Perspectives of multimessenger astrophysics

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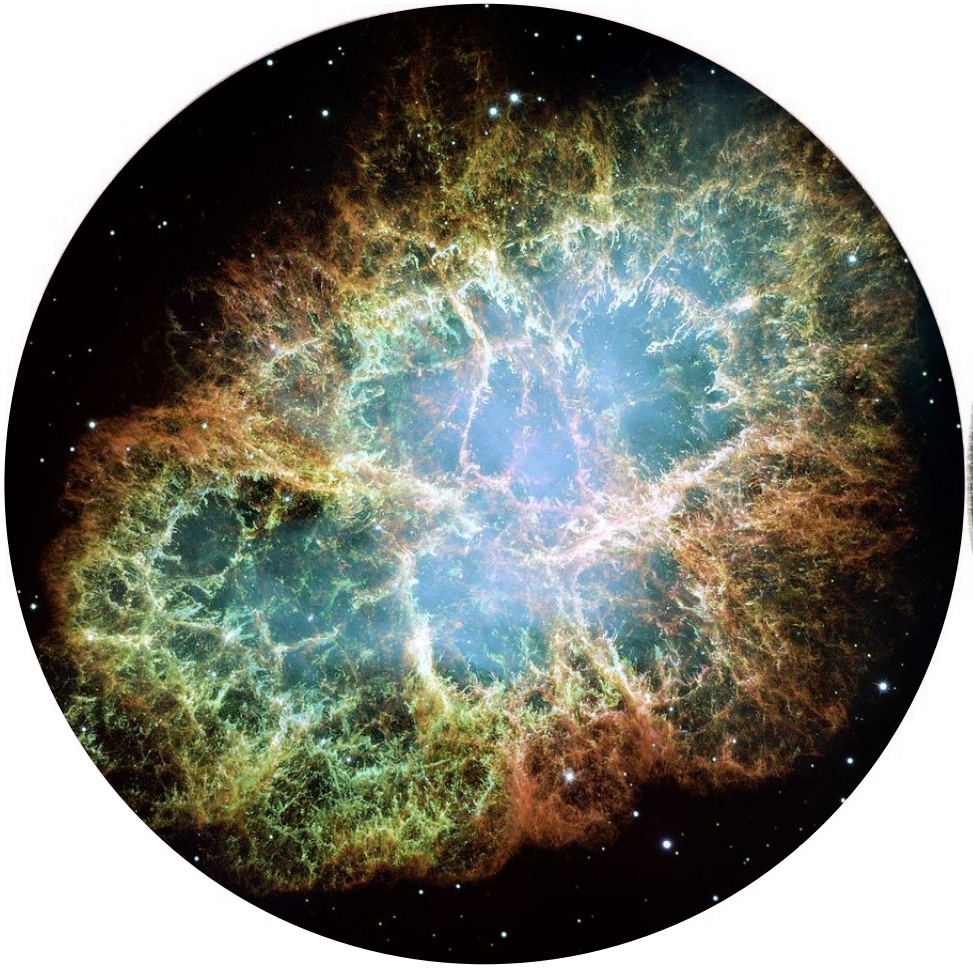
Niels Bohr Institute, University of Copenhagen

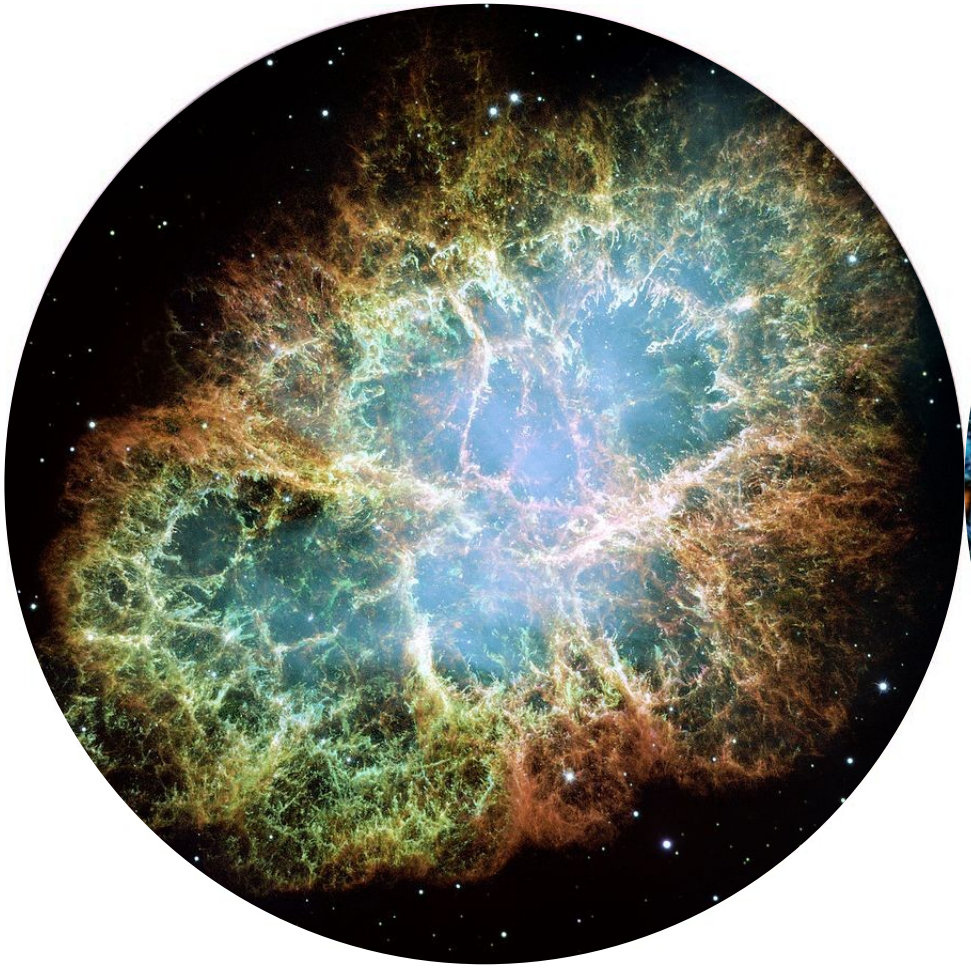
UNIVERSITY OF COPENHAGEN

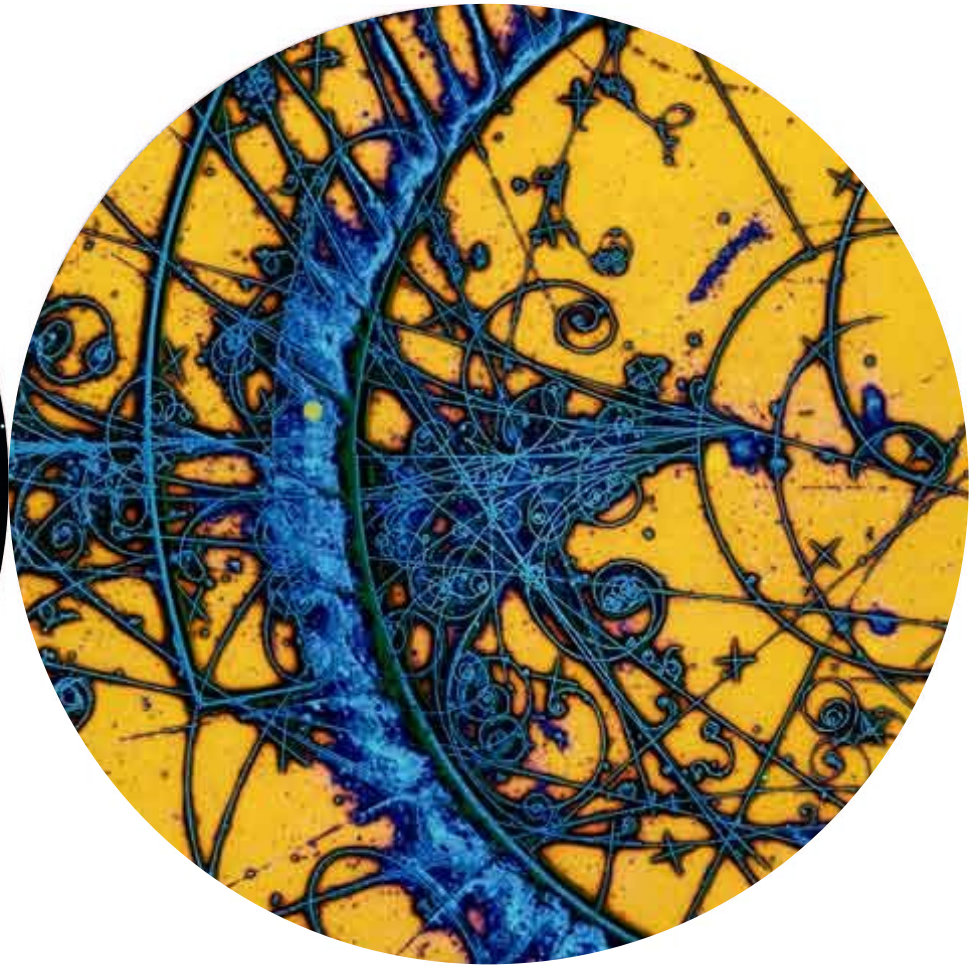
VILLUM FONDEN

Invisibles23 School
August 21–26, 2023



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





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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 with high-energy cosmic neutrinos

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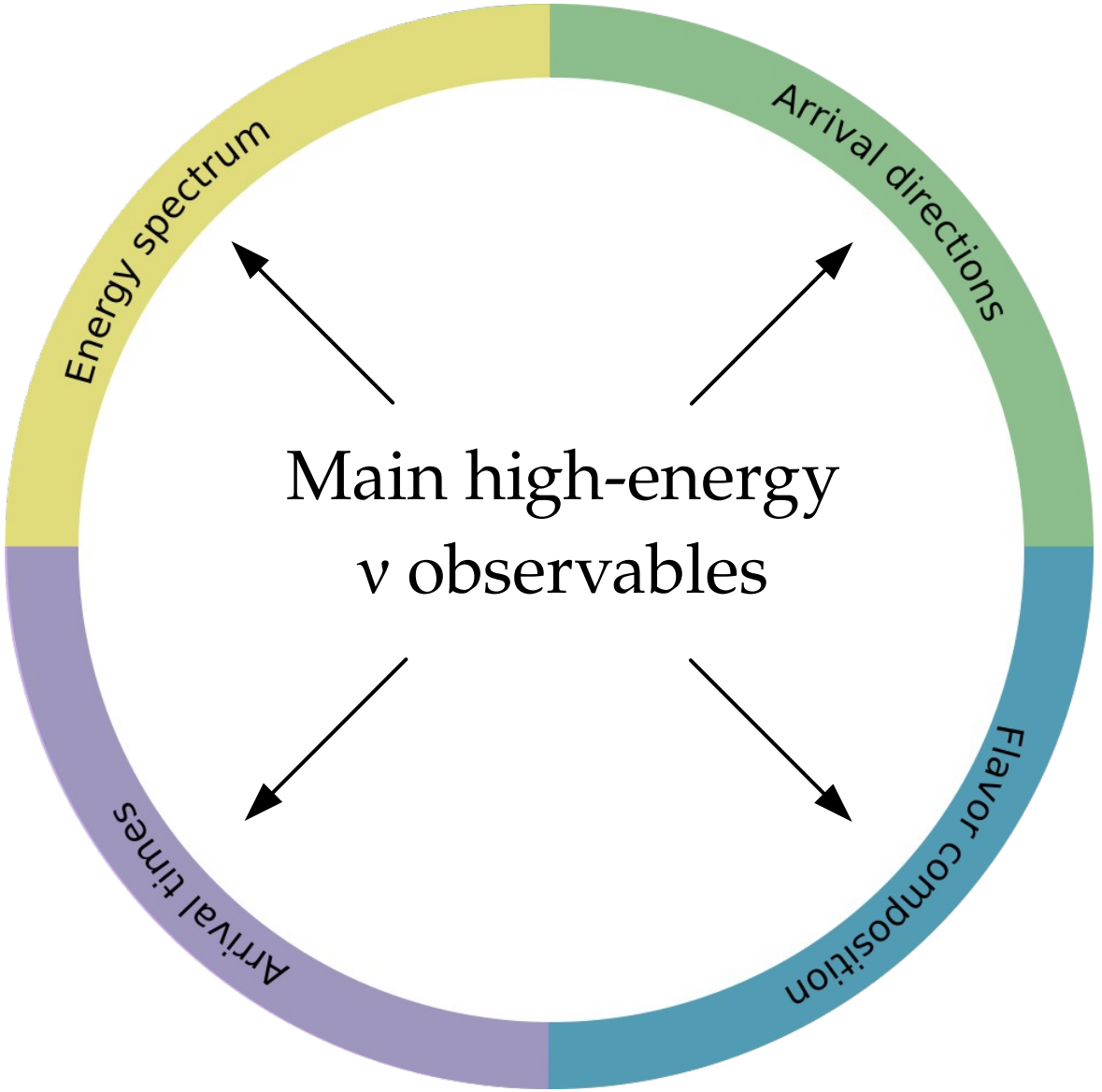
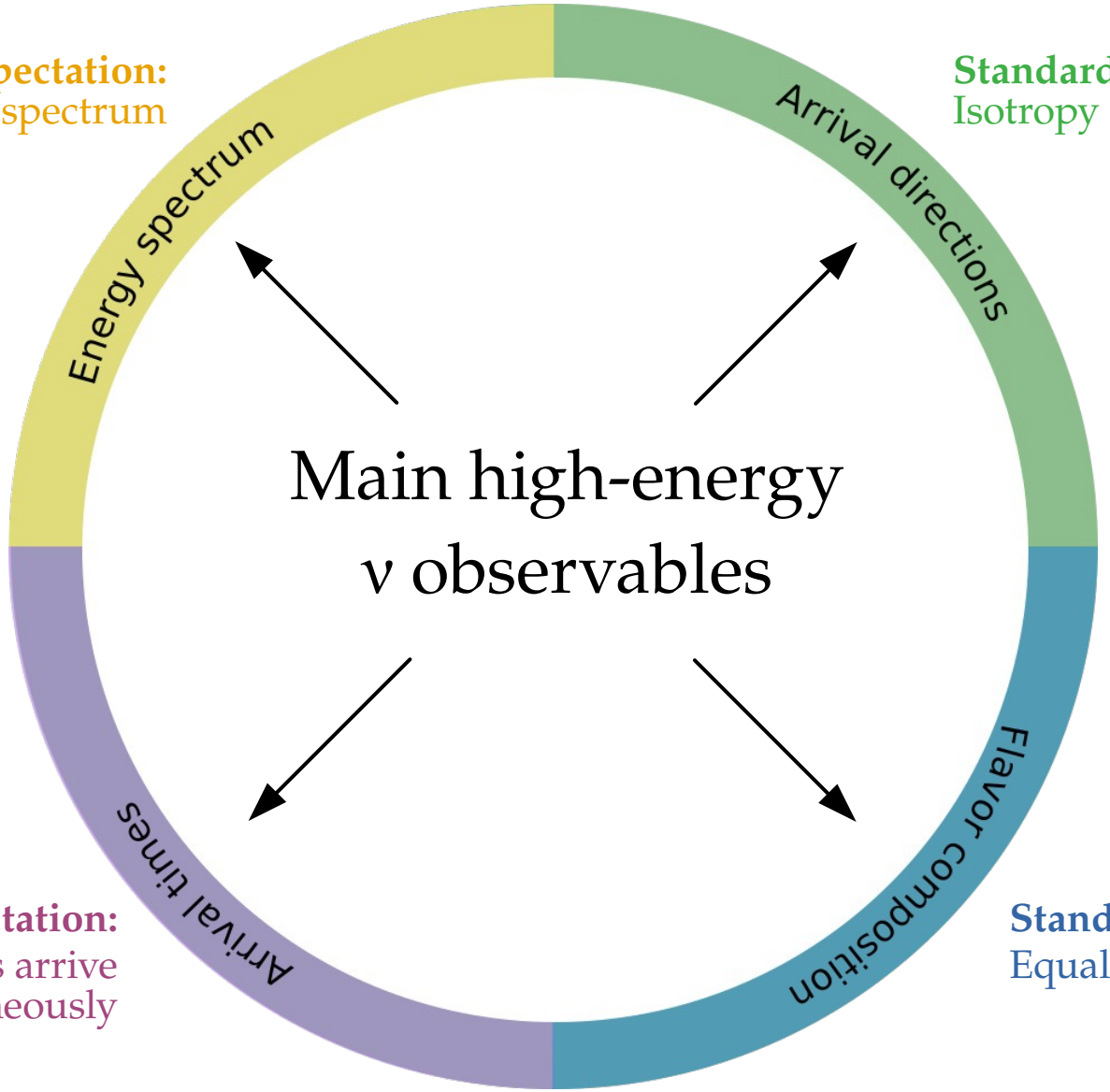

Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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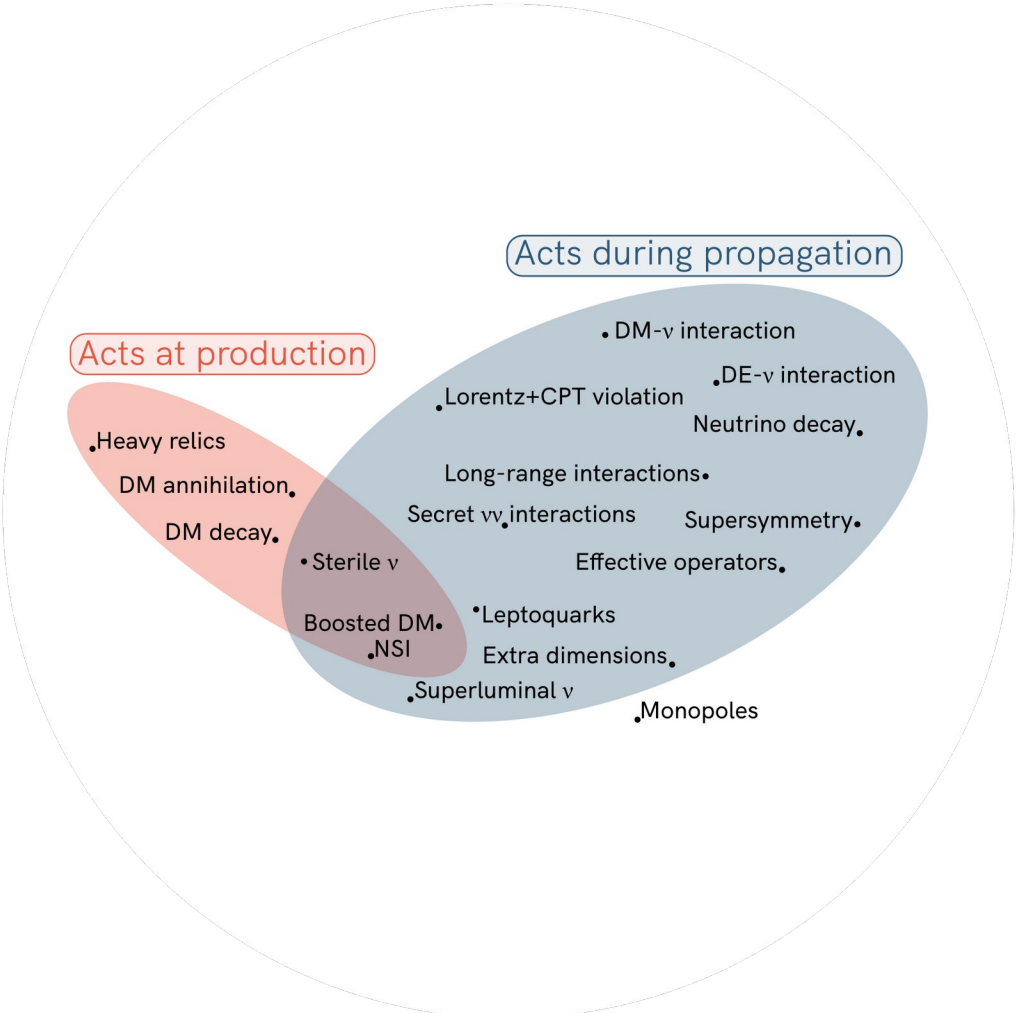

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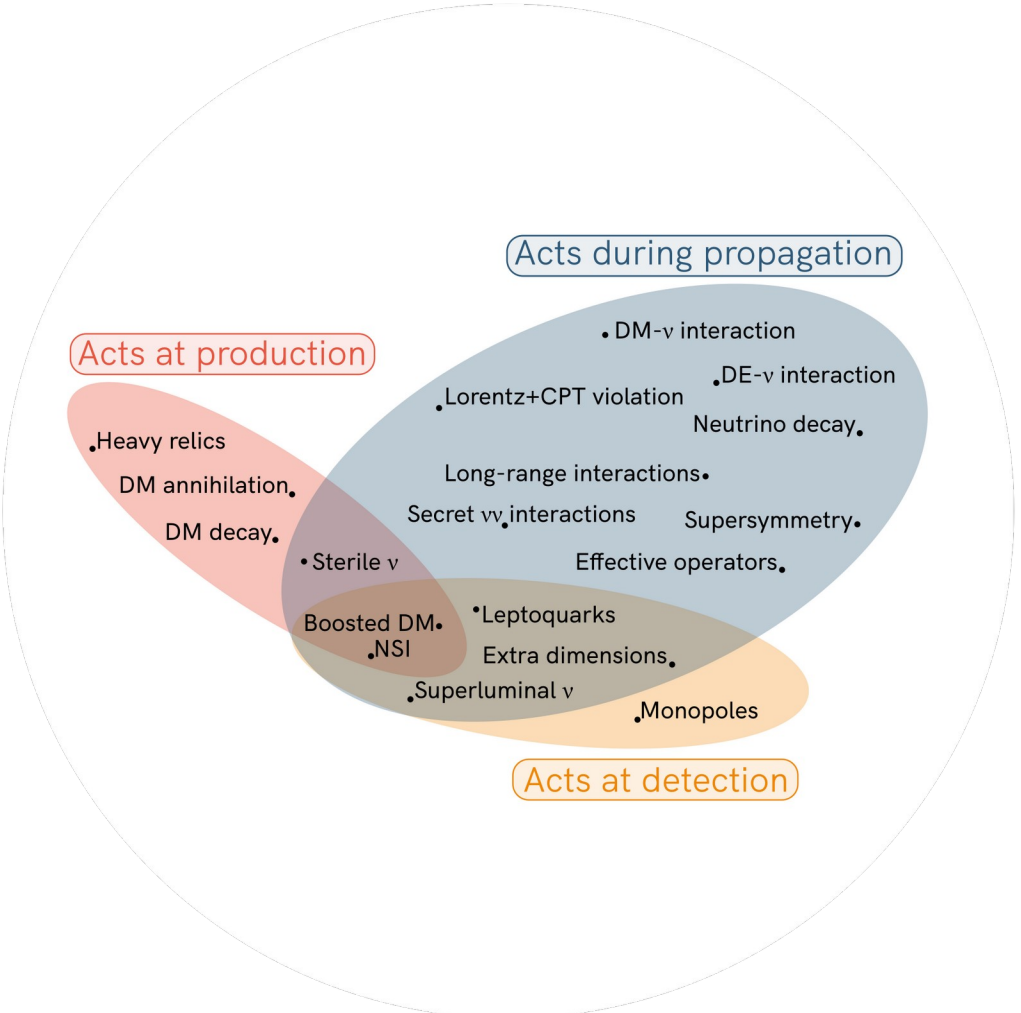

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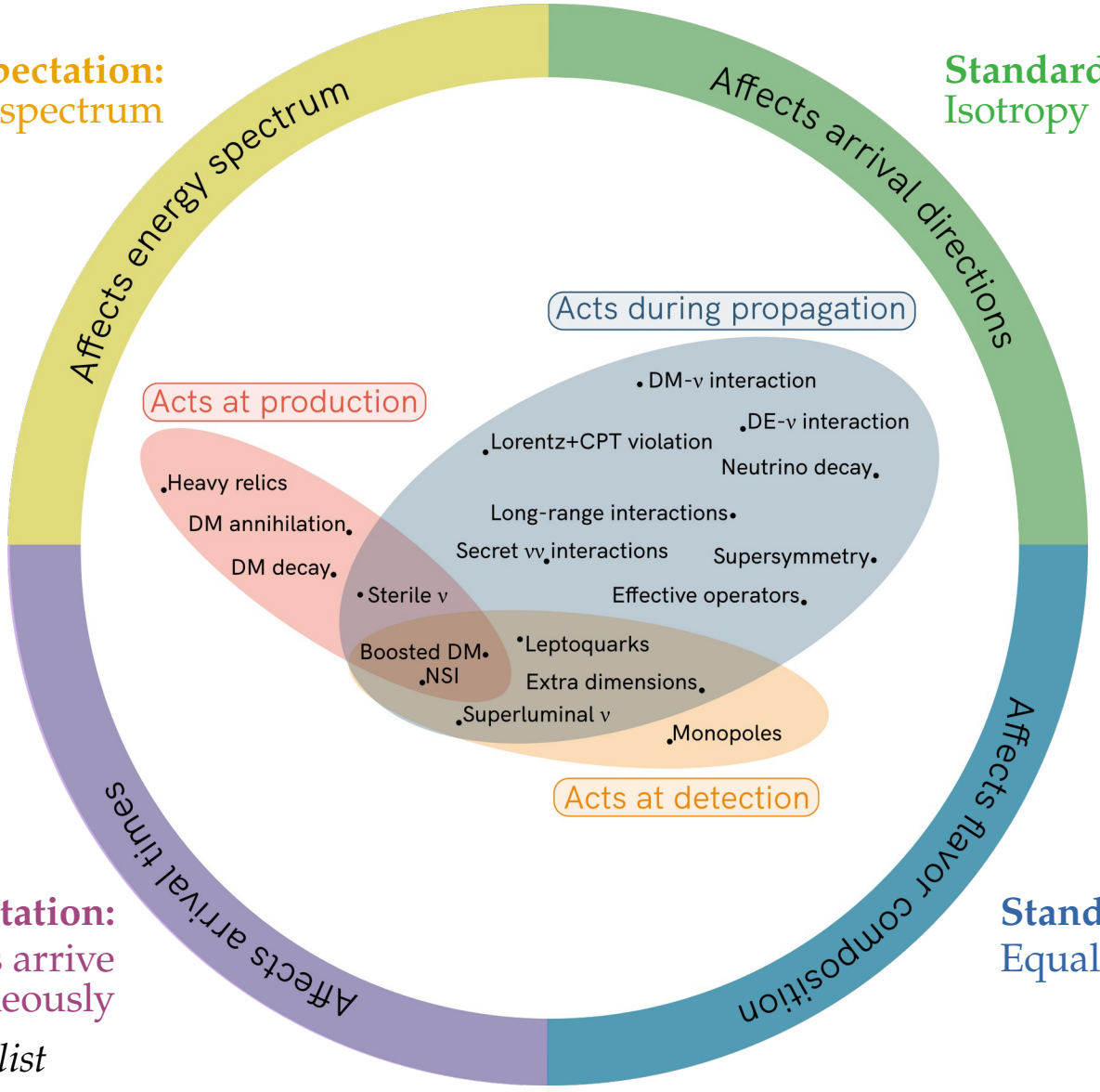

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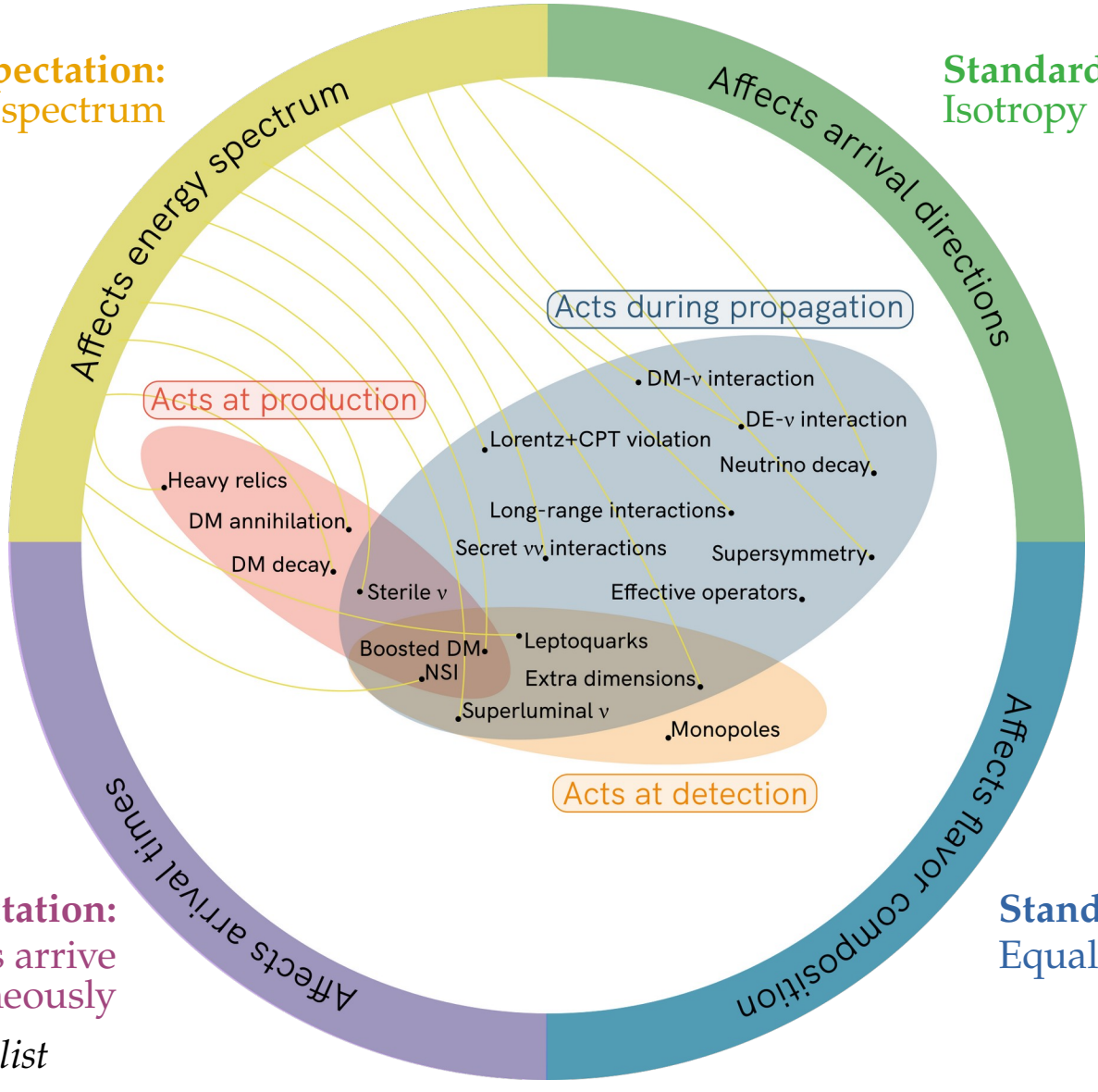

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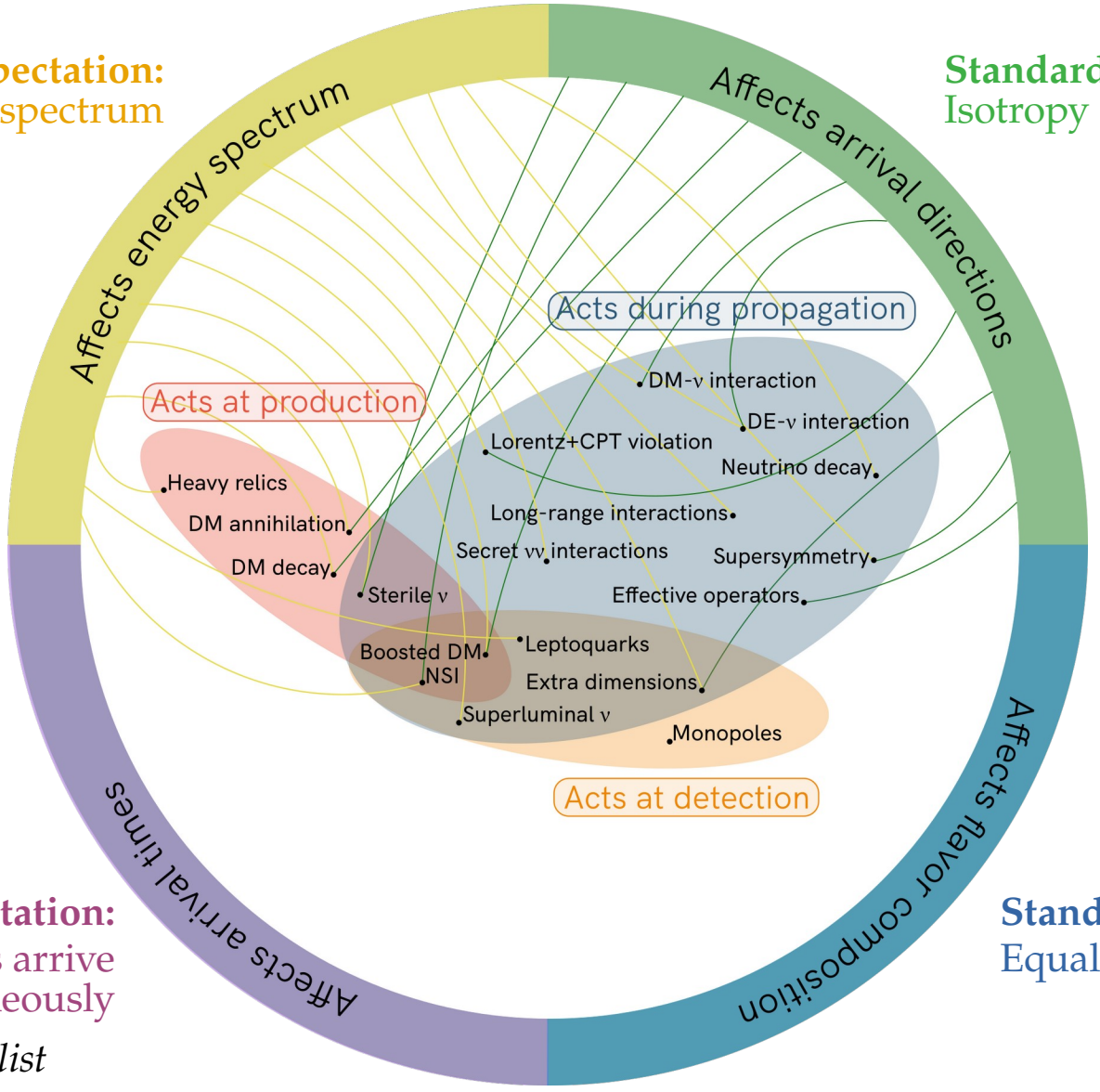

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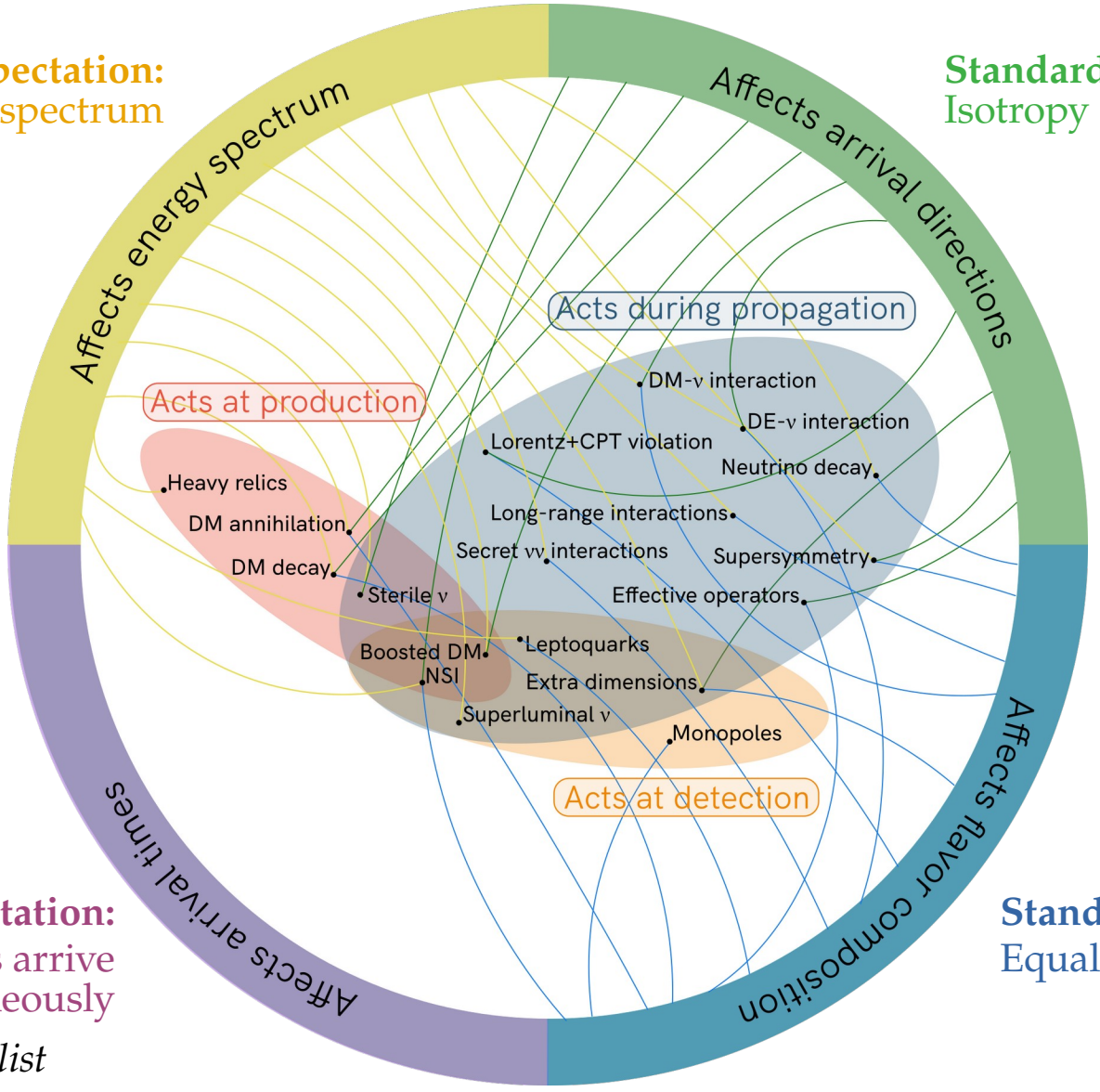

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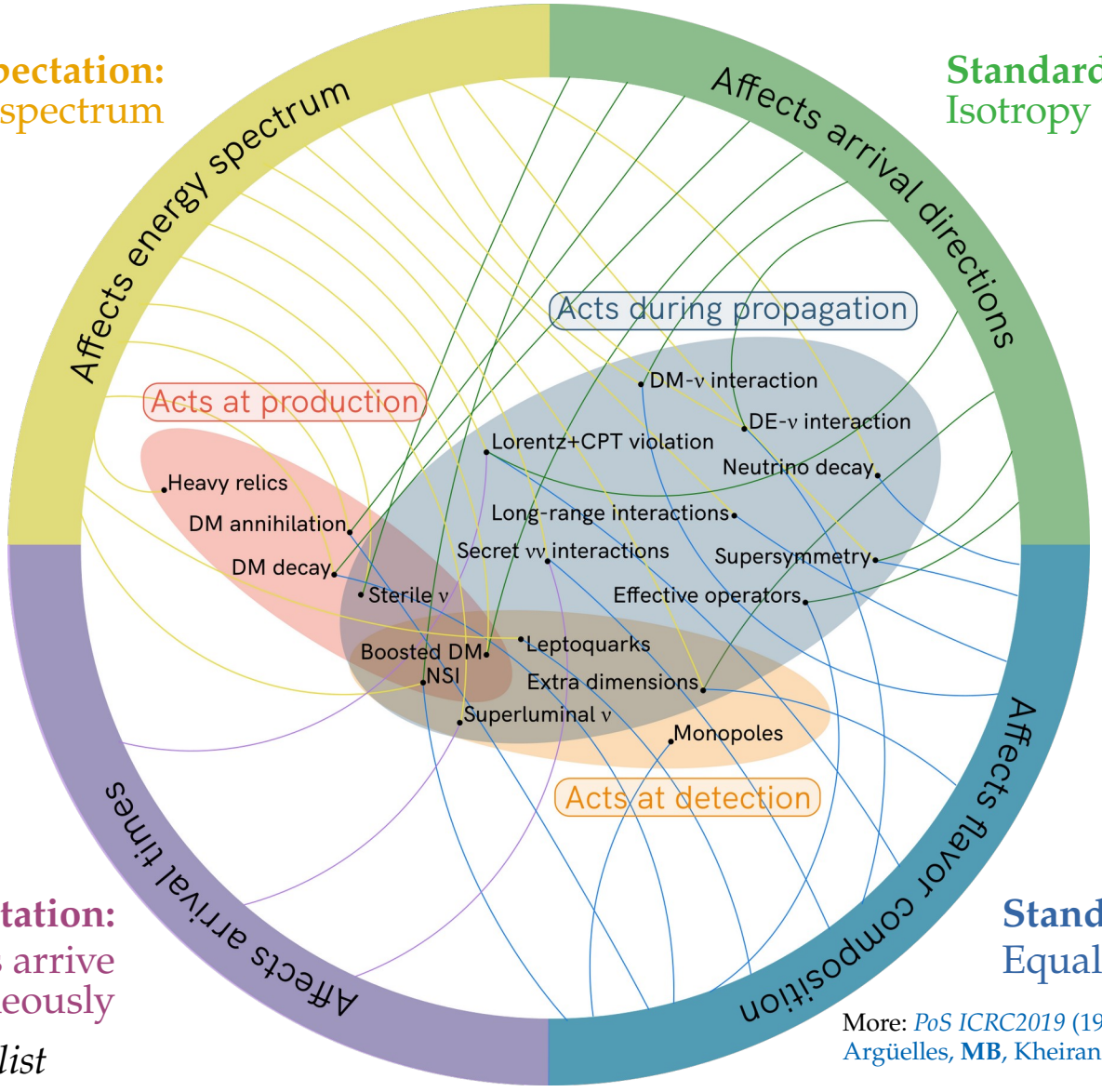

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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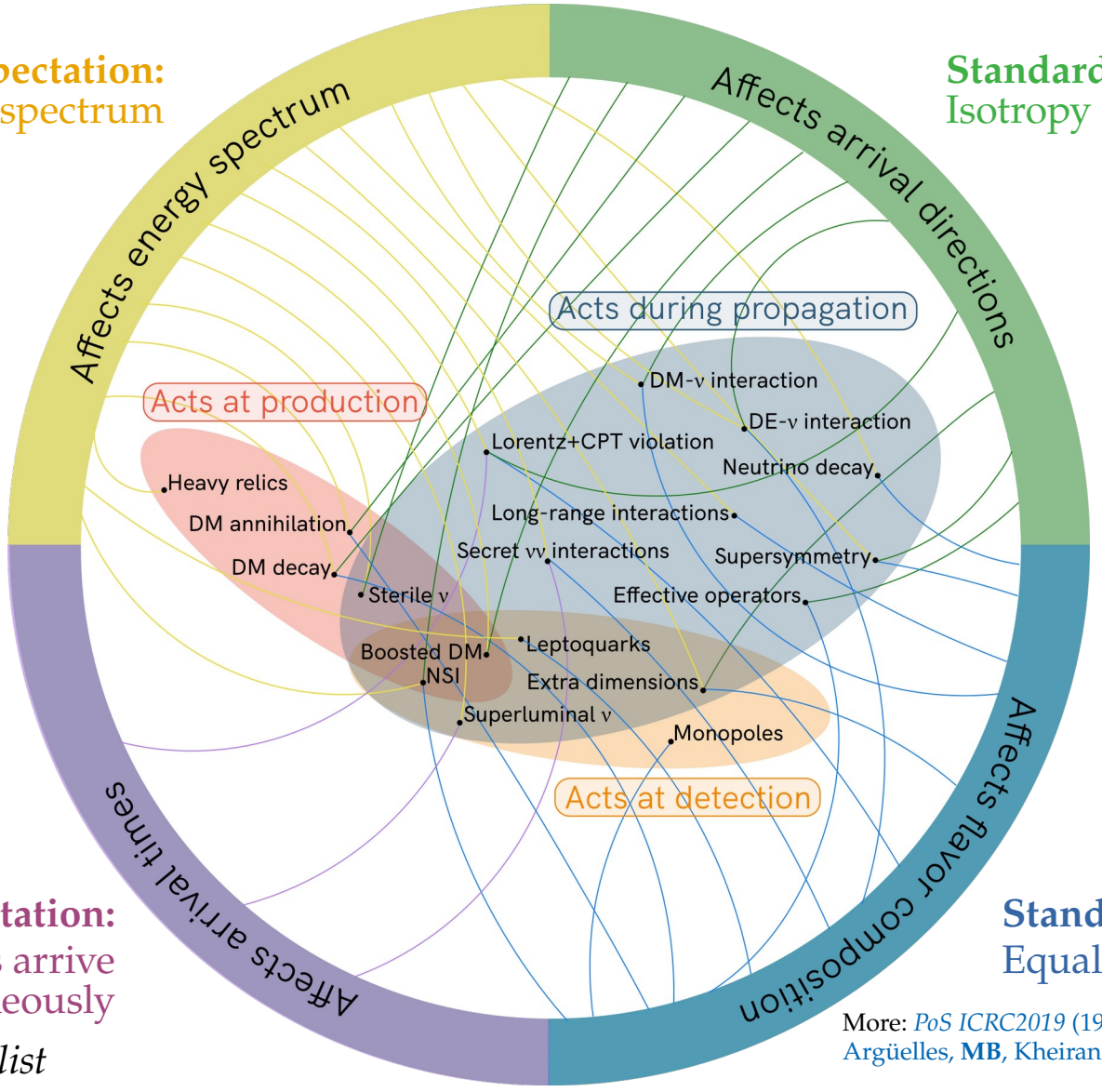

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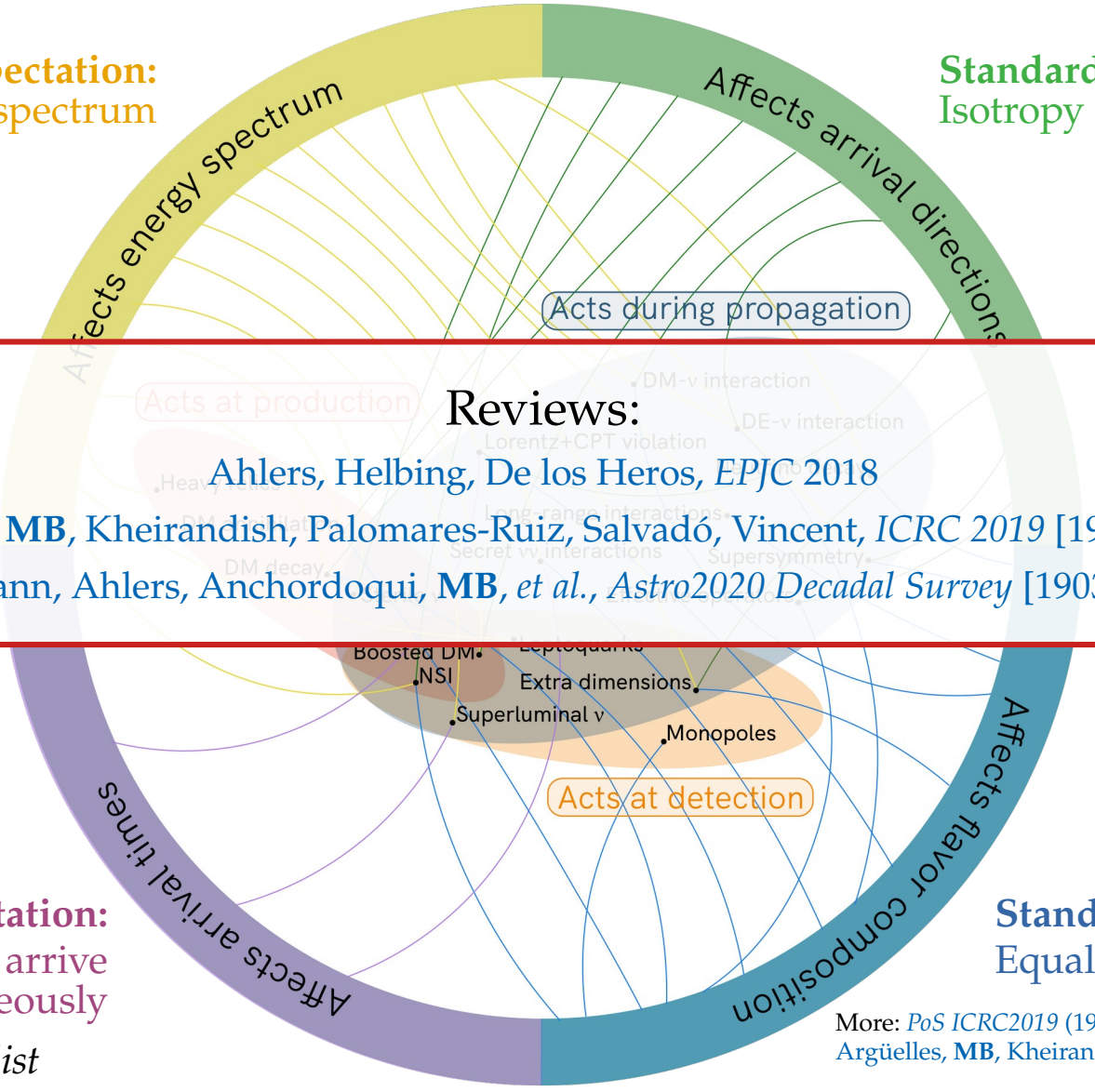

Reviews:

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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A selection of neutrino physics

1. Discovering the Glashow resonance
2. Neutrino-matter cross section
3. New physics via flavor
4. Secret neutrino interactions
5. Neutrino decay

1. Glashow resonance: *Long-sought, finally seen*

First observation of a Glashow resonance

Predicted in 1960:

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

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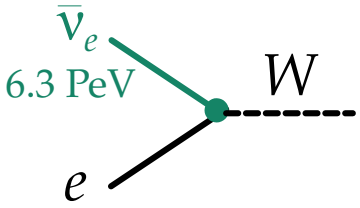

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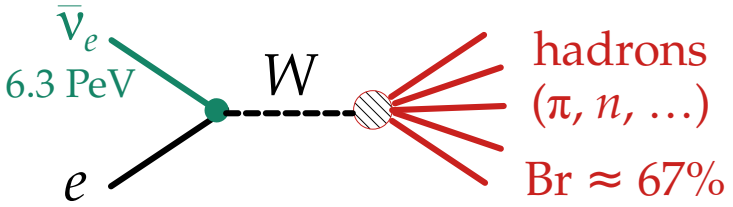

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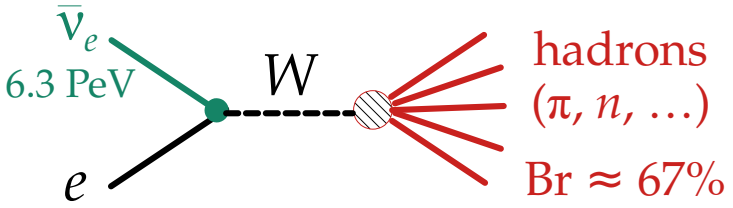

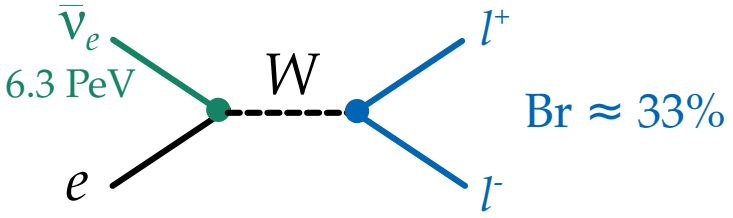

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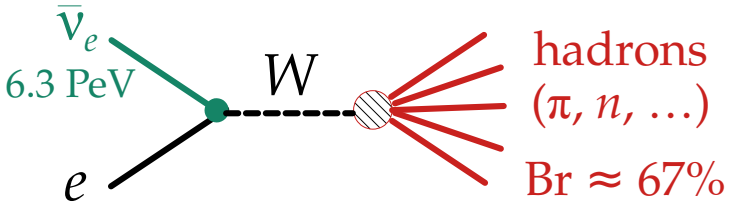

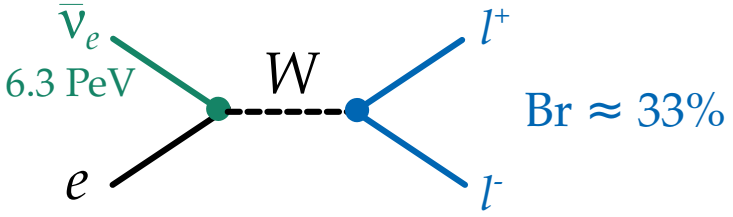

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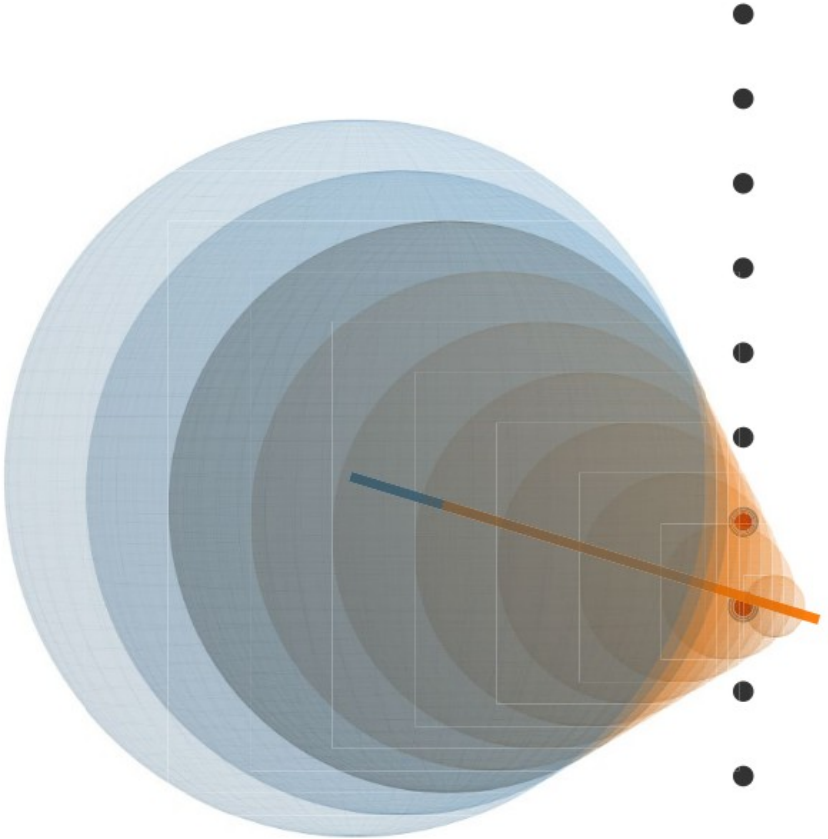

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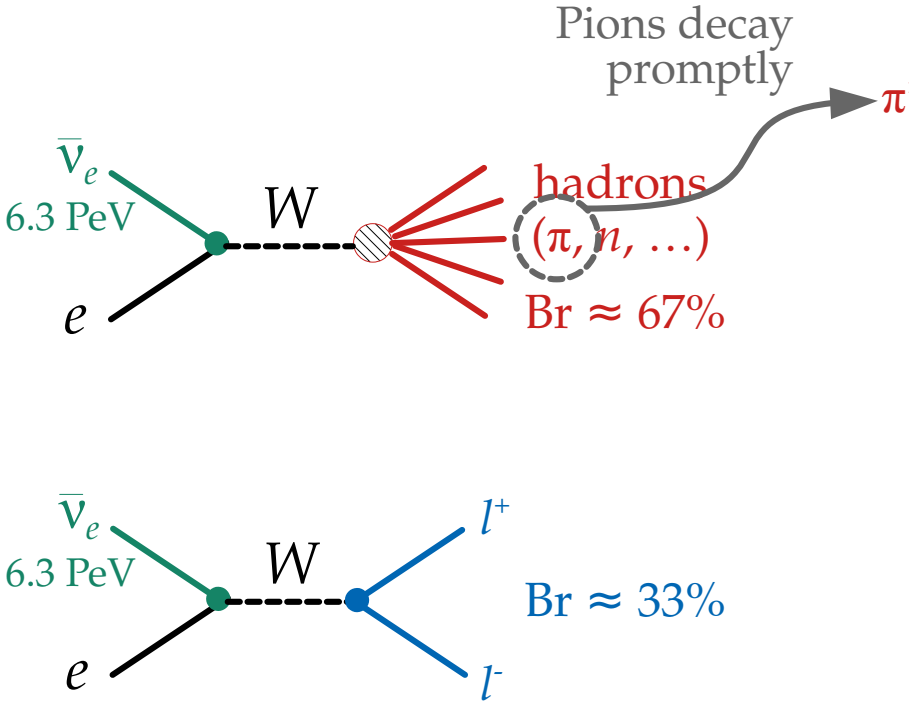

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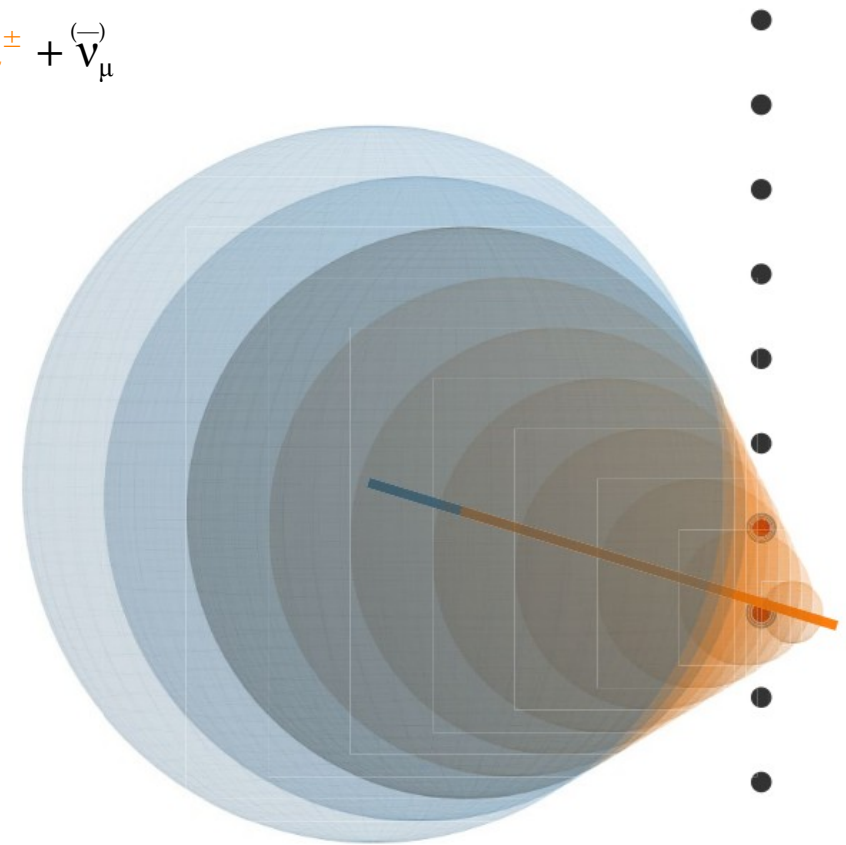

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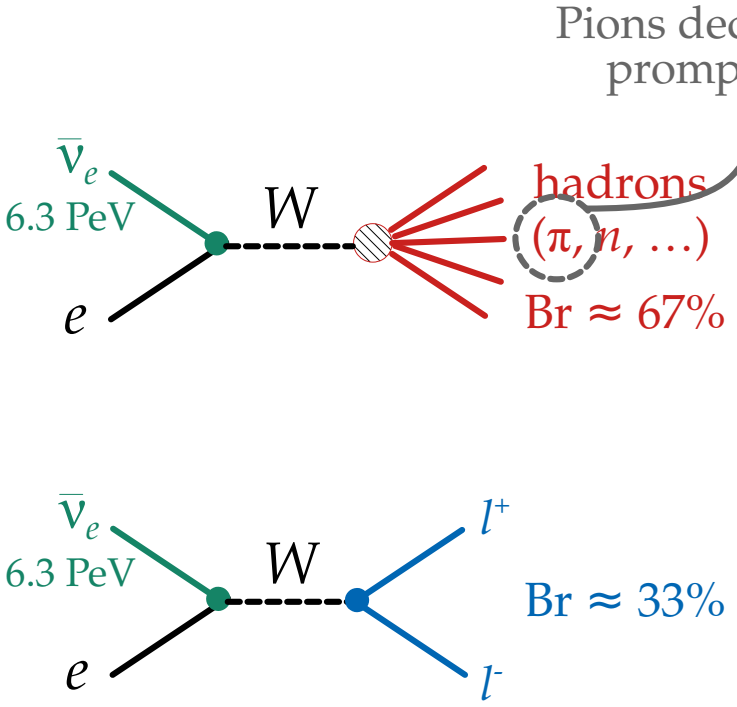

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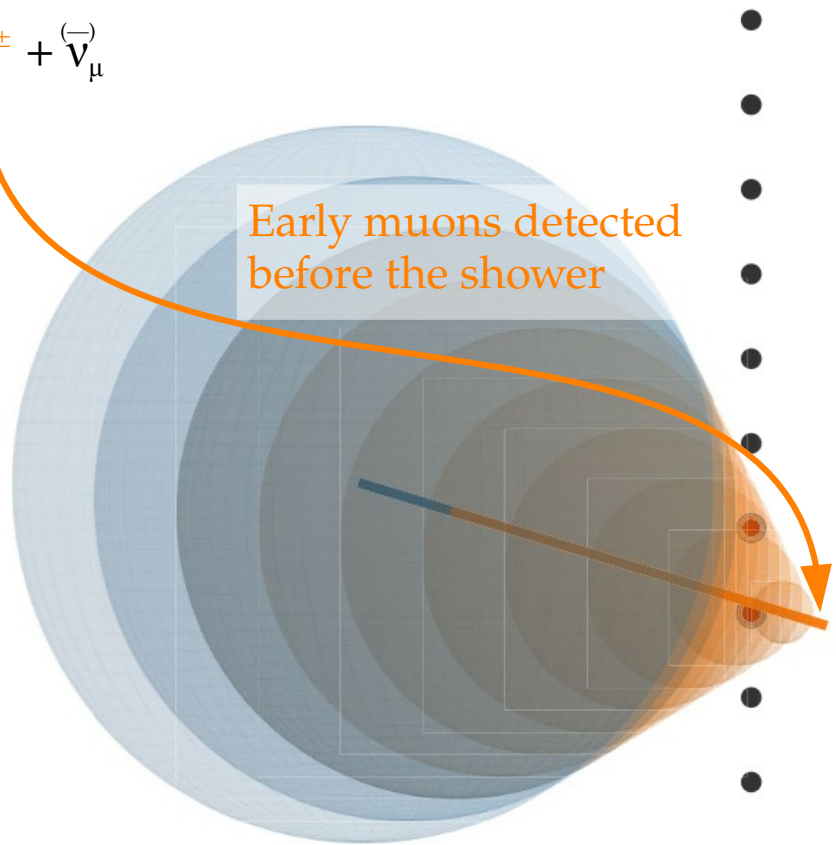

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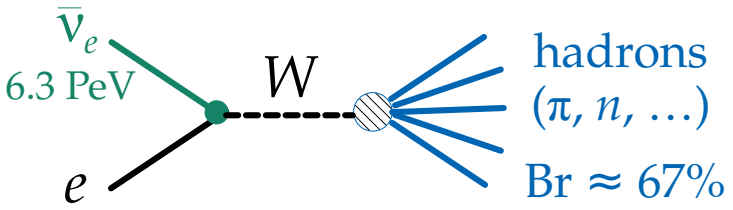

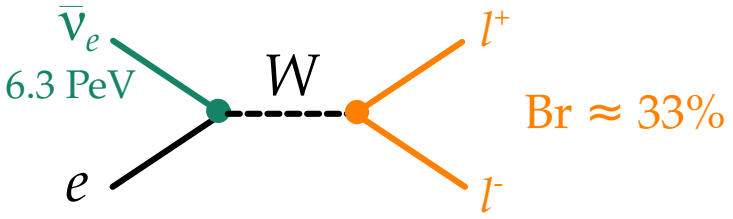

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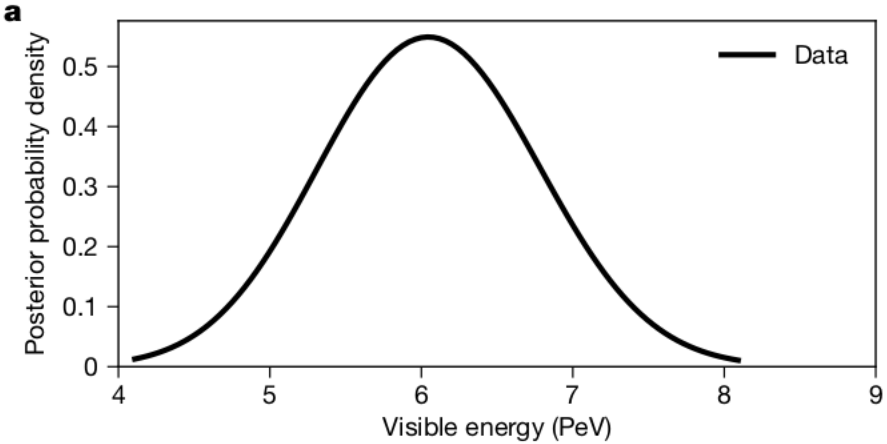

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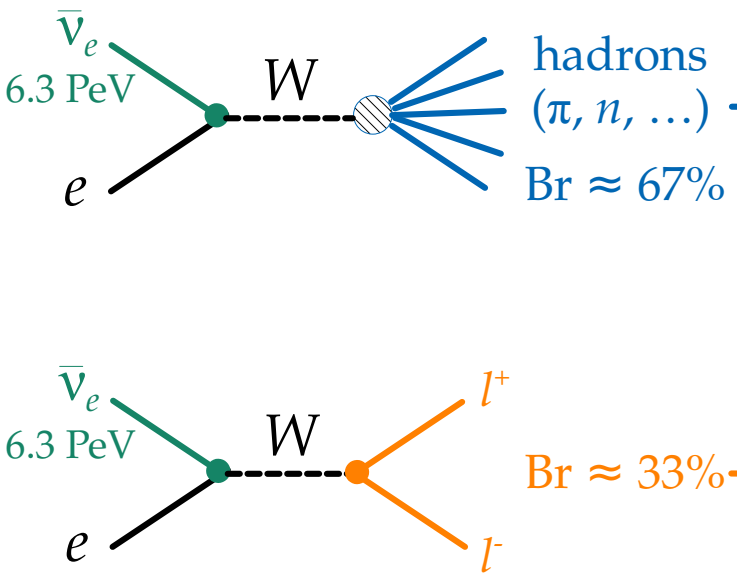

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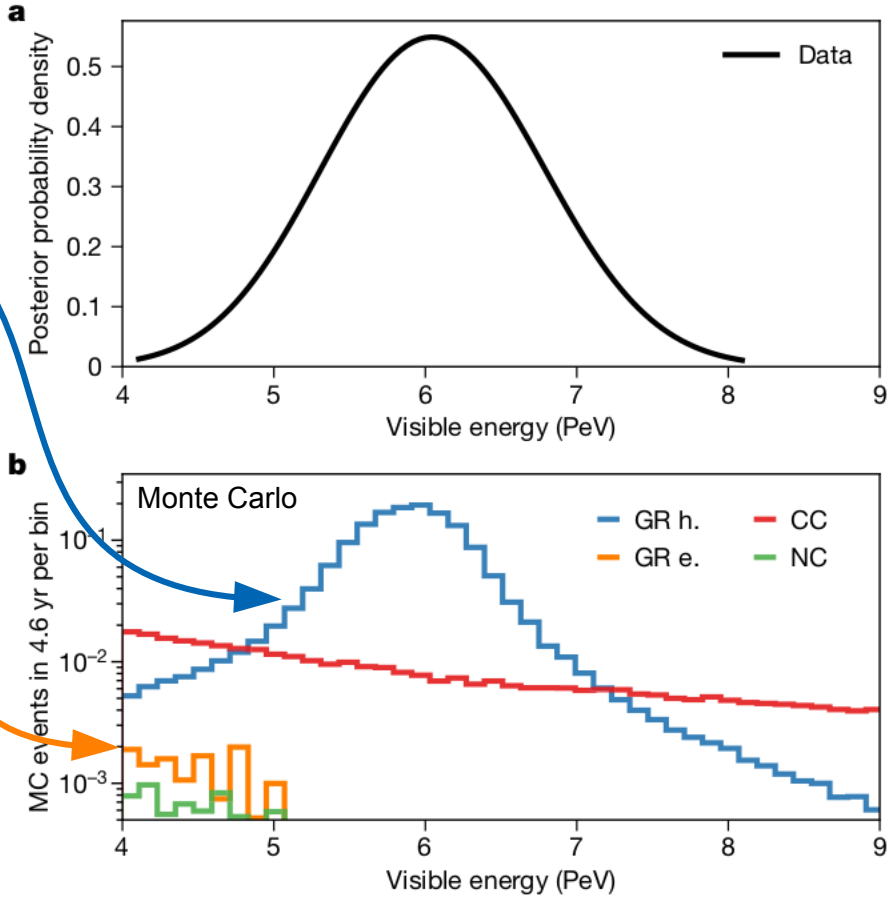

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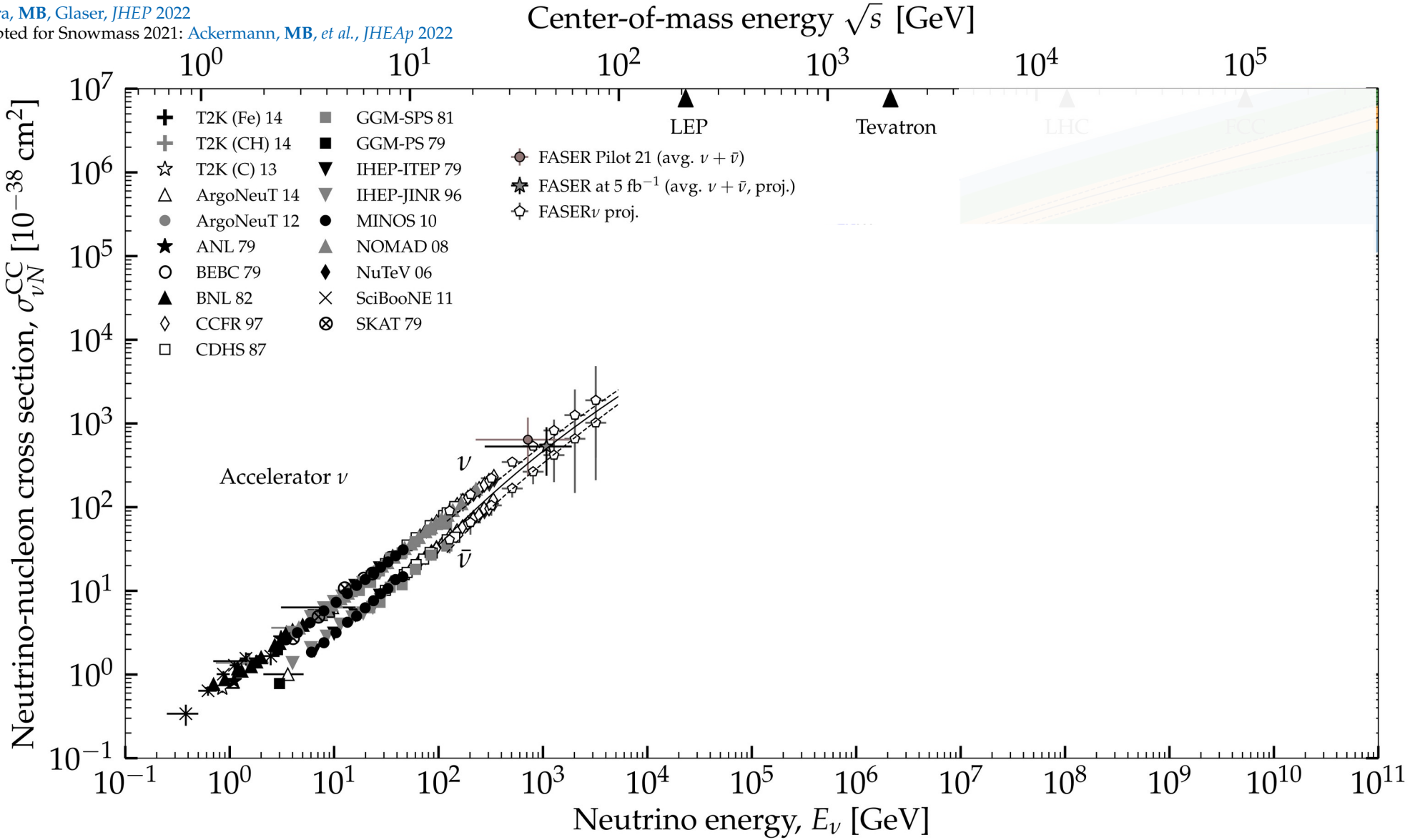
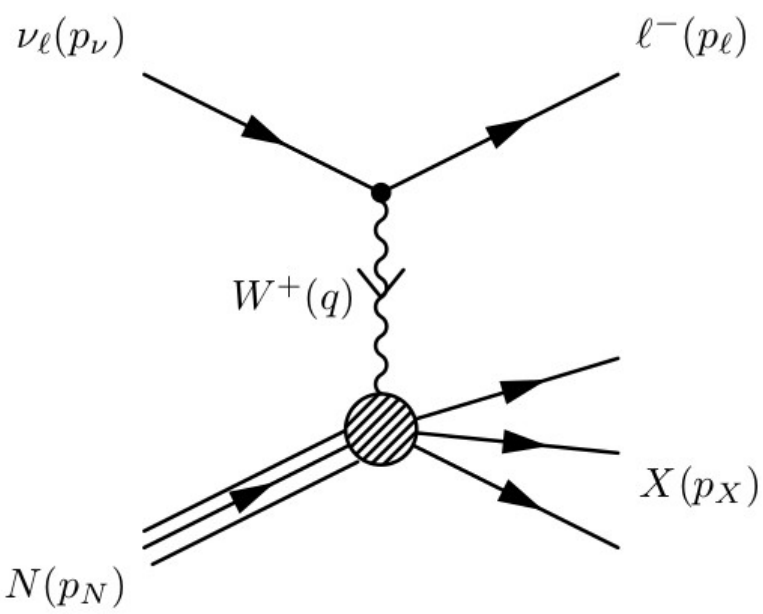
2. Neutrino-matter cross section: *From TeV to EeV*

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

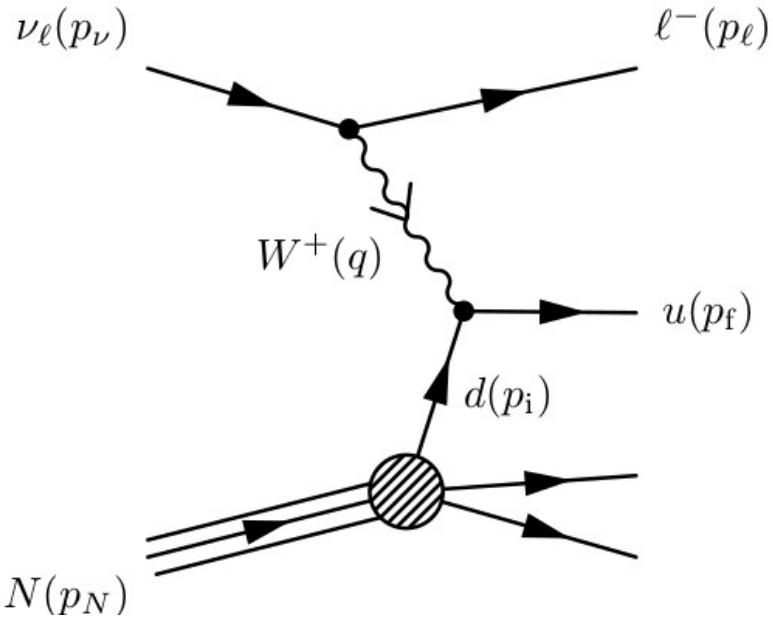


How does DIS probe nucleon structure?

What you see

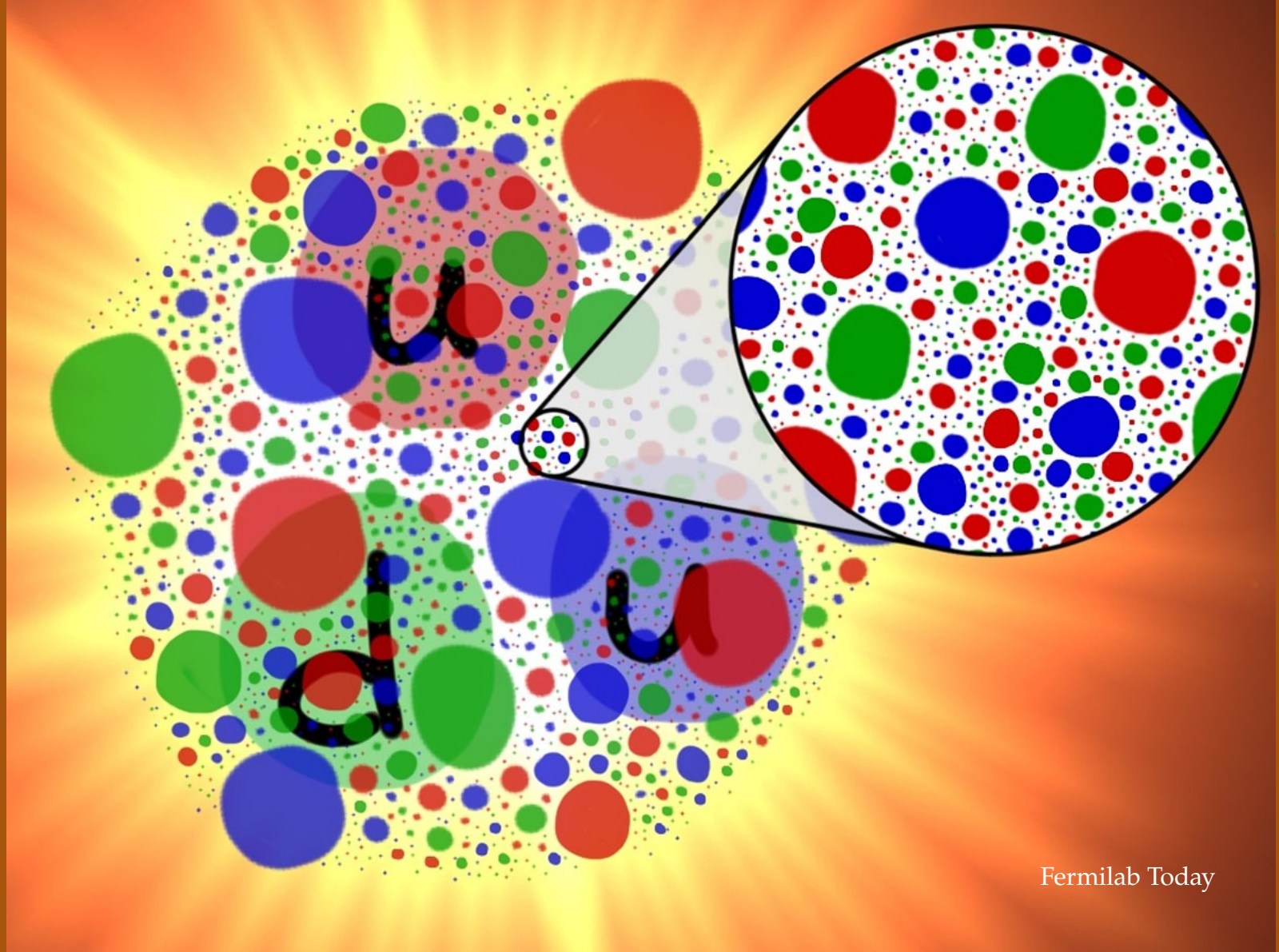


Beneath the hood



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

Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*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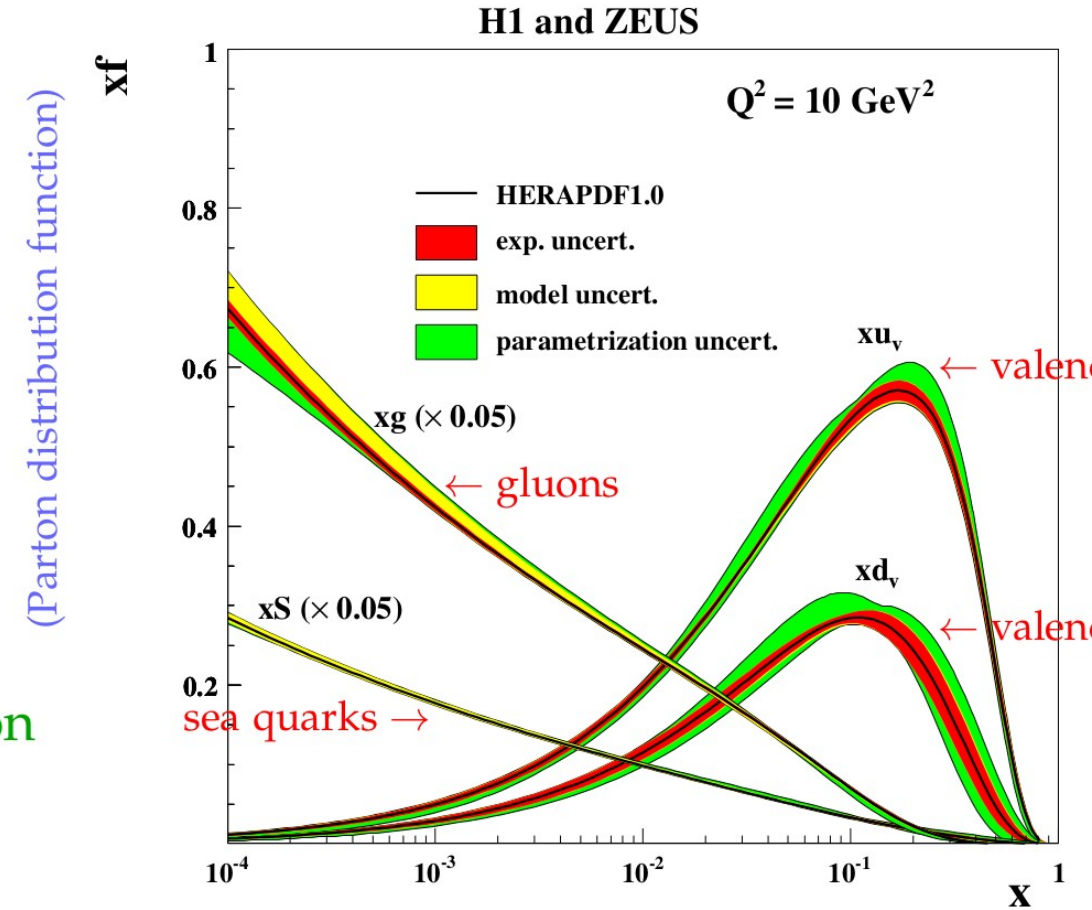
Fermilab Today

Peeking inside a proton



(Parton distribution function)

← valence up quark

← gluons

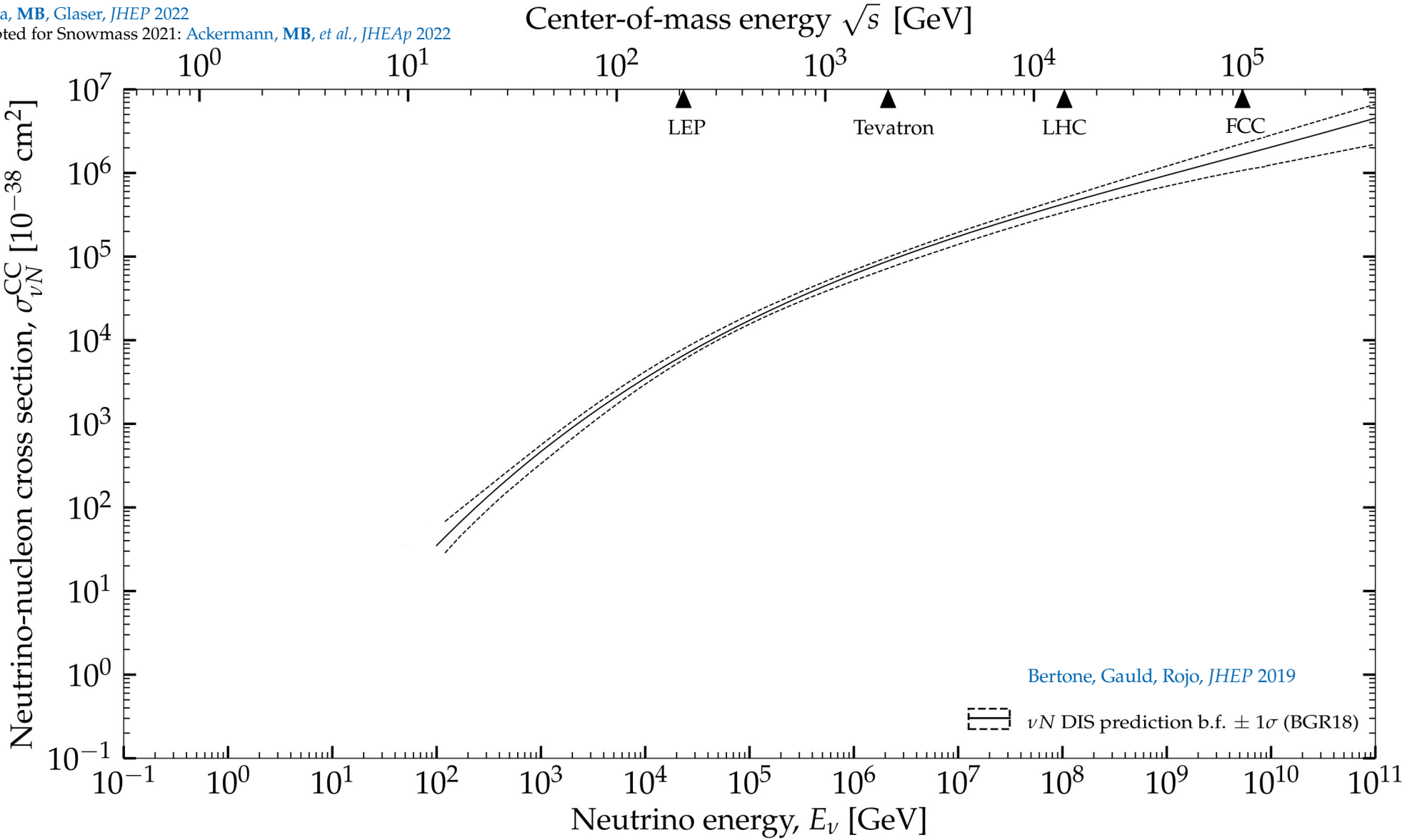
← valence down quark

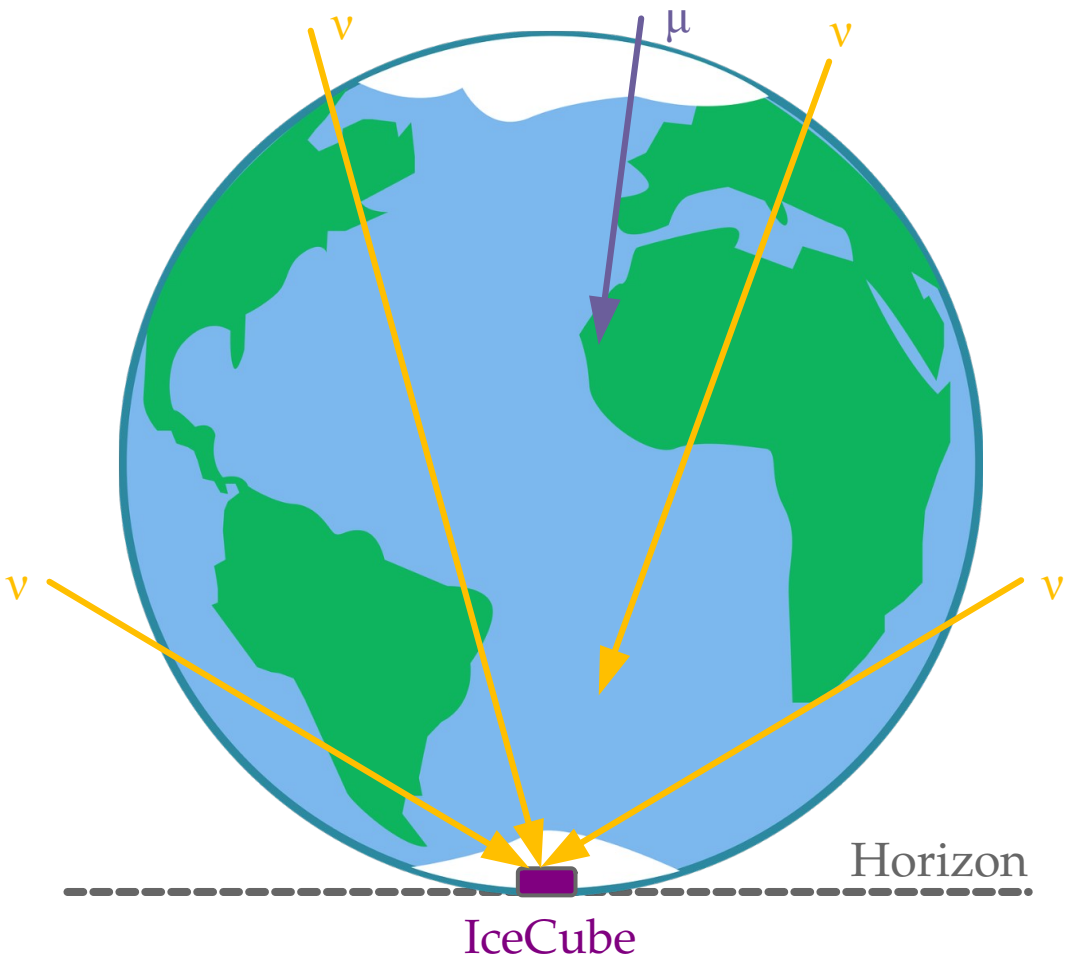
← Extrapolation

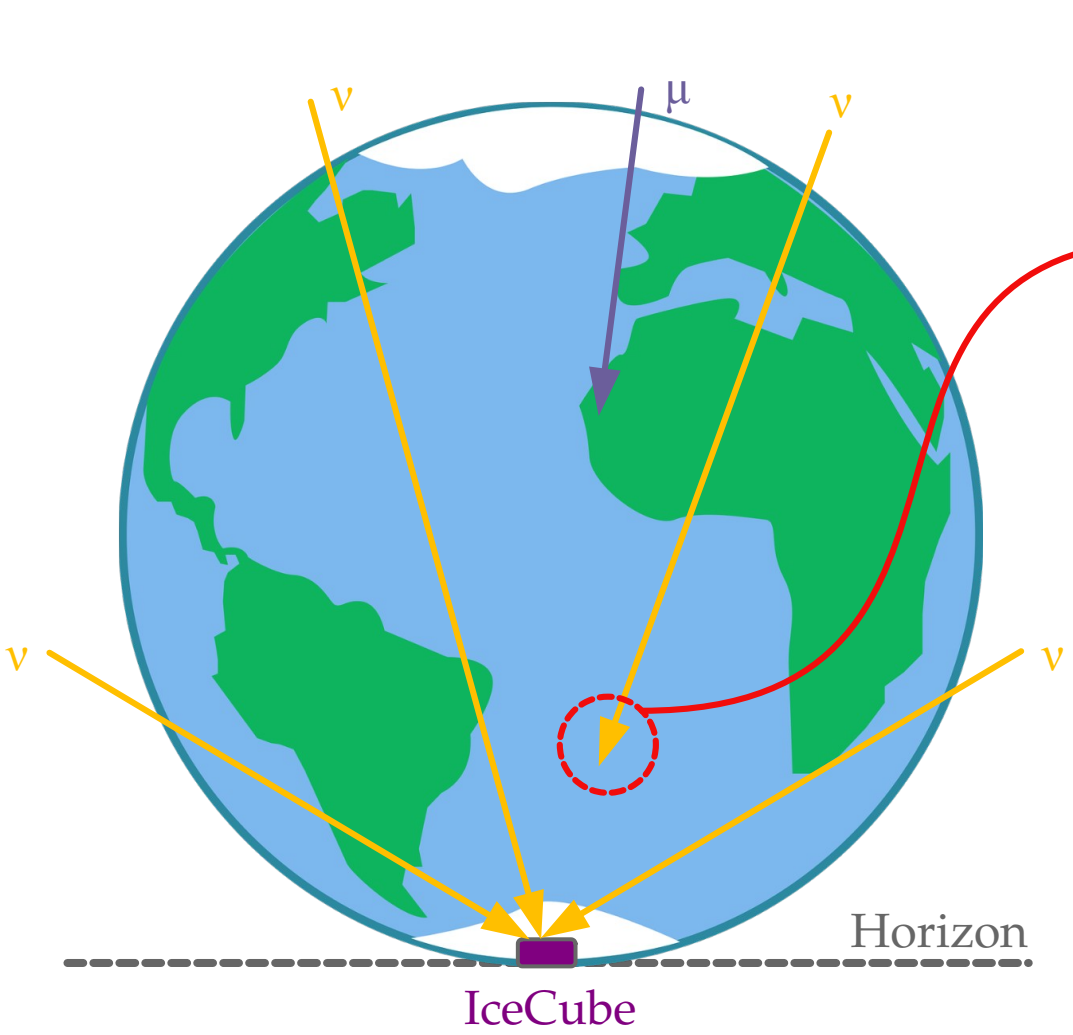
sea quarks →

(Fraction of momentum carried by parton)

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




ν
μ
ν
ν
ν
Horizon
IceCube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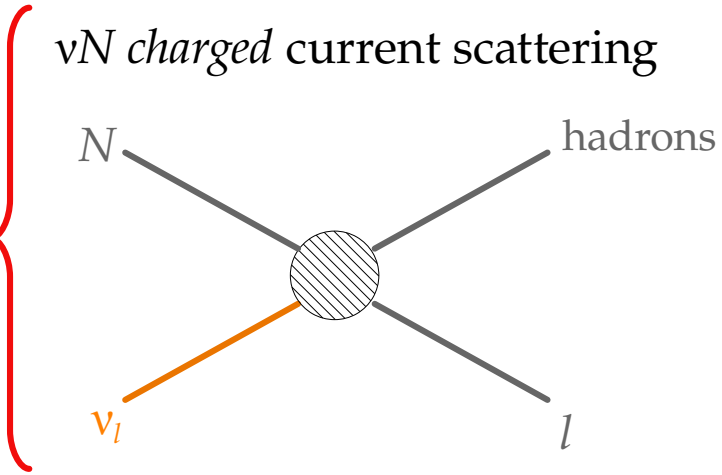
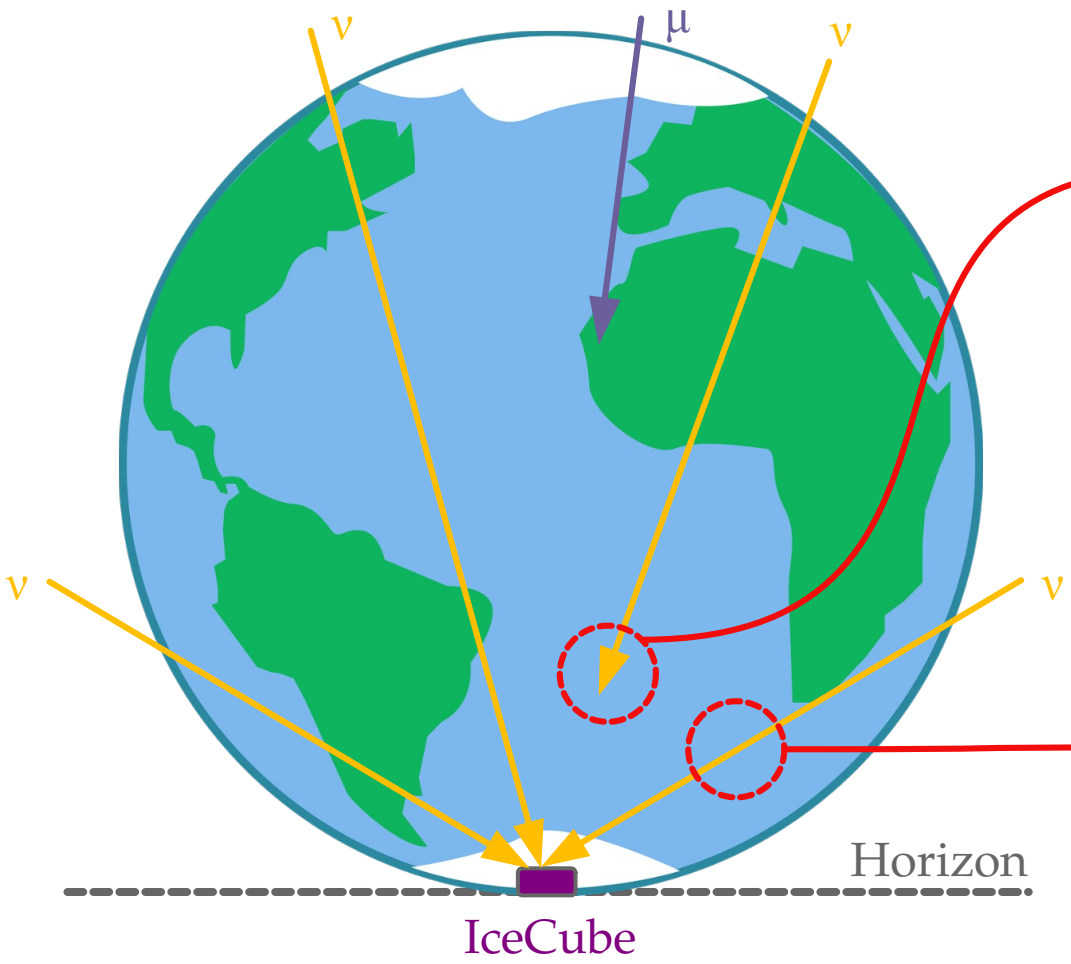
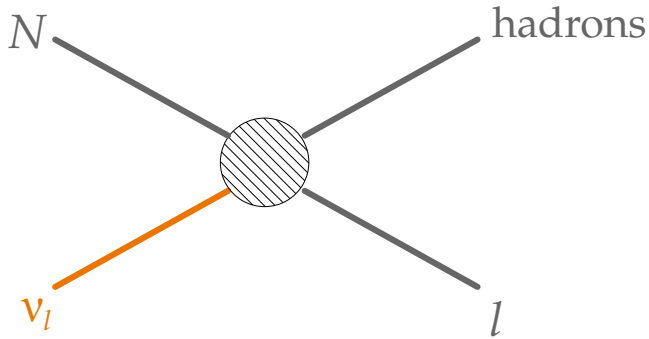
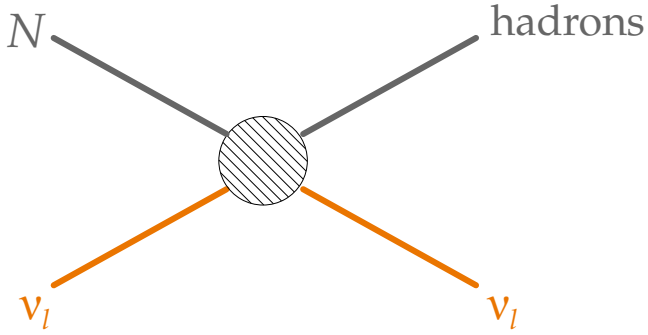

νN charged current scattering
N
hadrons
ν_l
l

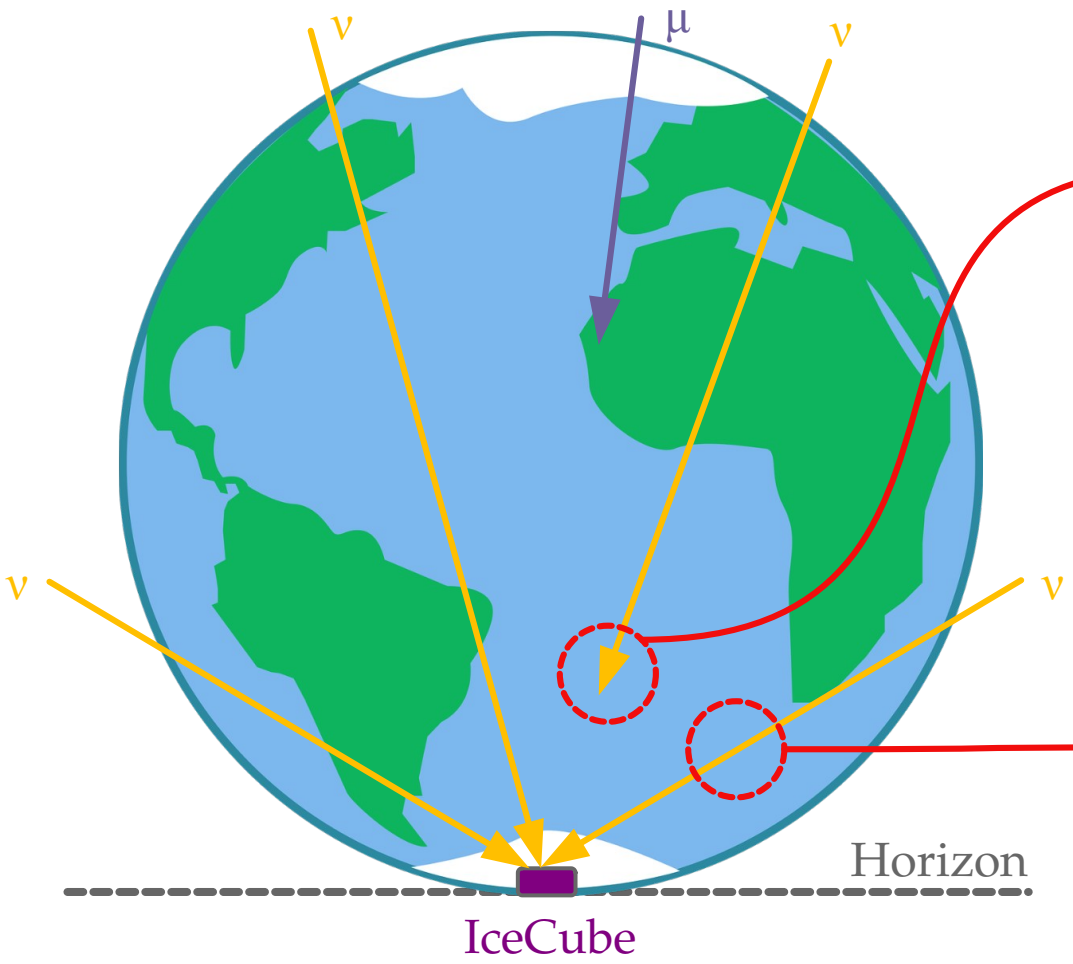


νN *charged* current scattering

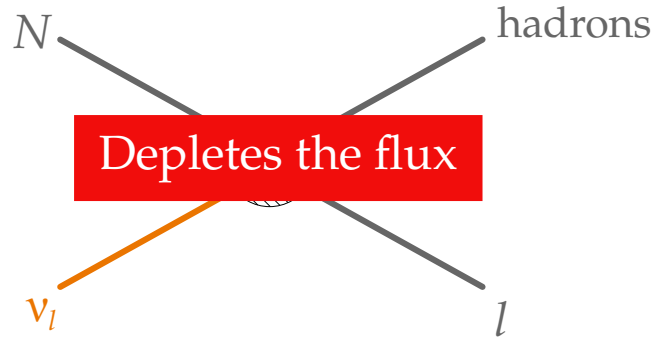


νN *neutral* current scattering

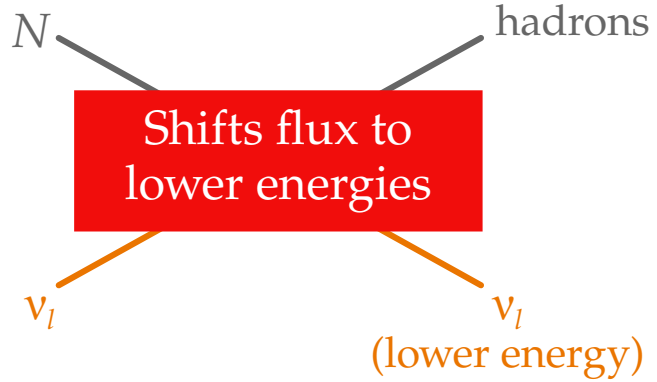




νN charged current scattering



νN neutral current scattering



Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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

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

Number of detected neutrinos (simplified for presentation):

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

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

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

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Upgoing neutrinos
(L long → lots of matter)

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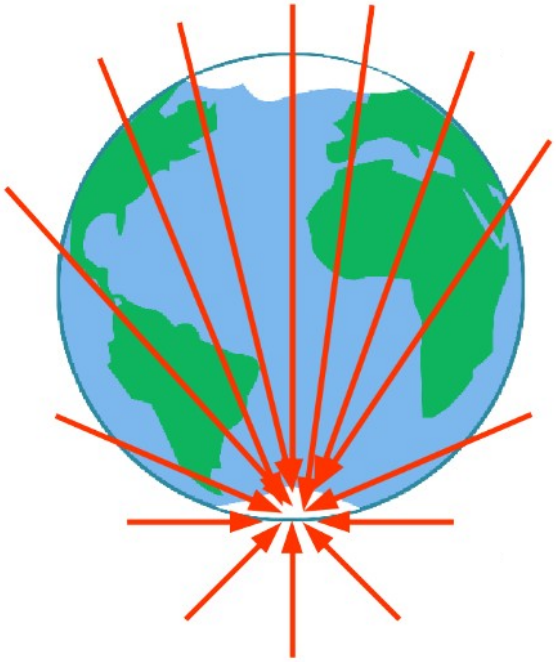
Upgoing neutrinos
(L long → lots of matter)

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

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



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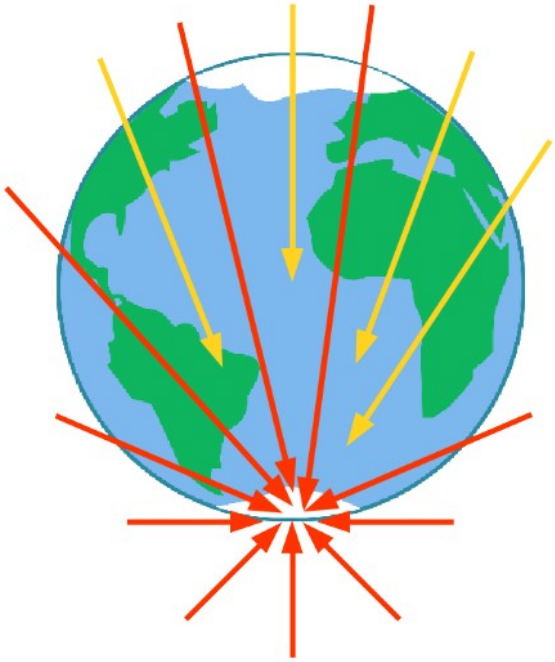

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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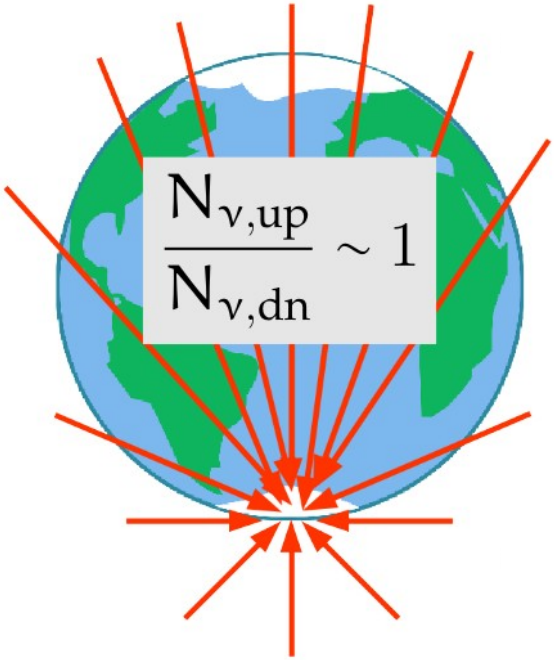

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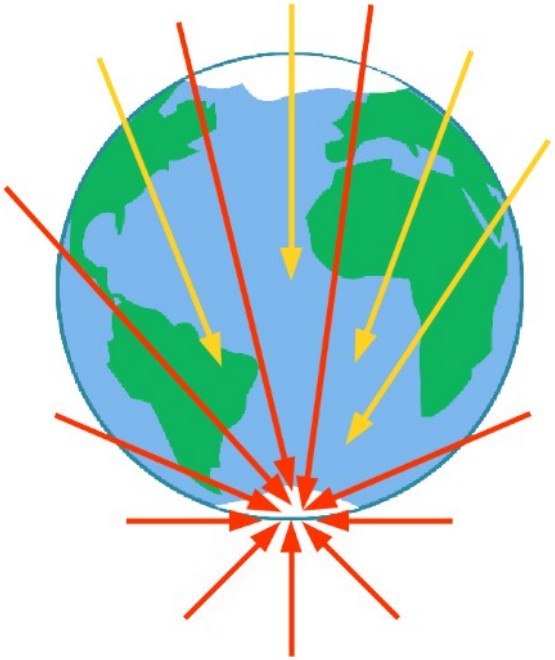

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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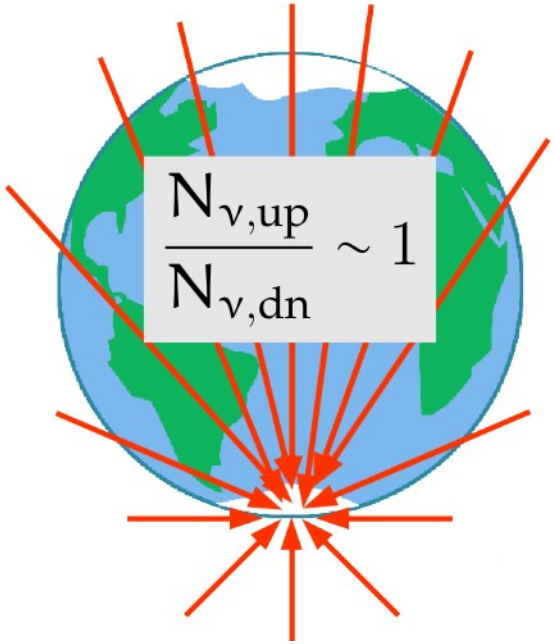

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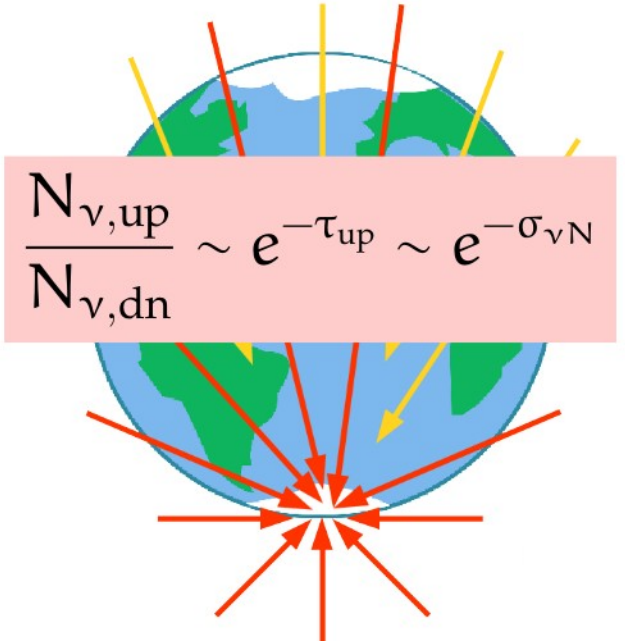

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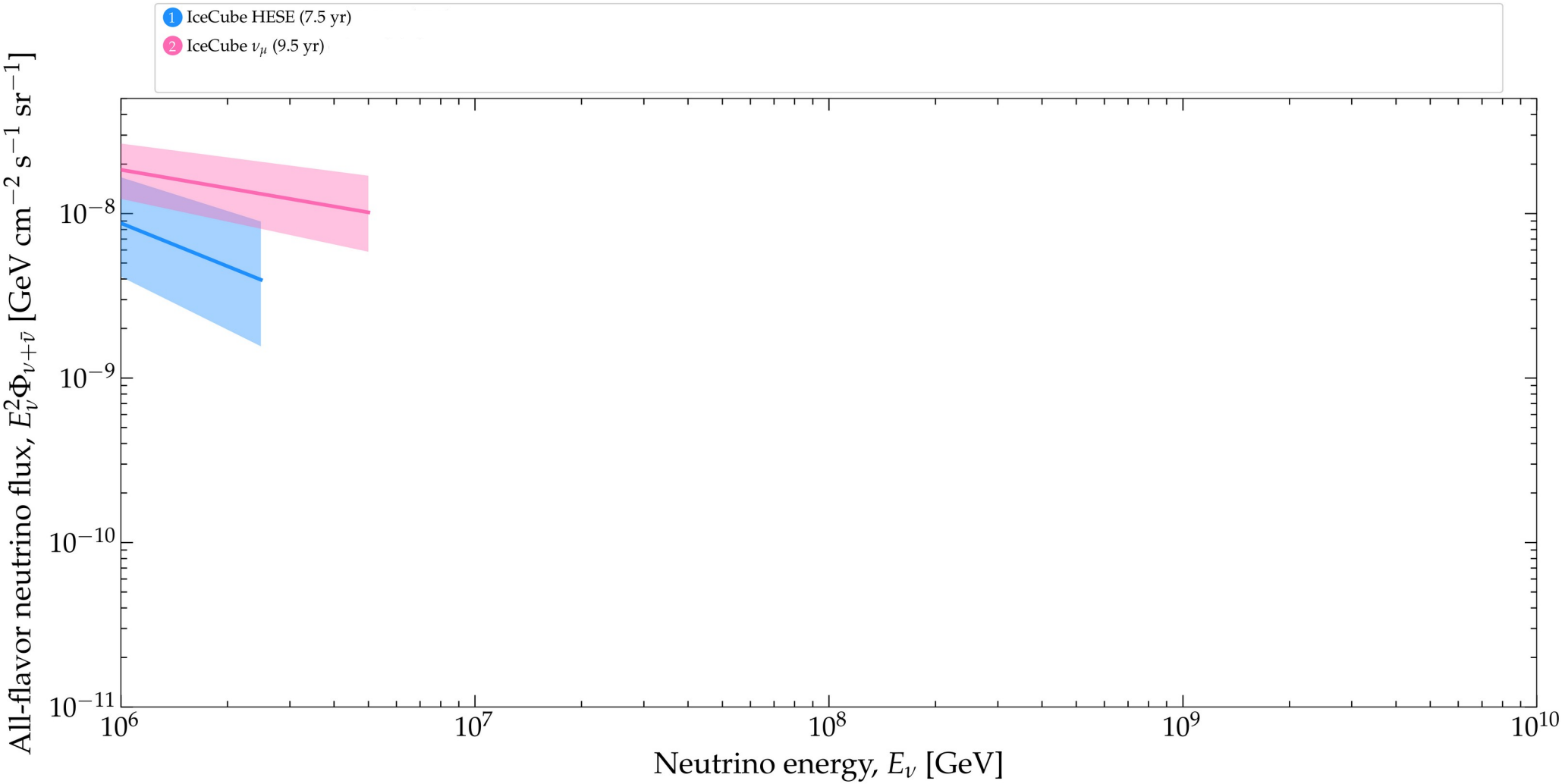
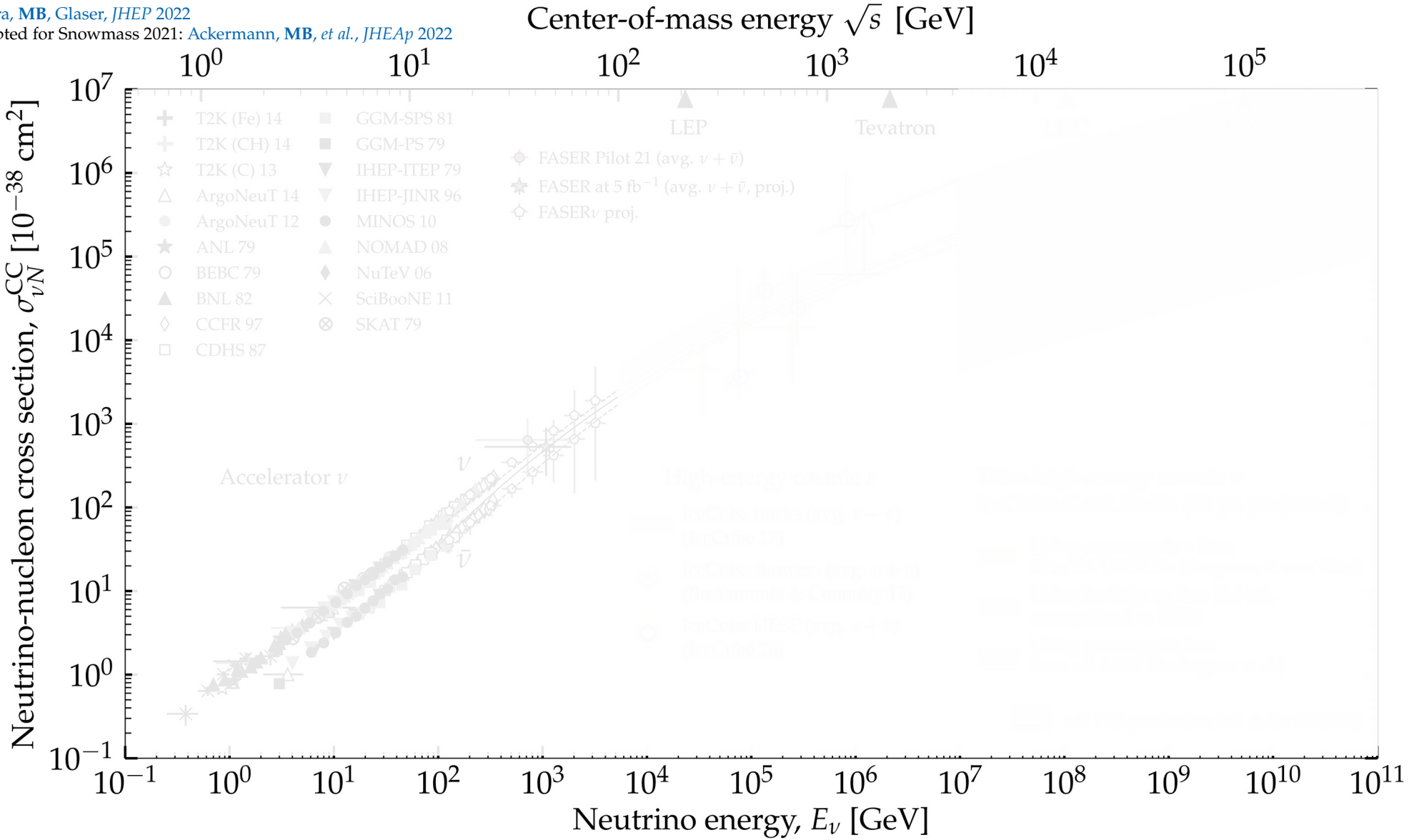
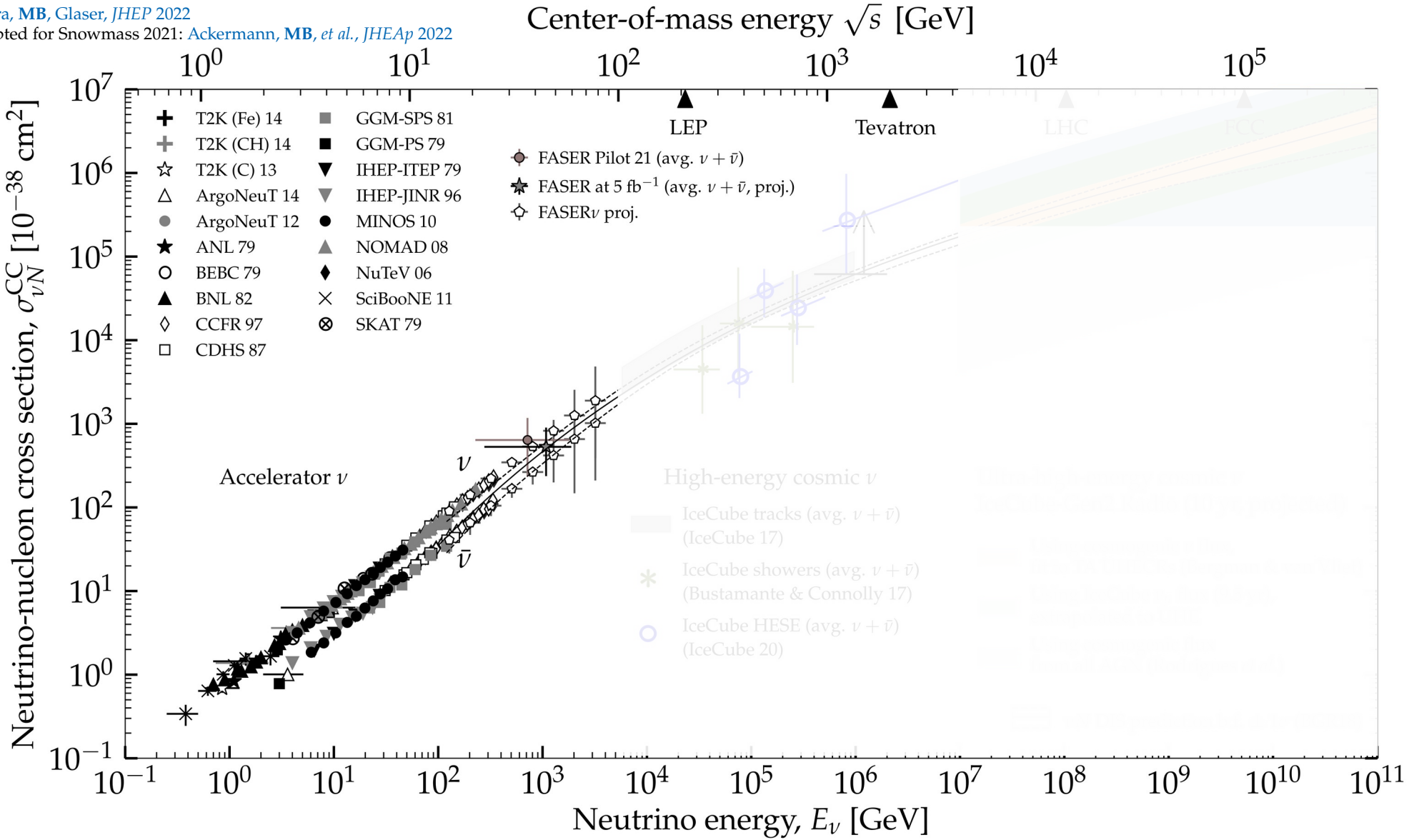
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015


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

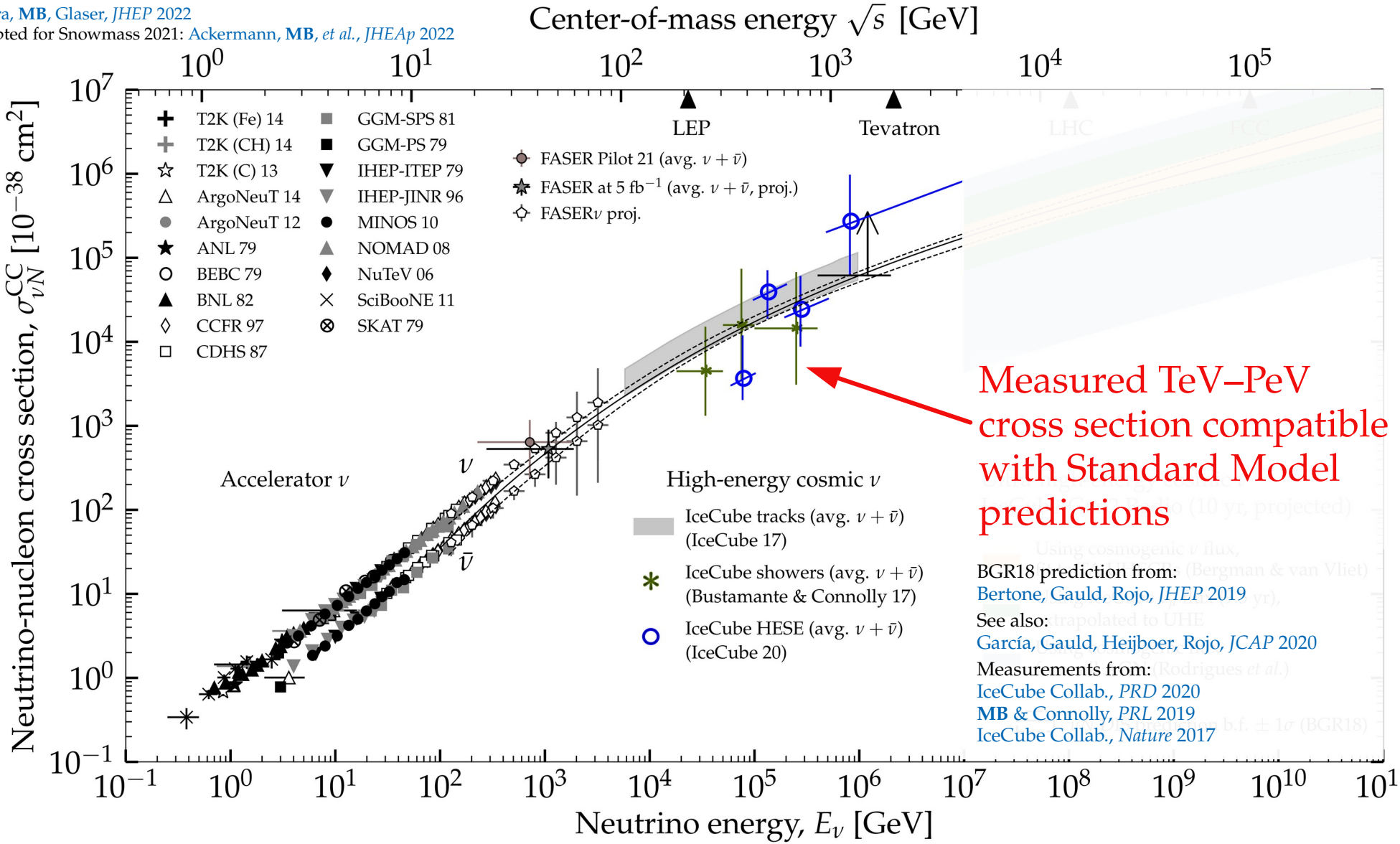
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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



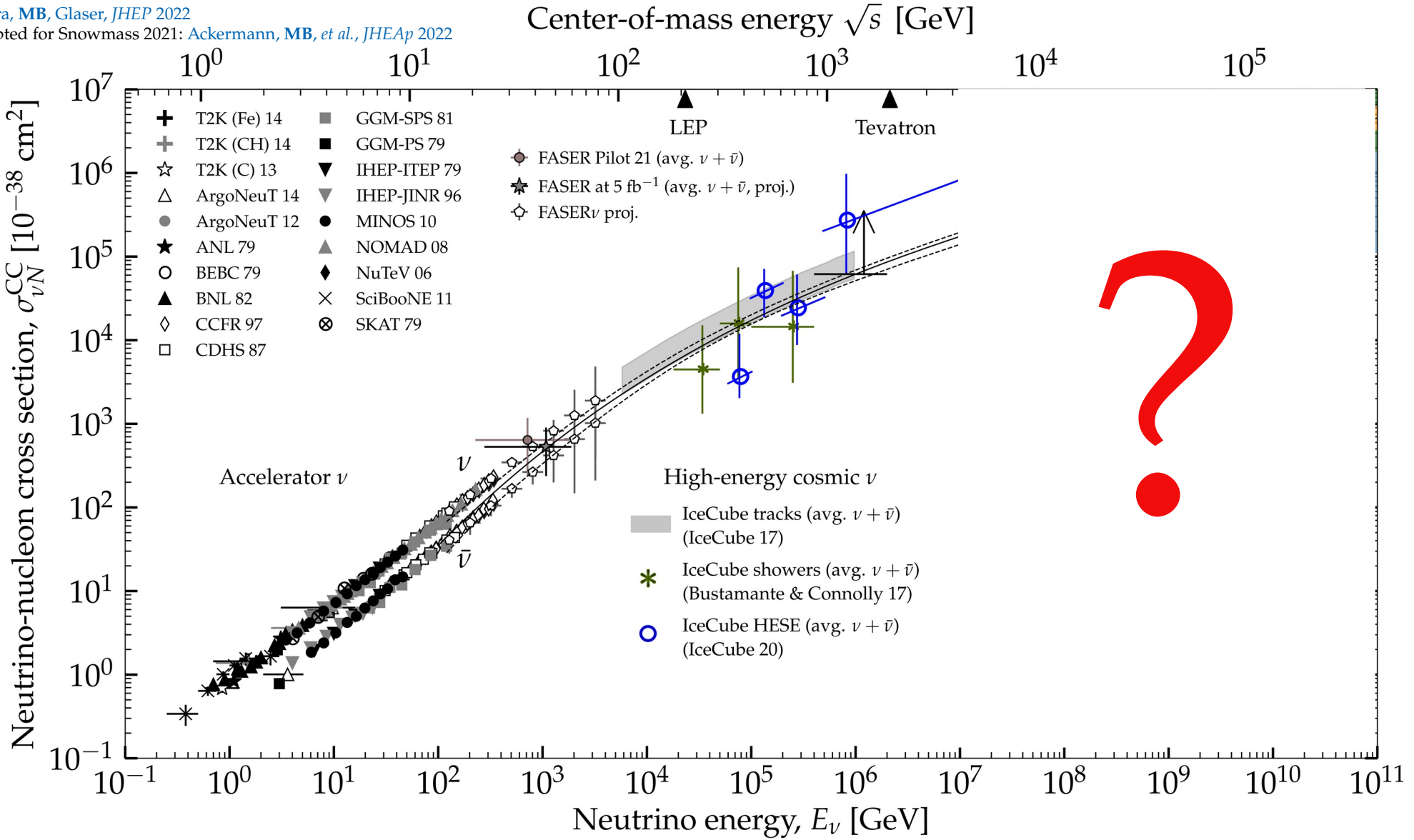
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



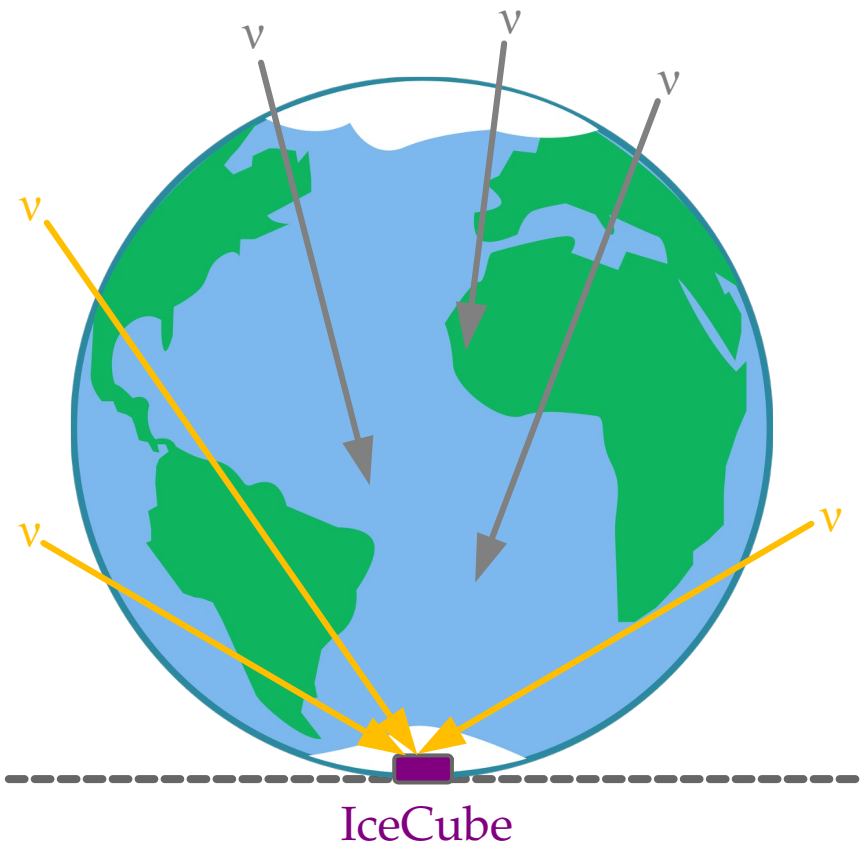
Measured TeV–PeV cross section compatible with Standard Model predictions

BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube Collab., *PRD* 2020
MB & Connolly, *PRL* 2019
IceCube Collab., *Nature* 2017

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

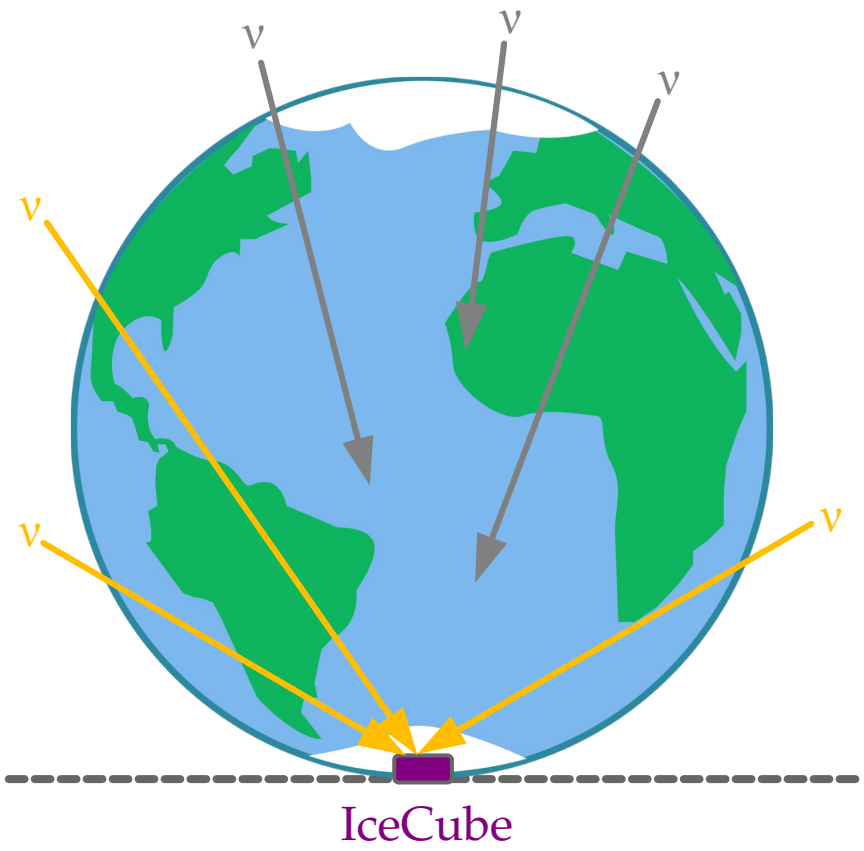


TeV–PeV:



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

TeV–PeV:



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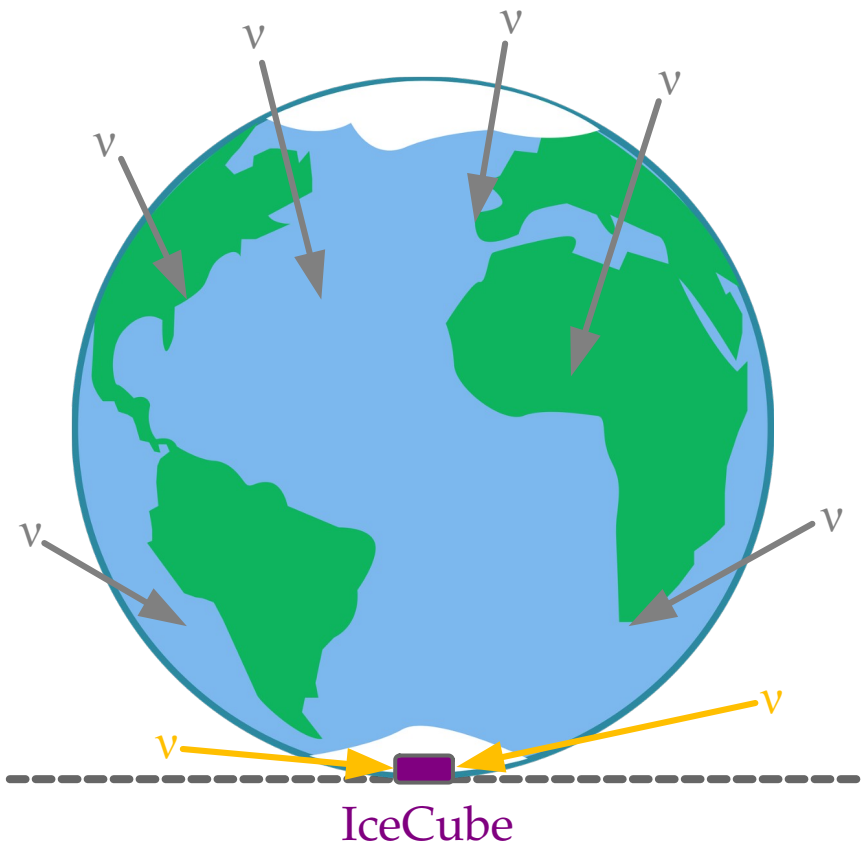
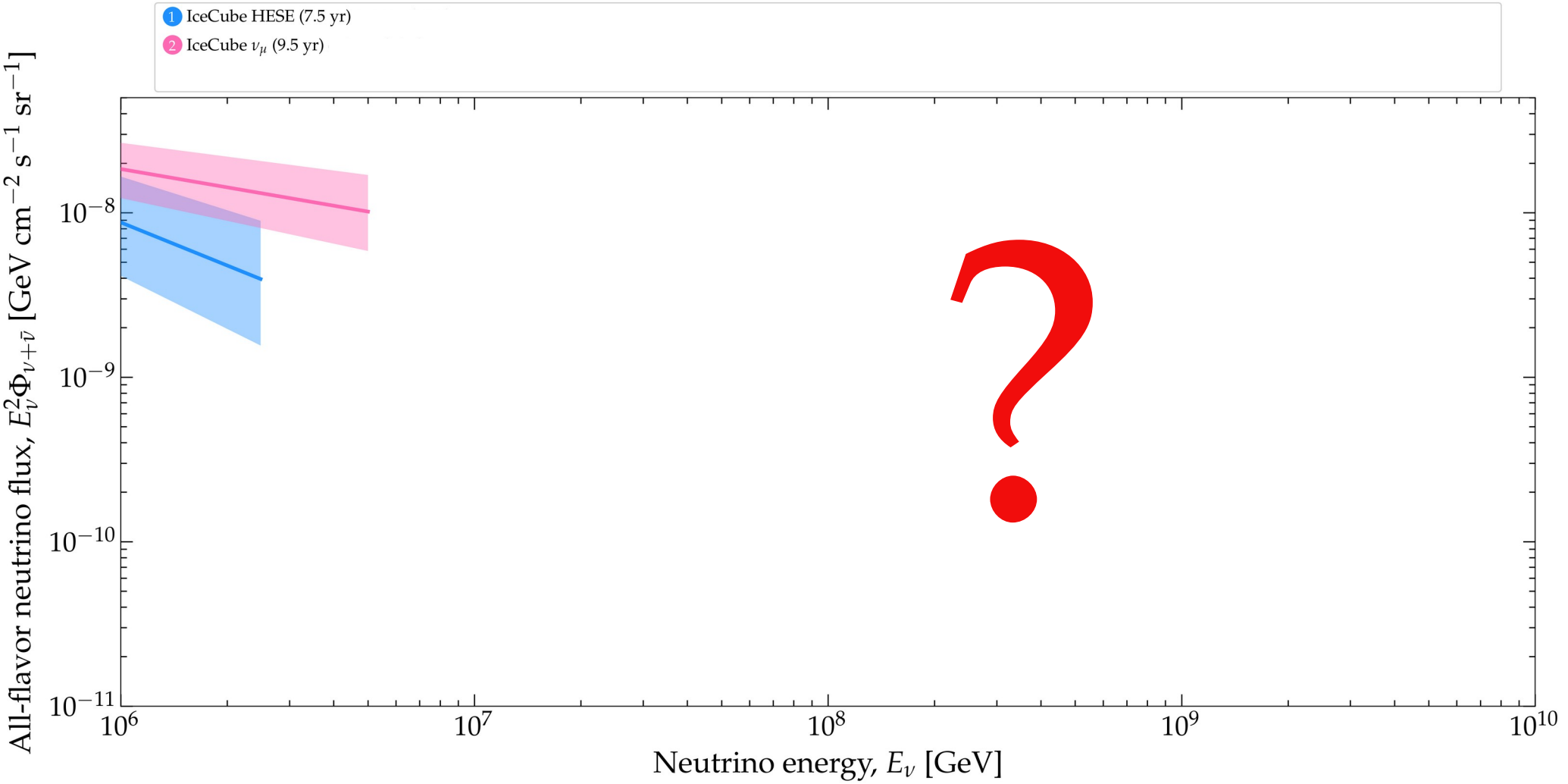
> 100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through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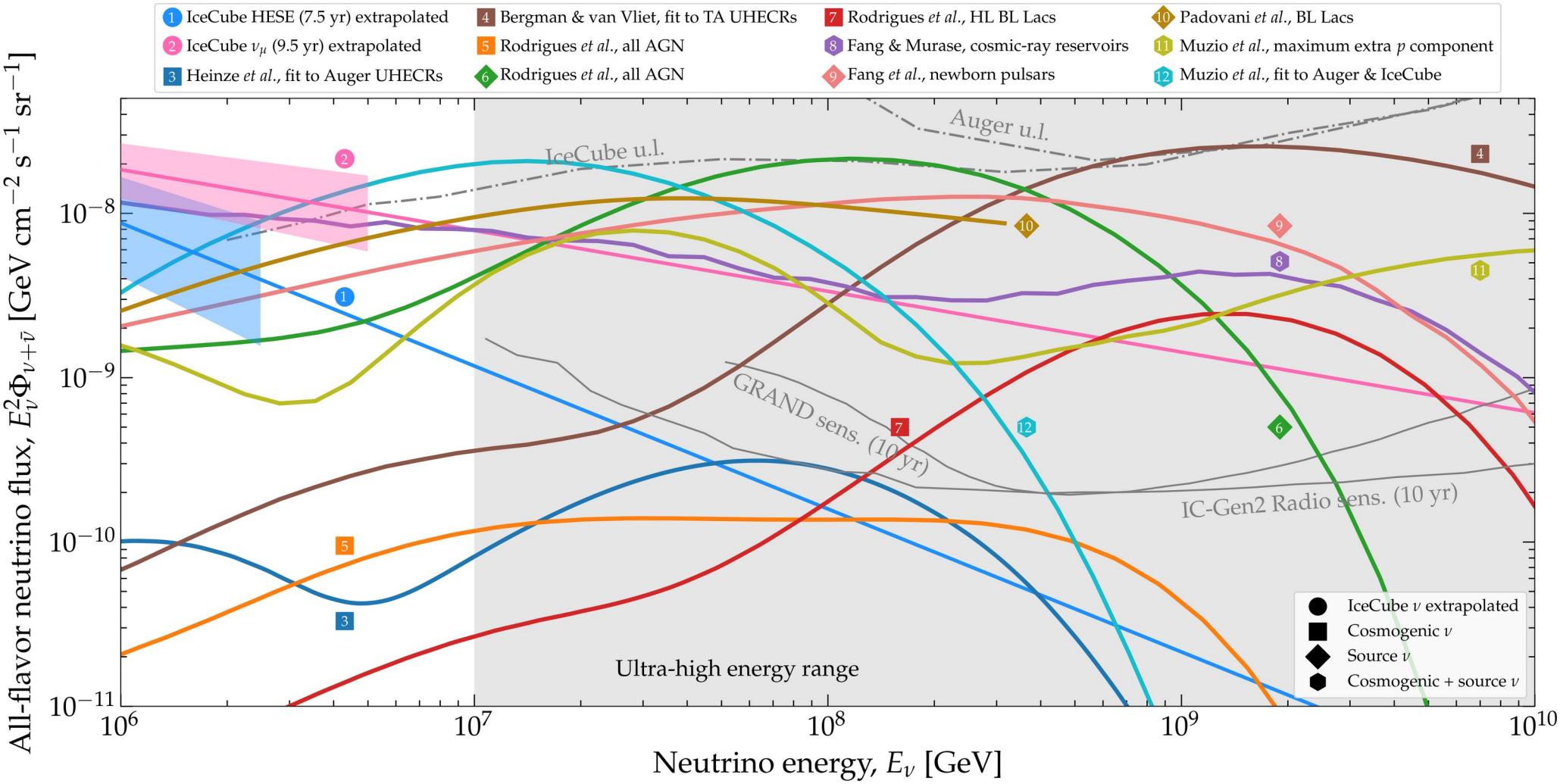
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?


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

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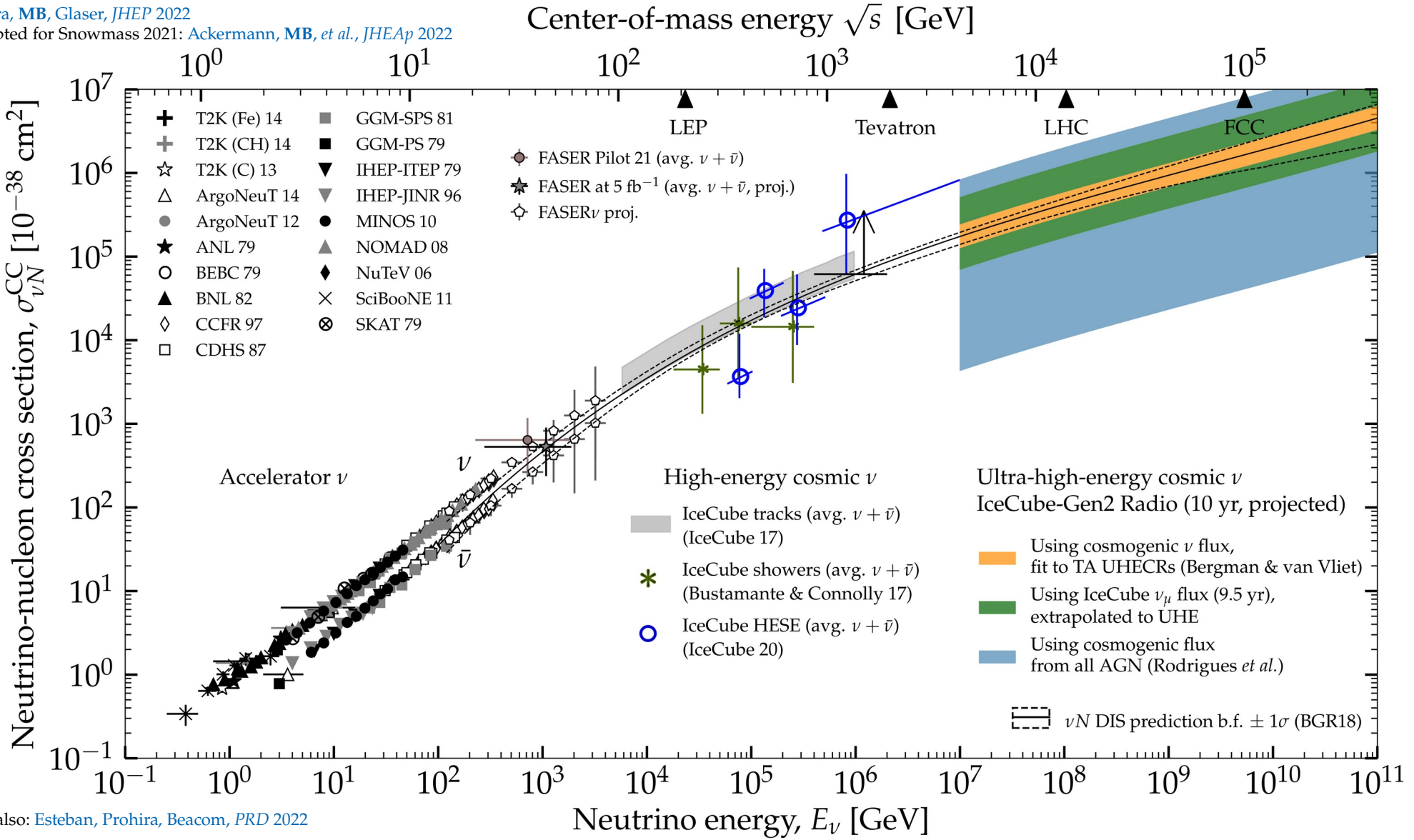

See also: Esteban, Prohira, Beacom, *PRD* 2022

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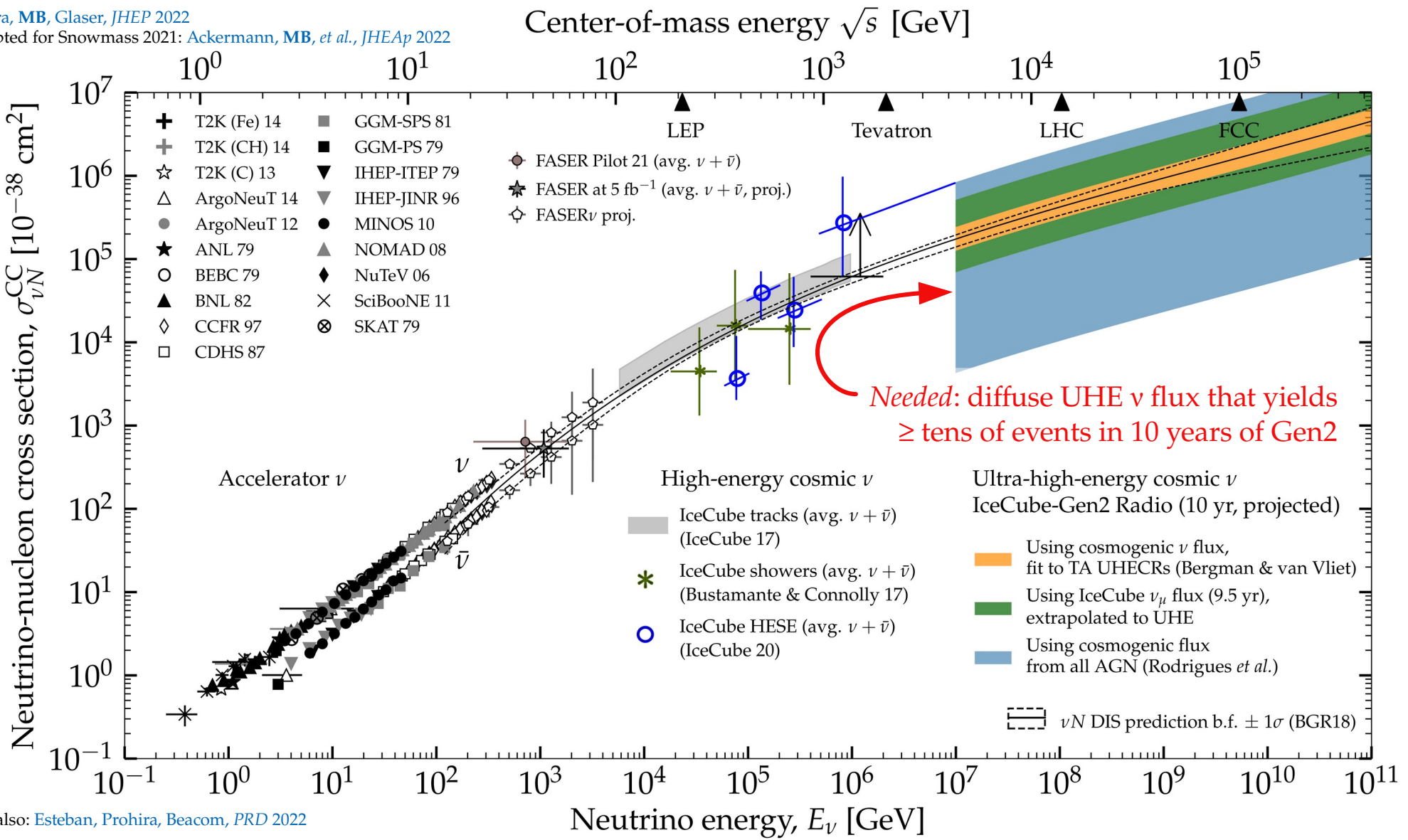
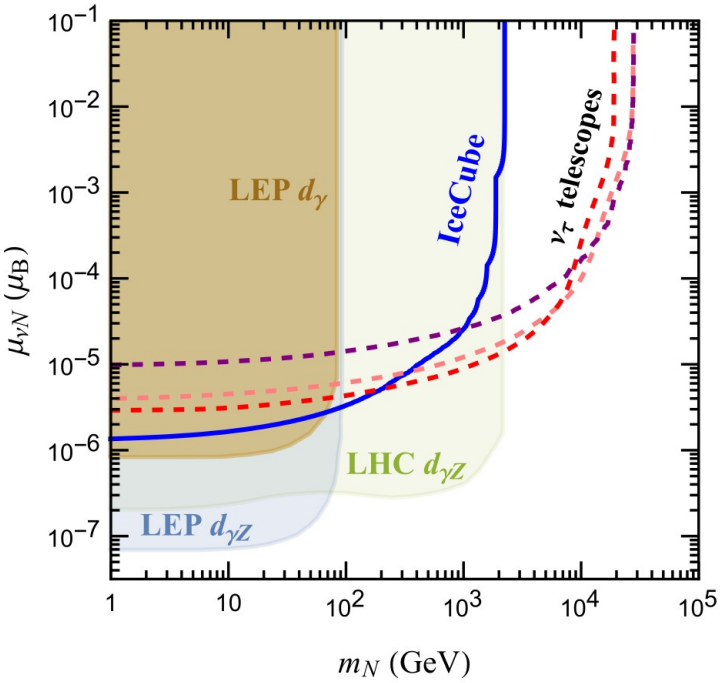


See also: Esteban, Prohira, Beacom, *PRD* 2022

New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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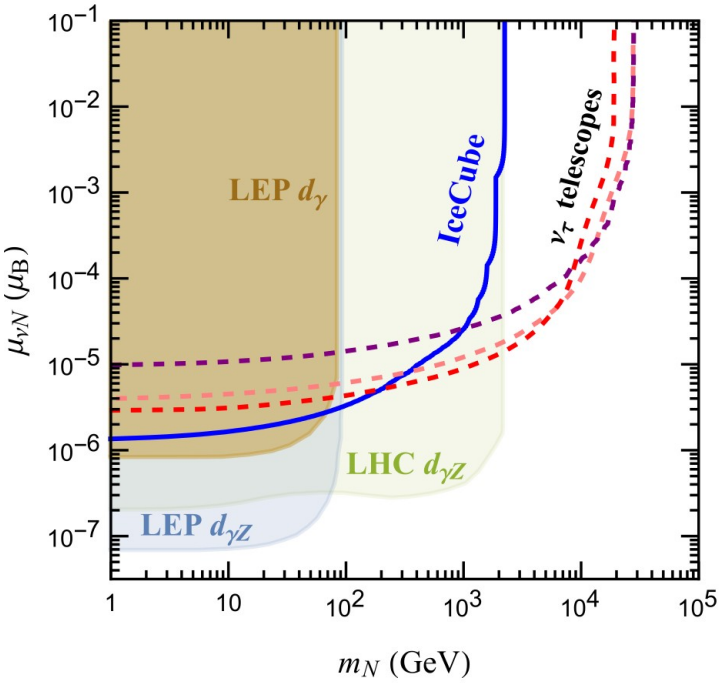
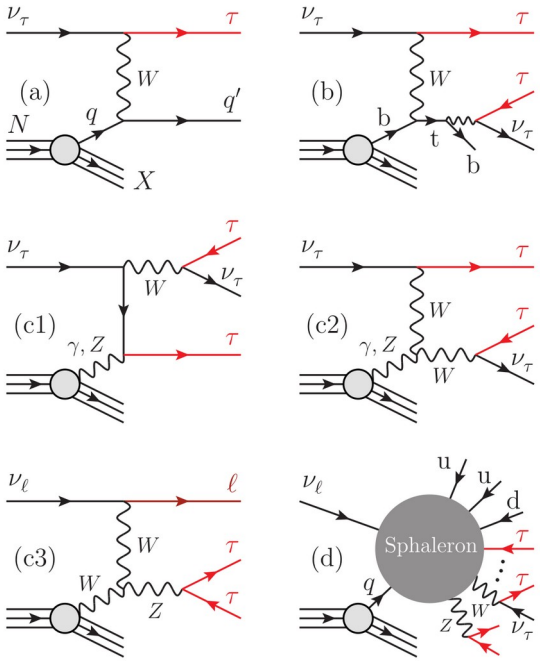


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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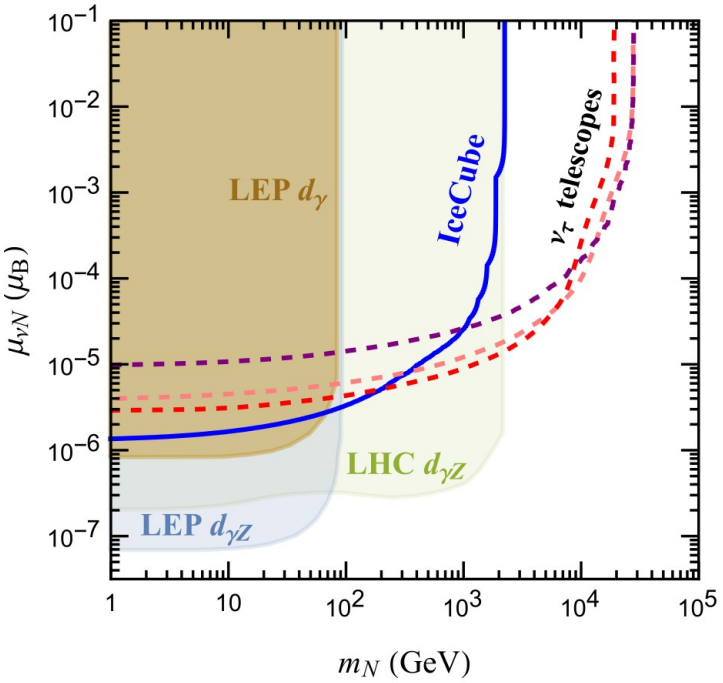

Huang, Jana, Lindner, Rodejohann, 2204.10347

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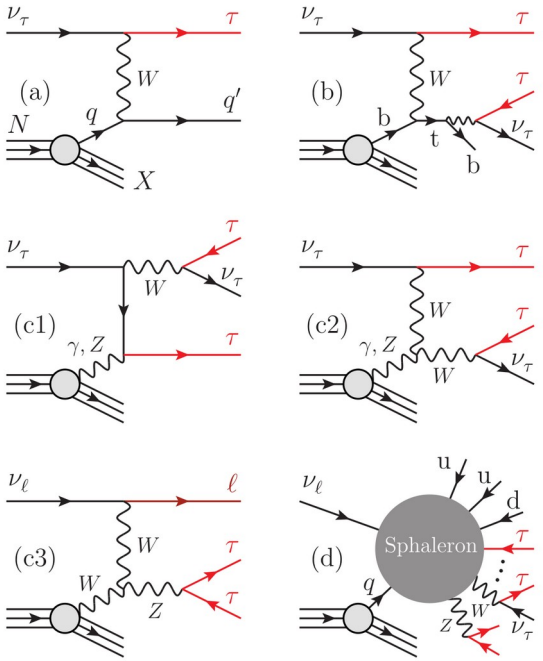
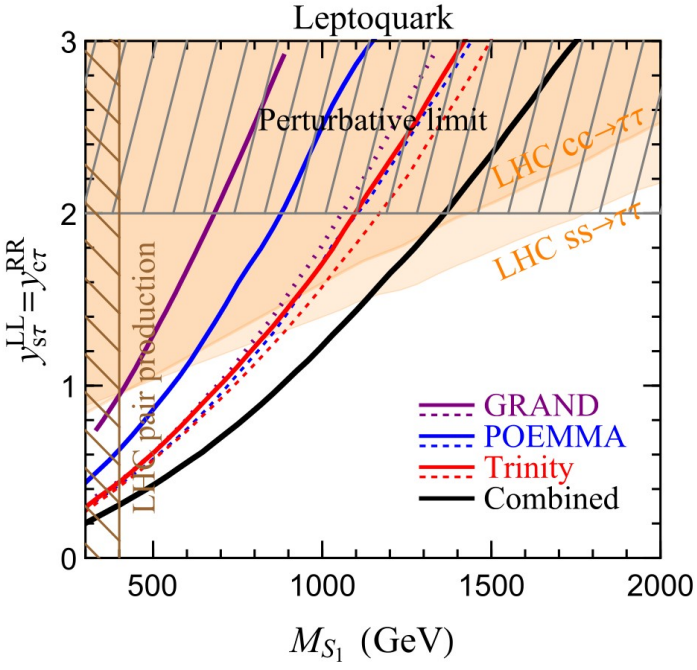


Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc.*



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

3. Flavor:
Towards precision, finally

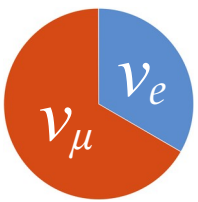
(with the help of lower-energy experiments)

Astrophysical sources

Earth

Up to a few Gpc

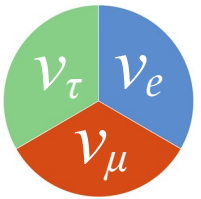
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



Different production mechanisms yield different flavor ratios:

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

Flavor ratios at Earth (α = e, μ, τ):

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

Astrophysical sources

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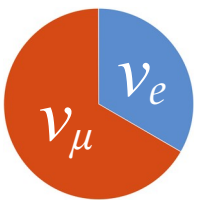

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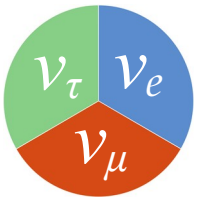

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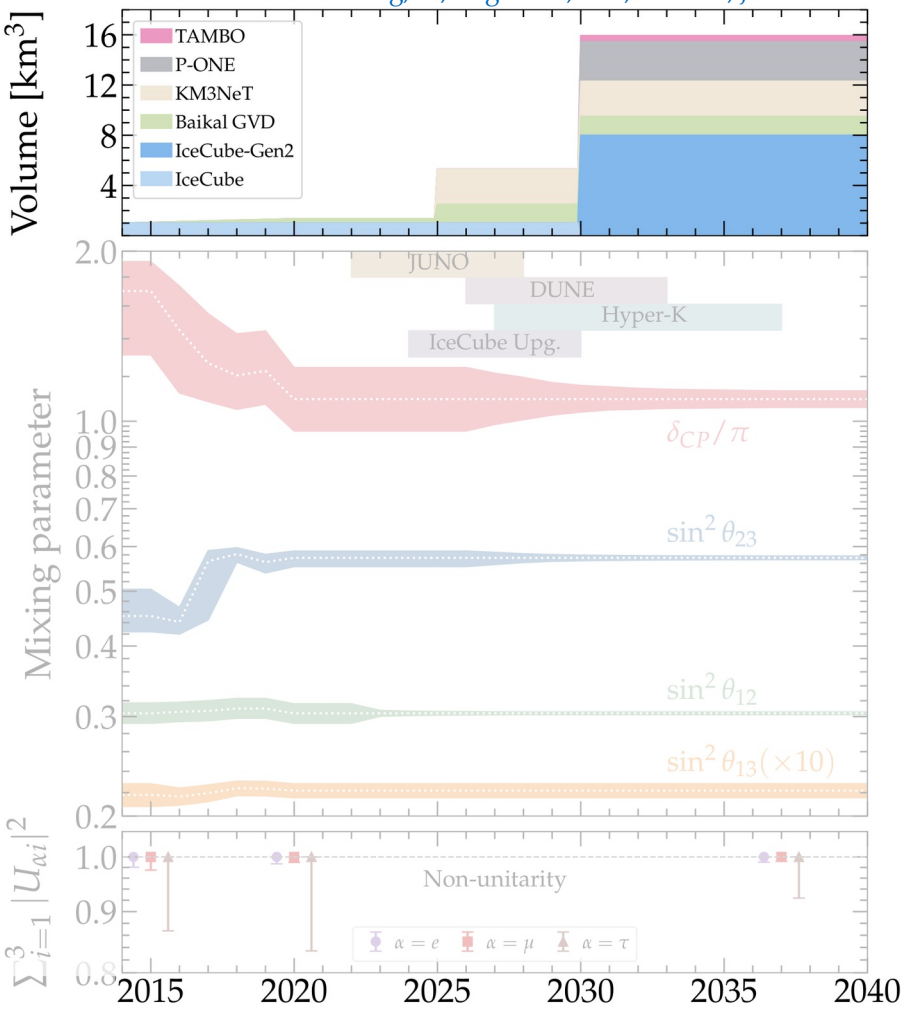
Standard oscillations
or
new physics

Measuring flavor composition: 2015–2040

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



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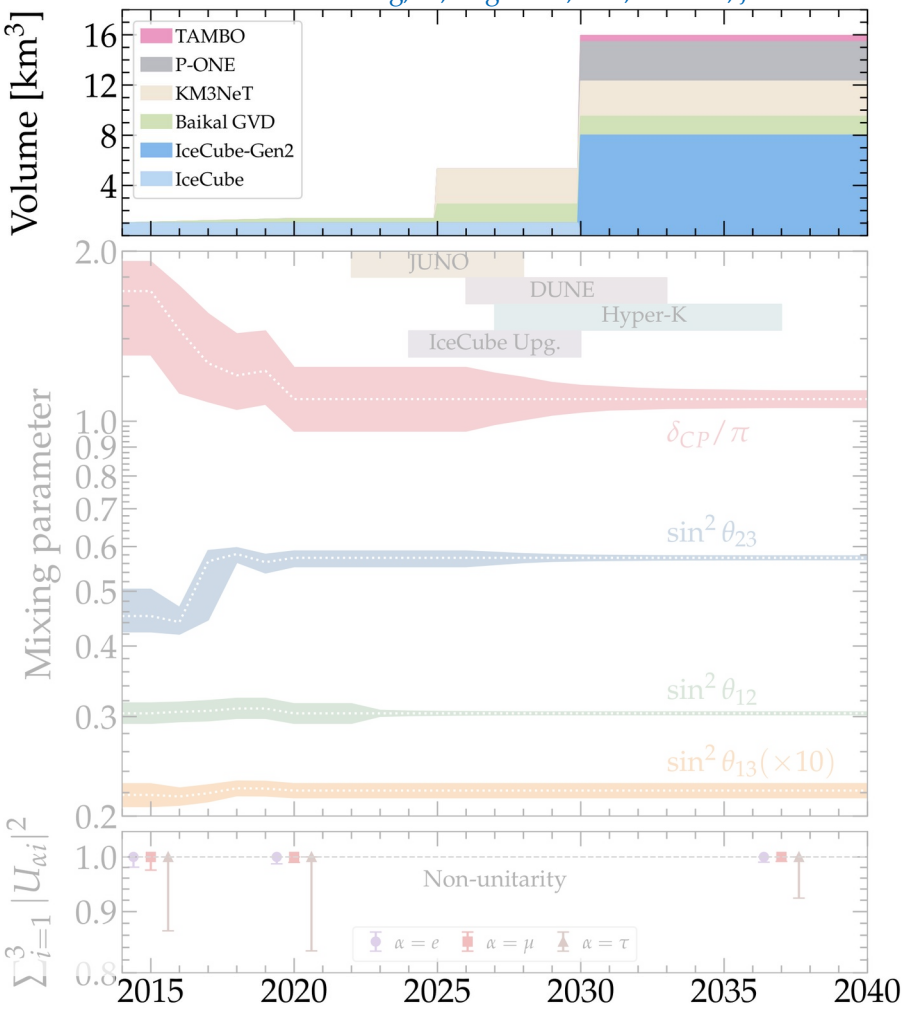

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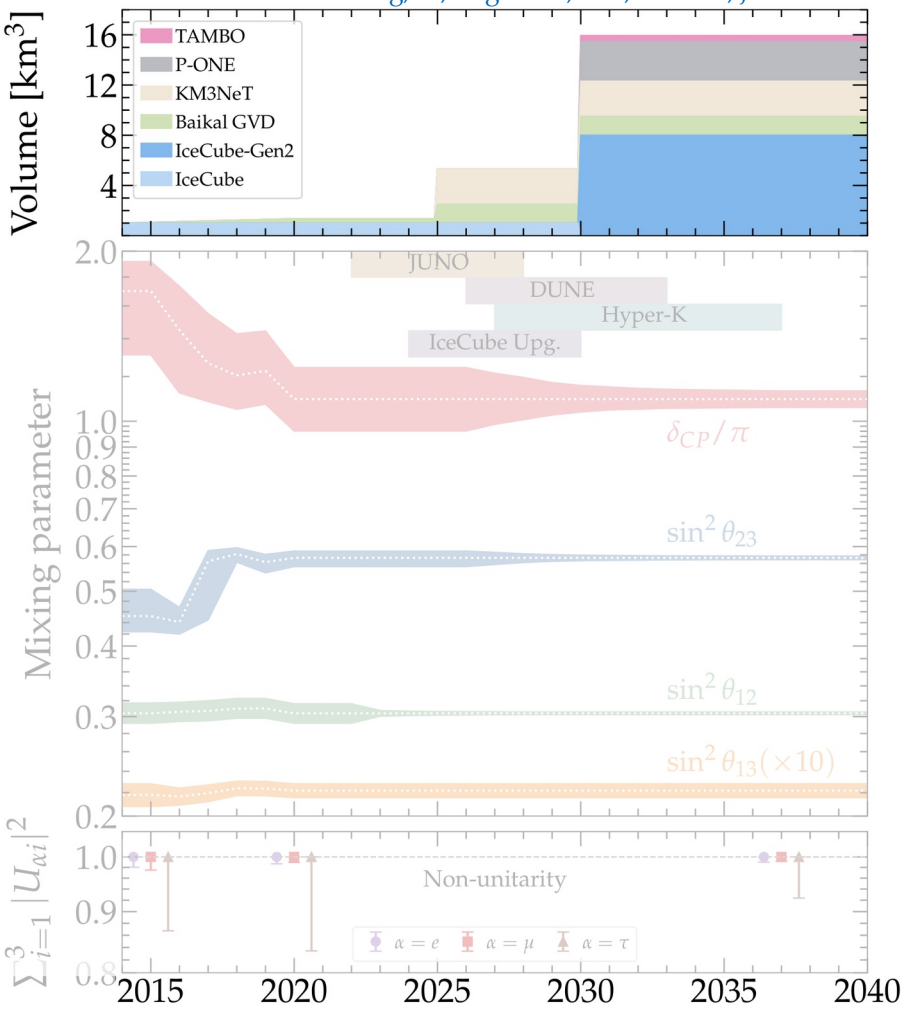
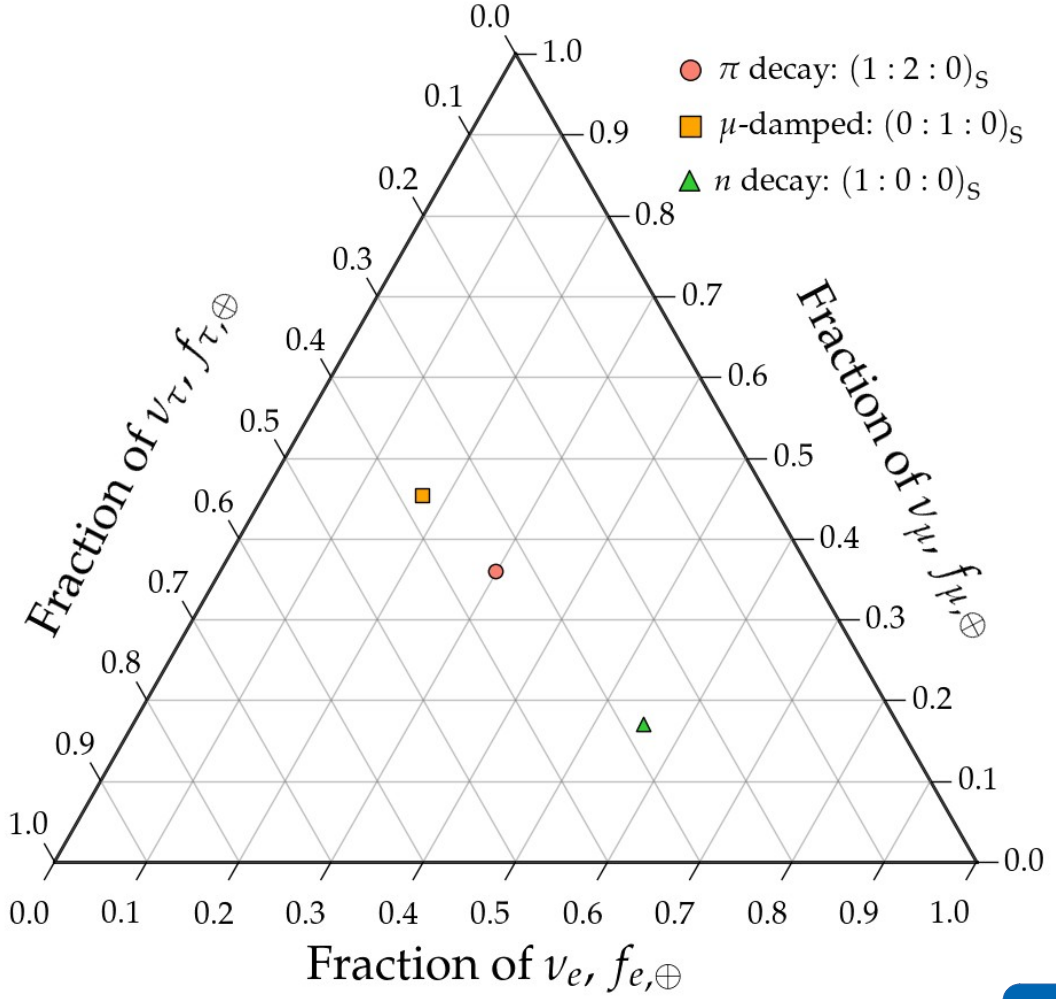
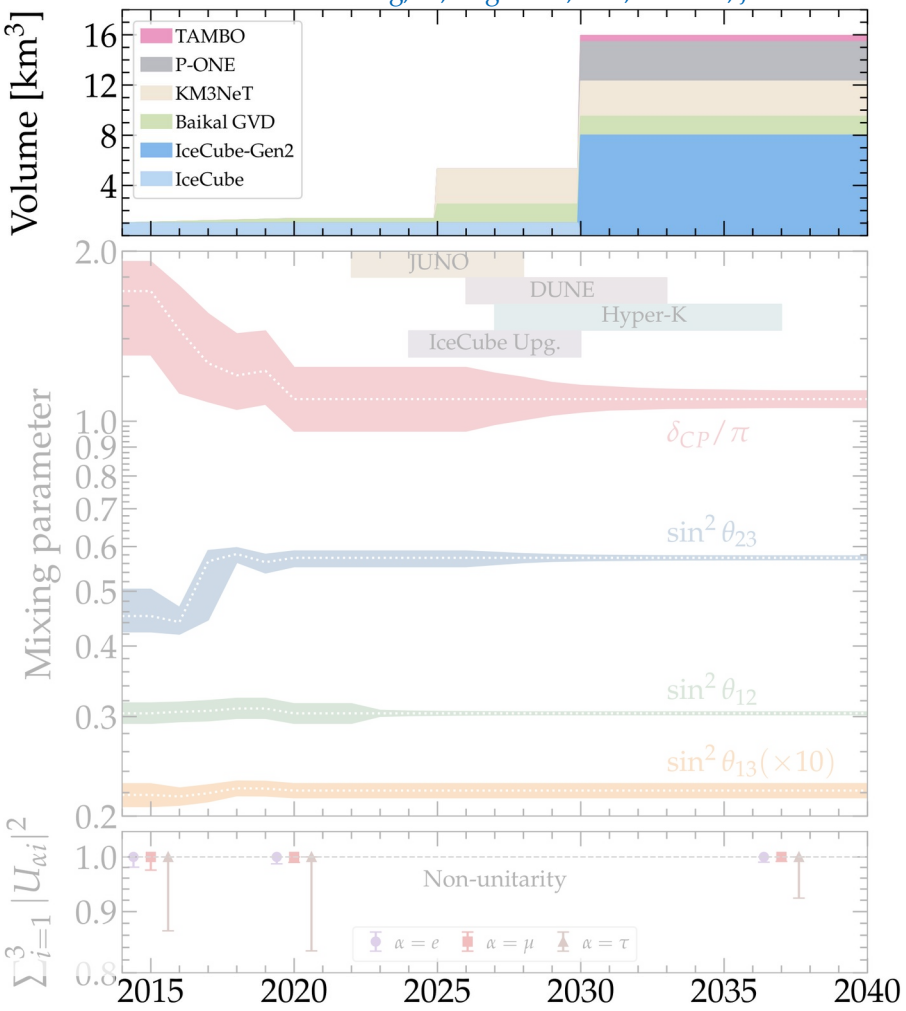
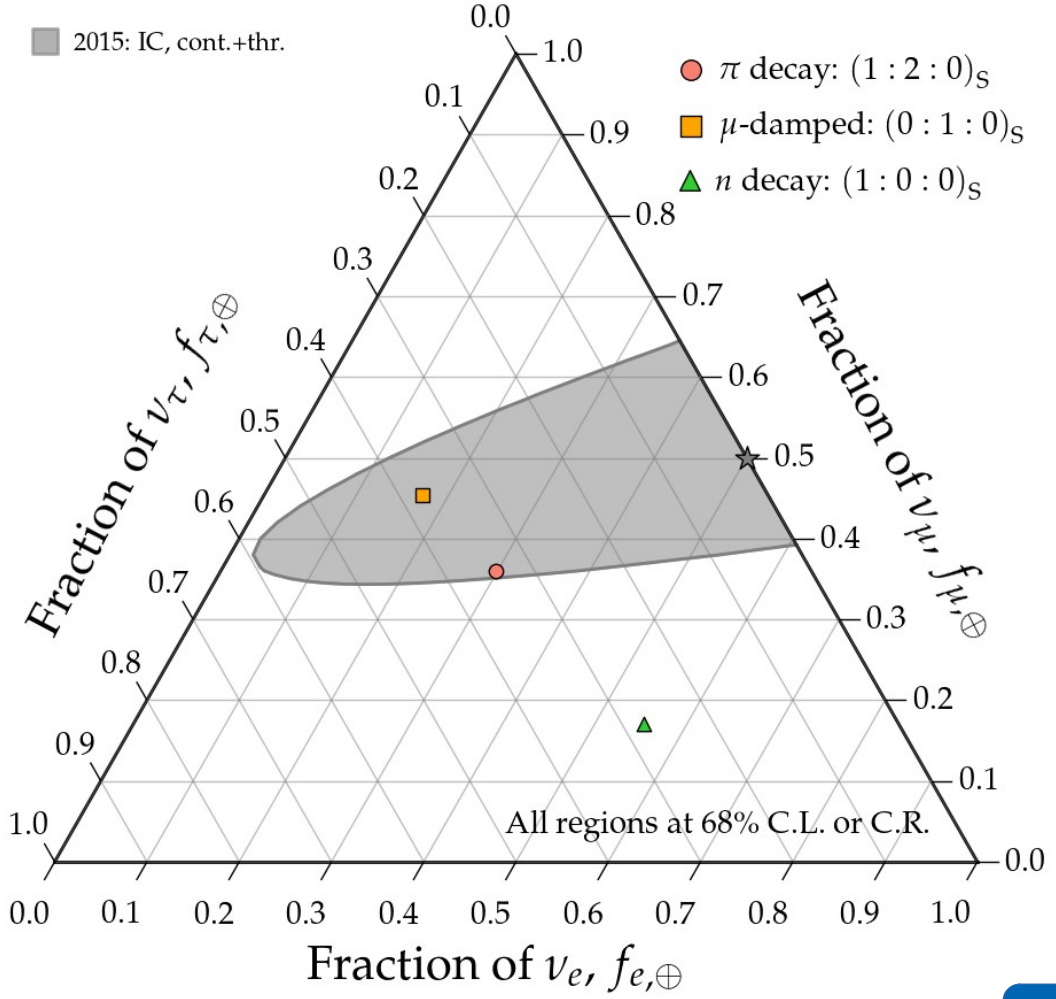




Measuring flavor composition: 2015–2040

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





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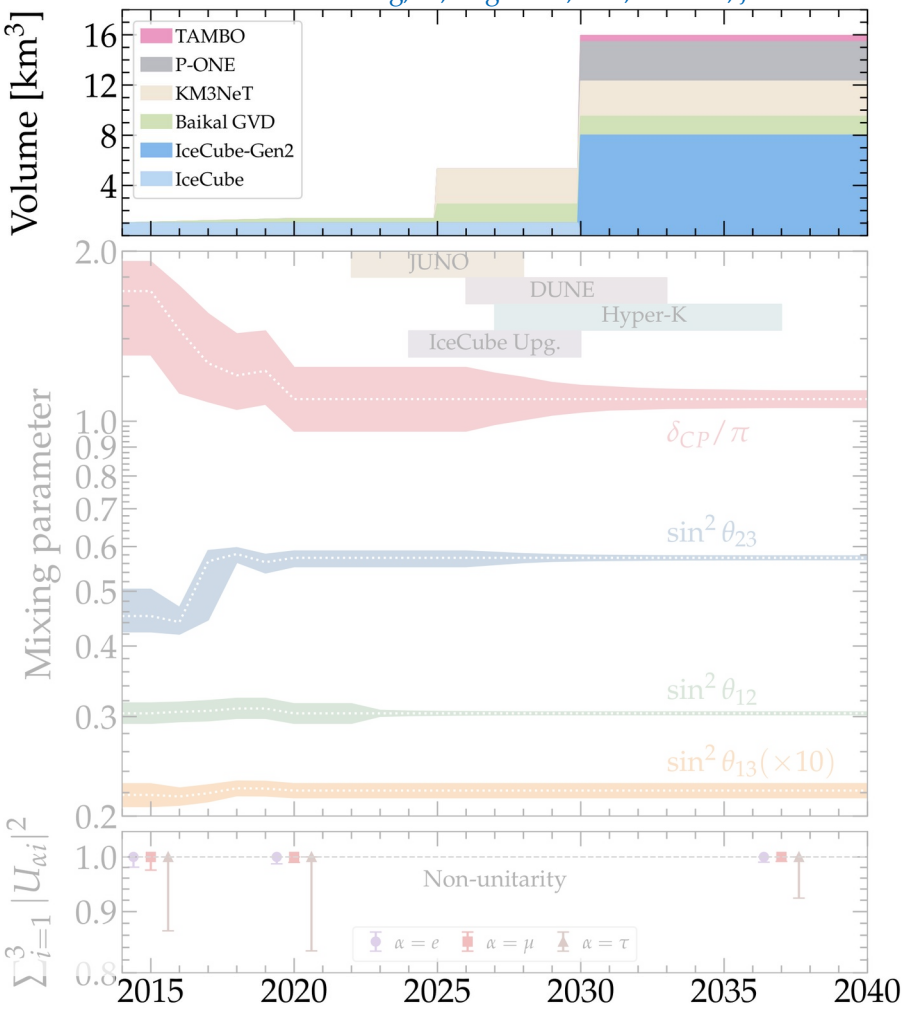
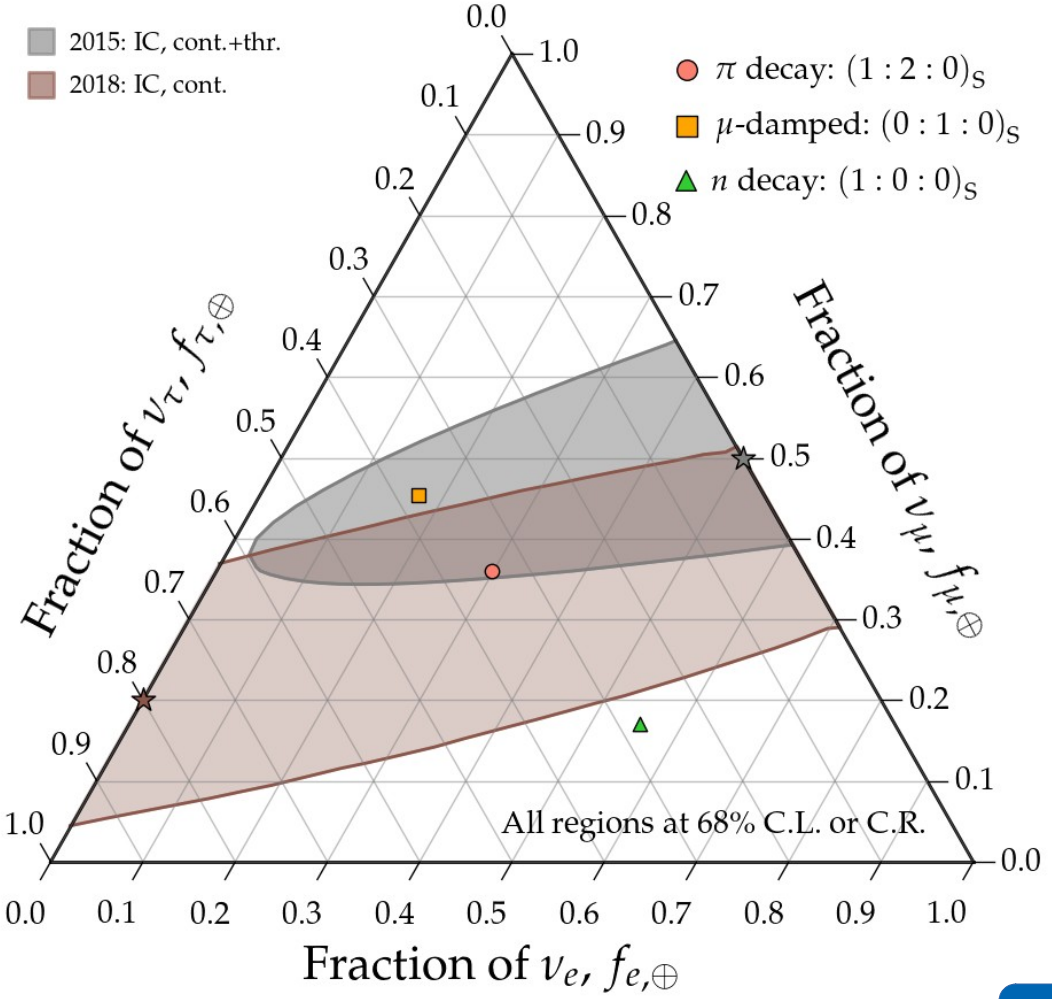
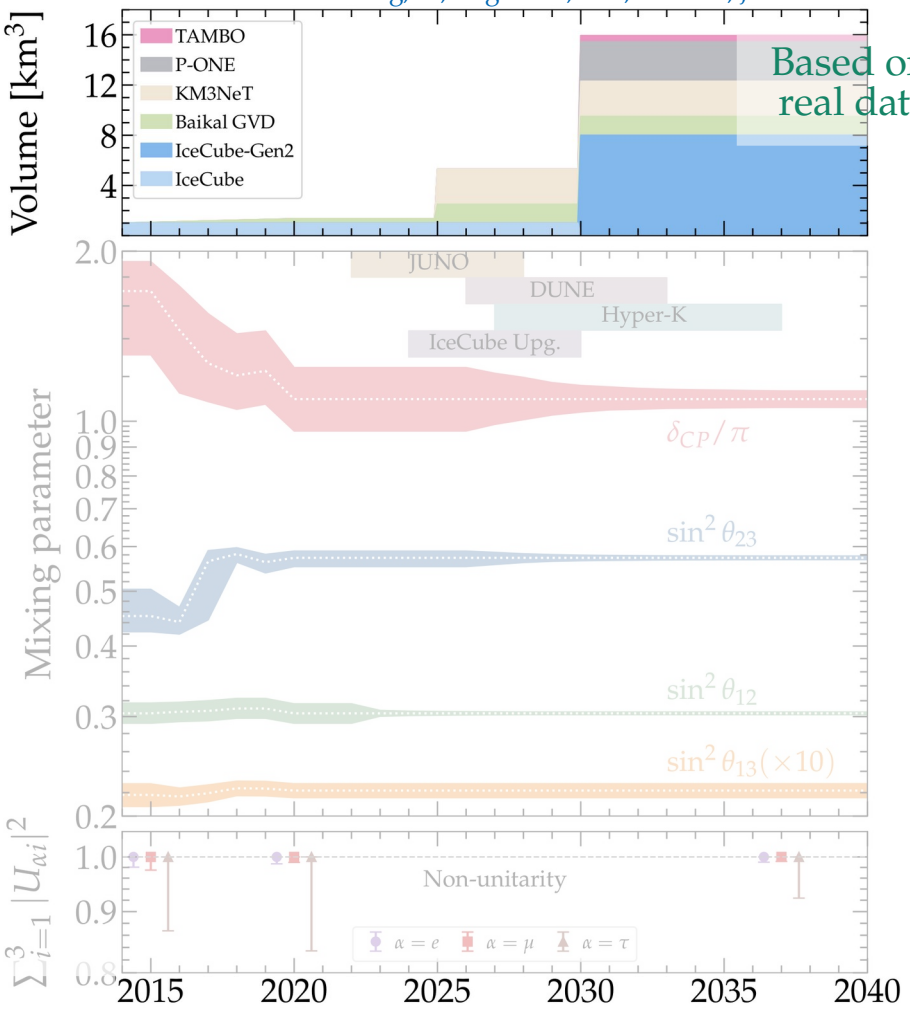
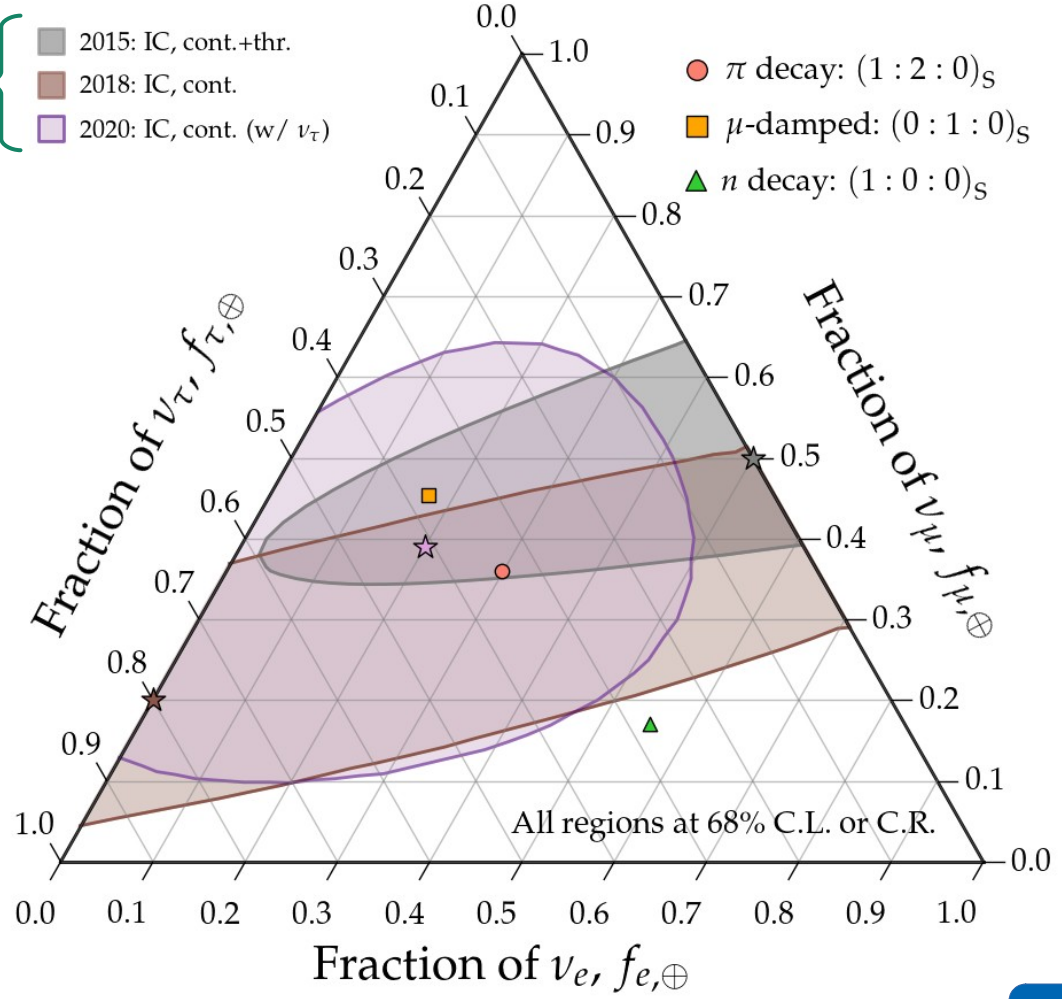




Measuring flavor composition: 2015–2040

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





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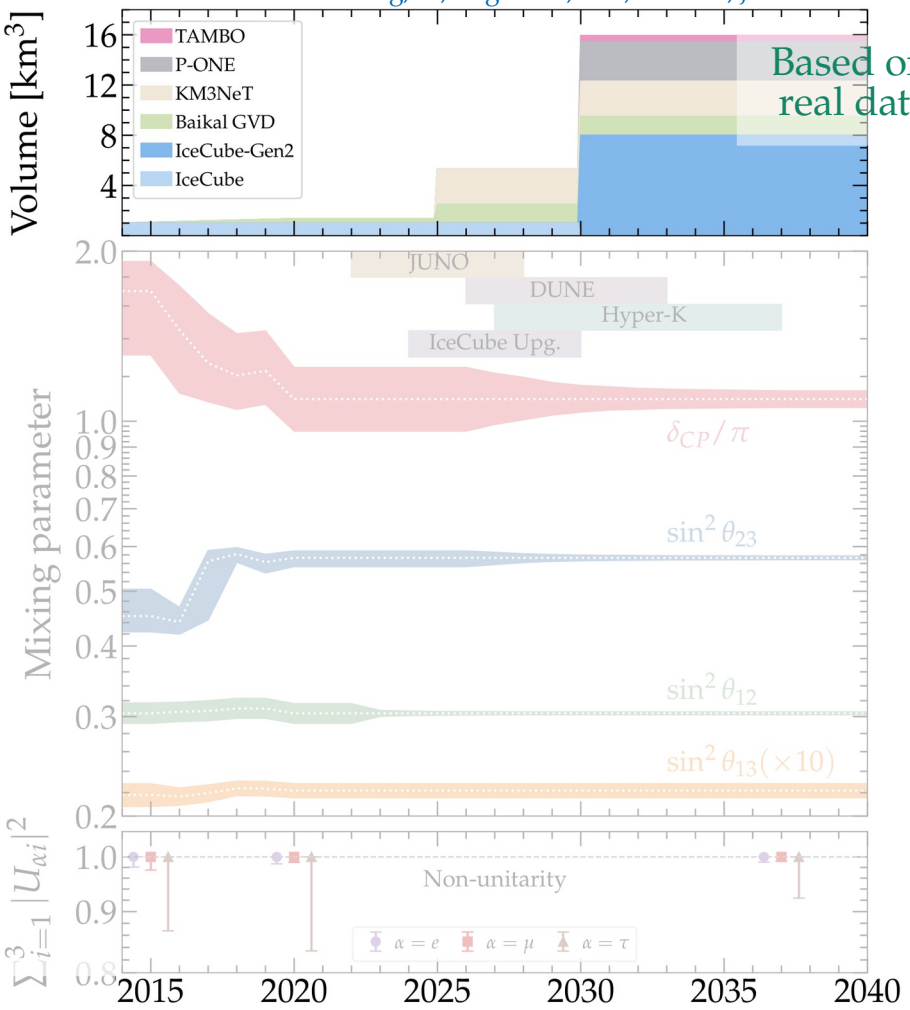
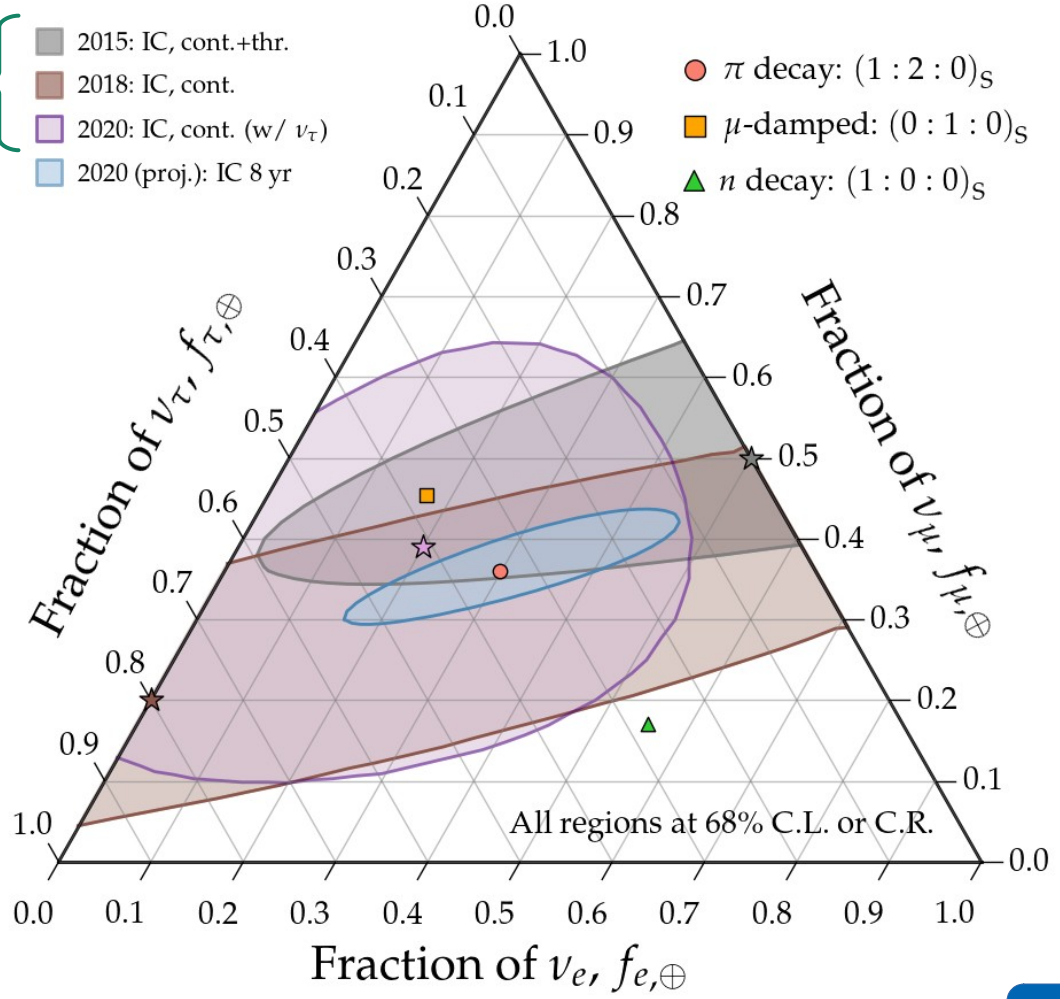
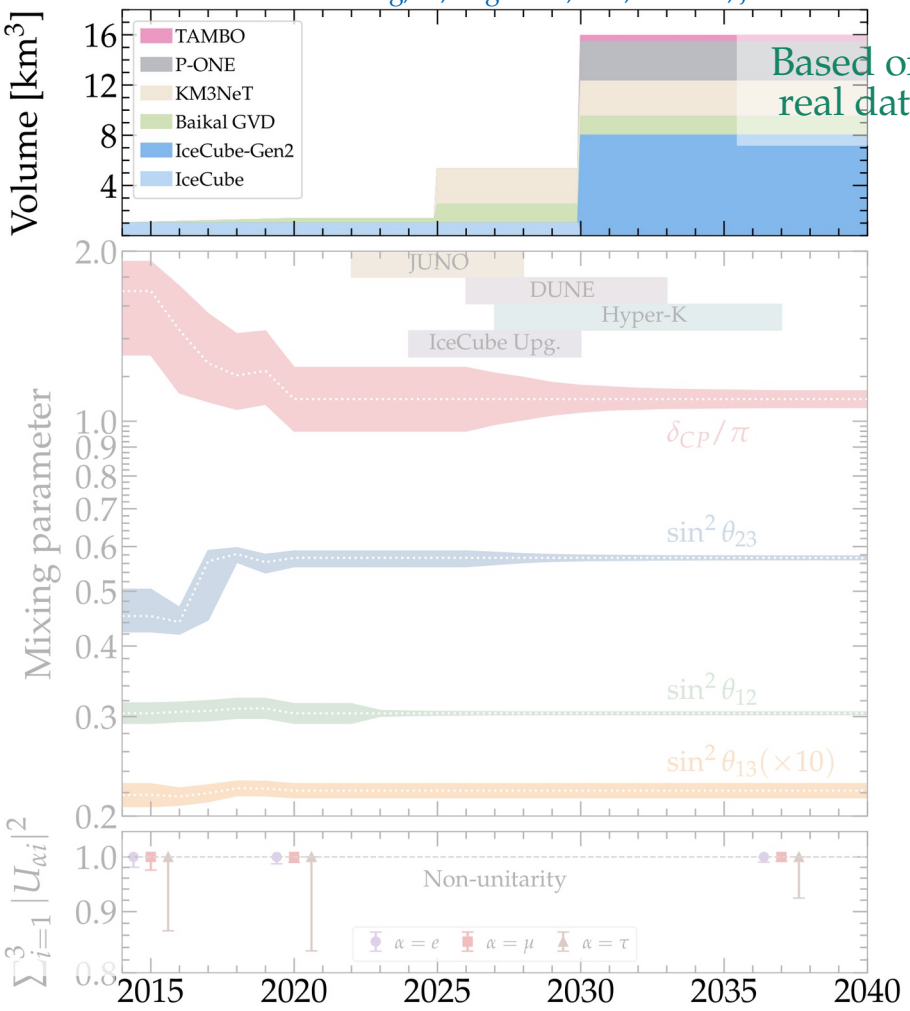
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



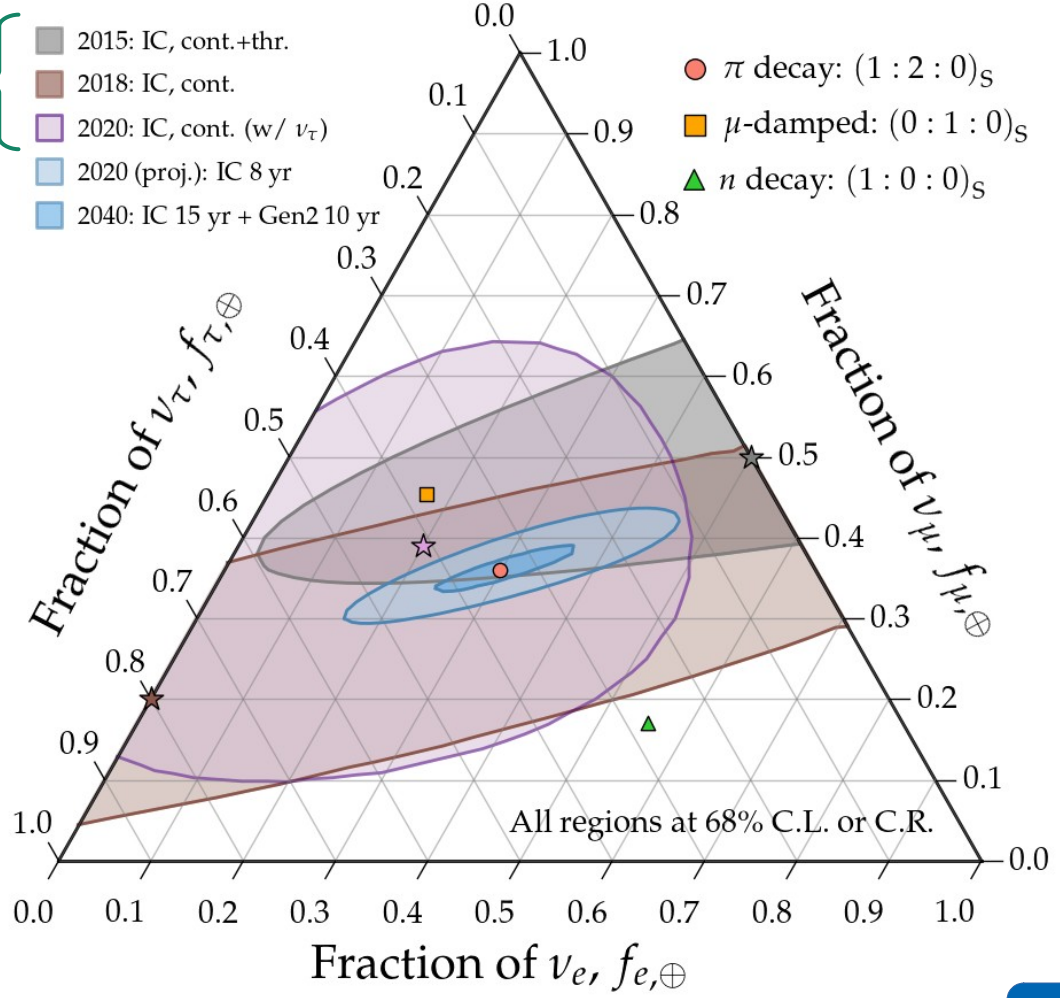


Measuring flavor composition: 2015–2040

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



Based on real data



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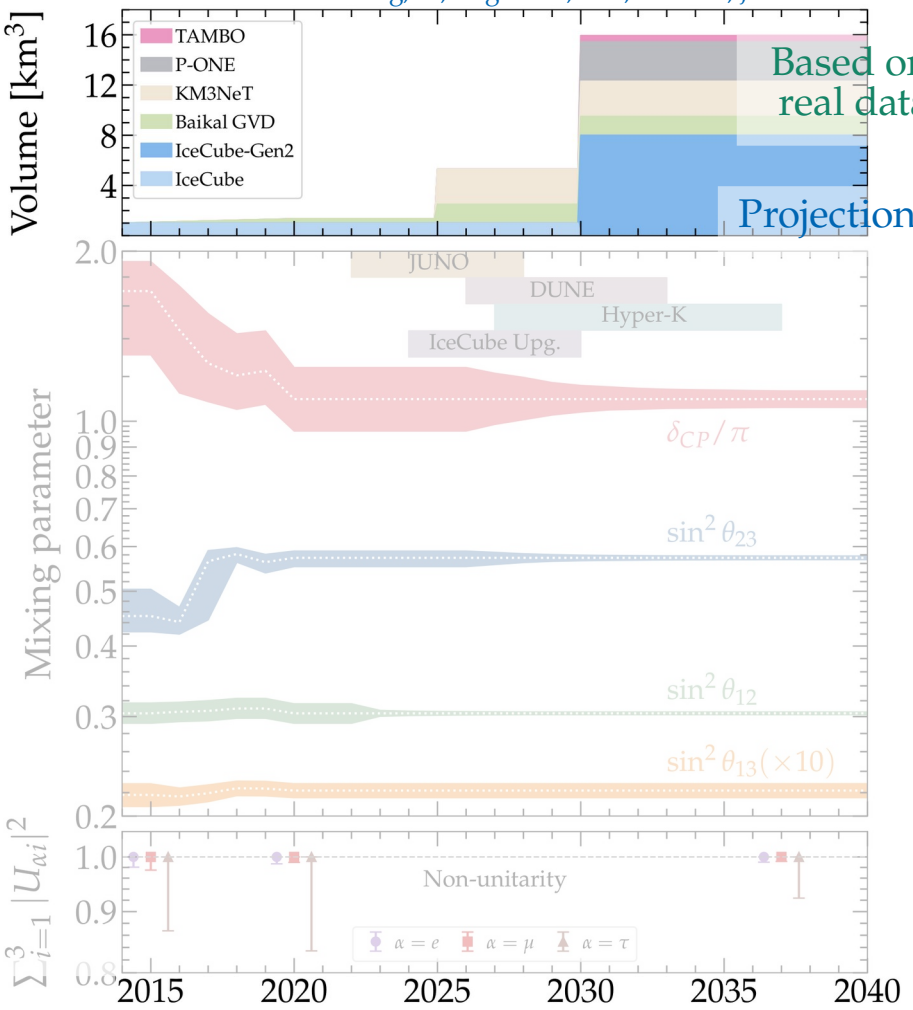
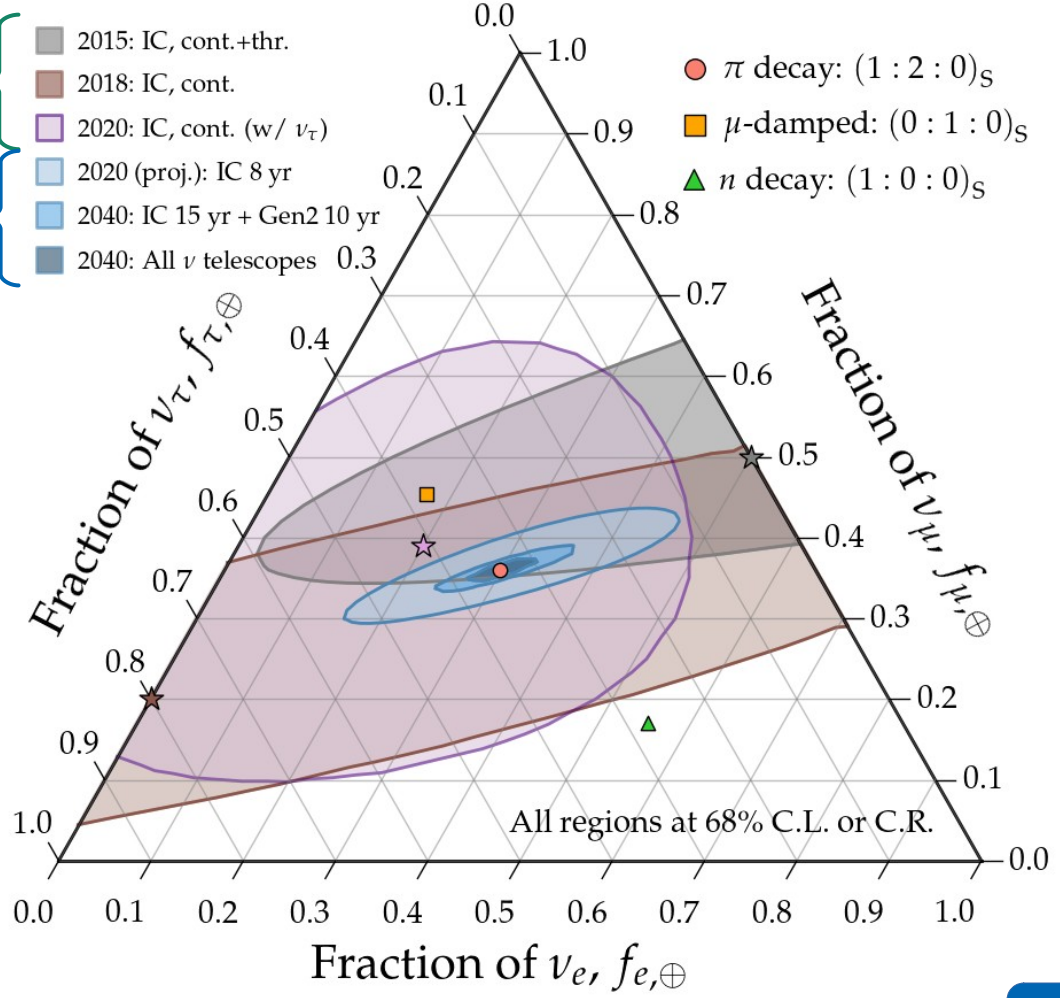
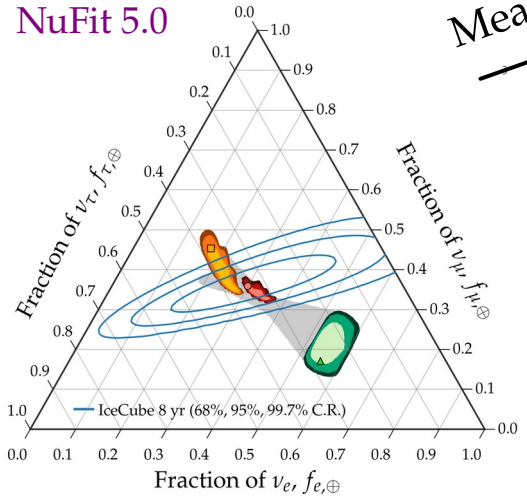




How knowing the mixing parameters better helps

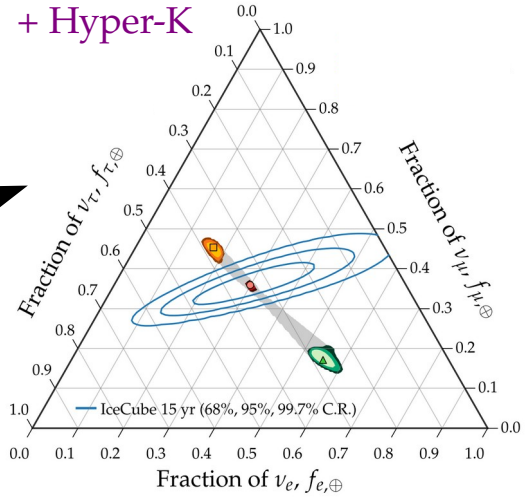
2020

NuFit 5.0

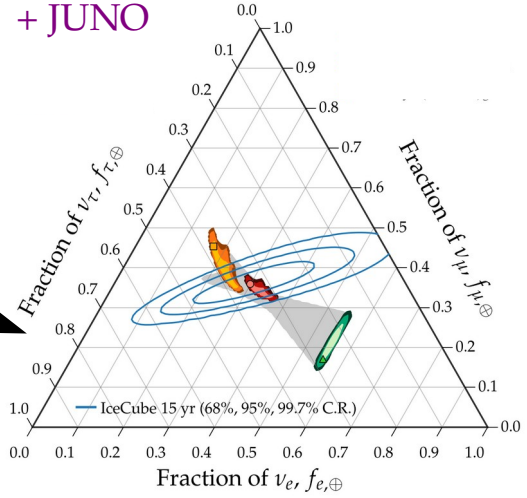


Measure θ_{23} better

+ Hyper-K



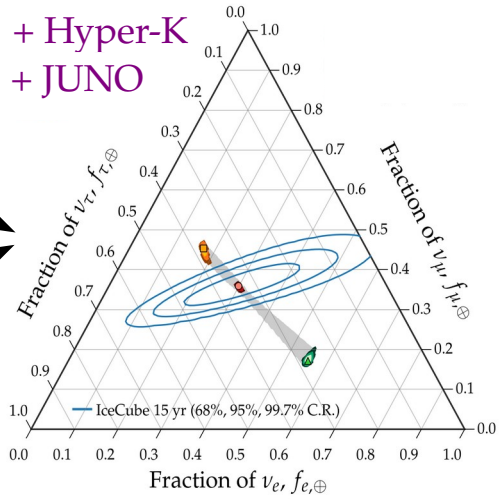
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO

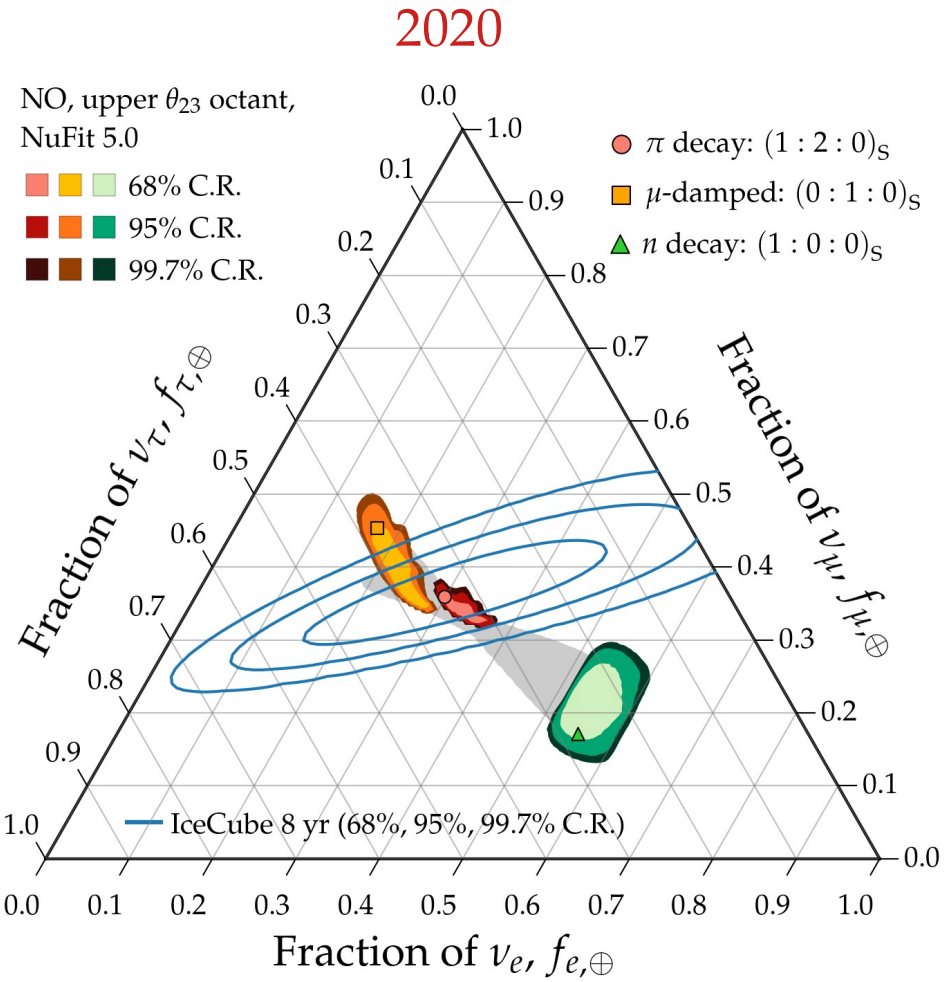


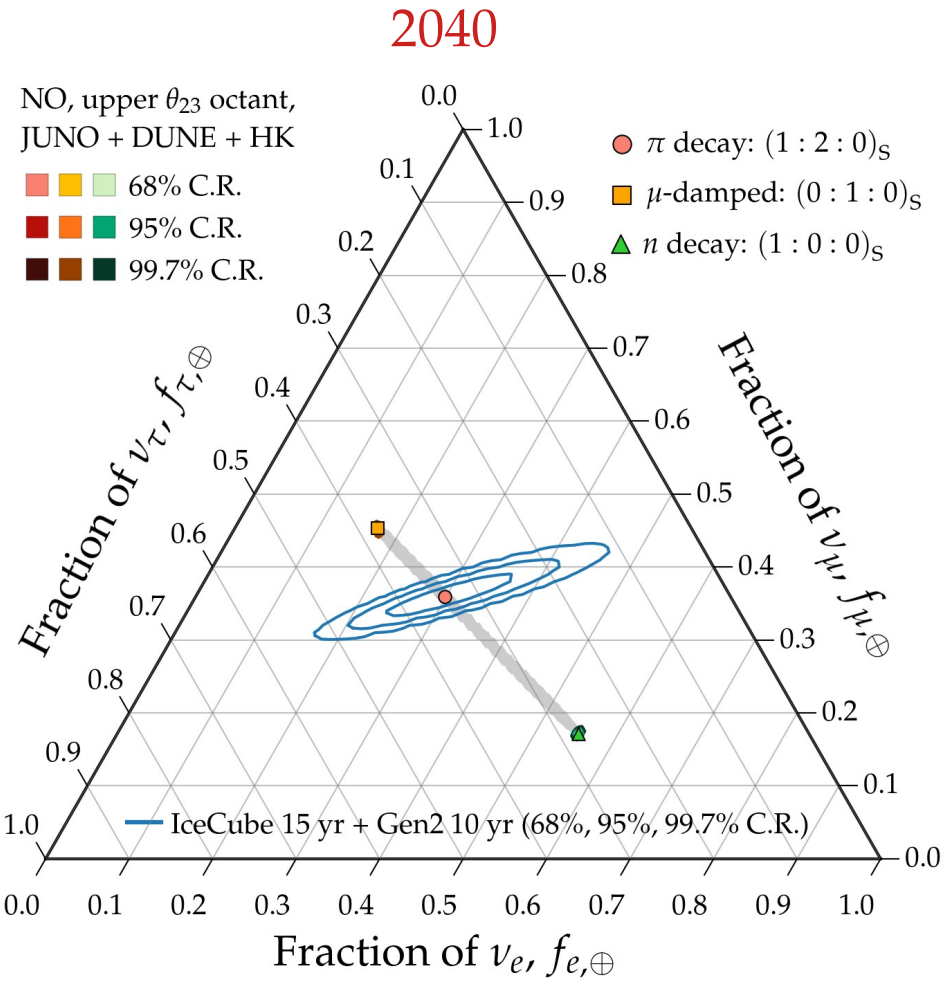
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Theoretically palatable regions: 2020 → 2040

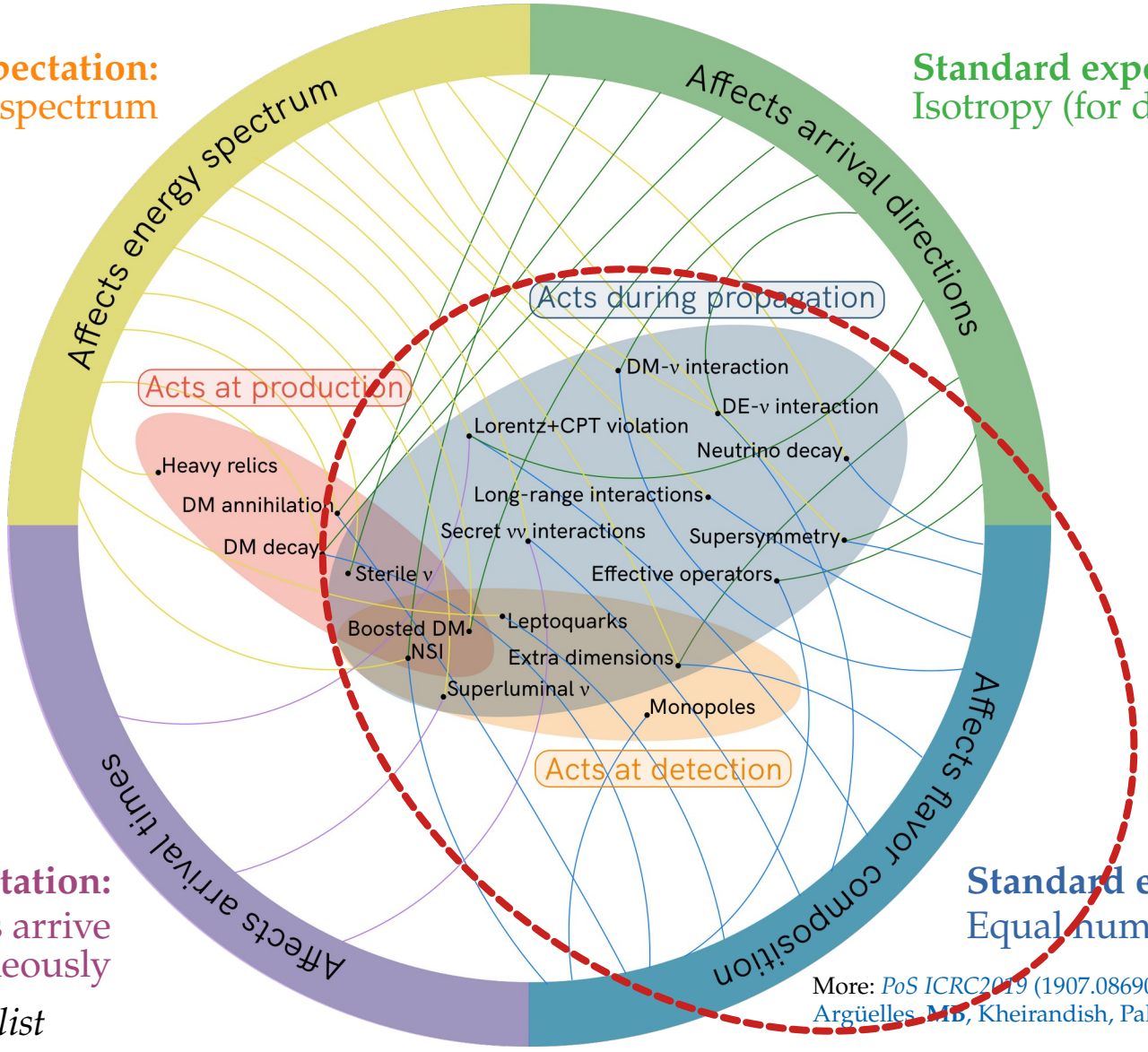




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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

Repurpose the flavor sensitivity to test new physics:

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

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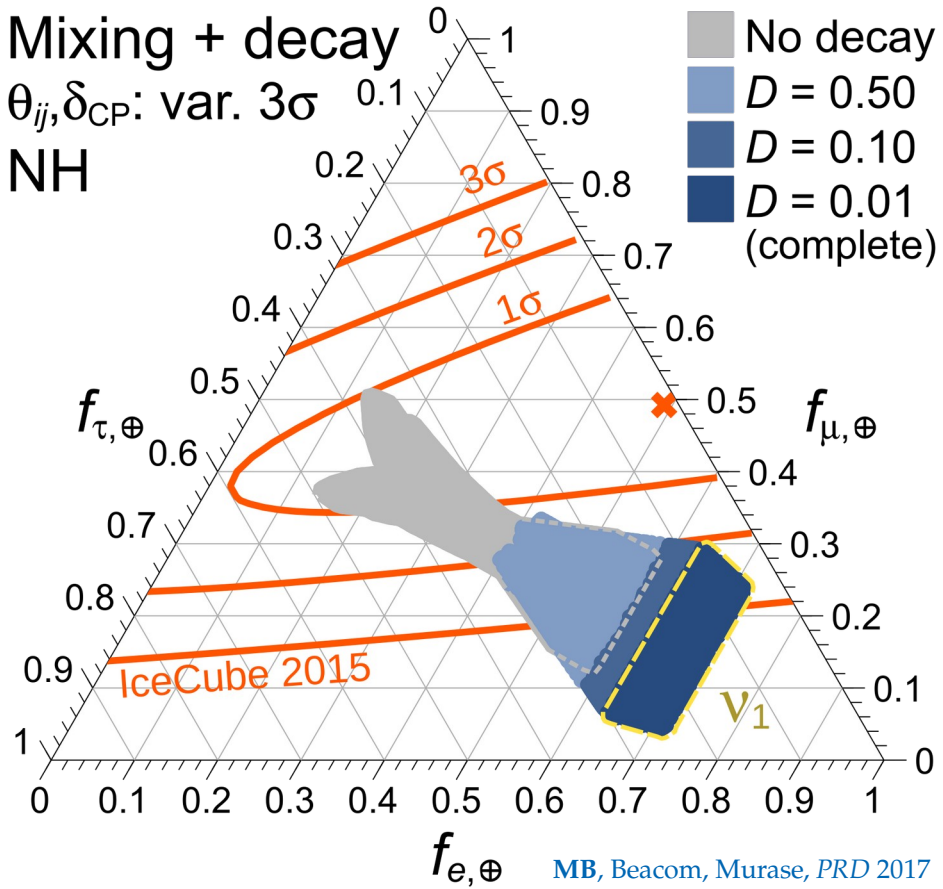

MB, Beacom, Murase, *PRD* 2017

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

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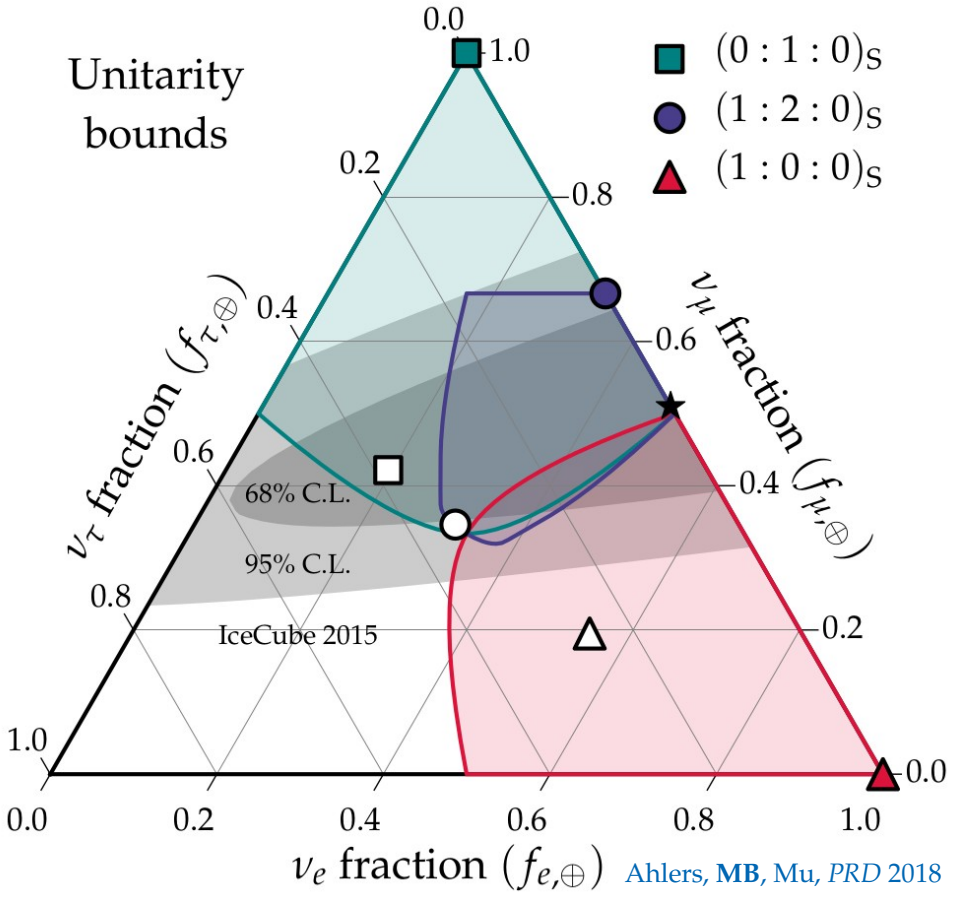

Ahlers, **MB**, Mu, *PRD* 2018

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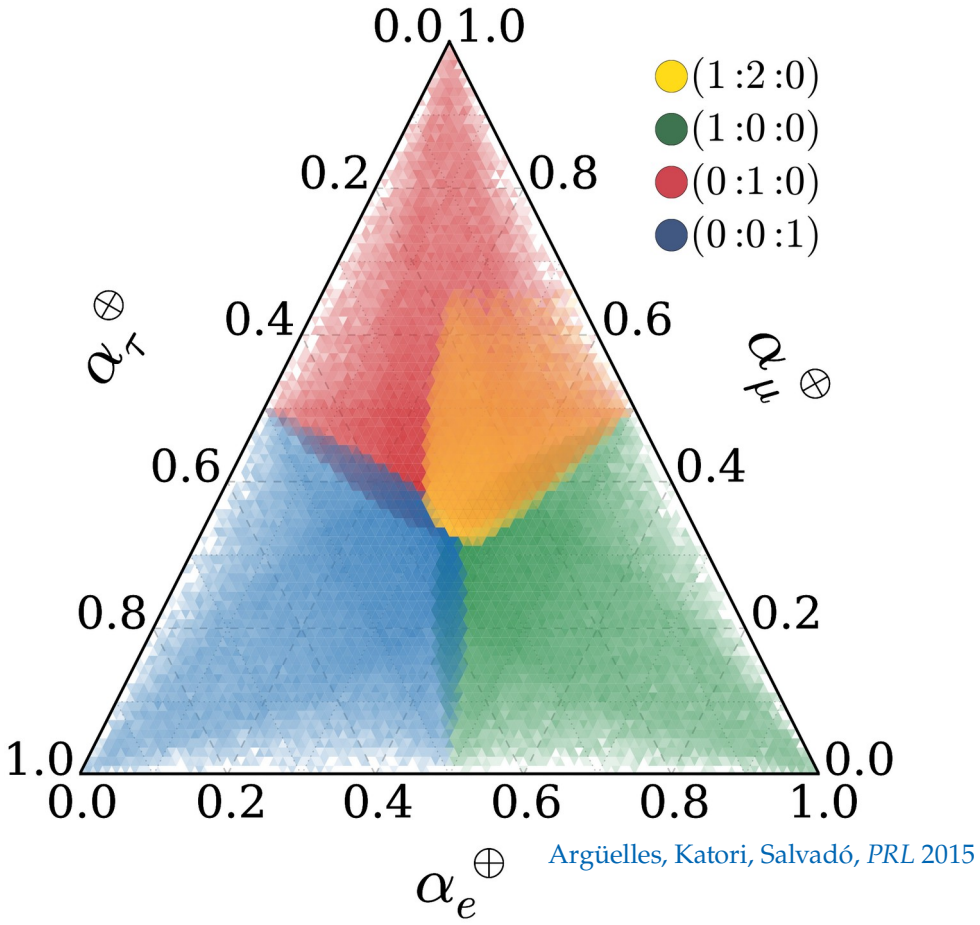

Argüelles, Katori, Salvadó, *PRL* 2015

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

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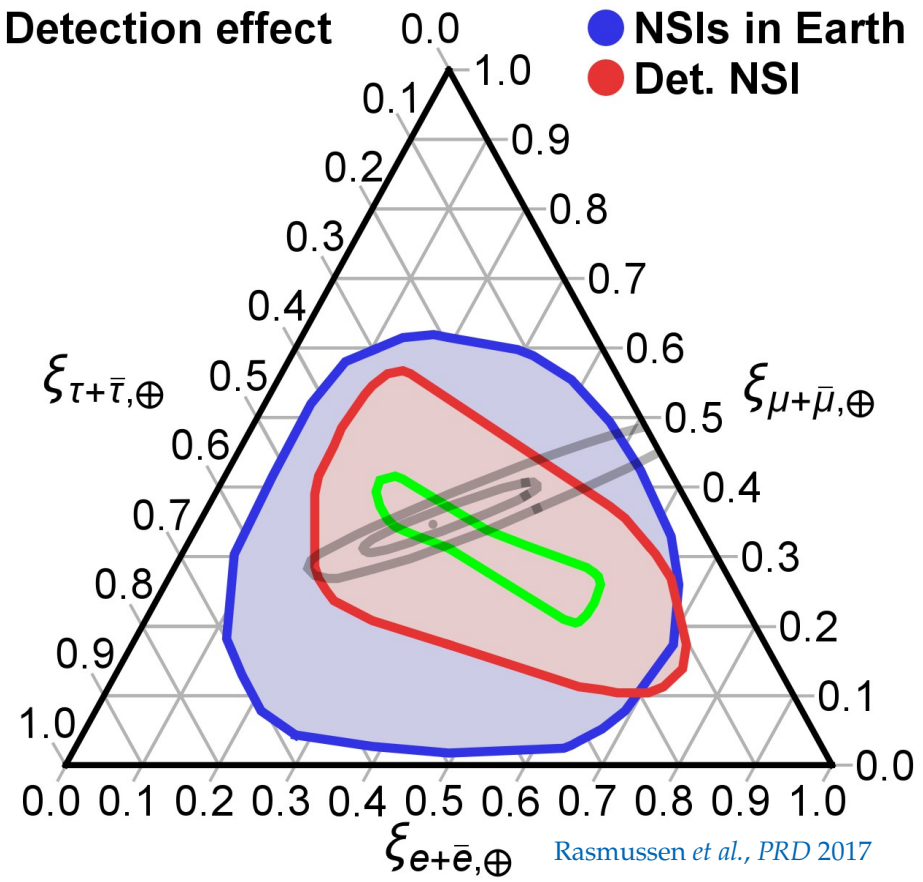

Rasmussen *et al.*, *PRD* 2017

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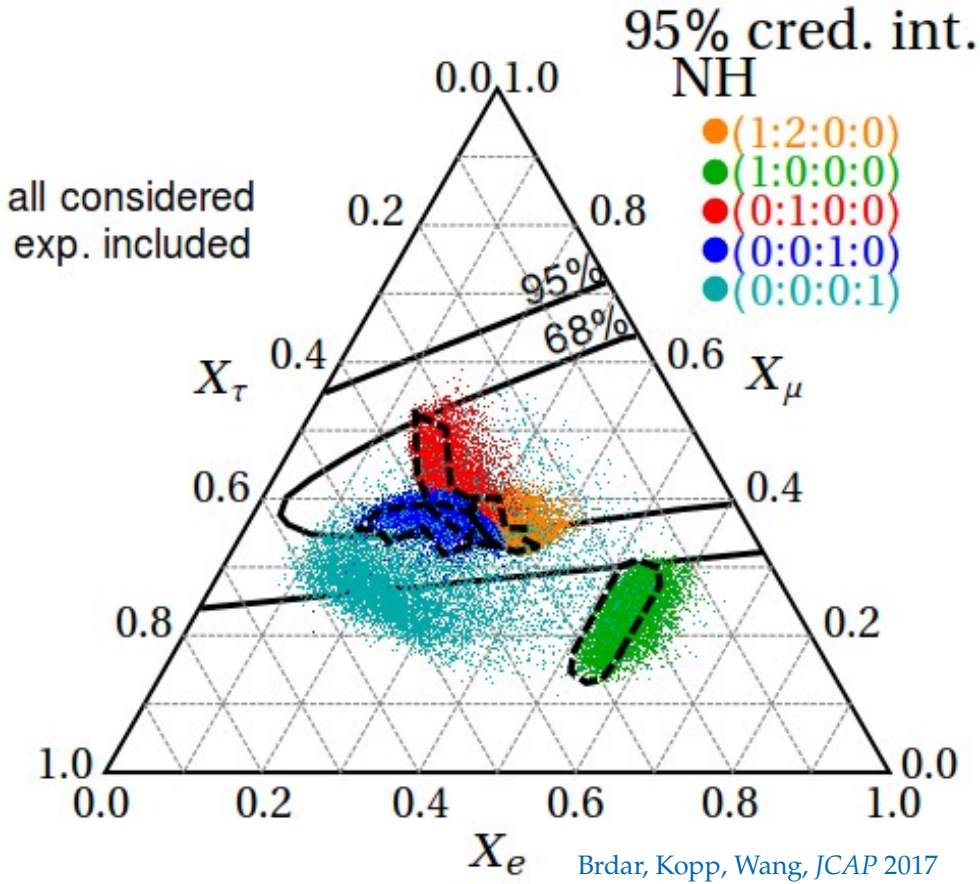

Brdar, Kopp, Wang, *JCAP* 2017

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

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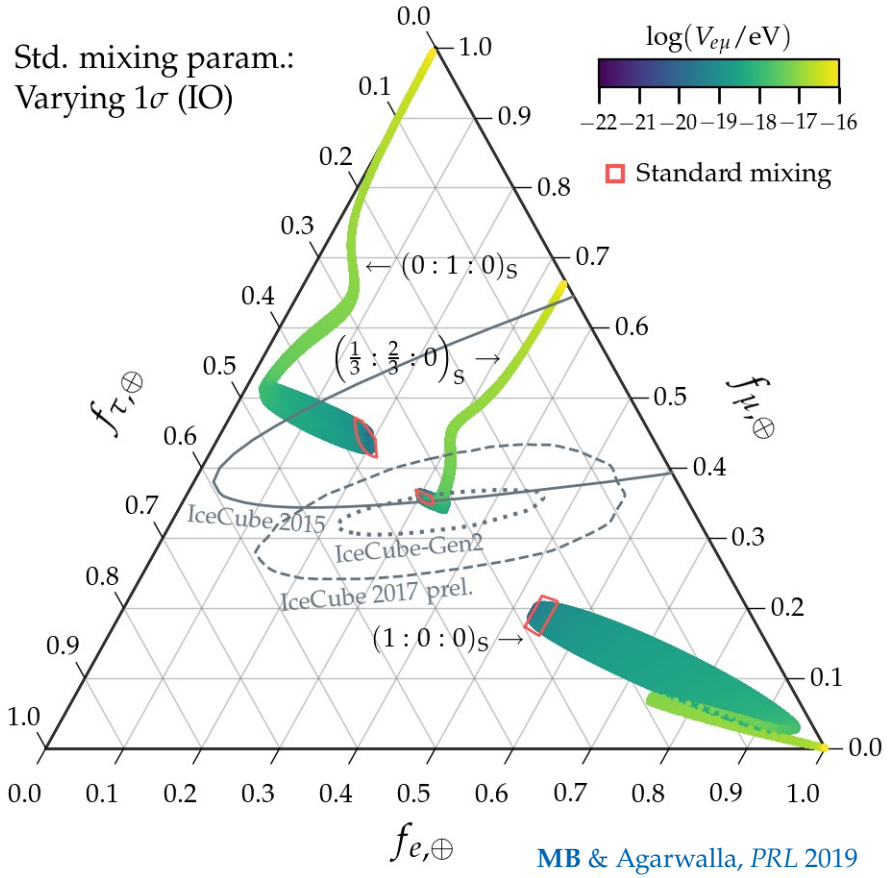
- Long-range *eν* interactions
  [**MB** & Agarwalla, *PRL* 2019]

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



MB & Agarwalla, *PRL* 2019

4. New neutrino interactions:
Are there secret νν interactions?

Astrophysical neutrino sources

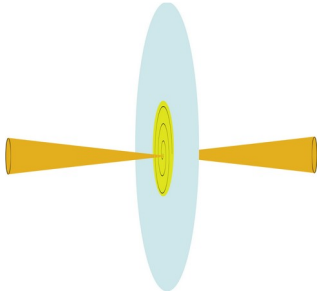
Earth

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

Astrophysical neutrino sources

Earth

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



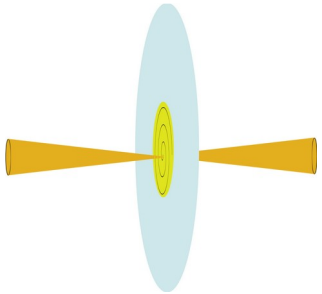
Standard case: ν free-stream

(And oscillate)

Astrophysical neutrino sources

Earth

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



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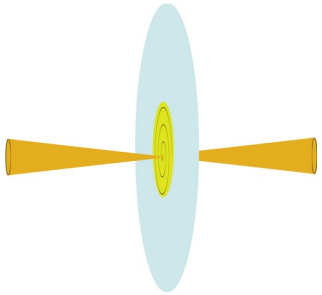

Non-standard case: high-energy ν scatter of CνB

Astrophysical neutrino sources

Earth

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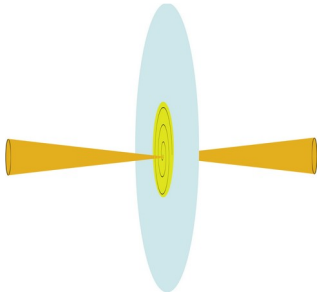

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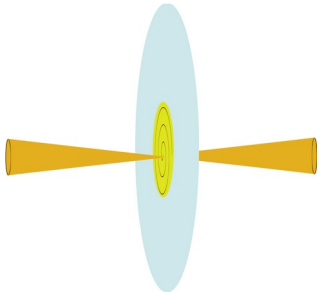

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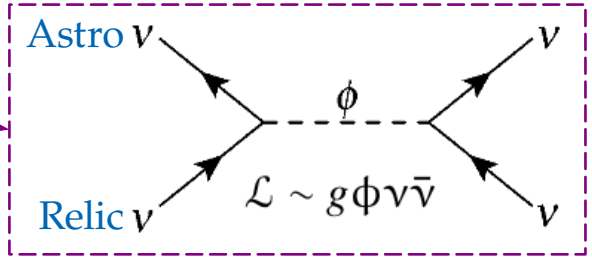
"Secret" ν interactions ≡ BSM ν self-interactions



Astrophysical neutrino sources

Earth

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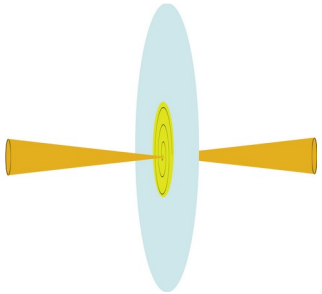
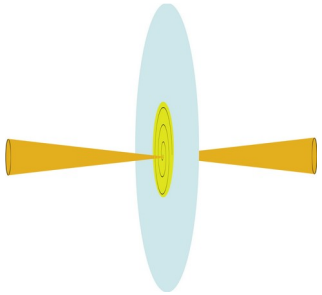


Standard case: ν free-stream

(And oscillate)



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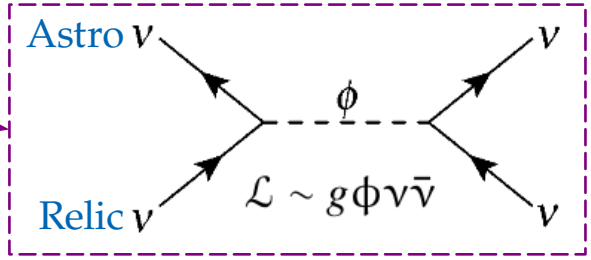
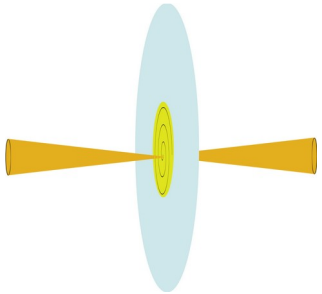


Can change:

Astrophysical neutrino sources

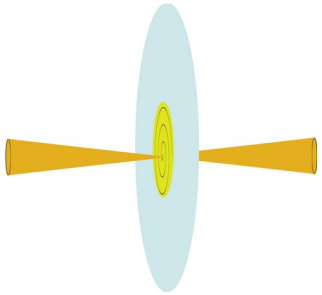
Earth

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



Standard case: ν free-stream

(And oscillate)



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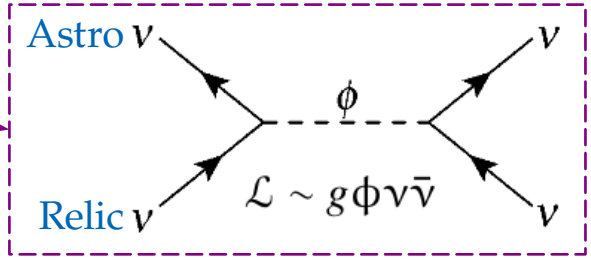


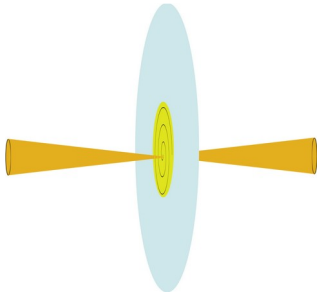
Can change:

- Energy spectrum

Astrophysical neutrino sources

Earth

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



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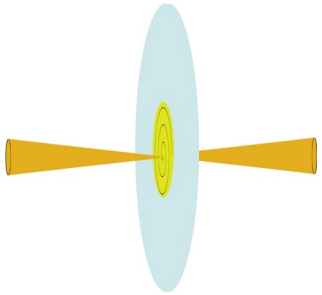

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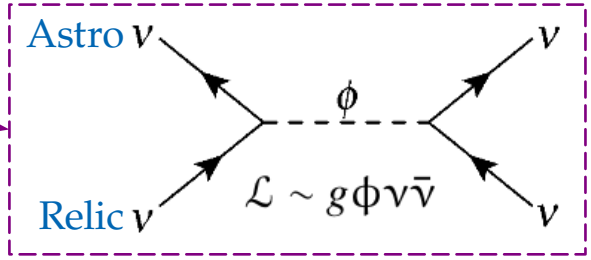

Can change:

- Energy spectrum
- Flavor composition

Astrophysical neutrino sources

Earth

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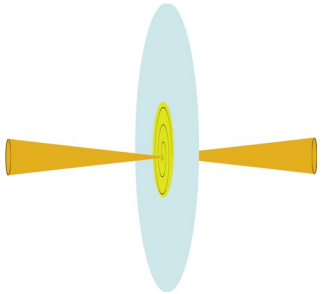

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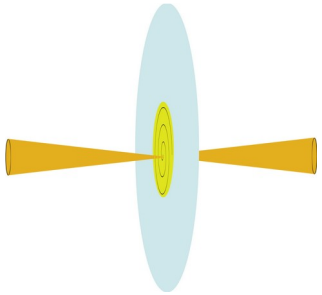

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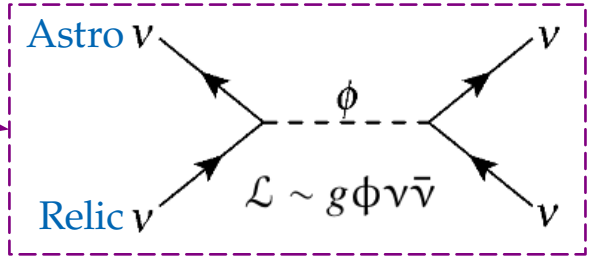

Can change:

- Energy spectrum
- Flavor composition
- Direction

Astrophysical neutrino sources

Earth

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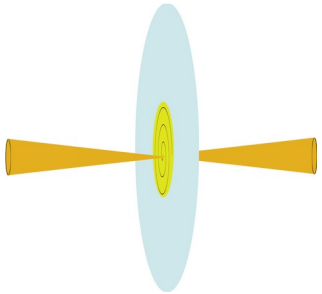

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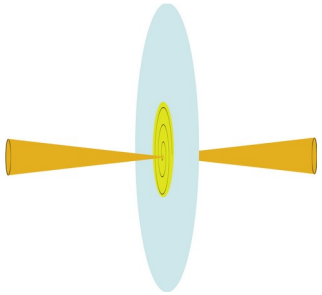

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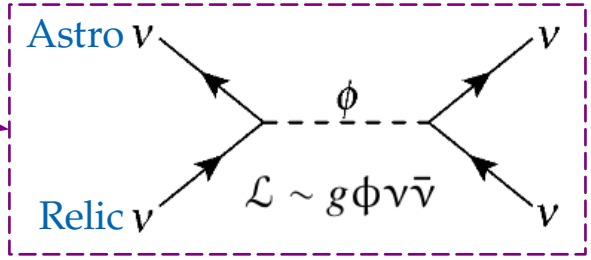
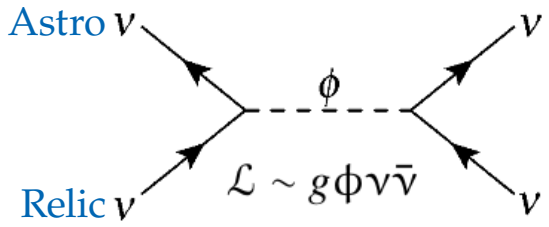


Can change:

- Energy spectrum
- Flavor composition
- Direction
- Arrival times

Secret interactions of high-energy astrophysical neutrinos

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



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

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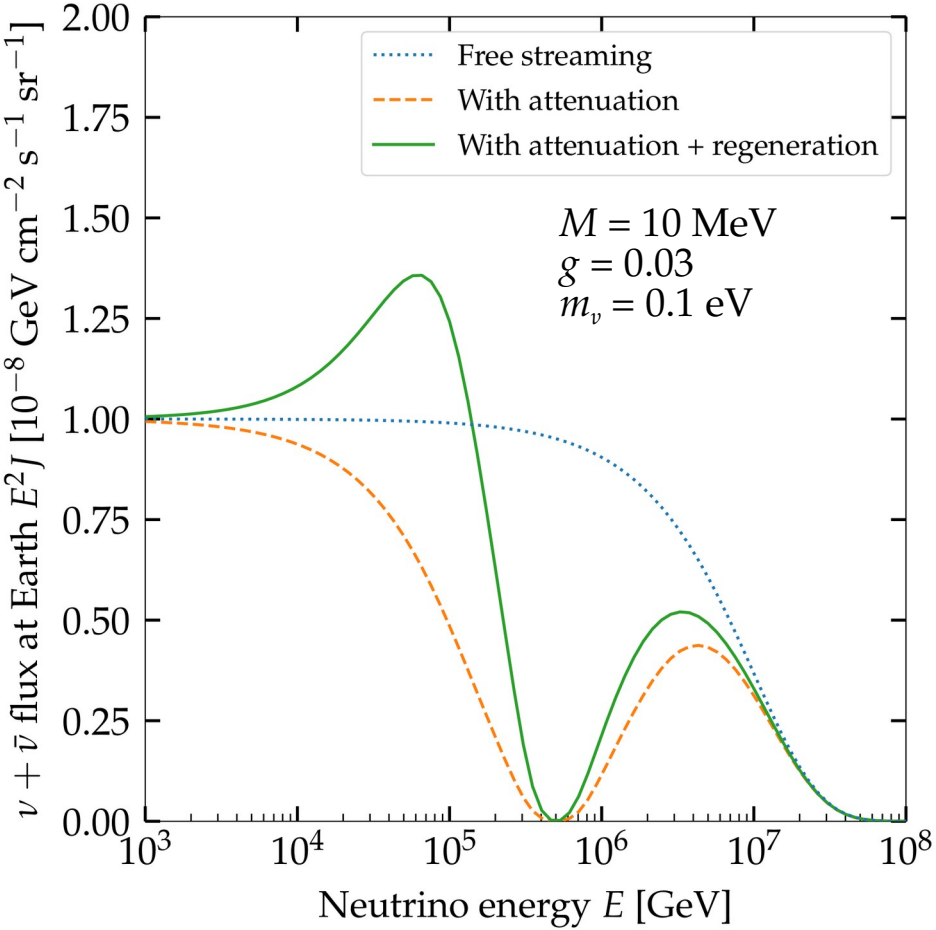
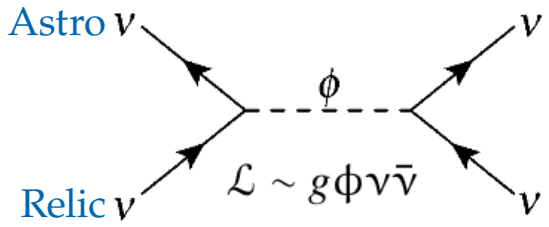


Secret interactions of high-energy astrophysical neutrinos

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



New coupling

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Mediator mass

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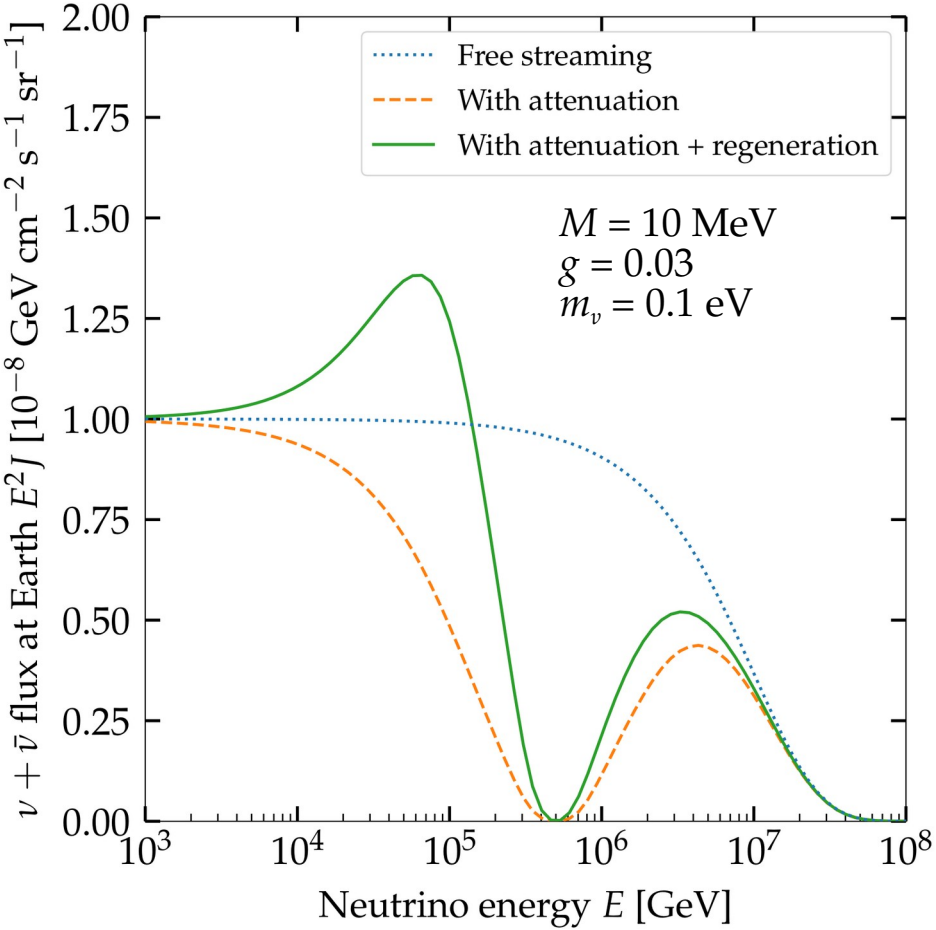

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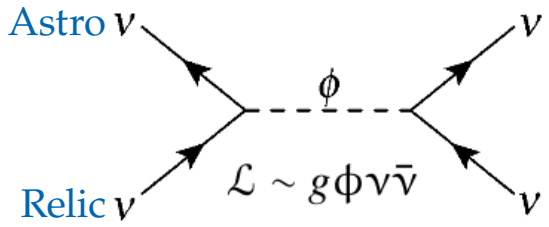

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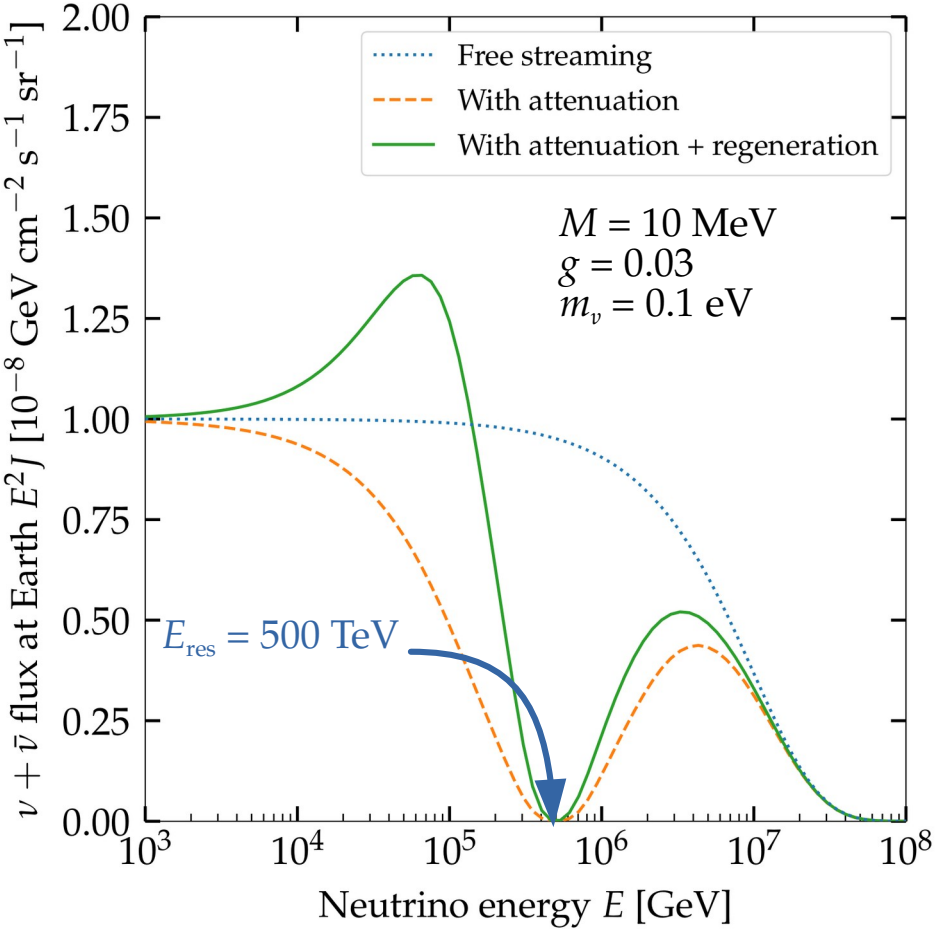

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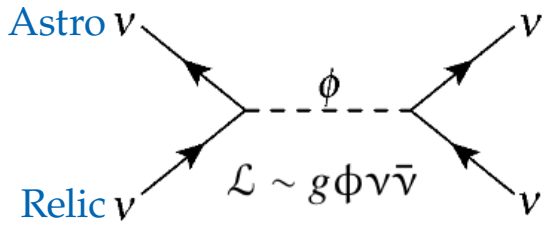

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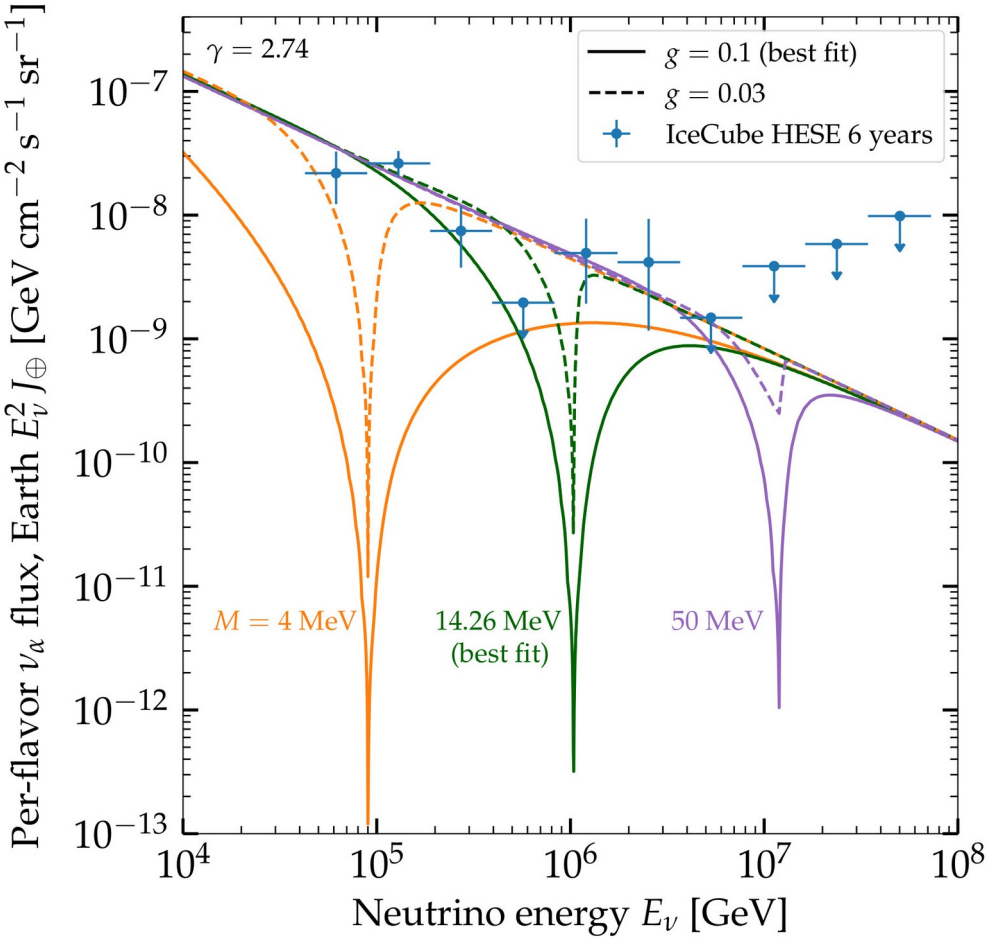

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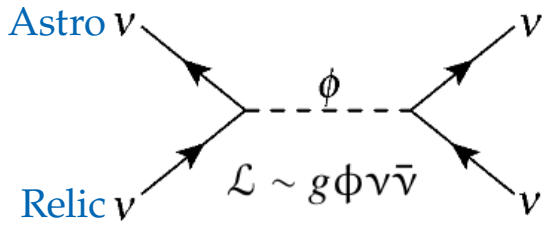

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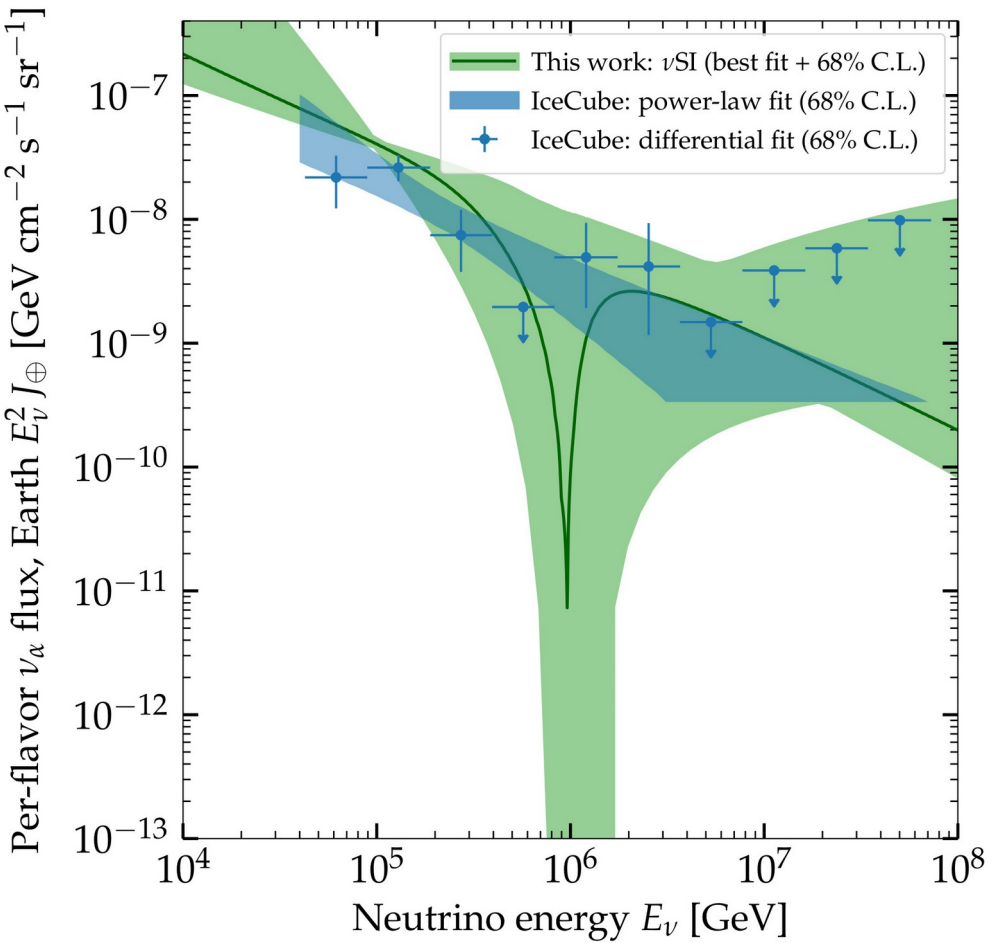
Looking for evidence of νSI

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

No significant (> 3σ) evidence for a spectral dip …



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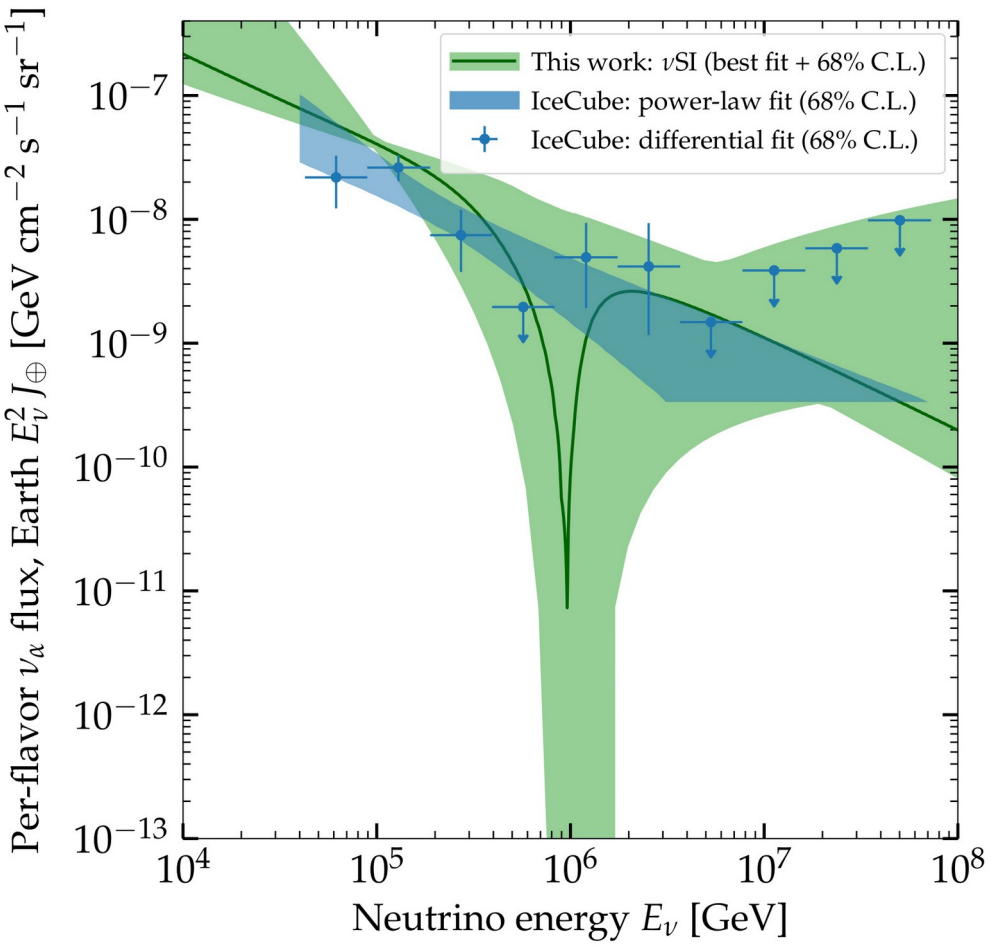

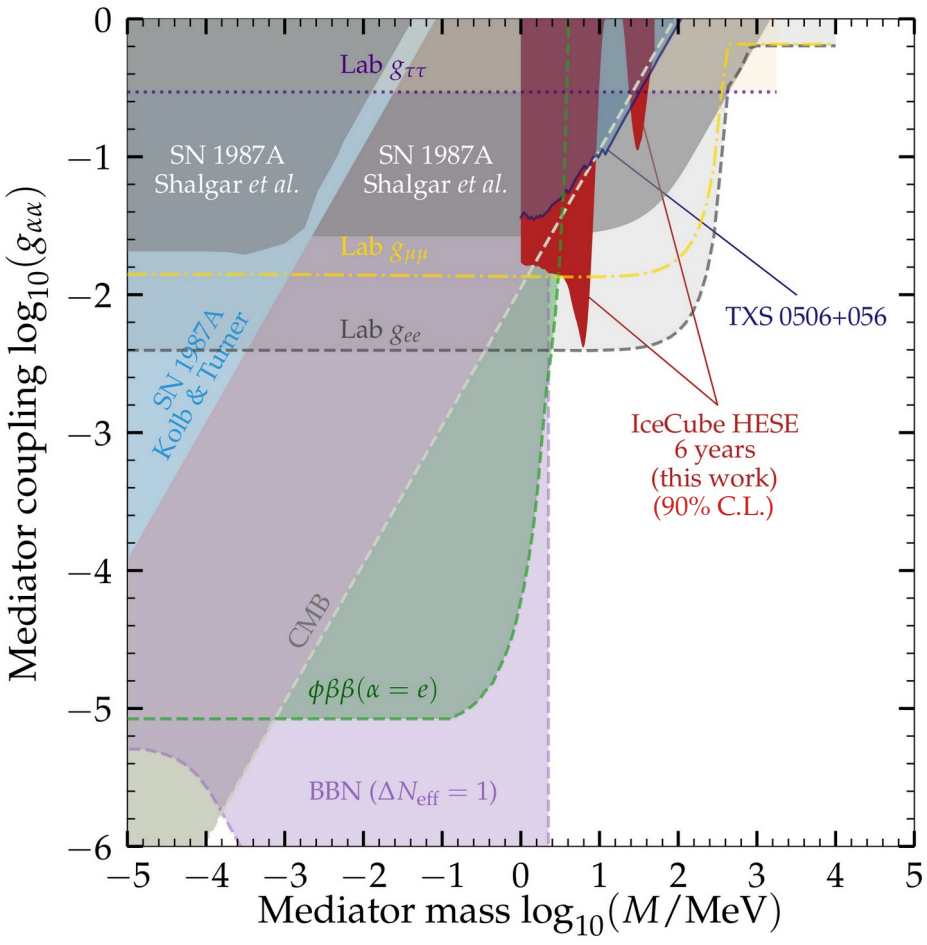

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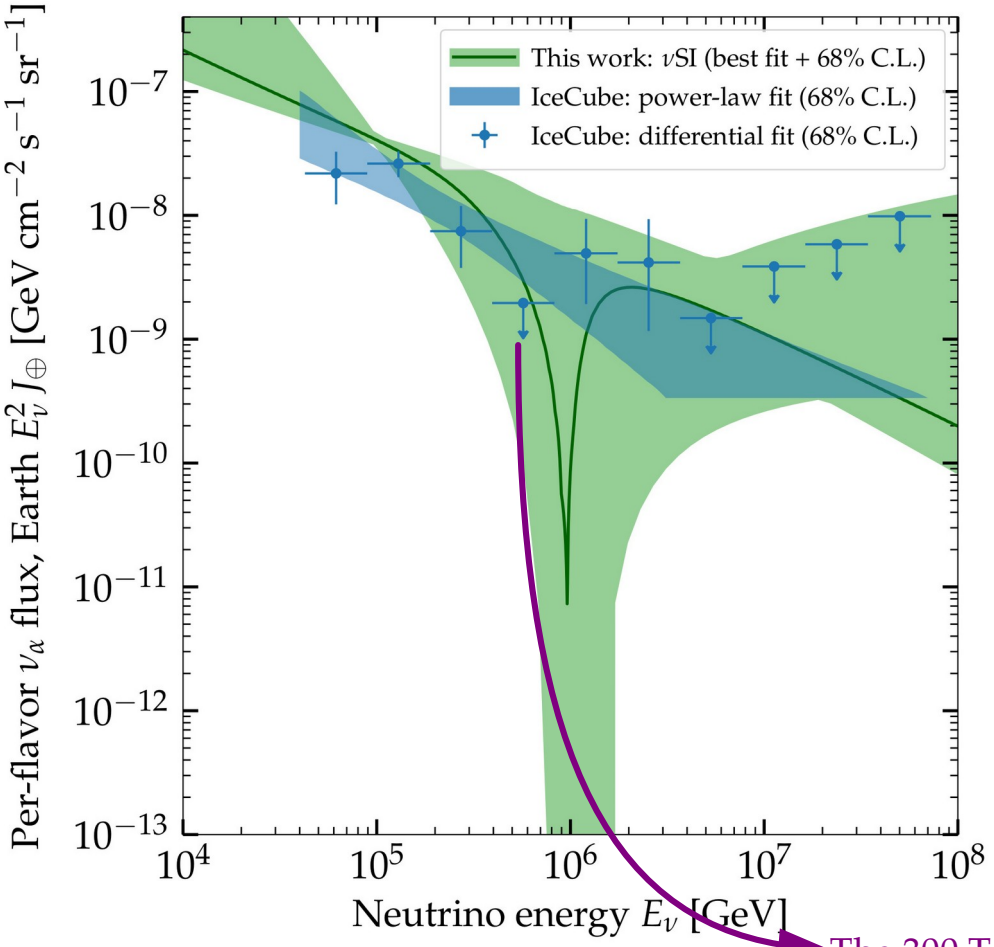

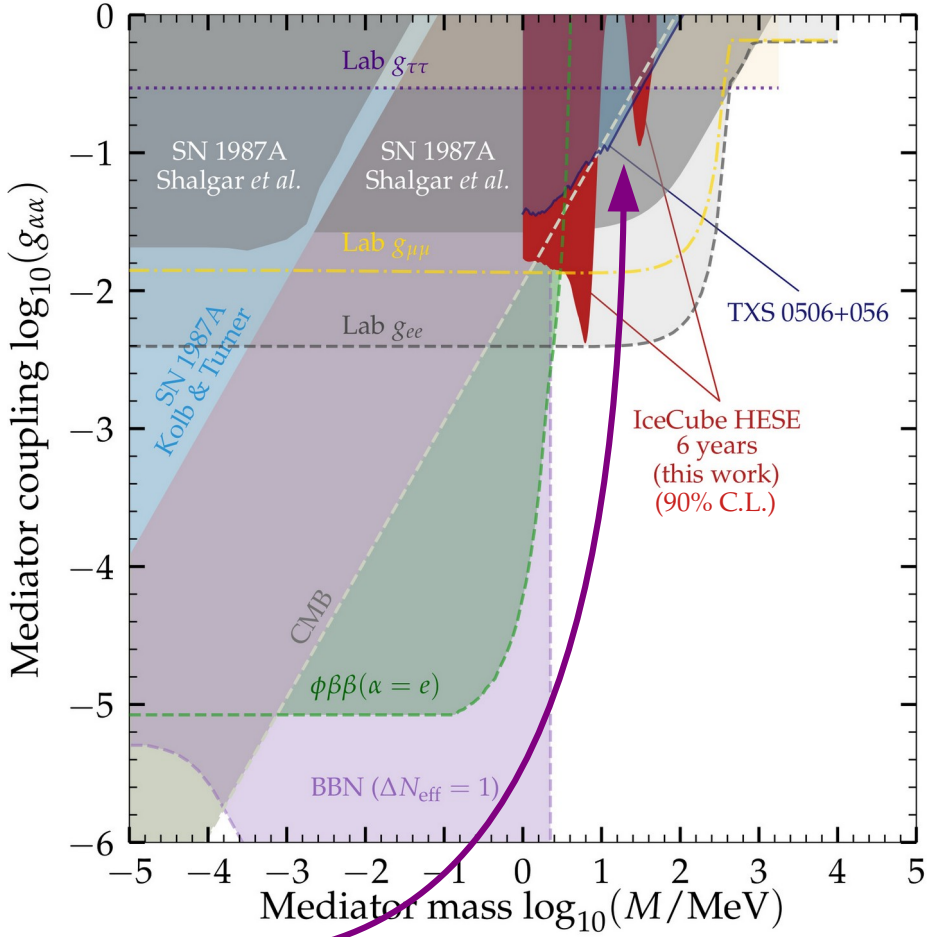

The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

5. Unstable neutrinos:
Are neutrinos for ever?

Are neutrinos forever?

- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\ (m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\ (m_i/\mathrm{eV})^{-9}$ yr
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  } » Age of Universe (~ 14.5 Gyr)

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

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- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$ — Nambu-Goldstone boson of a broken symmetry

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Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

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Only sensitive to their ratio

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Mass of ν_i Lifetime of ν_i

Astrophysical sources

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E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

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

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Astrophysical sources

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$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)

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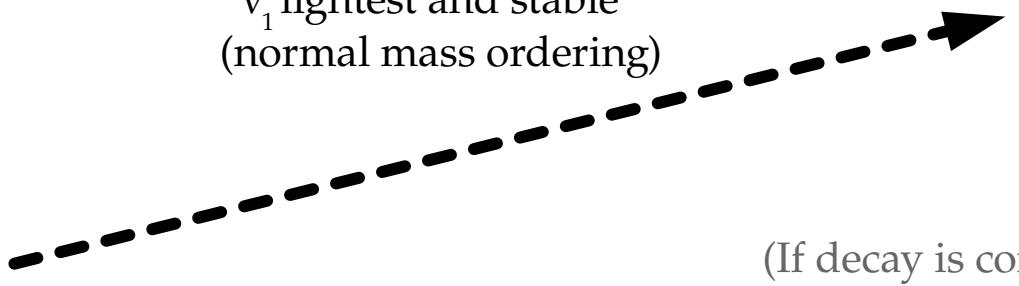

(If decay is complete)

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$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
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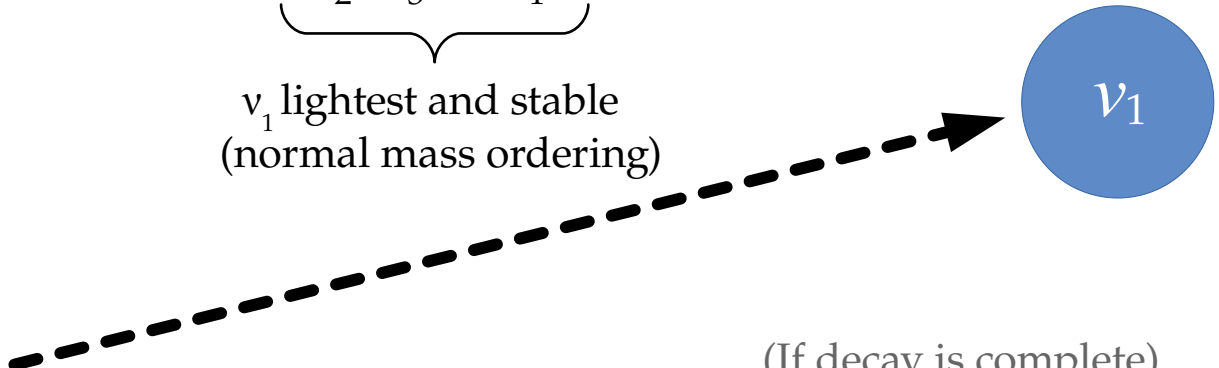

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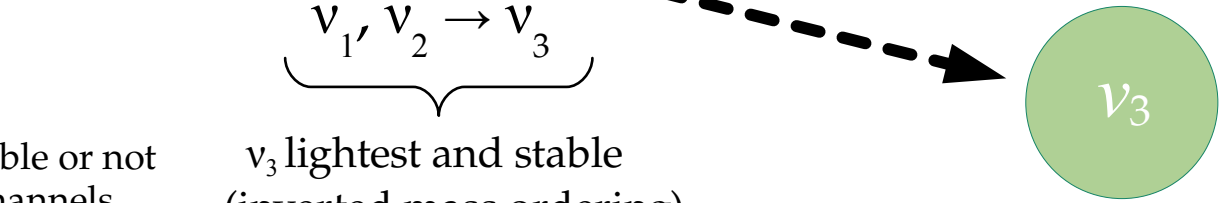

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

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

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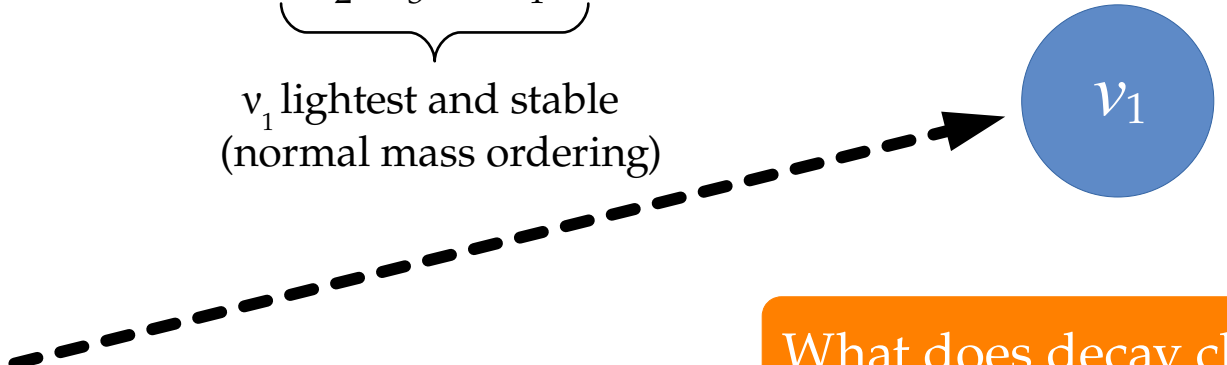

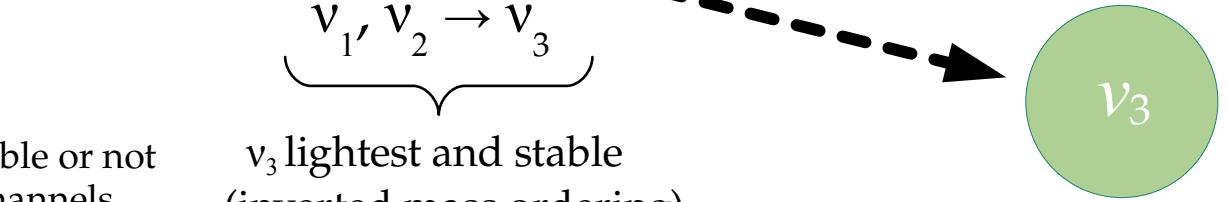

What does decay change?

$\nu_1, \nu_2 \to \nu_3$

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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

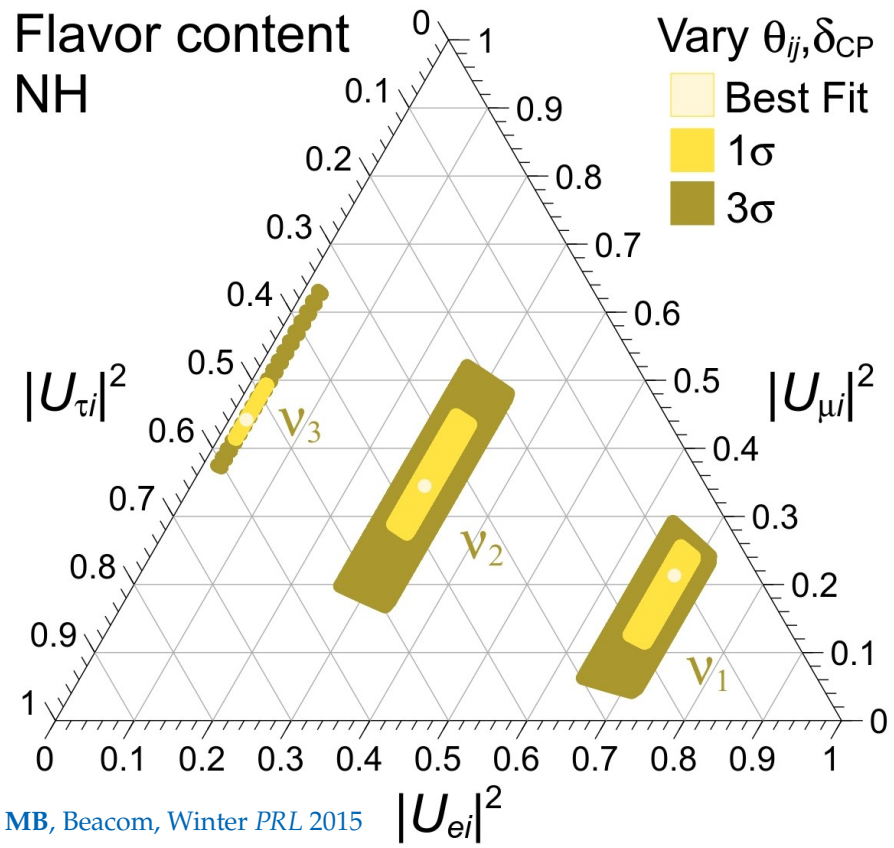
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

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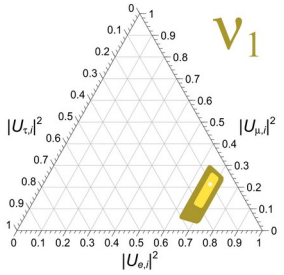

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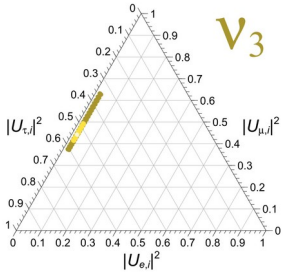

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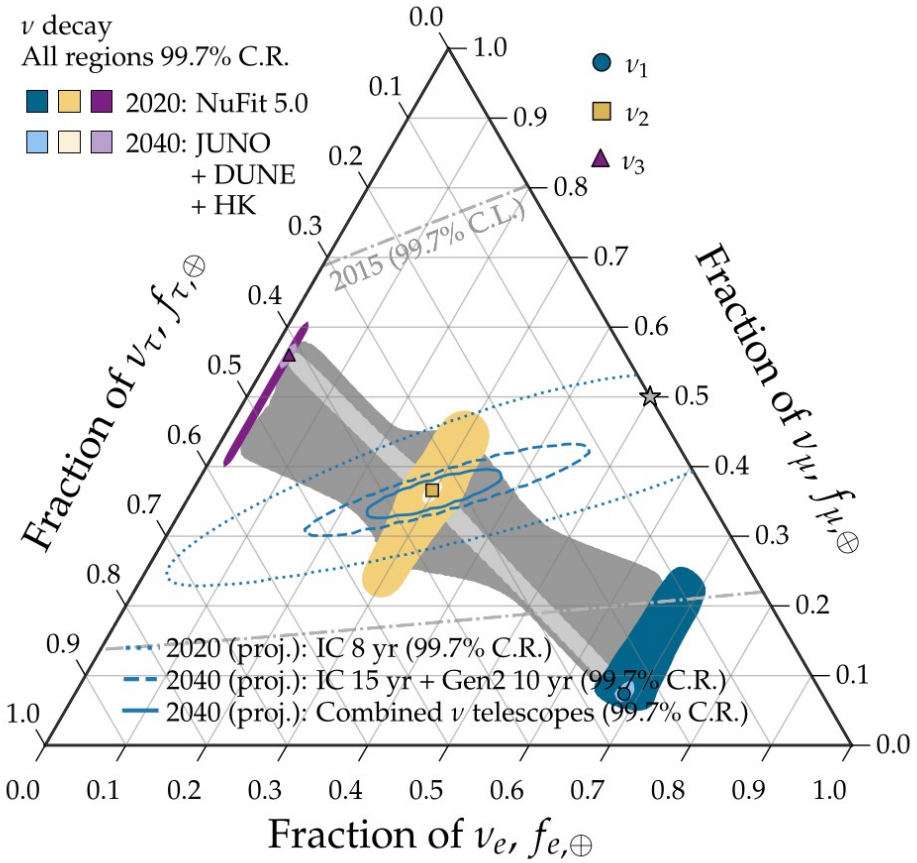

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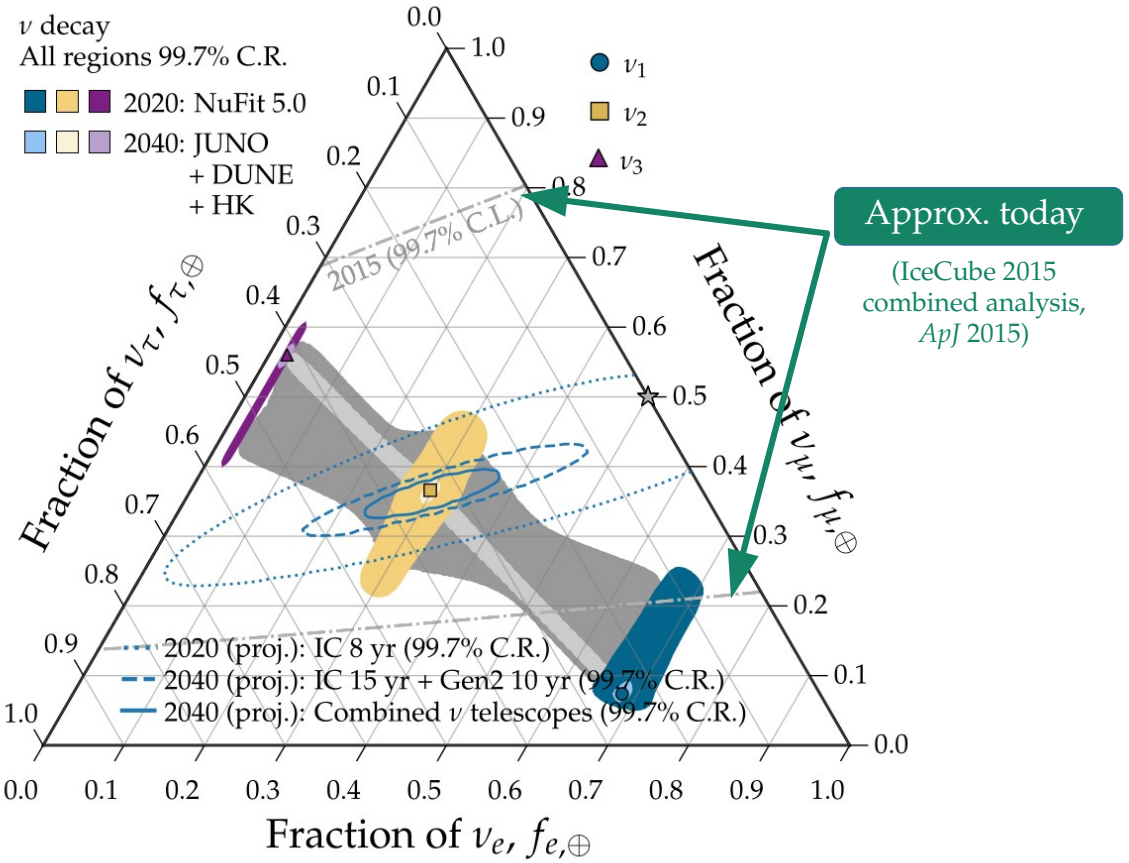

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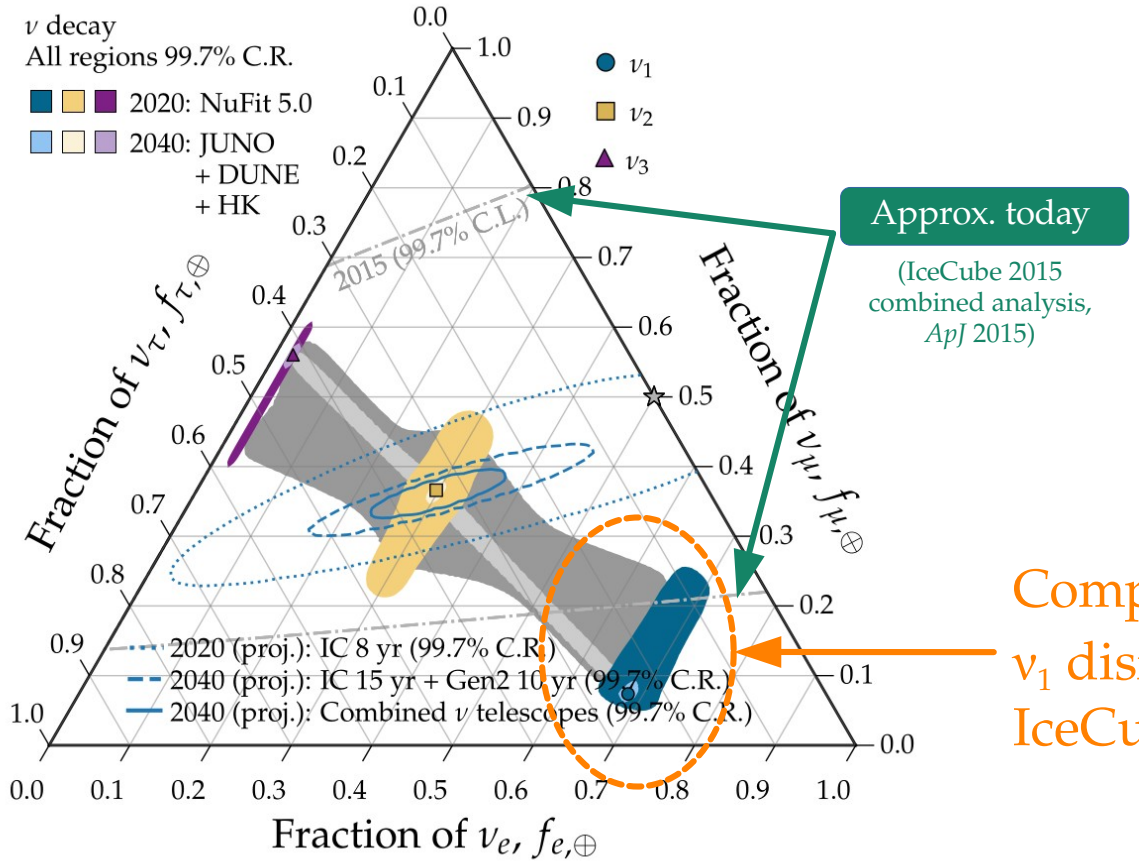

Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

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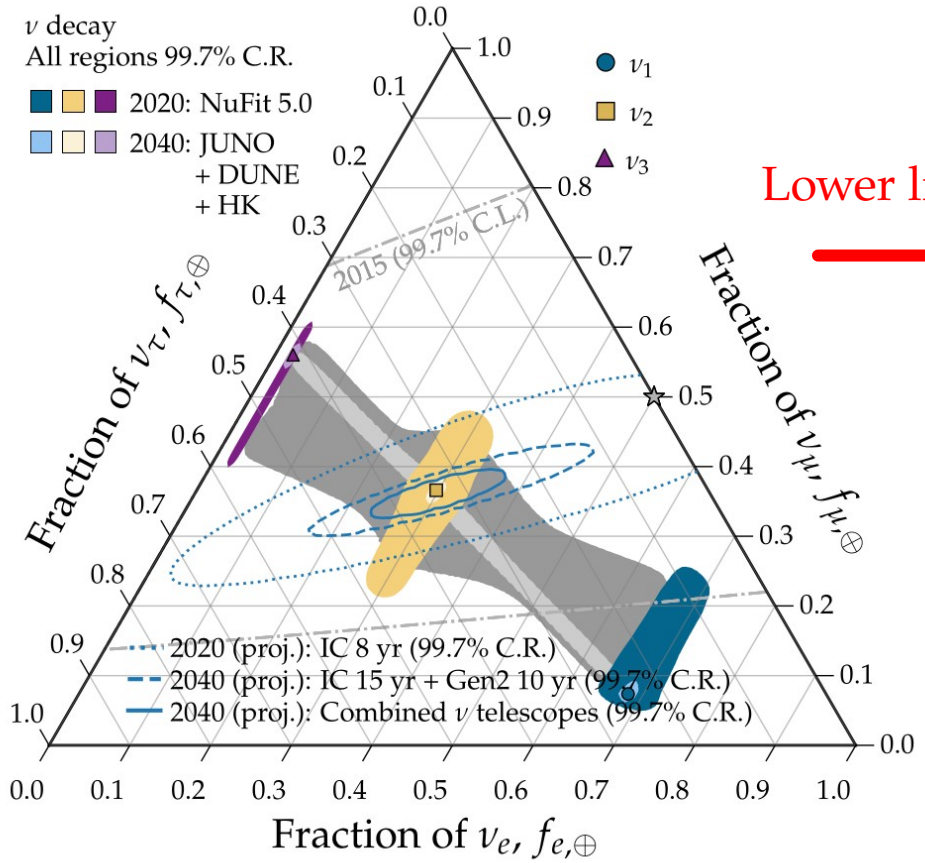

Lower limit on τ/m →

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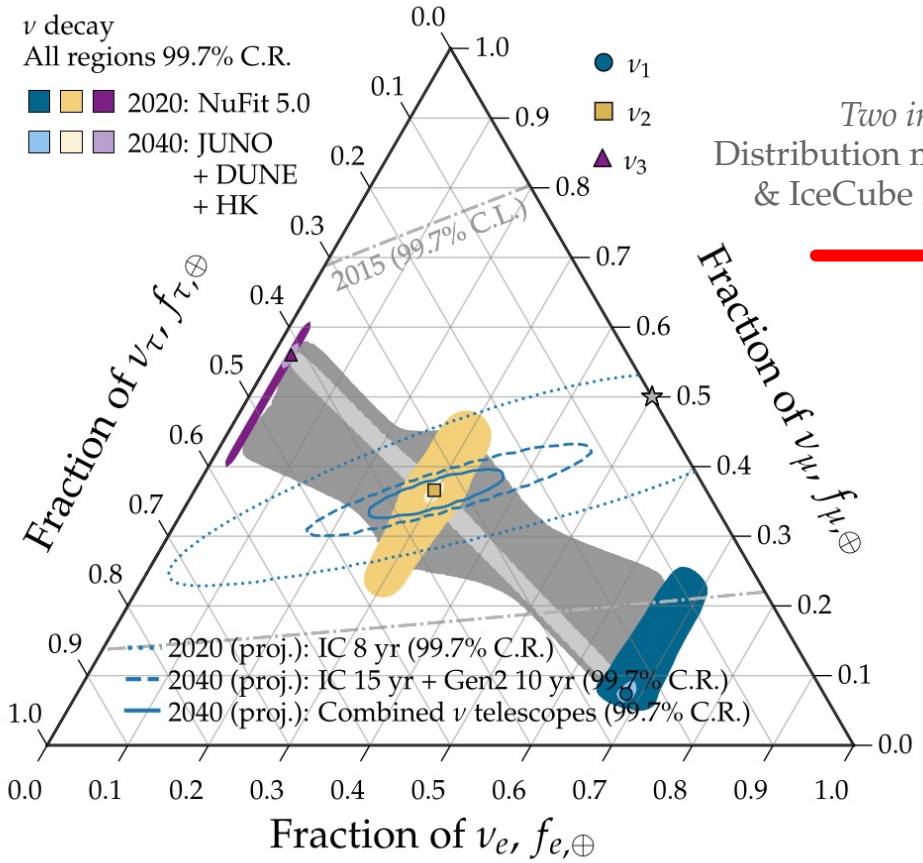

Two ingredients:
Distribution mixing parameters
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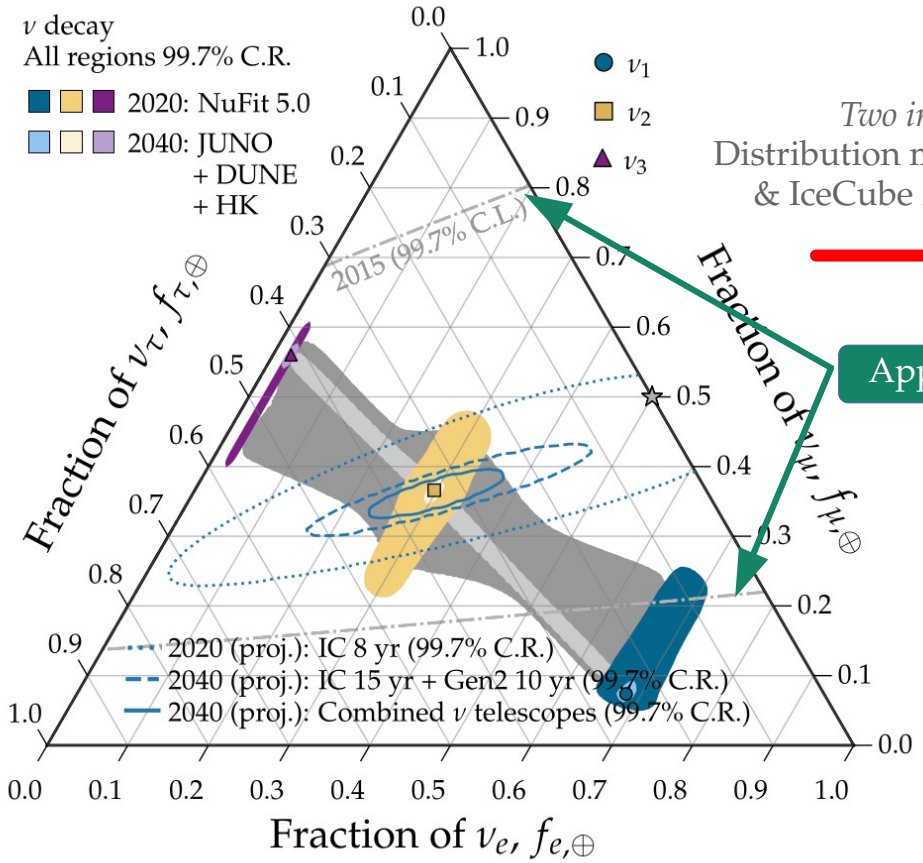

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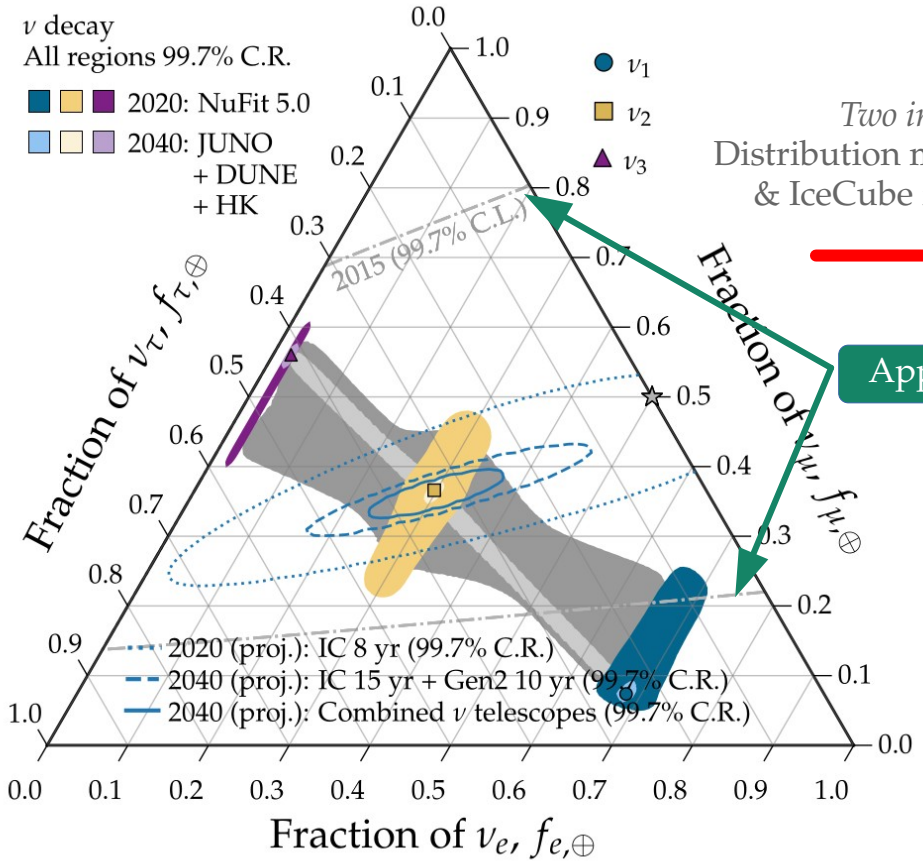

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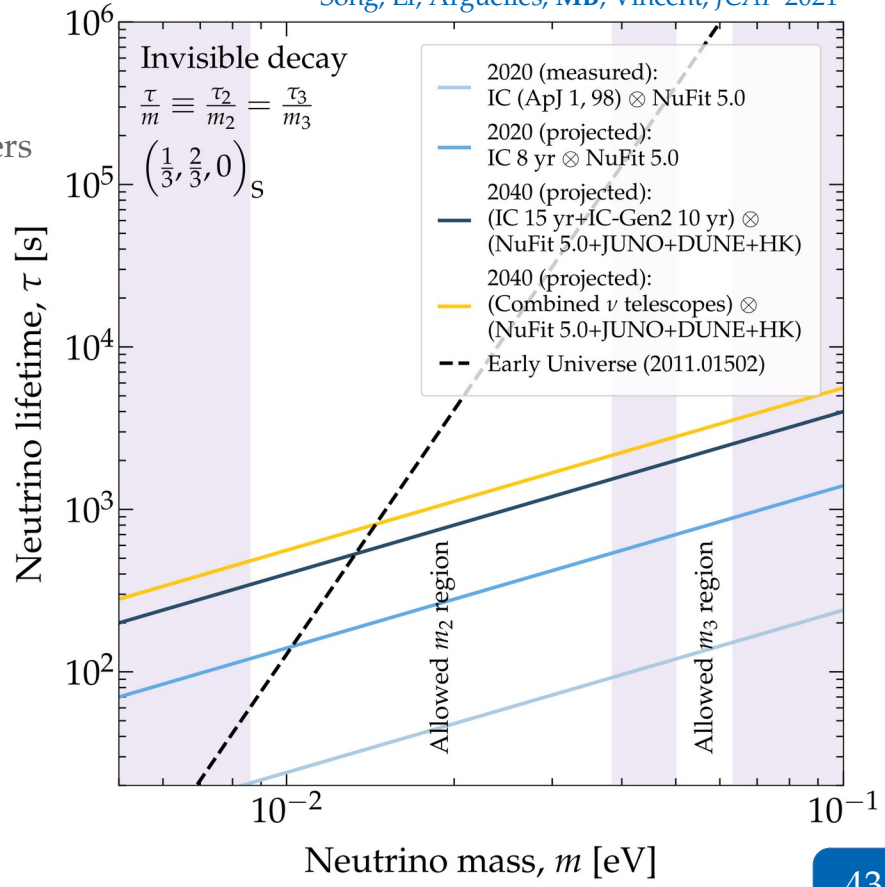
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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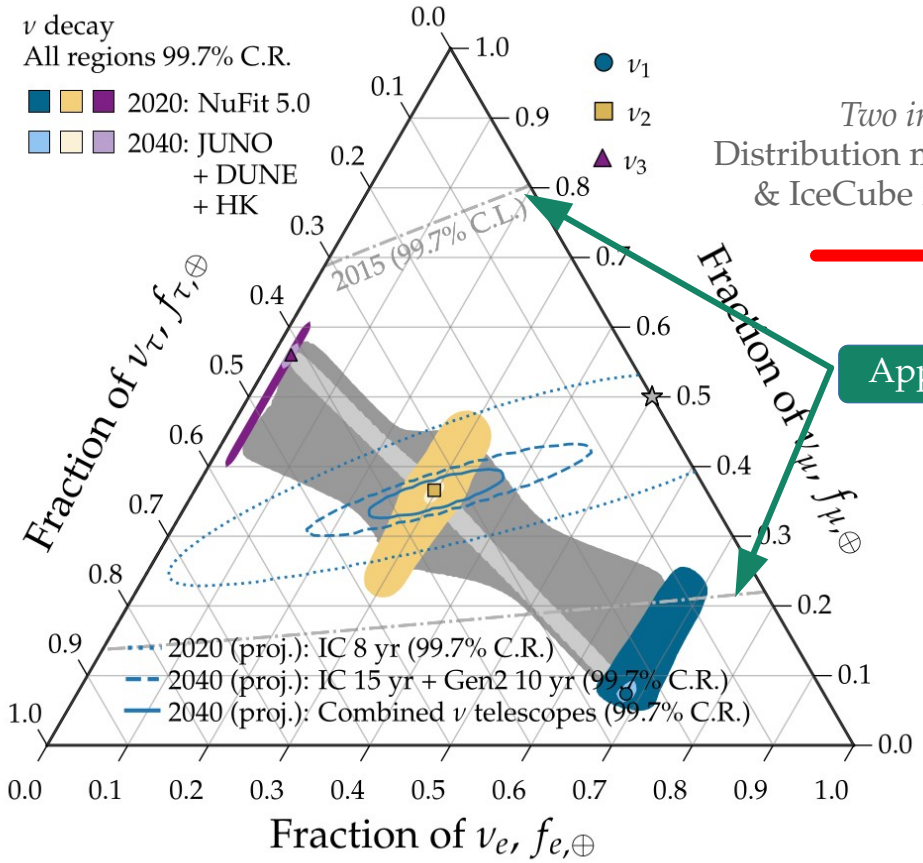

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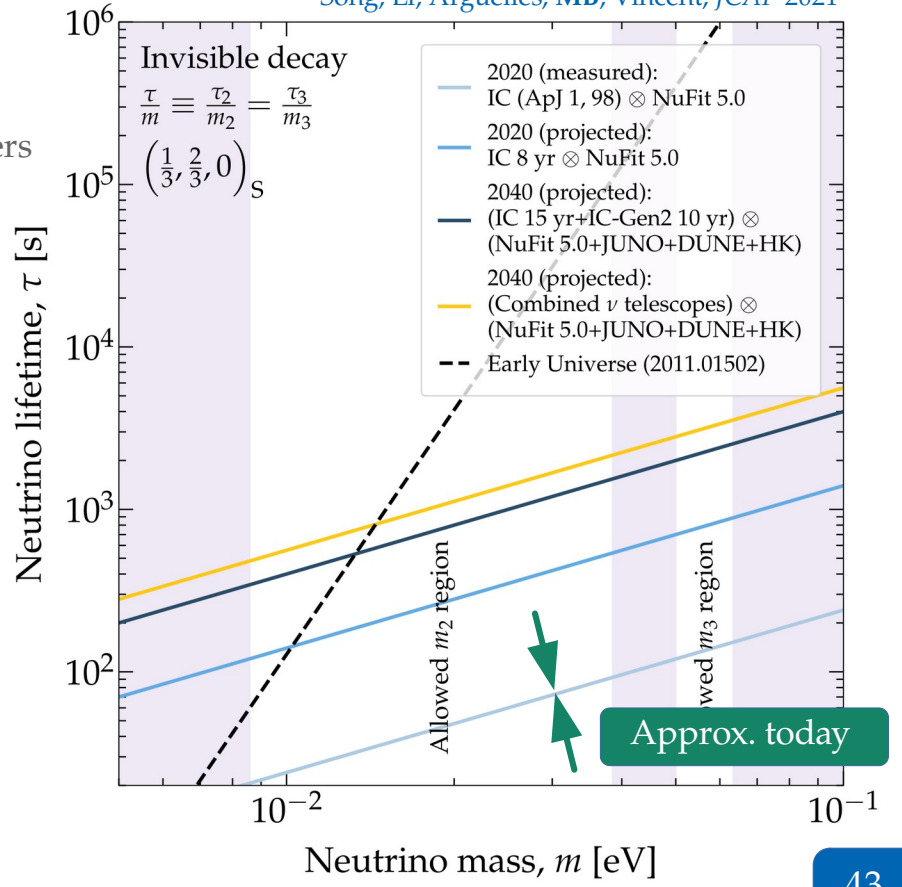
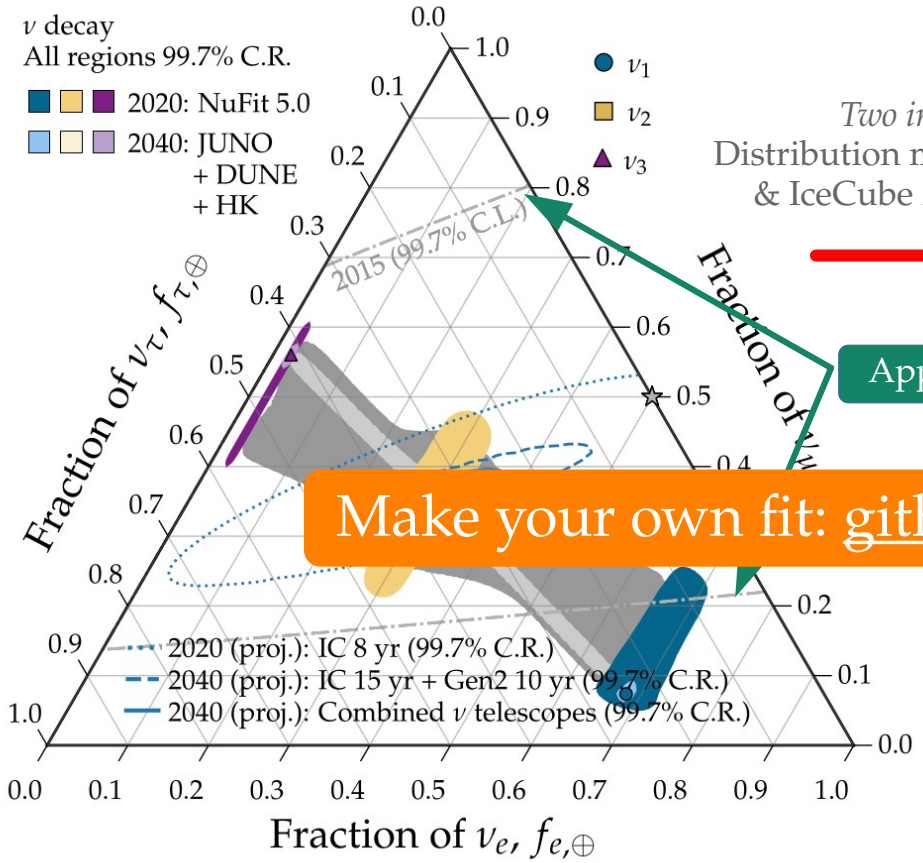


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

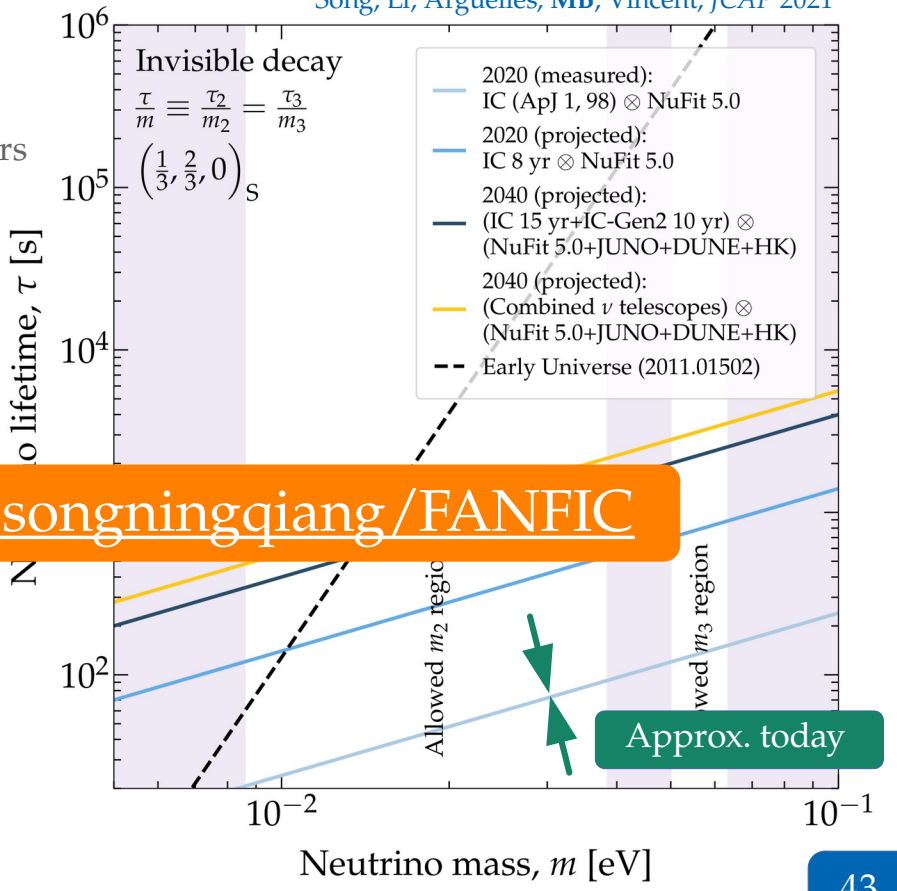


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

Approx. today

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

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

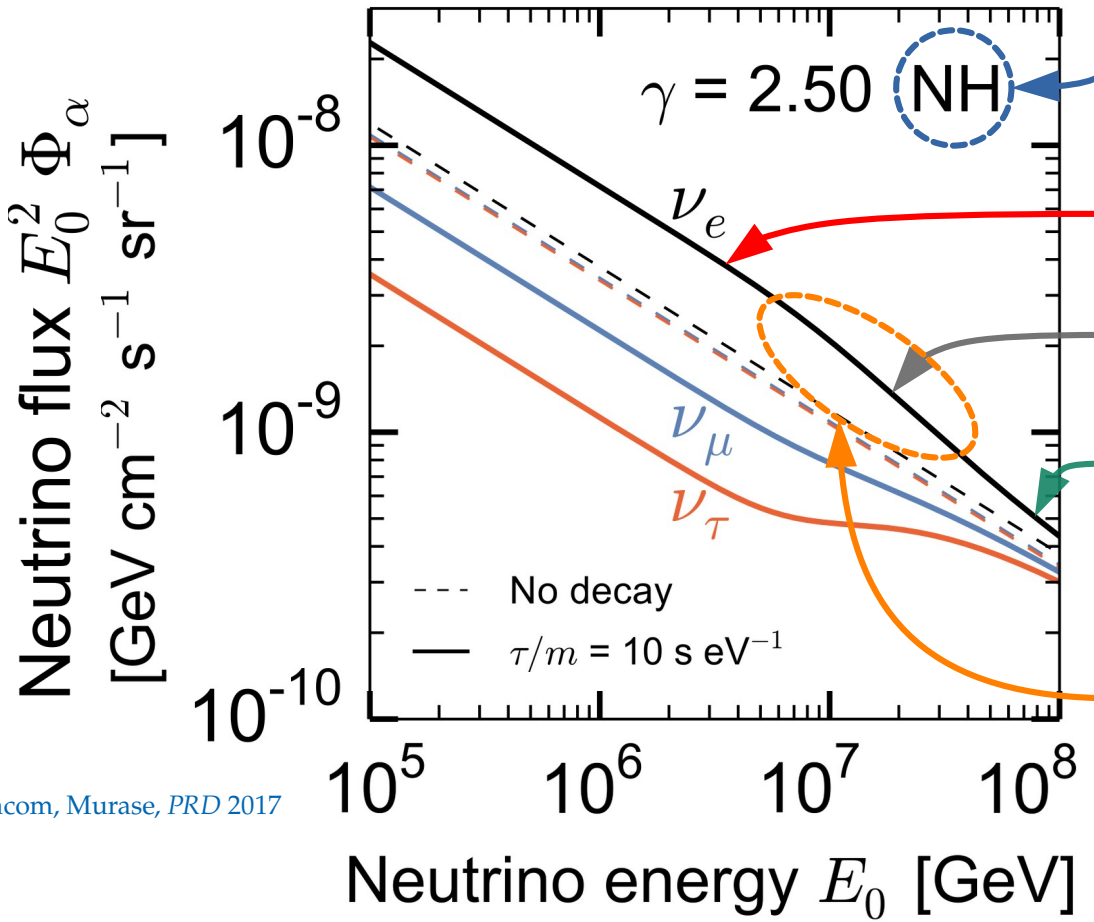


Approx. today

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*!

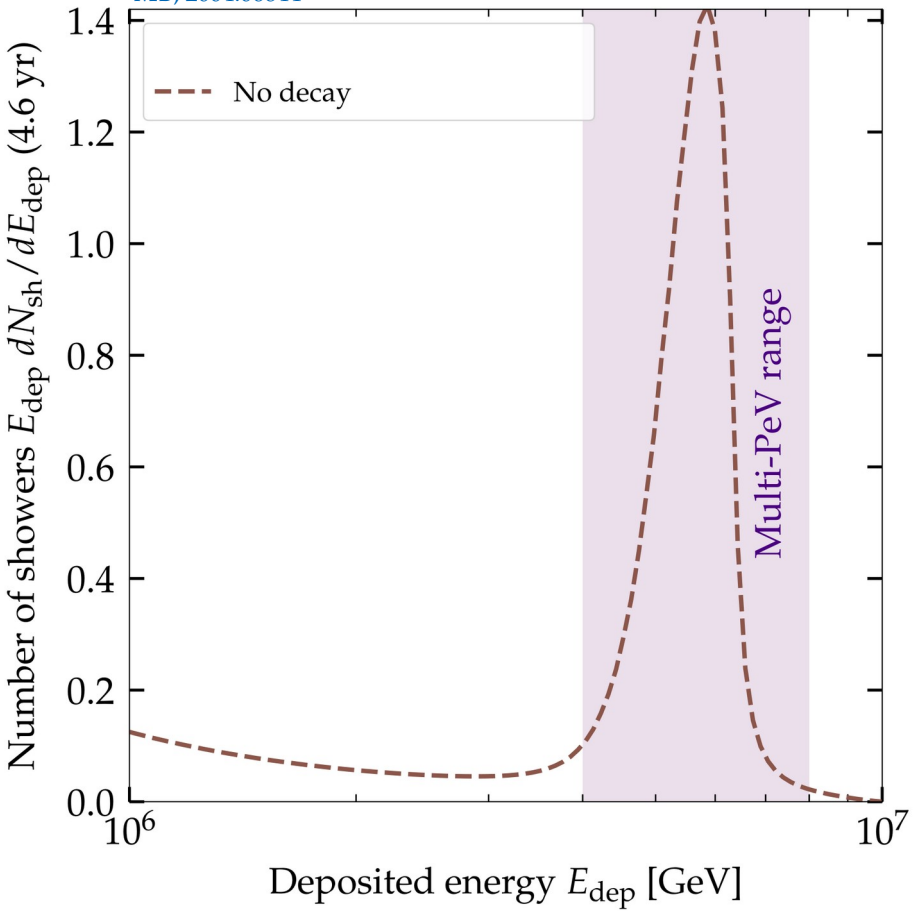
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

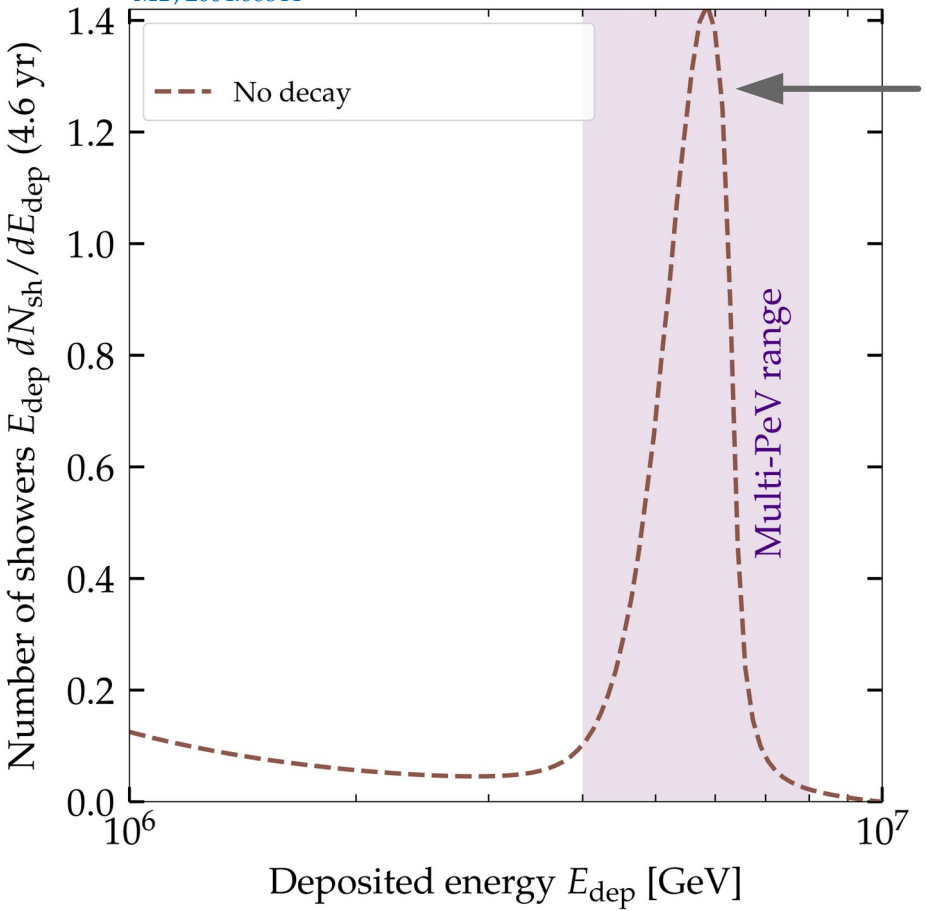


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



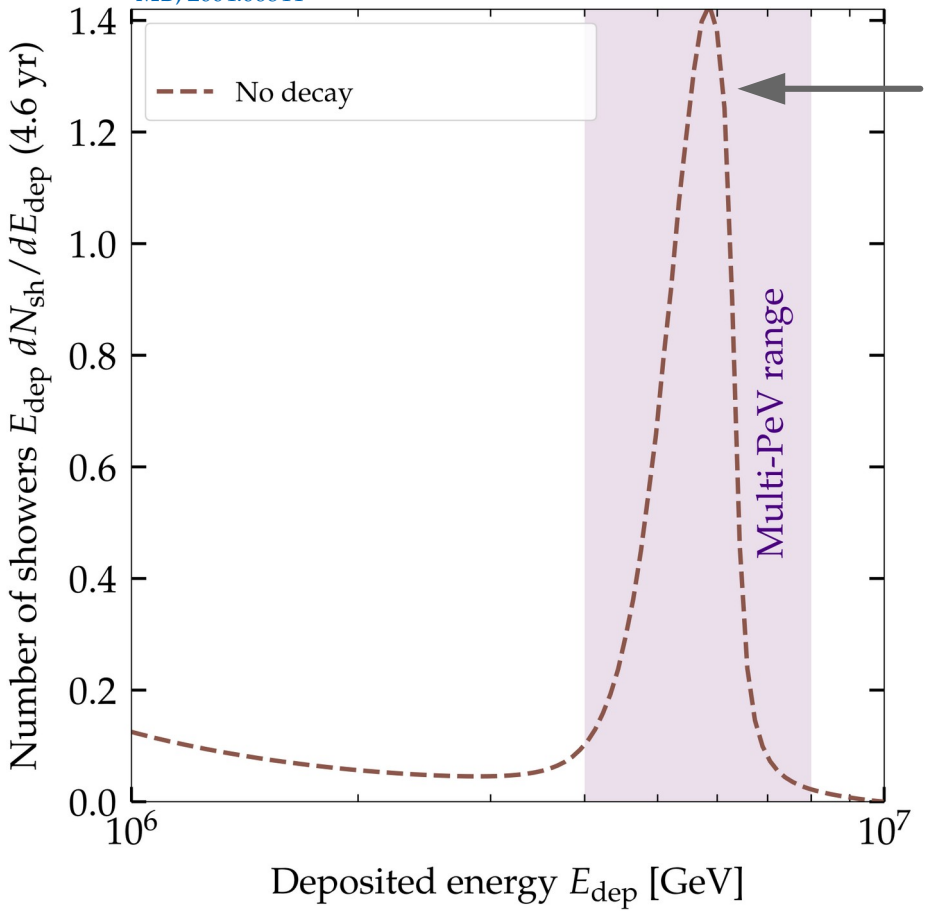
Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to \text{hadrons} \to \text{shower}$

What does neutrino decay change?

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

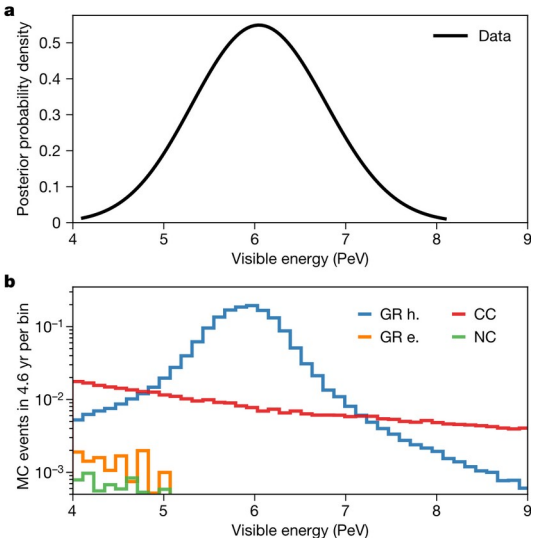
Flavor composition ⟺ Spectrum shape ⟺ Event rate

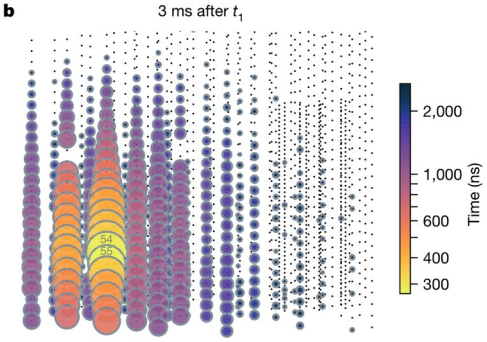
MB, 2004.06844



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

IceCube has seen one GR candidate in 4.6 years:





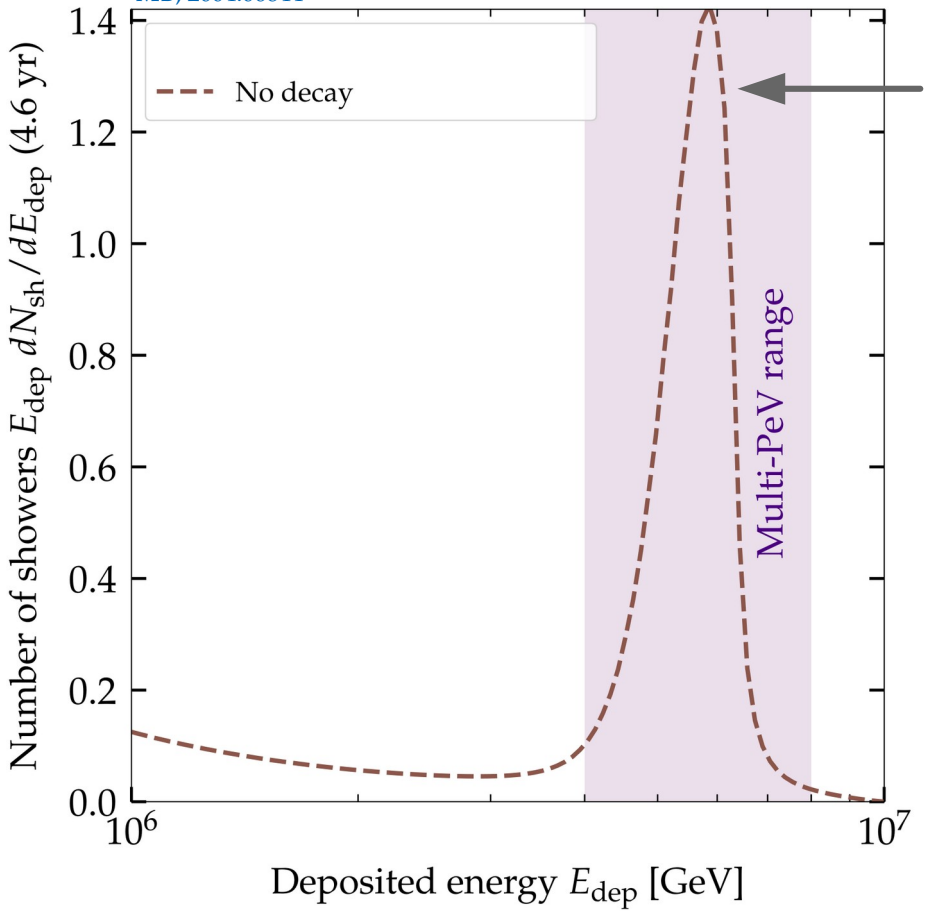
IceCube Collab., *Nature* 2021

What does neutrino decay change?

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

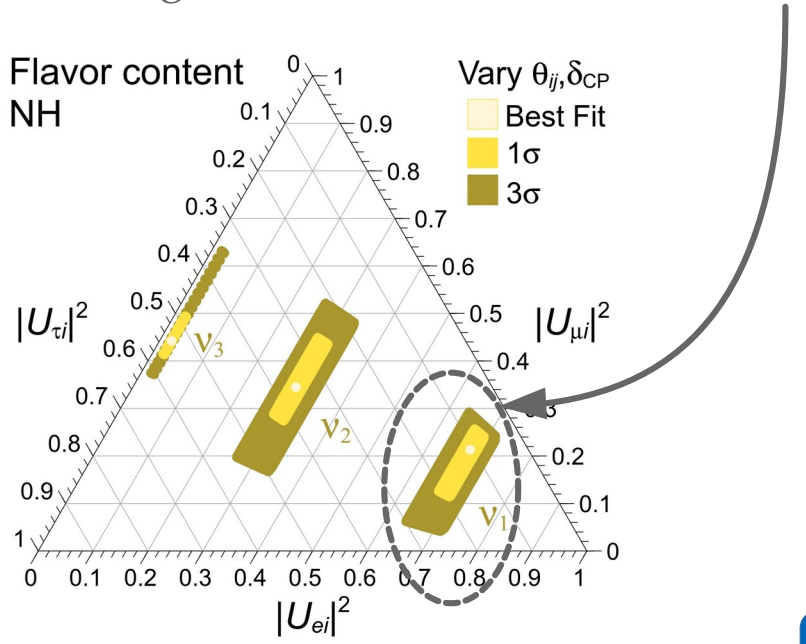
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

ν_1 is the mass eigenstate with the most e flavor

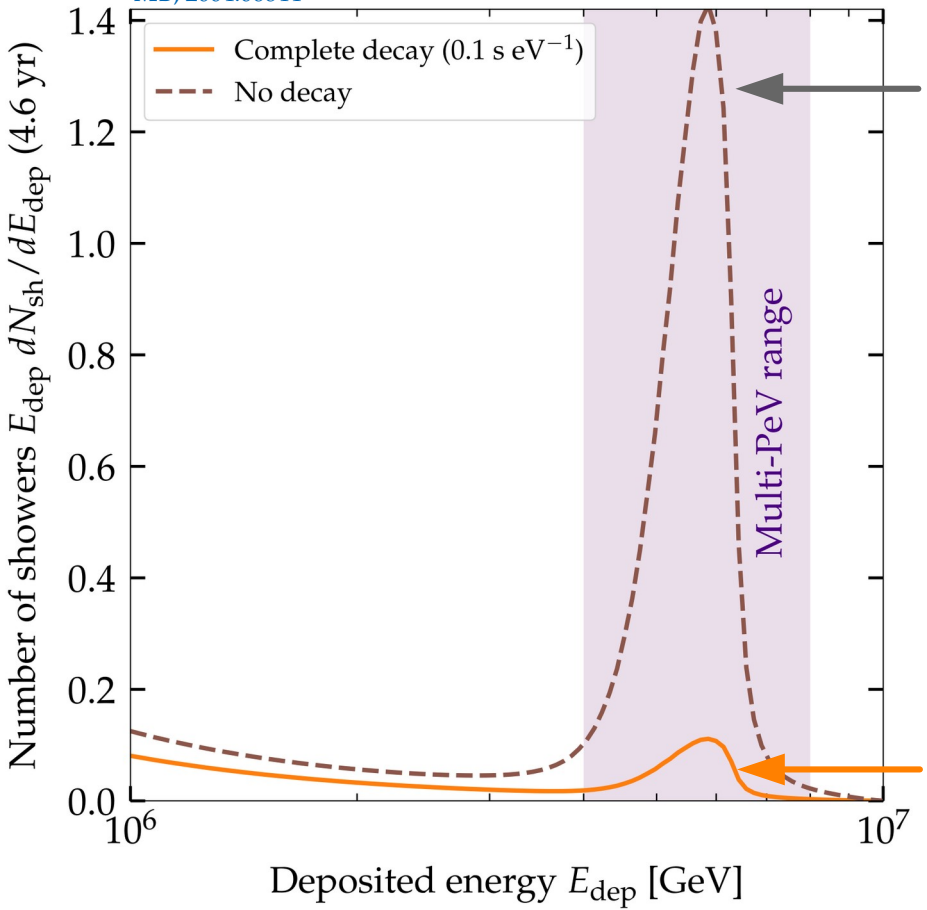


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

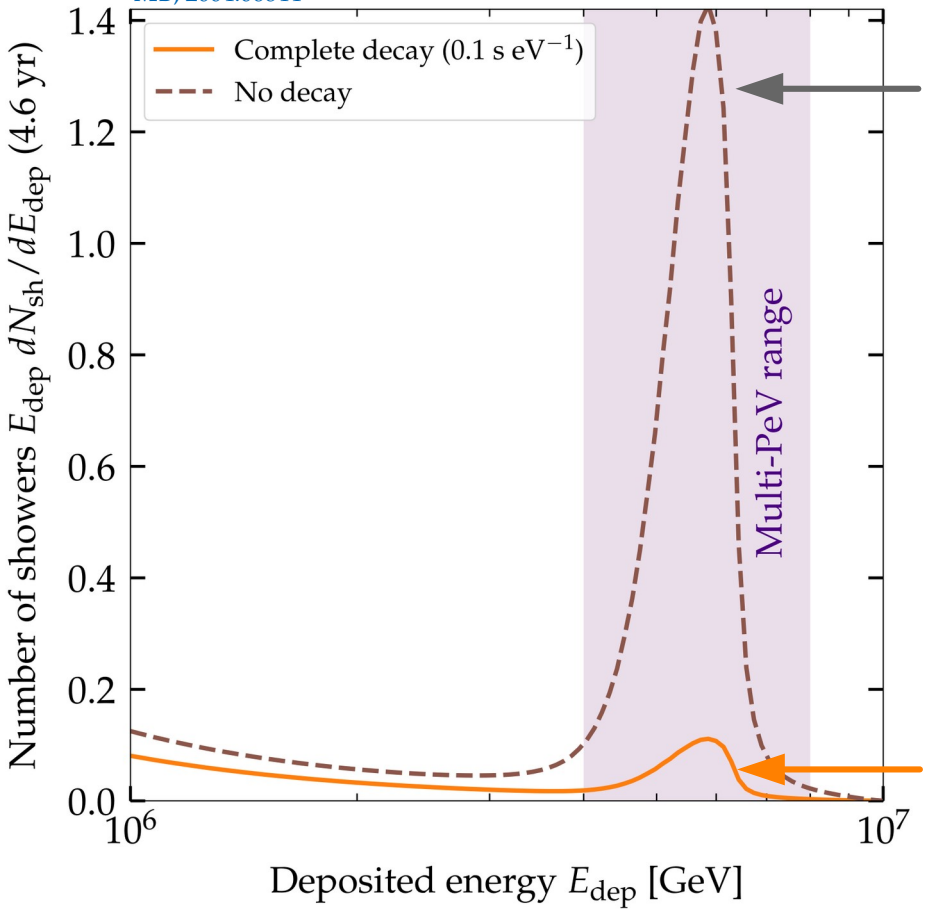
If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

So by having observed 1 GR event we can place a *lower* limit on the lifetime of $\bar{\nu}_1$ (= ν_1)

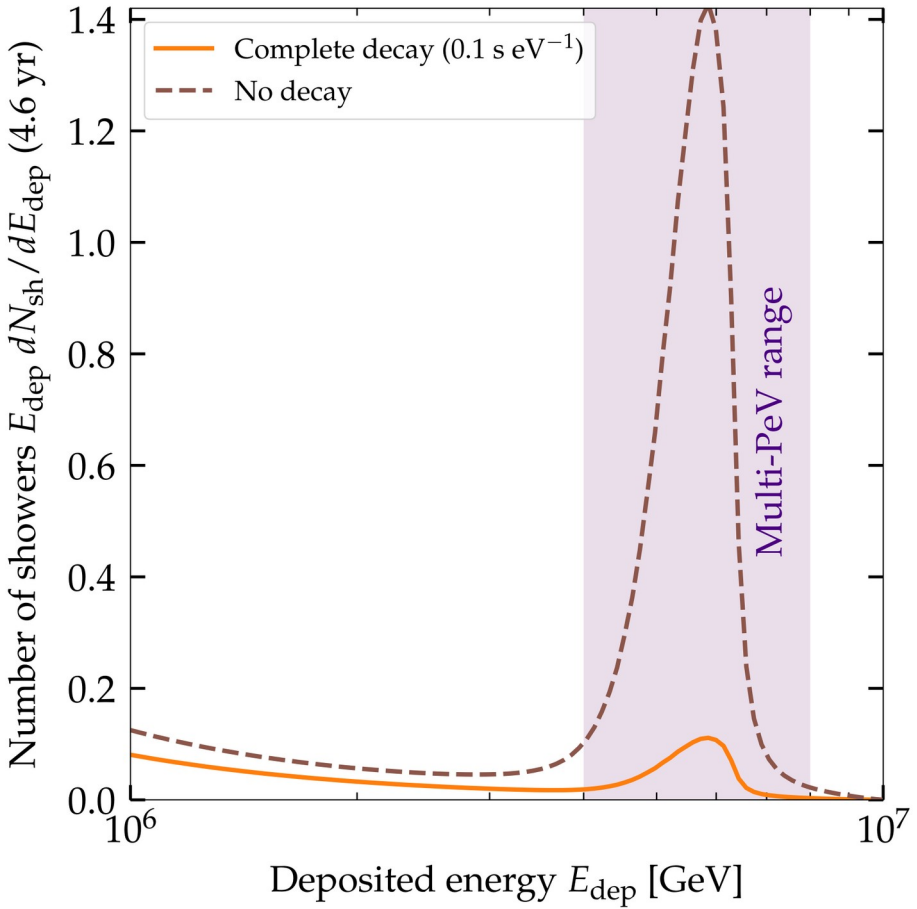
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



What does neutrino decay change?

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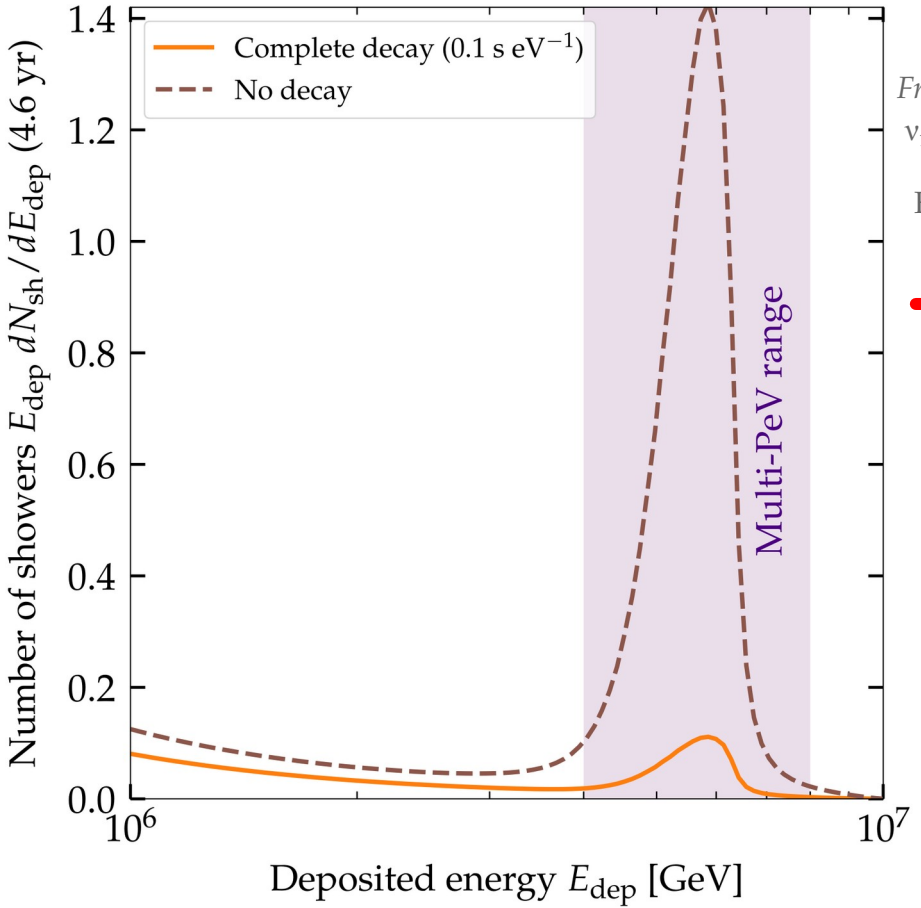
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

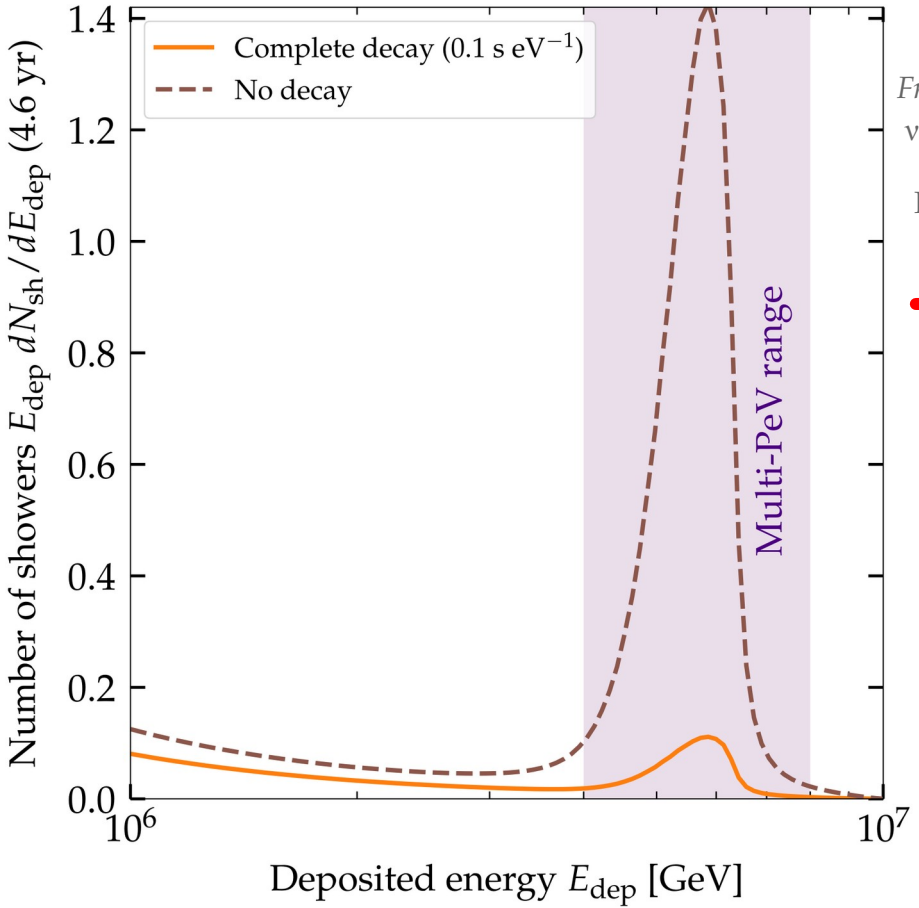


Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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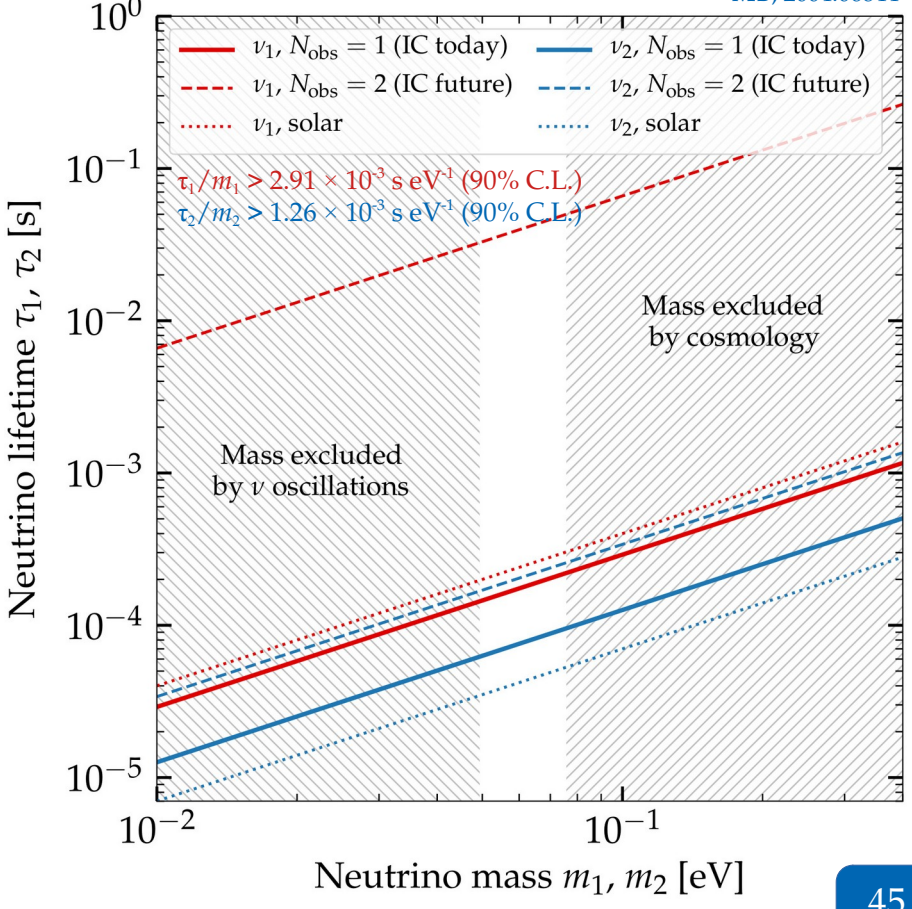
MB, 2004.06844



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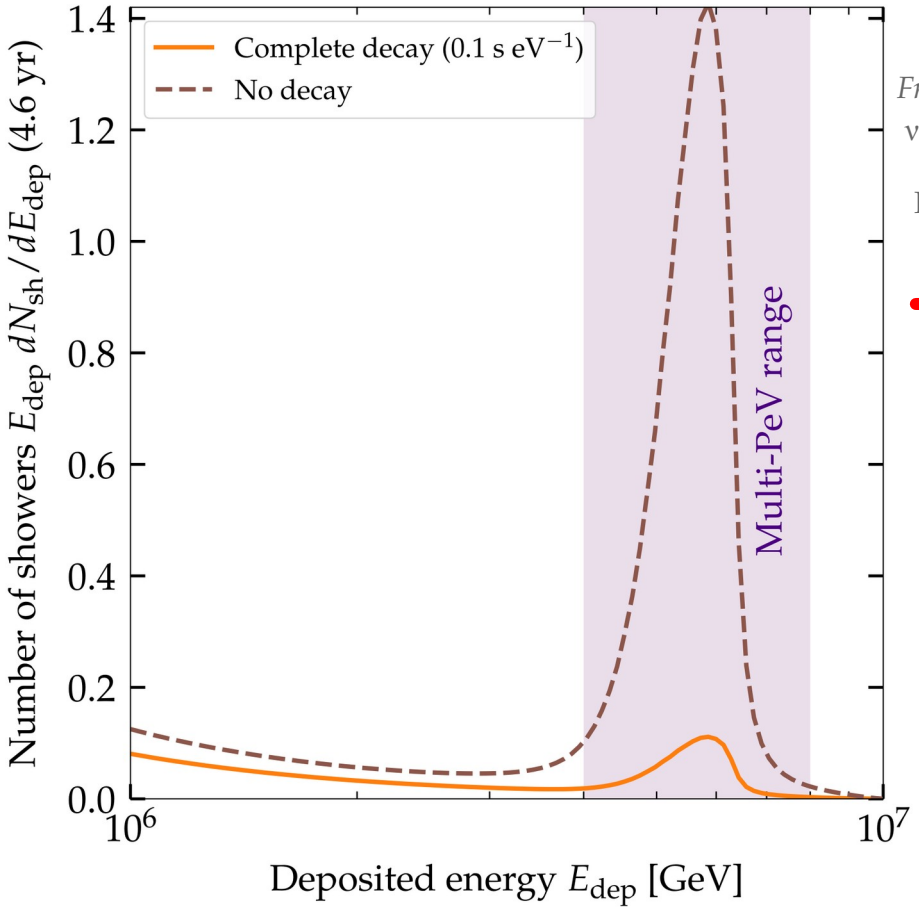
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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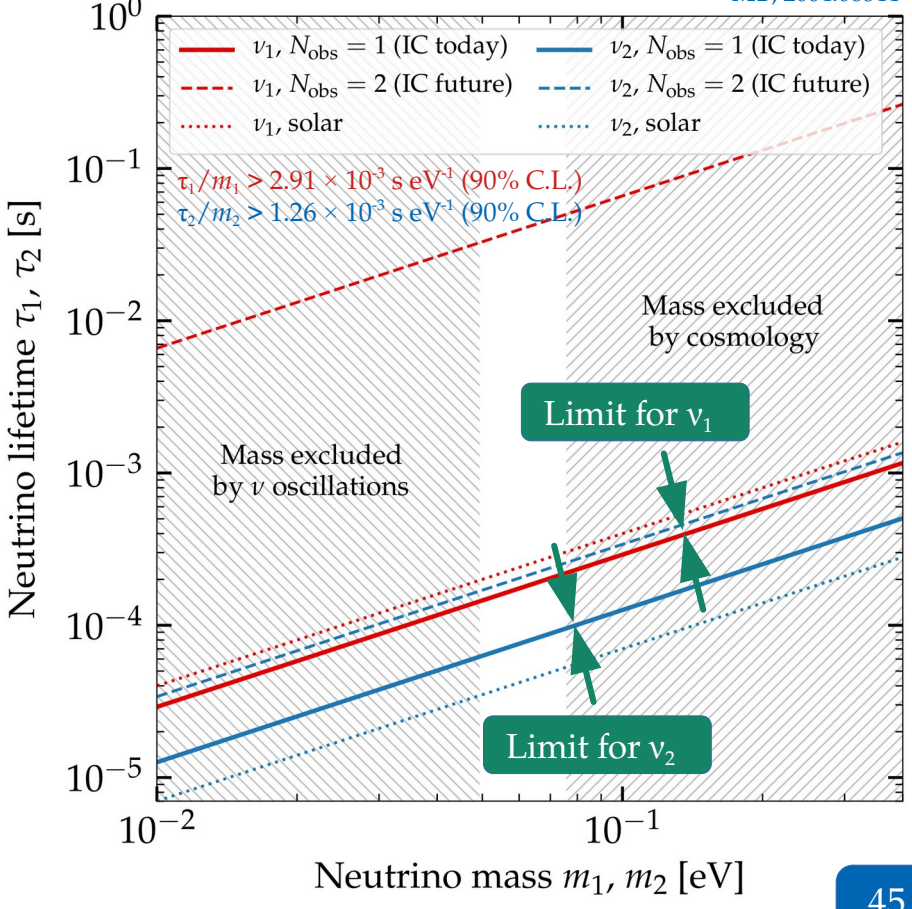
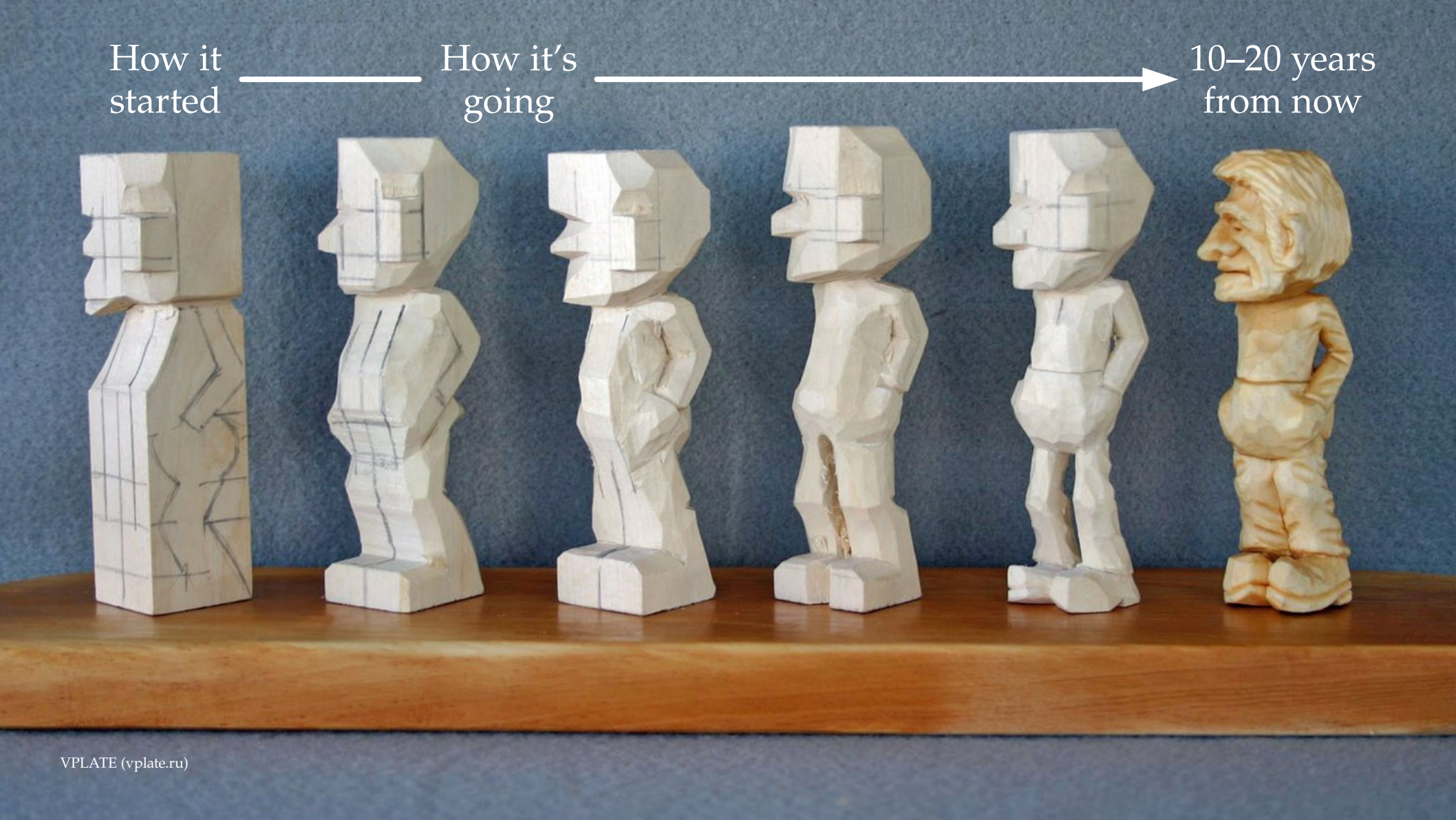
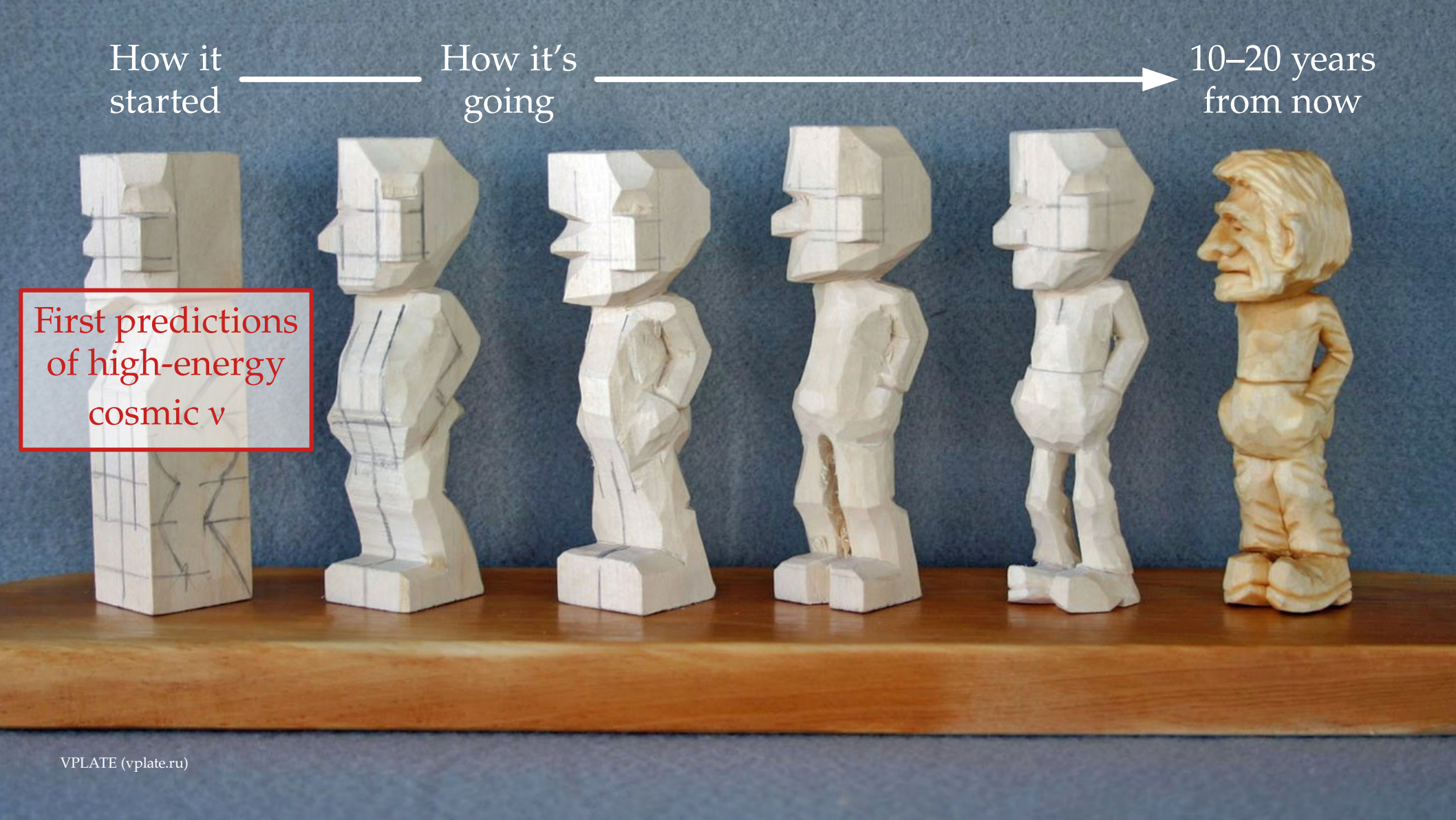
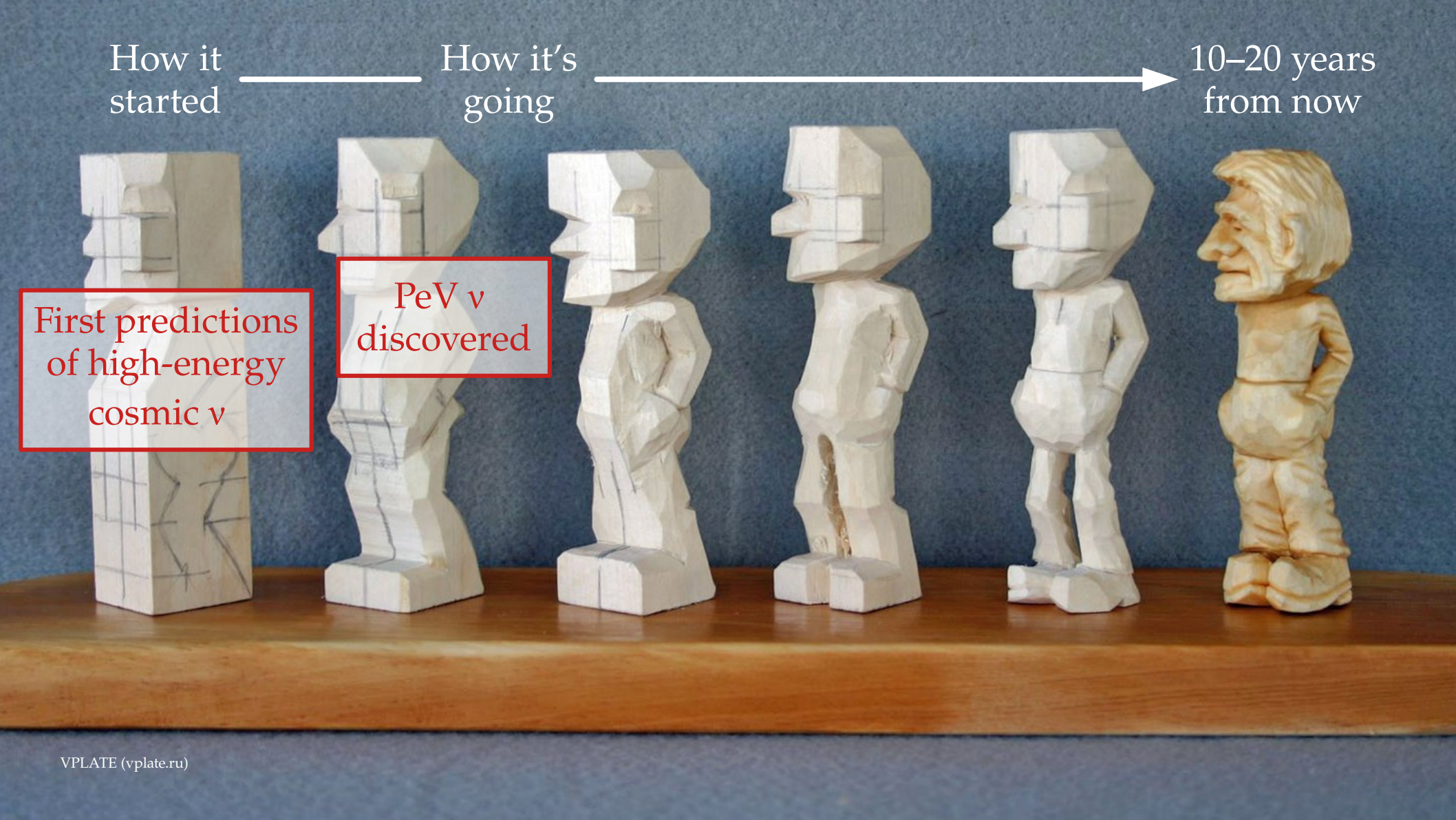


So…


How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)


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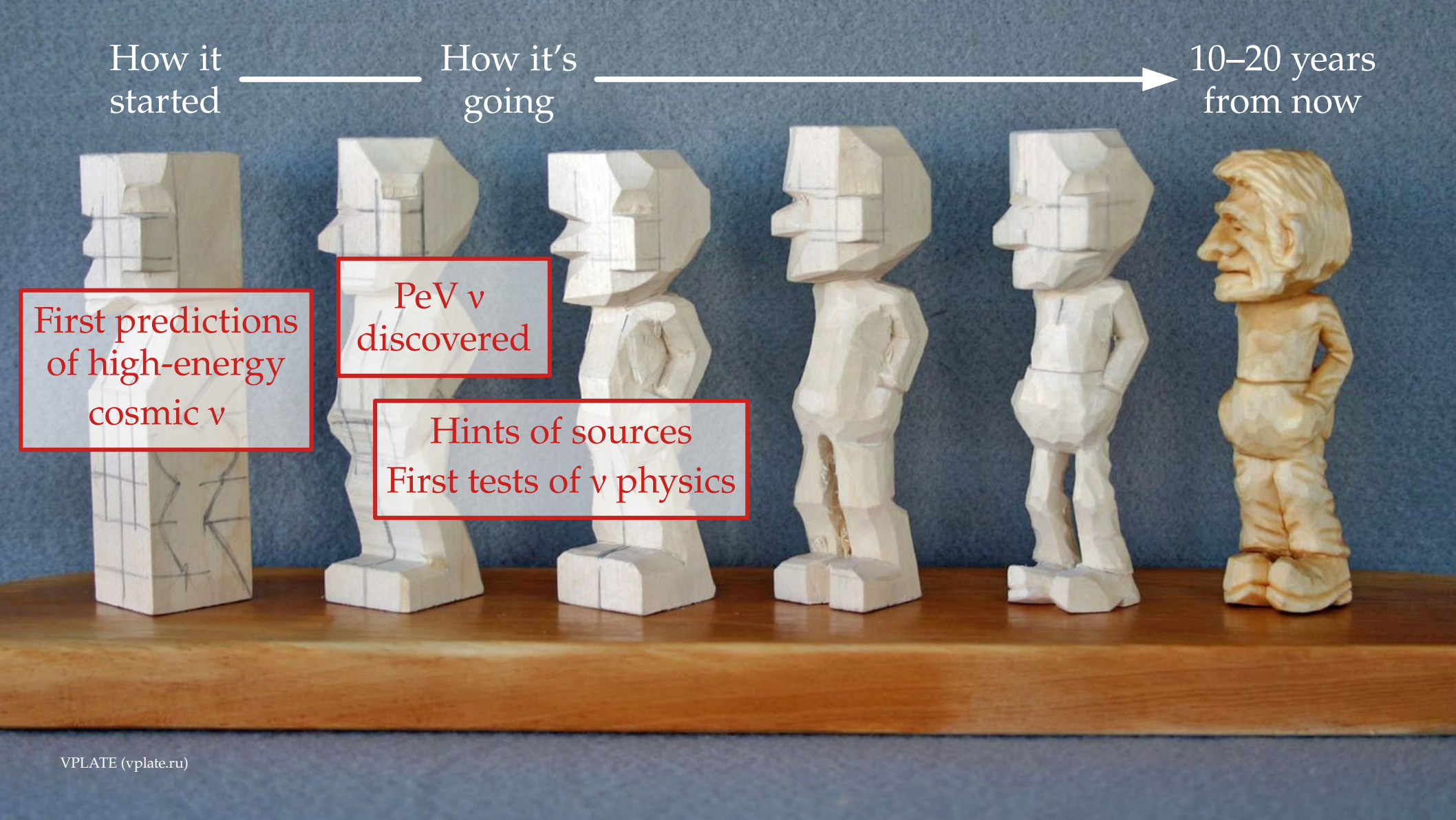
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
VPLATE (vplate.ru)


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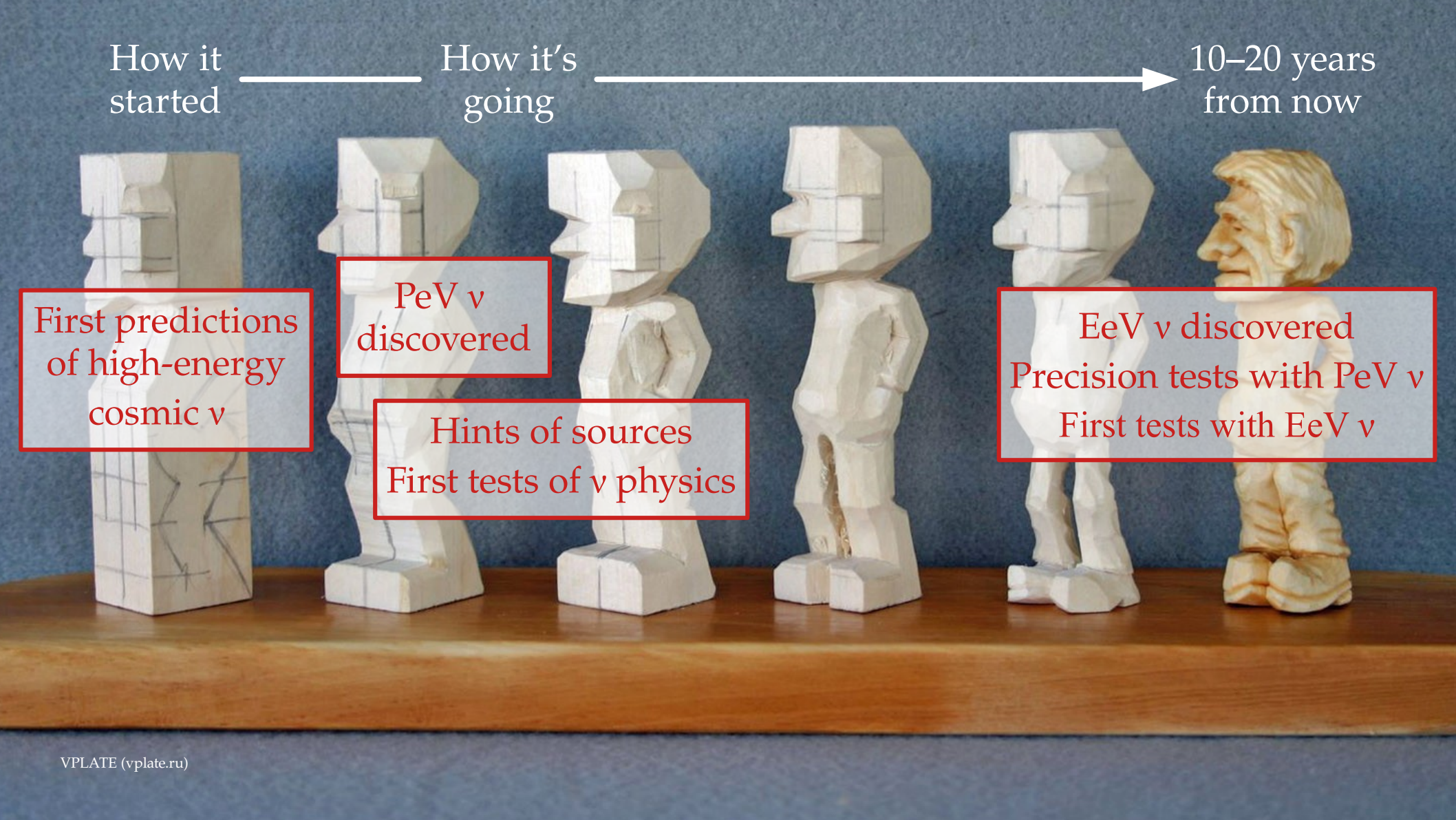
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
VPLATE (vplate.ru)


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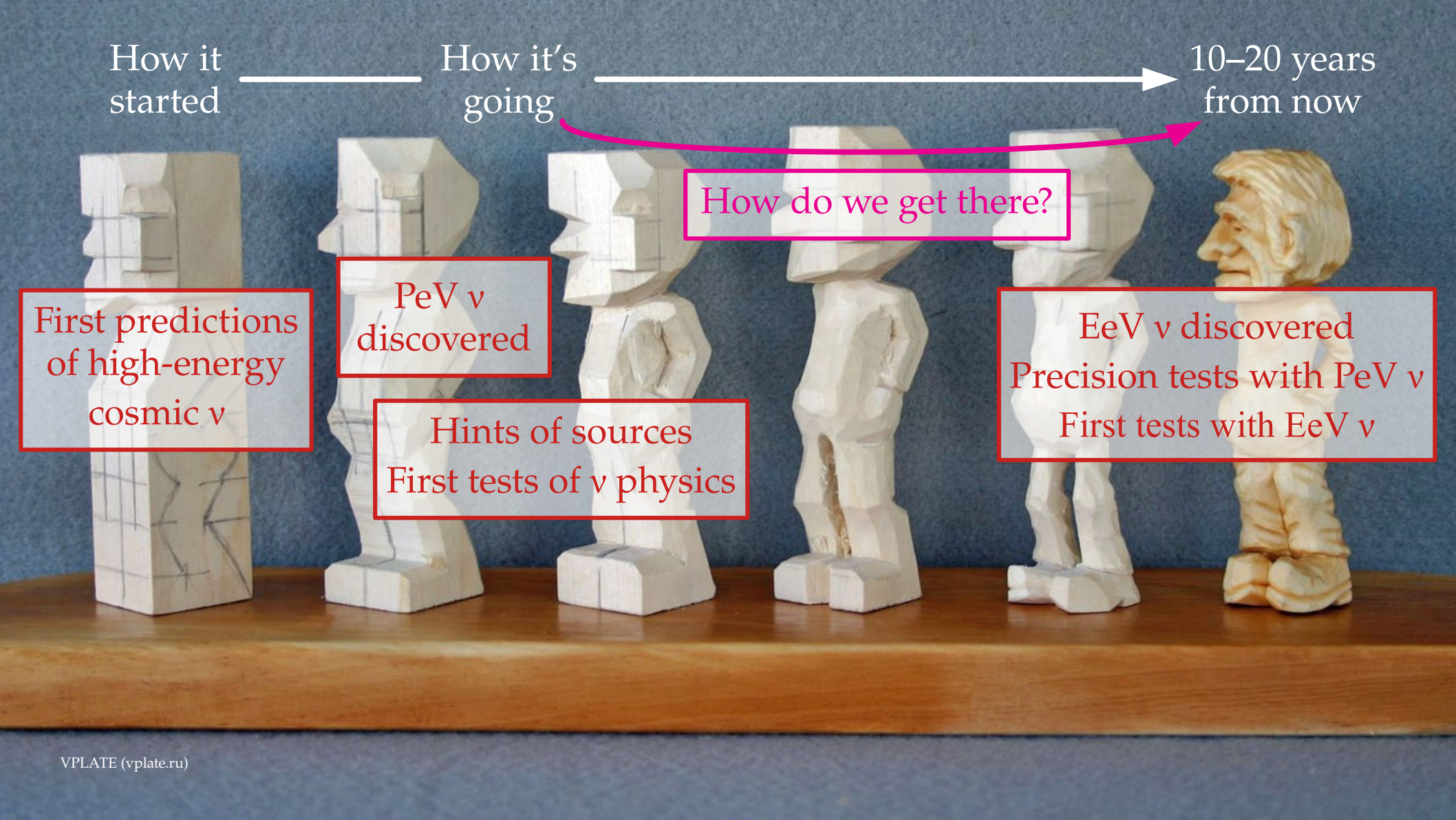
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)


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

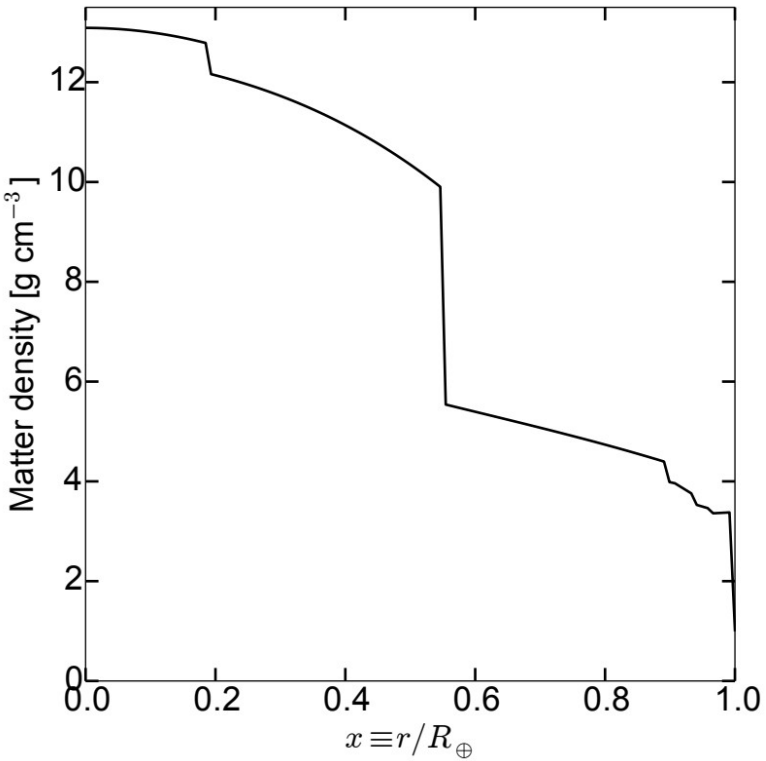
Thanks!

Backup slides

A feel for the in-Earth attenuation

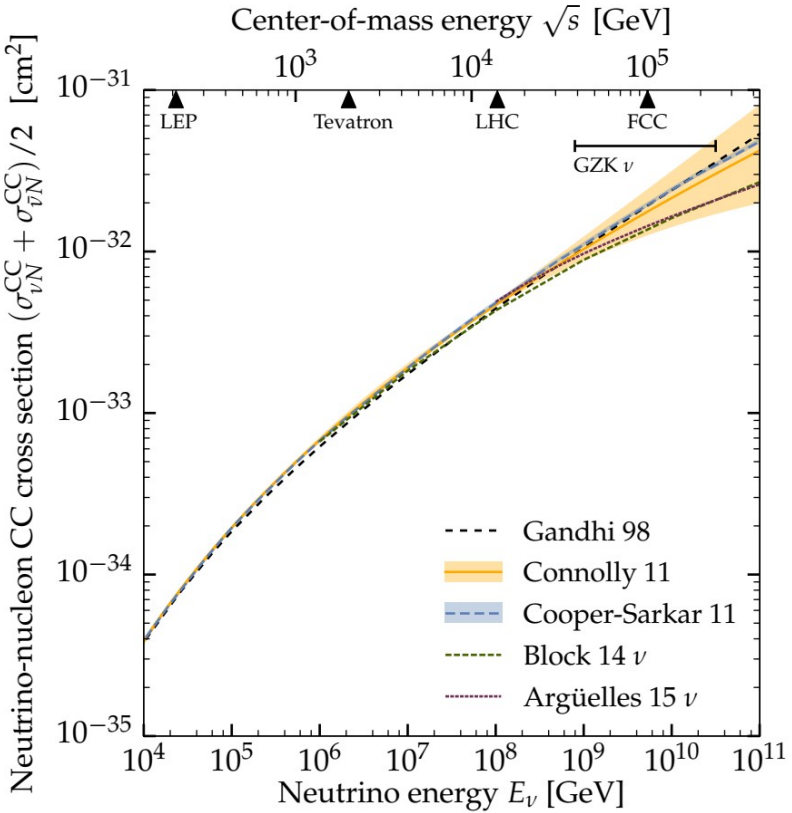
Earth matter density

(Preliminary Reference Earth Model)



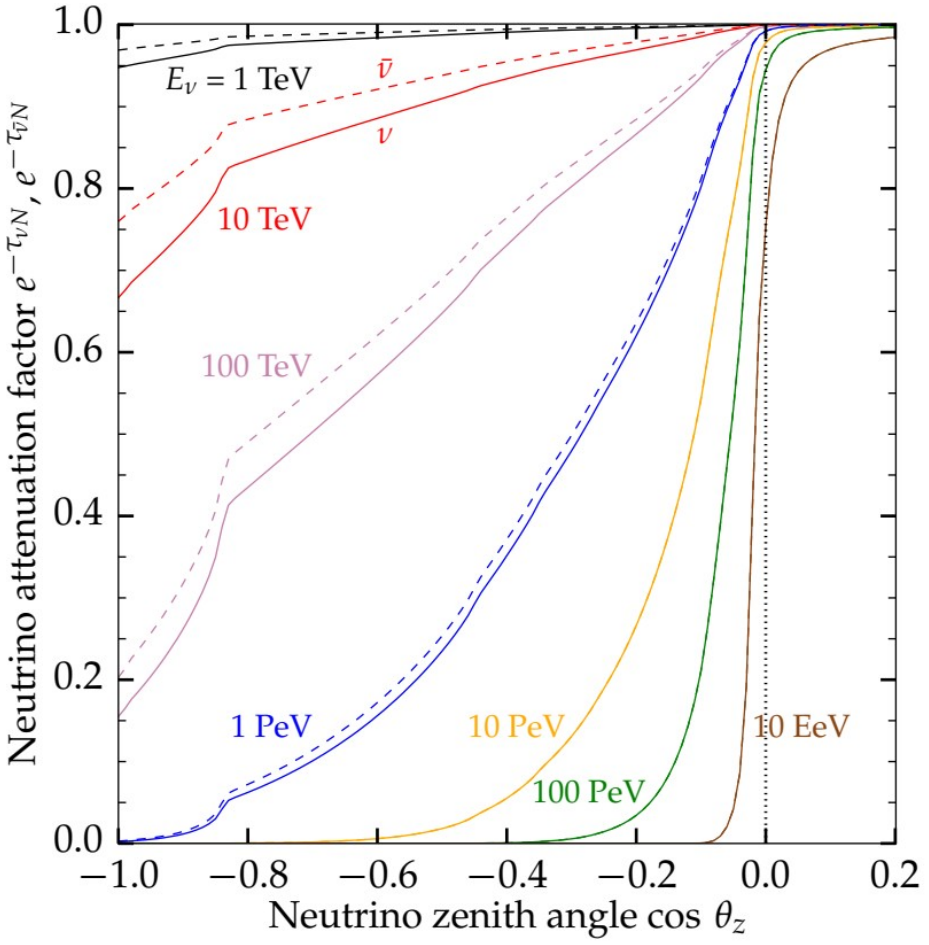
+

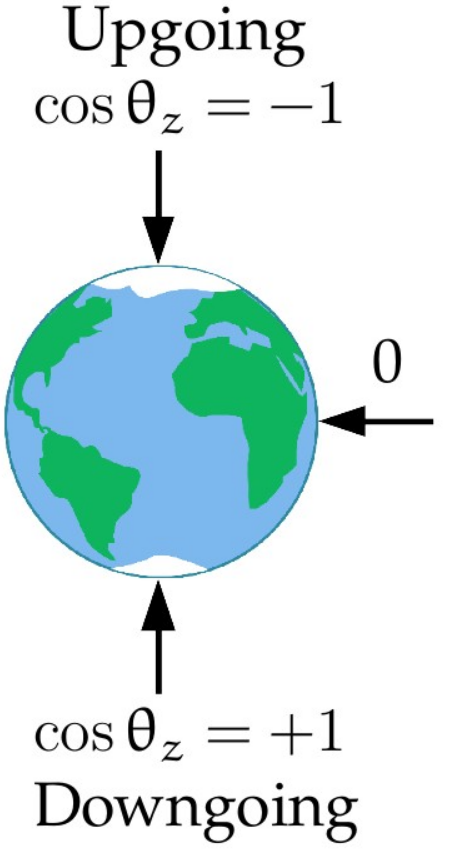
Neutrino-nucleon cross section



A feel for the in-Earth attenuation

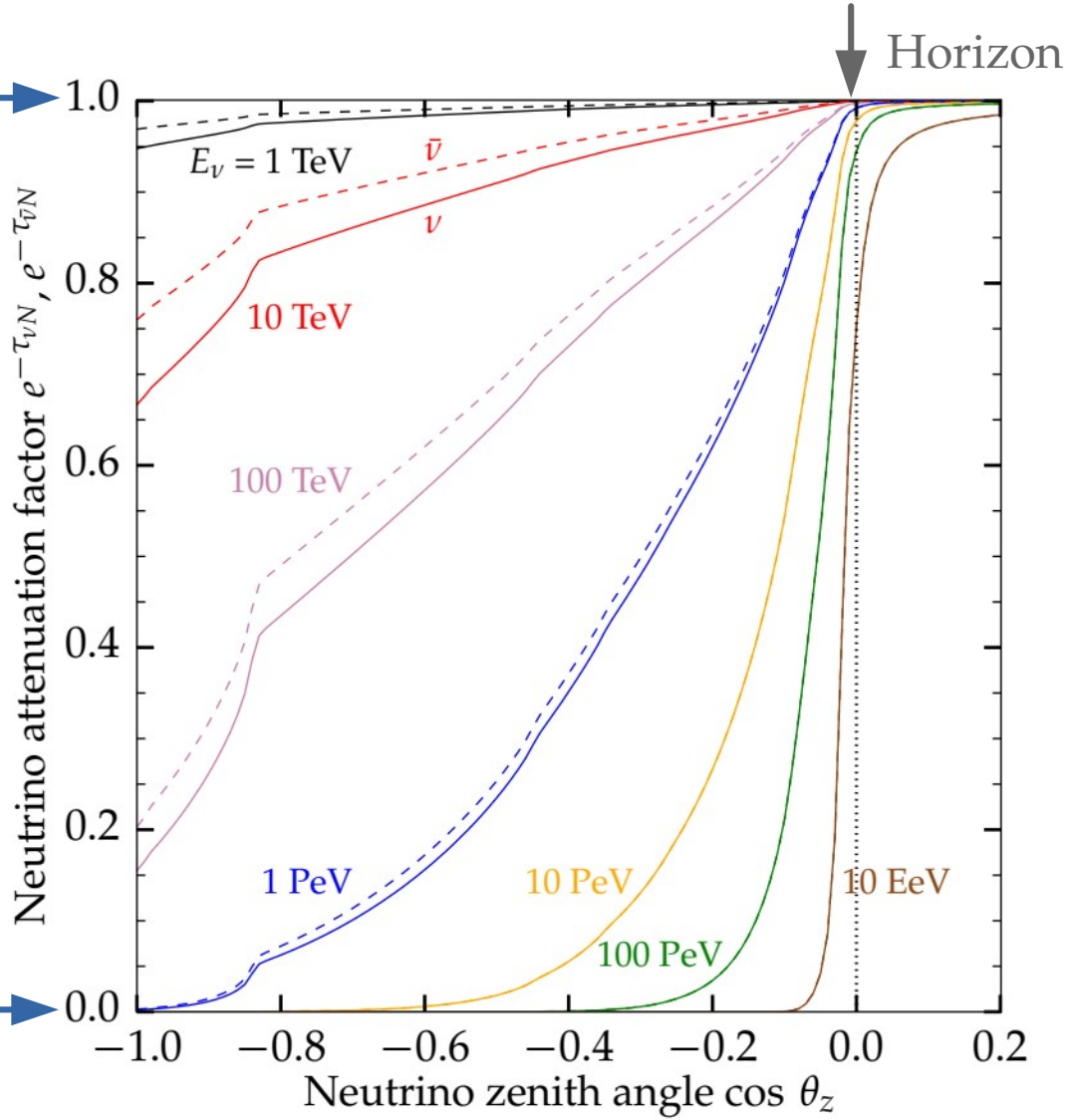
=

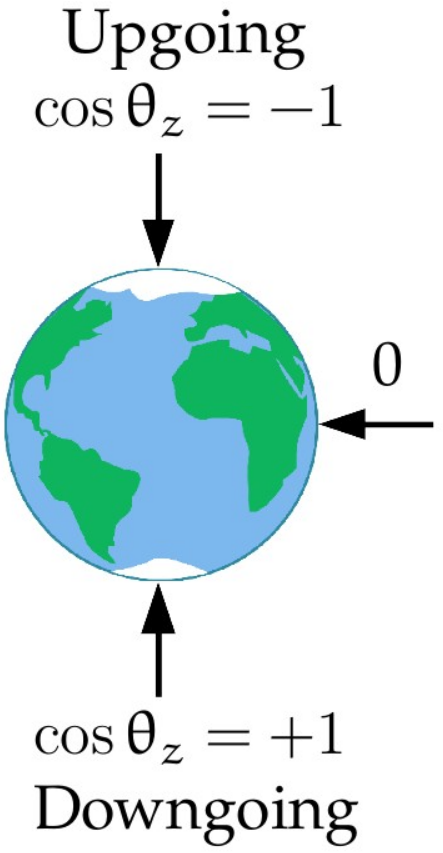




No attenuation

Full attenuation

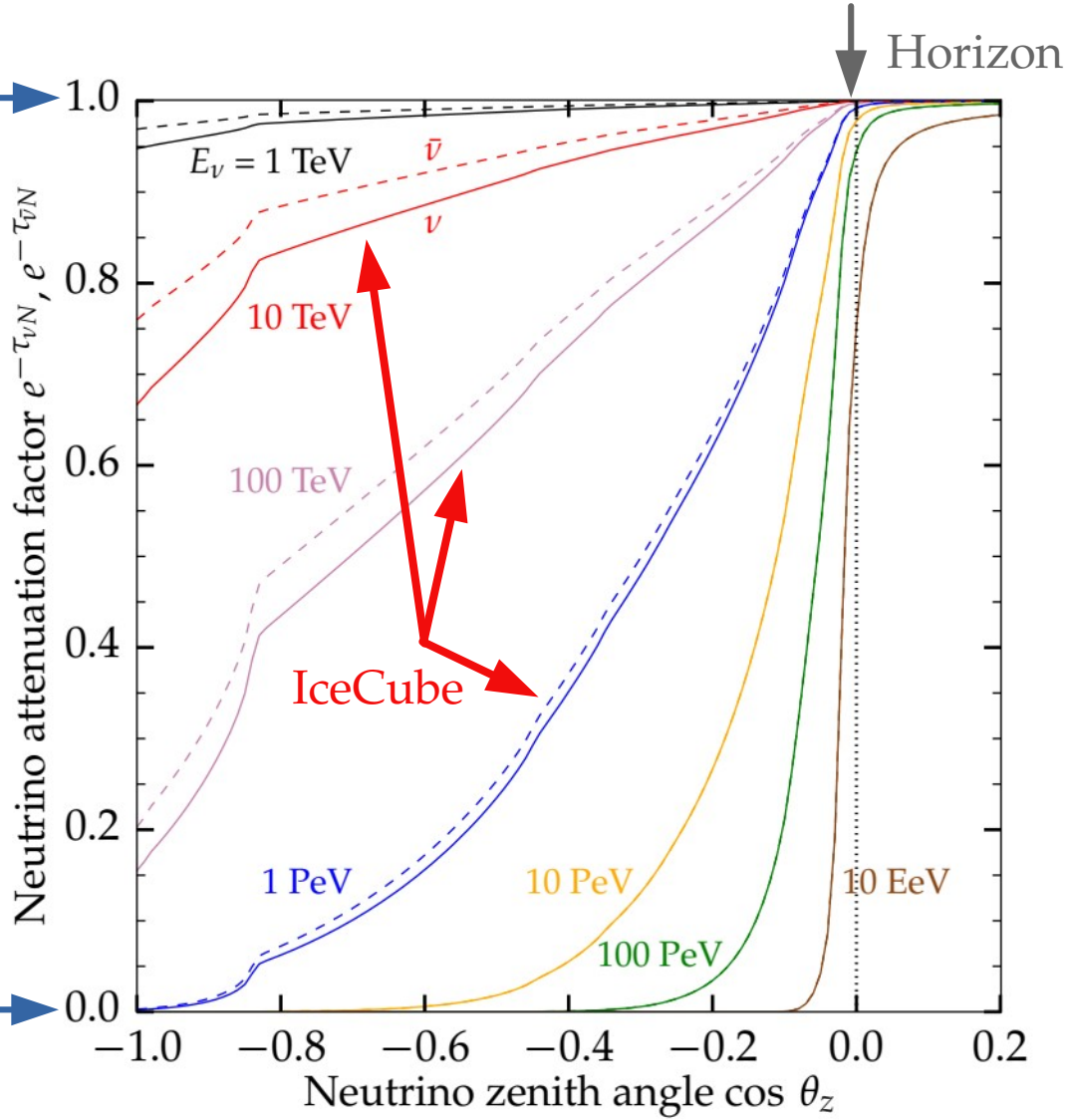


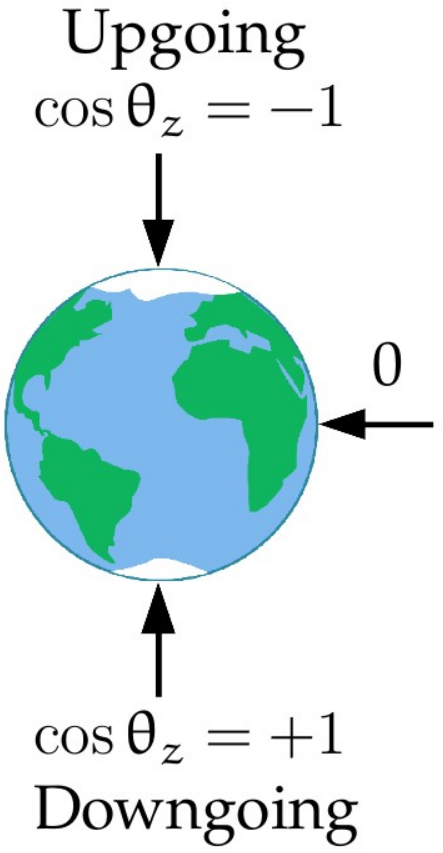


MB & Connolly, *PRL* 2019

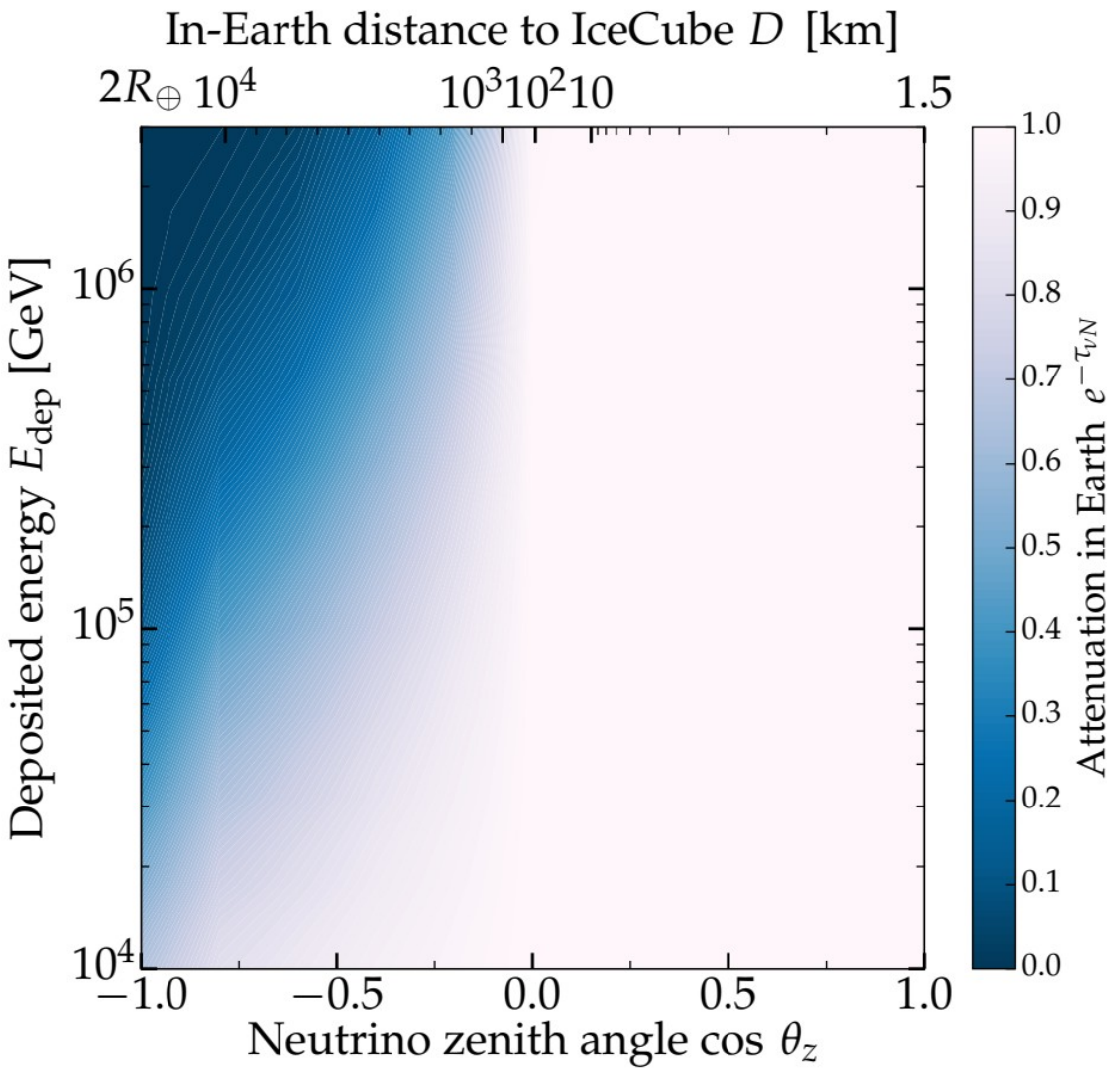
No attenuation

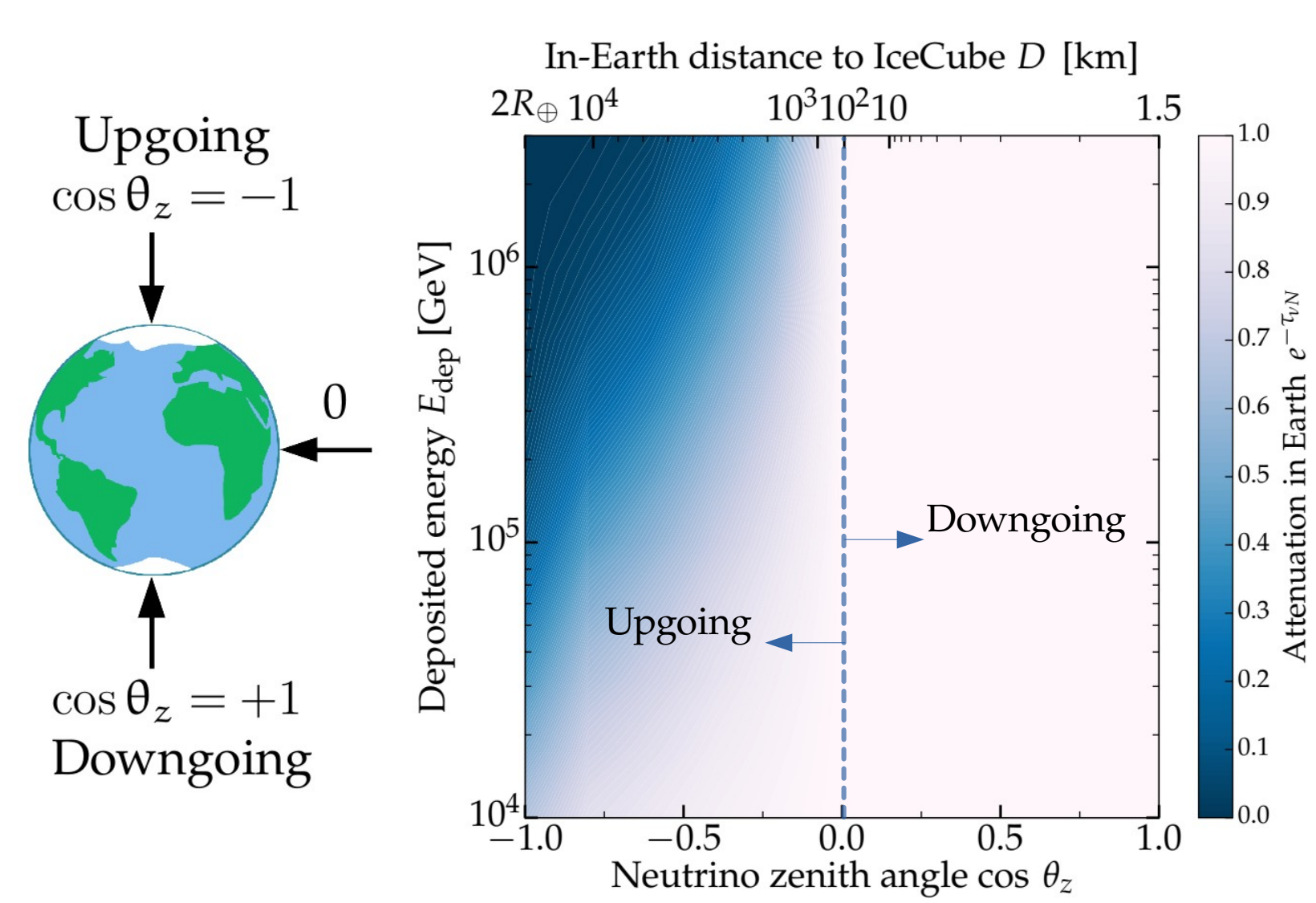
Full attenuation

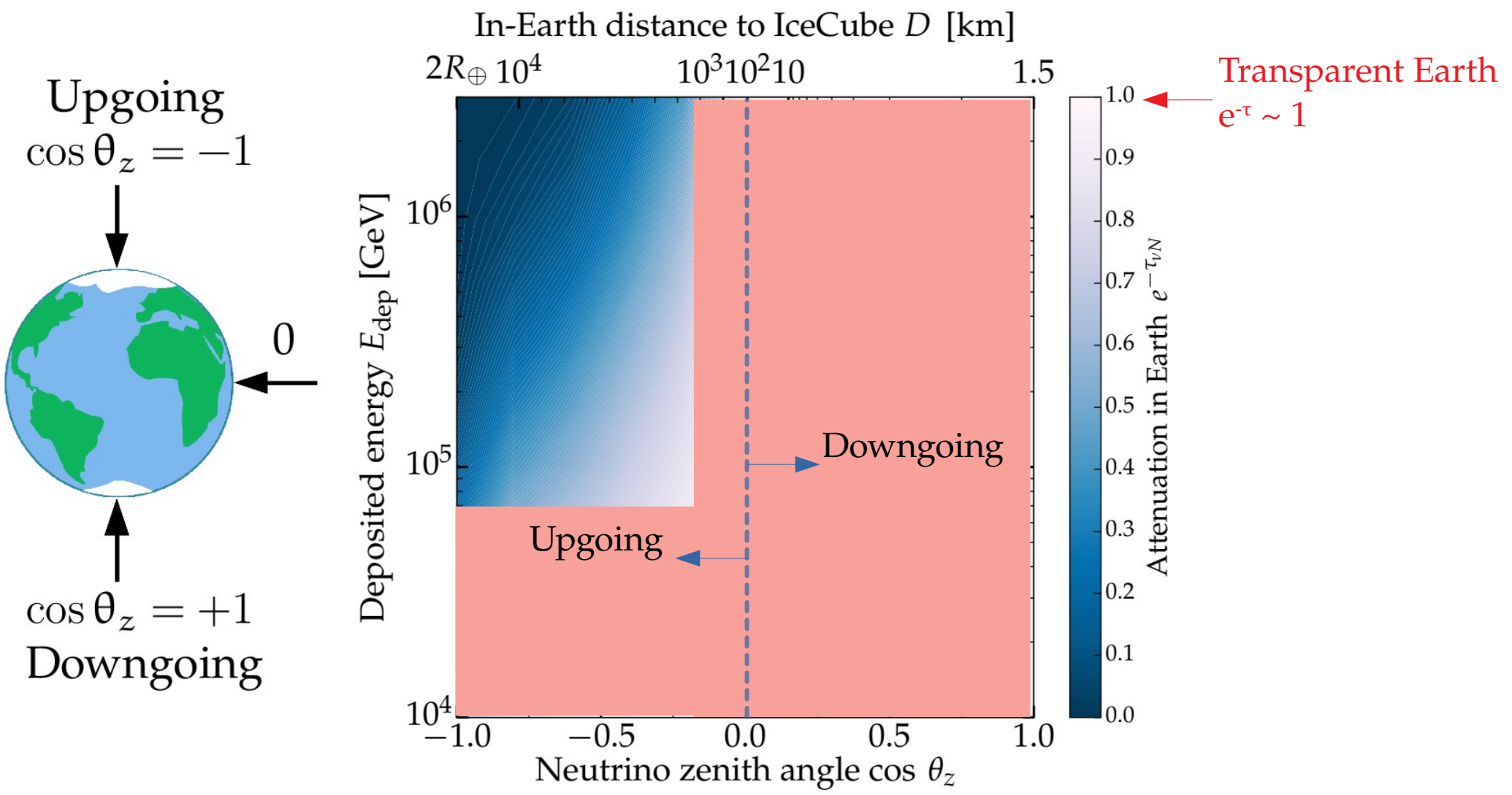


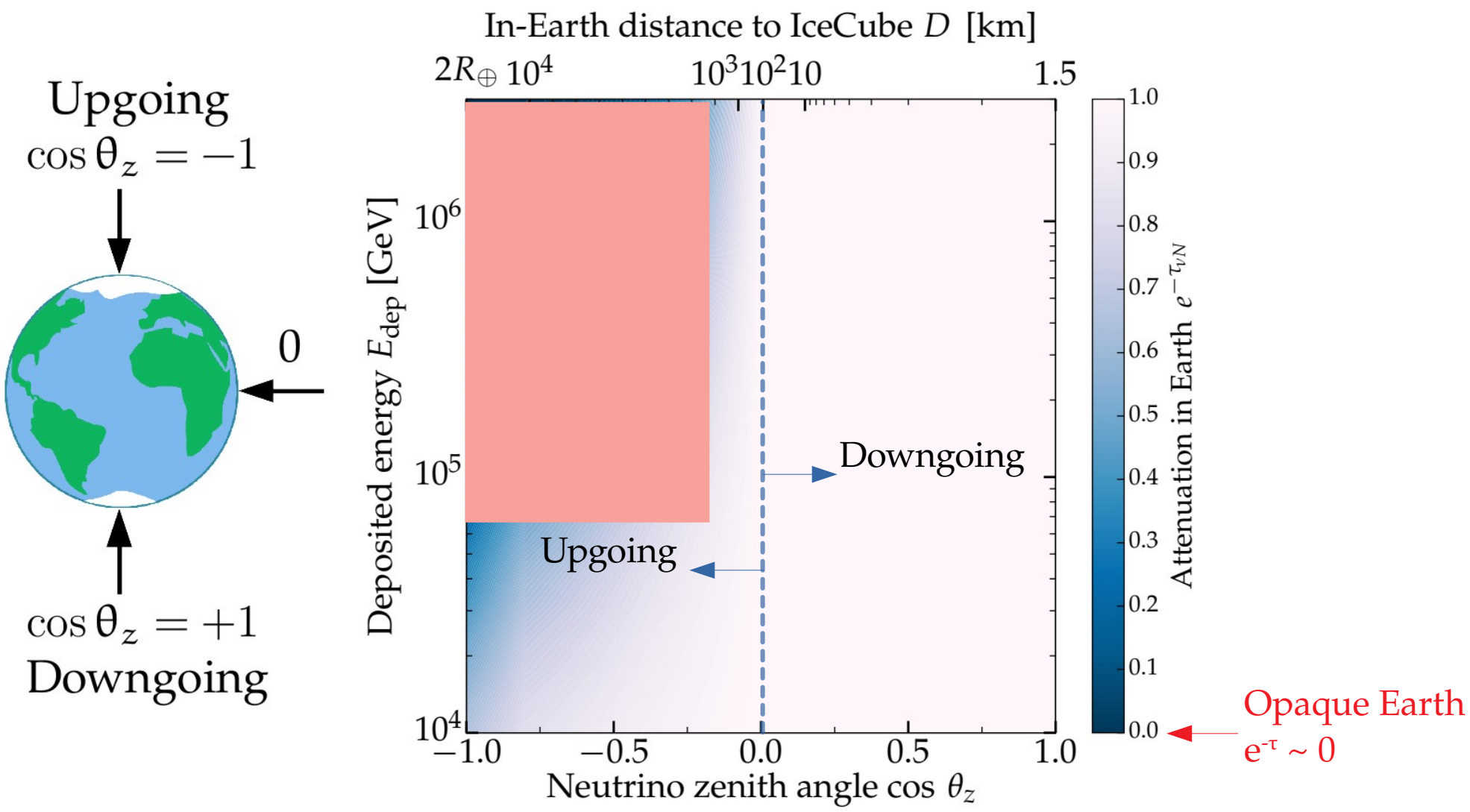


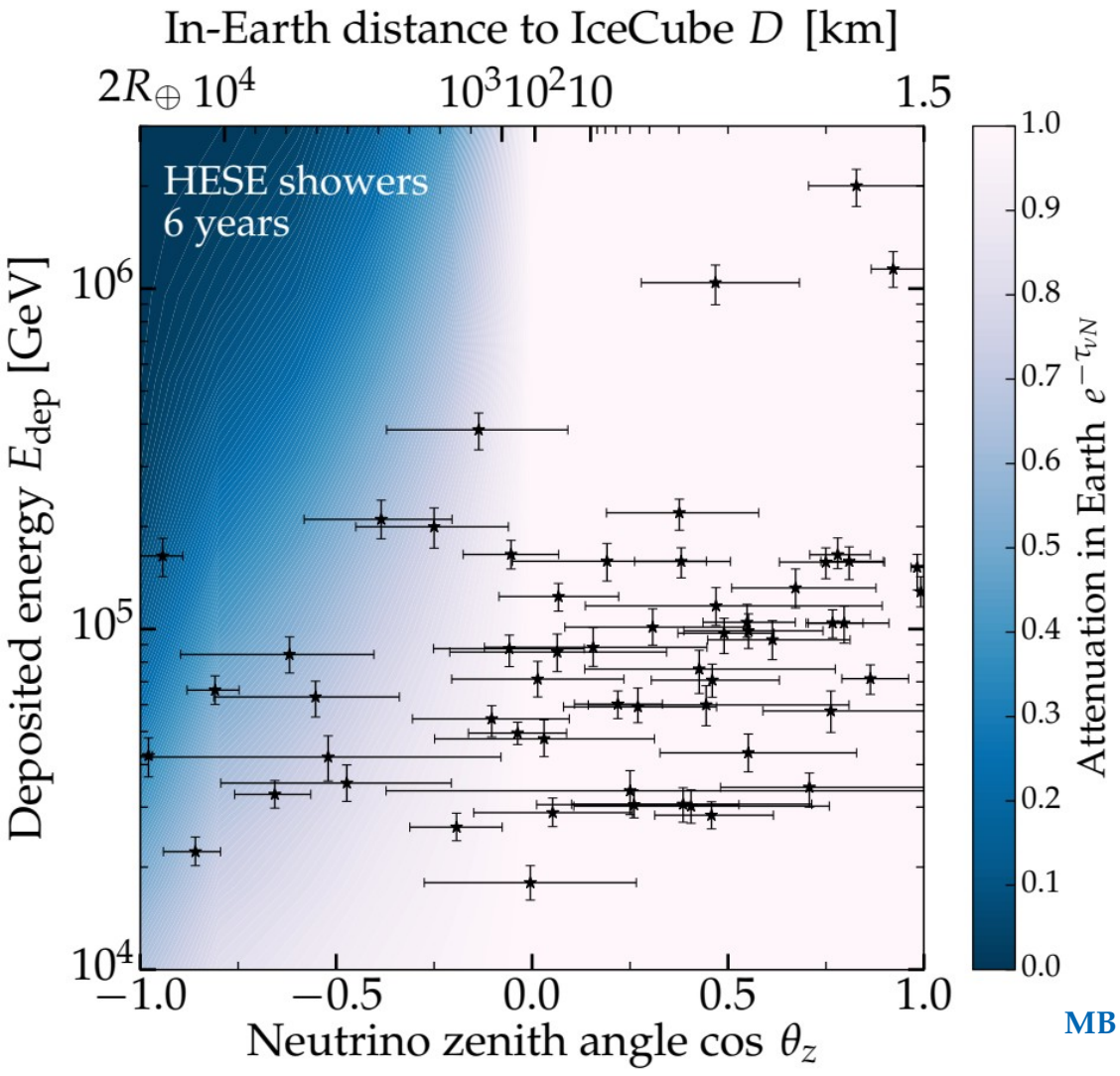
MB & Connolly, *PRL* 2019


In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
−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

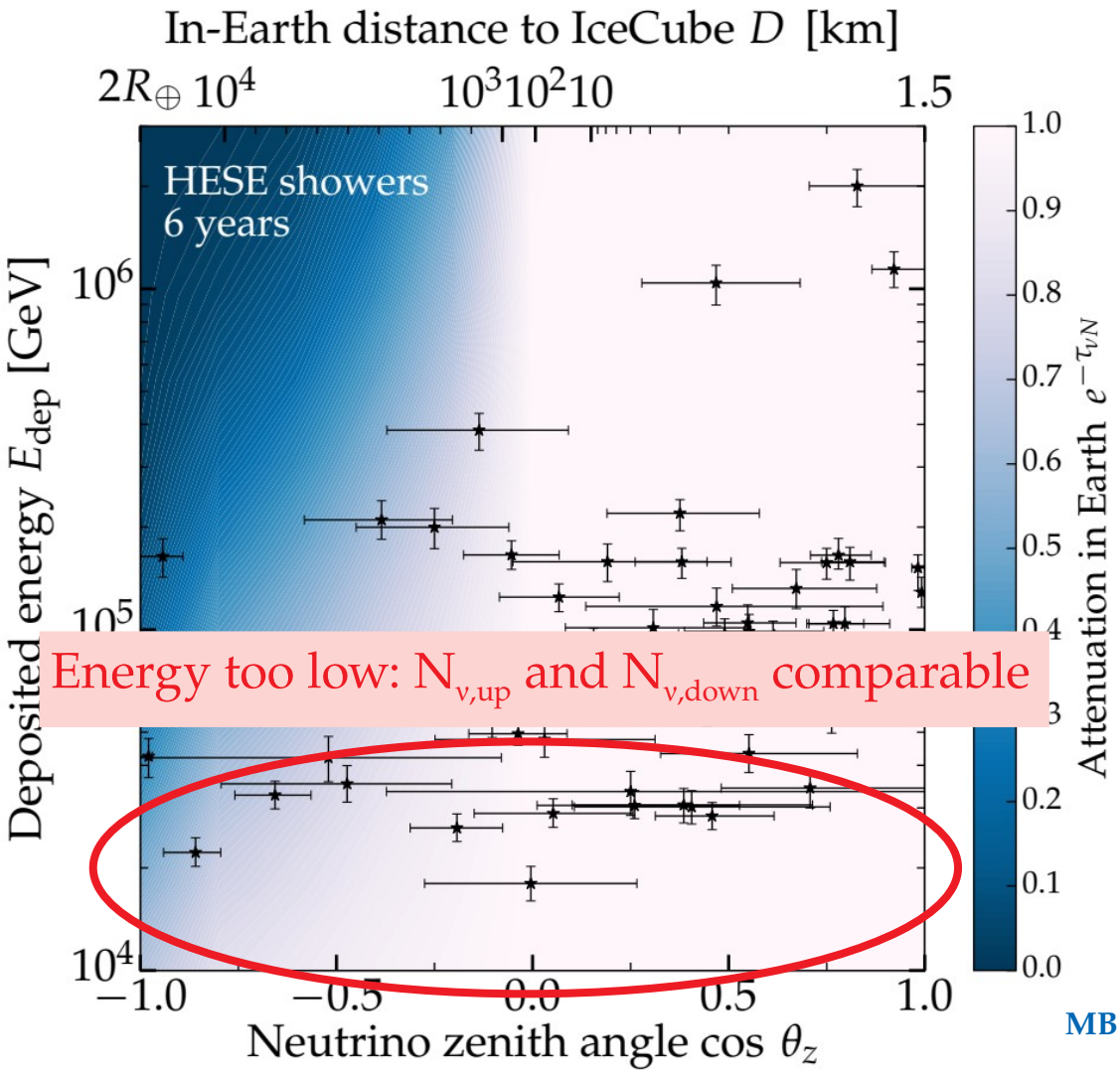

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4
10^3 10^2 10
1.5
Deposited energy $E_{\rm dep}$ [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9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


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
Transparent Earth
$e^{-\tau} \sim 1$
Deposited energy $E_{\rm dep}$ [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


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]
10^6
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
Opaque Earth
$e^{-\tau} \sim 0$

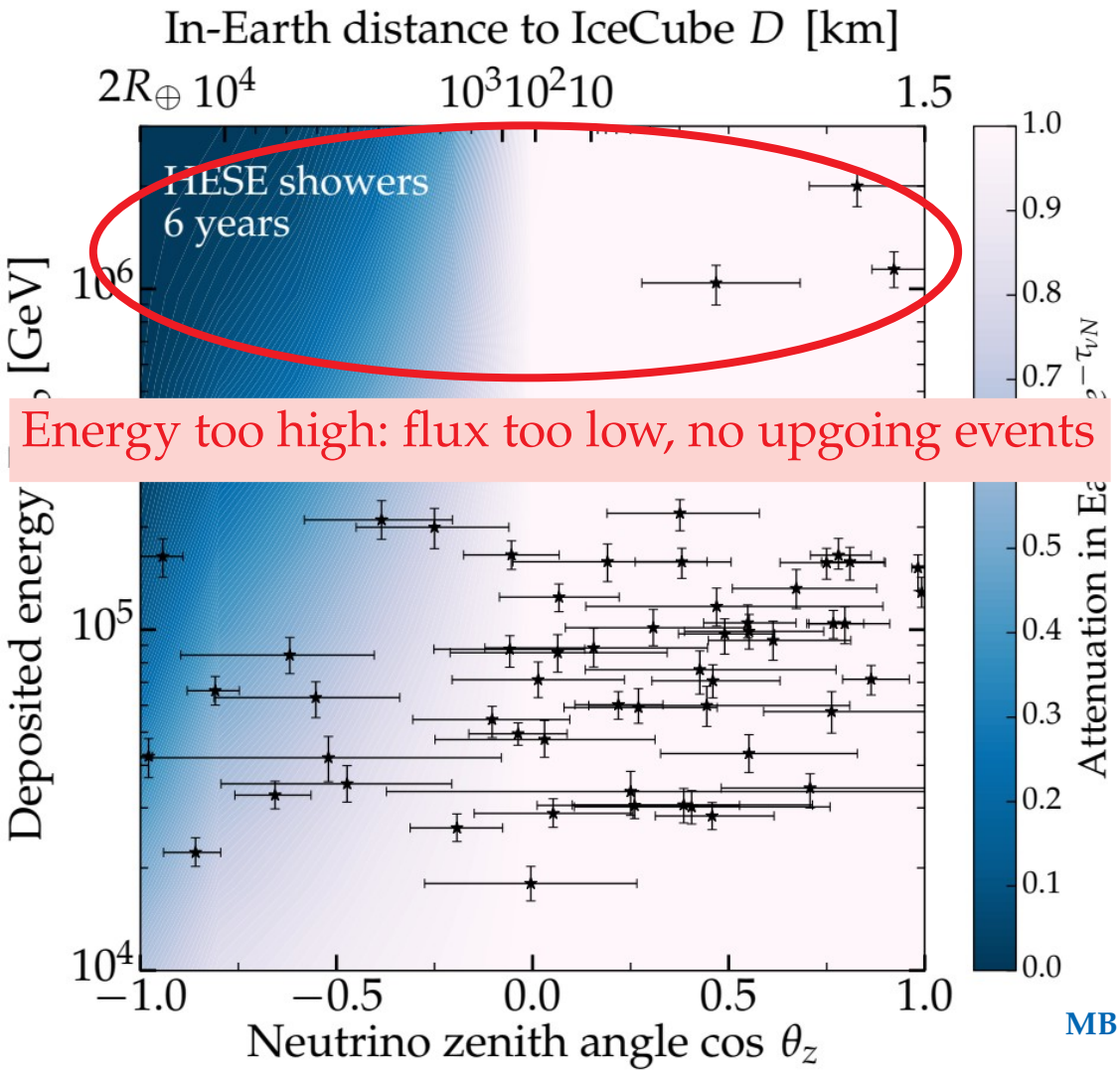


MB & Connolly, *PRL* 2019

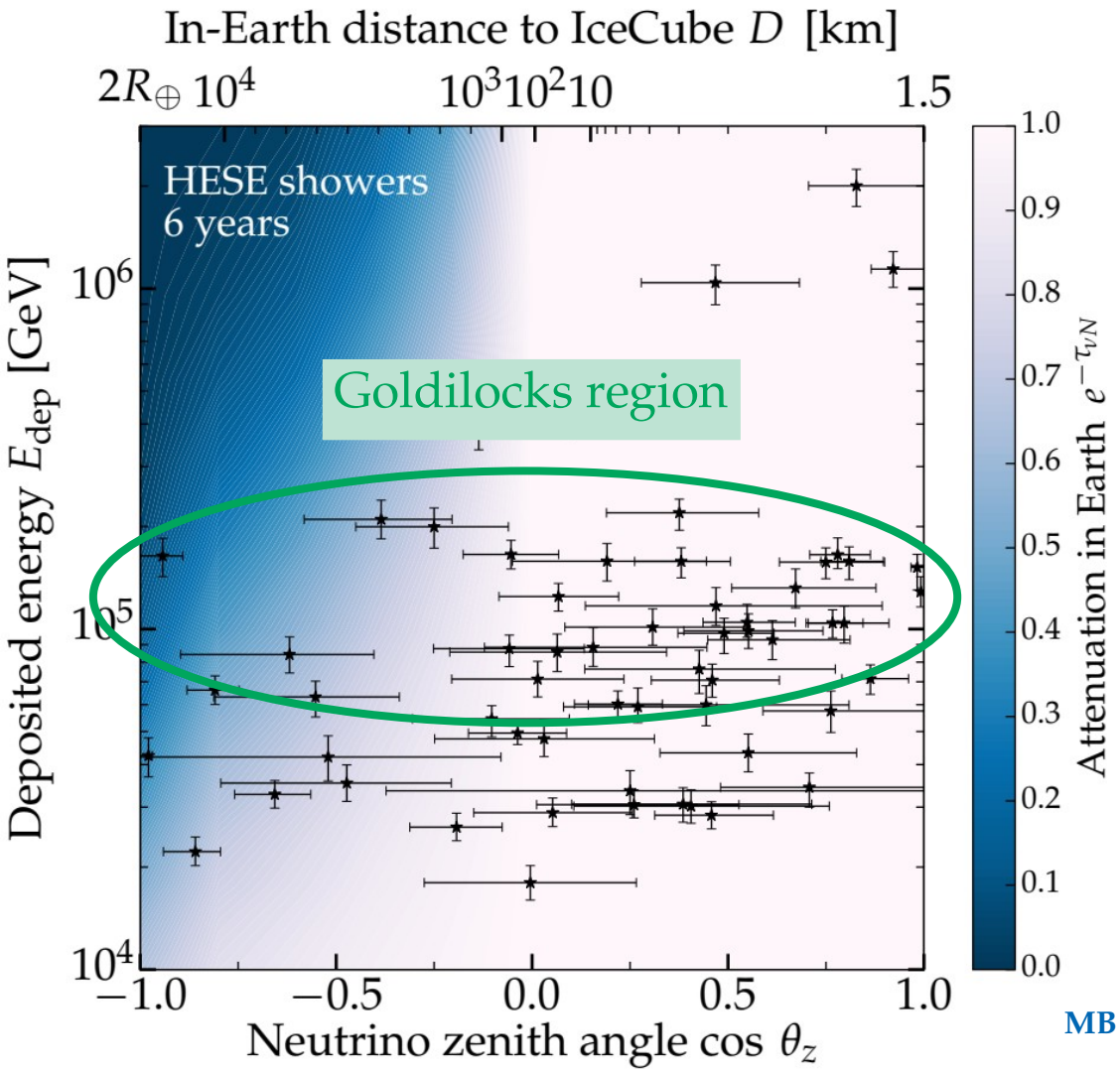


Energy too low: $N_{\nu,up}$ and $N_{\nu,down}$ comparable

MB & Connolly, *PRL* 2019

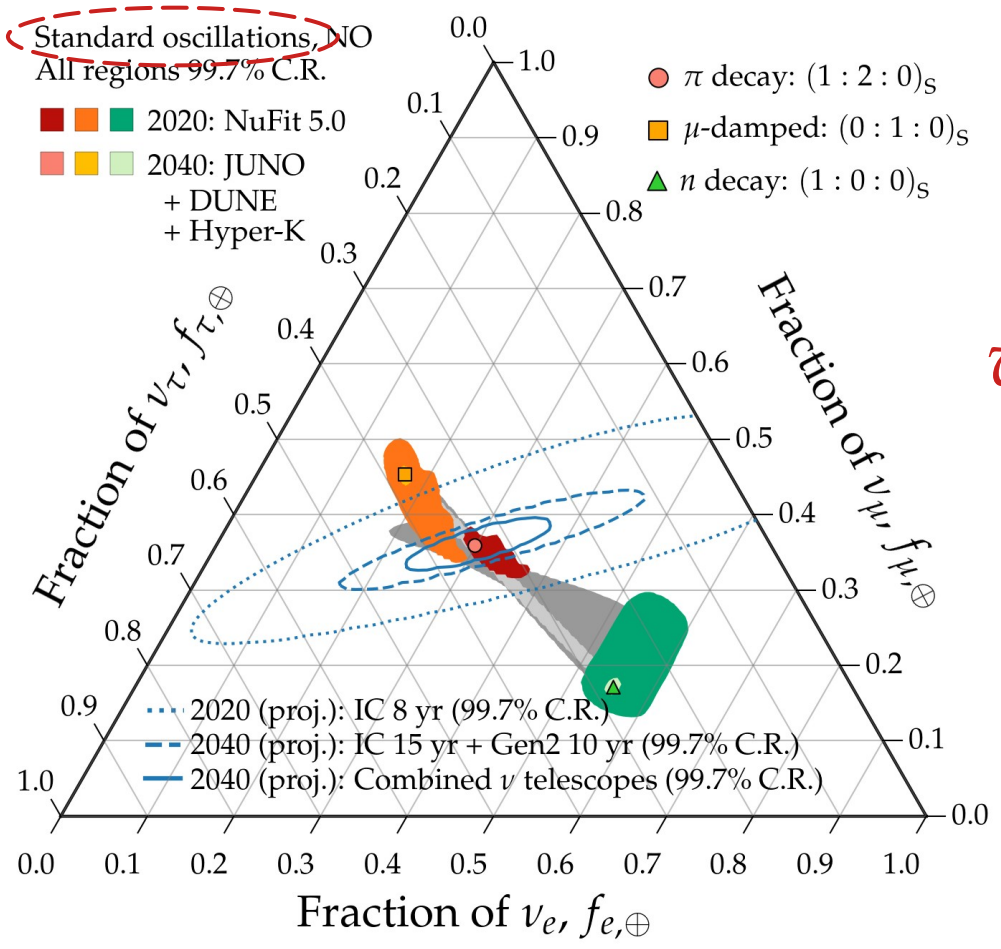


MB & Connolly, *PRL* 2019

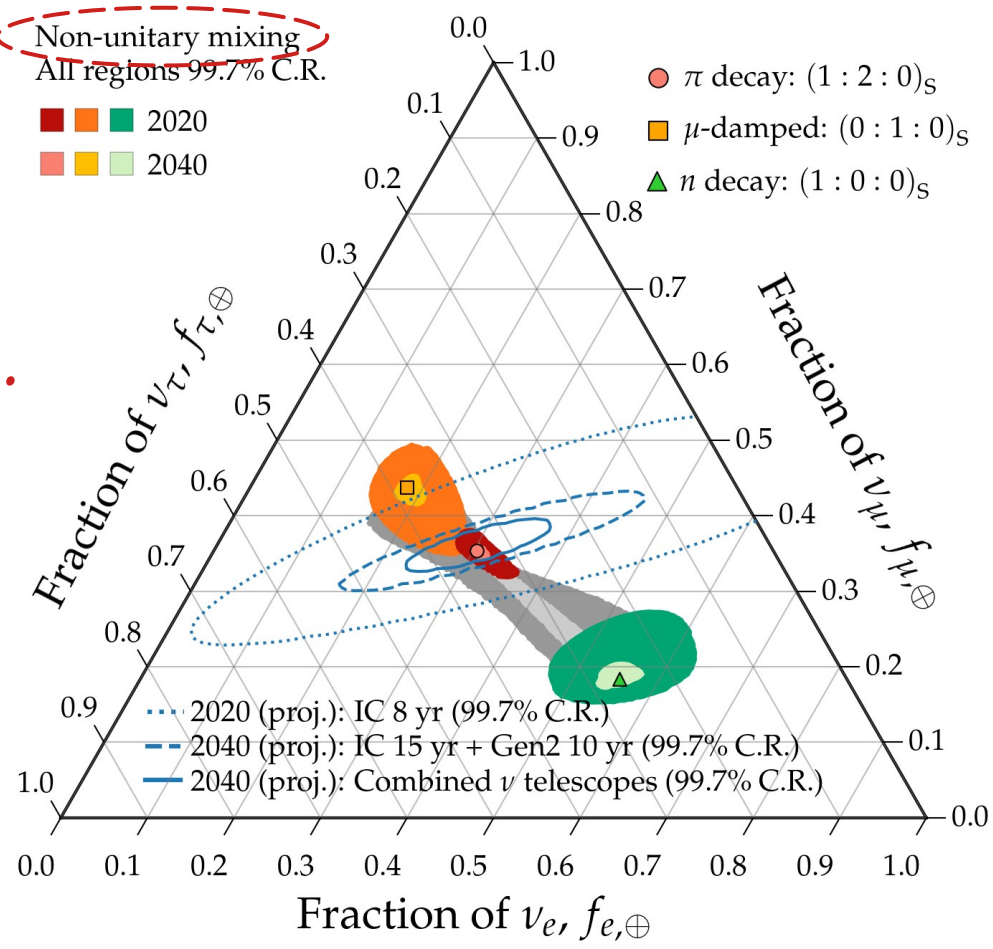


MB & Connolly, *PRL* 2019

No unitarity? *No problem*

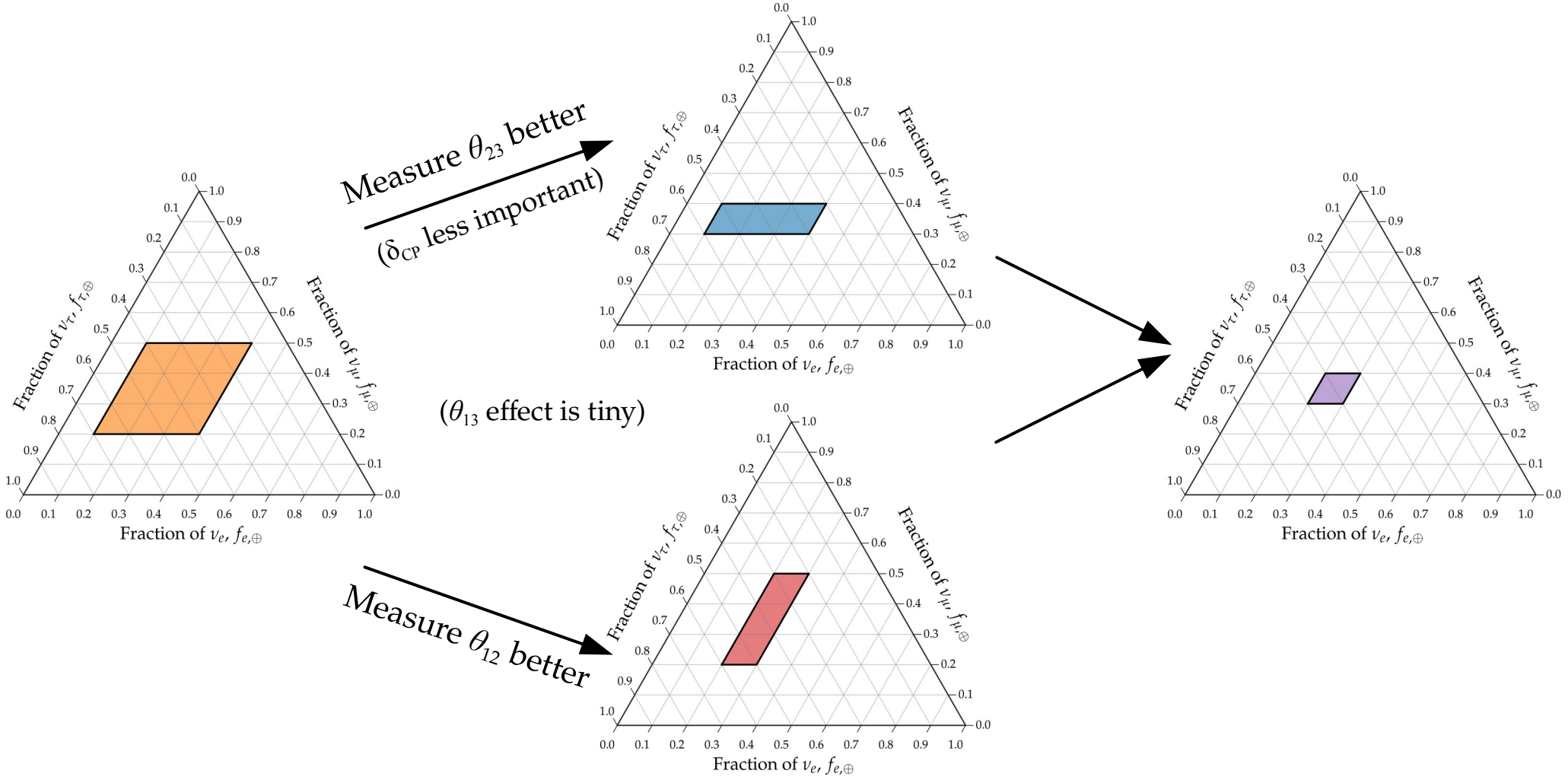


vs.



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

How knowing the mixing parameters better helps



What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

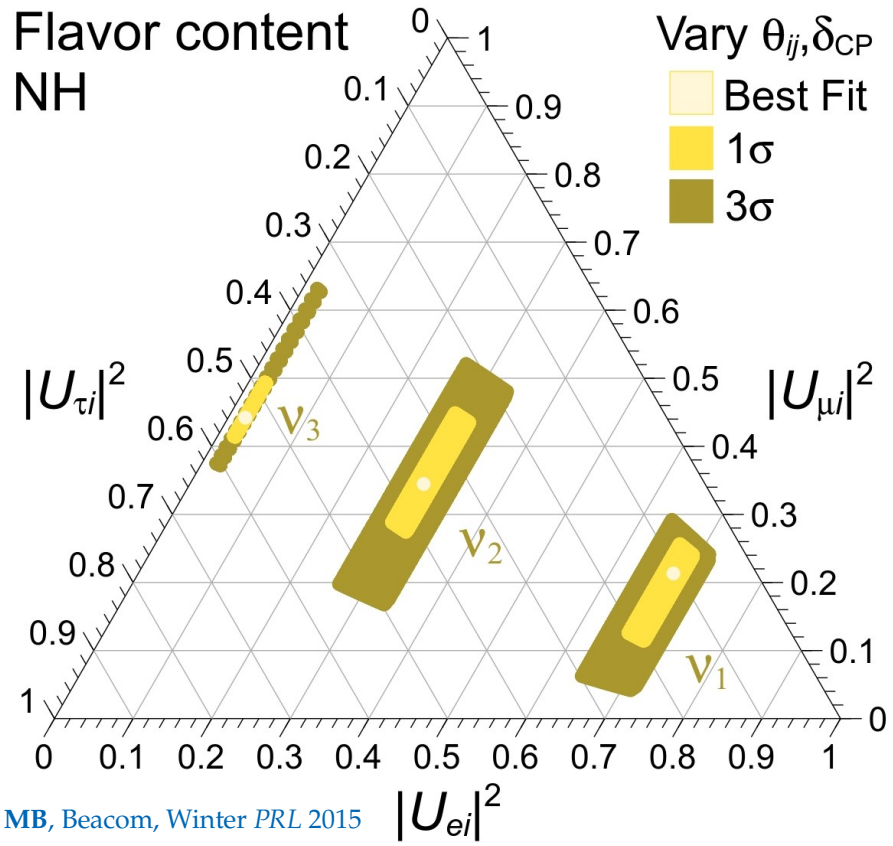
Flavor content of mass eigenstates:

Known to within 2%

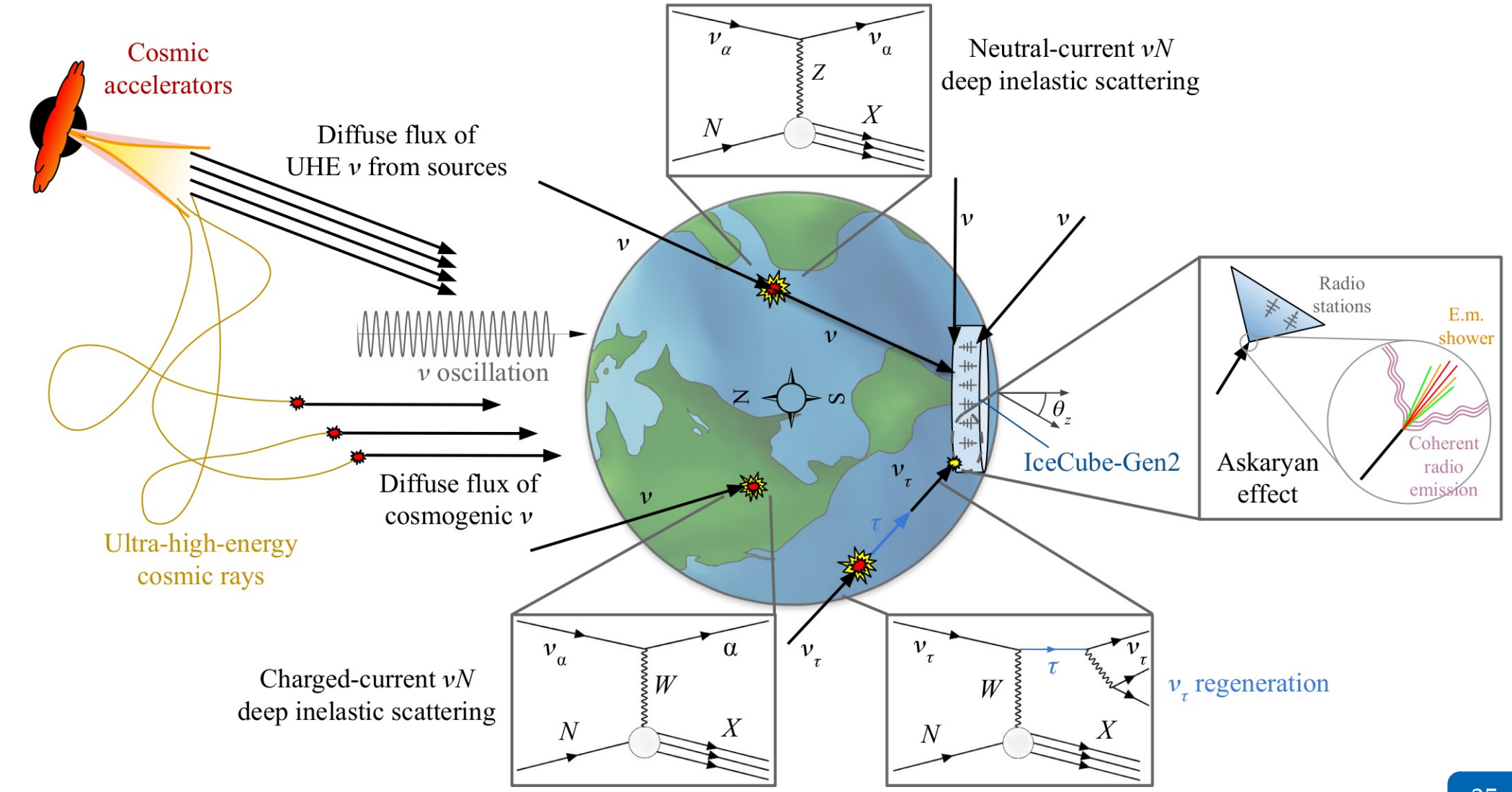
$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015



Valera, **MB**, Glaser, *JHEP* 2022 [2204.04237]