

Neutrino physics at the highest energies today and in the future

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

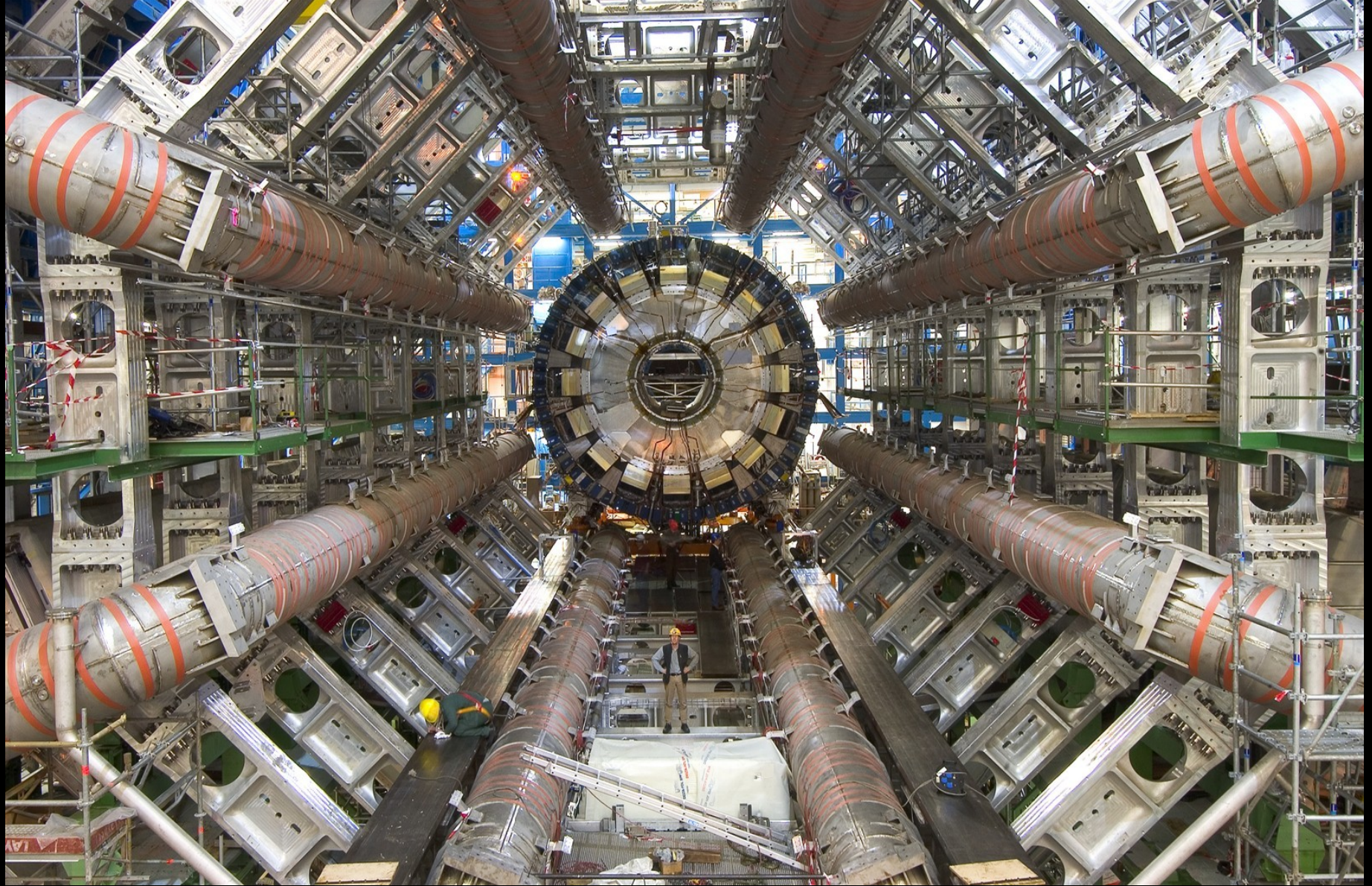
Uppsala University
February 08, 2023

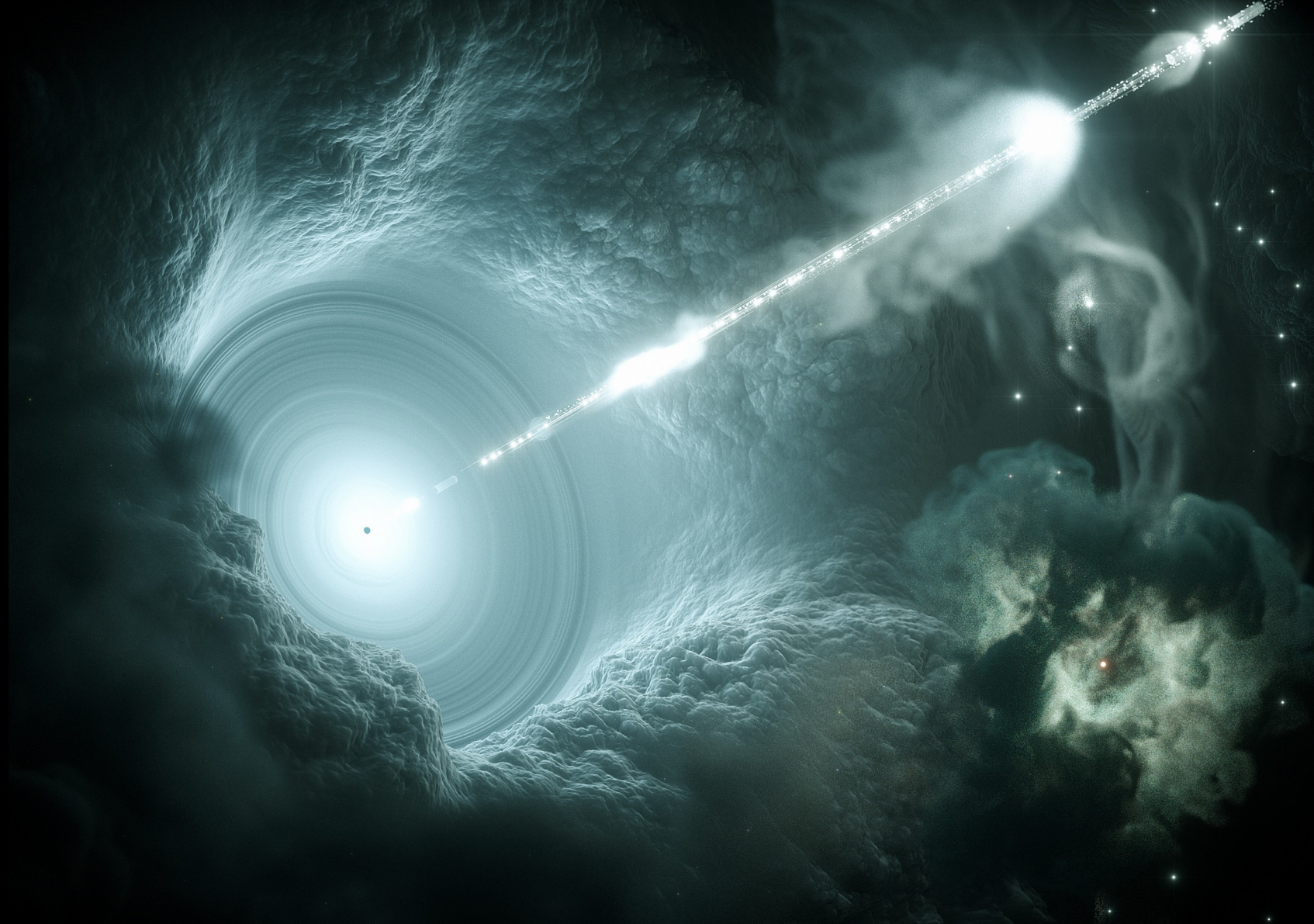
UNIVERSITY OF
COPENHAGEN

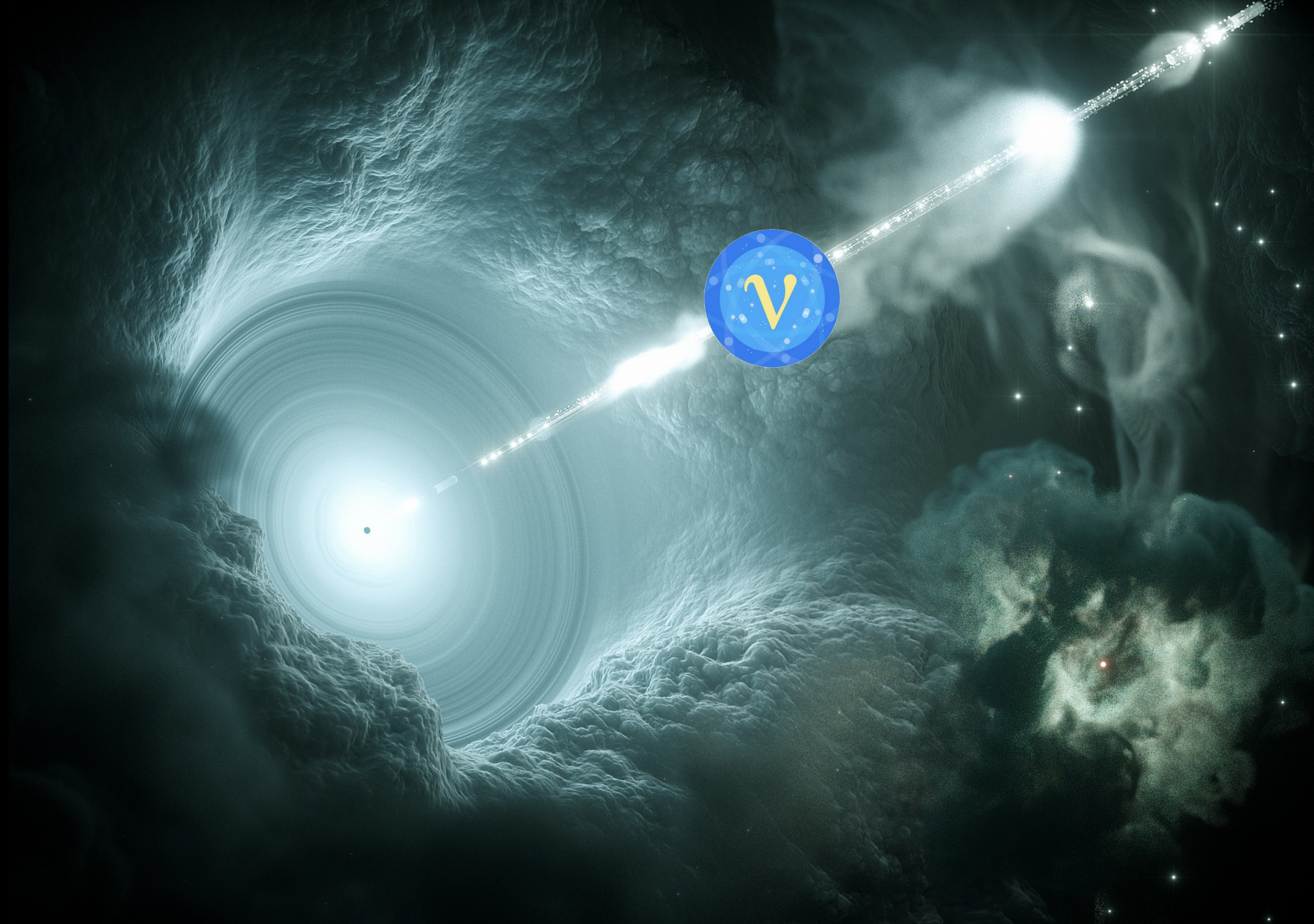


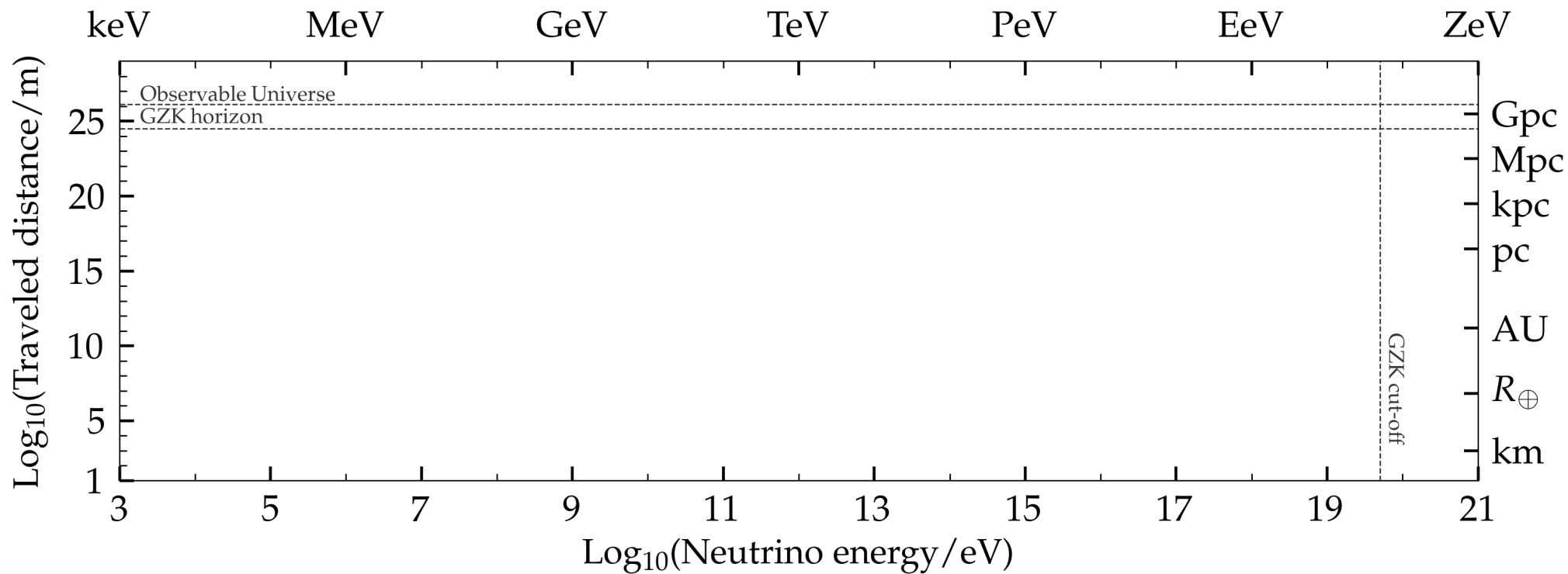
VILLUM FONDEN

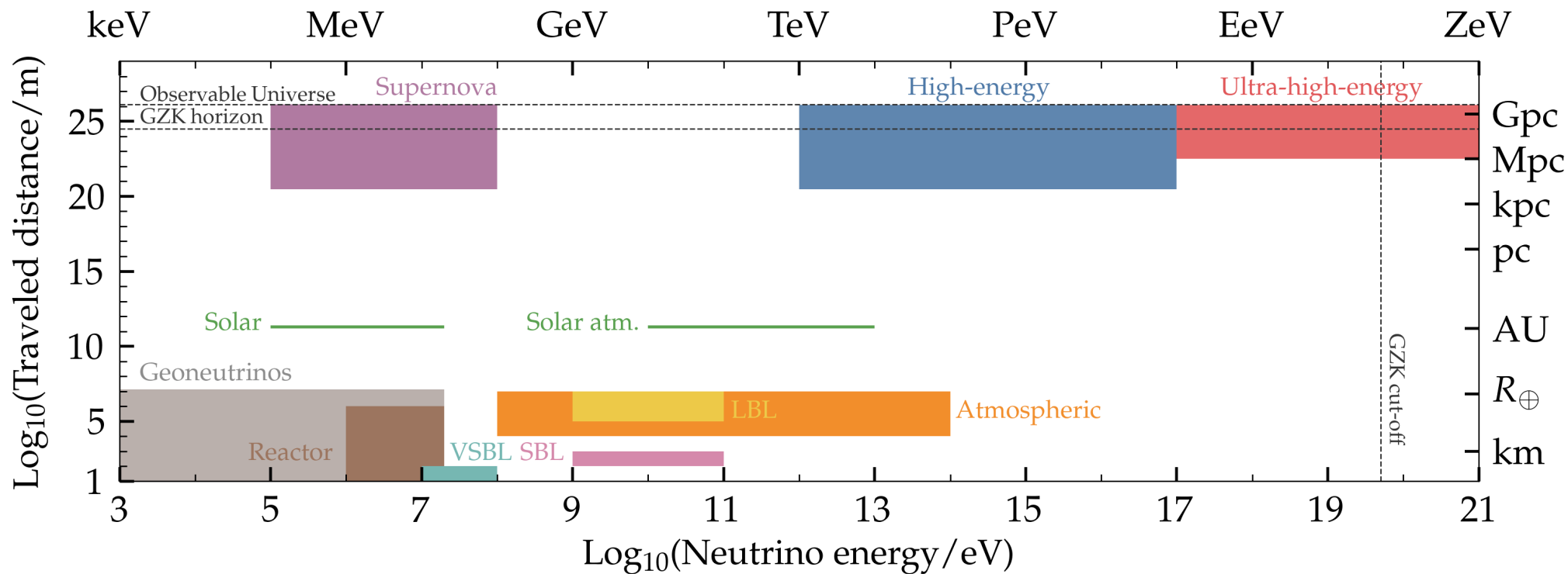




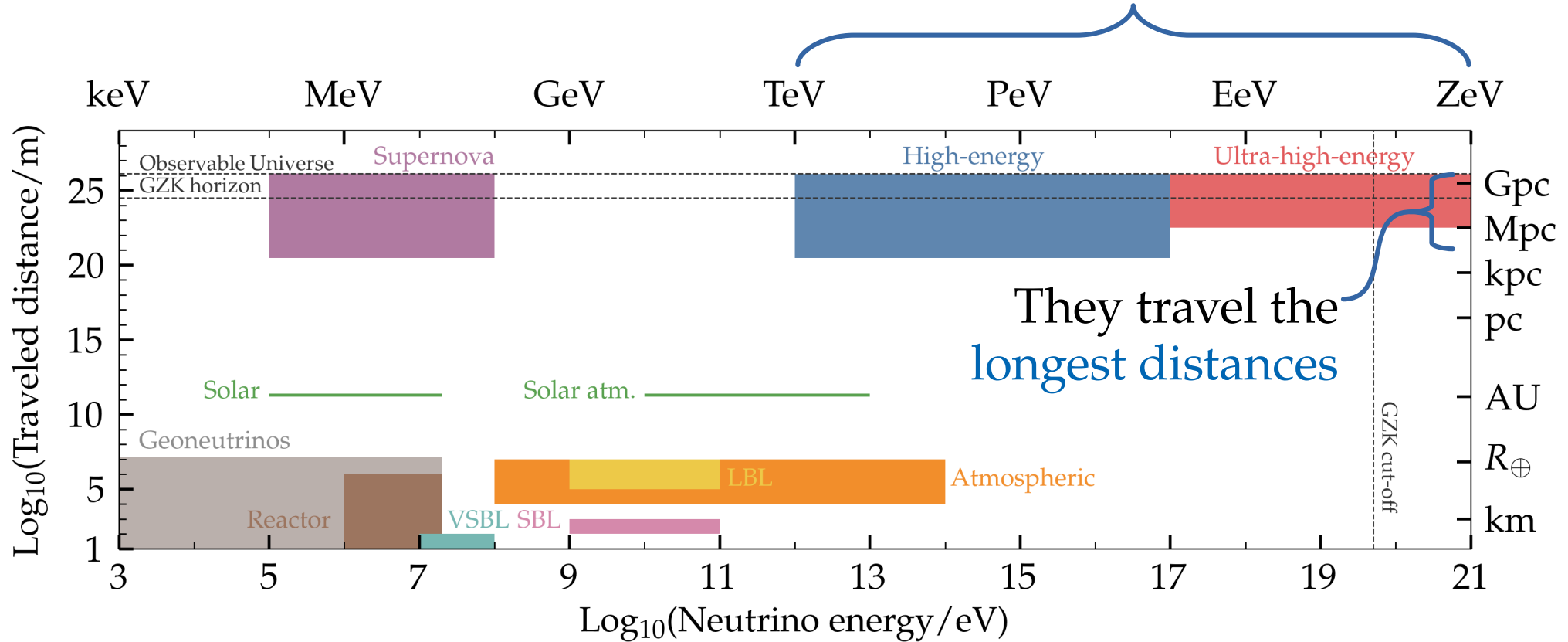


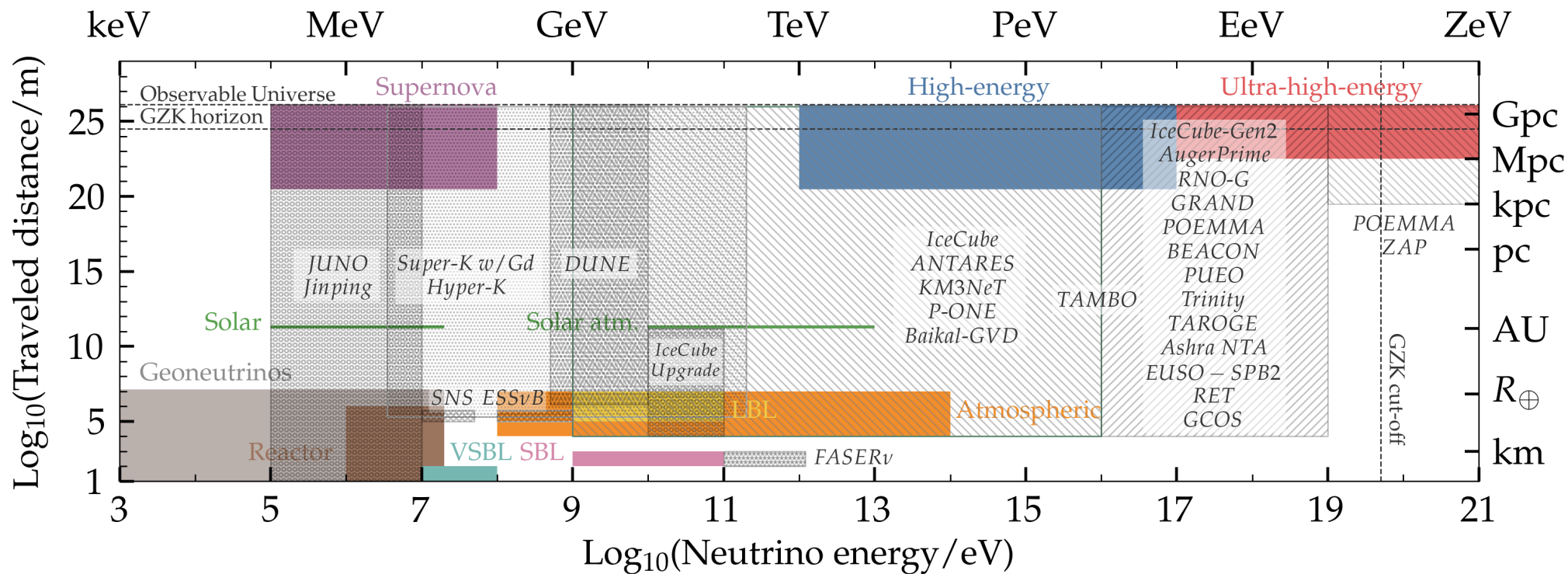


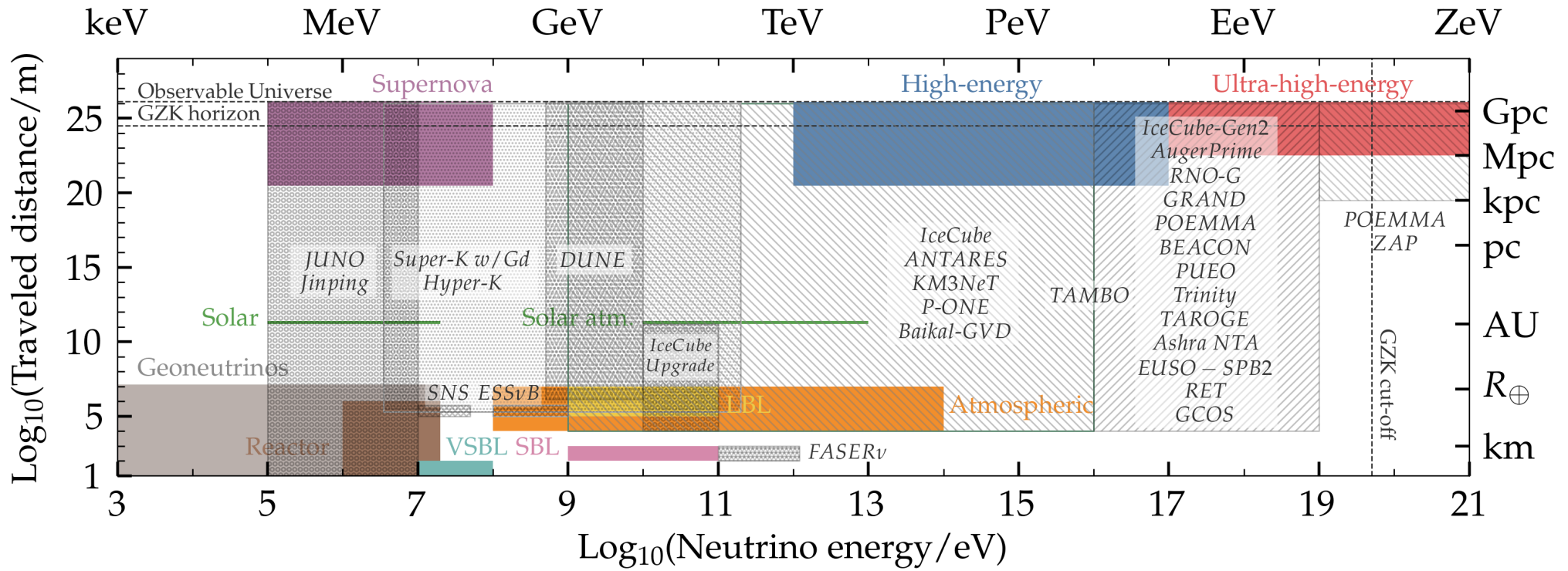




They have the **highest energies**

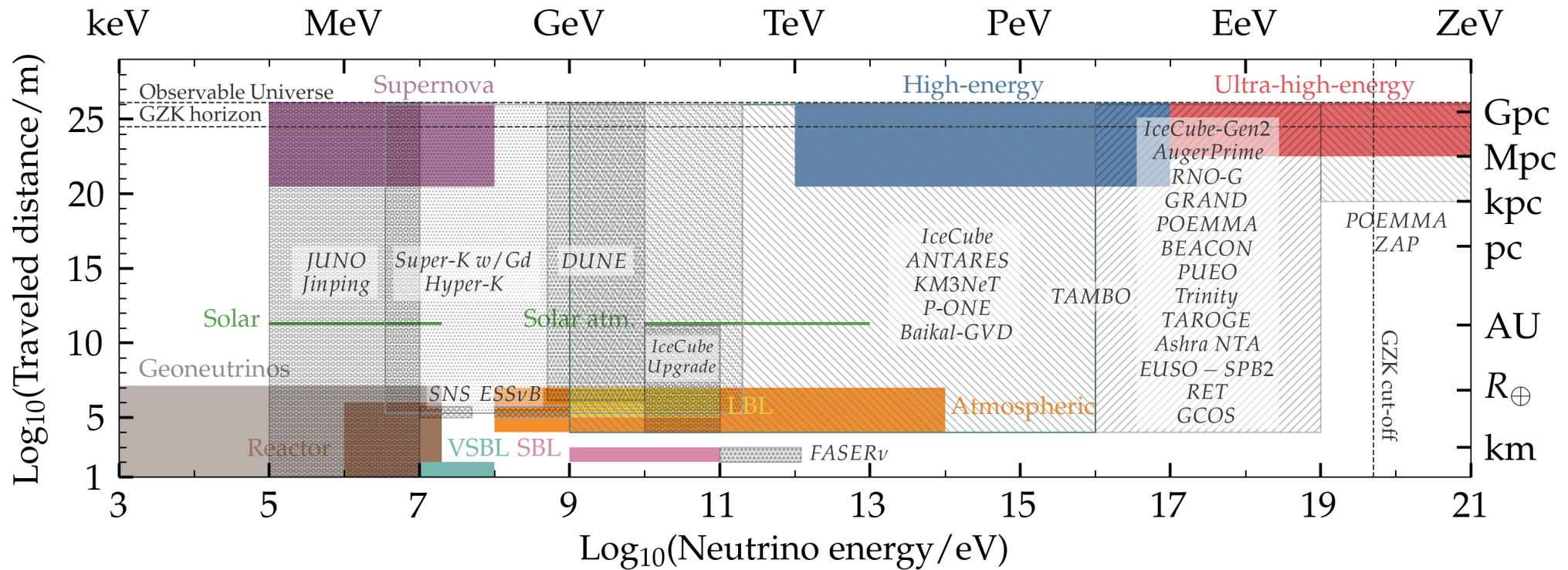




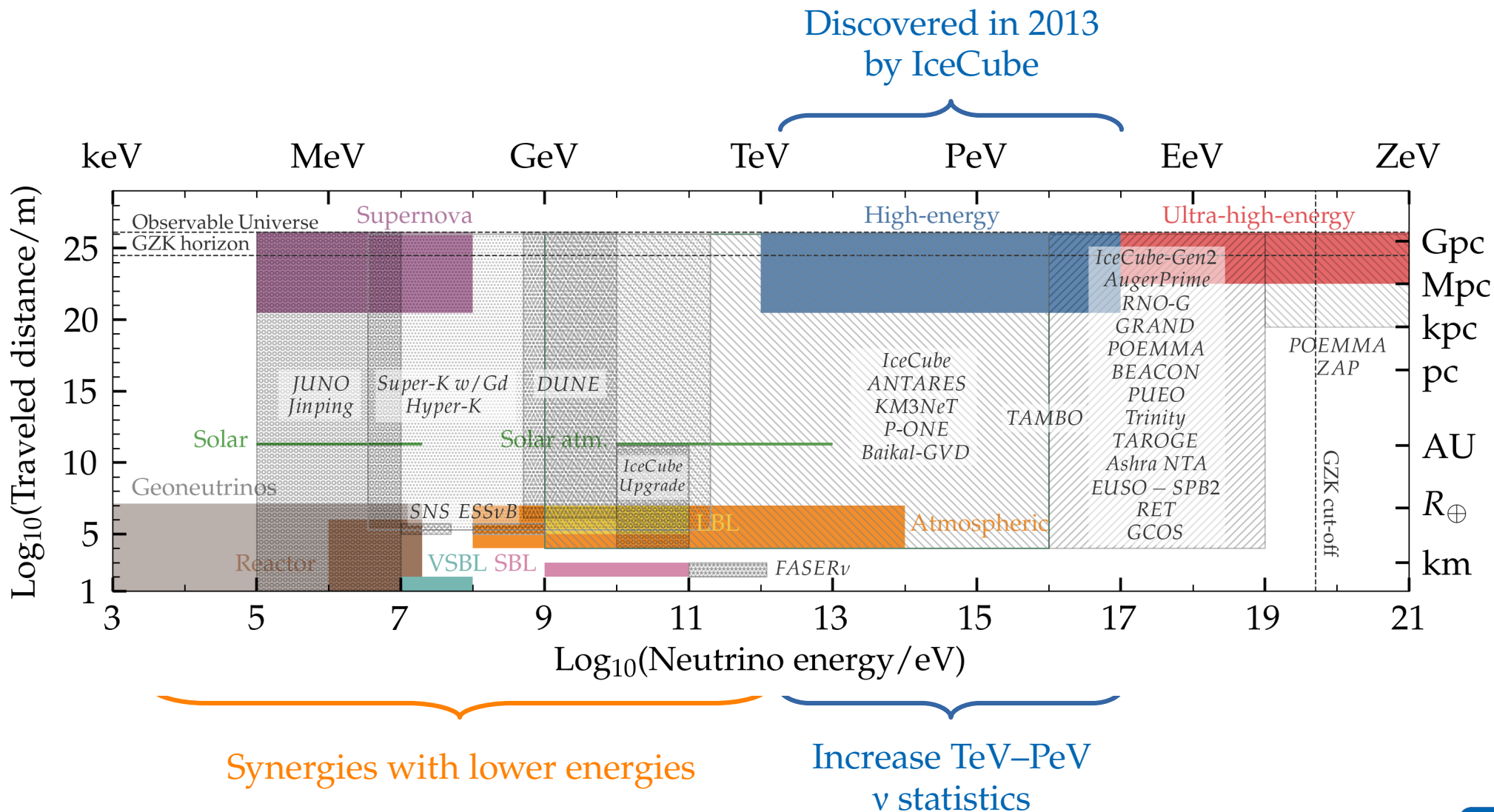


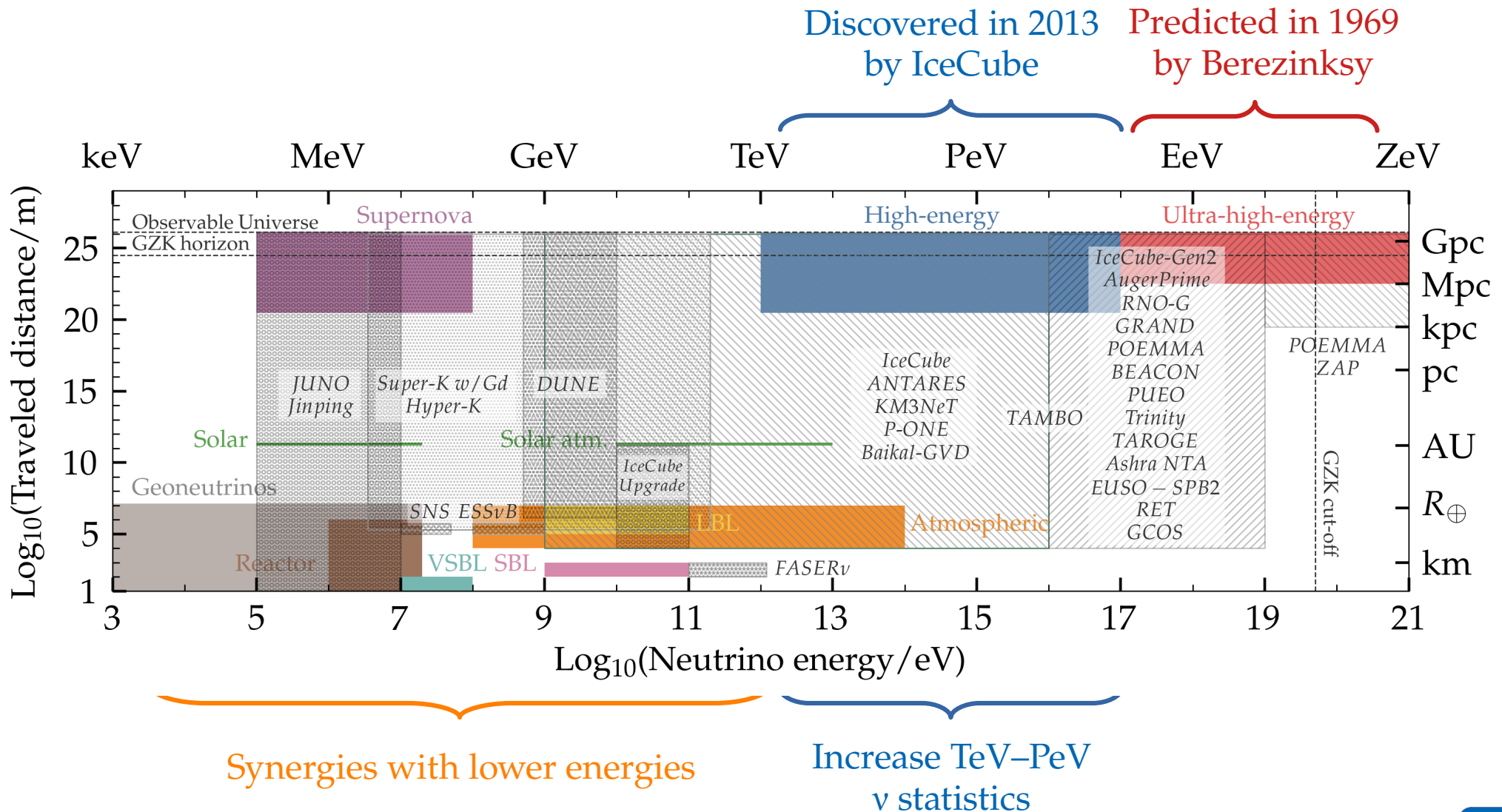
Synergies with lower energies

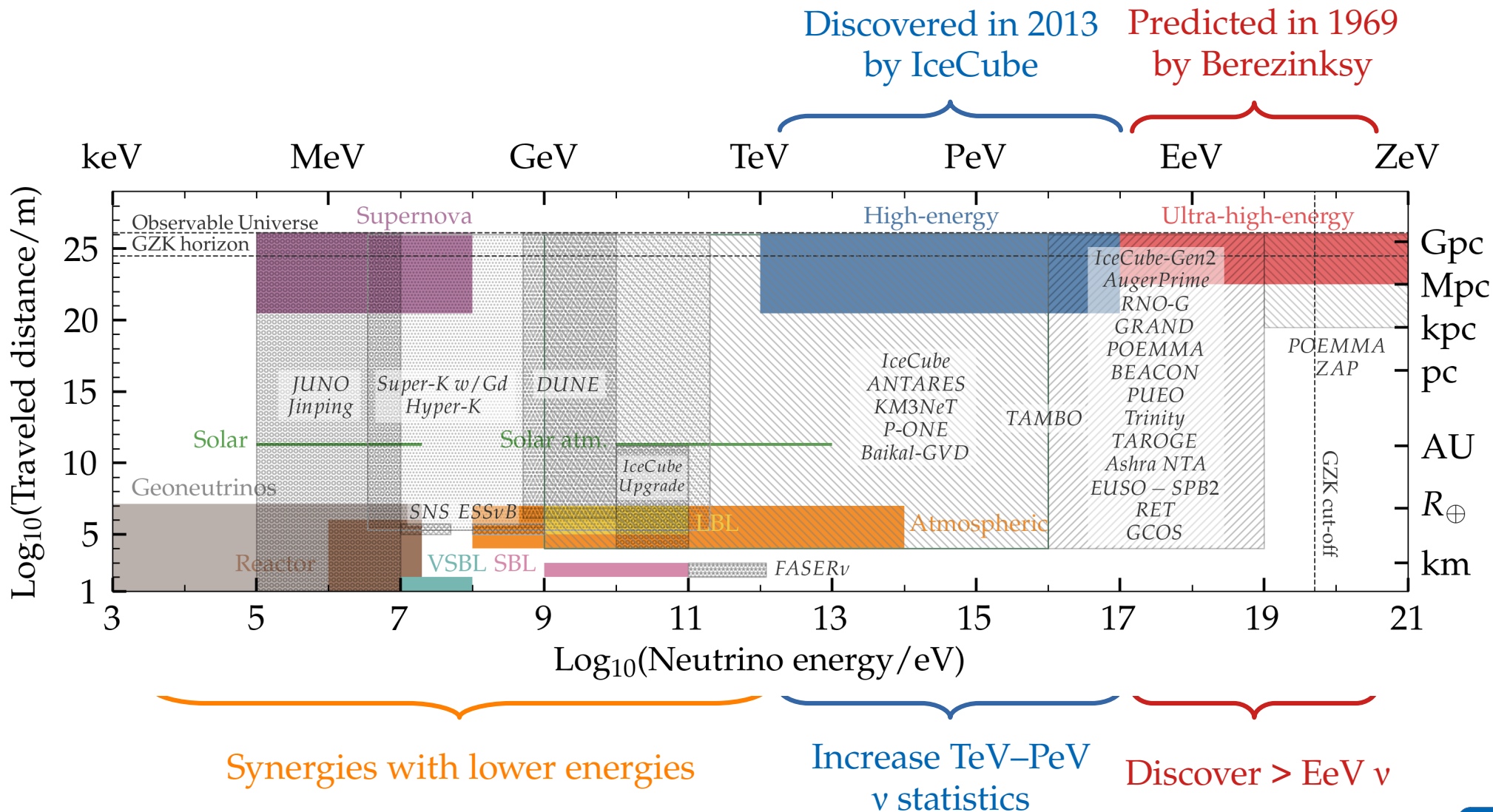
Discovered in 2013
by IceCube



Synergies with lower energies







Fundamental physics with high-energy cosmic neutrinos

- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$
- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing

Fundamental physics with high-energy cosmic neutrinos

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

Fundamental physics with high-energy cosmic neutrinos

- ▶ Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left. \vphantom{\begin{matrix} \kappa_n \\ E^n \\ L \end{matrix}} \right\} \begin{array}{l} \text{E.g.,} \\ n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array}$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over limits using atmospheric ν : $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$
- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing $\left. \vphantom{\begin{matrix} \text{Spectral shape} \\ \text{Angular distribution} \\ \text{Flavor composition} \\ \text{Timing} \end{matrix}} \right\} \begin{array}{l} \text{In spite of} \\ \text{poor energy, angular, flavor reconstruction} \\ \text{\& astrophysical unknowns} \end{array}$

High-energy cosmic neutrinos:

Basics and current status

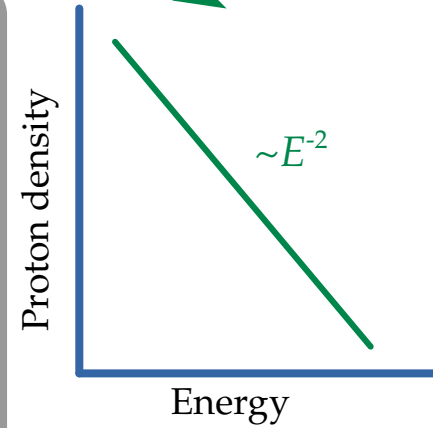
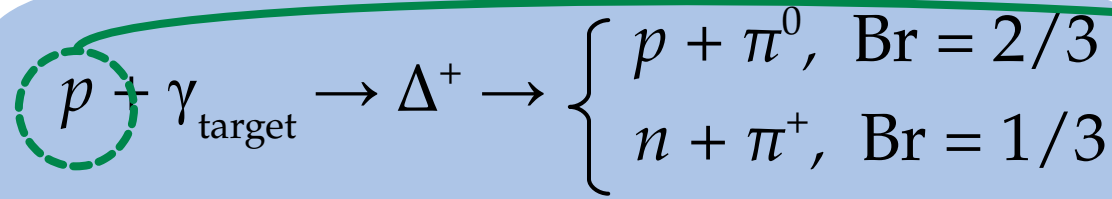
Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

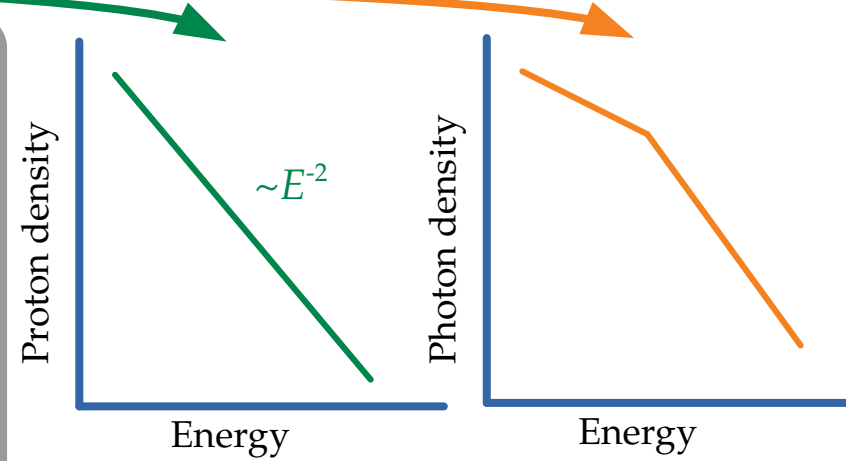
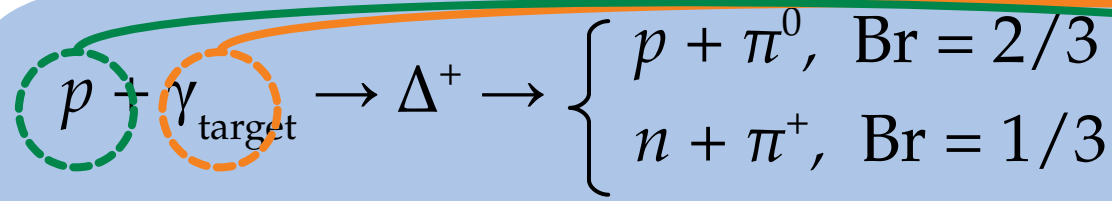
Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)



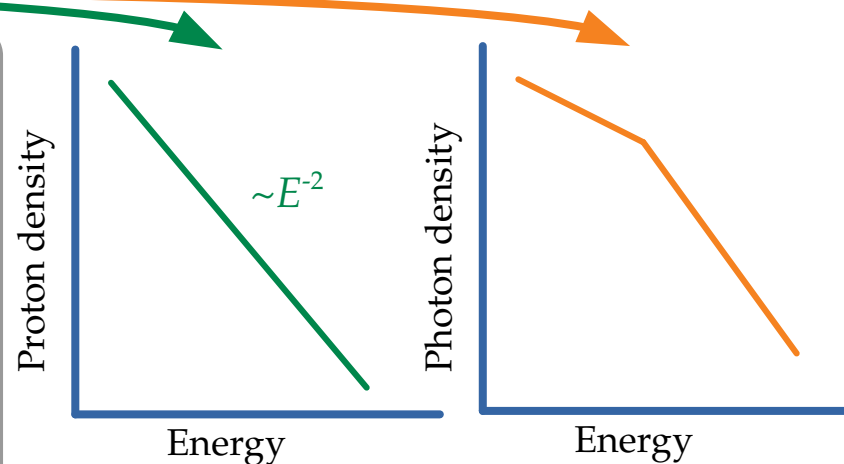
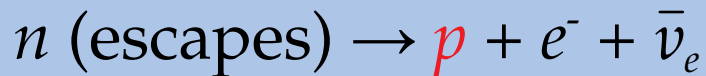
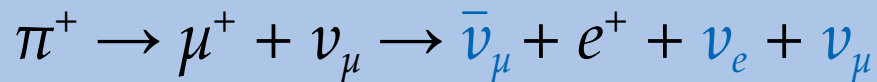
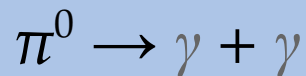
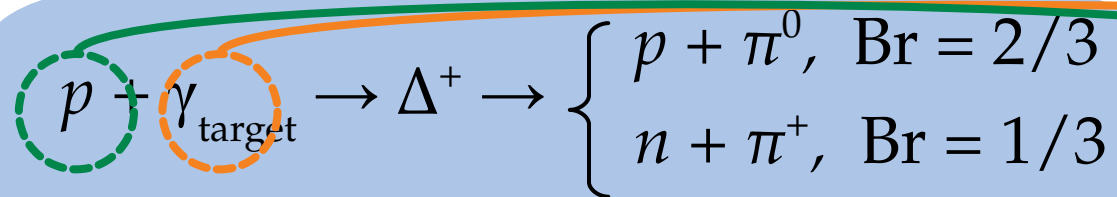
Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)



Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)



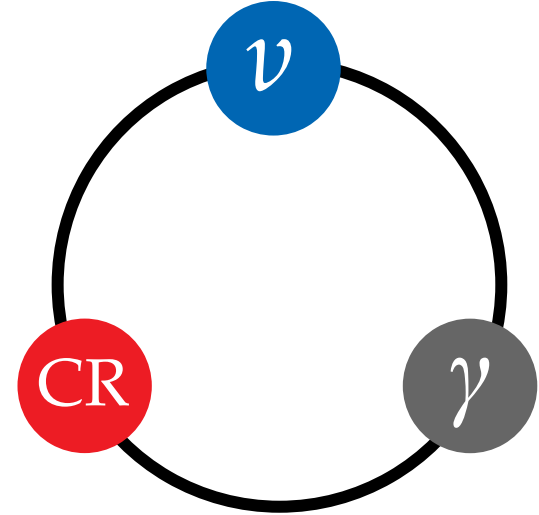
Making high-energy astrophysical neutrinos: a toy model (or $p + p$)

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

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

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

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



Neutrino energy = Proton energy / 20

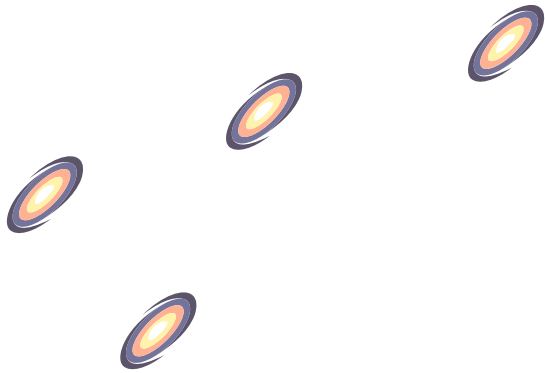
Gamma-ray energy = Proton energy / 10

Redshift



$z = 0$

Note: v sources can be steady-state or transient



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

“High-energy”

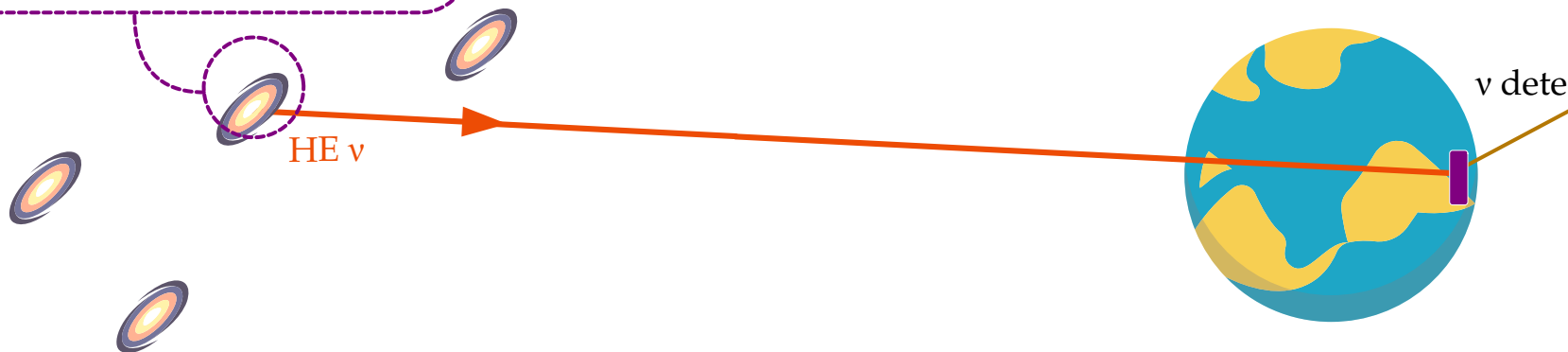
Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection

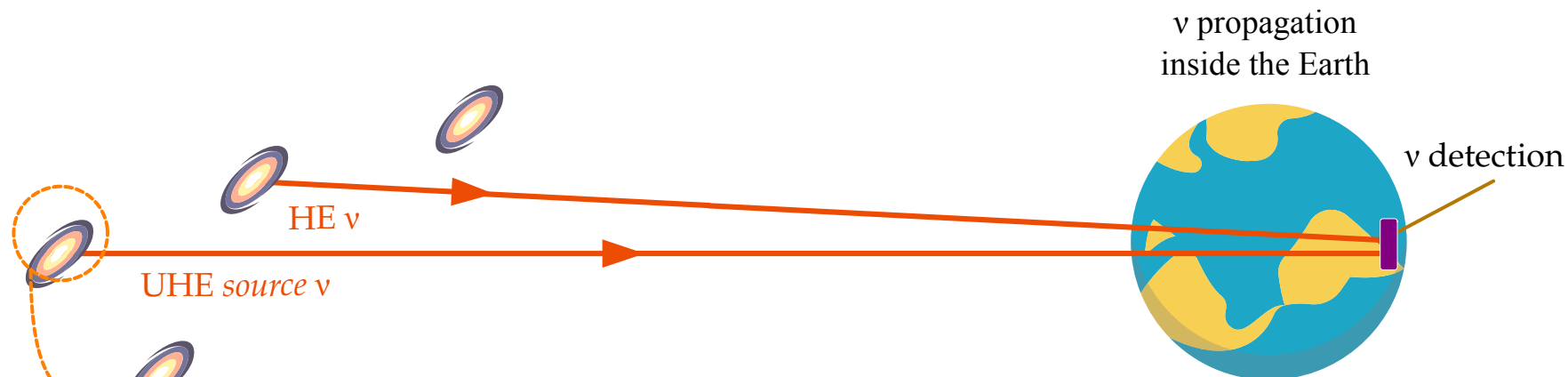
HE ν



Redshift

$z = 0$

Note: ν sources can be steady-state or transient



Undiscovered

meV γ

EeV p

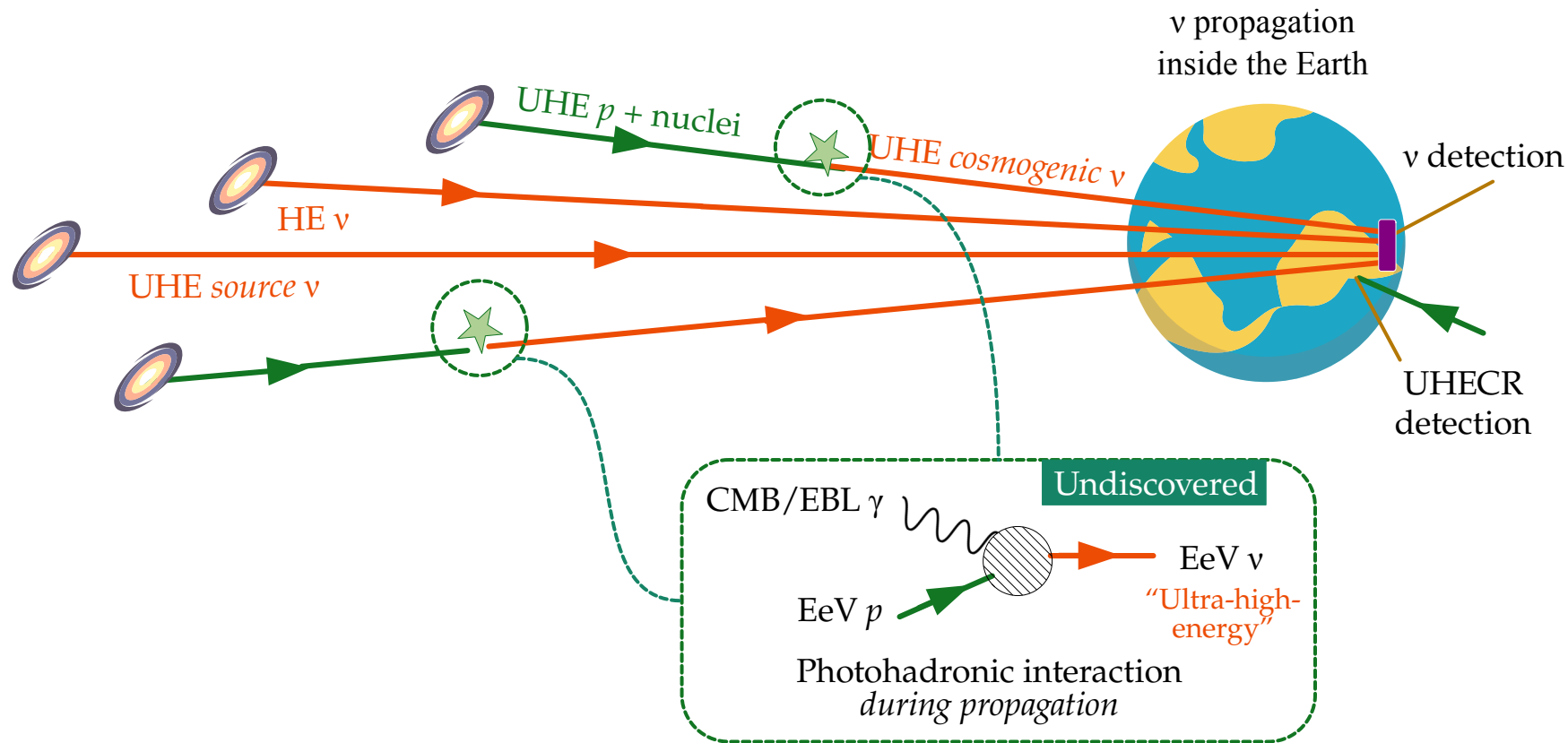
EeV ν

"Ultra-high-energy"

Photohadronic or pp interaction
inside the source

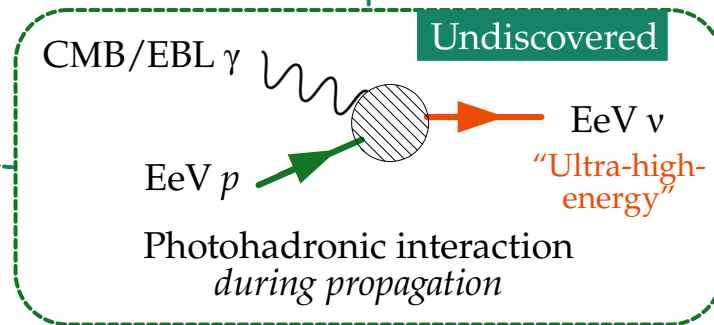
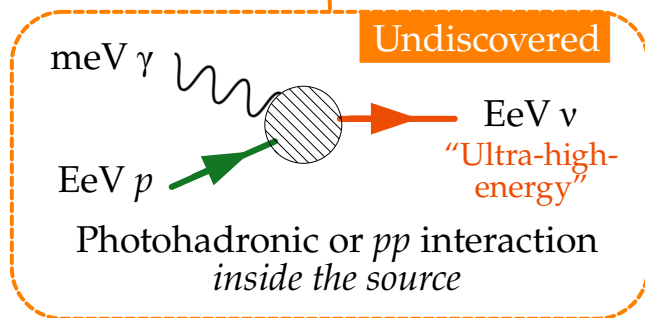
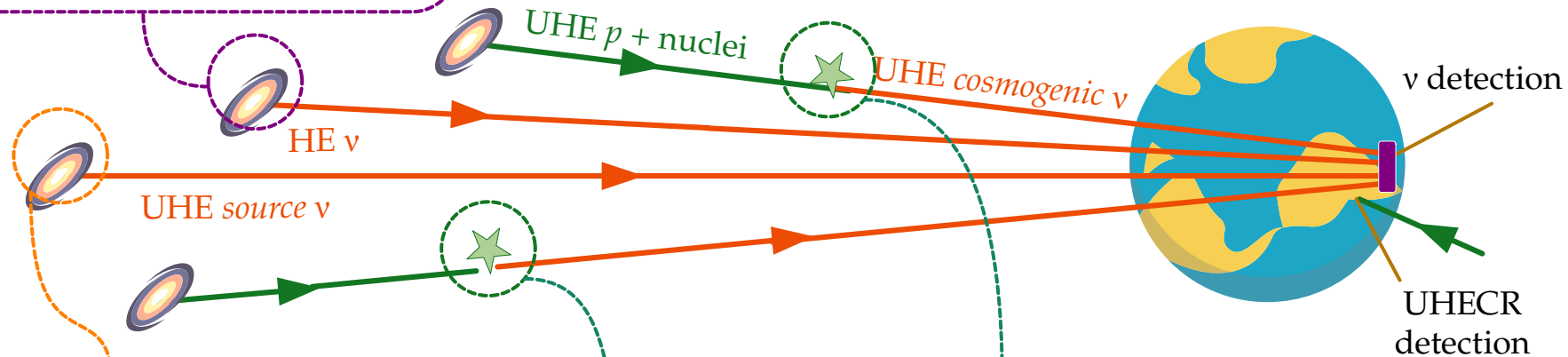
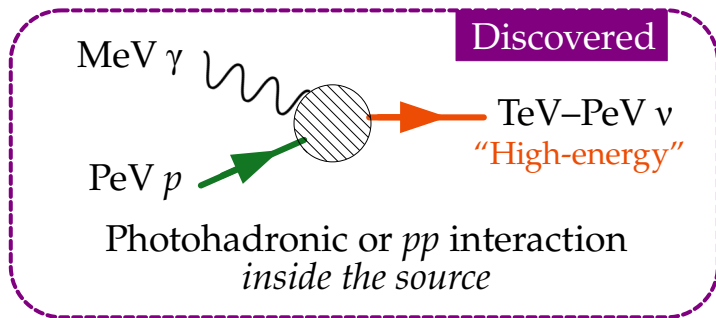
Redshift ← $z = 0$

Note: ν sources can be steady-state or transient



Redshift ← $z = 0$

Note: ν sources can be steady-state or transient



Redshift

$z = 0$

Discovered

MeV γ

PeV p

TeV–PeV ν

“High-energy”

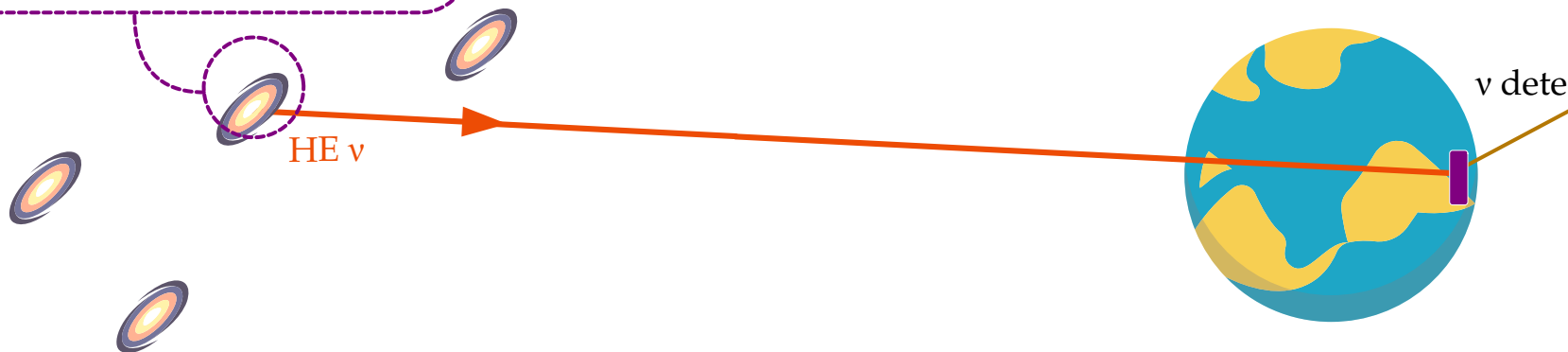
Photohadronic or pp interaction
inside the source

Note: ν sources can be steady-state or transient

ν propagation
inside the Earth

ν detection

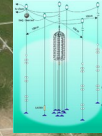
HE ν



TeV–PeV ν
telescopes,
~today

ANTARES

- ▶ Mediterranean Sea
- ▶ Completed 2008
- ▶ $V_{\text{eff}} \sim 0.2 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ (10 PeV)
- ▶ 12 strings, 900 OMs
- ▶ Sensitive to ν from the Southern sky



Baikal NT200+

- ▶ Lake Baikal
- ▶ Completed 1998 (upgraded 2005)
- ▶ $V_{\text{eff}} \sim 10^{-4} \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 PeV)
- ▶ 8 strings, 192+ OMs

IceCube

- ▶ South Pole
- ▶ Completed 2011
- ▶ $V_{\text{eff}} \sim 0.01 \text{ km}^3$ (10 TeV)
- ▶ $V_{\text{eff}} \sim 1 \text{ km}^3$ ($> 1 \text{ PeV}$)
- ▶ 86 strings, 5000+ OMs
- ▶ Sees high-energy astrophysical ν

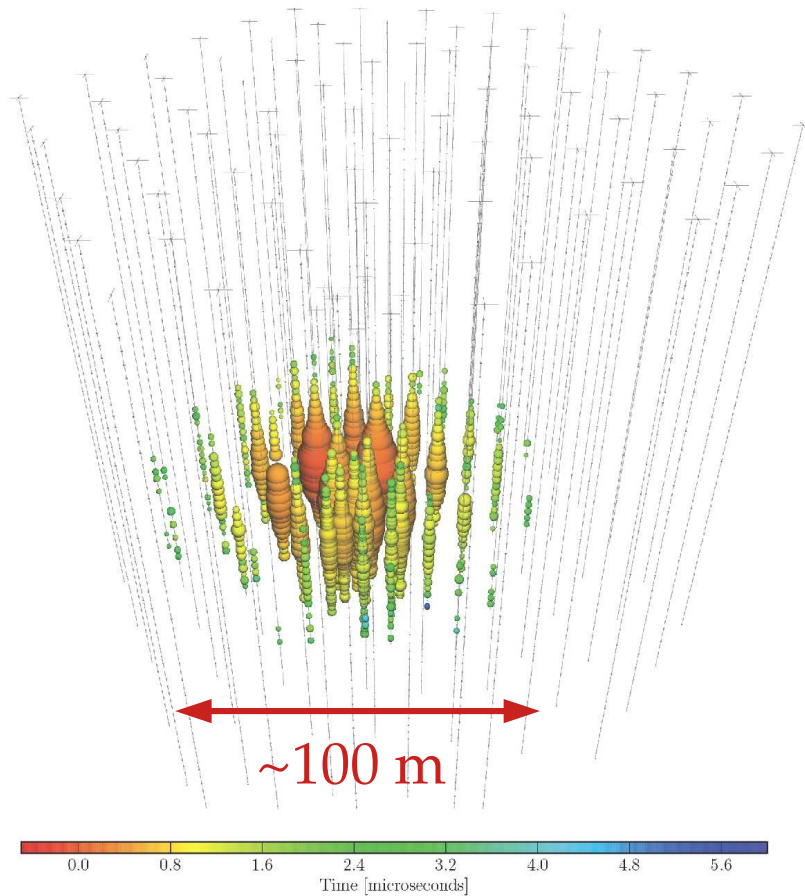


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

OM: optical module

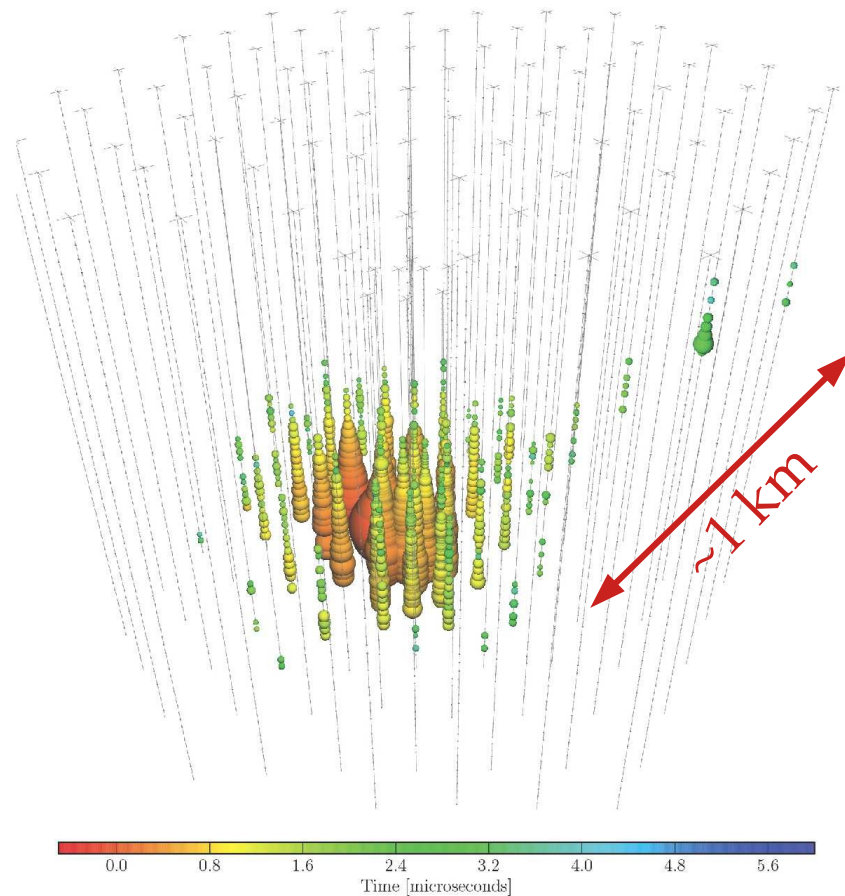
Strebe/Wikipedia

Shower (mainly from ν_e and ν_τ)

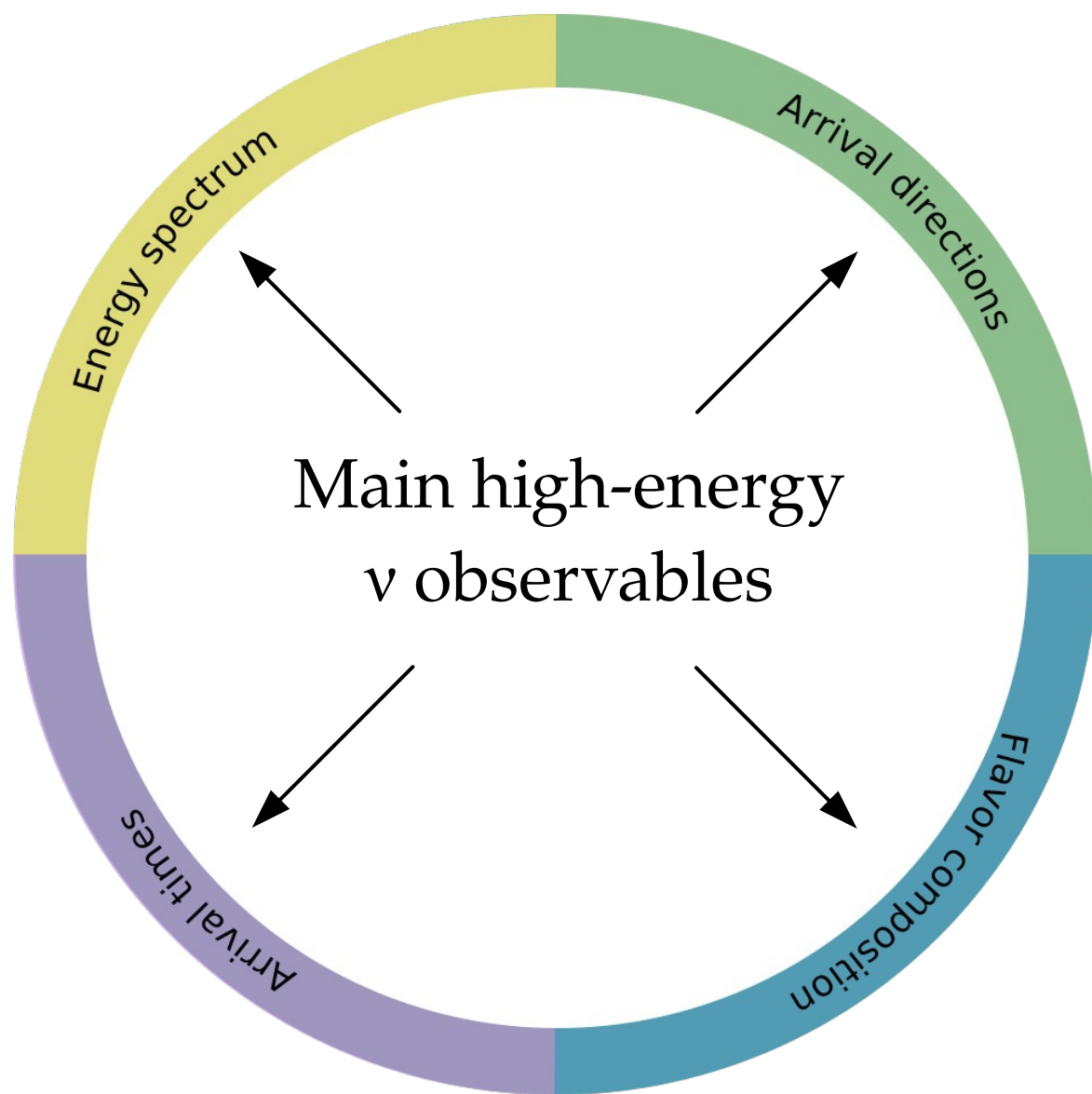


Poor angular resolution: $\sim 10^\circ$

Track (mainly from ν_μ)



Angular resolution: $< 1^\circ$

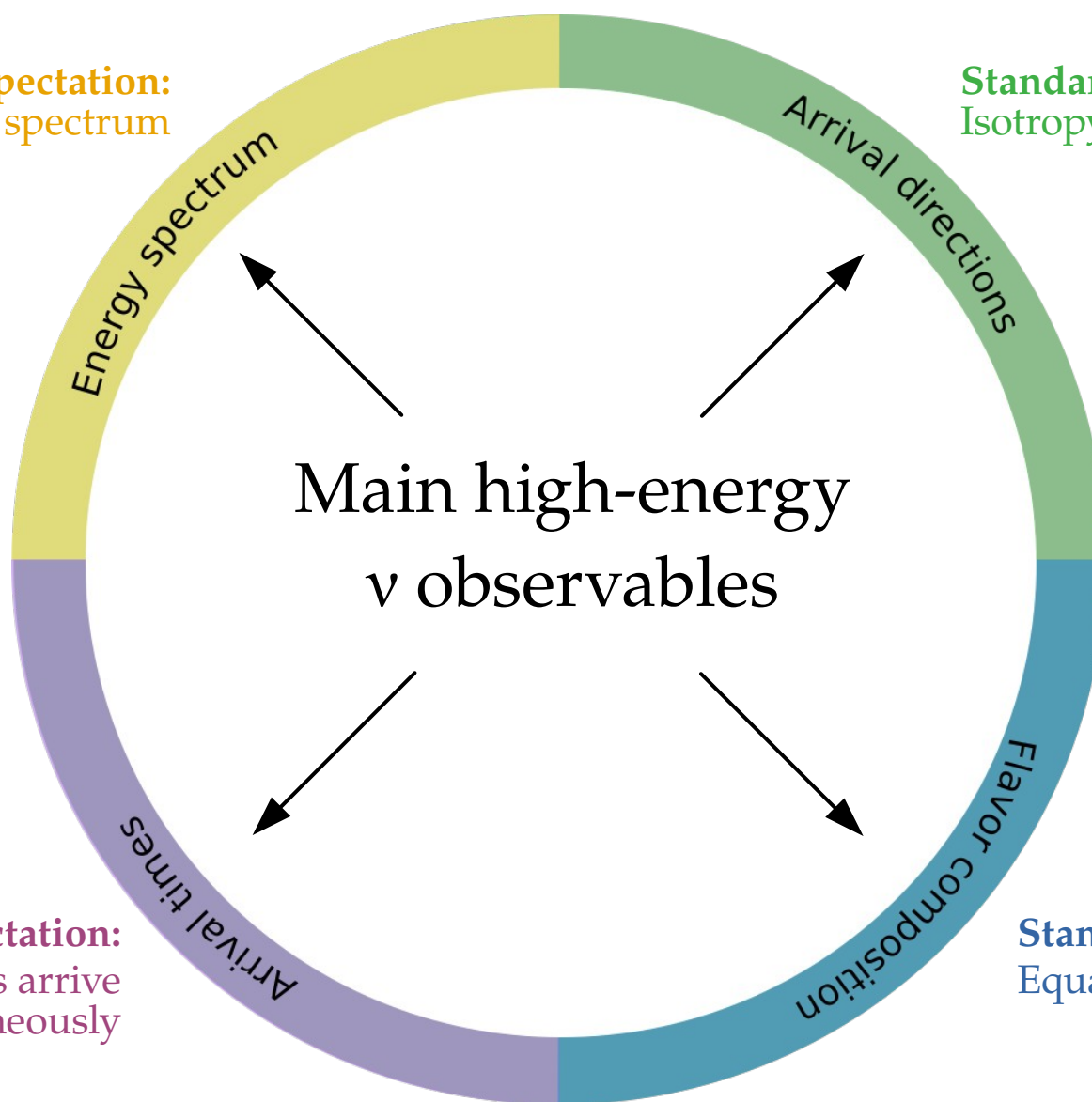


Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

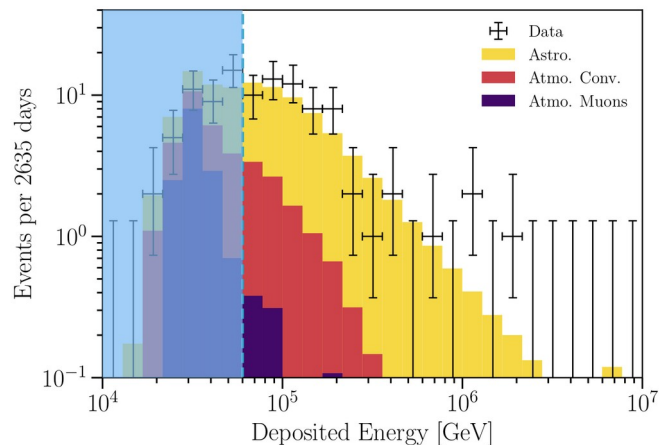
Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

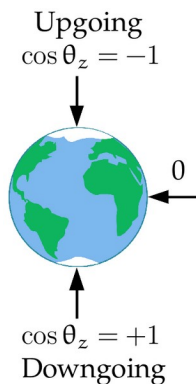
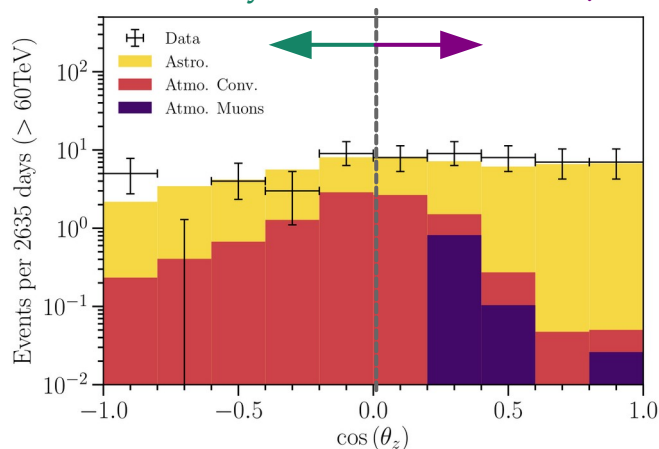


Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

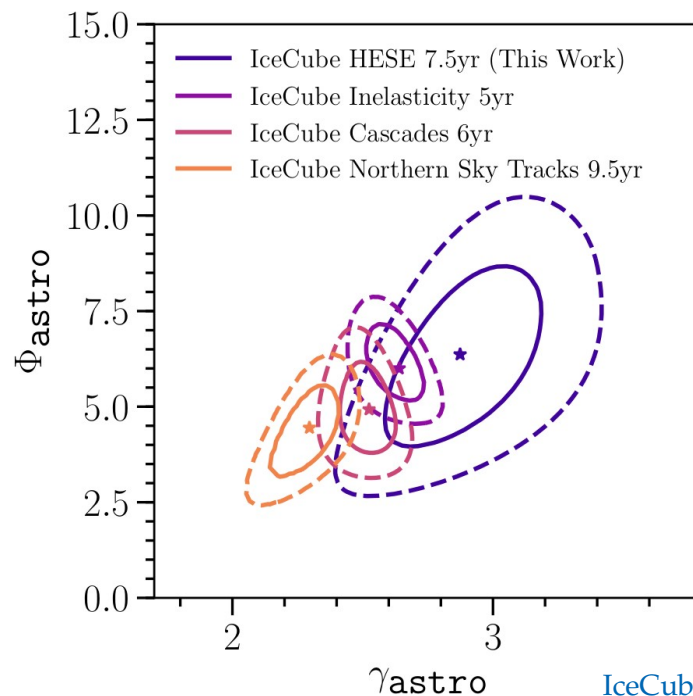


ν attenuated by Earth Atm. ν and μ vetoed



Data is fit well by a single power law:

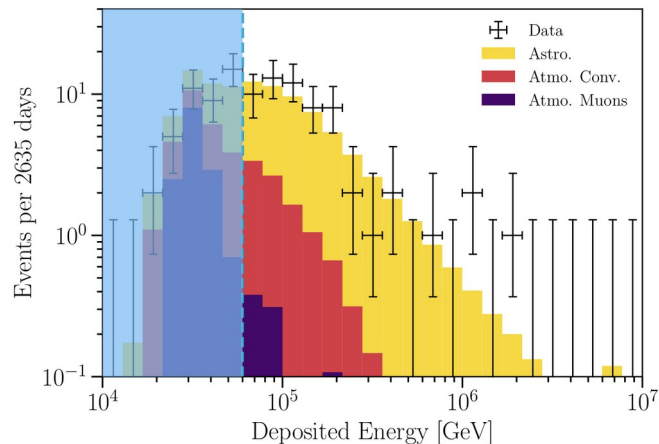
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100 \text{ TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$



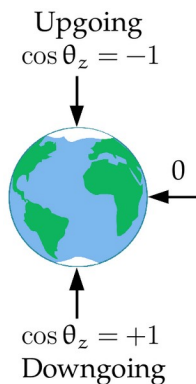
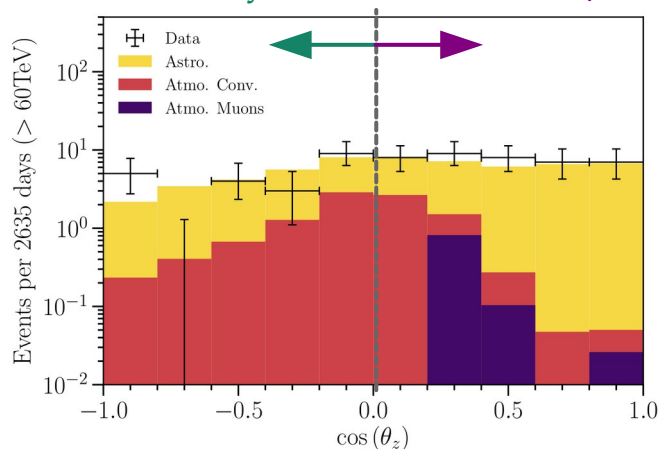
IceCube, 2011.03545

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

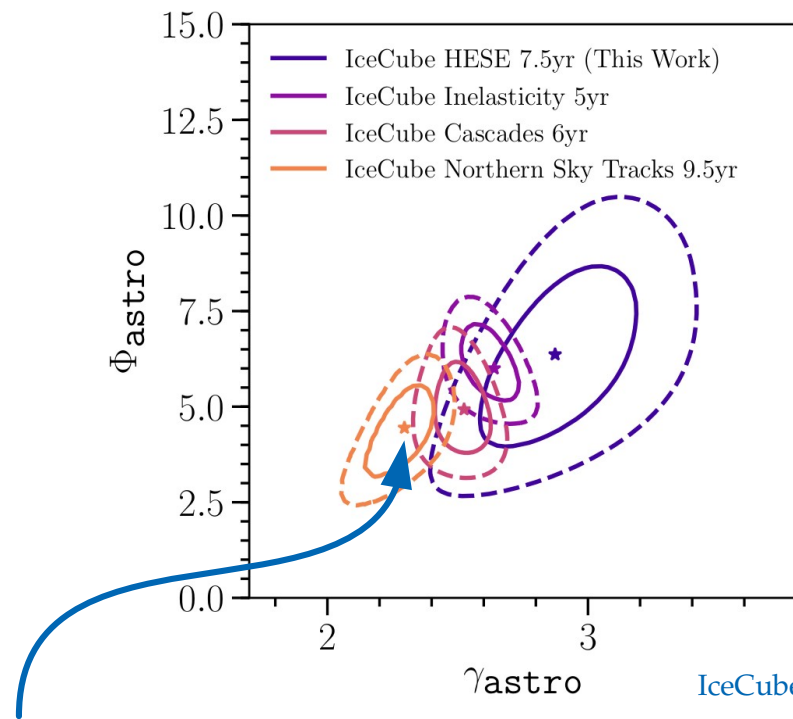


ν attenuated by Earth Atm. ν and μ vetoed



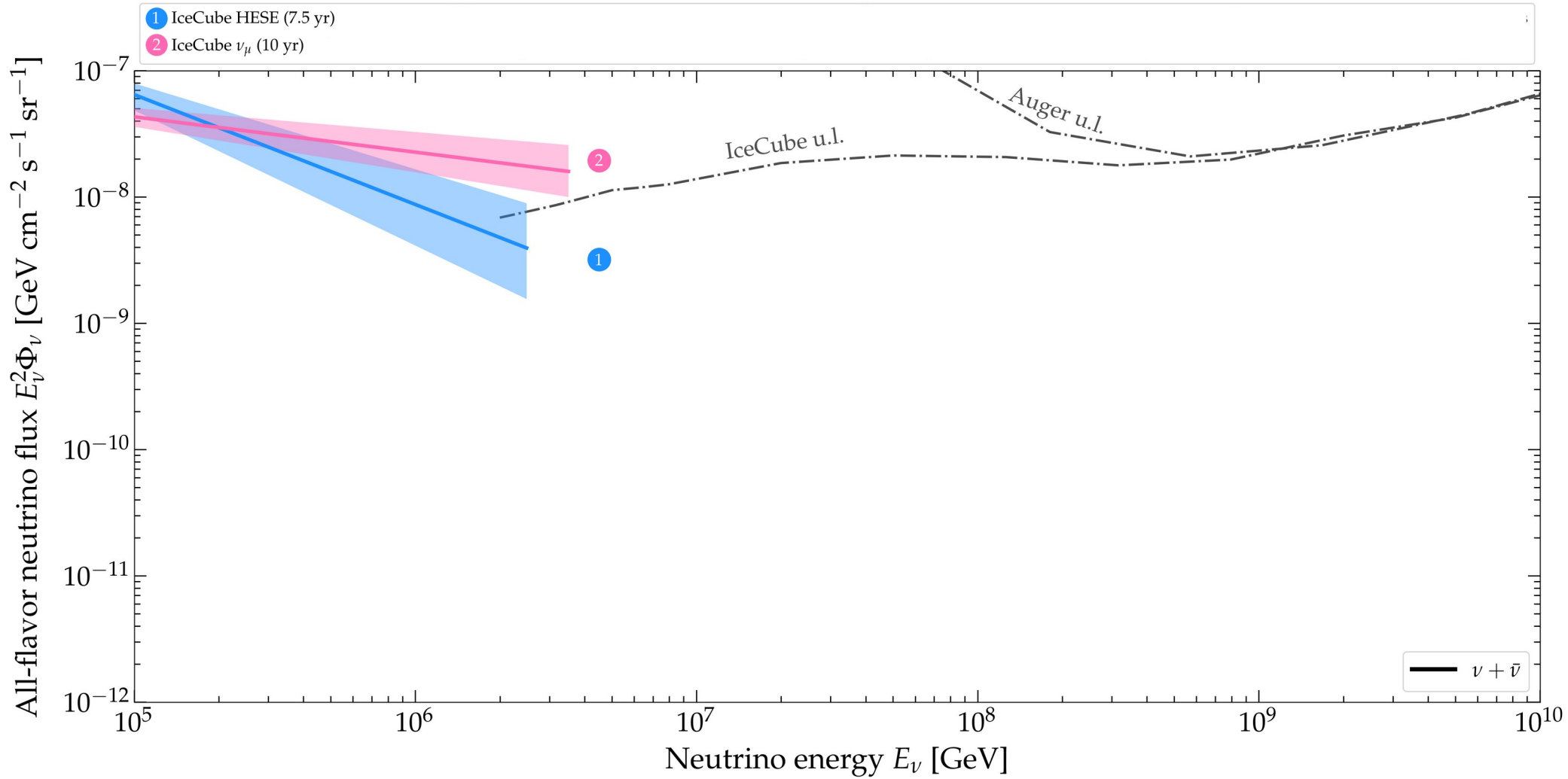
Data is fit well by a single power law:

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



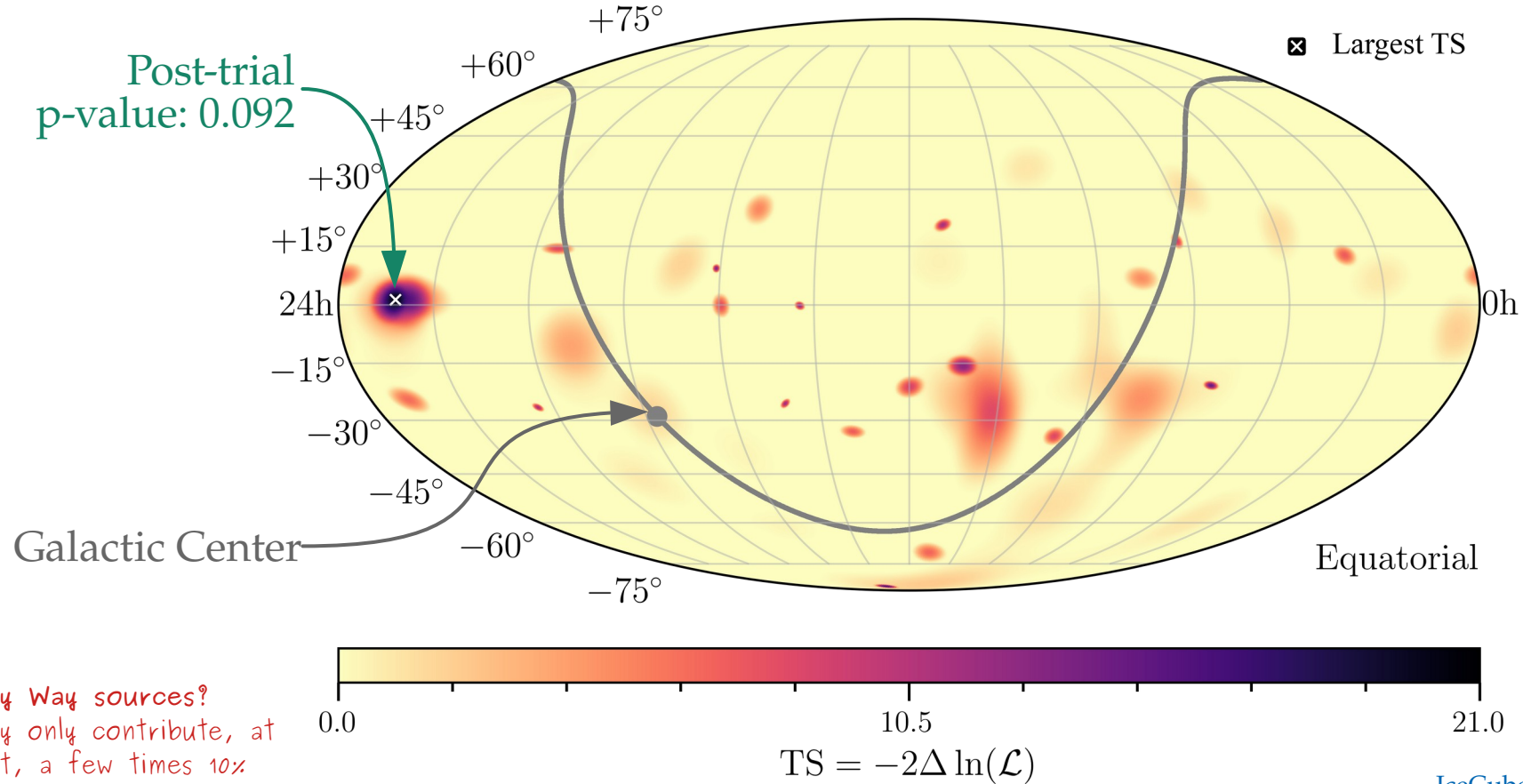
IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ



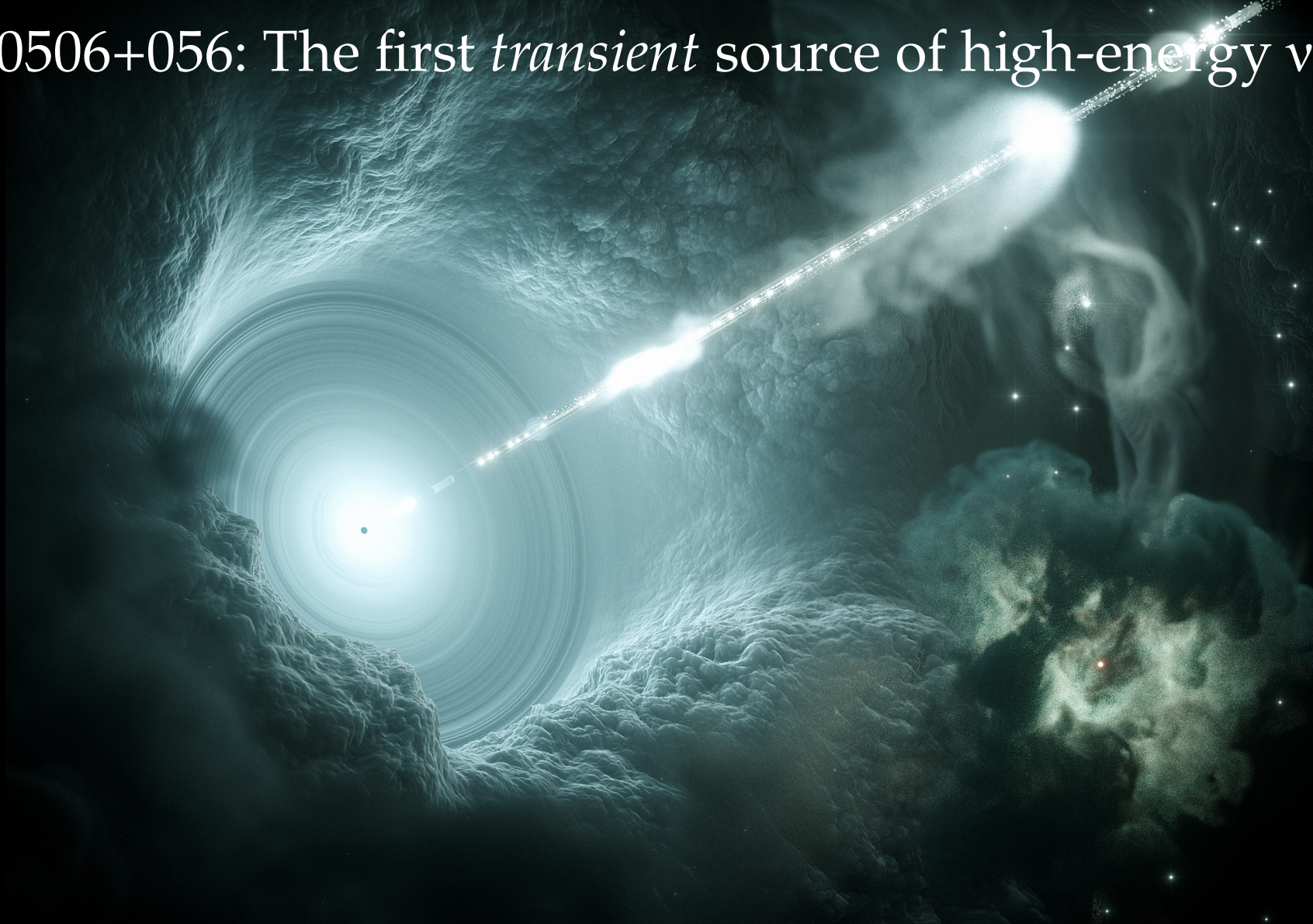
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



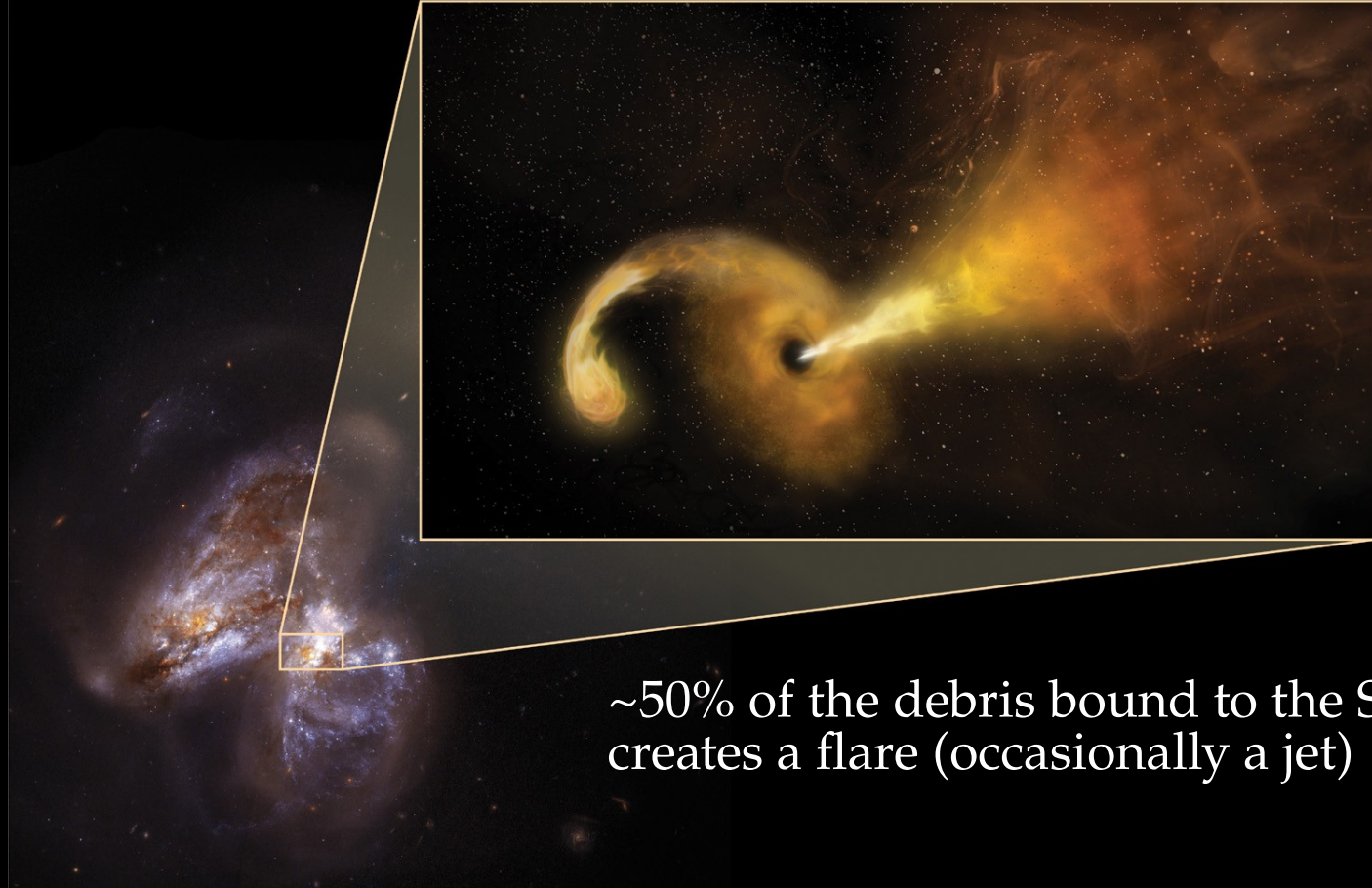
Milky Way sources?
They only contribute, at
most, a few times 10%
of the total diffuse flux

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



Tidal disruption events

Solar-mass star disrupted by SMBH ($>10^5 M_{\odot}$)



~50% of the debris bound to the SMBH,
creates a flare (occasionally a jet)

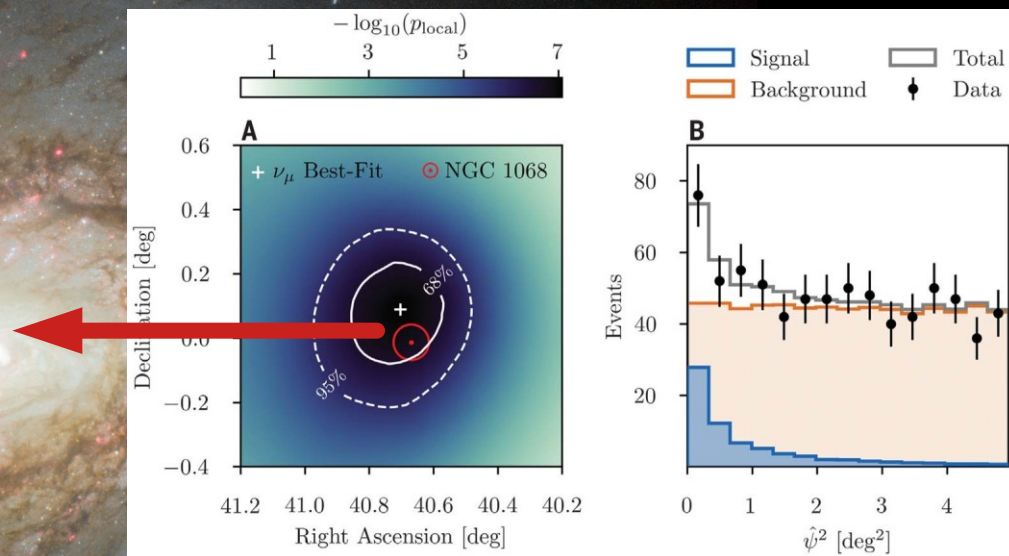
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

79_{-20}^{+22} ν of TeV energy

Significance: 4.2σ (global)



Today
TeV–PeV ν

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Today

TeV–PeV ν

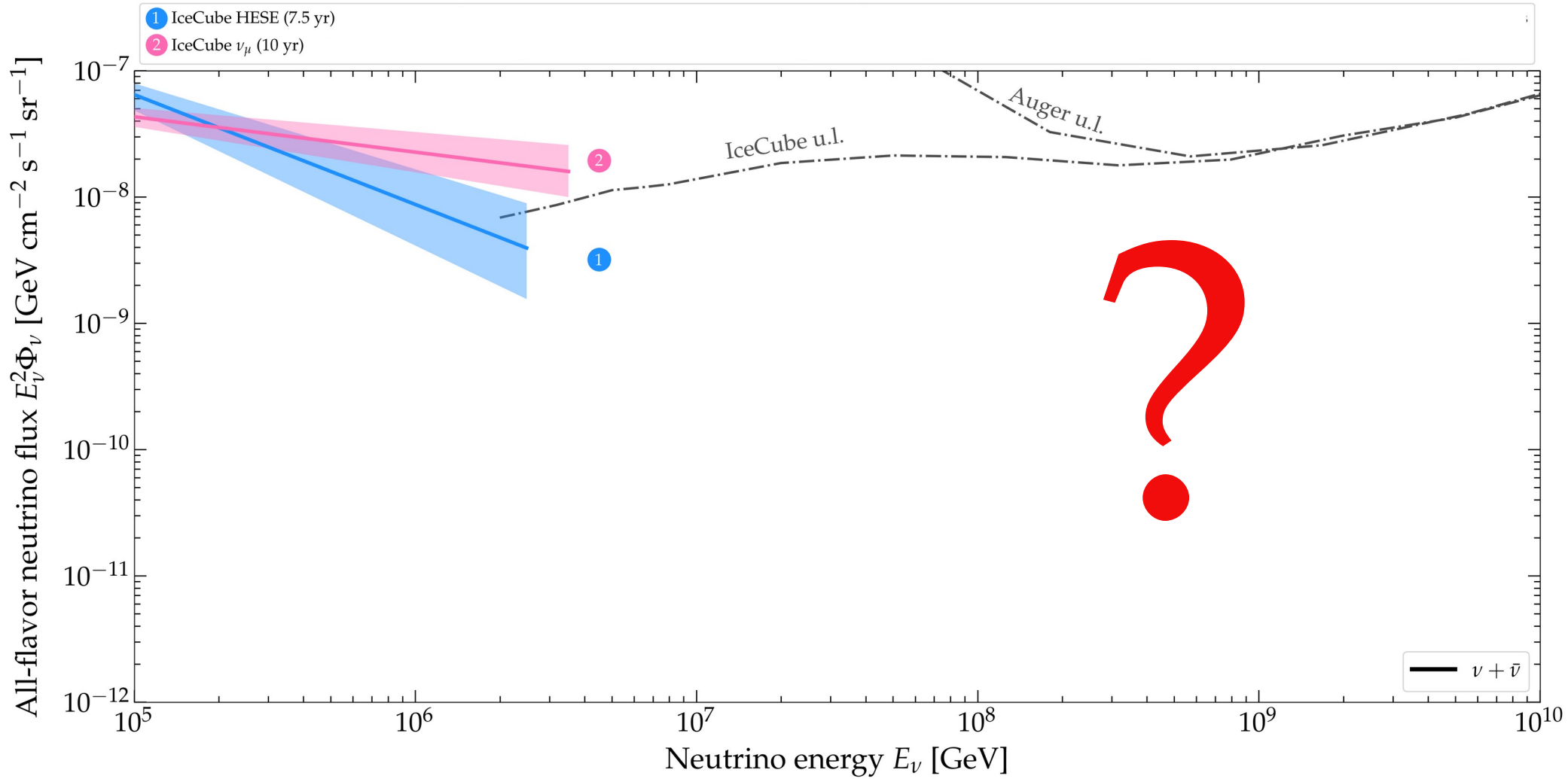
Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

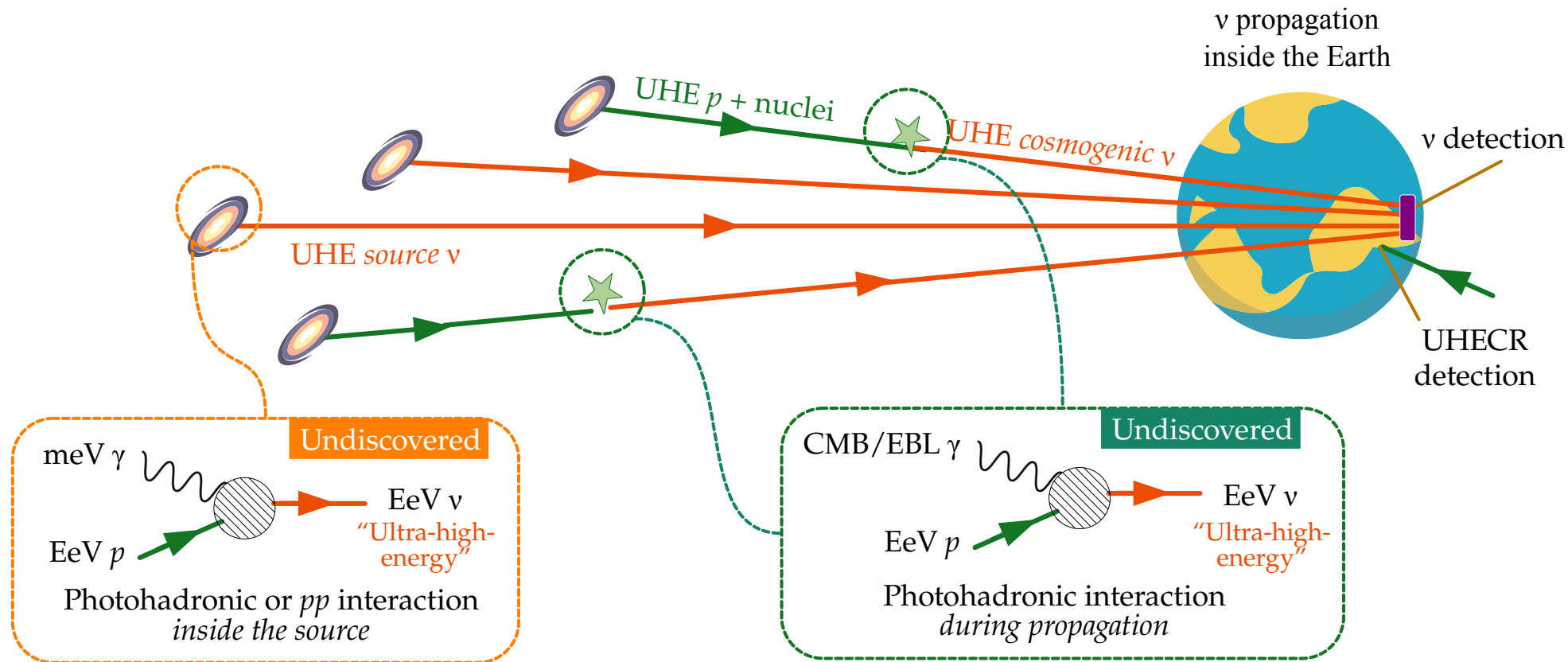
Better reconstruction

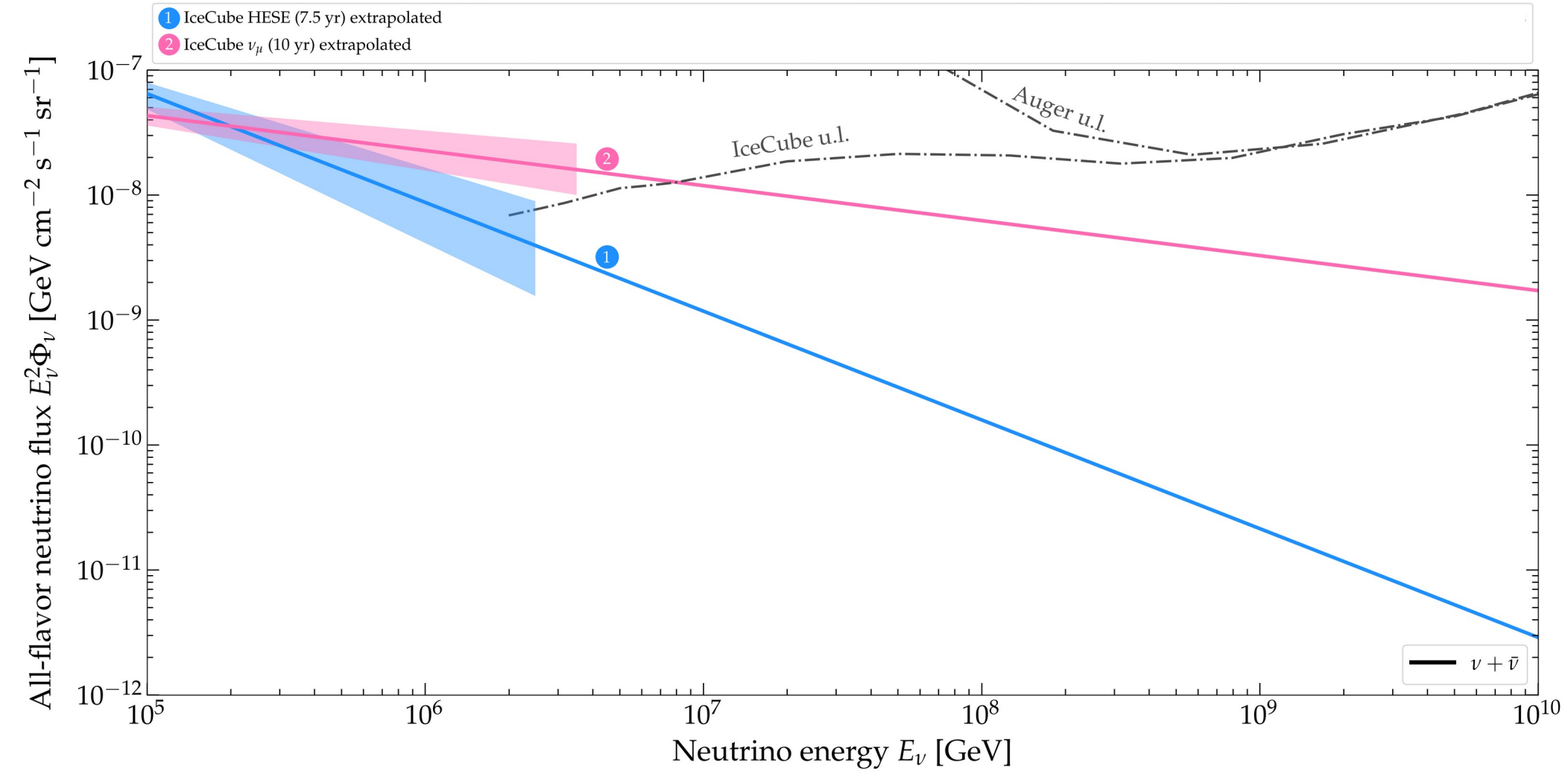
Smaller astrophysical uncertainties

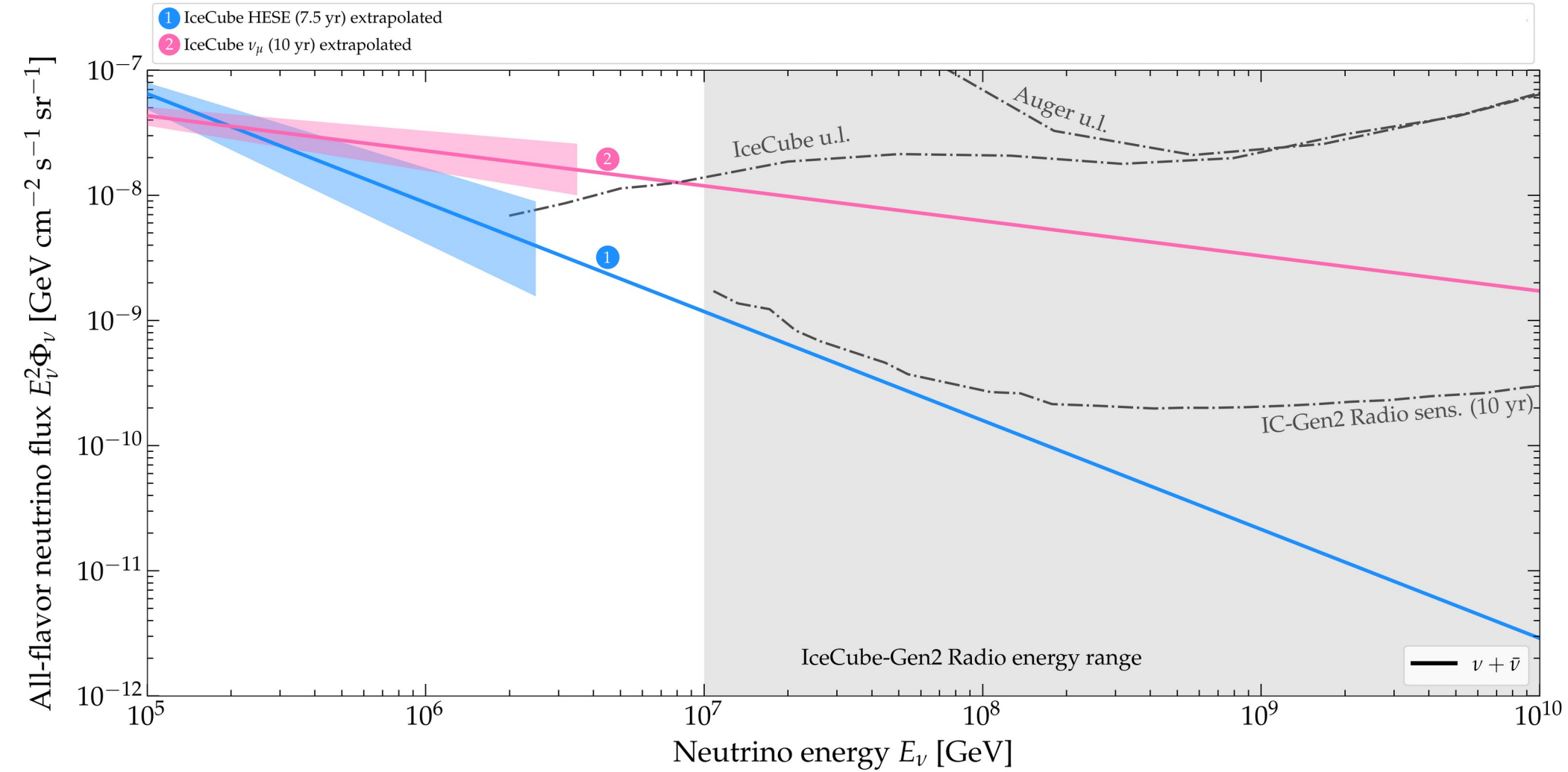


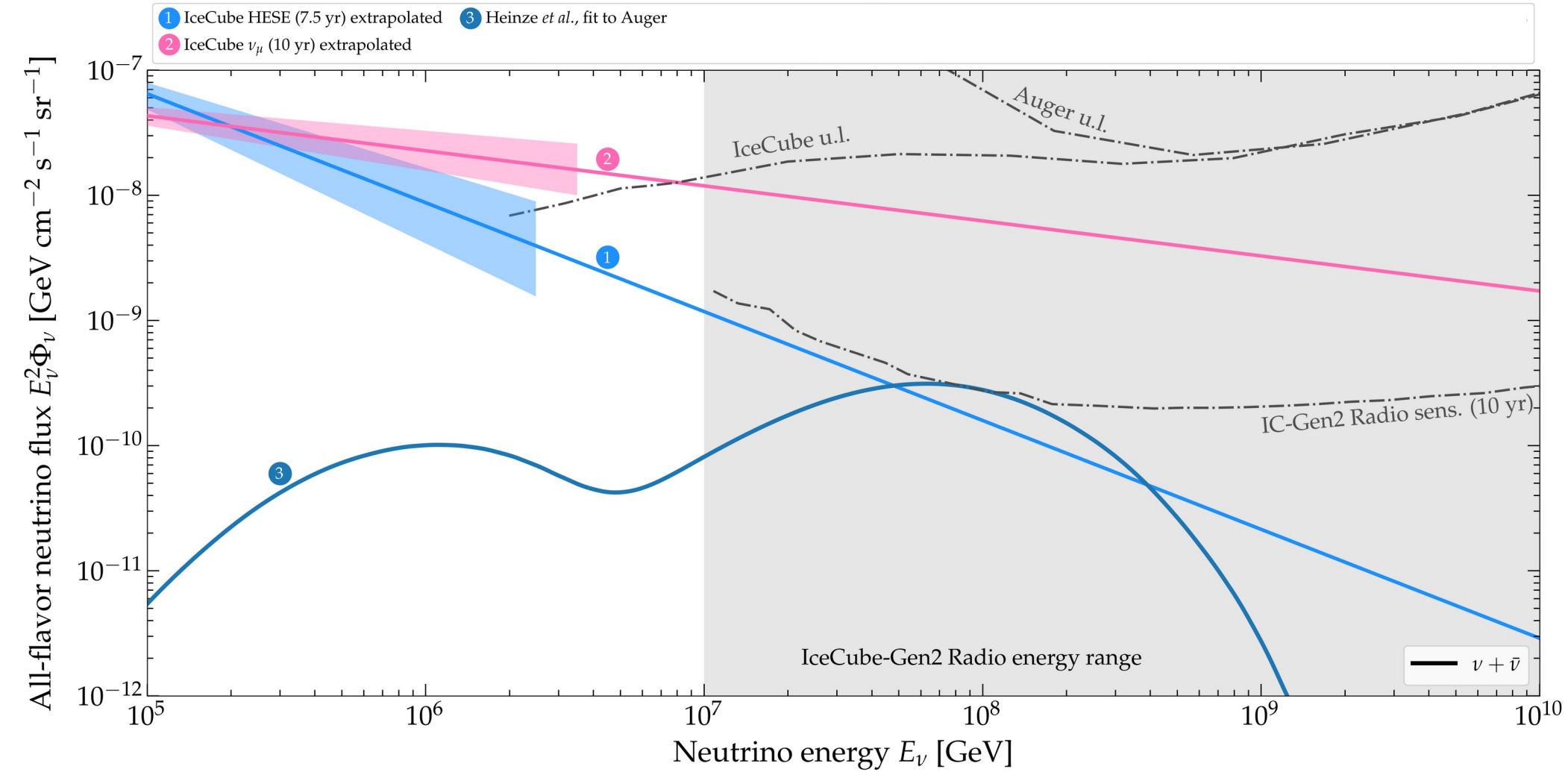
Redshift ← $z = 0$

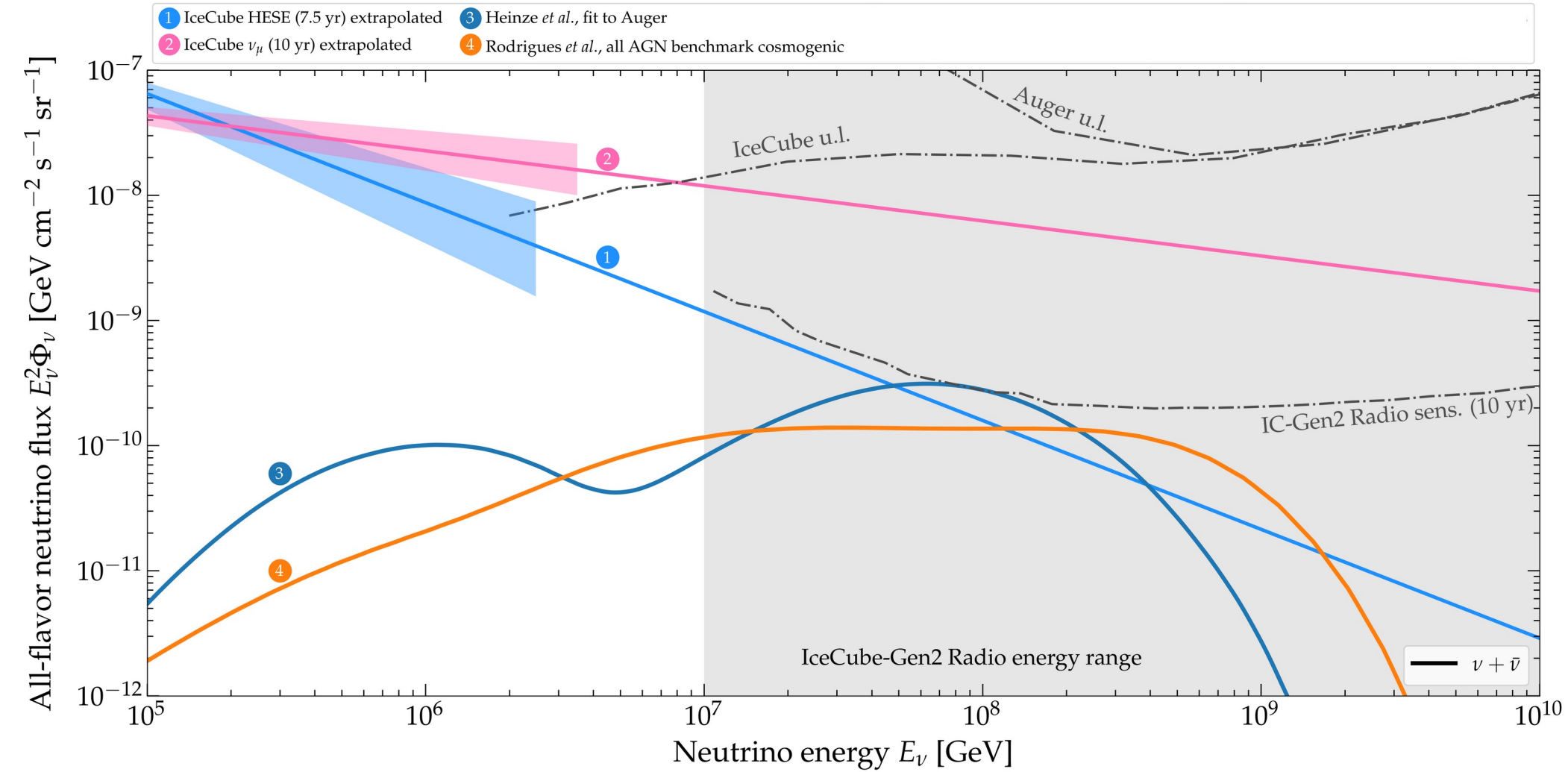
Note: ν sources can be steady-state or transient

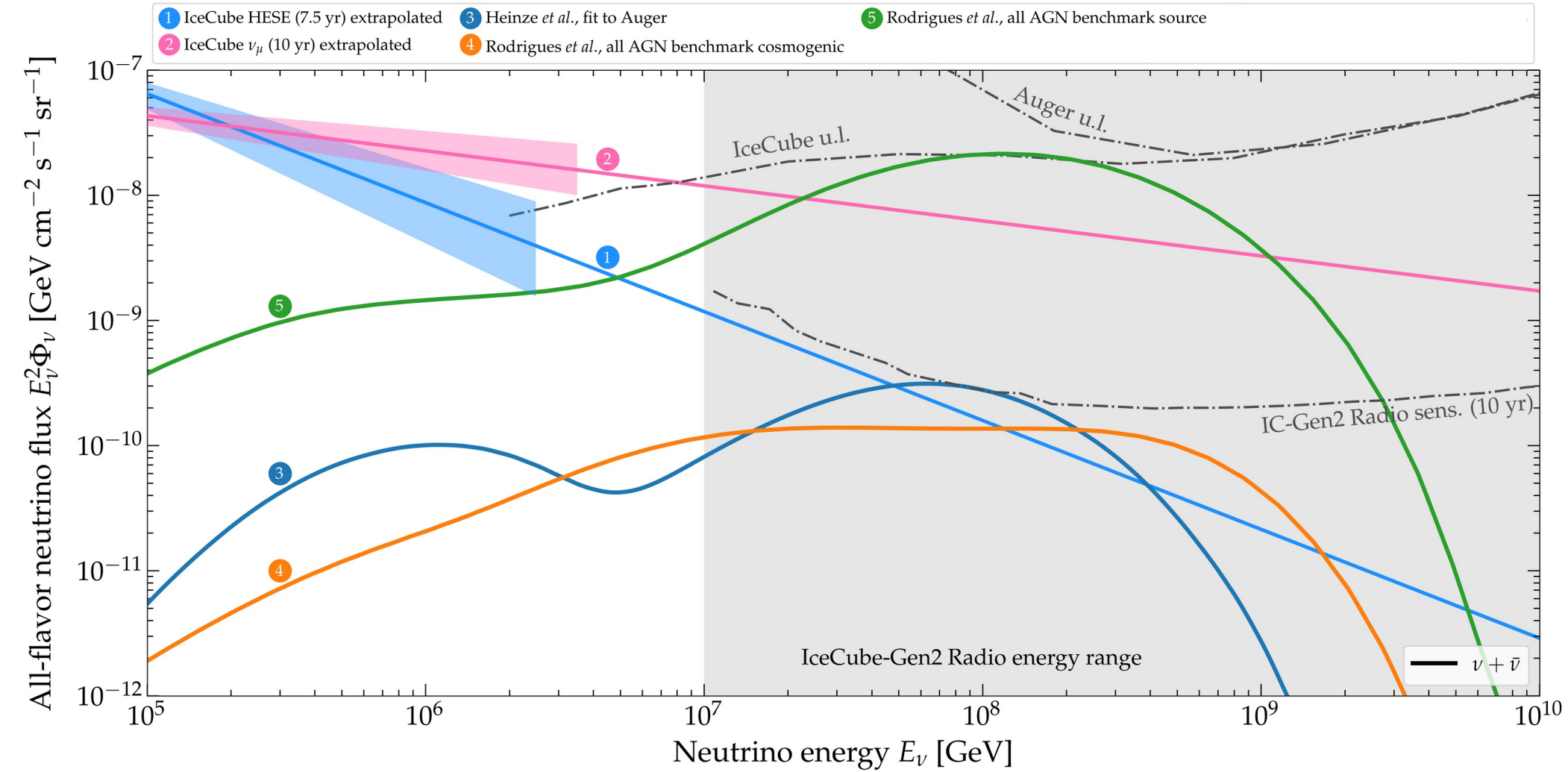


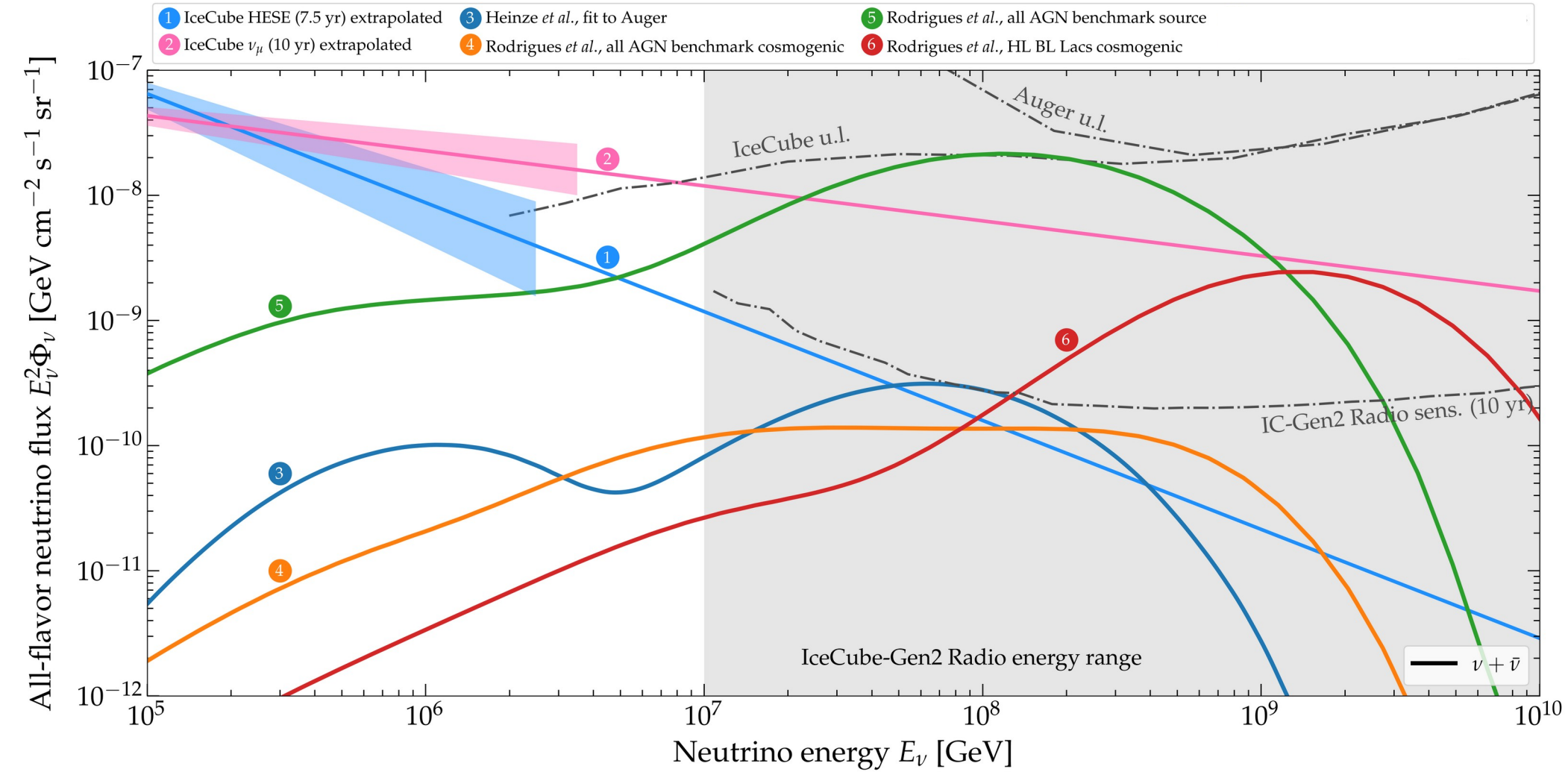


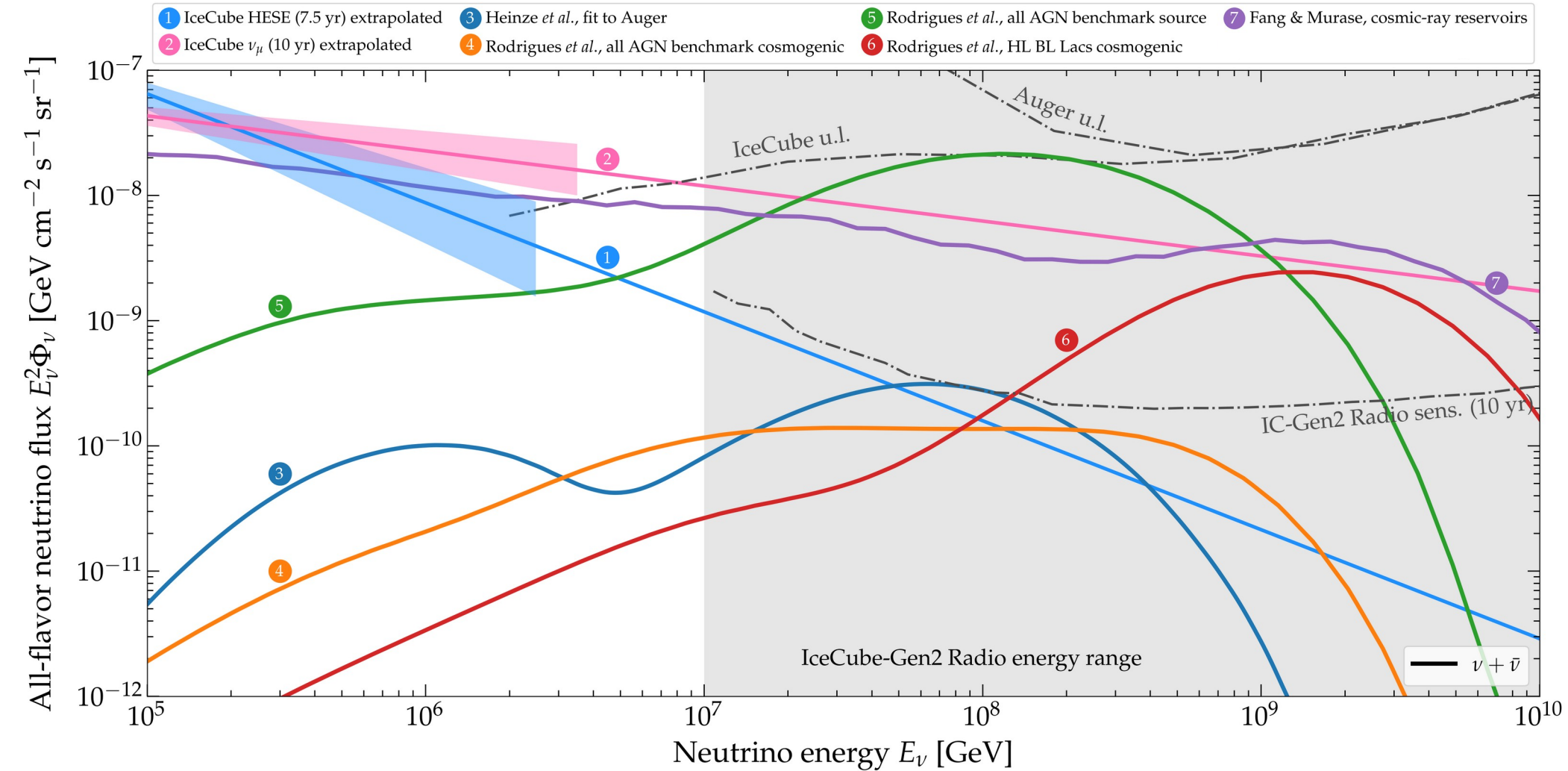


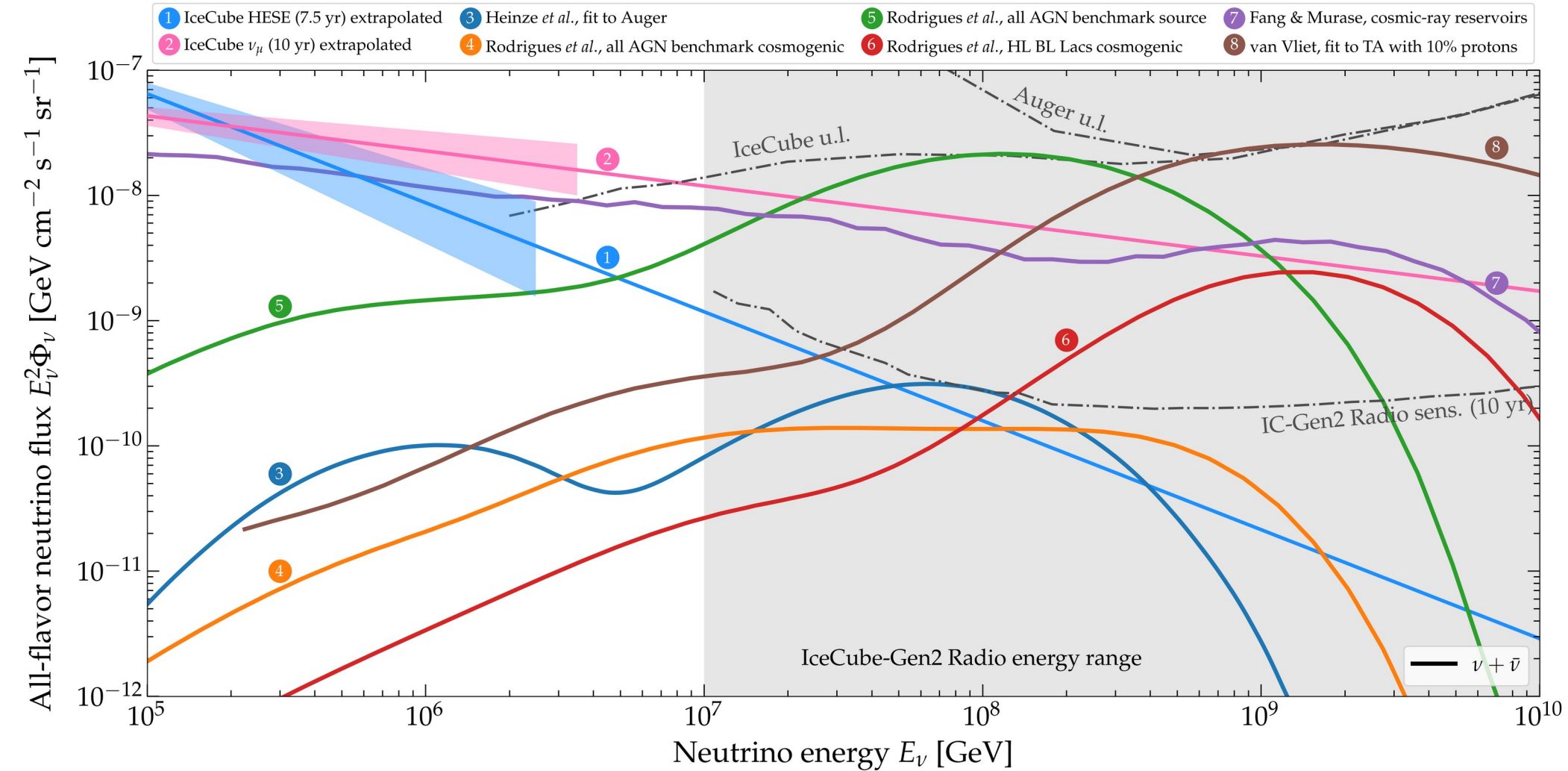












Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 > 100 -PeV ν

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 $> 100\text{-PeV } \nu$

Make predictions for
a new energy regime

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 > 100 -PeV ν

Make predictions for
a new energy regime

Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 > 100 -PeV ν

Make predictions for
a new energy regime

Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

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

Today
TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors $\rightarrow$ larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade
 $> 100\text{-PeV } \nu$

Make predictions for
a new energy regime

Key developments:

Discovery

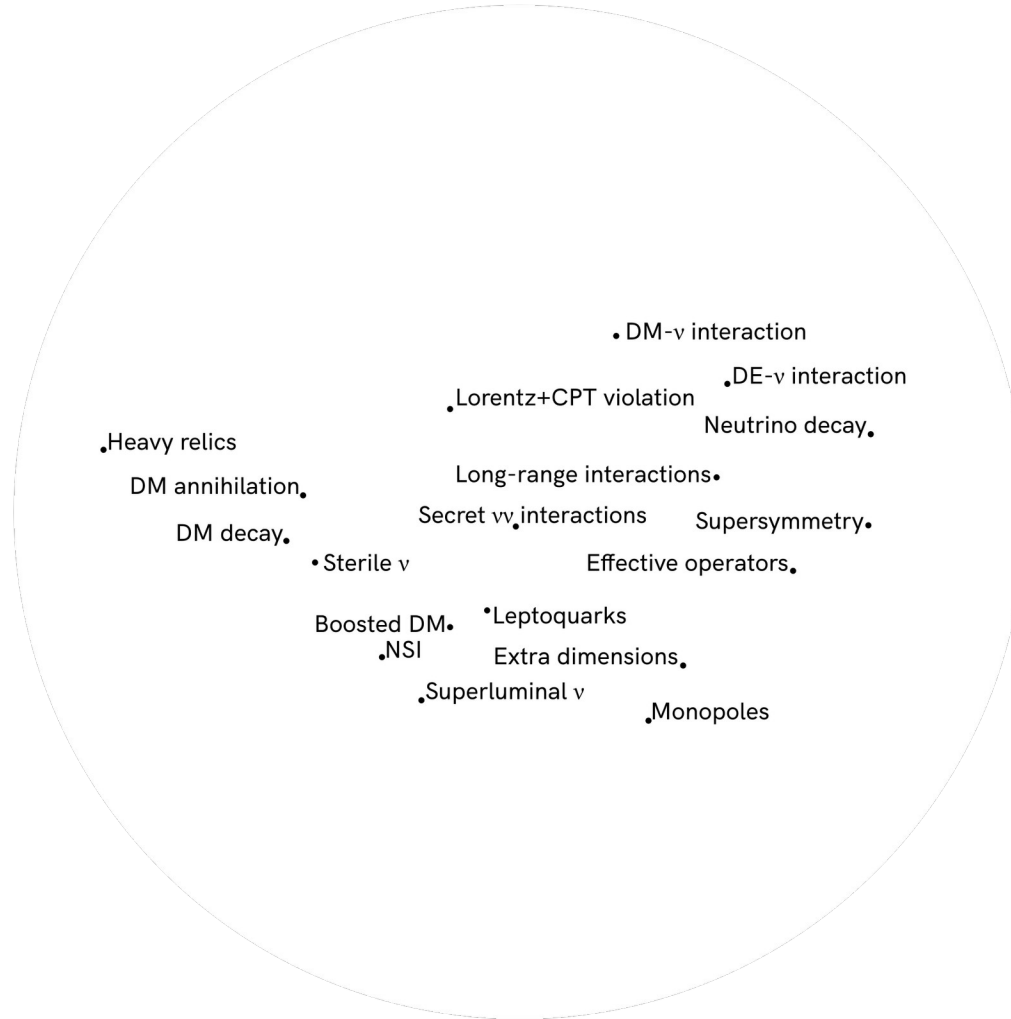
New detection techniques

Better UHE ν flux predictions

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



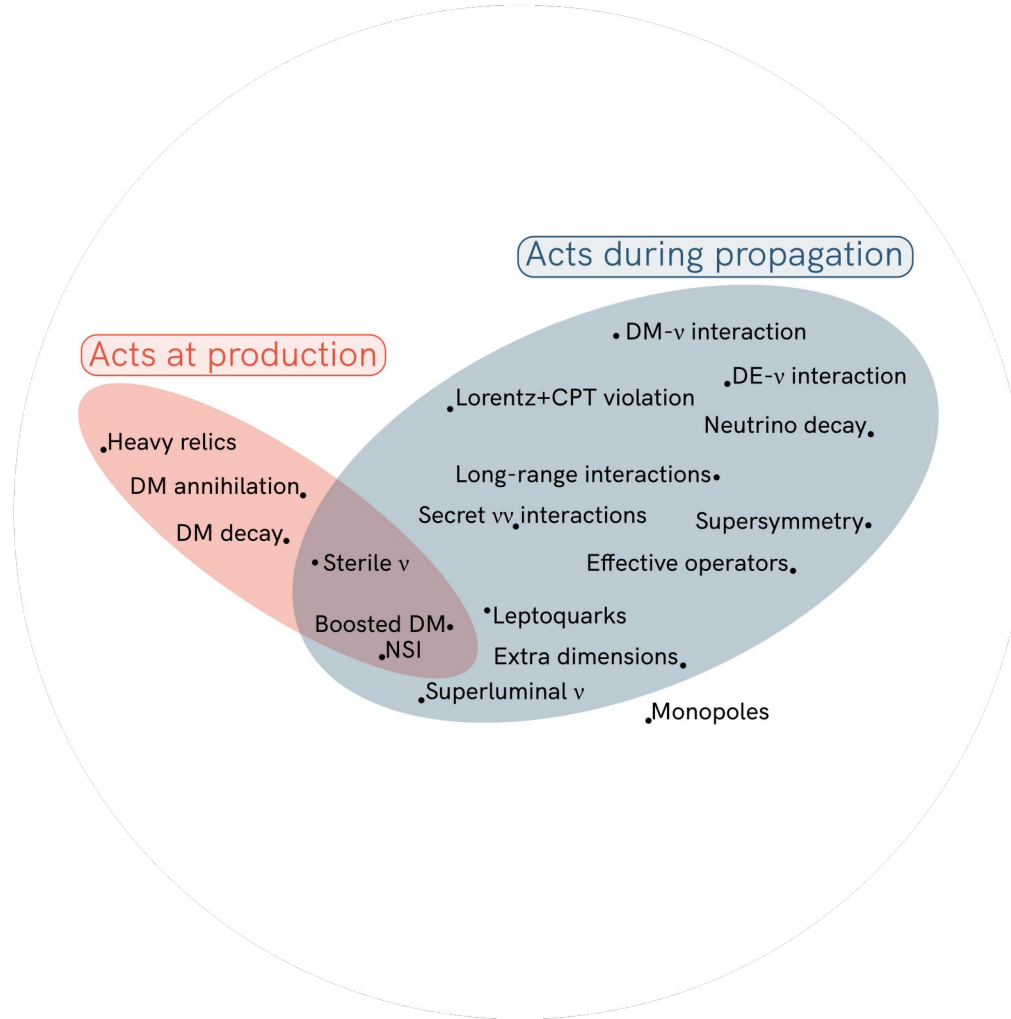
Made robust and meaningful by accounting
for all relevant particle and astrophysics uncertainties



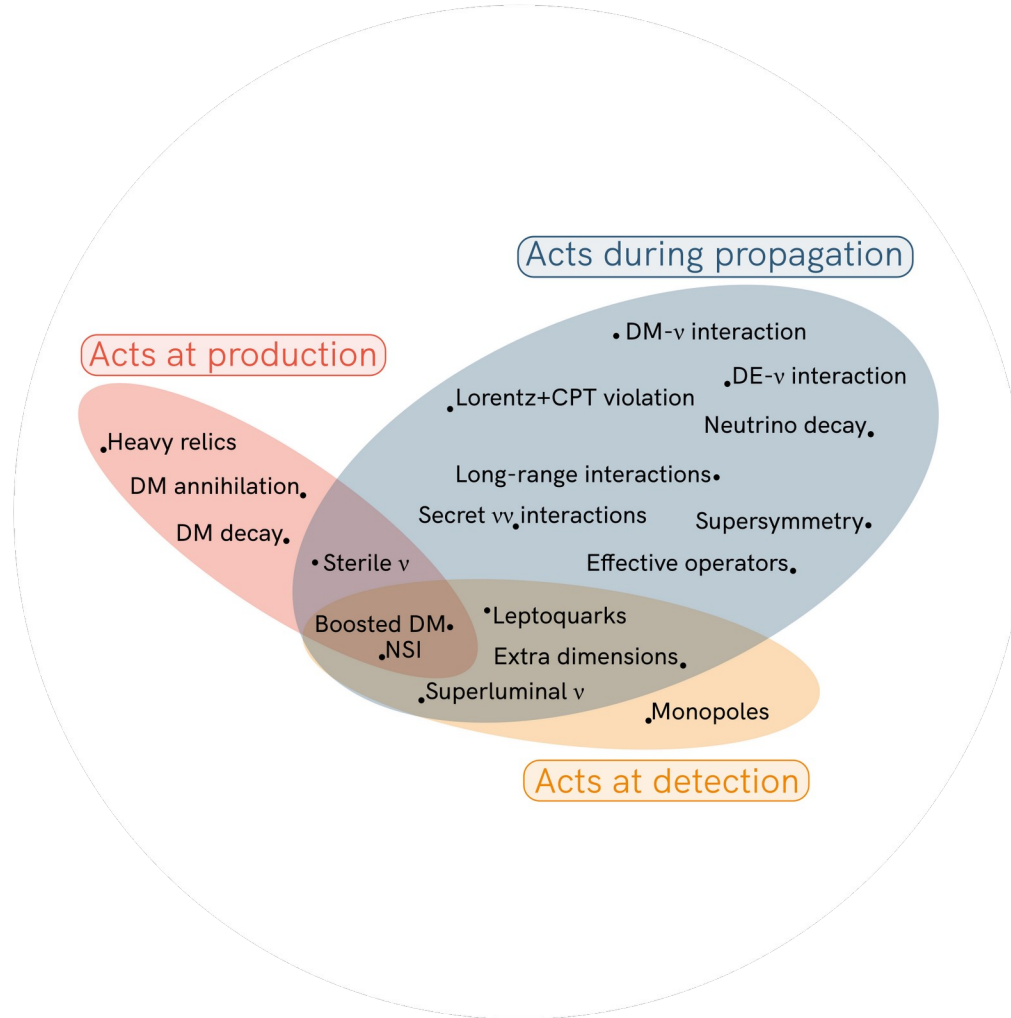
Note: Not an exhaustive list



Note: Not an exhaustive list



Note: Not an exhaustive list



Note: Not an exhaustive list

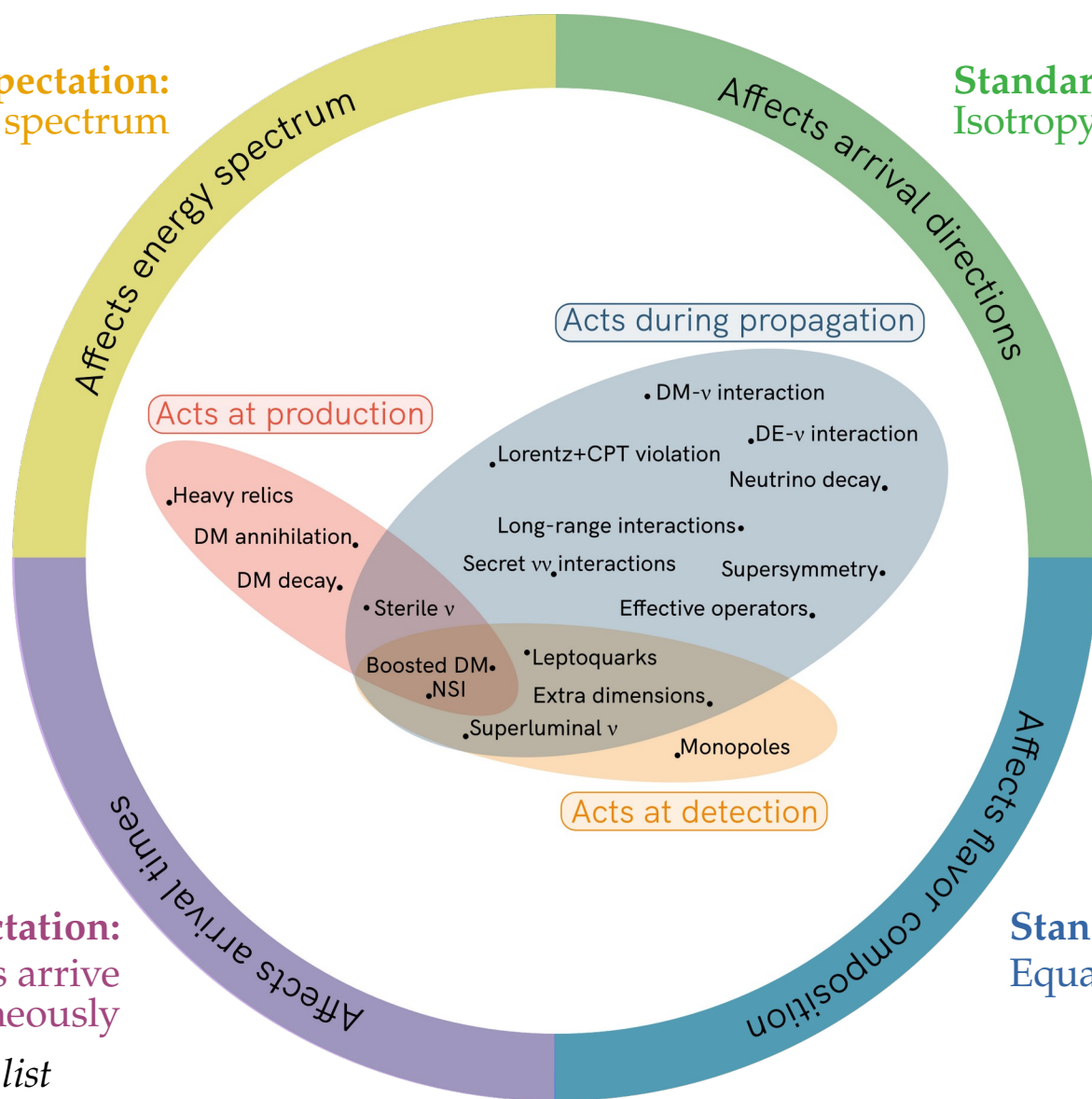
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



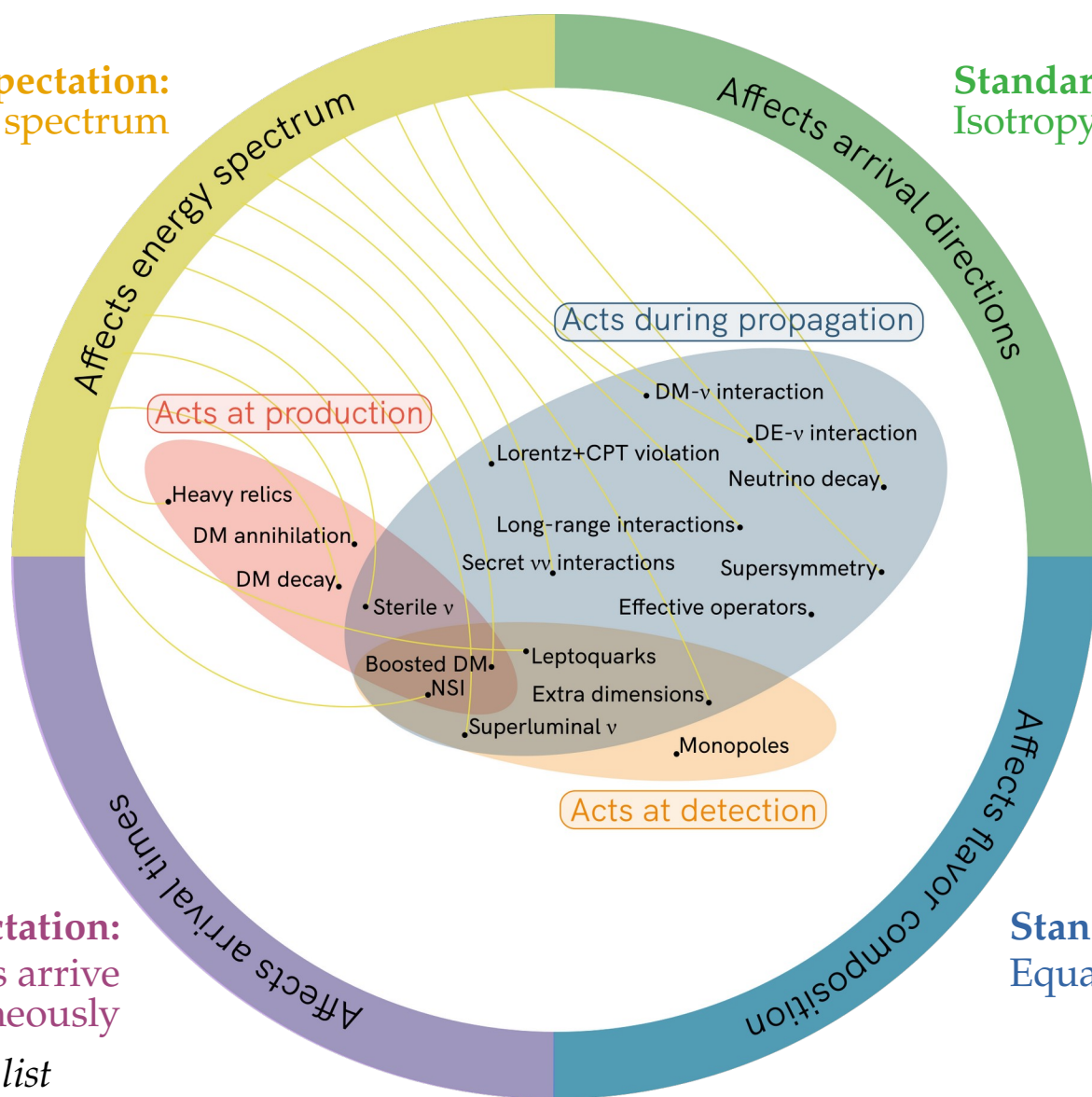
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



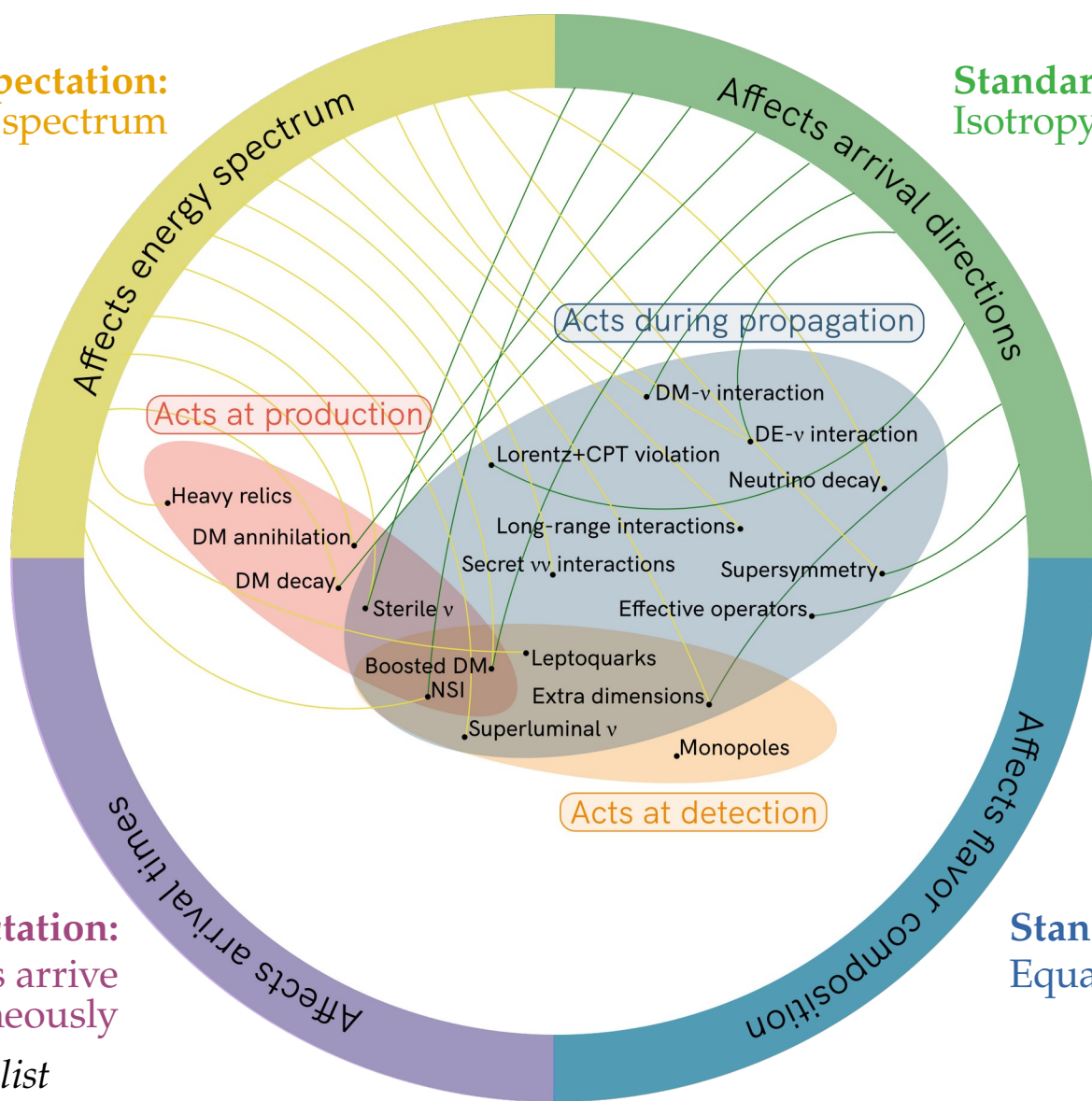
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list



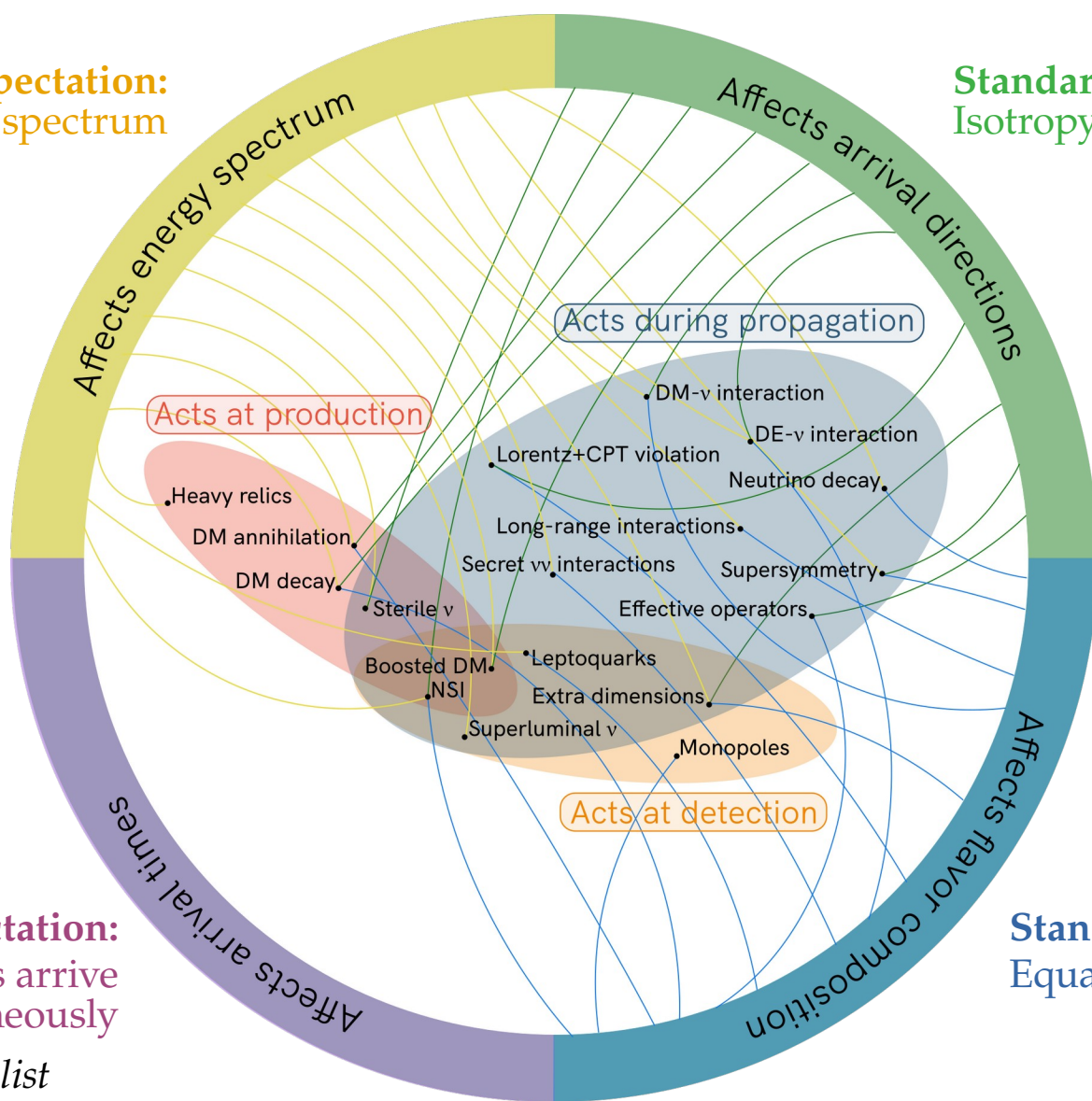
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list



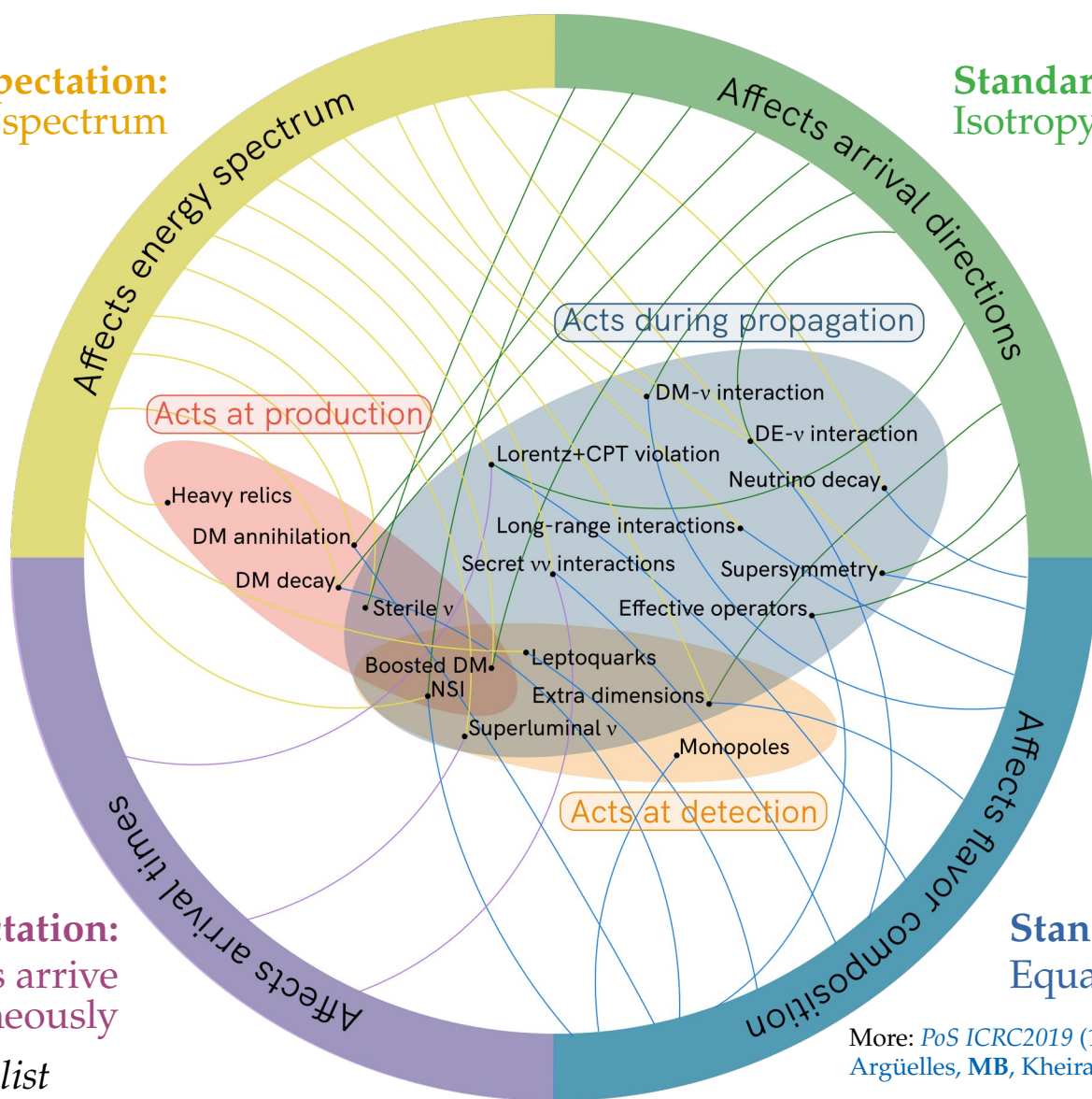
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



More: *PoS ICRC2019* (1907.08690)

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

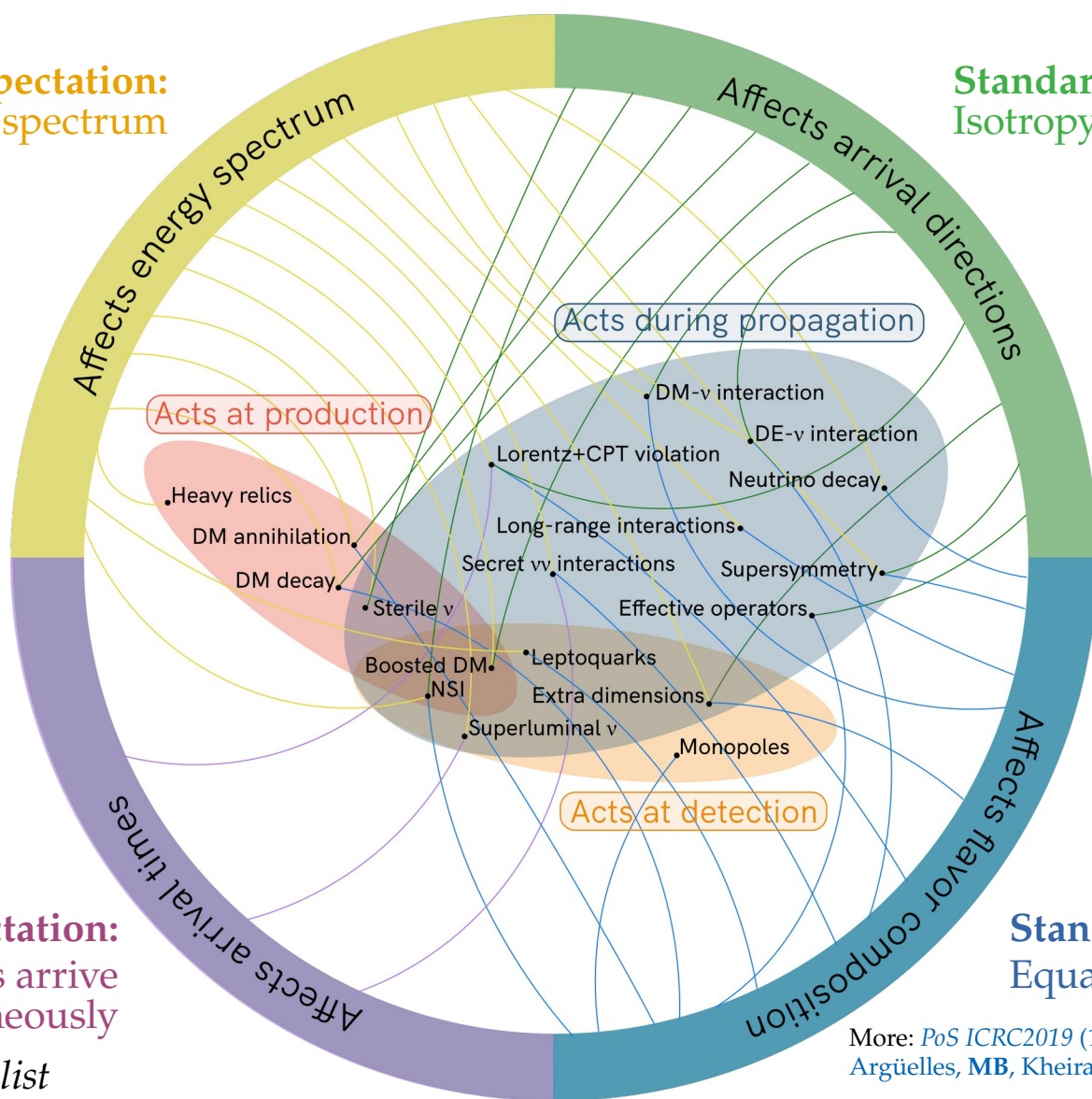
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



More: *PoS ICRC2019* (1907.08690)

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Reviews:
Ahlers, Helbing, De los Heros, *EPJC* 2018
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent, *ICRC* 2019 [1907.08690]
Ackermann, Ahlers, Anchordoqui, MB, et al., *Astro2020 Decadal Survey* [1903.04333]

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list

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

A selection of neutrino physics

- 1 Discovering the Glashow resonance
- 2 Neutrino-matter cross section
- 3 New physics via flavor
- 4 Unstable neutrinos
(If time allows)
- 5 New neutrino interactions
(If time allows)

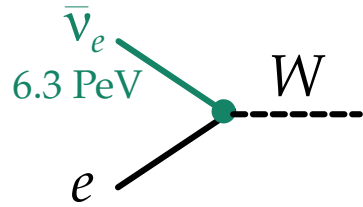
1. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

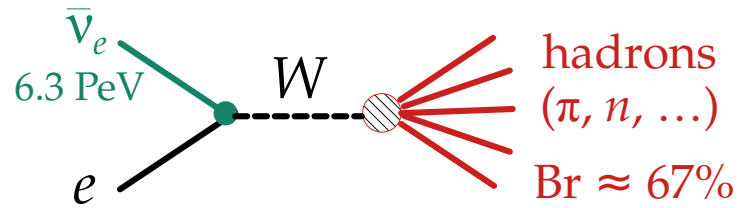
First observation of a Glashow resonance

Predicted in 1960:



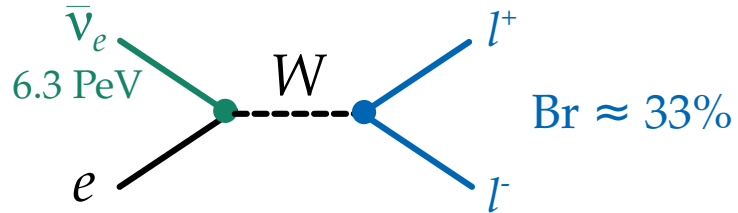
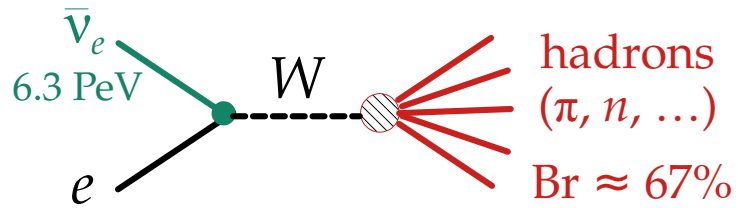
First observation of a Glashow resonance

Predicted in 1960:



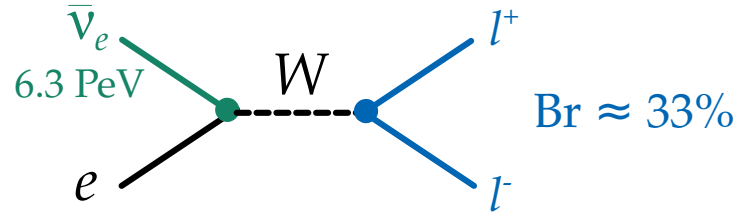
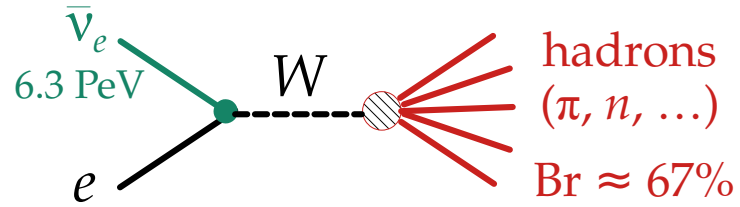
First observation of a Glashow resonance

Predicted in 1960:

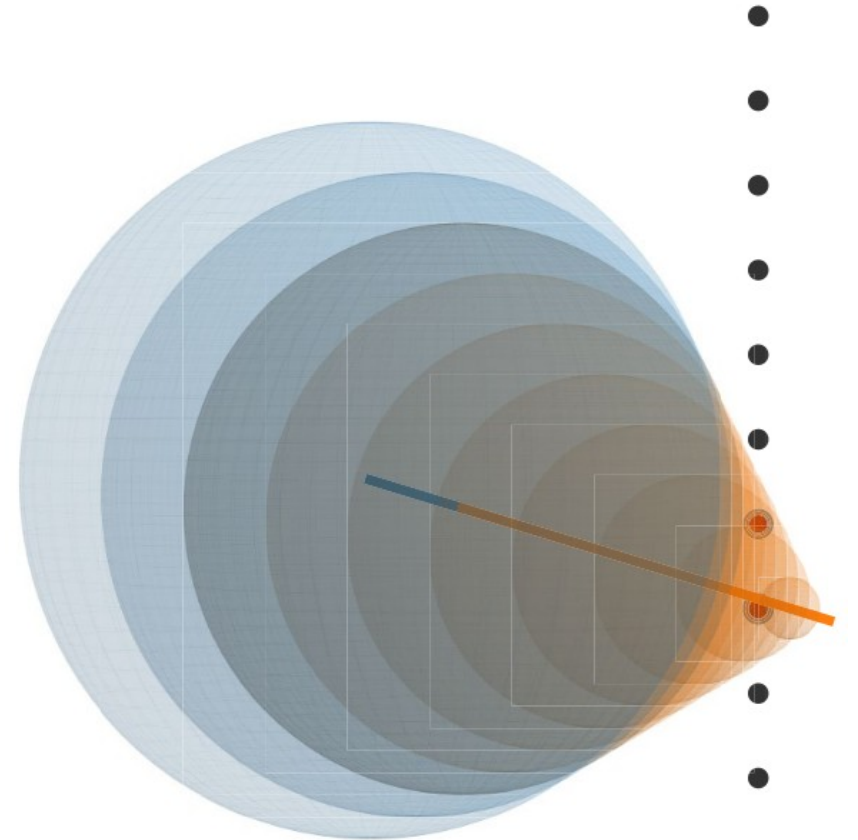


First observation of a Glashow resonance

Predicted in 1960:

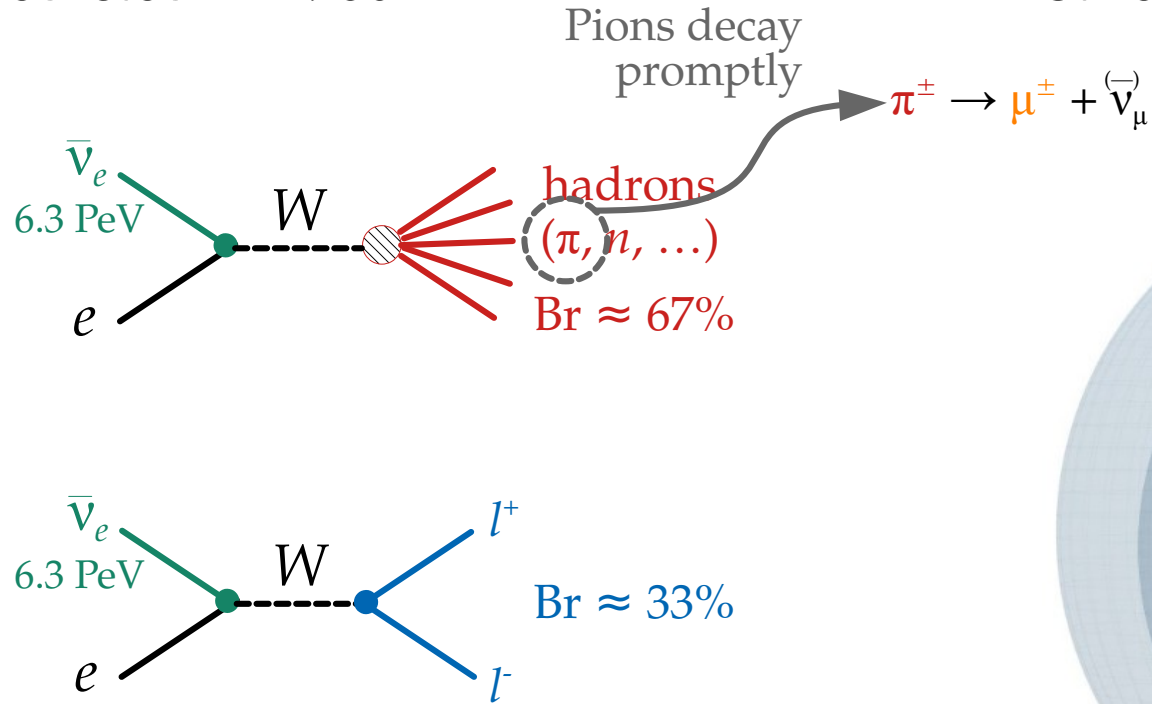


First reported by IceCube in 2021:

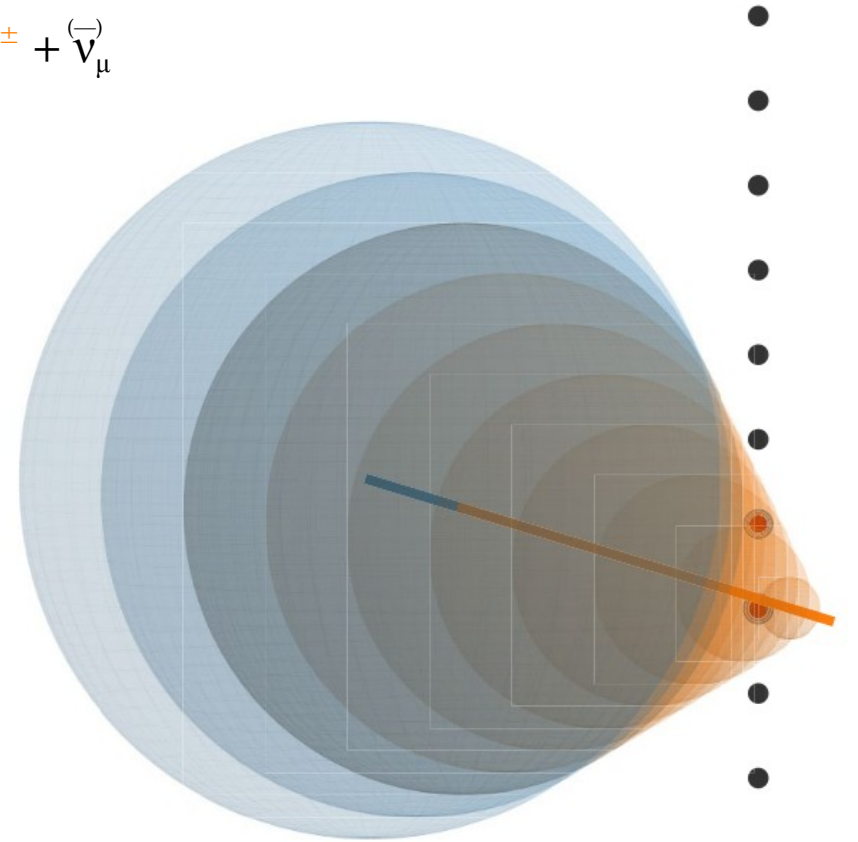


First observation of a Glashow resonance

Predicted in 1960:

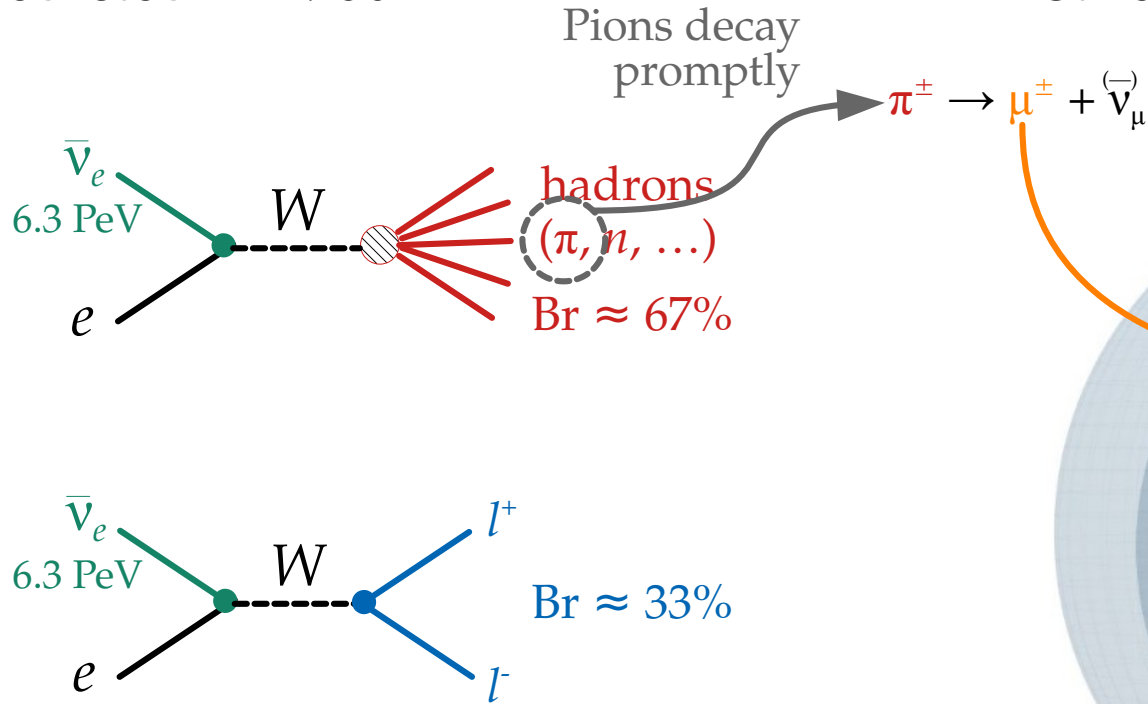


First reported by IceCube in 2021:

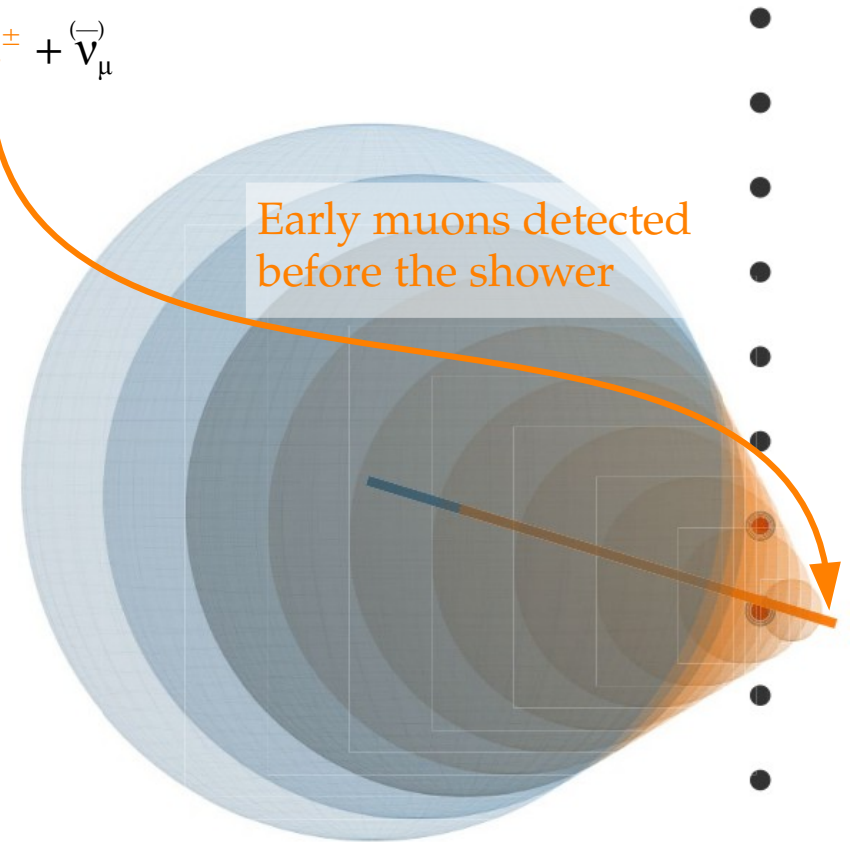


First observation of a Glashow resonance

Predicted in 1960:

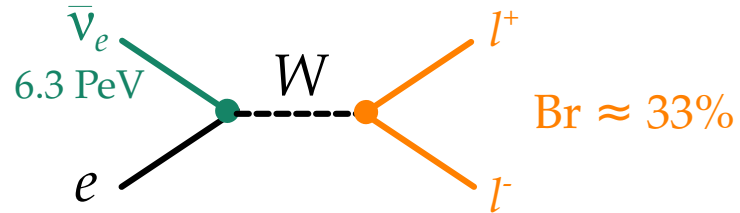
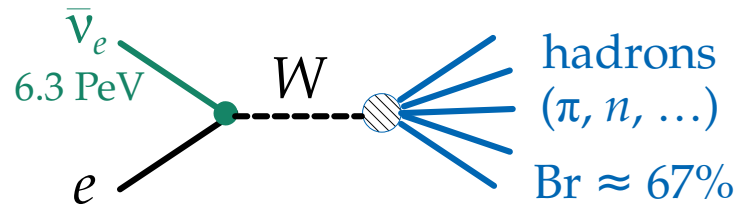


First reported by IceCube in 2021:

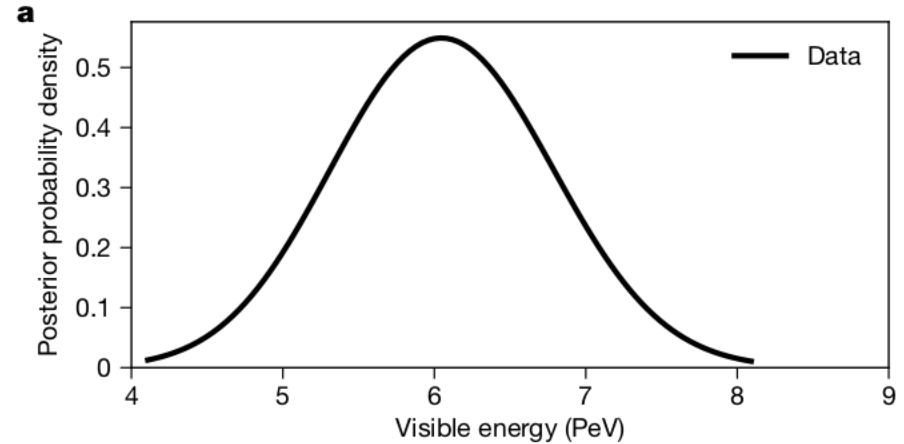


First observation of a Glashow resonance

Predicted in 1960:

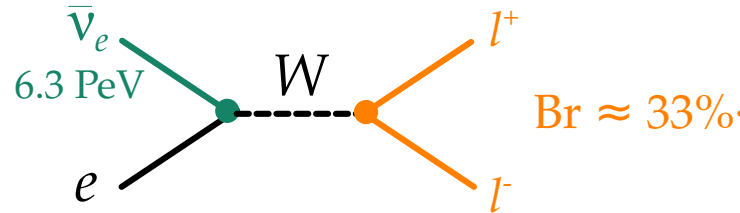
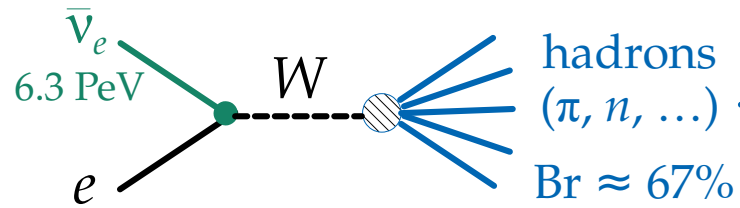


First reported by IceCube in 2021:

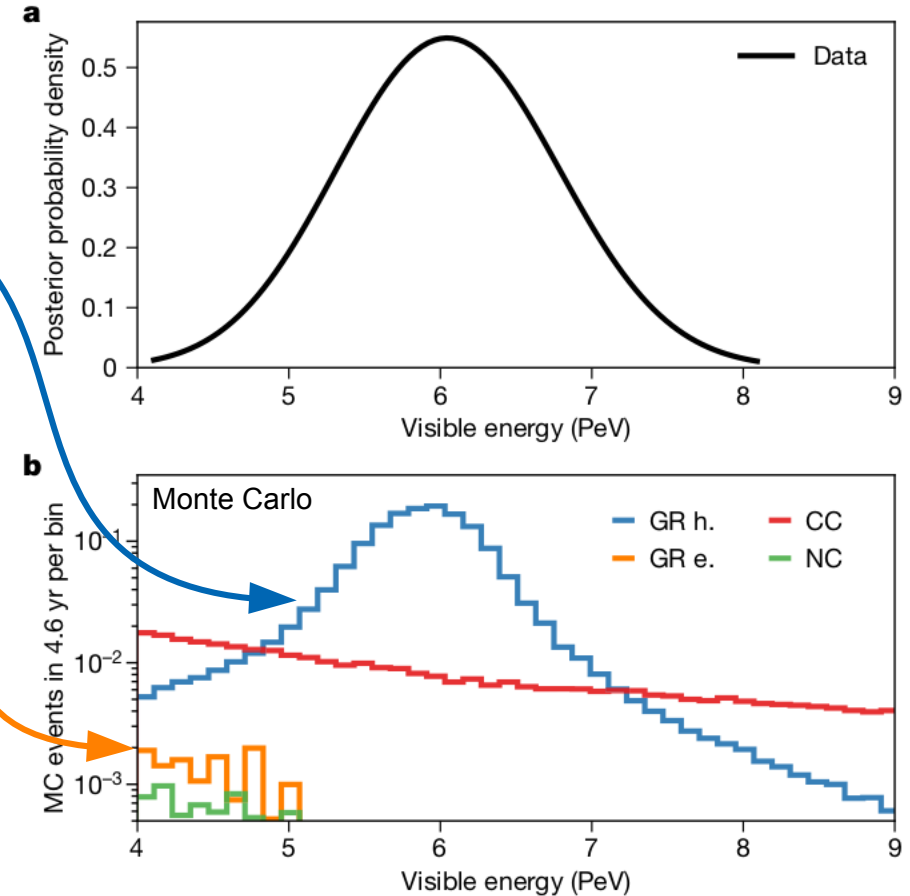


First observation of a Glashow resonance

Predicted in 1960:

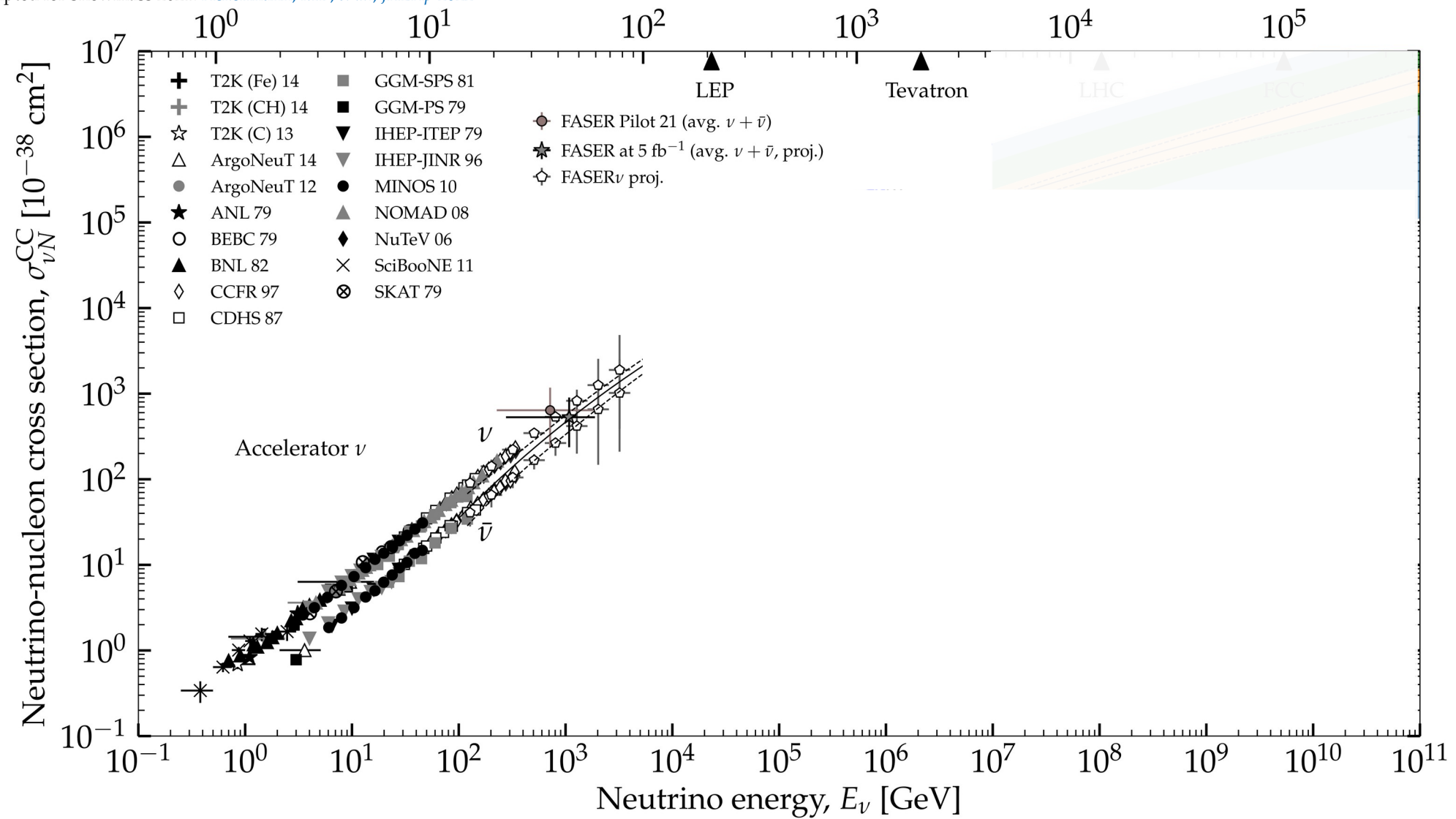


First reported by IceCube in 2021:

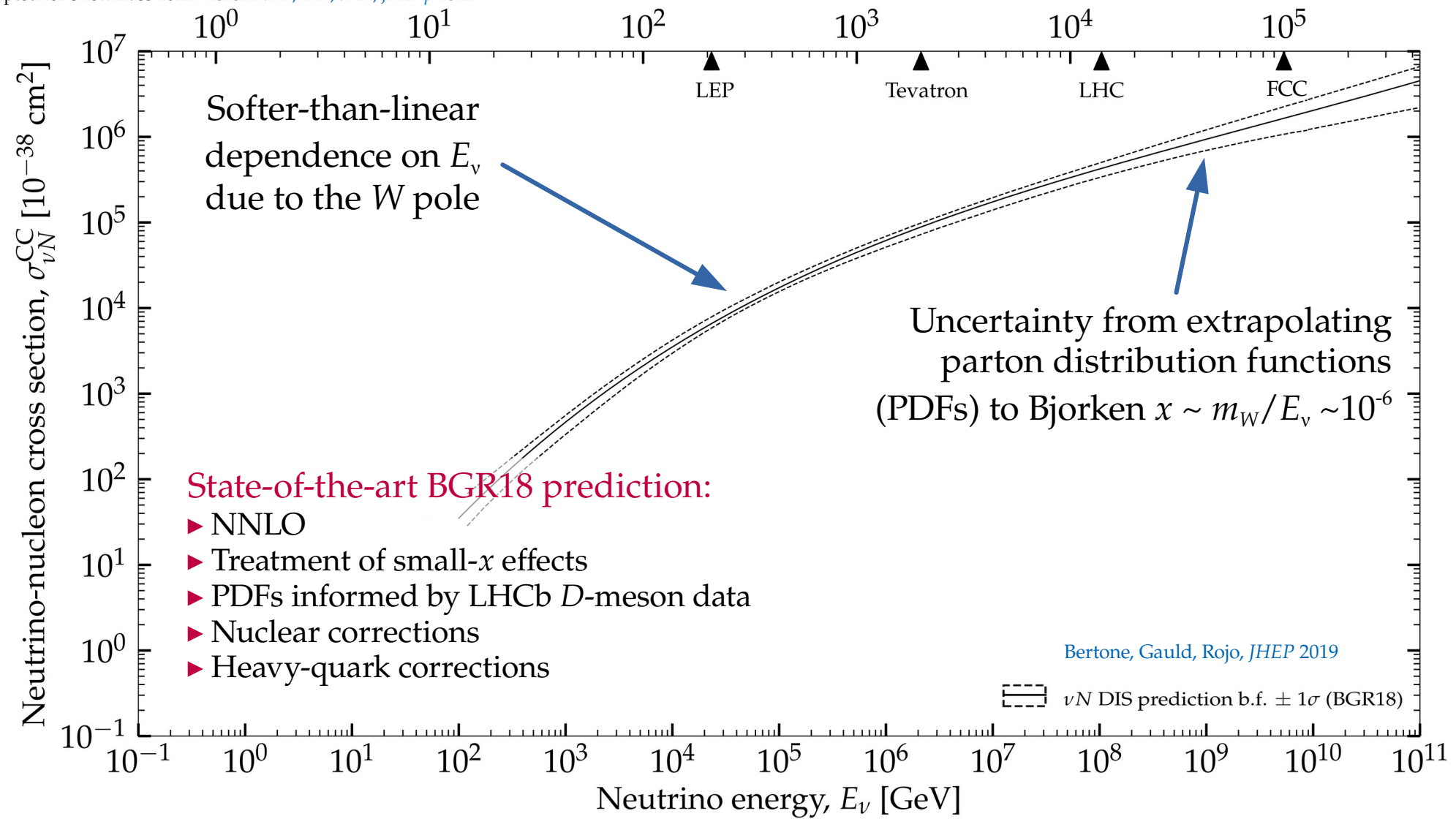


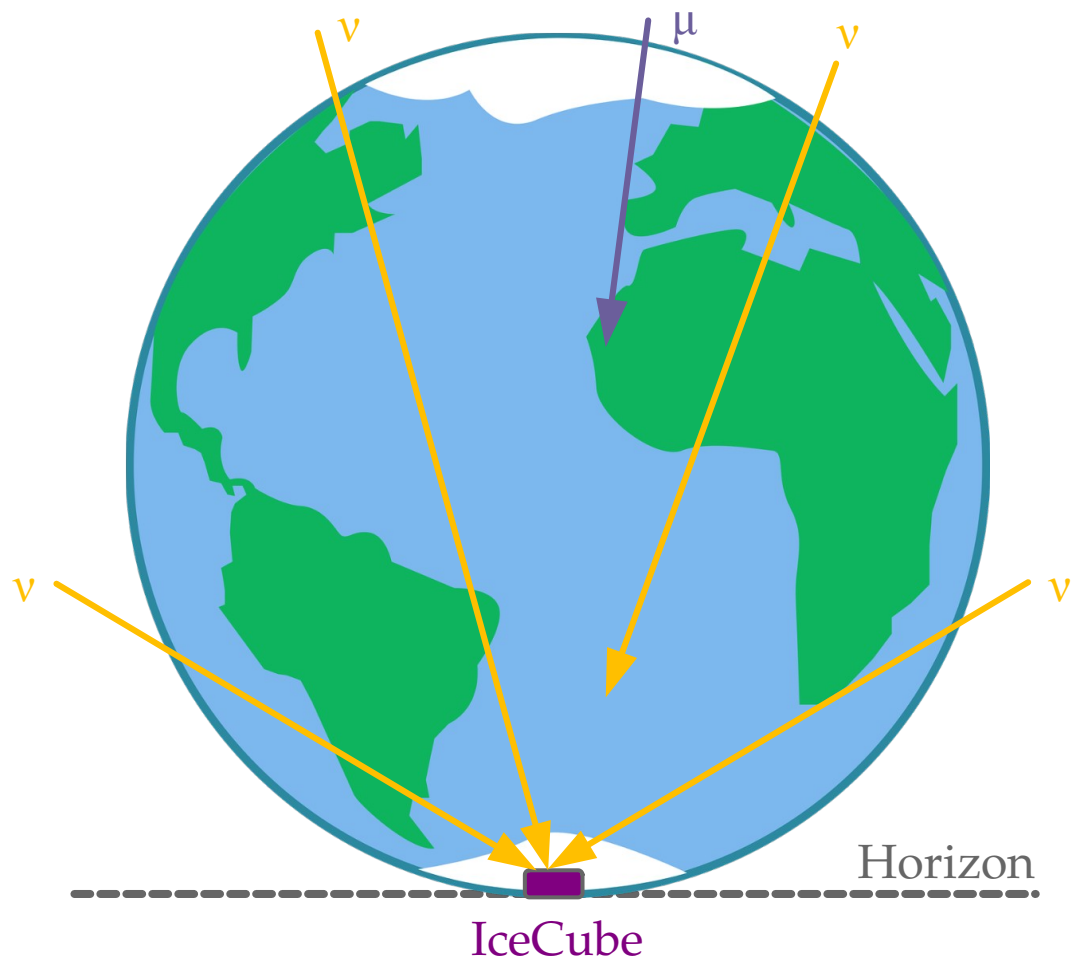
2. Neutrino-matter cross section: *From TeV to EeV*

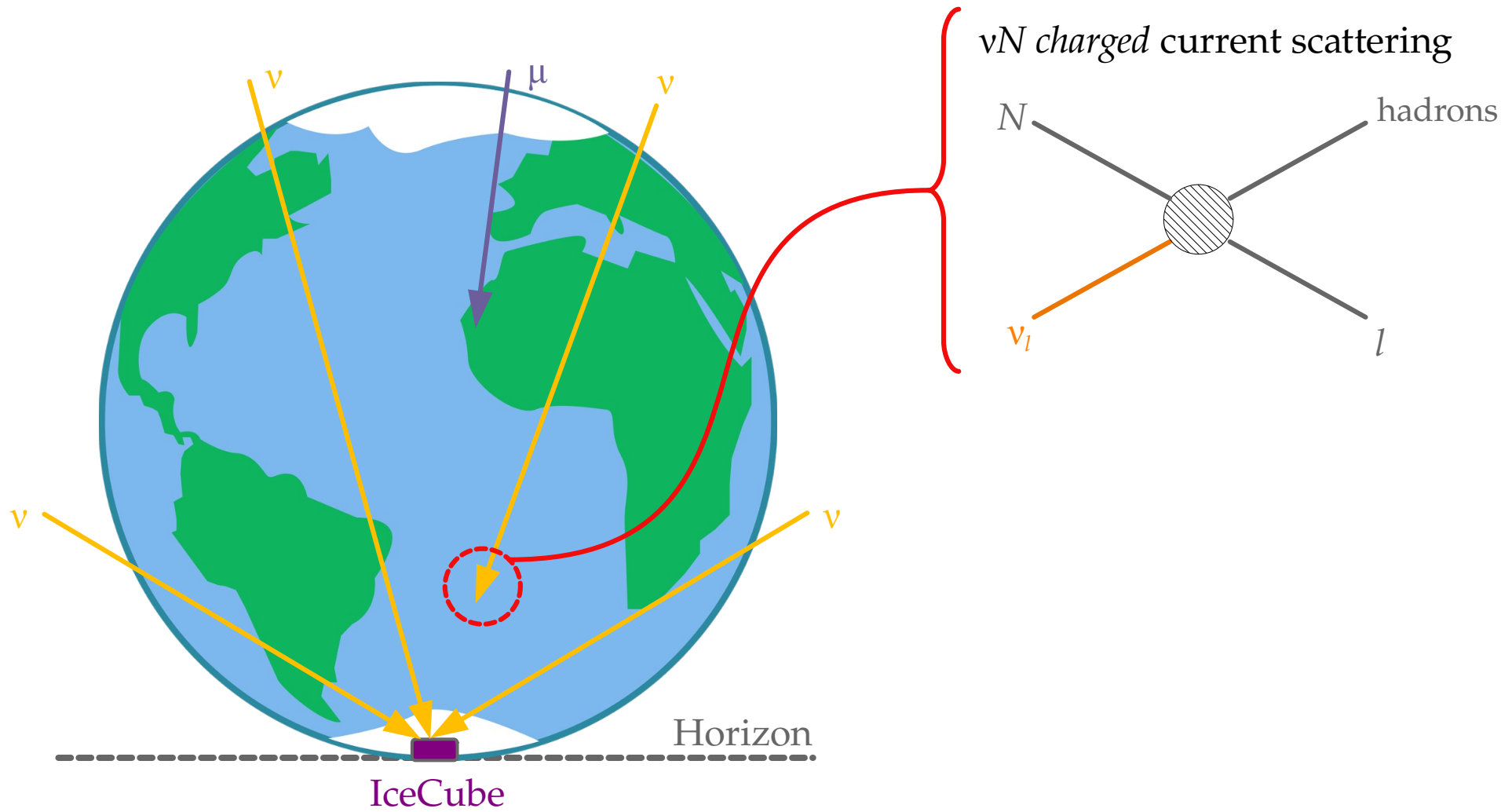
Center-of-mass energy $\sqrt{s}$ [GeV]

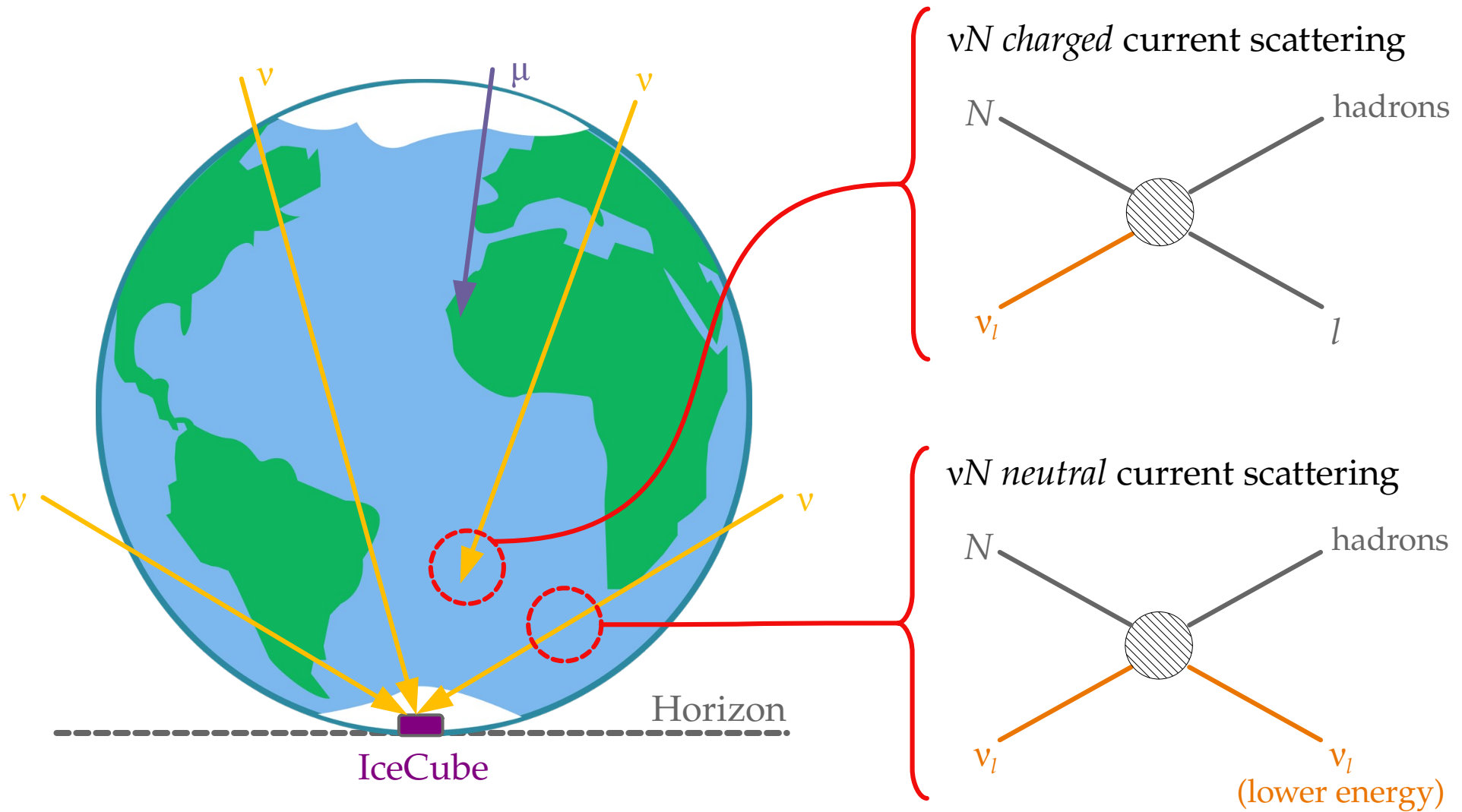


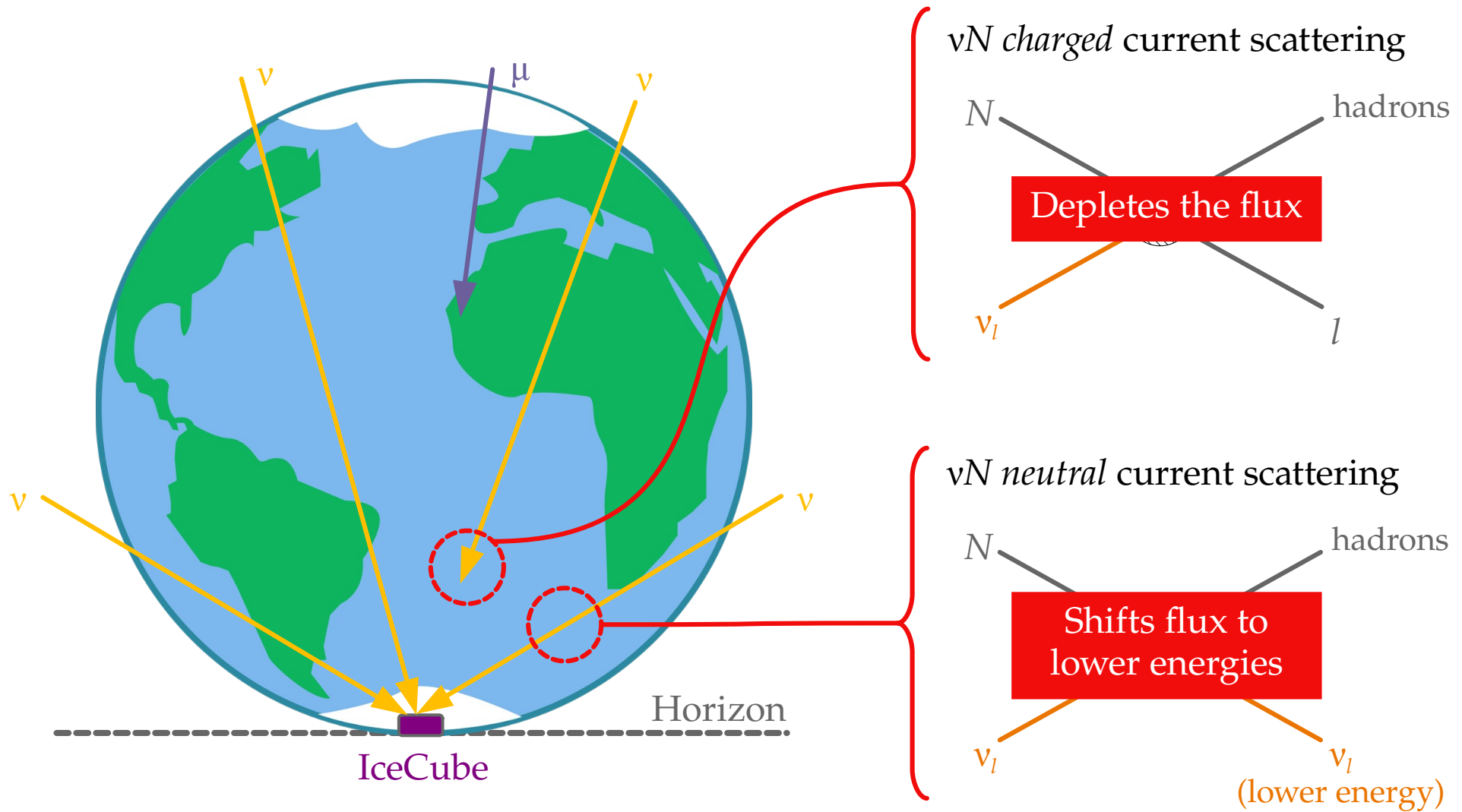
Center-of-mass energy $\sqrt{s}$ [GeV]







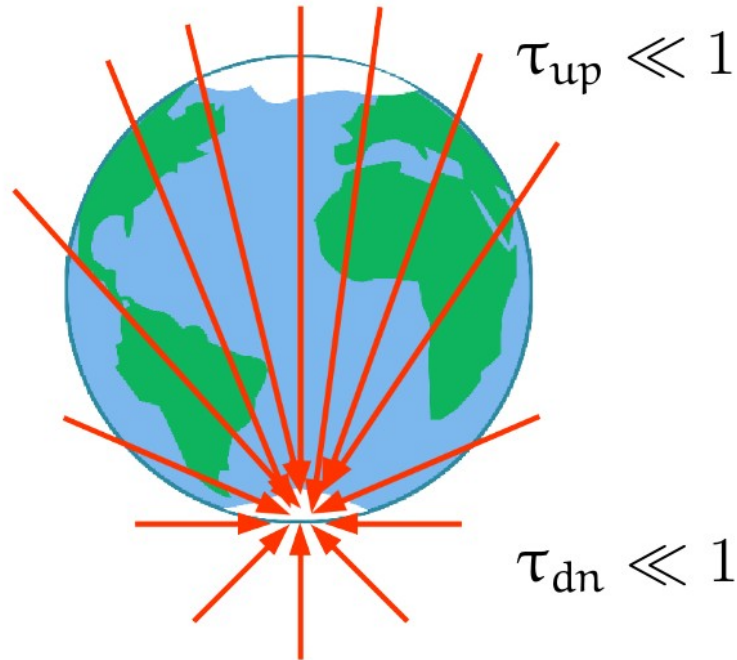




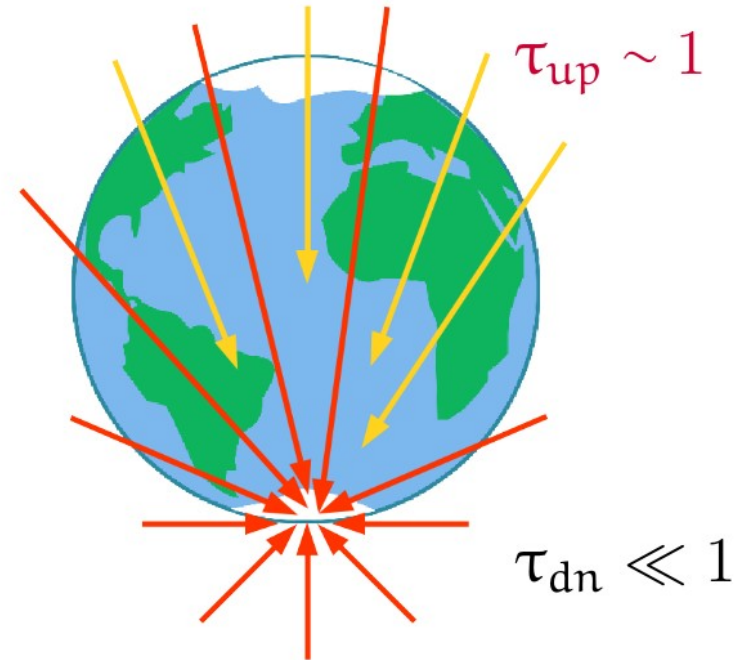
Measuring the high-energy νN cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



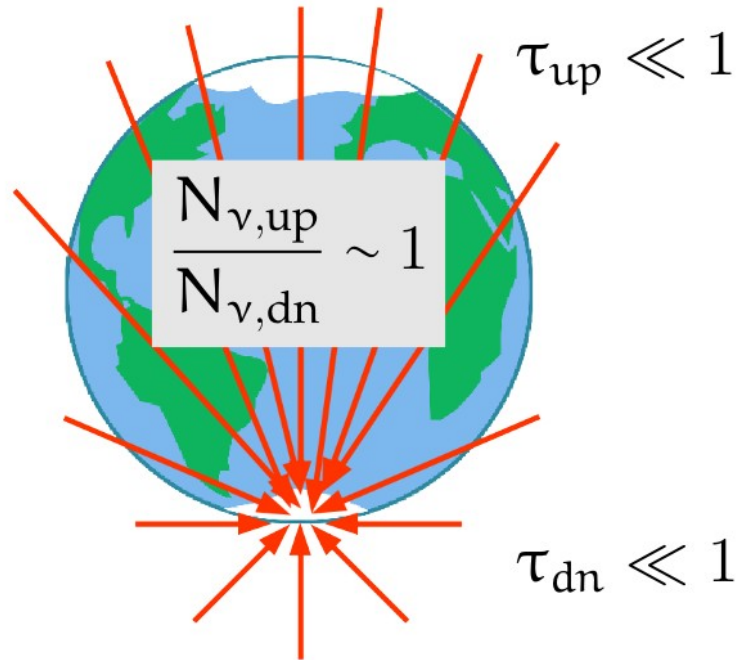
Above ~ 10 TeV: Earth is opaque



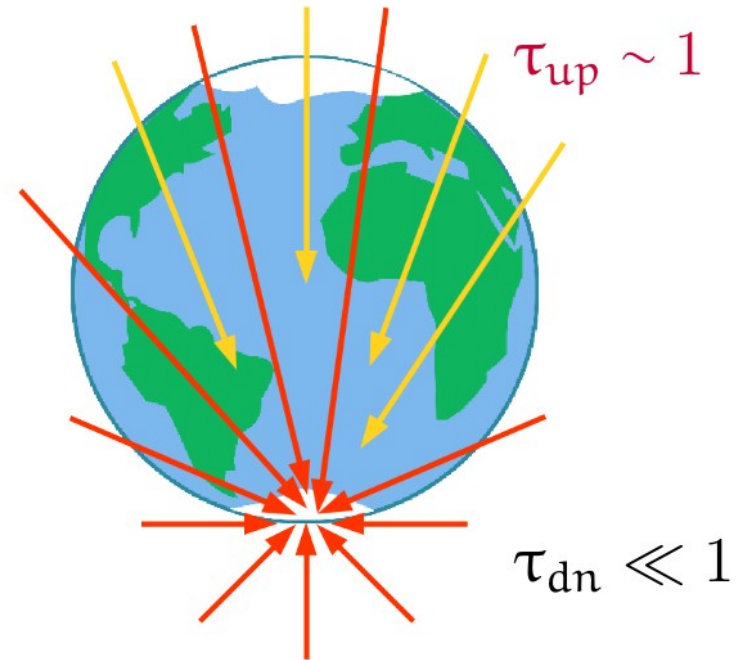
Measuring the high-energy νN cross section

$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



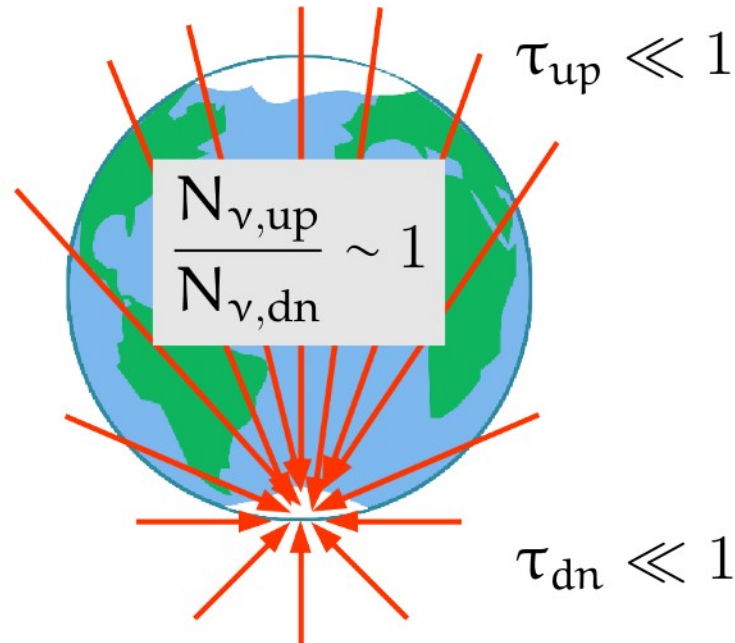
Above ~ 10 TeV: Earth is opaque



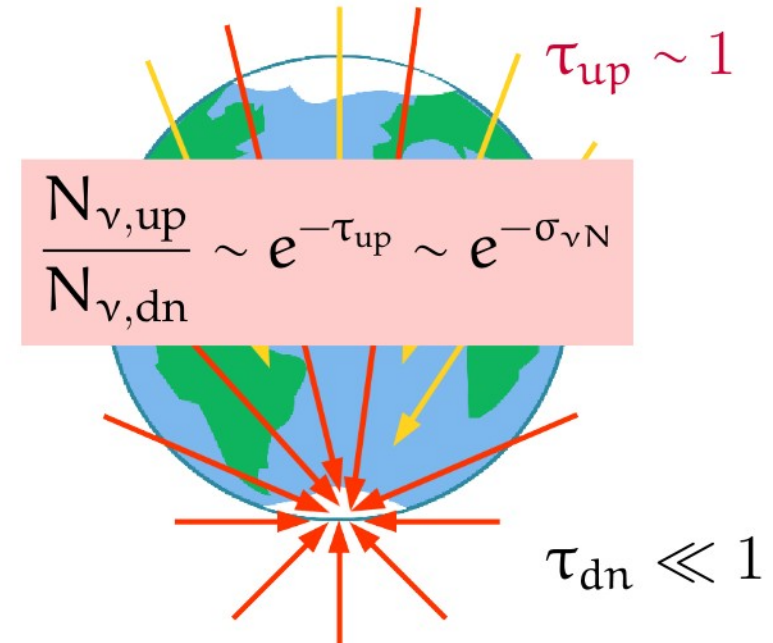
Measuring the high-energy νN cross section

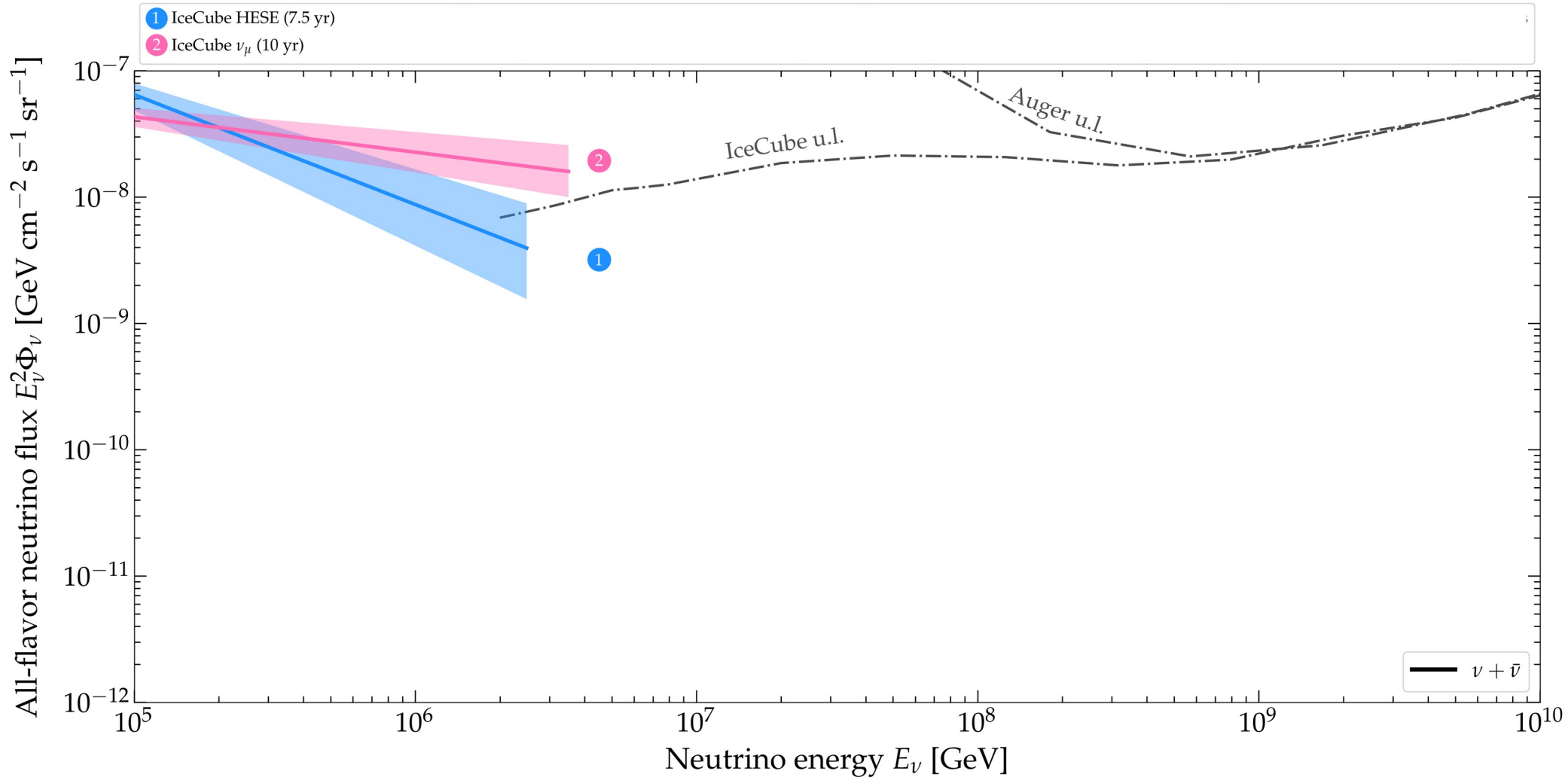
$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent

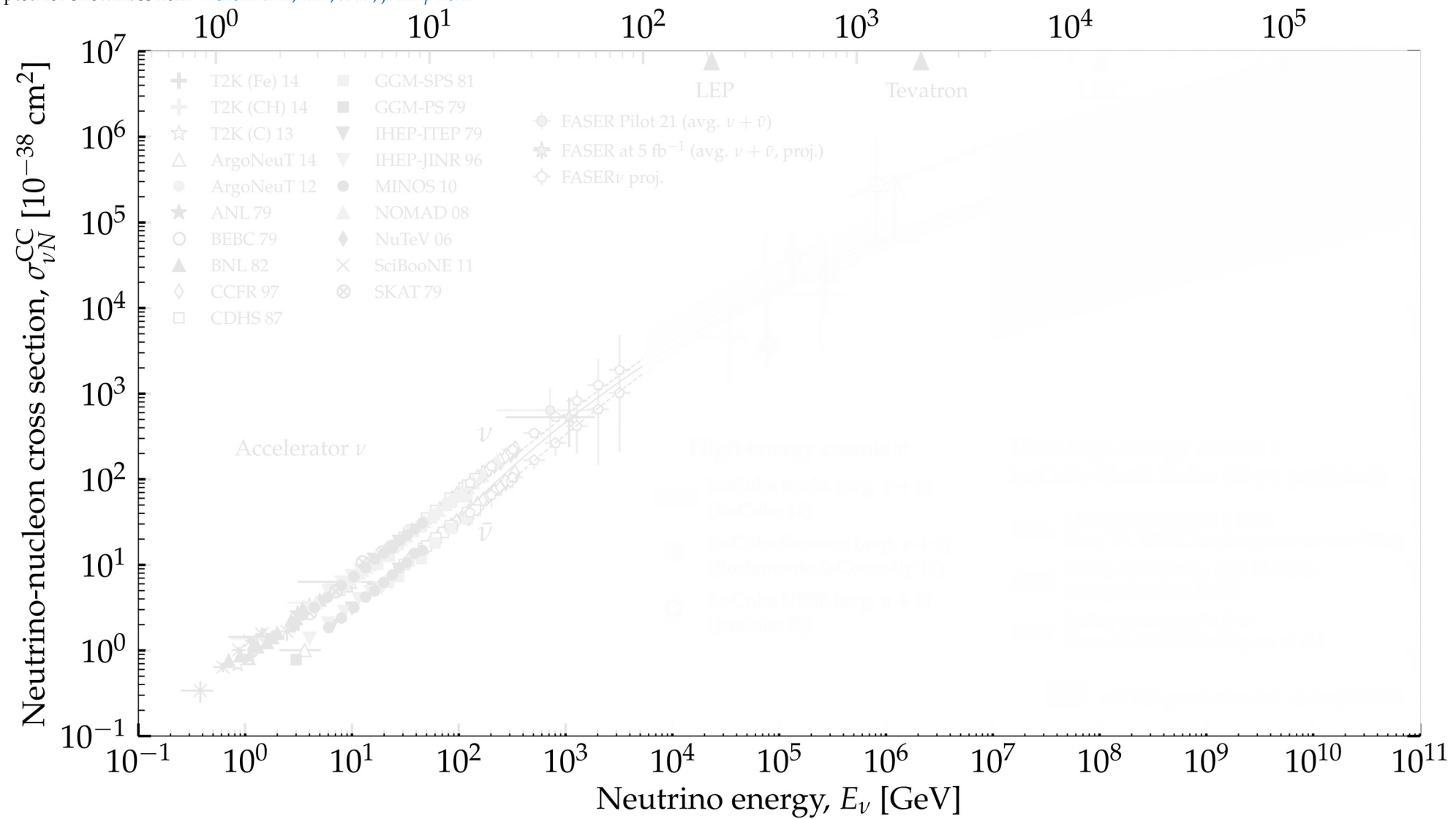


Above ~ 10 TeV: Earth is opaque

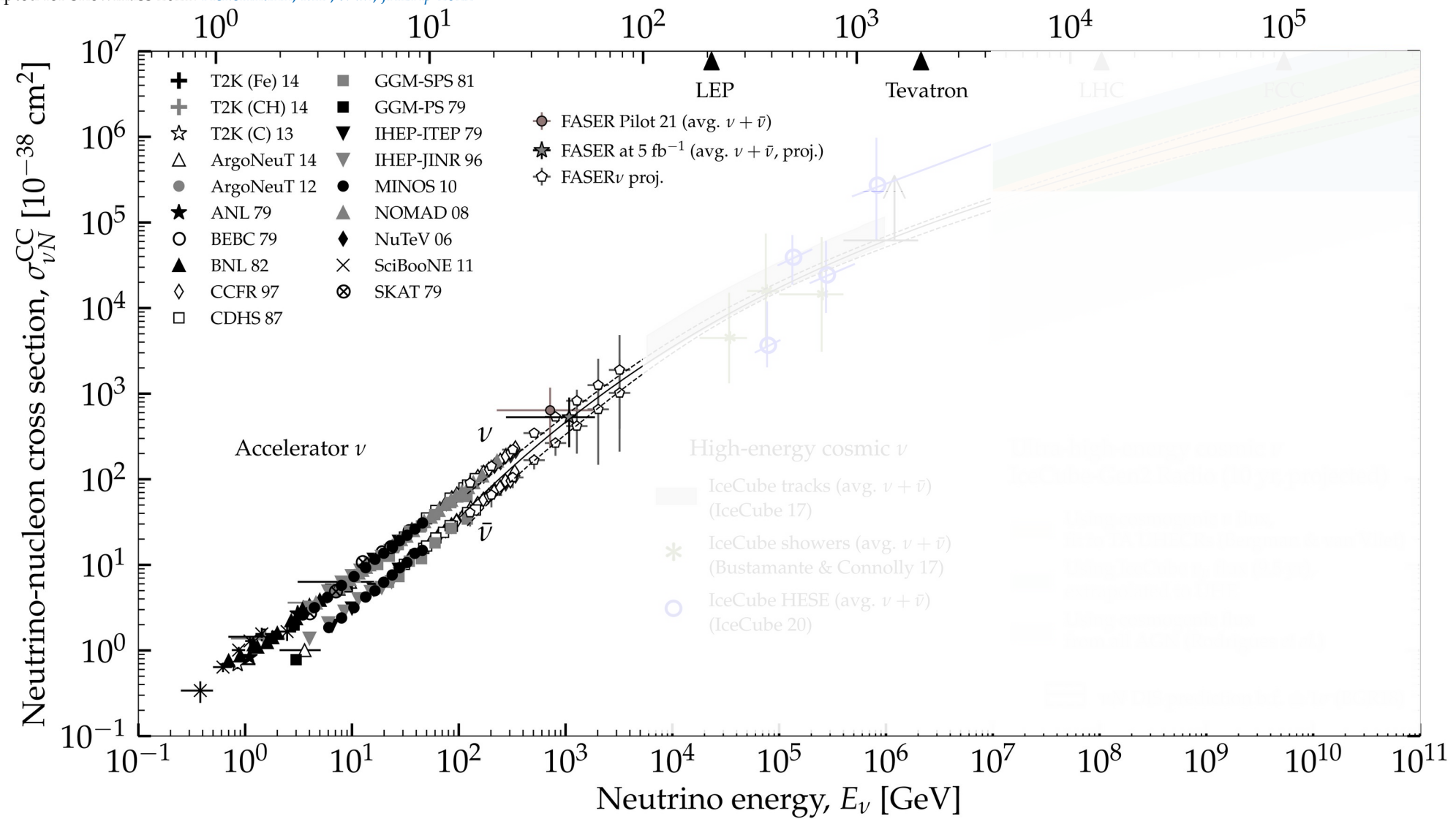




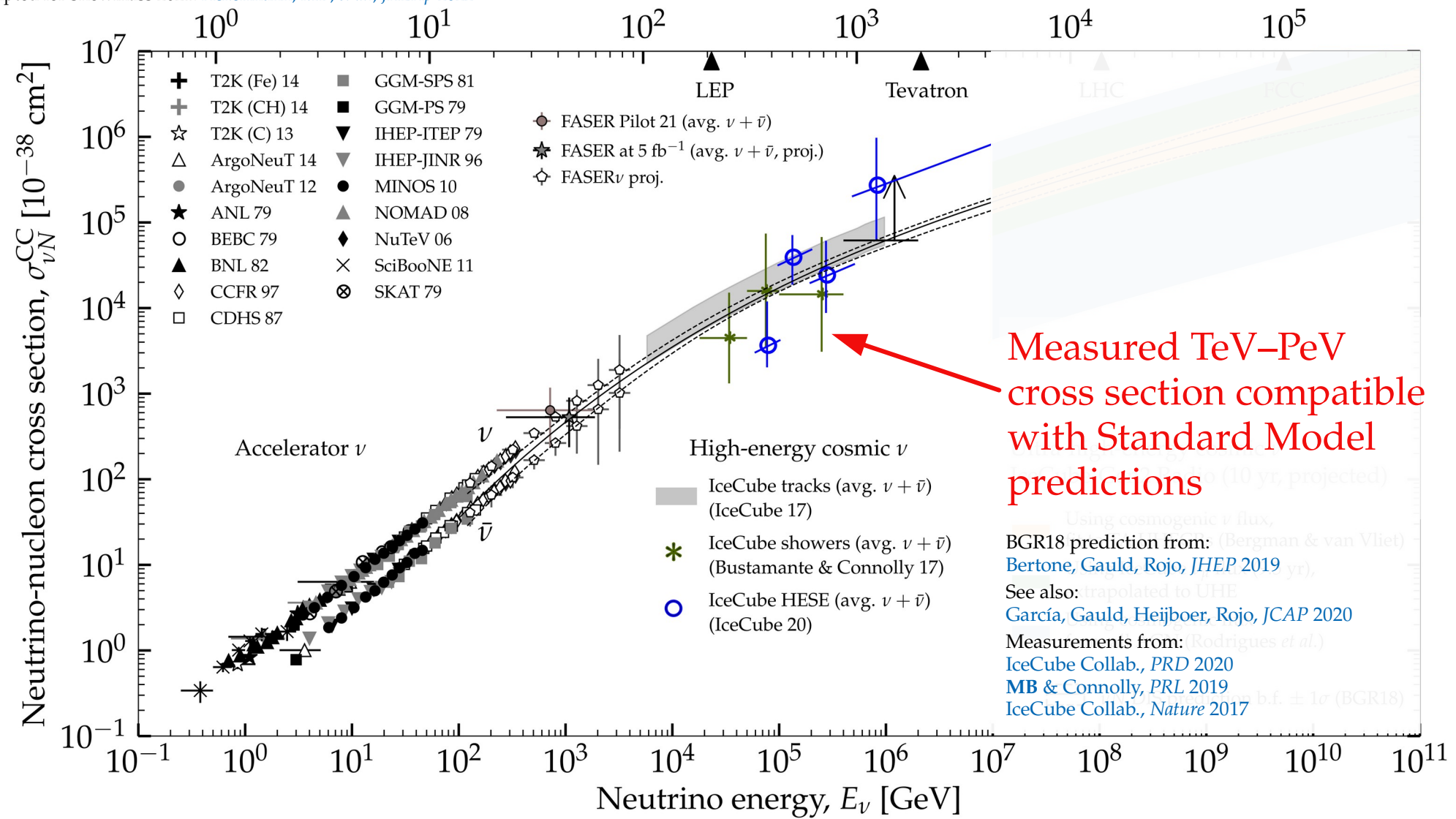
Center-of-mass energy $\sqrt{s}$ [GeV]



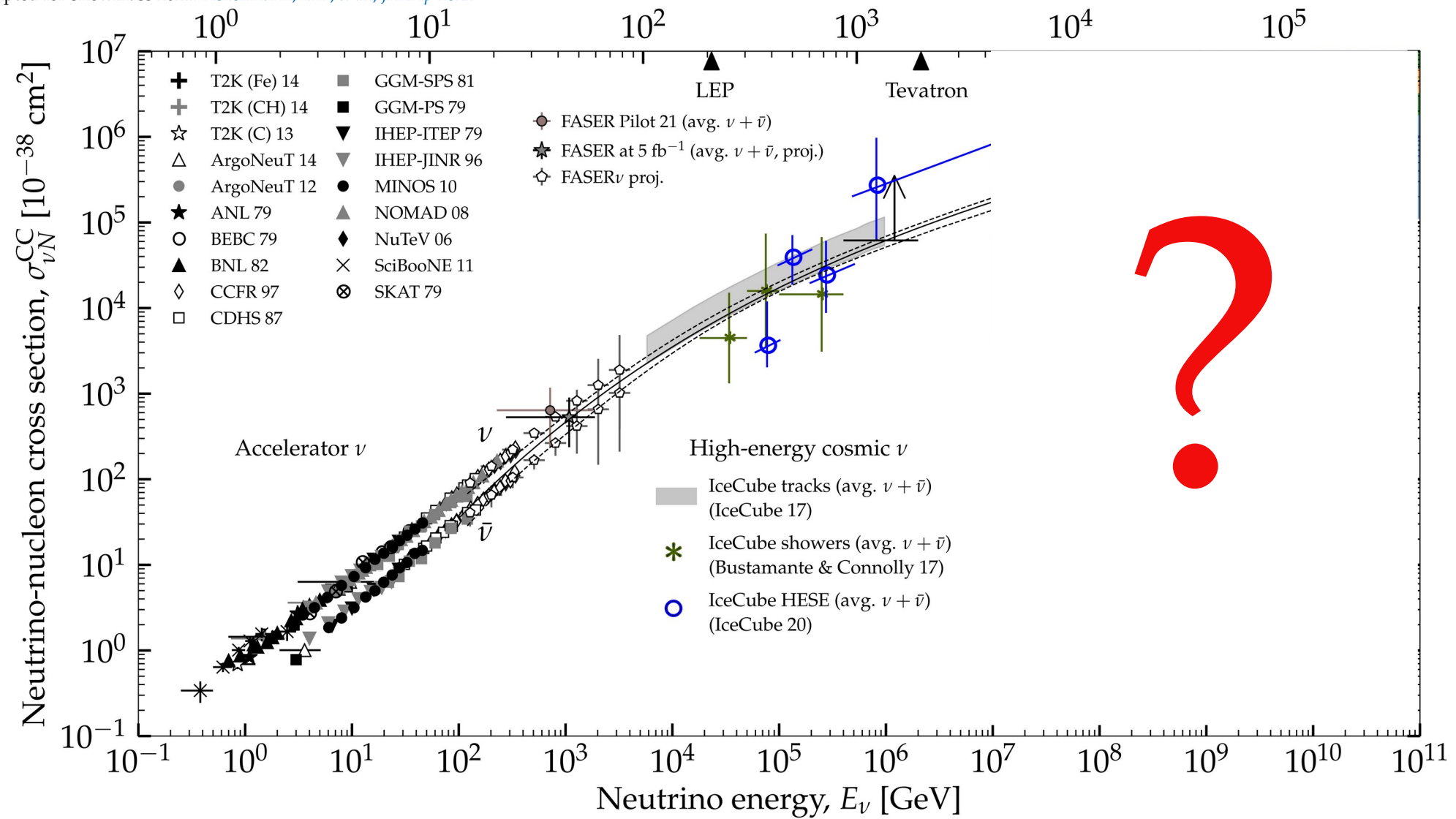
Center-of-mass energy $\sqrt{s}$ [GeV]



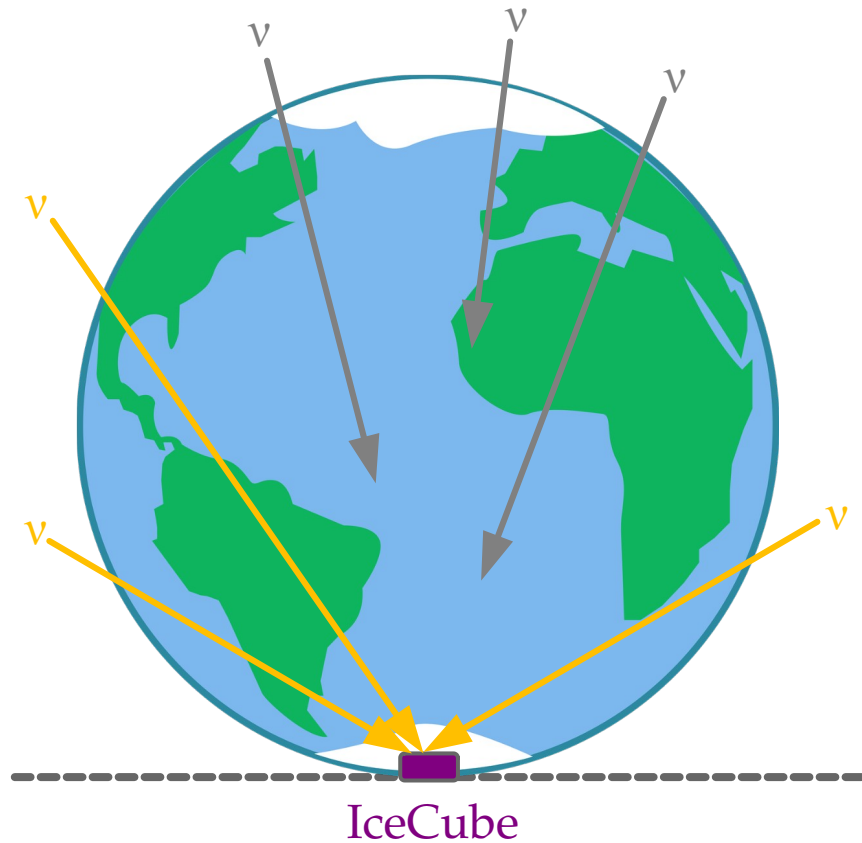
Center-of-mass energy $\sqrt{s}$ [GeV]



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

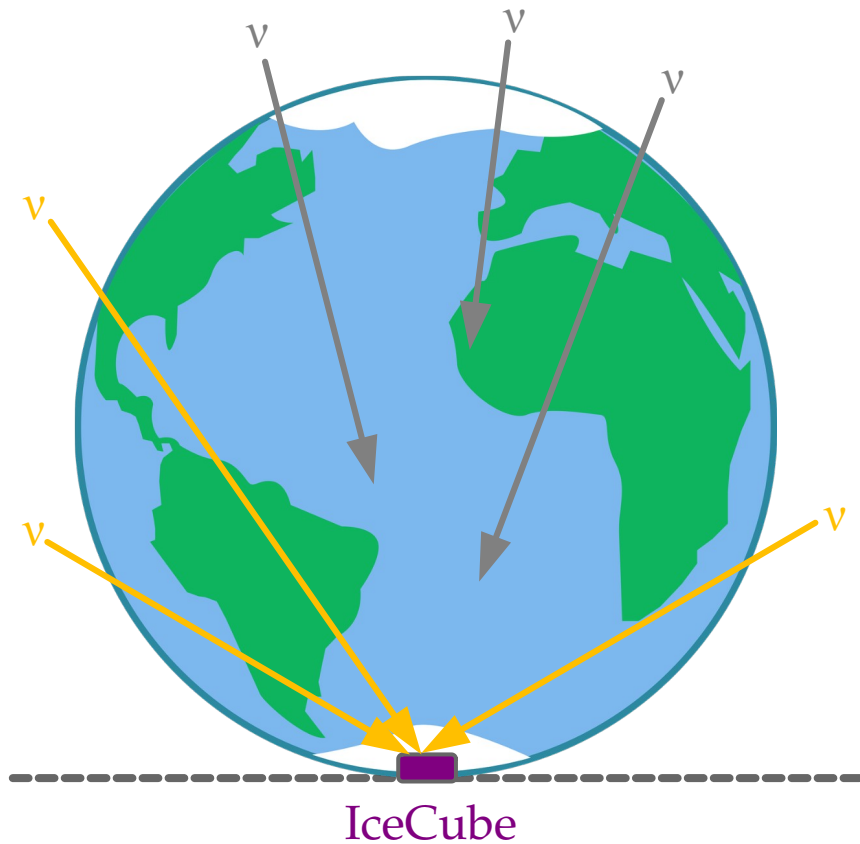


TeV–PeV:



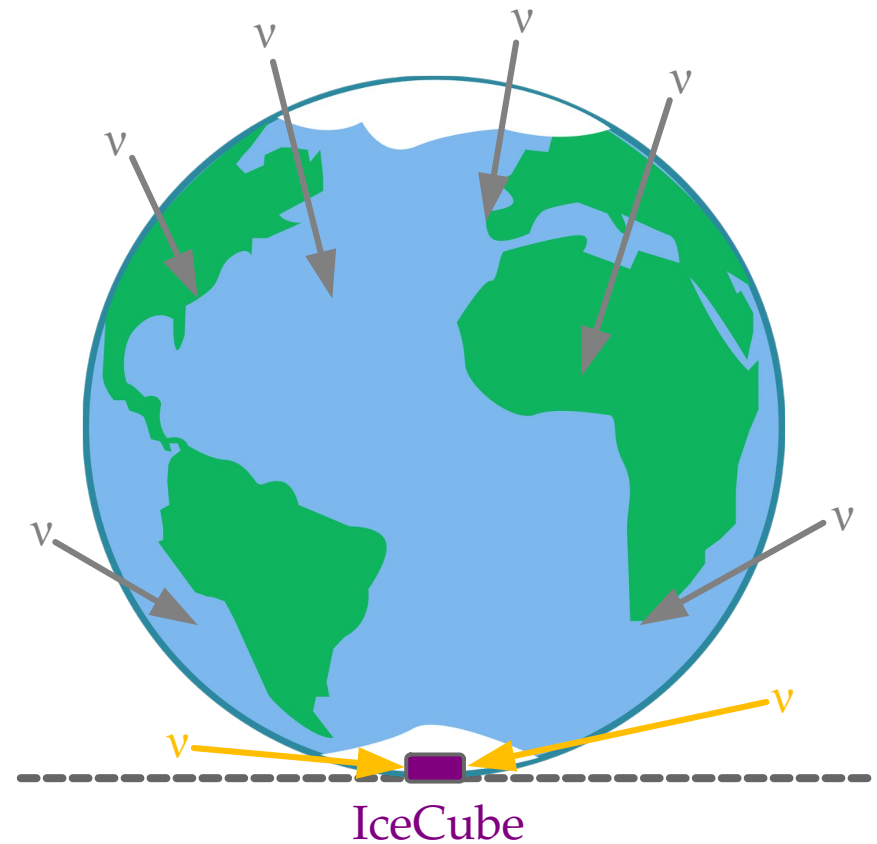
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:

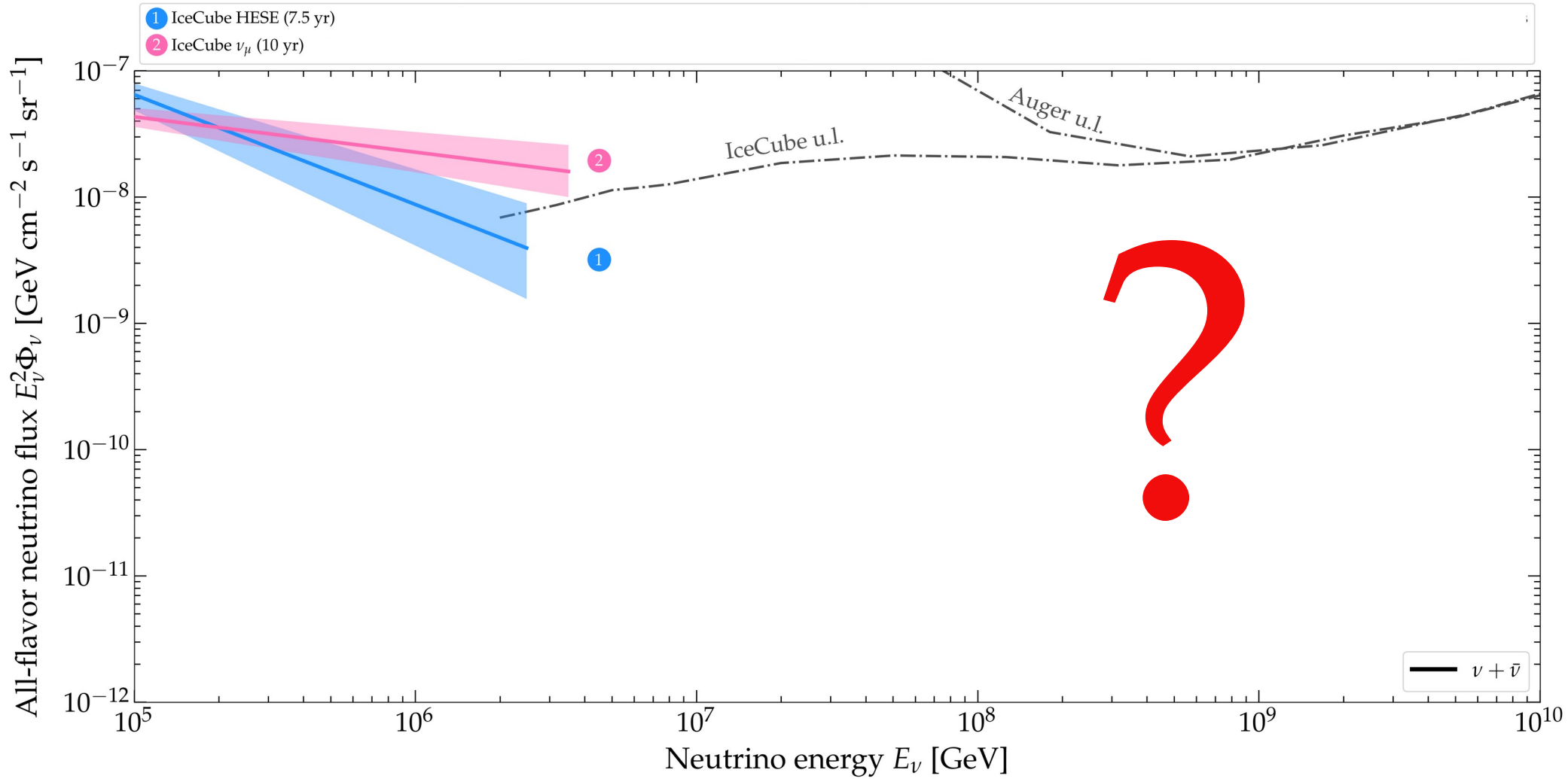


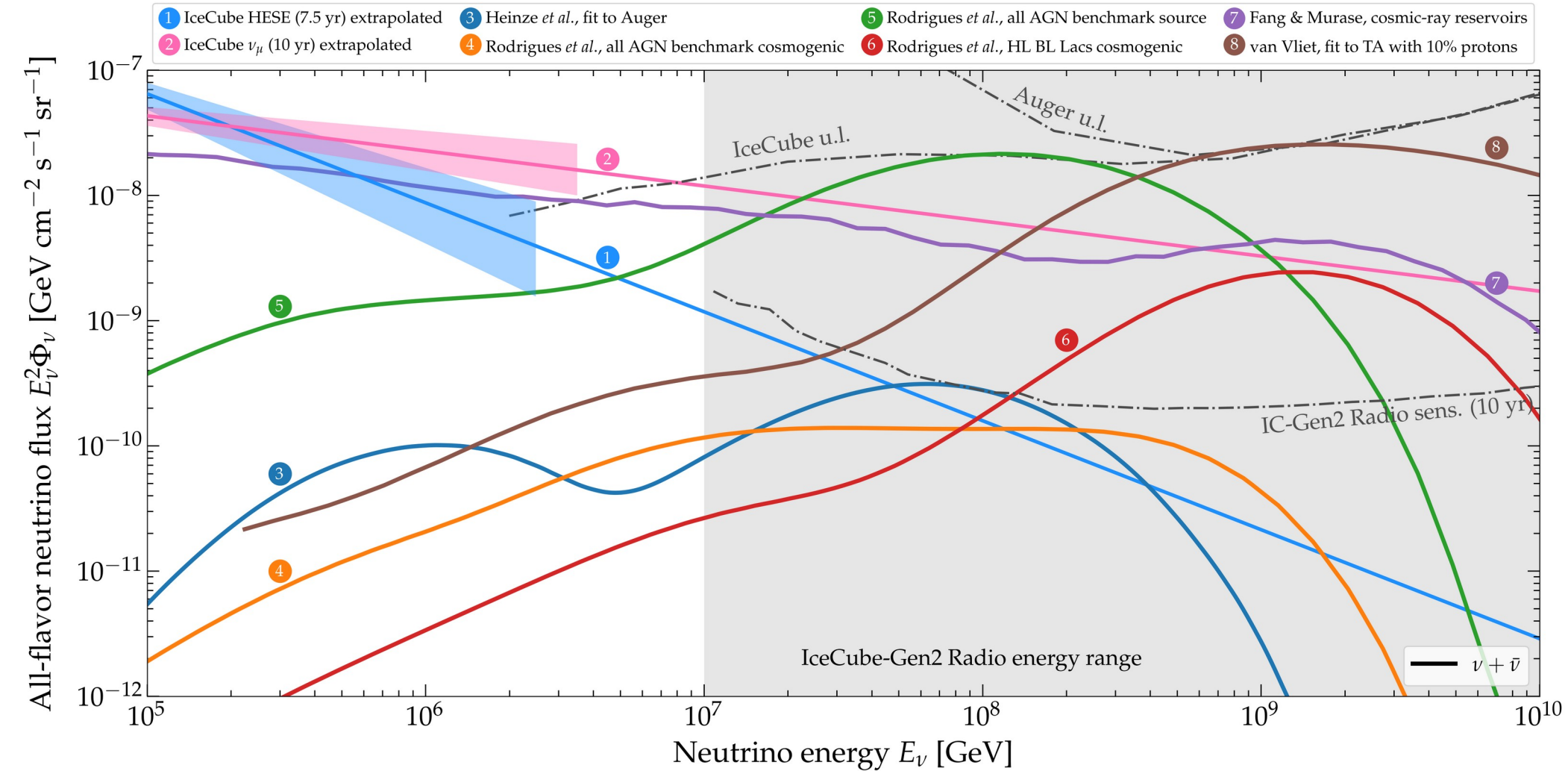
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:

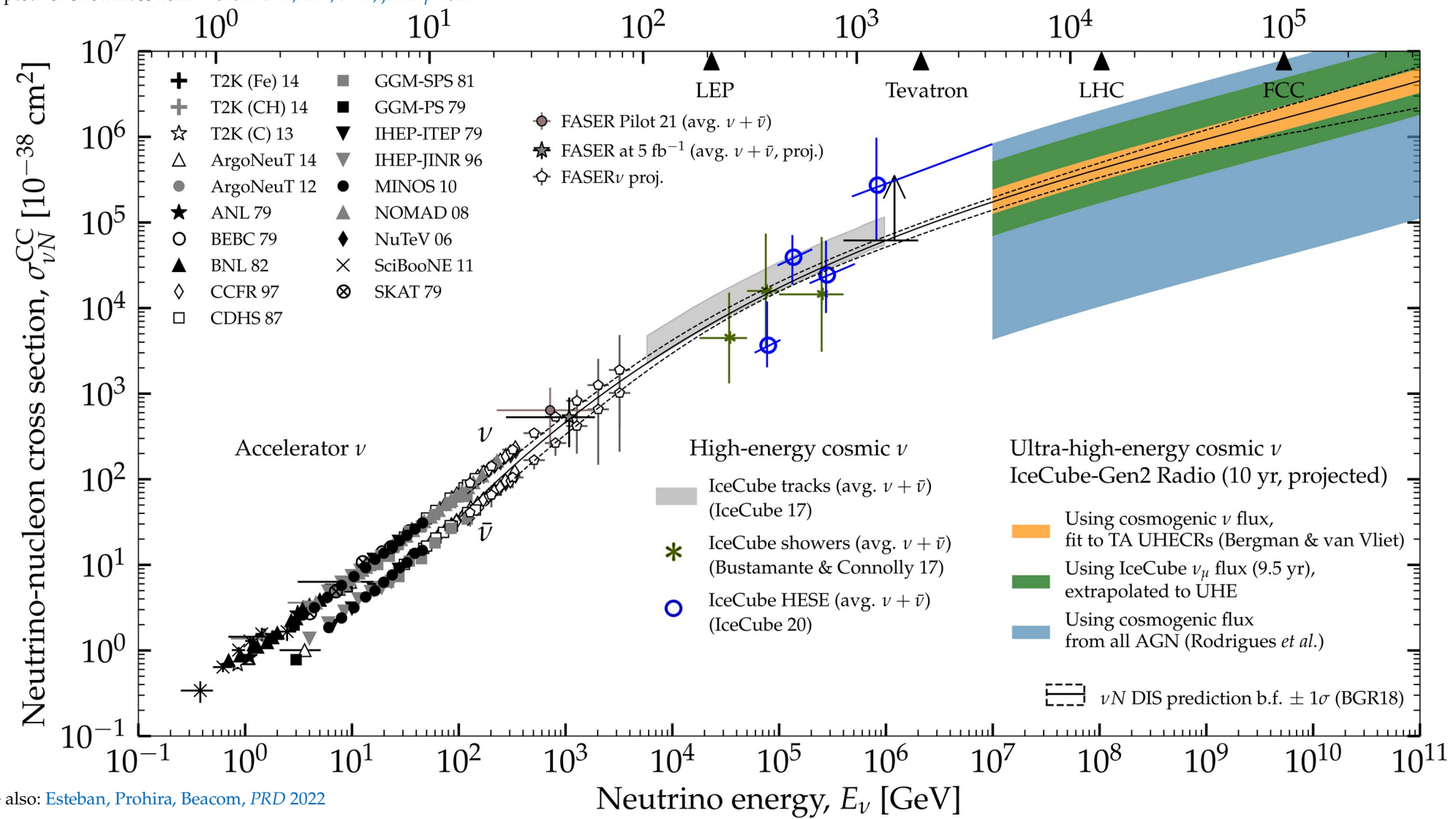


Earth is *completely* opaque,
but horizontal ν still make it through

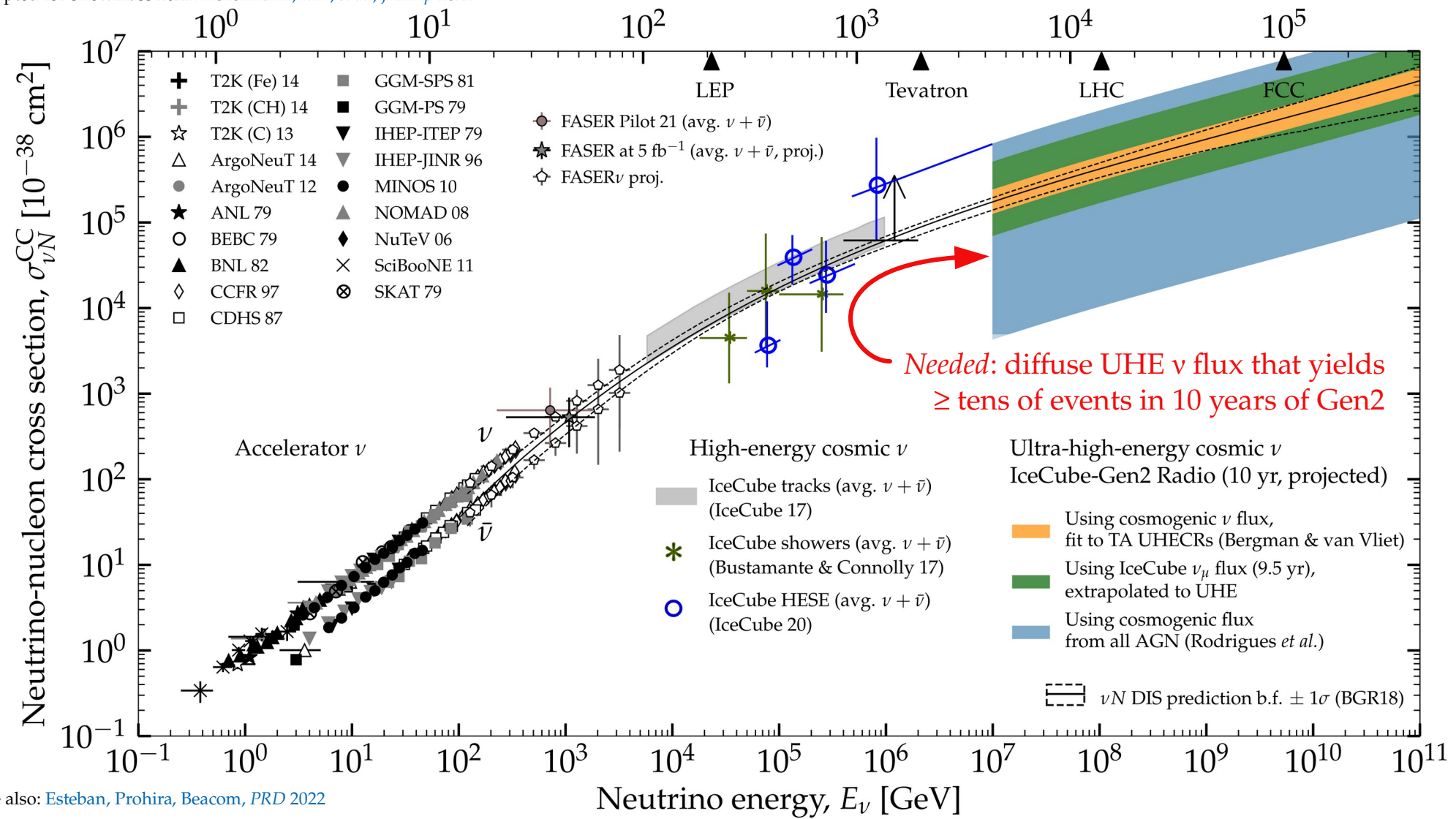




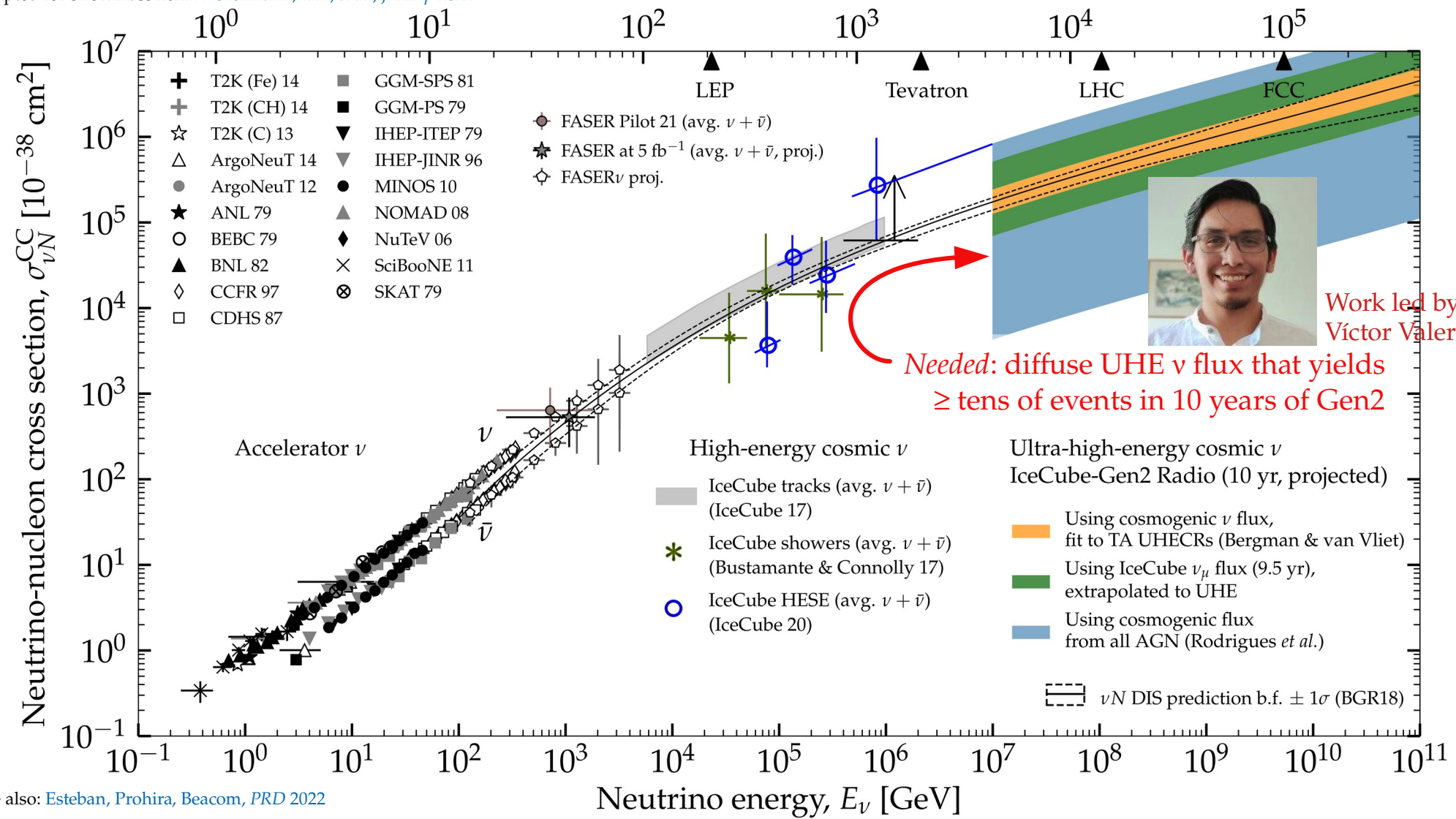
Center-of-mass energy $\sqrt{s}$ [GeV]



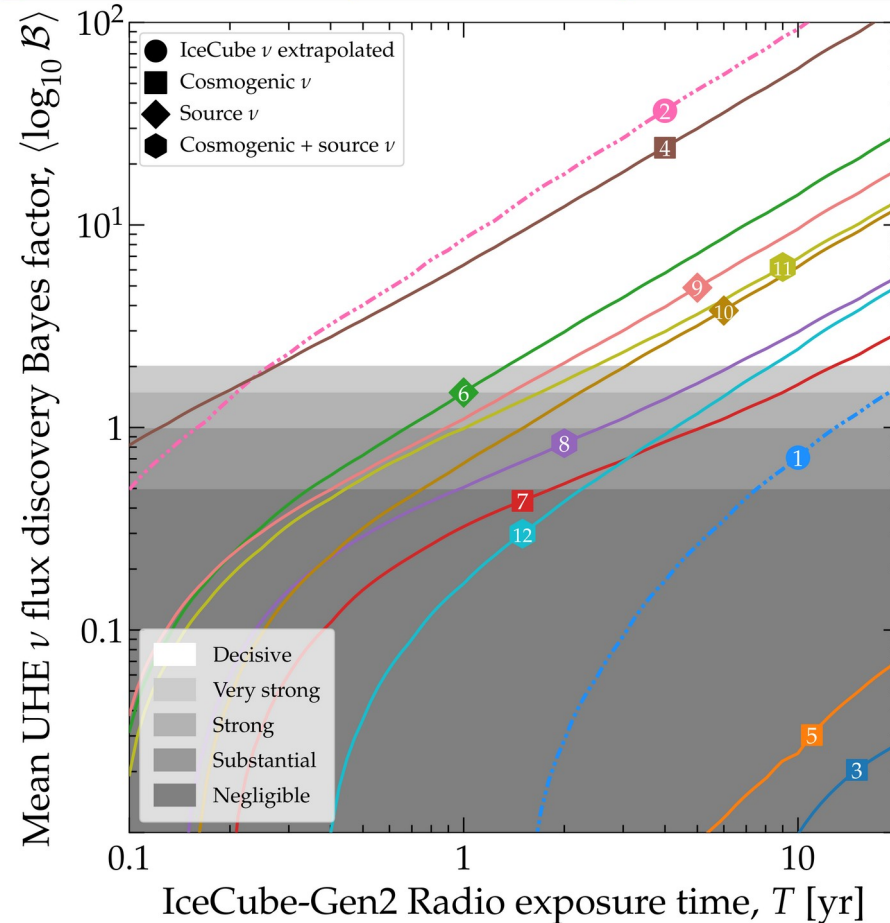
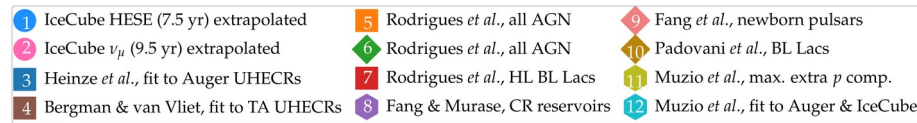
Center-of-mass energy $\sqrt{s}$ [GeV]



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



Side note: Discovering the diffuse flux of UHE neutrinos



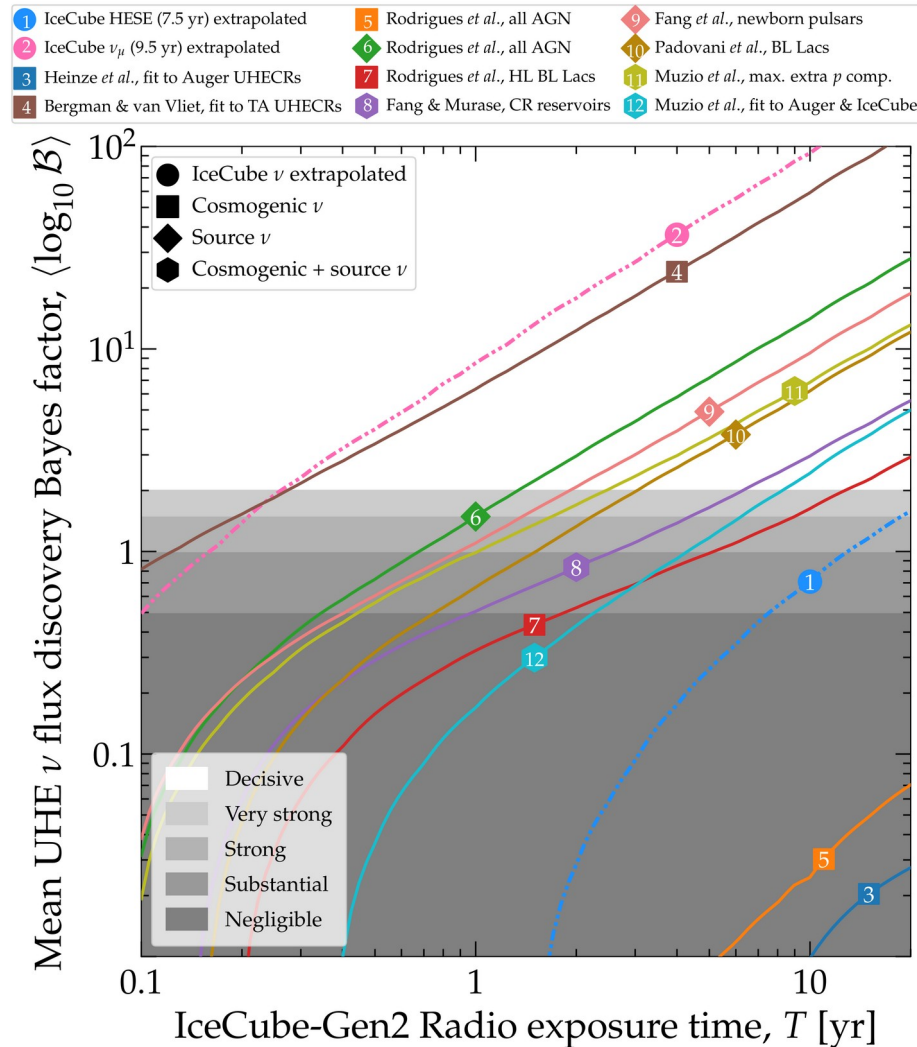
Work led by
Víctor Valera

Side note: Discovering the diffuse flux of UHE neutrinos



Work led by
Víctor Valera

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



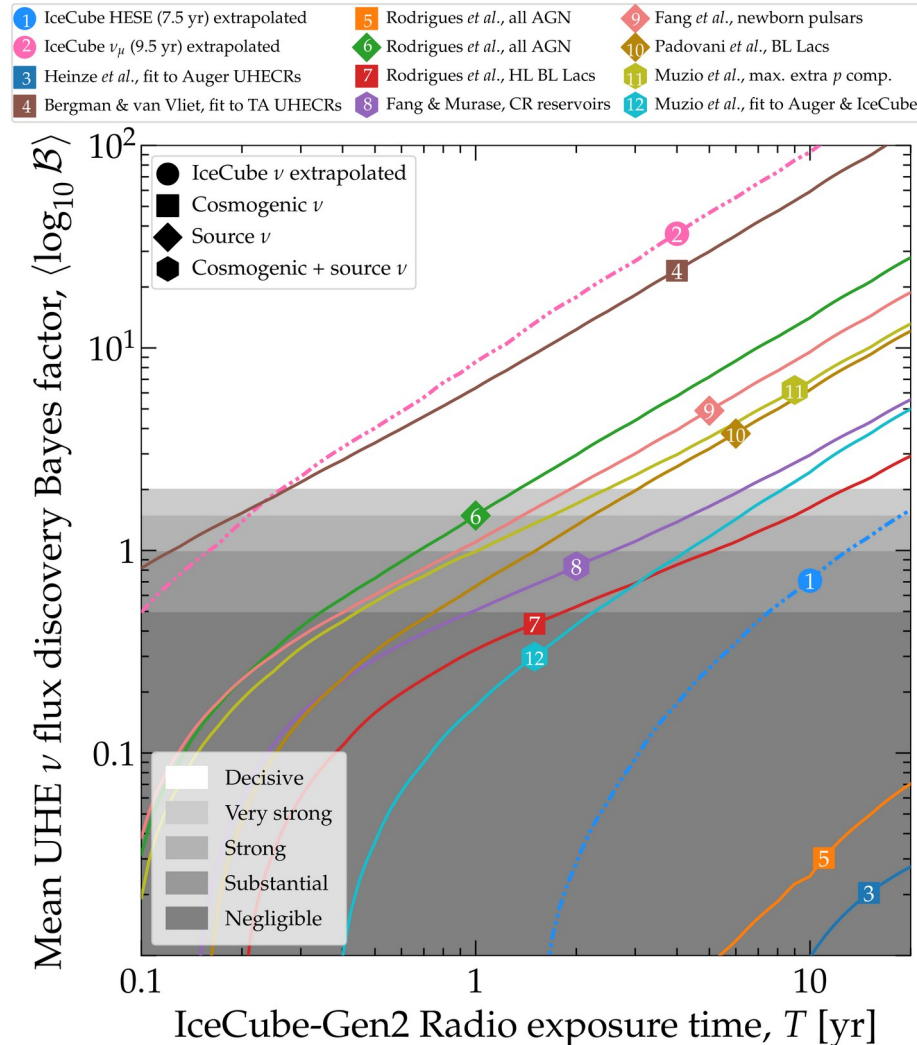
Large Bayes factor
=
decisive flux discover

Side note: Discovering the diffuse flux of UHE neutrinos



Work led by
Víctor Valera

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



Large Bayes factor
=
decisive flux discover

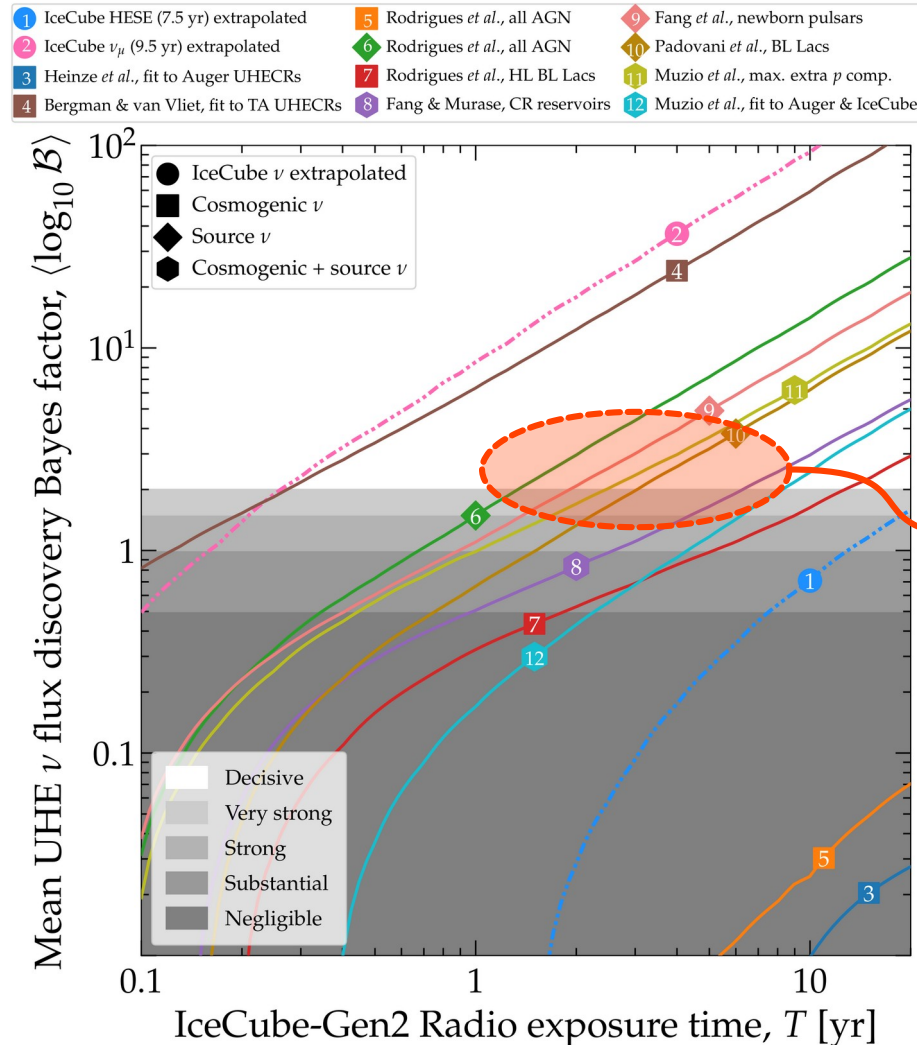
Forecasts are state-of-the-art:
Neutrino propagation inside Earth
Detailed simulation of radio in ice
Detailed antenna response
Detector energy & angular resolution
Statistical fluctuations

Side note: Discovering the diffuse flux of UHE neutrinos



Work led by
Víctor Valera

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



Large Bayes factor
=
decisive flux discover

Most flux models are
discoverable with a few years

Forecasts are state-of-the-art:
Neutrino propagation inside Earth
Detailed simulation of radio in ice
Detailed antenna response
Detector energy & angular resolution
Statistical fluctuations

3. Flavor:

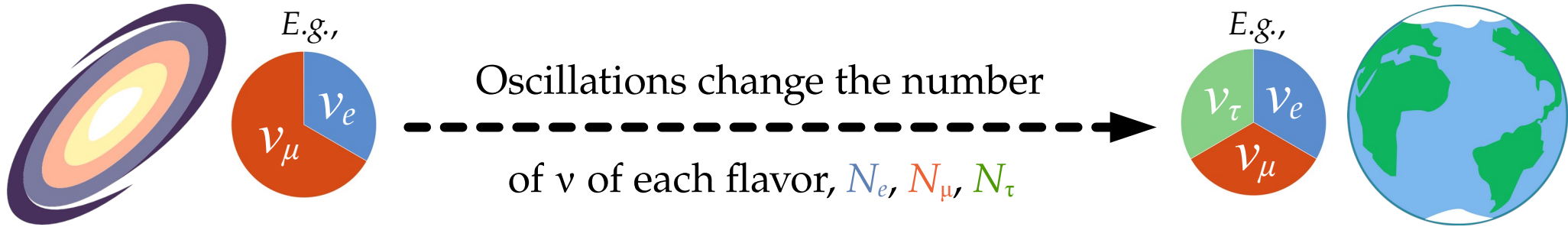
Towards precision, finally

(with the help of lower-energy experiments)

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

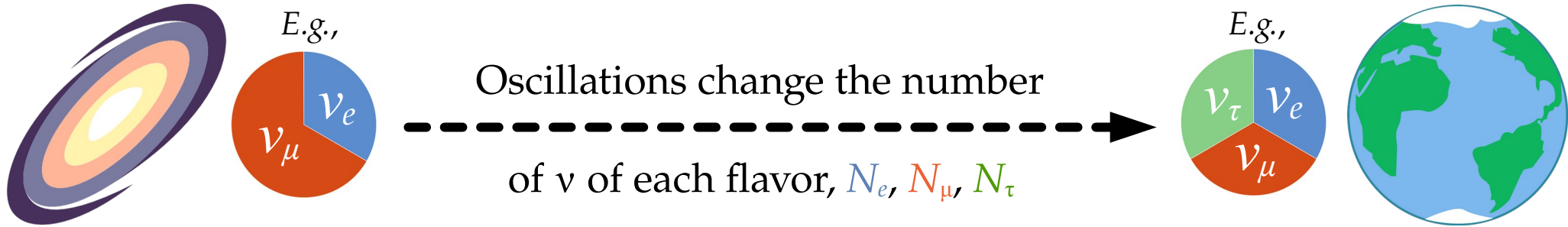
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Astrophysical sources

Earth

Up to a few Gpc



Different production mechanisms yield different flavor ratios:

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

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

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

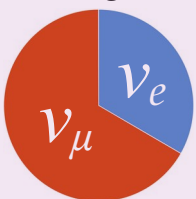
Standard oscillations
or
new physics

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

Sources



E.g.,



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

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

Earth



$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

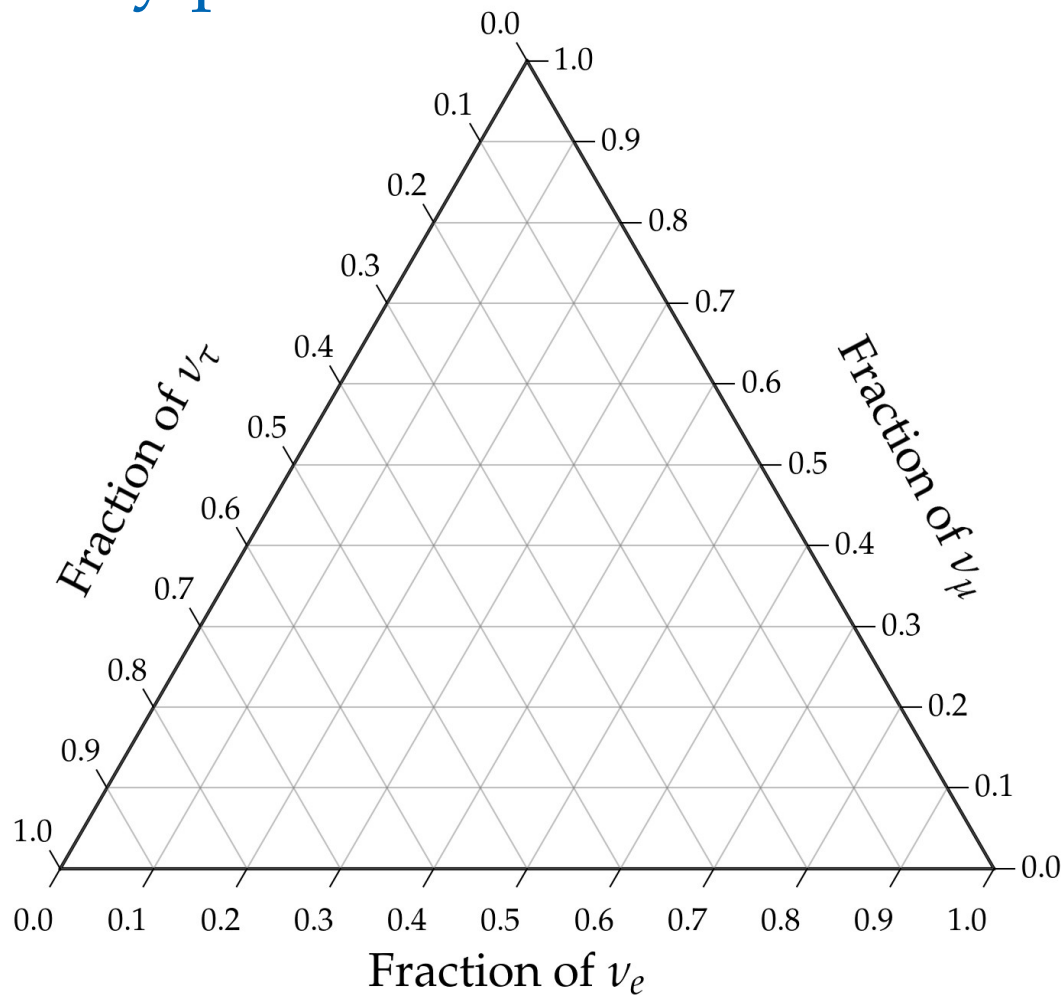
Quick aside: how to read a ternary plot

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)



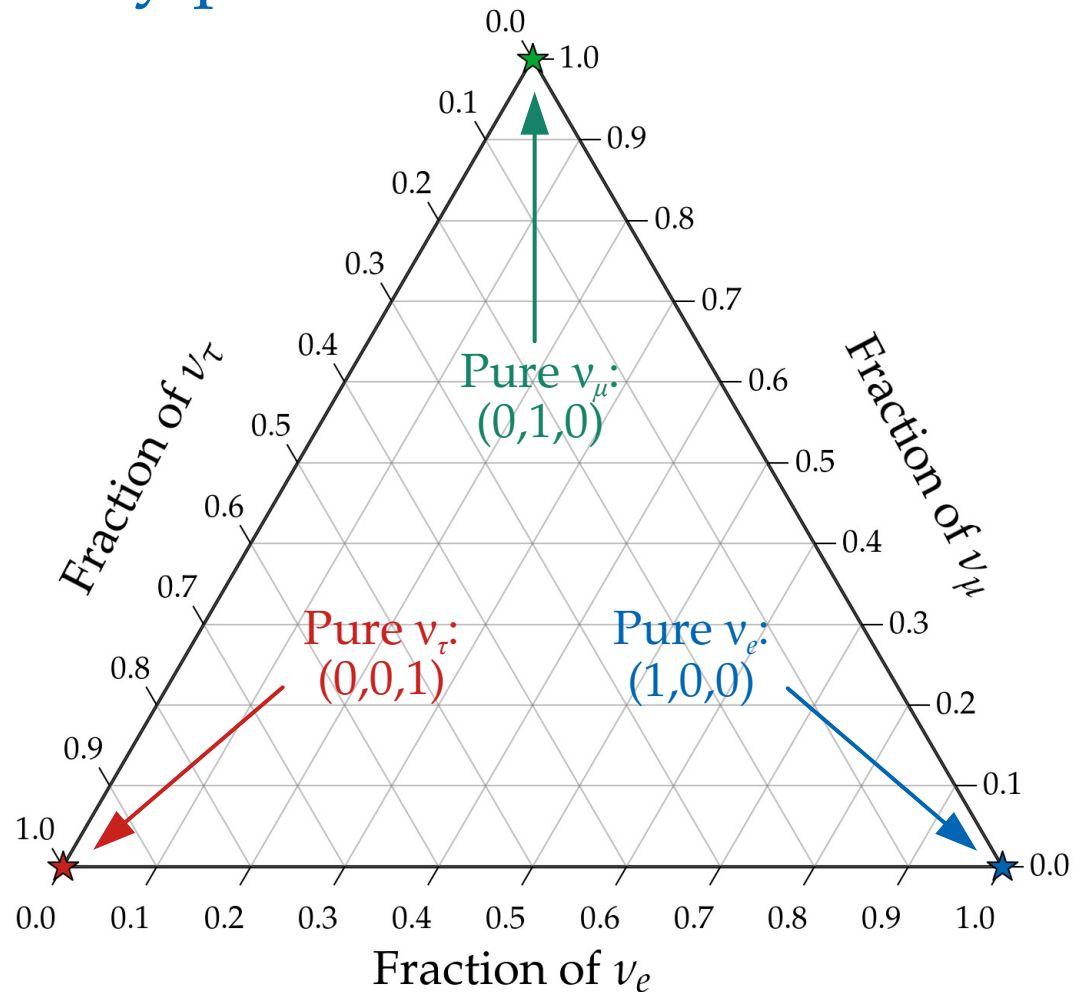
Quick aside: how to read a ternary plot

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)



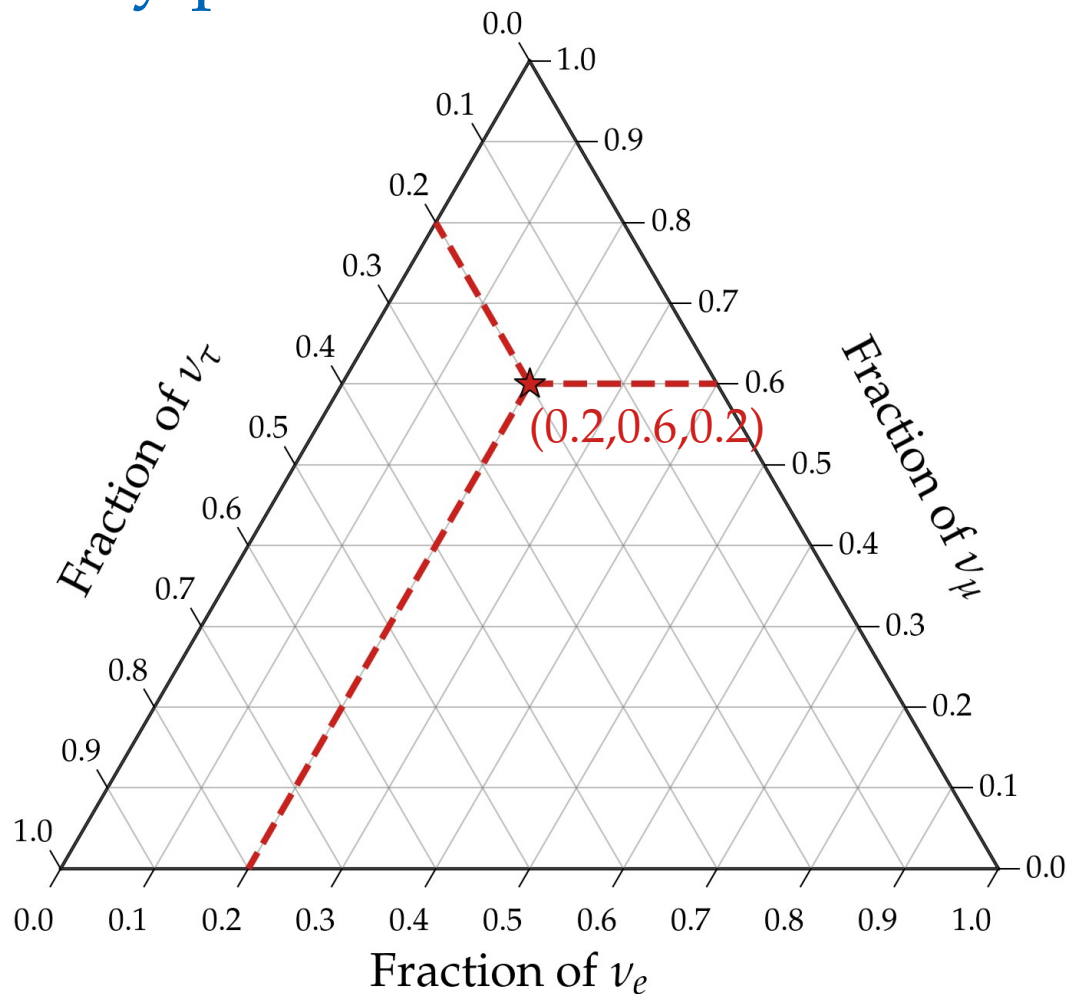
Quick aside: how to read a ternary plot

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)



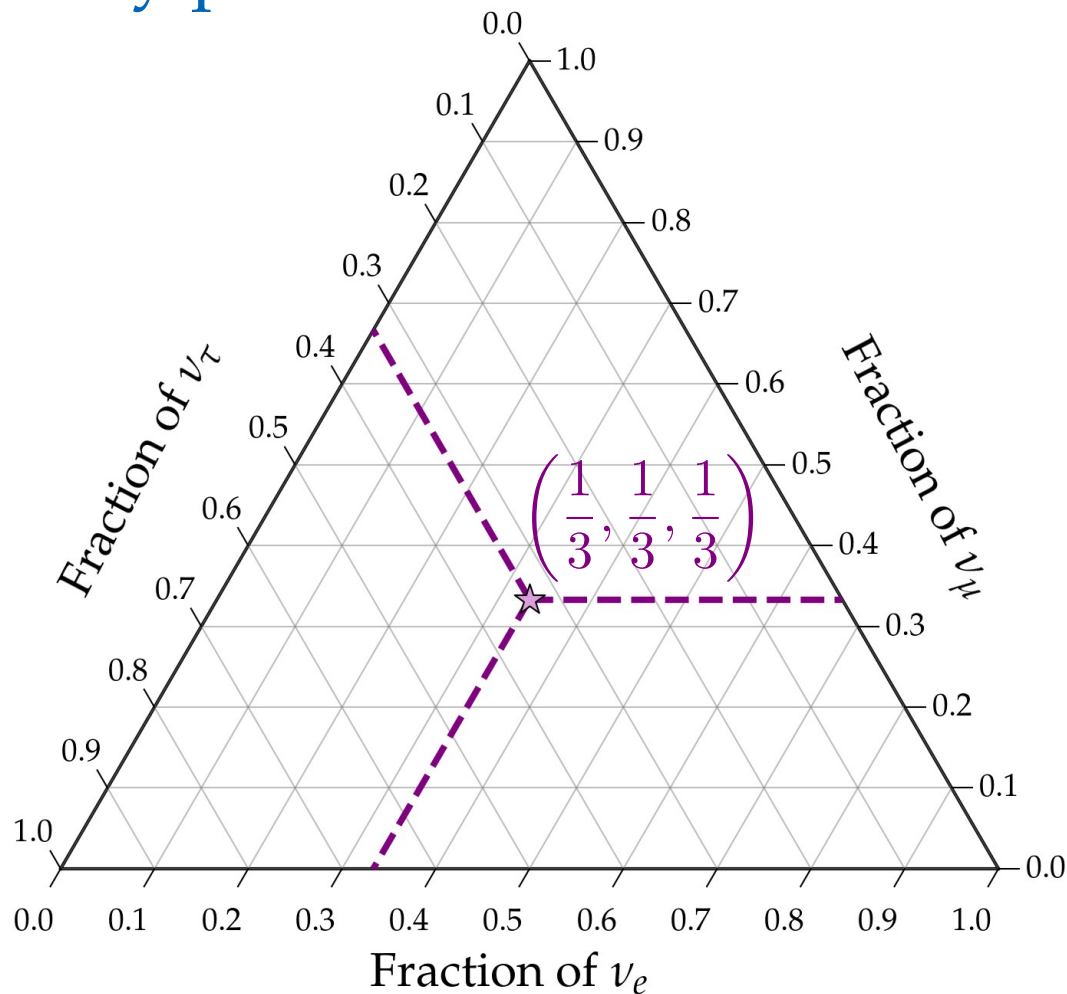
Quick aside: how to read a ternary plot

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)



One likely TeV–PeV ν production scenario:

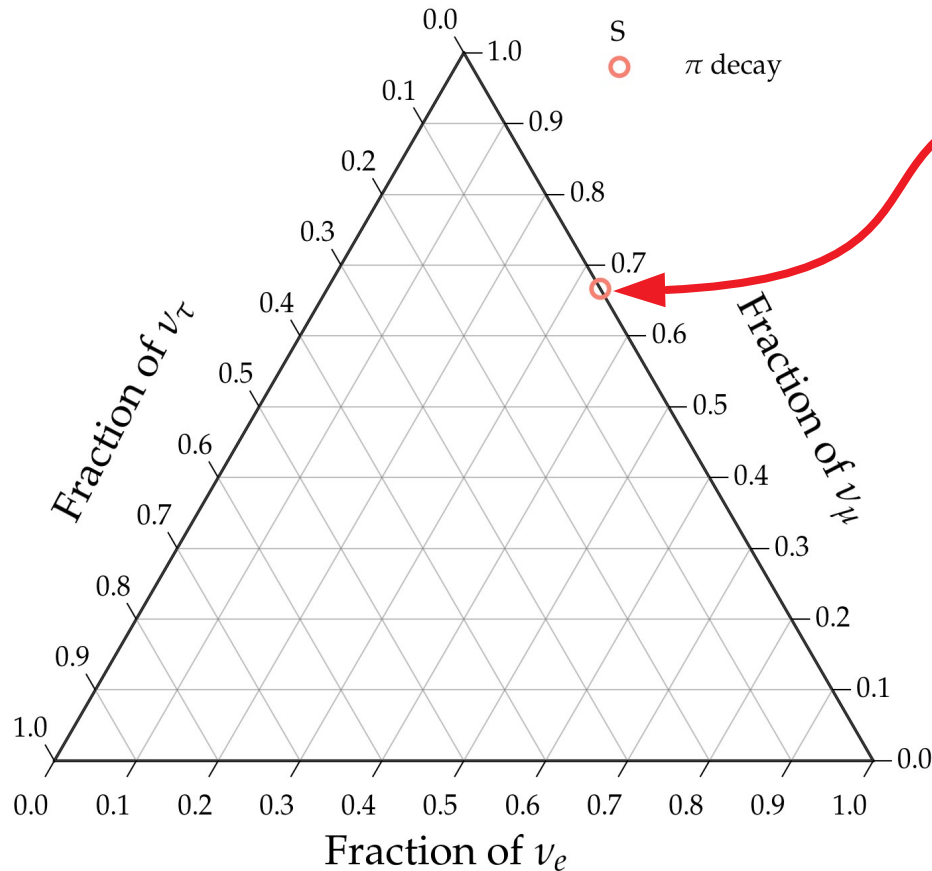
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

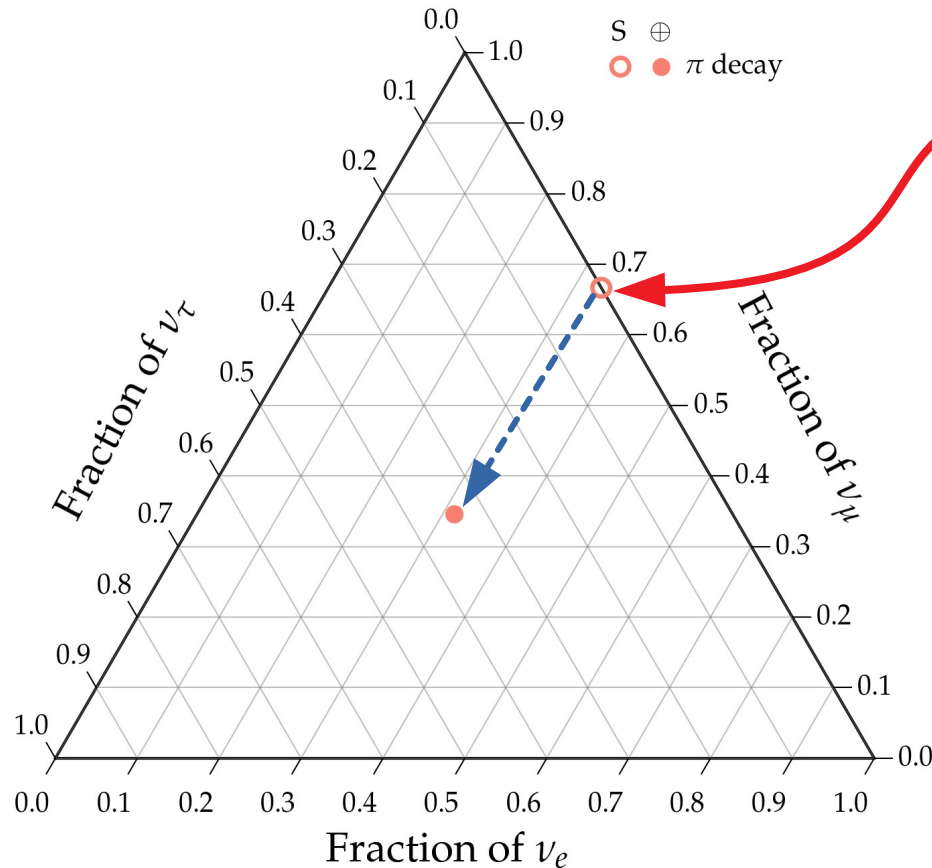


Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

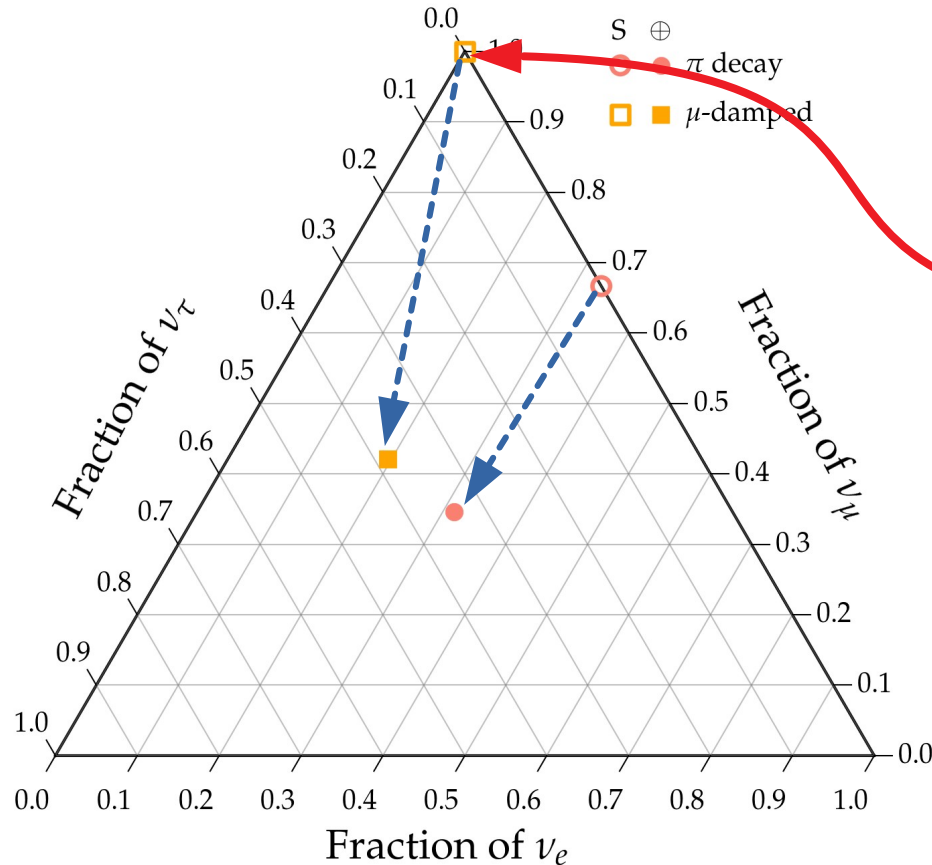


Full π decay chain

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

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

One likely TeV–PeV ν production scenario:



Full π decay chain

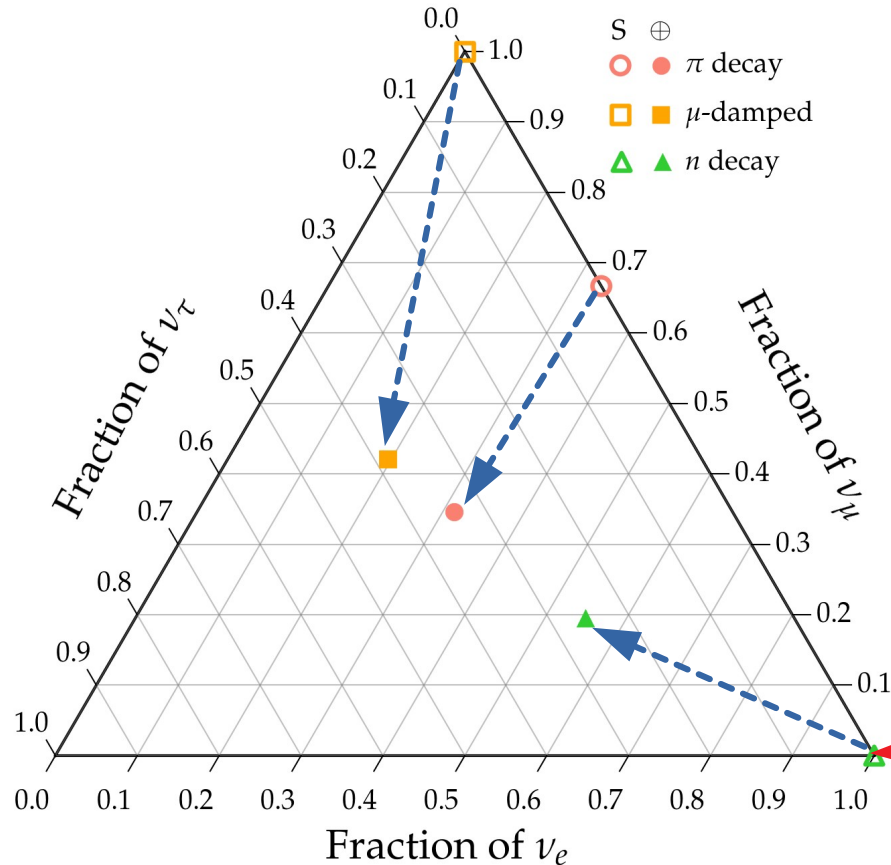
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:



Full π decay chain

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

Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

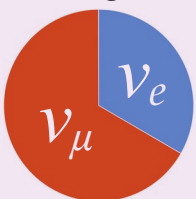
Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes

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

Sources



E.g.,



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

Oscillations

$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

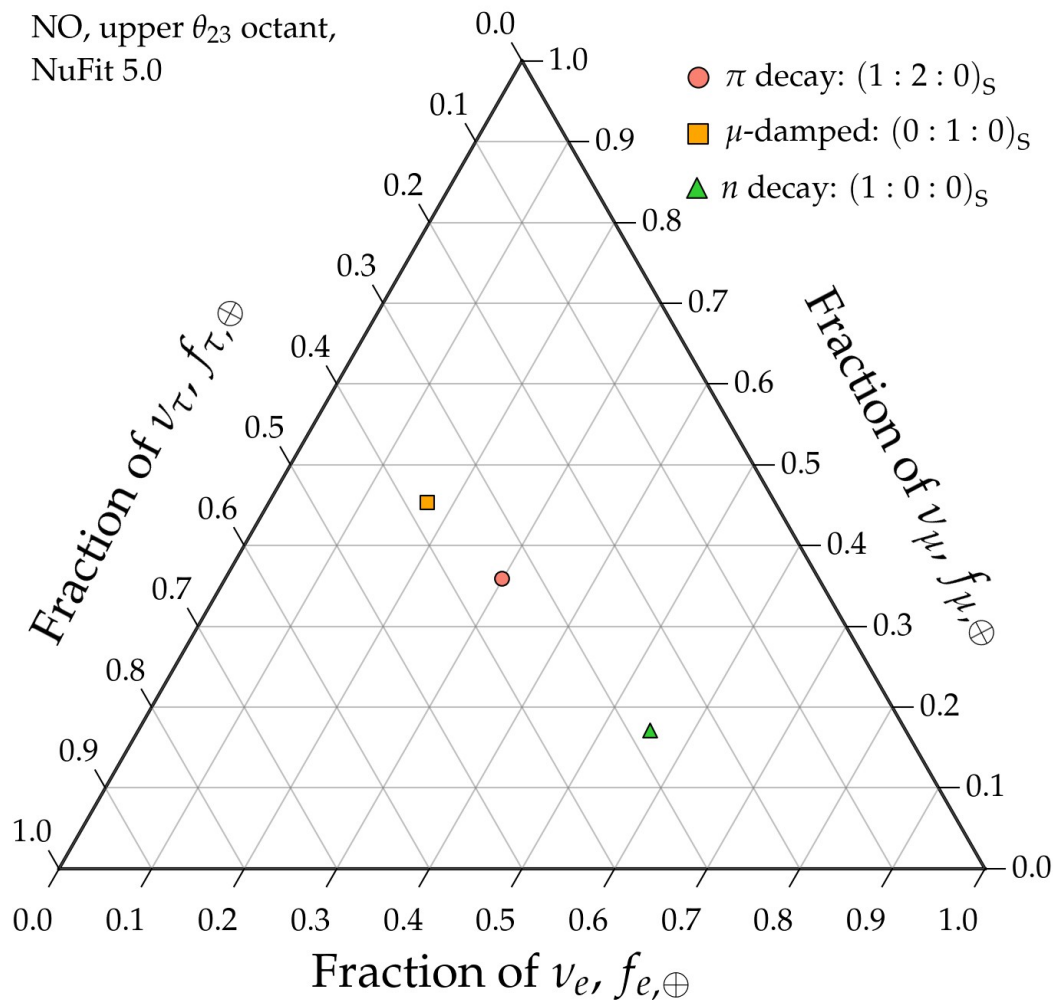
Earth



Known from oscillation
experiments, to different
levels of precision

Theoretically palatable regions: today

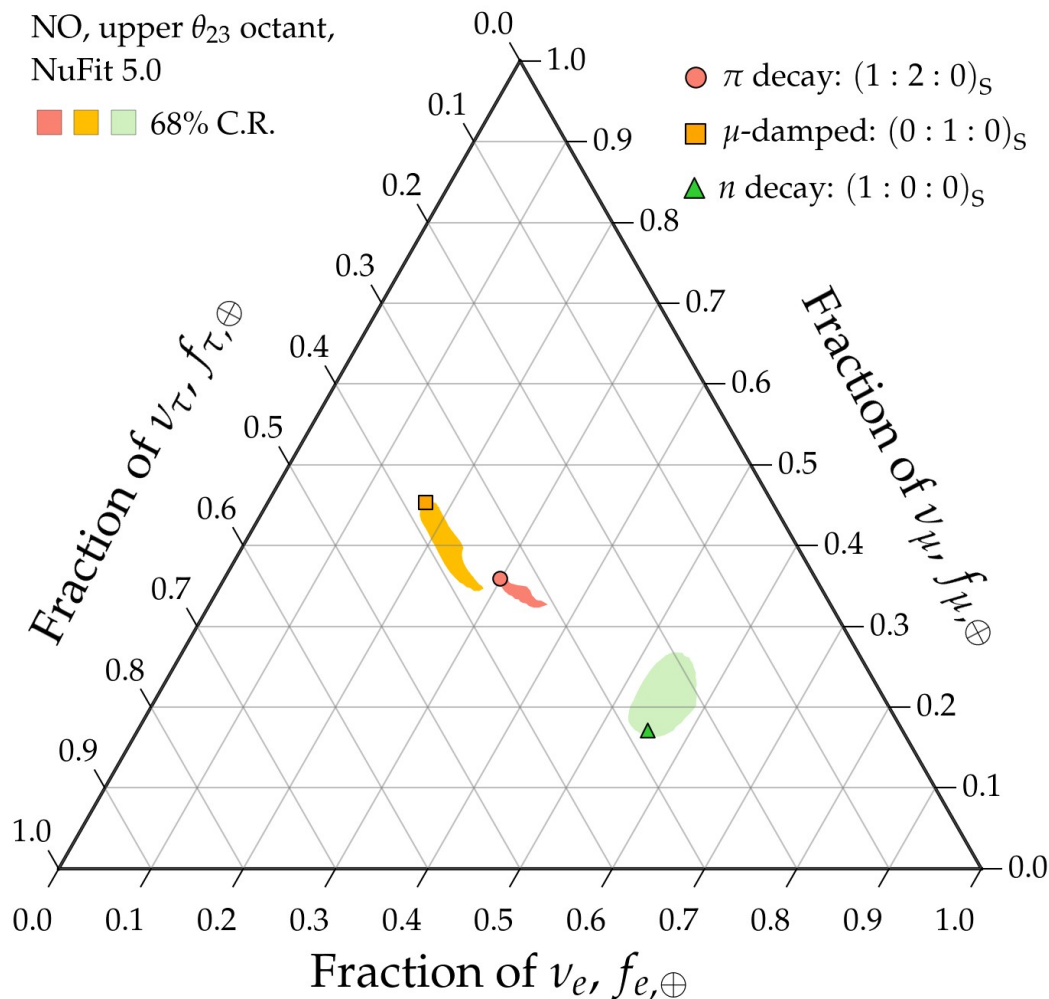
NO, upper θ_{23} octant,
NuFit 5.0



Note:

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

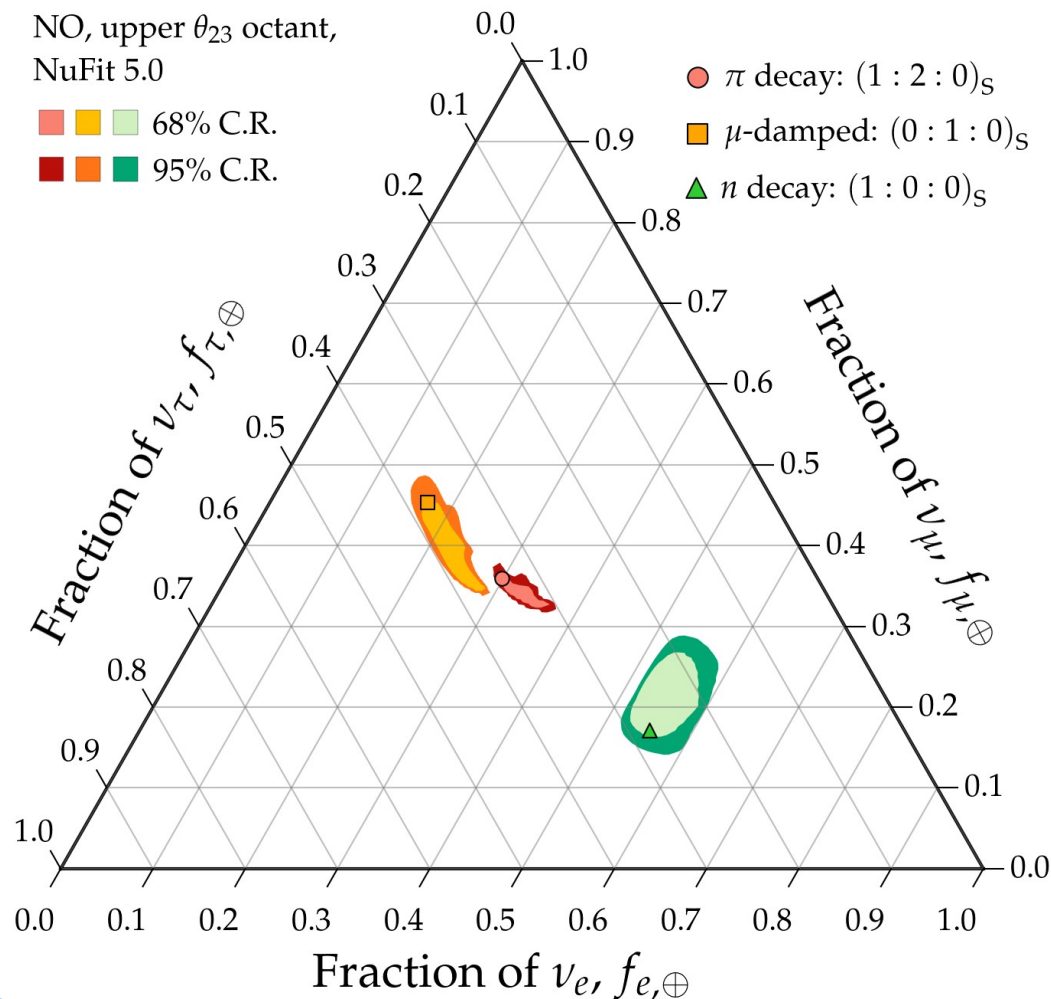
Theoretically palatable regions: today



Note:

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

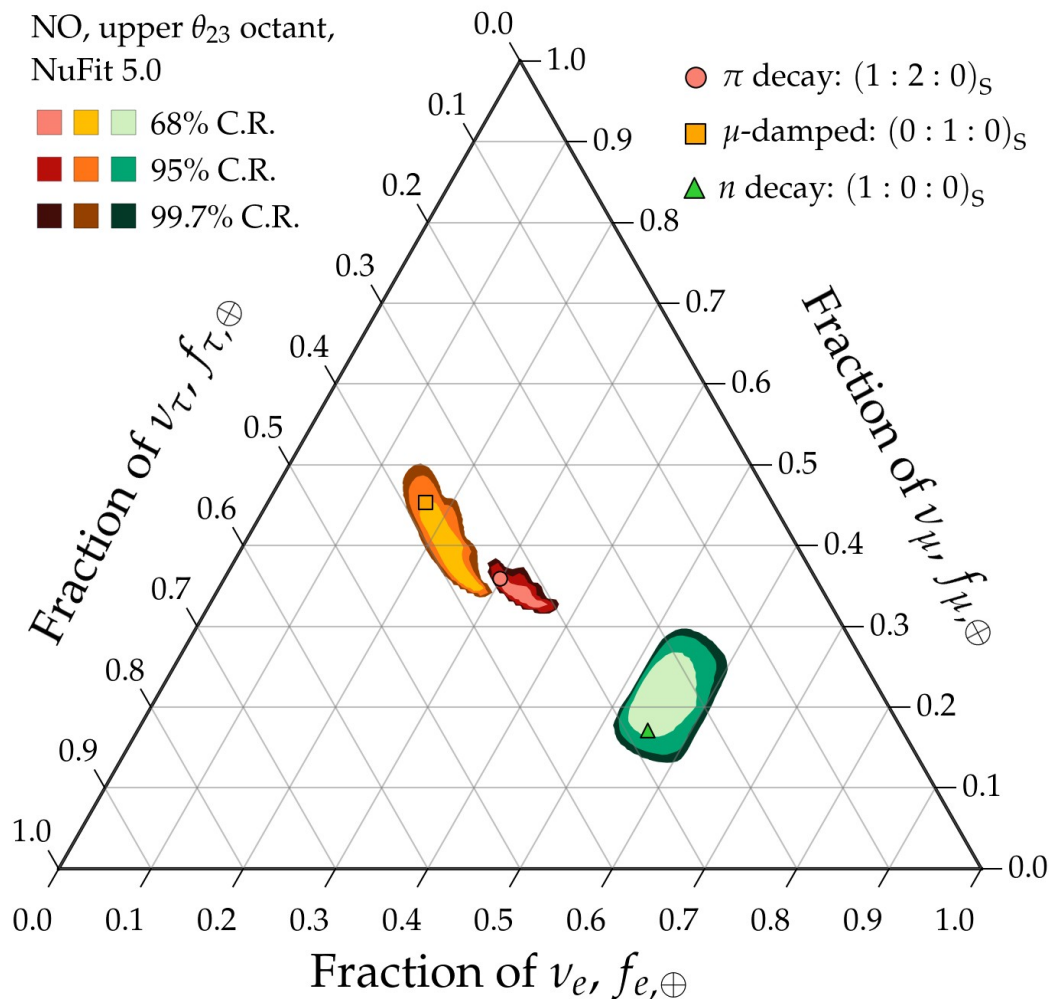
Theoretically palatable regions: today



Note:

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

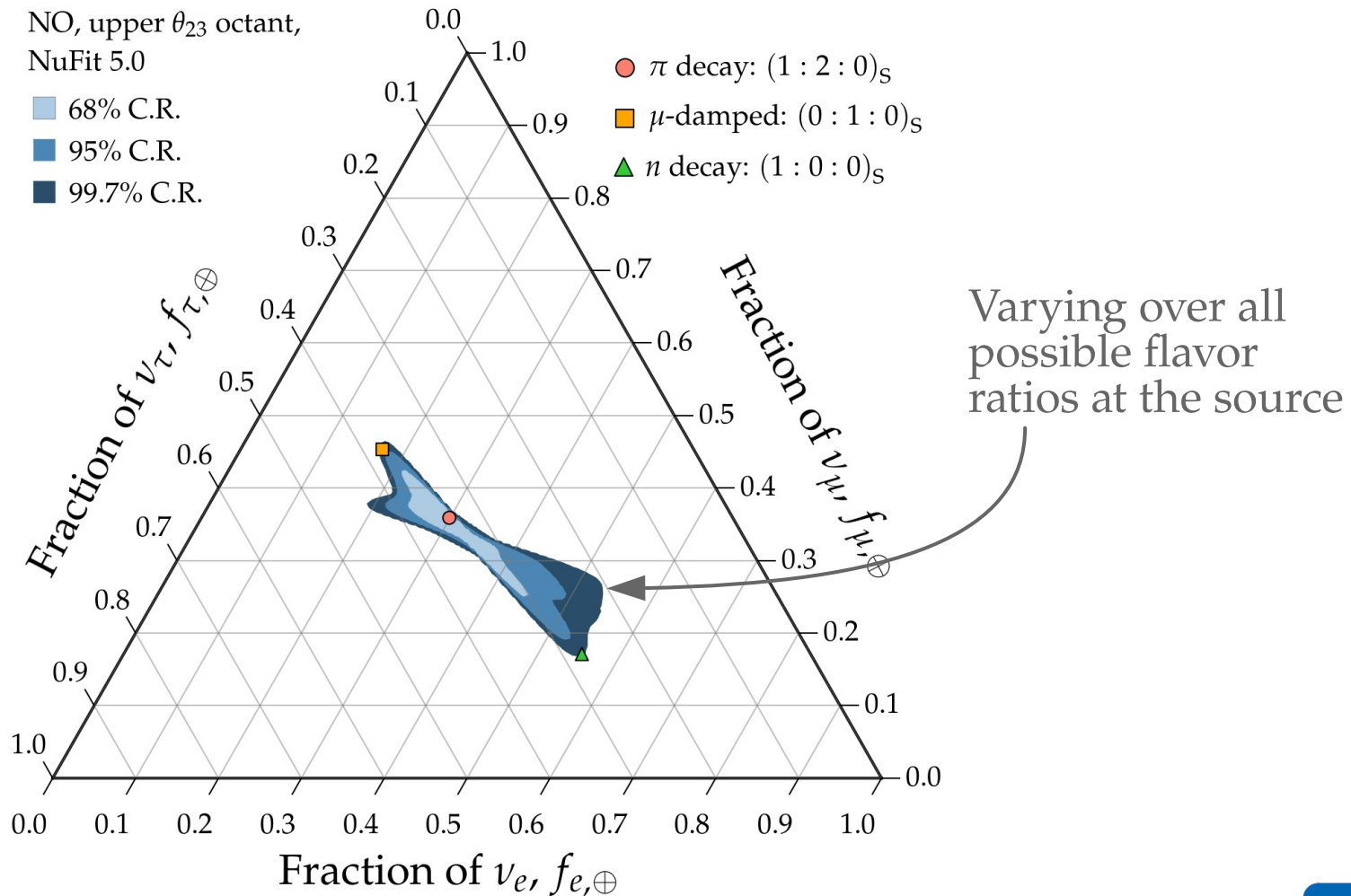
Theoretically palatable regions: today



Note:

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

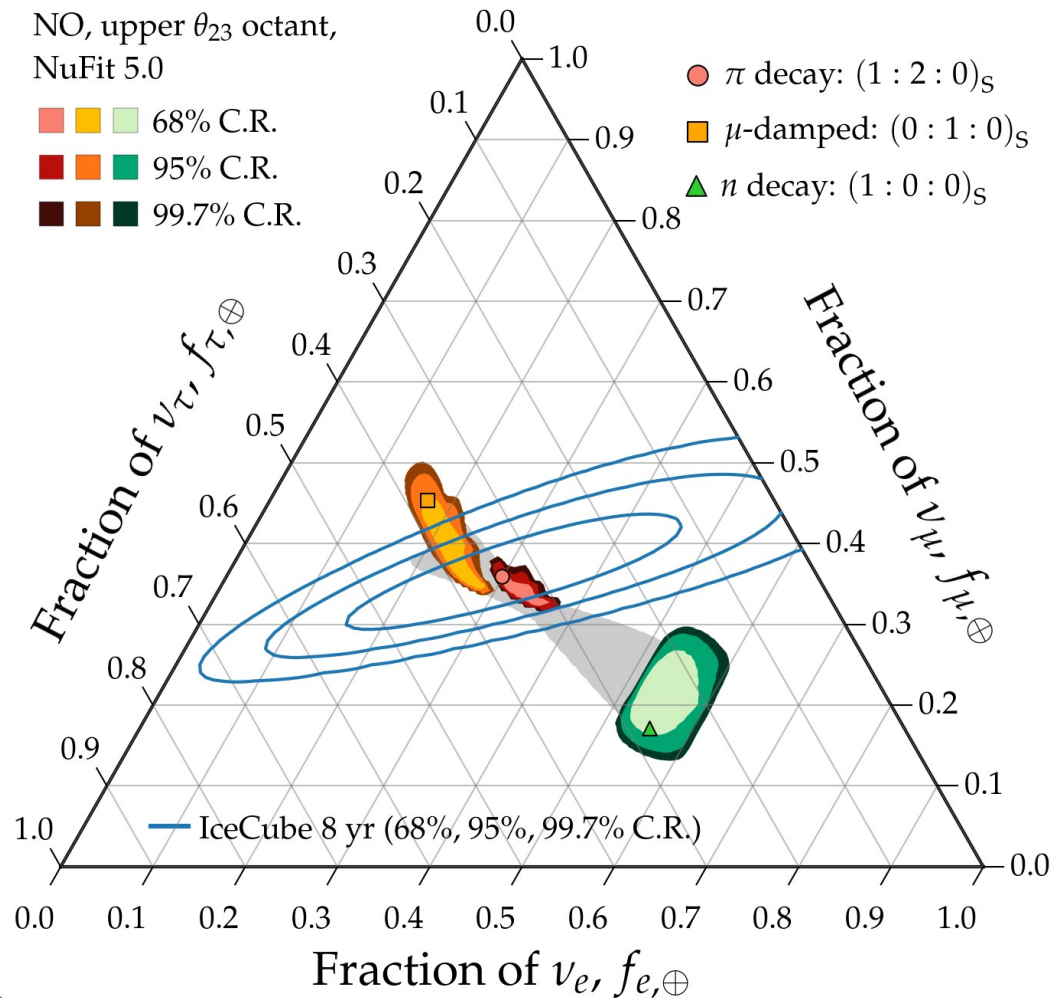
Theoretically palatable regions: today



Note:

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

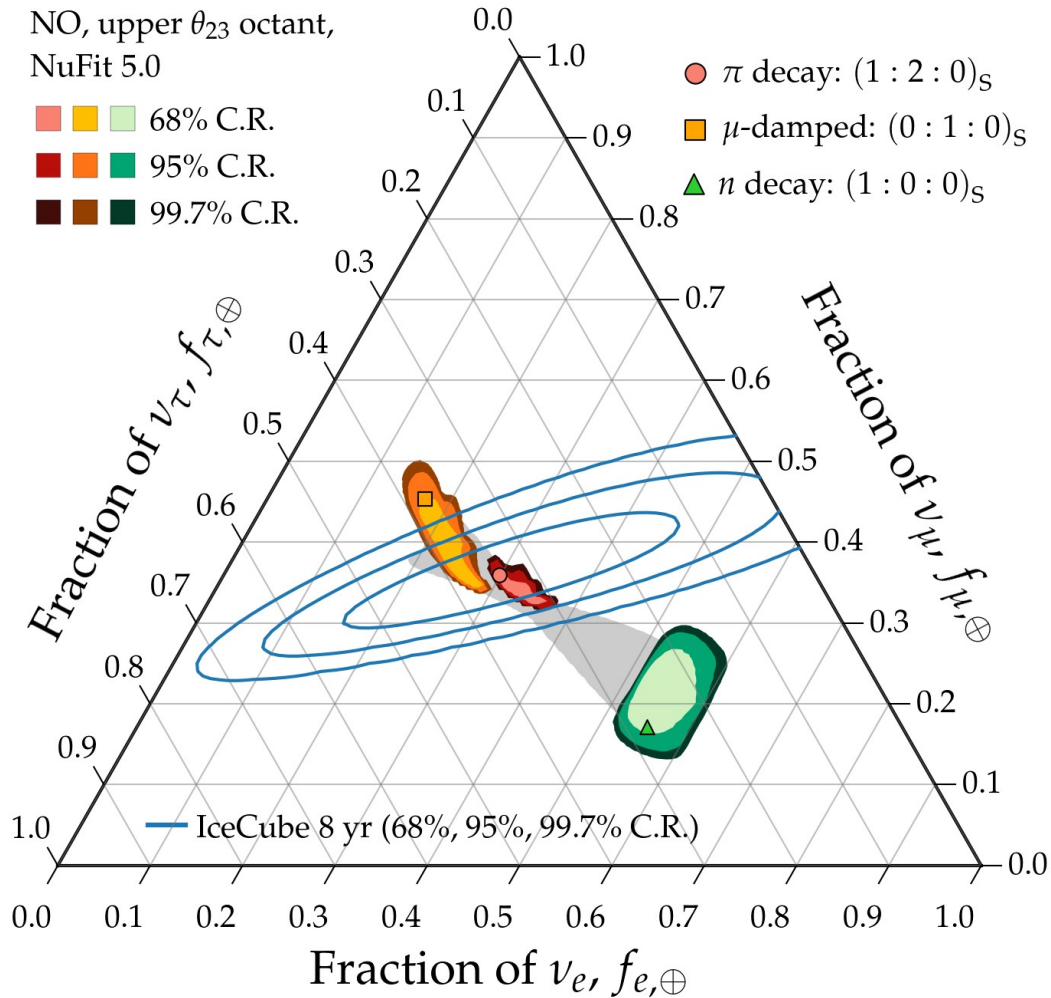
Theoretically palatable regions: today



Note:

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

Theoretically palatable regions: today

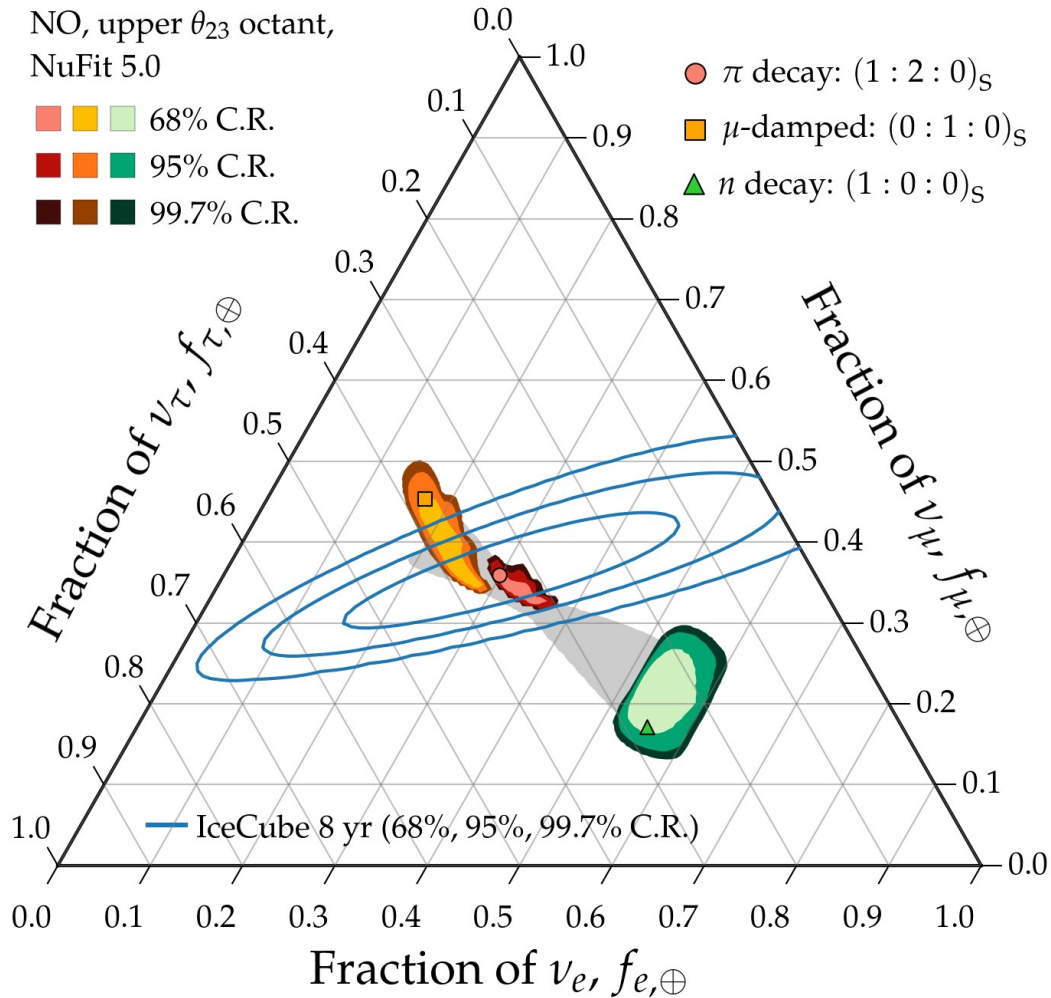


Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

Measurement of flavor ratios –
Cannot distinguish between
pion-decay and muon-damped
benchmarks even at 68% C.R. (1σ)

Theoretically palatable regions: today



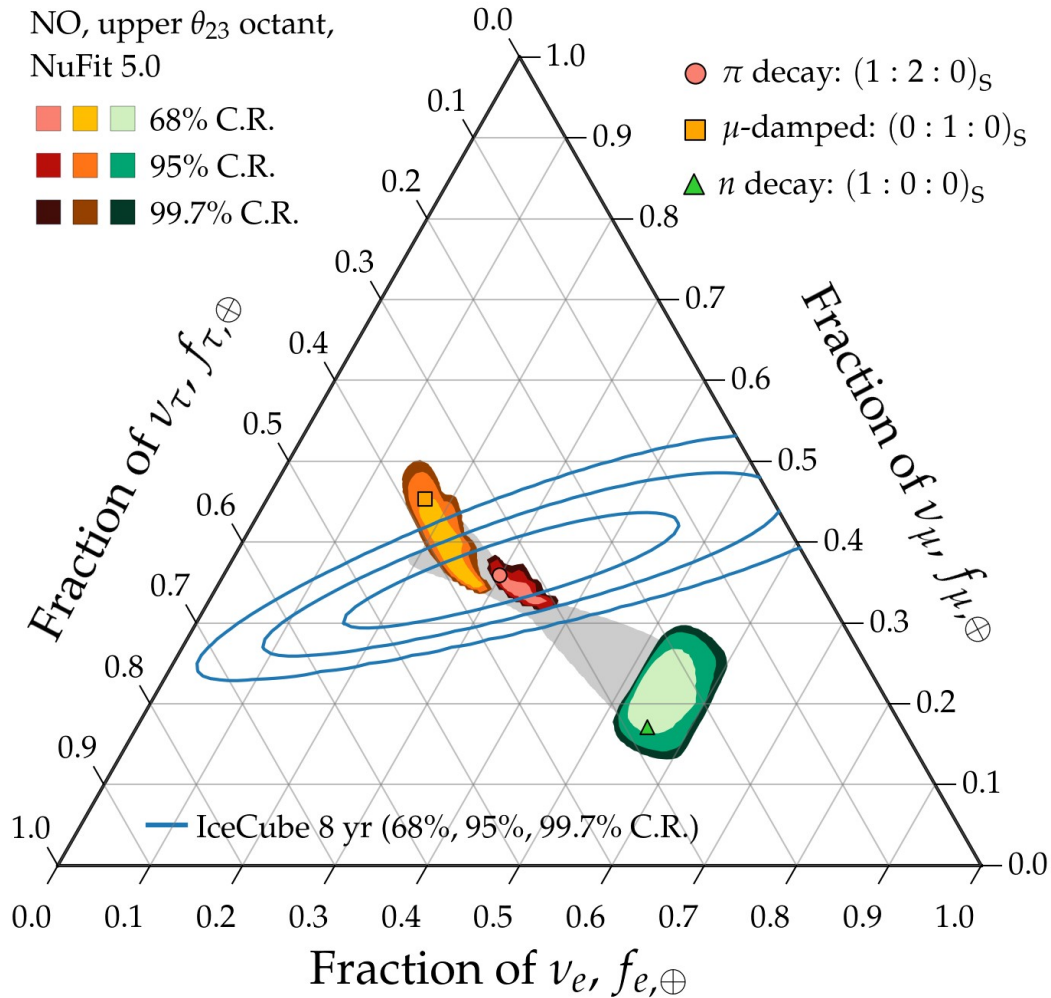
Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

Will be overcome by 2030

Measurement of flavor ratios –
Cannot distinguish between
pion-decay and muon-damped
benchmarks even at 68% C.R. (1σ)

Theoretically palatable regions: today



Two limitations:

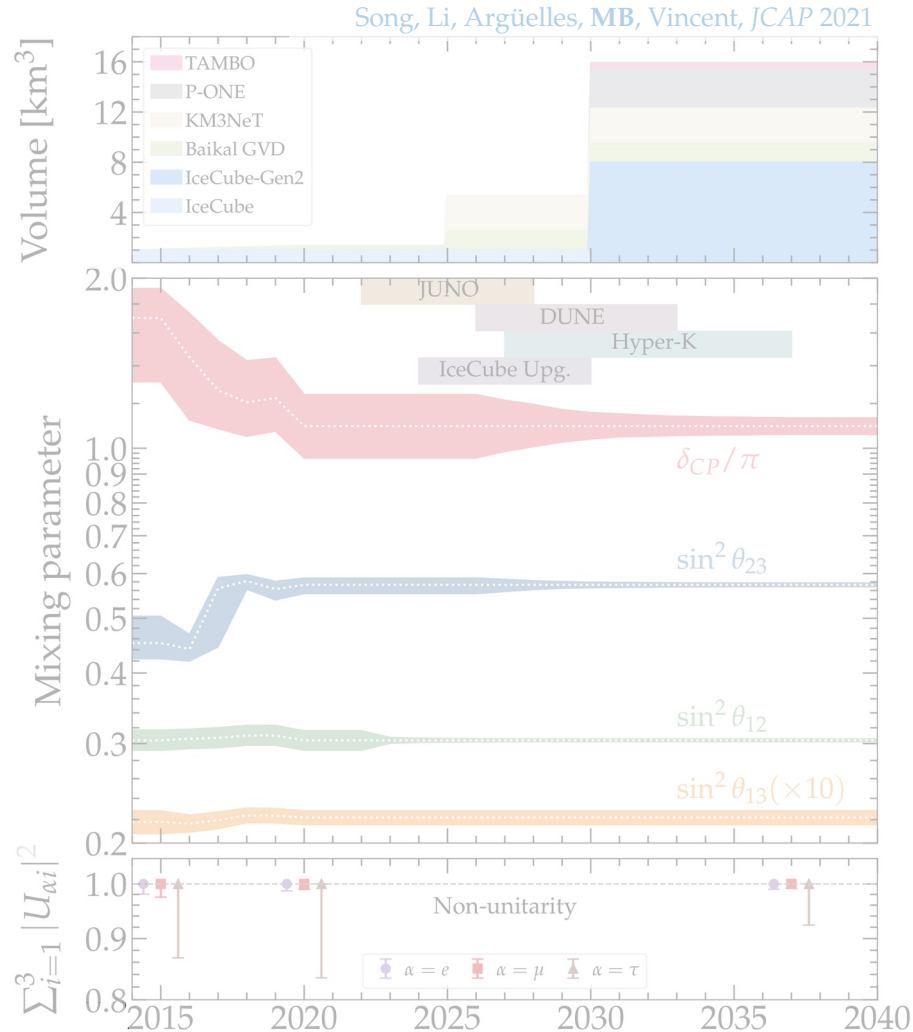
Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

Will be overcome by 2030

Measurement of flavor ratios –
Cannot distinguish between
pion-decay and muon-damped
benchmarks even at 68% C.R. (1σ)

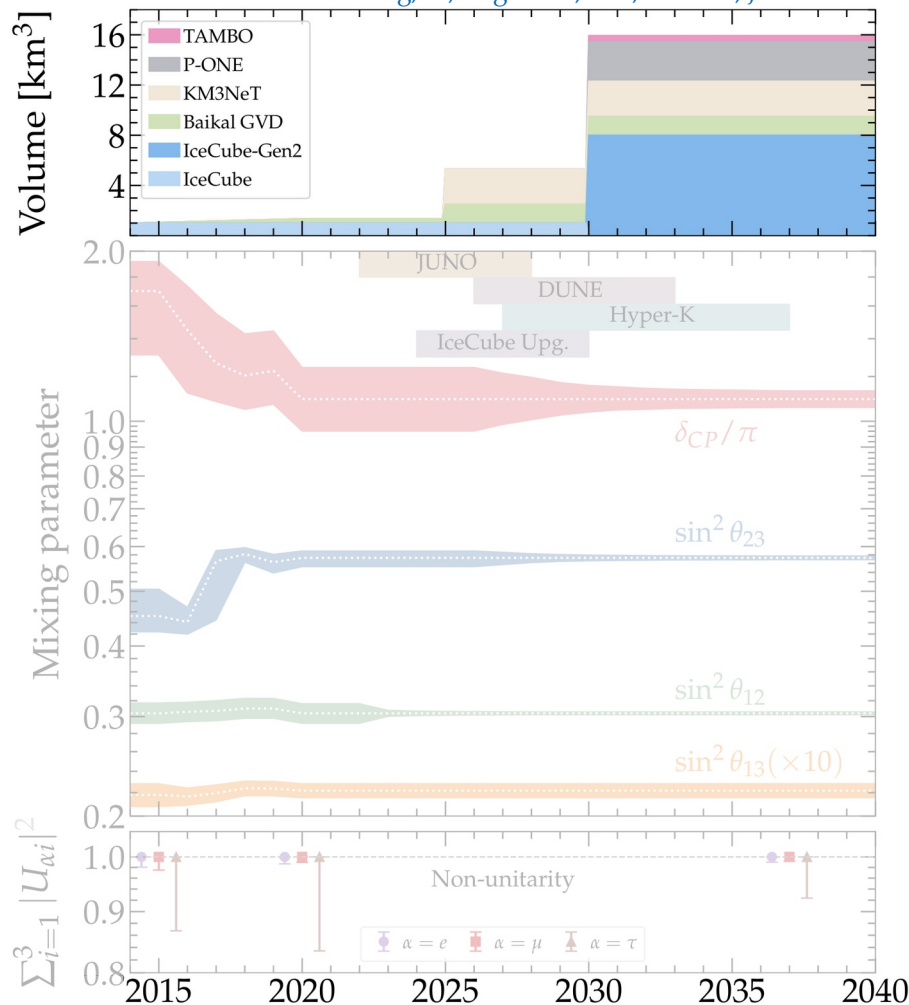
Will be overcome by 2040

Three reasons to be excited



Three reasons to be excited

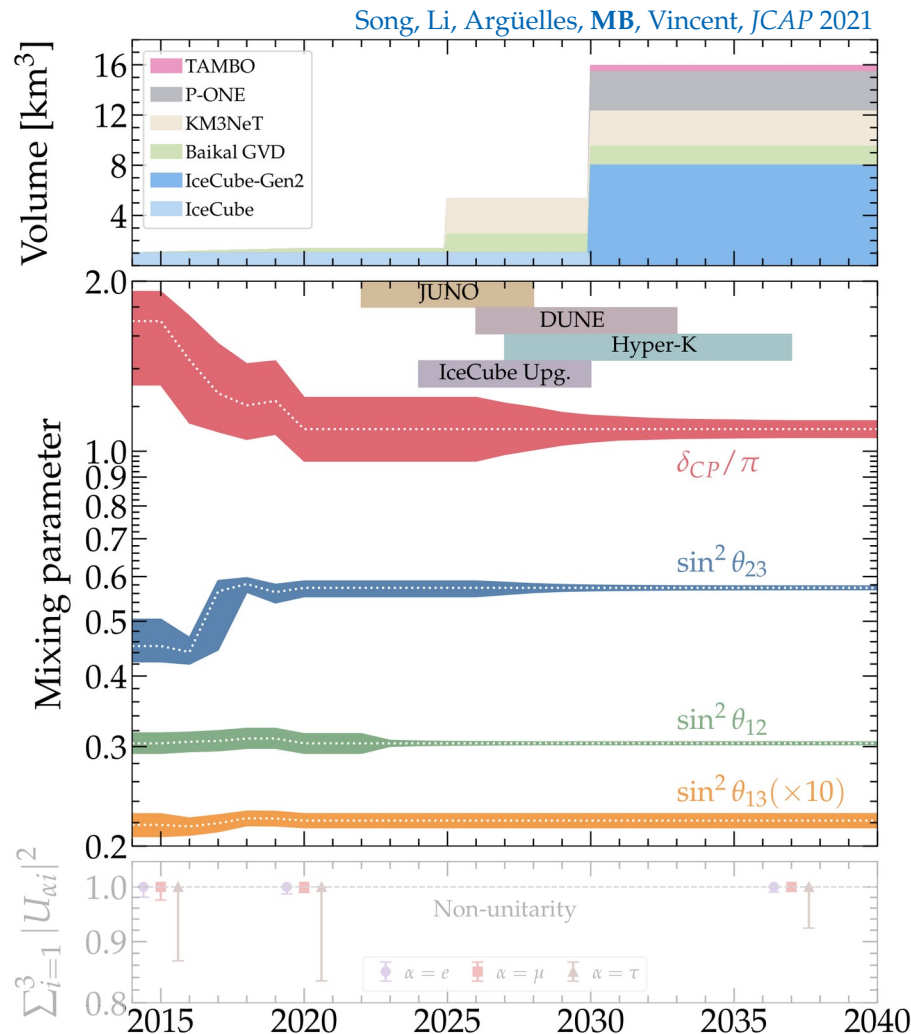
Song, Li, Argüelles, MB, Vincent, JCAP 2021



Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited



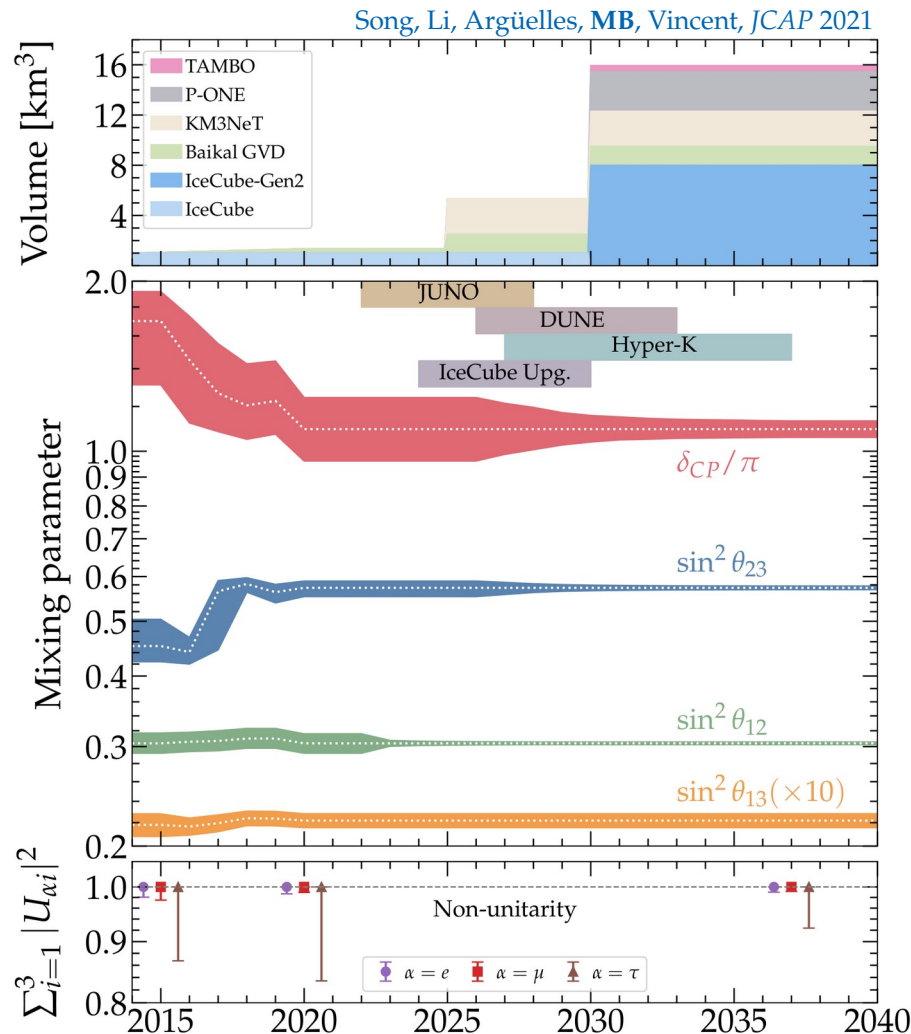
Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Oscillation physics:

We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Three reasons to be excited



Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Oscillation physics:

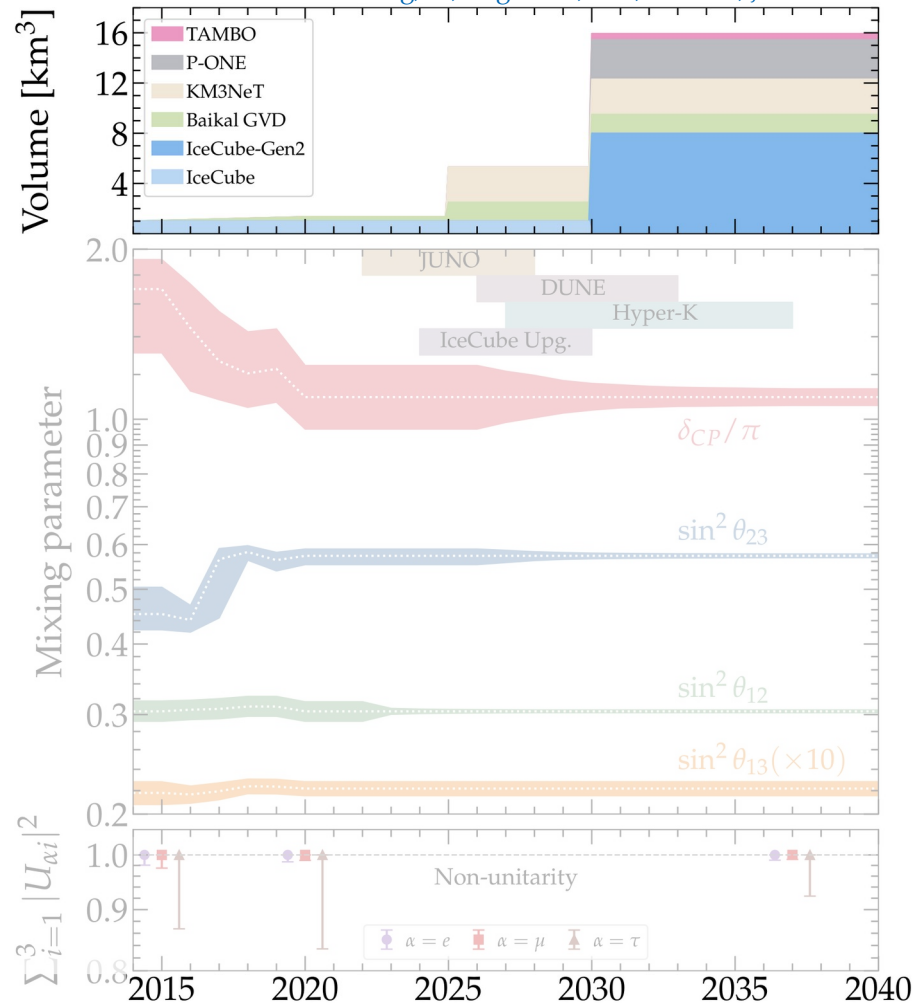
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

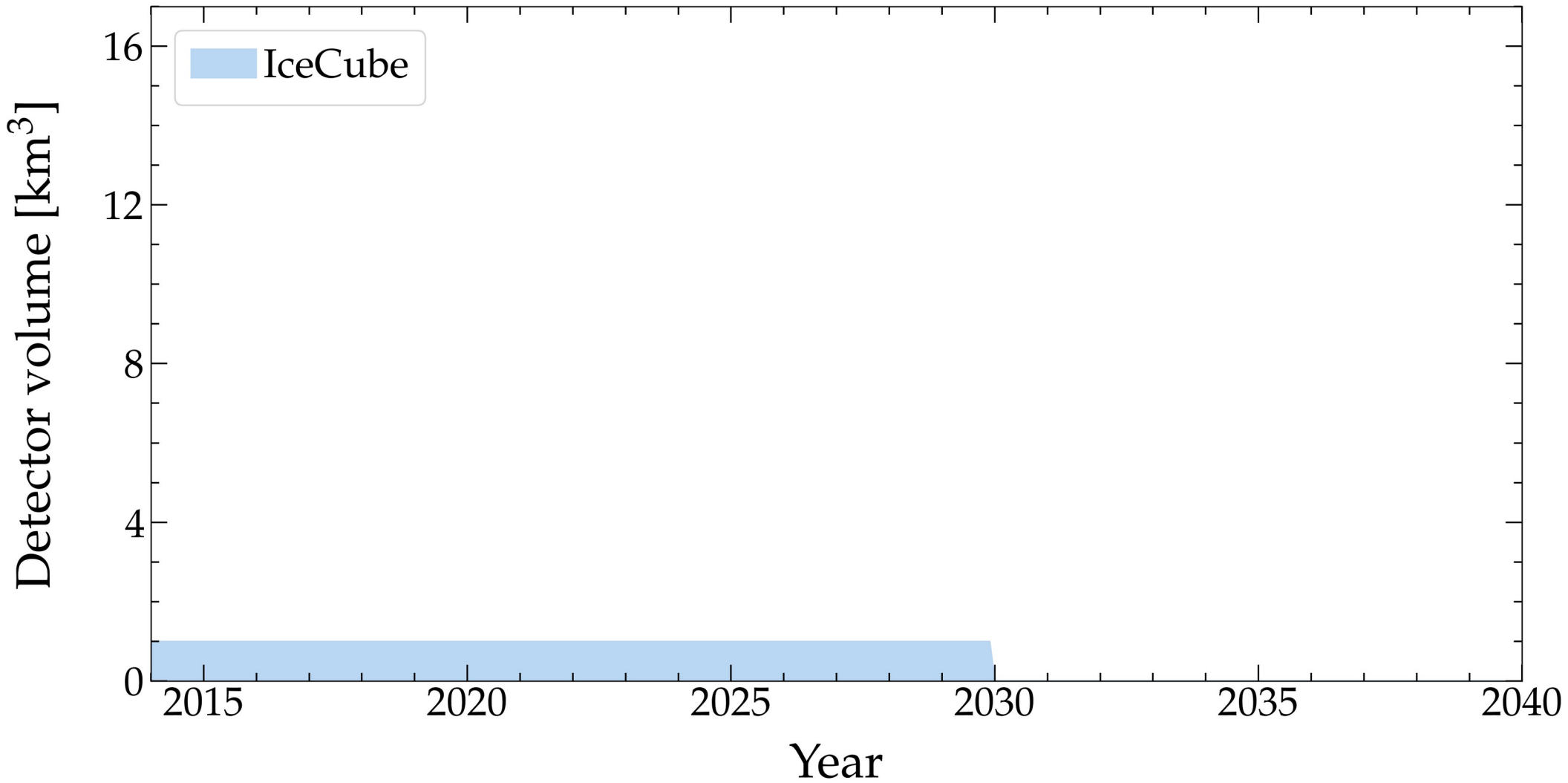
Test of the oscillation framework:

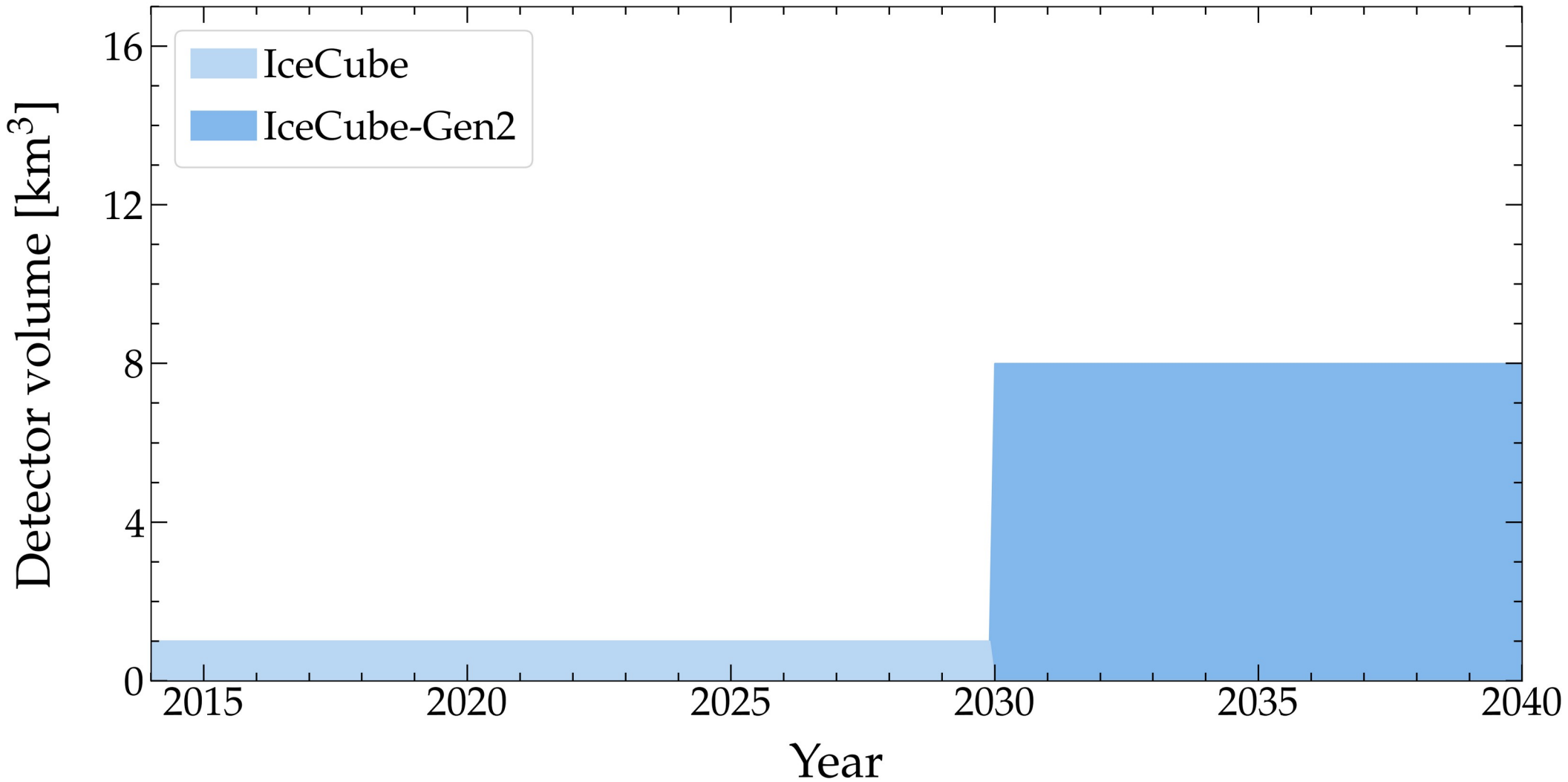
We will be able to do what we want even if oscillations are non-unitary

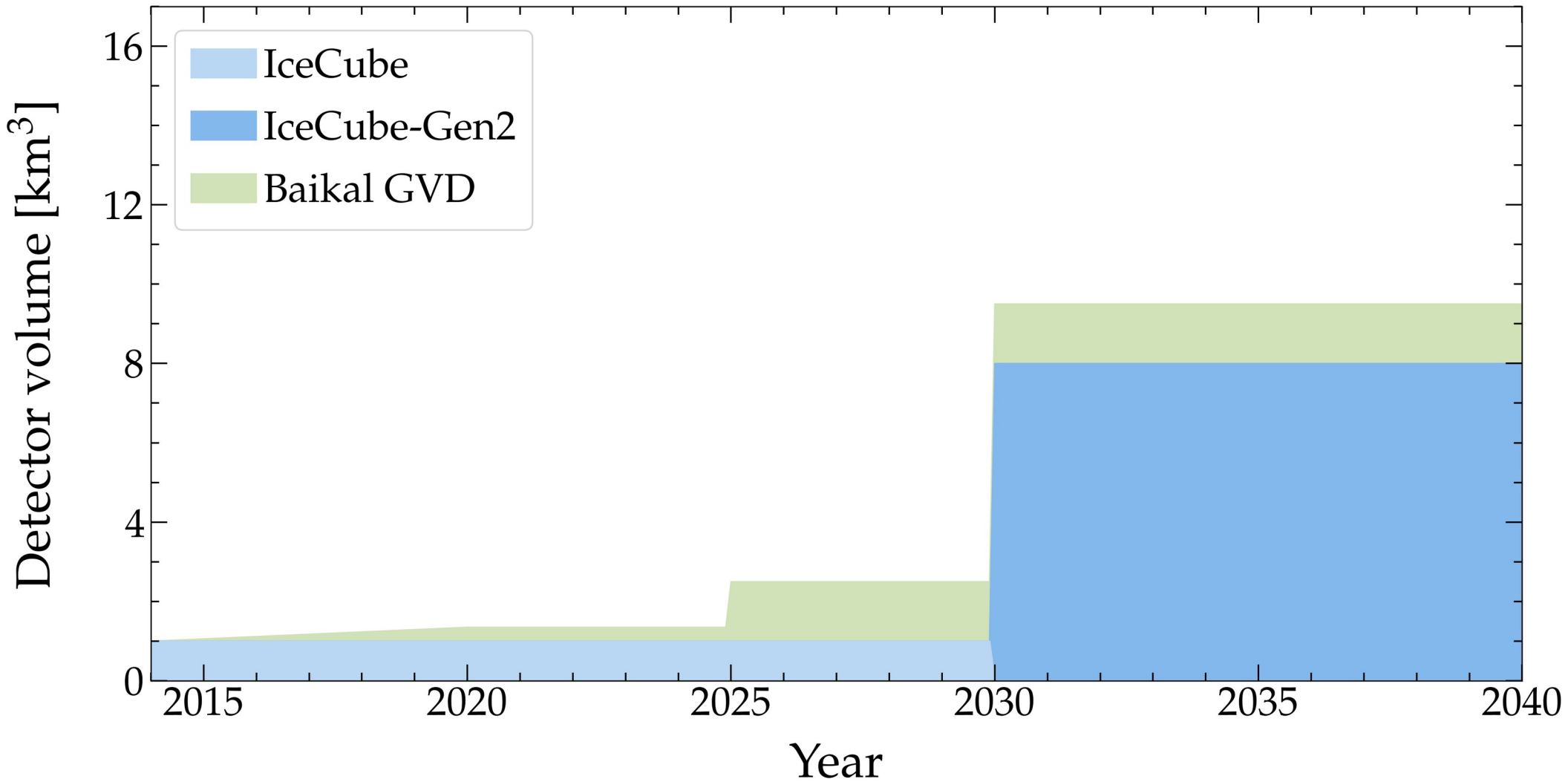
Measuring flavor composition: 2015–2040

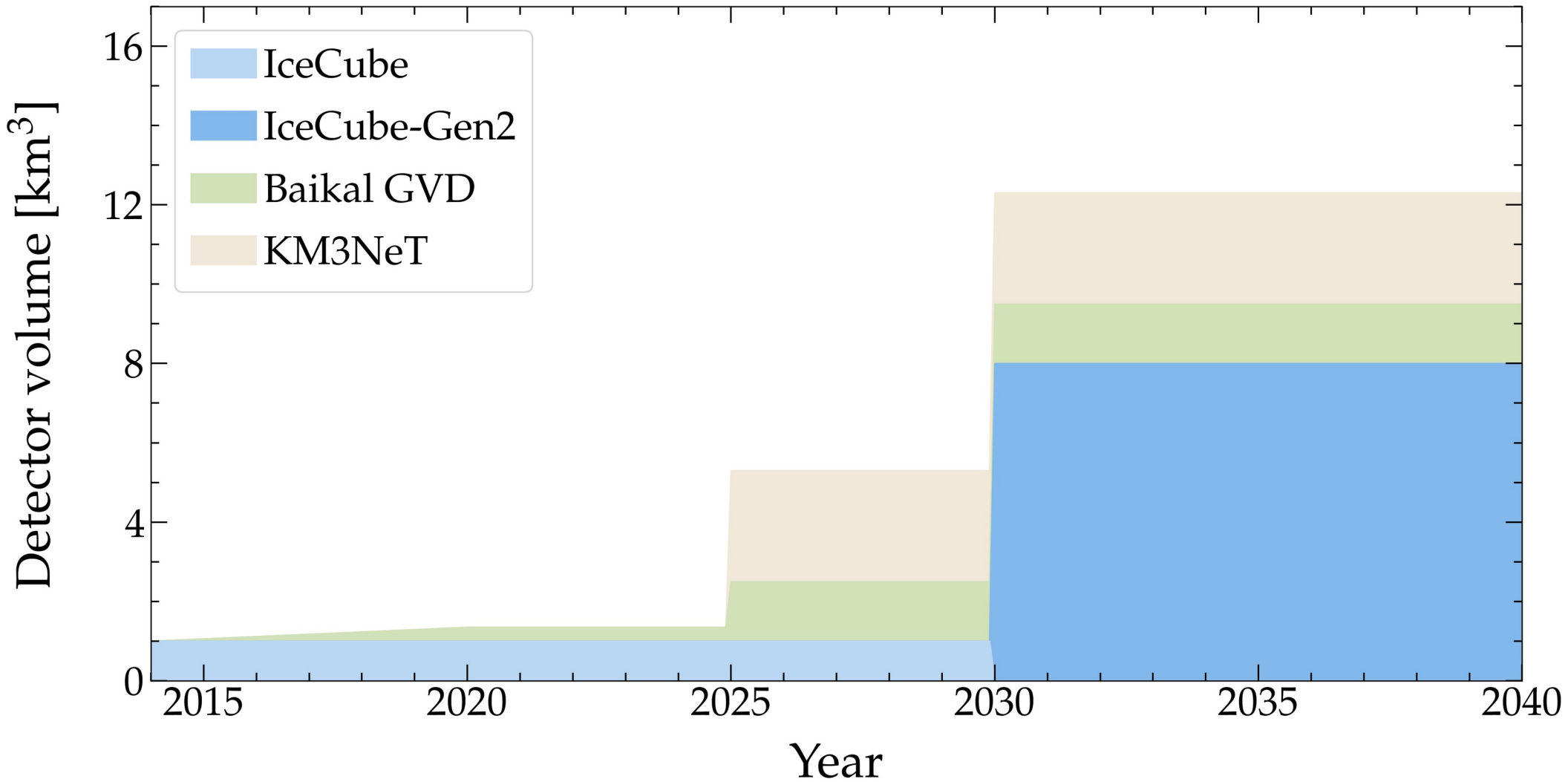
Song, Li, Argüelles, MB, Vincent, JCAP 2021

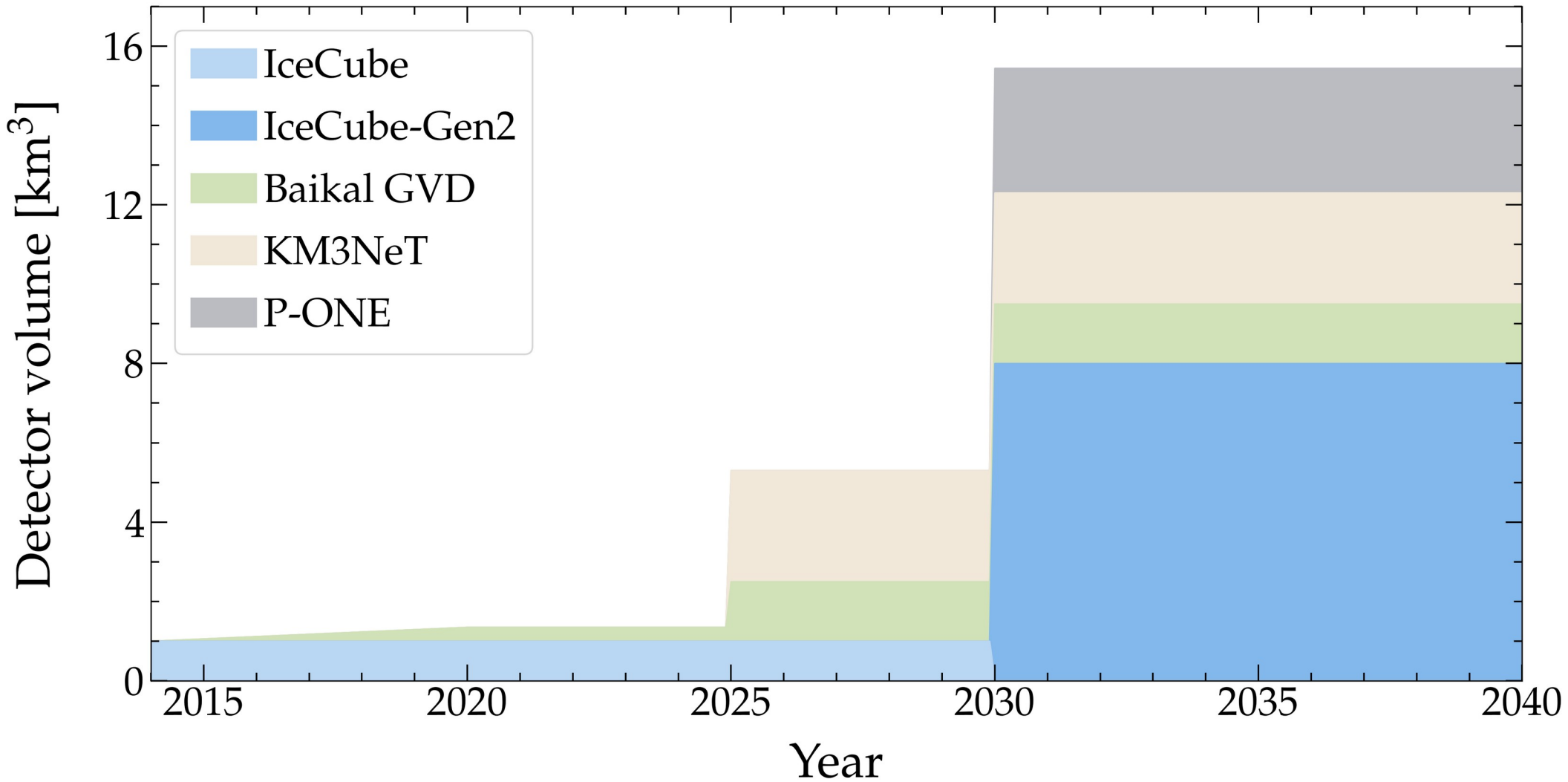


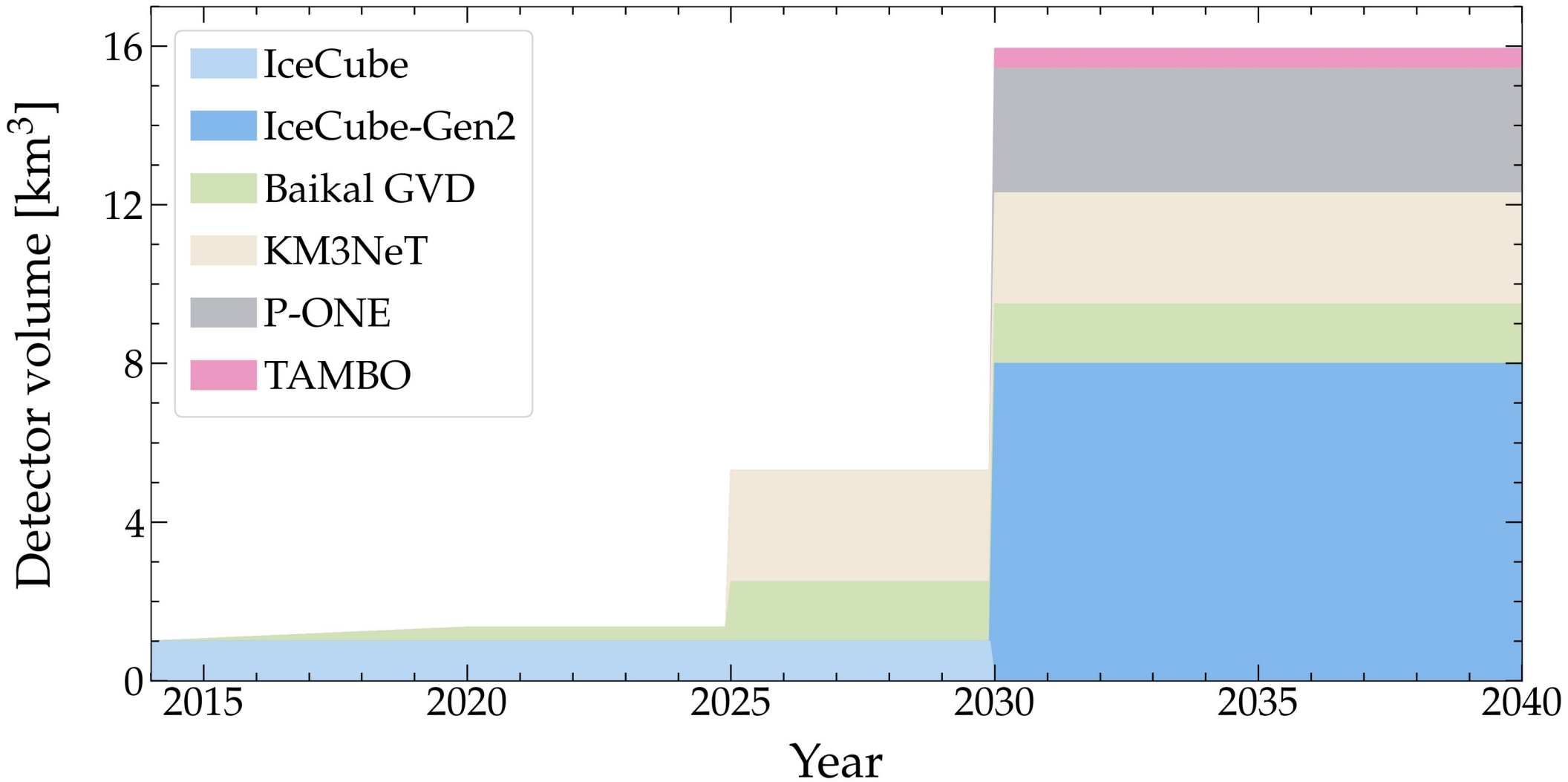


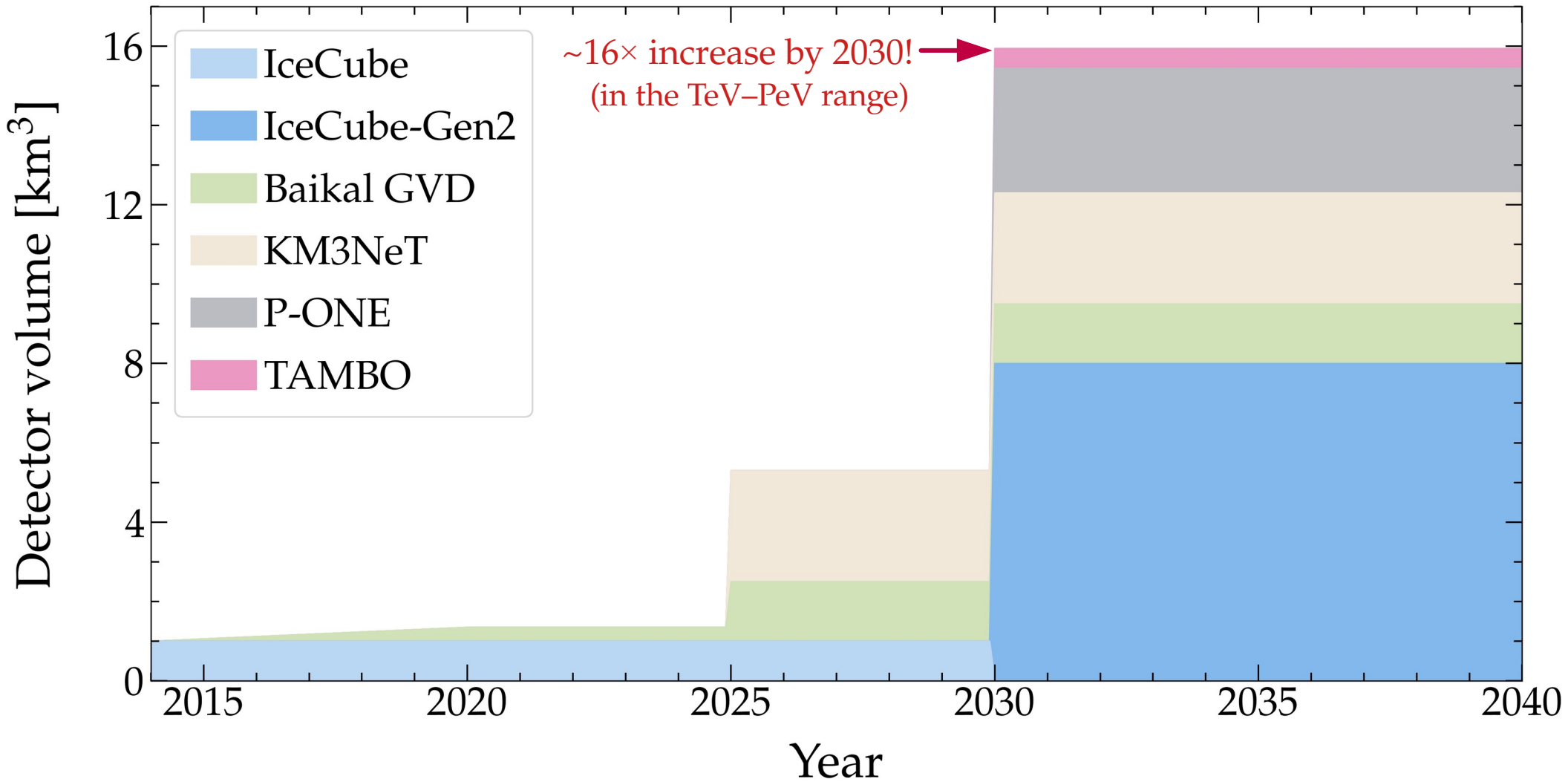






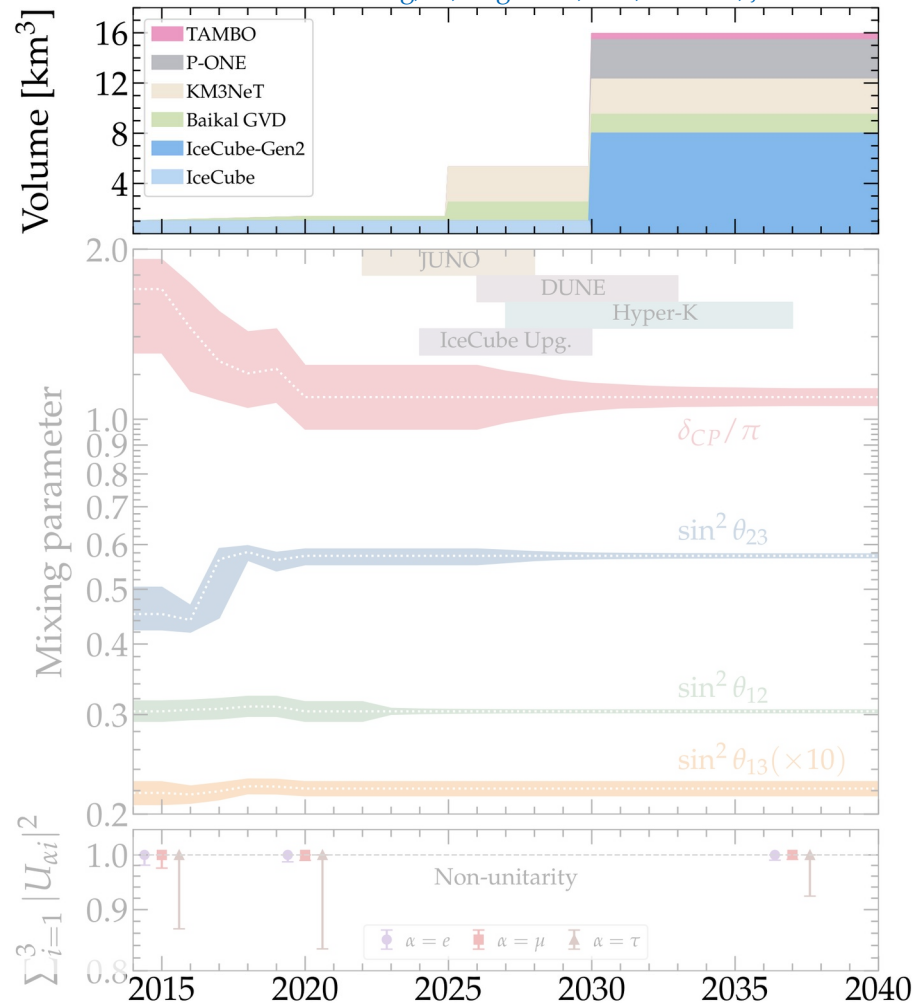






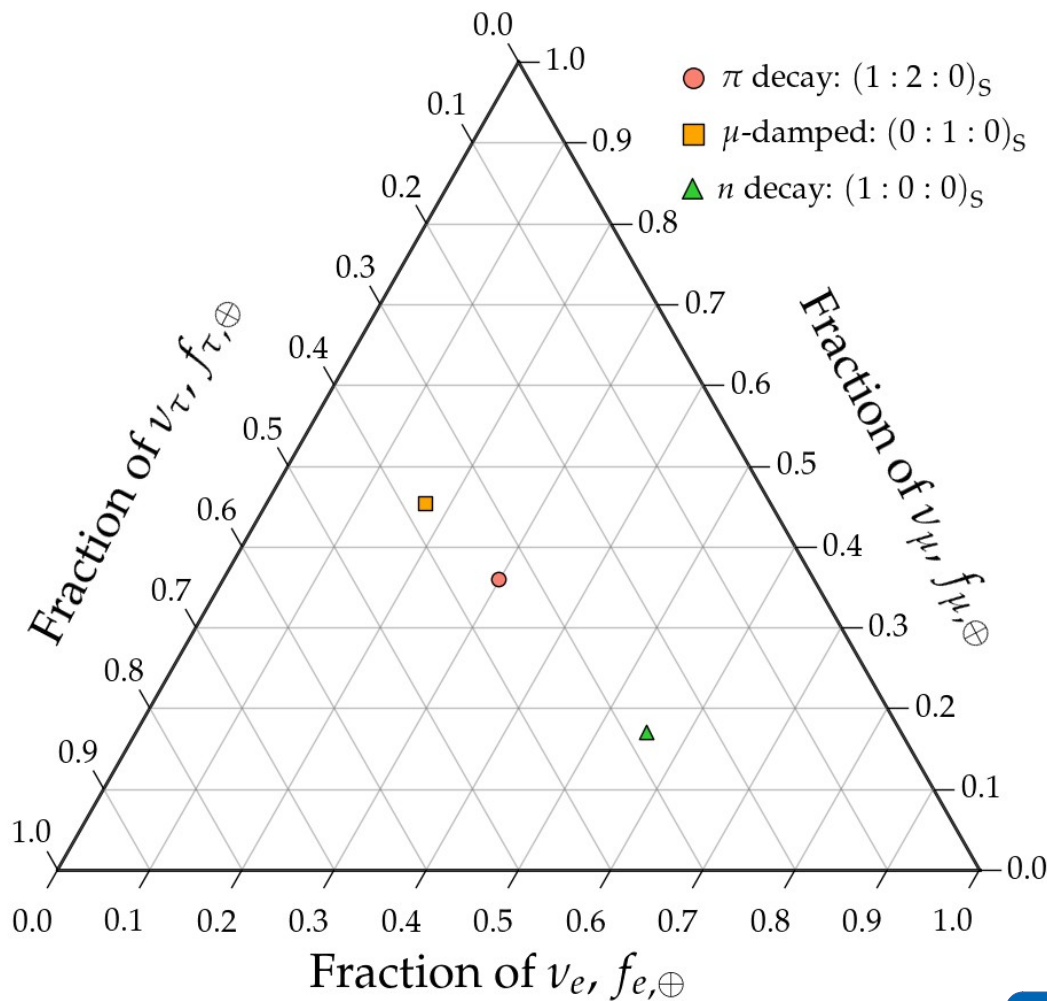
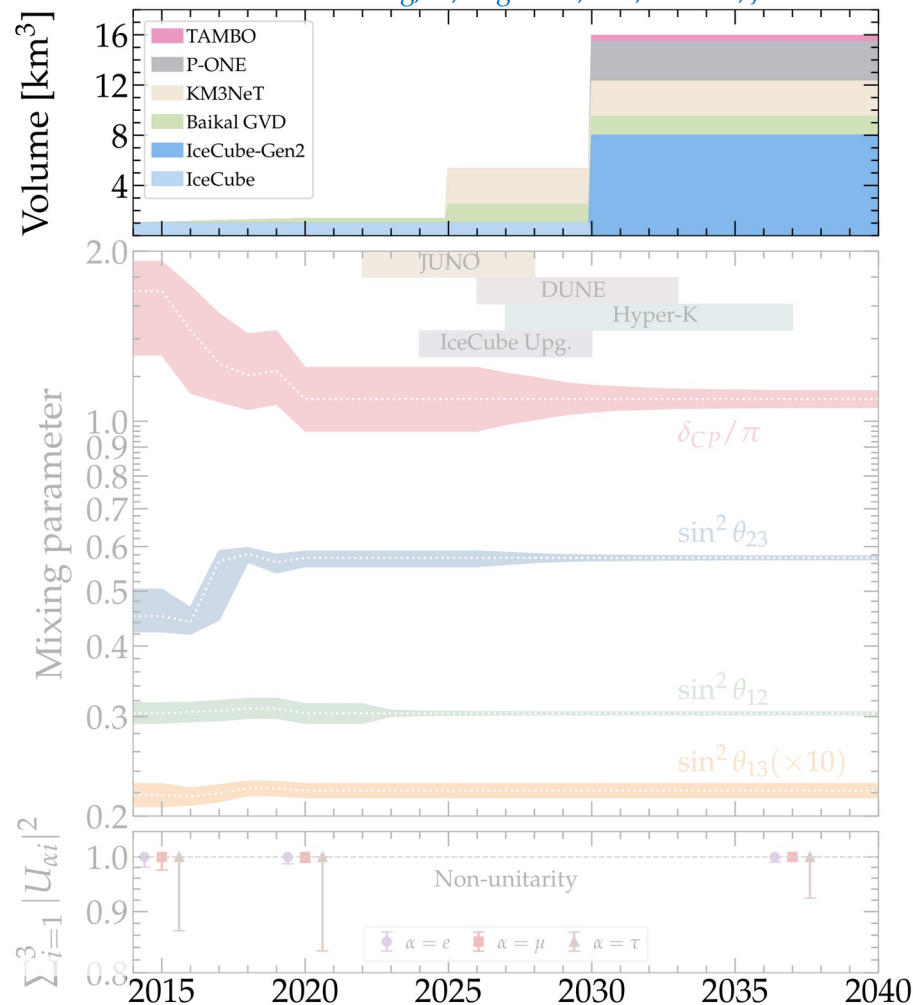
Measuring flavor composition: 2015–2040

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



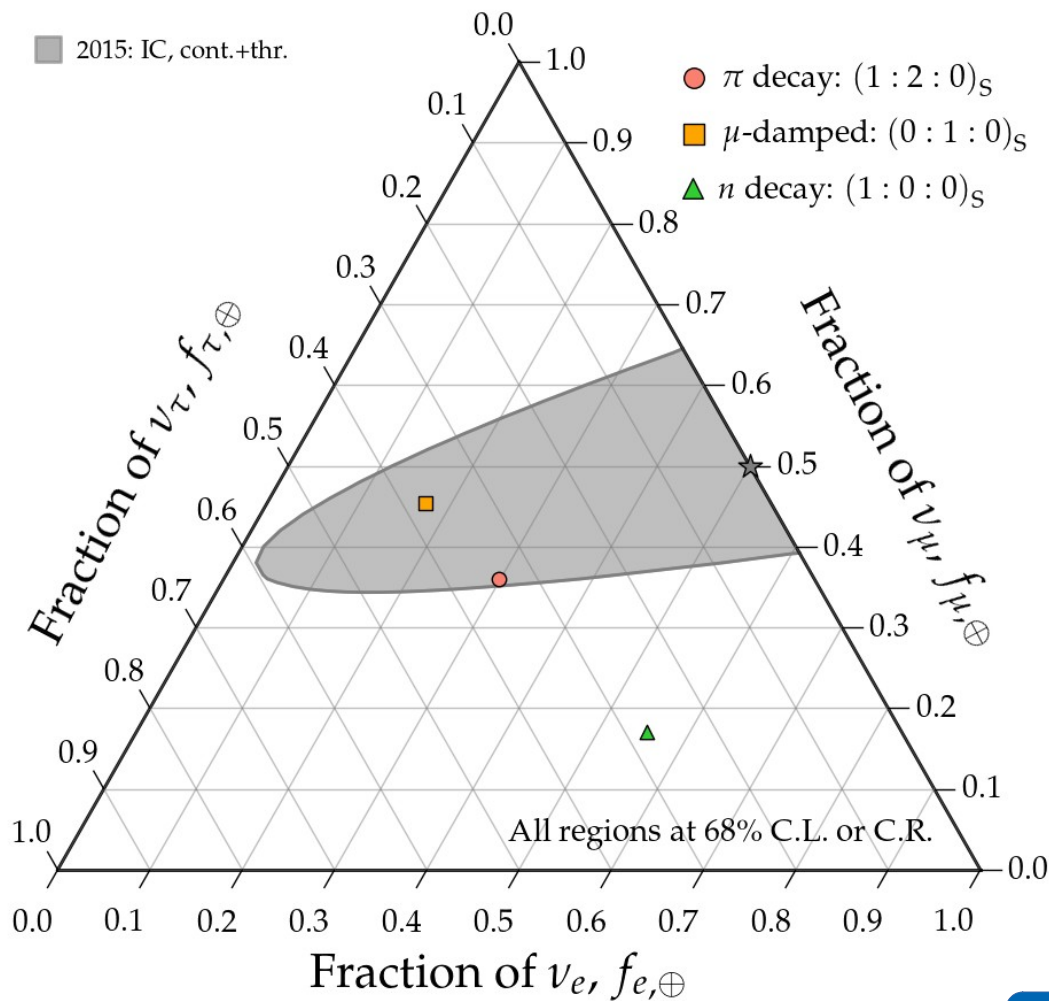
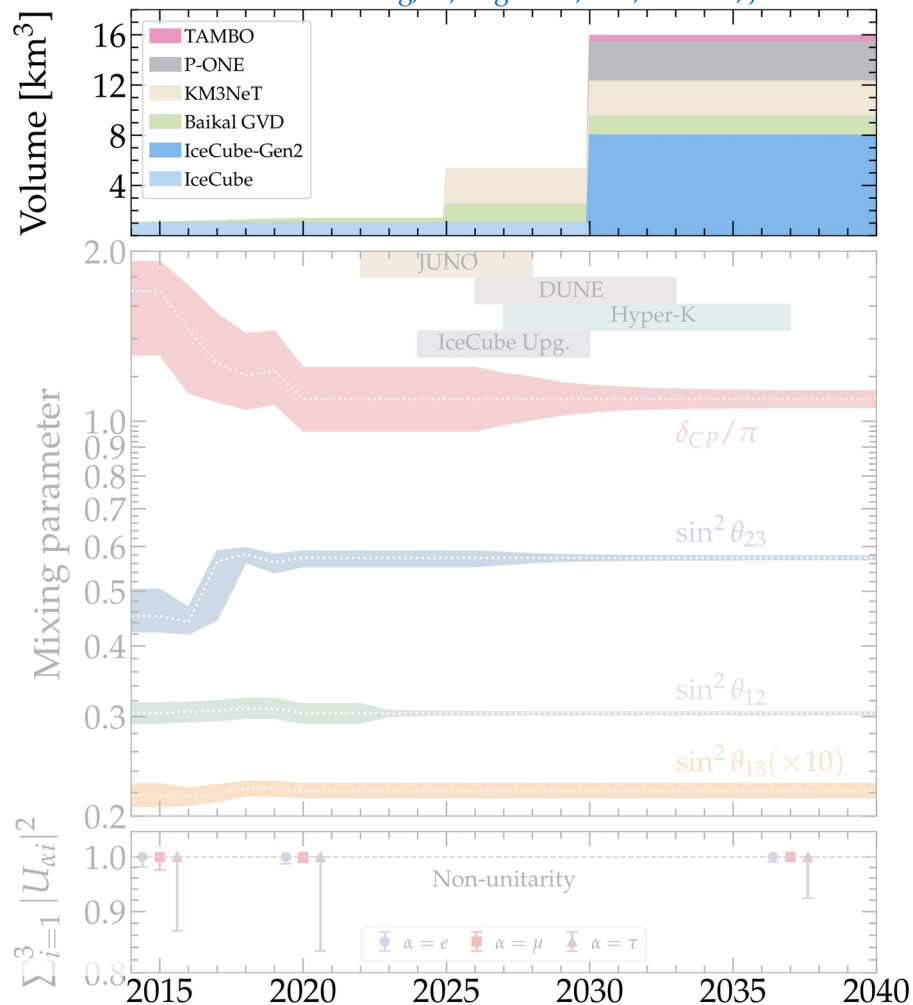
Measuring flavor composition: 2015–2040

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



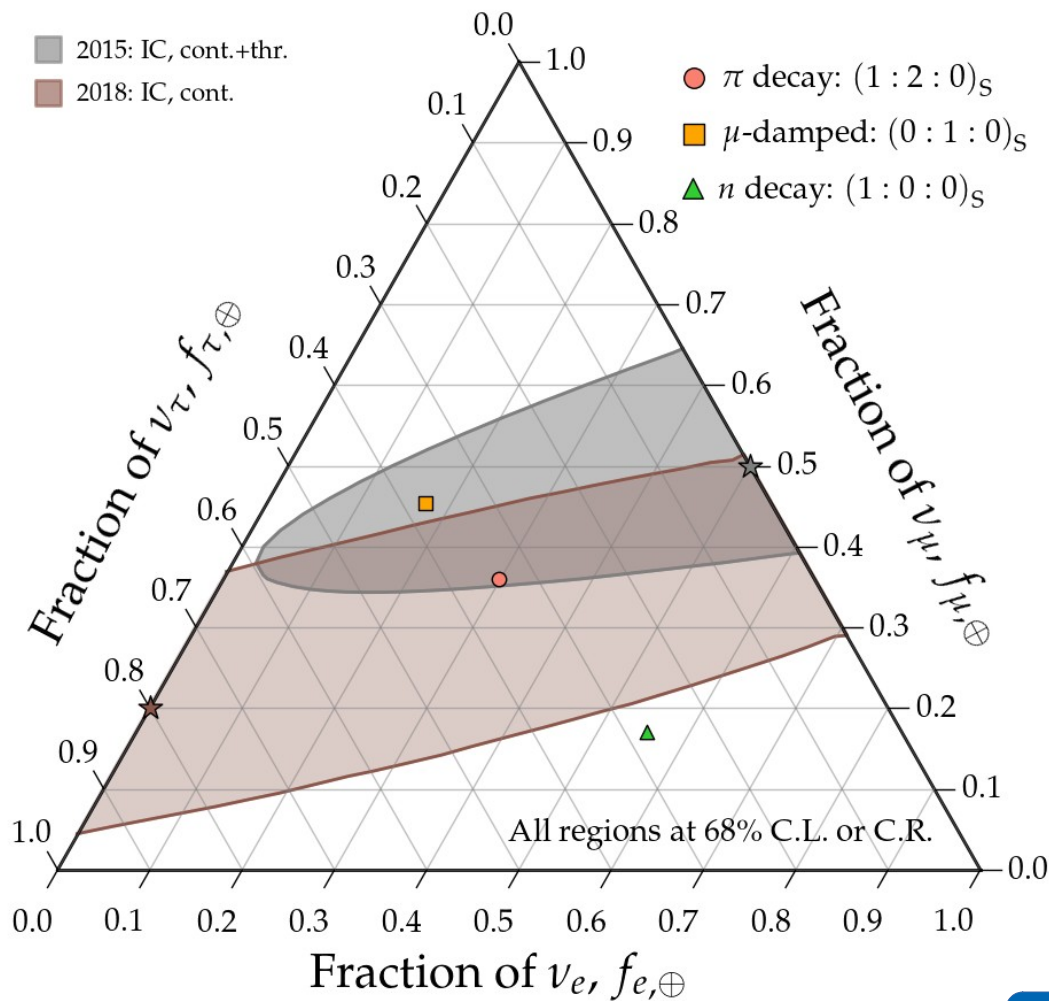
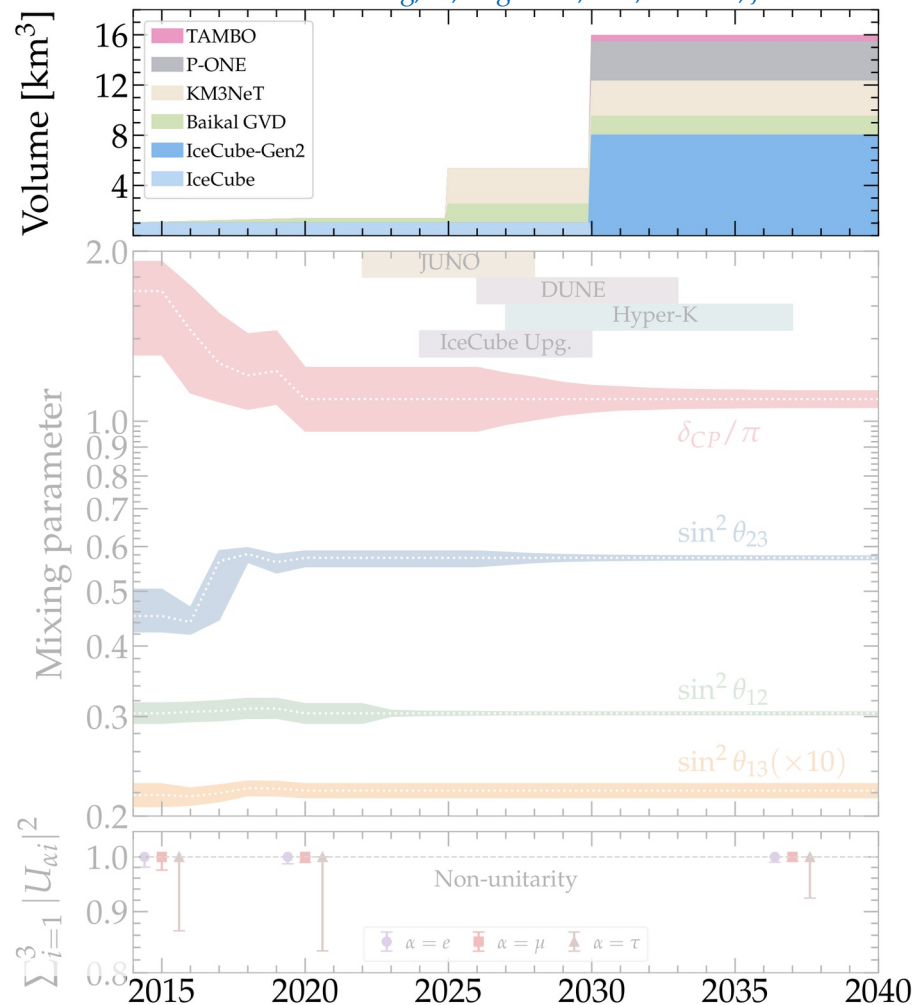
Measuring flavor composition: 2015–2040

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



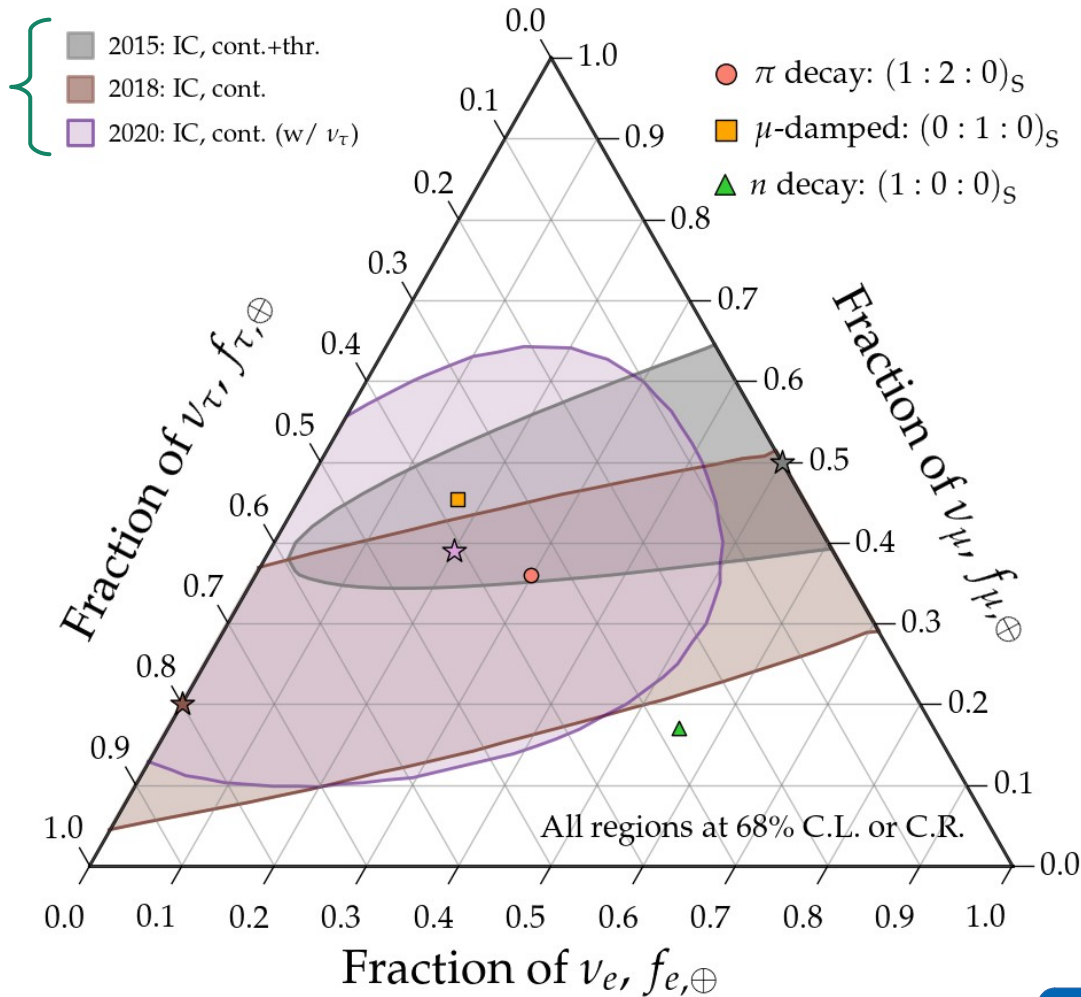
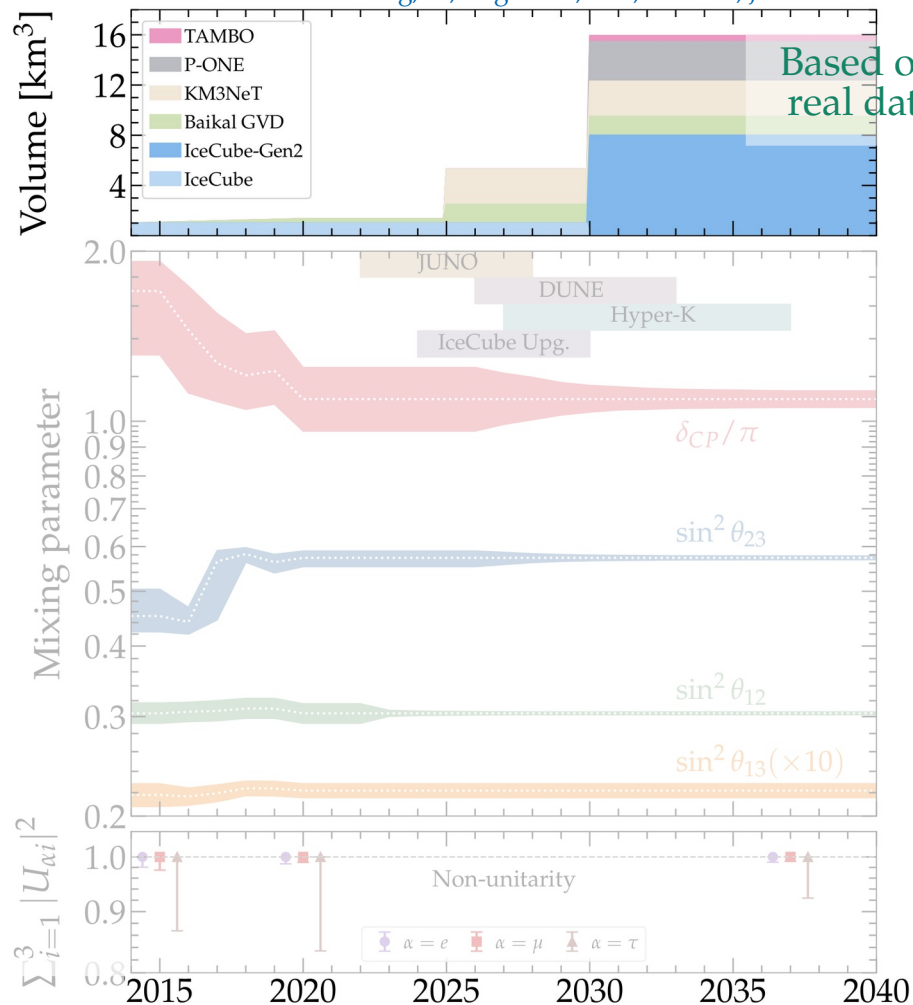
Measuring flavor composition: 2015–2040

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



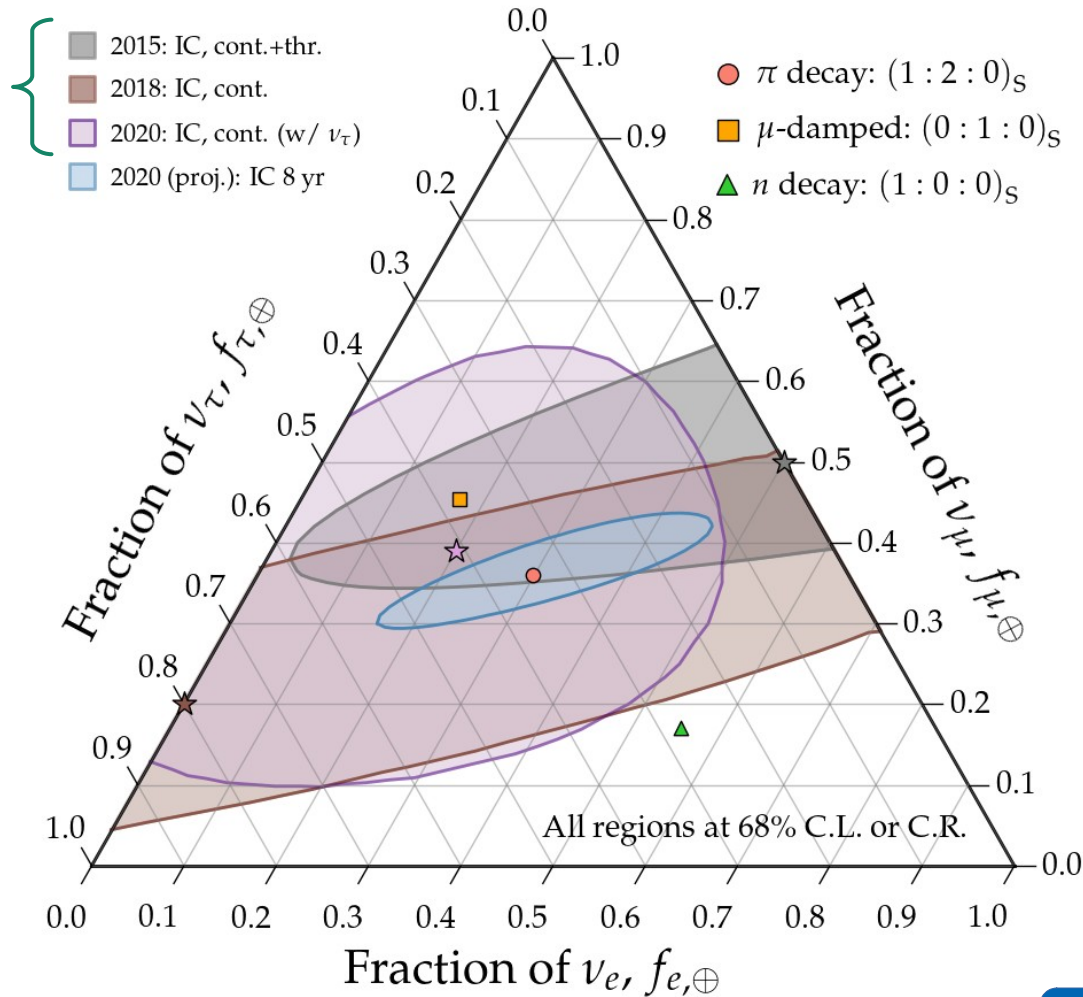
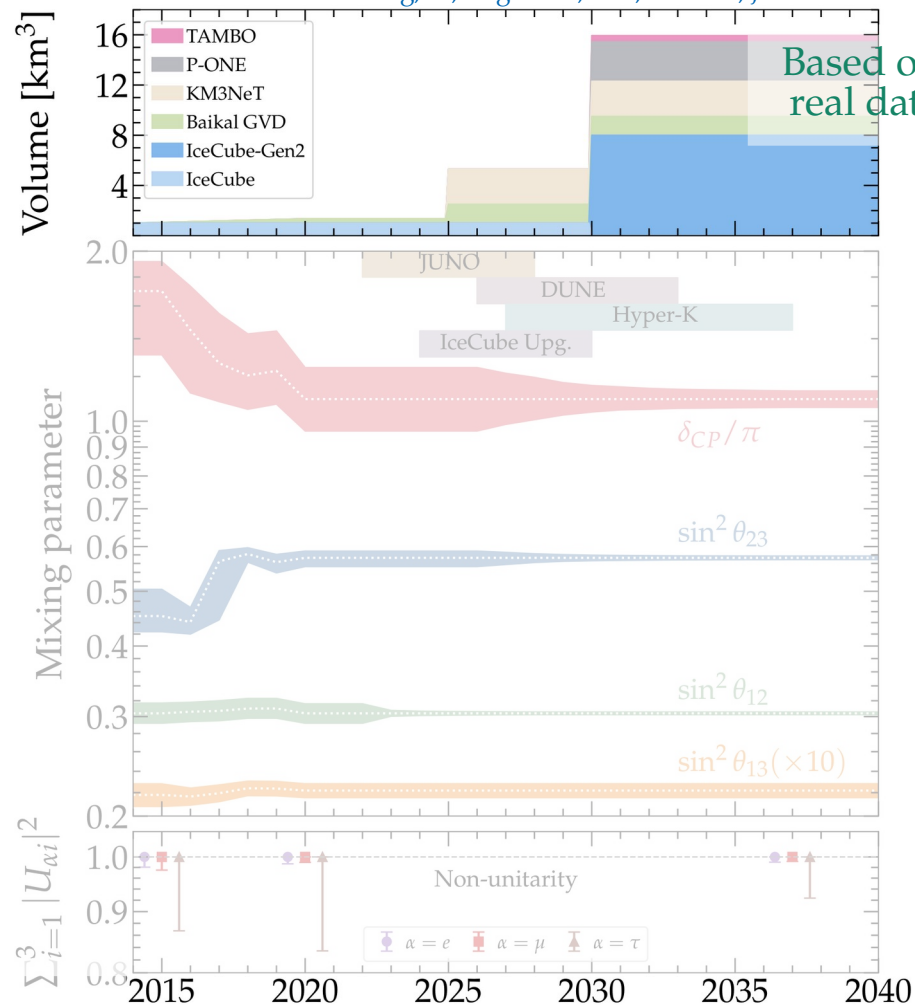
Measuring flavor composition: 2015–2040

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



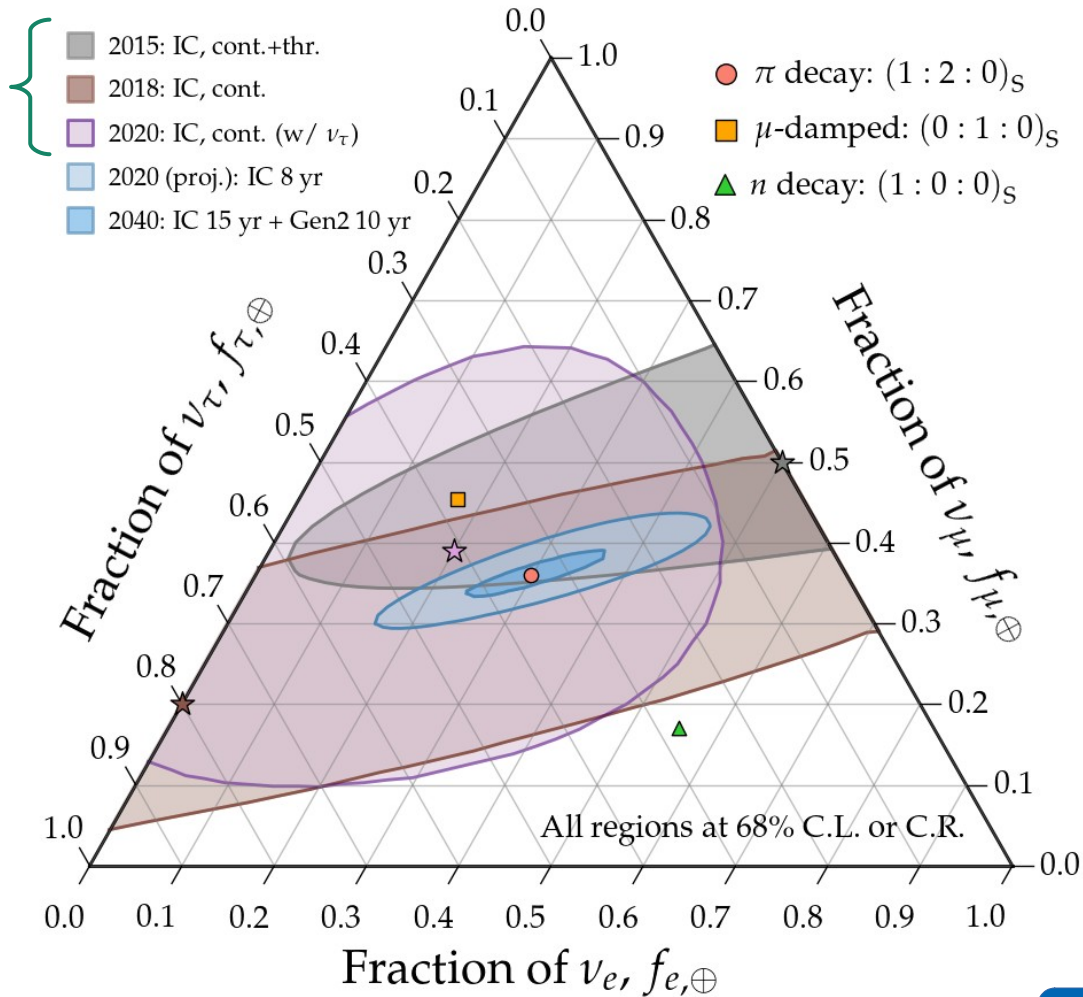
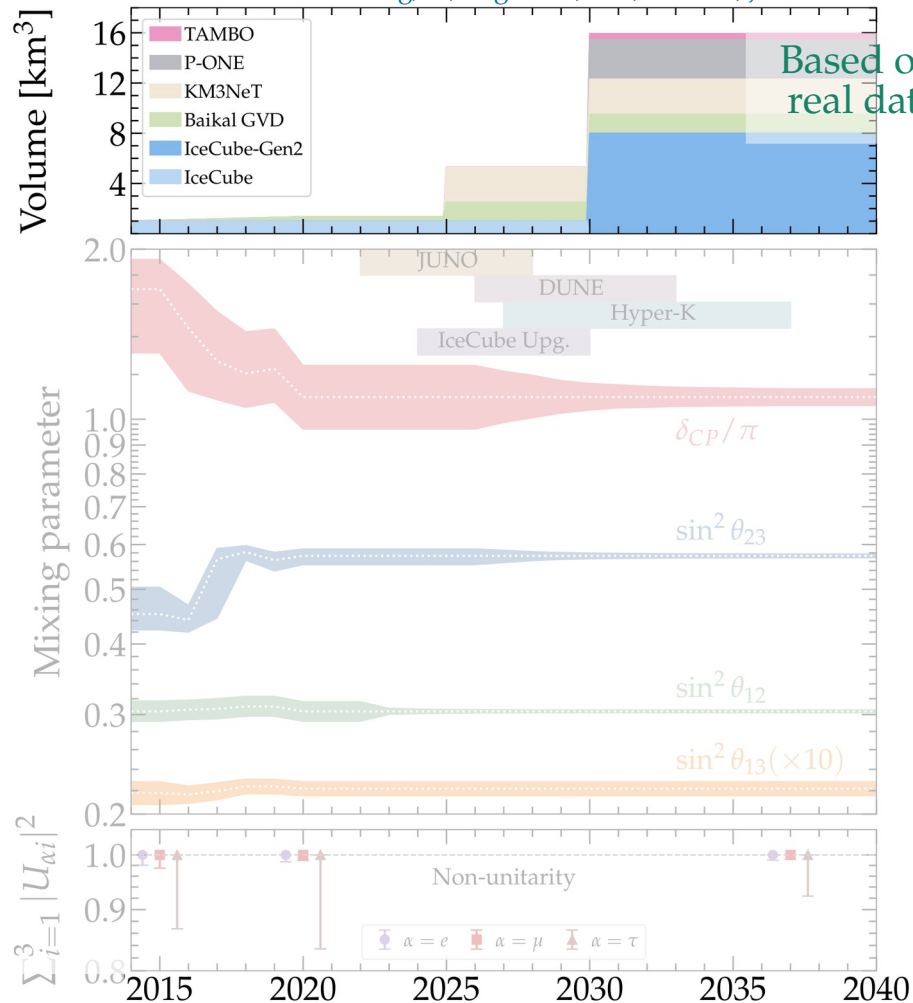
Measuring flavor composition: 2015–2040

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



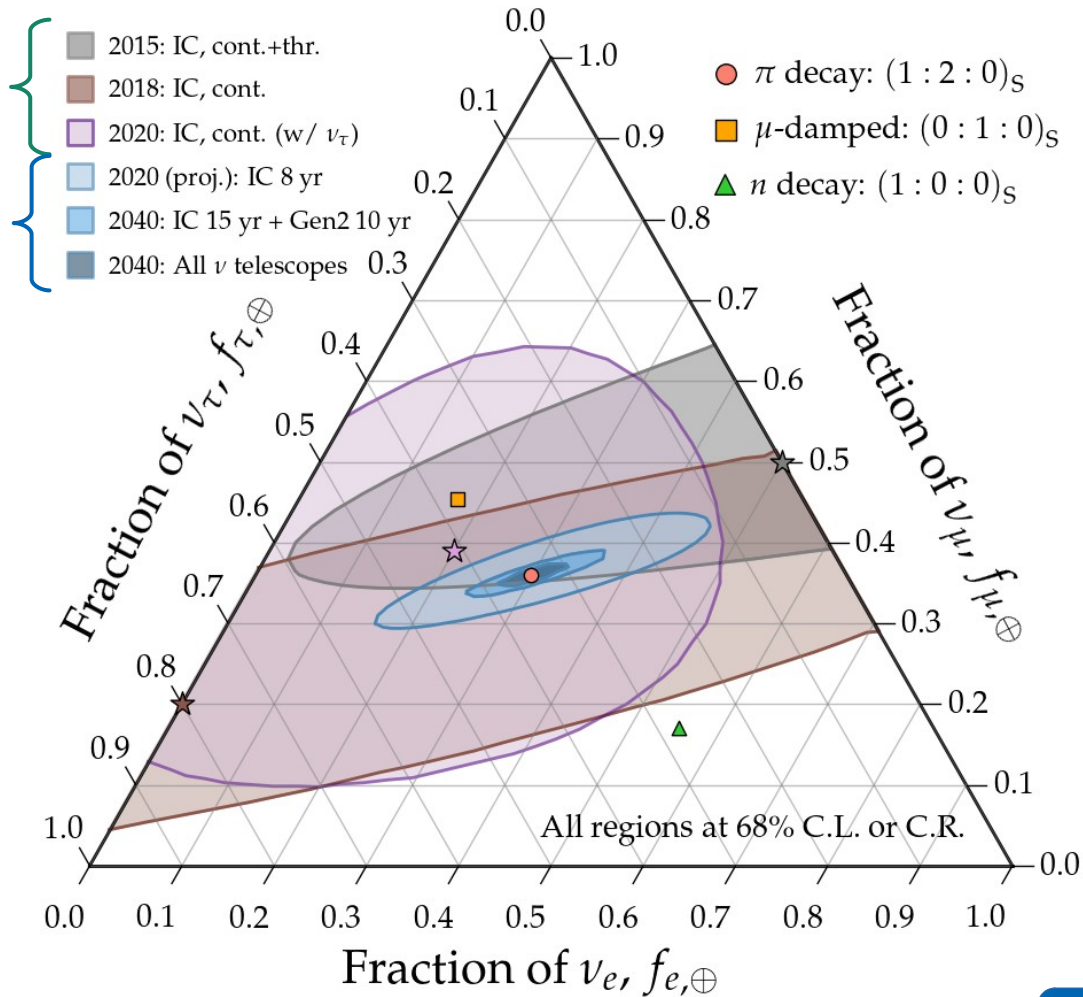
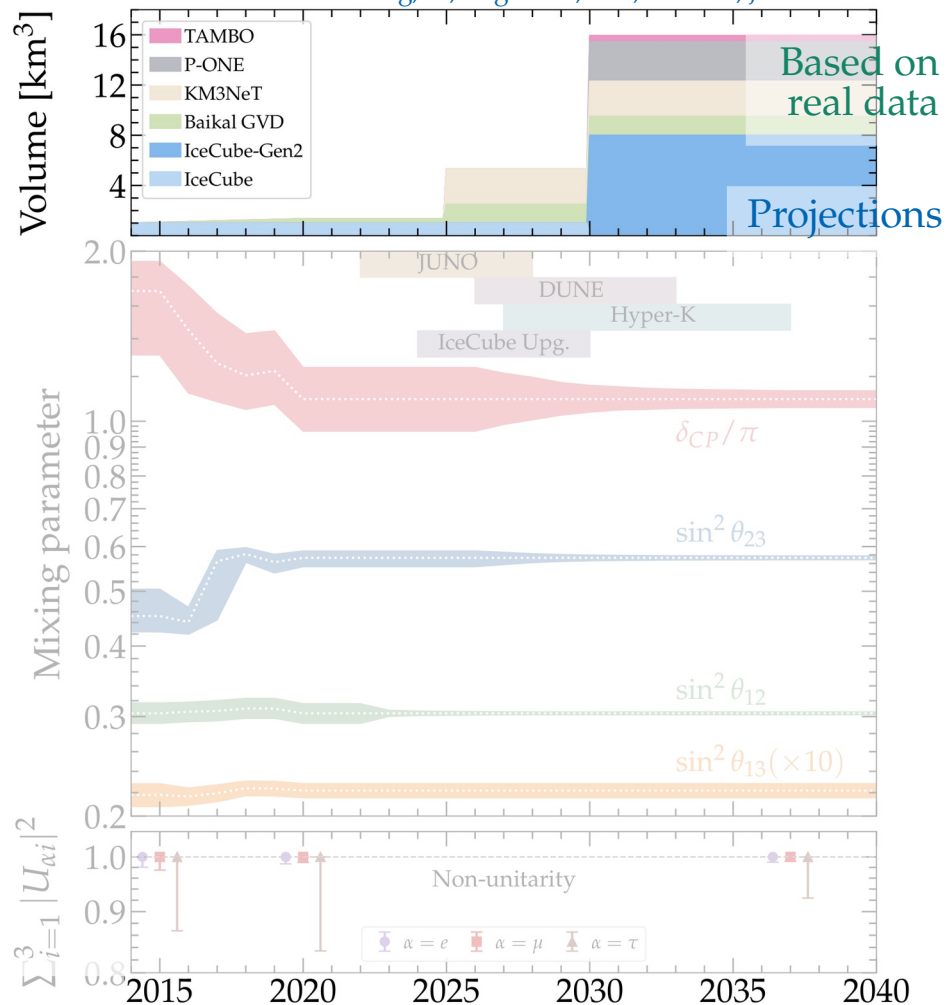
Measuring flavor composition: 2015–2040

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

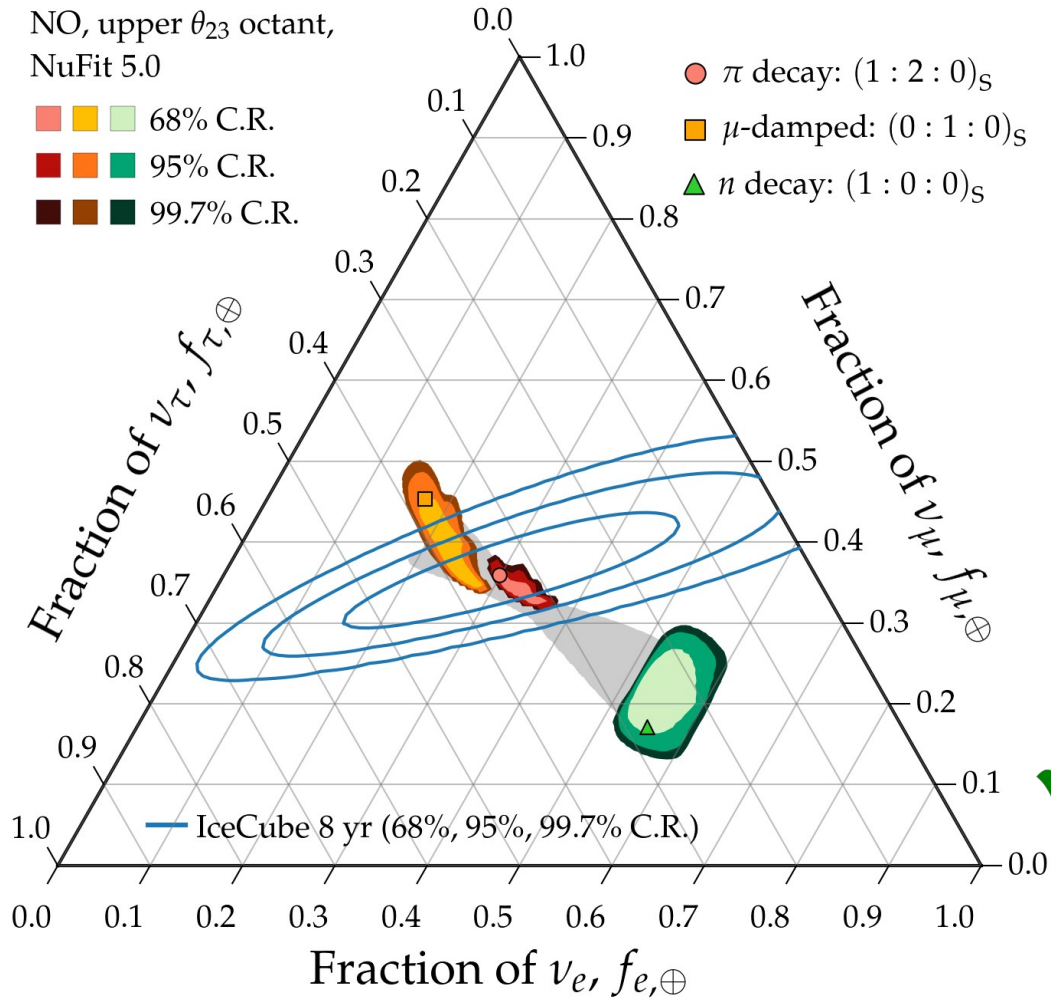


Measuring flavor composition: 2015–2040

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



Theoretically palatable regions: today



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the
mixing parameters

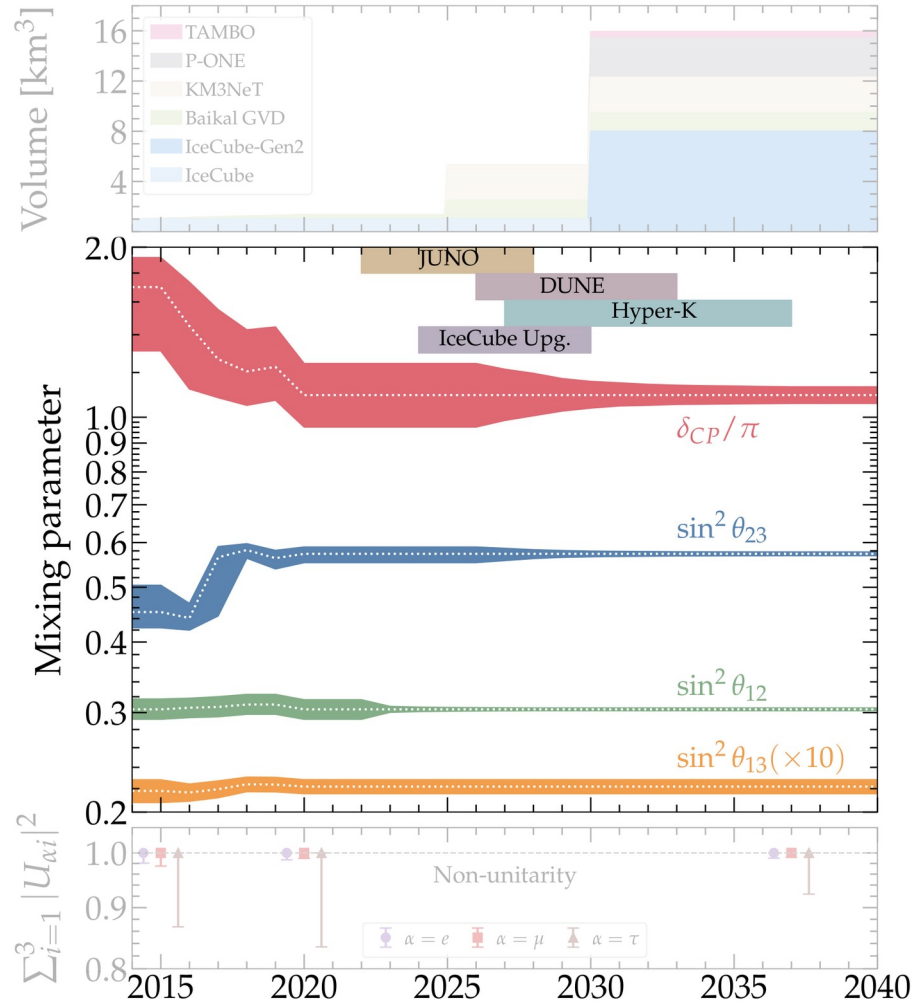
Will be overcome by 2030

Measurement of flavor ratios –
~~Cannot distinguish between
pion-decay and muon-damped
benchmarks even at 68% C.R. (1σ)~~



Will be overcome by 2040

How knowing the mixing parameters better helps



We can compute the oscillation probability more precisely:

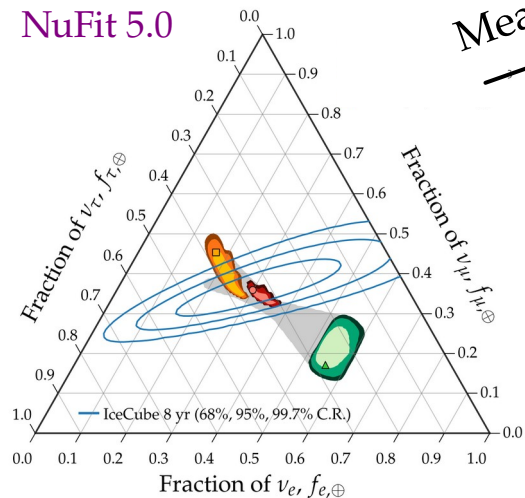
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\beta\alpha} f_{\beta,S}$$

So we can convert back and forth between source and Earth more precisely

How knowing the mixing parameters better helps

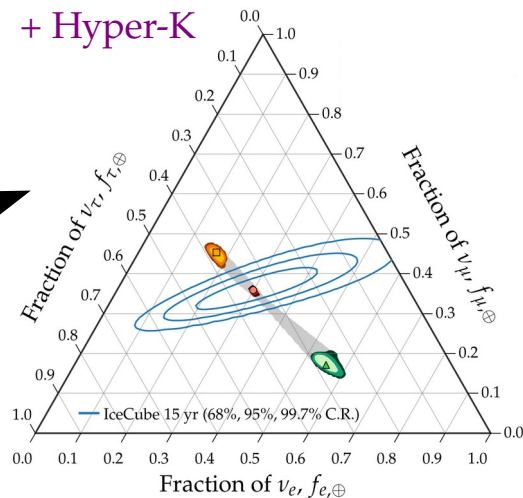
2020

NuFit 5.0

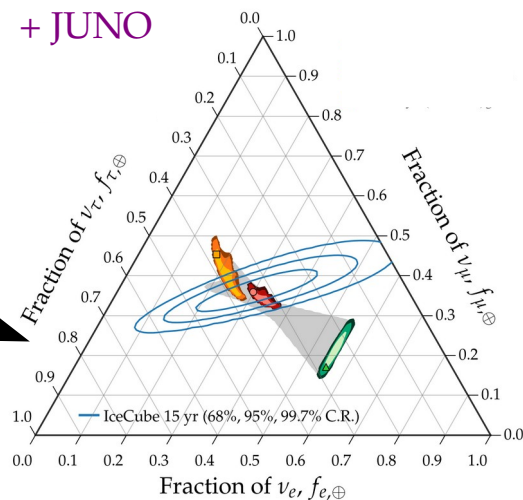


Measure θ_{23} better

+ Hyper-K



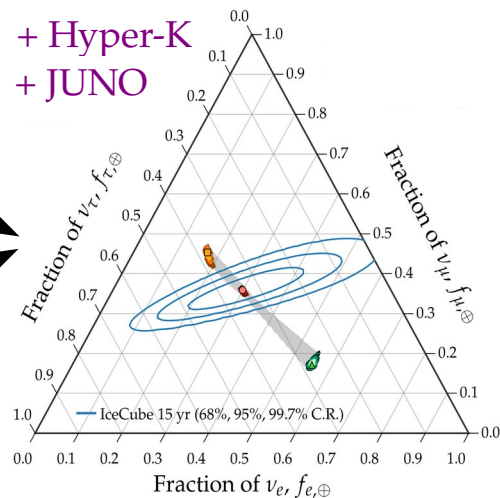
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



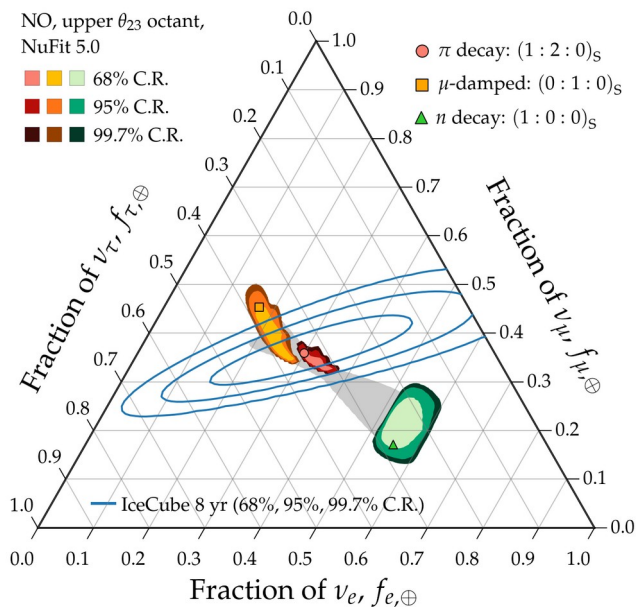
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

2020

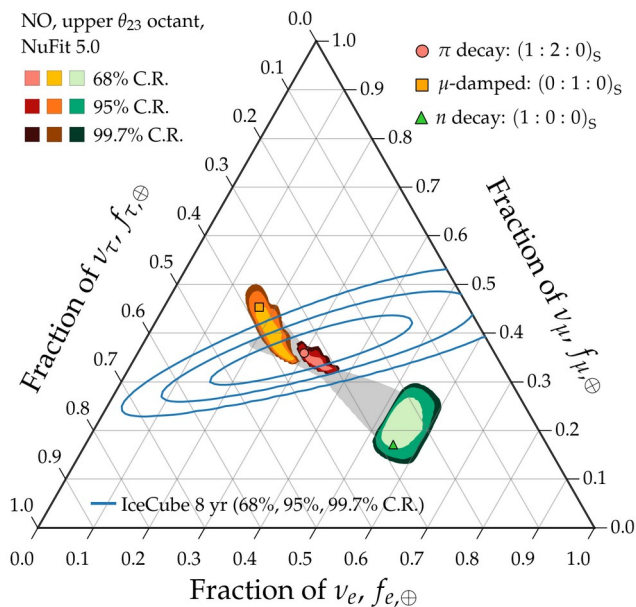


Allowed regions: overlapping

Measurement: imprecise

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

2020



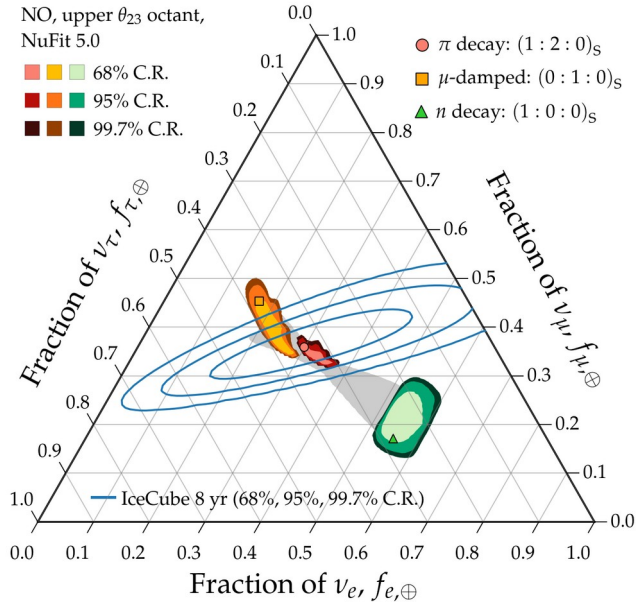
Allowed regions: overlapping

Measurement: imprecise

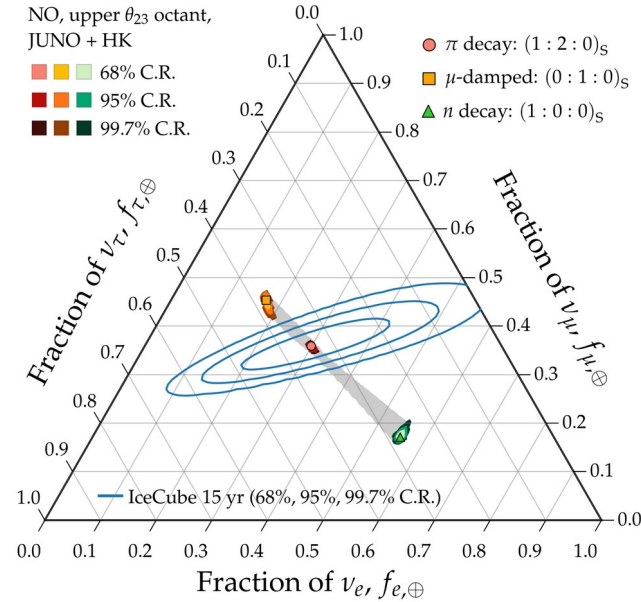
Not ideal

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

2020



2030



Allowed regions: overlapping

Measurement: imprecise

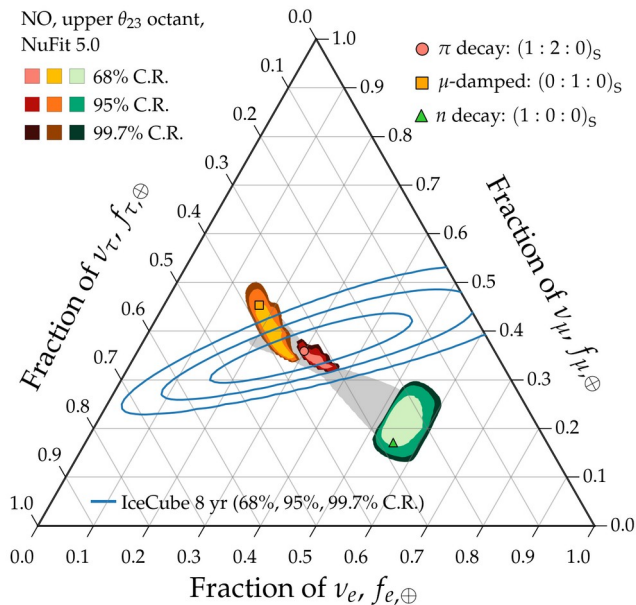
Allowed regions: well separated

Measurement: improving

Not ideal

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

2020

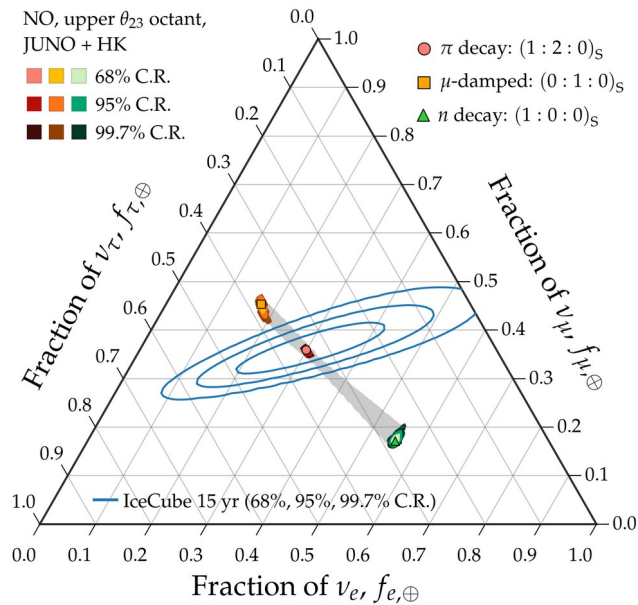


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



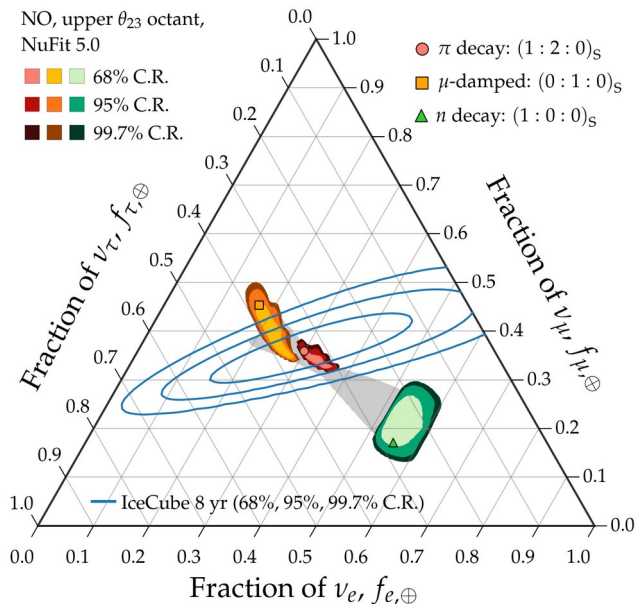
Allowed regions: well separated

Measurement: improving

Nice

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

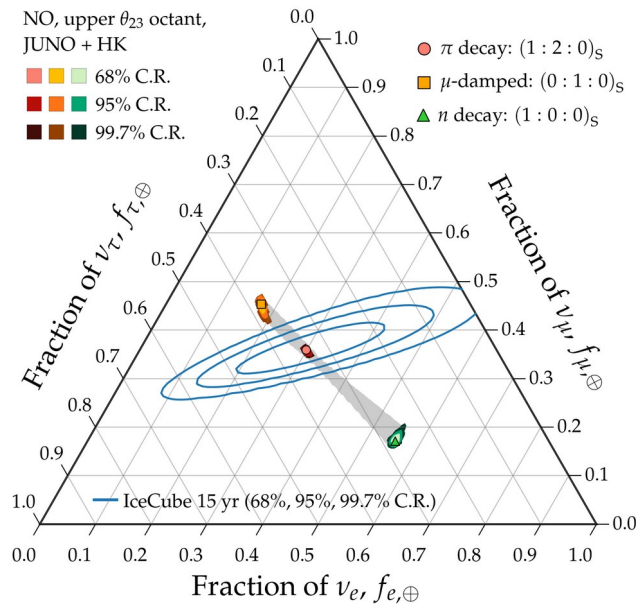
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

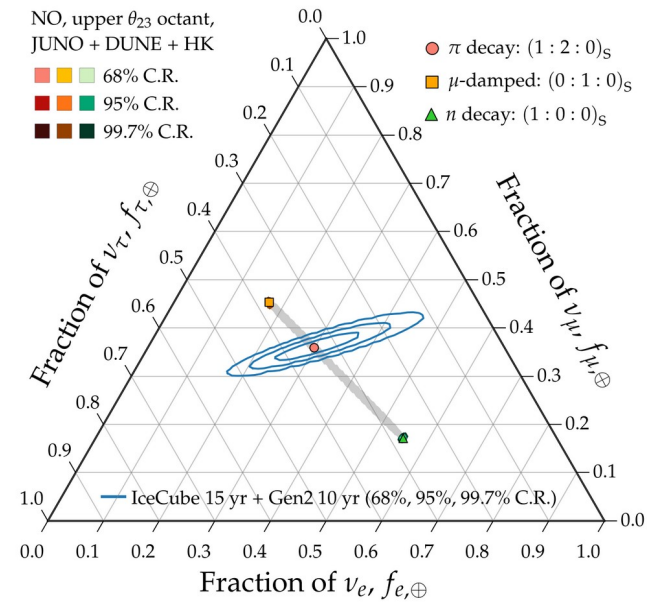
2030



Allowed regions: well separated
Measurement: improving

Nice

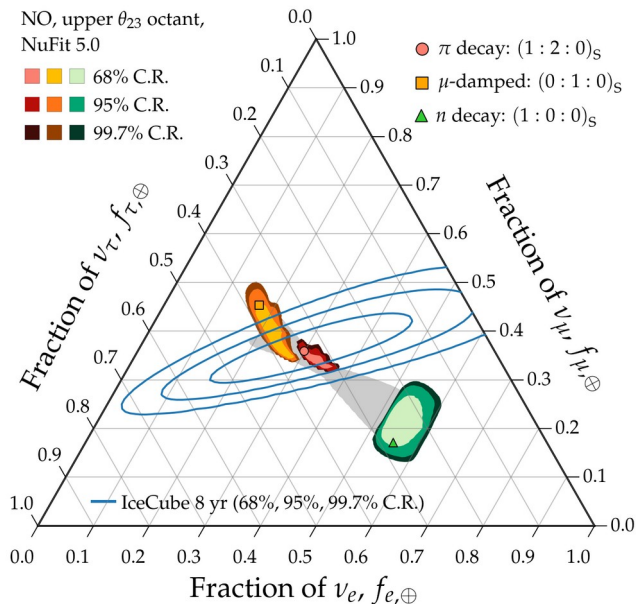
2040



Allowed regions: well separated
Measurement: precise

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

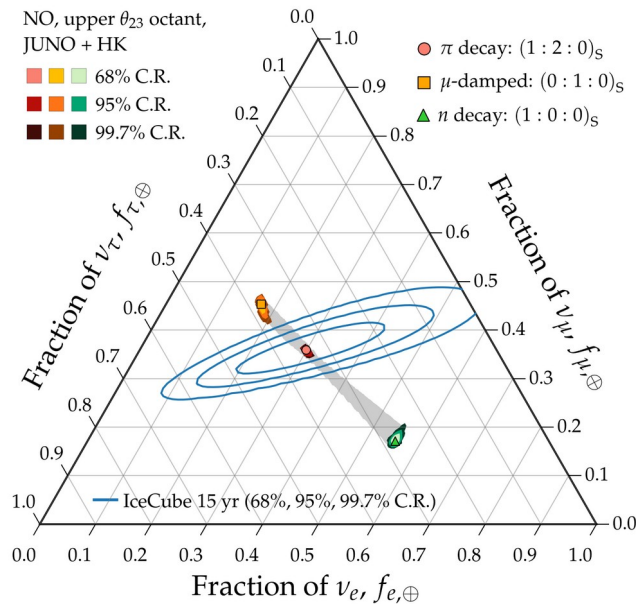
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

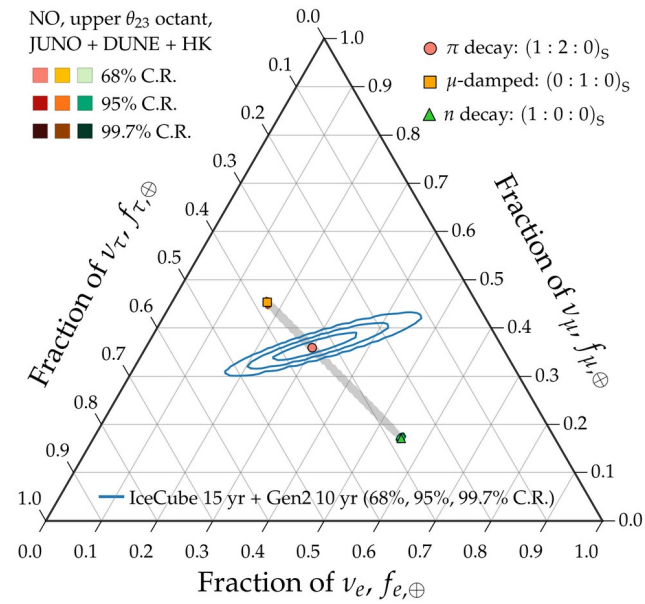
2030



Allowed regions: well separated
Measurement: improving

Nice

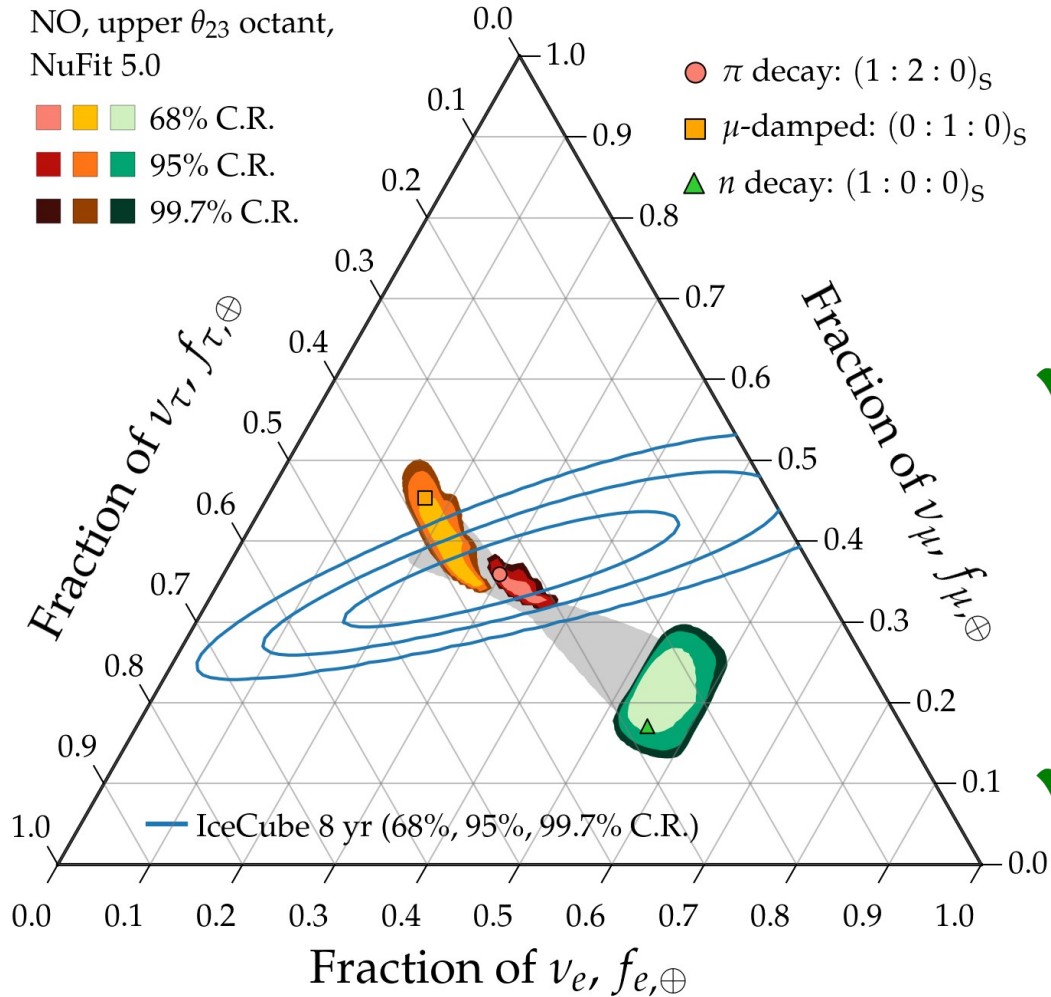
2040



Allowed regions: well separated
Measurement: precise

Success

Theoretically palatable regions: today



Two limitations:

Allowed flavor regions overlap –
 Insufficient precision in the
 mixing parameters

✓ *Will be overcome by 2030*

Measurement of flavor ratios –
 Cannot distinguish between
 pion-decay and muon-damped
 benchmarks even at 68% C.R. (1σ)

✓ *Will be overcome by 2040*

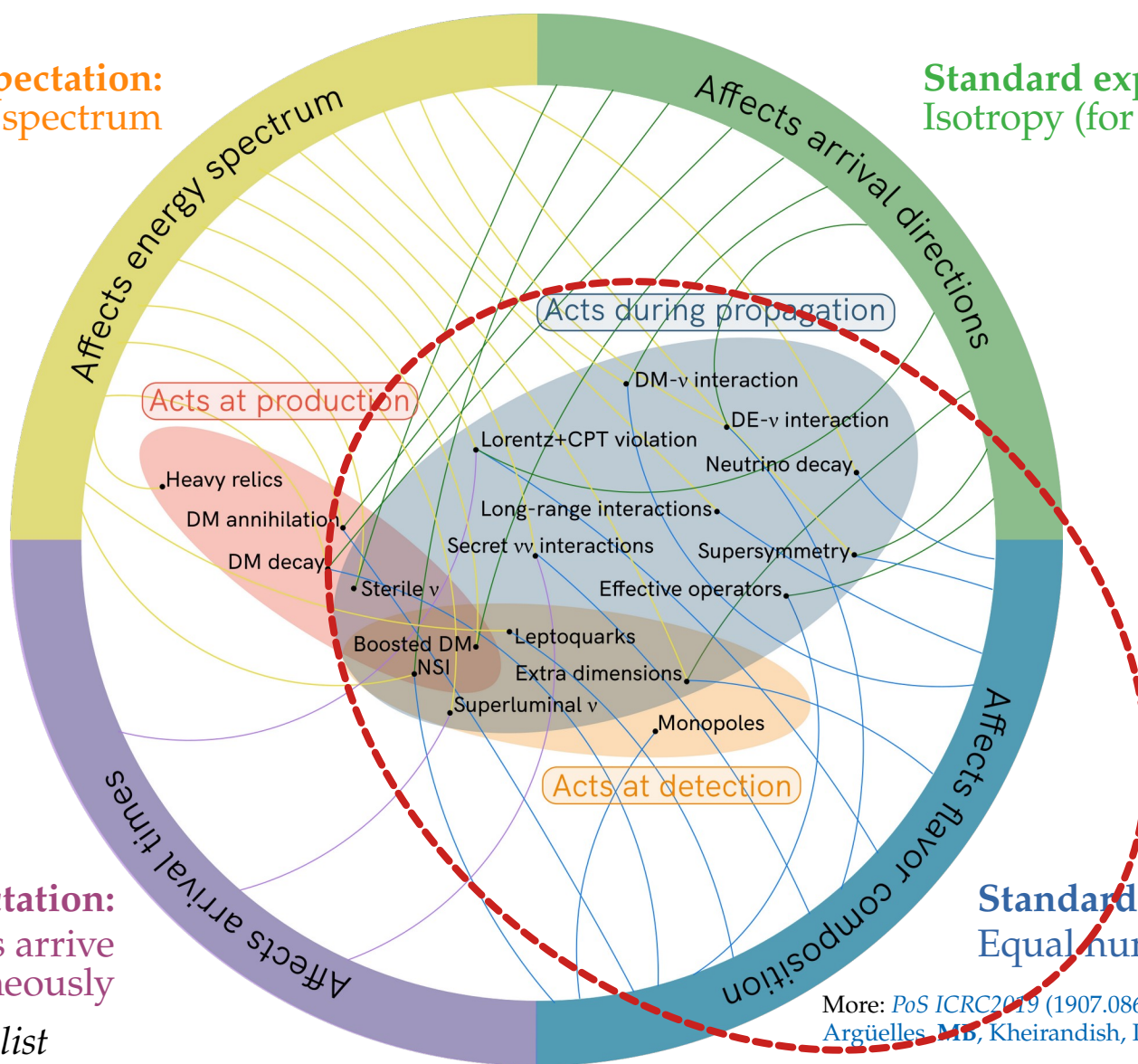
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list



More: *PoS ICRC2019* (1907.08690)

Argüelles, M.B., Kheirandish, Palomares-Ruiz, Salvadó, Vincent

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

Reviews:

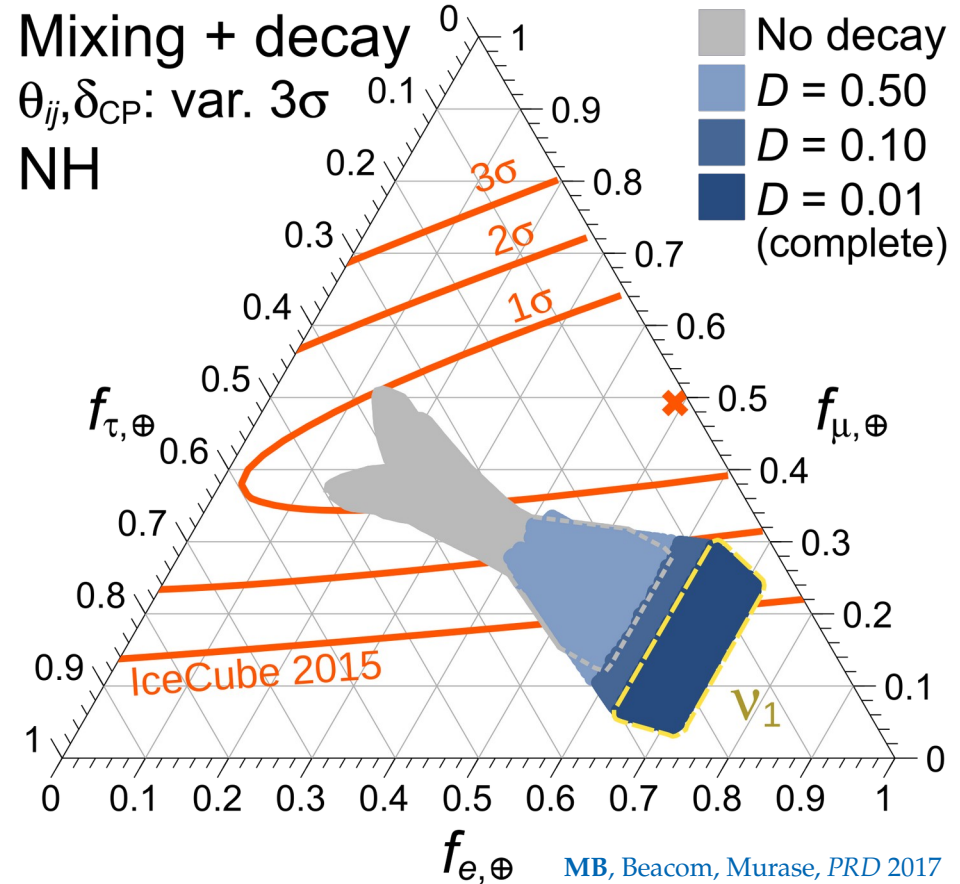
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

► Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, MB, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; MB, Beacom, Murase, *PRD* 2017]



Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

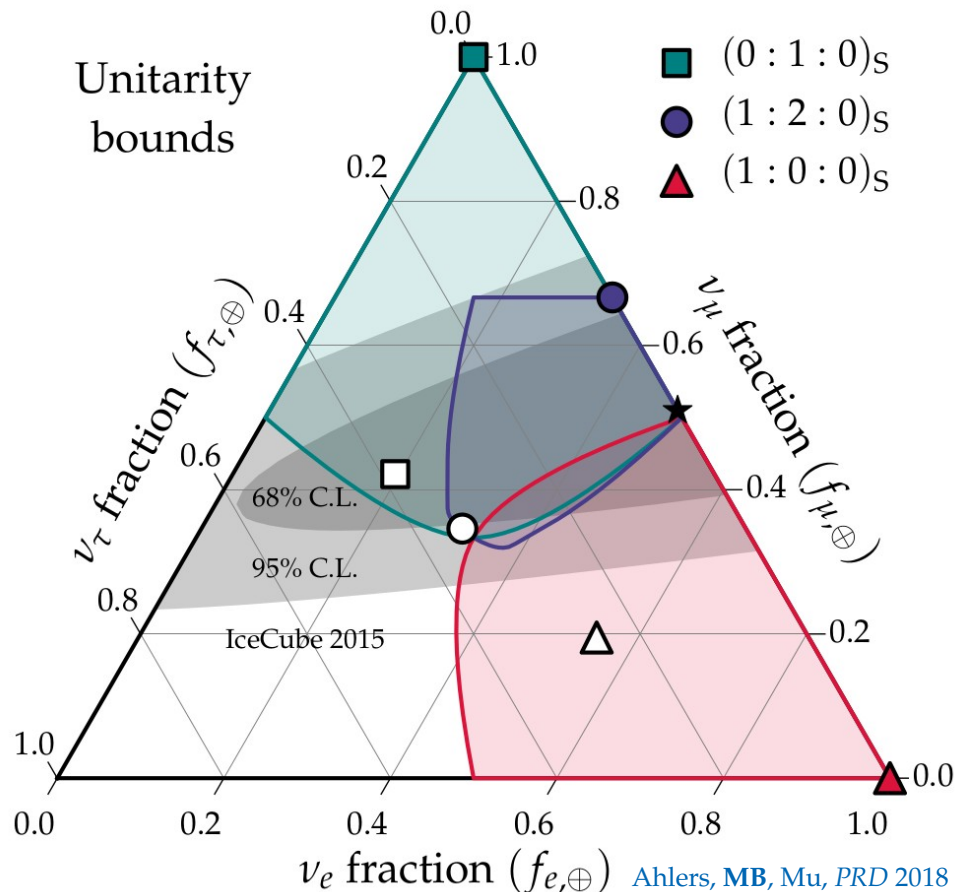
Repurpose the flavor sensitivity to test new physics:

► Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

► Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]



Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay

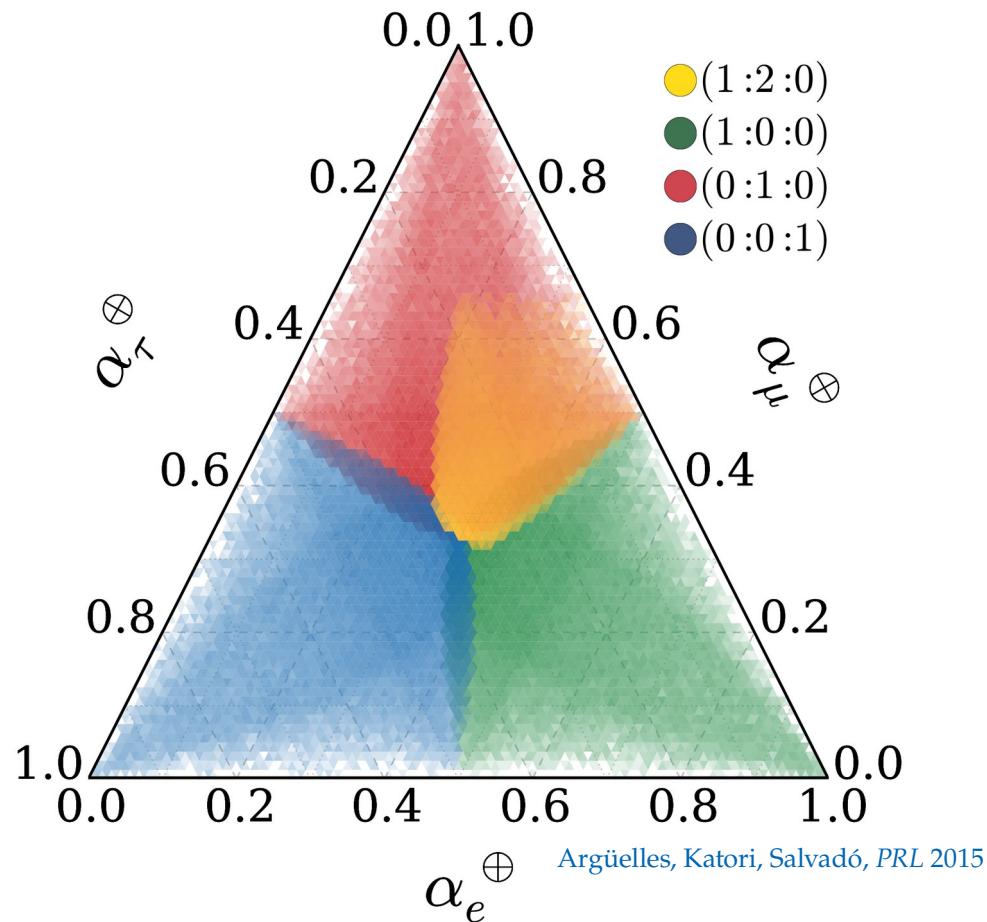
[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

- Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]

- Lorentz- and CPT-invariance violation

[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- ▶ Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

- ▶ Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]

- ▶ Lorentz- and CPT-invariance violation

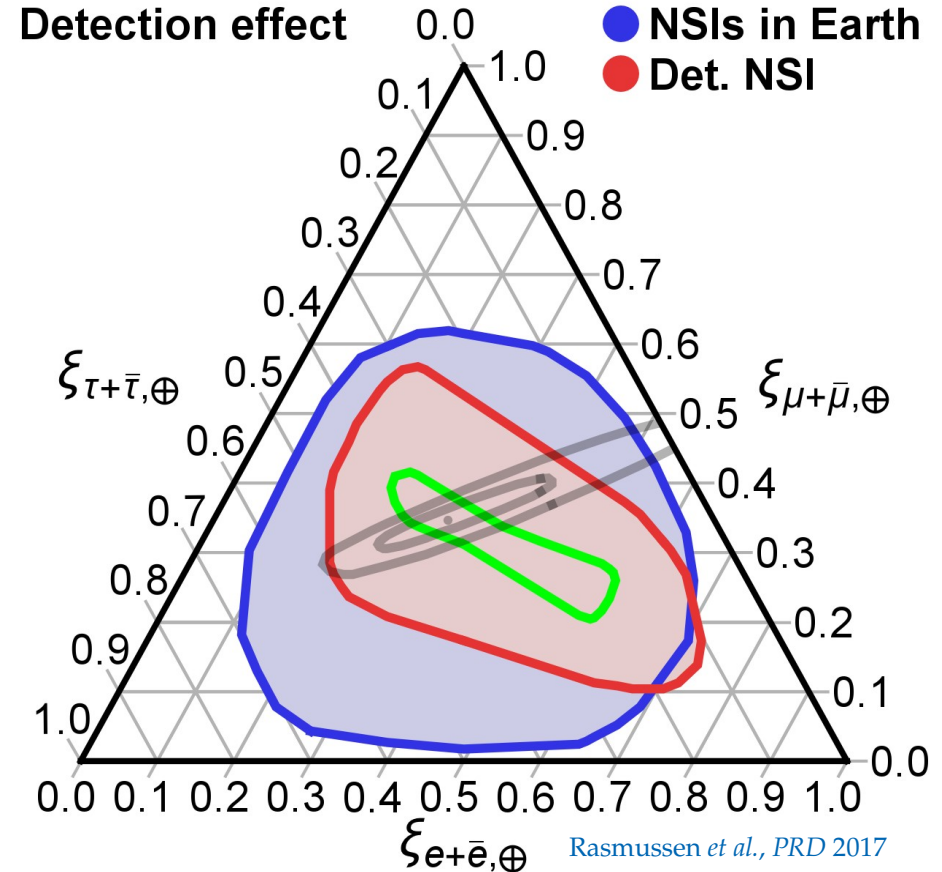
[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- ▶ Non-standard interactions

[González-García *et al.*, *Astropart. Phys.* 2016;
Rasmussen *et al.*, *PRD* 2017]

Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- ▶ Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

- ▶ Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]

- ▶ Lorentz- and CPT-invariance violation

[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- ▶ Non-standard interactions

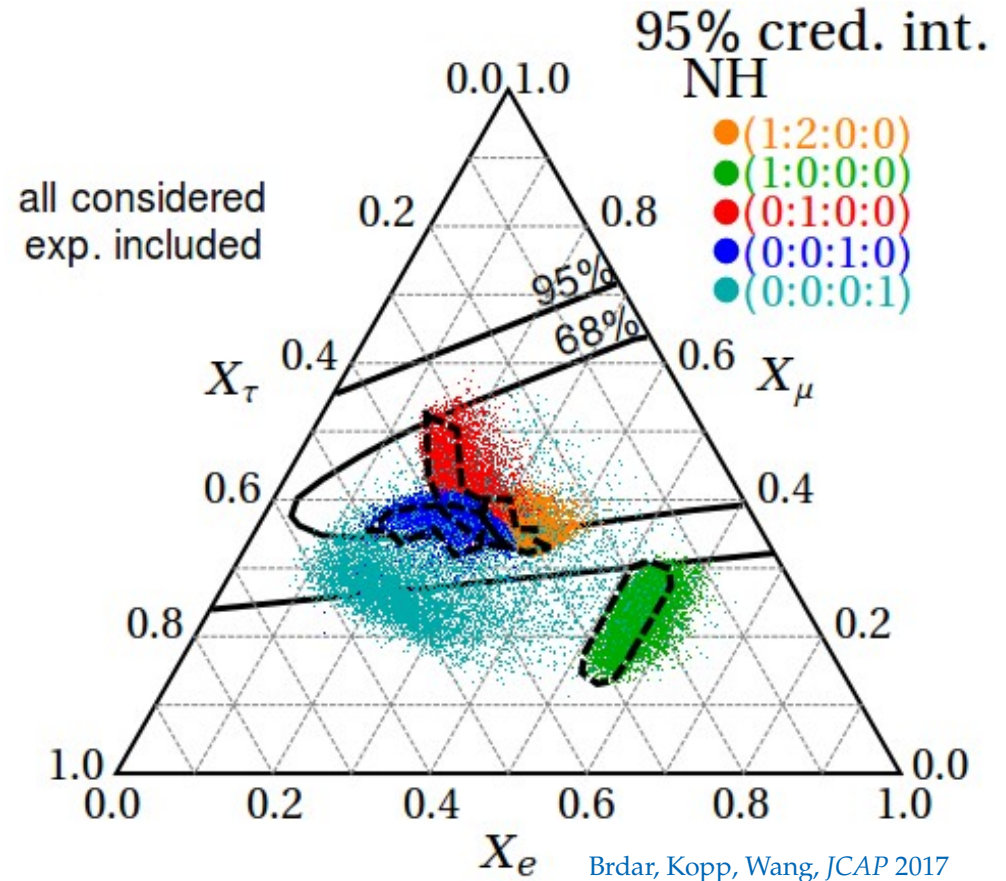
[González-García *et al.*, *Astropart. Phys.* 2016;
Rasmussen *et al.*, *PRD* 2017]

- ▶ Active-sterile ν mixing

[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]

Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- Neutrino decay

[Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, *JCAP* 2010;
MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]

- Tests of unitarity at high energy

[Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
Ahlers, **MB**, Nortvig, *JCAP* 2021]

- Lorentz- and CPT-invariance violation

[Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]

- Non-standard interactions

[González-García *et al.*, *Astropart. Phys.* 2016;
Rasmussen *et al.*, *PRD* 2017]

- Active-sterile ν mixing

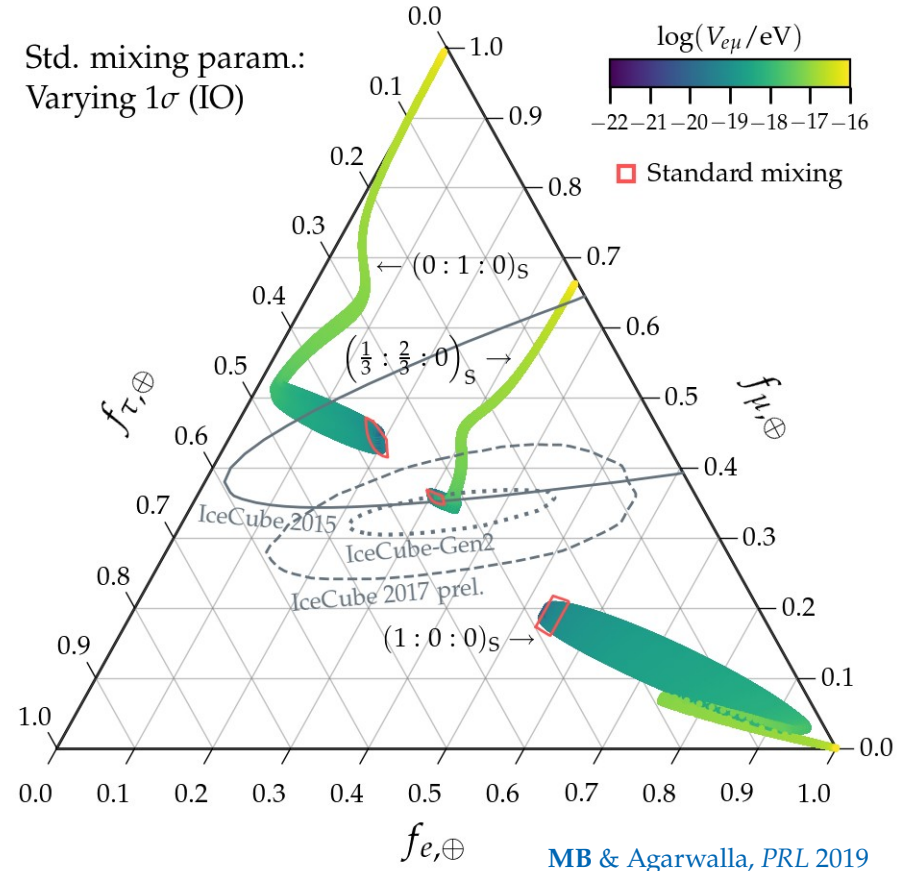
[Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]

- Long-range $e\nu$ interactions

[**MB** & Agarwalla, *PRL* 2019]

Reviews:

Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



4. Unstable neutrinos: *Are neutrinos for ever?*

Are neutrinos forever?

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

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

Are neutrinos forever?

- ▶ In the Standard Model (vSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):

- ▶ One-photon decay ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36} (m_i/\text{eV})^{-5}$ yr

- ▶ Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57} (m_i/\text{eV})^{-9}$ yr

- ▶ Three-neutrino decay ($\nu_i \rightarrow \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55} (m_i/\text{eV})^{-5}$ yr

» Age of Universe
(~ 14.5 Gyr)

- ▶ BSM decays may have significantly higher rates: $\nu_i \rightarrow \nu_j + \phi$

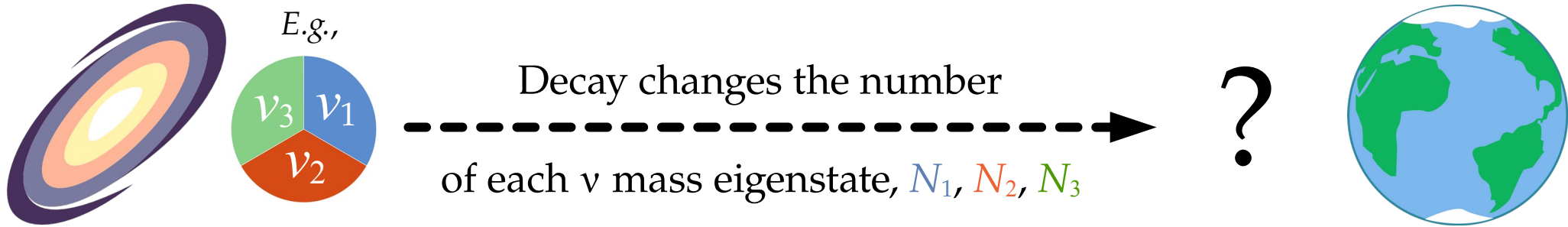
Nambu-Goldstone
boson of a broken
symmetry

- ▶ We work in a model-independent way:
the nature of ϕ is unimportant if it is invisible to neutrino detectors

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (\underbrace{m_i}_{\text{Mass of } \nu_i} / \underbrace{\tau_i}_{\text{Lifetime of } \nu_i})]$

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



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

?



Only sensitive to their ratio

The flux of ν_i is attenuated by $\exp[- (L/E) \cdot \overbrace{(m_i/\tau_i)}^{\text{Mass of } \nu_i \text{ Lifetime of } \nu_i}]$

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



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

?



Lower- E ν are longer-lived...

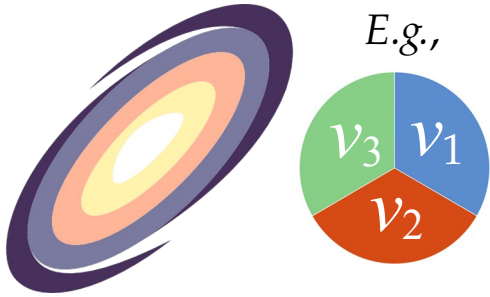
The flux of ν_i is attenuated by $\exp[- (L/E) \cdot (m_i/\tau_i)]$

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

Astrophysical sources

Earth

$L \sim$ up to a few Gpc



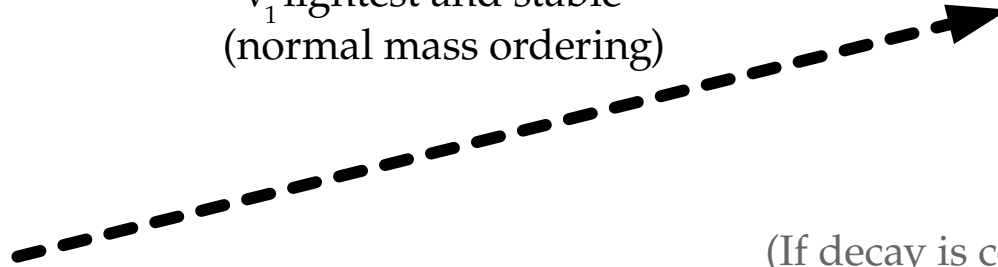
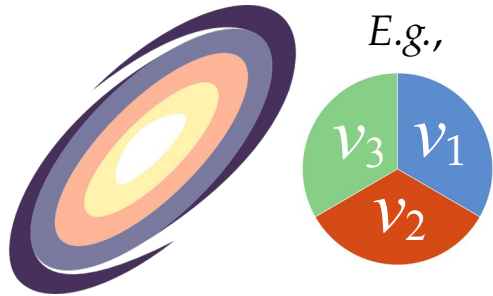
Astrophysical sources

Earth

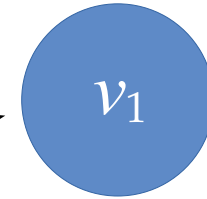
$L \sim \text{up to a few Gpc}$

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

ν_1 lightest and stable
(normal mass ordering)



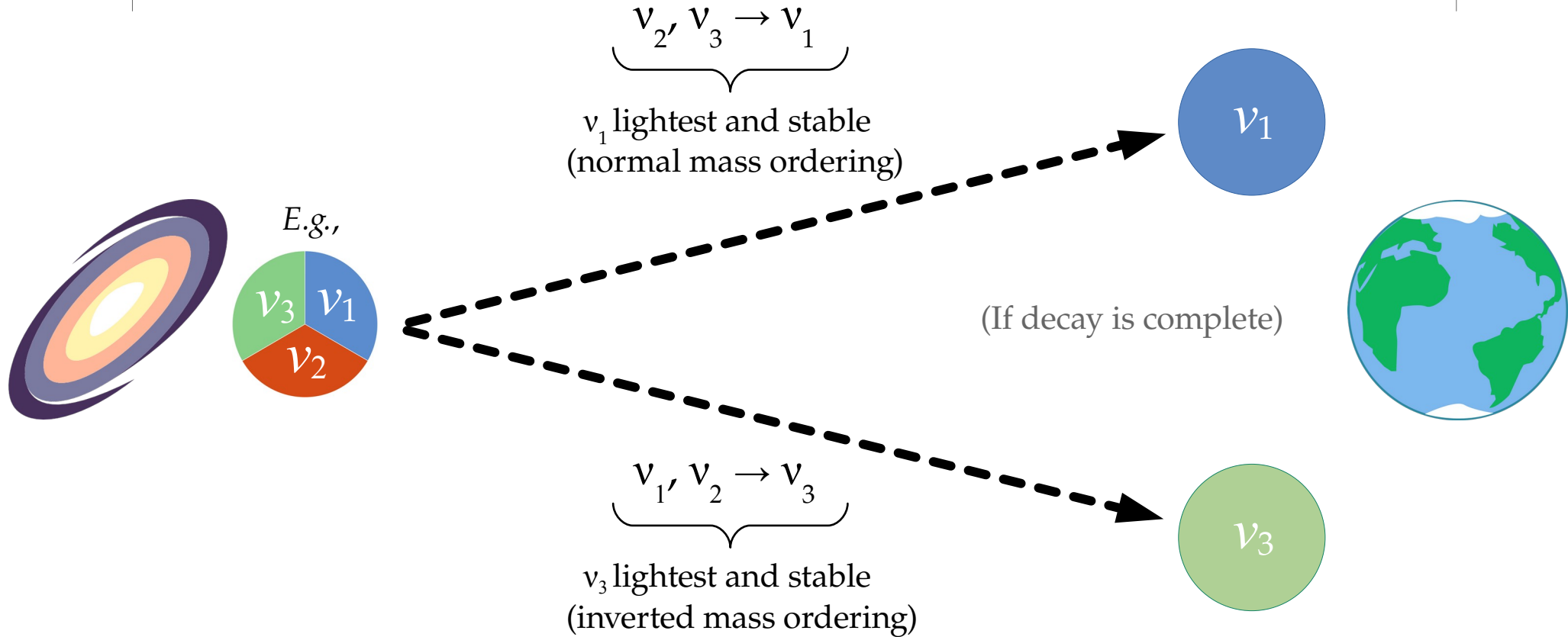
(If decay is complete)



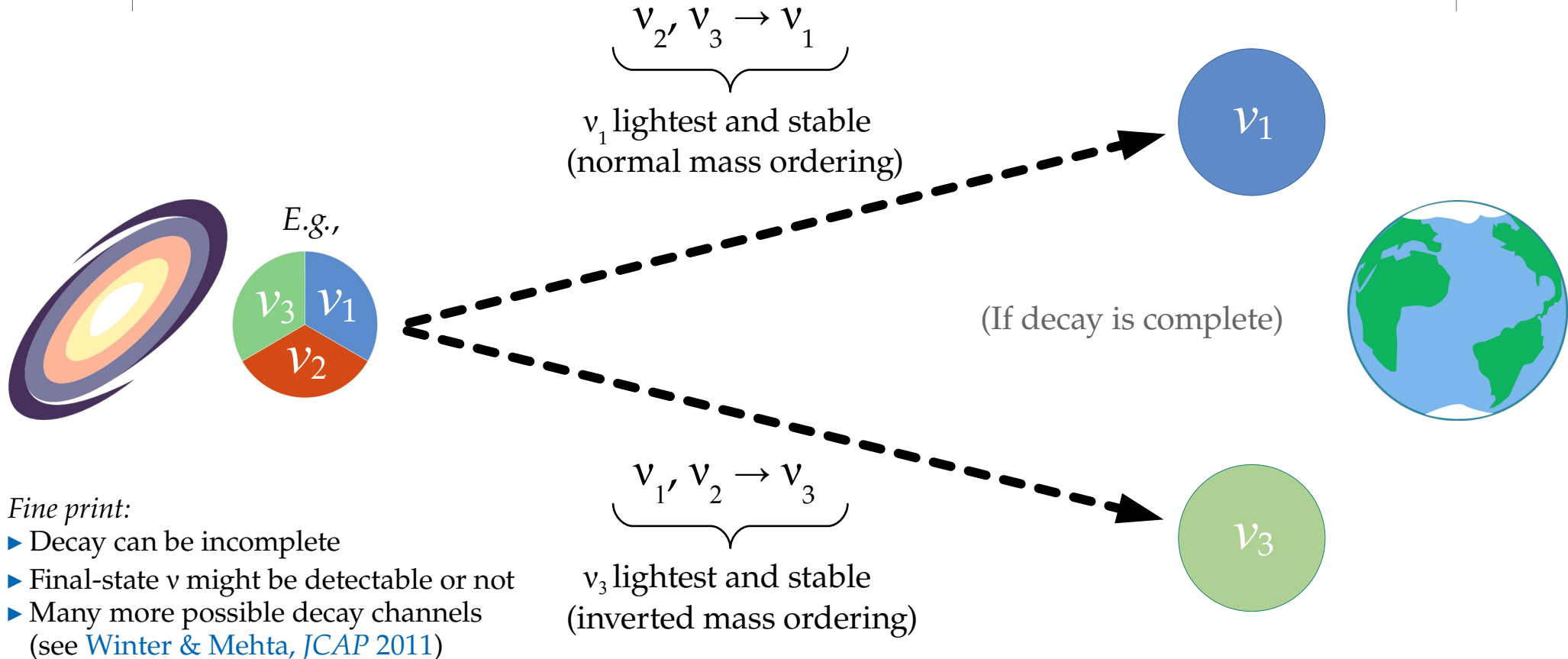
Astrophysical sources

Earth

$L \sim \text{up to a few Gpc}$



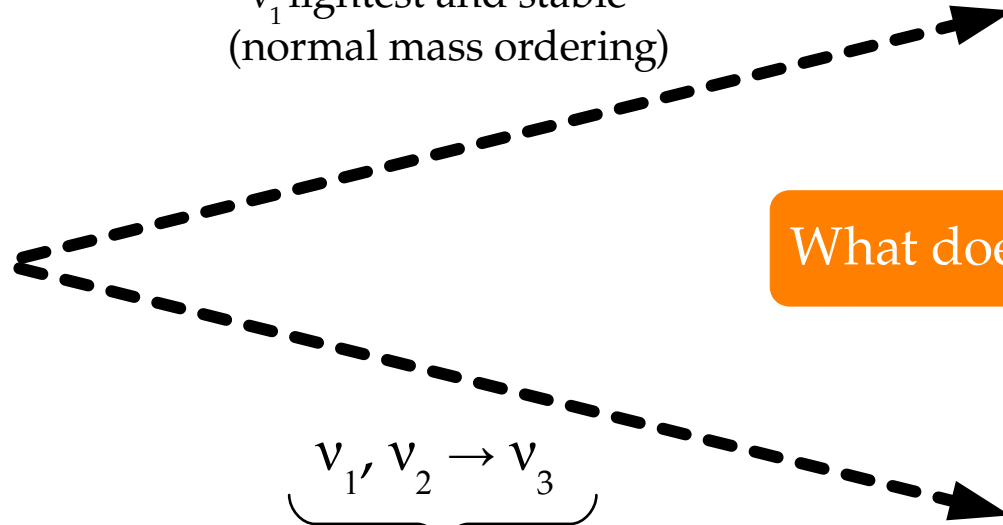
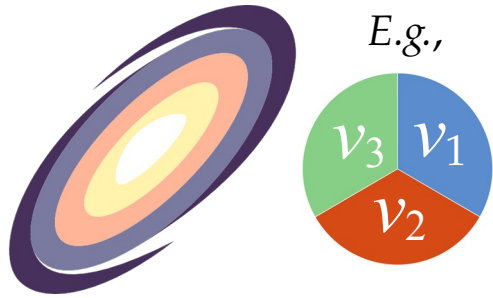
$L \sim \text{up to a few Gpc}$



$L \sim \text{up to a few Gpc}$

$$\nu_{2'}, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)



What does decay change?



$$\nu_{1'}, \nu_2 \rightarrow \nu_3$$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

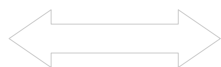
- Decay can be incomplete
- Final-state ν might be detectable or not
- Many more possible decay channels
(see [Winter & Mehta, JCAP 2011](#))

What does neutrino decay change?

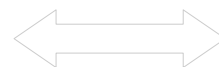
Flavor composition $\longleftrightarrow$ Spectrum shape $\longleftrightarrow$ Event rate

What does neutrino decay change?

Flavor composition



Spectrum shape



Event rate

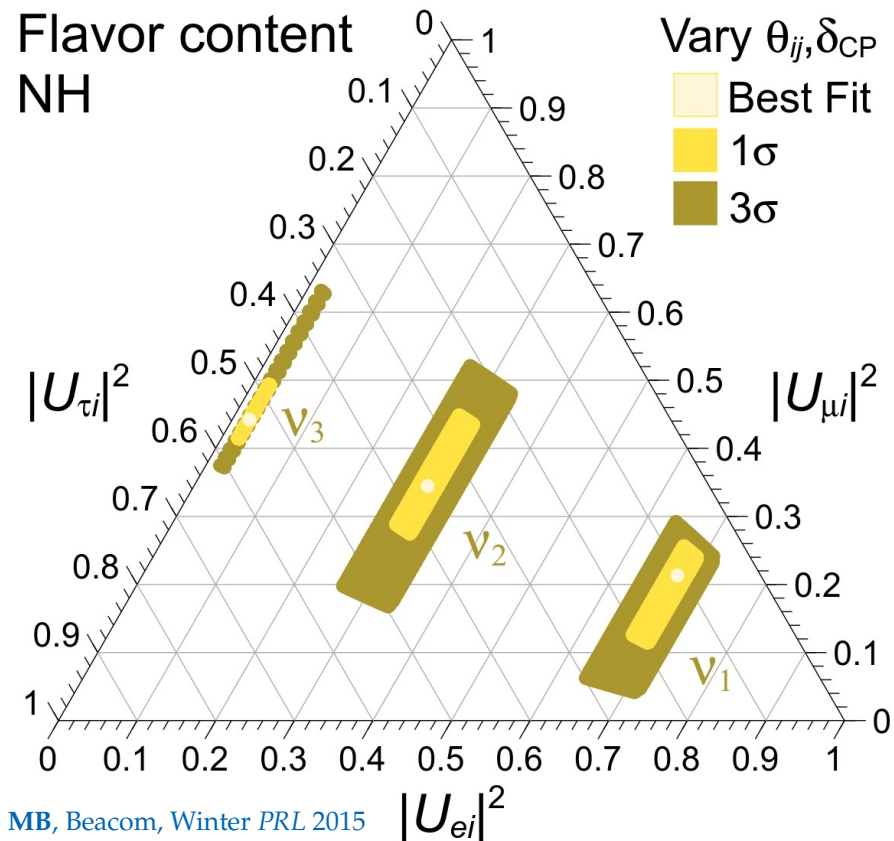
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20%
(or worse)



What does neutrino decay change?

Flavor composition



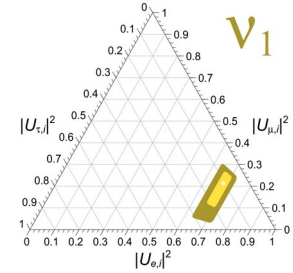
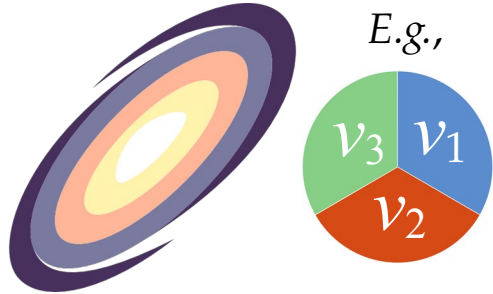
Spectrum shape



Event rate

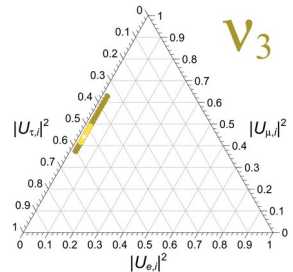
$$\nu_{2'}, \nu_3 \rightarrow \nu_1$$

ν_1 lightest and stable
(normal mass ordering)



$$\nu_{1'}, \nu_2 \rightarrow \nu_3$$

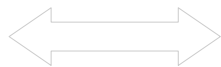
ν_3 lightest and stable
(inverted mass ordering)



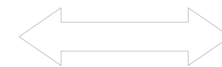
What does neutrino decay change?

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

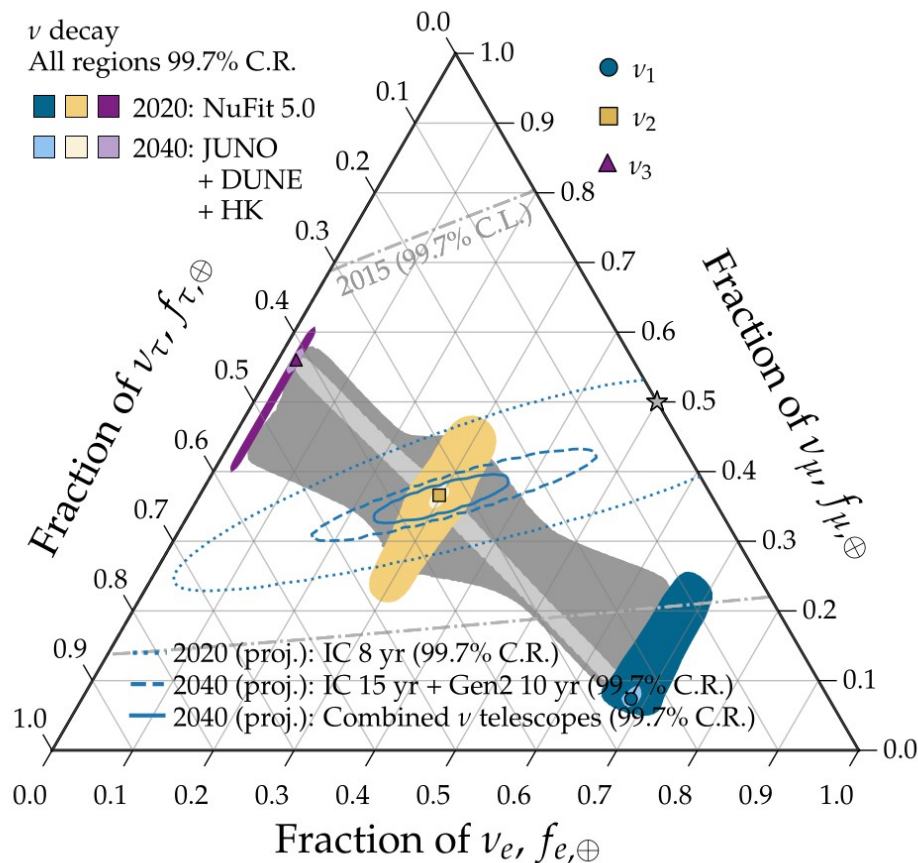
Flavor composition



Spectrum shape



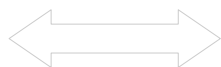
Event rate



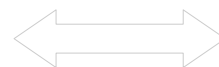
What does neutrino decay change?

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

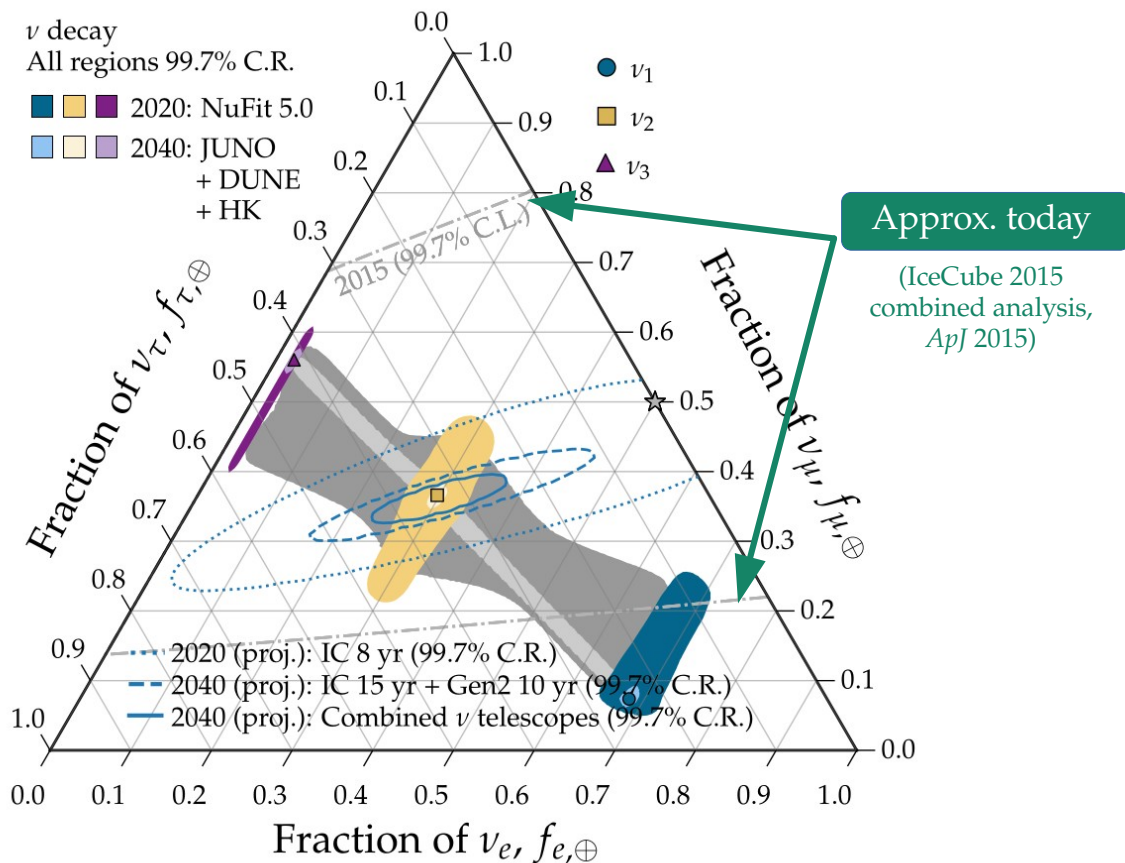
Flavor composition



Spectrum shape



Event rate



What does neutrino decay change?

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

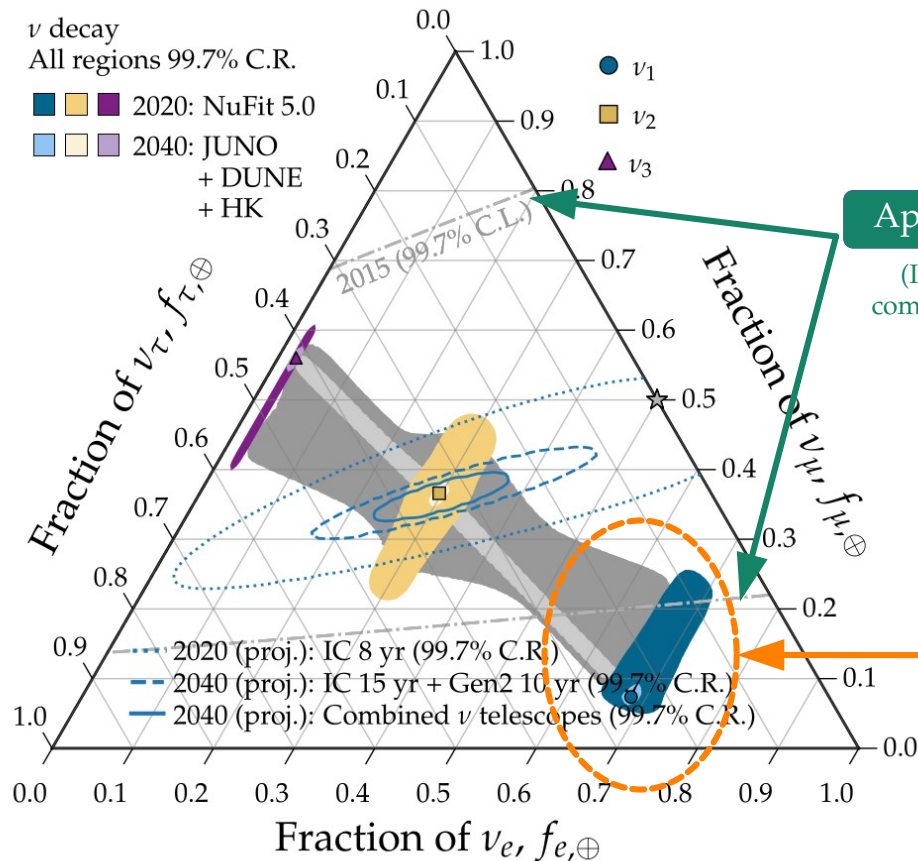
Flavor composition



Spectrum shape



Event rate



Approx. today

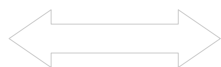
(IceCube 2015
combined analysis,
ApJ 2015)

Complete decay into
 ν_1 disfavored by 2015
IceCube flavor measurement

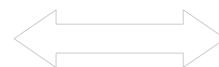
What does neutrino decay change?

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

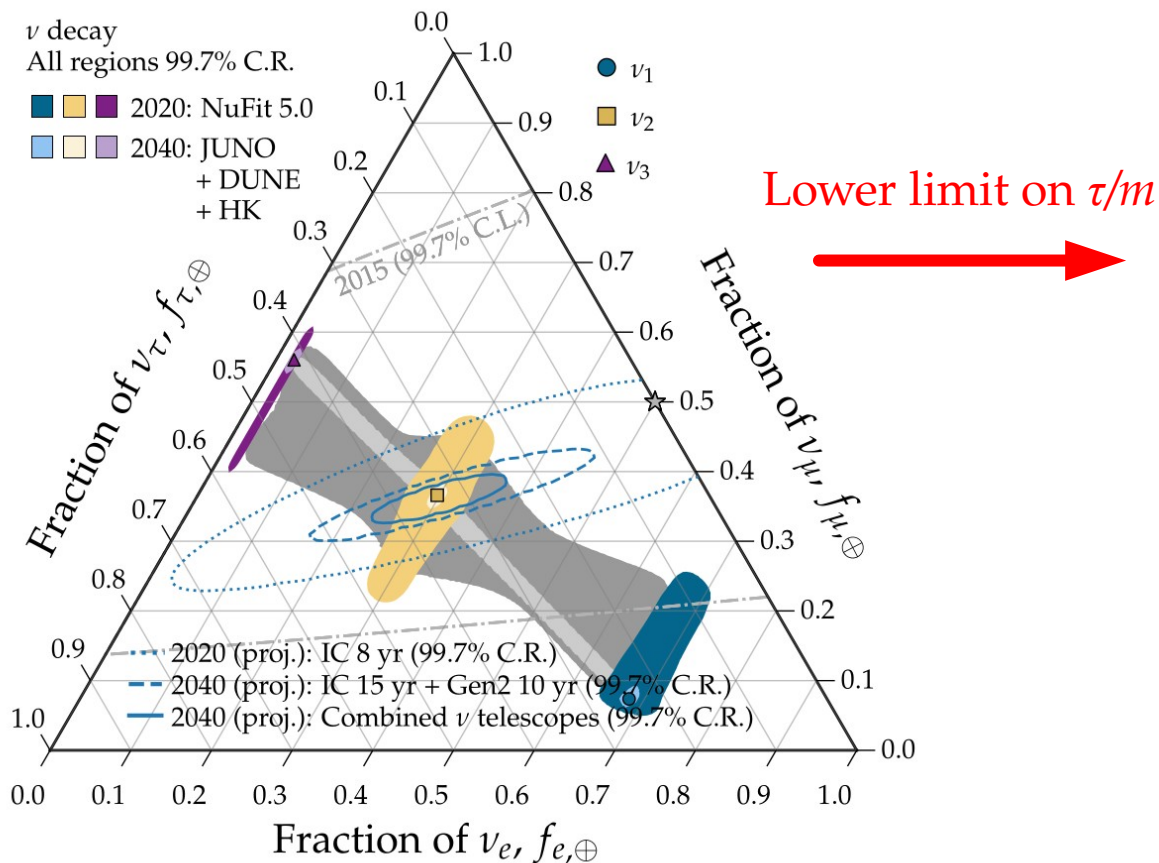
Flavor composition



Spectrum shape



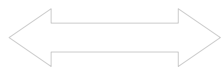
Event rate



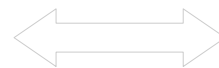
What does neutrino decay change?

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

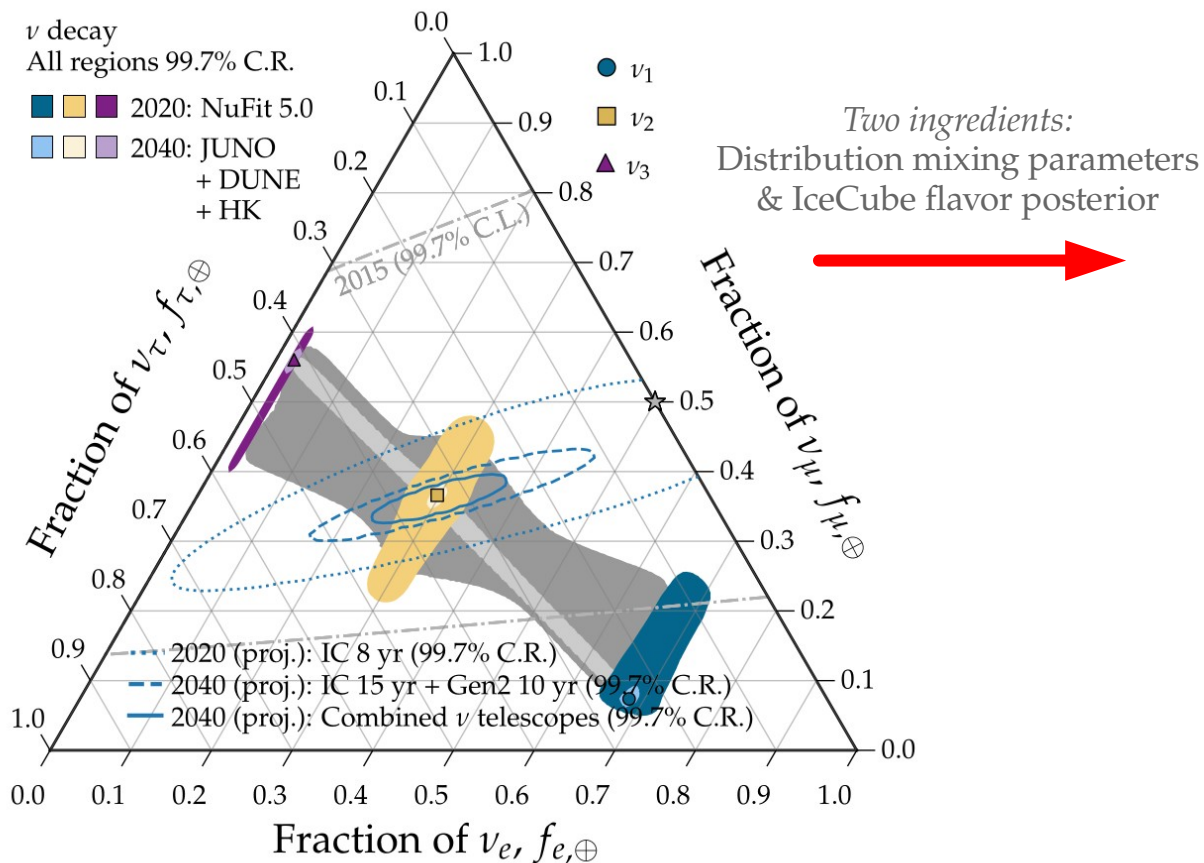
Flavor composition



Spectrum shape



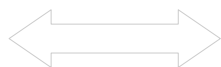
Event rate



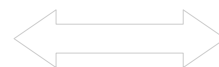
What does neutrino decay change?

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

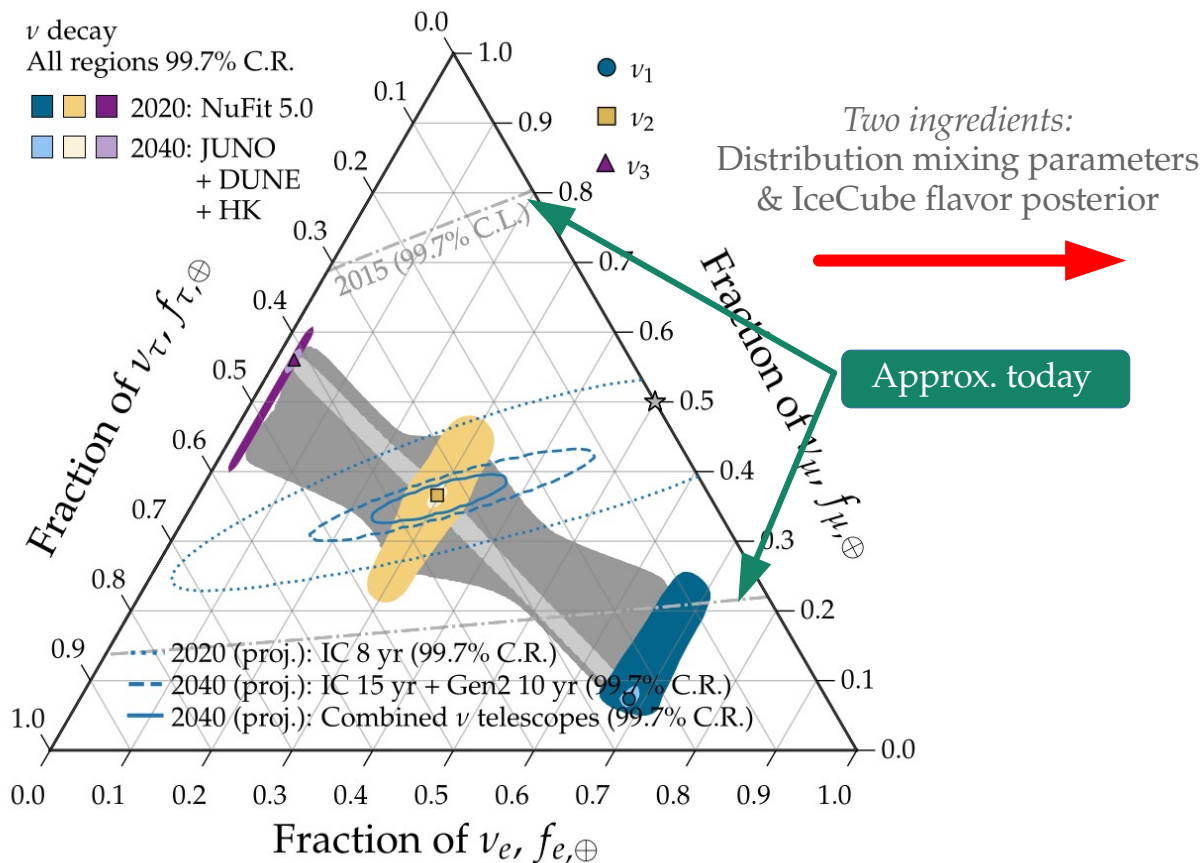
Flavor composition



Spectrum shape



Event rate



What does neutrino decay change?

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

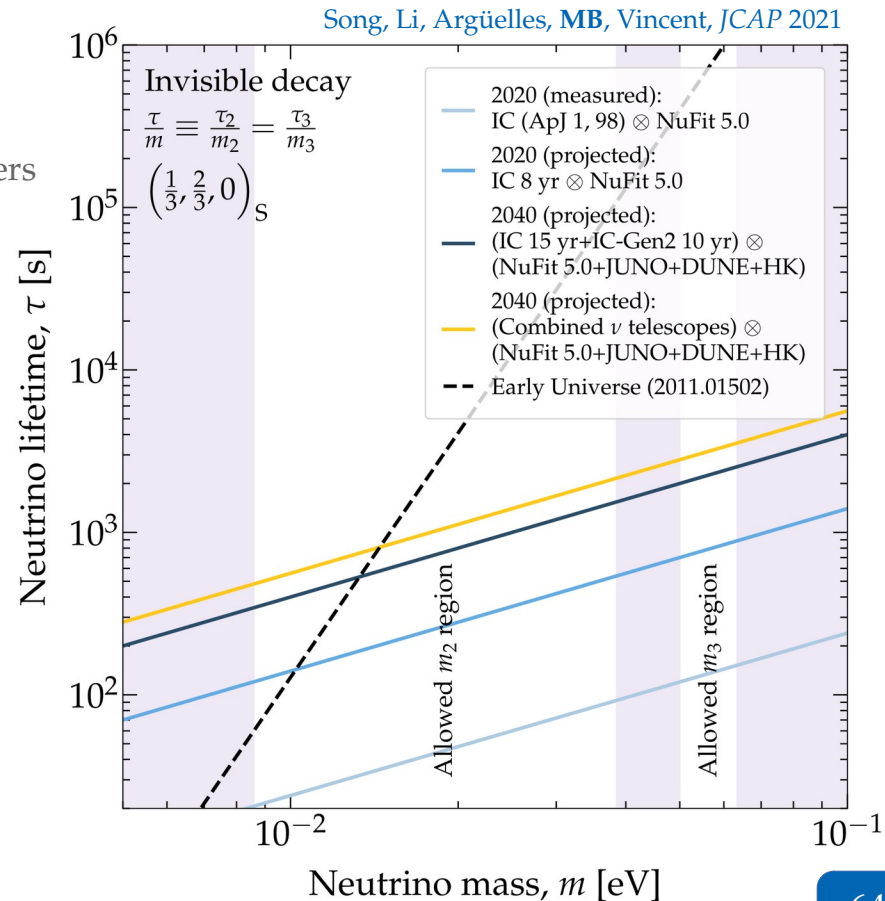
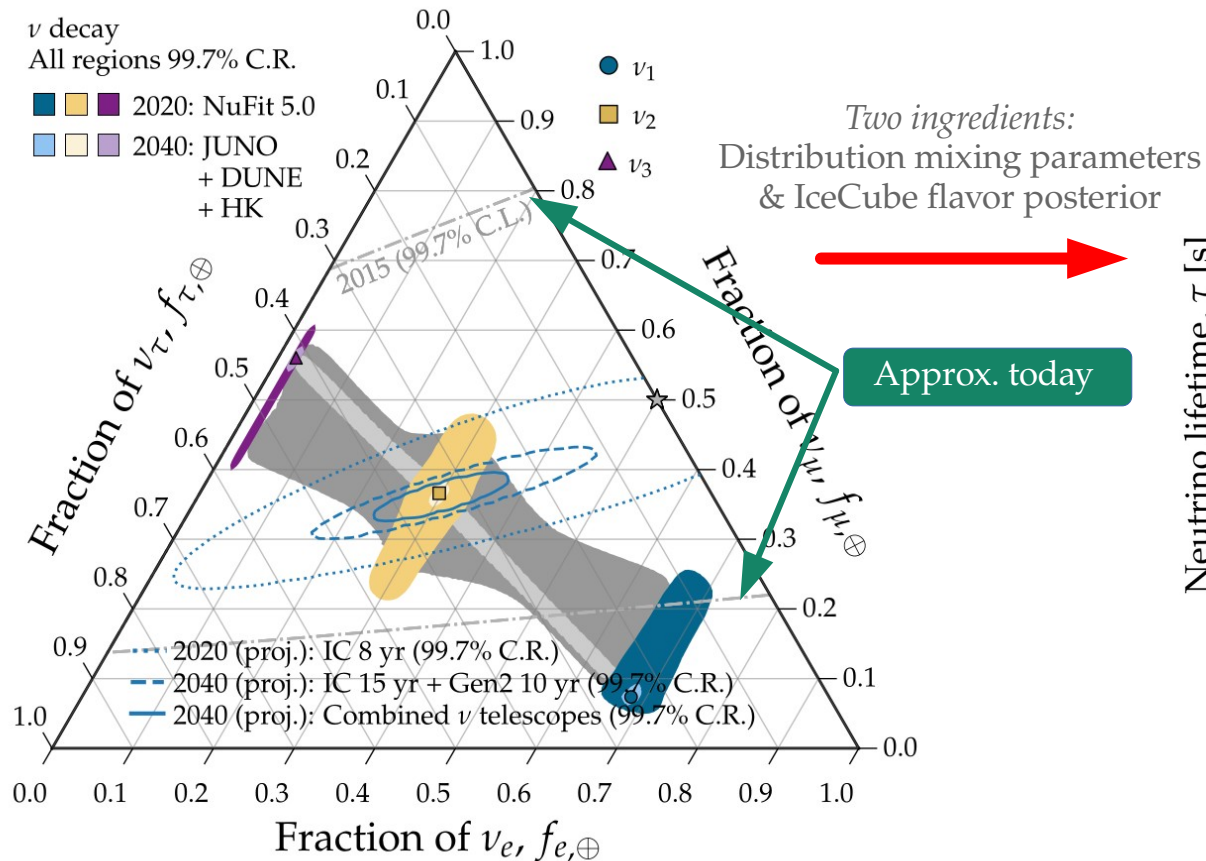
Flavor composition



Spectrum shape



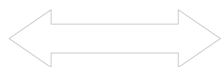
Event rate



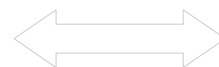
What does neutrino decay change?

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

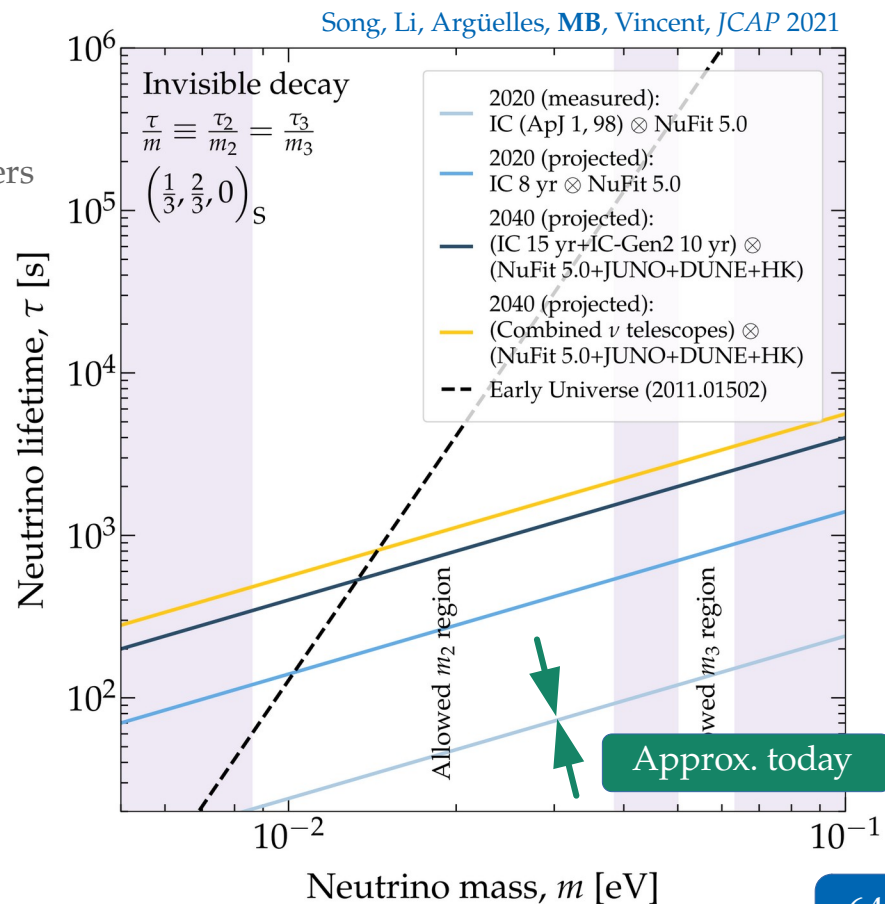
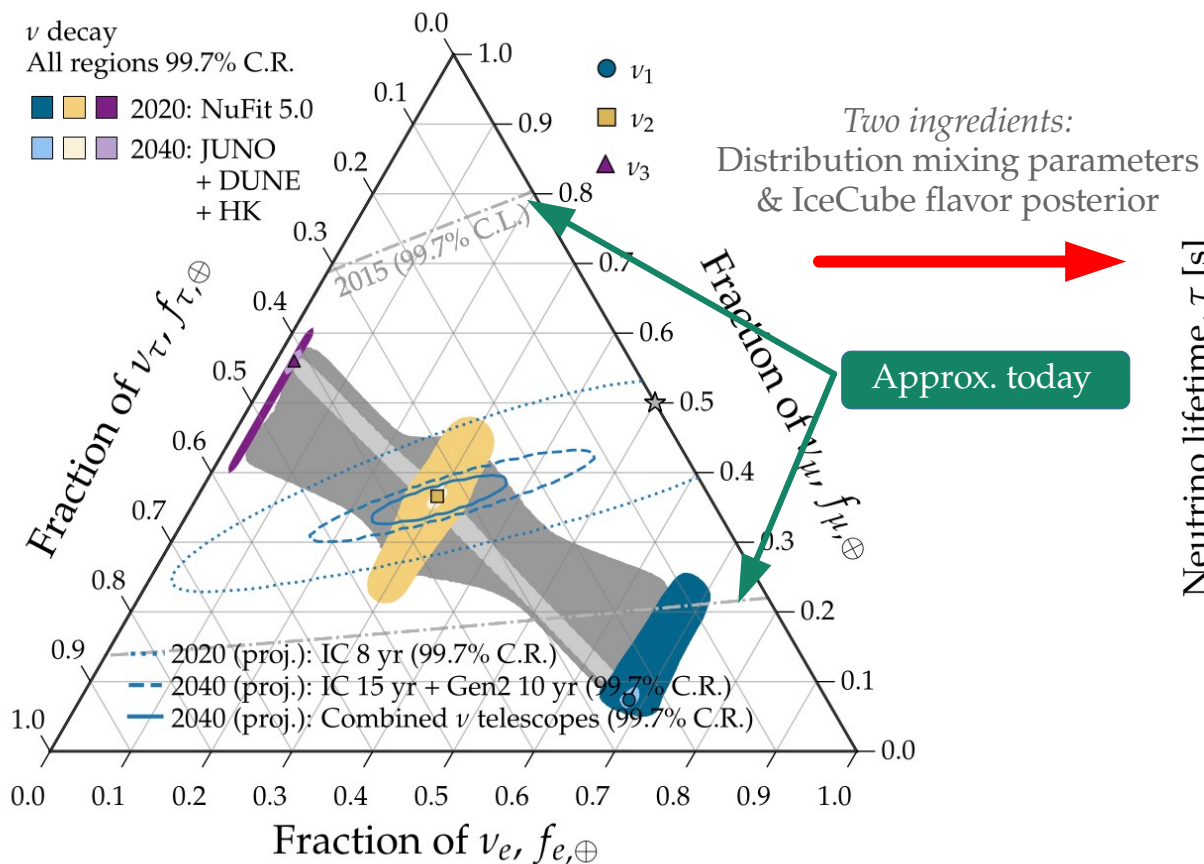
Flavor composition



Spectrum shape



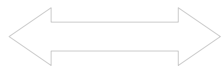
Event rate



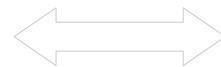
What does neutrino decay change?

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

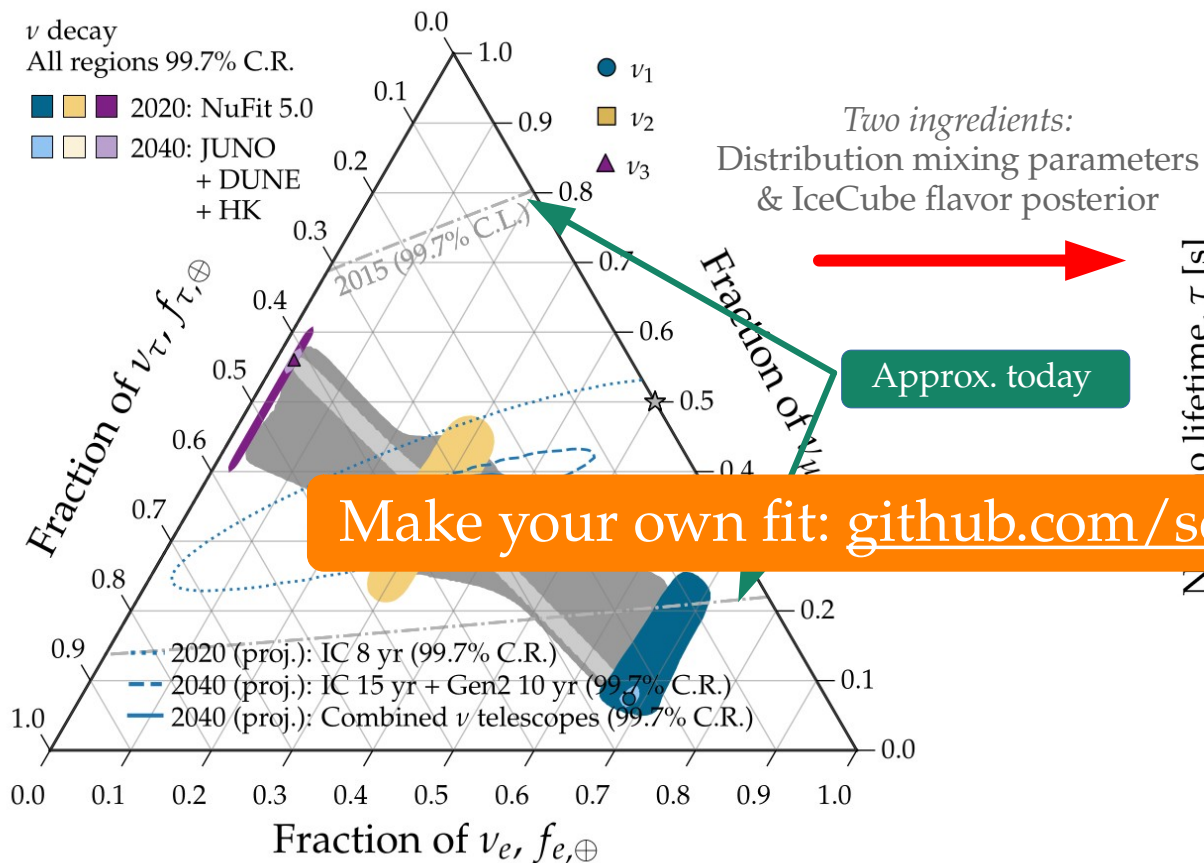
Flavor composition



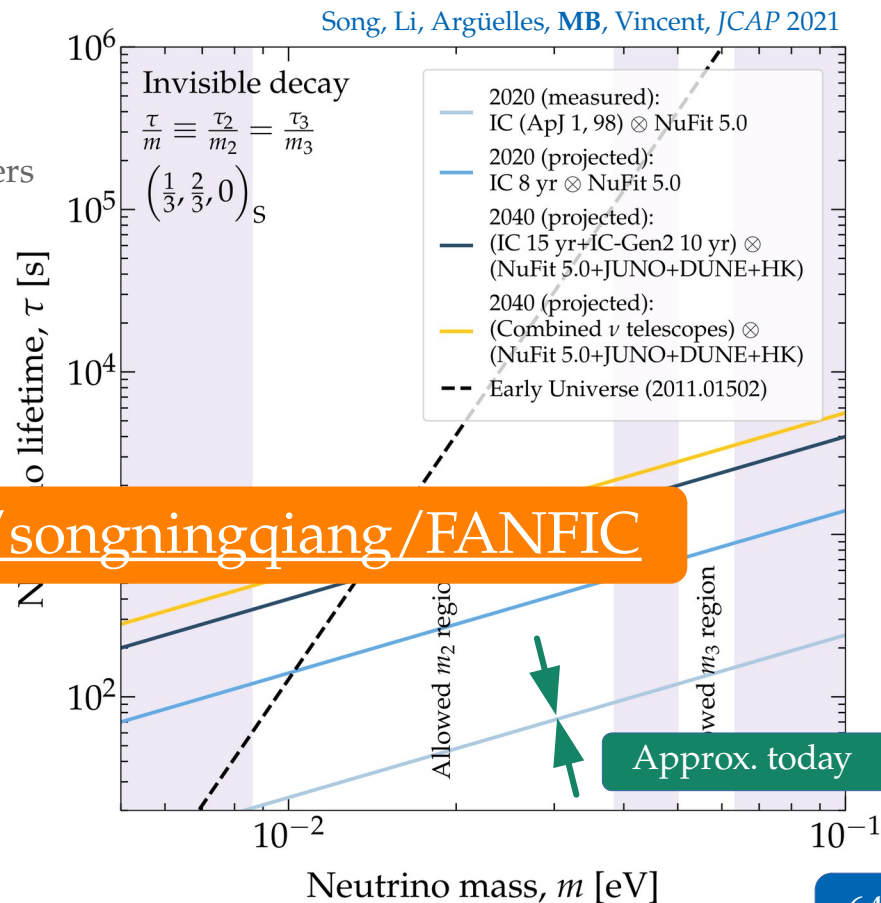
Spectrum shape



Event rate



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



What does neutrino decay change?

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

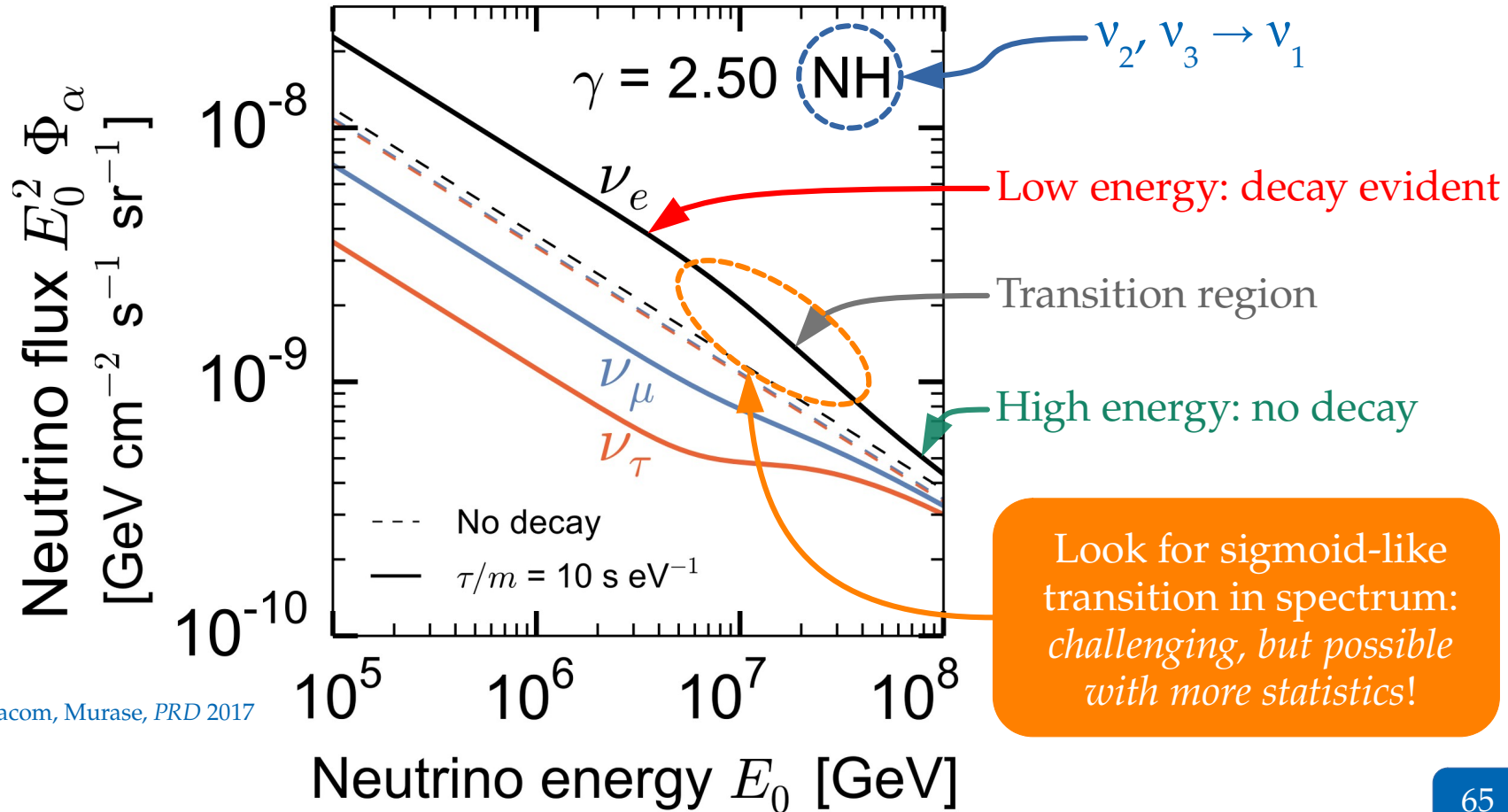
Flavor composition



Spectrum shape



Event rate

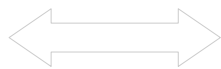


MB, Beacom, Murase, *PRD* 2017

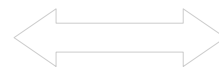
What does neutrino decay change?

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

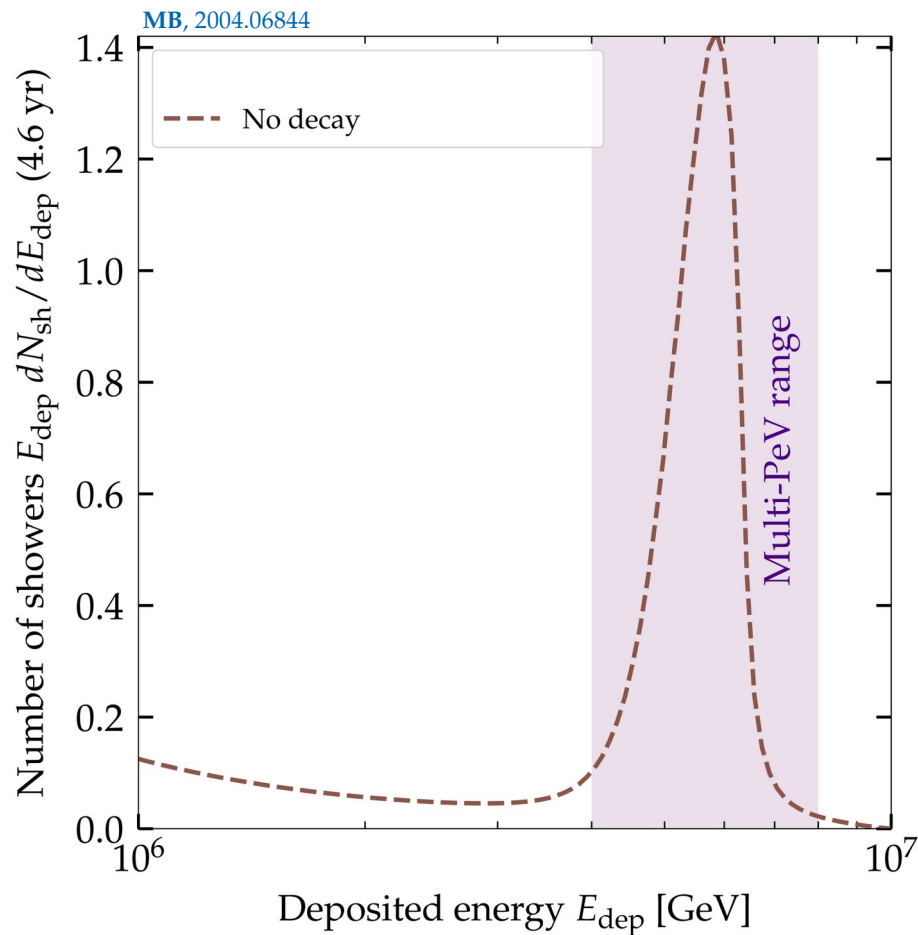
Flavor composition



Spectrum shape



Event rate



What does neutrino decay change?

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

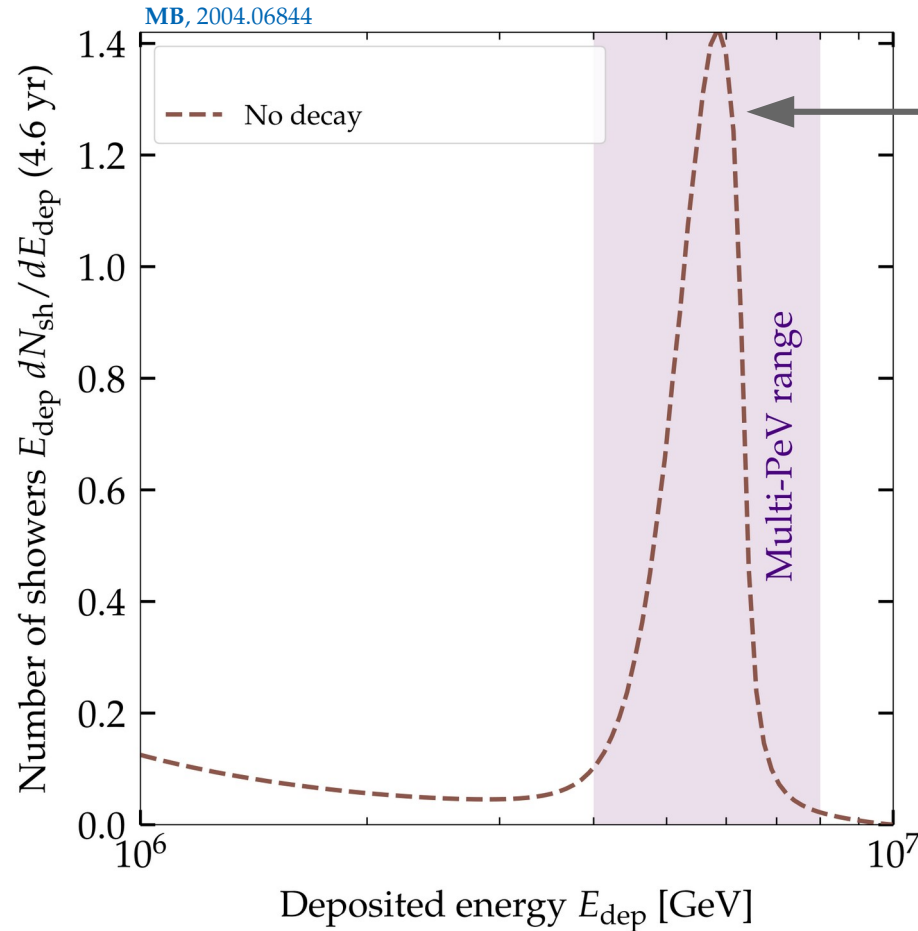
Flavor composition



Spectrum shape



Event rate

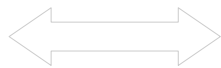


Glashow resonance (GR):
 $\bar{\nu}_e + e \rightarrow W \rightarrow \text{hadrons} \rightarrow \text{shower}$

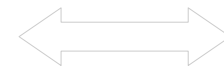
What does neutrino decay change?

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

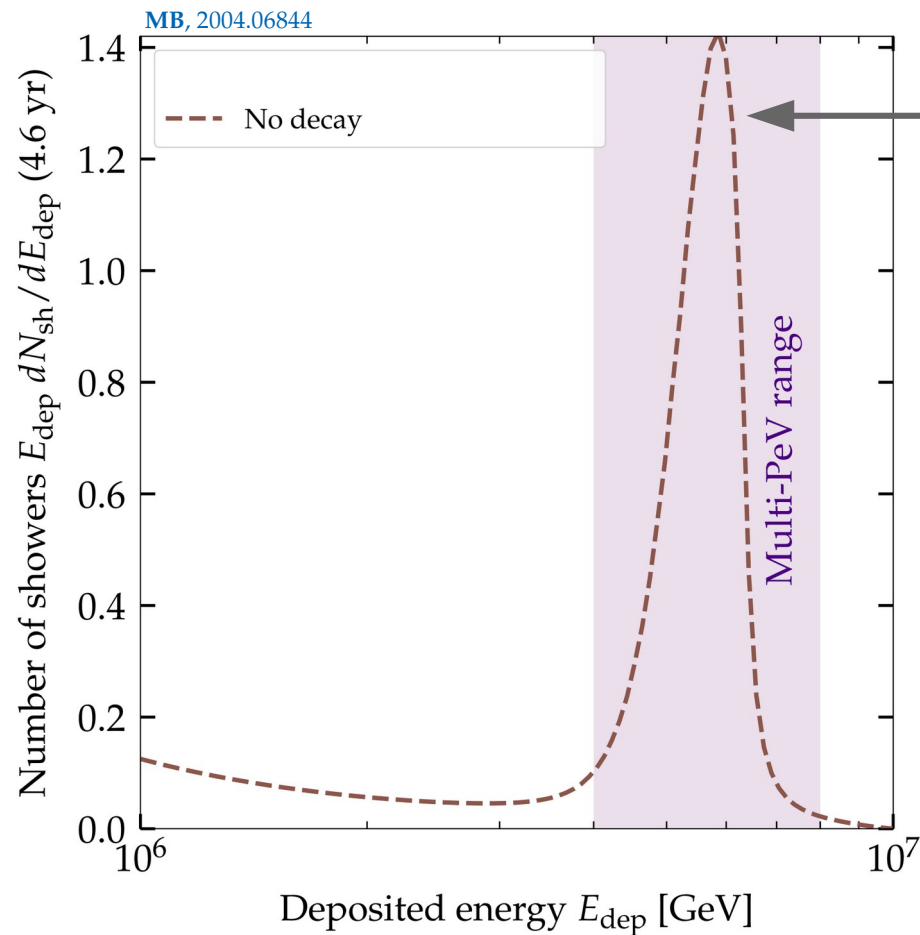
Flavor composition



Spectrum shape



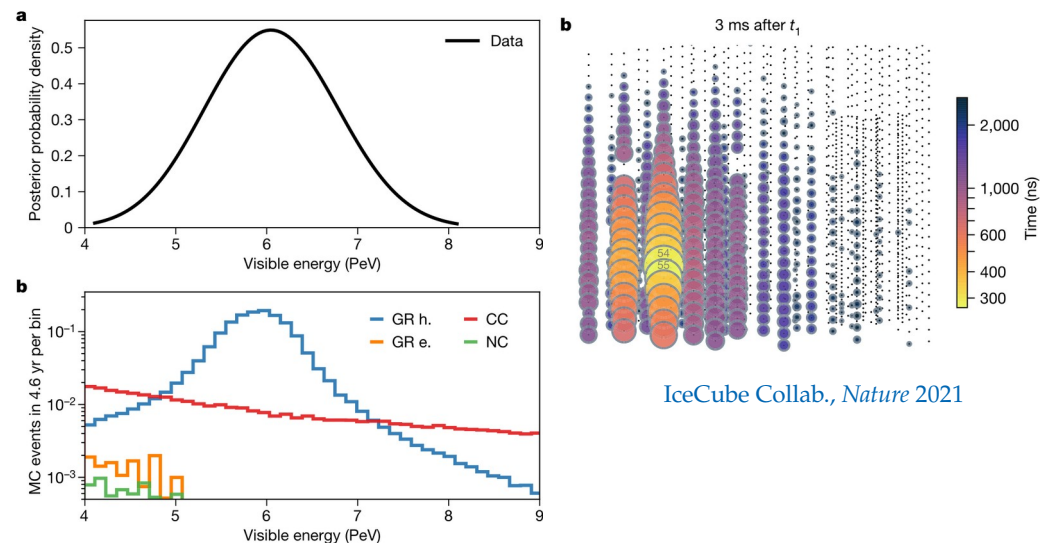
Event rate



Glashow resonance (GR):

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

IceCube has seen one GR candidate in 4.6 years:



IceCube Collab., *Nature* 2021

What does neutrino decay change?

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

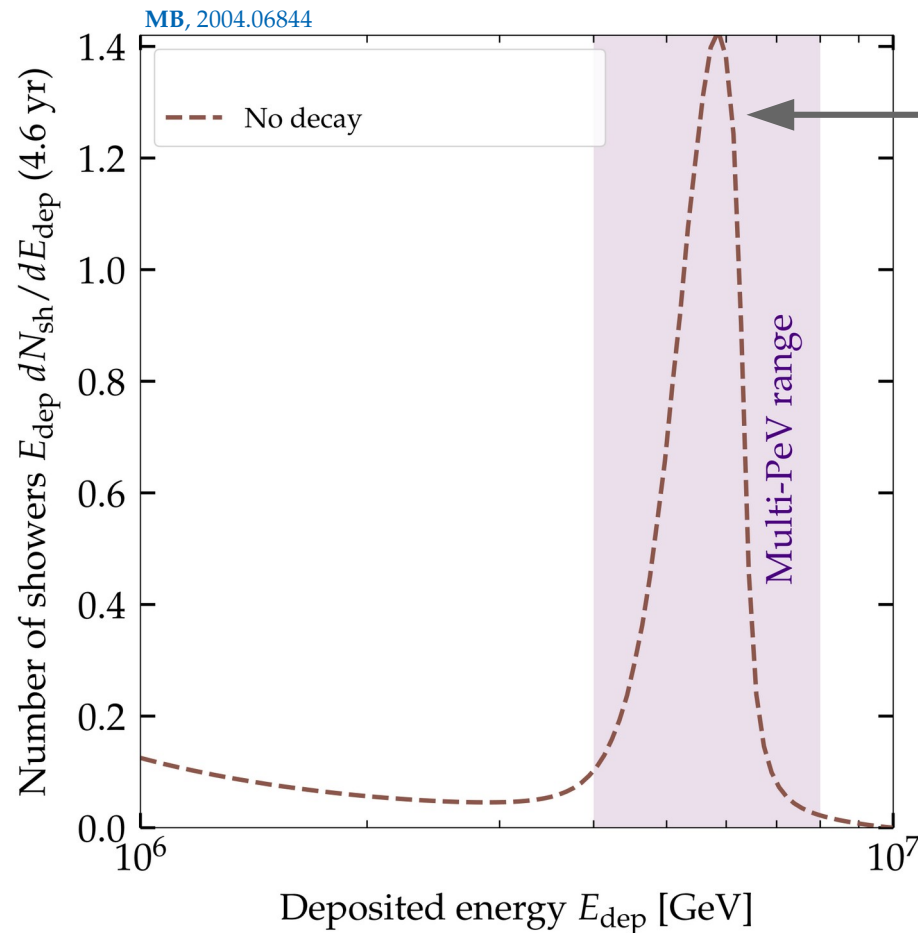
Flavor composition



Spectrum shape



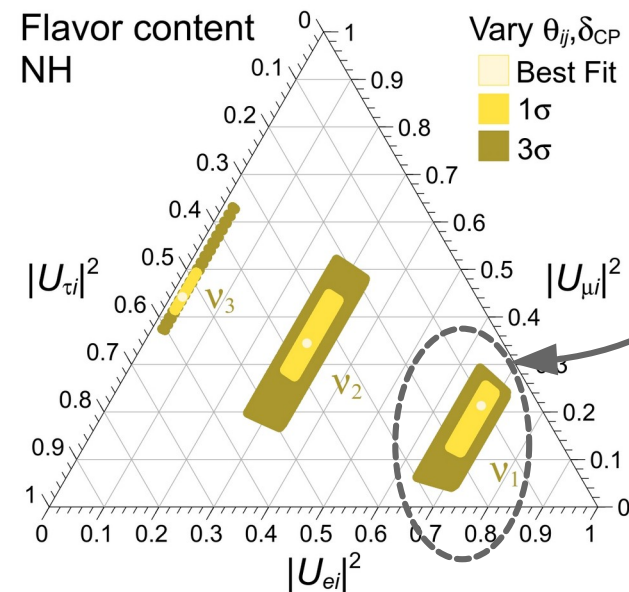
Event rate



Glashow resonance (GR):

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

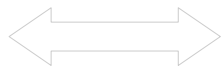
ν_1 is the mass eigenstate with the most e flavor



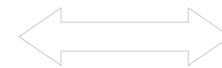
What does neutrino decay change?

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

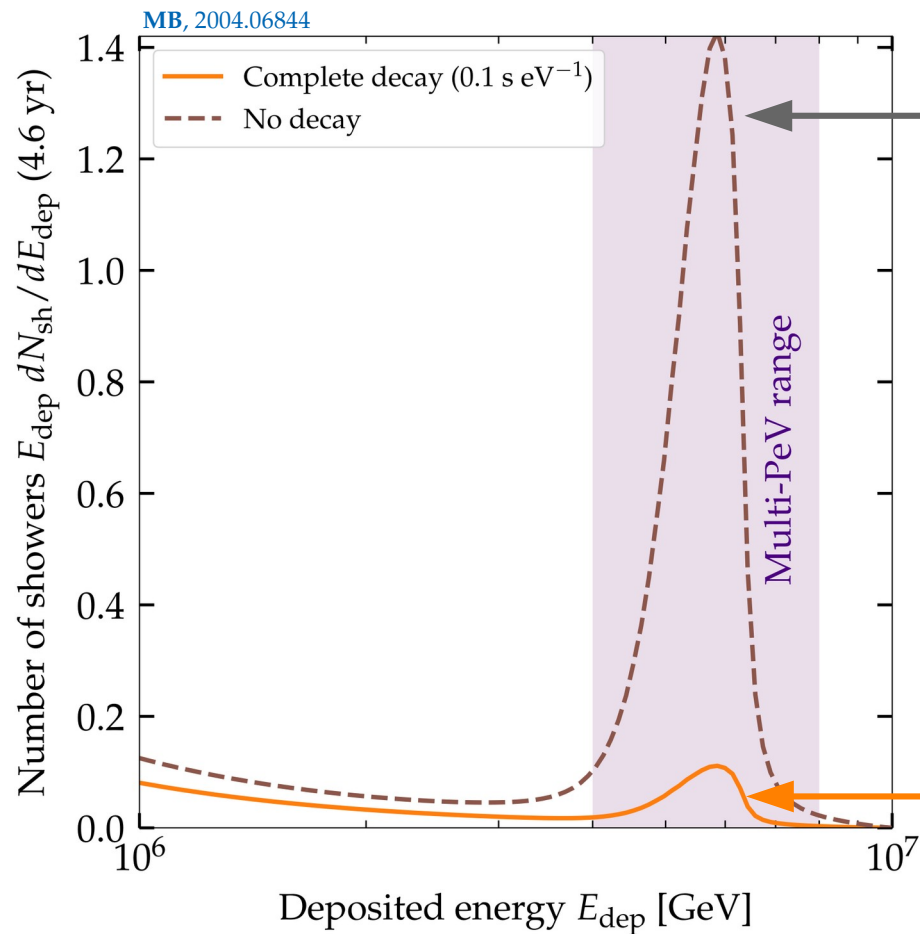
Flavor composition



Spectrum shape



Event rate



Glashow resonance (GR):

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

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

What does neutrino decay change?

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

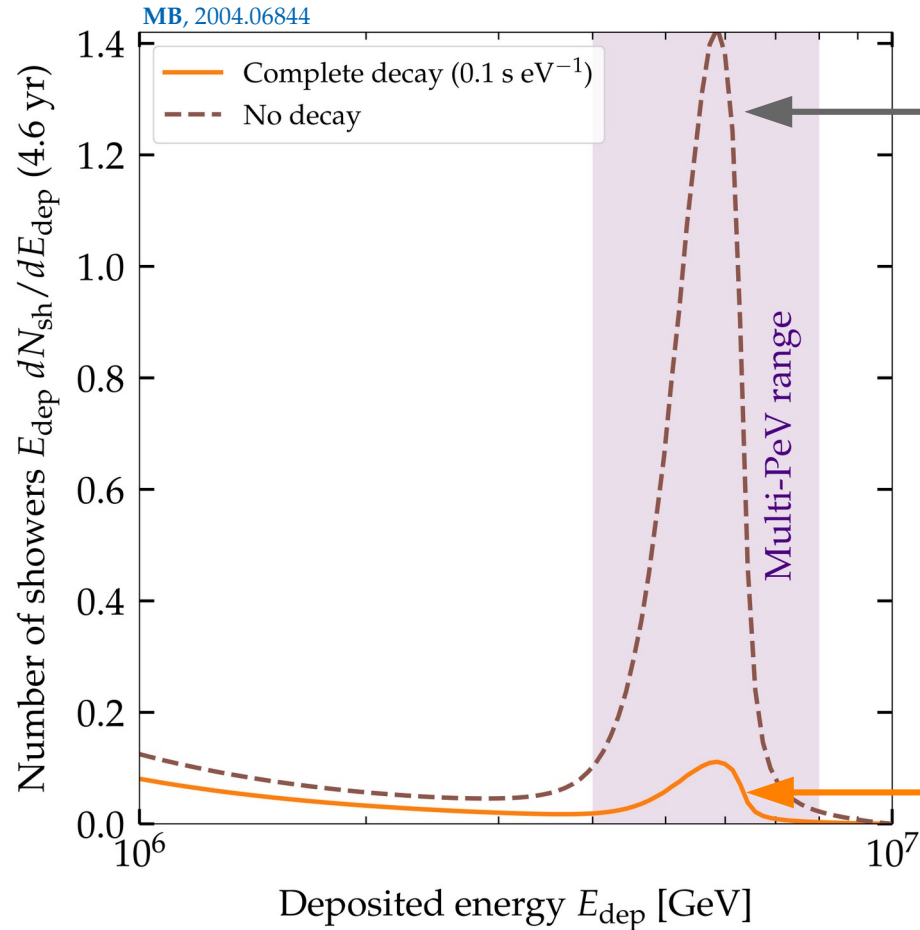
Flavor composition



Spectrum shape



Event rate



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

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

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

What does neutrino decay change?

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

Flavor composition

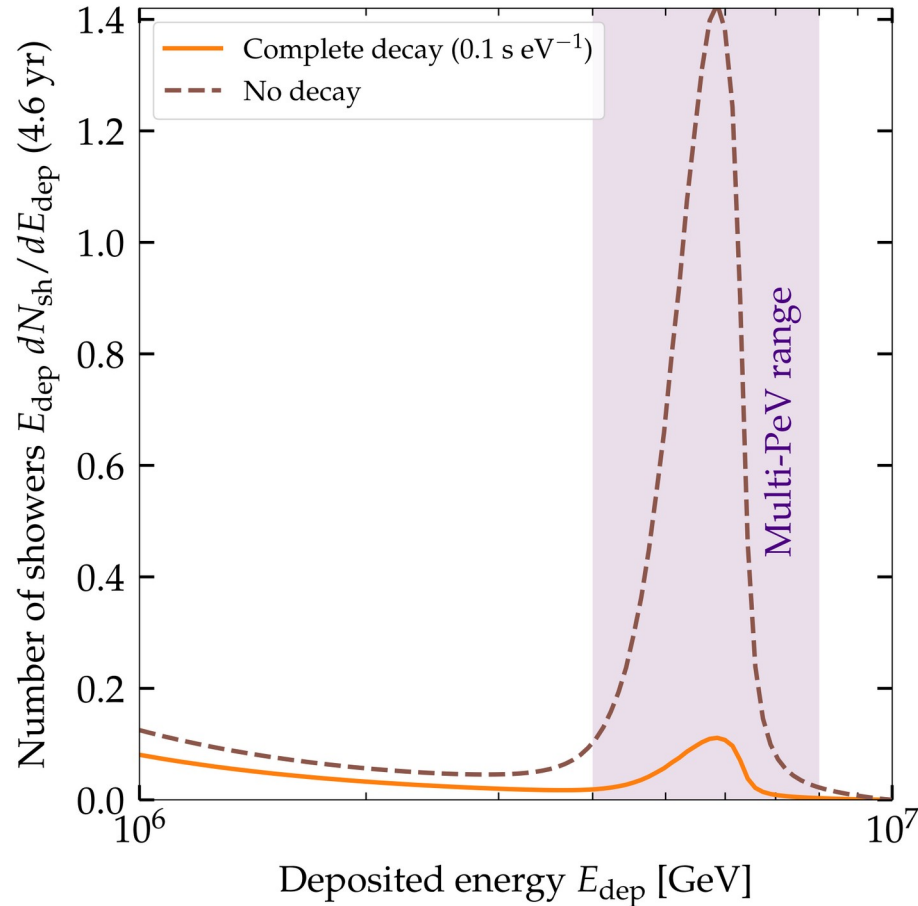


Spectrum shape



Event rate

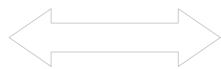
MB, 2004.06844



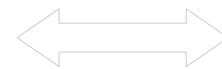
What does neutrino decay change?

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

Flavor composition

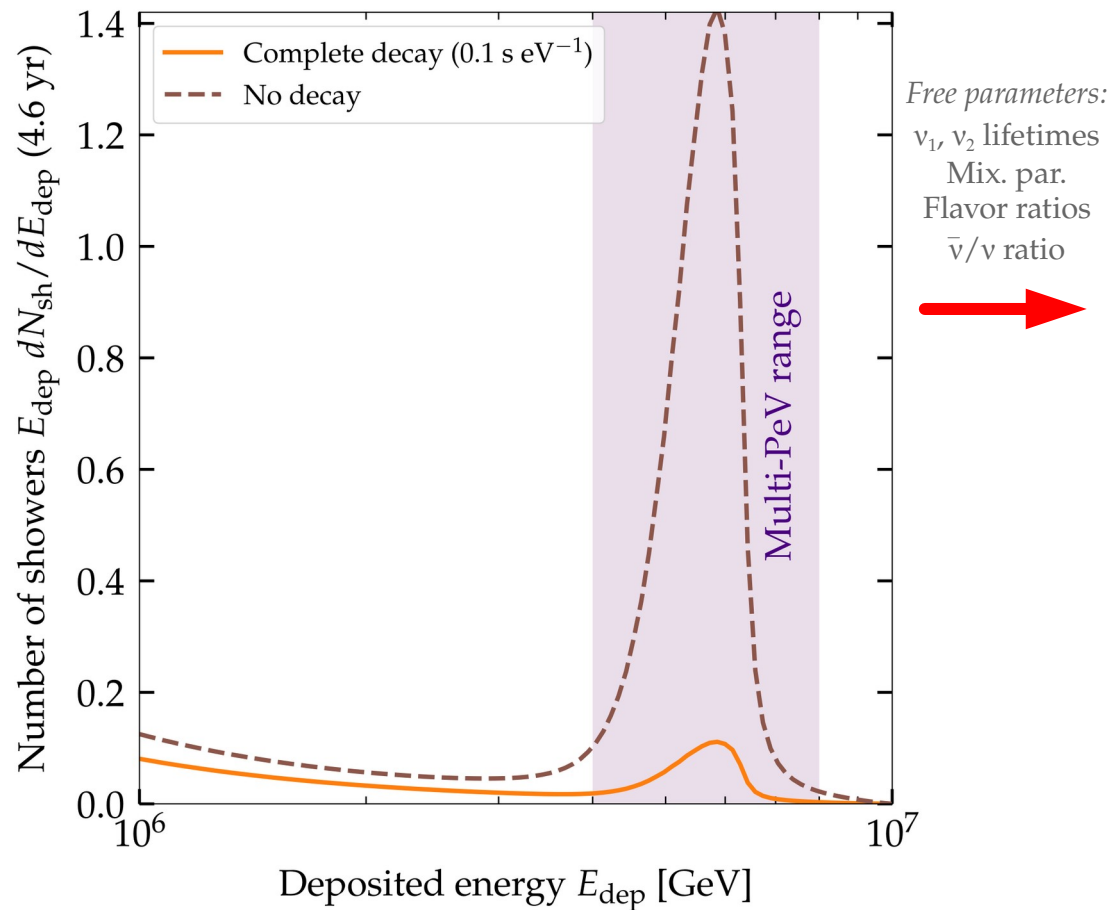


Spectrum shape



Event rate

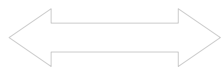
MB, 2004.06844



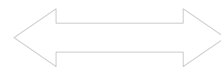
What does neutrino decay change?

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

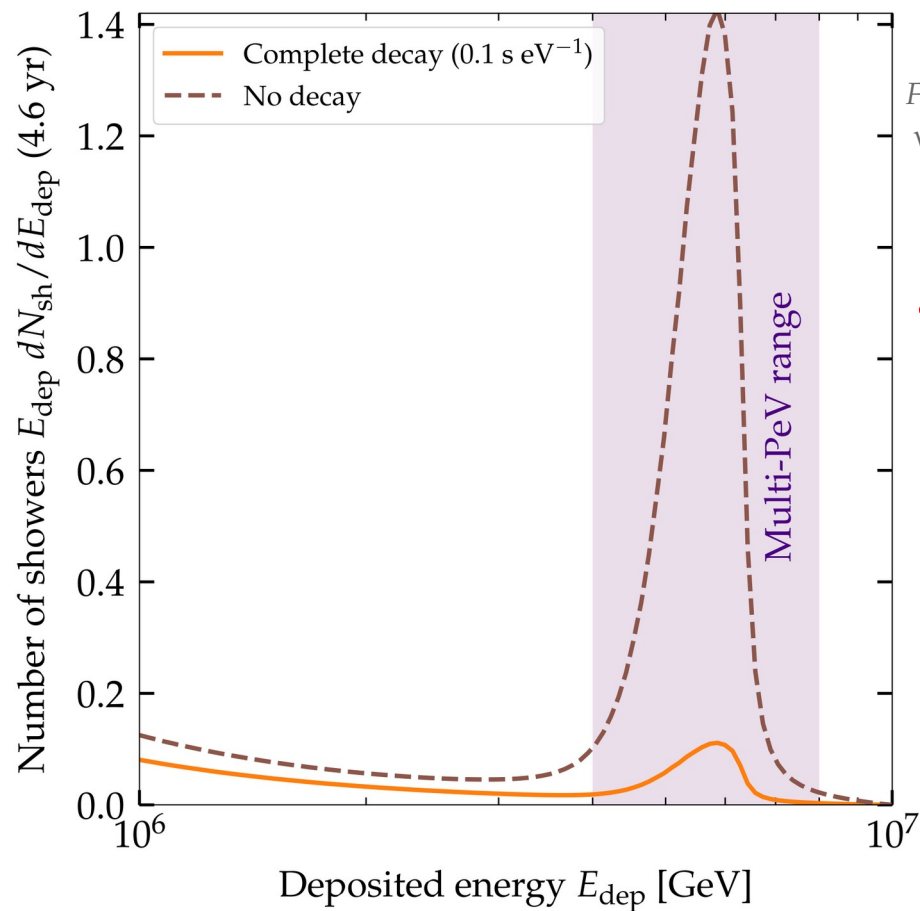
Flavor composition



Spectrum shape



Event rate



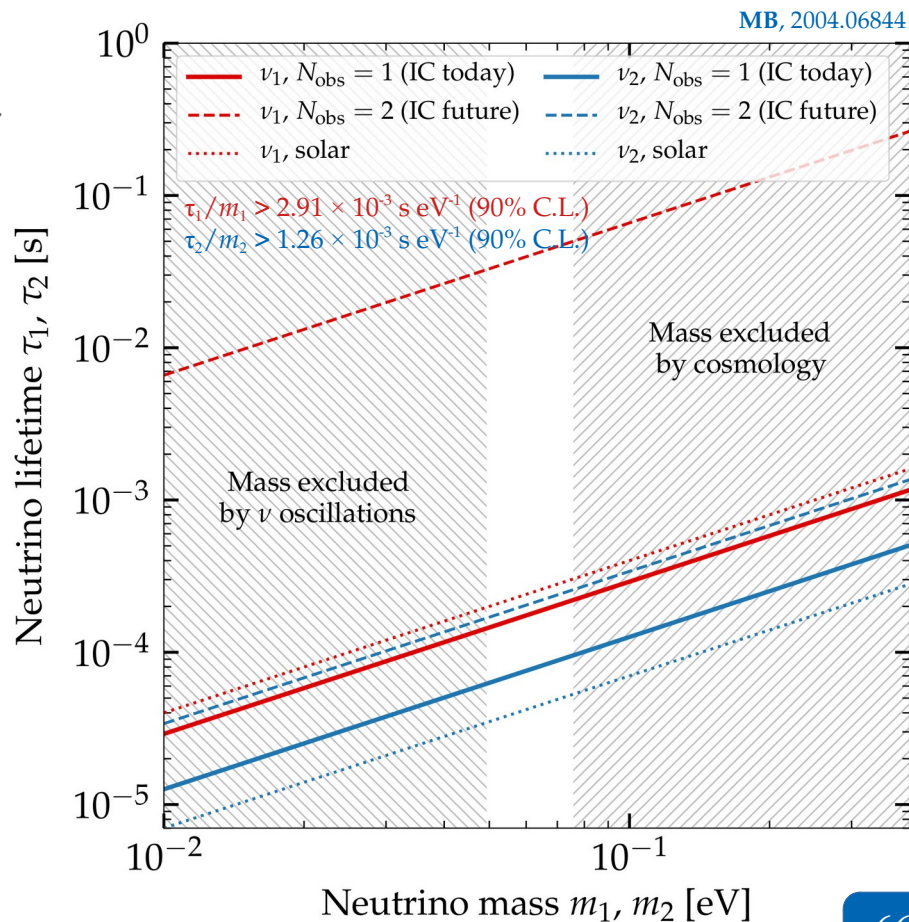
Free parameters:

ν_1, ν_2 lifetimes

Mix. par.

Flavor ratios

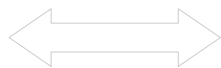
$\bar{\nu}/\nu$ ratio



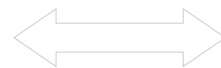
What does neutrino decay change?

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

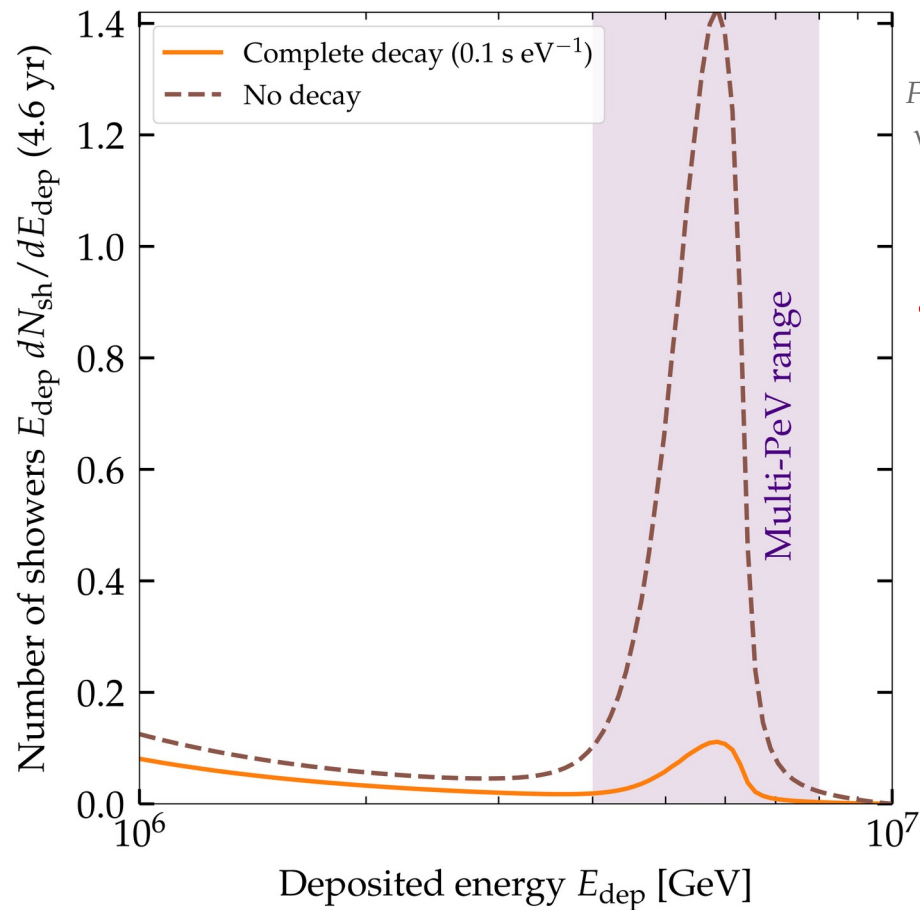
Flavor composition



Spectrum shape

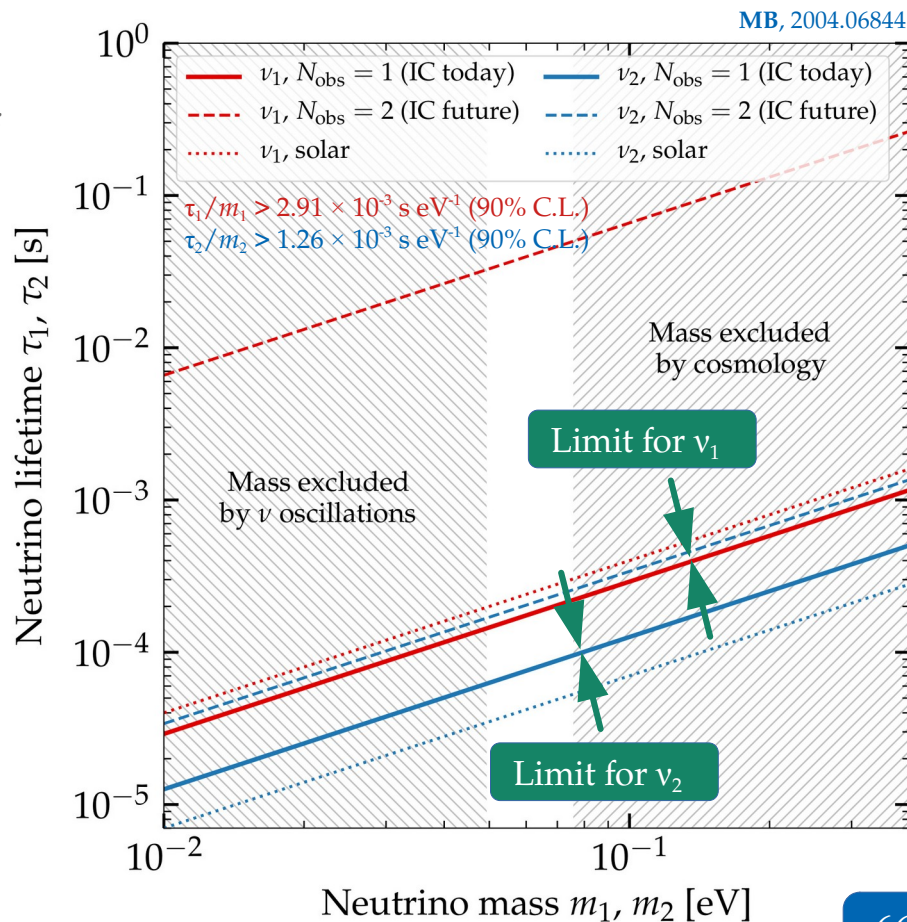


Event rate



Free parameters:

ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
 $\bar{\nu}/\nu$ ratio



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

Astrophysical neutrino sources

Earth

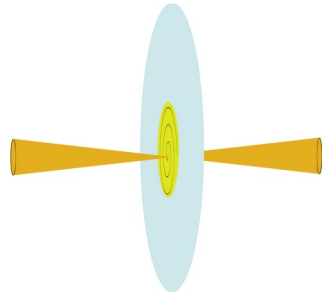


Galactic (kpc) or extragalactic (Mpc – Gpc) distance

Astrophysical neutrino sources

Earth

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

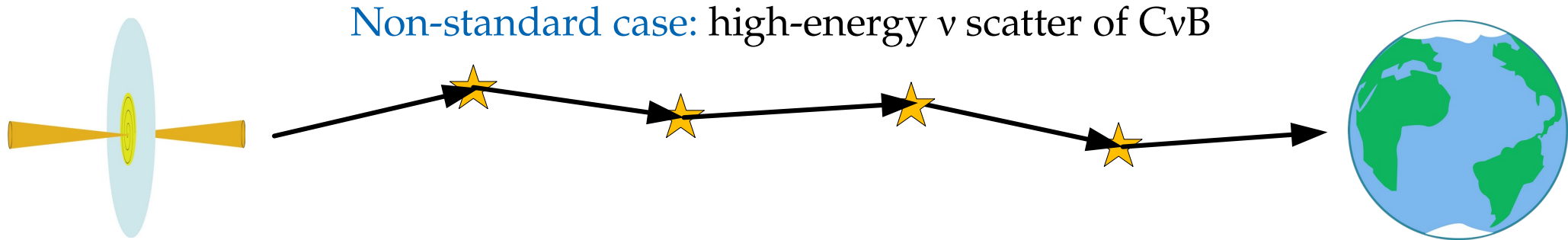
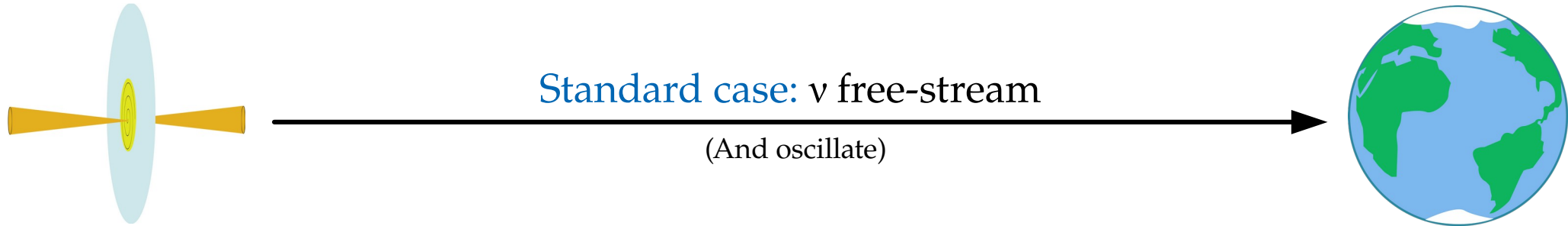


Standard case: ν free-stream

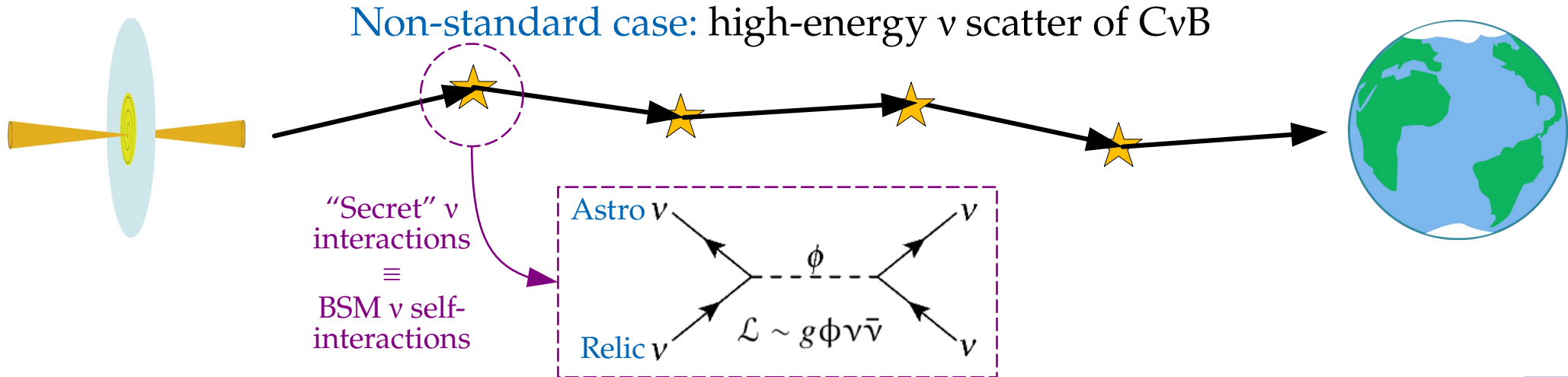
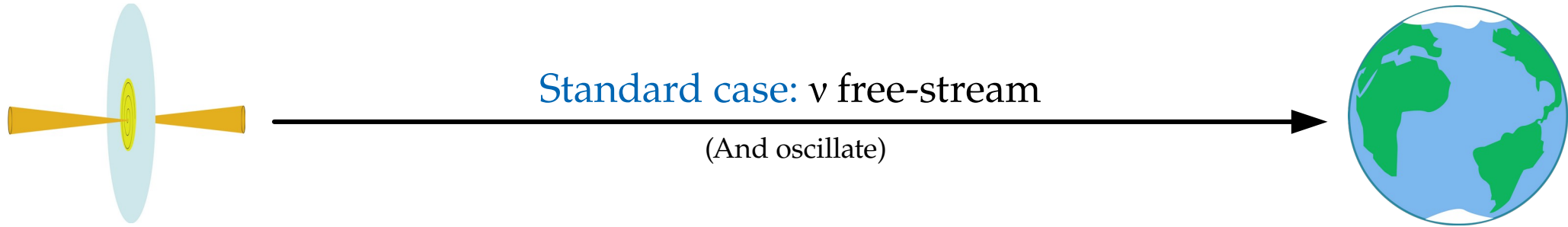
(And oscillate)



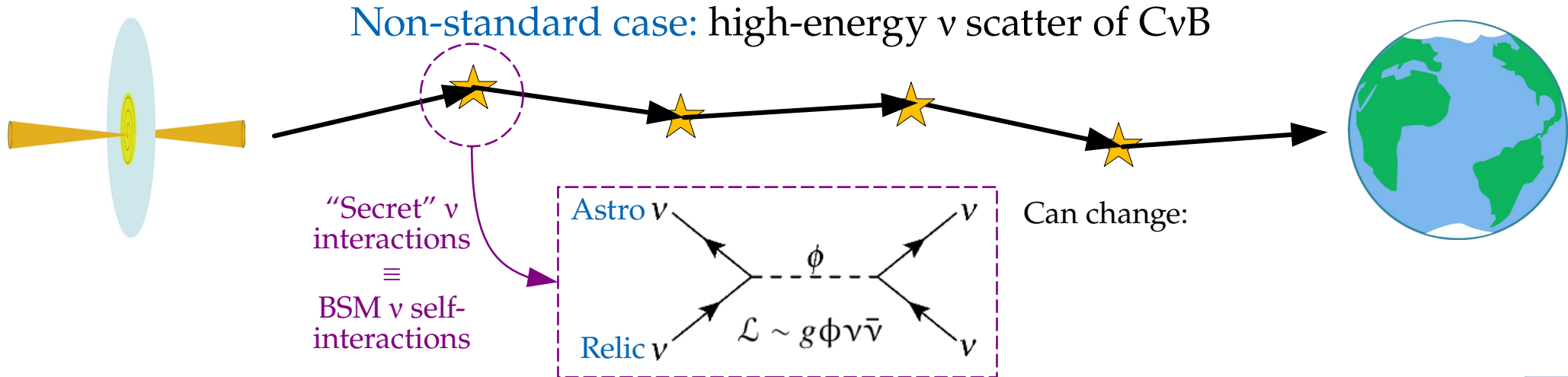
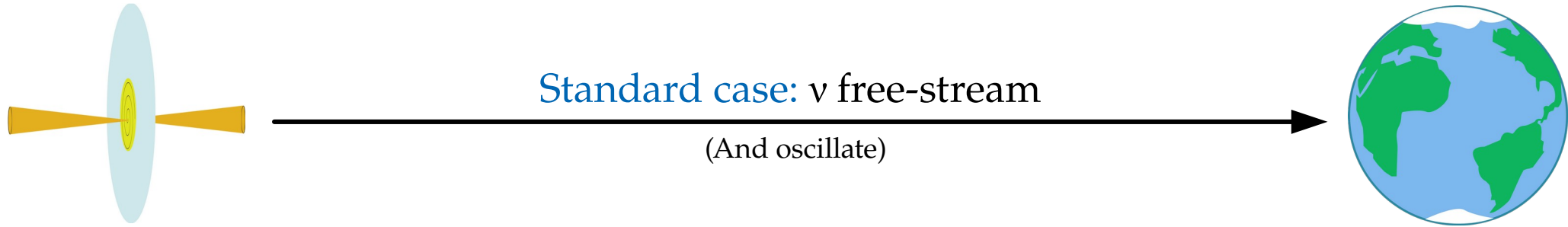
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



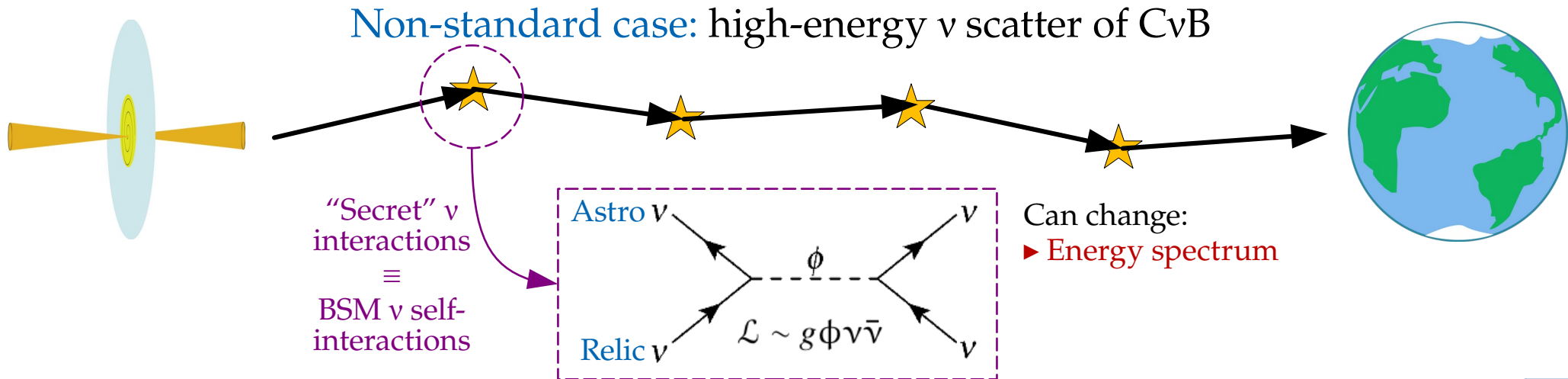
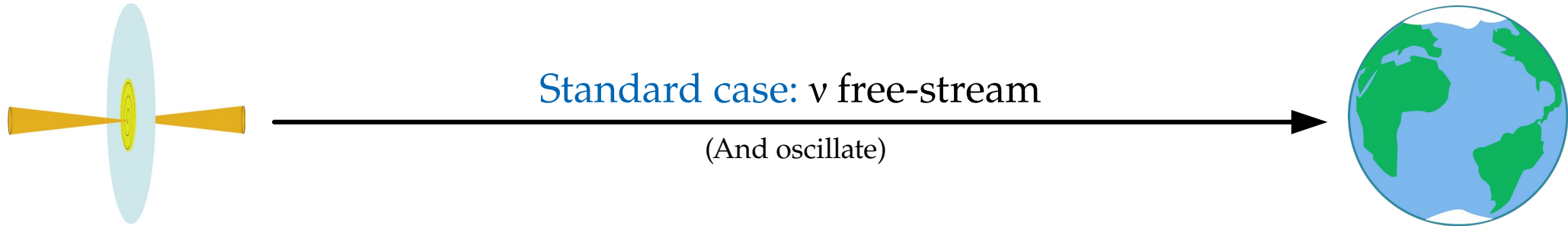
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



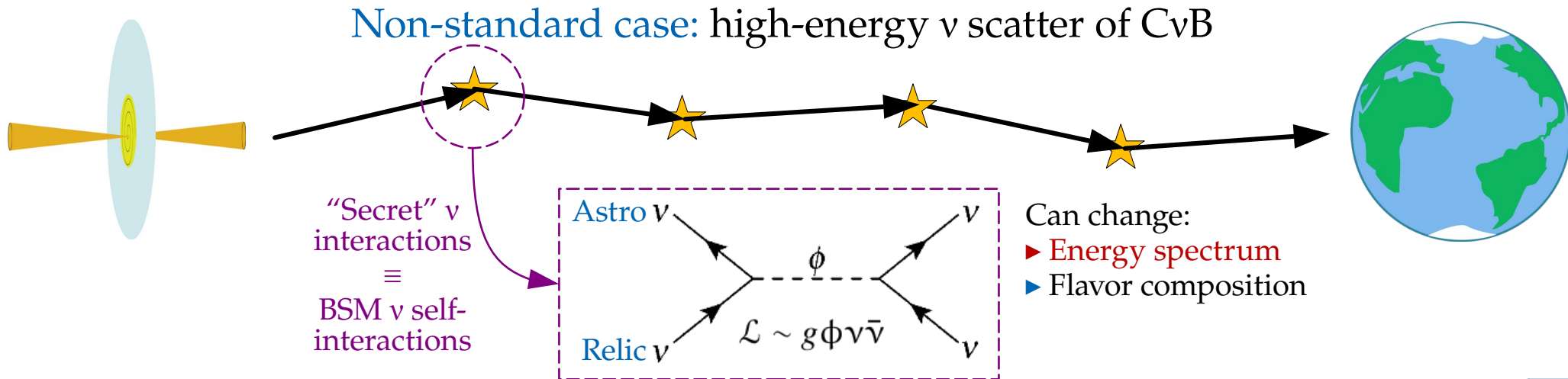
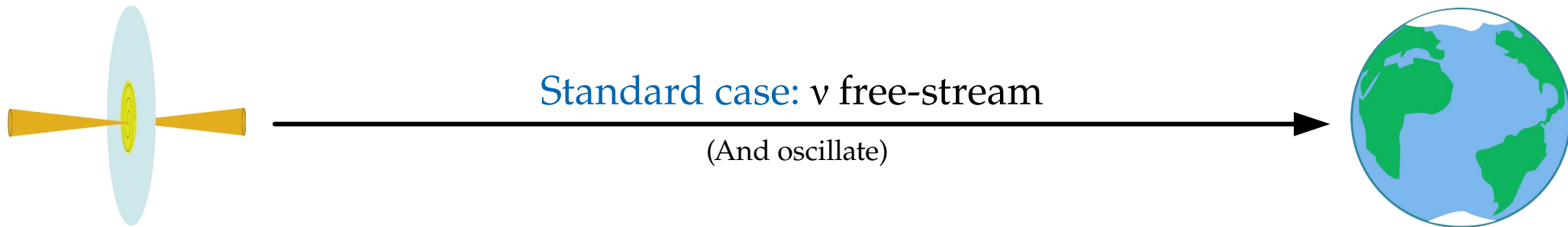
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



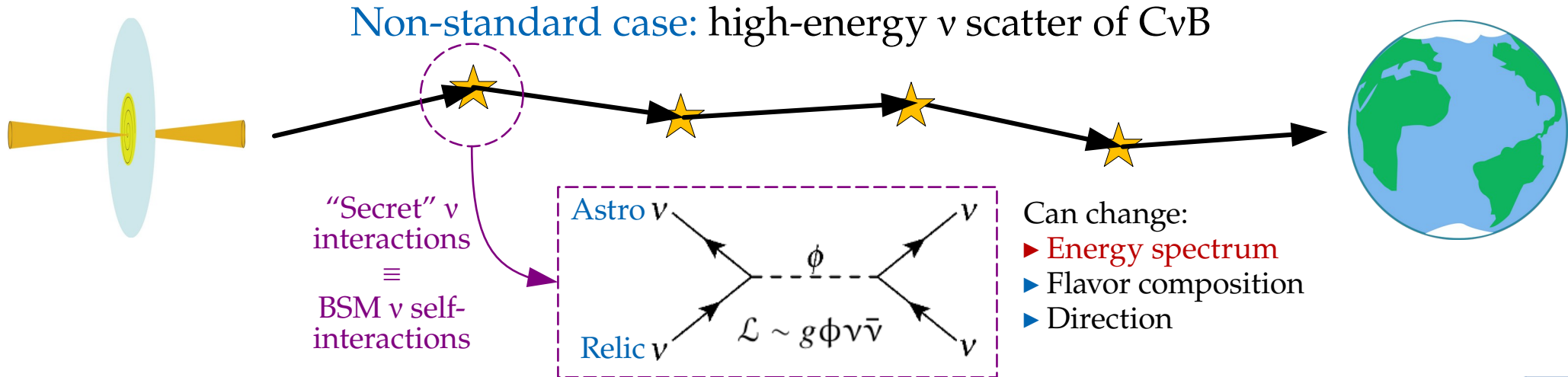
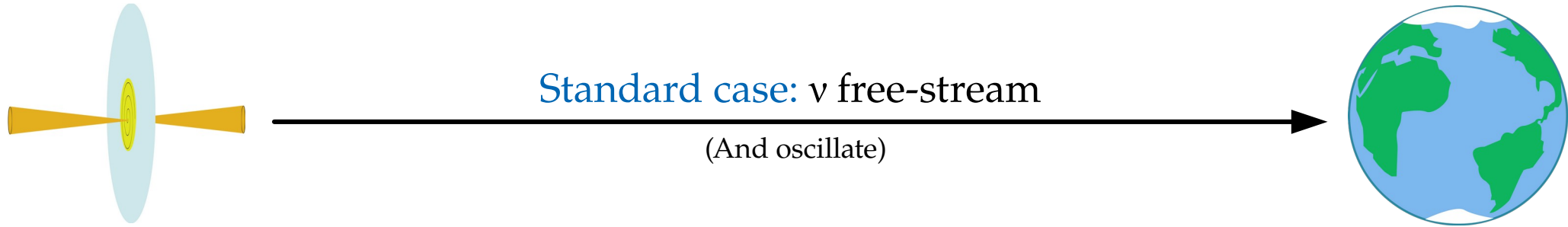
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



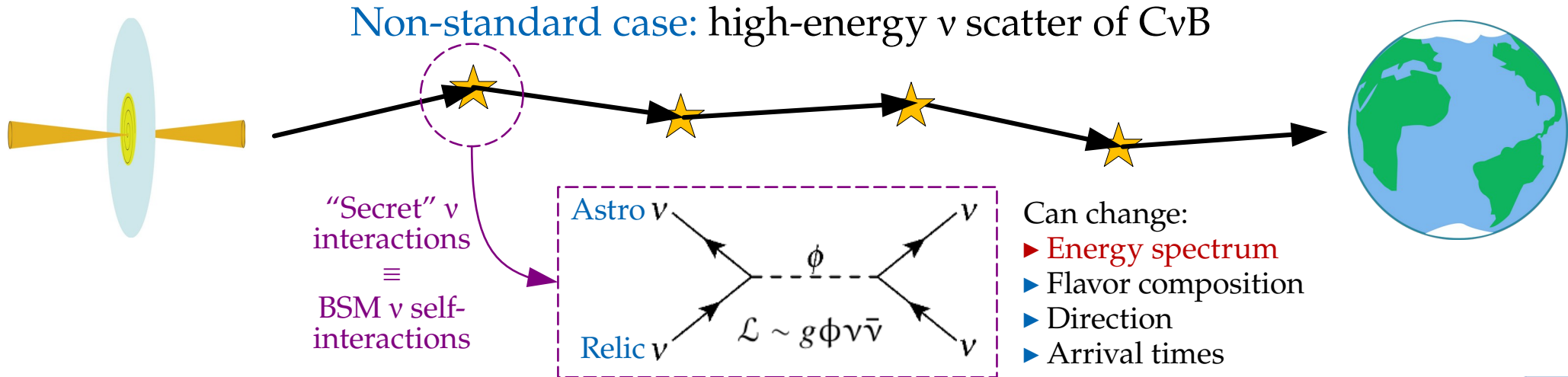
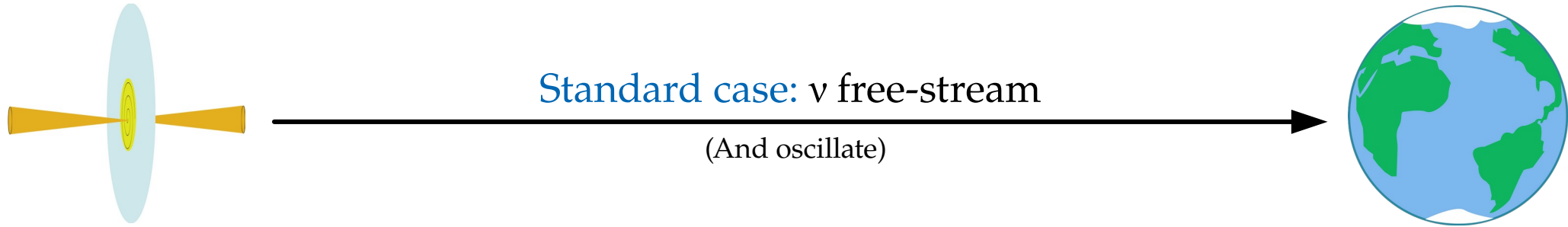
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



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

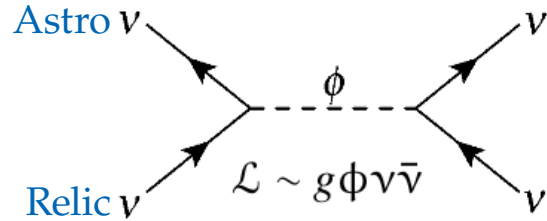


Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Secret interactions of high-energy astrophysical neutrinos

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



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

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

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

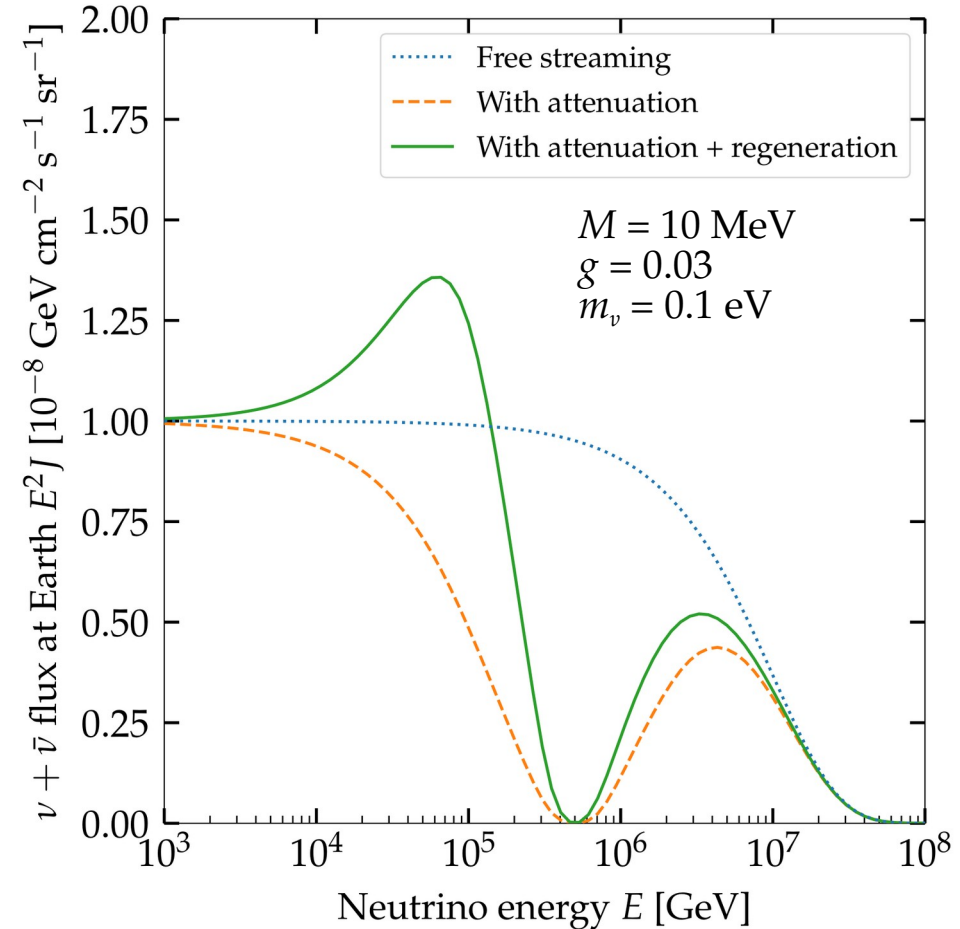
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021

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

Ng & Beacom, *PRD* 2014

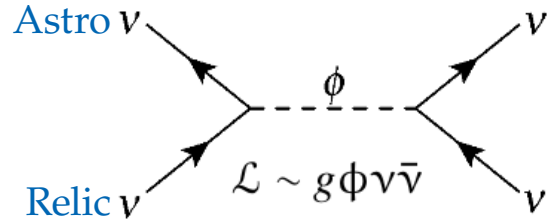
Cherry, Friedland, Shoemaker, 1411.1071

Blum, Hook, Murase, 1408.3799



Secret interactions of high-energy astrophysical neutrinos

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

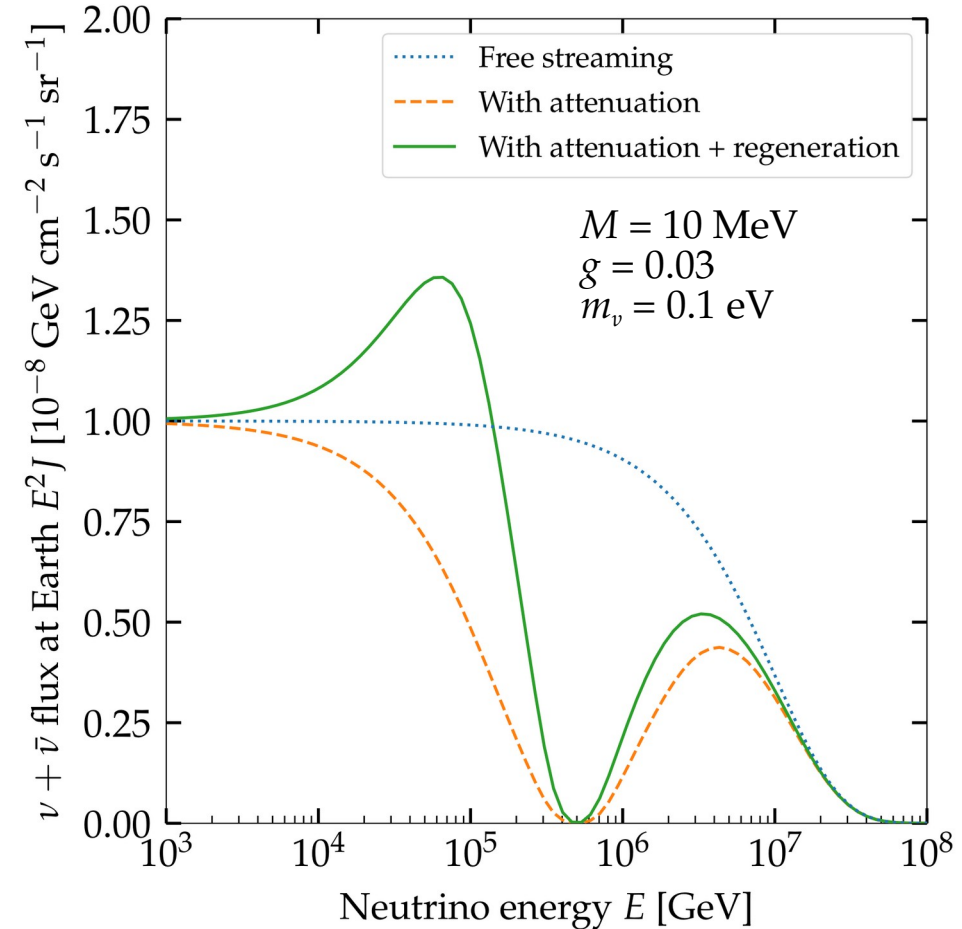


Cross section:
$$\sigma = \frac{g^4 s}{4\pi (s - M^2)^2 + M^2\Gamma^2}$$

New coupling Mediator mass

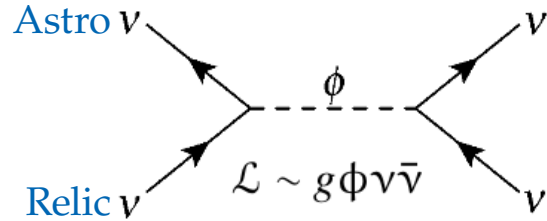
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
 See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
 Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
 Ng & Beacom, *PRD* 2014
 Cherry, Friedland, Shoemaker, 1411.1071
 Blum, Hook, Murase, 1408.3799



Secret interactions of high-energy astrophysical neutrinos

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

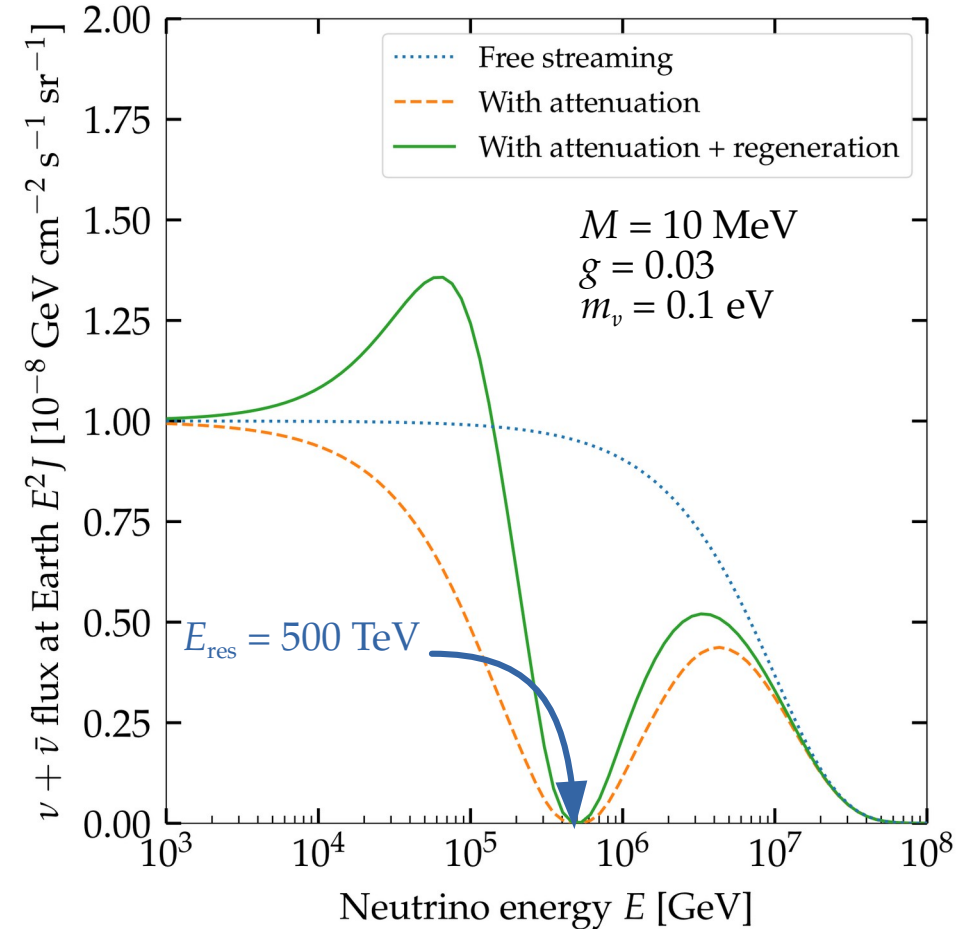


Cross section:
$$\sigma = \frac{g^4 s}{4\pi (s - M^2)^2 + M^2\Gamma^2}$$

New coupling Mediator mass

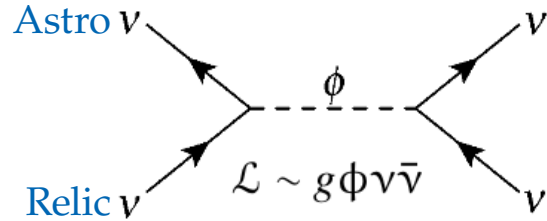
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
 See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
 Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
 Ng & Beacom, *PRD* 2014
 Cherry, Friedland, Shoemaker, 1411.1071
 Blum, Hook, Murase, 1408.3799



Secret interactions of high-energy astrophysical neutrinos

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

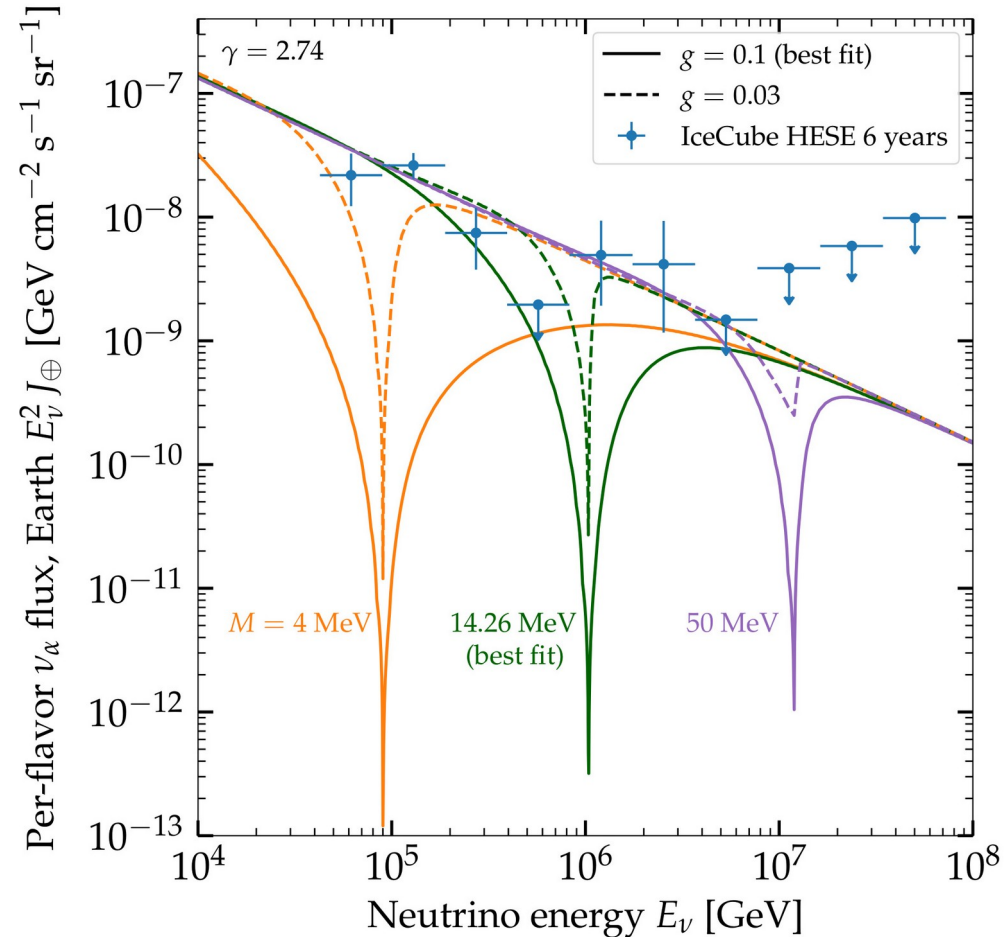


Cross section:
$$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

New coupling Mediator mass

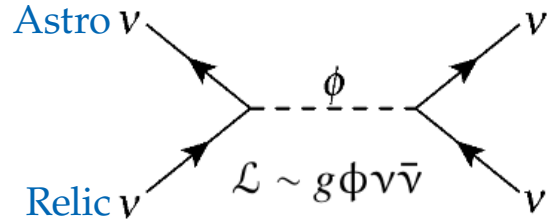
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
 See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
 Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
 Ng & Beacom, *PRD* 2014
 Cherry, Friedland, Shoemaker, 1411.1071
 Blum, Hook, Murase, 1408.3799



Secret interactions of high-energy astrophysical neutrinos

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



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

New coupling (circled in red) and Mediator mass (circled in green).

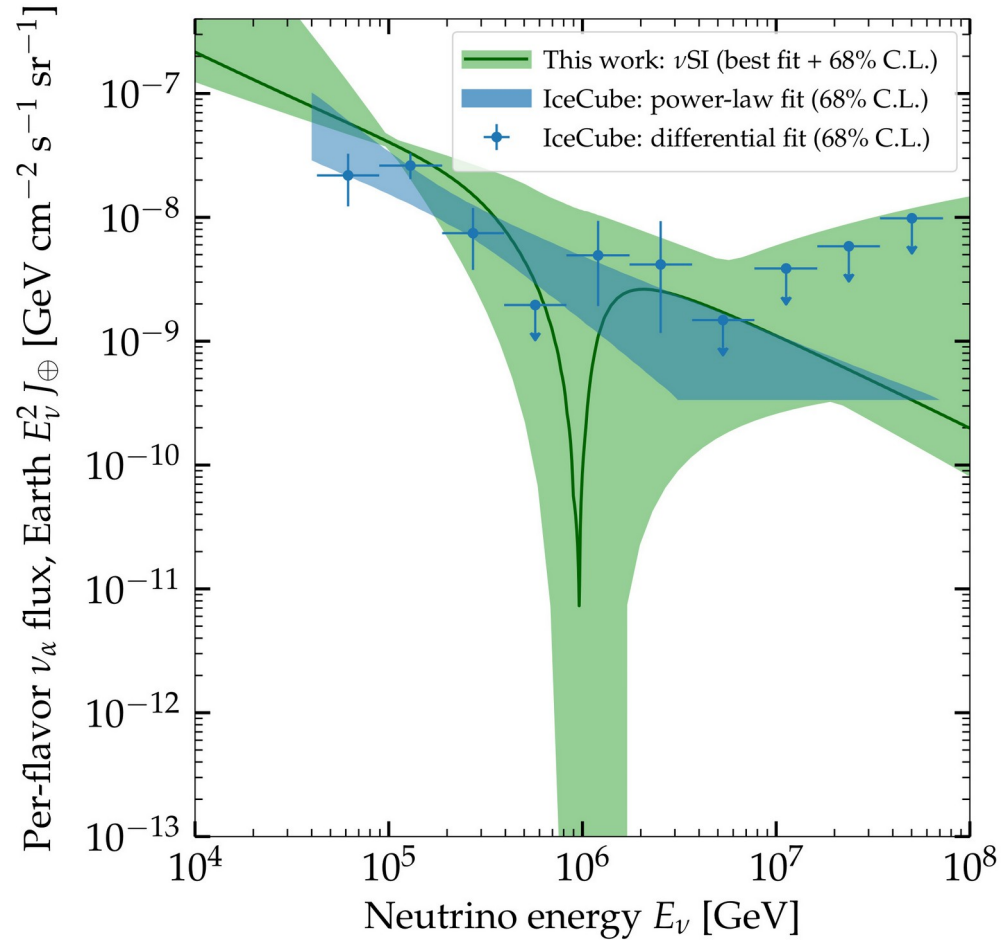
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

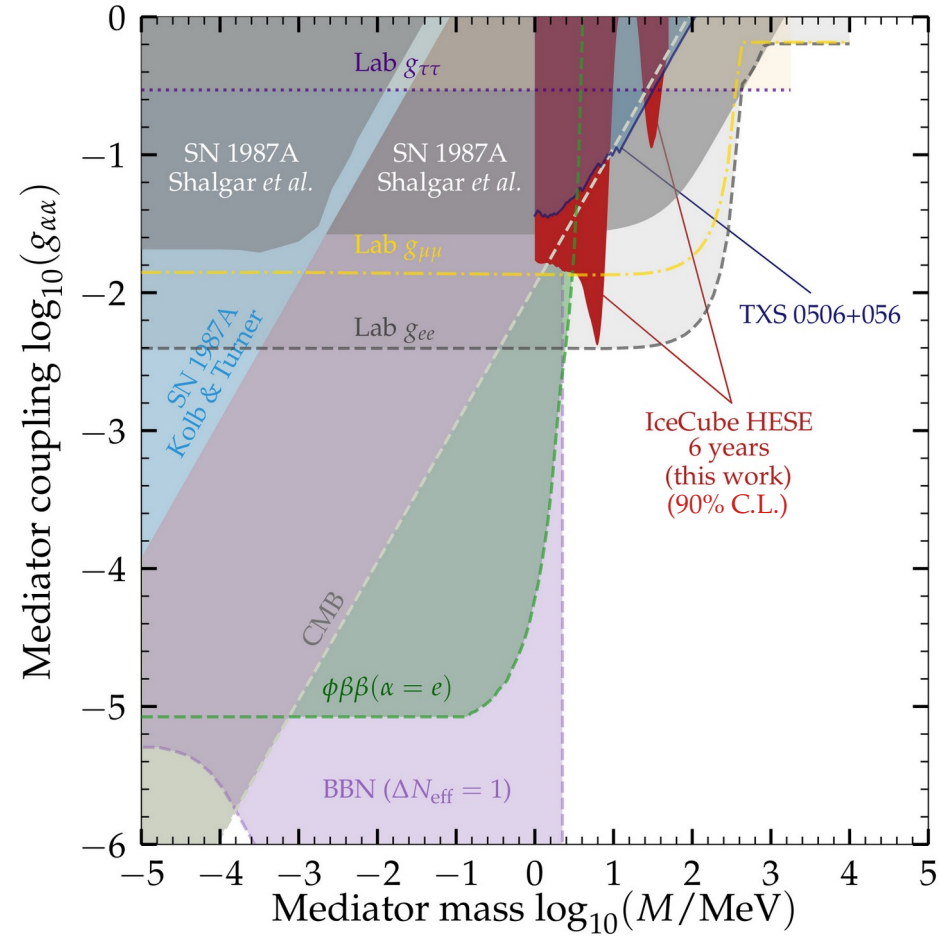
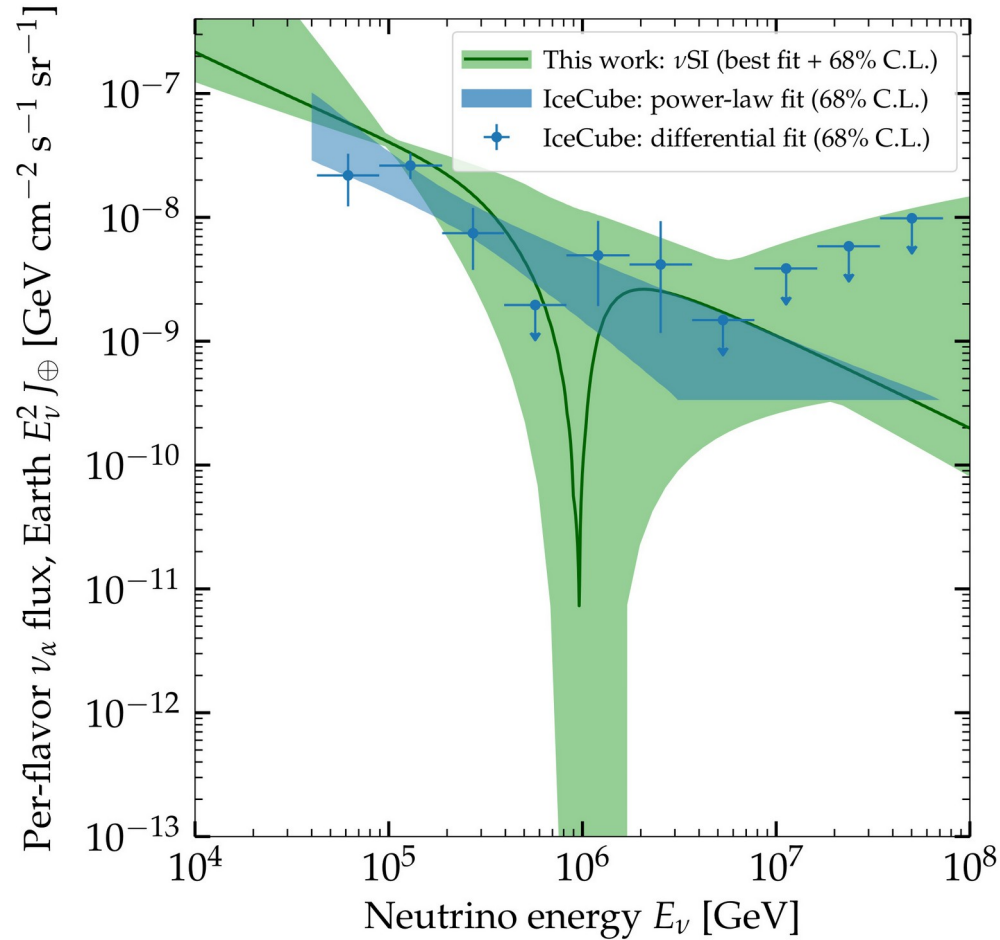
Looking for evidence of ν SI

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

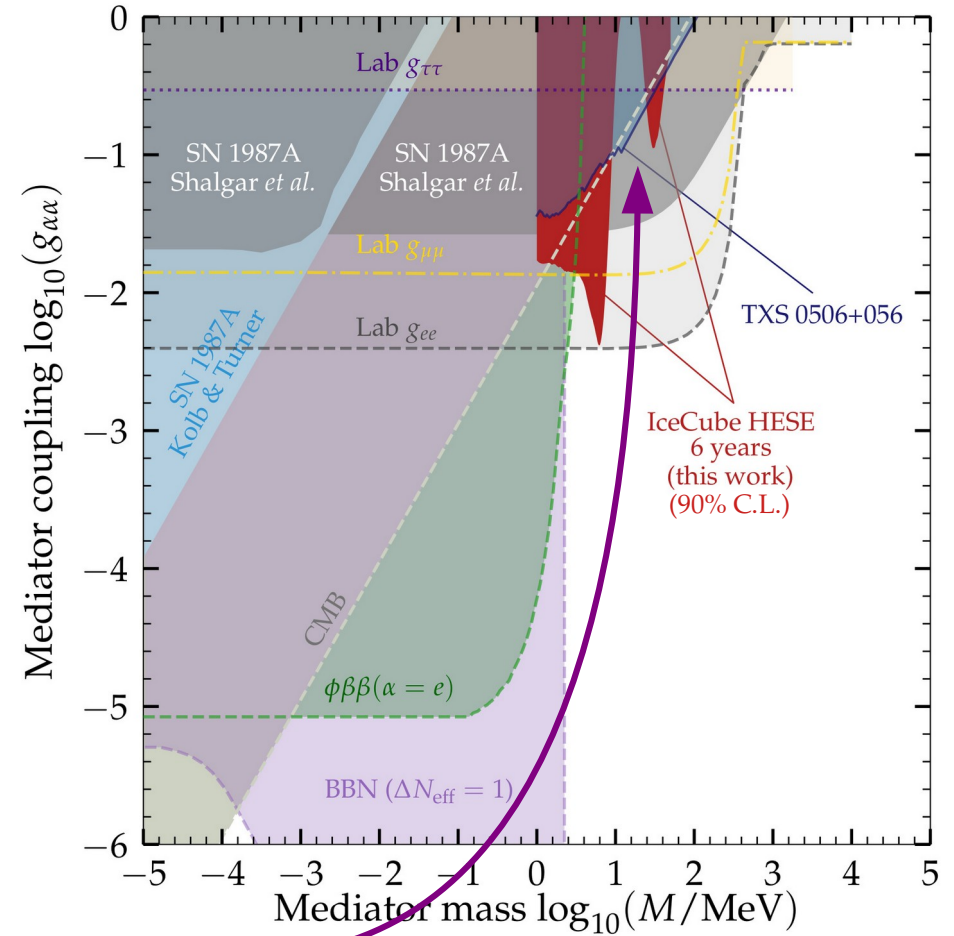
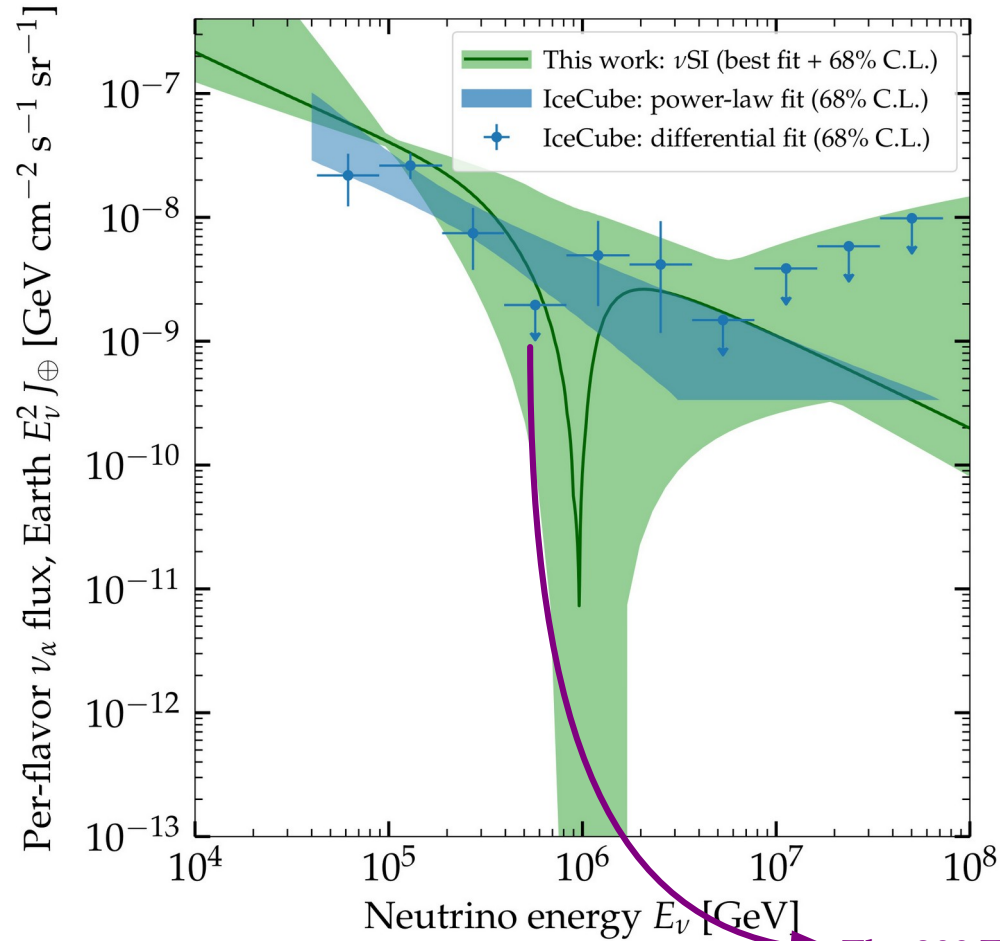
No significant ($> 3\sigma$) evidence for a spectral dip ...



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

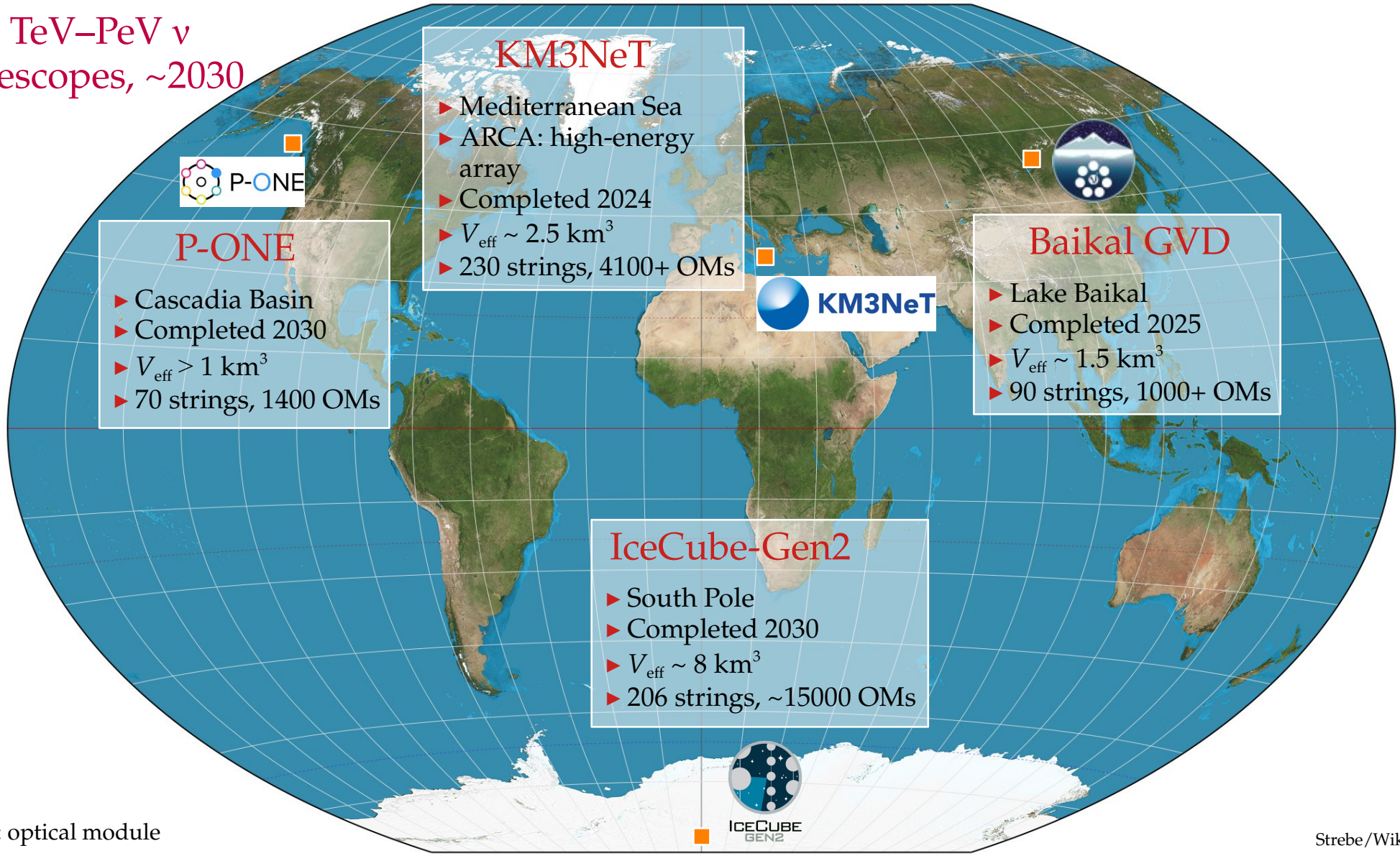


No significant ($> 3\sigma$) evidence for a spectral dip so we set upper limits on the coupling g



What's next?

TeV–PeV ν
telescopes, ~2030



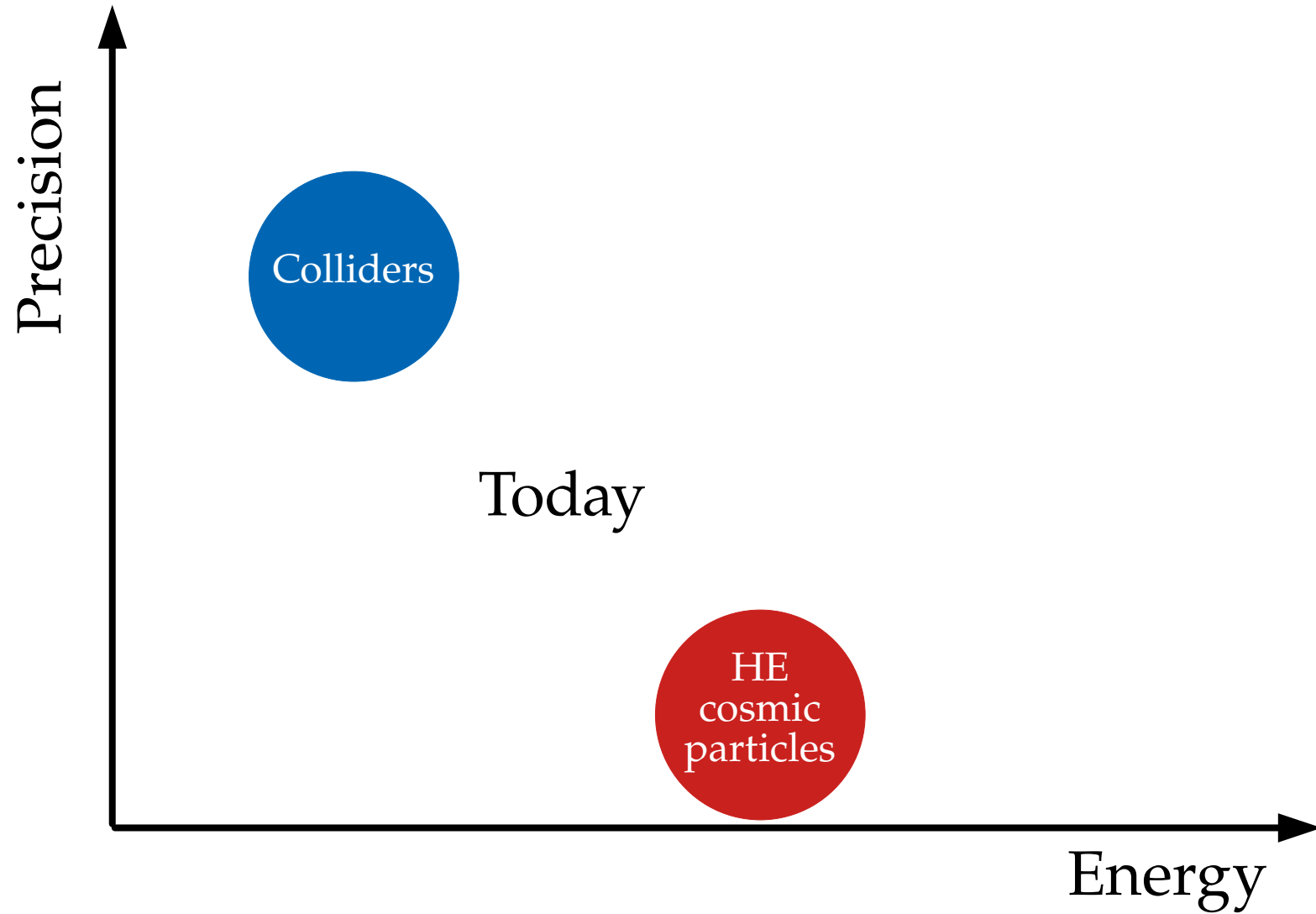
OM: optical module

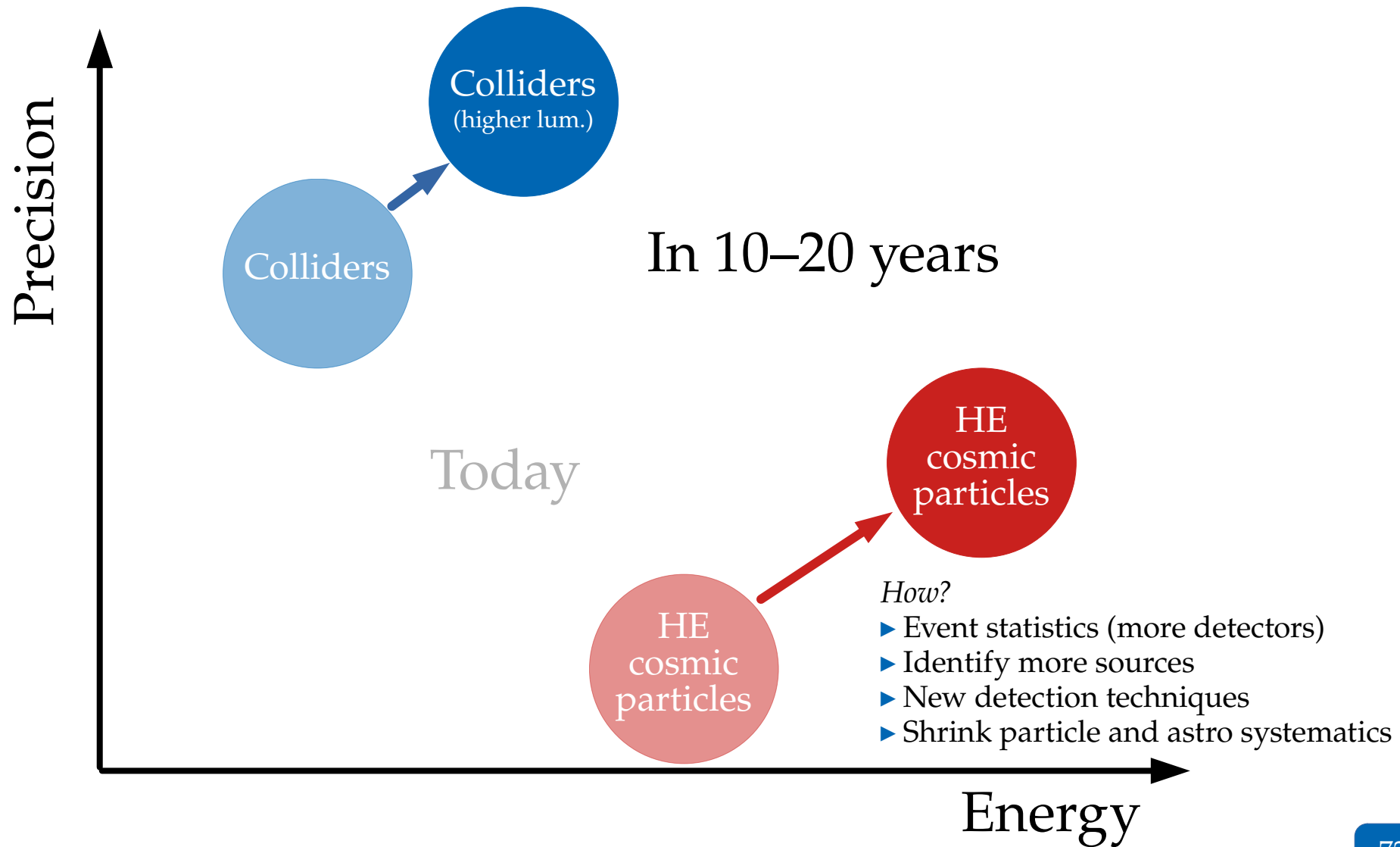
Many TeV–EeV
v telescopes
in planning for
2020–2040

				Flavor	Technique		Neutrino Target			Geometry			
Experiments	Phase & Online Date	Energy Range	Site	All Flavor Tau	Optical / UV	Showers Radio	H ₂ O Atmosphere	Earth's limb Topography	Lunar Regolith	Planar Arrays Embedded	Valley Mountains	Balloon	Satellite
IceCube	2010	TeV–EeV	South Pole	✓	✓		✓			✓			
KM3NeT	2021	TeV–PeV	Mediterranean	✓	✓		✓			✓			
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	✓		✓		✓	✓				
TAROG-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 prototype operations began or begin
Planning		Projected full operations

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

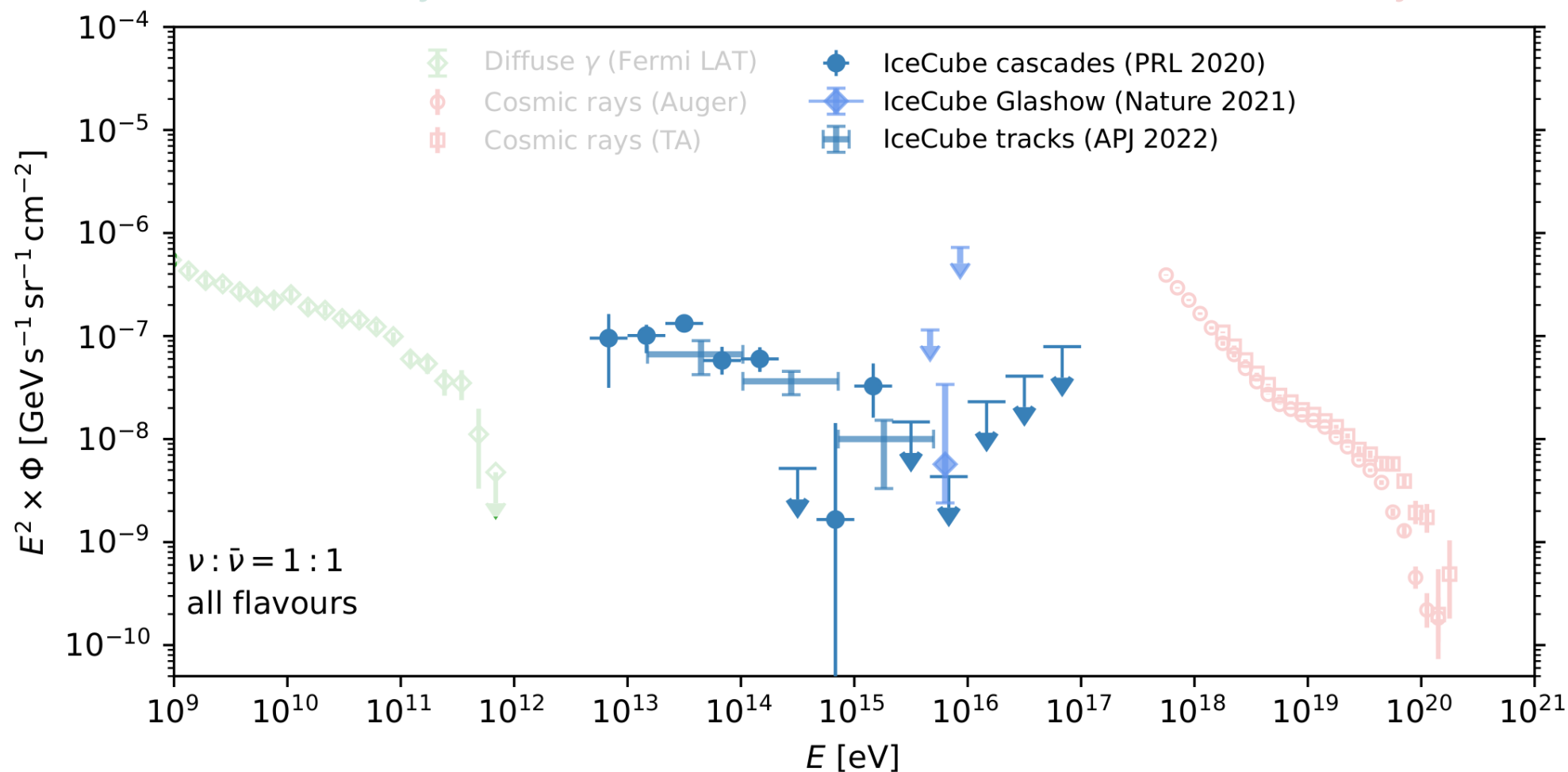




Gamma rays

Neutrinos

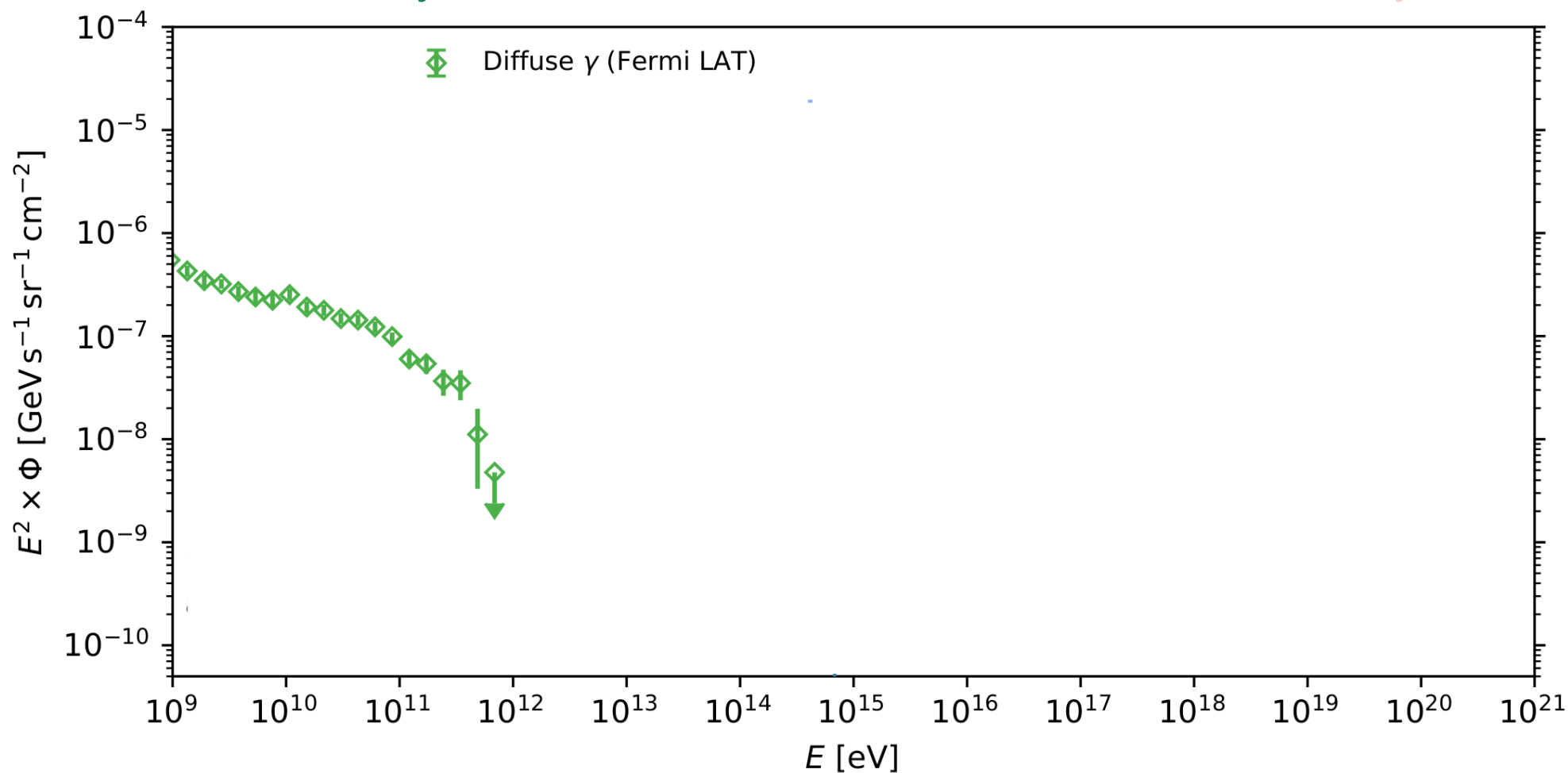
Cosmic rays



Gamma rays

Neutrinos

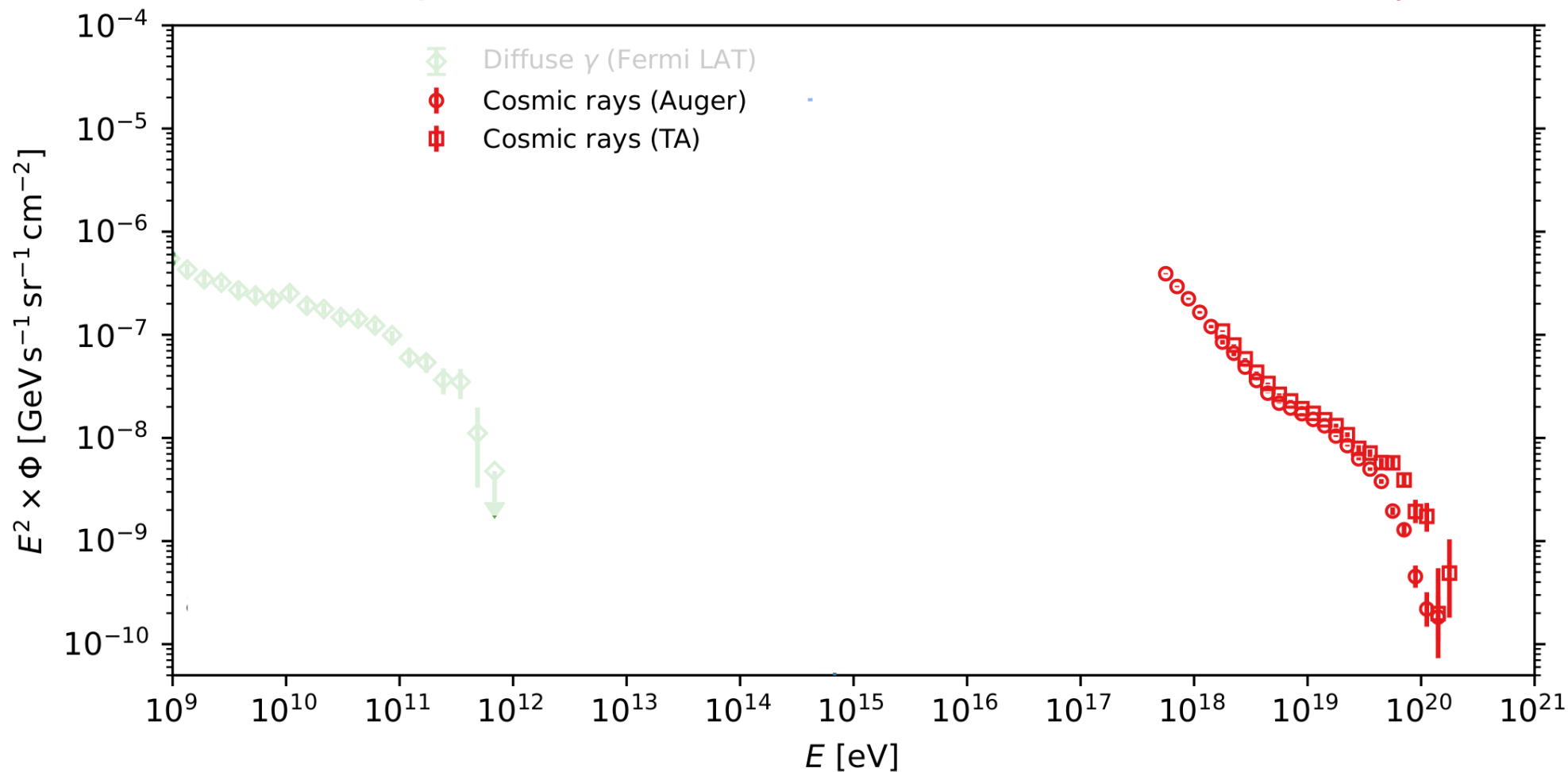
Cosmic rays



Gamma rays

Neutrinos

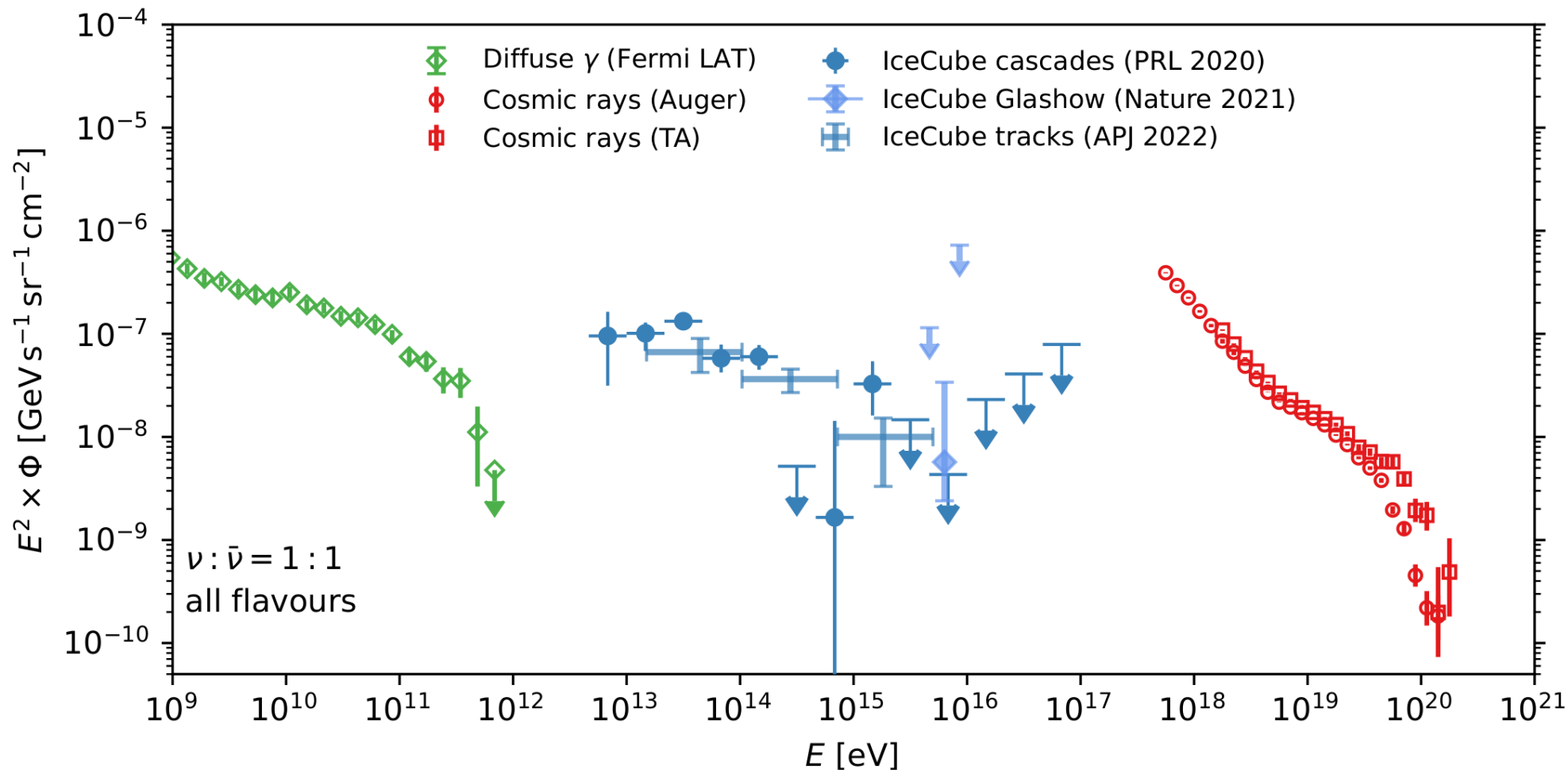
Cosmic rays



Gamma rays

Neutrinos

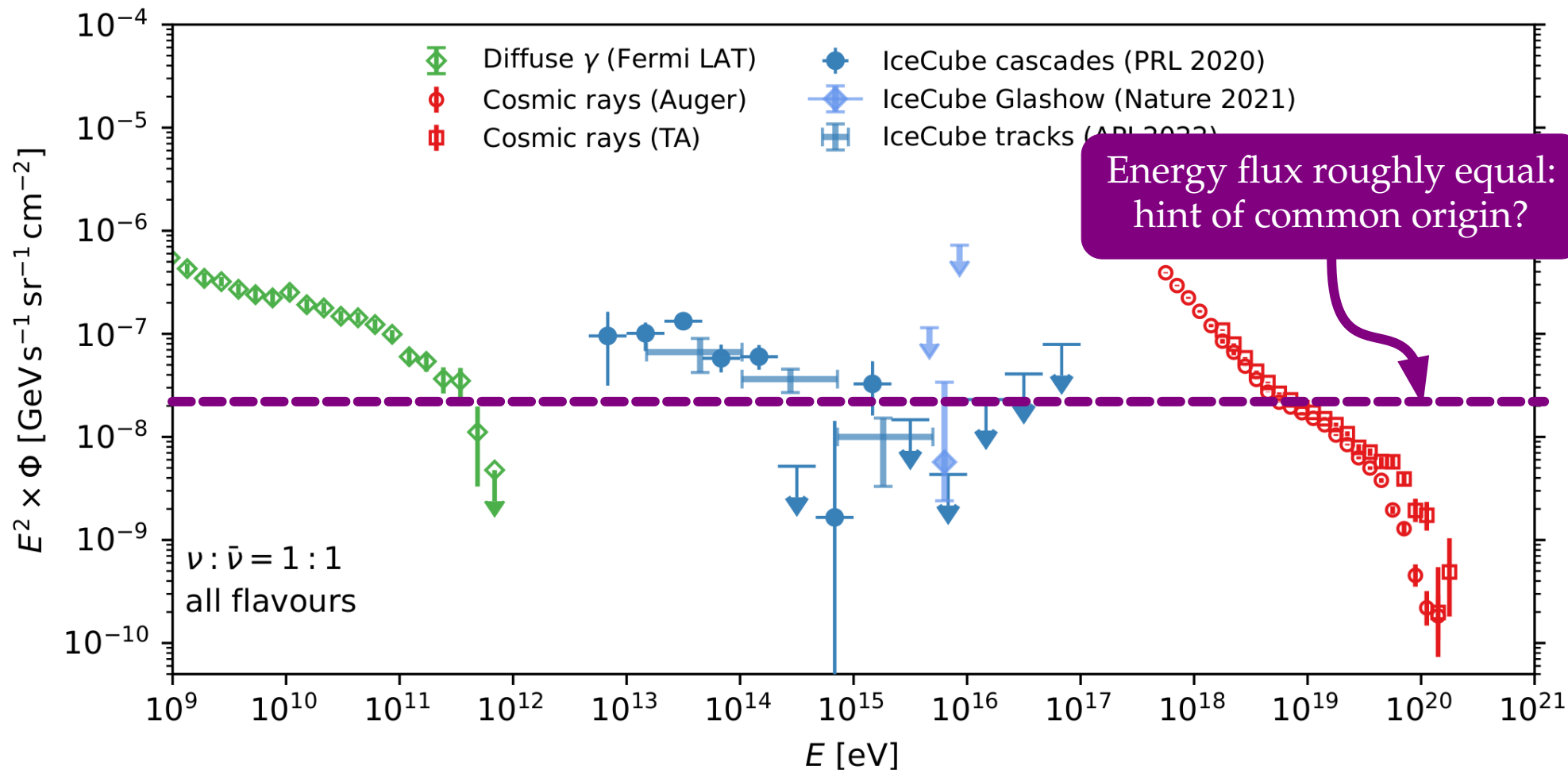
Cosmic rays

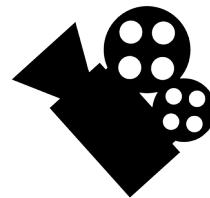
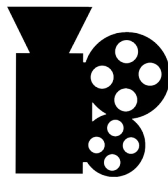
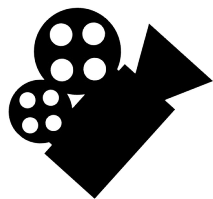


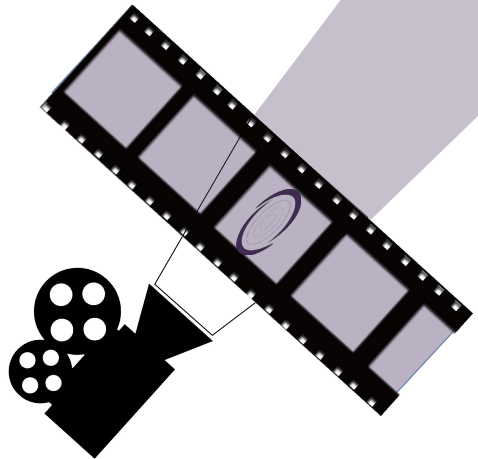
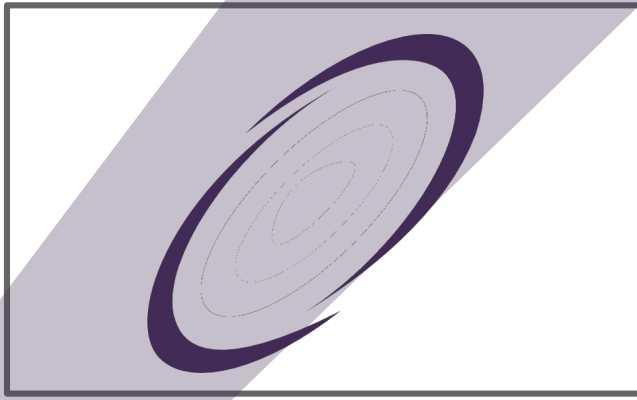
Gamma rays

Neutrinos

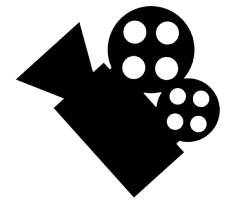
Cosmic rays

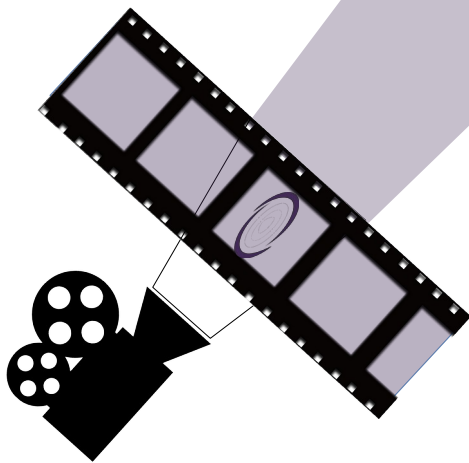
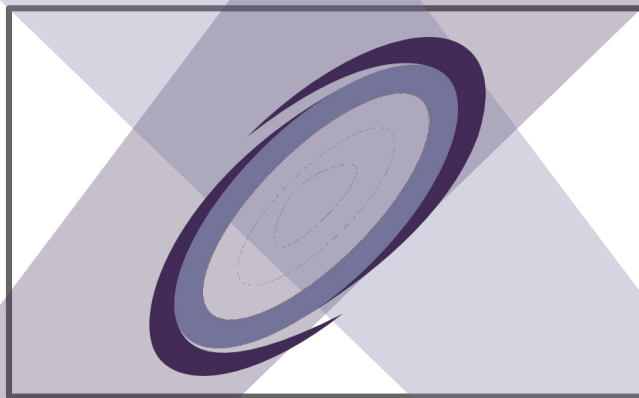




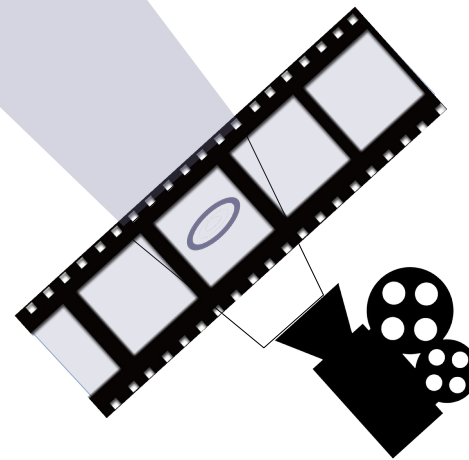


Radio, infrared, optical

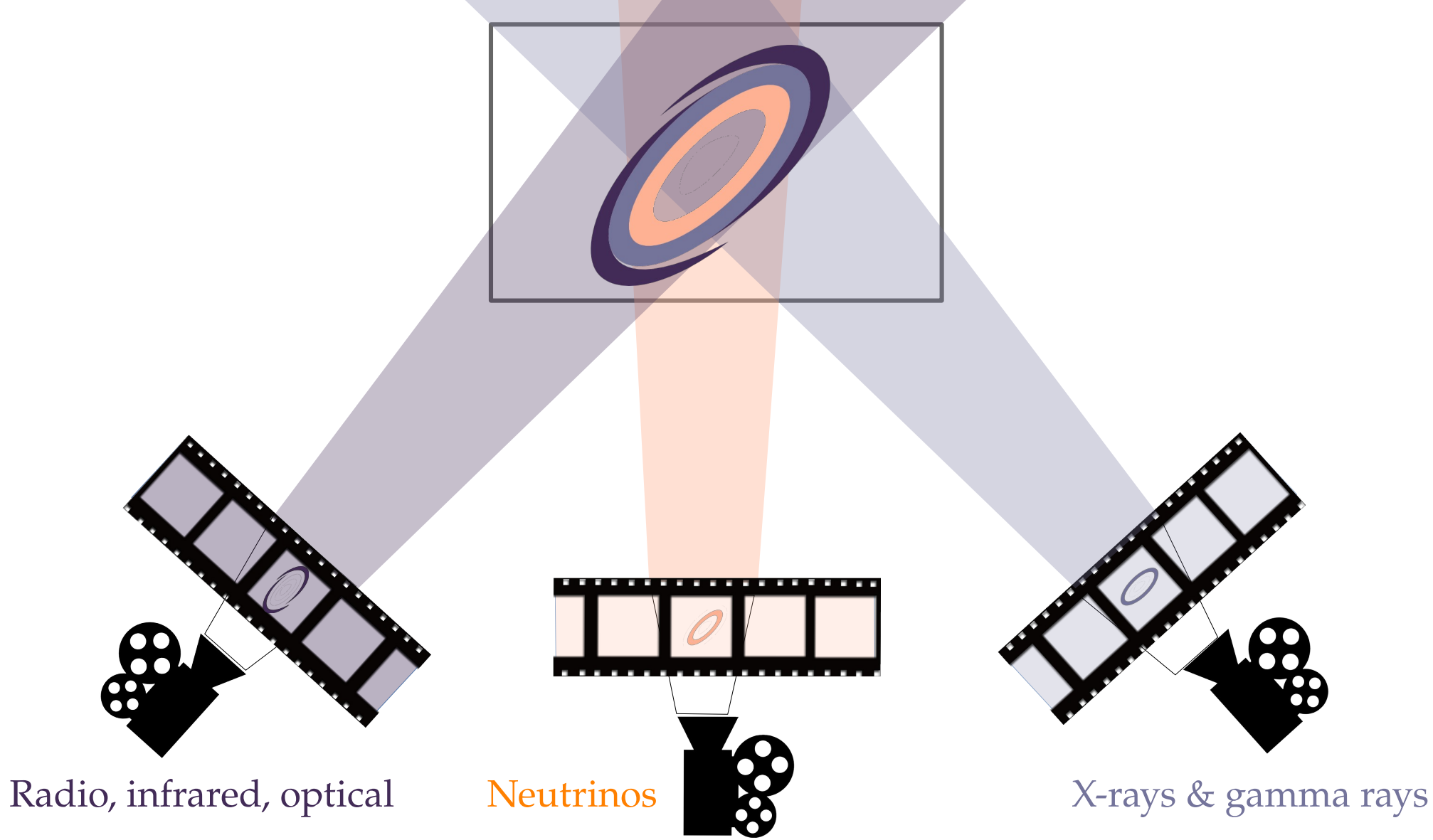




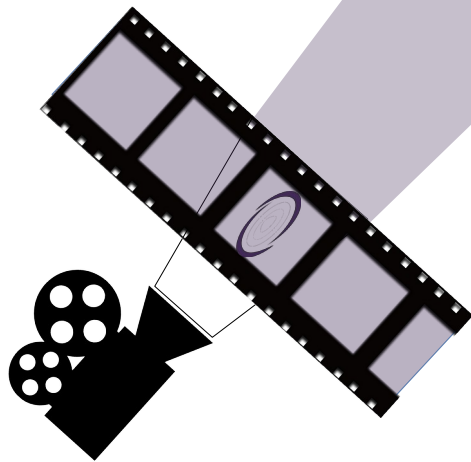
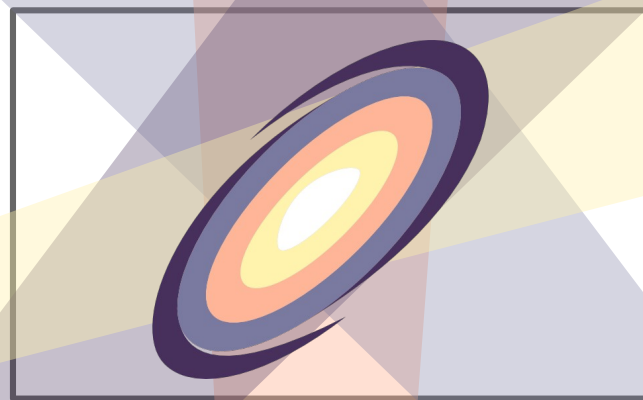
Radio, infrared, optical



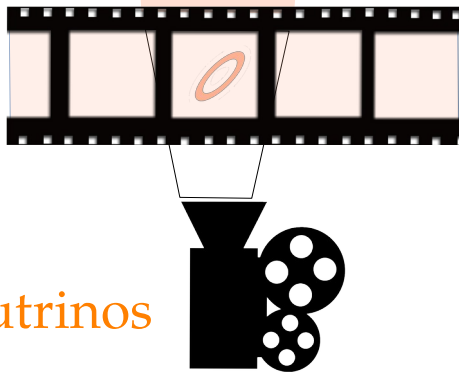
X-rays & gamma rays



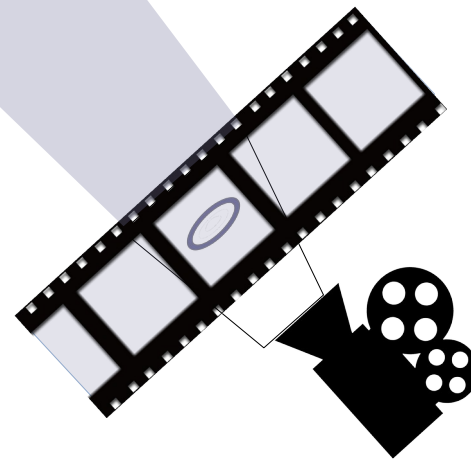
Gravitational waves



Radio, infrared, optical



Neutrinos



X-rays & gamma rays

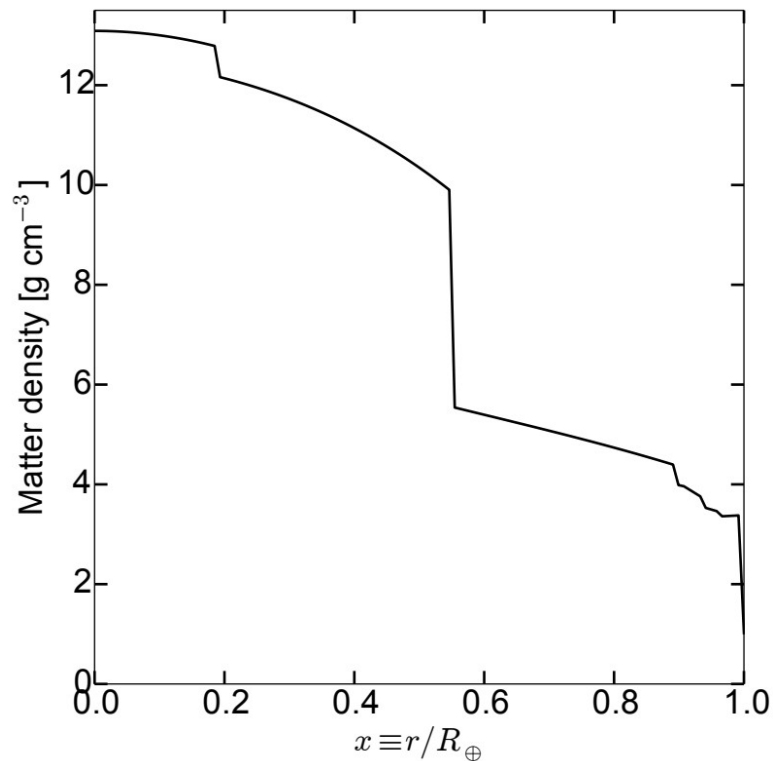
Thanks!

Backup slides

A feel for the in-Earth attenuation

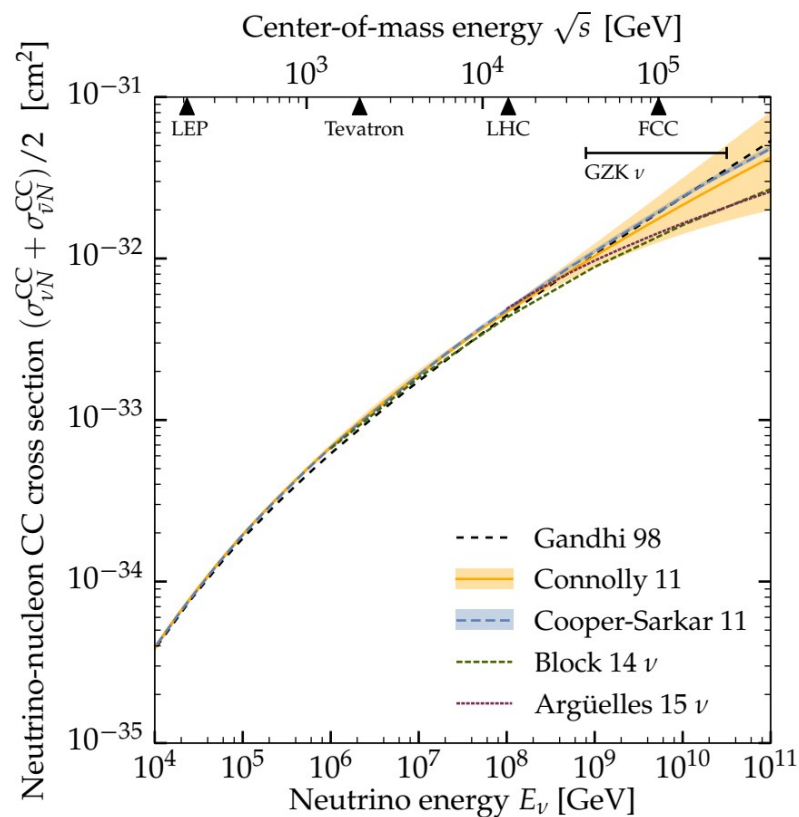
Earth matter density

(Preliminary Reference Earth Model)

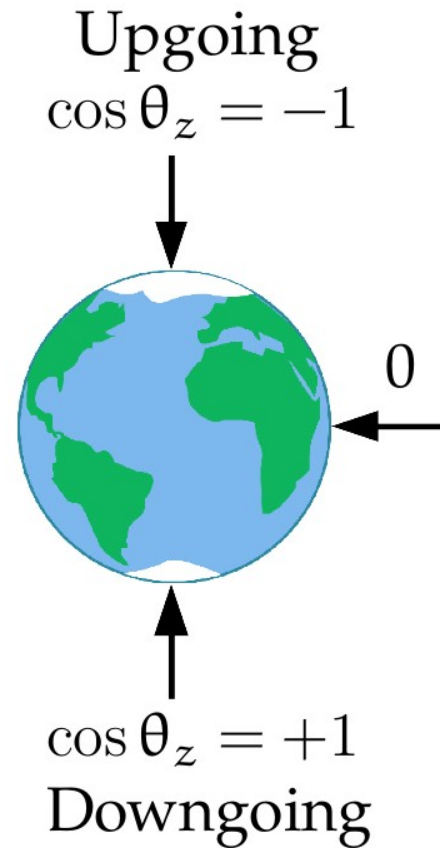
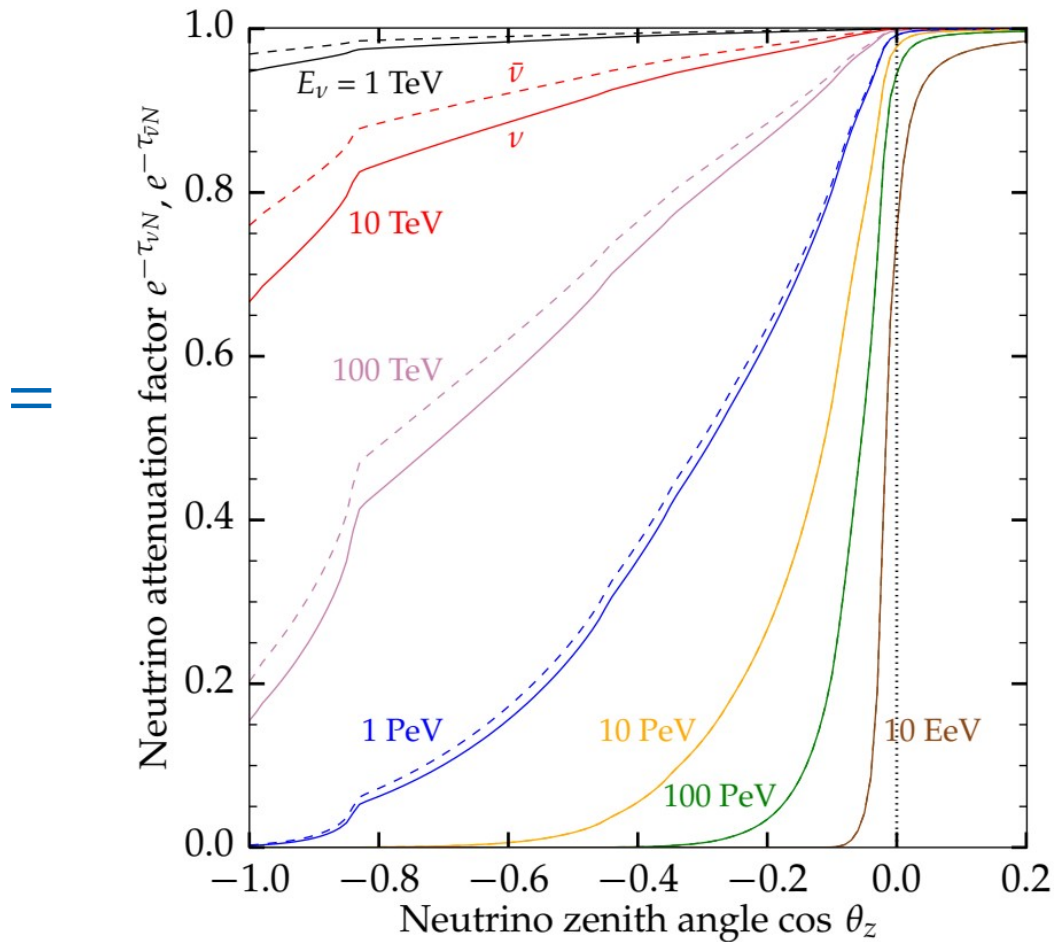


+

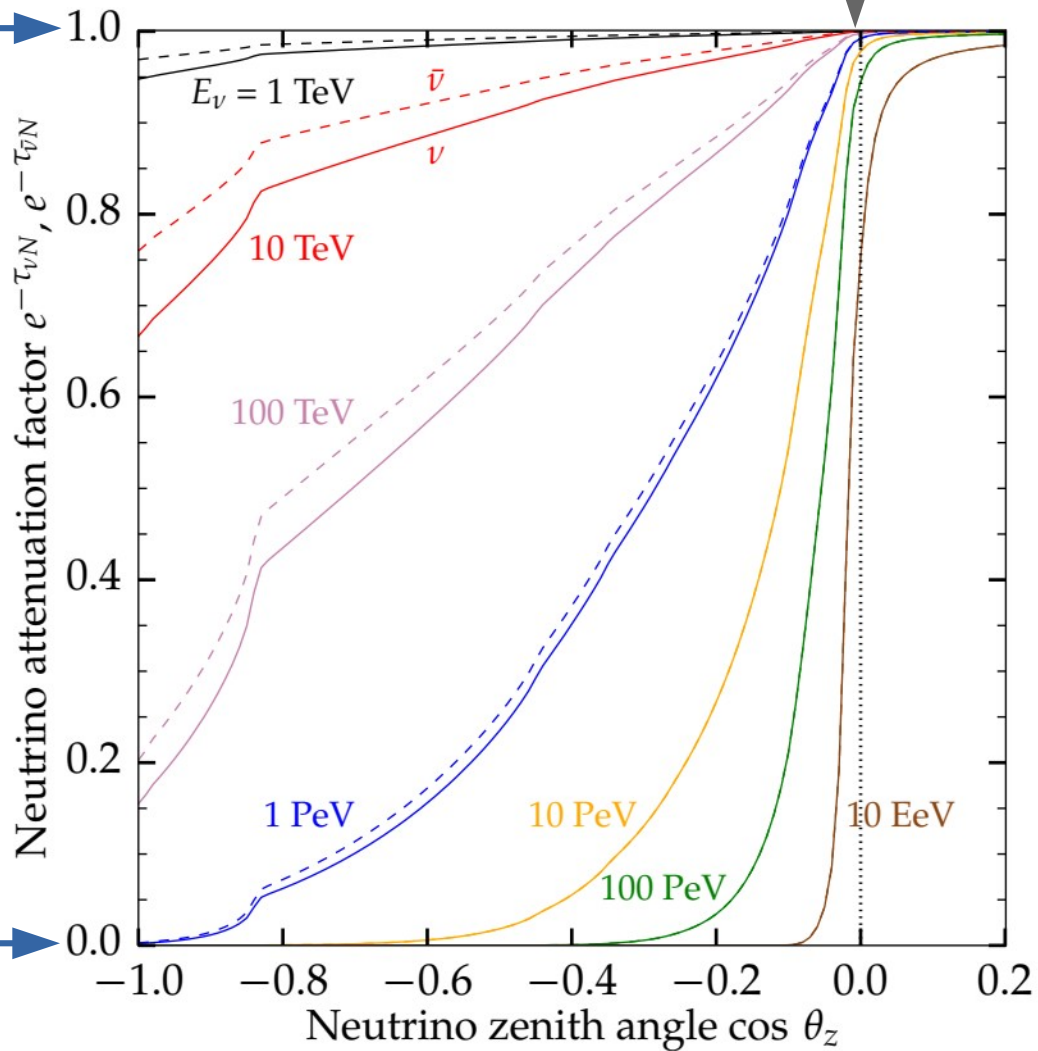
Neutrino-nucleon cross section



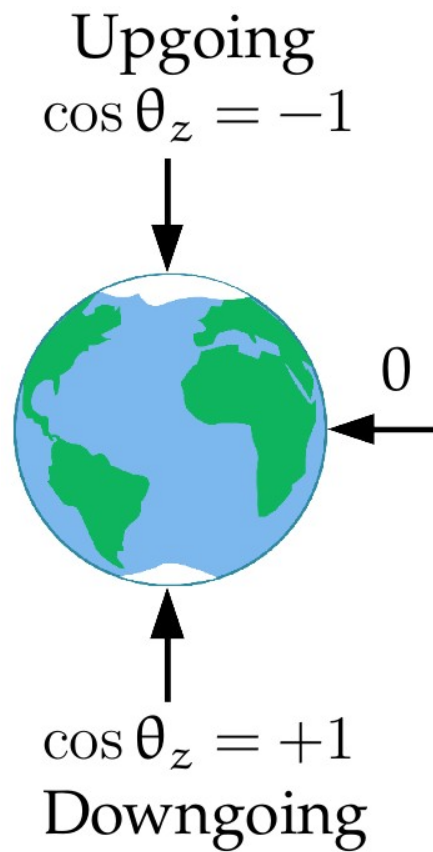
A feel for the in-Earth attenuation



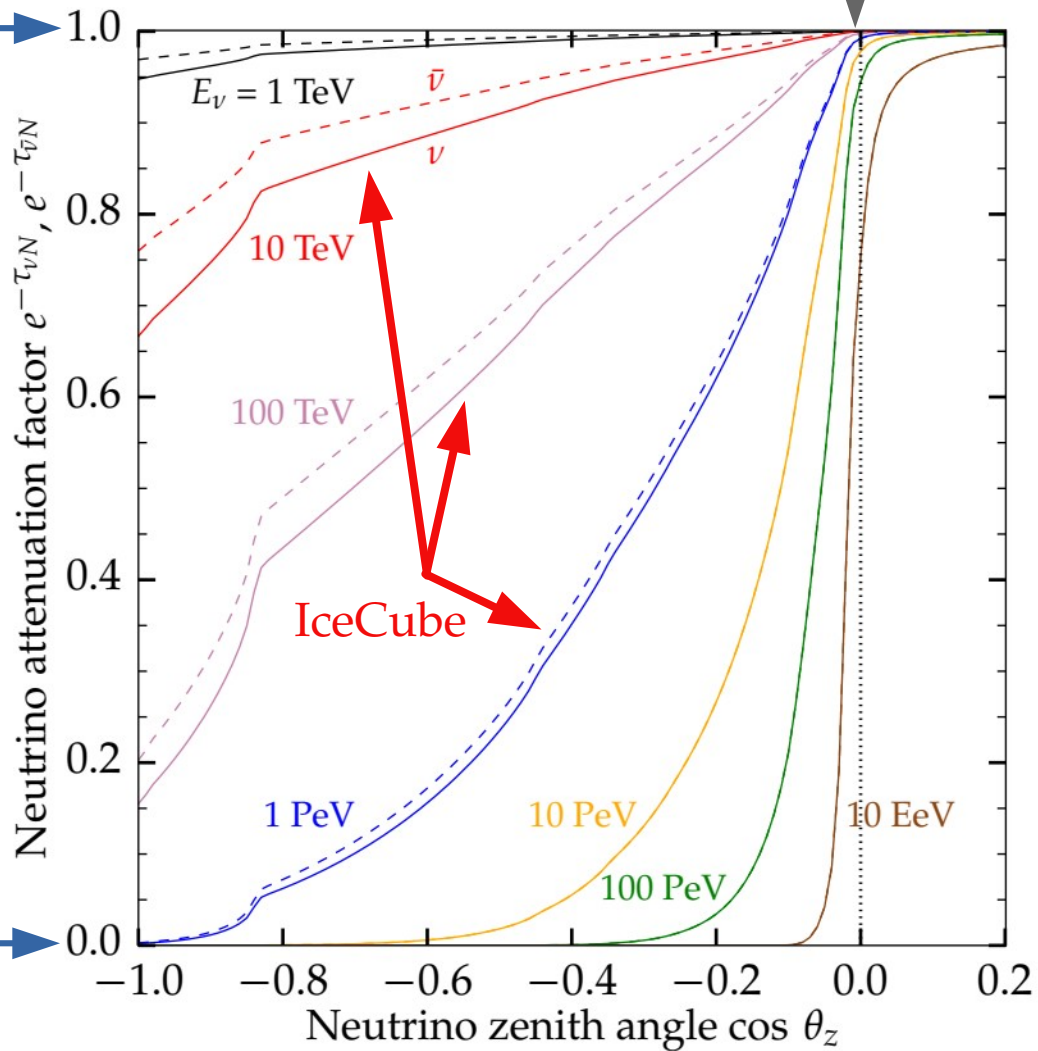
No
attenuation



Full
attenuation

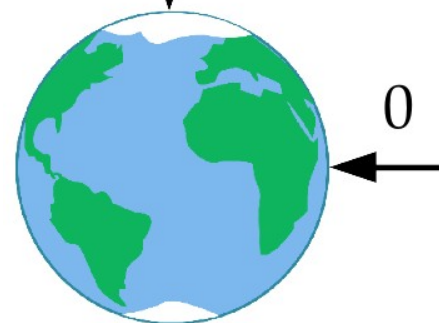


No
attenuation

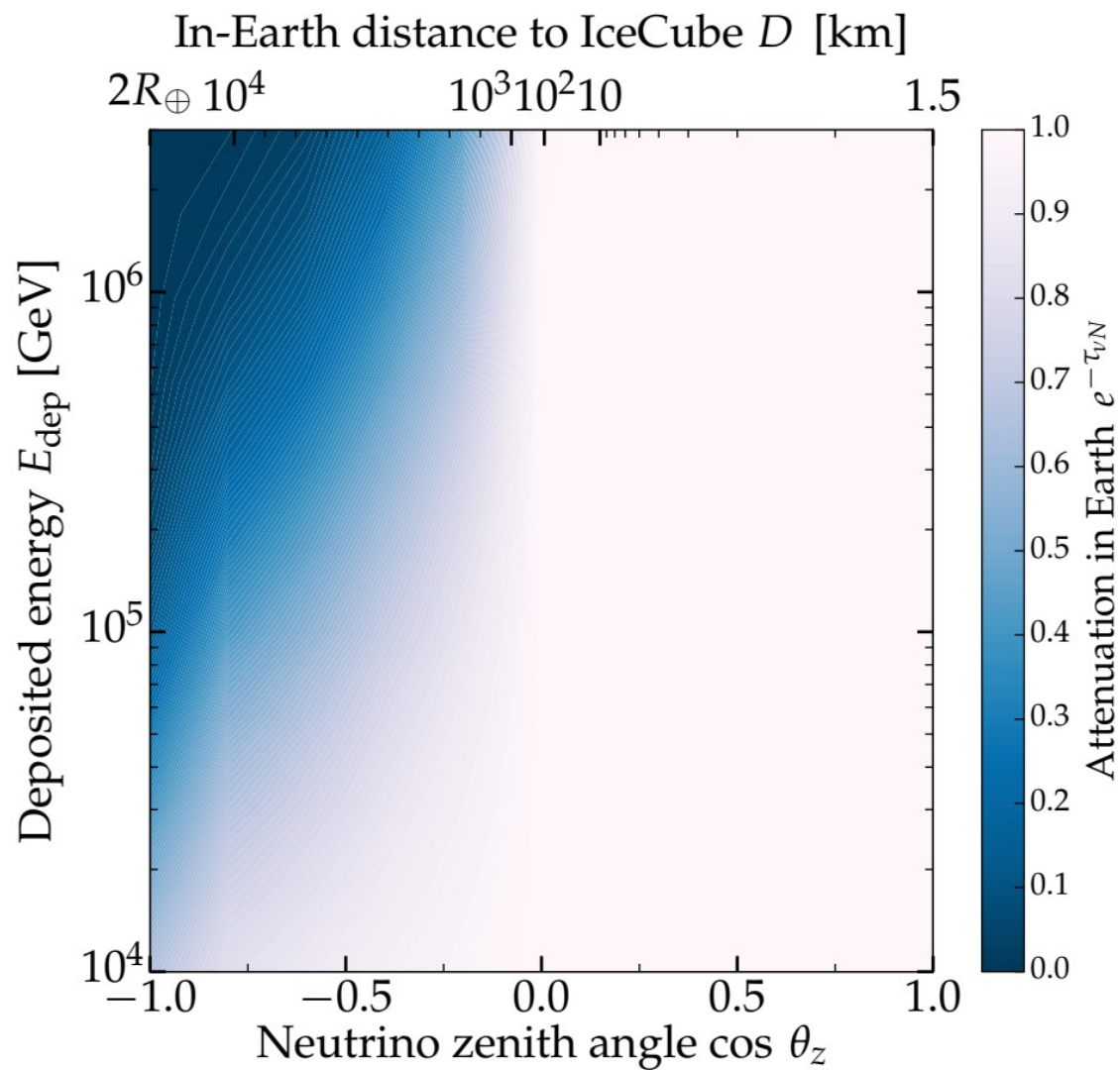


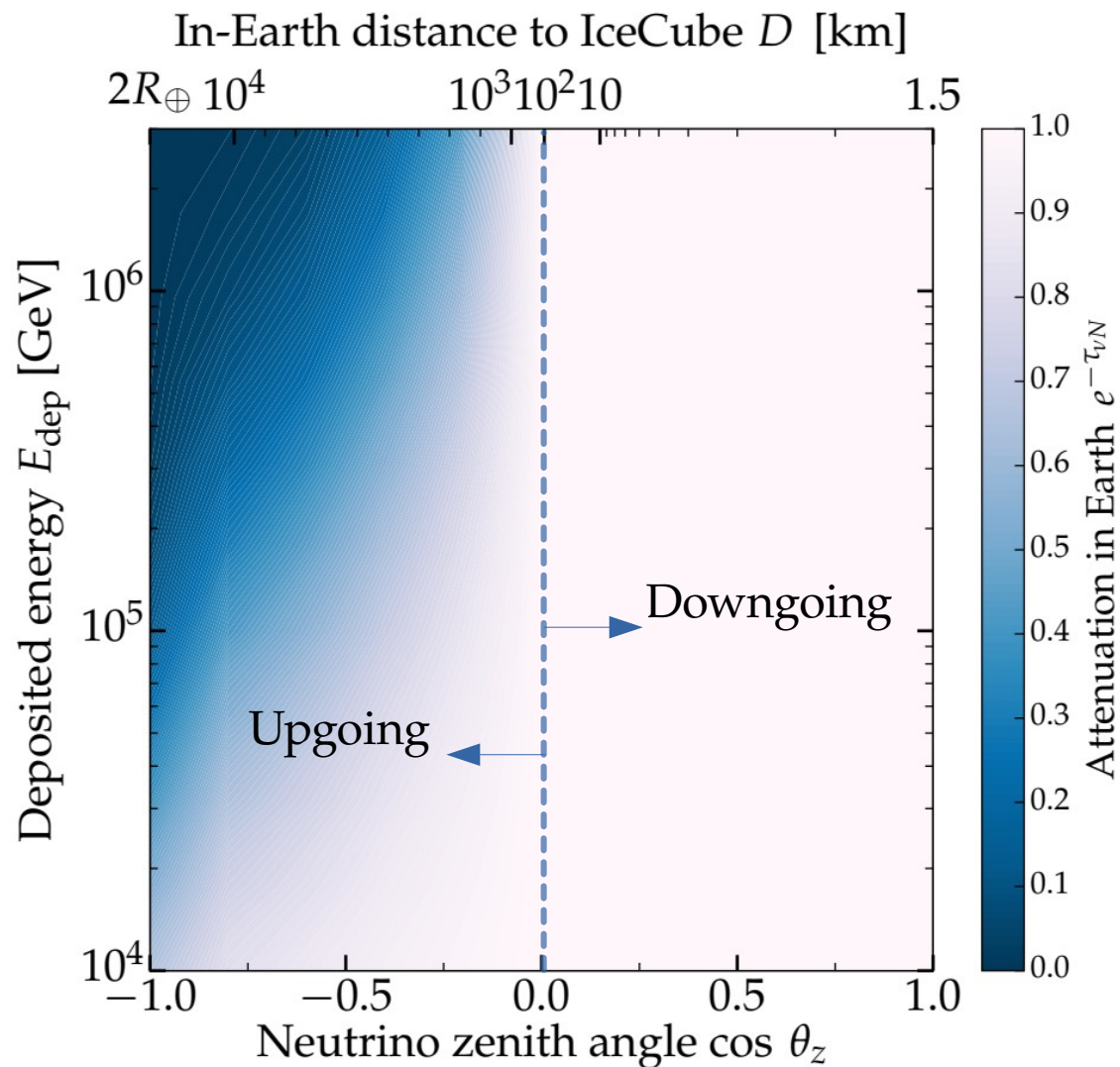
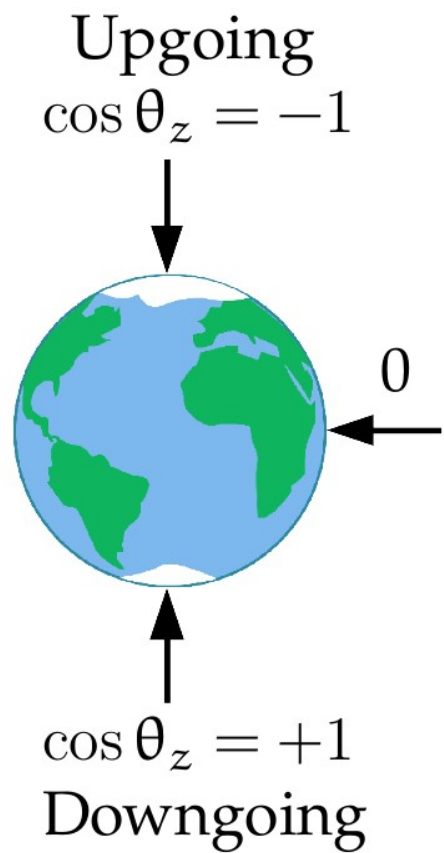
Full
attenuation

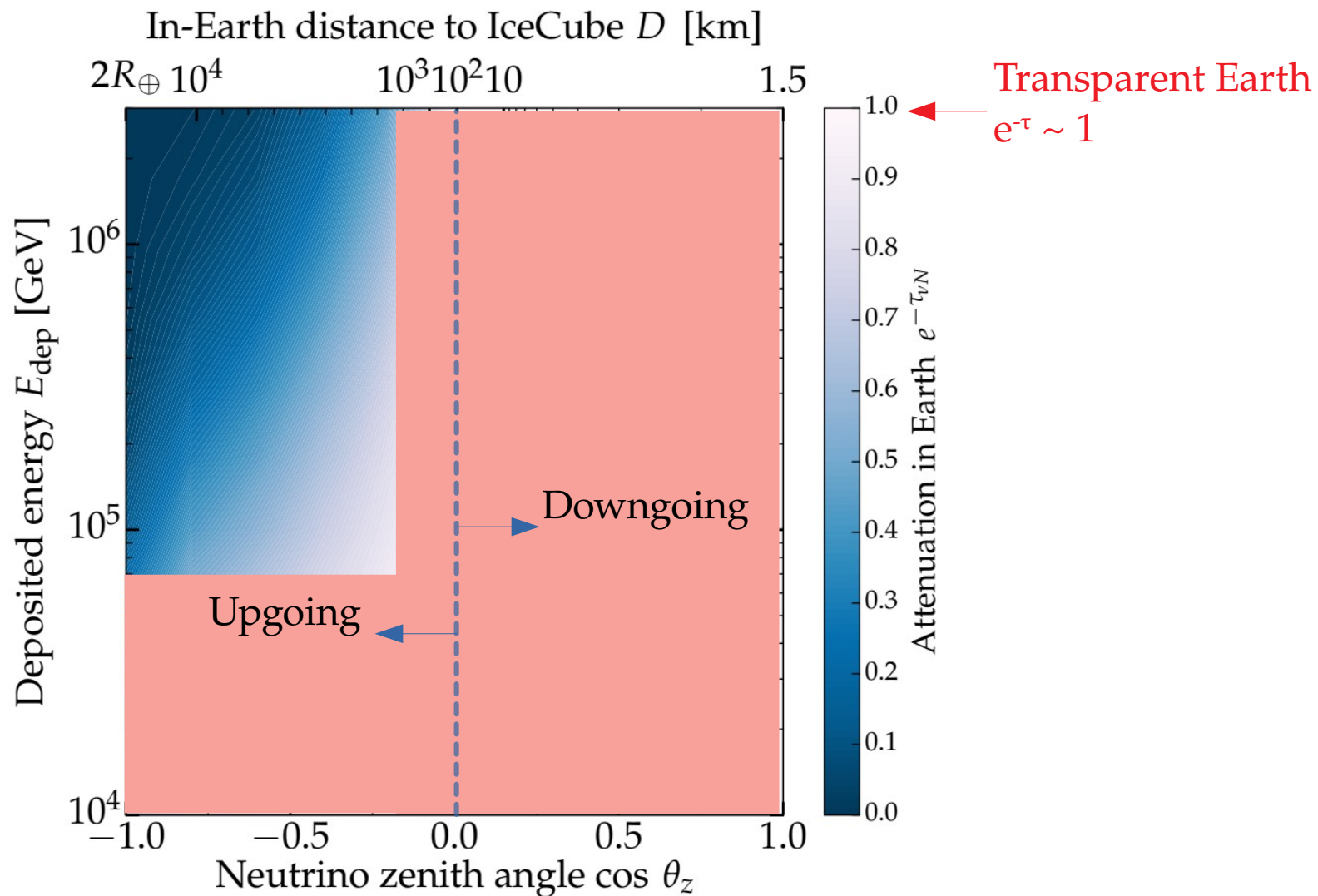
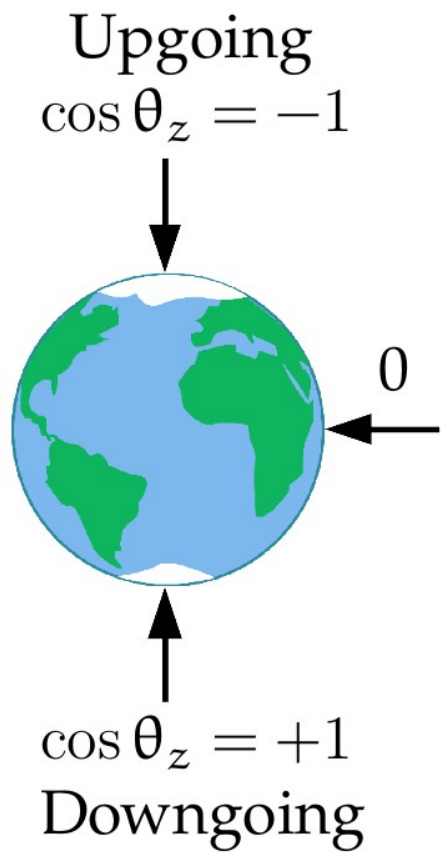
Upgoing
 $\cos \theta_z = -1$

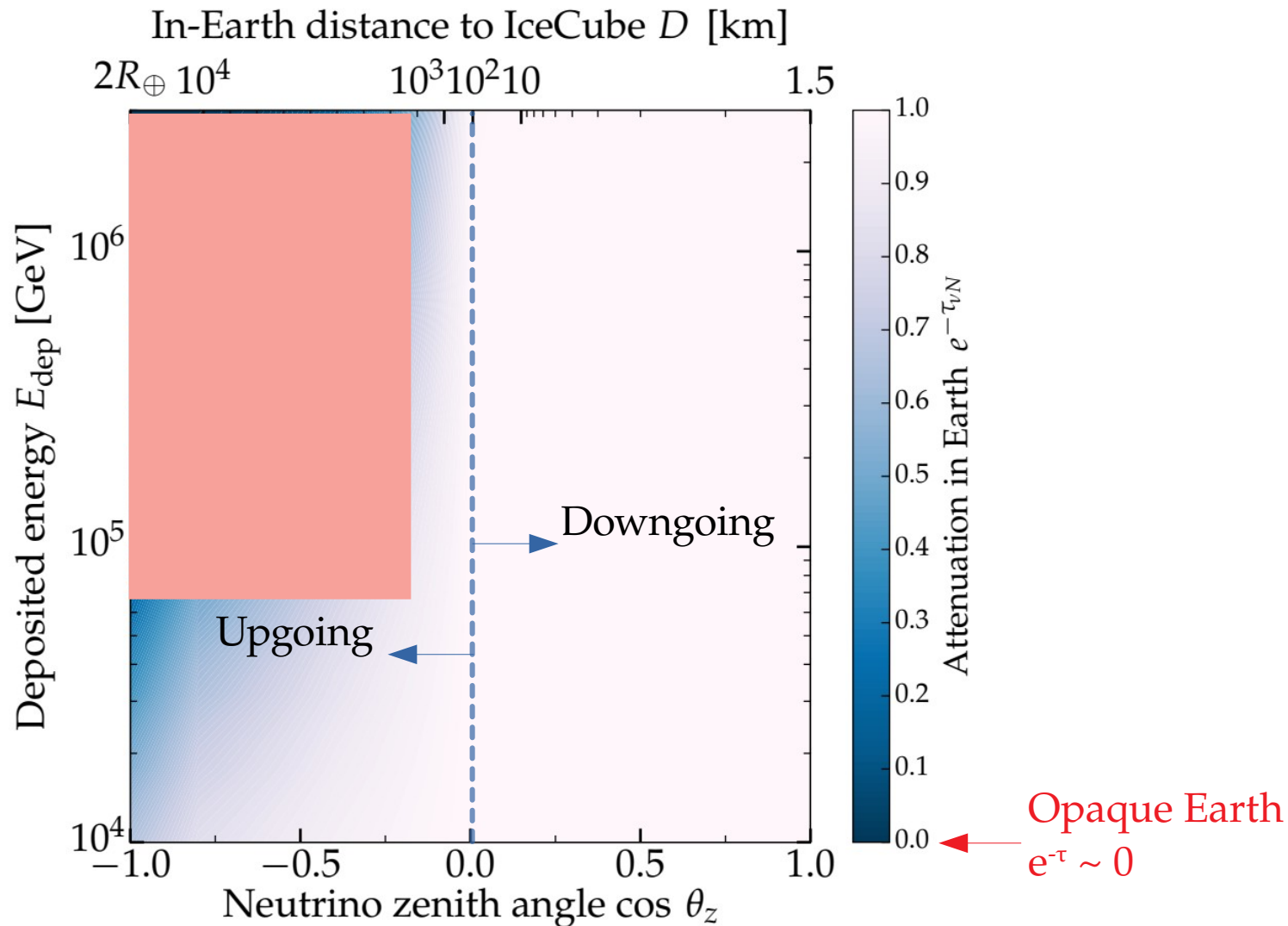
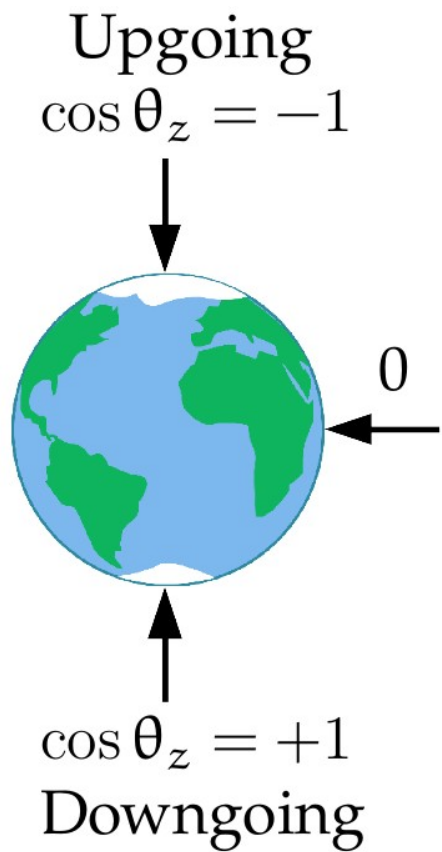


$\cos \theta_z = +1$
Downgoing

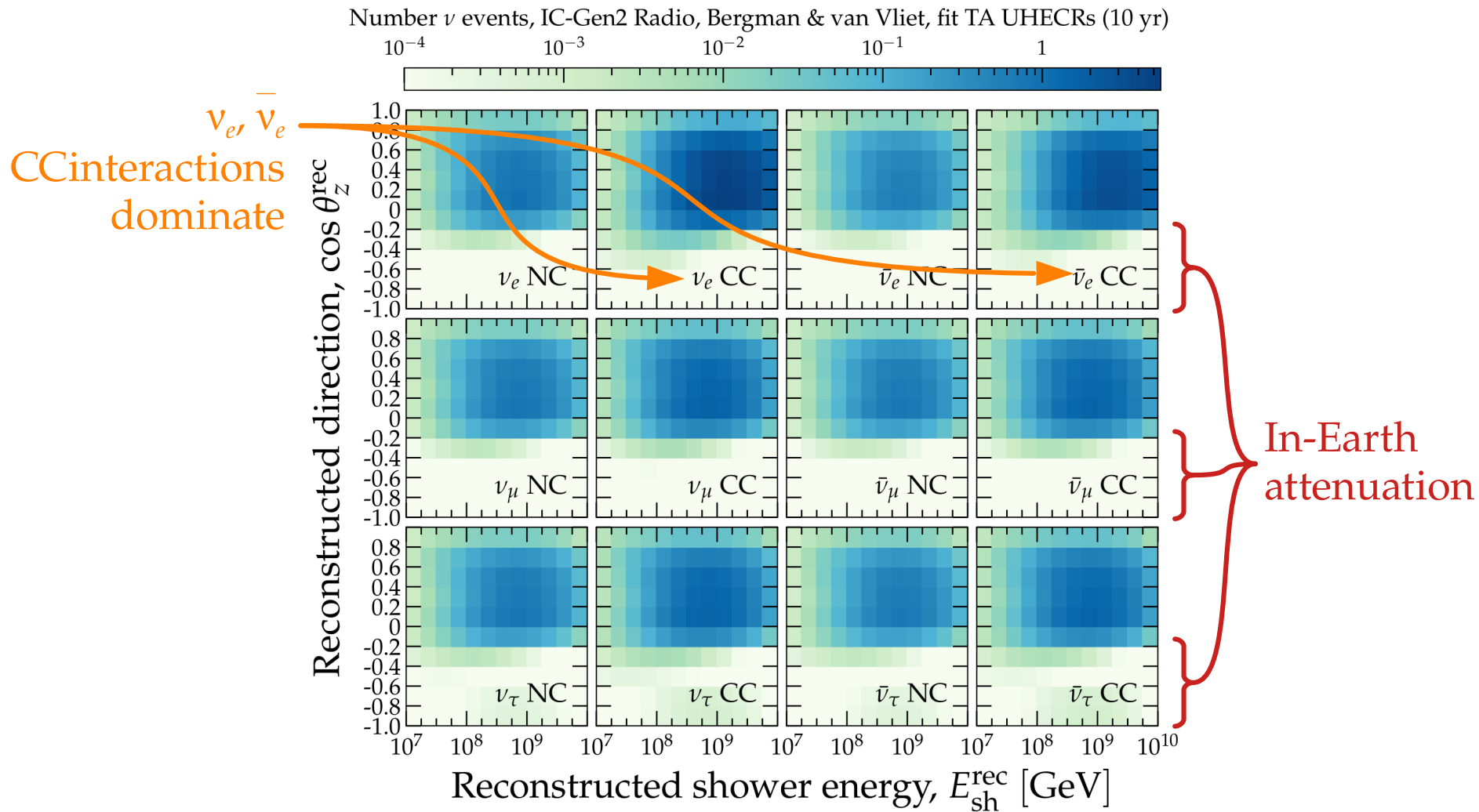


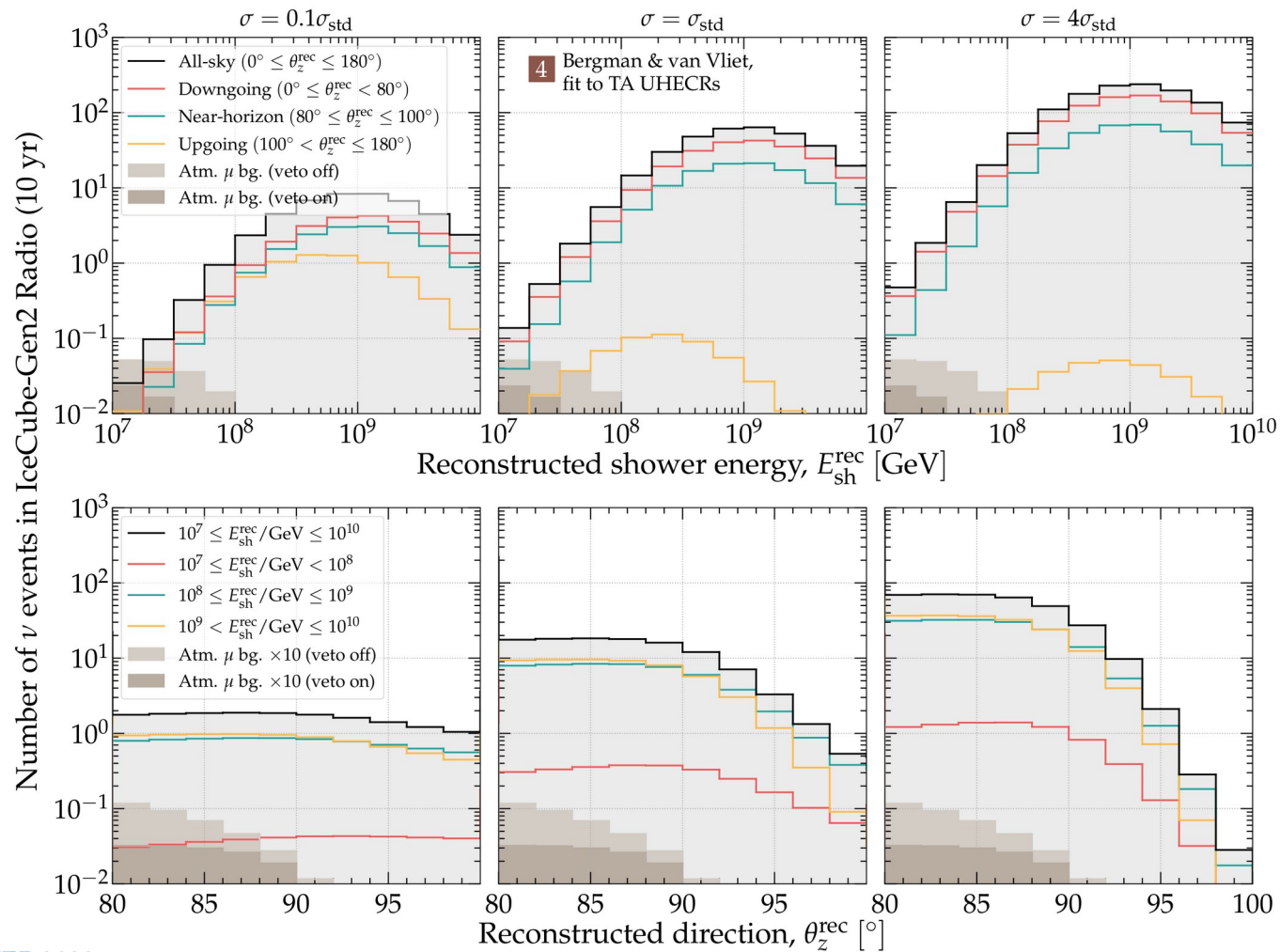




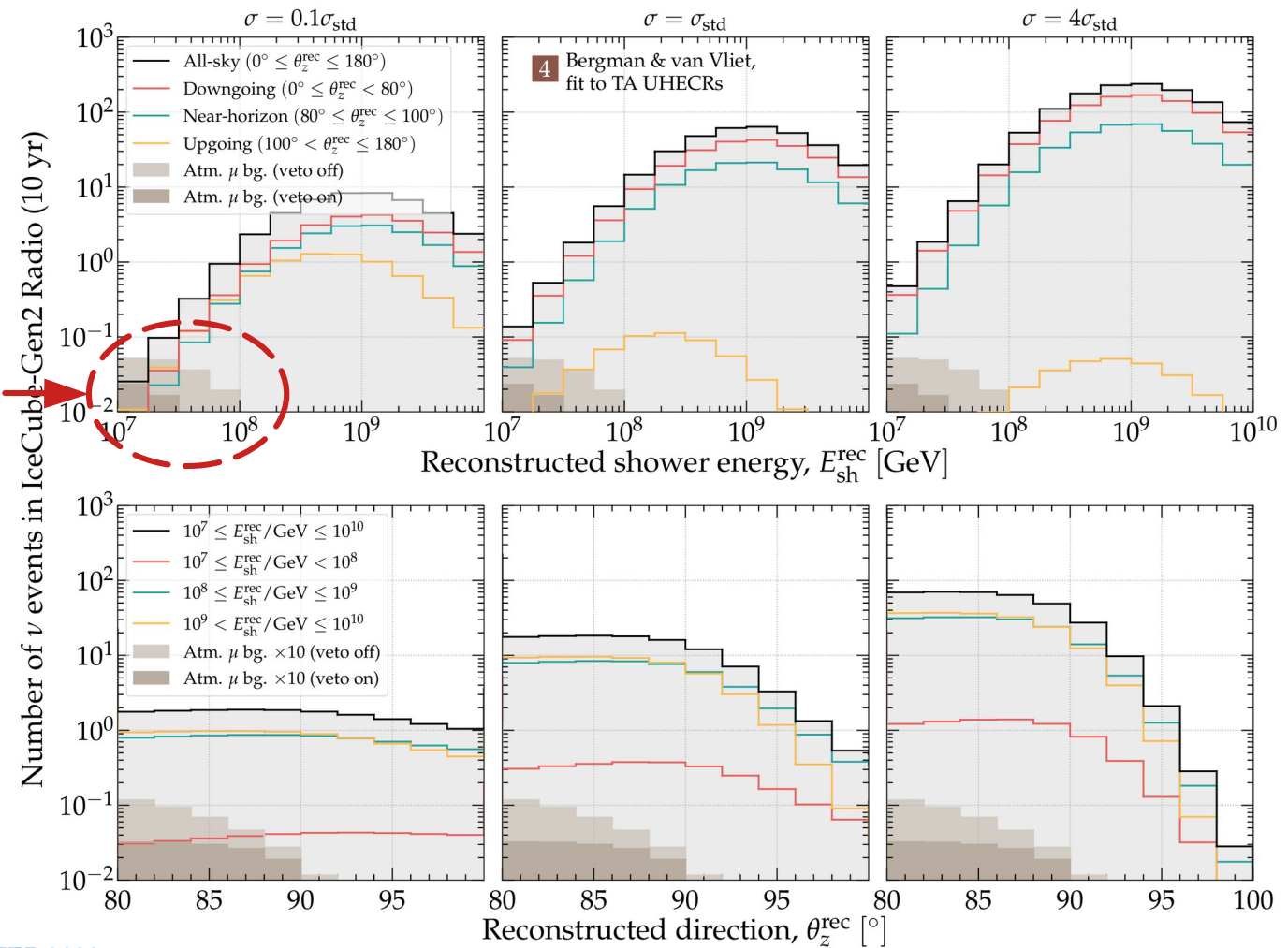


Event rates per channel

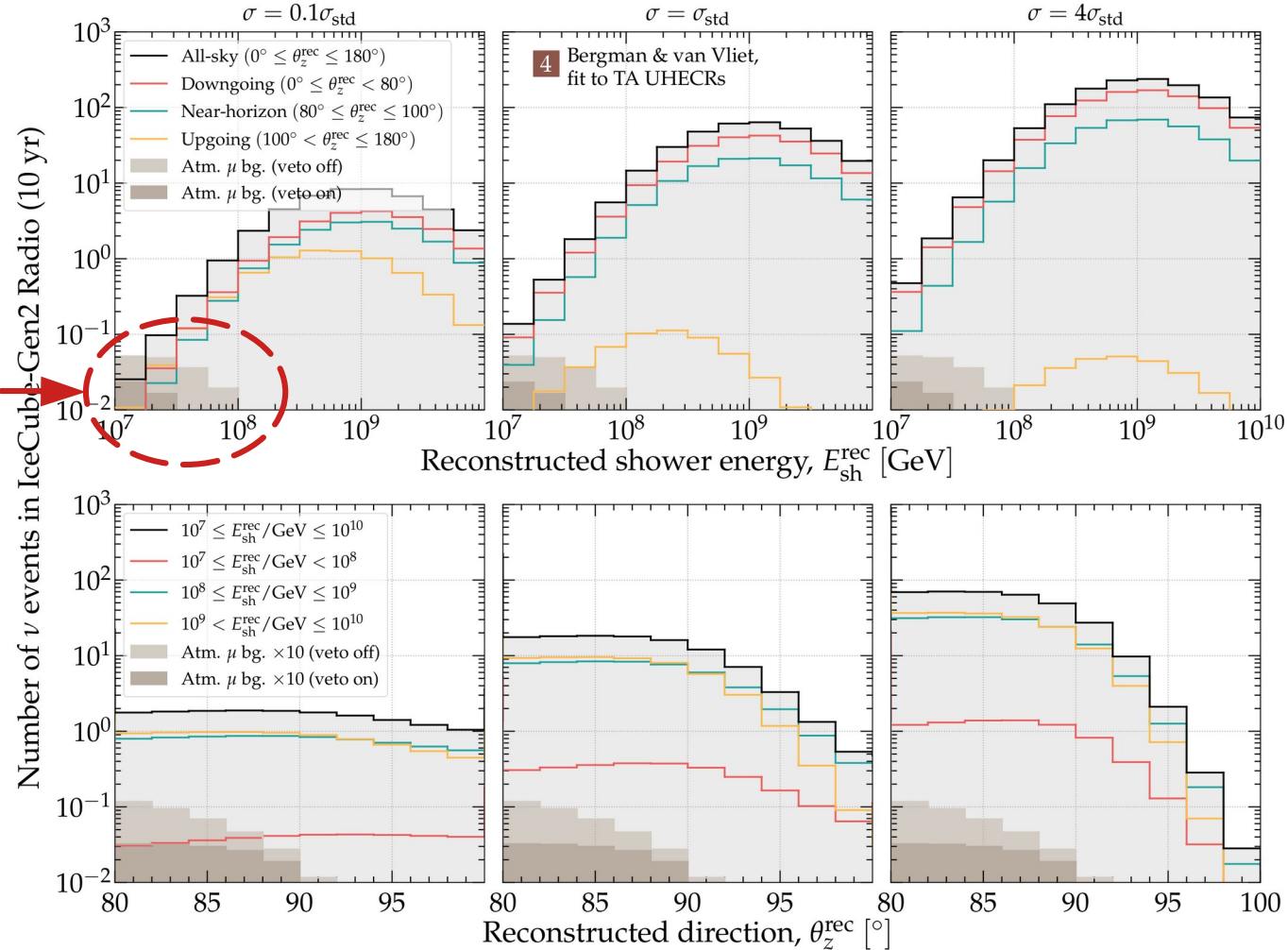




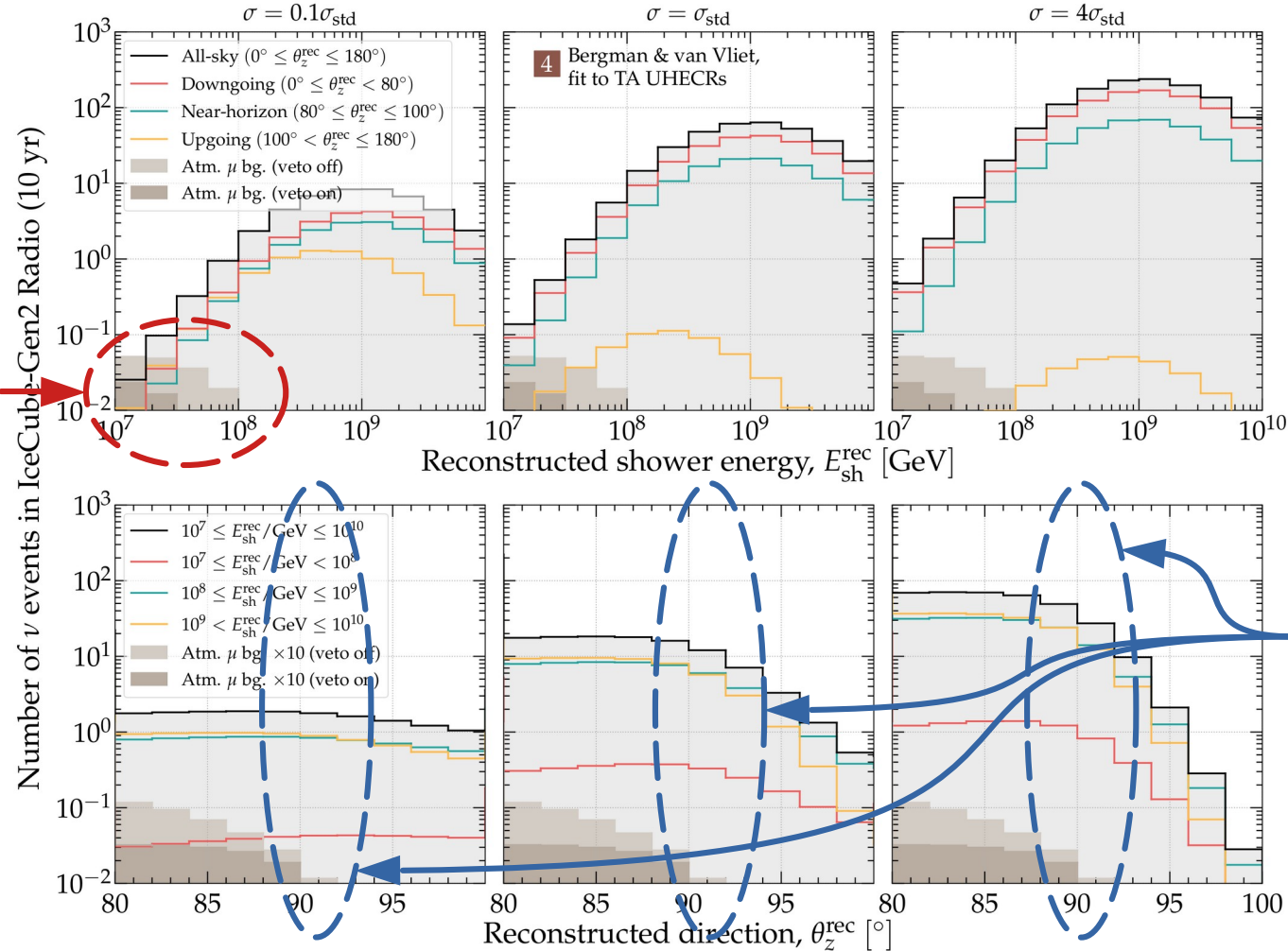
Atmospheric
muon
background



Larger neutrino-nucleon cross section



Larger neutrino-nucleon cross section



Sensitivity to cross section comes from horizontal neutrinos

Measuring cross section *and* flux normalization

Two physical parameters:

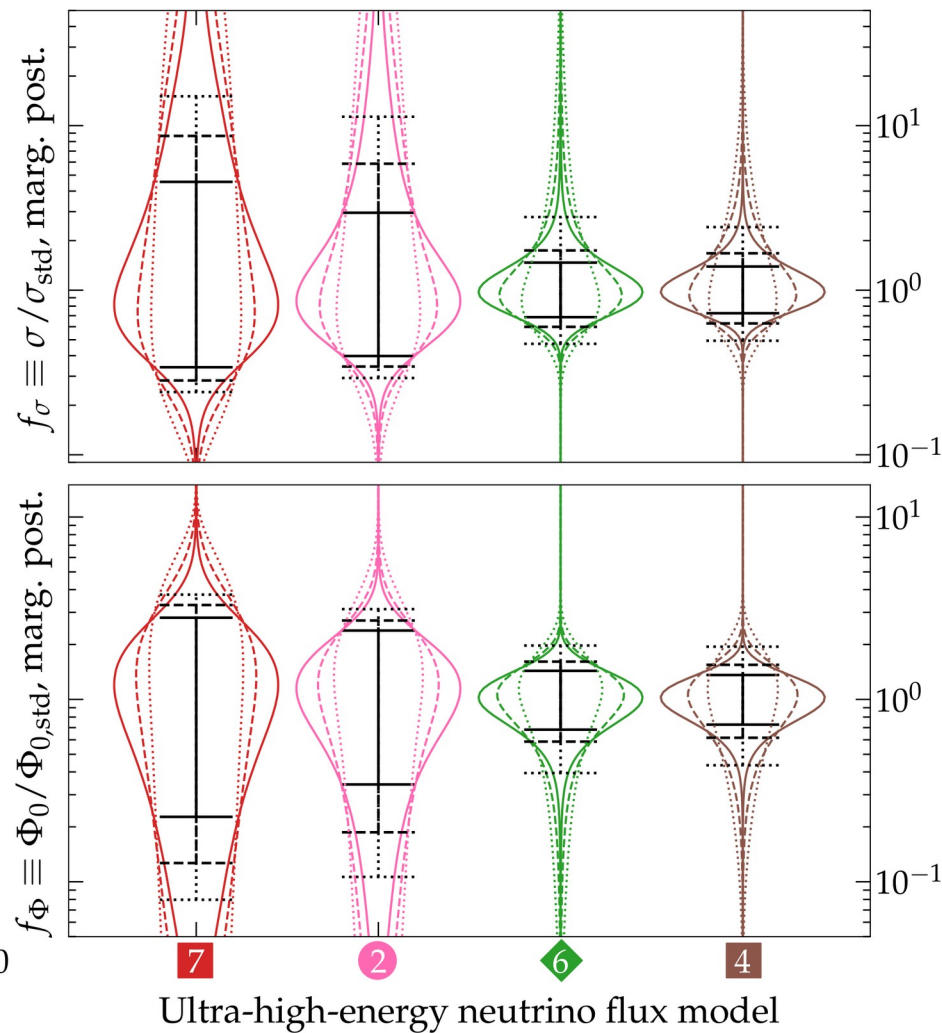
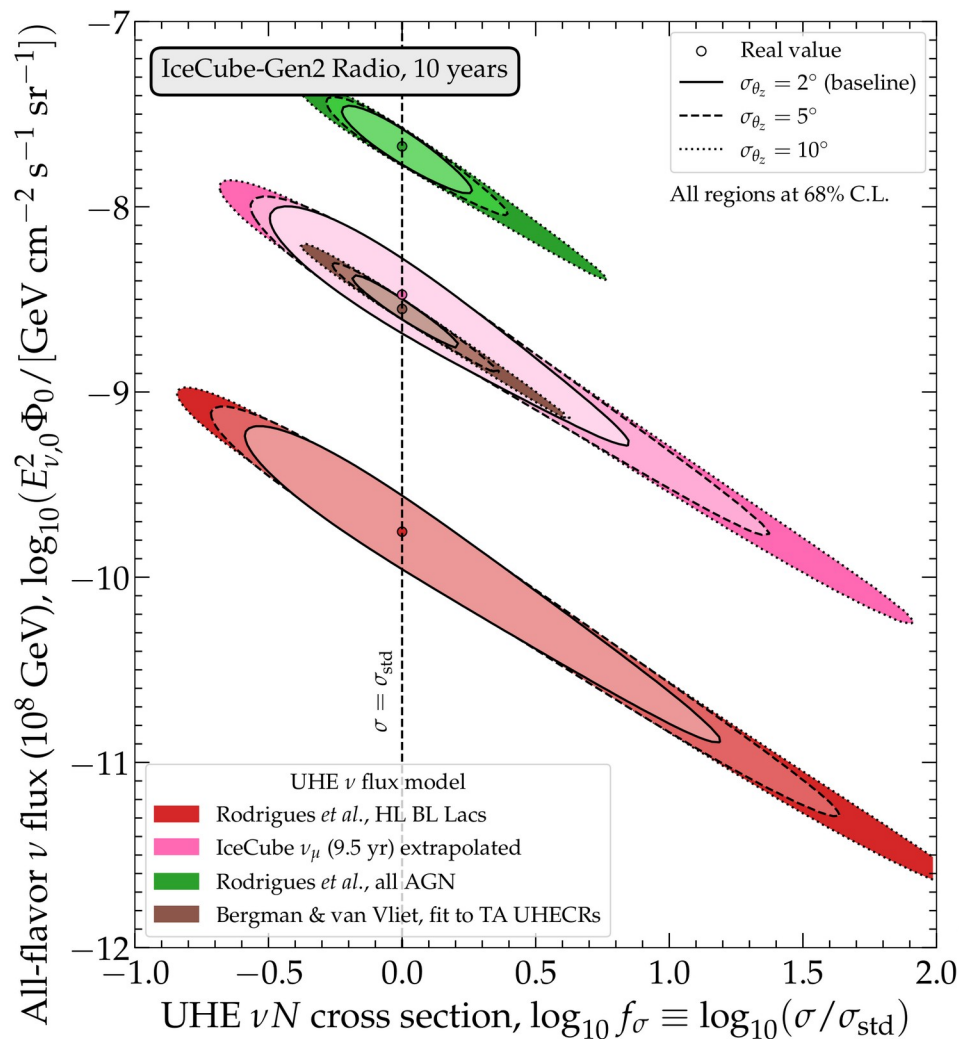
Neutrino-nucleon cross section: $f_\sigma = \frac{\sigma}{\sigma_{\text{std}}}$

Neutrino flux normalization:
(Keep the spectral shape fixed for now) $f = \frac{\Phi_\nu(10^8 \text{ GeV})}{\Phi_{\nu,\text{std}}(10^8 \text{ GeV})}$

We vary and extract both simultaneously *always*,
and marginalize over each at a time

Effect of angular resolution

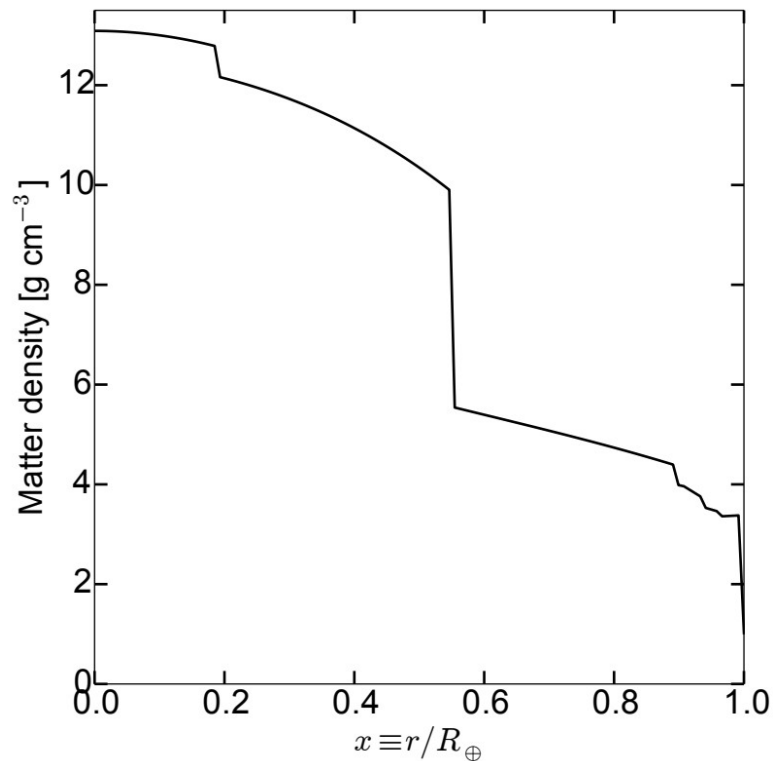
Valera, MB, Glaser, 2204.04237



A feel for the in-Earth attenuation

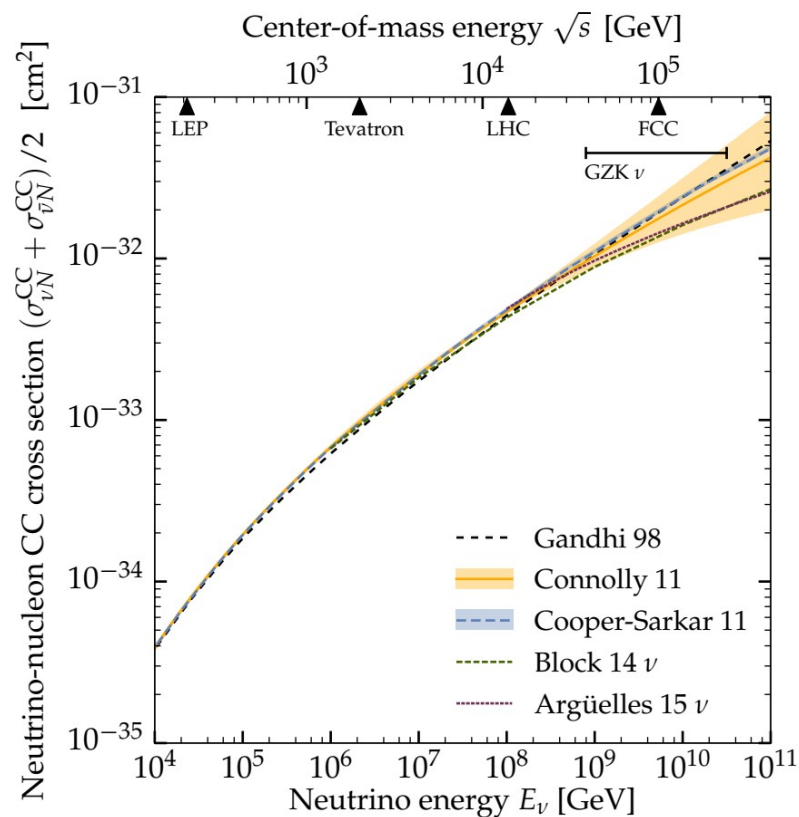
Earth matter density

(Preliminary Reference Earth Model)

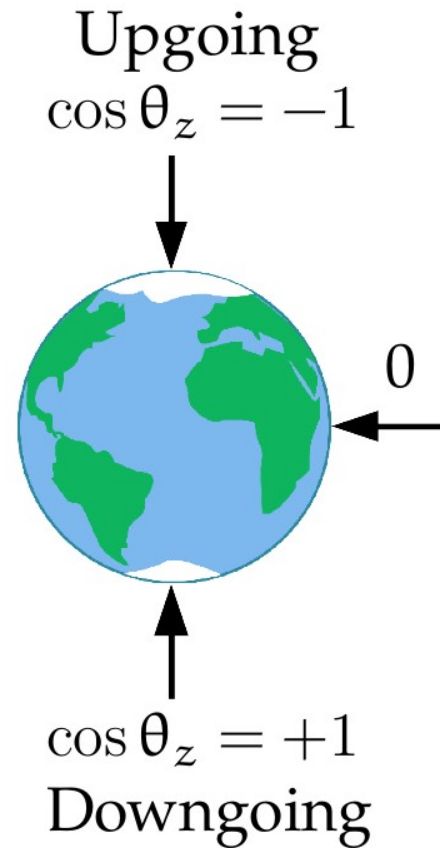
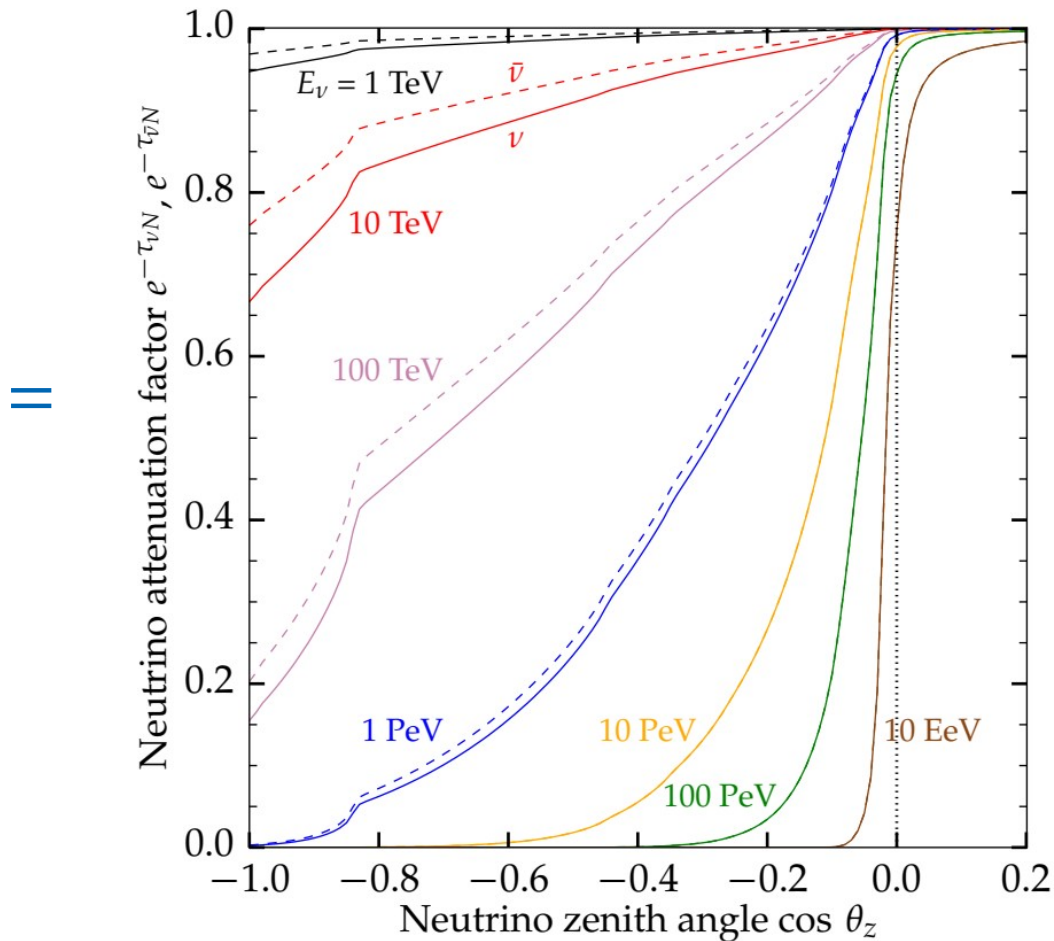


+

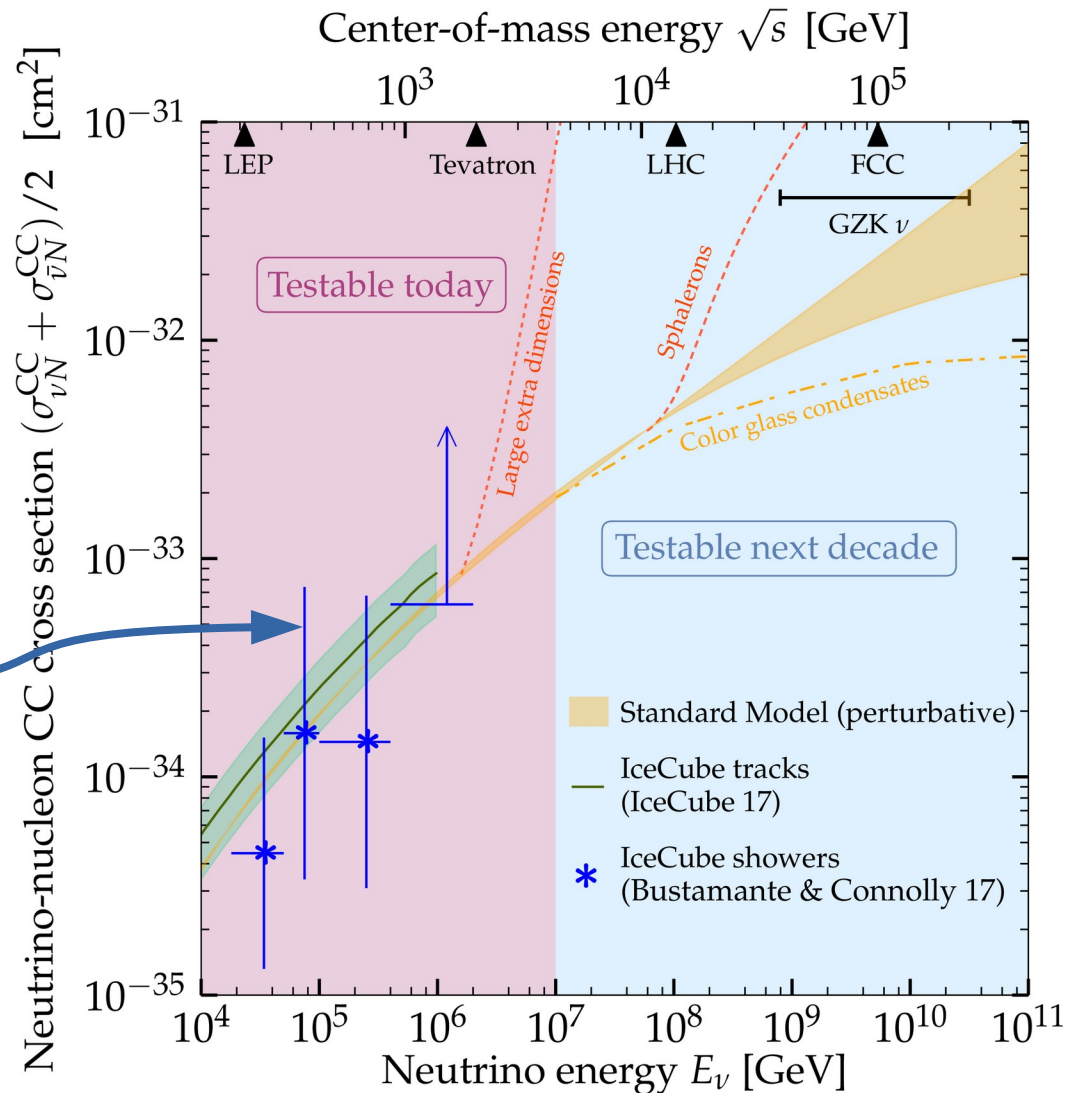
Neutrino-nucleon cross section

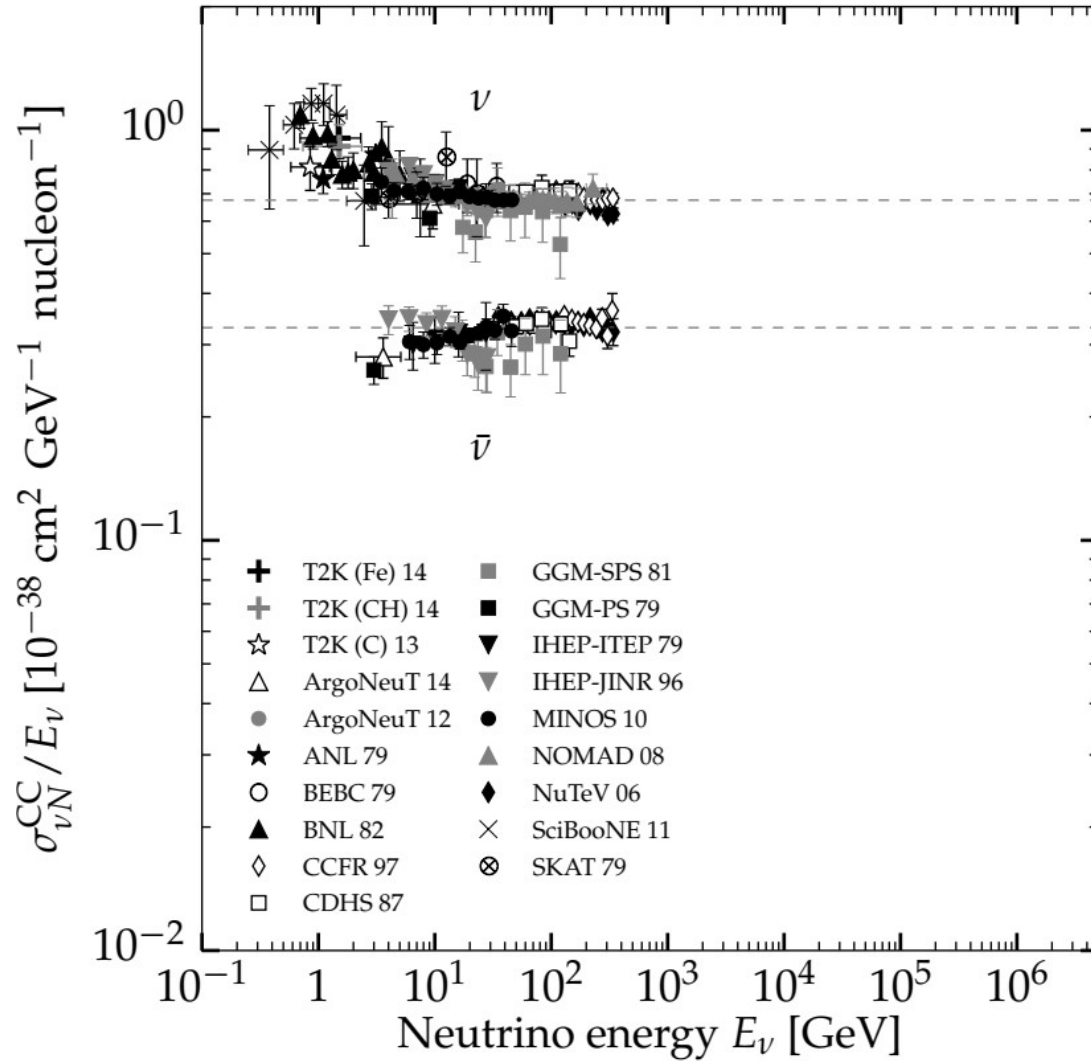


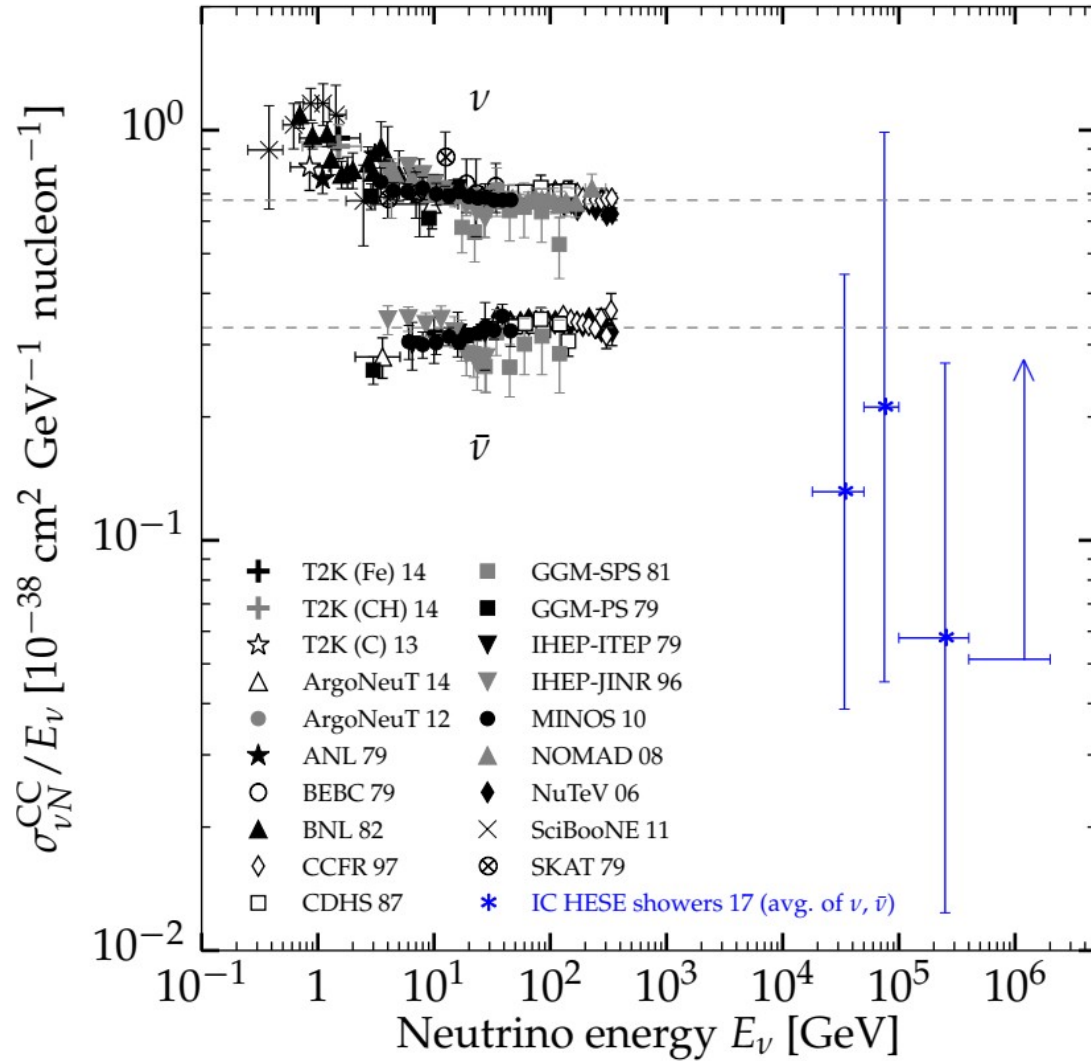
A feel for the in-Earth attenuation

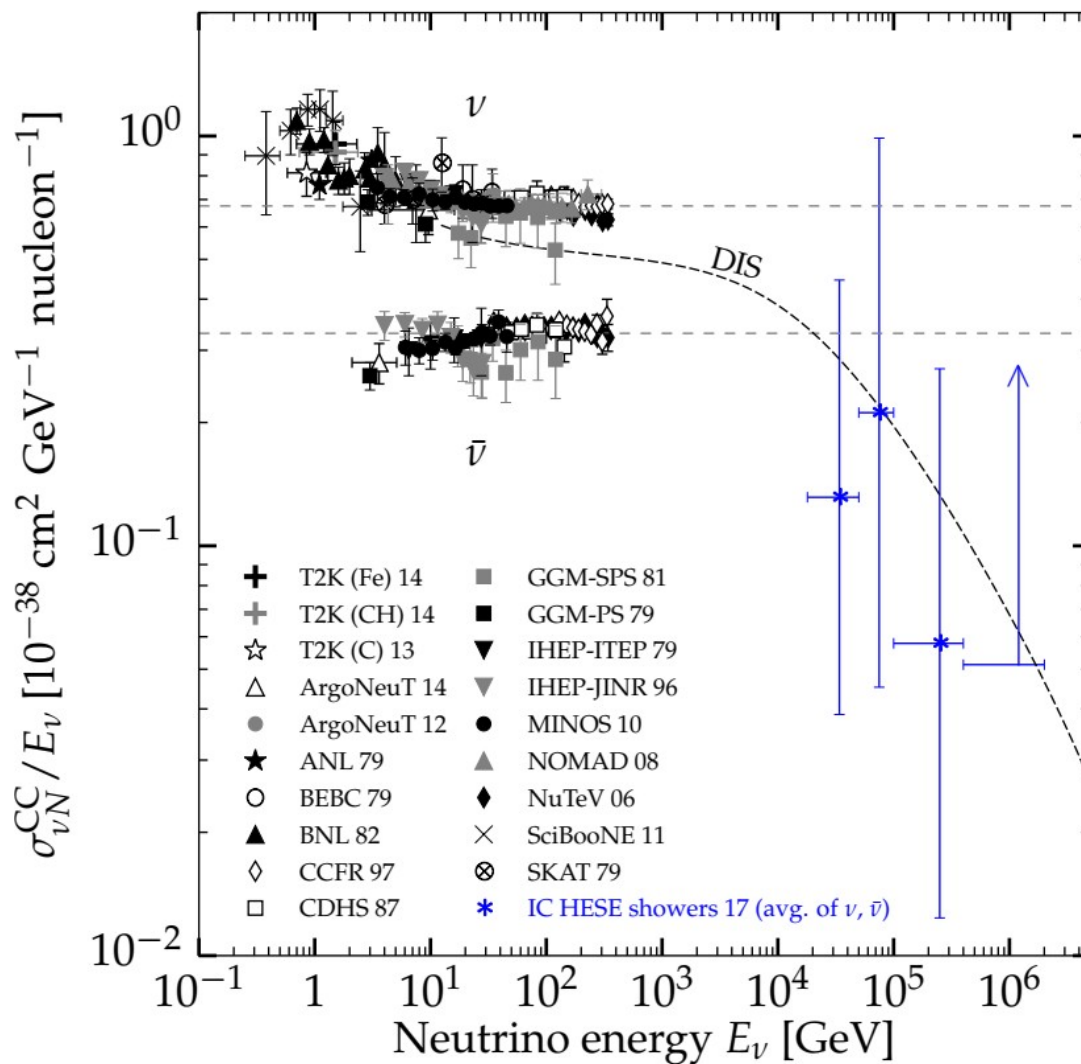


- ▶ Fold in astrophysical unknowns (spectral index, normalization)
- ▶ Compatible with SM predictions
- ▶ Still room for new physics
- ▶ Today, using IceCube:
 - ▶ Extracted from ~60 showers in 6 yr
 - ▶ Limited by statistics
- ▶ Future, using IceCube-Gen2:
 - ▶ $\times 5$ volume $\Rightarrow$ 300 showers in 6 yr
 - ▶ Reduce statistical error by 40%

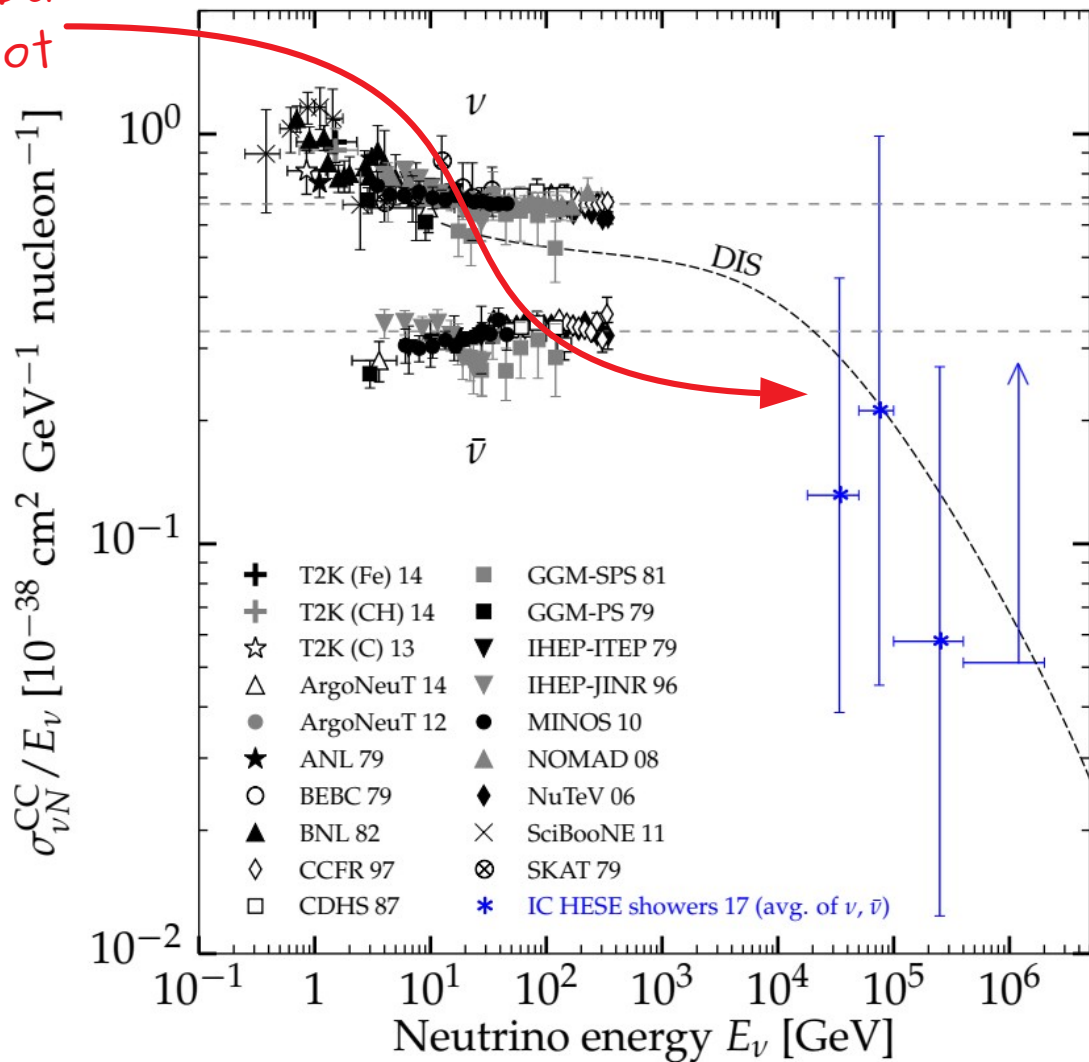








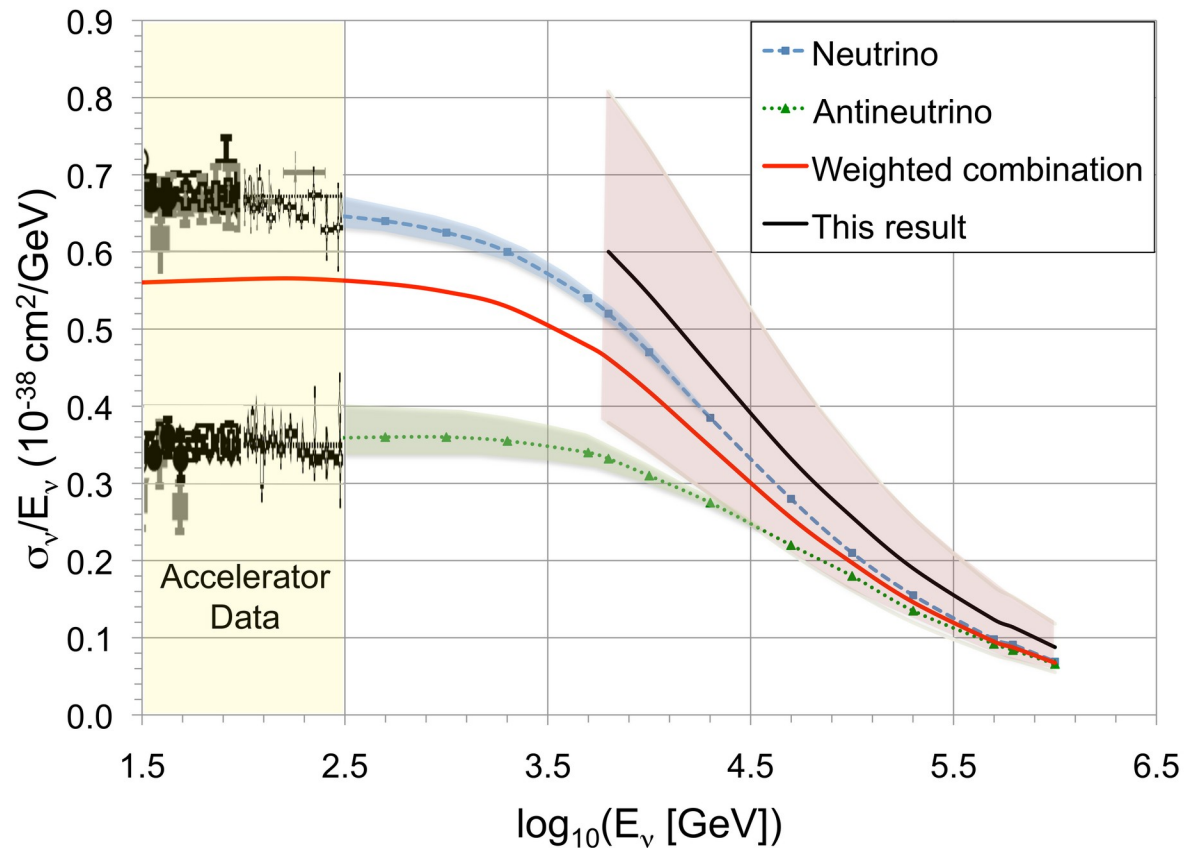
Extending the PDG
cross-section plot



MB & Connolly PRL 2019
See also: IceCube, Nature 2017

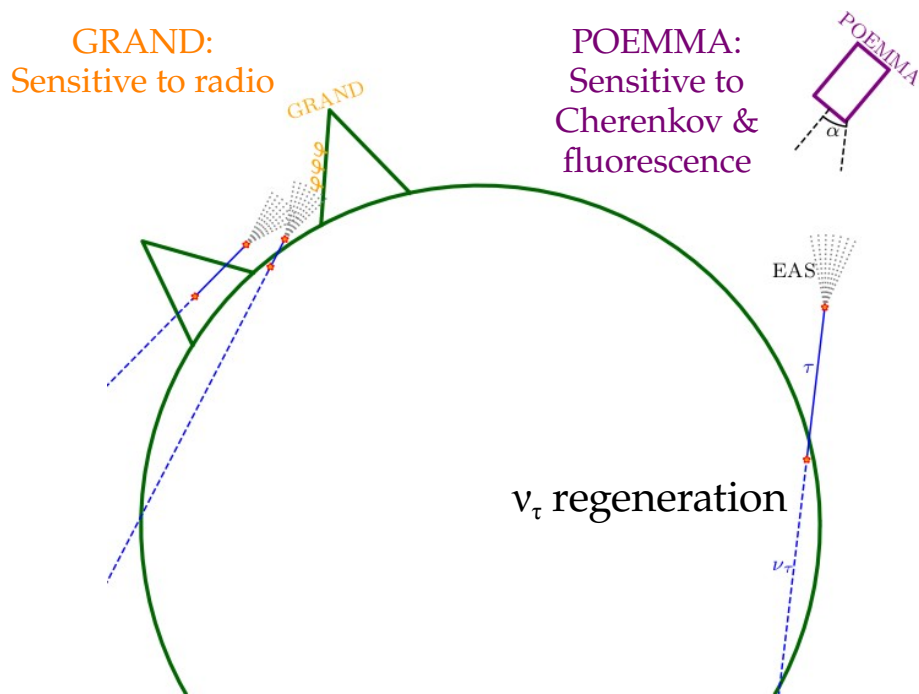
Using through-going muons instead

- ▶ Use $\sim 10^4$ through-going muons
- ▶ Measured: dE_μ/dx
- ▶ Inferred: $E_\mu \approx dE_\mu/dx$
- ▶ From simulations (uncertain):
most likely E_ν given E_μ
- ▶ Fit the ratio $\sigma_{\text{obs}}/\sigma_{\text{SM}}$
 $1.30^{+0.21}_{-0.19}(\text{stat.})^{+0.39}_{-0.43}(\text{syst.})$
- ▶ All events grouped in a single
energy bin 6–980 TeV

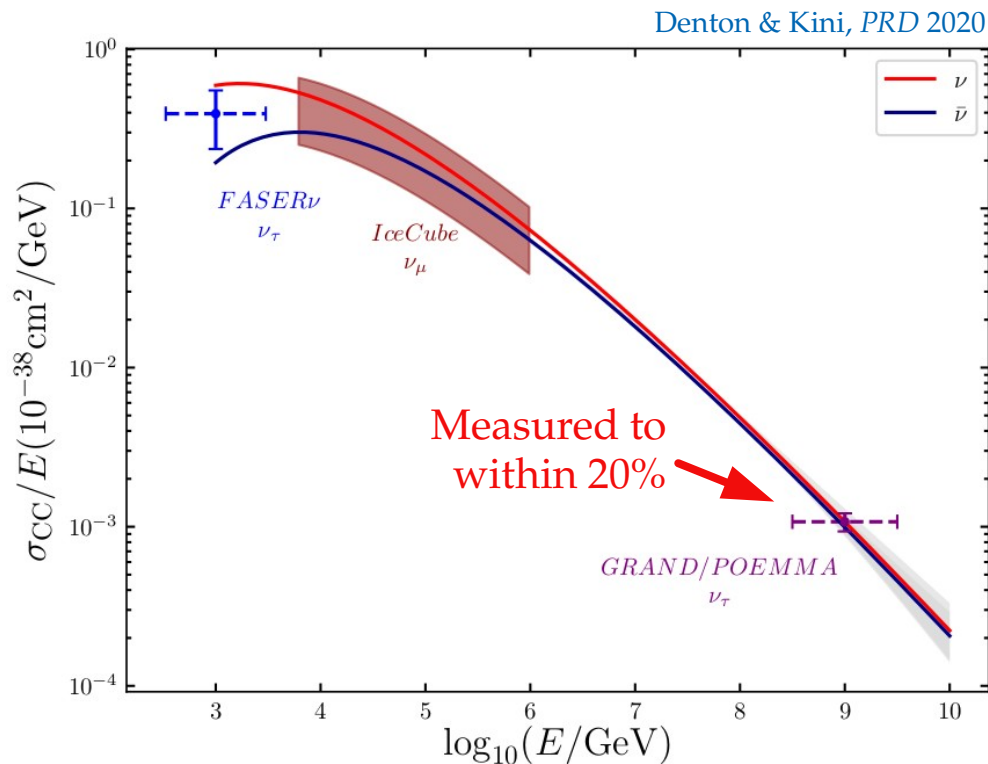


GRAND & POEMMA

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):



Bonus: Measuring the inelasticity $\langle y \rangle$

- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

$$E_X = y E_\nu \quad \text{and} \quad E_\mu = (1-y) E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$$

- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

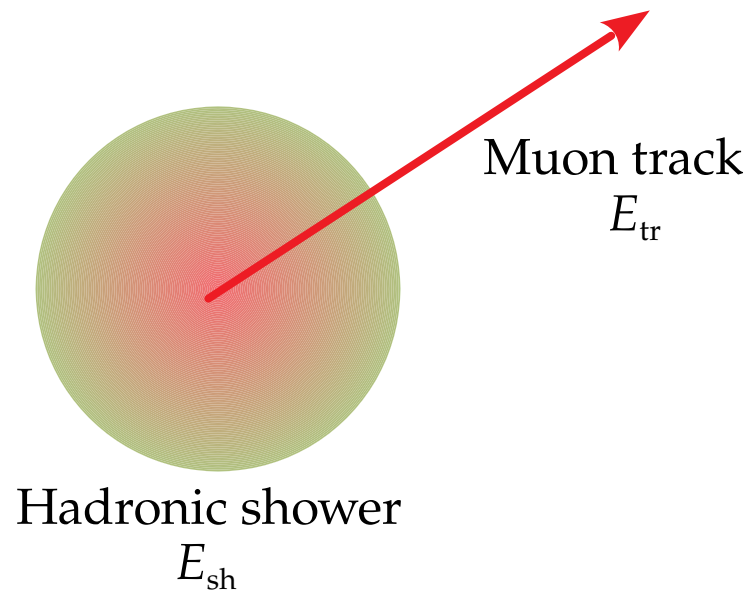
$$E_X = E_{\text{sh}} \text{ (energy of shower)}$$

$$E_\mu = E_{\text{tr}} \text{ (energy of track)}$$

$$\left. \begin{array}{l} E_X = E_{\text{sh}} \text{ (energy of shower)} \\ E_\mu = E_{\text{tr}} \text{ (energy of track)} \end{array} \right\} y = (1 + E_{\text{tr}}/E_{\text{sh}})^{-1}$$

- ▶ New IceCube analysis:

- ▶ 5 years of starting-track data (2650 tracks)
- ▶ Machine learning separates shower from track
- ▶ Different y distributions for ν and $\bar{\nu}$



Bonus: Measuring the inelasticity $\langle y \rangle$

- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

$$E_X = y E_\nu \quad \text{and} \quad E_\mu = (1-y) E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$$

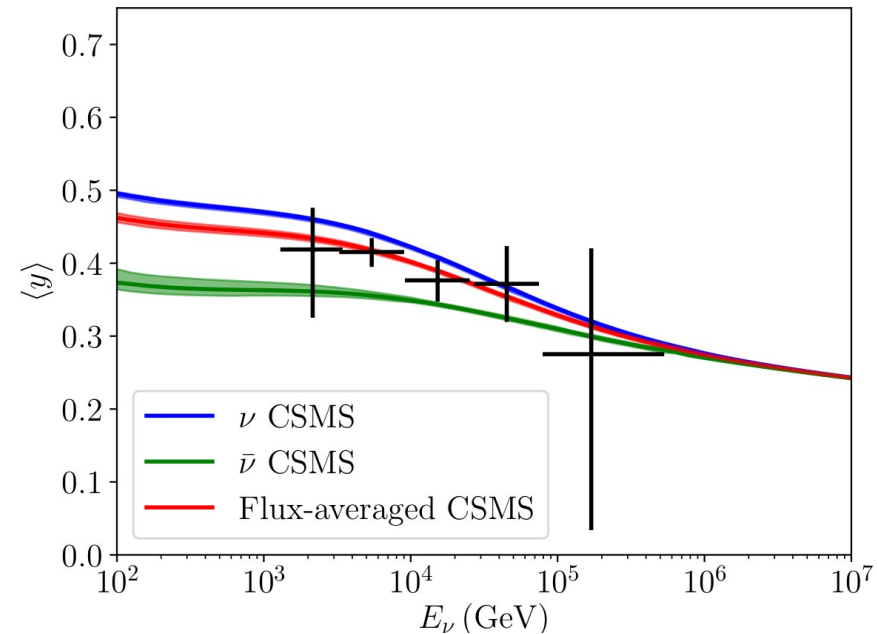
- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

$$\left. \begin{array}{l} E_X = E_{\text{sh}} \text{ (energy of shower)} \\ E_\mu = E_{\text{tr}} \text{ (energy of track)} \end{array} \right\} y = (1 + E_{\text{tr}}/E_{\text{sh}})^{-1}$$

- ▶ New IceCube analysis:

- ▶ 5 years of starting-track data (2650 tracks)
- ▶ Machine learning separates shower from track
- ▶ Different y distributions for ν and $\bar{\nu}$

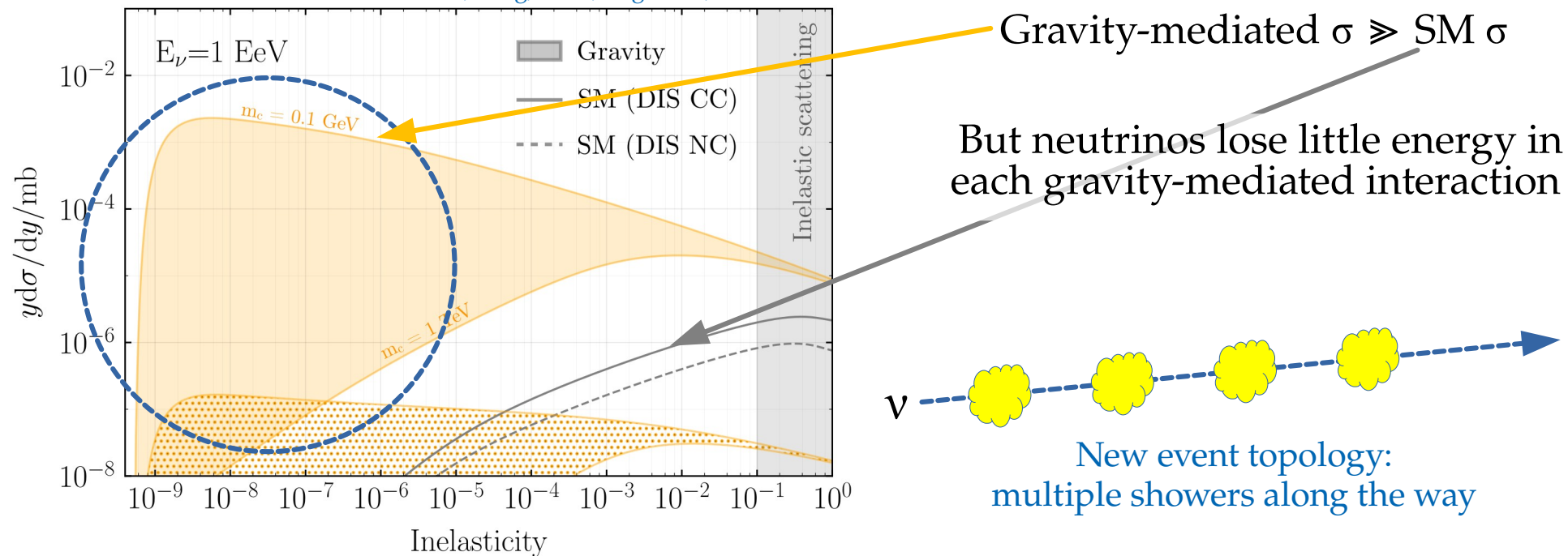


IceCube Collab., PRD 2019

Warning: UHE BSM that changes inelasticity needs care

TeV-scale gravity may induce EeV-scale *elastic* neutrino interactions, *i.e.*, with low y :

Garcia Soto, Garg, Reno, Argüelles, 2209.06282



Inelasticity-changing BSM needs dedicated analysis

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
 Search for new high-energy physics

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
 Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
 Use the Earth as target

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

When? With TeV–PeV ν : already now (IceCube)
With EeV ν : in 10–20 yr (IceCube-Gen2)[†]

Measuring high-energy neutrino-matter interactions

Why? Probe nucleons deeper than ever
Search for new high-energy physics

How? Use high-energy & ultra-high-energy cosmic neutrinos
Use the Earth as target

When? With TeV–PeV ν : already now (IceCube)
With EeV ν : in 10–20 yr (IceCube-Gen2)[†]

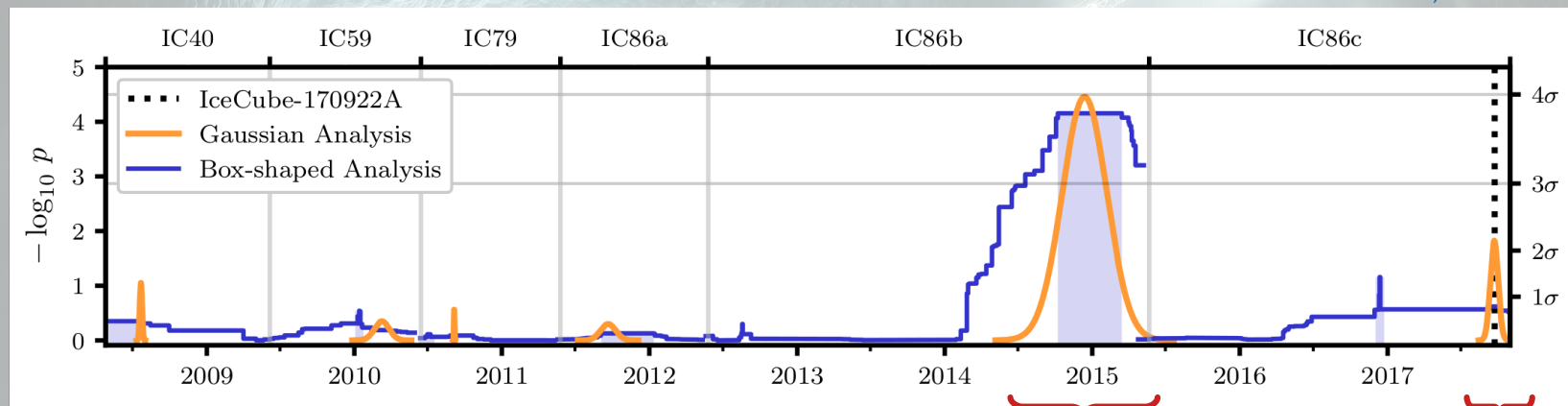
Why hard? Limited event statistics
At UHE, need to have decent angular resolution ($\sim 2^\circ$)

[†]Fingers crossed

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

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

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

Combined (pre-trial): 4.1 σ

Flux normalization

Cross section

All-flavor ν flux (10^8 GeV), $\log_{10}(E_{\nu,0}^2 \Phi_0 / [\text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}])$

IceCube-Gen2 Radio, 10 years

UHE ν flux model

- Rodrigues *et al.*, HL BL Lacs
- IceCube ν_μ (9.5 yr) extrapolated
- Rodrigues *et al.*, all AGN
- Bergman & van Vliet, fit to TA UHECRs

UHE νN cross section, $\log_{10} f_\sigma \equiv \log_{10}(\sigma / \sigma_{\text{std}})$

○ Real value
☆ Best fit
68% C.L.
95% C.L.
99.7% C.L.

$\log_{10} \sigma / \sigma_{\text{std}}$

- 0.09^{+0.75}_{-0.37}
- 0.07^{+0.54}_{-0.33}
- 0.01^{+0.18}_{-0.15}
- 0.01^{+0.16}_{-0.13}

$\log_{10} E_{\nu,0}^2 \Phi_0$

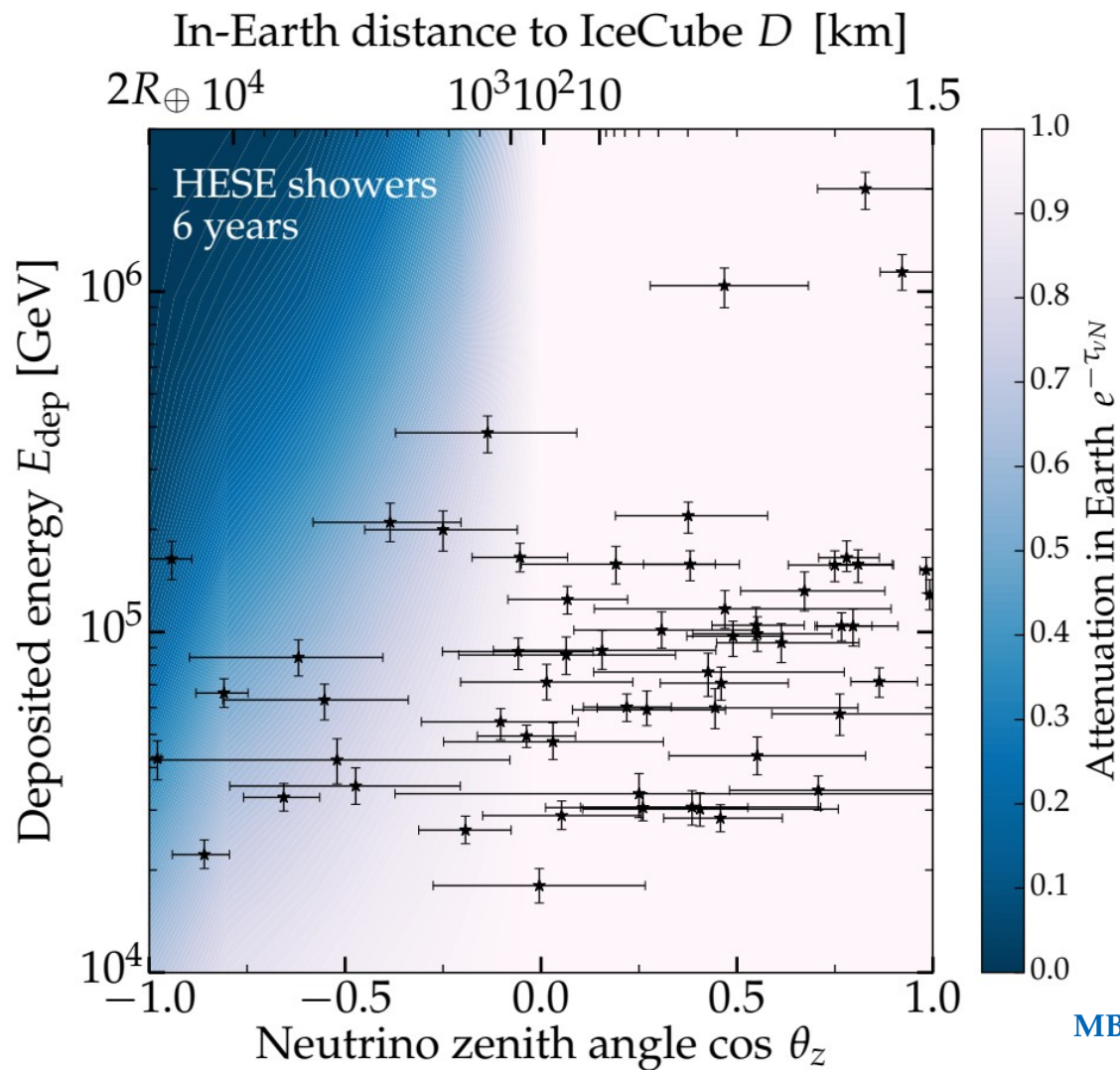
- 9.66^{+0.36}_{-0.74}
- 8.41^{+0.32}_{-0.53}
- 7.66^{+0.15}_{-0.18}
- 8.54^{+0.12}_{-0.15}

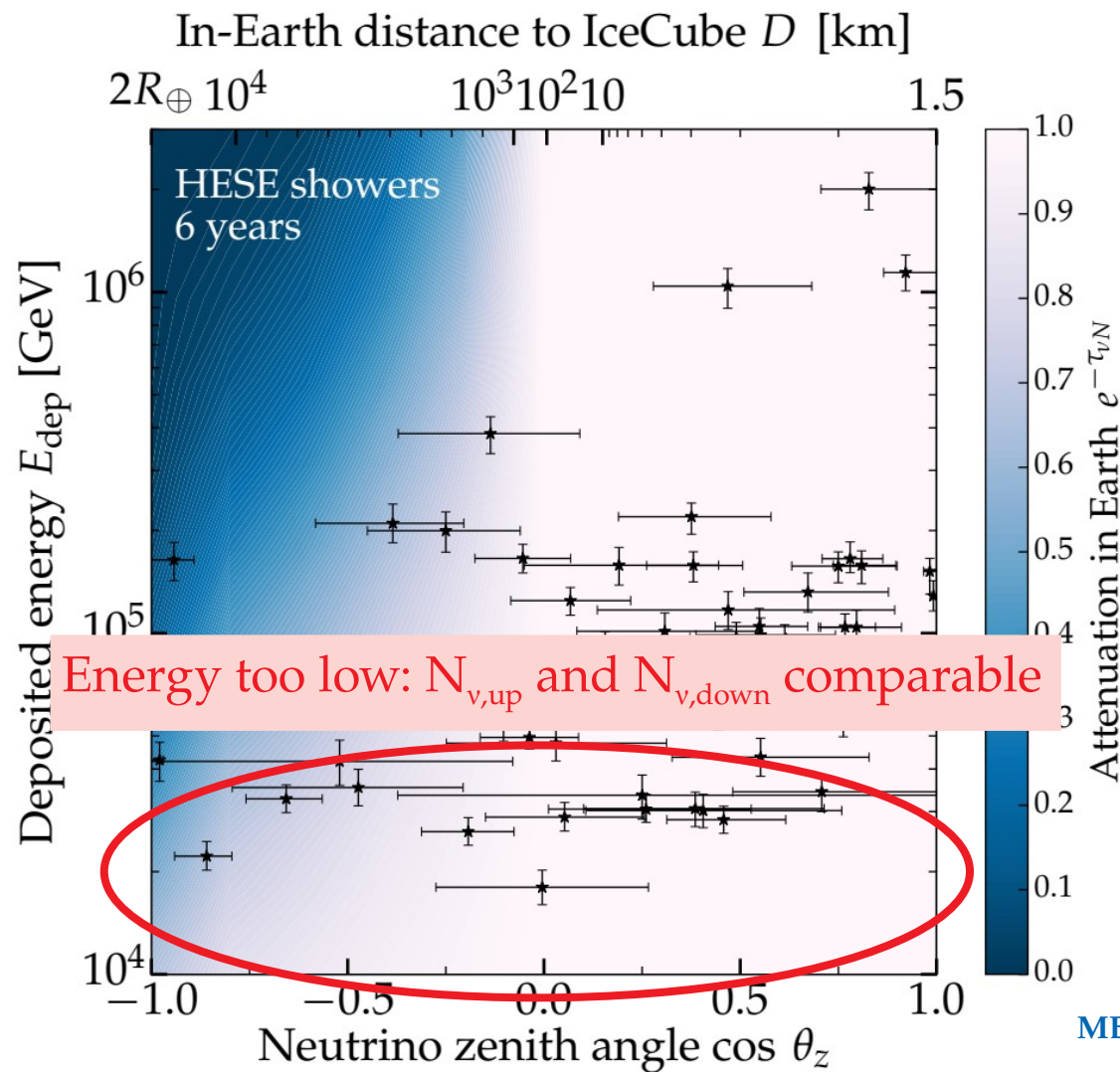
Needed to measure the cross section?

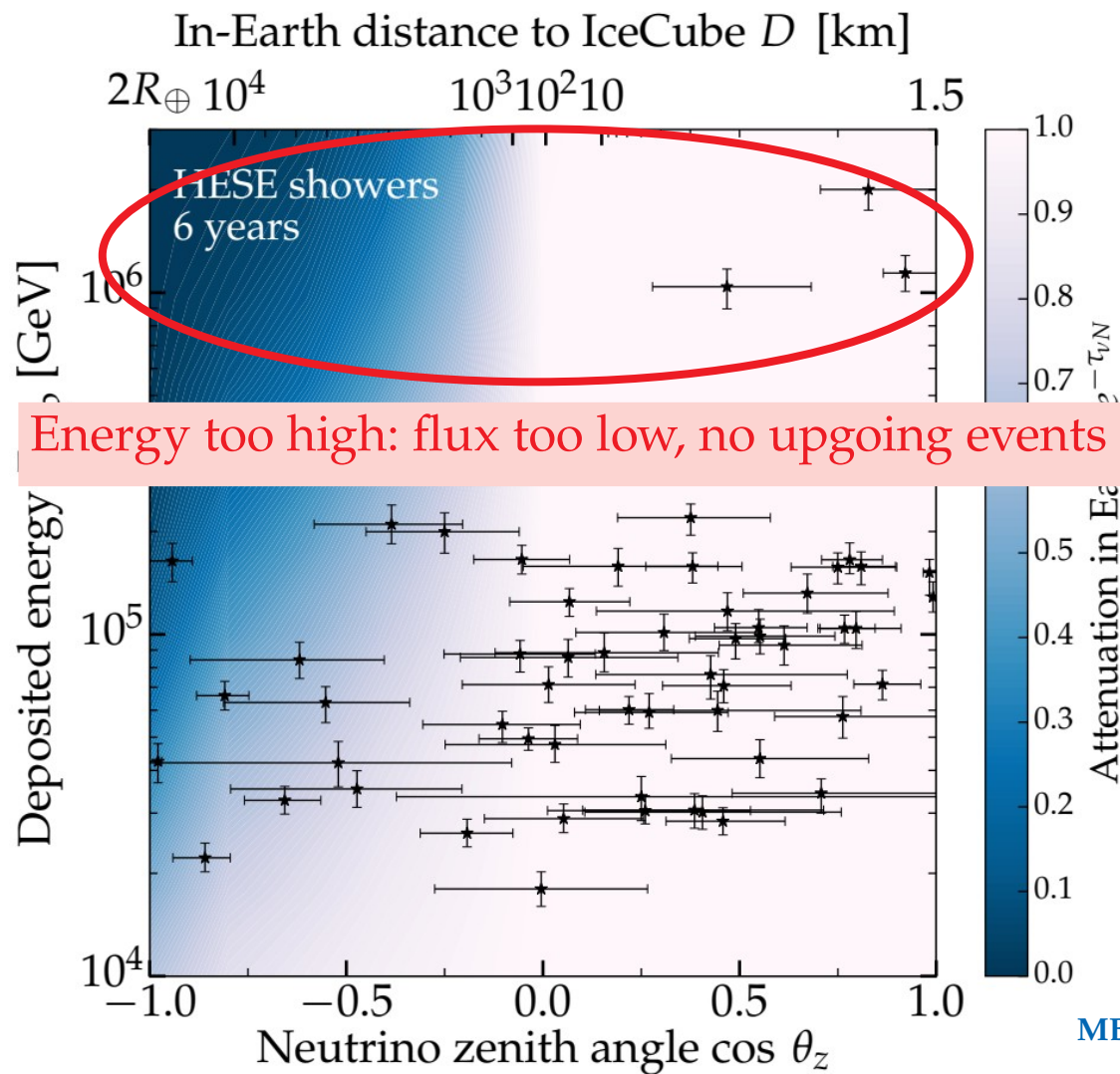
~30–300 events

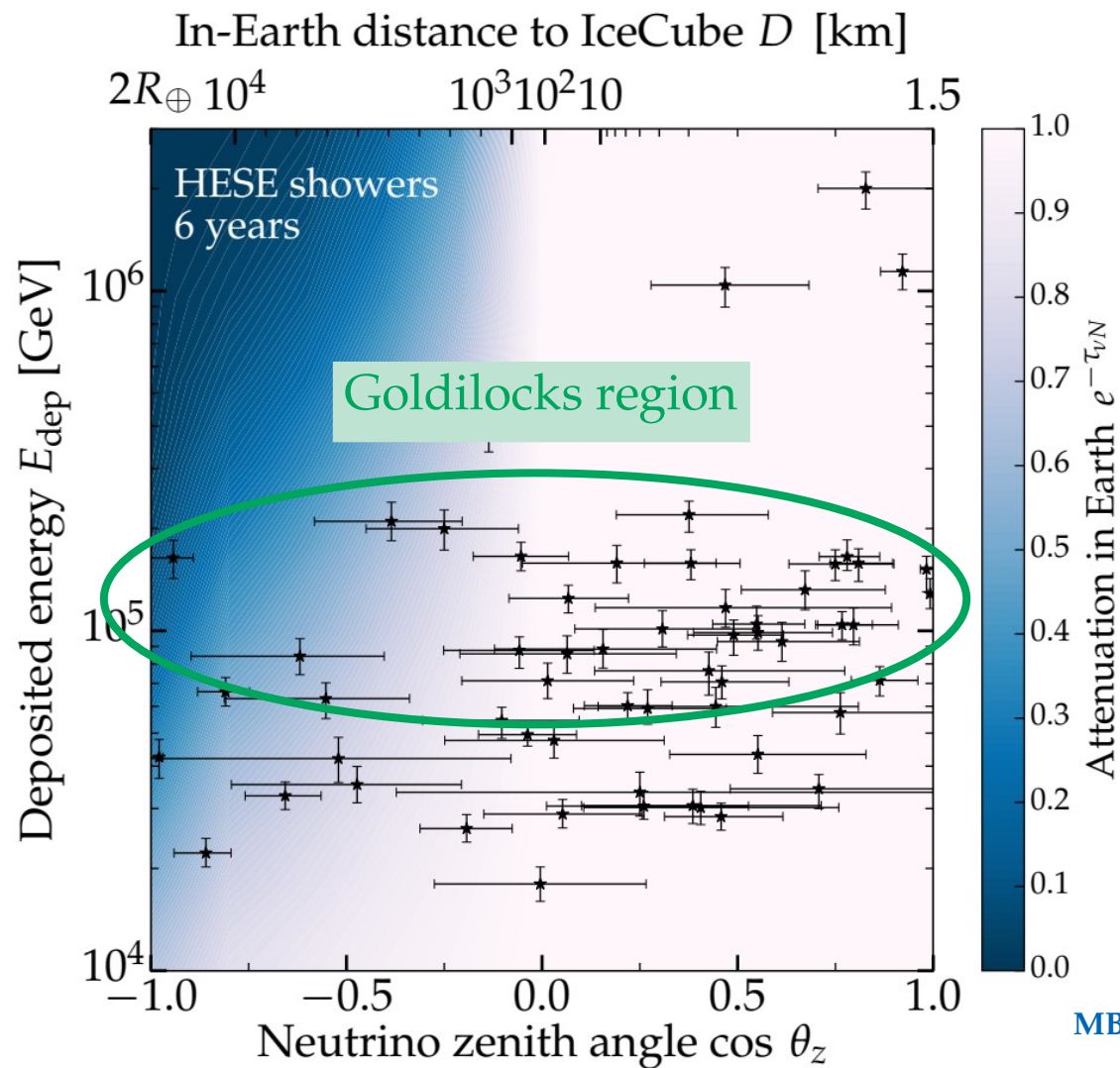
In this work:
We fix the energy dependence of flux and cross section (but explore many alternatives)

Soon to come:
Measure the energy dependence of the flux and cross section









Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

Note:

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

Ingredient #2:

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

or

Explore all possible combinations

Note:

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, PRL 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

Ingredient #2:

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

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

or

Explore all possible combinations

Note:

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

Ingredient #2:

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

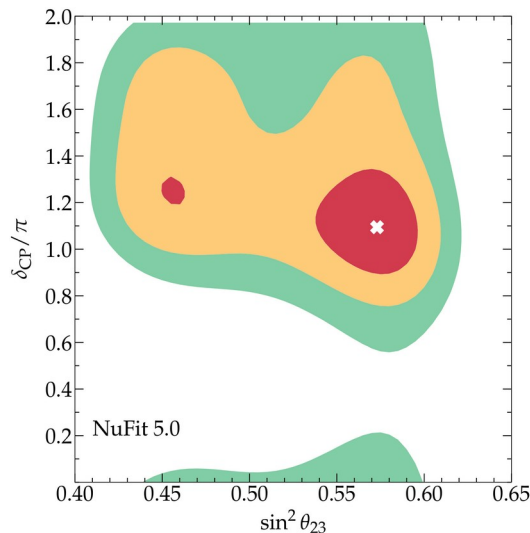
Fix at one of the benchmarks
(pion decay, muon-damped, neutron decay)

or

Explore all possible combinations

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



Note:

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

≡

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

Ingredient #2:

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

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

or

Explore all possible combinations

Note:

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

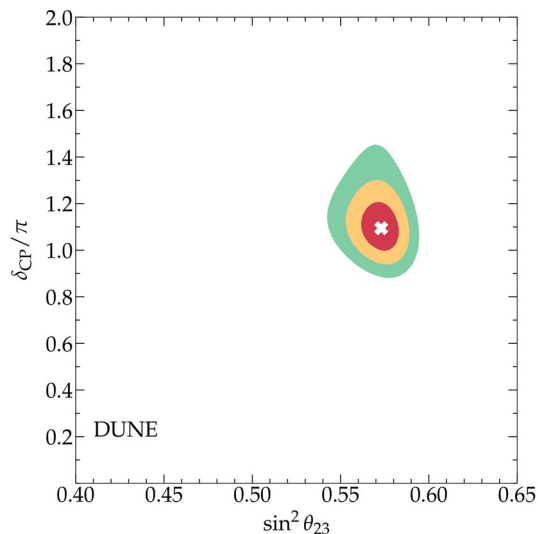
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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

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



Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Downgoing neutrinos
(L short $\rightarrow$ no matter)

$$N \propto \Phi_\nu \sigma_{\nu N}$$

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Downgoing neutrinos
(L short $\rightarrow$ no matter)

$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Downgoing neutrinos
(L short $\rightarrow$ no matter)

$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

$$N \propto \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

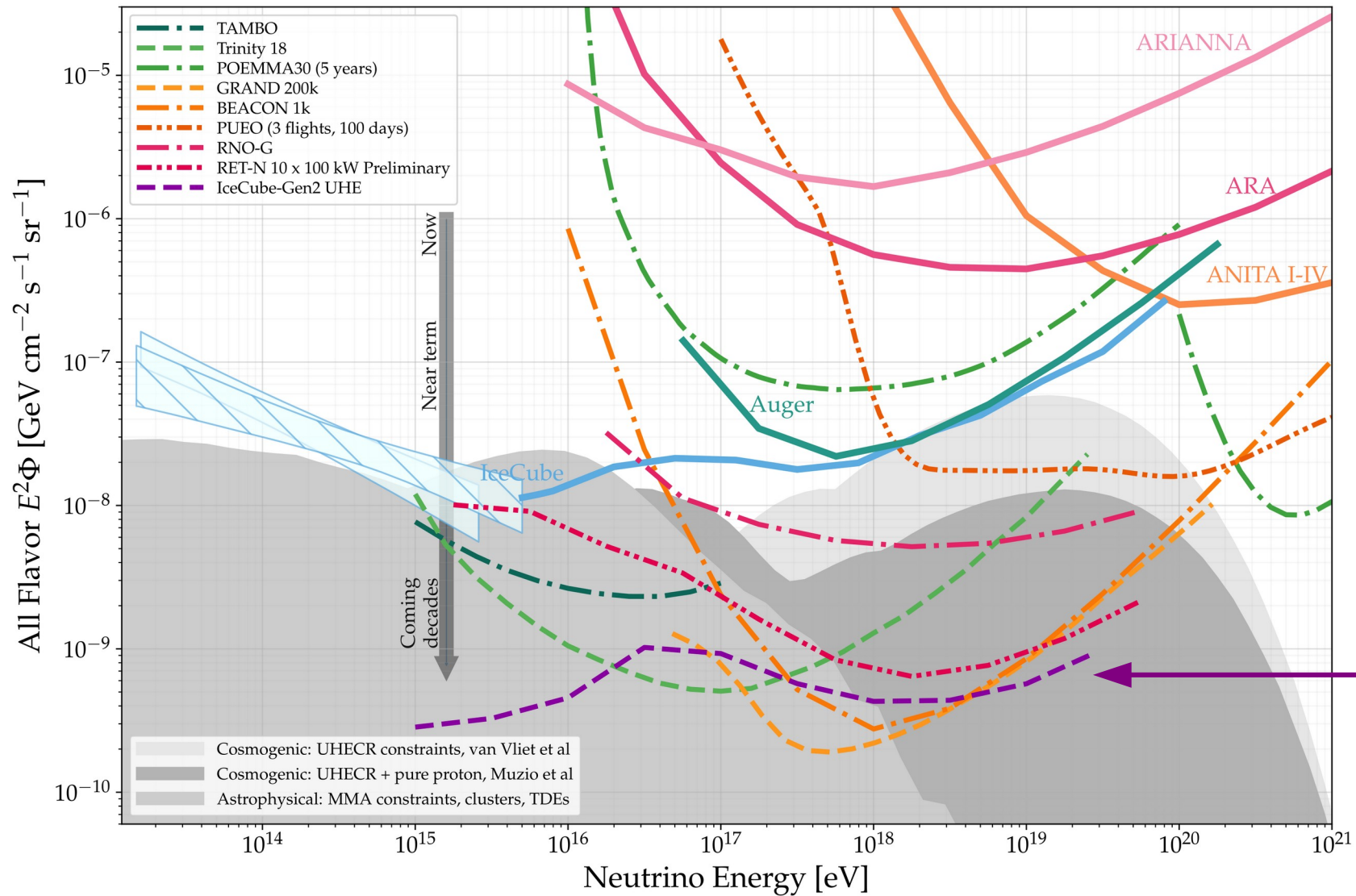
$$N \propto \underbrace{\Phi_\nu}_{\text{Neutrino flux}} \underbrace{\sigma_{\nu N}}_{\text{Cross section}} e^{-\tau_{\nu N}} = \Phi_\nu \sigma_{\nu N} e^{-L \sigma_{\nu N} n_N}$$

Downgoing neutrinos
(L short $\rightarrow$ no matter)

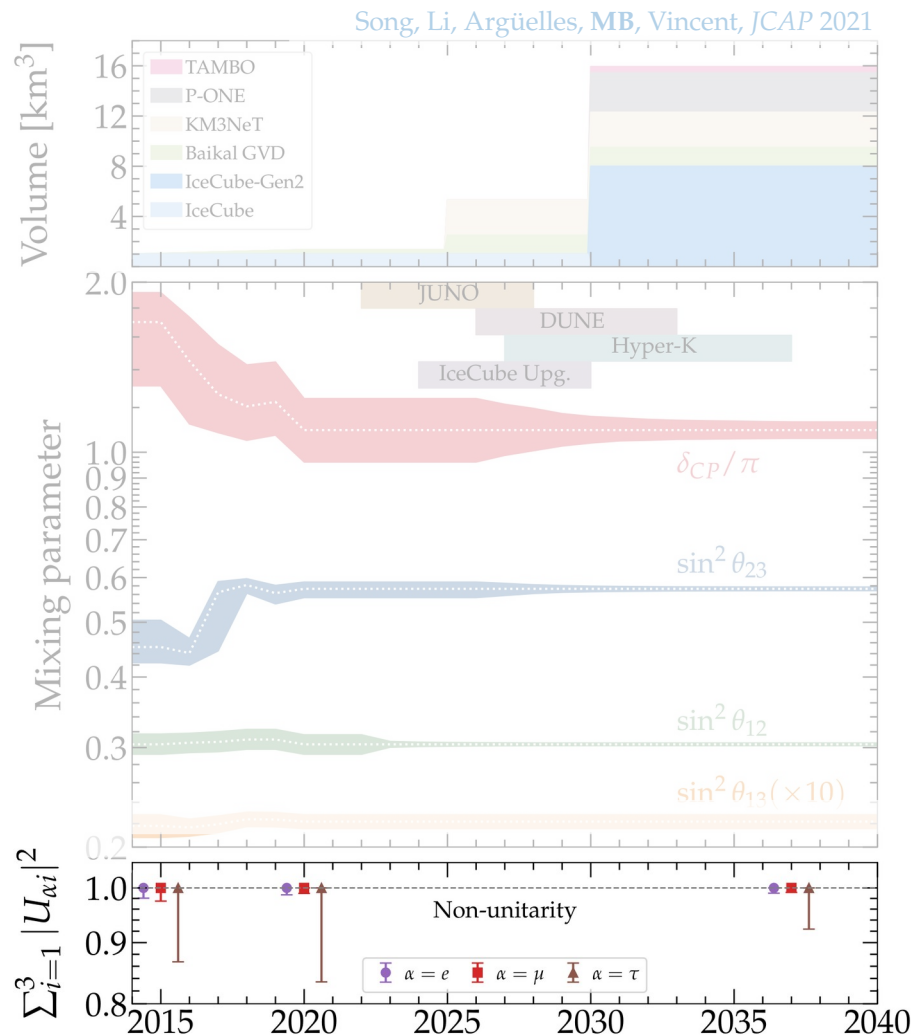
$$N \propto \underbrace{\Phi_\nu \sigma_{\nu N}}_{\text{Degeneracy}}$$

Upgoing neutrinos
(L long $\rightarrow$ lots of matter)

$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$



Three reasons to be excited



Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

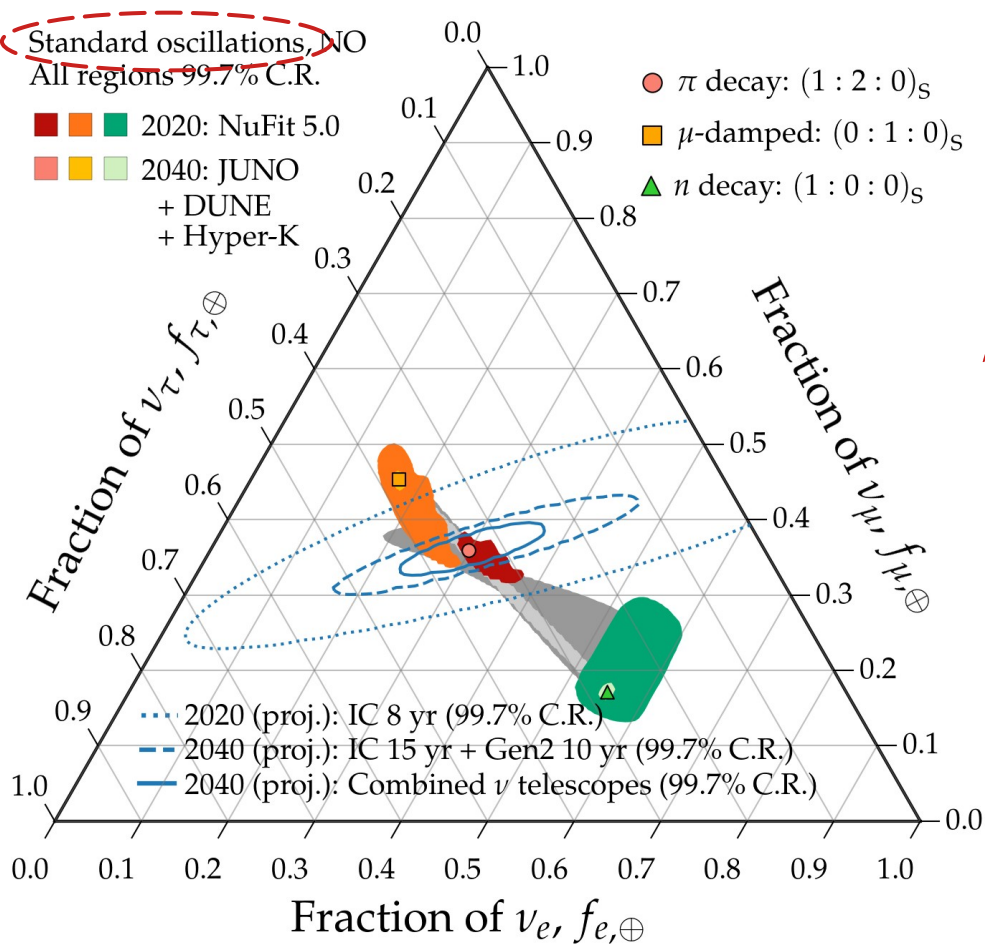
Oscillation physics:

We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

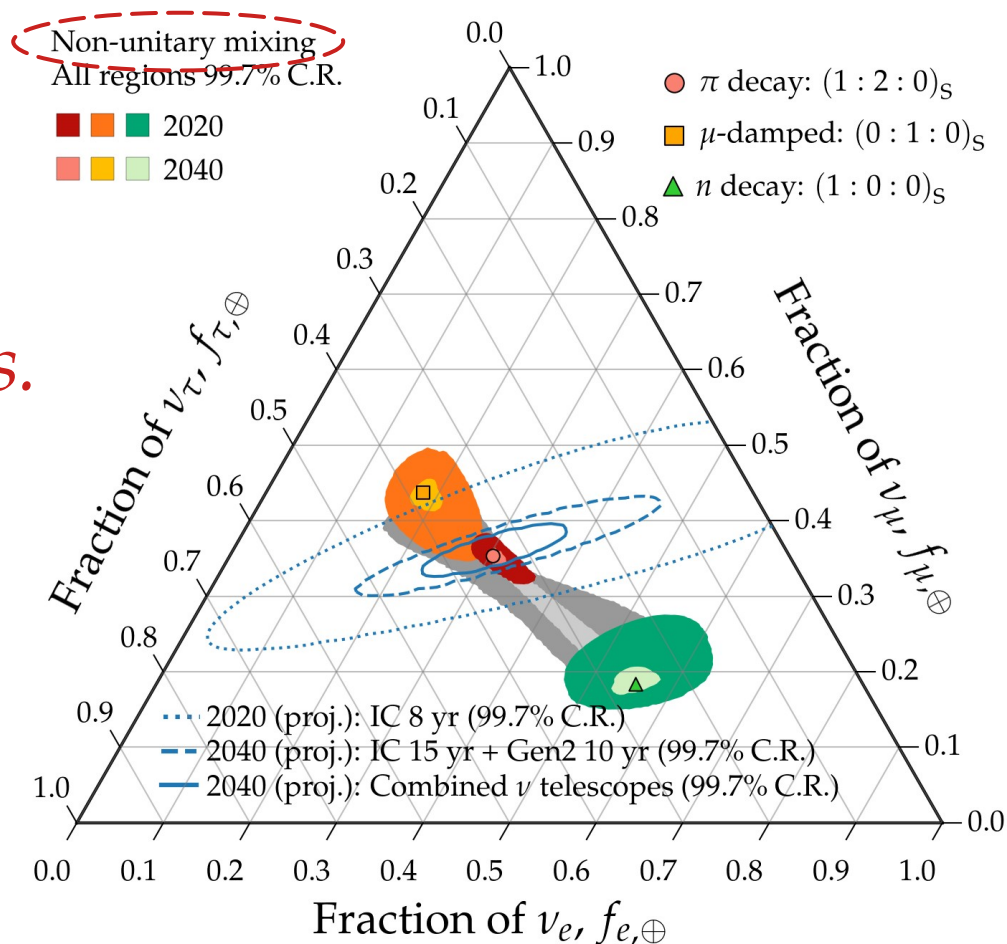
Test of the oscillation framework:

We will be able to do what we want even if oscillations are non-unitary

No unitarity? No problem



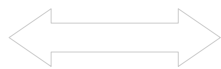
VS.



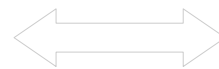
What does neutrino decay change?

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

Flavor composition

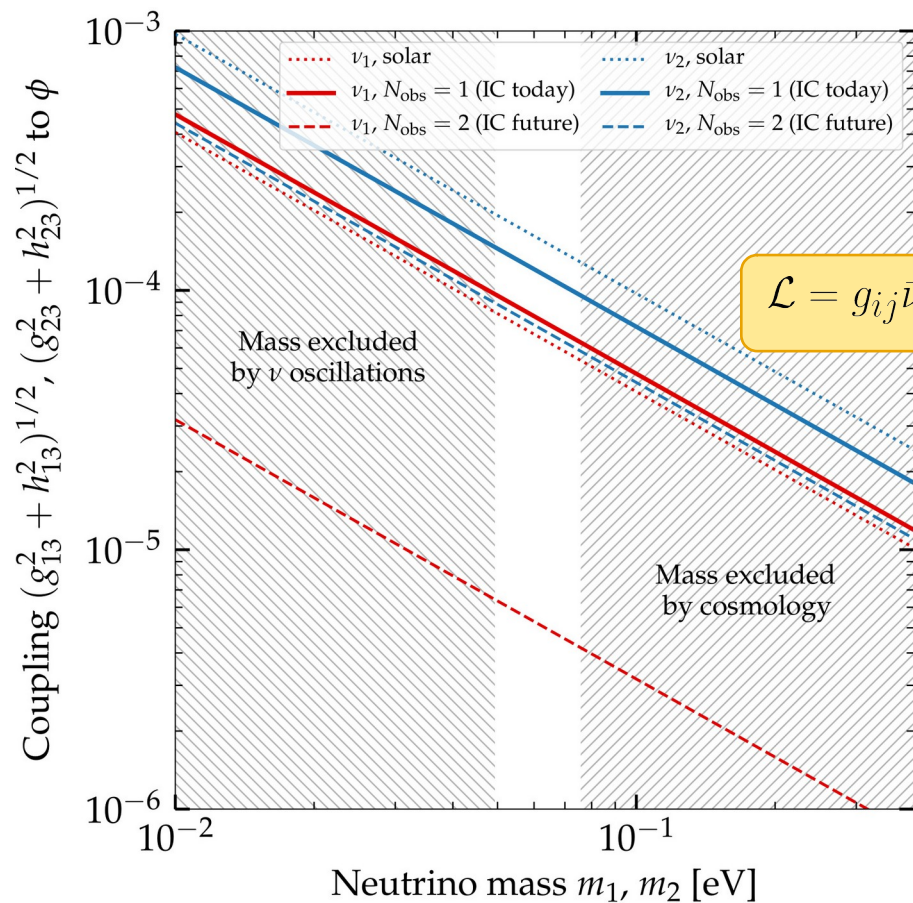


Spectrum shape



Event rate

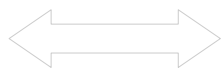
MB, 2004.06844



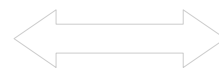
What does neutrino decay change?

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

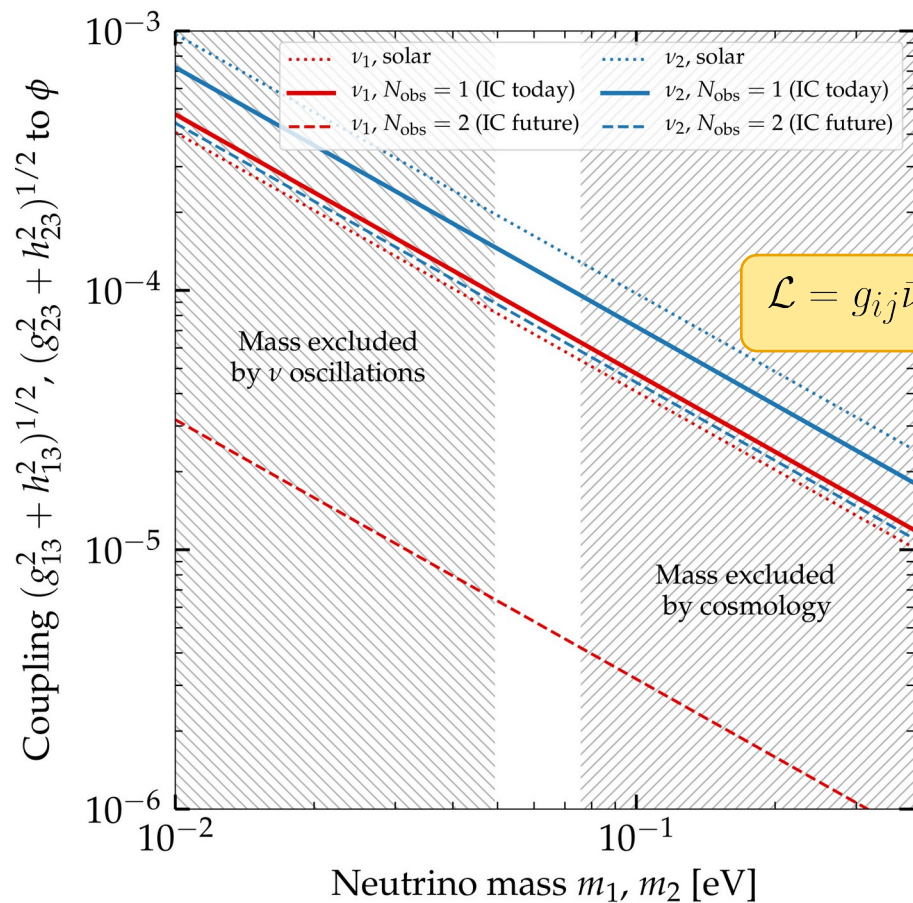
Flavor composition



Spectrum shape

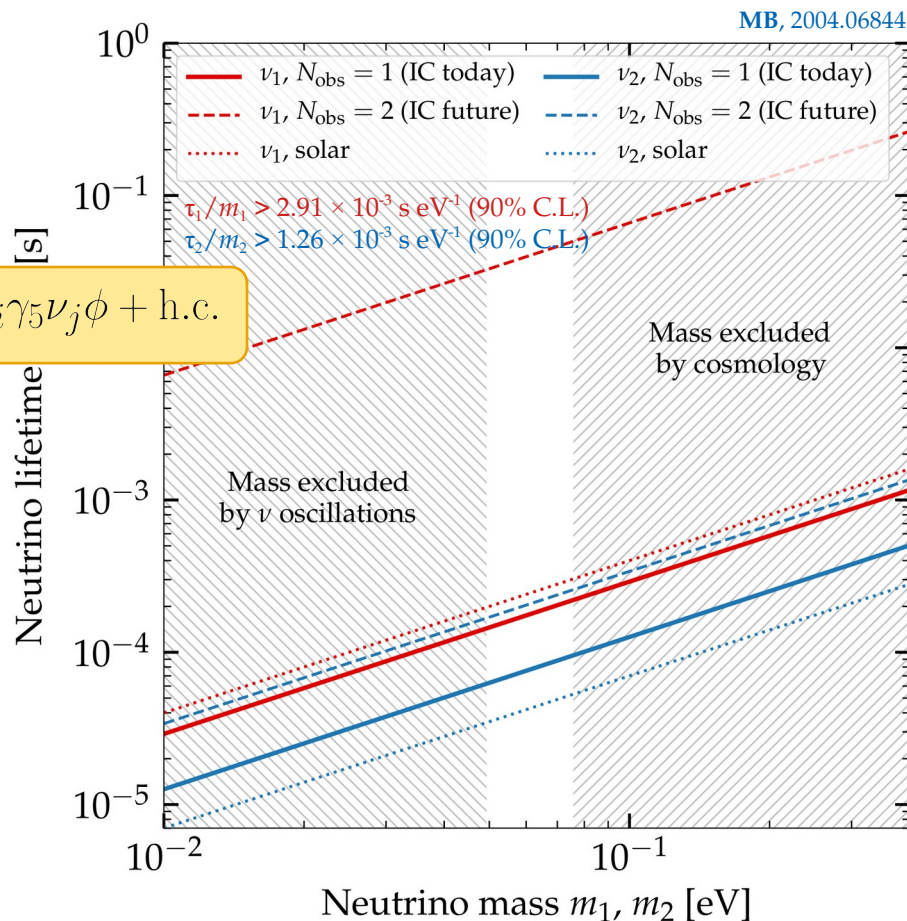


Event rate



$$\mathcal{L} = g_{ij} \bar{\nu}_i \nu_j \phi + h_{ij} \bar{\nu}_i \gamma_5 \nu_j \phi + \text{h.c.}$$

Lower limits on couplings

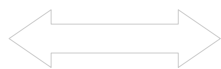


MB, 2004.06844

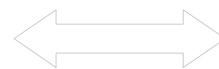
What does neutrino decay change?

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

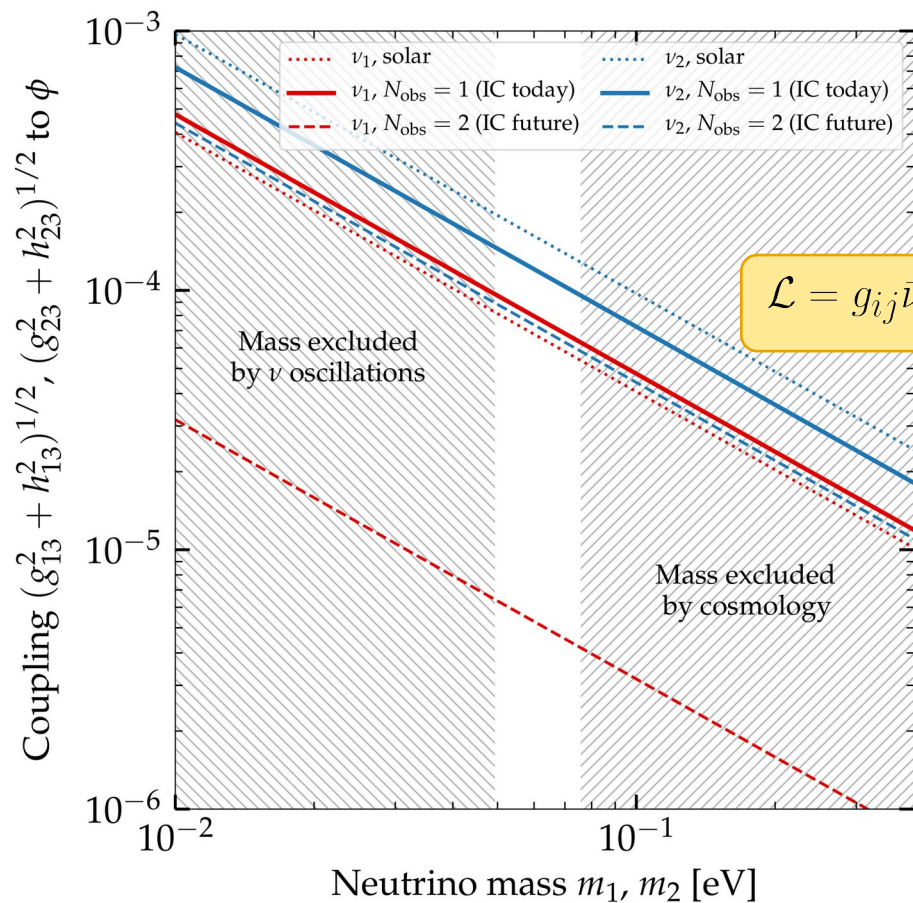
Flavor composition



Spectrum shape

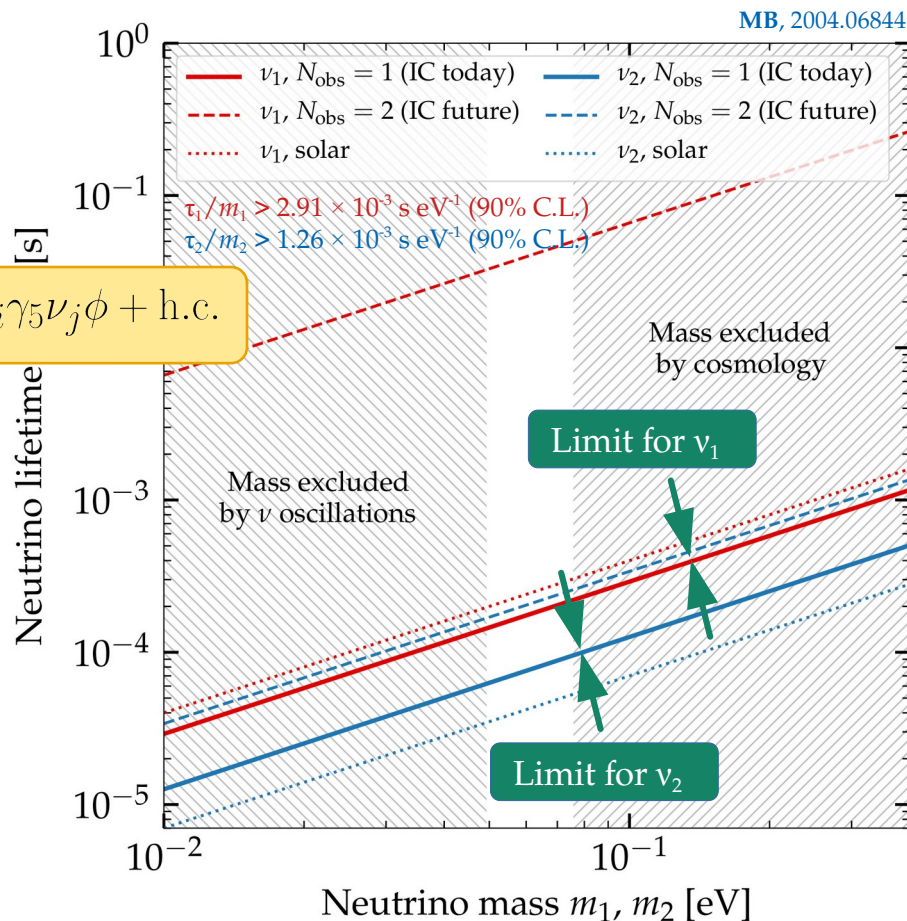


Event rate

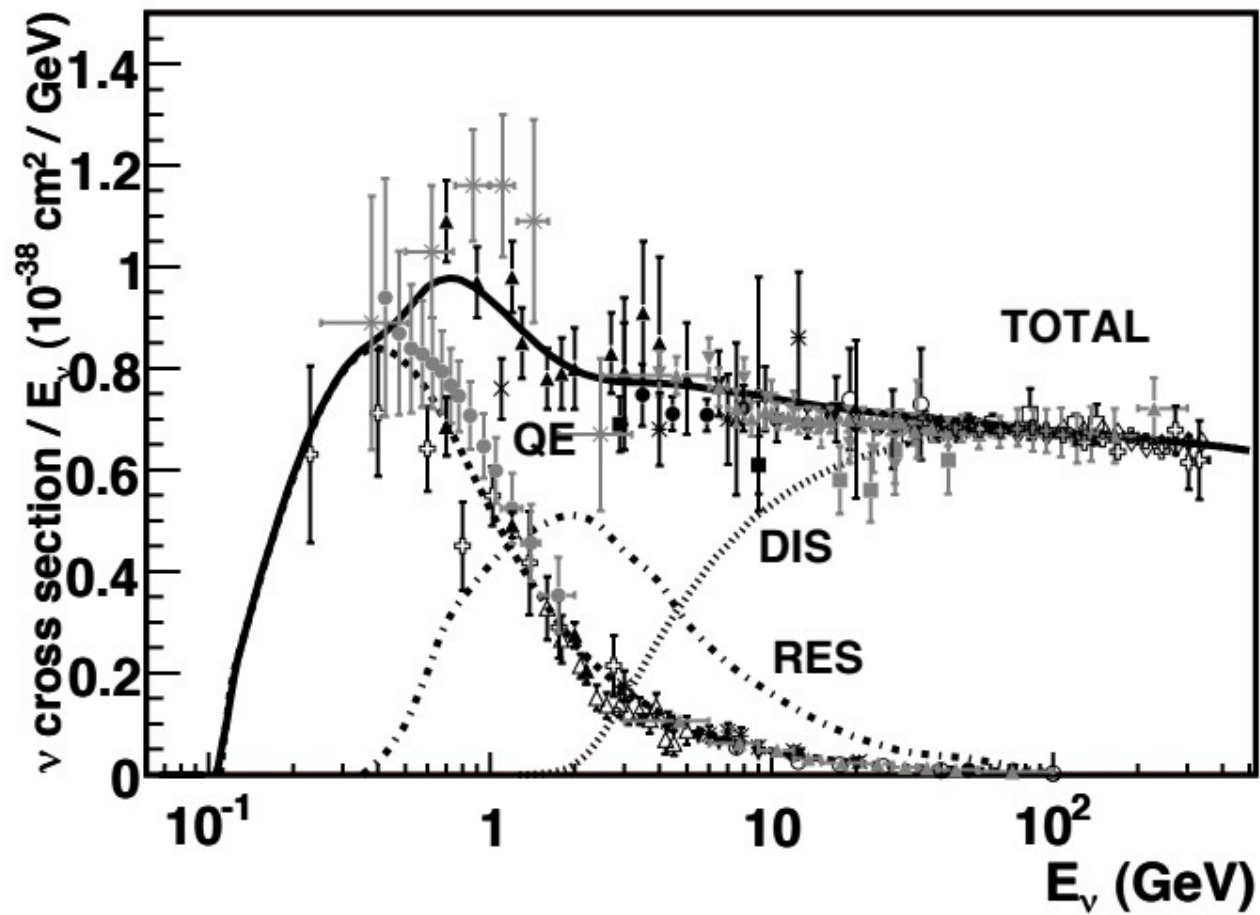


$$\mathcal{L} = g_{ij} \bar{\nu}_i \nu_j \phi + h_{ij} \bar{\nu}_i \gamma_5 \nu_j \phi + \text{h.c.}$$

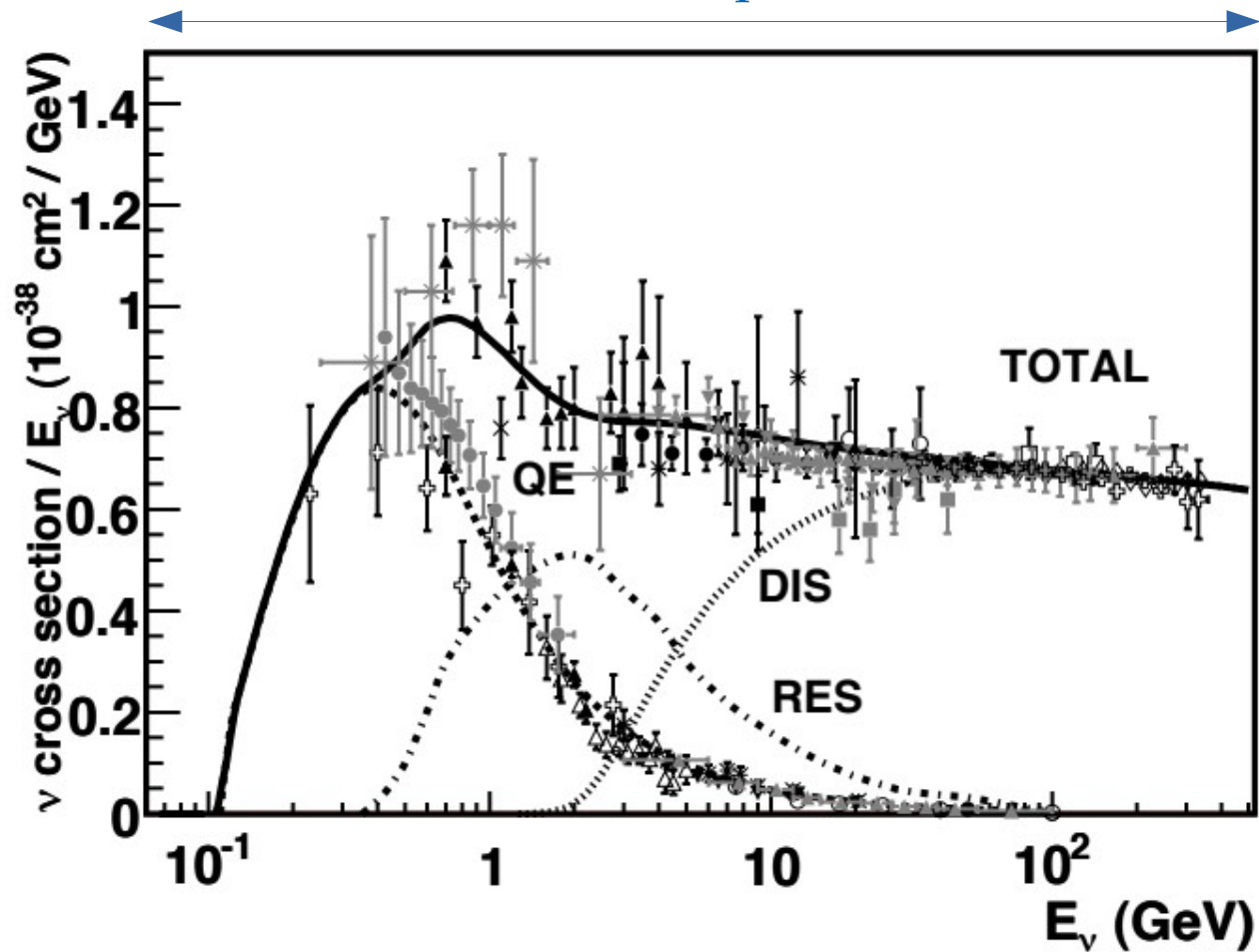
Lower limits on couplings



MB, 2004.06844

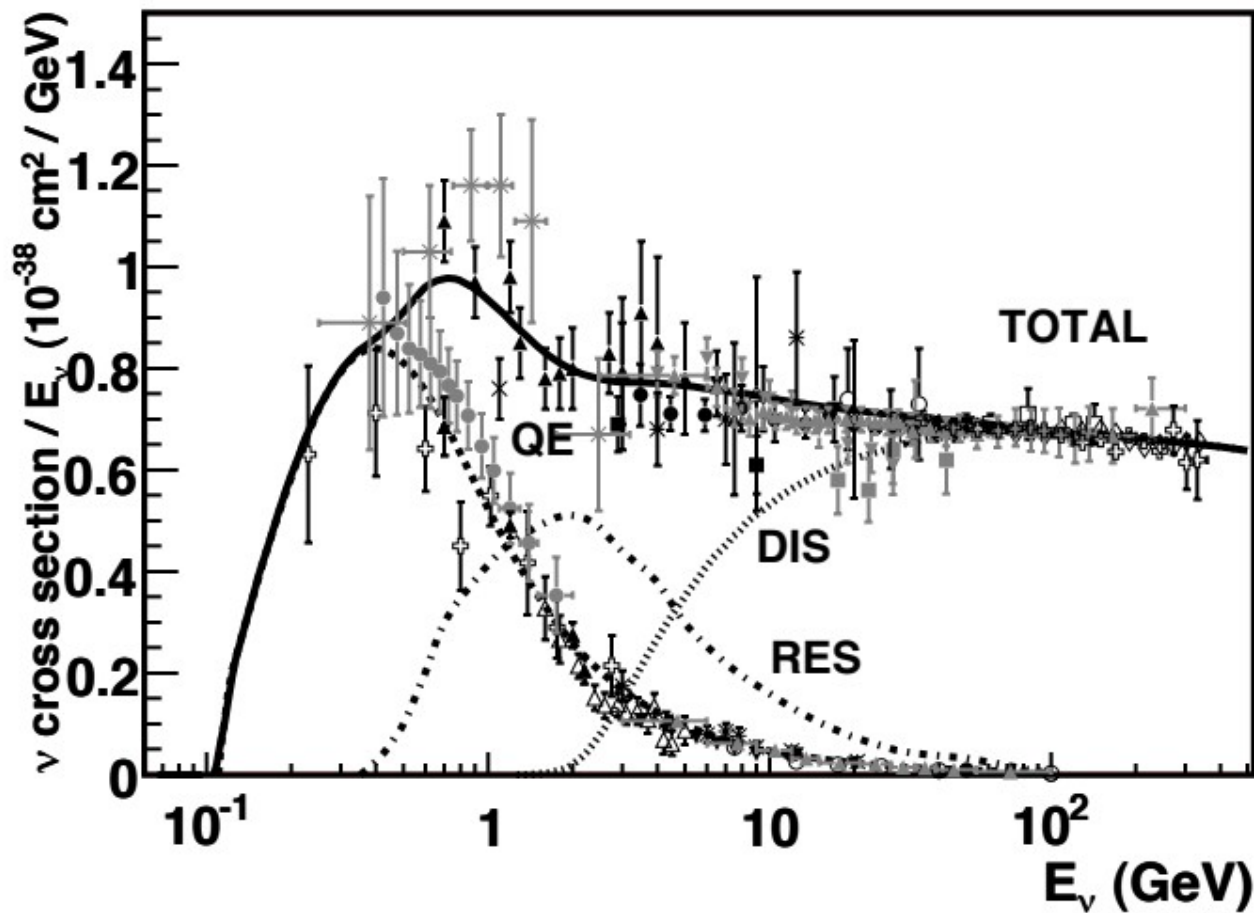


Accelerator experiments



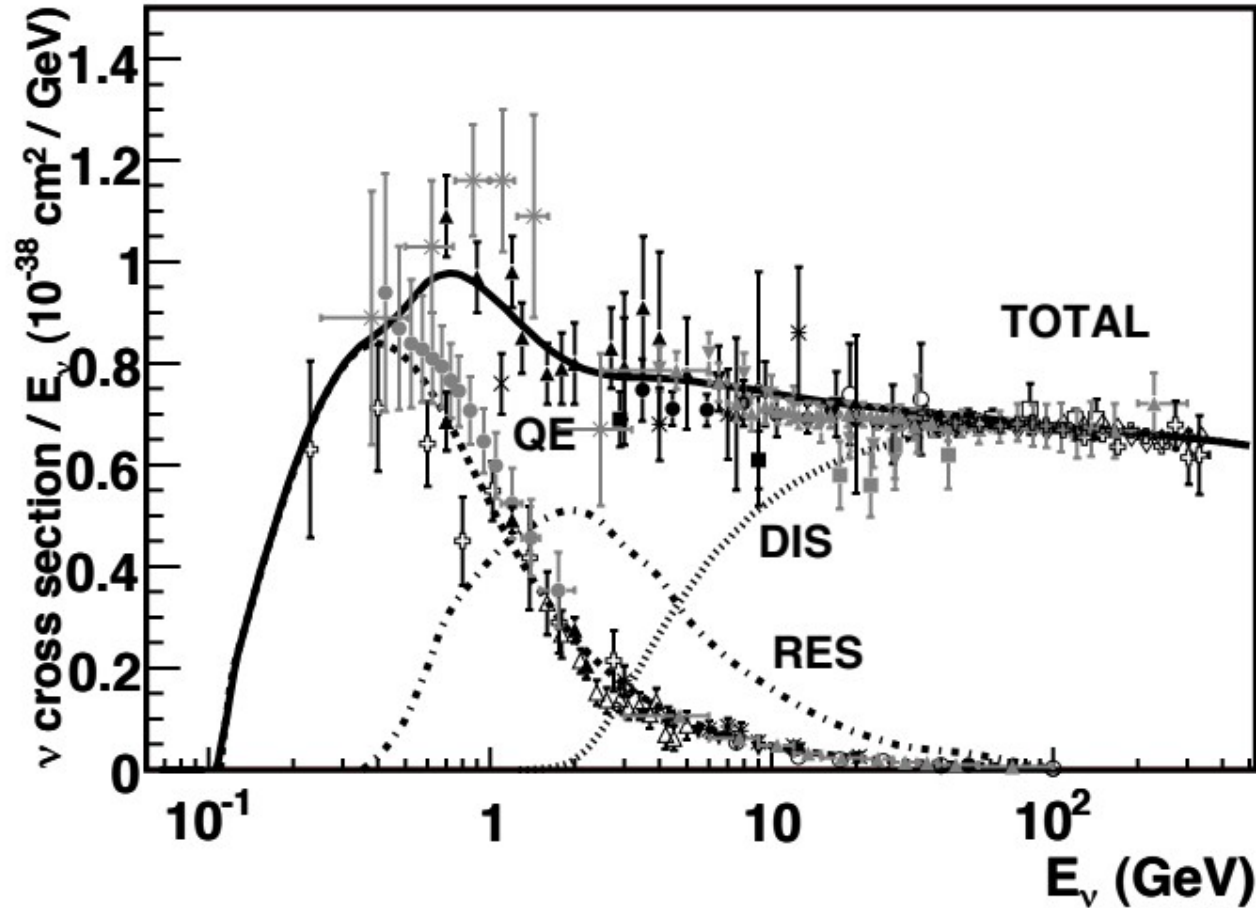
Accelerator experiments

Coherent
neutrino
scattering



Accelerator experiments

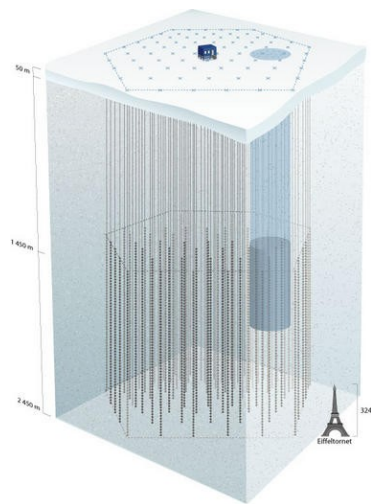
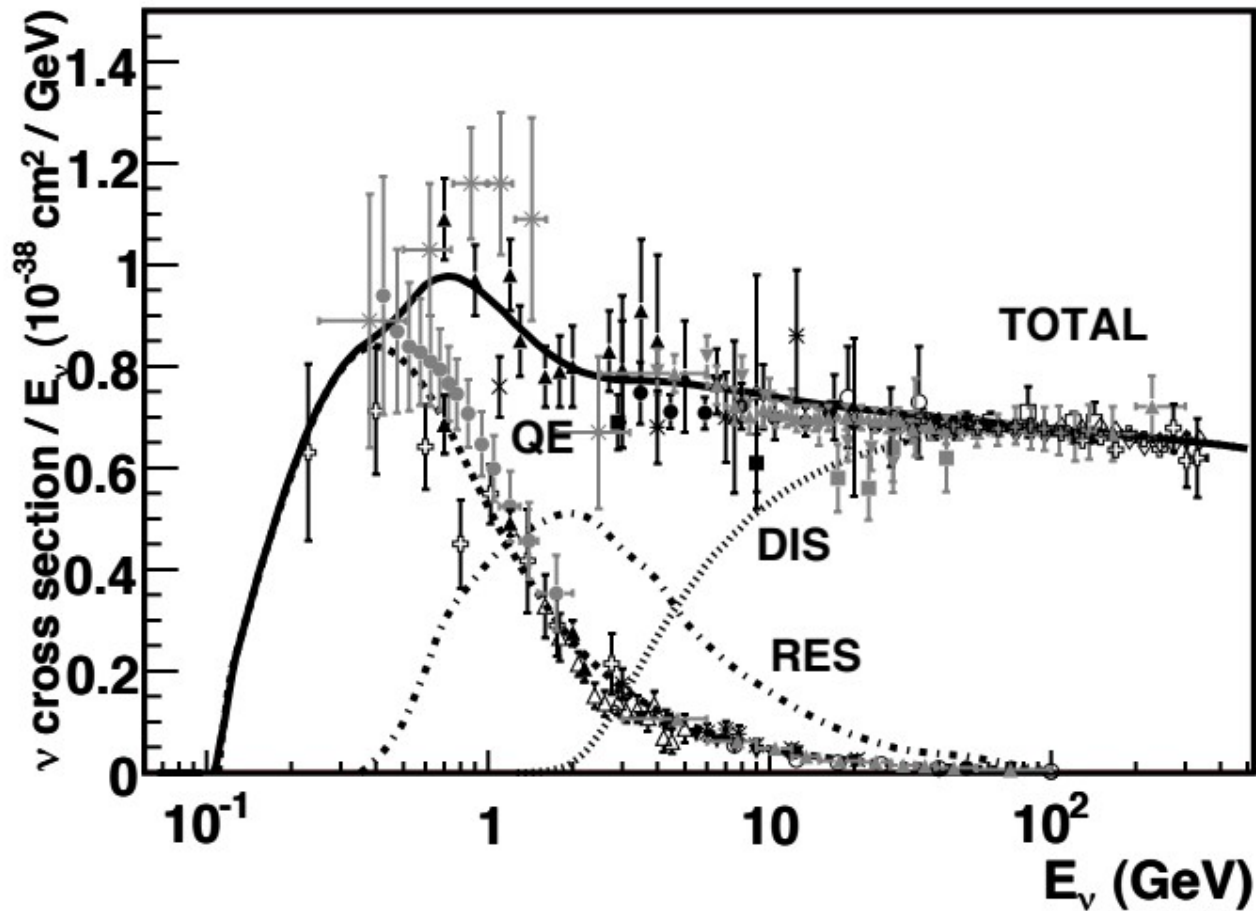
Coherent
neutrino
scattering

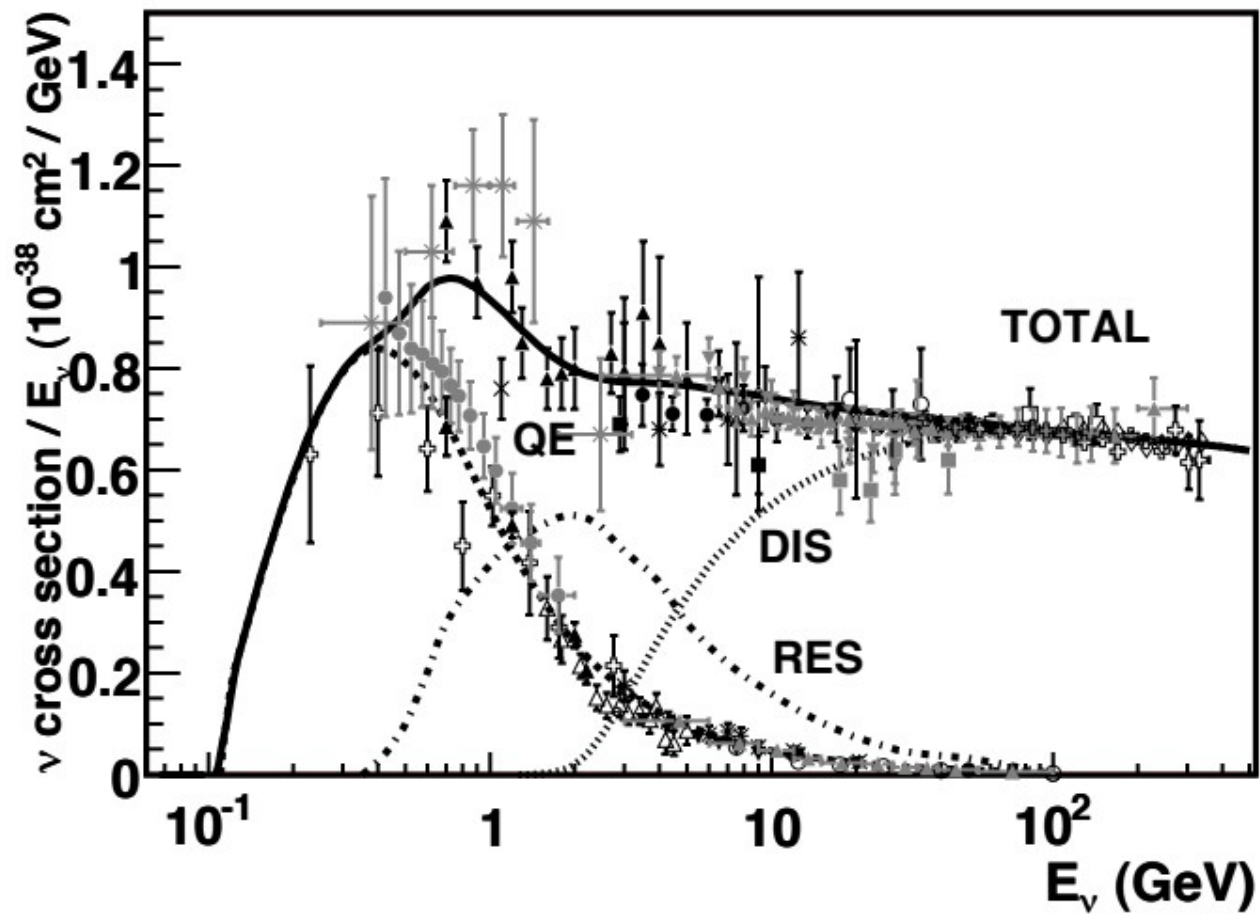


No
measurements
... until recently!

Accelerator experiments

Coherent
neutrino
scattering

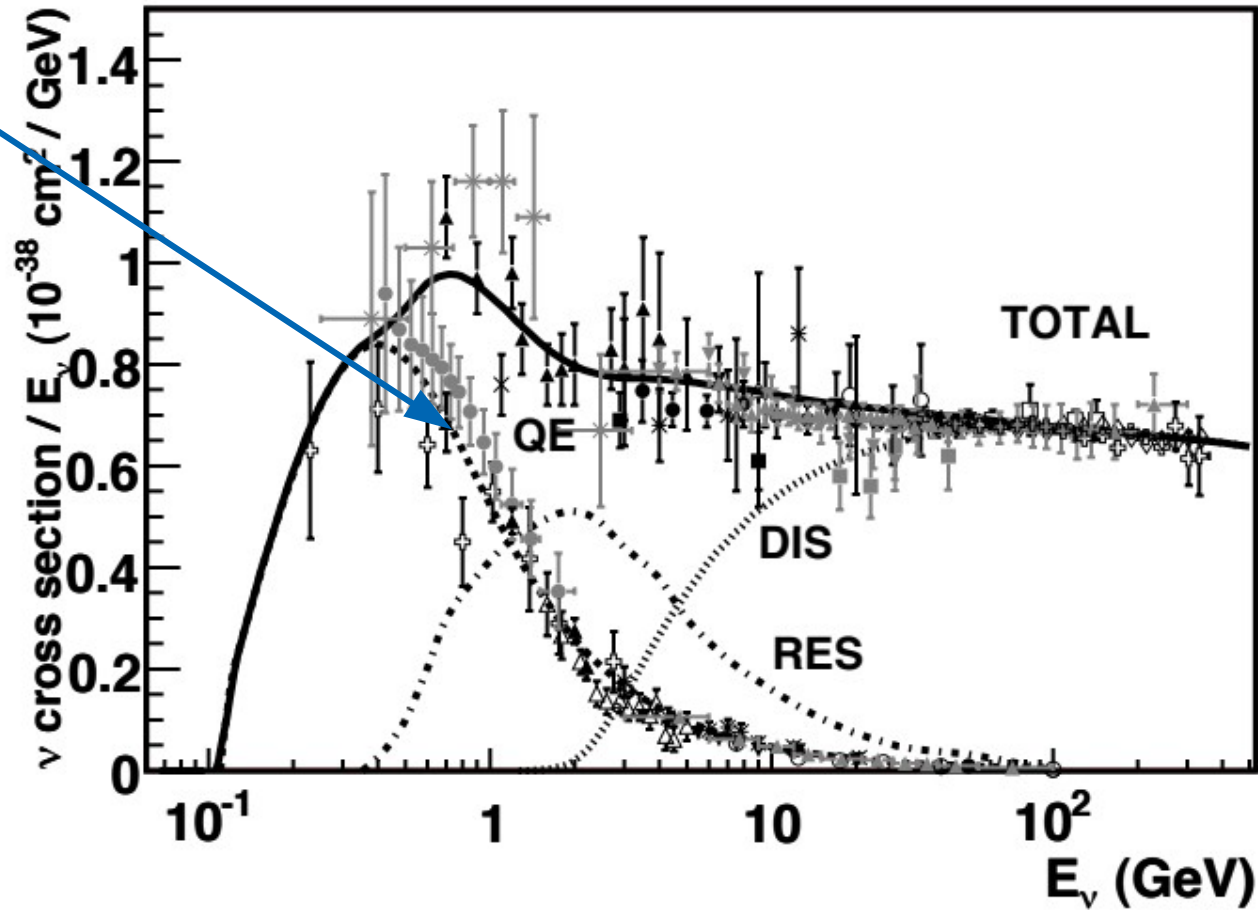




Quasi-elastic
scattering:

$$\nu_l + n \rightarrow l^- + p$$

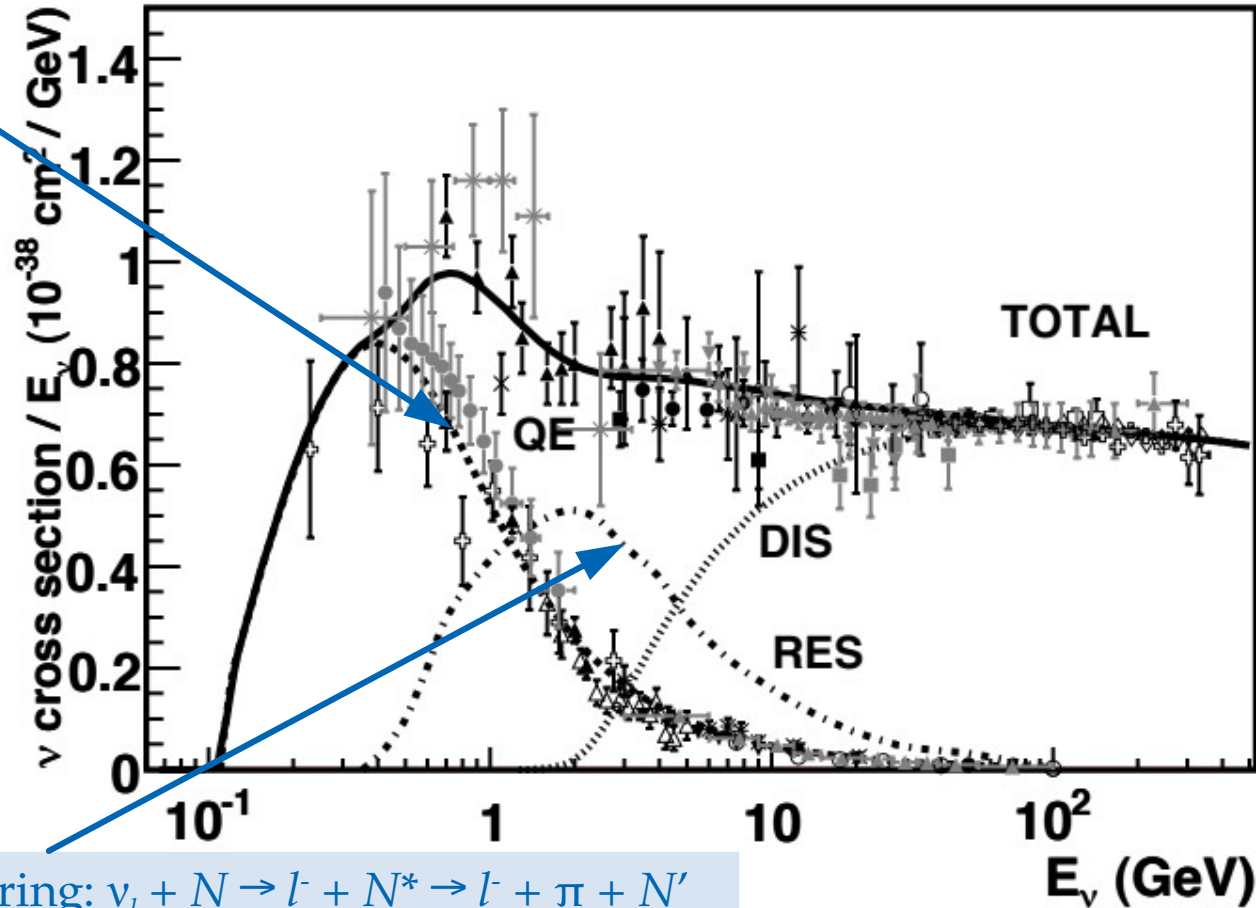
$$\bar{\nu}_l + p \rightarrow l^+ + n$$



Quasi-elastic
scattering:

$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$

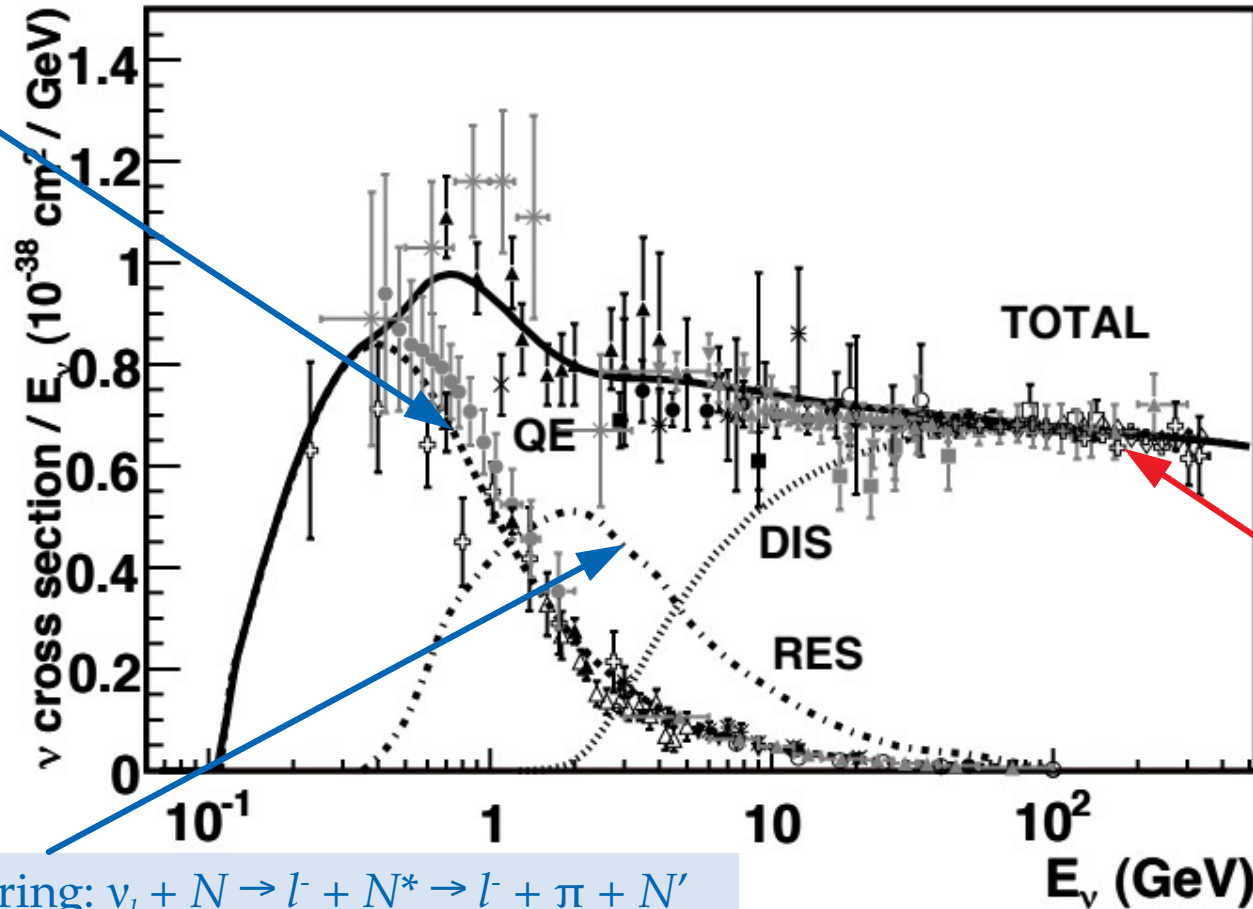


Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Quasi-elastic
scattering:

$$\nu_l + n \rightarrow l^- + p$$

$$\bar{\nu}_l + p \rightarrow l^+ + n$$



Deep inelastic
scattering:

$$\nu_l + N \rightarrow l^- + X$$

$$\bar{\nu}_l + N \rightarrow l^+ + X$$

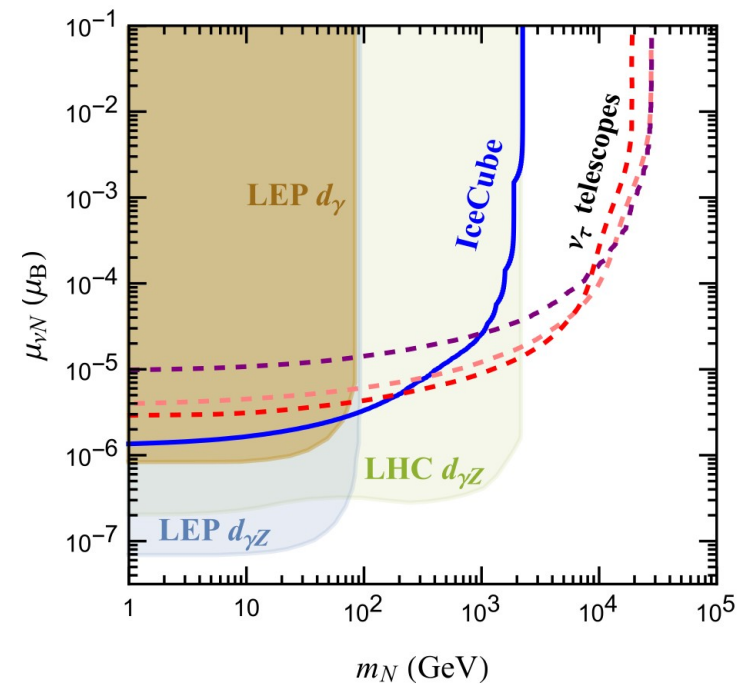
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

New physics in the UHE νN cross section

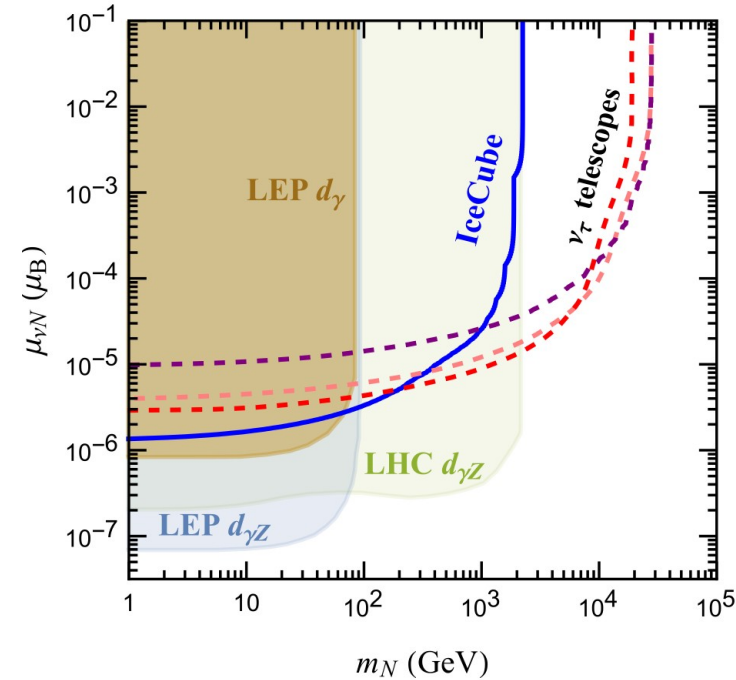
New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



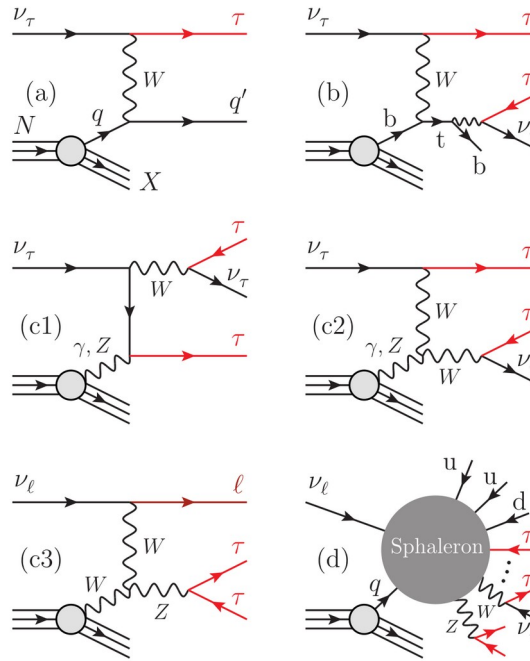
New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

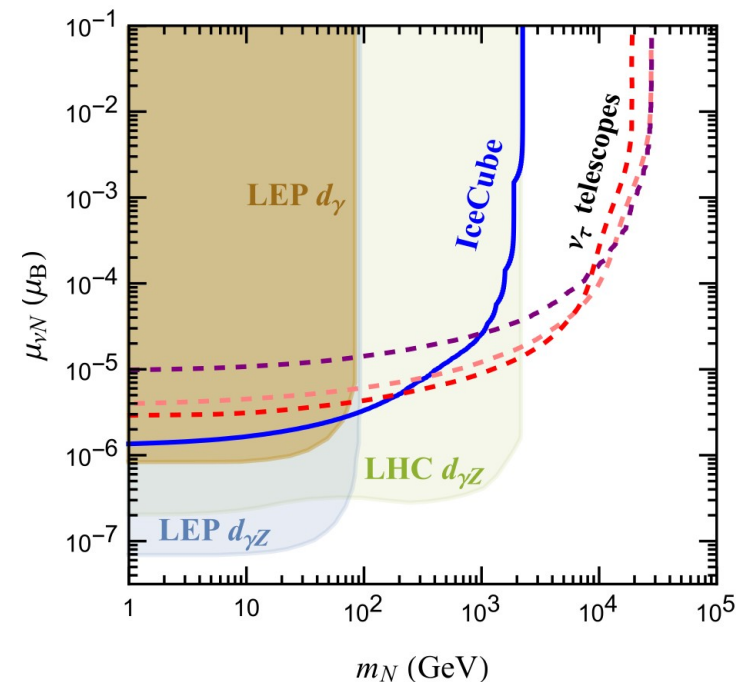
Multiple ν_τ -induced
bangs



Huang, EPJC 2022 [2207.02222]

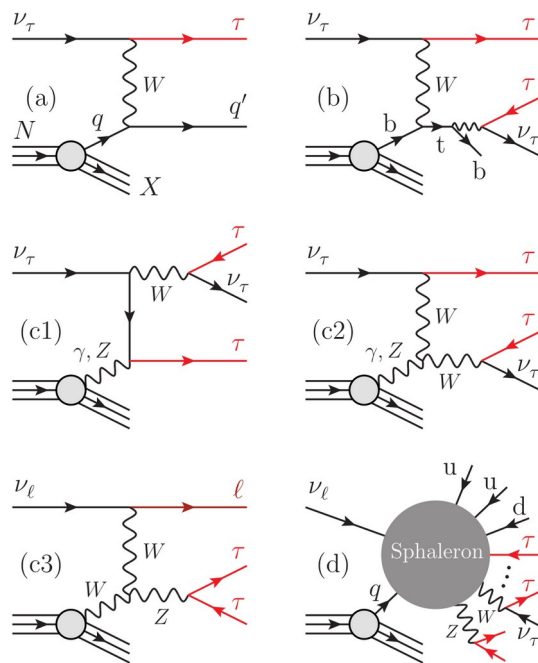
New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



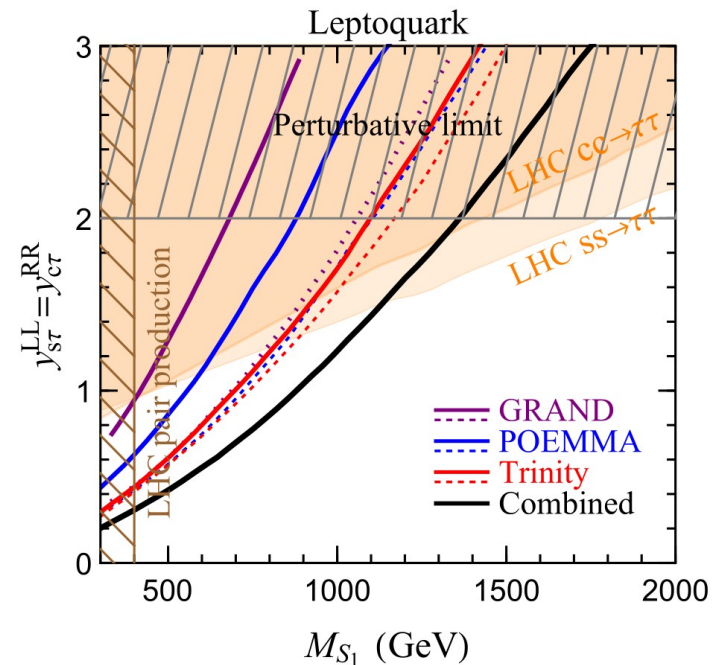
Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ -induced
bangs



Huang, EPJC 2022 [2207.02222]

Leptoquarks,
charged Higgs, etc.



Huang, Jana, Lindner, Rodejohann, JCAP 2022 [2112.09476]

How knowing the mixing parameters better helps

