High-Energy and Ultra-High-Energy Neutrinos Whitepaper

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Niels Bohr Institute, University of Copenhagen

Co-editors:
Markus Ackermann, Lu Lu, Nepomuk Otte,
Mary Hall Reno, Stephanie Wissel

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UNIVERSITY OF COPENHAGEN

VILLUM FONDEN


High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper

Editors: Markus Ackermann[a], Mauricio Bustamante[b], Lu Lu[c], Nepomuk Otte[d], Mary Hall Reno[e], Stephanie Wissel[f]

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arXiv: 2203.08096

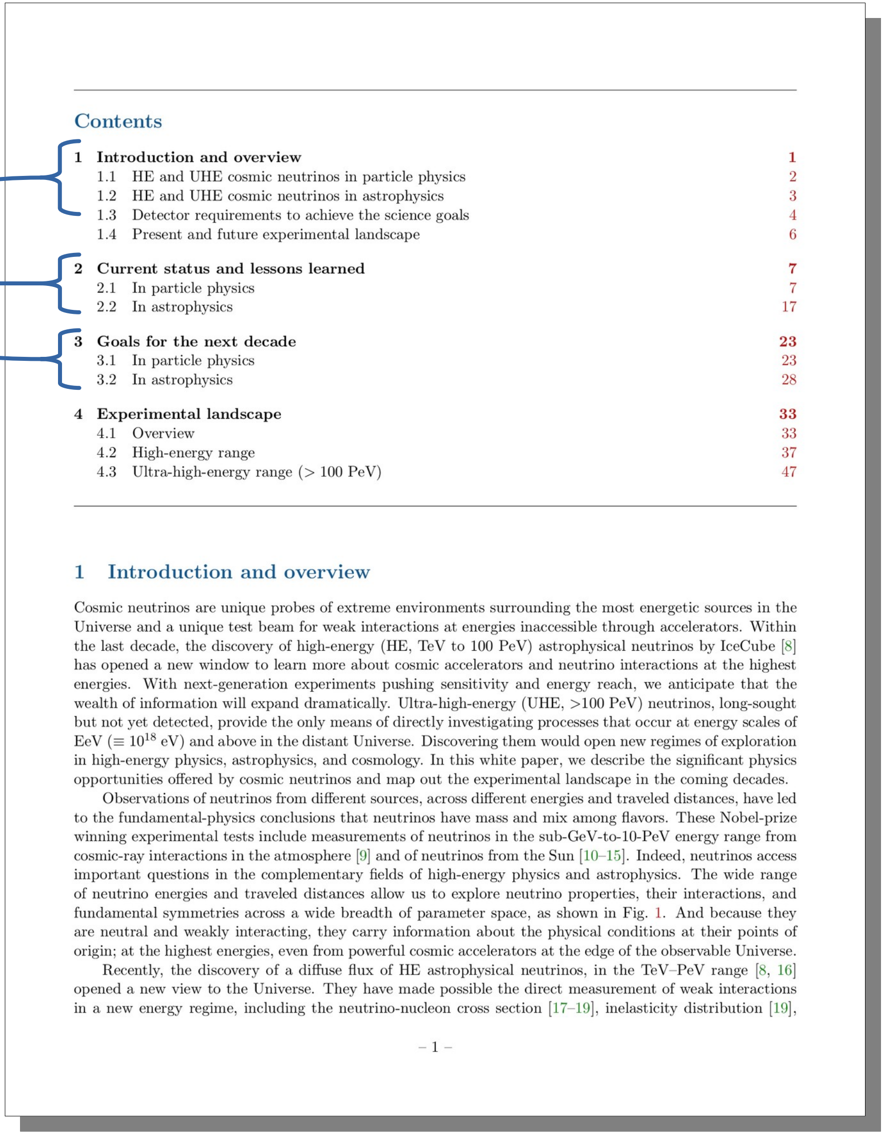
(Will be submitted for publication)

46 authors

~100 pages

Several overview plots

Particle physics & astrophysics are inextricably linked



Contents

1 Introduction and overview

Cosmic neutrinos are unique probes of extreme environments surrounding the most energetic sources in the Universe and a unique test beam for weak interactions at energies inaccessible through accelerators. Within the last decade, the discovery of high-energy (HE, TeV to 100 PeV) astrophysical neutrinos by IceCube [8] has opened a new window to learn more about cosmic accelerators and neutrino interactions at the highest energies. With next-generation experiments pushing sensitivity and energy reach, we anticipate that the wealth of information will expand dramatically. Ultra-high-energy (UHE, >100 PeV) neutrinos, long-sought but not yet detected, provide the only means of directly investigating processes that occur at energy scales of EeV ($\equiv 10^{18}$ eV) and above in the distant Universe. Discovering them would open new regimes of exploration in high-energy physics, astrophysics, and cosmology. In this white paper, we describe the significant physics opportunities offered by cosmic neutrinos and map out the experimental landscape in the coming decades.

Observations of neutrinos from different sources, across different energies and traveled distances, have led to the fundamental-physics conclusions that neutrinos have mass and mix among flavors. These Nobel-prize winning experimental tests include measurements of neutrinos in the sub-GeV-to-10-PeV energy range from cosmic-ray interactions in the atmosphere [9] and of neutrinos from the Sun [10–15]. Indeed, neutrinos access important questions in the complementary fields of high-energy physics and astrophysics. The wide range of neutrino energies and traveled distances allow us to explore neutrino properties, their interactions, and fundamental symmetries across a wide breadth of parameter space, as shown in Fig. 1. And because they are neutral and weakly interacting, they carry information about the physical conditions at their points of origin; at the highest energies, even from powerful cosmic accelerators at the edge of the observable Universe.

Recently, the discovery of a diffuse flux of HE astrophysical neutrinos, in the TeV–PeV range [8, 16] opened a new view to the Universe. They have made possible the direct measurement of weak interactions in a new energy regime, including the neutrino-nucleon cross section [17–19], inelasticity distribution [19],

– 1 –

For Snowmass: focus on particle-physics opportunities, point out complementarity

Complementarity highlighted in the Astro2020 Decadal Survey:

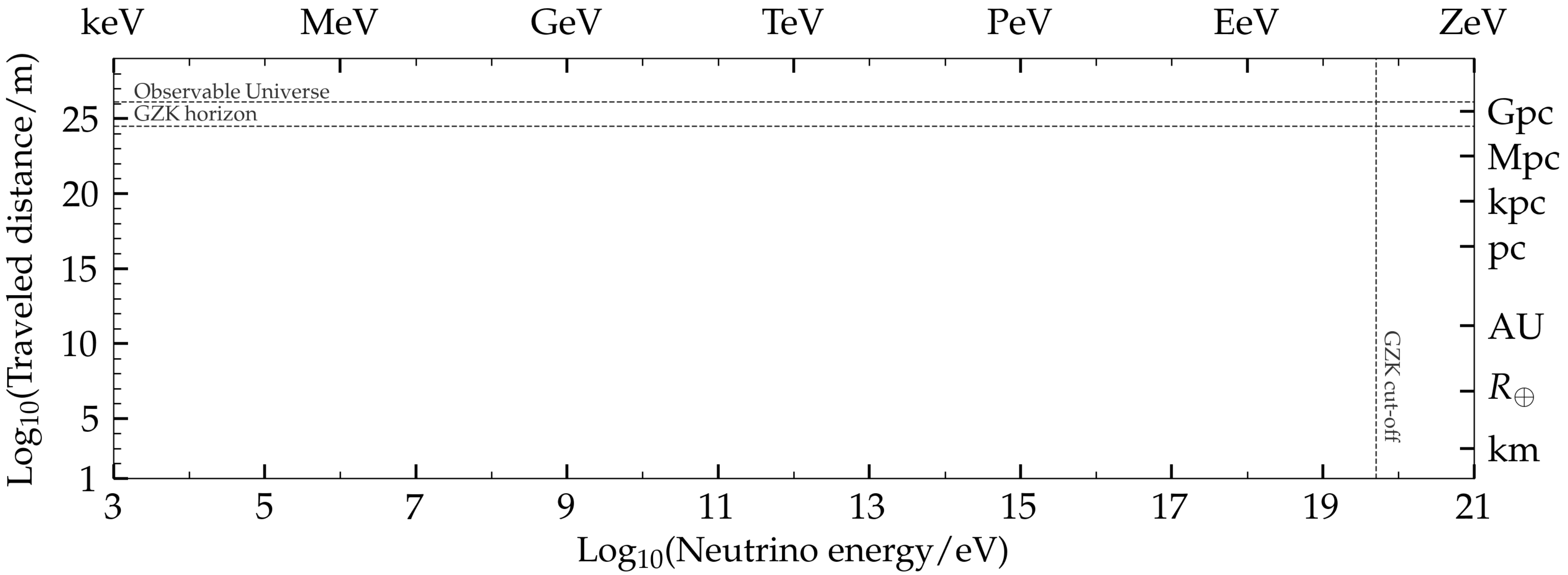
- *Fundamental Physics with High-Energy Cosmic Neutrinos*, 1903.04333
- *Astrophysics Uniquely Enabled by Observations of High-Energy Cosmic Neutrinos*, 1903.04334

High-energy neutrinos: TeV–PeV

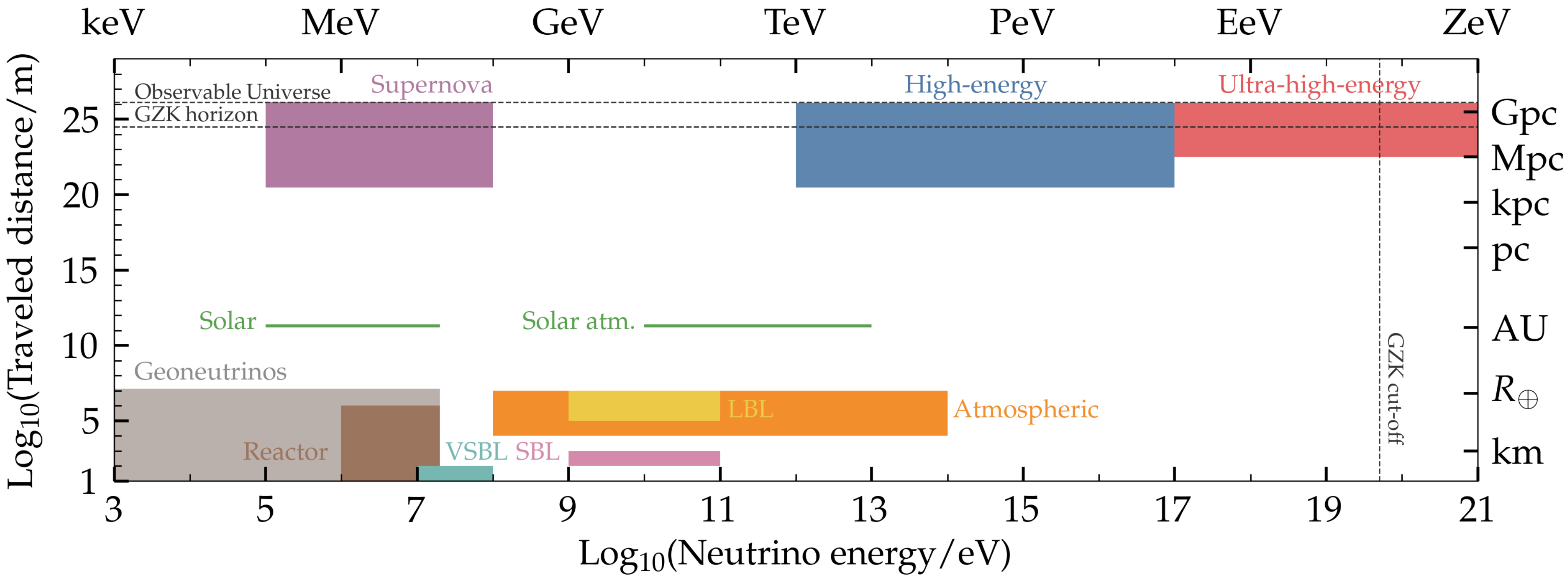
(*Discovered*)

Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

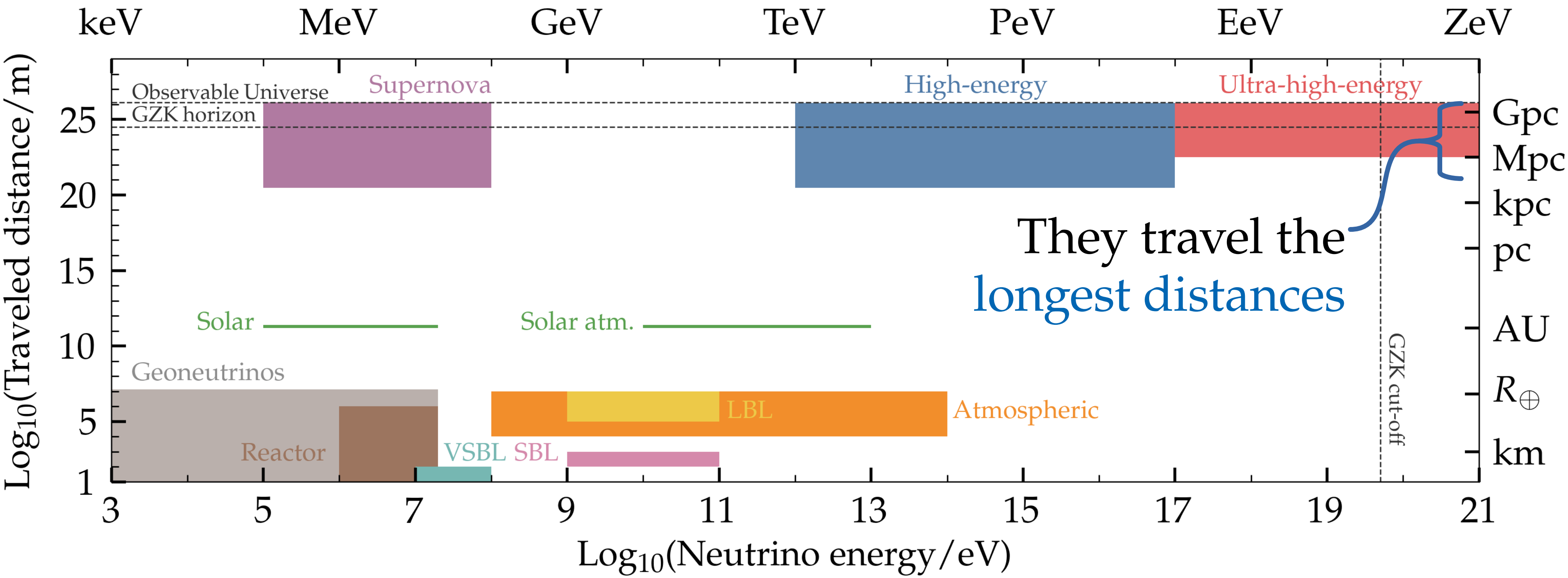


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



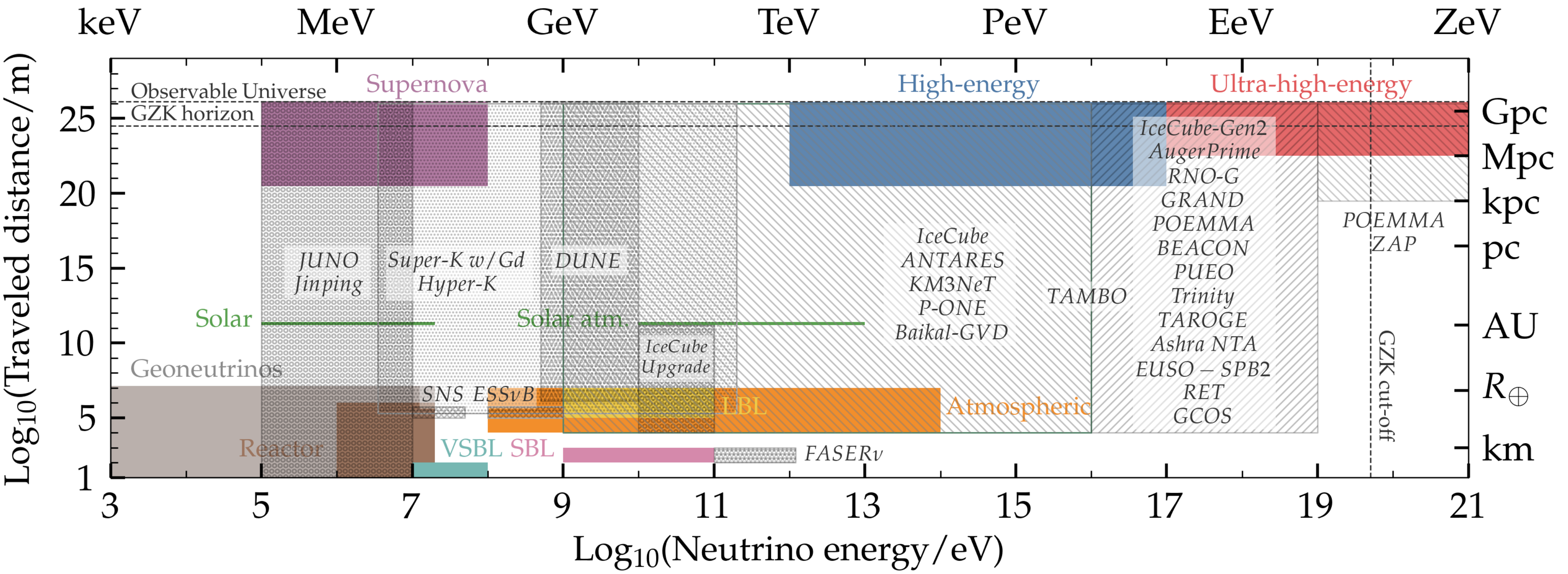
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

They have the highest energies



They travel the longest distances

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



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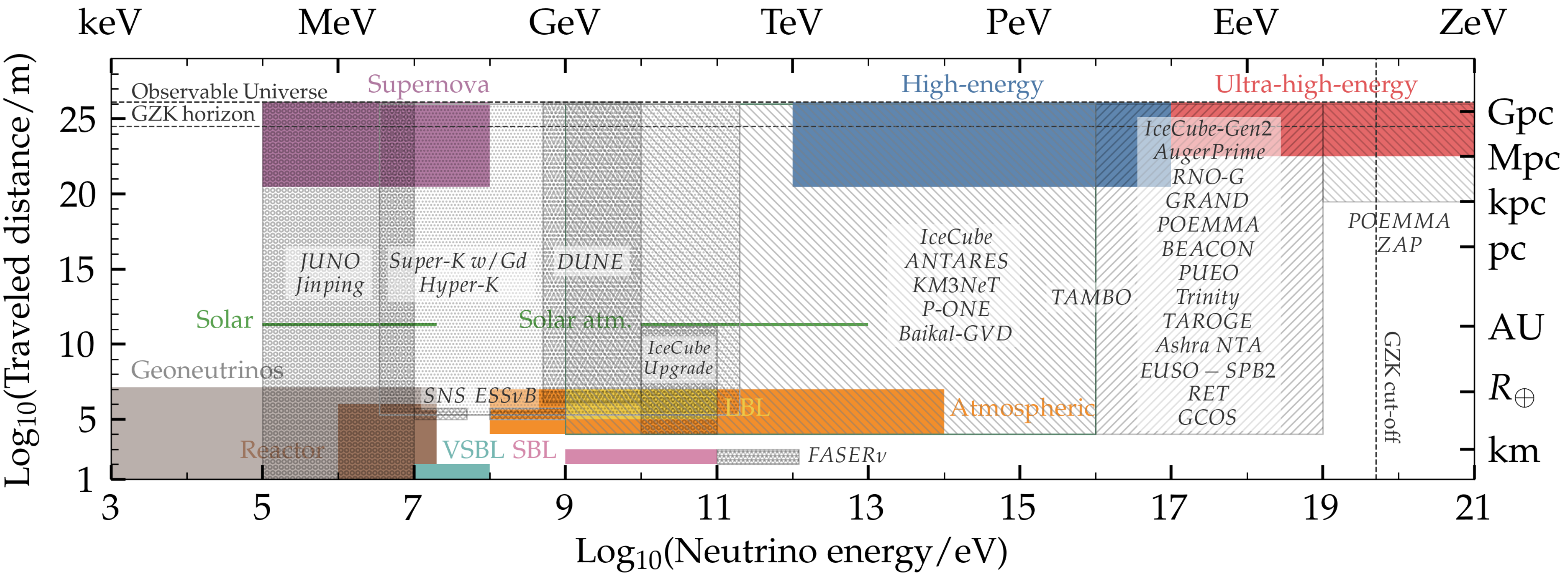


Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

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

TeV–PeV ν

High-energy

Current status:

Discovered (by IceCube, 2013)

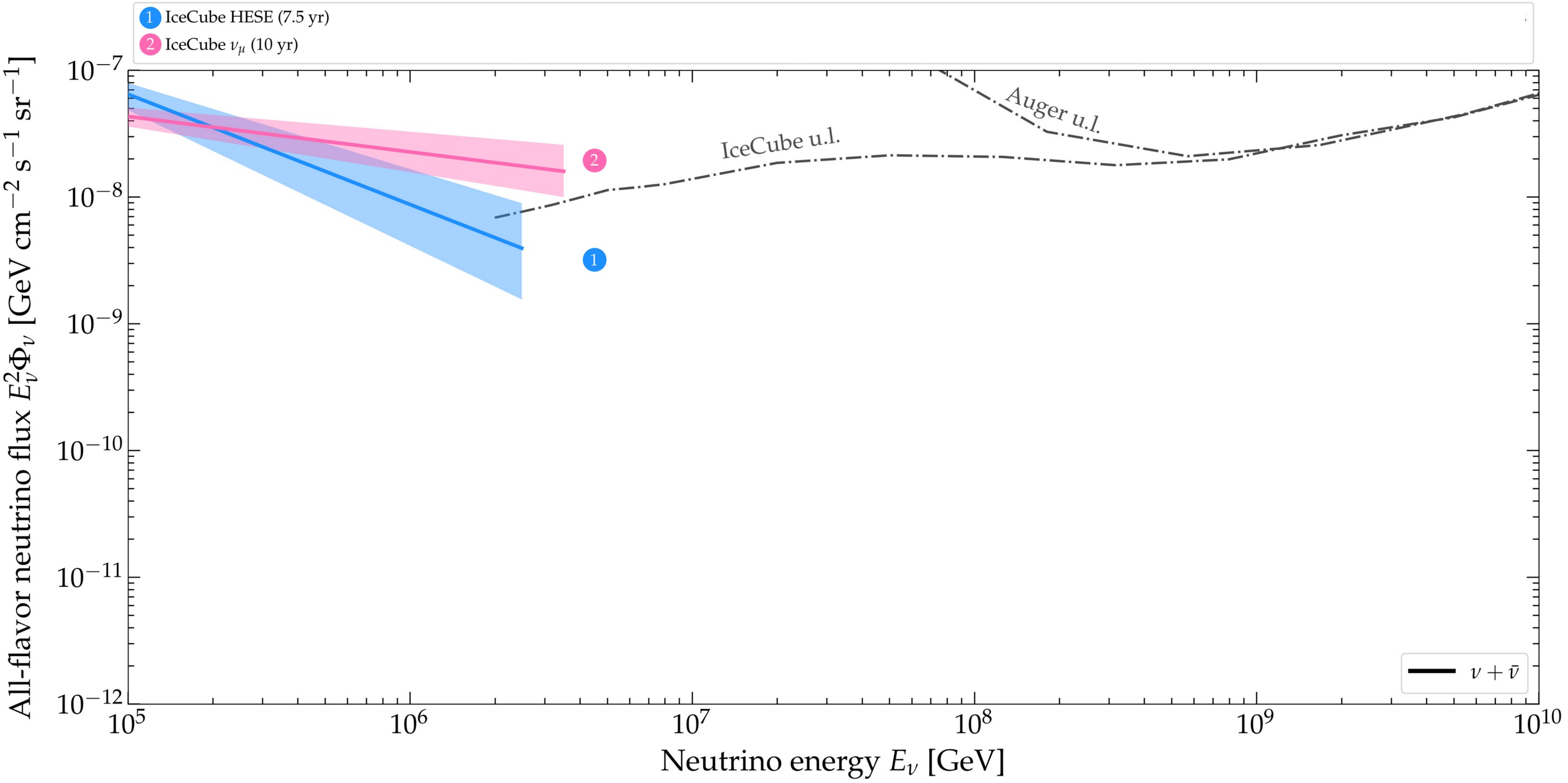
Accumulating statistics

First tests of high-energy ν physics

First promising source candidates

$>$ 100-PeV ν

Ultra-high-energy



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]

TeV–PeV ν

High-energy

Current status

Discovered (by IceCube, 2013)

Accumulating statistics

First tests of high-energy ν physics

First promising source candidates

$>$ 100-PeV ν

Ultra-high-energy

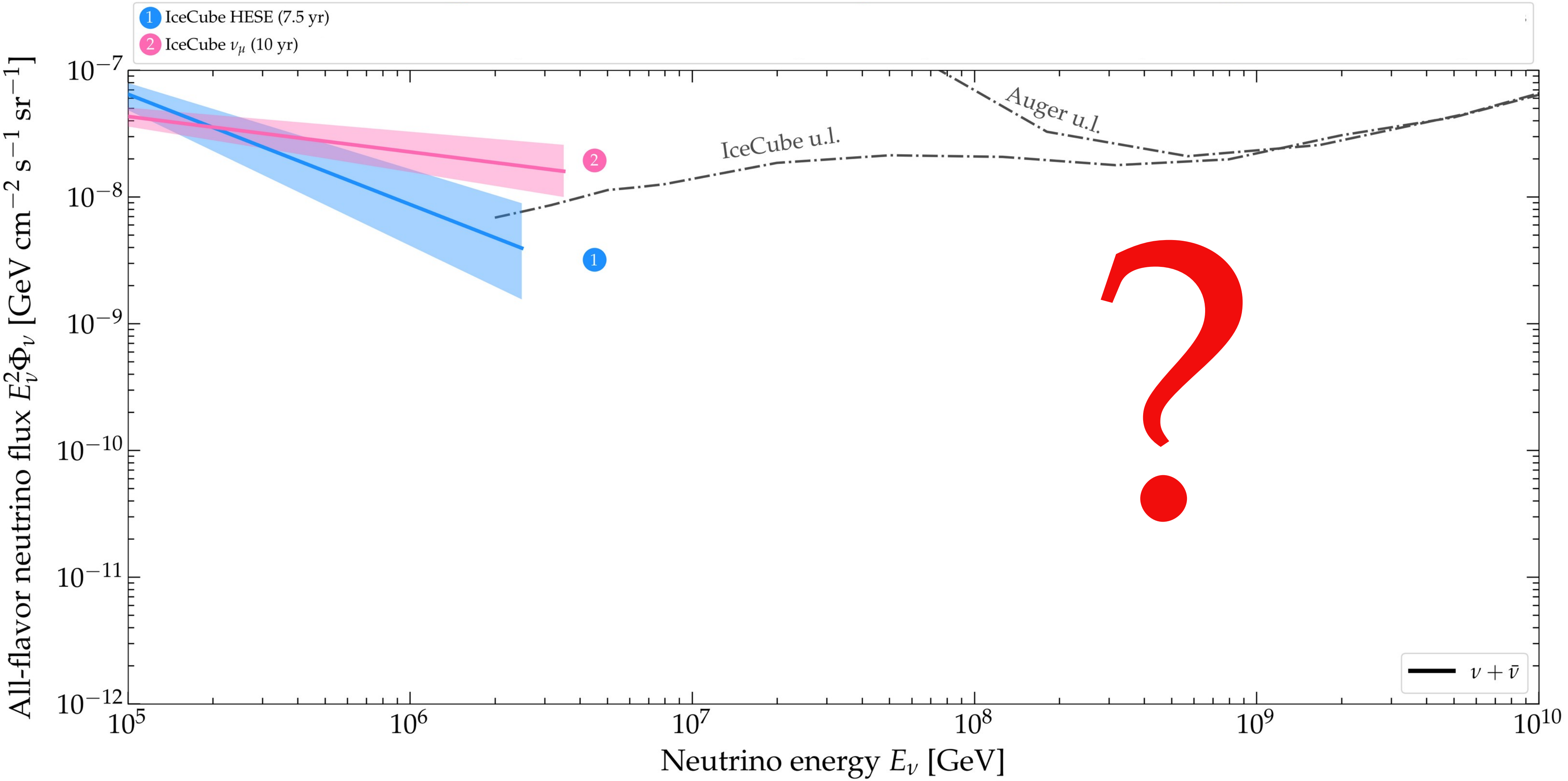
Current status

Predicted (1960s), but undiscovered

Upper limits on their flux

Flux predictions uncertain, improving

Aim for discovery in next-gen detectors



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

1. What are the main physics goals for the next 10–20 years?
2. What theoretical developments do we need to realize these goals?
3. What experiments do we need to realize these goals?
4. Take-home messages

1. What are the main physics goals for the next 10–20 years?
2. What theoretical developments do we need to realize these goals?
3. What experiments do we need to realize these goals?
4. Take-home messages

TeV–PeV ν

High-energy

> 100-PeV ν

Ultra-high-energy

TeV–PeV ν

High-energy

Two energy regimes

$\updownarrow$

Two science thrusts

> 100-PeV ν

Ultra-high-energy

TeV–PeV ν

High-energy

Two energy regimes

$\updownarrow$

Two science thrusts

> 100-PeV ν

Ultra-high-energy

Explore with high statistics

Discover

TeV–PeV ν

High-energy

Two energy regimes

$\updownarrow$

Two science thrusts

$>$ 100-PeV ν

Ultra-high-energy

Explore with high statistics

Discover

Particle physics

Measure high-energy SM predictions

Test BSM predictions

Astrophysics

Find the neutrino sources

Characterize the diffuse flux precisely

TeV–PeV ν

High-energy

Two energy regimes

$\updownarrow$

Two science thrusts

$>$ 100-PeV ν

Ultra-high-energy

Explore with high statistics

Particle physics

Measure high-energy SM predictions

Test BSM predictions

Astrophysics

Find the neutrino sources

Characterize the diffuse flux precisely

Discover

Particle physics

Test physics at highest expected energies

Astrophysics

Find sources of UHE cosmic rays

TeV–PeV ν

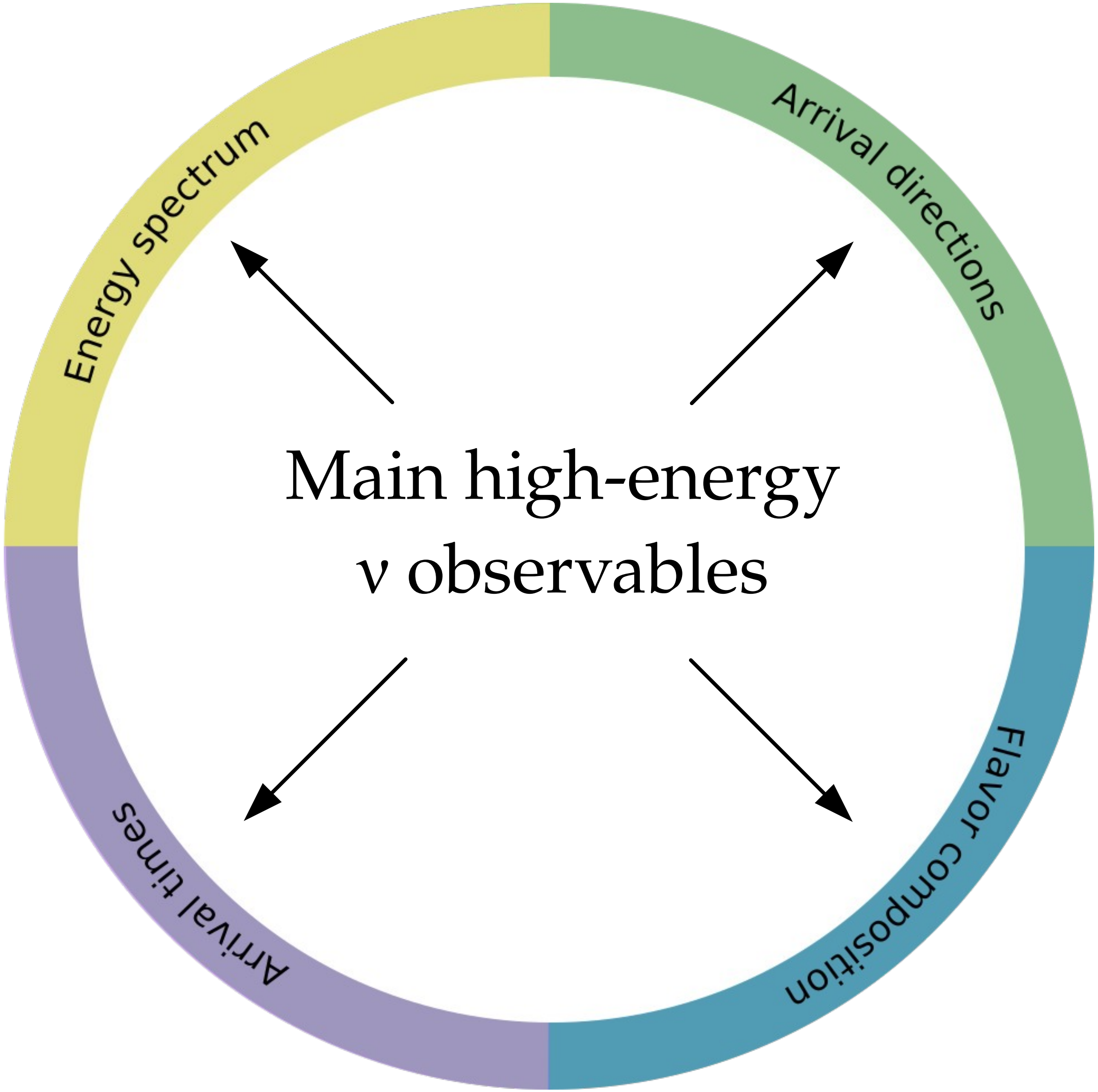
High-energy

Potential also in the multi-PeV transition regime

> 100-PeV ν

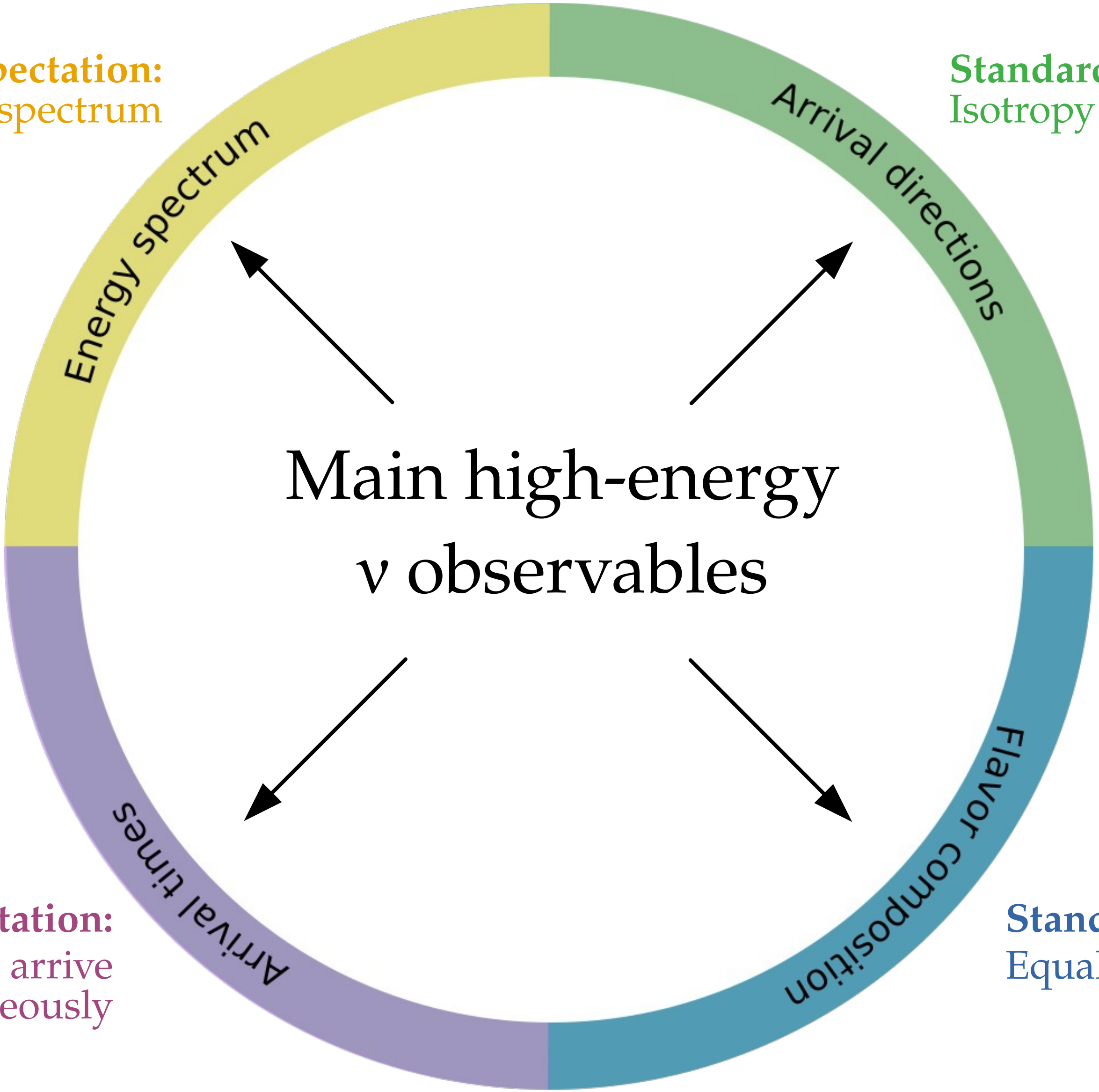
Ultra-high-energy

TeV–PeV ν	> 100-PeV ν
Explore with high statistics	*Discover*
Particle physics	*Particle physics*
Measure high-energy SM predictions Test BSM predictions	Test physics at highest expected energies
Astrophysics	*Astrophysics*
Find the neutrino sources Characterize the diffuse flux precisely	Find sources of UHE cosmic rays


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

Note: Not an exhaustive list

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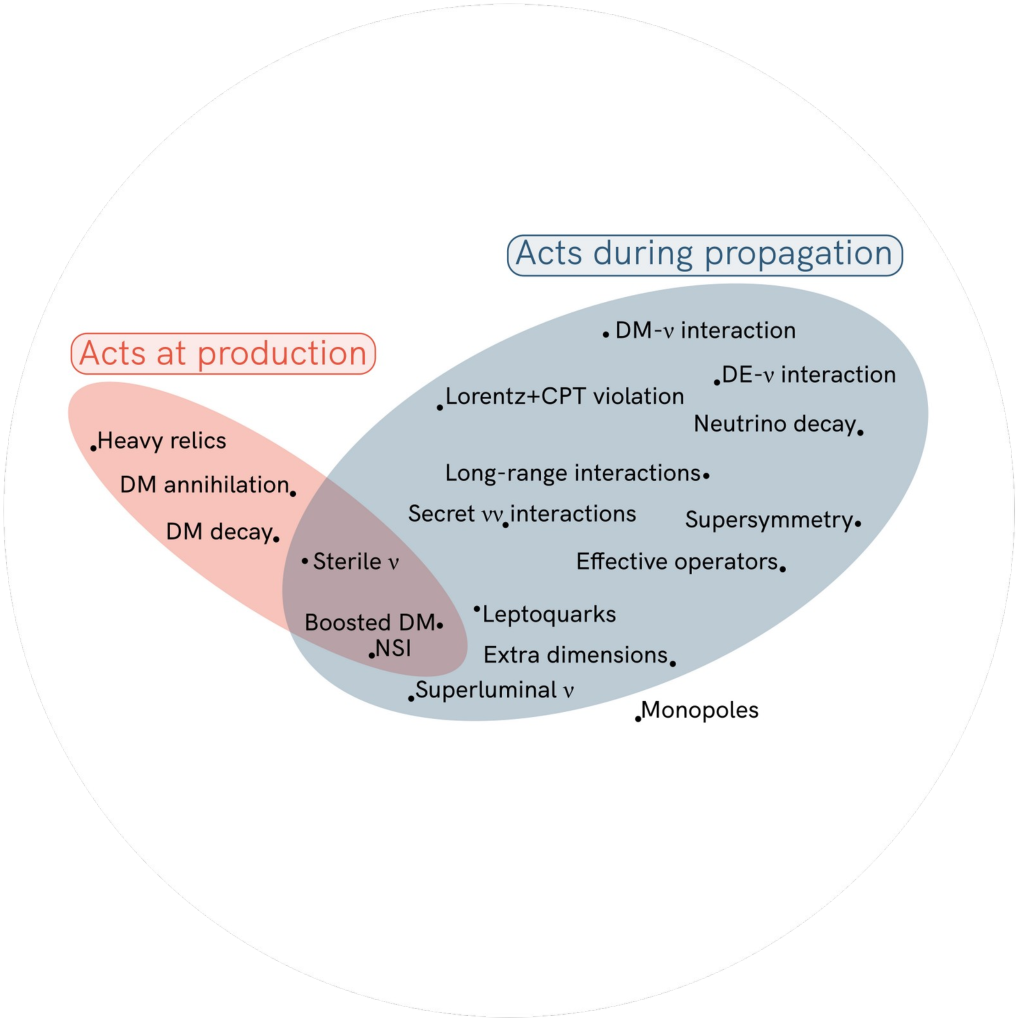

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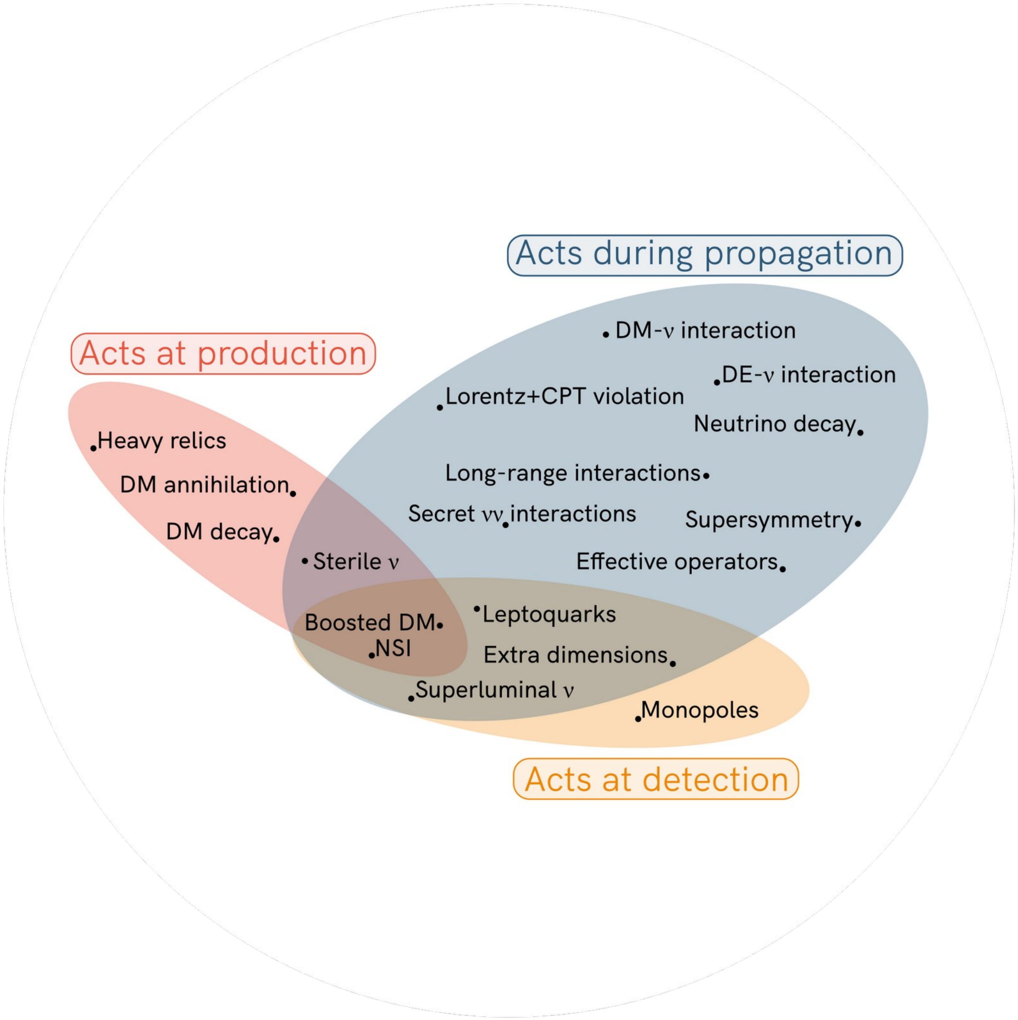

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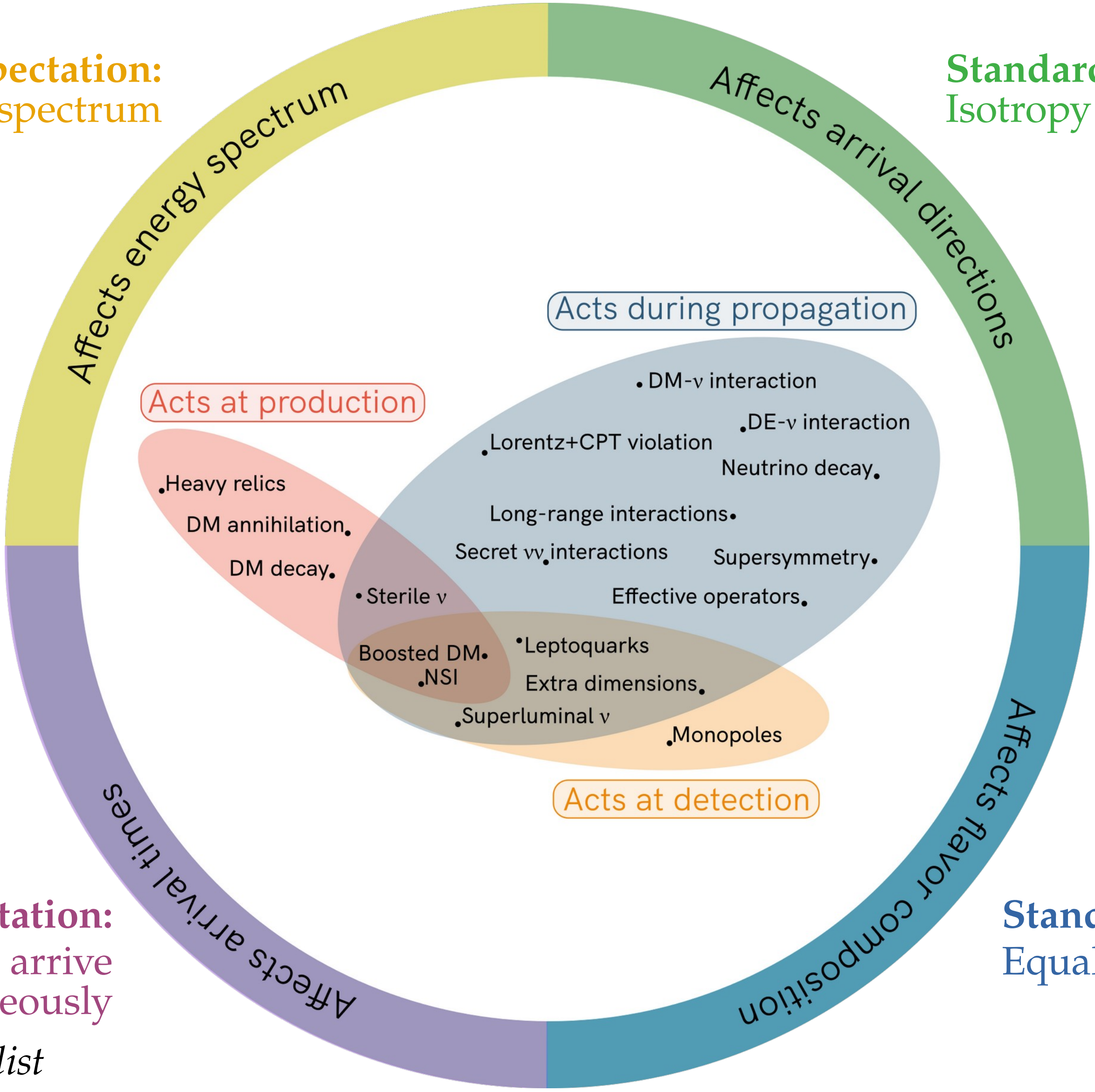

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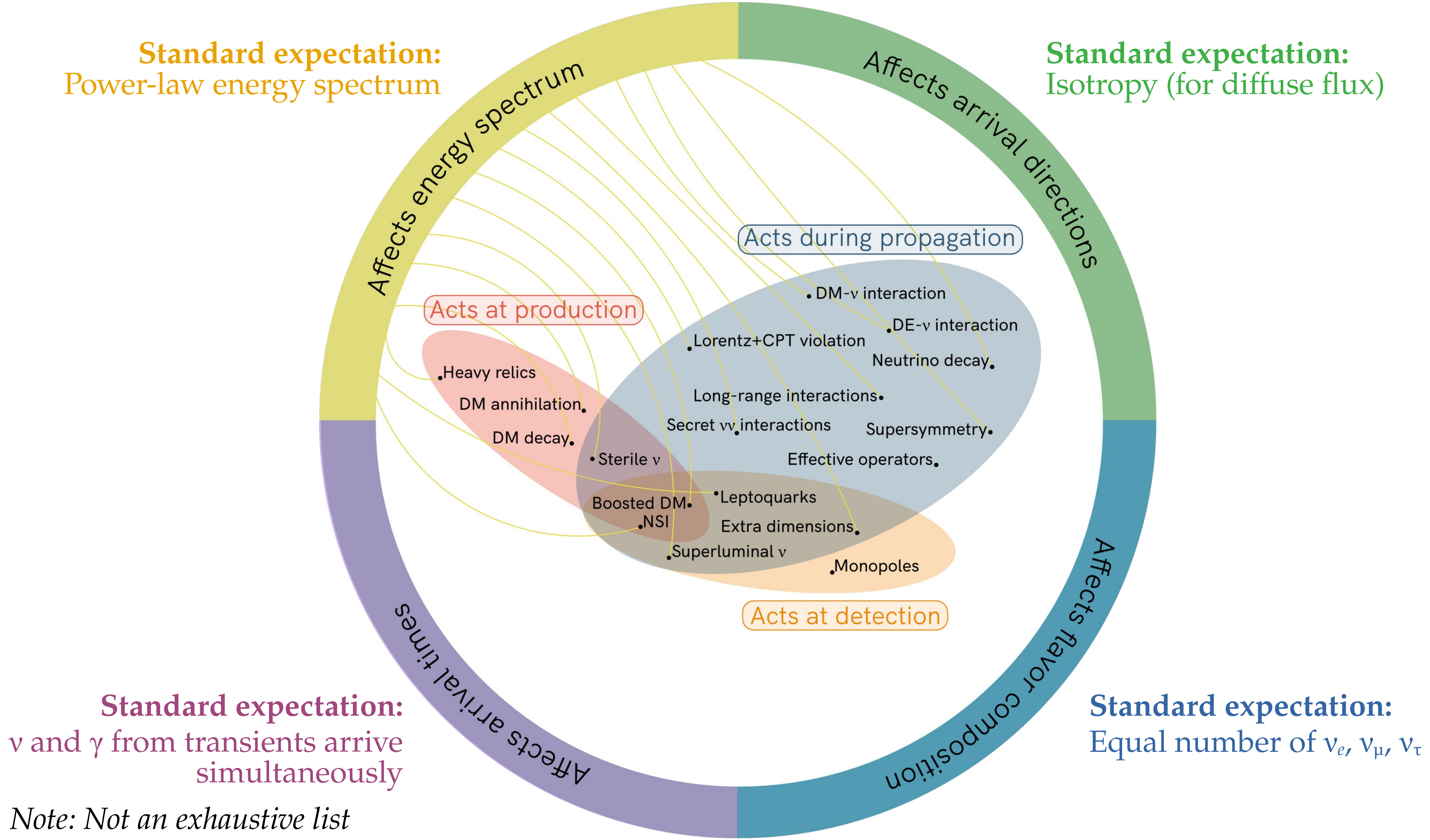

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret νν interactions
Supersymmetry
Sterile ν
Effective operators
Leptoquarks
Boosted DM
NSI
Extra dimensions
Superluminal ν
Monopoles
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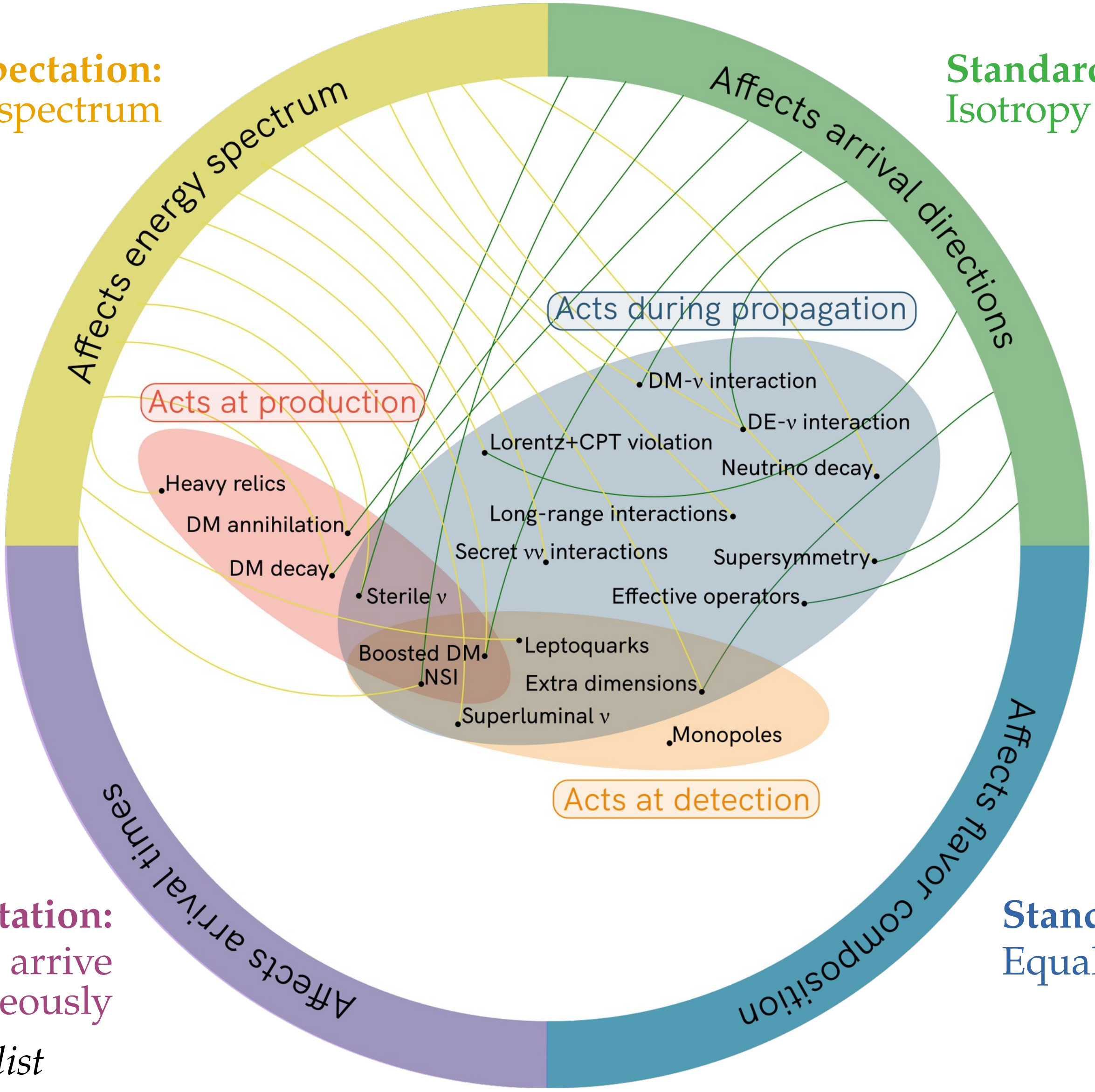

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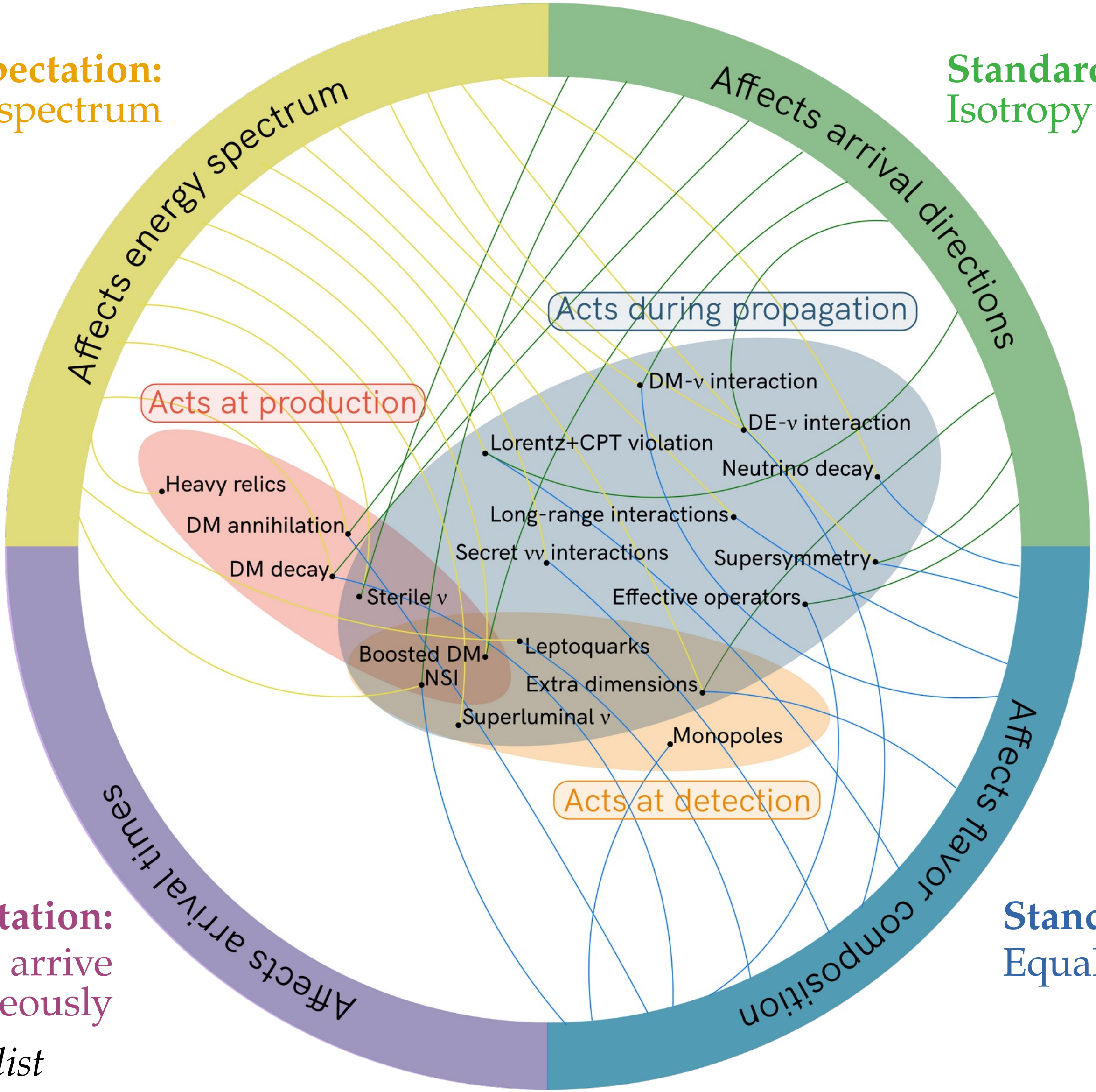

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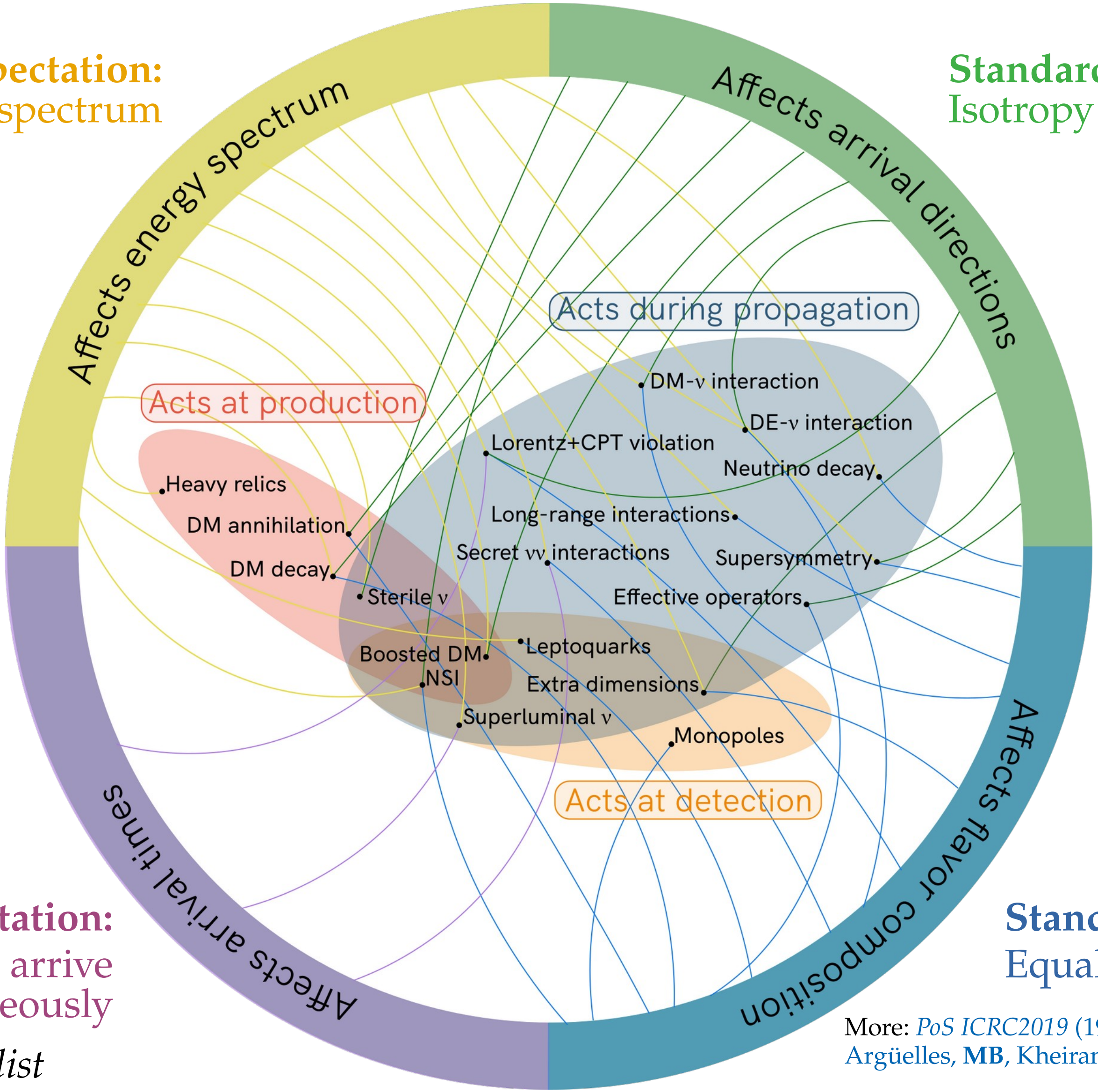

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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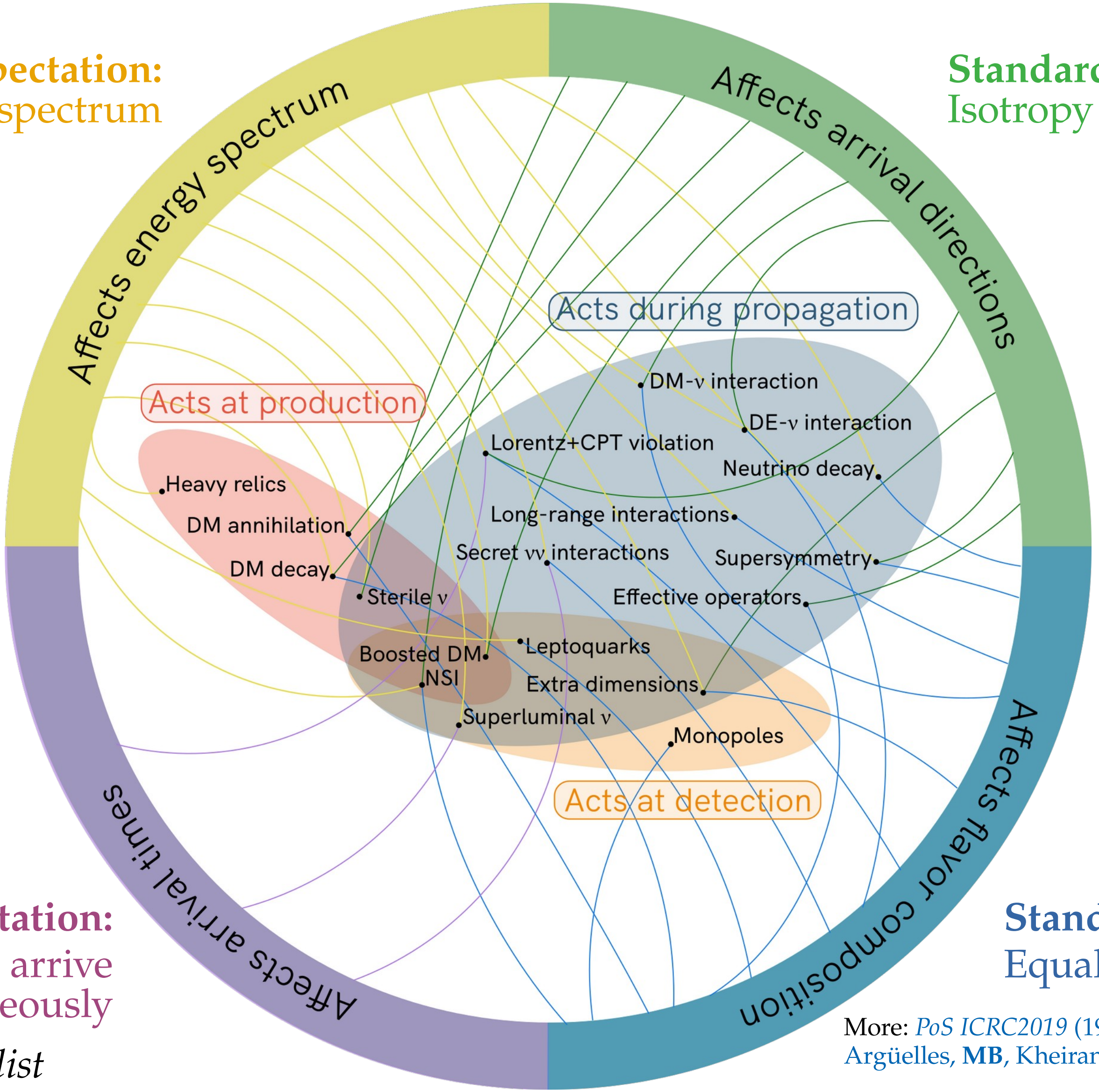

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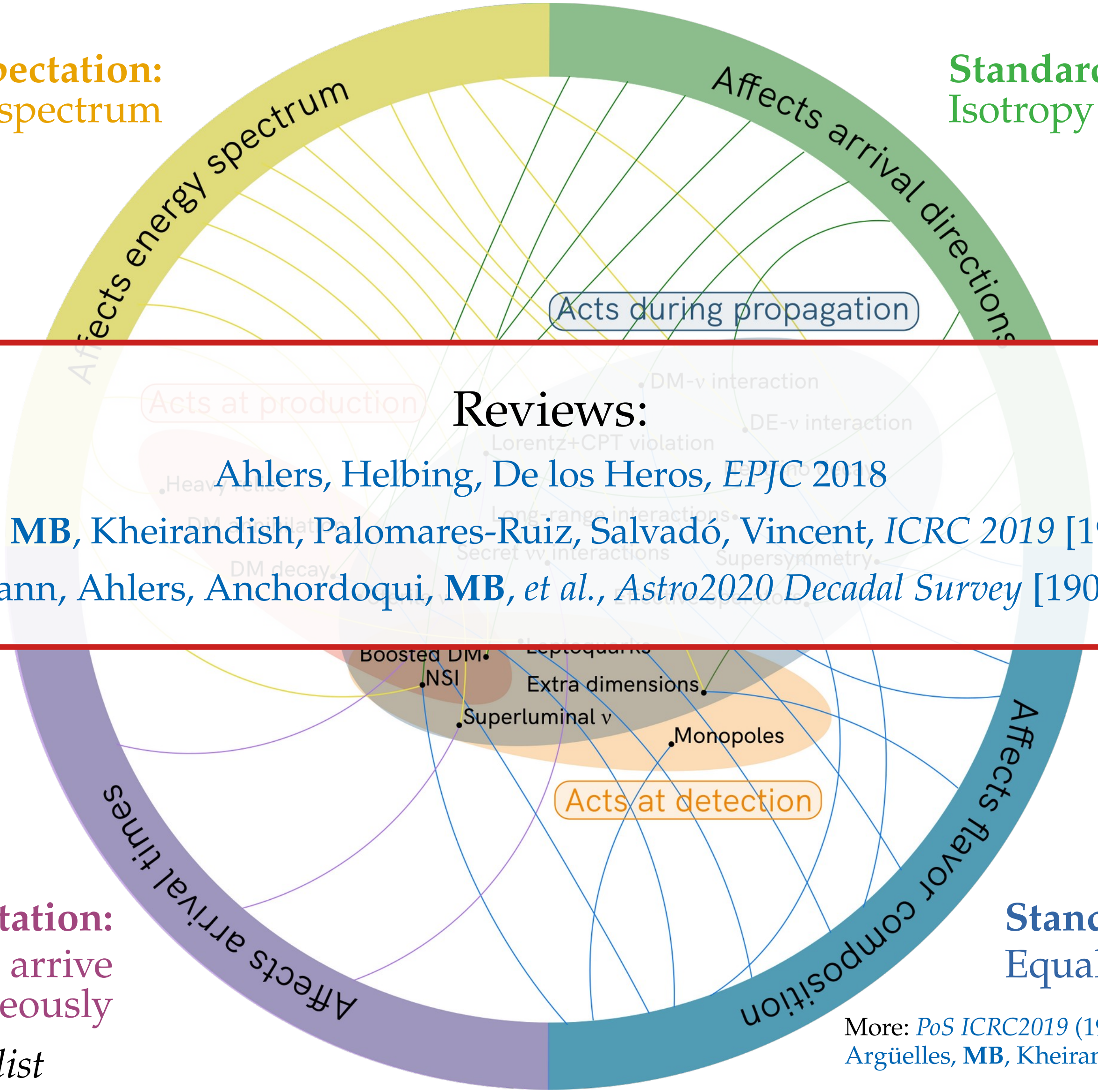

Reviews:

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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First observation of a Glashow resonance

Predicted in 1960:

IceCube, *Nature* 2021
Glashow, *PR* 1960

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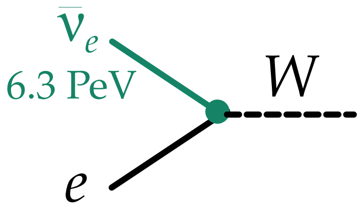

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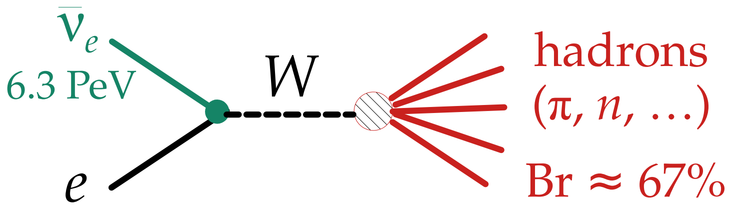

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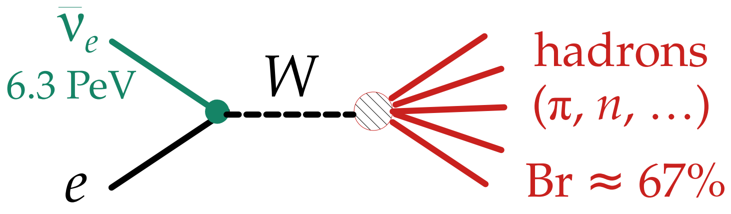

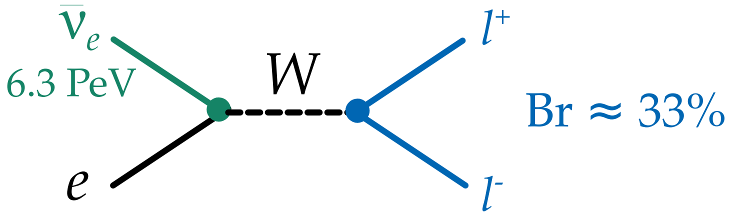

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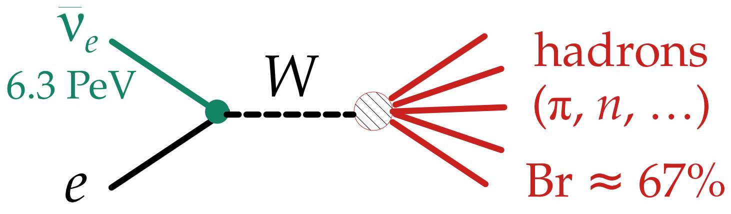
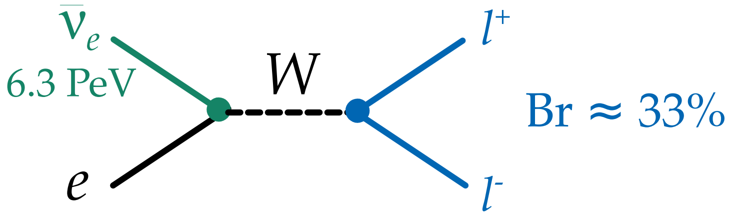
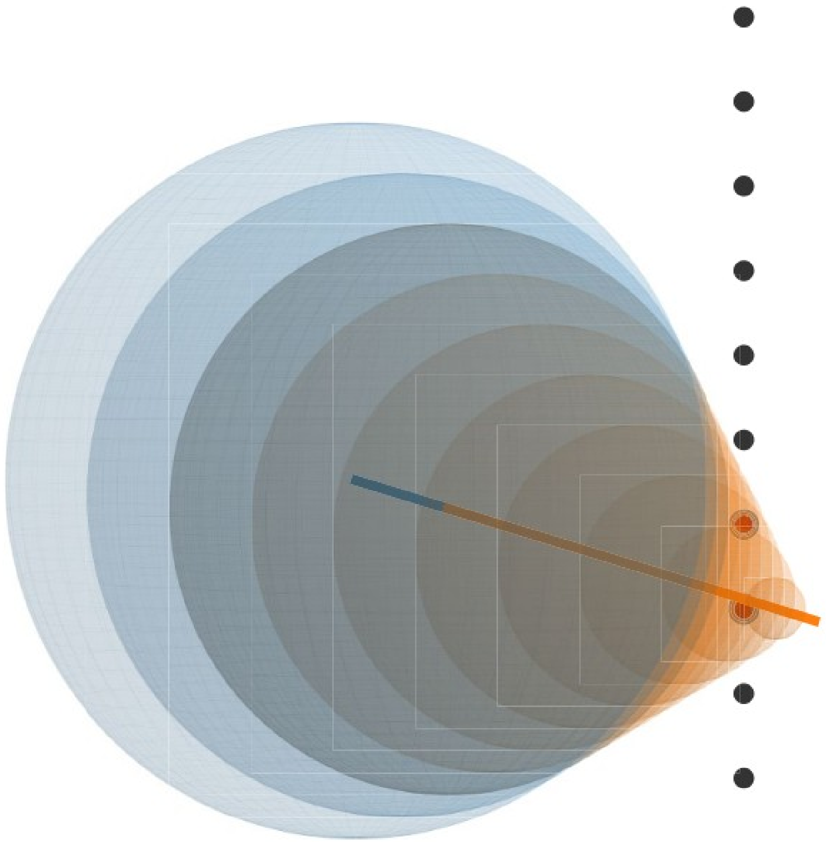


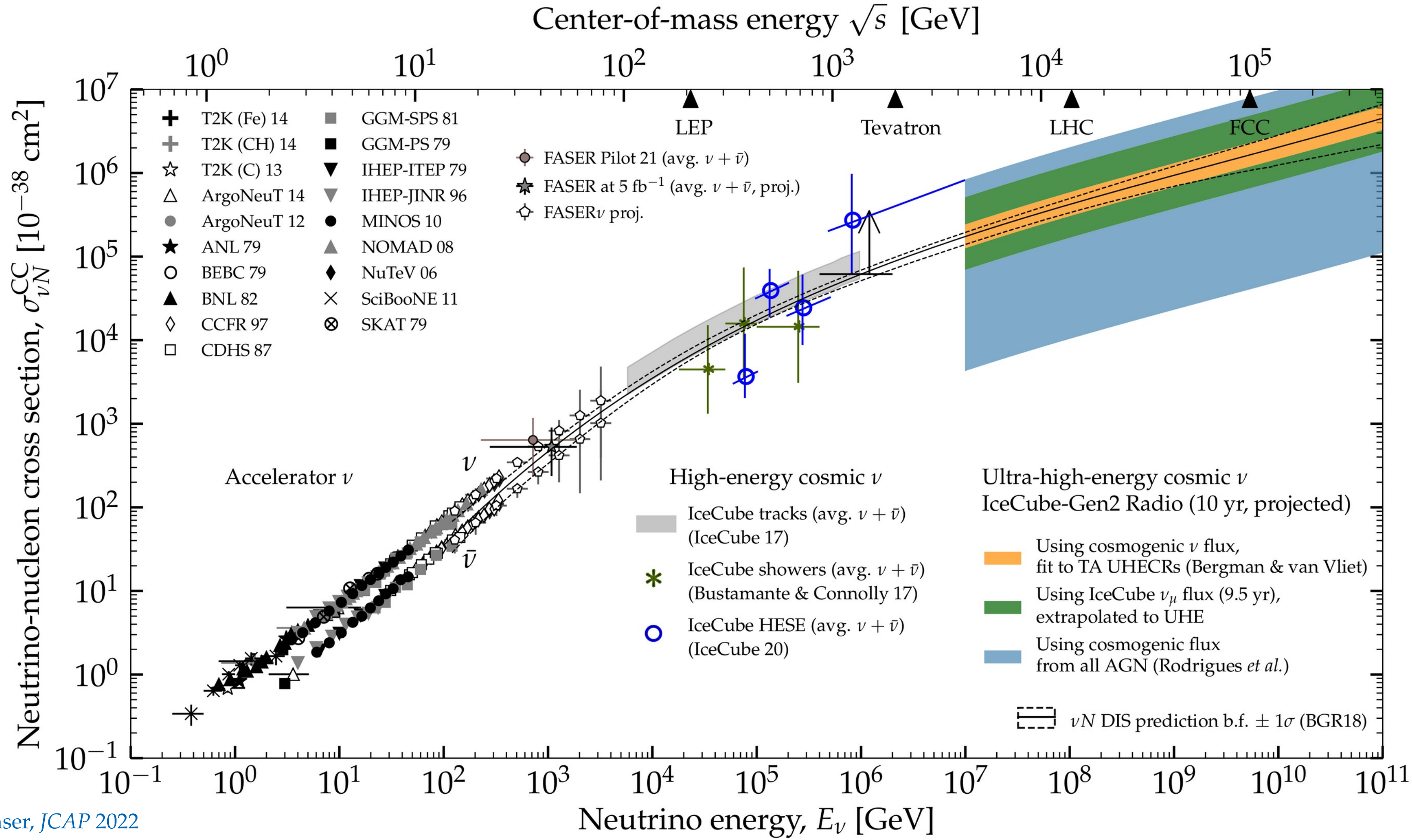


First reported by IceCube in 2021:



IceCube, *Nature* 2021
Glashow, *PR* 1960

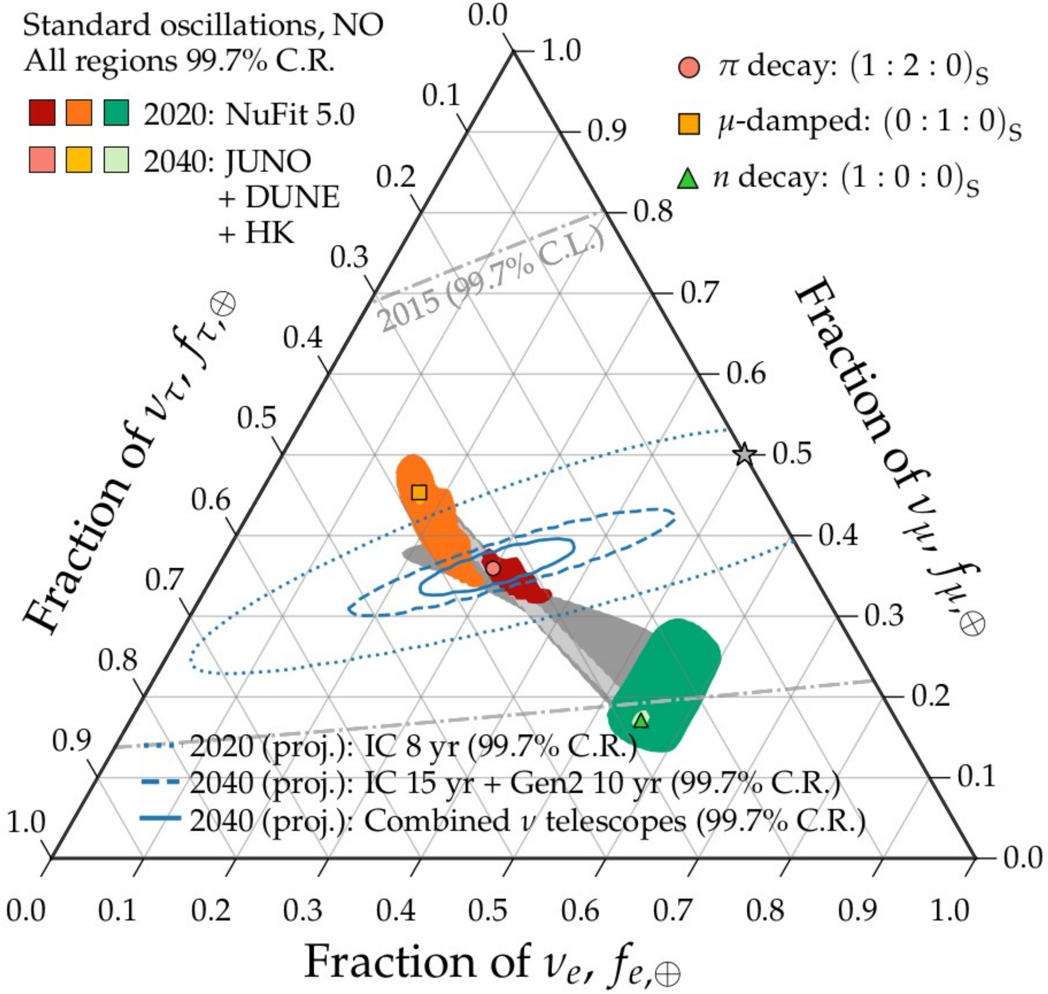
Measuring the high-energy neutrino-nucleon cross section



Valera, **MB**, Glaser, *JCAP* 2022
Adapted for Snowmass

Physics in the flavor composition

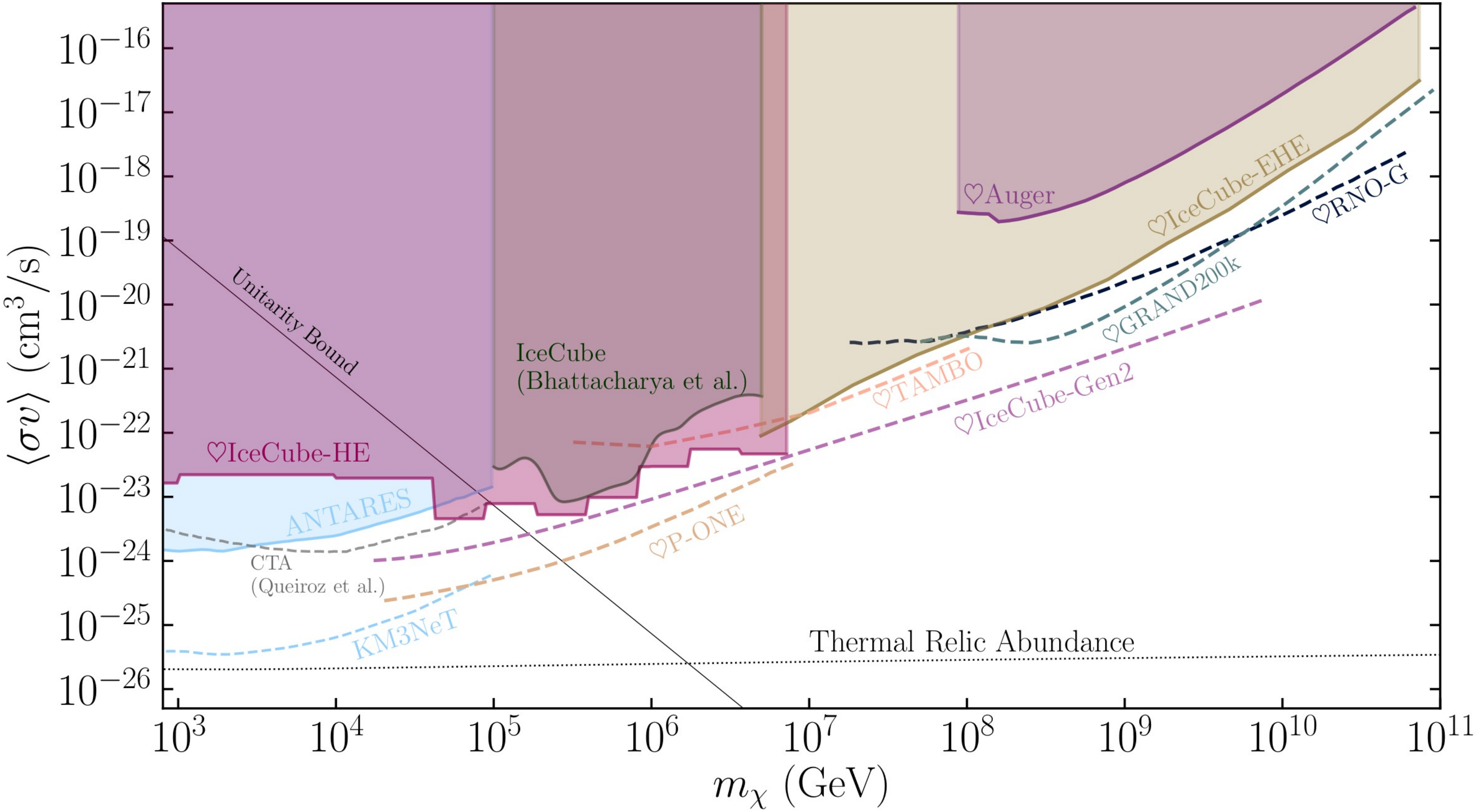
Important:
Improvement possible *only* from synergy with mixing-parameter measurements in oscillations experiments (DUNE, JUNO, Hyper-K, IceCube Upgrade)



See the talk by Teppei Katori

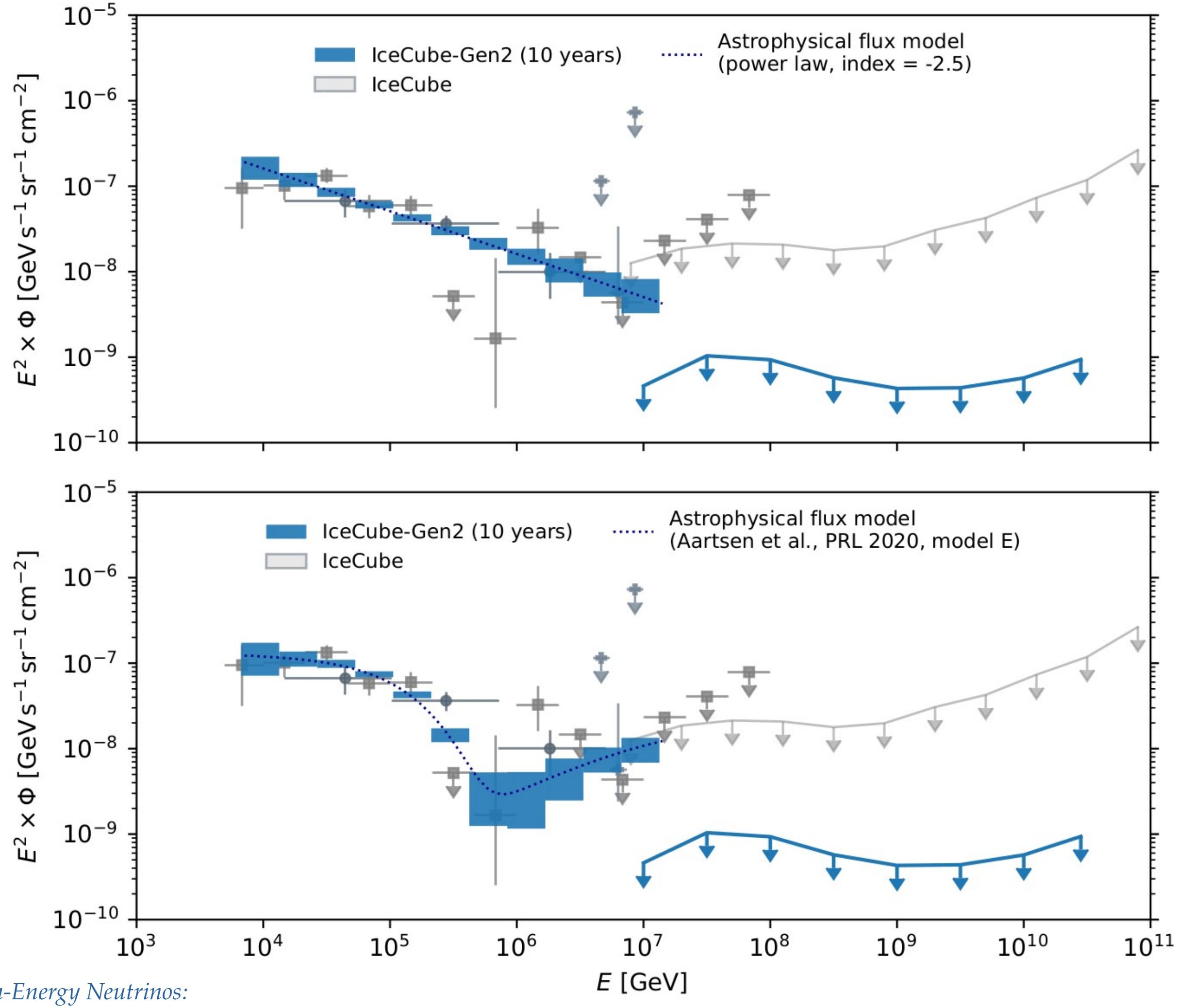
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Neutrinos from heavy dark-matter annihilation



Argüelles, Diaz, Kheirandish, Olivares del Campo, Safa, Vincent, *RMP* 2021

Characterizing the TeV–PeV neutrino flux



Ackermann *et al.*, *High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper*, 2203.08096

1. What are the main physics goals for the next 10–20 years?
2. What theoretical developments do we need to realize these goals?
3. What experiments do we need to realize these goals?
4. Take-home messages

Make predictions & analyses more sophisticated

Particle physics

Explore larger model parameter spaces

Fully account for astrophysical uncertainties

Astrophysics

Abandon assumption that all sources are identical

More complete multi-messenger models

1. What are the main physics goals for the next 10–20 years?
2. What theoretical developments do we need to realize these goals?
3. **What experiments do we need to realize these goals?**
4. Take-home messages

TeV–PeV ν

High-energy

Strategy

Multi km-scale in-ice & in-water Cherenkov detectors

Status

Under design, prototype, deployment

(IceCube, IceCube-Gen2, KM3NeT, Baikal-GVD, P-ONE)

Challenges

Familiar tech; mainly logistical + funding

> 100-PeV ν

Ultra-high-energy

TeV–PeV ν

High-energy

Strategy

Multi km-scale in-ice & in-water Cherenkov detectors

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Under design, prototype, deployment

(IceCube, IceCube-Gen2, KM3NeT, Baikal-GVD, P-ONE)

Challenges

Familiar tech; mainly logistical + funding

> 100-PeV ν

Ultra-high-energy

Strategy

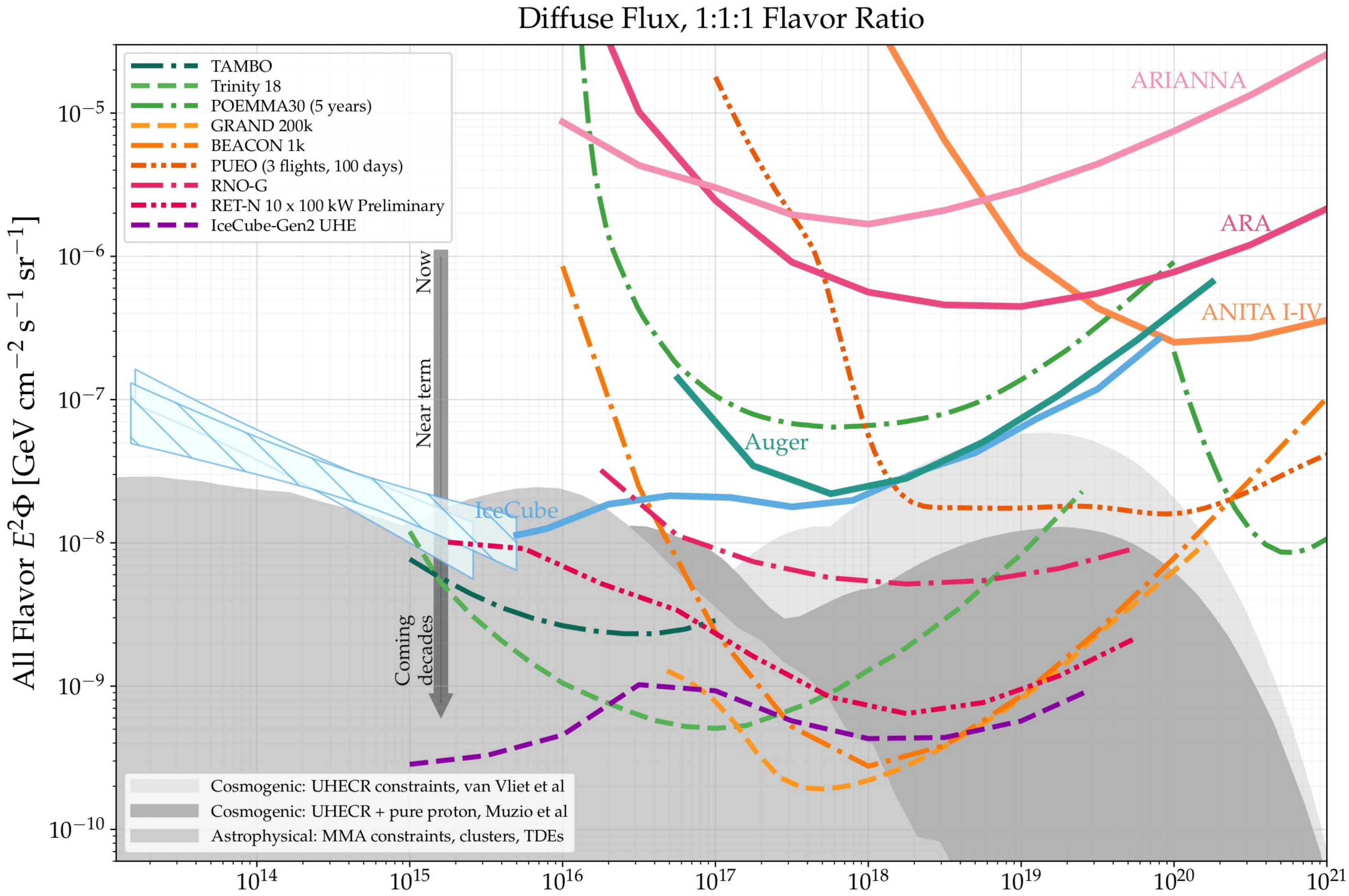
In-ice & in-water Cherenkov too expensive; use more scalable techniques

Status

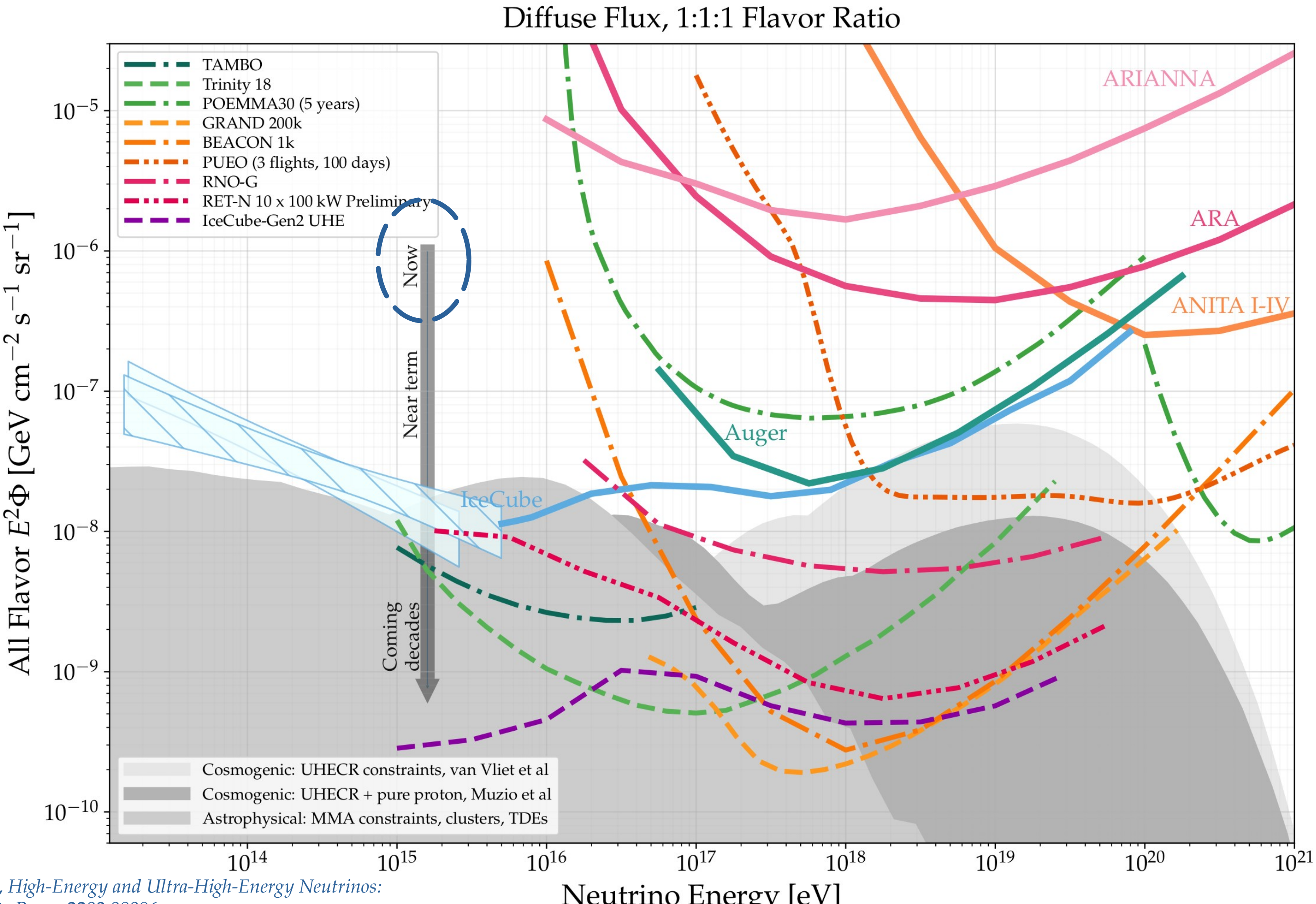
Multiple techniques under consideration & in pathfinding stage (radio in-ice, in-air, from ground, radar, imaging, fluorescence, particles on ground)

Challenges

New techniques, capabilities in flux

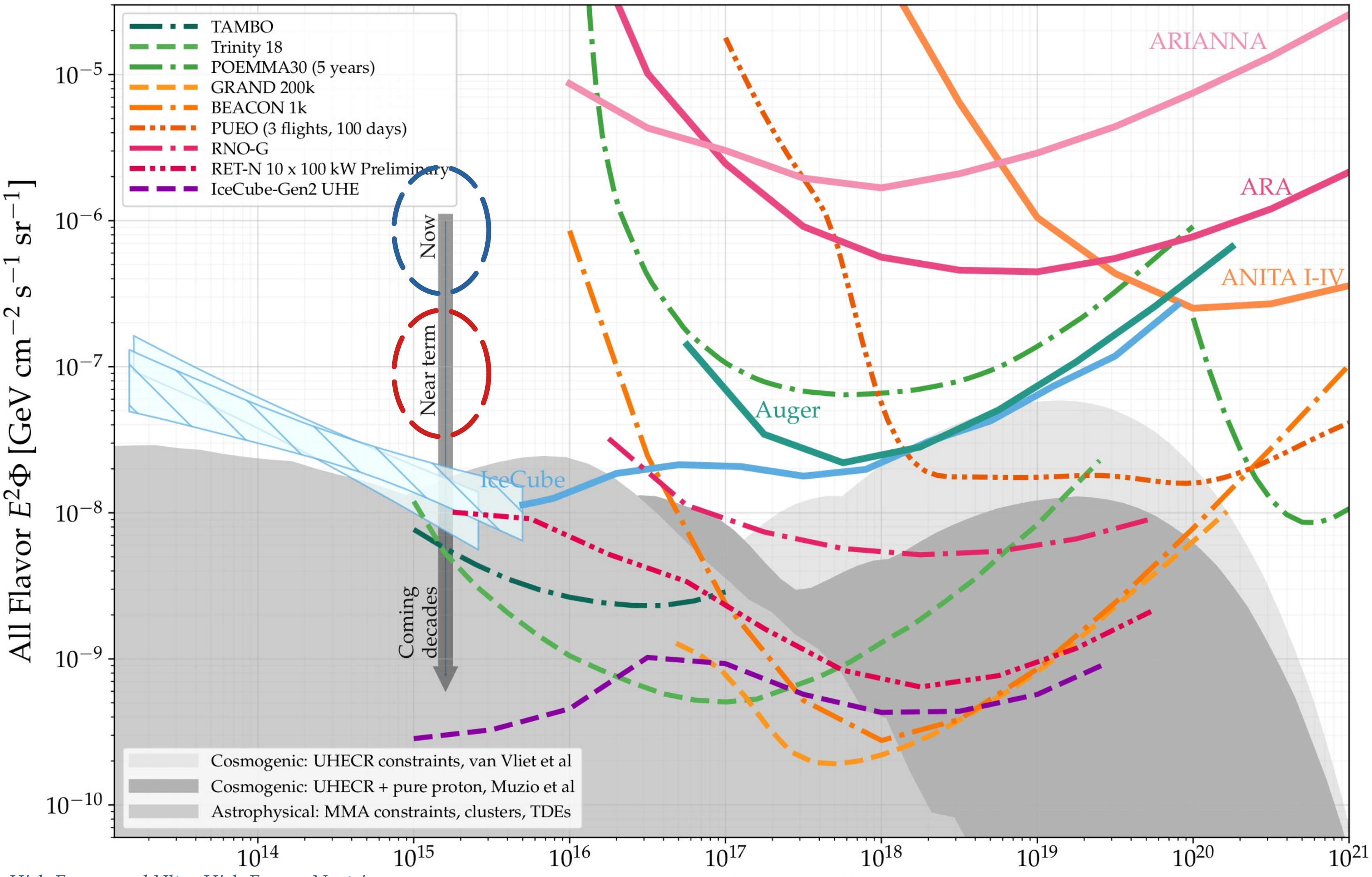


Ackermann *et al.*, *High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper*, 2203.08096



Ackermann *et al.*, *High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper*, 2203.08096

Diffuse Flux, 1:1:1 Flavor Ratio



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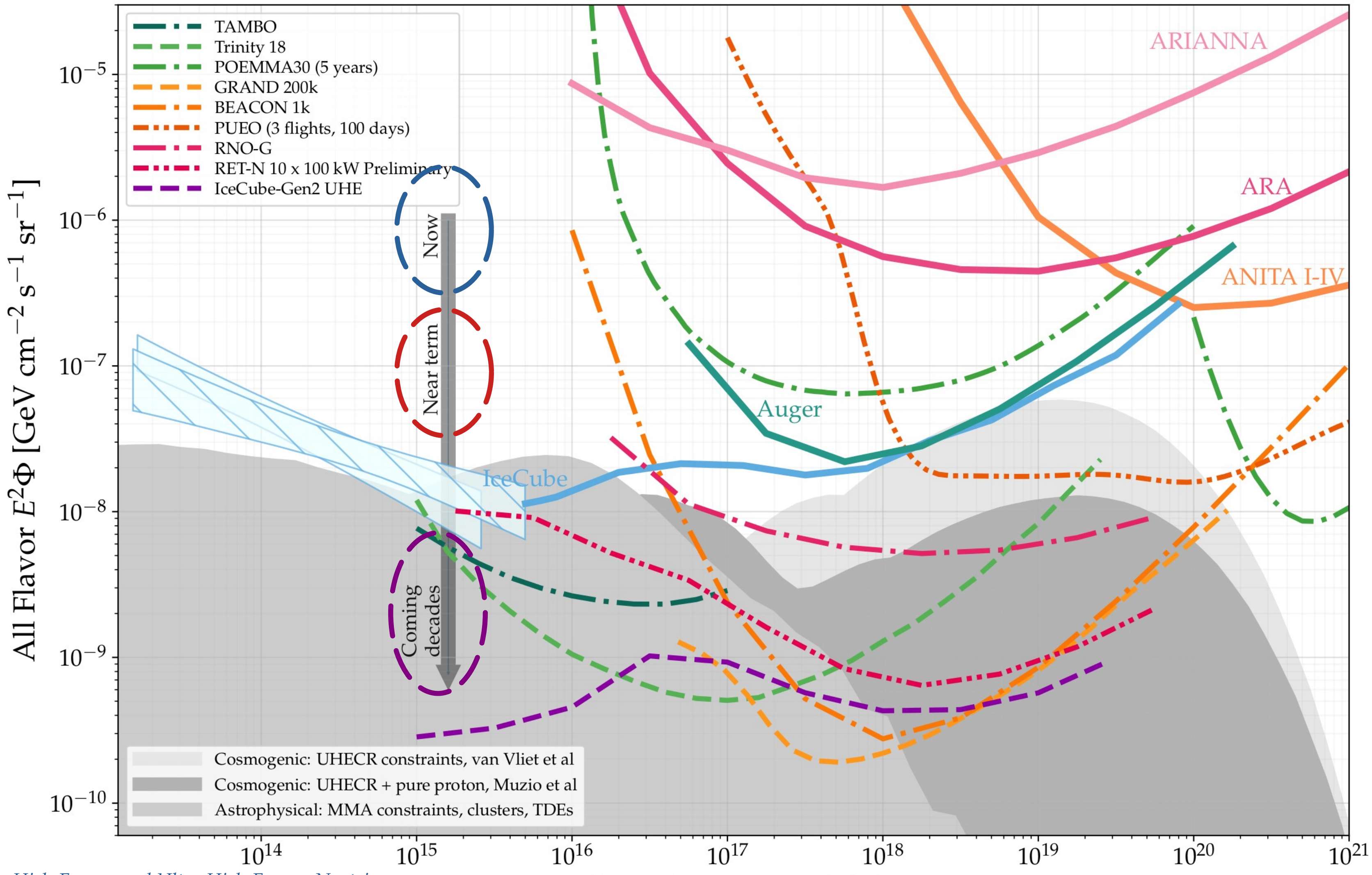
Diffuse Flux, 1:1:1 Flavor Ratio



Ackermann *et al.*, *High-Energy and Ultra-High-Energy Neutrinos: A Snowmass White Paper*, 2203.08096

1. What are the main physics goals for the next 10–20 years?

2. What theoretical developments do we need to realize these goals?

3. What experiments do we need to realize these goals?

4. Take-home messages

The potential

High-energy and ultra-high-energy neutrinos have vast potential for particle physics (& astrophysics!)

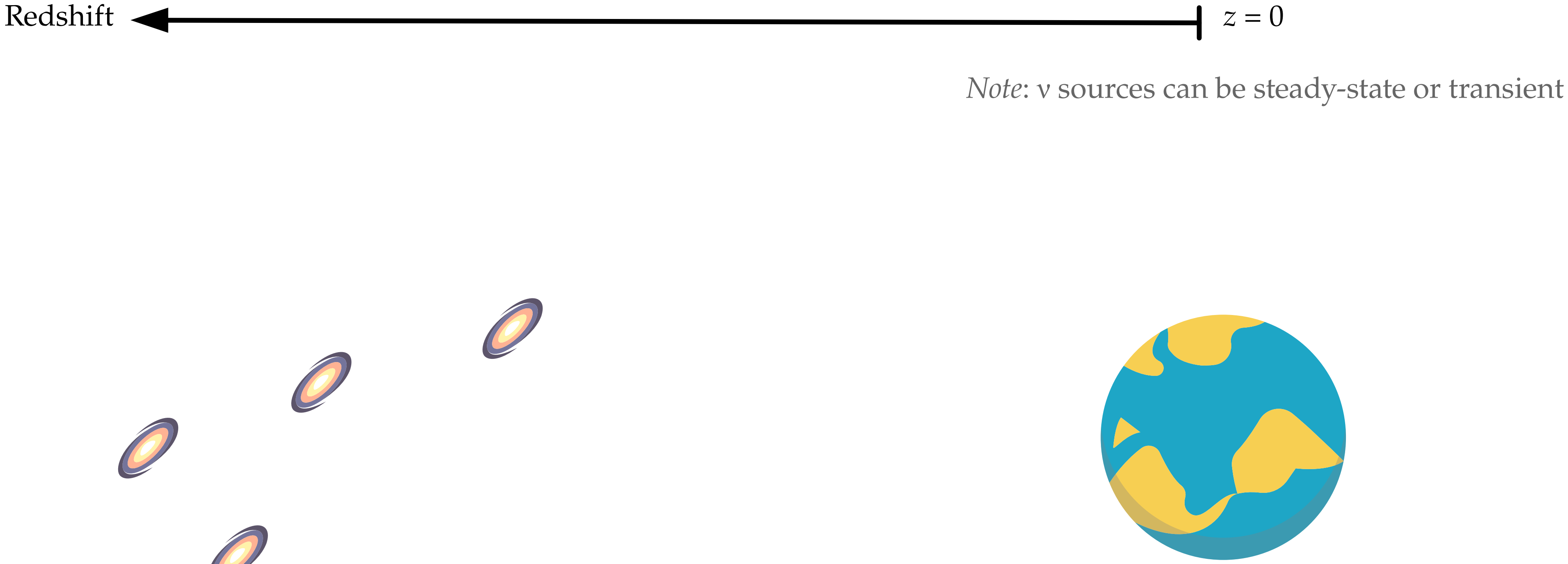
The delivery

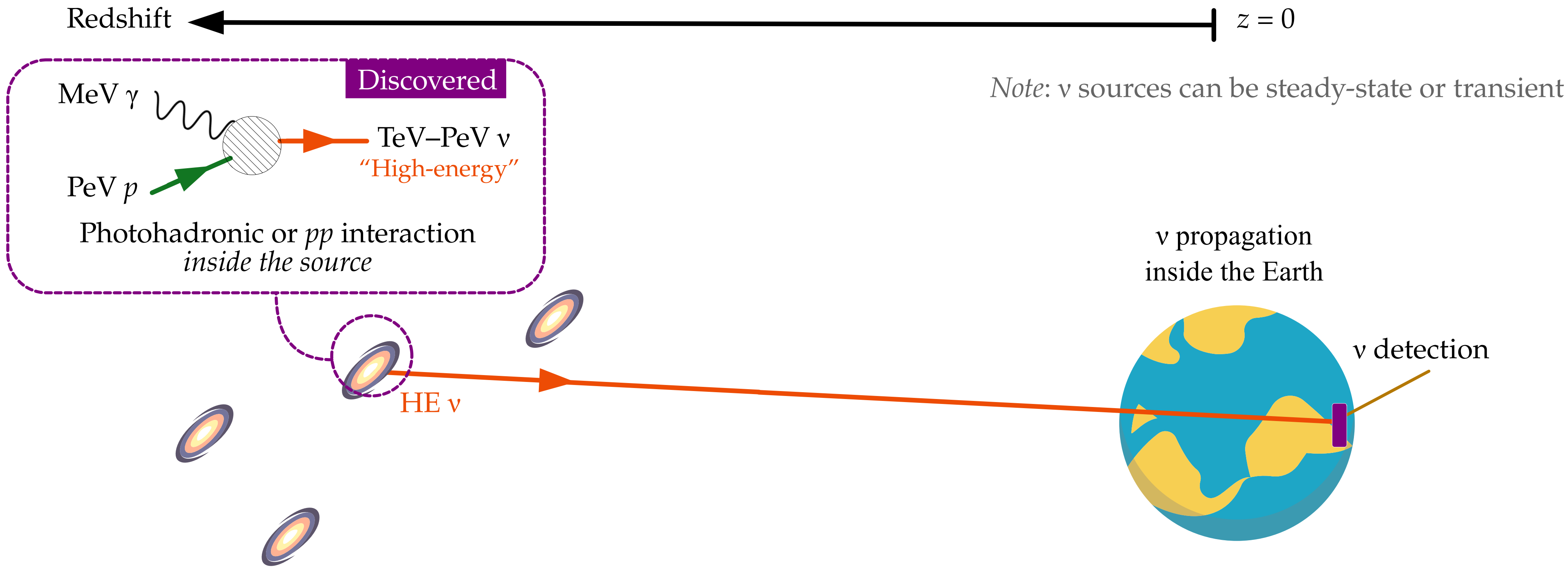
These studies are being done already today, in spite of limited statistics and astrophysical unknowns

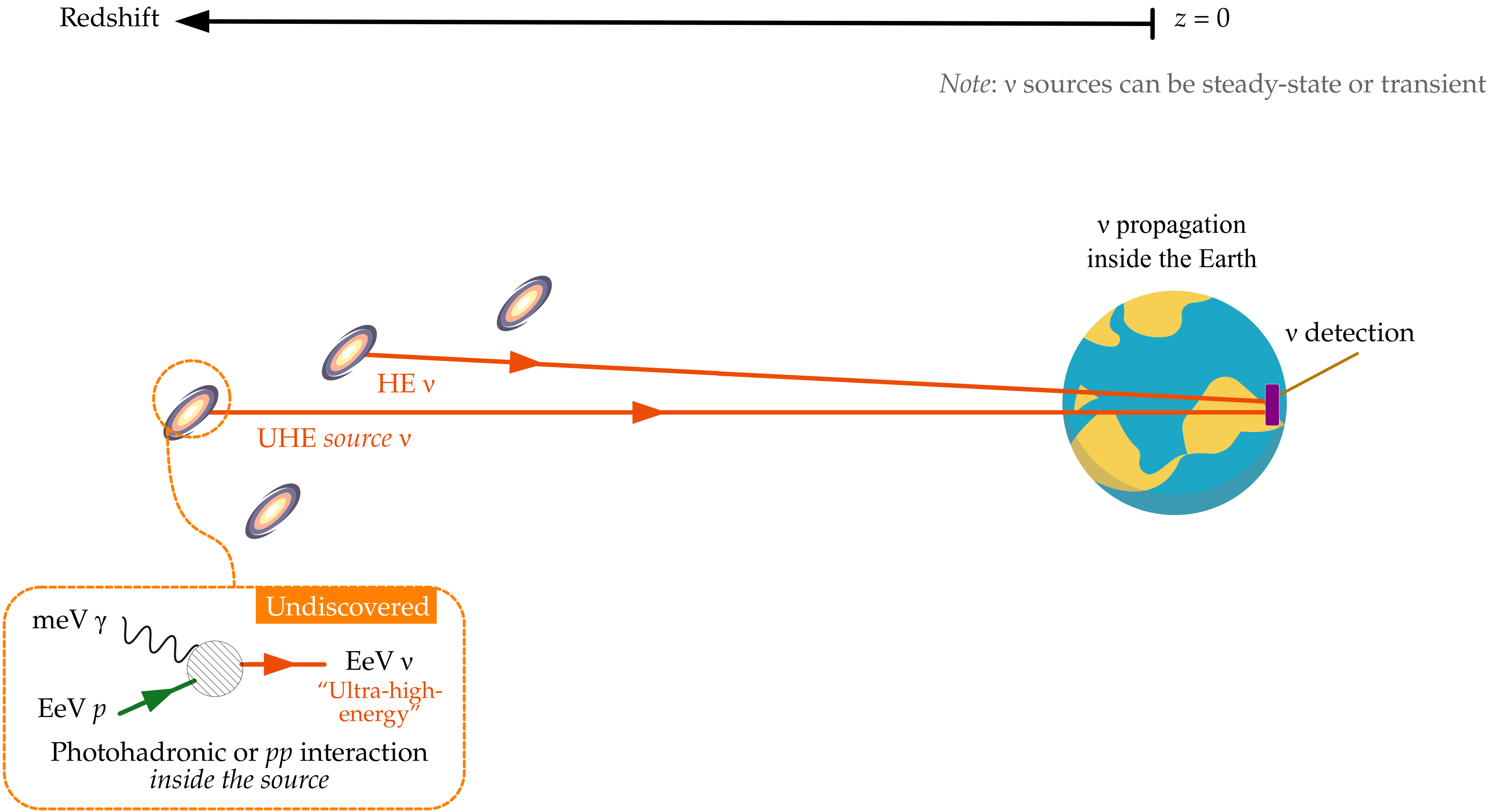
Theory: *need more nuance to achieve robustness*—
- Particle physics: factor in astrophysical uncertainties
- Astrophysics: move beyond identical-source estimates

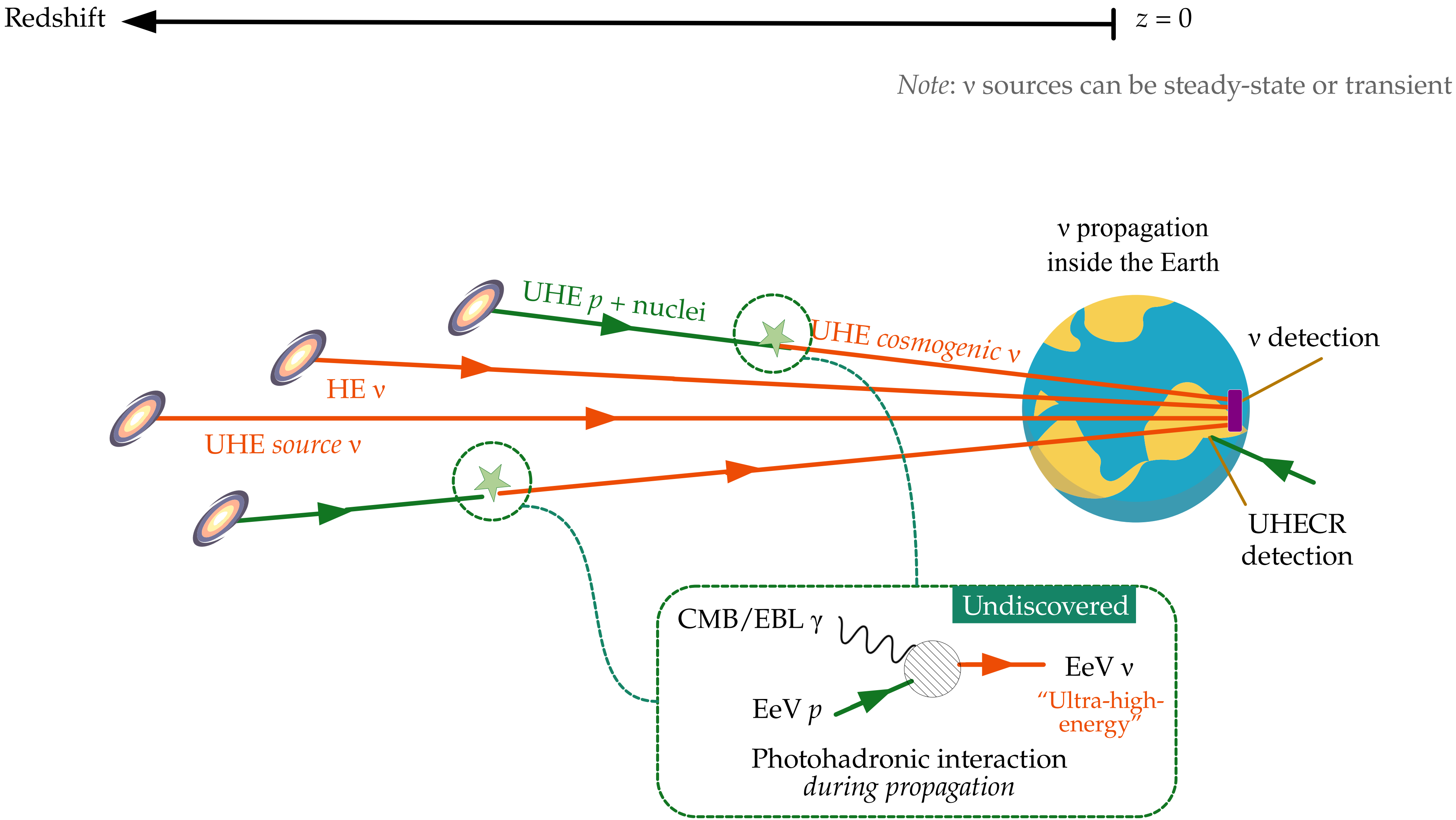
Experiment: *need new detectors for statistics & discovery*—
- Build bigger: more statistics in the TeV–PeV range
- Study the tail end of the PeV neutrino spectrum
- Build different: discover > 100 PeV neutrinos
- Ongoing work to study new detection techniques

Thanks!

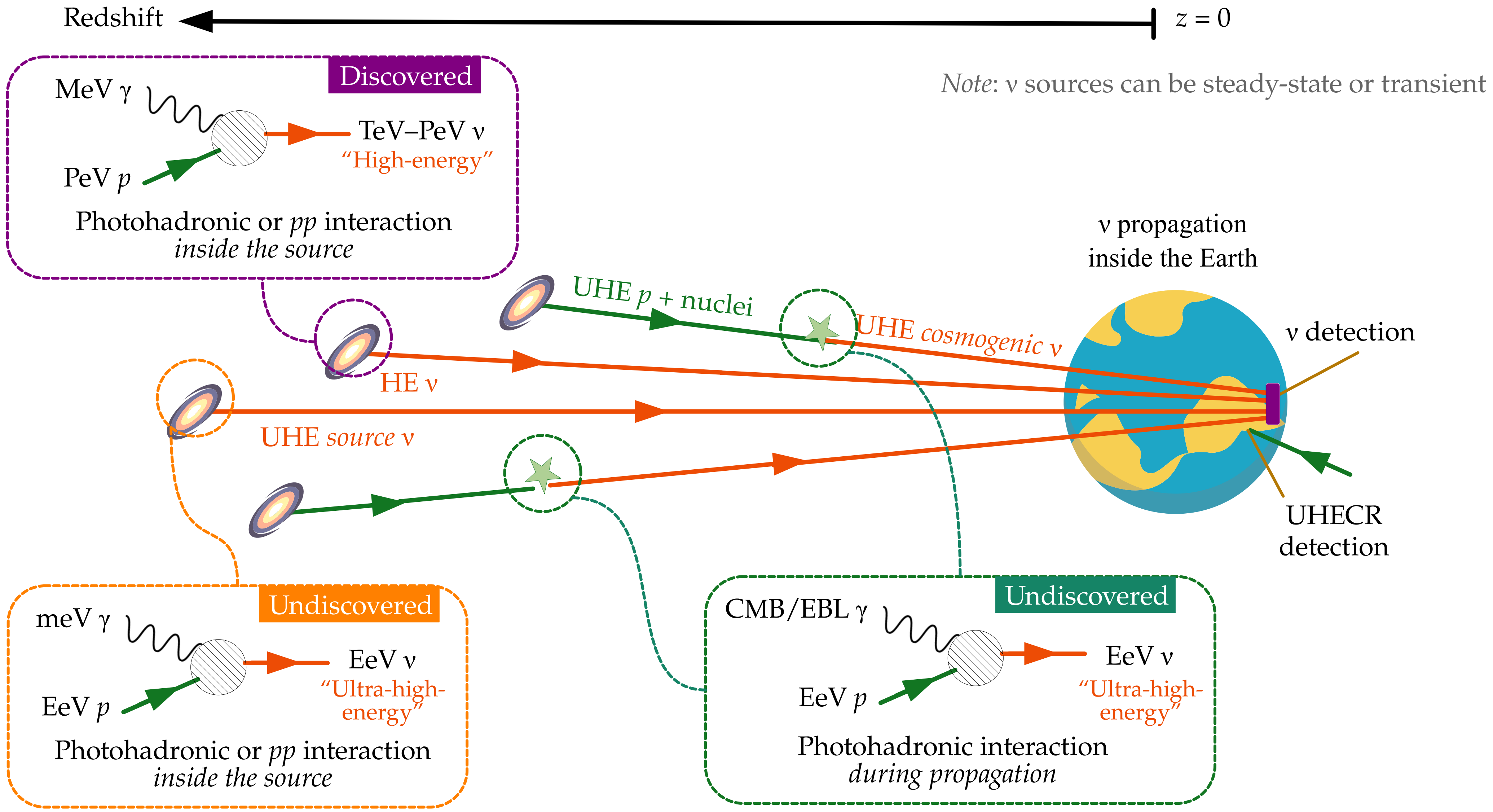

Redshift
$z = 0$
Note: ν sources can be steady-state or transient


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


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
EeV p
"Ultra-high-
energy"
Photohadronic interaction
during propagation



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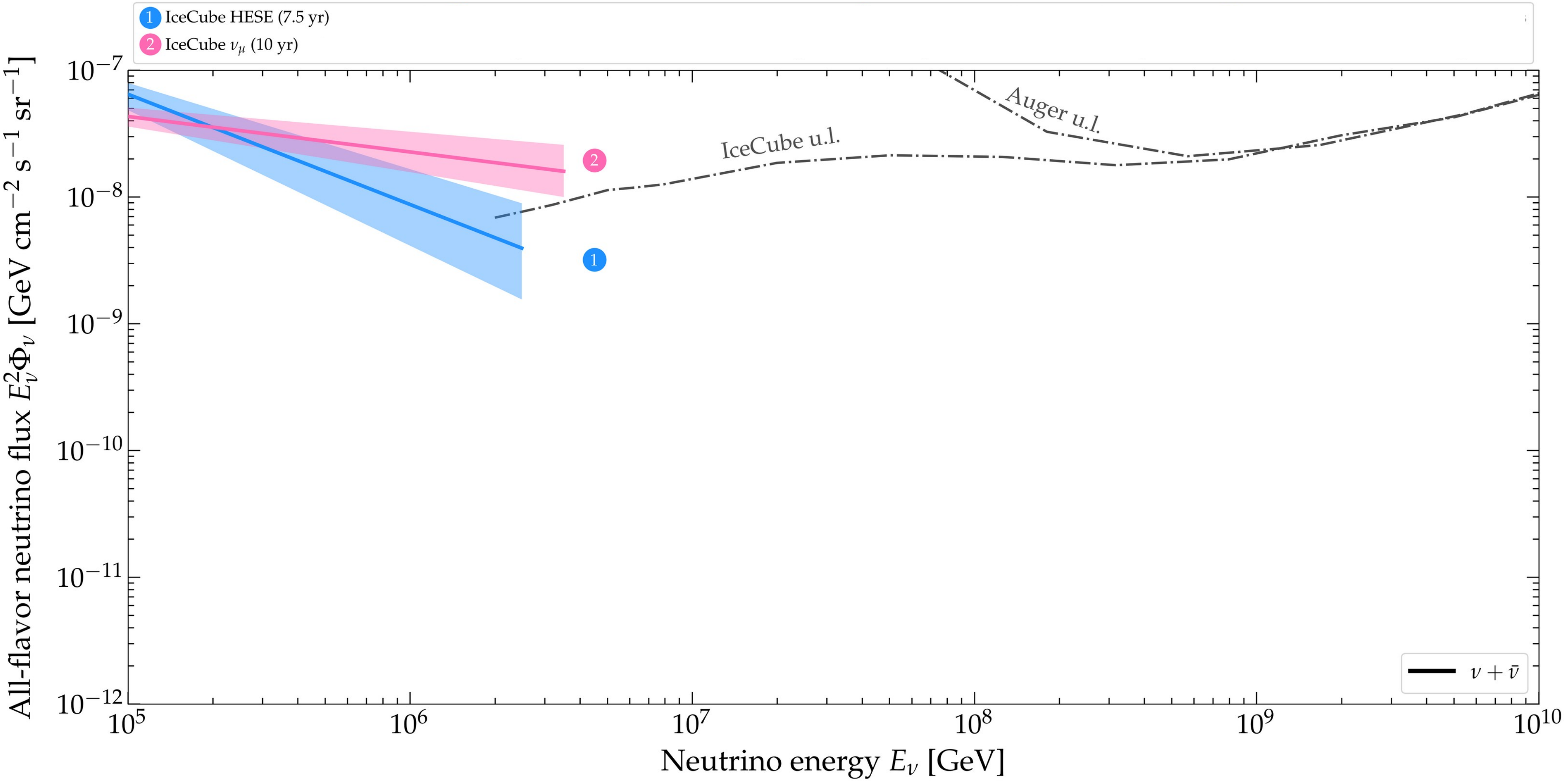
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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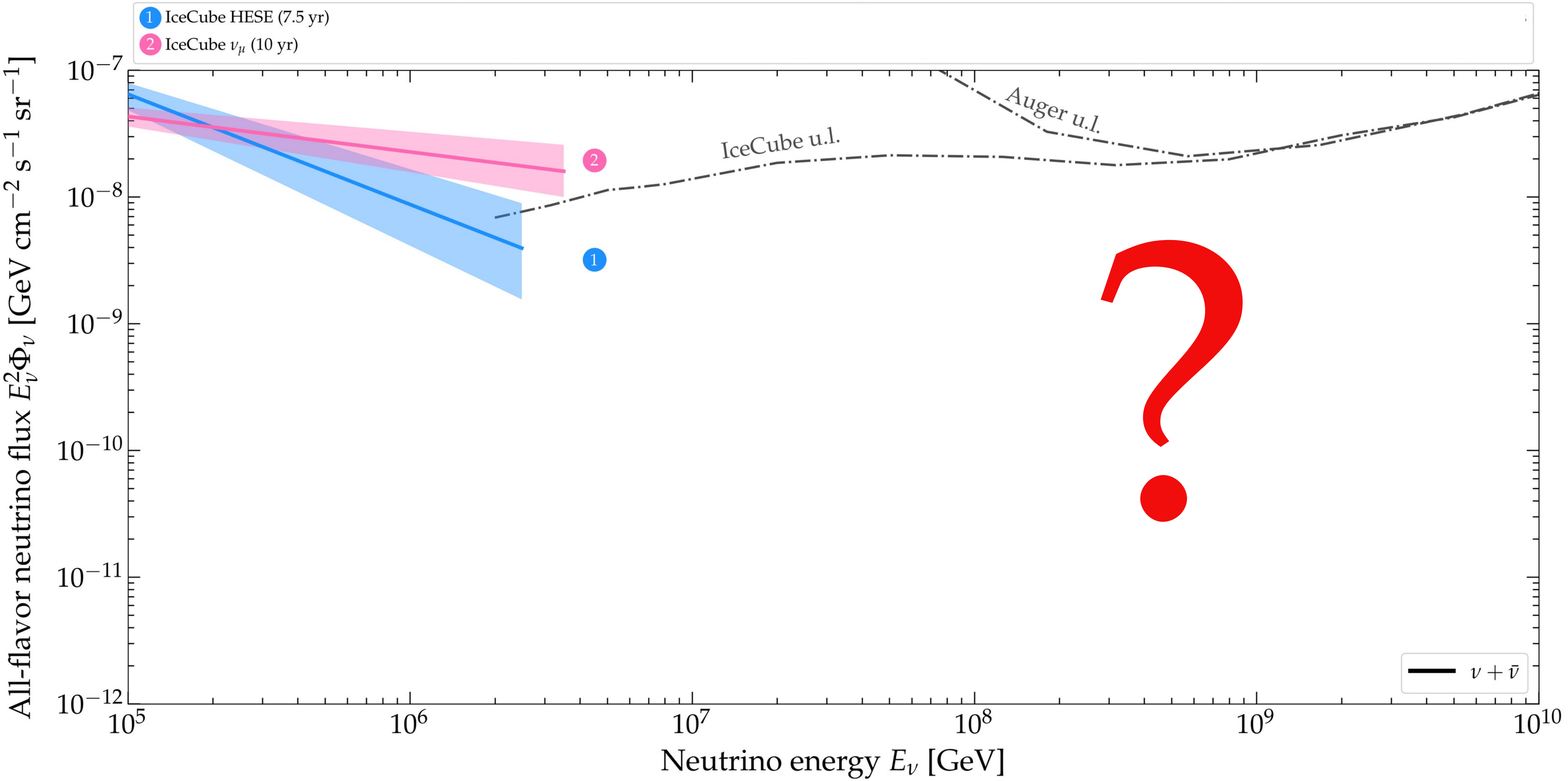
Neutrino energy E_ν [GeV]



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All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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Auger u.l.
IceCube u.l.
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$\nu + \bar{\nu}$
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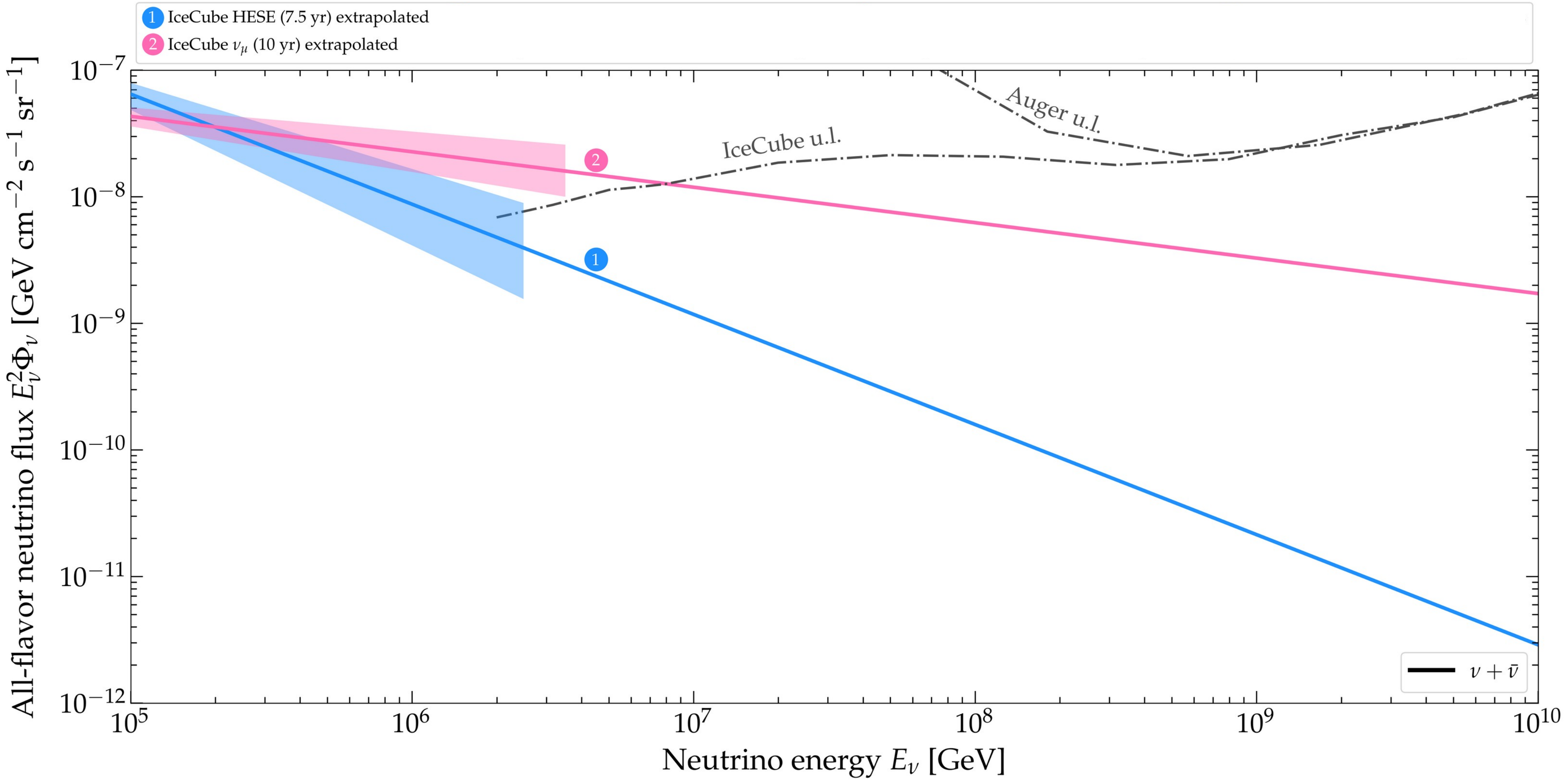
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
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Auger u.l.
IceCube u.l.
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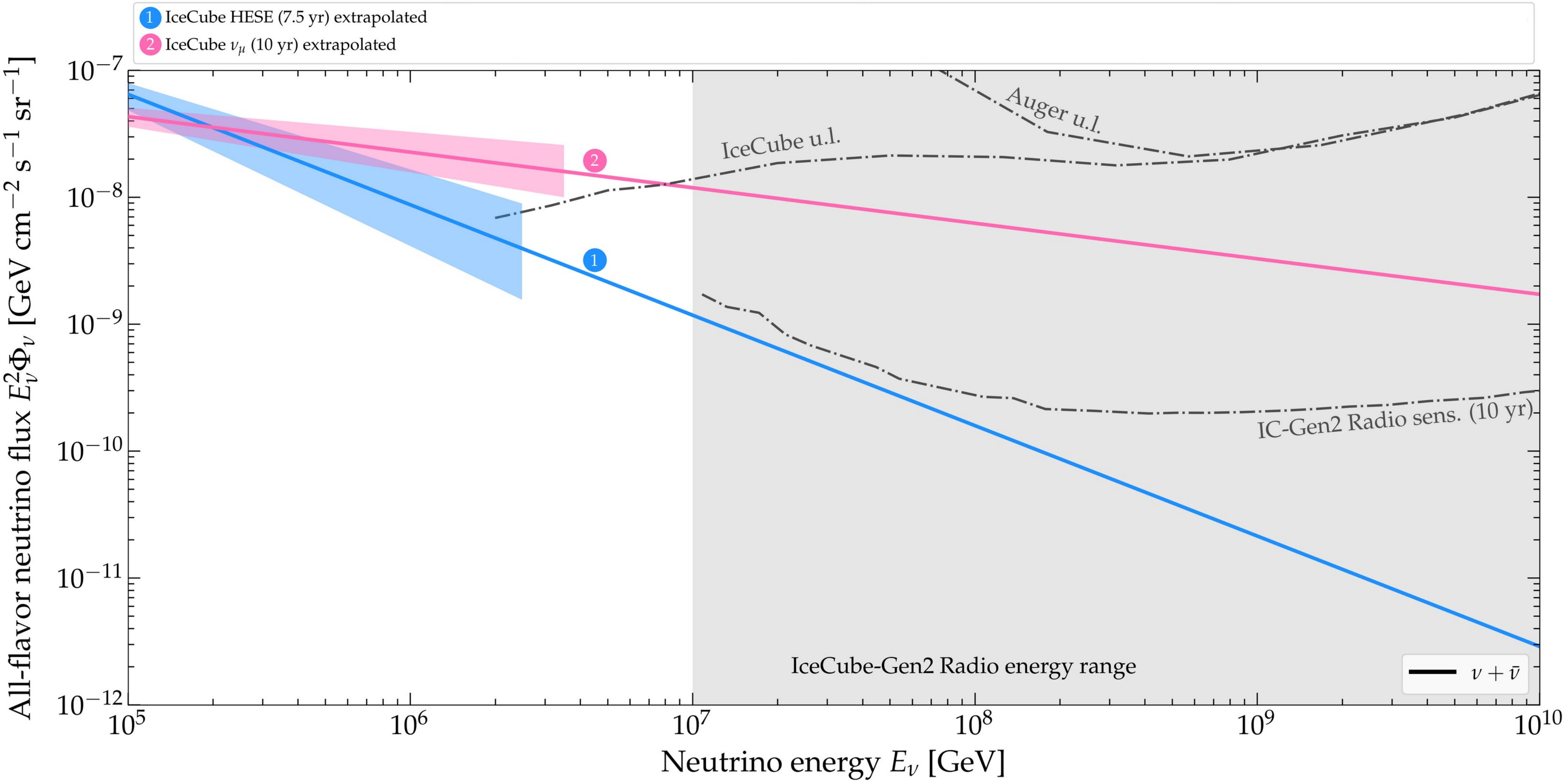

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10^{-12}
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
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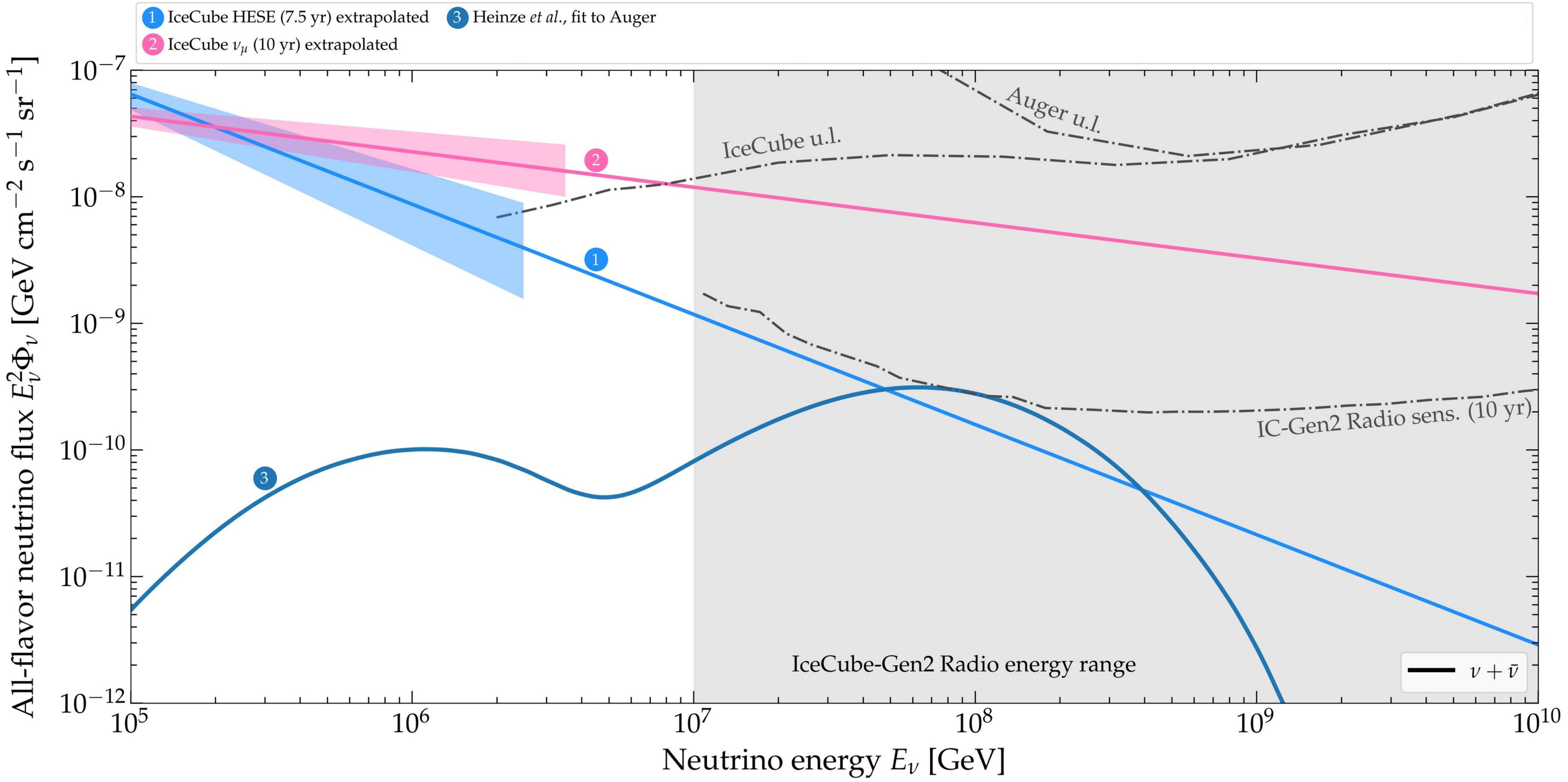
10^{10}
Neutrino energy E_ν [GeV]



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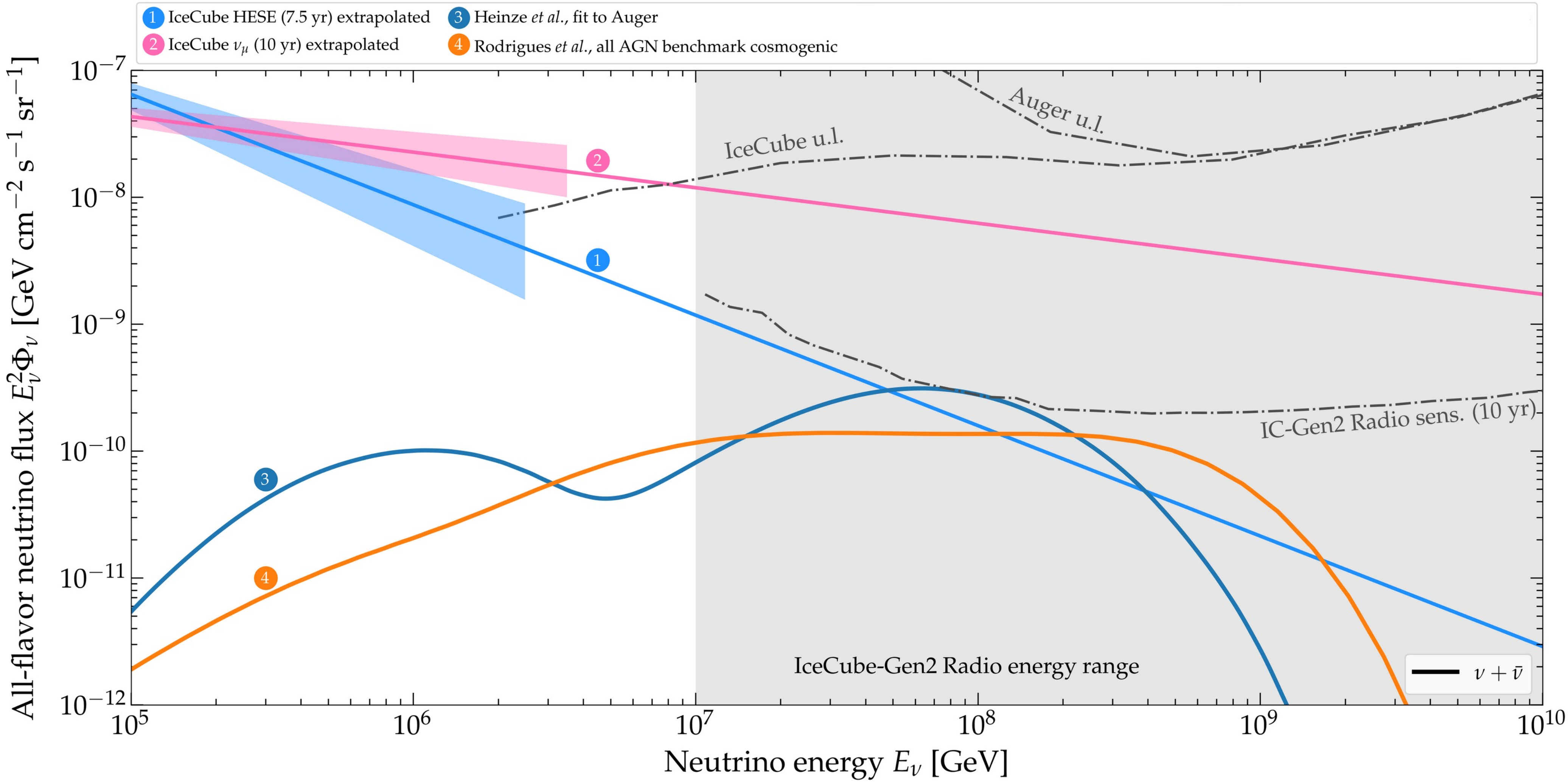

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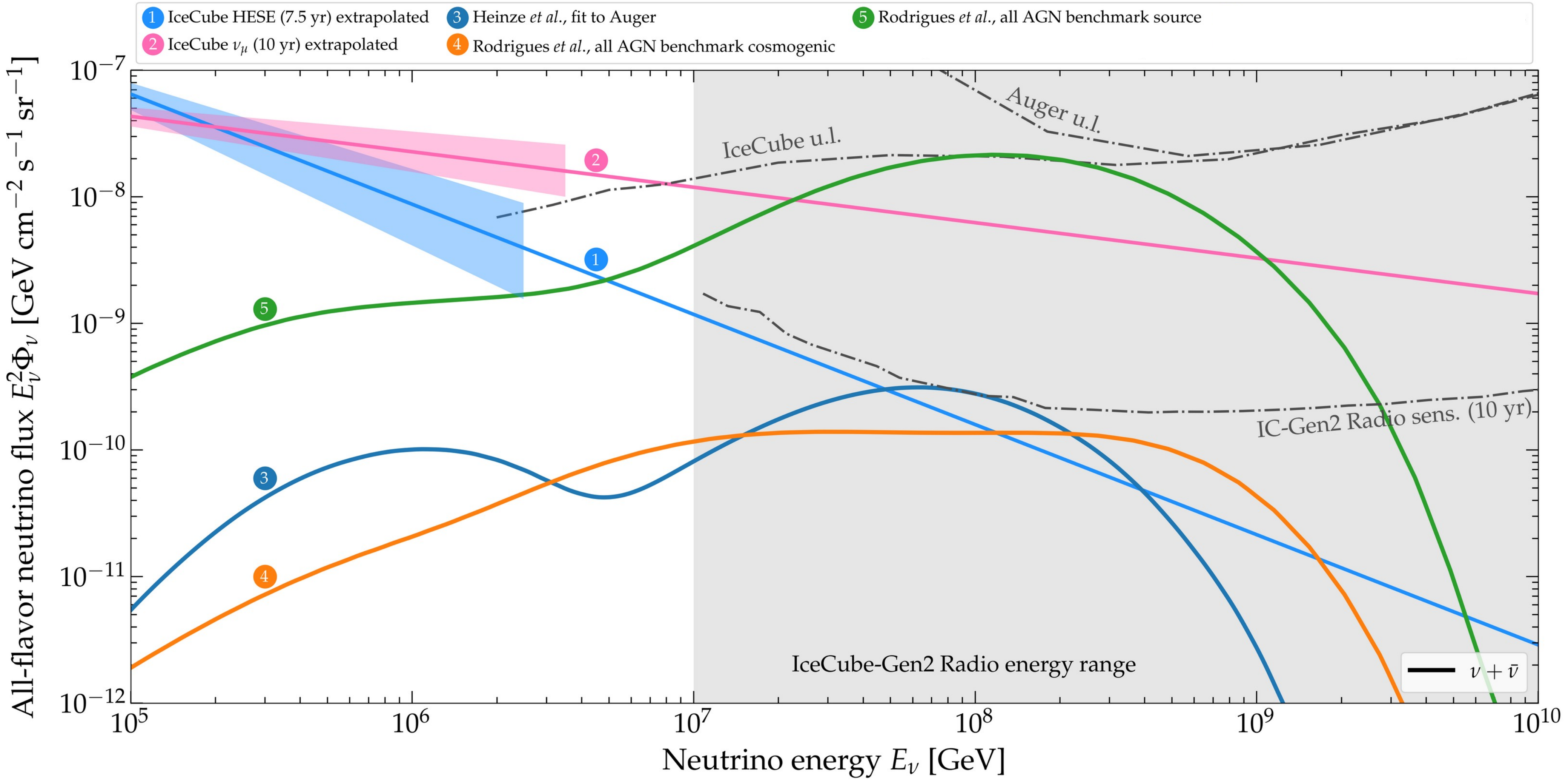

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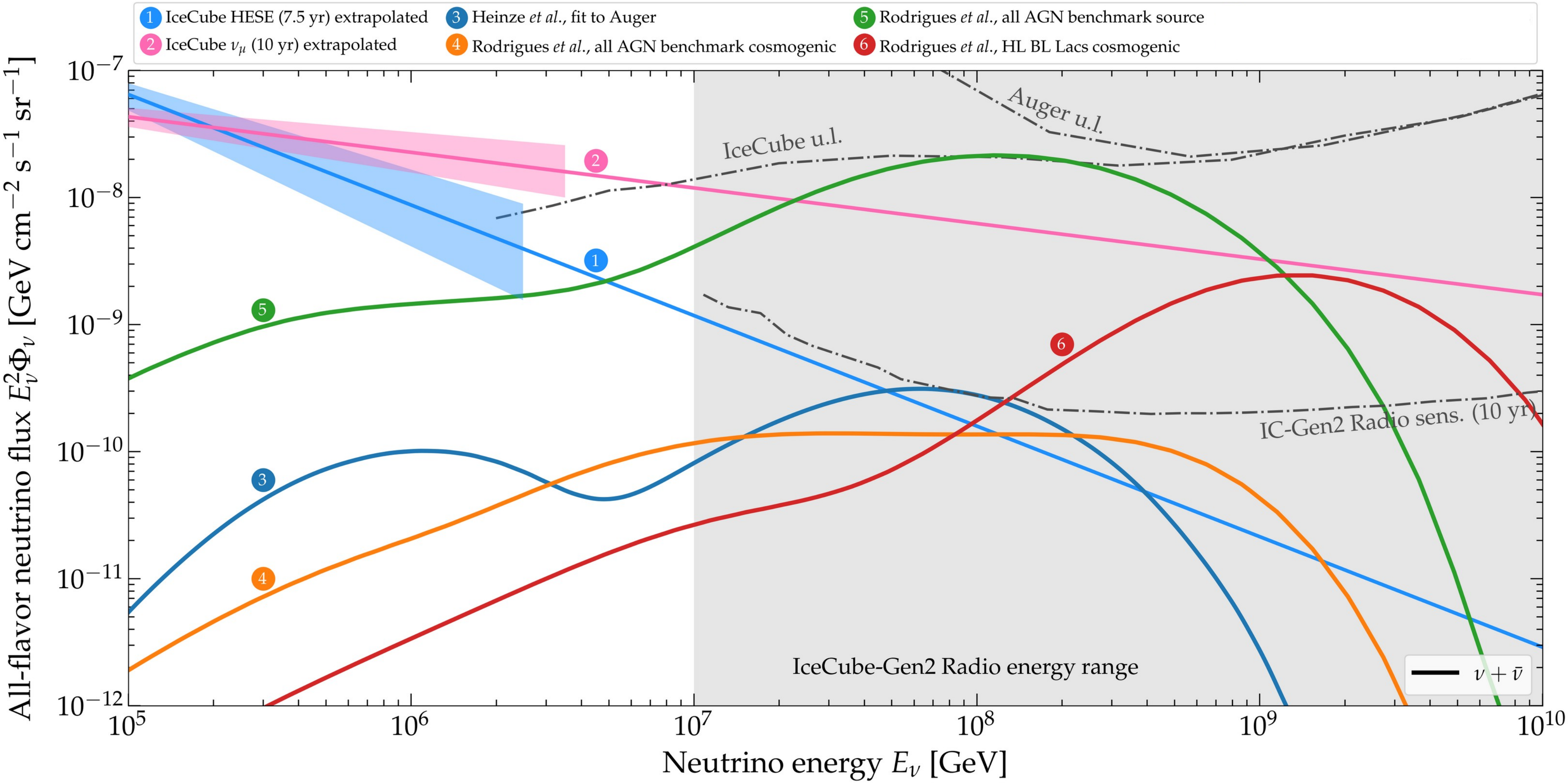

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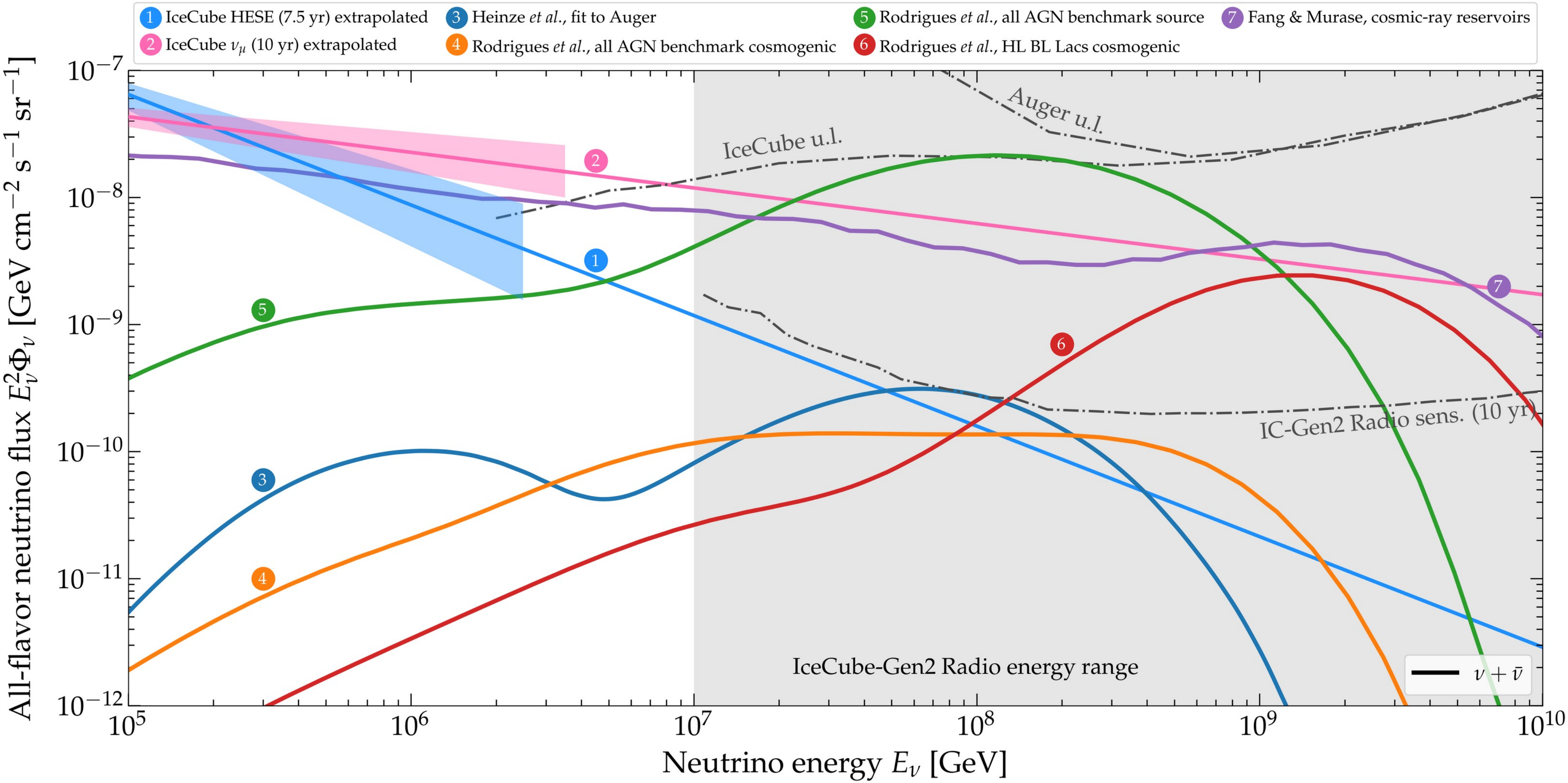

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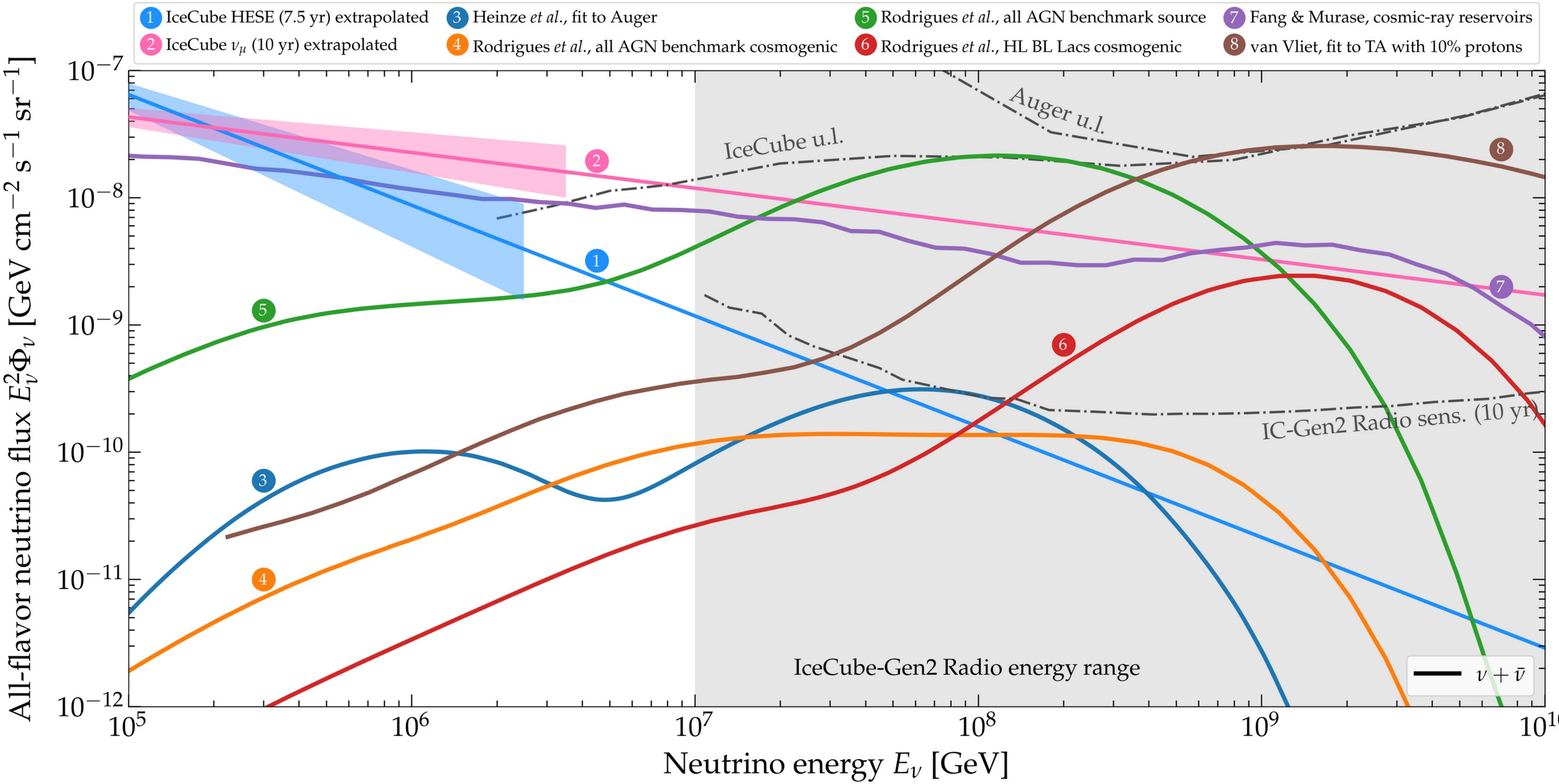

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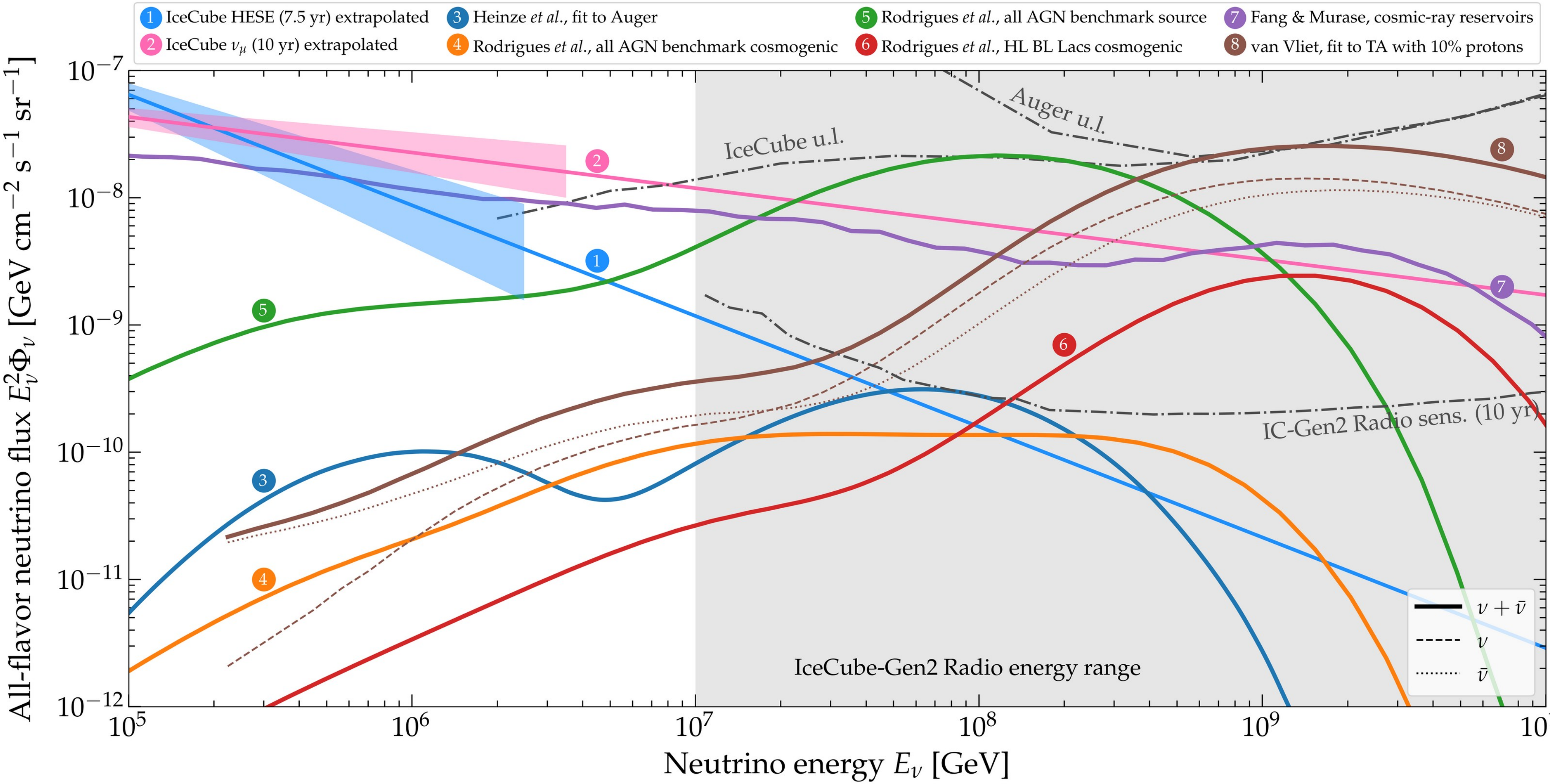

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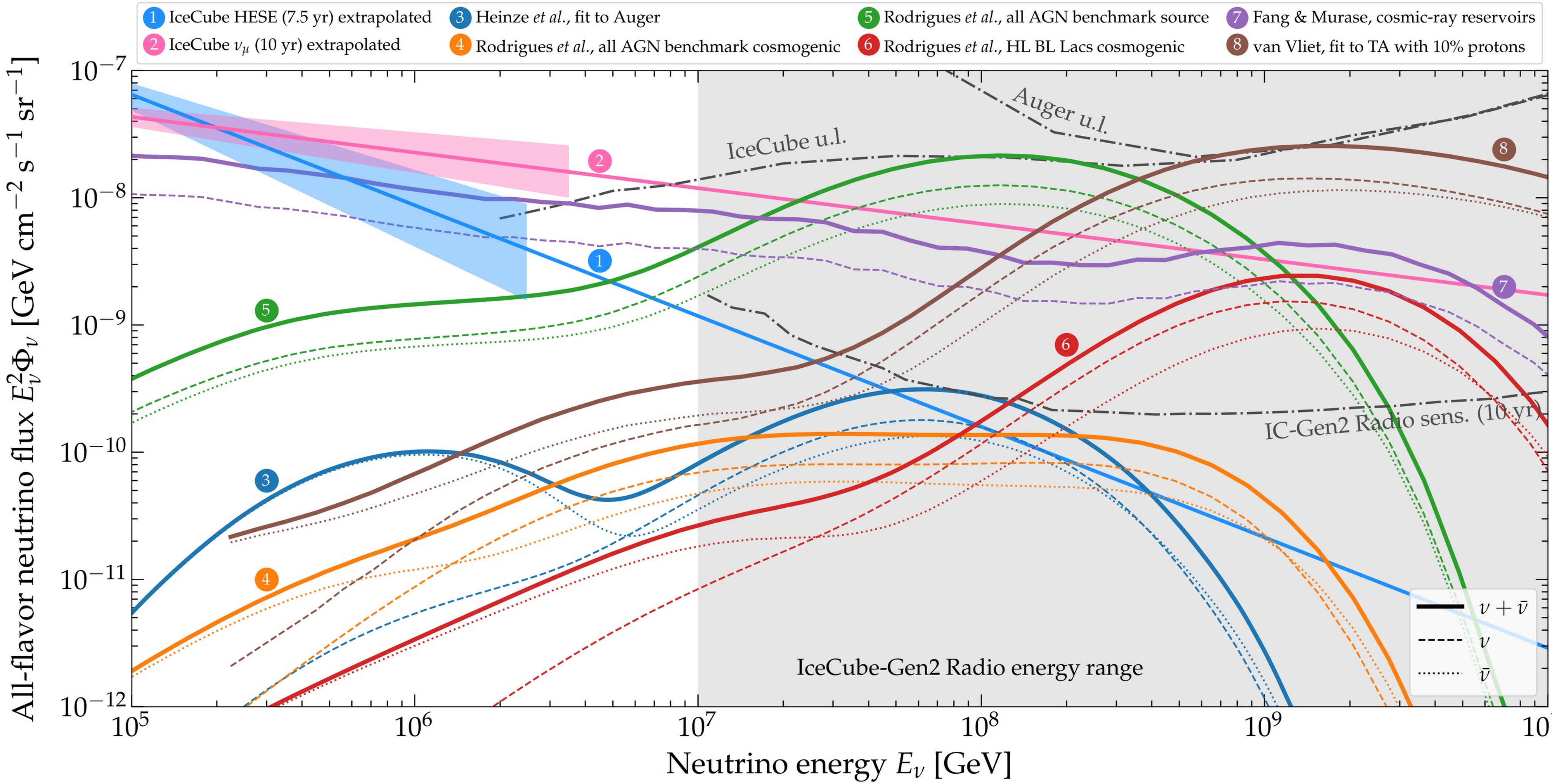

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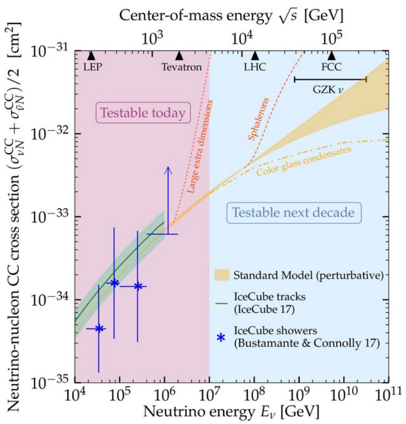
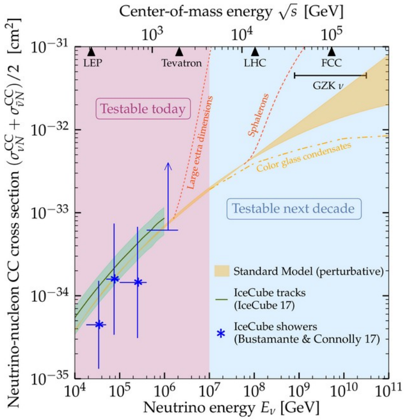
Neutrino energy E_ν [GeV]

TeV–EeV ν cross sections



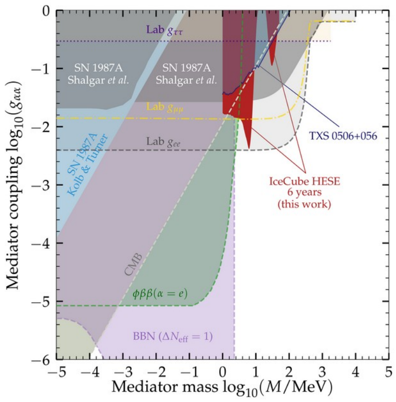
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



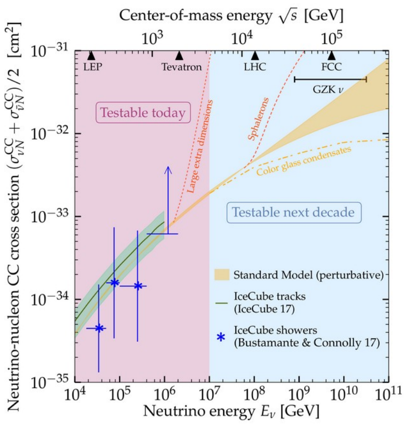
MB & Connolly, *PRL* 2019

ν self-interactions



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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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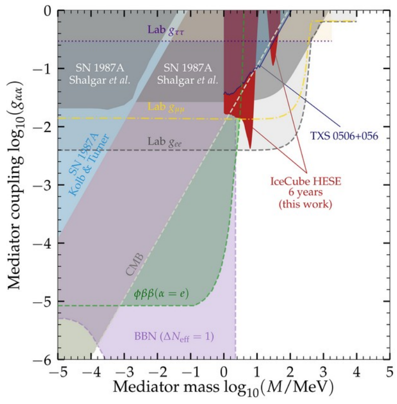
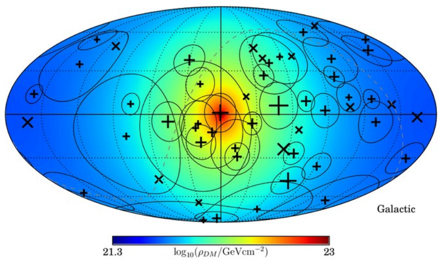


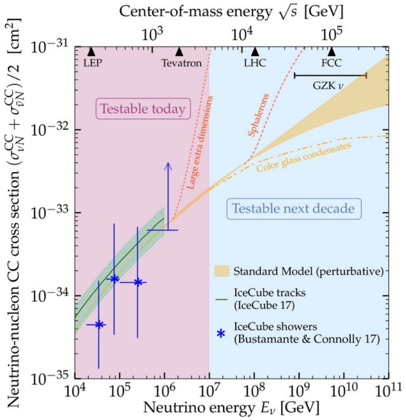
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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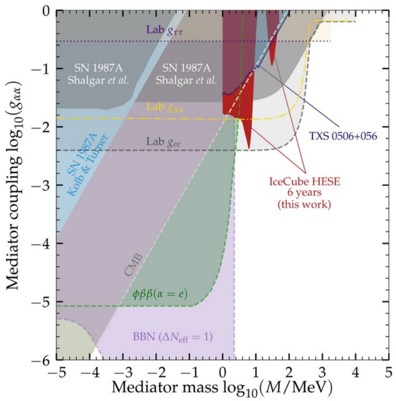
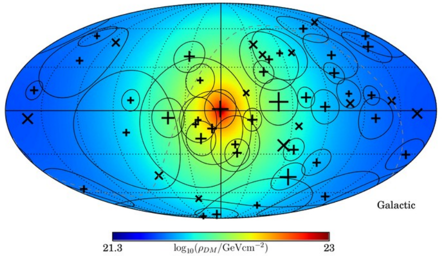


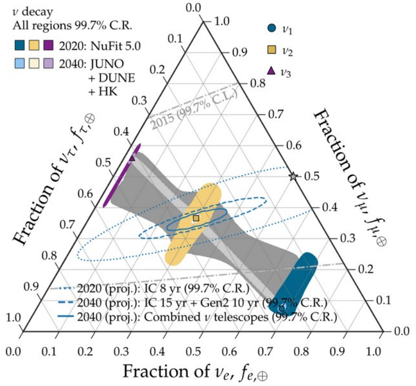
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



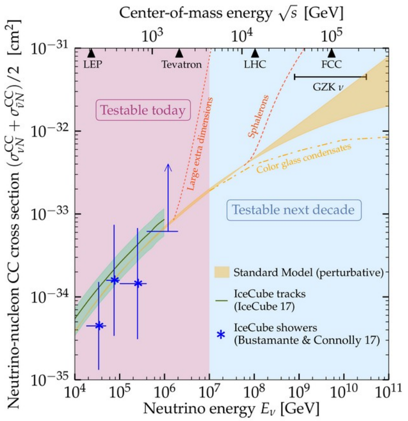
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



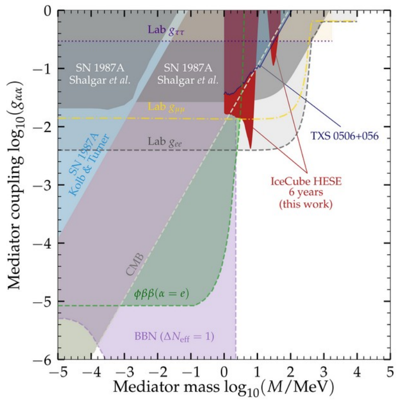
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

ν TeV–EeV ν cross sections



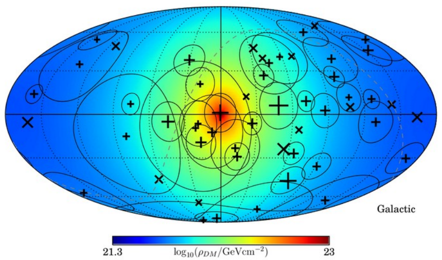
MB & Connolly, *PRL* 2019

ν self-interactions



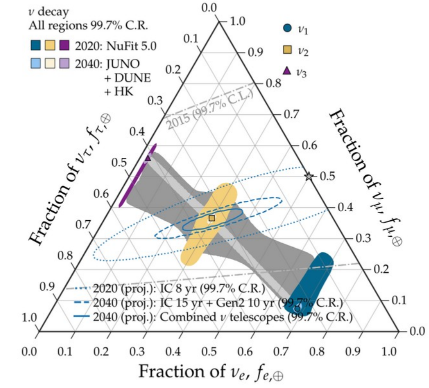
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



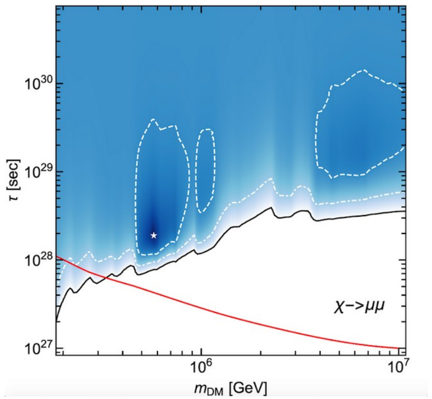
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



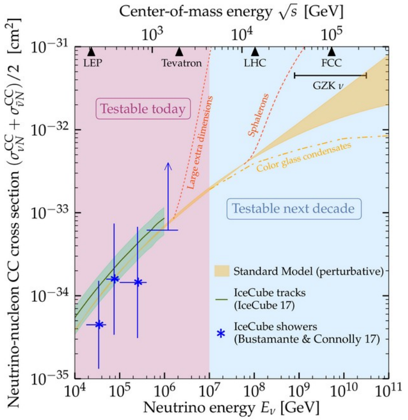
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



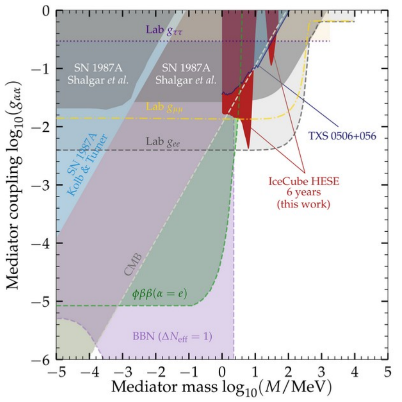
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

TeV–EeV ν cross sections



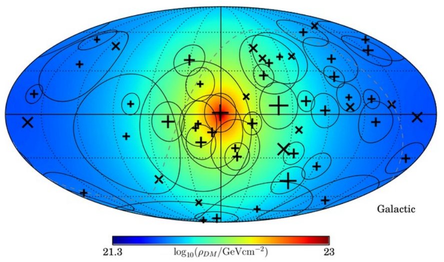
MB & Connolly, *PRL* 2019

ν self-interactions



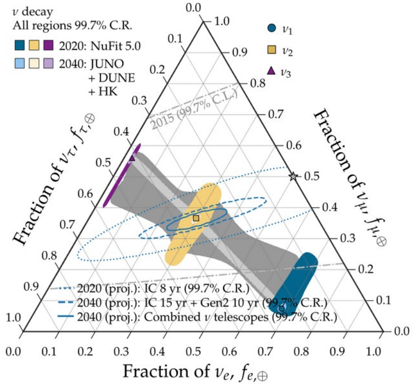
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



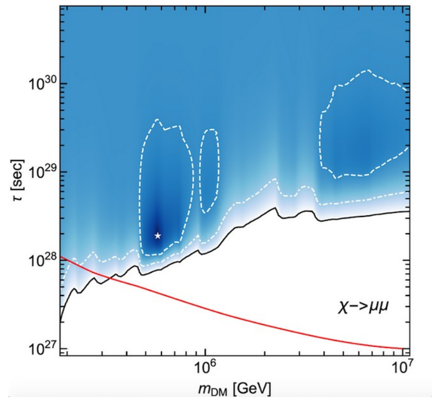
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



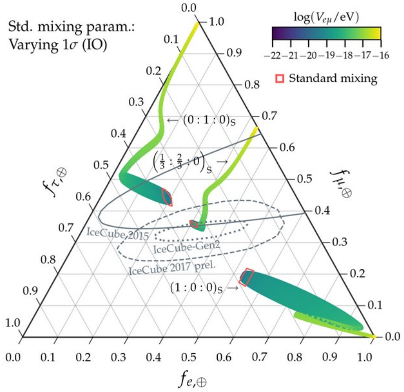
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



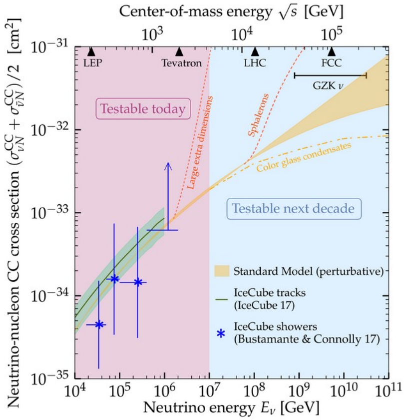
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



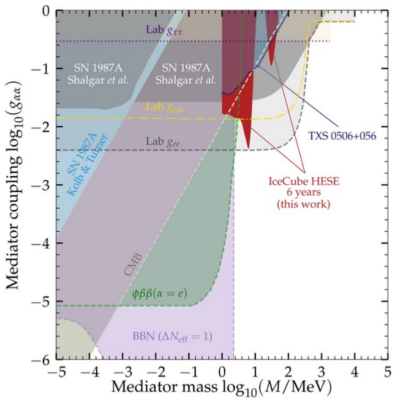
MB & Agarwalla, *PRL* 2019

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

ν self-interactions



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

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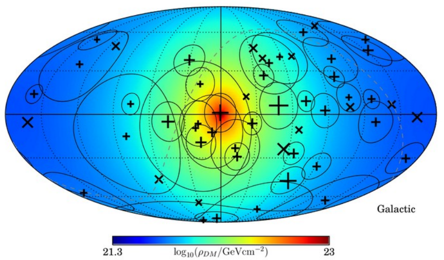

Argüelles, Kheirandish, Vincent, *PRL* 2017

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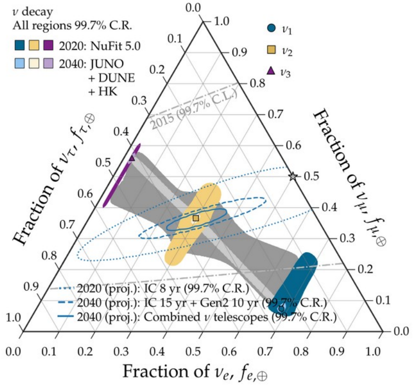

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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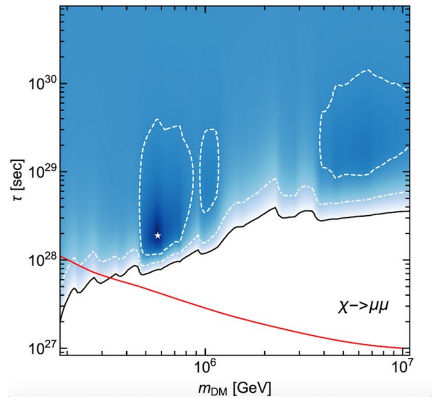

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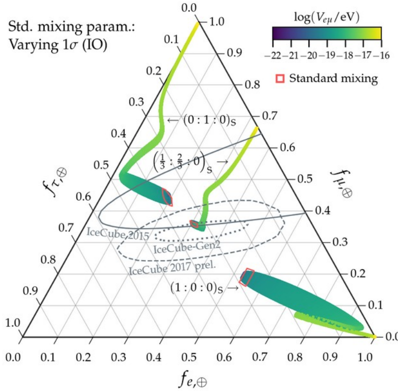
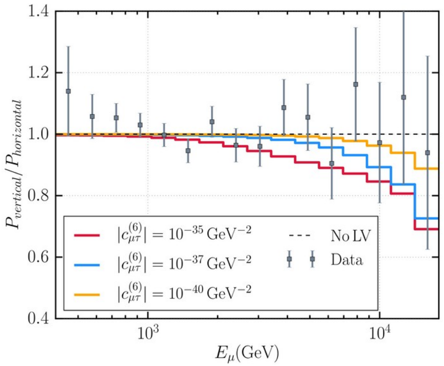


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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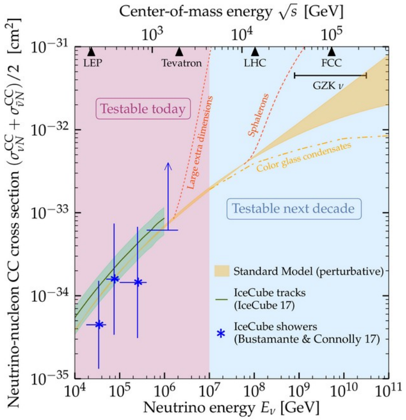

MB & Connolly, *PRL* 2019

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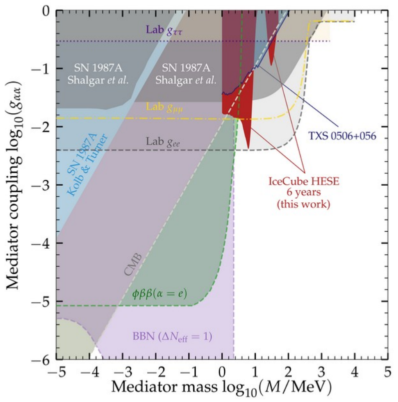

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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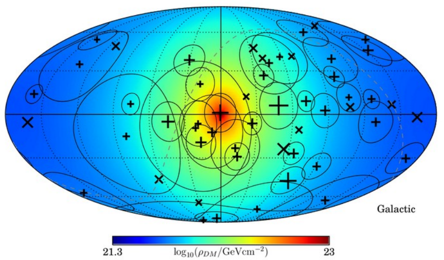

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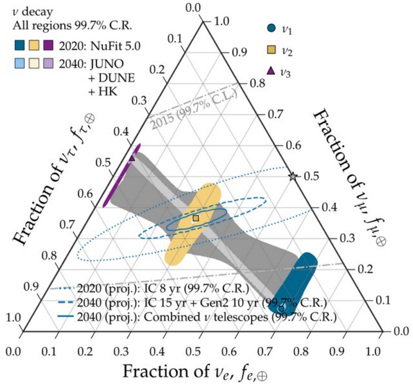

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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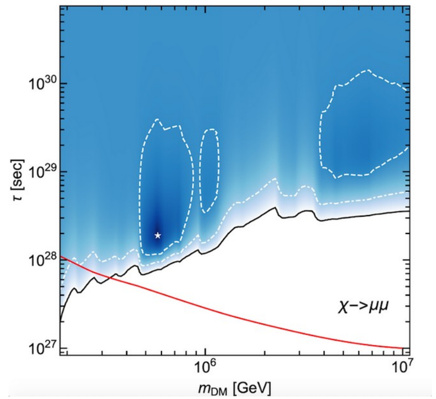

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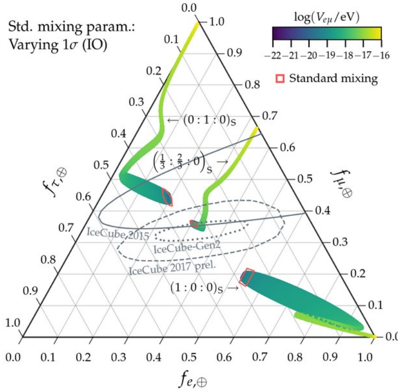

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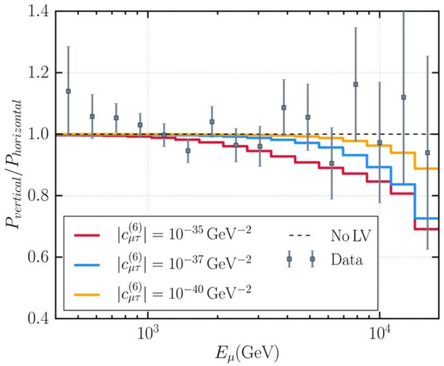
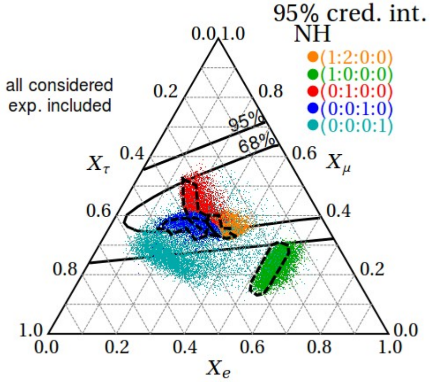


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

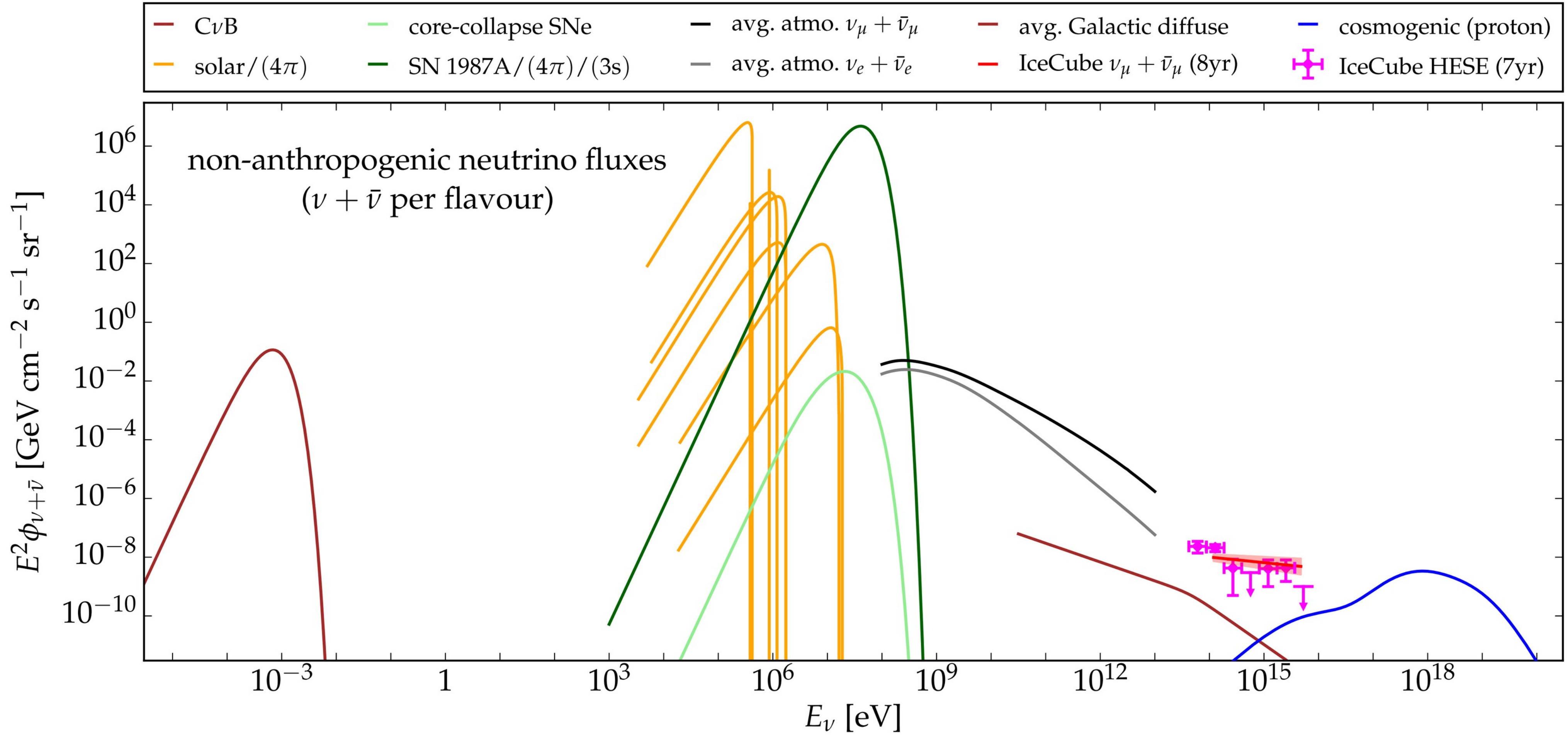
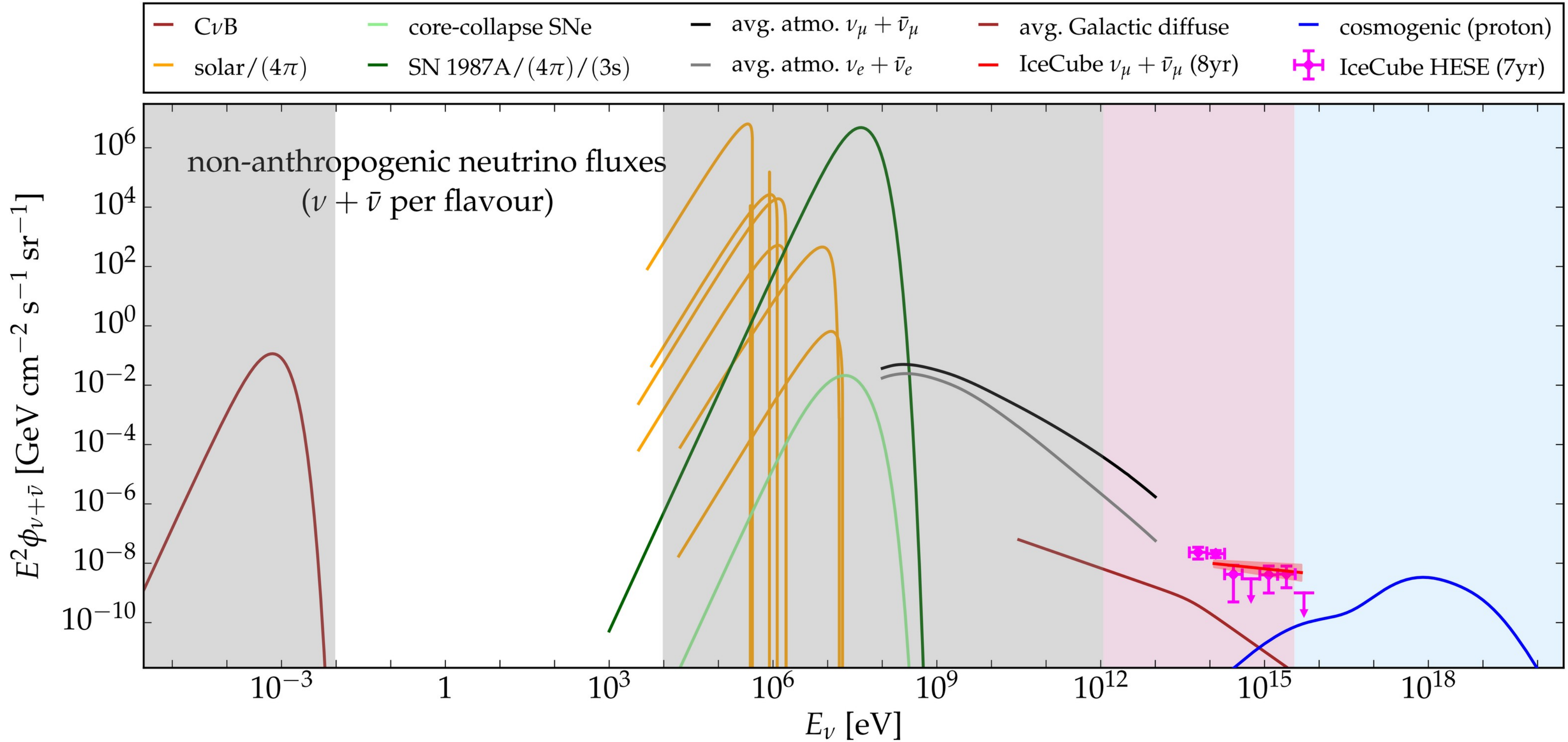


Figure courtesy of Markus Ahlers

Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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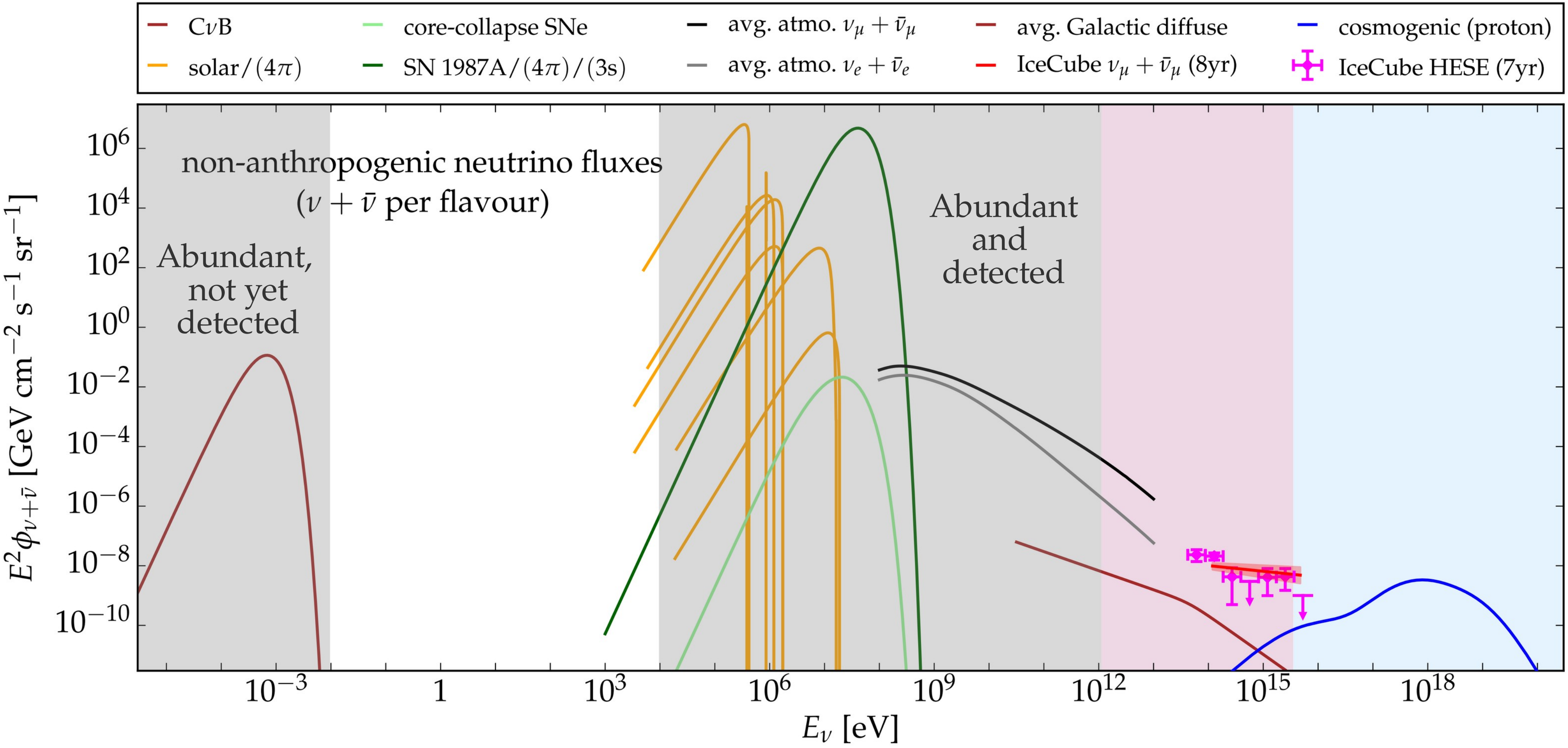
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023



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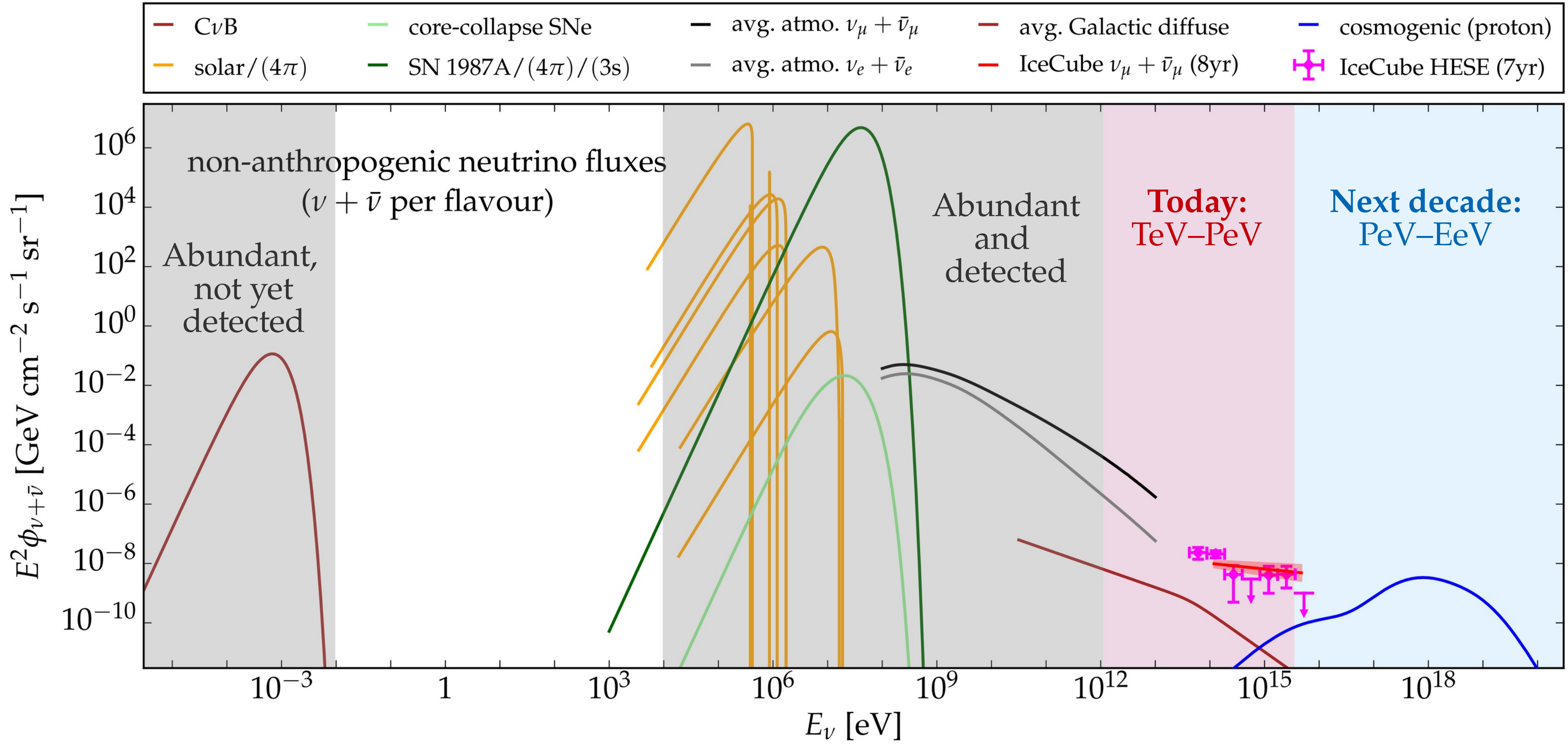

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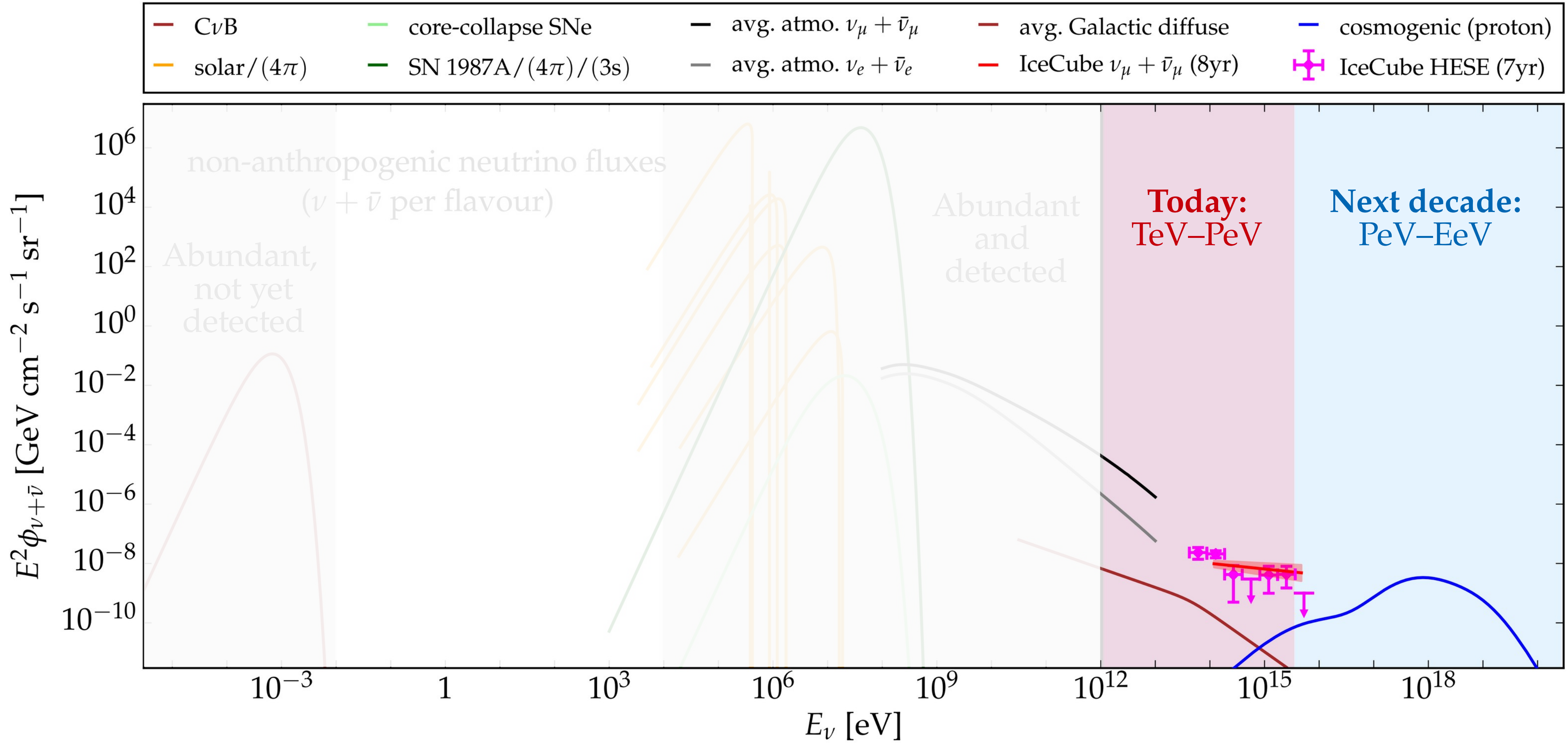

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Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

Fundamental physics with high-energy cosmic neutrinos

- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$

- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

Making high-energy astrophysical neutrinos

(or $p + p$)

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

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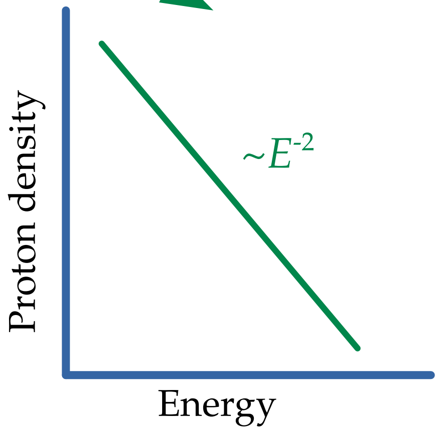

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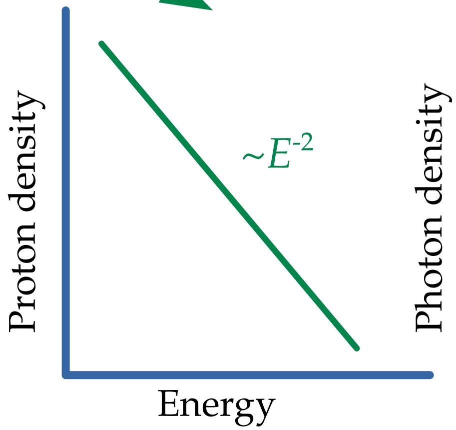

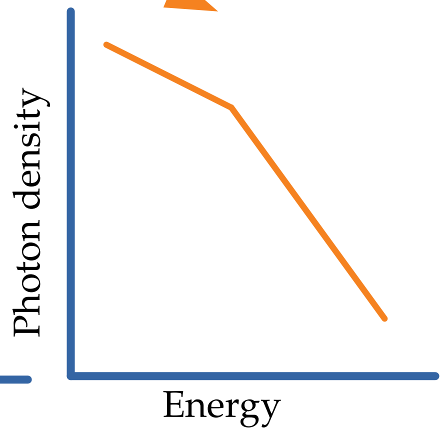

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$$\pi^0 \longrightarrow \gamma + \gamma$$

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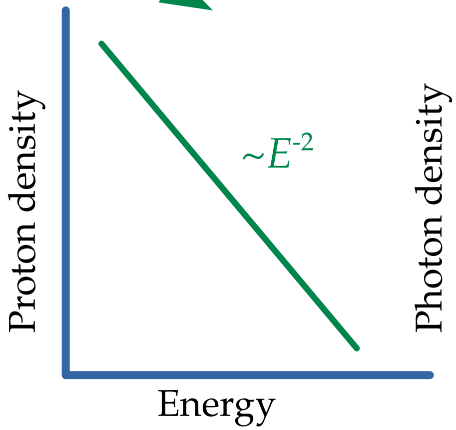
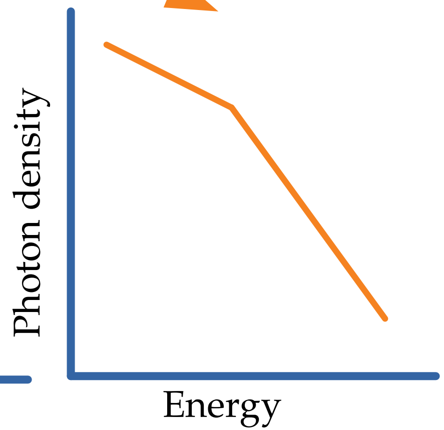
$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$





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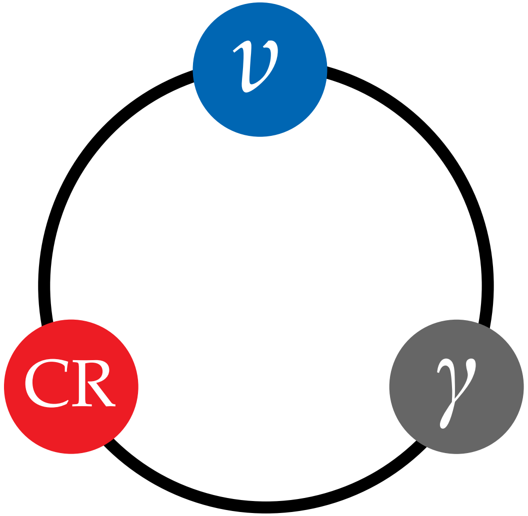
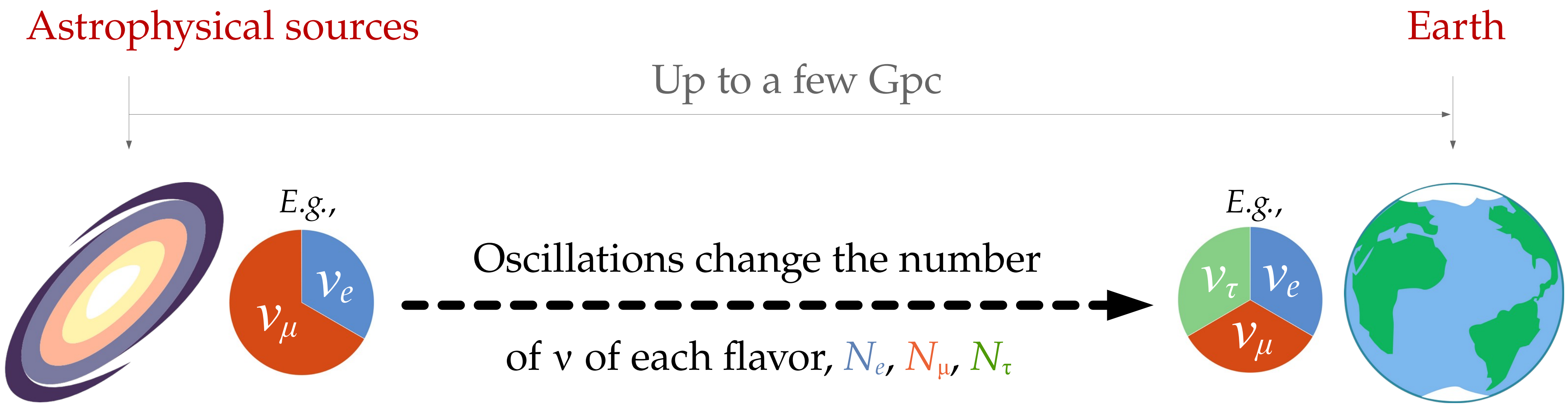


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

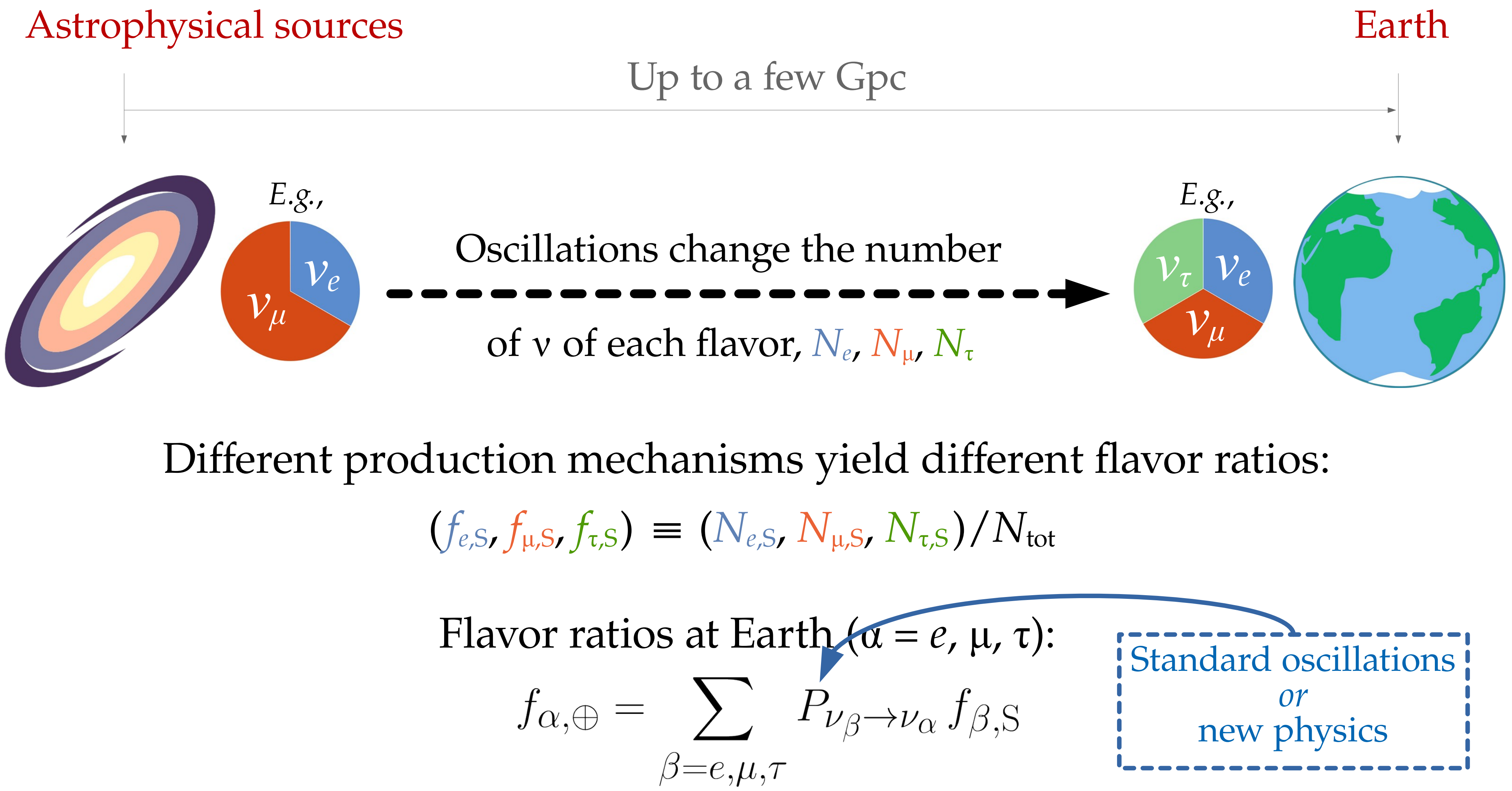


Different production mechanisms yield different flavor ratios:

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

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

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



Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
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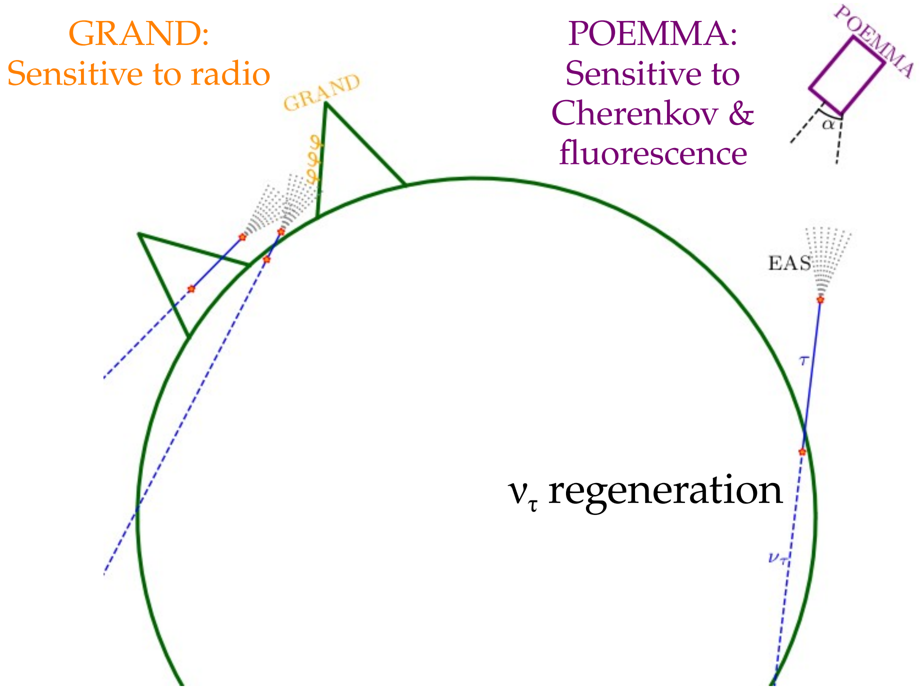
Standard oscillations
or
new physics

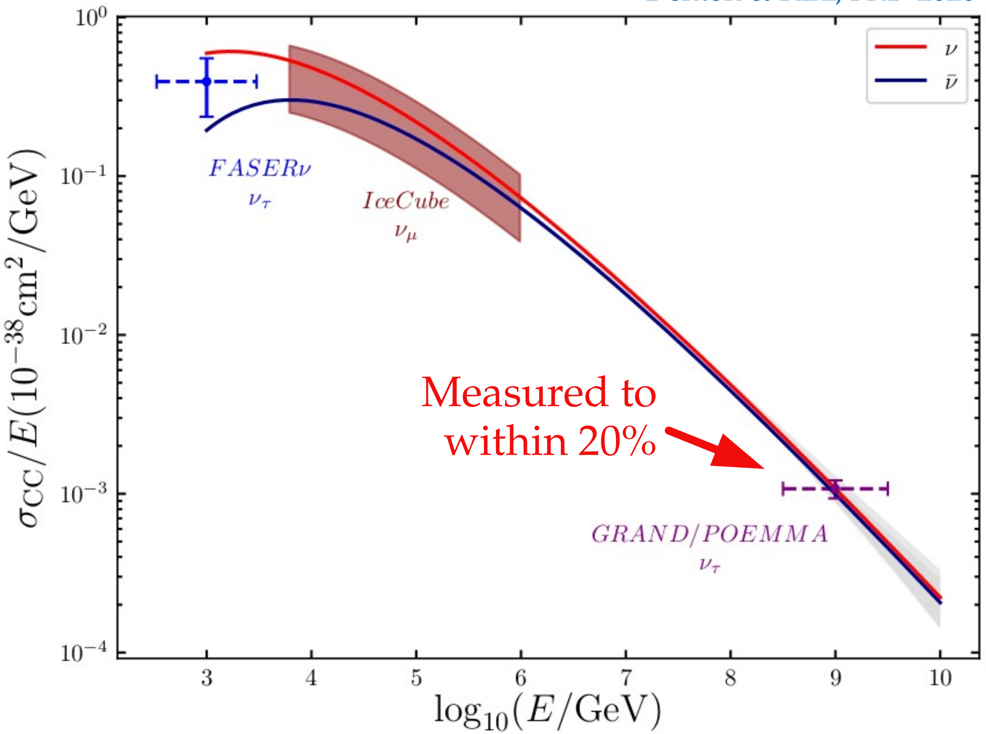
GRAND & POEMMA

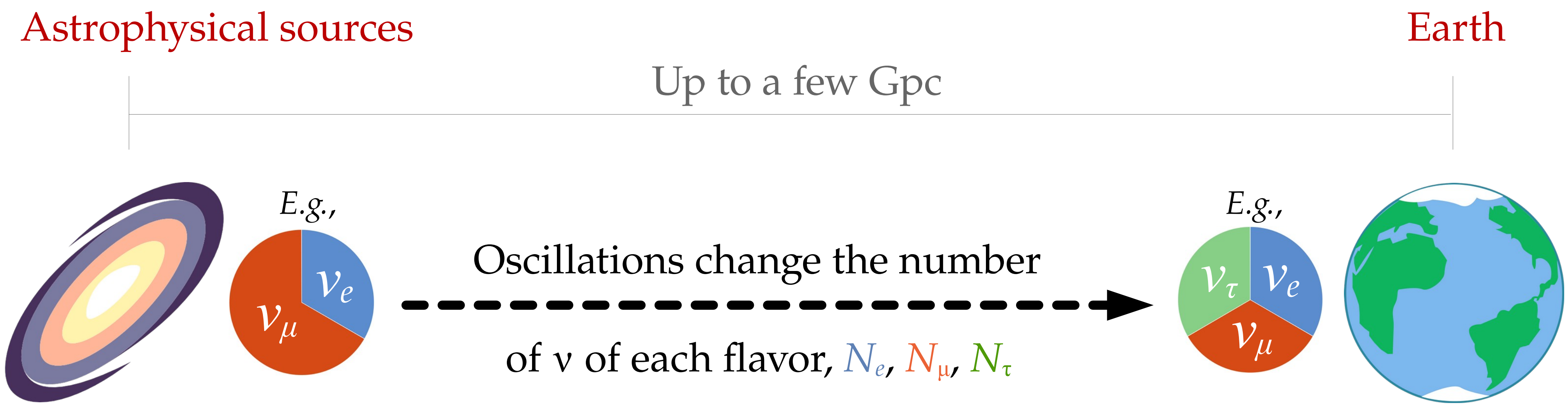
Both sensitive to extensive air showers induced by Earth-skimming UHE ν_τ



If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):

Denton & Kini, *PRD* 2020





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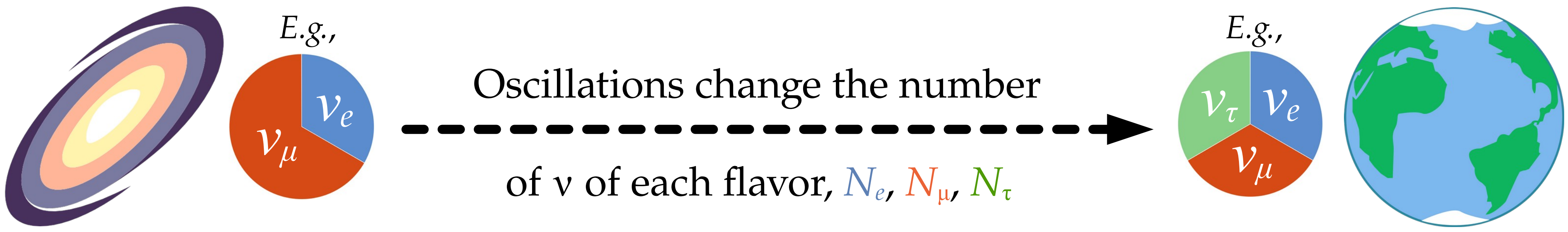

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Standard oscillations
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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Note:
The original palatable regions were frequentist [**MB**, Beacom, Winter, *PRL* 2015]; the new ones are Bayesian

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Ingredient #1:

Flavor ratios at the source,

$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$

Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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

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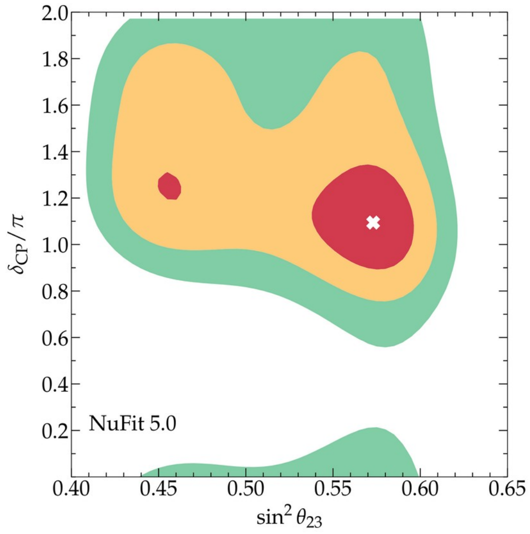
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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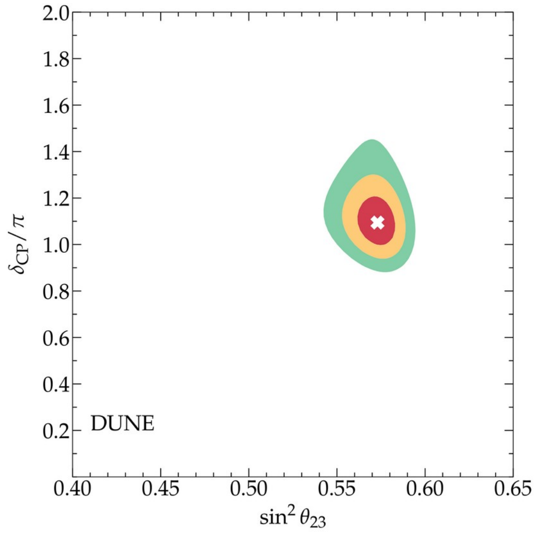
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

An *et al.*, *J. Phys. G* 2016
DUNE, 2002.03005
Huber, Lindner, Winter, *Nucl. Phys. B* 2002



One likely TeV–PeV ν production scenario:

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

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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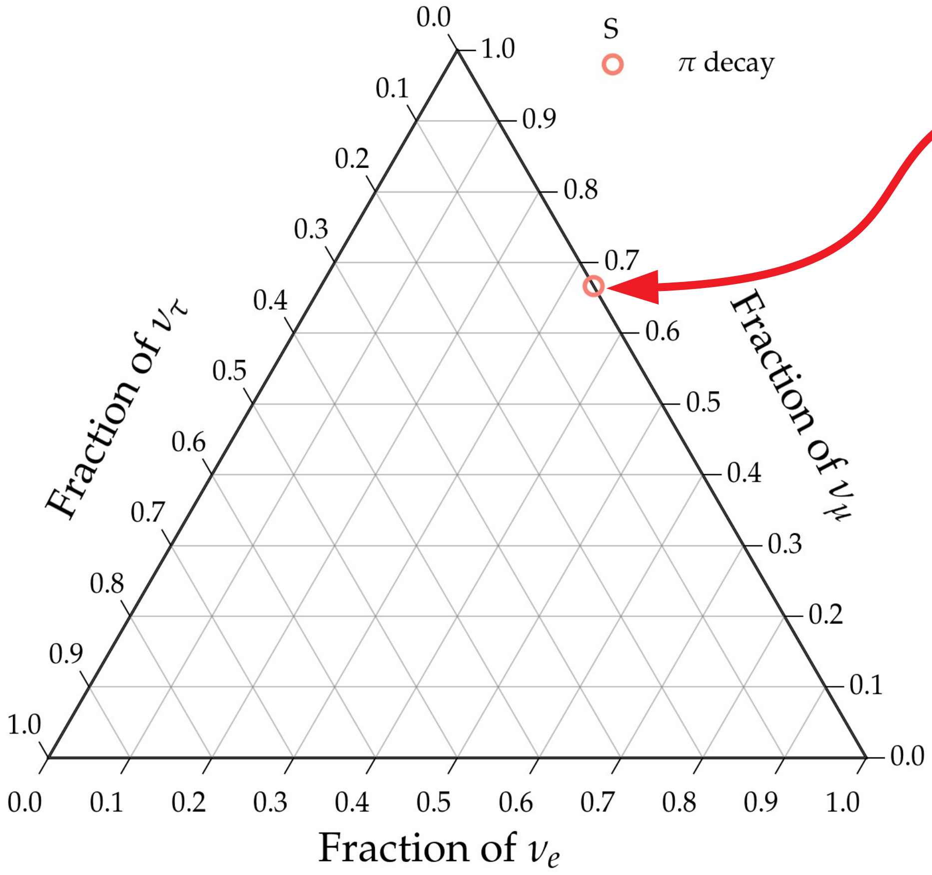

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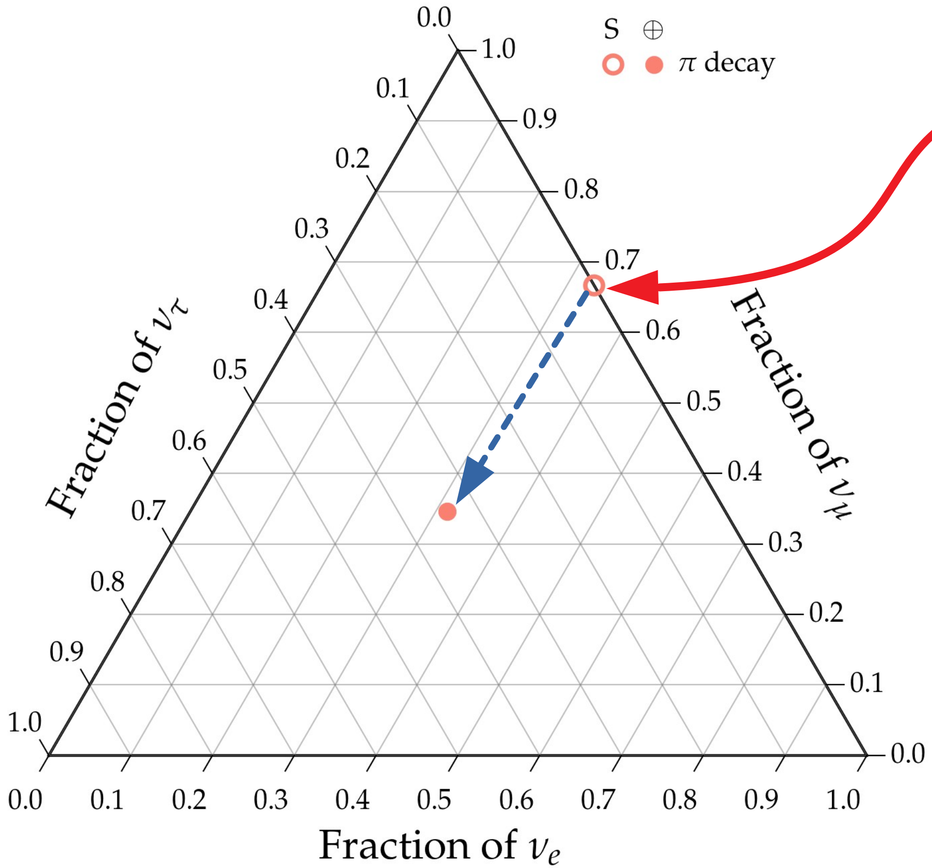


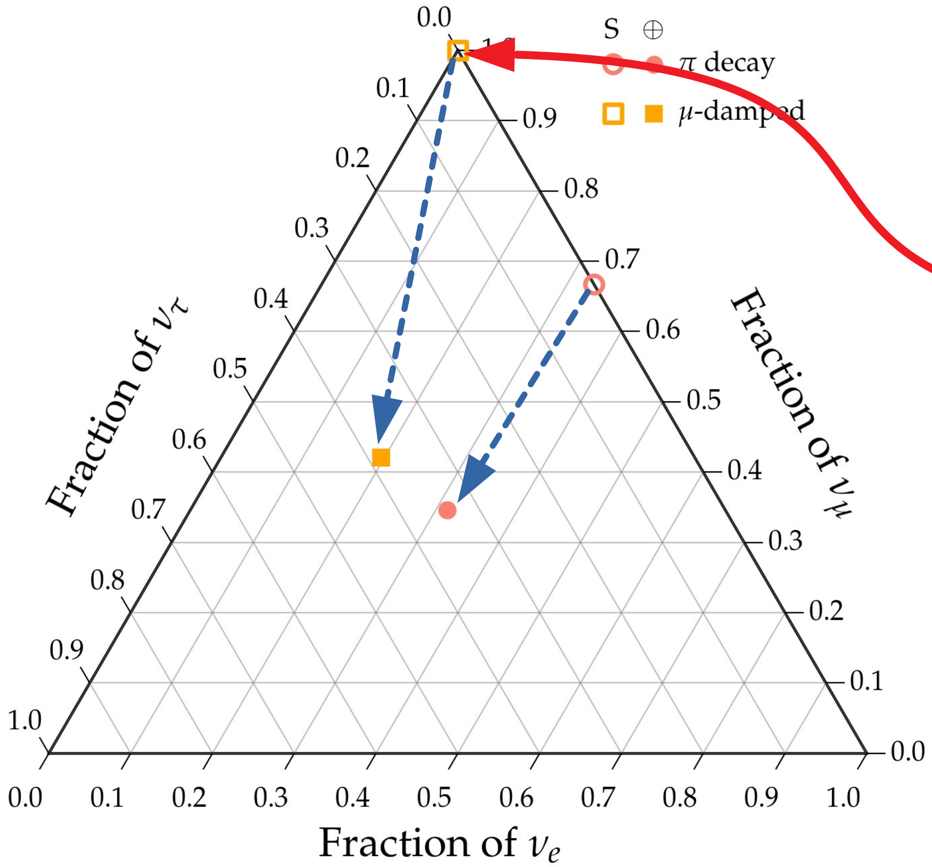
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

$(0:1:0)_S$

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One likely TeV–PeV ν production scenario:

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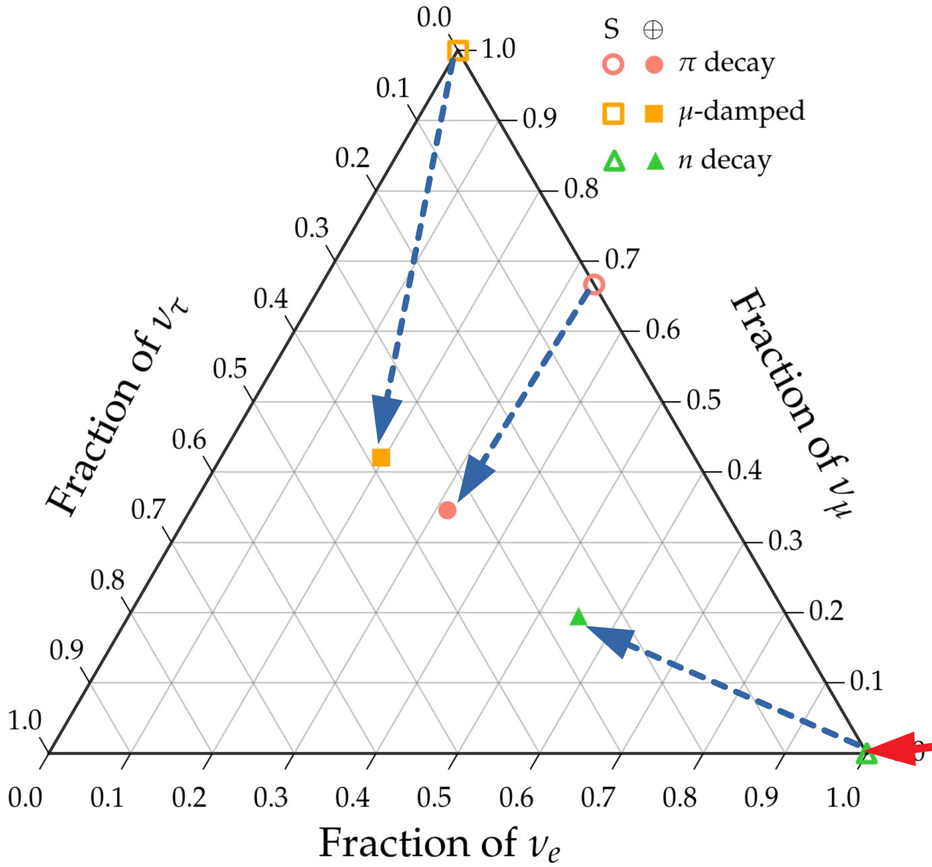


Full π decay chain

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

Muon damped

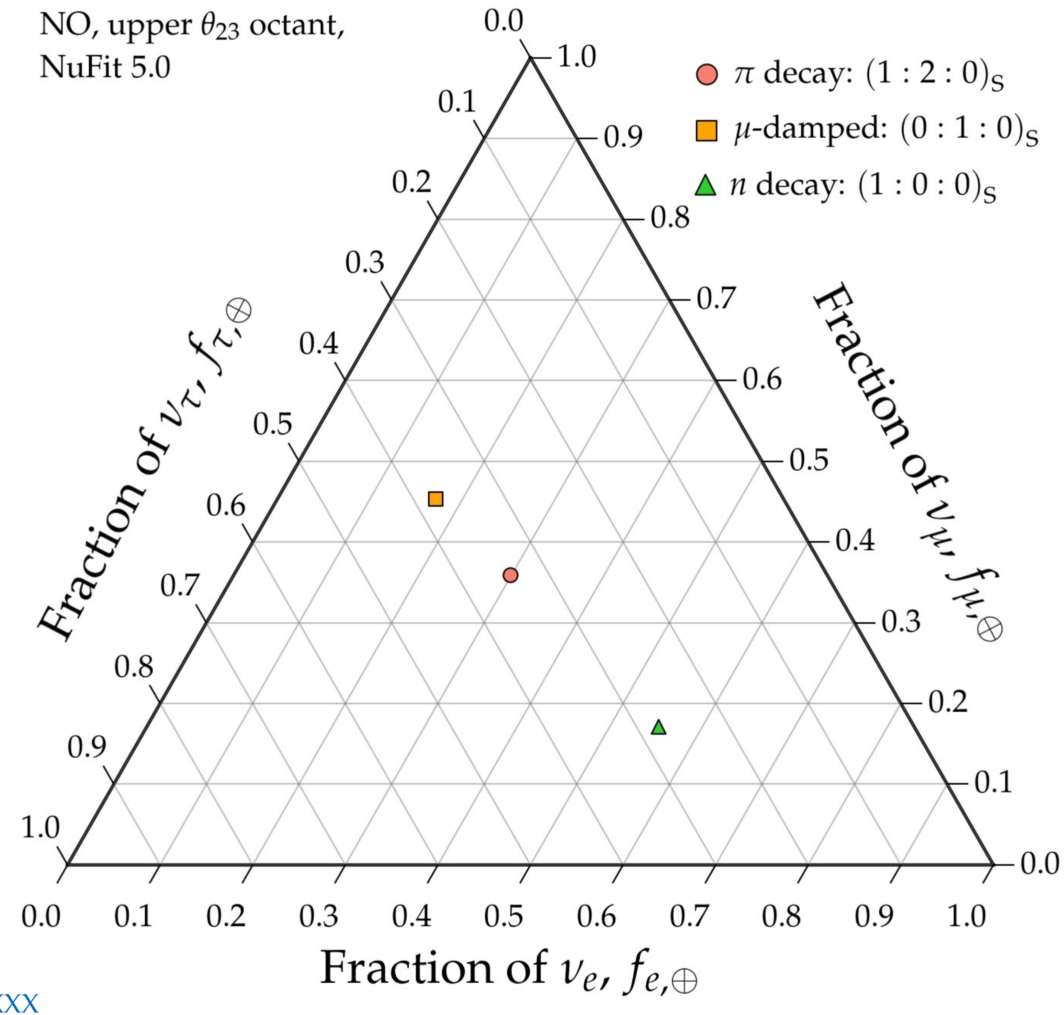
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

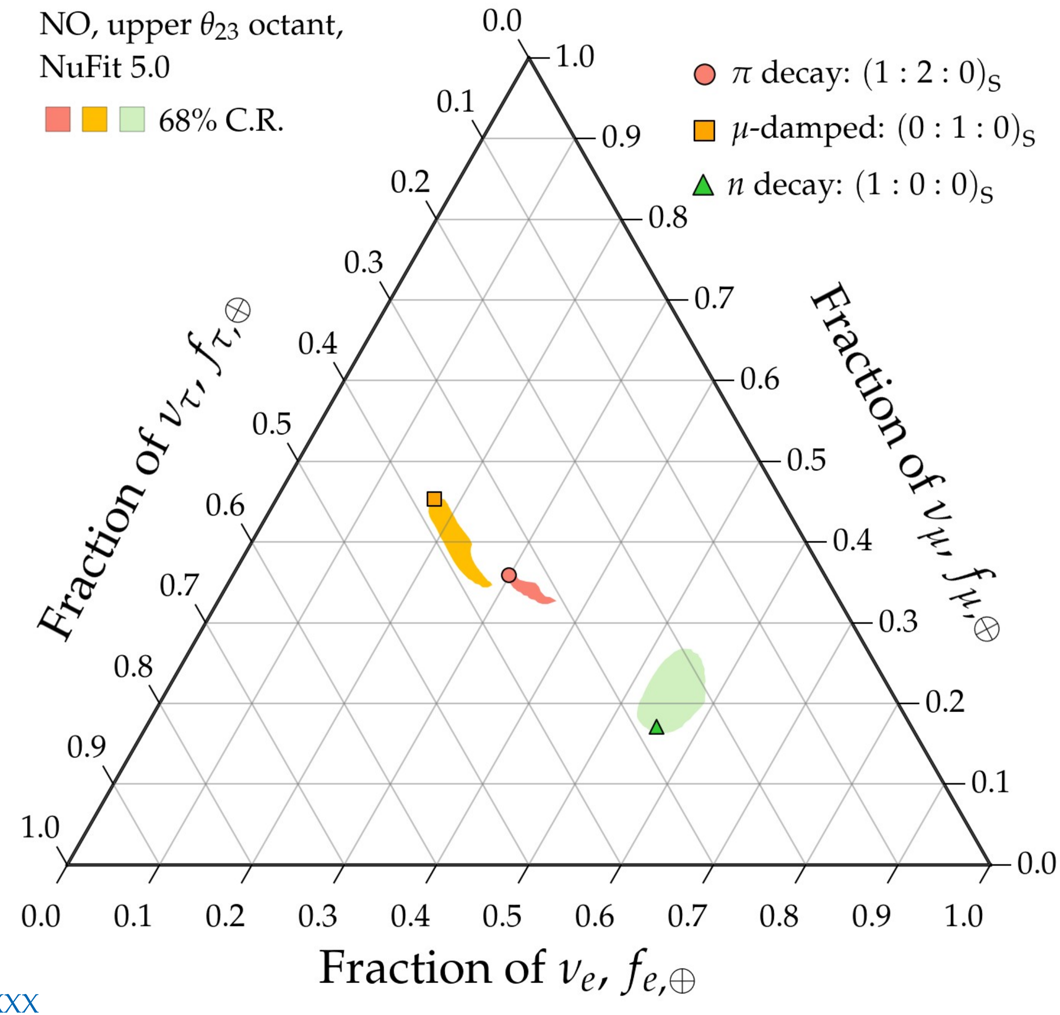
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: today (2020)



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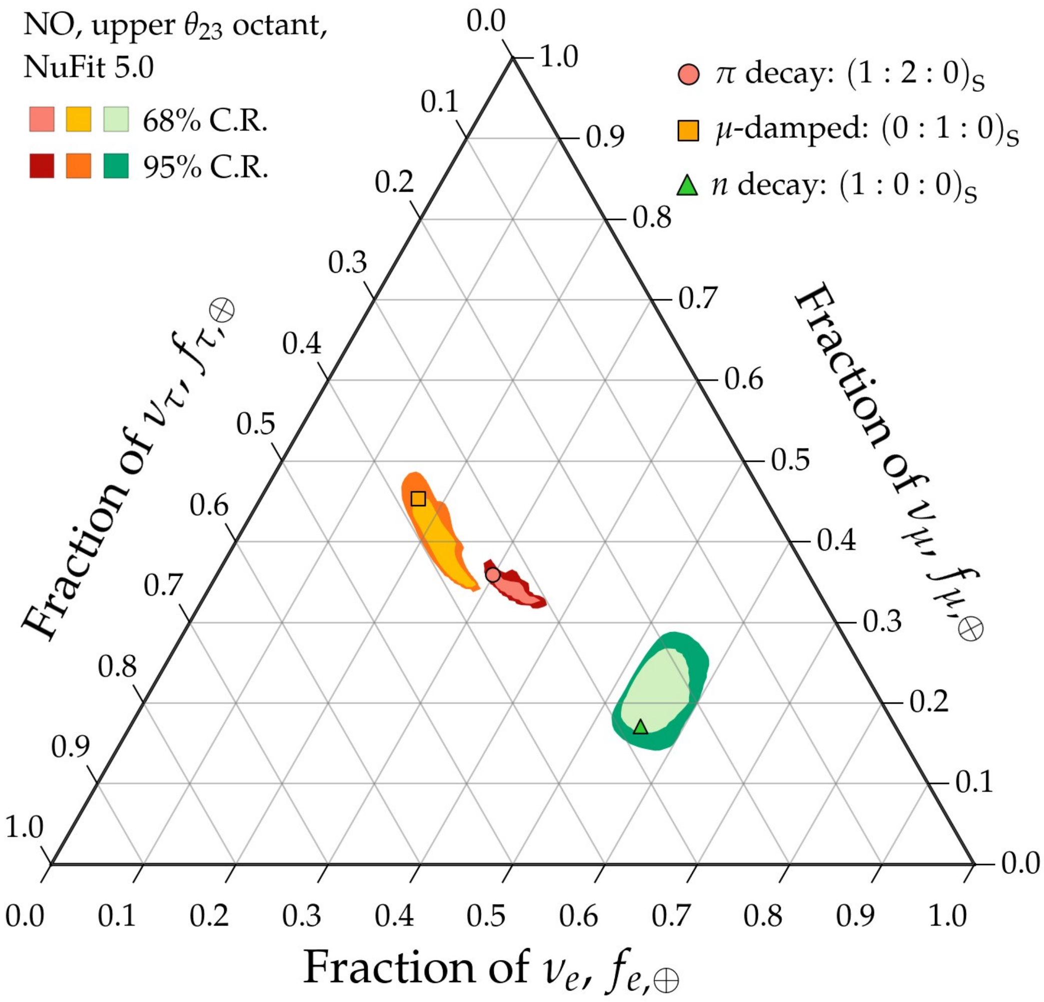

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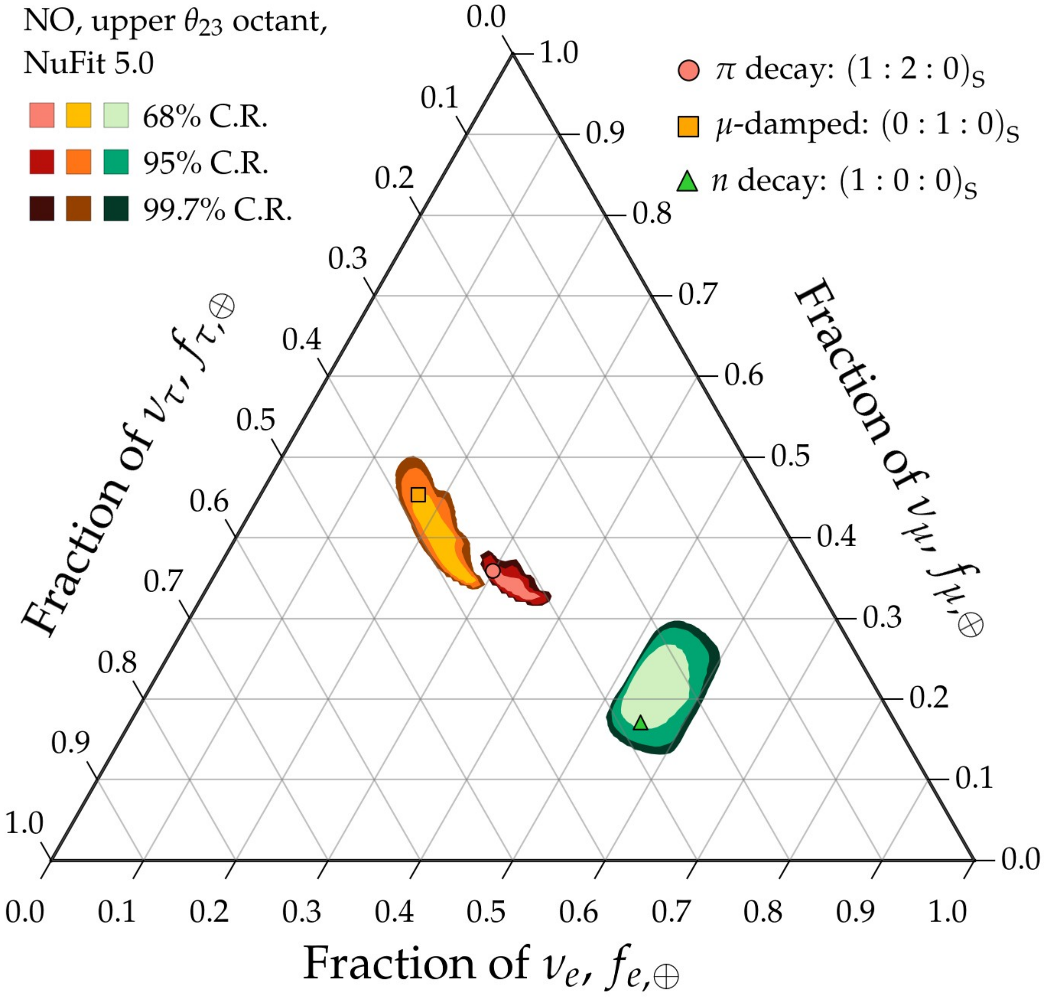
Theoretically palatable regions: today (2020)



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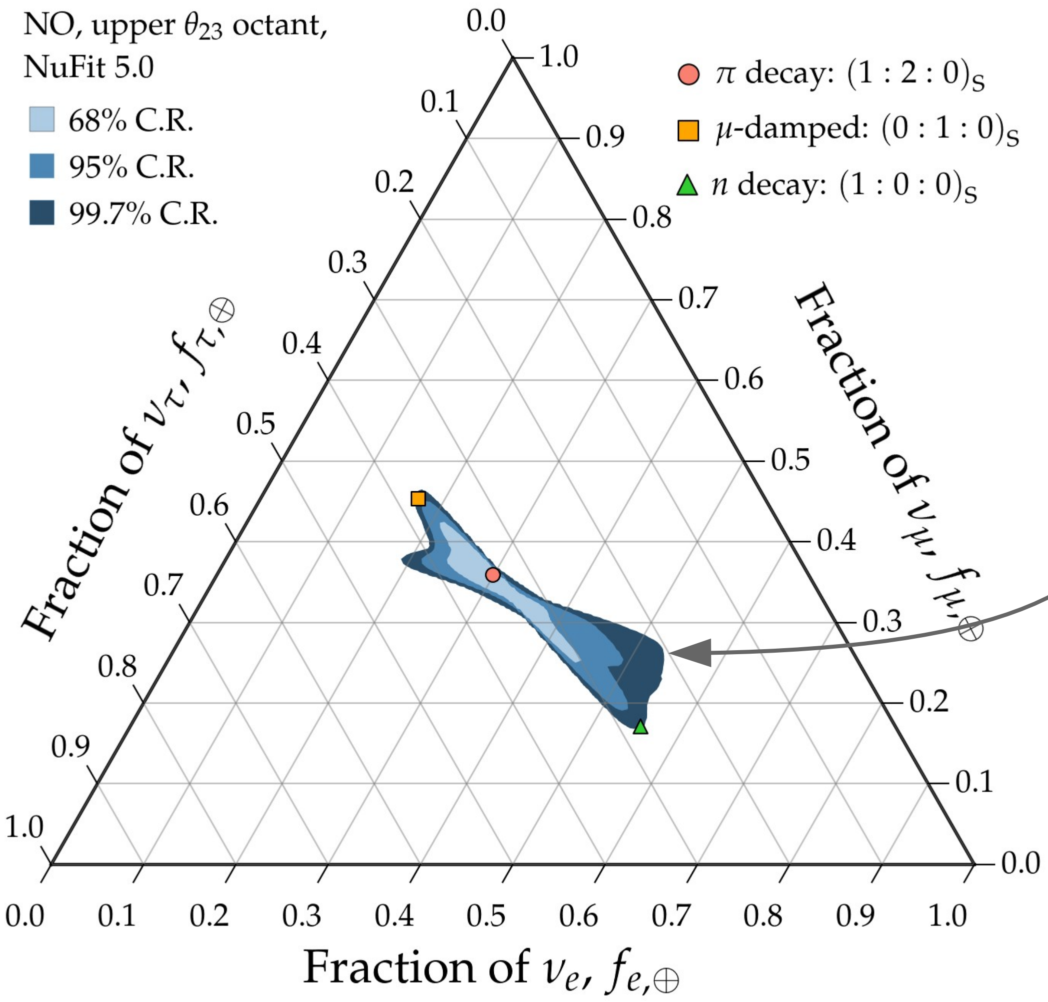
Theoretically palatable regions: today (2020)

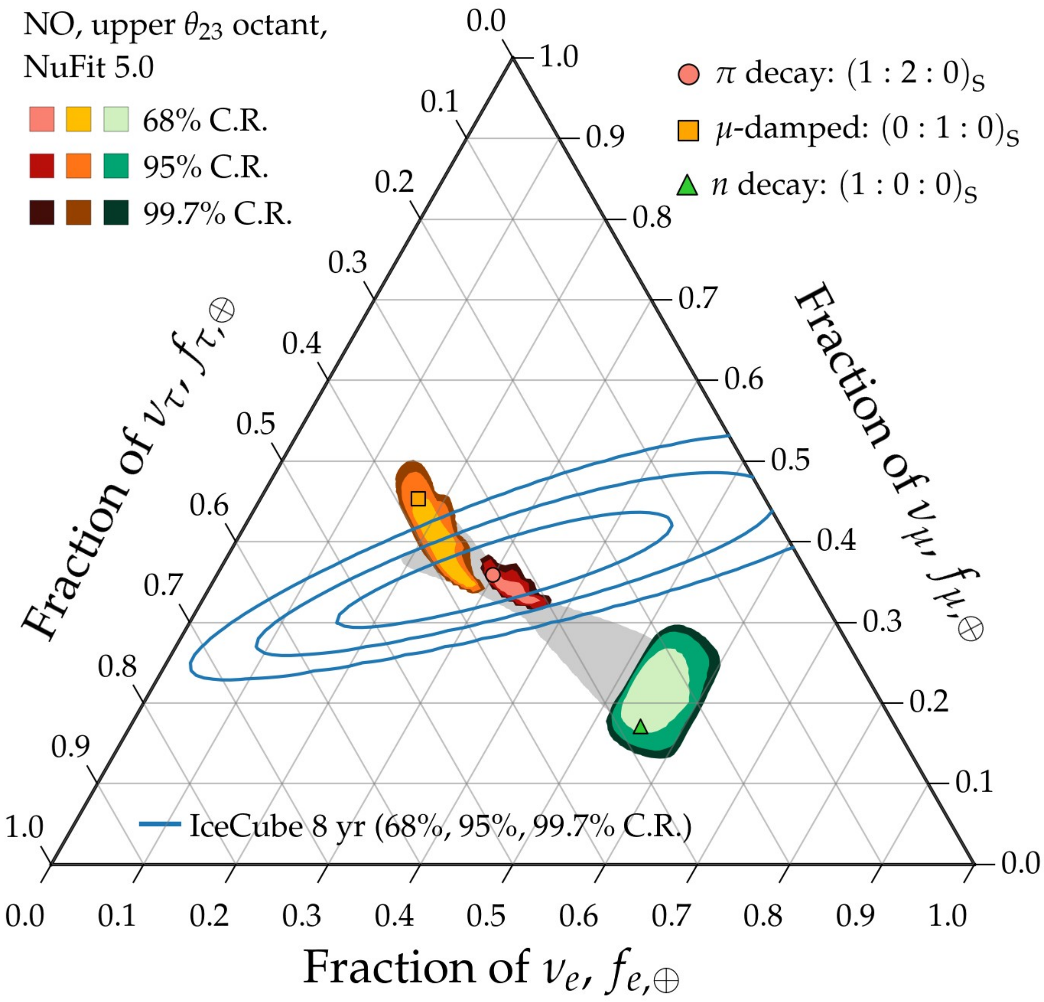


Varying over all possible flavor ratios at the source

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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

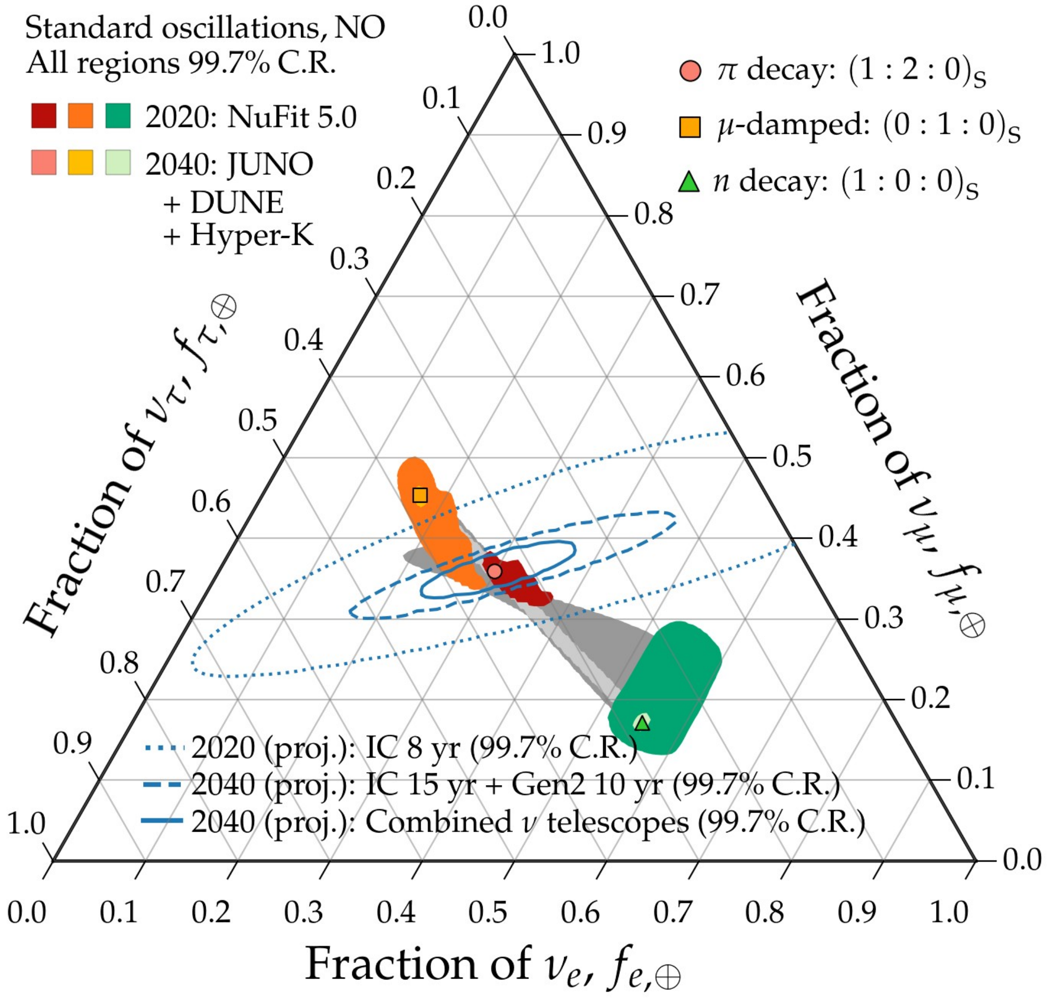
Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

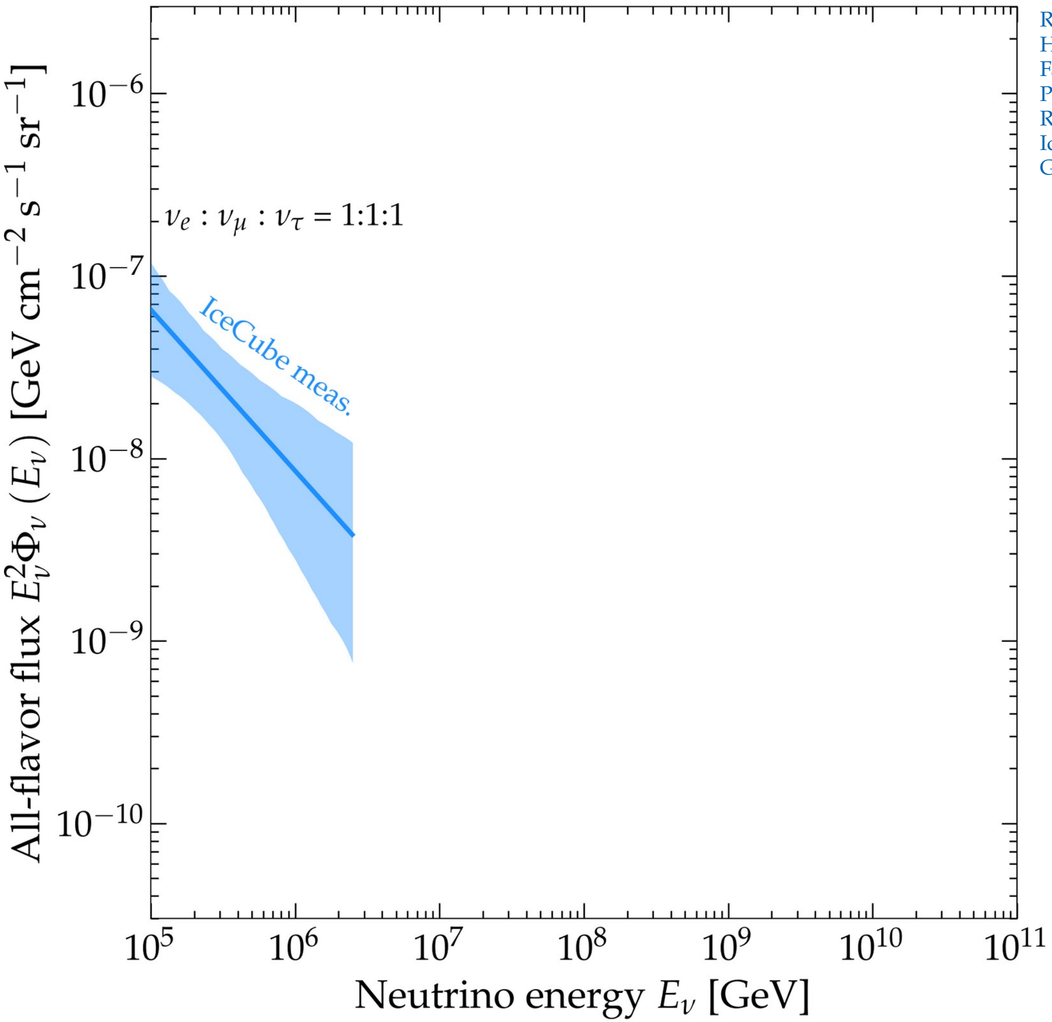
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

Can finally use the full power of flavor composition for astrophysics and neutrino physics

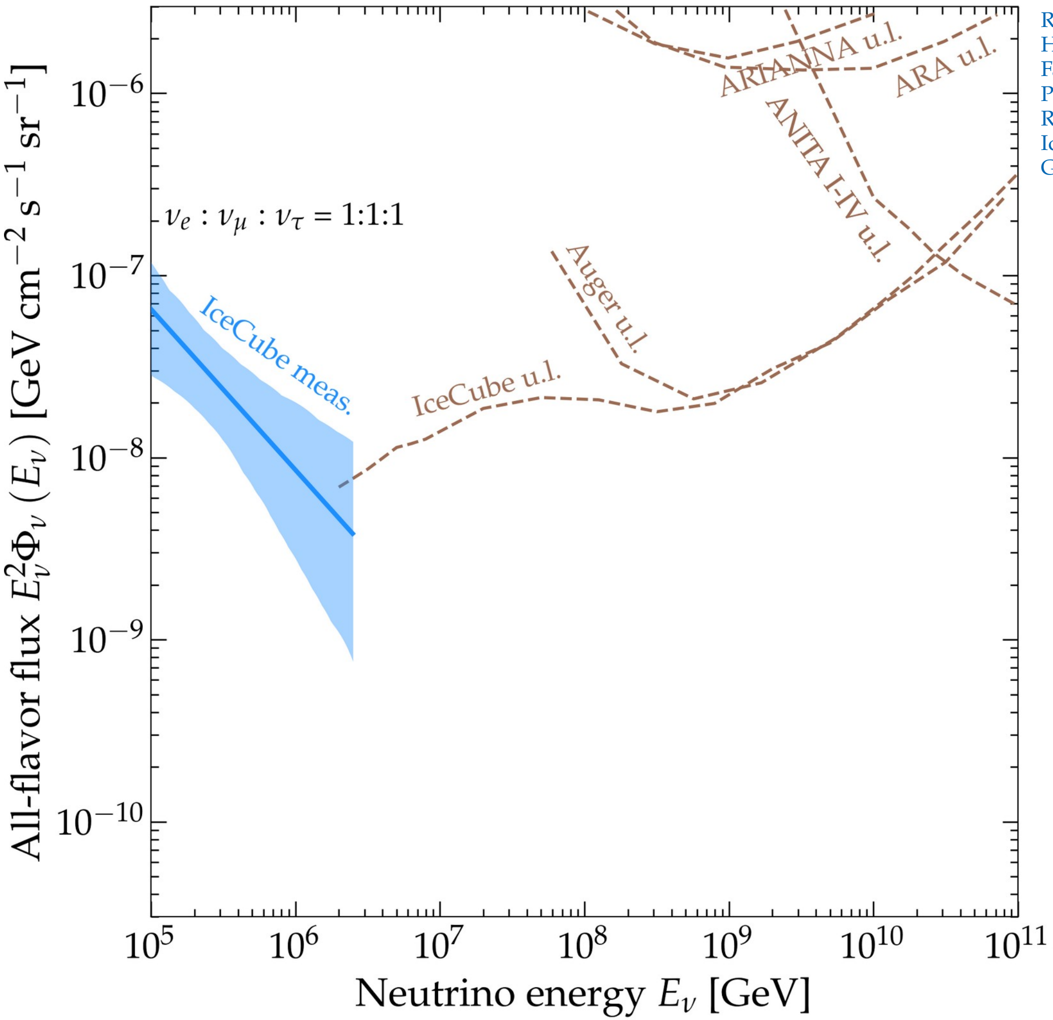
Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

UHE neutrinos: *steady-state sources*



Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
Fang & Murase, *Nature Phys.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

UHE neutrinos: *steady-state sources*



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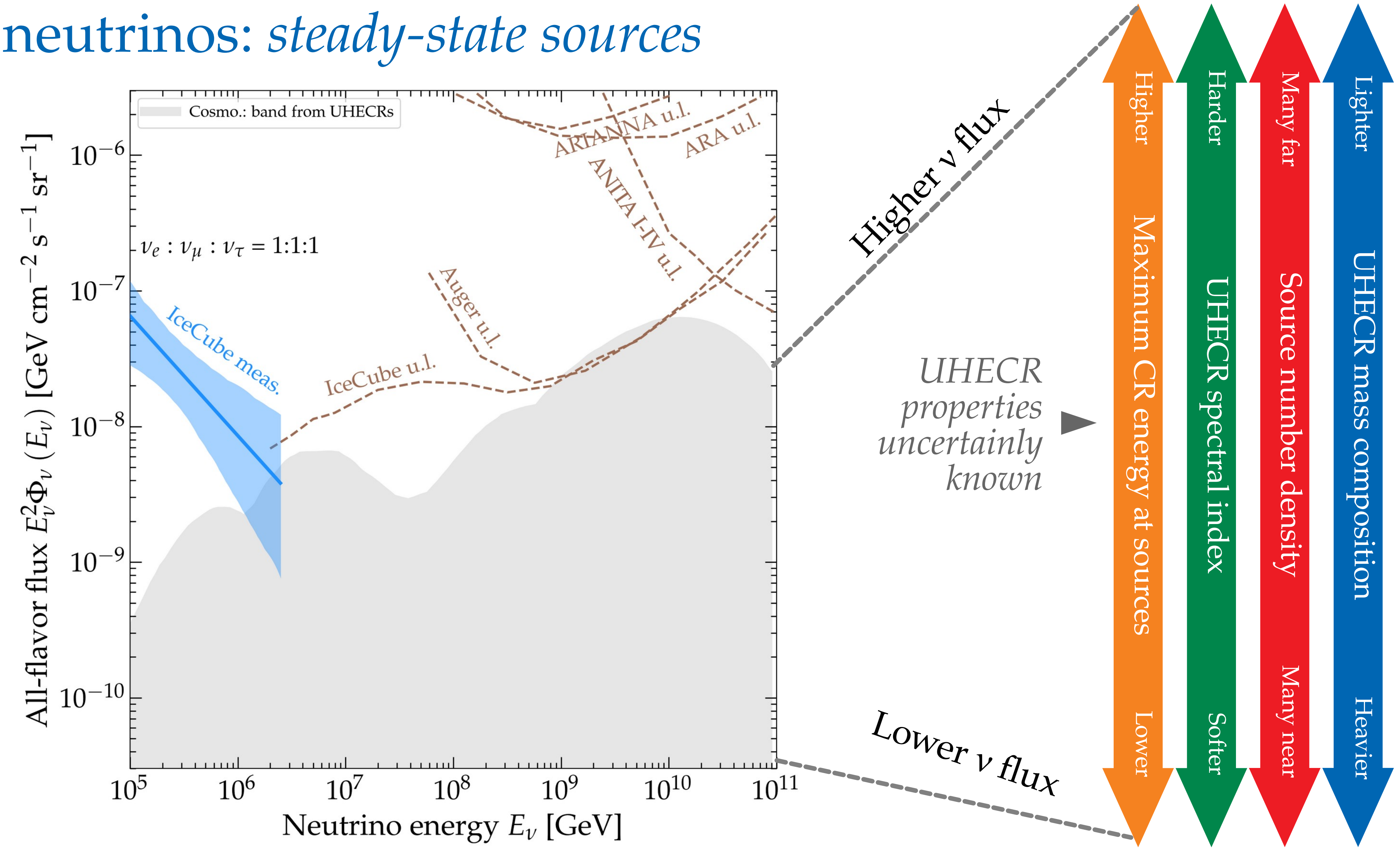
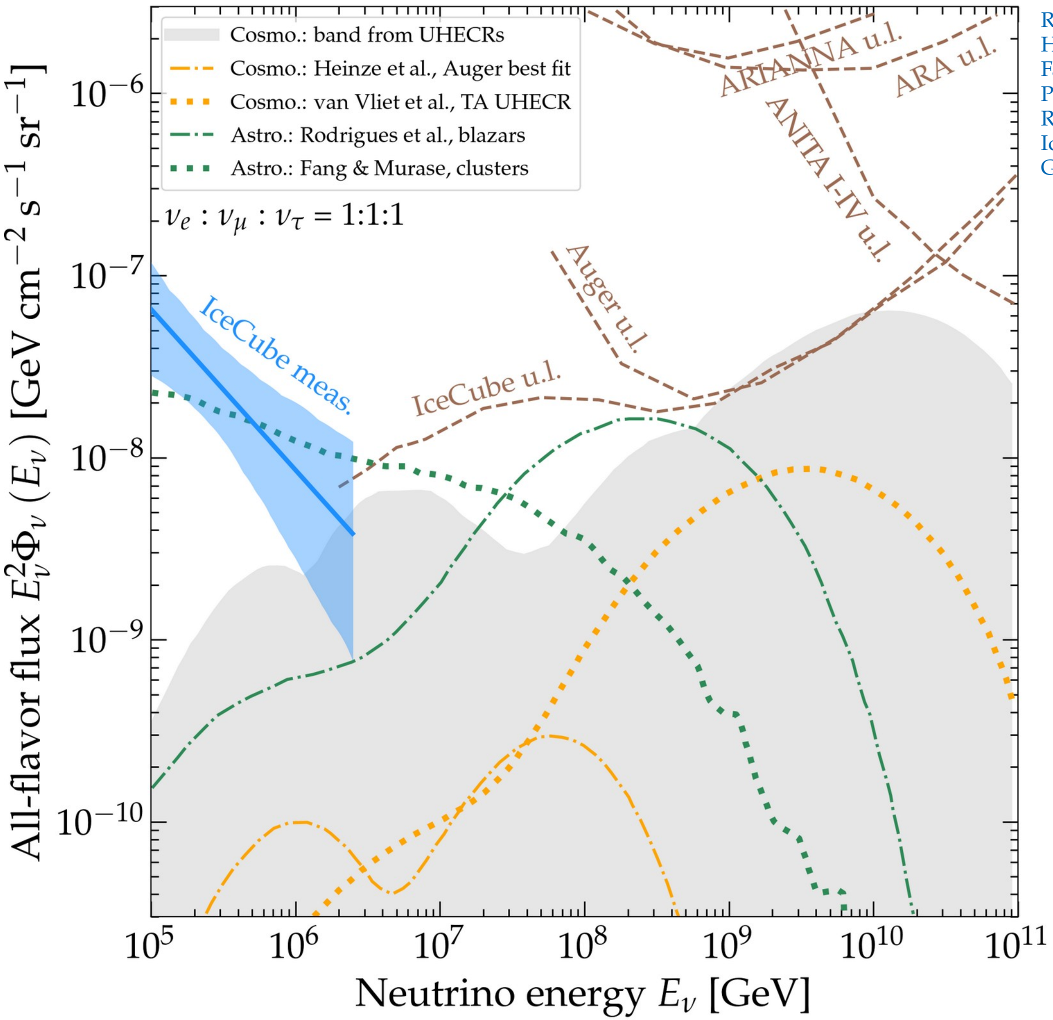
UHE neutrinos: *steady-state sources*



UHE neutrinos: *steady-state sources*



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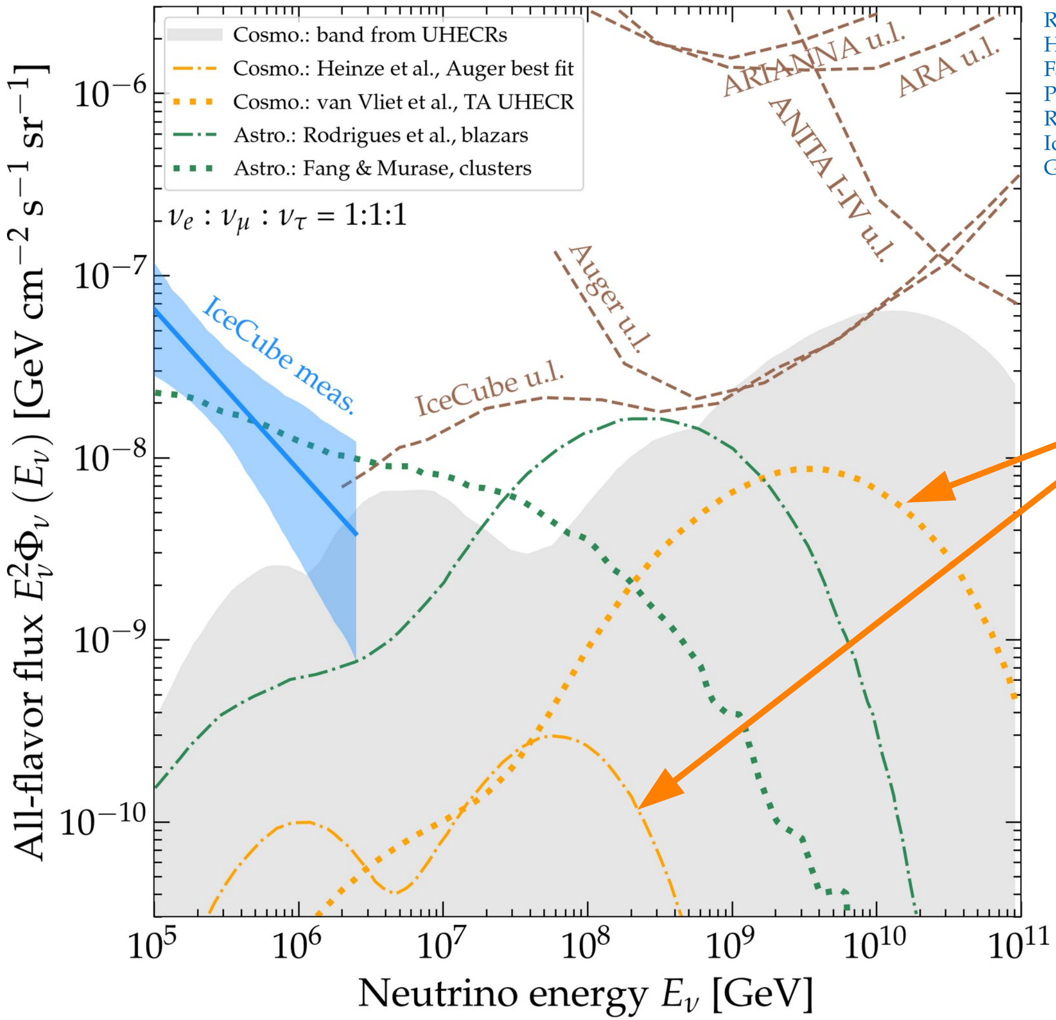

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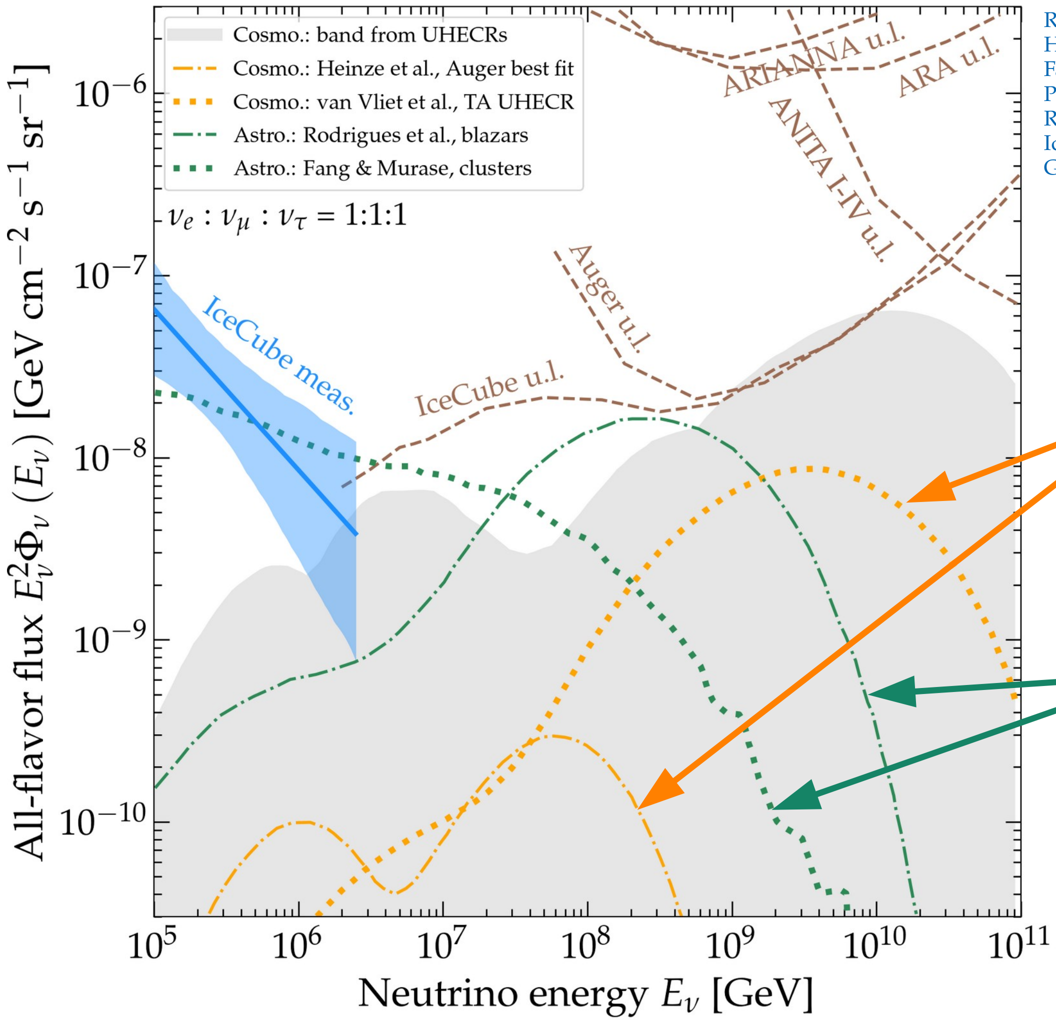

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Heinze, Fedynitch, Boncioli, Winter *ApJ* 2019
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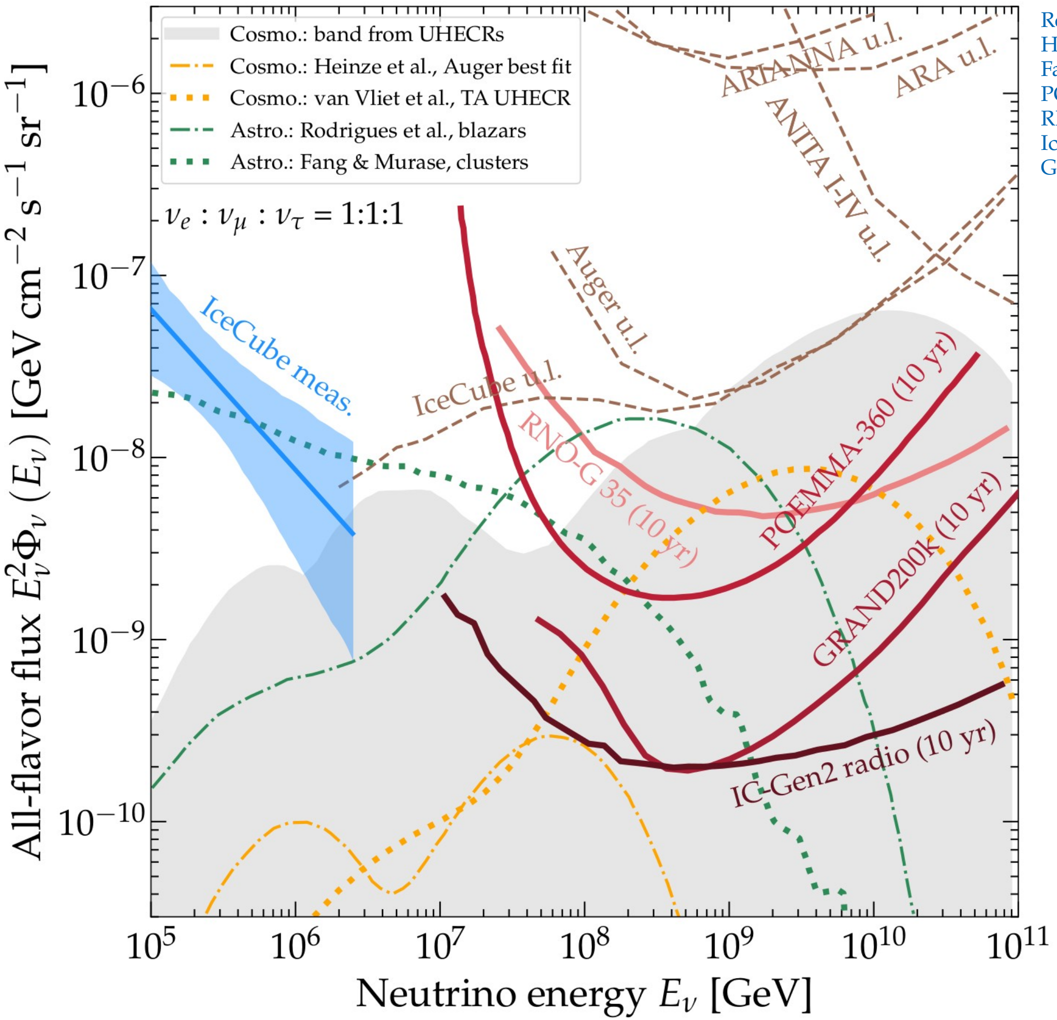
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020

Cosmogenic neutrinos

Neutrinos from the sources
(possibly dominant flux!)

UHE neutrinos: *steady-state sources*



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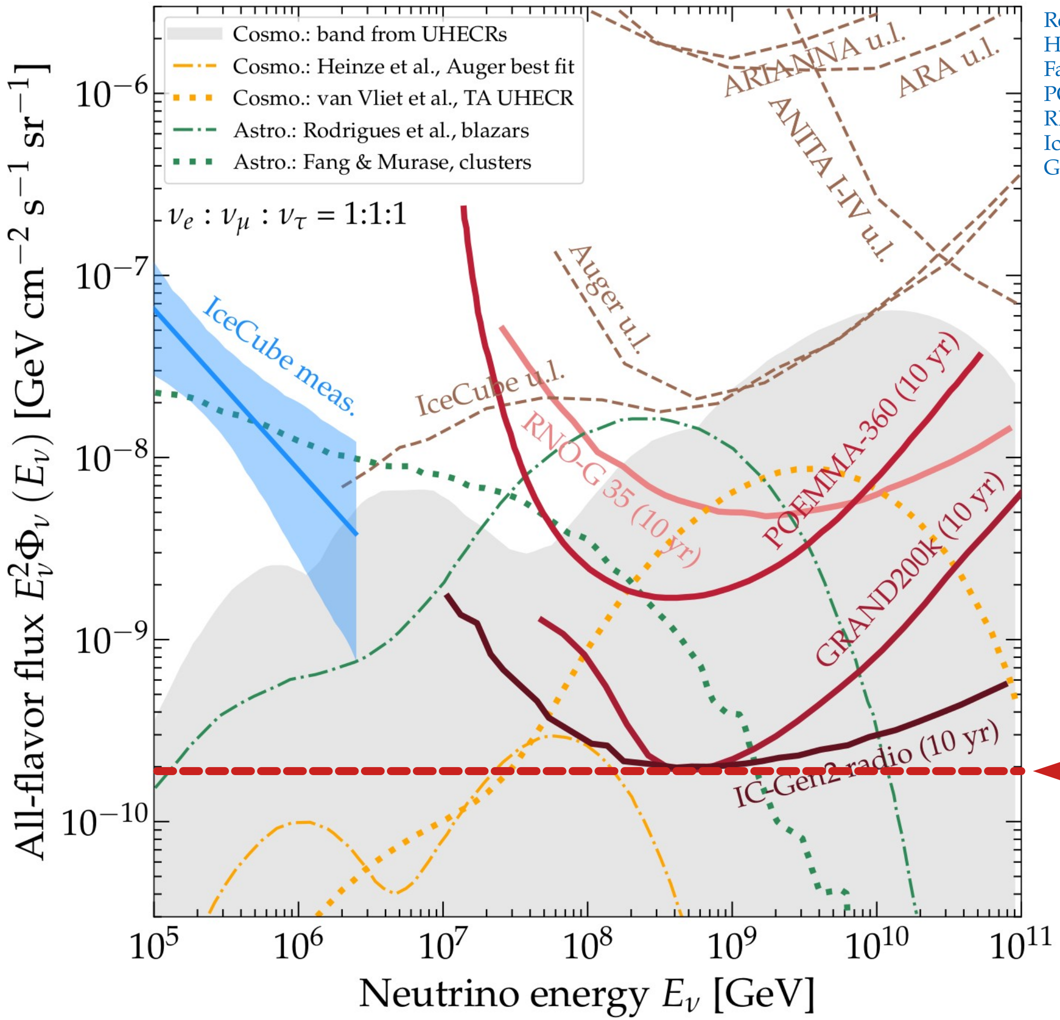

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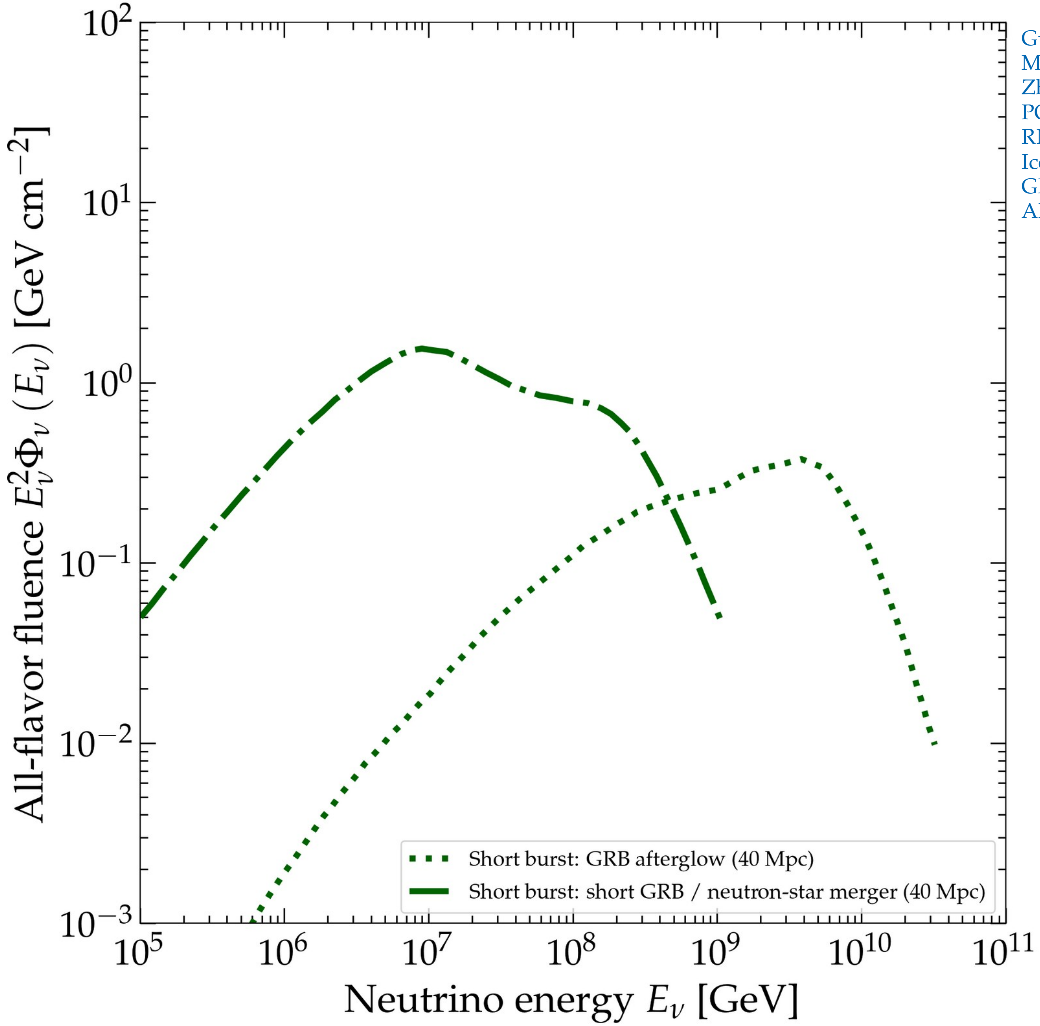
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

Ultimate target sensitivity for next-gen detectors

(if protons are ~10% of the highest-energy UHECRs)

UHE neutrinos: *transient sources*



Guépin, Kotera, Barausse, Fang, Murase, *A&A* 2018
Murase, *PRD* 2017
Zhang *et al.*, *Nature Commun.* 2018
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

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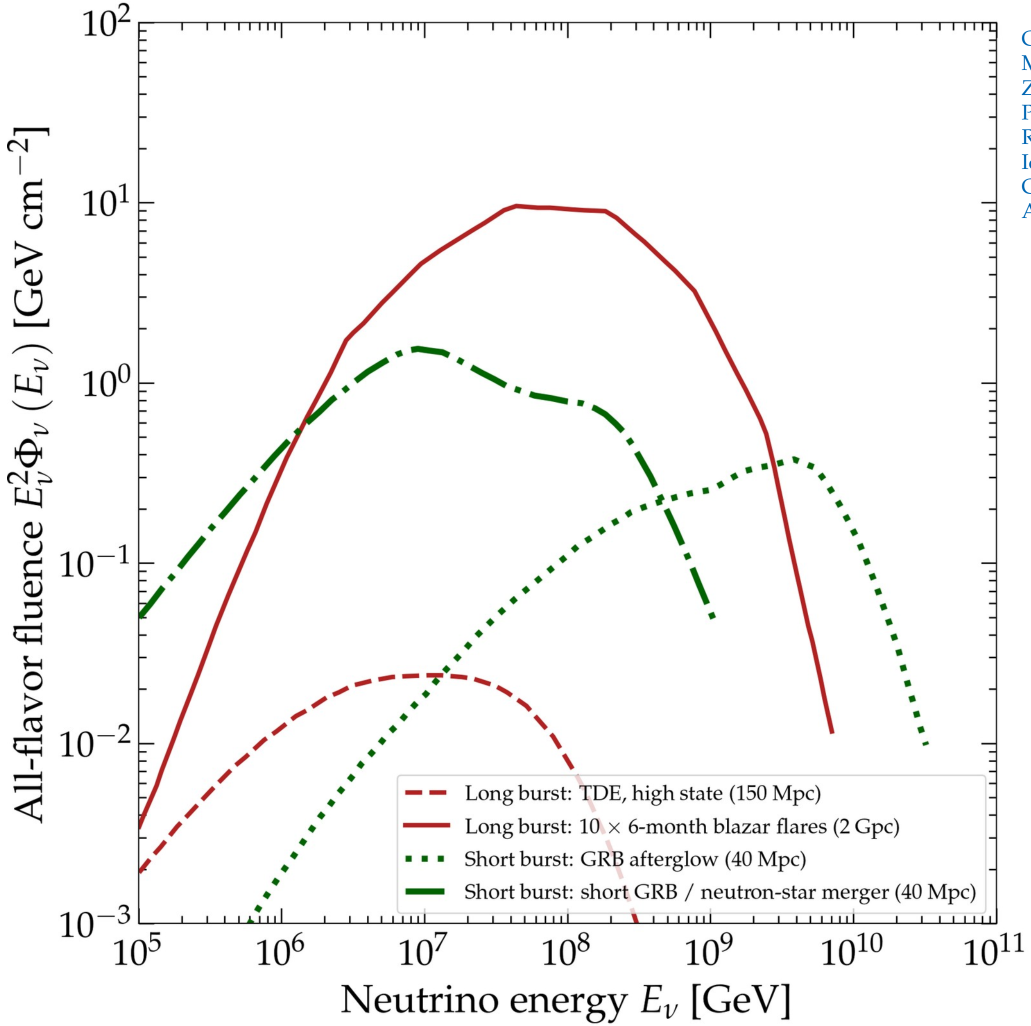

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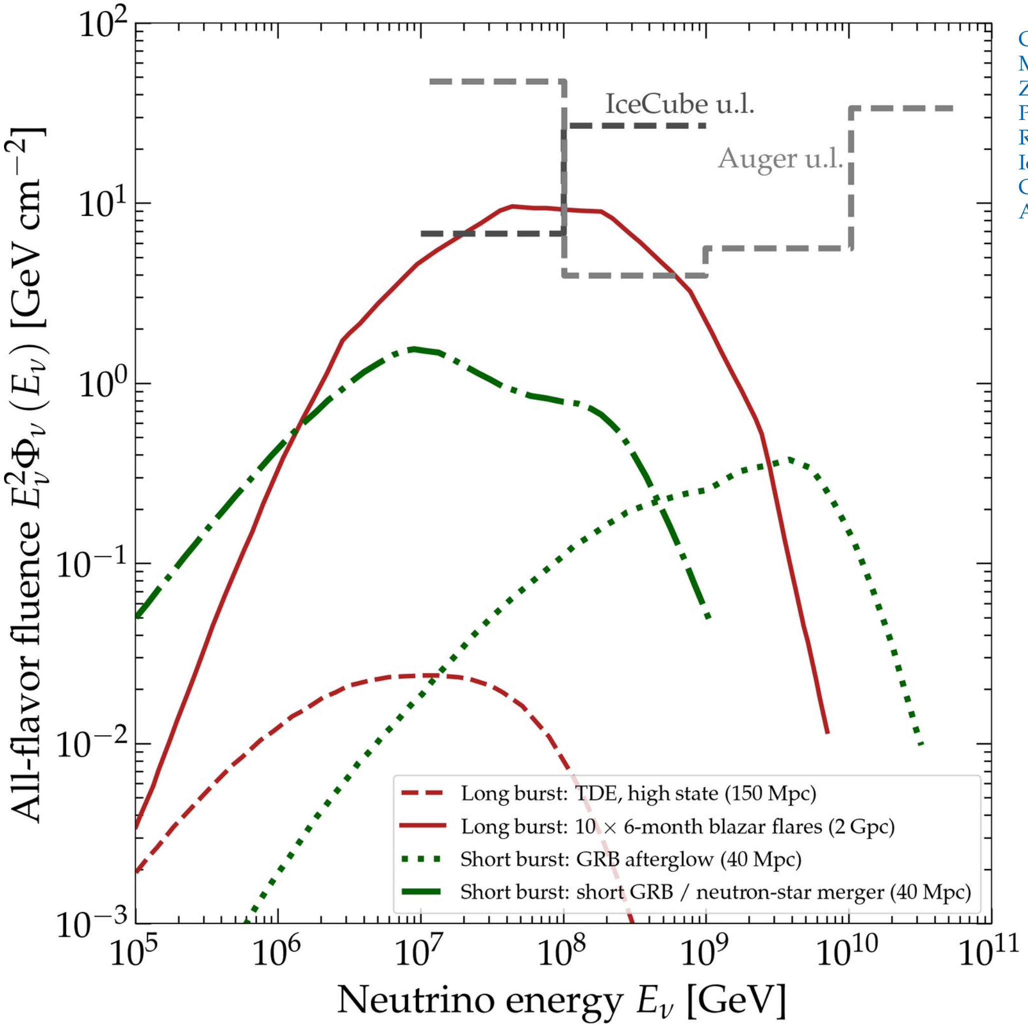

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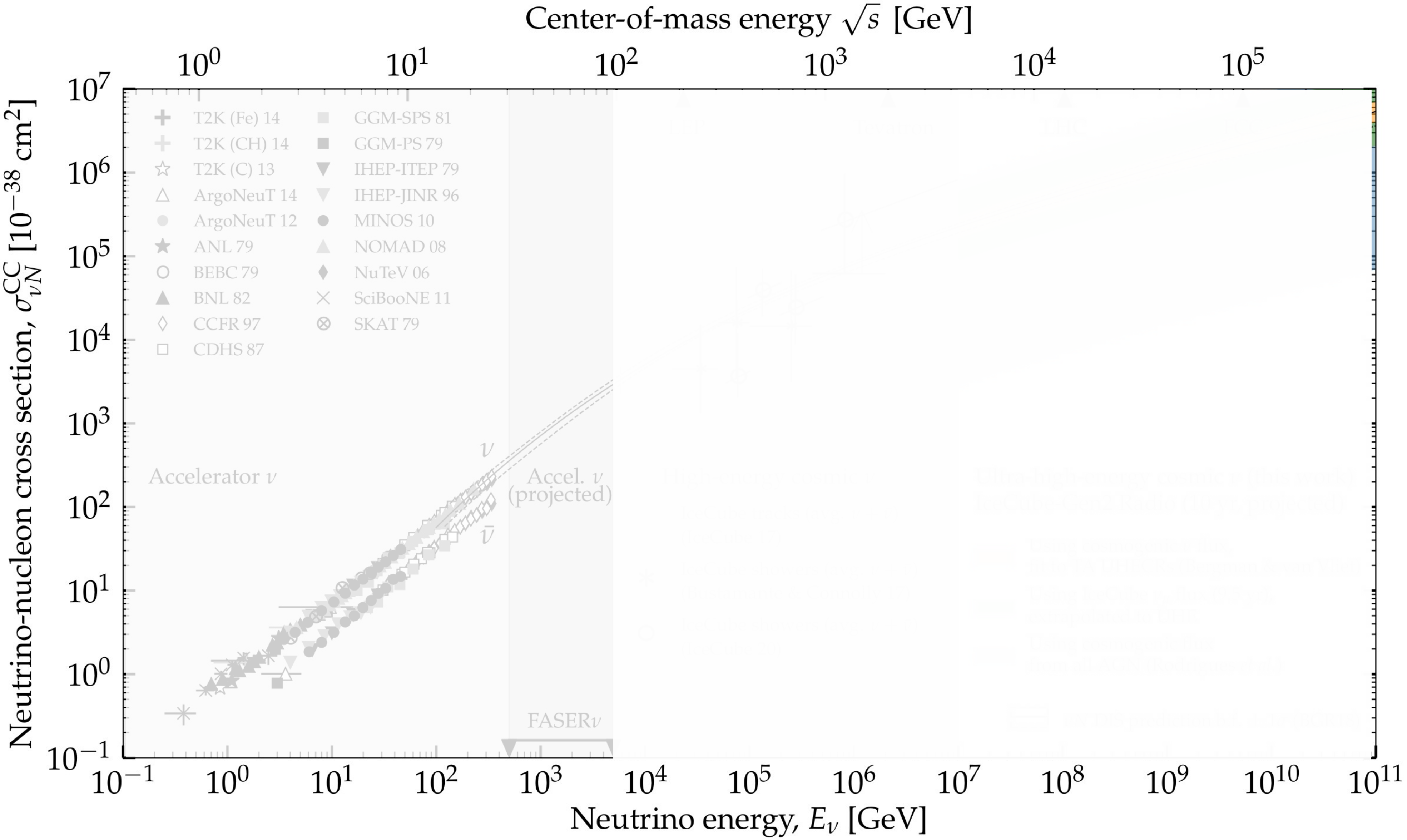
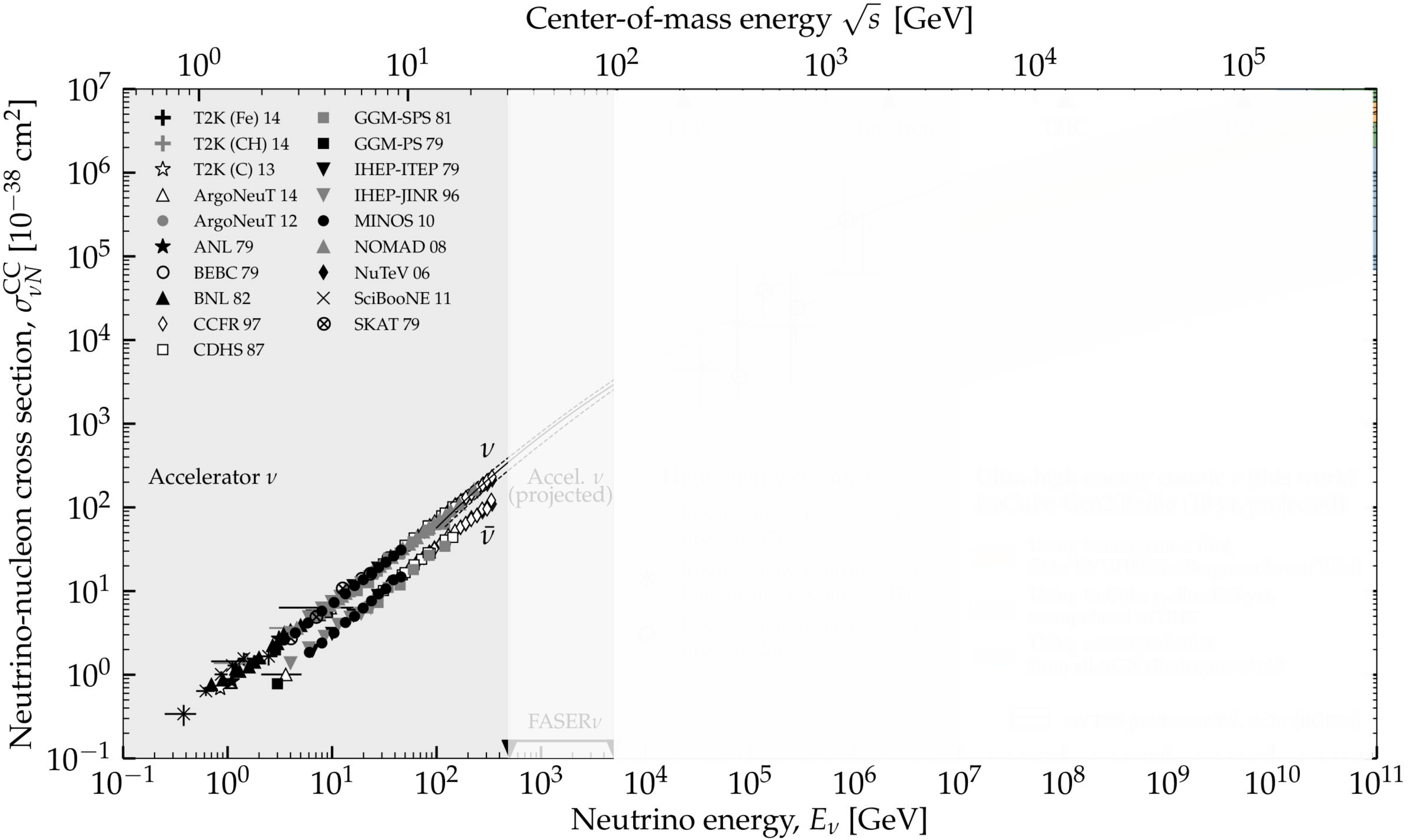

Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Accelerator ν
Accel. ν
(projected)
ν
$\bar{\nu}$
FASERν
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]
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Neutrino-nucleon cross section, $\sigma^{CC}_{\nu N}$ [10^{-38} cm^2]
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T2K (Fe) 14
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ArgoNeuT 14
ArgoNeuT 12
ANL 79
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Accelerator ν
Accel. ν
(projected)
ν
$\bar{\nu}$
FASERν
10^{-1}
10^0
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10^{10}
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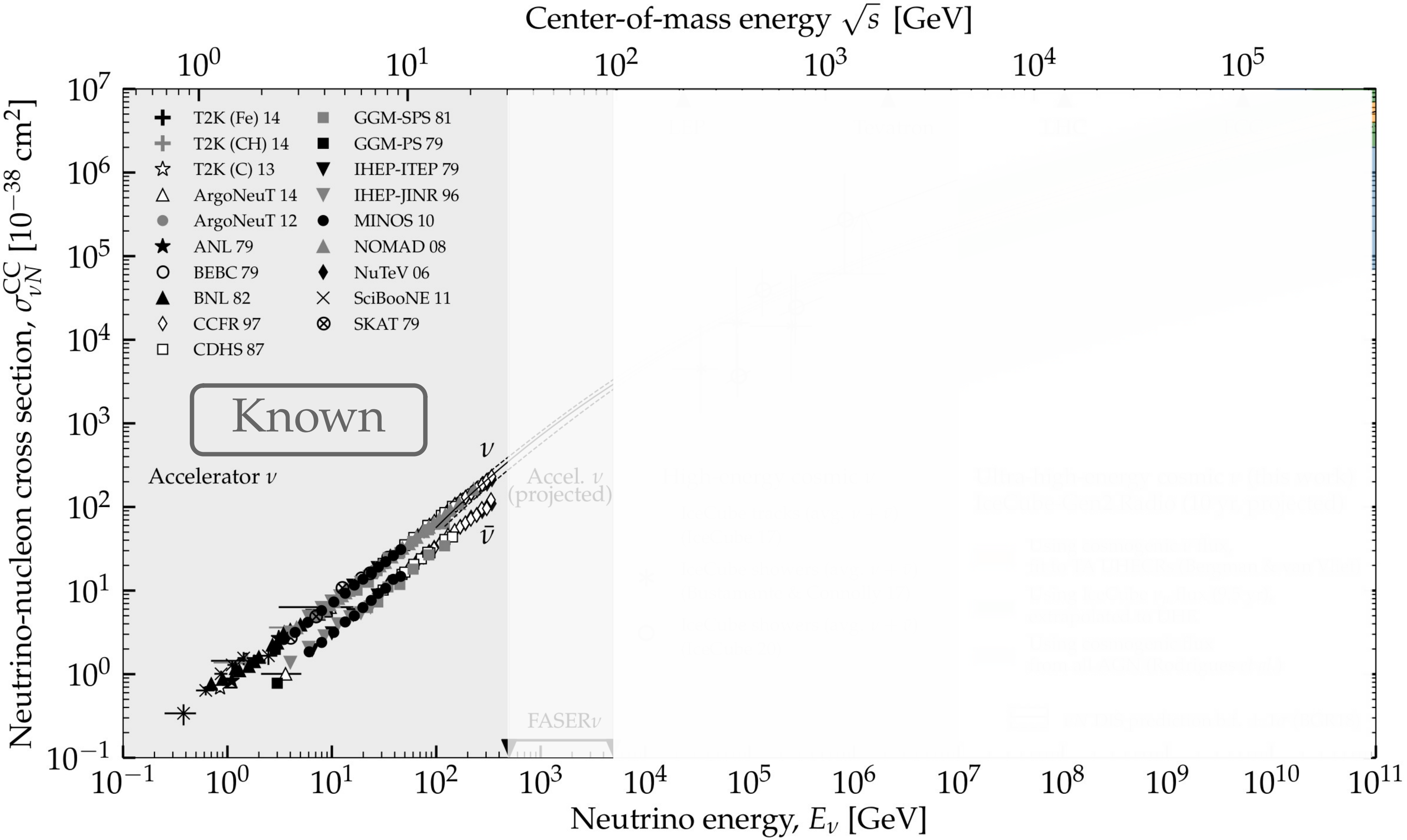
Neutrino energy, E_ν [GeV]



Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
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Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
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T2K (Fe) 14
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Known
Accelerator ν
ν
$\bar{\nu}$
Accel. ν
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FASERν
10^{-1}
10^0
10^1
10^2
10^3
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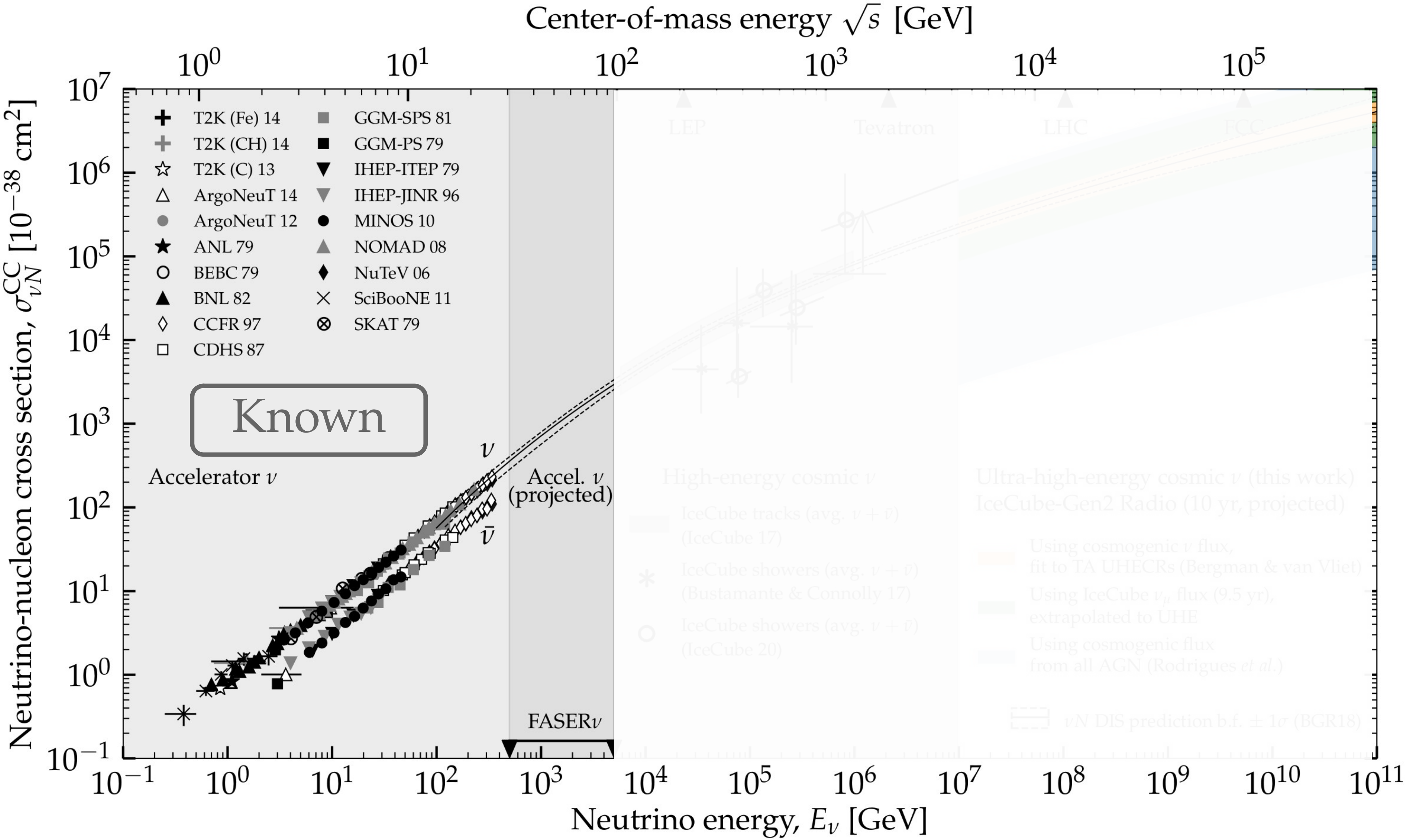
Neutrino energy, E_ν [GeV]



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Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
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ANL 79
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MINOS 10
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SciBooNE 11
SKAT 79
Known
Accelerator ν
ν
$\bar{\nu}$
Accel. ν (projected)
FASERν
LEP
Tevatron
LHC
FCC
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
Using cosmogenic ν flux, fit to TA UHECRs (Bergman & van Vliet)
Using IceCube ν_μ flux (9.5 yr), extrapolated to UHE
Using cosmogenic flux from all AGN (Rodrigues et al.)
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)