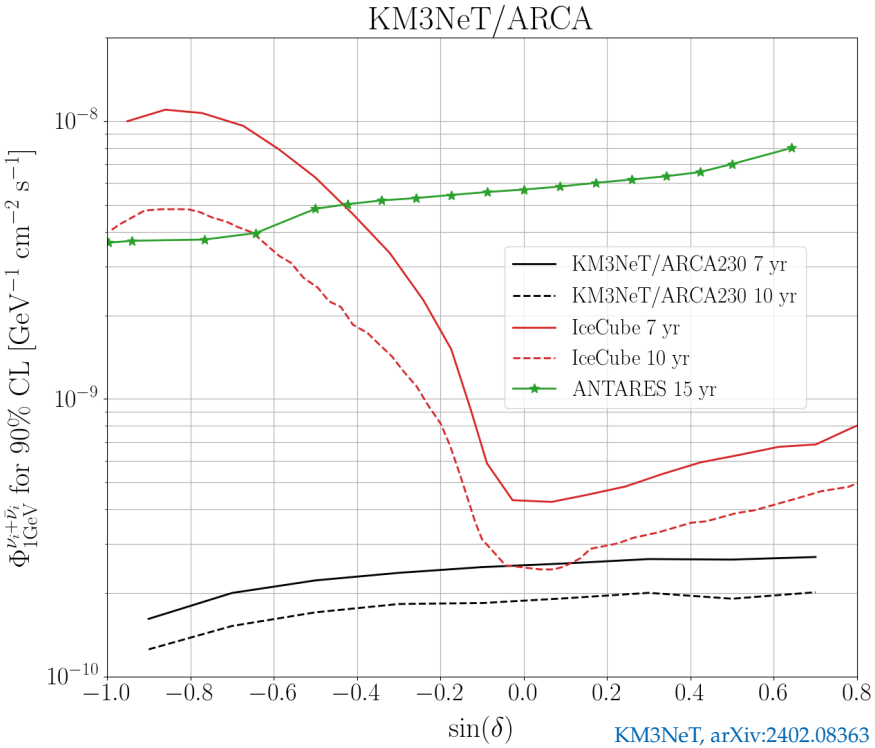
Northern sky



IceCube-Gen2, *J. Phys. G* 2021

KM3NeT

Southern sky



KM3NeT, arXiv:2402.08363

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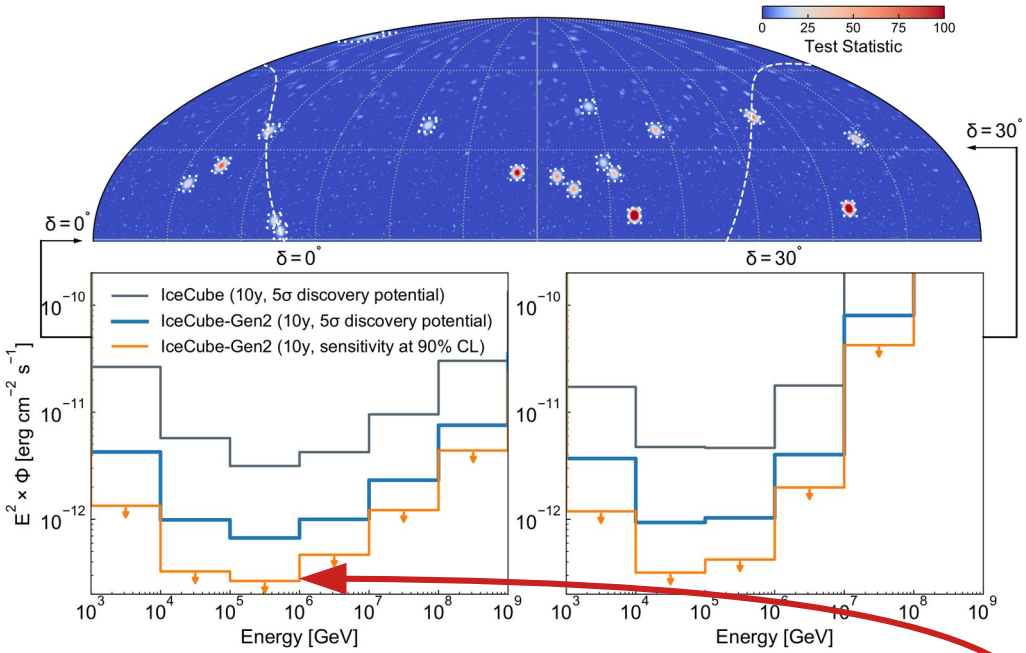
IceCube-Gen2 (optical)

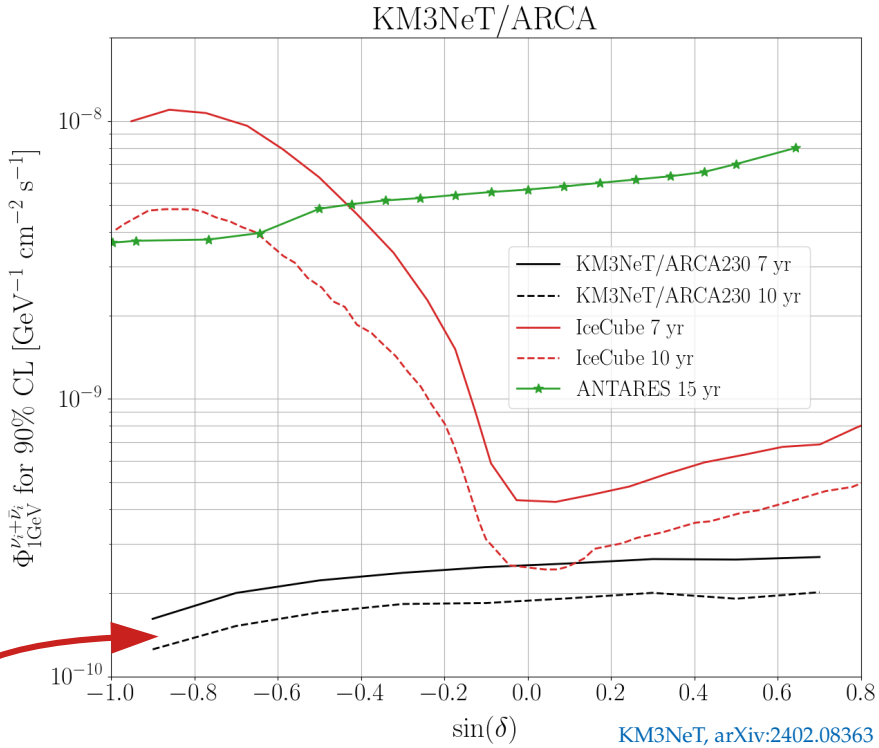
Northern sky



IceCube-Gen2, *J. Phys. G* 2021

KM3NeT

Southern sky



KM3NeT, arXiv:2402.08363

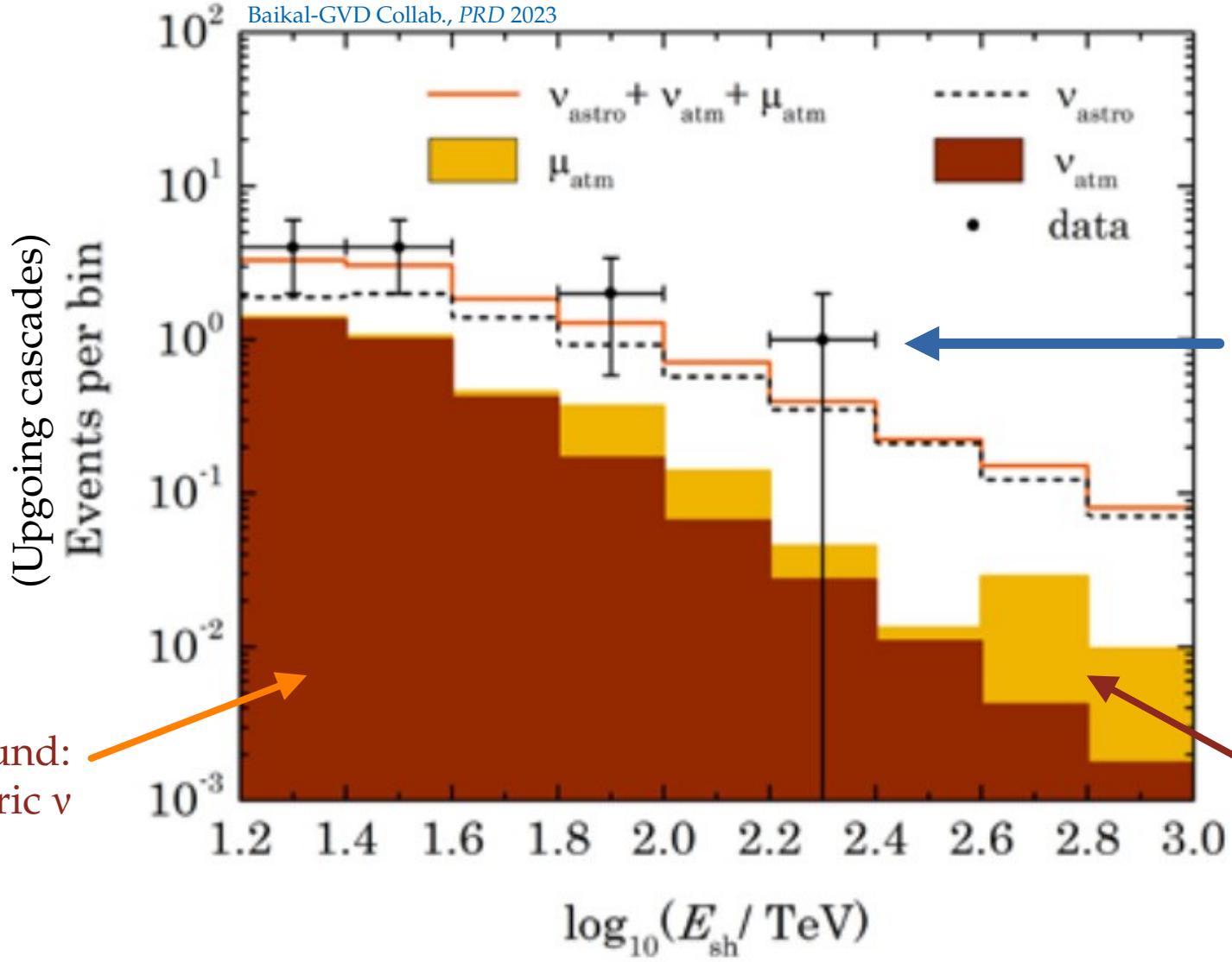
We will reach IceCube+ sensitivity in both hemispheres

Baikal-GVD

Lake Baikal, Russia
Effective volume: ~ 1.5 km3
90 strings, 1000+ optical modules

JINR

Baikal-GVD Collab., *PRD* 2023



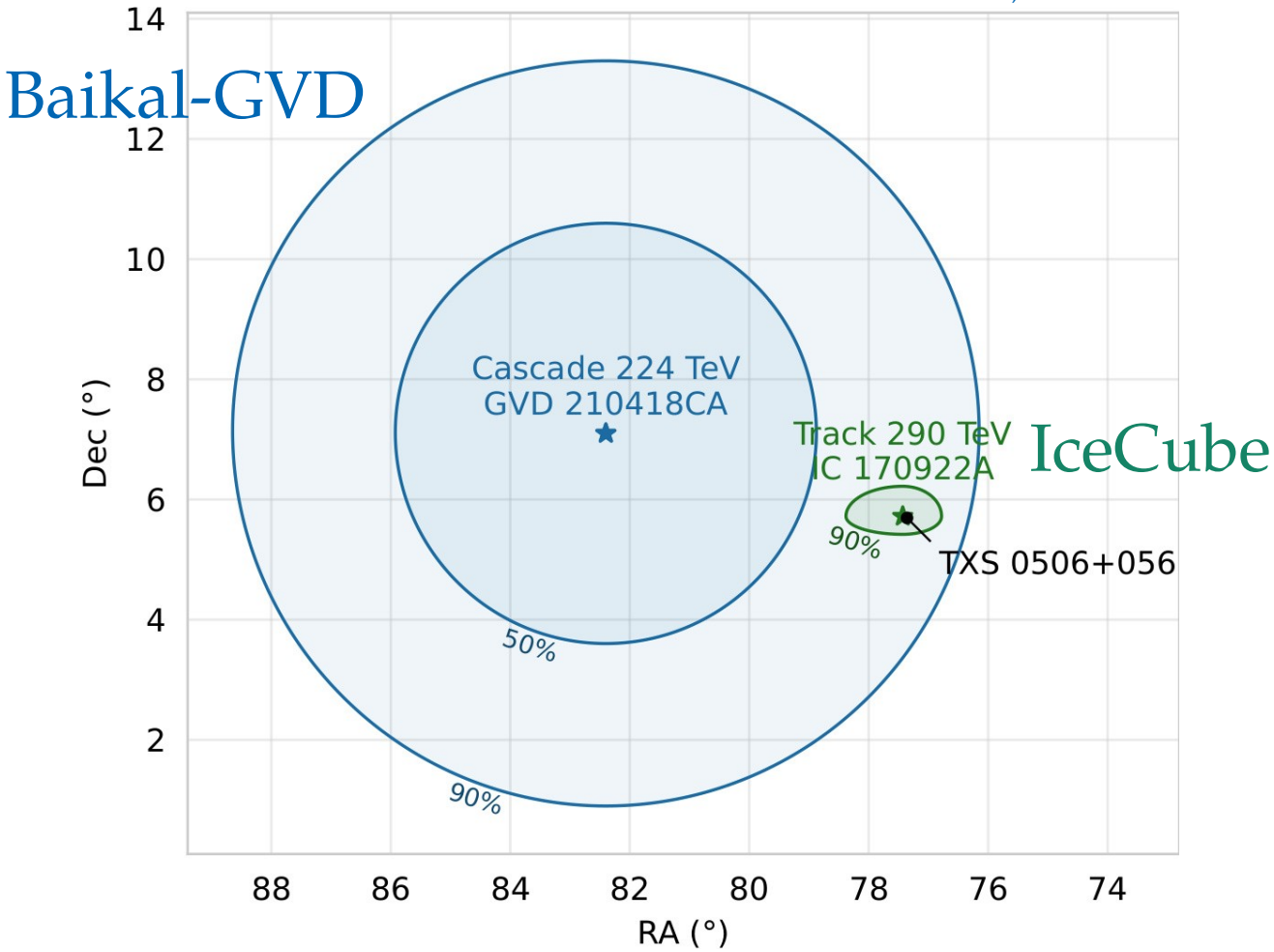
Astrophysical ν flux seen at 3σ

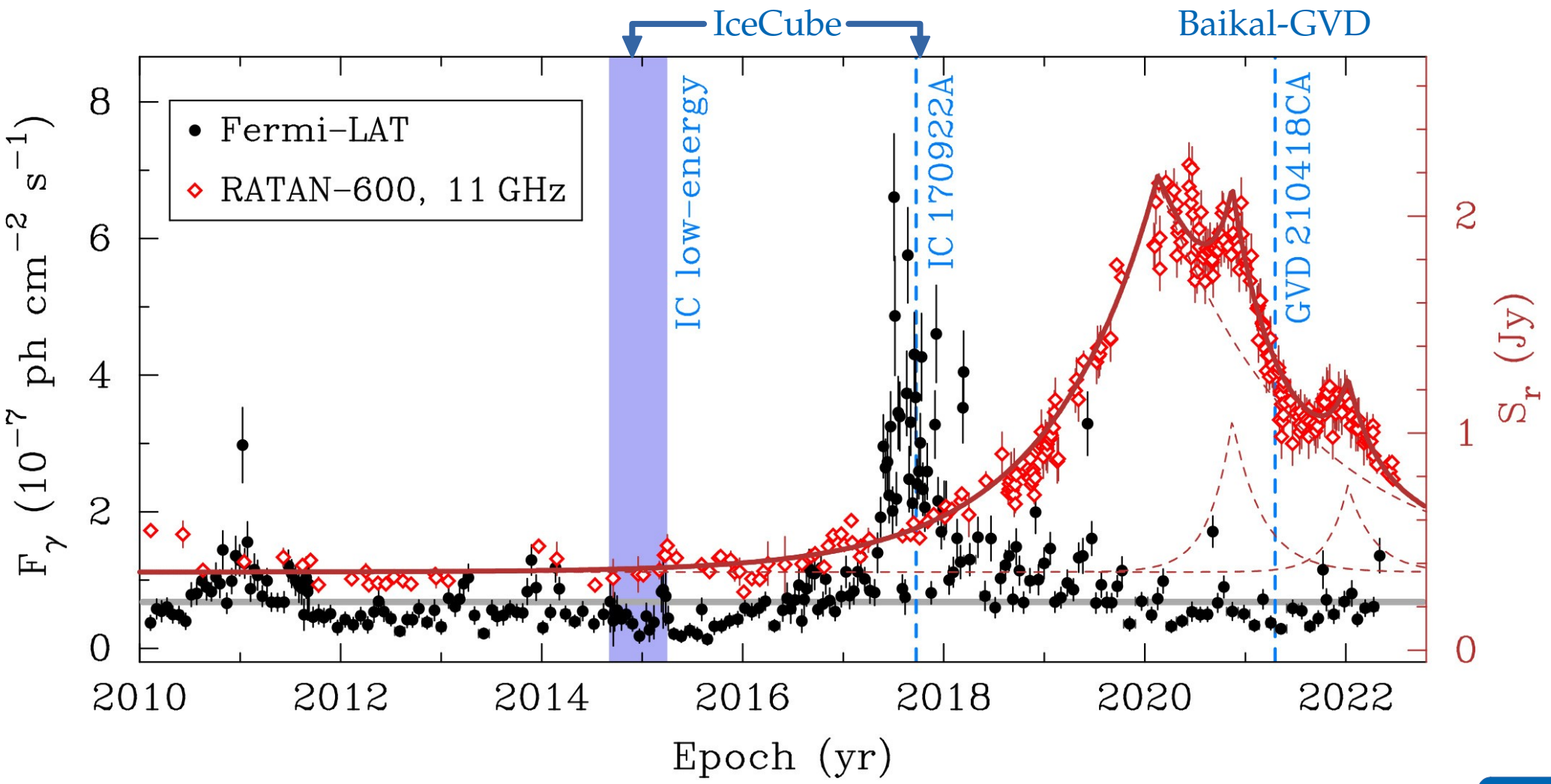
Background: atmospheric ν

Background: atmospheric μ

Did Baikal-GVD see a neutrino from TXS 0506+056?

Baikal-GVD Collab., *MNRAS* 2023

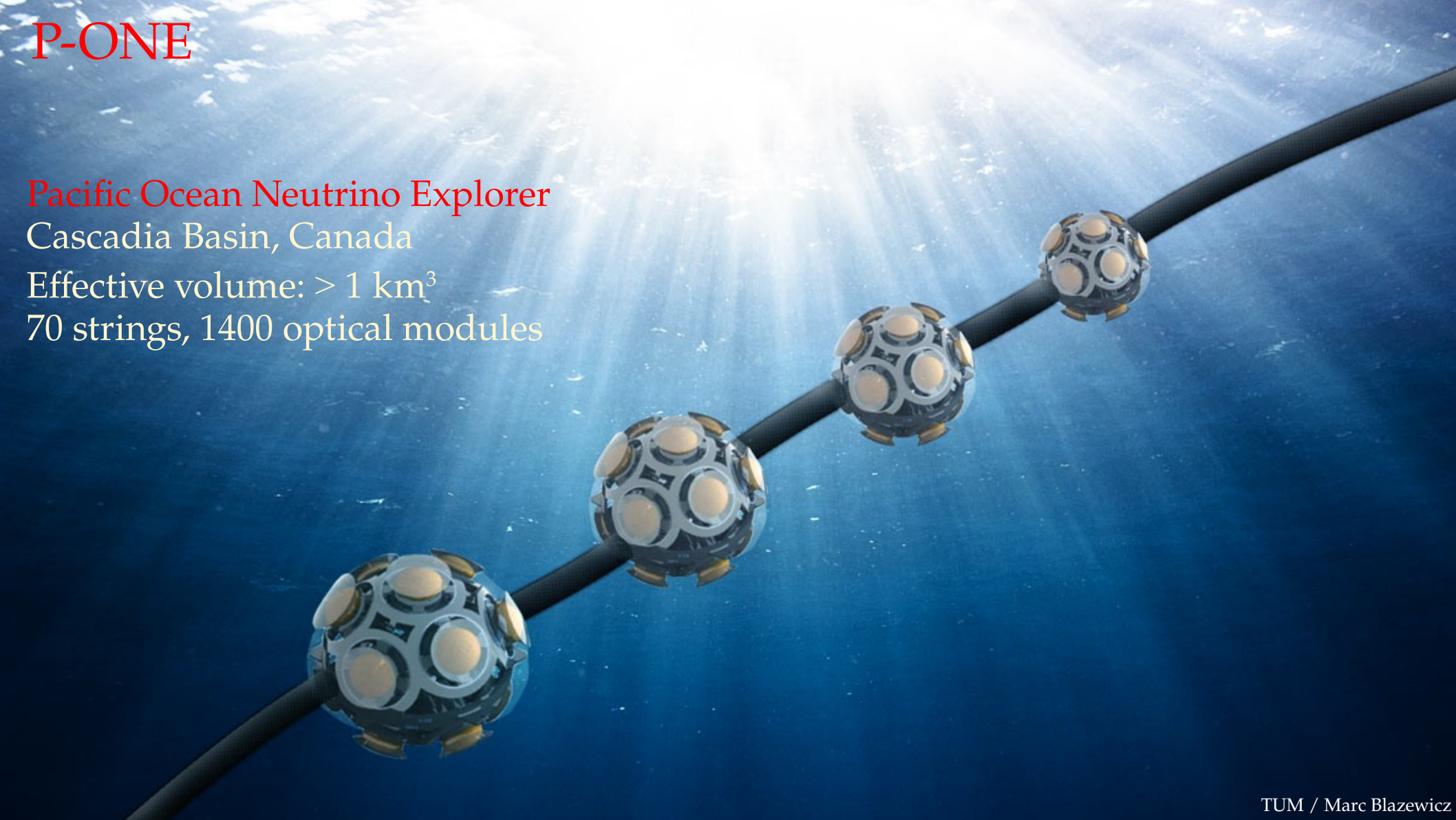




Baikal-GVD Collab., *MNRAS* 2023

P-ONE

Pacific Ocean Neutrino Explorer
Cascadia Basin, Canada
Effective volume: > 1 km^3
70 strings, 1400 optical modules



TUM / Marc Blazewicz

TRIDENT

The tRopIcal Deep-sea Neutrino Telescope

South China Sea

Effective volume: 8 km^3

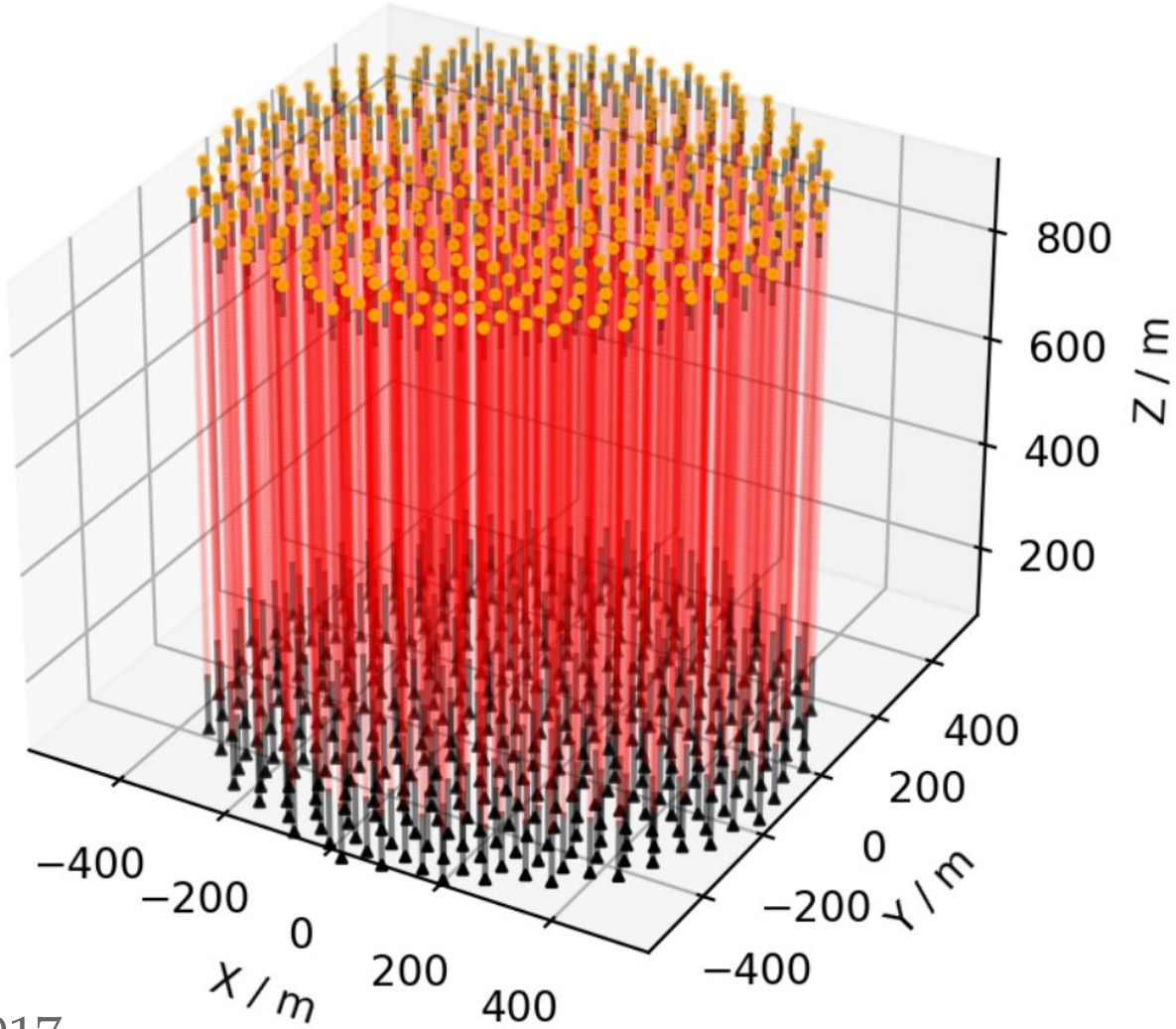
1000 strings, 20,000 optical modules

Would have seen the TXS 0506+056 at 10σ

More information: *Nature Astron.* 2023, trident.sjtu.edu.cn/en

NEON

Neutrino Observatory in the Nanhai
South China Sea
Effective volume: 0.8 km^3 (dense!)
400 strings, 40,000 optical modules



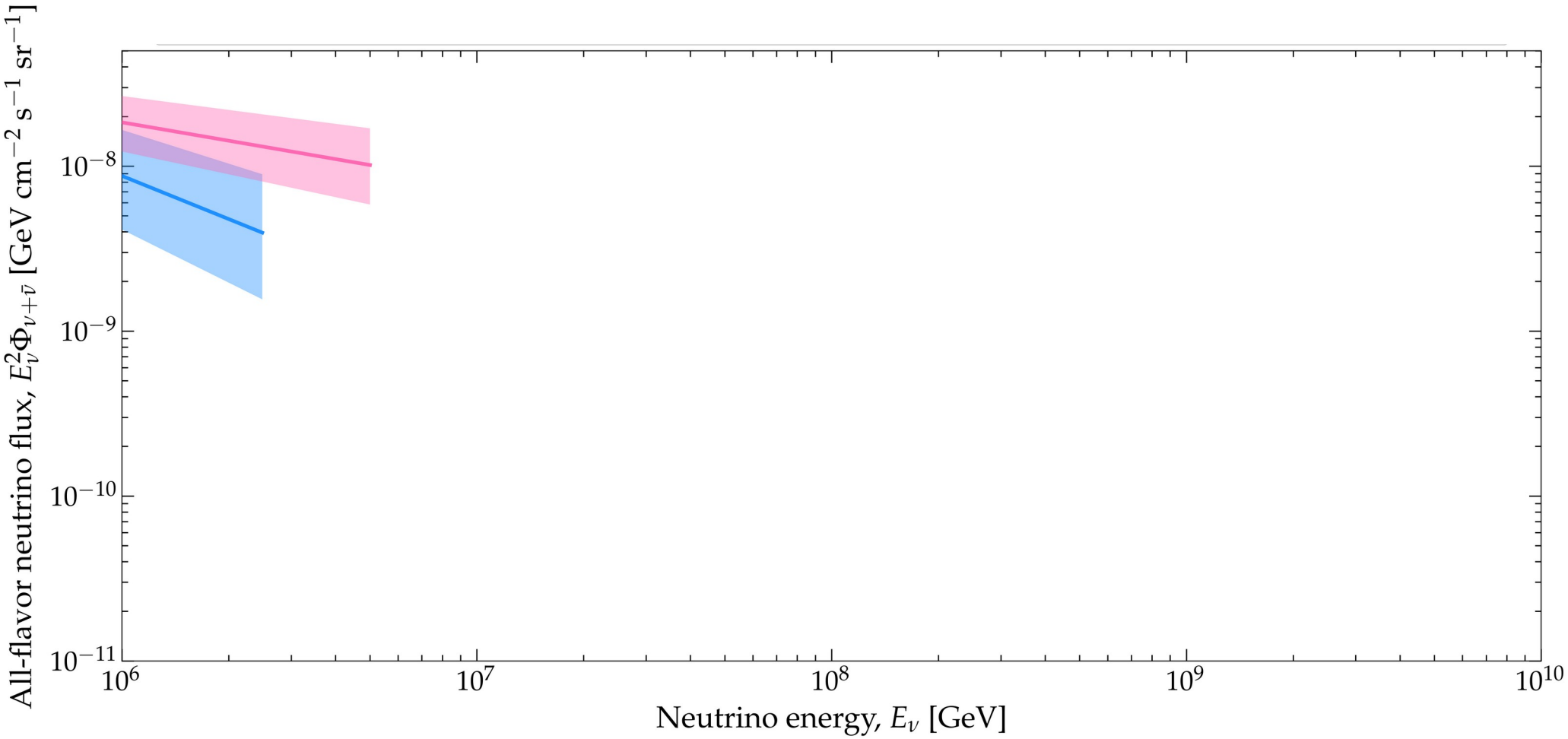
More information: PoS (ICRC2023) 1017

HUNT

High-energy Underwater Neutrino Telescope
South China Sea or Lake Baikal
Effective volume: 30 km^3
2304 strings, 55,296 optical modules

Muon track angular resolution
as good as 0.05°
(for tracks of 6 km in length)

More information: hunt.ihep.ac.cn


All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
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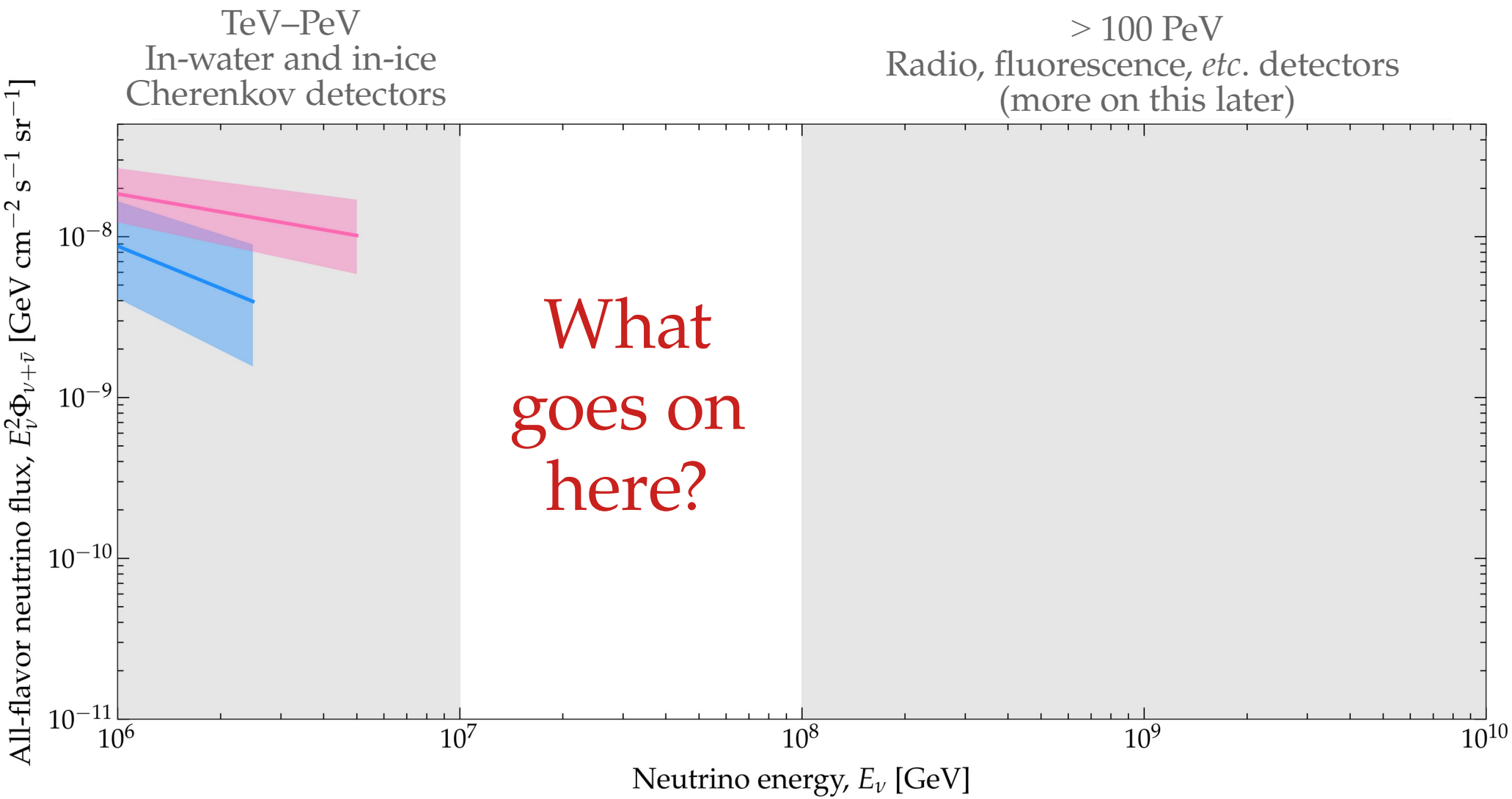
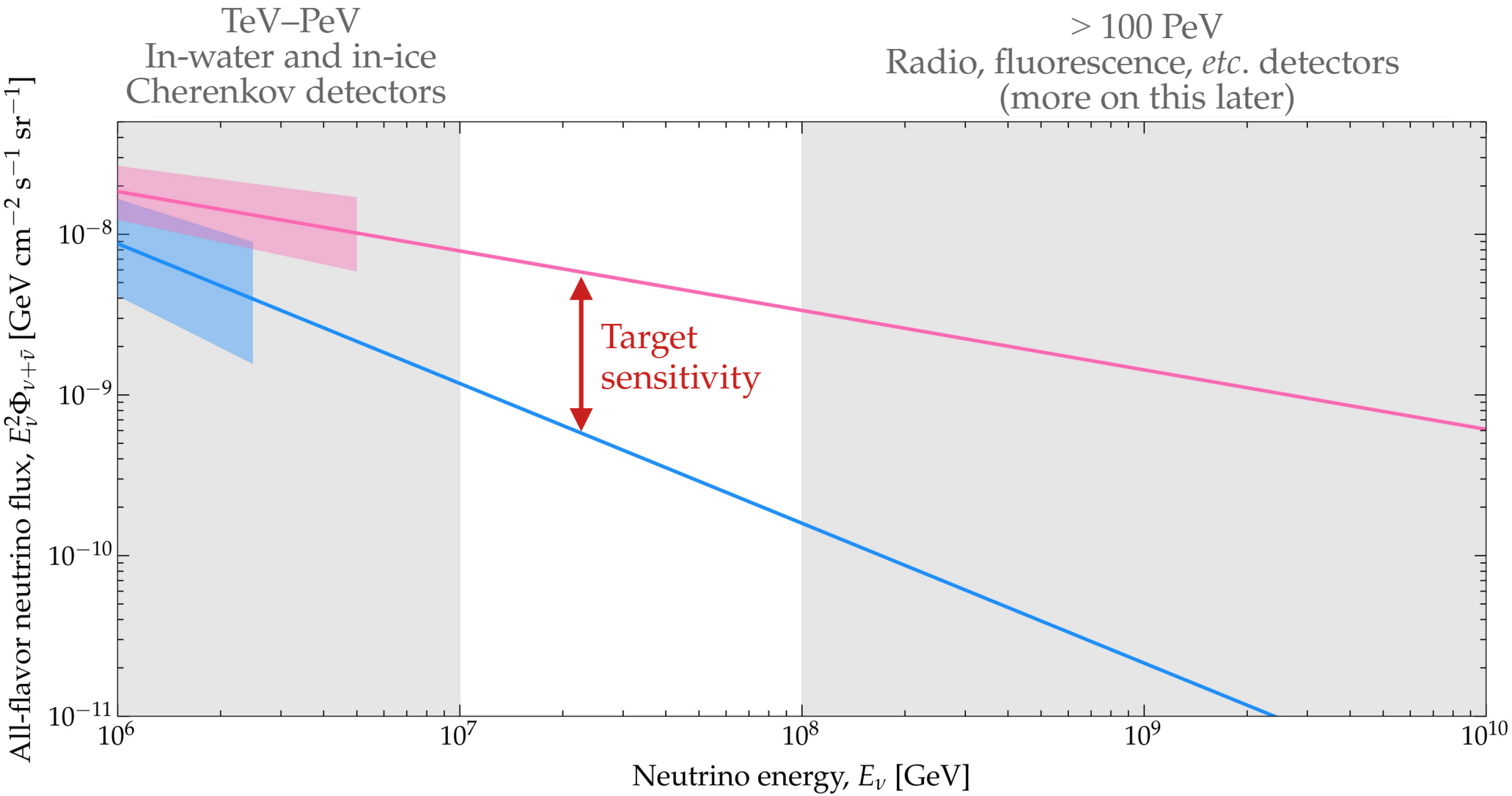
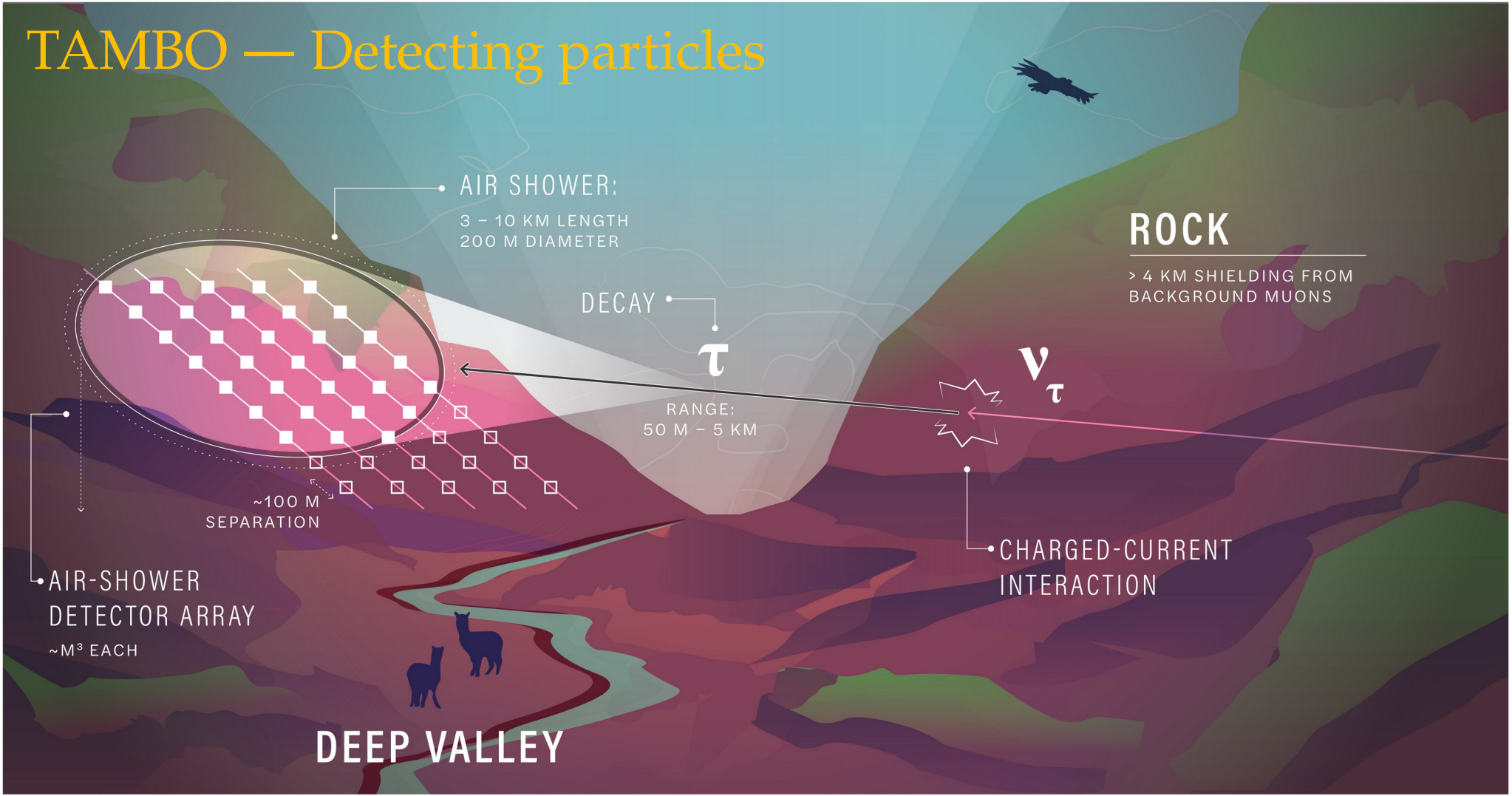
Neutrino energy, E_ν [GeV]


TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, *etc*. detectors
(more on this later)
What
goes on
here?
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, *etc*. detectors
(more on this later)
Target
sensitivity
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

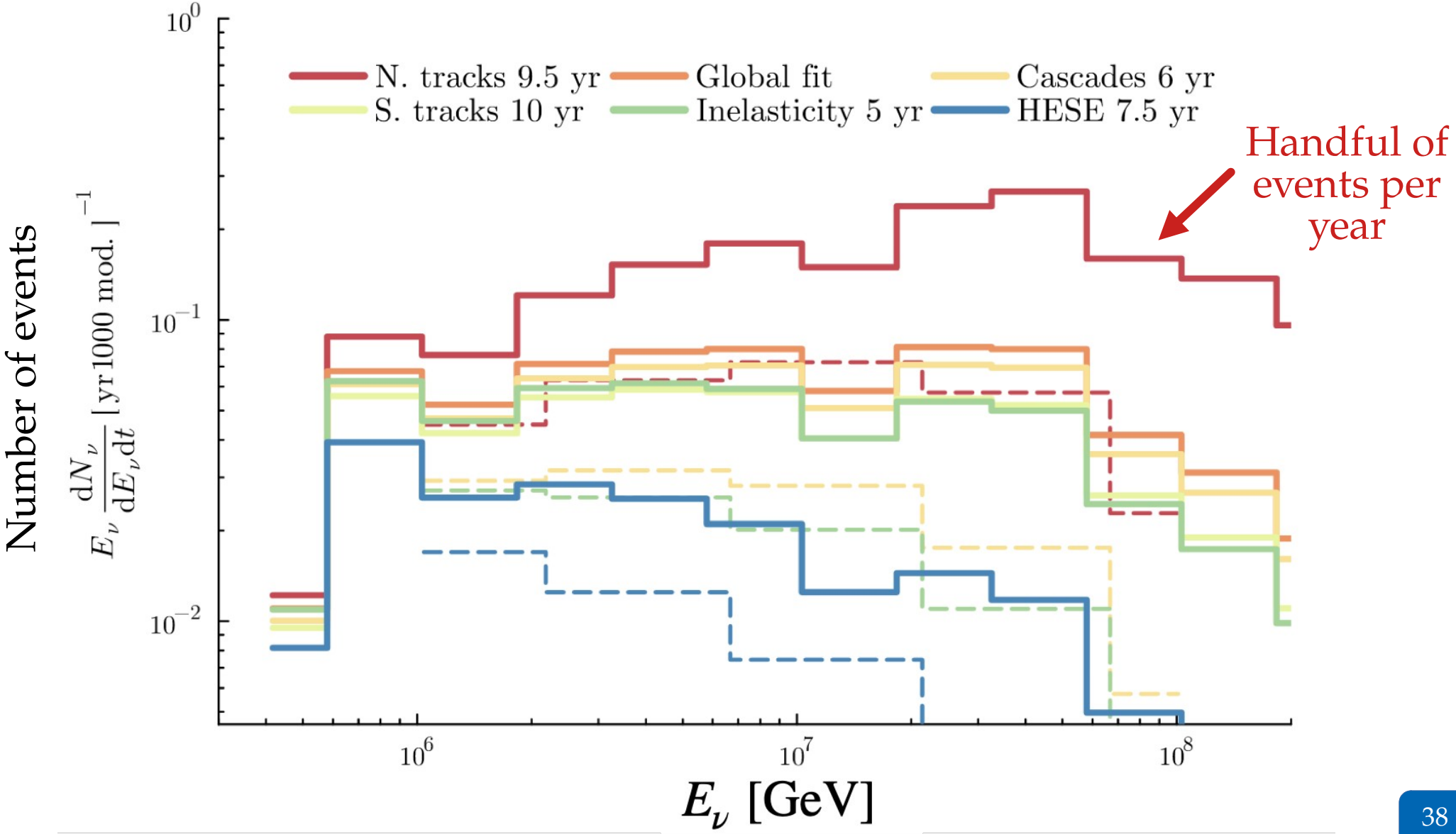
TAMBO — Detecting particles



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

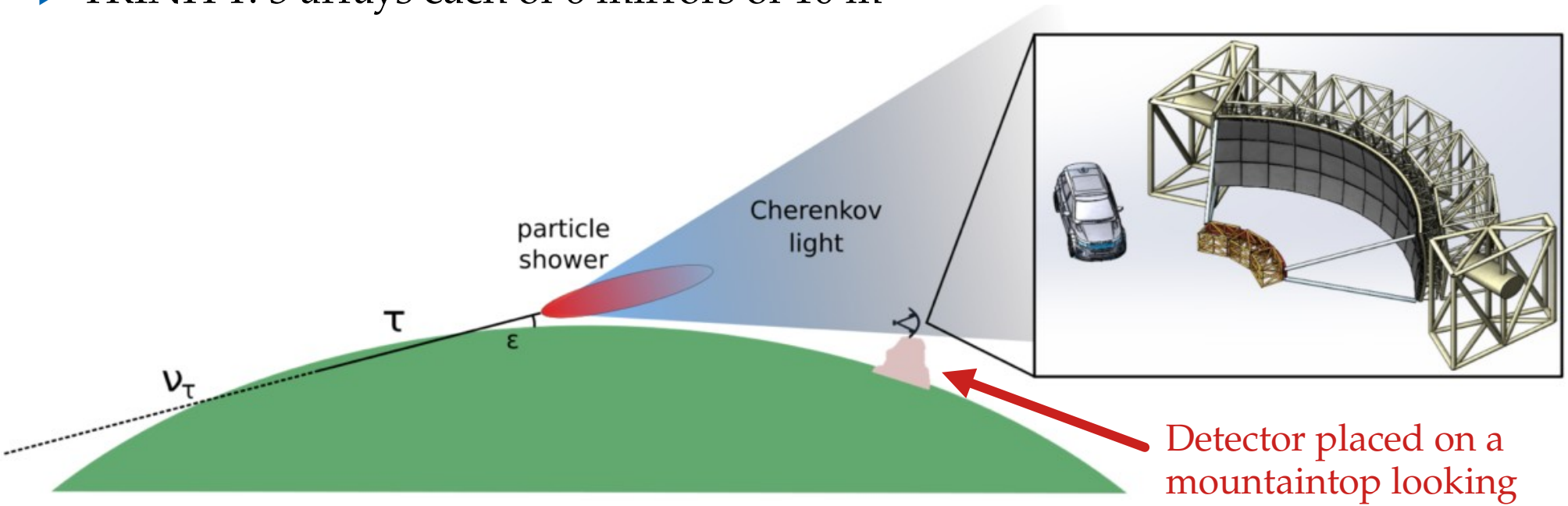

Colca Valley, Peru
2000 (bottom) to 4000 (top) m.a.s.l.


Harvard TAMBO team
Site survey 2022


N. tracks 9.5 yr
Global fit
Cascades 6 yr
S. tracks 10 yr
Inelasticity 5 yr
HESE 7.5 yr
Handful of events per year
Number of events
$E_\nu \frac{dN_\nu}{dE_\nu dt}$ [yr 1000 mod.]$^{-1}$
10^0
10^{-1}
10^{-2}
10^6
10^7
10^8
E_ν [GeV]

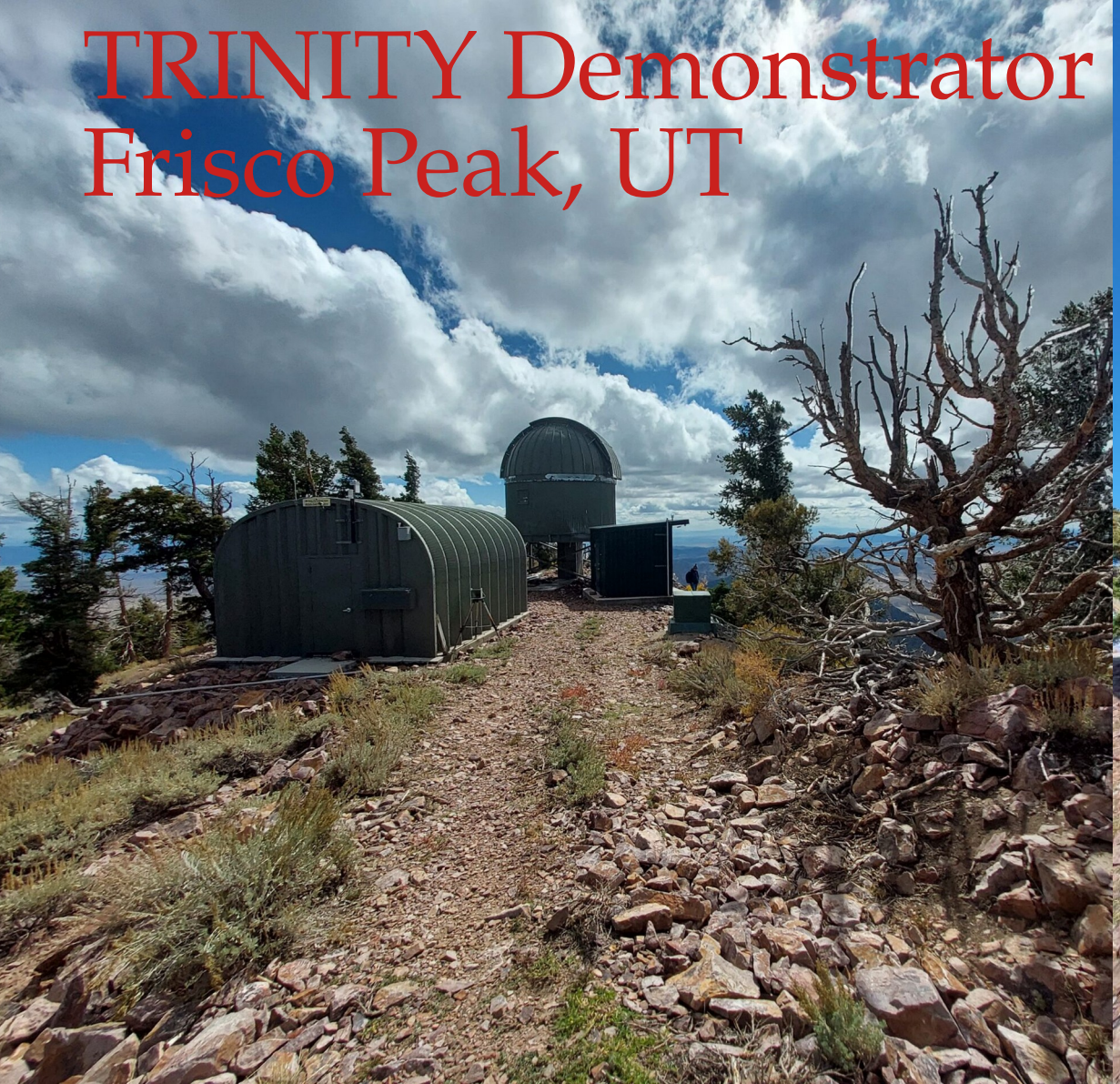
TRINITY — Detecting Cherenkov light

- Atmospheric Cherenkov imaging applied to PeV neutrinos
- Pioneered by MAGIC (pointing at Atlantic), ASHRA, and NTA (Mauna Kea)
- TRINITY: 3 arrays each of 6 mirrors of 10 m^2

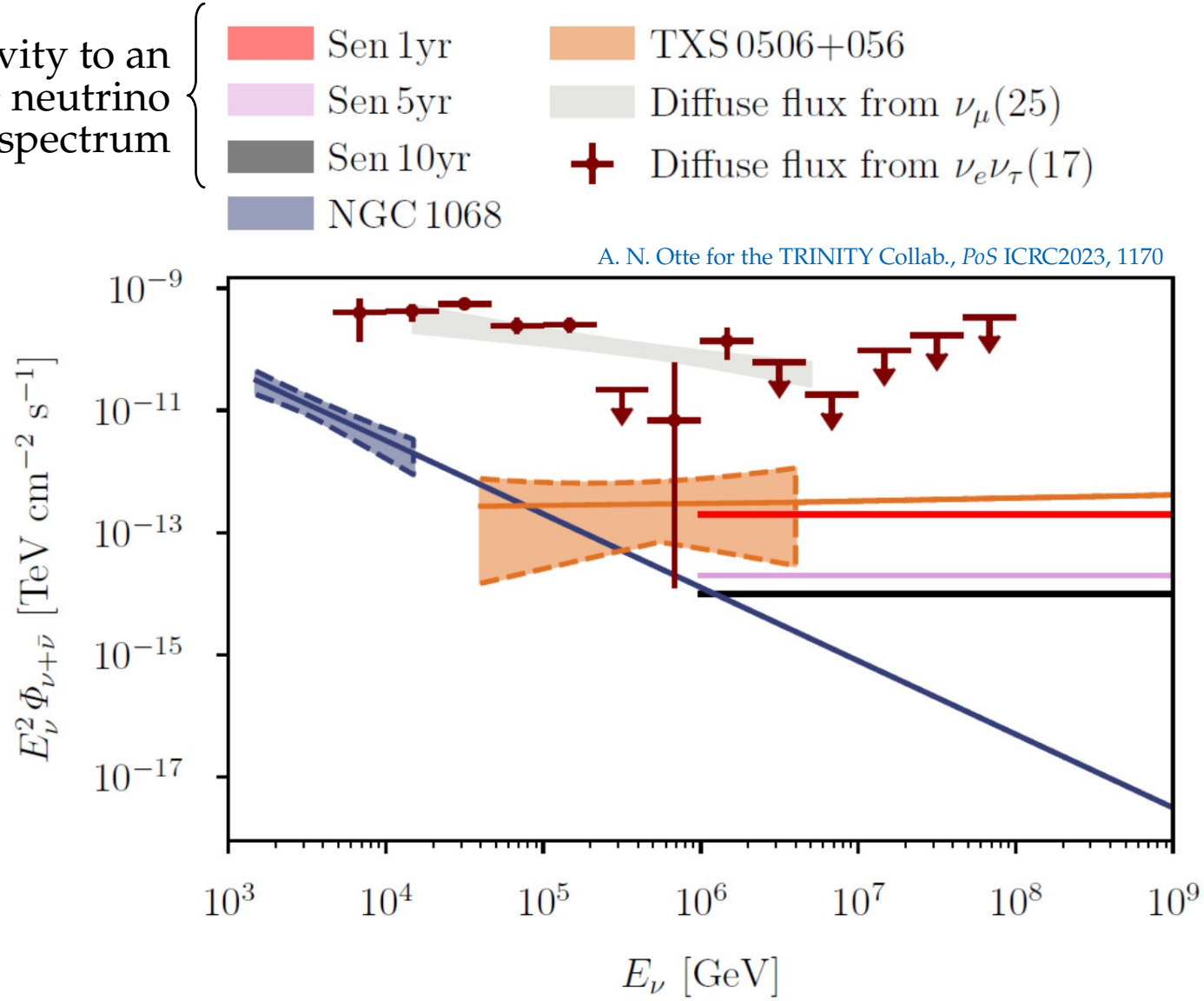


Detector placed on a mountaintop looking towards the horizon

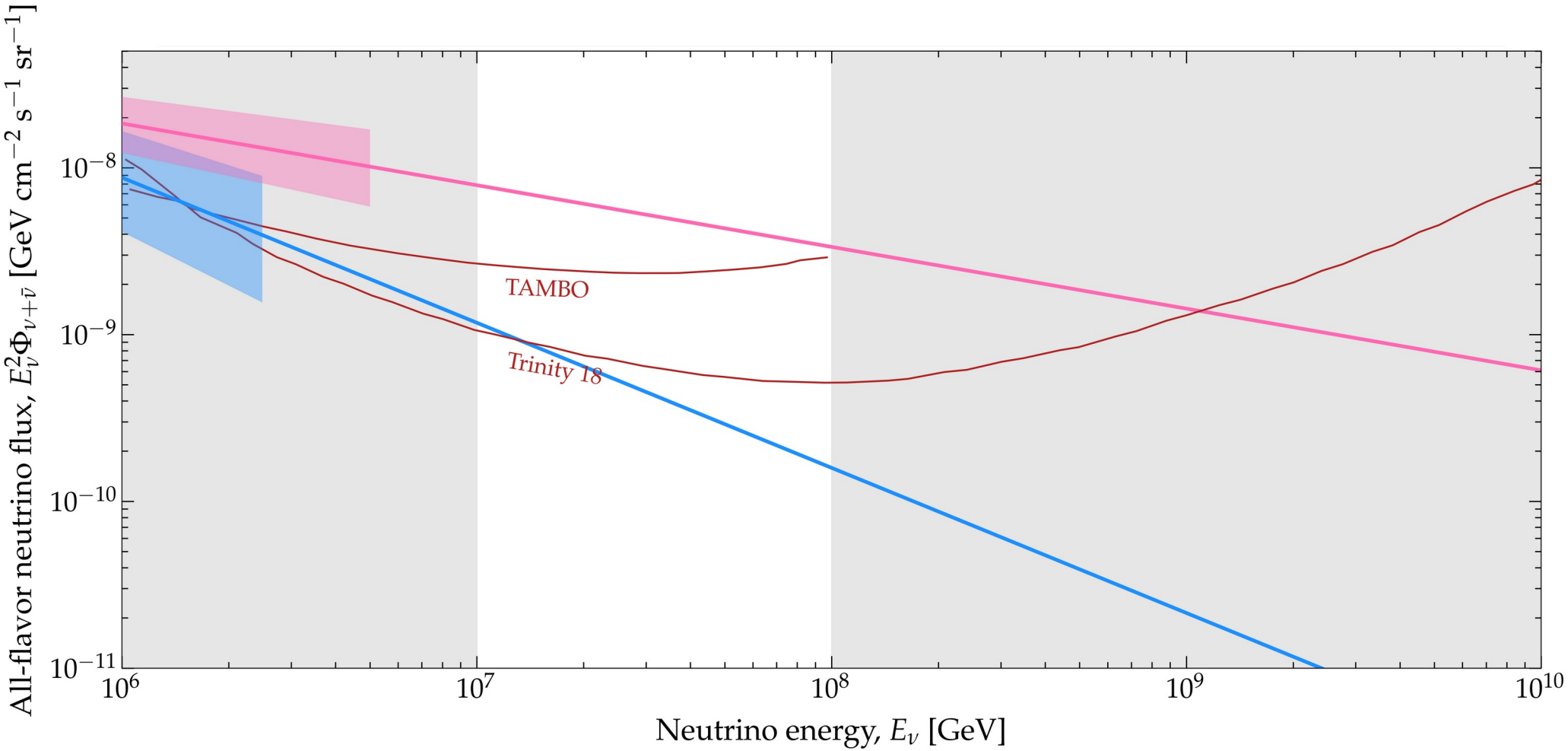
TRINITY Demonstrator
Frisco Peak, UT

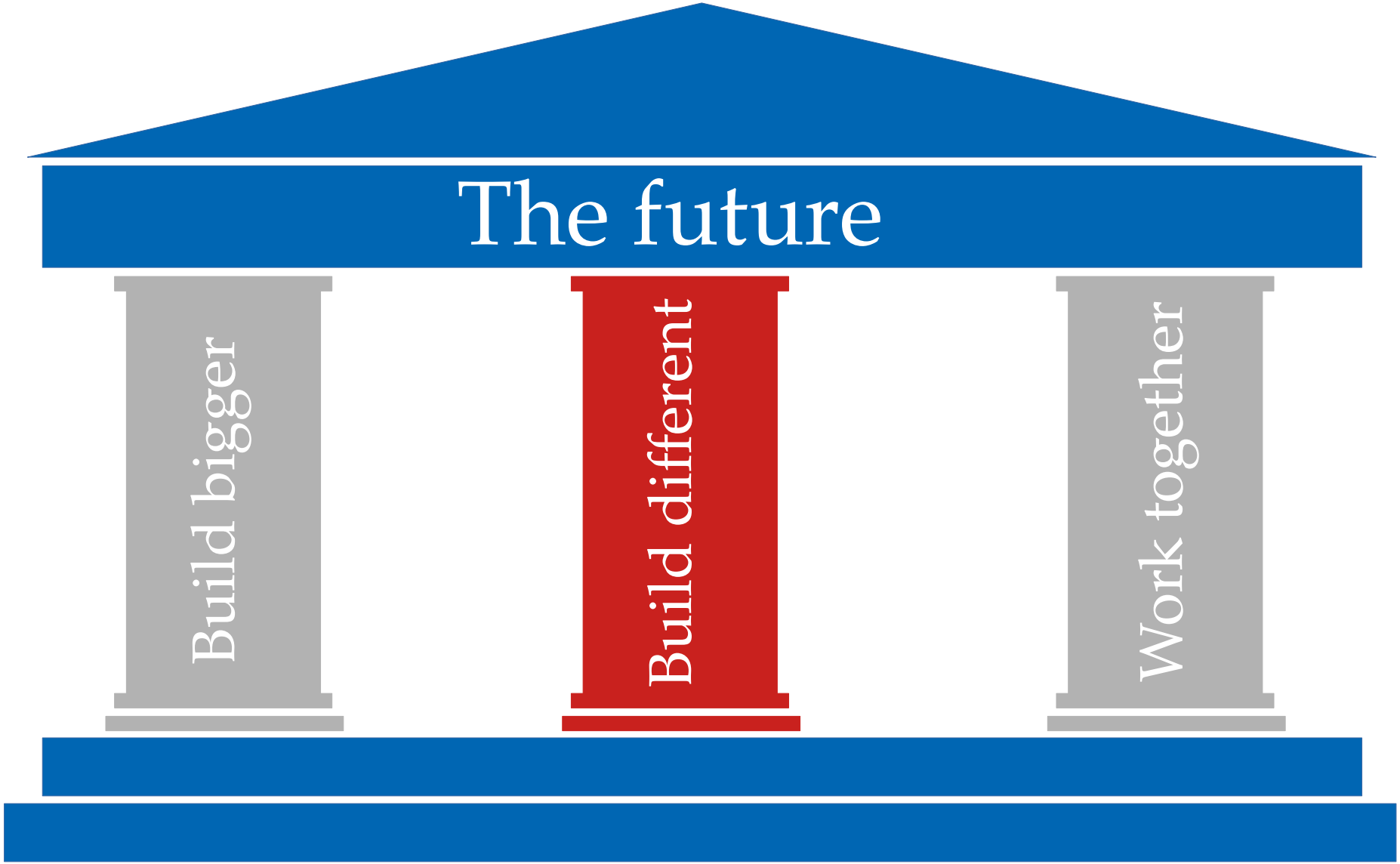


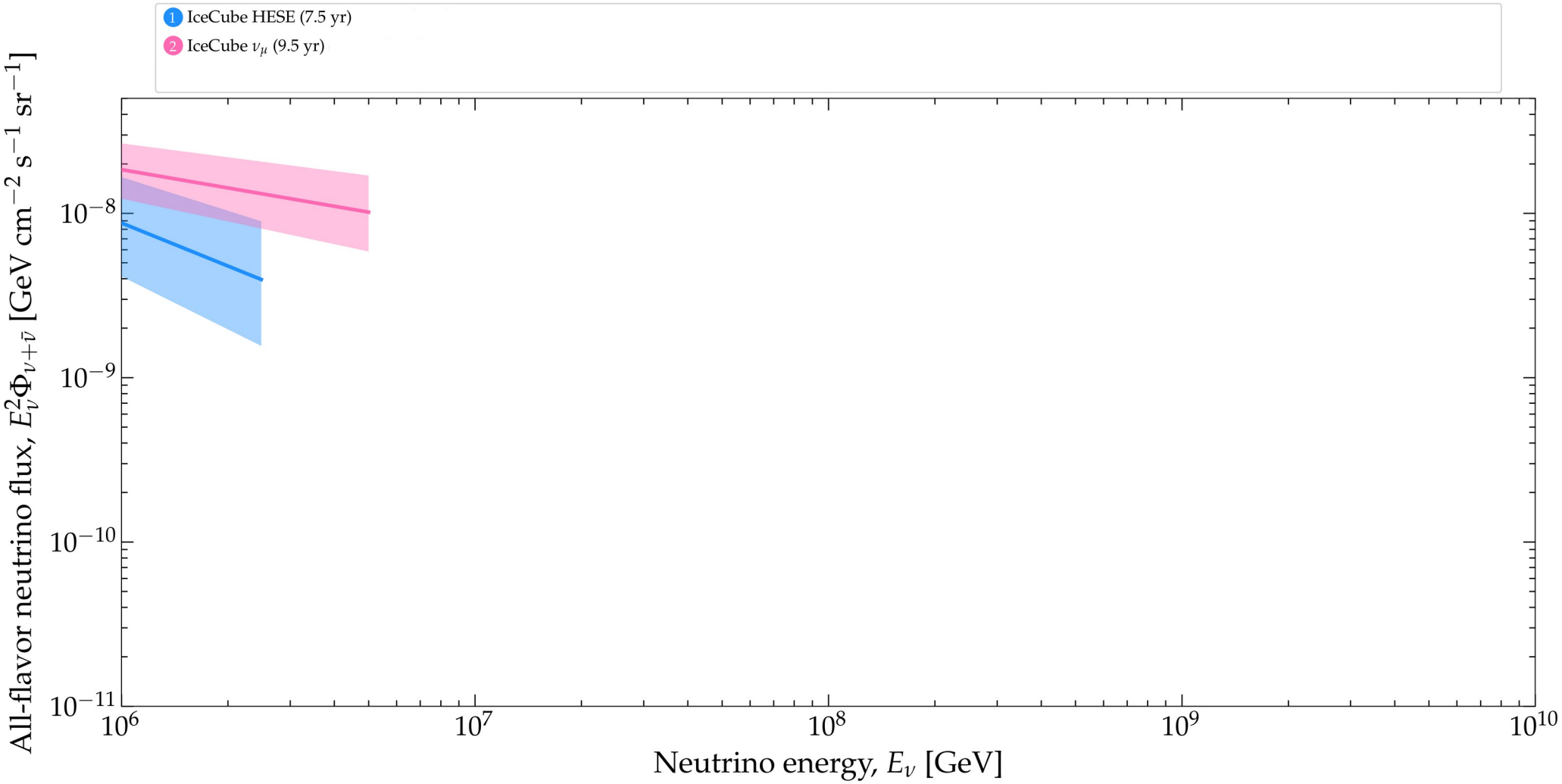
Sensitivity to an E^{-2} neutrino spectrum

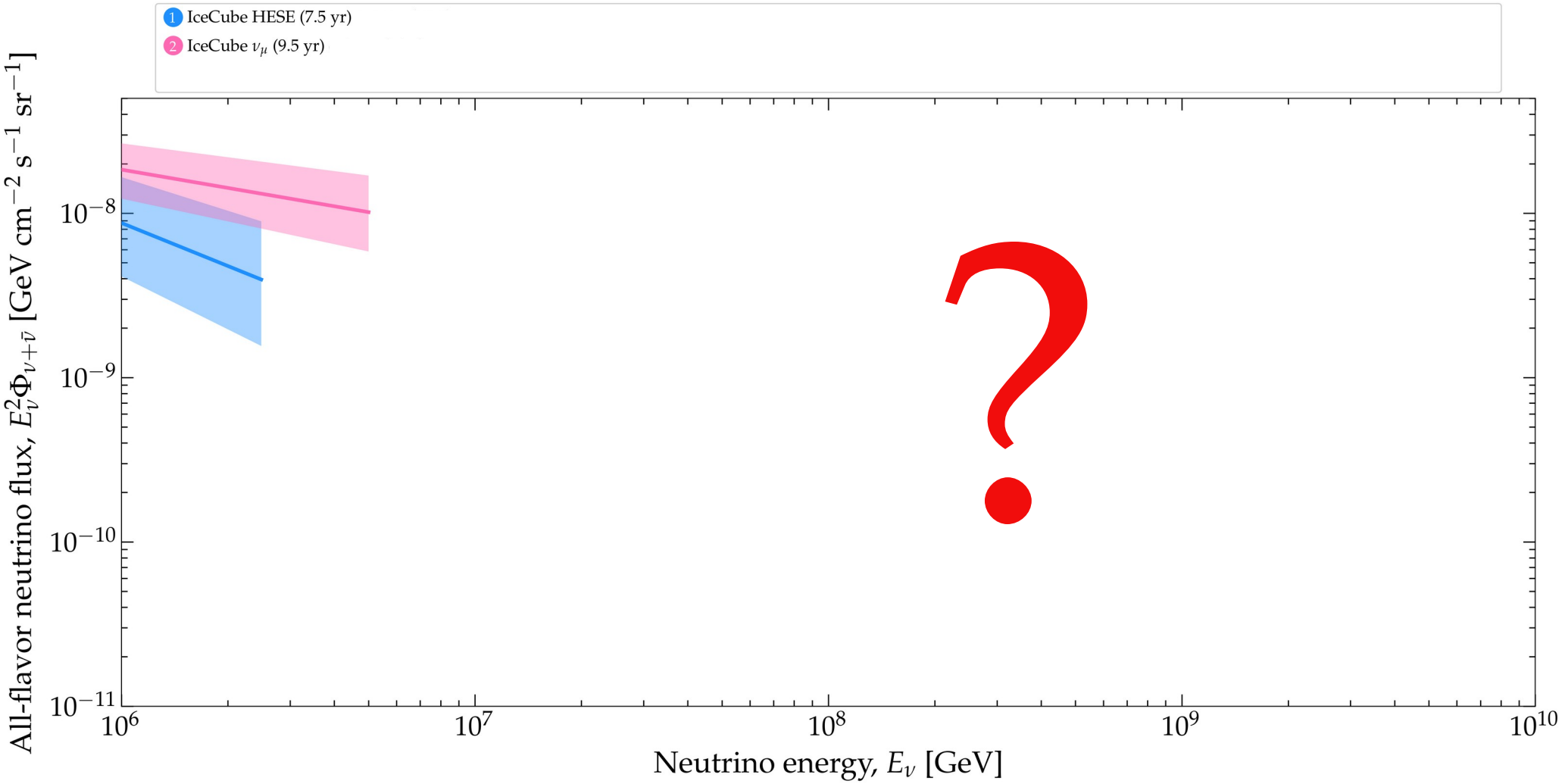


A. N. Otte for the TRINITY Collab., *PoS* ICRC2023, 1170


All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
TAMBO
Trinity 18
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


The future
Build bigger
Build different
Work together


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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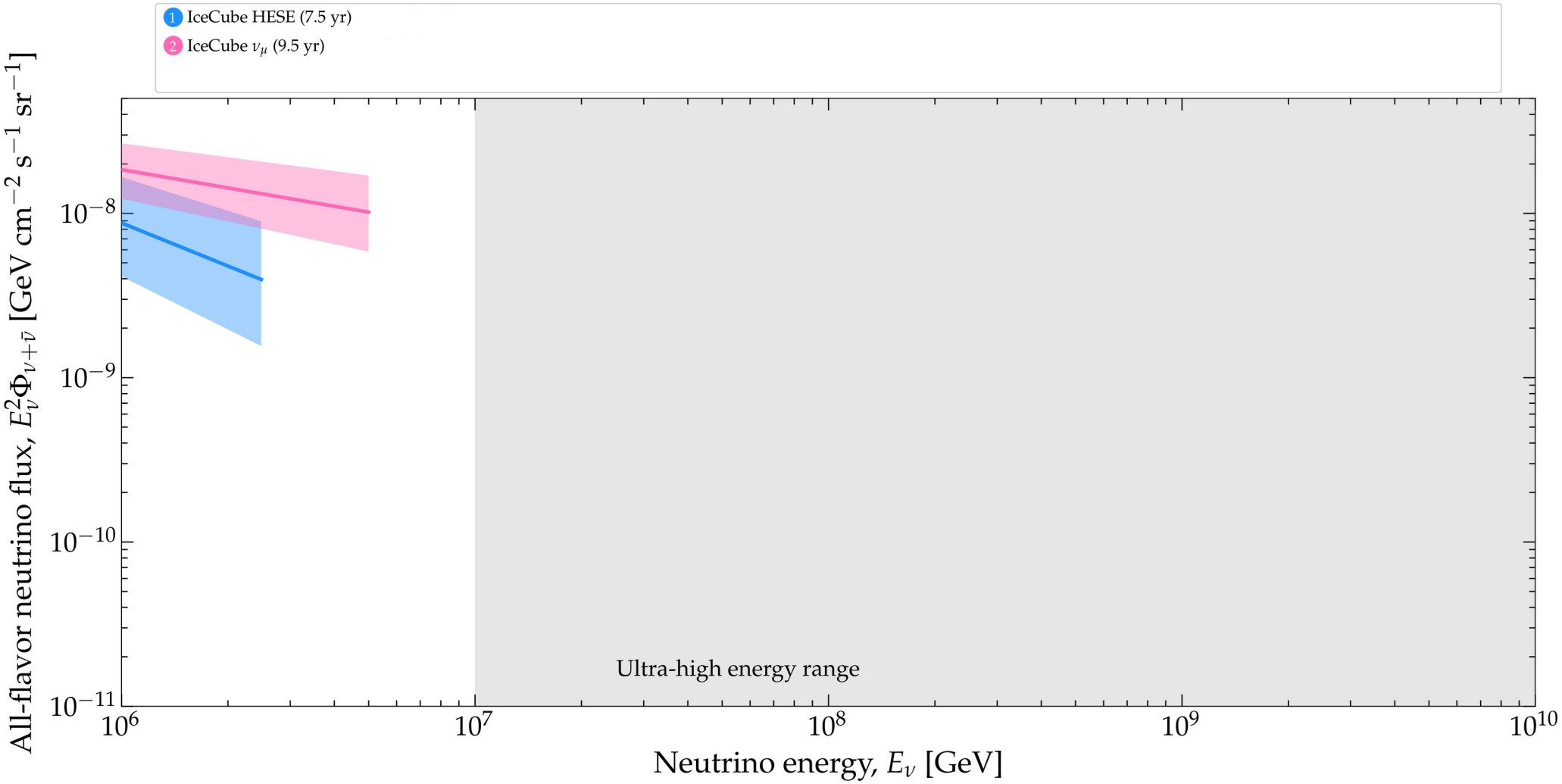
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?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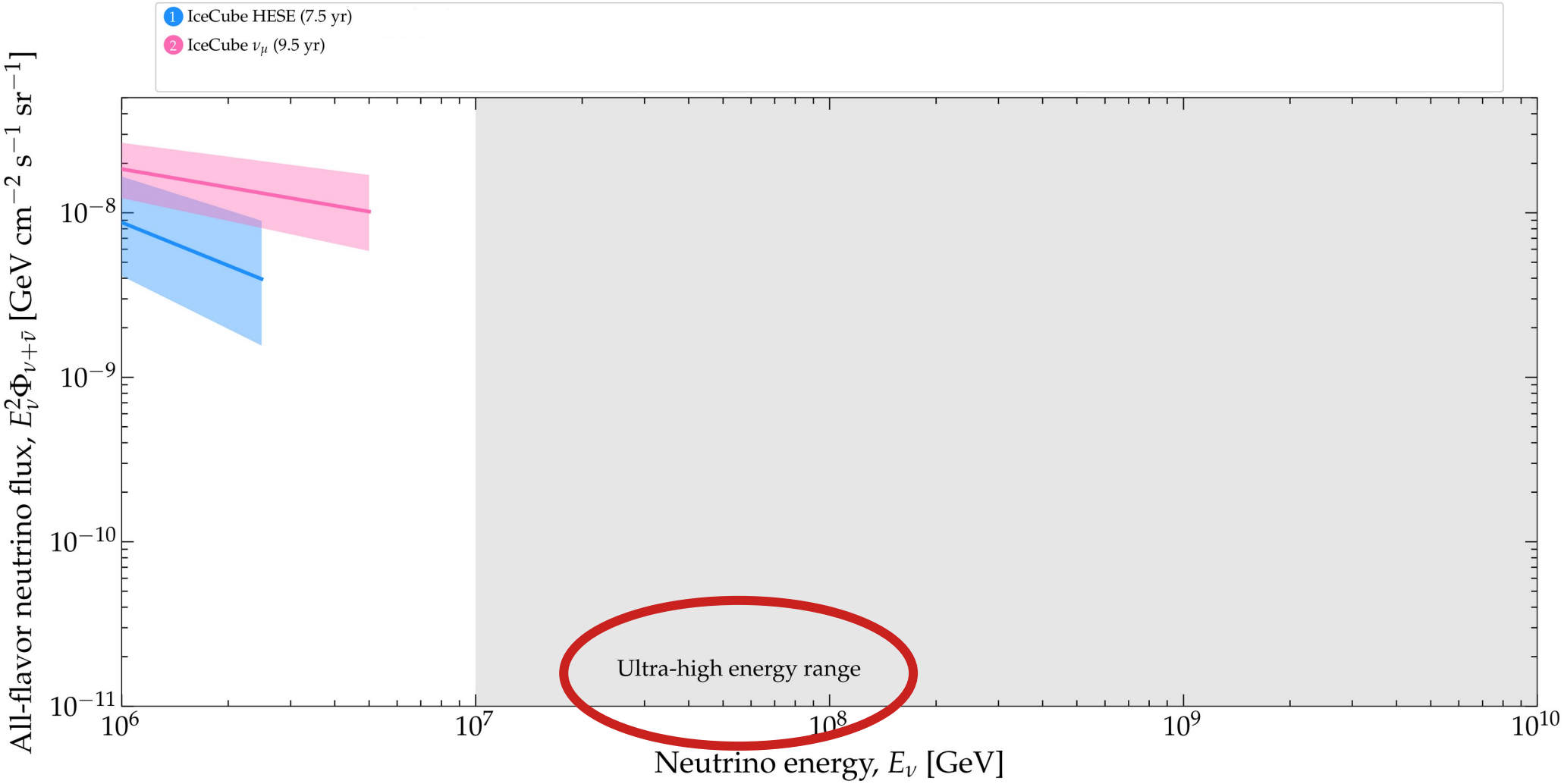
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Ultra-high energy range
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]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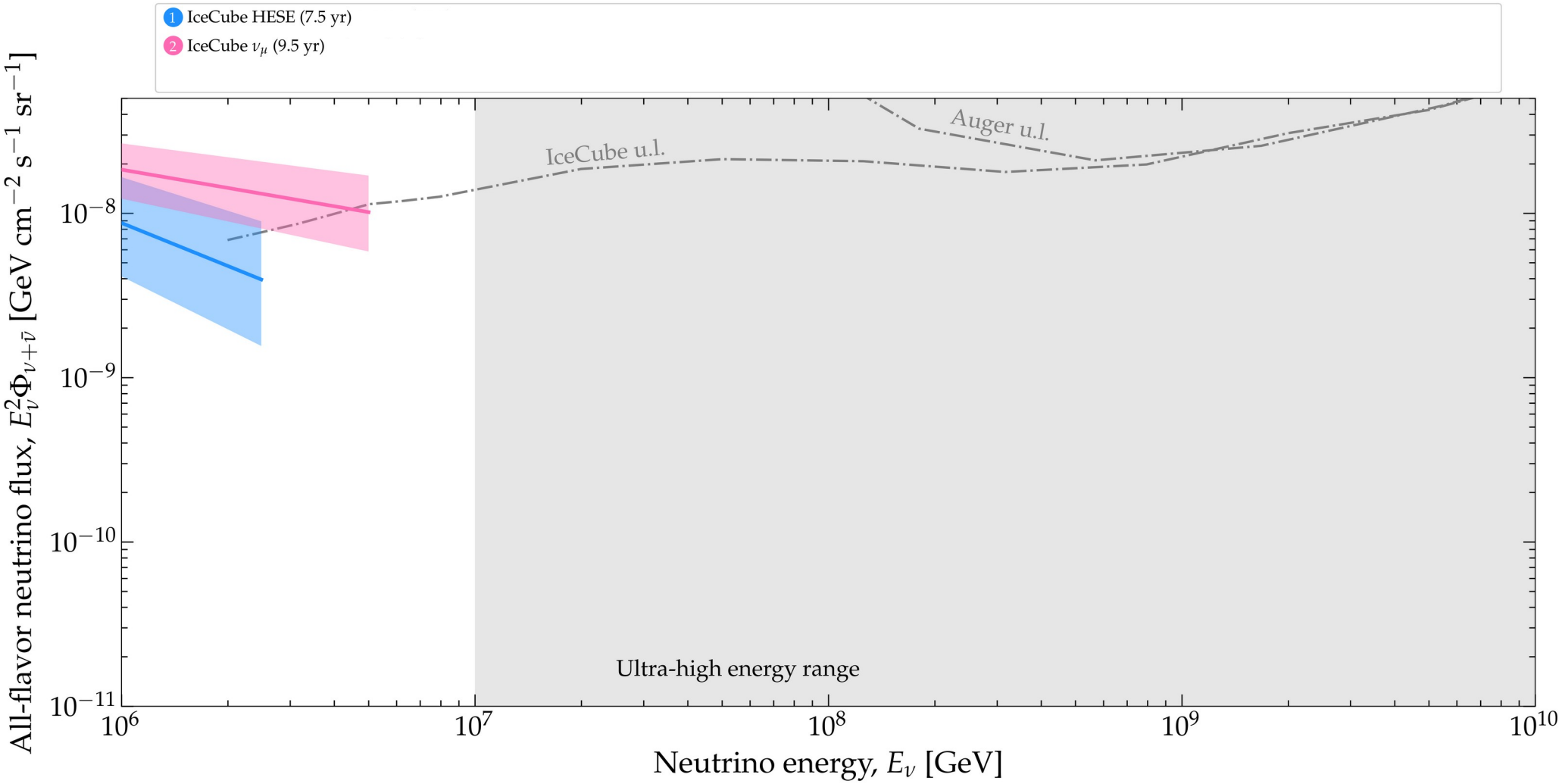
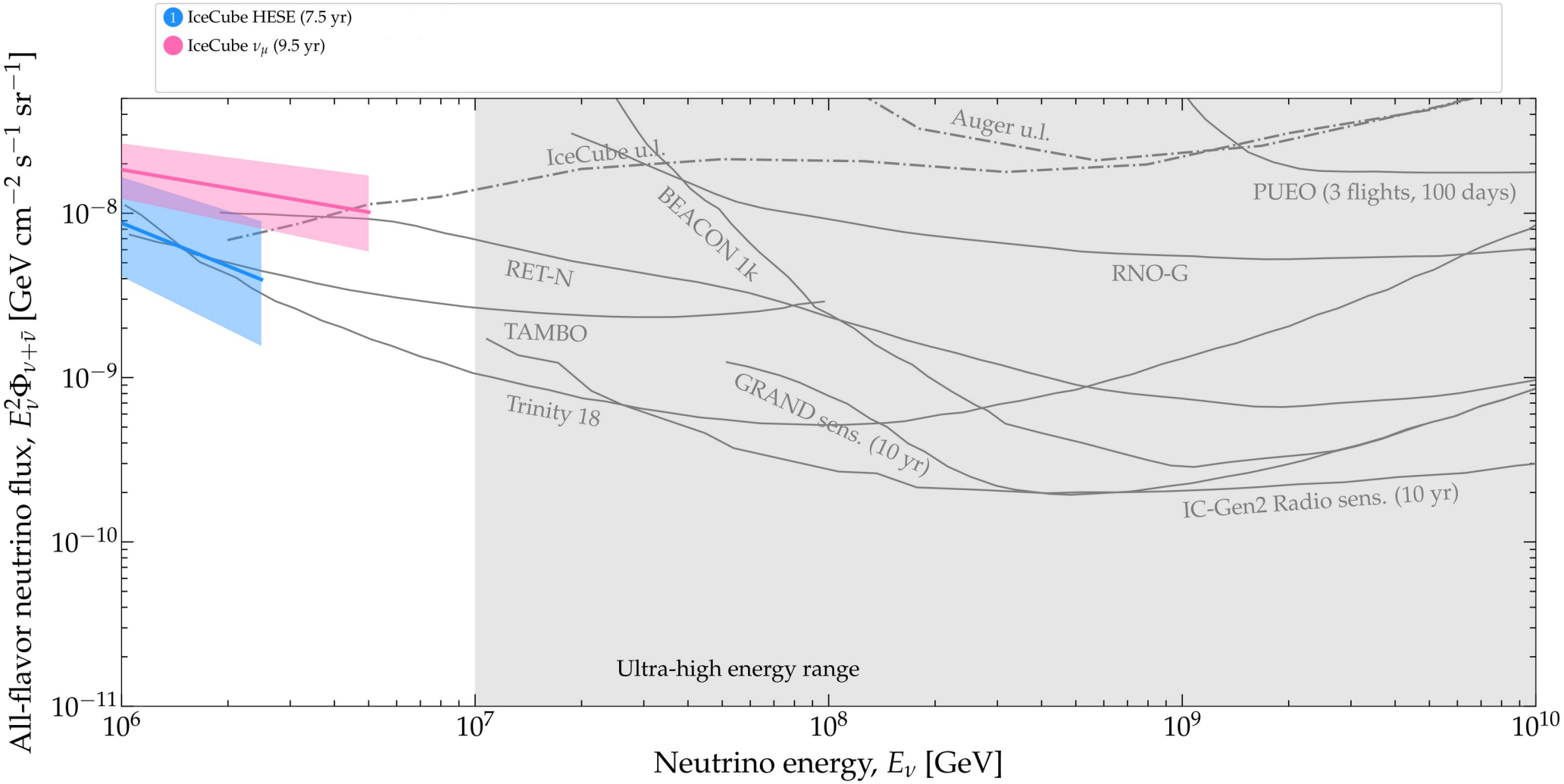
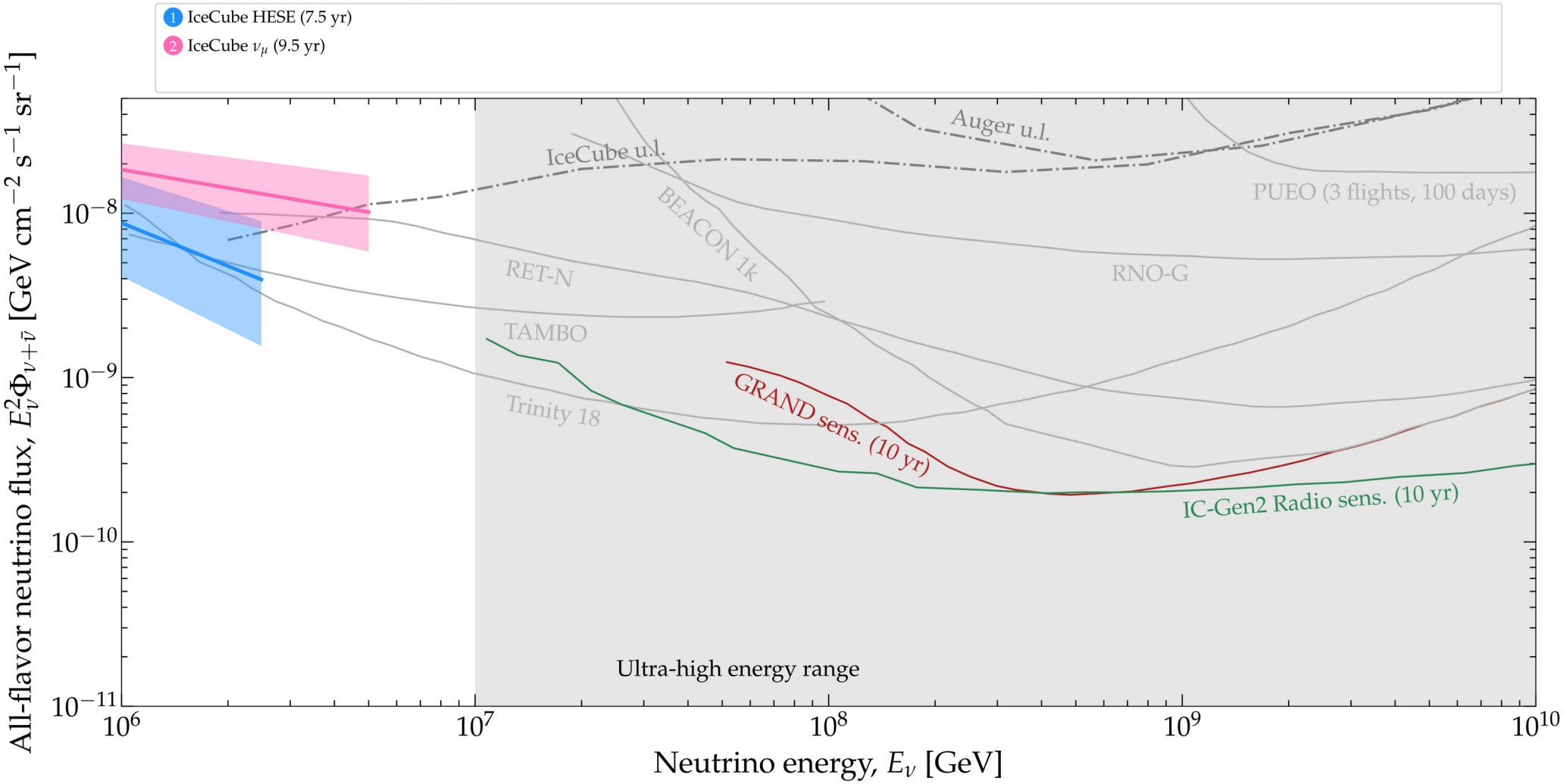
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
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10^{-8}
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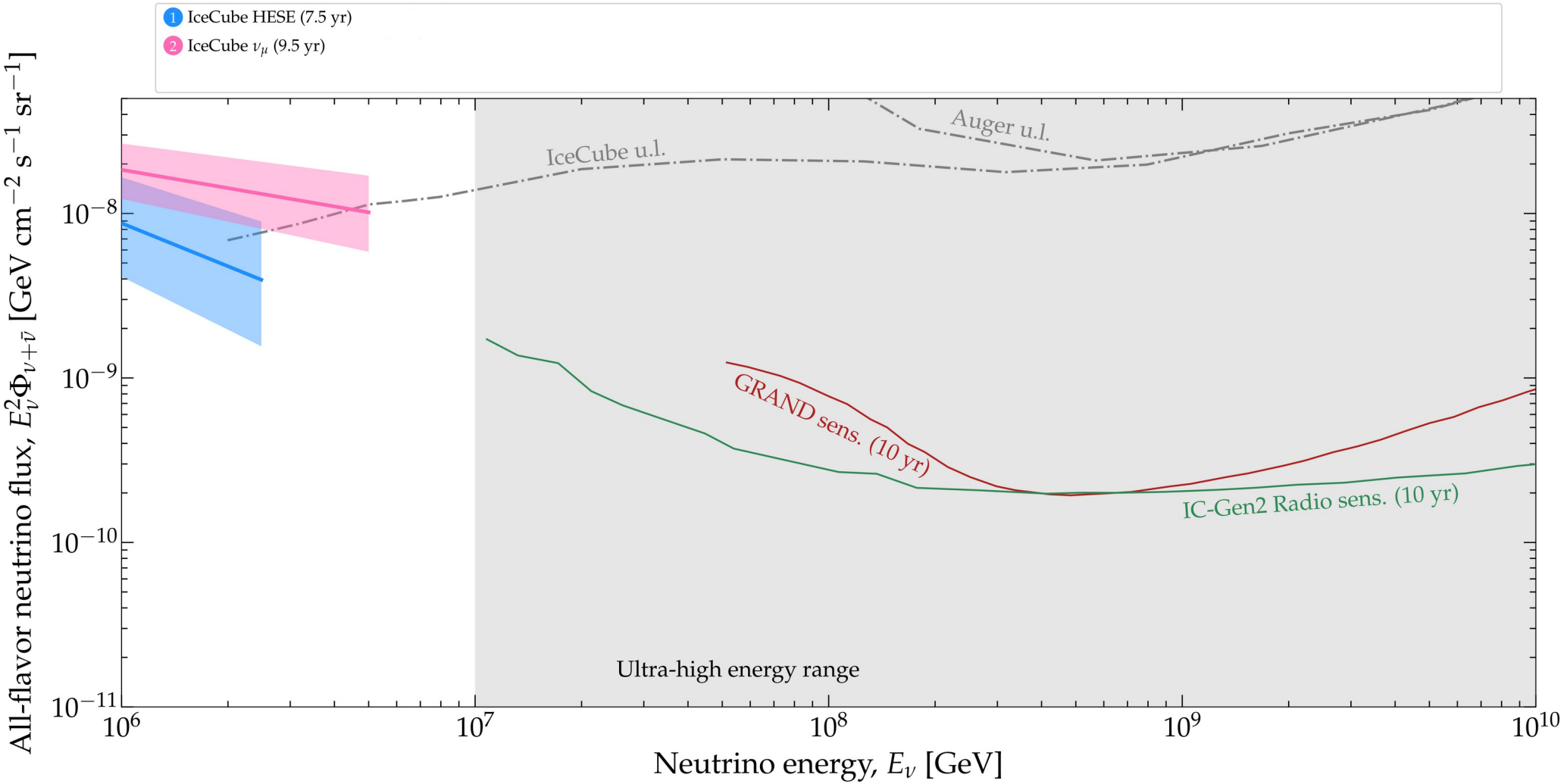
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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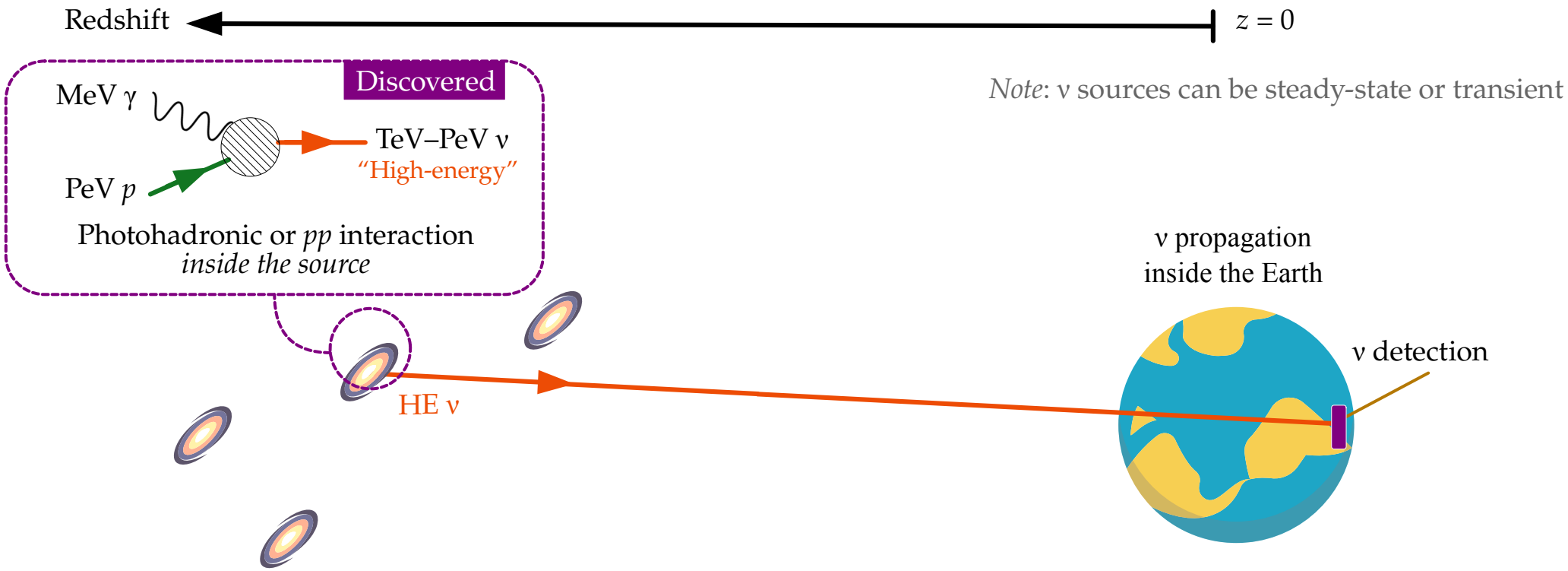
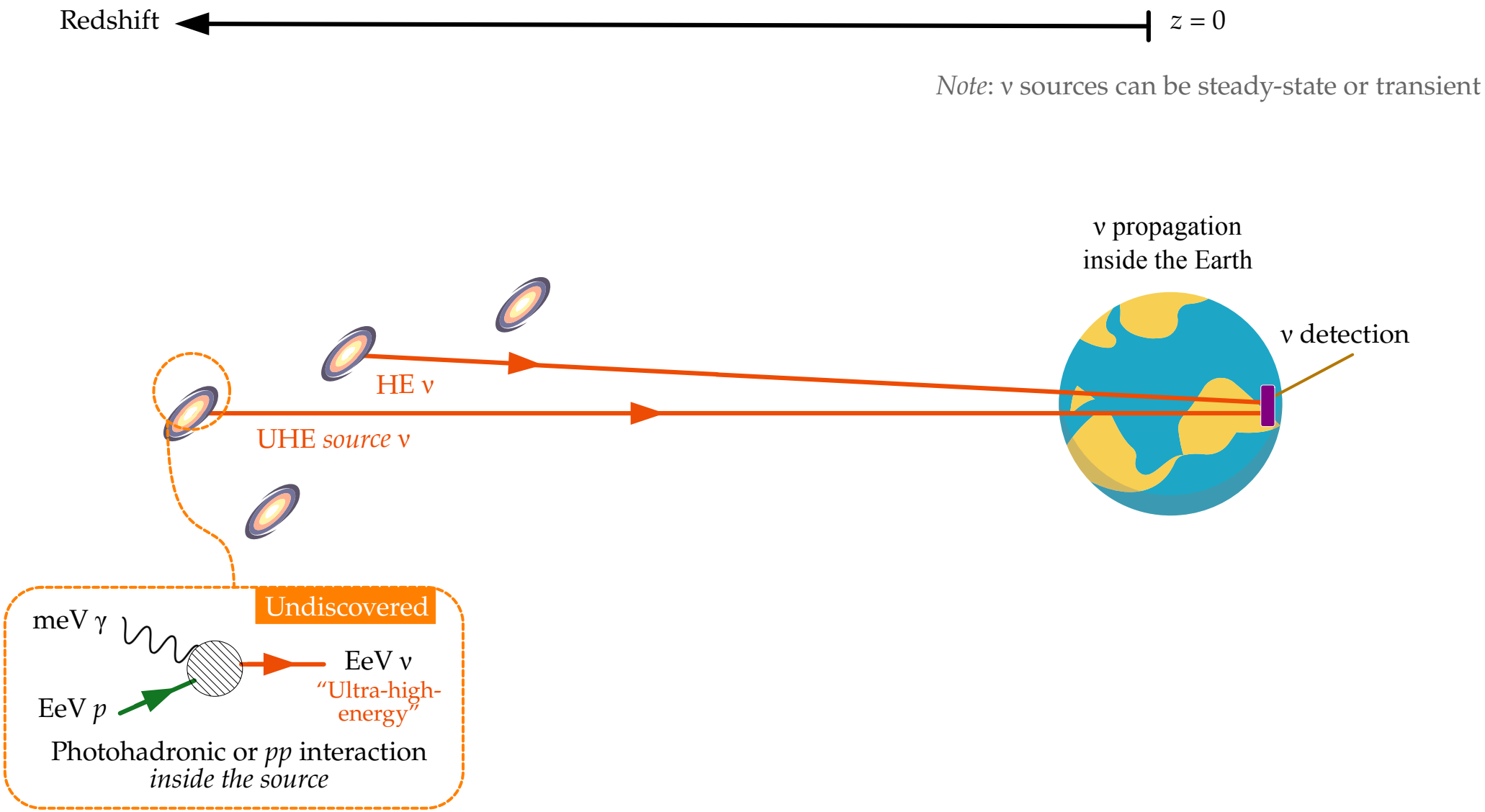
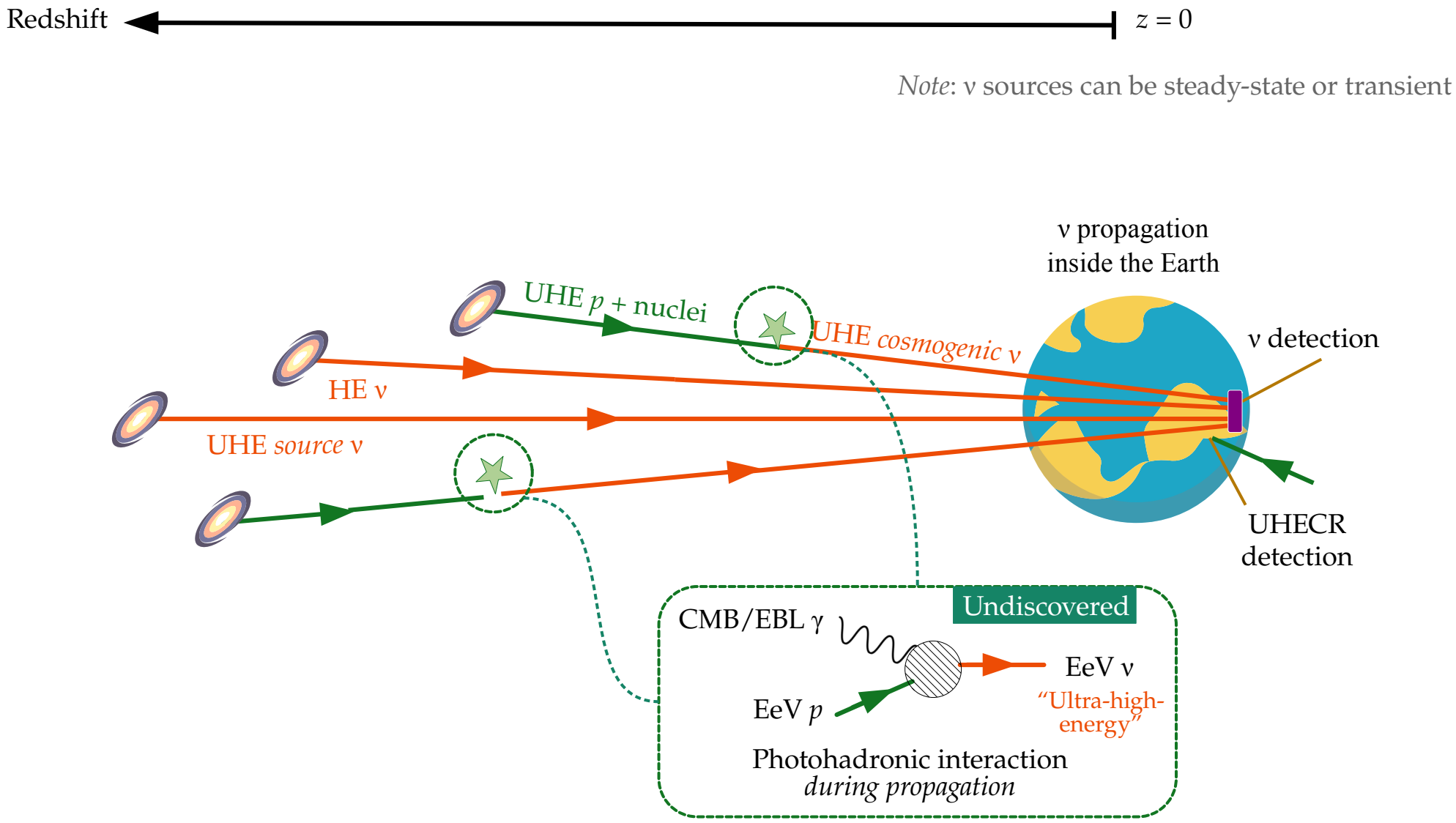
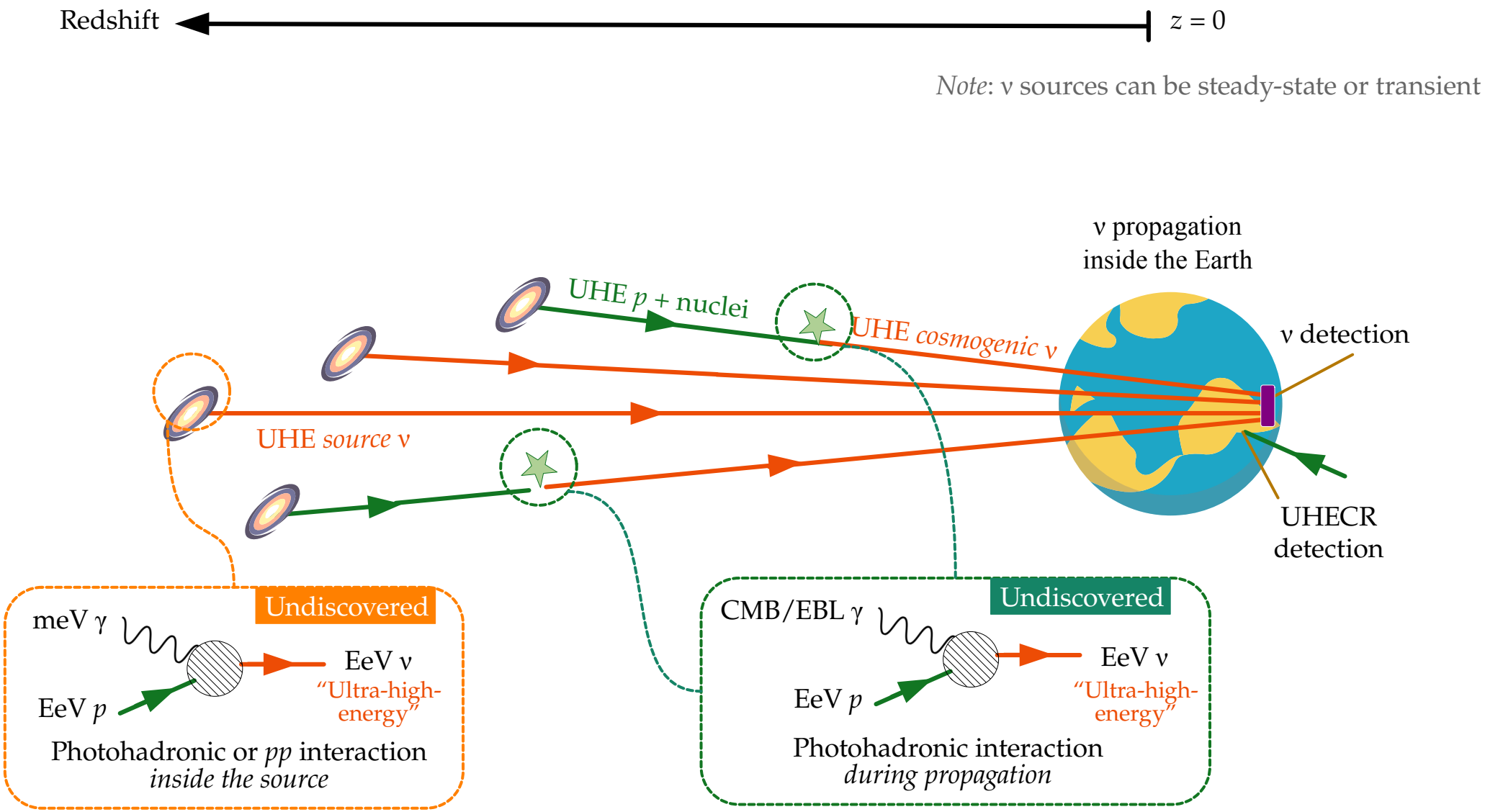
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]


Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν


Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic or pp interaction
inside the source


Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation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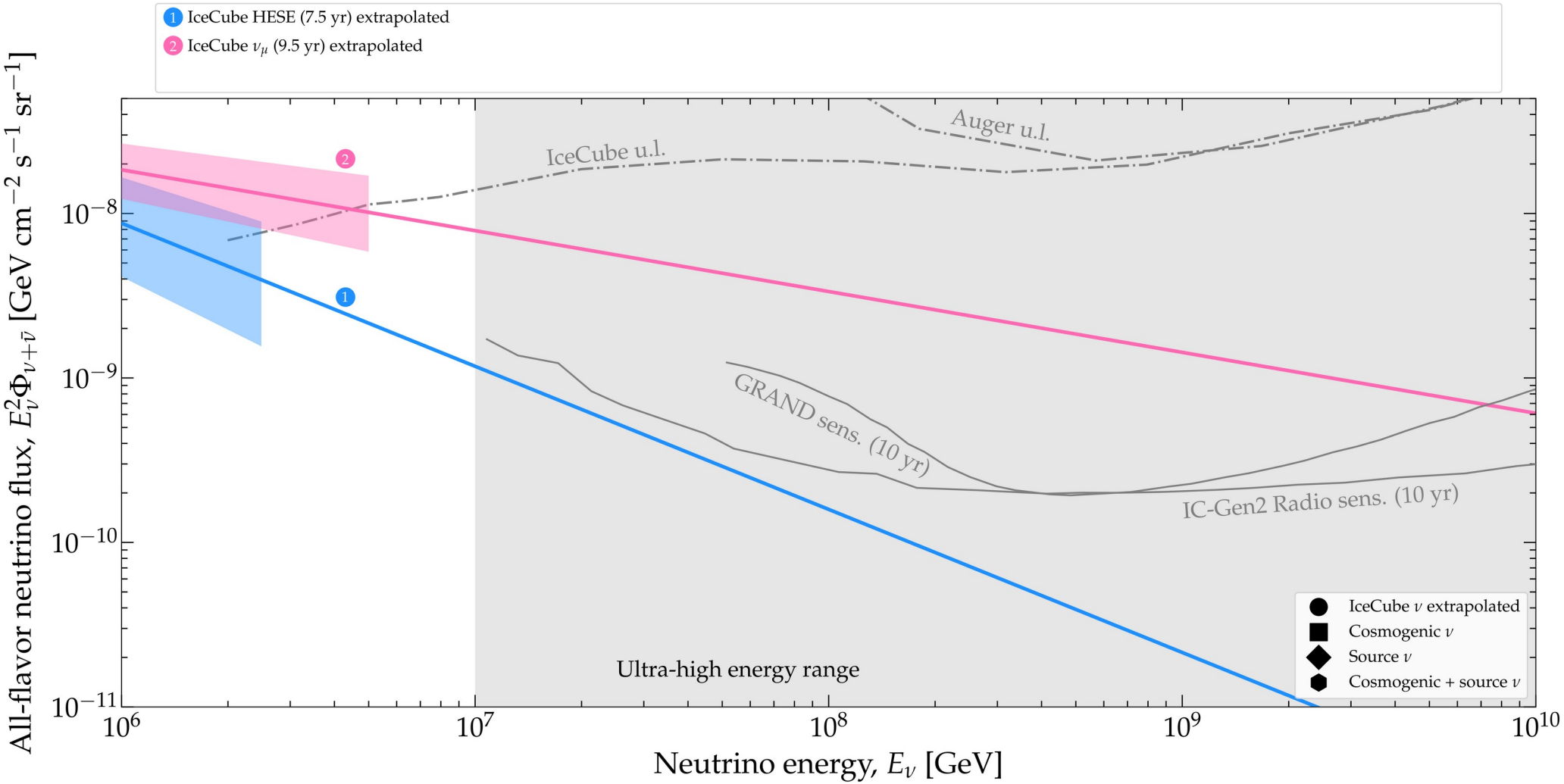
1 IceCube HESE (7.5 yr) extrapolated
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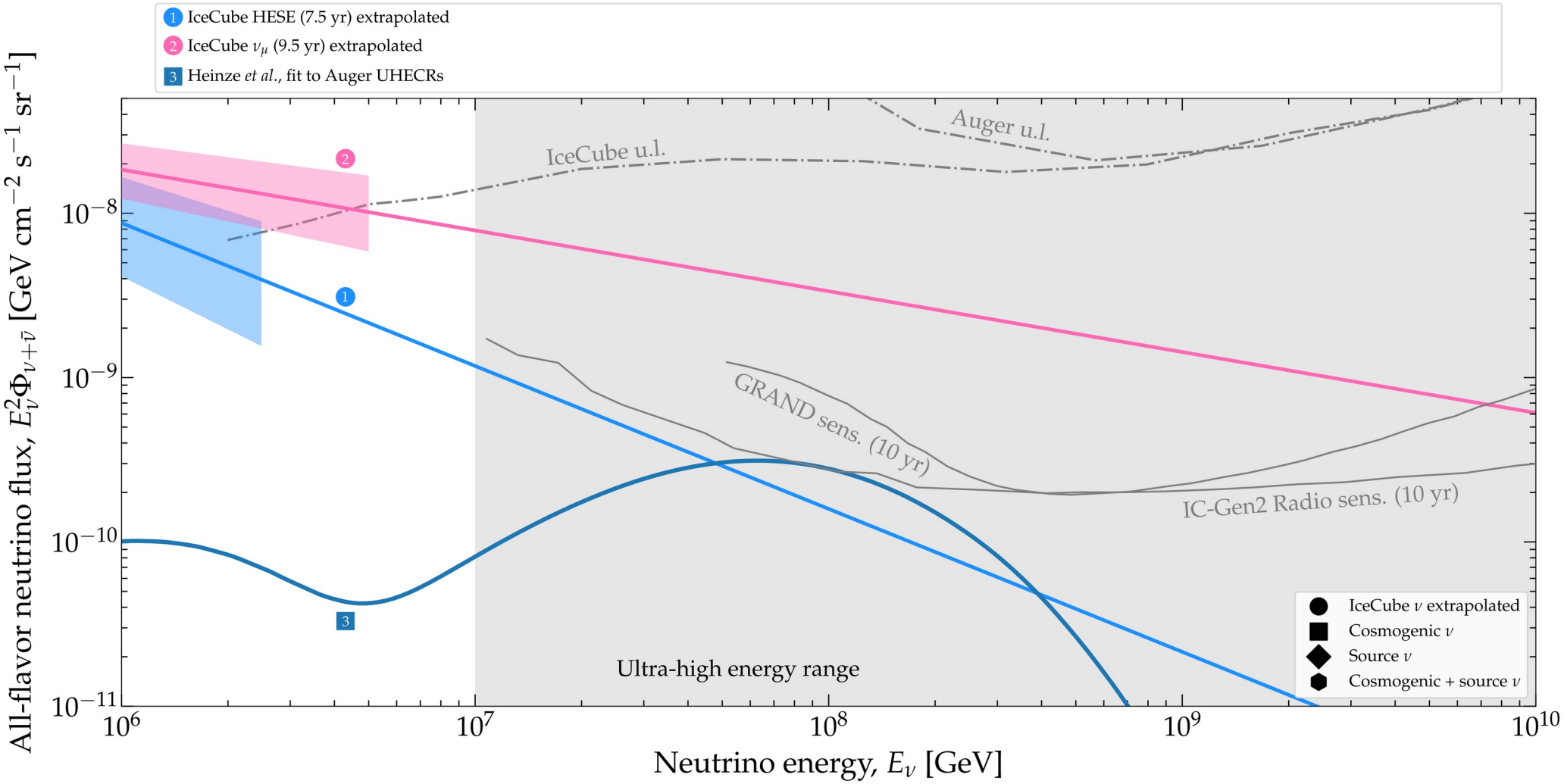
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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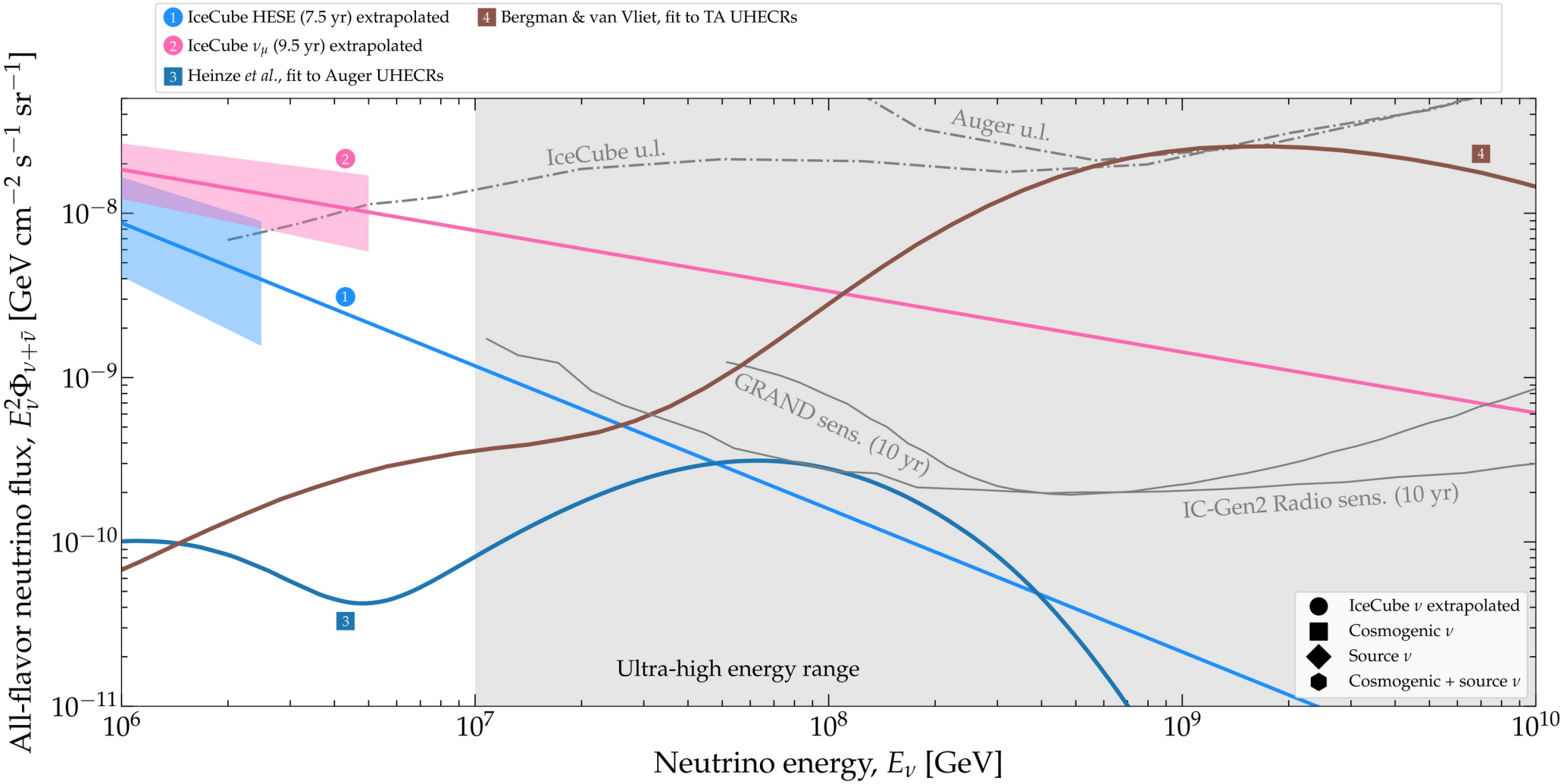
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
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Cosmogenic ν
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10^6
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10^9
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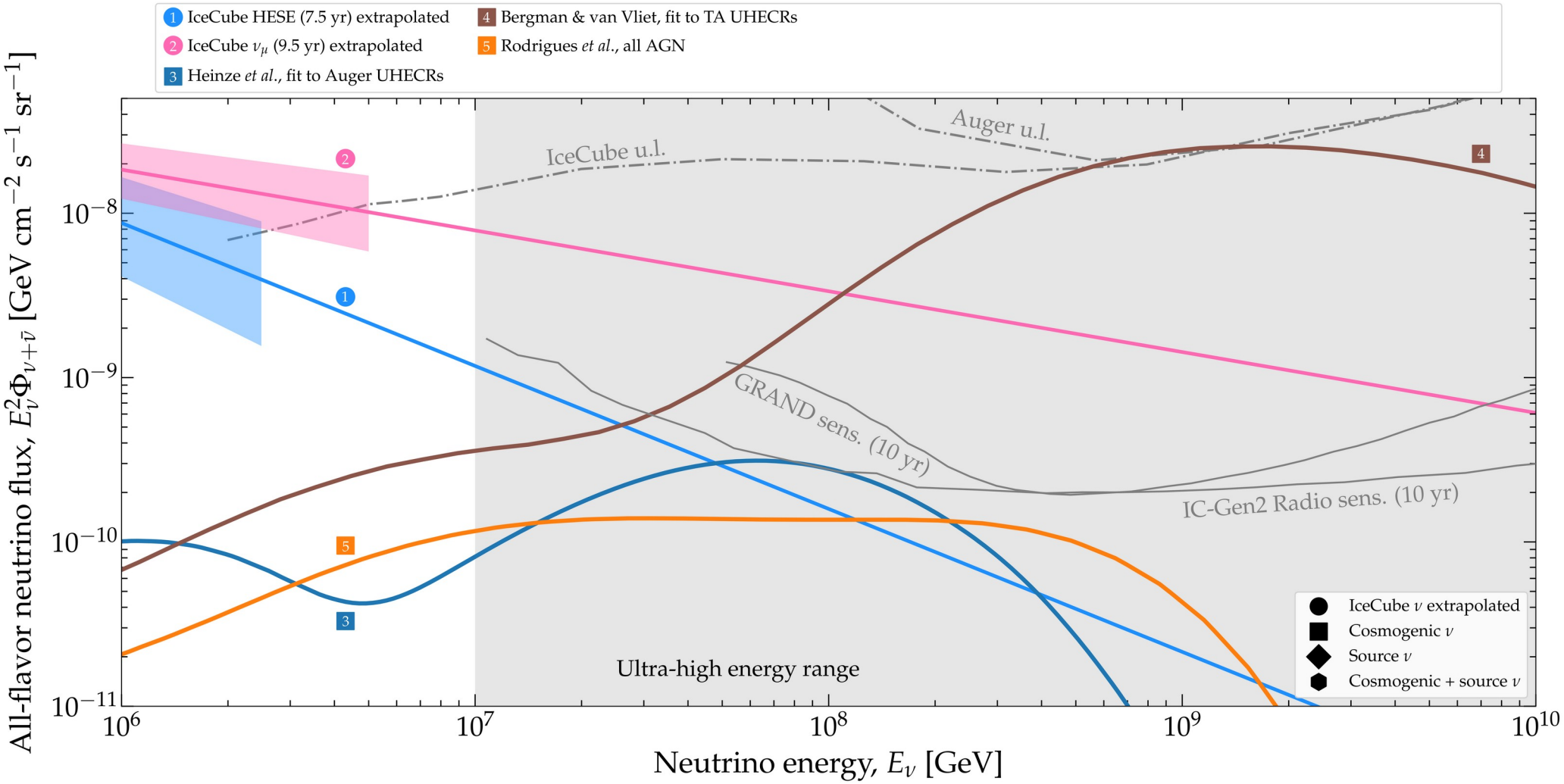
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2 IceCube ν_μ (9.5 yr) extrapolated
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5 Rodrigues et al., all AGN
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^6
10^7
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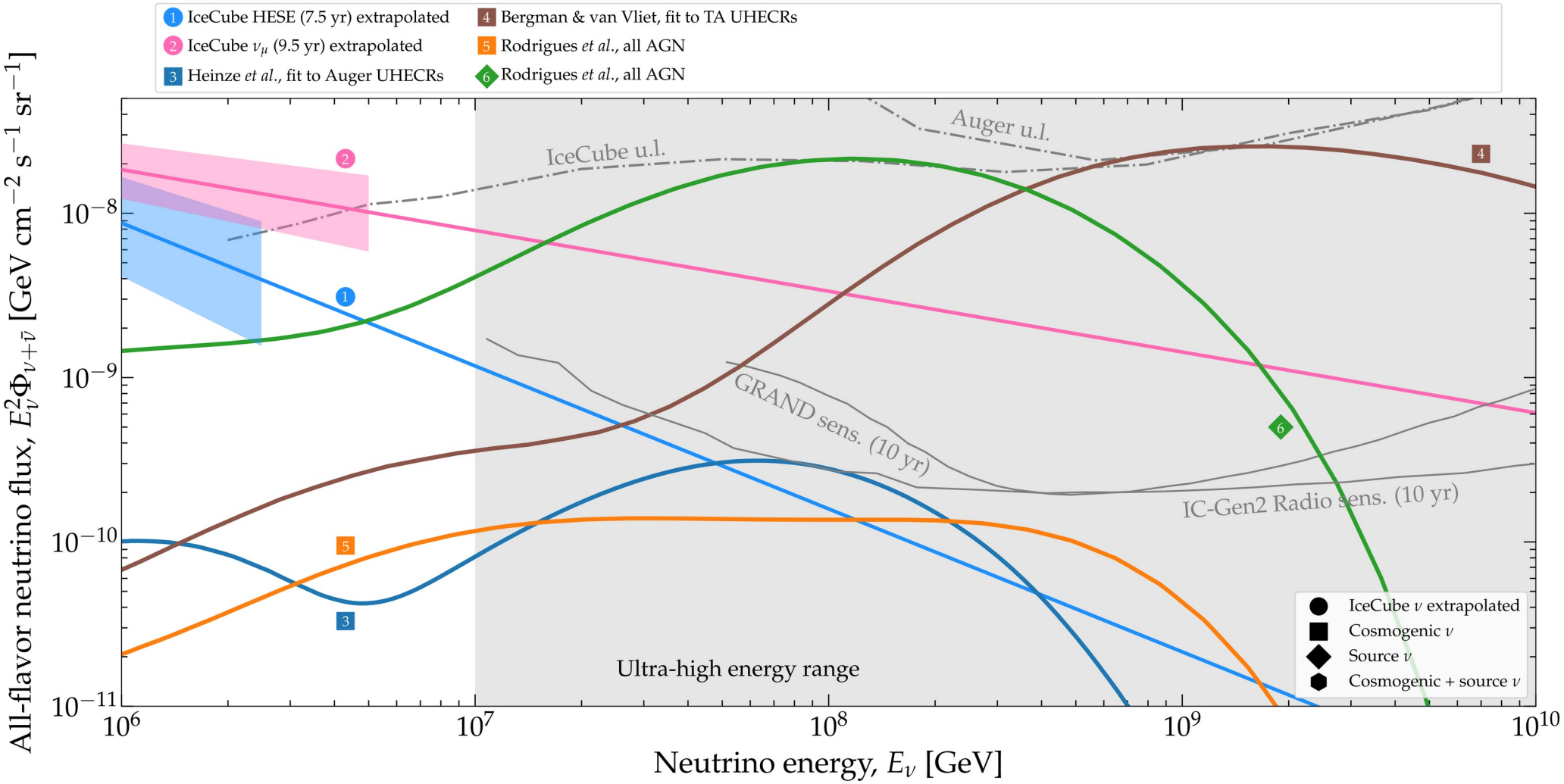
10^{10}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Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^{-8}
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10^{-11}
10^6
10^7
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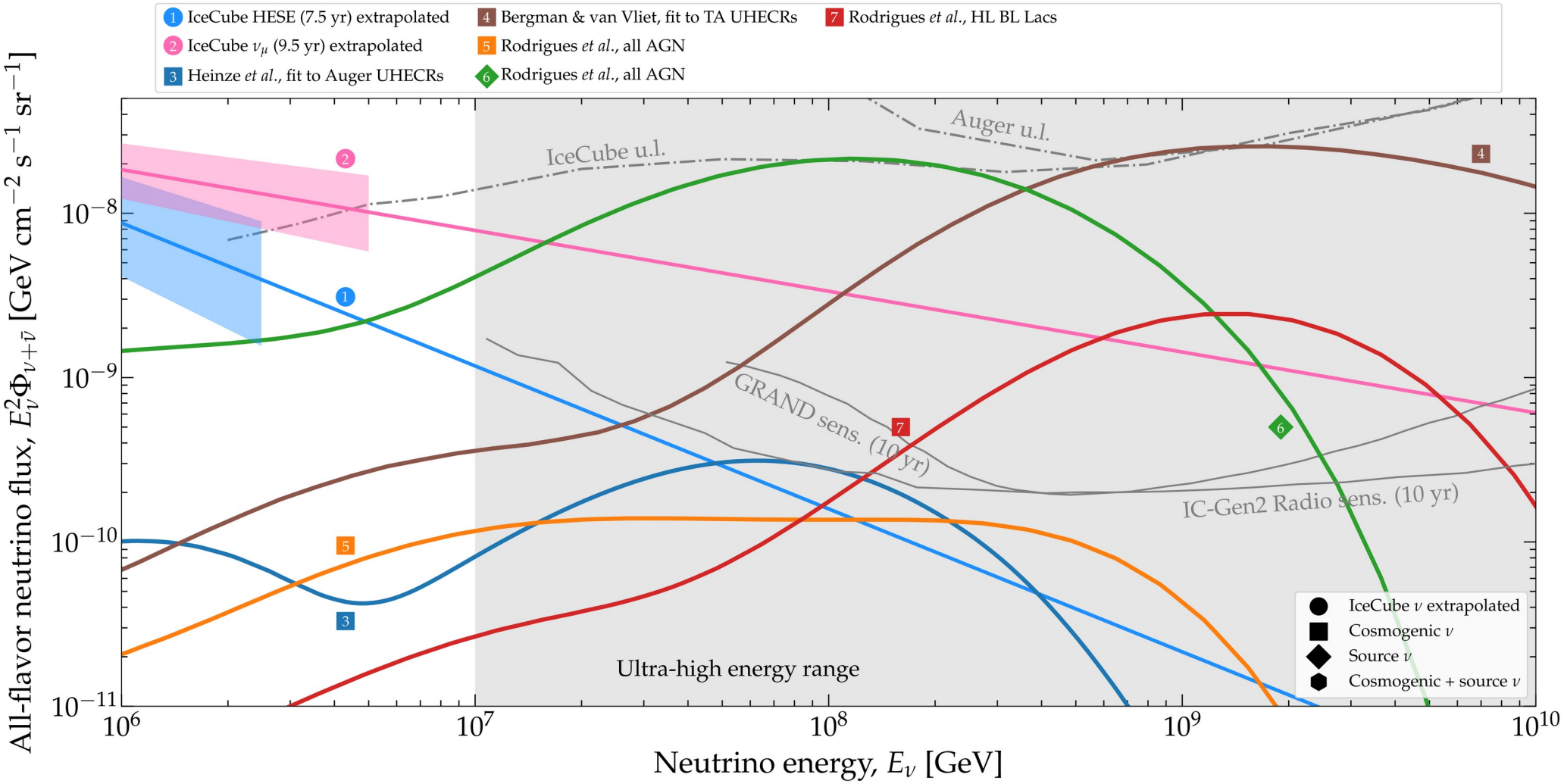
10^{10}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6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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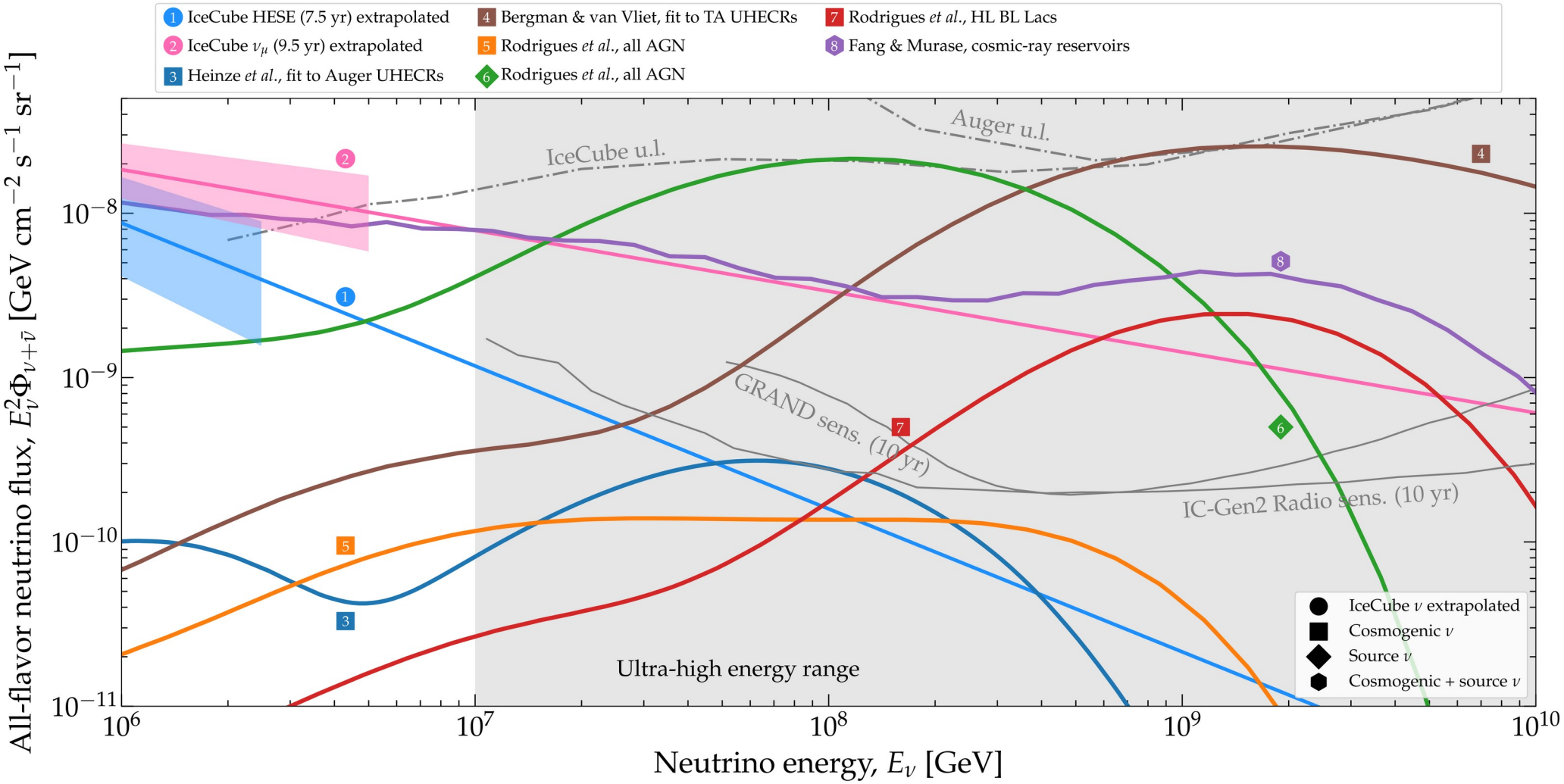
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8 Fang & Murase, cosmic-ray reservoirs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
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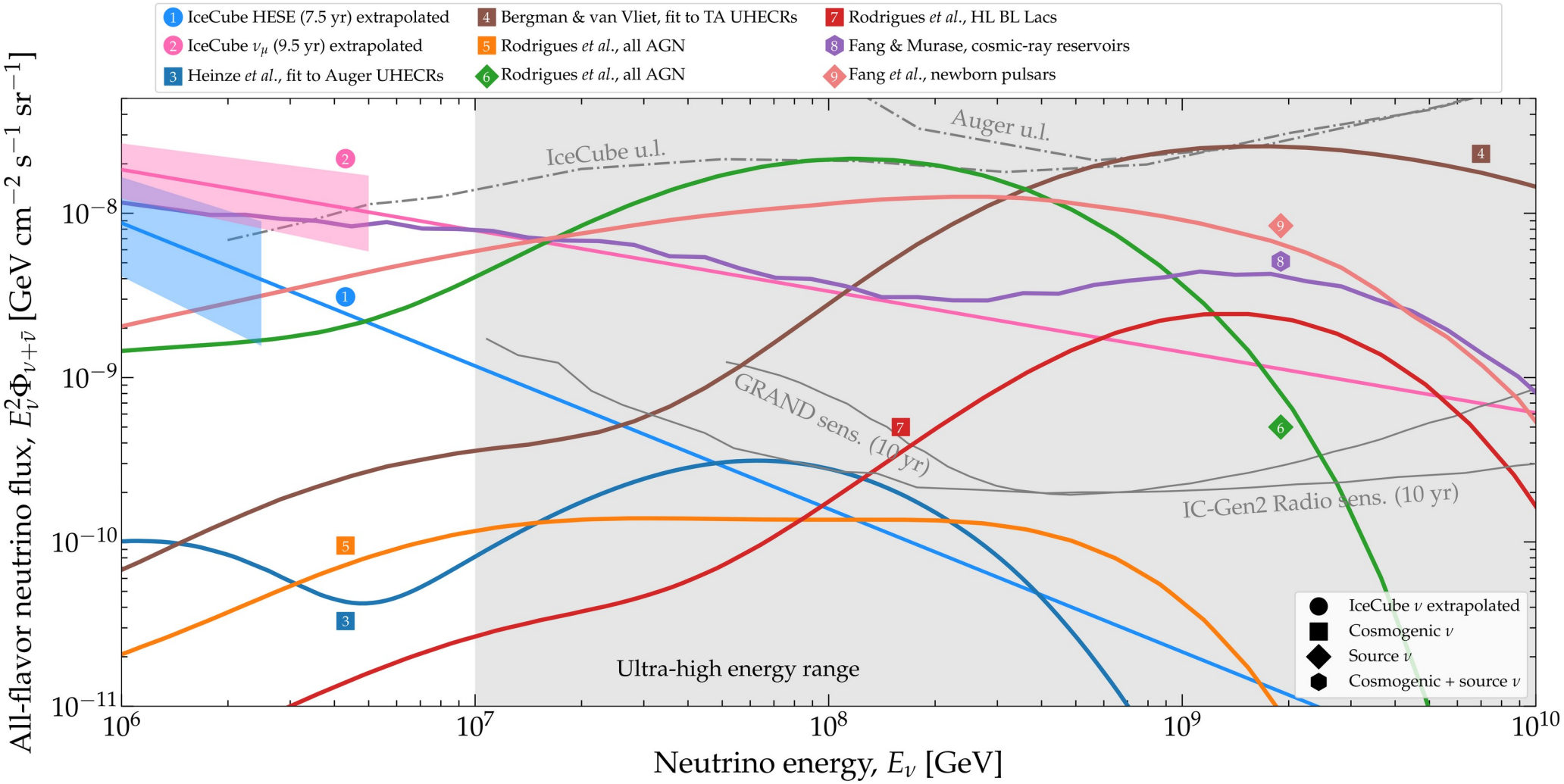
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5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
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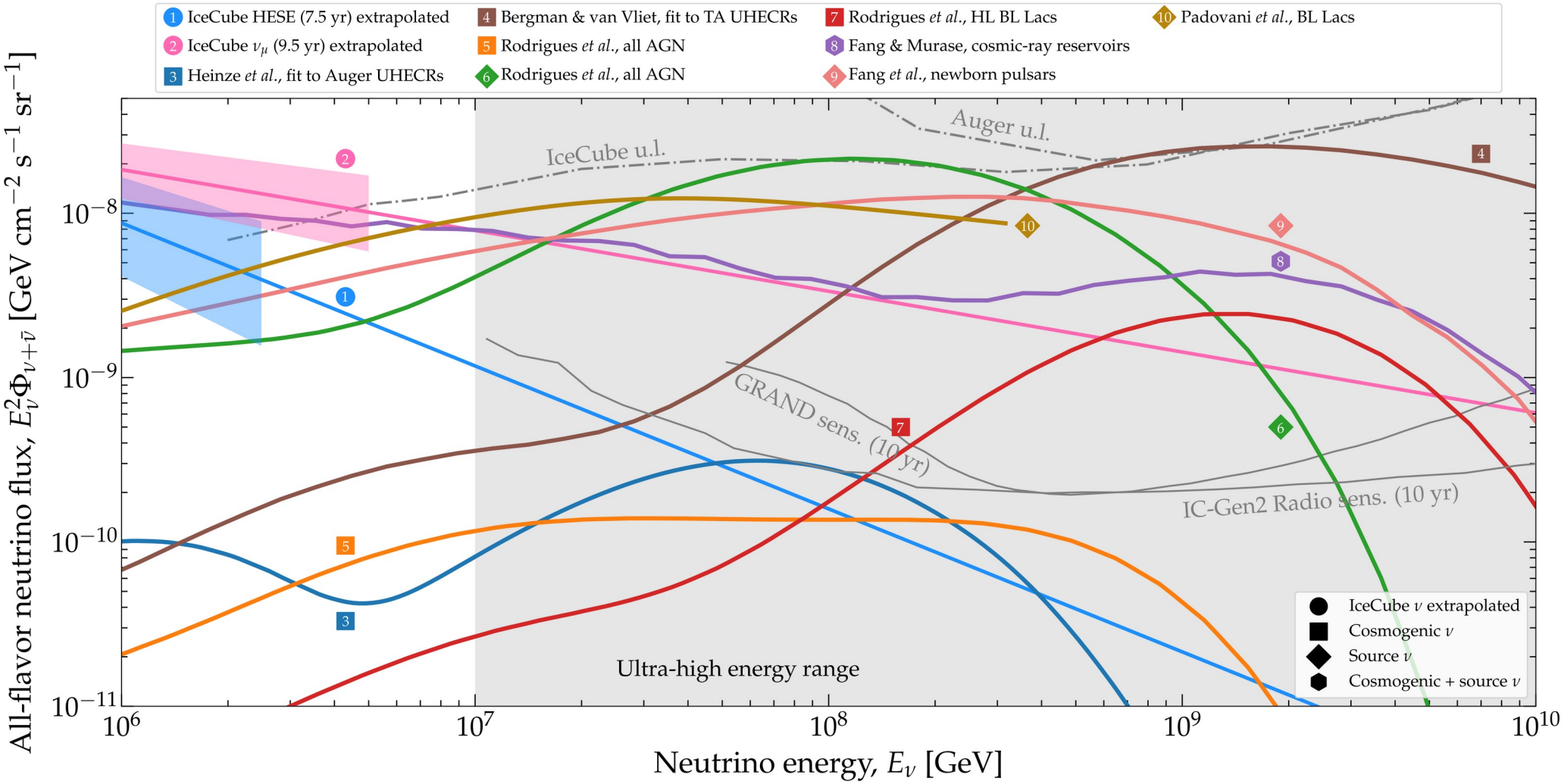
10^6
10^7
10^8
10^9
10^{10}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8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
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10^6
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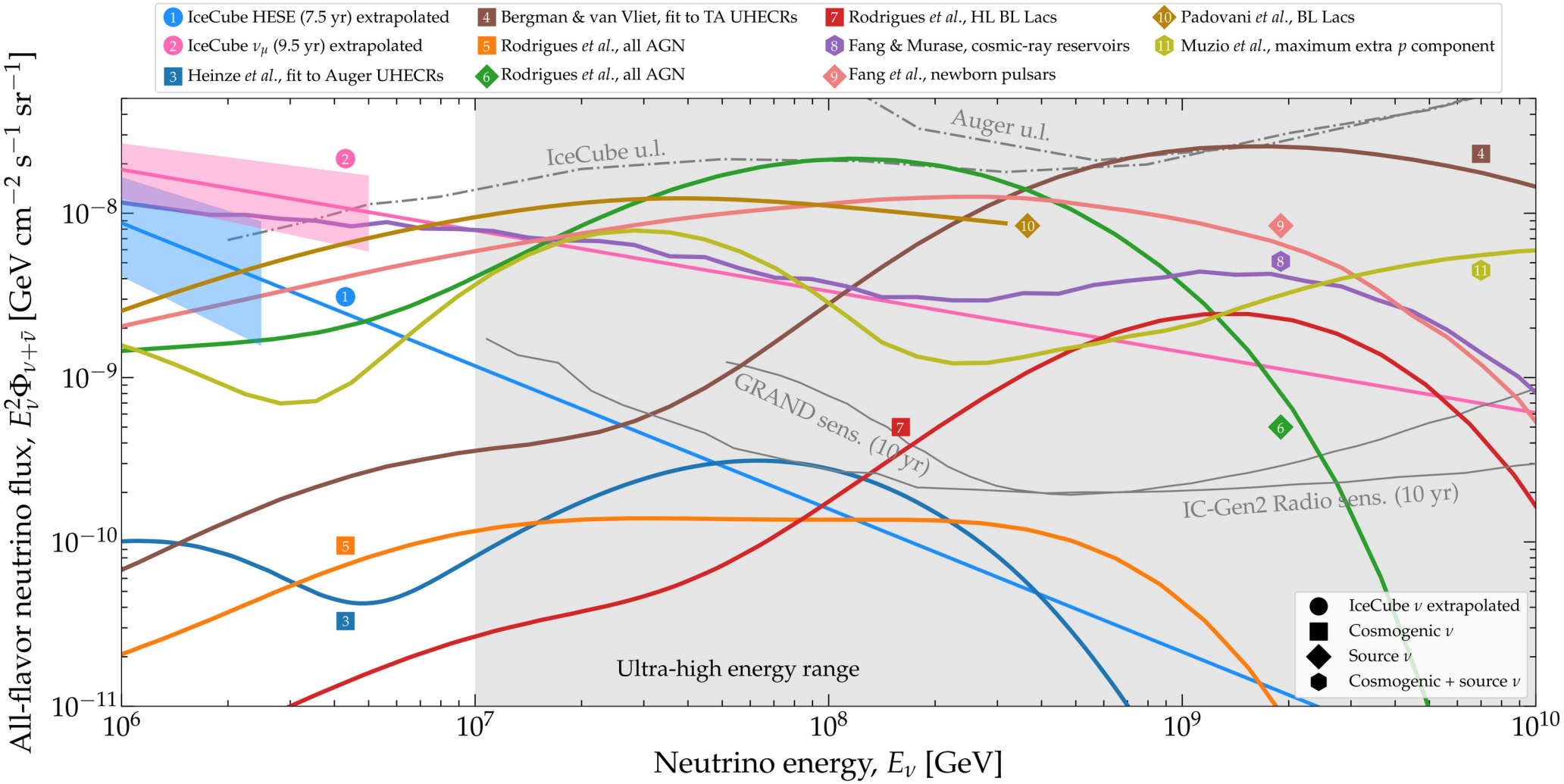
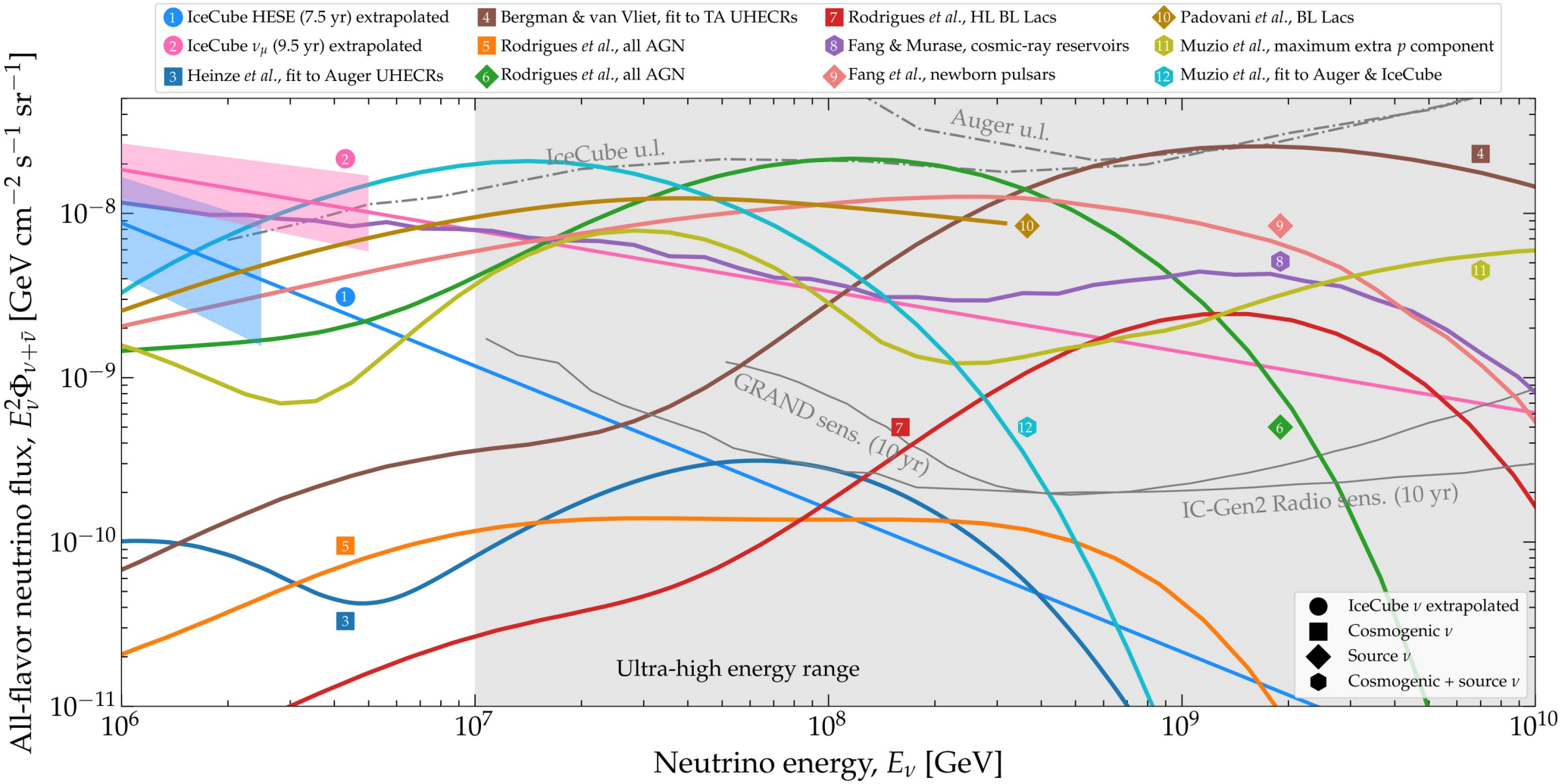
10^9
10^{10}


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}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12 Muzio et al., fit to Auger & IceCube
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
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Ultra-high energy range
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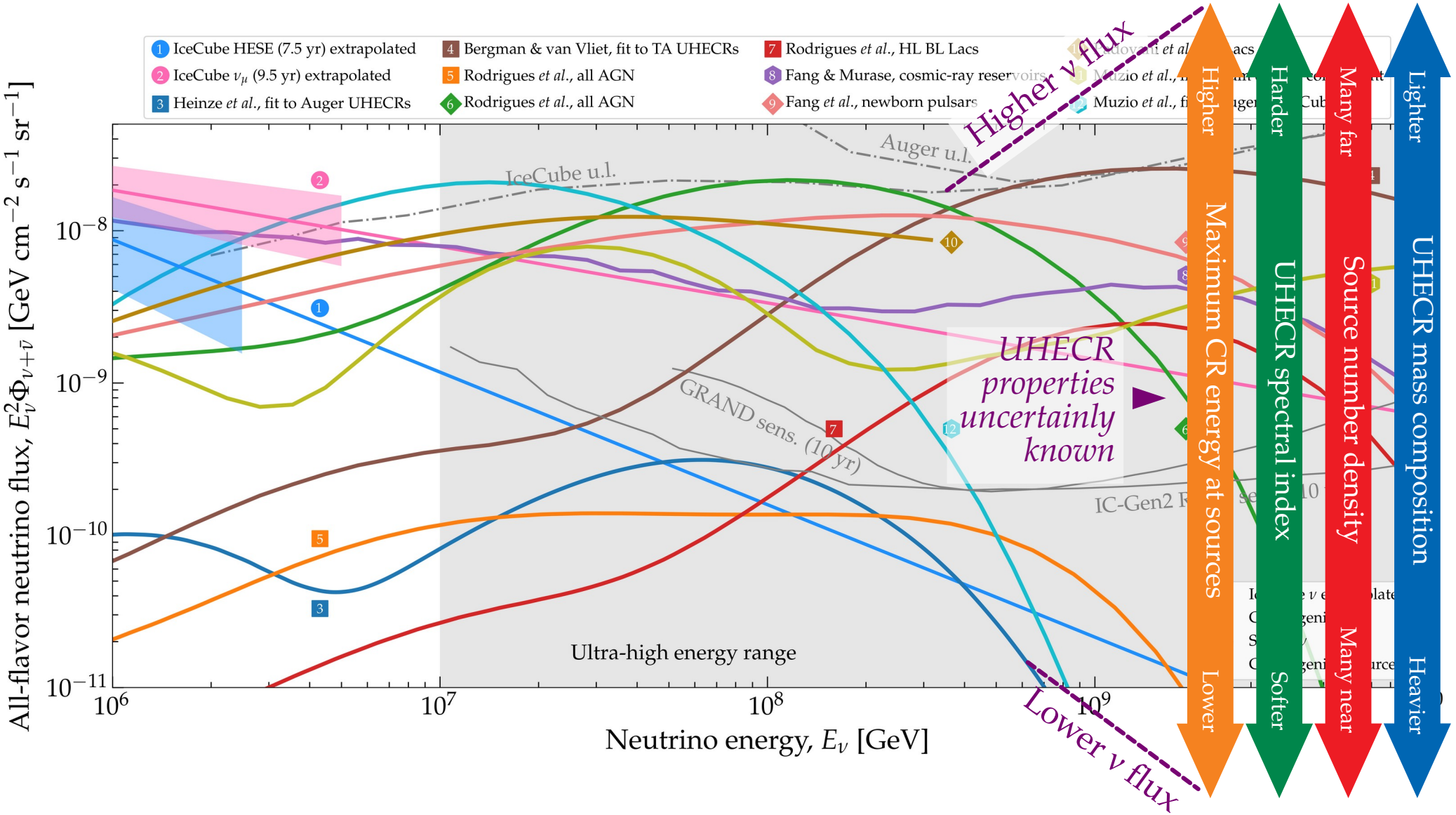
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}


1 IceCube HESE (7.5 yr) extrapolated
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3 Heinze et al., fit to Auger UHECRs
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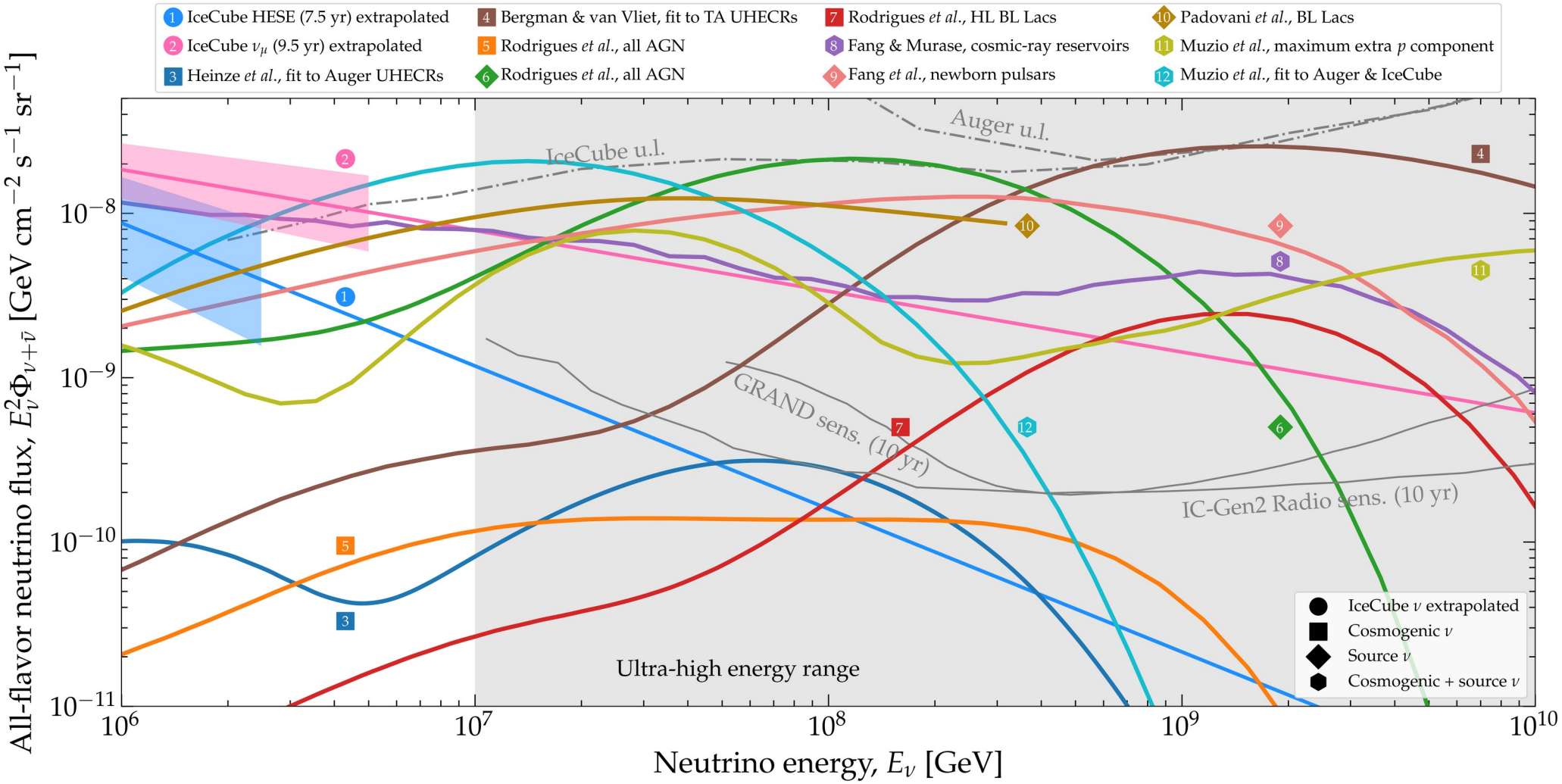
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
Higher ν flux
Lower ν flux
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2
UHECR properties uncertainly known
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier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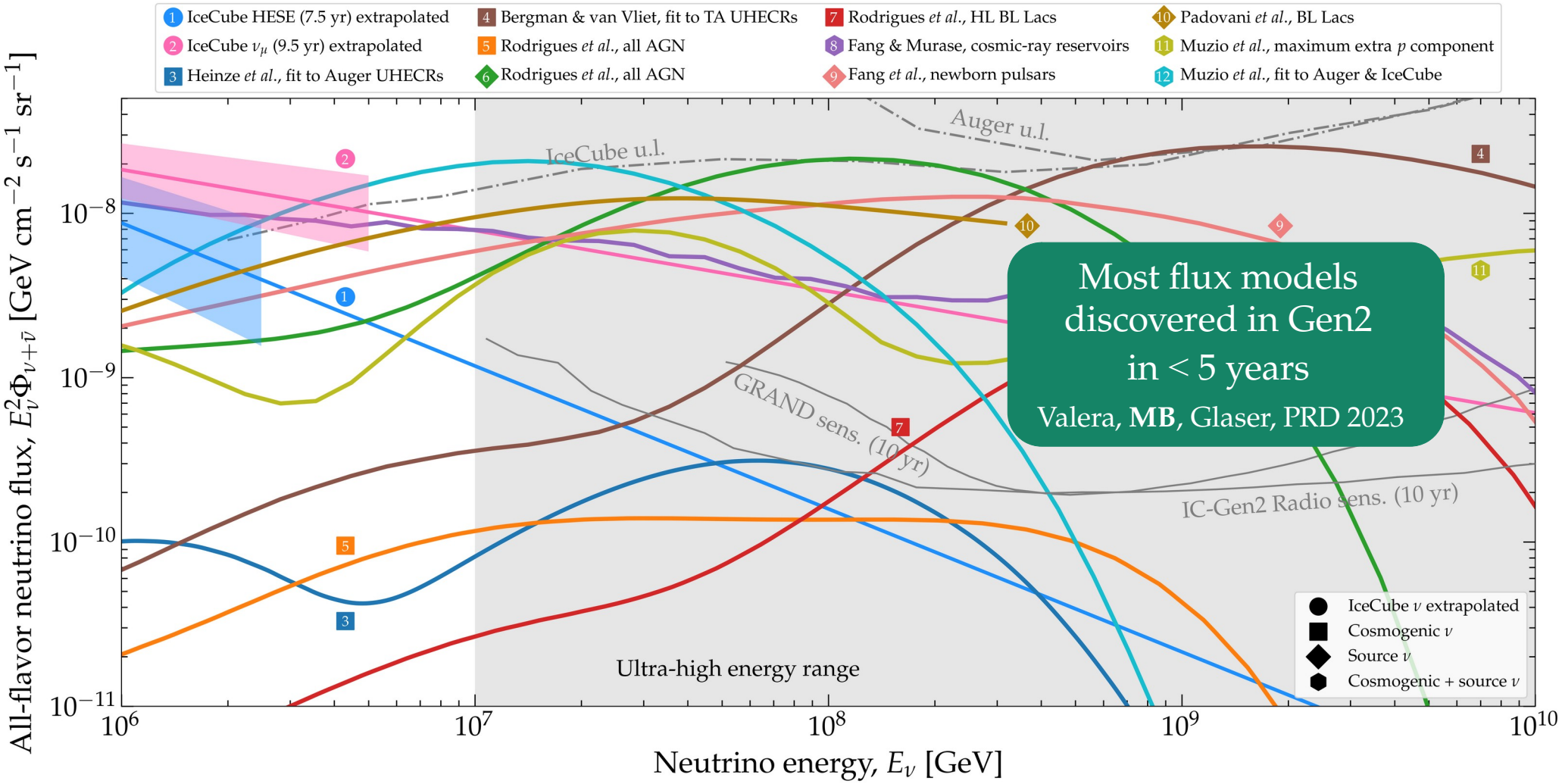
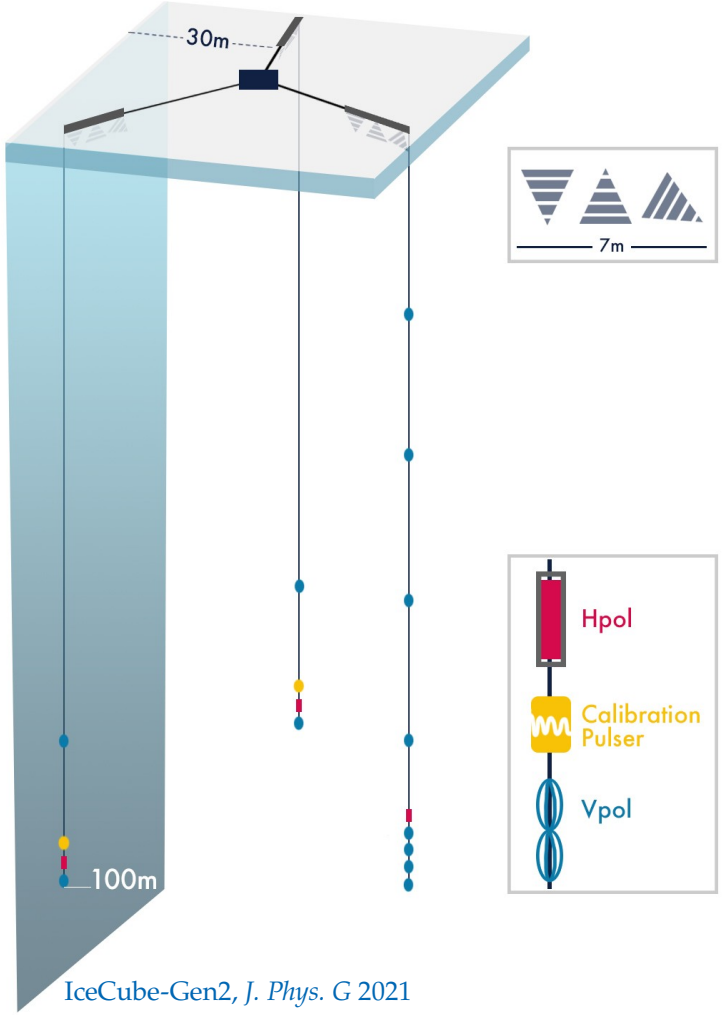
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



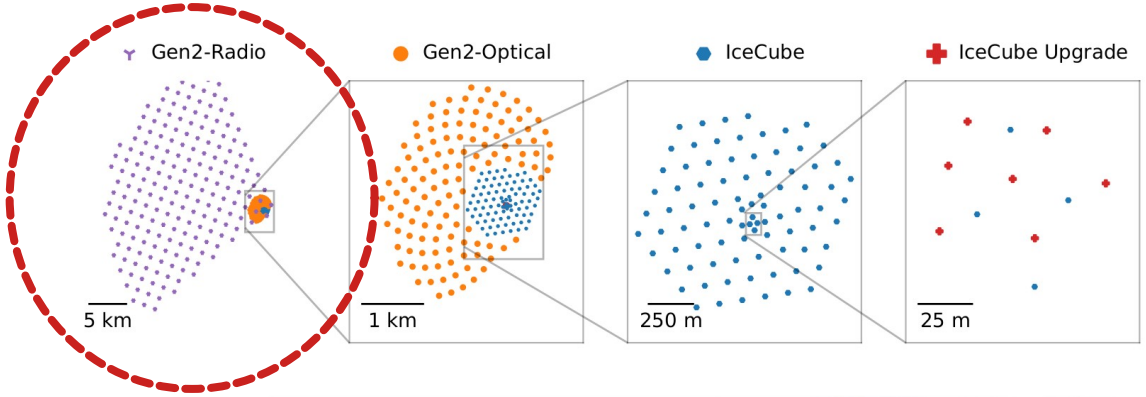
Most flux models discovered in Gen2 in < 5 years

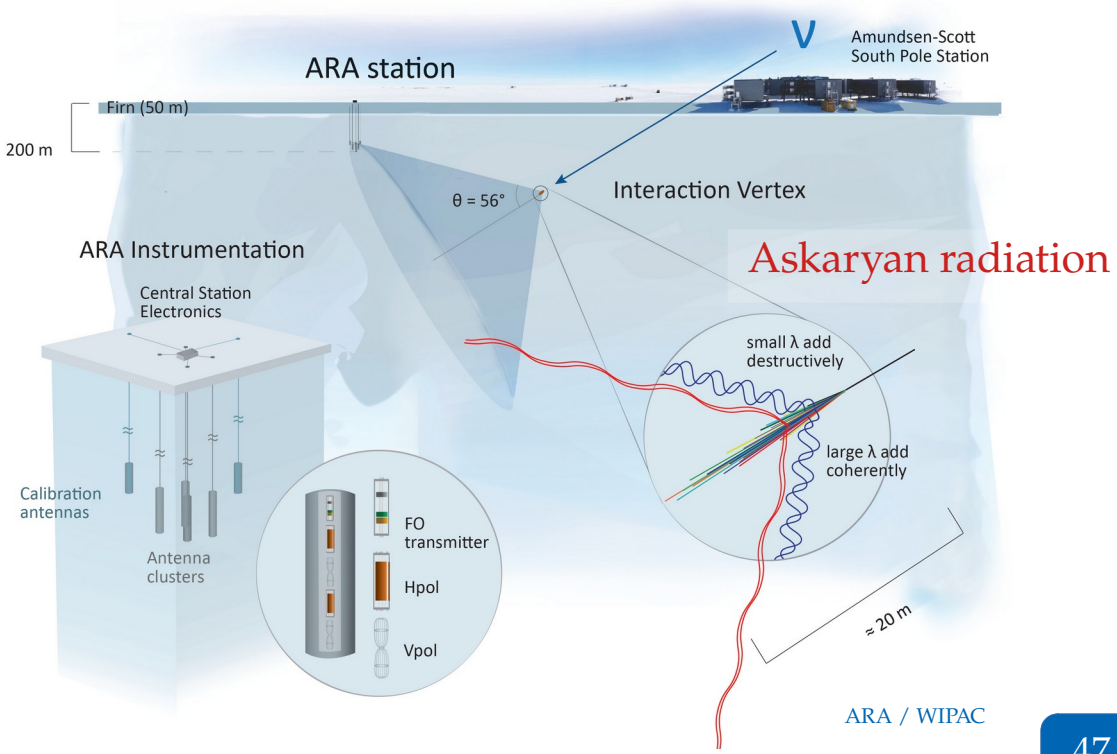
Valera, **MB**, Glaser, PRD 2023

IceCube-Gen2 Radio



IceCube-Gen2, *J. Phys. G* 2021



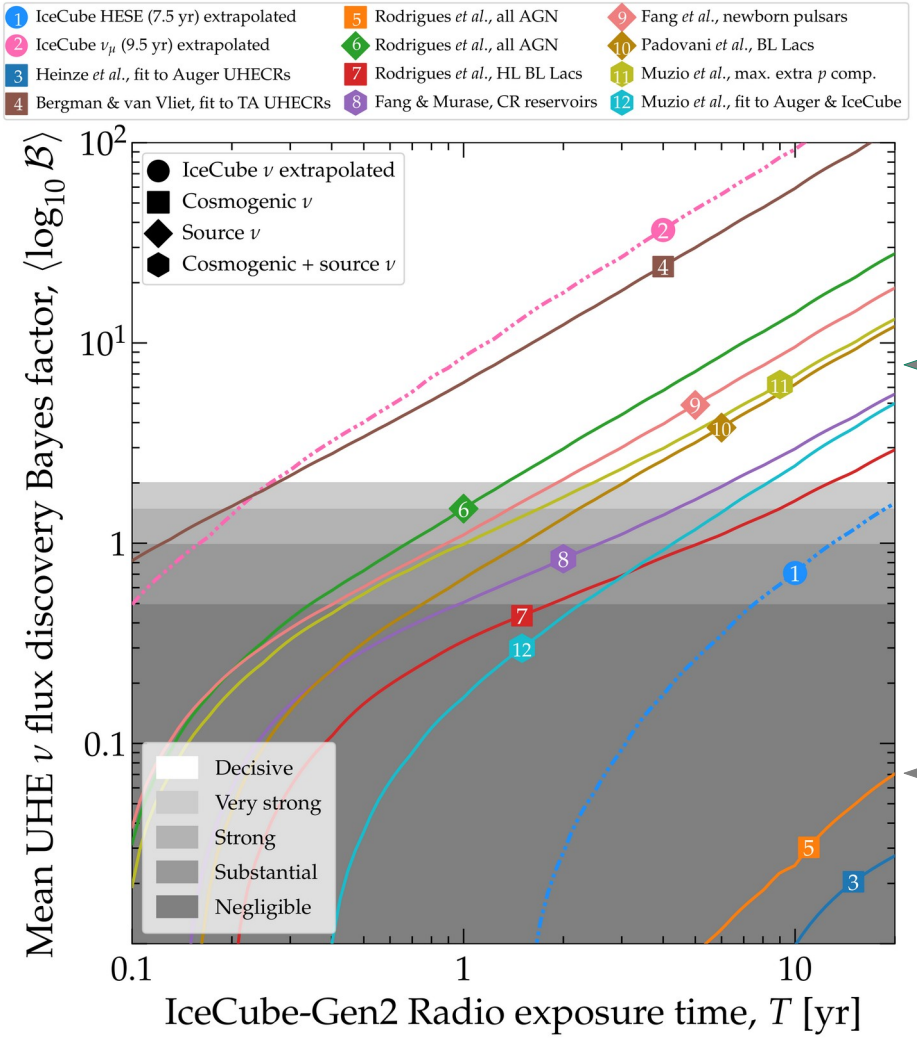


Askaryan radiation

ARA / WIPAC

Discovering the diffuse flux of UHE neutrinos

Bayes factor compares signal+bkg. *vs.* bkg.-only



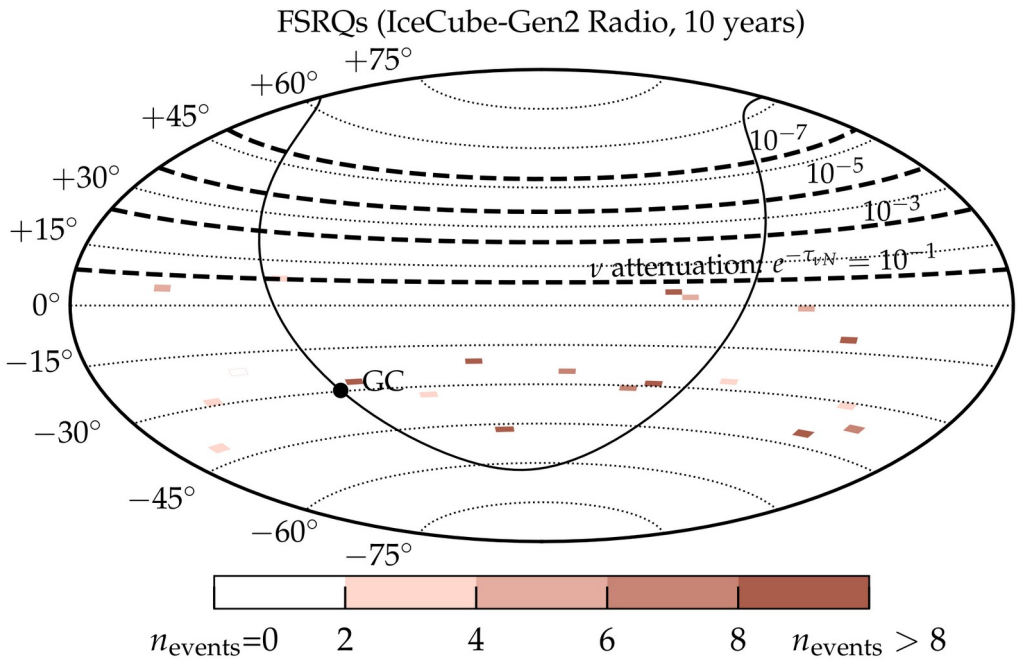
High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser, *PRD* 2023 [2210.03756]

Discovering point sources using UHE neutrino multiplets

Number of events detected
from a population of sources



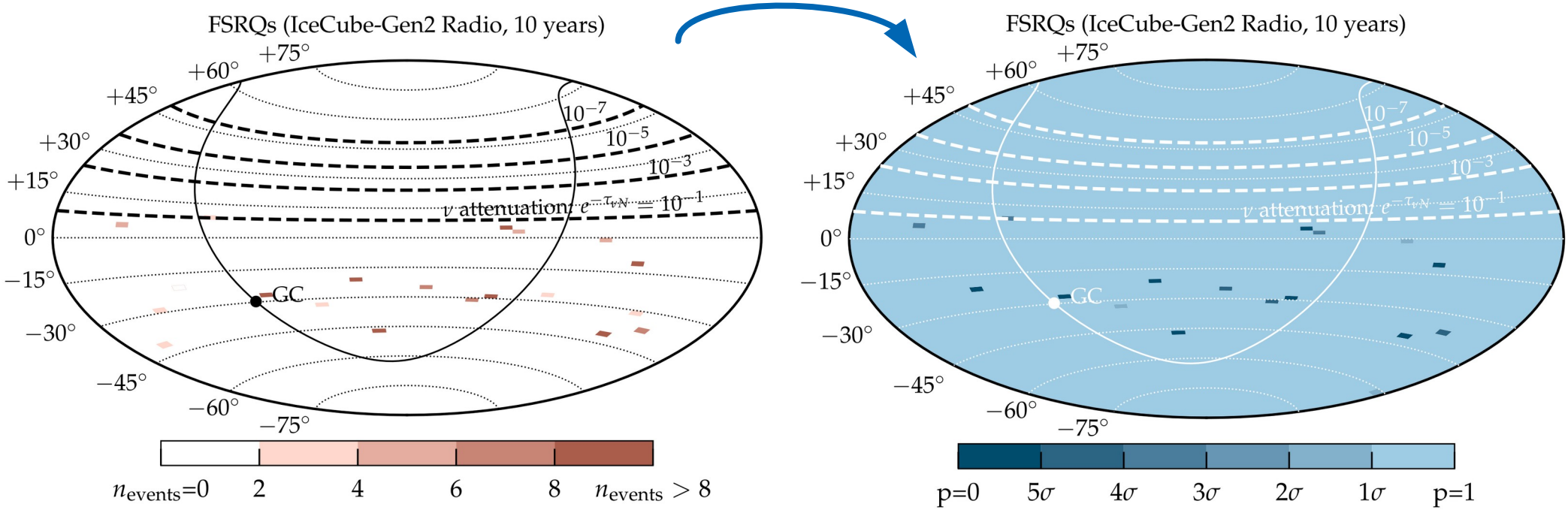
Above: angular resolution of 2° → GRAND aims for ~0.1°!

Fiorillo, **MB**, Valera,
JCAP 2023 [2205.15985]

Discovering point sources using UHE neutrino multiplets

Number of events detected from a population of sources

(Global) significance of a point-source discovery



Above: angular resolution of 2° → GRAND aims for ~0.1°!

Fiorillo, **MB**, Valera, *JCAP* 2023 [2205.15985]

Discovering point sources using UHE neutrino multiplets

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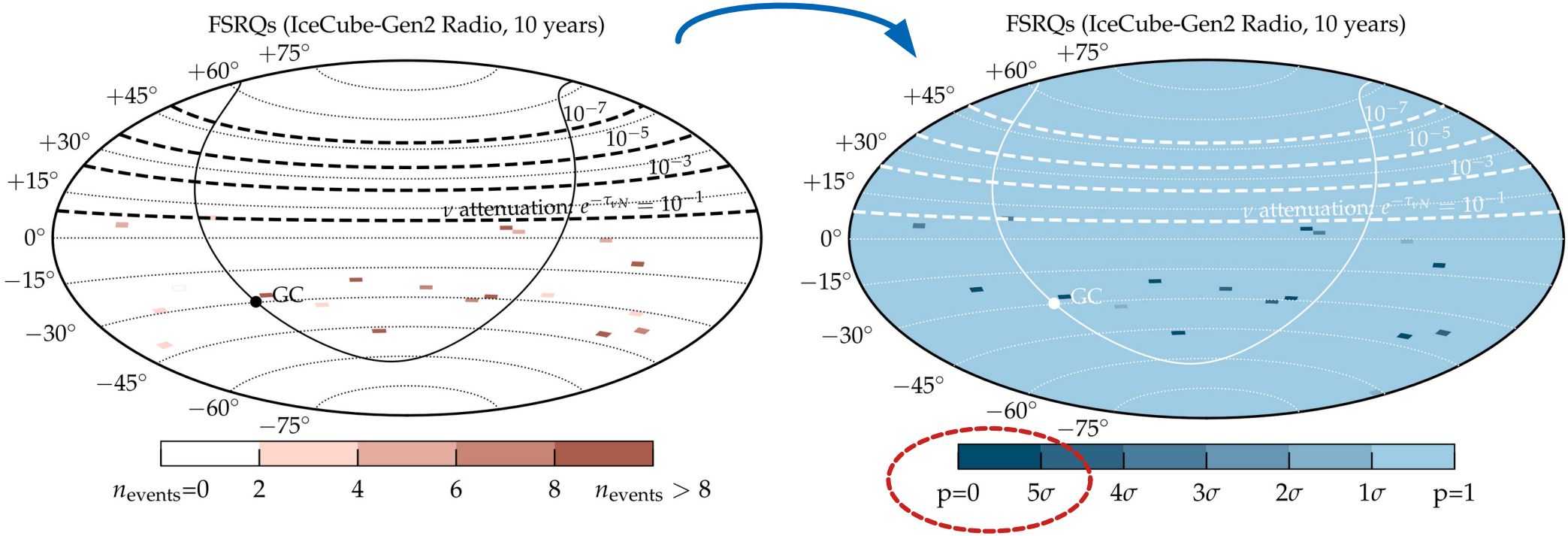
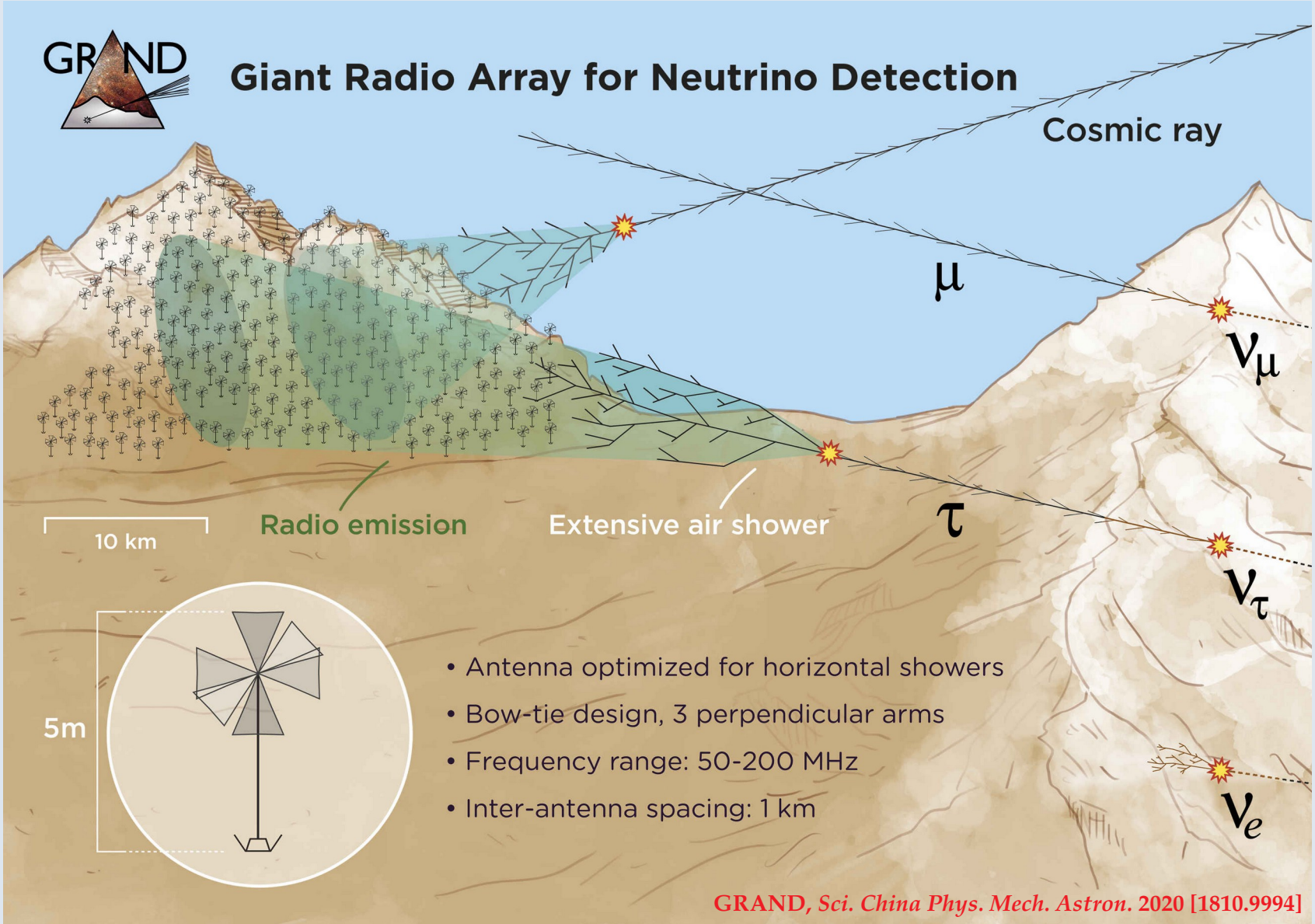


Above: angular resolution of 2° → GRAND aims for ~0.1°!

Fiorillo, **MB**, Valera, *JCAP* 2023 [2205.15985]


GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
Radio emission
Extensive air shower
10 km
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
GRAND, Sci. China Phys. Mech. Astron. 2020 [1810.9994]

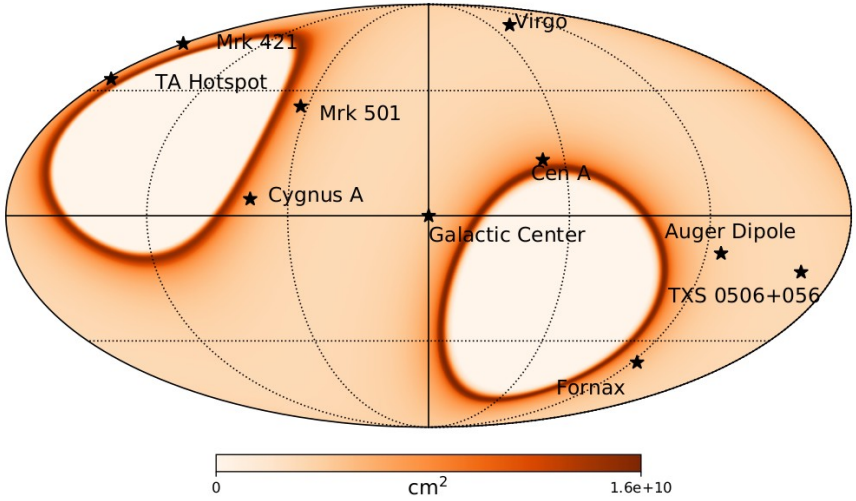
GRANDProto300@China

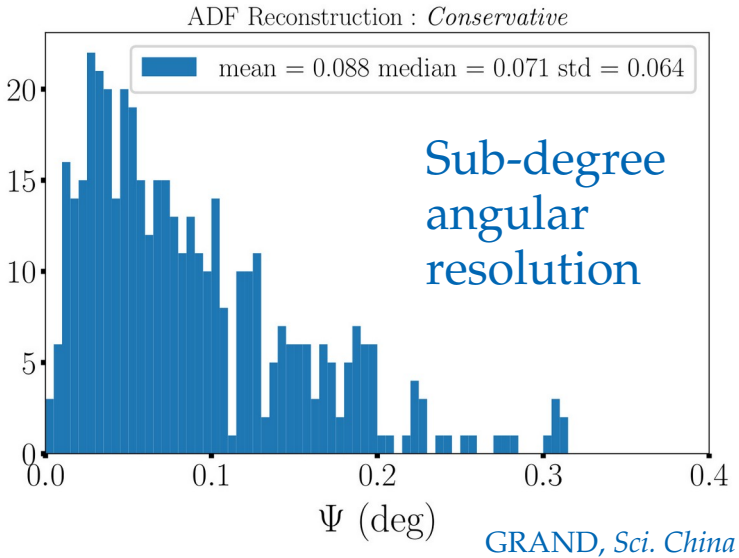
GRAND@Nançay

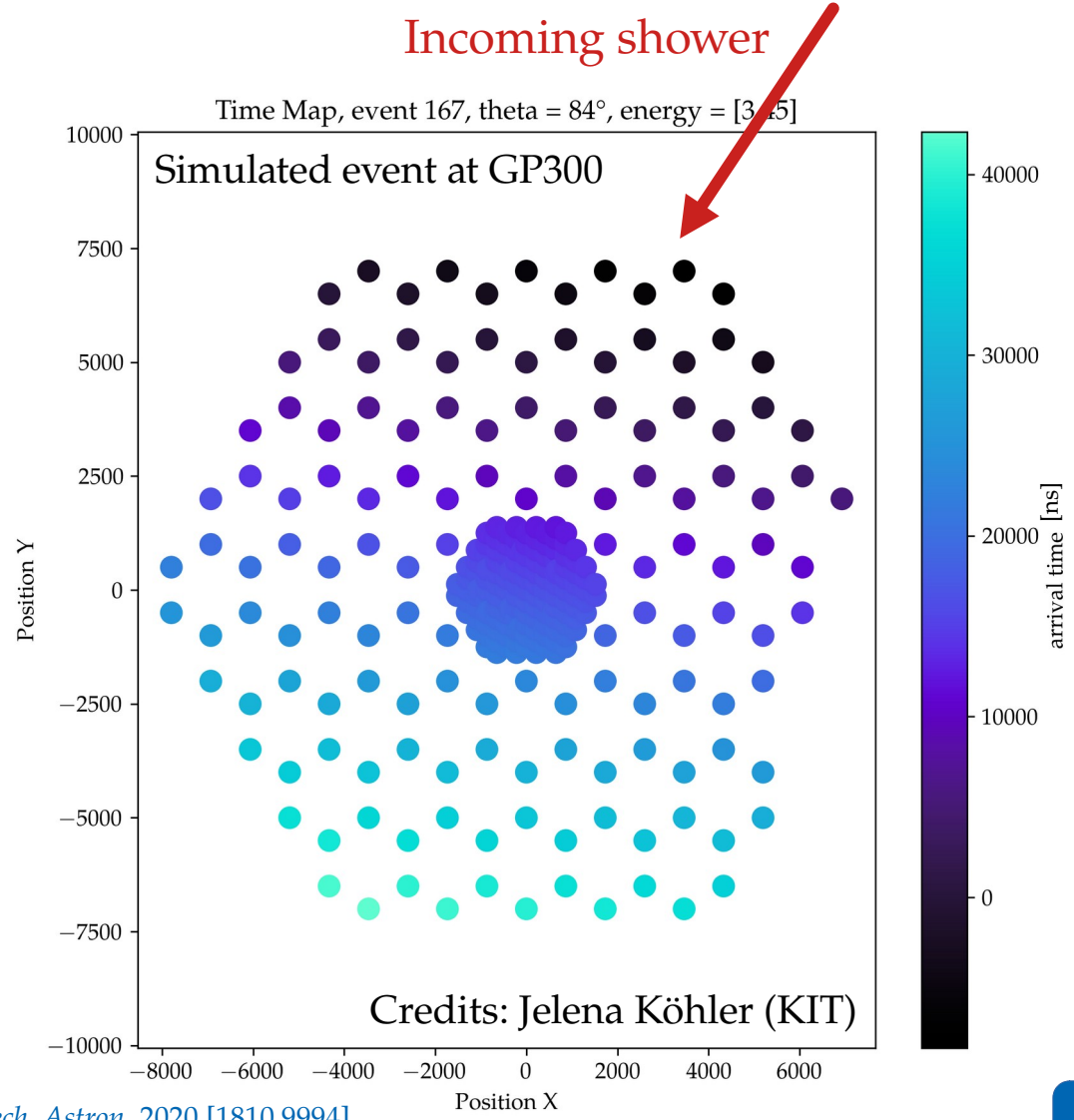
GRAND@Auger

GRAND, Sci. China Phys. Mech. Astron. 2020 [1810.9994]

GRANDProto300 campaign Oct 2023

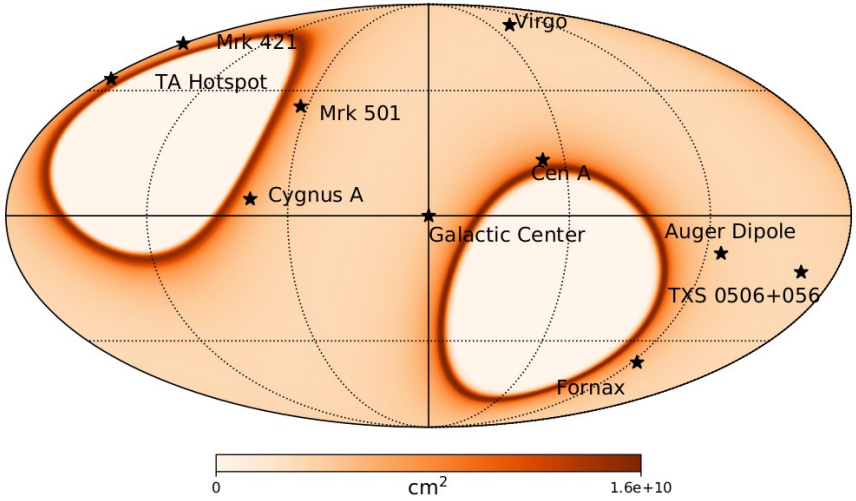


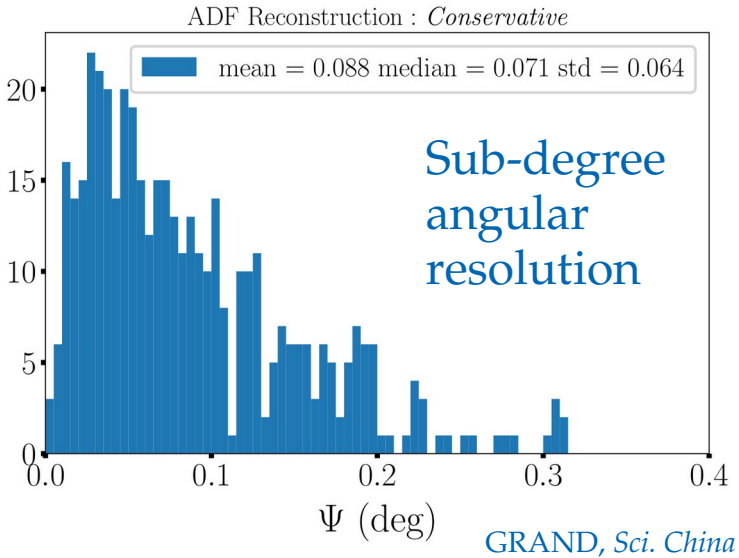


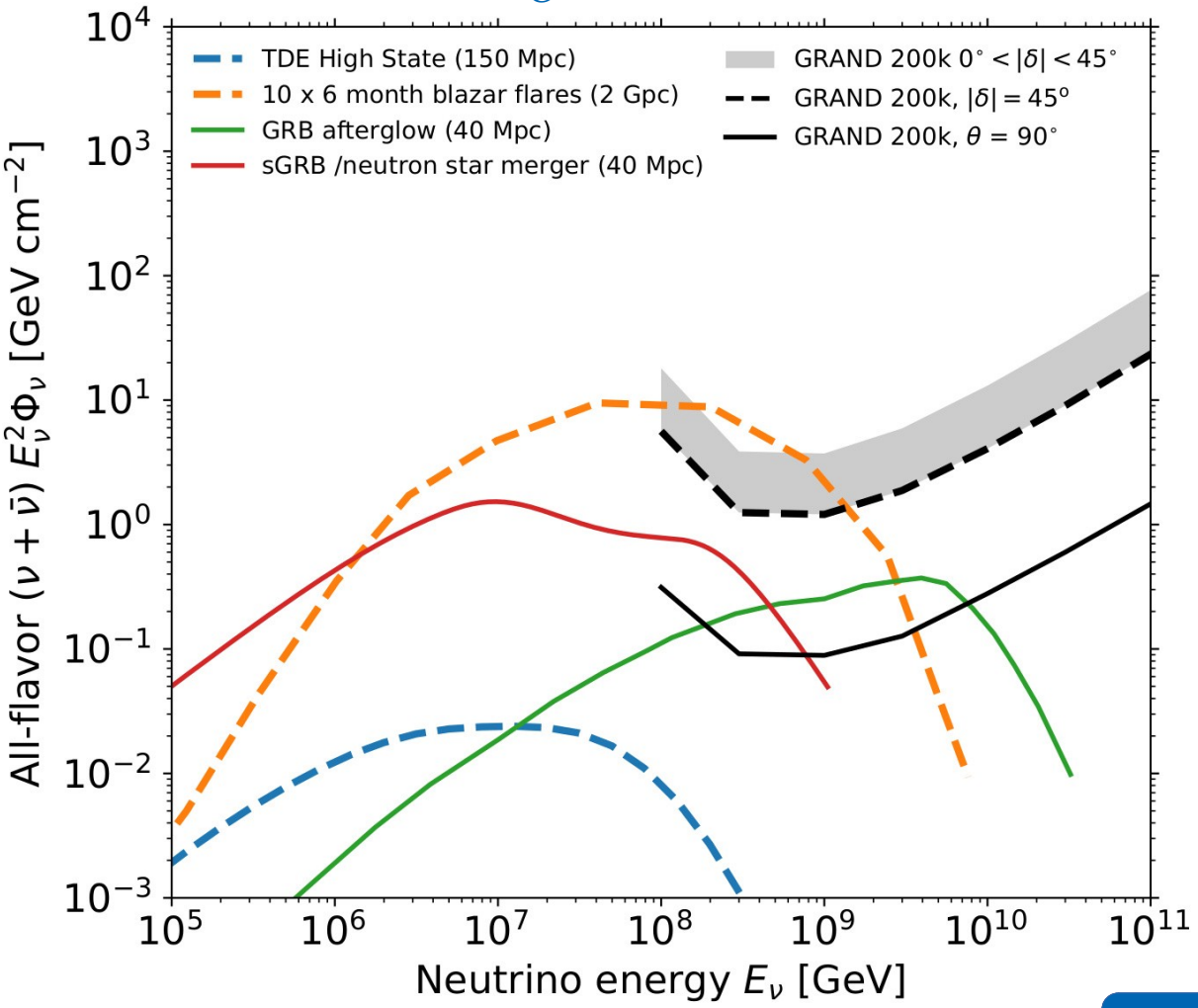


GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

Discovering UHE transient sources



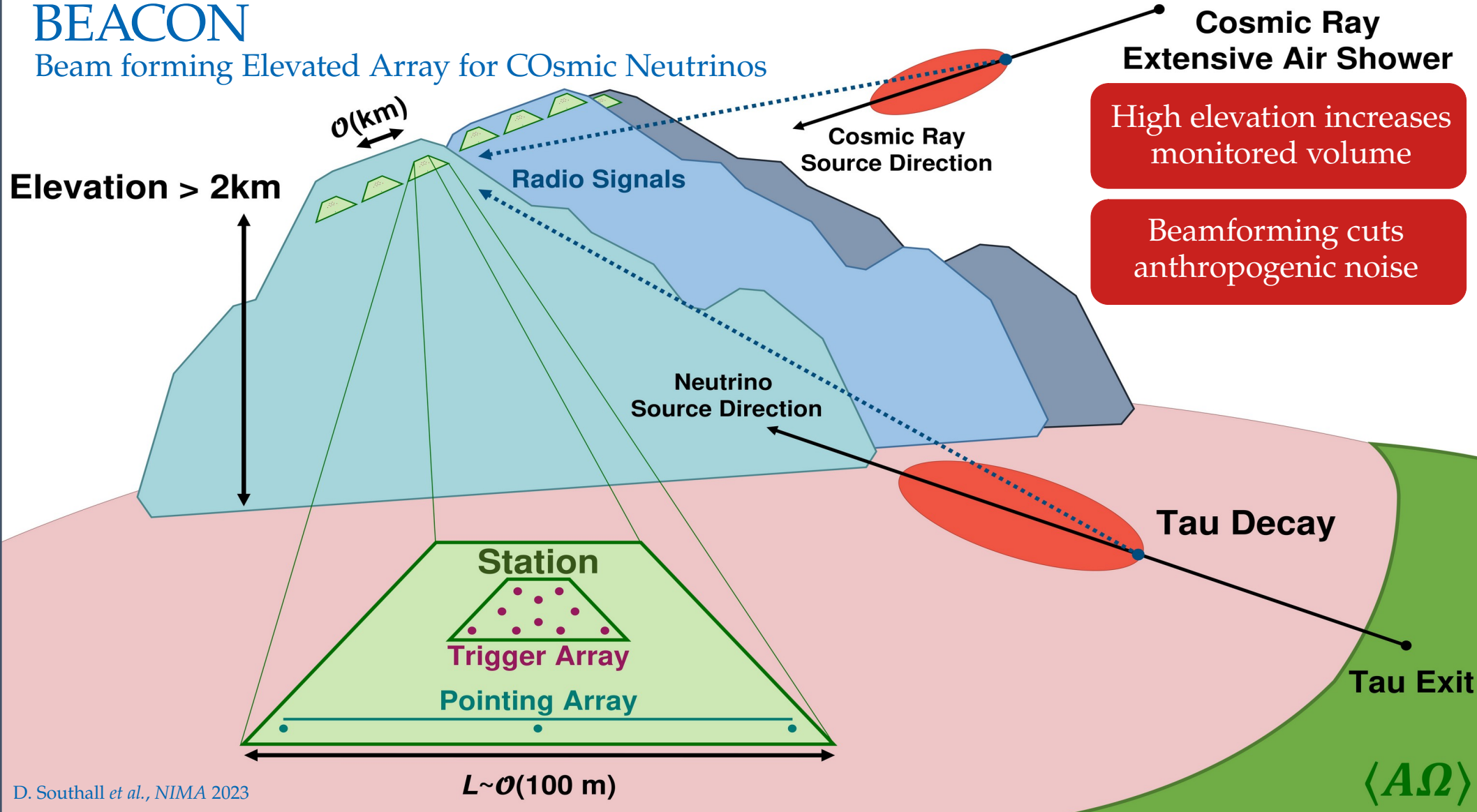




GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

BEACON

Beam forming Elevated Array for COsmic Neutrinos



High elevation increases monitored volume

Beamforming cuts anthropogenic noise

D. Southall *et al.*, *NIMA* 2023

Prototype array running since 2018 at White Mountain Research Station, California

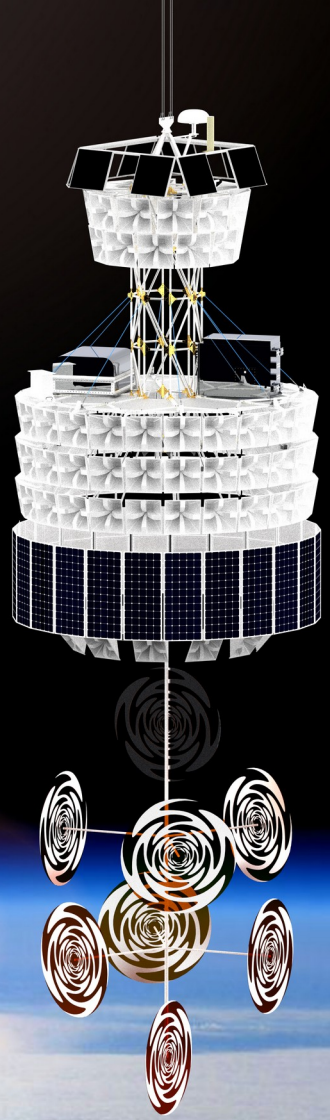
D. Southall *et al.*, *NIMA* 2023

PUEO

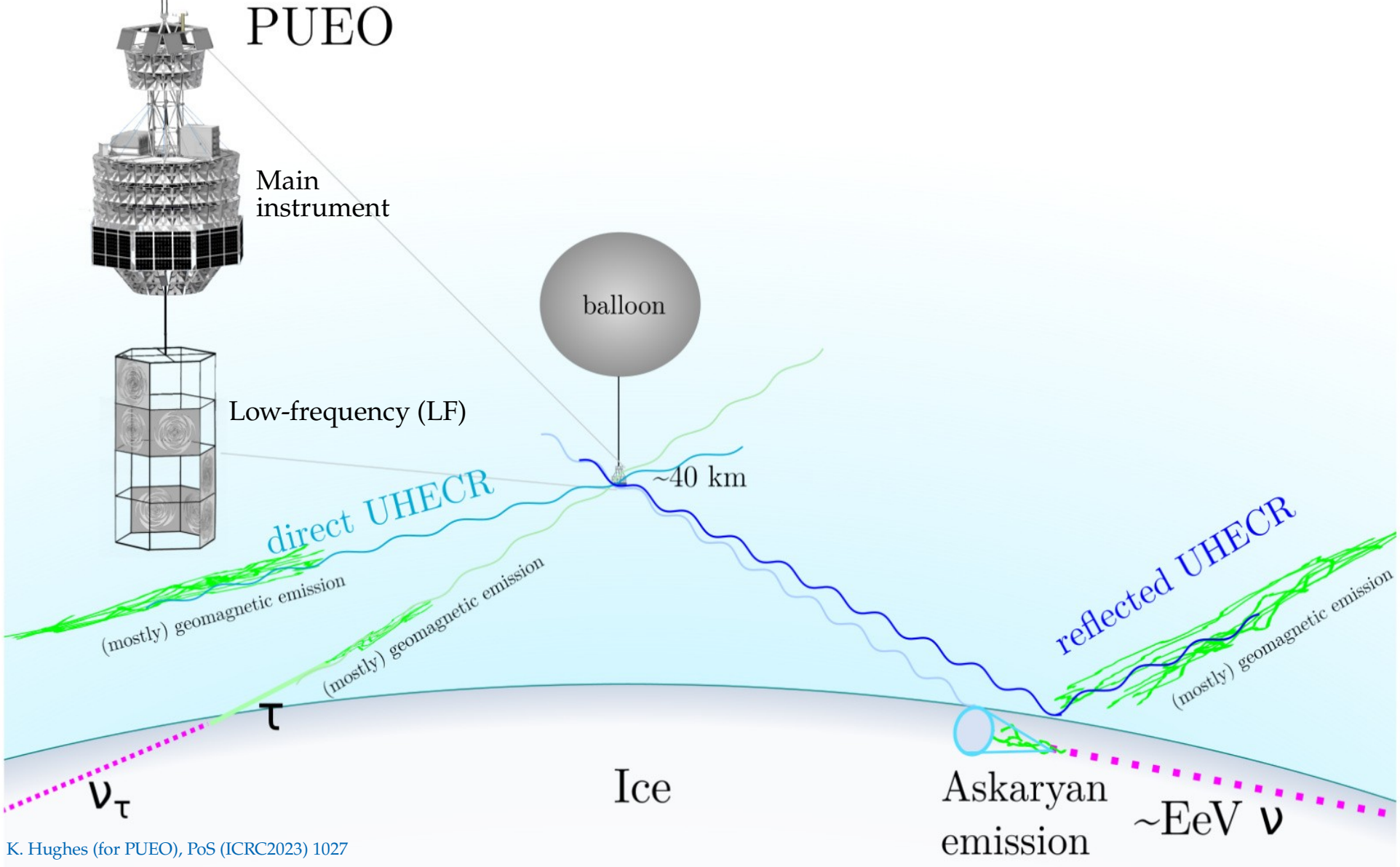
Payload for Ultrahigh Energy Observations

30-day flight above Antarctica

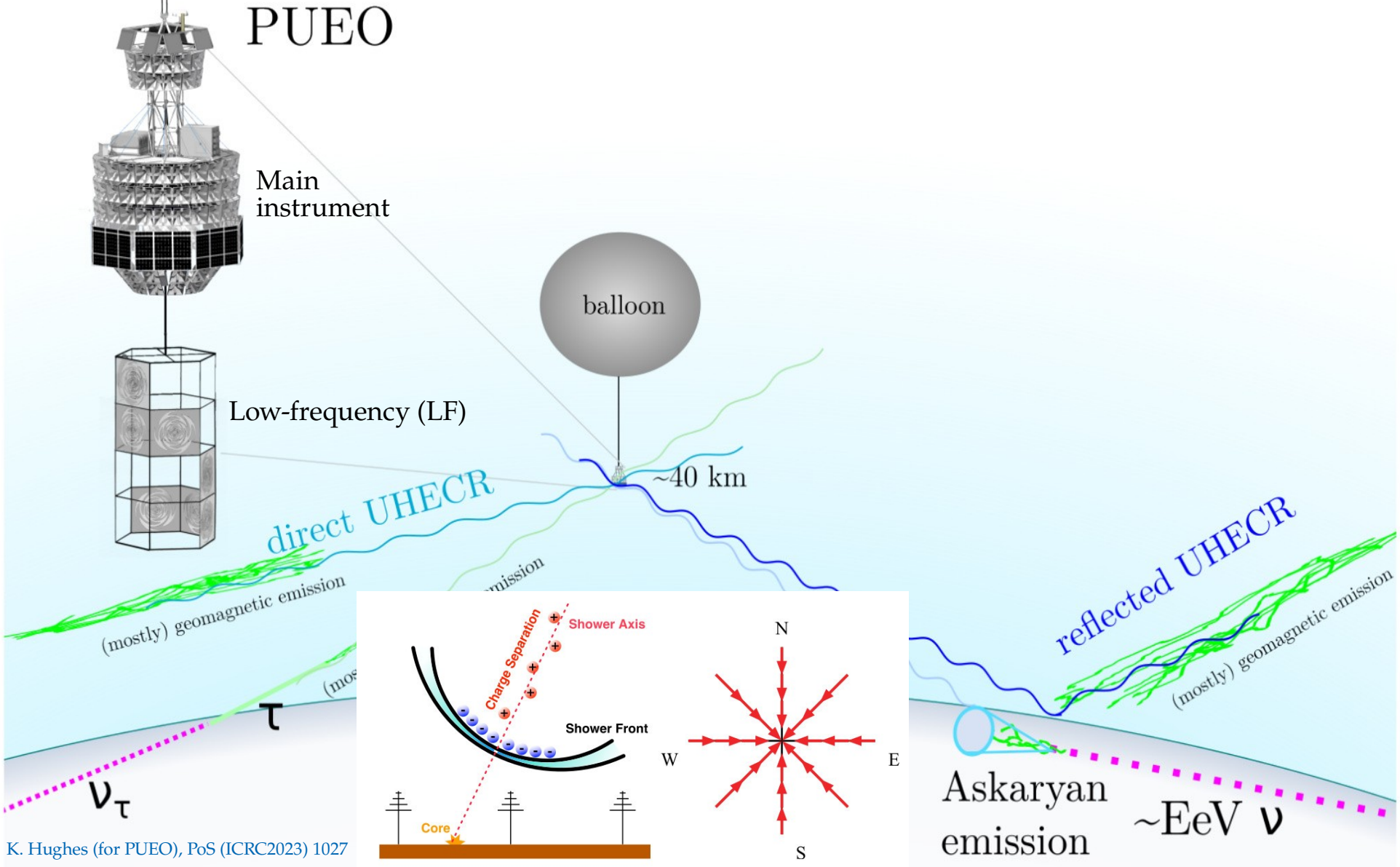
Builds on earlier ANITA I–IV flights



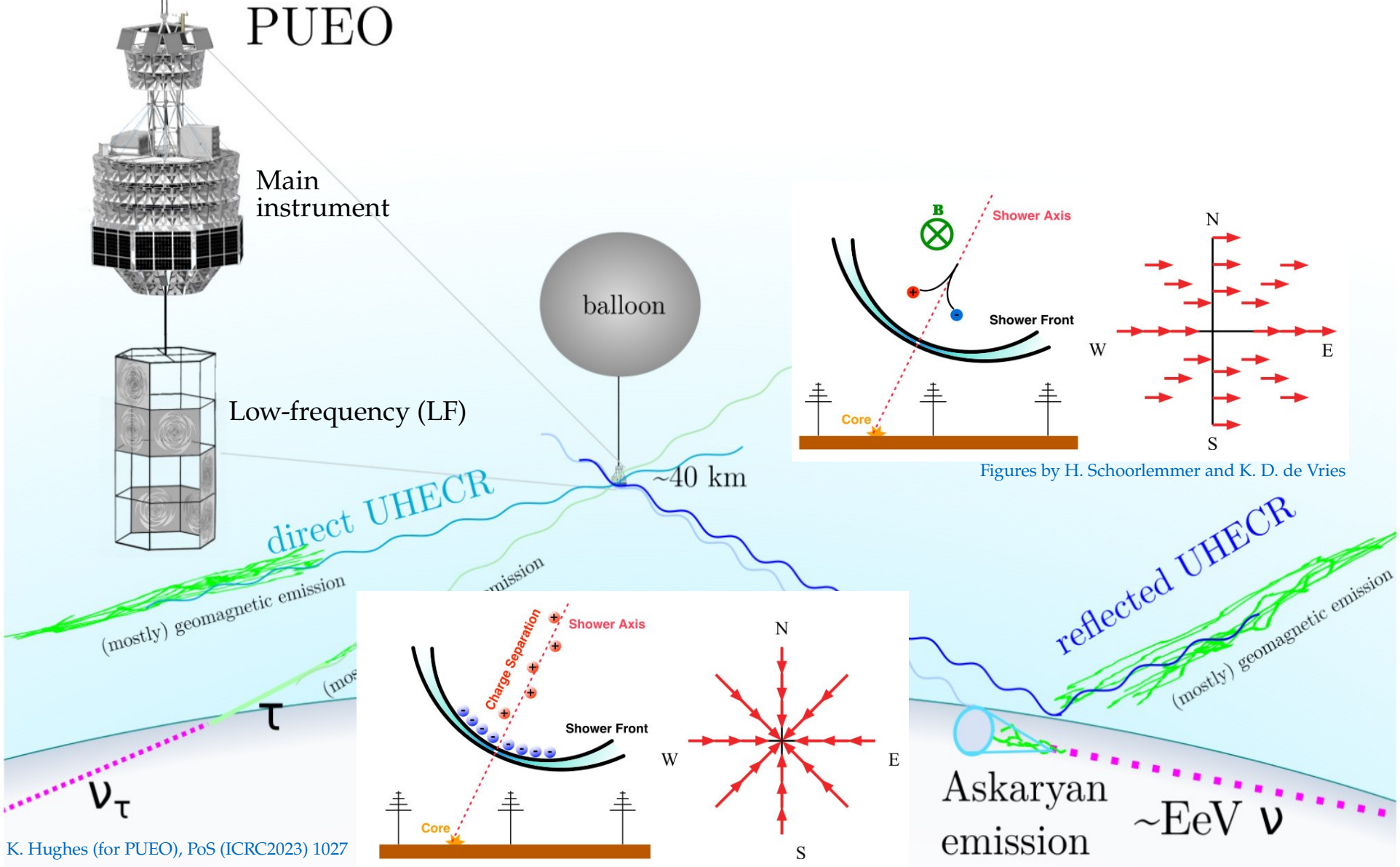
PUEO Collaboration



K. Hughes (for PUEO), PoS (ICRC2023) 1027

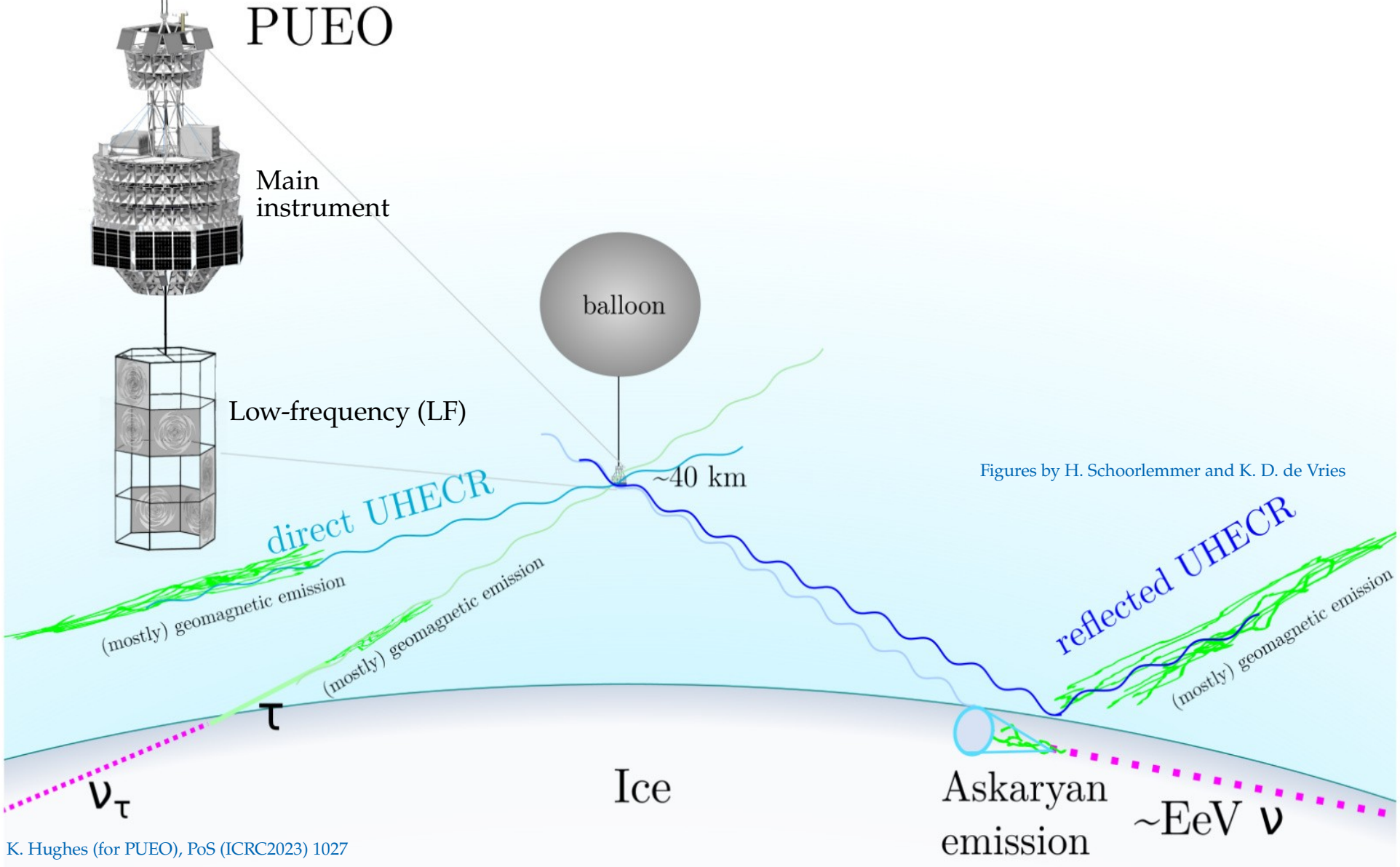


K. Hughes (for PUEO), PoS (ICRC2023) 1027



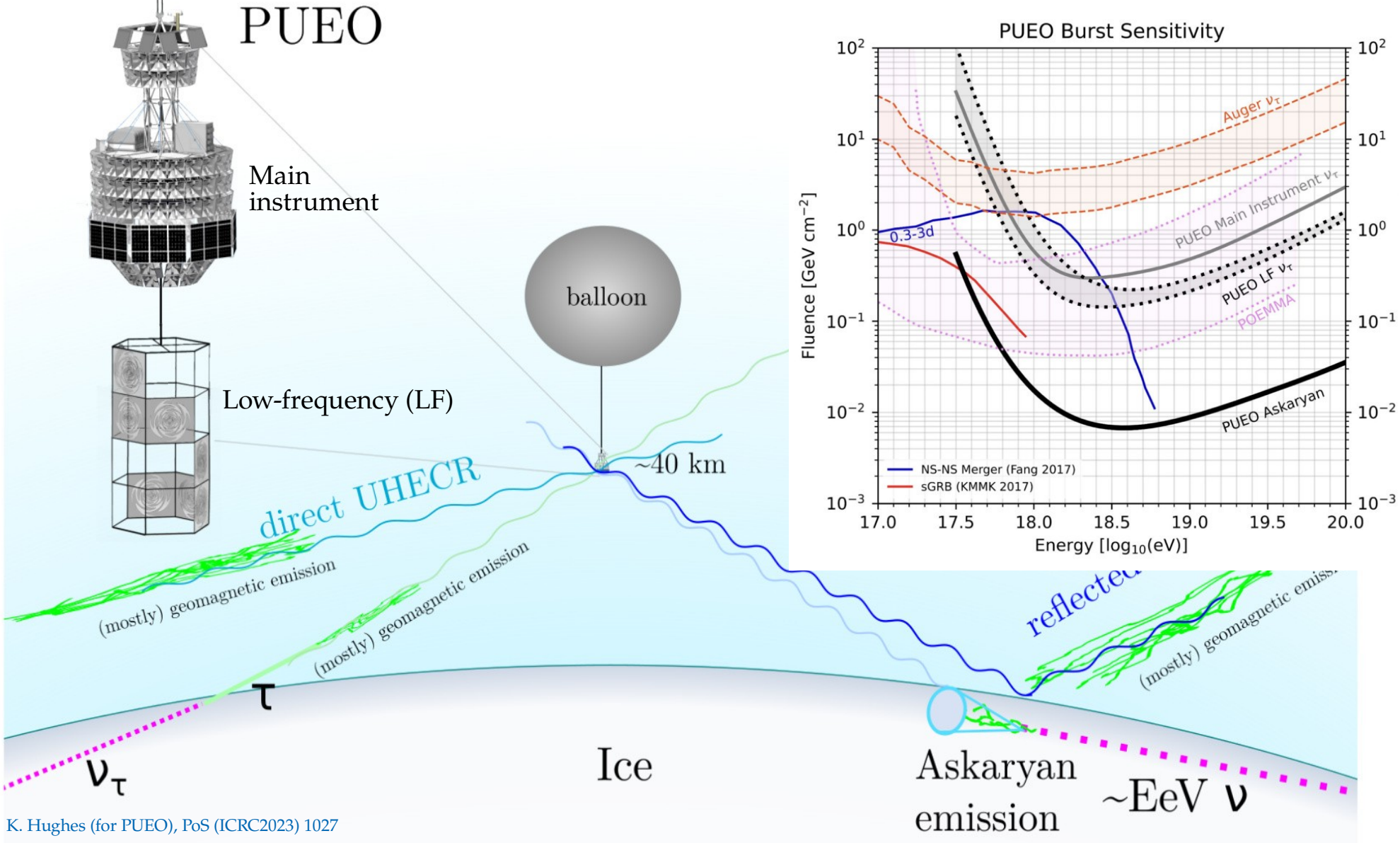
Figures by H. Schoorlemmer and K. D. de Vries

K. Hughes (for PUEO), PoS (ICRC2023) 1027



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

K. Hughes (for PUEO), PoS (ICRC2023) 1027



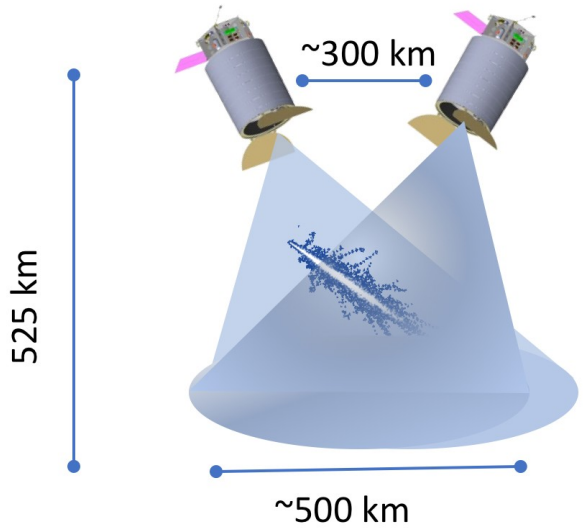
K. Hughes (for PUEO), PoS (ICRC2023) 1027

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

Observing fluorescence and Cherenkov radiation from space using twin satellites

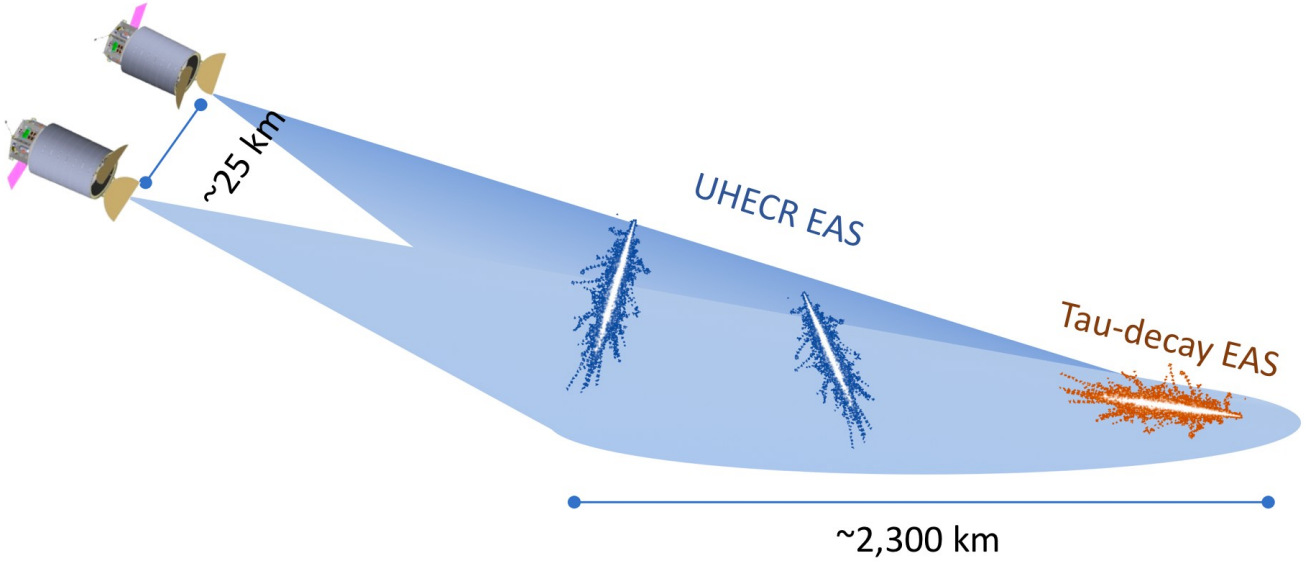
Fluorescence

POEMMA-Stereo



Cherenkov radiation

POEMMA-Limb



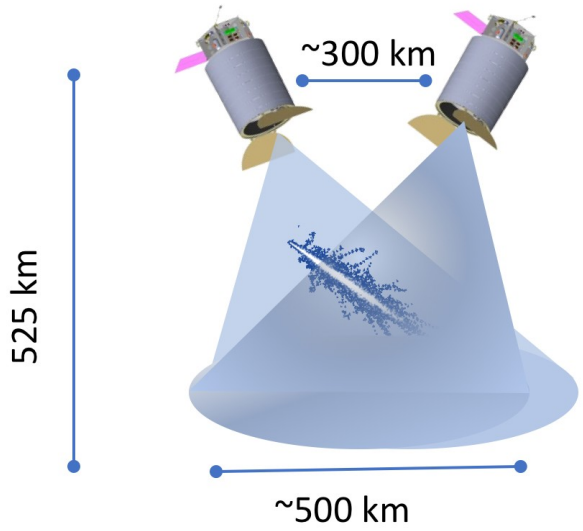
POEMMA, *JCAP* 2021 (2012.07945)

POEMMA: Probe of Extreme Multi-Messenger Astrophysics

Observing fluorescence and Cherenkov radiation from space using twin satellites

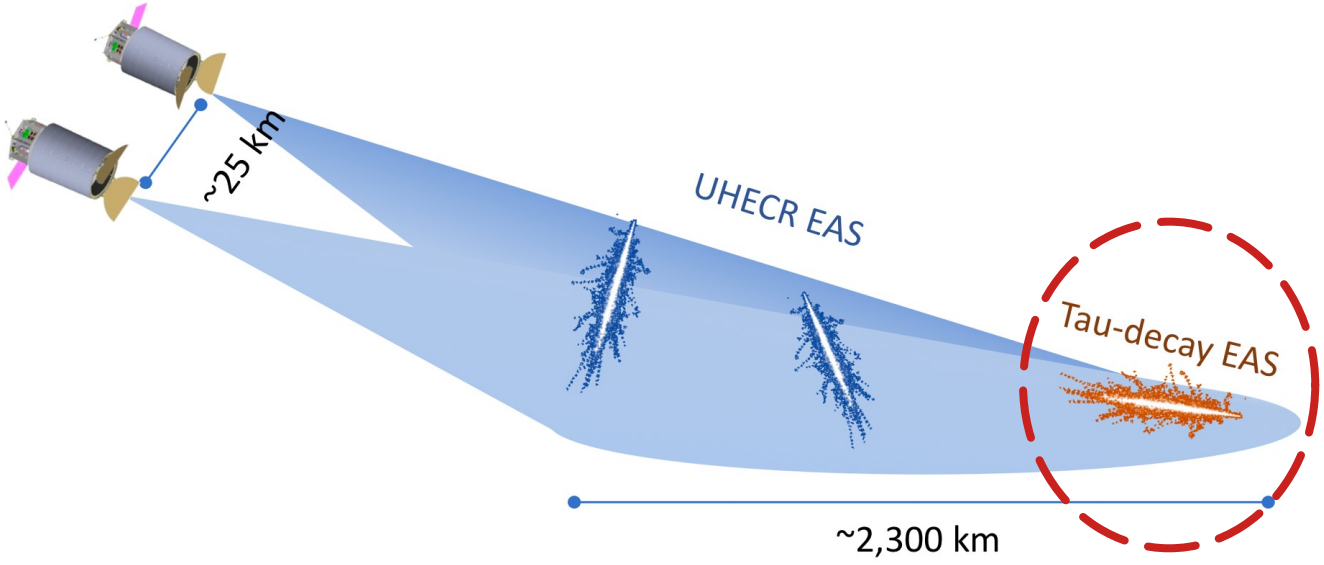
Fluorescence

POEMMA-Stereo



Cherenkov radiation

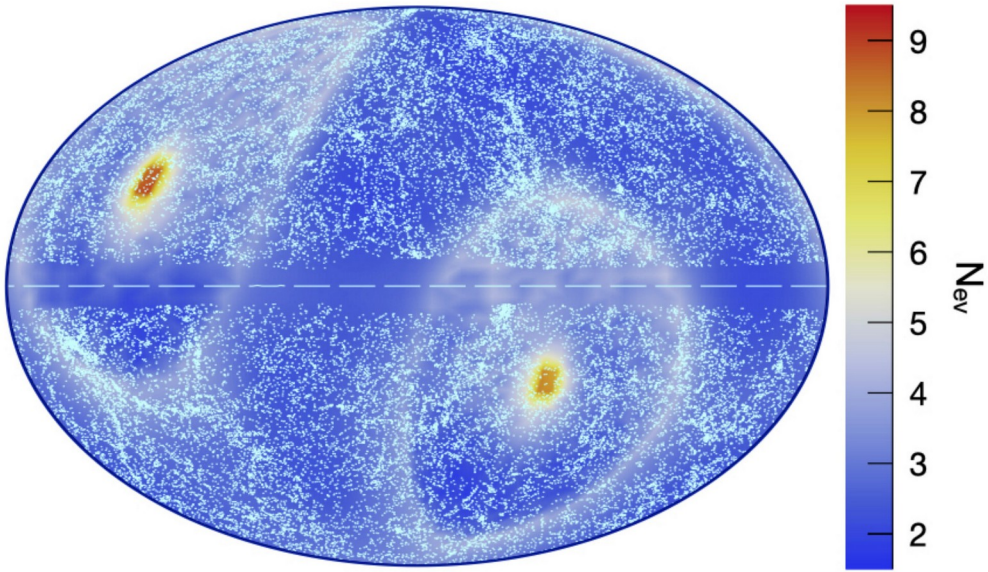
POEMMA-Limb



POEMMA, *JCAP* 2021 (2012.07945)

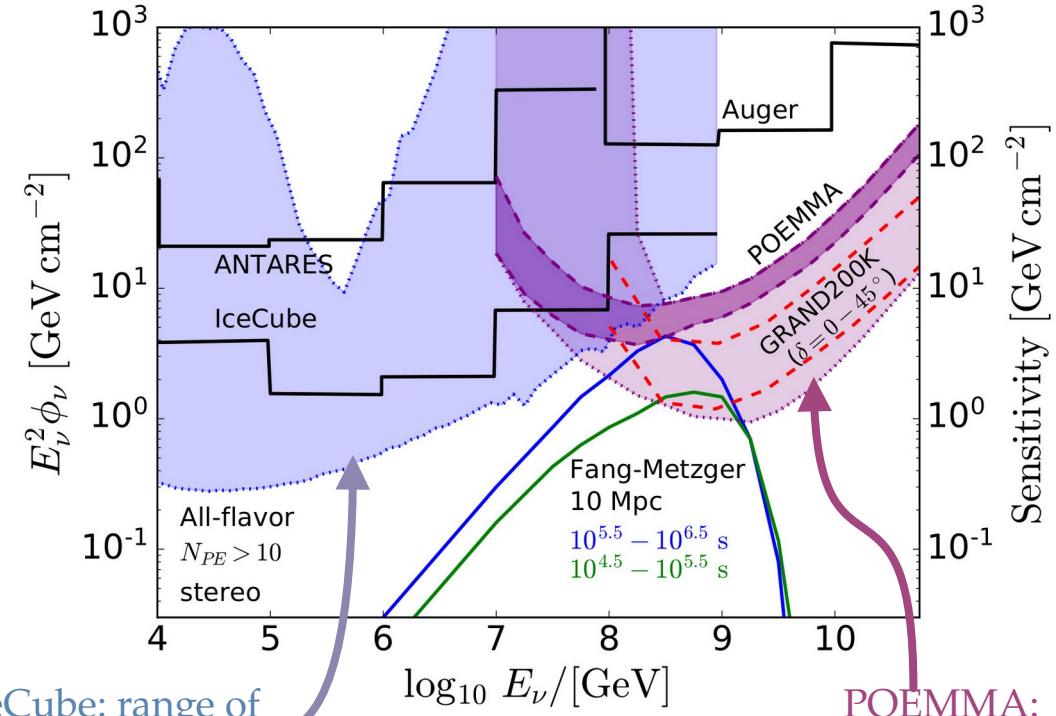
By slewing, POEMMA can observe targets of opportunity

Number of events,
binary neutron star merger



14 days, 10 Mpc away,
model by Fang & Metzger

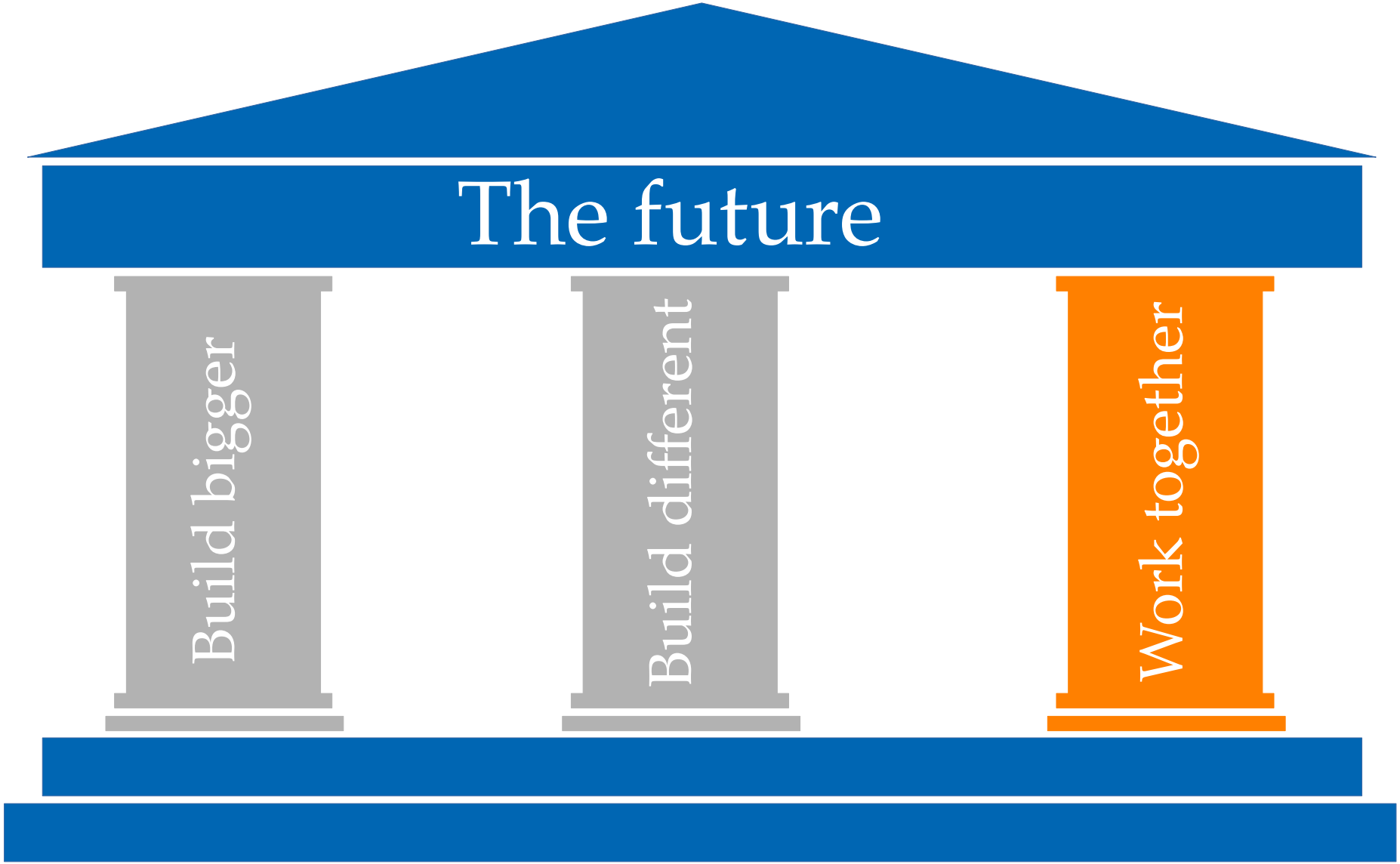
Sensitivity to a long burst
(14 days, 10 Mpc away)



IceCube: range of
source positions

POEMMA:
range of source positions

POEMMA, *JCAP* 2021 (2012.07945)


The future
Build bigger
Build different
Work together

TeV–PeV ν telescopes, ~2030

Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

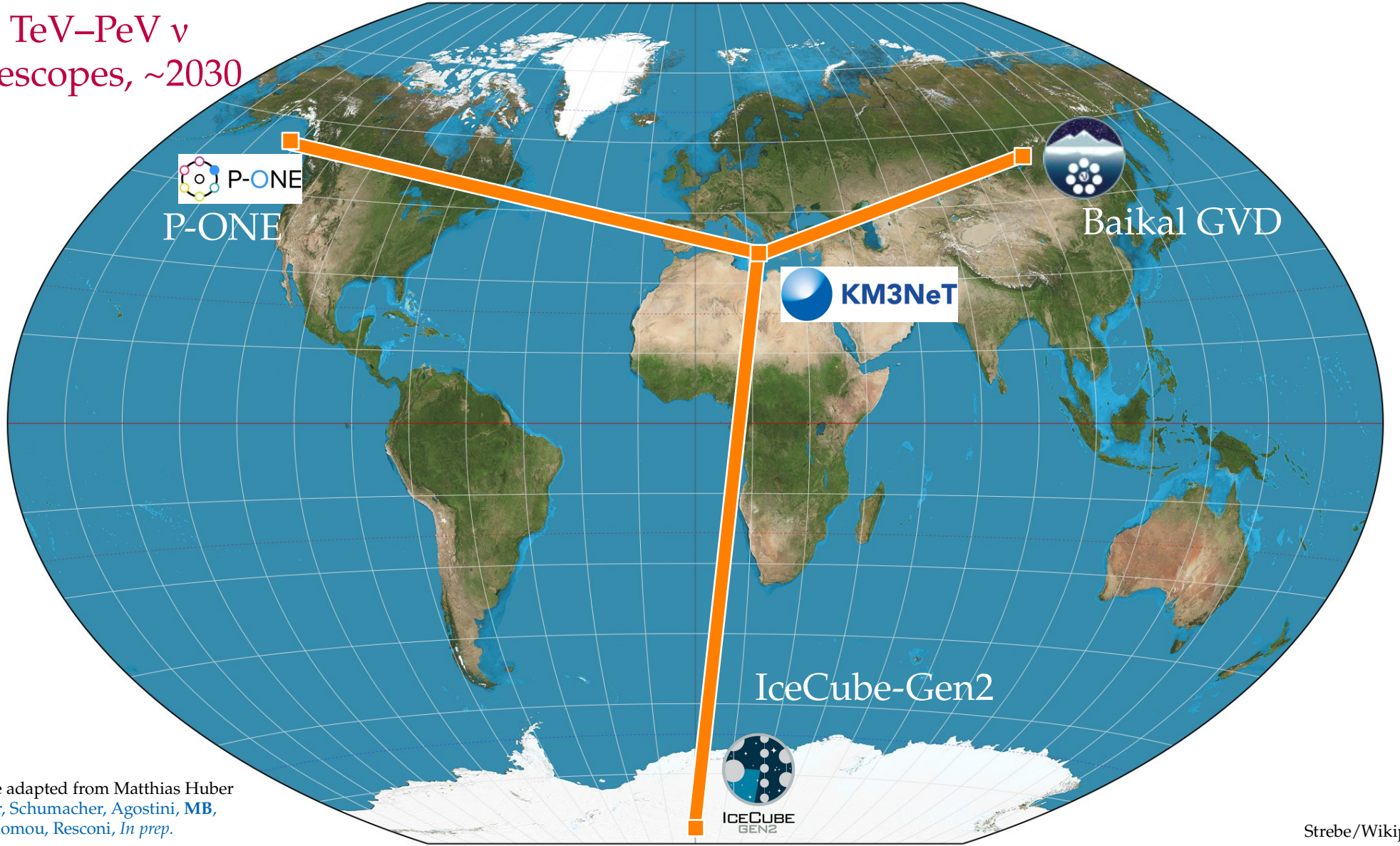


Figure adapted from Matthias Huber
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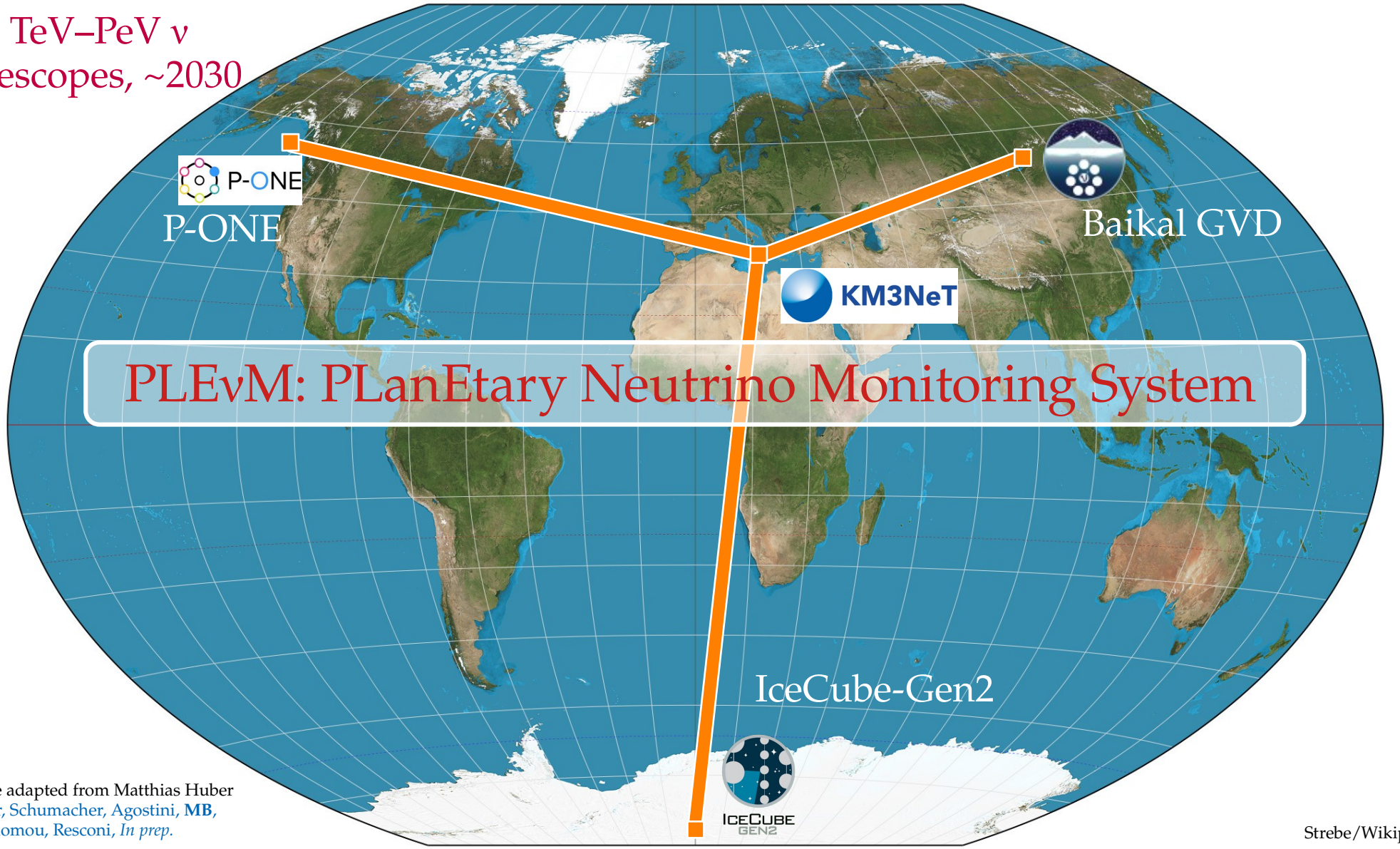
TeV–PeV ν telescopes, ~2030



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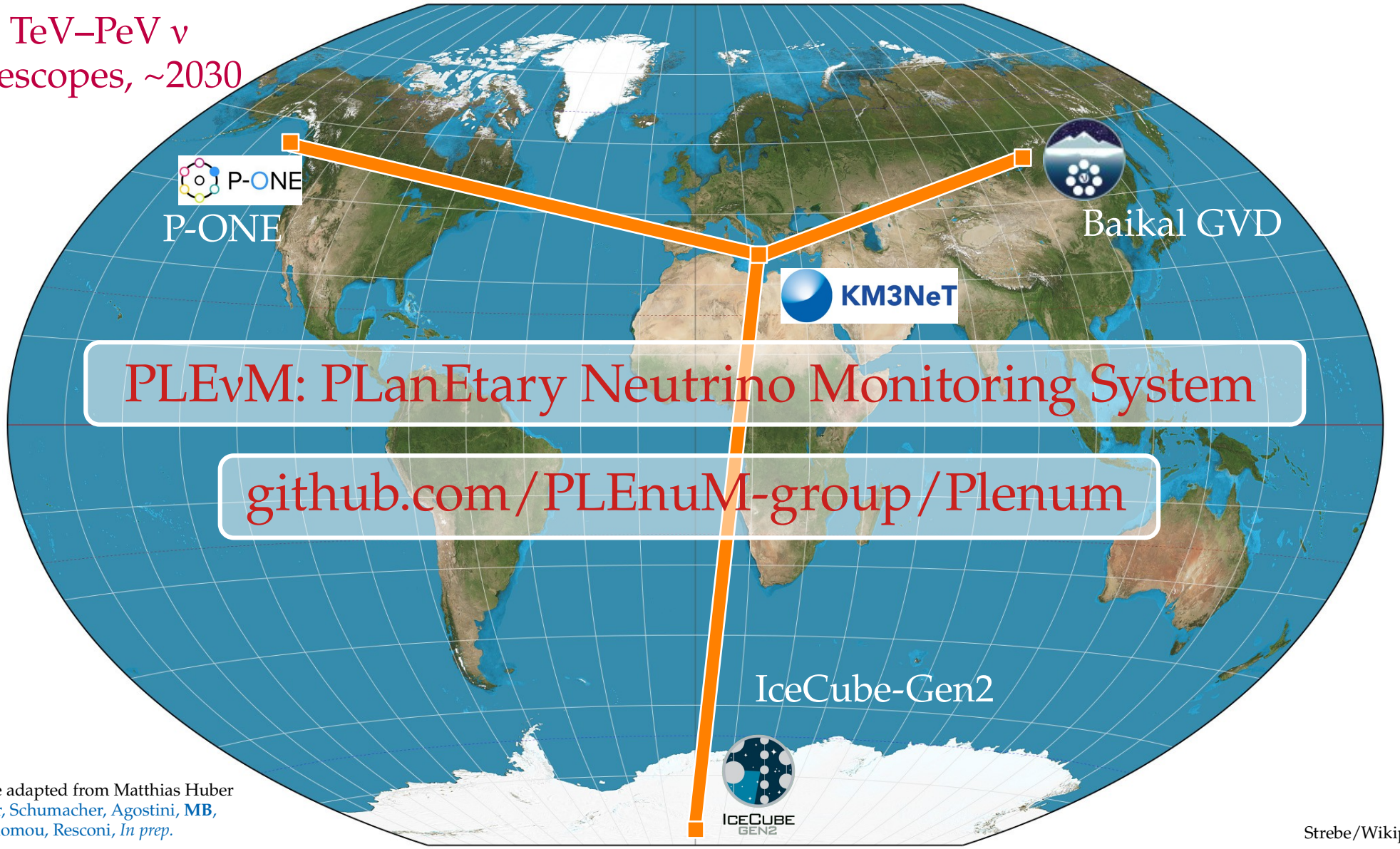
Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

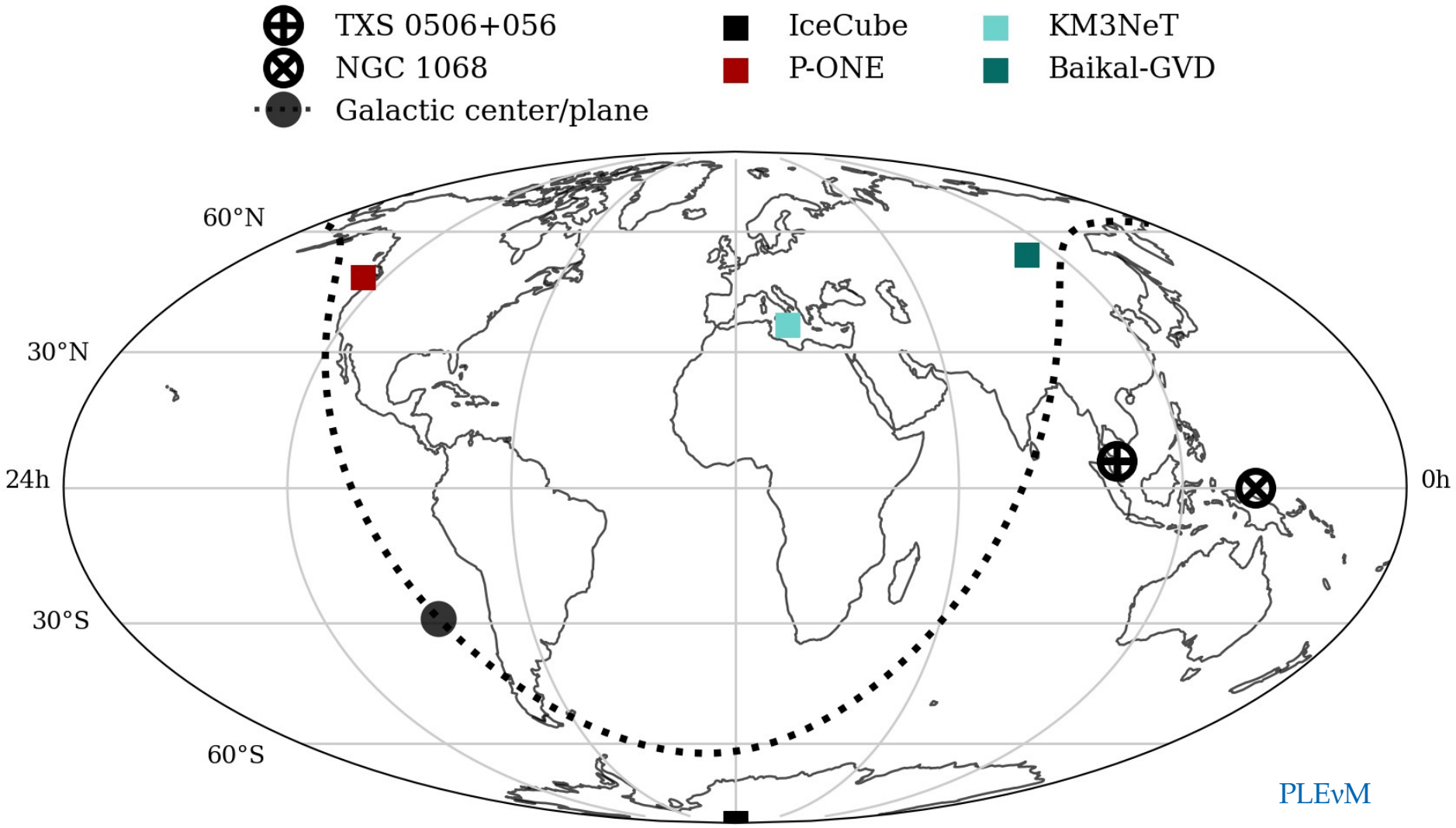


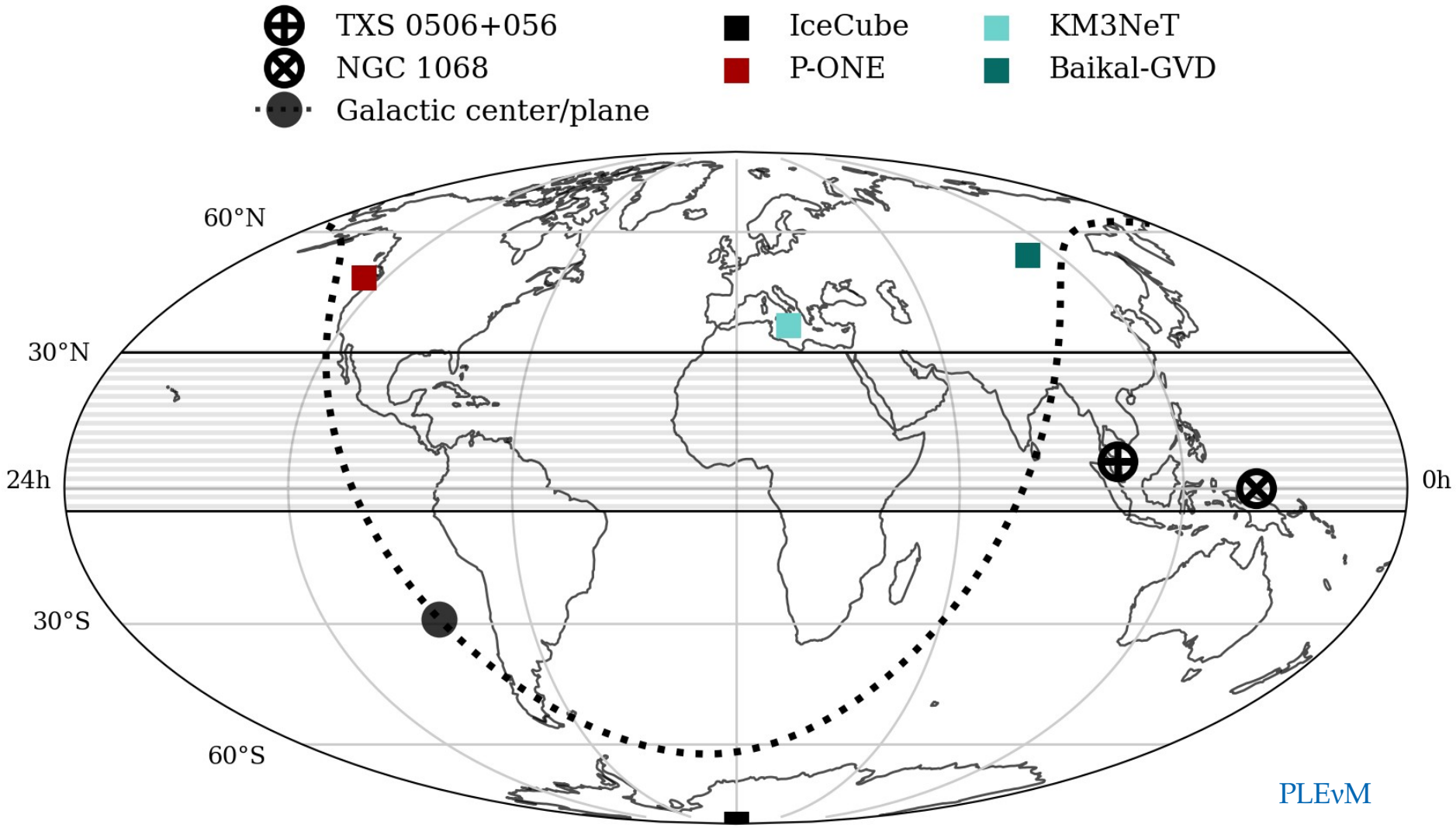
PLEvM: PLanEtary Neutrino Monitoring System

github.com/PLEnuM-group/Plenum

Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia


TXS 0506+056
NGC 1068
Galactic center/plane
IceCube
P-ONE
KM3NeT
Baikal-GVD
60°N
30°N
24h
0h
30°S
60°S
PLEνM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0h
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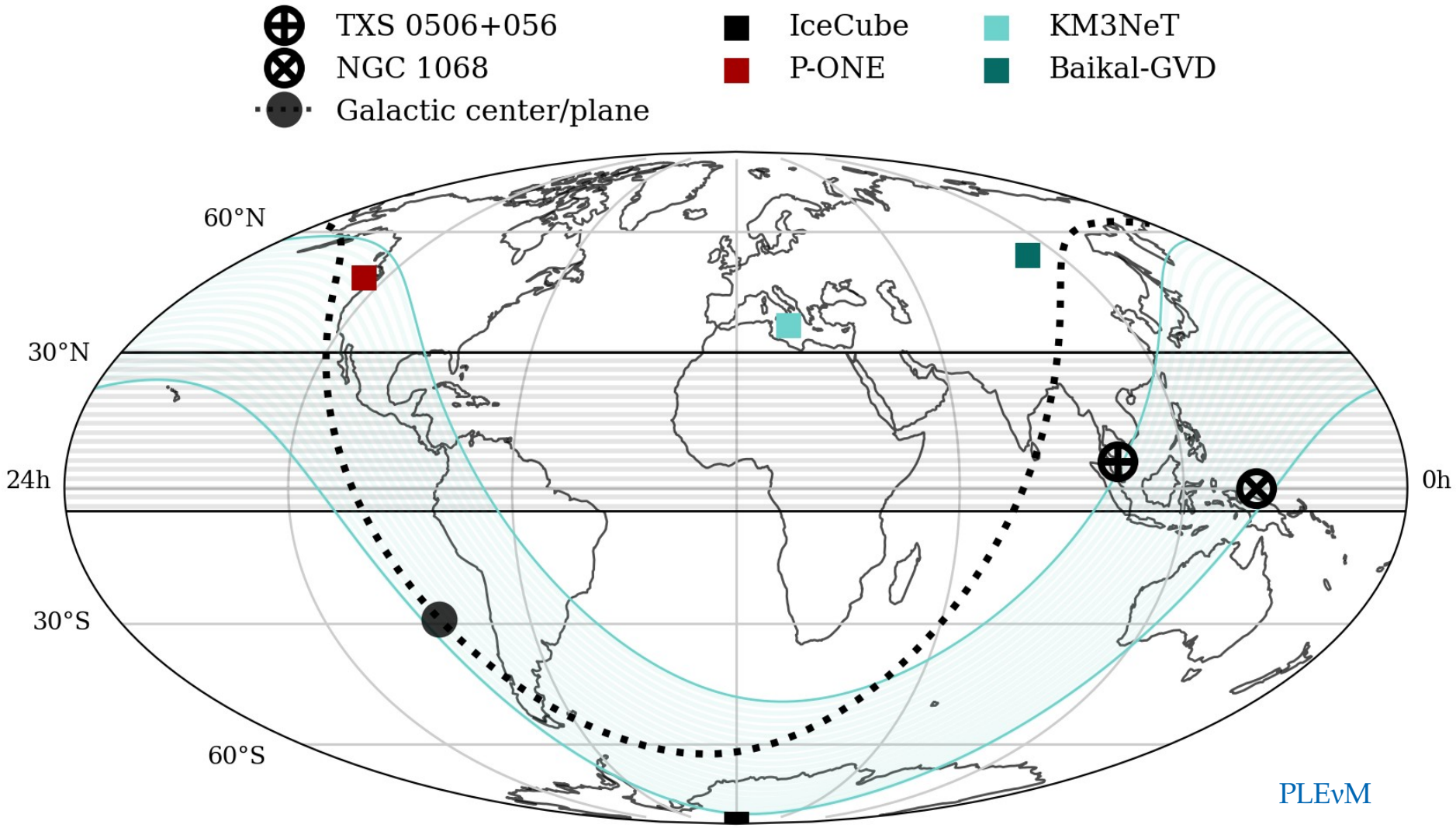
60°S
PLEνM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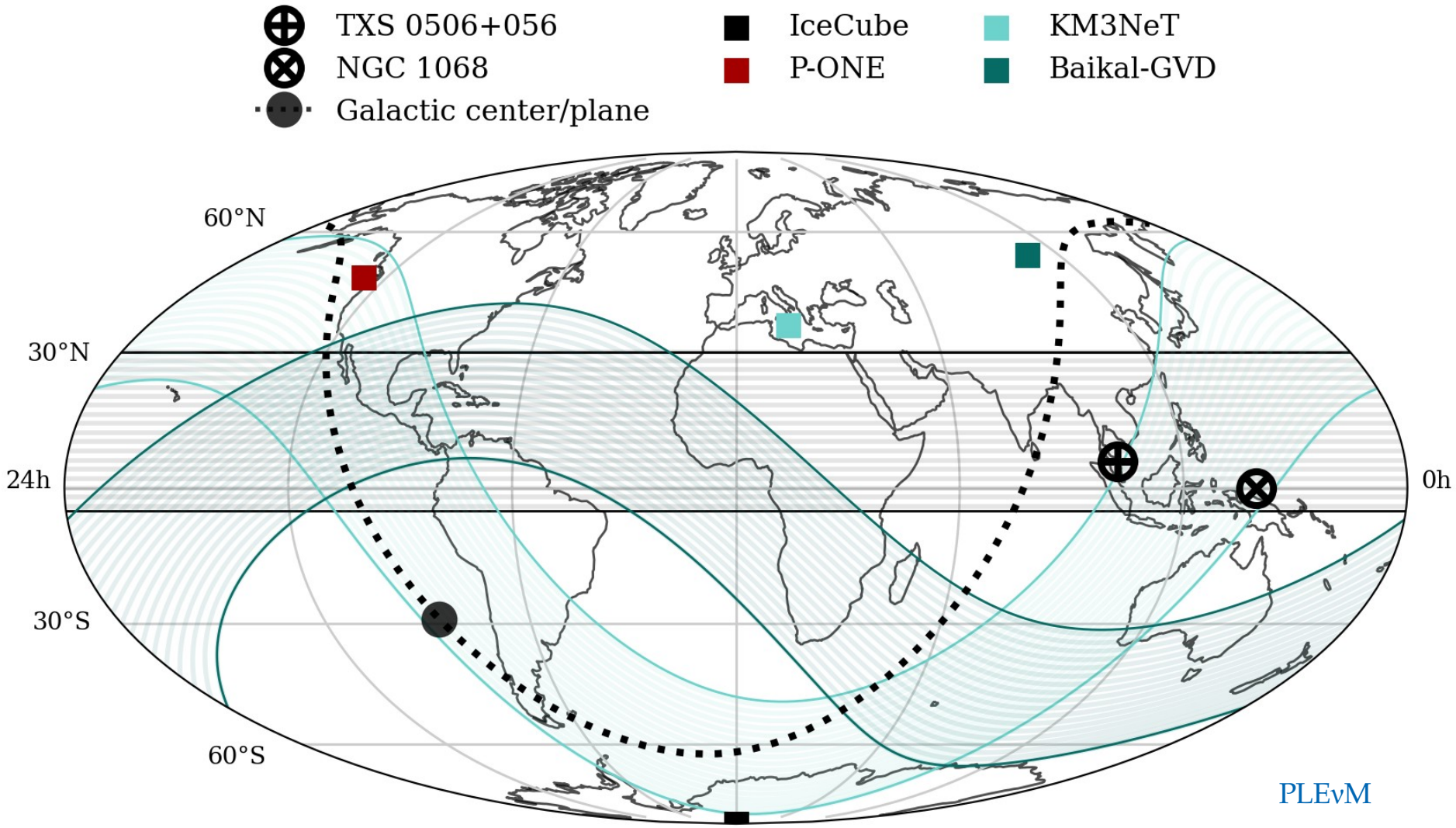
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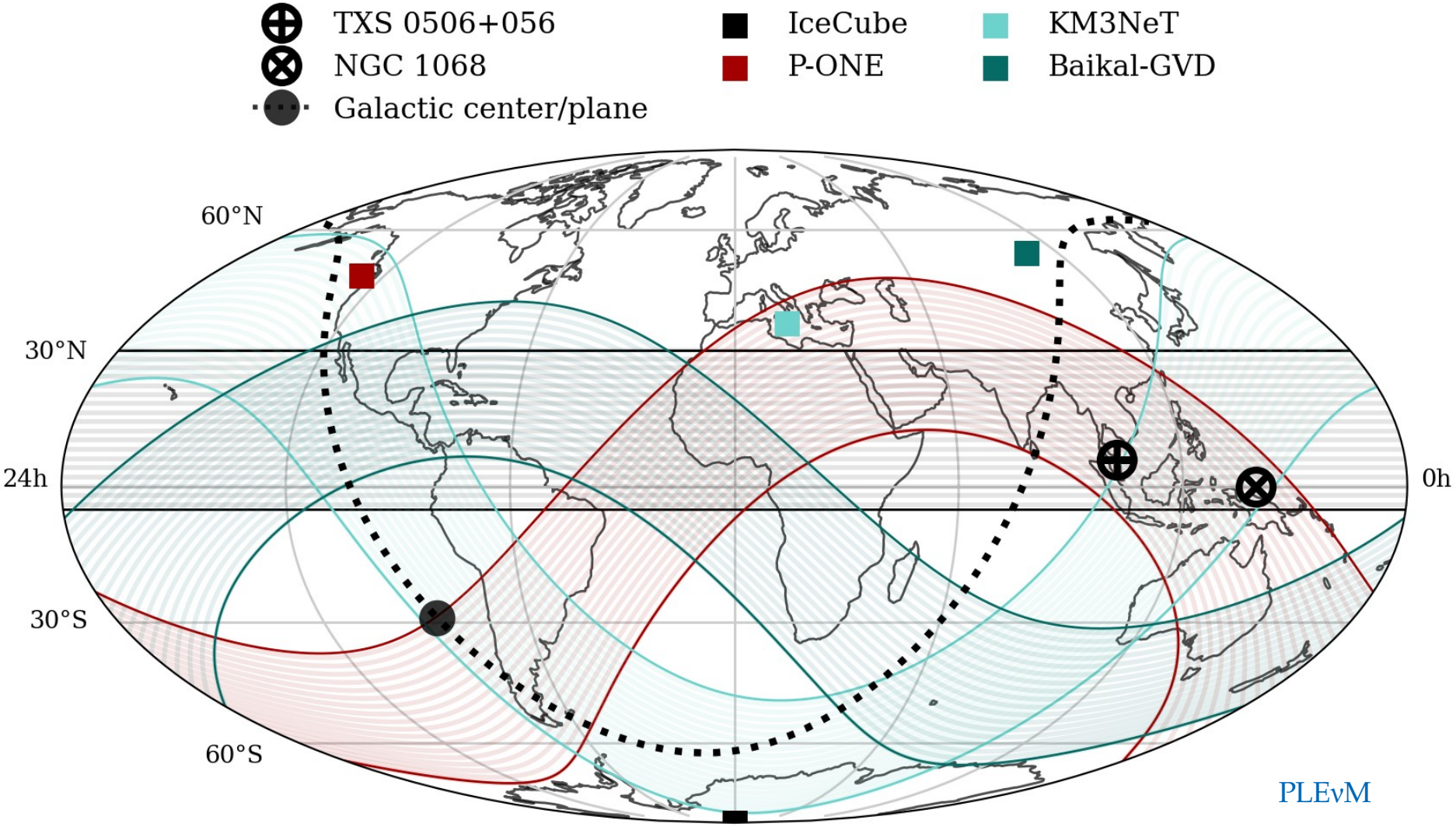
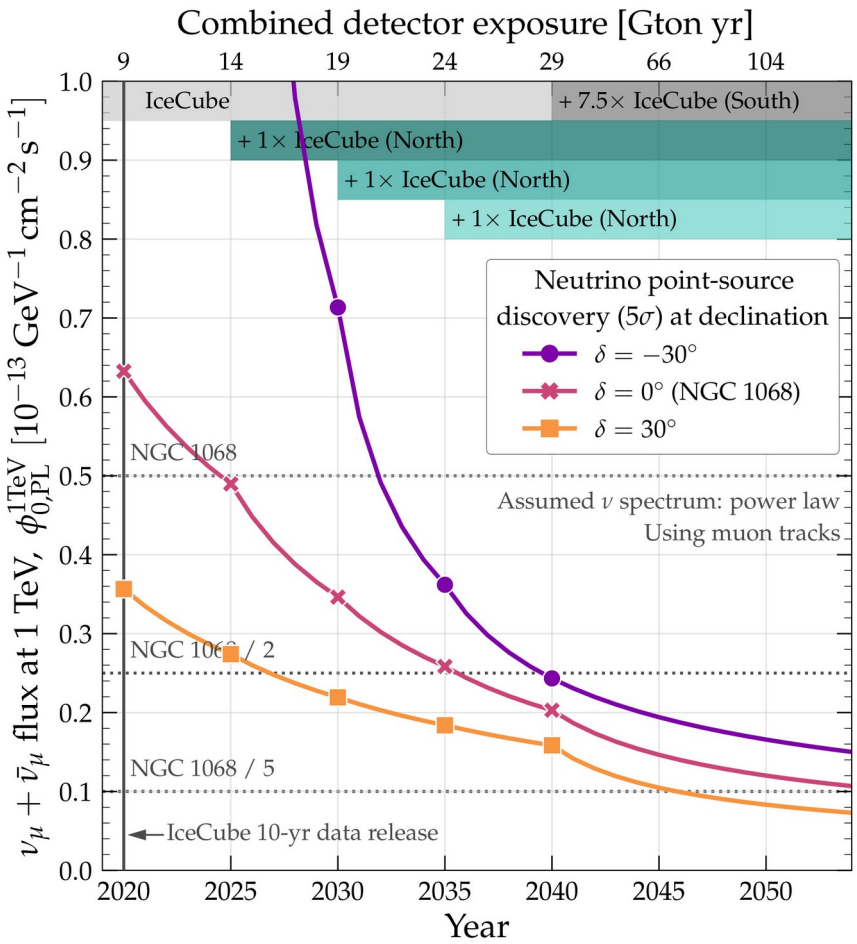
24h
0h
30°S
60°S
PLEνM

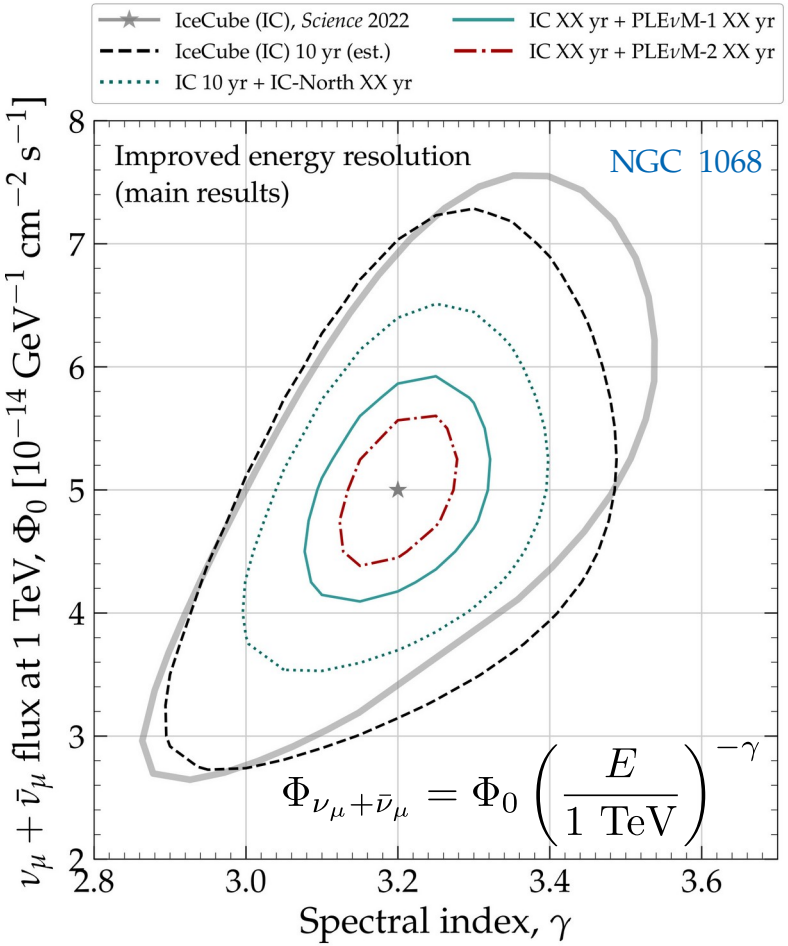

TXS 0506+056
NGC 1068
Galactic center/plane
IceCube
P-ONE
KM3NeT
Baikal-GVD
60°N
30°N
24h
0h
30°S
60°S
PLEνM

High-statistics, full-sky neutrino astronomy

Discovering dimmer sources, faster



Fitting the ν spectrum from a source



Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

Characterizing the diffuse power-law flux in PLEνM

$$E^2\phi = \phi_{100\mathrm{TeV}} \left(\frac{E}{100\ \mathrm{TeV}} \right)^{2-\gamma}$$

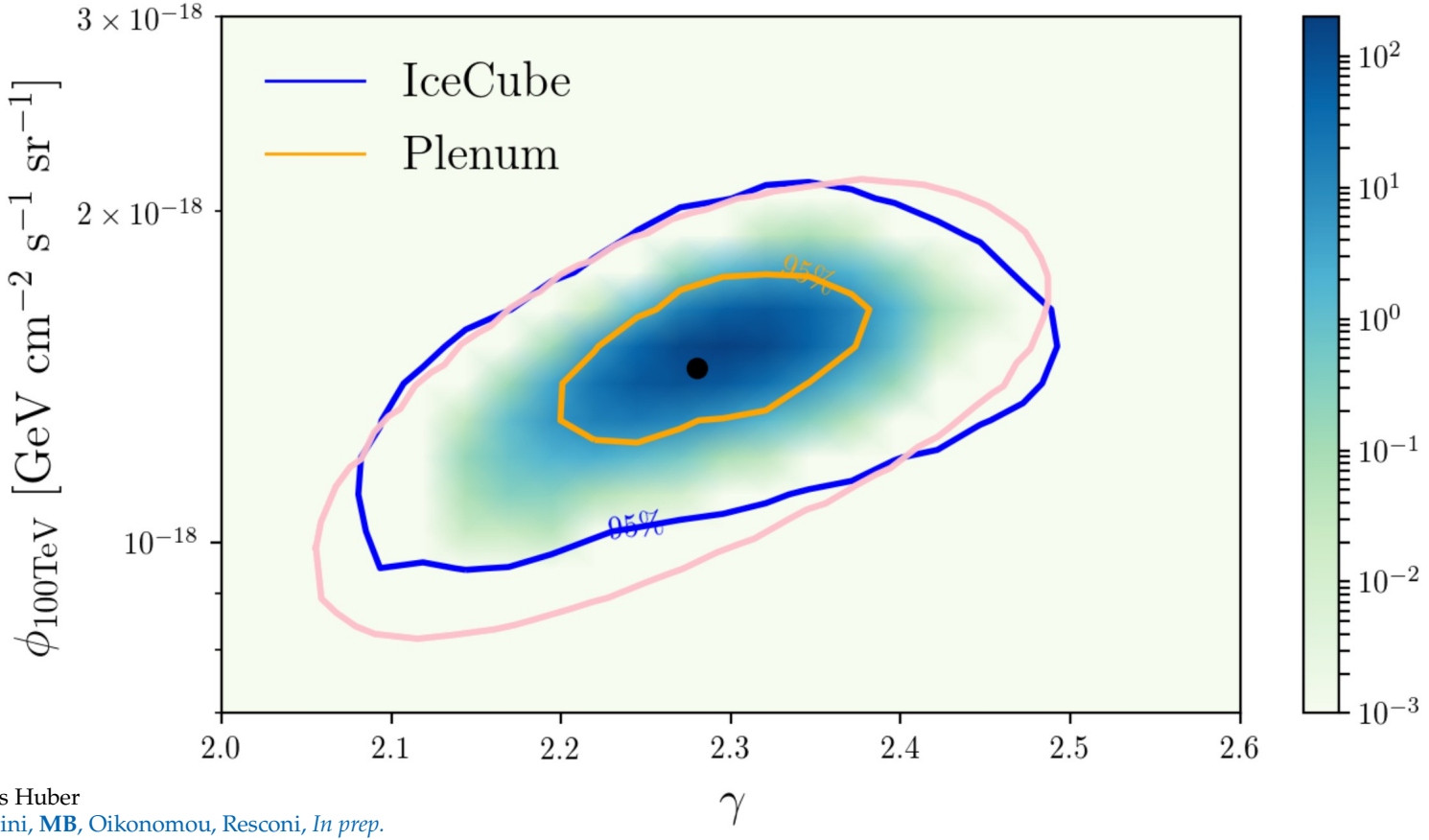
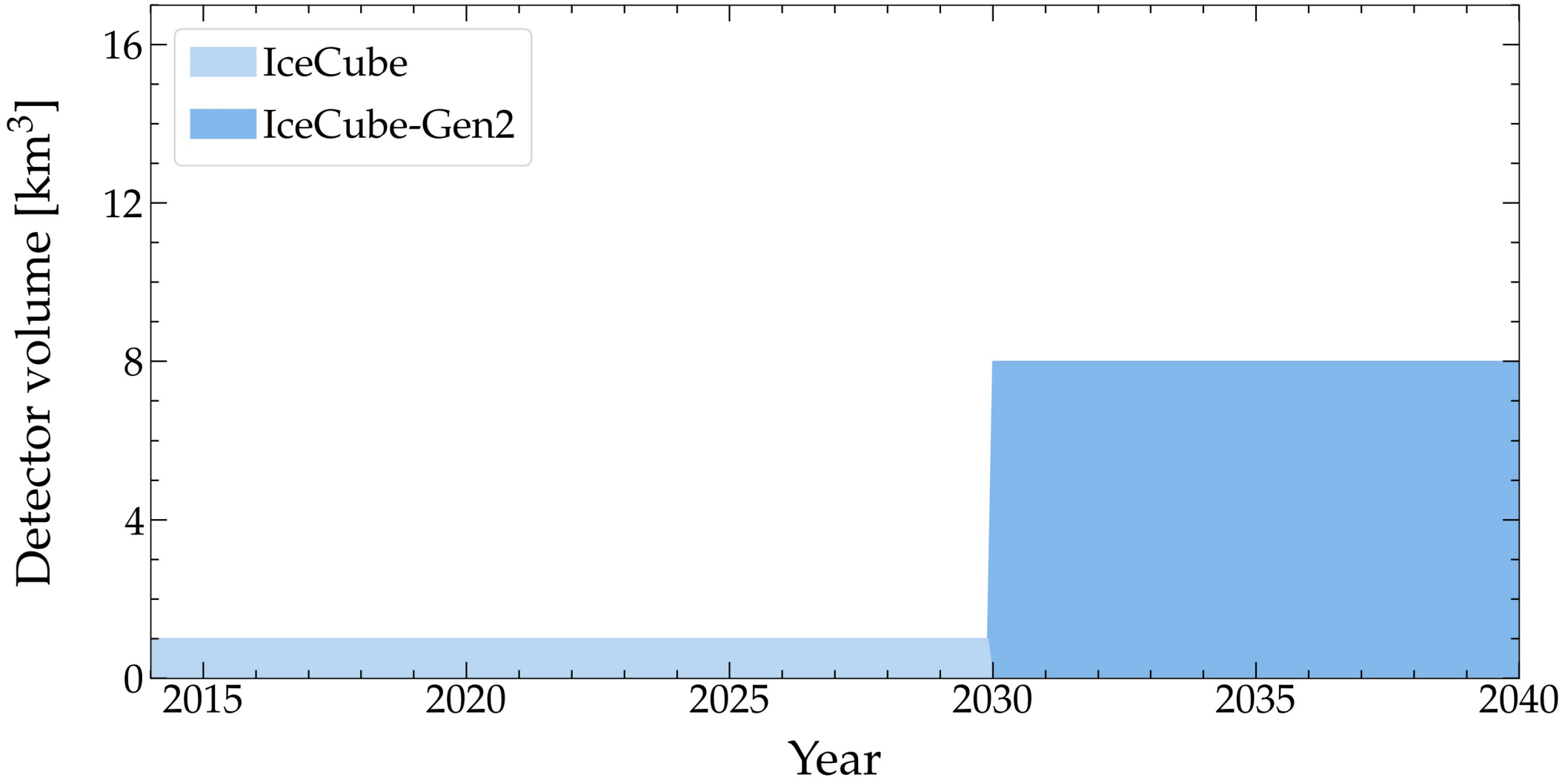
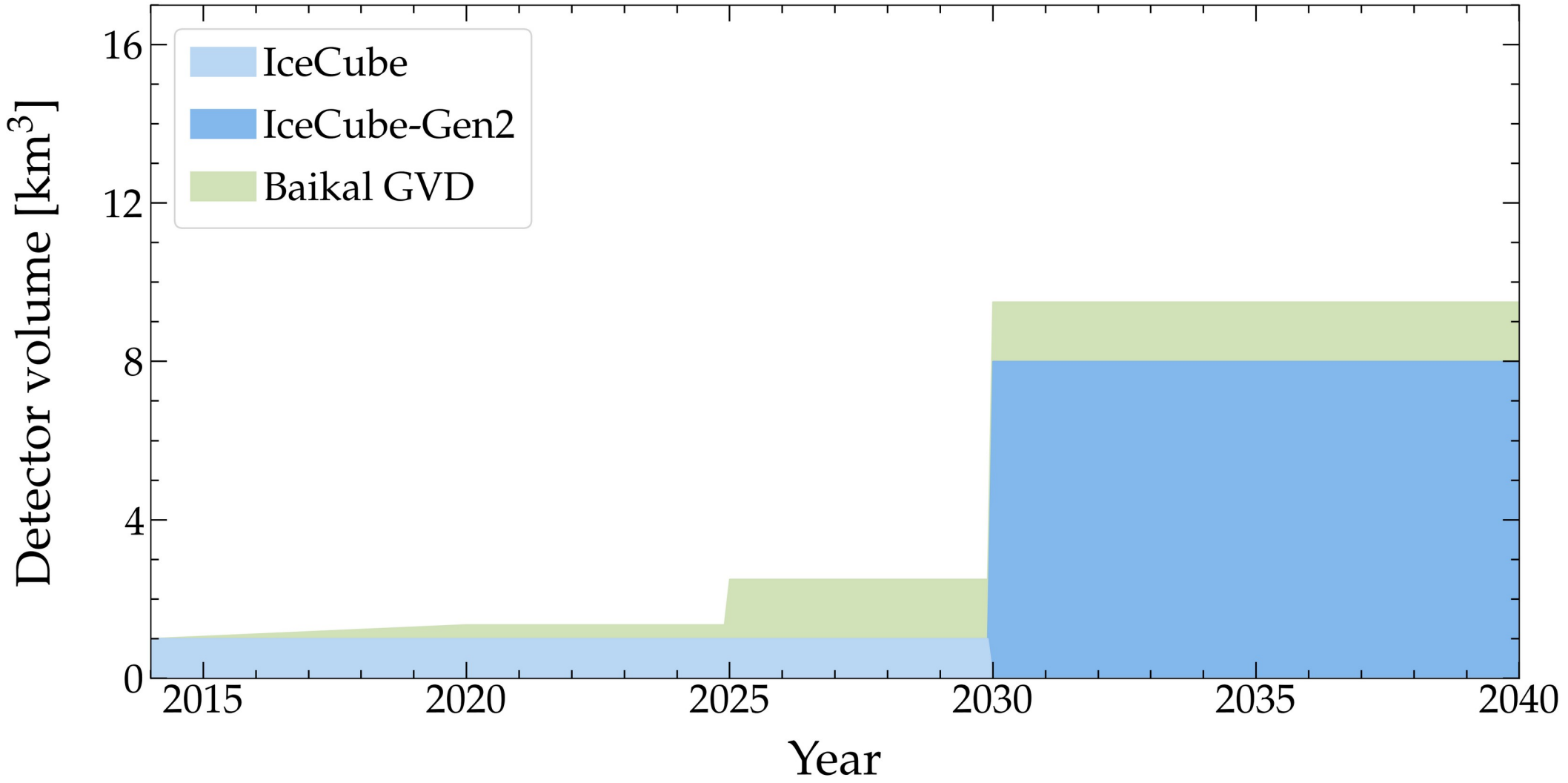


Figure courtesy of Matthias Huber

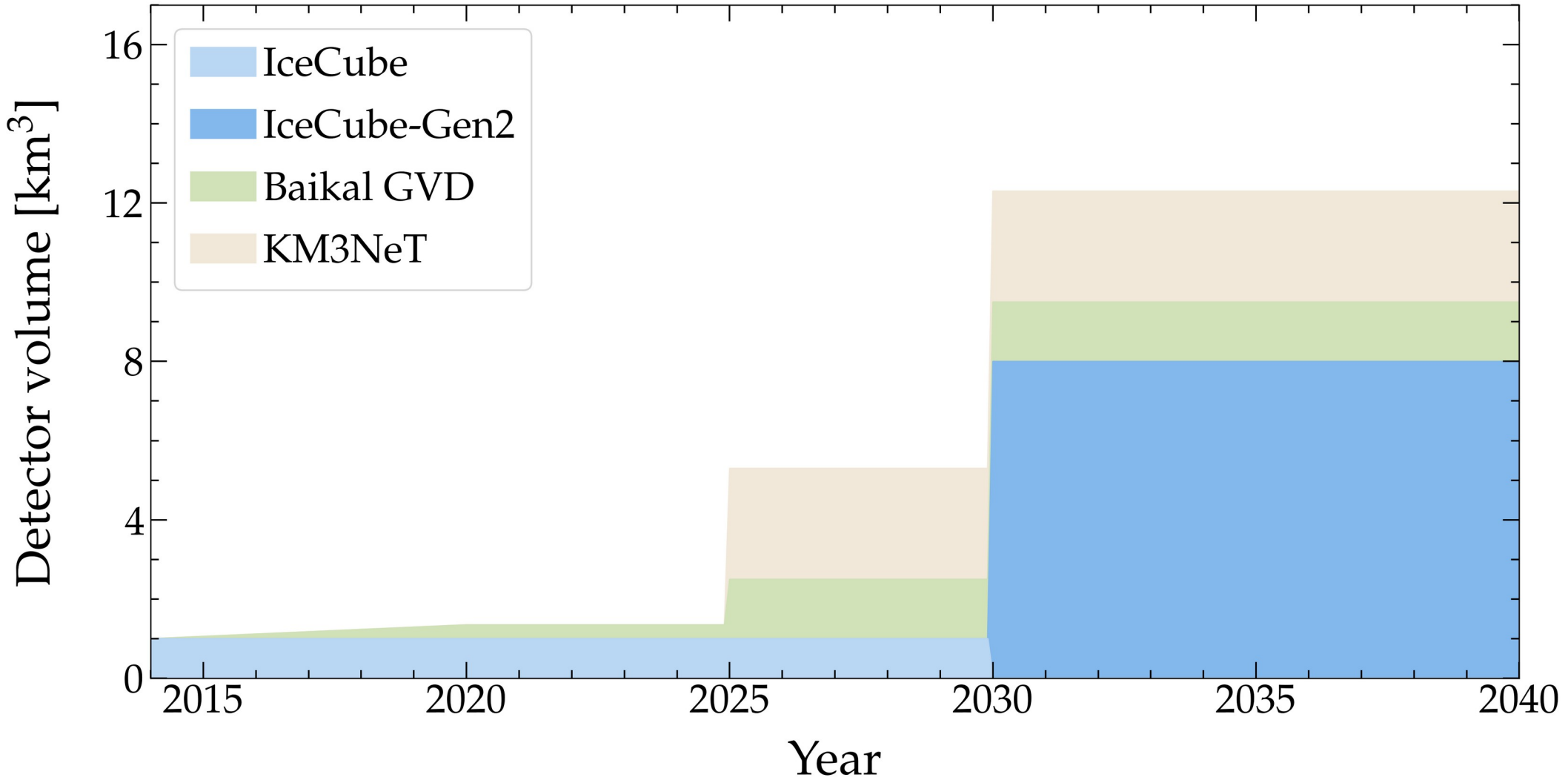
Huber, Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



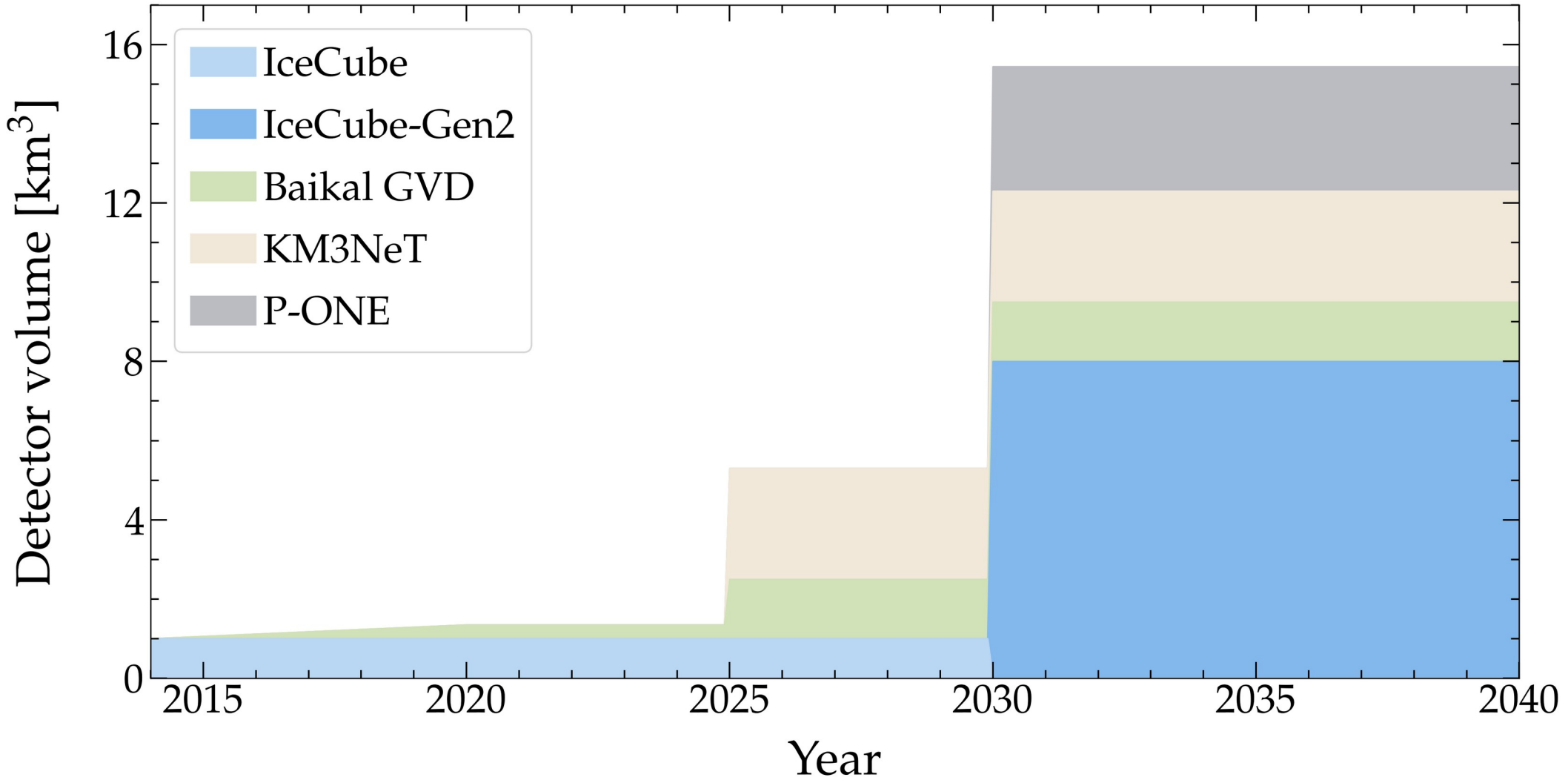
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



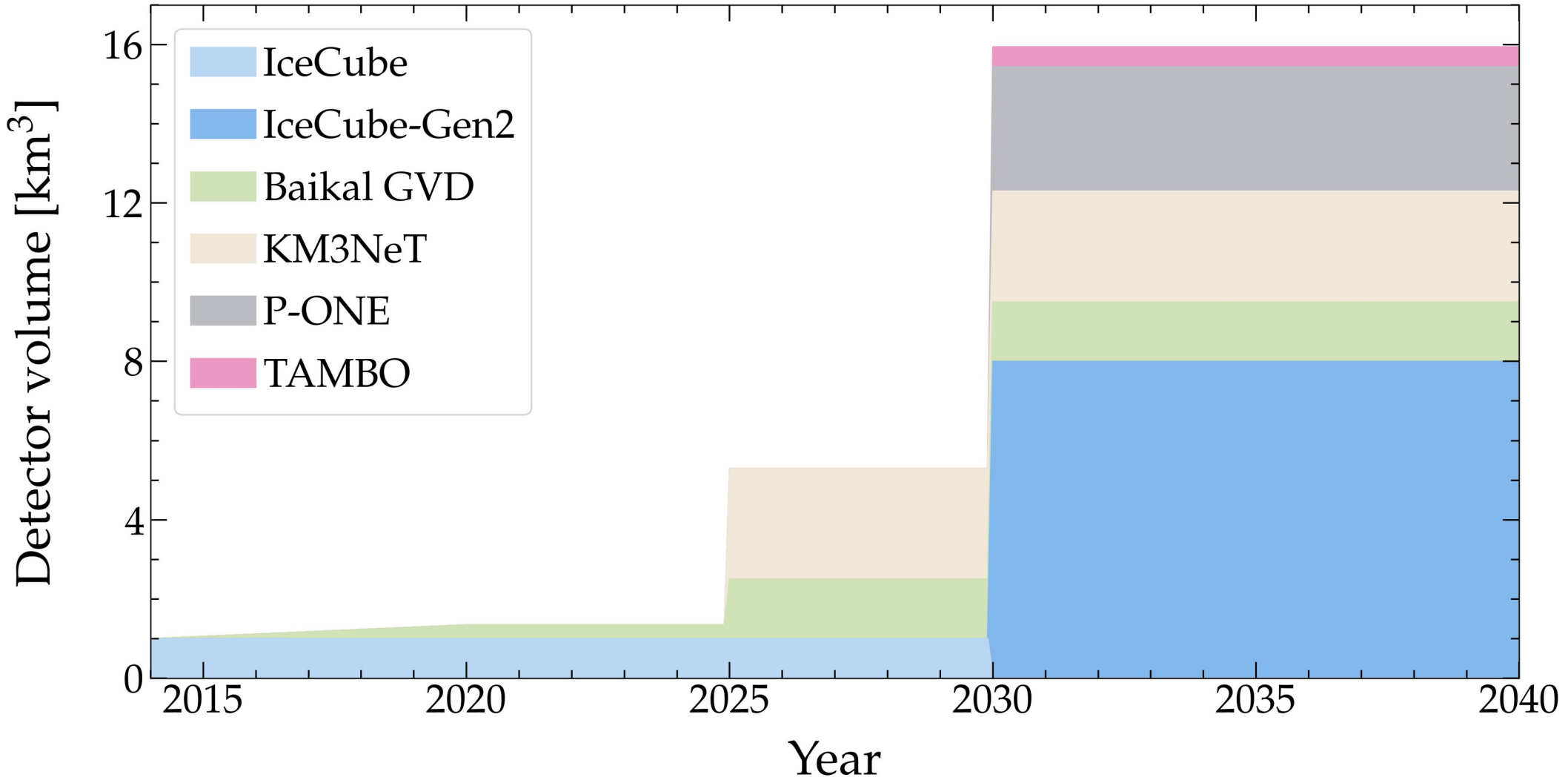
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



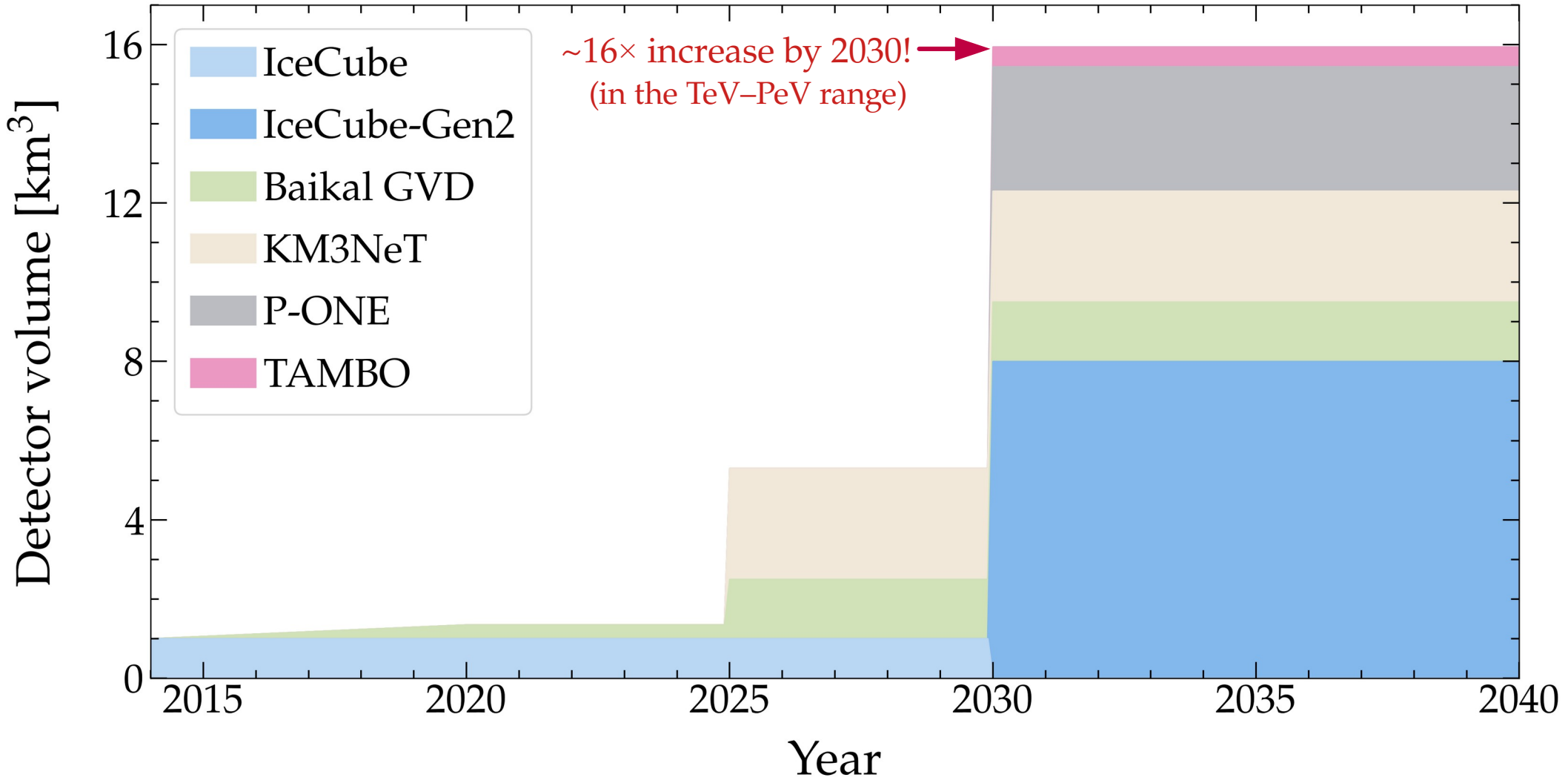
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



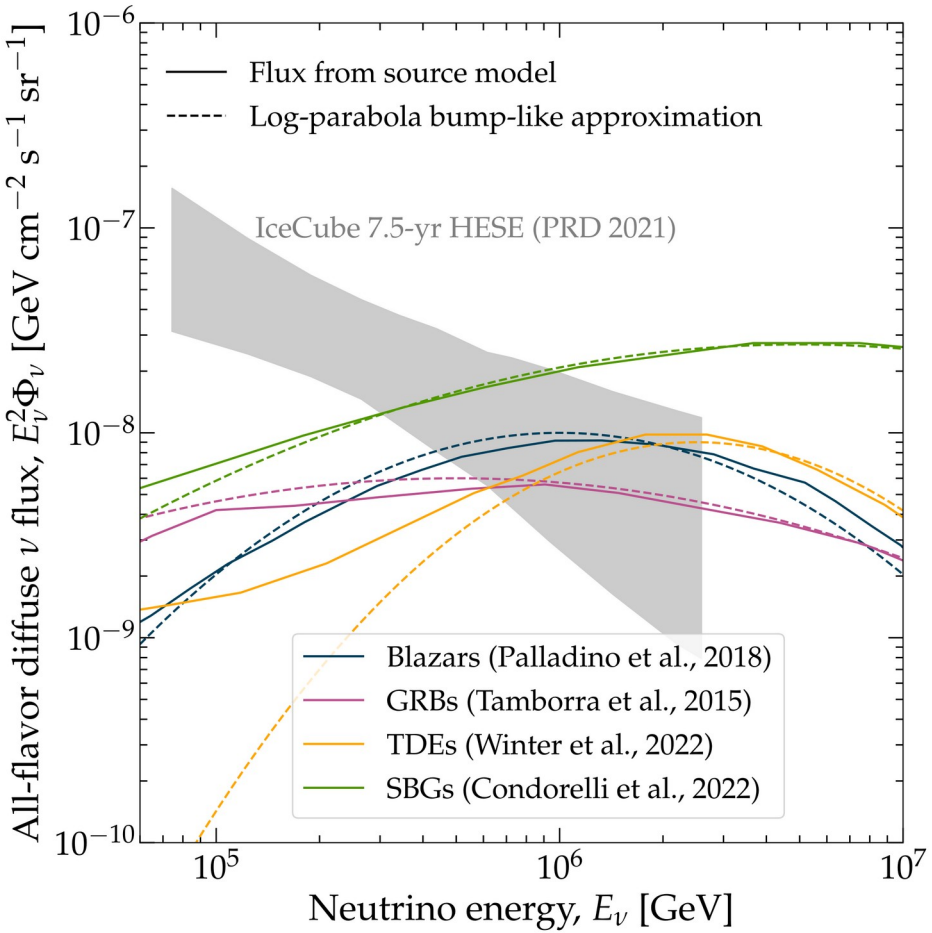
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$:



D. F. G. Fiorillo, **MB**, *PRD* 2023

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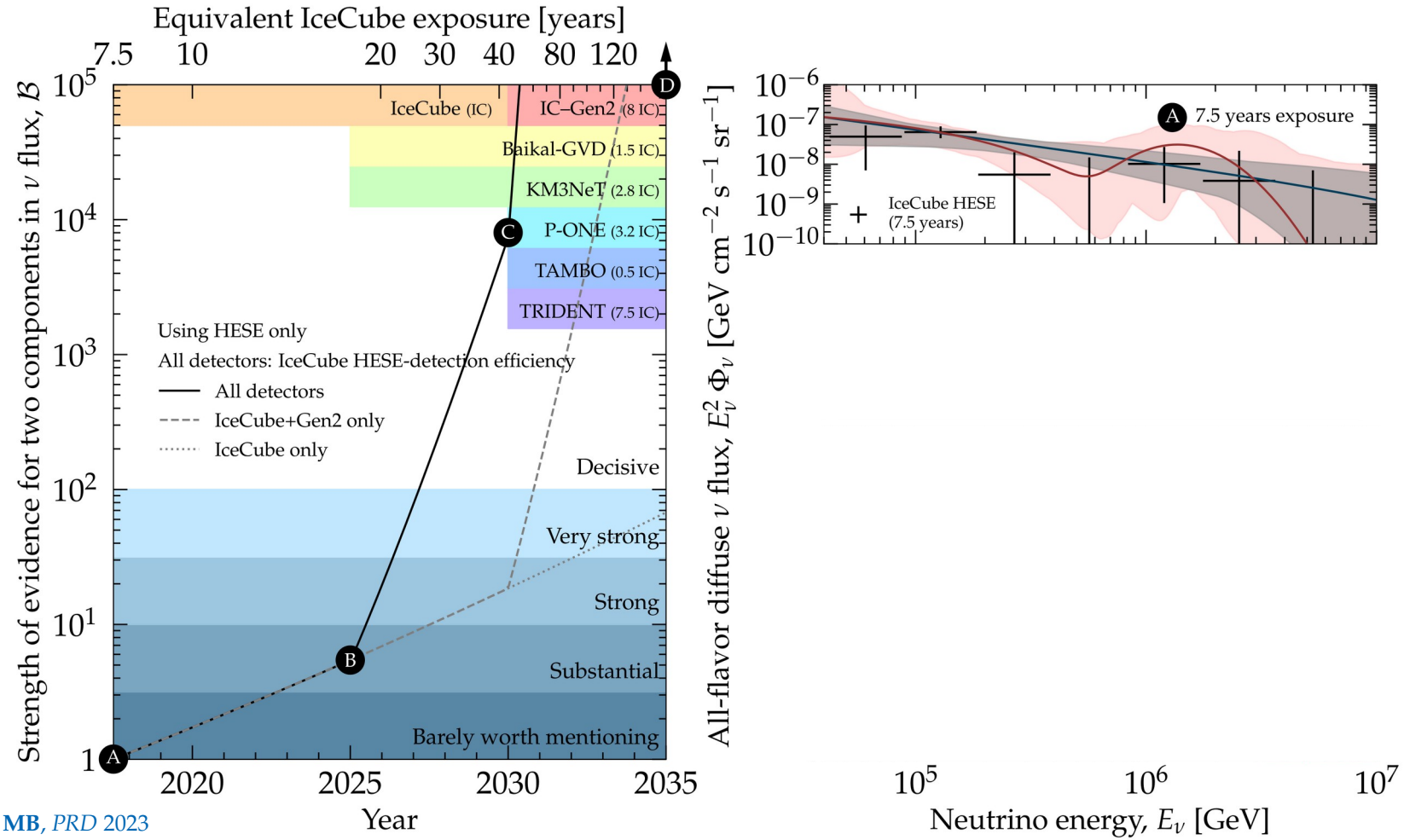

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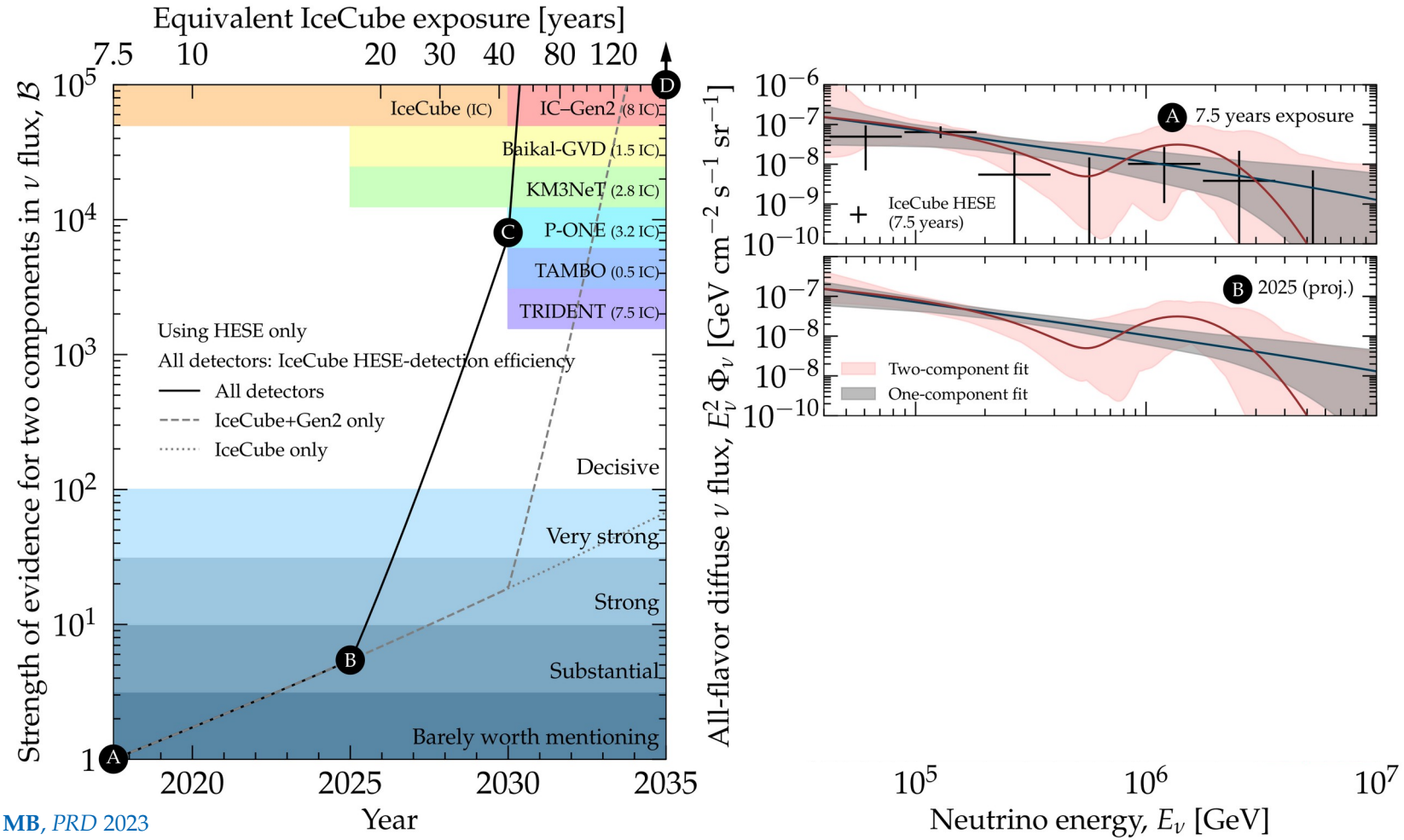

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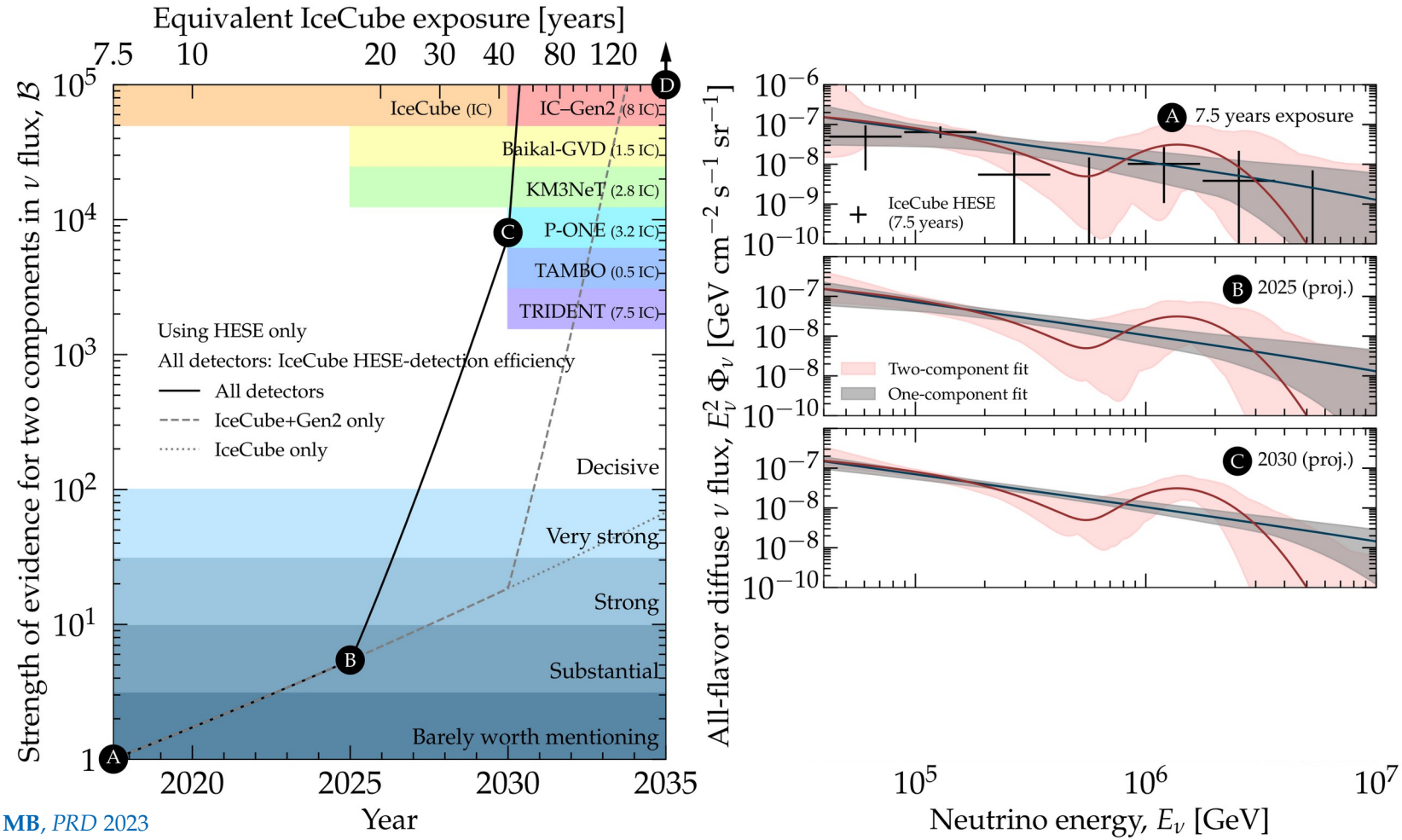

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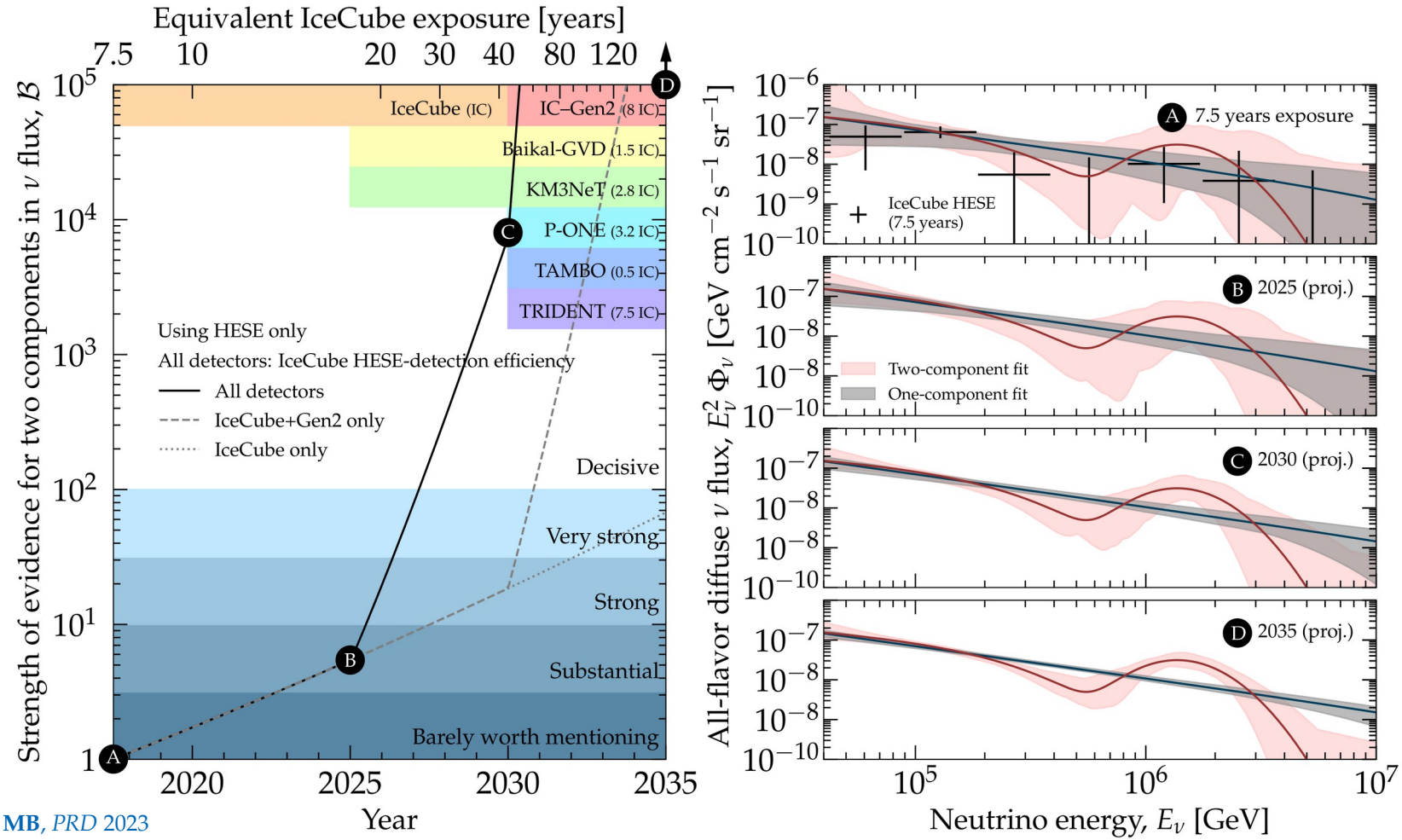
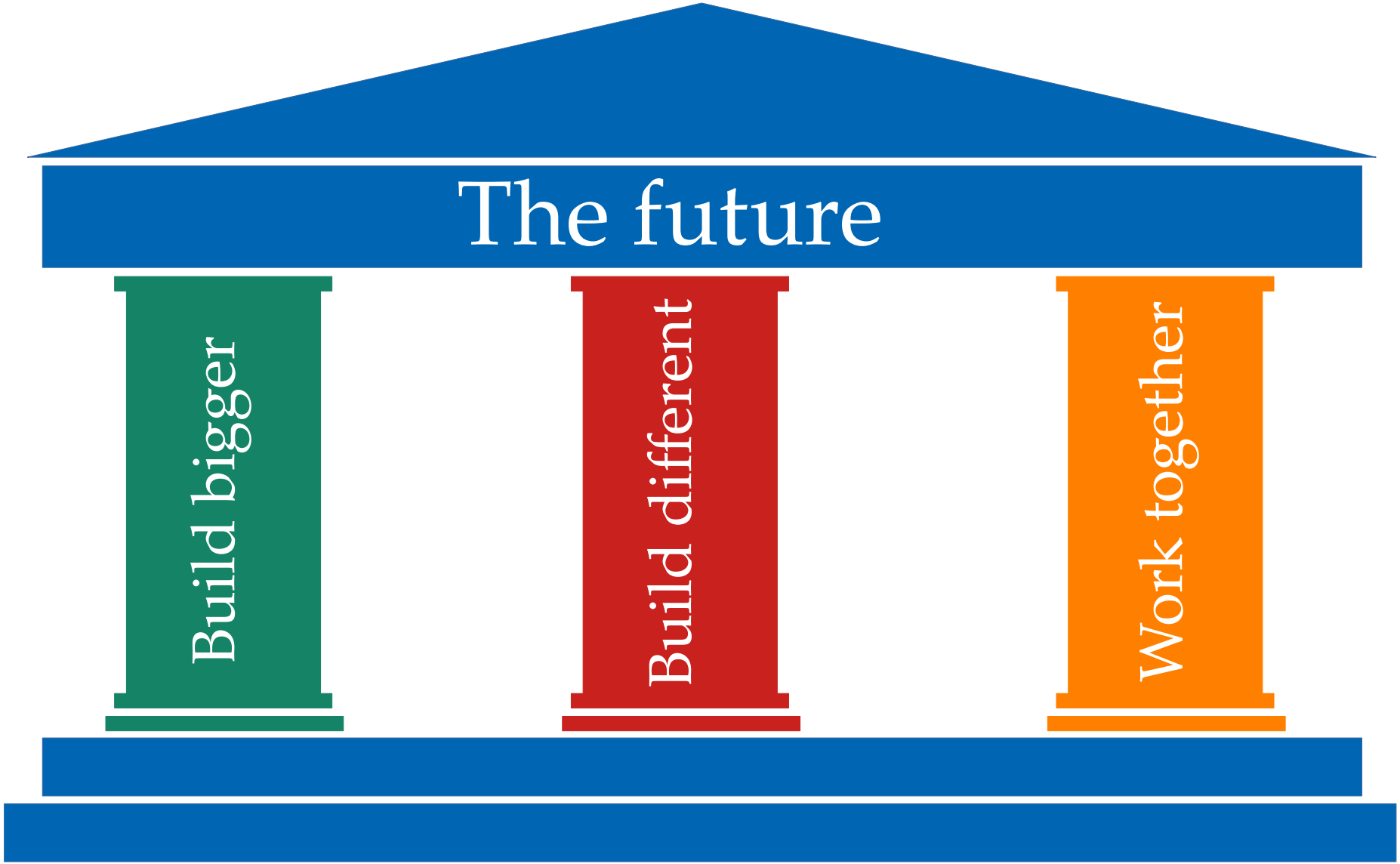


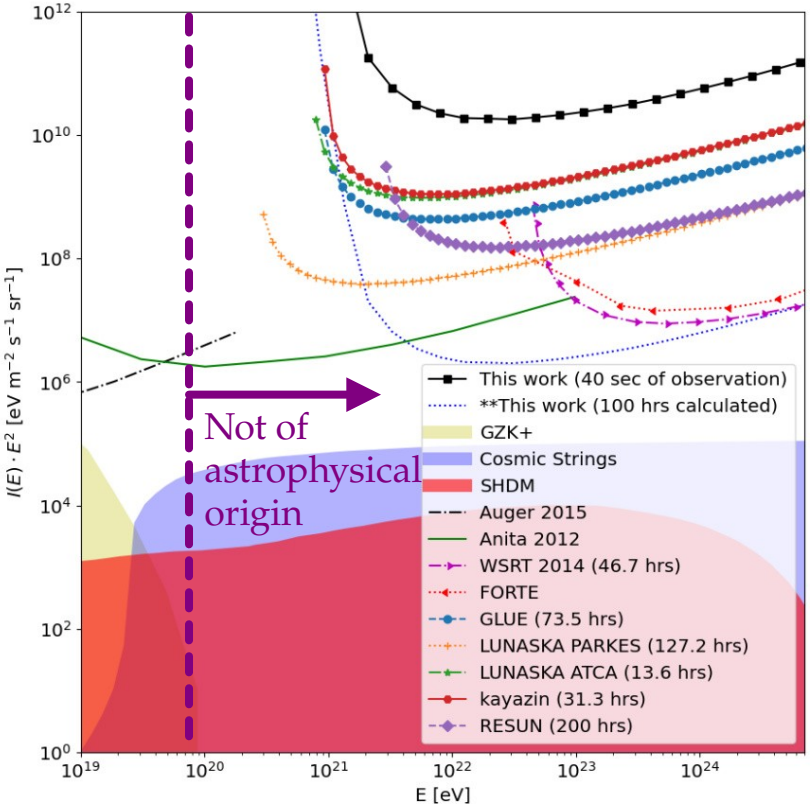
D. F. G. Fiorillo, **MB**, *PRD* 2023


The future
Build bigger
Build different
Work together

Thinking outside the box — hard, but rewarding

Radio-detection of ν using the Moon

Test exotic neutrinos at > 10^{20} eV



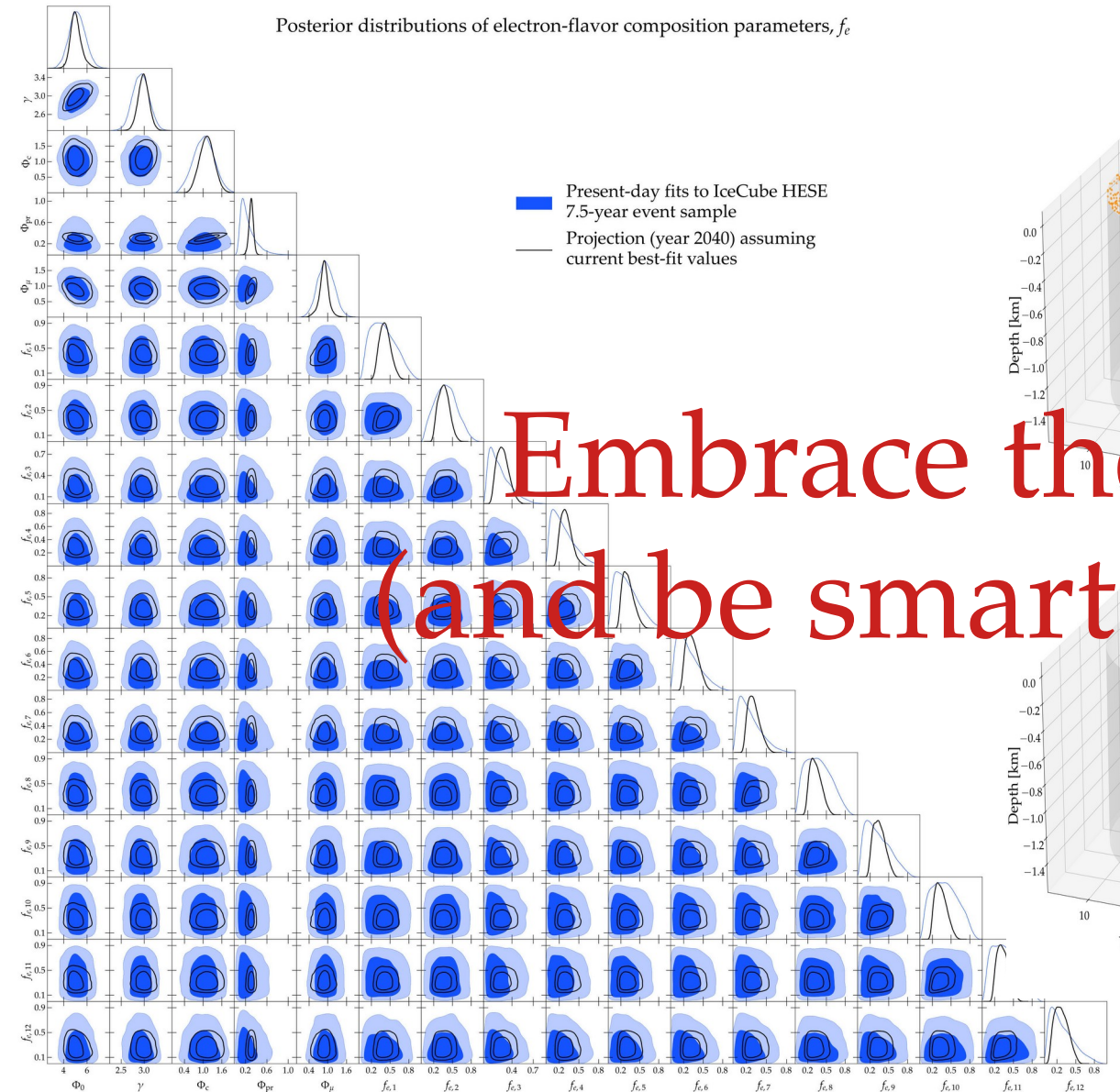
G. K. Krampah *et al.*, ARENA 2022
O. Scholten *et al.*, ICRC 2007

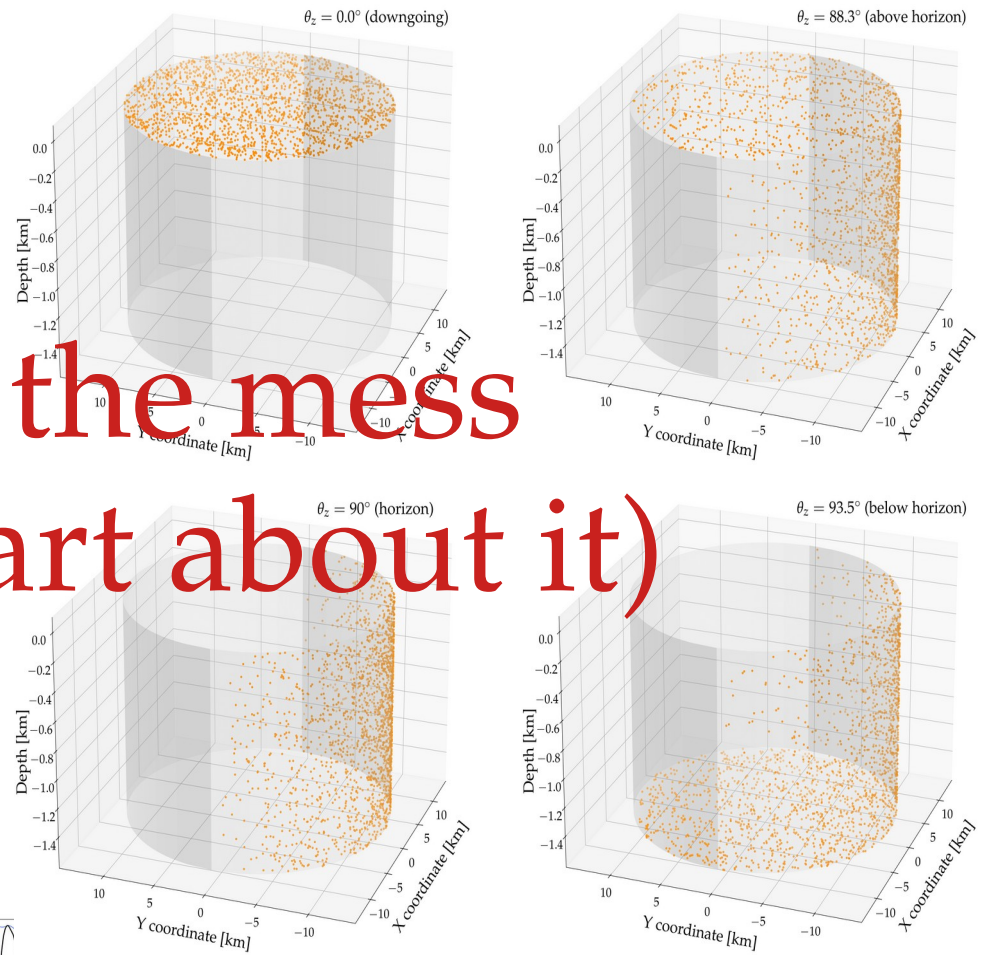
The forest as a neutrino detector

Let Nature grow your radio array

Trees are broadband (kHz, MHz) and abundant

S. Prohira., arXiv:2401.14454





Embrace the mess (and be smart about it)

Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

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Next decade

> 100-PeV ν

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Next decade

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Make predictions for
a new energy regime

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Make predictions for
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<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

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Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties

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TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

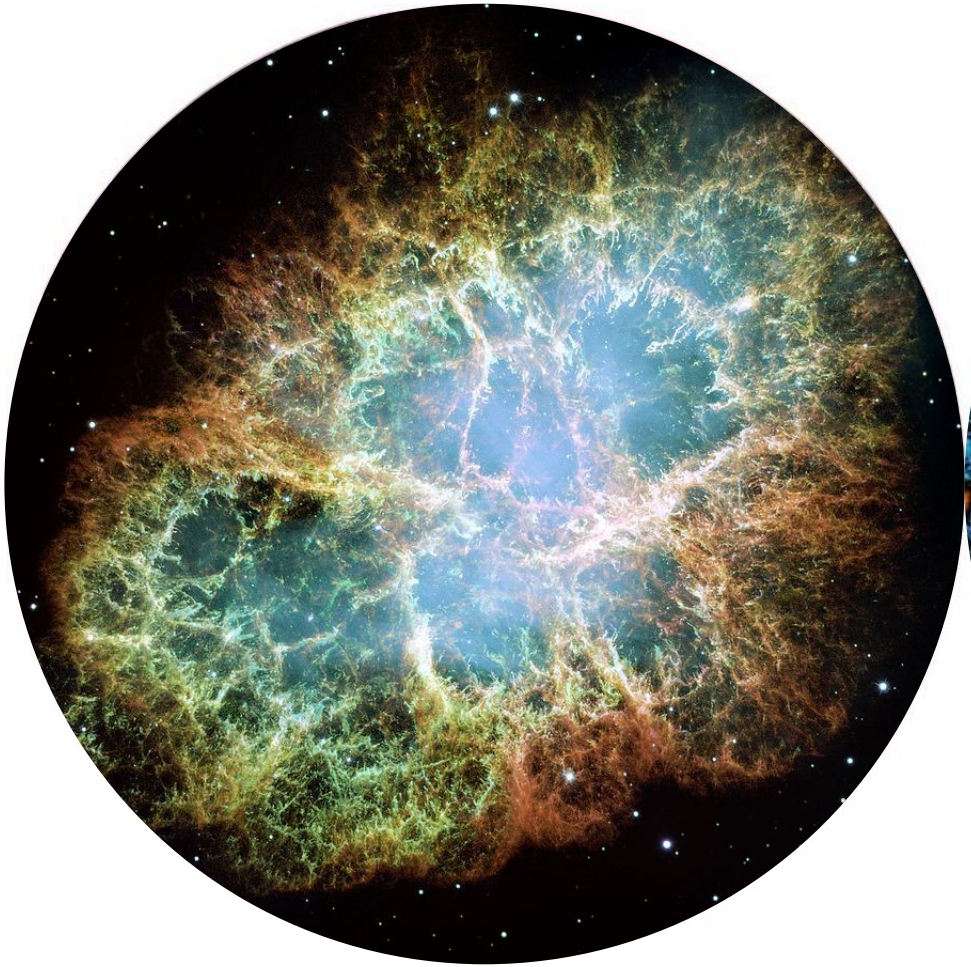
Next decade
> 100-PeV ν

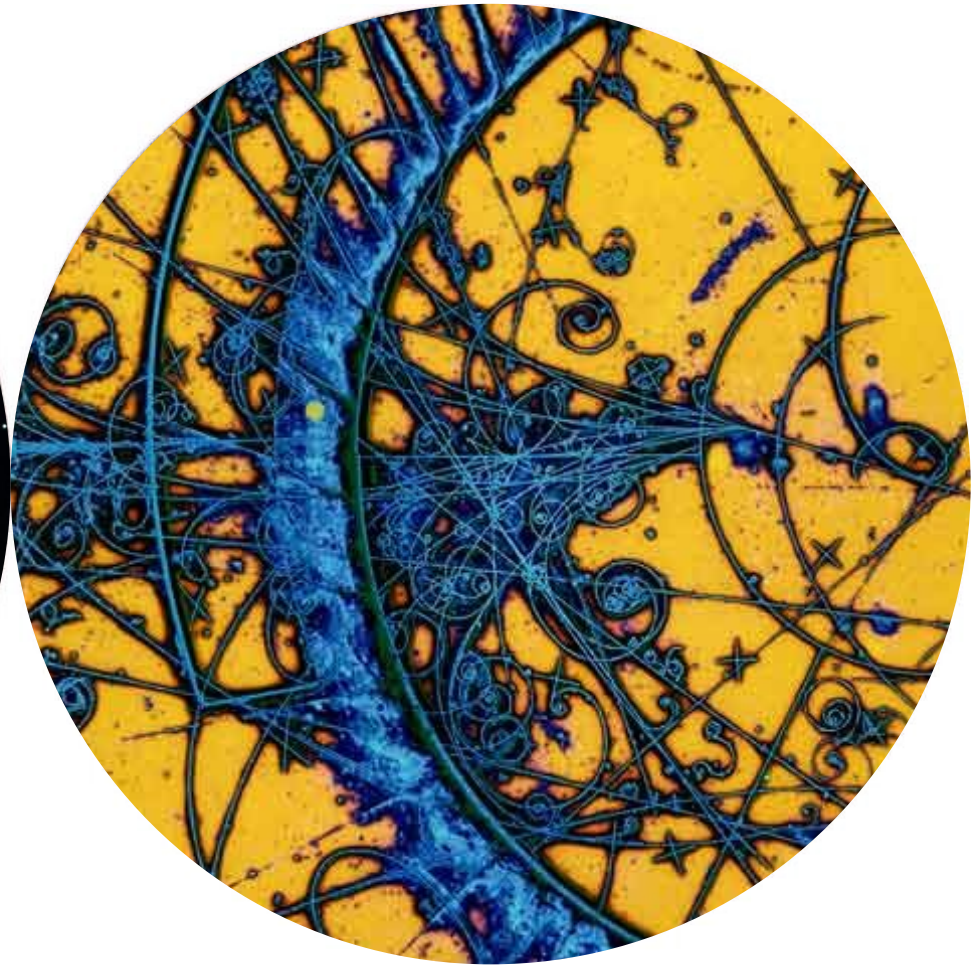
Make predictions for
a new energy regime

<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

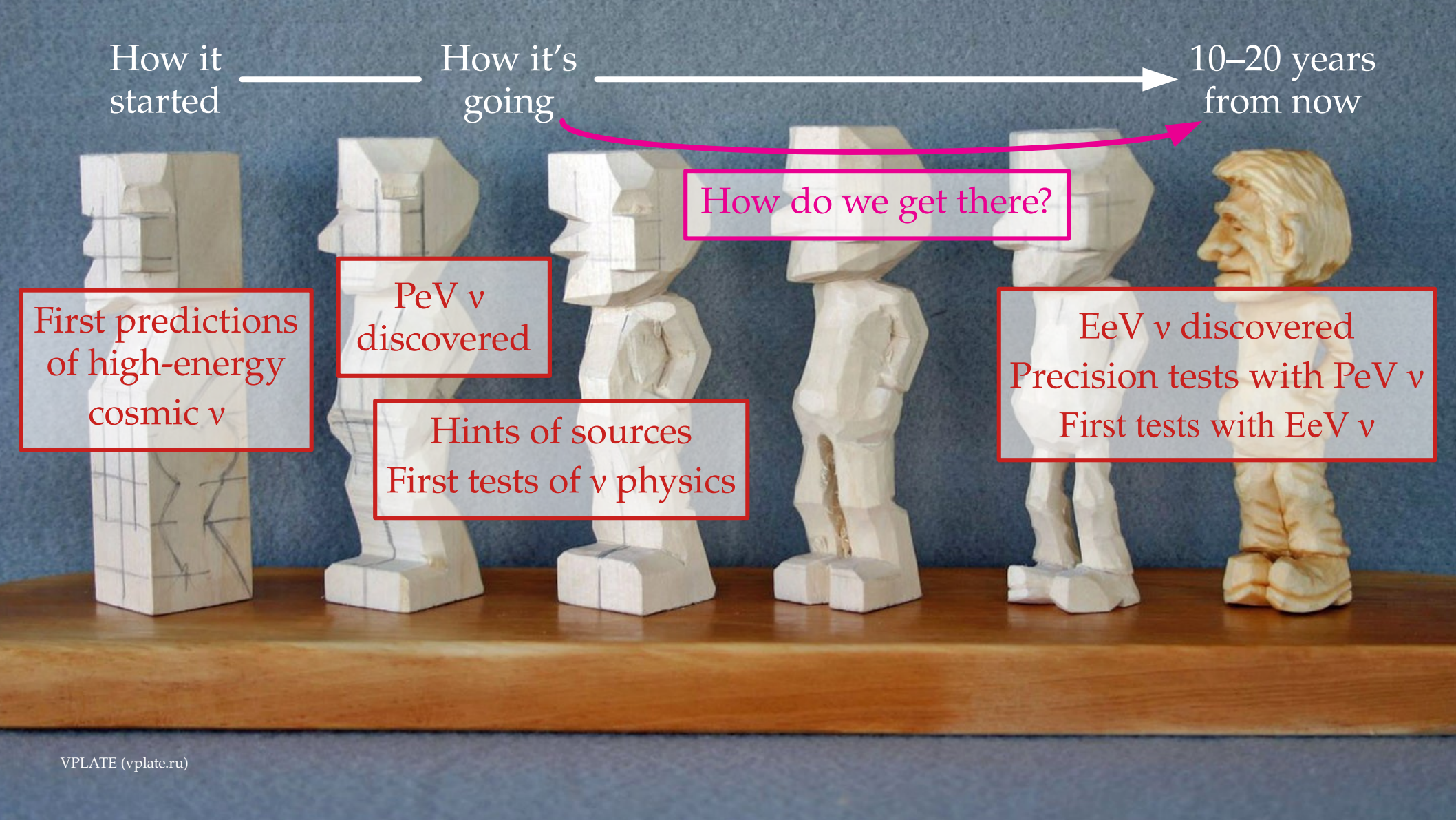
Similar to the evolution of cosmology to a high-precision field in the 1990s

Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties





Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine


How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)

Thanks!

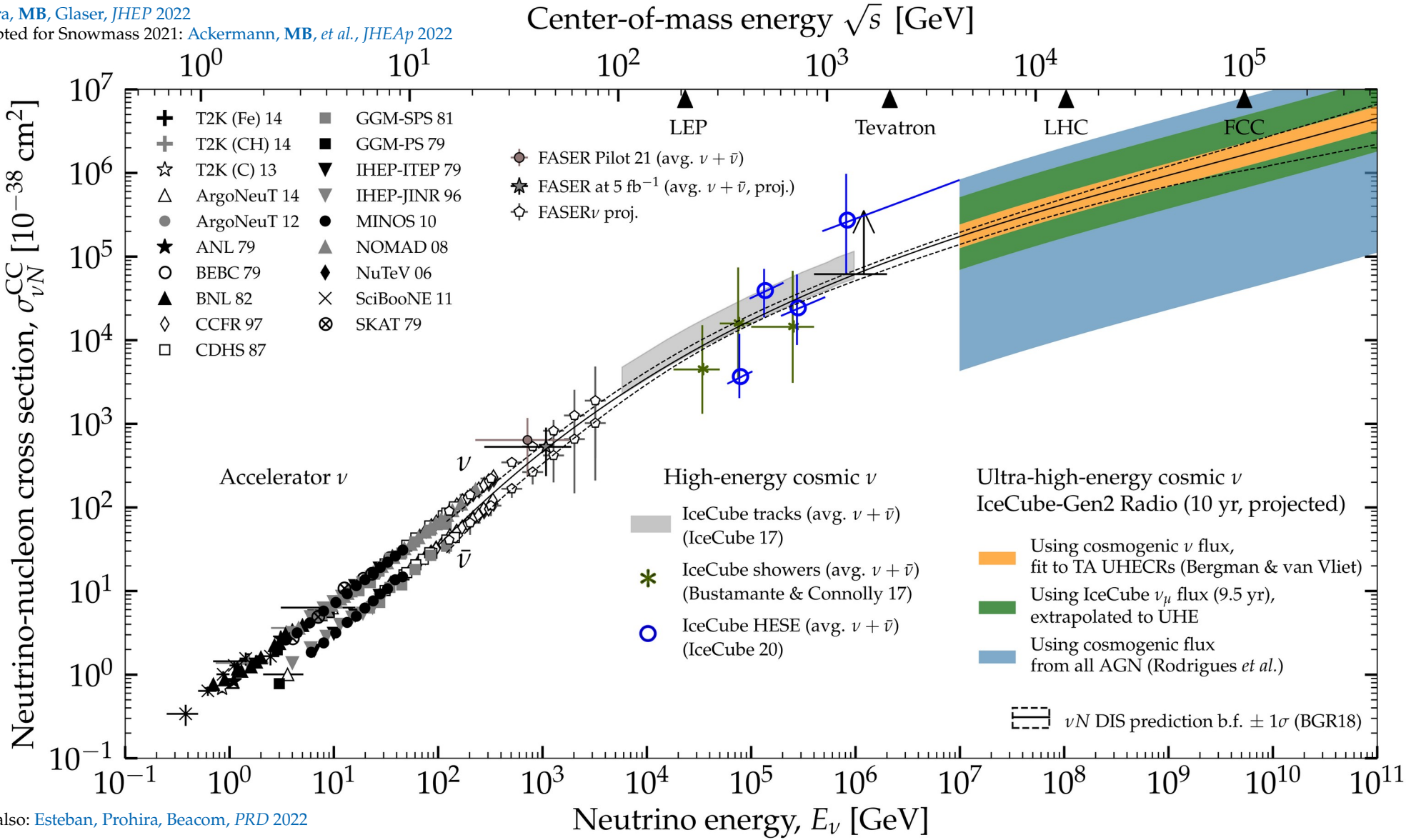
28th European Cosmic Ray Symposium (ECRS)

September 23–27, Hvar, Croatia

Abstract submission deadline: Friday, May 31!

Backup slides

Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



See also: Esteban, Prohira, Beacom, *PRD* 2022

Valera, **MB**, Glaser, *JHEP* 2022
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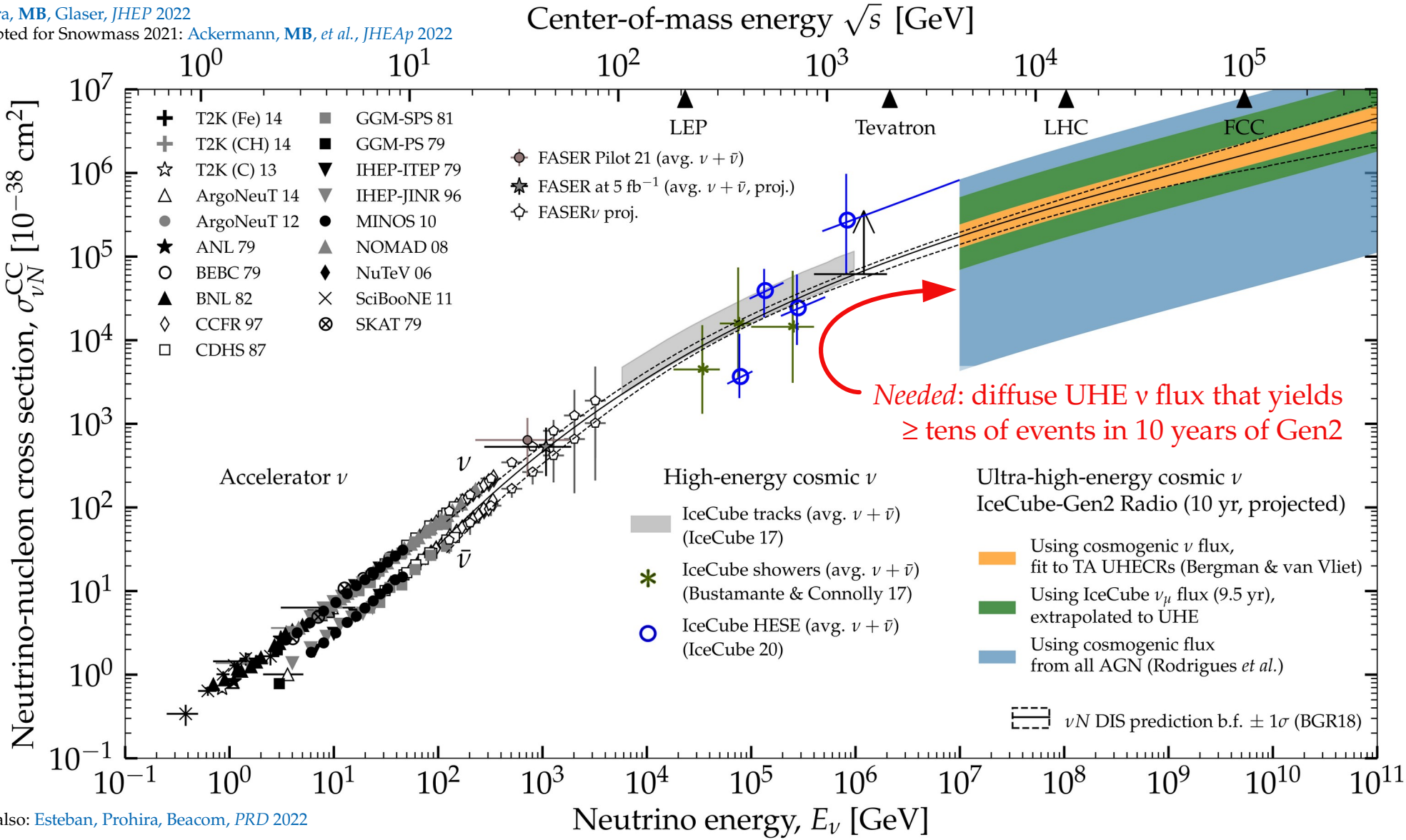
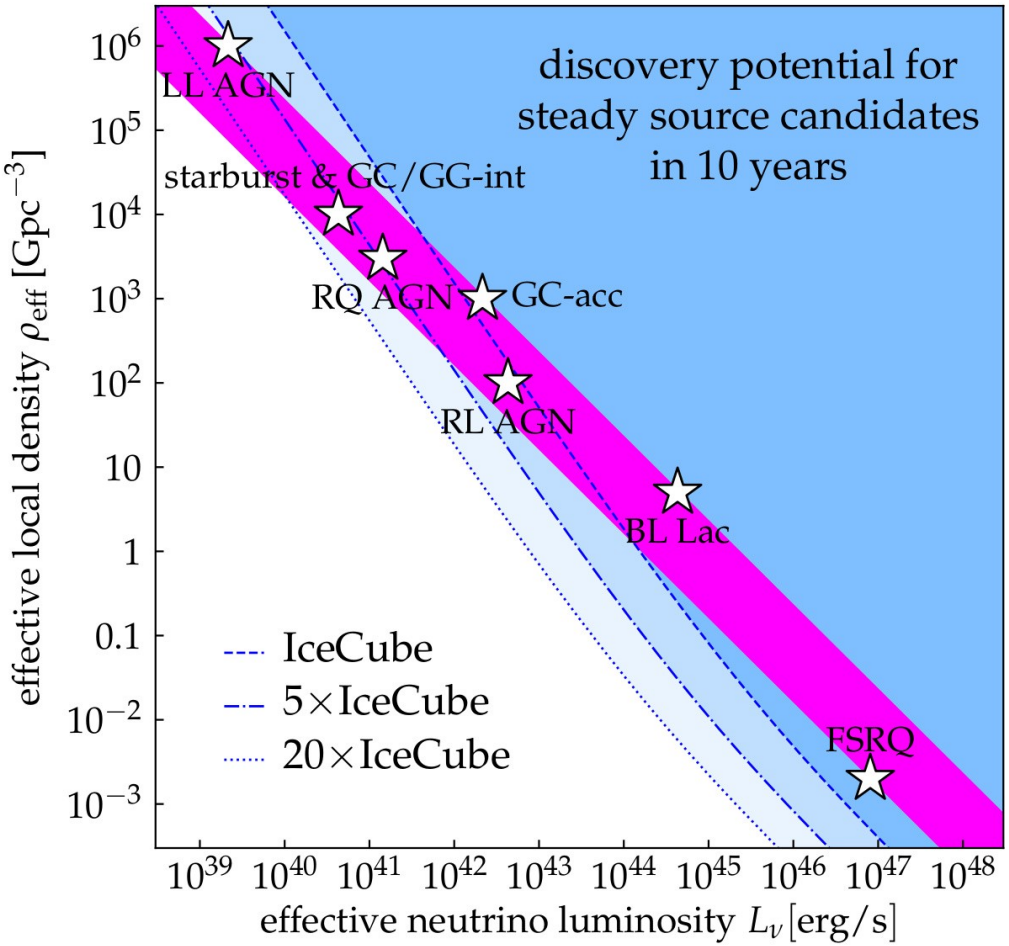
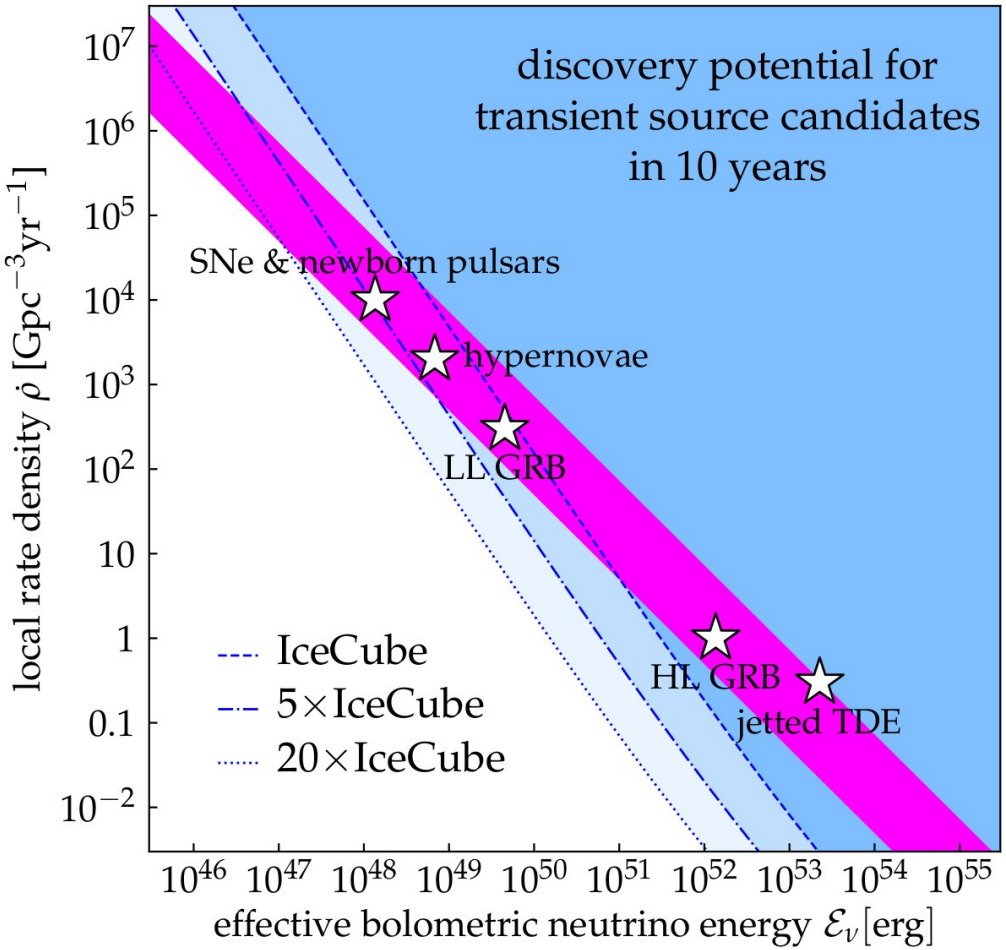


See also: Esteban, Prohira, Beacom, *PRD* 2022

Constraining candidate source populations





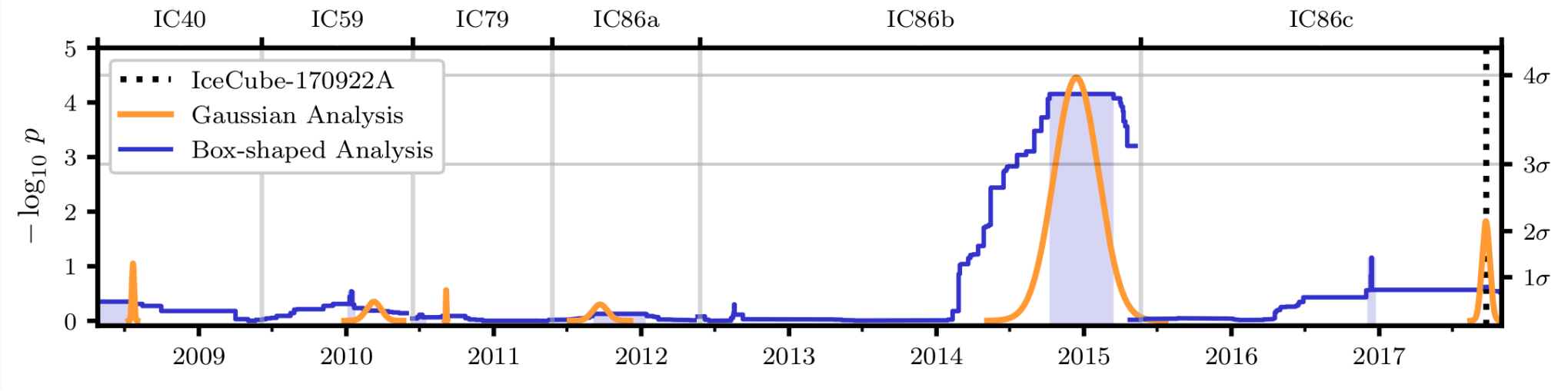
Many TeV–EeV ν telescopes in planning for 2020–2040

				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
KM3NeT	2021	TeV-PeV	Mediteranean		✓	✓			✓					✓					
Baikal-GVD	2021	TeV-PeV	Lake Baikal		✓	✓			✓					✓					
P-ONE	2020	TeV-PeV	Pacific Ocean		✓	✓			✓					✓					
IceCube-Gen2	2030+	TeV-EeV	South Pole		✓	✓	✓		✓					✓					
ARIANNA	2014	>30 PeV	Moore's Bay		✓		✓		✓					✓					
ARA	2011	>30 PeV	South Pole		✓		✓		✓					✓					
RNO-G	2021	>30 PeV	Greenland		✓		✓		✓					✓					
RET-N	2024	PeV-EeV	Antarctica		✓		✓		✓					✓					
ANITA	2008,2014,2016	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
PUEO	2024	EeV	Antarctica	✓	✓		✓		✓		✓							✓	
GRAND	2020	EeV	China / Worldwide	✓			✓			✓	✓	✓			✓		✓		
BEACON	2018	EeV	CA, USA/ Worldwide	✓			✓				✓	✓					✓		
TAROGE-M	2018	EeV	Antarctica	✓			✓				✓	✓					✓		
SKA	2029	>100 EeV	Australia		✓		✓						✓		✓				
Trinity	2022	PeV-EeV	Utah, USA	✓		✓					✓						✓		
POEMMA		>20 PeV	Satellite	✓	✓	✓				✓	✓								✓
EUSO-SPB	2022	EeV	New Zealand	✓		✓					✓							✓	
Pierre Auger	2008	EeV	Argentina	✓	✓			✓		✓	✓	✓			✓				
AugerPrime	2022	EeV	Argentina	✓	✓		✓	✓		✓	✓	✓			✓				
Telescope Array	2008	EeV	Utah, USA	✓	✓			✓		✓					✓				
TAx4		EeV	Utah, USA	✓	✓			✓											
TAMBO	2025-2026	PeV-EeV	Peru	✓				✓				✓				✓			

Operational		Date full operations began
Prototype		Date protoype operations began or begin
Planning		Projected full operations

Abraham *et al.* (inc. **MB**), *J. Phys. G: Nucl. Part. Phys.* 59, 11 (2022) [2203.05591]

IceCube, *Science* 2018



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

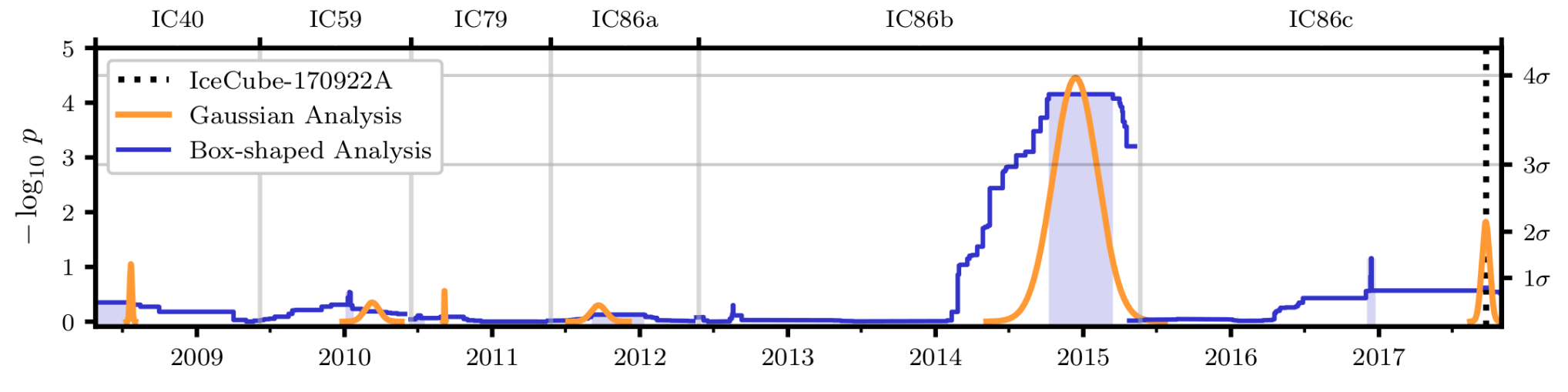
2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

Combined (pre-trial): 4.1σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.1\pm0.2}\ \mathrm{TeV\ cm^{-2}}$

Joint modeling of the two periods is challenging!

IceCube, *Science* 2018



After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

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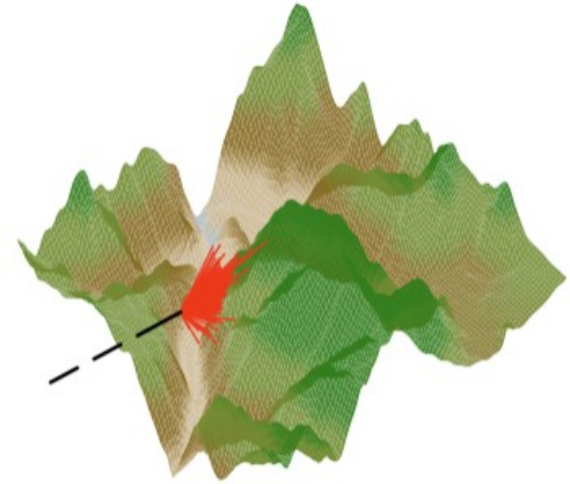
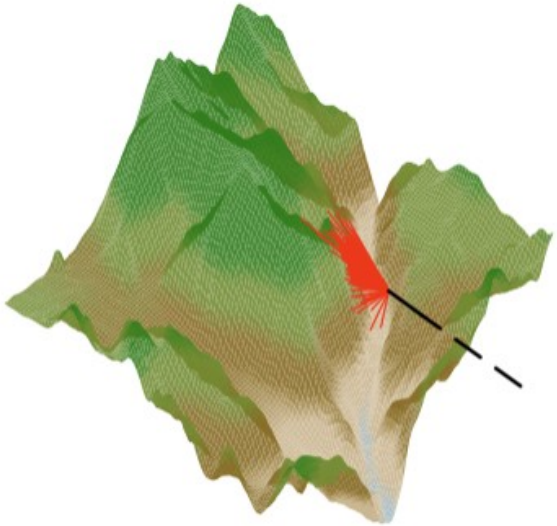
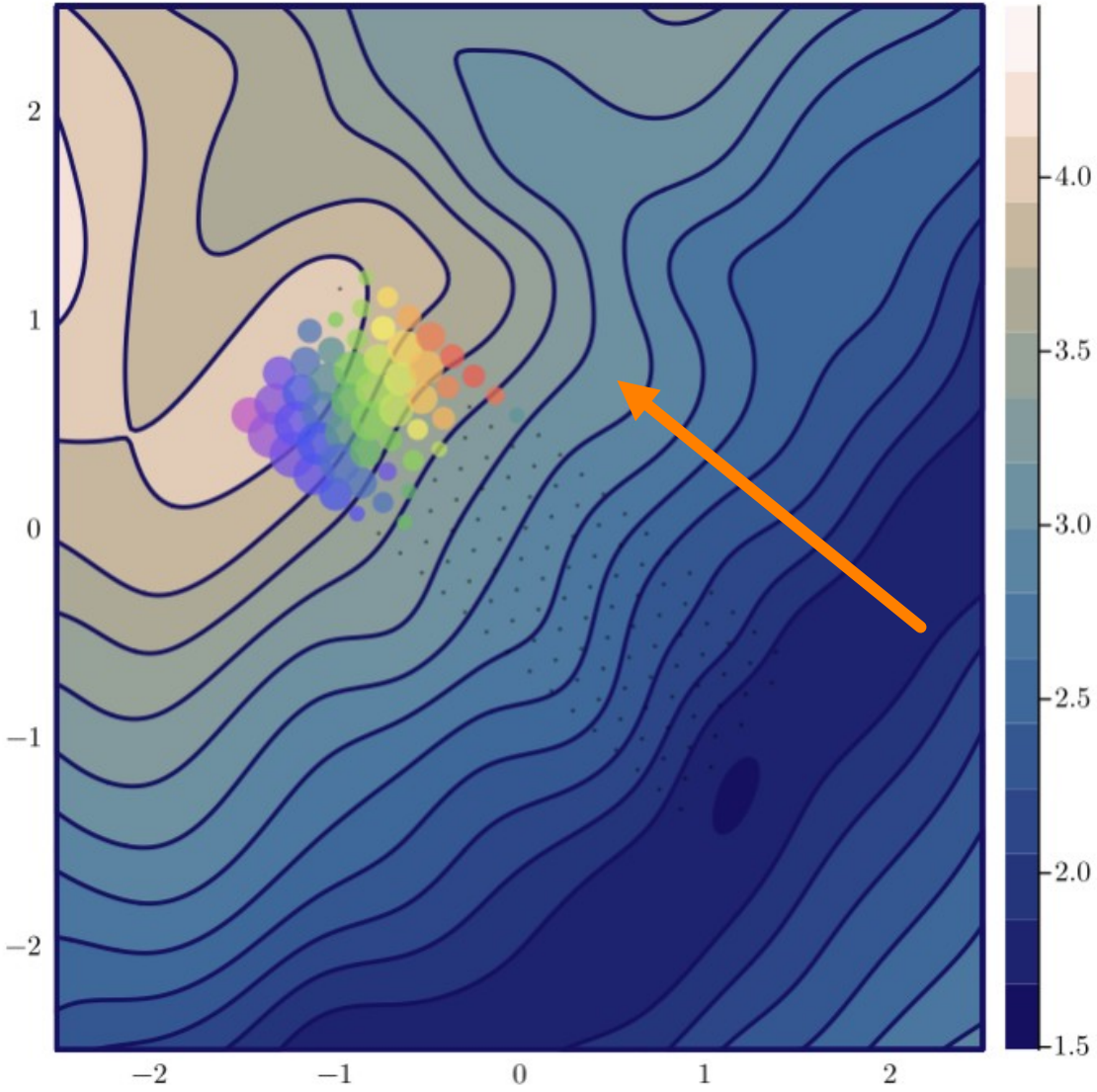
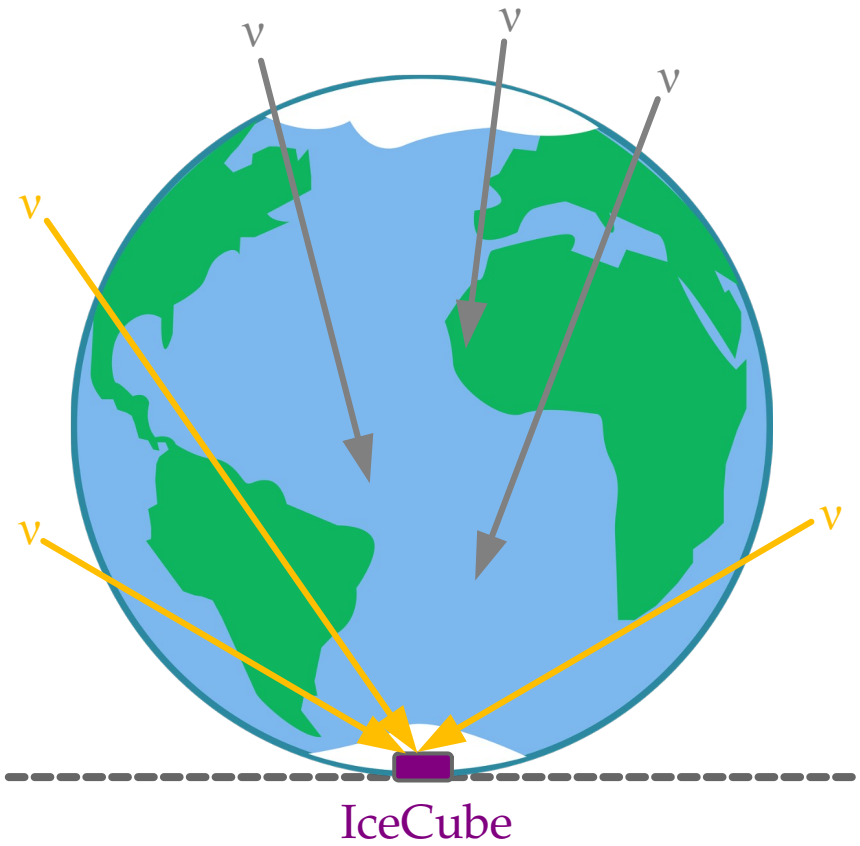
TAMBO Harvard team





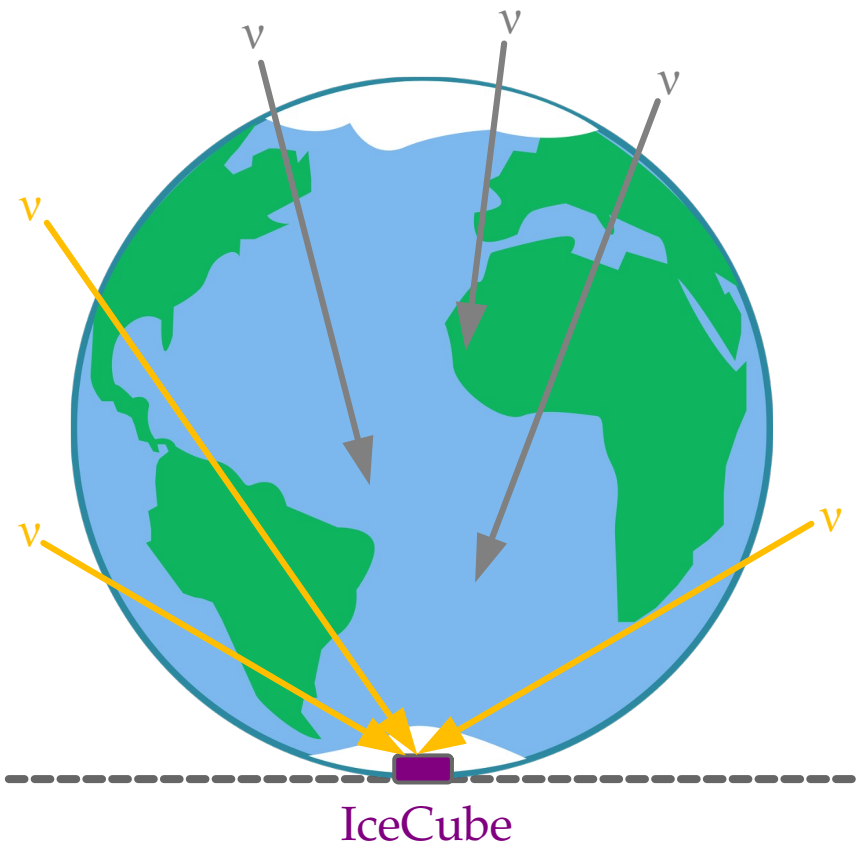


TeV–PeV:



Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



Earth is *almost fully* opaque,
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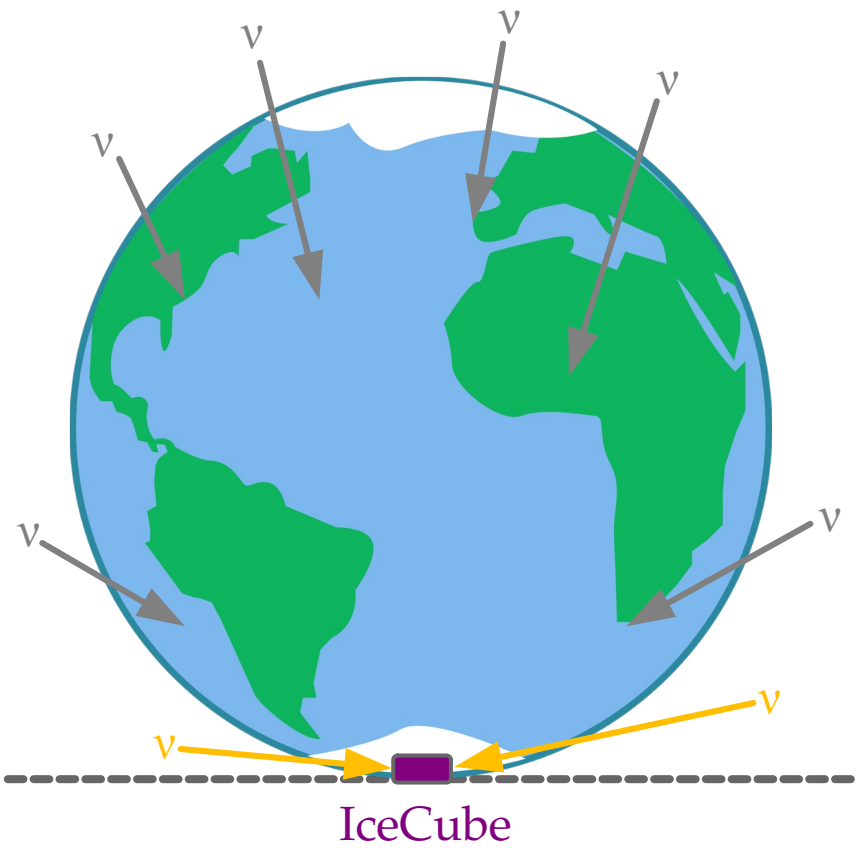
> 100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through

Note: Not an exhaustive list

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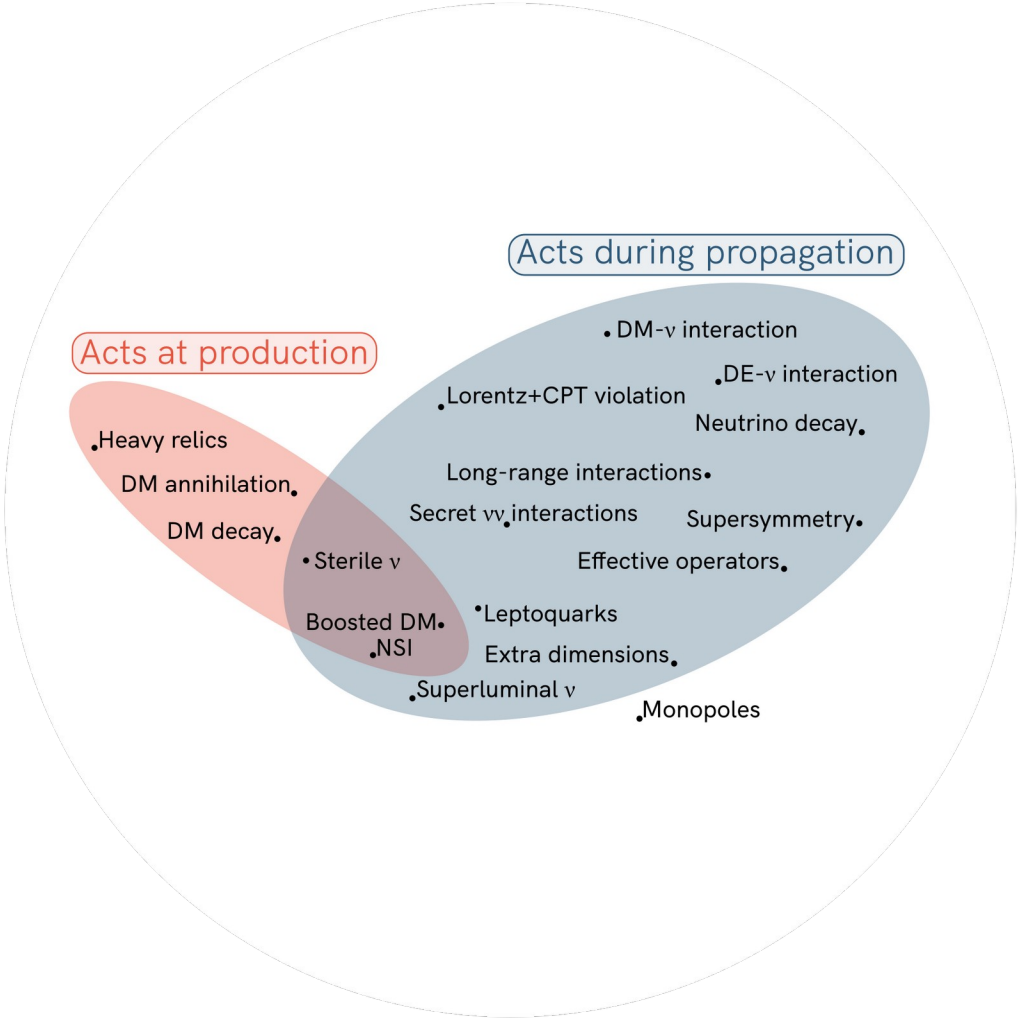

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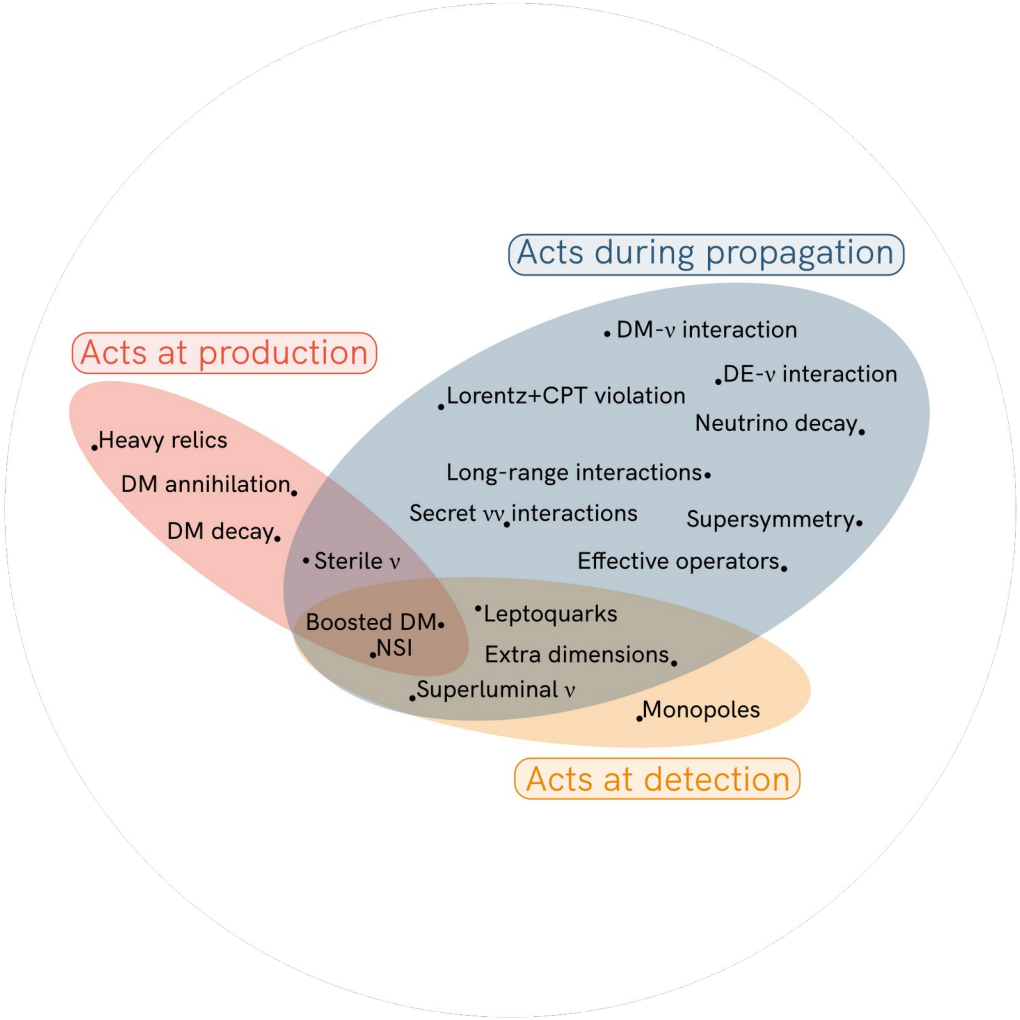
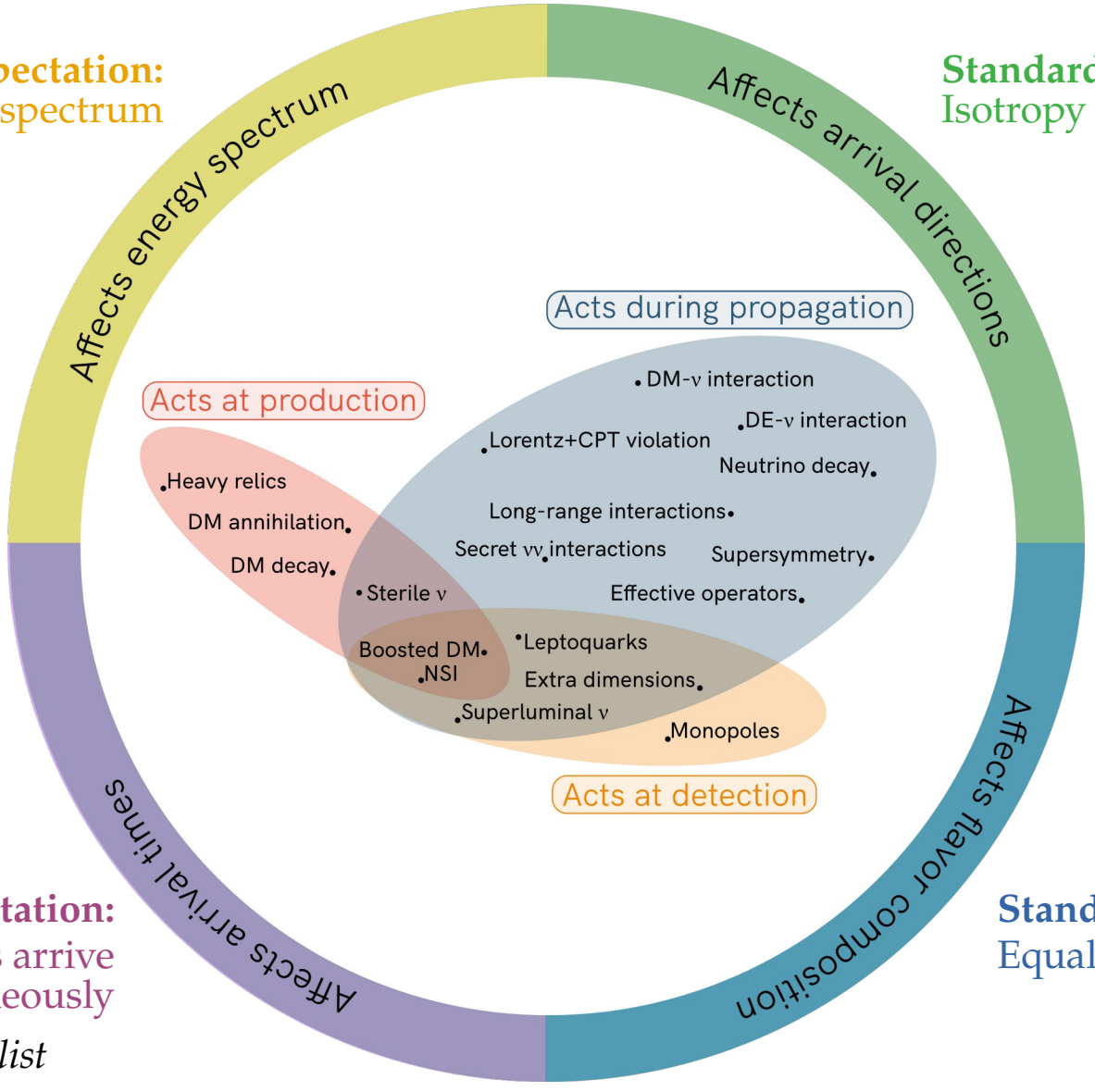


Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

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Equal number of ν_e, ν_μ, ν_τ

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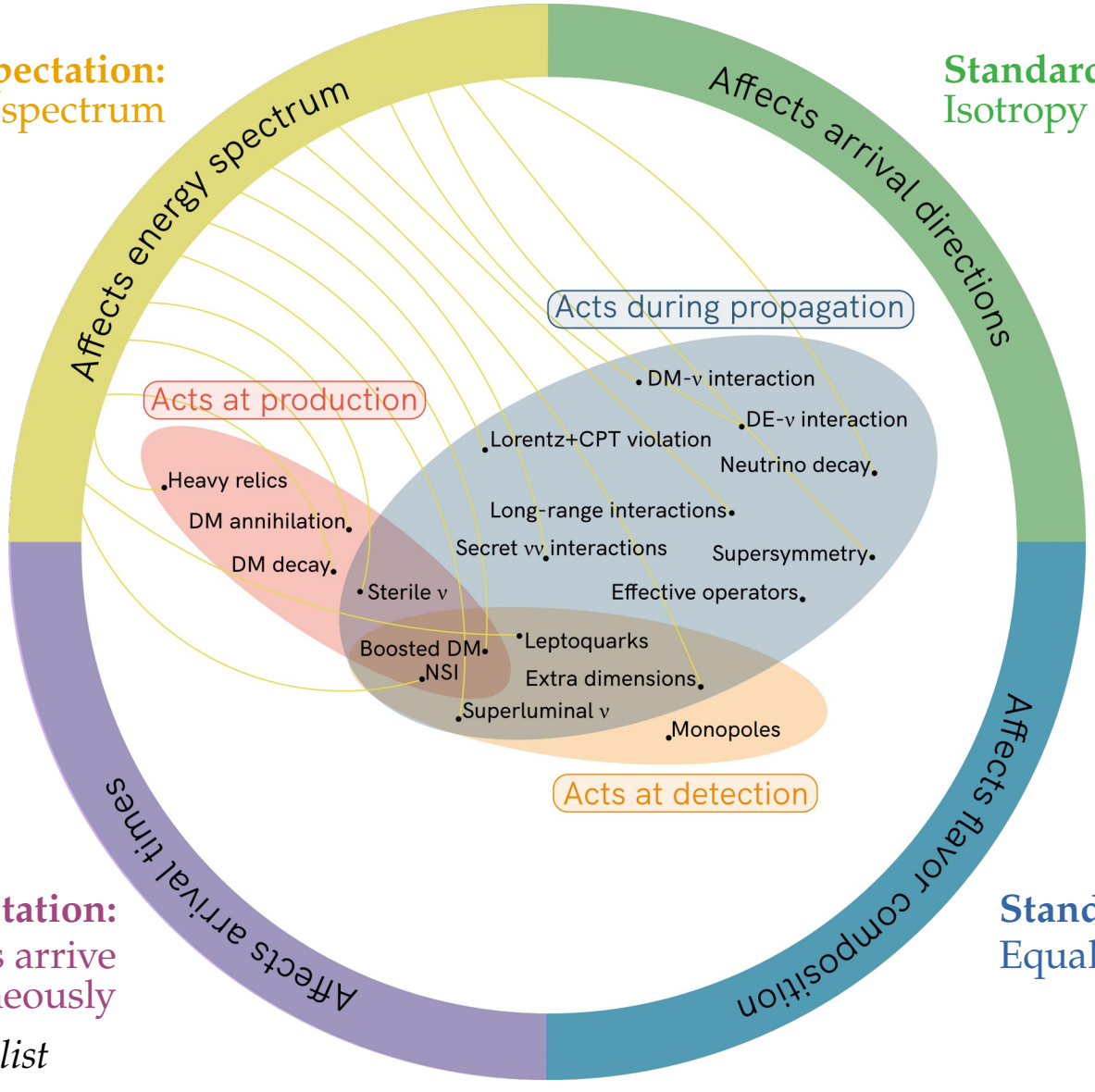

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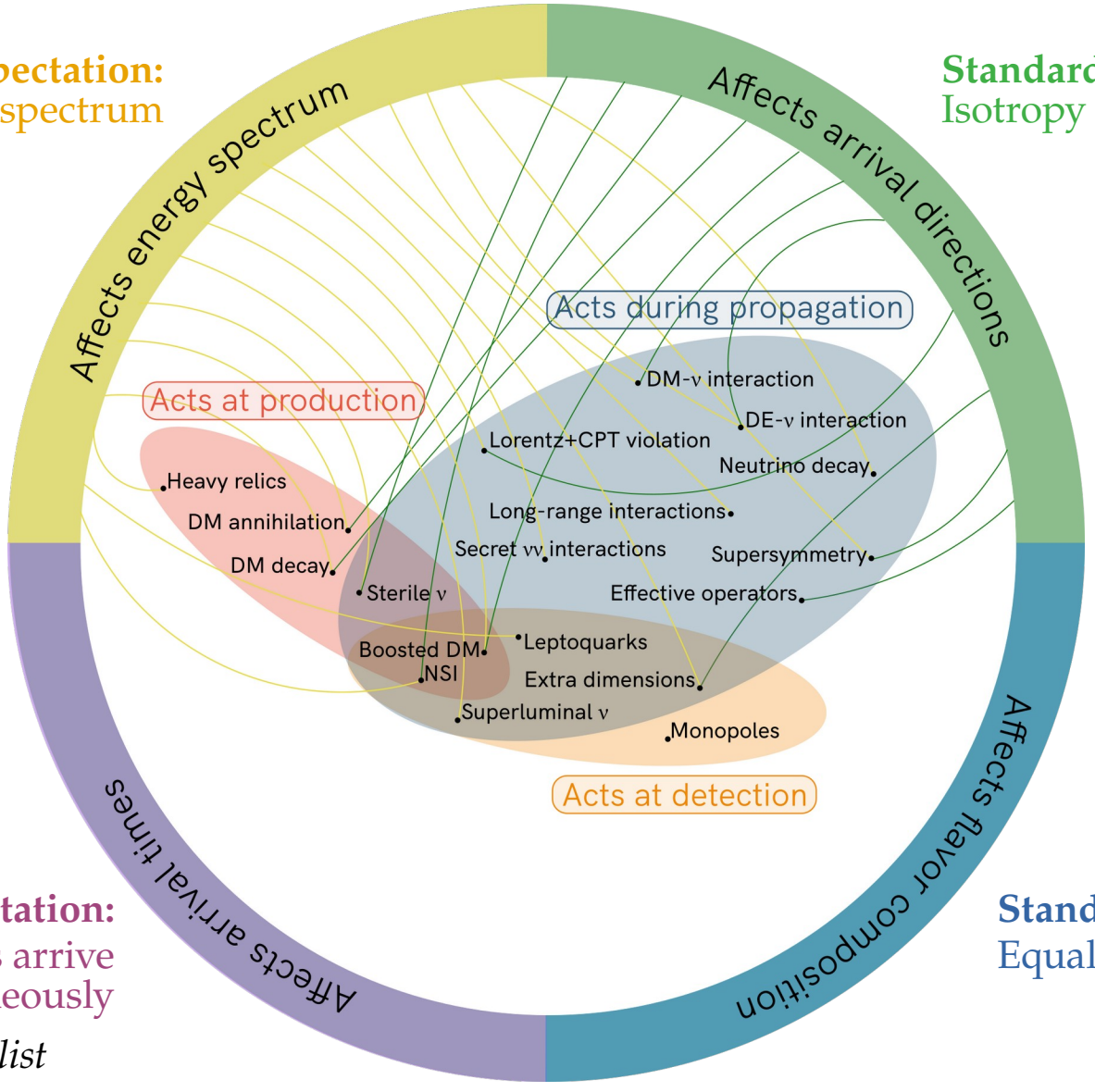

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

Standard expectation:
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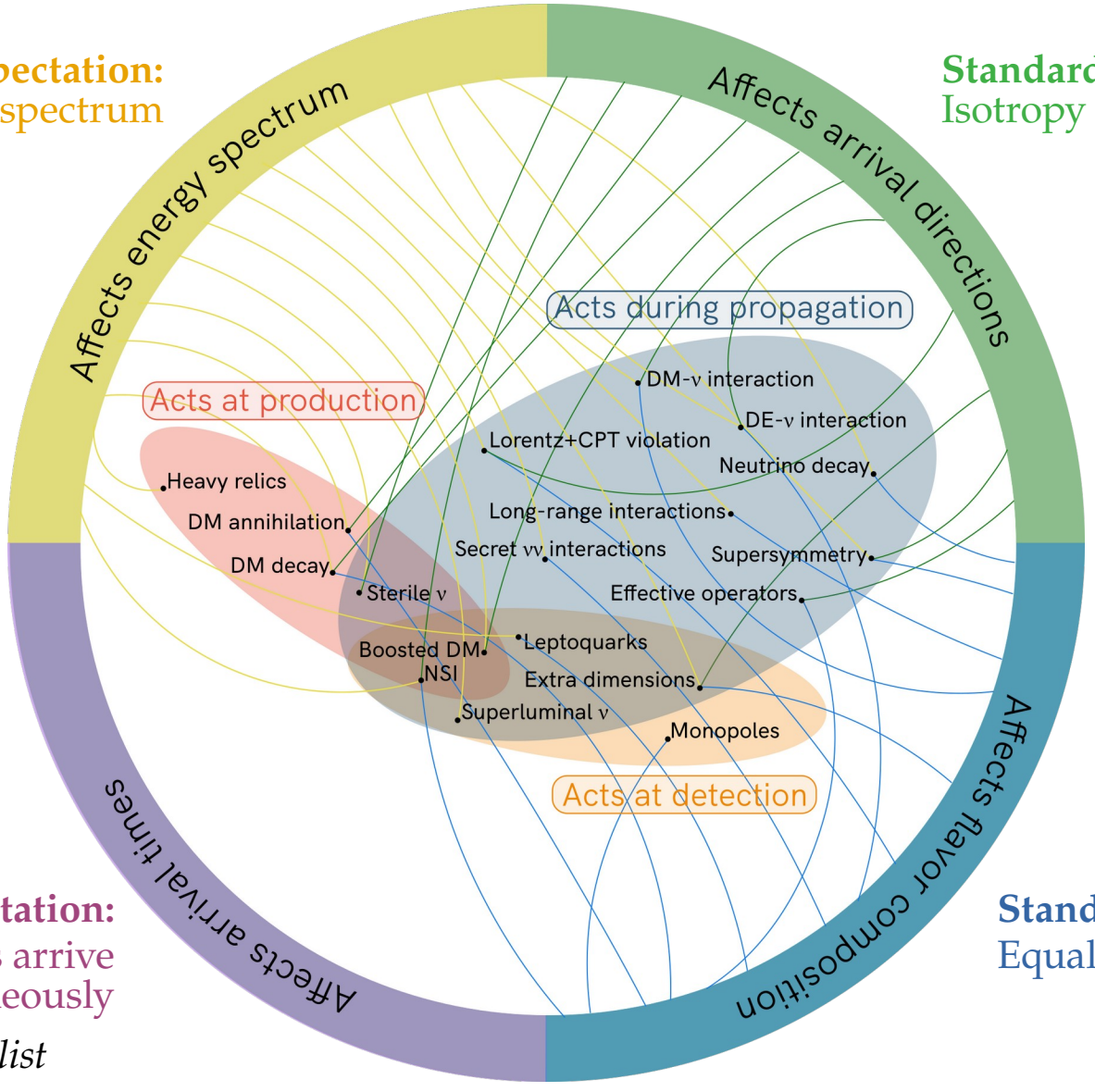

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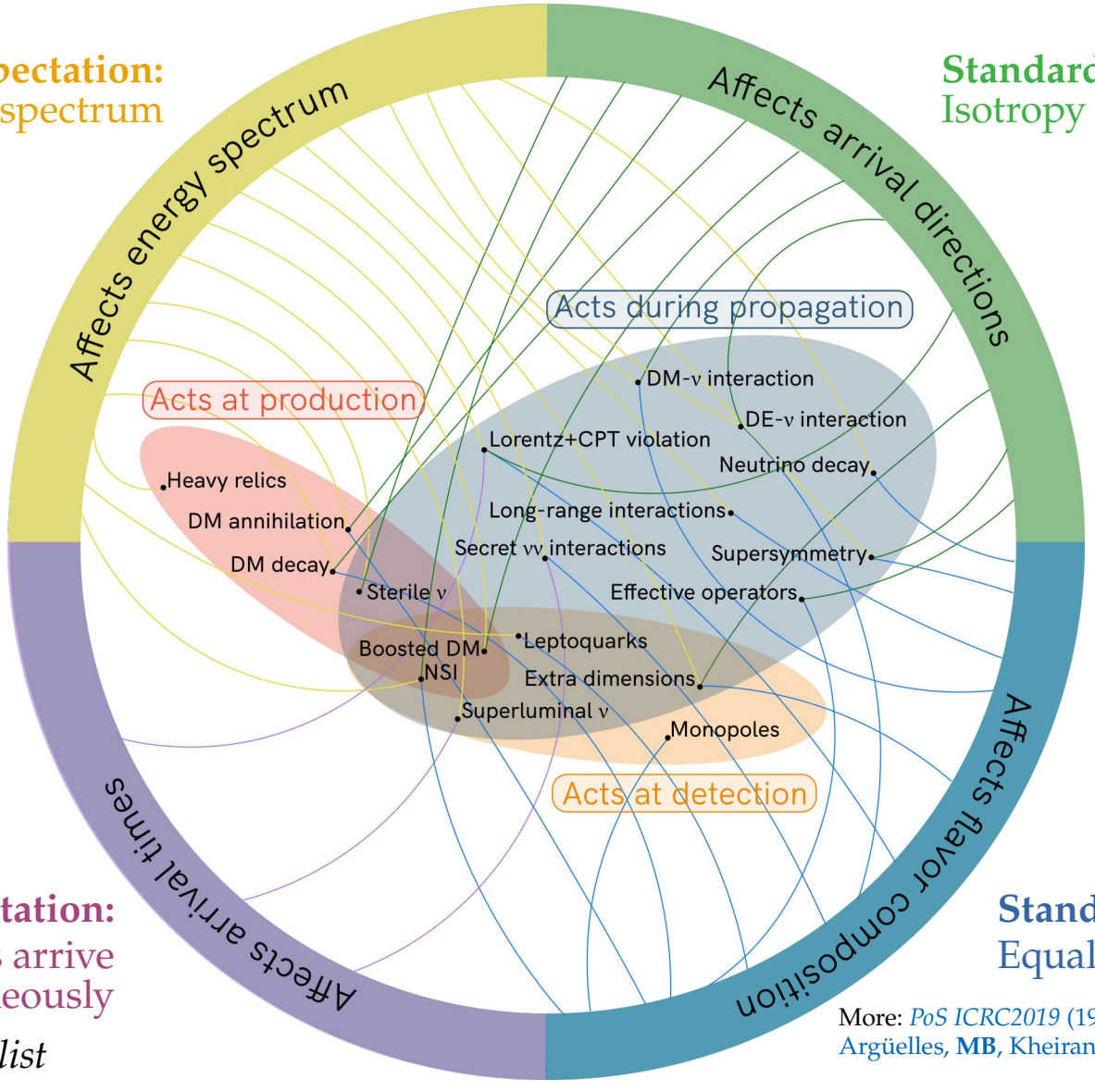

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Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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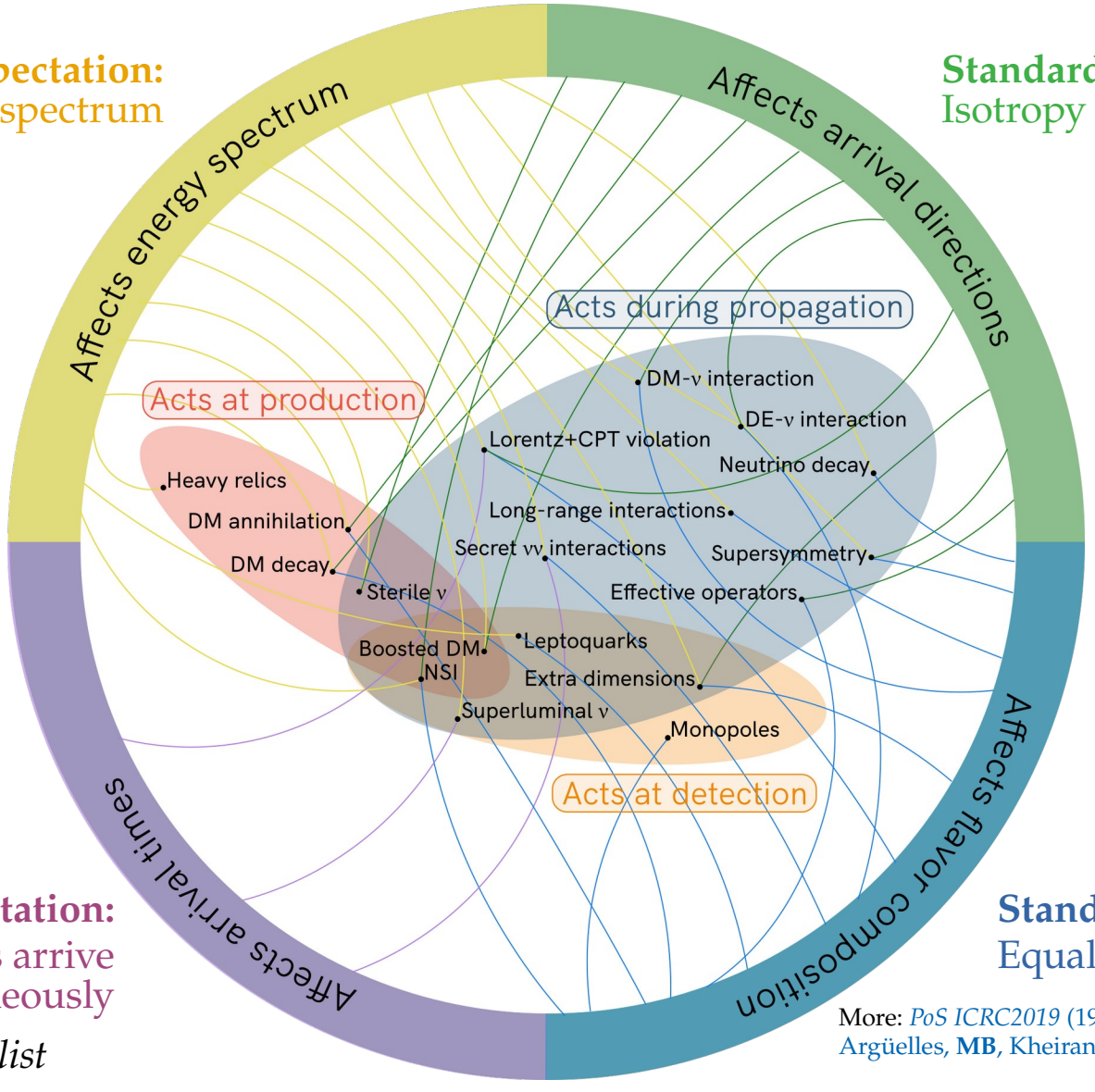

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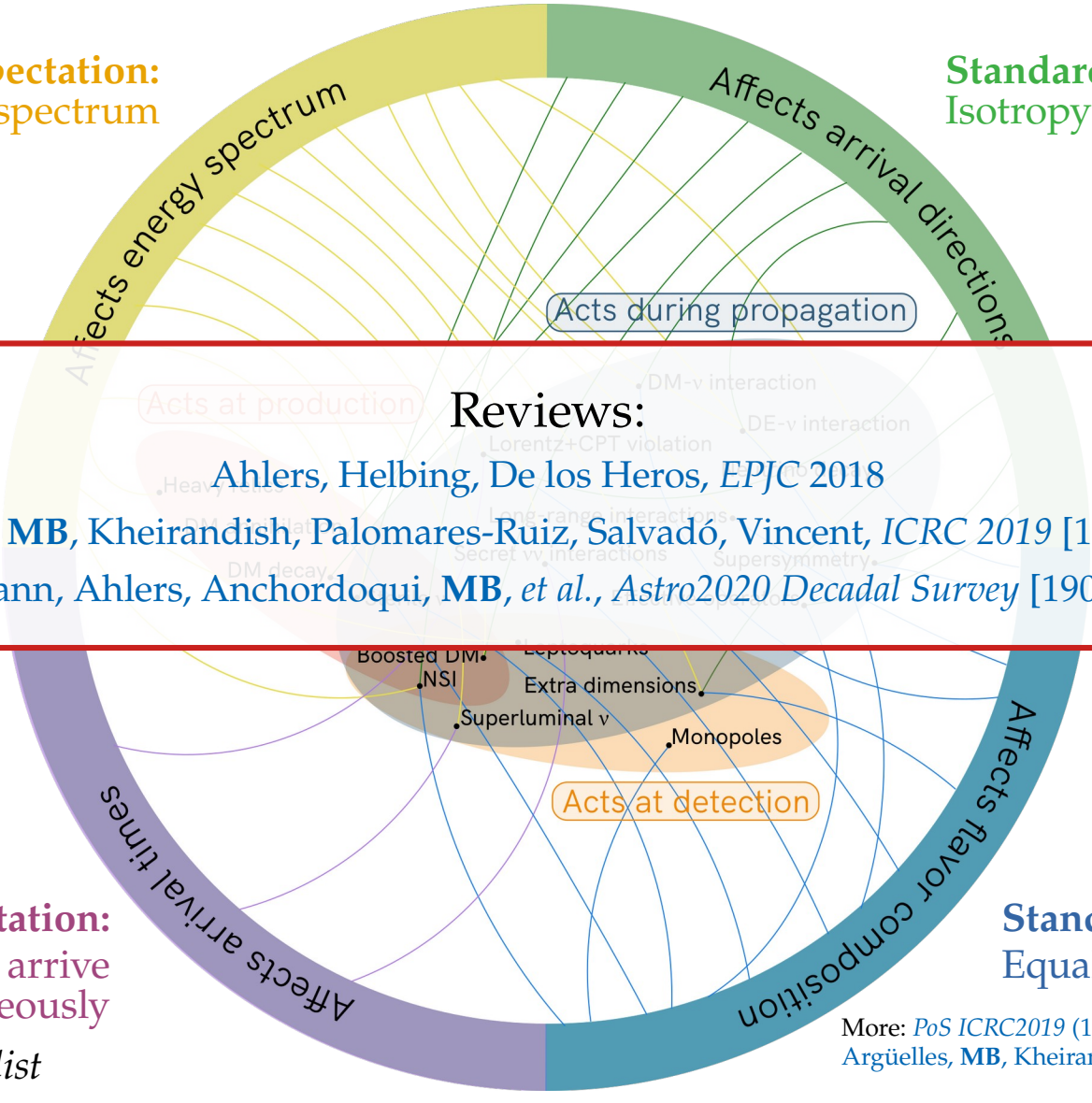

Reviews:

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]

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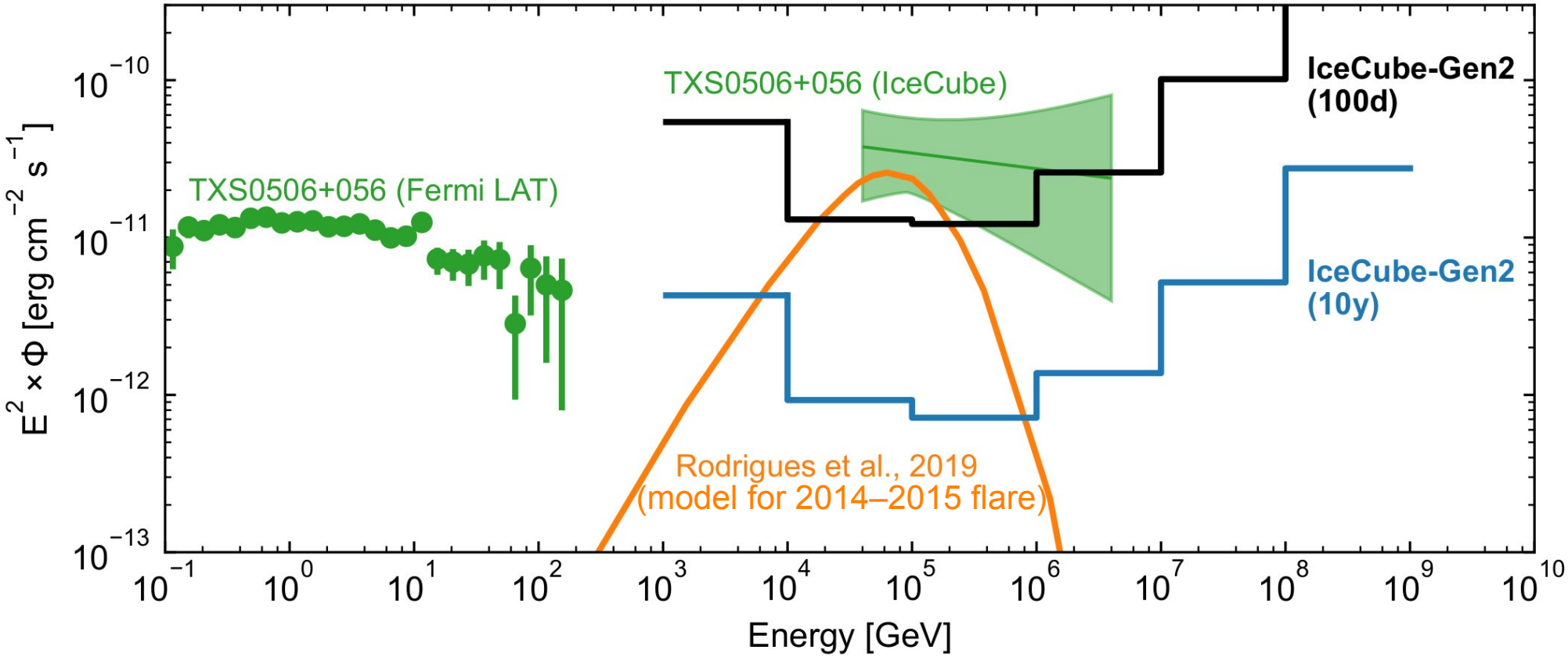
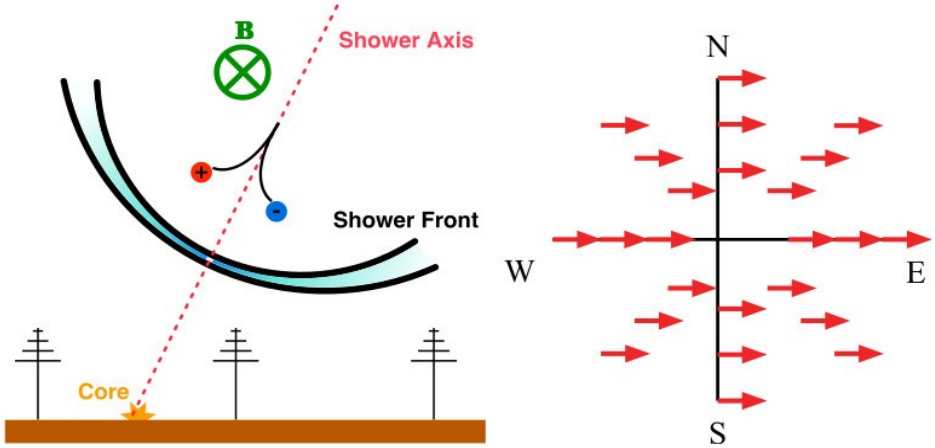
High-statistics neutrino blazar flares

Observing the 2014–2015 TXS 0506+056 at 5σ:



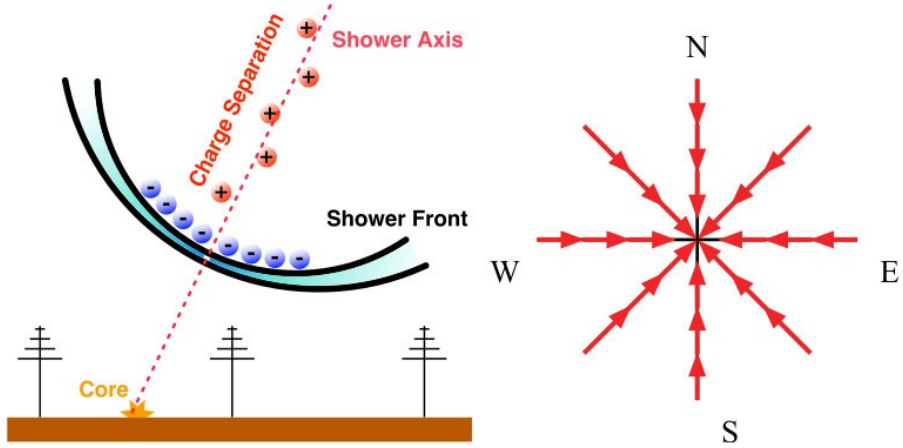
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan

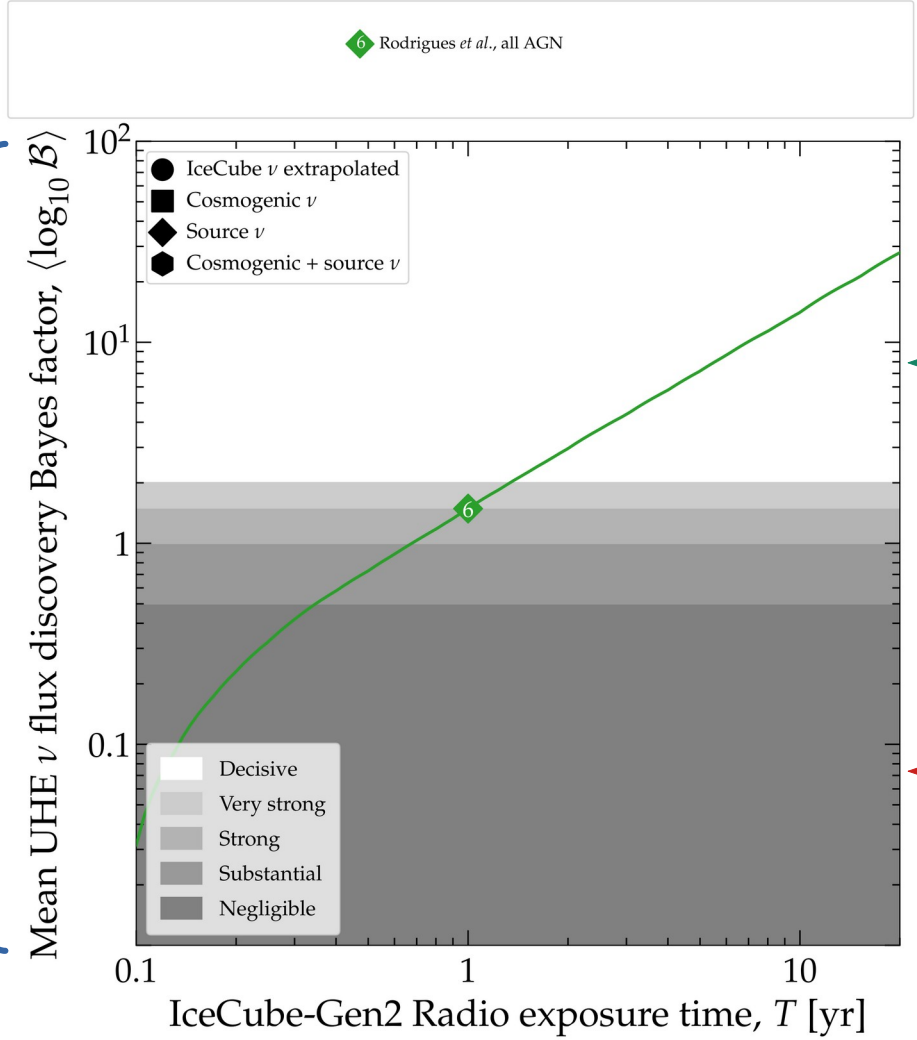


- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

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

Radio emission: geomagnetic and Askaryan

Discovering the diffuse flux of UHE neutrinos



Bayes factor compares signal+bkg. *vs.* bkg.-only

High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

Valera, **MB**, Glaser, *PRD* 2023 (to appear) [2210.03756]

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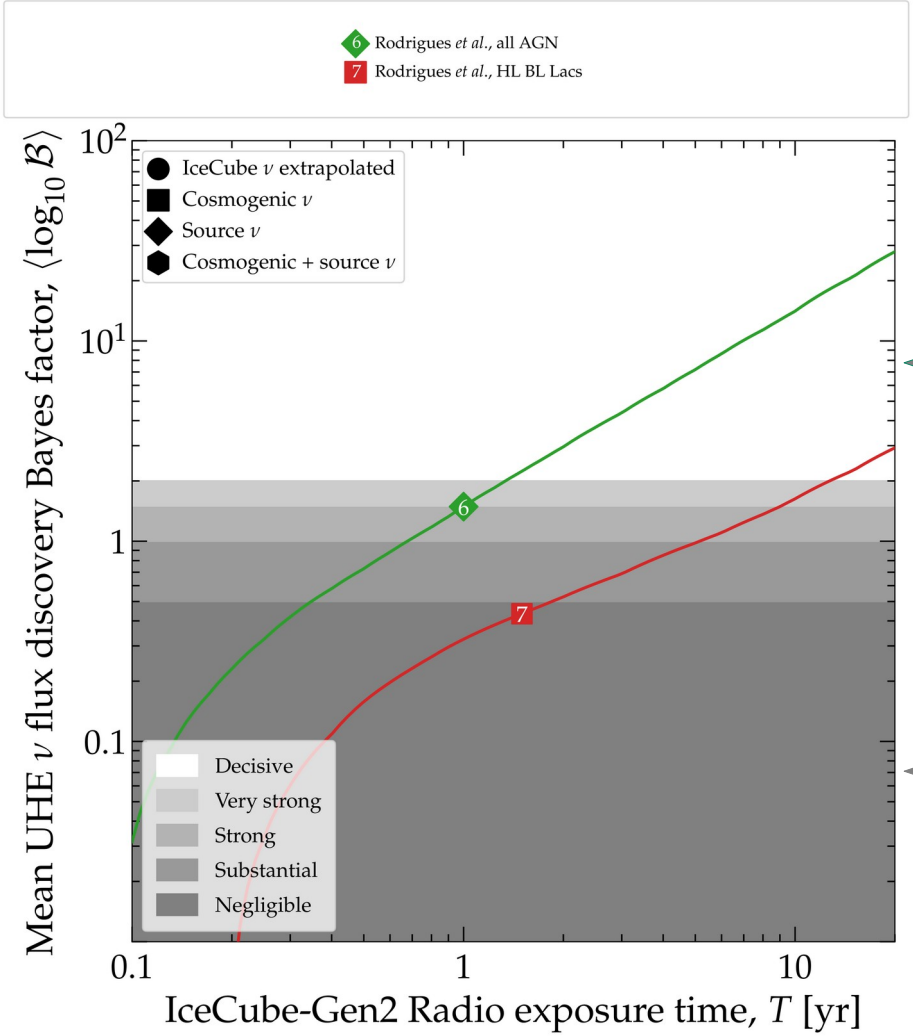

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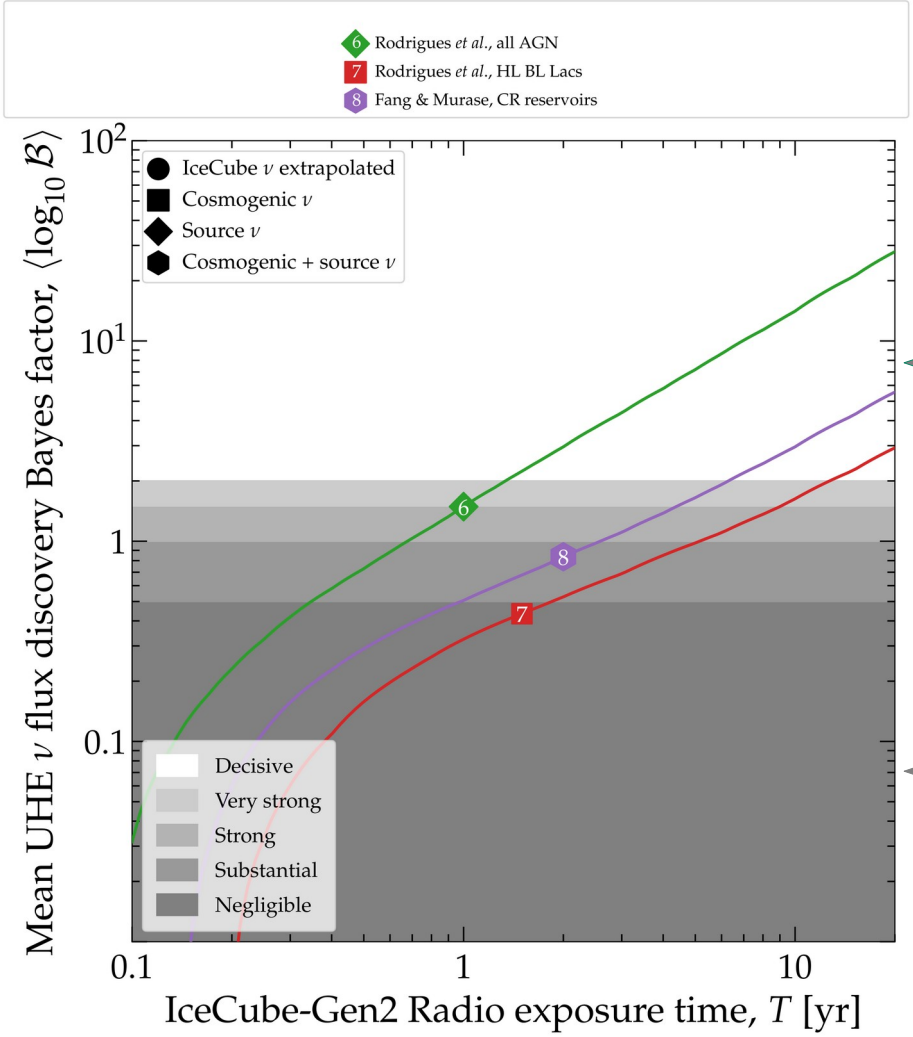

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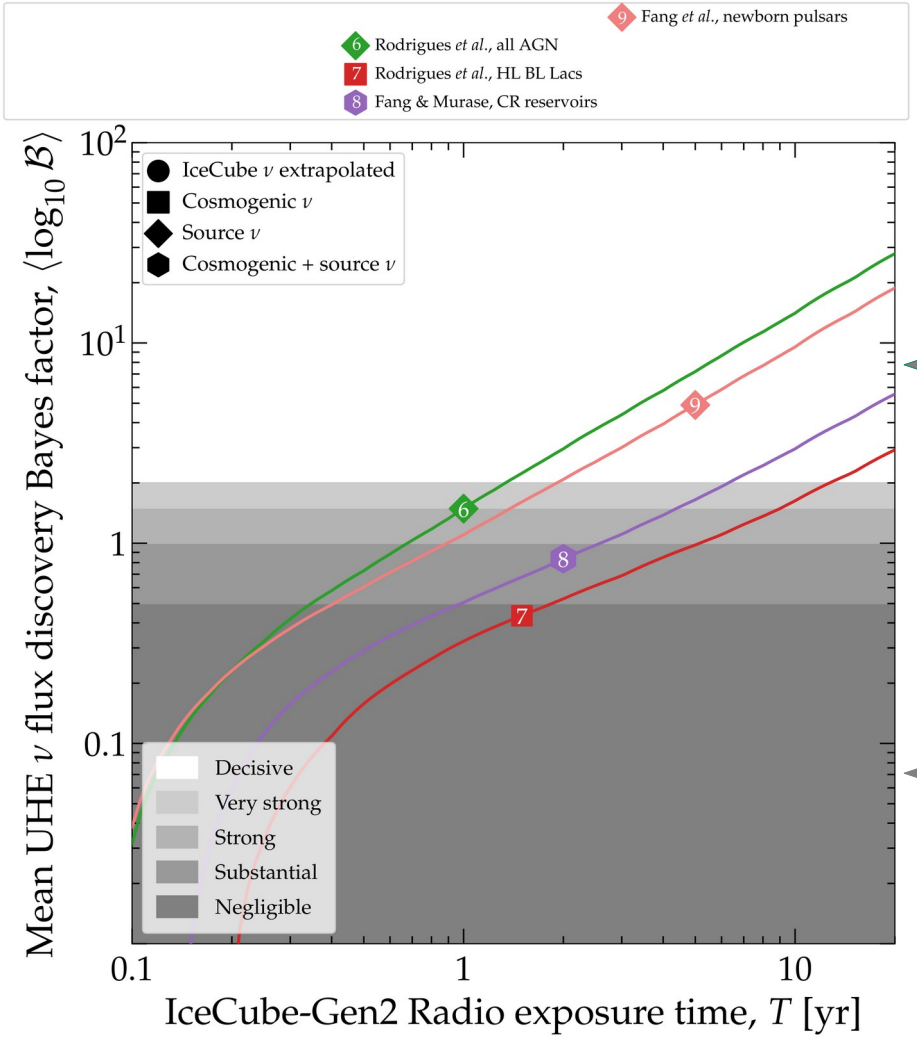

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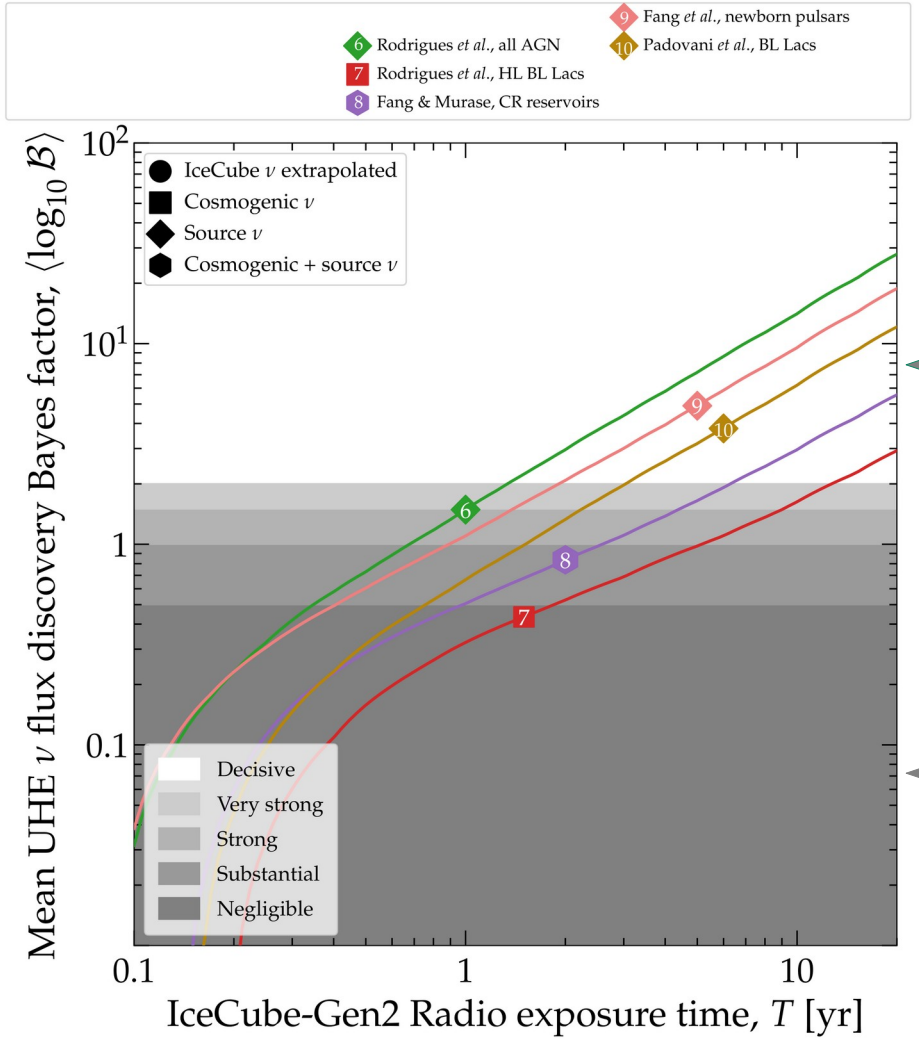

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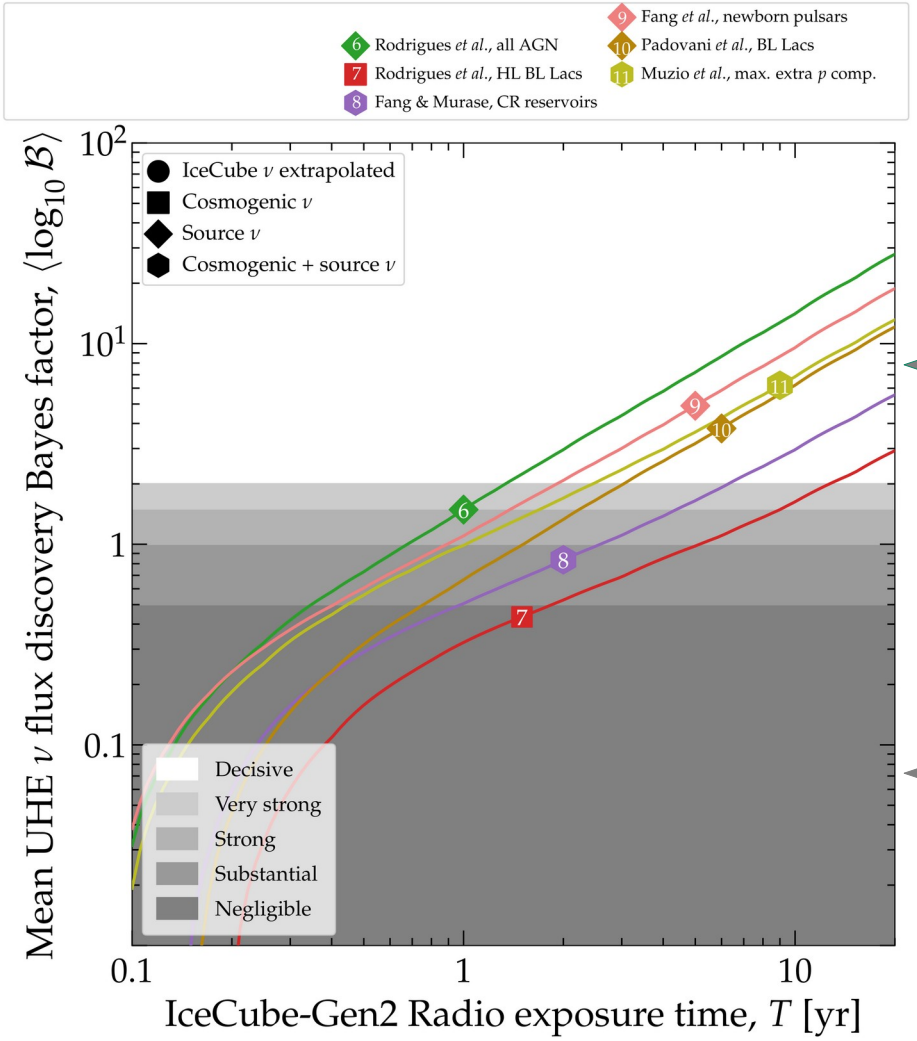

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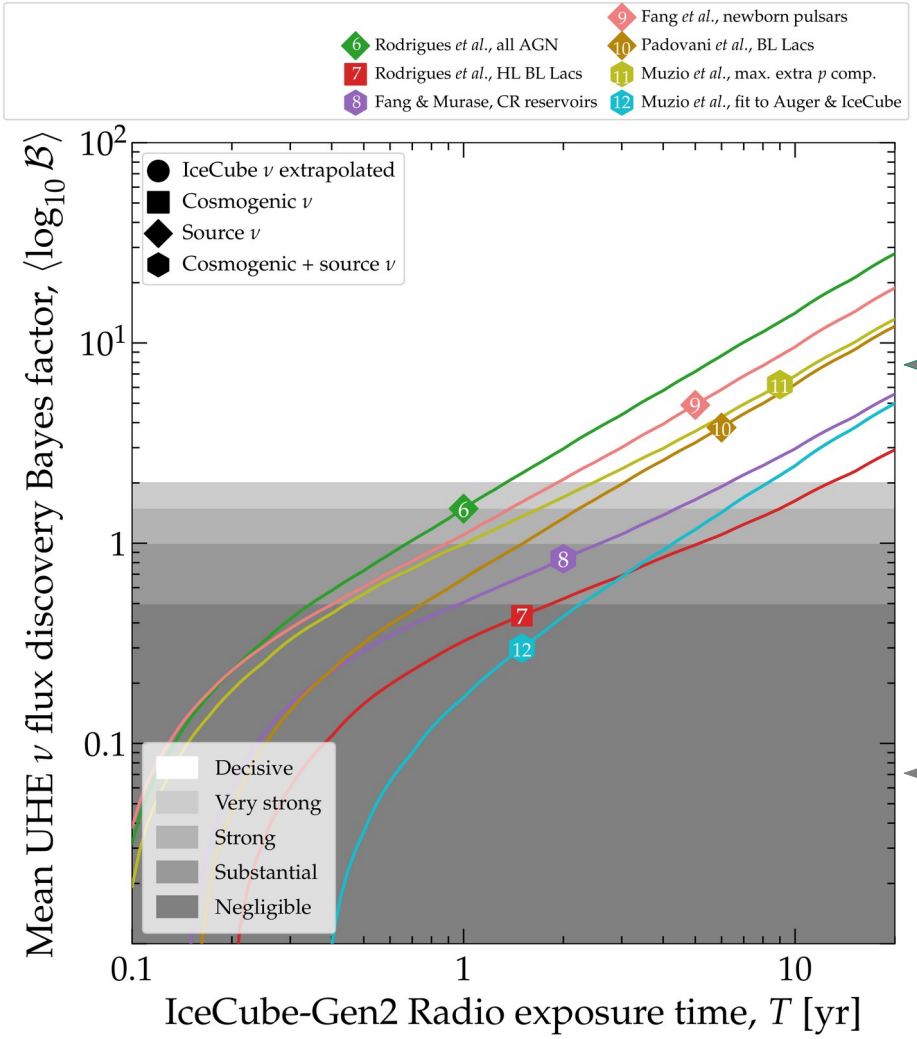

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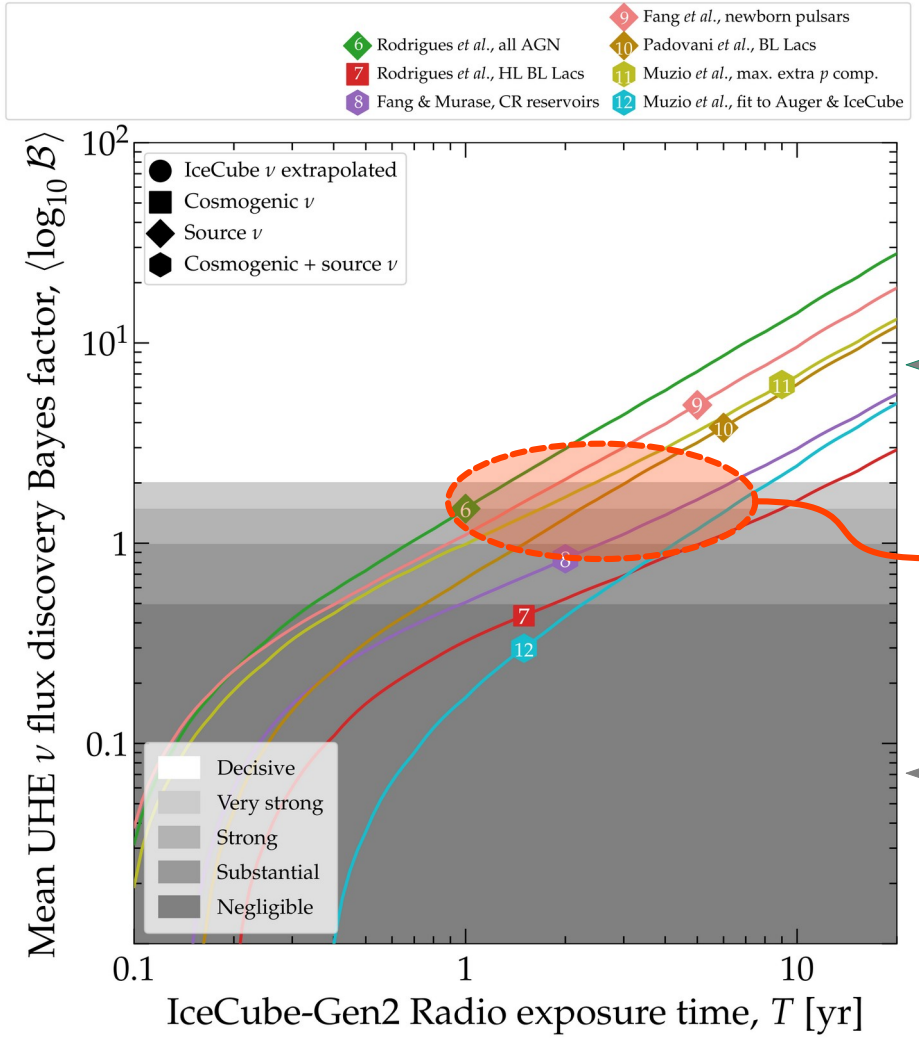

High Bayes factor
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Most flux models are discoverable within a few years

Low Bayes factor
→ No flux discovered

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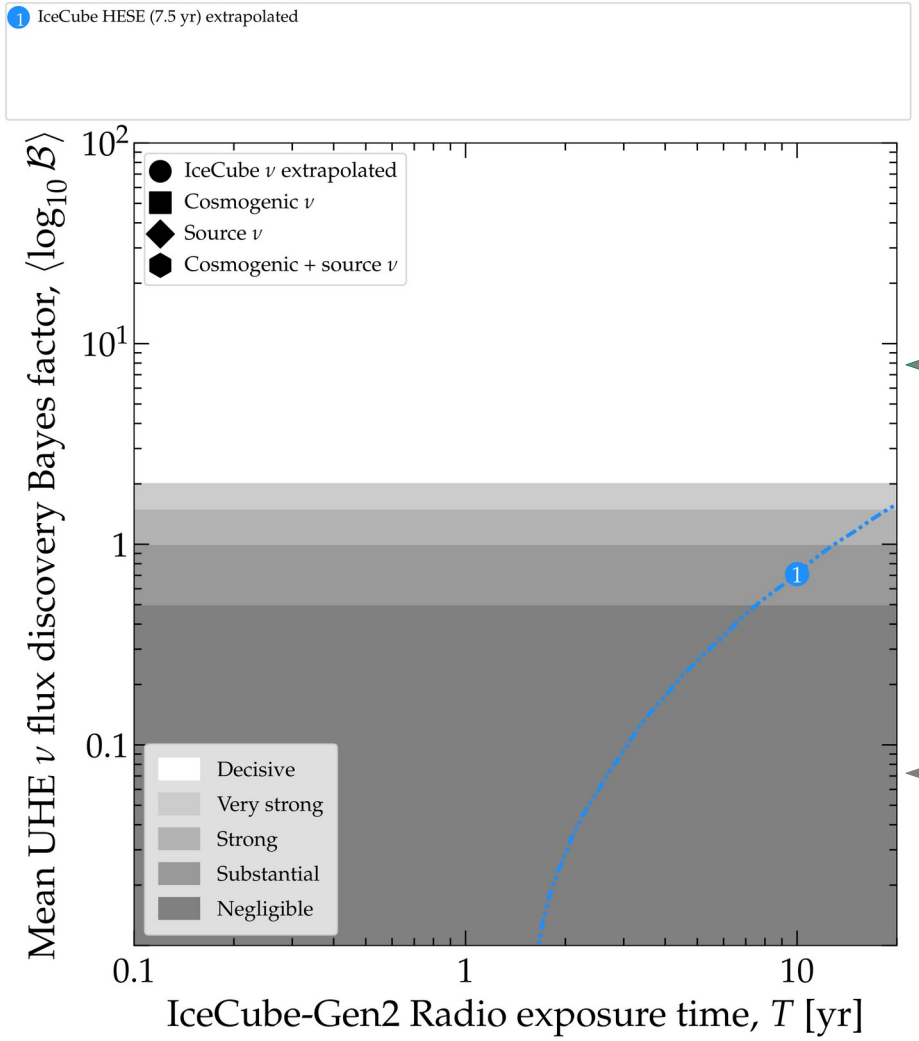

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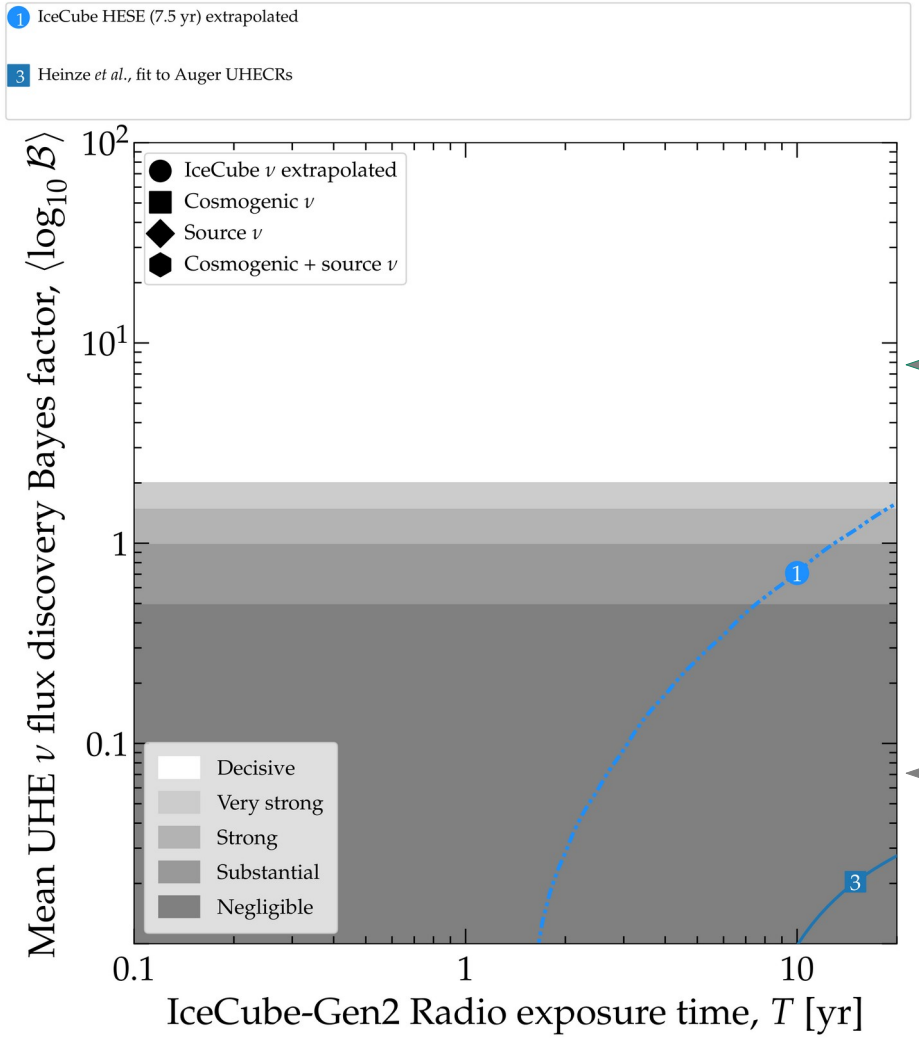

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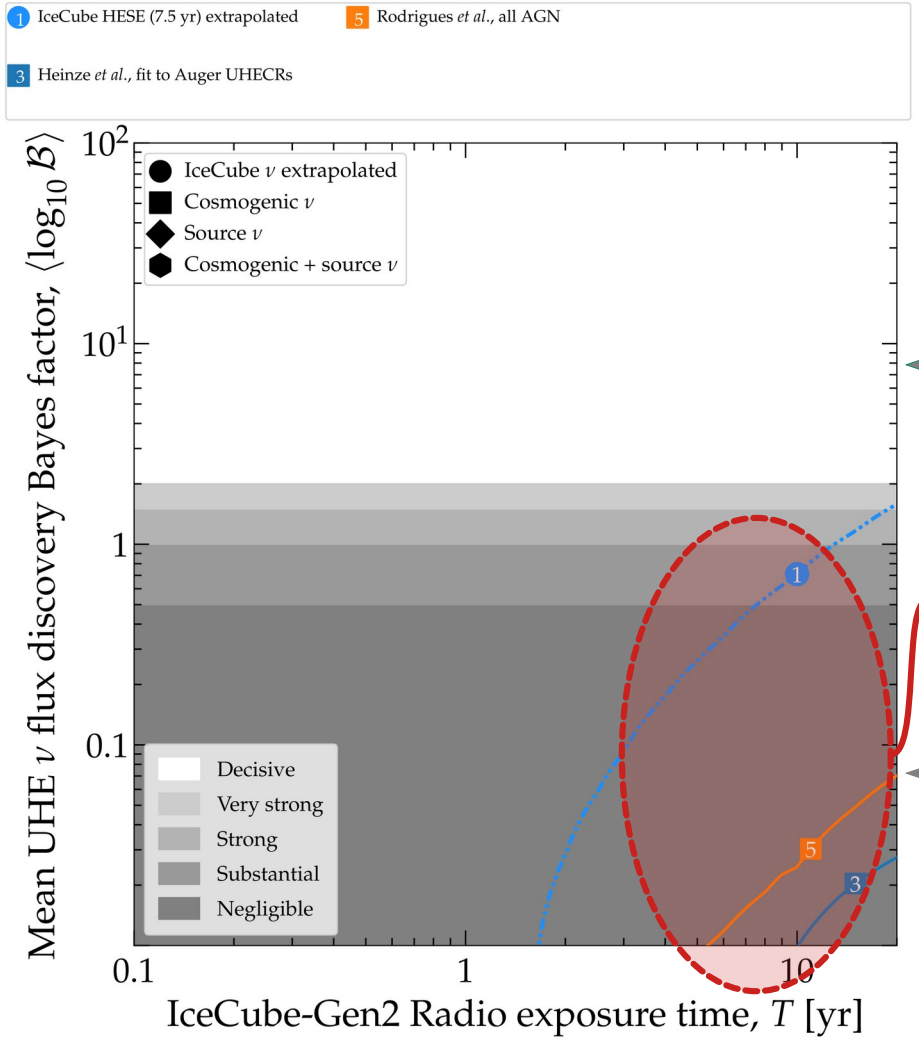

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Some models will *not* be discovered

Low Bayes factor
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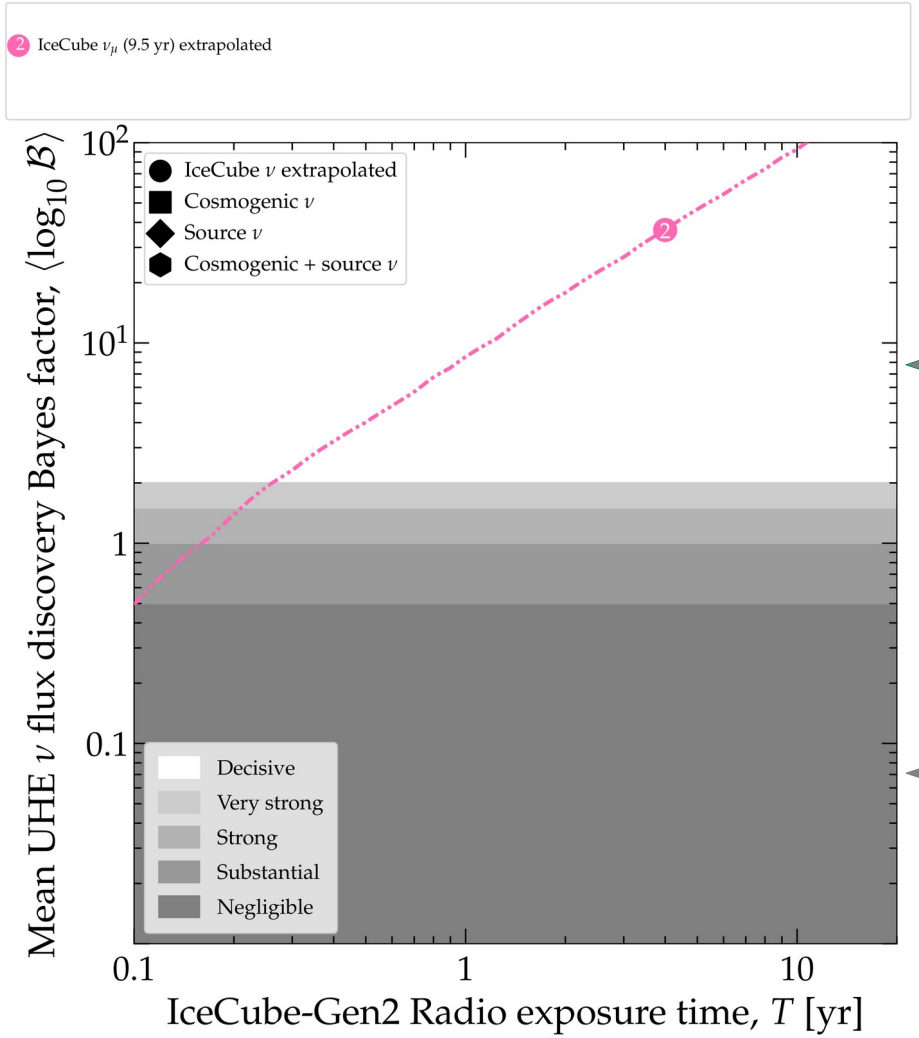

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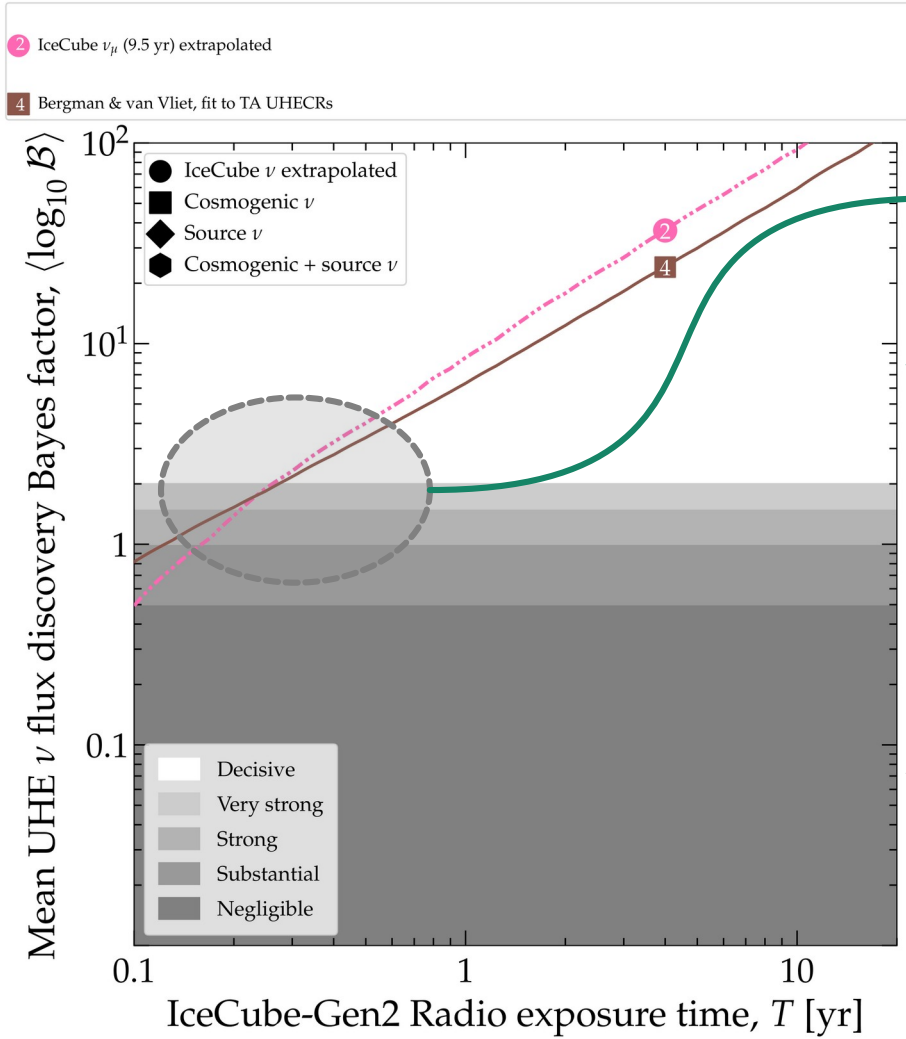

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Some models will be discovered right away

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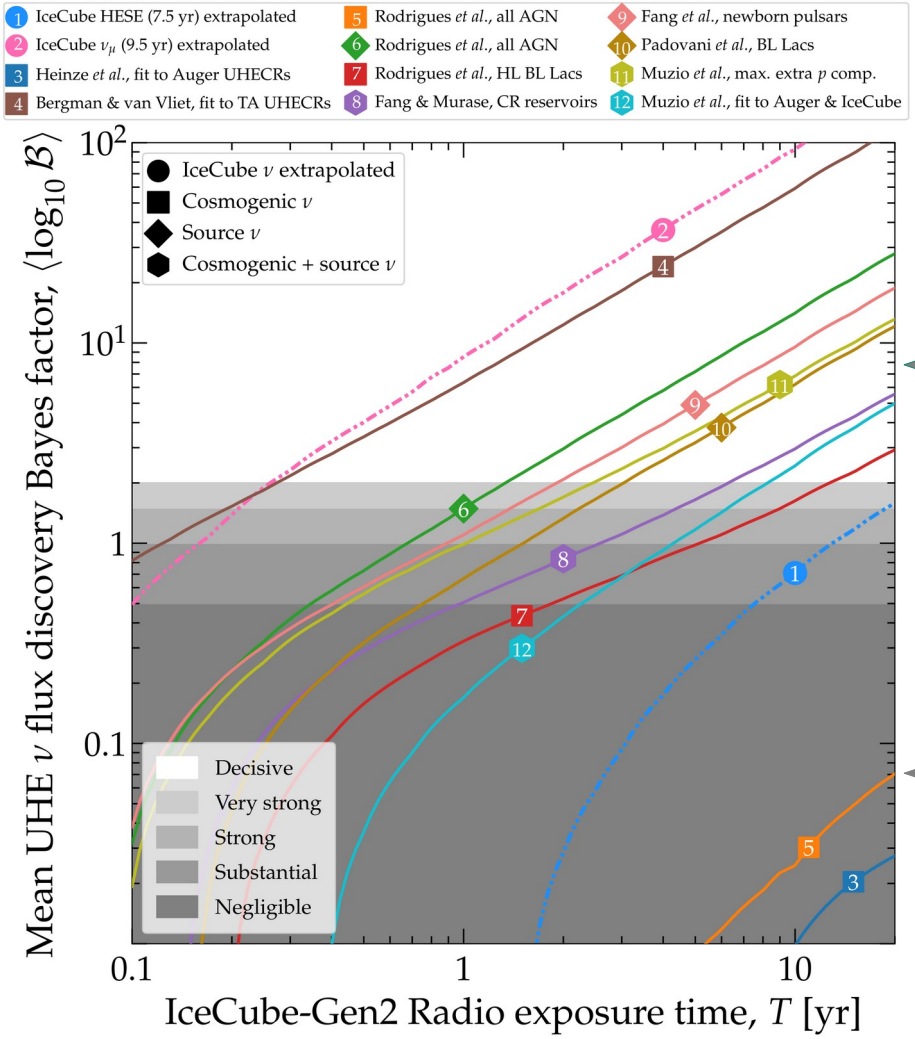

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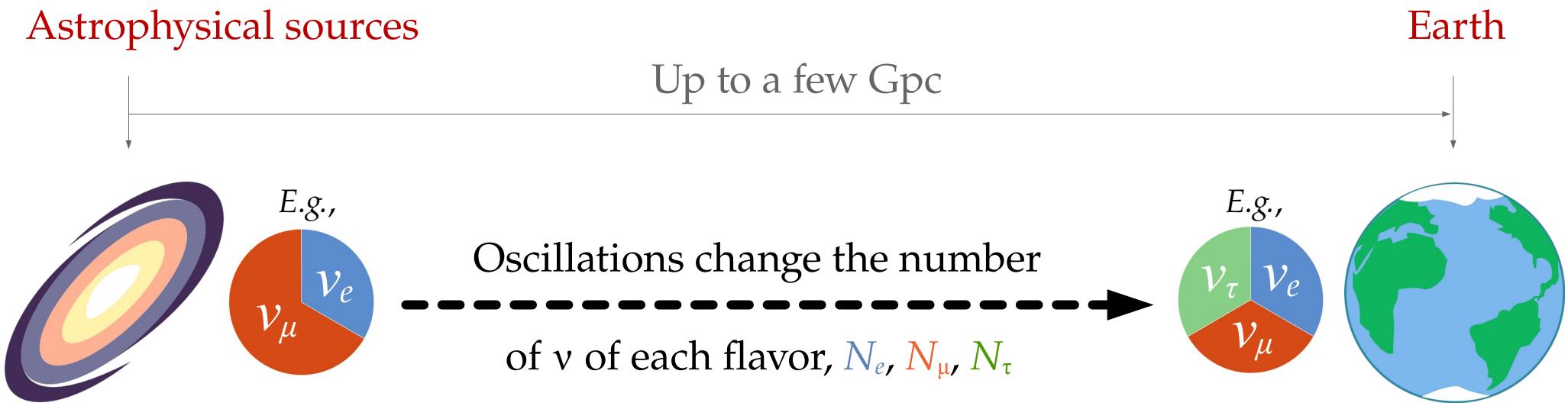


Different production mechanisms yield different flavor ratios:

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

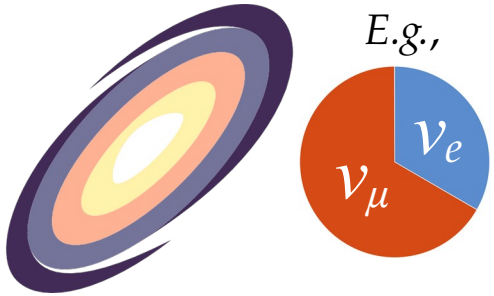
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

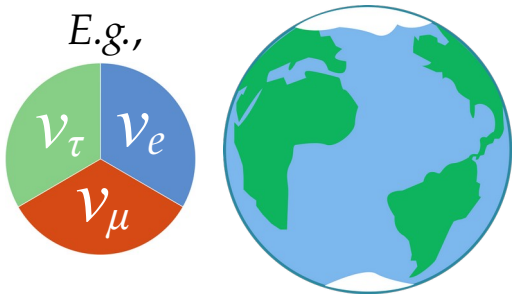
Earth

Up to a few Gpc



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ



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Standard oscillations
or
new physics

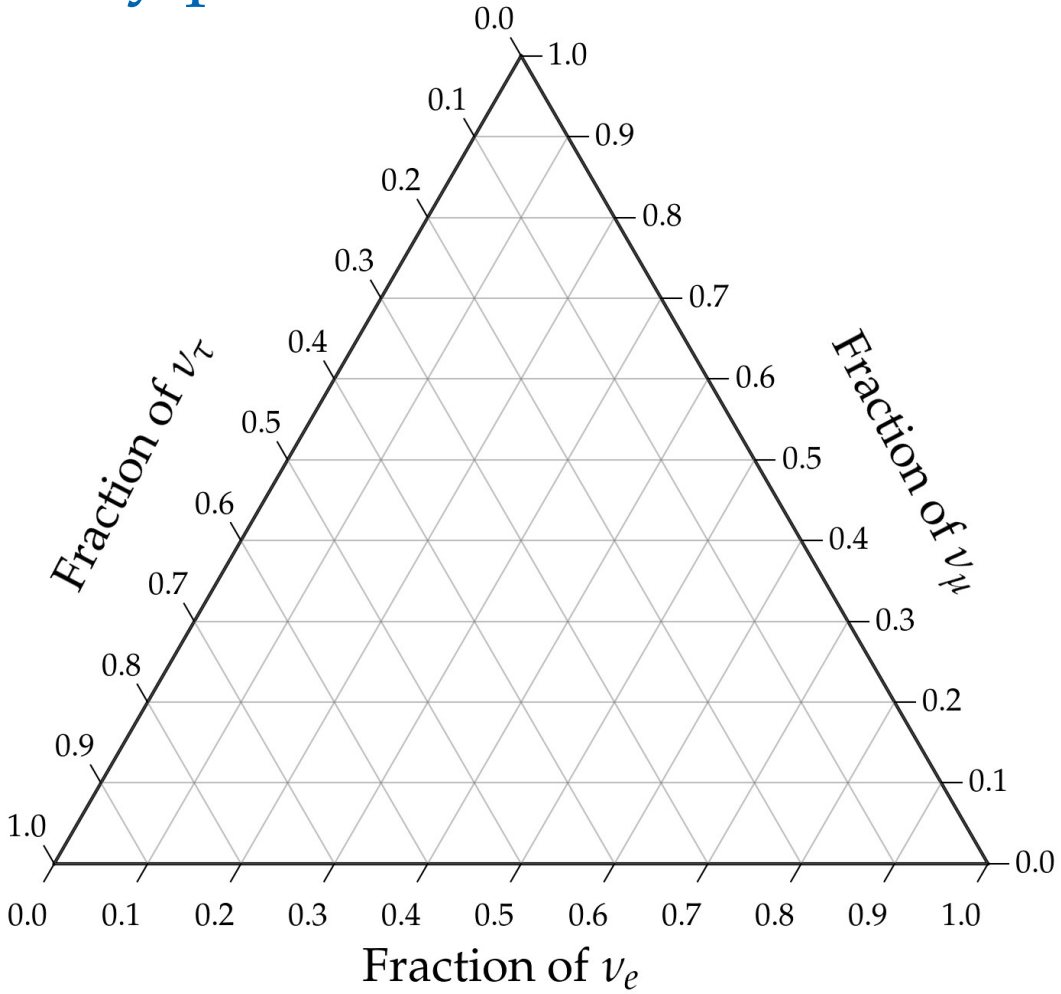
Quick aside: how to read a ternary plot

Assumes underlying unitarity –
sum of projections on each axis is 1

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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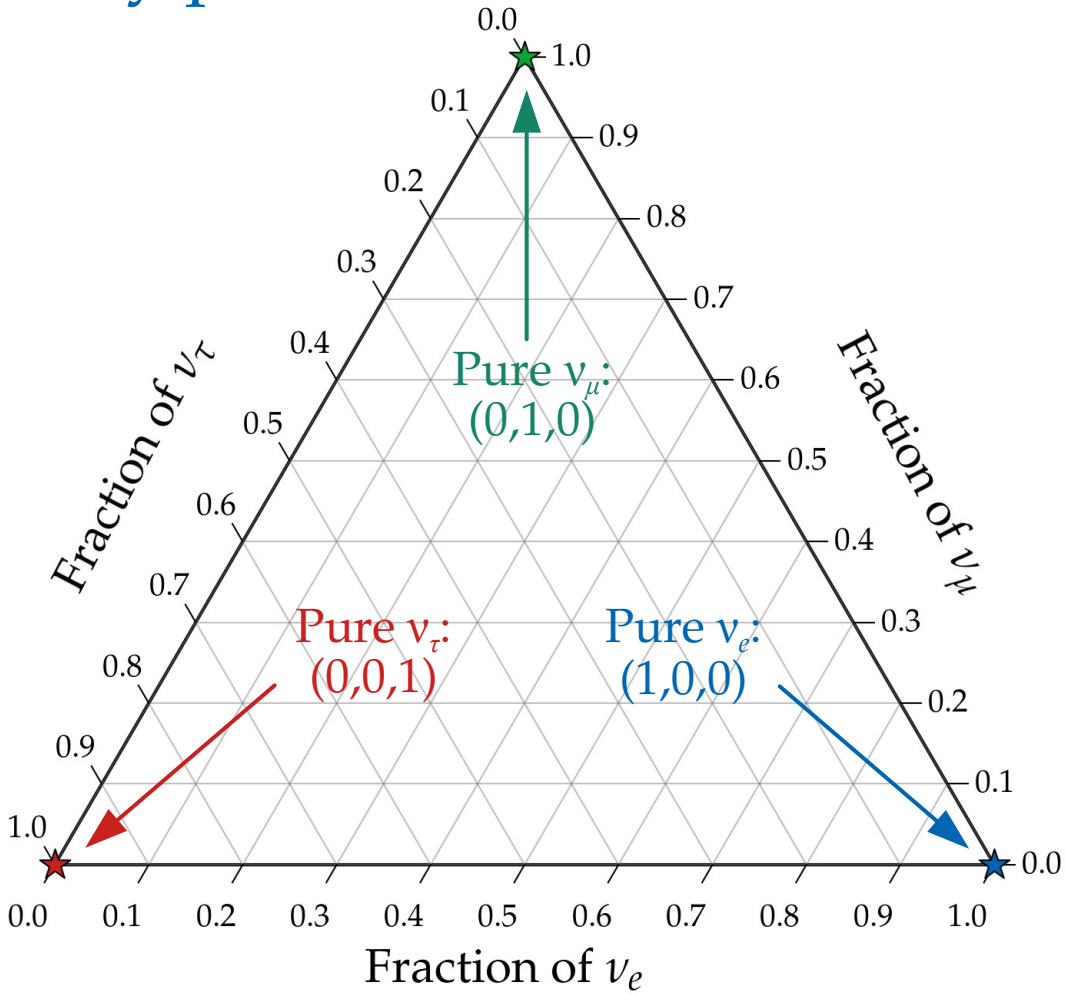

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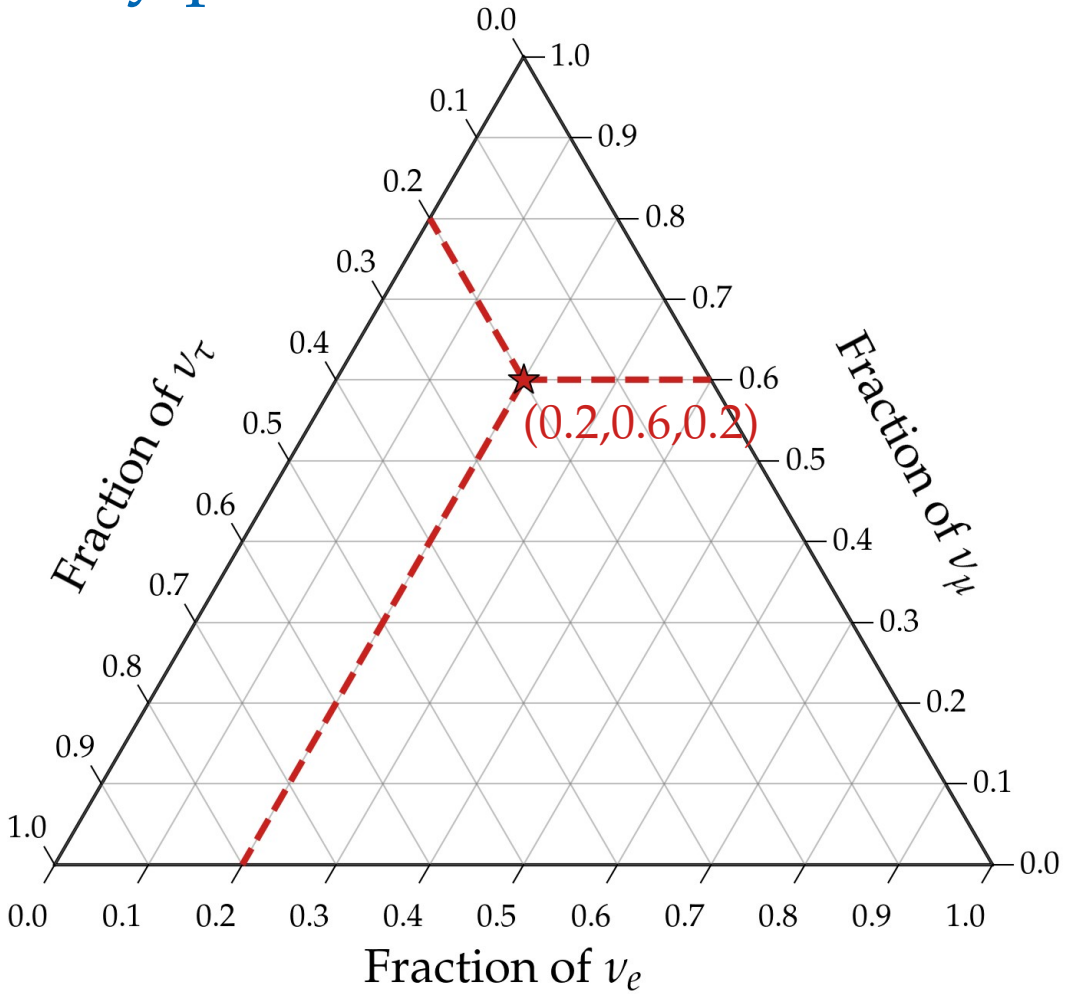

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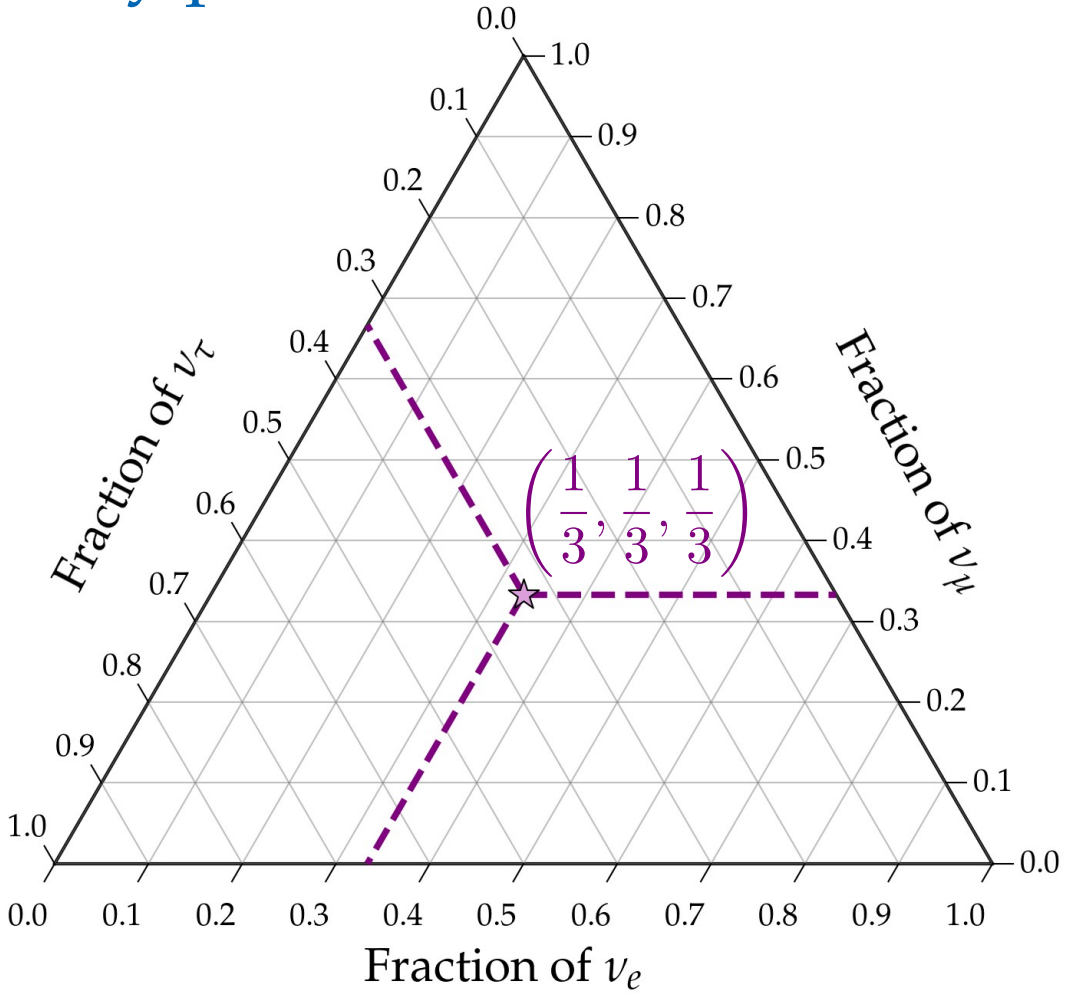
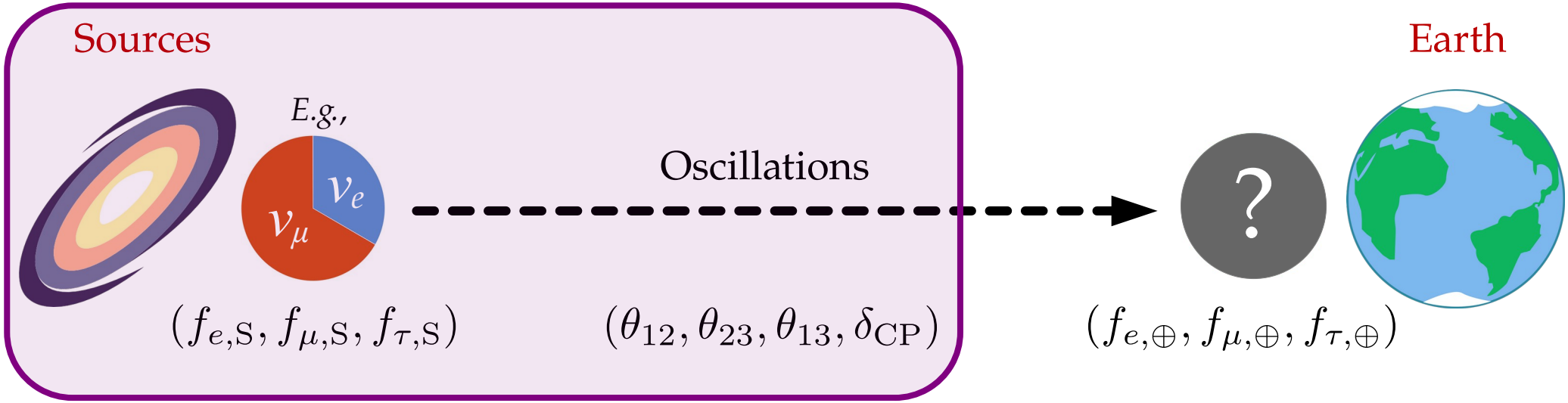


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$



One likely TeV–PeV ν production scenario:

$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ 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

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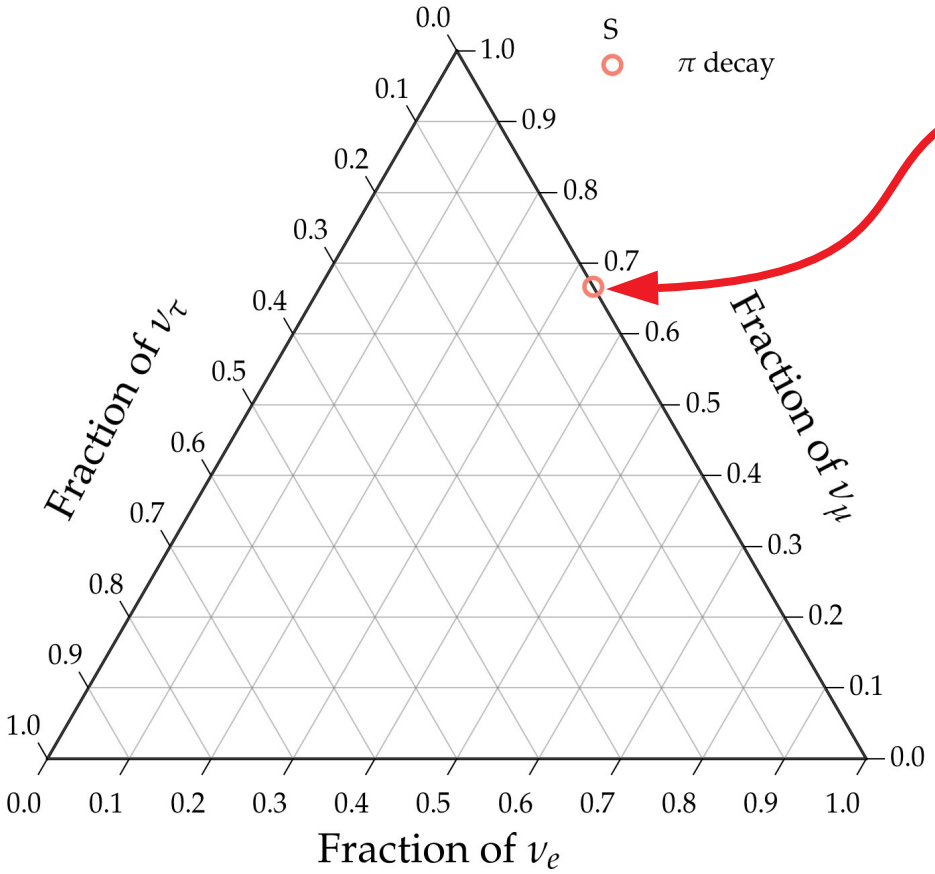

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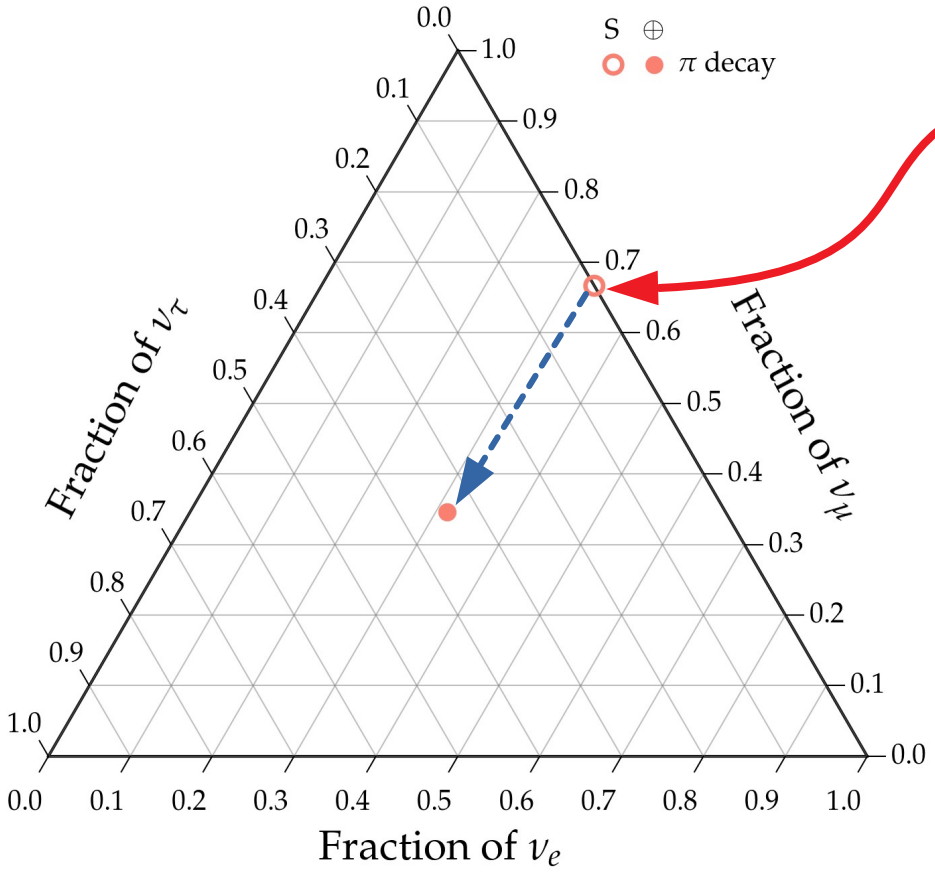

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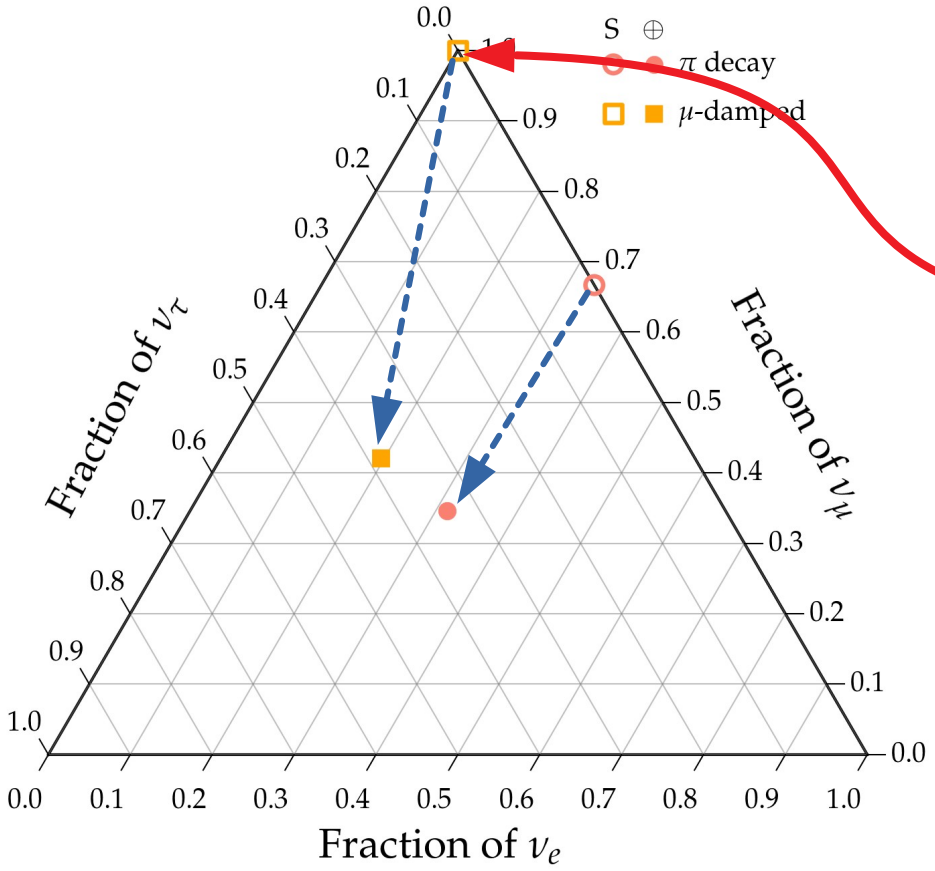

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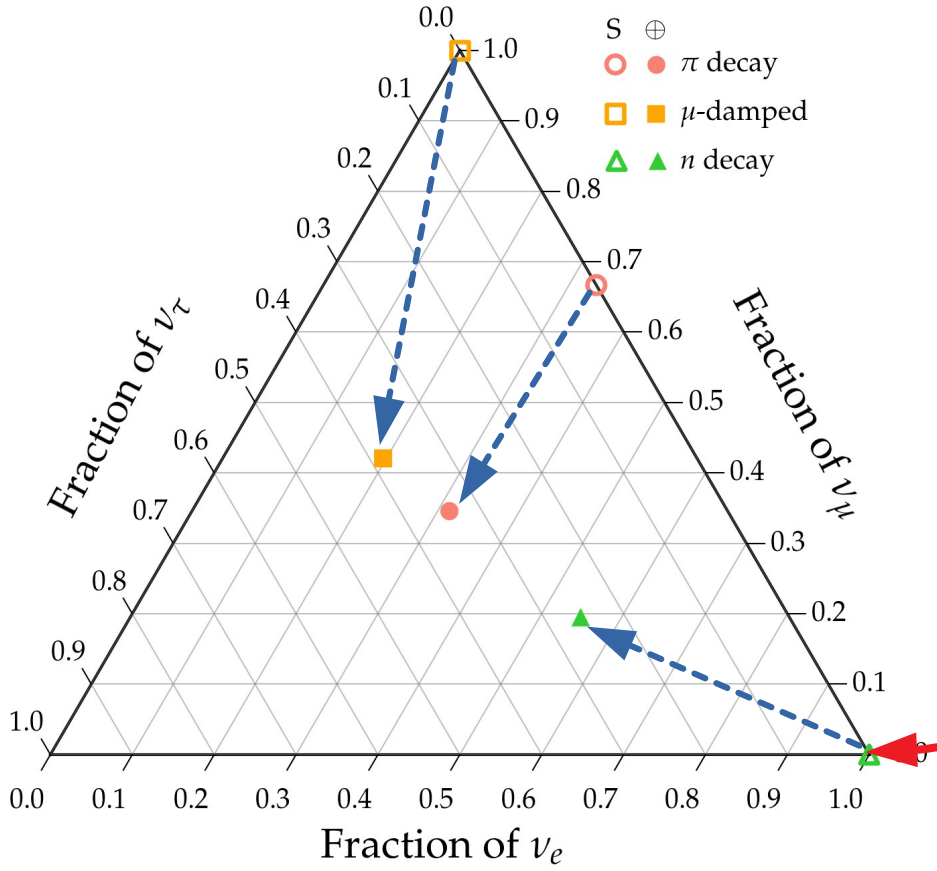

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Muon damped

$(0{:}1{:}0)_S$

Neutron decay

$(1{:}0{:}0)_S$

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Measuring flavor composition: 2015–2020

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
IceCube Collab., *ApJ* 2015

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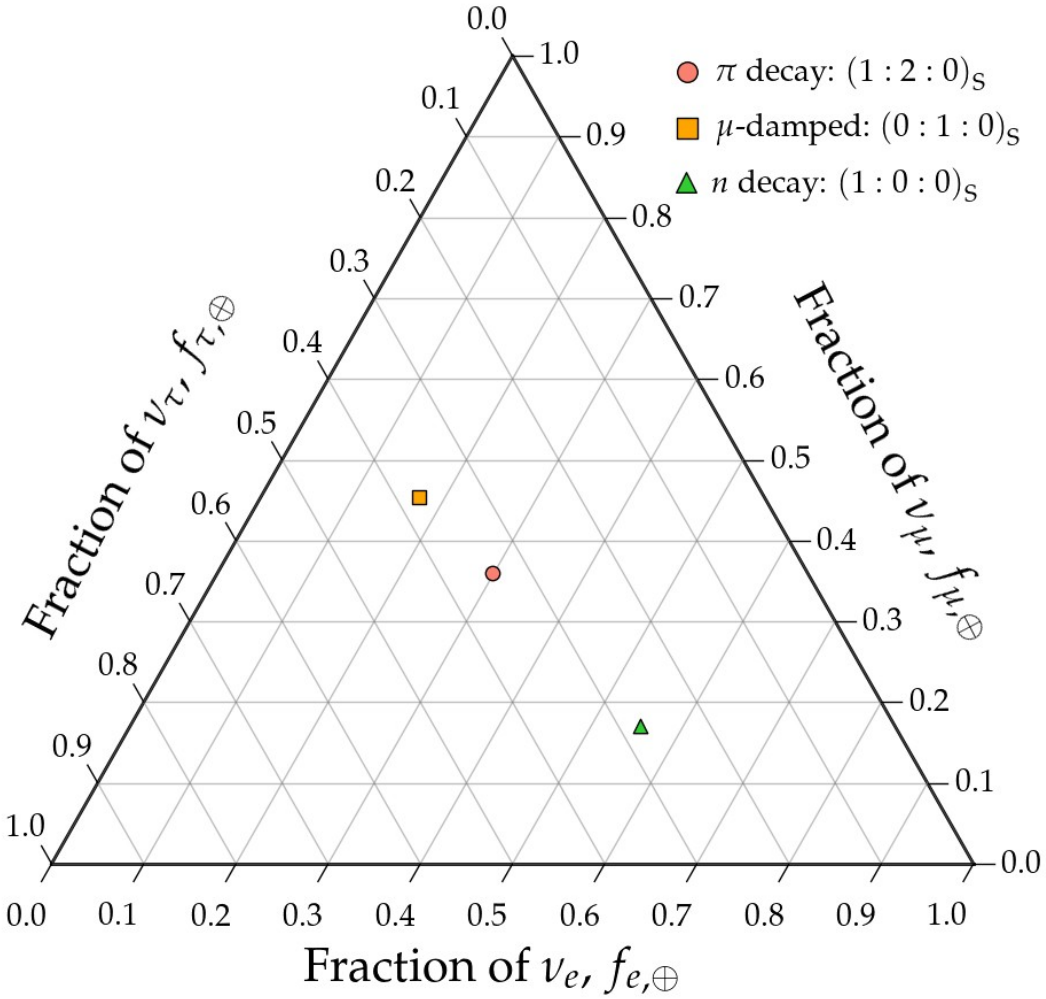

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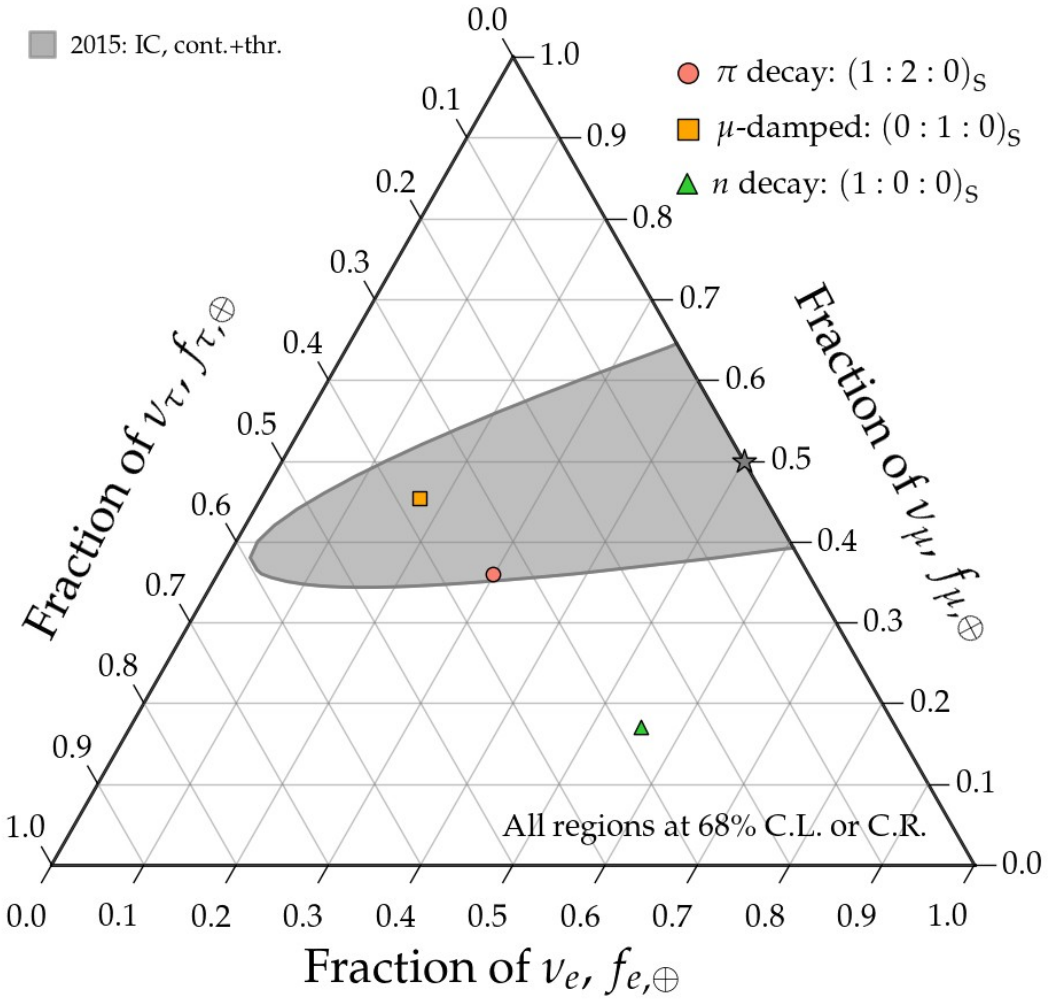

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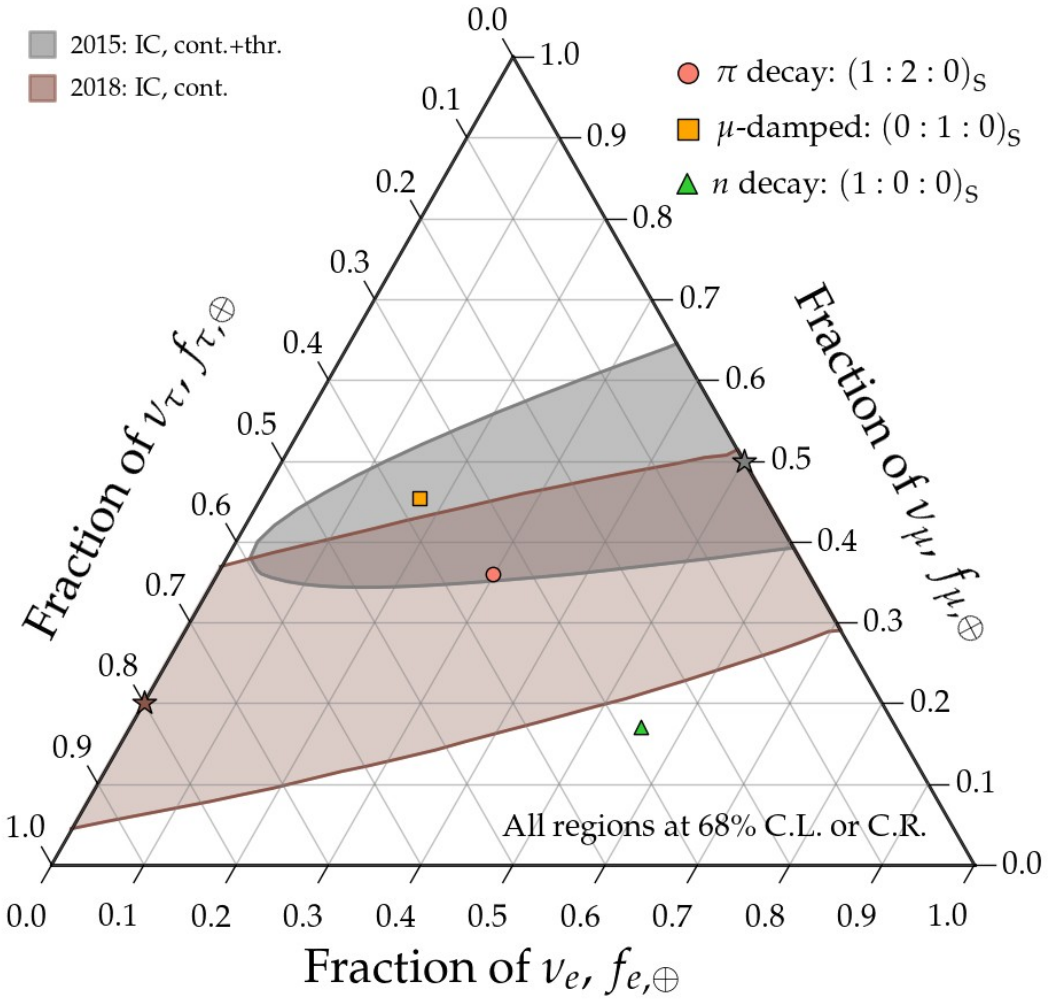

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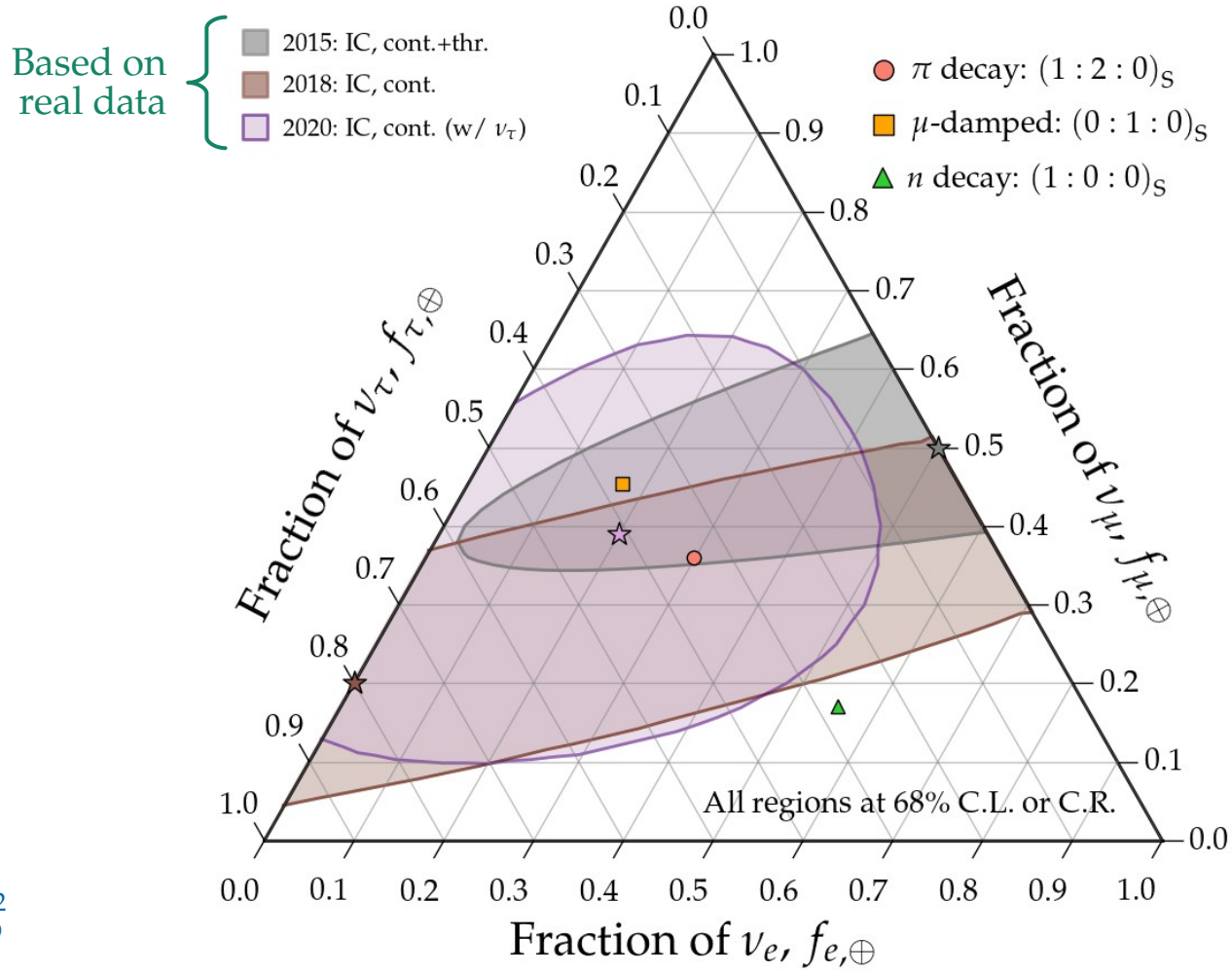

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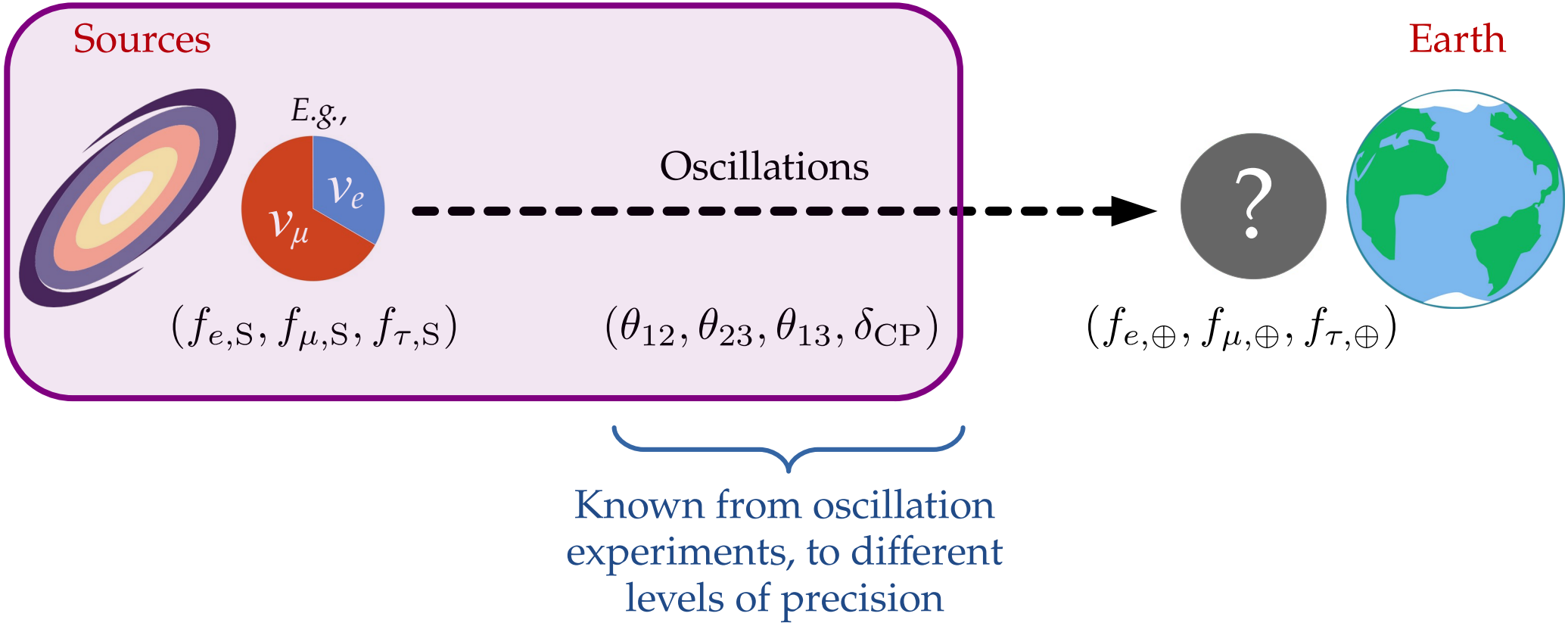
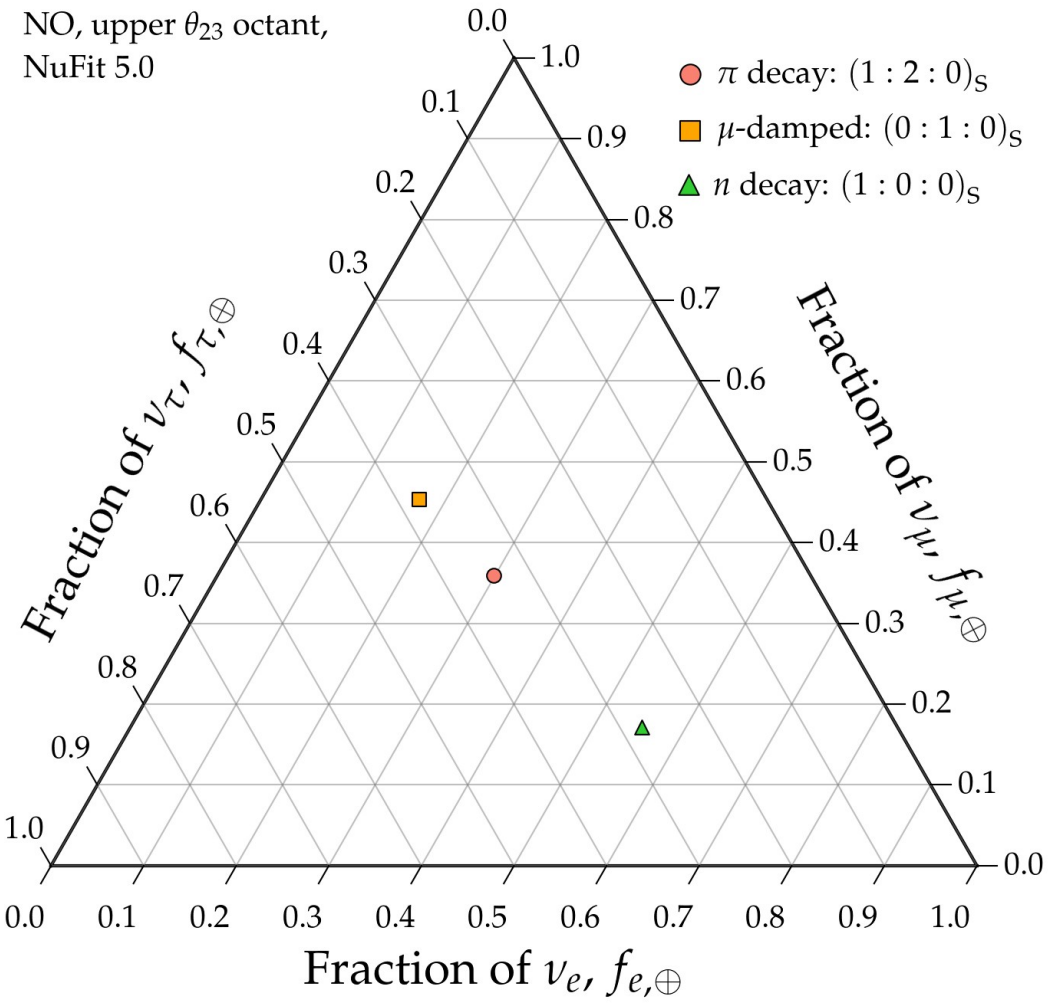


Theoretically palatable regions: today



Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB, Beacom, Winter, *PRL* 2015

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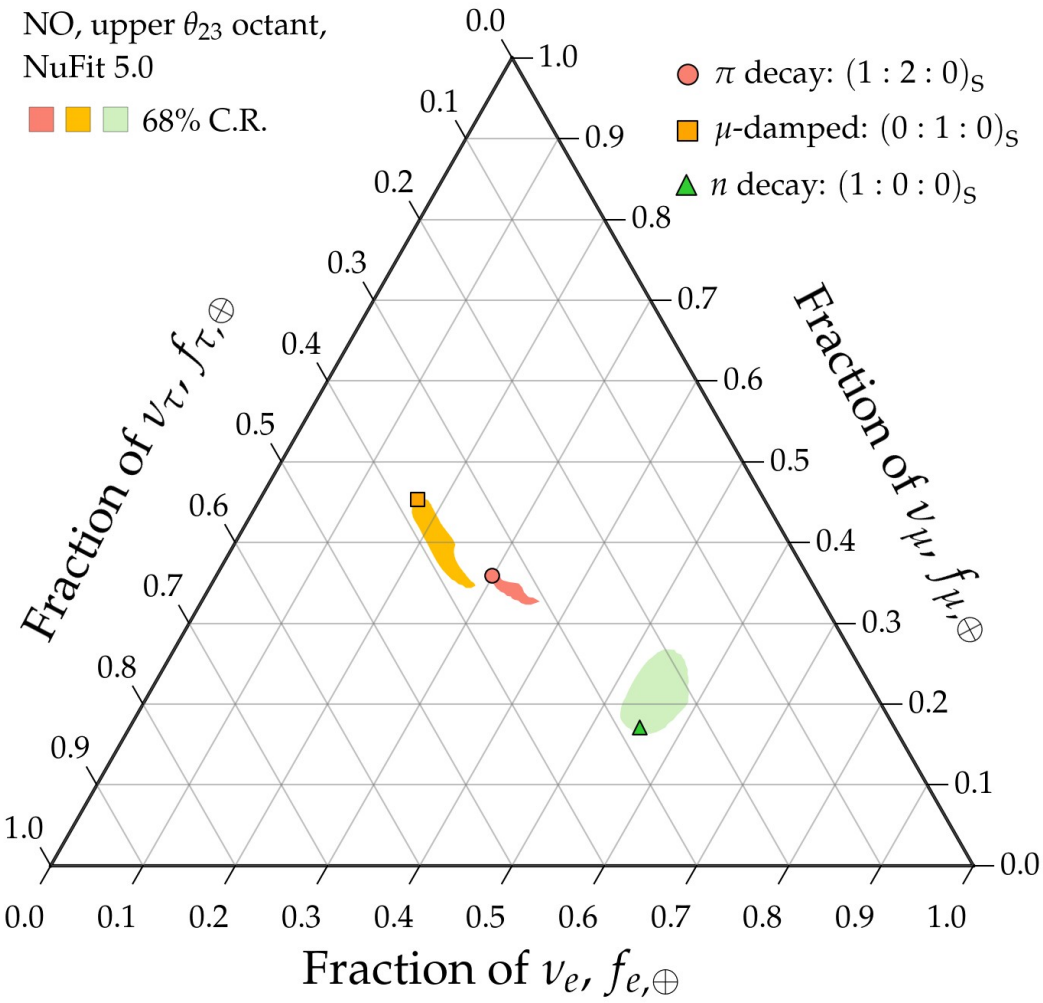

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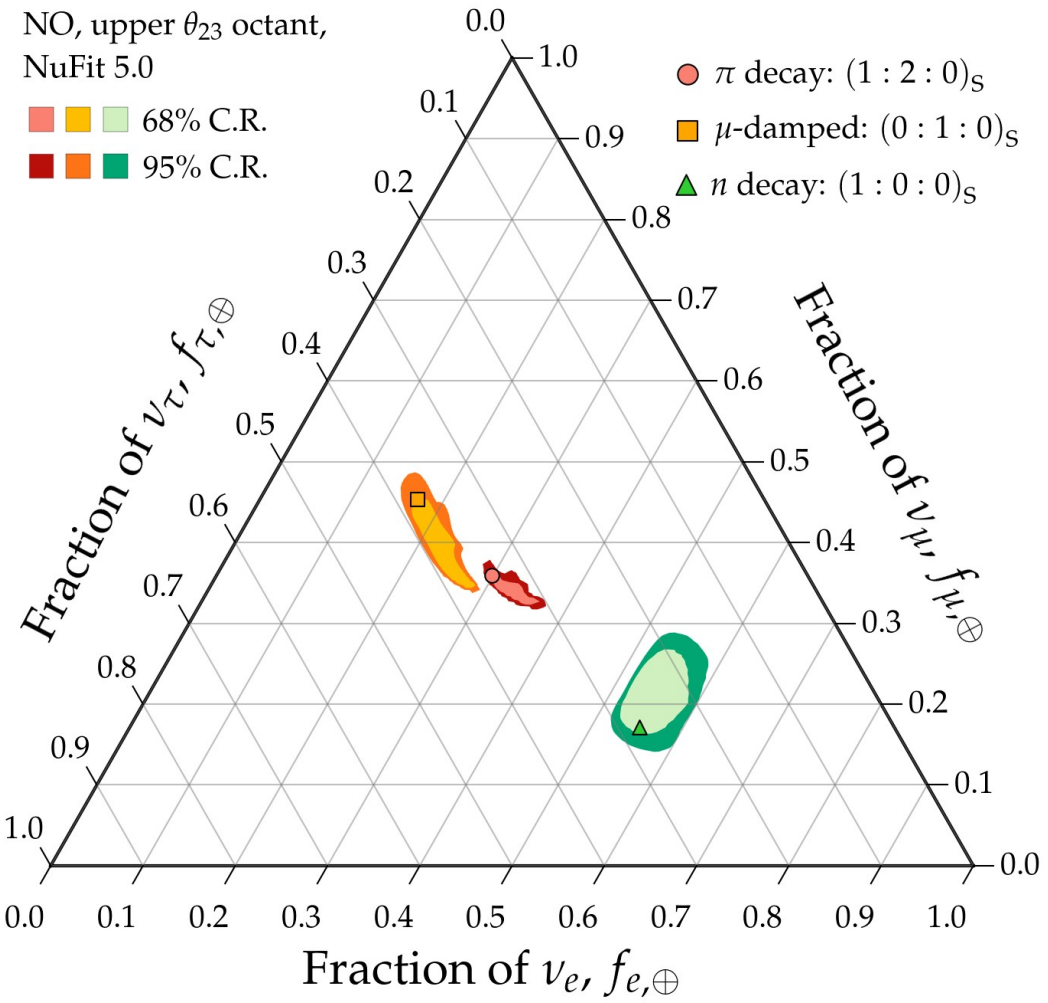

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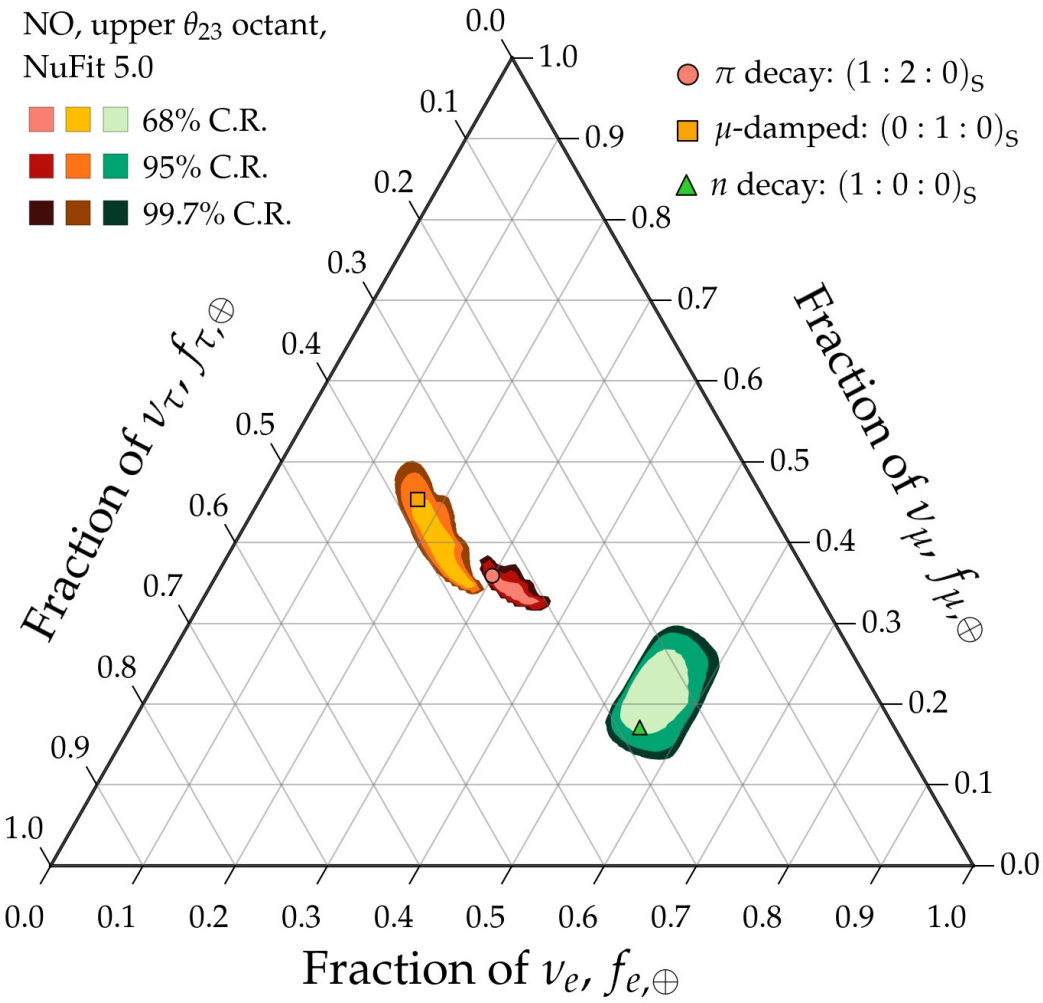

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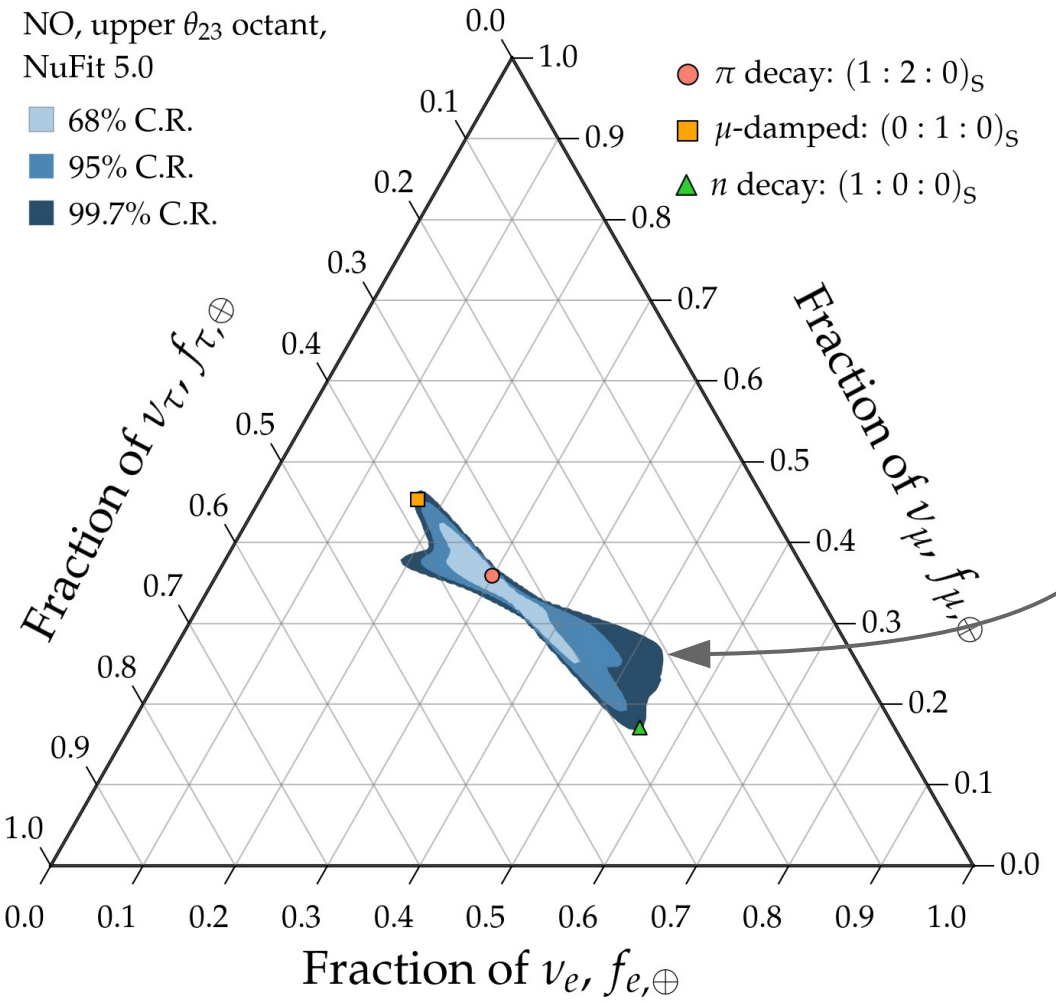

Varying over all possible flavor ratios at the source

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Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

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

$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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

MB, Tamborra, *PRD* 2020
Winter, *PRD* 2013

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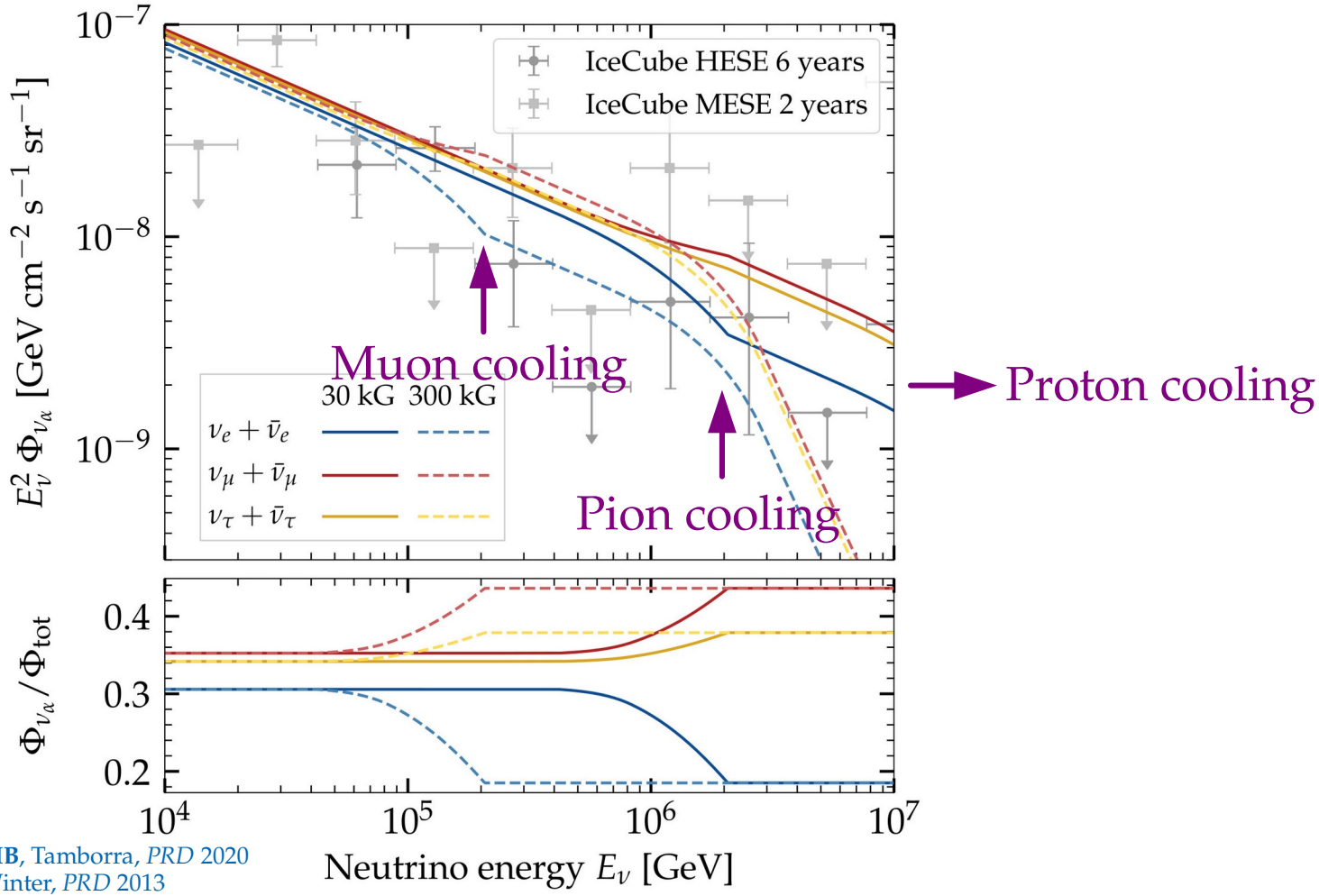

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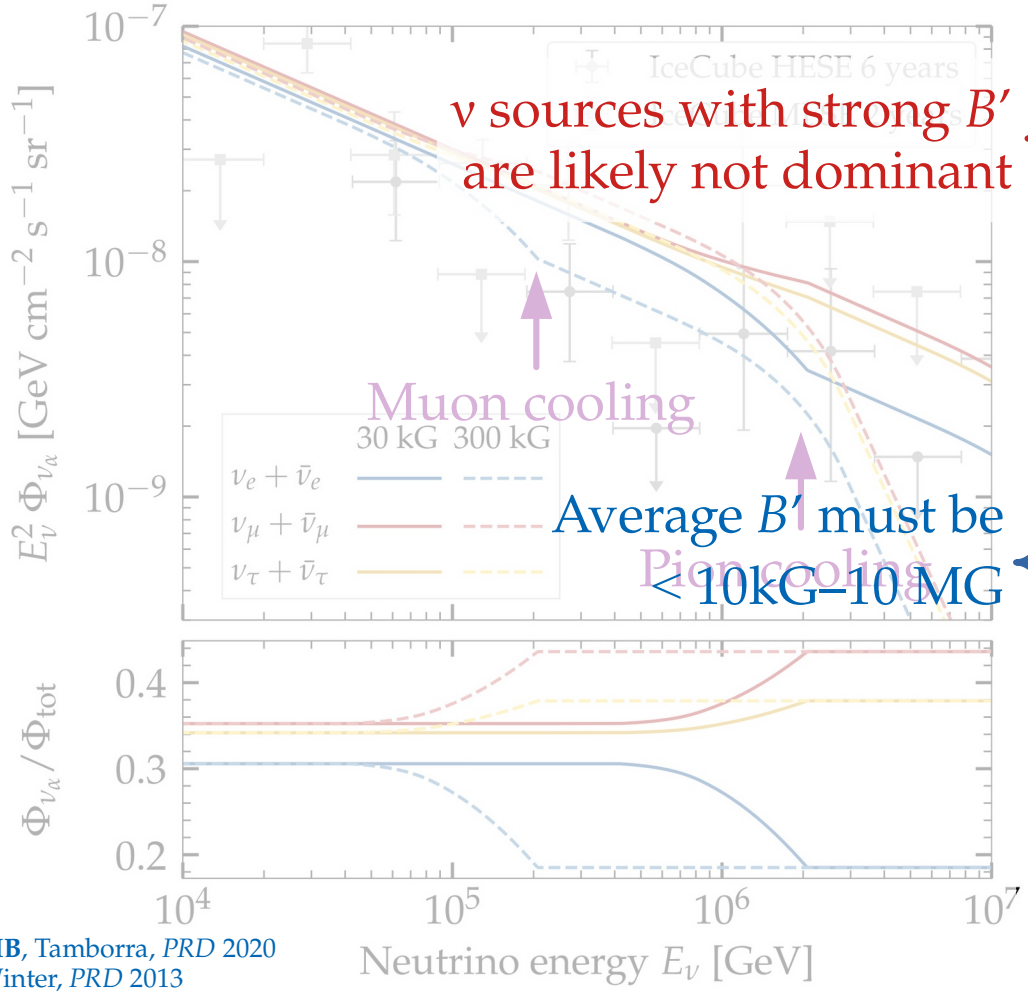

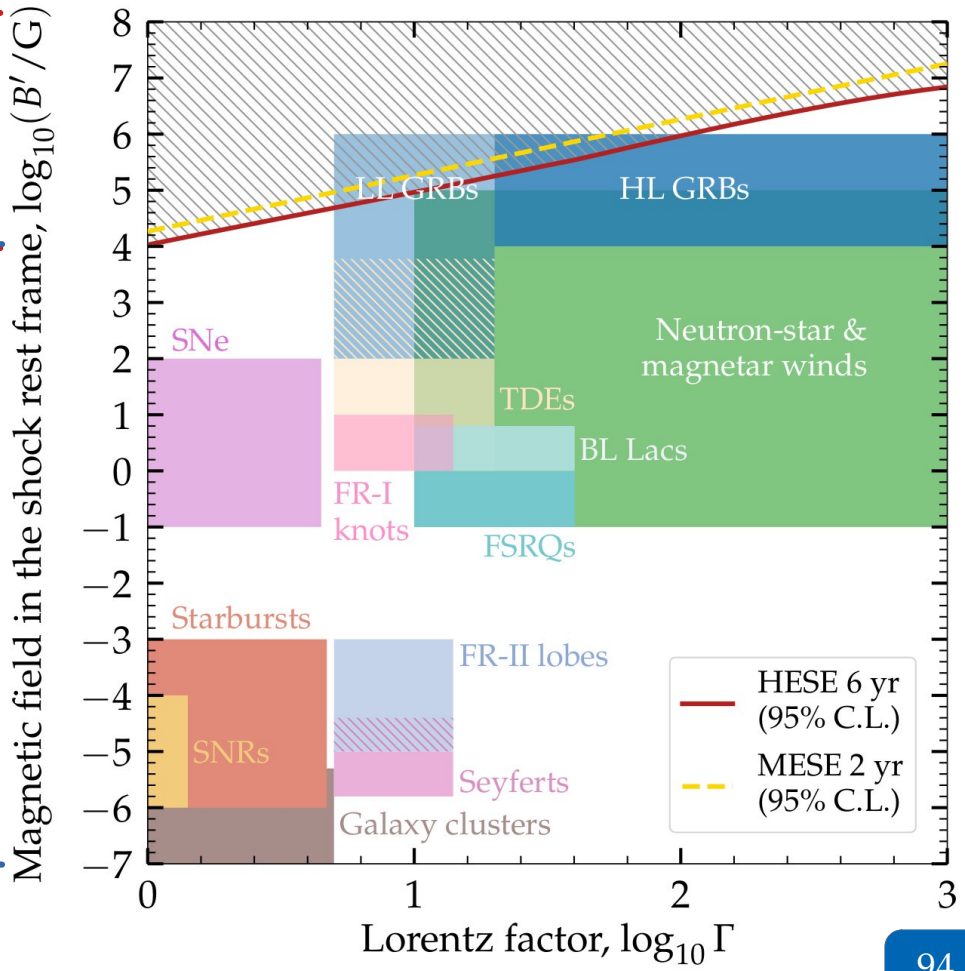

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New physics in flavor composition

Use the flavor sensitivity to test new physics:

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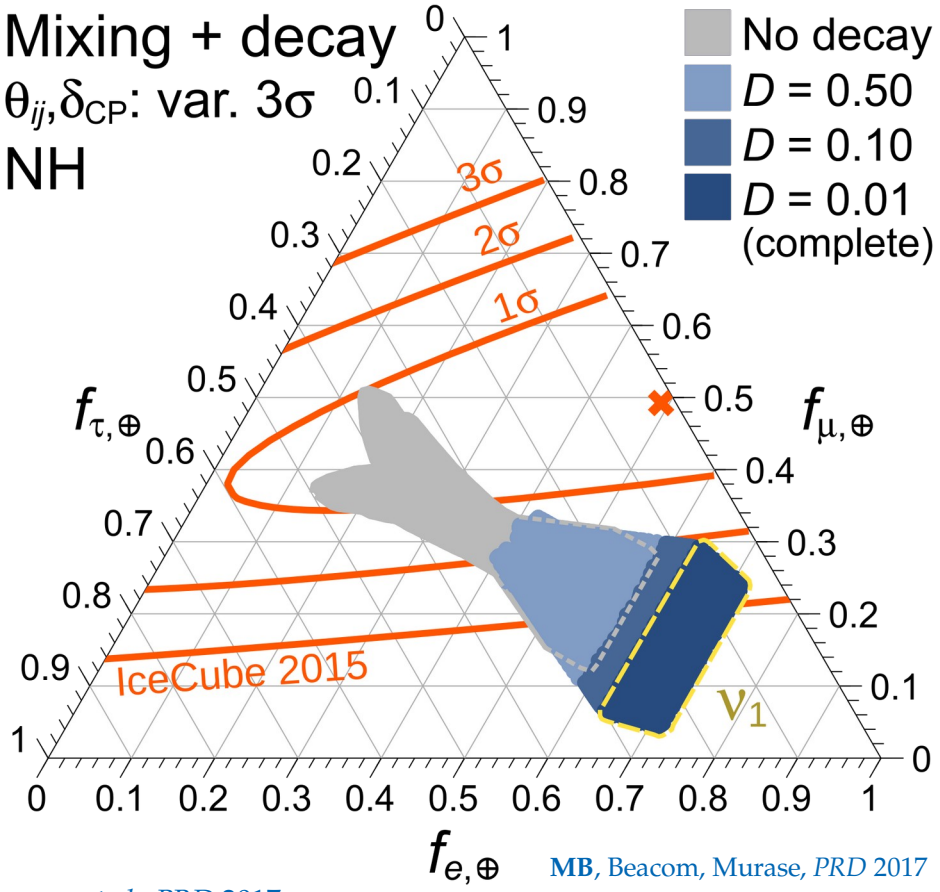

MB, Beacom, Murase, *PRD* 2017

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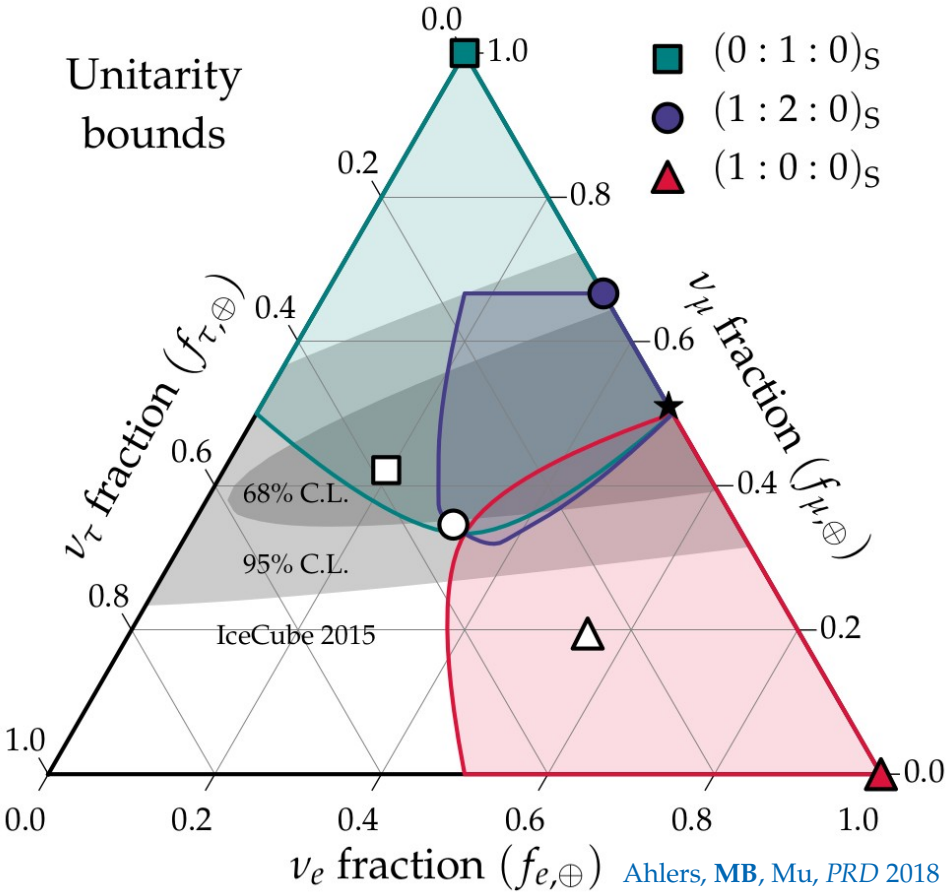

Ahlers, **MB**, Mu, *PRD* 2018

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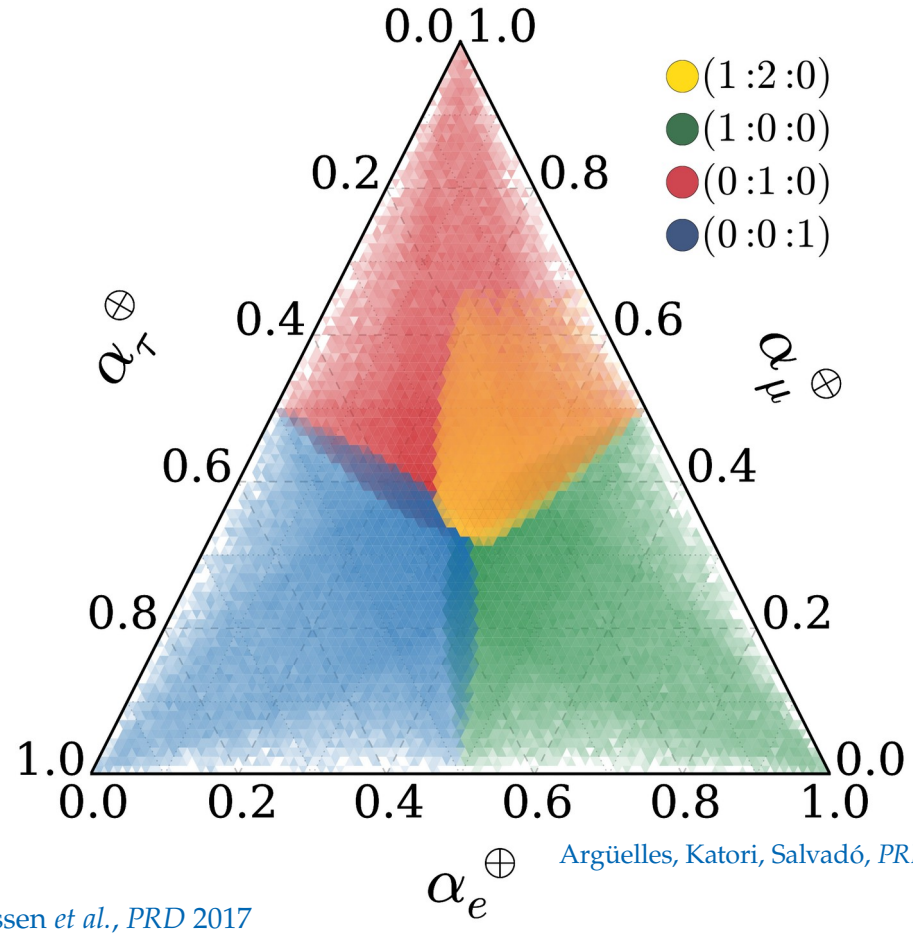

Argüelles, Katori, Salvadó, *PRL* 2015

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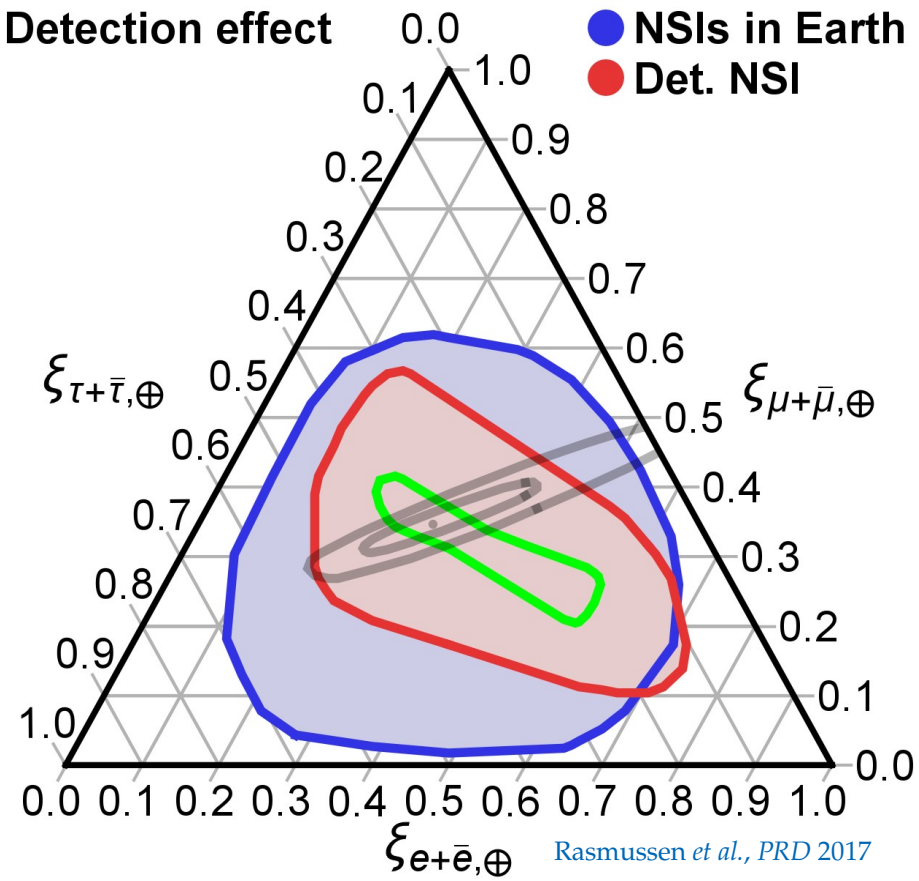

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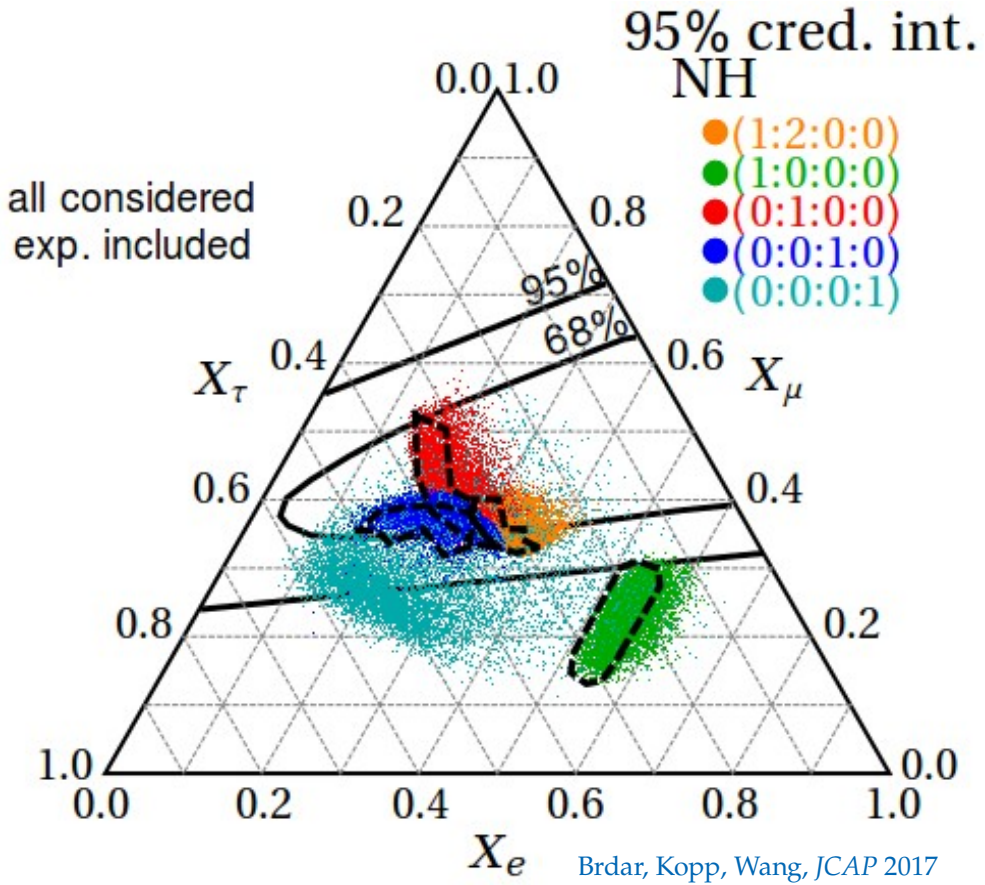

Brdar, Kopp, Wang, *JCAP* 2017

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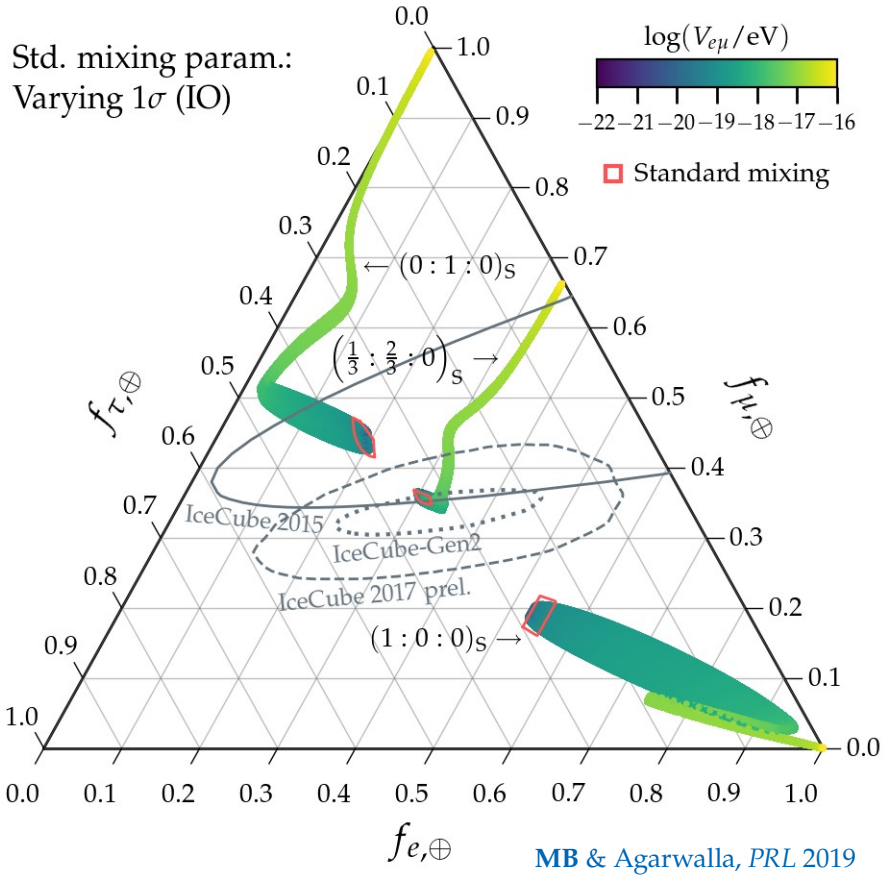

MB & Agarwalla, *PRL* 2019

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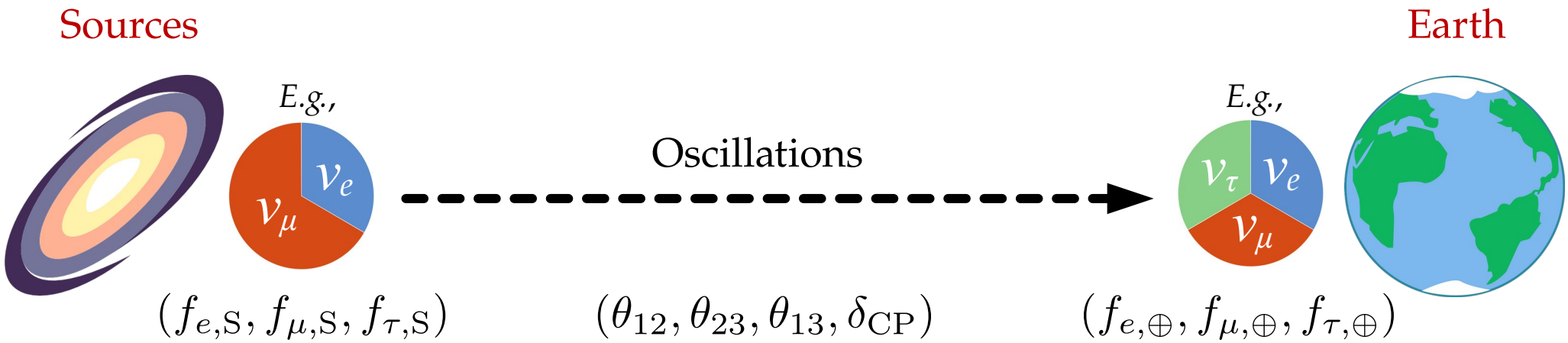
From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$

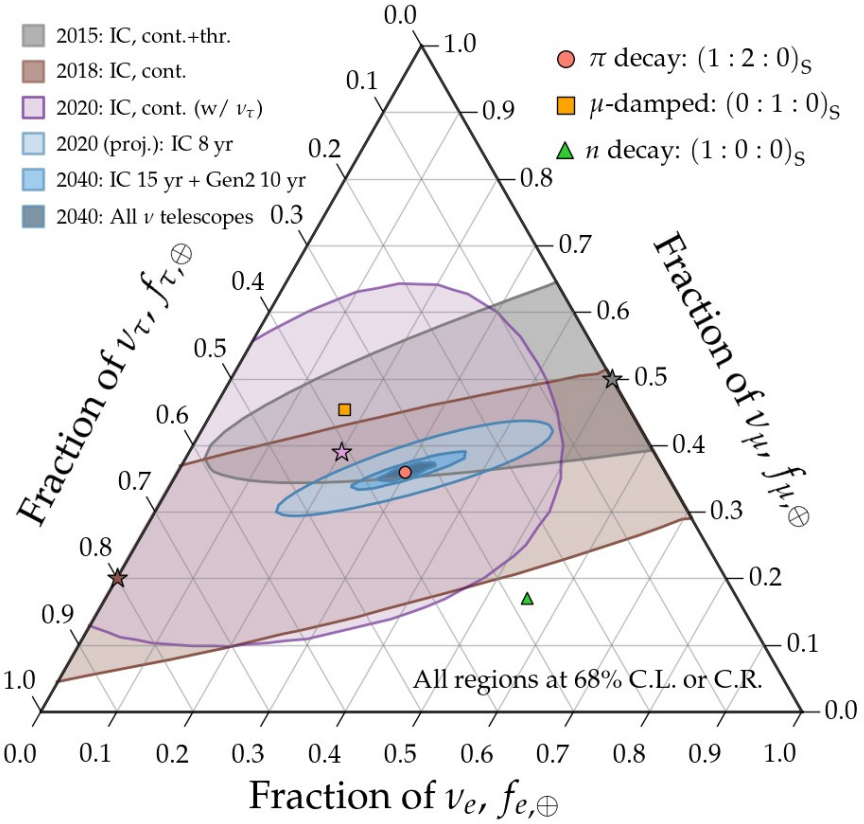


From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$

Inferring the flavor composition at the sources

Ingredient #1:

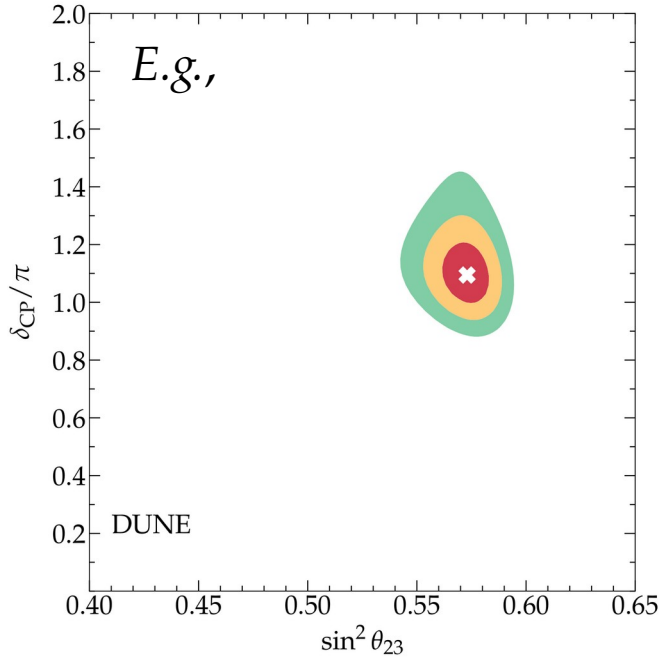
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$\mathcal{L}(\boldsymbol{\vartheta})$



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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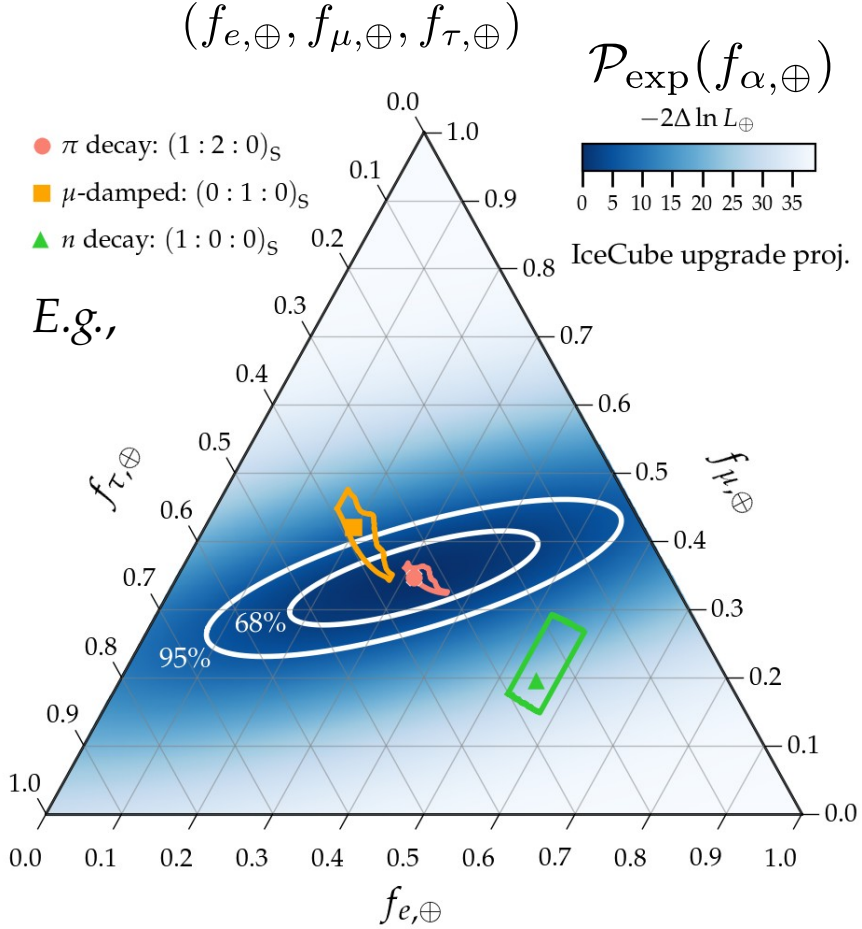

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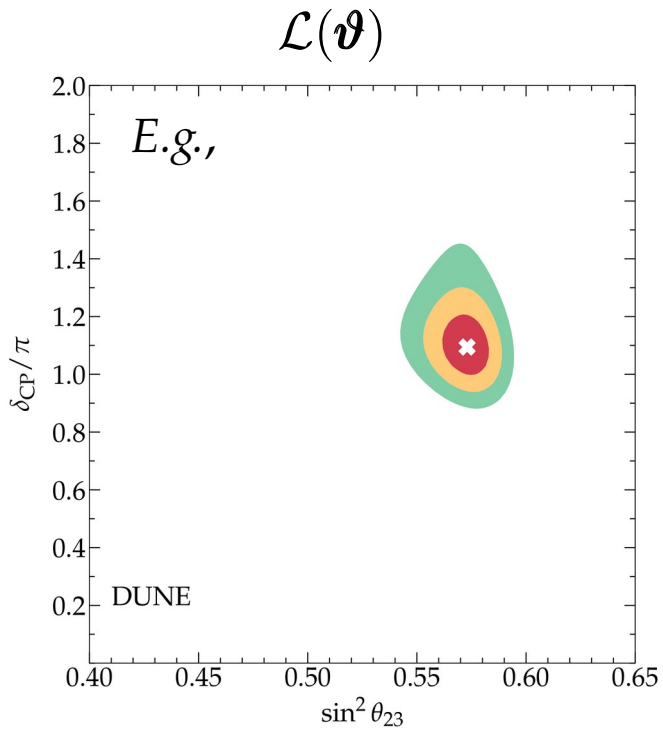

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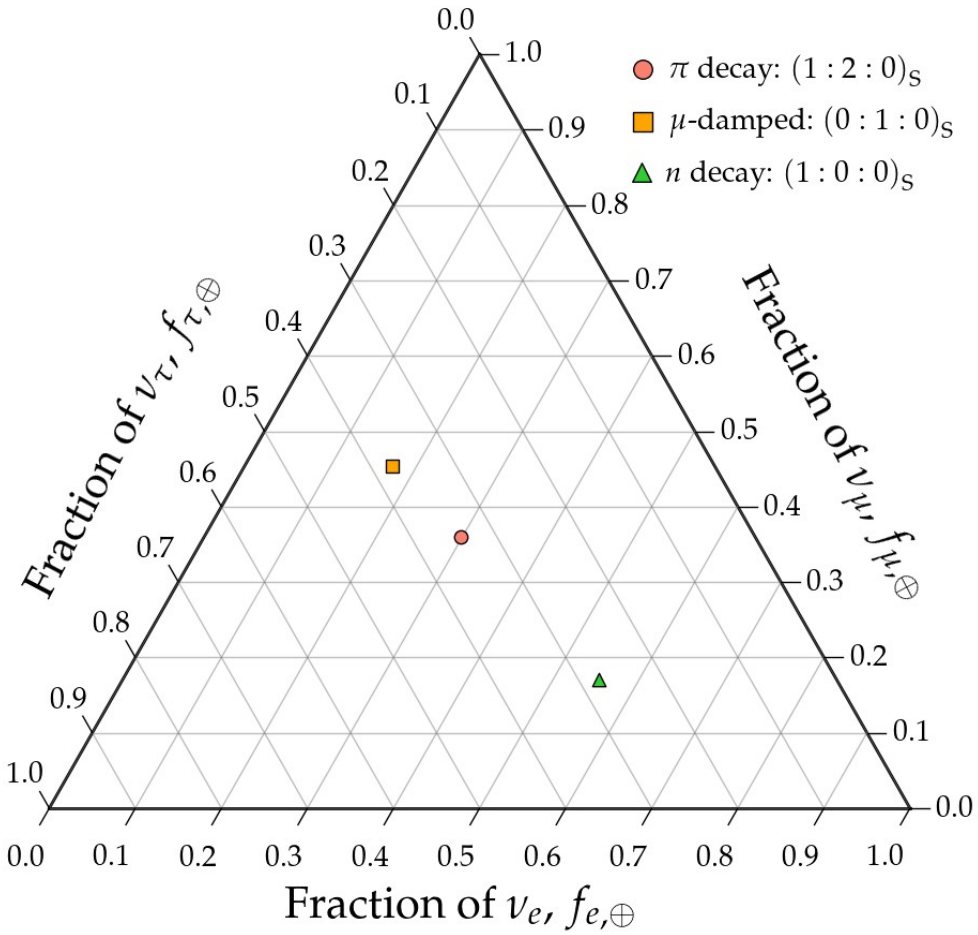

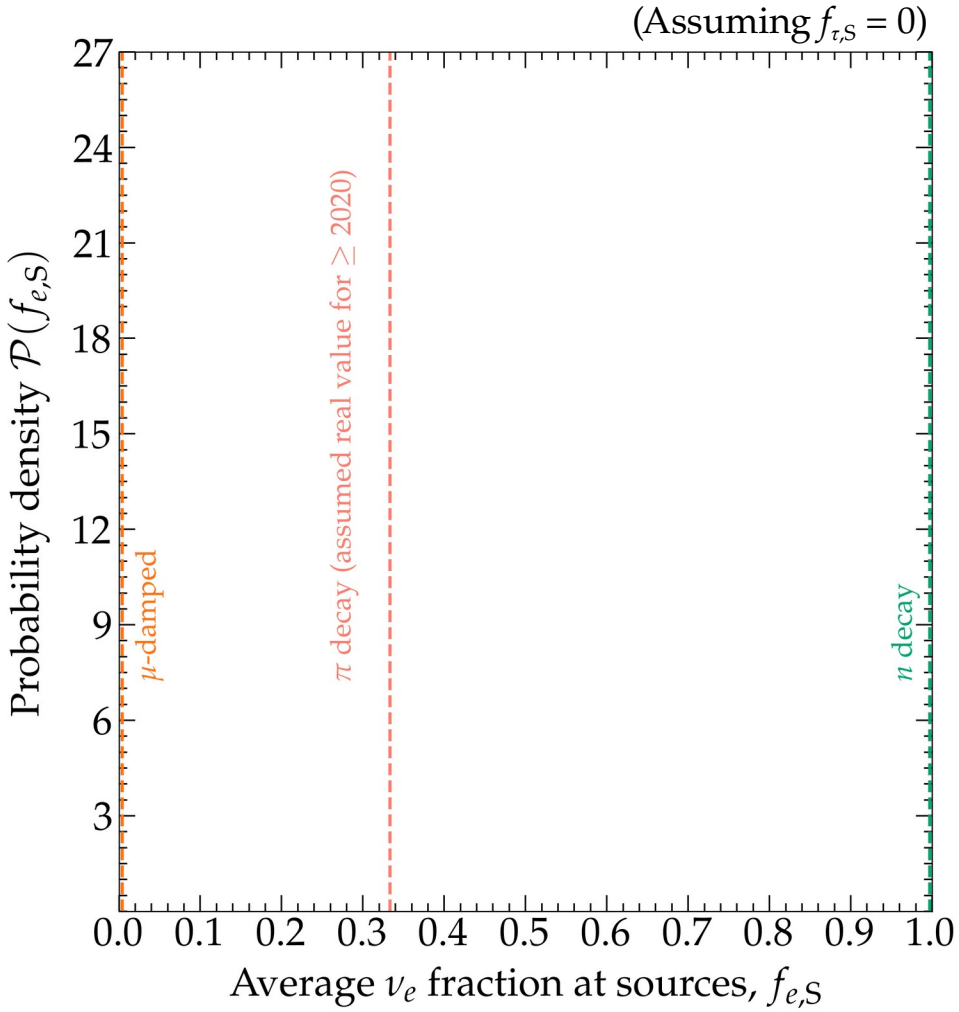

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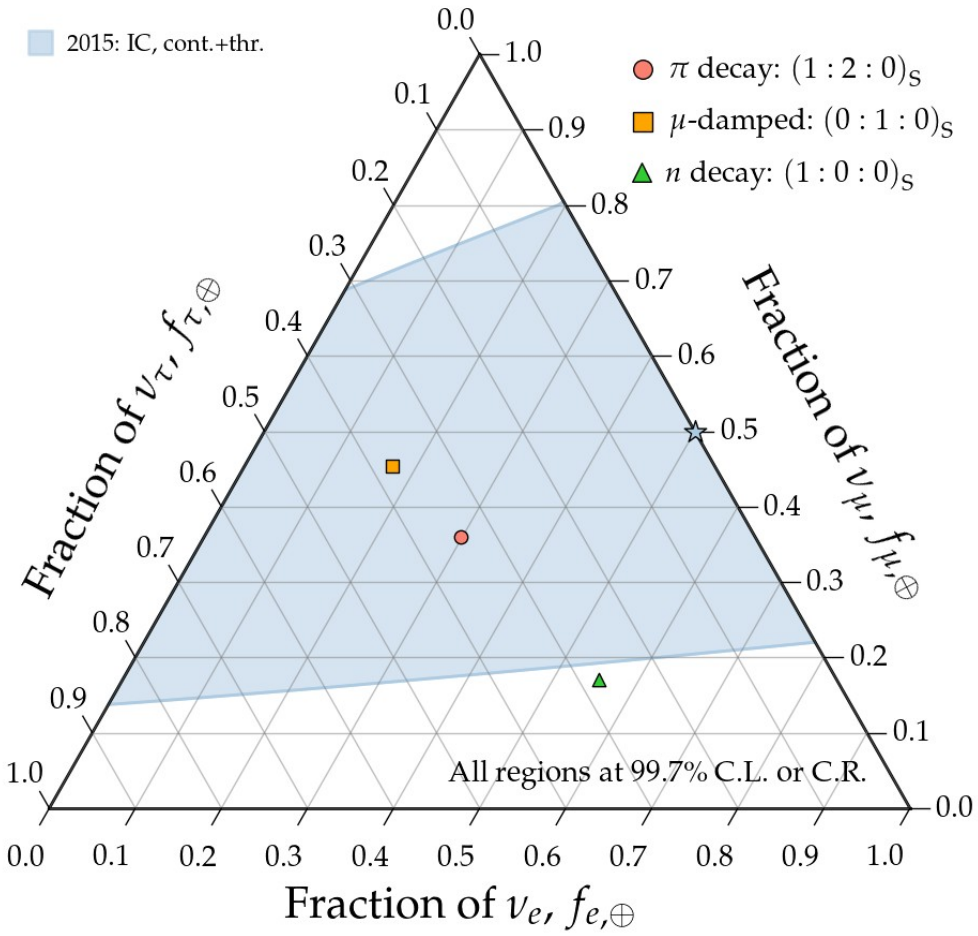

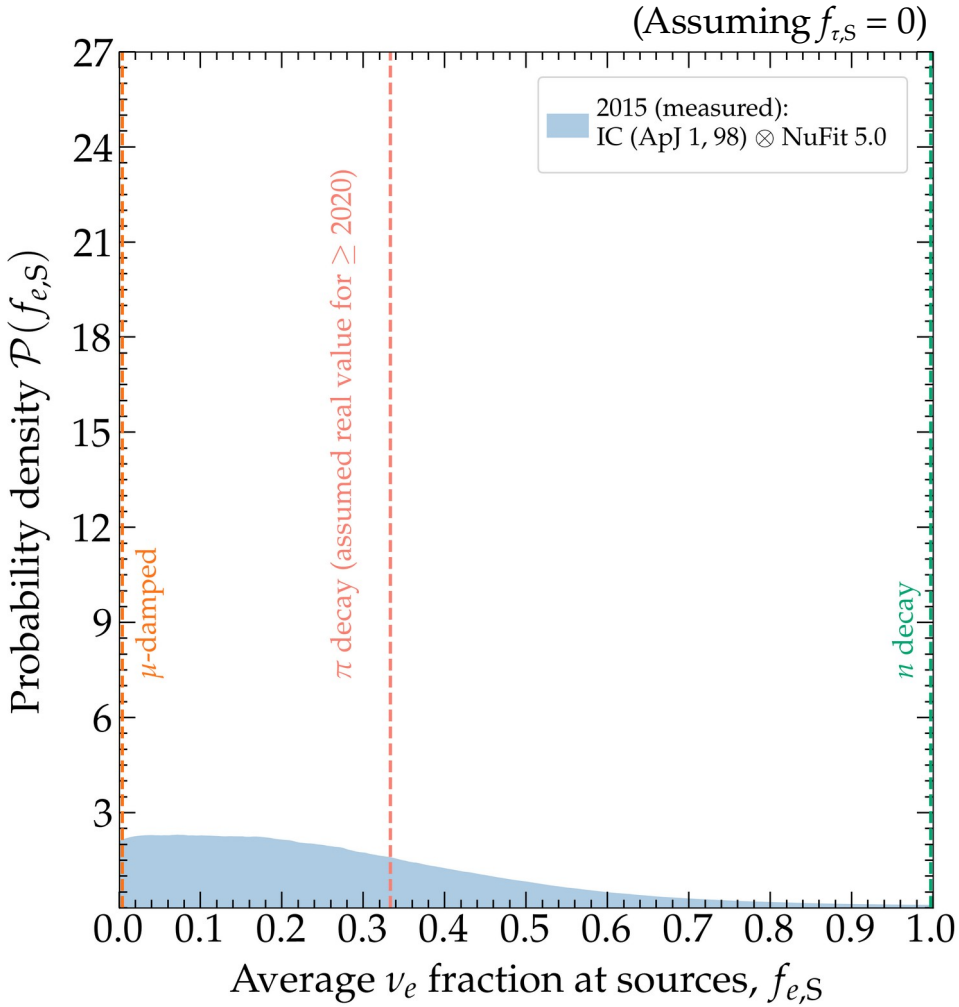

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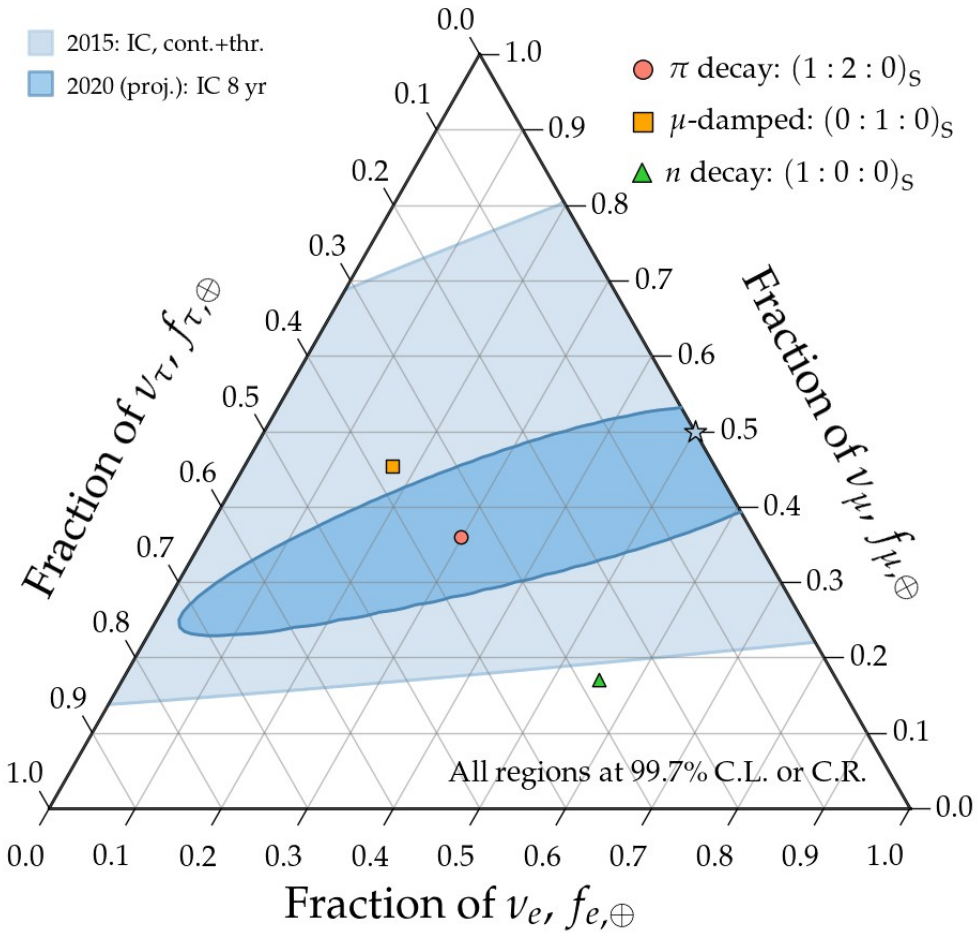

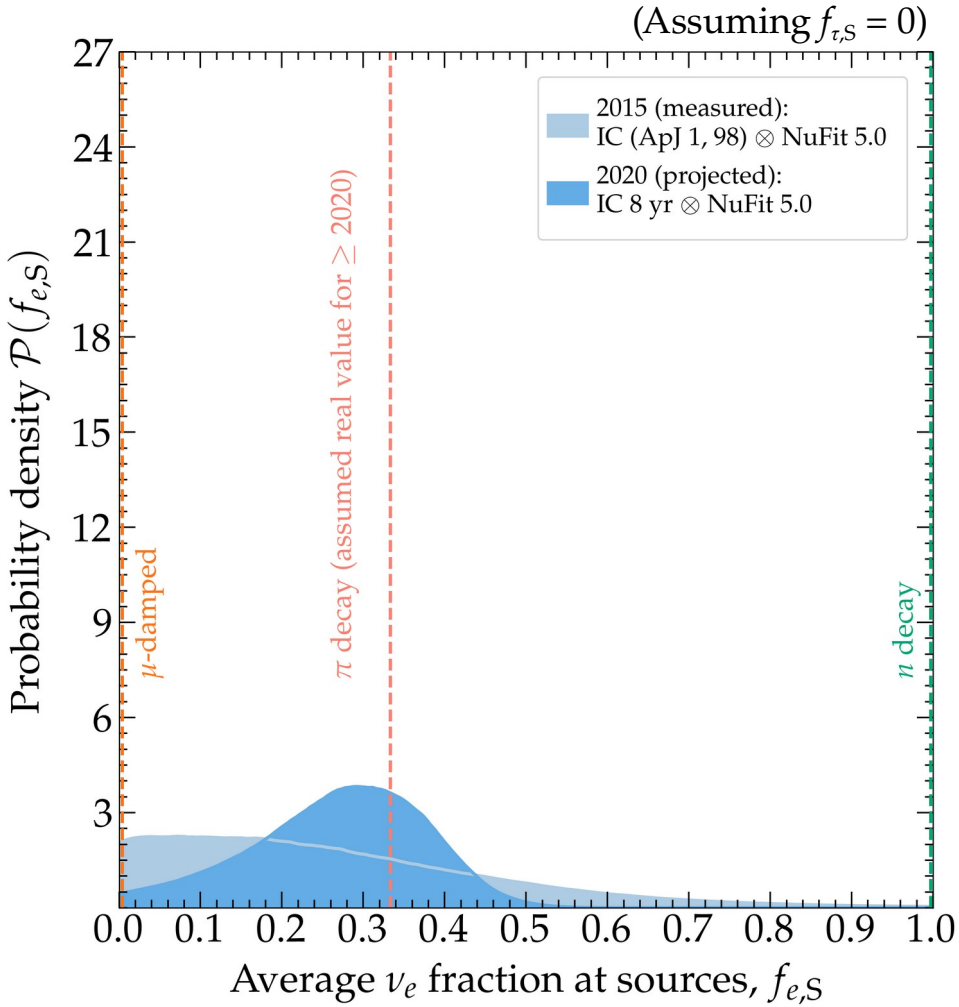

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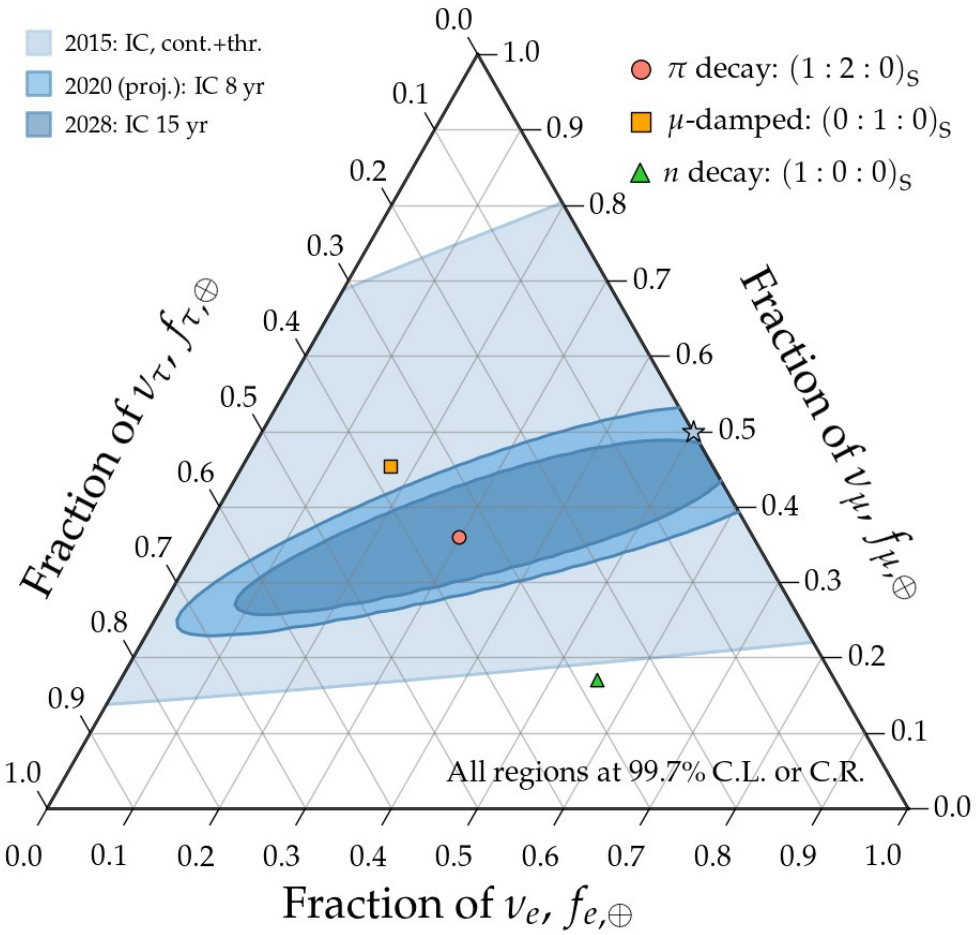

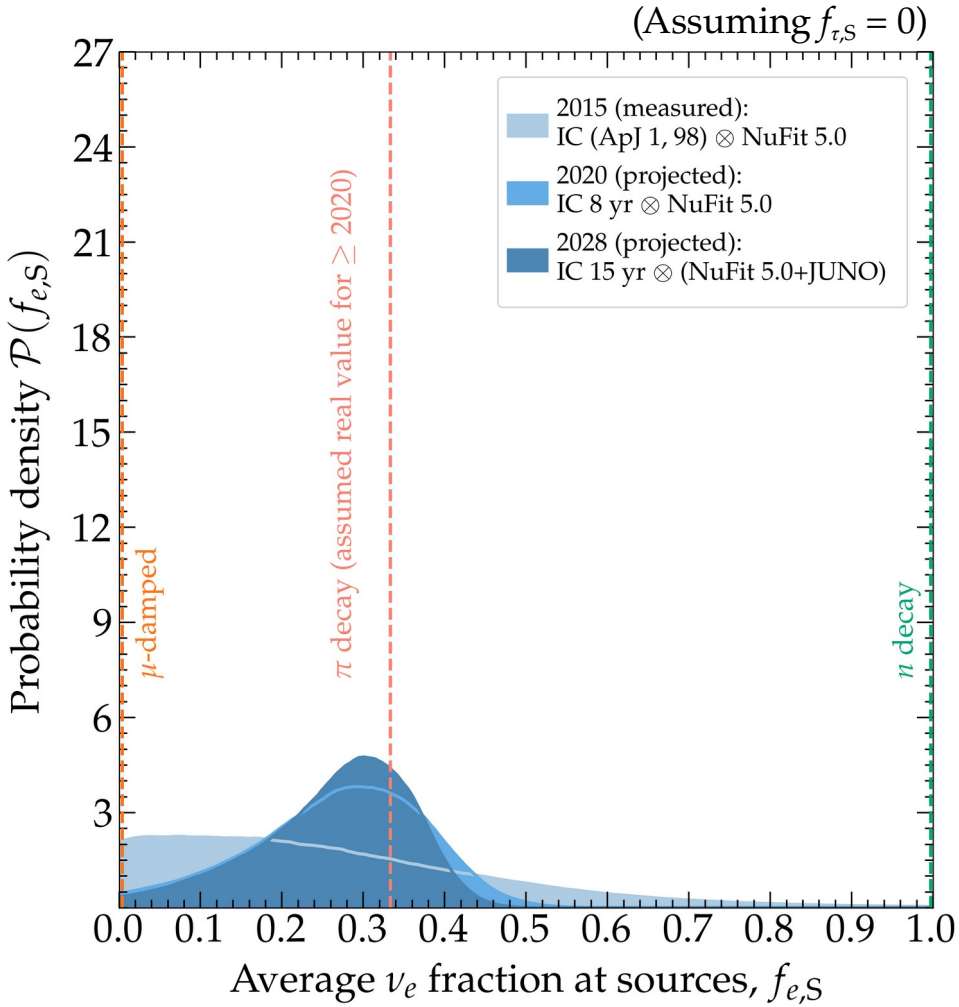

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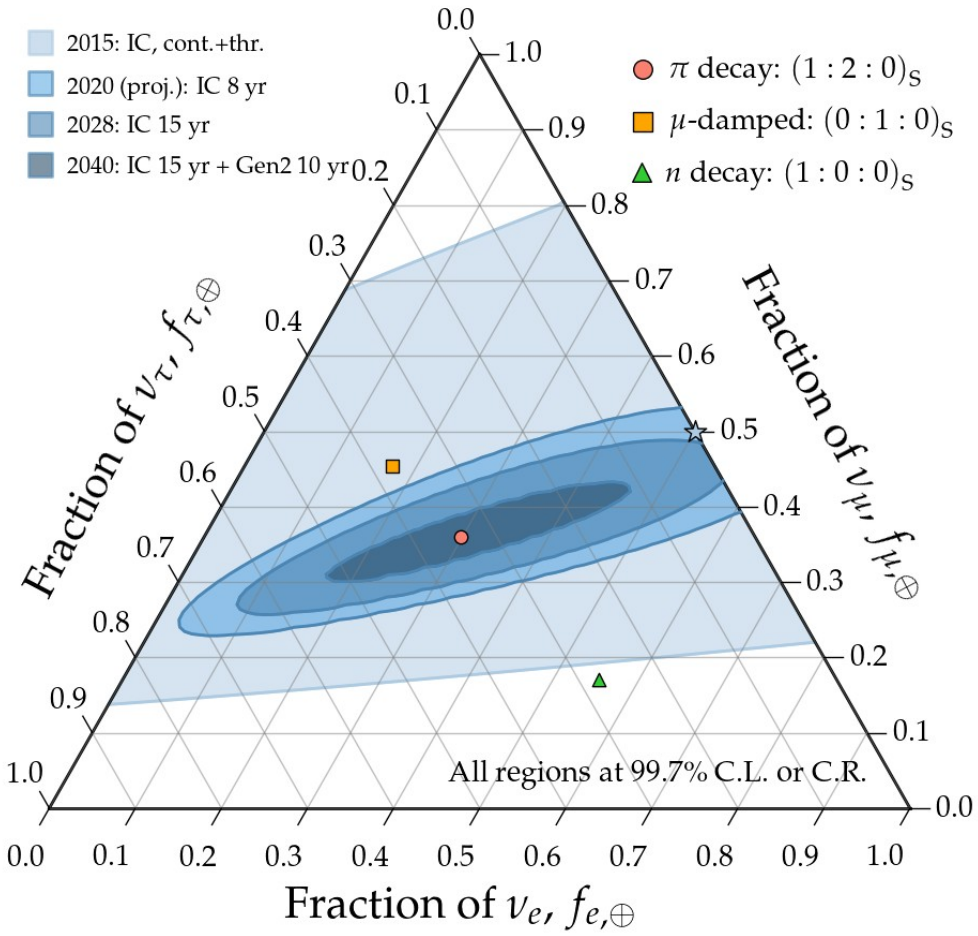

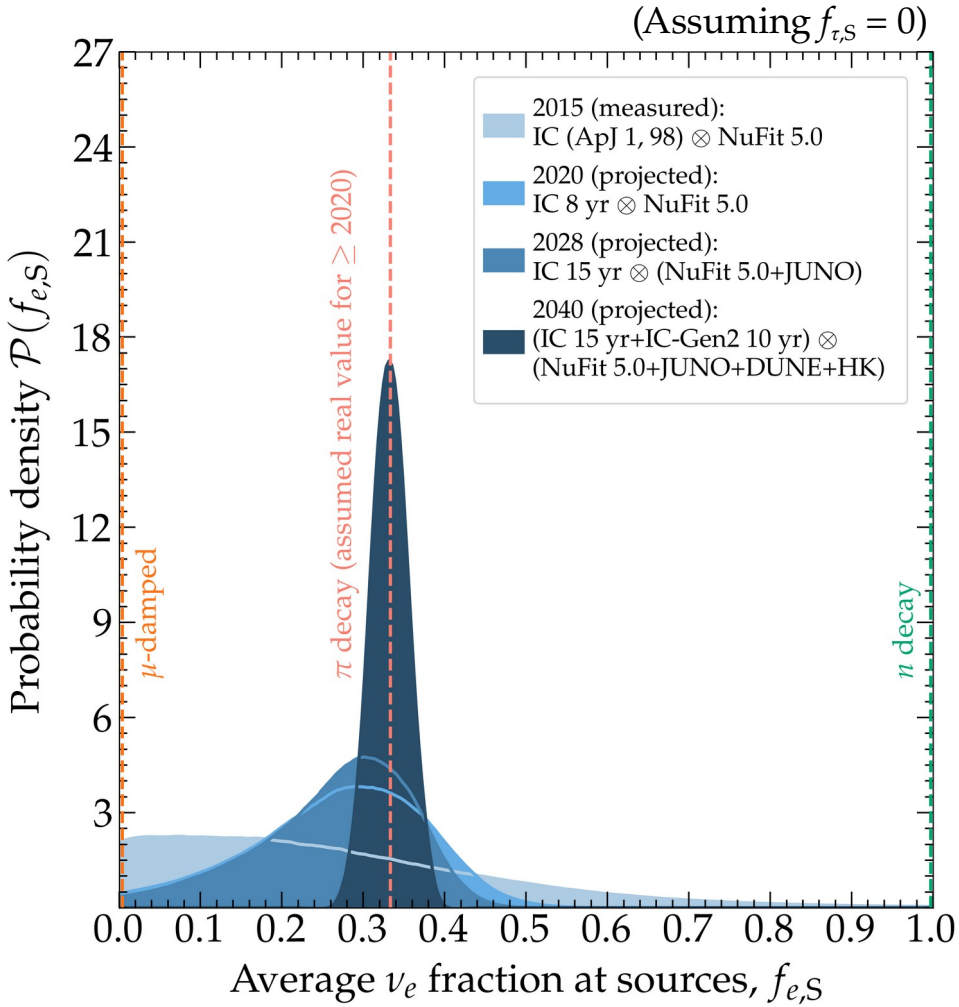

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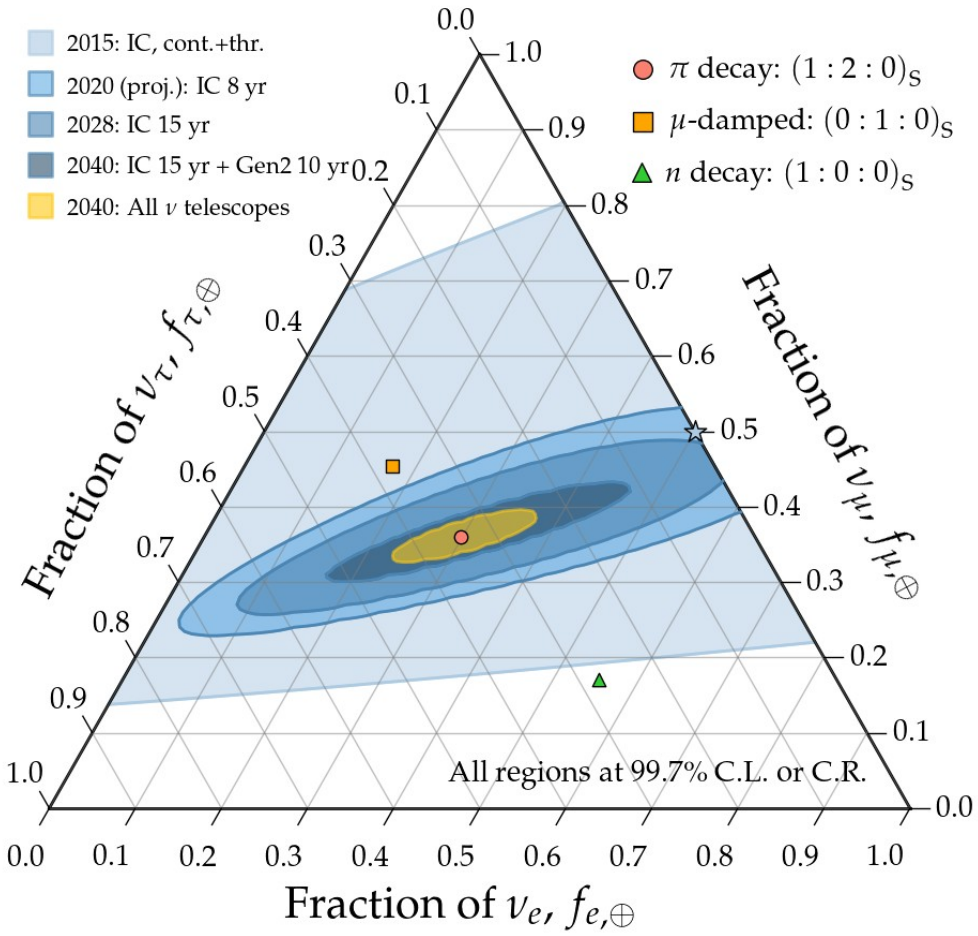

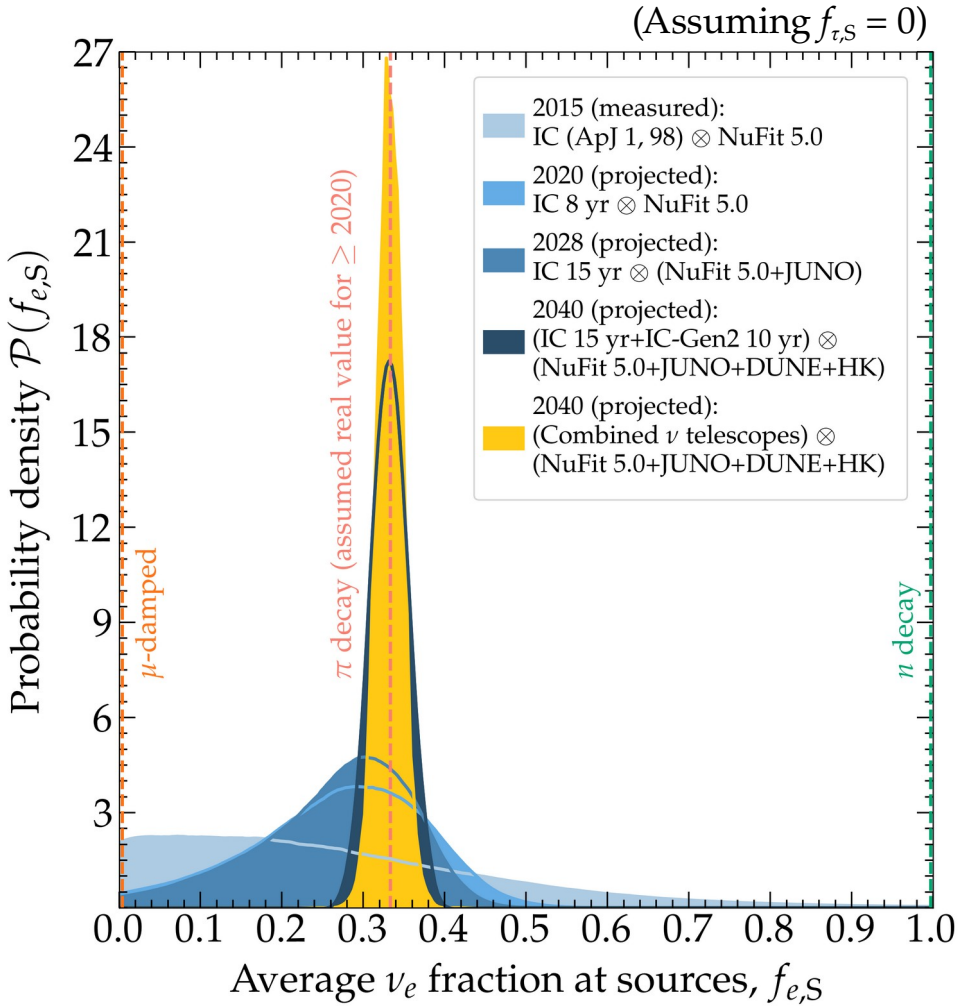

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