Pushing high-energy neutrino physics to the cosmic frontier

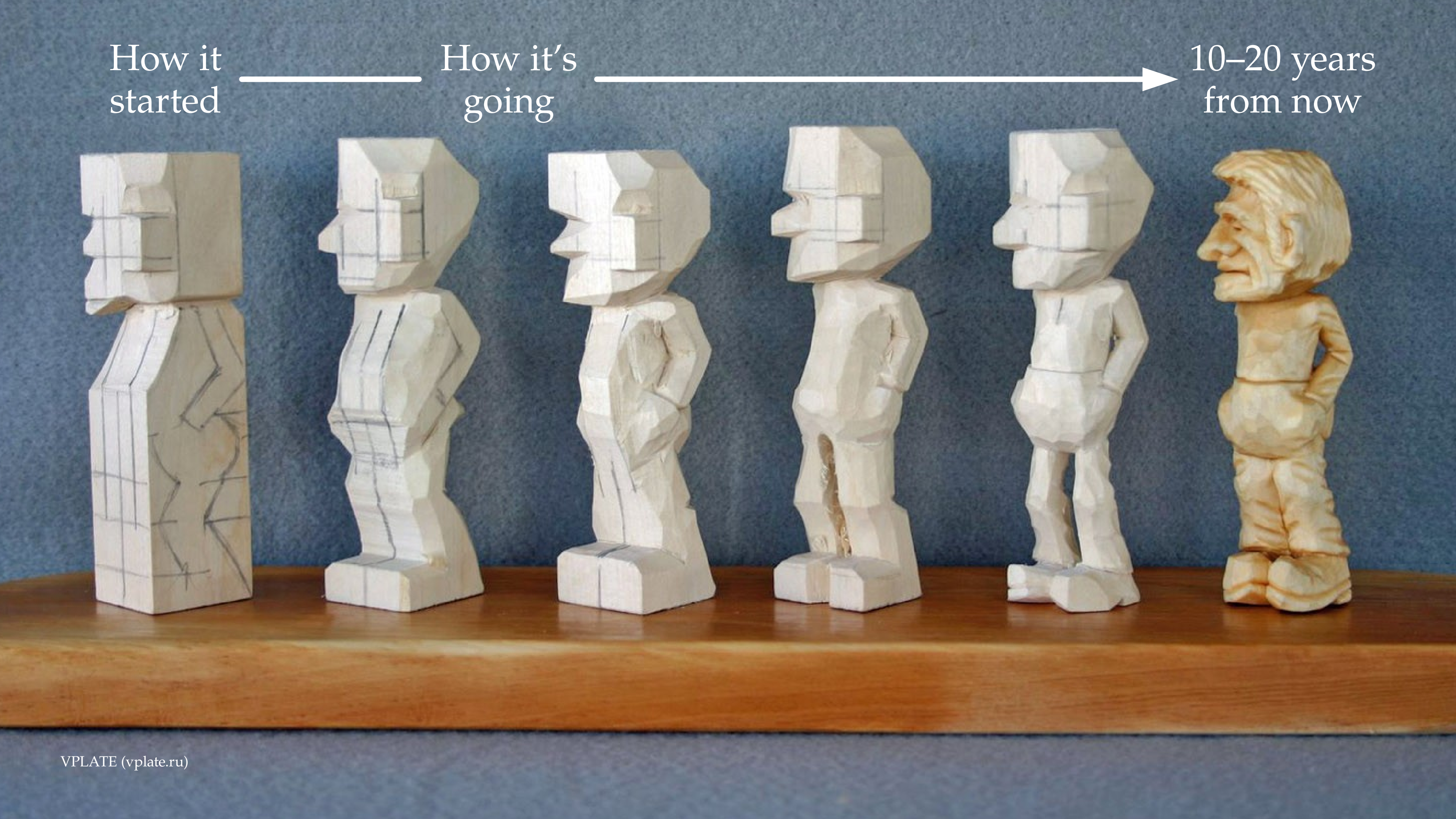
Mauricio Bustamante

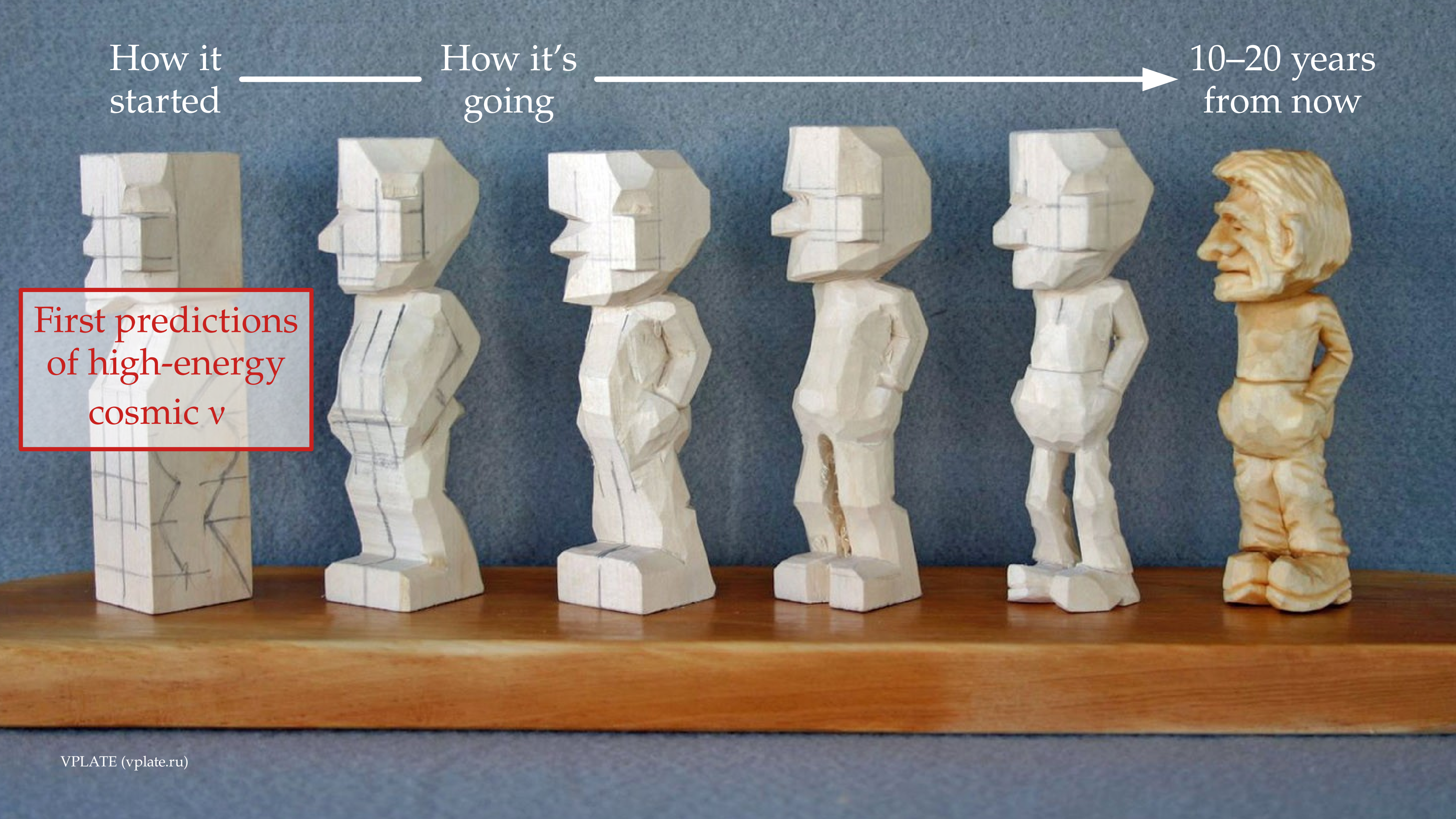
Niels Bohr Institute, University of Copenhagen

CERN Theory Colloquium
October 13, 2021

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN


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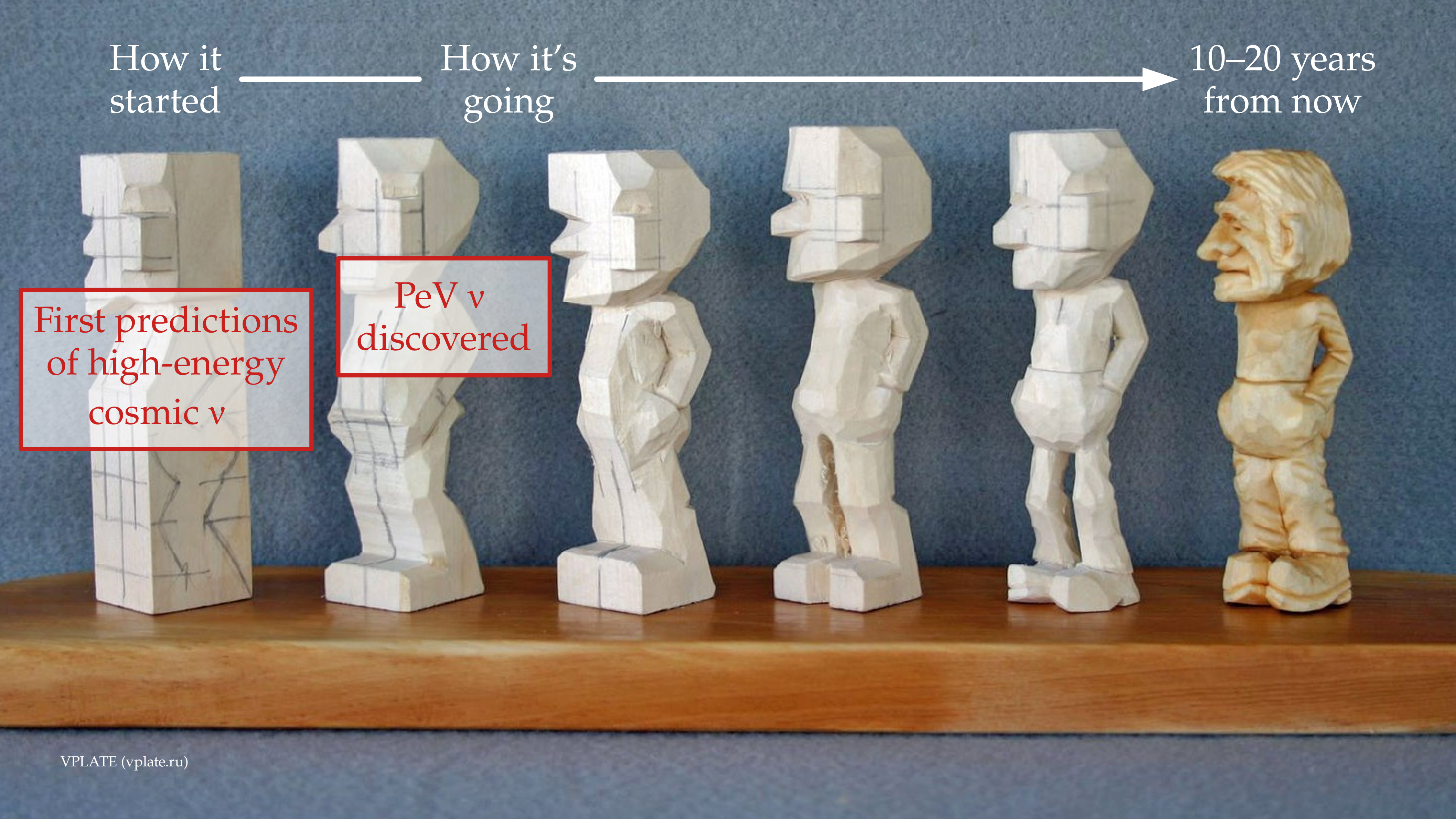
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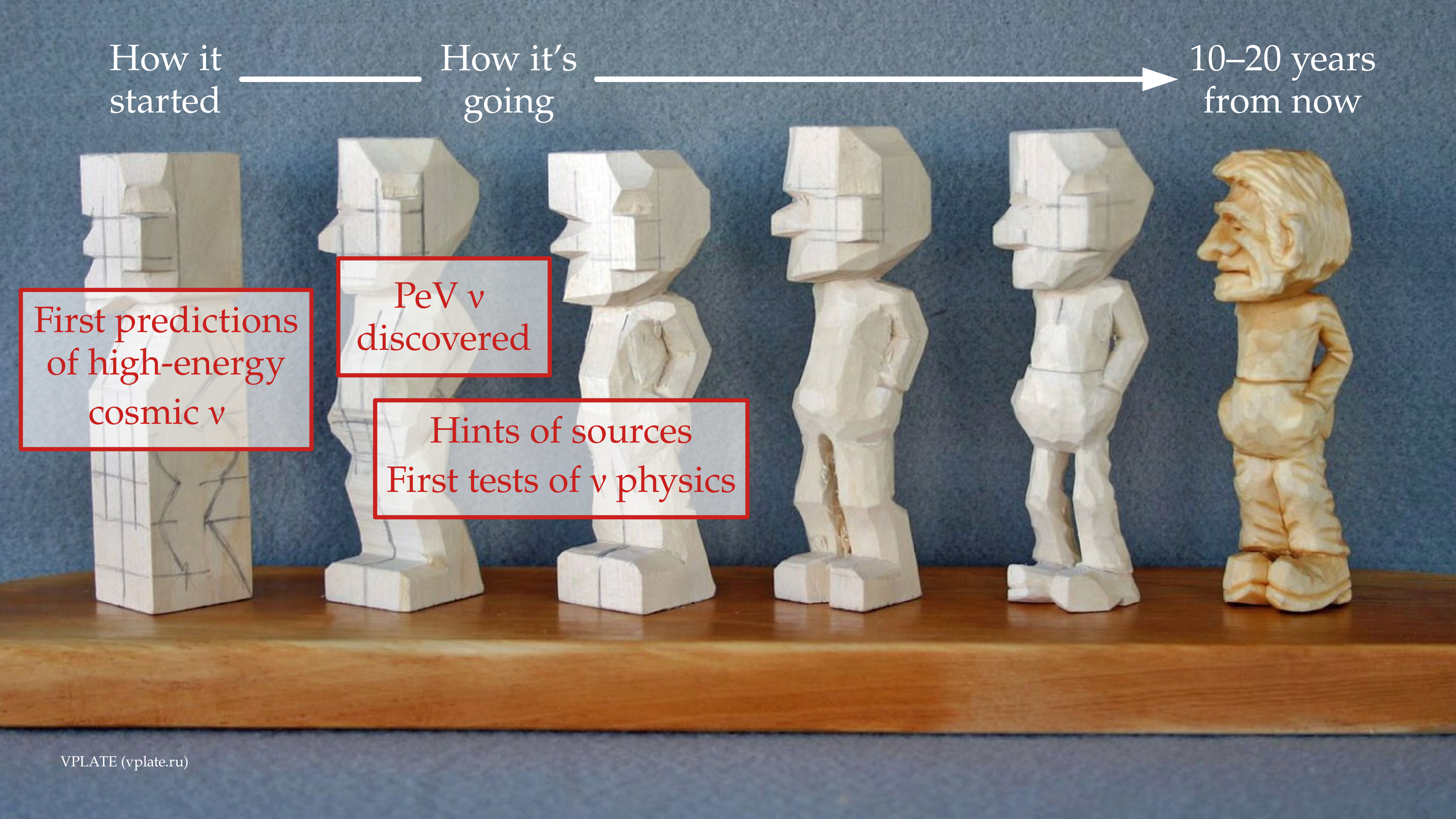
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First tests of ν physics
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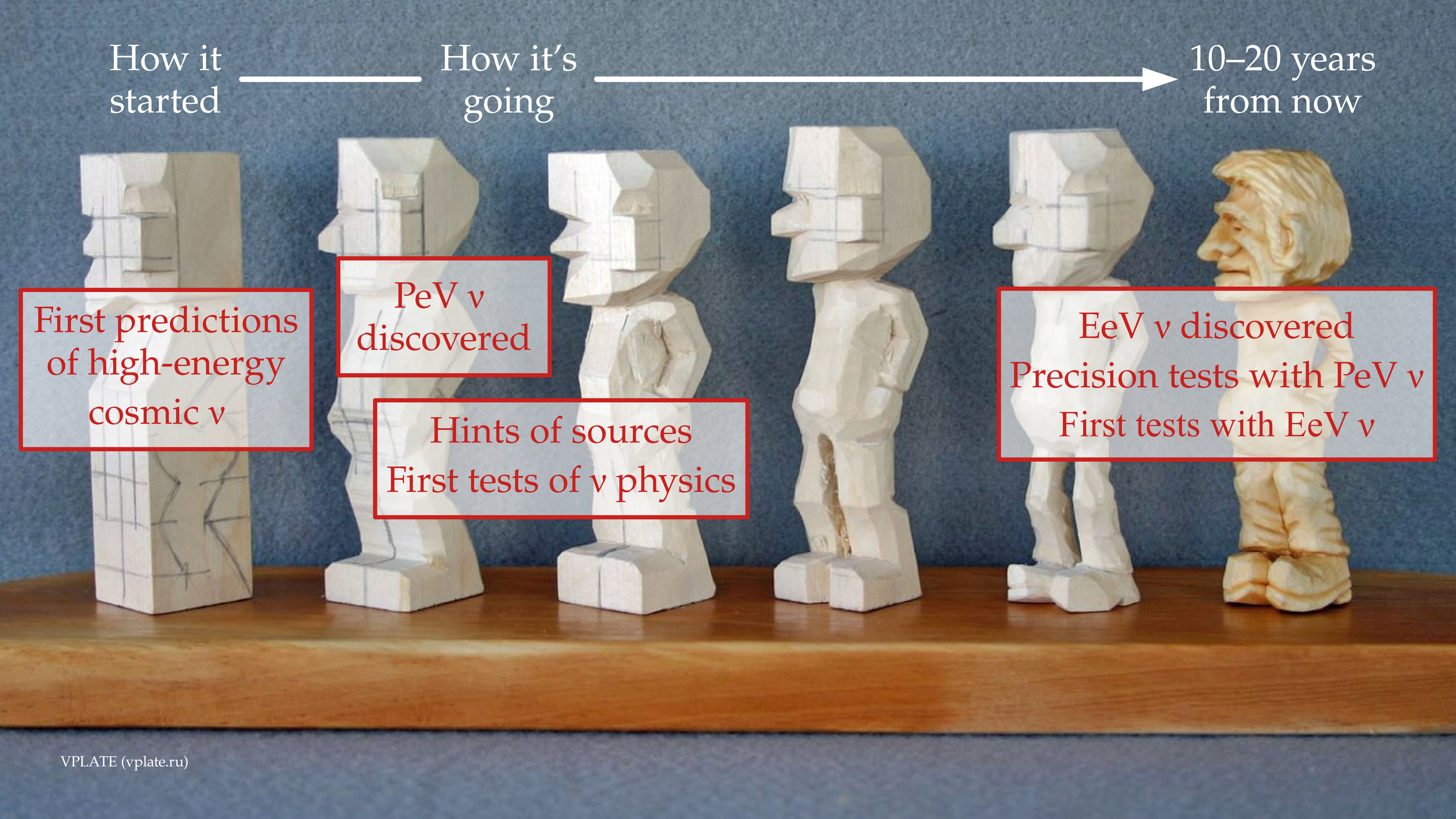
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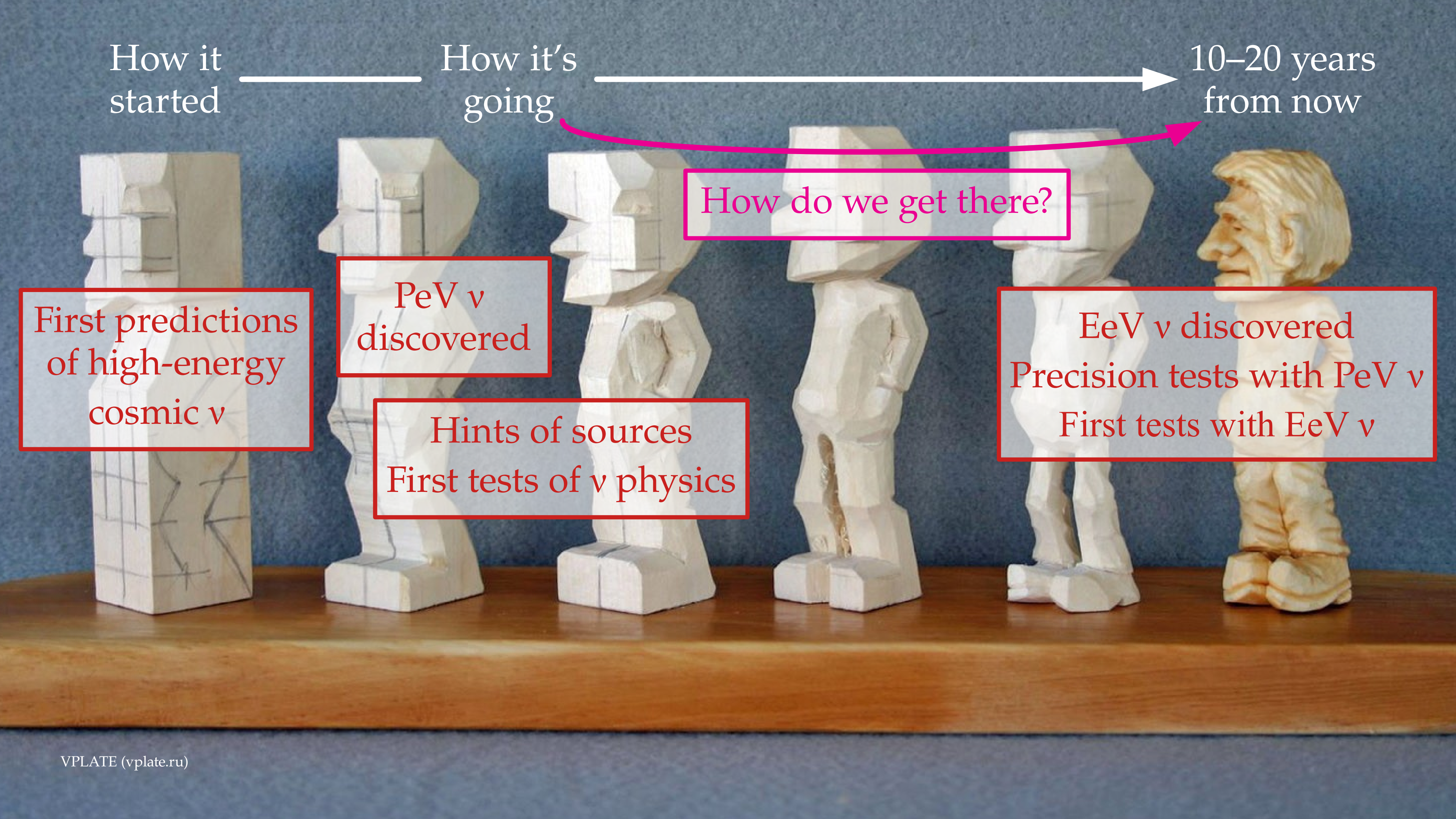
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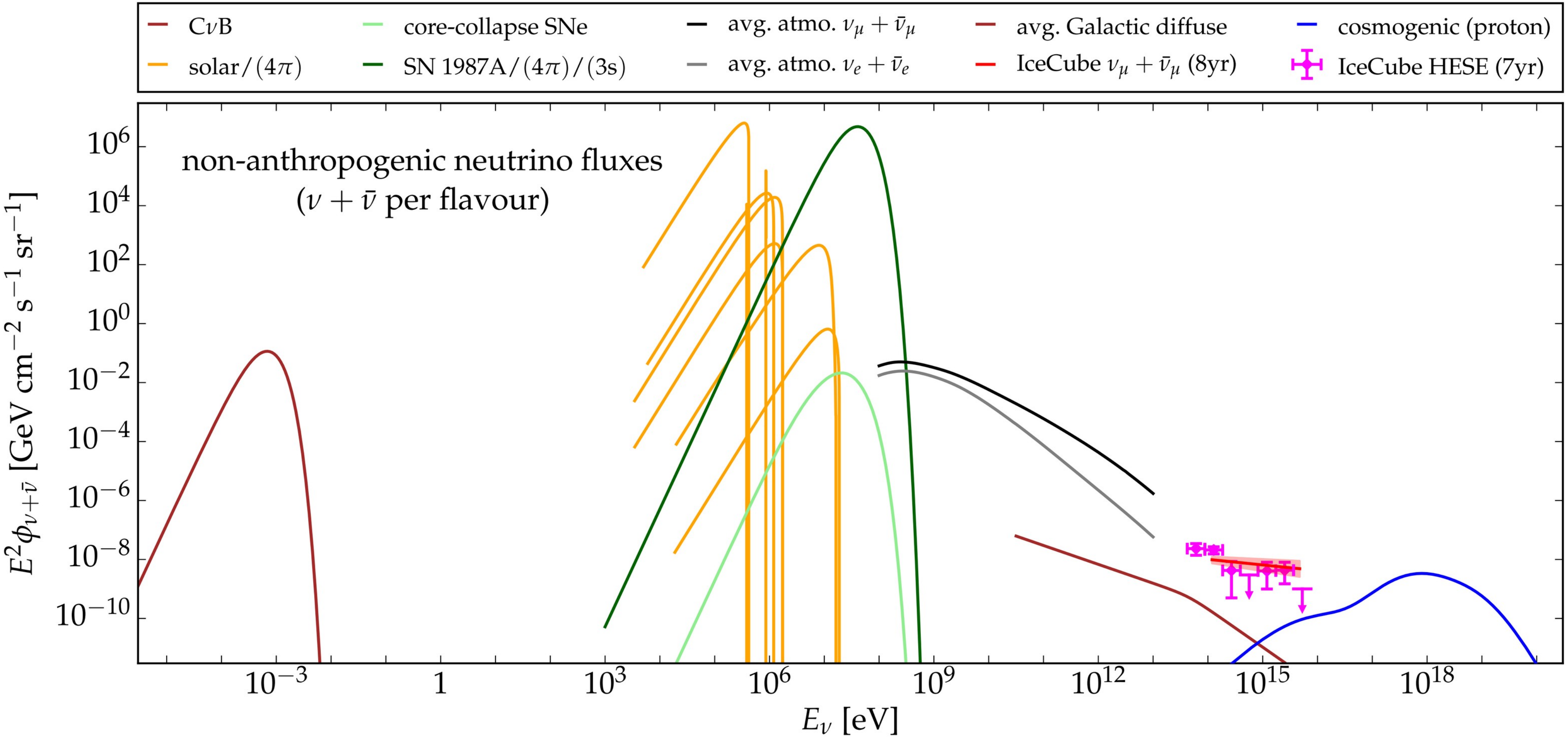
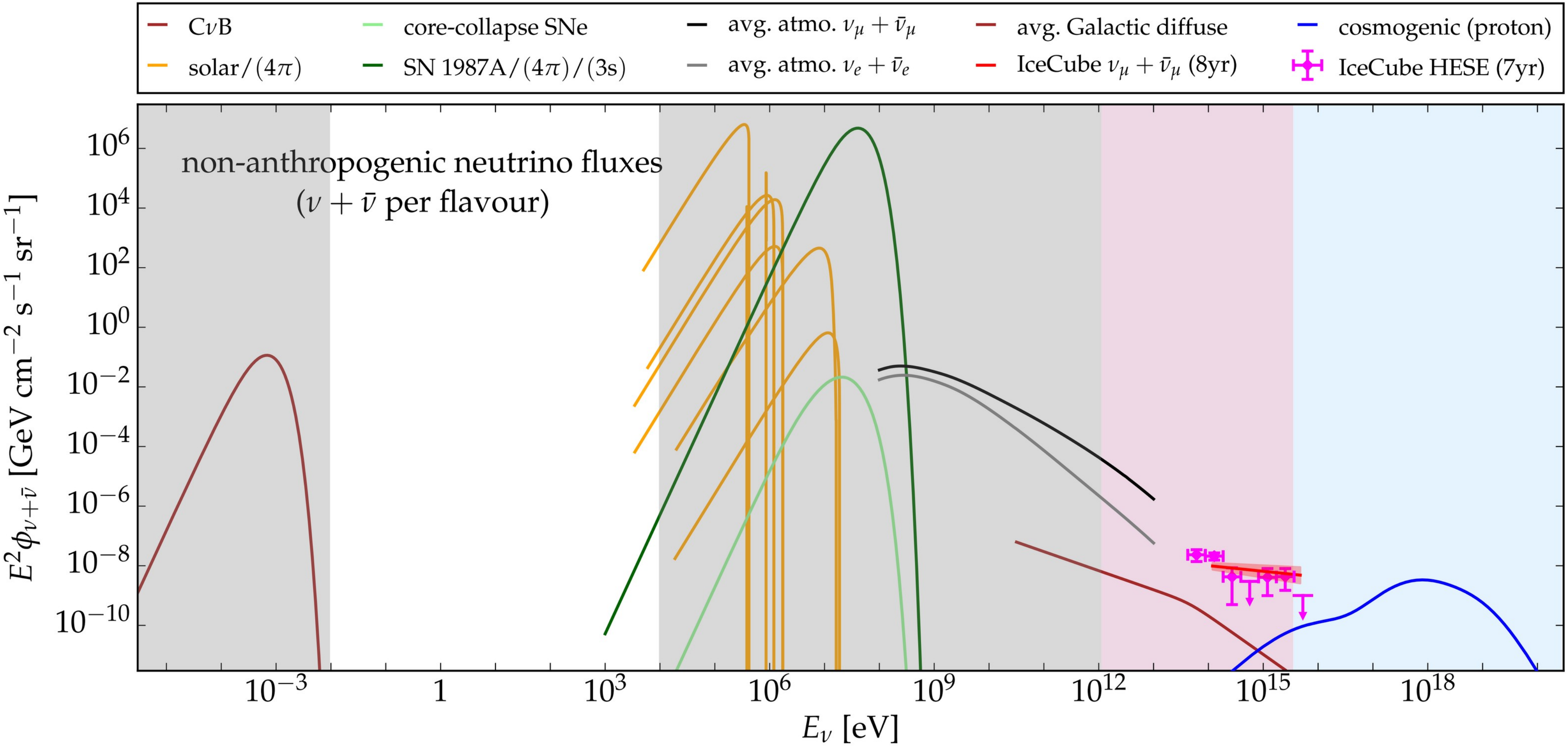


Figure courtesy of Markus Ahlers

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



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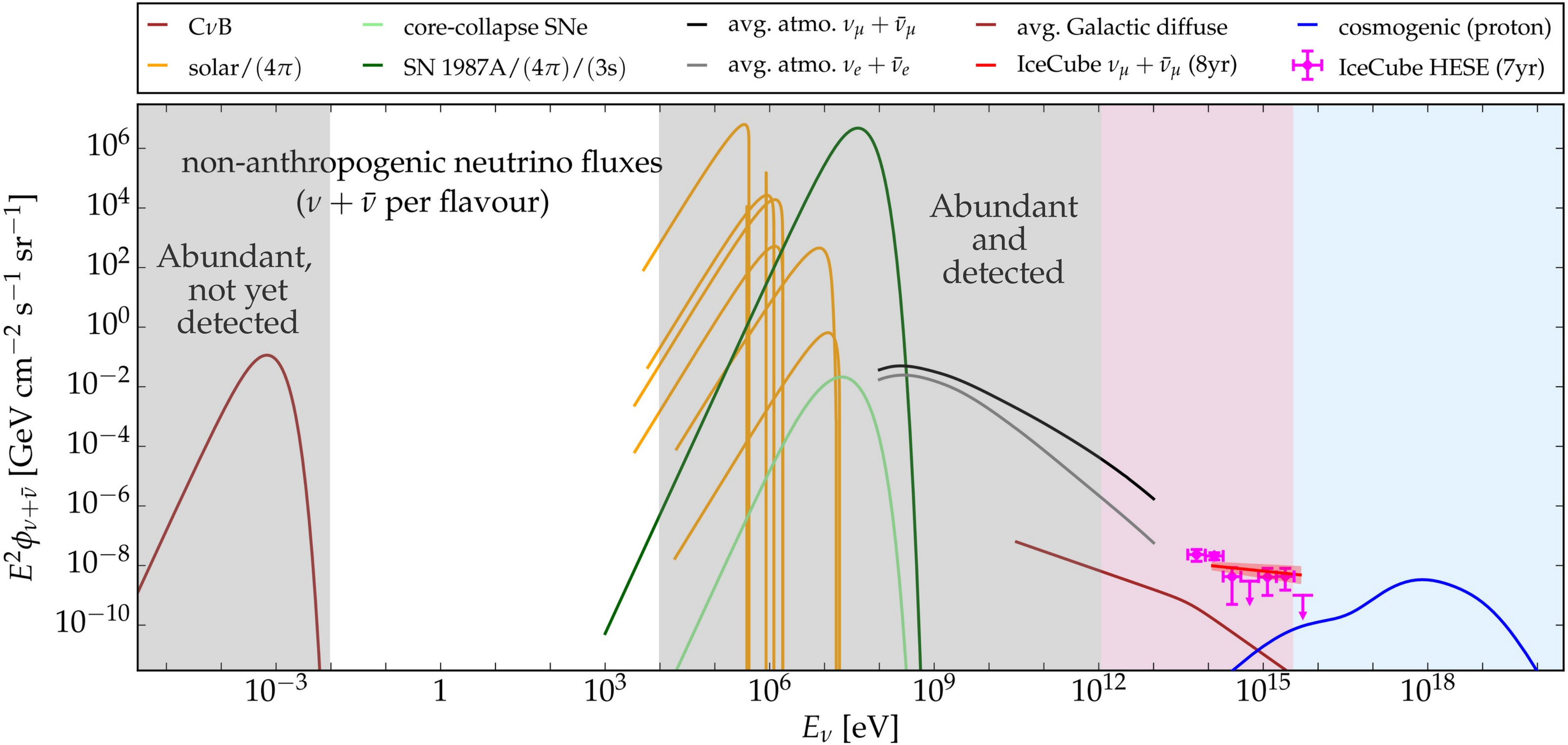

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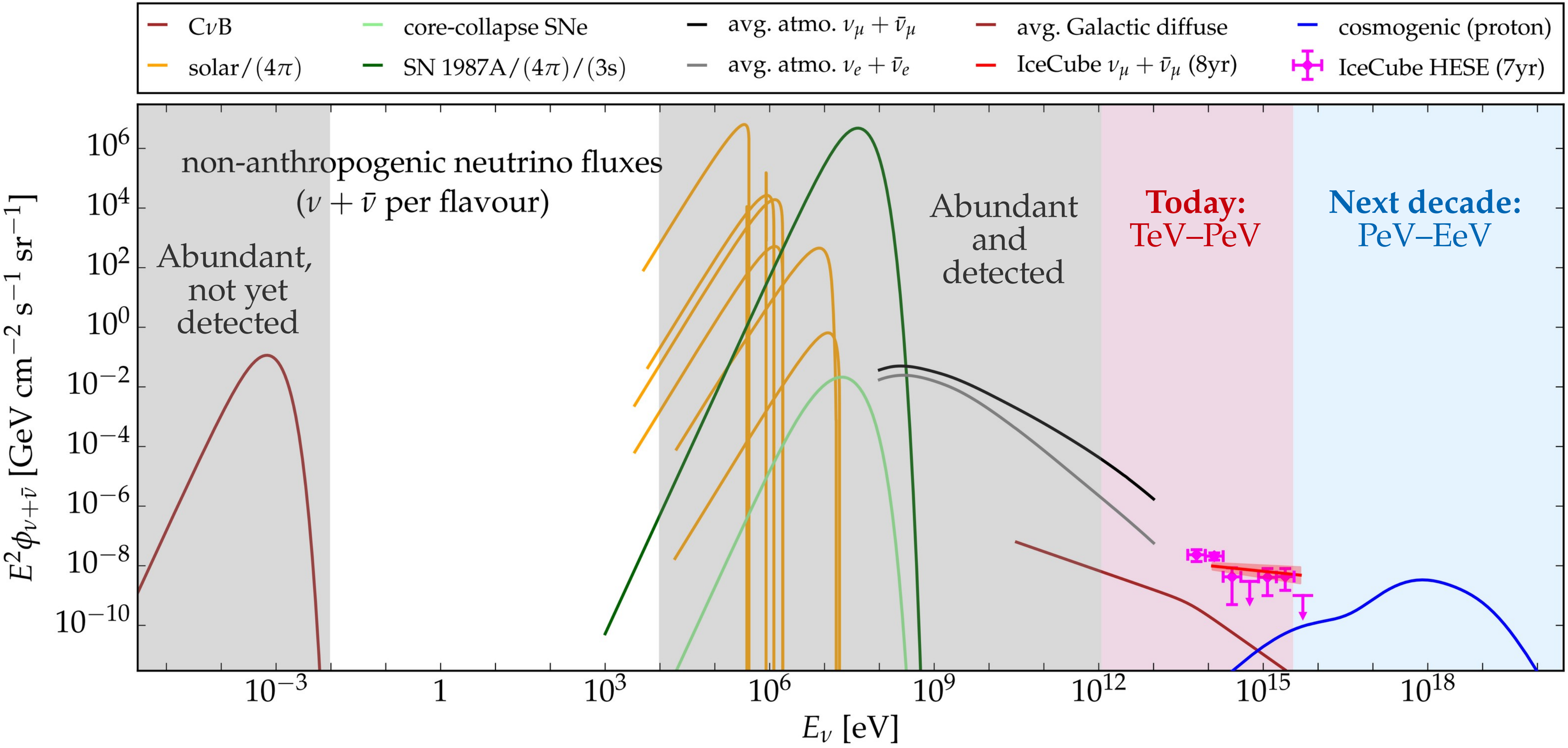

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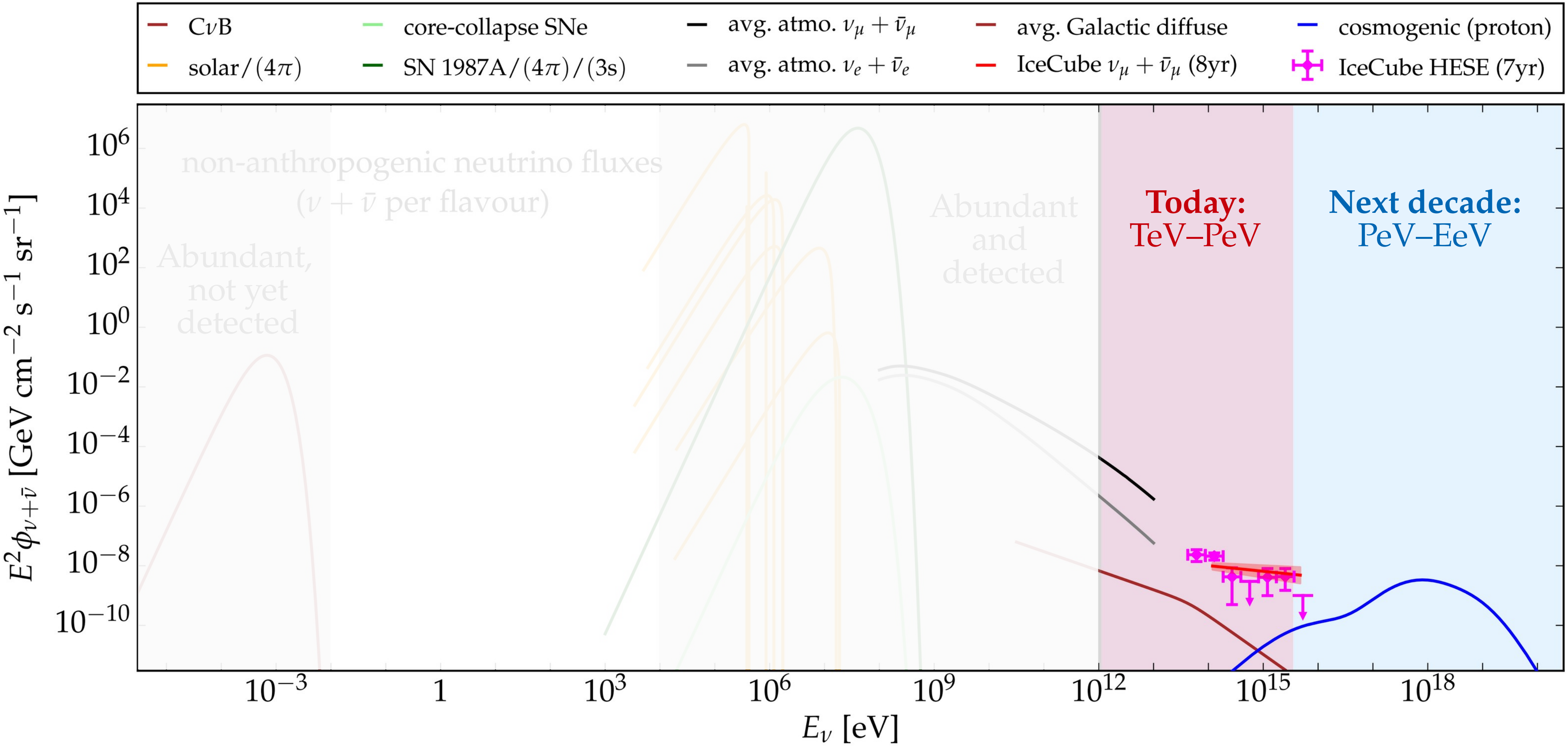

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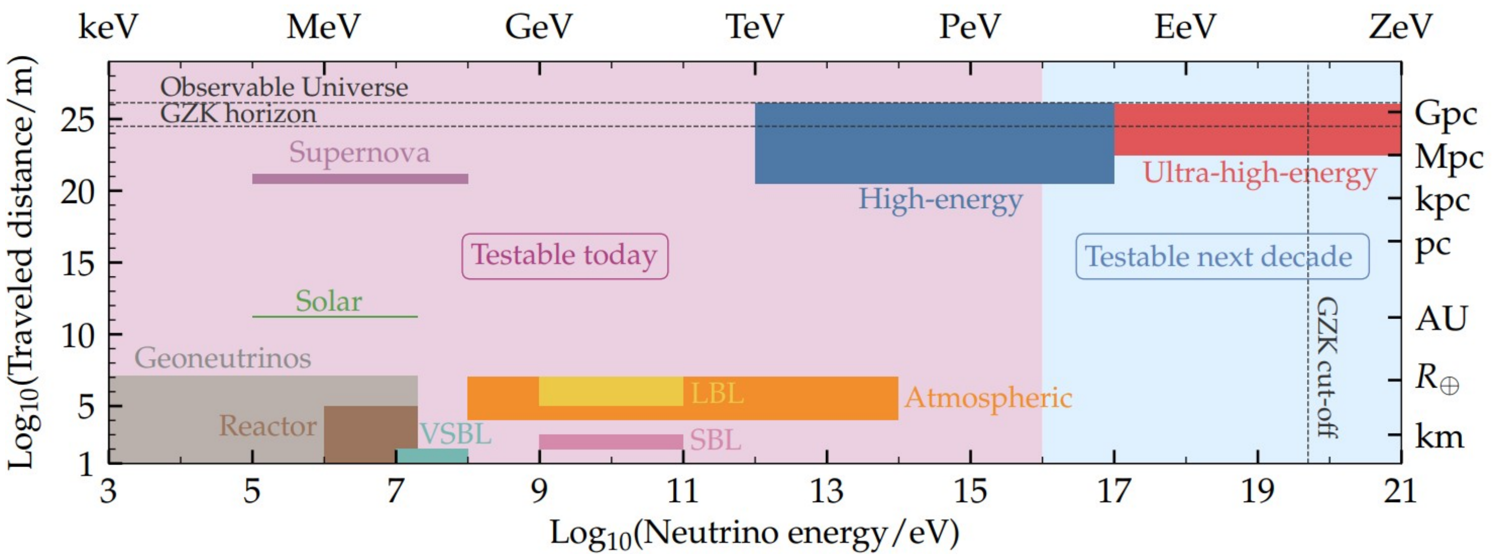
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

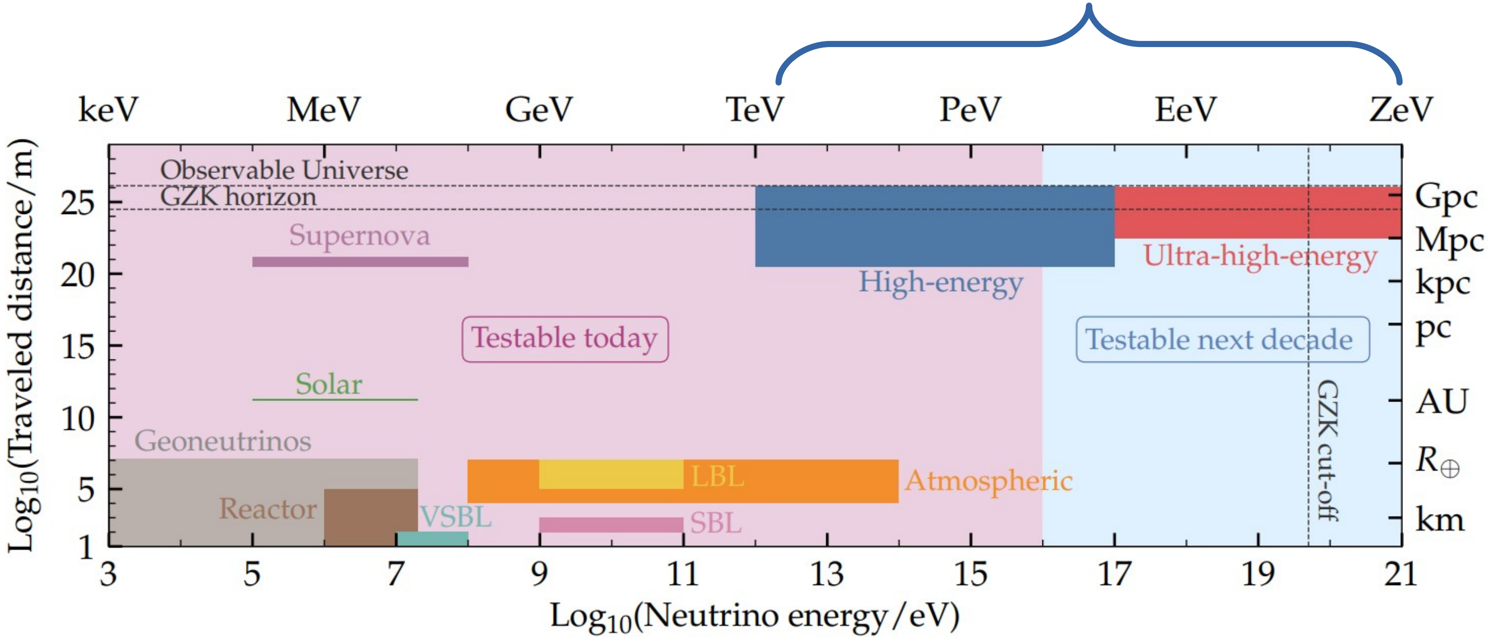
What makes high-energy cosmic ν exciting?



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

What makes high-energy cosmic ν exciting?

They have the highest energies



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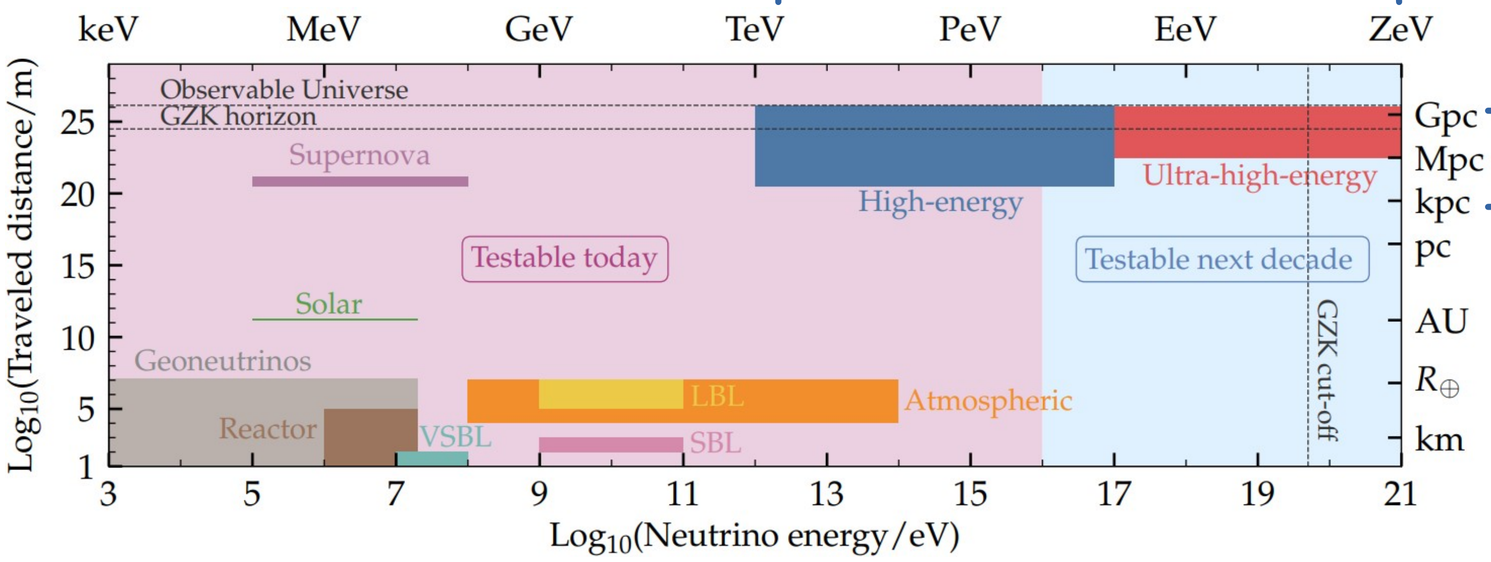
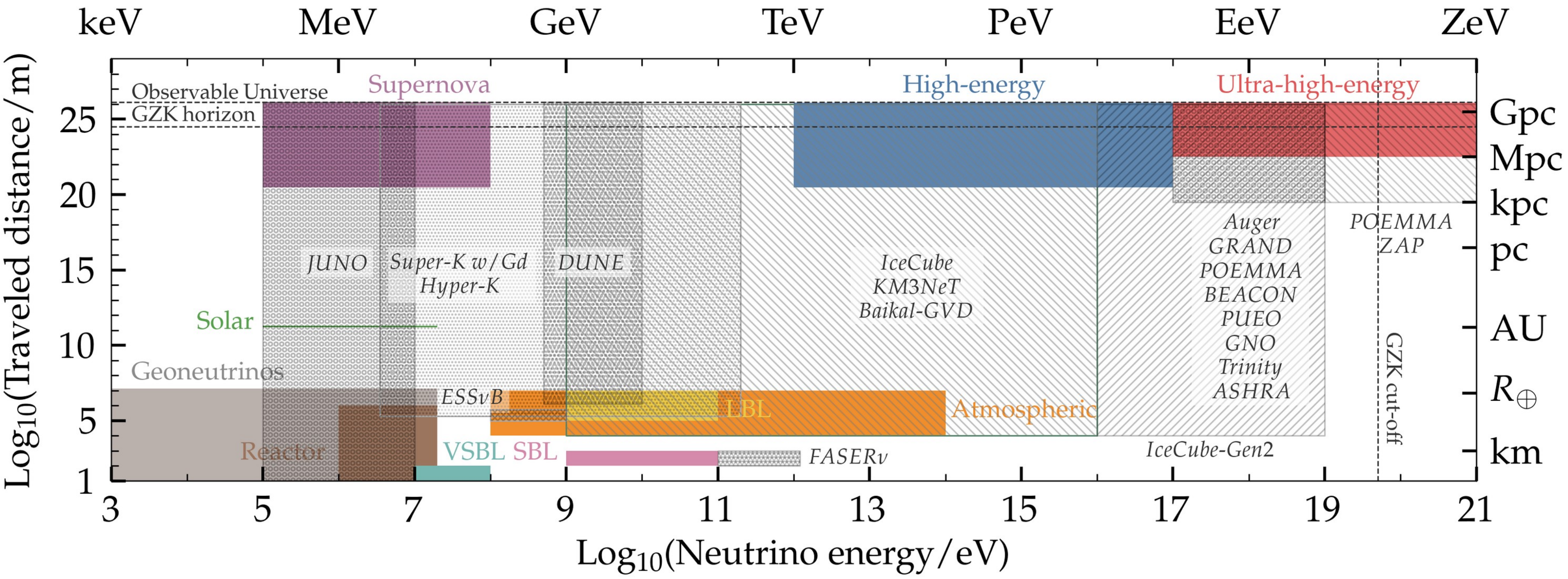


They travel the longest distances

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

Next decade: a host of planned neutrino detectors



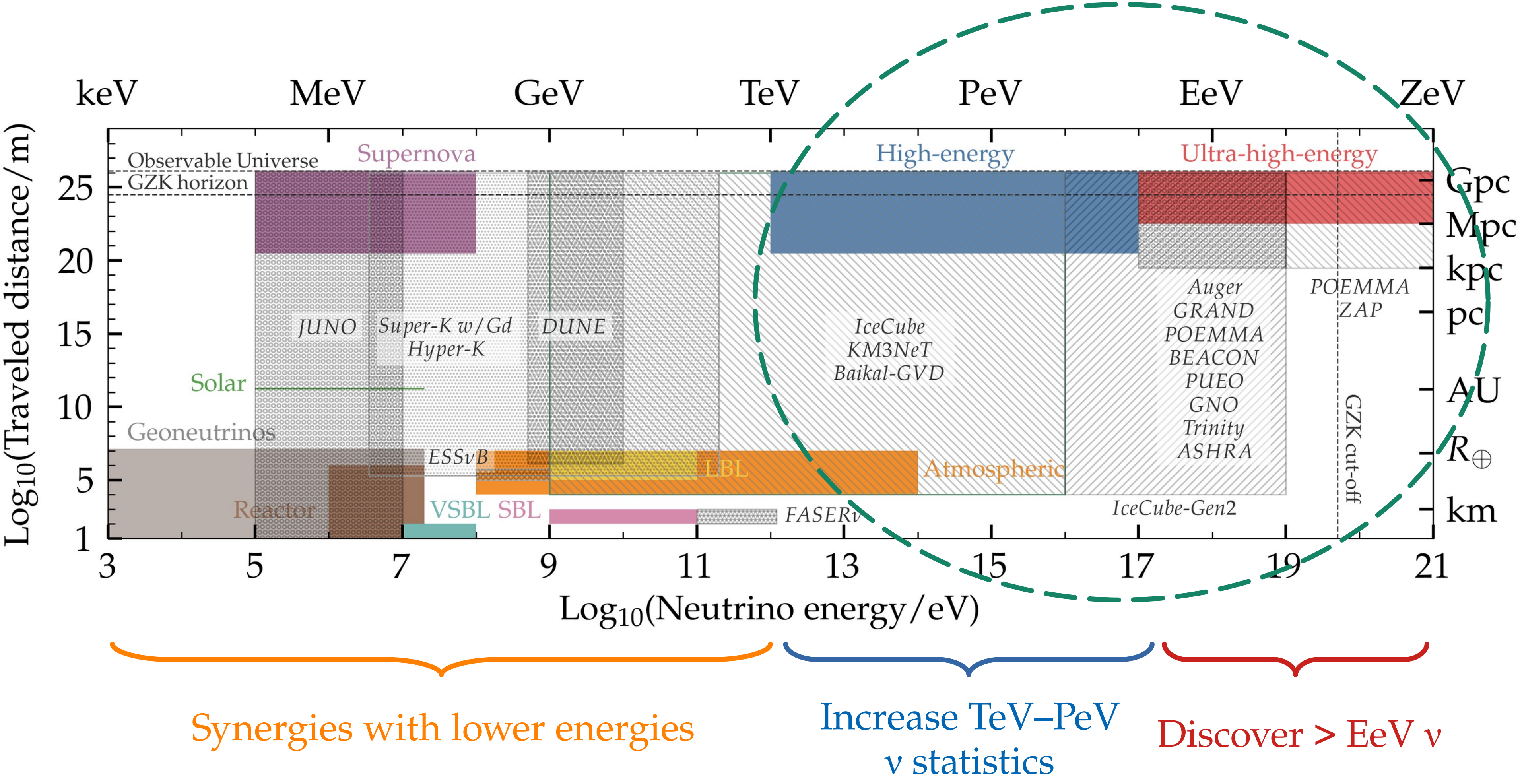
Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest

Next decade: a host of planned neutrino detectors



MB *et al.*, Snowmass 20201 Letter of interest

High-energy neutrinos: TeV–PeV

(*Discovered*)

Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

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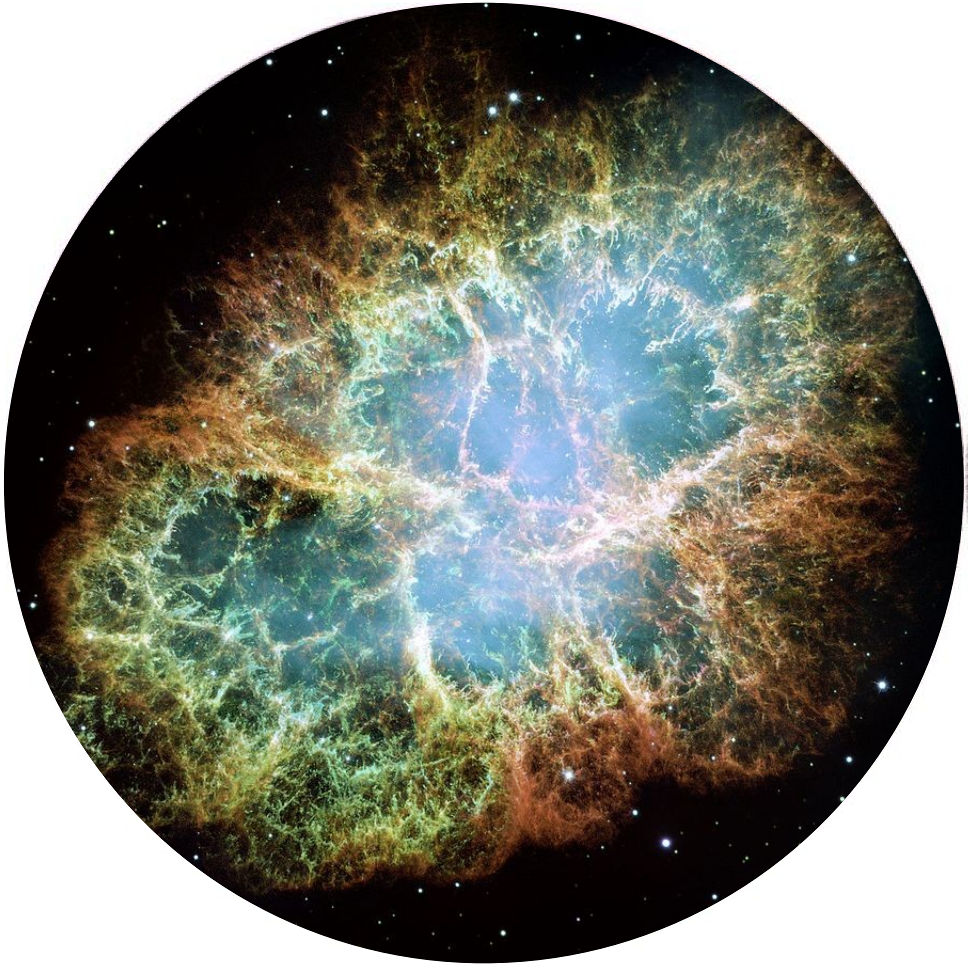

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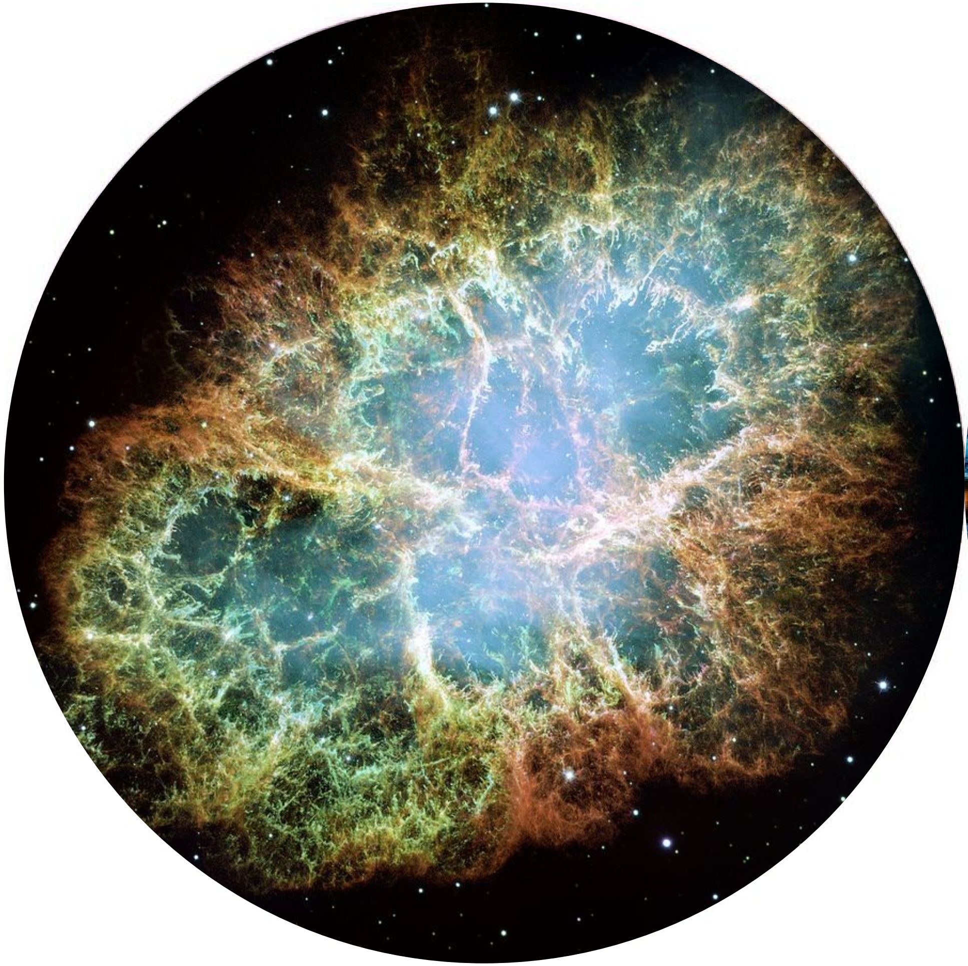

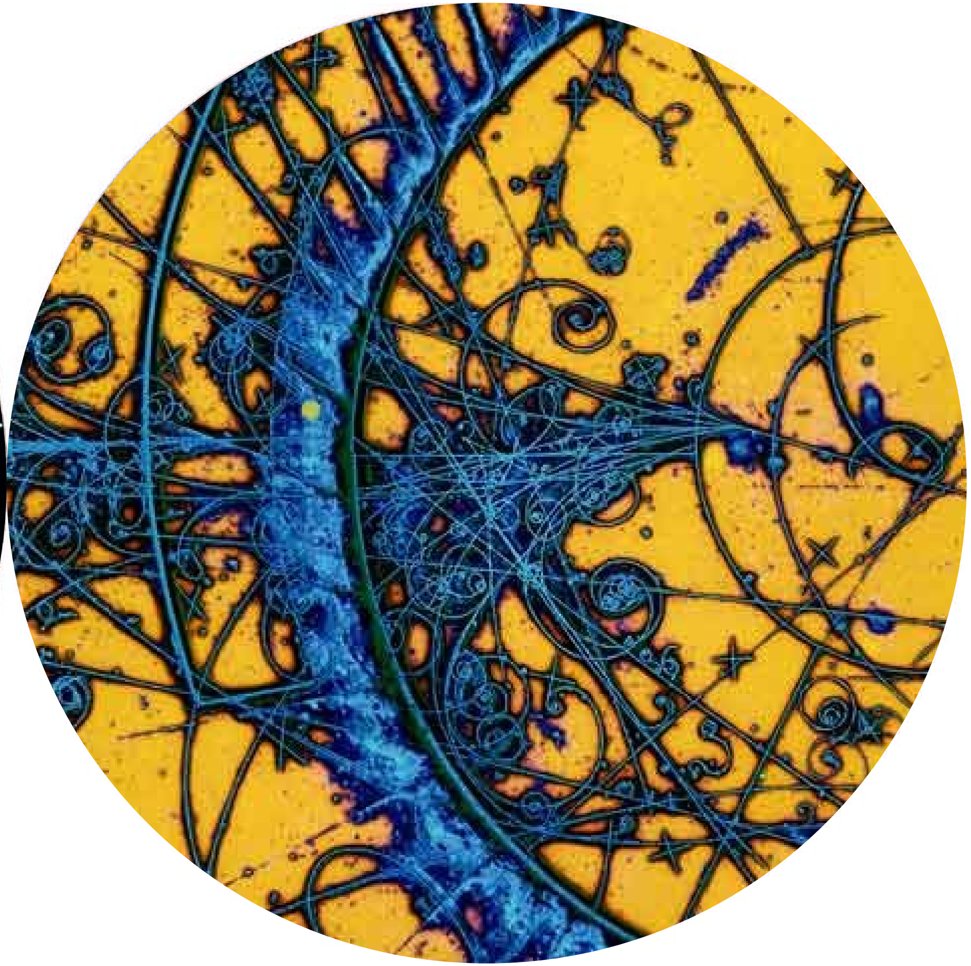

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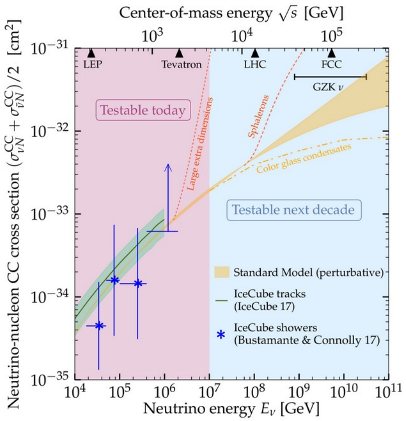
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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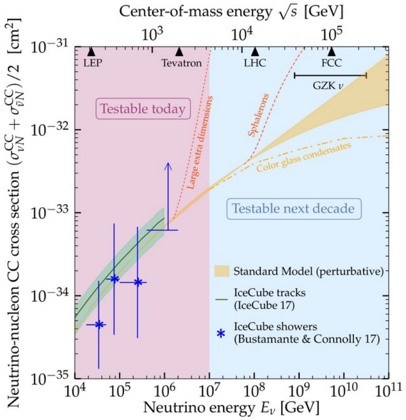
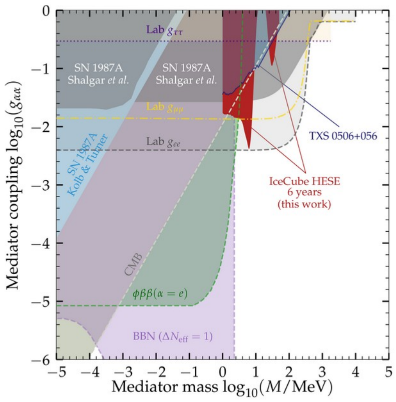


MB & Connolly, *PRL* 2019

ν self-interactions



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

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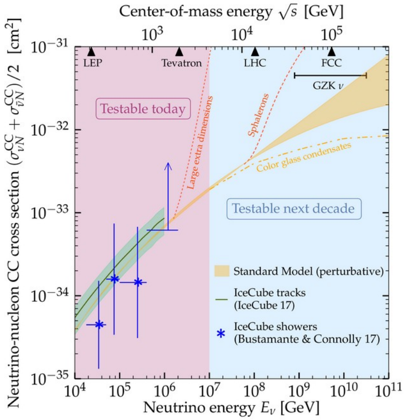

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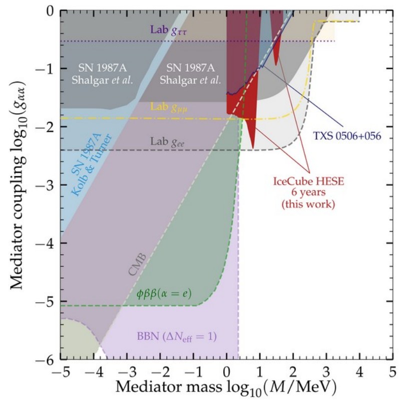
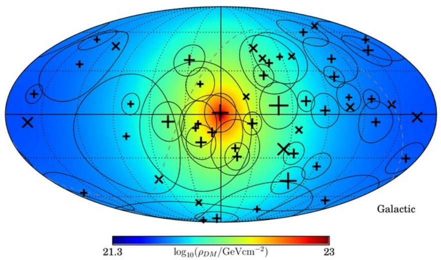


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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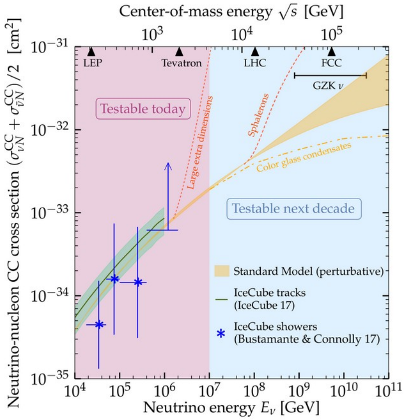

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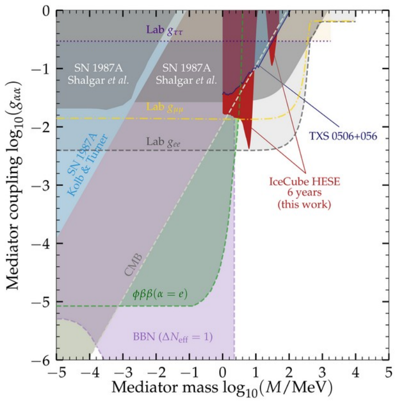

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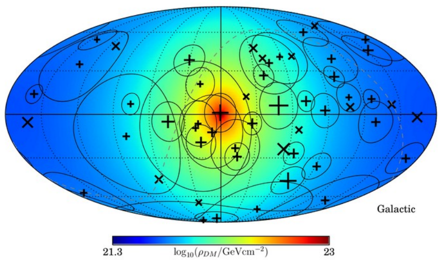
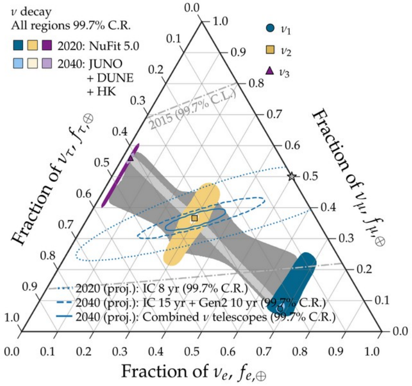


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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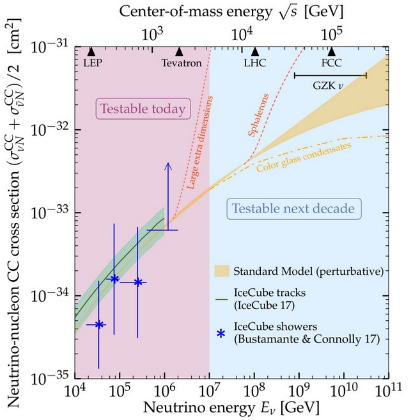

MB & Connolly, *PRL* 2019

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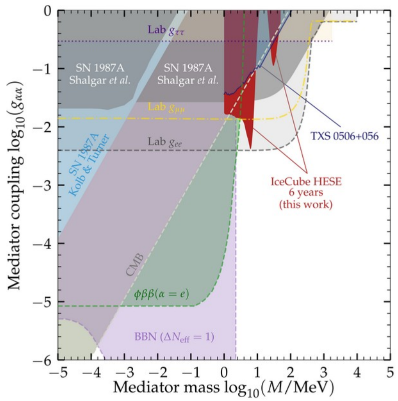

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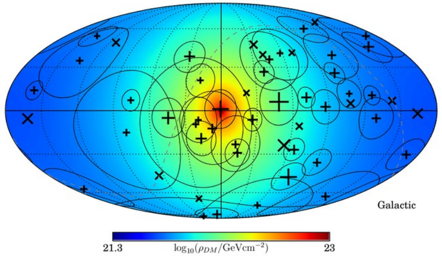

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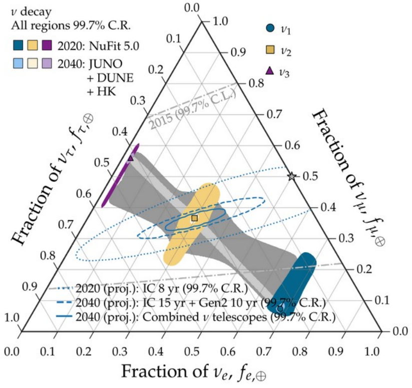
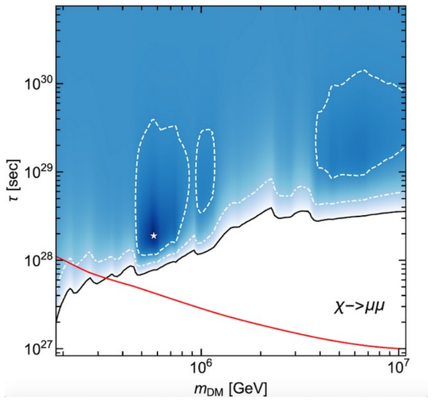


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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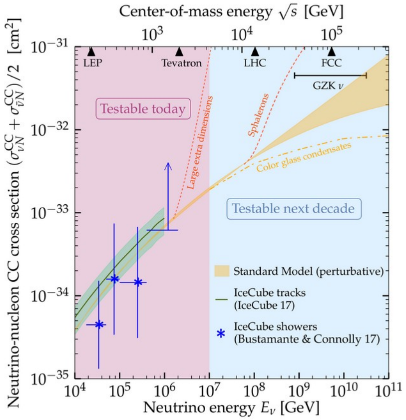

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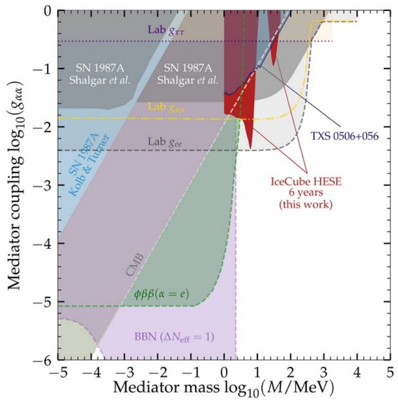

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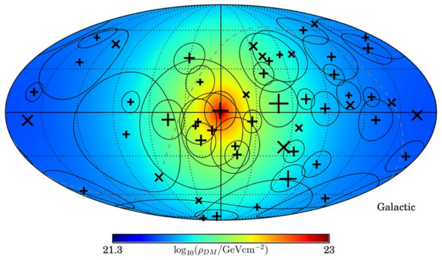

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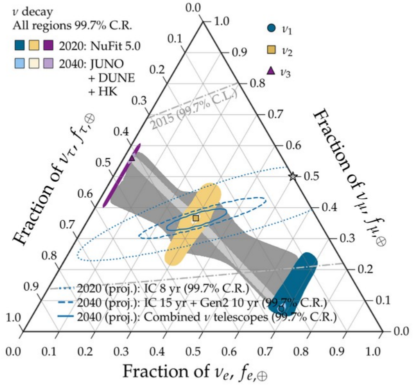

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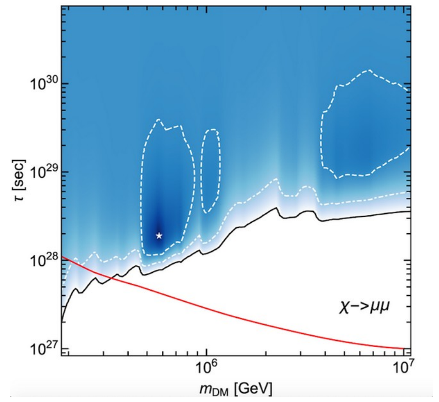
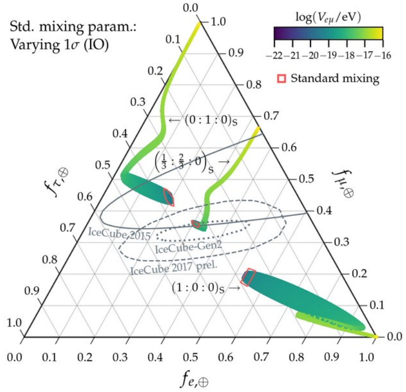


Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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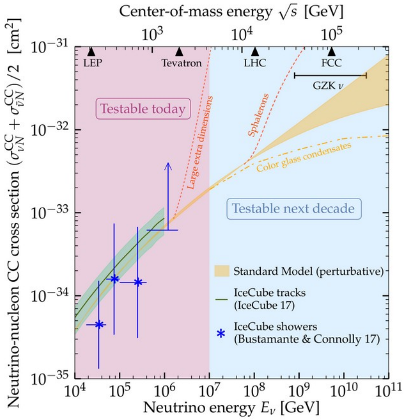

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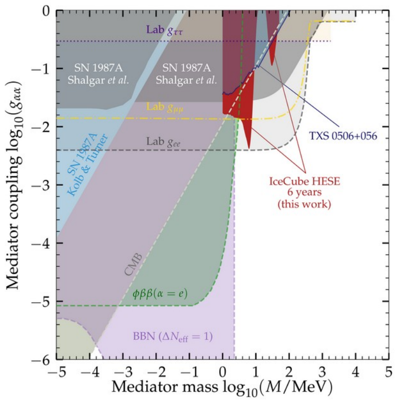

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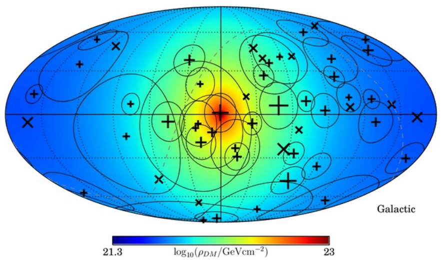

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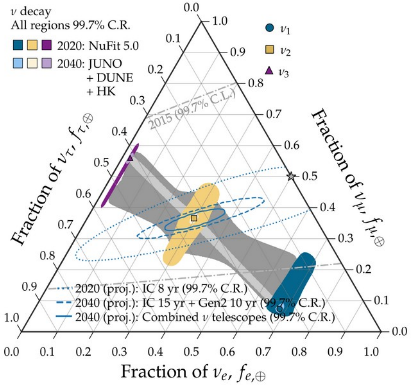

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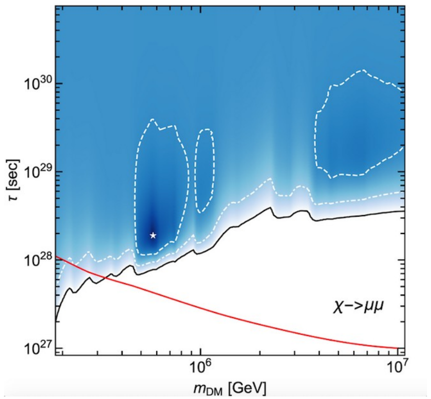

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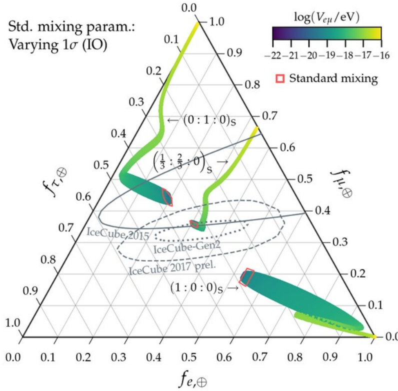
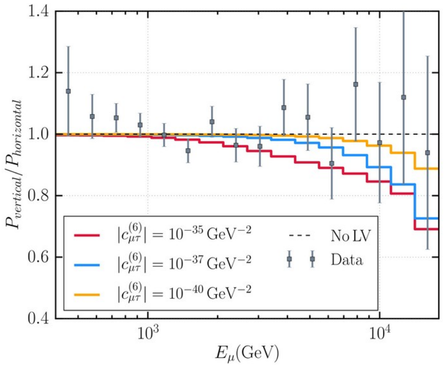


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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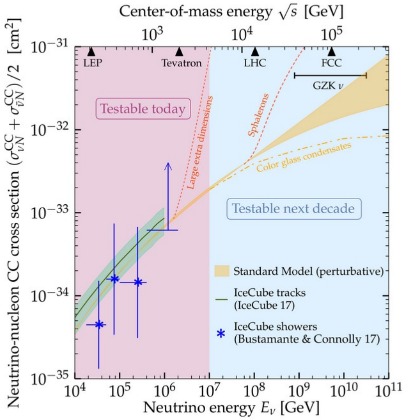

MB & Connolly, *PRL* 2019

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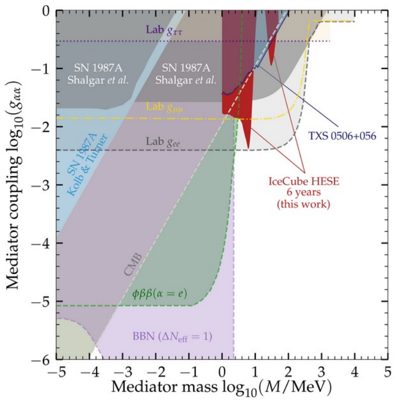

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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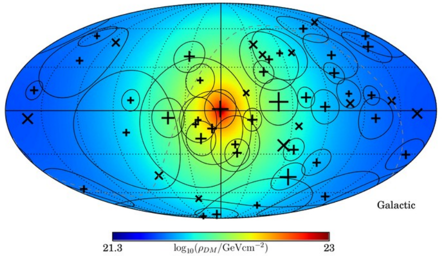

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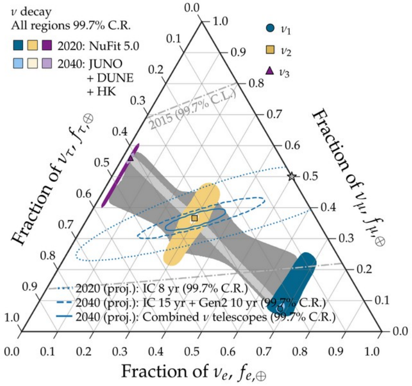

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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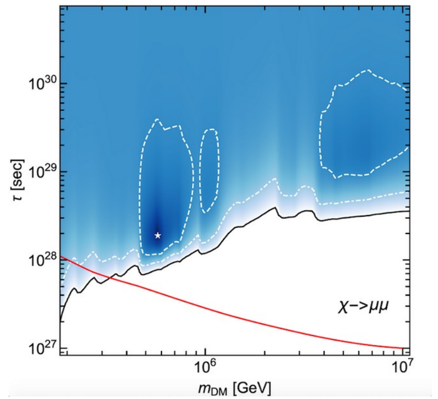

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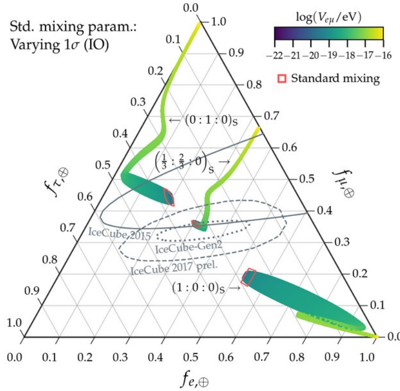

MB & Agarwalla, *PRL* 2019

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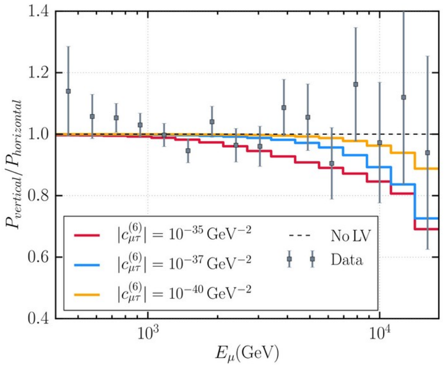
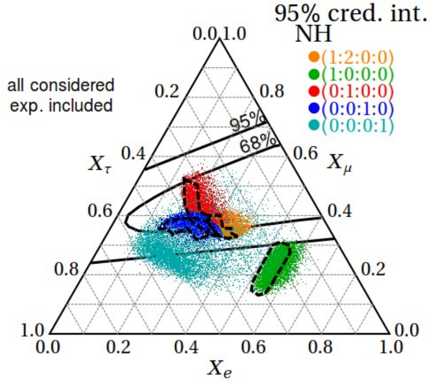


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Fundamental physics with high-energy cosmic neutrinos

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

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

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

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

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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

I.
The story so far

Making high-energy astrophysical neutrinos

(or $p + p$)

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

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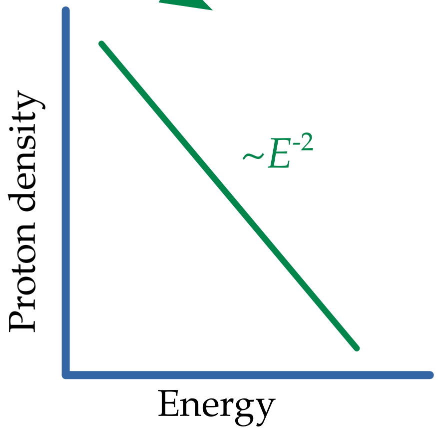

Making high-energy astrophysical neutrinos

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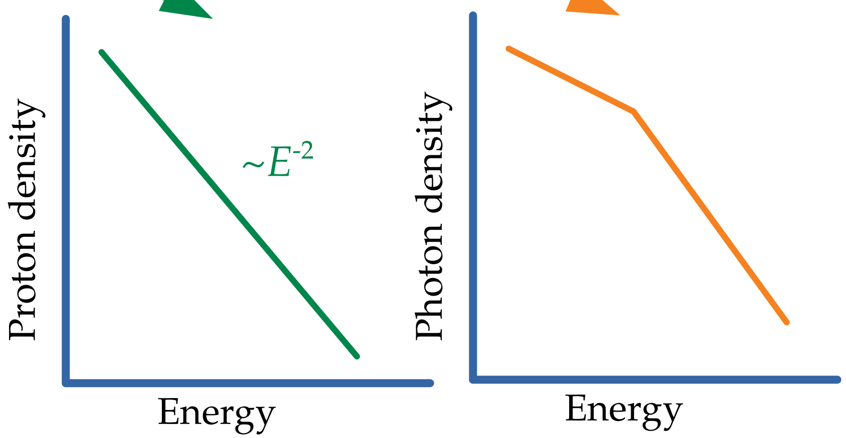

Making high-energy astrophysical neutrinos

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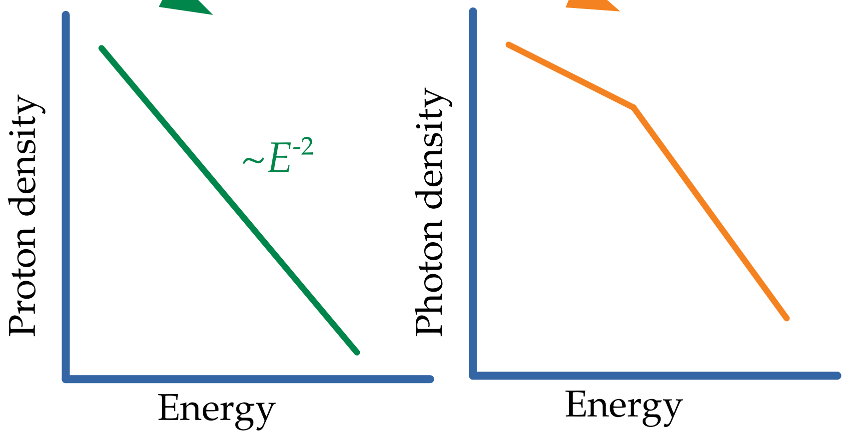
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



Making high-energy astrophysical neutrinos

(or $p + p$)

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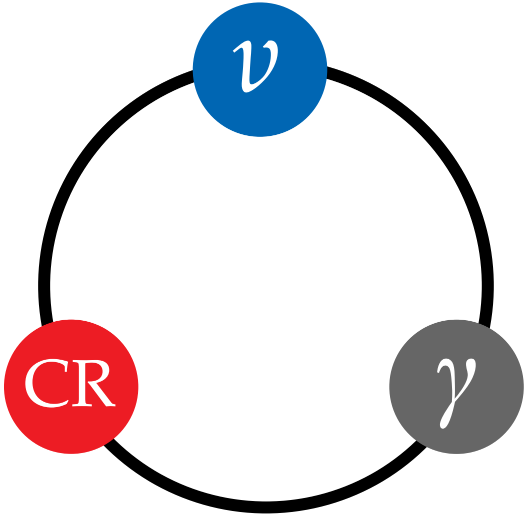
$$\pi^{0} \longrightarrow \gamma + \gamma$$

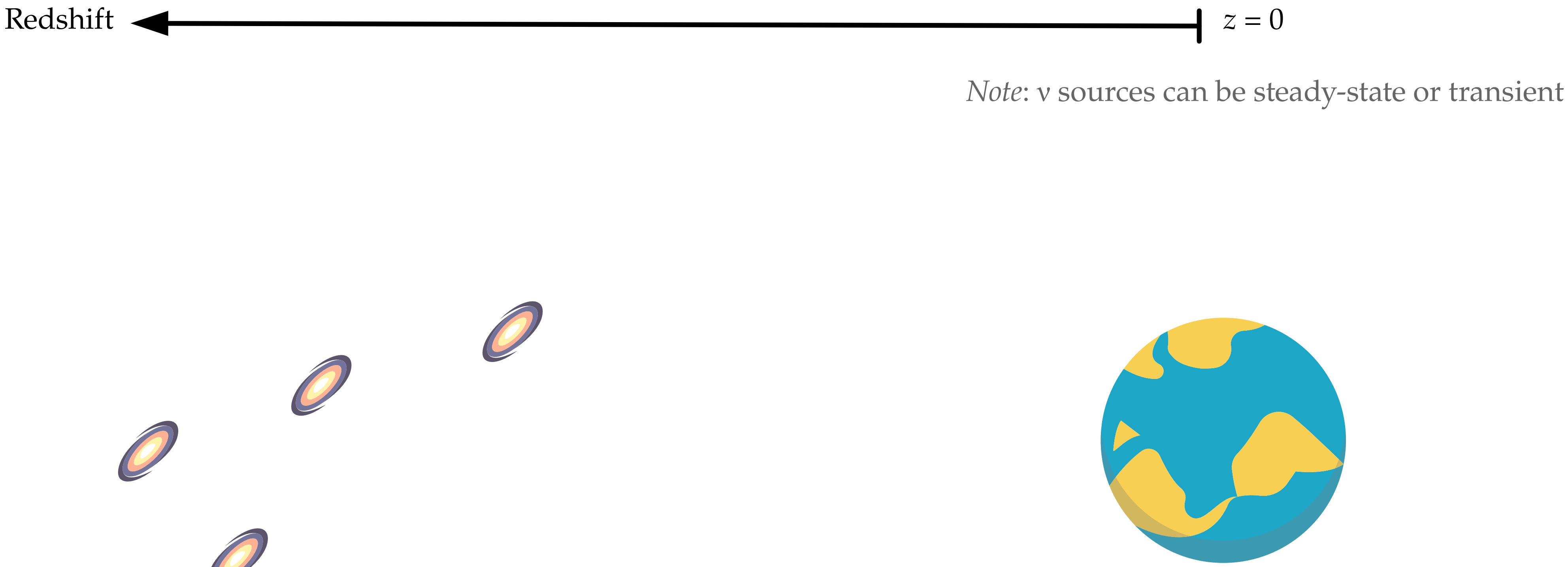
$$\pi^{+} \longrightarrow \mu^{+} + \nu_{\mu} \longrightarrow \bar{\nu}_{\mu} + e^{+} + \nu_{e} + \nu_{\mu}$$

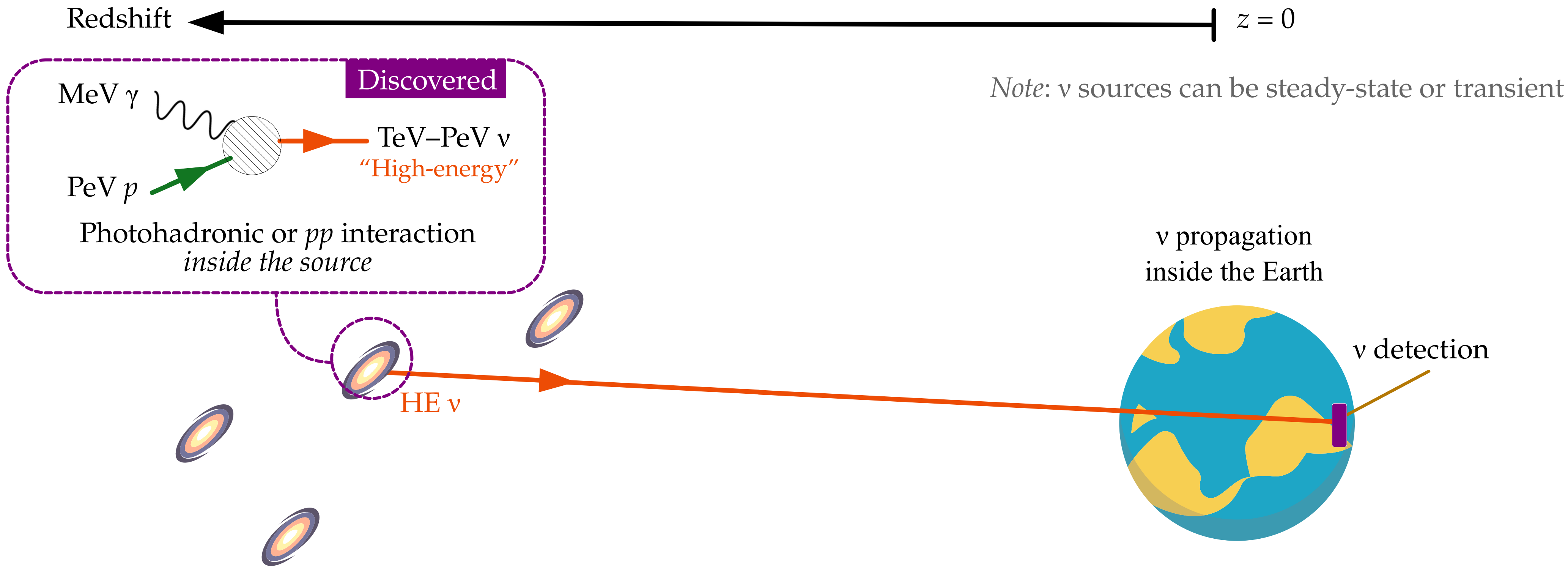
$$n \text{ (escapes)} \longrightarrow p + e^{-} + \bar{\nu}_{e}$$

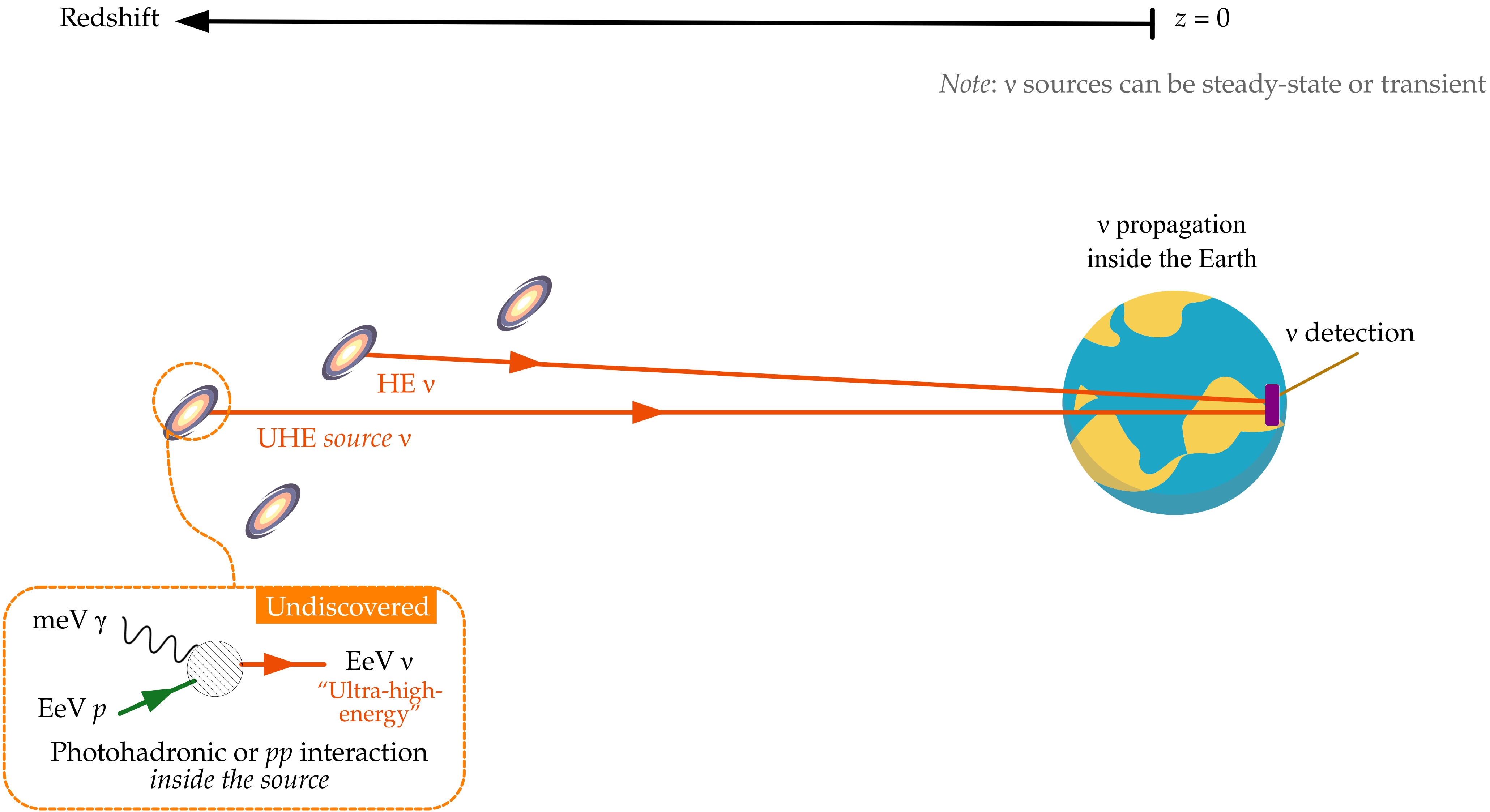


Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10


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


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



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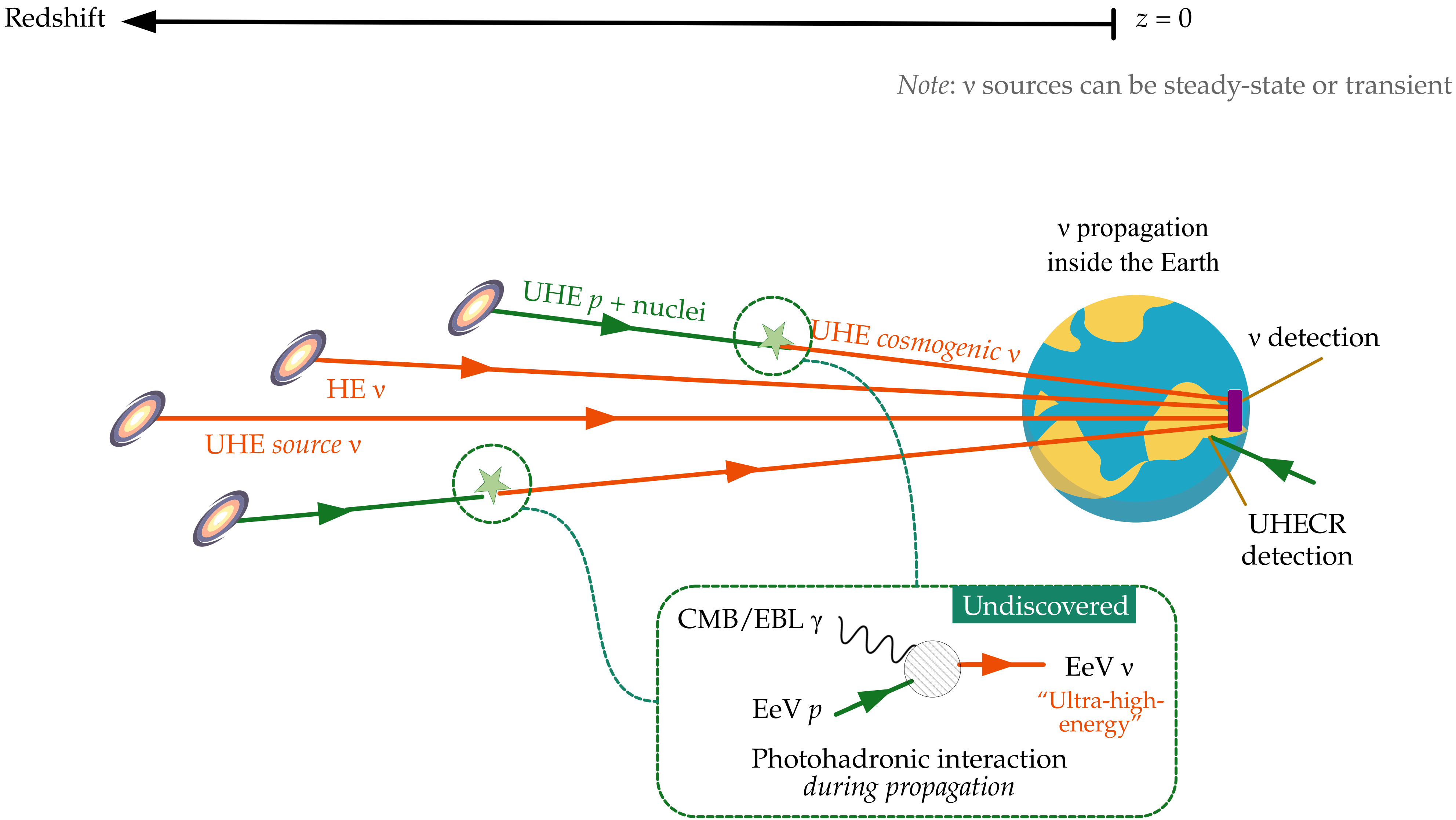
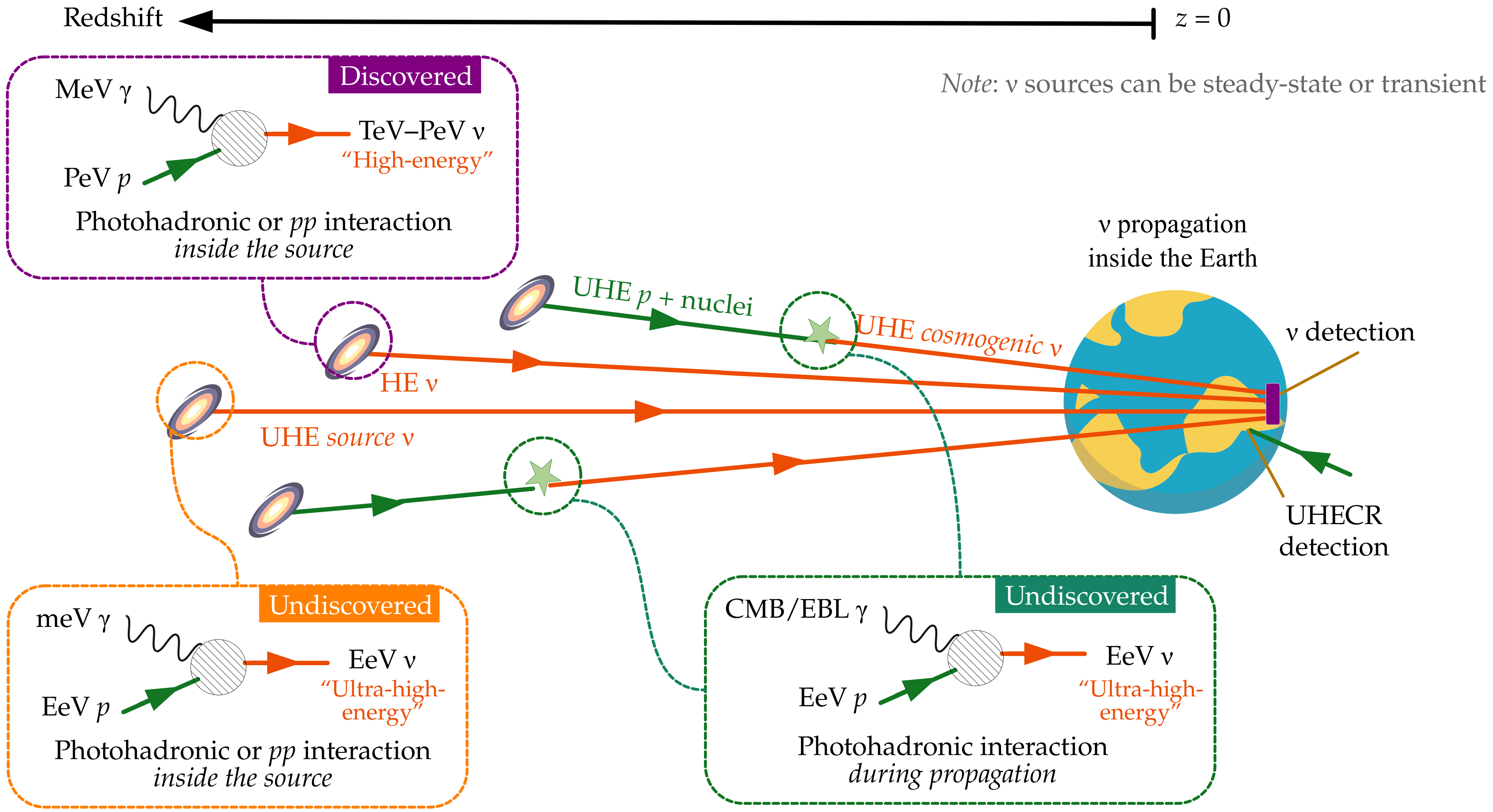


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE *cosmogenic* ν
ν detection
HE ν
UHE *source* ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic interaction
during propagation



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Undiscovered
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Photohadronic interaction
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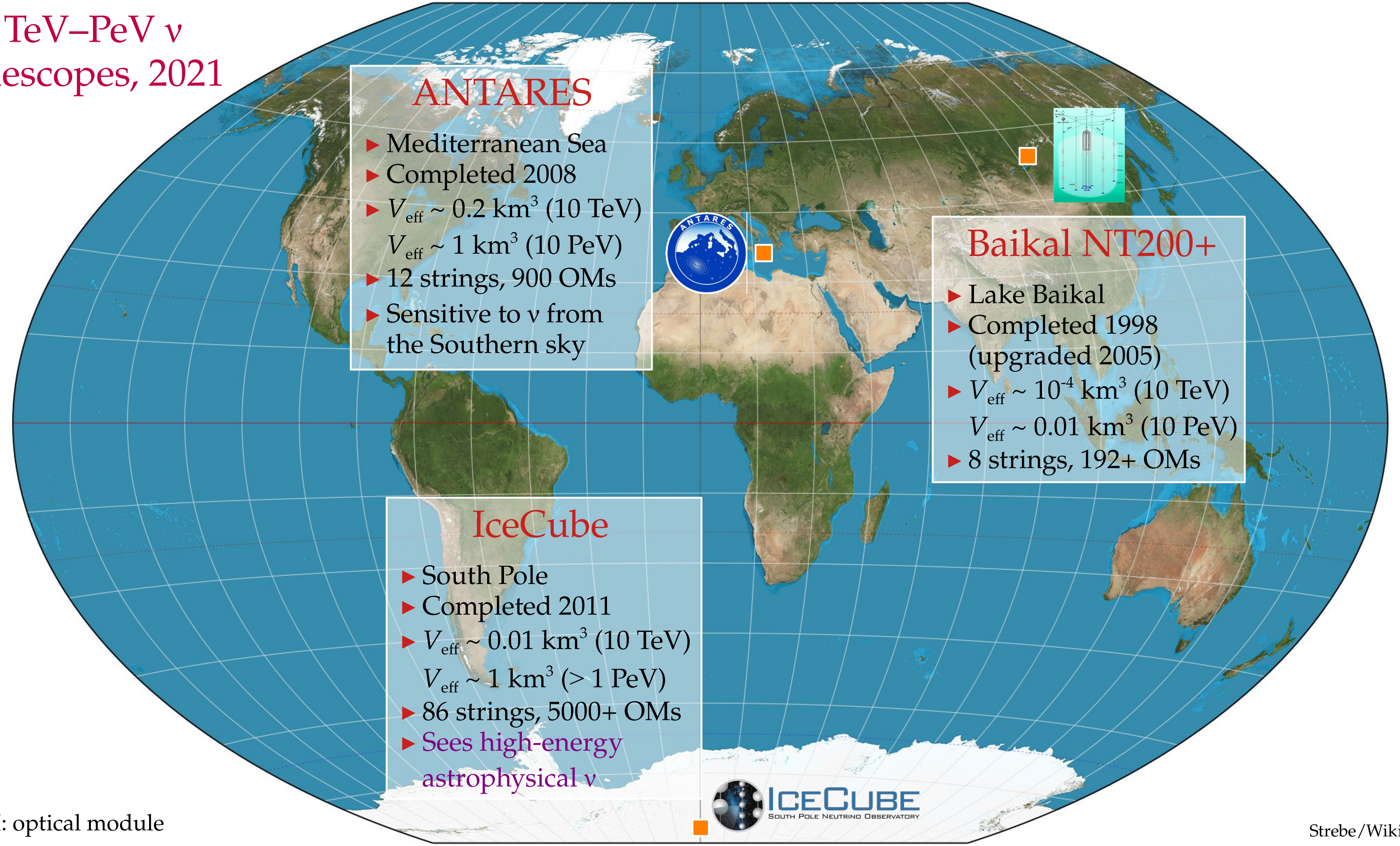
TeV–PeV ν telescopes, 2021



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

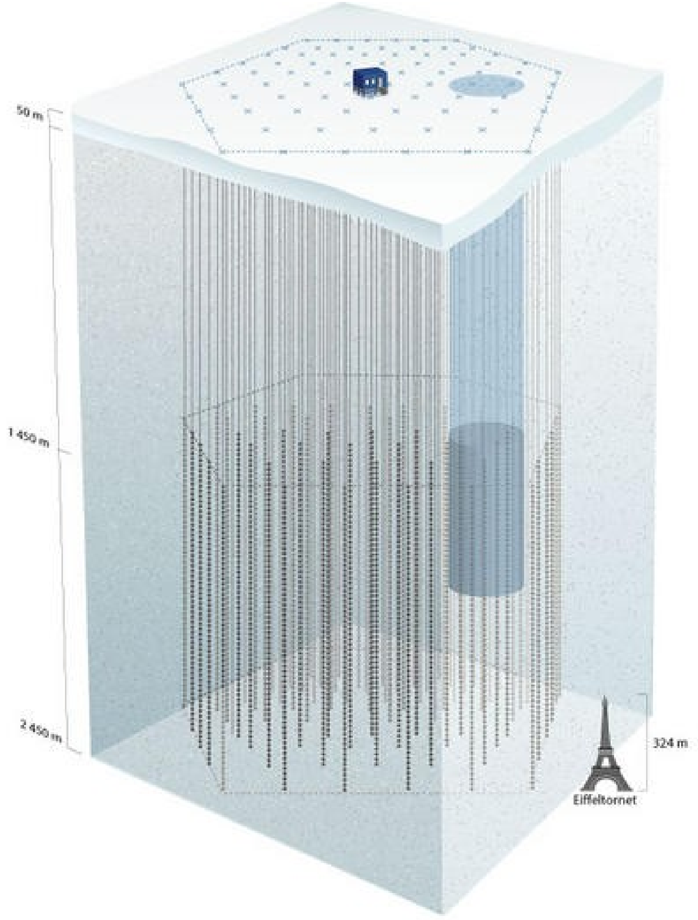
- South Pole
- Completed 2011
- $V_{\text{eff}} \sim 0.01\ \text{km}^3$ (10 TeV)
  $V_{\text{eff}} \sim 1\ \text{km}^3$ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia


Yuya Makino, IceCube/NSF

IceCube – What is it?



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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$$\nu_x + N \rightarrow \nu_x + X$$

Charged current (CC)

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

Charged current (CC)

Receives $(1\text{-}\langle y \rangle)E_\nu$

Receives $\langle y \rangle E_\nu$

$$\nu_x + N \rightarrow \nu_x + X$$

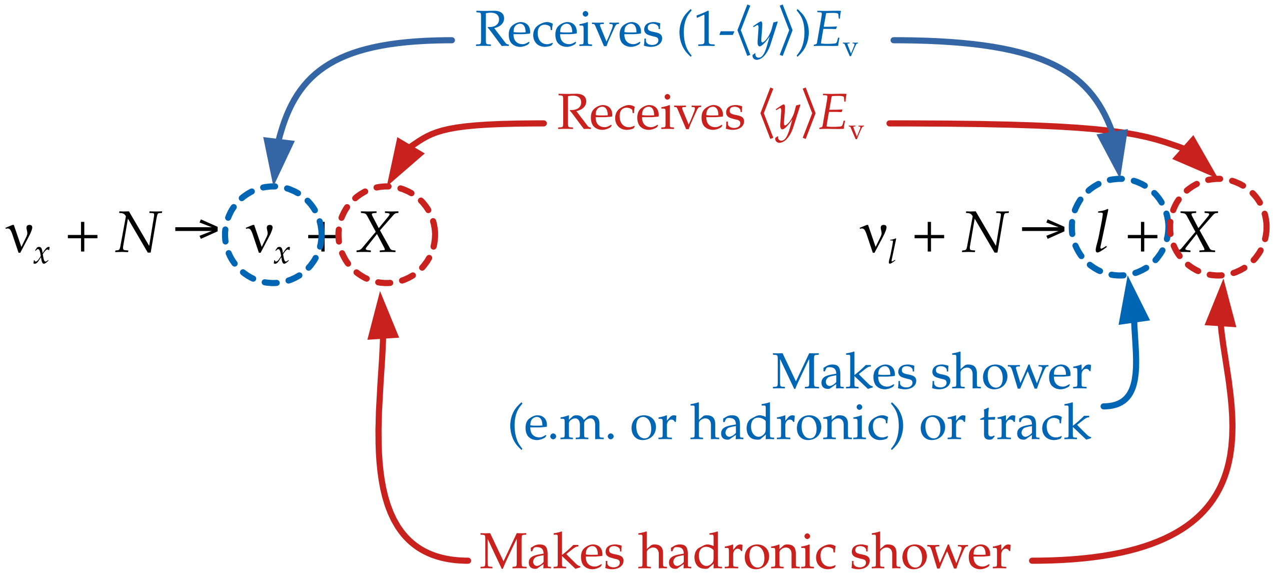
$$\nu_l + N \rightarrow l + X$$

At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25$–0.30

How does IceCube see TeV–PeV neutrinos?

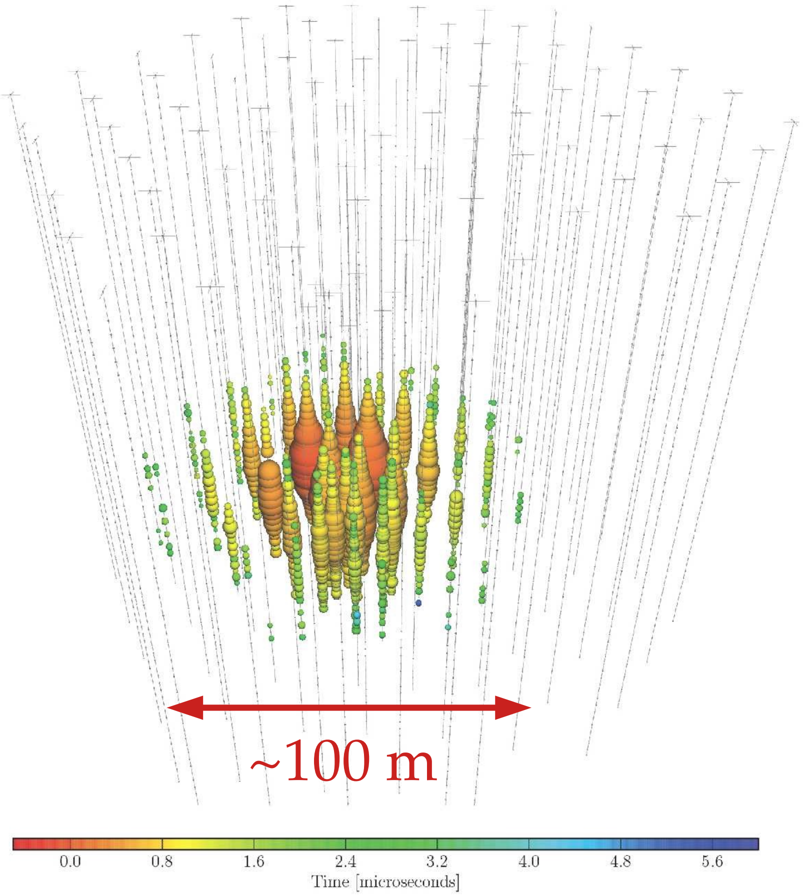
Deep inelastic neutrino-nucleon scattering

Neutral current (NC) | Charged current (CC)



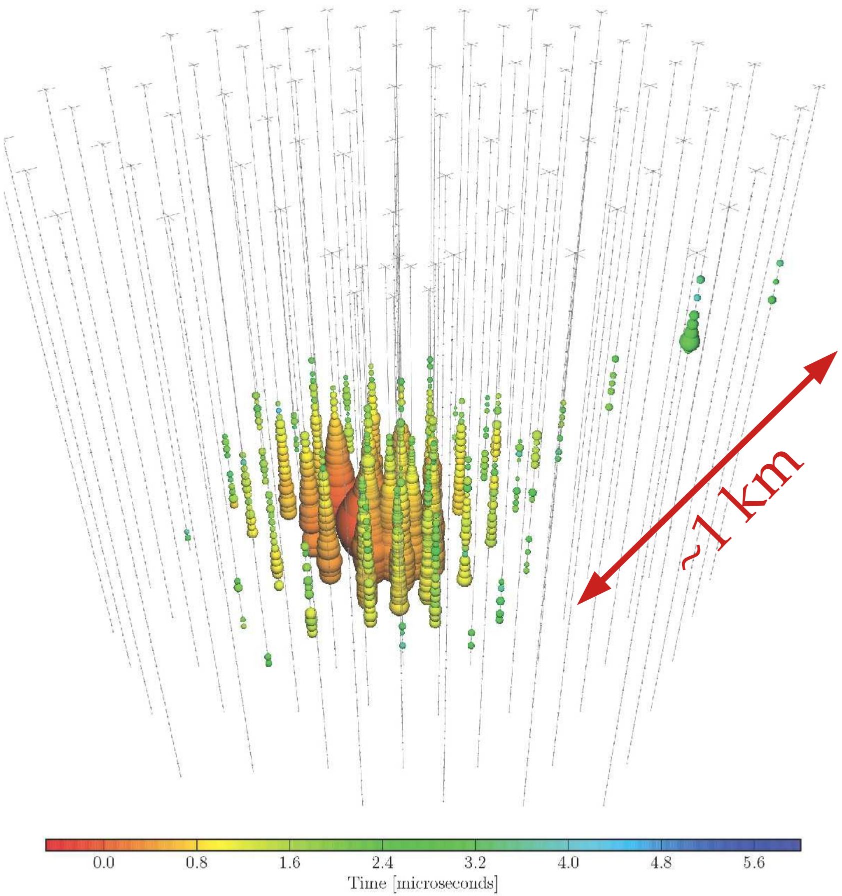
At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25–0.30$

Shower
(mainly from ν_e and ν_τ)

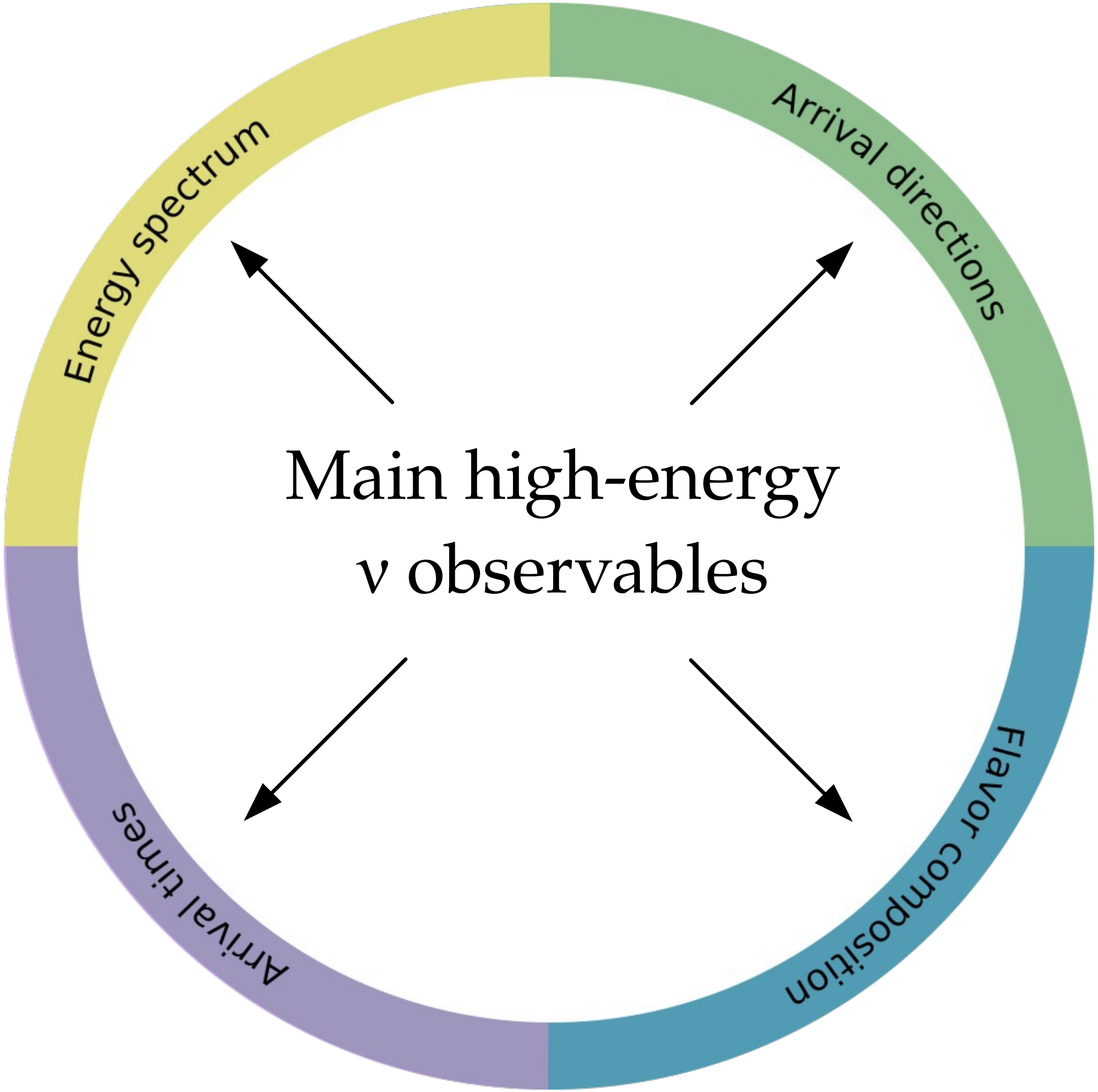


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

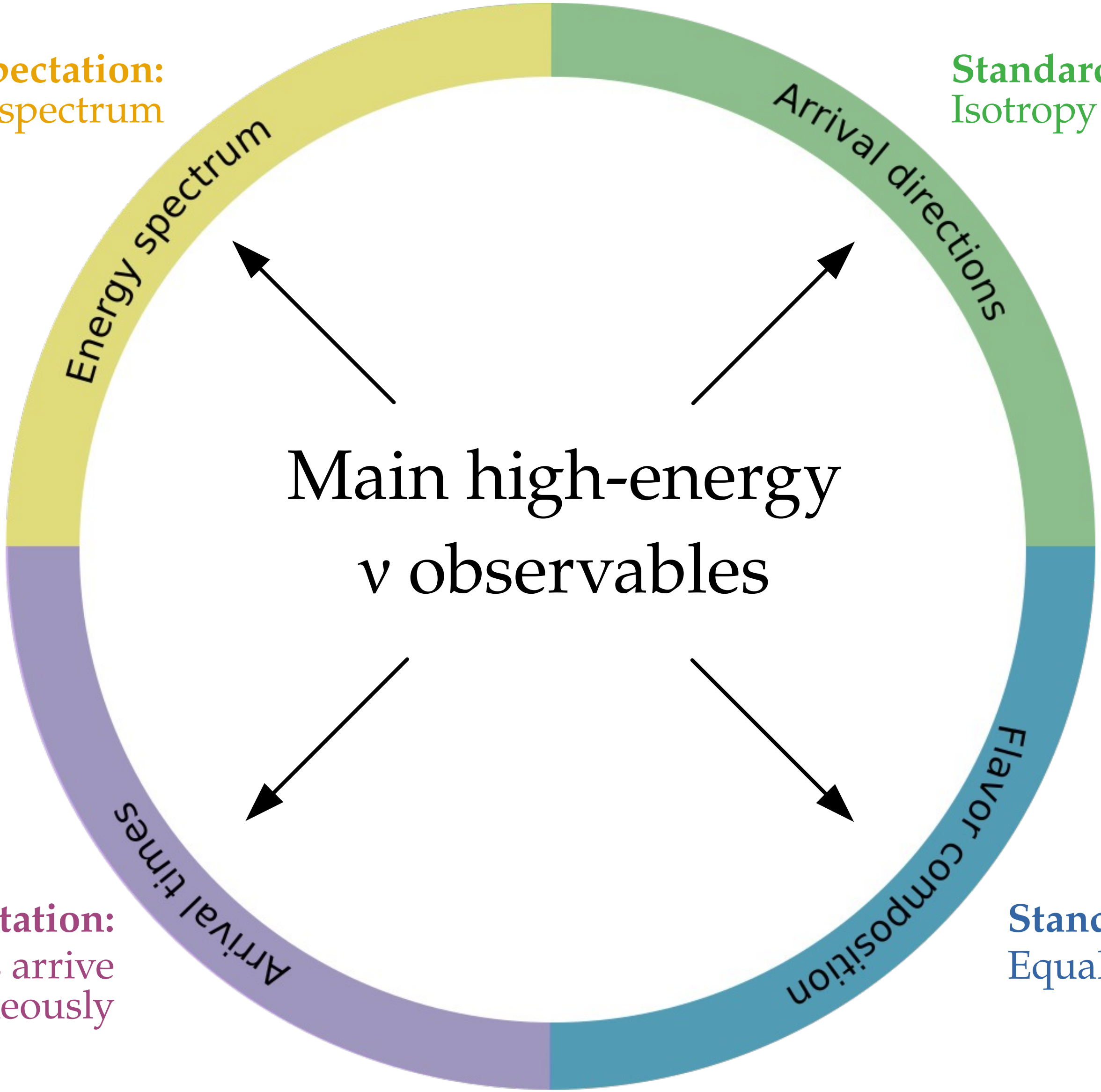


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

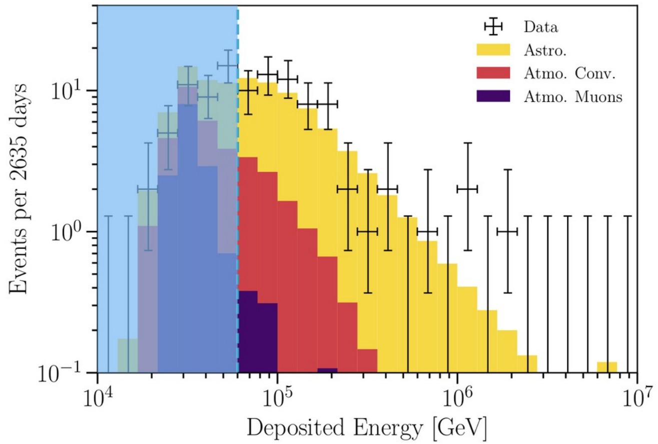


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

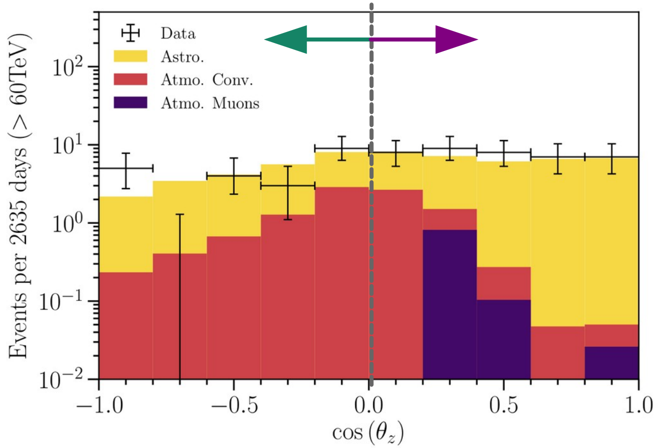
Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



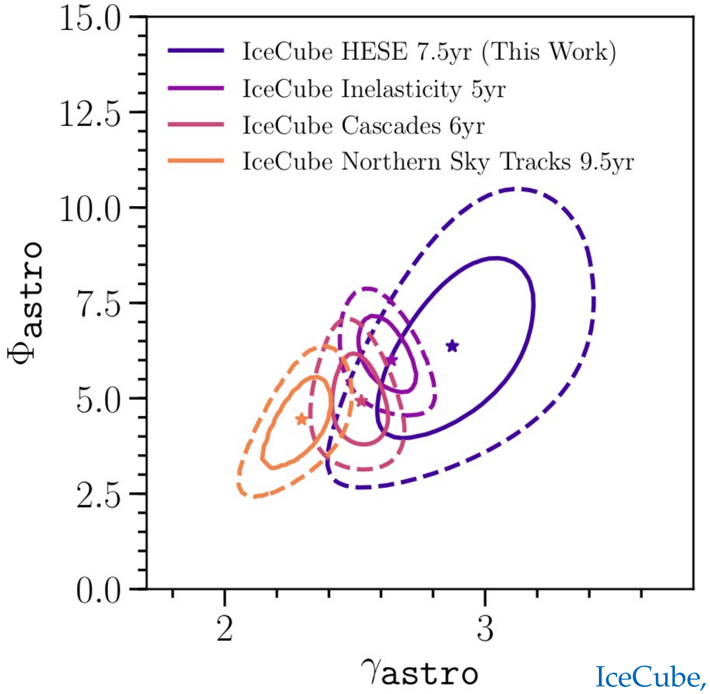
ν attenuated by Earth

Atm. ν and μ vetoed



Data is fit well by a single power law:

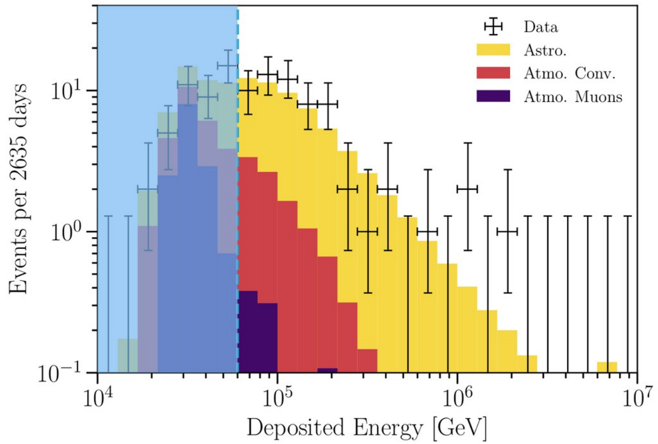
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



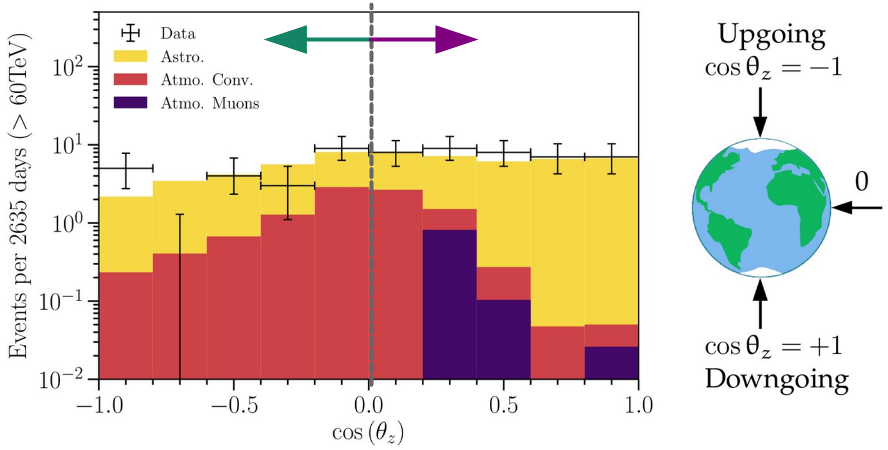
IceCube, 2011.03545

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:



ν attenuated by Earth   Atm. ν and μ vetoed



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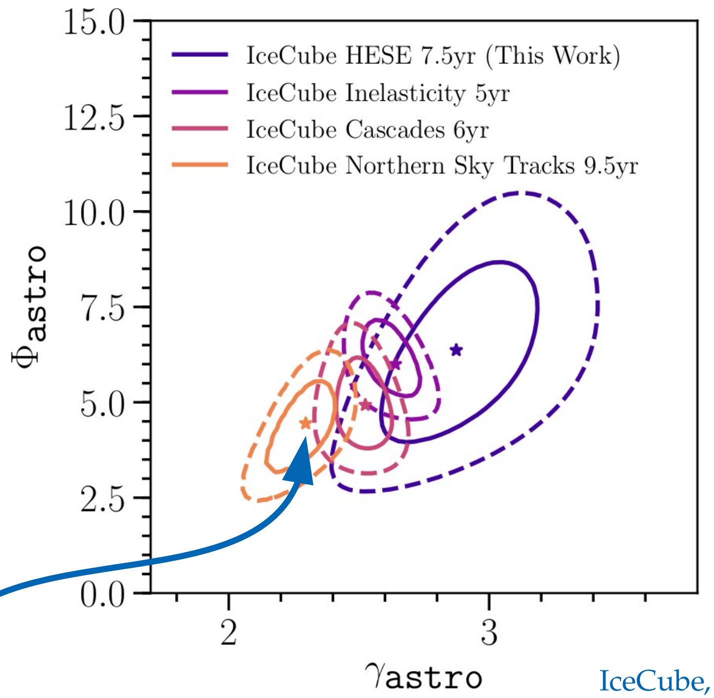
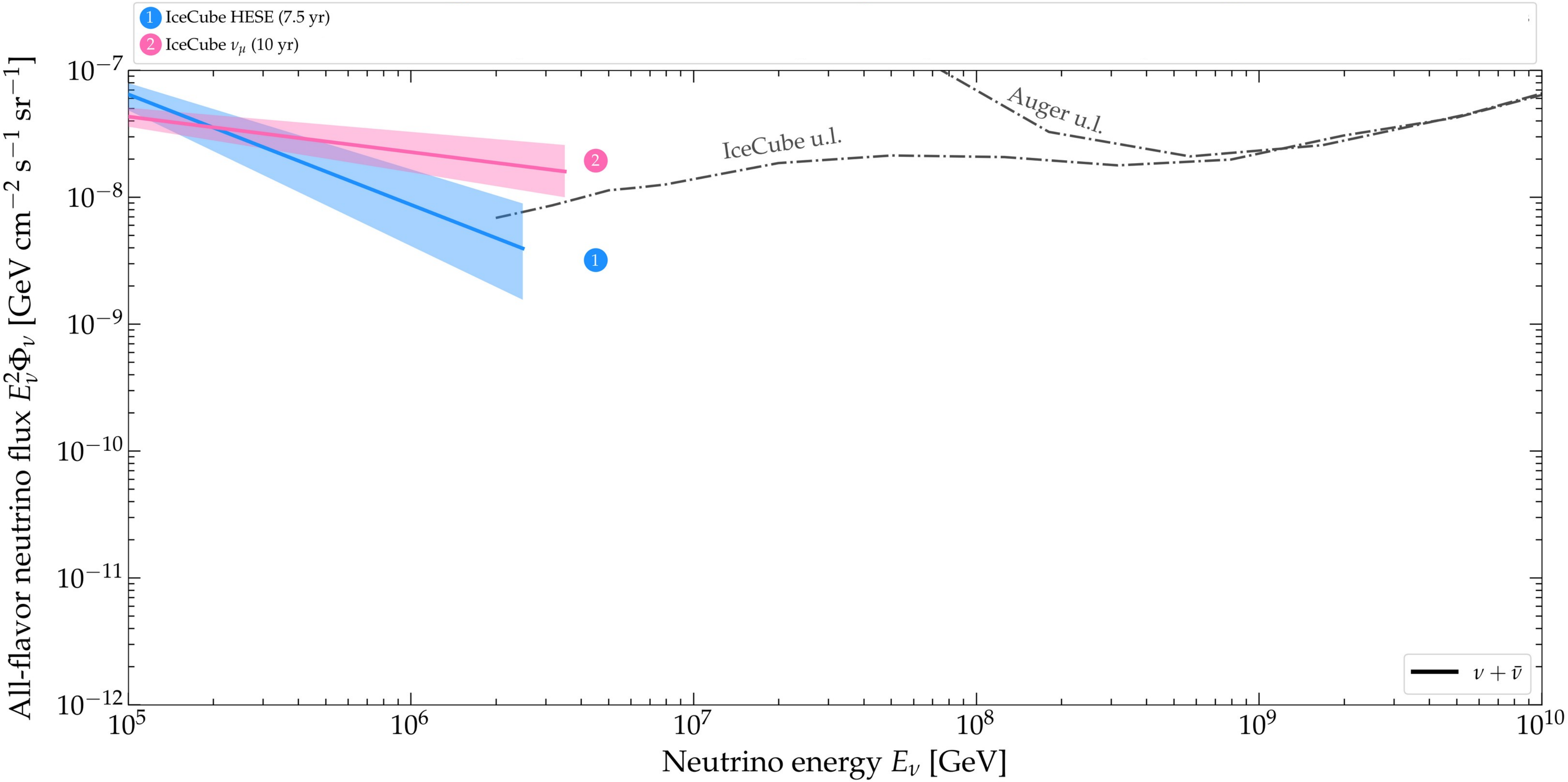


IceCube, 2011.03545

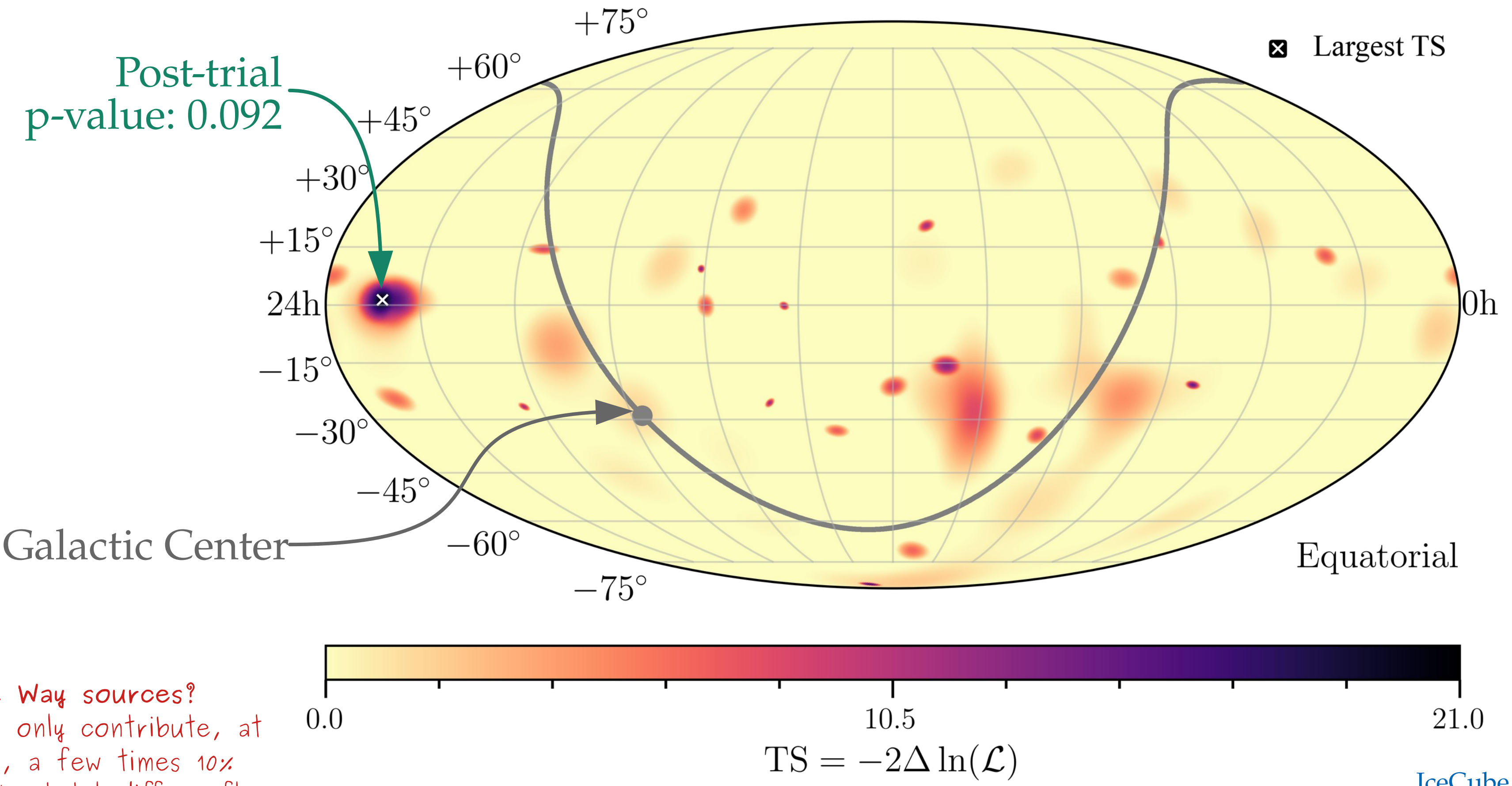
Spectrum looks harder for through-going ν_μ



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

Arrival directions (7.5 yr)

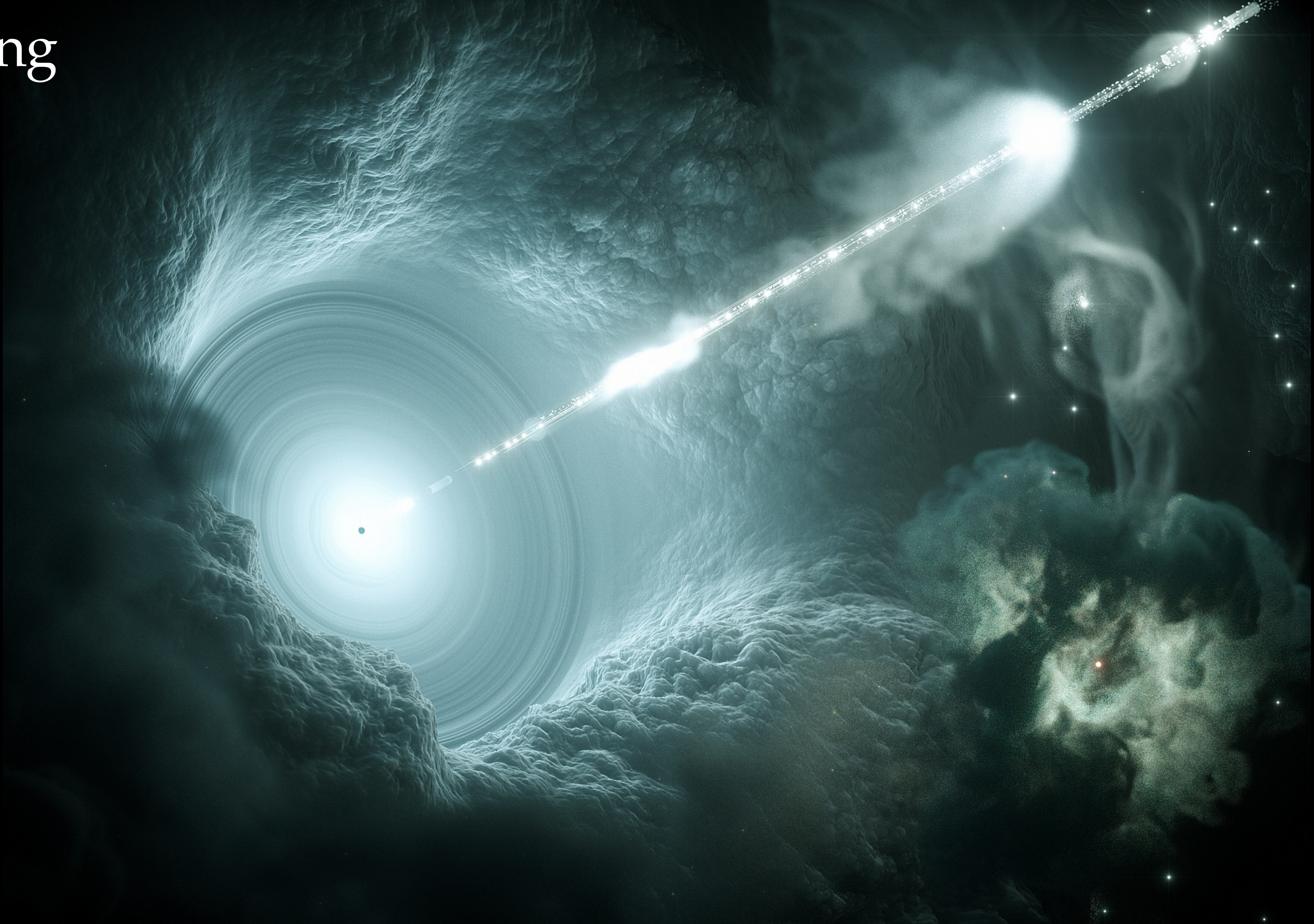
No significant excess in the neutrino sky map:



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

IceCube, 2011.03545

Timing

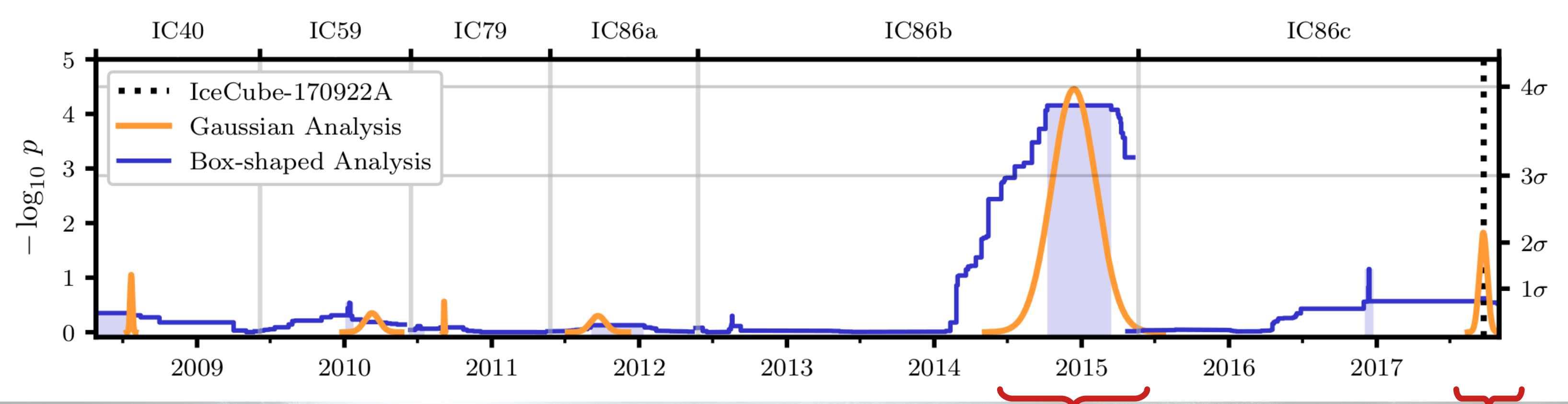


DESY

Timing

Blazar TXS 0506+056:

IceCube, *Science* 2018

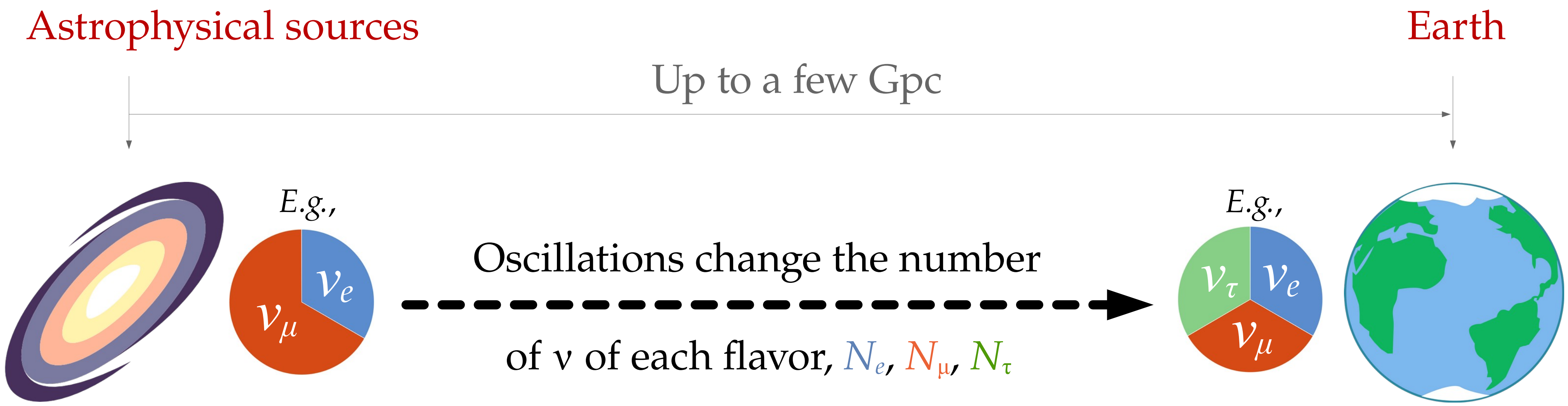


After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

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

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

Combined (pre-trial): 4.1σ

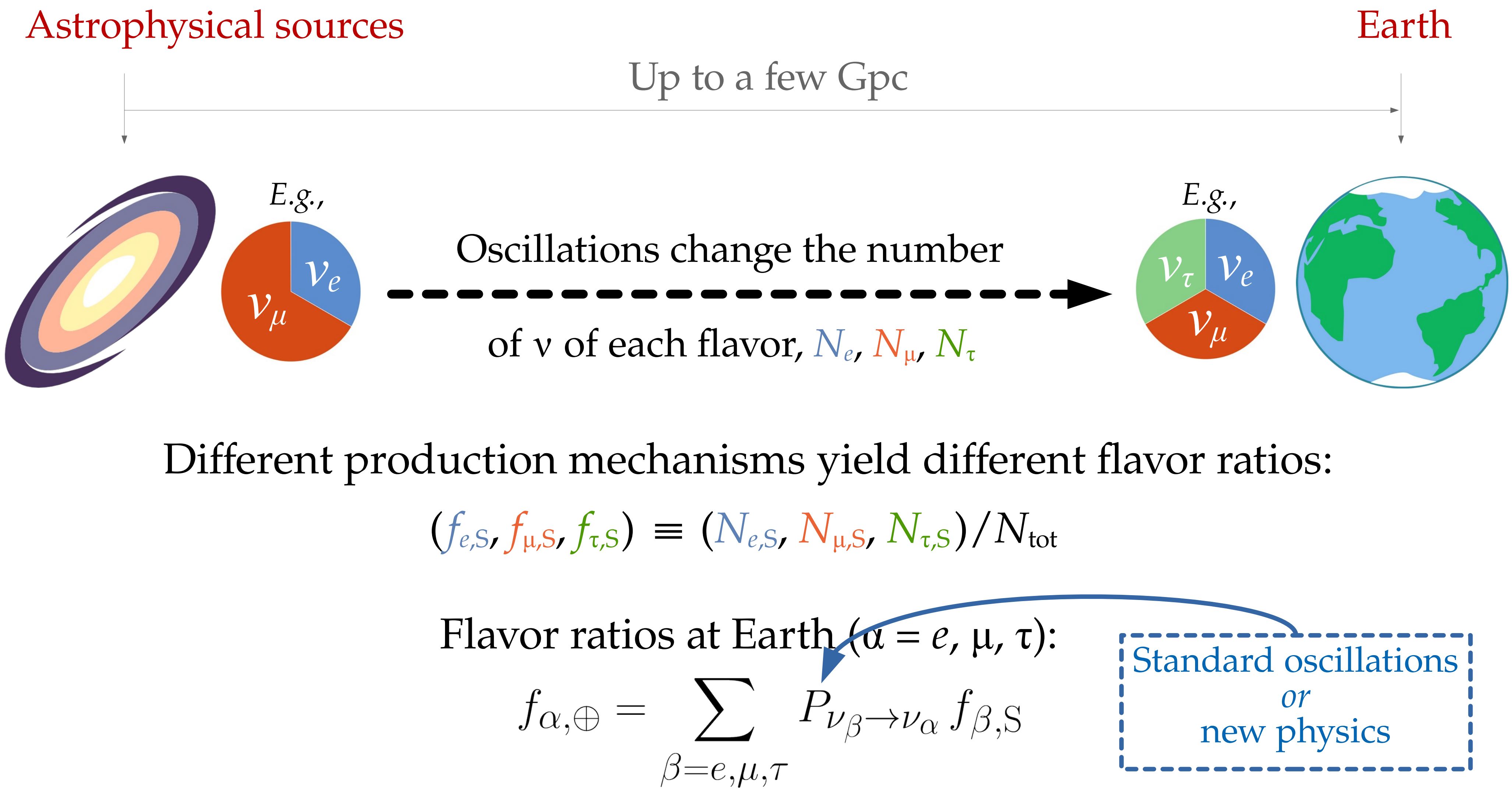


Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics

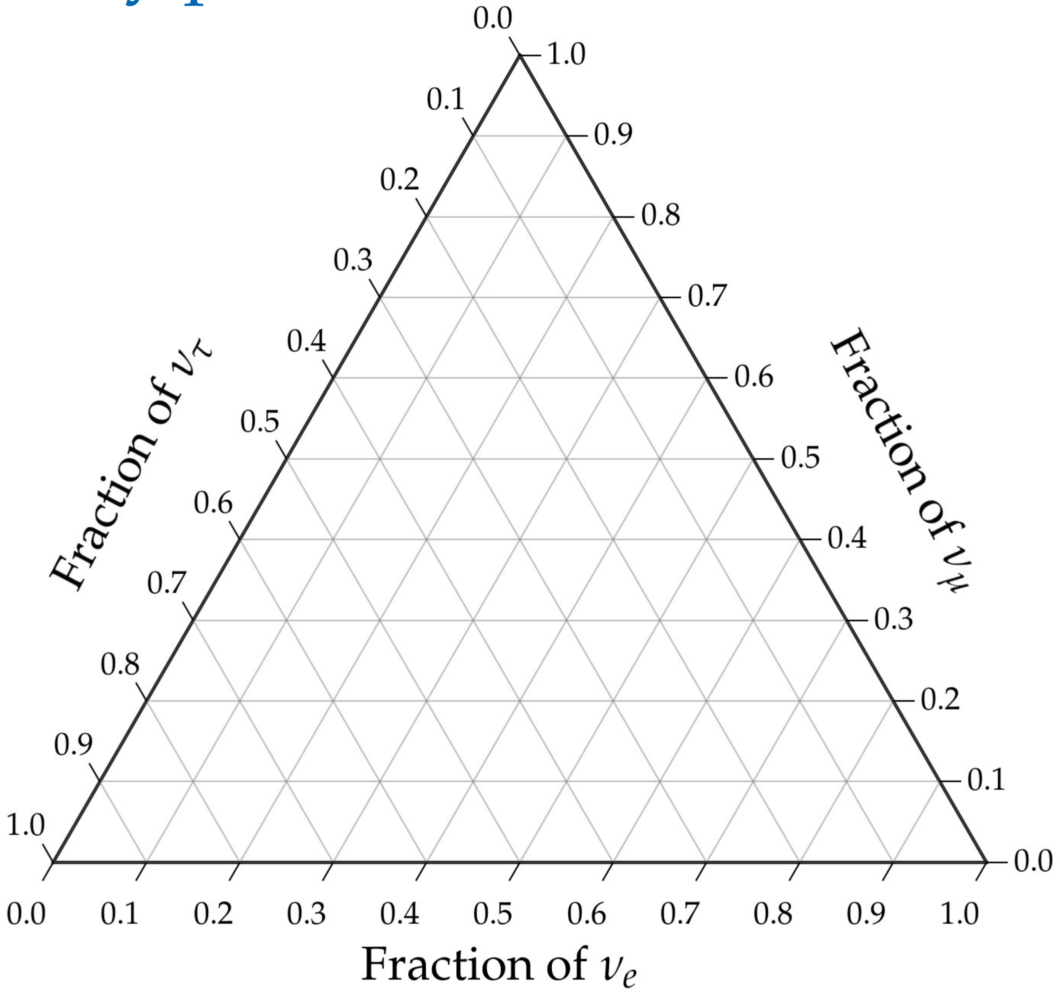
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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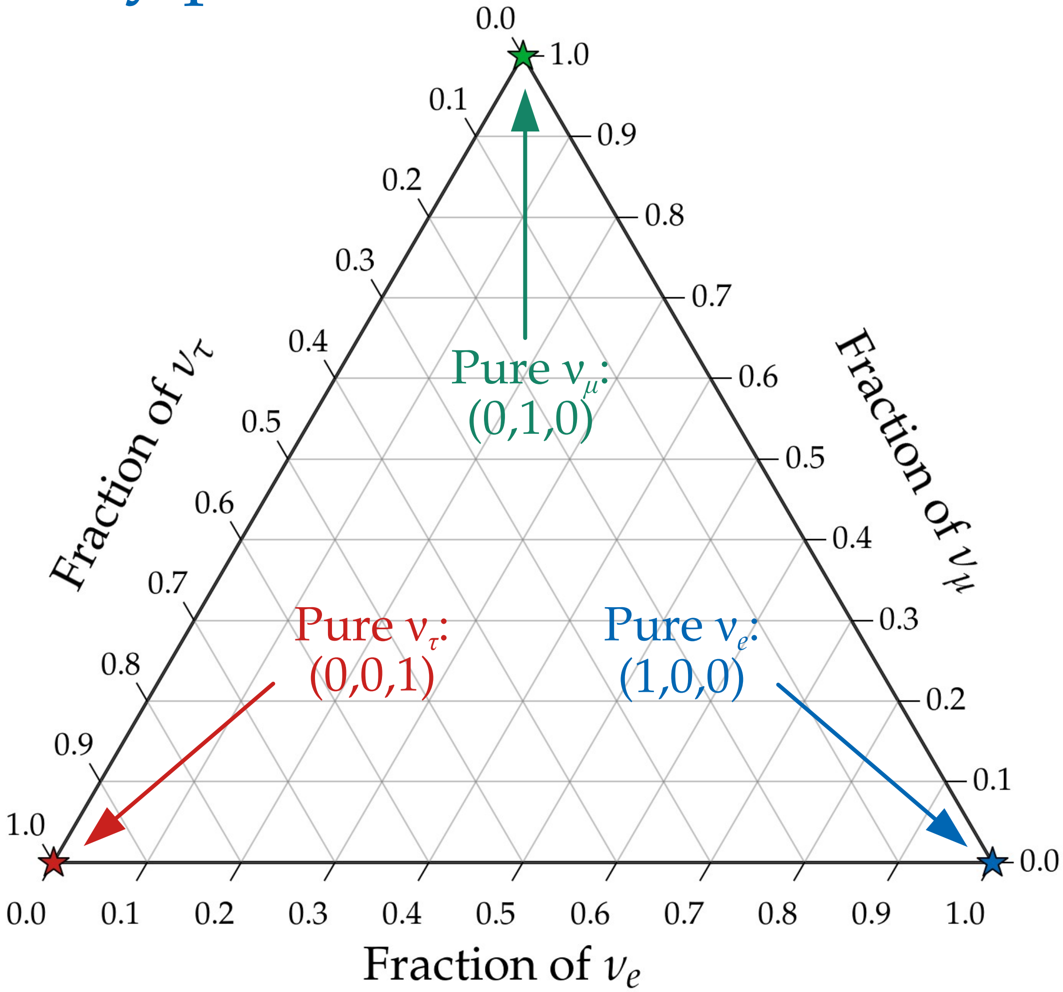

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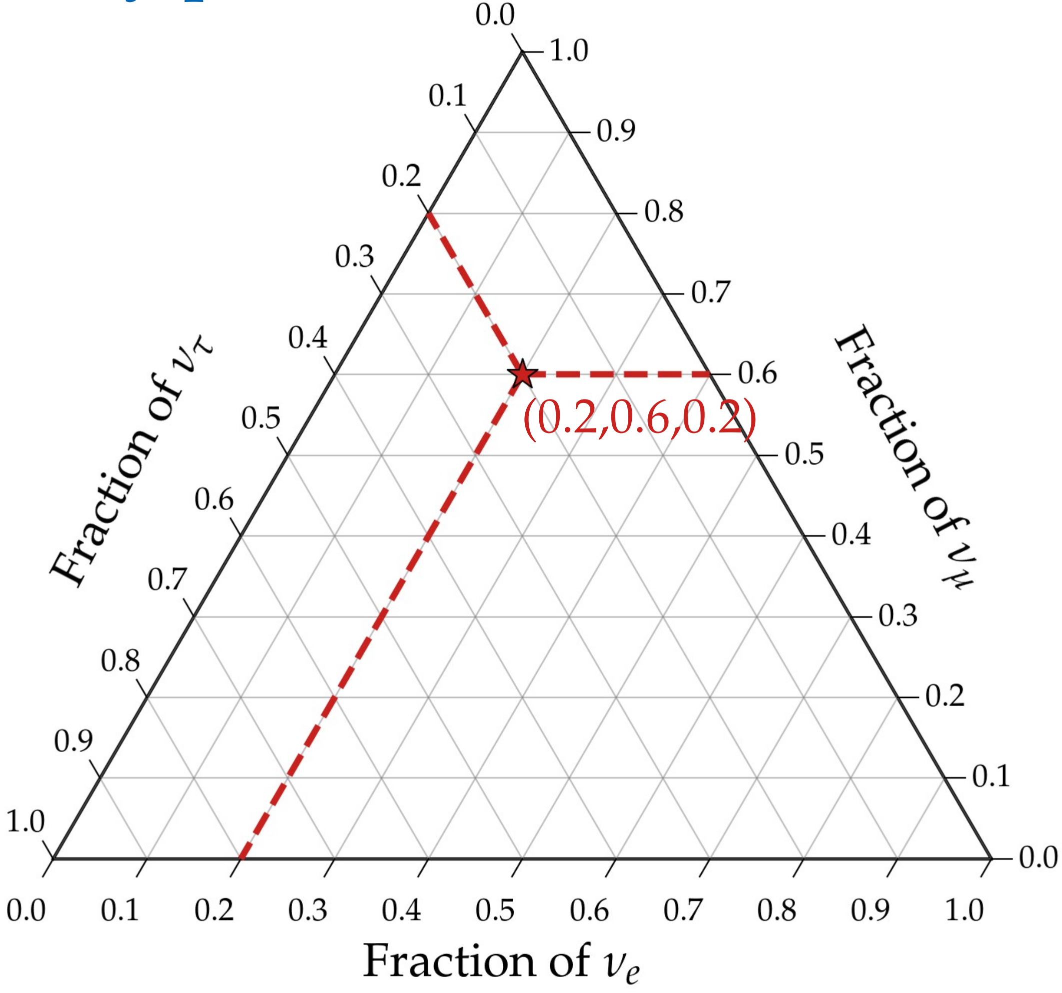

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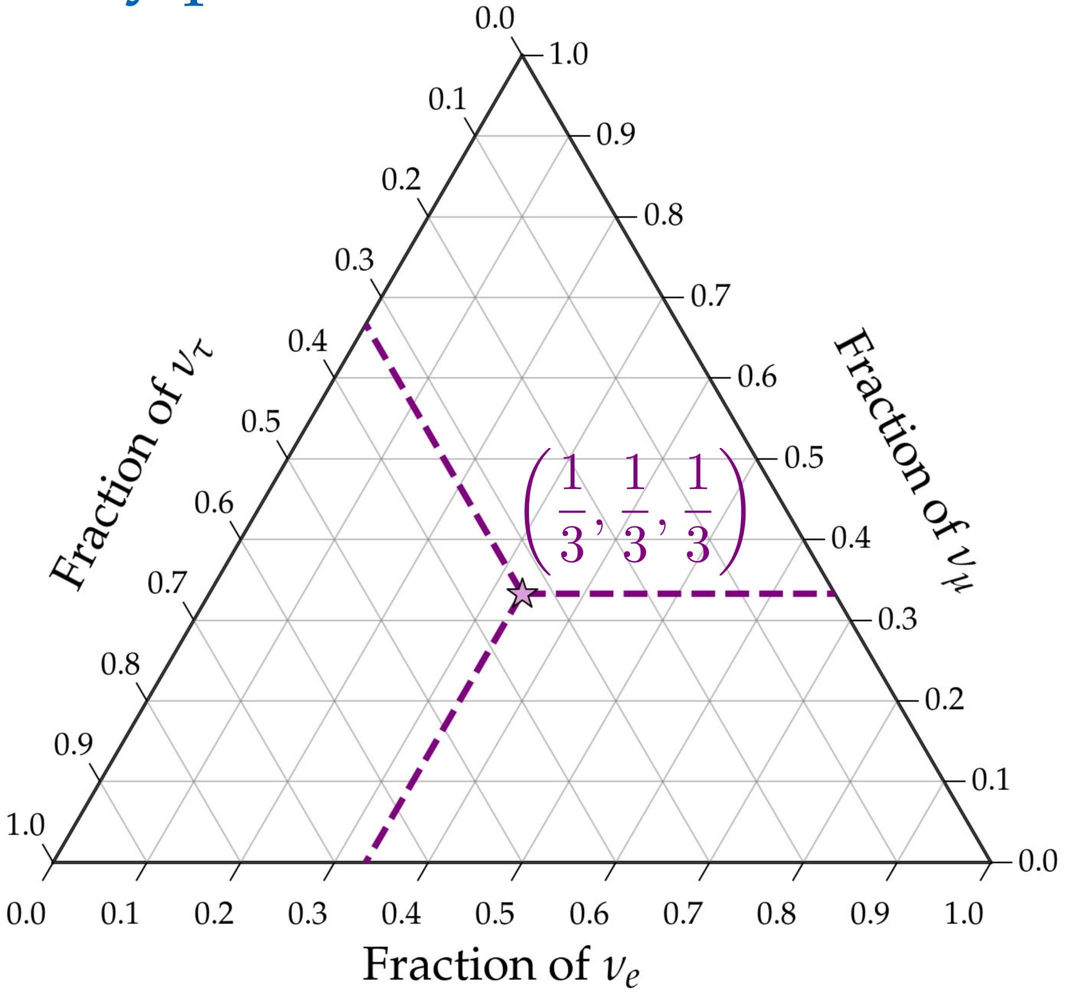

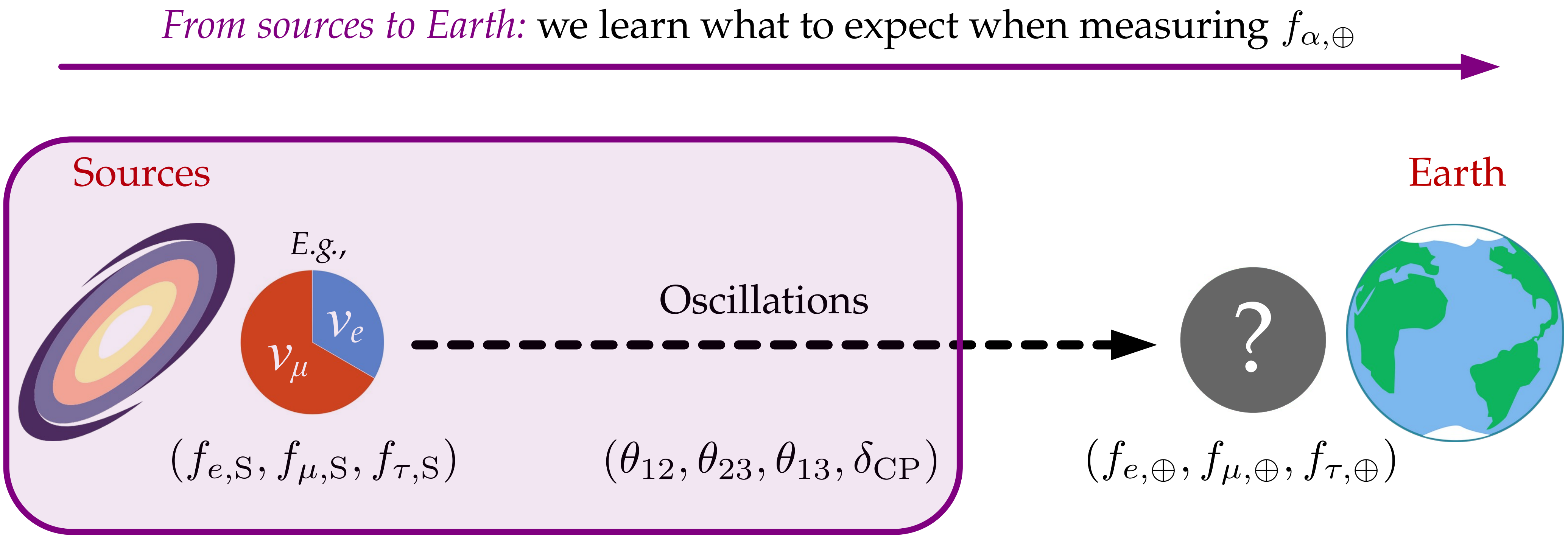

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
E.g.,
ν_e
ν_μ
Oscillations
Earth
?
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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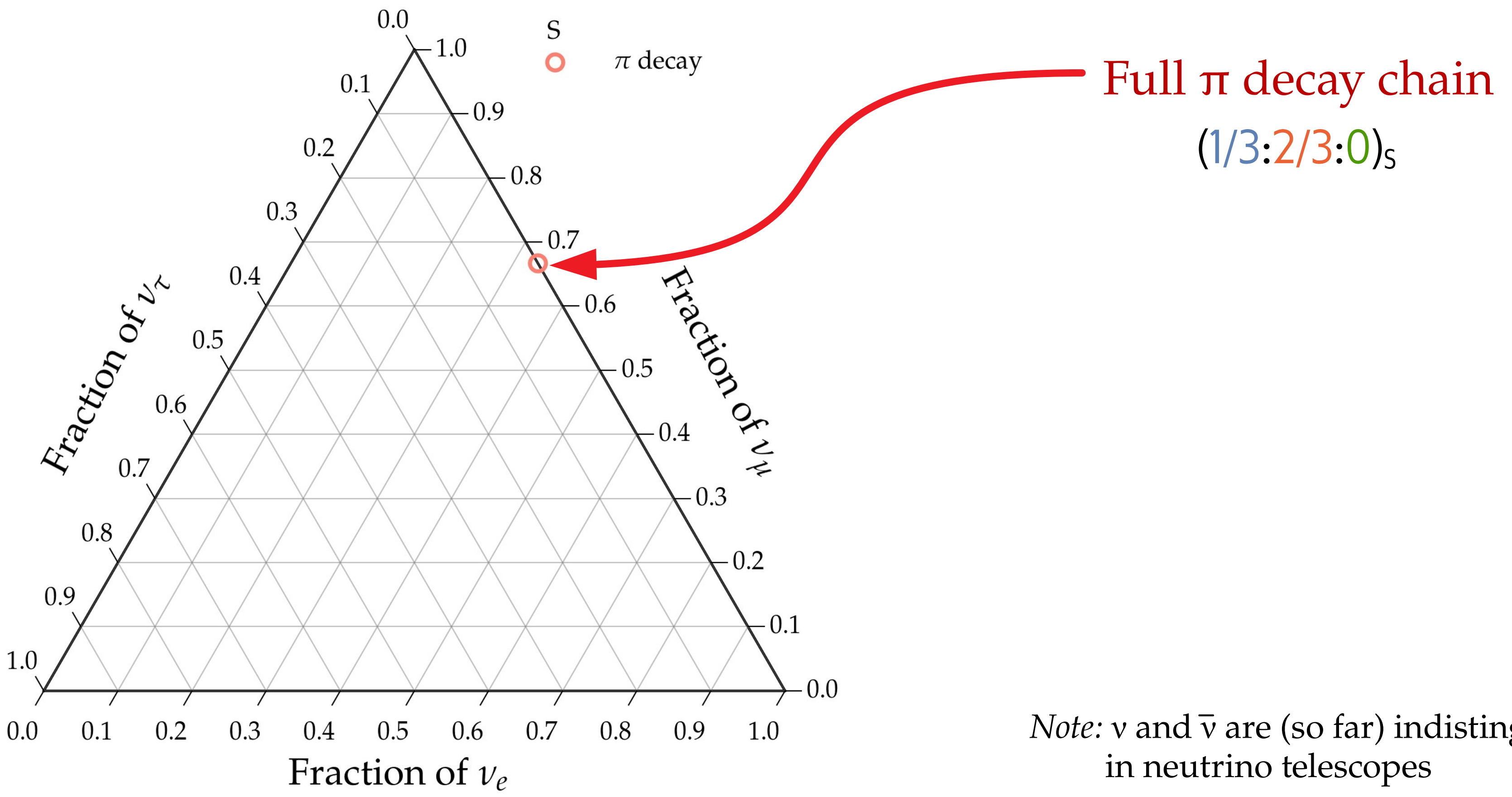

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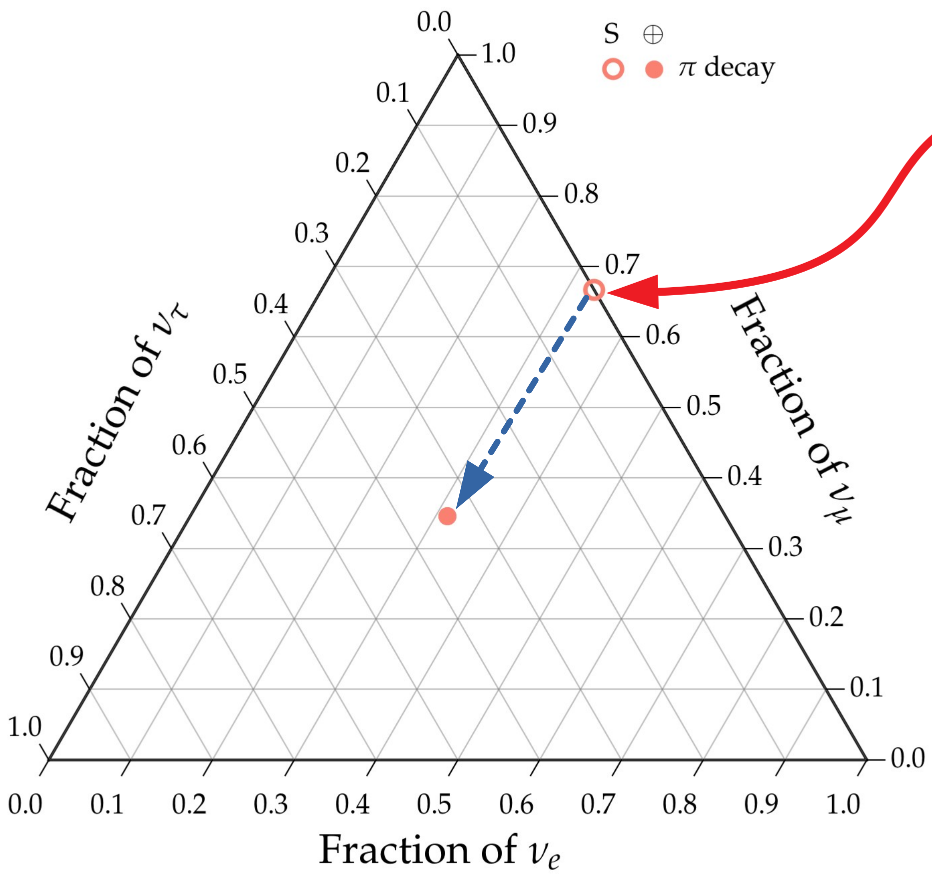

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$(1/3 : 2/3 : 0)_S$

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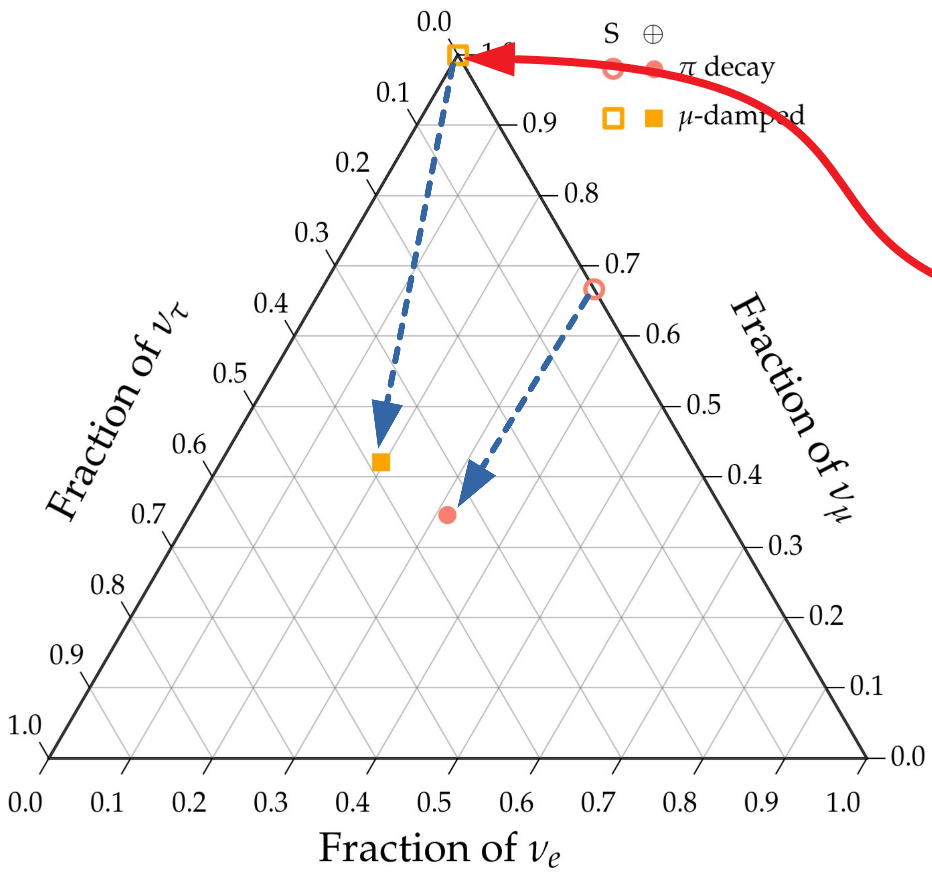

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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

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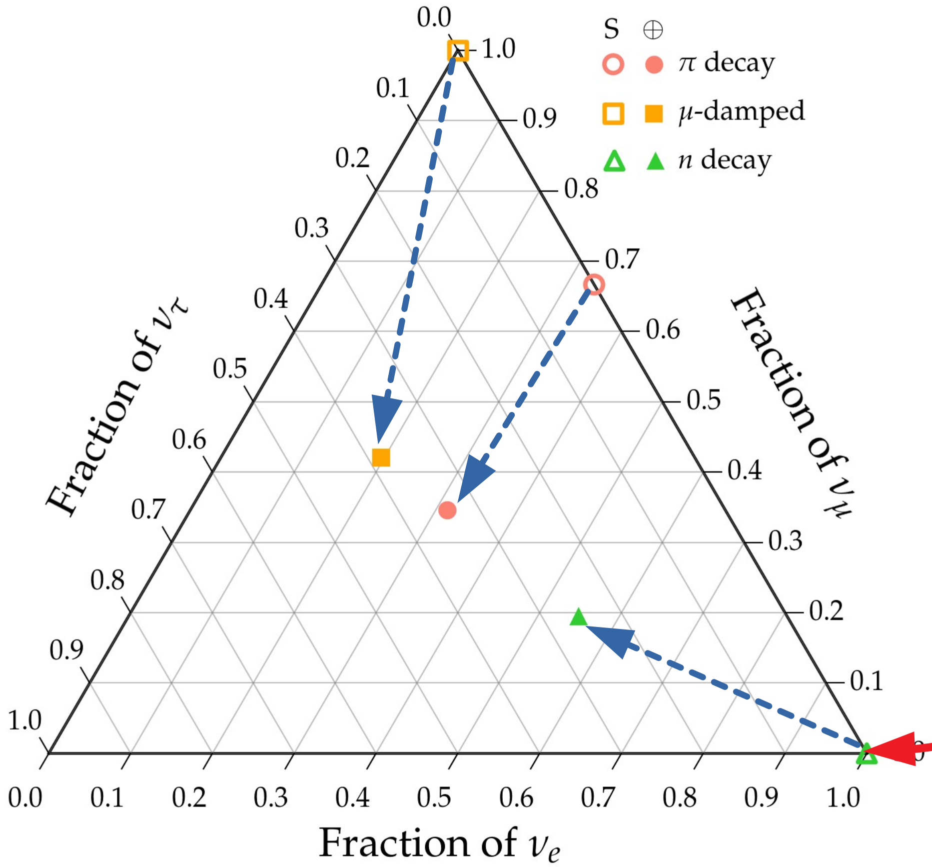
$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



Full π decay chain

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

Muon damped

$(0 : 1 : 0)_S$

Neutron decay

$(1 : 0 : 0)_S$

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

II.
High-energy and ultra-high-energy neutrino physics

Note: Not an exhaustive list

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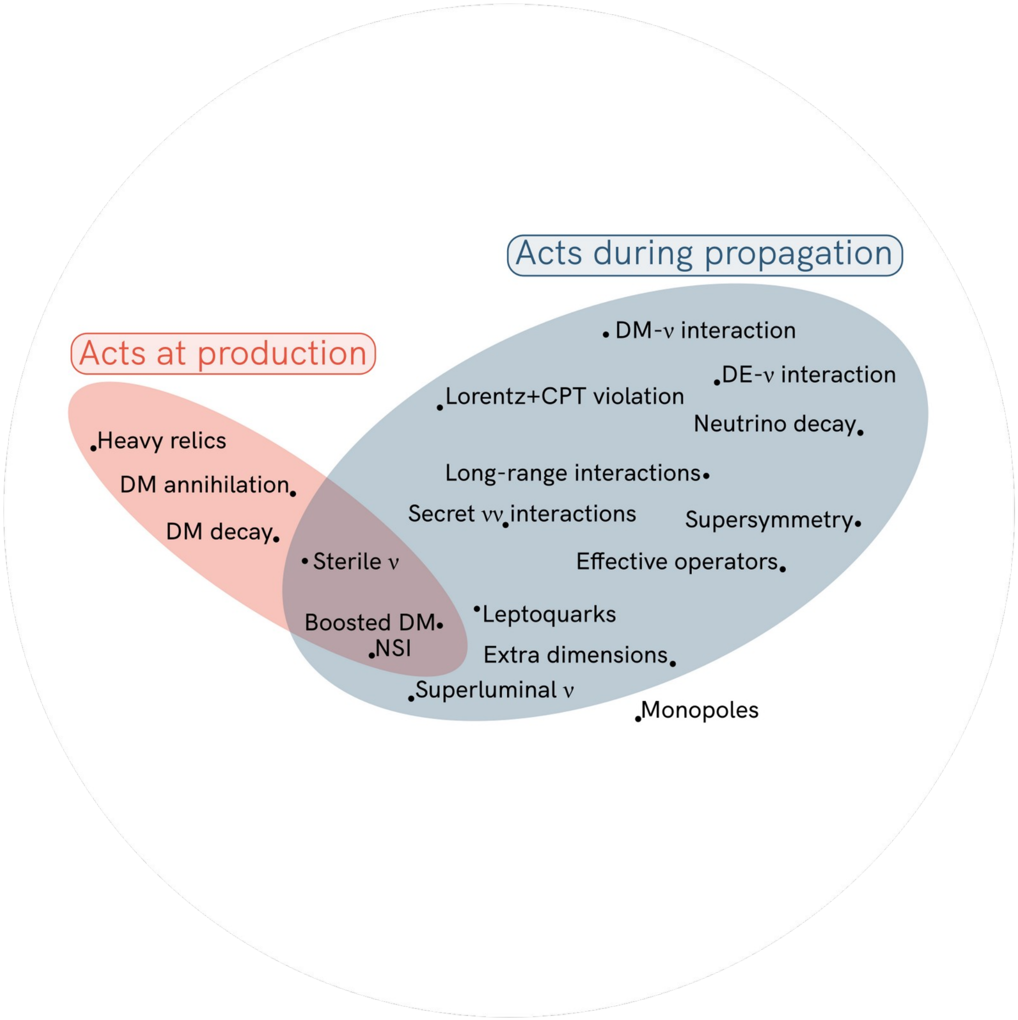

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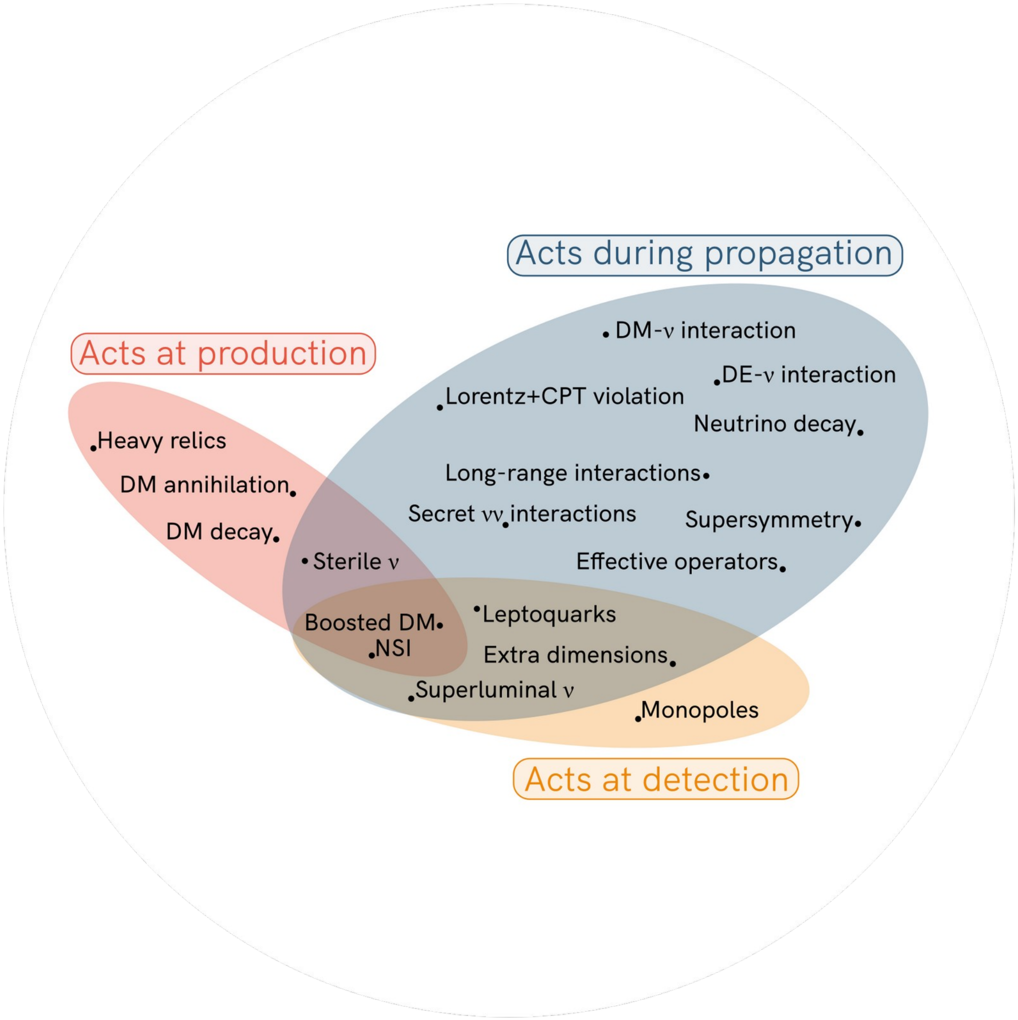

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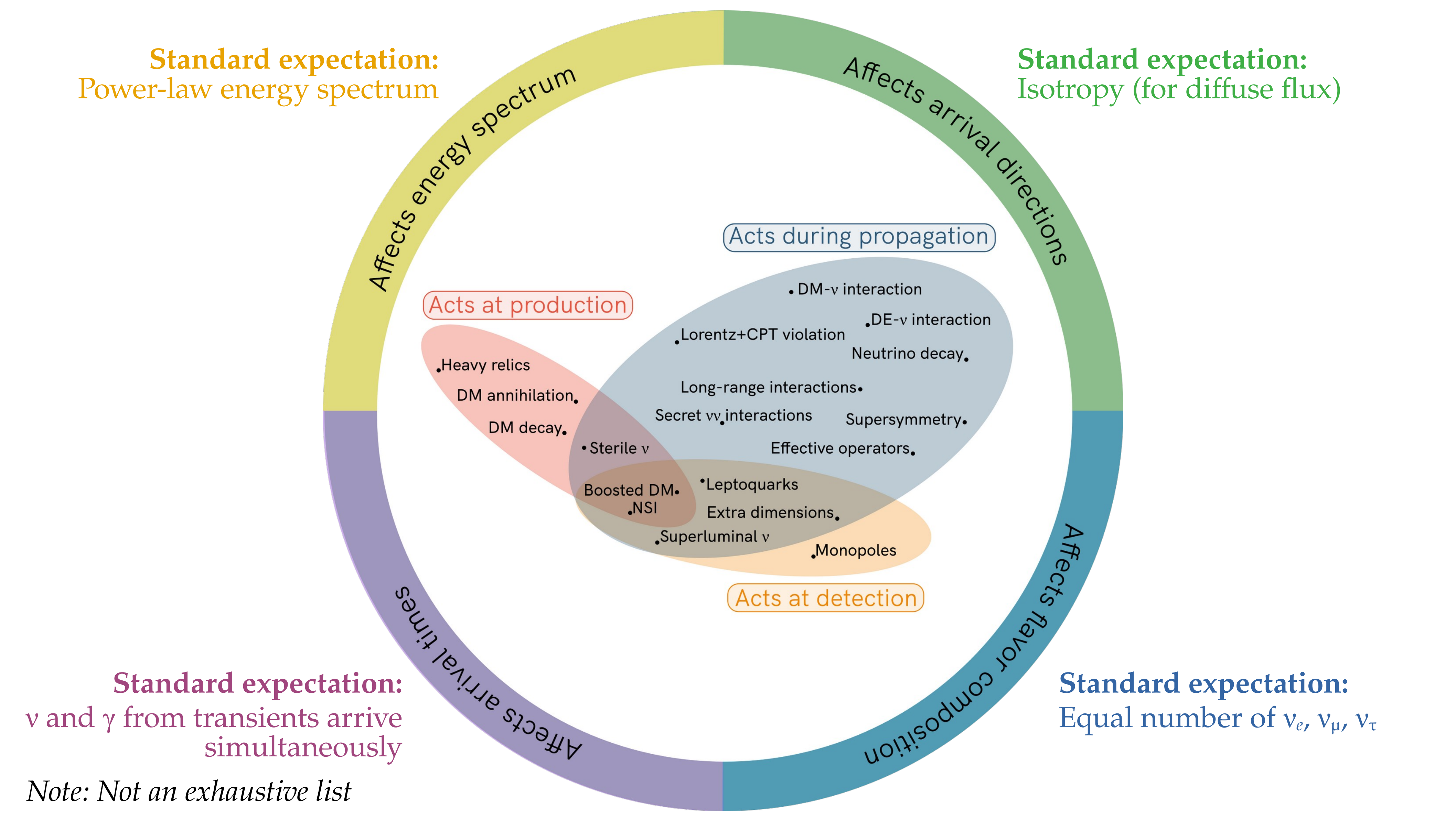
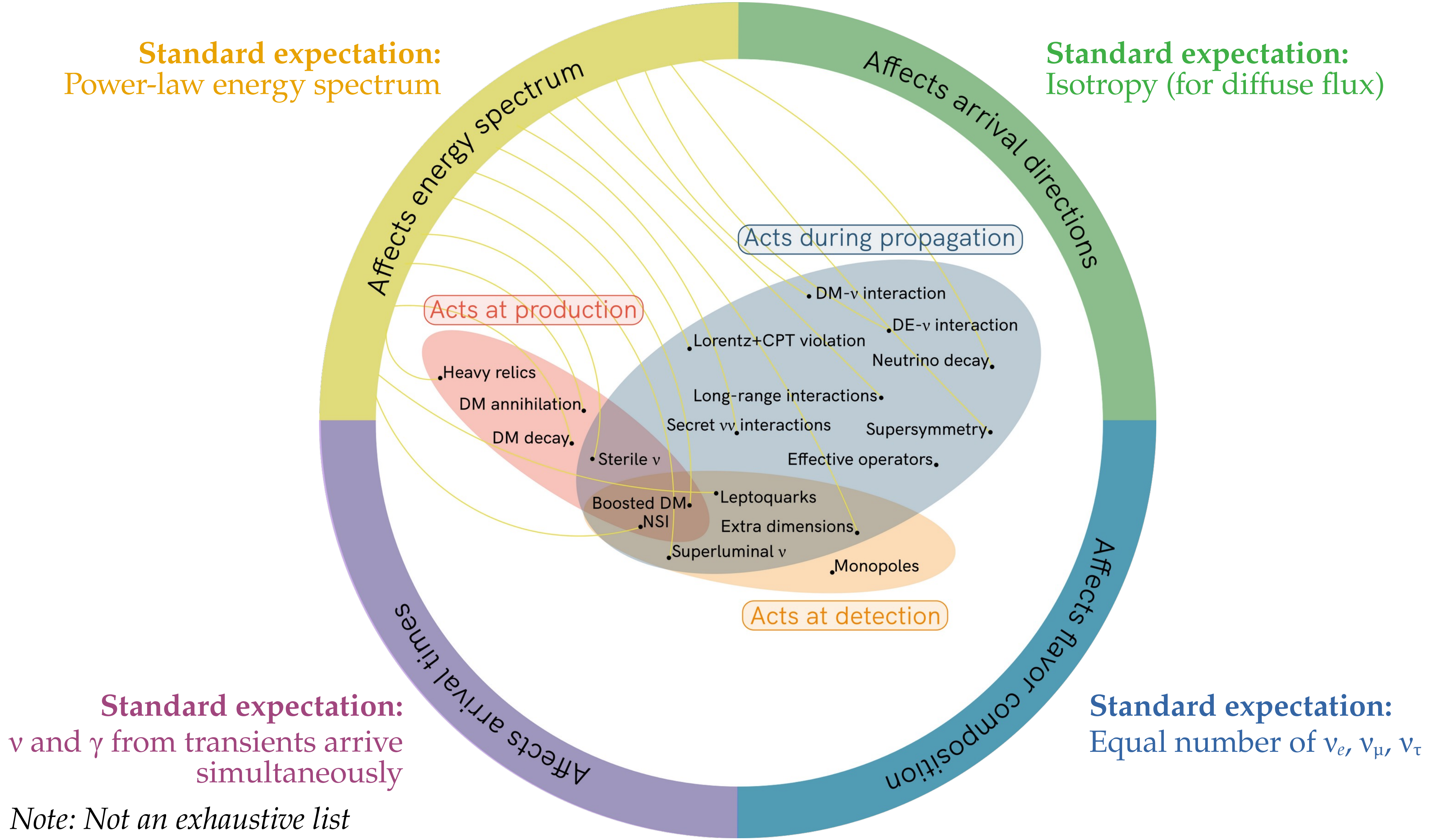


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT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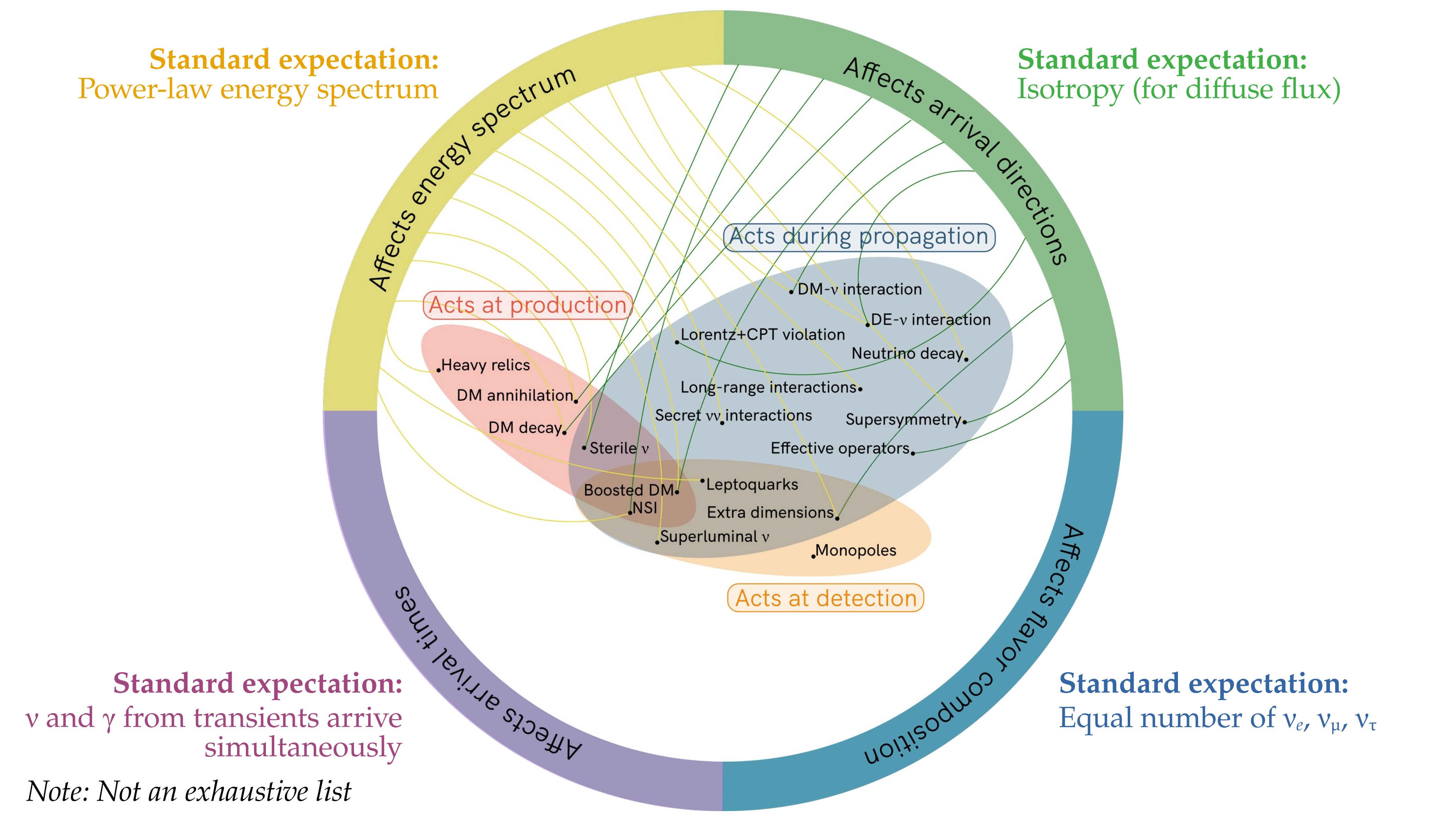
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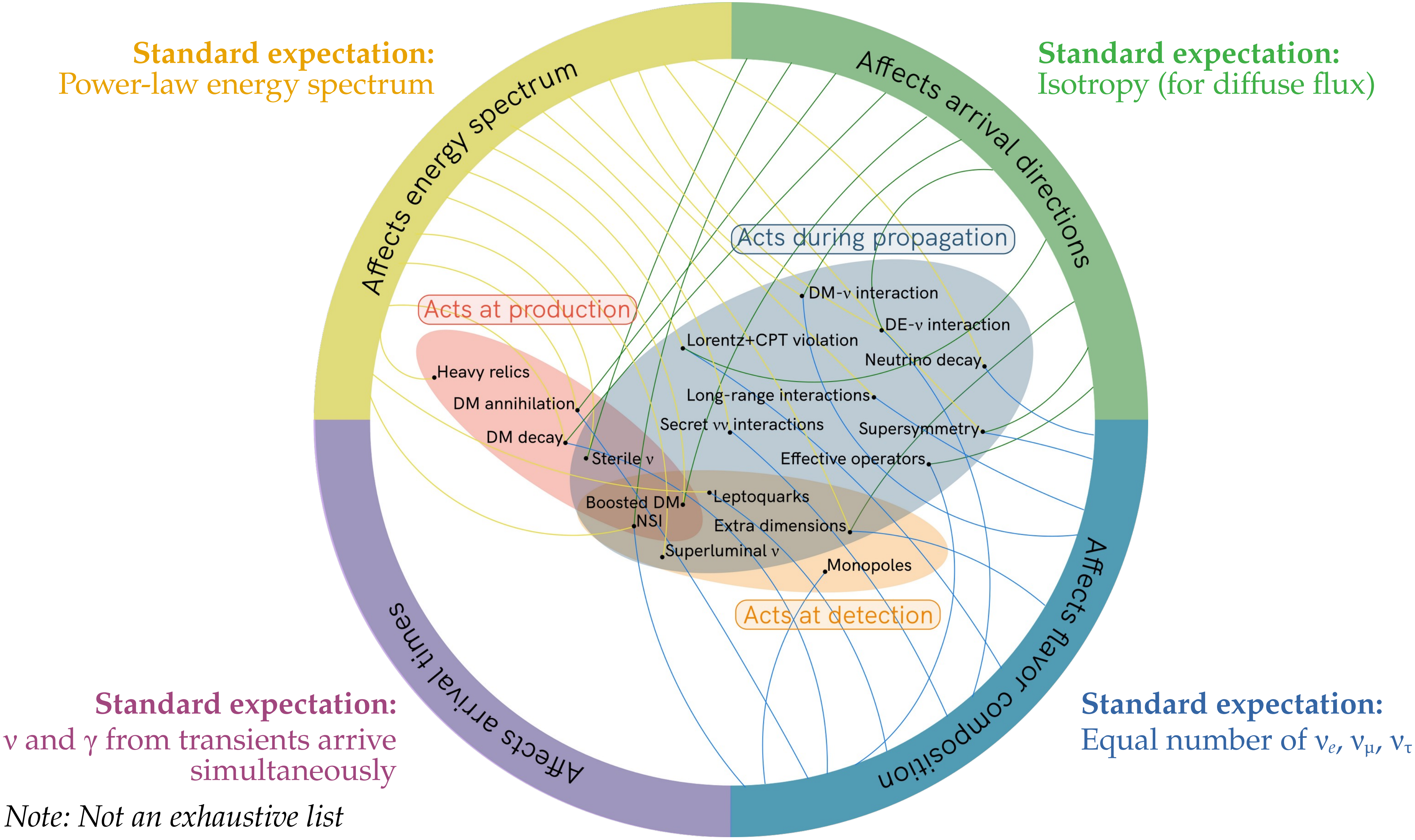

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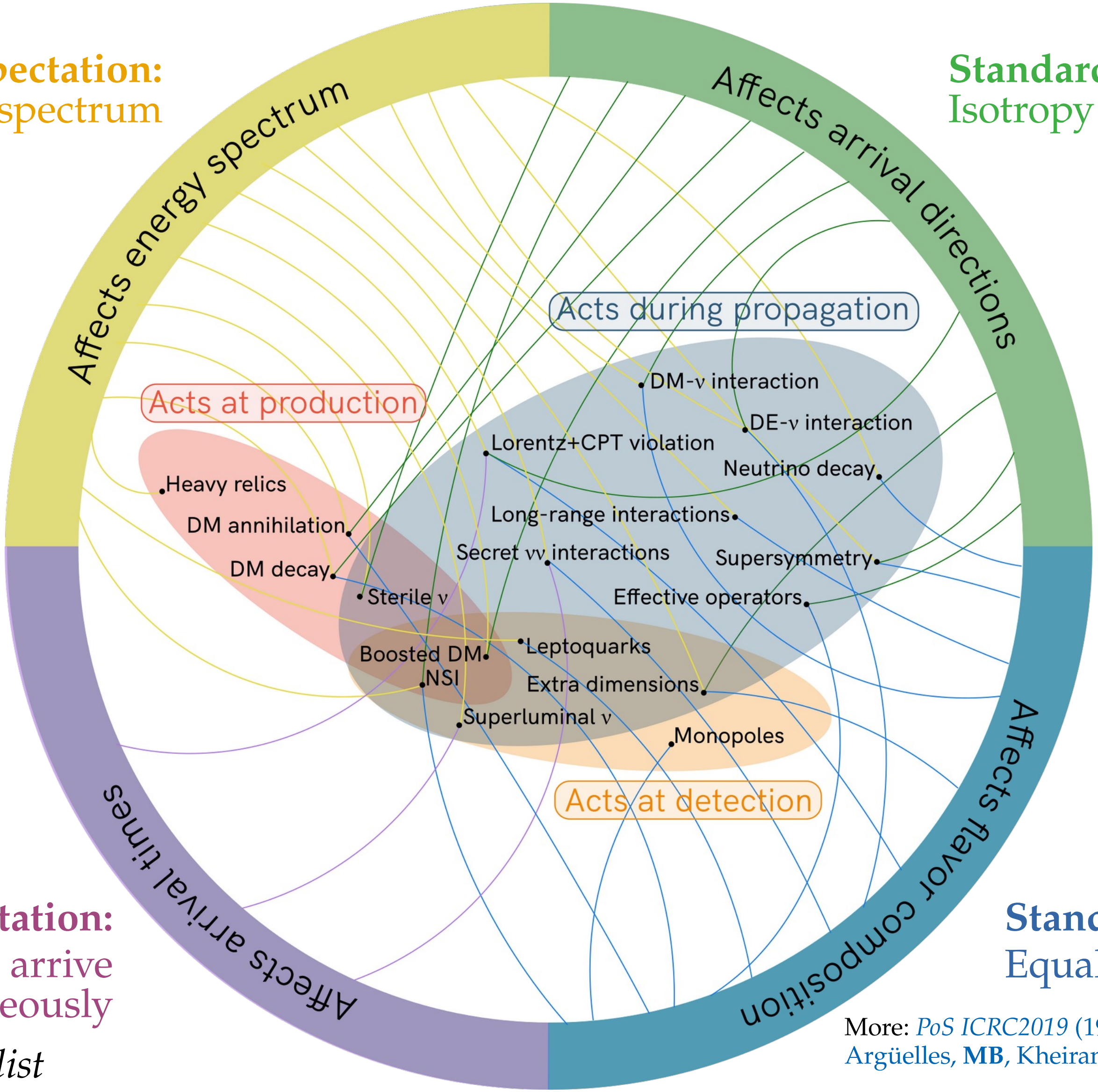

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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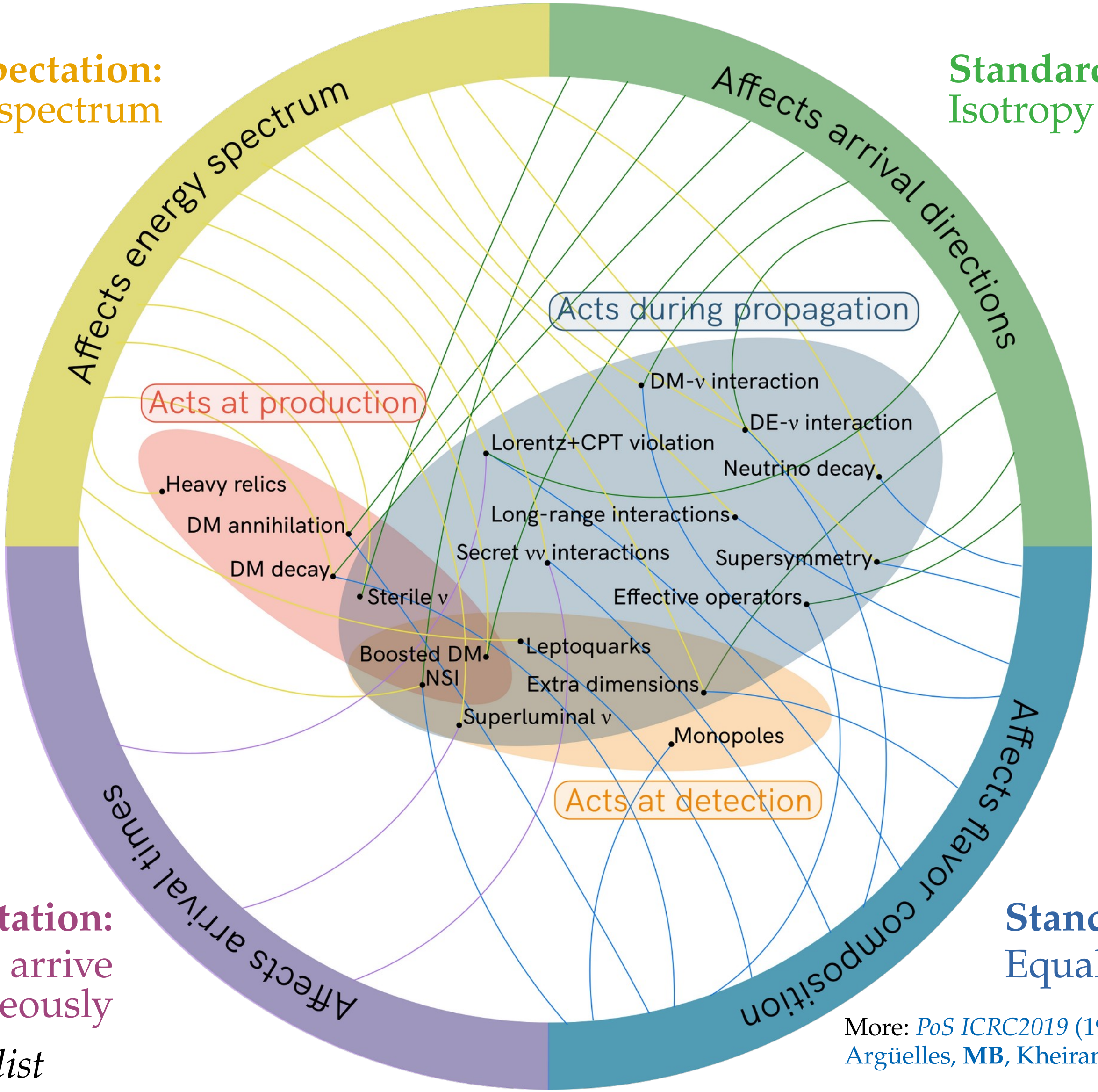

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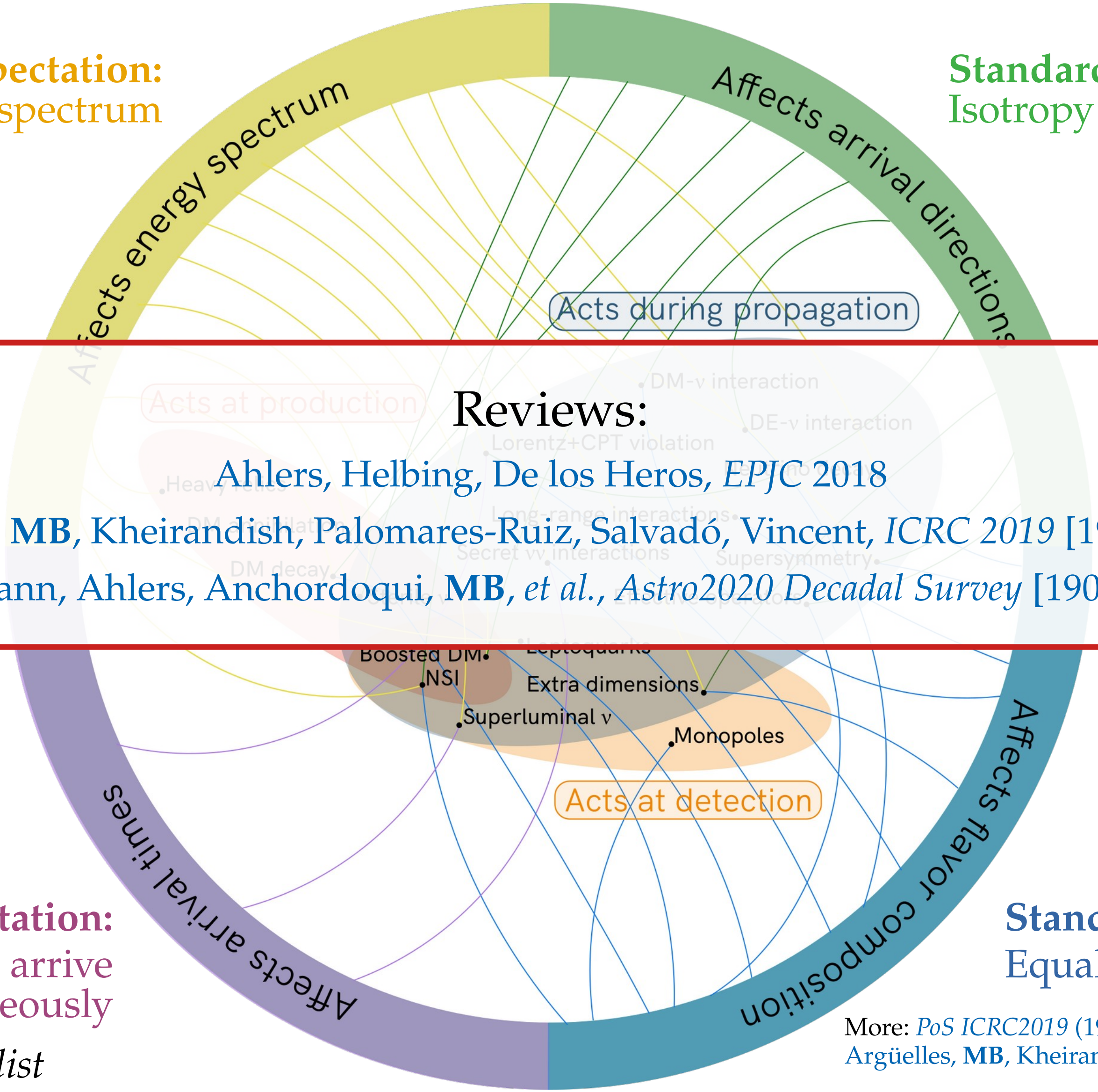

Reviews:

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

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

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

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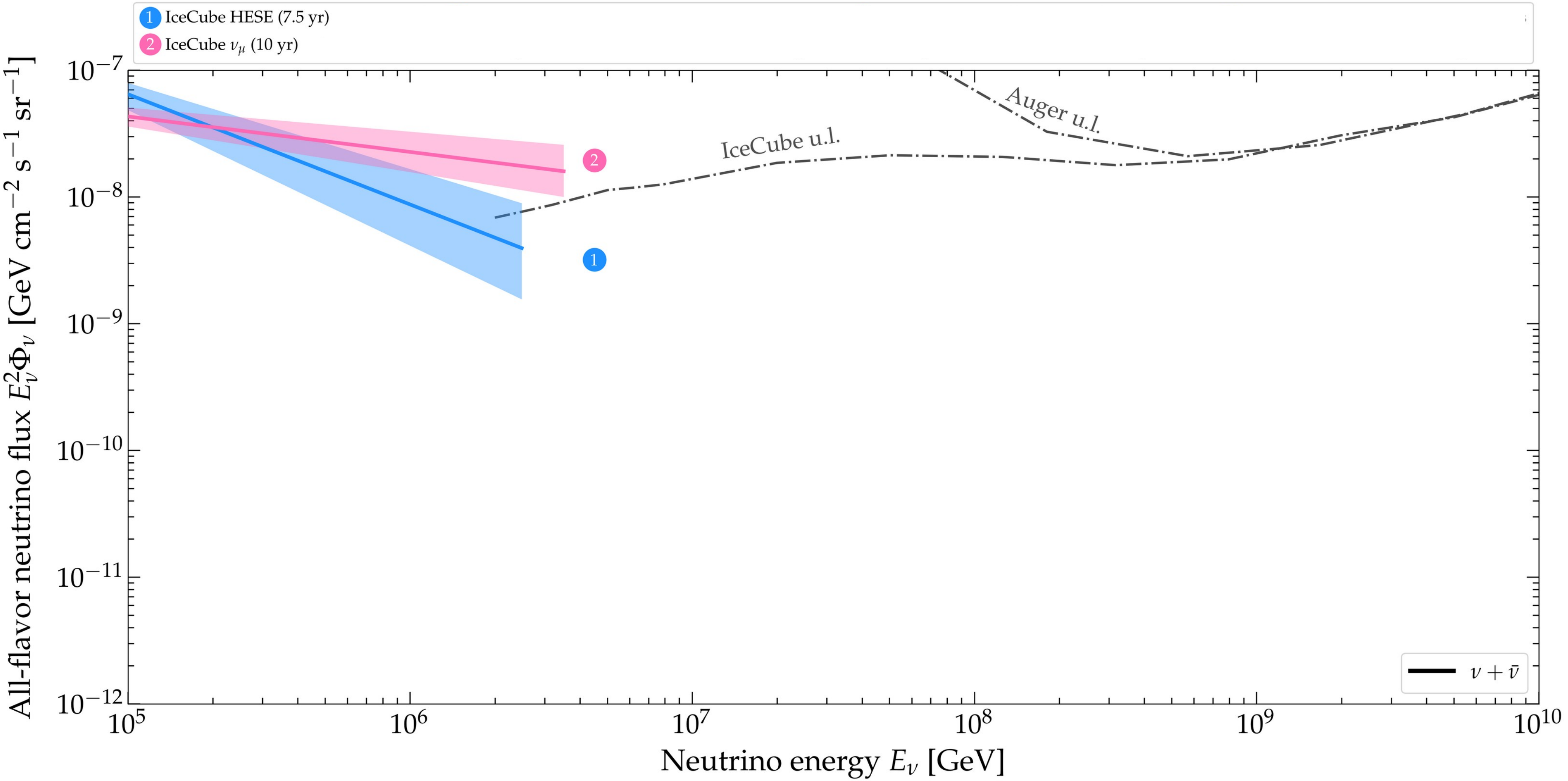

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

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TeV–PeV ν

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TeV–PeV ν

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into data-driven tests

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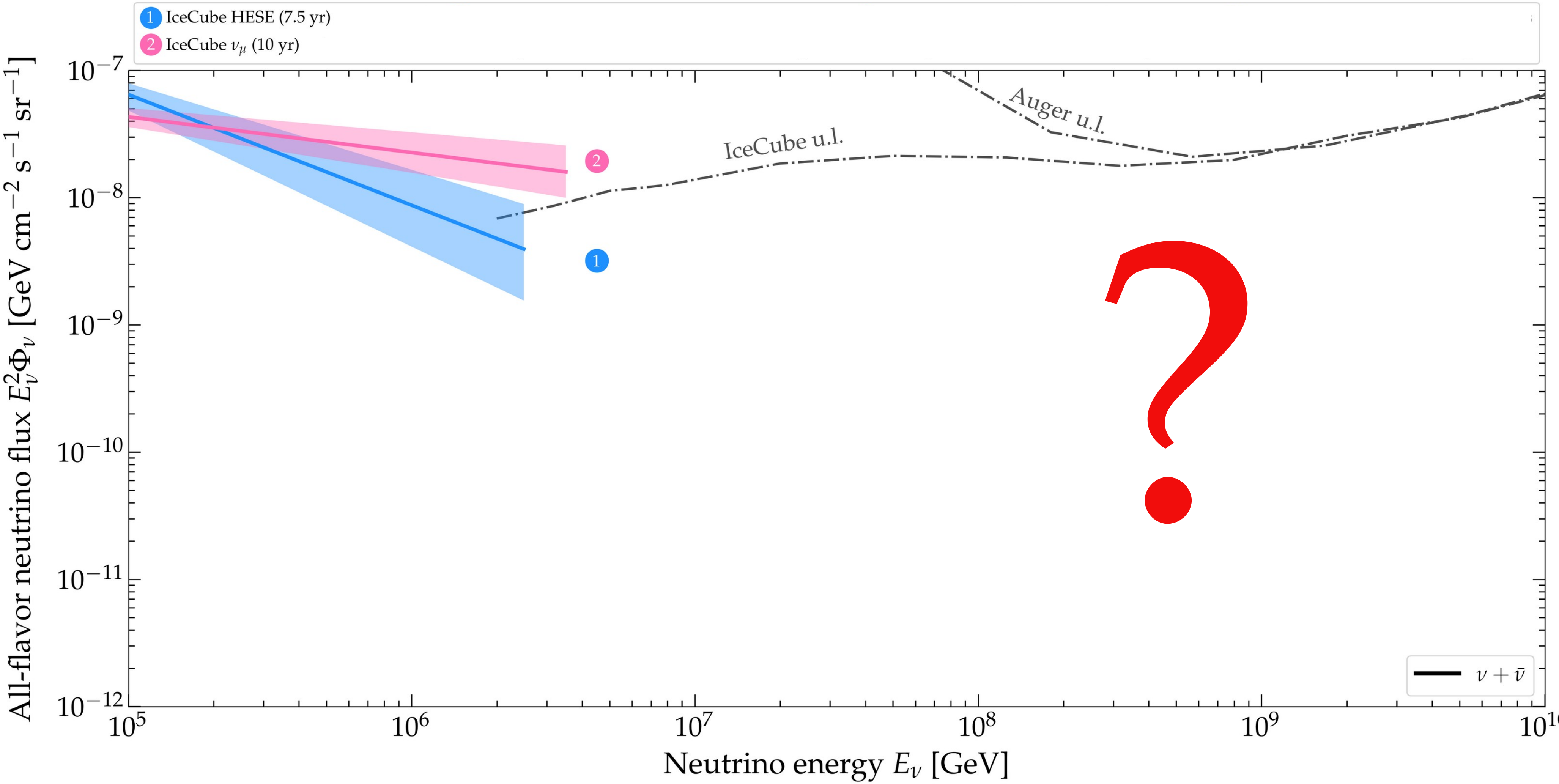
<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties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10^{-11}
10^{-12}
10^5
10^6
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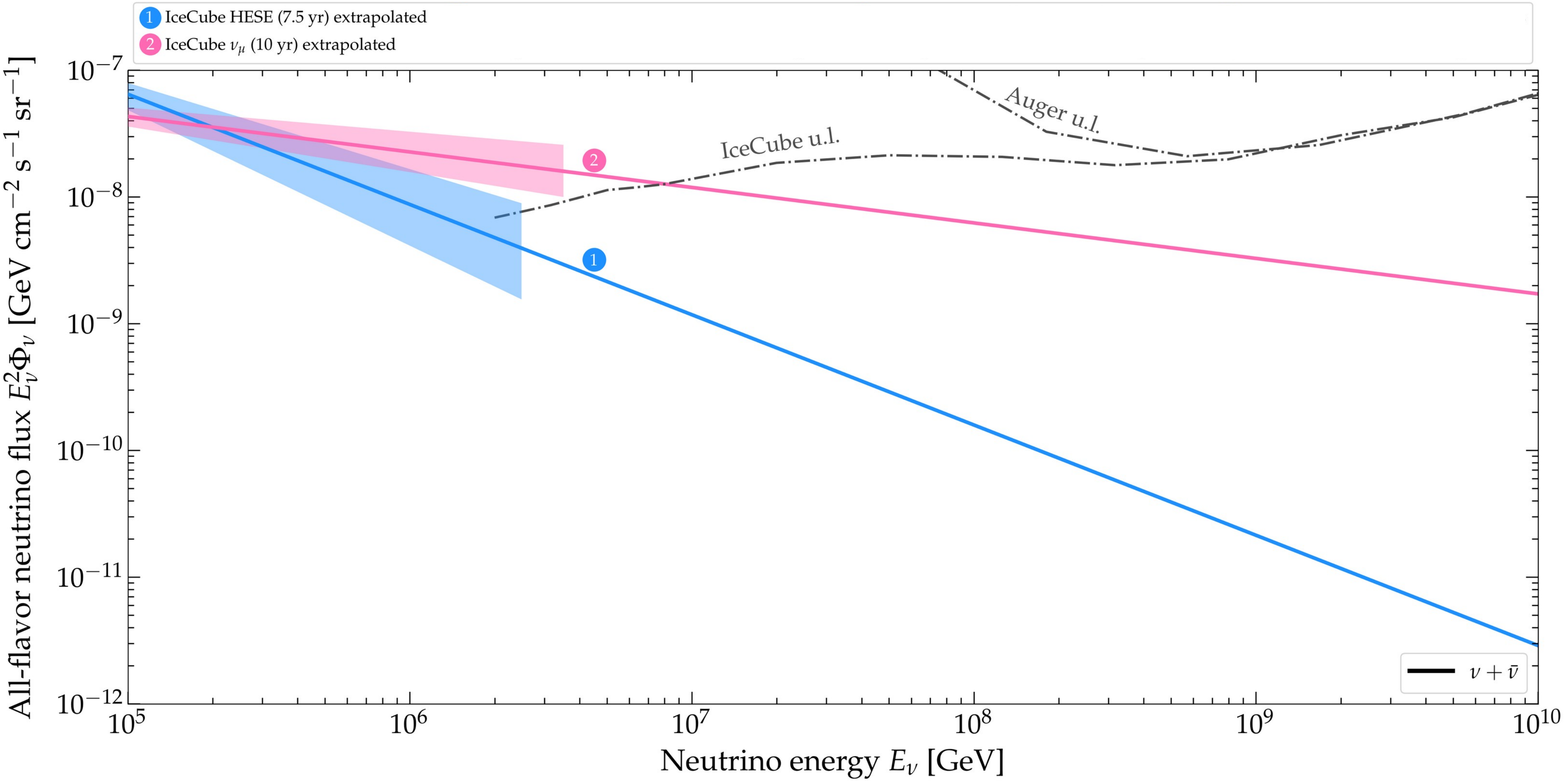
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]
IceCube u.l.
Auger u.l.
$\nu + \bar{\nu}$
?



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2
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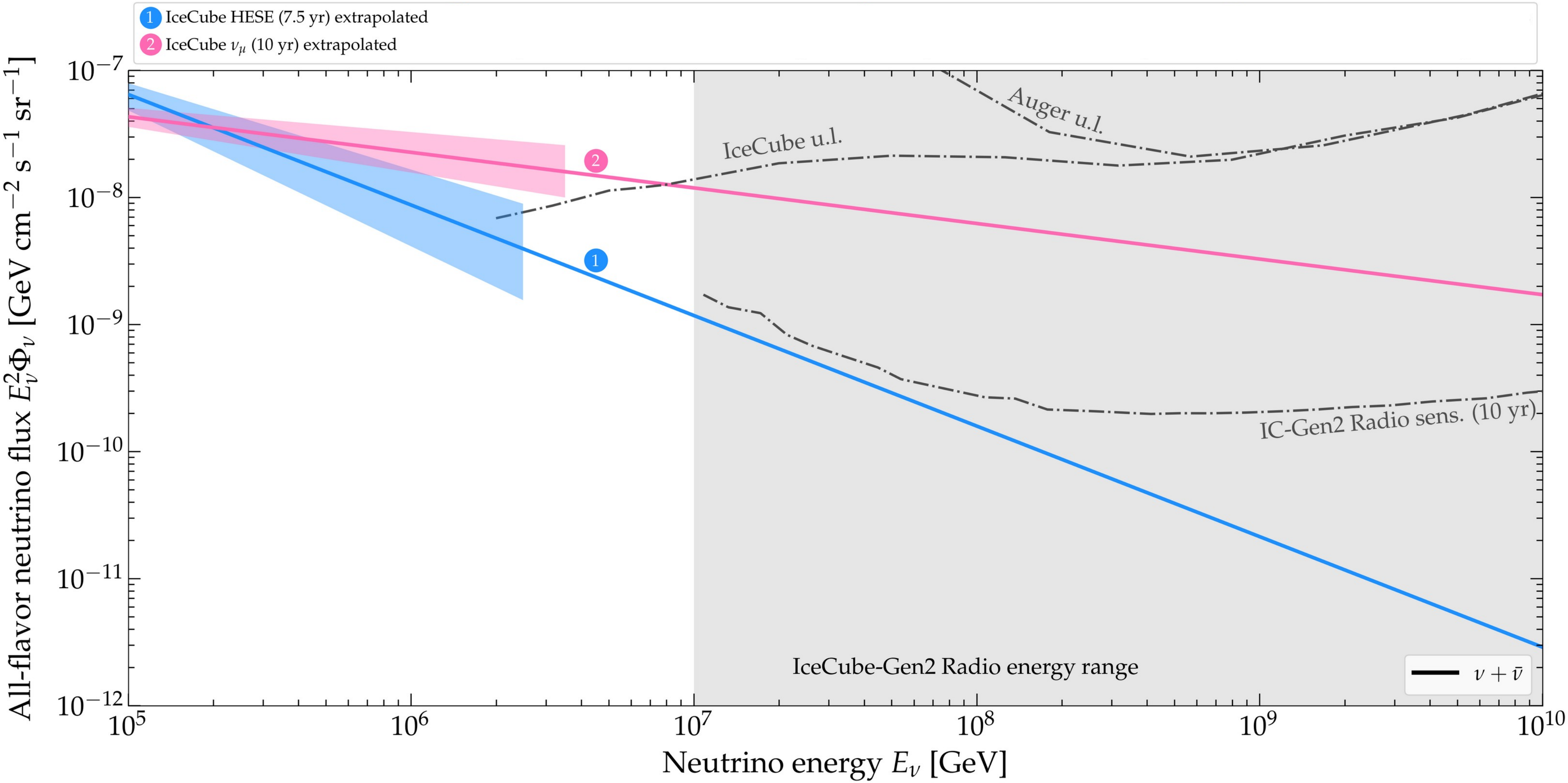
Neutrino energy E_ν [GeV]



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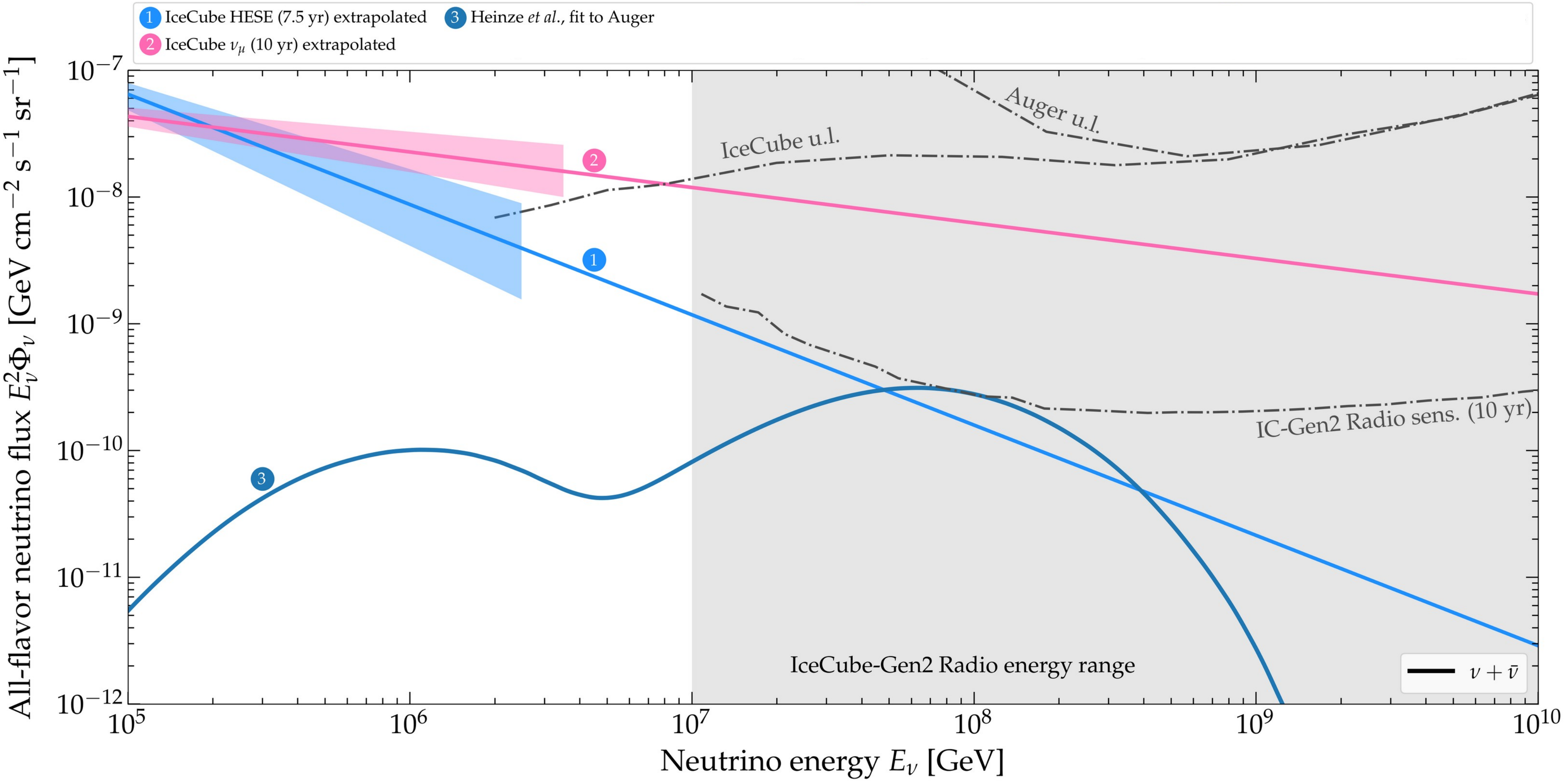
10^{10}
Neutrino energy E_ν [GeV]



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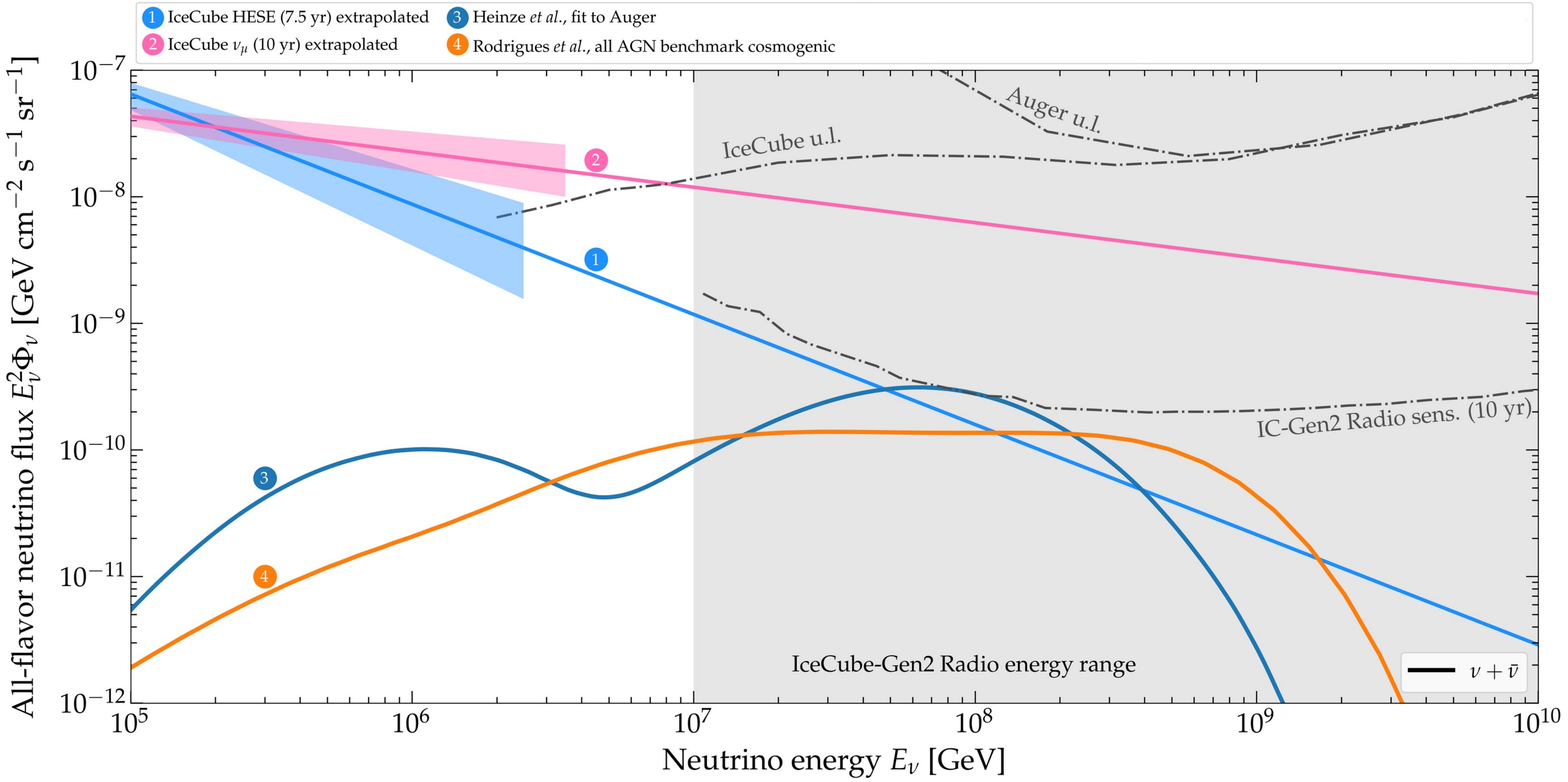

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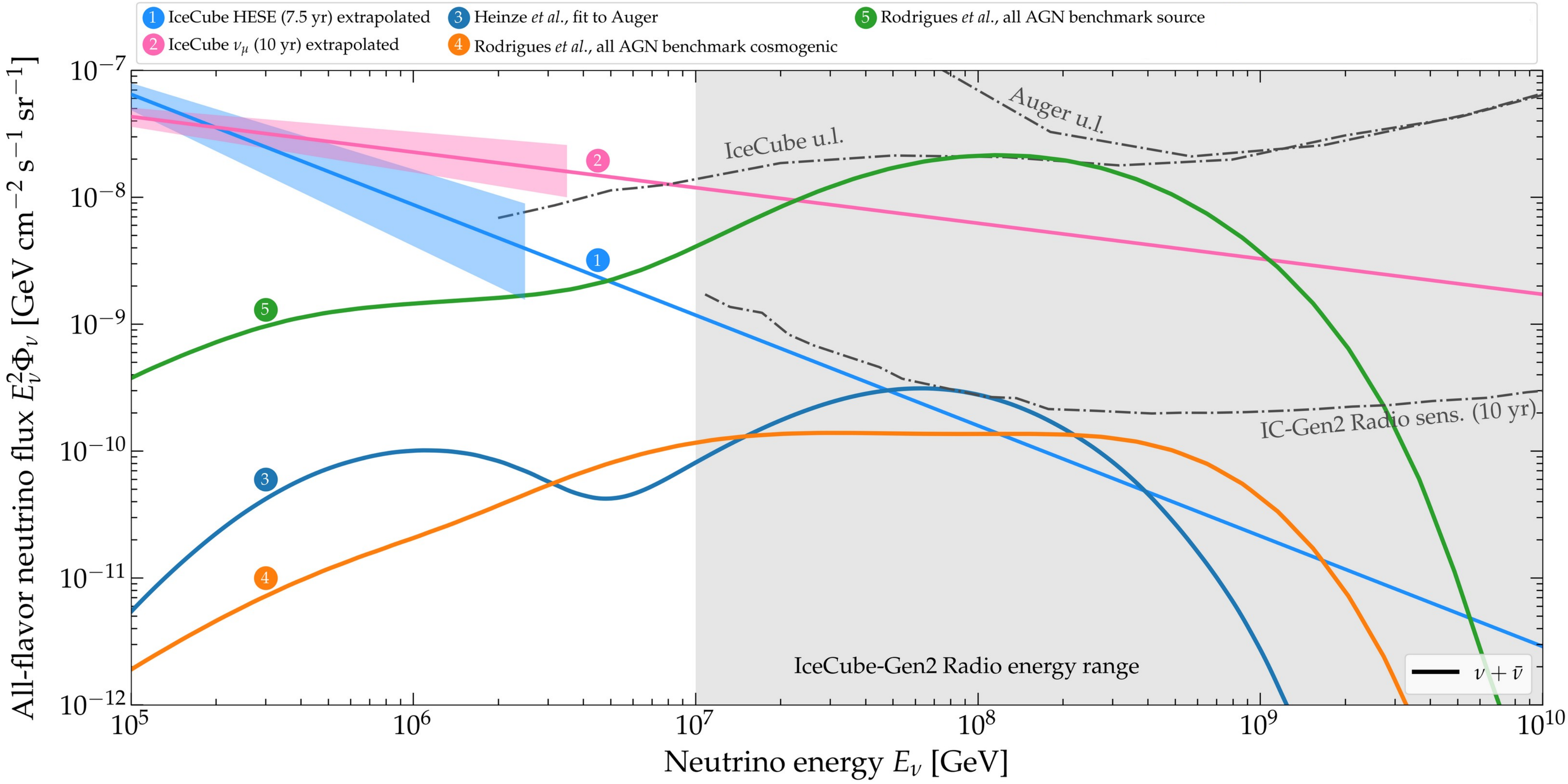
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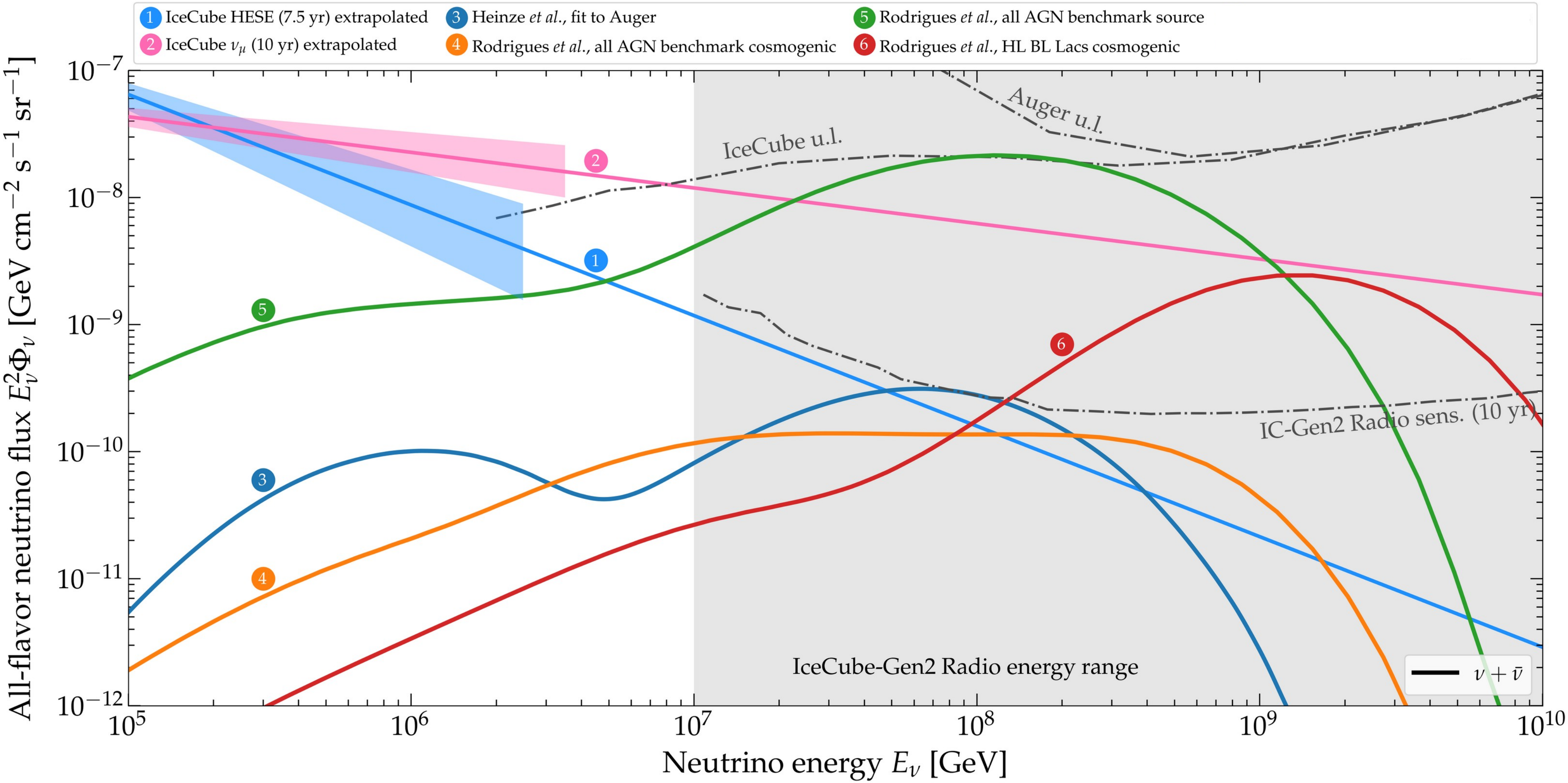

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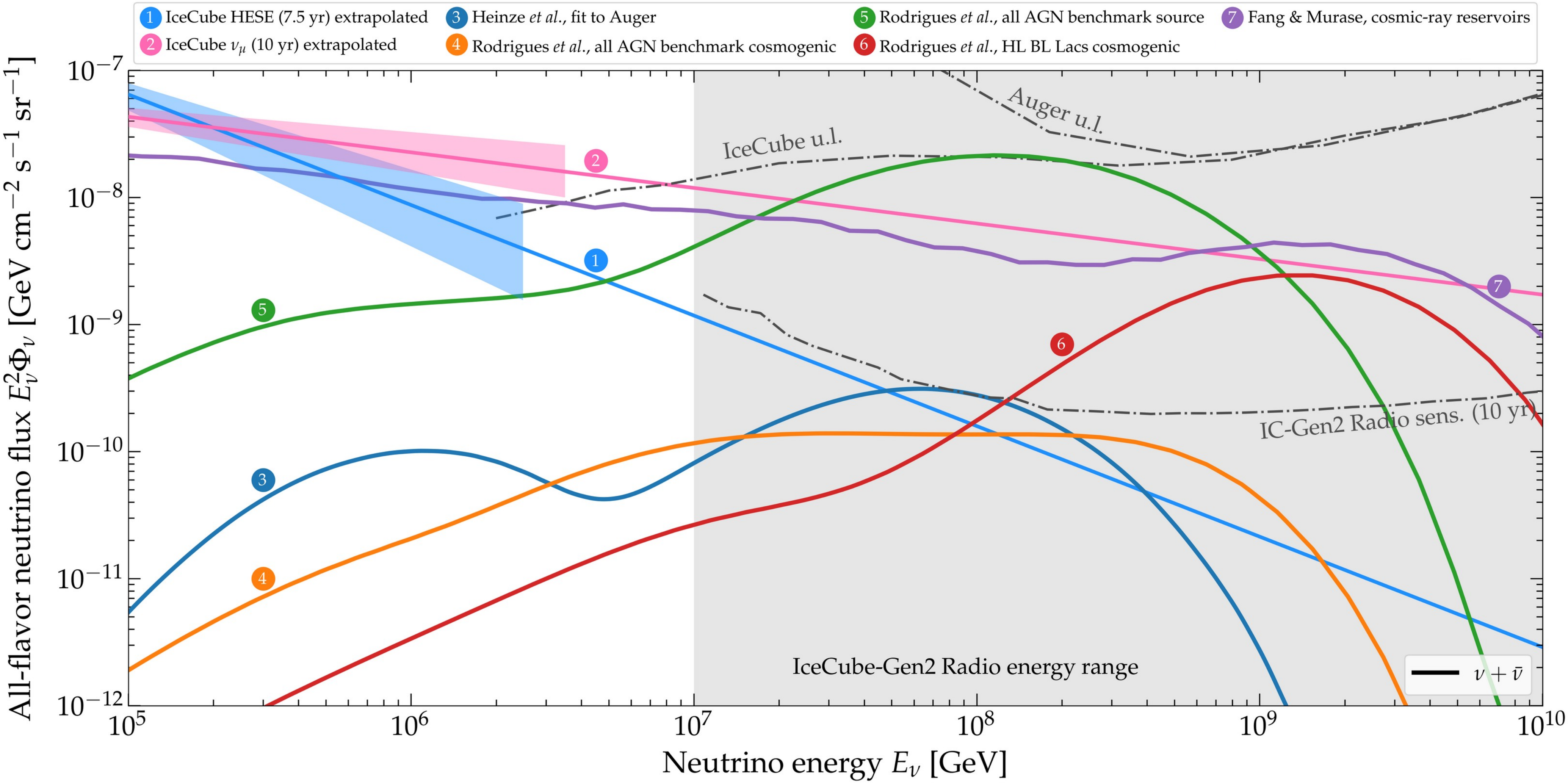
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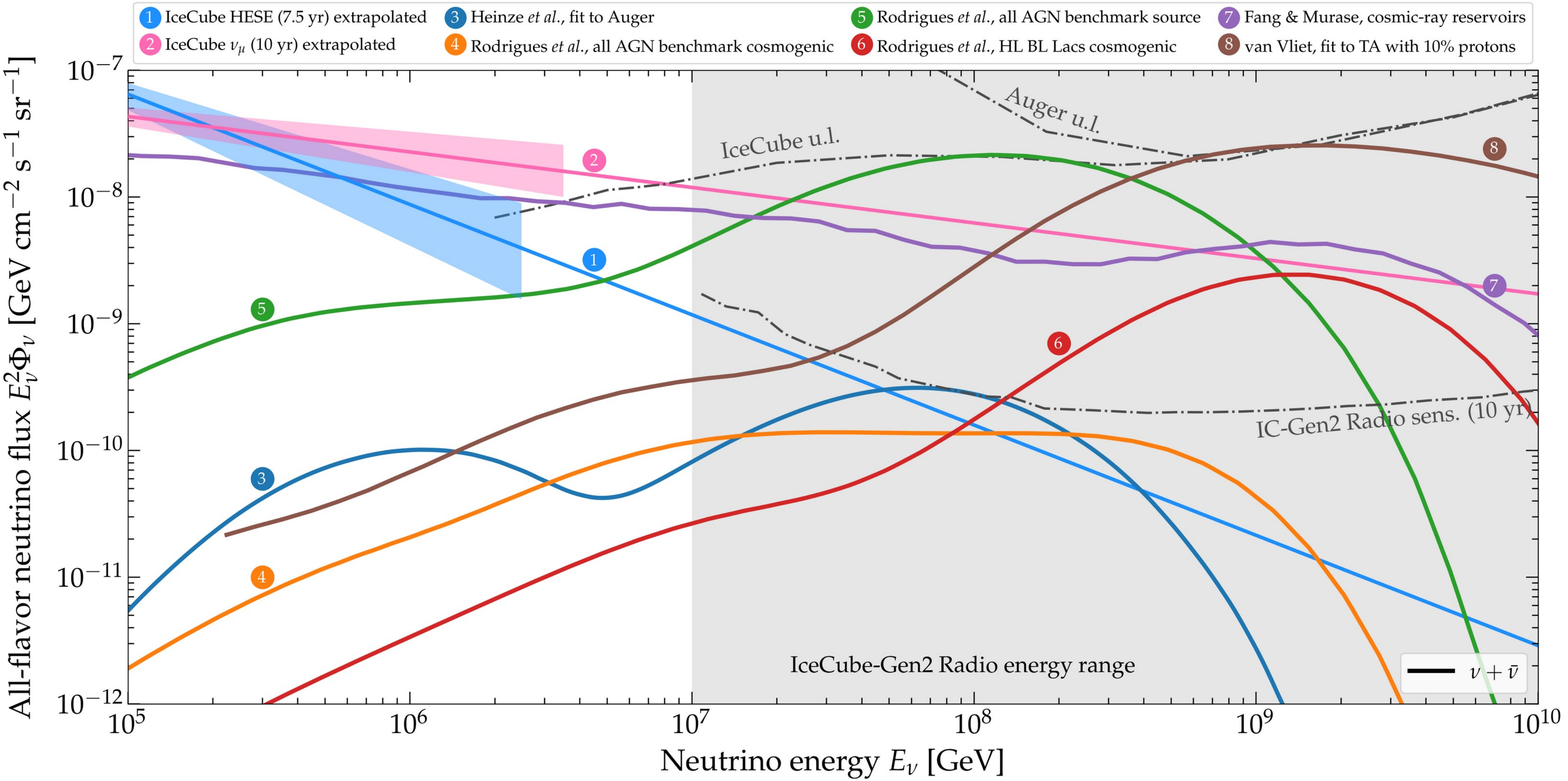

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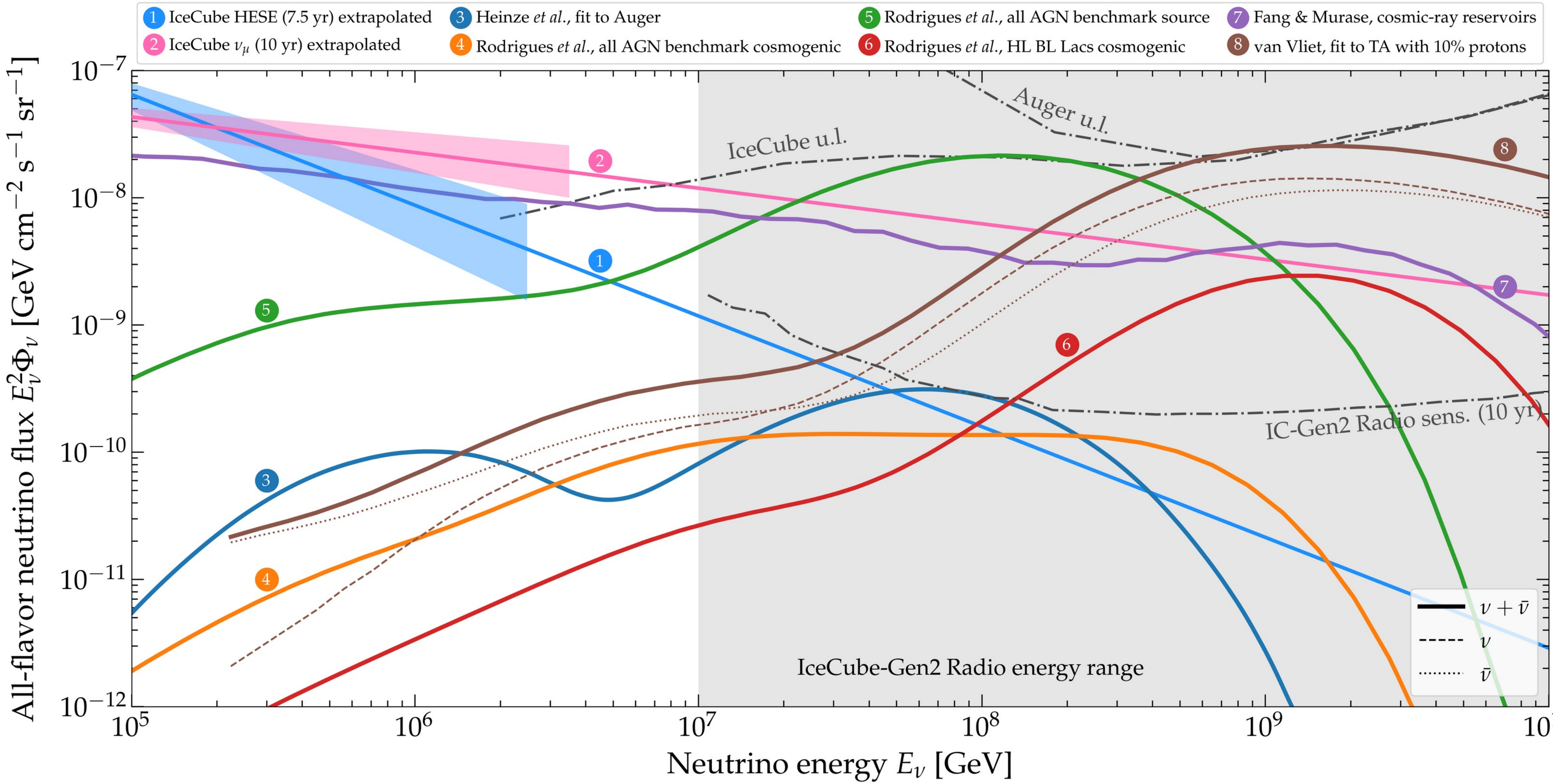
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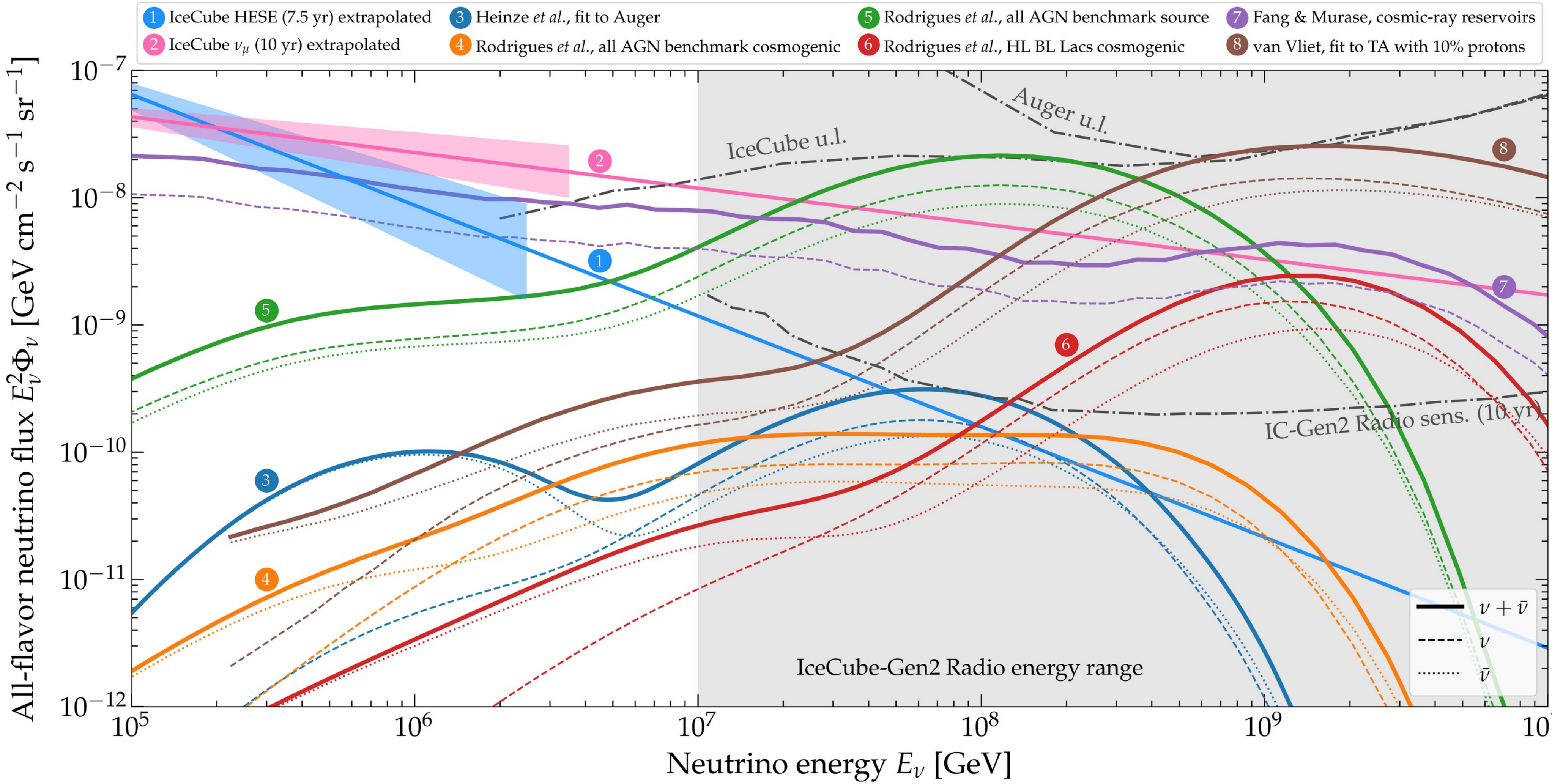

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TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

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Next decade

> 100-PeV ν

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New detection techniques
Better UHE ν flux predictions

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

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Key developments:
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New detection techniques
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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

Not knowing the sources
Not knowing the ν production mechanism
(Us)
BSM using TeV– EeV ν
Low statistics / limited reconstruction


(Also us)
(*If* we factor in all the uncertainties)

Two examples

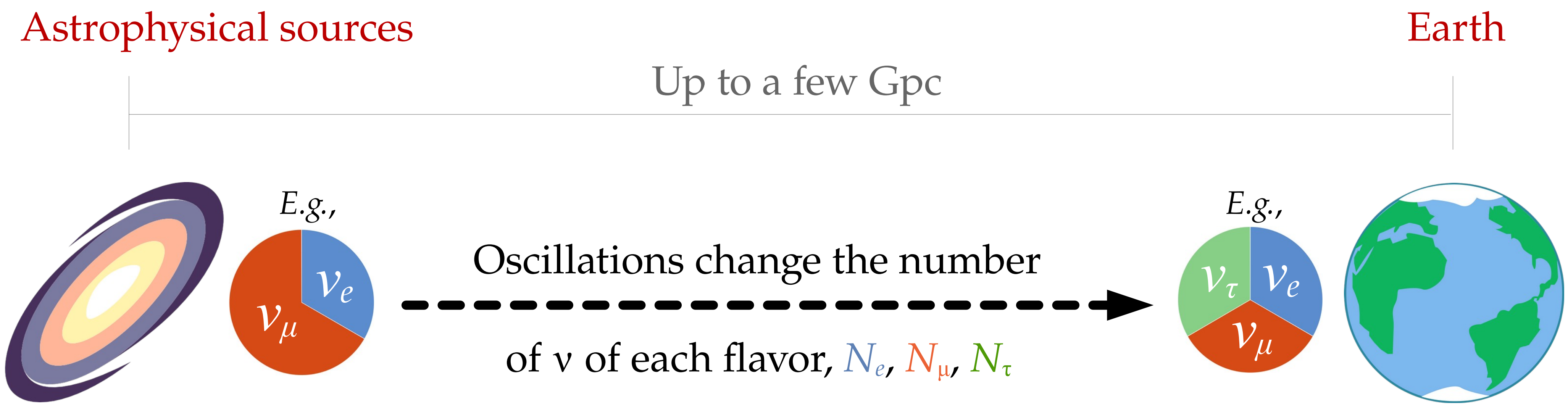
1. Flavor stuff
2. Cross-section stuff

Good chances of discovery or setting strong bounds

Keep ourselves grounded by accounting for all relevant particle and astrophysics unknowns

Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

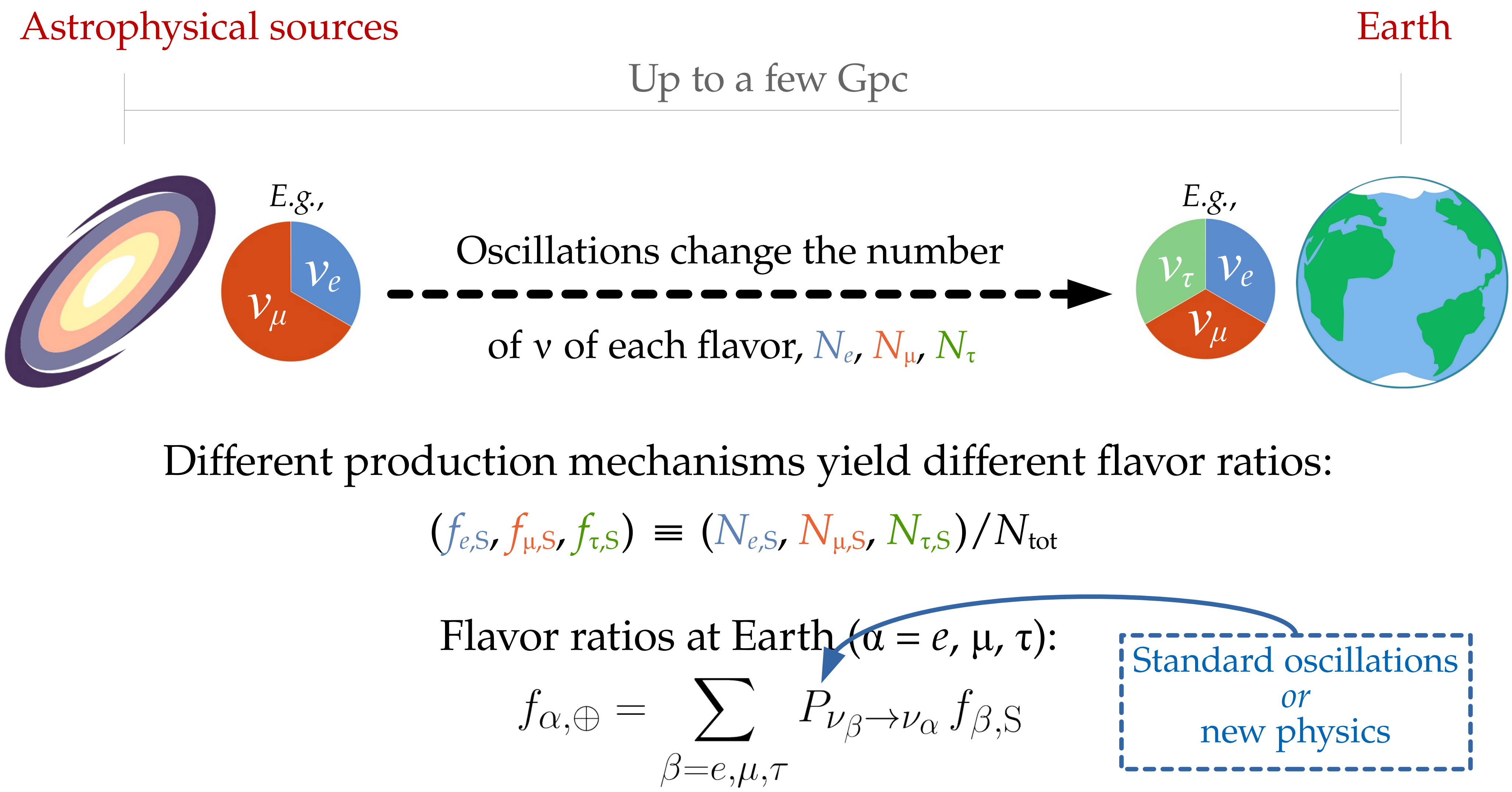


Different production mechanisms yield different flavor ratios:

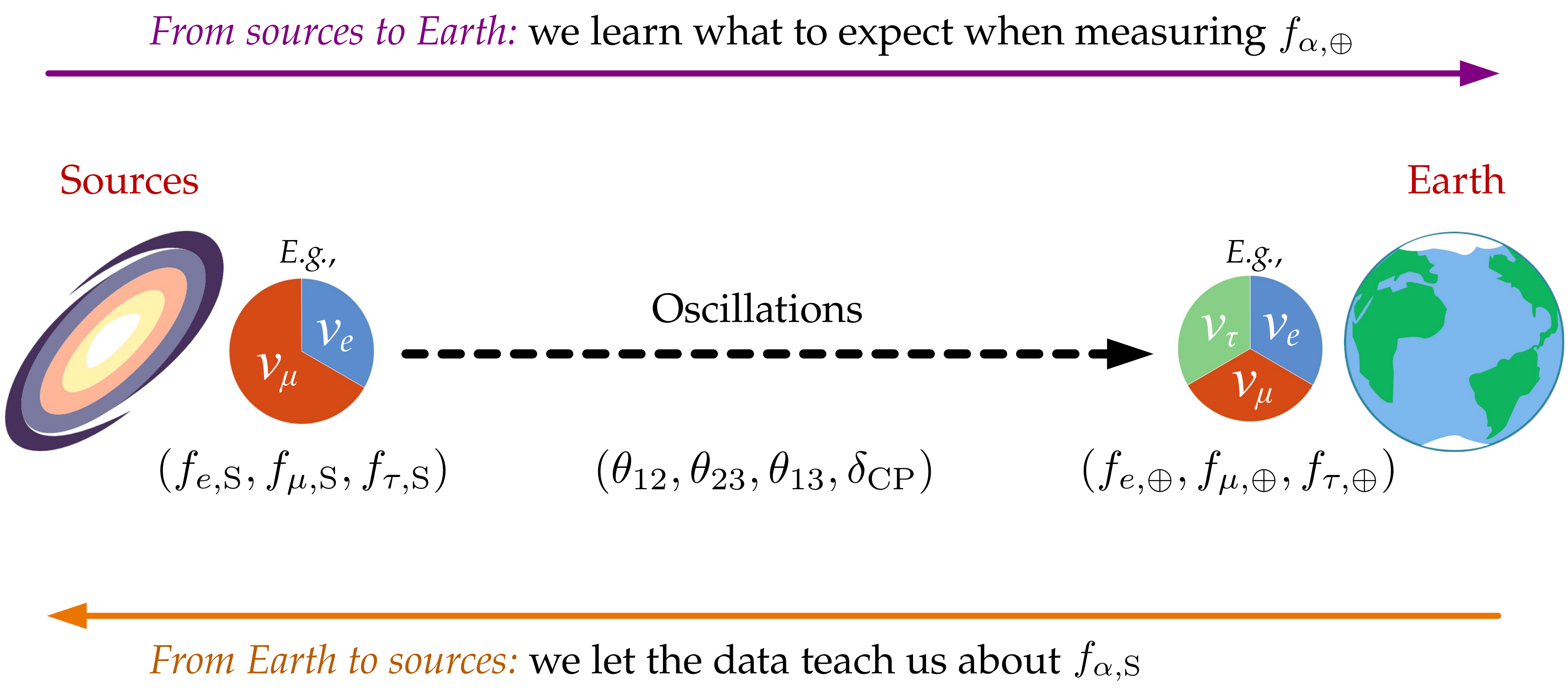
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

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

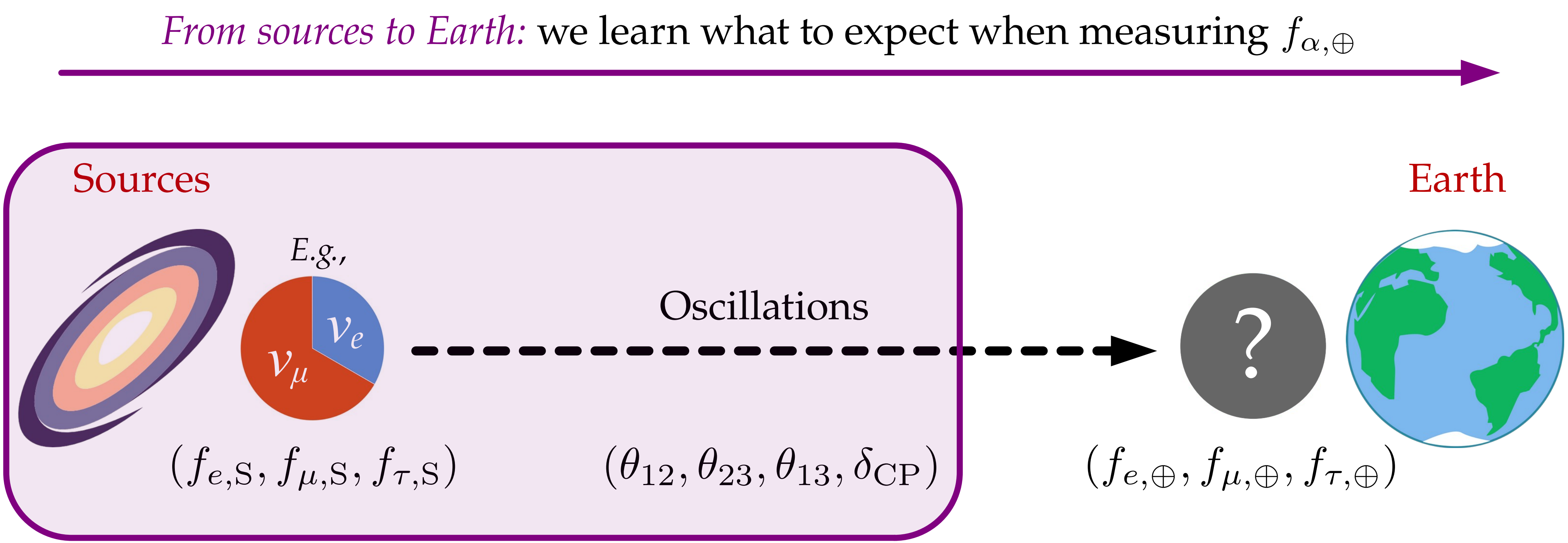
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$



Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$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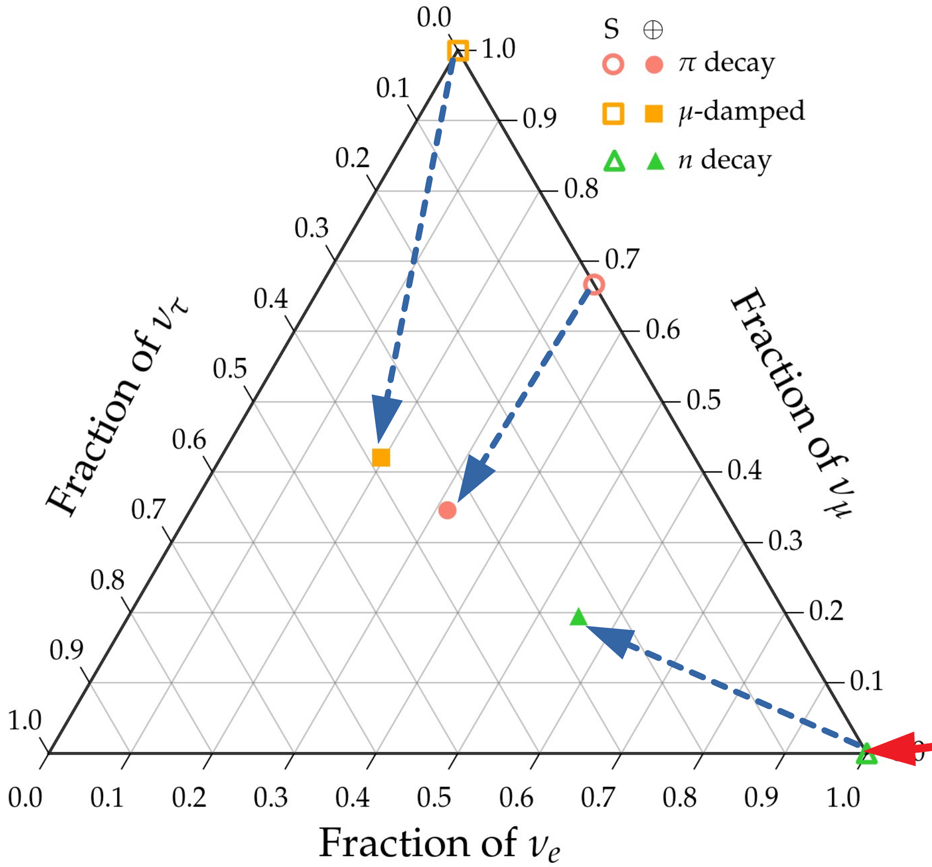
E.g.,
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
Earth
?
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

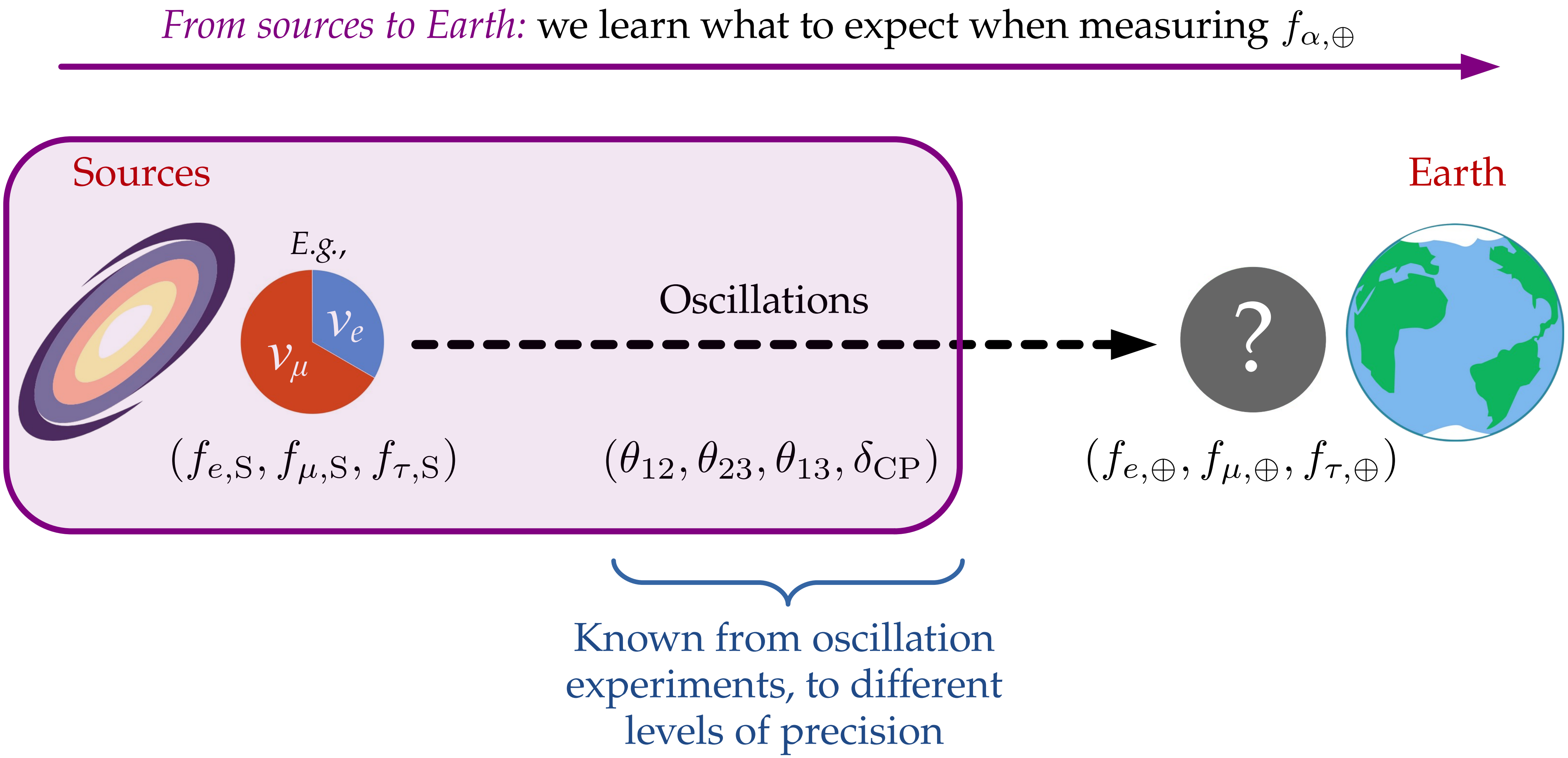
Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

Note: ν and $\bar{\nu}$ are (so far) indistinguishable in neutrino telescopes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E.g.,
ν_e
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$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

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*

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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

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Ingredient #2:

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

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Ingredient #1:
Flavor ratios at the source,
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$

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

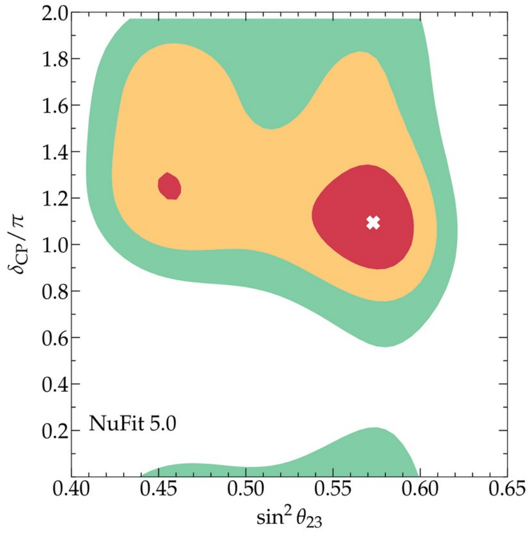
or

Explore all possible combinations

Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$

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

$\equiv$

MB, Beacom, Winter, *PRL* 2015

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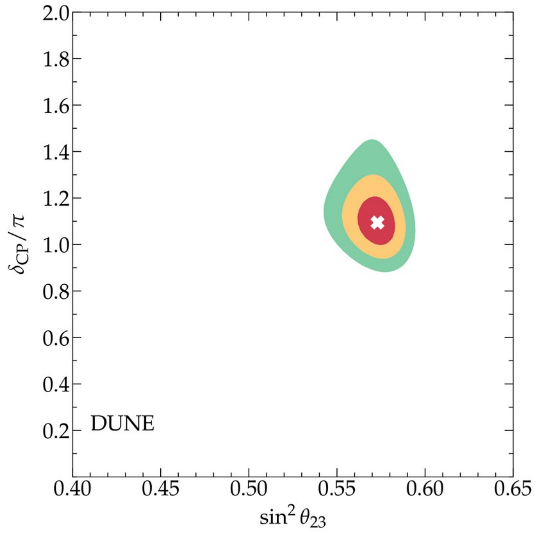
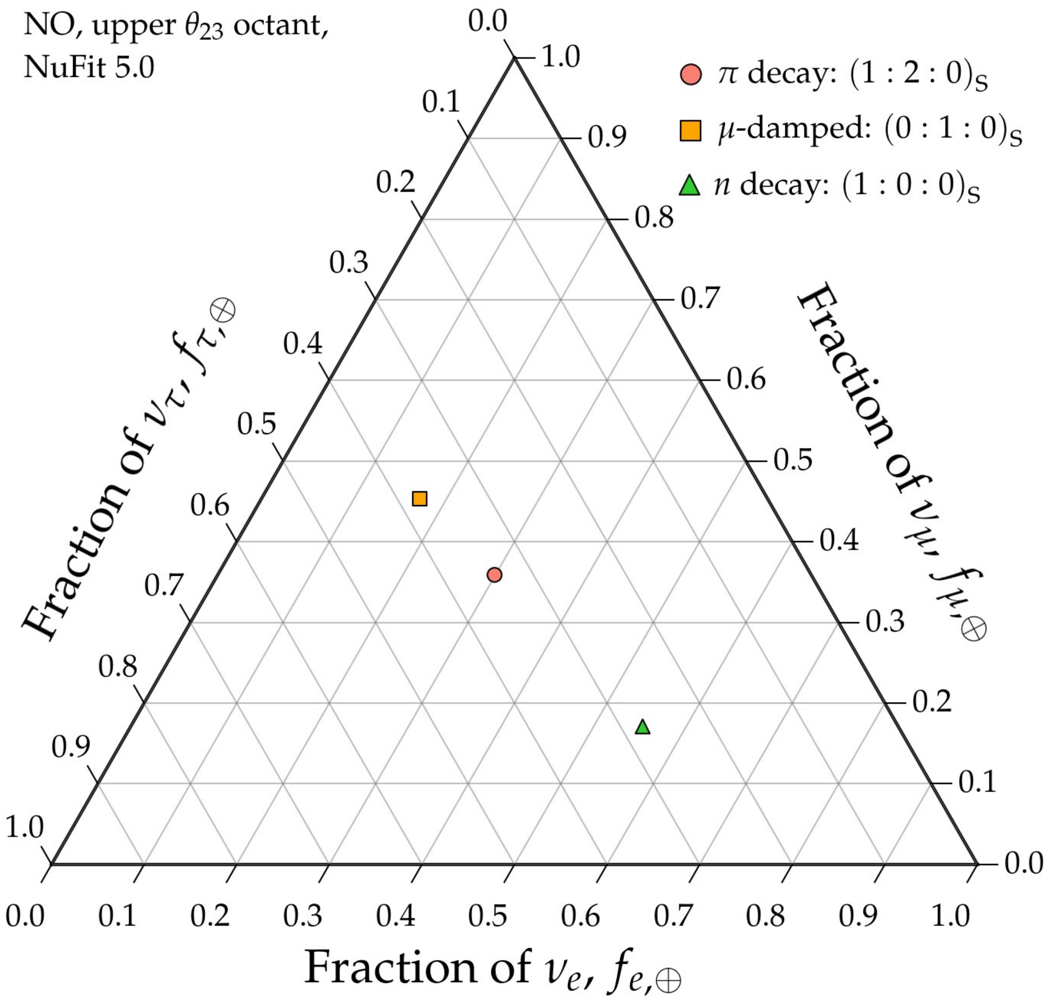
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



Theoretically palatable regions: today (2021)



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

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

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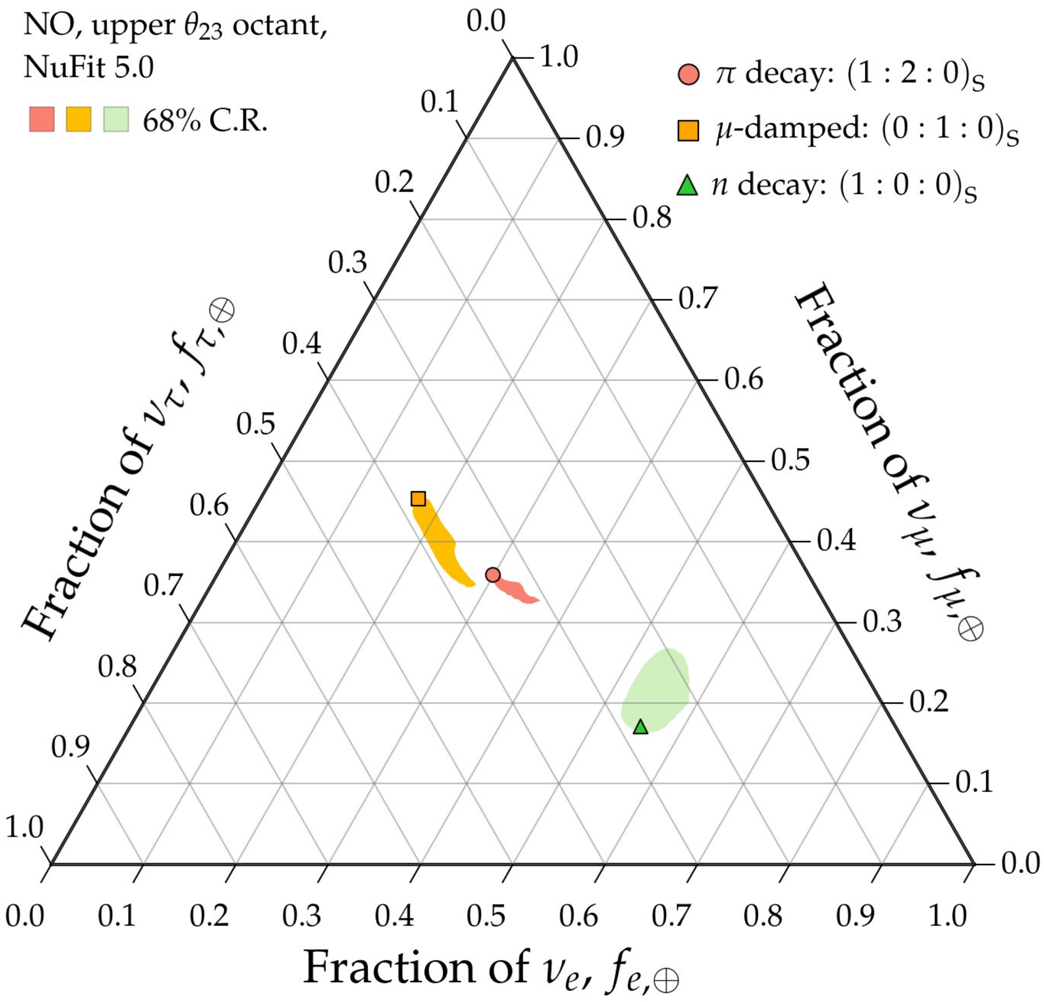

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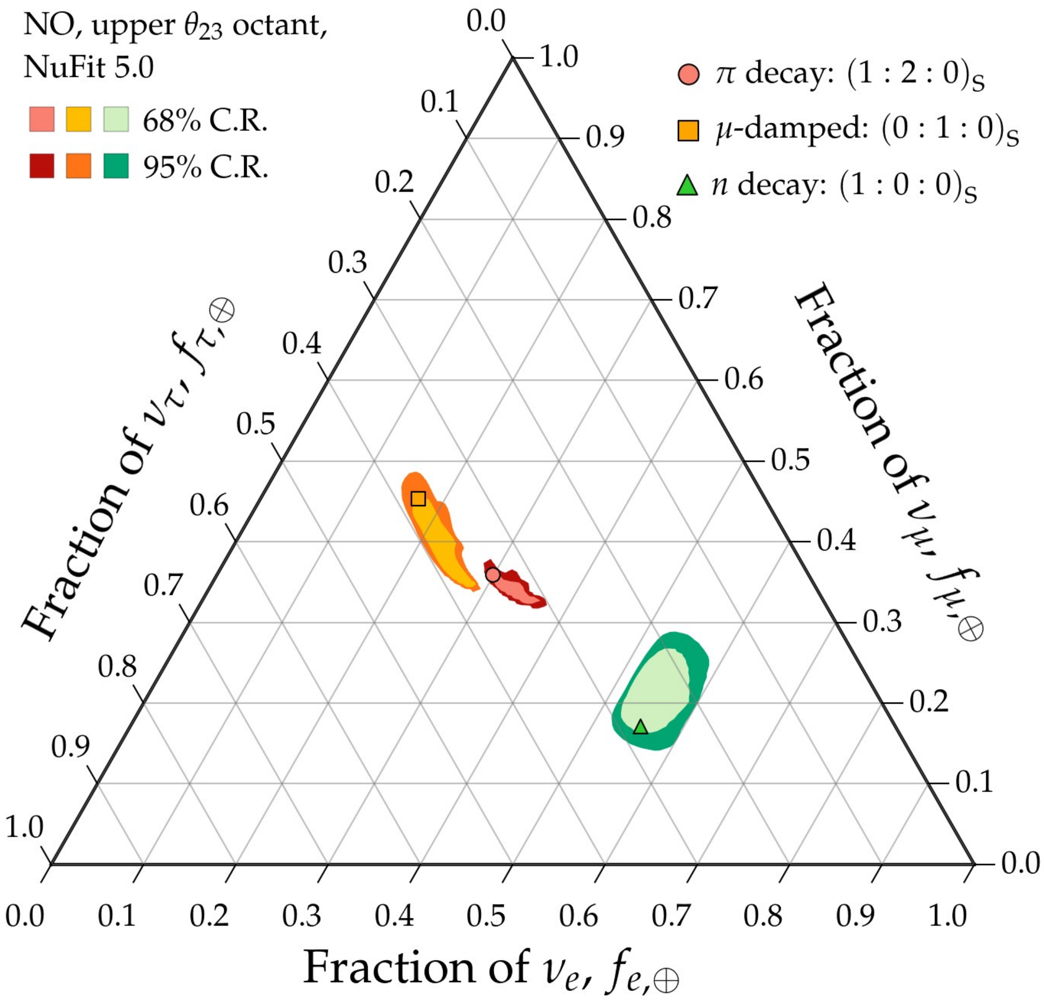

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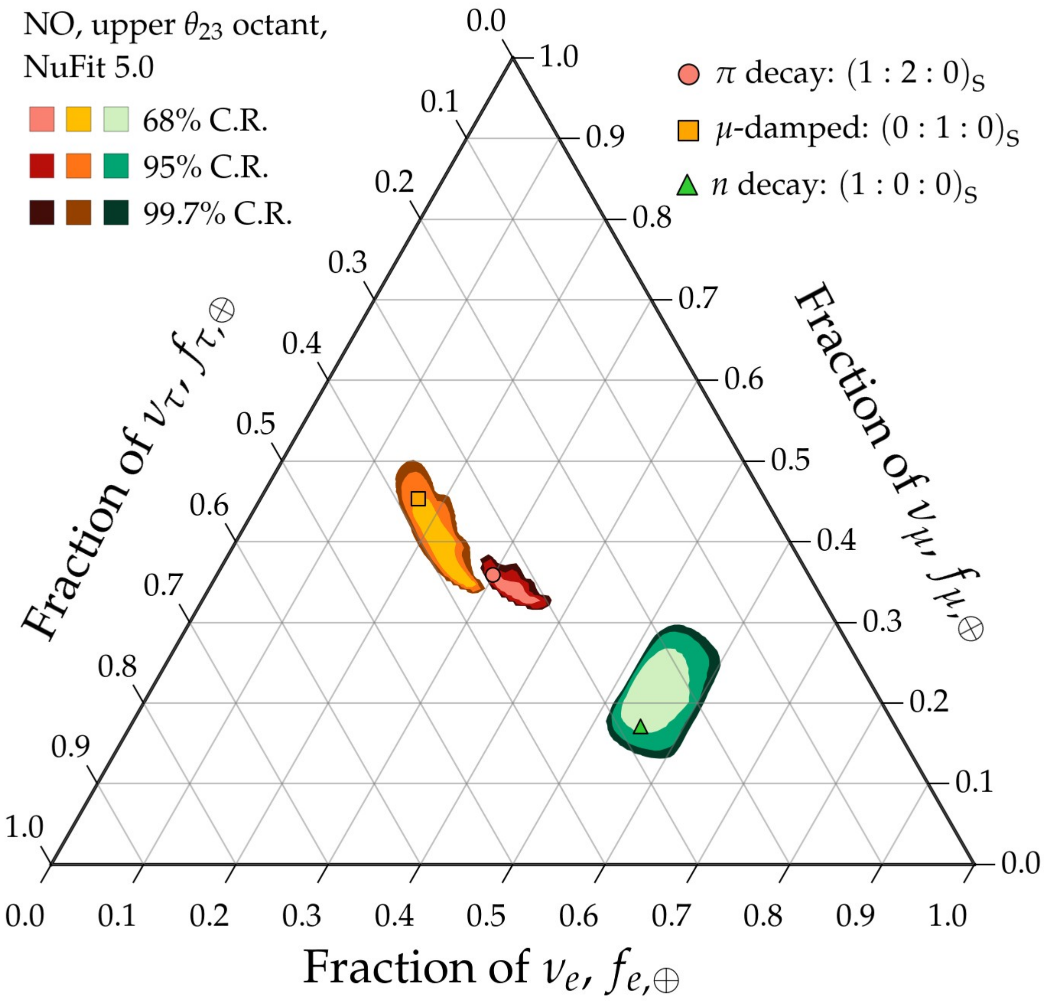

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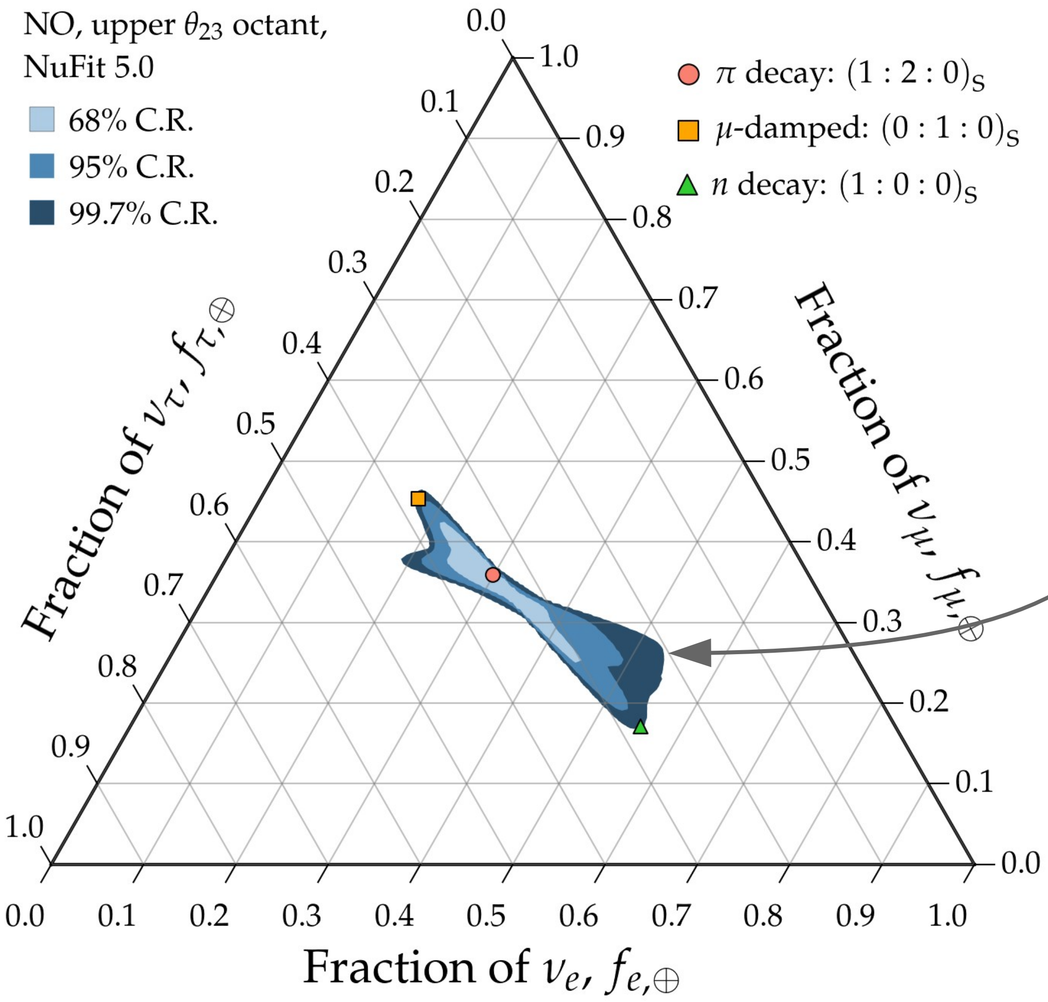

Varying over all possible flavor ratios at the source

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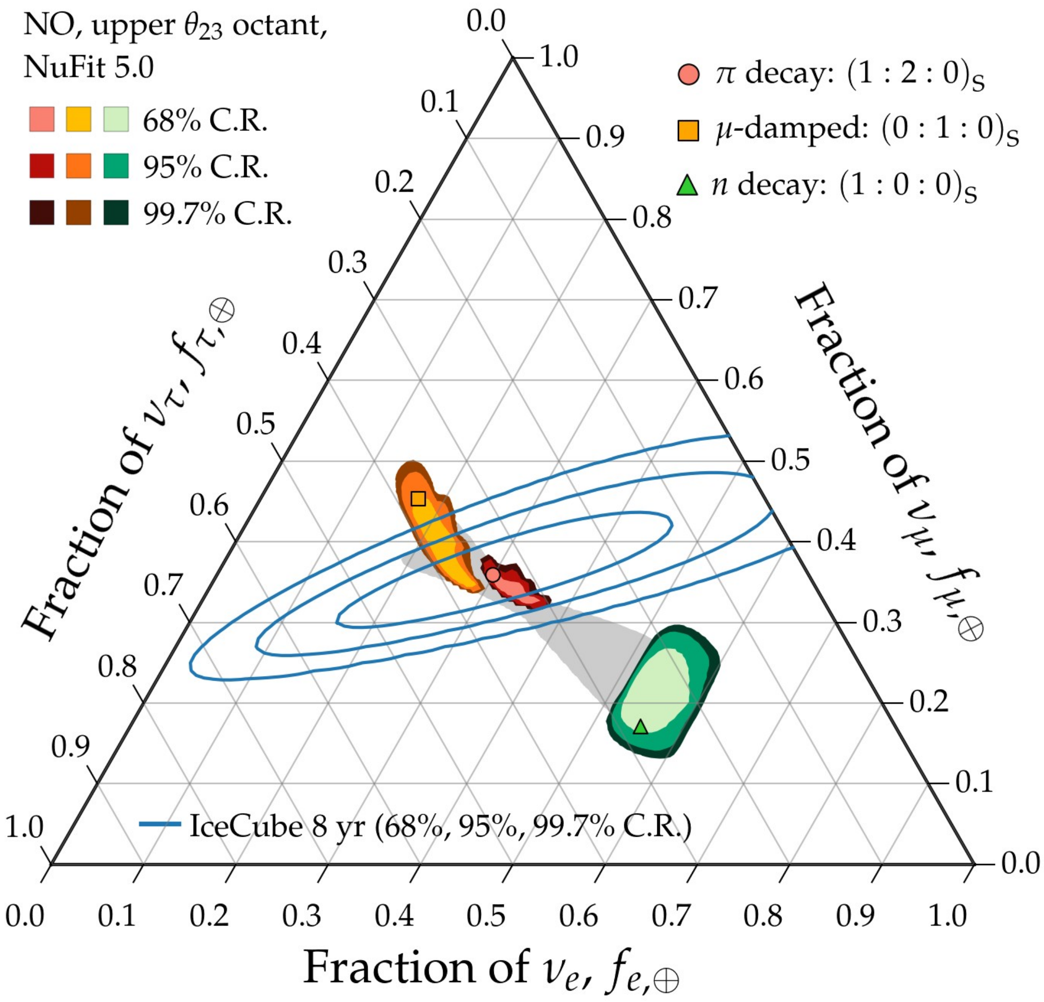
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



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

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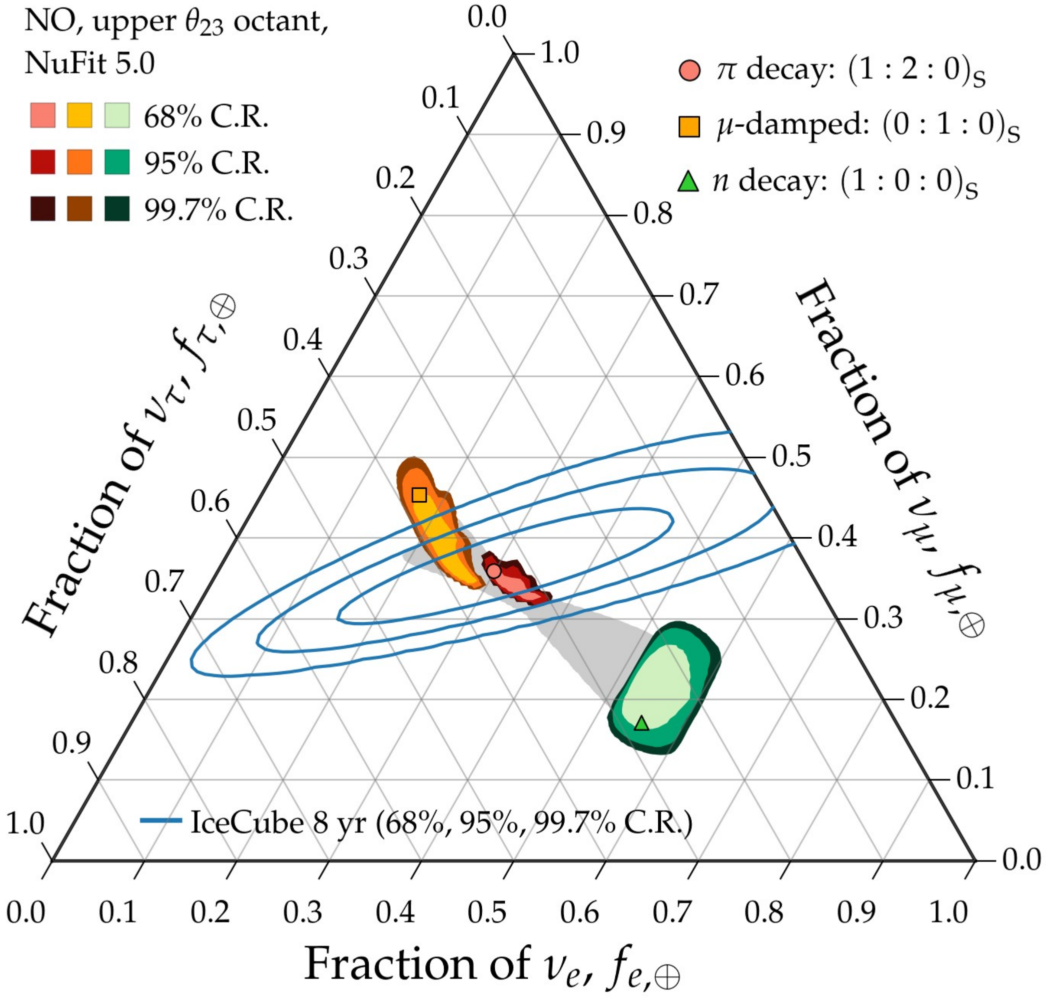

Two limitations:

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)

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

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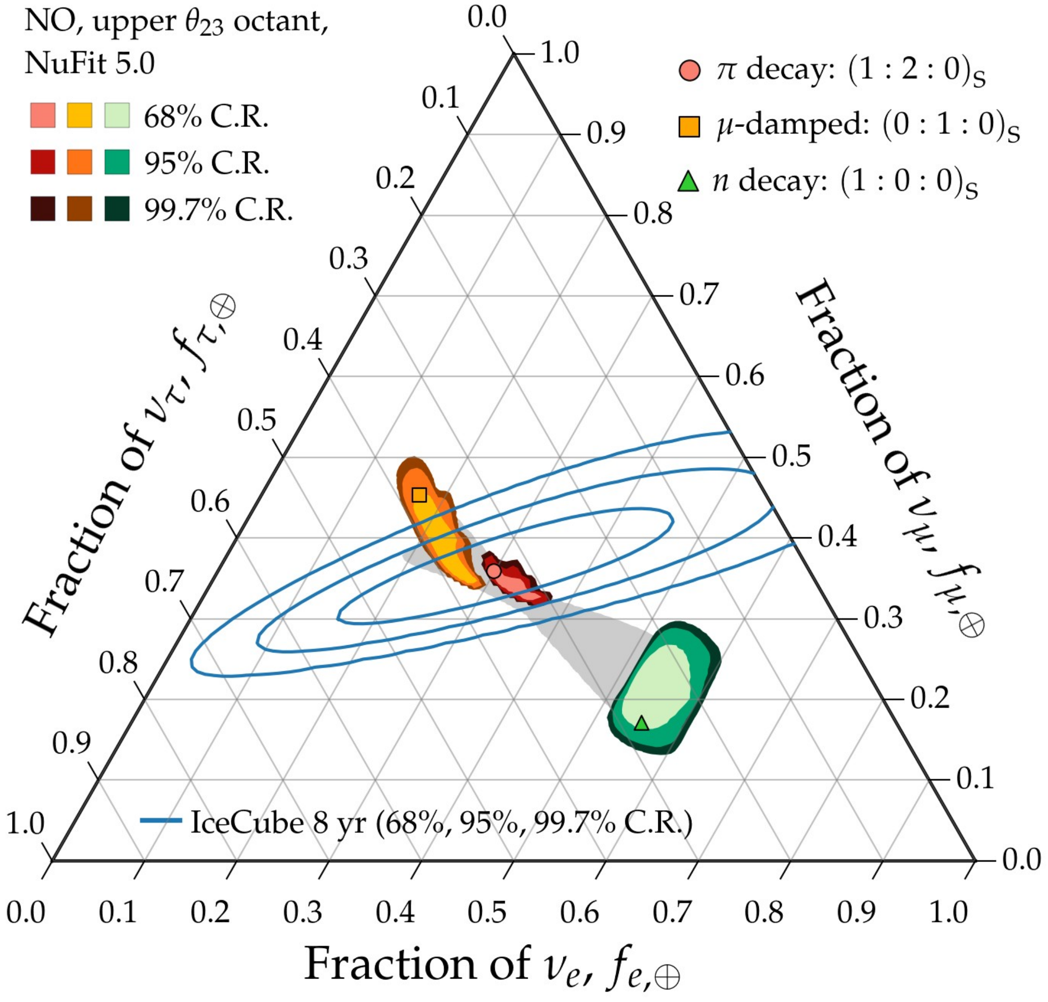

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Will be overcome by 2030

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

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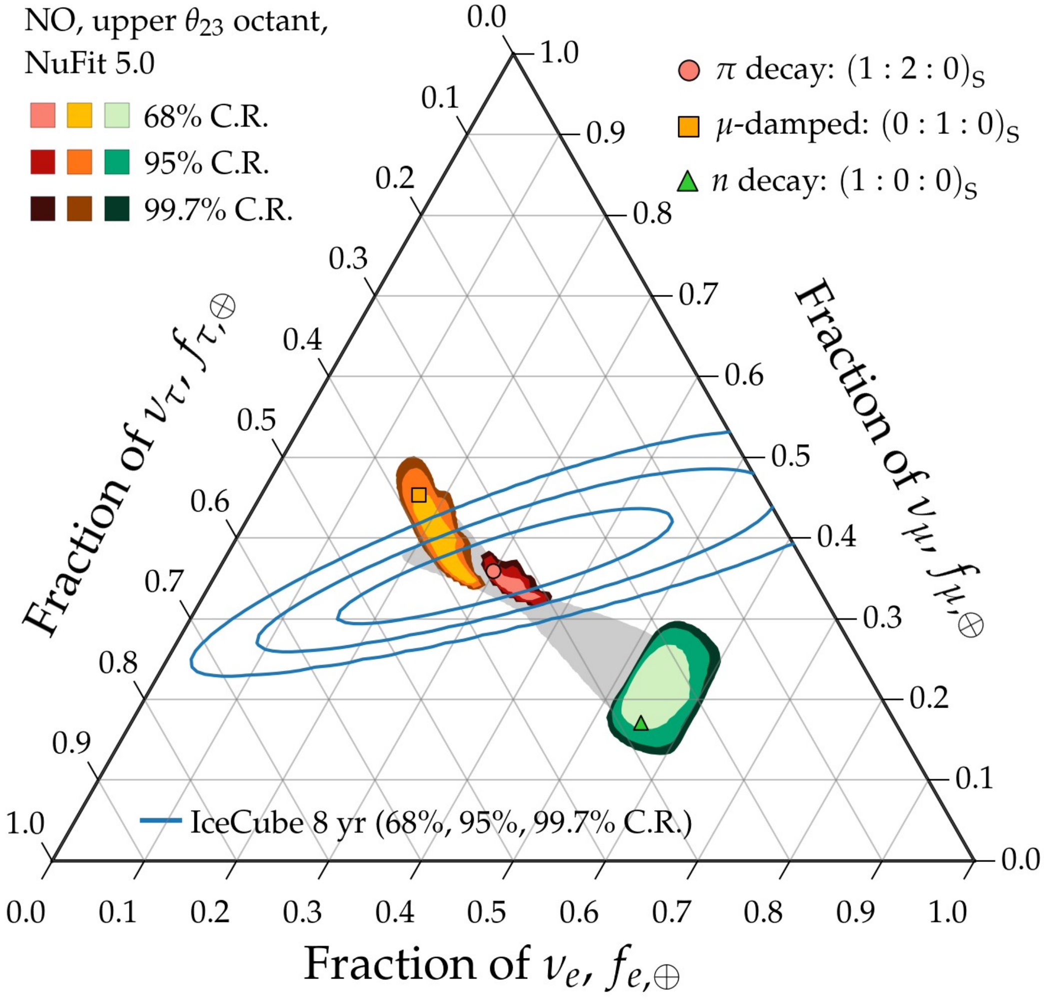

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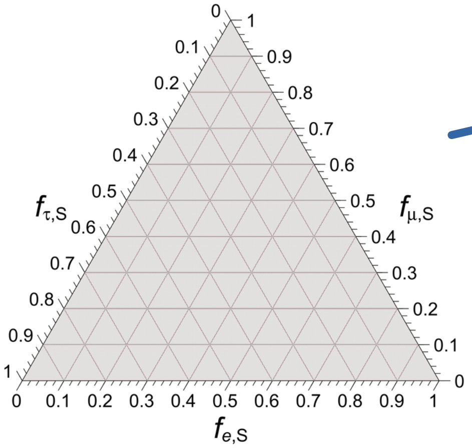
Will be overcome by 2040

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

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

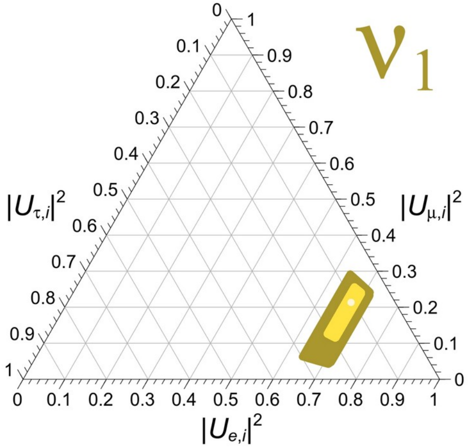
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

$\nu_1, \nu_2 \to \nu_3$

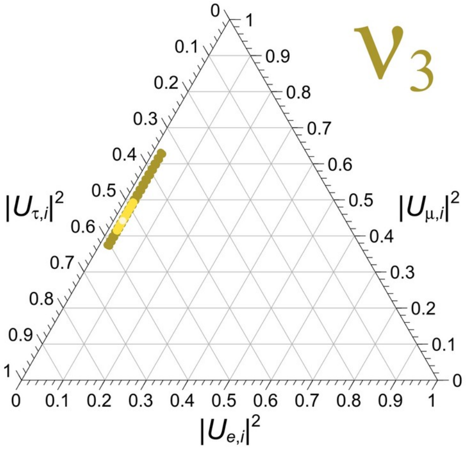
ν_3 lightest and stable
(inverted mass ordering)

Earth



ν_1

$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$



ν_3

$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Measuring the neutrino lifetime

Earth

$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$

ν_1 lightest and stable
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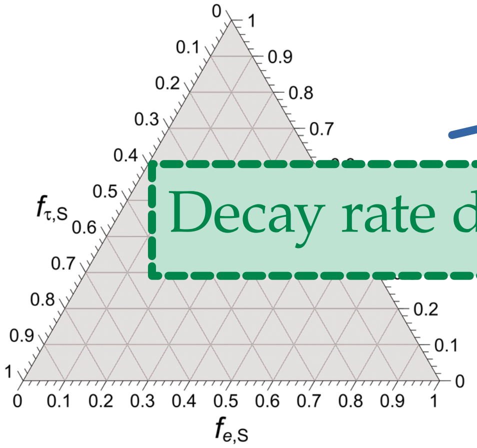
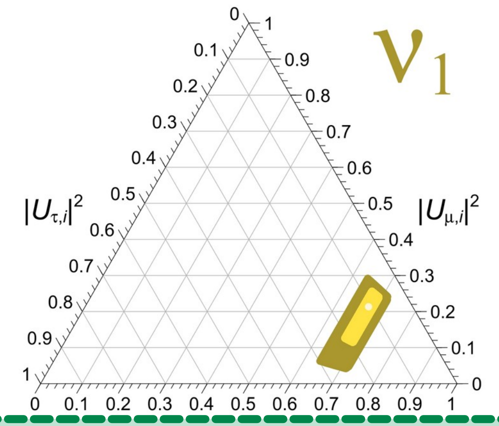
Sources



Decay rate depends on $\exp[- t\ /\ (\gamma\ \tau_i)] = \exp[- (L/E) \cdot (m_i/\tau_i)]$



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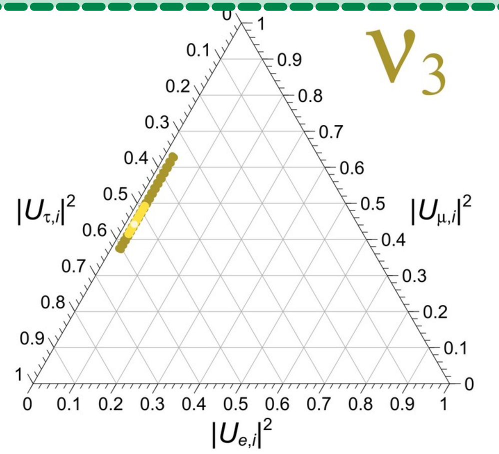

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$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}$

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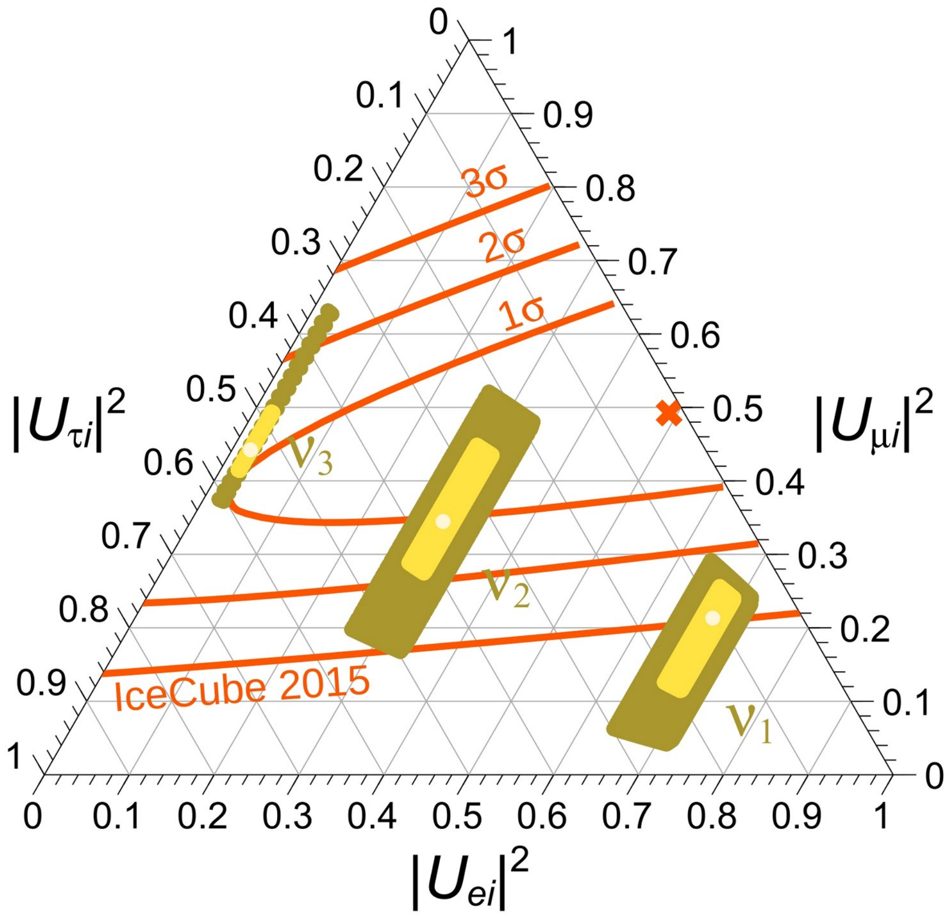
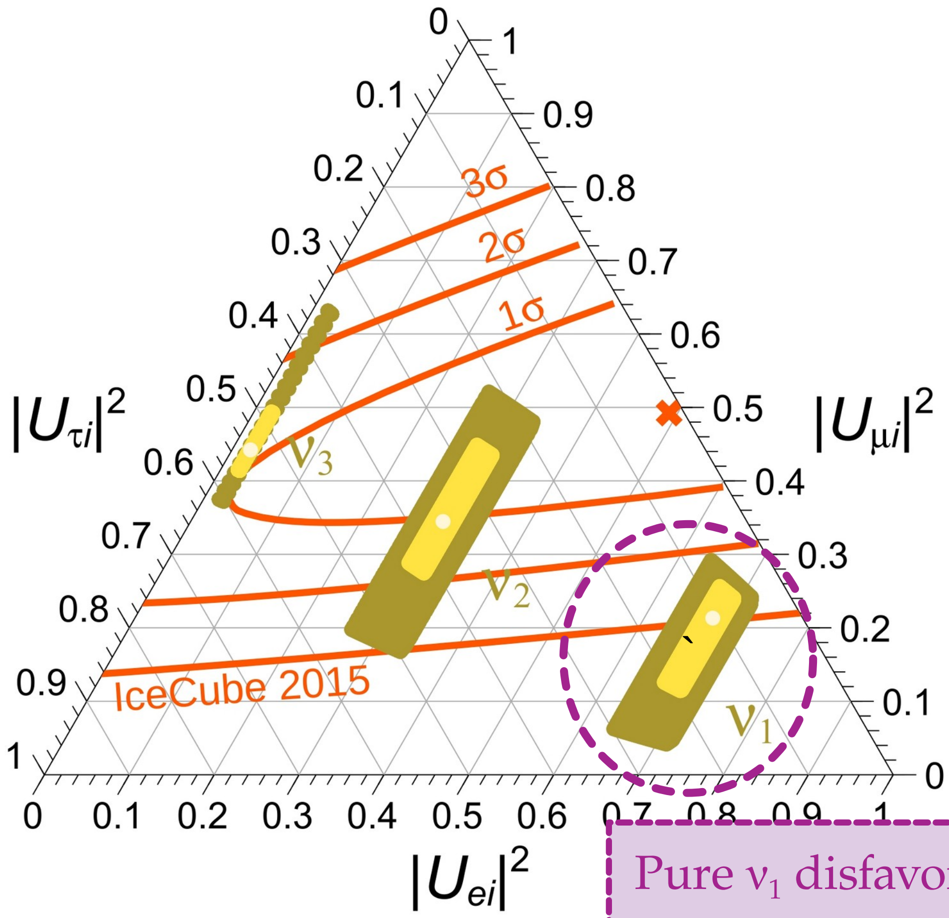


MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012



Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017
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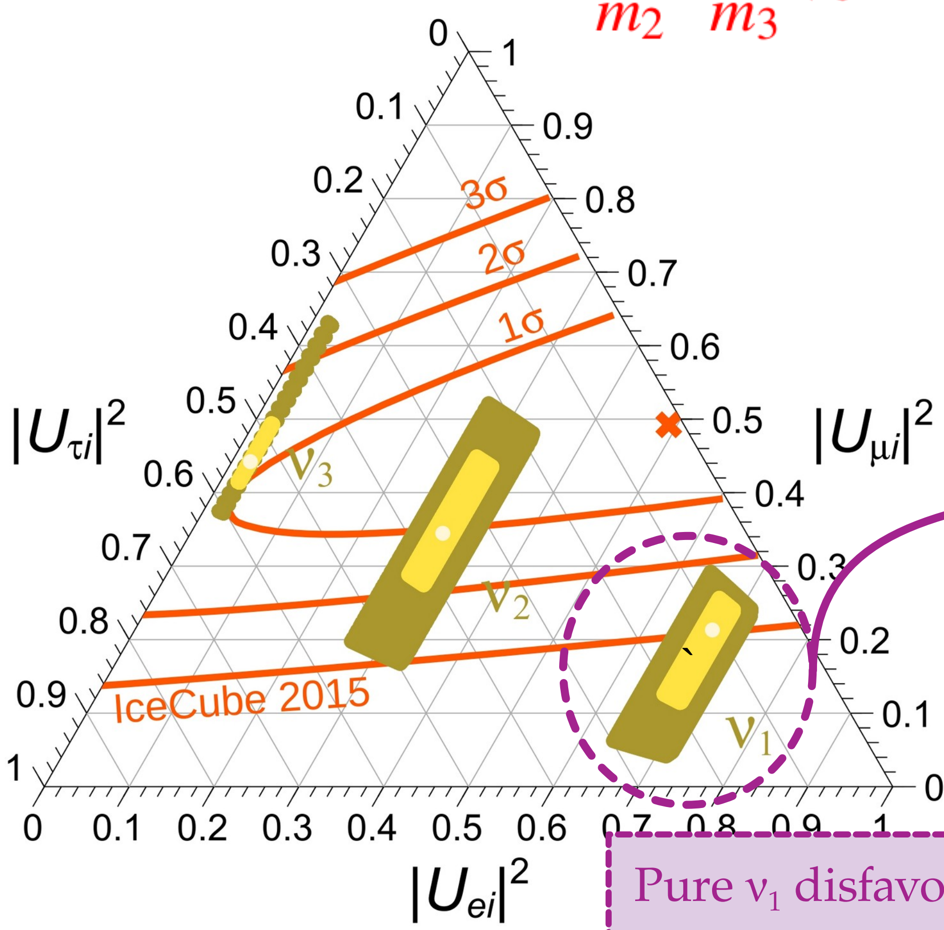
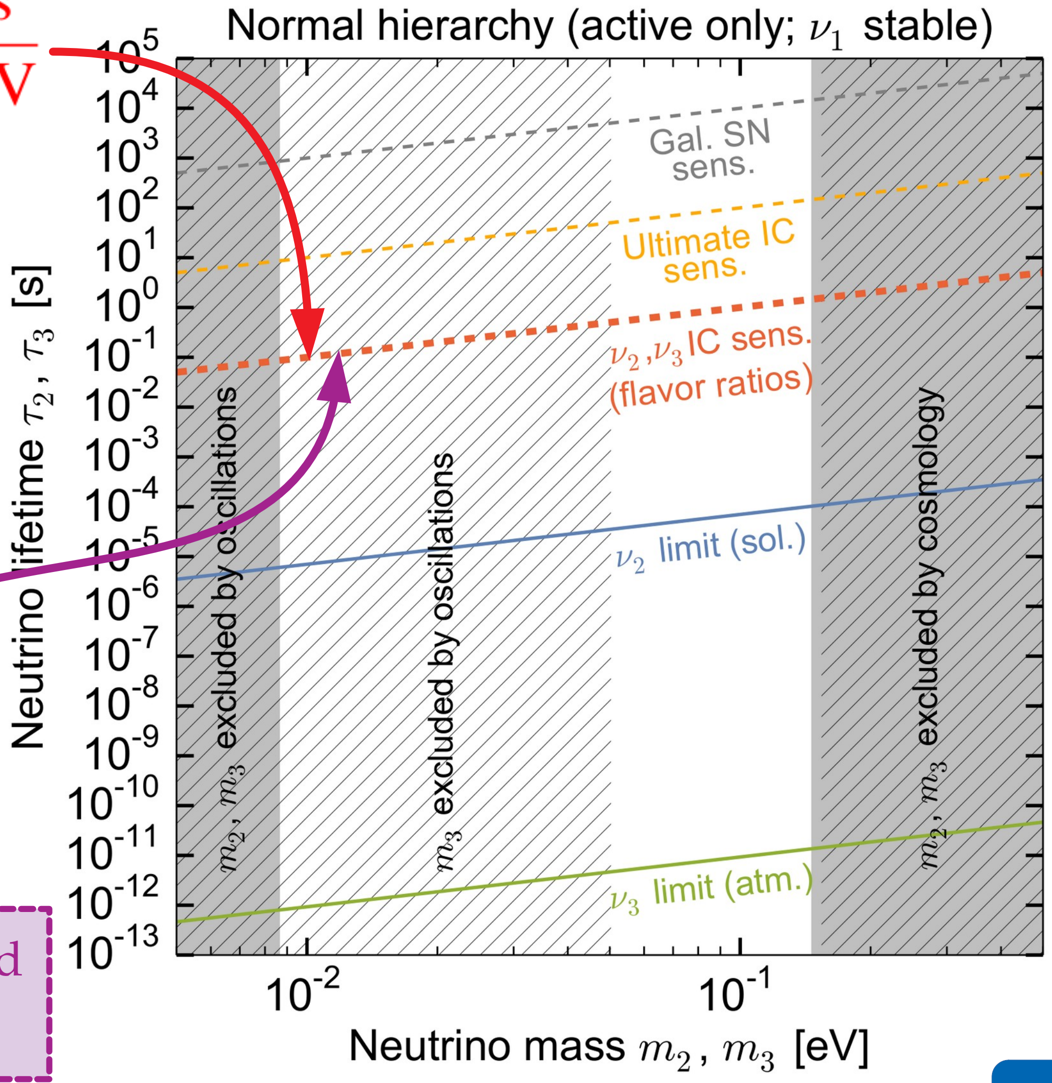
$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\text{s}}{\text{eV}}$$





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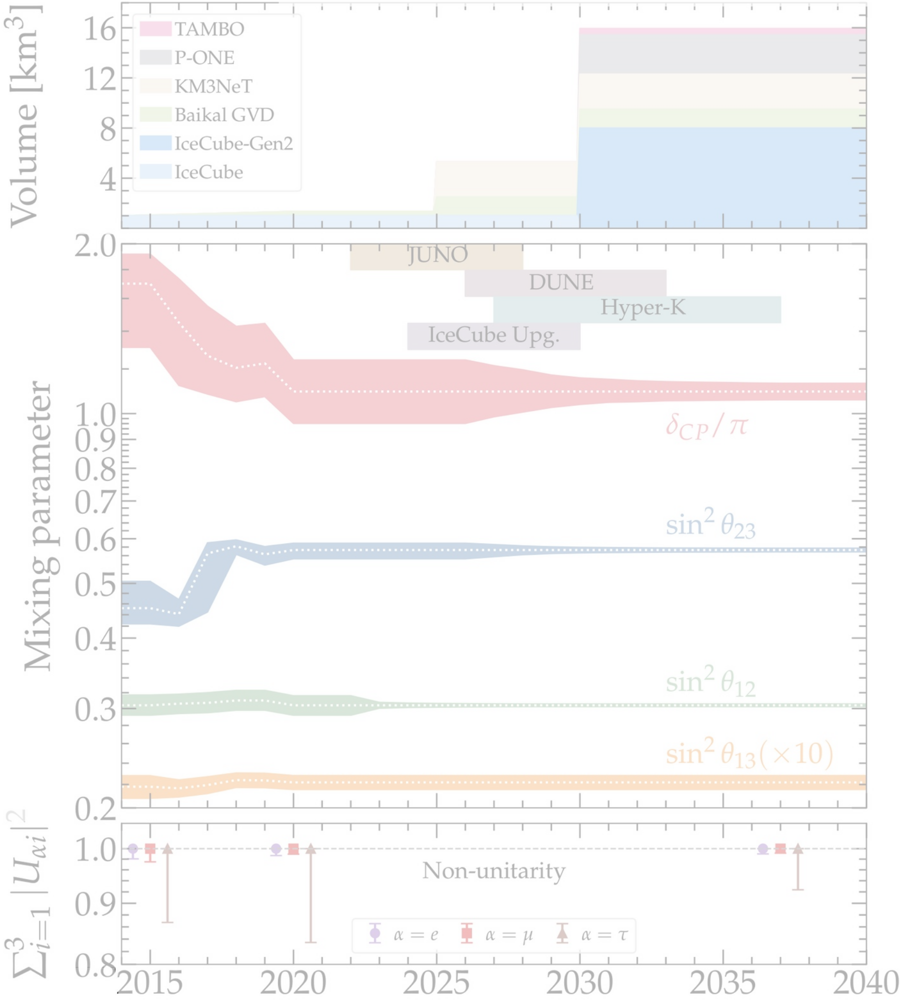
MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

Three reasons to be excited

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



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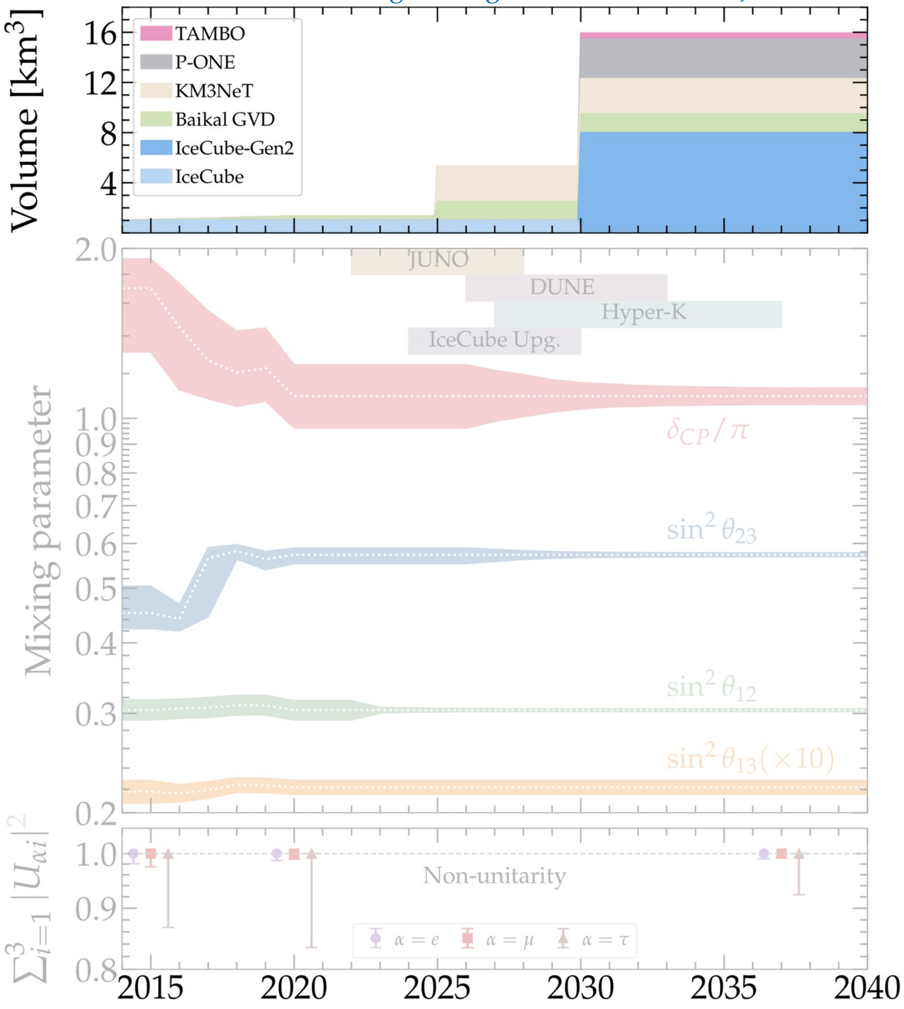

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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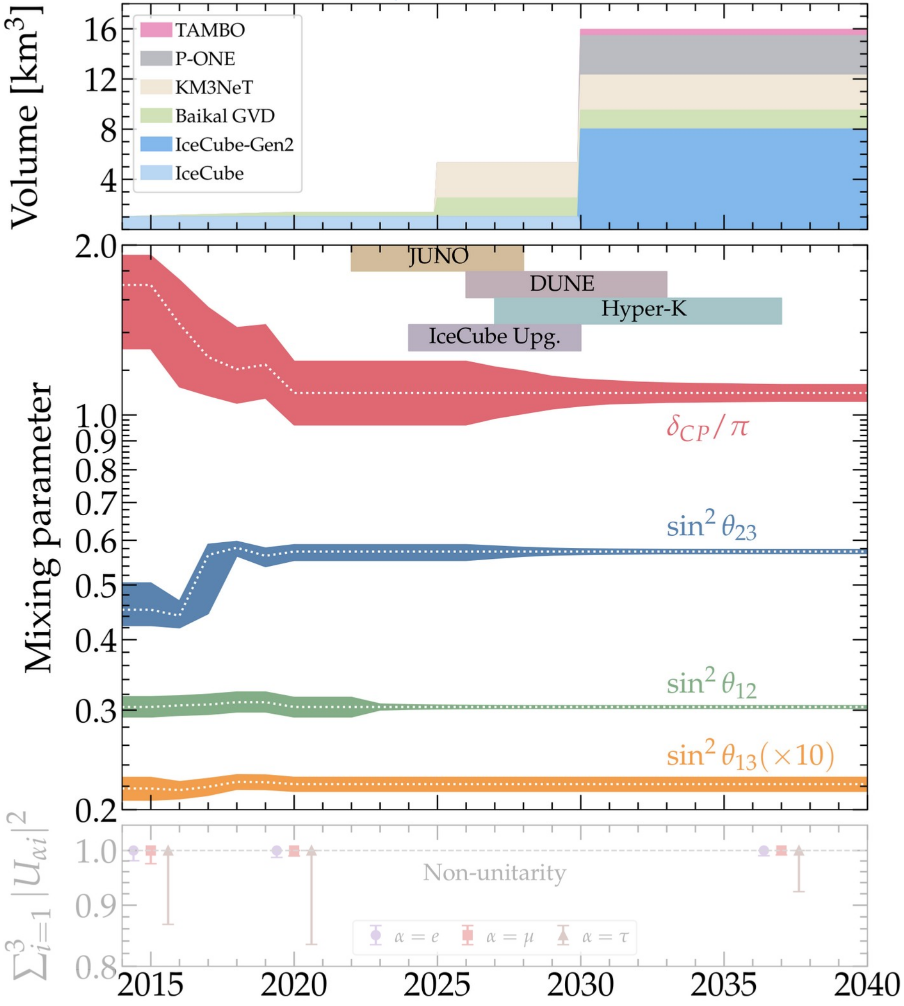
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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

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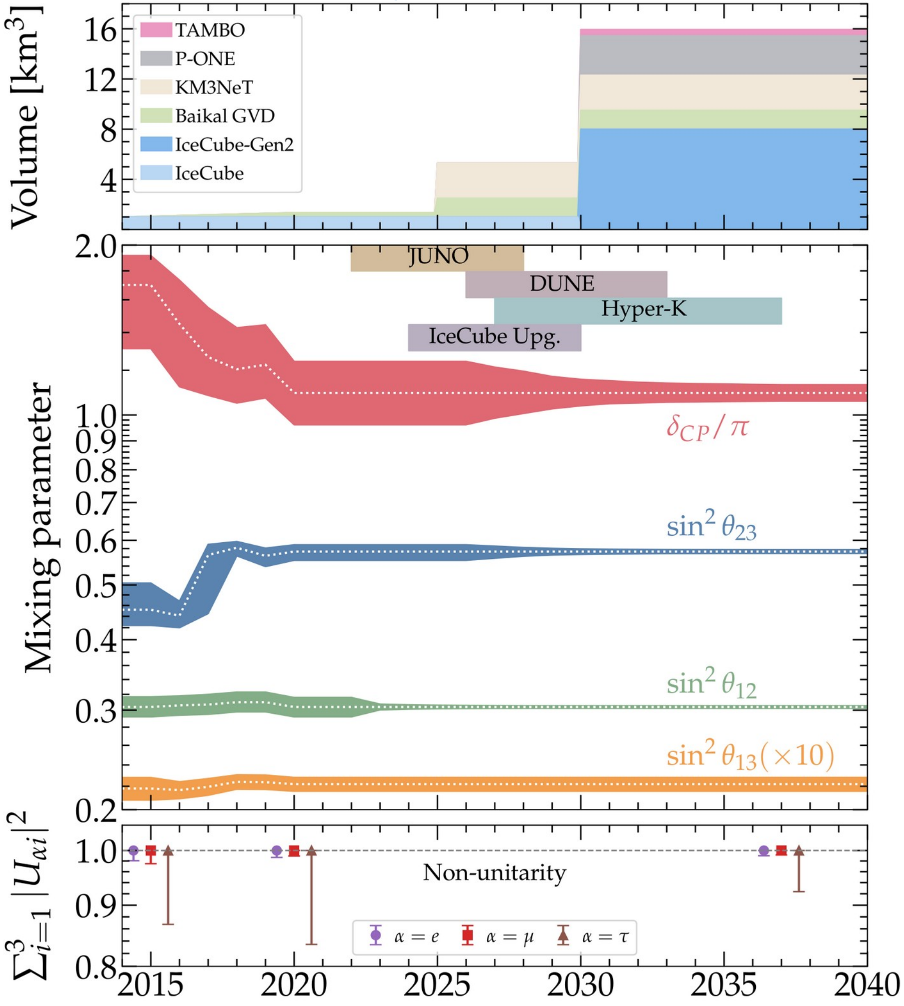


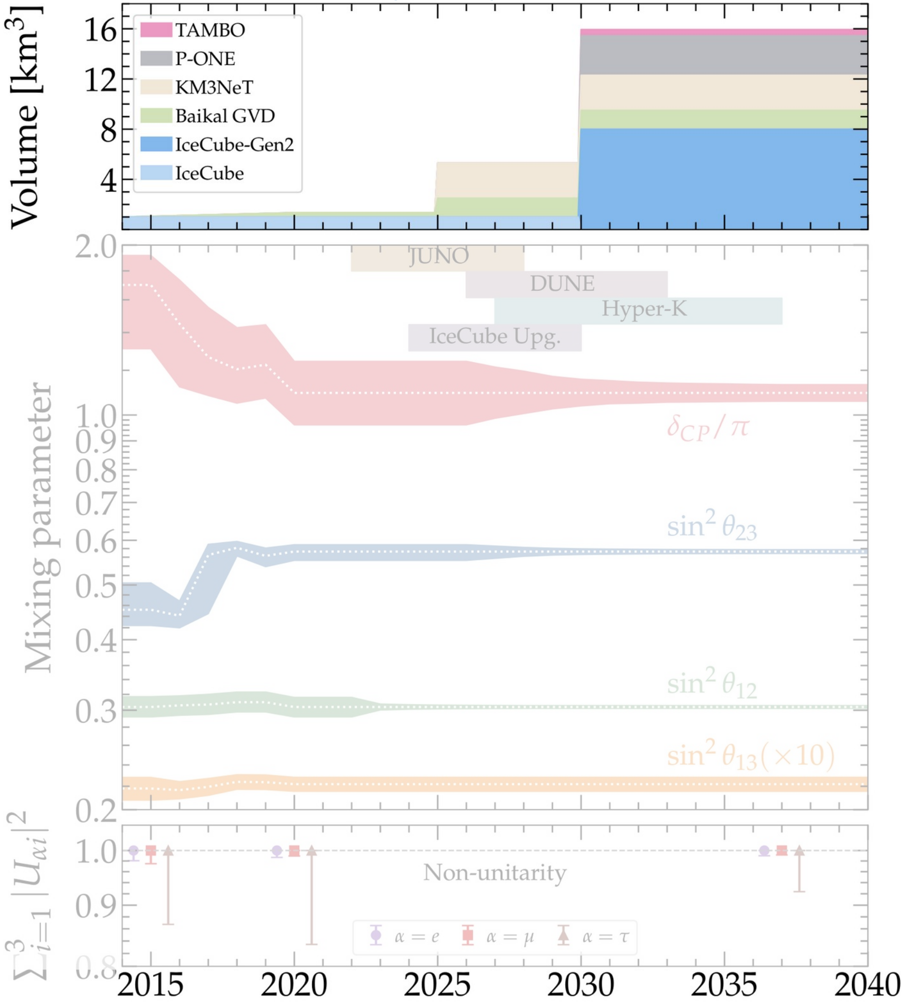
Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

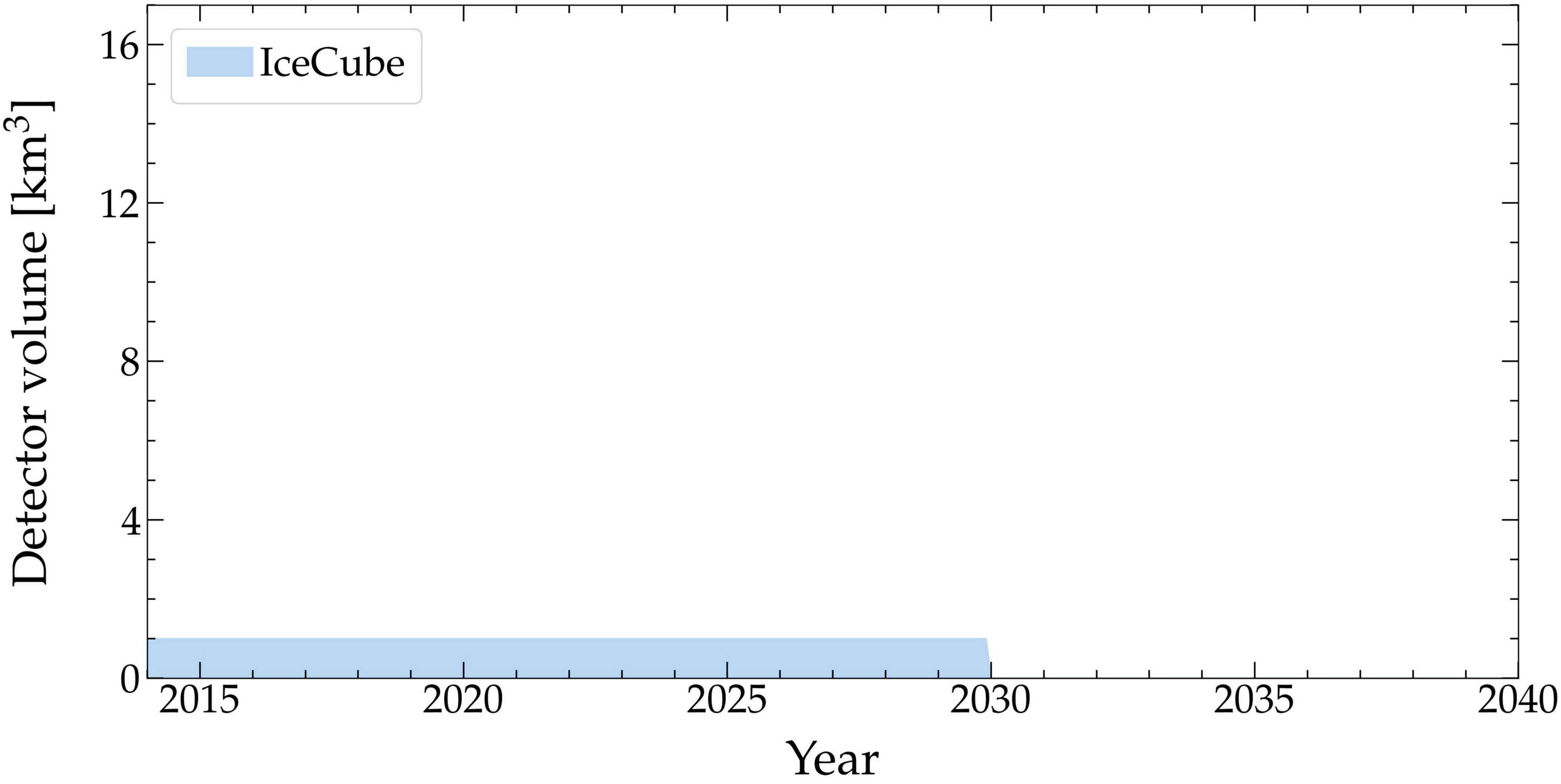
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

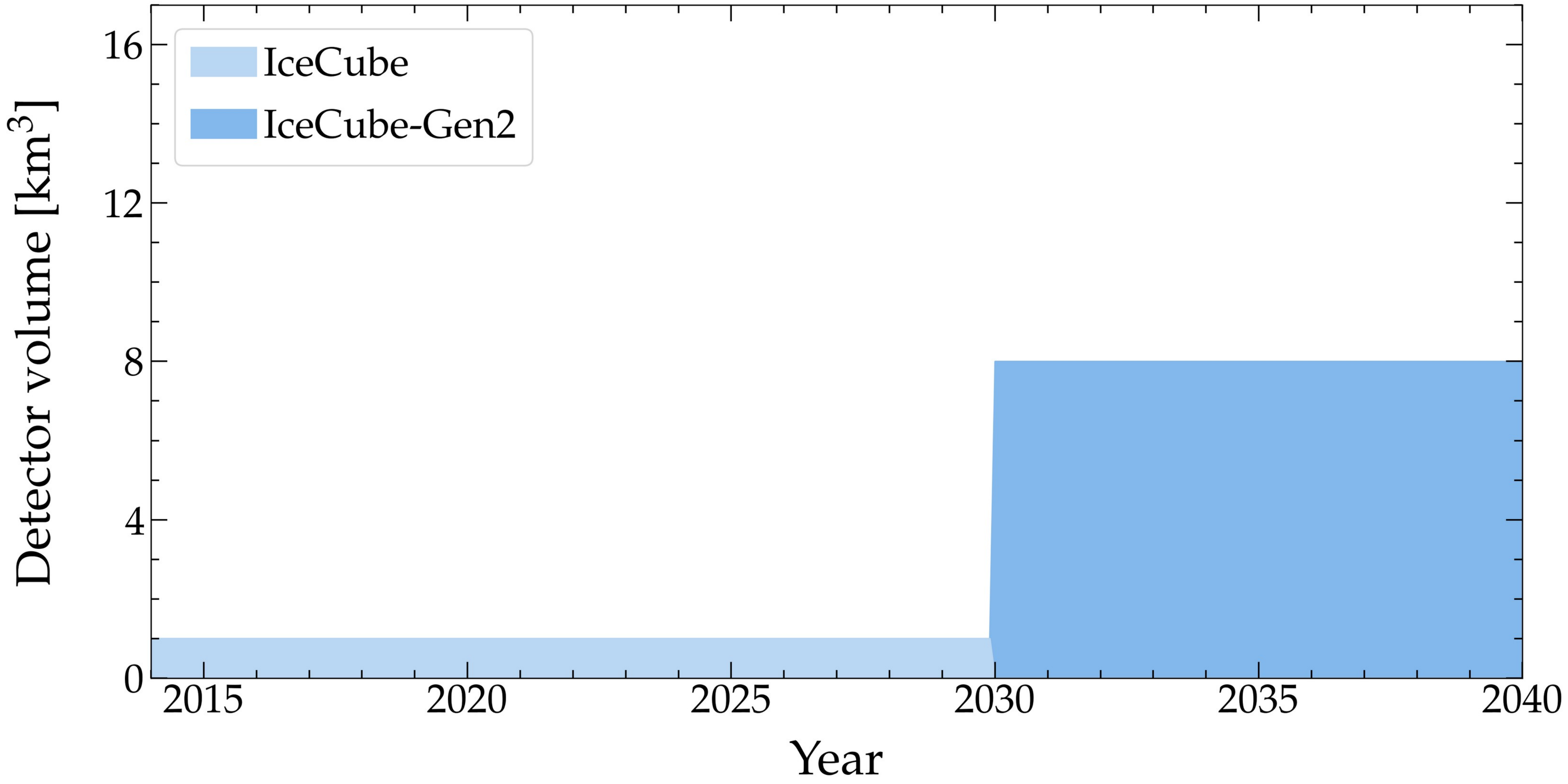
Measuring flavor composition: 2015–2040

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

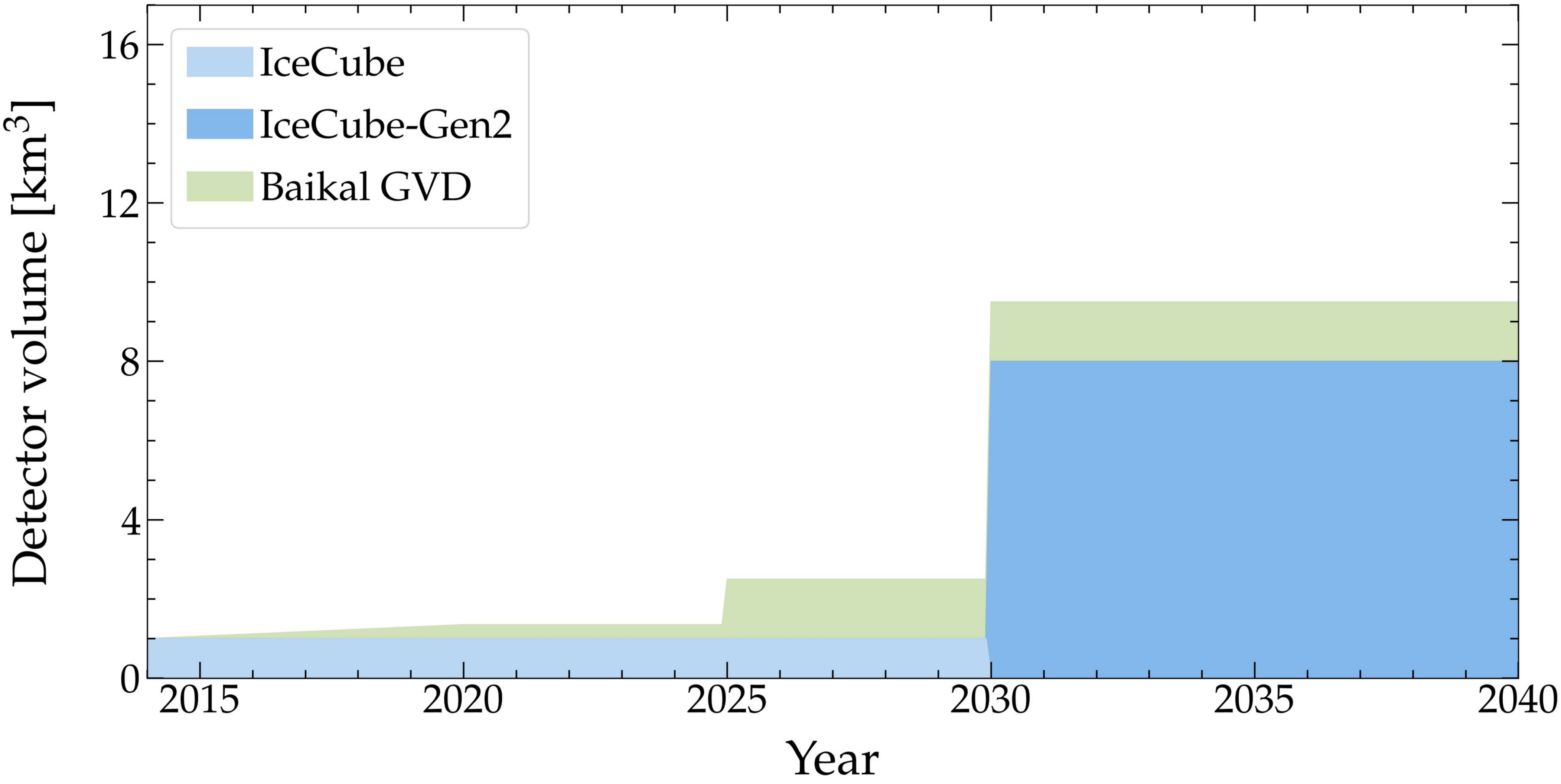




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



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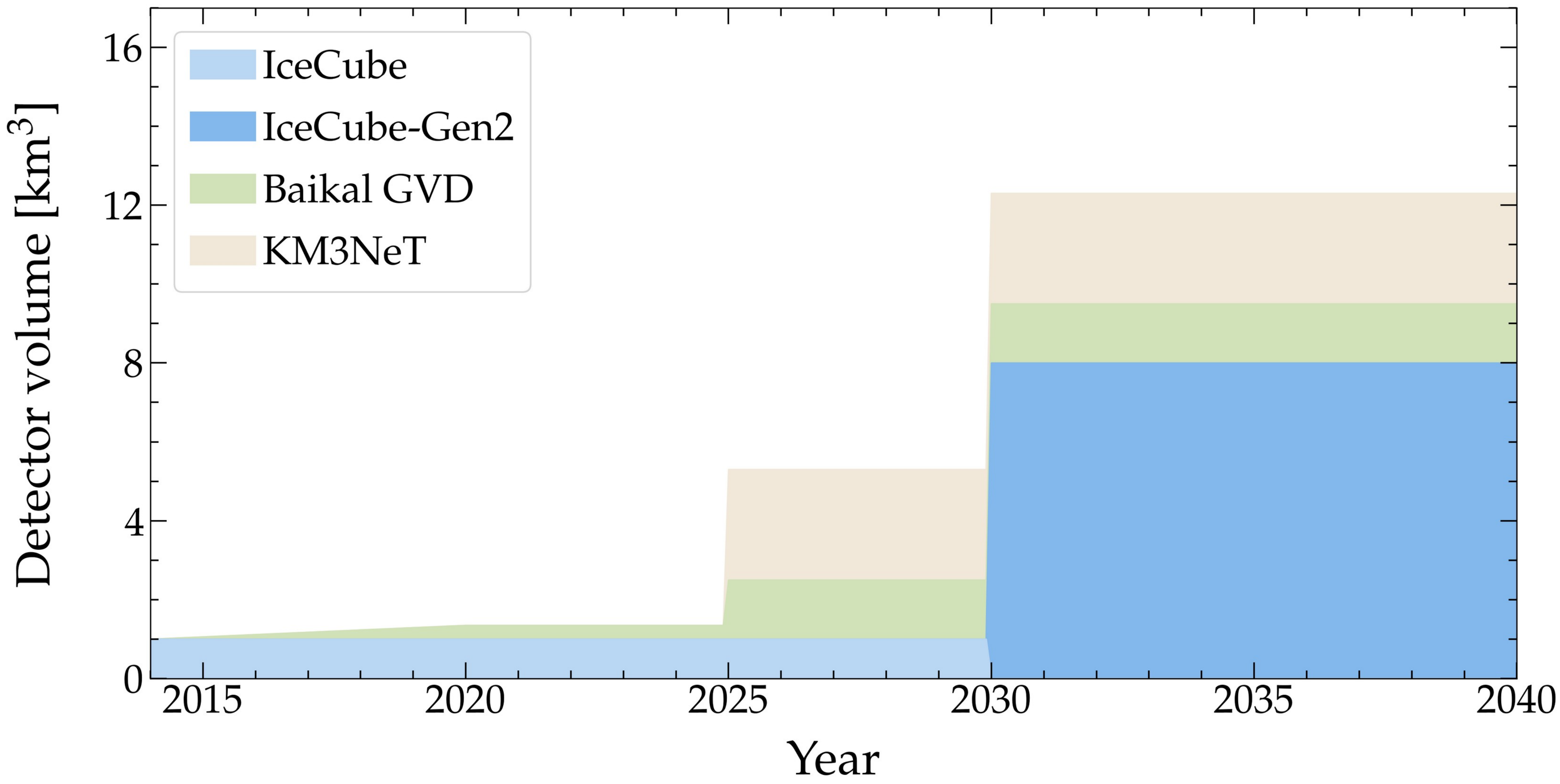

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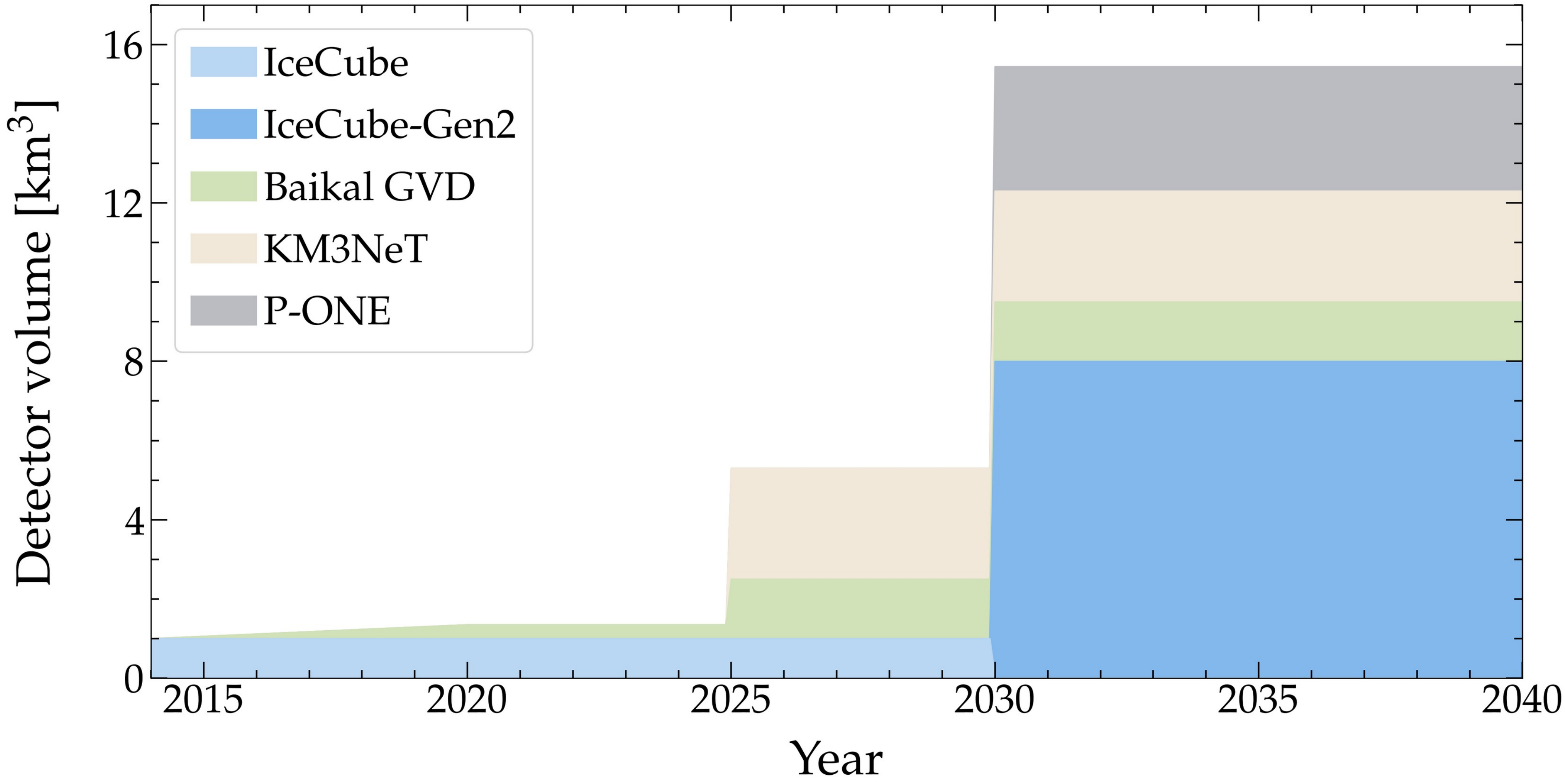

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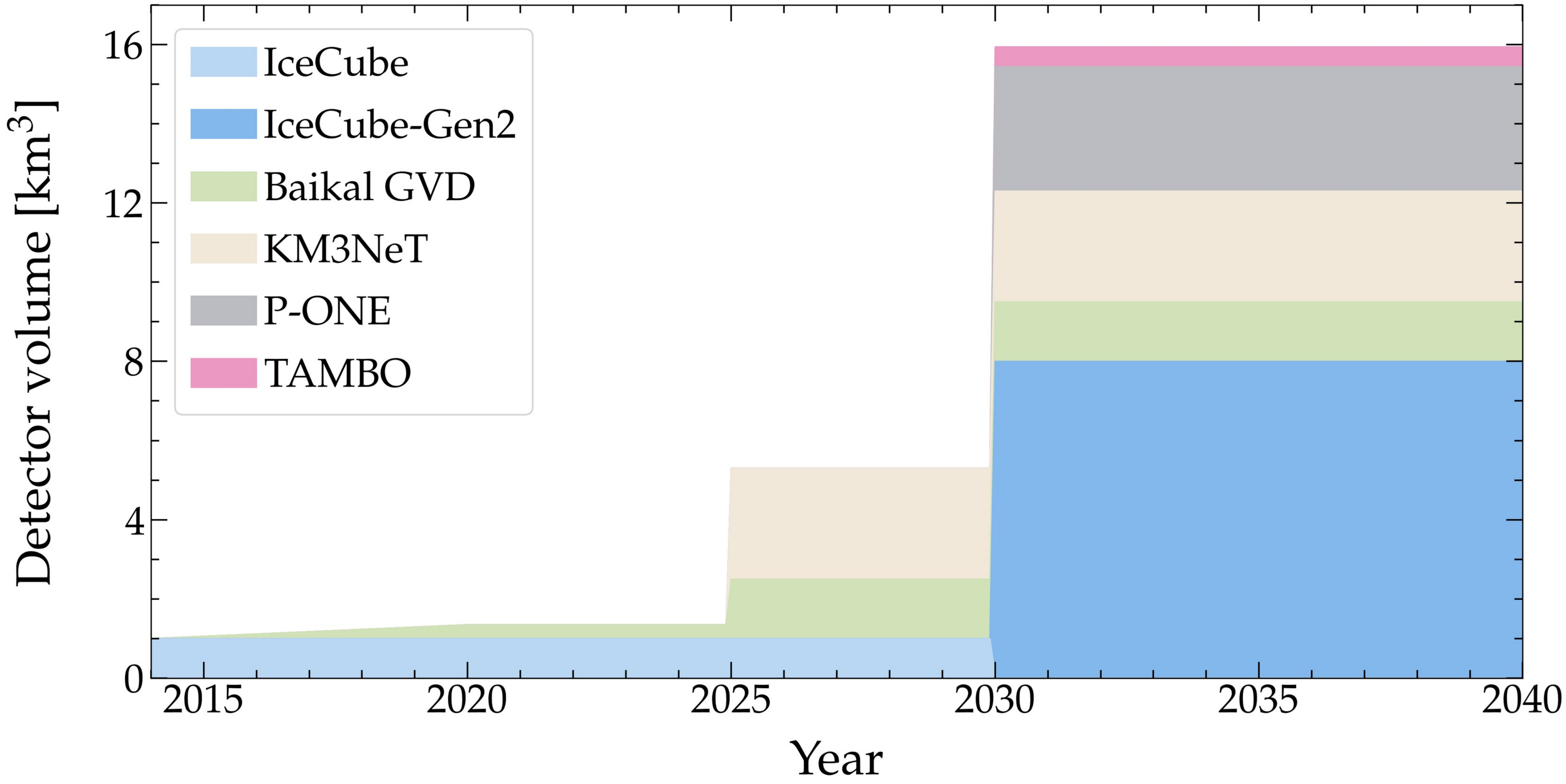

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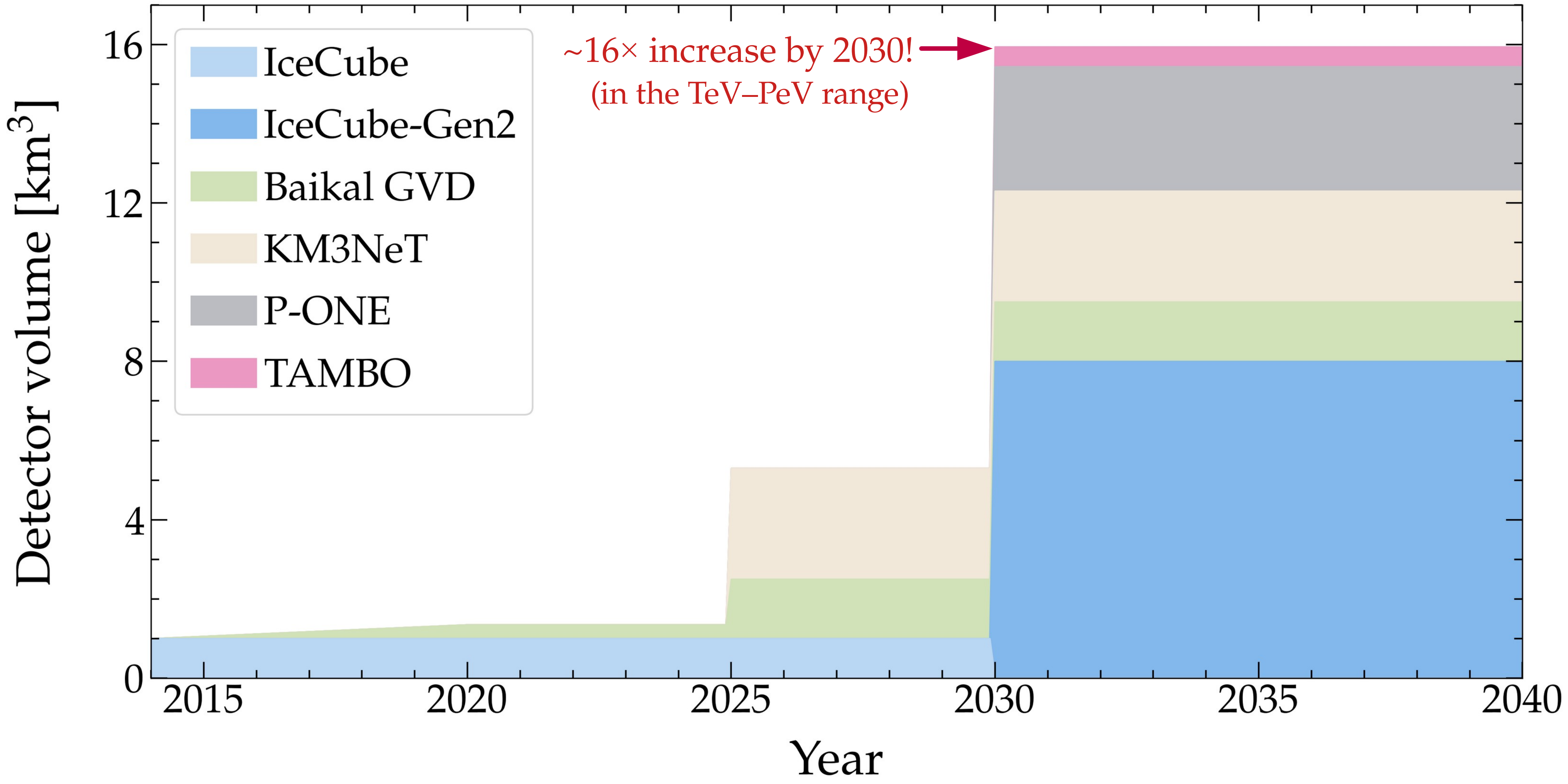
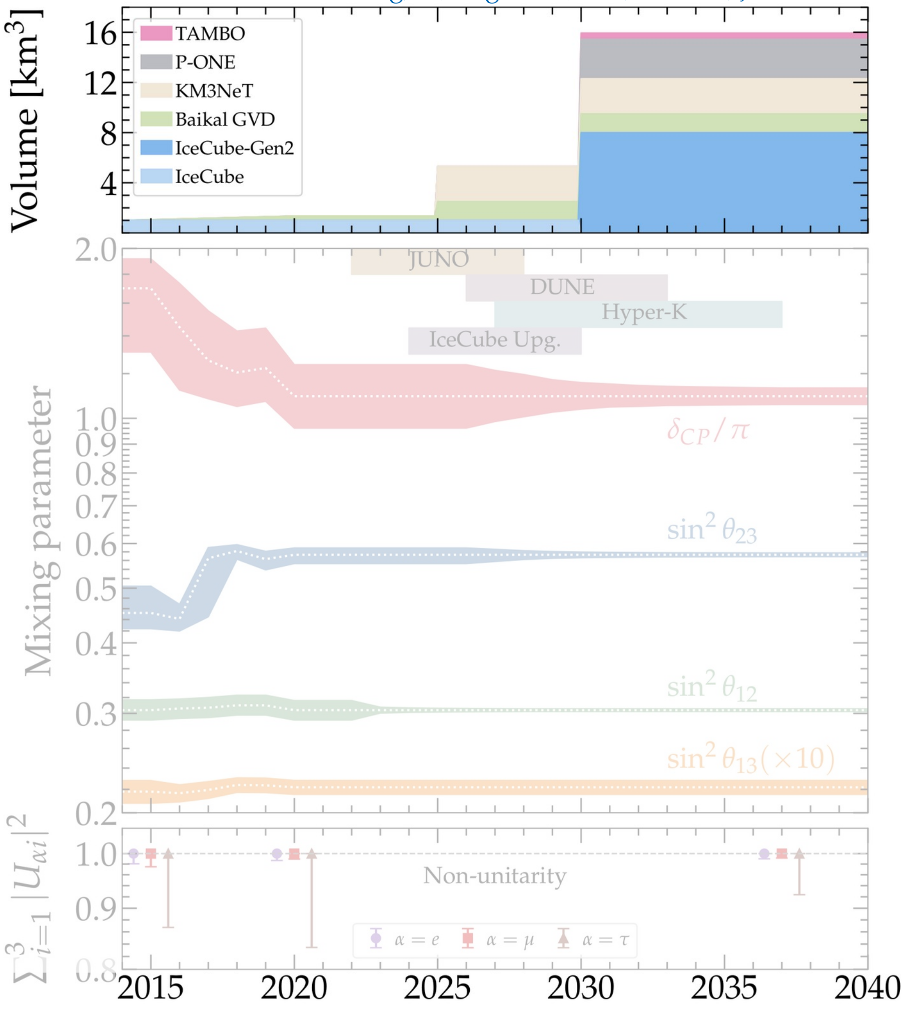


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

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



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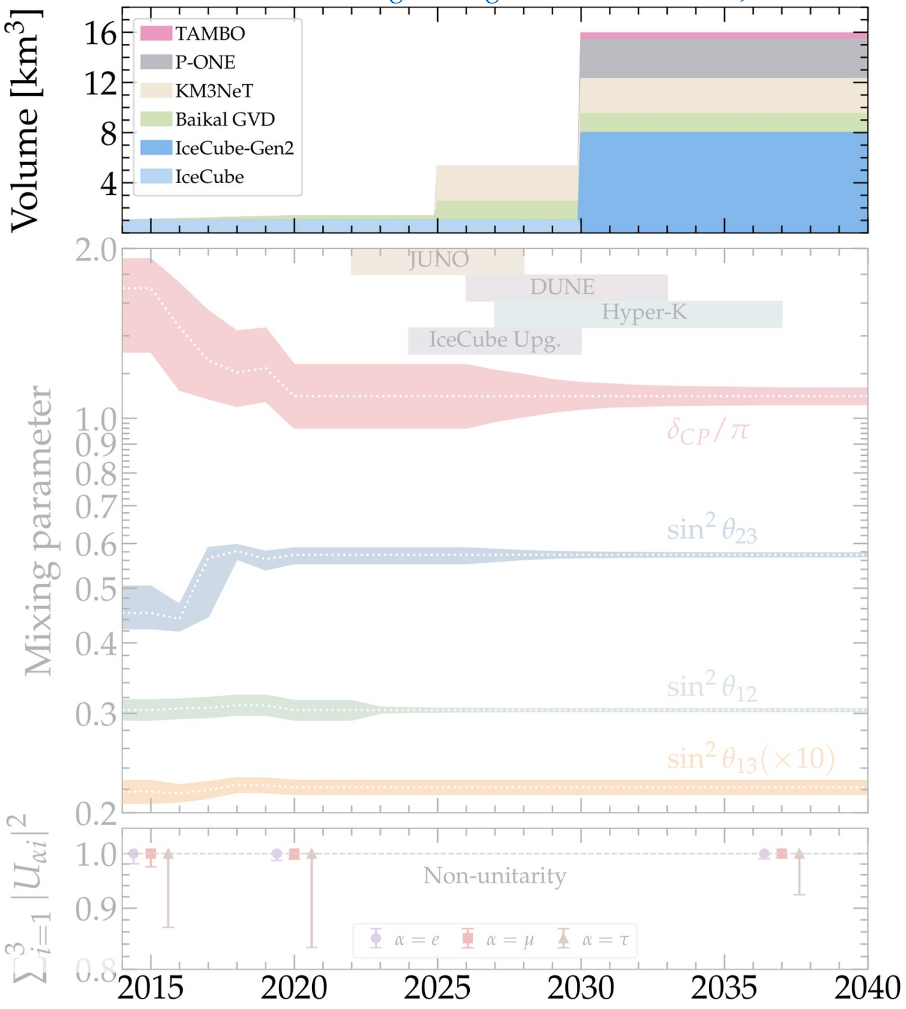

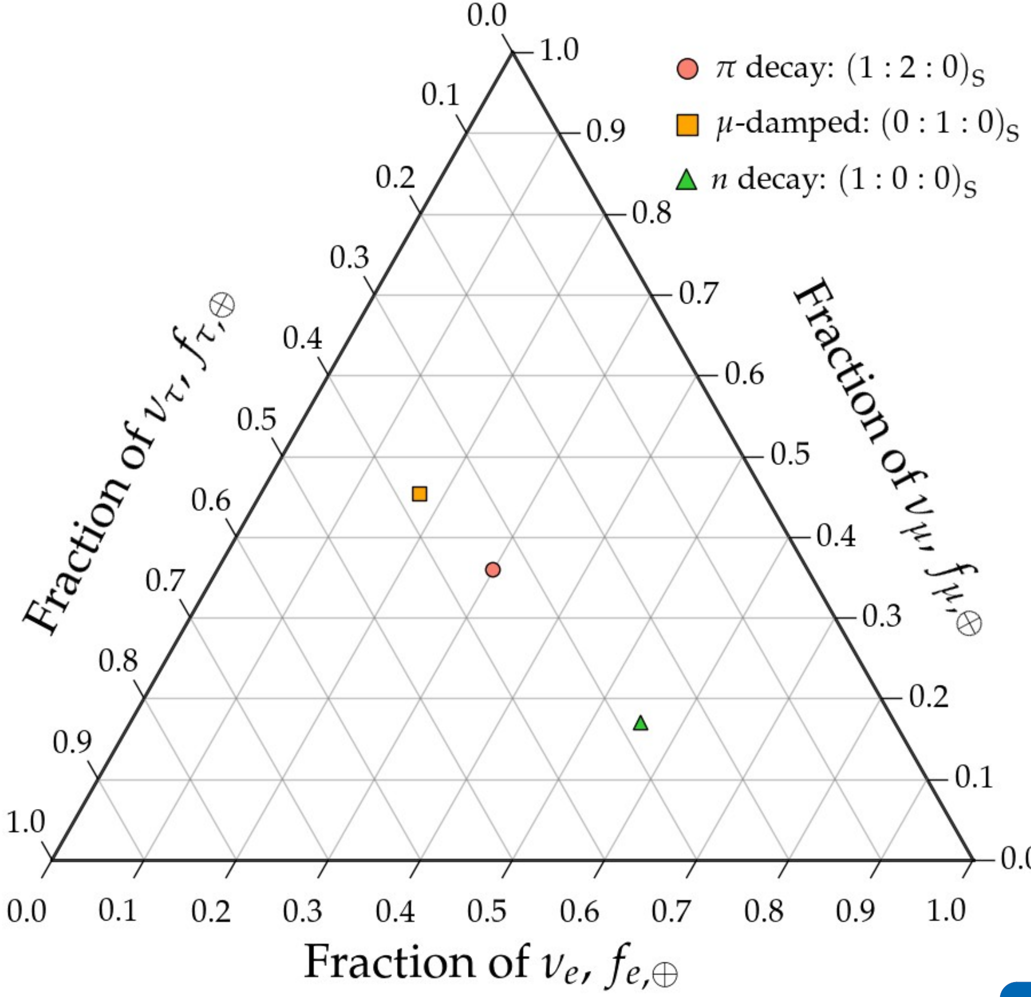

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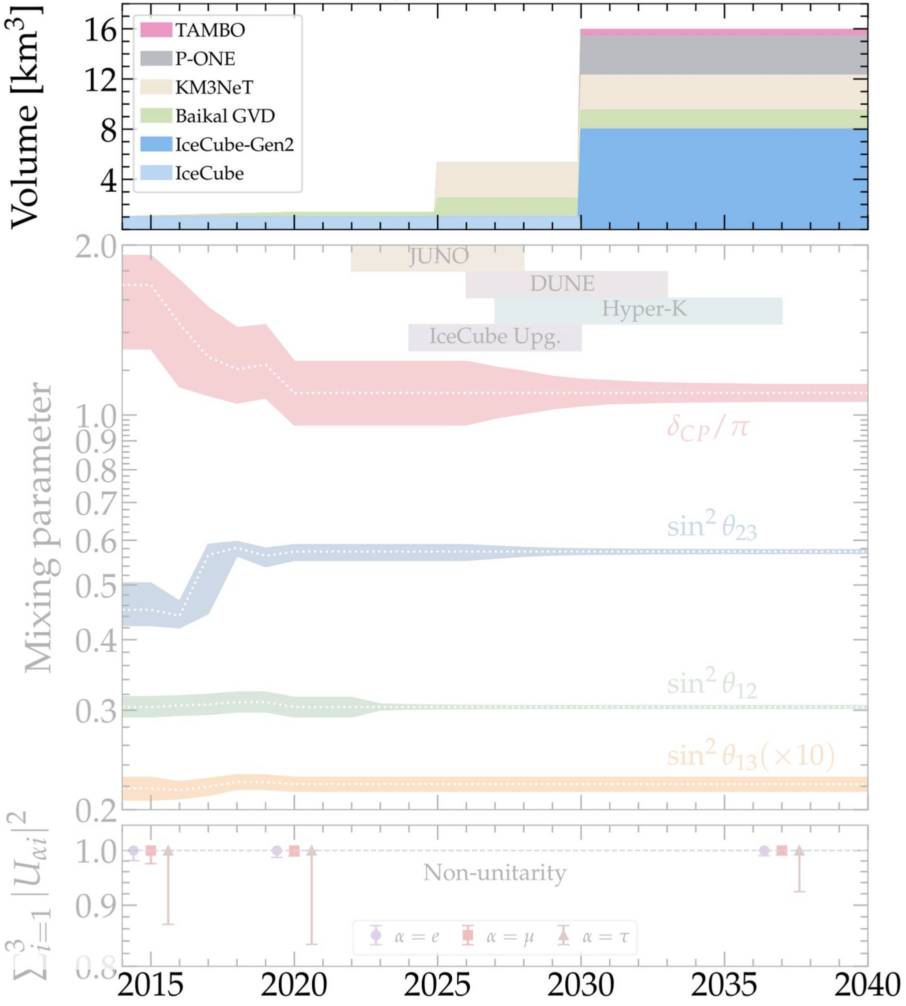

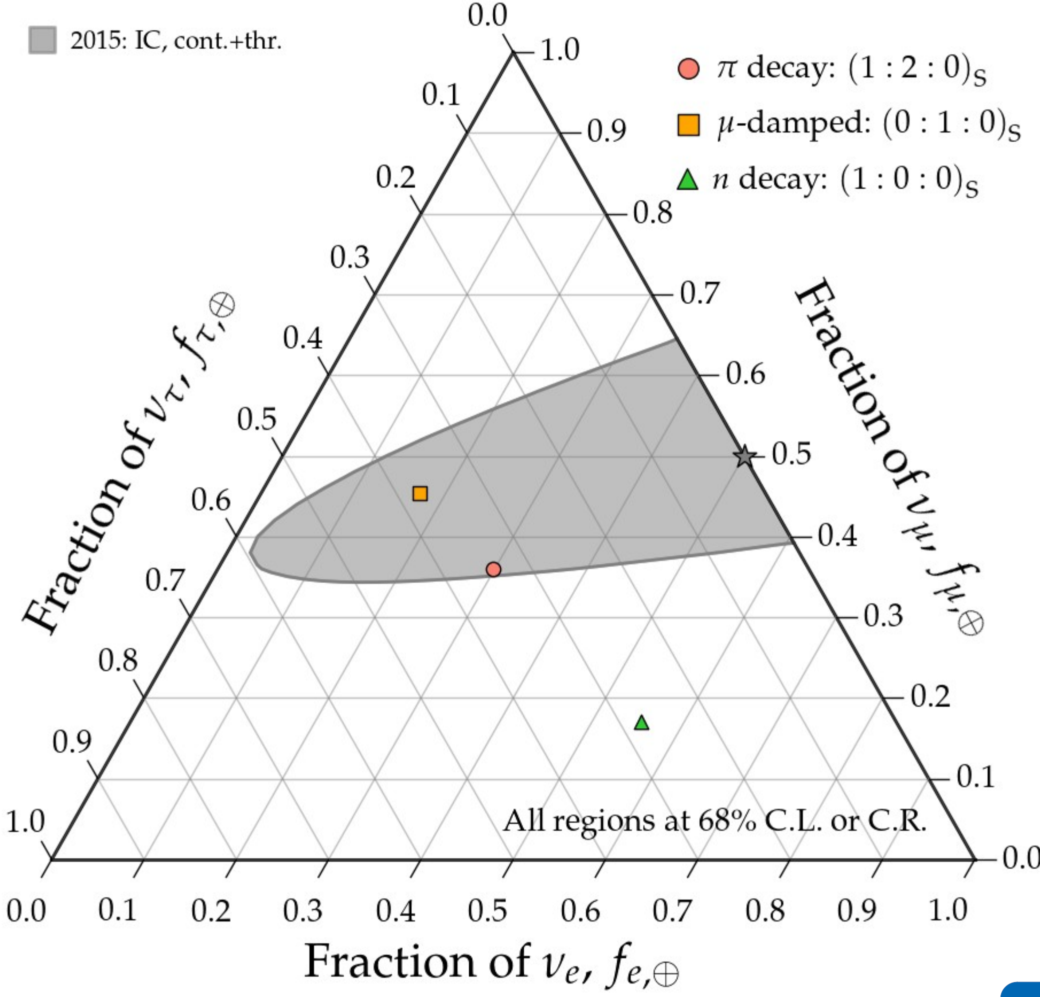

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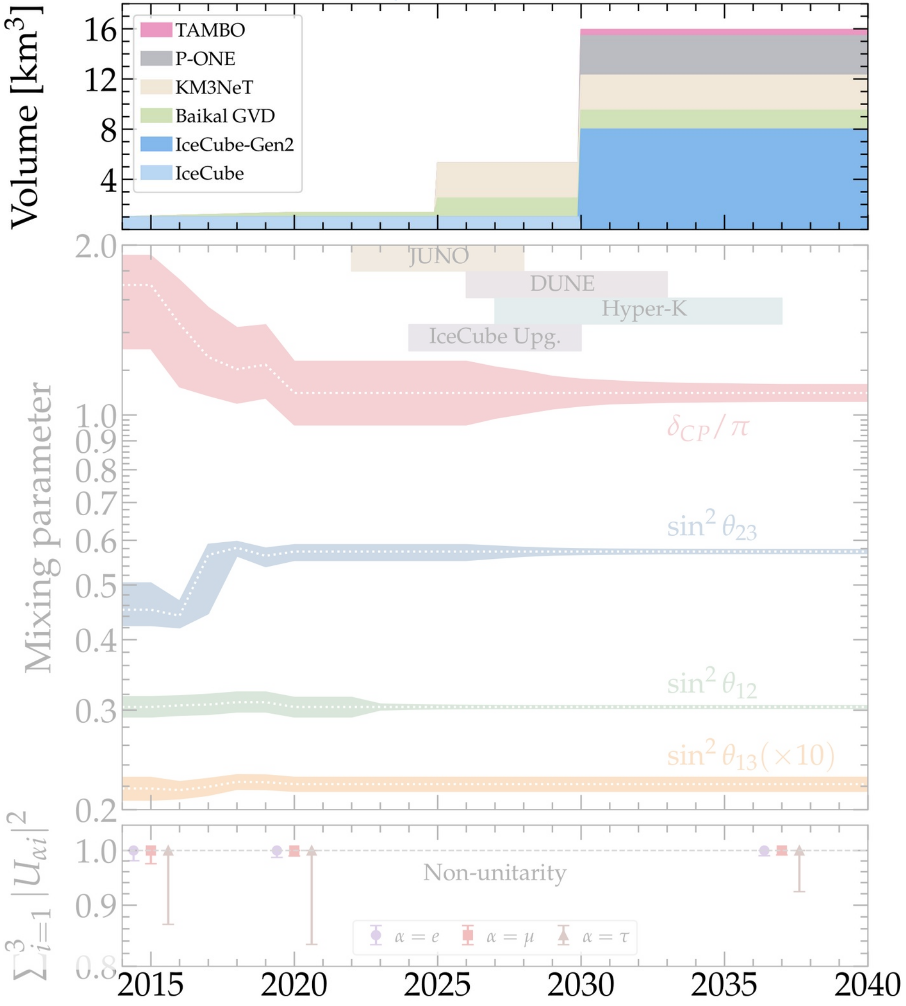

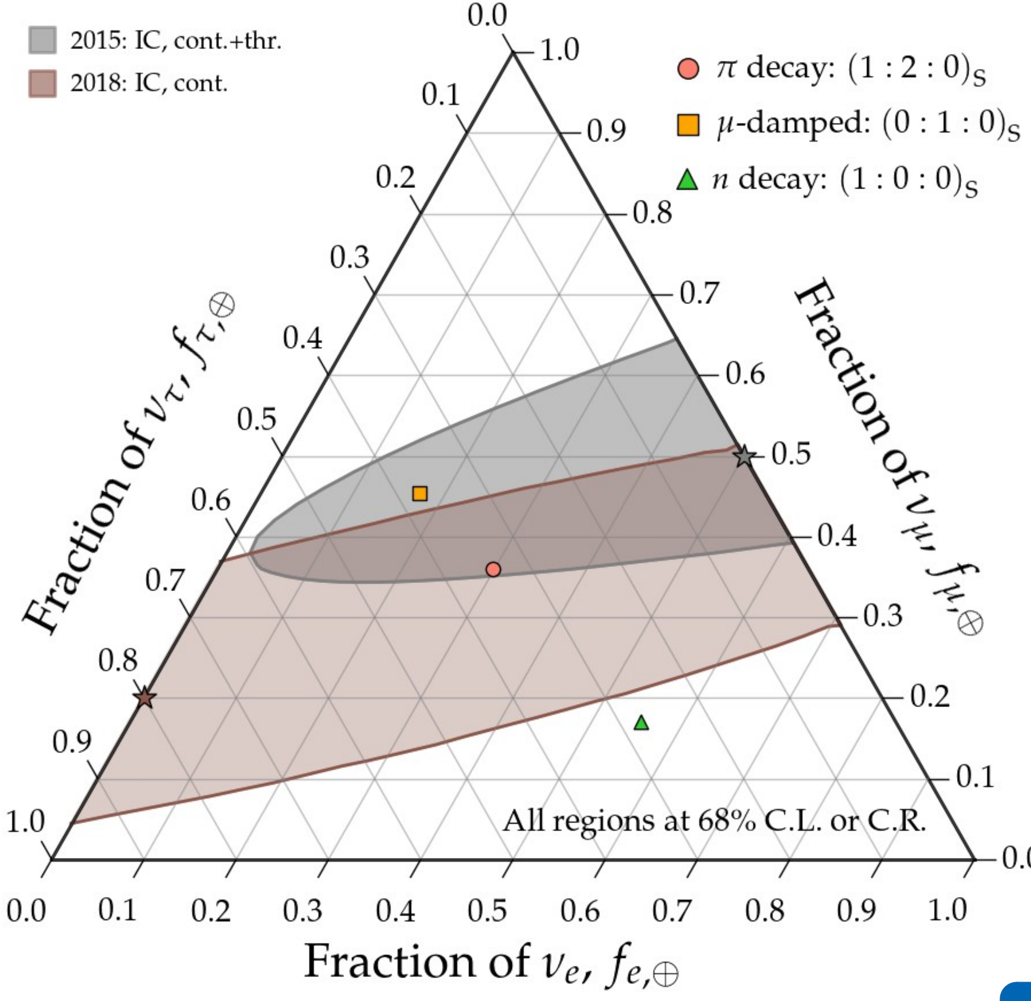

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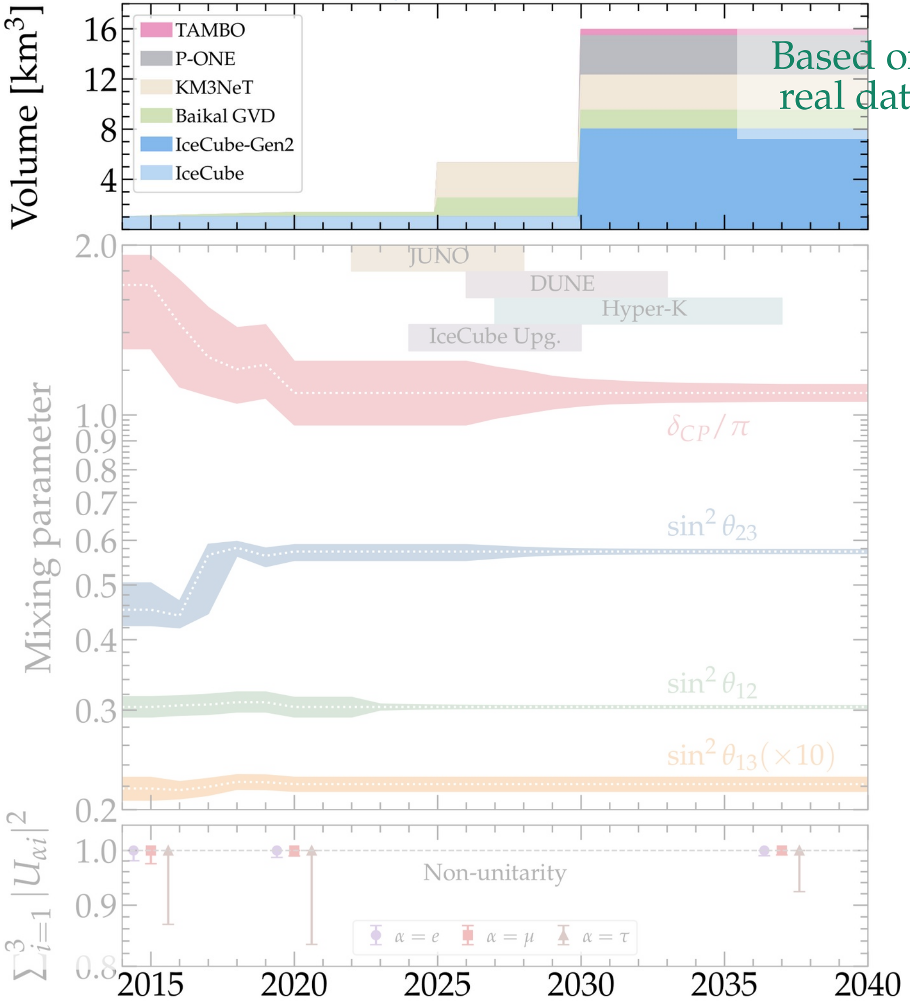

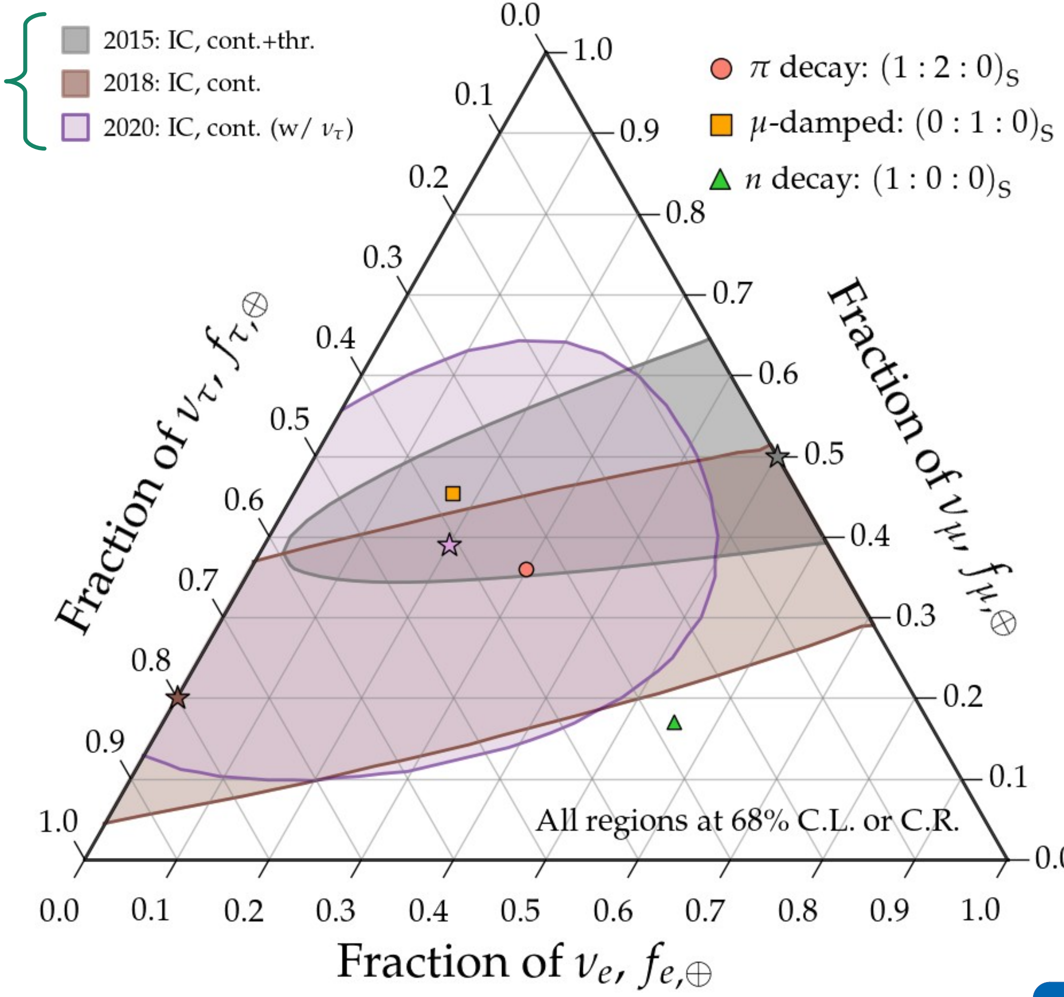

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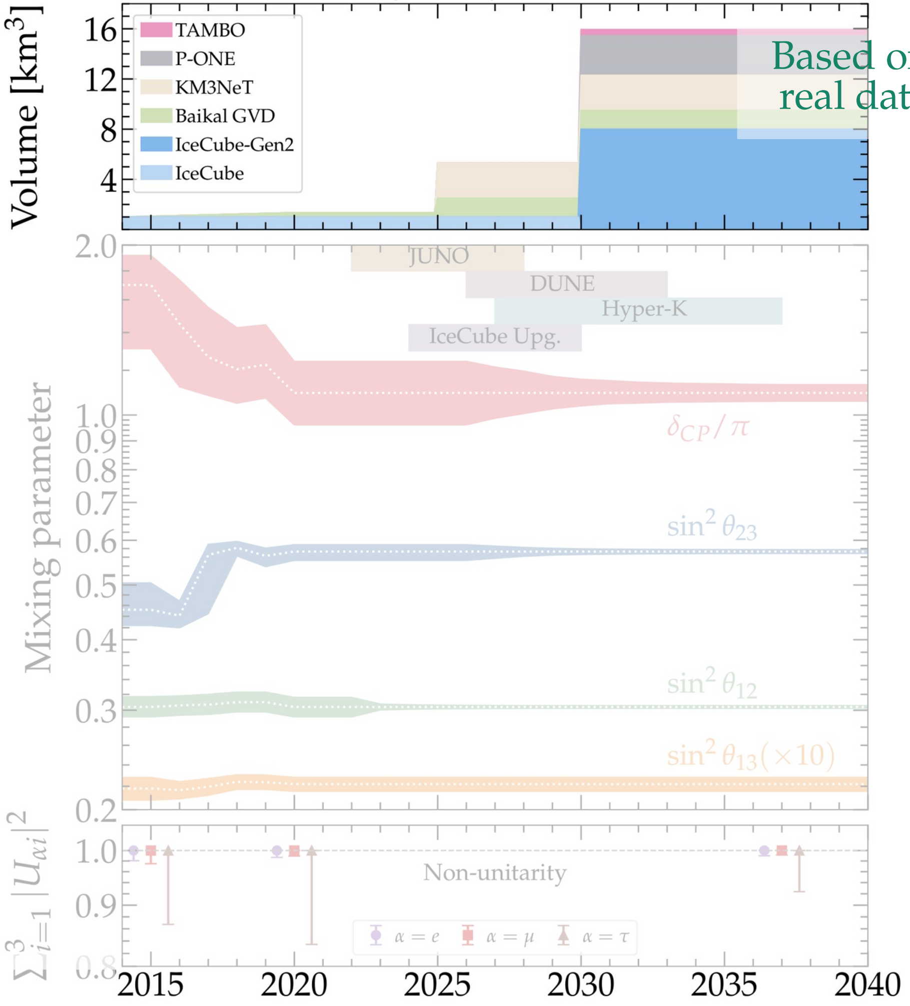
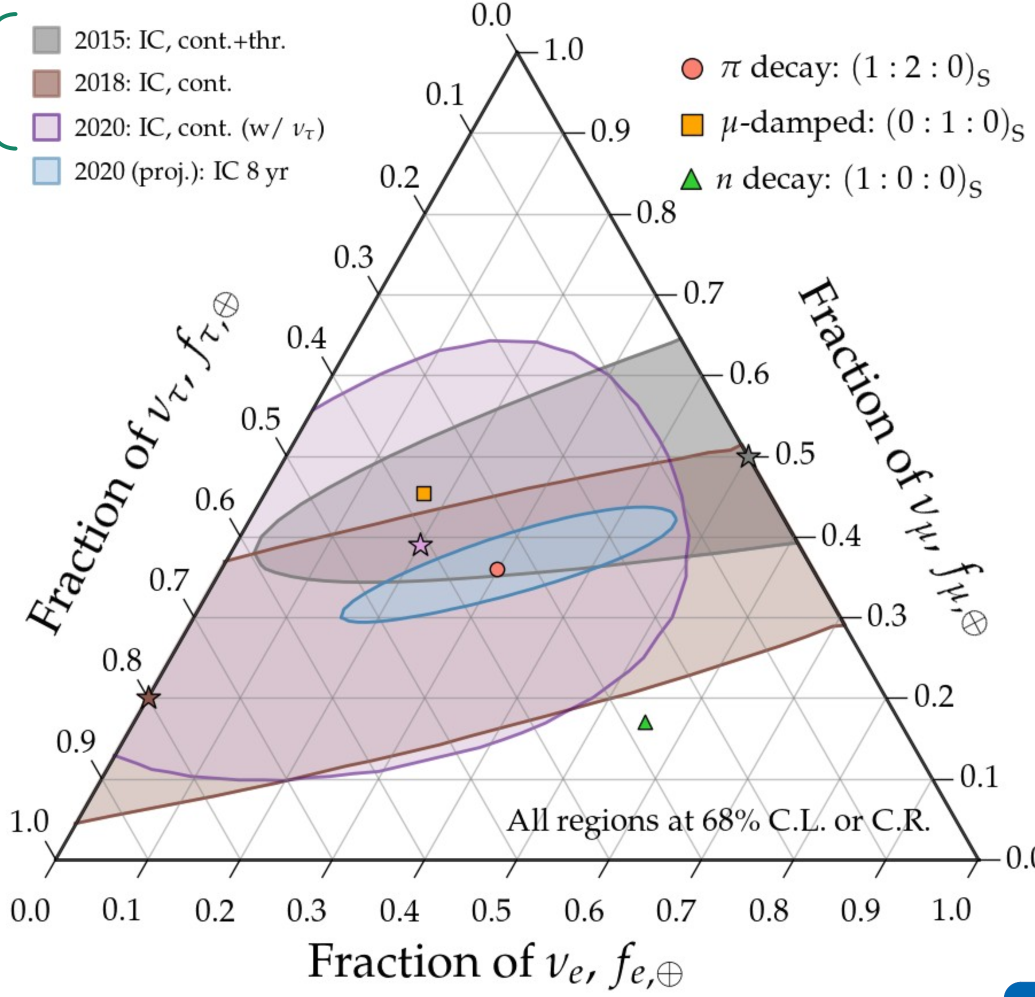


Based on real data



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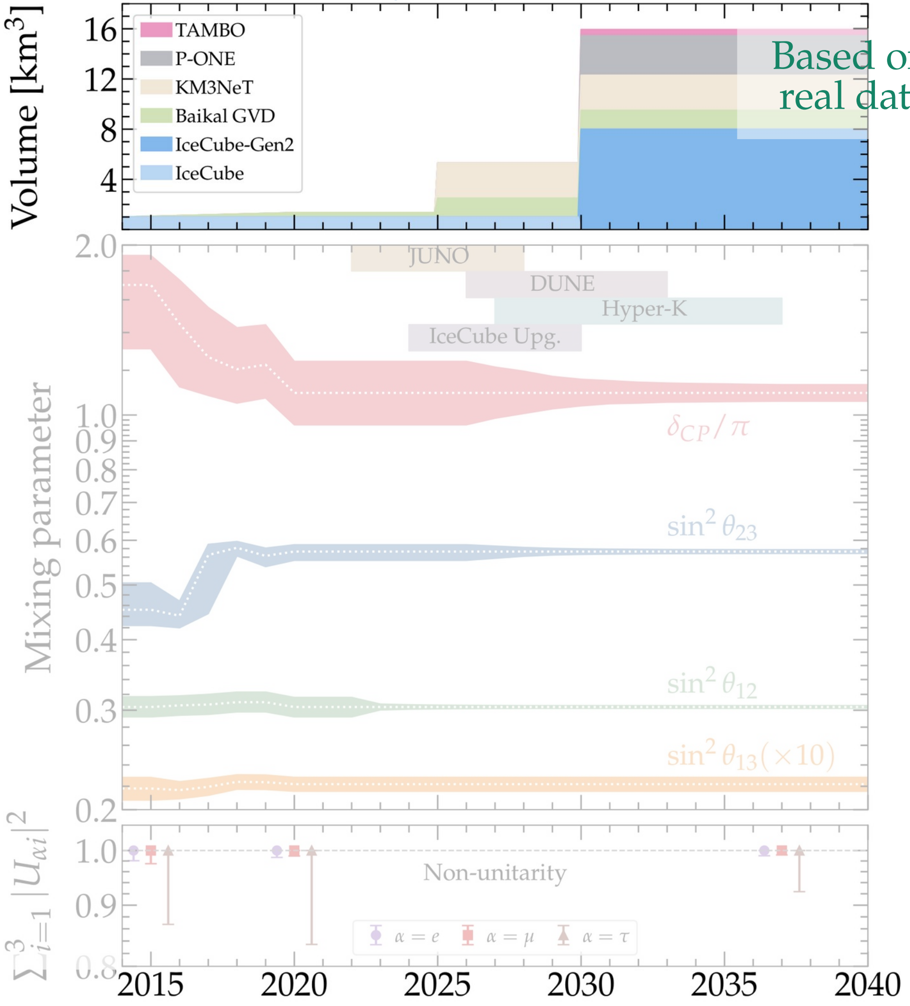

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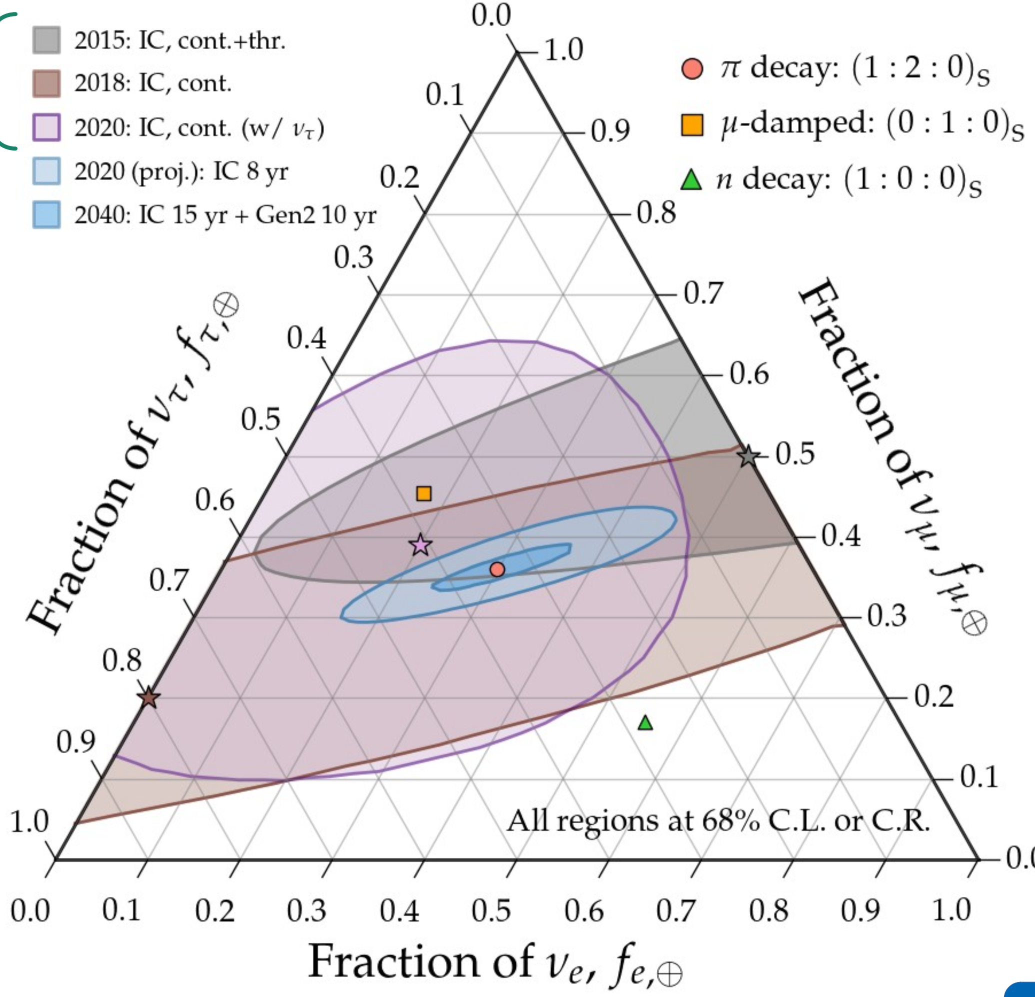

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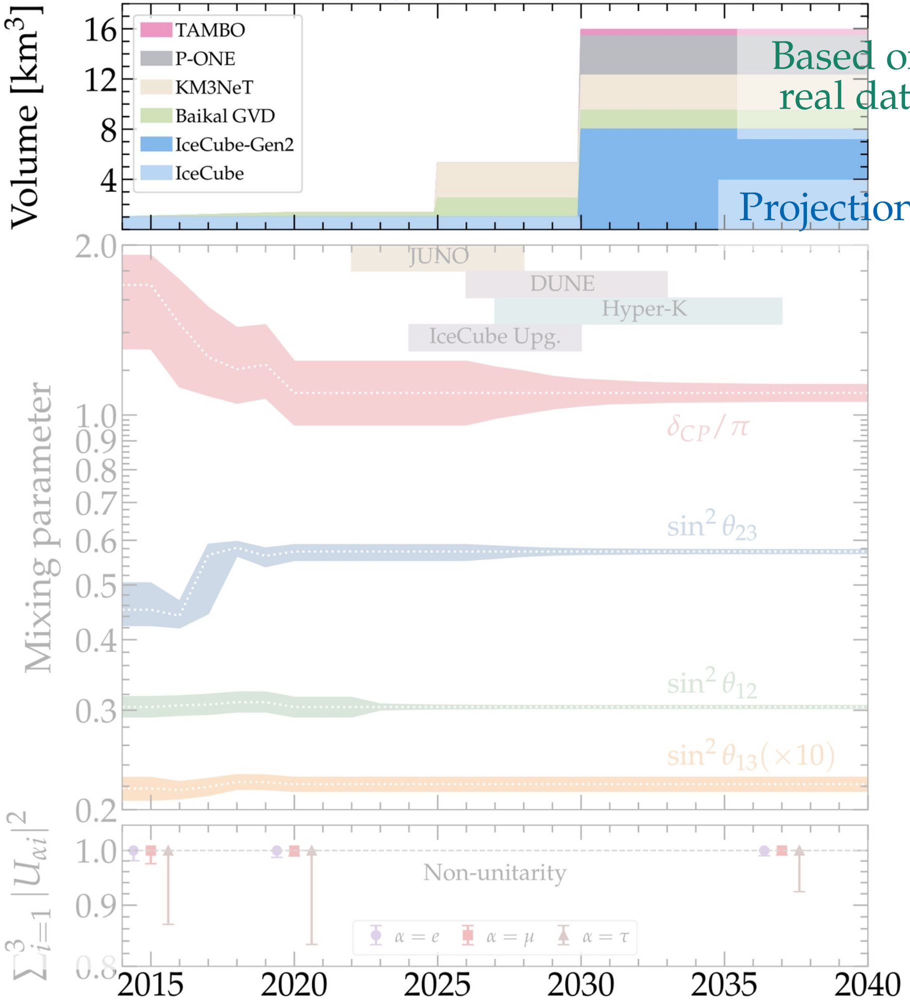
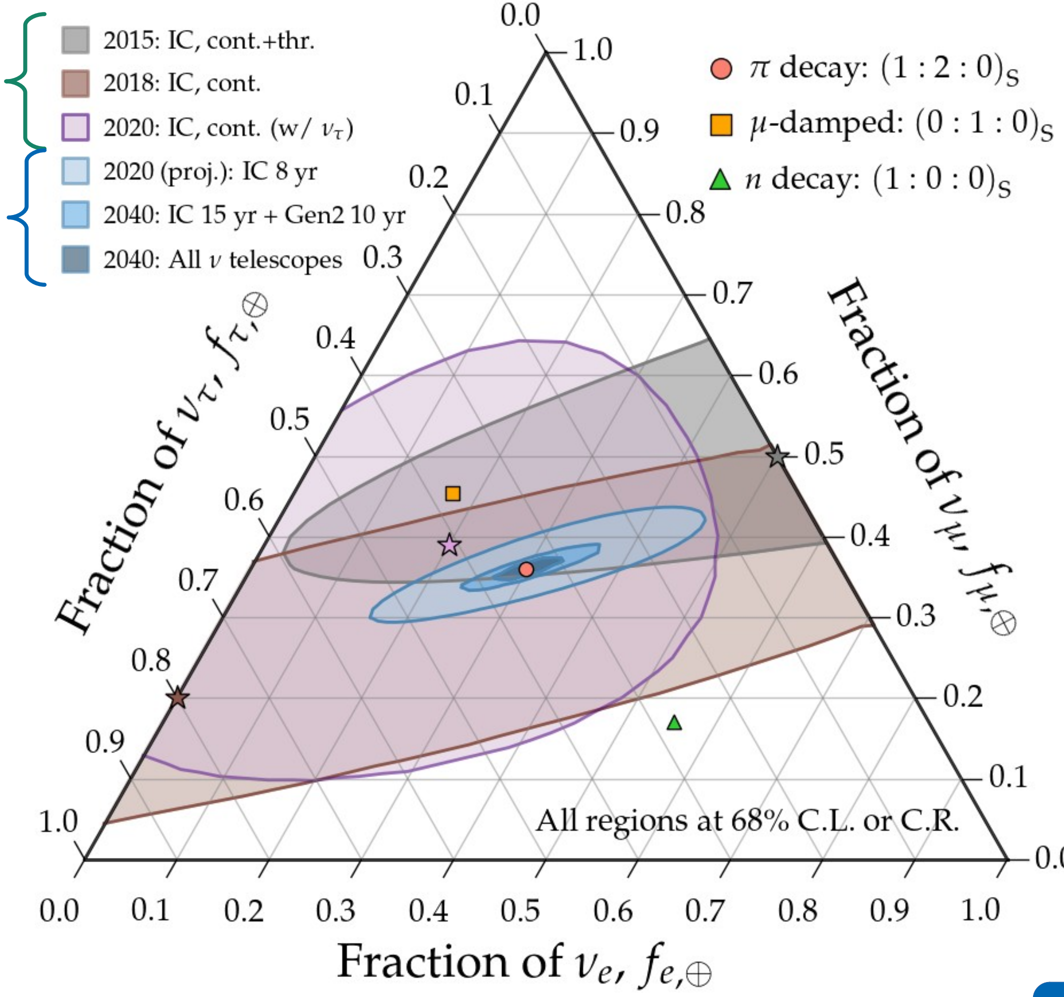
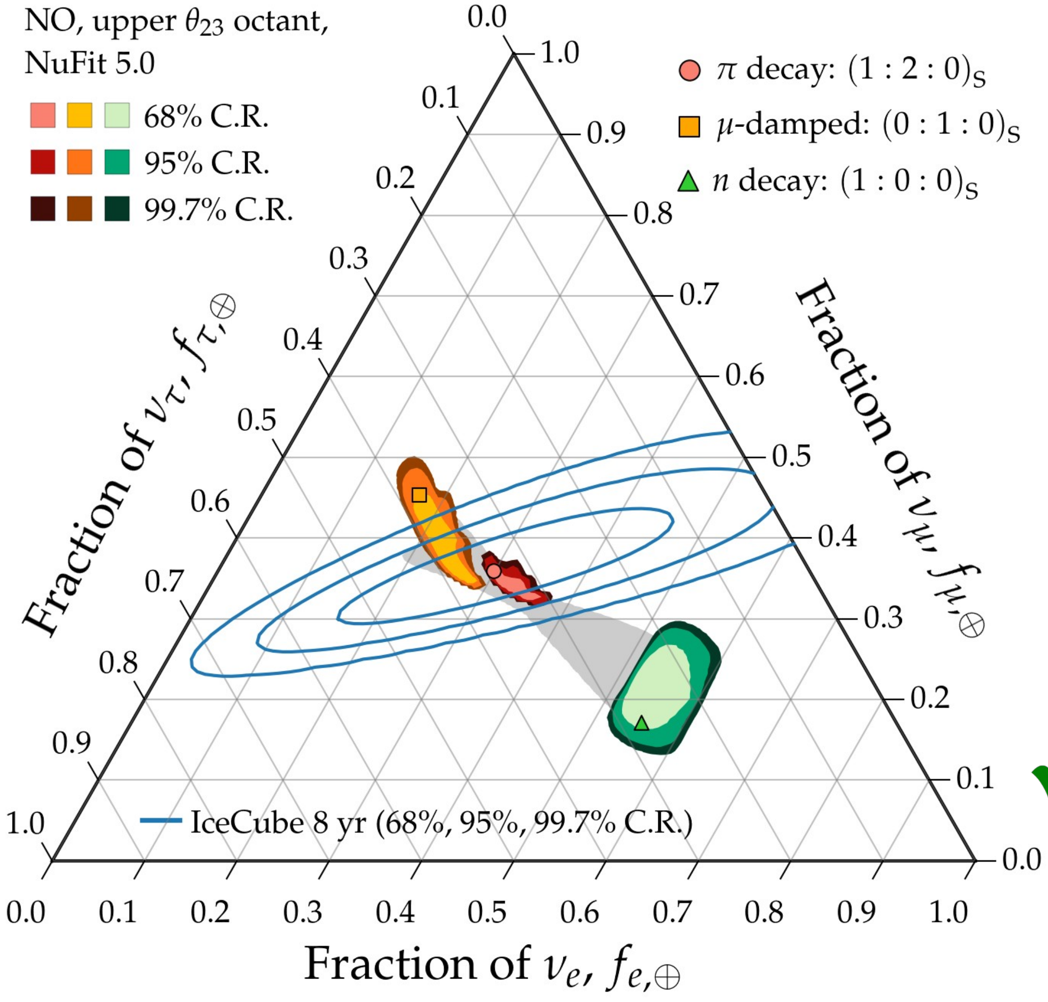




Theoretically palatable regions: today (2021)



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Insufficient precision in the mixing parameters

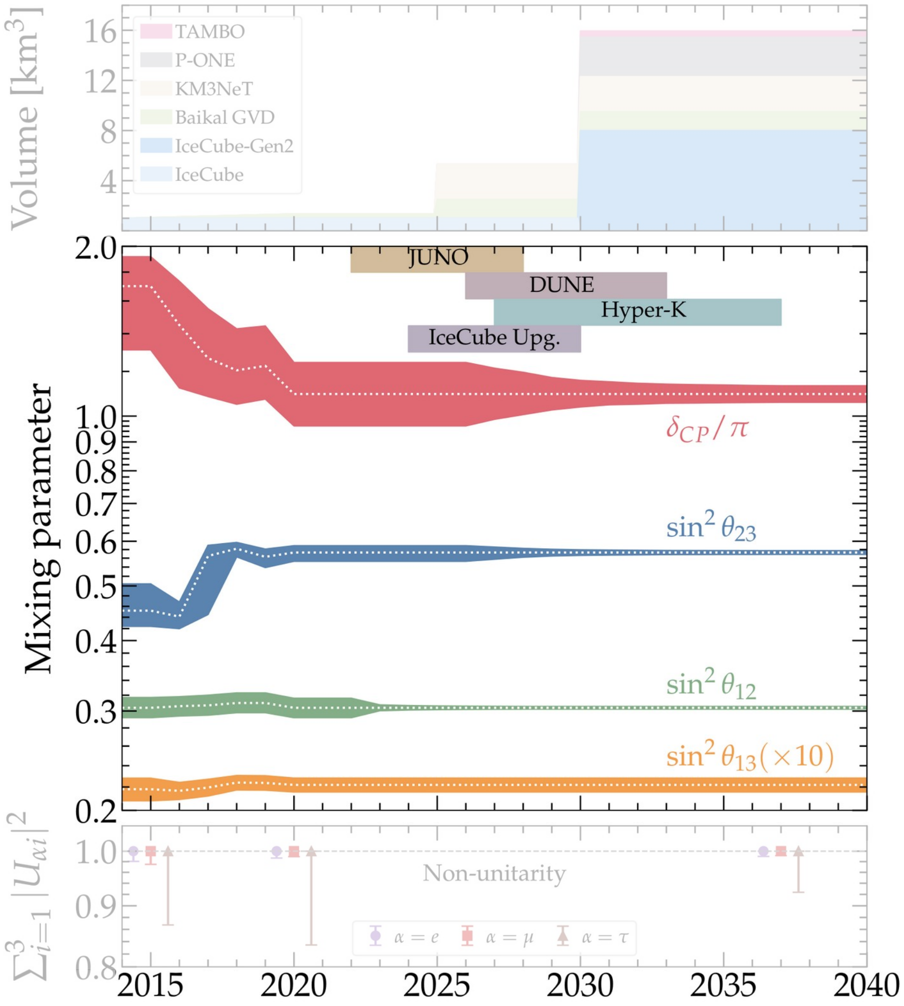
Will be overcome by 2030

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

✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps

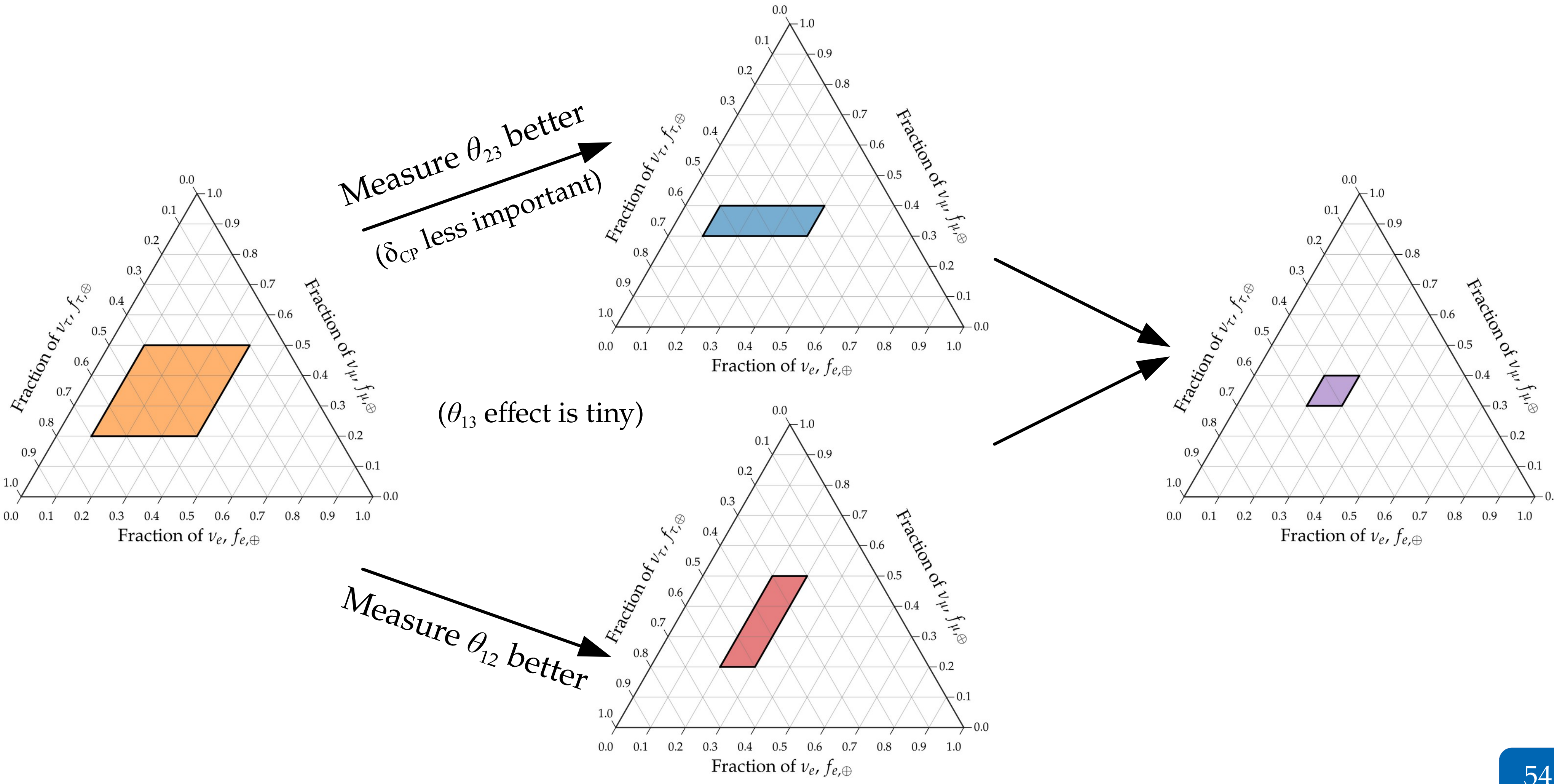


We can compute the oscillation probability more precisely:

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

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

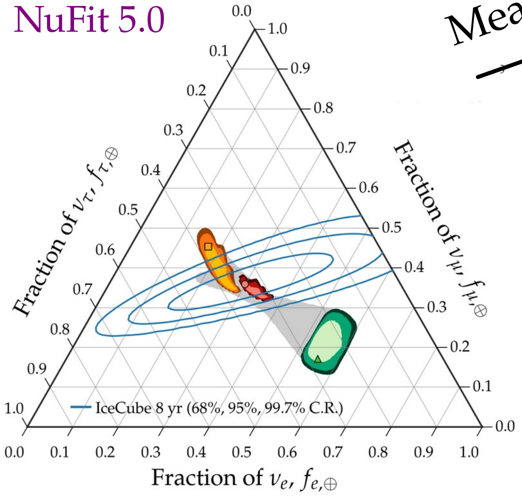
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

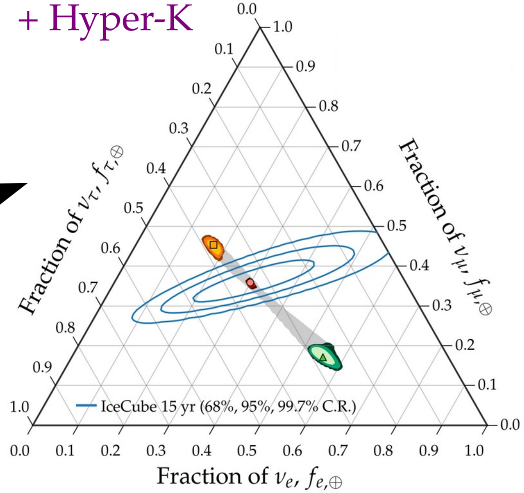
2020

NuFit 5.0



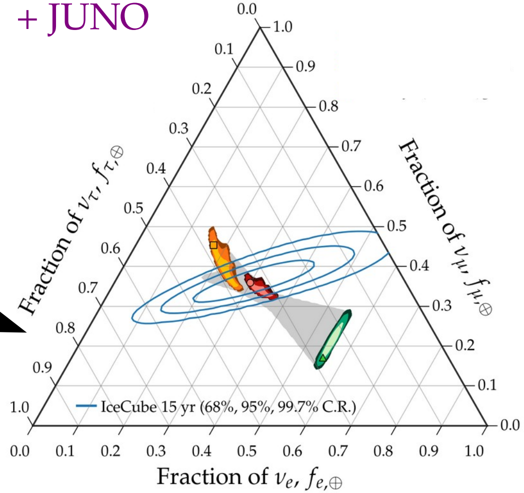
Measure θ_{23} better

+ Hyper-K



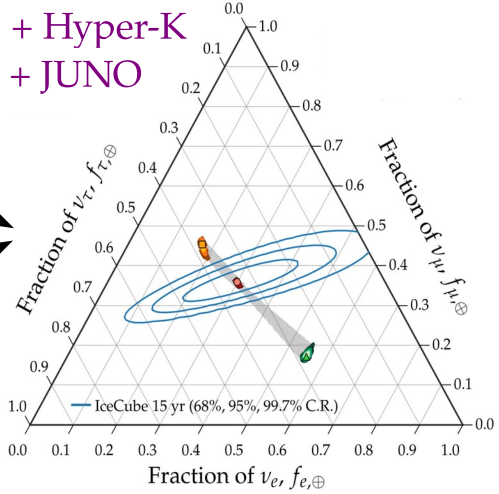
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

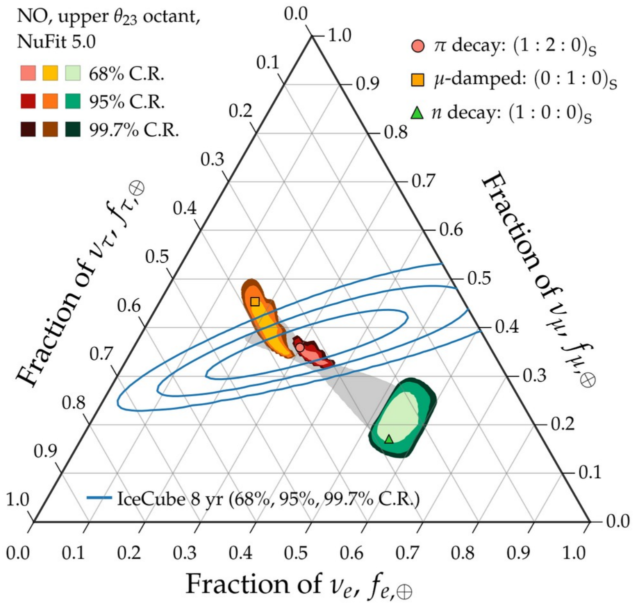
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



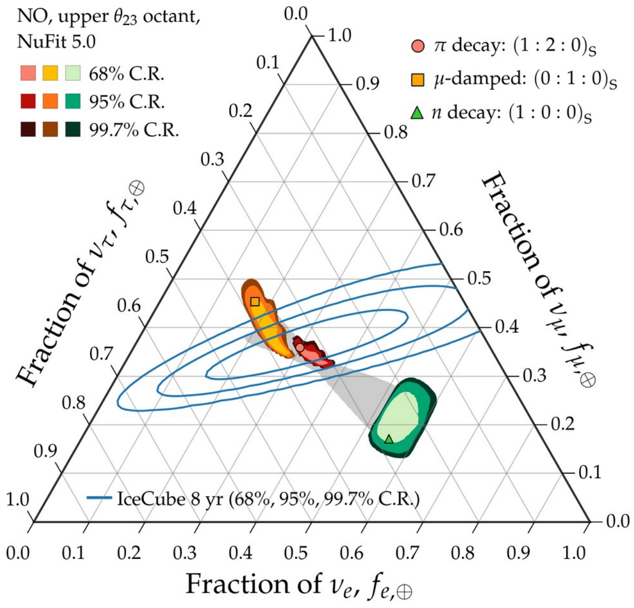
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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Not ideal

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

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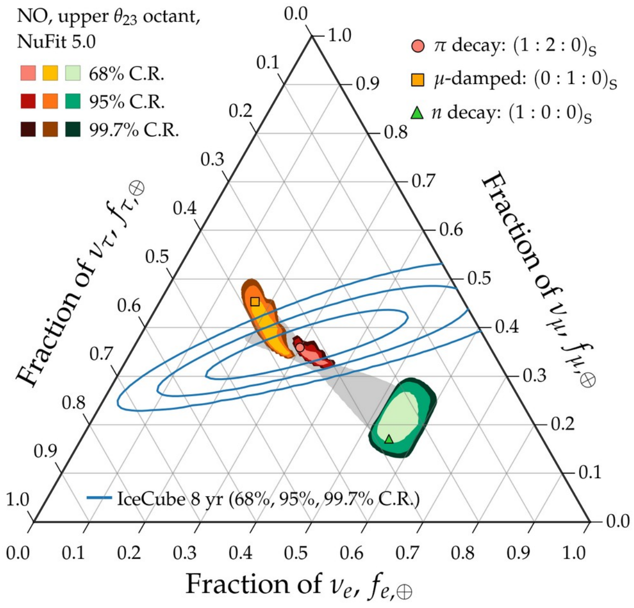

Allowed regions: overlapping

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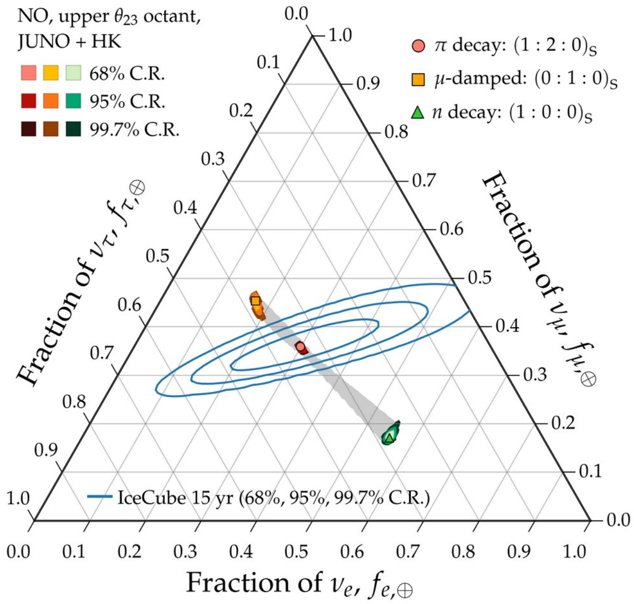
2030



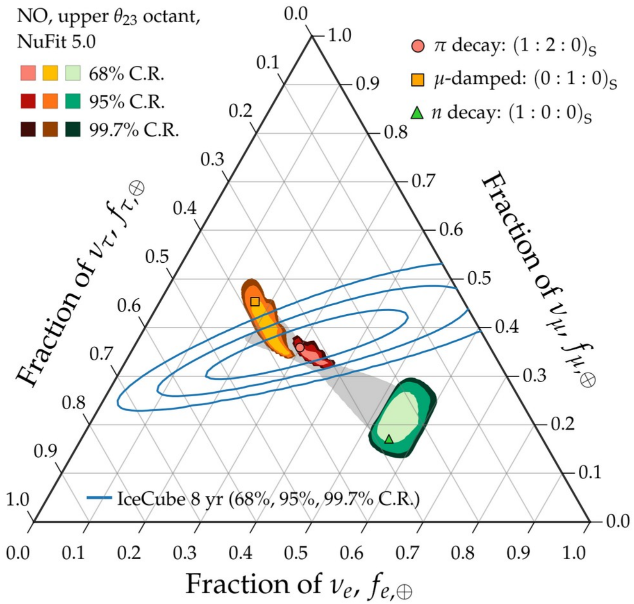
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

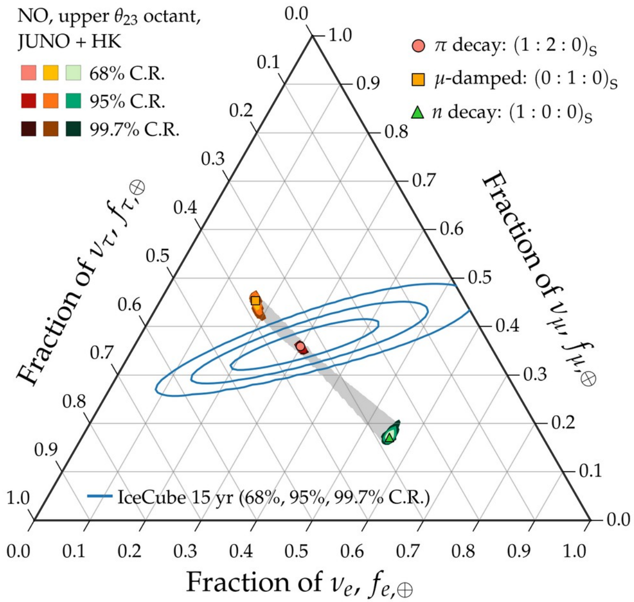


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



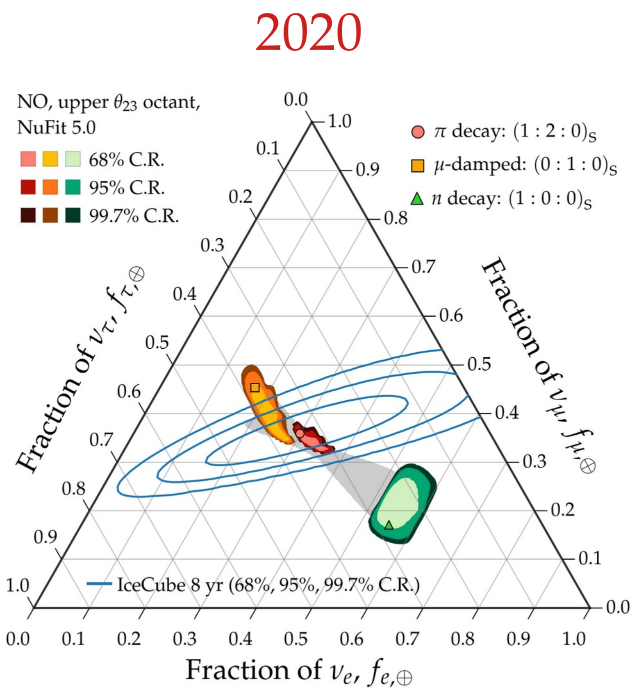
Allowed regions: well separated

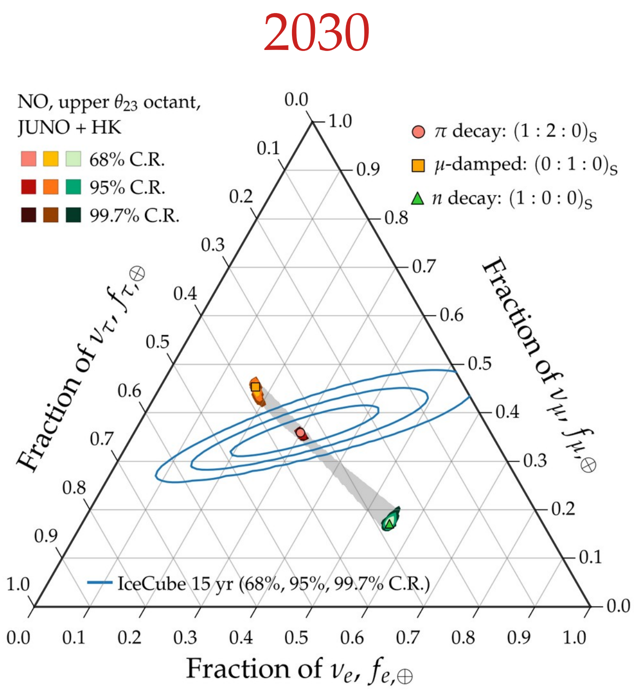
Measurement: improving

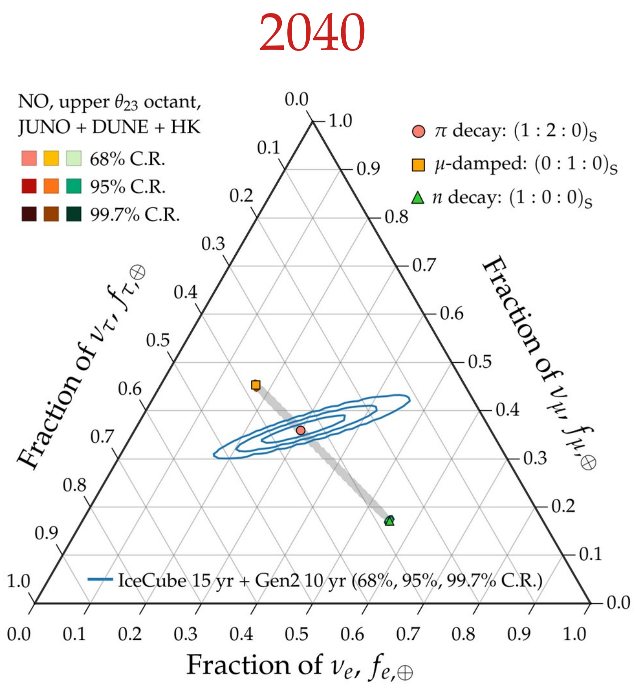
Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040





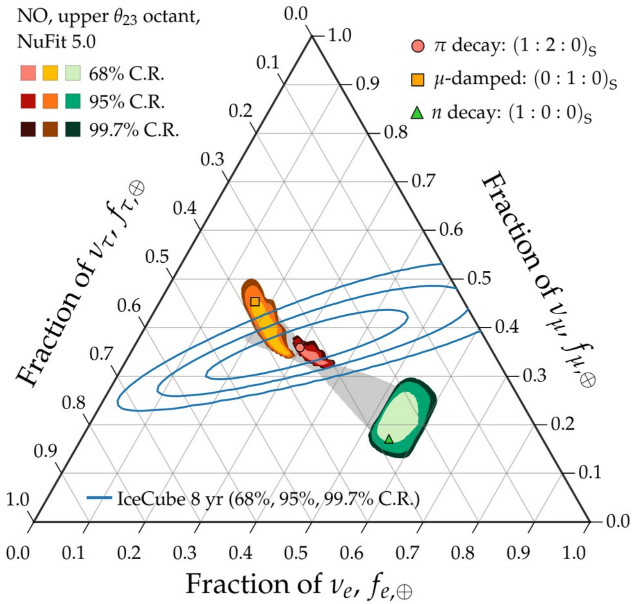


2020	2030	2040
Allowed regions: overlapping	Allowed regions: well separated	Allowed regions: well separated
Measurement: imprecise	Measurement: improving	Measurement: precise
Not ideal	*Nice*	

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

Theoretically palatable regions: 2020 → 2030 → 2040

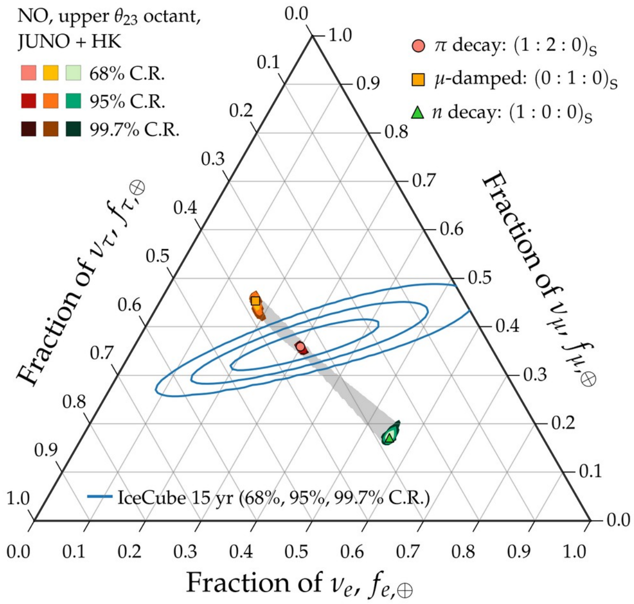
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

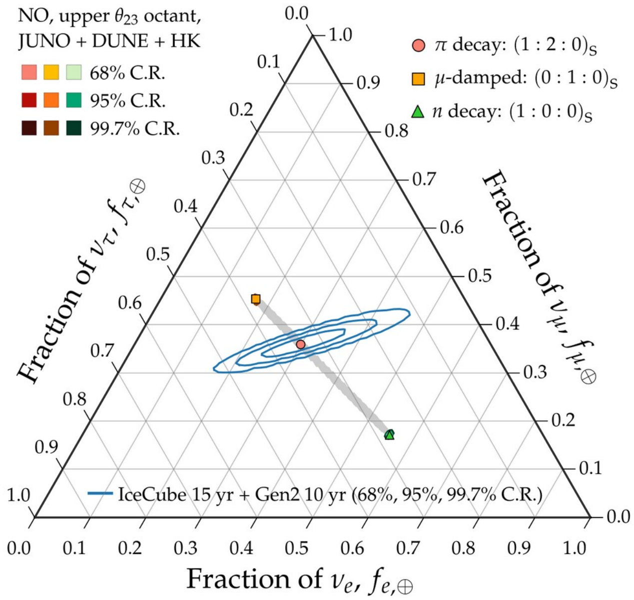
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

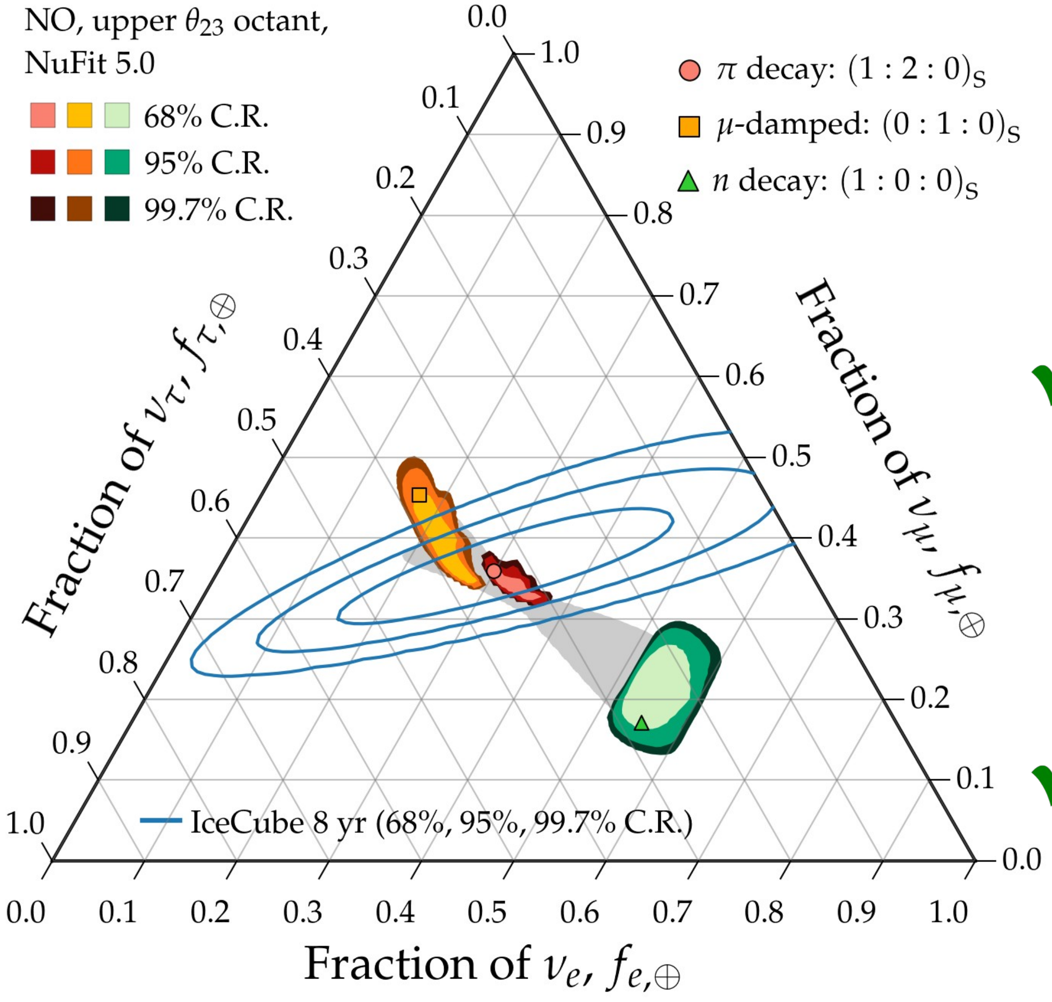


Allowed regions: well separated
Measurement: precise

Success

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

Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –

~~Insufficient precision in the mixing parameters~~

✓ *Will be overcome by 2030*

Measurement of flavor ratios –

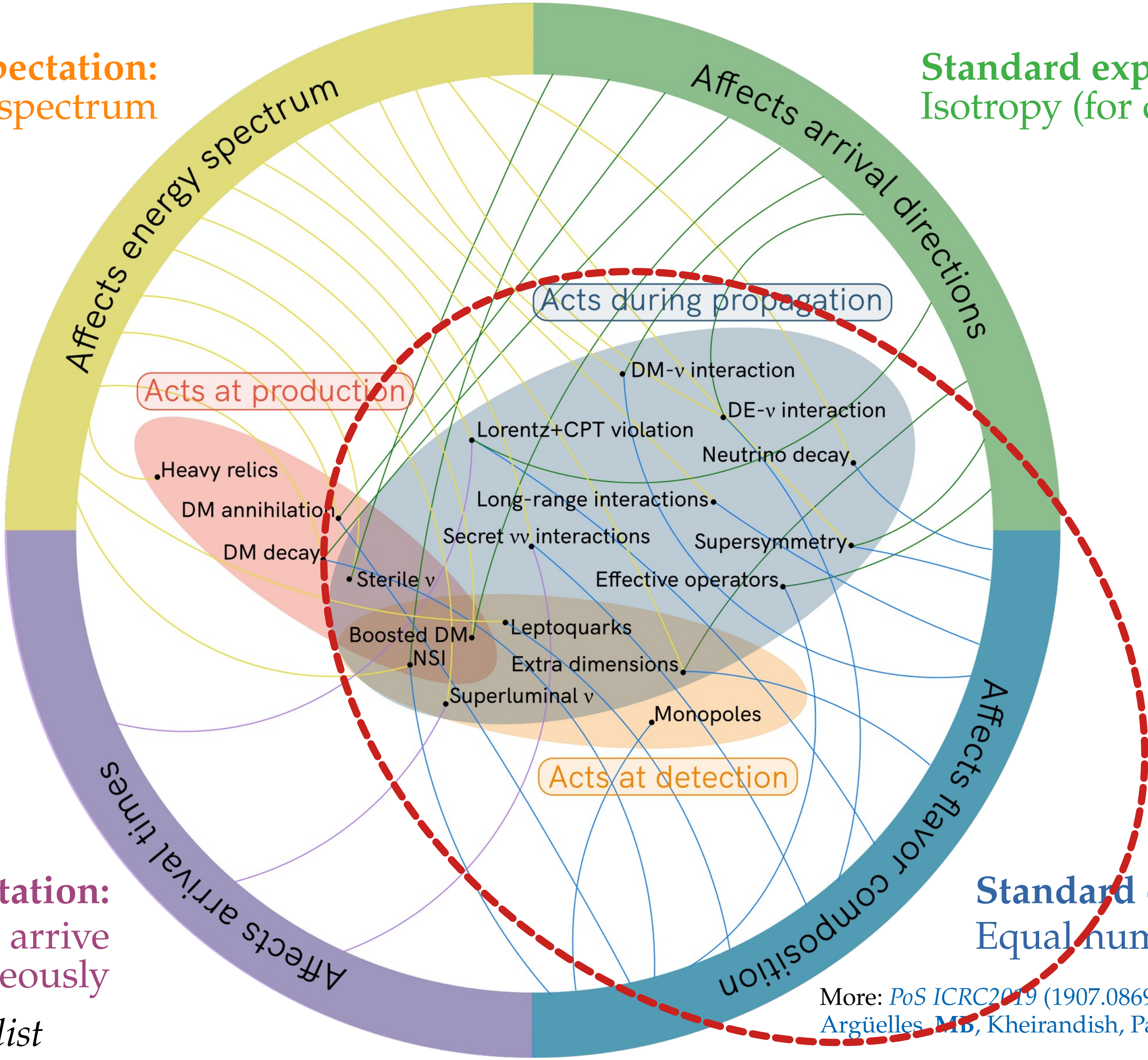
~~Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)~~

✓ *Will be overcome by 2040*

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

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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

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- Neutrino decay
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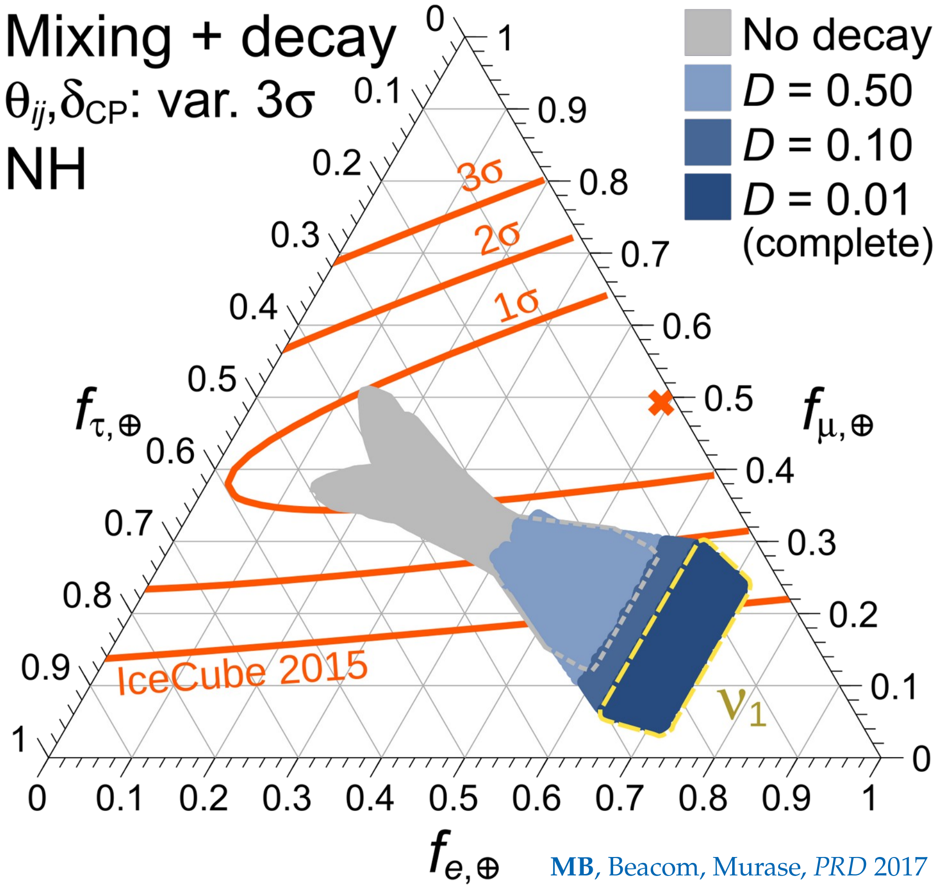

MB, Beacom, Murase, *PRD* 2017

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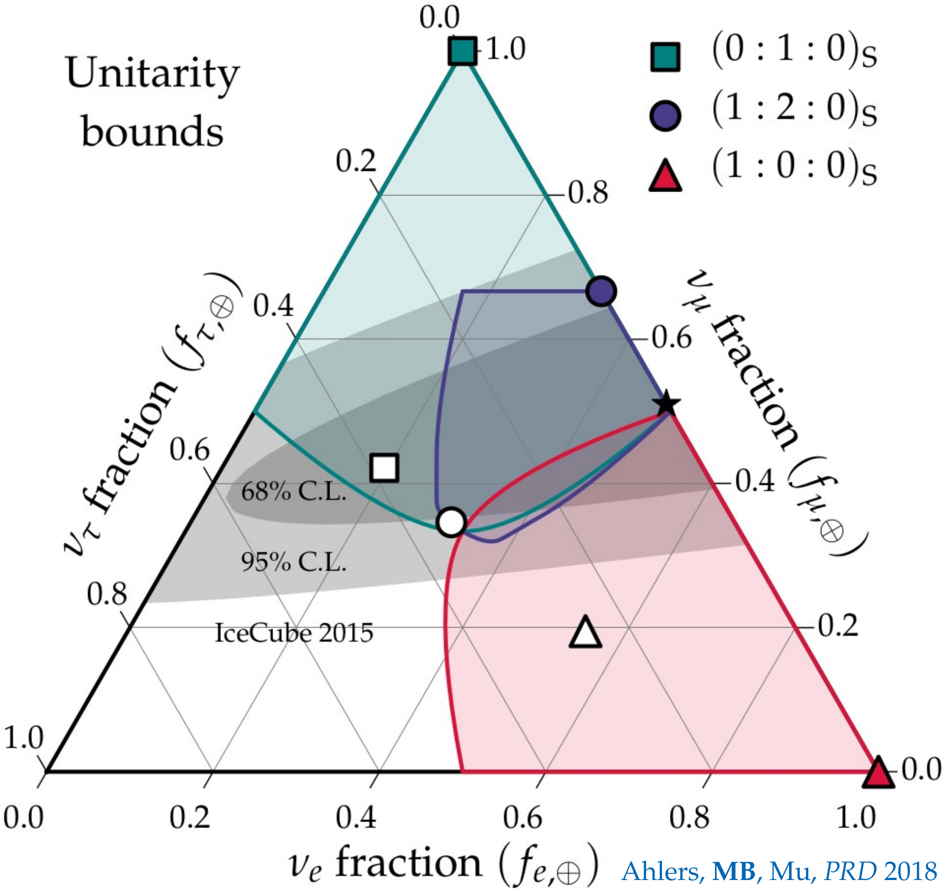

Ahlers, **MB**, Mu, *PRD* 2018

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

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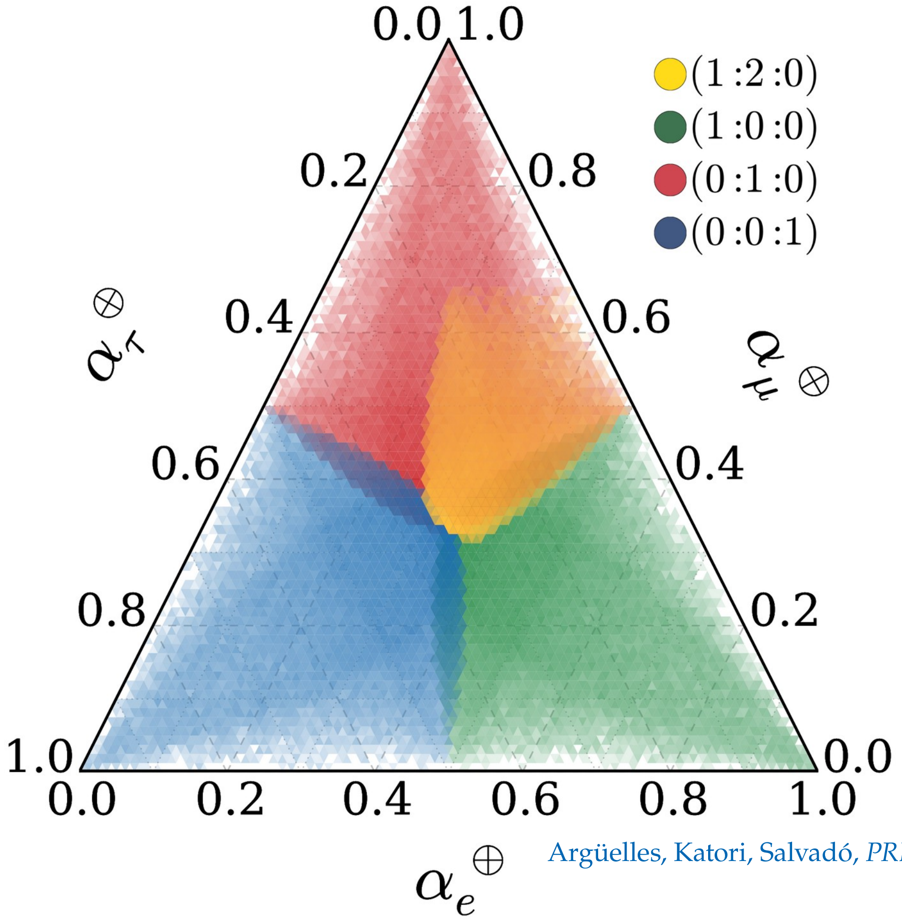

Argüelles, Katori, Salvadó, *PRL* 2015

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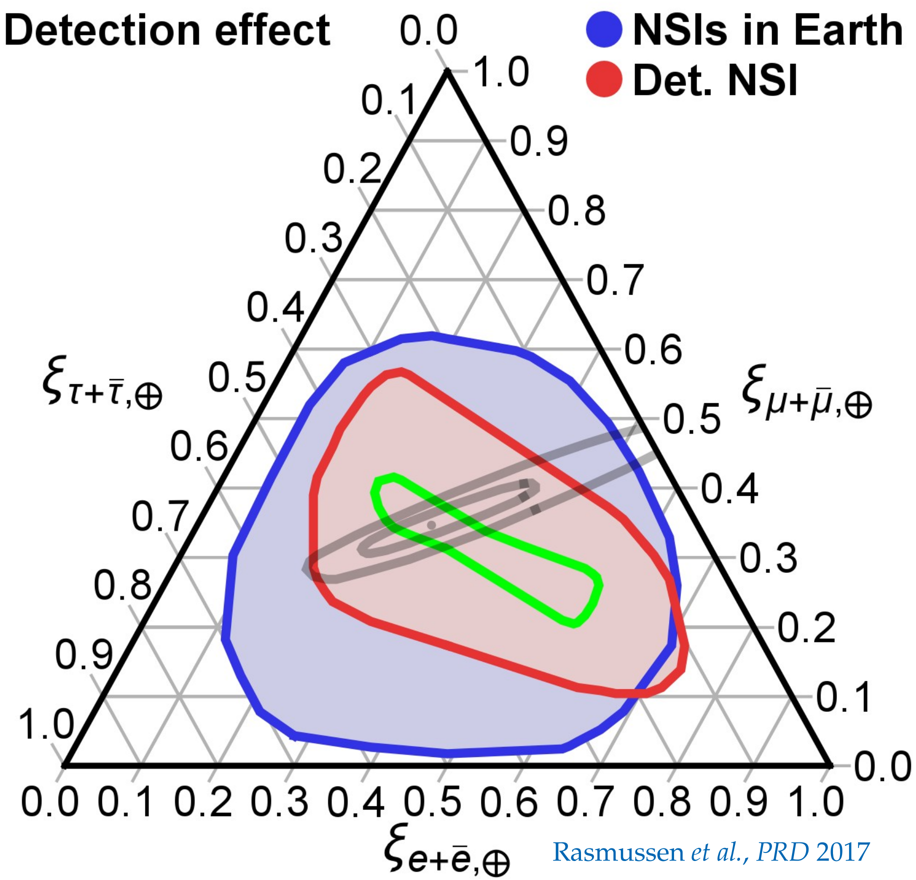

Rasmussen *et al.*, *PRD* 2017

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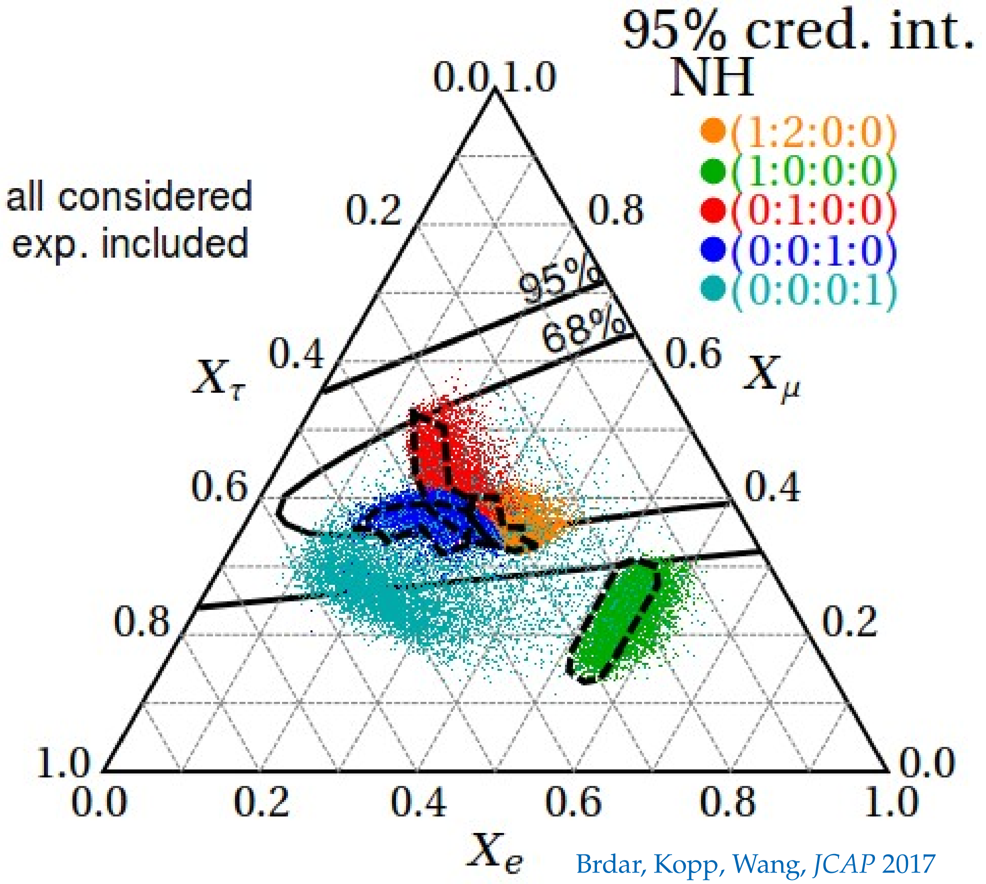

Brdar, Kopp, Wang, *JCAP* 2017

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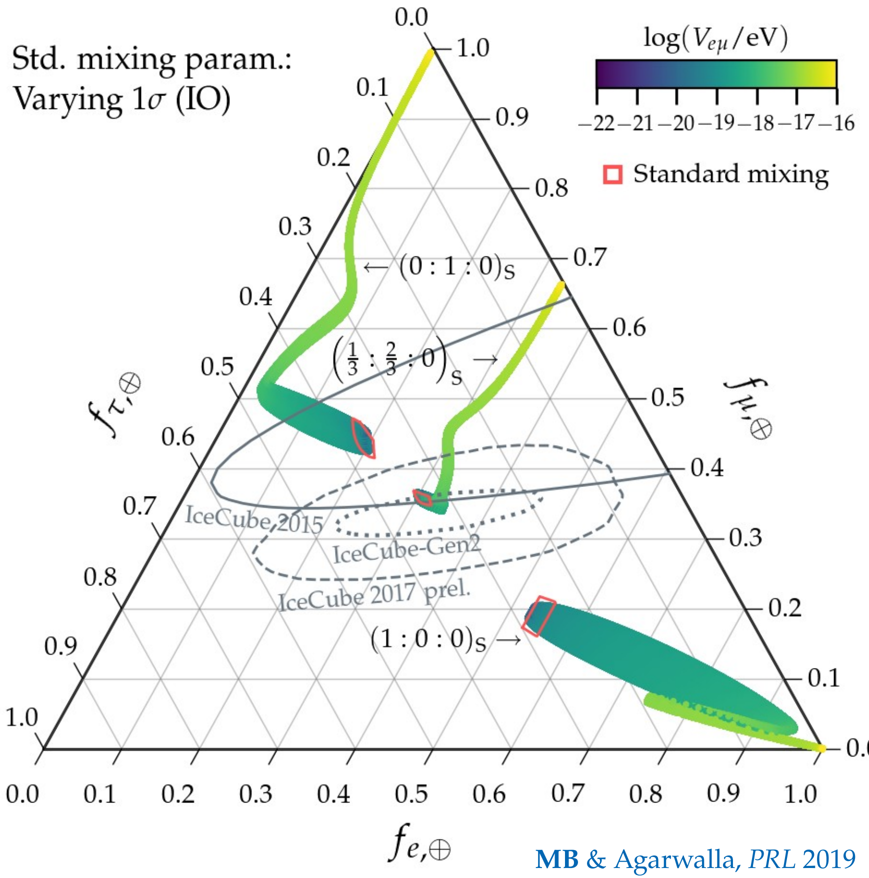
  Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]
- ▶ Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

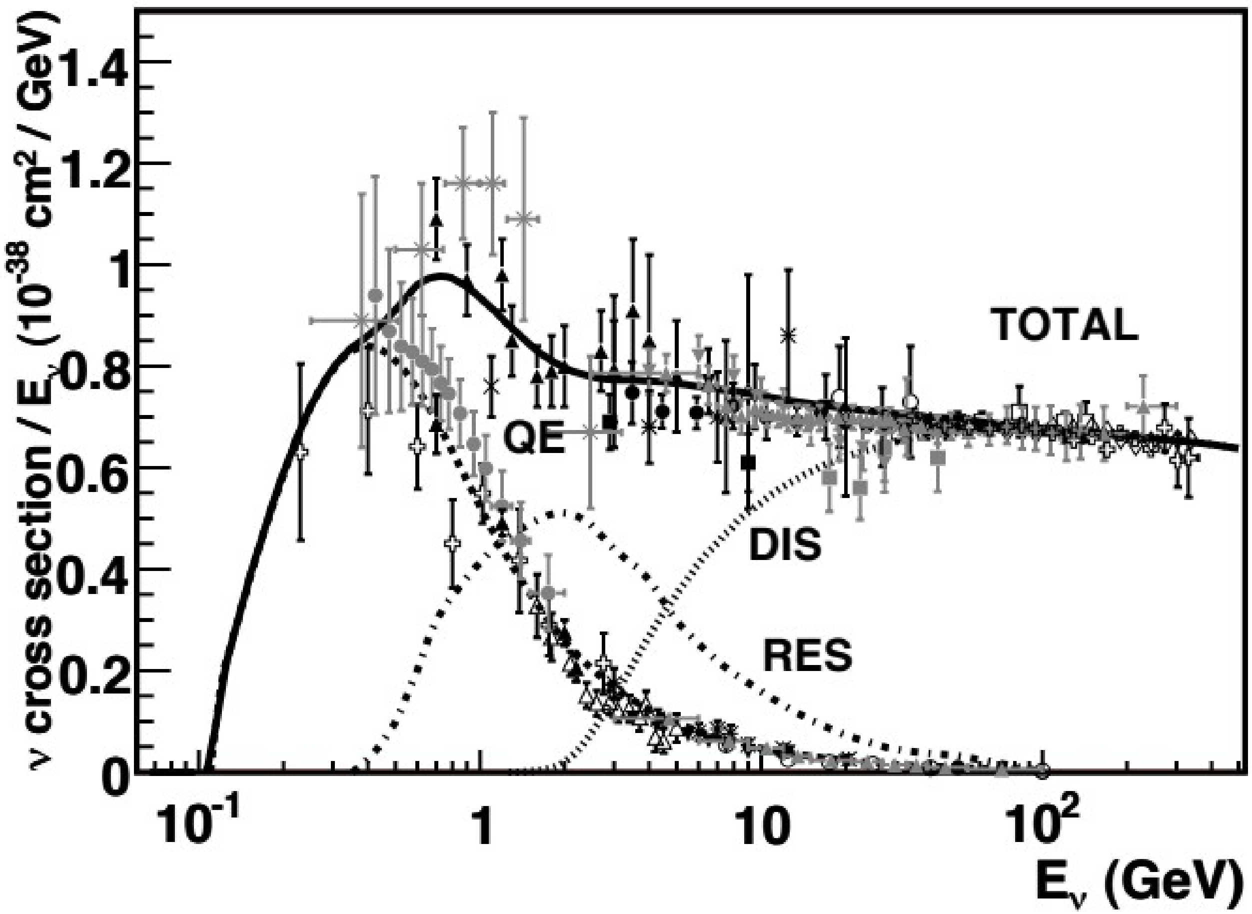
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



MB & Agarwalla, *PRL* 2019

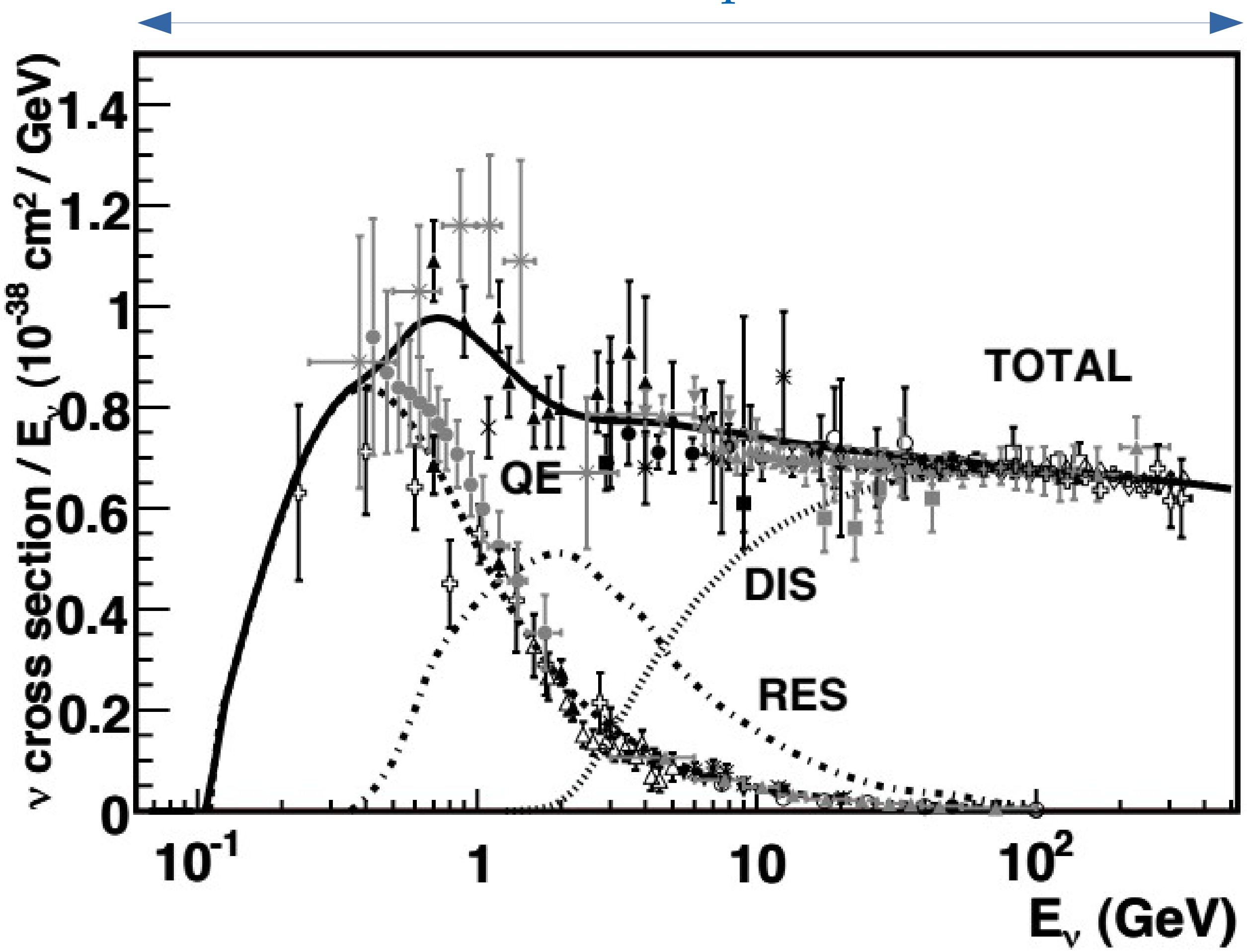
Neutrino-nucleon cross section:

From high to ultra-high energies



Particle Data Group

Accelerator experiments



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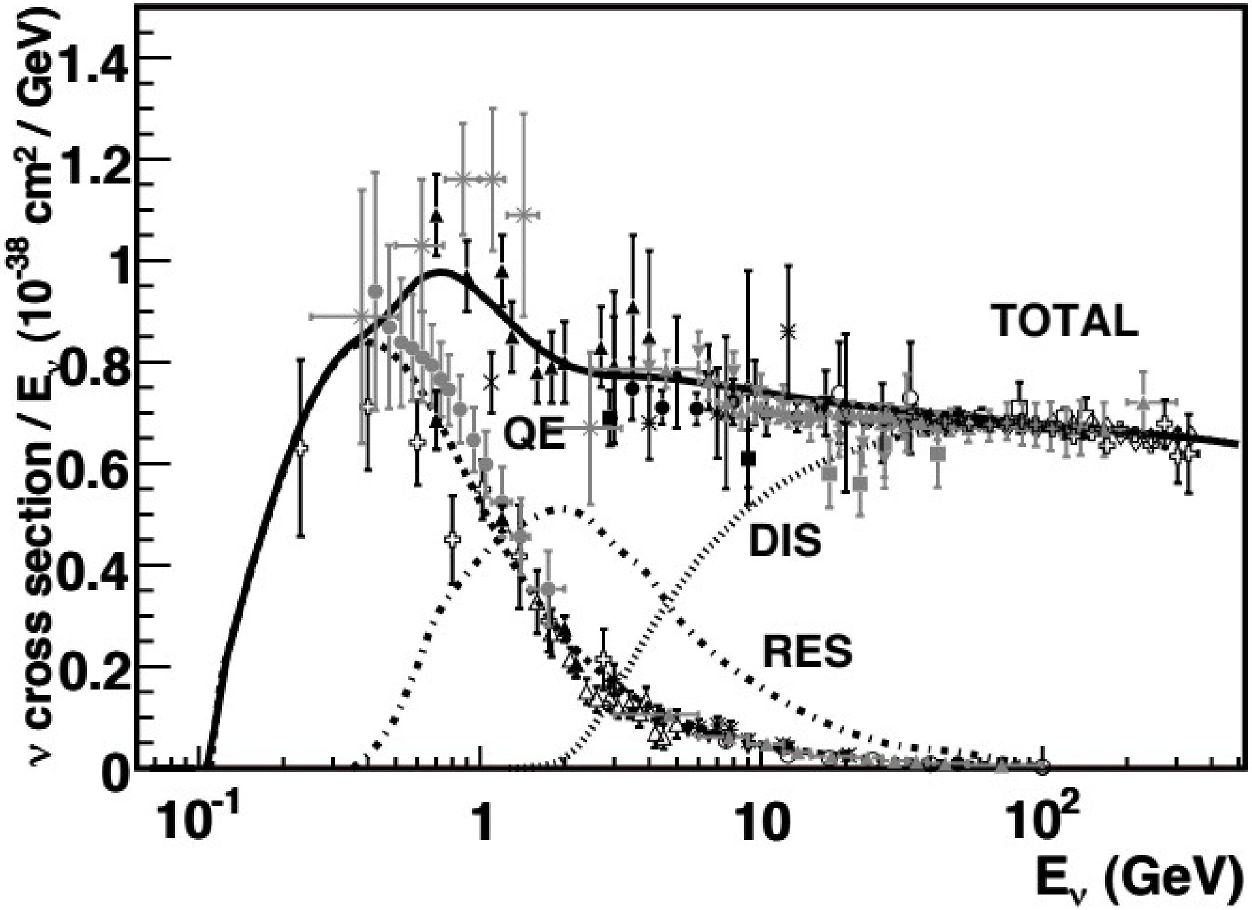

One recent measurement (COHERENT)

Particle Data Group

Accelerator experiments

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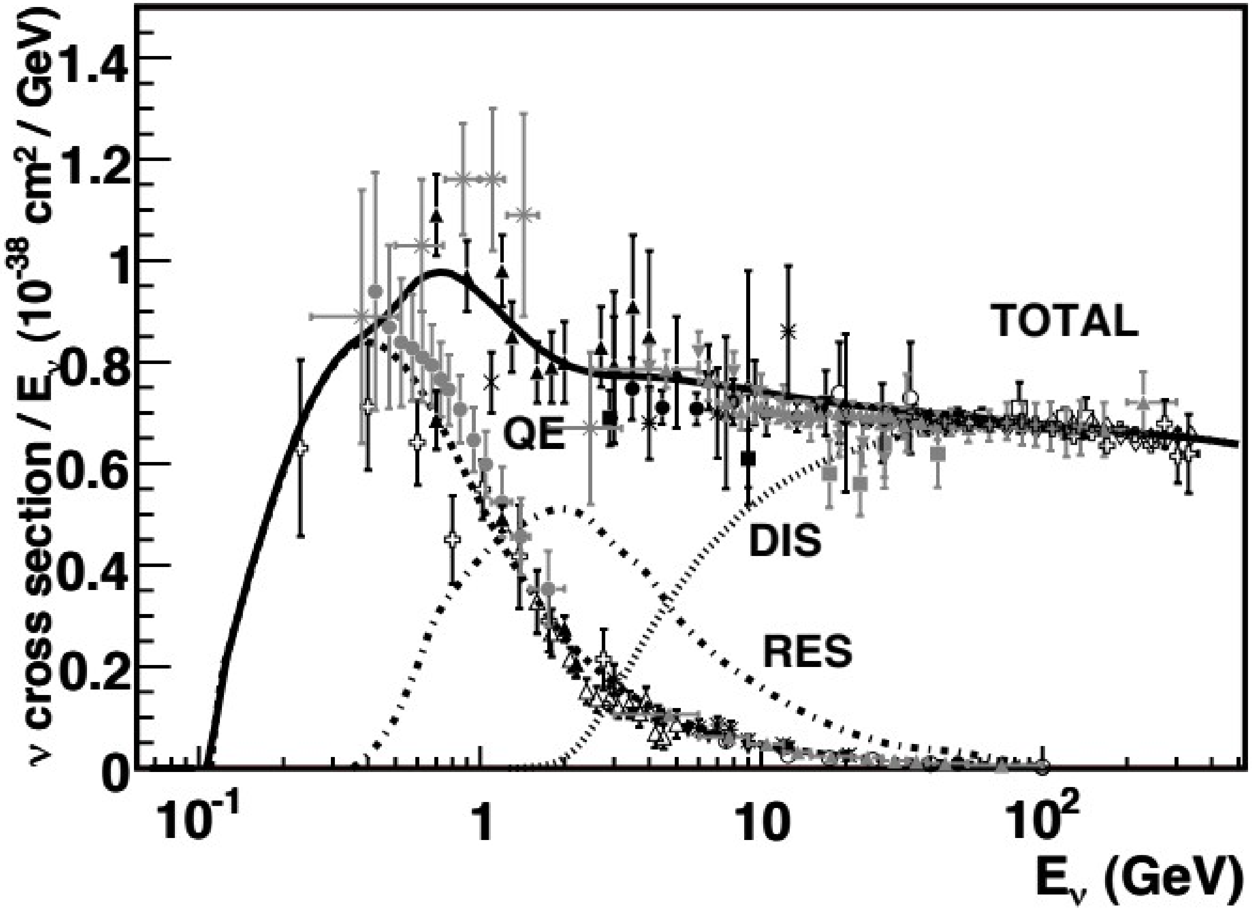
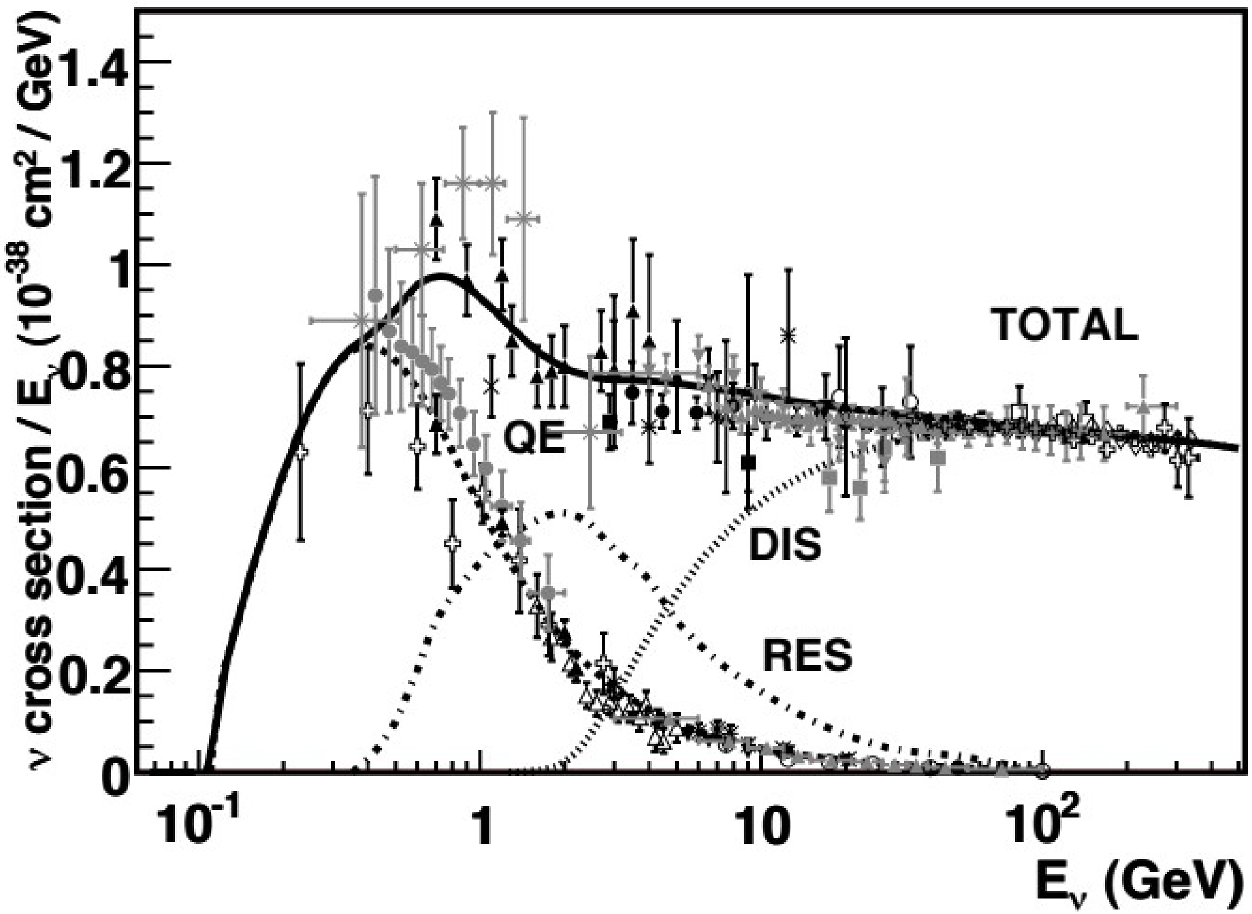


Particle Data Group

No measurements … until recently!

Accelerator experiments

One recent measurement (COHERENT)



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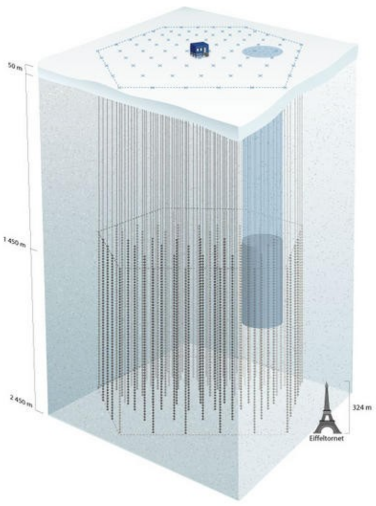
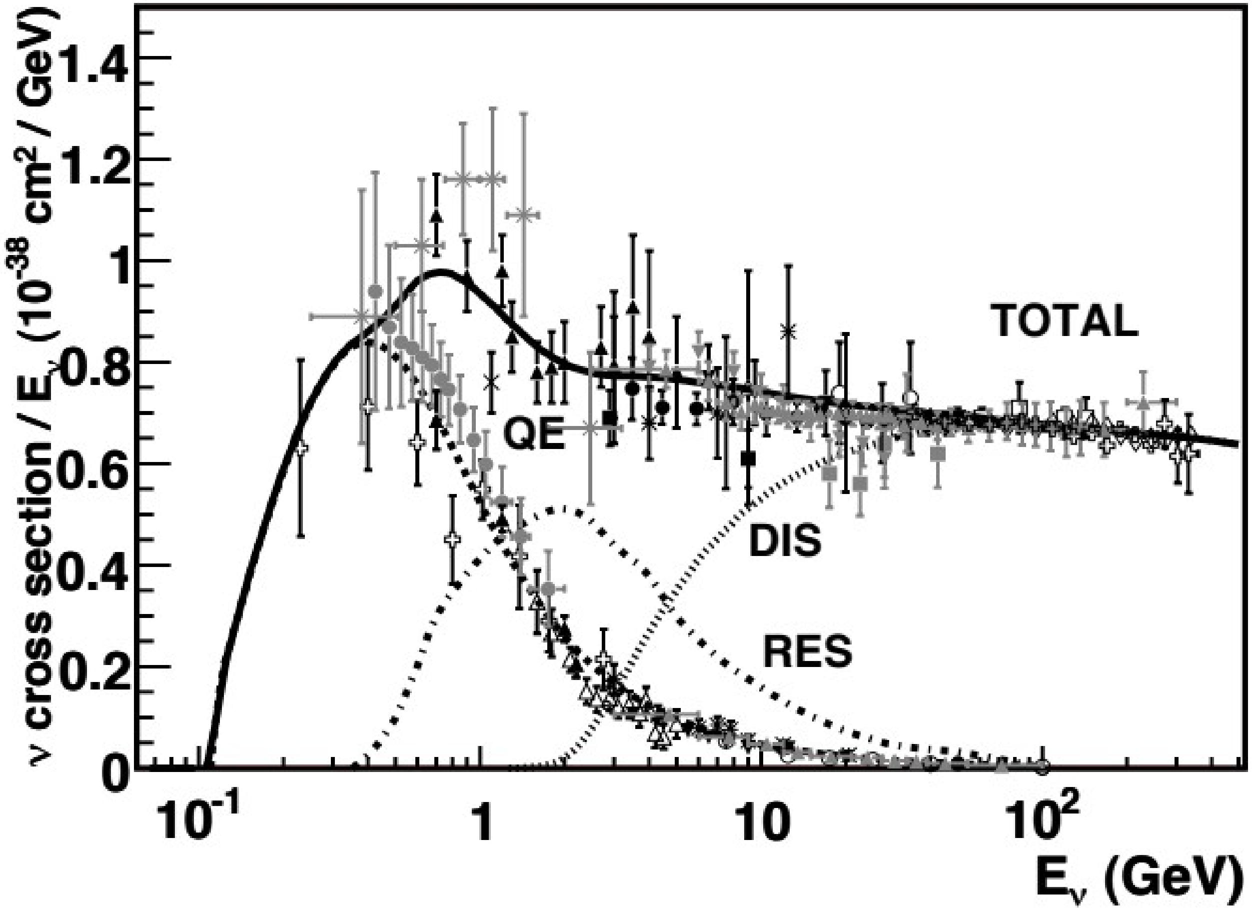


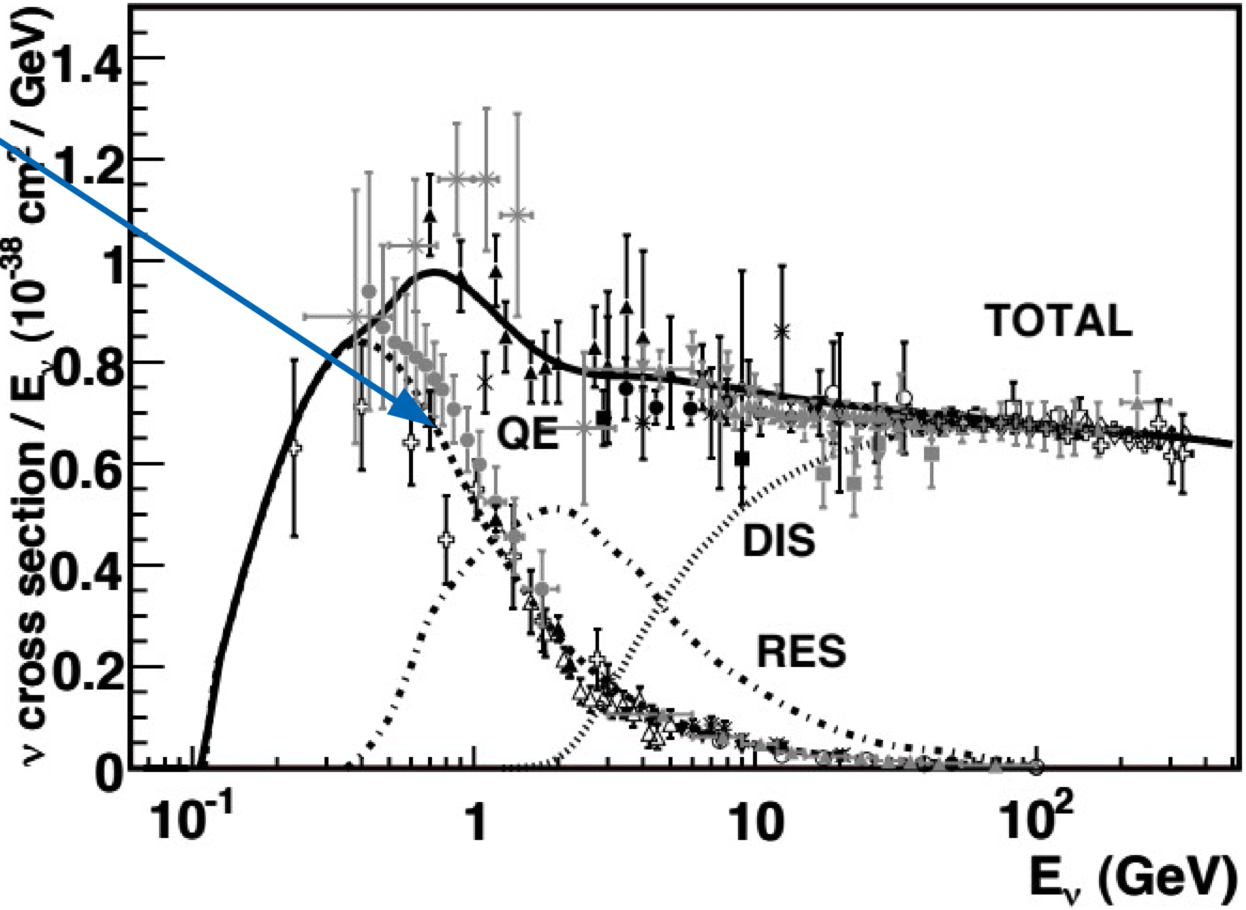


Particle Data Group

Quasi-elastic scattering:

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

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



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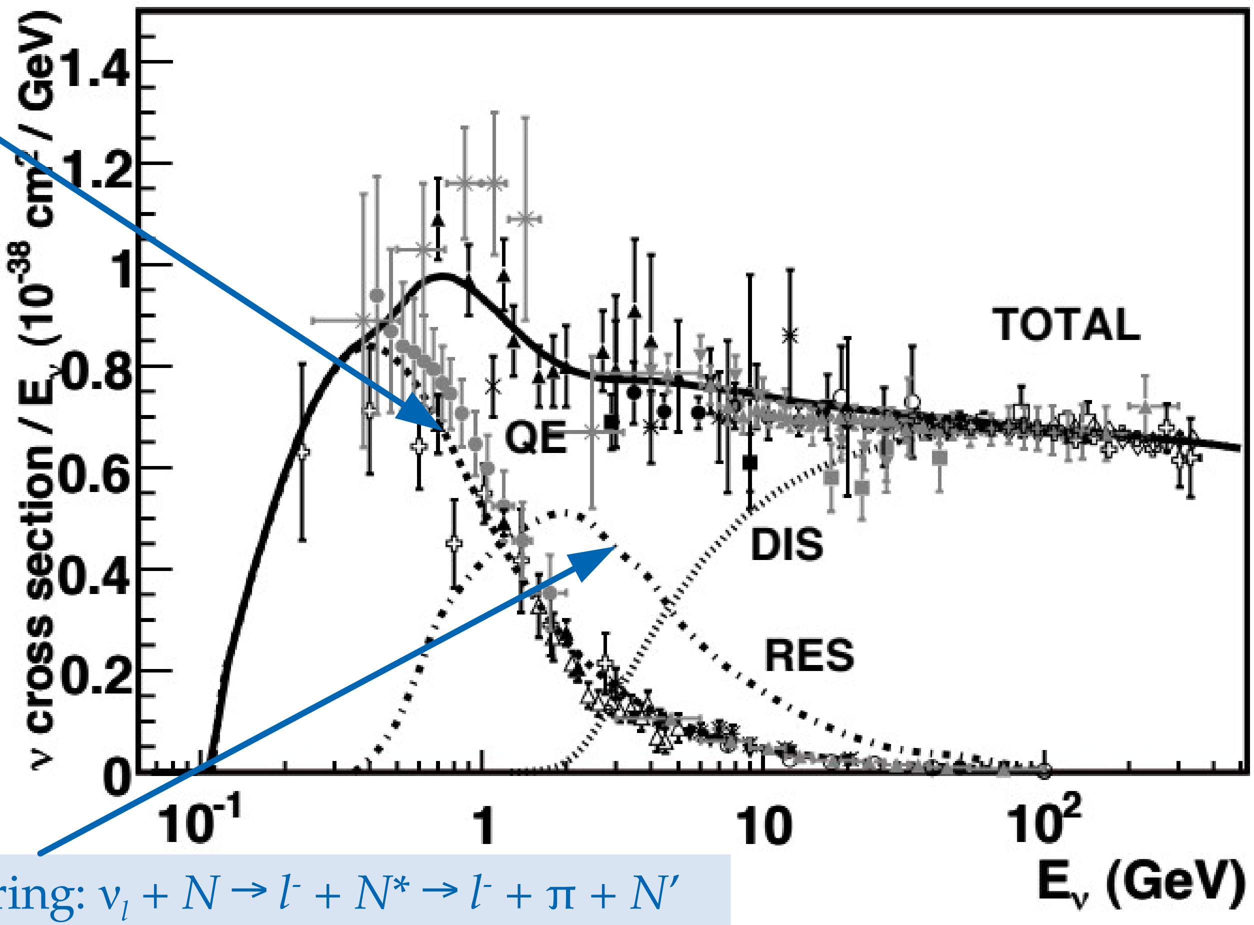


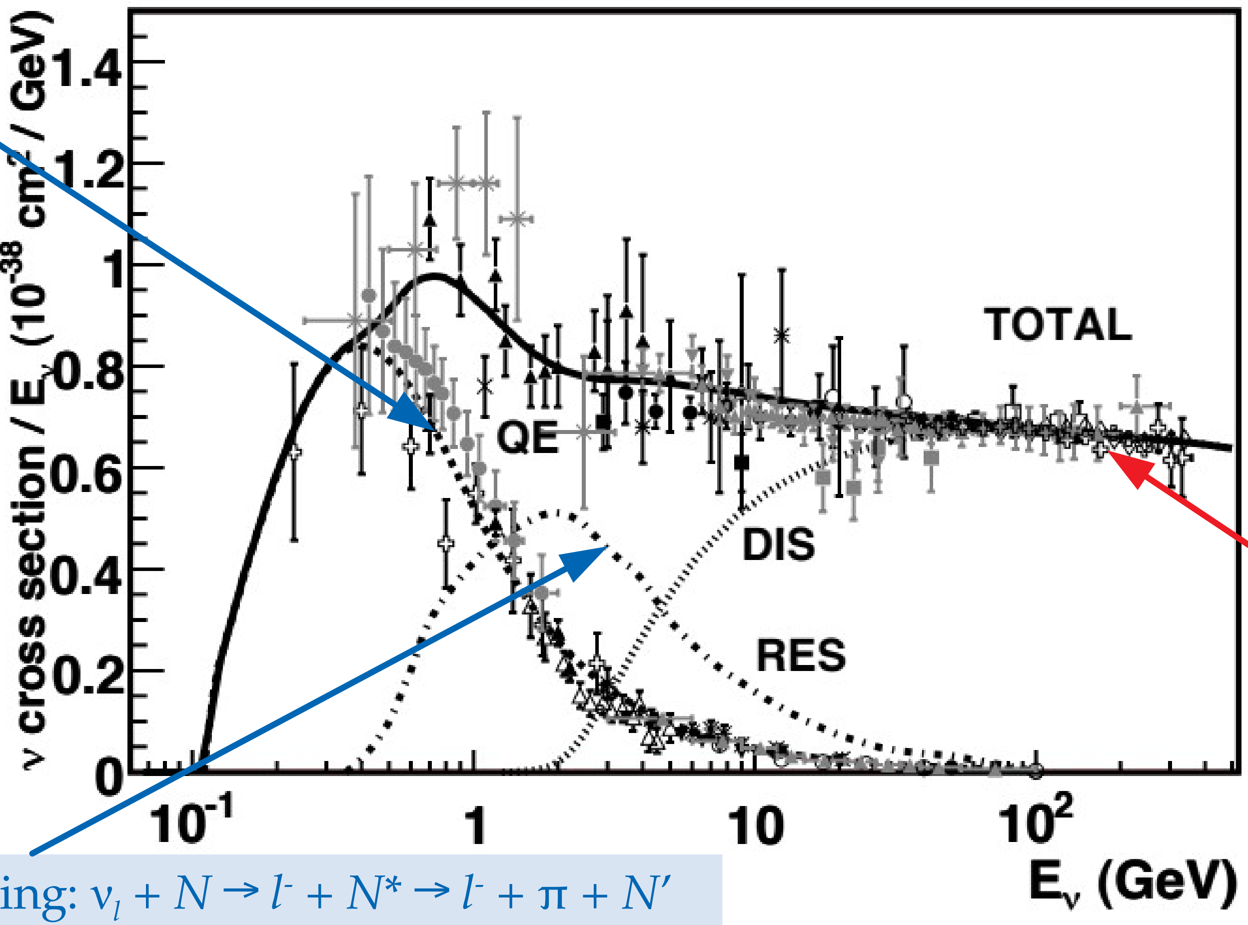
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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

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



Deep inelastic scattering:

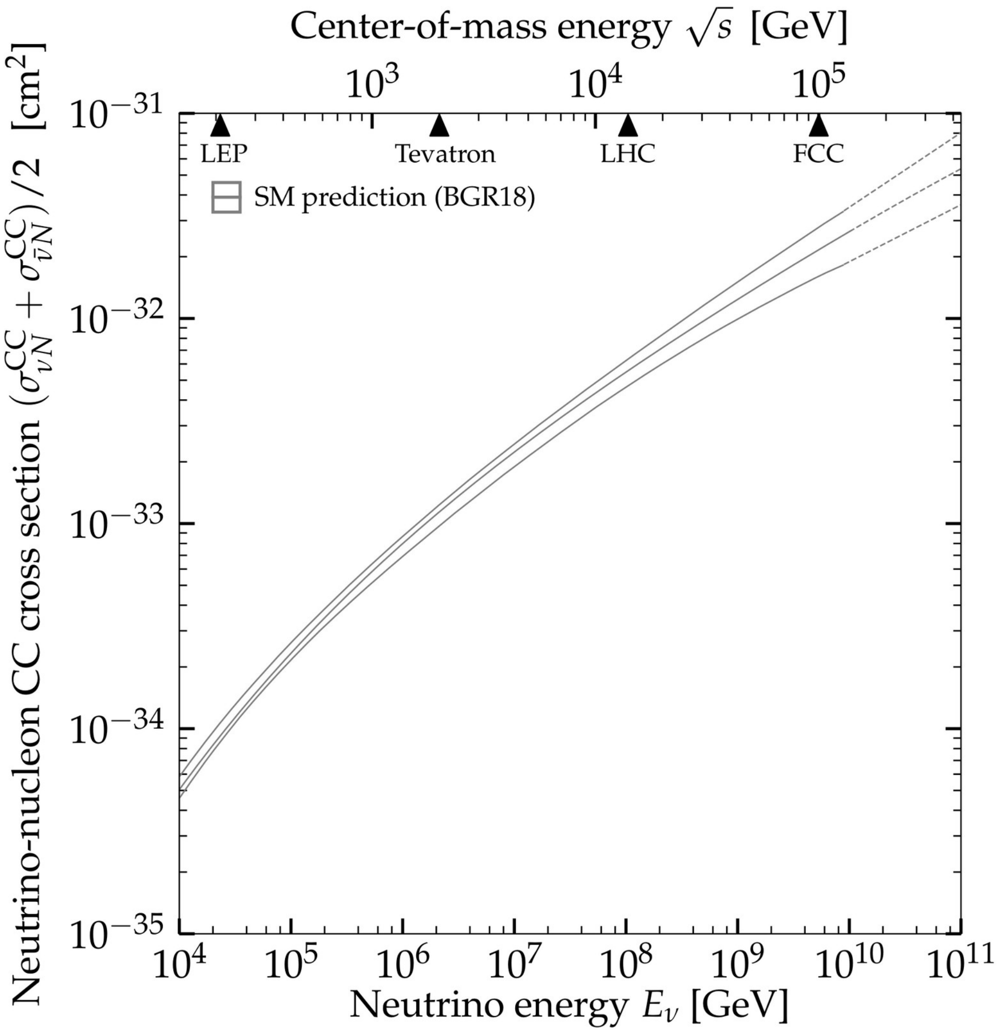
$\nu_l + N \rightarrow l^- + X$

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

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

Particle Data Group

High-energy νN cross section: *prediction*

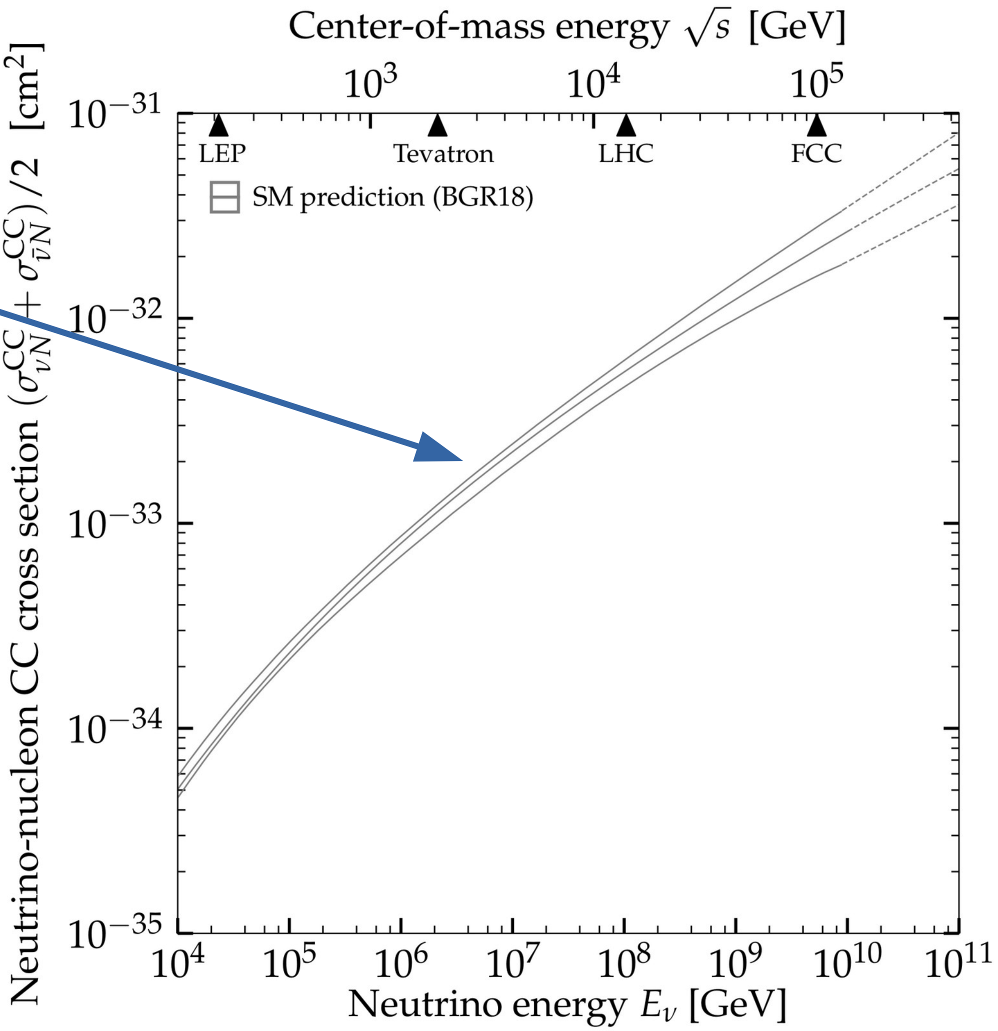


Bertone, Gauld, Rojo, *JHEP* 2019

High-energy νN cross section: *prediction*

Softer-than-linear dependence on E_ν due to the W pole

Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W / E_\nu \sim 10^{-6}$



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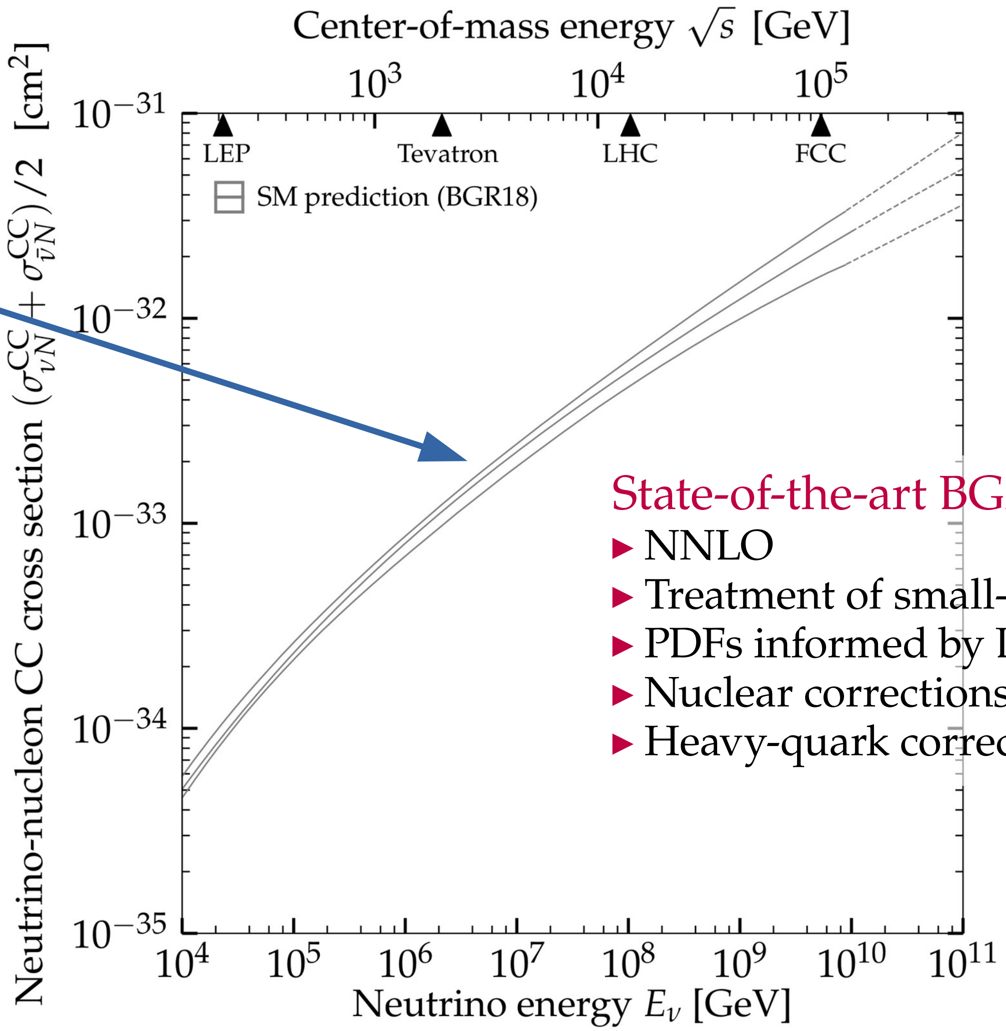


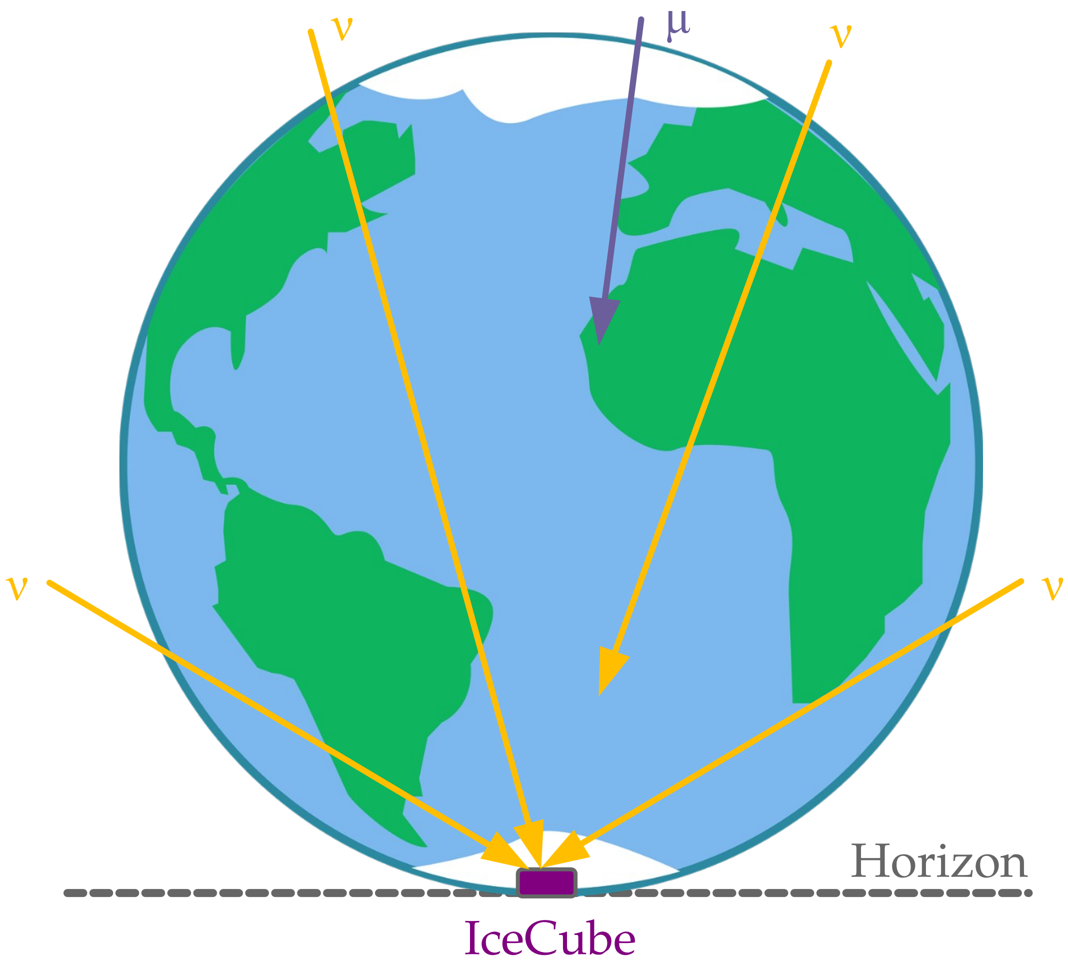
Softer-than-linear dependence on E_ν due to the W pole

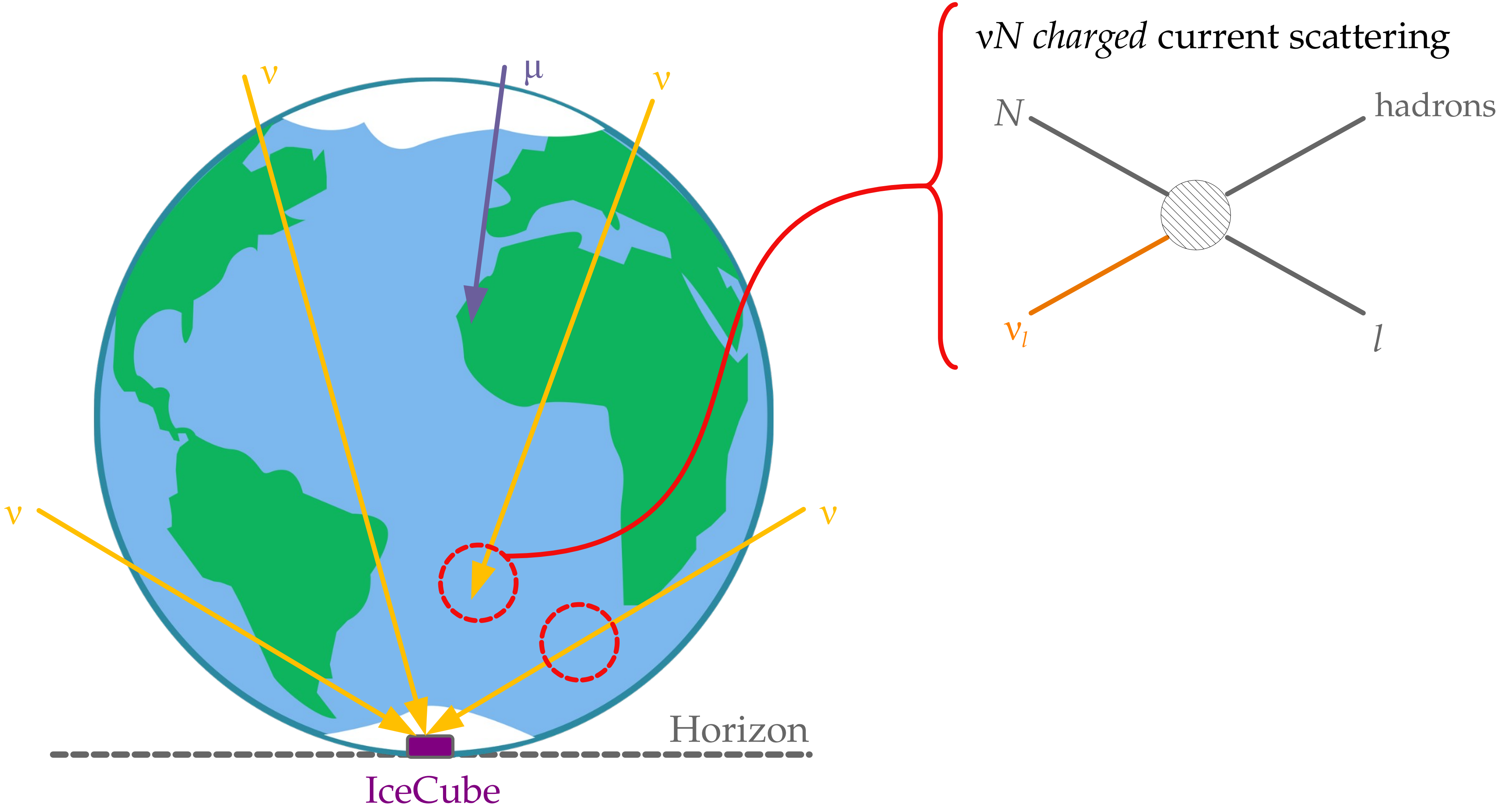
Uncertainty from extrapolating parton distribution functions (PDFs) to Bjorken $x \sim m_W / E_\nu \sim 10^{-6}$

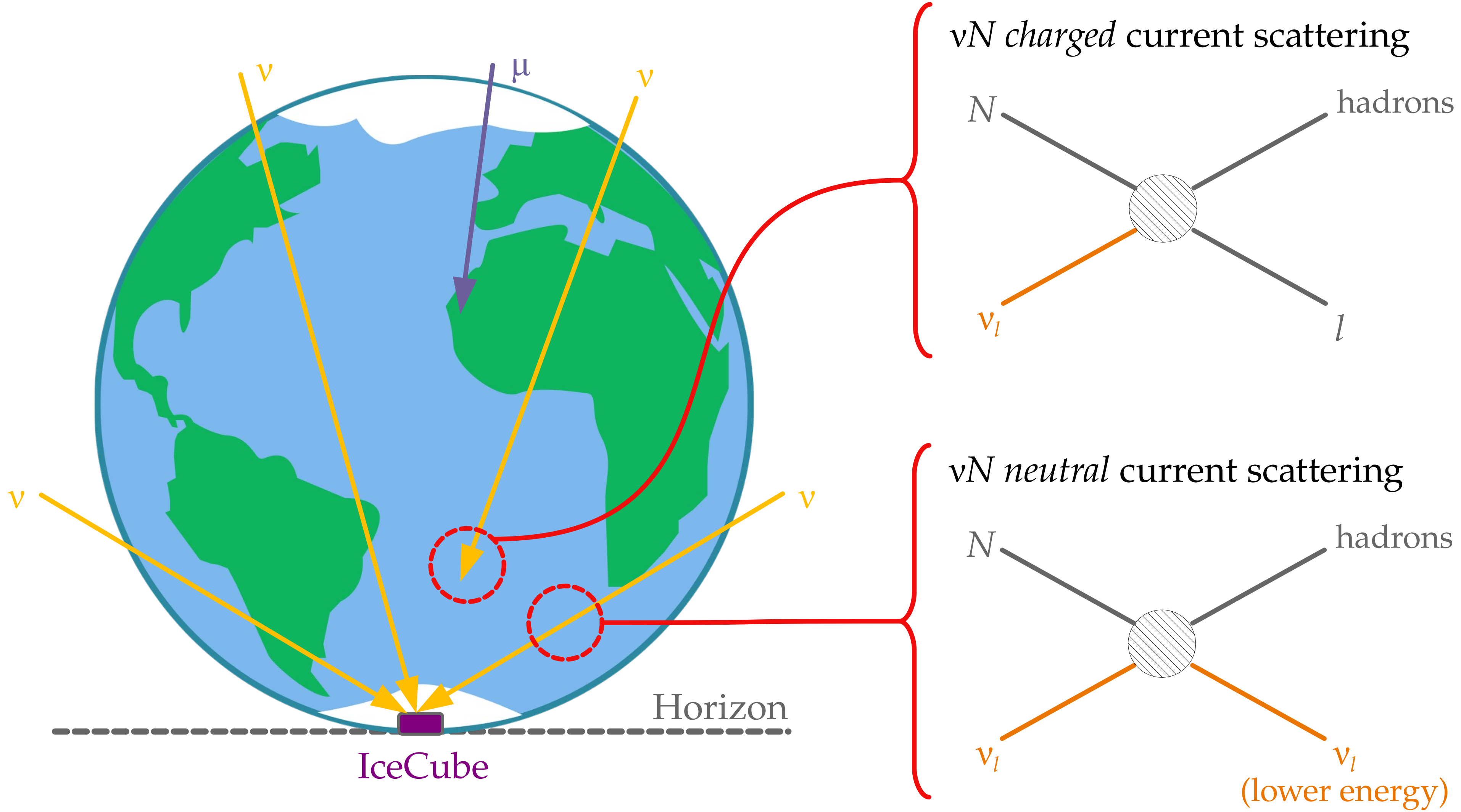
State-of-the-art BGR18 prediction:

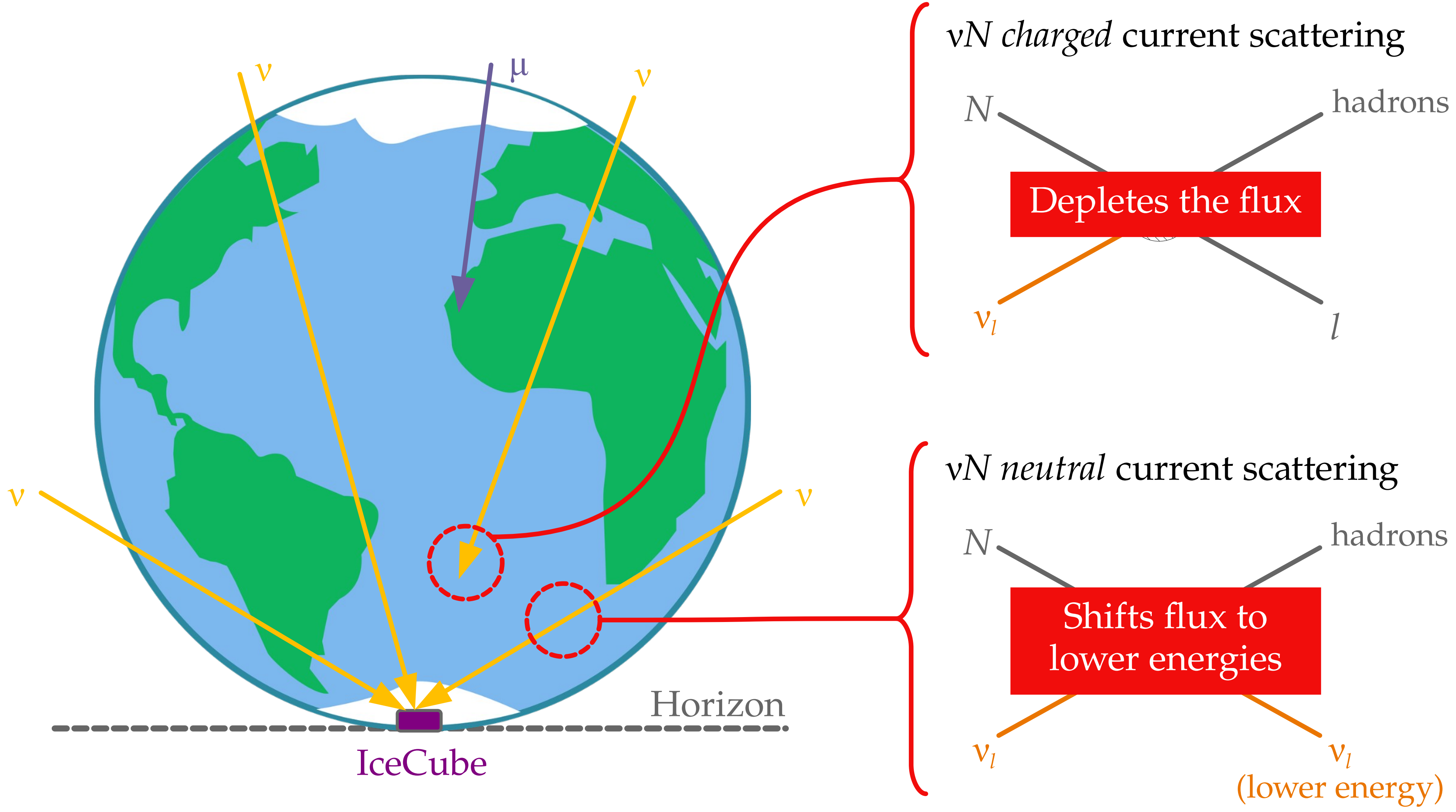
- NNLO
- Treatment of small-x effects
- PDFs informed by LHCb D-meson data
- Nuclear corrections
- Heavy-quark corrections

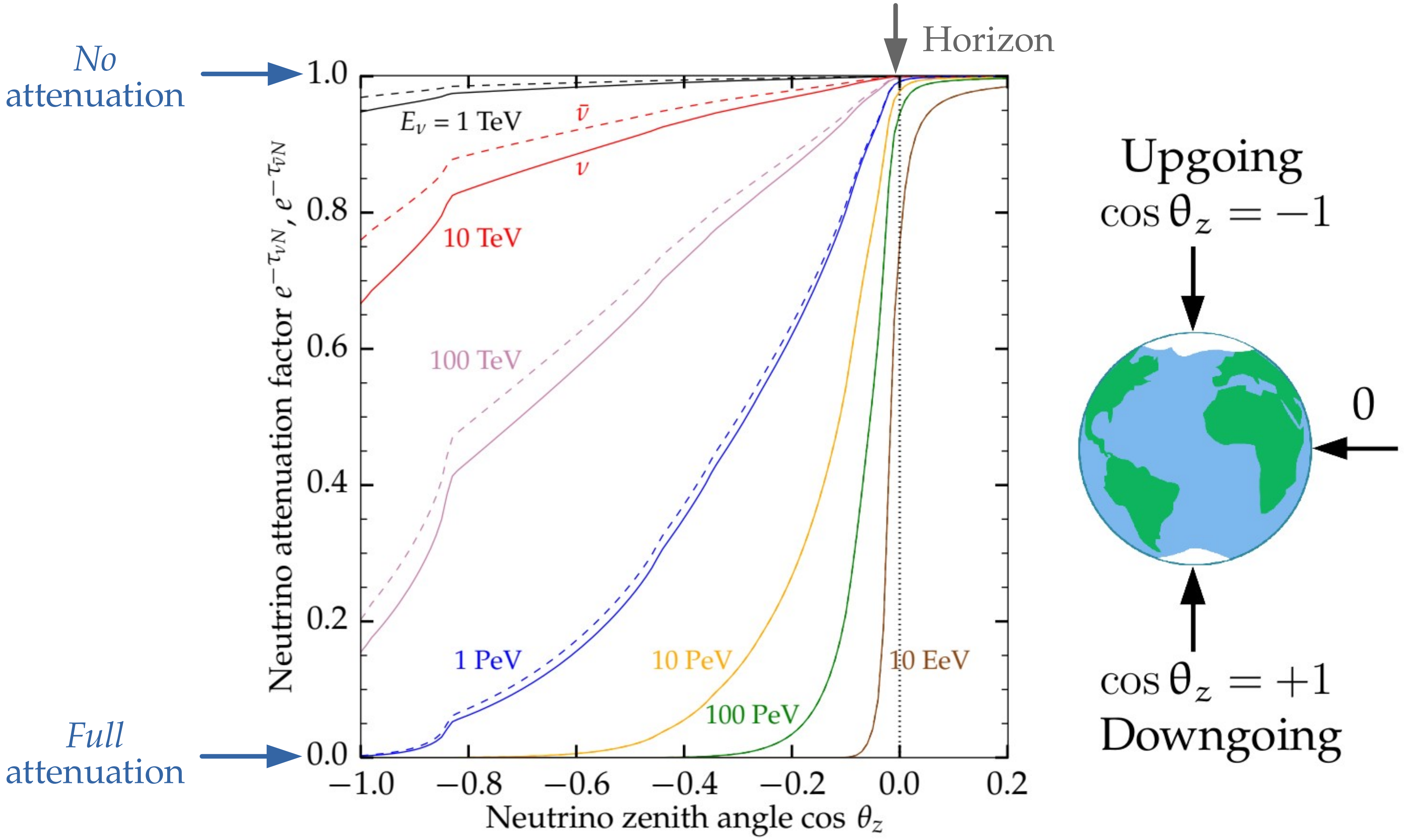
Bertone, Gauld, Rojo, *JHEP* 2019


ν
μ
ν
ν
ν
Horizon
IceCube

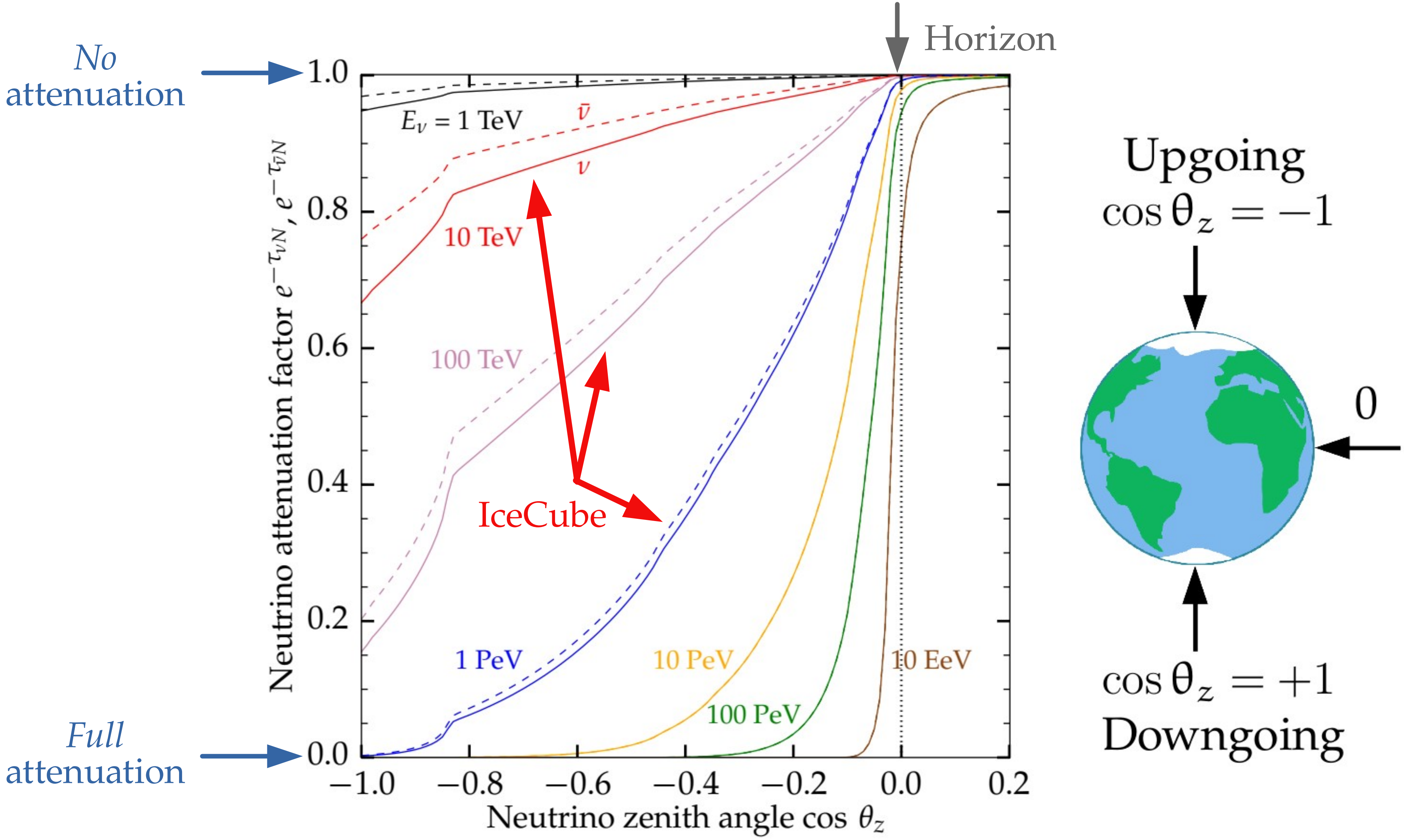

νN charged current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
ν_l
l
νN *neutral* current scattering
N
hadrons
ν_l
ν_l
(lower energy)


νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)
ν
μ
ν
ν
ν
Horizon
IceCube



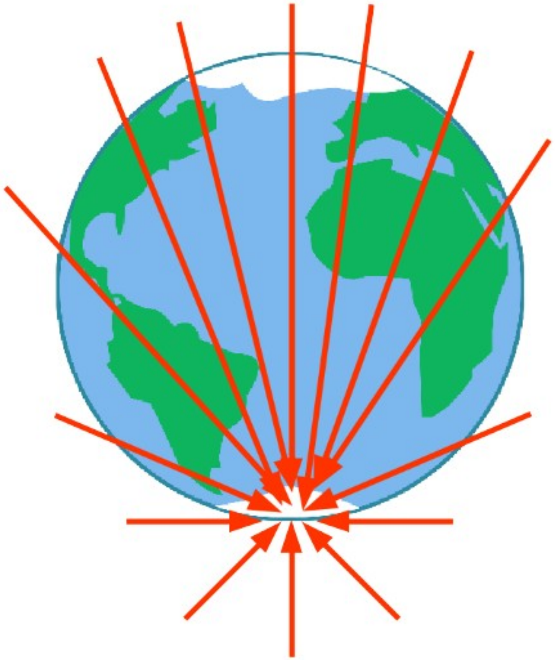
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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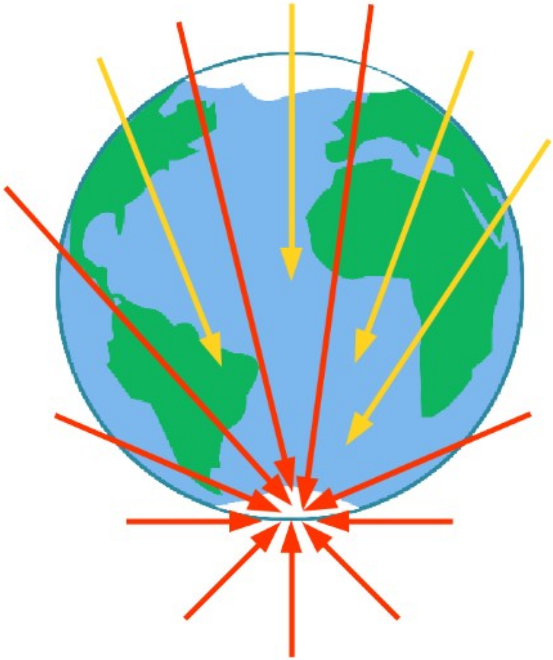

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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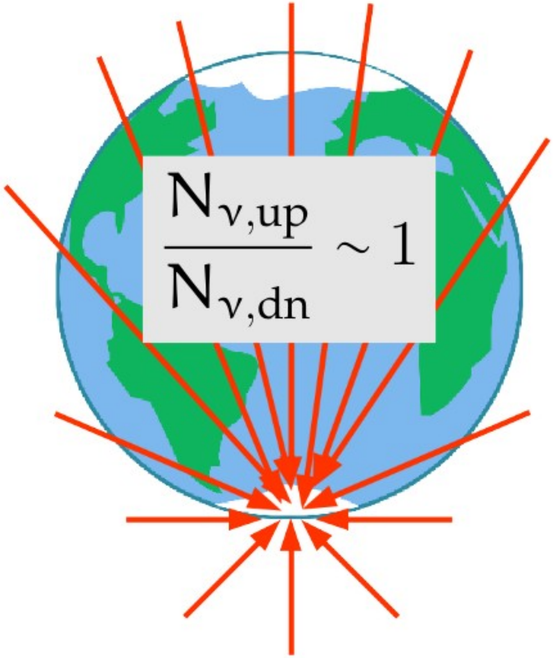
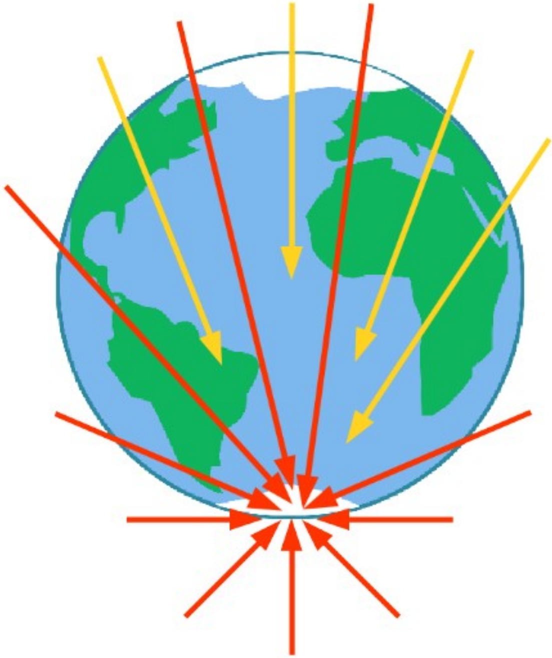


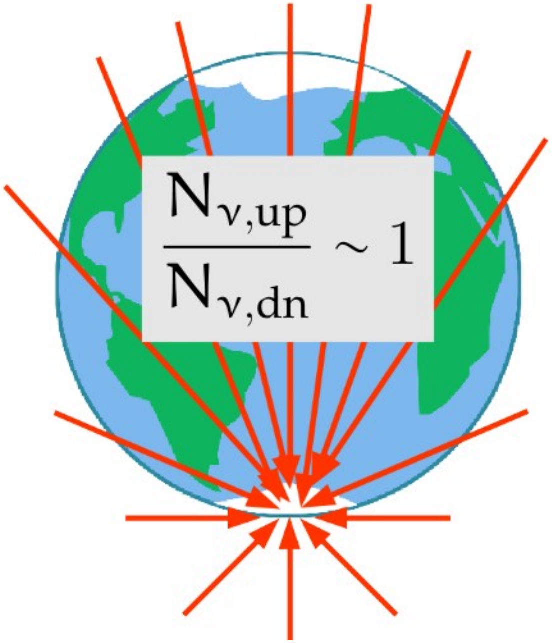
Above ~ 10 TeV: Earth is opaque



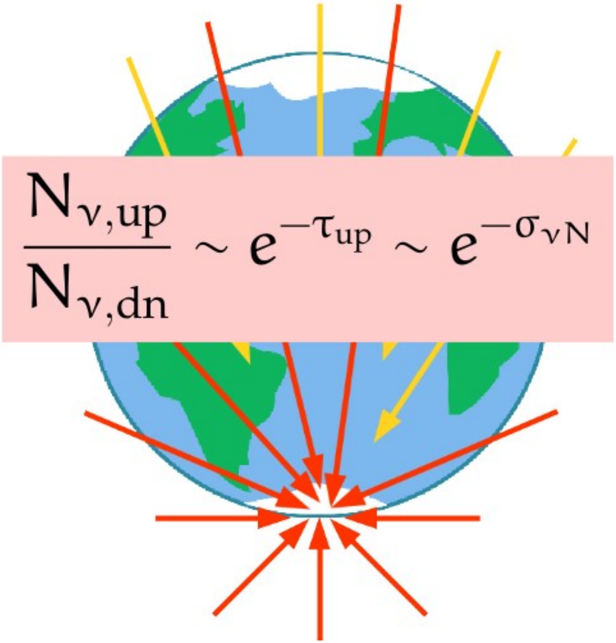
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

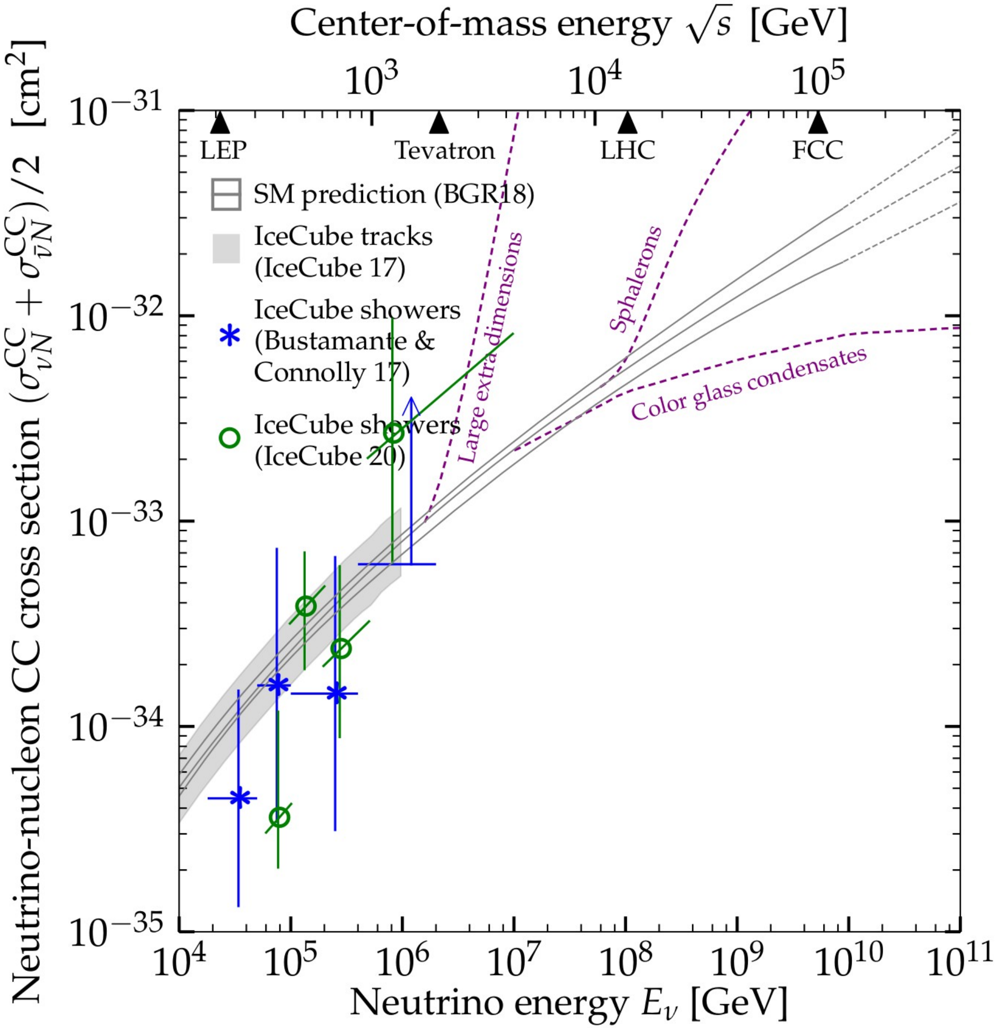


Above ~ 10 TeV: Earth is opaque



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

High-energy νN cross section: *today*

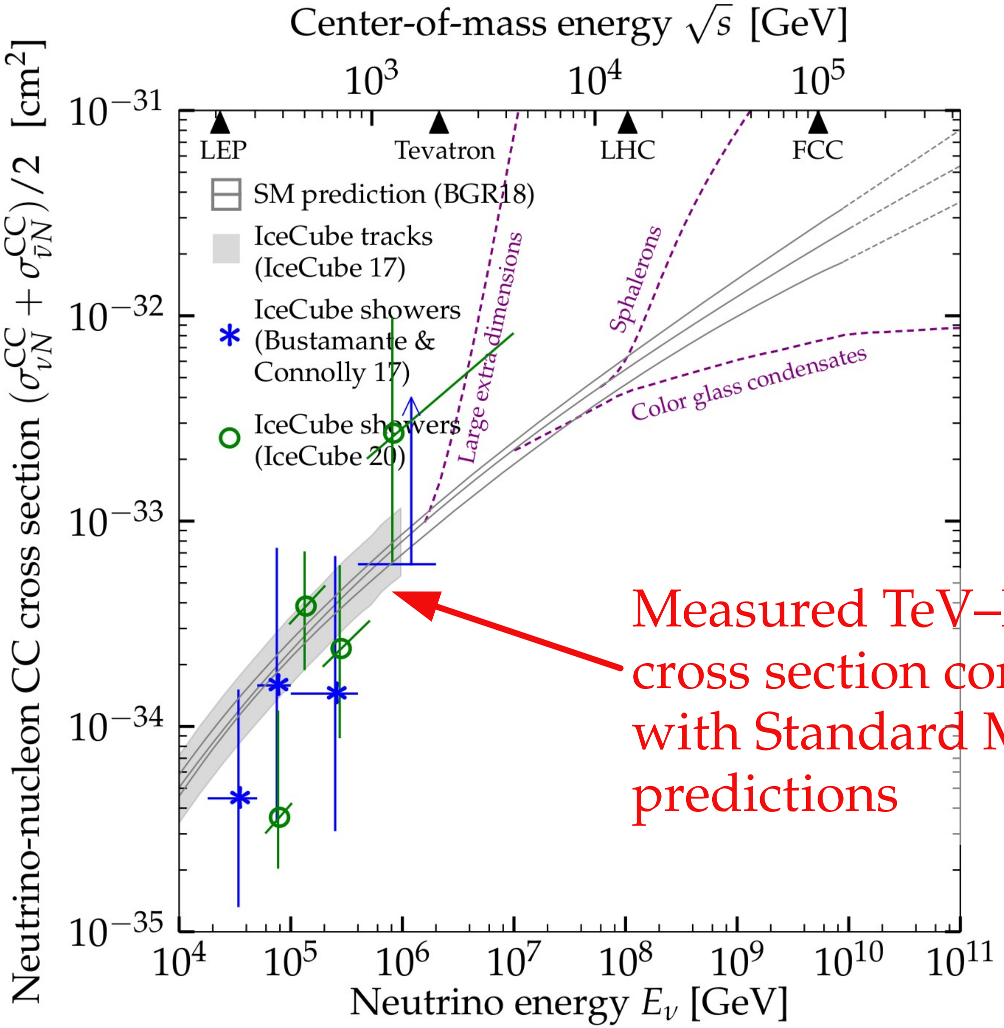


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



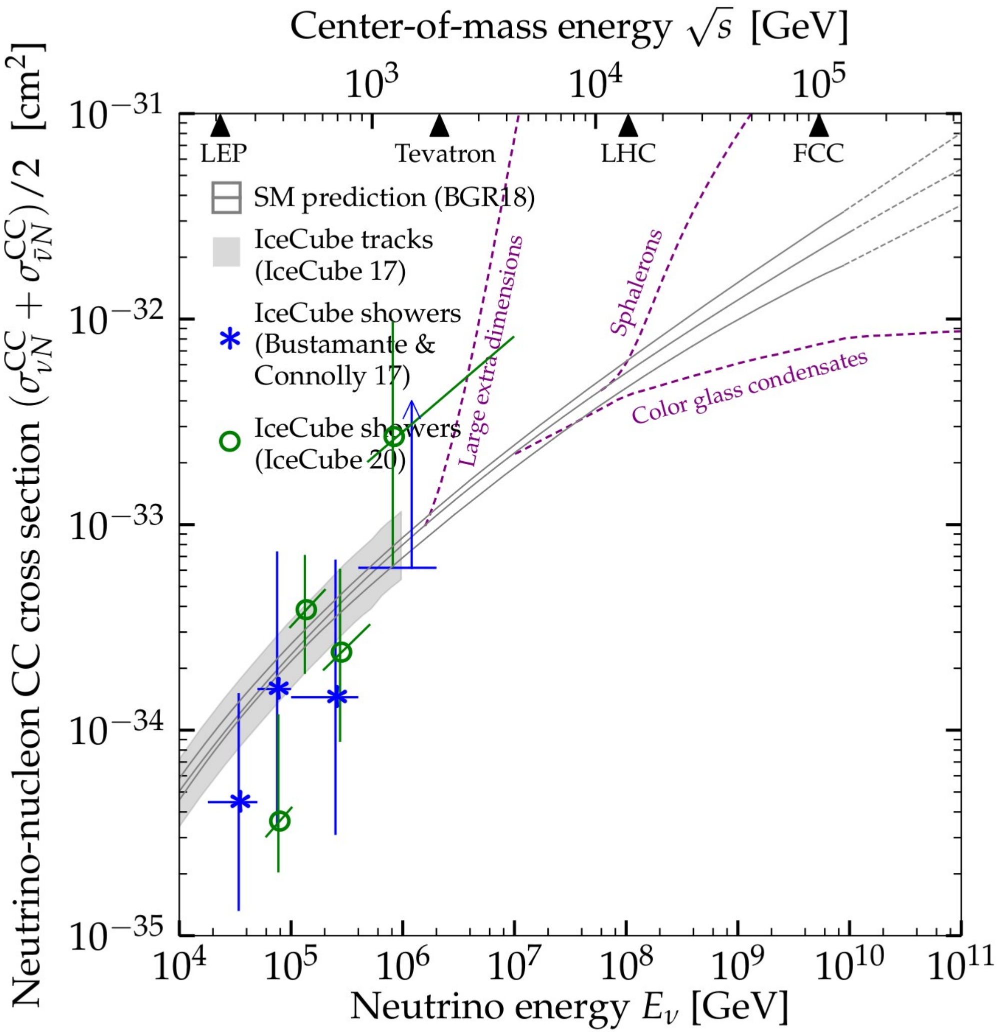
Measured TeV–PeV cross section compatible with Standard Model predictions

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*



BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
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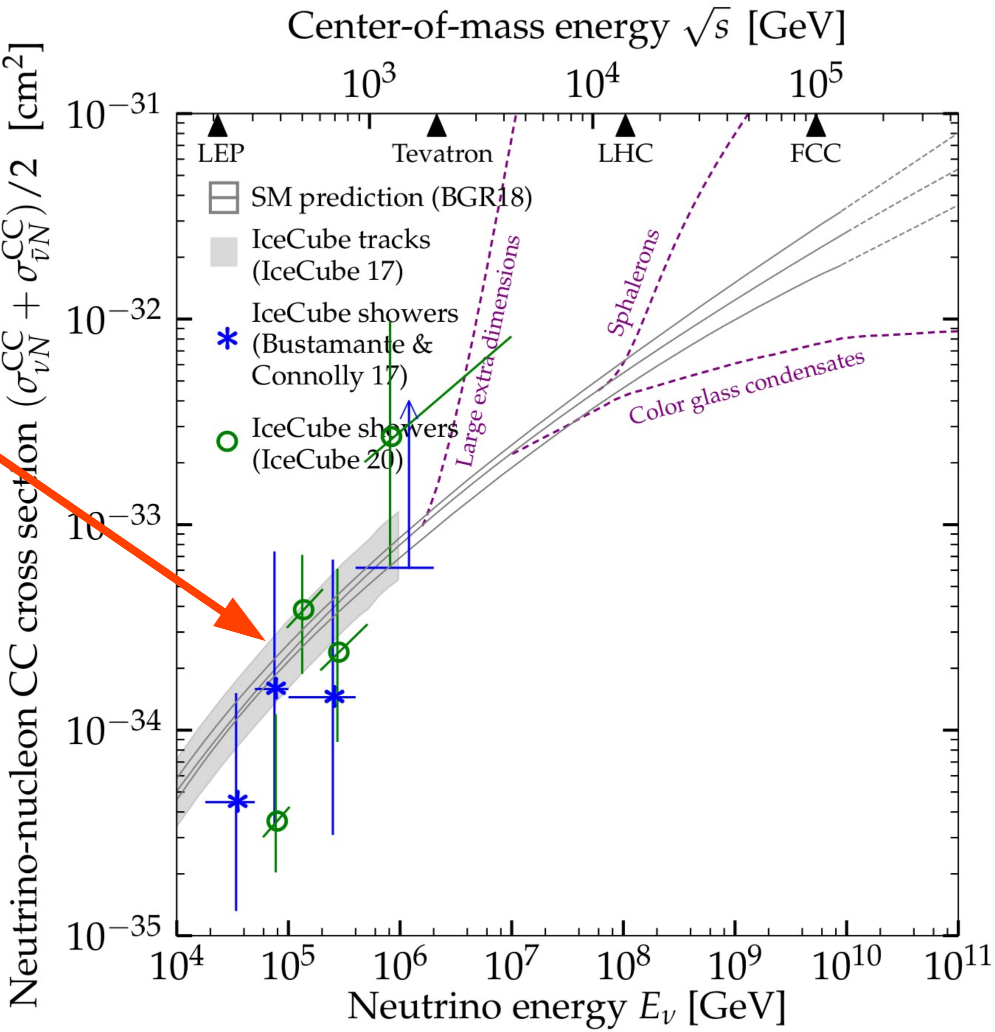
Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section



BGR18 prediction from:
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Measurements from:
IceCube, 2011.03560
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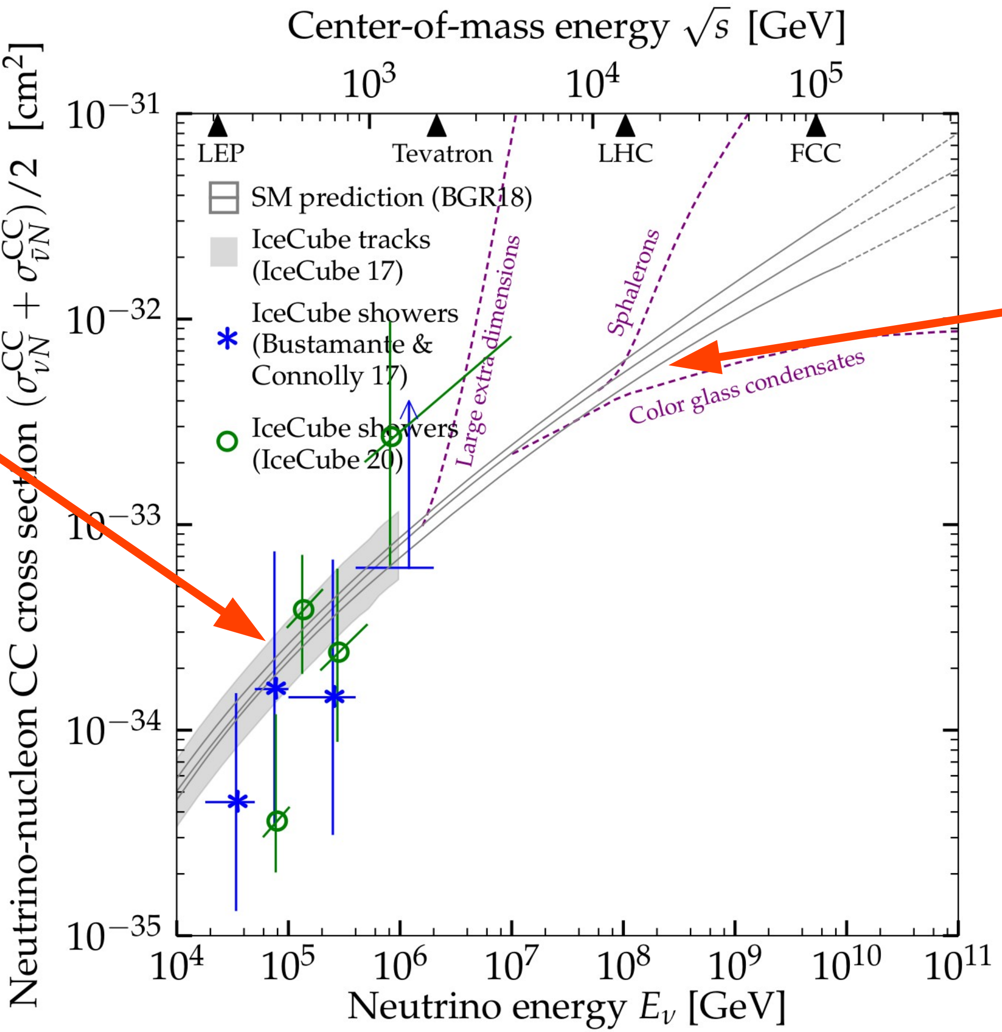
High-energy νN cross section: *today*

Measured:
TeV – PeV
cross section

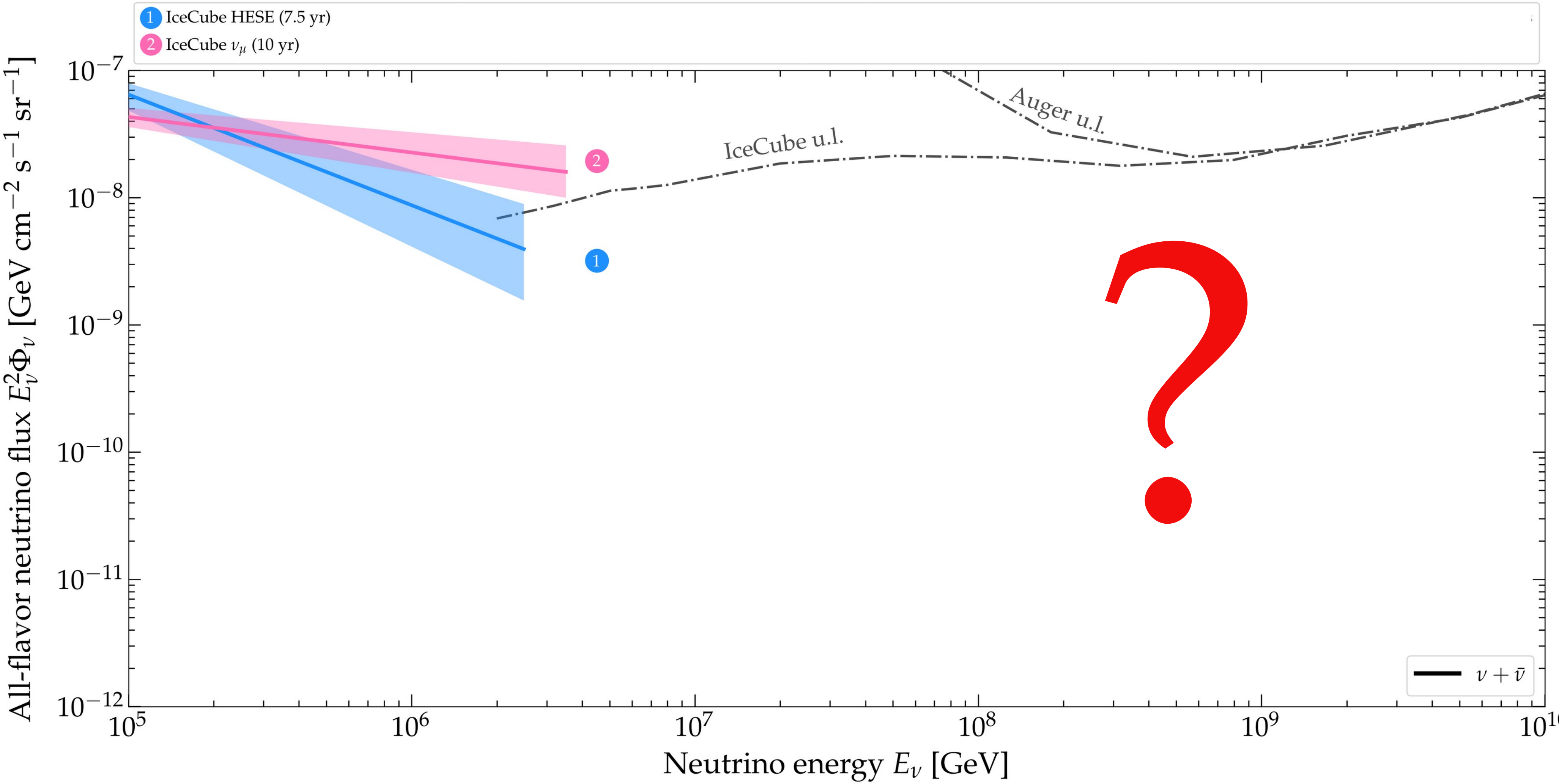


Not measured:
> 10-PeV
cross section

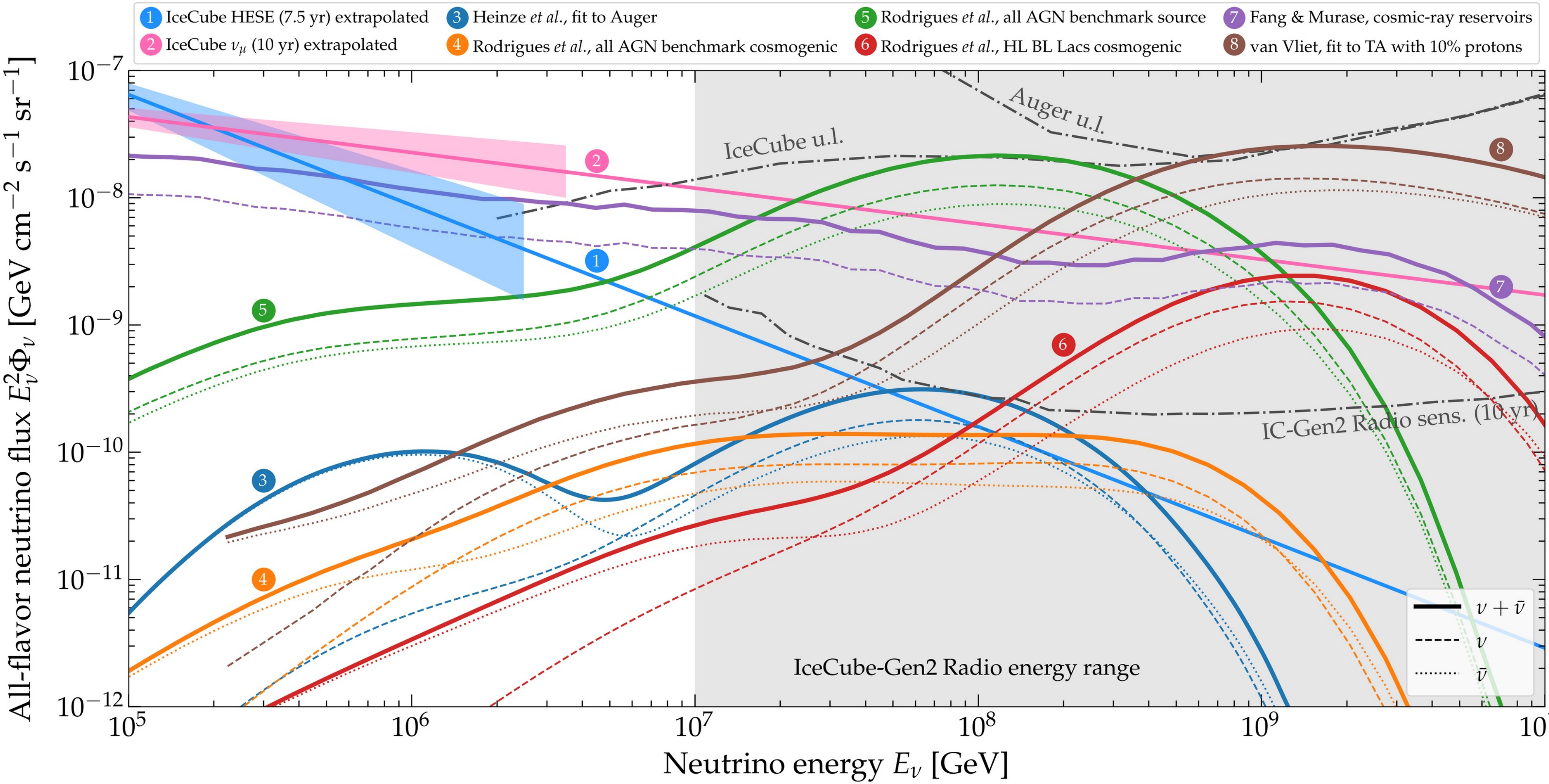
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020

Measurements from:
IceCube, 2011.03560
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

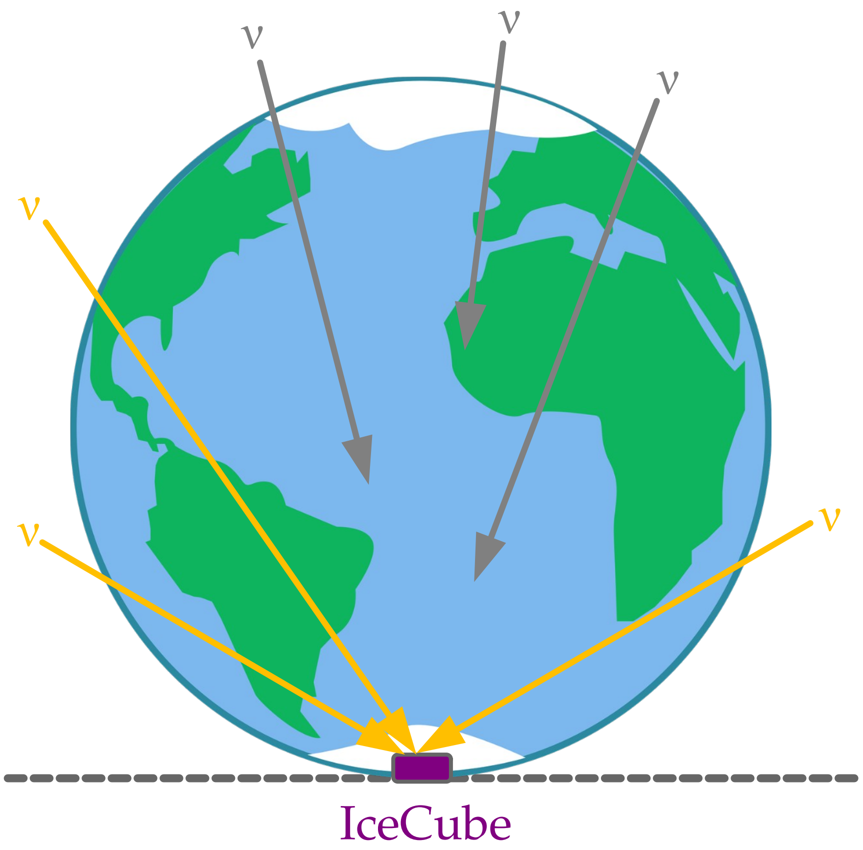


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
IceCube u.l.
Auger u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



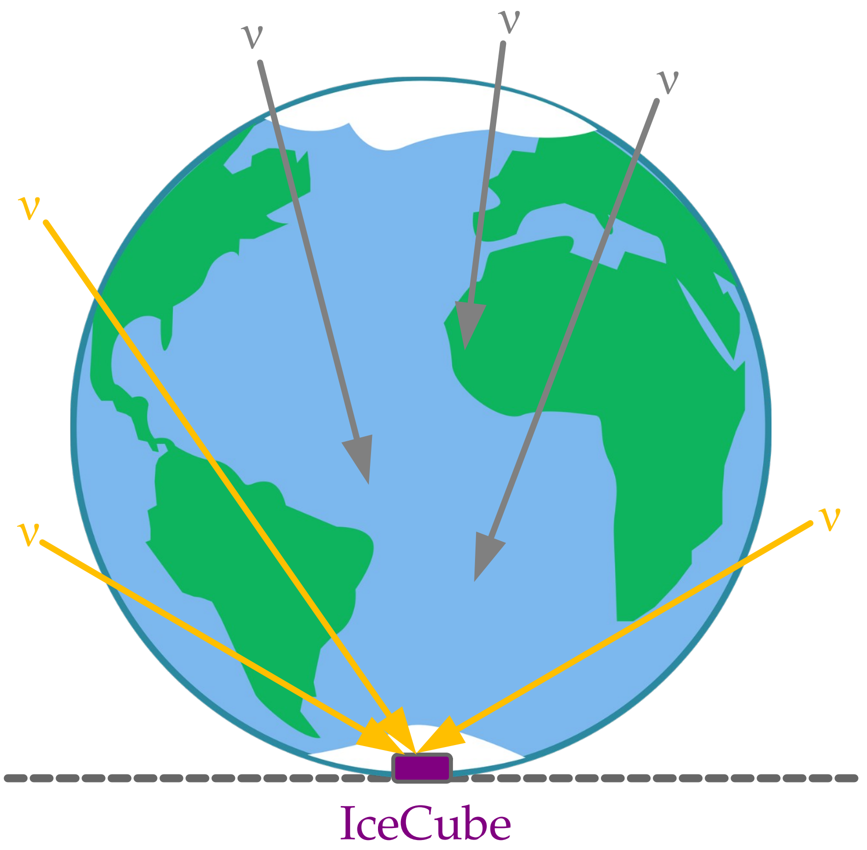
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
ν
$\bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

TeV–PeV:



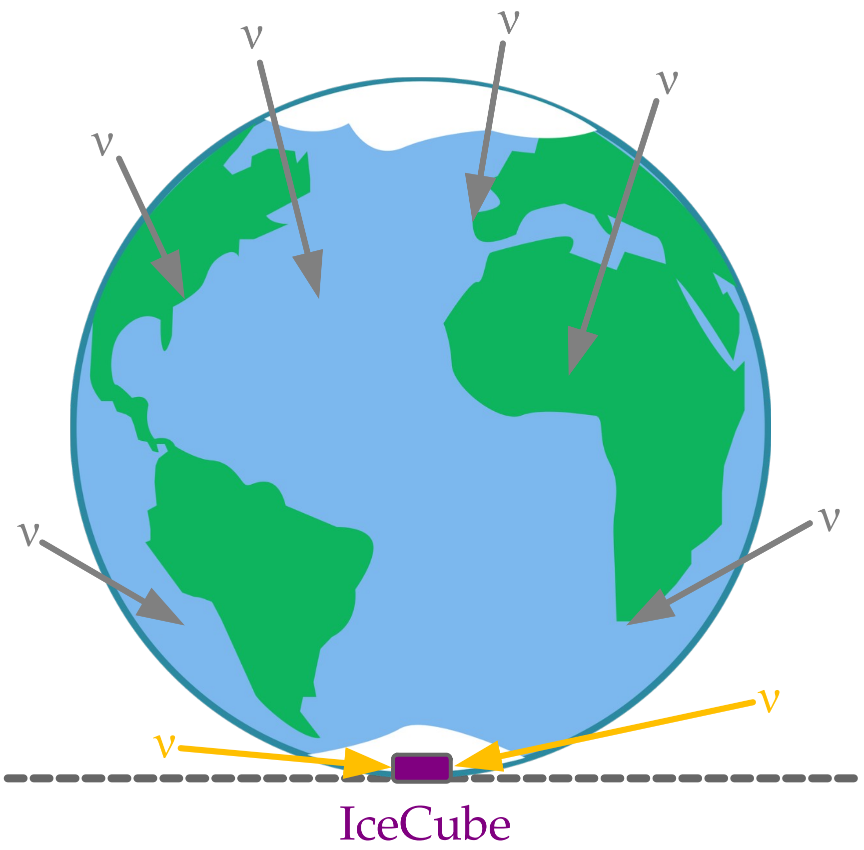
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



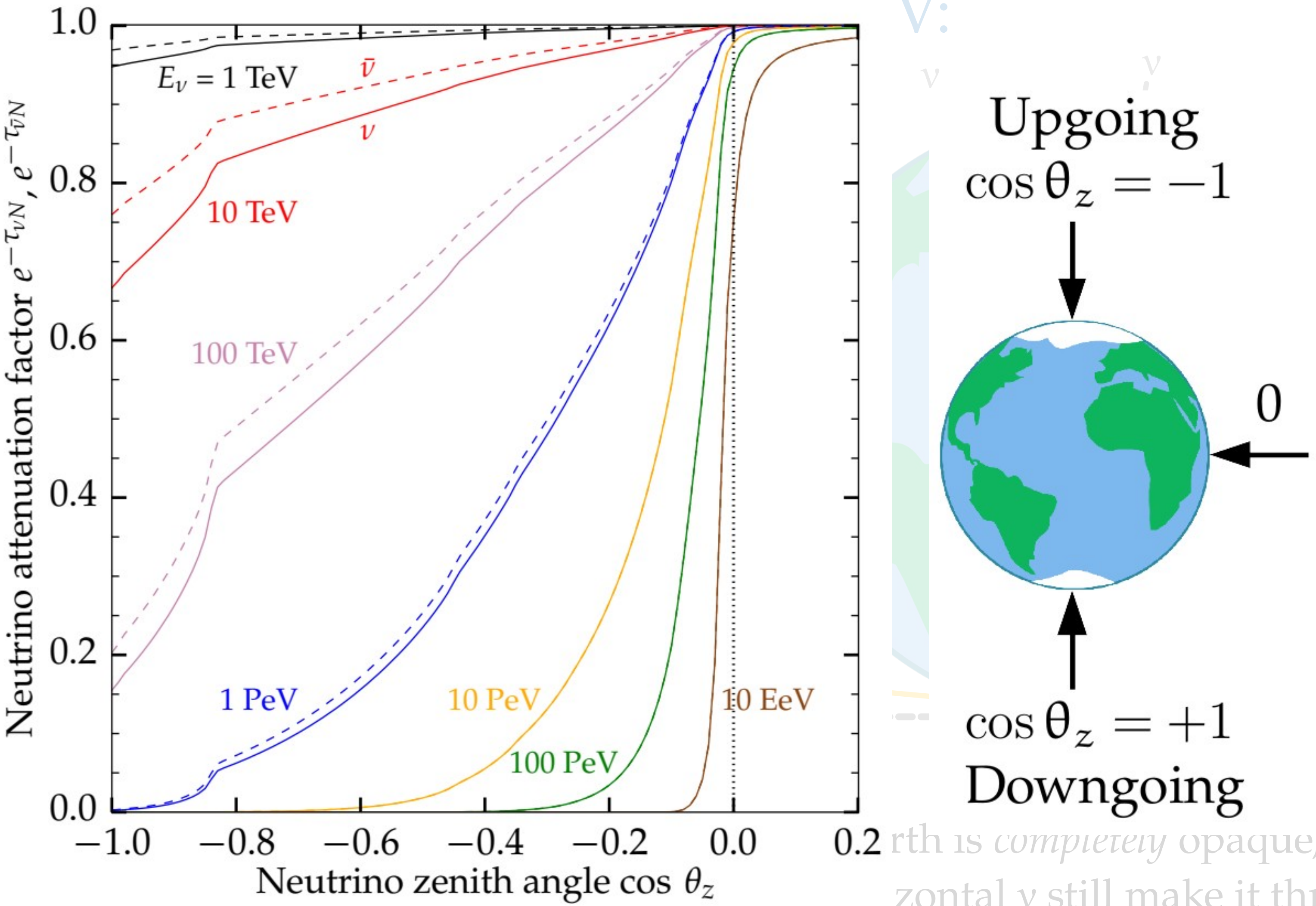
Earth is *almost fully* opaque,
some upgoing ν still make it through

$>$ 100 PeV:



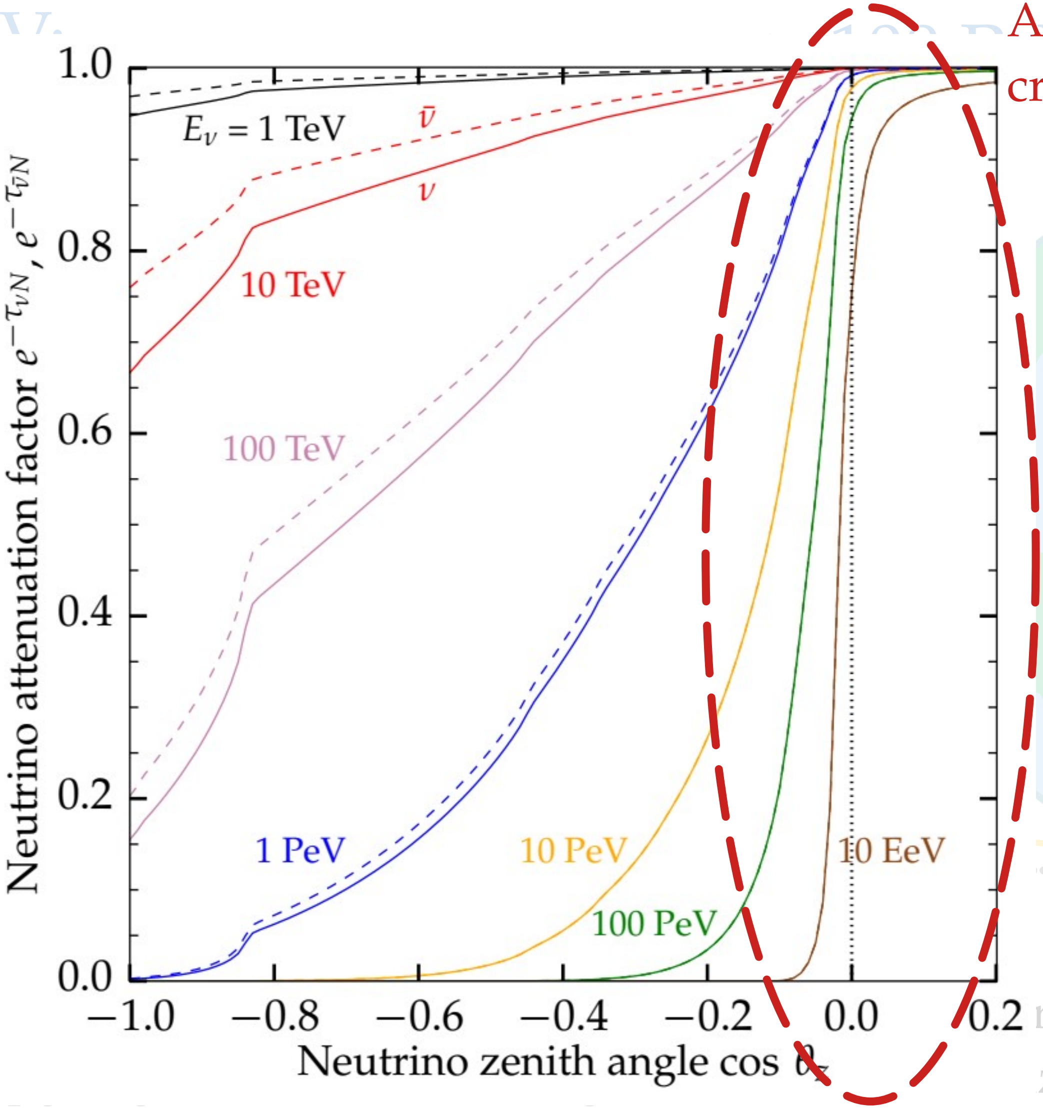
Earth is *completely* opaque,
but horizontal ν still make it through

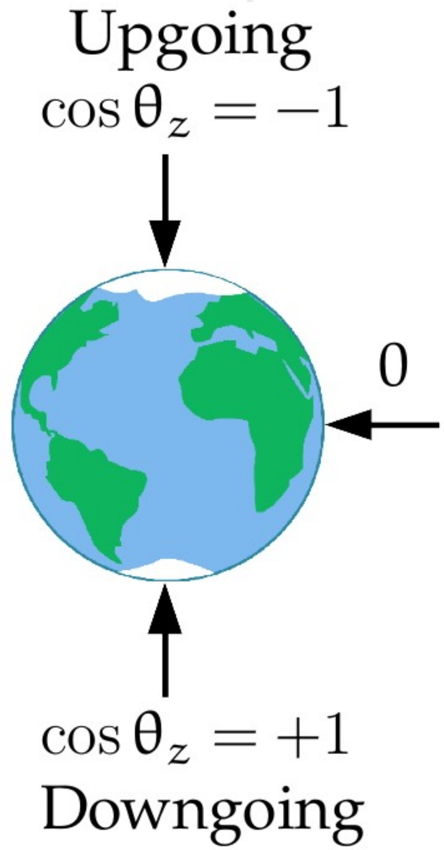
TeV–PeV ... 100 PeV:

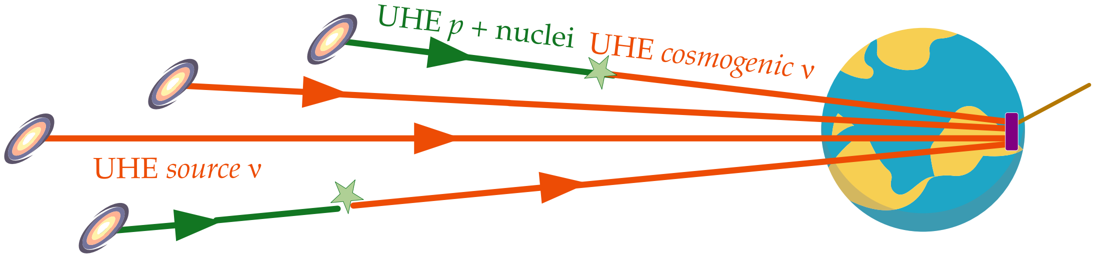


Ea... rth is *completely* opaque,
some ... zontal ν still make it through

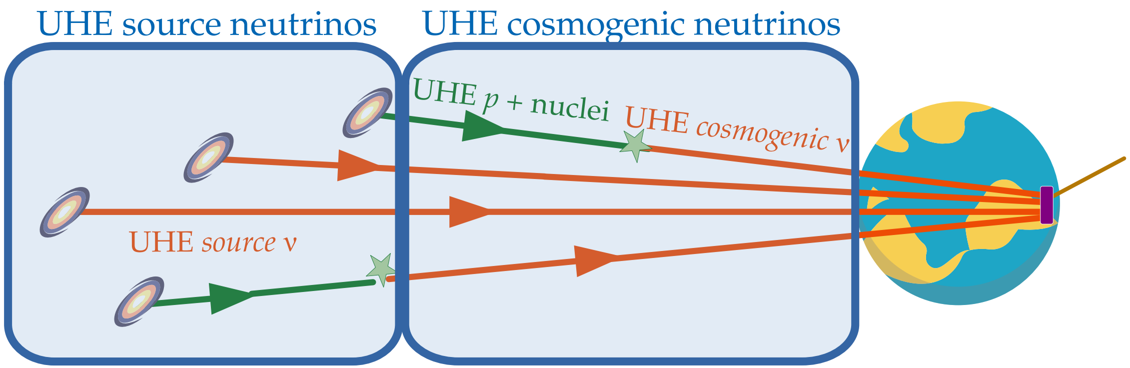
At UHE, we can only extract the cross section using horizontal ν

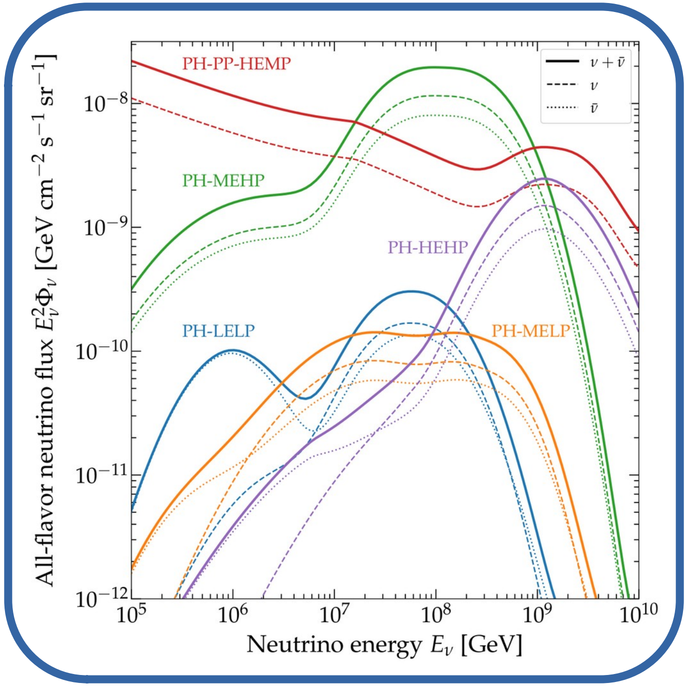




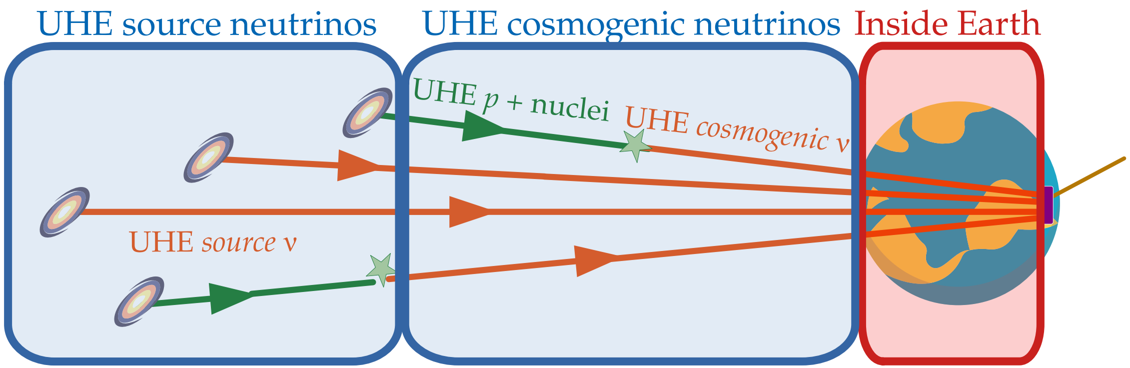


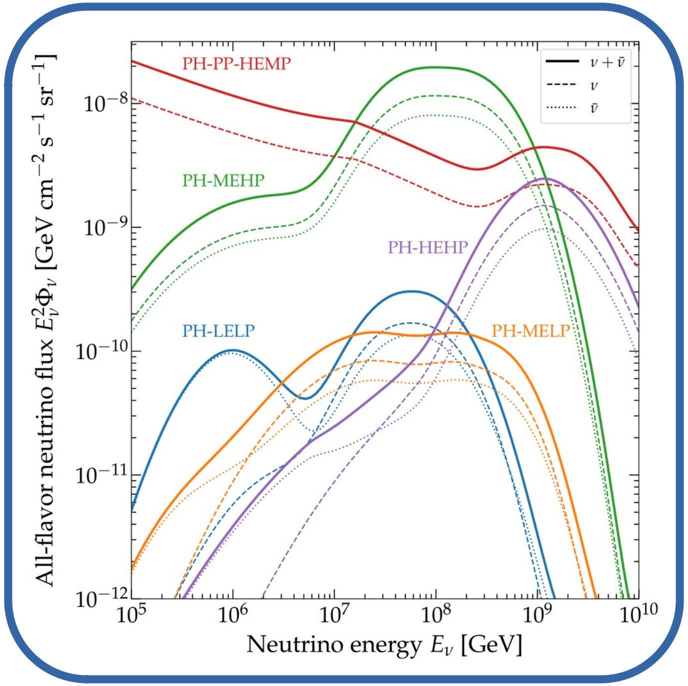
UHE p + nuclei
UHE cosmogenic ν
UHE source ν



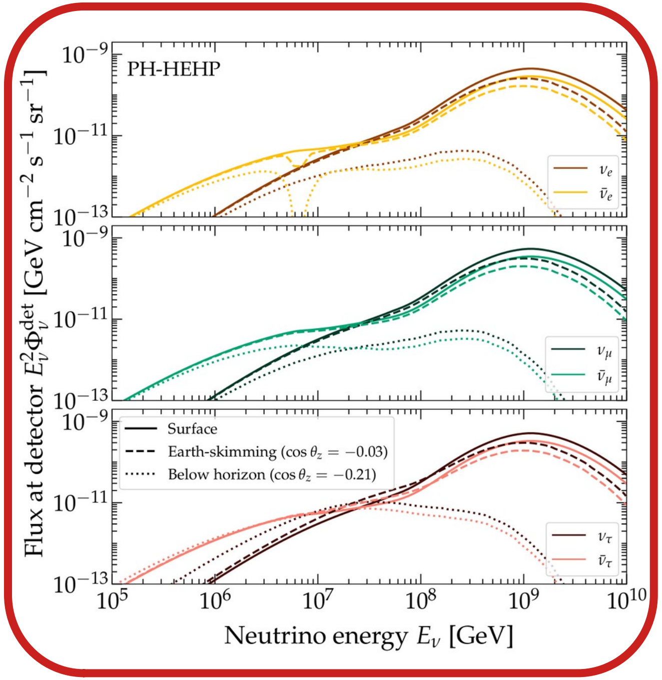


UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties

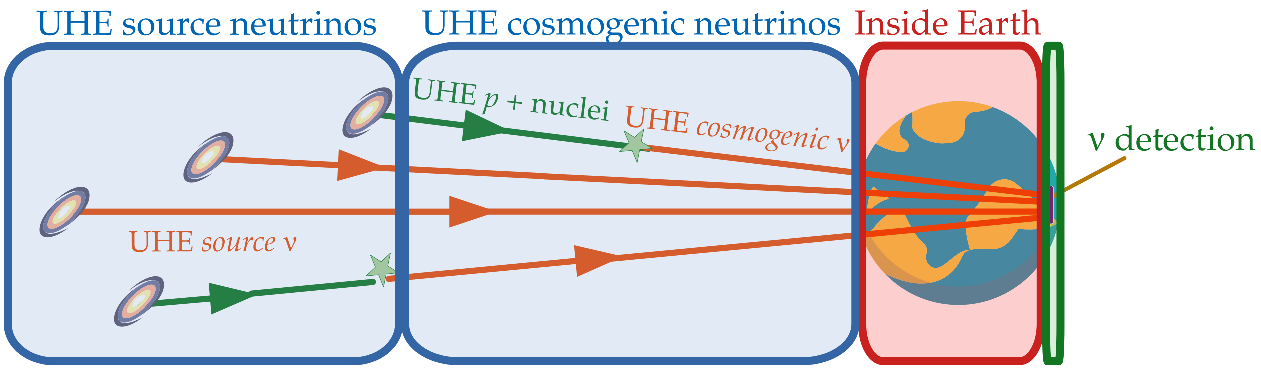


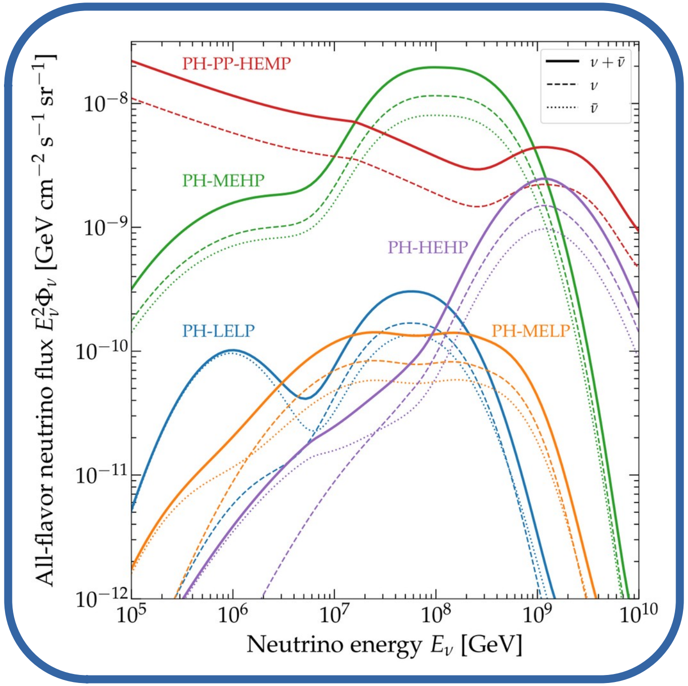


UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties

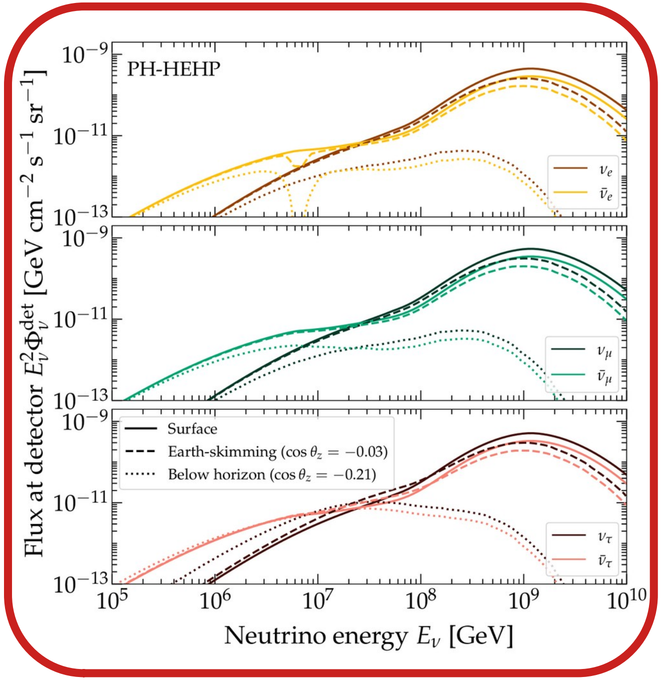


Propagate each flavor of ν and $\bar{\nu}$ separately: deep inelastic scattering, diffractive scattering, ν_τ regeneration





UHE ν from *pp* and *pγ* interactions, account for cosmic-ray spectrum & mass composition, source properties



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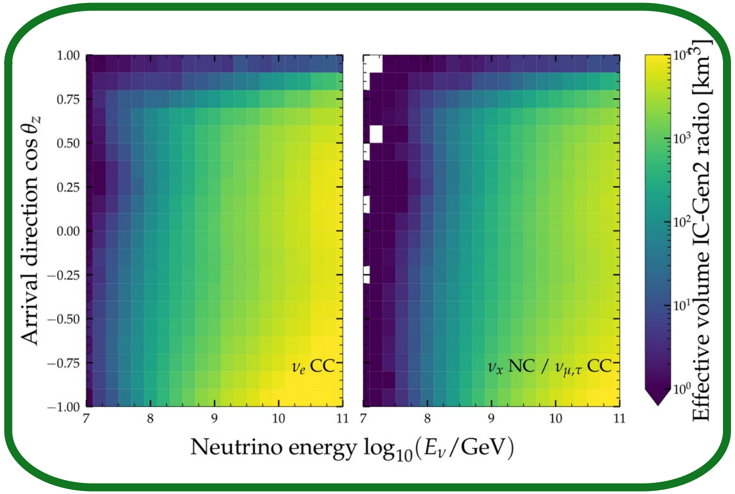
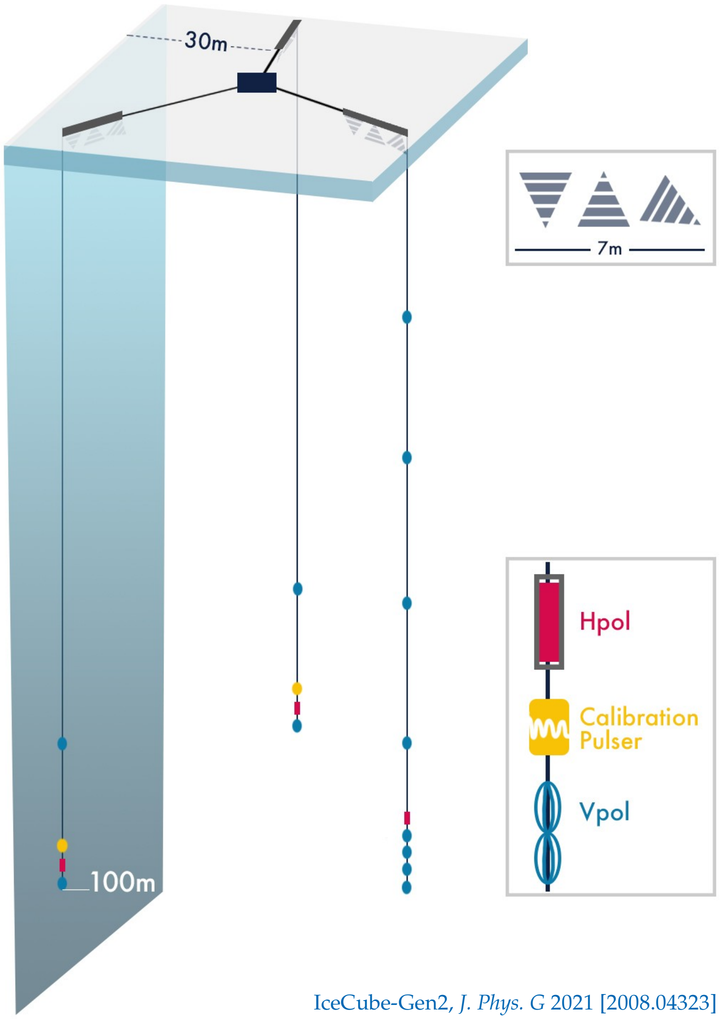
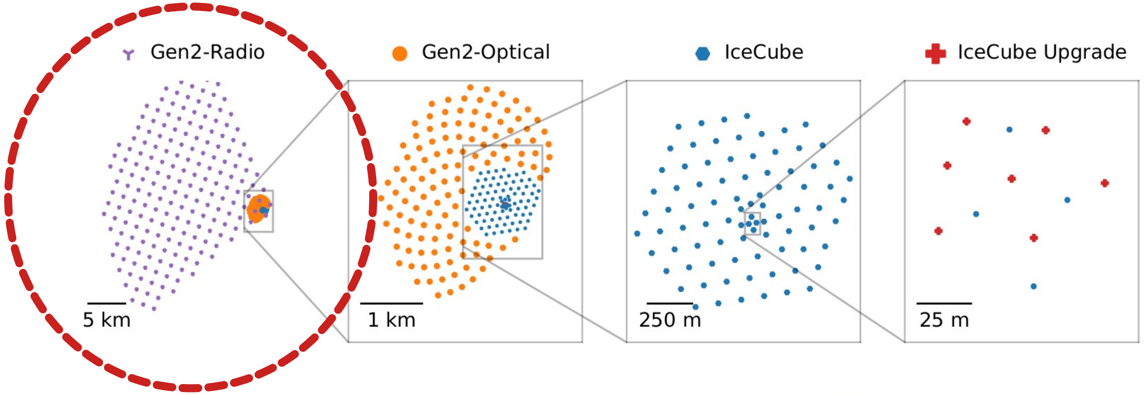


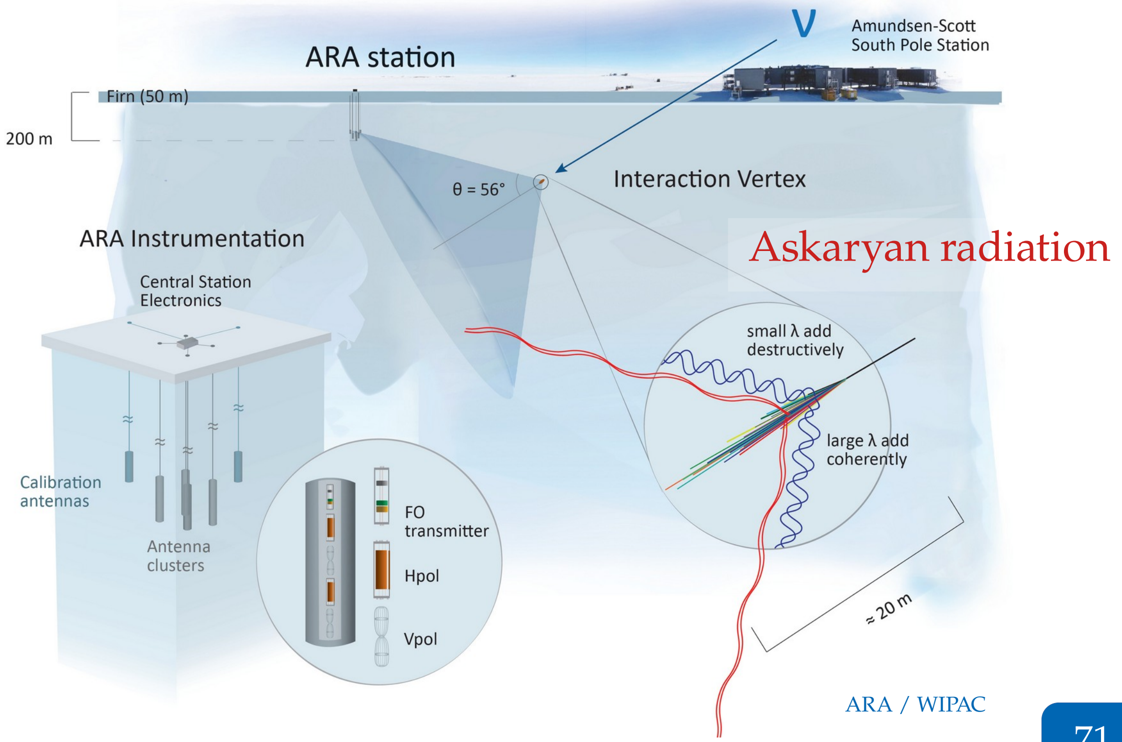
Model radio propagation in ice, antenna response, angular and energy resolution, inelasticity distribution

IceCube-Gen2 Radio



IceCube-Gen2, *J. Phys. G* 2021 [2008.04323]





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PHYSICS

Searching for the Universe's Most Energetic Particles, Astronomers Turn on the Radio

New radio-based observatories could soon detect ultrahigh-energy neutrinos, opening a new window on extreme cosmic physics

By Katrina Miller on April 27, 2021

Artist's composite of the IceCube Neutrino Observatory in Antarctica, accompanied by a distant astrophysical source emitting neutrinos that are detected in IceCube's subsurface sensors. Credit: IceCube and NSF

Ever since their discovery in the 1960s, ultrahigh-energy cosmic rays have

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December 1, 2015 — Francis Halzen

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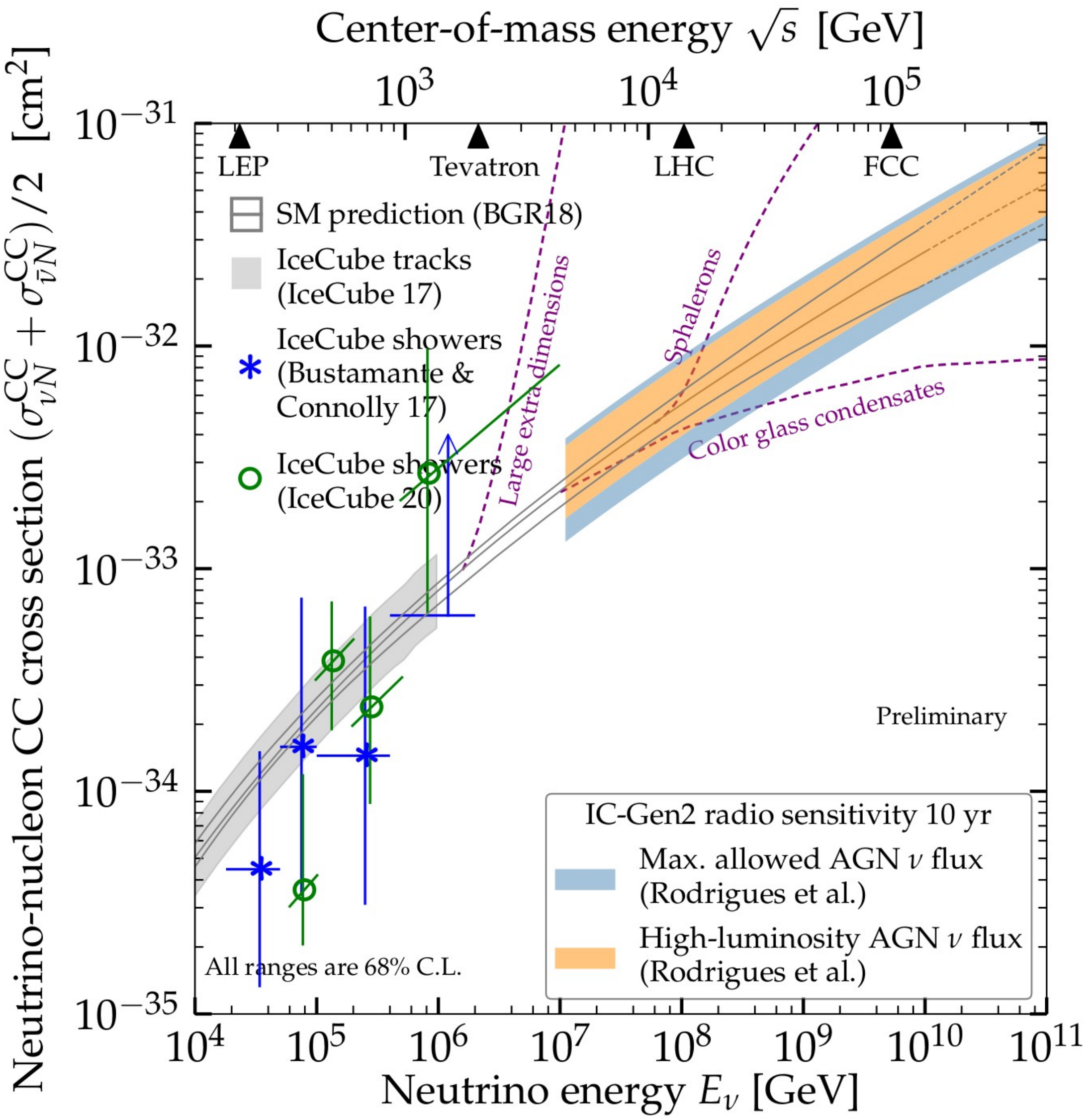
SPACE
Didn't Scientists Already Know Where Cosmic Rays Come from?
September 22, 2017 — Yvette Cendes

Katrina Miller for *Scientific American*, April 27, 2021 [link]

After 10 years of IceCube-Gen2 Radio (~2040):

(If the UHE ν fluxes are high)

Valera, **MB**, Glaser, *In preparation*



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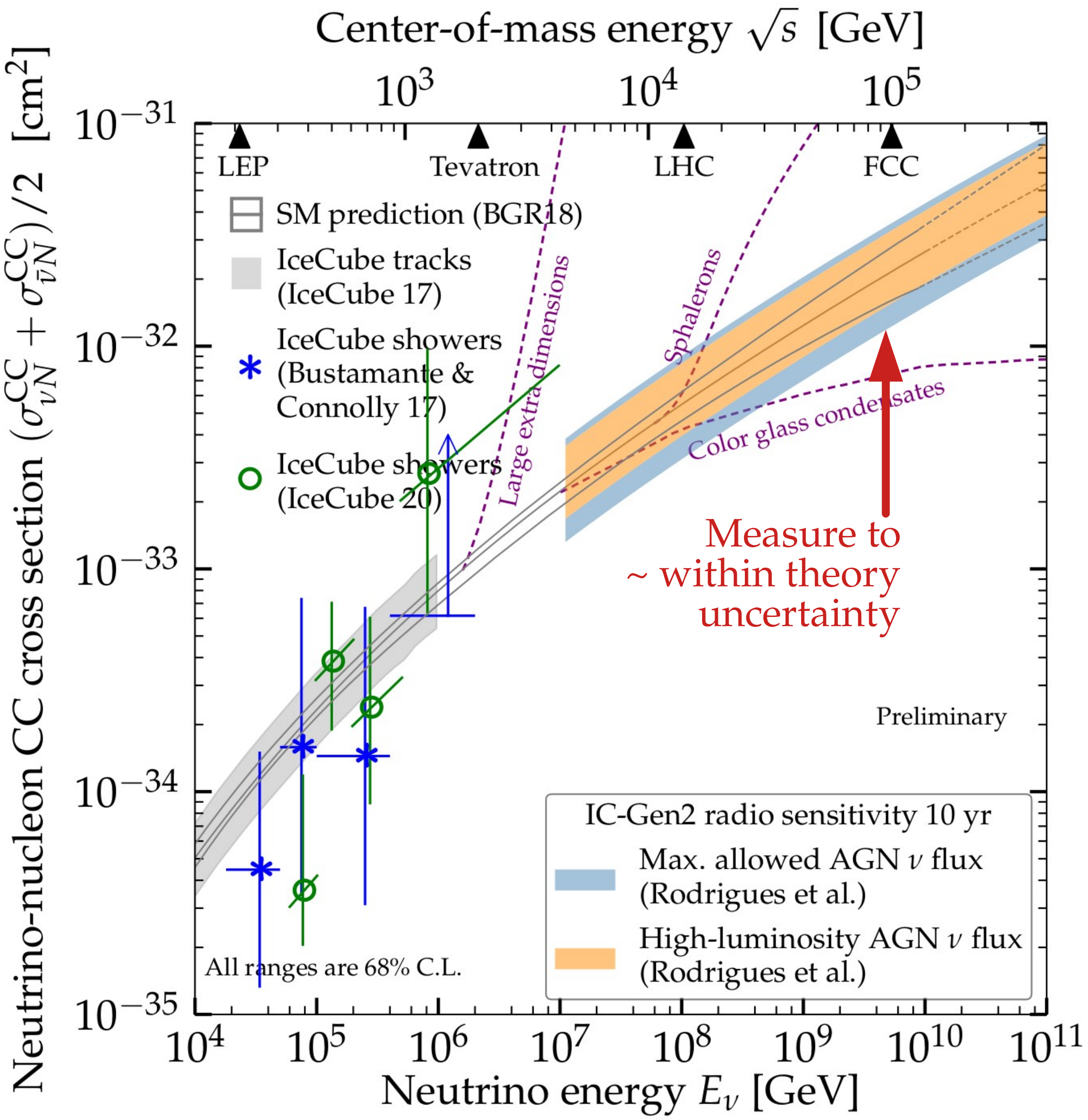
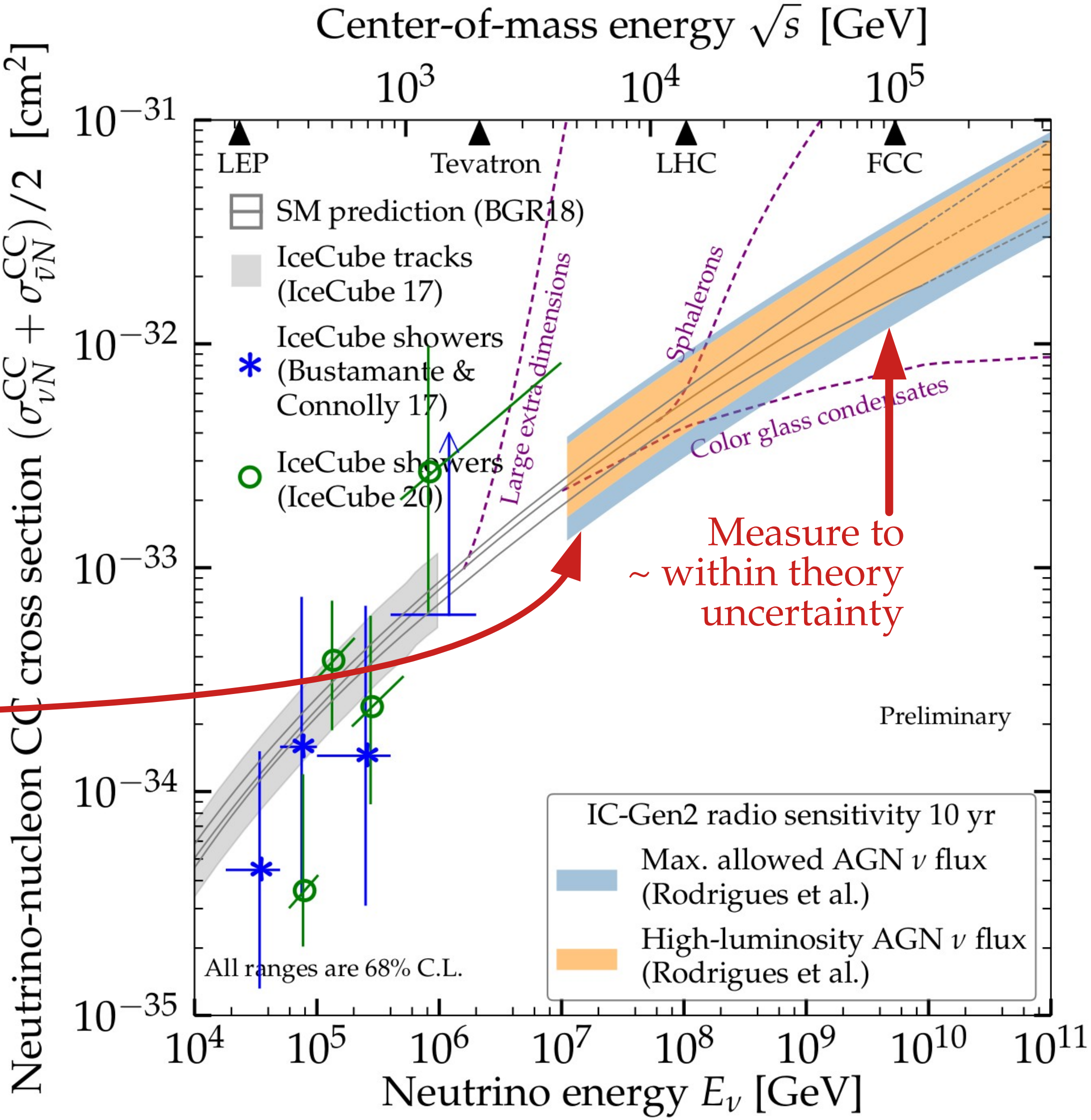


After 10 years of IceCube-Gen2 Radio (~2040):

(If the UHE ν fluxes are high)

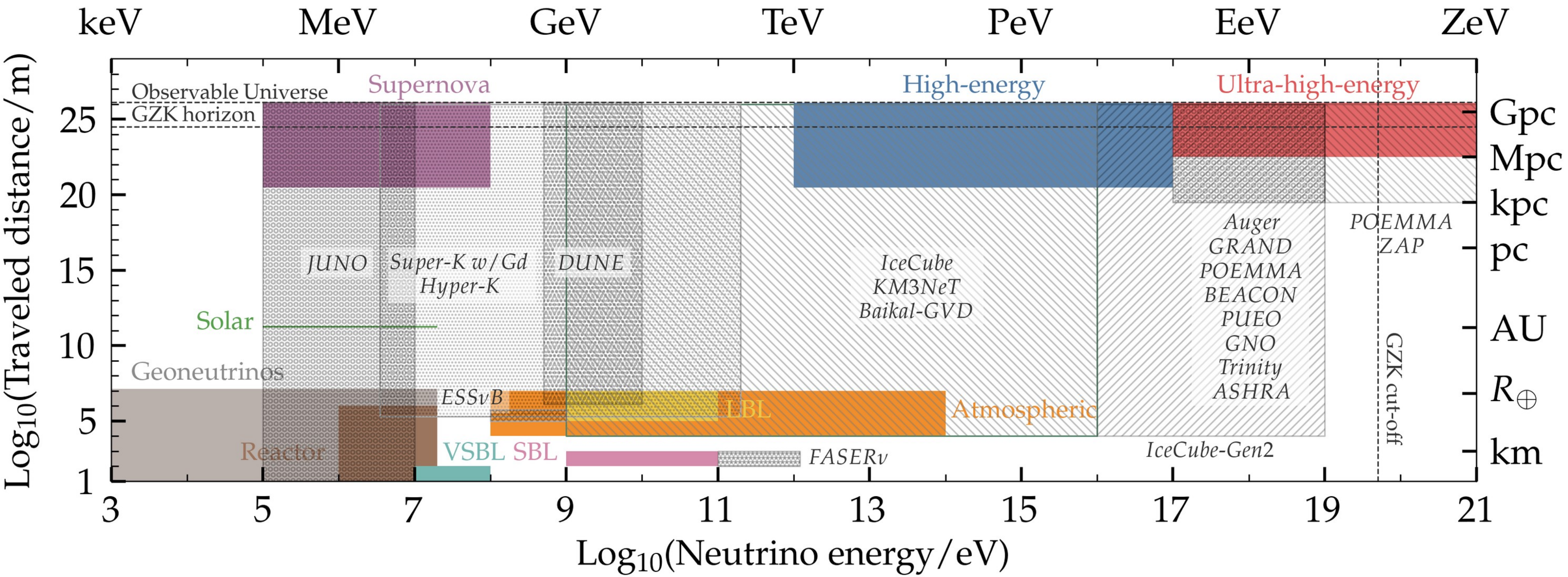
Valera, **MB**, Glaser, *In preparation*

Work led by
Víctor Valera



III.
The future

Next decade: a host of planned neutrino detectors



Synergies with lower energies

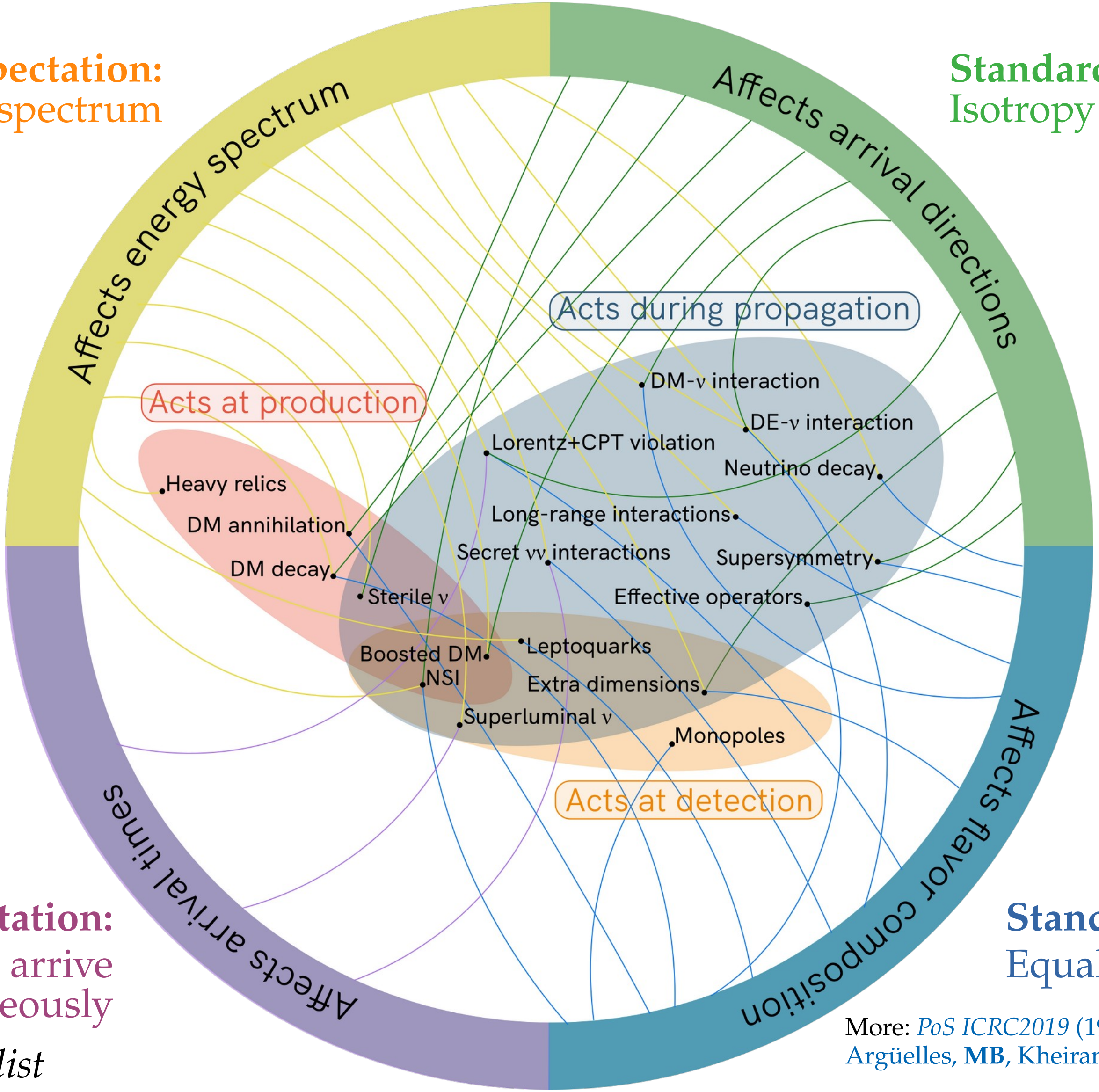
Increase TeV–PeV ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



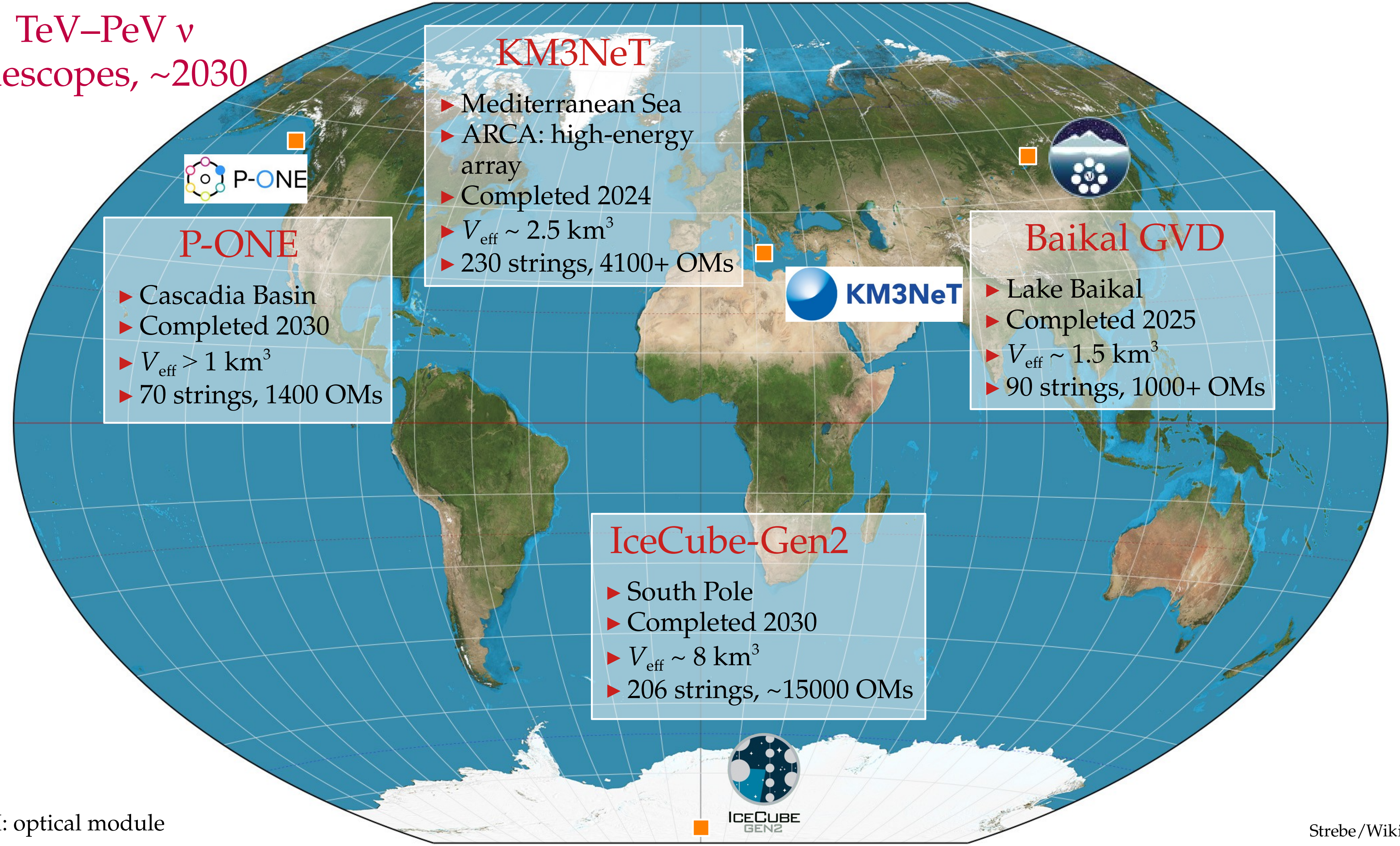
Standard expectation:
ν and γ from transients arrive simultaneously

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

TeV–PeV ν telescopes, ~2030



OM: optical module

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

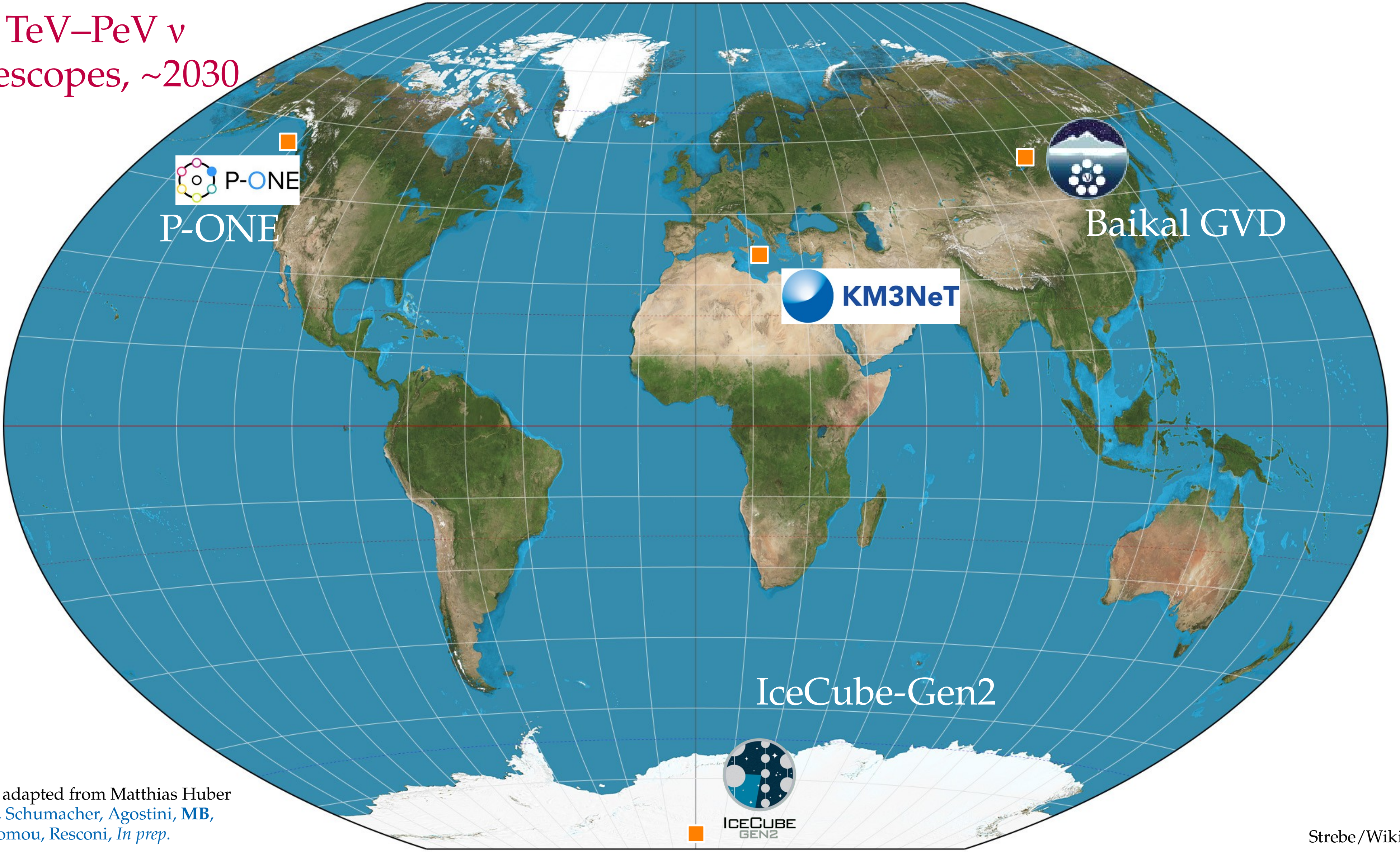


Figure adapted from Matthias Huber
Huber, Schumacher, Agostini, **MB**,
Oikonomou, Resconi, *In prep.*

Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

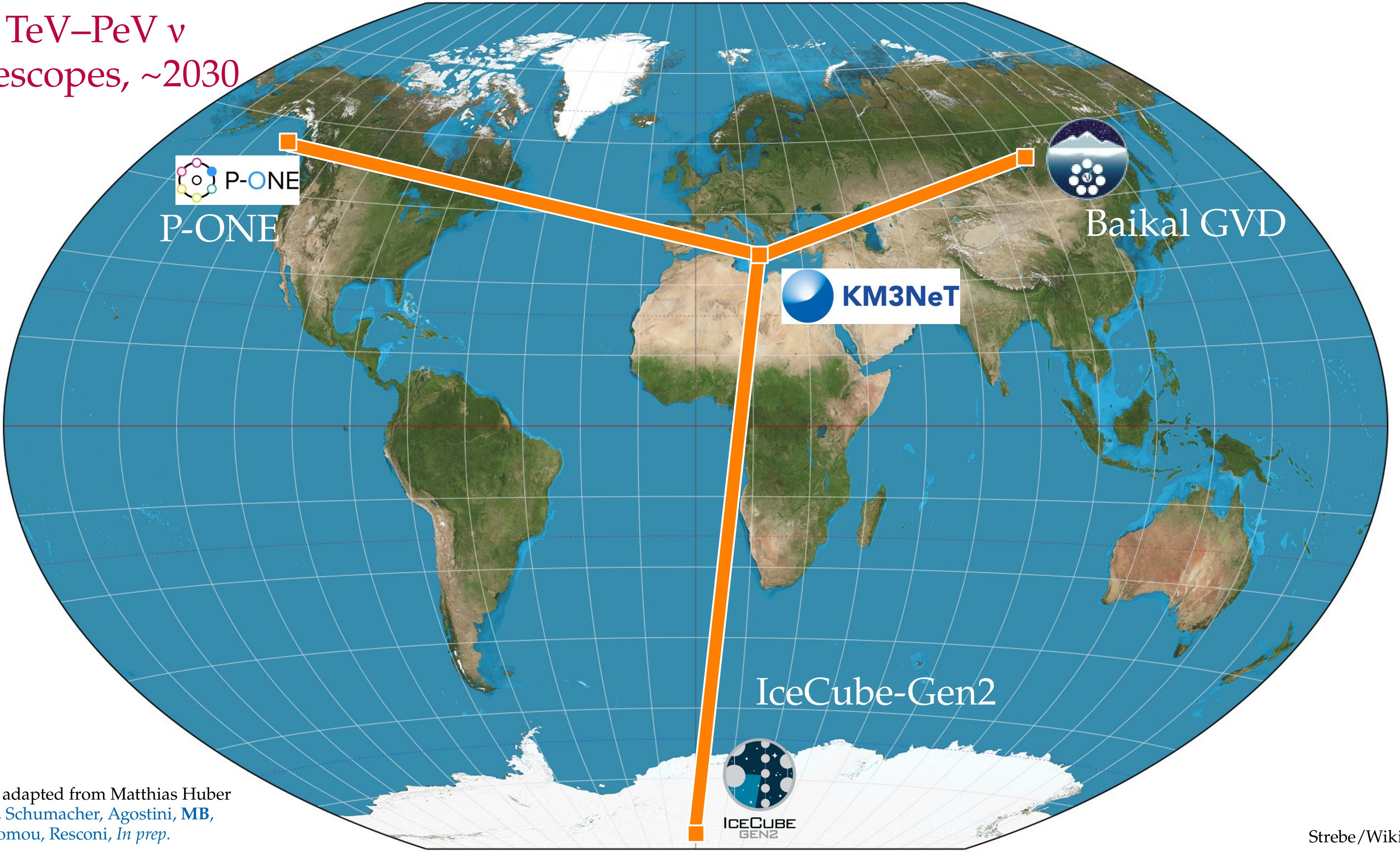


Figure adapted from Matthias Huber
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Strebe/Wikipedia

TeV–PeV ν telescopes, ~2030

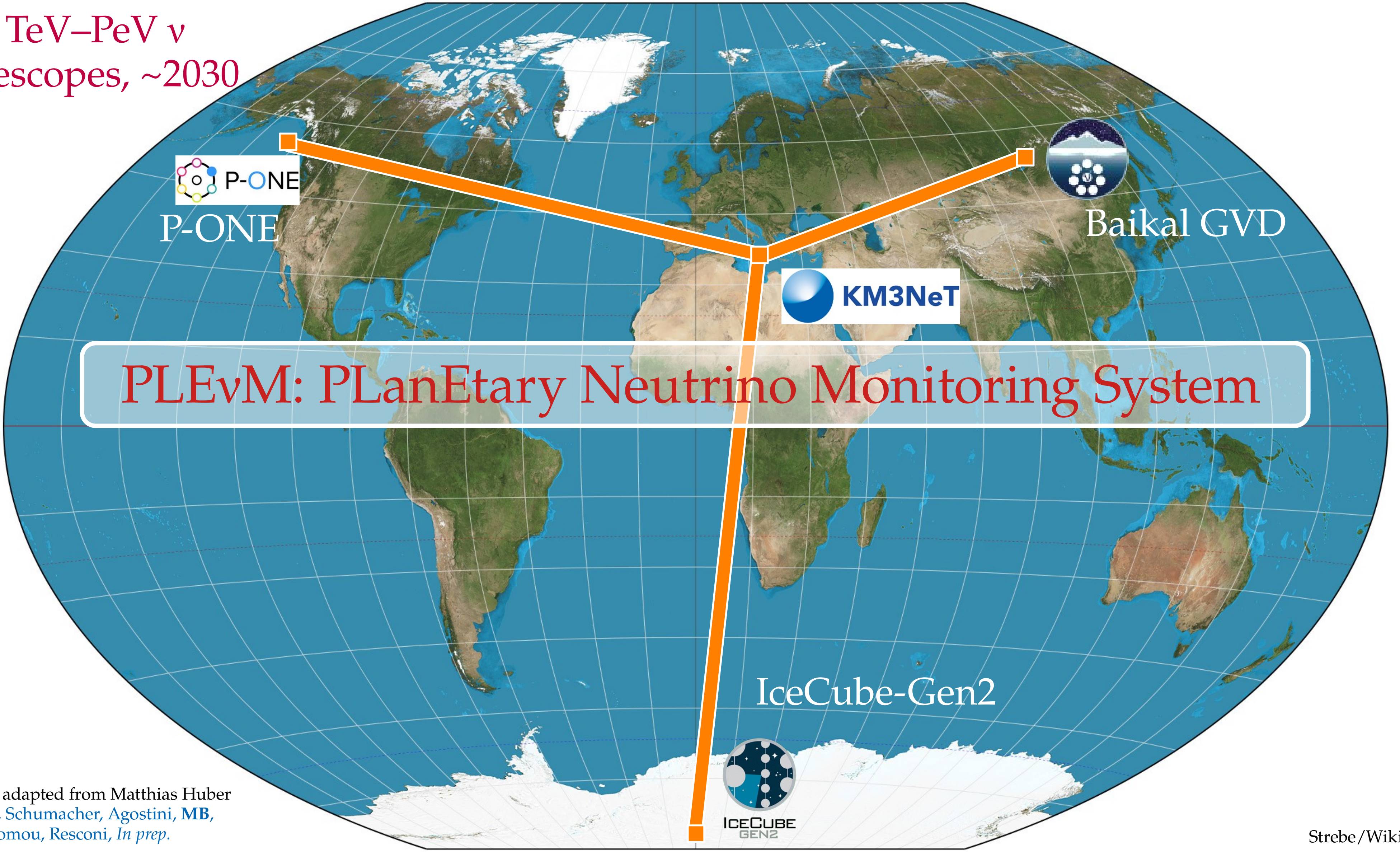

Figure adapted from Matthias Huber
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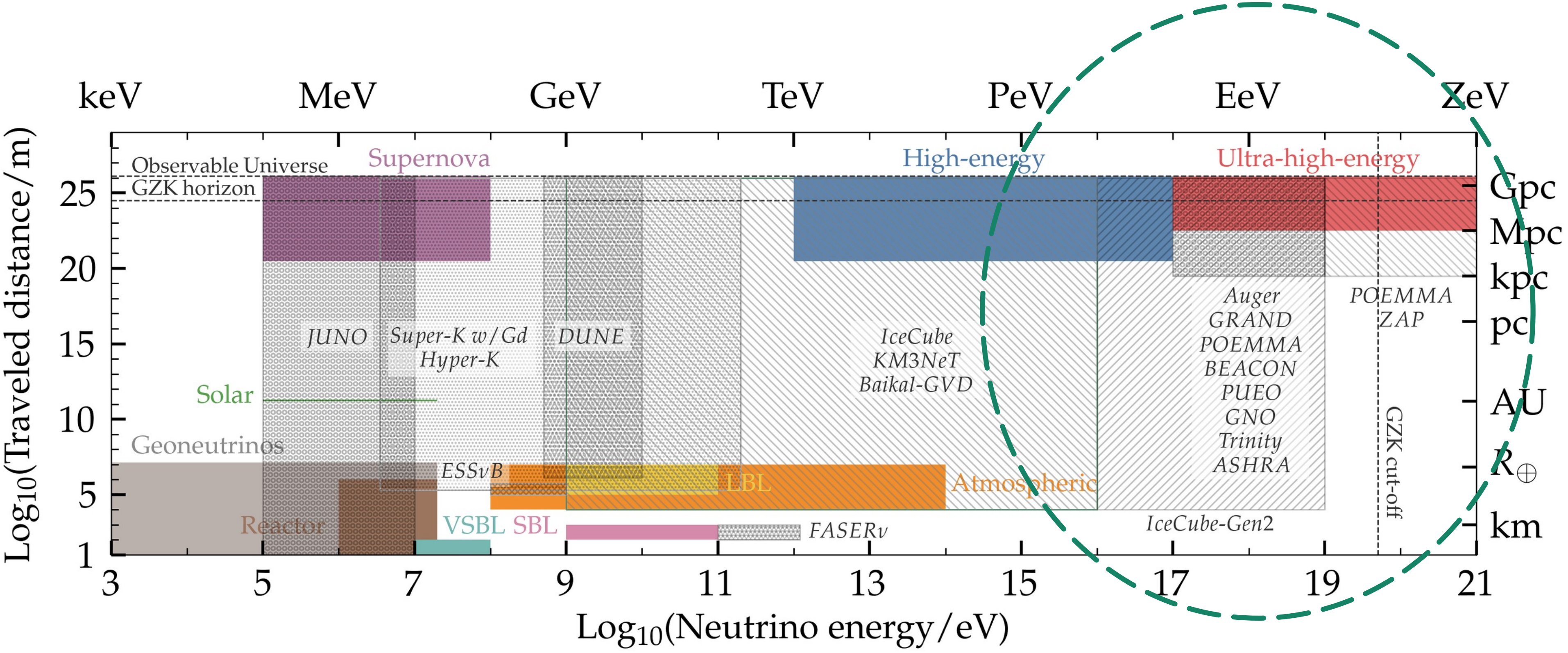
Strebe/Wikipedia

Next decade: a host of planned neutrino detectors

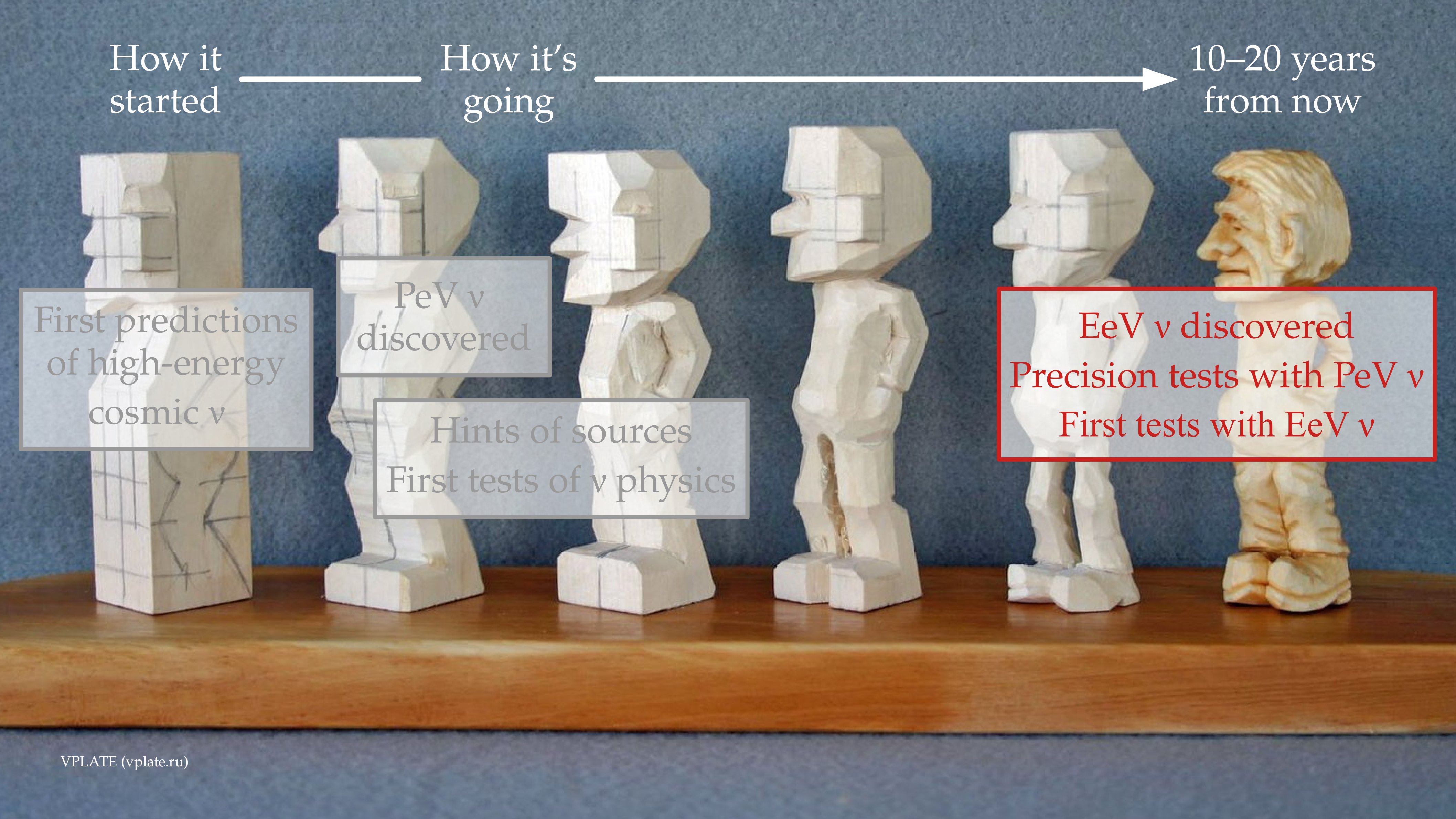


Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest


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

PhD position in high-energy cosmic neutrino physics ← INSPIRE ad

Bohr Inst. • Europe

astro-ph hep-ph hep-th PhD

Deadline on Oct 31, 2021

Contact:
Mauricio Bustamante (Niels Bohr Institute)
mbustamante@nbi.ku.dk

Job description:
The Niels Bohr International Academy invites applications for a PhD studentship in high-energy neutrino physics with cosmic neutrinos.

The preferred starting date is April 01, 2022 (earlier dates can be discussed).

Applicants are requested to submit their electronic applications including a cover letter, CV, research statement, BSc and MSc academic transcripts, and two reference letters via AcademicJobsOnline. Please see application instructions below.

In order to receive full consideration, complete applications should be received by **October 31, 2021**.

Pushing neutrino physics to the cosmic frontier

What is Nature like at its most fundamental level? What are its building blocks and how do they interact? What are its organizing principles? These questions lie at the core of Physics, science, and human curiosity. During the last century, we steadily found deeper answers, using increasingly powerful particle accelerators that revealed fundamental particles, interactions, and symmetries. Yet, ample territory remains unexplored at higher energies, ripe for discoveries.

Today, accelerators still churn out valuable data, but, so far, fail to guide us in furthering our view of fundamental physics. Observing particle processes at higher energies would provide guidance, but they lie beyond the reach of accelerator technology. Fortunately, Nature itself provides a way forward: we must turn from man-made particle accelerators to naturally occurring cosmic accelerators. These are extreme phenomena---exploding and colliding stars, black holes---that emit particles with energies millions of times higher than man-made accelerators. Among these, neutrinos stand out as incisive probes of particle physics.

During your PhD, you will learn how to harness the vast potential of high-energy cosmic neutrinos to unearth the particle physics that awaits at the highest, unexplored energies. You will look especially for signs of new physics, beyond the Standard Model.

The principal supervisor will be Assistant Prof. Mauricio Bustamante (INSPIRE profile) at the Niels Bohr International Academy. Your PhD will be part of the project "Pushing Neutrino Physics to the Cosmic Frontier", funded by the Villum Fonden (project no. 29388).

End

Backup slides

Basics

Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
- The precise flavor composition
- Is there new physics?

Status quo of high-energy cosmic neutrinos

But we have solid theory expectations
+ fast experimental progress

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
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- The precise flavor composition
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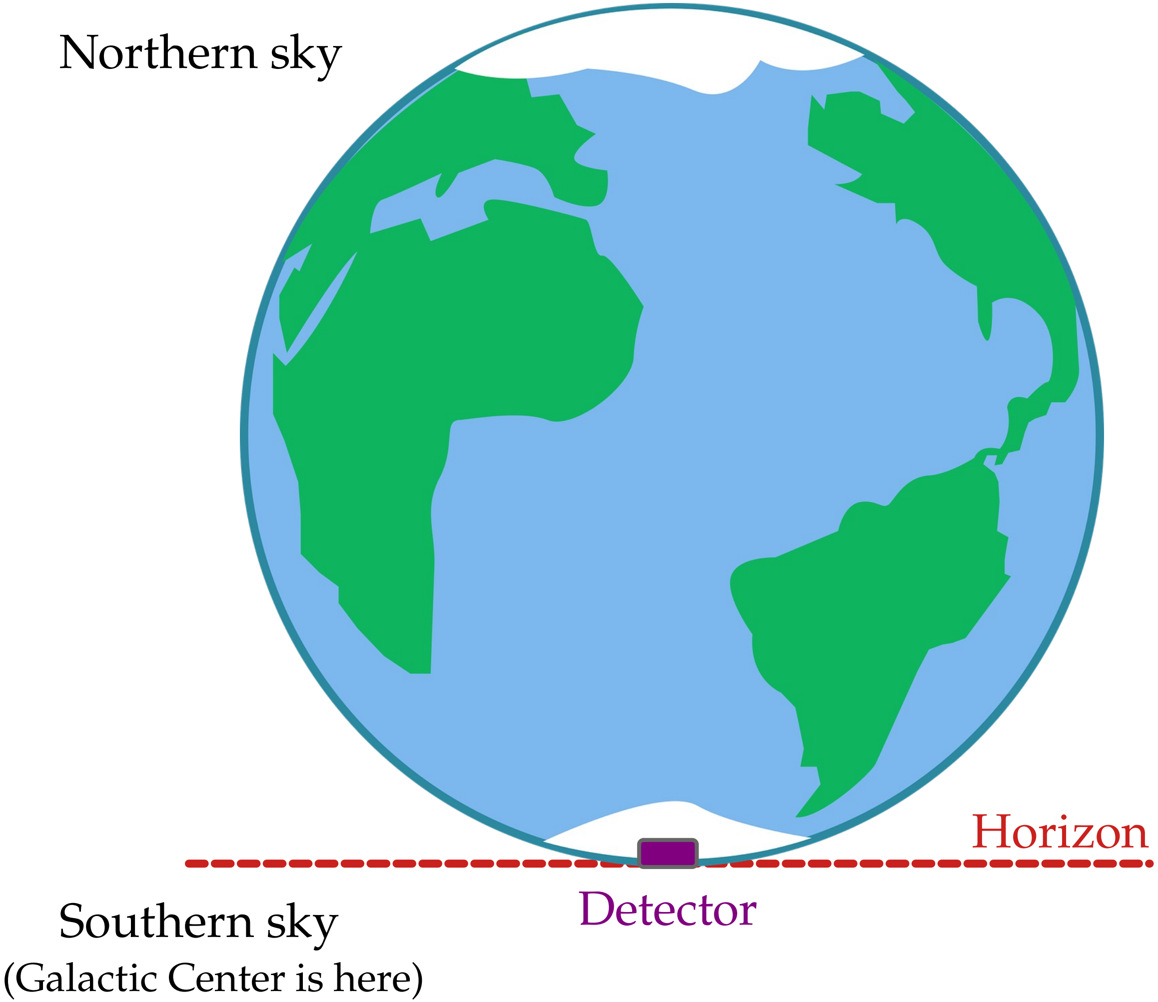
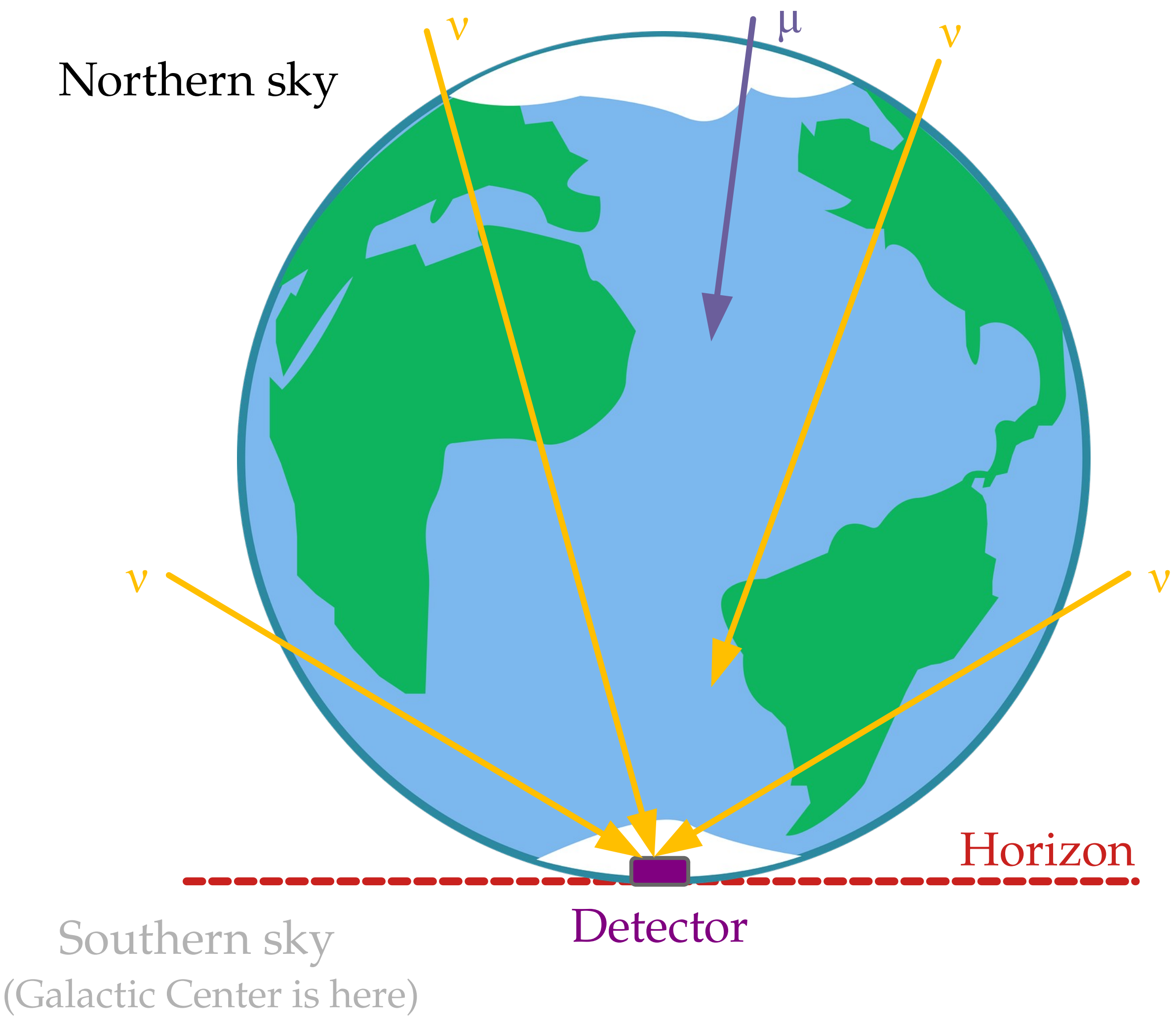
Upgoing *vs.* downgoing neutrinos



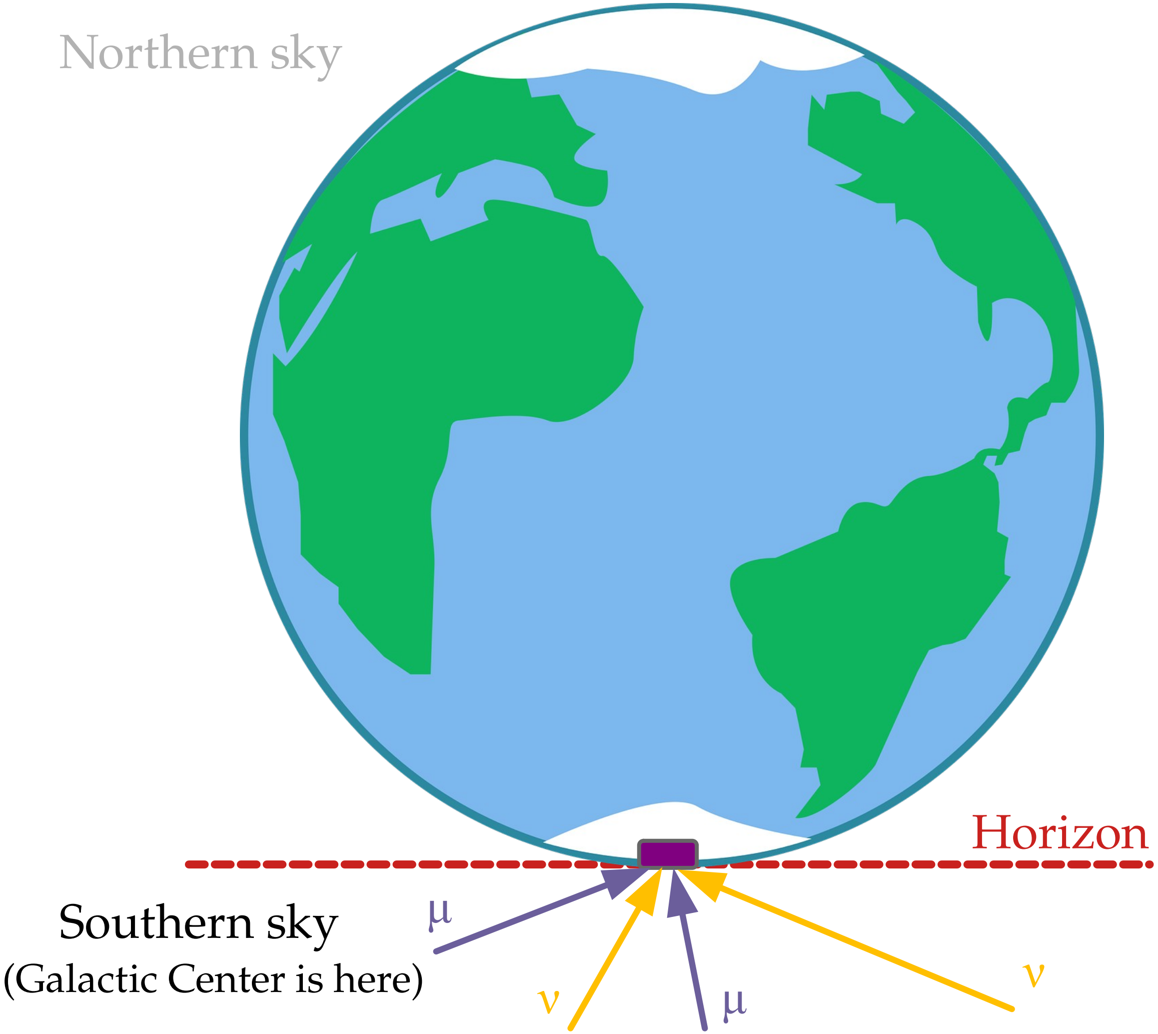
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

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

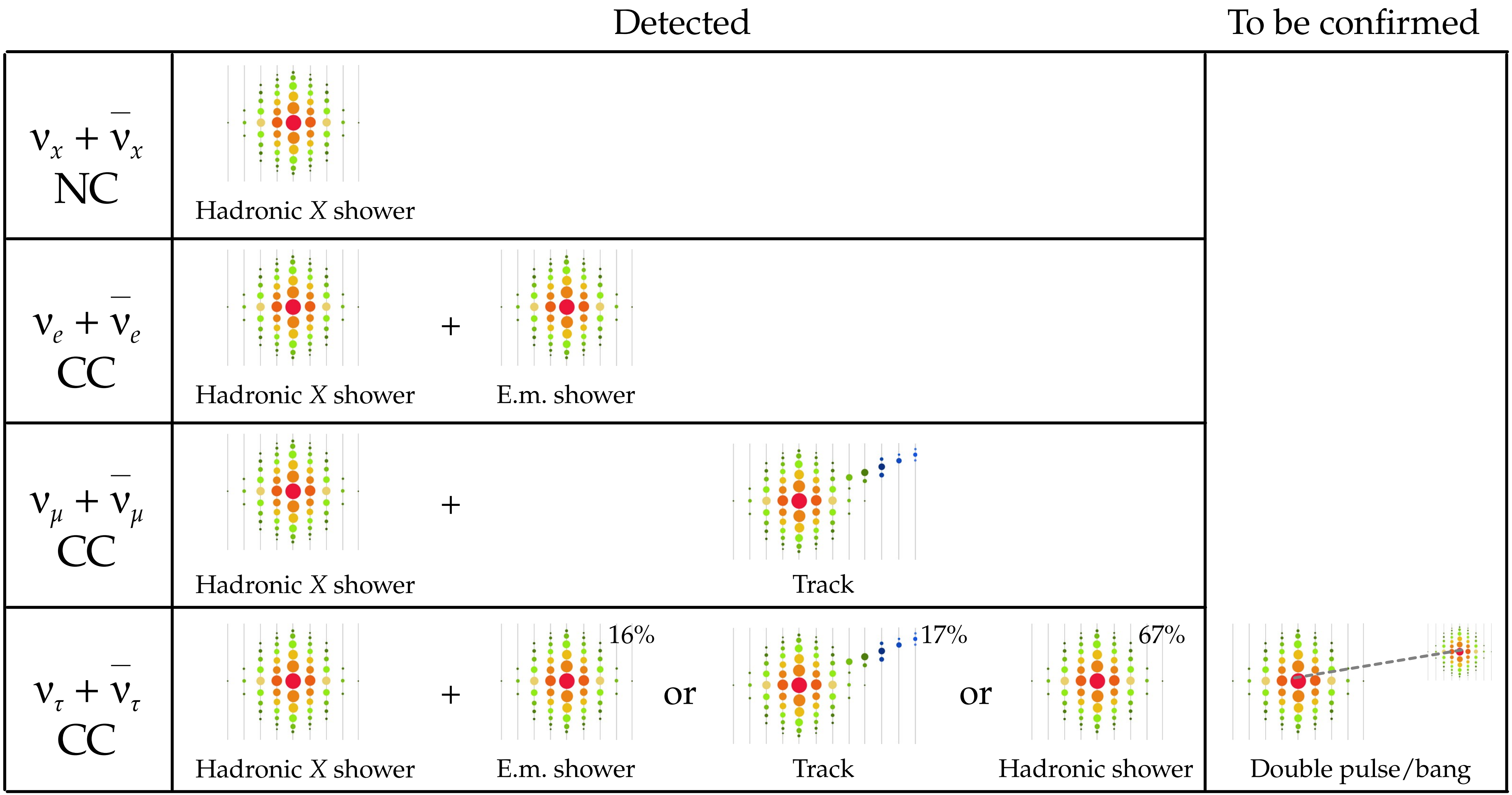
Downgoing *vs.* upgoing neutrinos

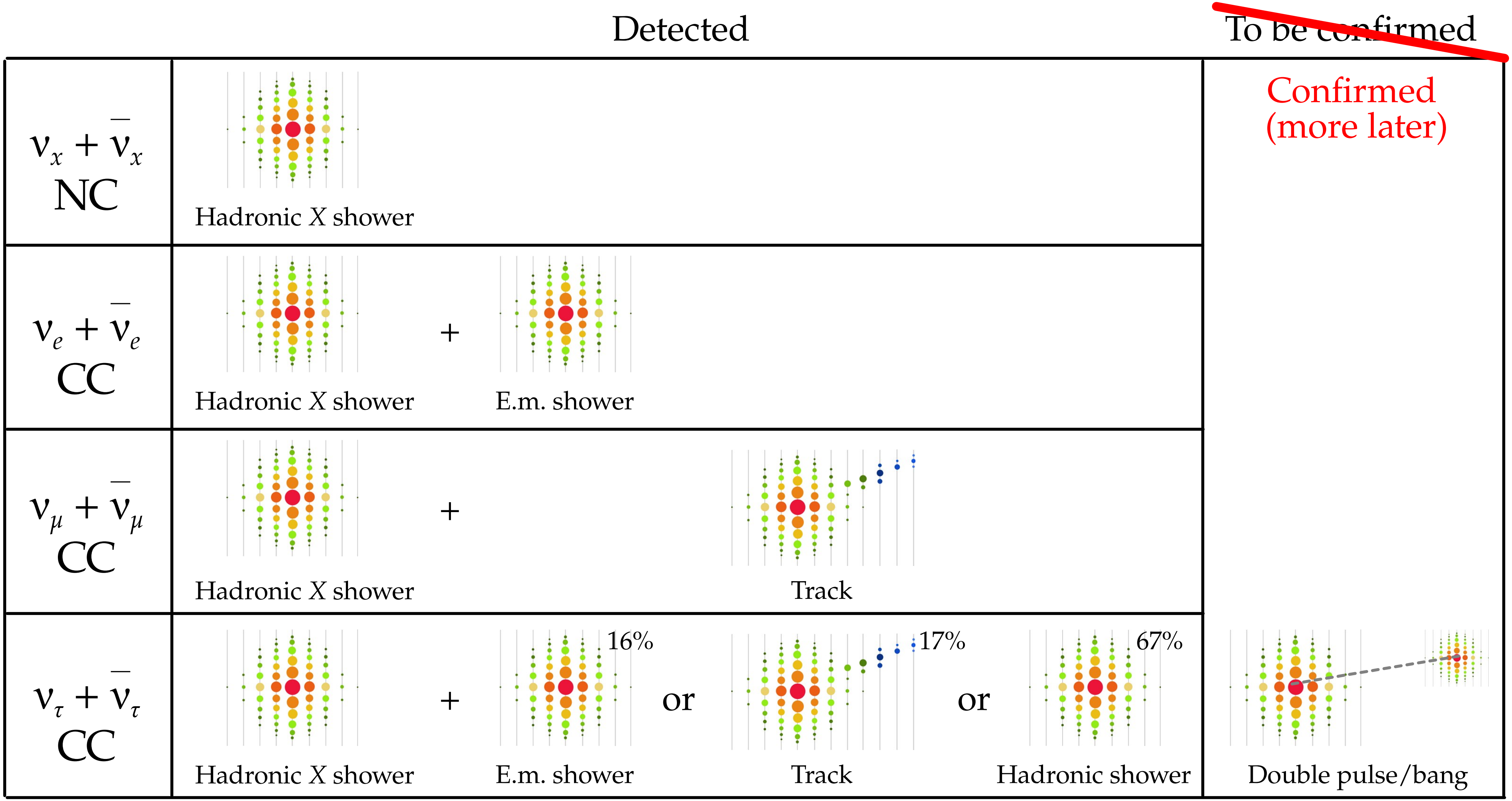


Neutrinos from the Southern sky
≡
Downgoing neutrinos

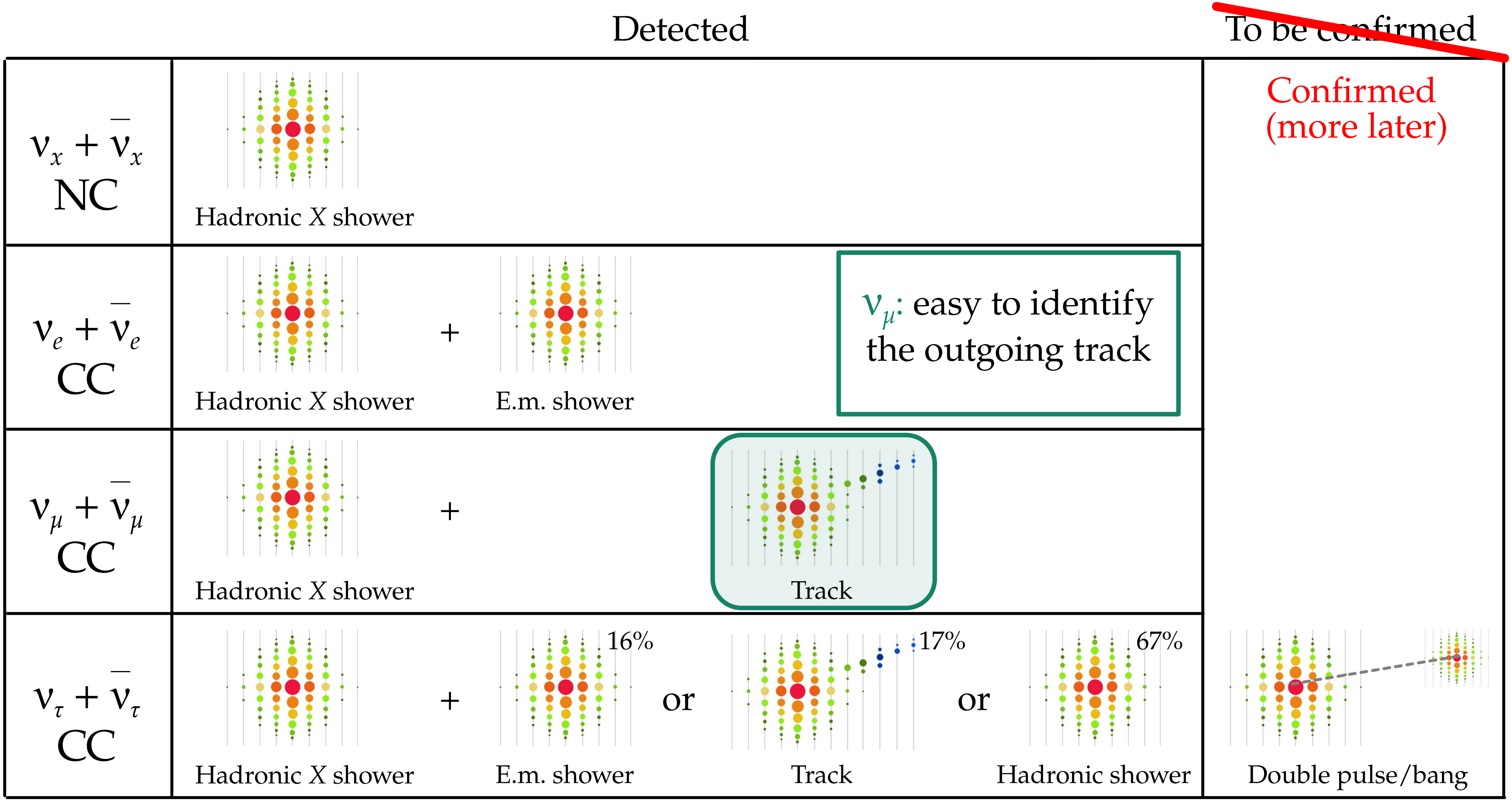
- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

IceCube

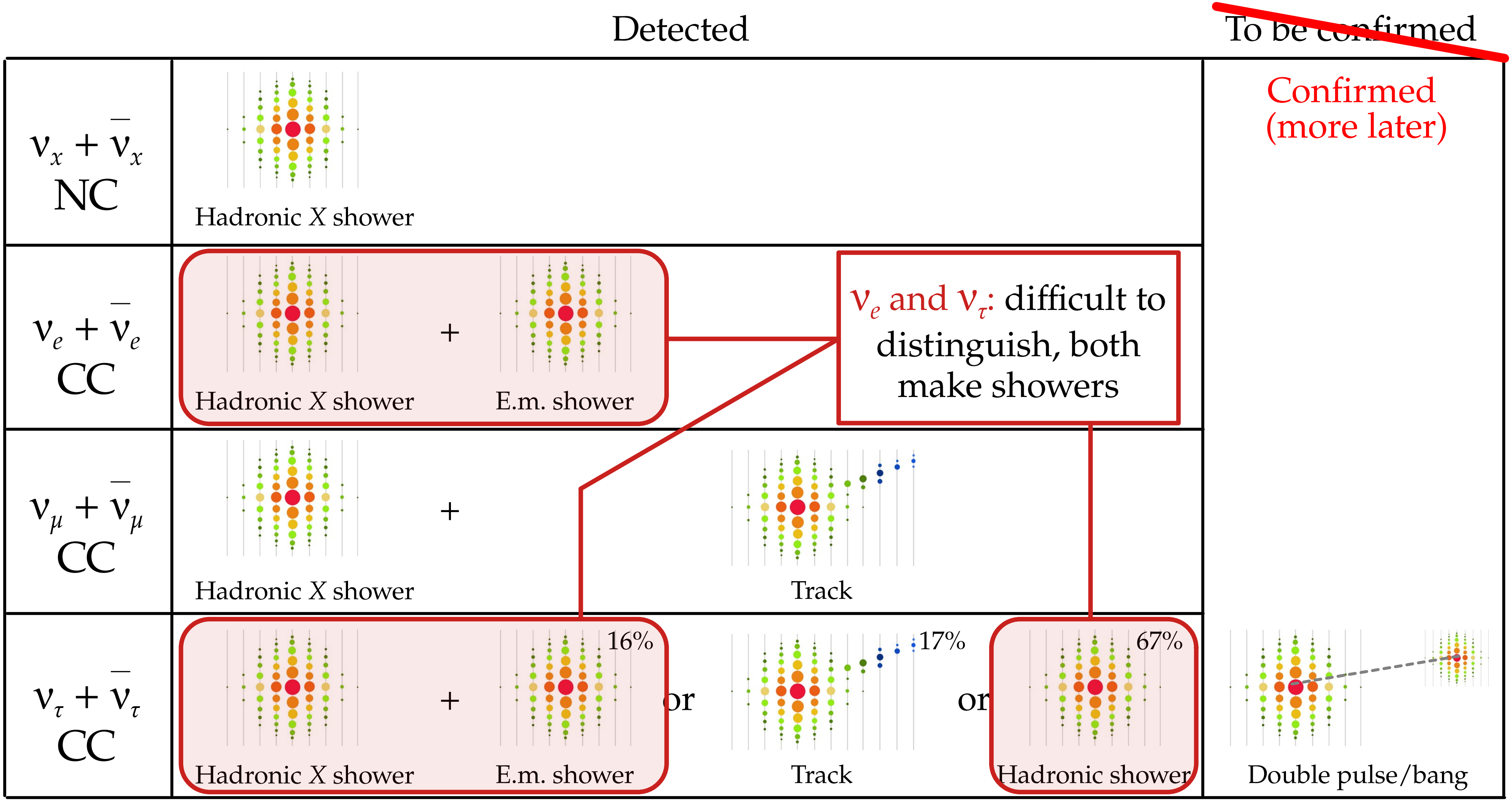

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

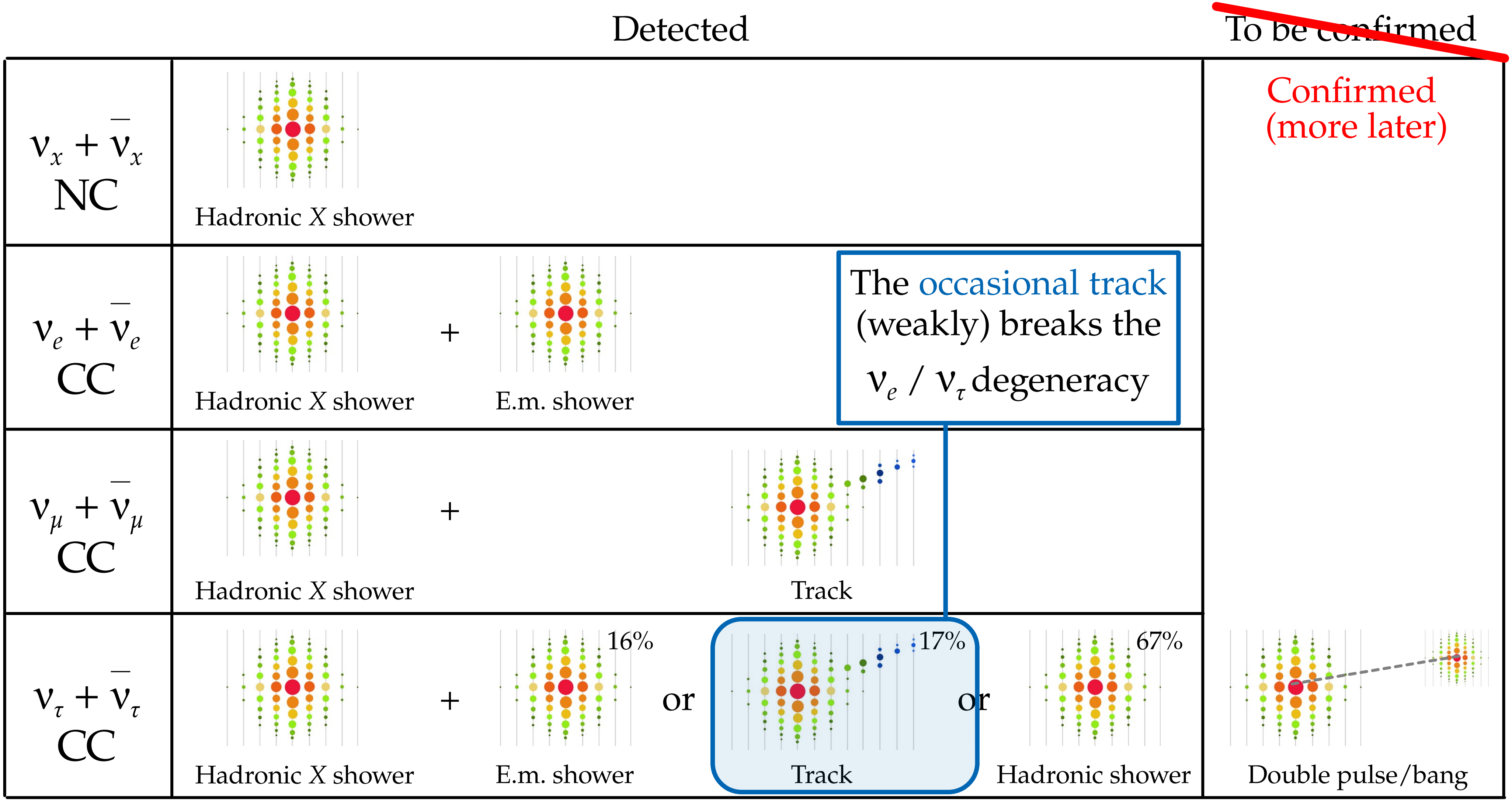


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

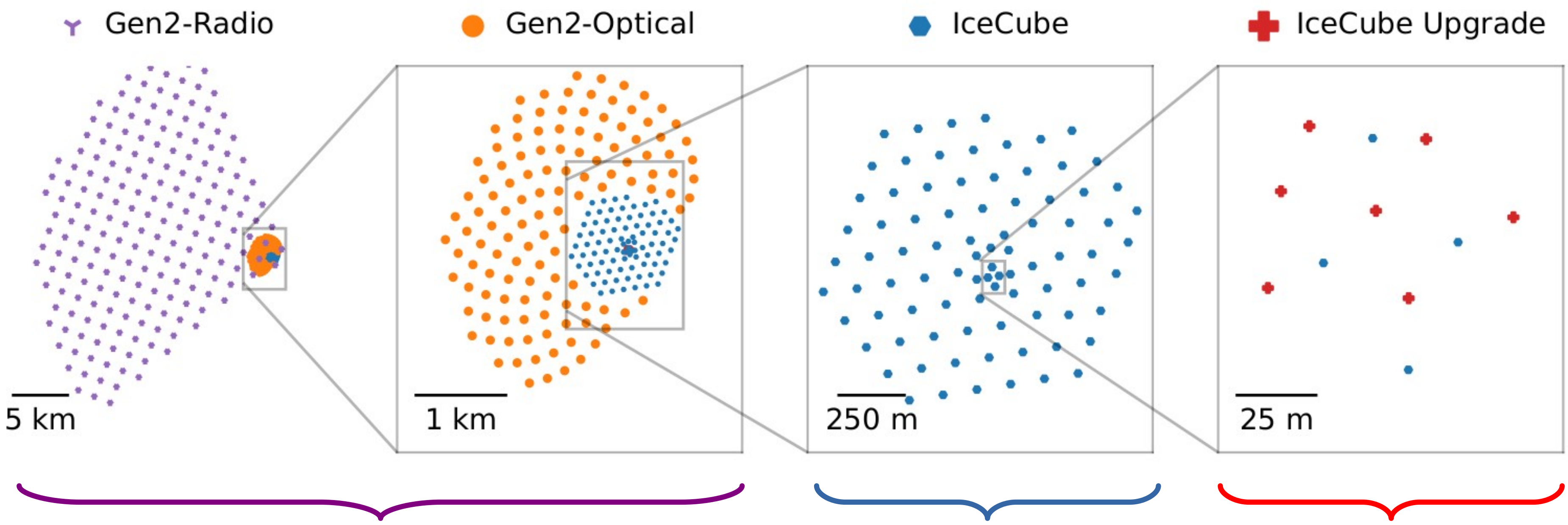


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic shower
67%
Double pulse/bang


Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang

IceCube-Gen2



~2040

Today

2023

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

1 km^3

TeV–few PeV ν

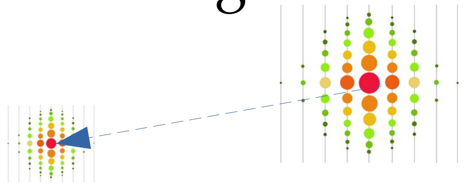
7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323

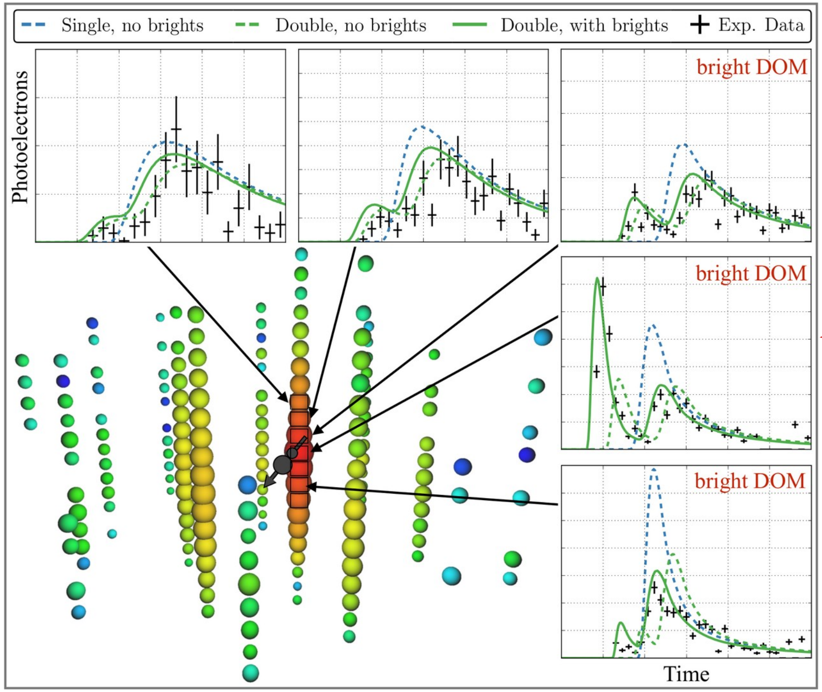
First identified high-energy astrophysical ν_τ

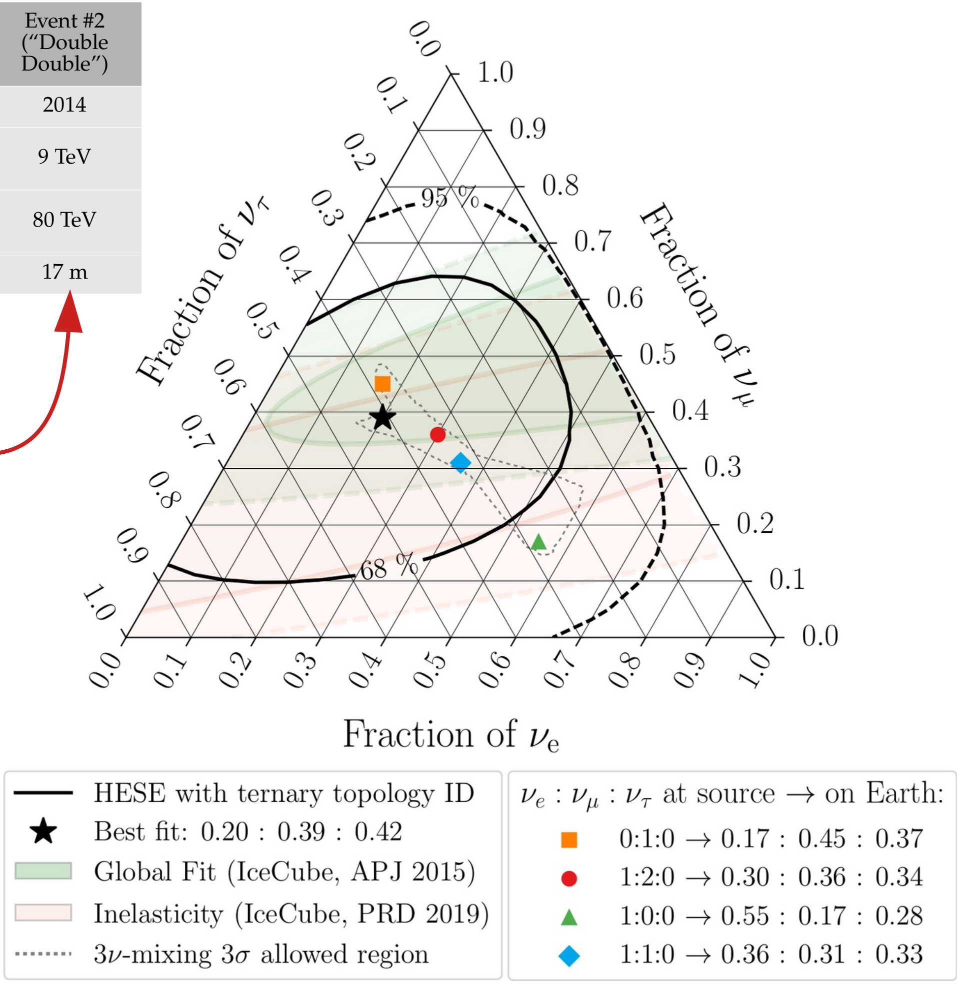
Double bang:



	Event #1 (“Big Bird”)	Event #2 (“Double Double”)
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ

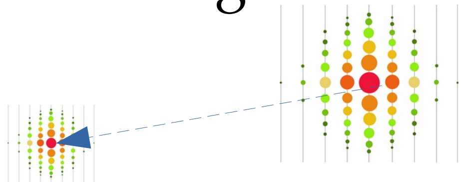




IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:

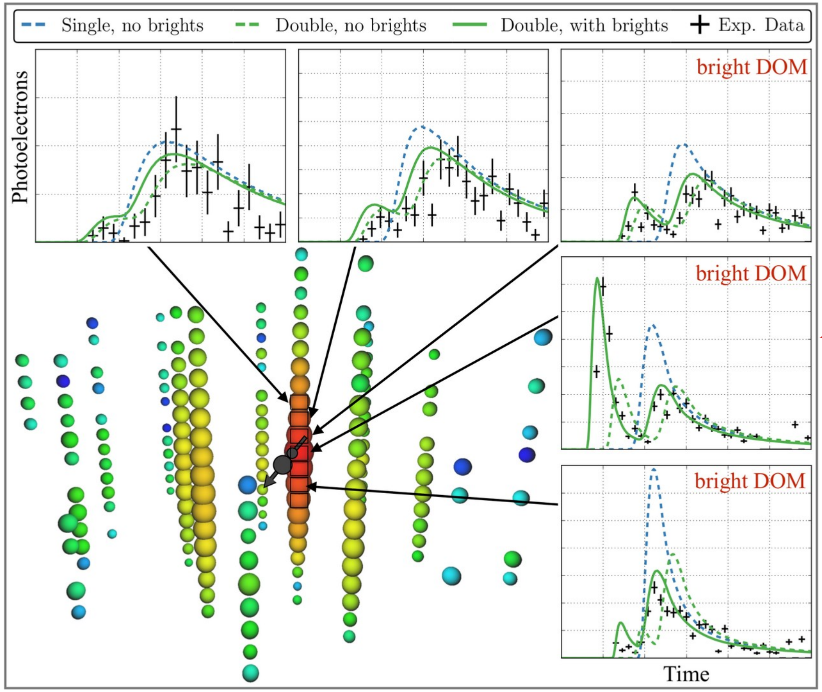


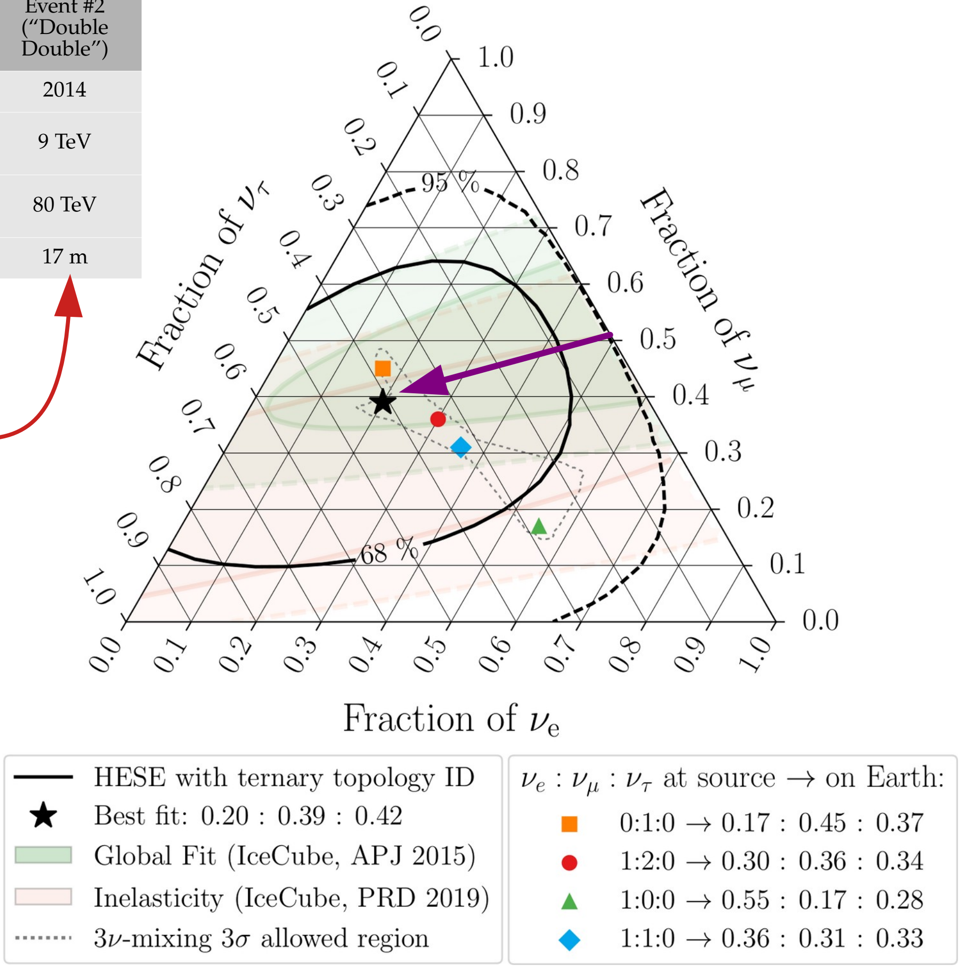
τ decay

$\nu_\tau N$ scattering

	Event #1 ("Big Bird")	Event #2 ("Double Double")
Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
Energy 2nd cascade	0.6 PeV	80 TeV
Length	16 m	17 m

Most likely to be a ν_τ





IceCube, 2011.03561

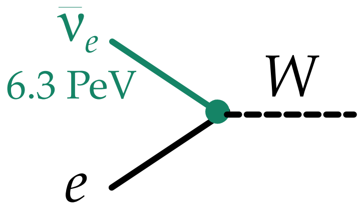
First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

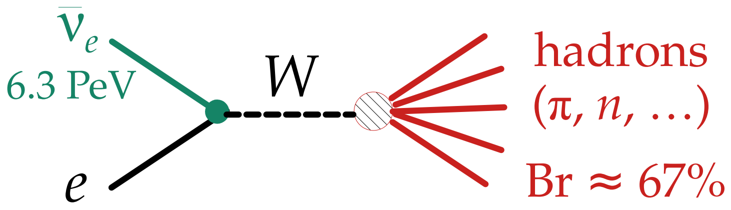
Predicted in 1960:



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

First observation of a Glashow resonance

Predicted in 1960:



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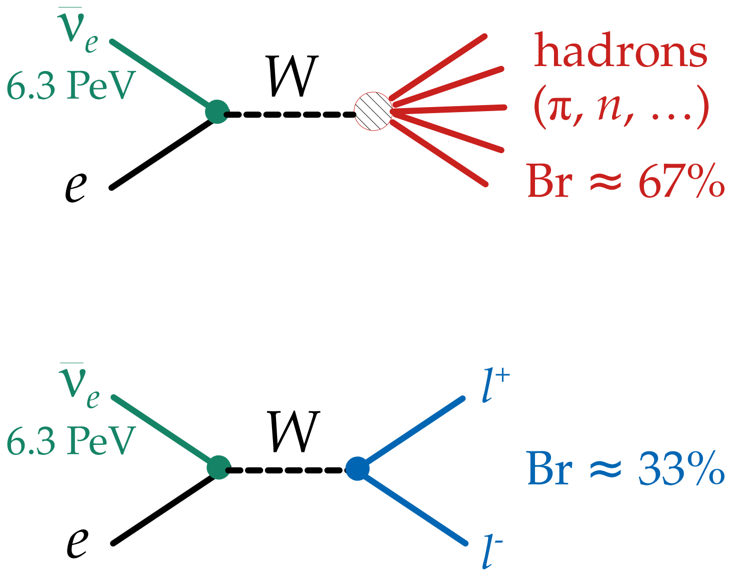

IceCube, *Nature* 2021
Glashow, *PR* 1960

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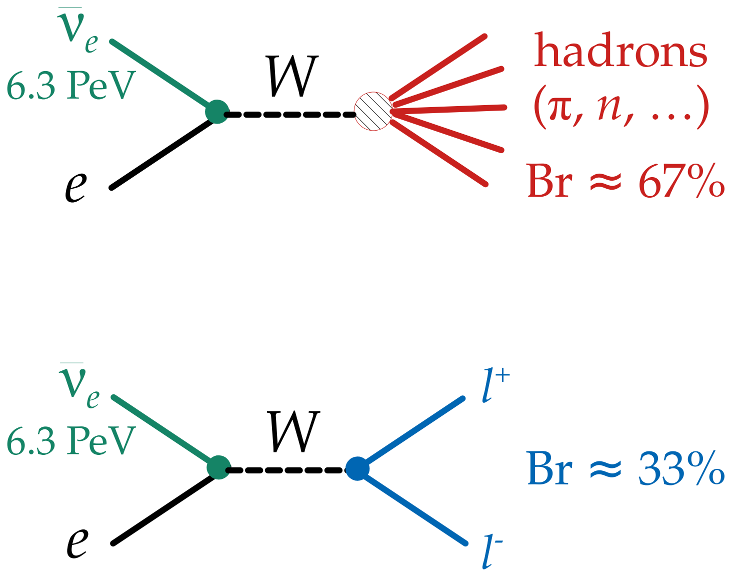
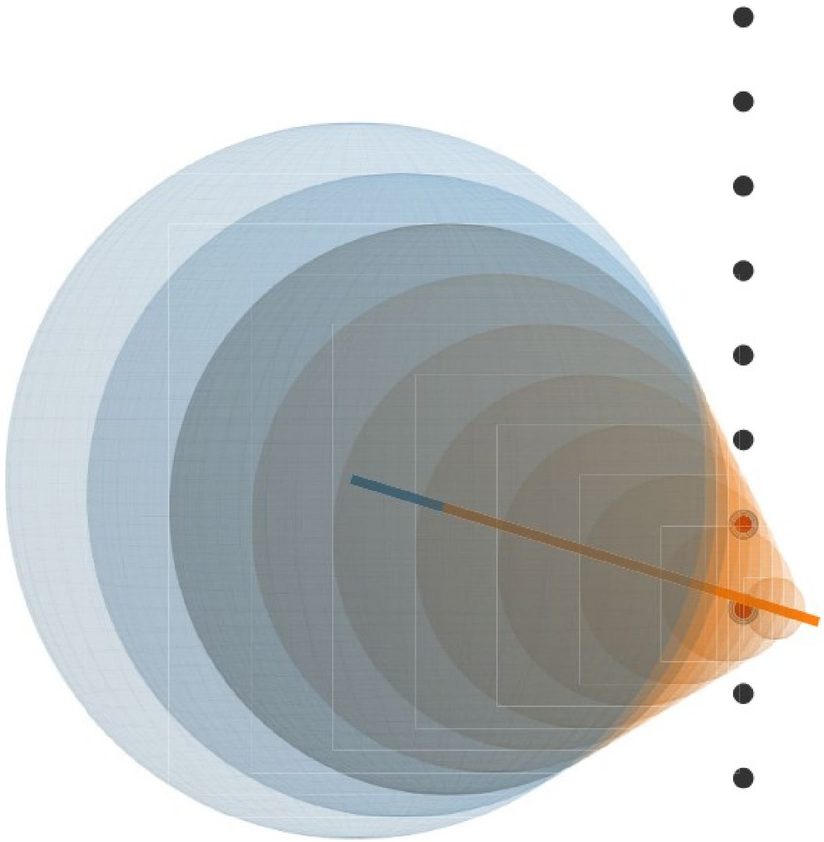


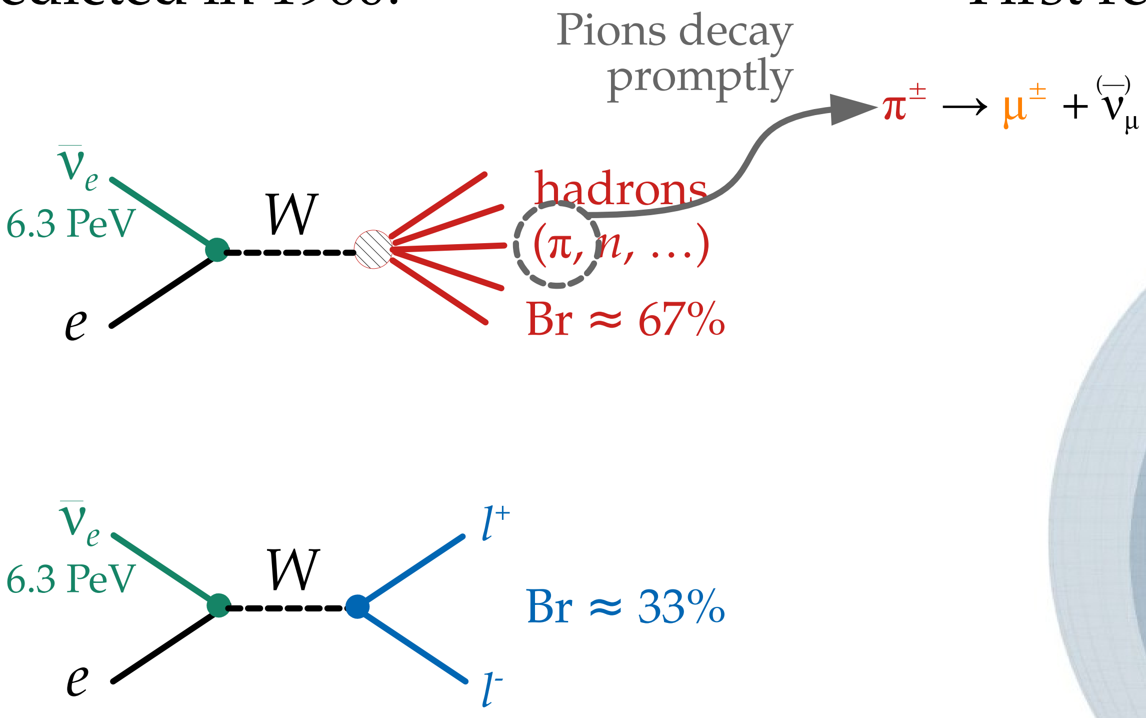
First reported by IceCube in 2021:



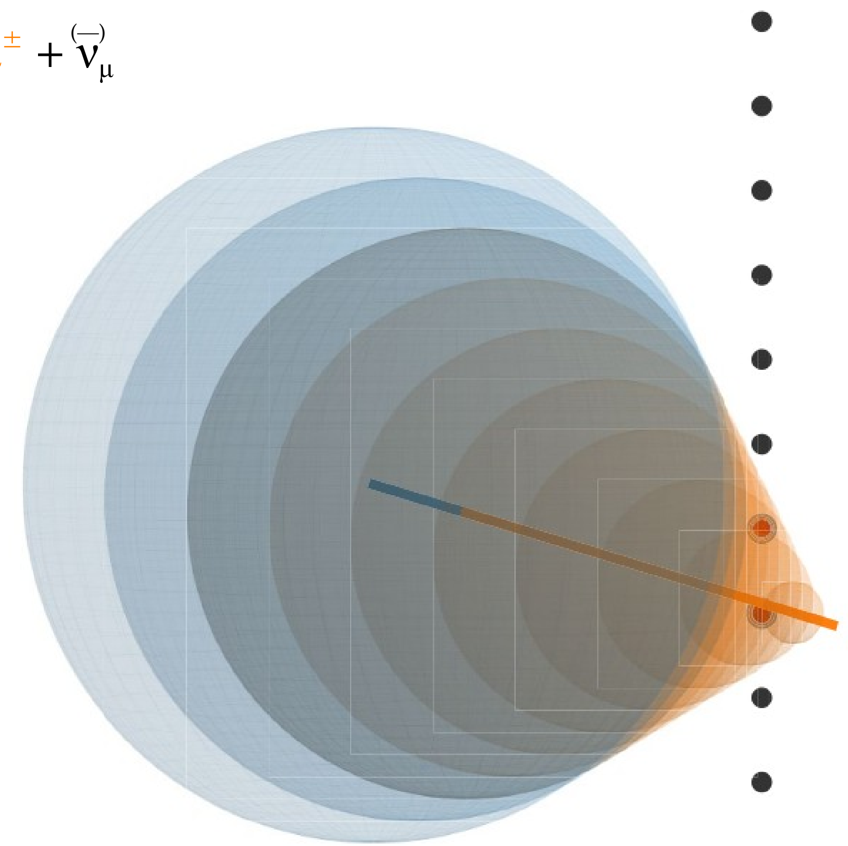
IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



First reported by IceCube in 2021:



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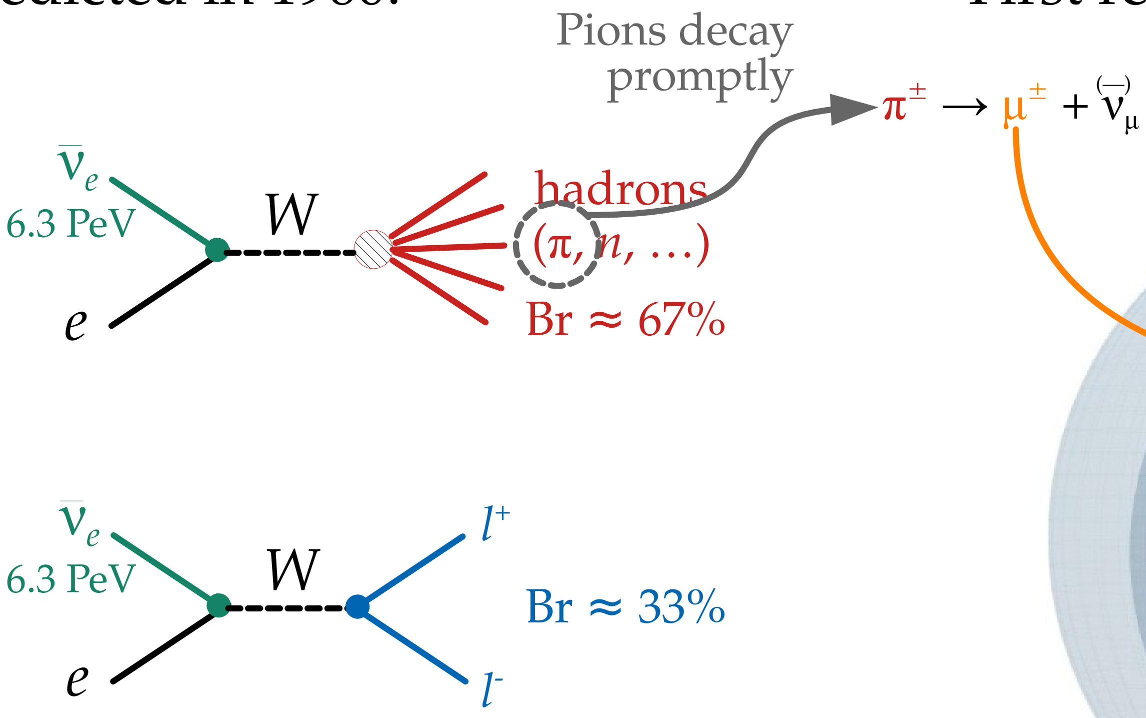

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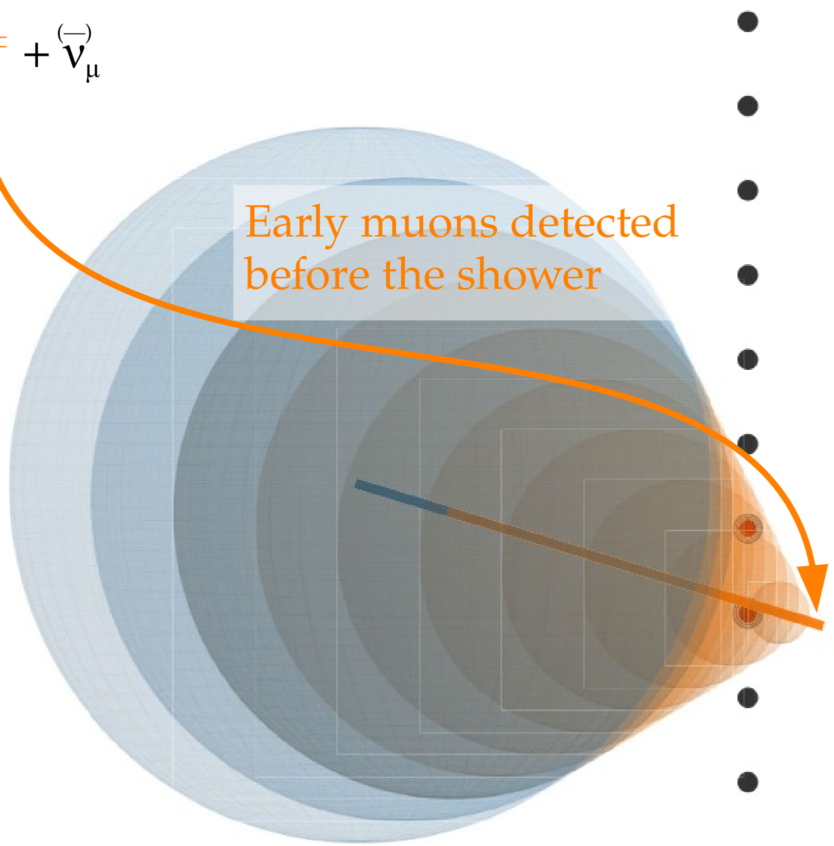

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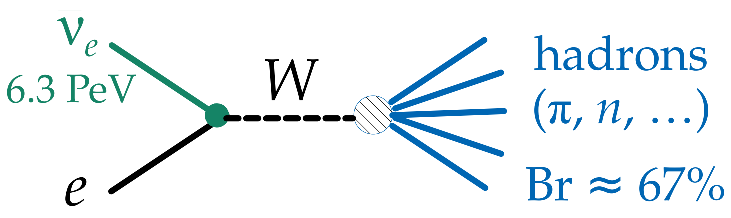
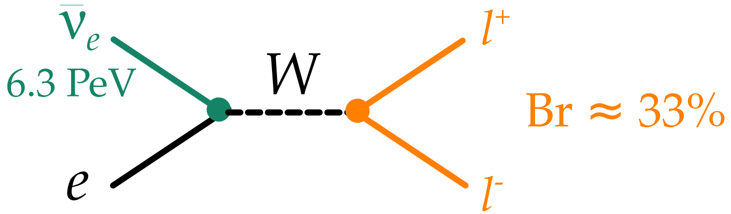
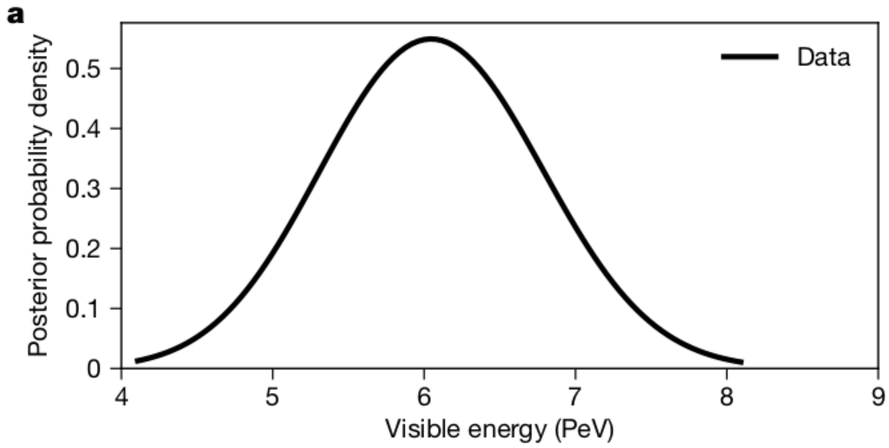




First reported by IceCube in 2021:



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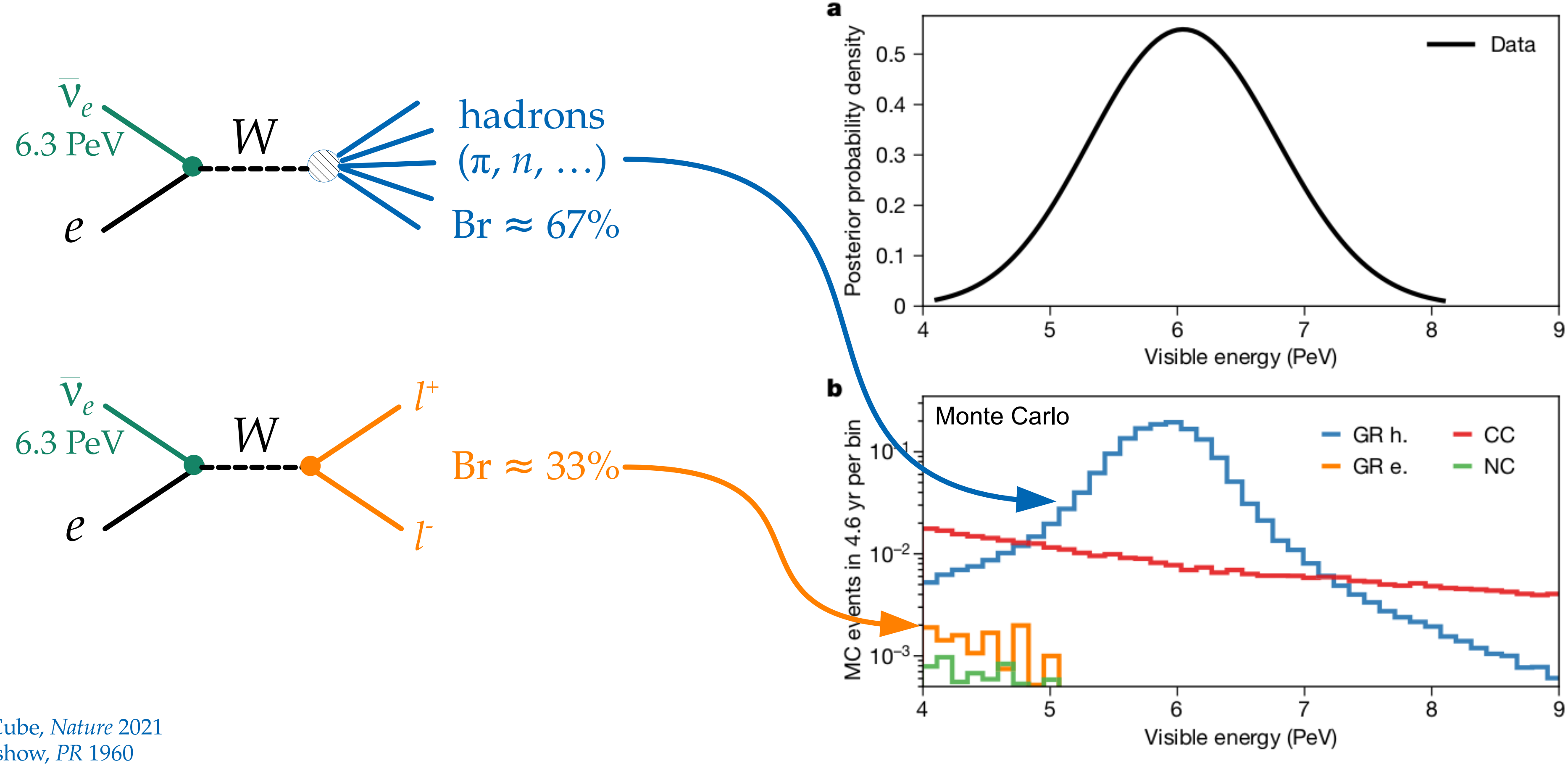

IceCube, *Nature* 2021
Glashow, *PR* 1960

Fundamental physics

Fundamental physics with HE cosmic neutrinos

- Numerous new-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: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
  - n = -1: neutrino decay
  - n = 0: CPT-odd Lorentz violation
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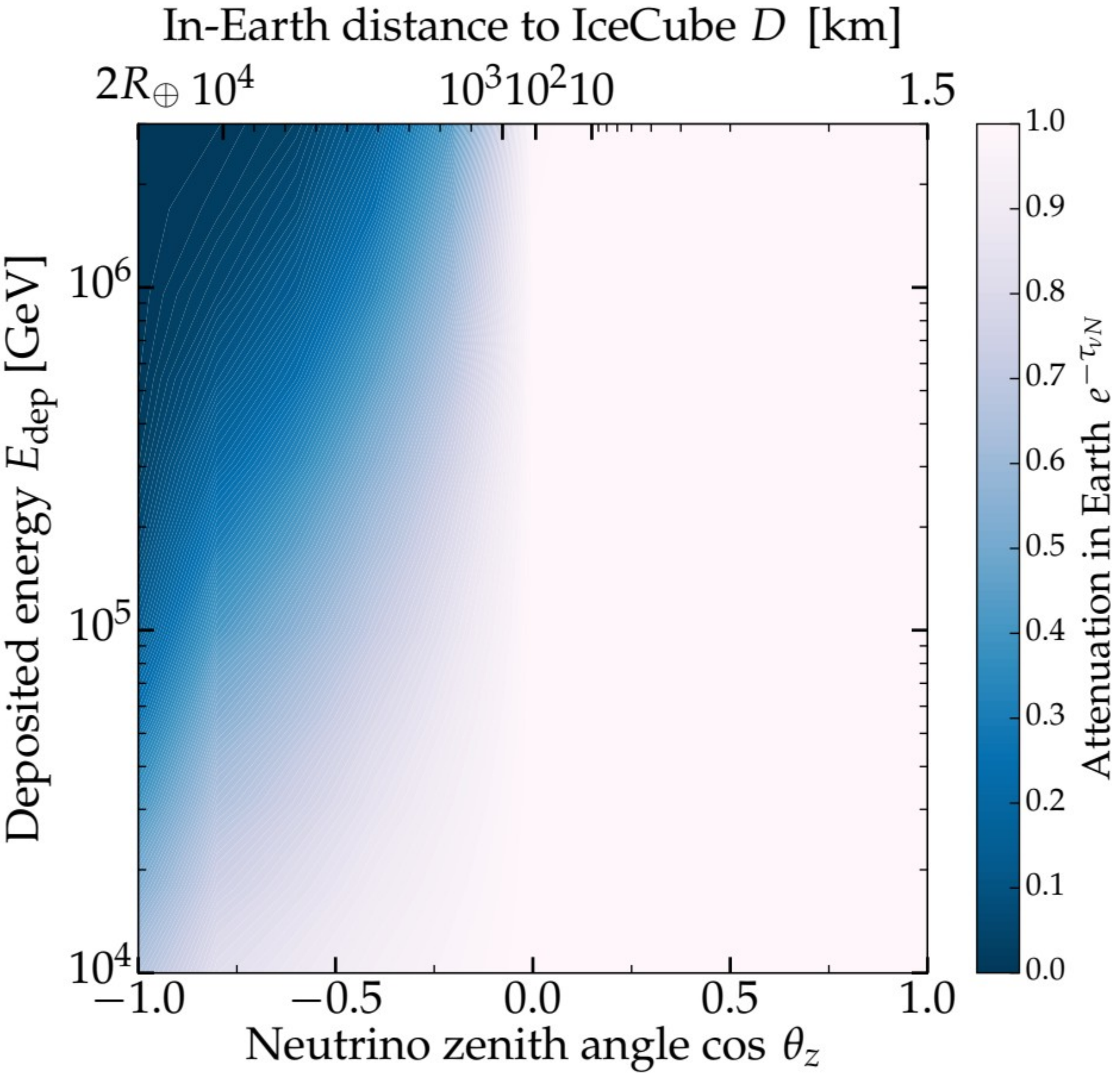
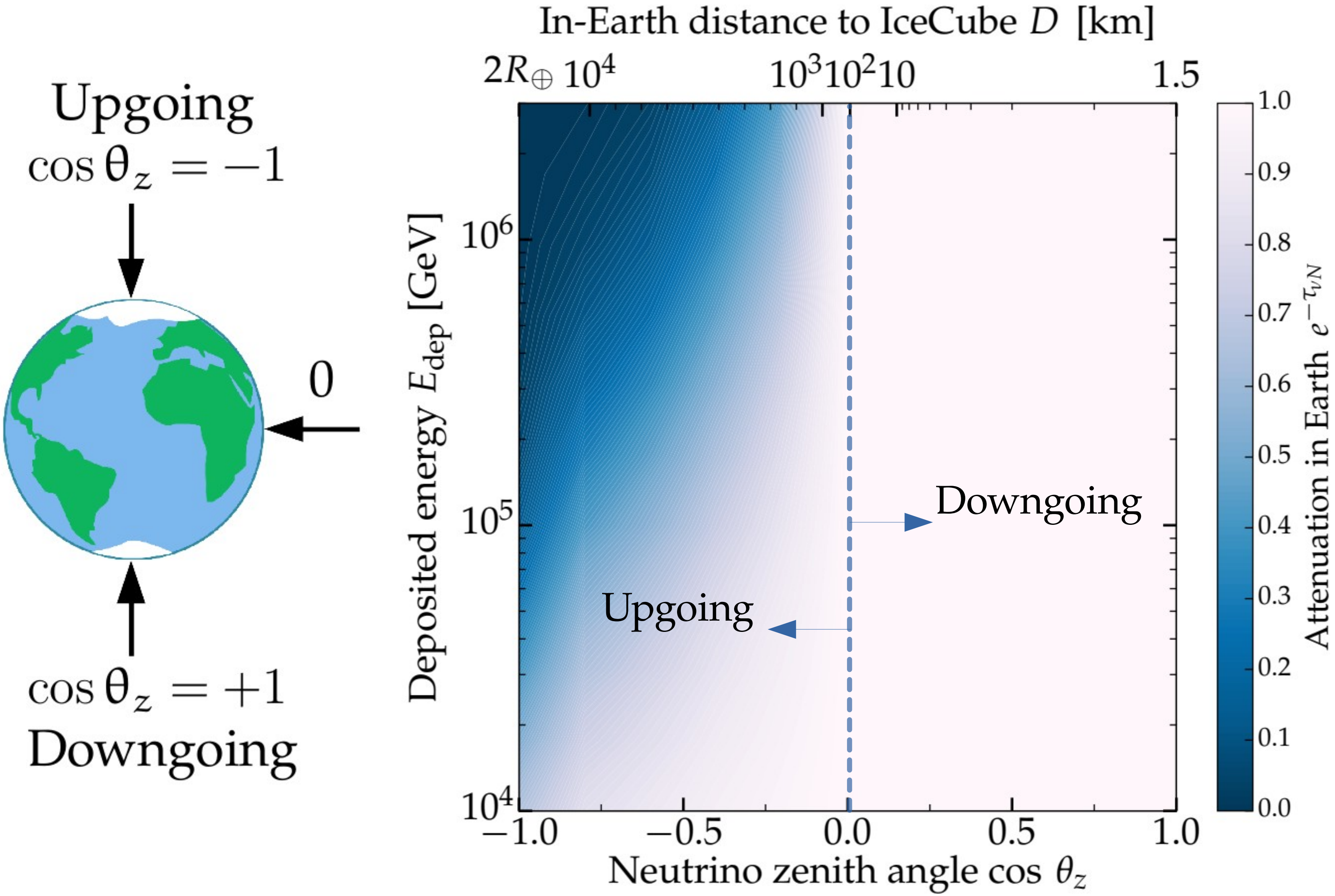
- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

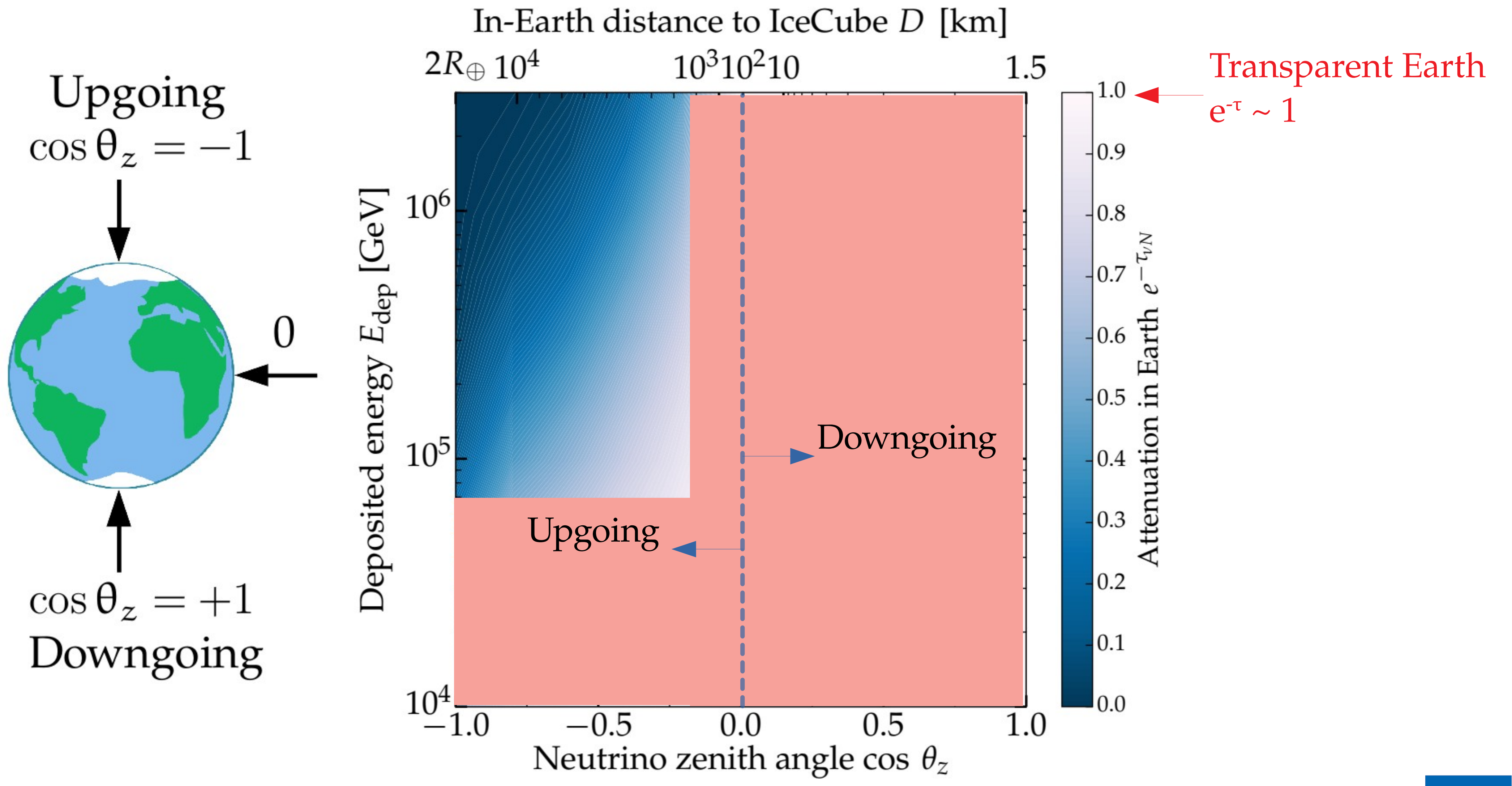
In spite of
poor energy, angular, flavor reconstruction
& astrophysical unknowns

Example 1:
Measuring TeV–PeV ν cross sections

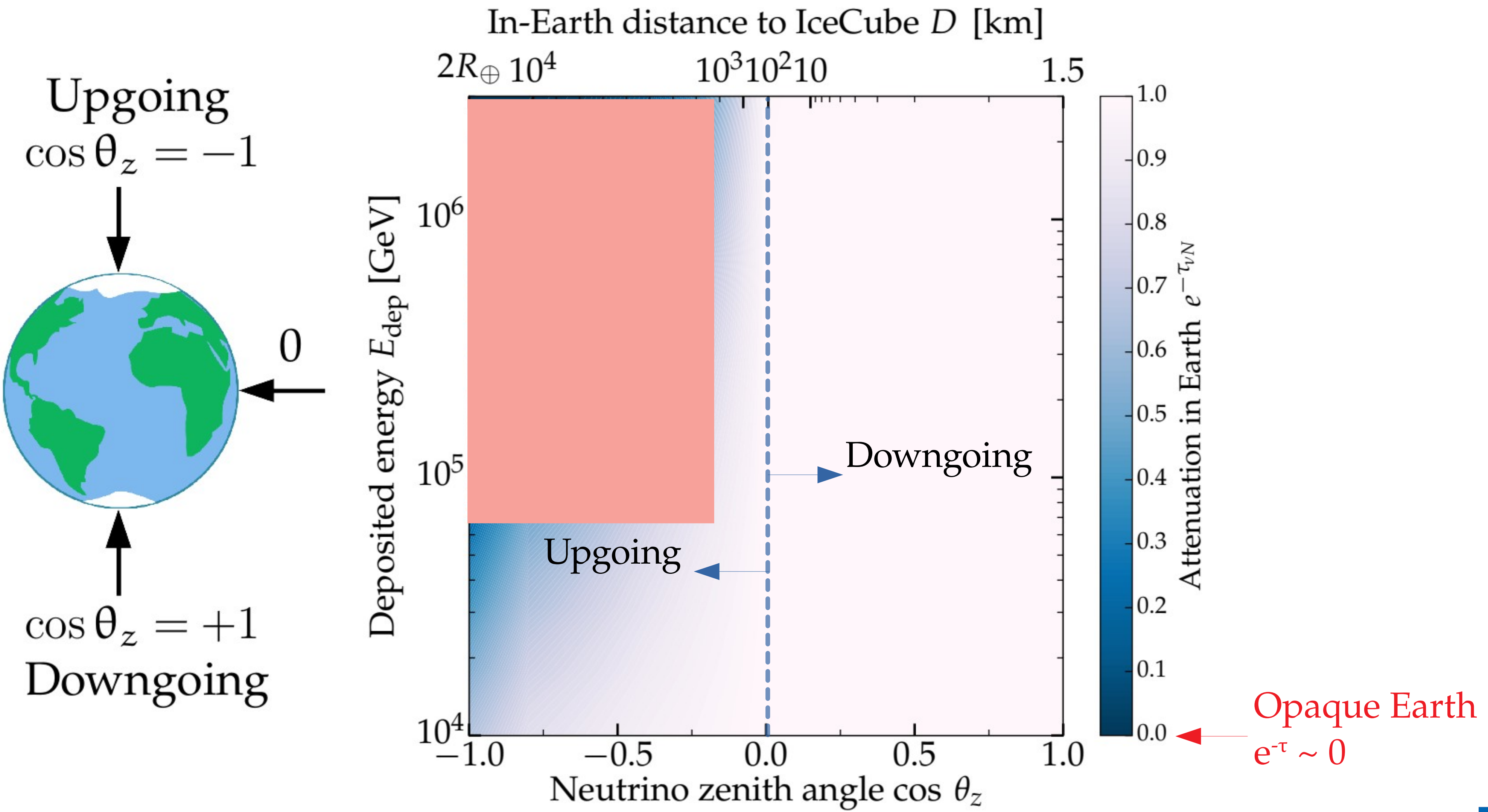

In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
10^6
10^5
10^4
Deposited energy E_dep [GeV]
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^{−τ_νN}



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^4
10^5
10^6
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0



Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Transparent Earth
$e^{-\tau} \sim 1$

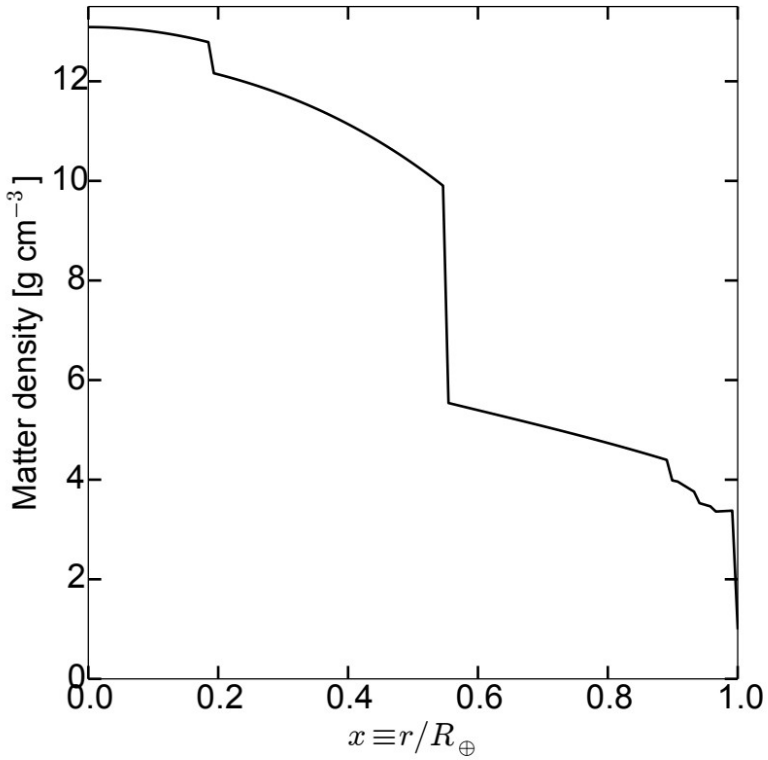


Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^4 10^5 10^6
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$

A feel for the in-Earth attenuation

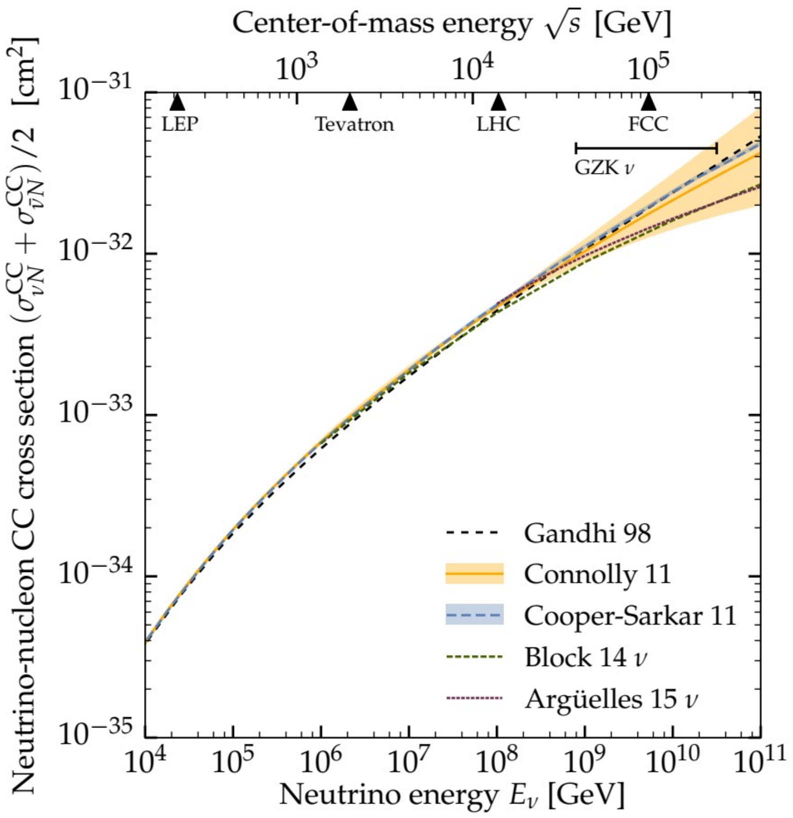
Earth matter density

(Preliminary Reference Earth Model)



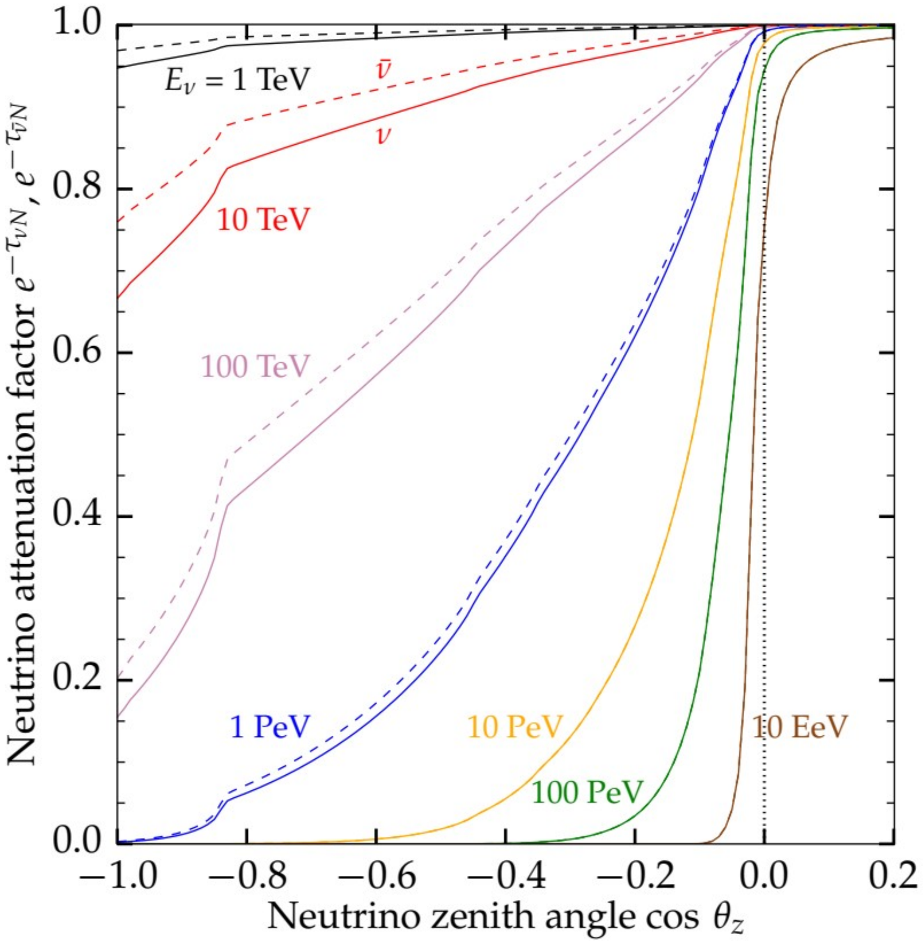
+

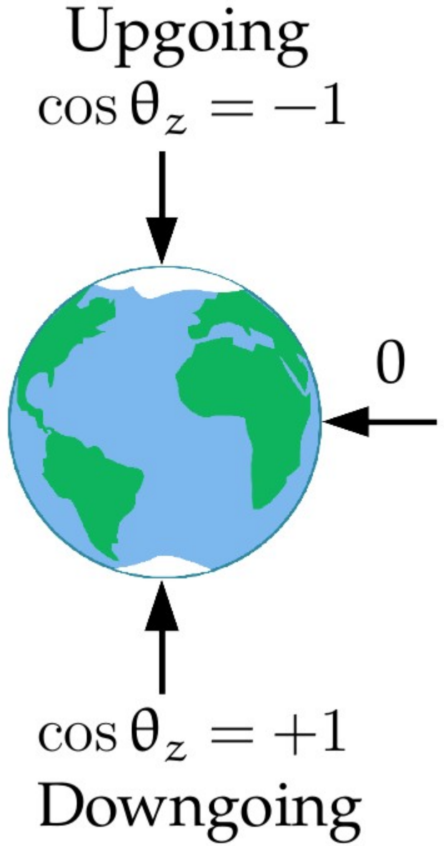
Neutrino-nucleon cross section



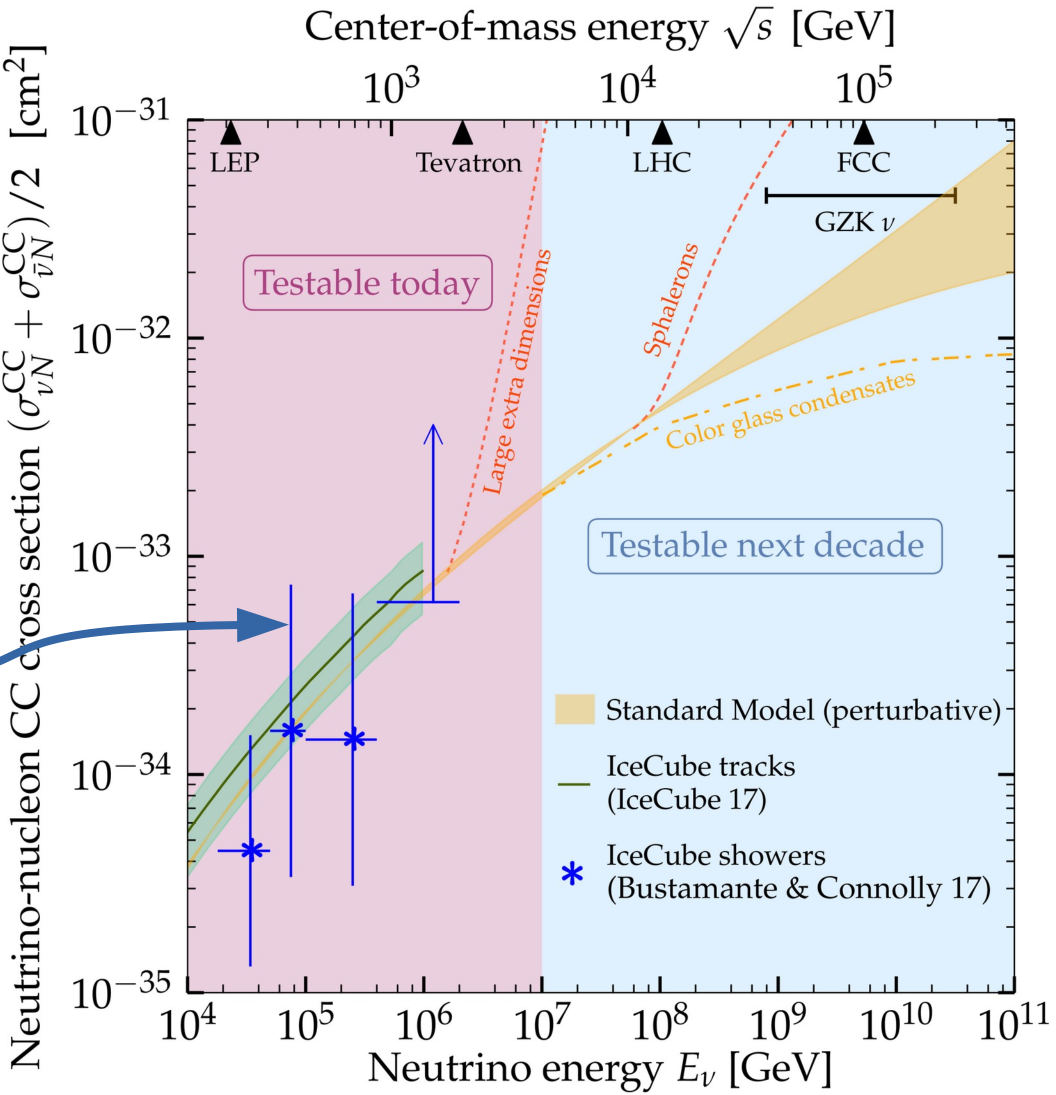
A feel for the in-Earth attenuation

=





- 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%

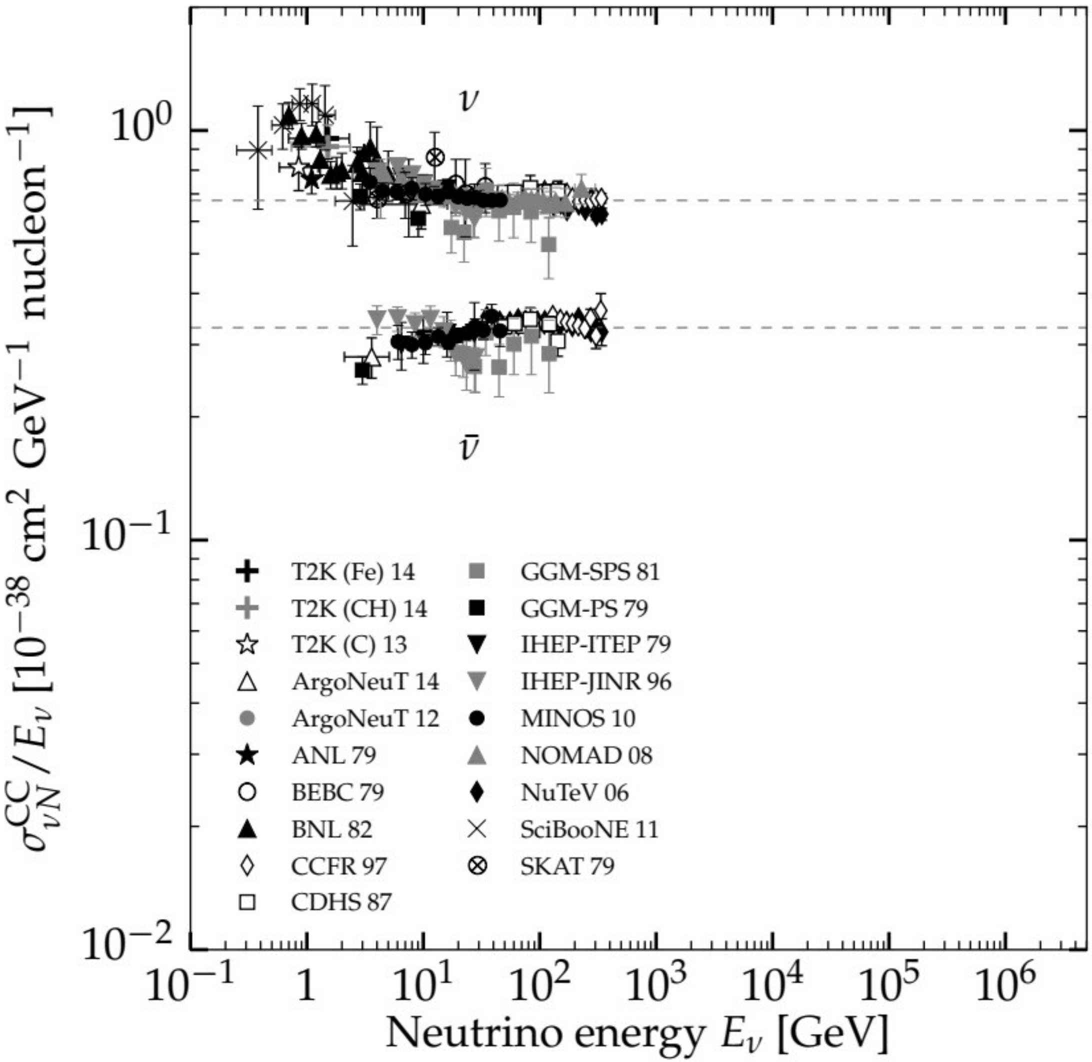


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

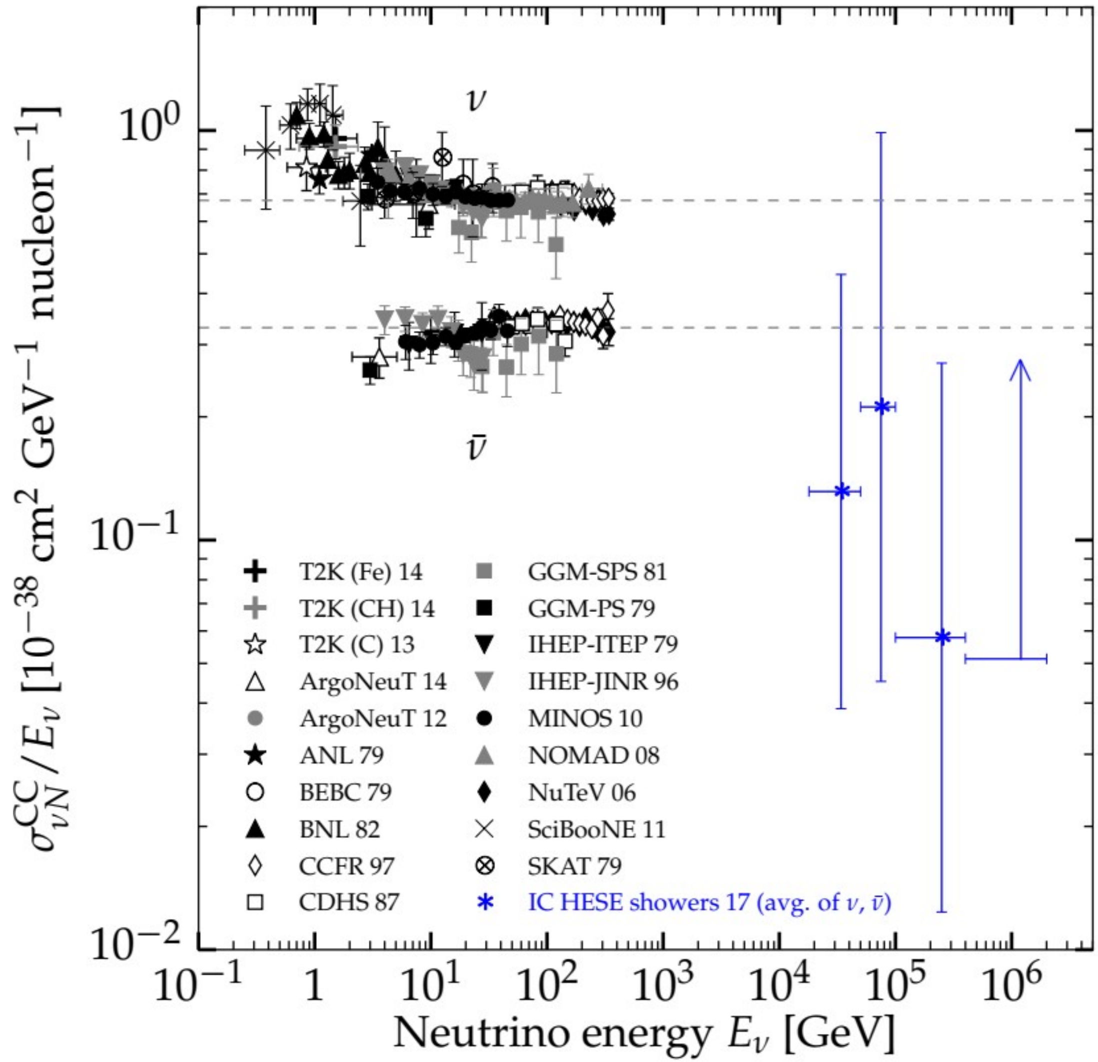
Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

Recent update:
IceCube, 2011.03560

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



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



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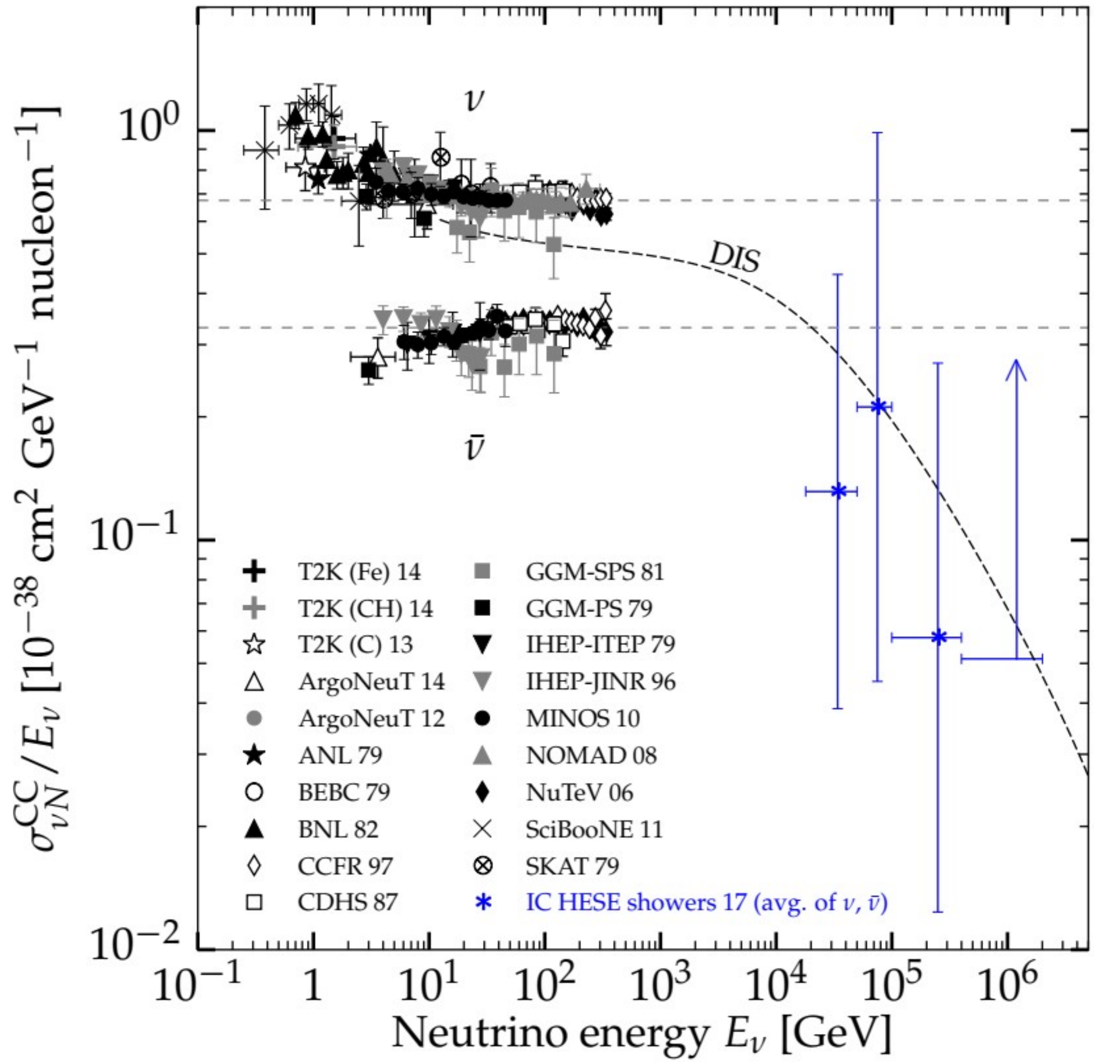
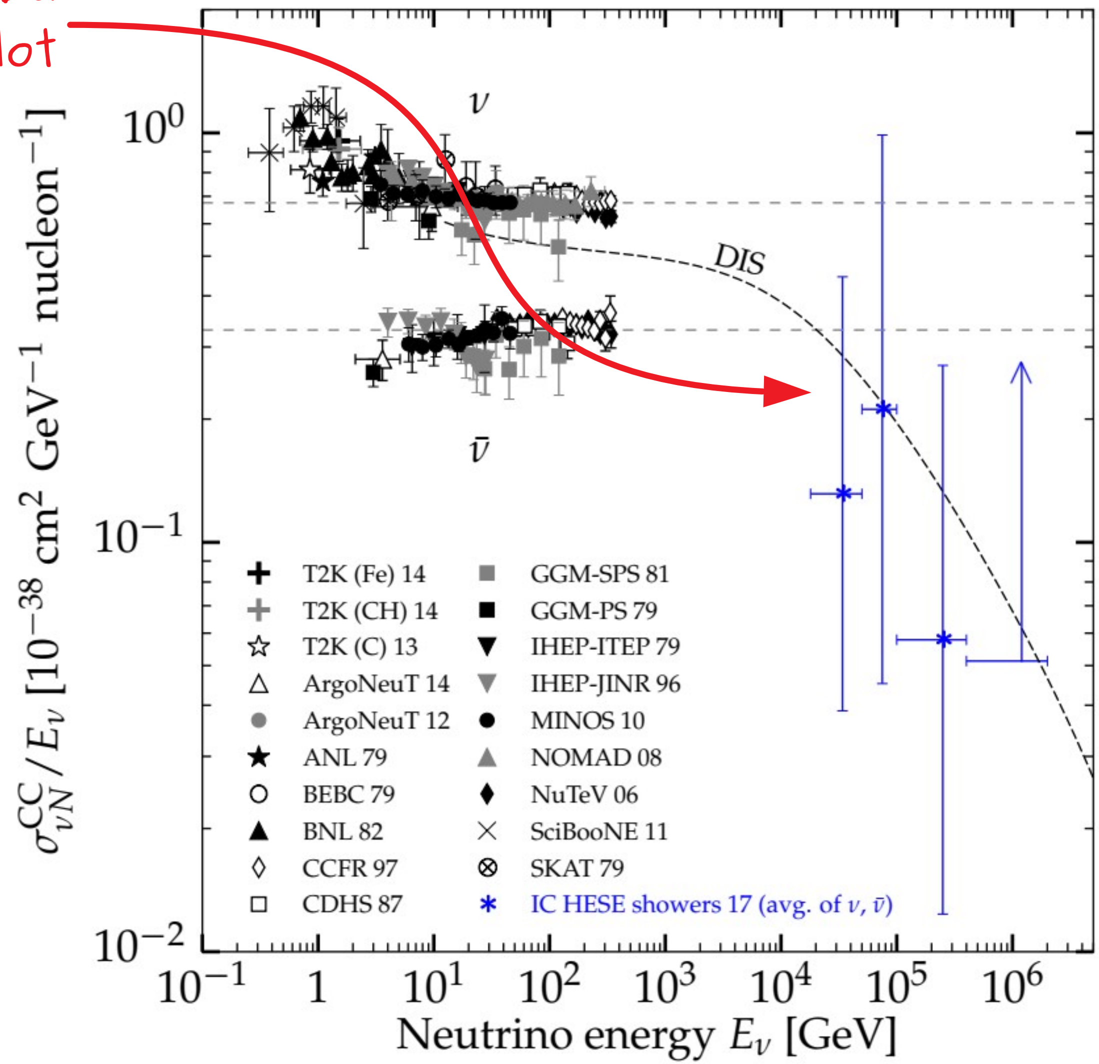


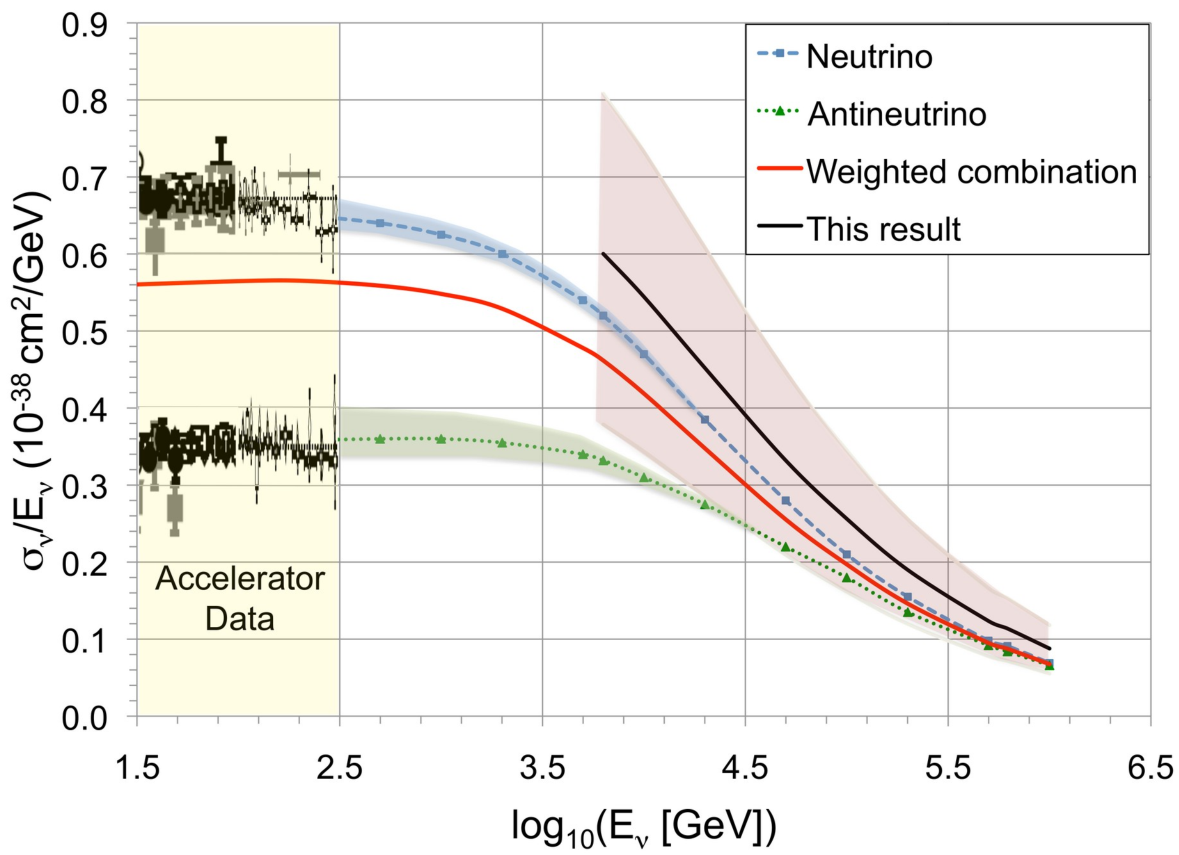
Extending the PDG cross-section plot

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



Using through-going muons instead

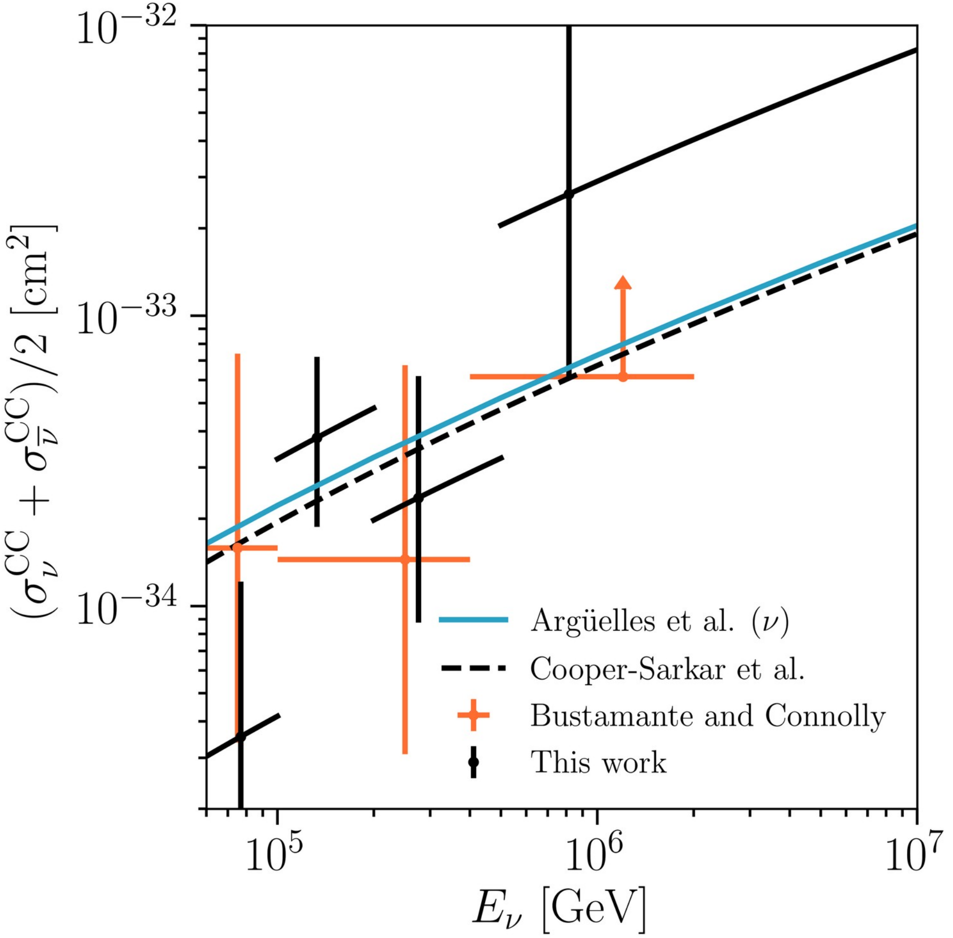
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30^{+0.21}_{-0.19}$(stat.) $^{+0.39}_{-0.43}$(syst.)
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & MB



IceCube, 2011.03560

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

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

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

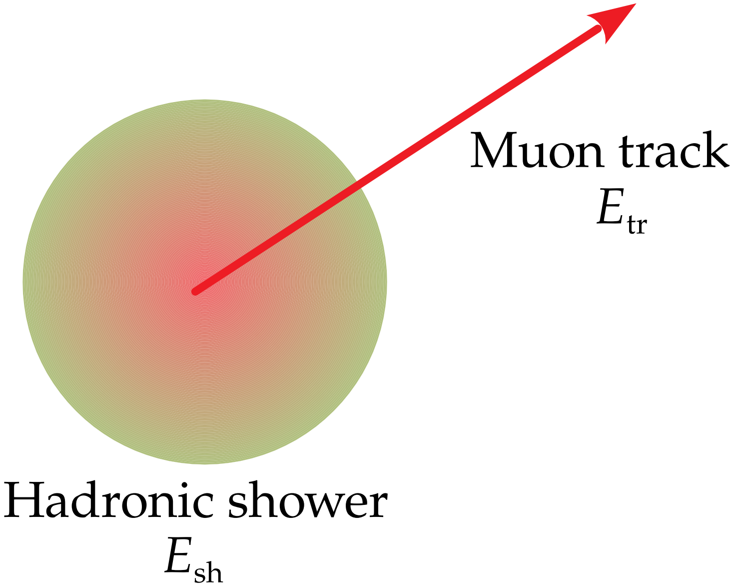
- The value of y follows a distribution $d\sigma/dy$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)

  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$

- 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, *PRD* 2019

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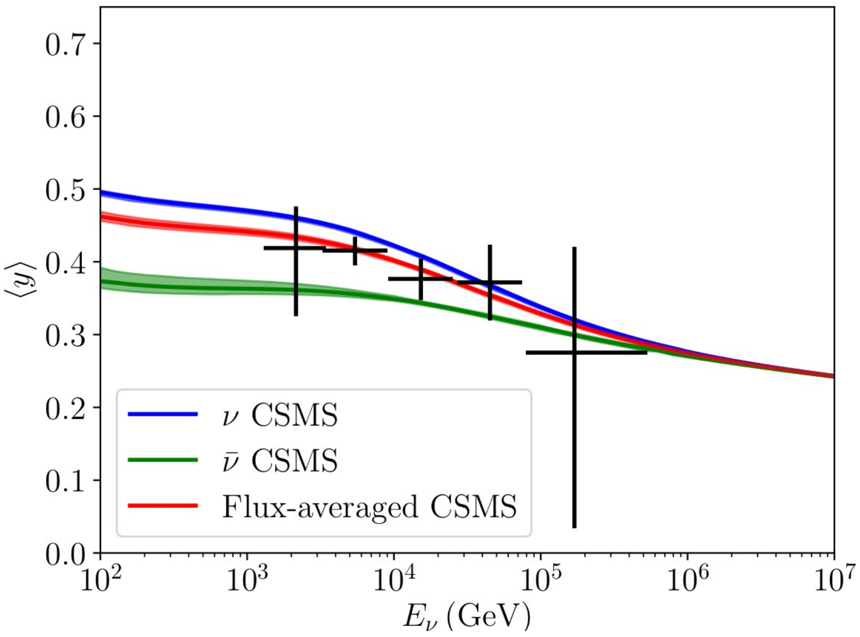
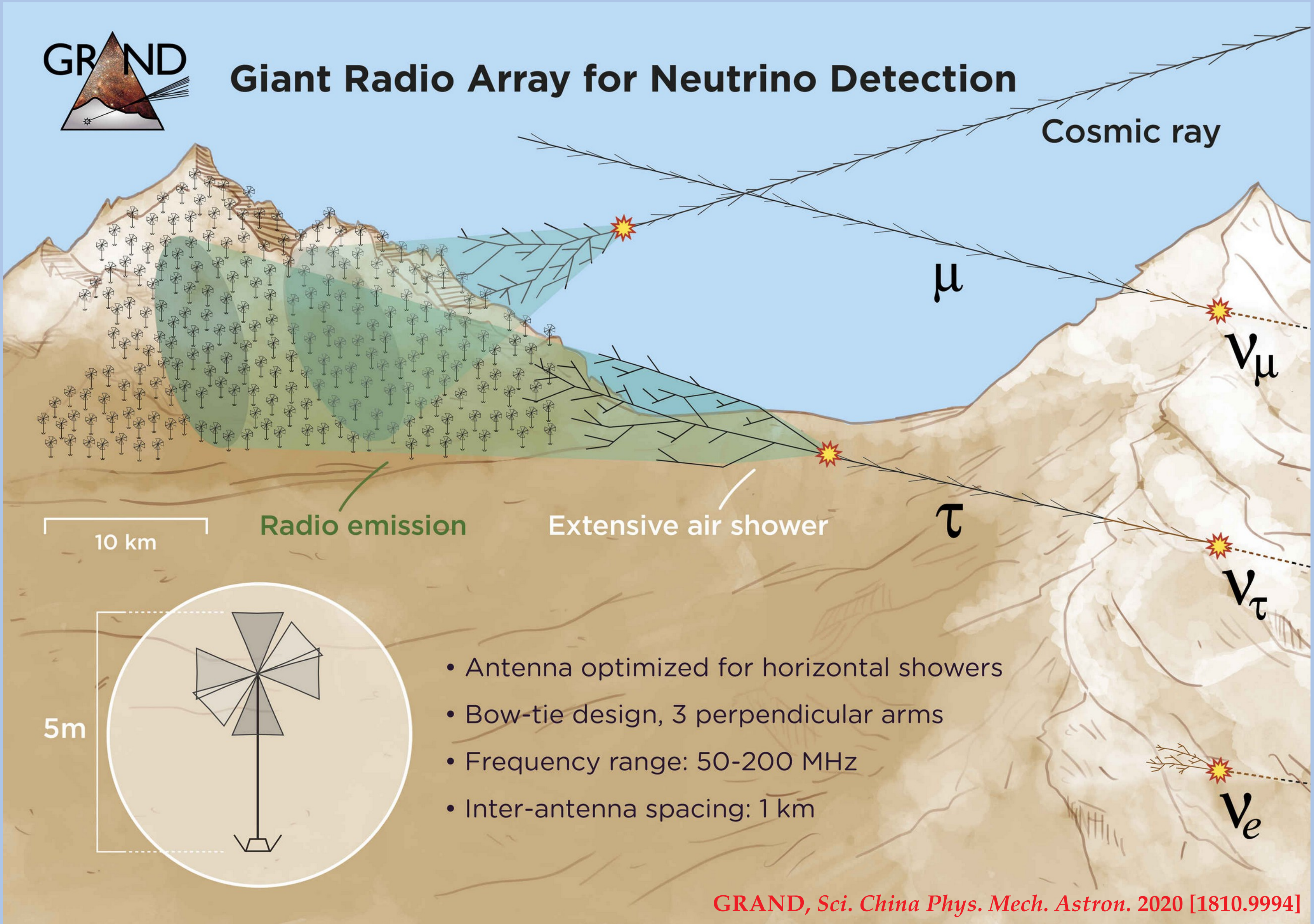
  $E_\mu = E_{tr}$ (energy of track)

  $y = (1 + E_{tr}/E_{sh})^{-1}$

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



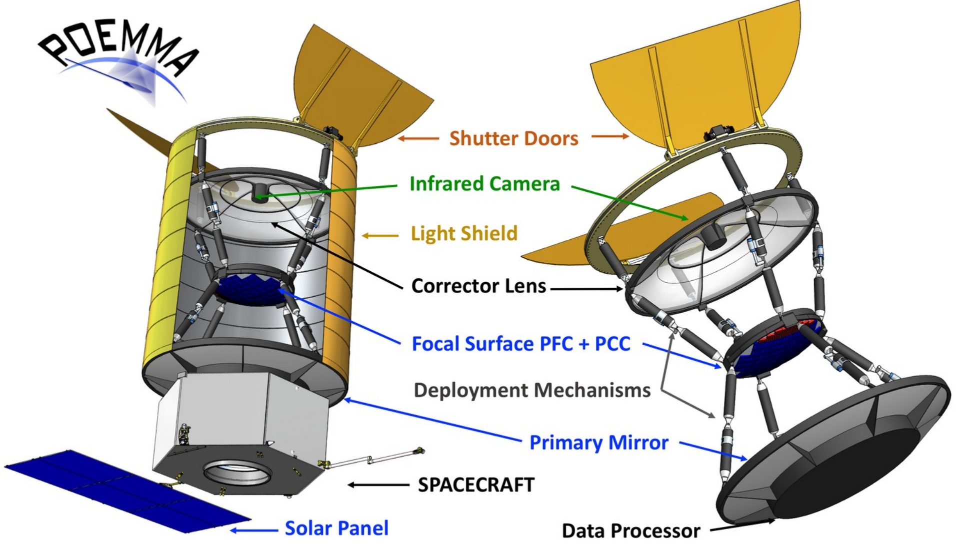
IceCube, *PRD* 2019

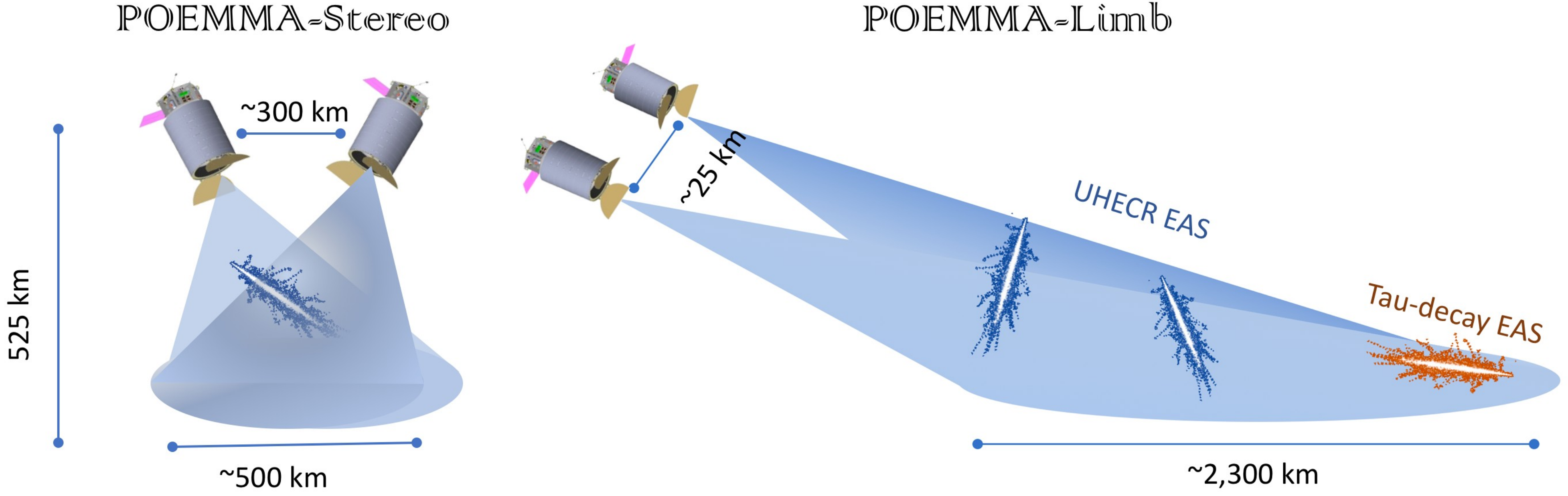


GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]

POEMMA:
Probe of Extreme Multi-Messenger Astrophysics

POEMMA, *JCAP* 2021 (2012.07945)





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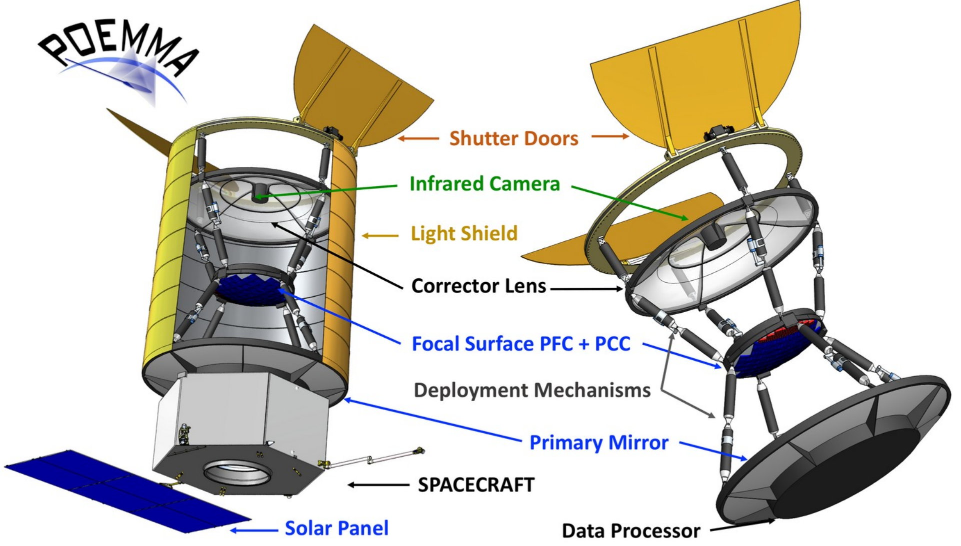
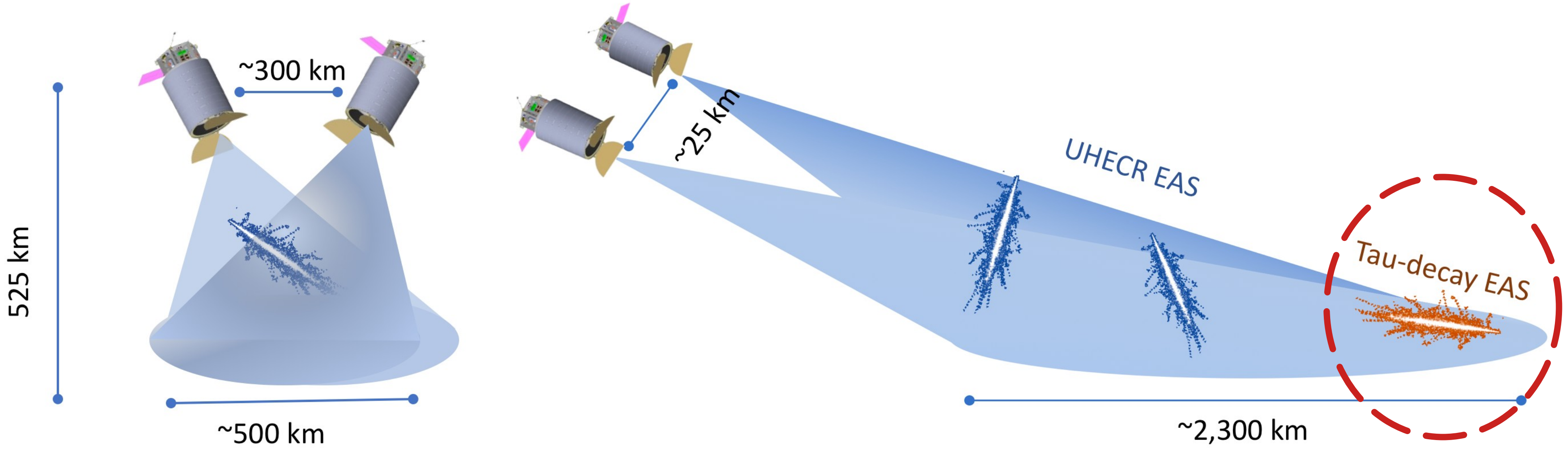


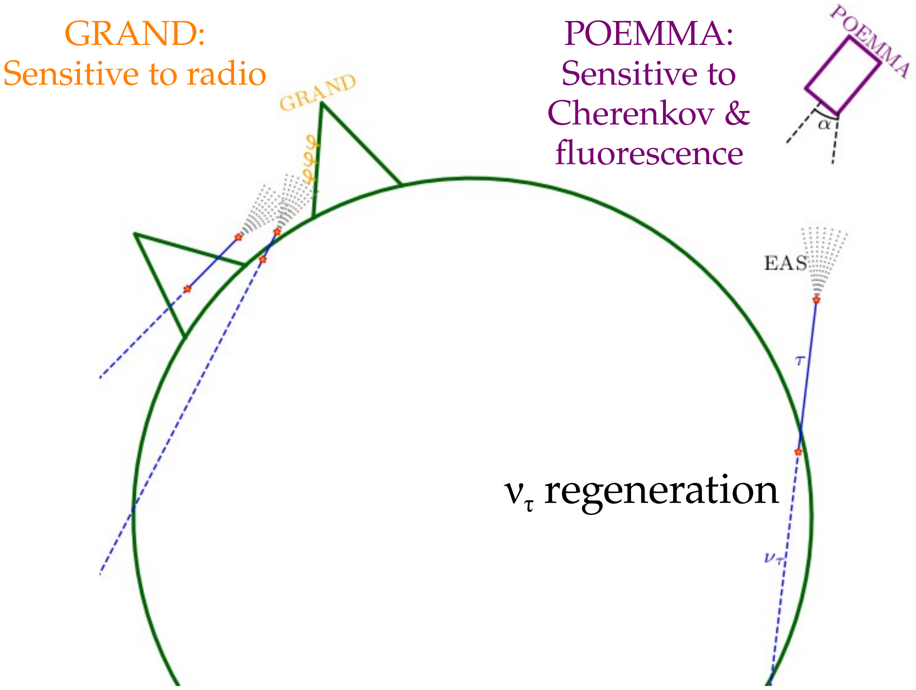
POEMMA-Stereo

POEMMA-Limb



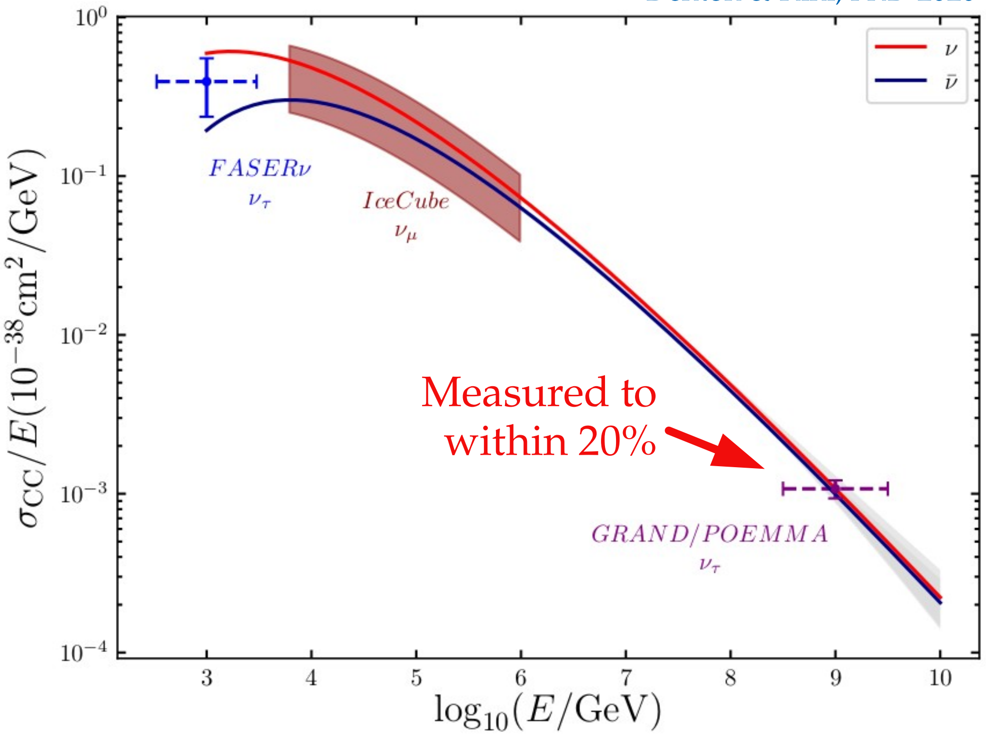
GRAND & POEMMA

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

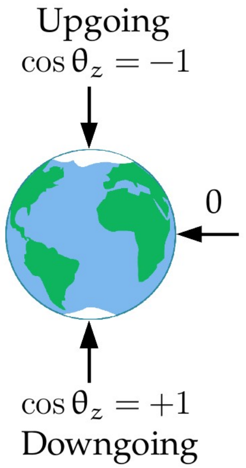


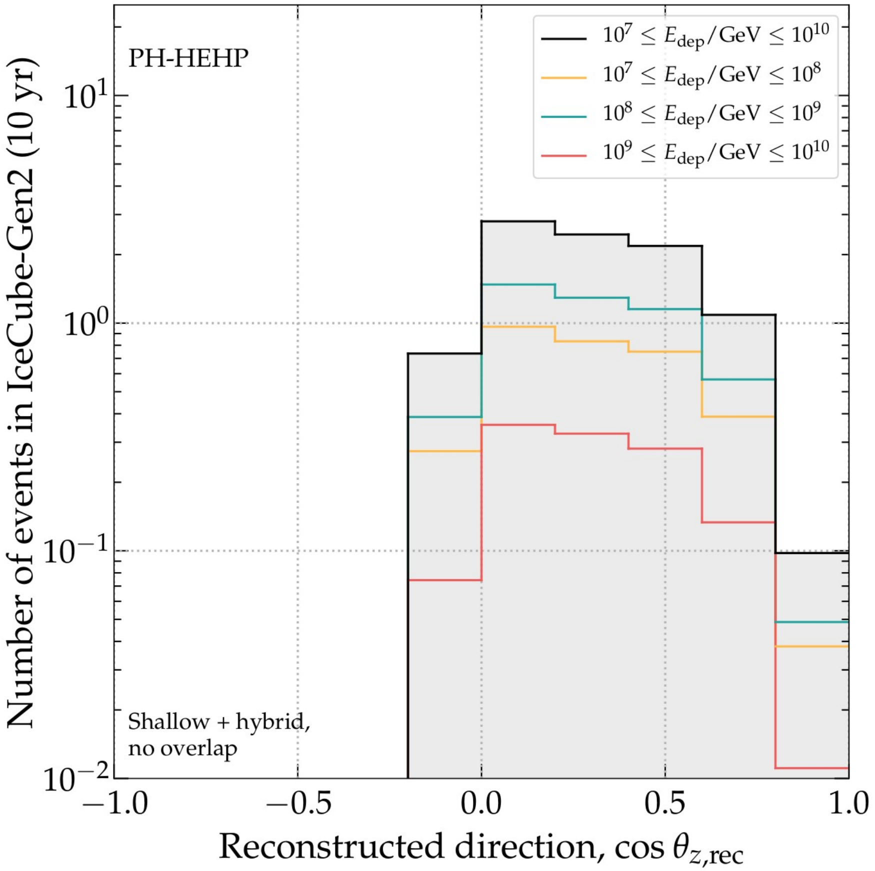
If they see 100 events from ν_τ with initial energy of 10^9 GeV (pre-attenuation):

Denton & Kini, *PRD* 2020

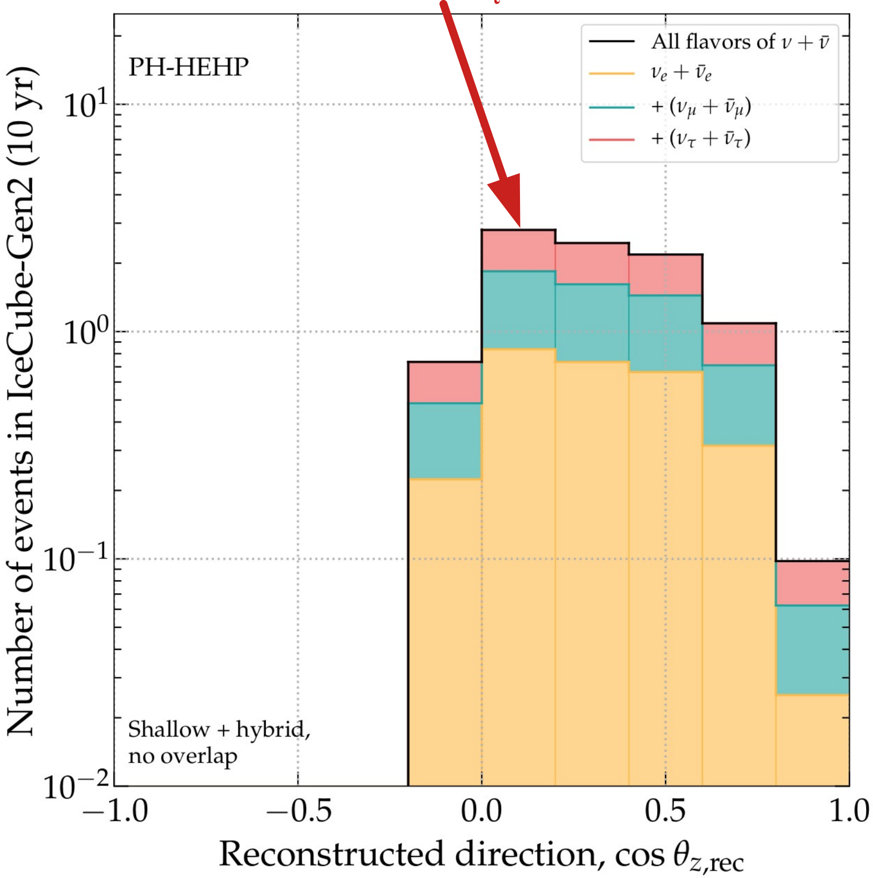


IceCube-Gen2 Radio





Contribution of ν_τ



(Angular resolution in $\theta_{z,\mathrm{rec}}$: 2°
Energy resolution in $\log_{10}(E_{dep}/\mathrm{GeV})$: 0.1)

Valera, **MB**, Glaser, *In preparation*

Example 2:
Secret neutrino interactions

νSI with the UHE diffuse flux

Resonance energy: $E_{\rm res} = \dfrac{M^2}{2m_\nu}$

Coupling matrix:

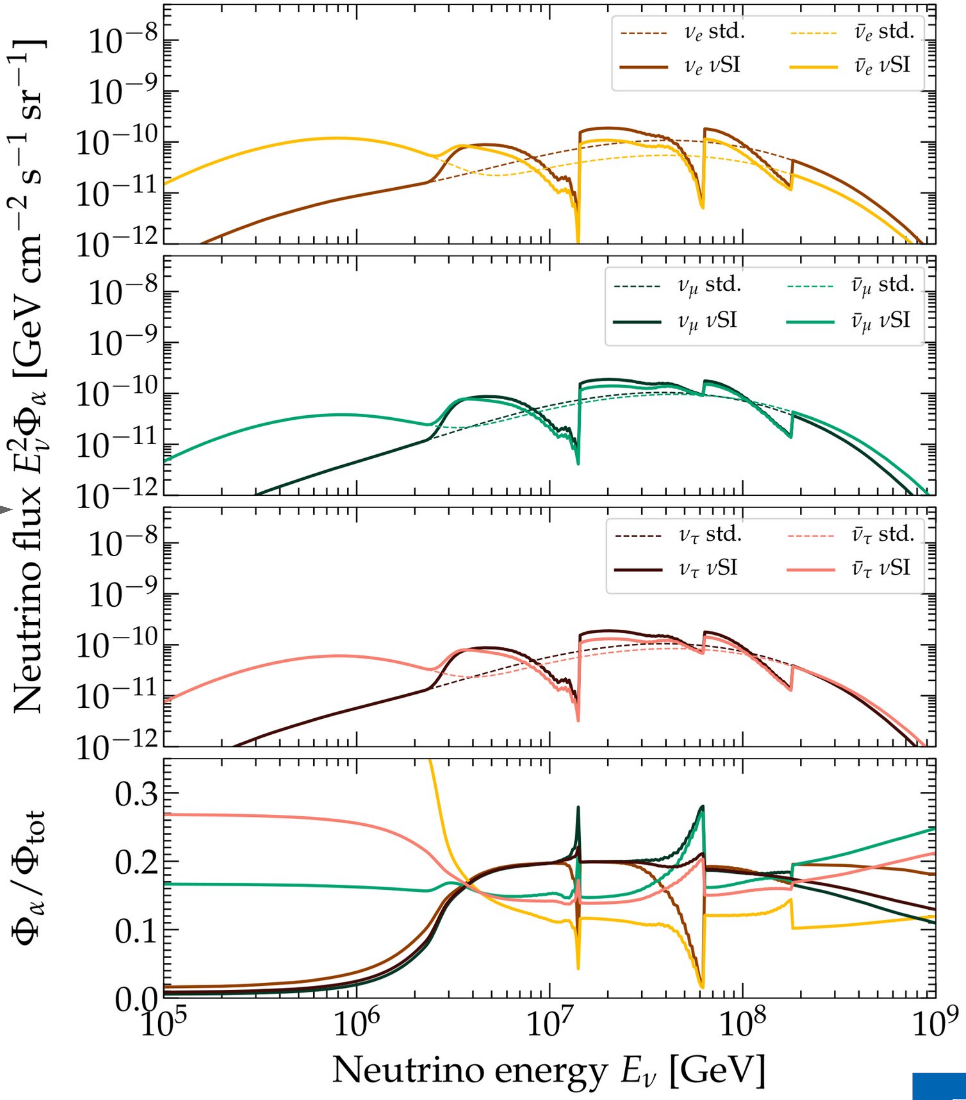
$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

Different flavors can have different couplings

νSI dips and bumps in the diffuse UHE ν flux:

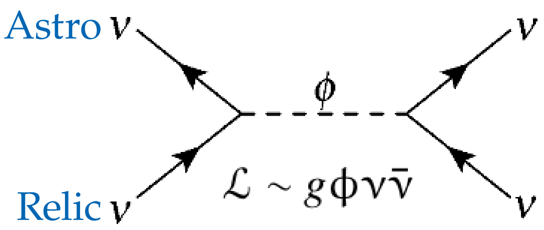
- In the cosmogenic flux
- In the flux from sources

But we need enough events to detect the spectral features – we need POEMMA-360!



MB, Másson, Valera, In prep.

νSI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

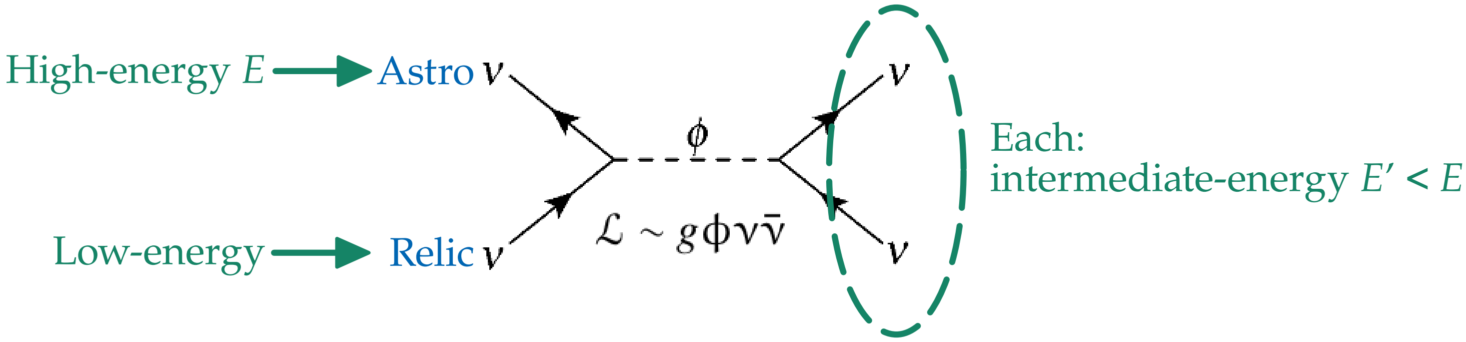
So, if we see high-energy neutrinos, we can set an upper limit on the νSI strength

Original idea by Kolb & Turner, using SN1987A (*PRD* 1987)

Mean free path of a ν of energy E: $l_{\rm int}(E) = [n_{{\rm C}\nu{\rm B}}\sigma_{\nu\nu}(E)]^{-1}$

Estimated optical depth if emitted by a source at a distance L: $\tau(E) = \dfrac{l_{\rm int}(E)}{L}$

νSI with the UHE transient flux



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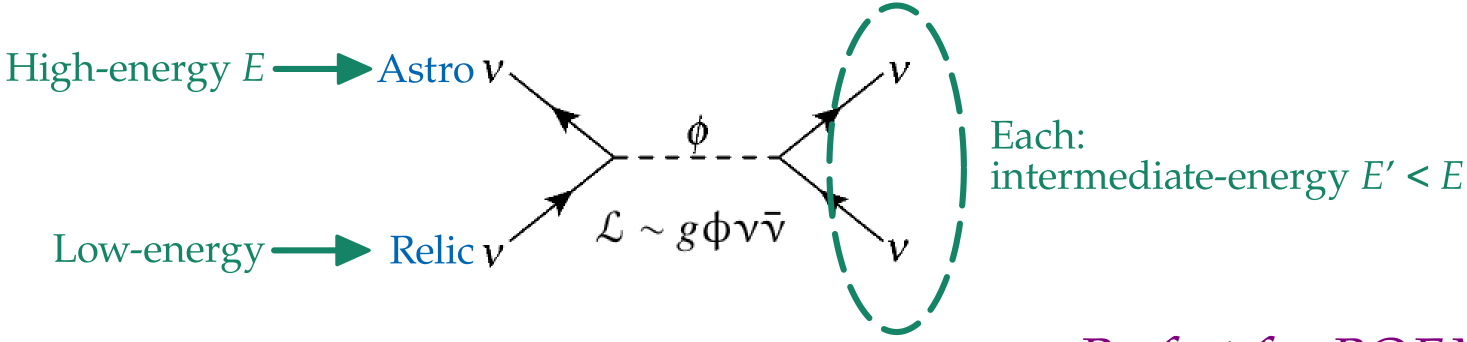

Perfect for POEMMA!

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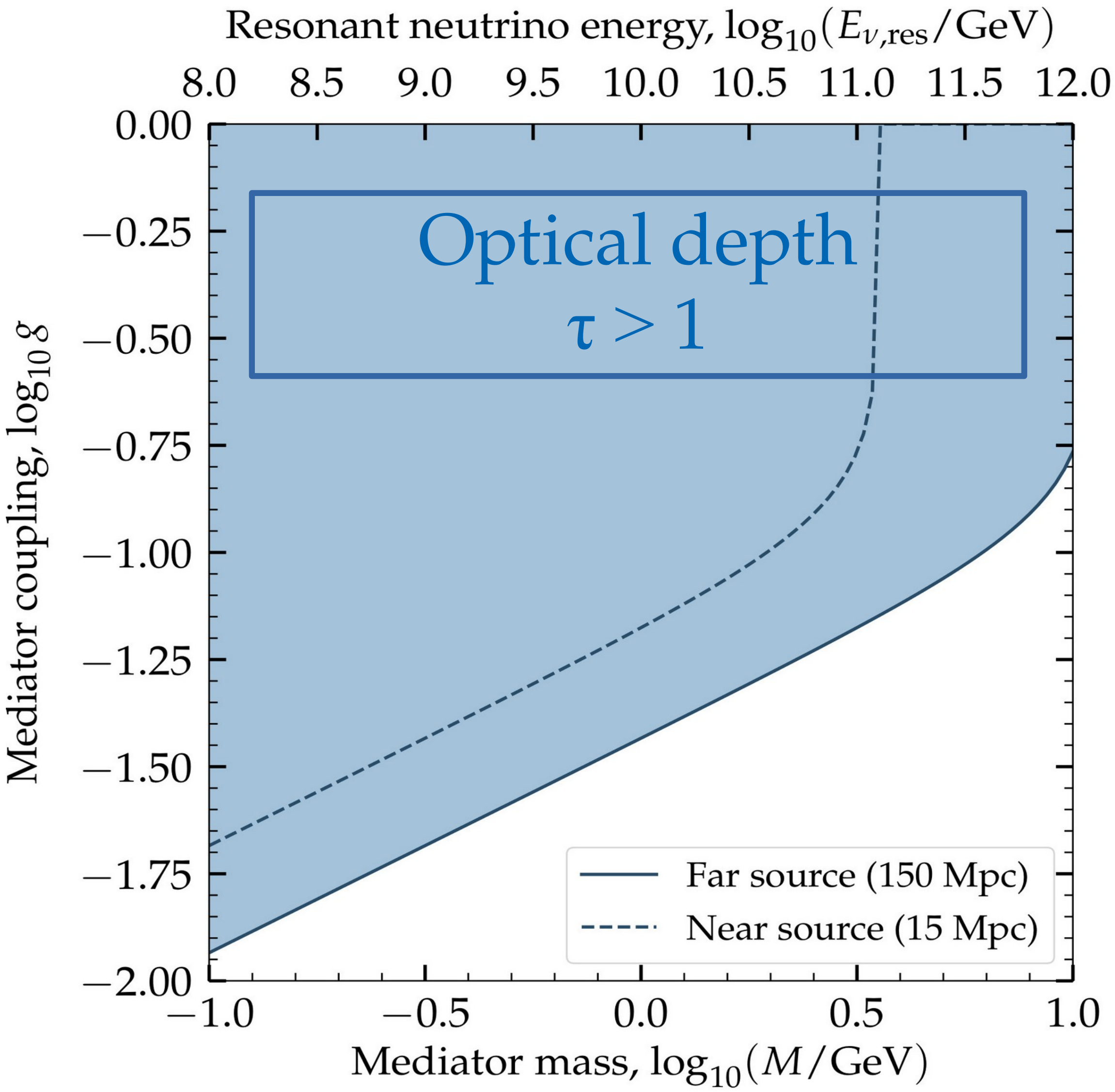
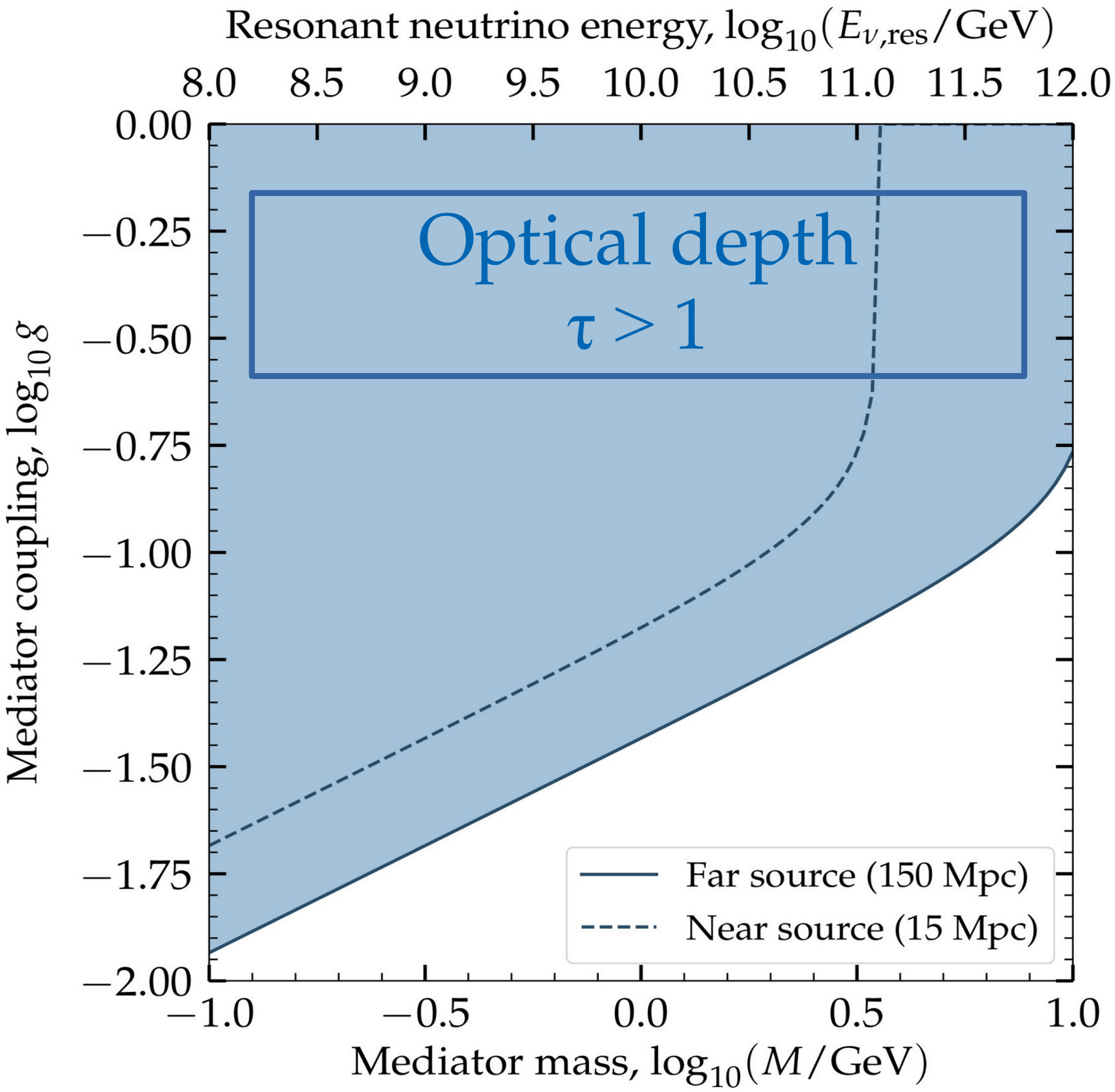
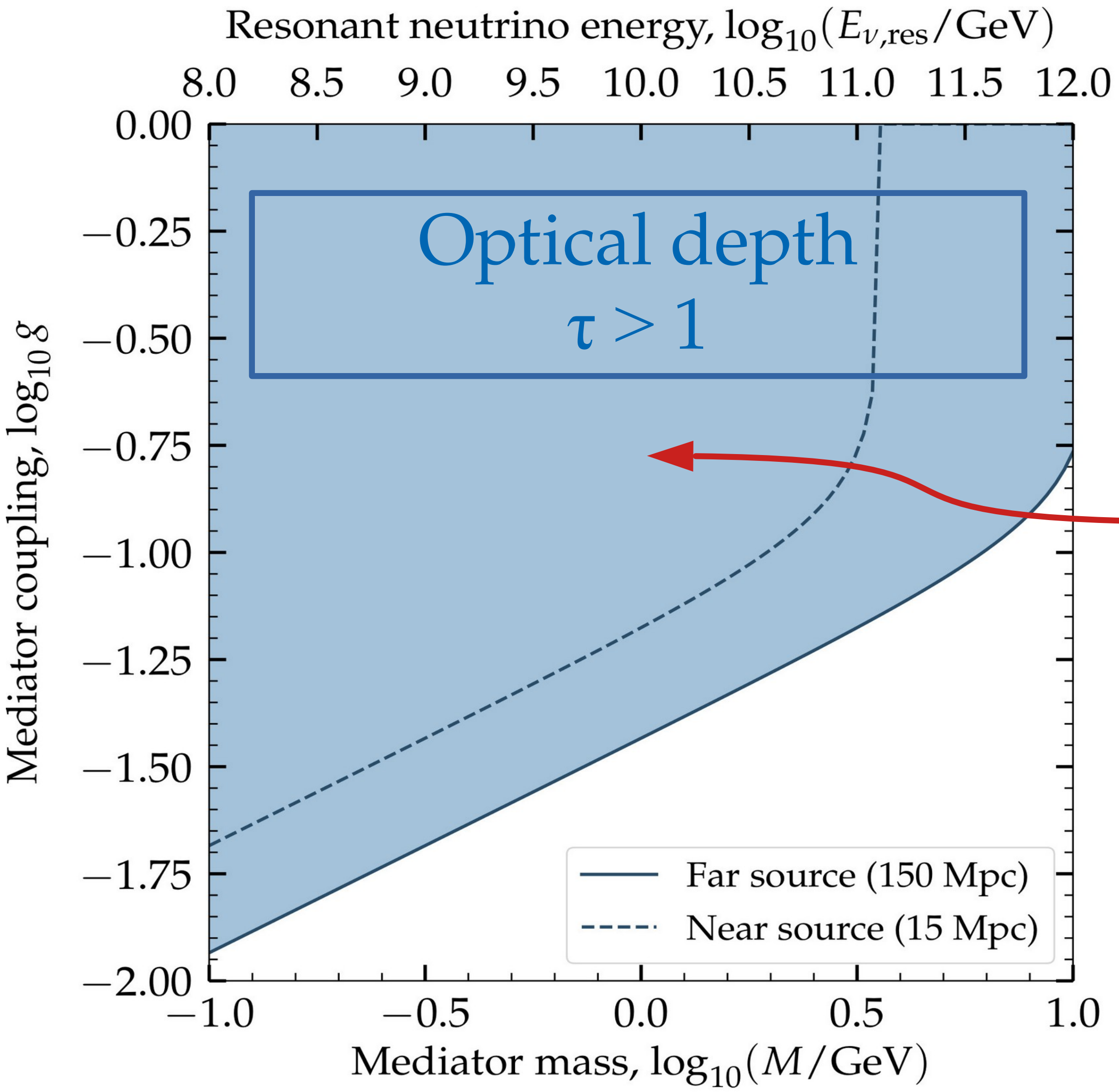


POEMMA Collab., *JCAP* 2021



POEMMA Collab., *JCAP* 2021



If POEMMA sees UHE ν from a flare, we can kill part of this parameter space

POEMMA Collab., *JCAP* 2021

Example 4:
Neutrino decay

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

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

- φ: Nambu-Goldstone boson of a broken symmetry (*e.g.*, Majoron)

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

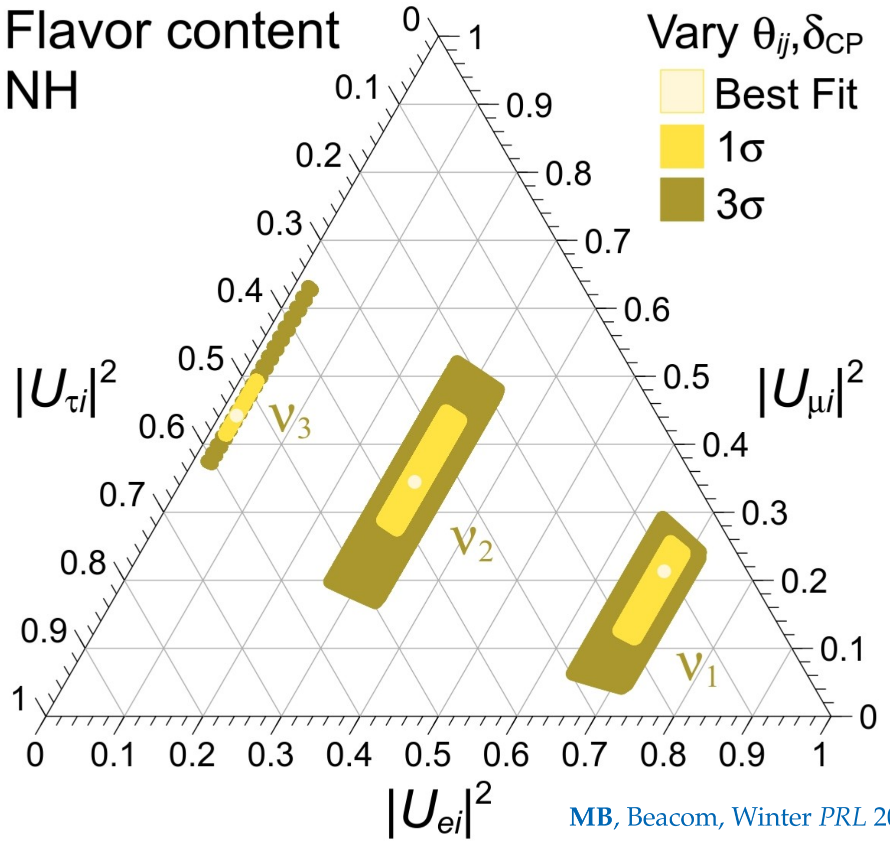
Flavor content of neutrino mass eigenstates

Known to within 2%

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

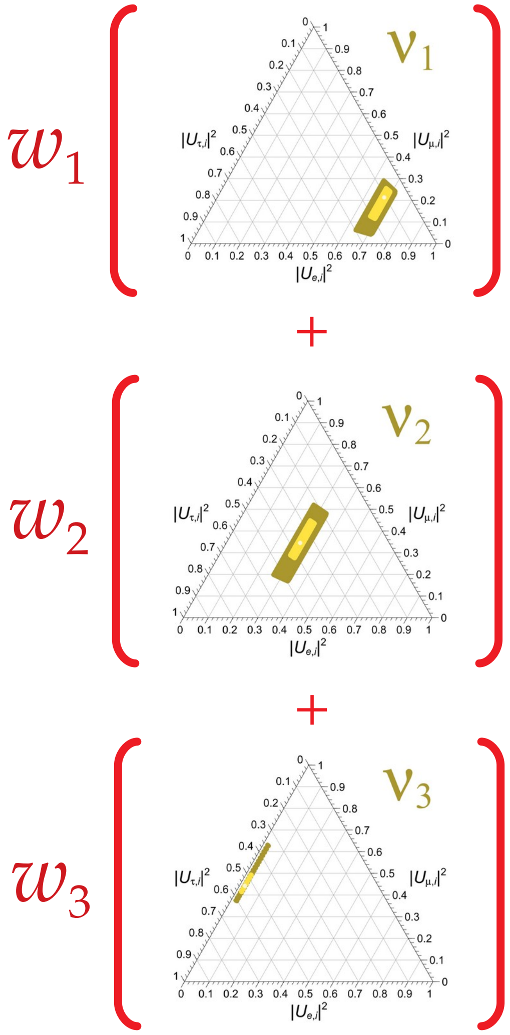
Known to within 8%

Known to within 20%
(or worse)

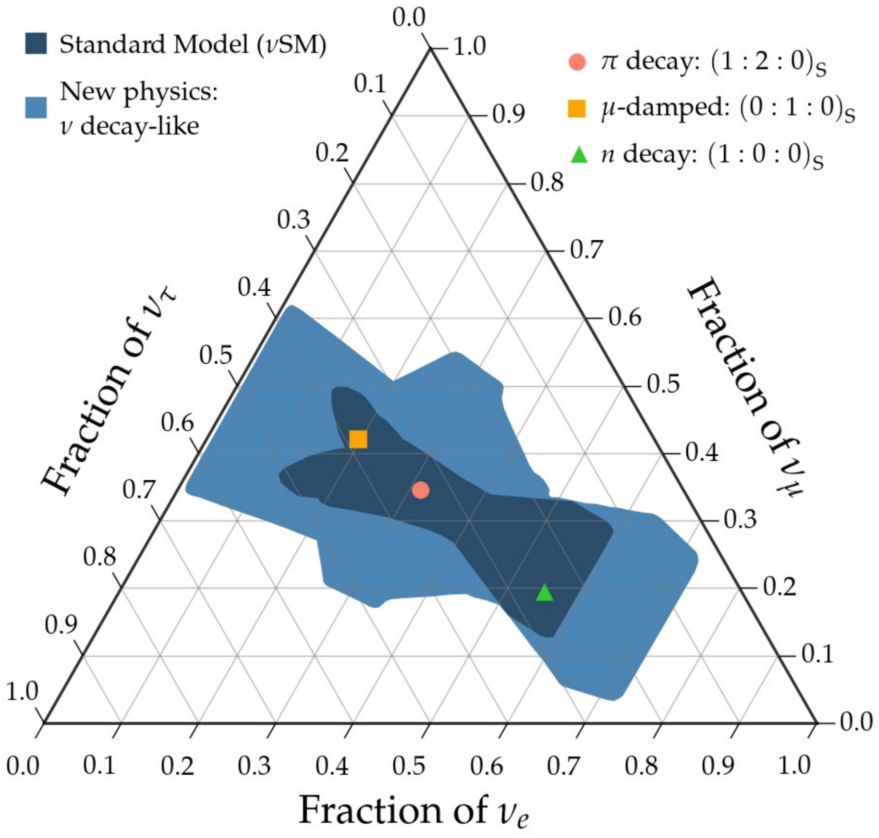


MB, Beacom, Winter *PRL* 2015

Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —



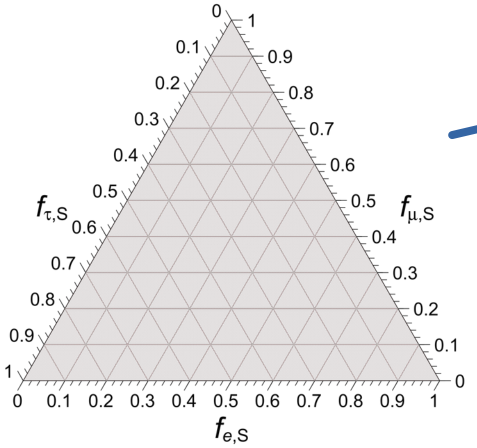
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸ with striking consequences for flavor

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \to \nu_1$

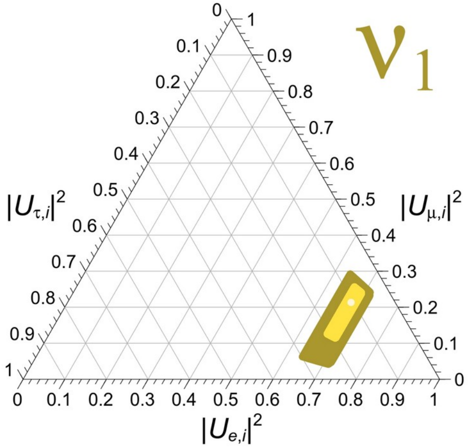
ν_1 lightest and stable
(normal mass ordering)

If all unstable neutrinos decay

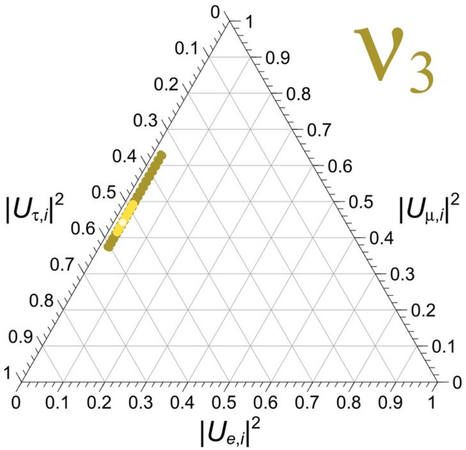
$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Earth



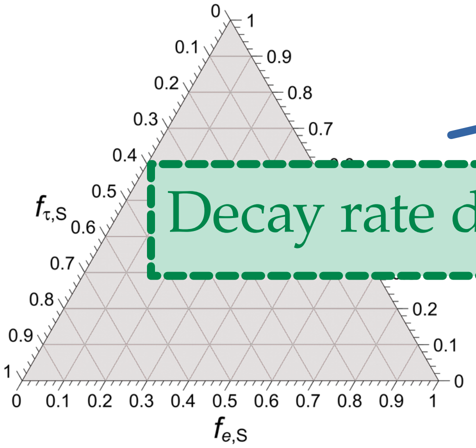
$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$
$(w_1 \sim 1; w_2, w_3 \sim 0)$



$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$
$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

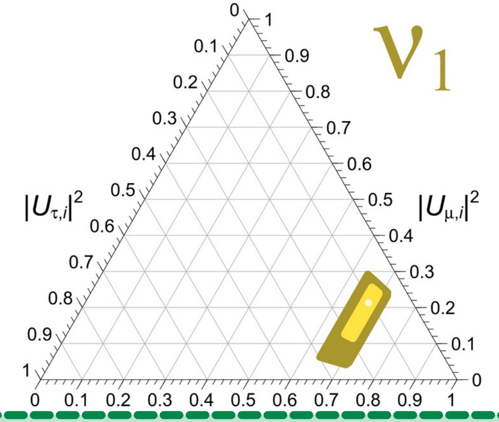
Sources



$\underbrace{\nu_2, \nu_3 \to \nu_1}$

ν_1 lightest and stable
(normal mass ordering)

Earth



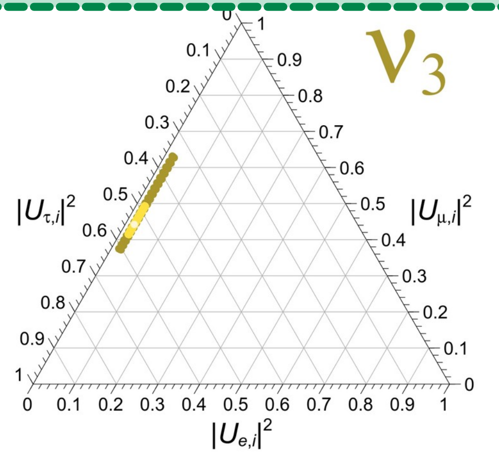
ν_1

$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$
$(w_1 \sim 1; w_2, w_3 \sim 0)$

Decay rate depends on $\exp[-\, t\ /\ (\gamma\ \tau_i)] = \exp[-\, (L/E) \cdot (m_i/\tau_i)]$

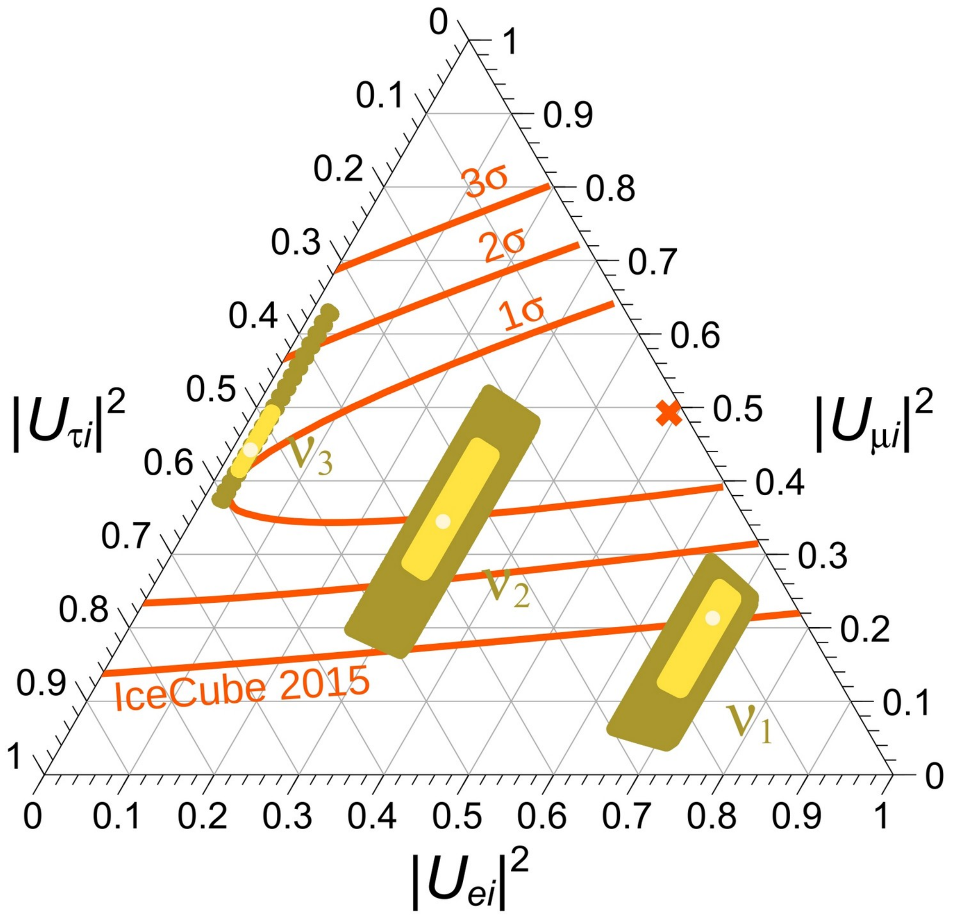
$\underbrace{\nu_1, \nu_2 \to \nu_3}$

ν_3 lightest and stable
(inverted mass ordering)



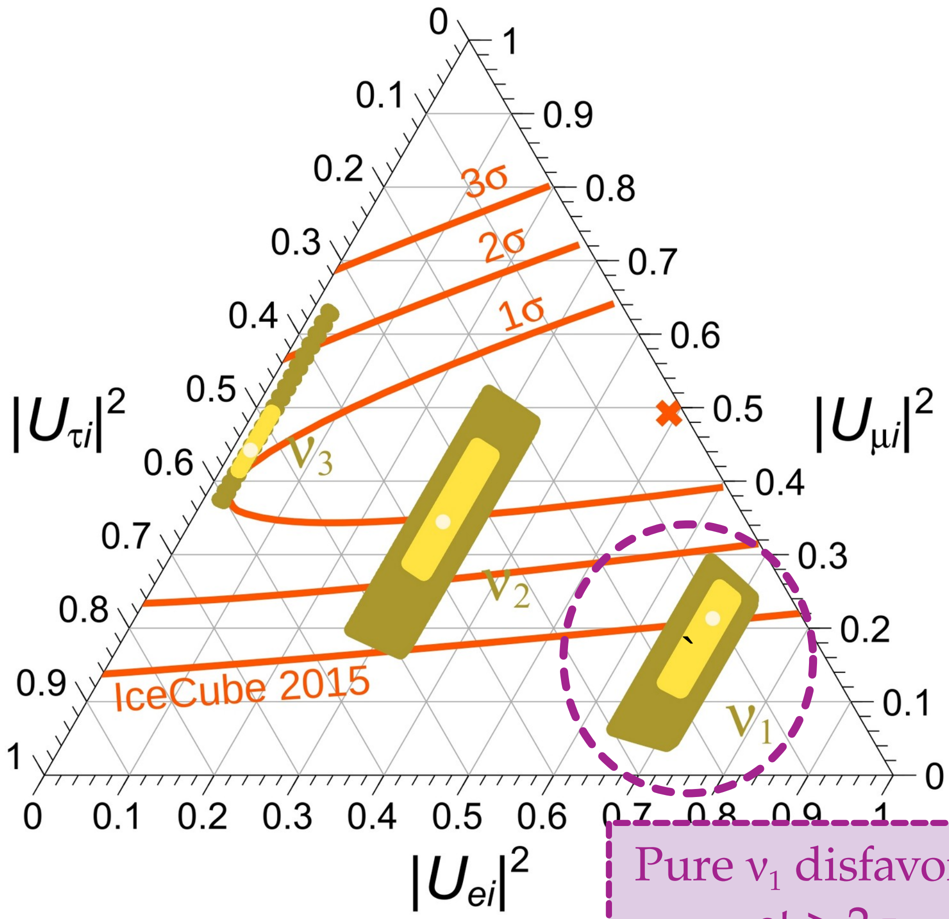
ν_3

$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$
$(w_3 \sim 1; w_1, w_2 \sim 0)$



MB, Beacom, Murase, *PRD* 2017

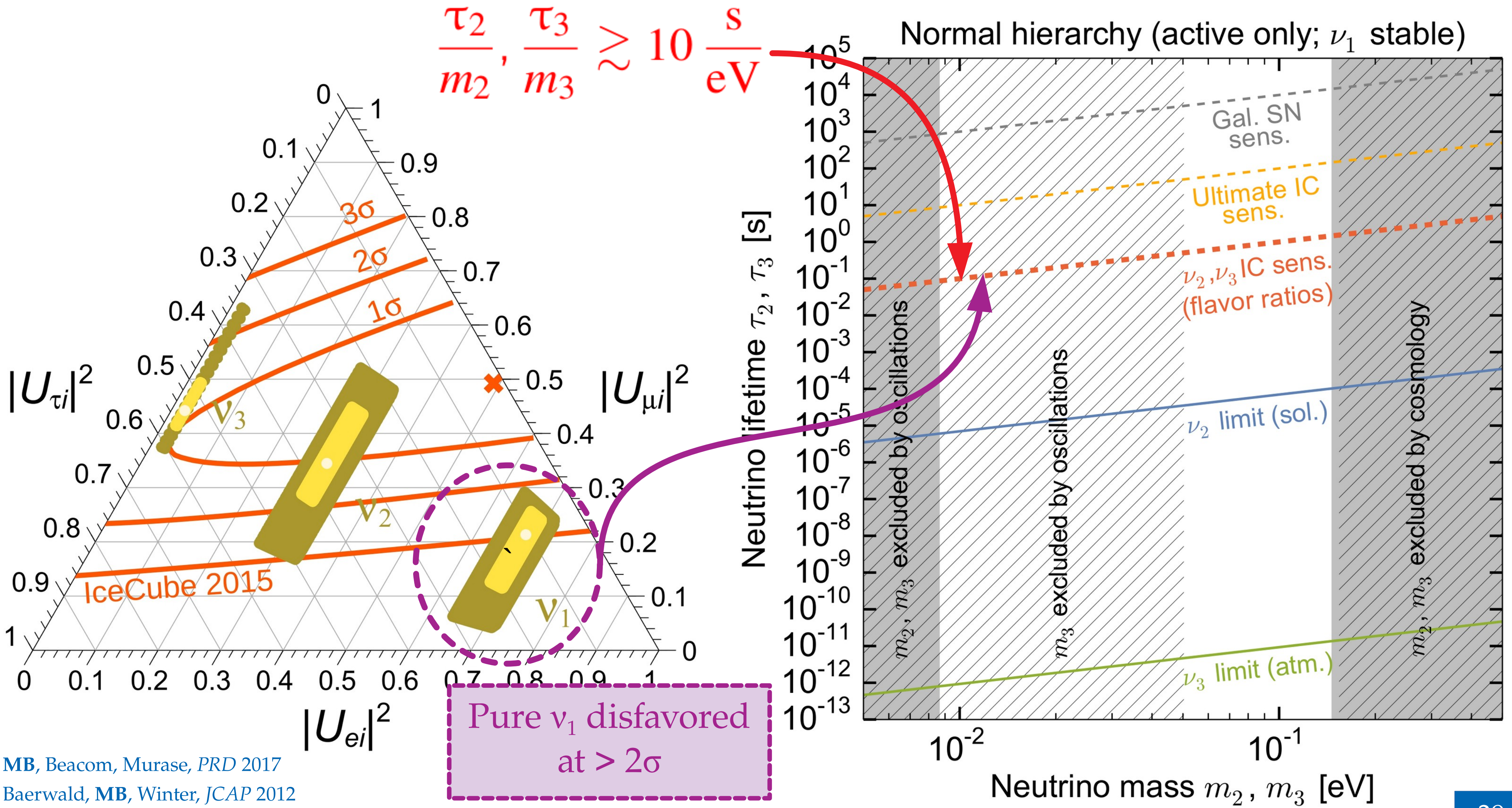
Baerwald, **MB**, Winter, *JCAP* 2012



Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017

Baerwald, **MB**, Winter, *JCAP* 2012



MB, Beacom, Murase, *PRD* 2017

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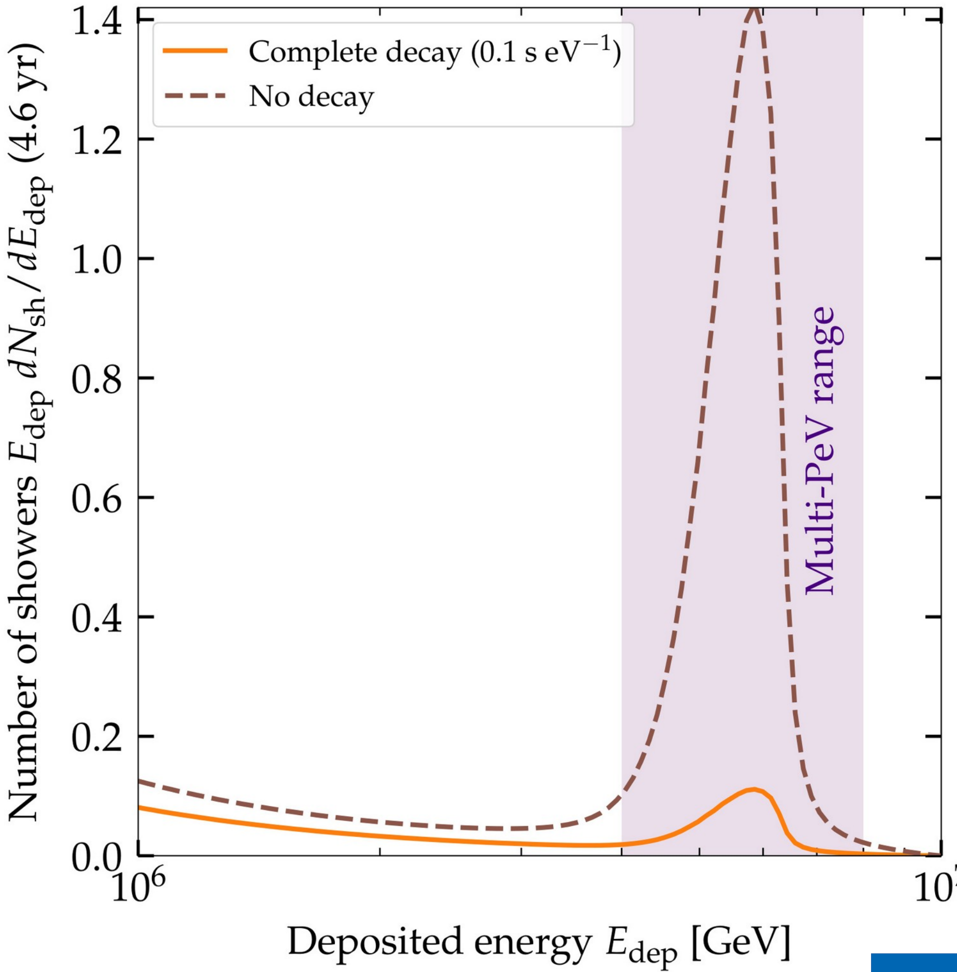
Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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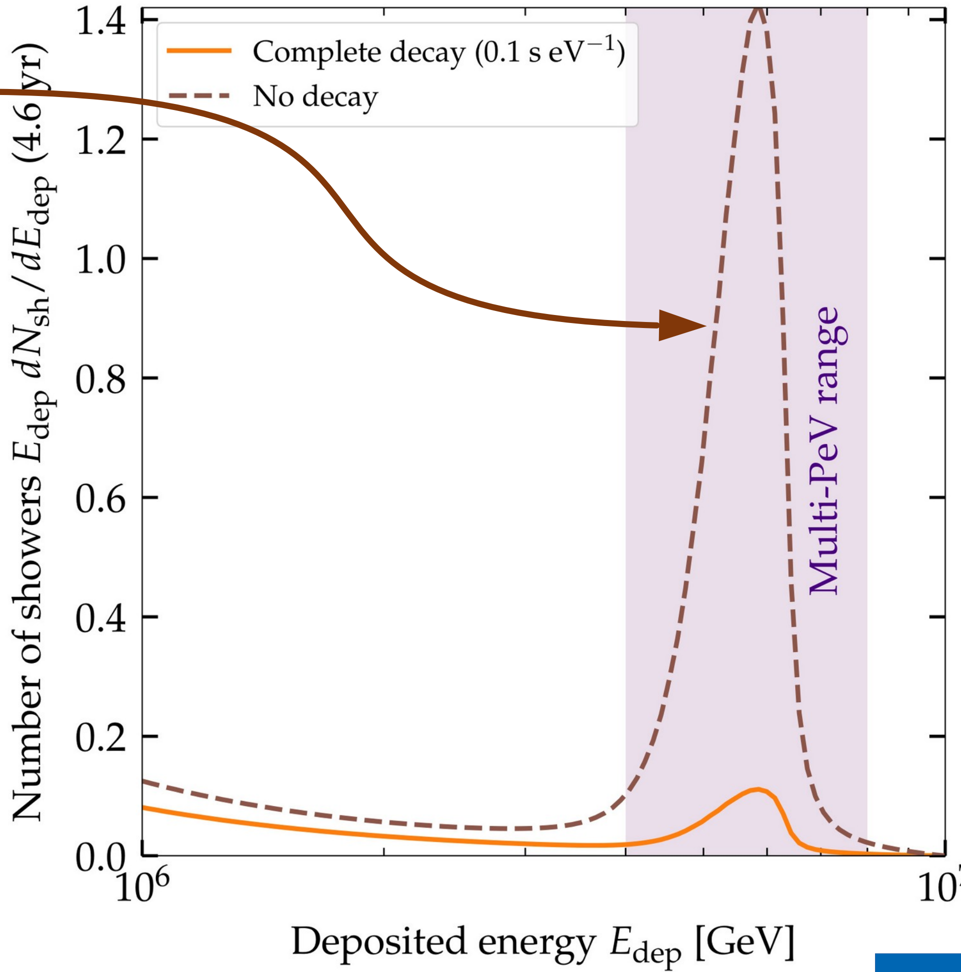

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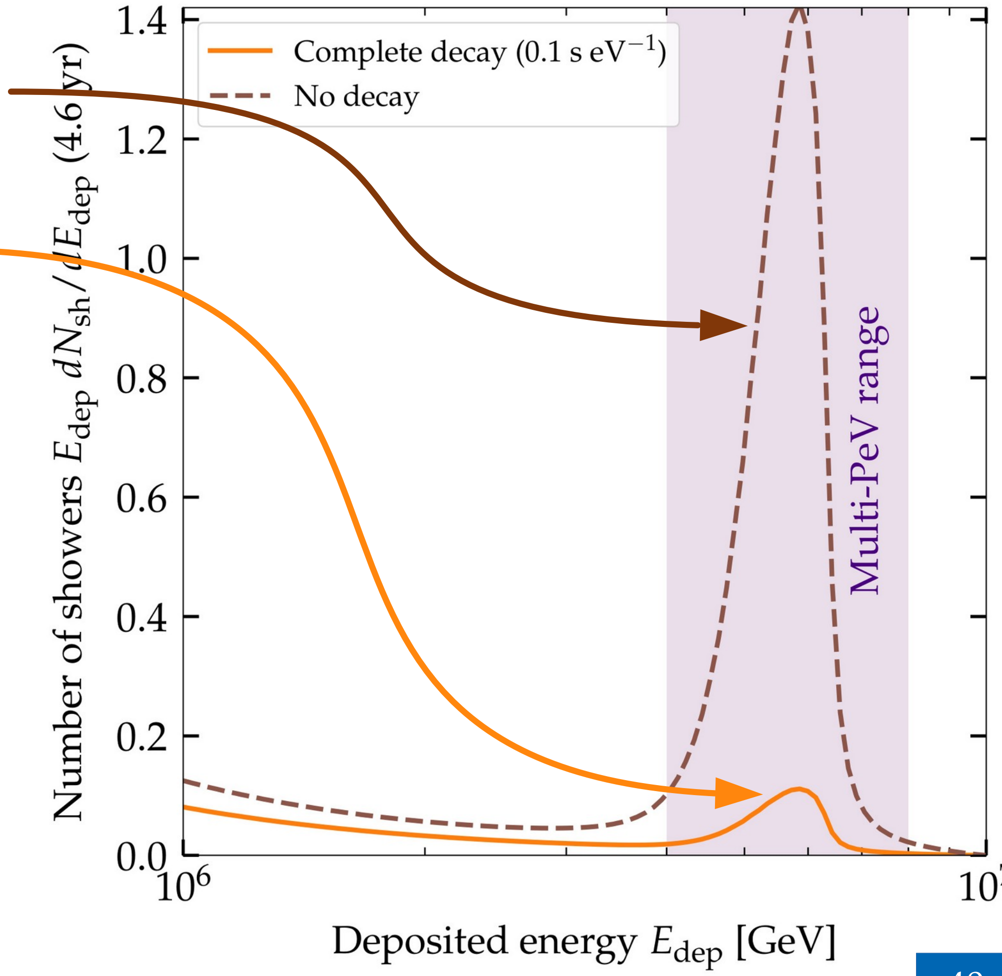

MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

Using the Glashow resonance to test decay

$\tau_1 / m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2 / m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \rightarrow W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
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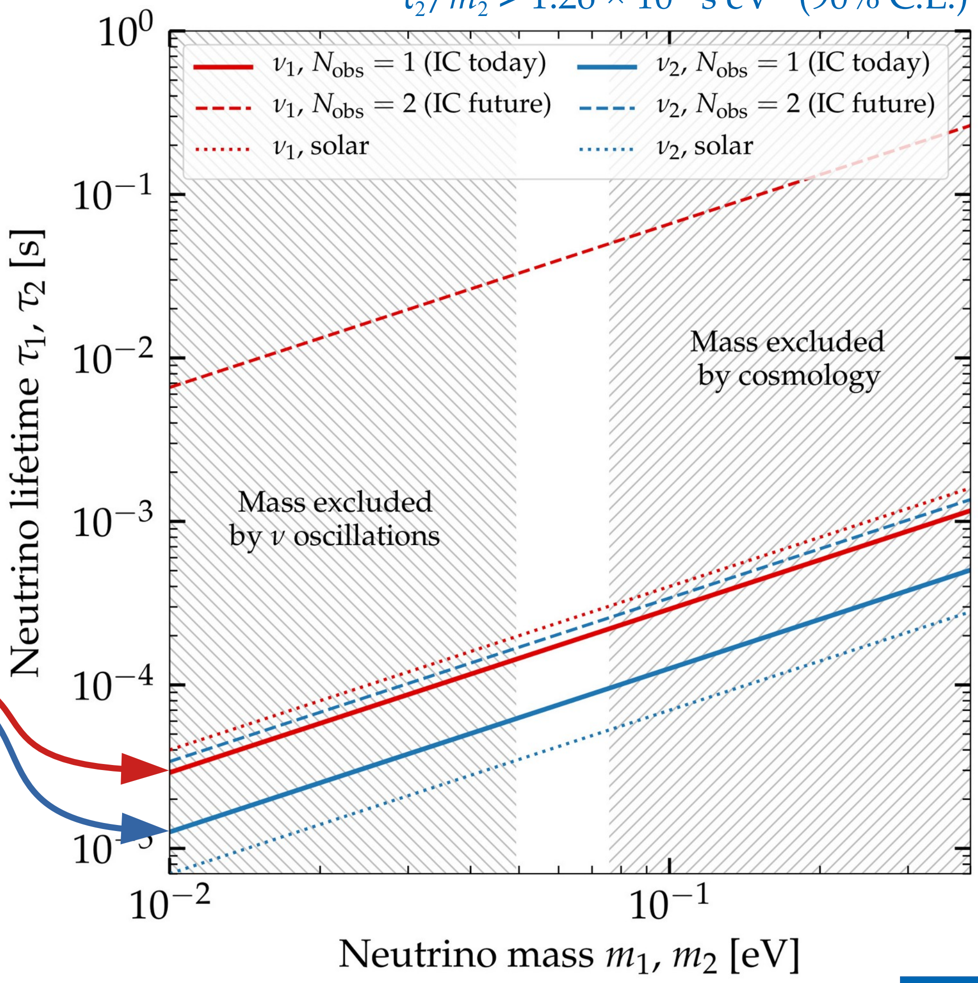

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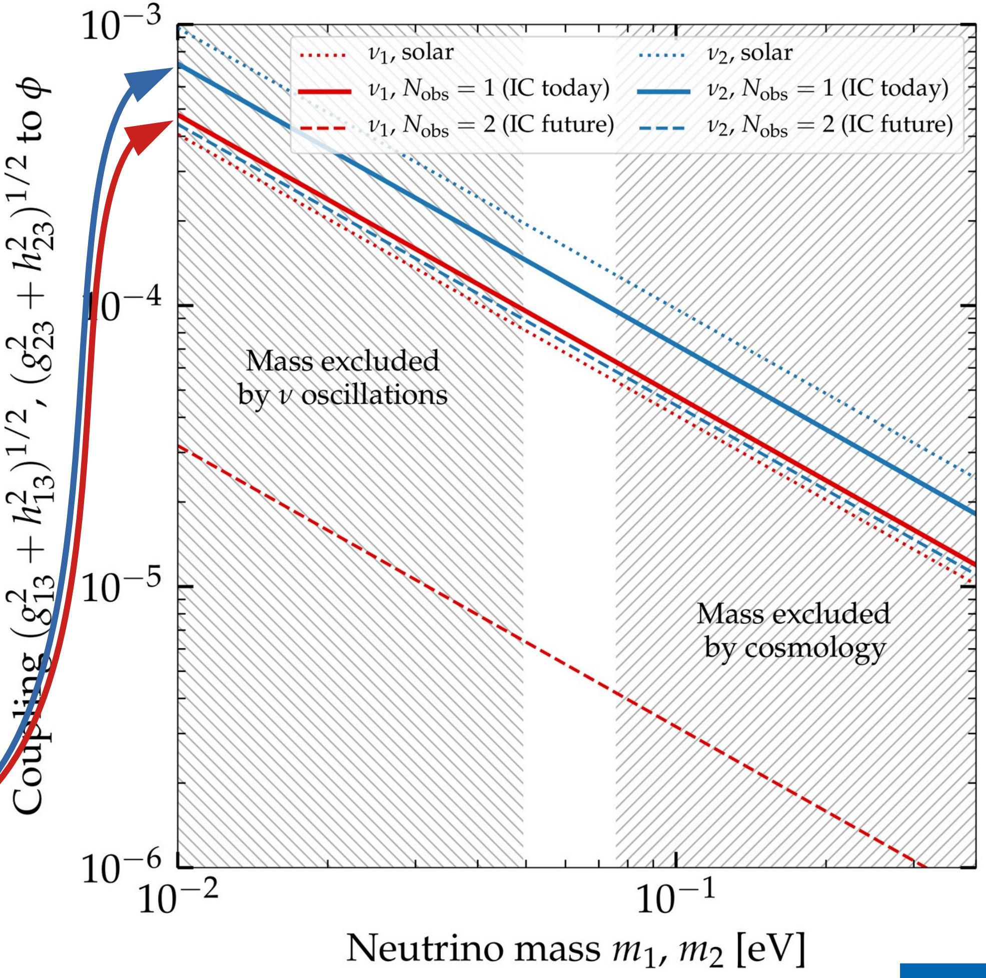
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$



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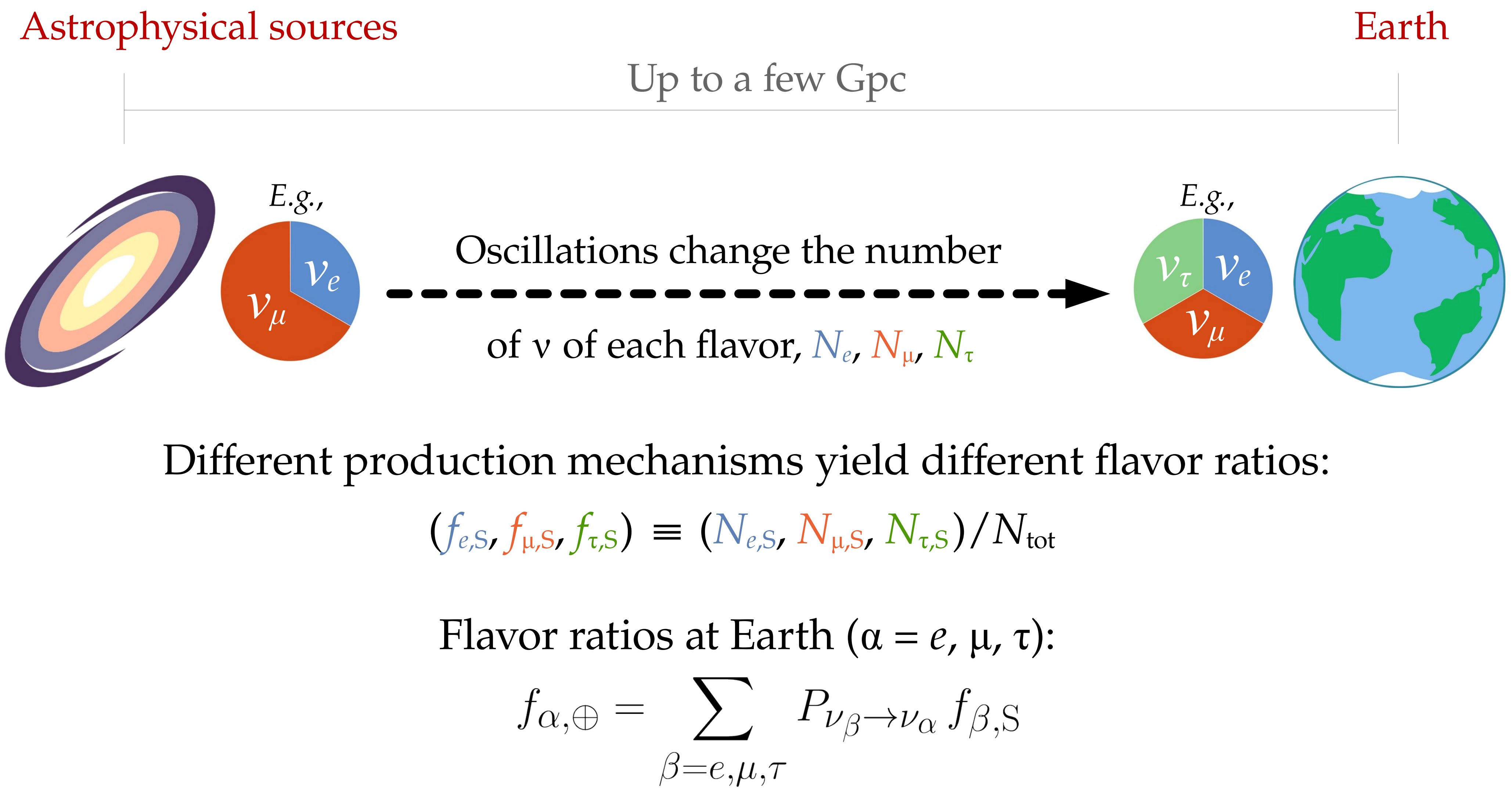
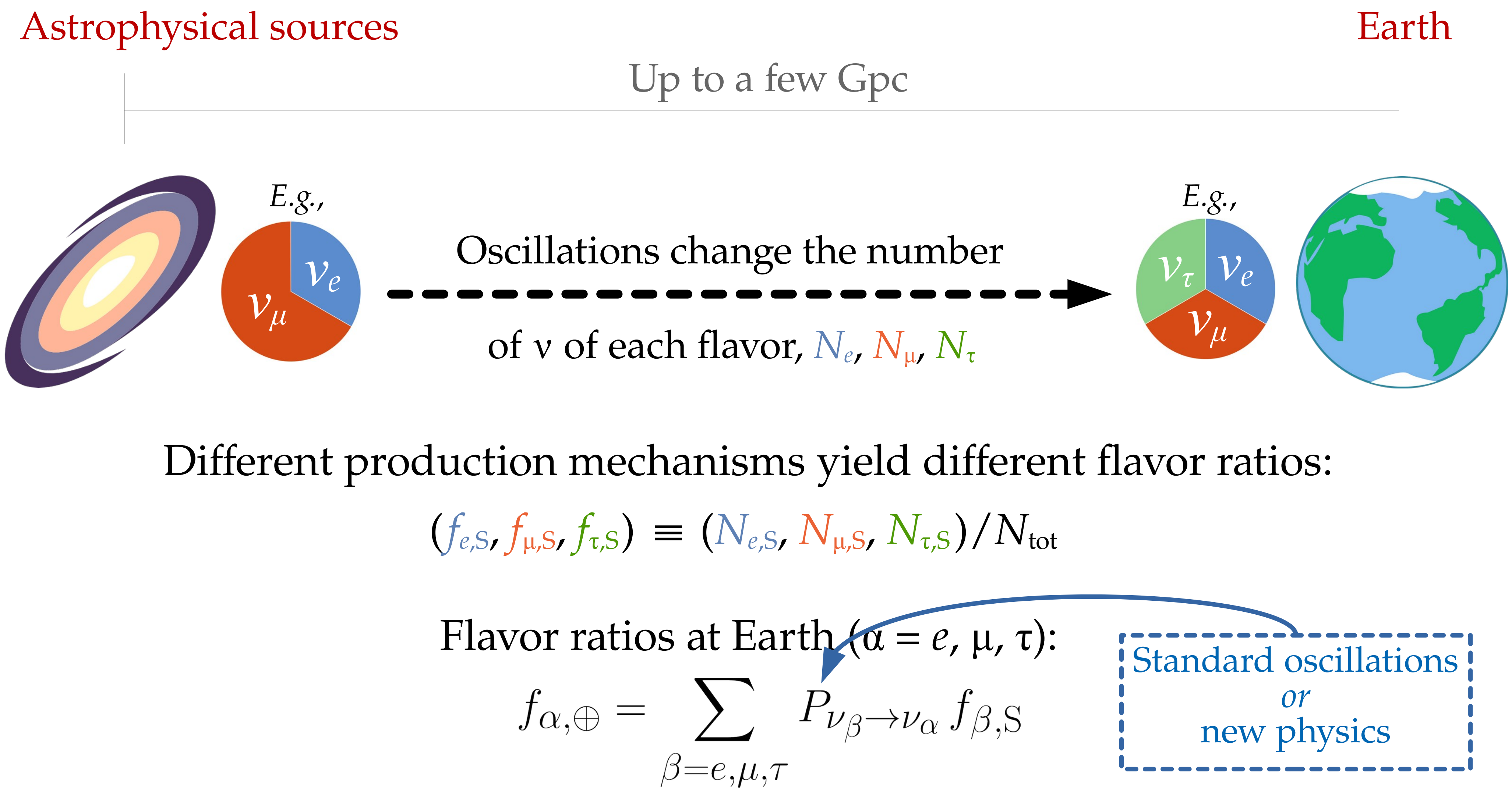
Flavor composition


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth (α = e, μ, τ):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta\to\nu_\alpha} f_{\beta,S}$



Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
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E.g.,
ν_τ
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ν_μ
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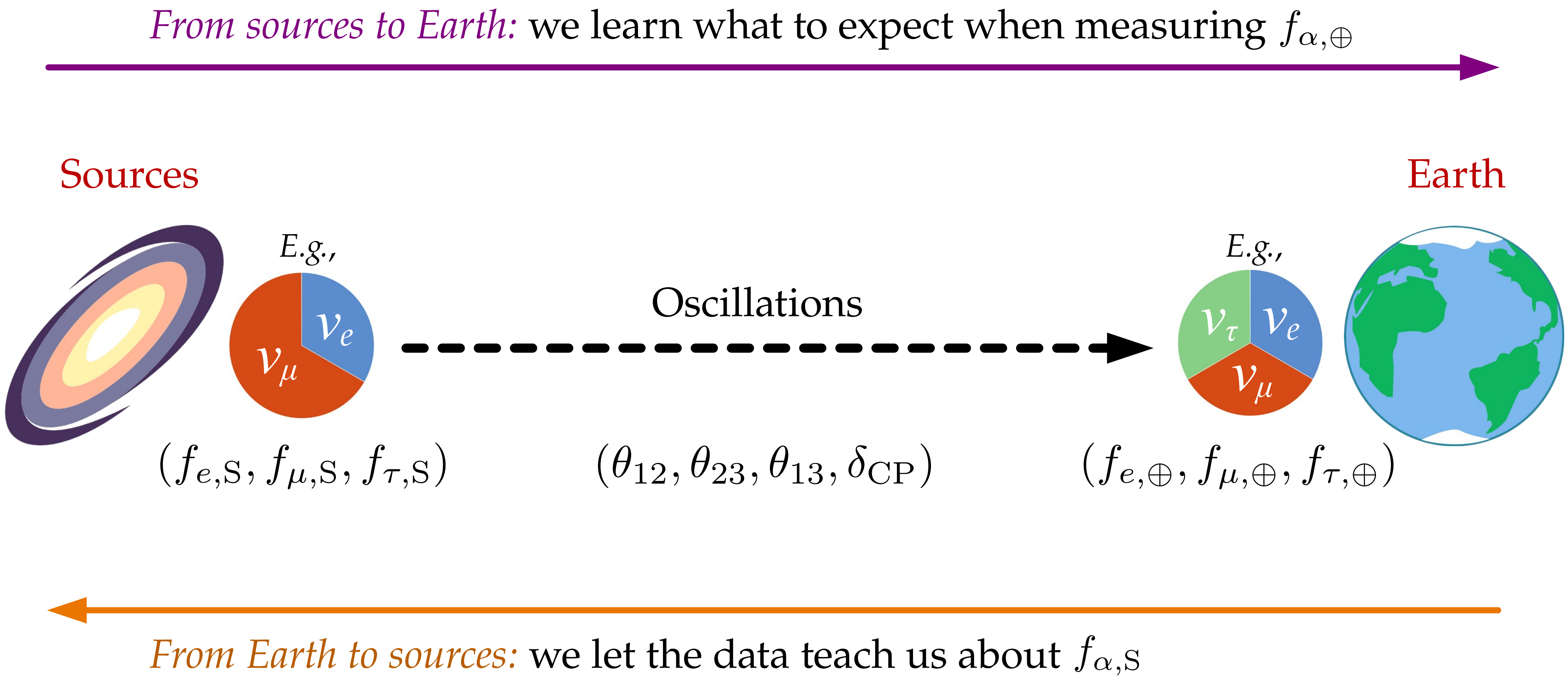
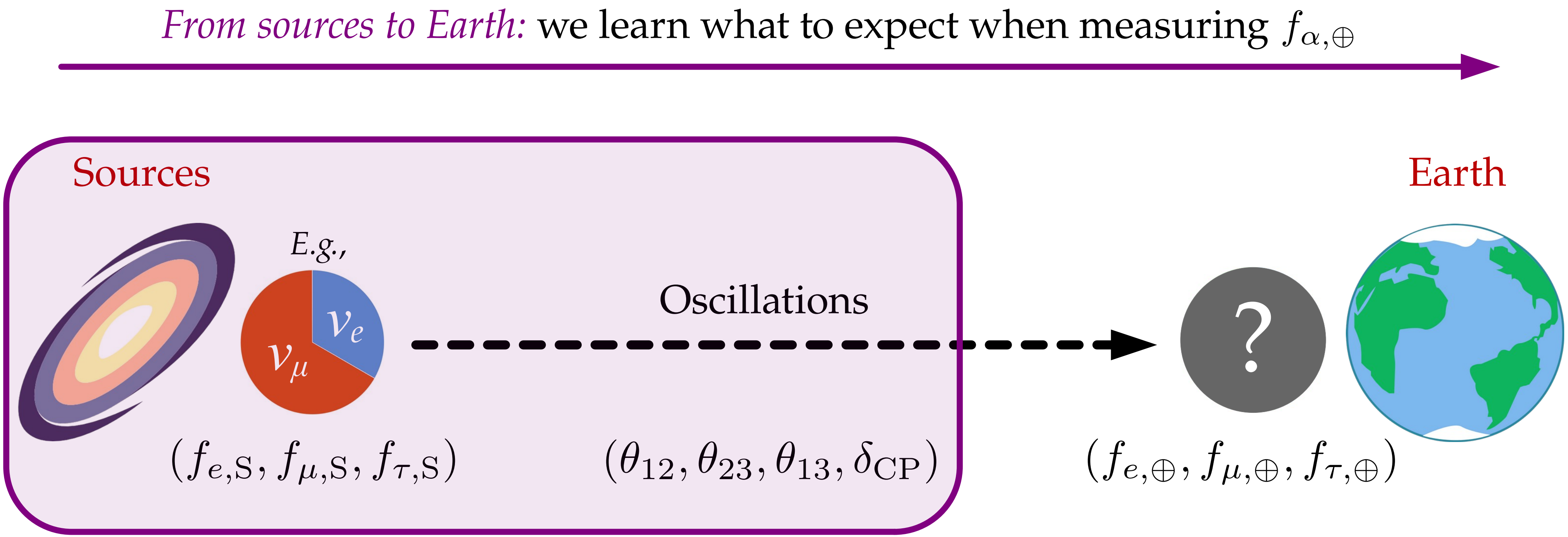
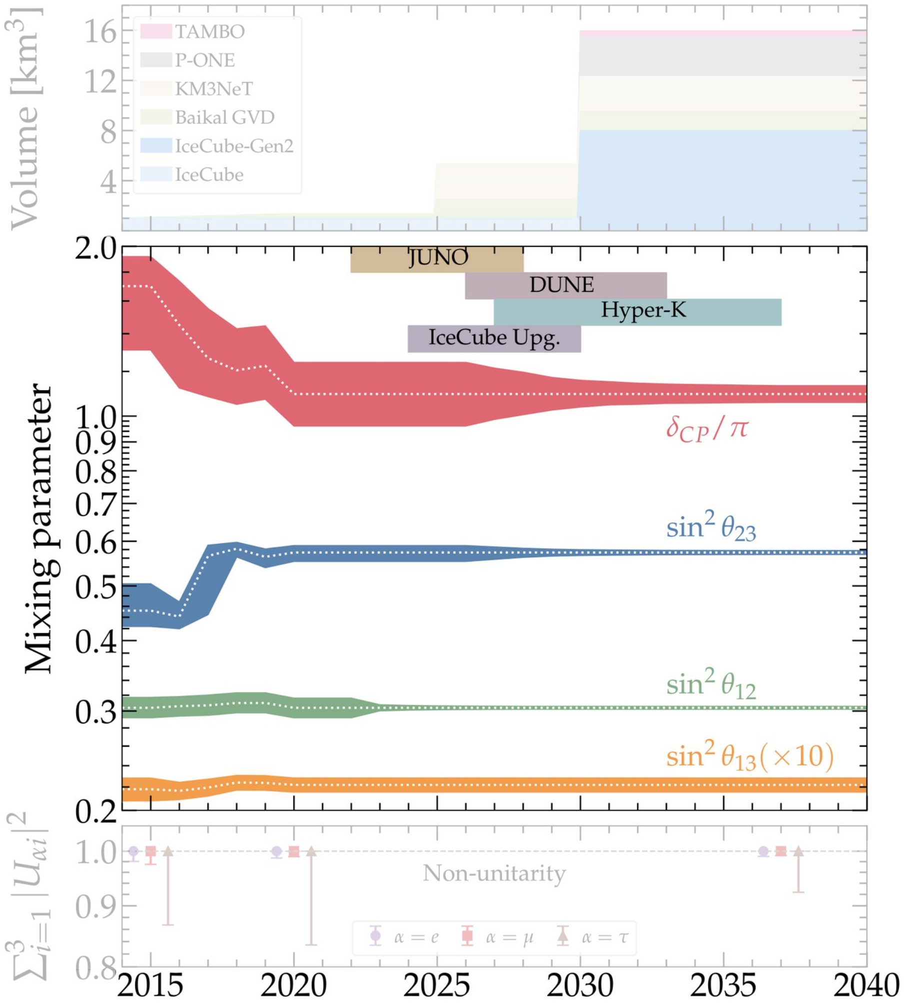
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
From Earth to sources: we let the data teach us about $f_{\alpha,\mathrm{S}}$


From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
E.g.,
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
?
Earth
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

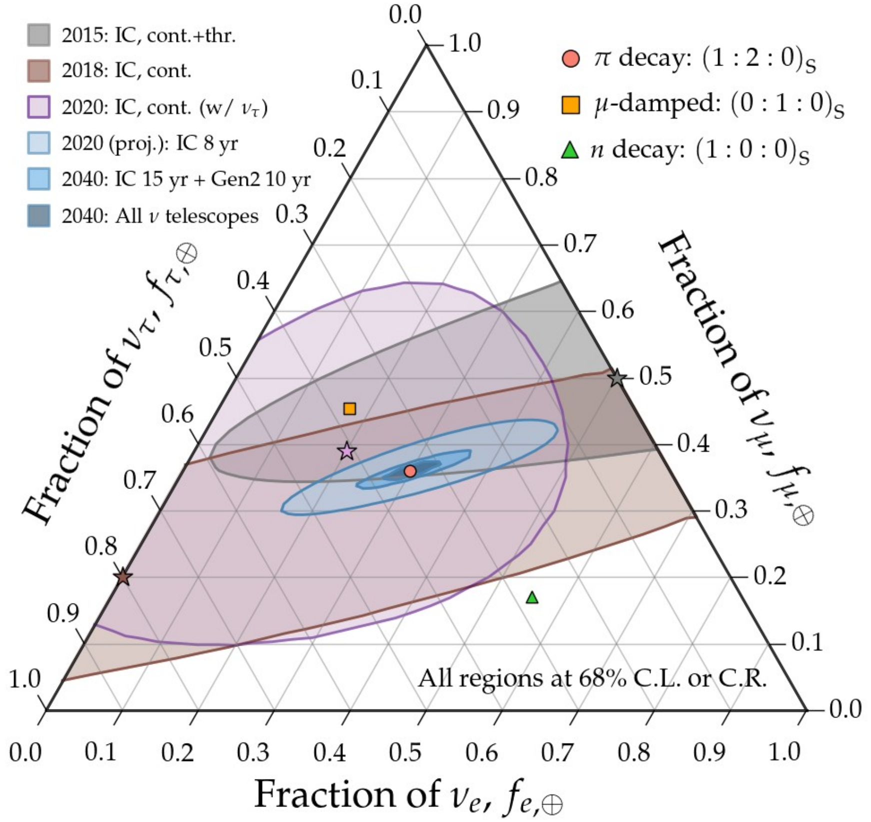
We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

Inferring the flavor composition at the sources

Ingredient #1:

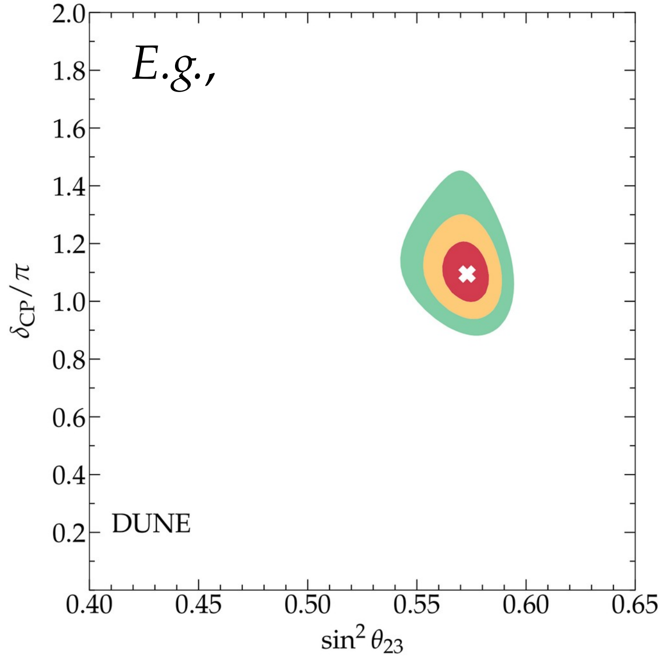
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

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



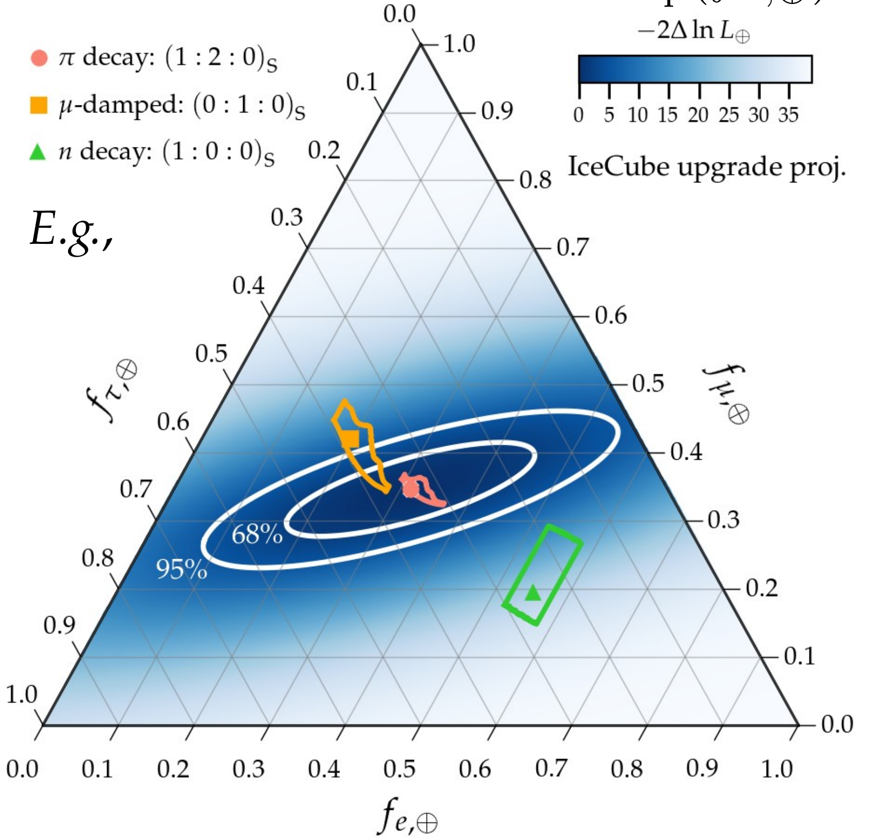
Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$

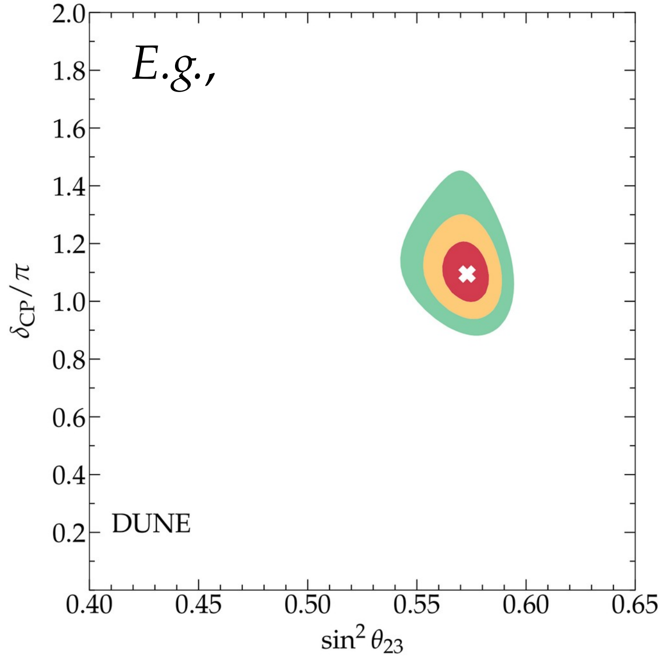
E.g.,



Ingredient #2:
Probability density of mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$

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

E.g.,



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MB & Ahlers, *PRL* 2019

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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

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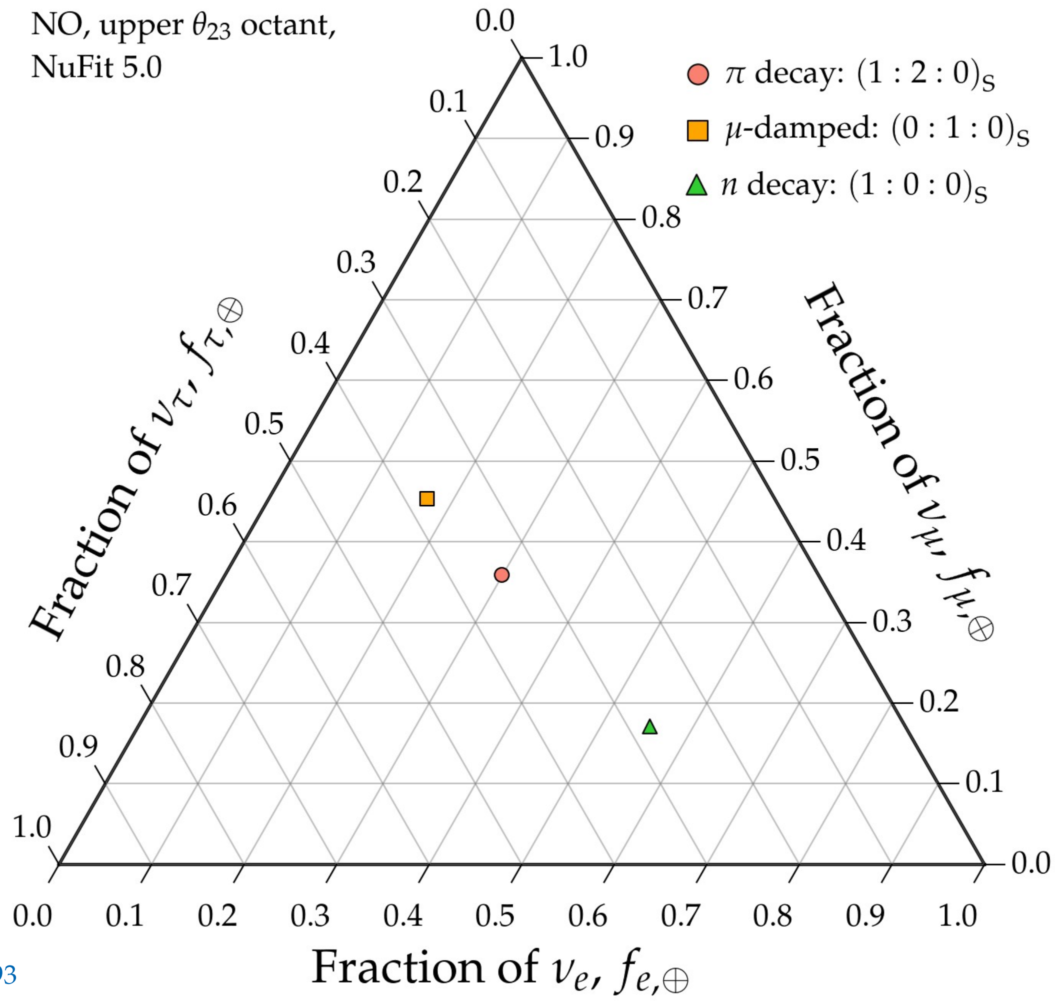
Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

Theoretically palatable regions: today (2020)



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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

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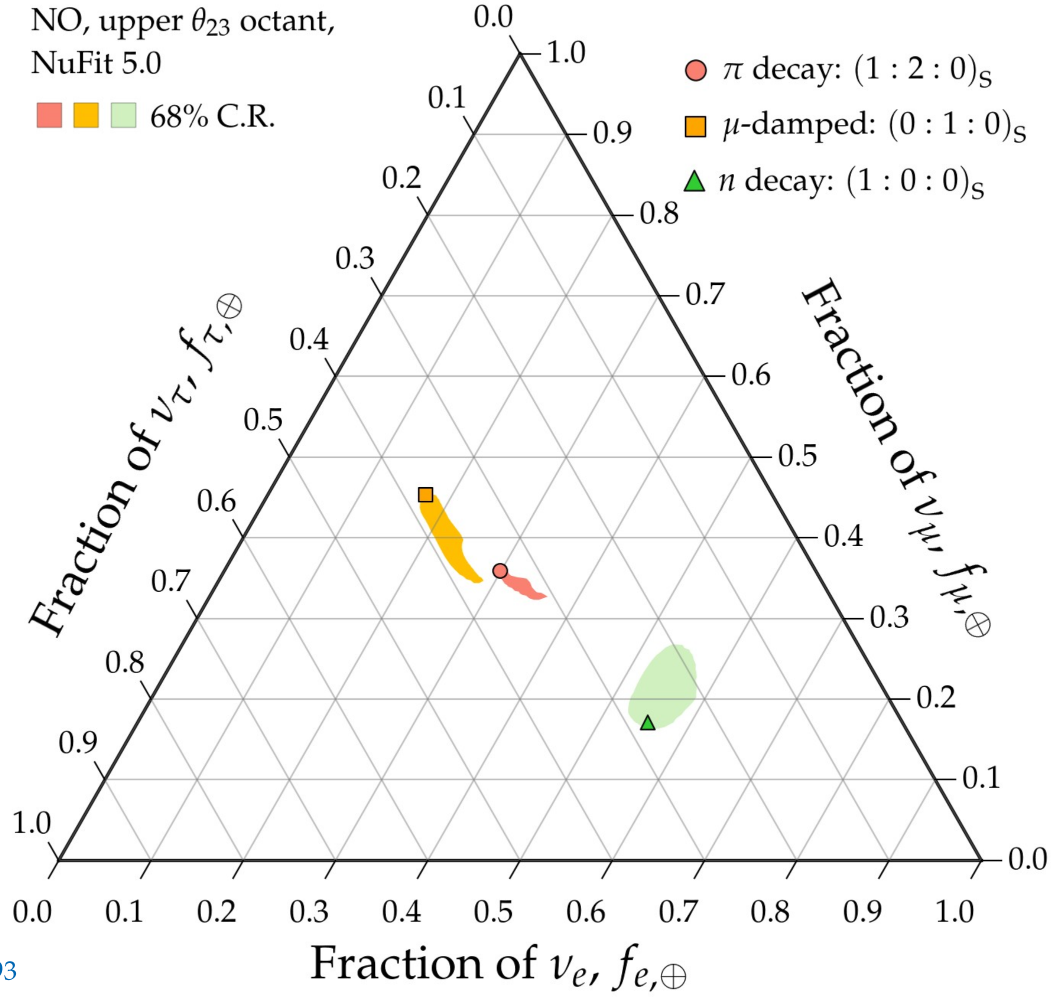

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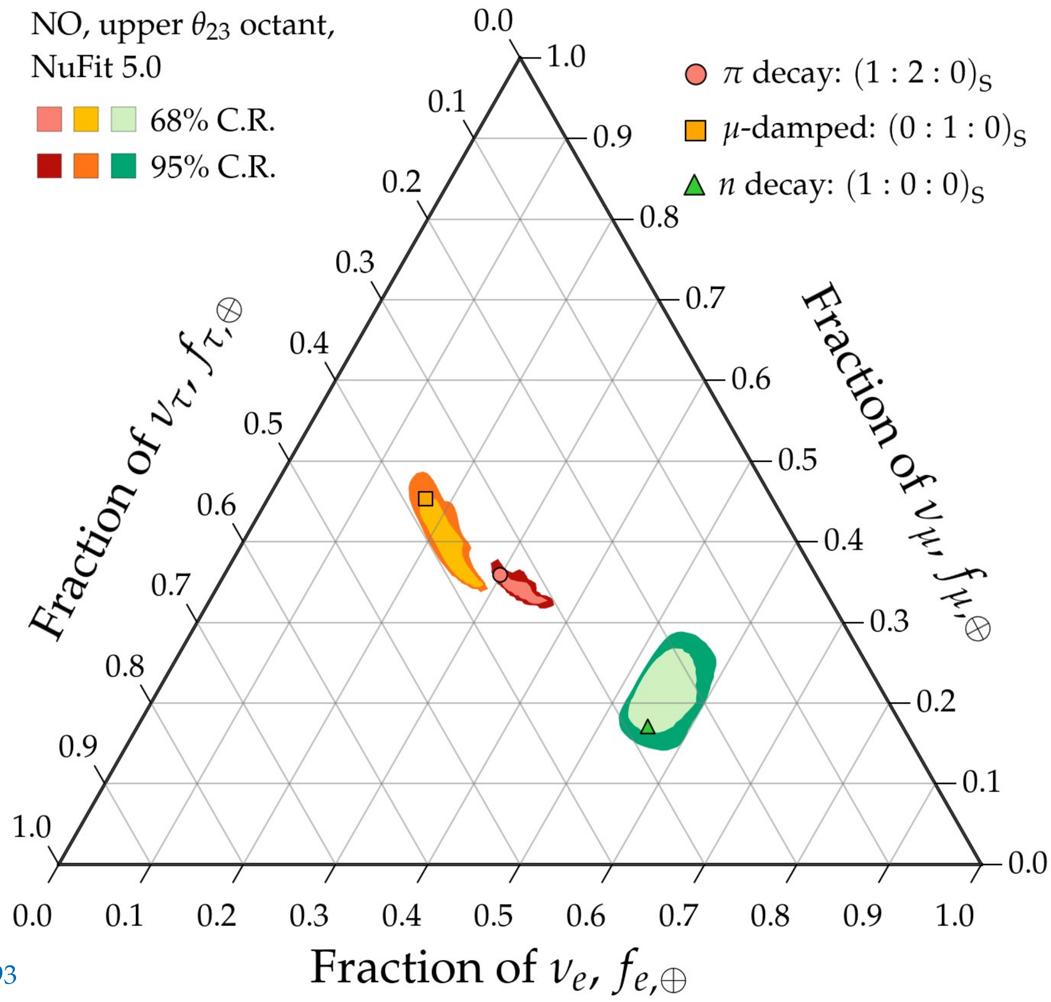

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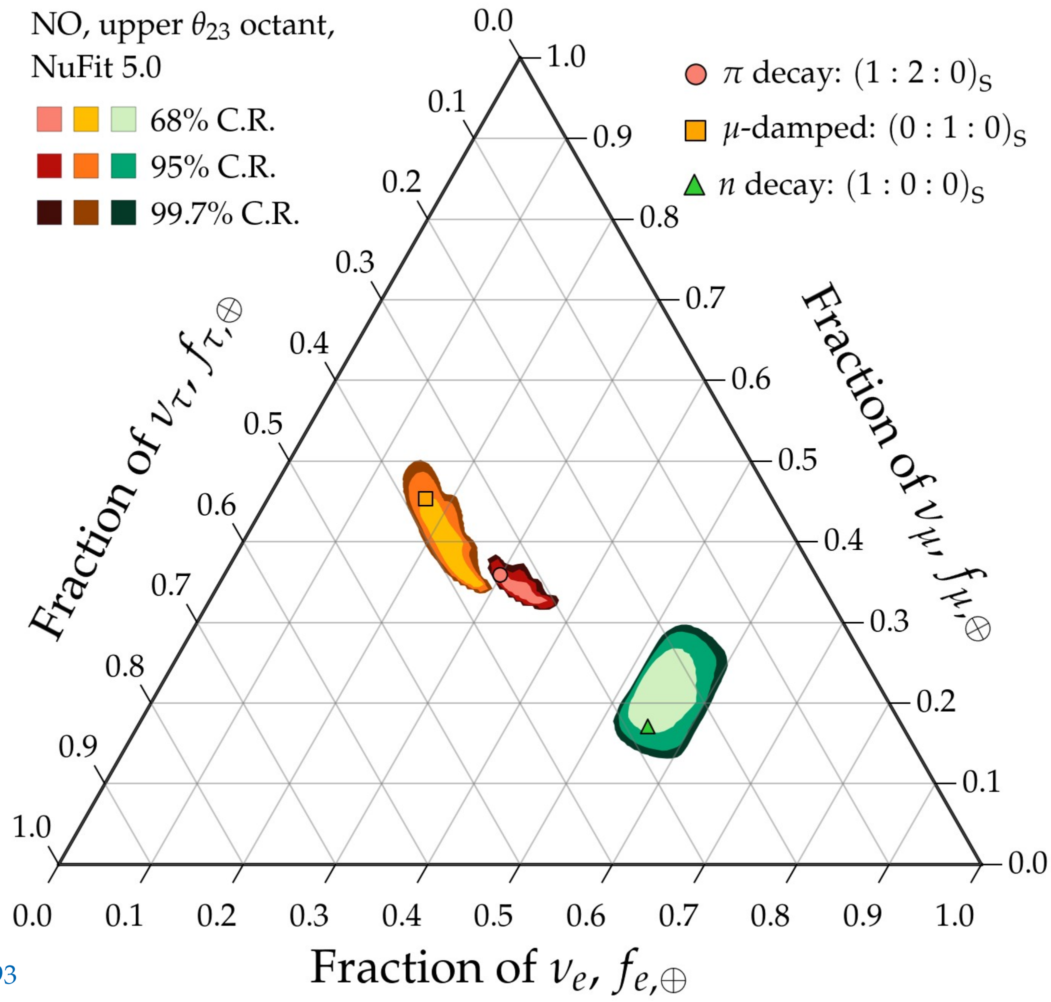

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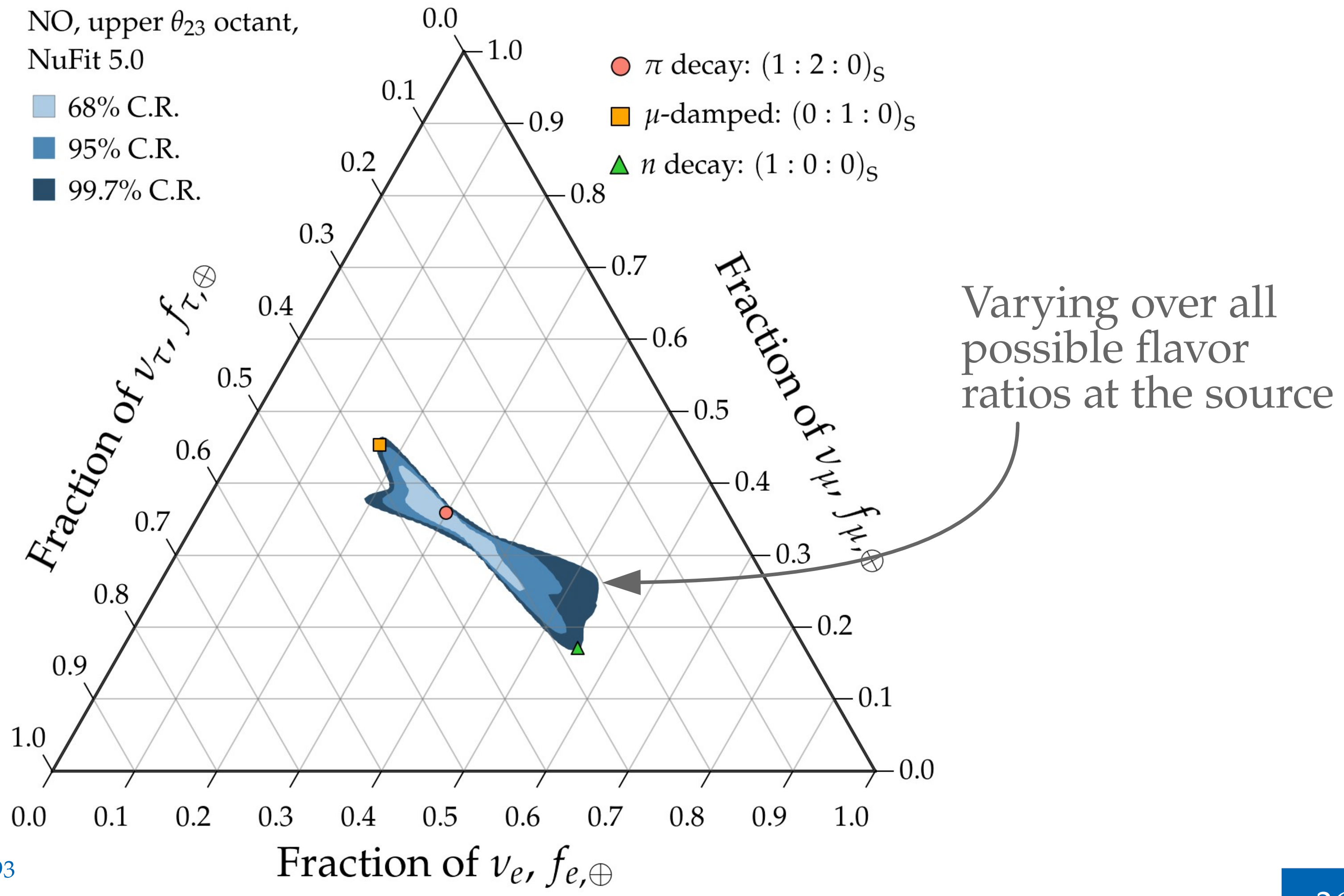

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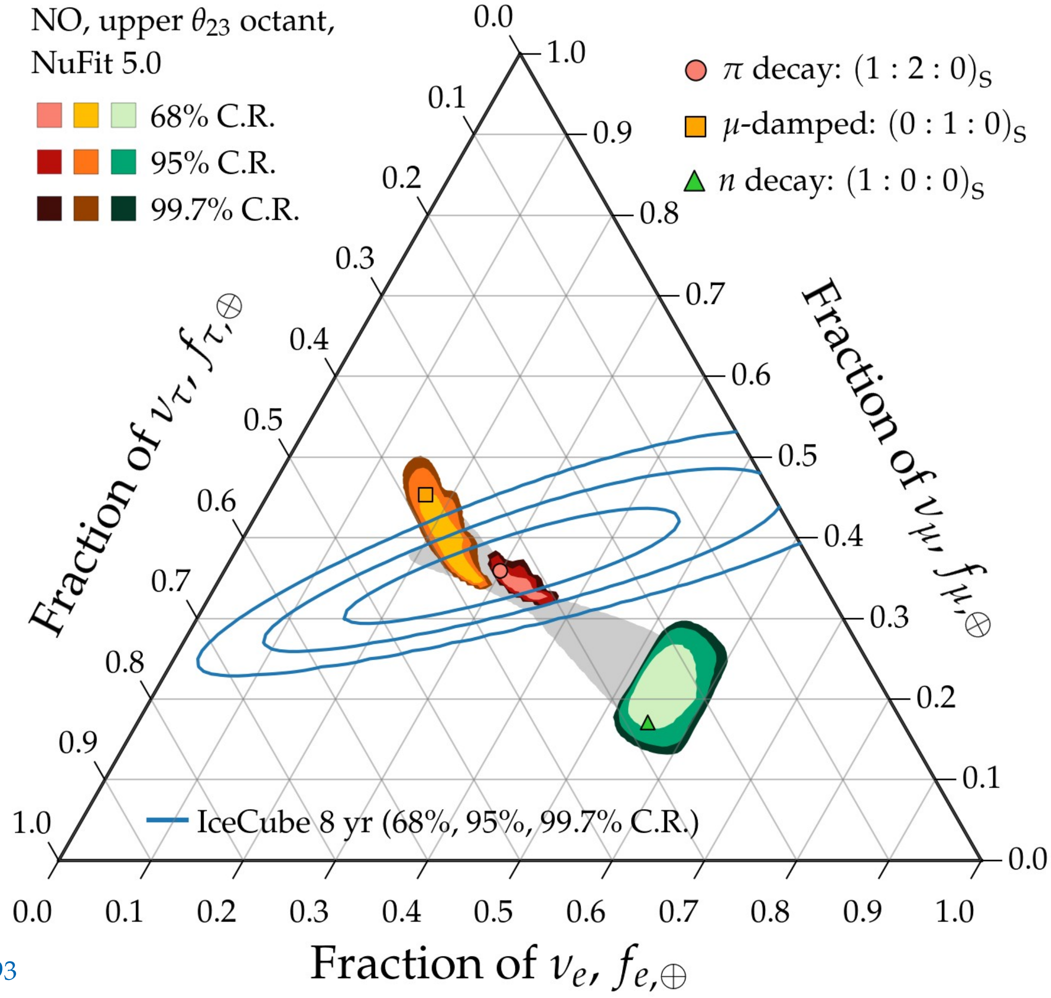

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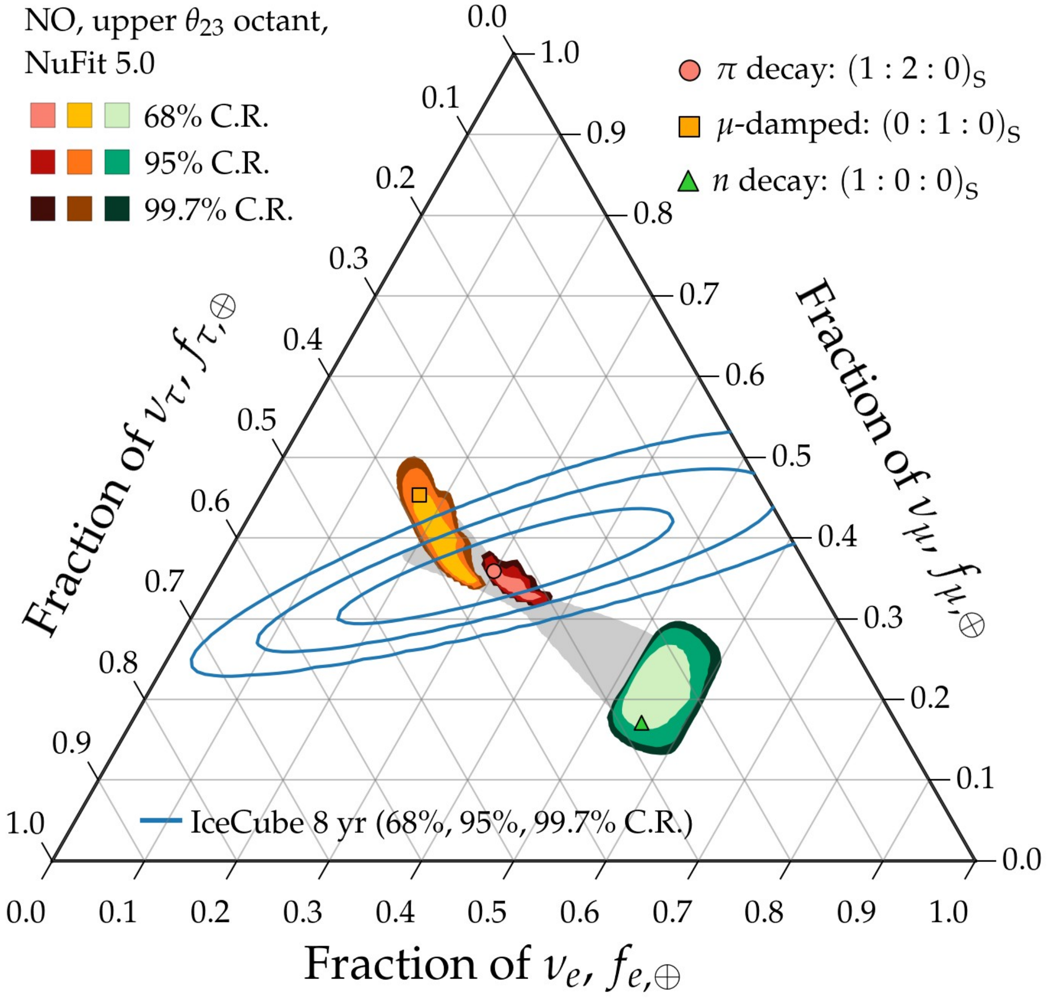

Two limitations:

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)

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
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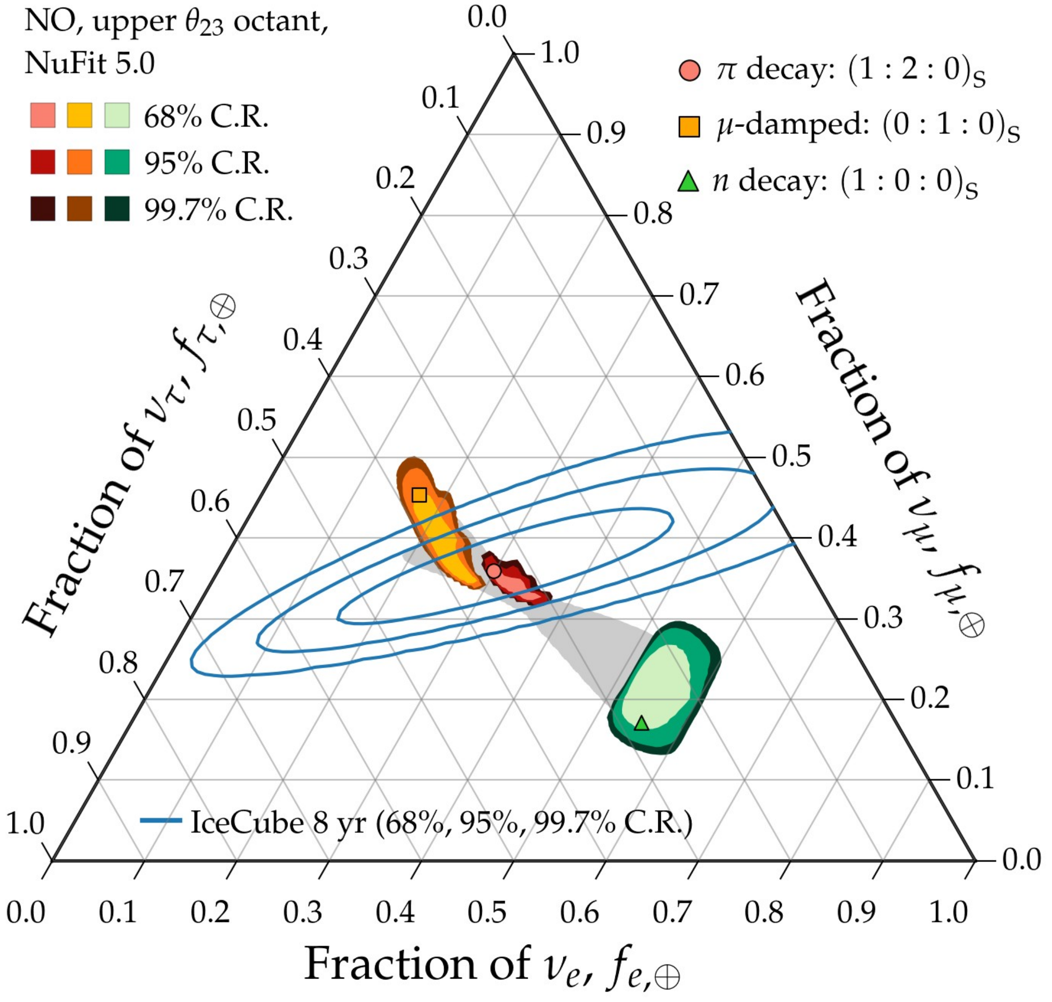
Theoretically palatable regions: today (2020)



Two limitations:

Allowed flavor regions overlap –
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Will be overcome by 2030

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See also: **MB**, Beacom, Winter, *PRL* 2015

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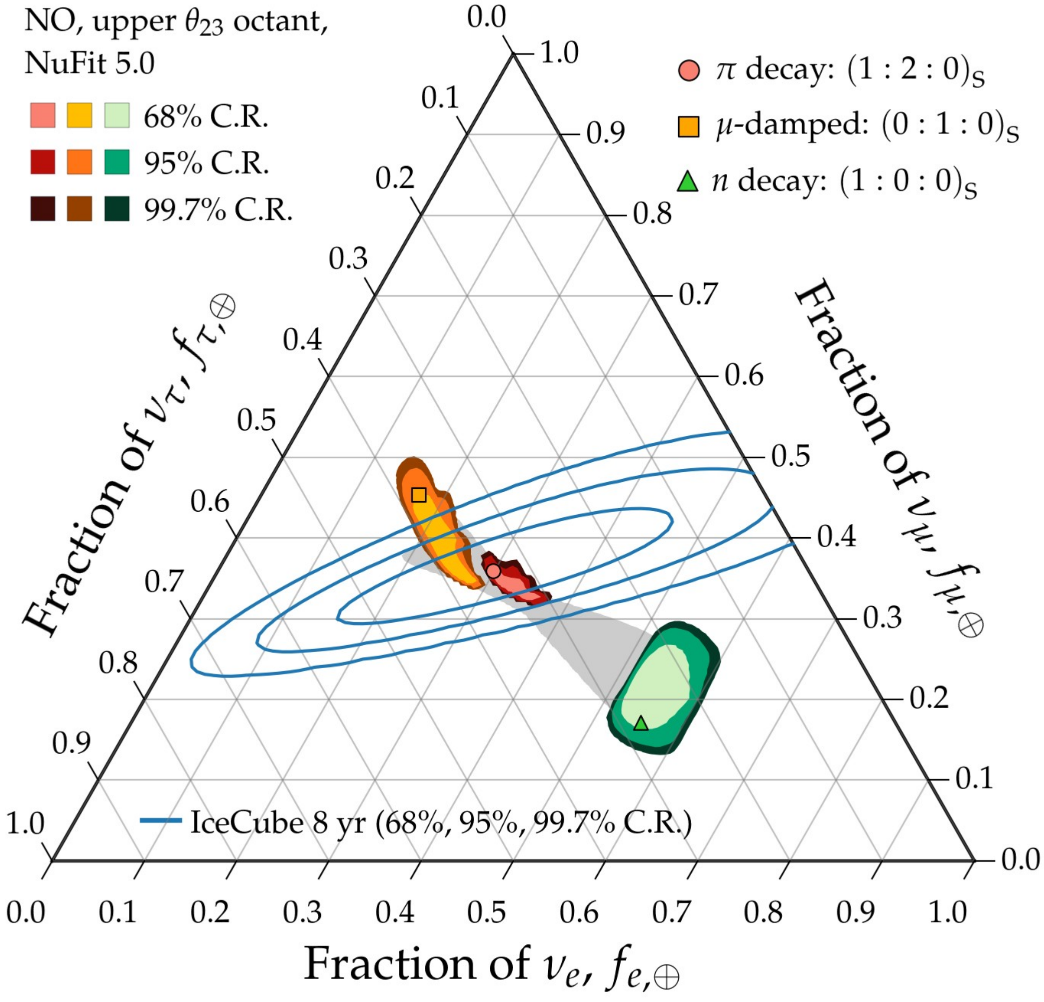

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Measurement of flavor ratios –
Cannot distinguish between pion-decay and muon-damped benchmarks even at 68% C.R. (1σ)

Will be overcome by 2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

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

≡

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Allowed regions of flavor ratios at Earth derived from oscillations

Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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Flavor at the Earth: *theoretically palatable regions*

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≡

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Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

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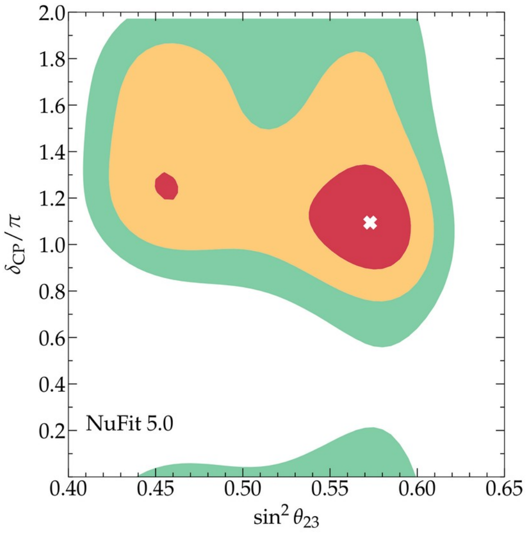
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

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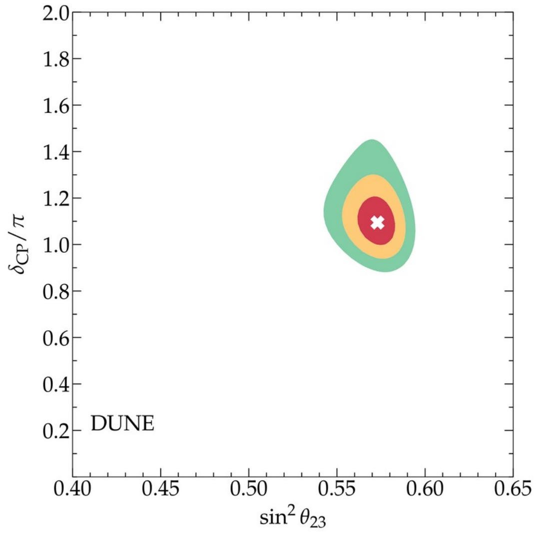
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

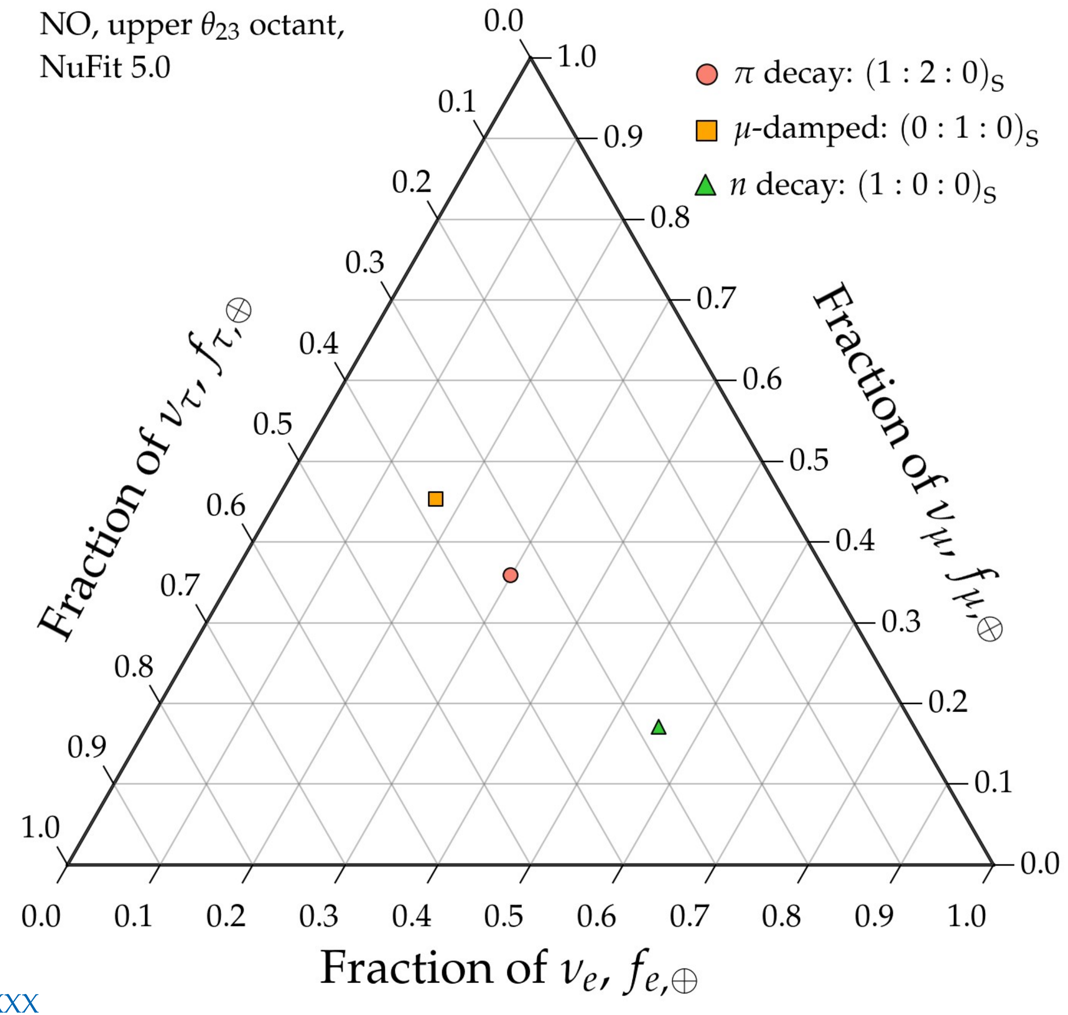
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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



Theoretically palatable regions: today (2020)



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

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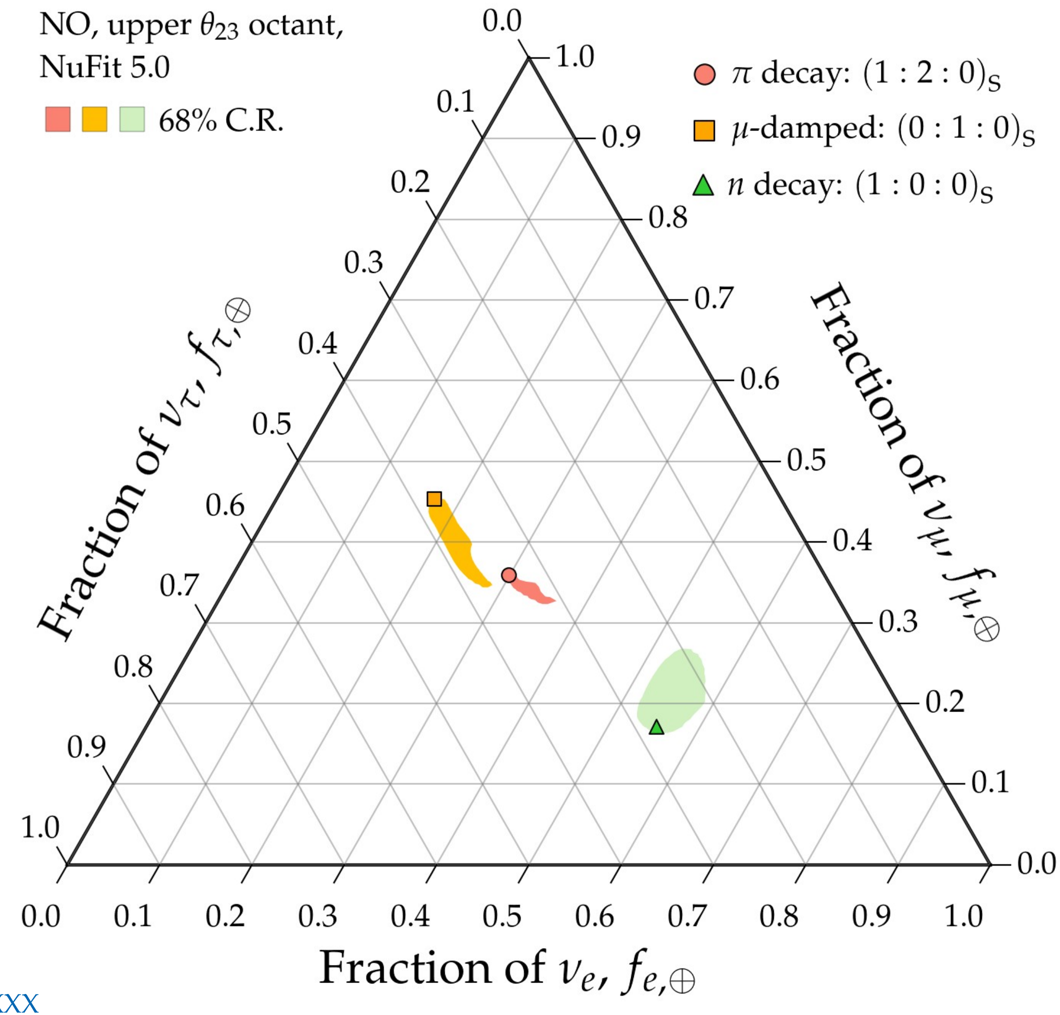

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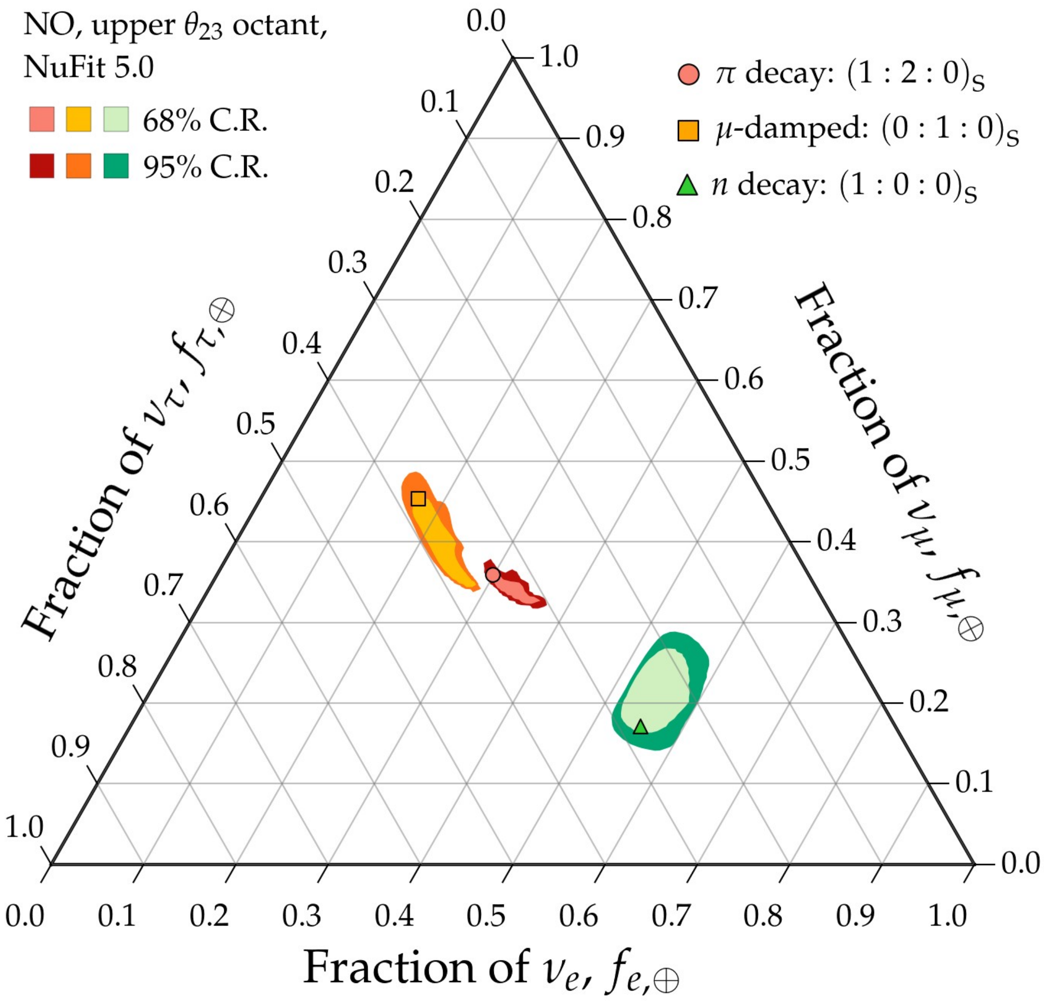

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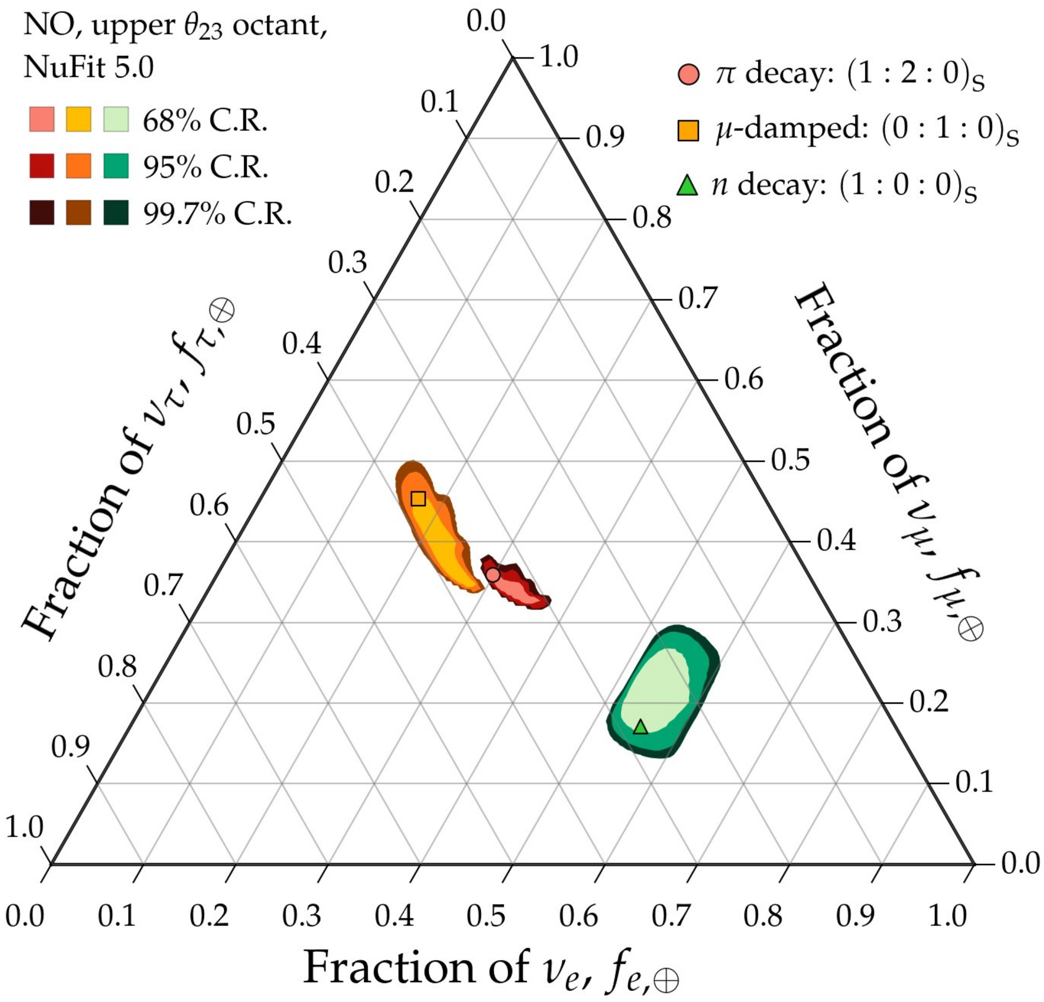

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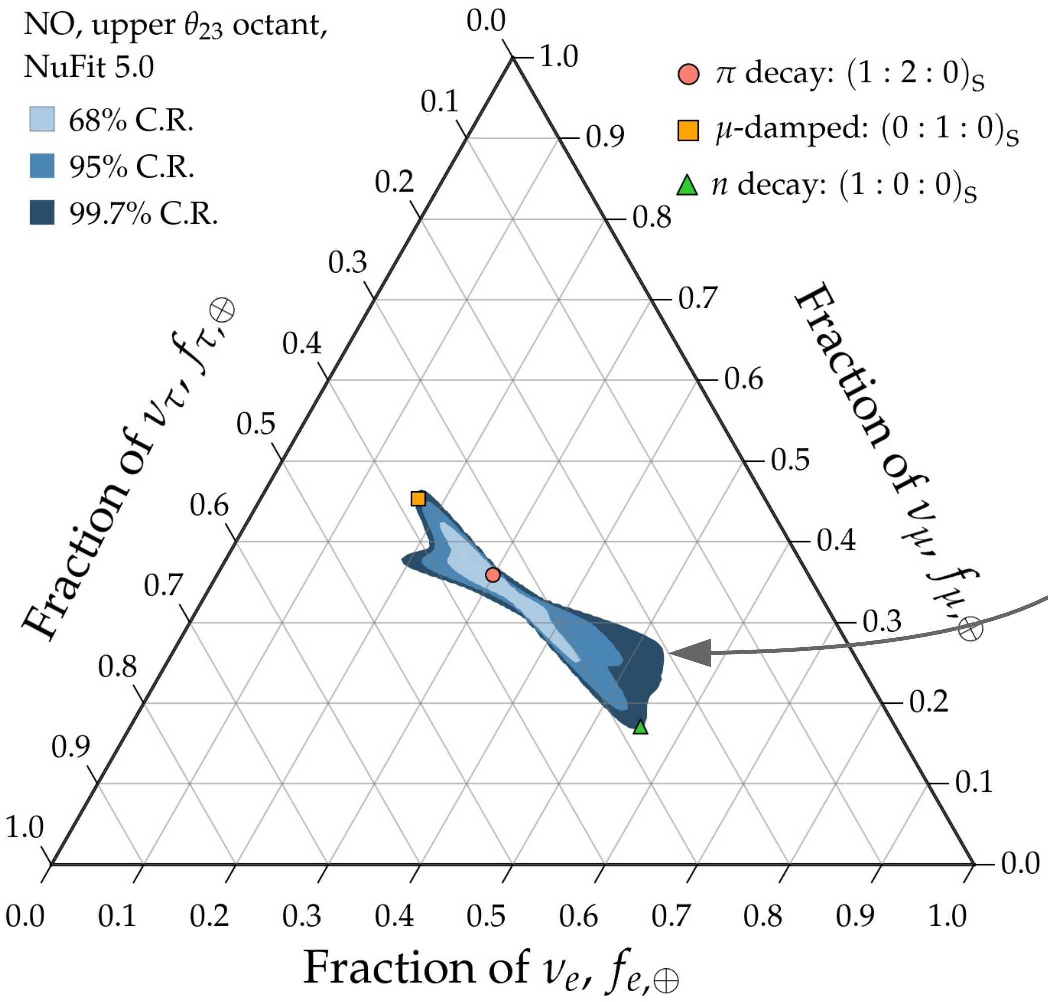

Varying over all possible flavor ratios at the source

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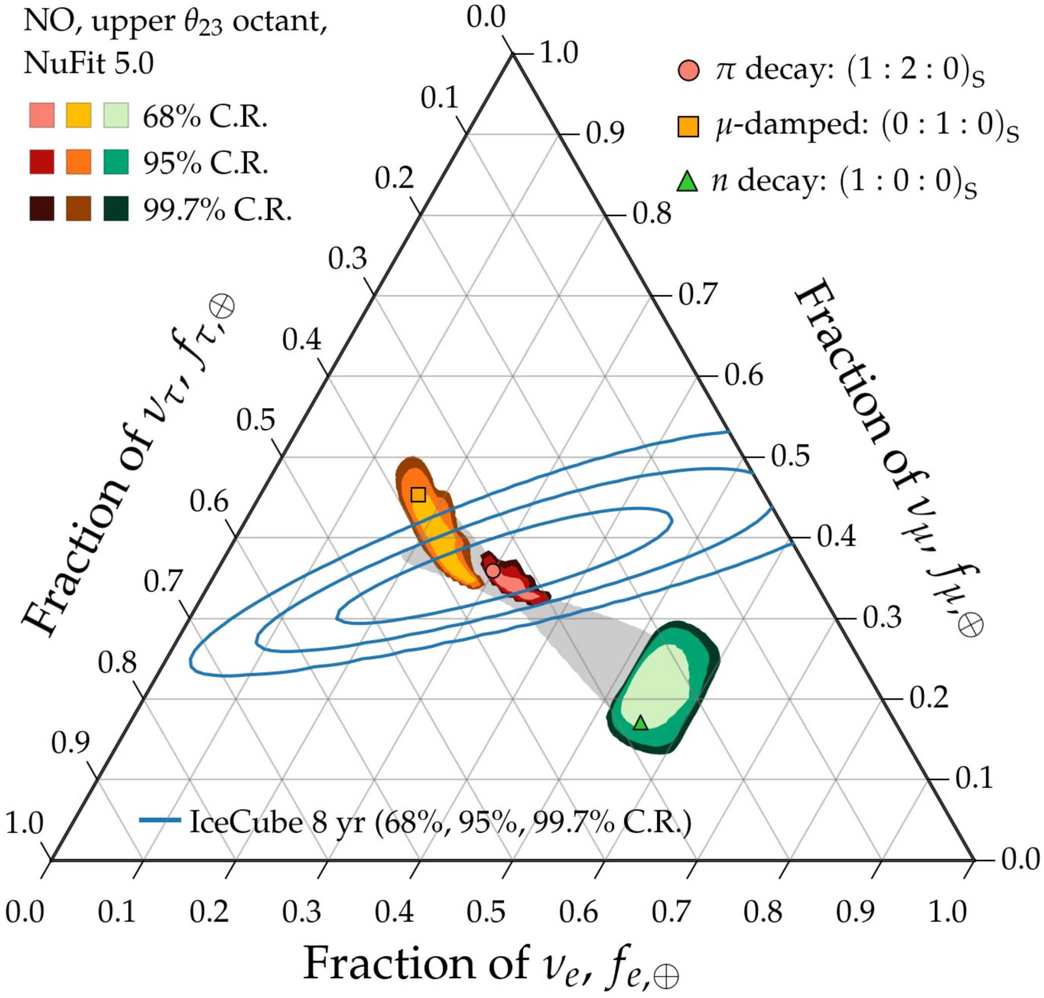
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



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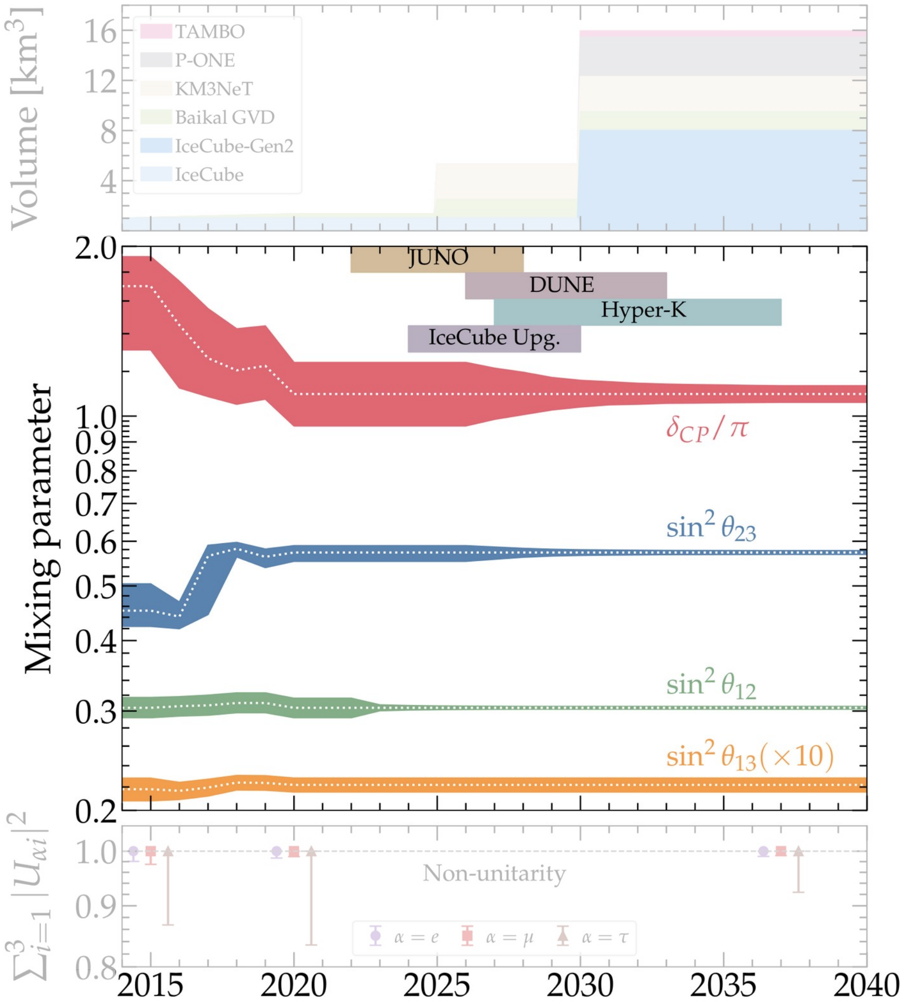
Song, Li, **MB**, Argüelles, Vincent, 2012.X

How knowing the mixing parameters better helps

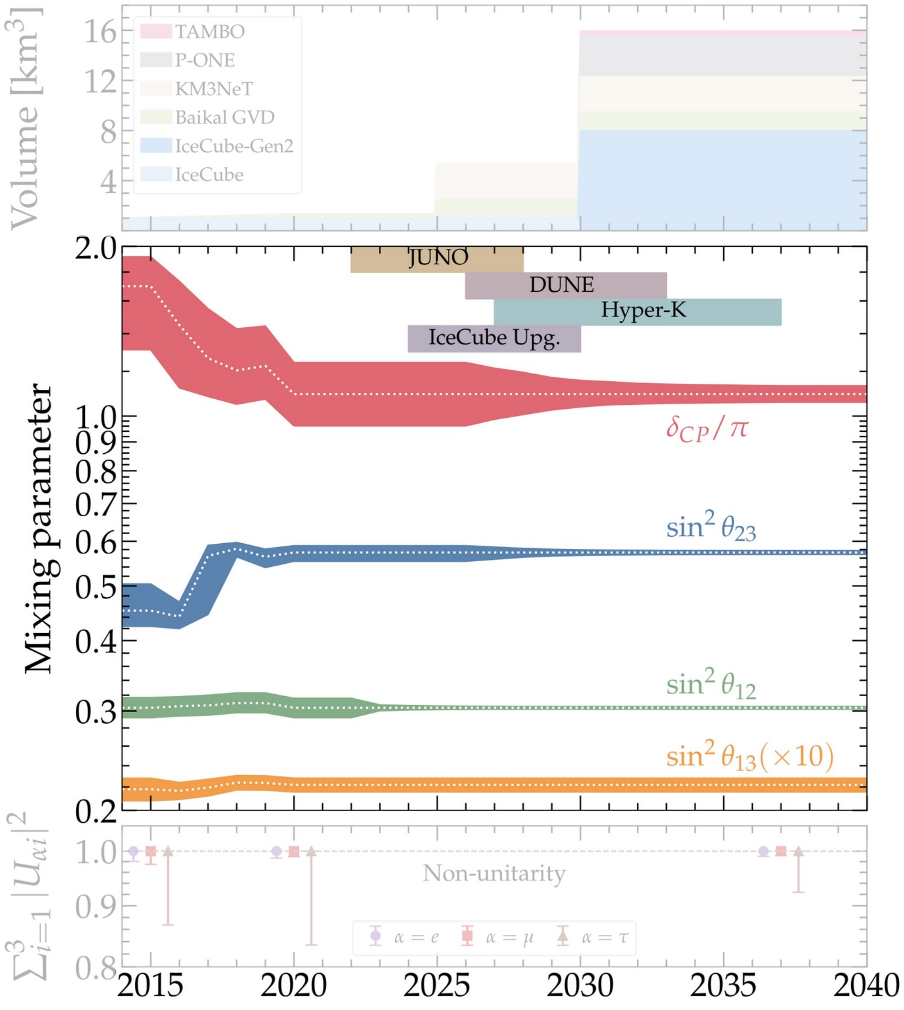


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

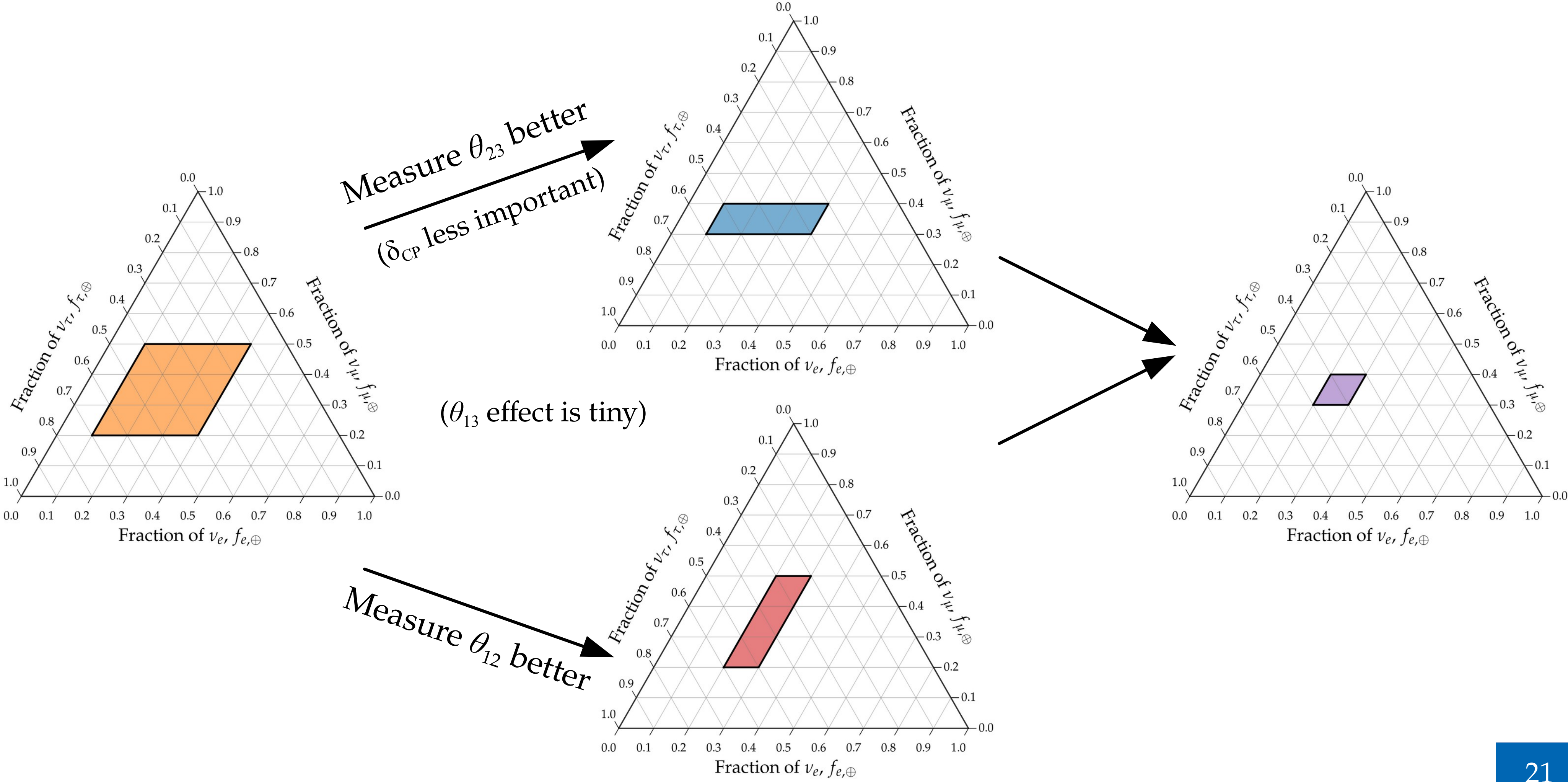
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

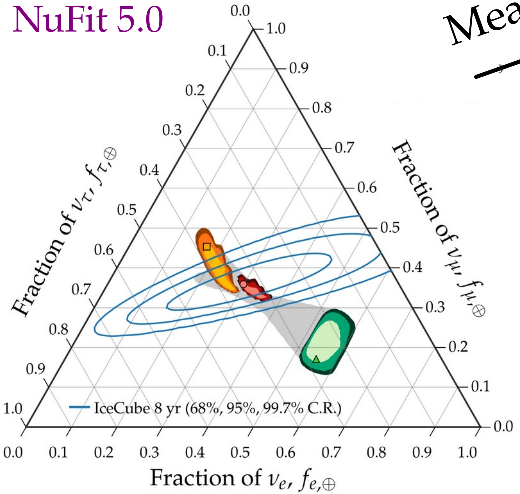
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

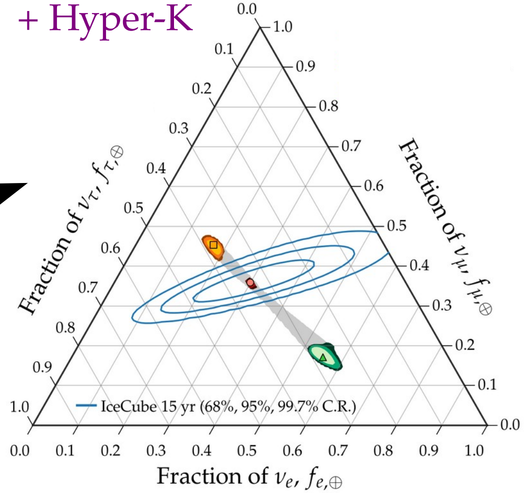
2020

NuFit 5.0



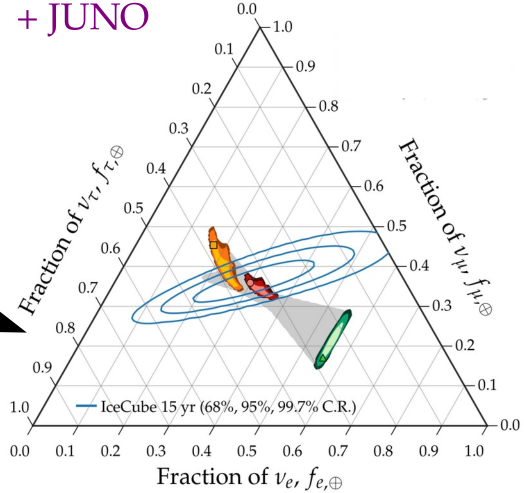
Measure θ_{23} better

+ Hyper-K



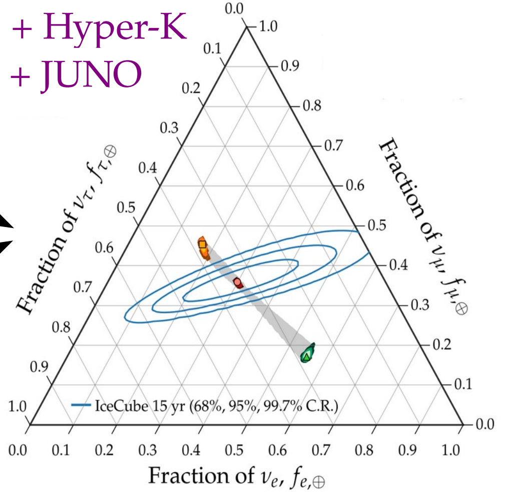
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

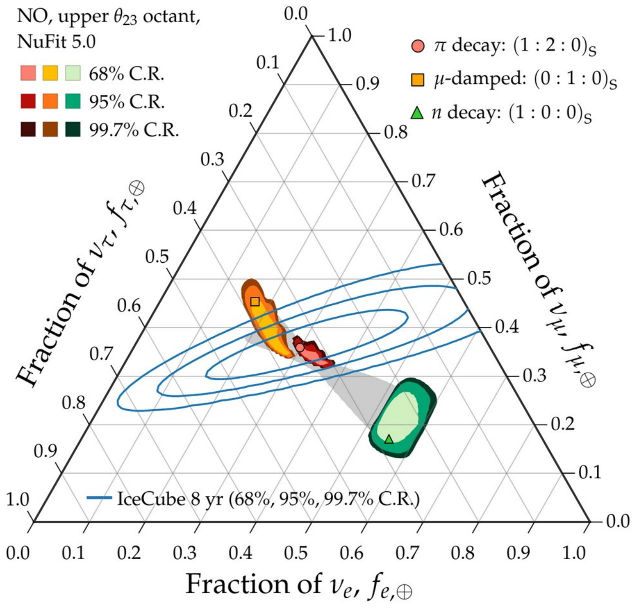
Marginal improvement til 2040

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

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



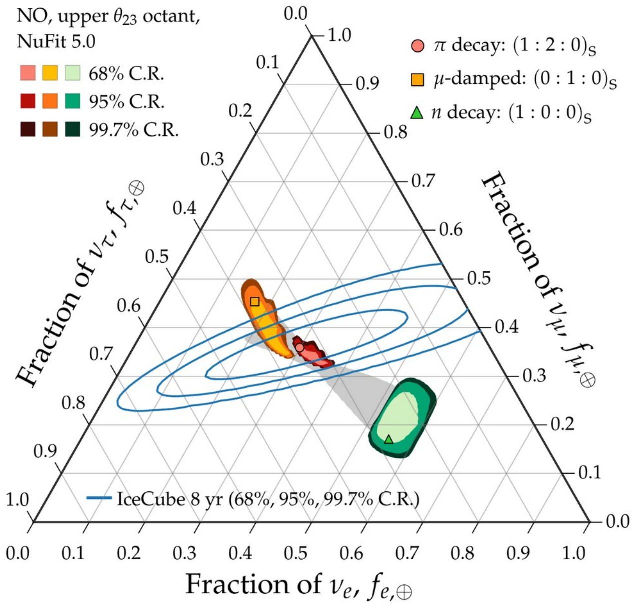
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

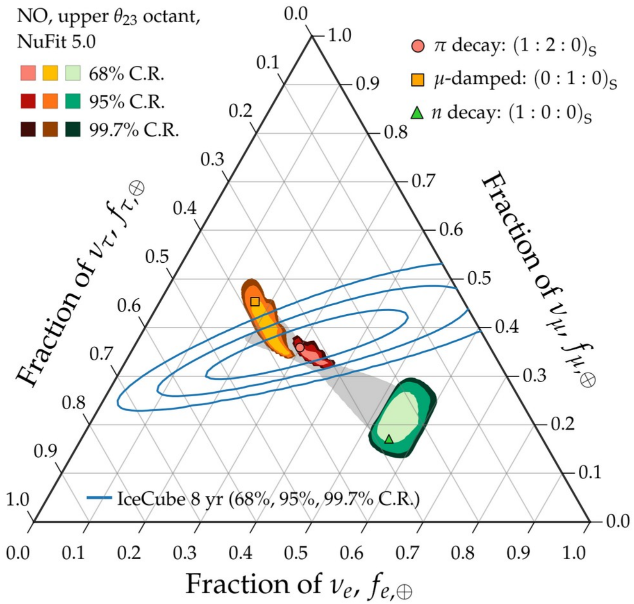
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

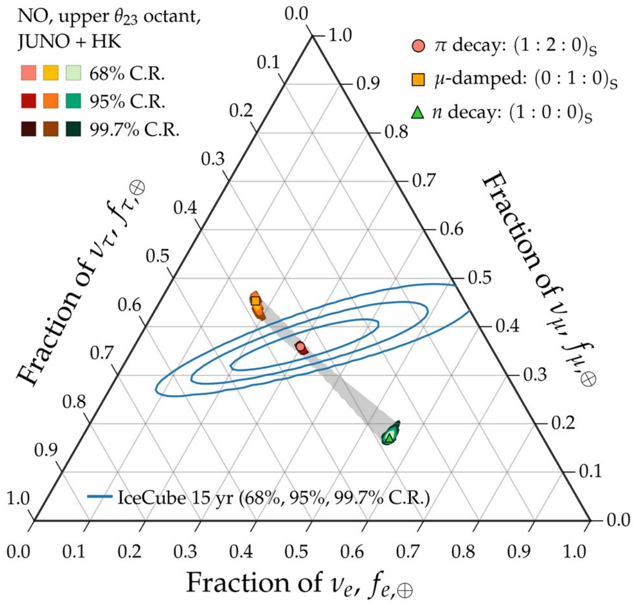


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



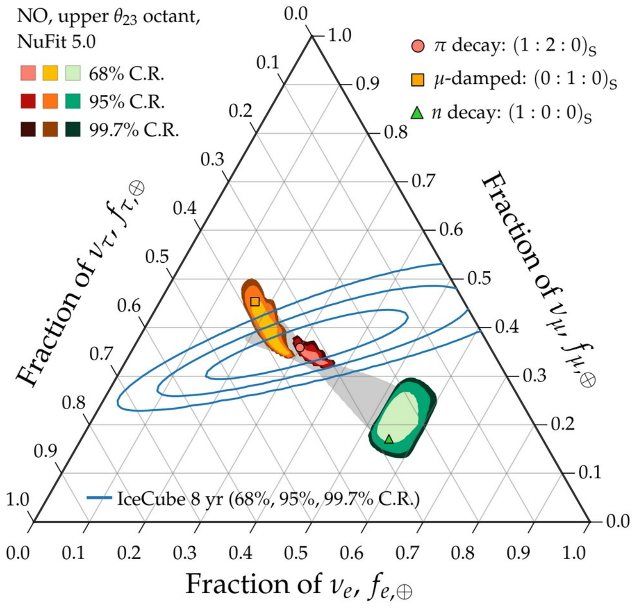
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

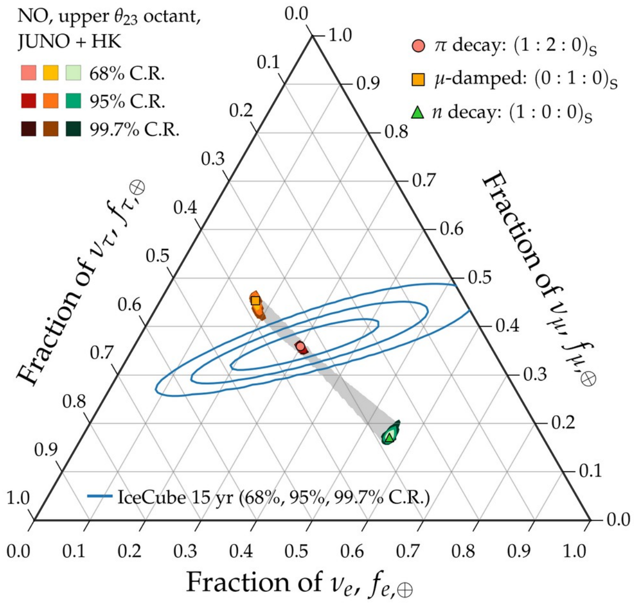


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



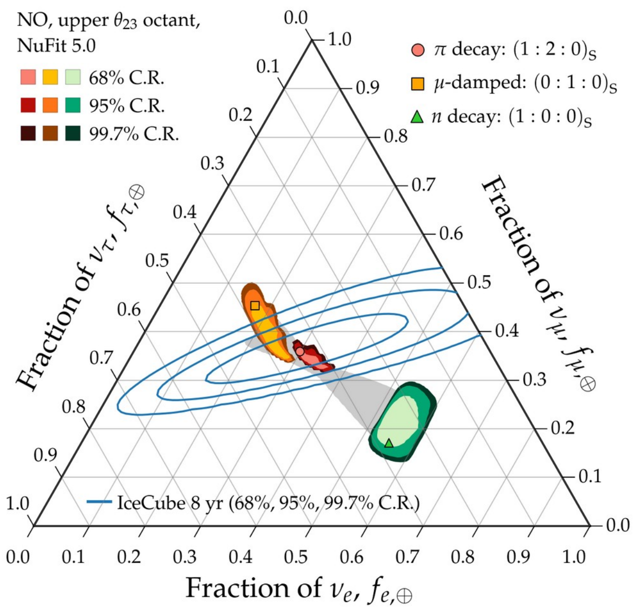
Allowed regions: well separated

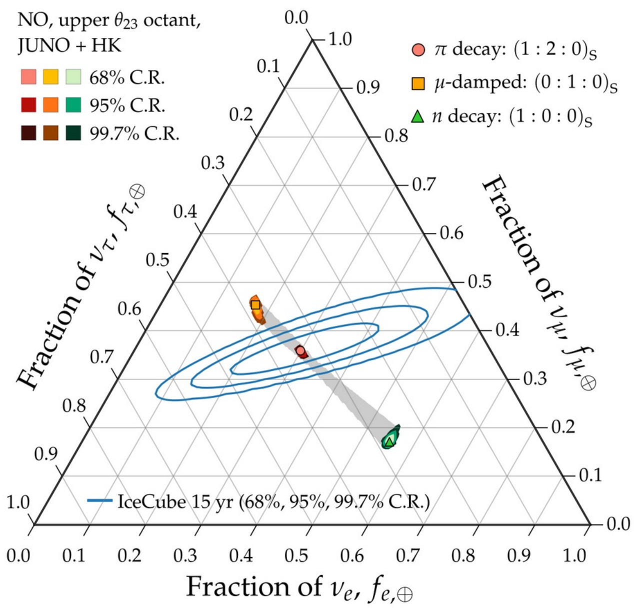
Measurement: improving

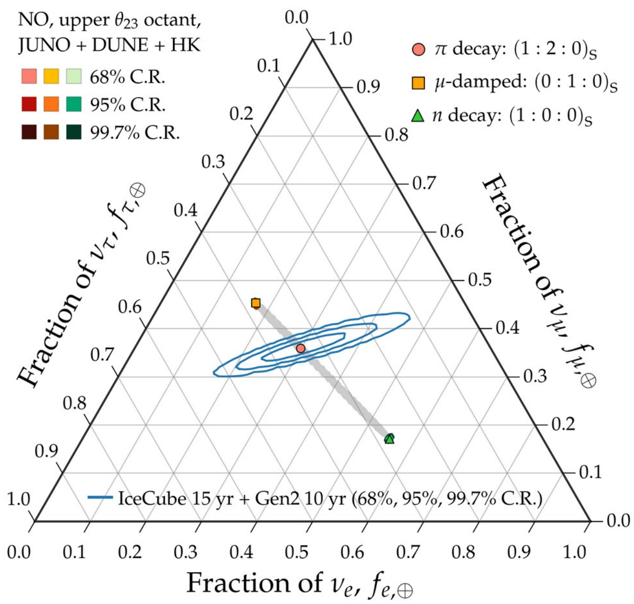
Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040





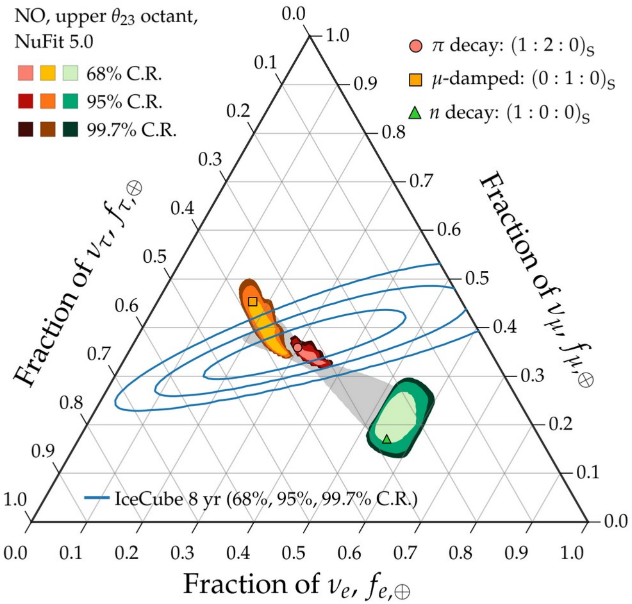


2020	2030	2040
Allowed regions: overlapping	Allowed regions: well separated	Allowed regions: well separated
Measurement: imprecise	Measurement: improving	Measurement: precise
Not ideal	*Nice*	

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

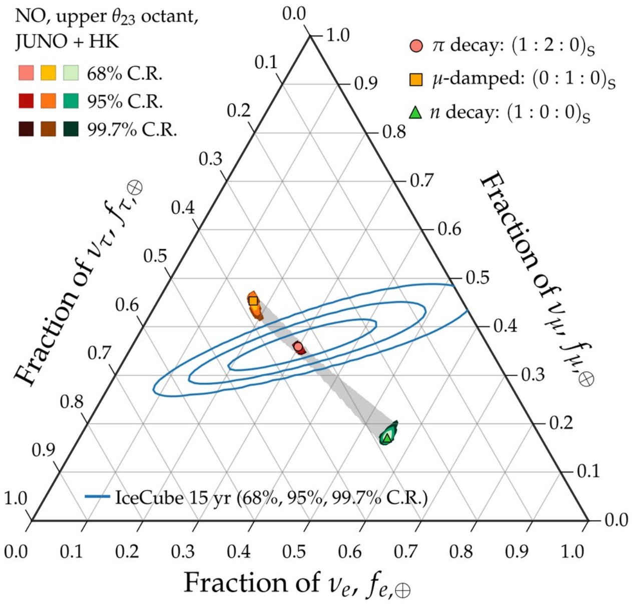


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

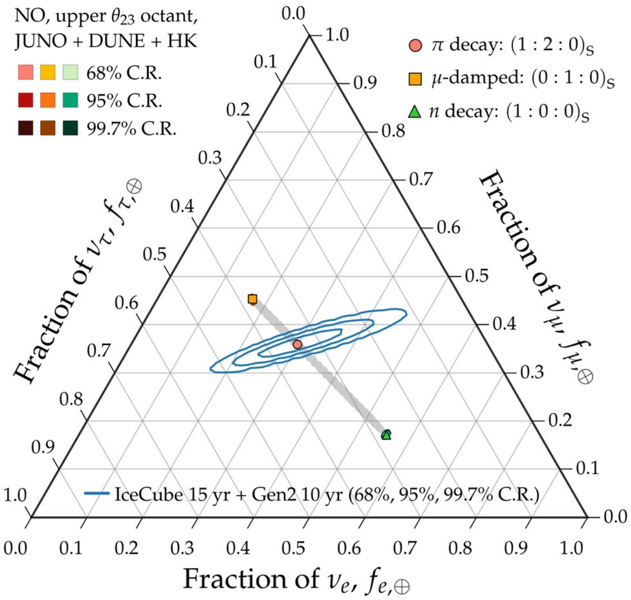


Allowed regions: well separated

Measurement: improving

Nice

2040



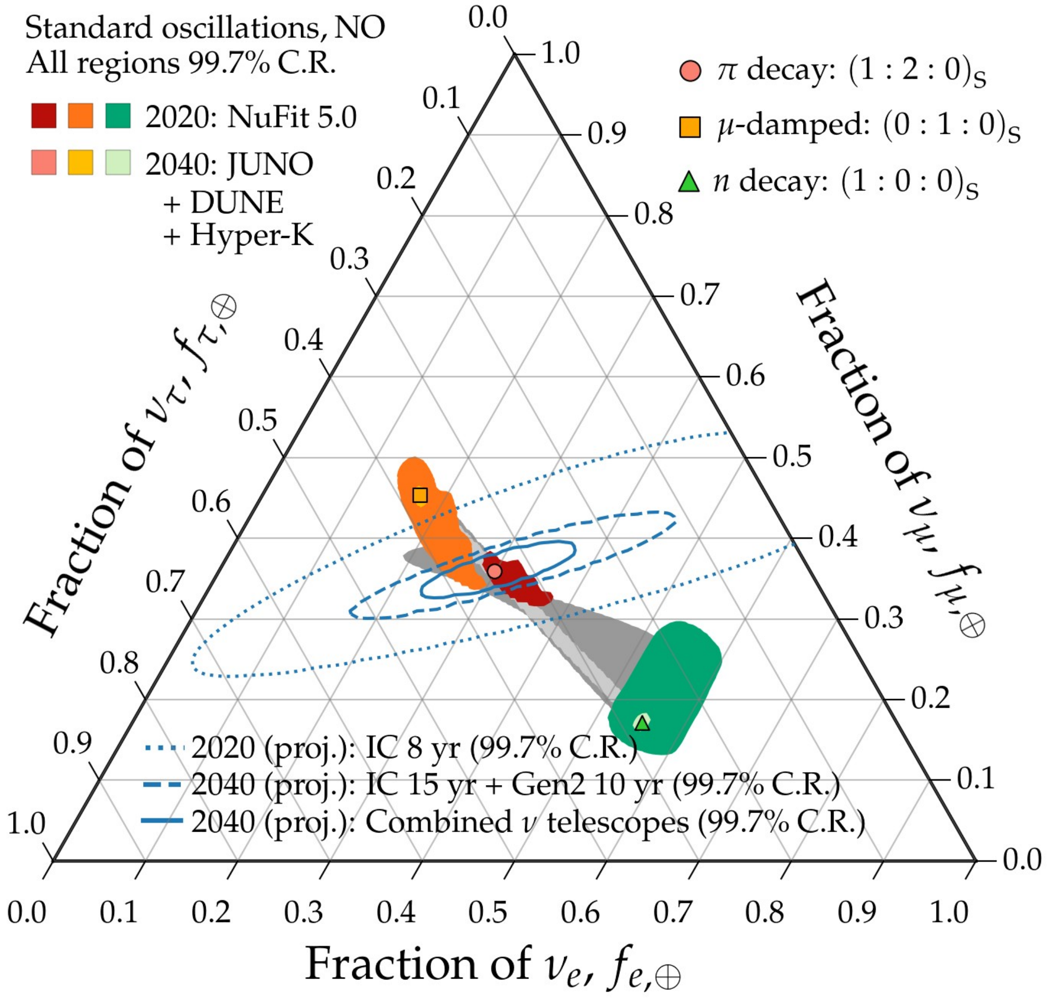
Allowed regions: well separated

Measurement: precise

Success

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

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

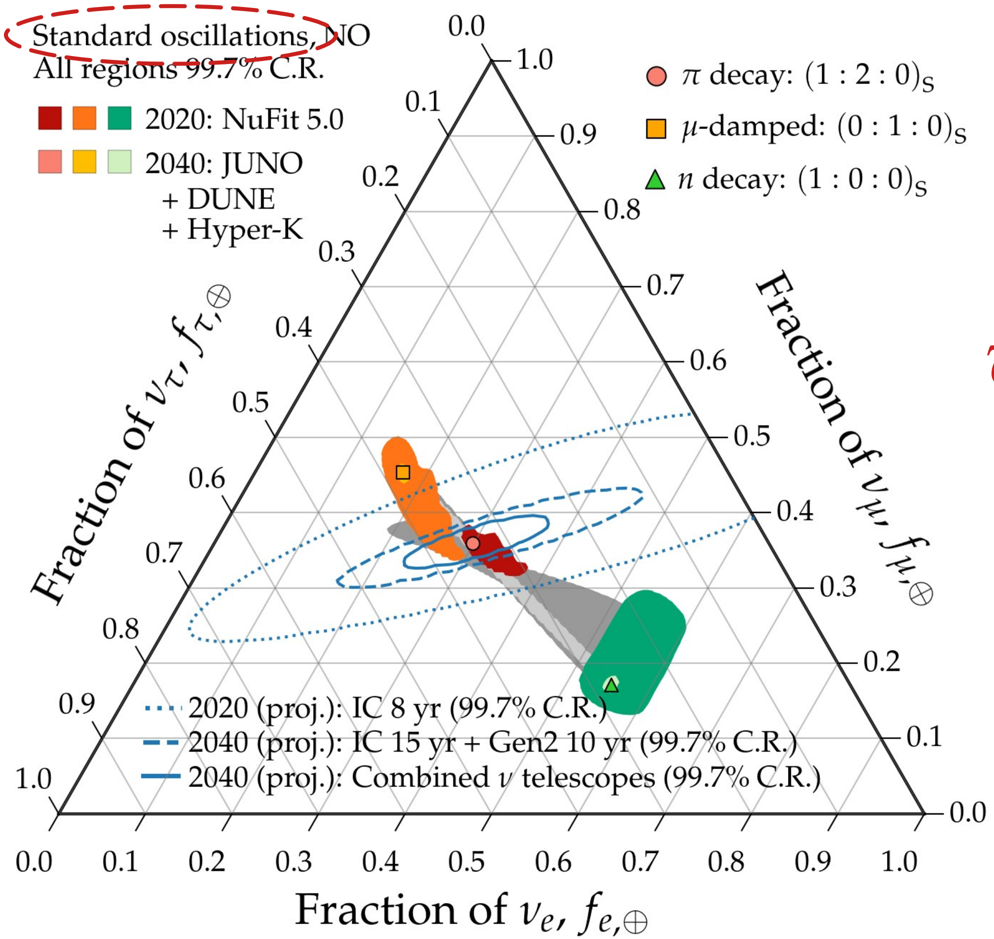
Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

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

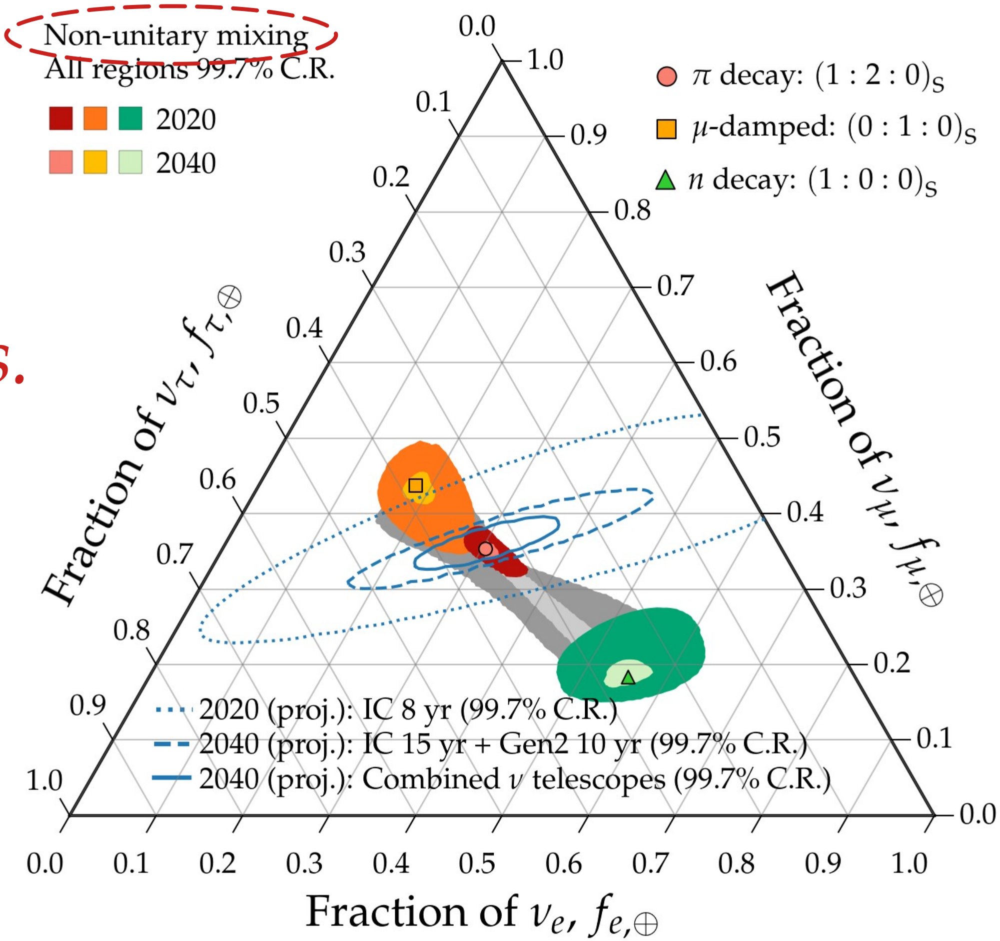
Can finally use the full power of flavor composition for astrophysics and neutrino physics

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

No unitarity? *No problem*



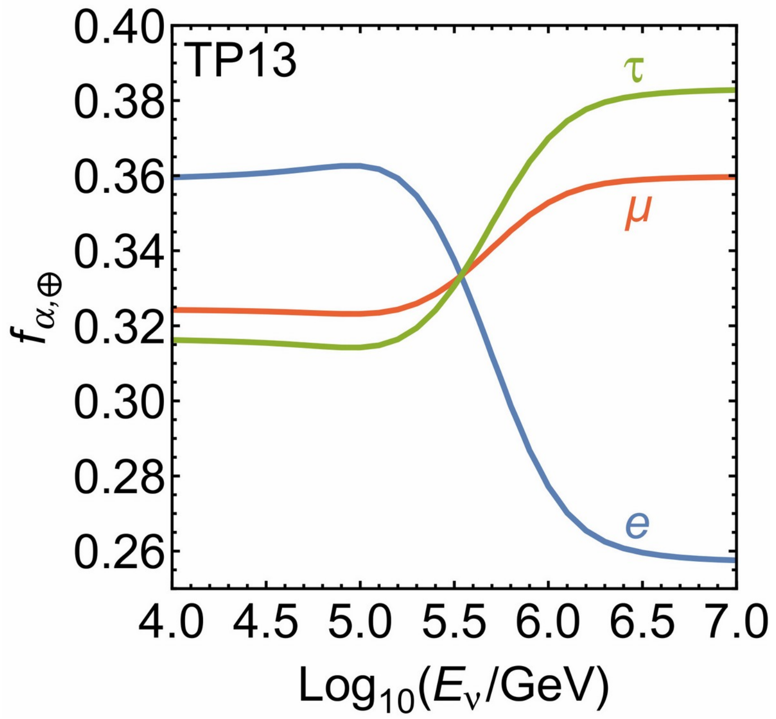
vs.

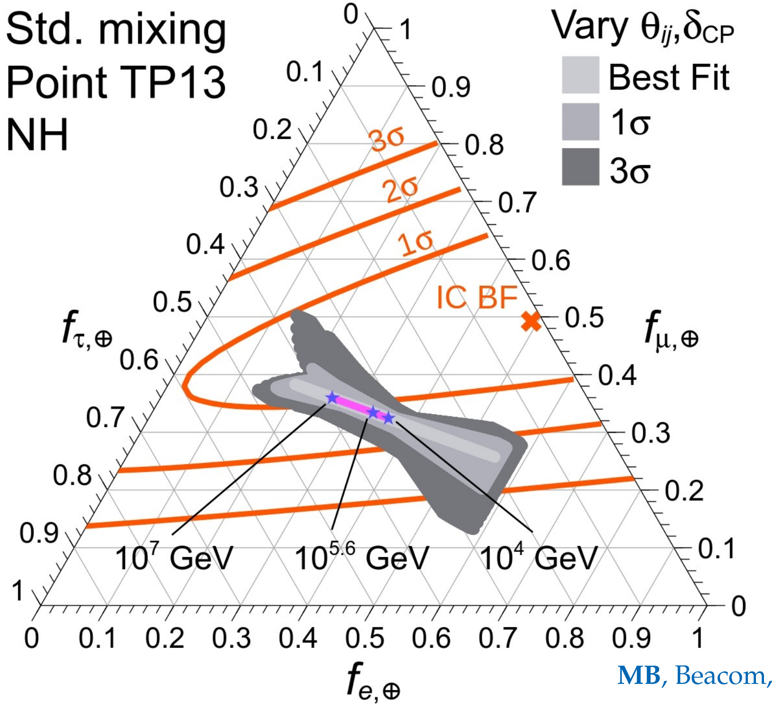


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



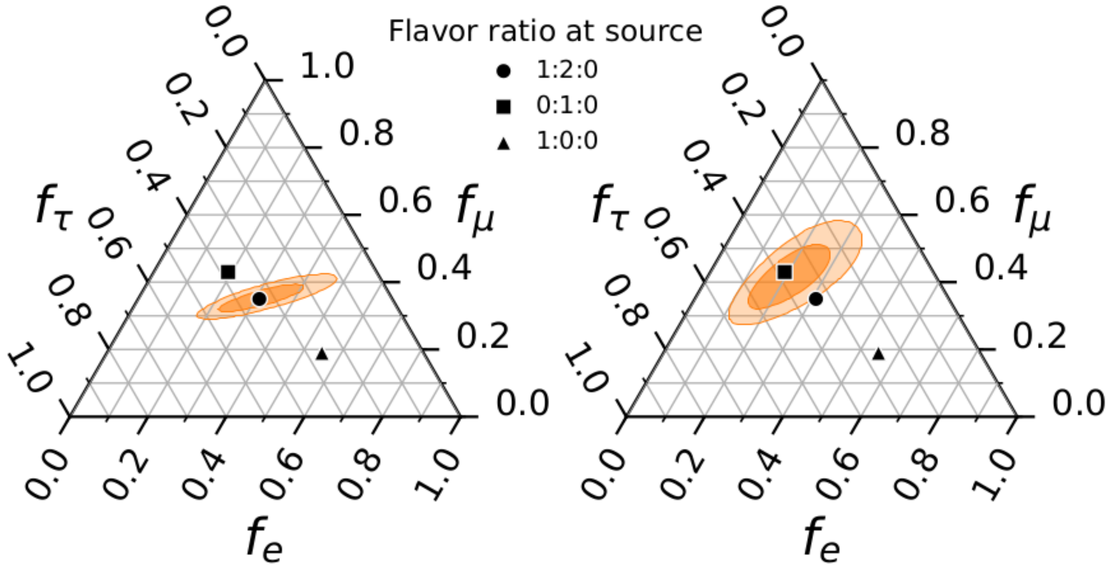


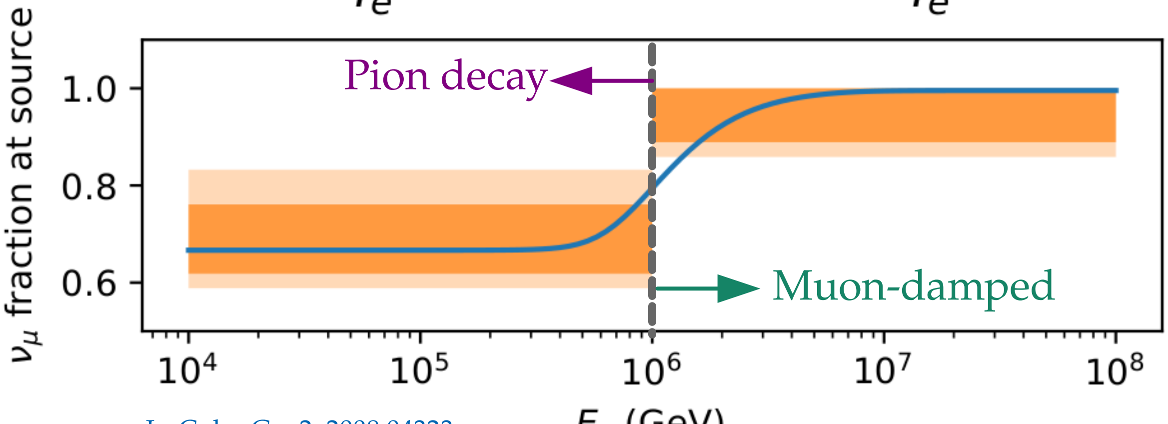
MB, Beacom, Winter, *PRL* 2015

- TP13: $p\gamma$ model, target photons from e^-e^+ annihilation [Hümmer+, *Astropart. Phys.* 2010]
- Will be difficult to resolve [Kashti, Waxman, *PRL* 2005; Lipari, Lusignoli, Meloni, *PRD* 2007]

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:





IceCube-Gen2, 2008.04323

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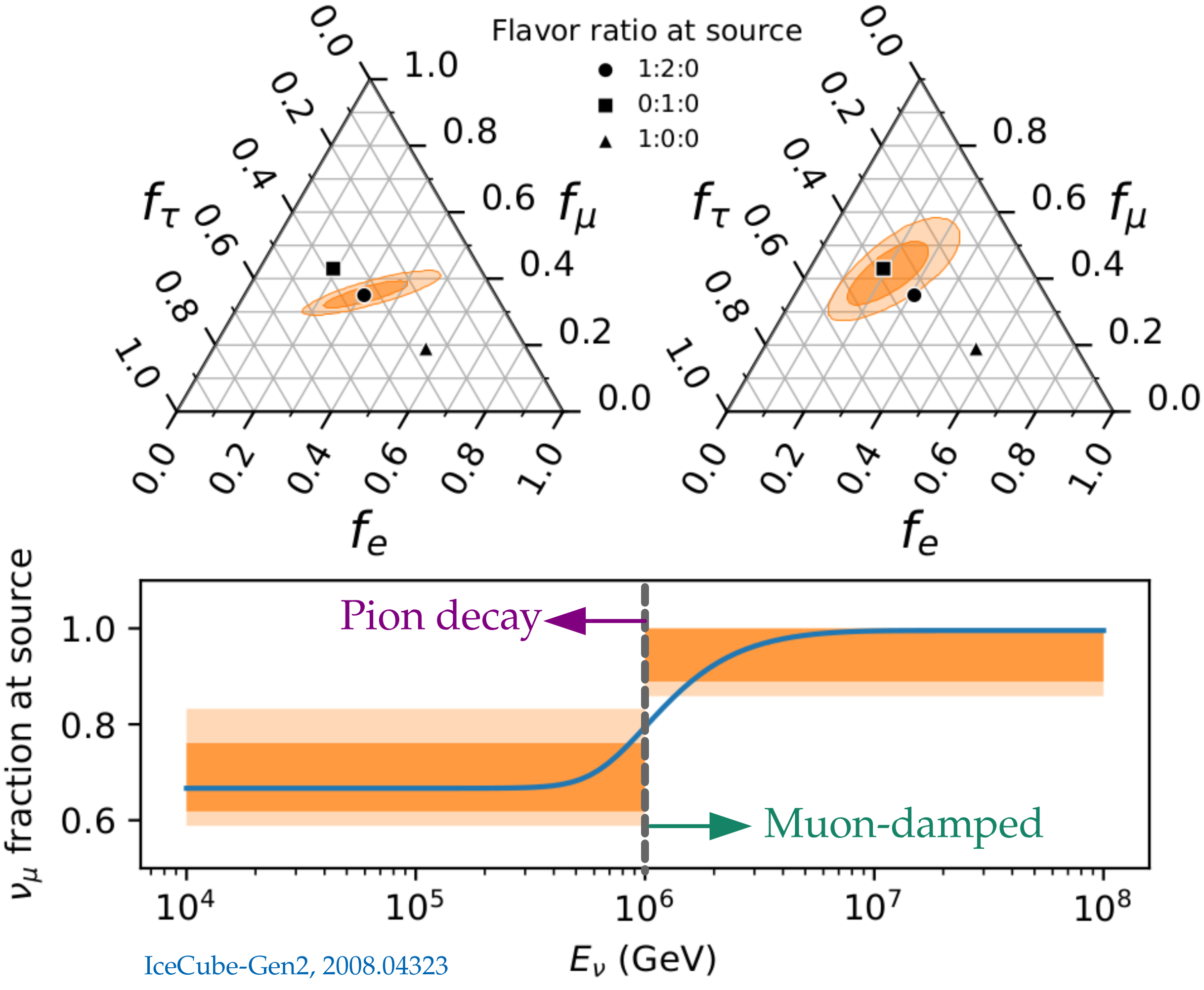
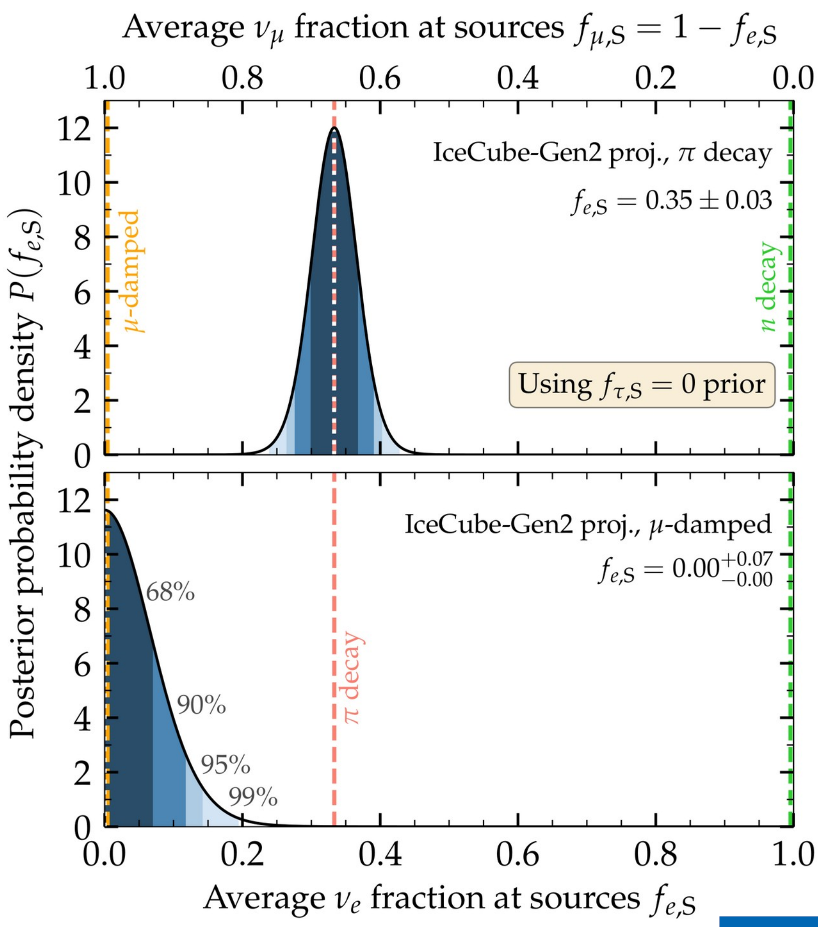


IceCube-Gen2, 2008.04323

Inferred (at sources):



MB & Ahlers, *PRL* 2019

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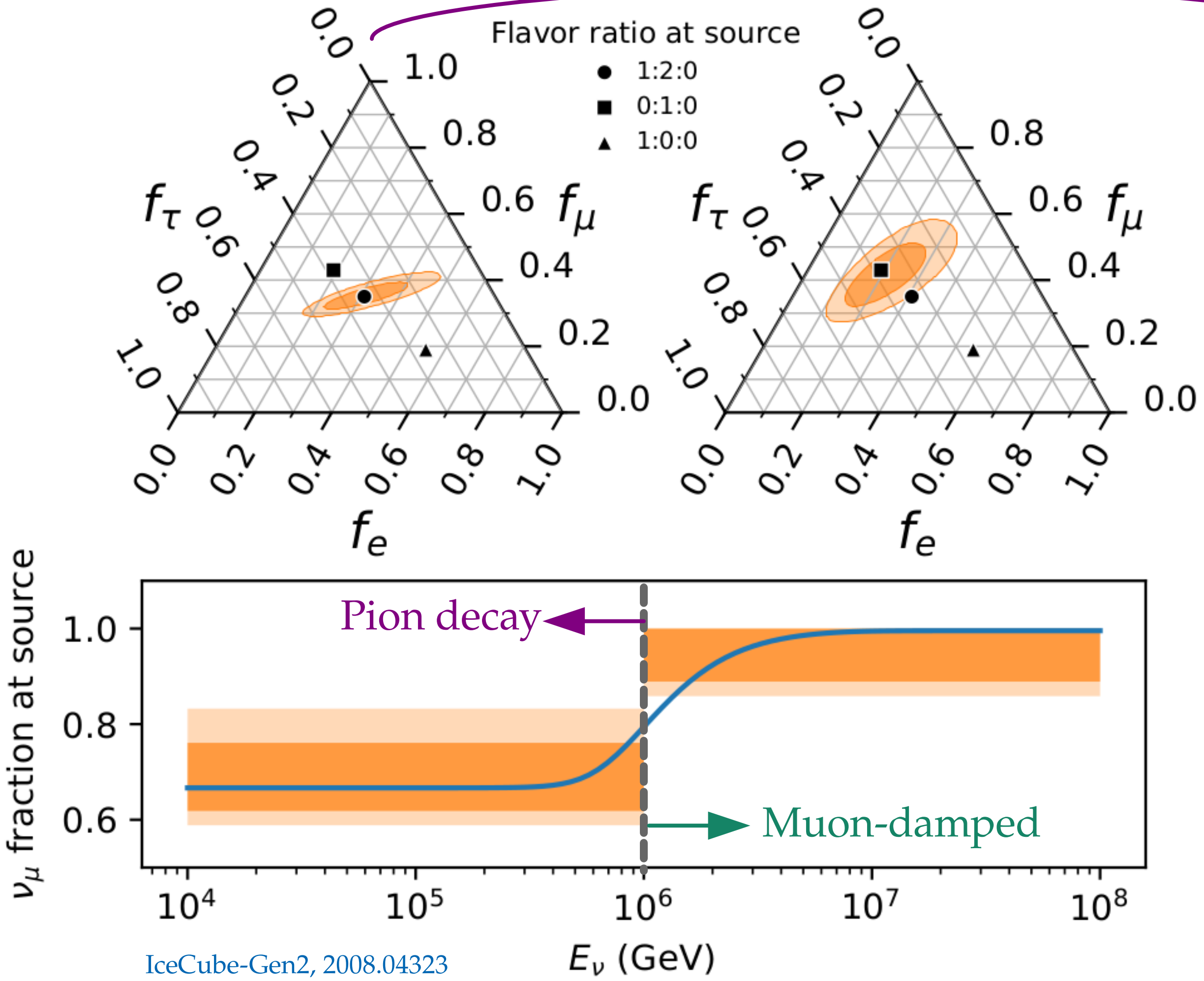

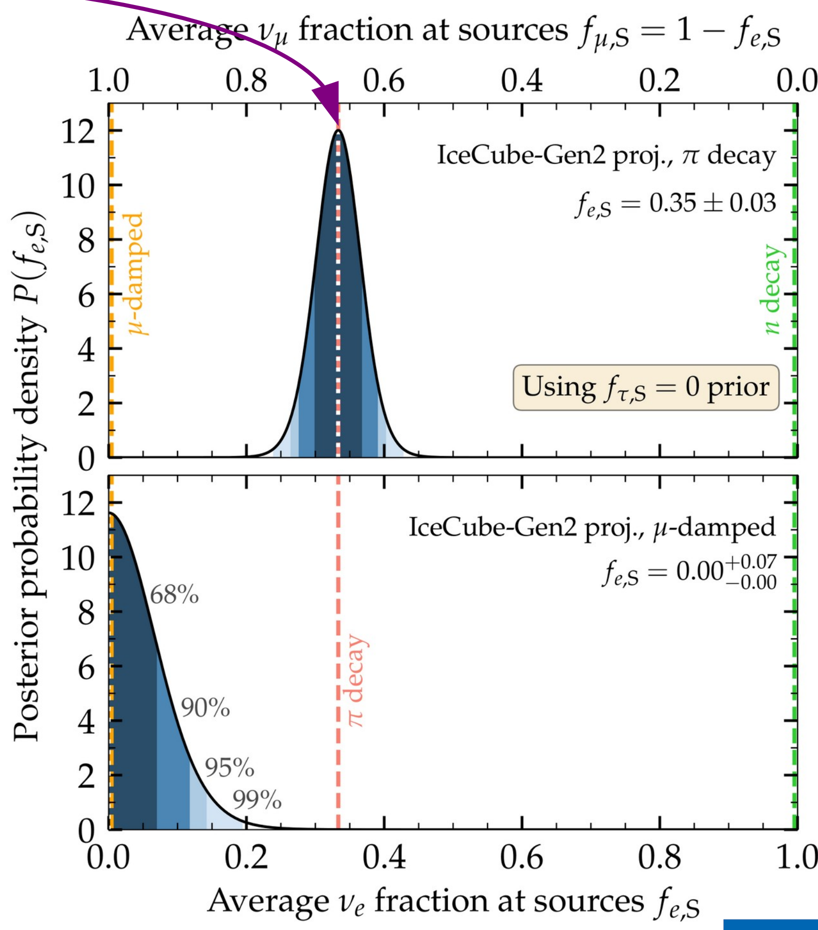

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MB & Ahlers, *PRL* 2019

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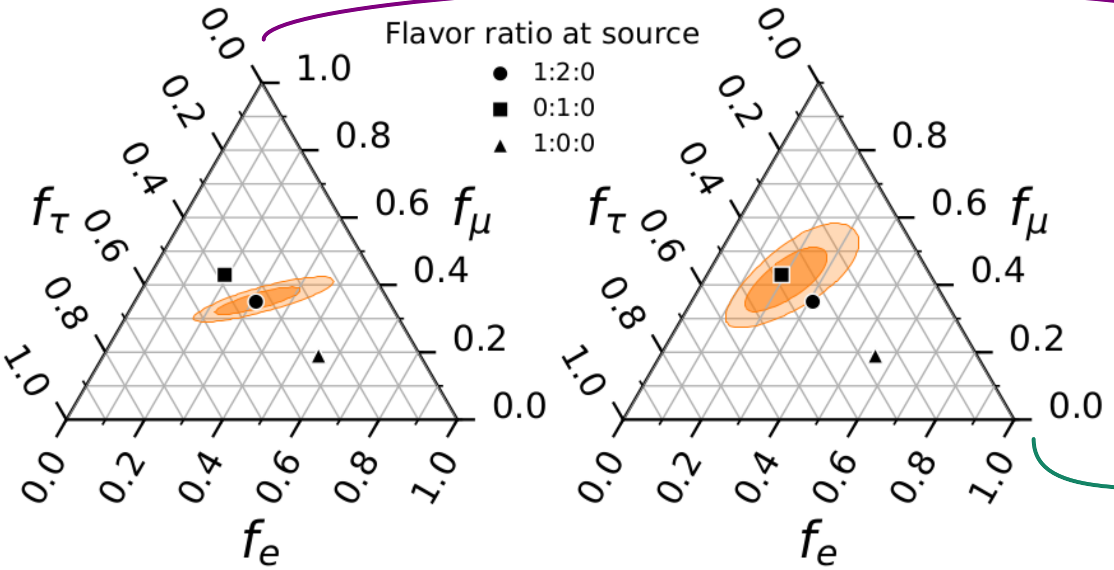

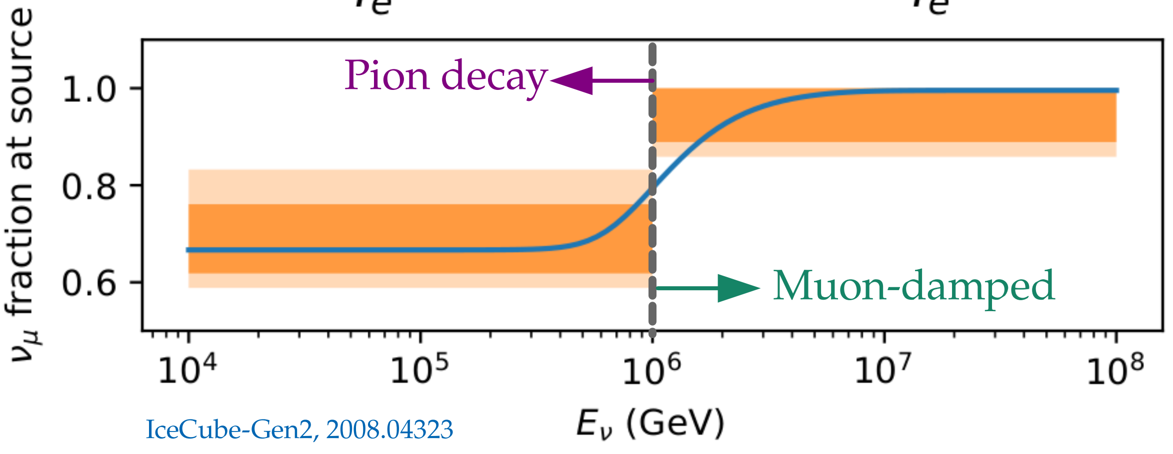

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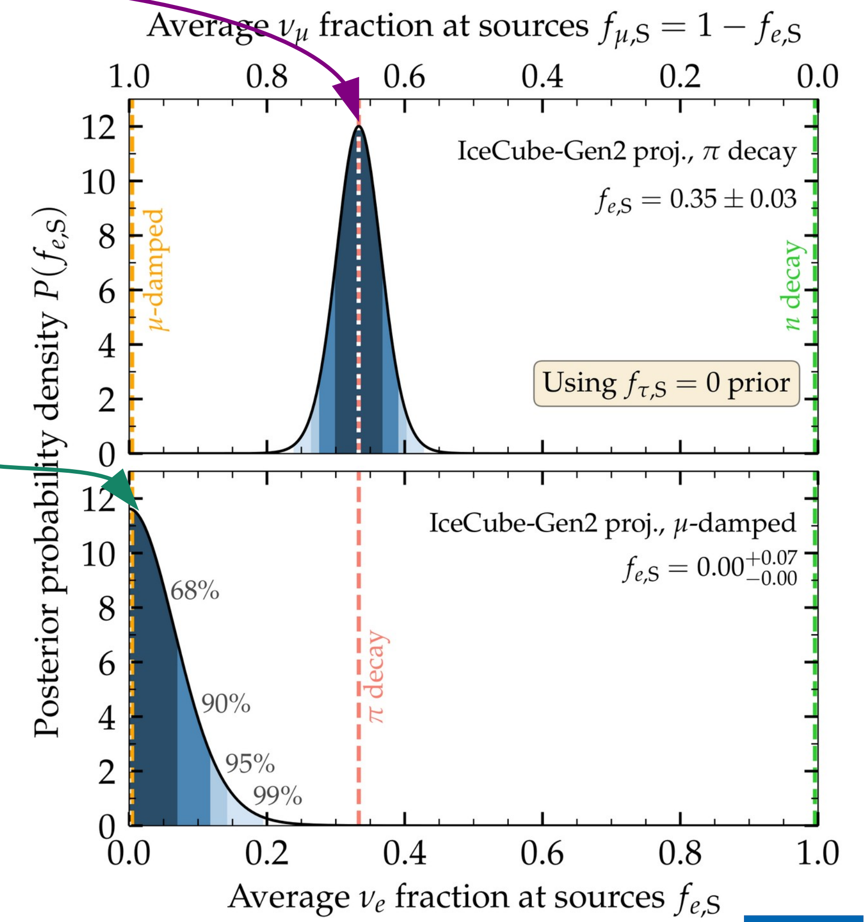

MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

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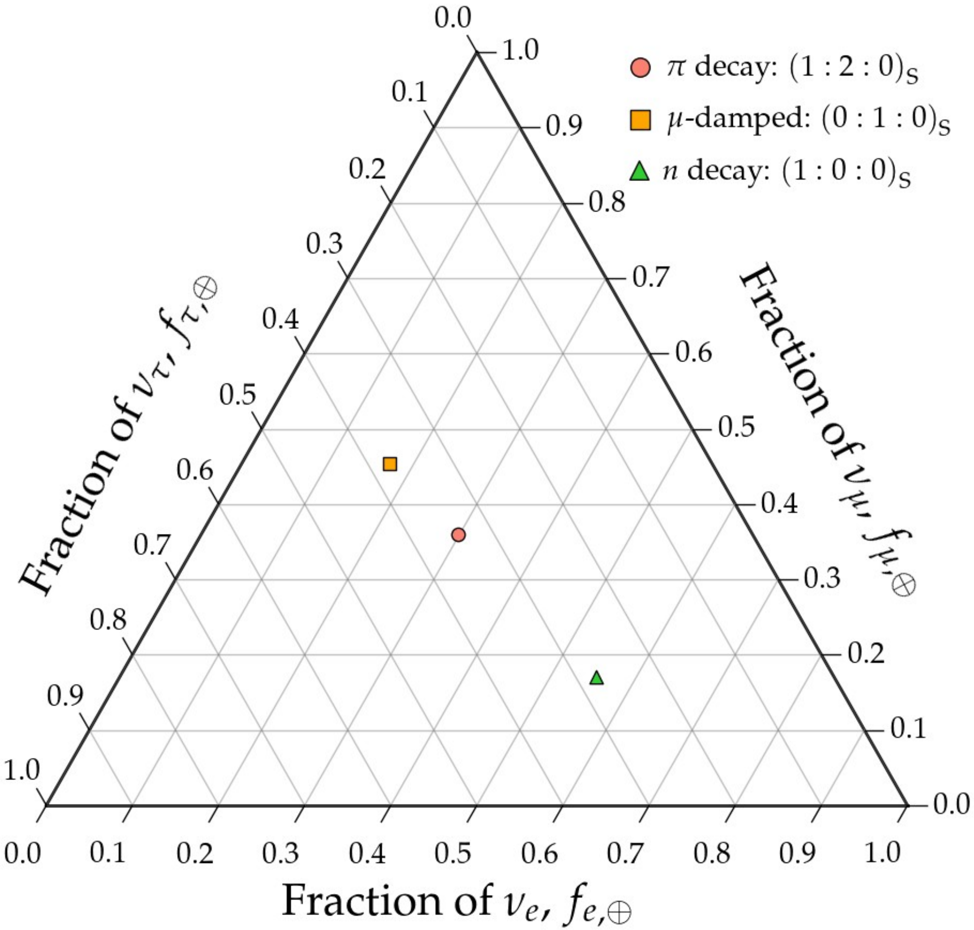

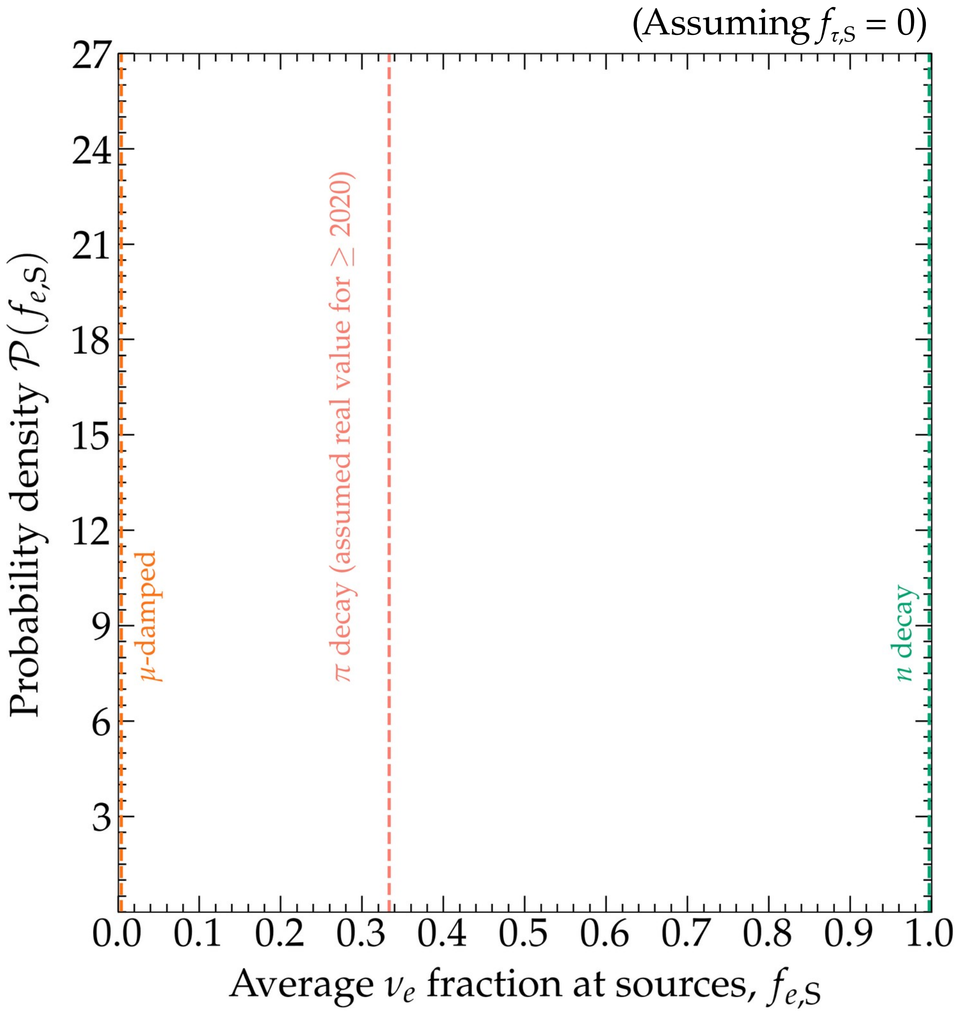

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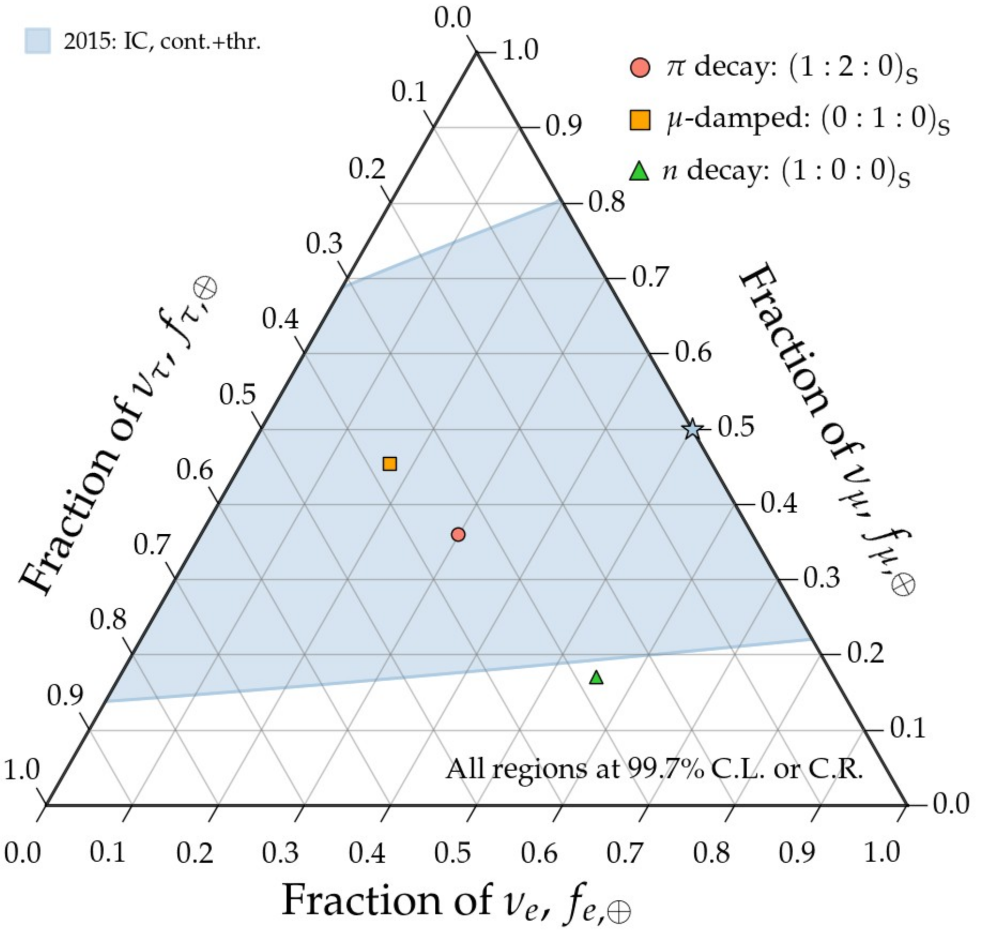
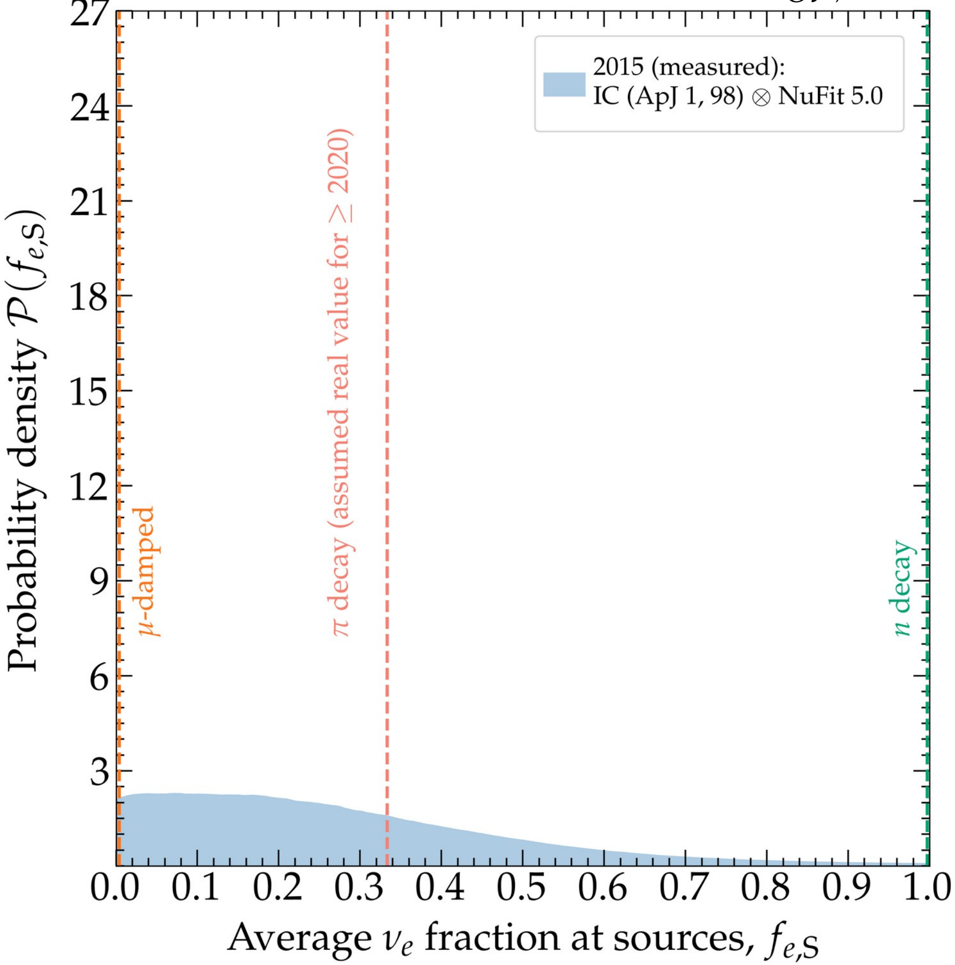


(Assuming $f_{\tau,S} = 0$)



Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

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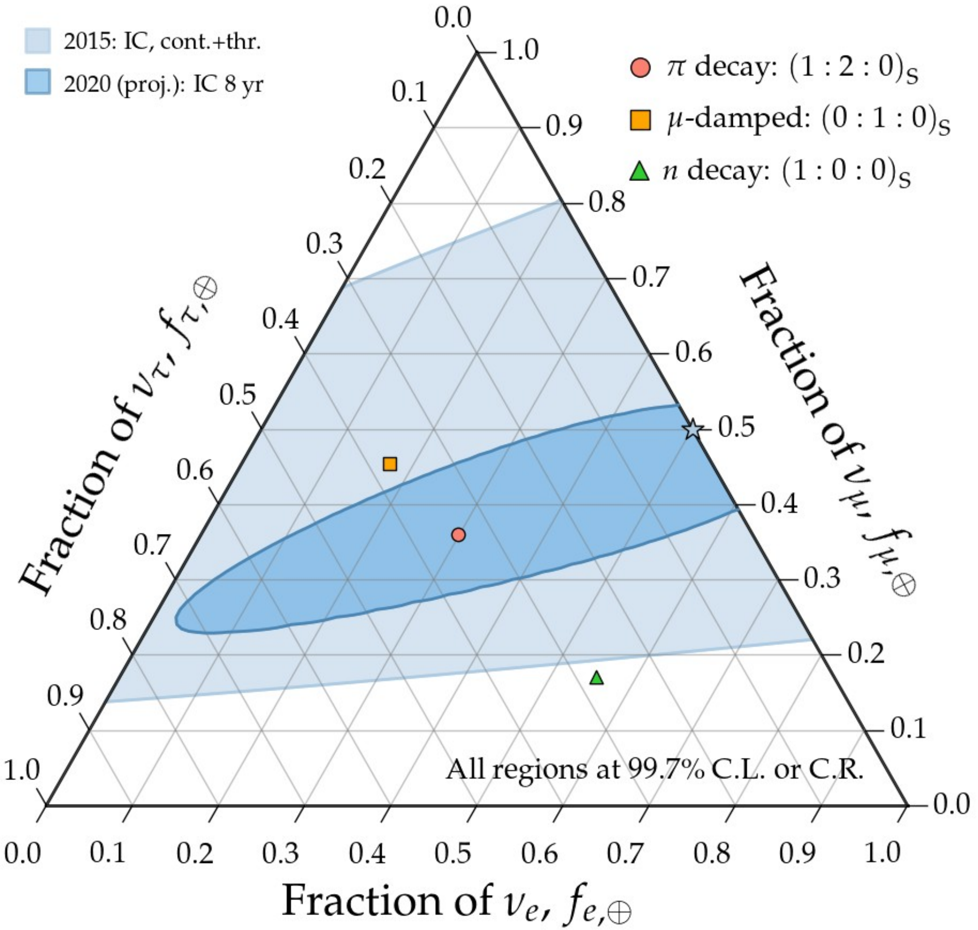

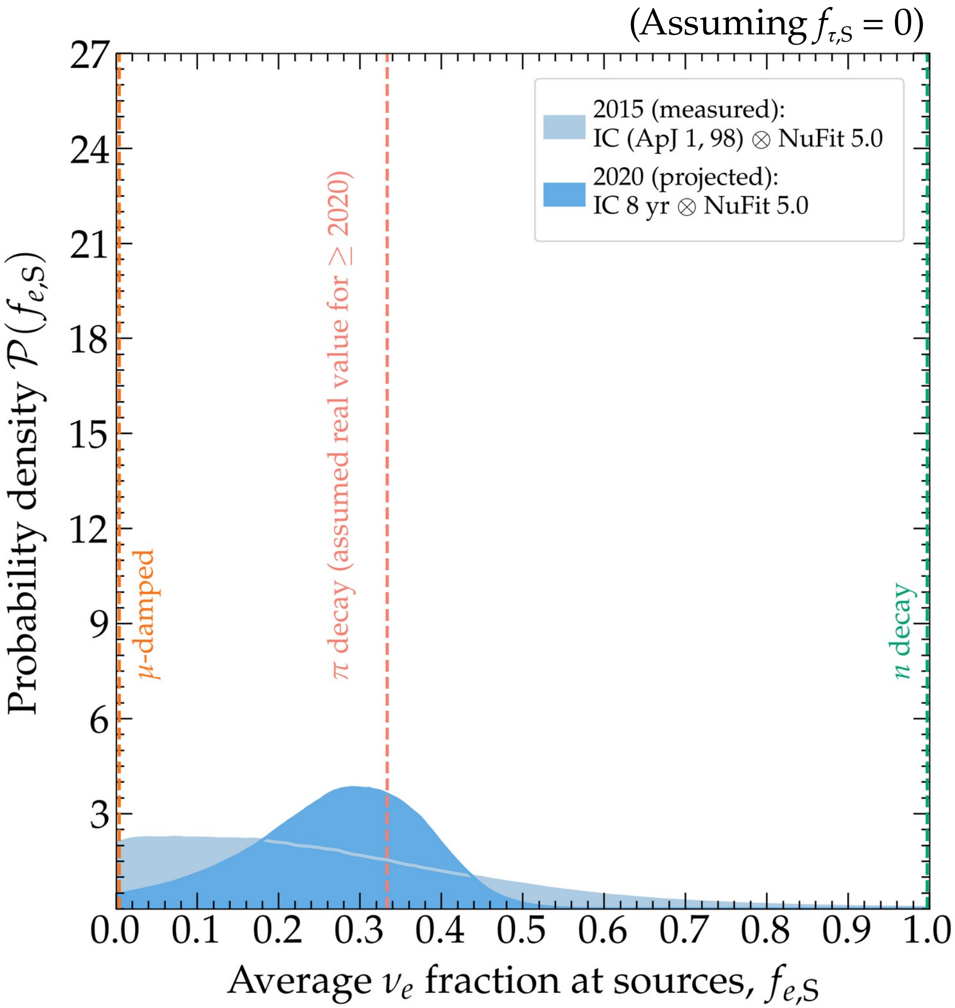

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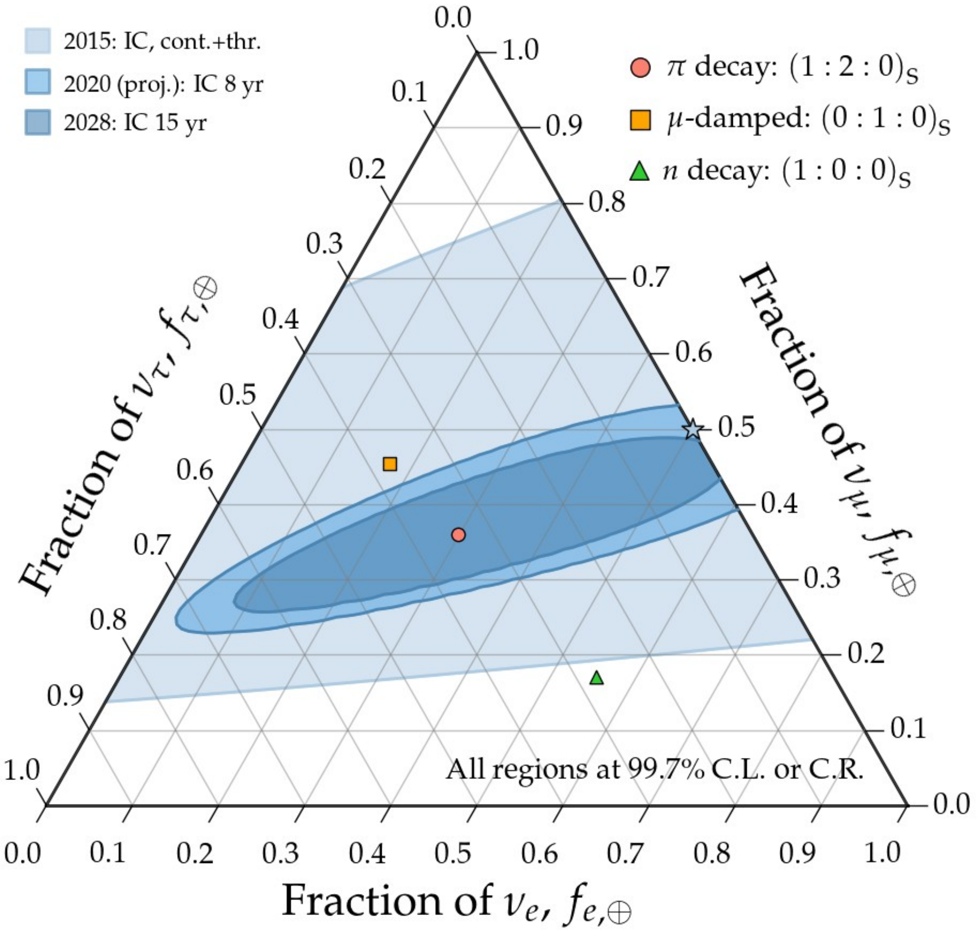

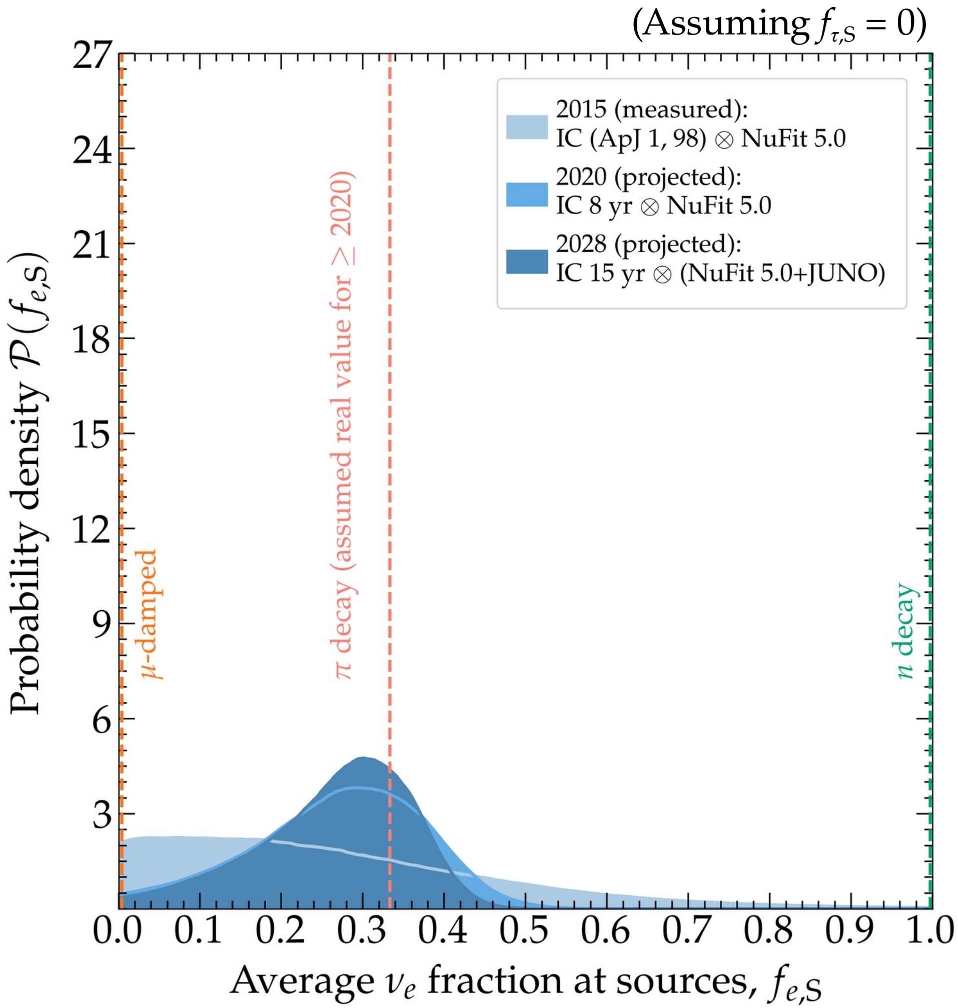

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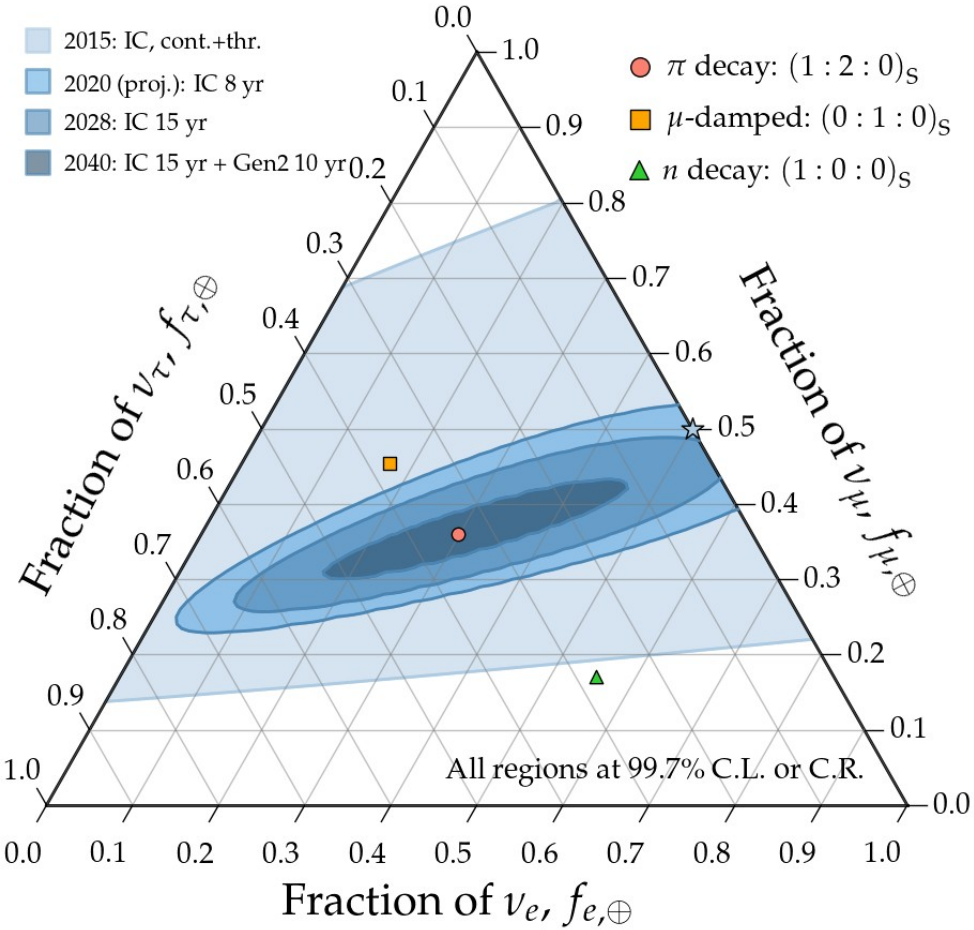

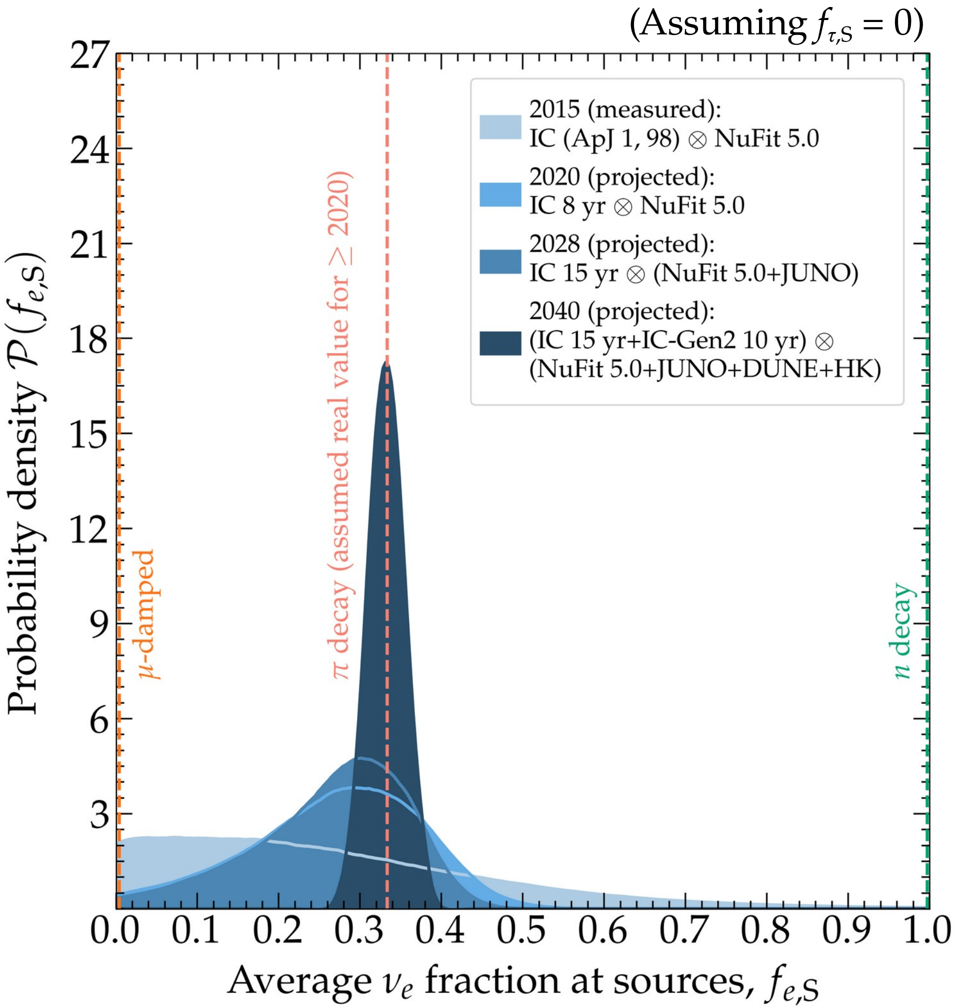

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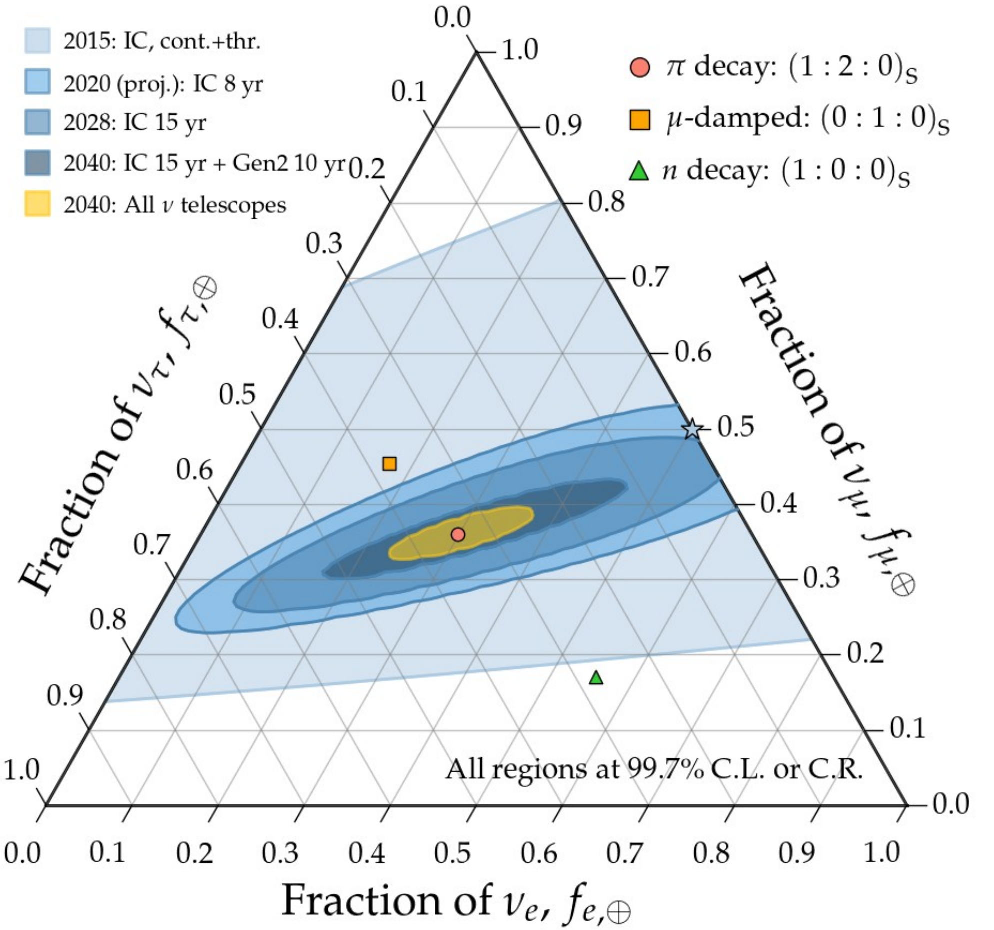

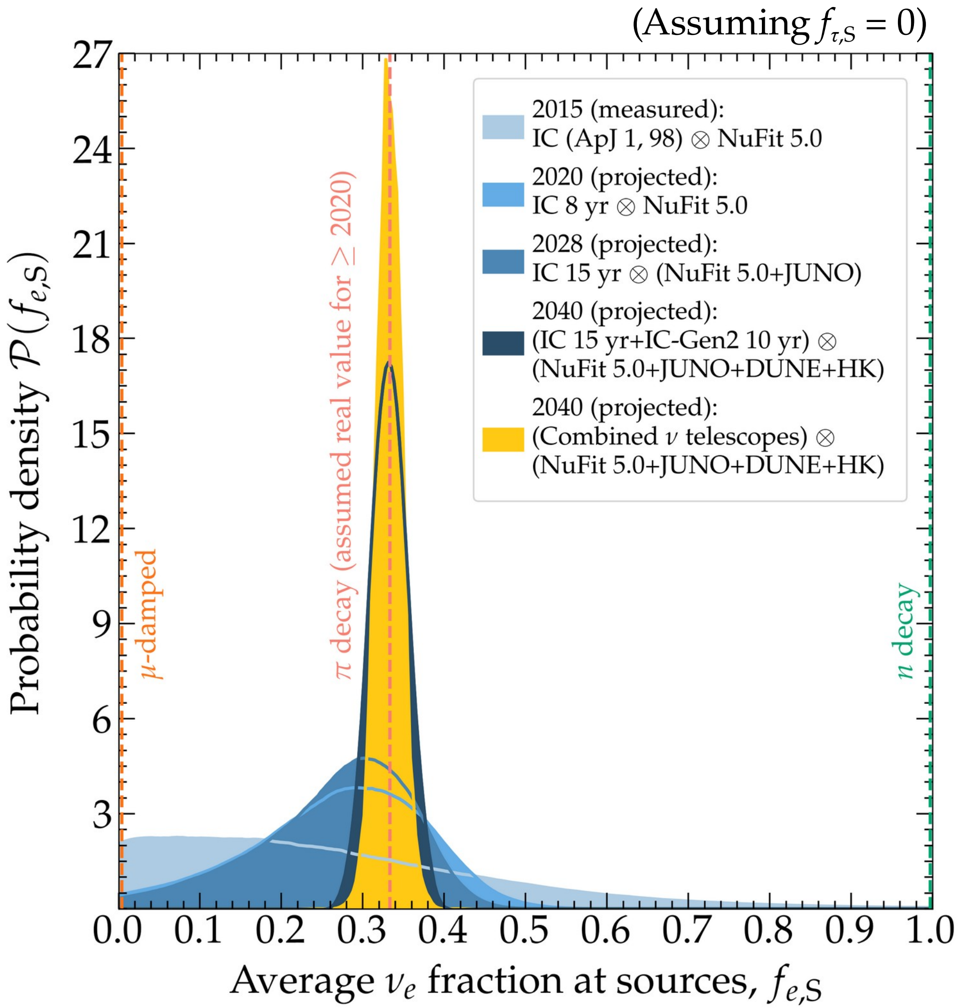

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = \underbrace{k_\pi \boldsymbol{f}_{\rm S}^\pi}_{} + \underbrace{k_\mu \boldsymbol{f}_{\rm S}^\mu}_{} + \underbrace{k_n \boldsymbol{f}_{\rm S}^n}_{}$$

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

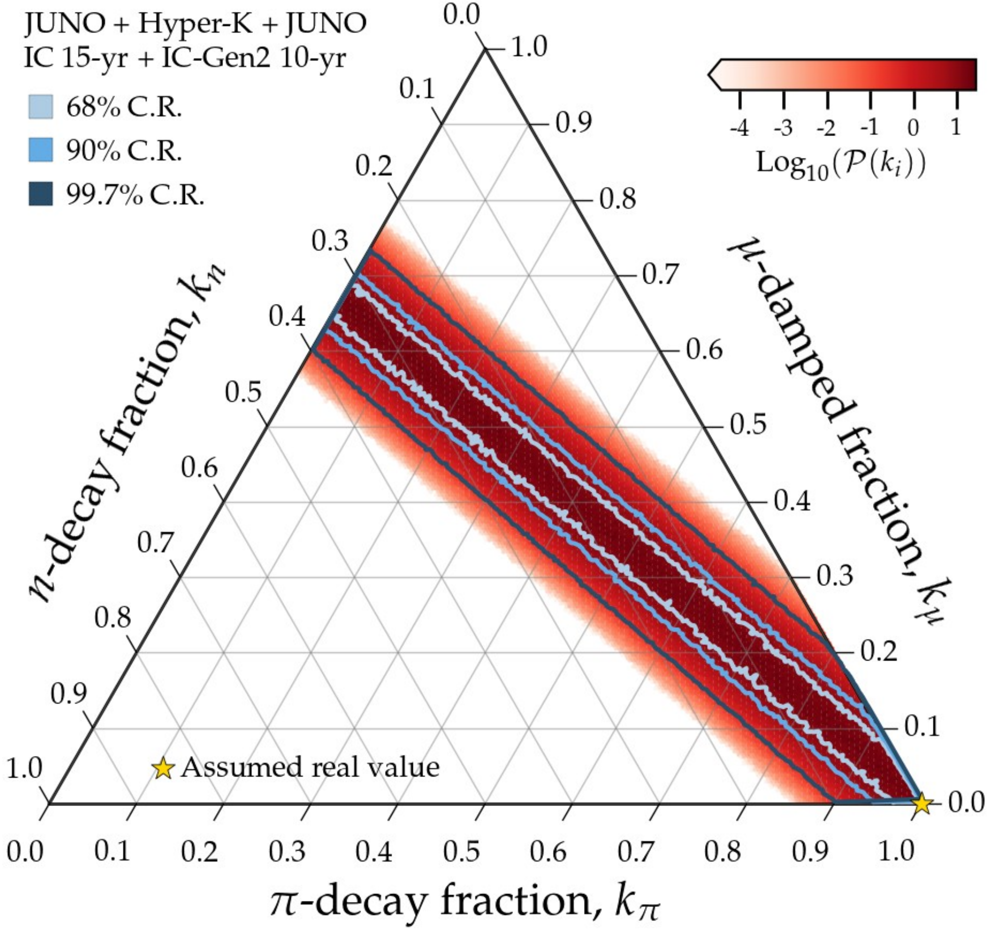
Propagate to Earth

$\boldsymbol{f}_\oplus$

Assume real value $k_\pi = 1$ ($k_\mu = k_n = 0$)

By 2040, how well will we recover the real value?

[Adding spectrum information (not shown) will likely help]



Song, Li, Argüelles, **MB**, Vincent, 2012.12893

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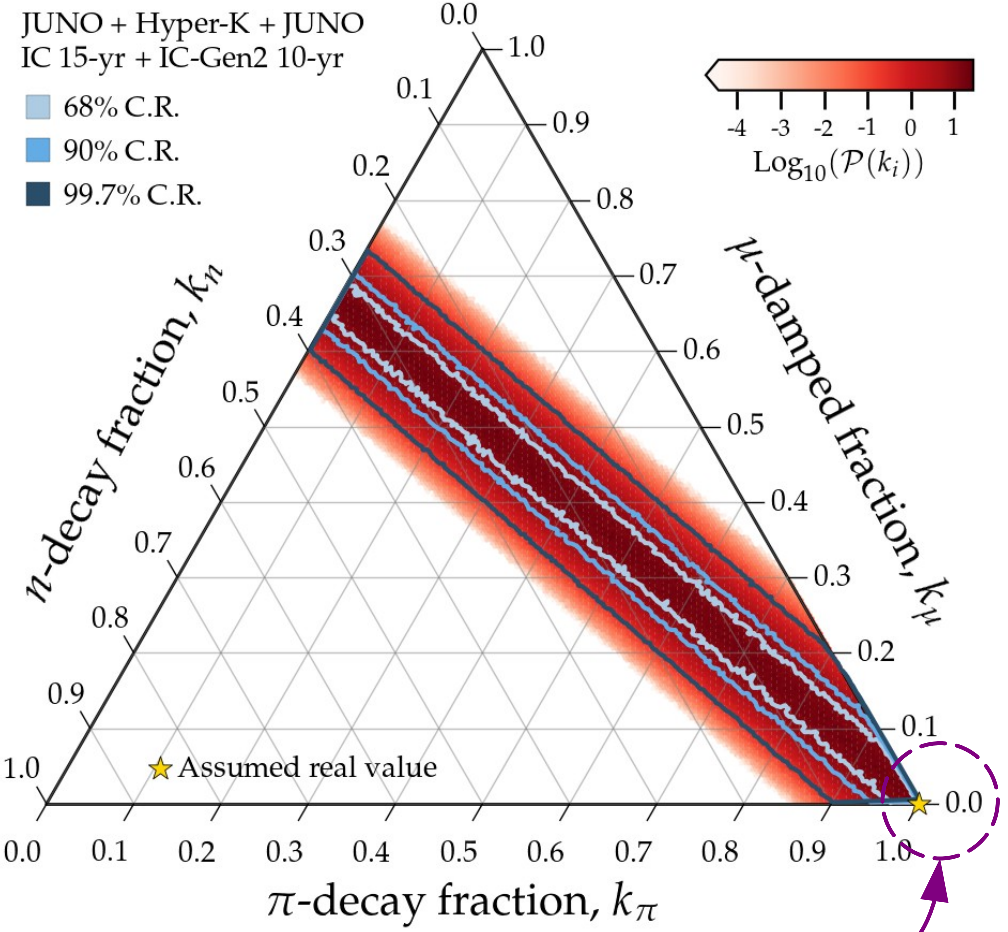

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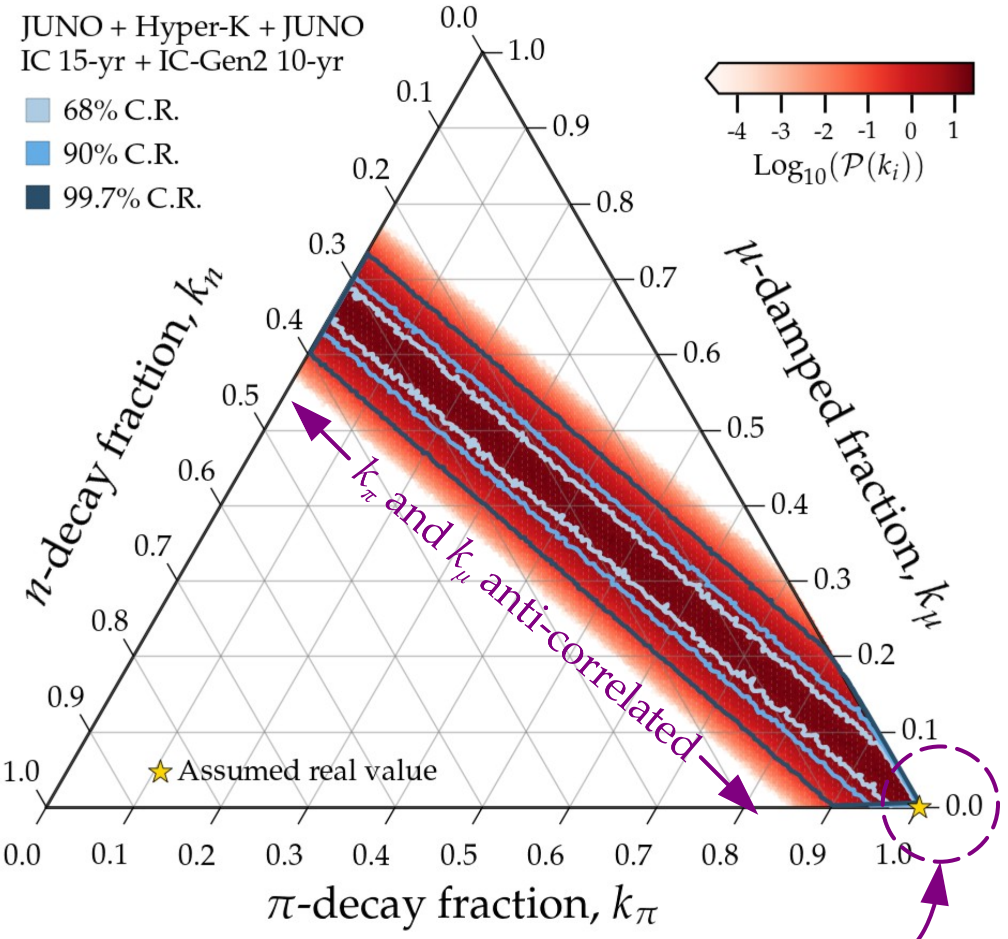

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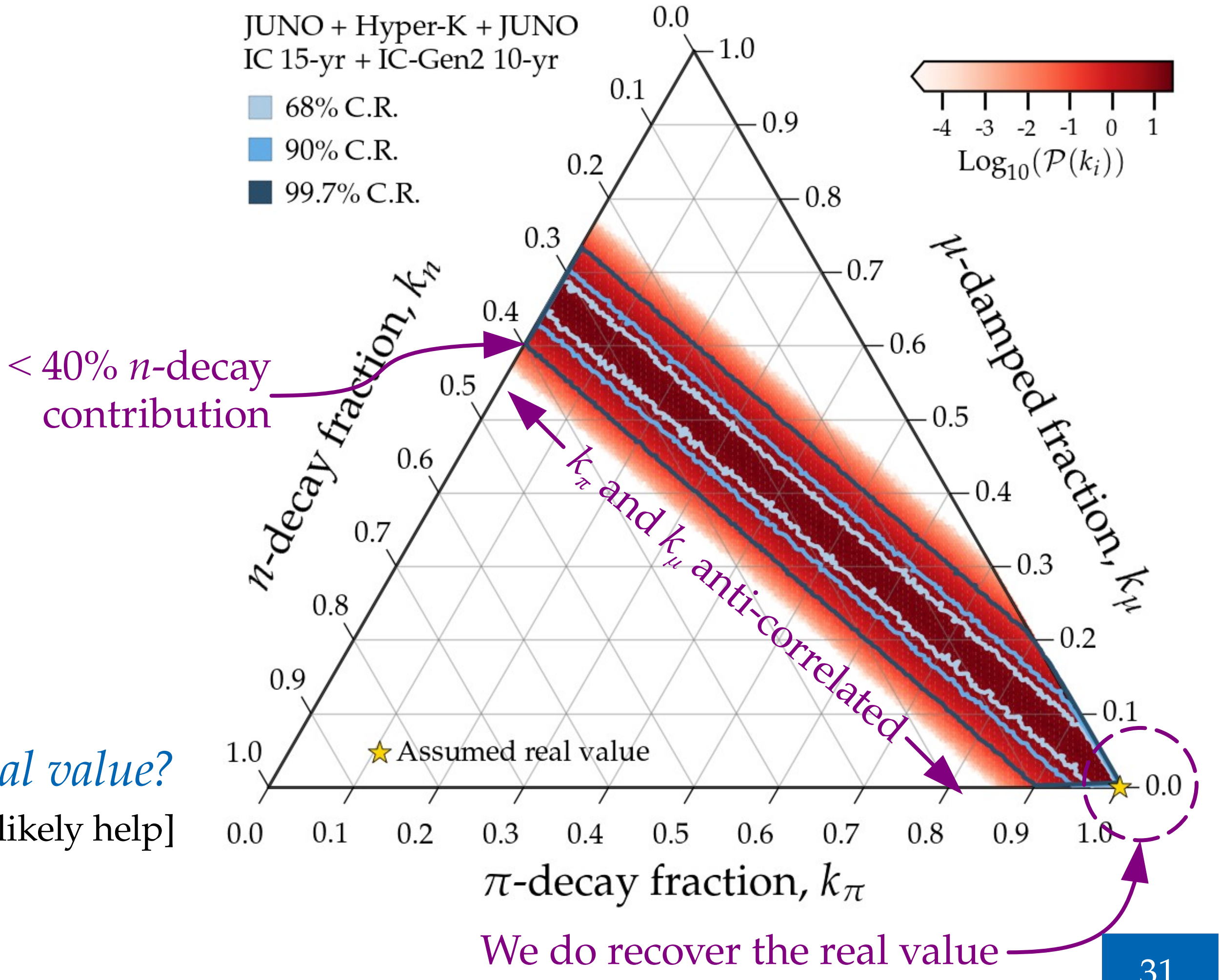

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Propagate to Earth ↓

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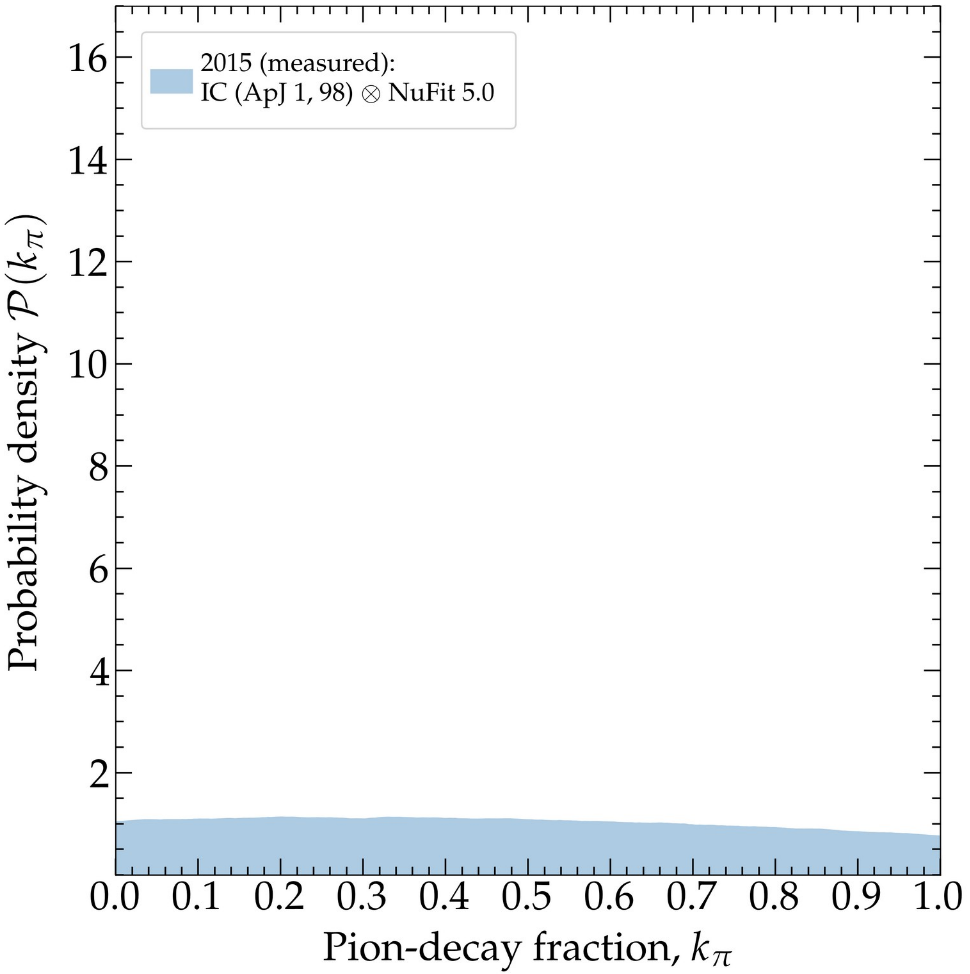

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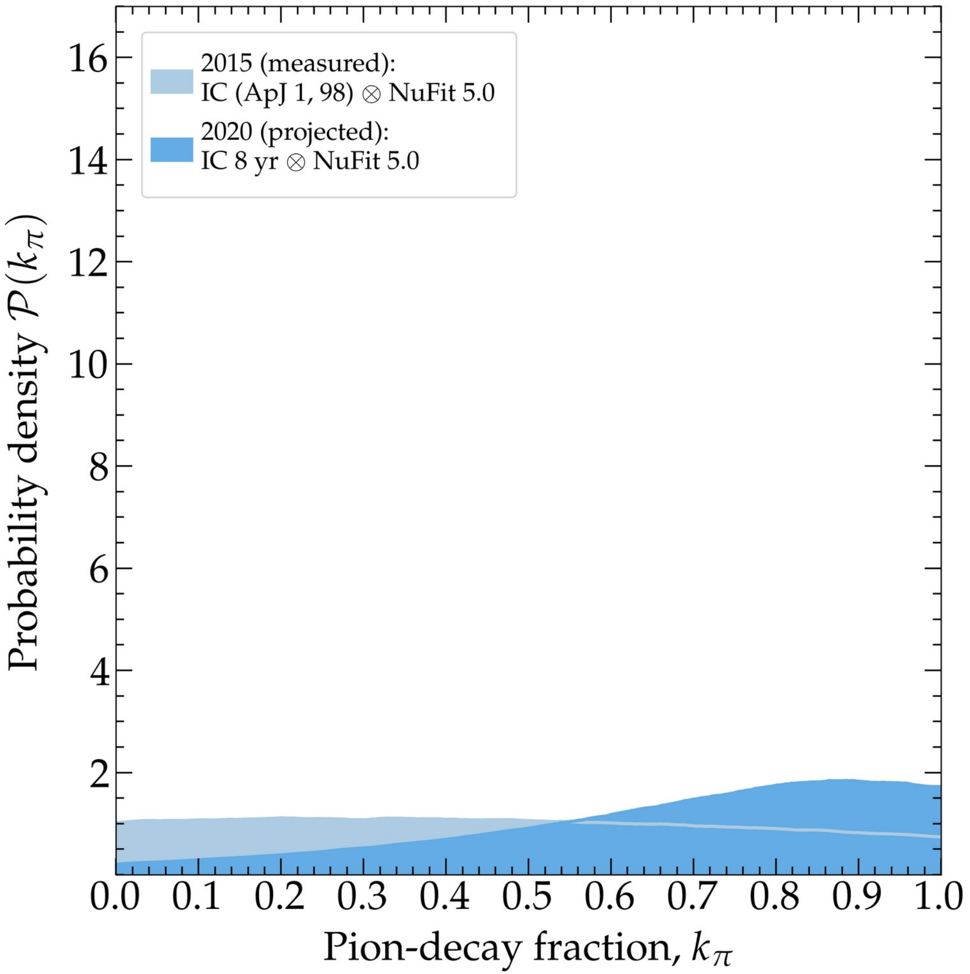

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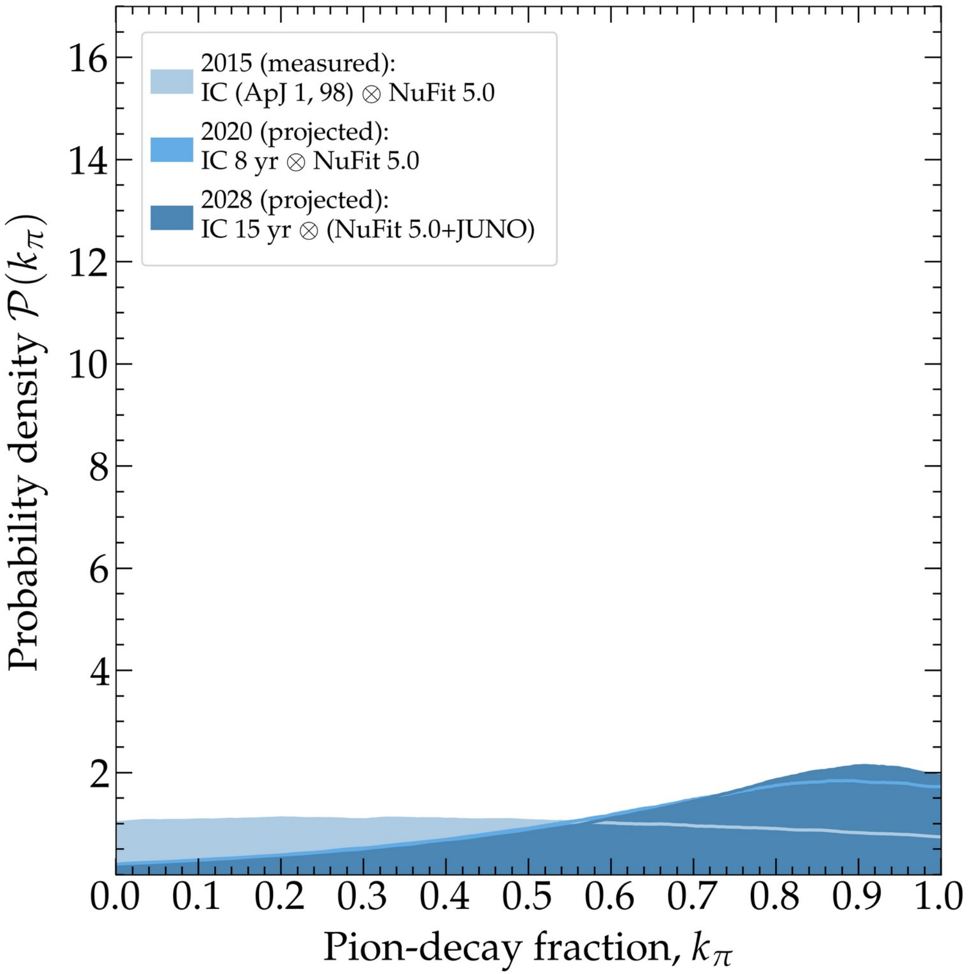

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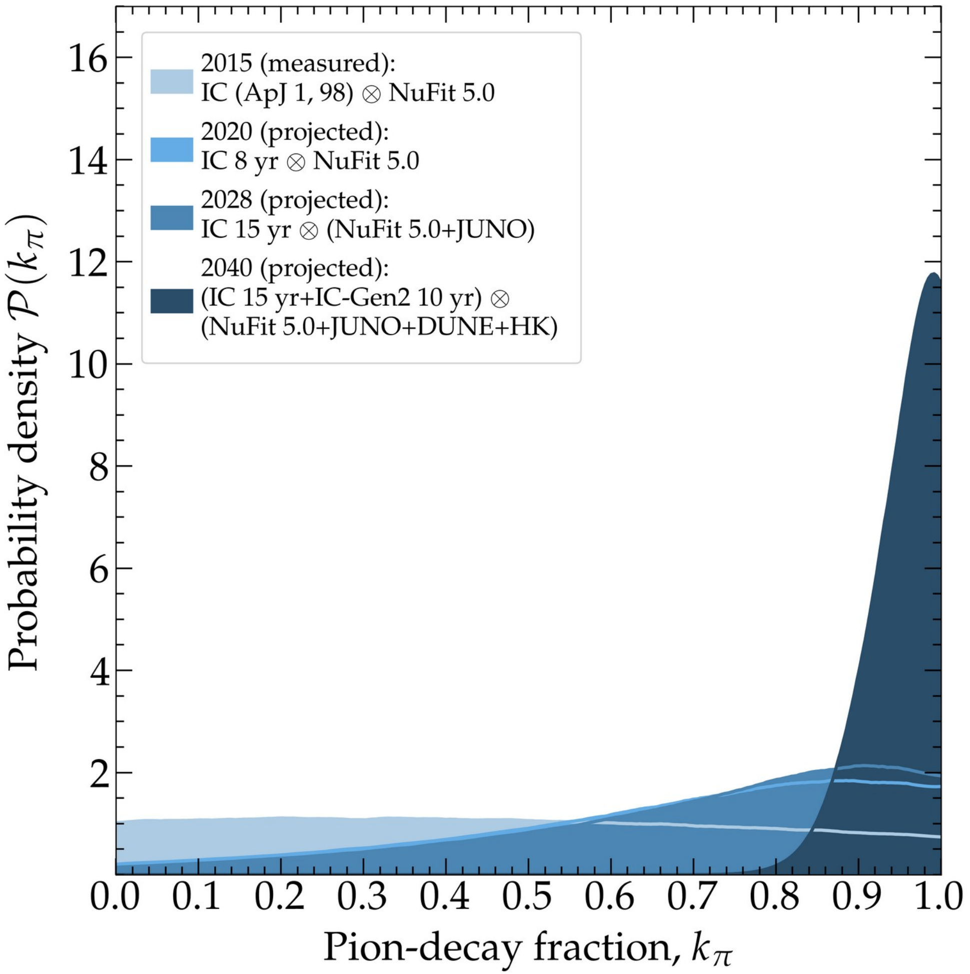

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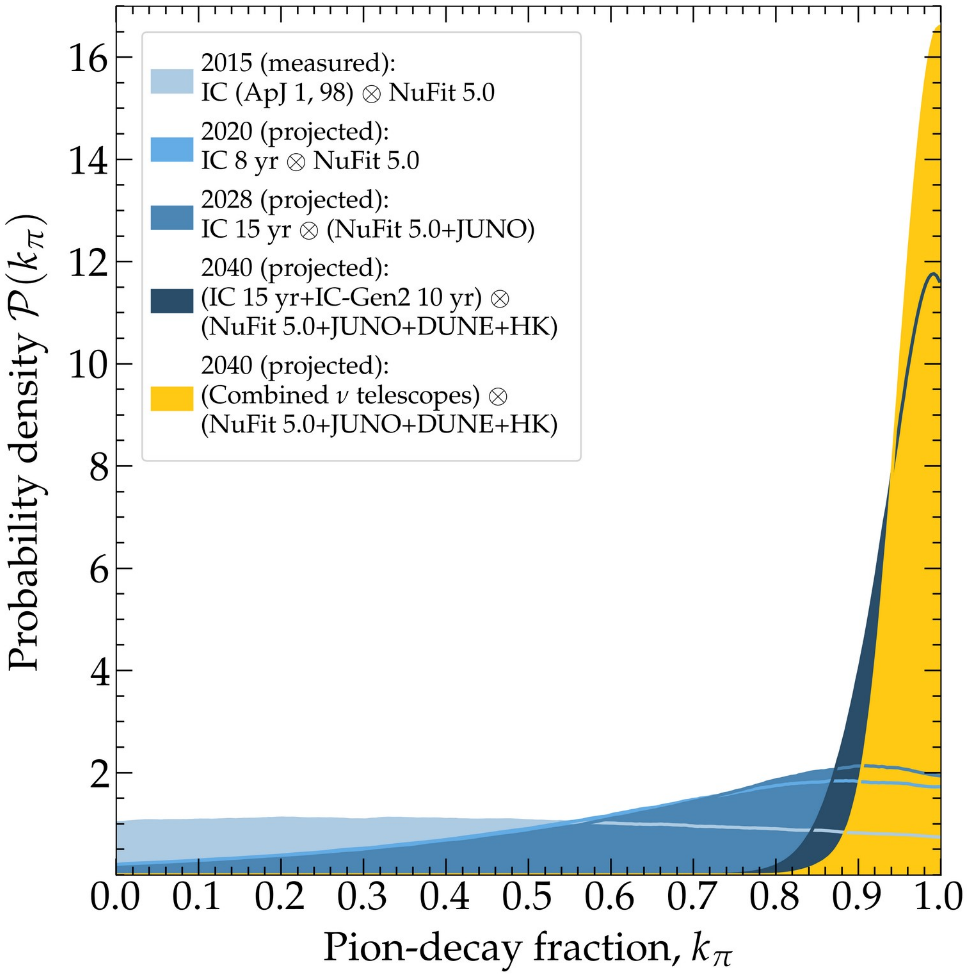
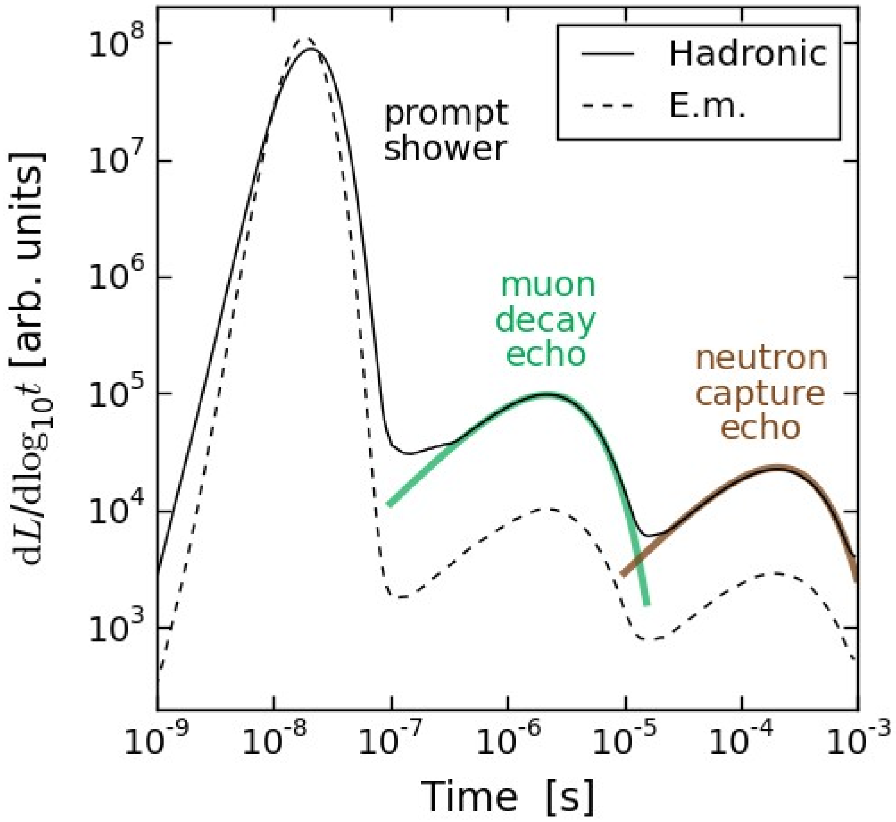
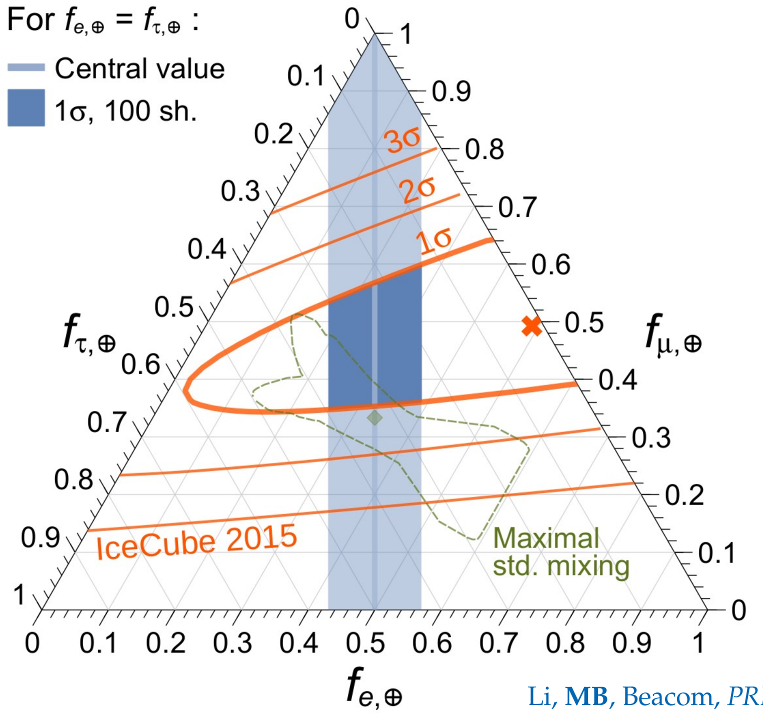


Song, Li, Argüelles, **MB**, Vincent, 2012.12893

Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by ν_e and ν_τ –





Li, **MB**, Beacom, *PRL* 2019

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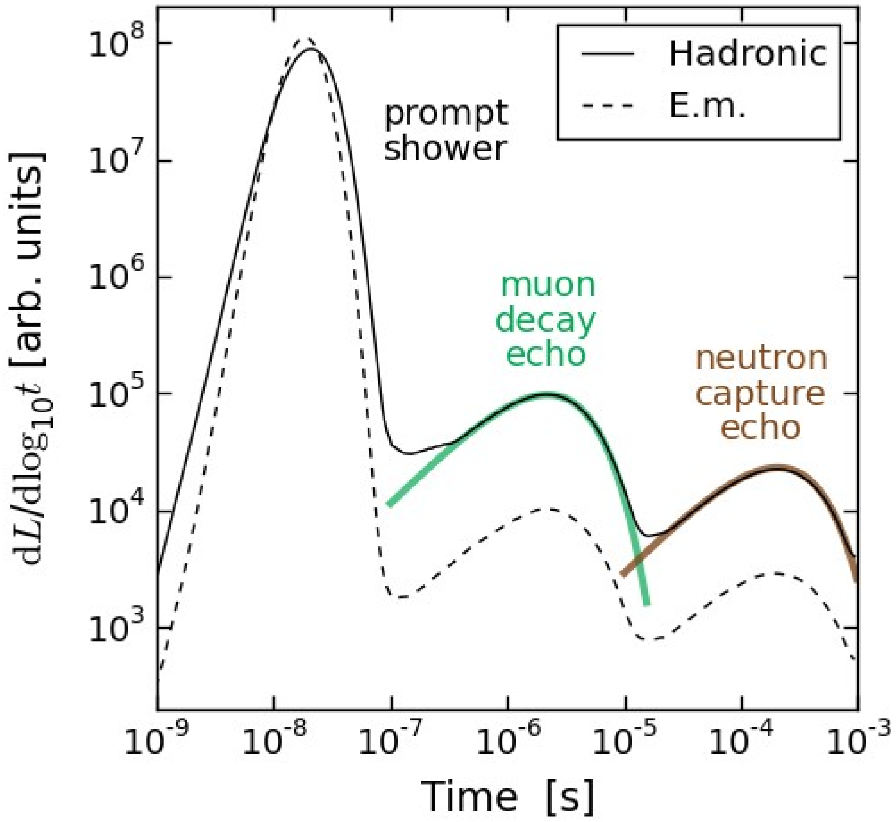
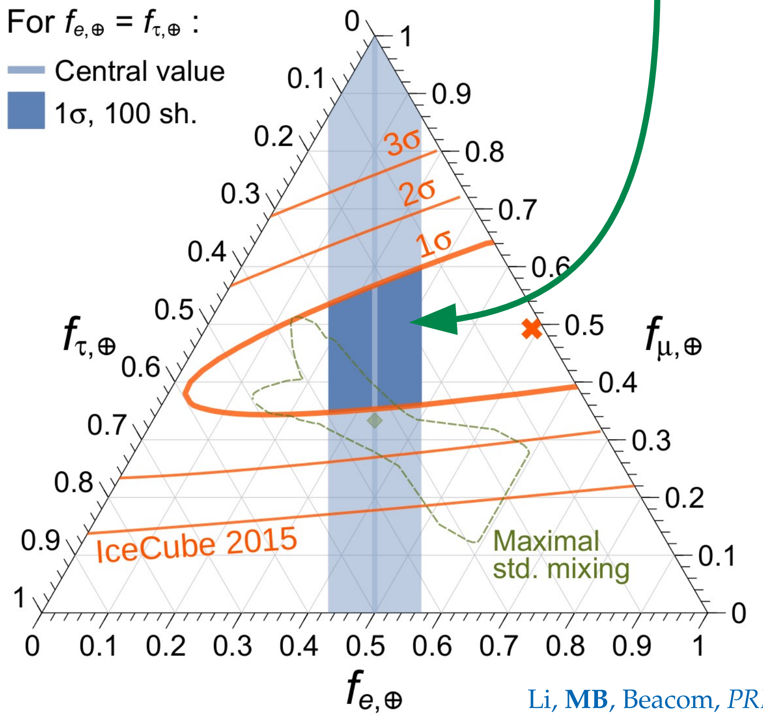


~10 × improvement over current measurement



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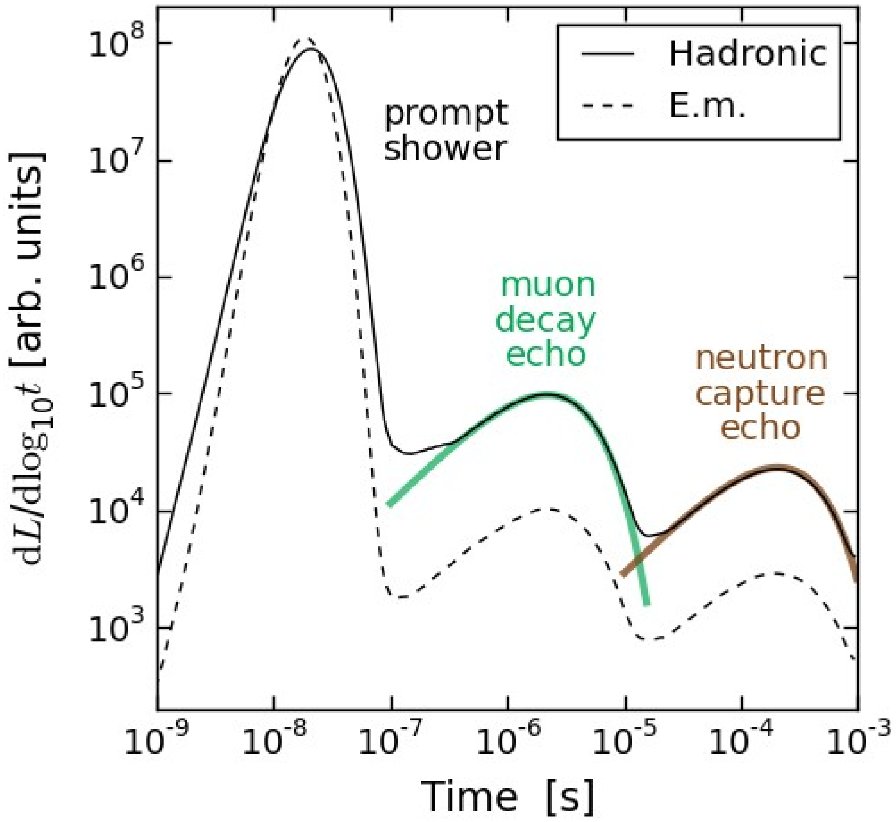

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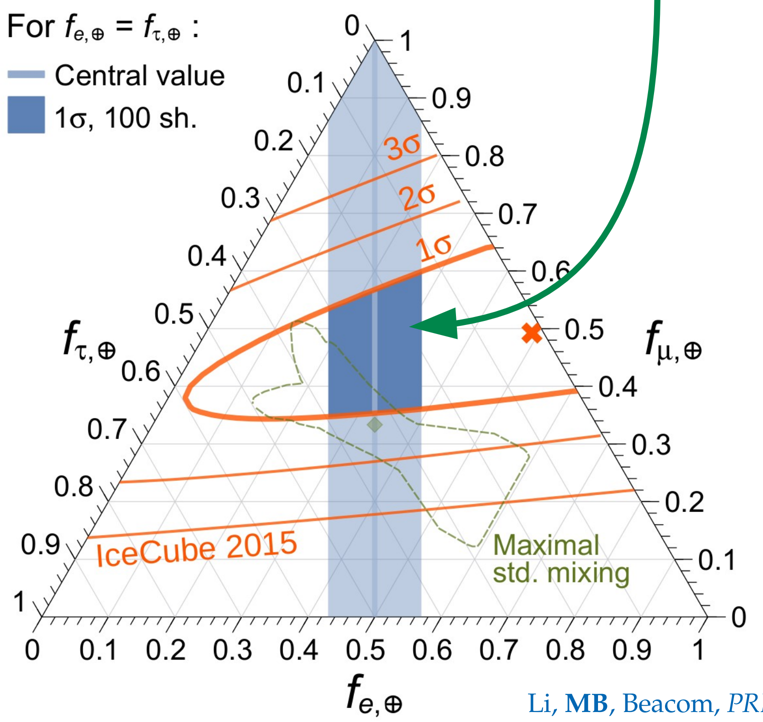
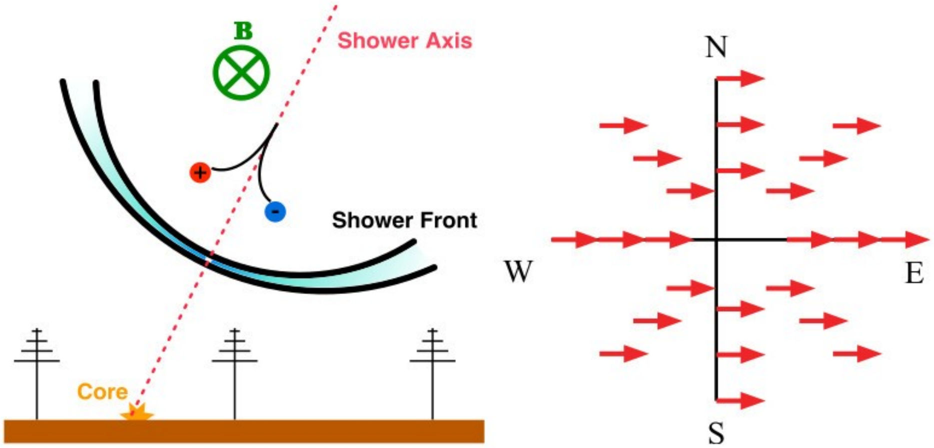


Li, **MB**, Beacom, *PRL* 2019

Detectors

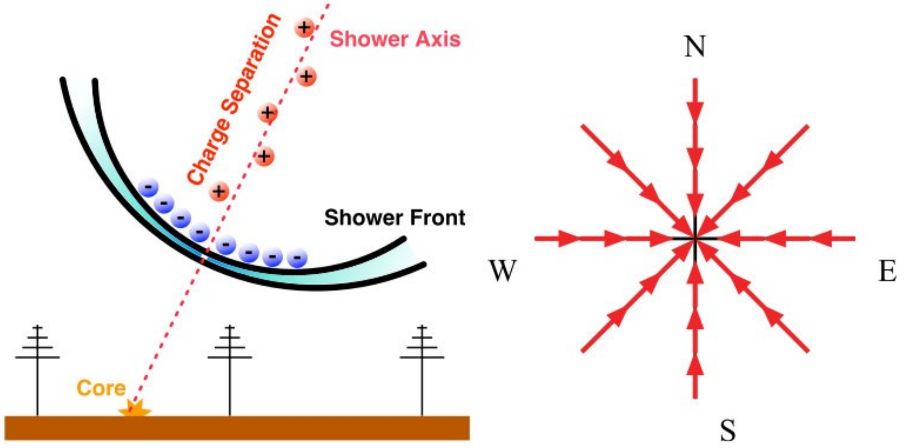
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

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

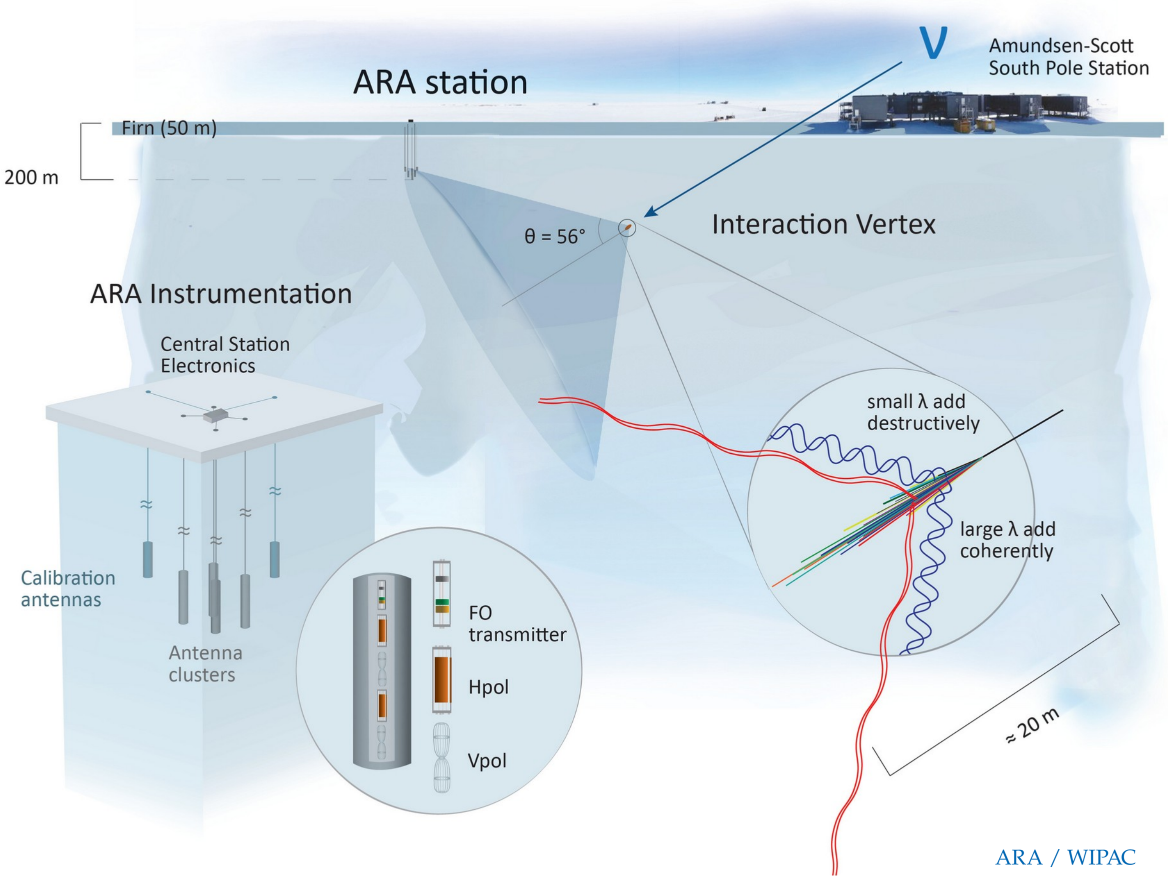
Radio emission: geomagnetic and Askaryan

Radio-detection of UHE neutrinos in ice

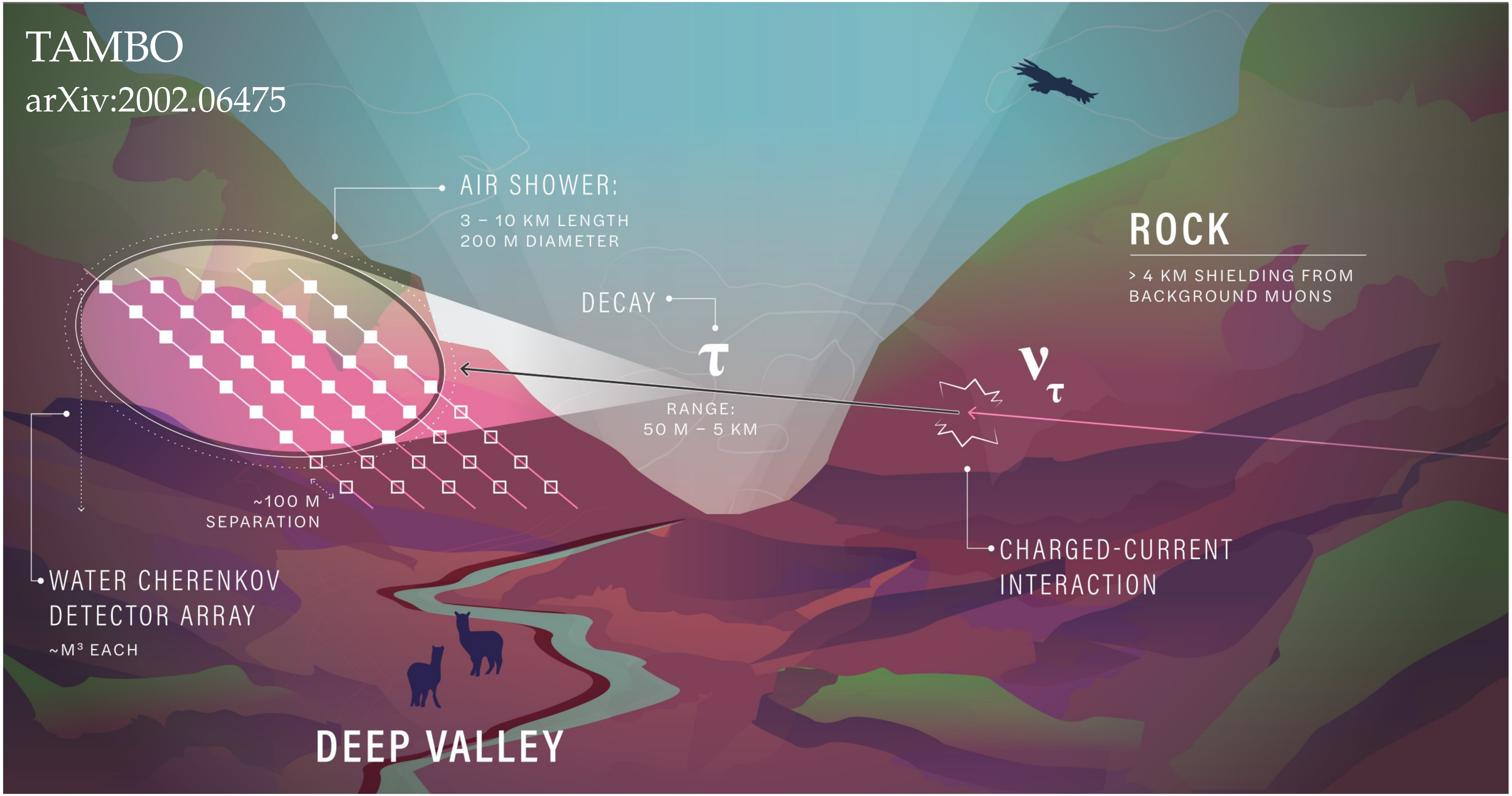
- Radio attenuation length in ice: few km (*vs.* 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

No ν detected yet

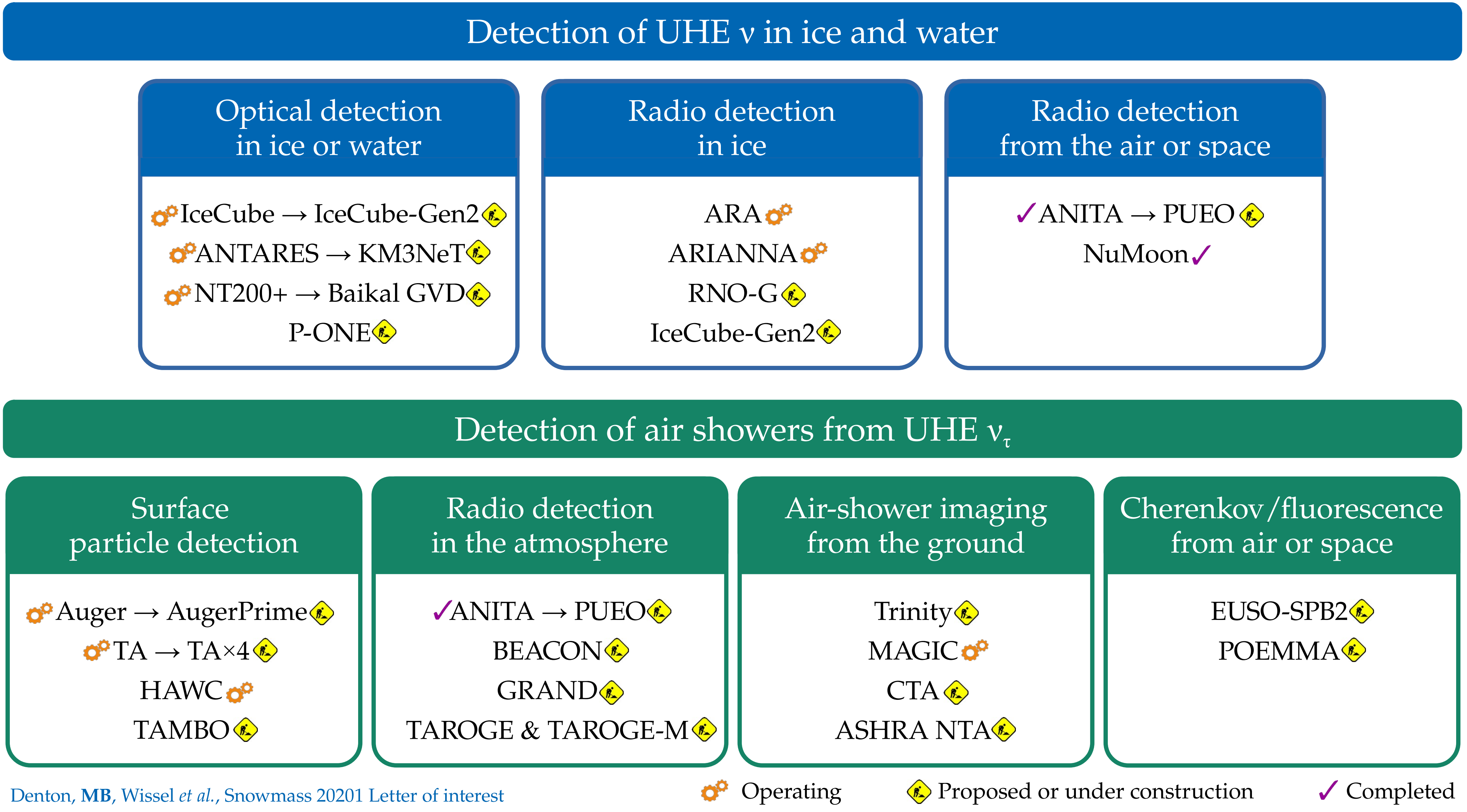
(But UHECRs detected regularly!)



ARA / WIPAC

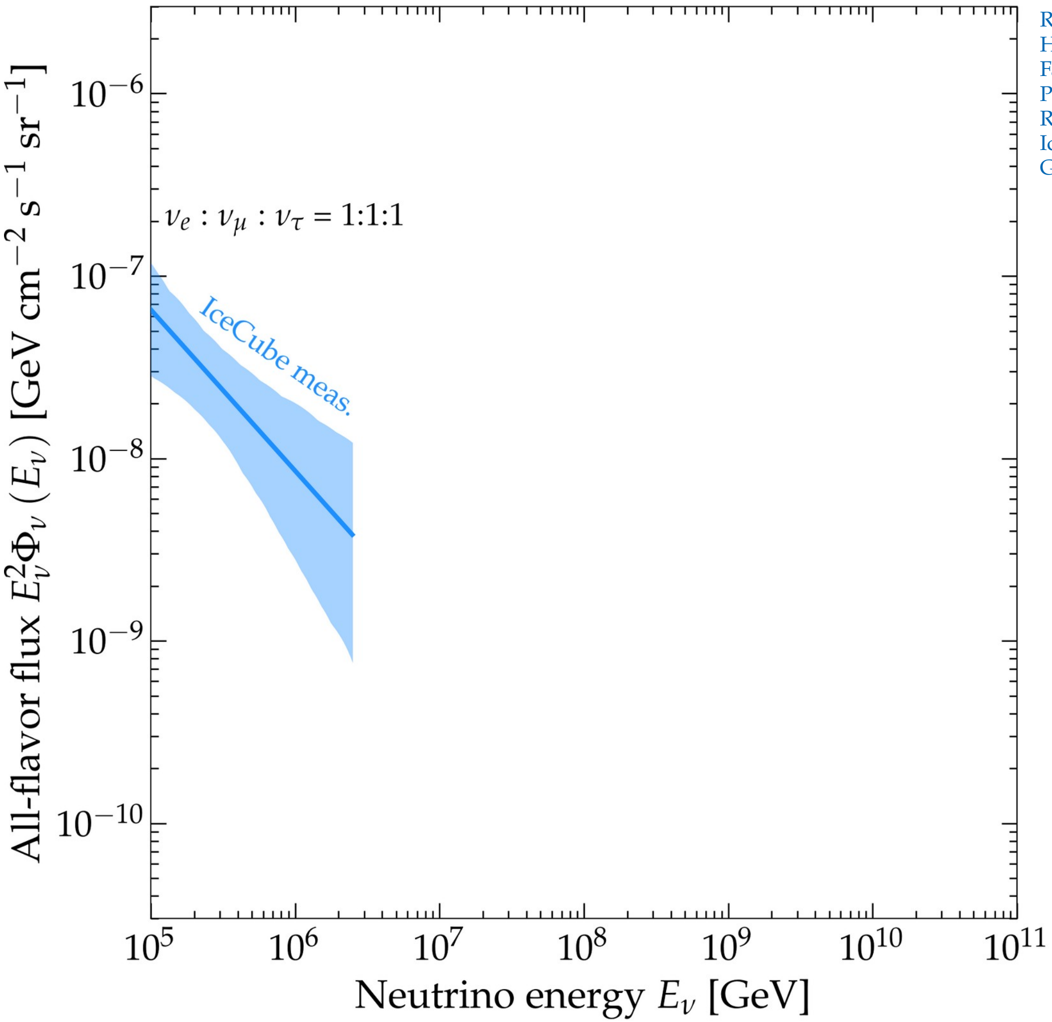


TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU



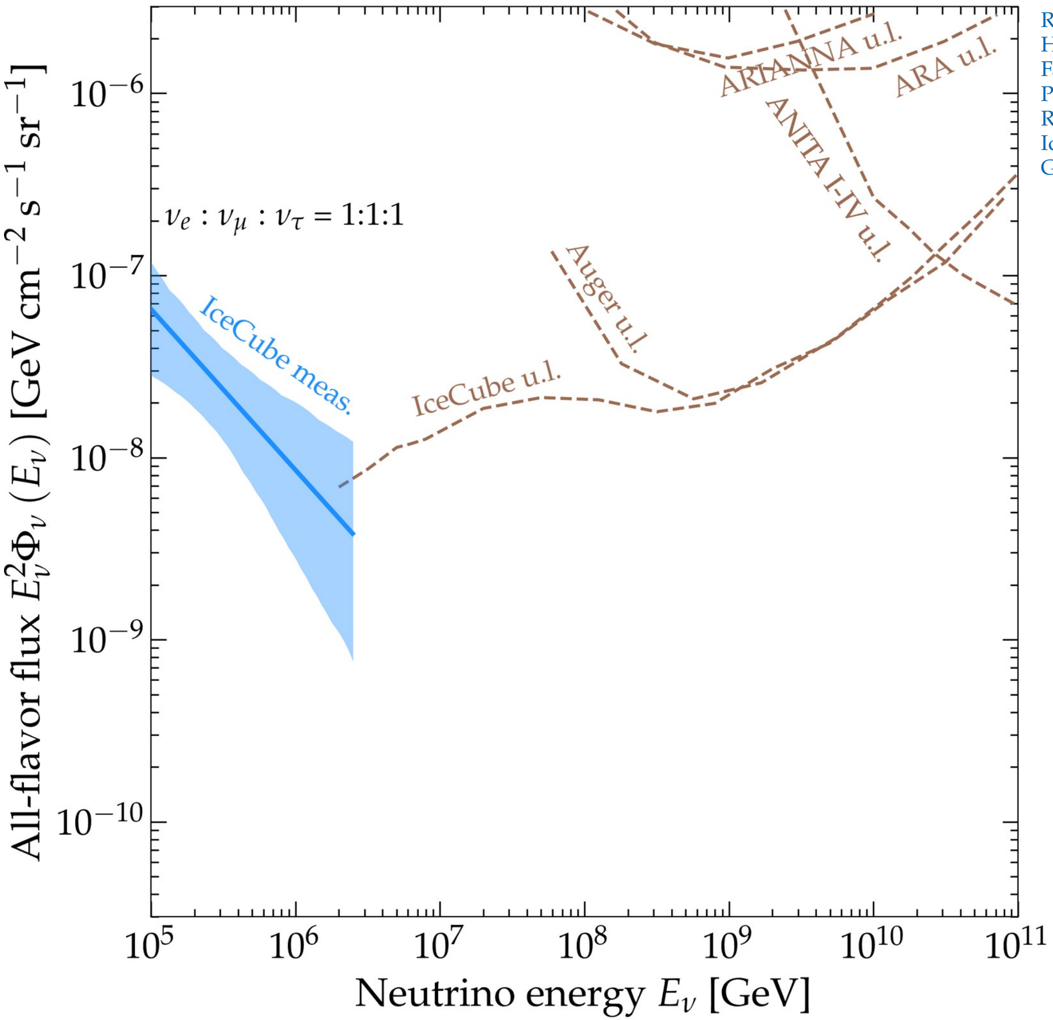
Detection of UHE ν in ice and water
Optical detection in ice or water
IceCube → IceCube-Gen2
ANTARES → KM3NeT
NT200+ → Baikal GVD
P-ONE
Radio detection in ice
ARA
ARIANNA
RNO-G
IceCube-Gen2
Radio detection from the air or space
✓ANITA → PUEO
NuMoon✓
Detection of air showers from UHE ντ
Surface particle detection
Auger → AugerPrime
TA → TA×4
HAWC
TAMBO
Radio detection in the atmosphere
✓ANITA → PUEO
BEACON
GRAND
TAROGE & TAROGE-M
Air-shower imaging from the ground
Trinity
MAGIC
CTA
ASHRA NTA
Cherenkov/fluorescence from air or space
EUSO-SPB2
POEMMA
Denton, MB, Wissel et al., Snowmass 20201 Letter of interest
Operating
Proposed or under construction
✓ Completed

UHE neutrinos: *steady-state sources*



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

UHE neutrinos: *steady-state sources*



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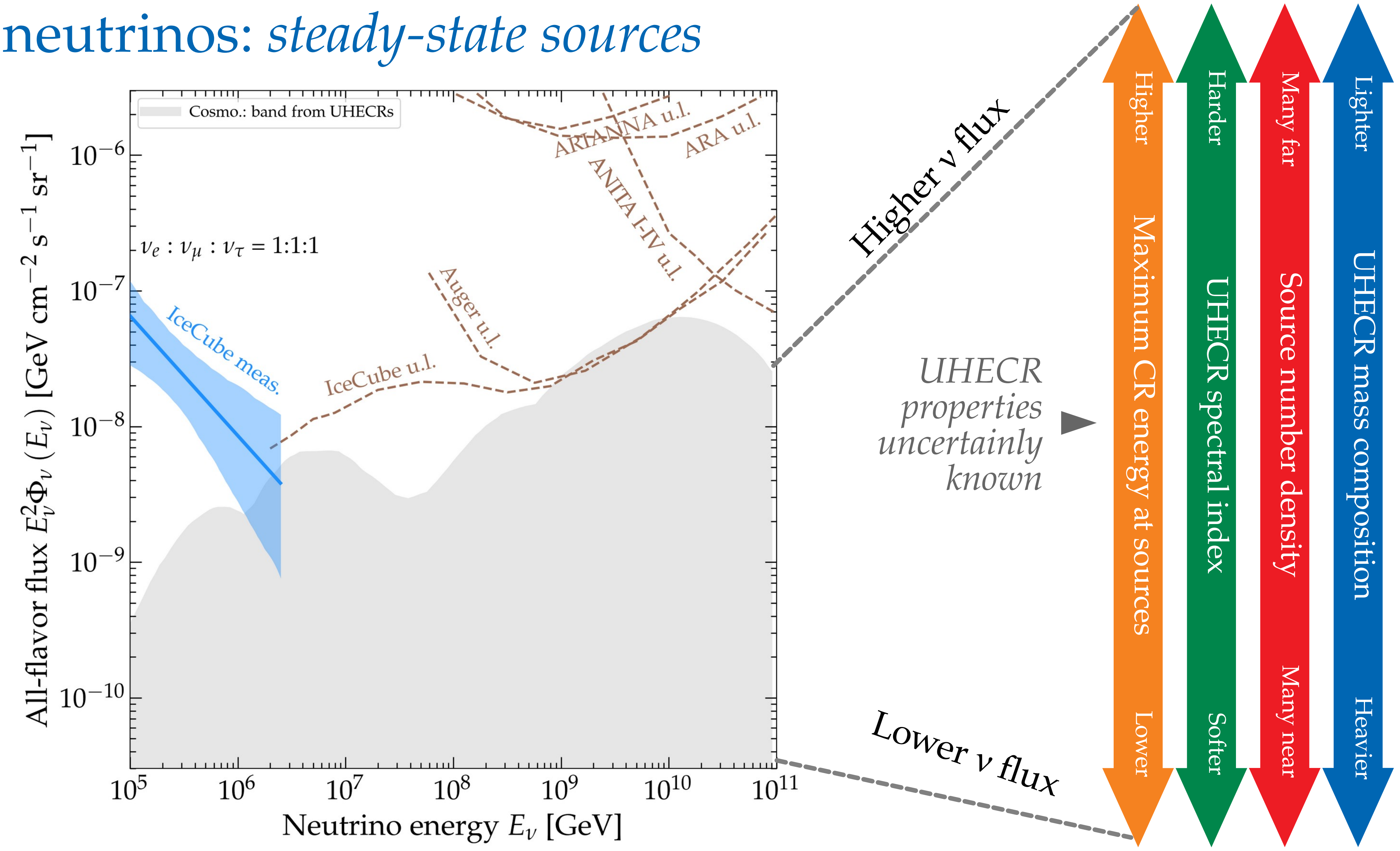
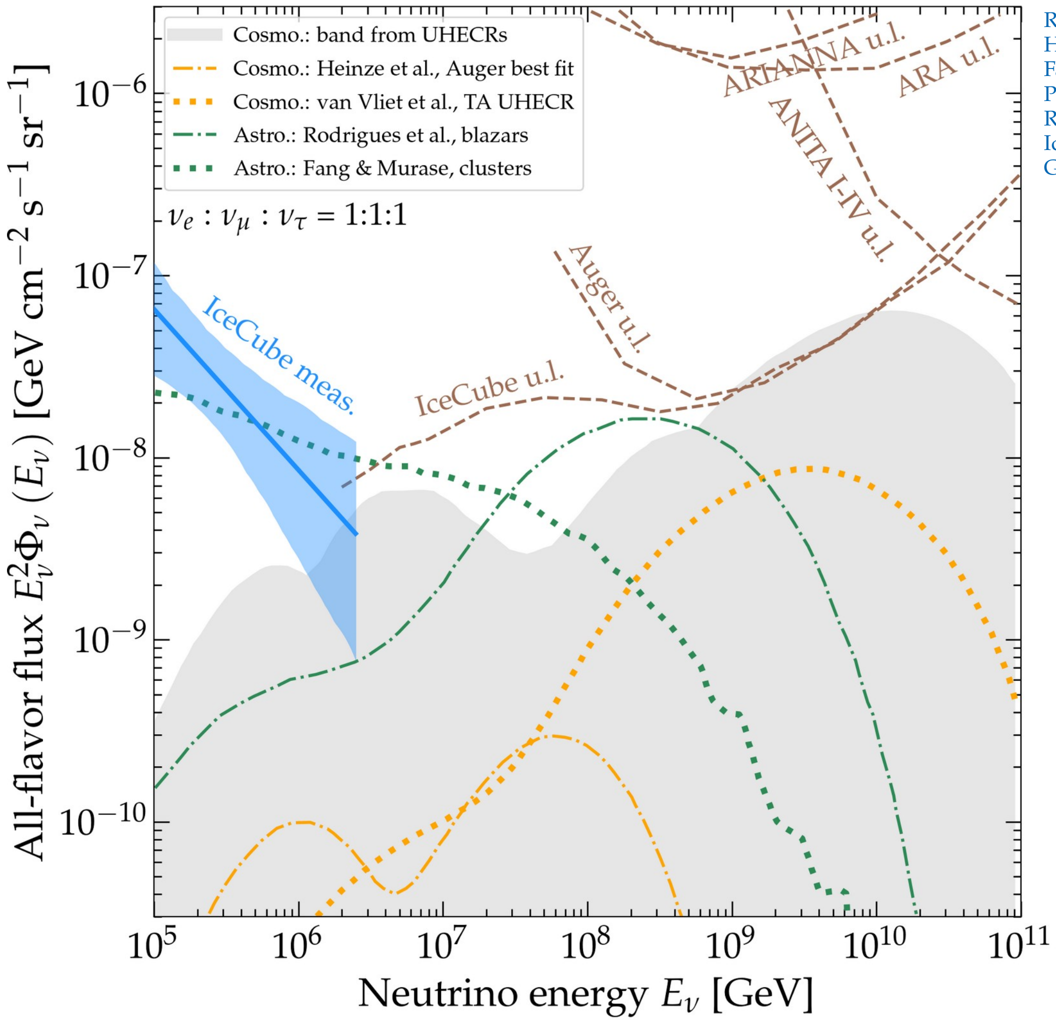
UHE neutrinos: *steady-state sources*



UHE neutrinos: *steady-state sources*



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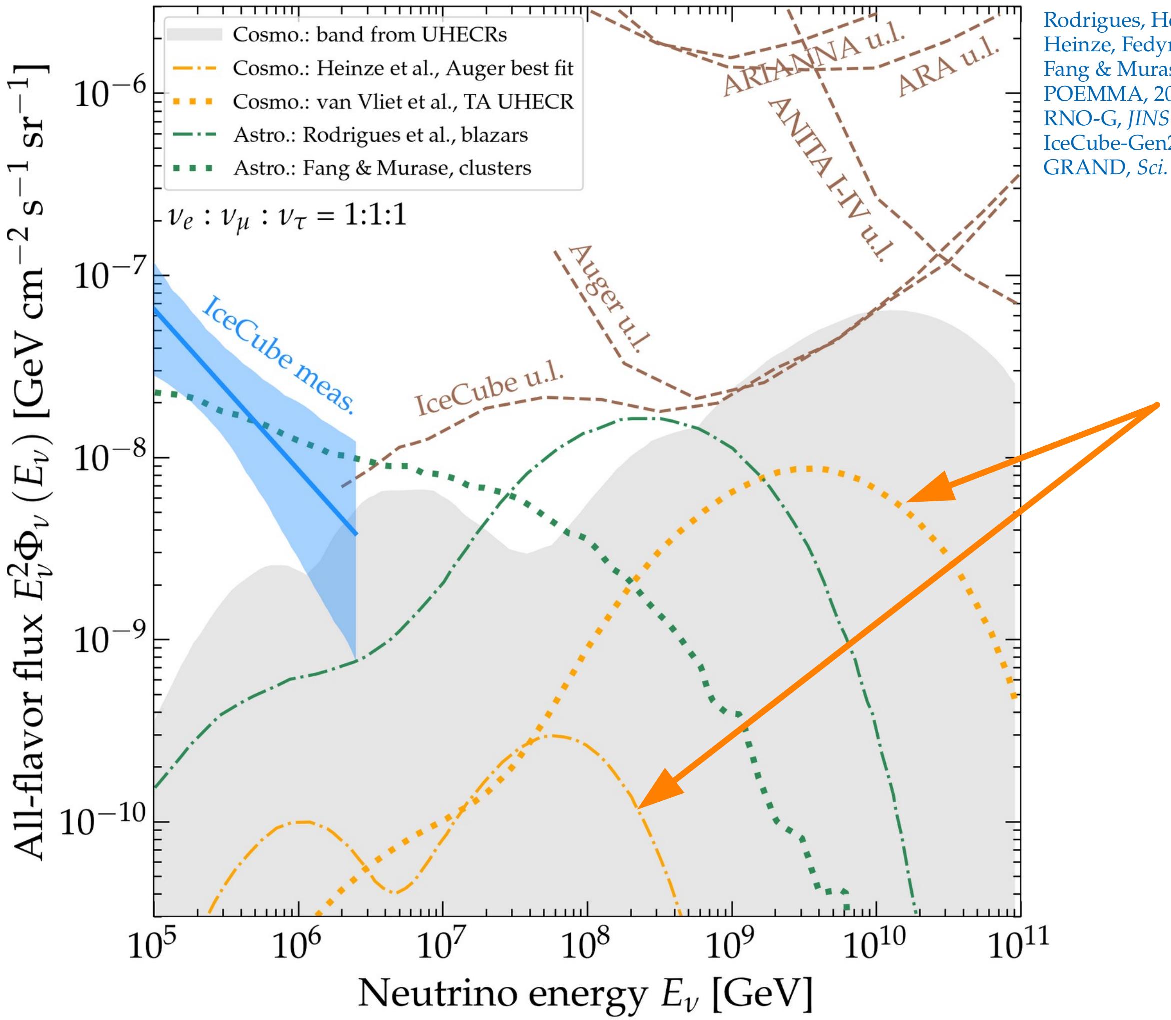
UHE neutrinos: *steady-state sources*



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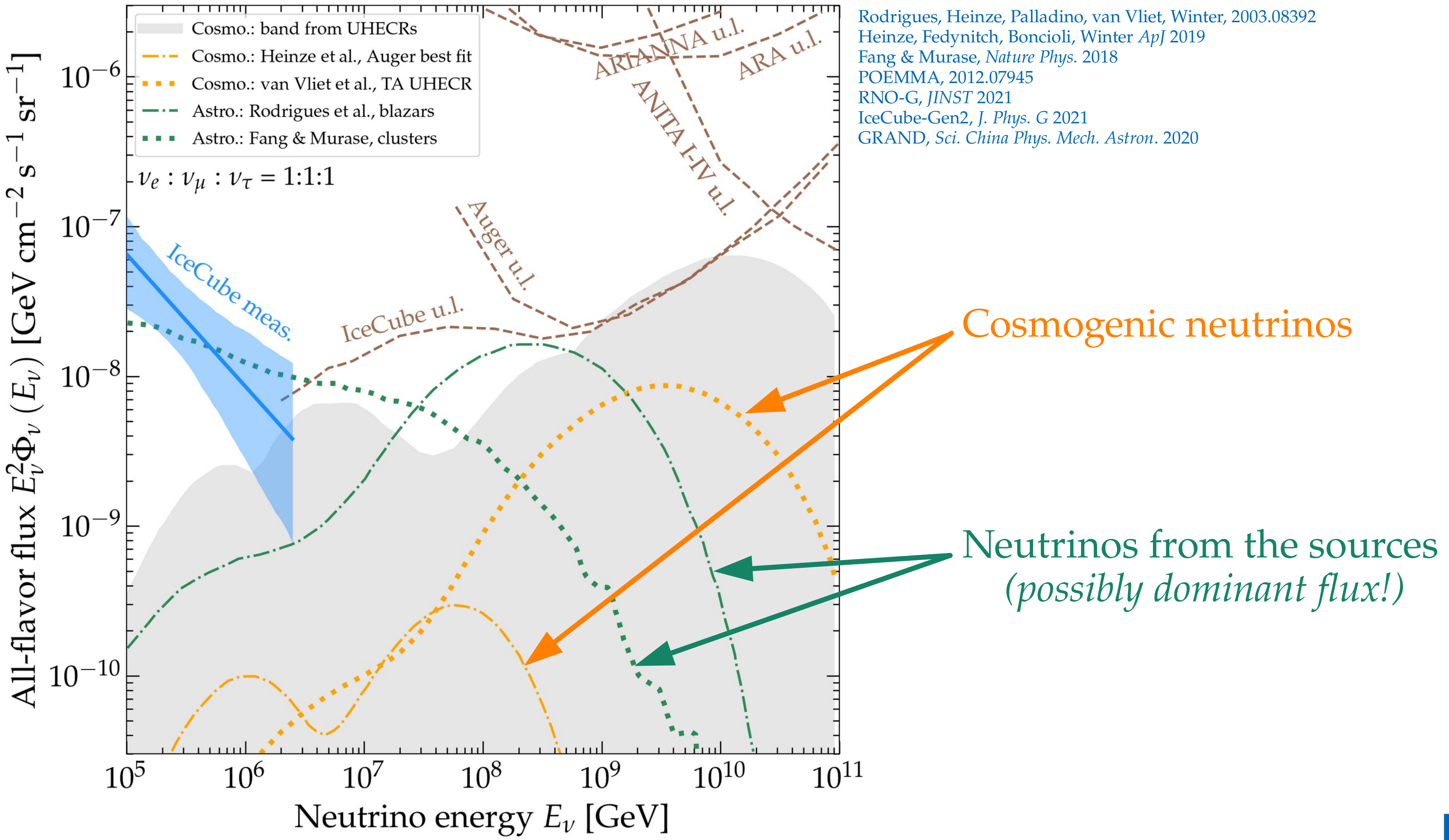
UHE neutrinos: *steady-state sources*



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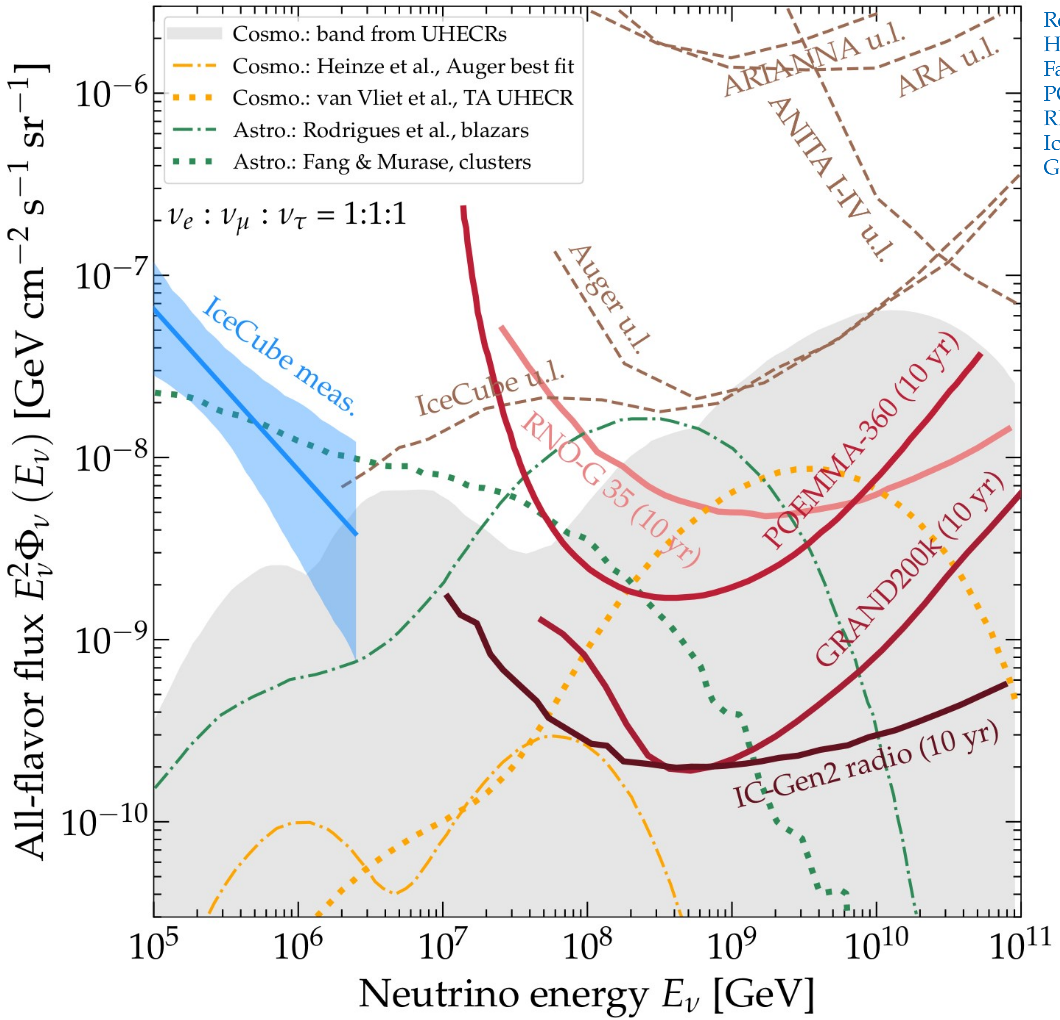
UHE neutrinos: *steady-state sources*



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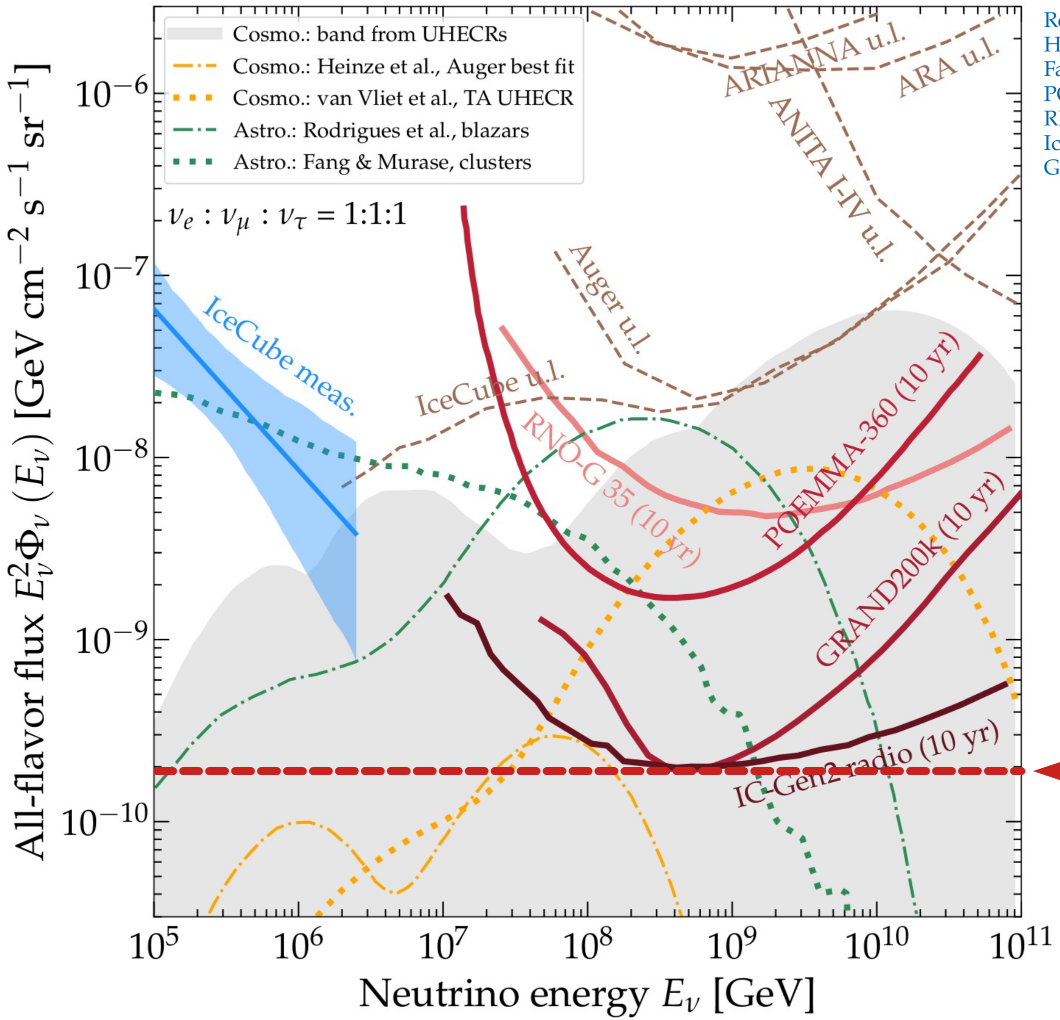
UHE neutrinos: *steady-state sources*



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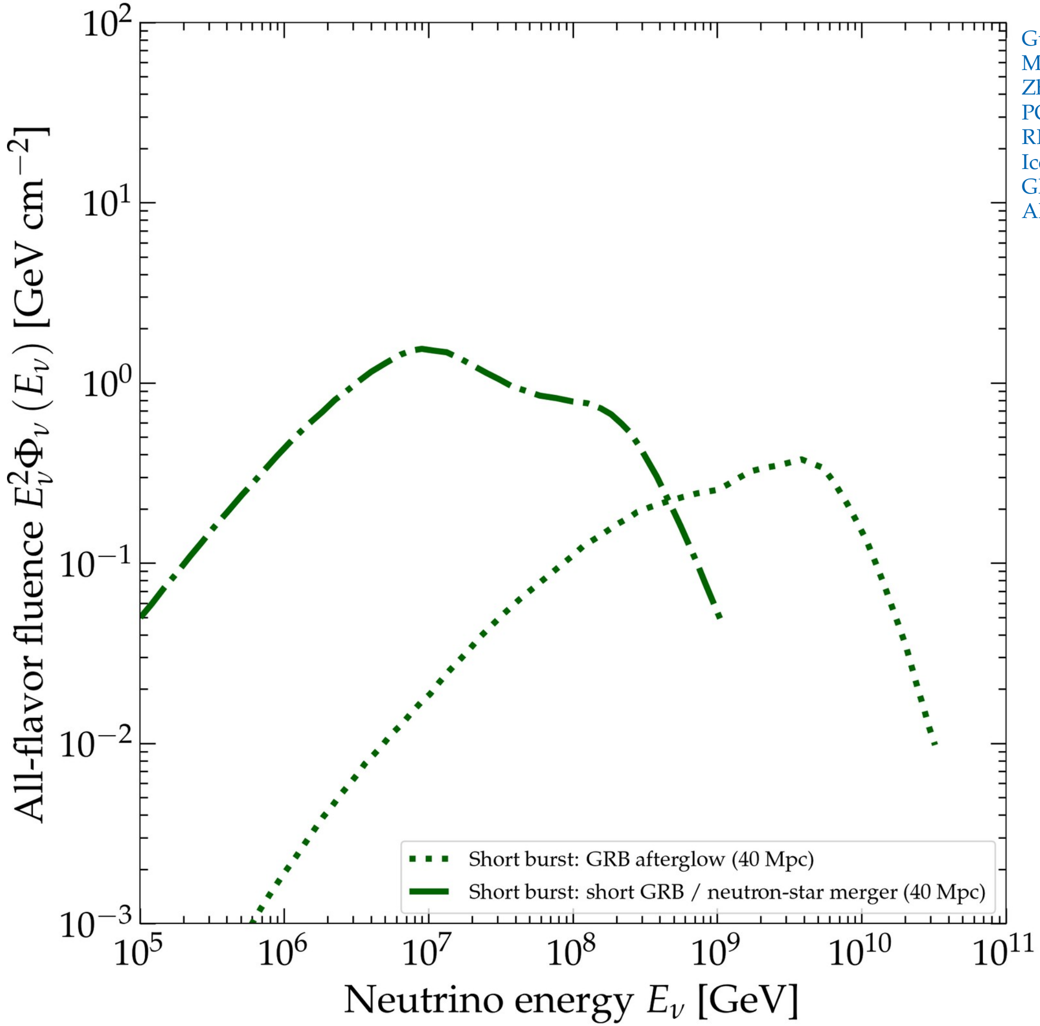
POEMMA, 2012.07945
RNO-G, *JINST* 2021
IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron*. 2020

Ultimate target sensitivity for next-gen detectors

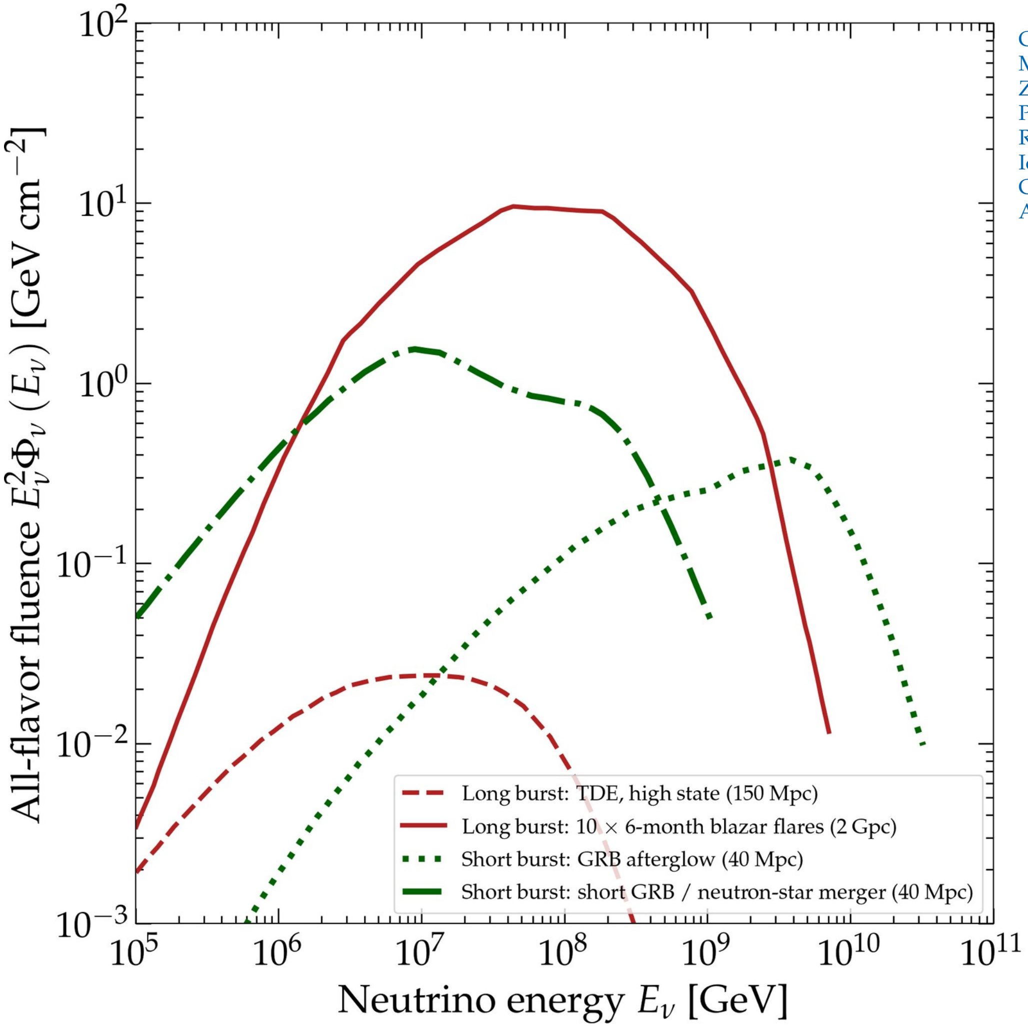
(if protons are ~10% of the highest-energy UHECRs)

UHE neutrinos: *transient sources*



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

UHE neutrinos: *transient sources*



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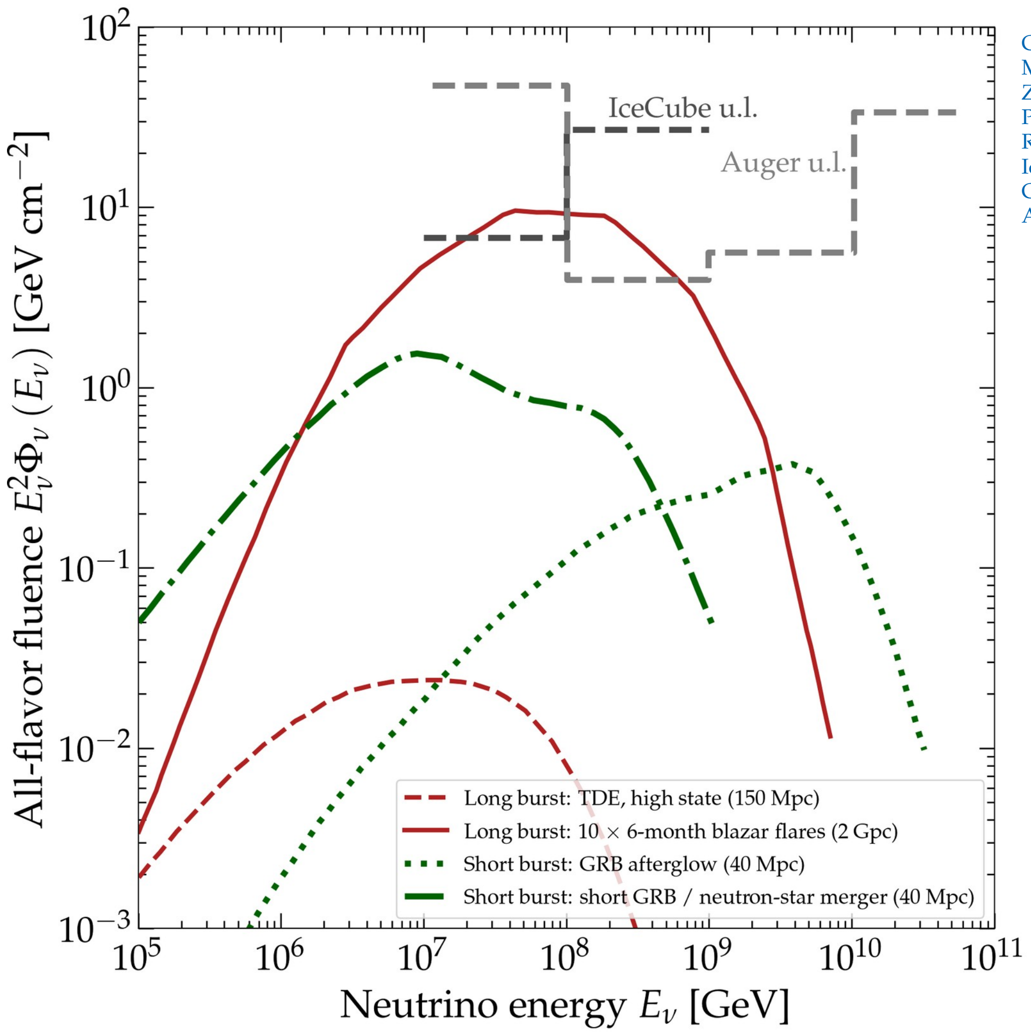
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

UHE neutrinos: *transient sources*



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Murase, *PRD* 2017
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IceCube-Gen2, *J. Phys. G* 2021
GRAND, *Sci. China Phys. Mech. Astron.* 2020
ANTARES, IceCube, Auger, LIGO, Virgo, *ApJ* 2017

PLEnuM

Characterizing the diffuse power-law flux in PLEνM

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

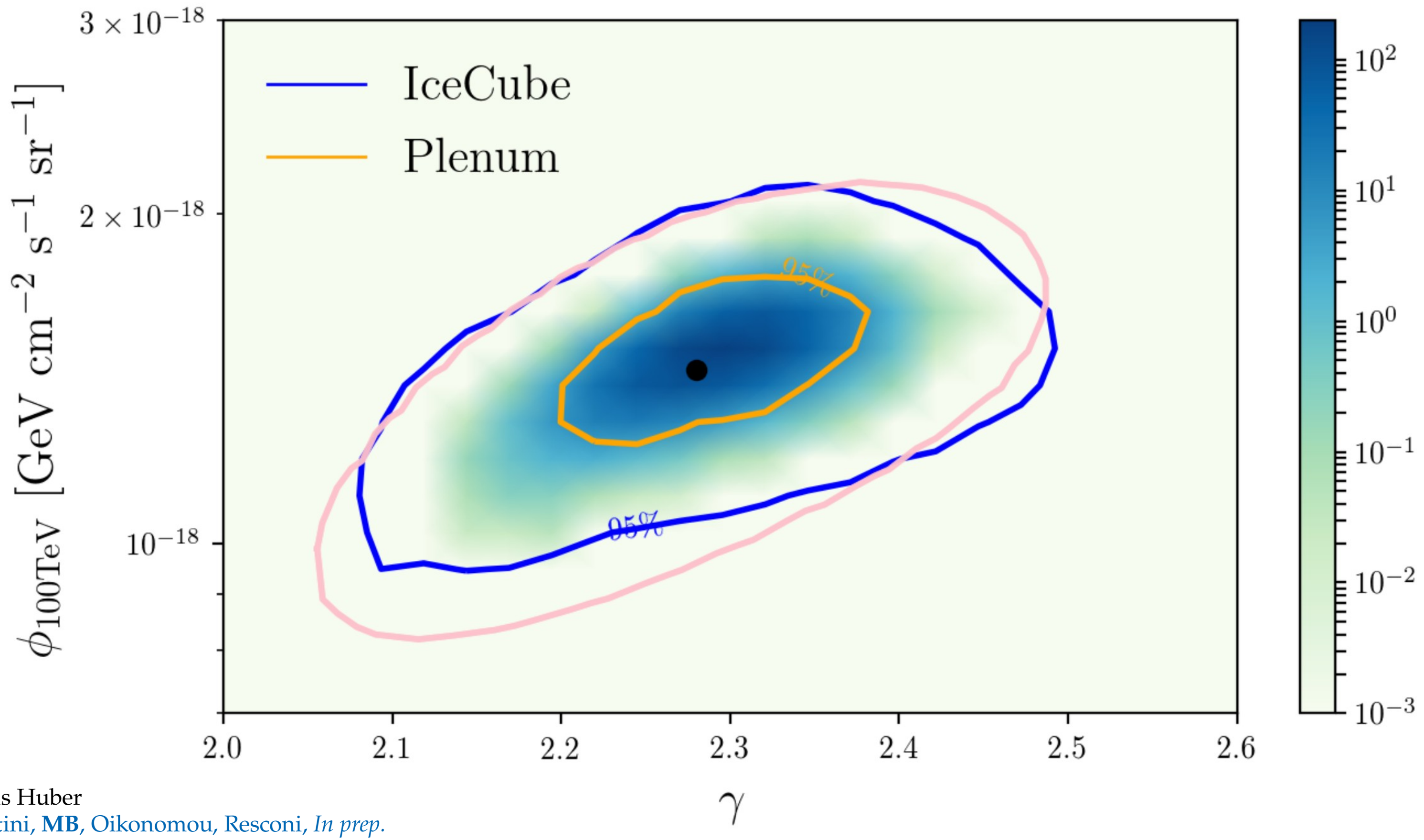
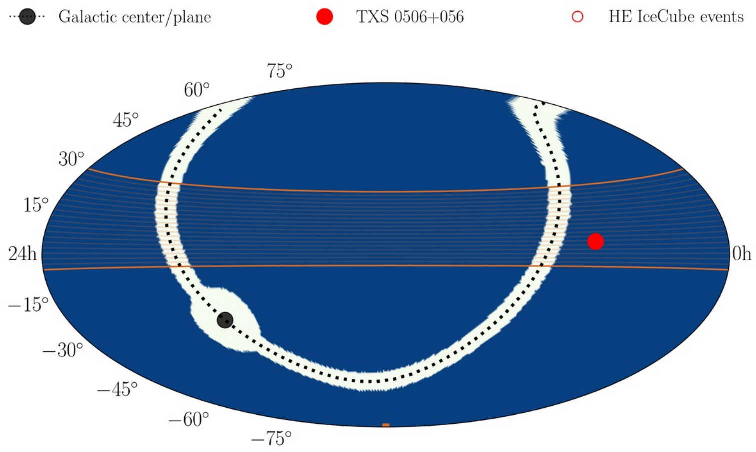


Figure courtesy of Matthias Huber

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

Discovering a Galactic ν flux in PLEνM

Galactic emission template:



Flux uniformly distributed:

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

5σ discovery potential (GC only)

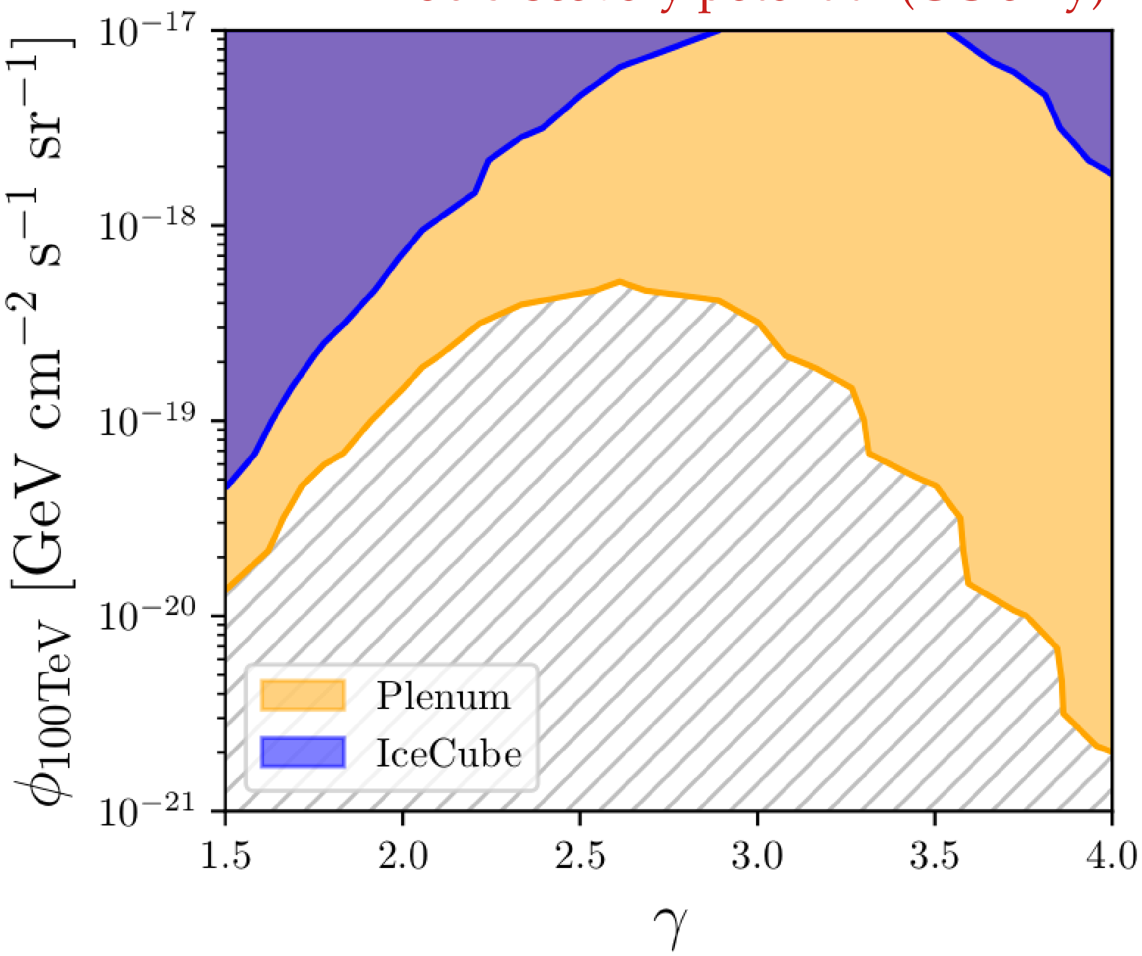


Figure courtesy of Matthias Huber

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