Physics beyond the Standard Model with high-energy cosmic neutrinos

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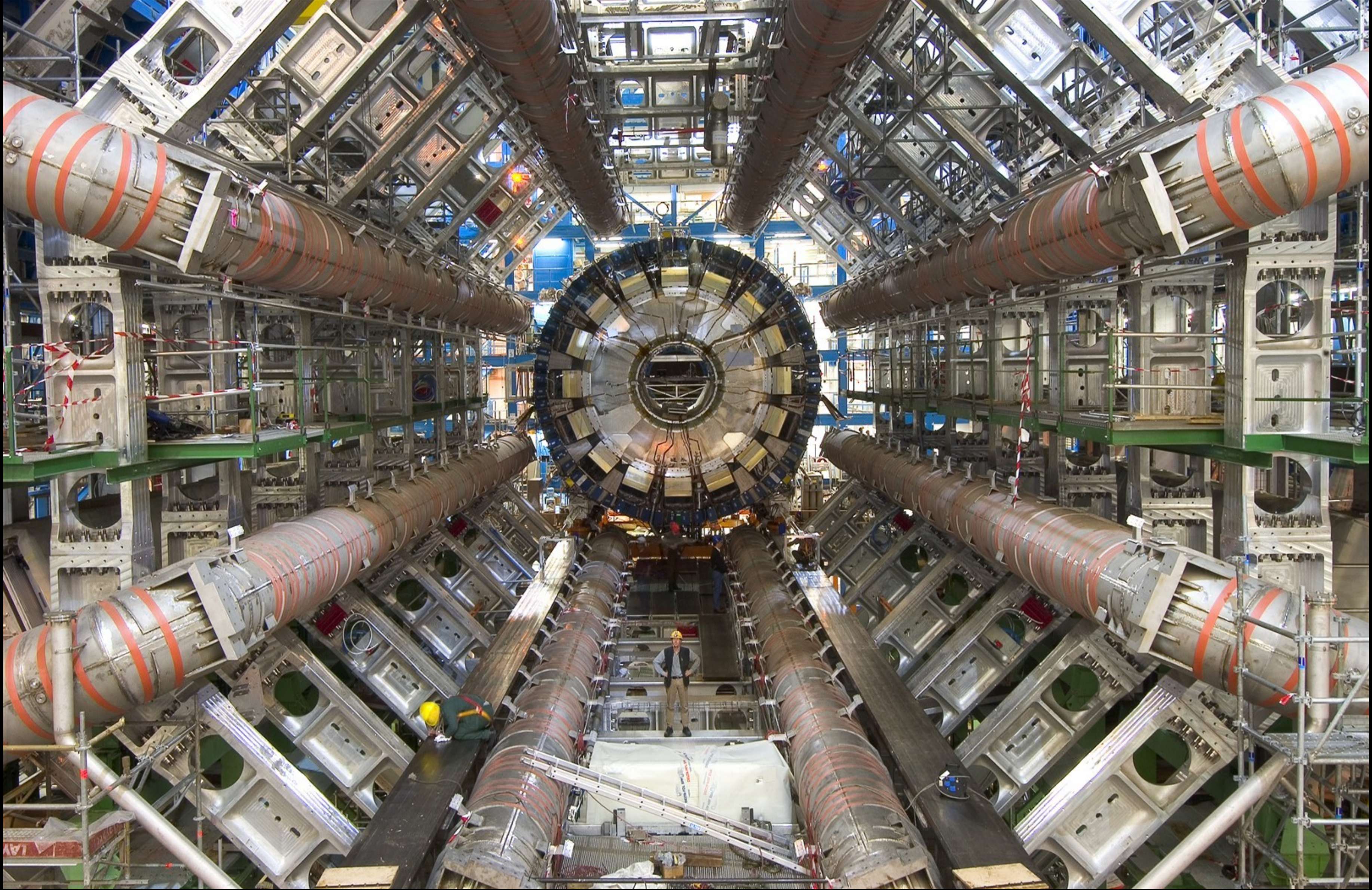
Niels Bohr Institute, University of Copenhagen

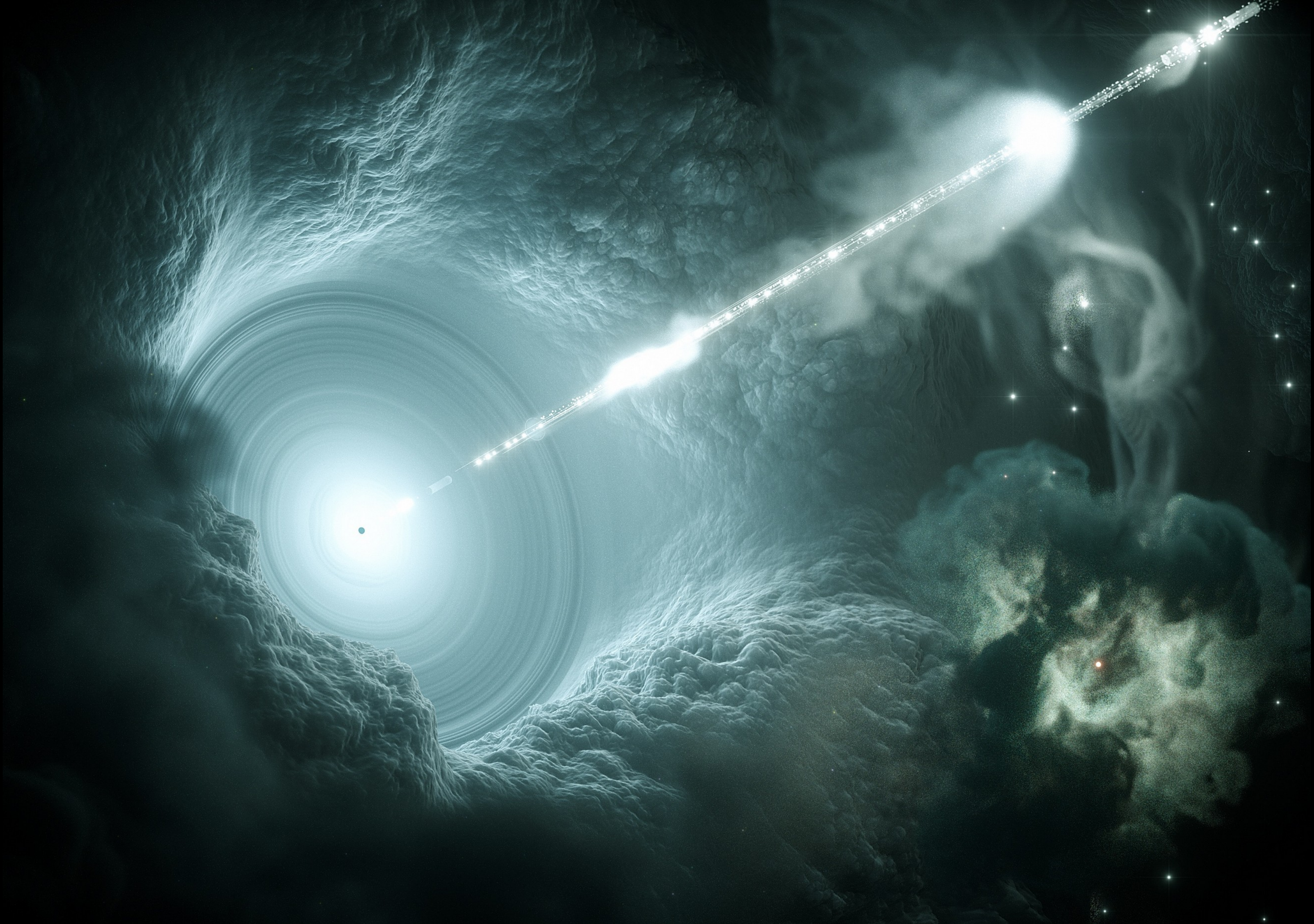
XX International Workshop on Neutrino Telescopes
Venice, October 26, 2023

UNIVERSITY OF COPENHAGEN

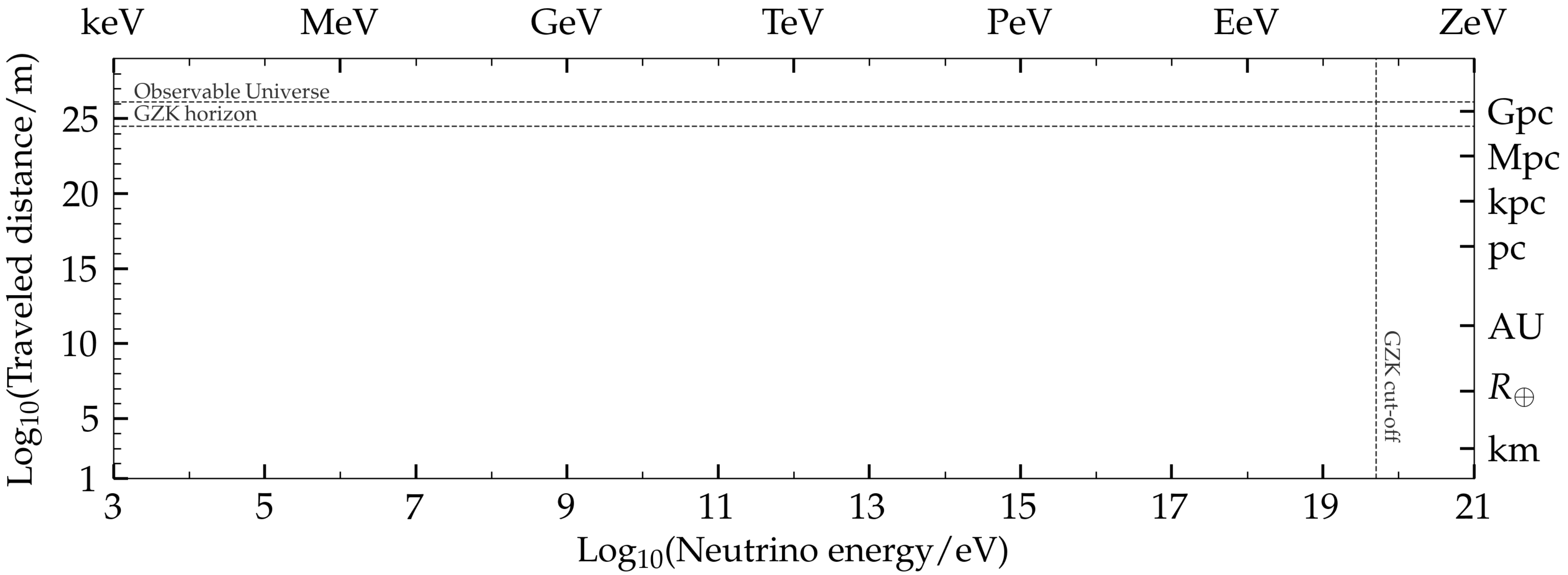
VILLUM FONDEN



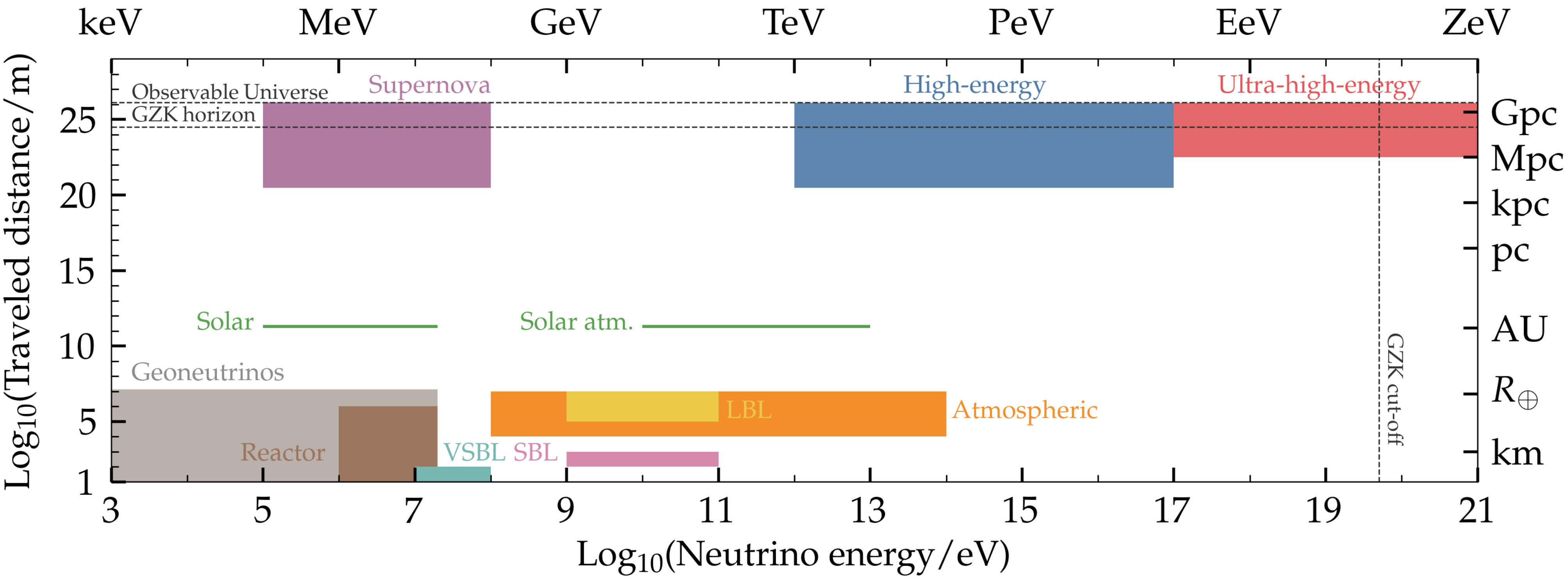
ATLAS



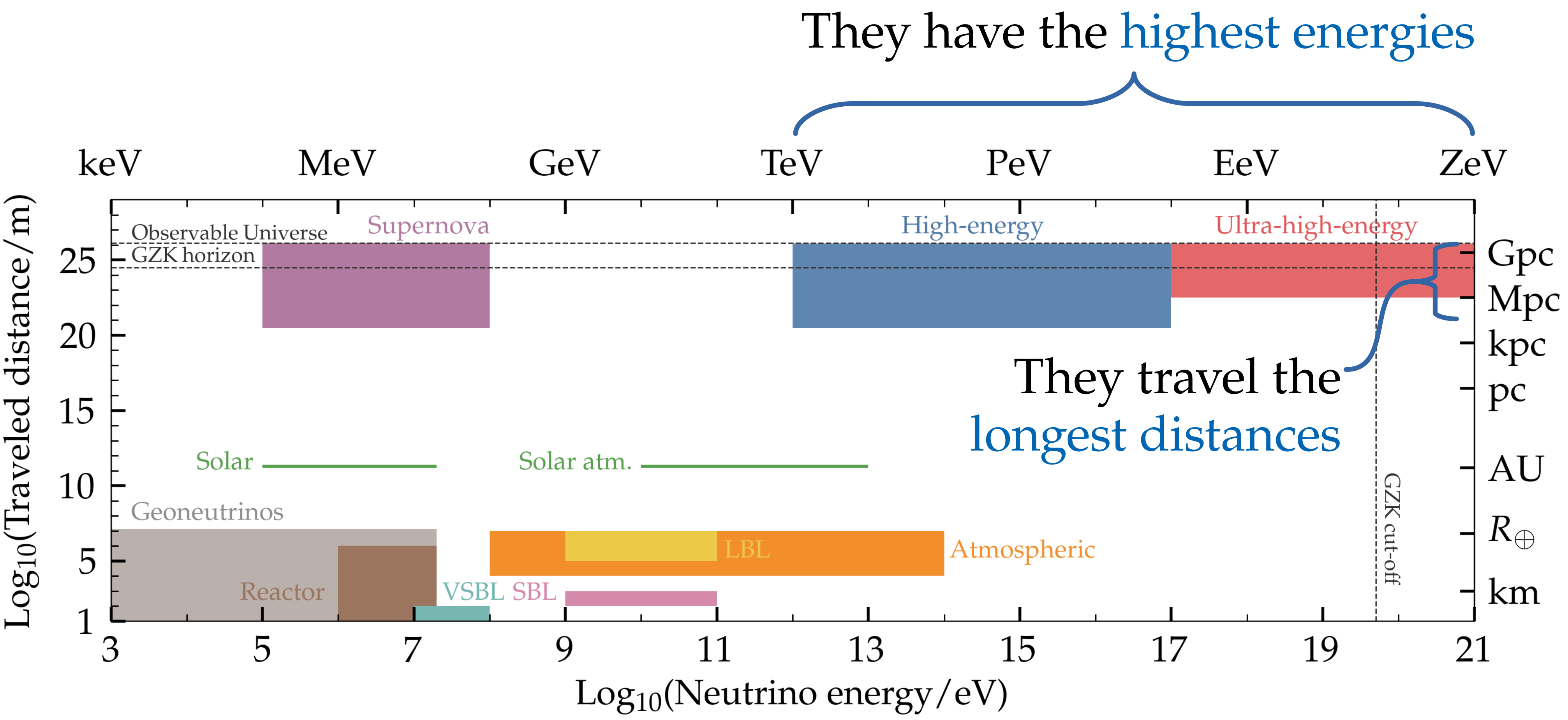
DESY



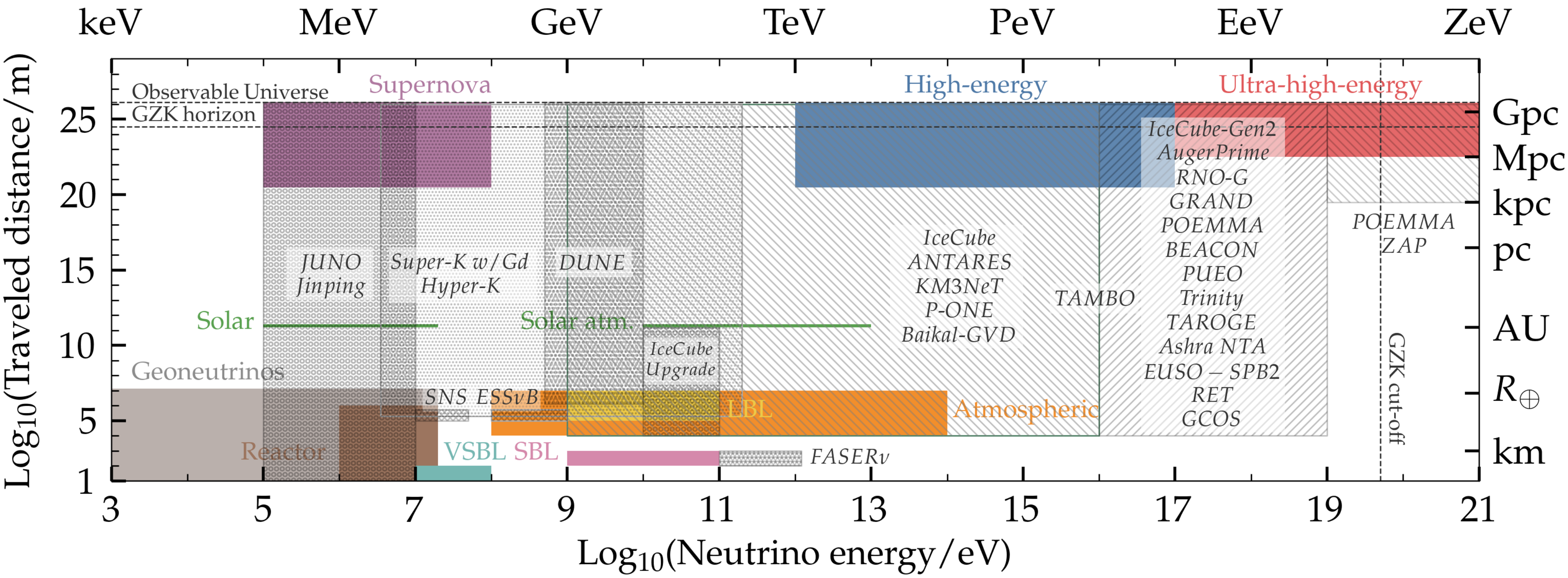
Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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



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



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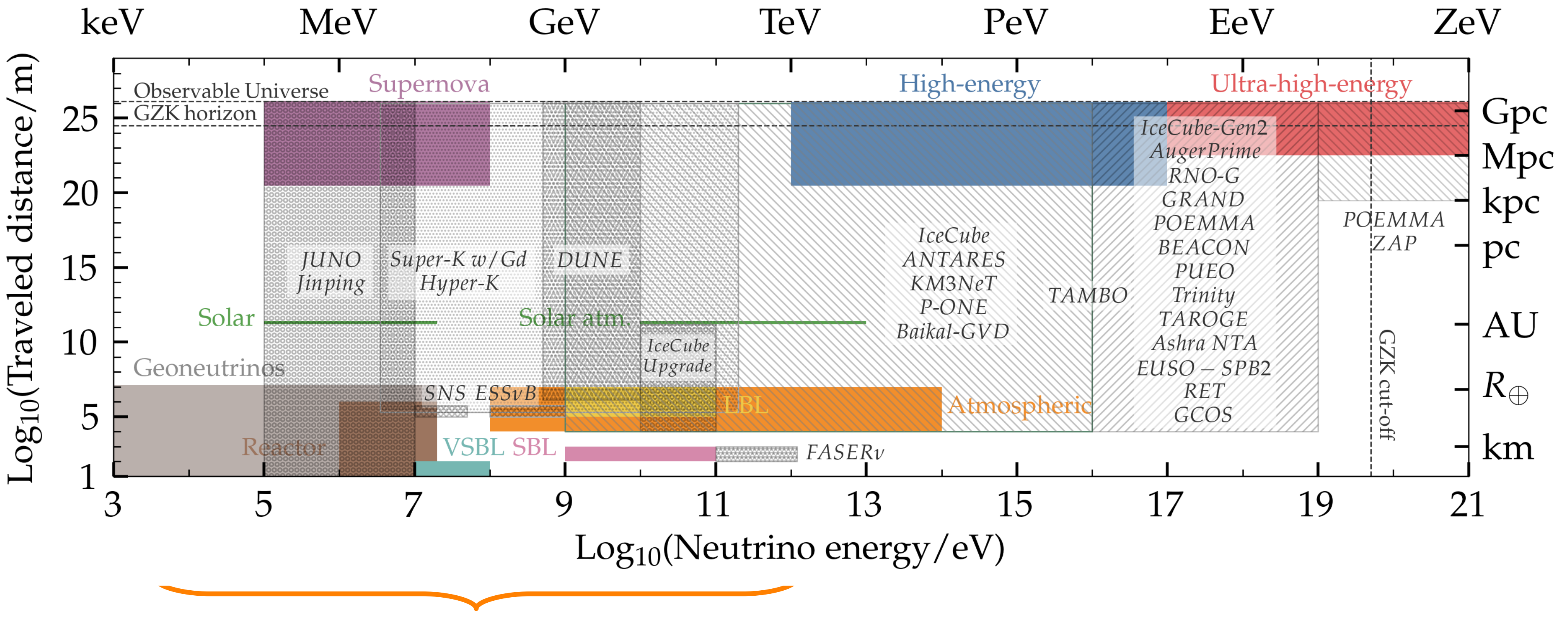
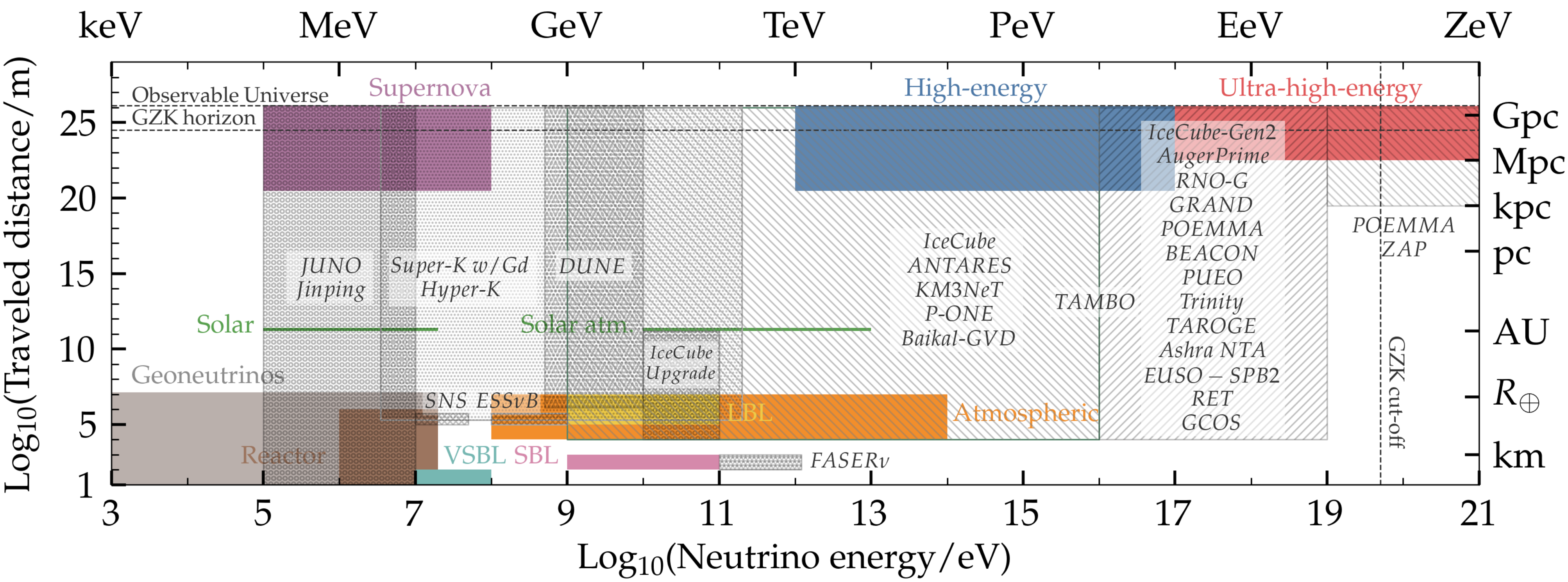


Synergies with lower energies

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

Discovered in 2013
by IceCube



Synergies with lower energies

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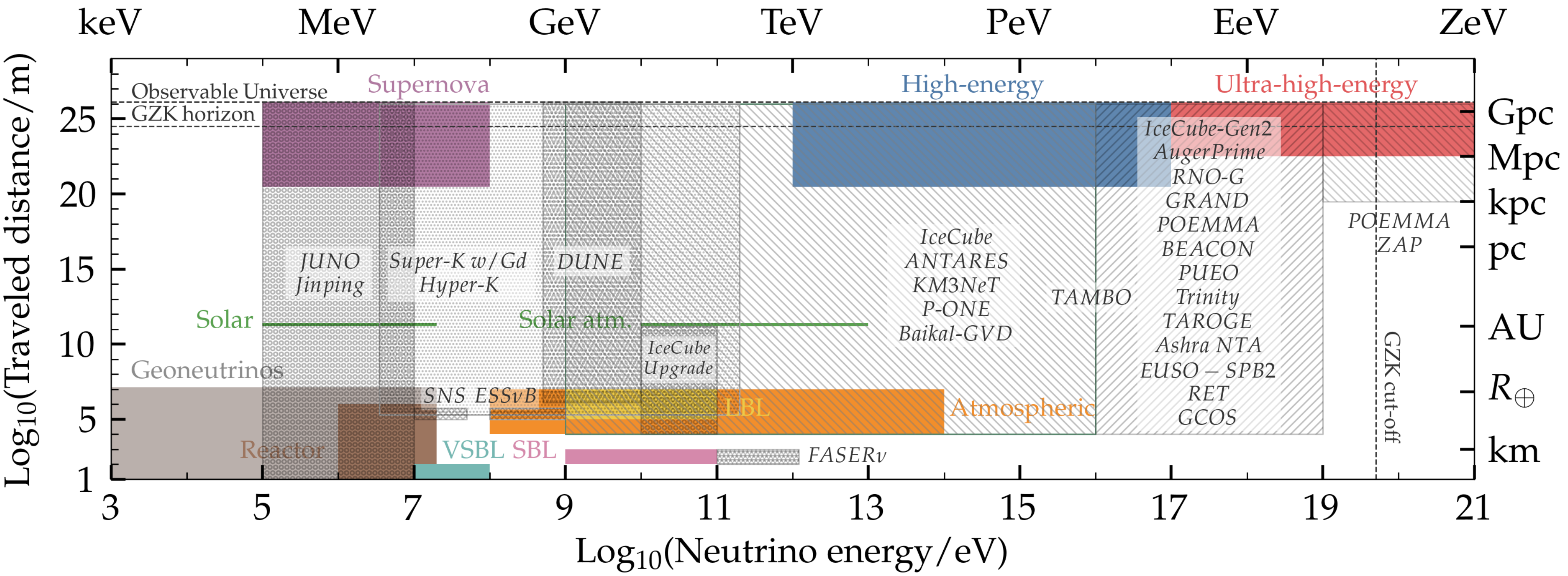
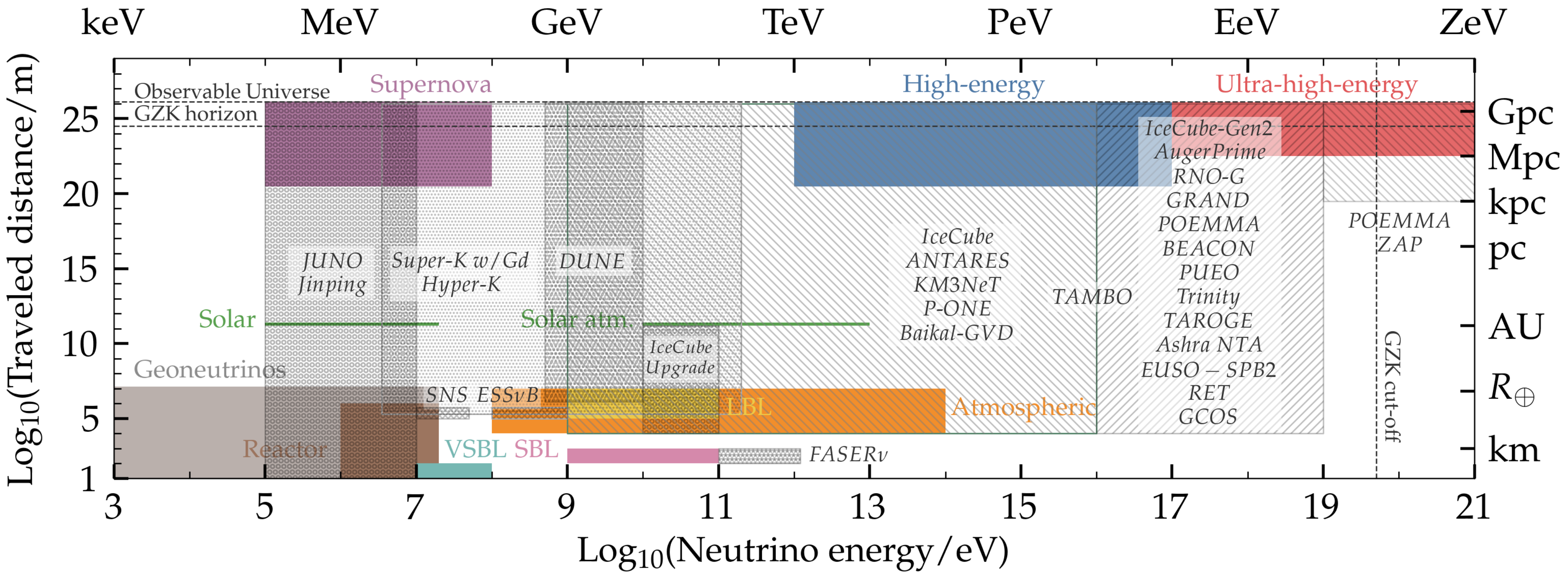


Synergies with lower energies

Increase TeV–PeV
ν statistics

Discovered in 2013
by IceCube

Predicted in 1969
by Berezinksy



Synergies with lower energies

Increase TeV–PeV
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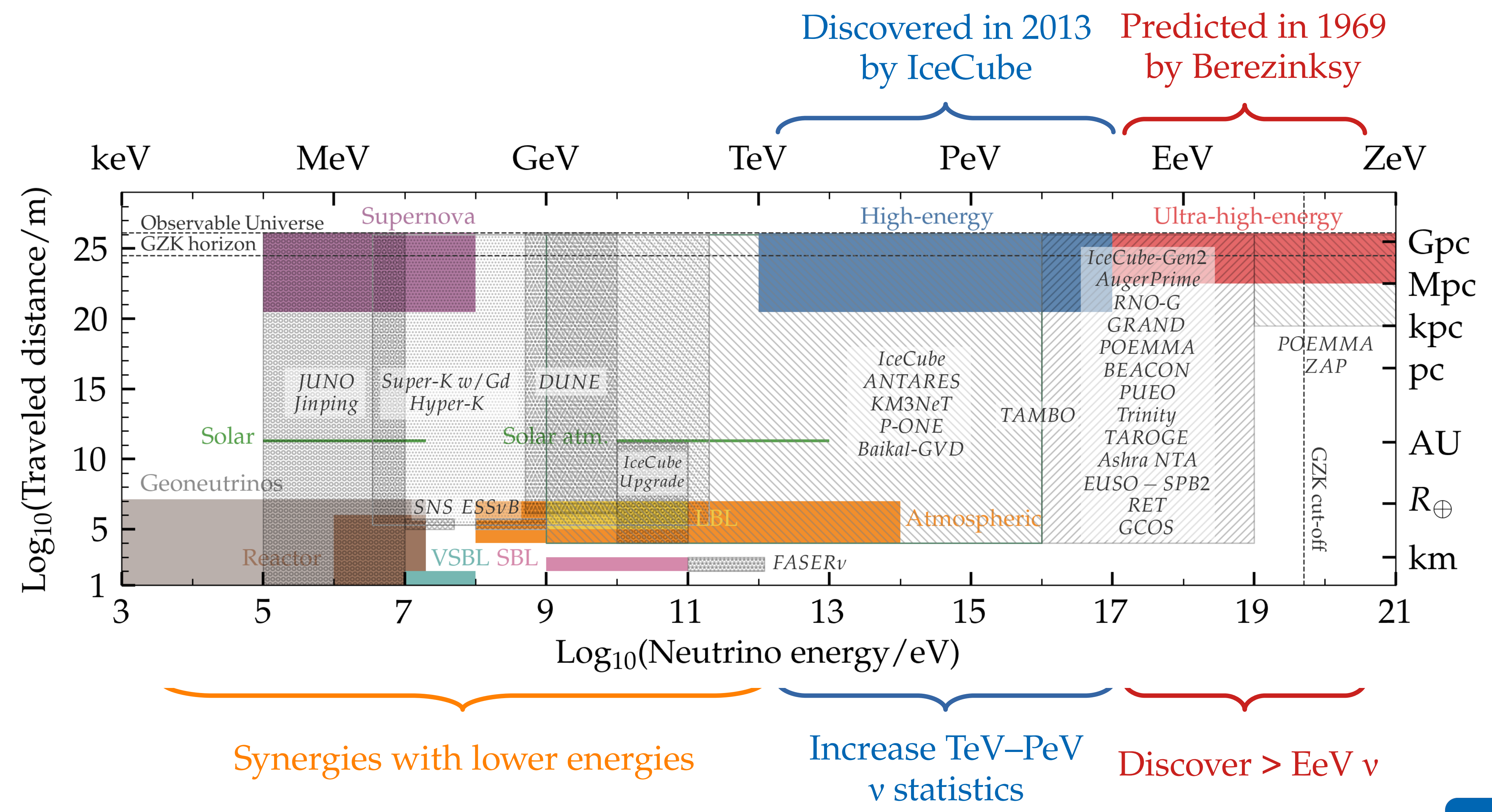


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

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

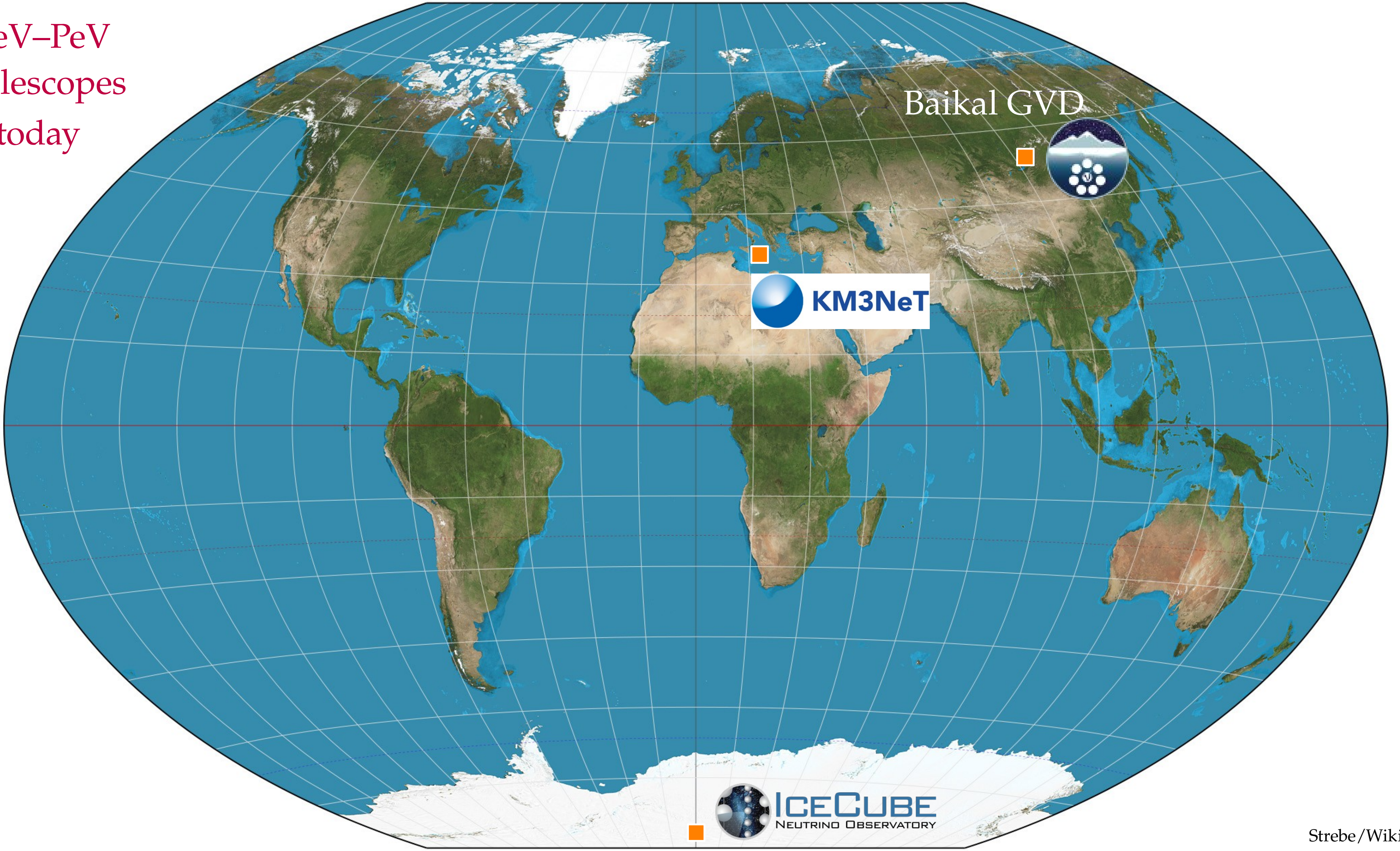
- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

E.g.,
n = -1: neutrino decay
n = 0: CPT-odd Lorentz violation
n = +1: CPT-even Lorentz violation

- 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, $\kappa_1 < 10^{-33}$

TeV–PeV
ν telescopes
today



Strebe/Wikipedia

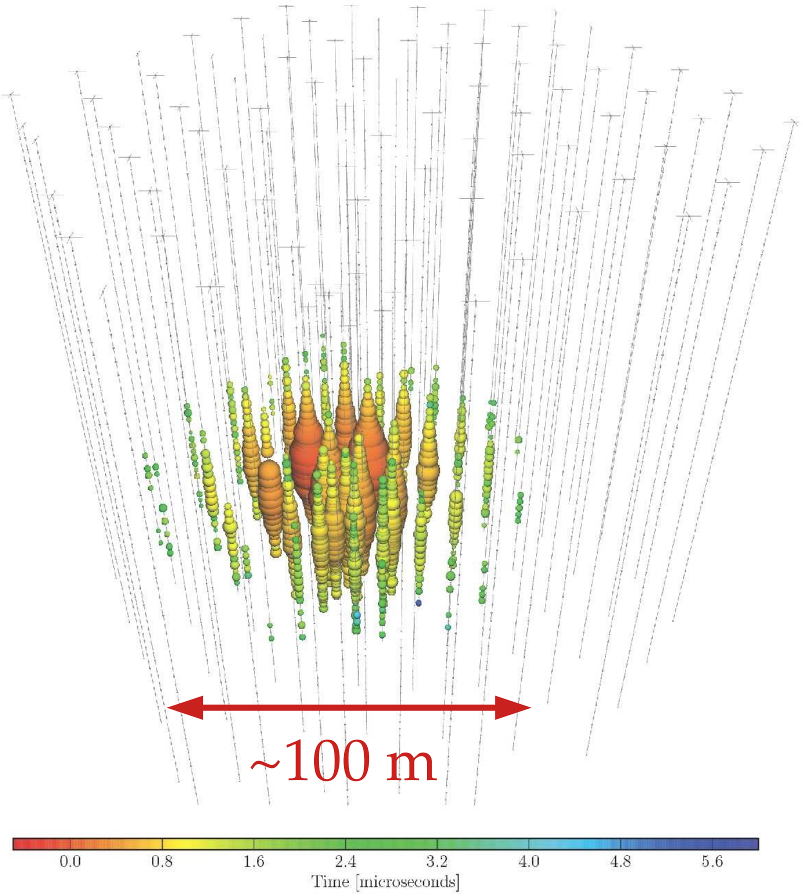
TeV–PeV

ν telescopes

2030s

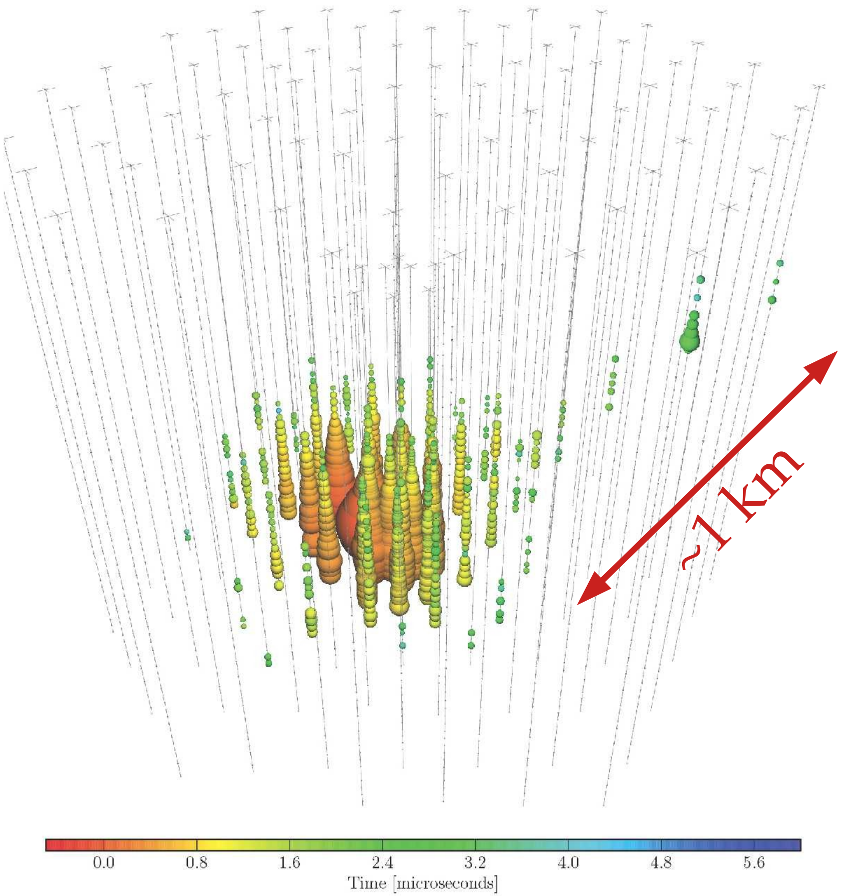
Strebe/Wikipedia

Shower
(mainly from ν_e and ν_τ)

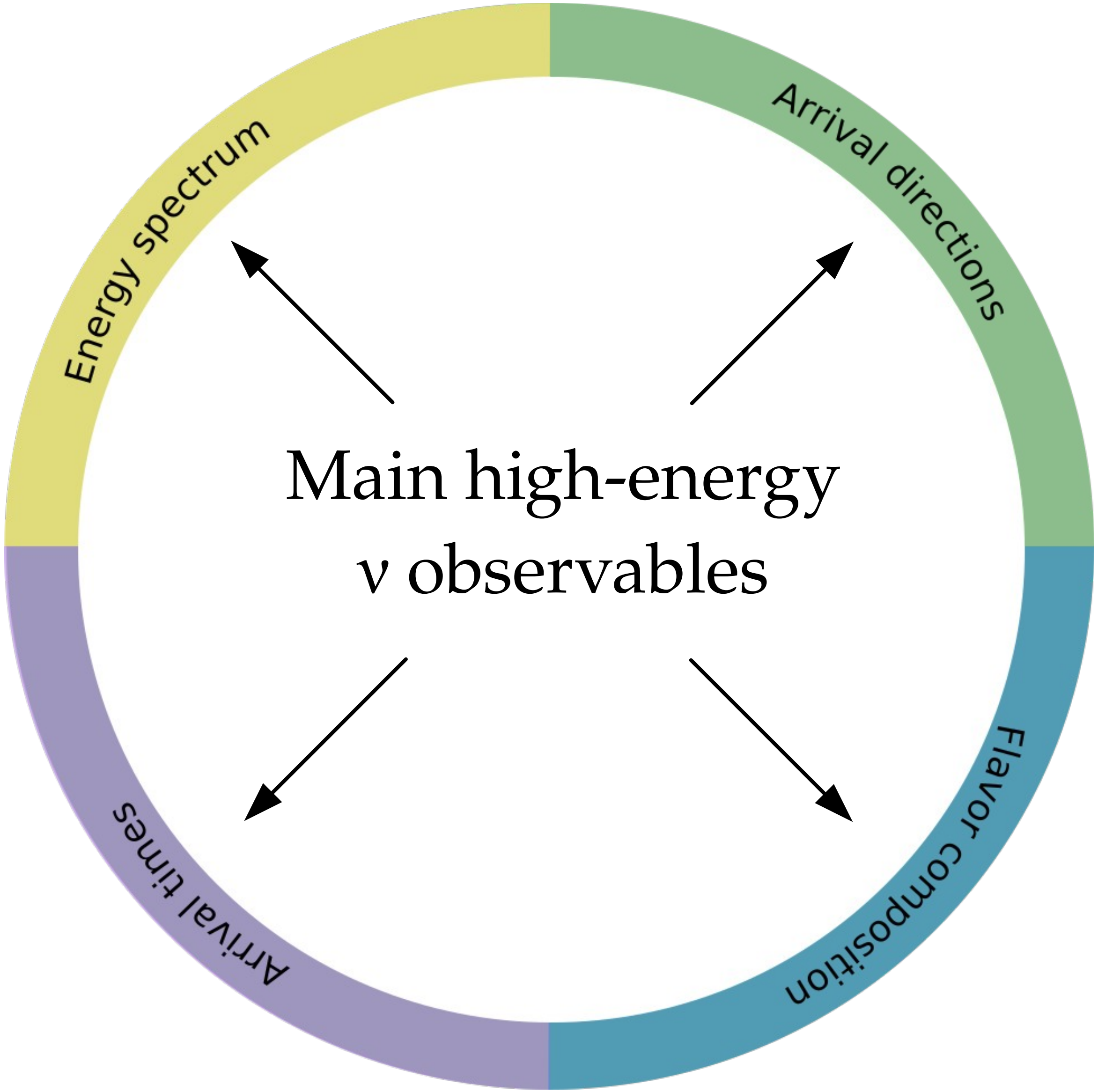


Poor angular resolution: ~10°

Track
(mainly from ν_μ)



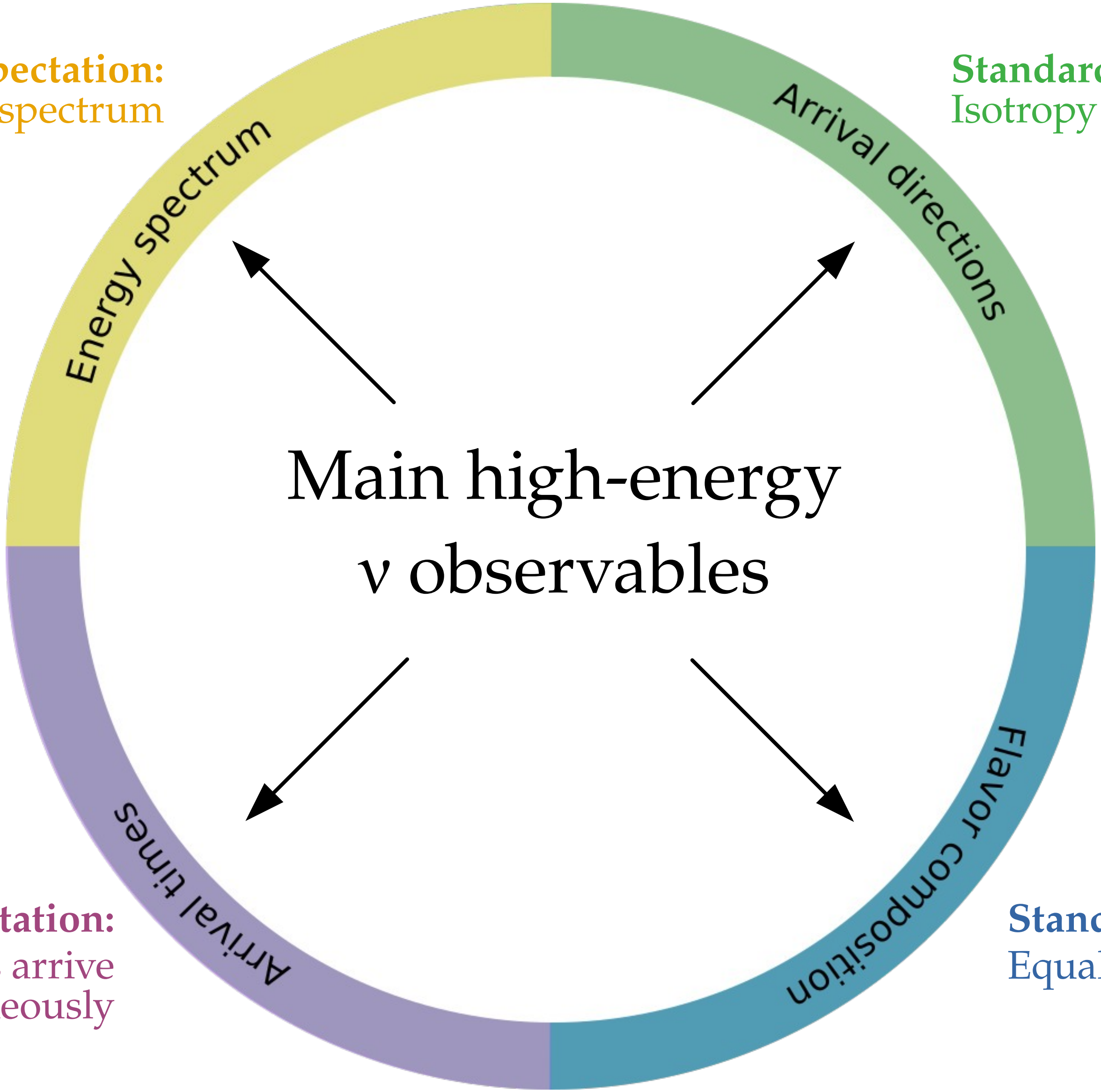
Angular resolution: < 1°



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

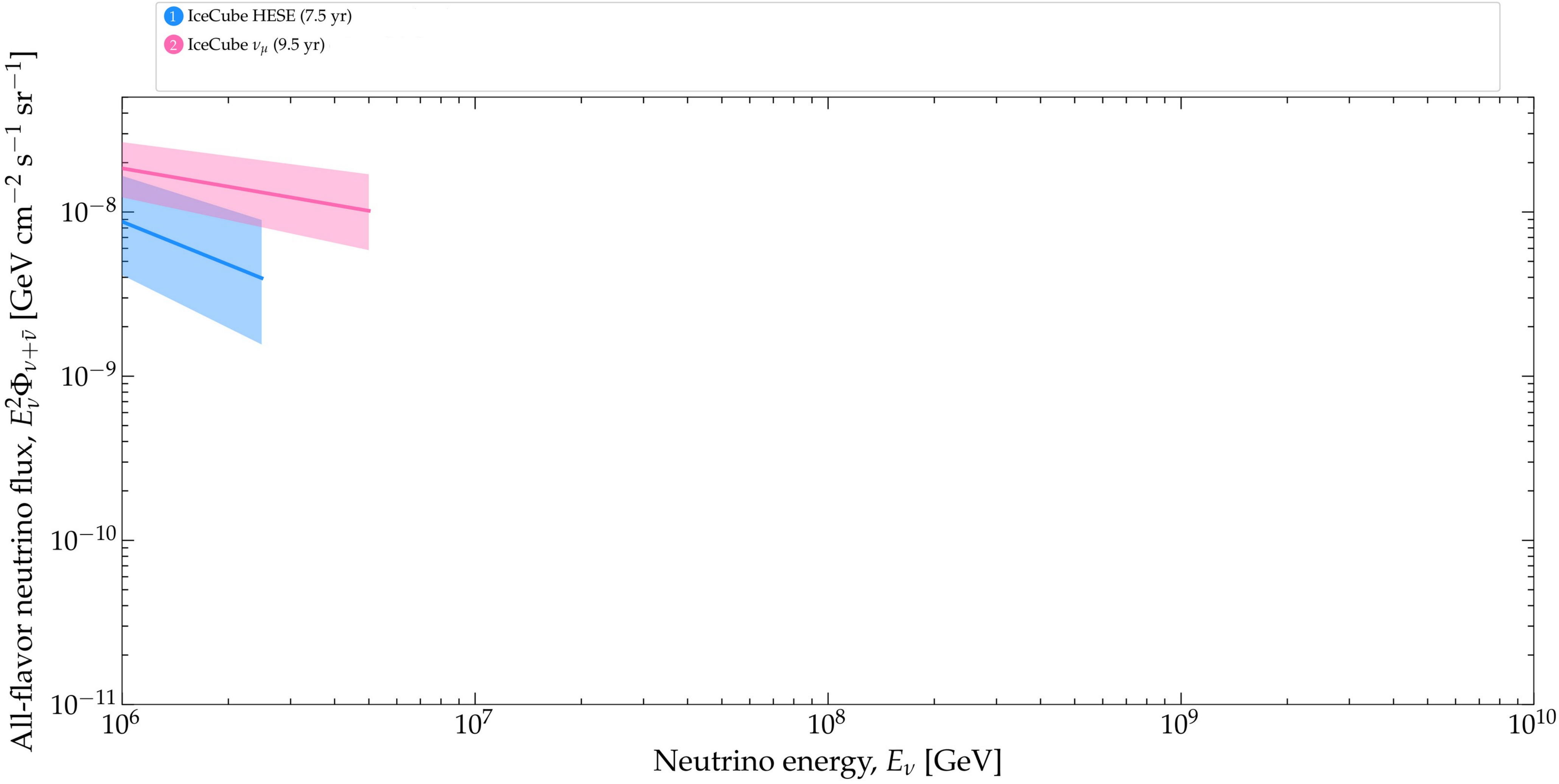
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ


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

Note: Not an exhaustive list

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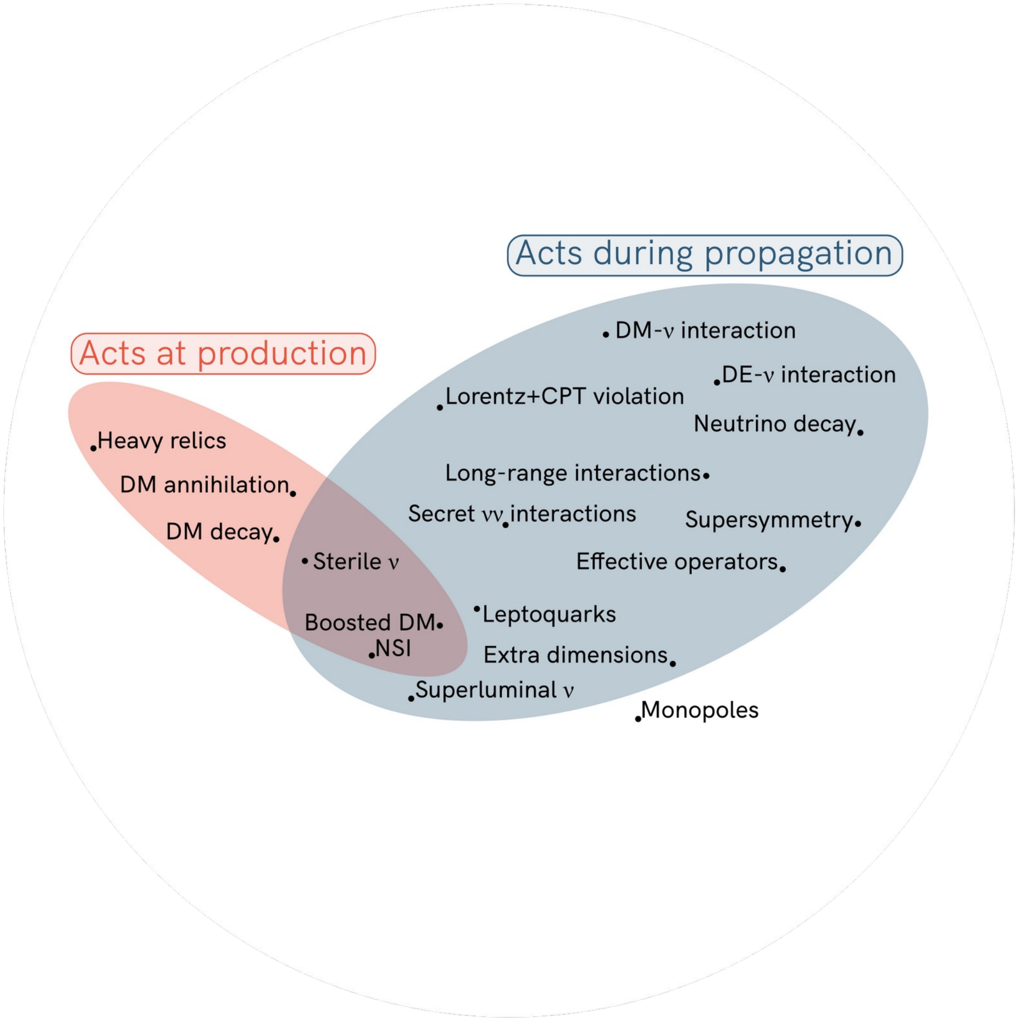

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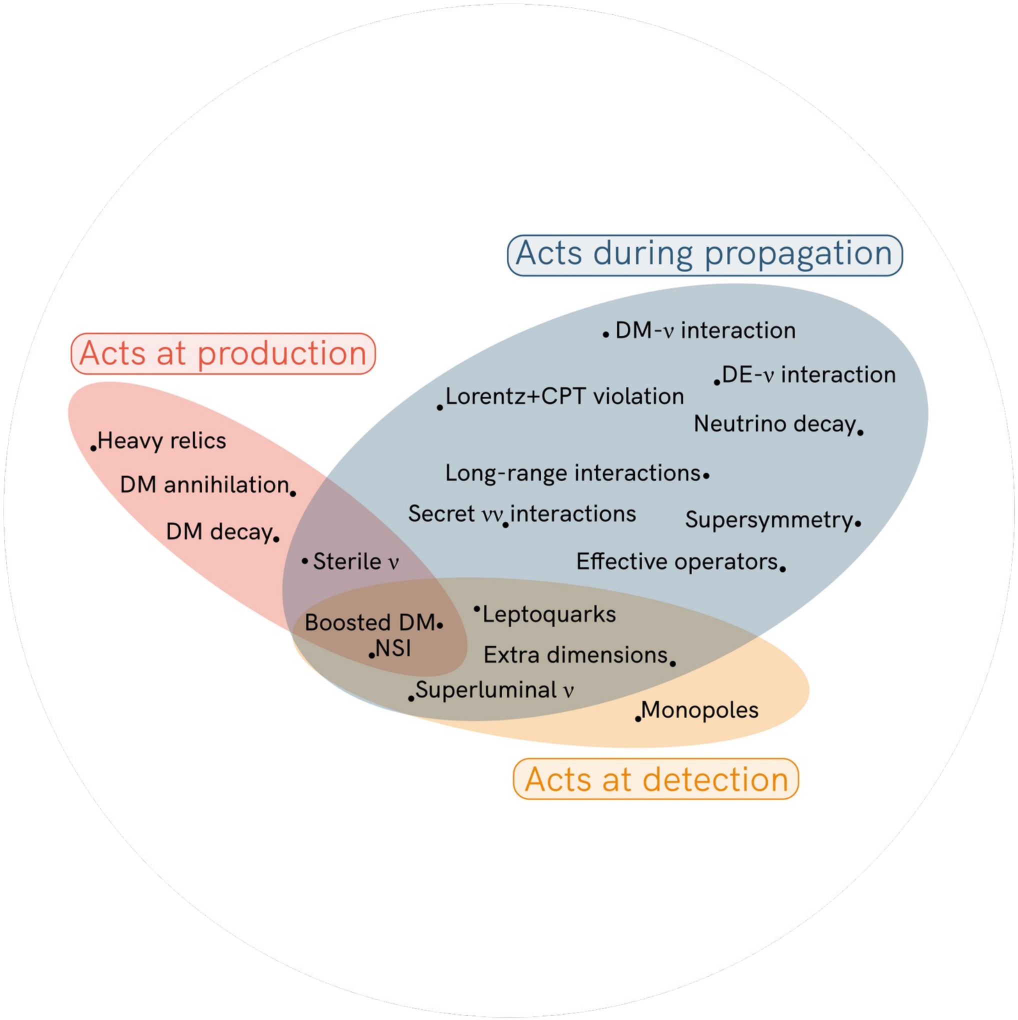

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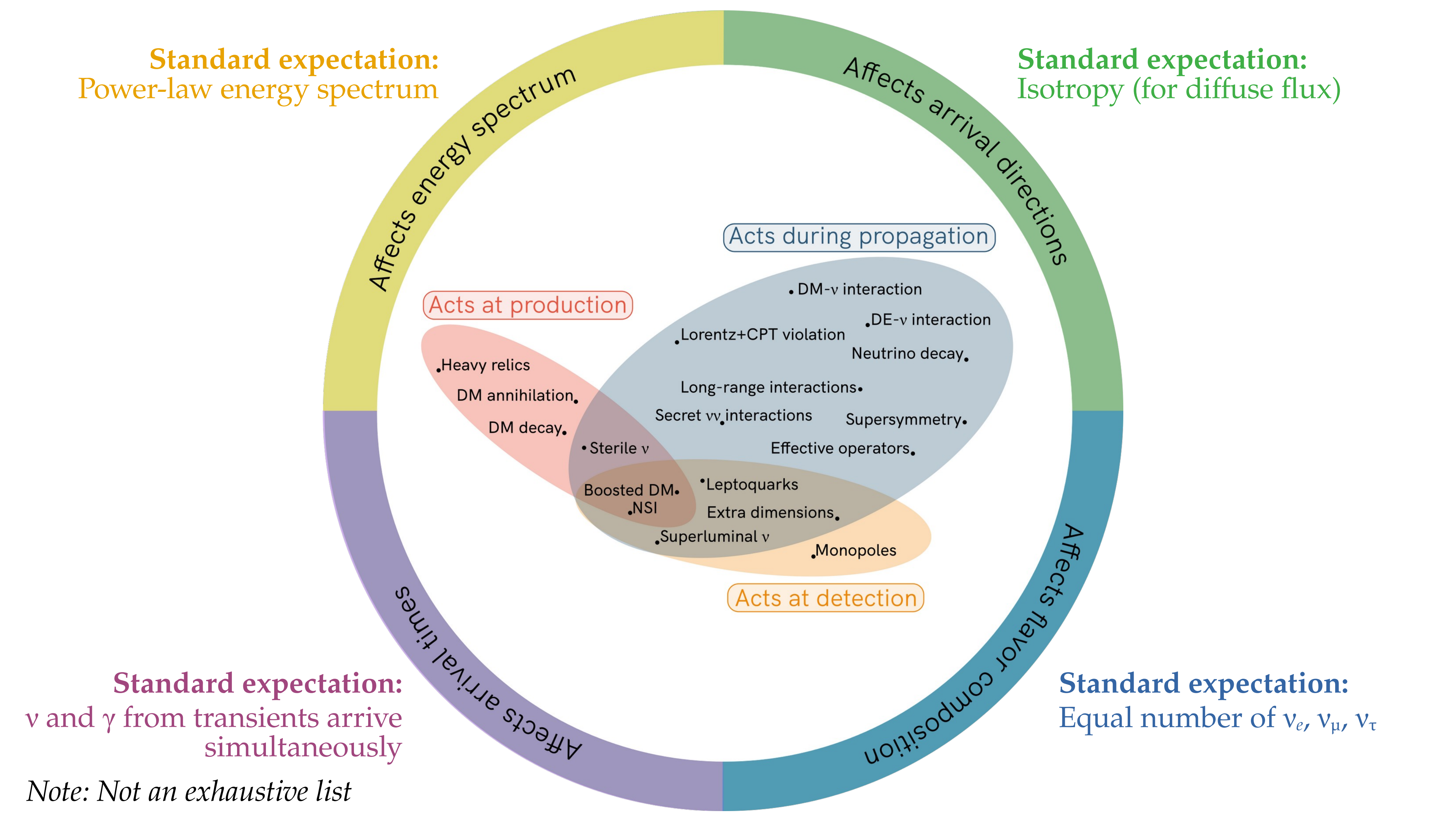
Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT 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
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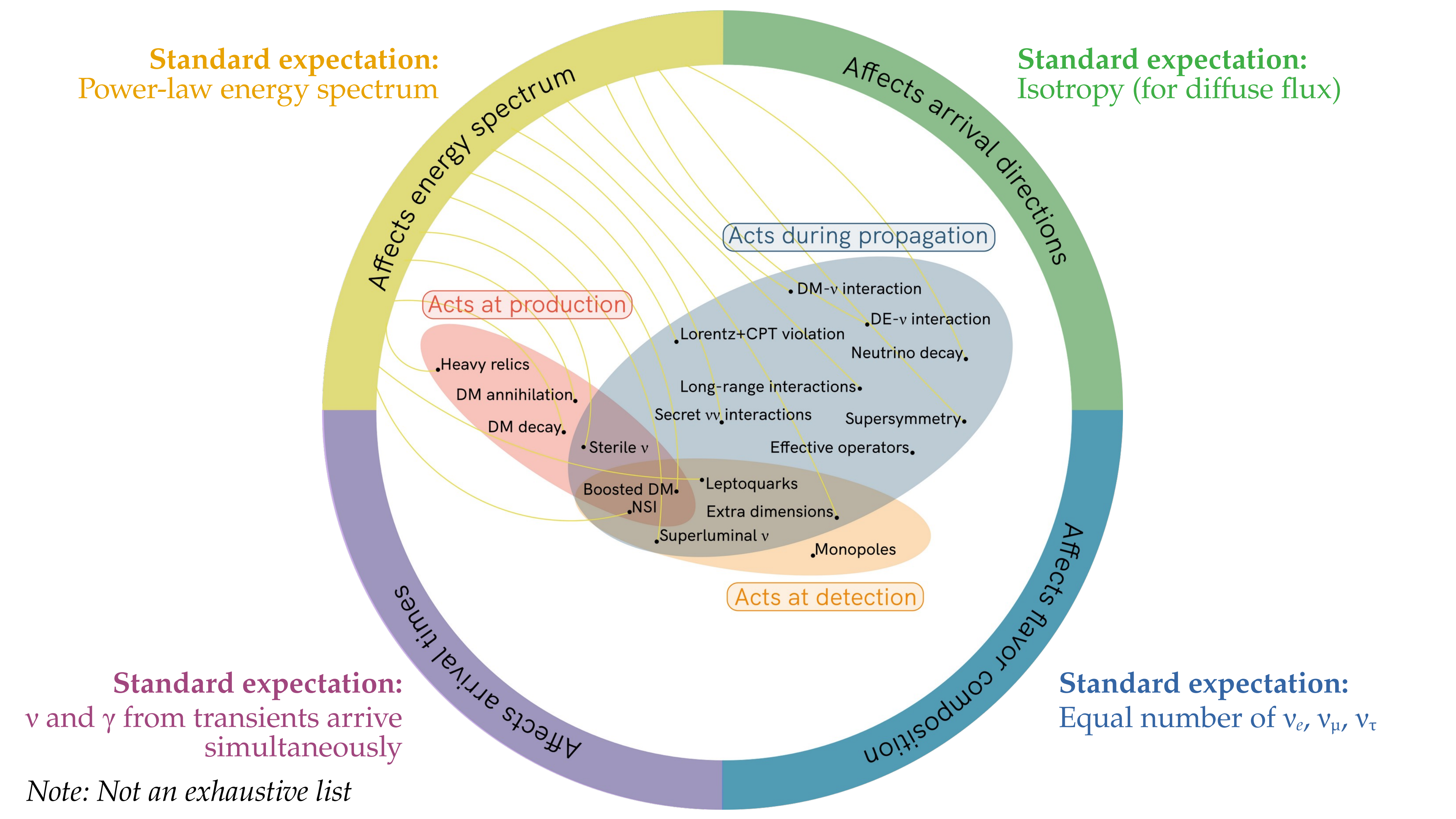

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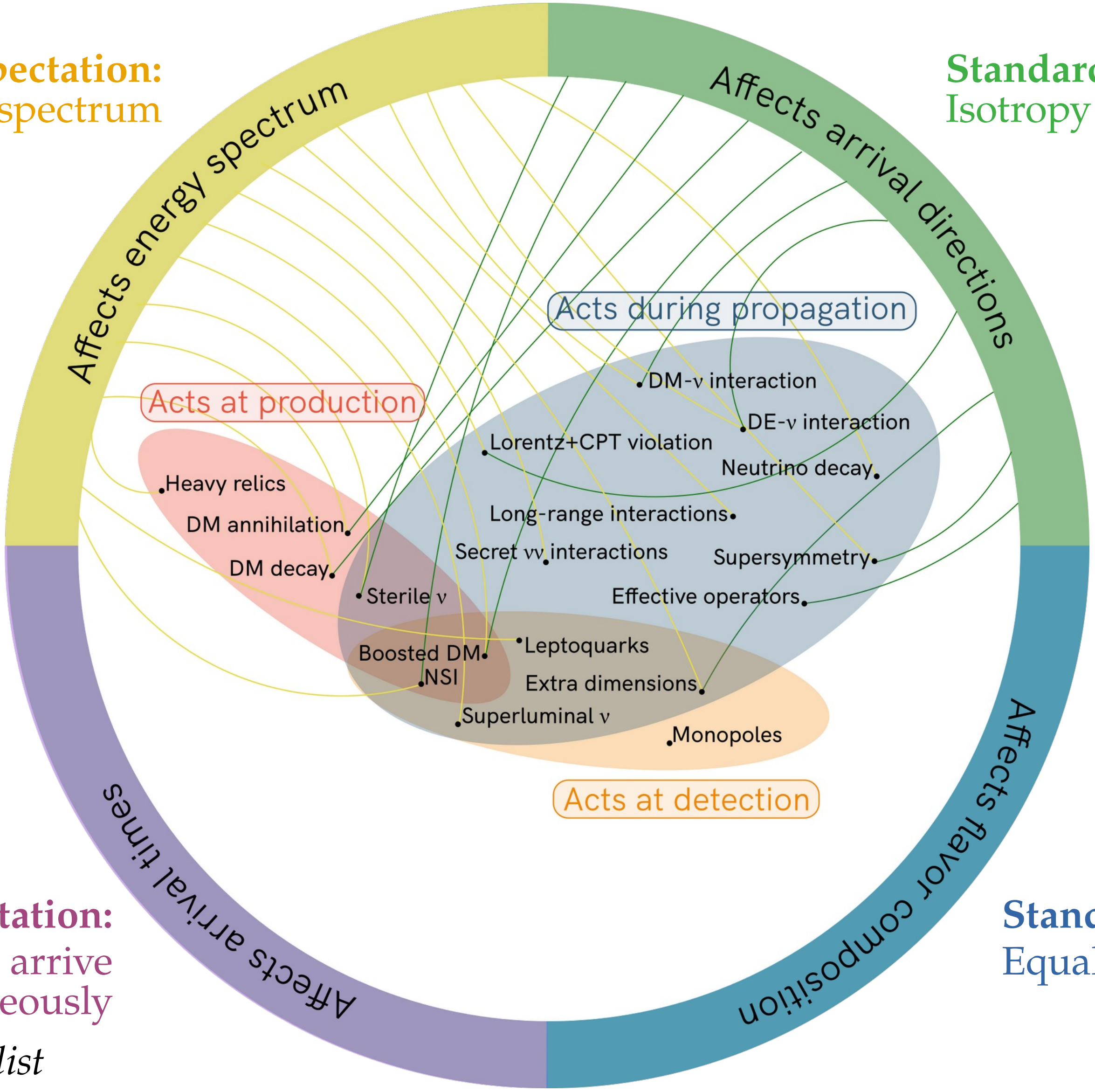

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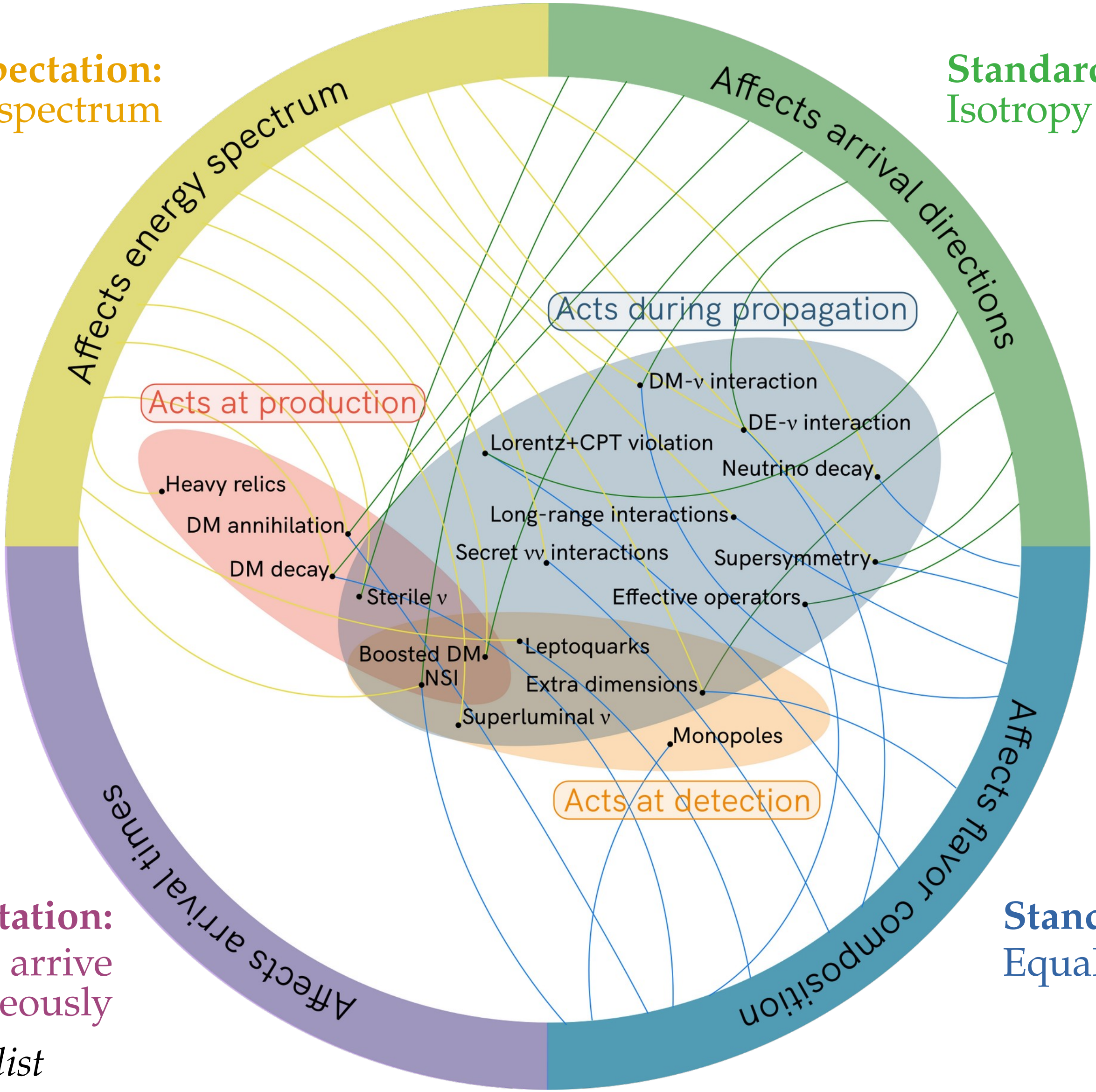

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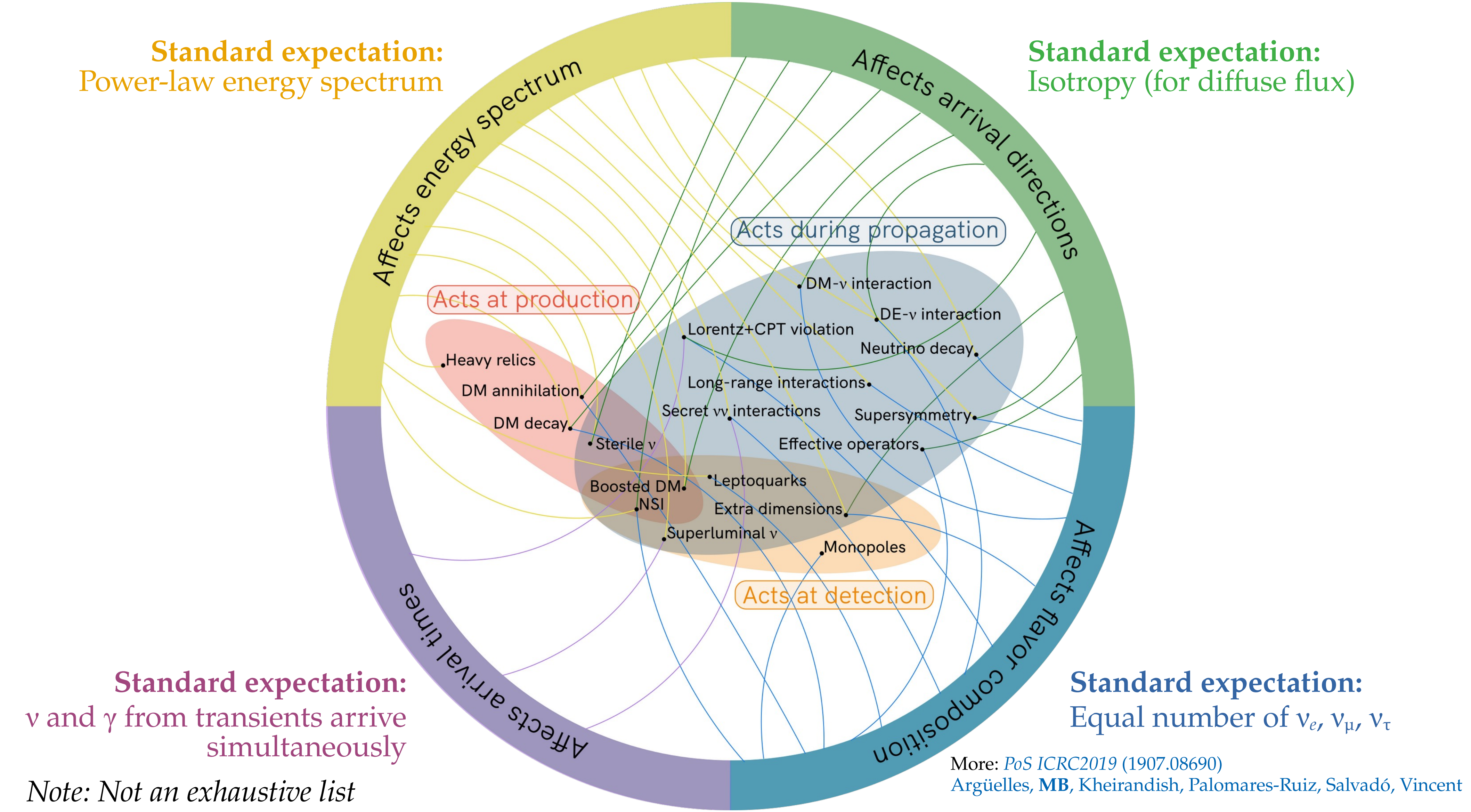

Note: Not an exhaustive list

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

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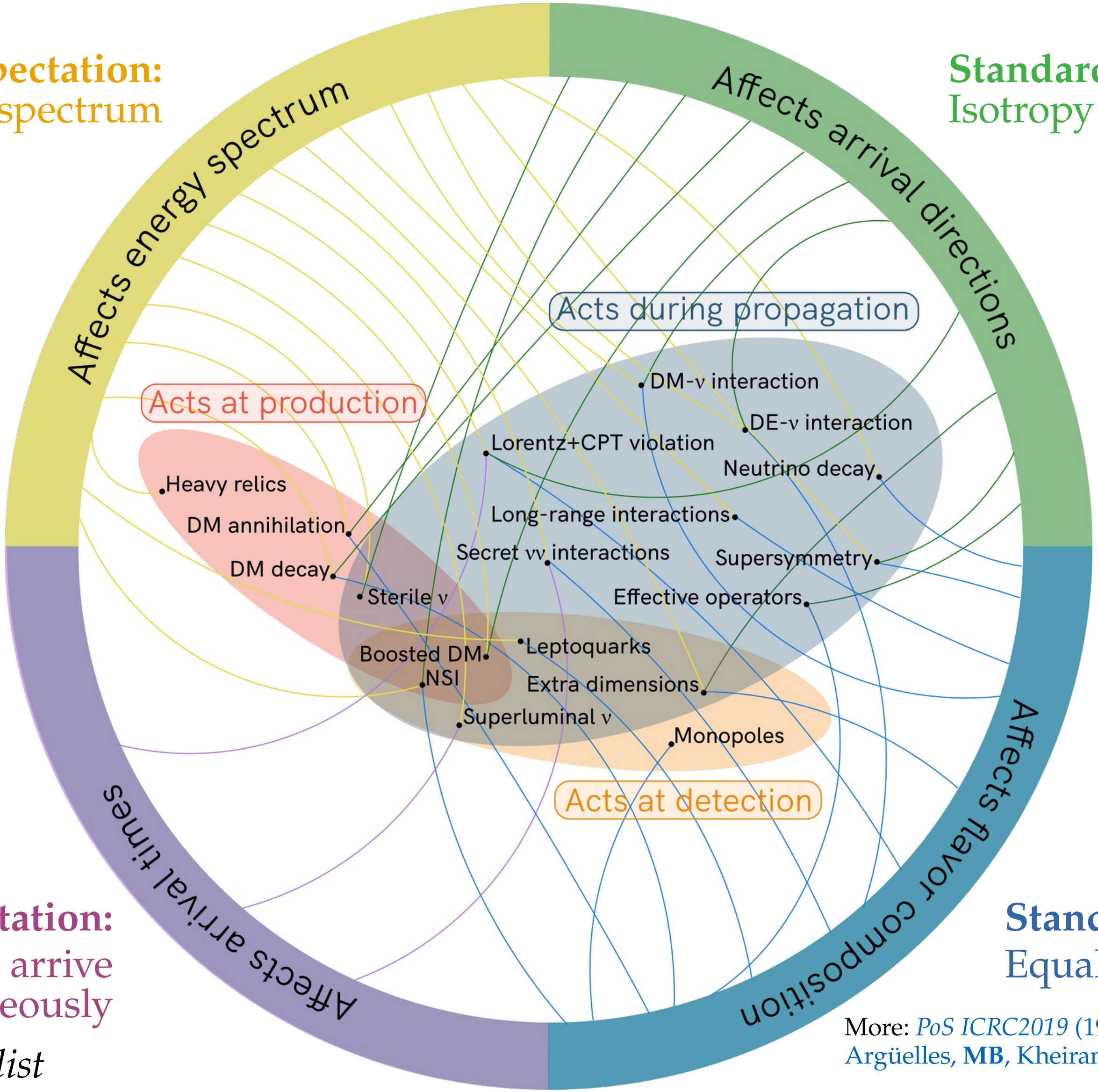

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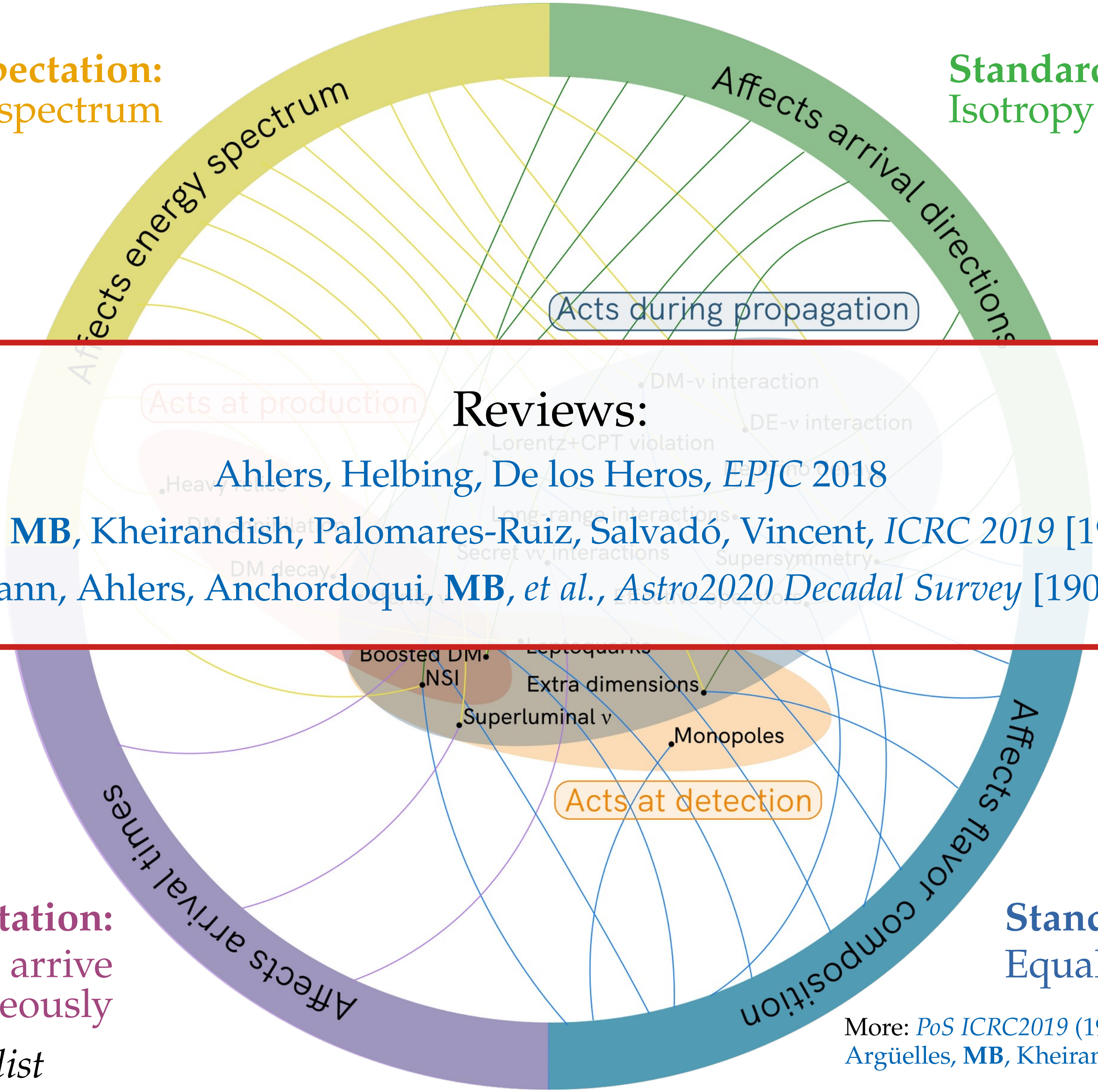

Reviews:

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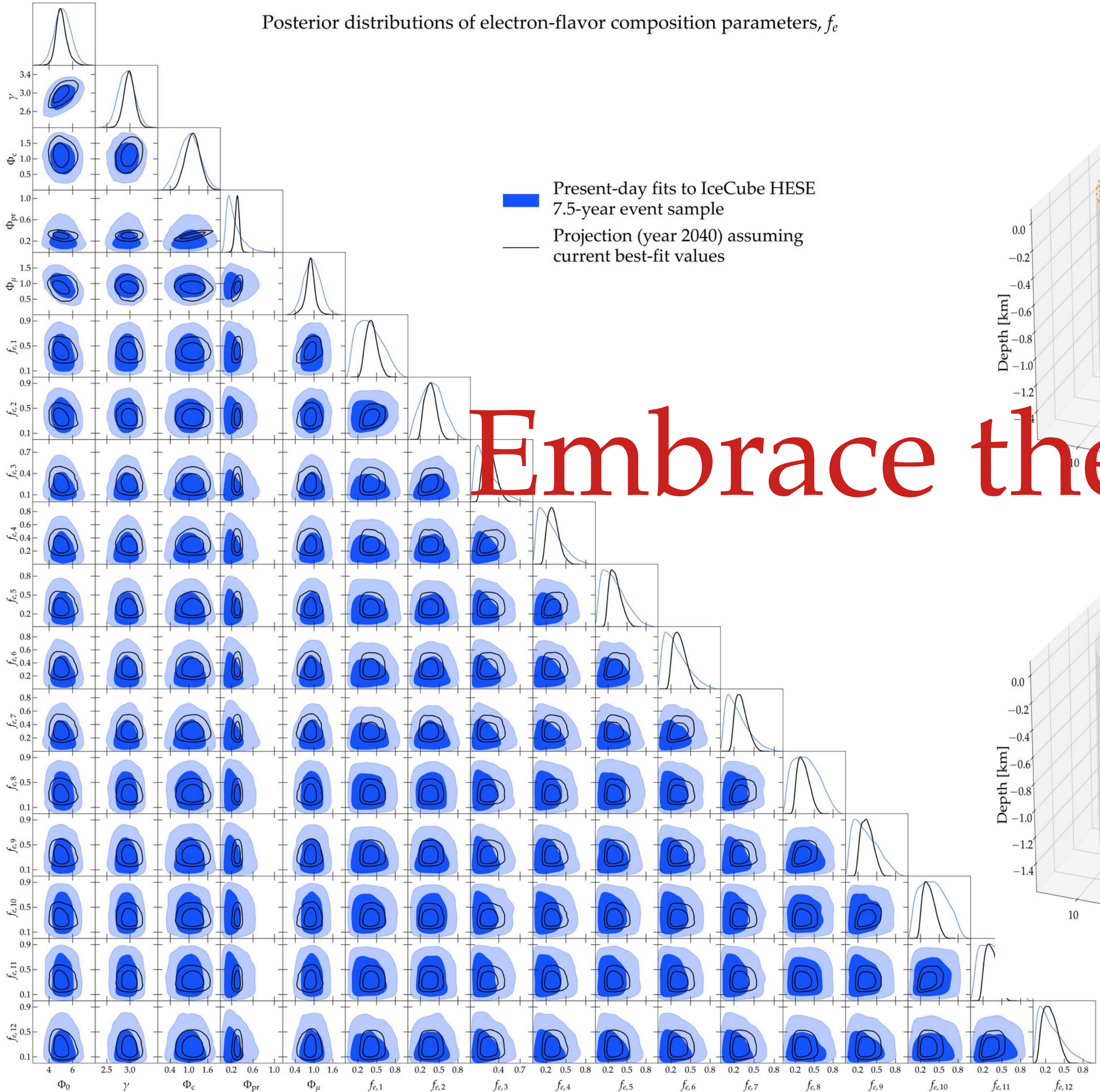
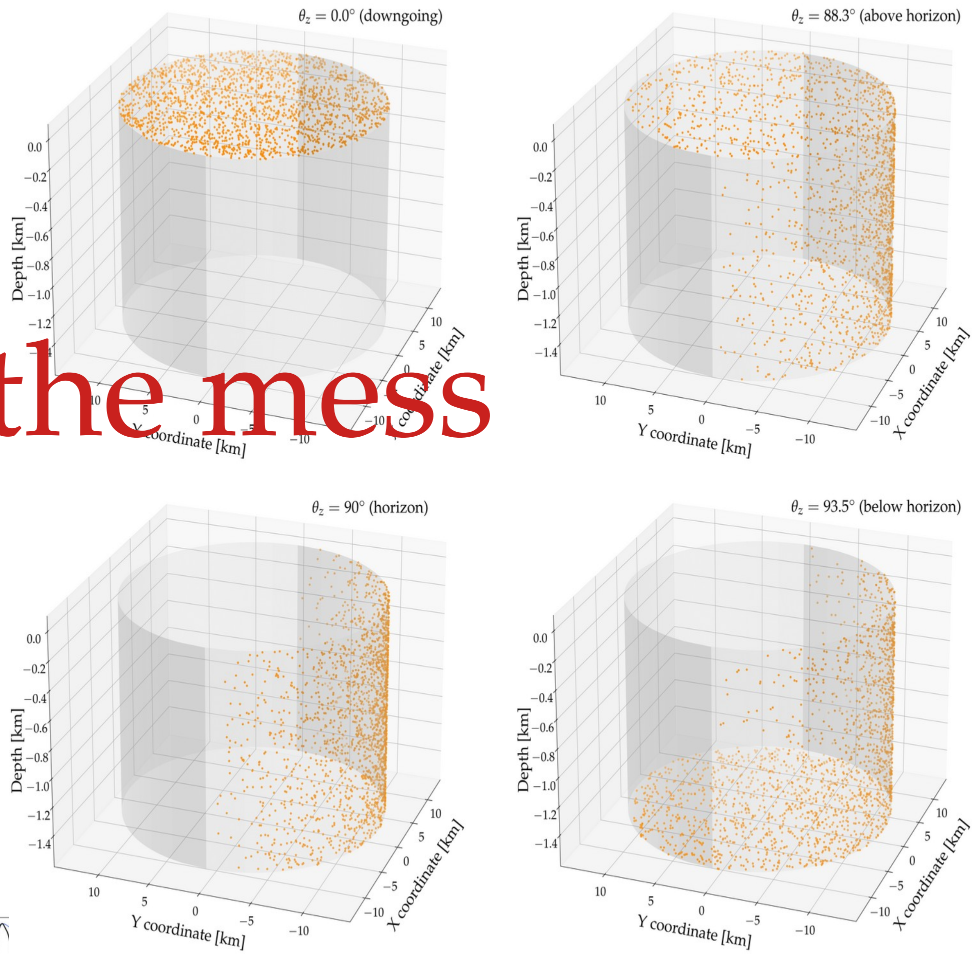
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

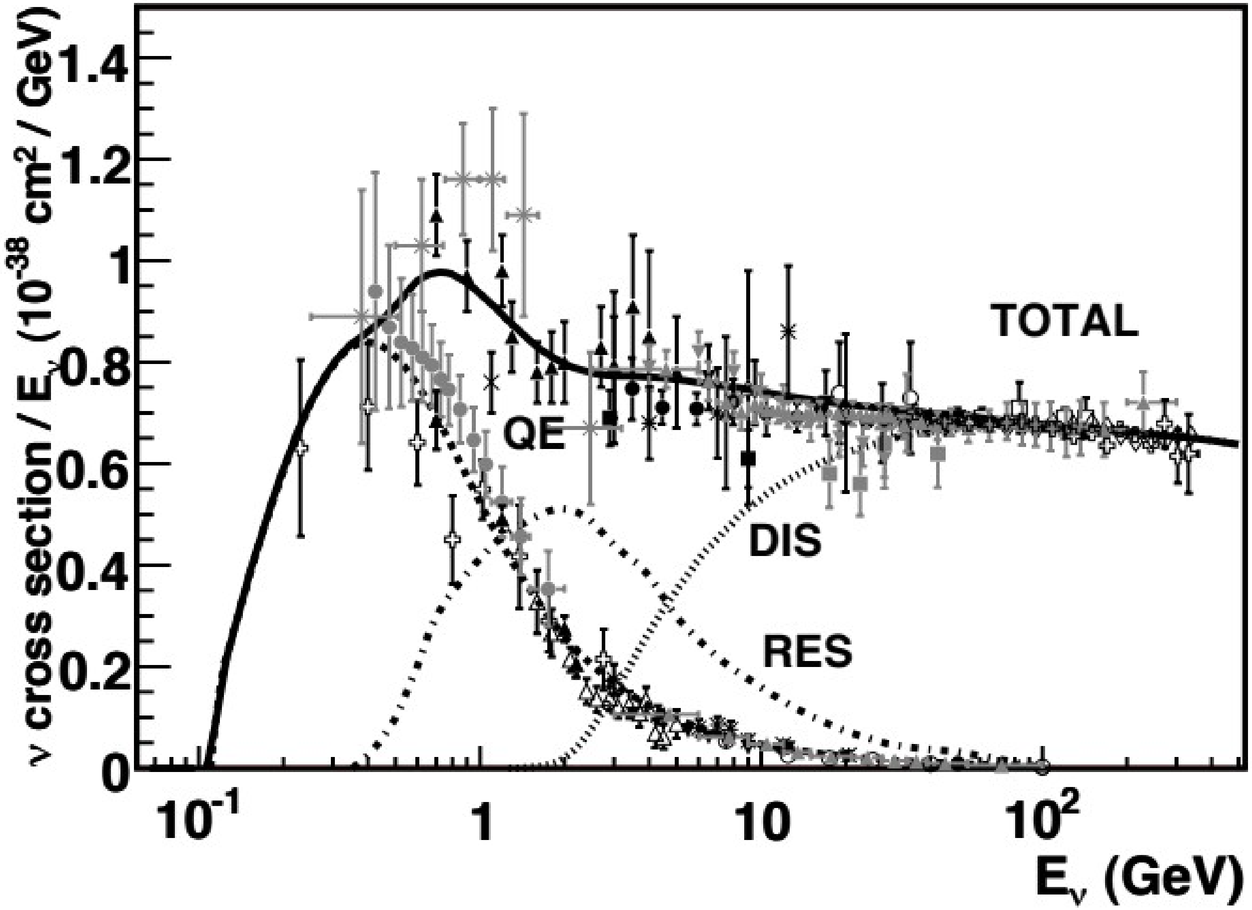
With high-energy cosmic neutrinos, fundamental physics and astrophysics are inseparable

Embrace the mess



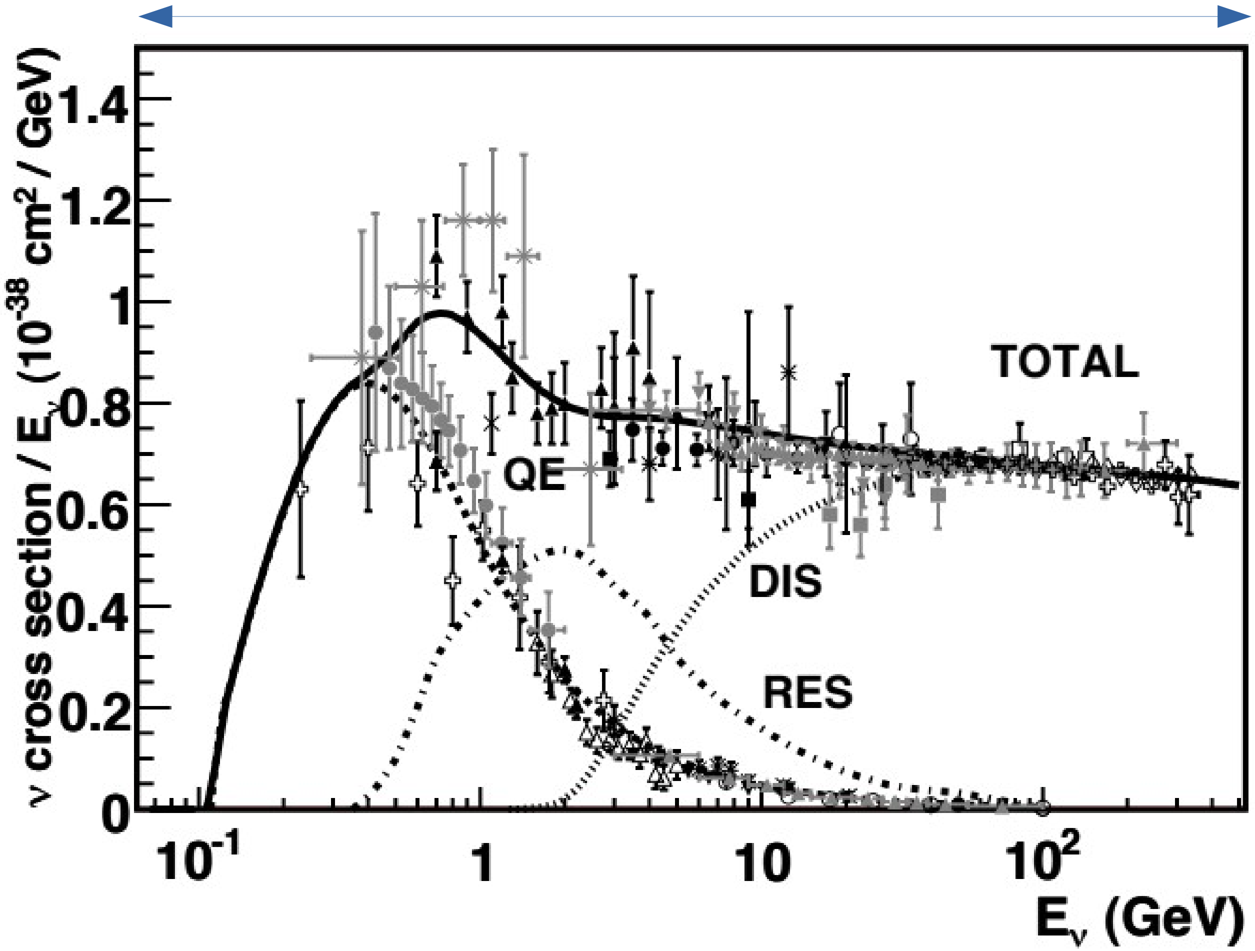


Measuring the TeV–PeV neutrino-nucleon cross section



Particle Data Group

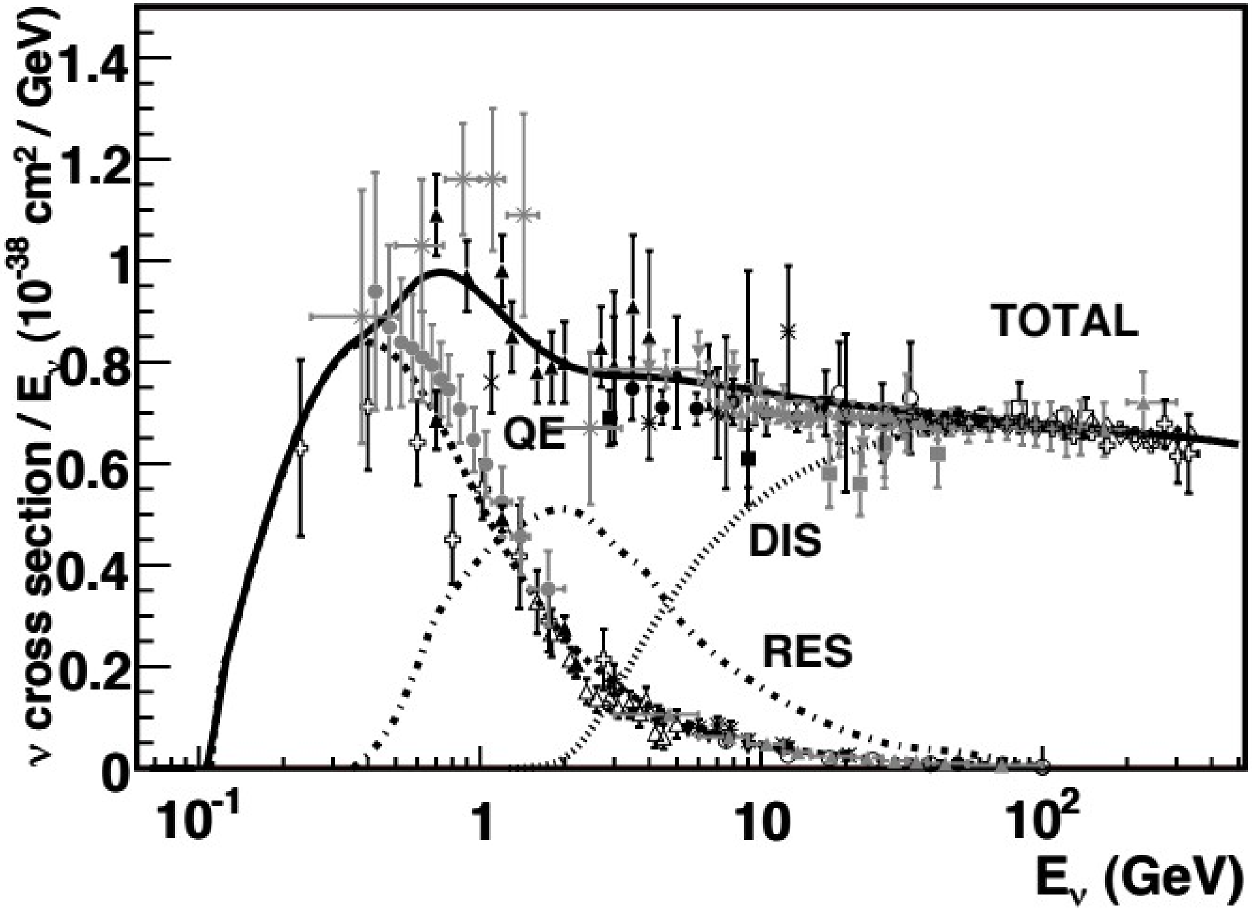
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



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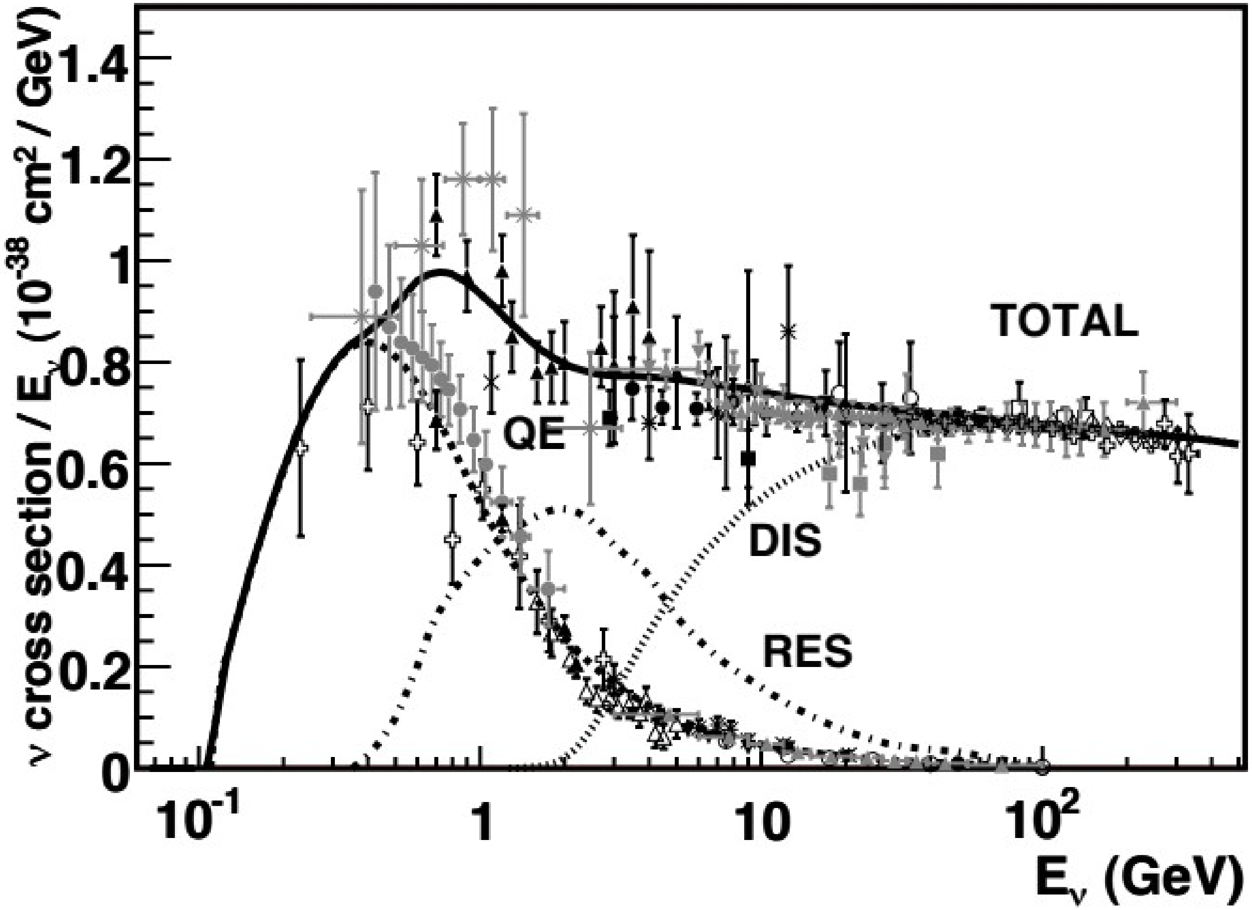
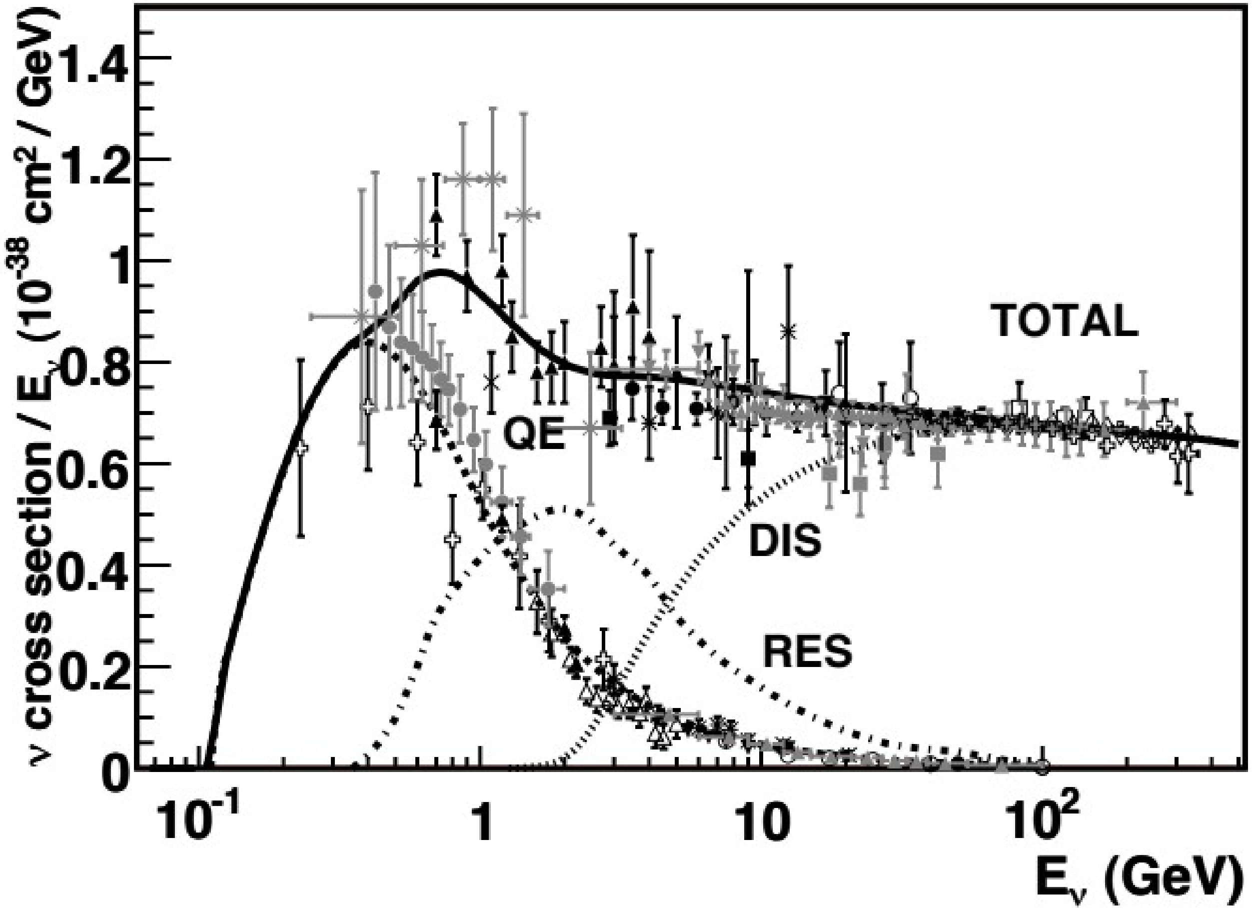


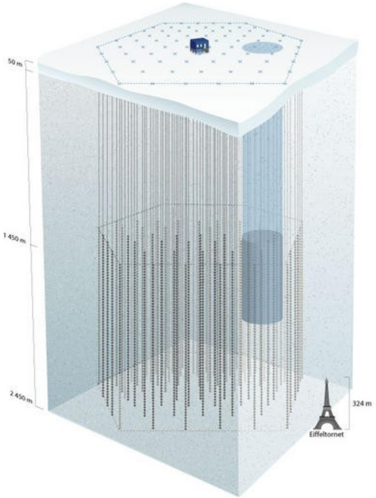
Particle Data Group

No measurements … until recently!

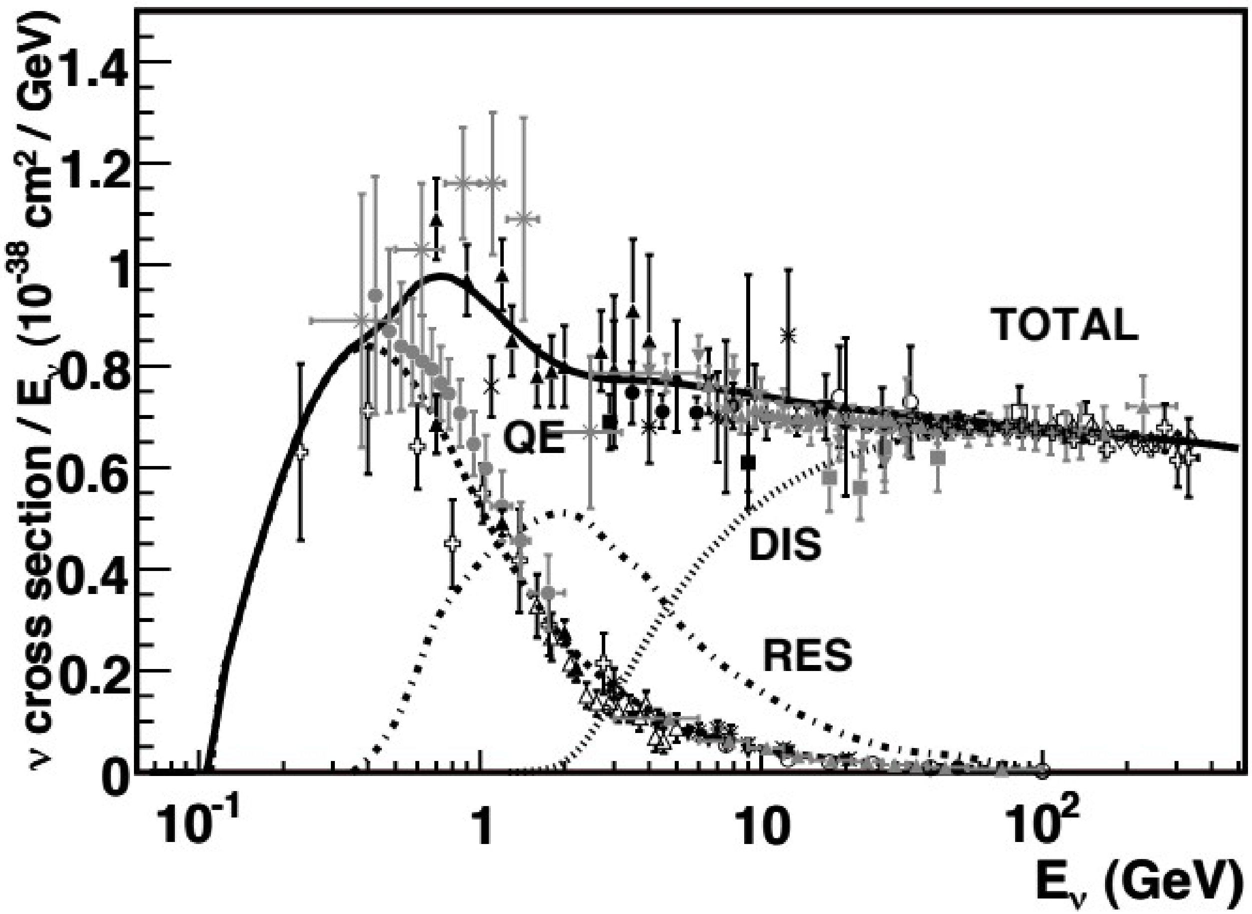
Accelerator experiments

One recent measurement (COHERENT)





Particle Data Group

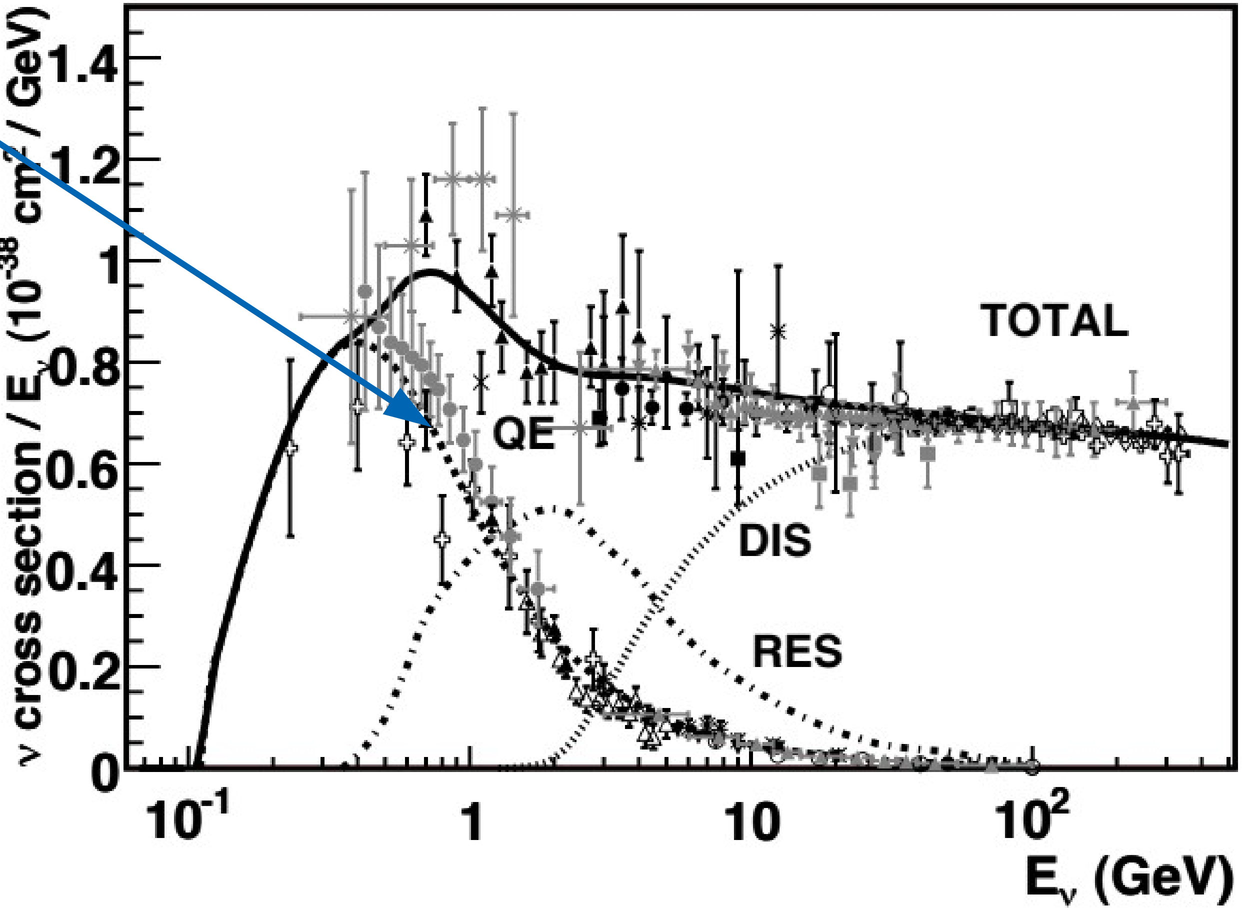


Particle Data Group

Quasi-elastic scattering:

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

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



Particle Data Group

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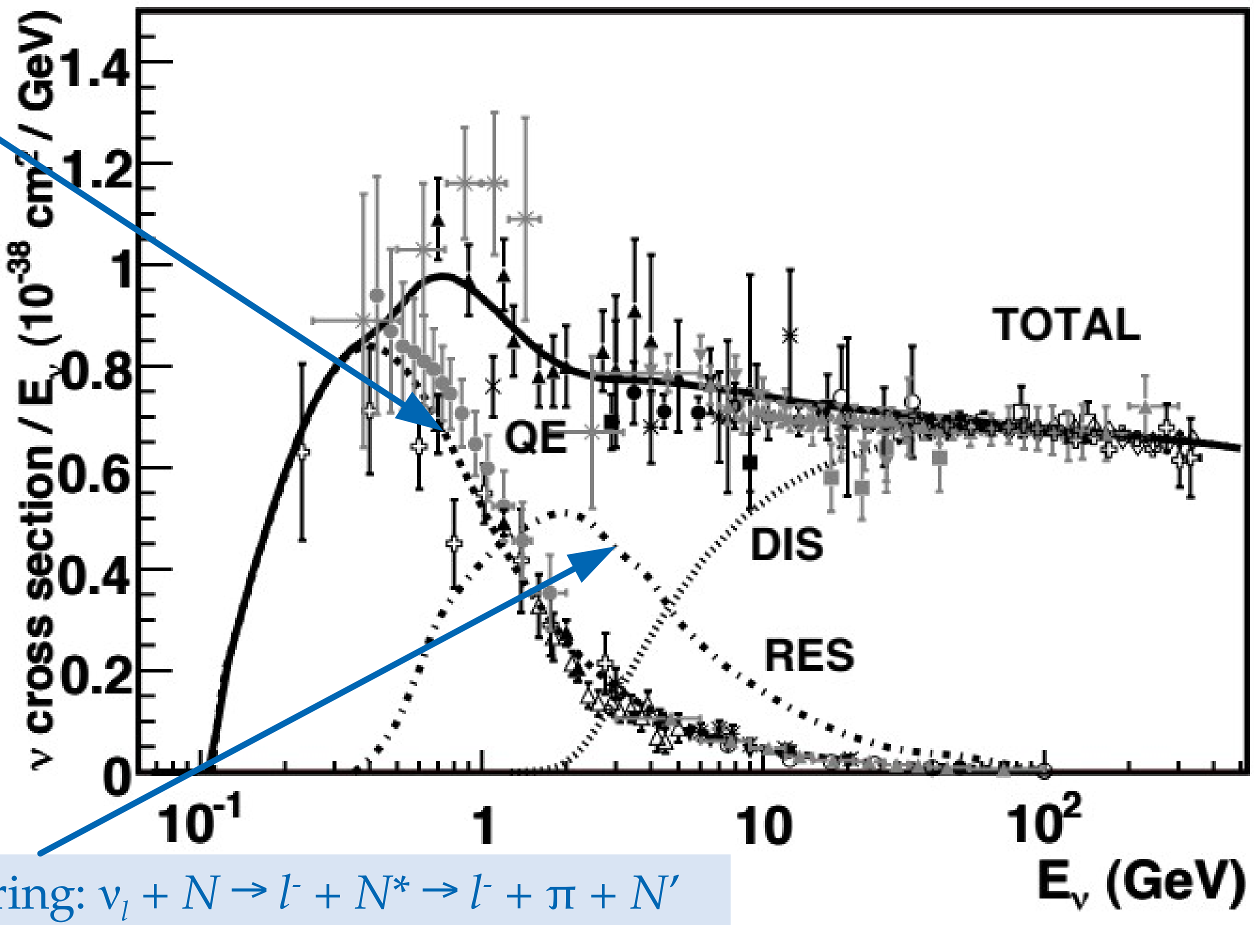
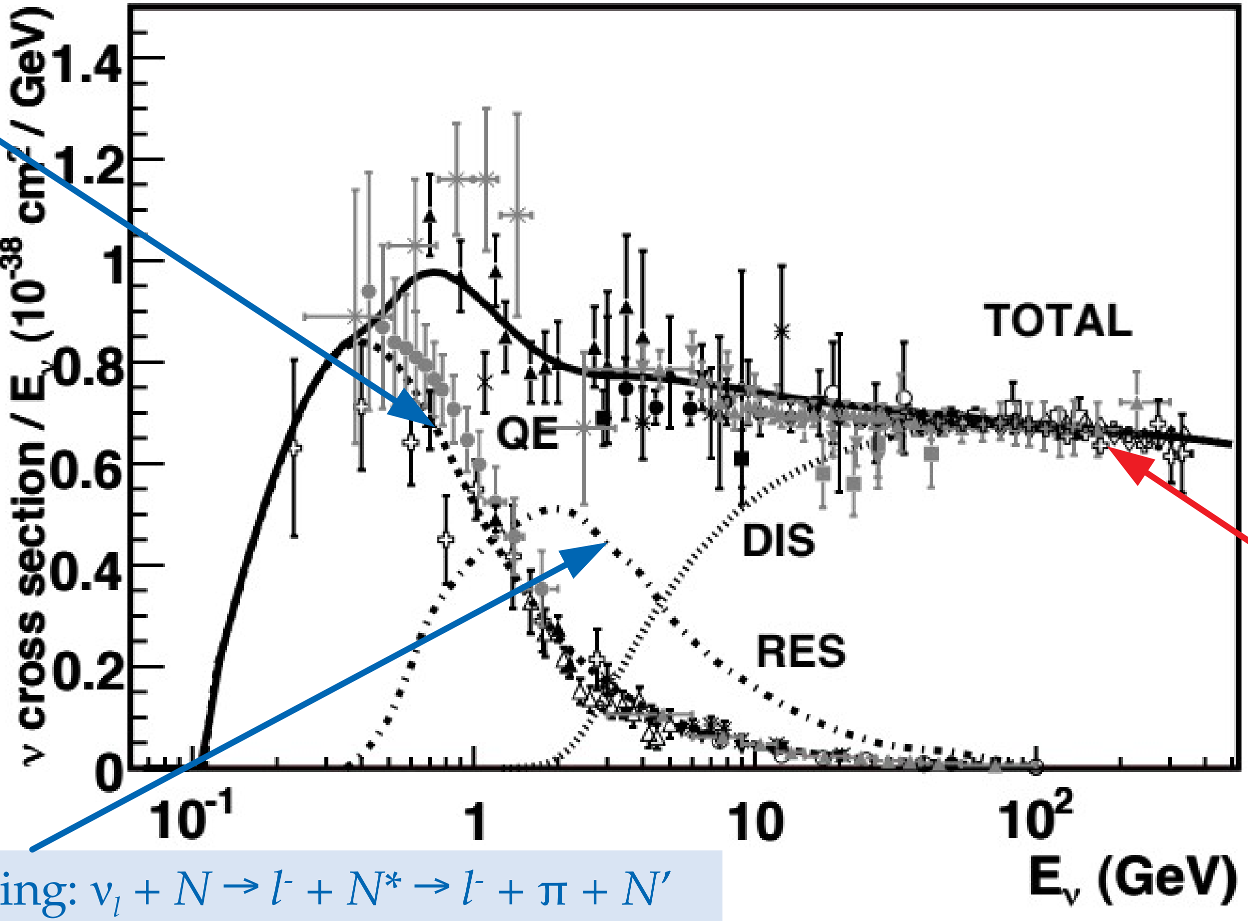


Particle Data Group

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

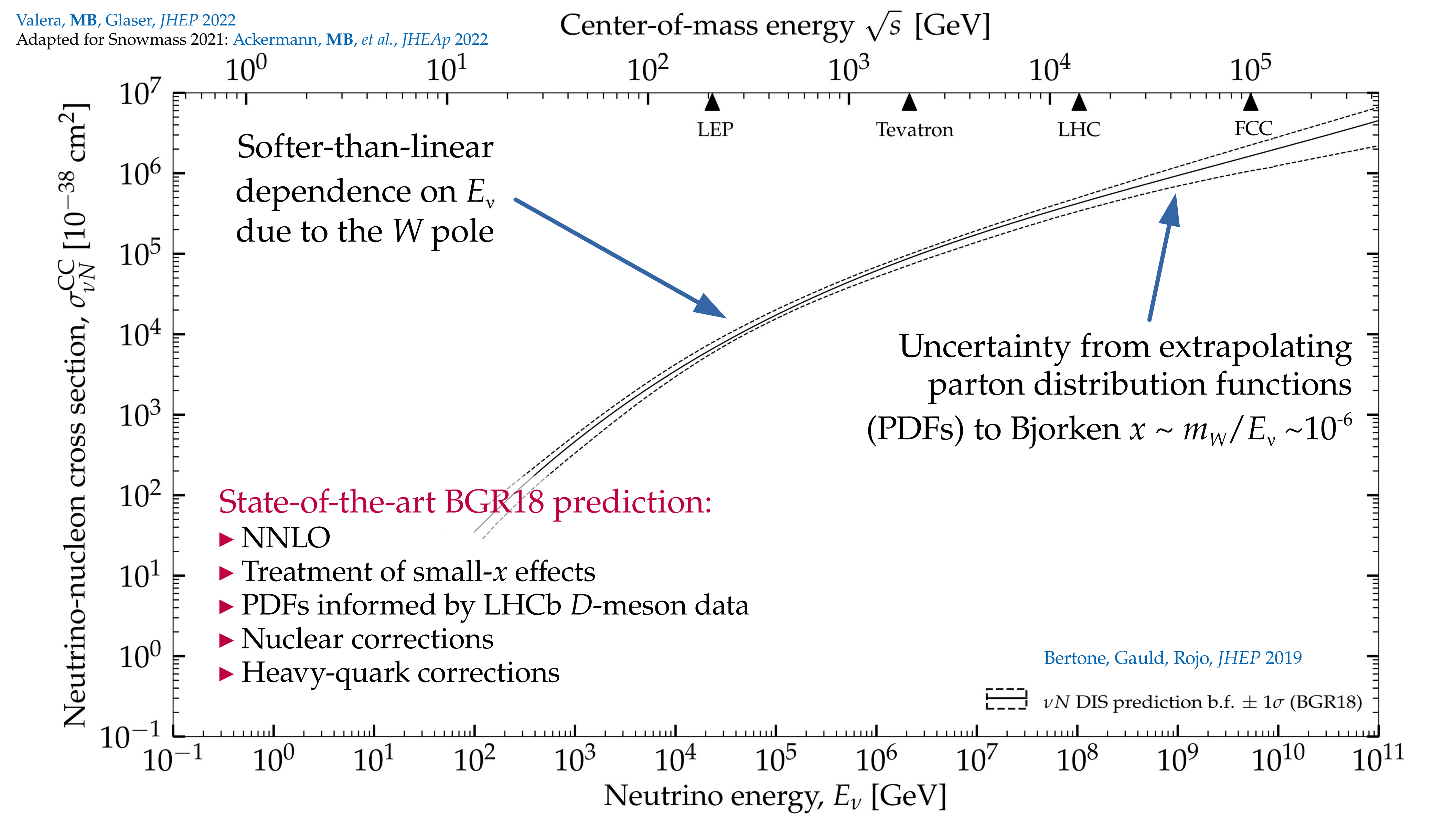
Quasi-elastic scattering:
$\nu_l + n \rightarrow l^- + p$
$\bar{\nu}_l + p \rightarrow l^+ + n$

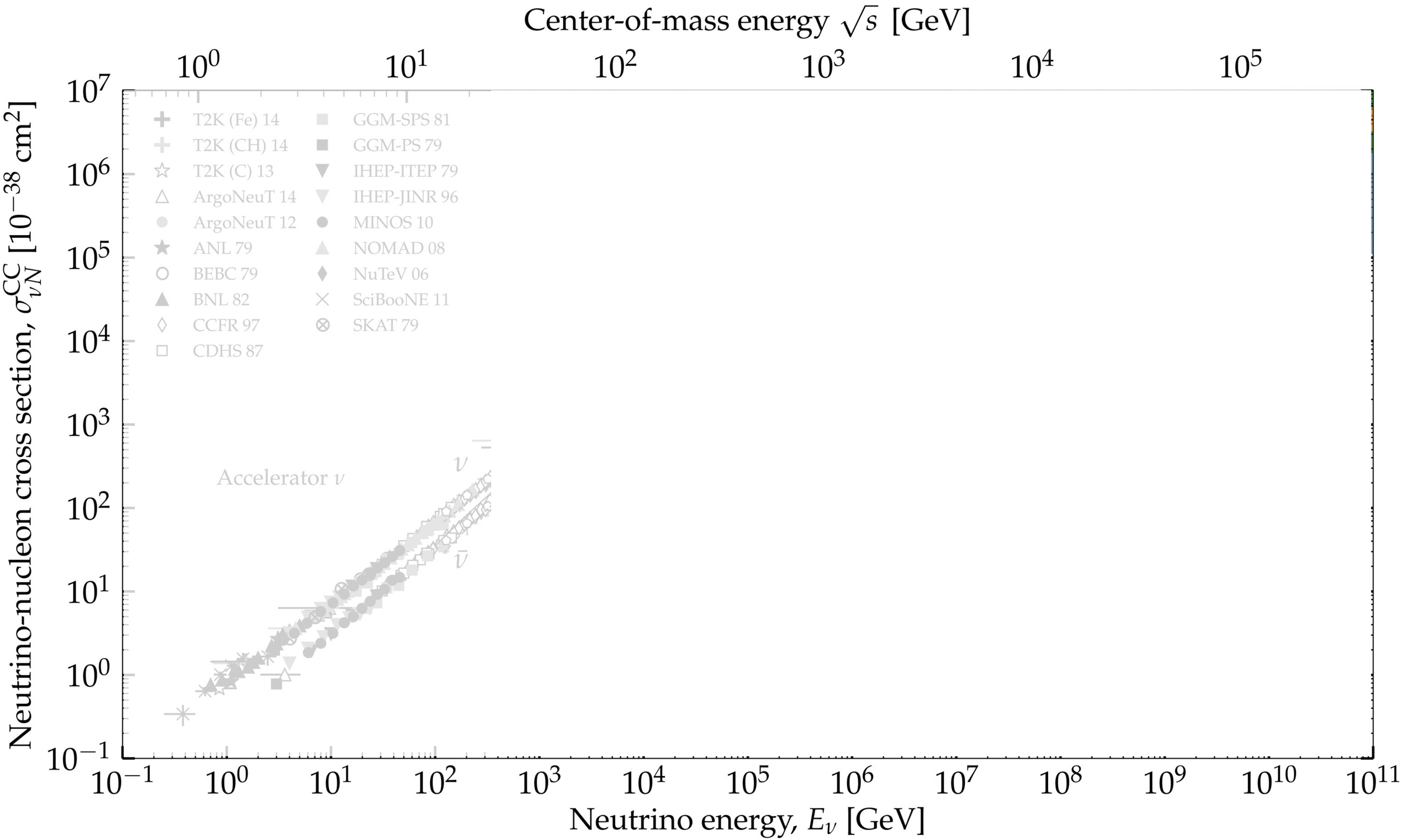


Deep inelastic scattering:
$\nu_l + N \rightarrow l^- + X$
$\bar{\nu}_l + N \rightarrow l^+ + X$

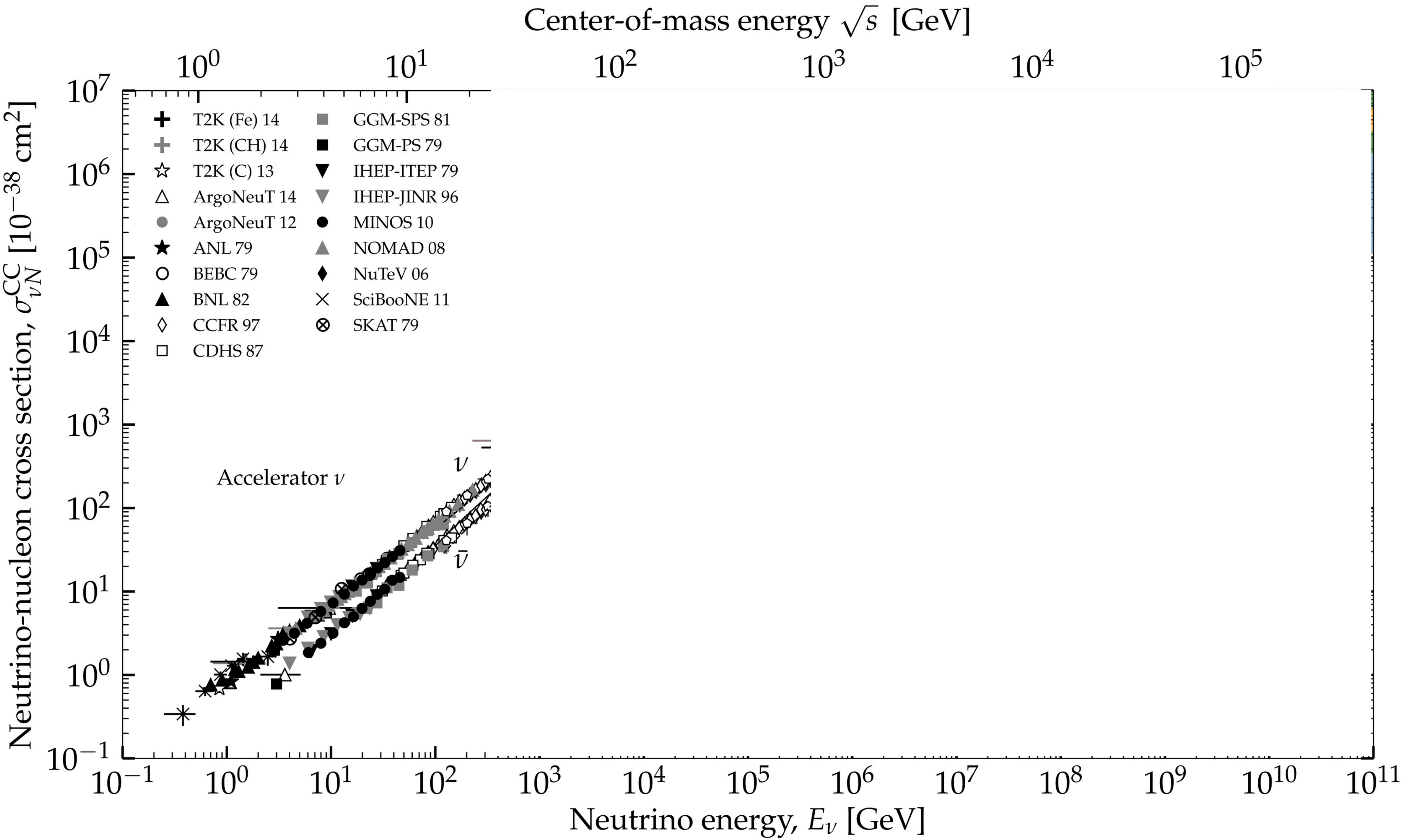
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group


Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
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
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]



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



Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma^{\mathrm{CC}}_{\nu N}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
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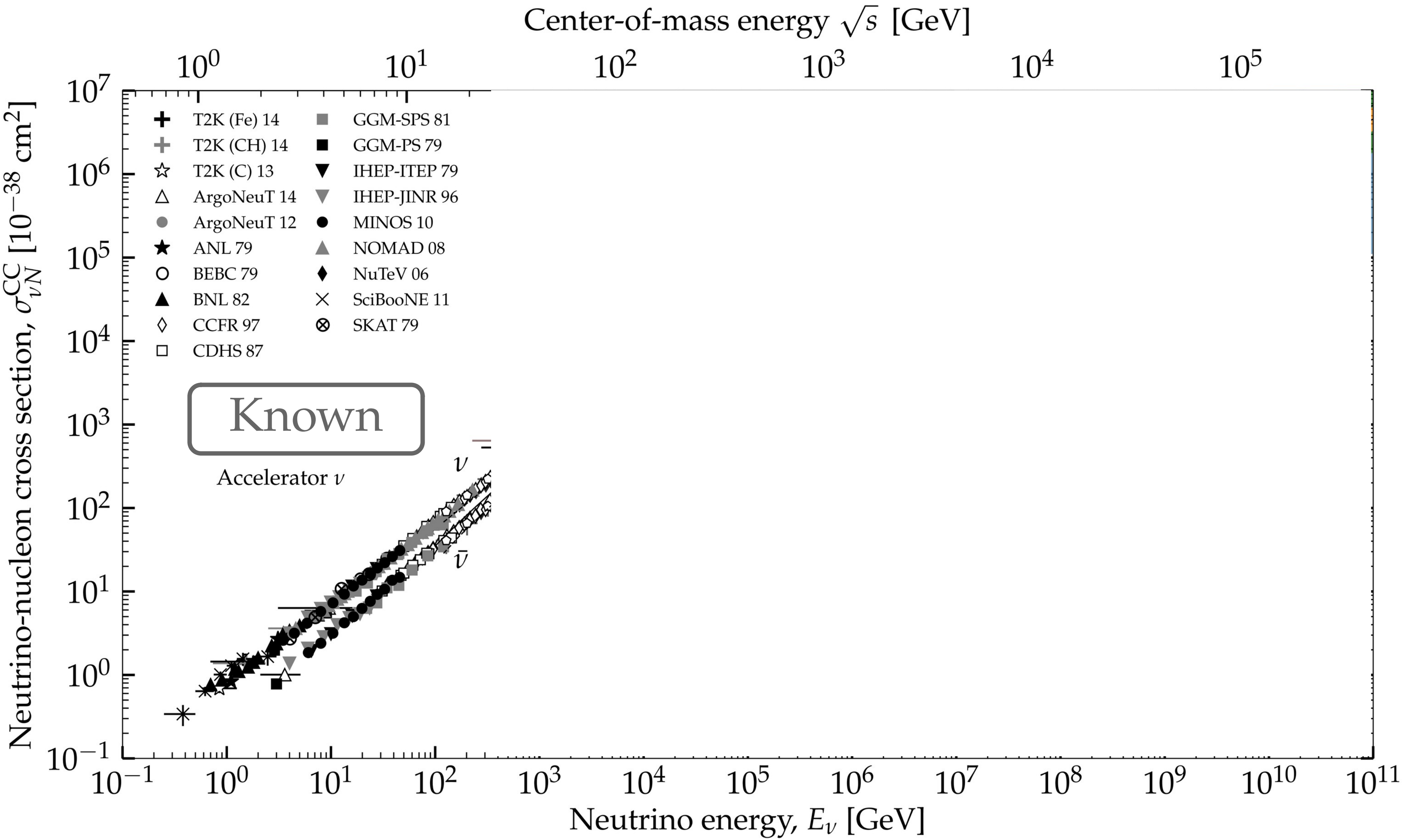

Center-of-mass energy $\sqrt{s}$ [GeV]
10^0 10^1 10^2 10^3 10^4 10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{\mathrm{CC}}$ [10^{-38} cm^2]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
T2K (Fe) 14
T2K (CH) 14
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ArgoNeuT 14
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MINOS 10
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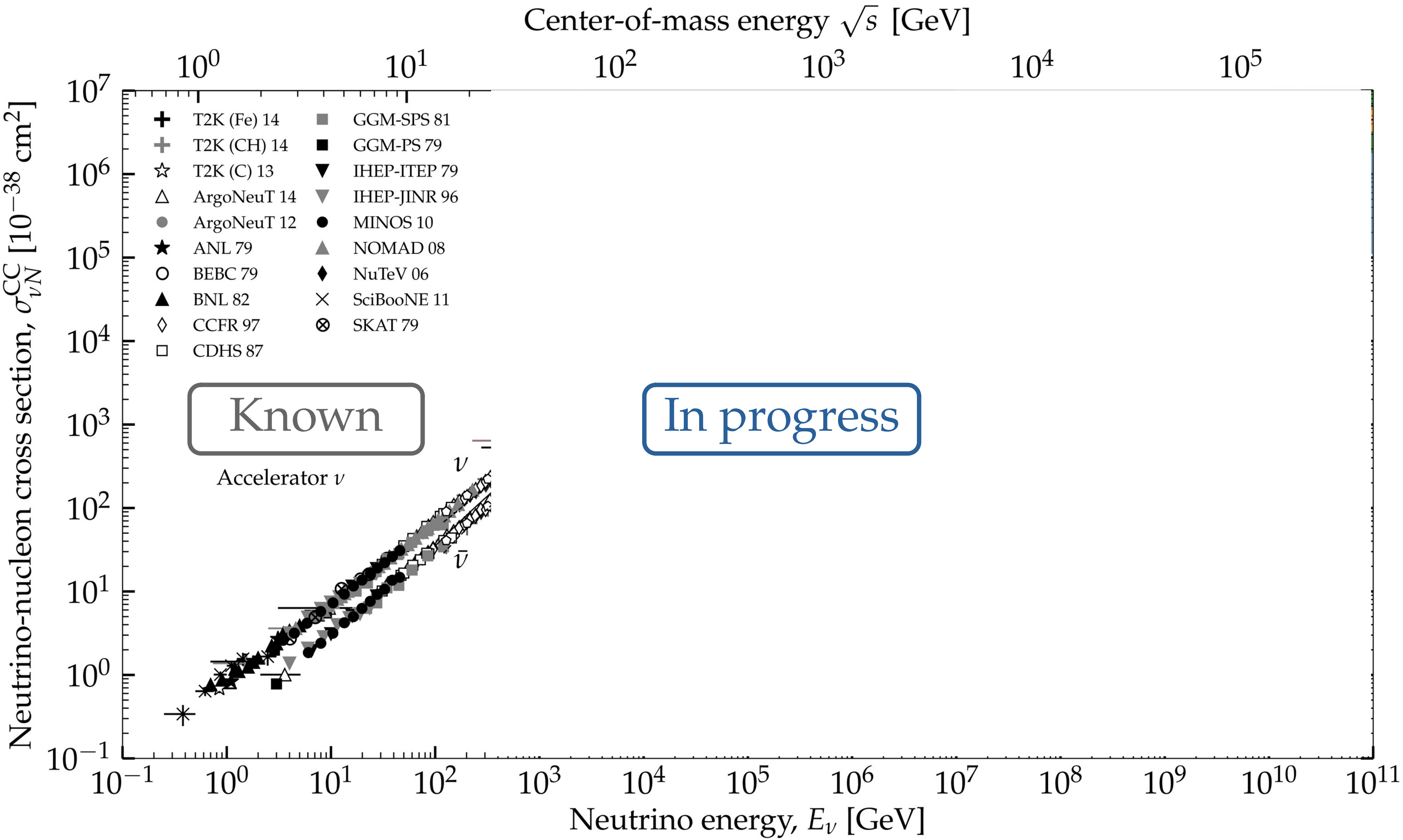
SciBooNE 11
SKAT 79
Known
Accelerator ν
ν
$\bar{\nu}$
Neutrino energy, E_ν [GeV]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}



Center-of-mass energy $\sqrt{s}$ [GeV]
10^0 10^1 10^2 10^3 10^4 10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
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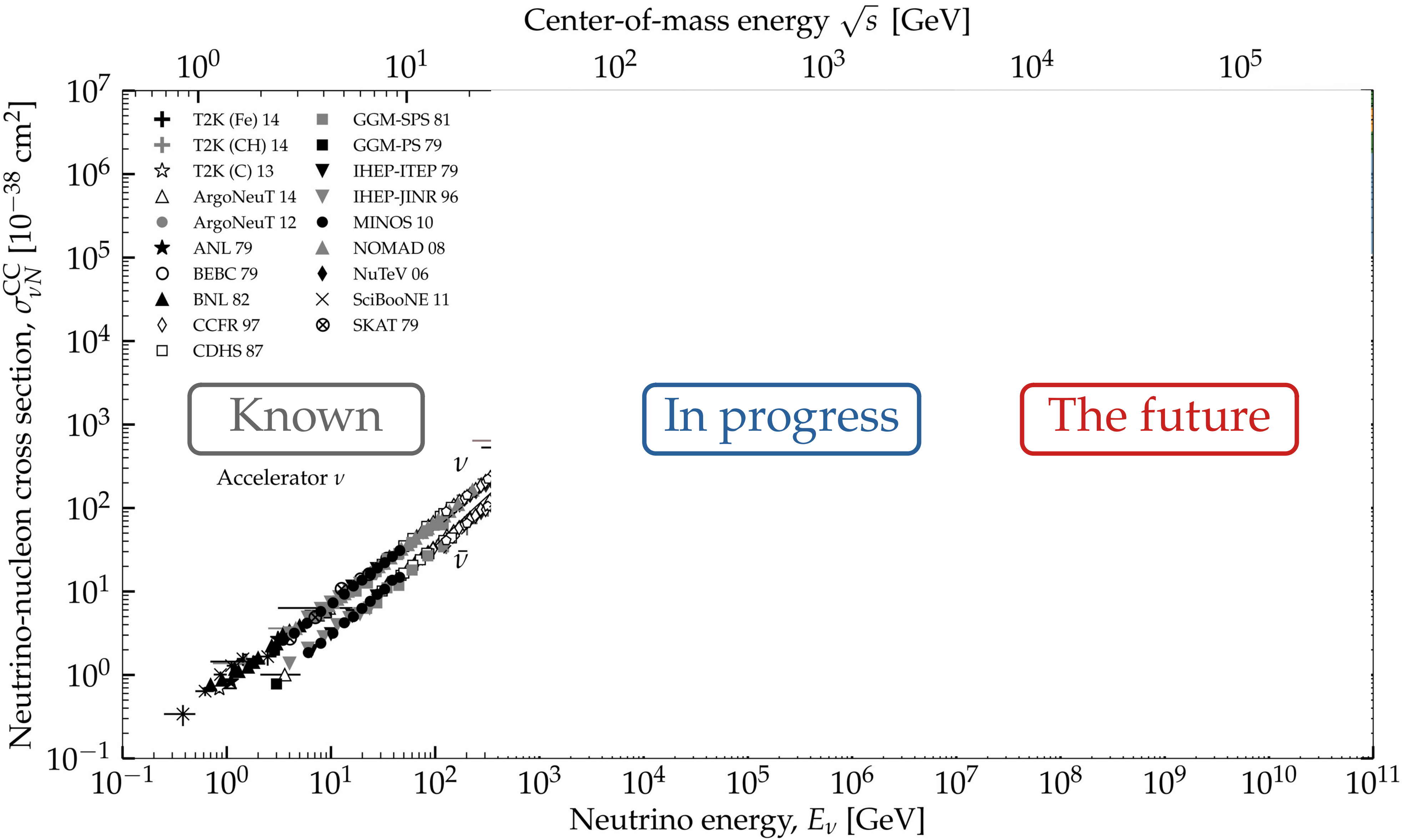
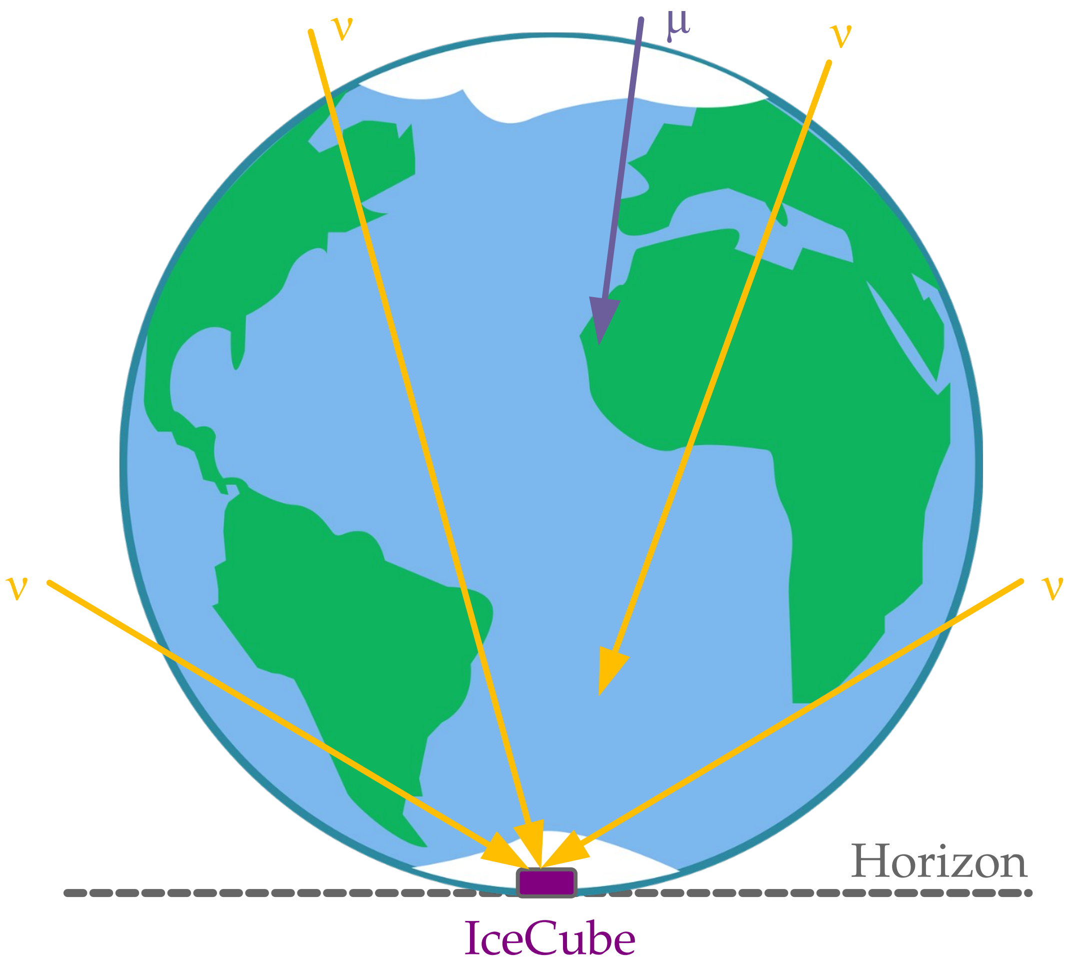
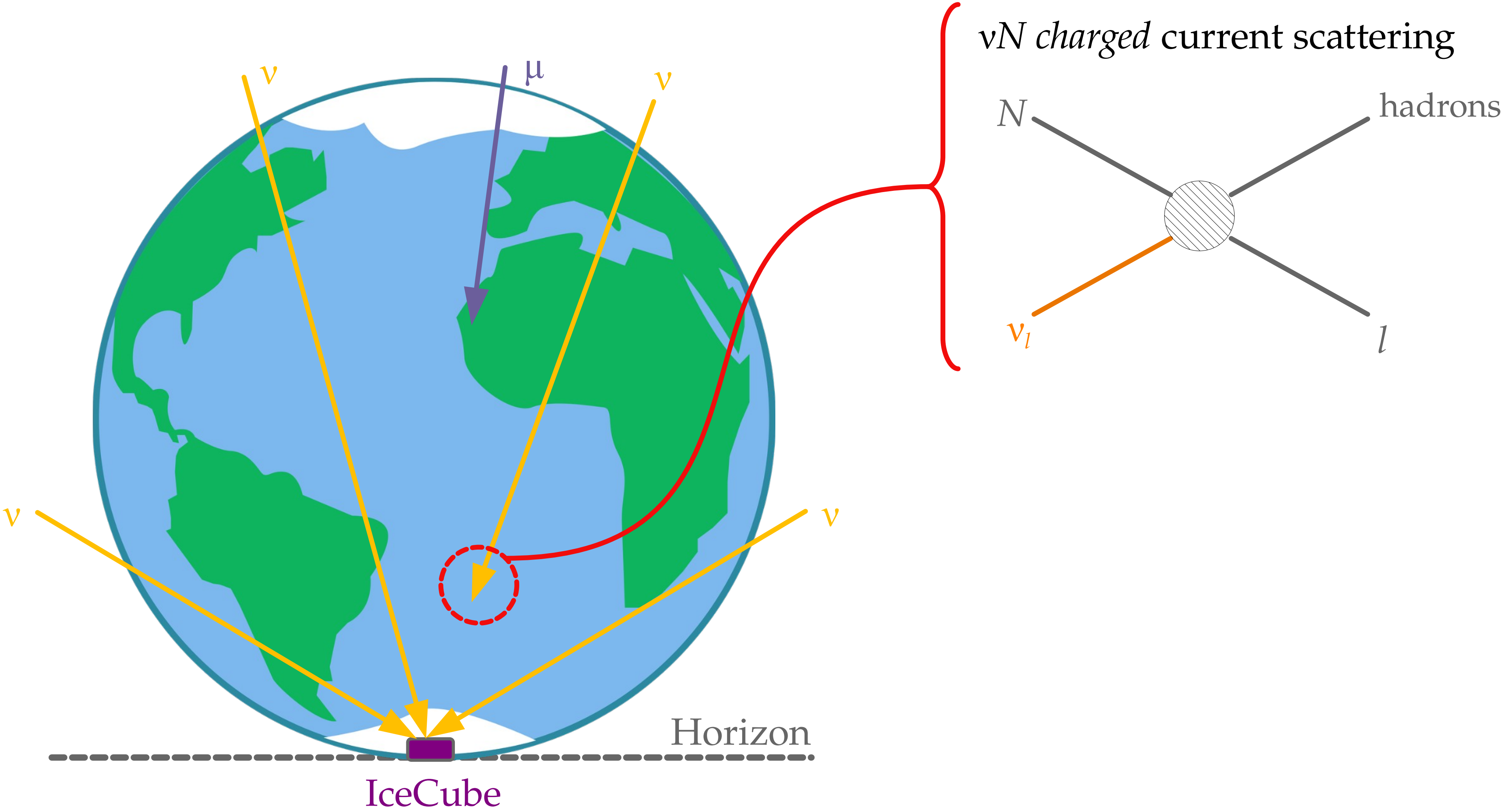
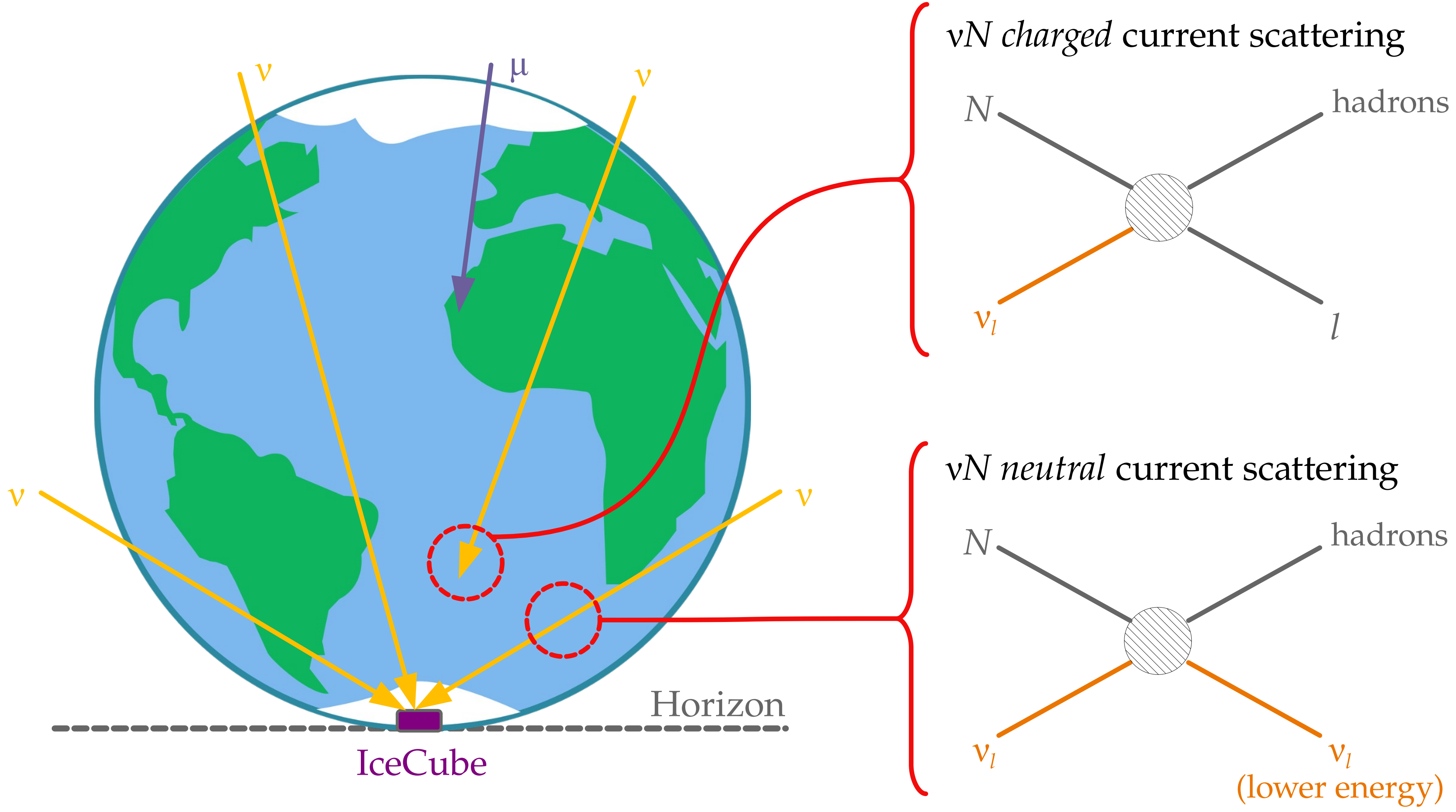
Known
In progress
Accelerator ν
ν
$\bar{\nu}$
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Neutrino energy, E_ν [GeV]

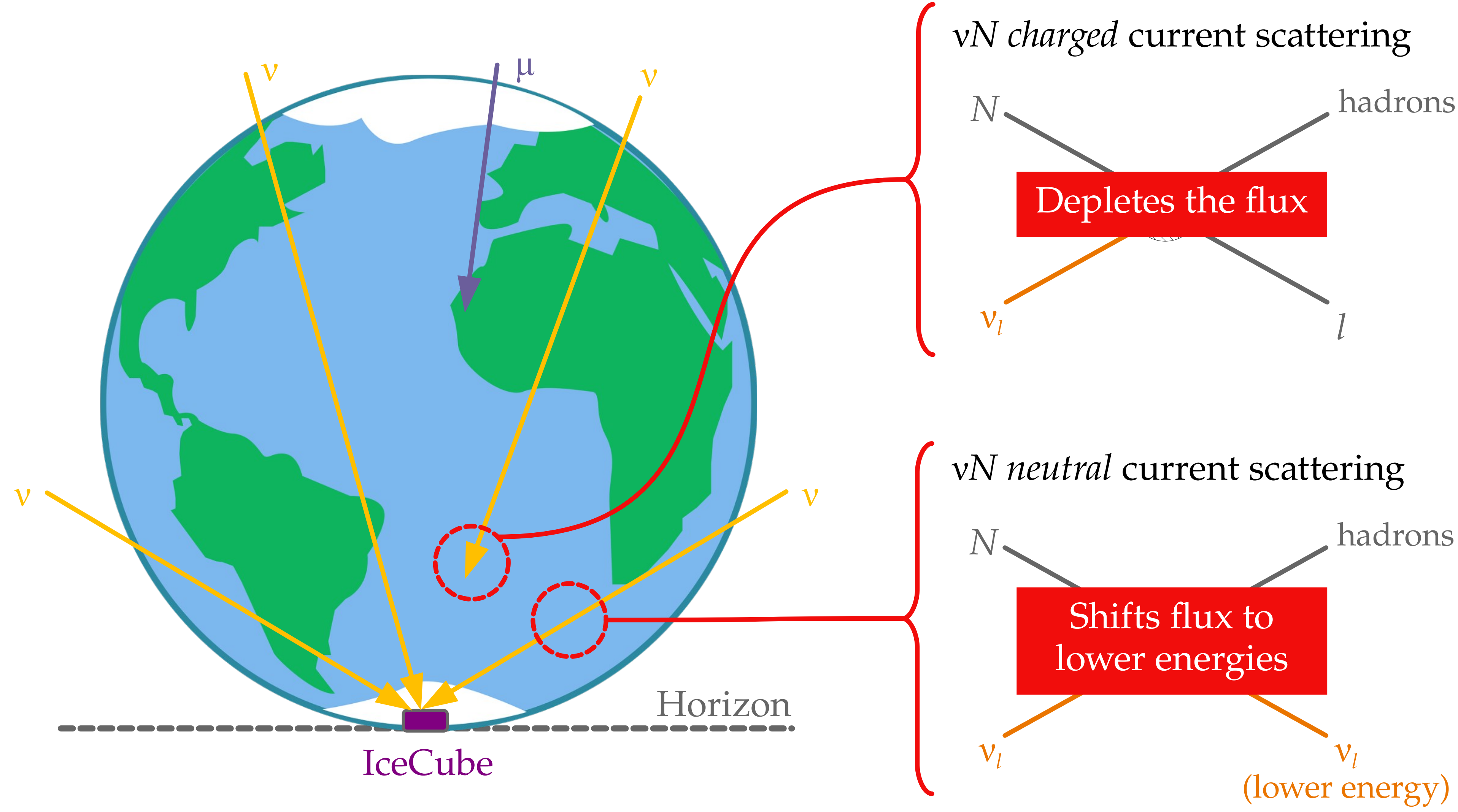


Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
Known
In progress
The future
Accelerator ν
ν
$\bar{\nu}$


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)

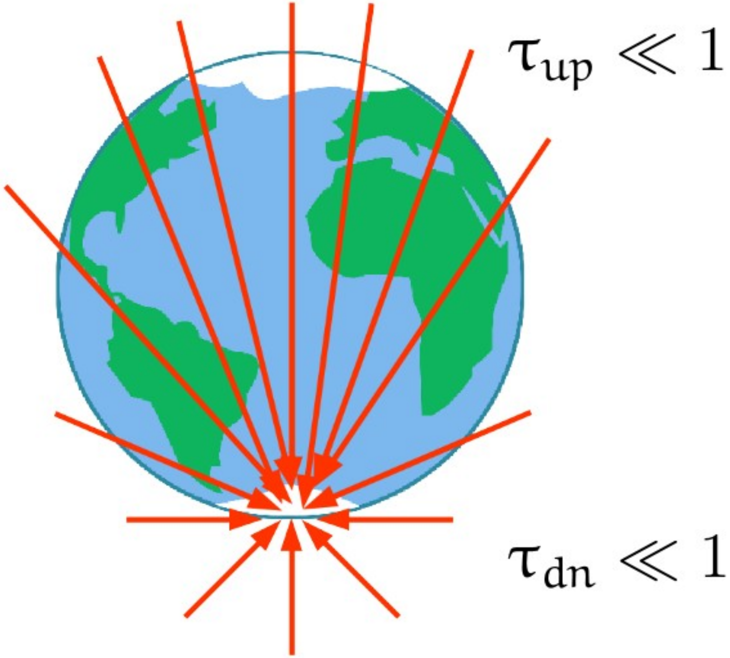

ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

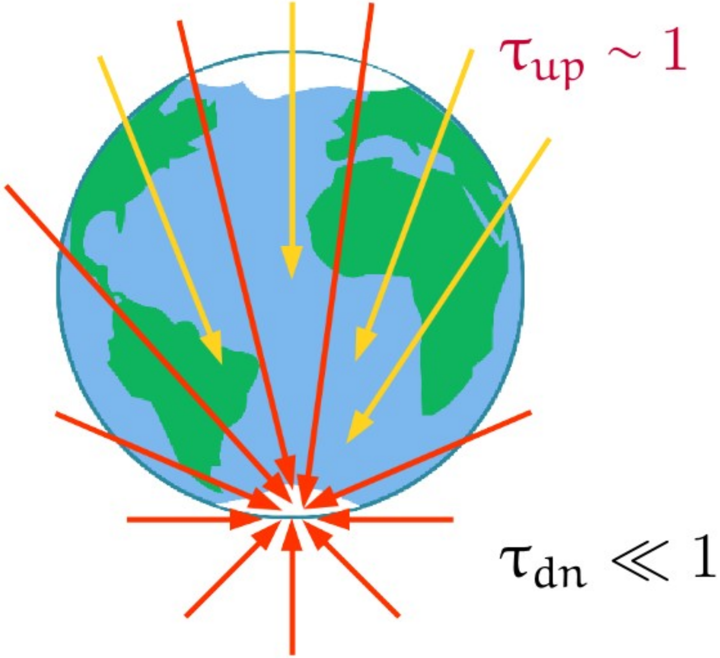
Measuring the high-energy νN cross section

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

Below ~ 10 TeV: Earth is transparent

Above ~ 10 TeV: Earth is opaque





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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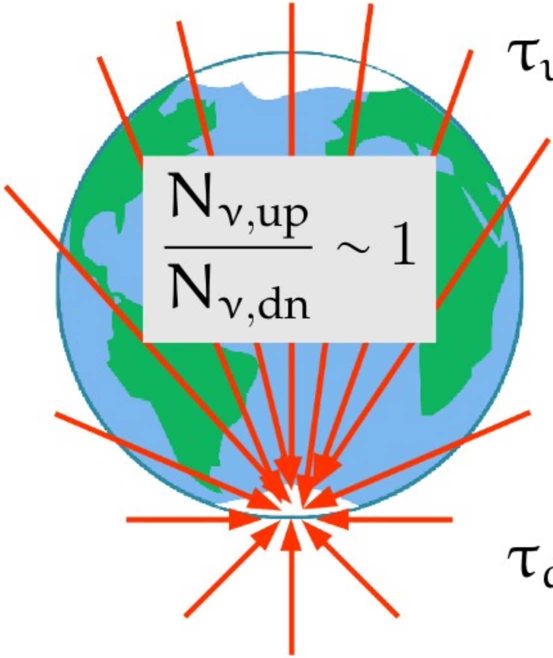
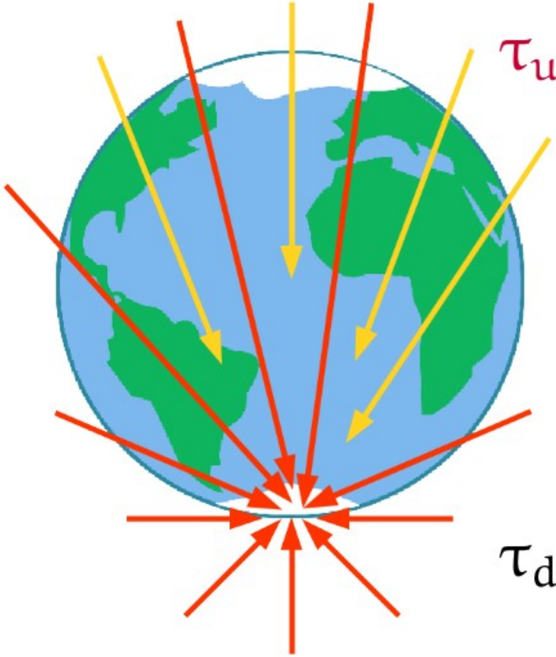


$\tau_{\text{up}} \ll 1$

$\tau_{\text{dn}} \ll 1$

Above ~ 10 TeV: Earth is opaque



$\tau_{\text{up}} \sim 1$

$\tau_{\text{dn}} \ll 1$

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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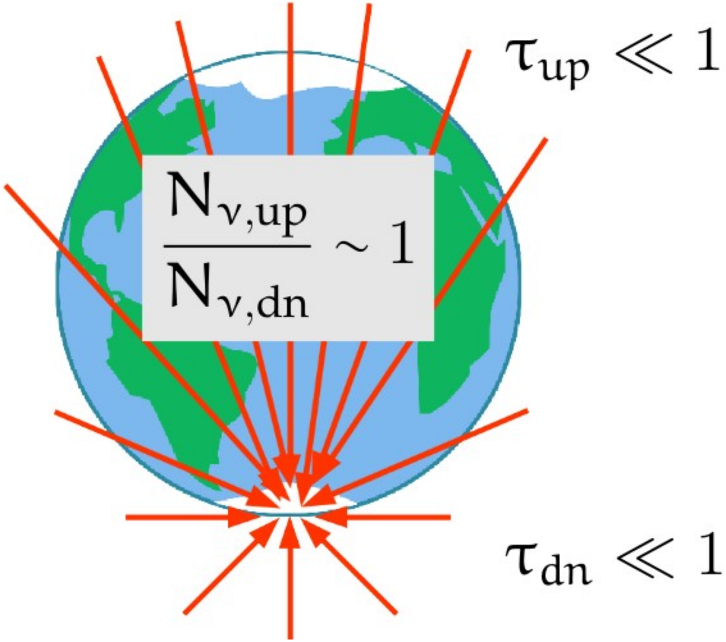

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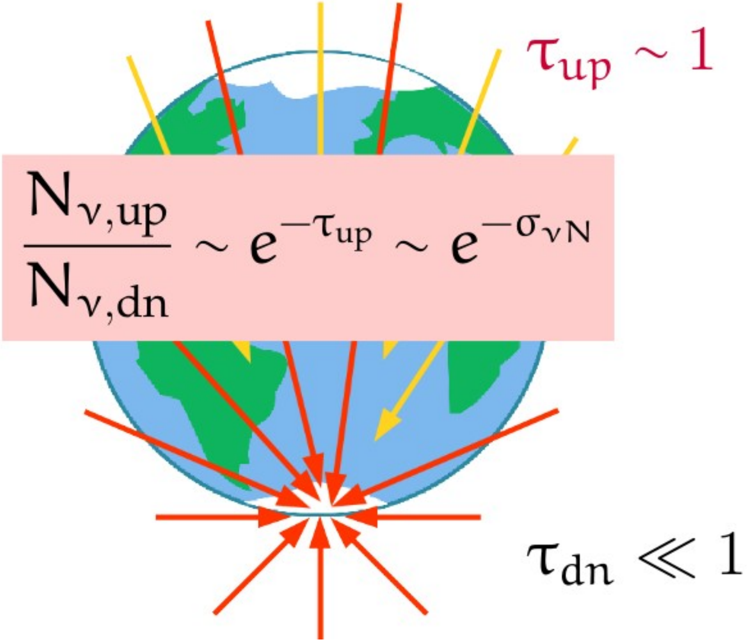

Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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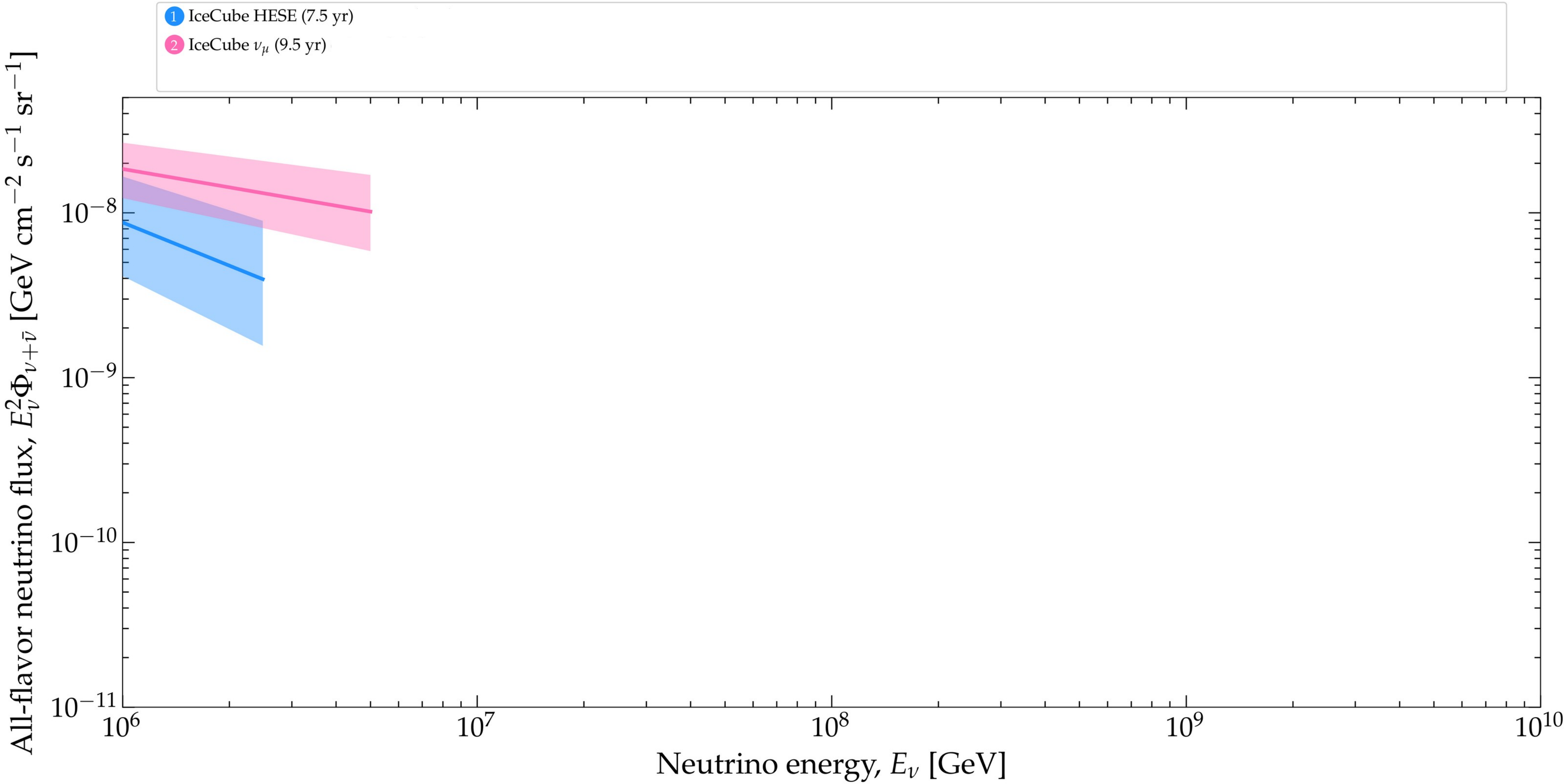
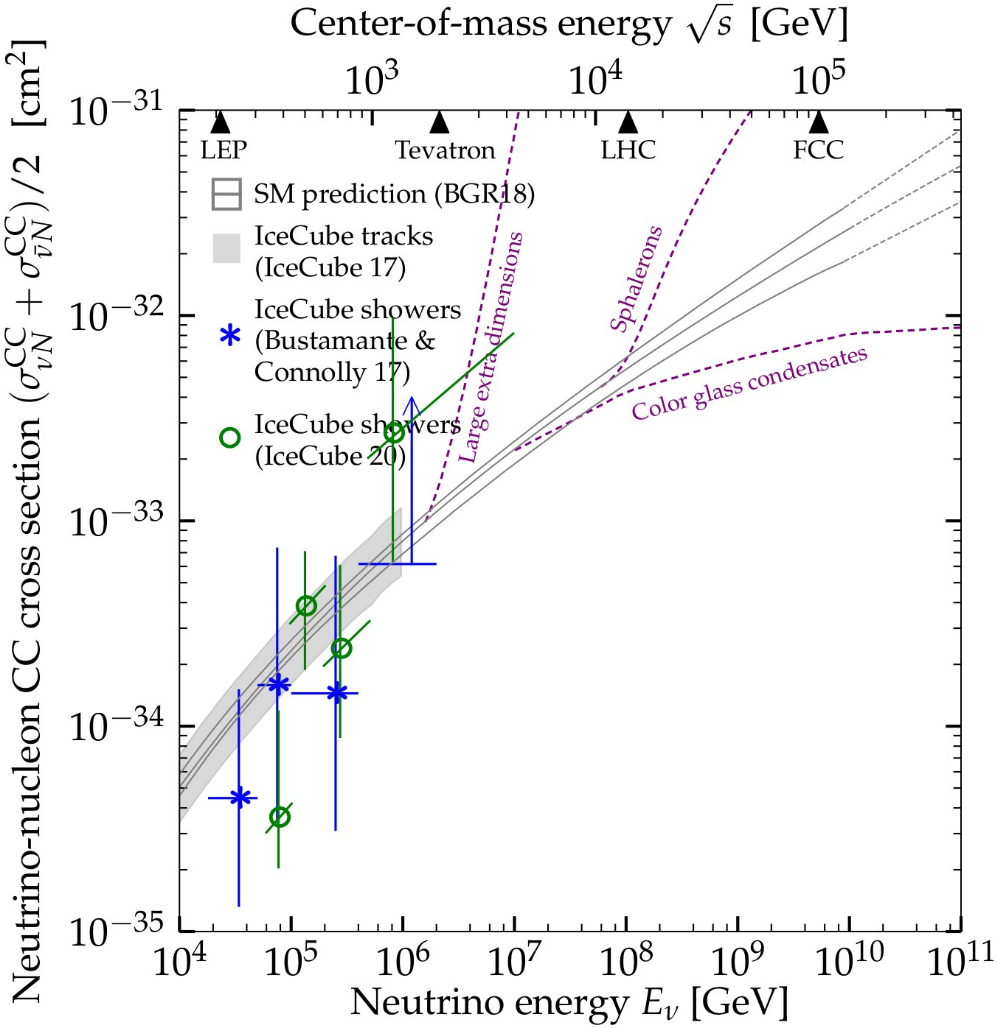

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

TeV–PeV νN cross section: *today*

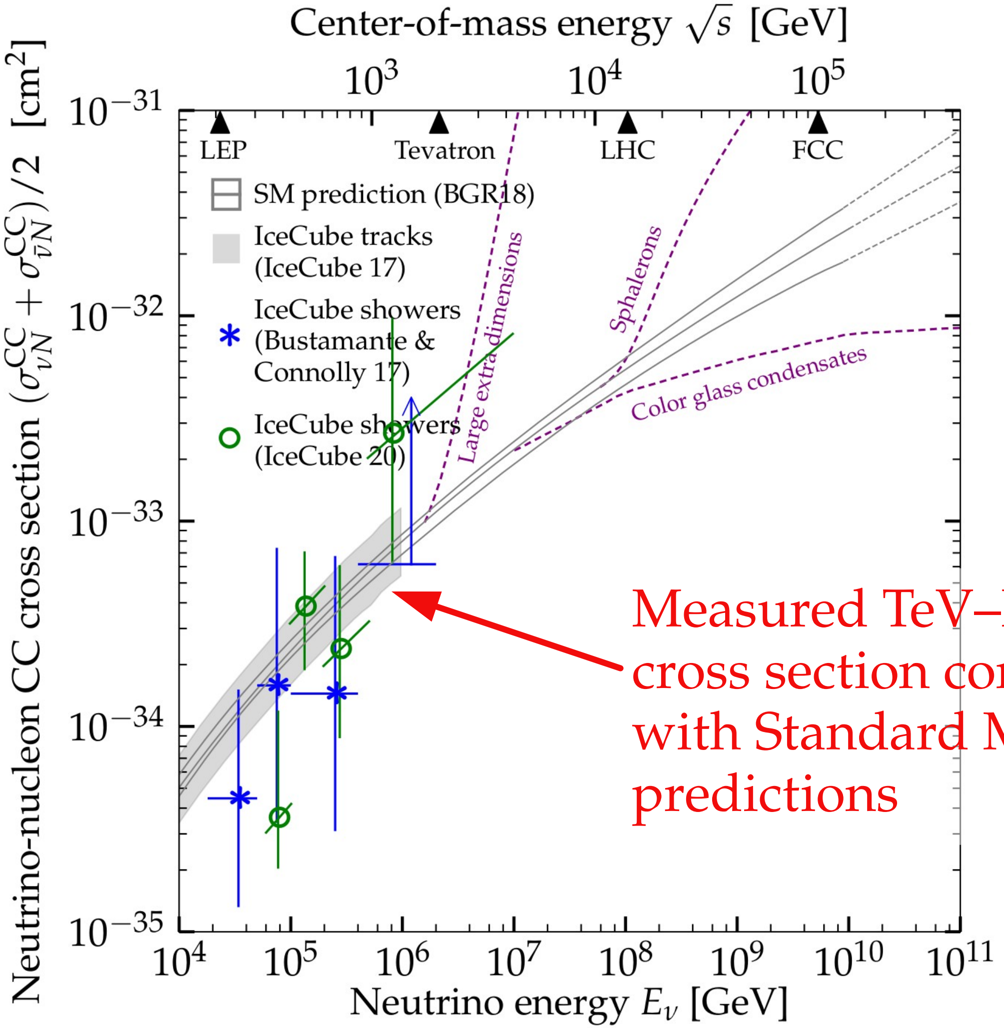


BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019

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

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

TeV–PeV νN cross section: *today*



Measured TeV–PeV cross section compatible with Standard Model predictions

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

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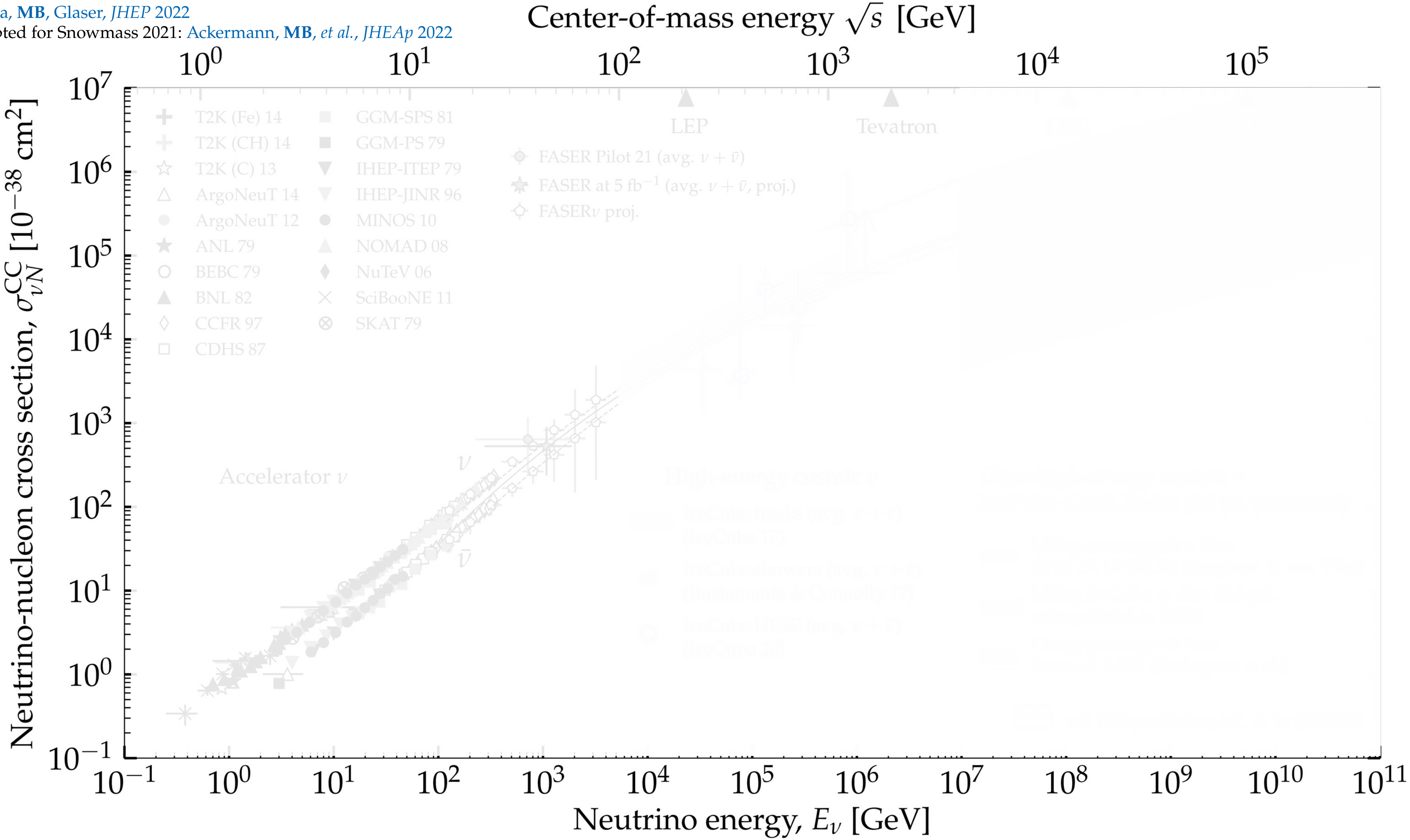
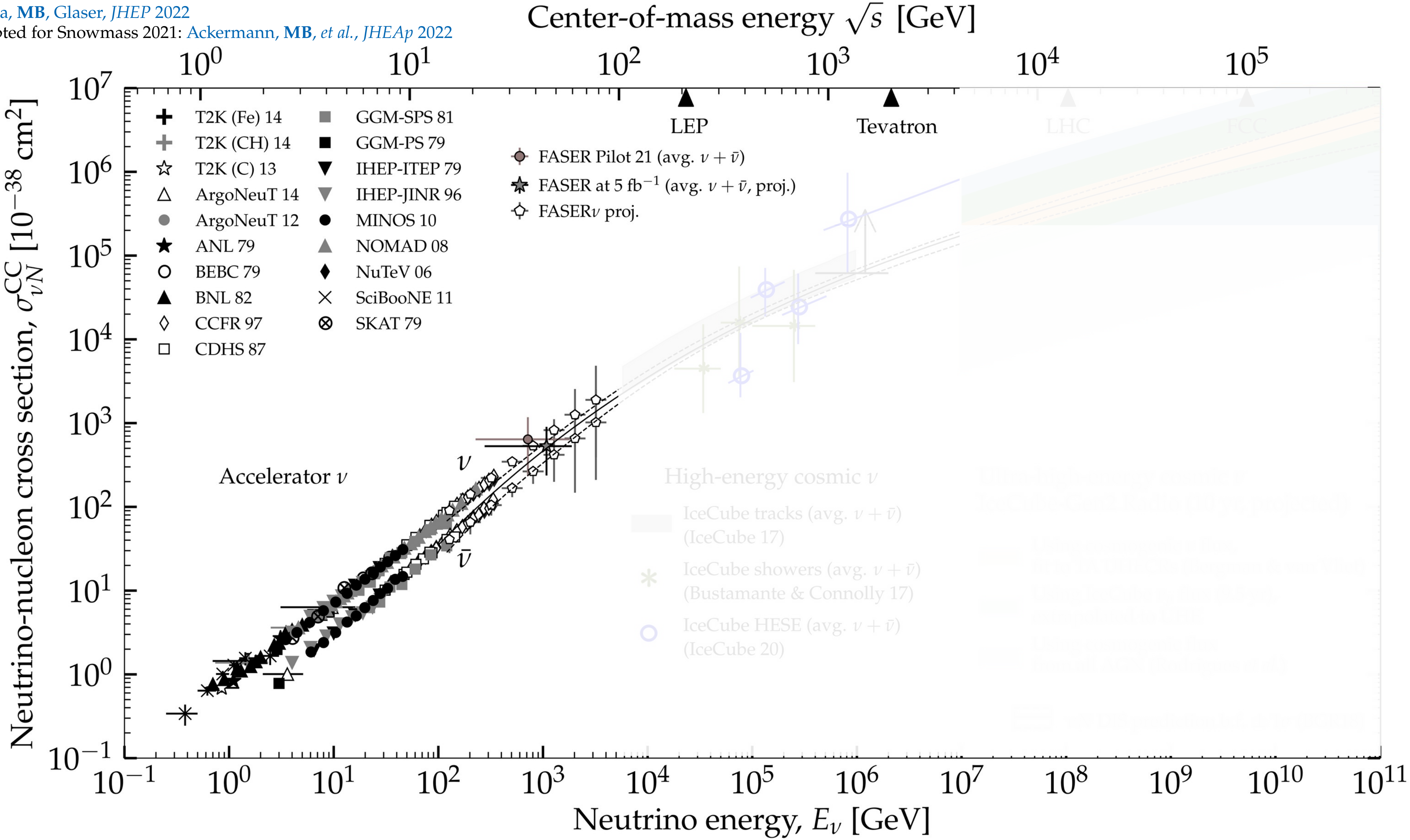
IceCube, *Nature* 2017

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



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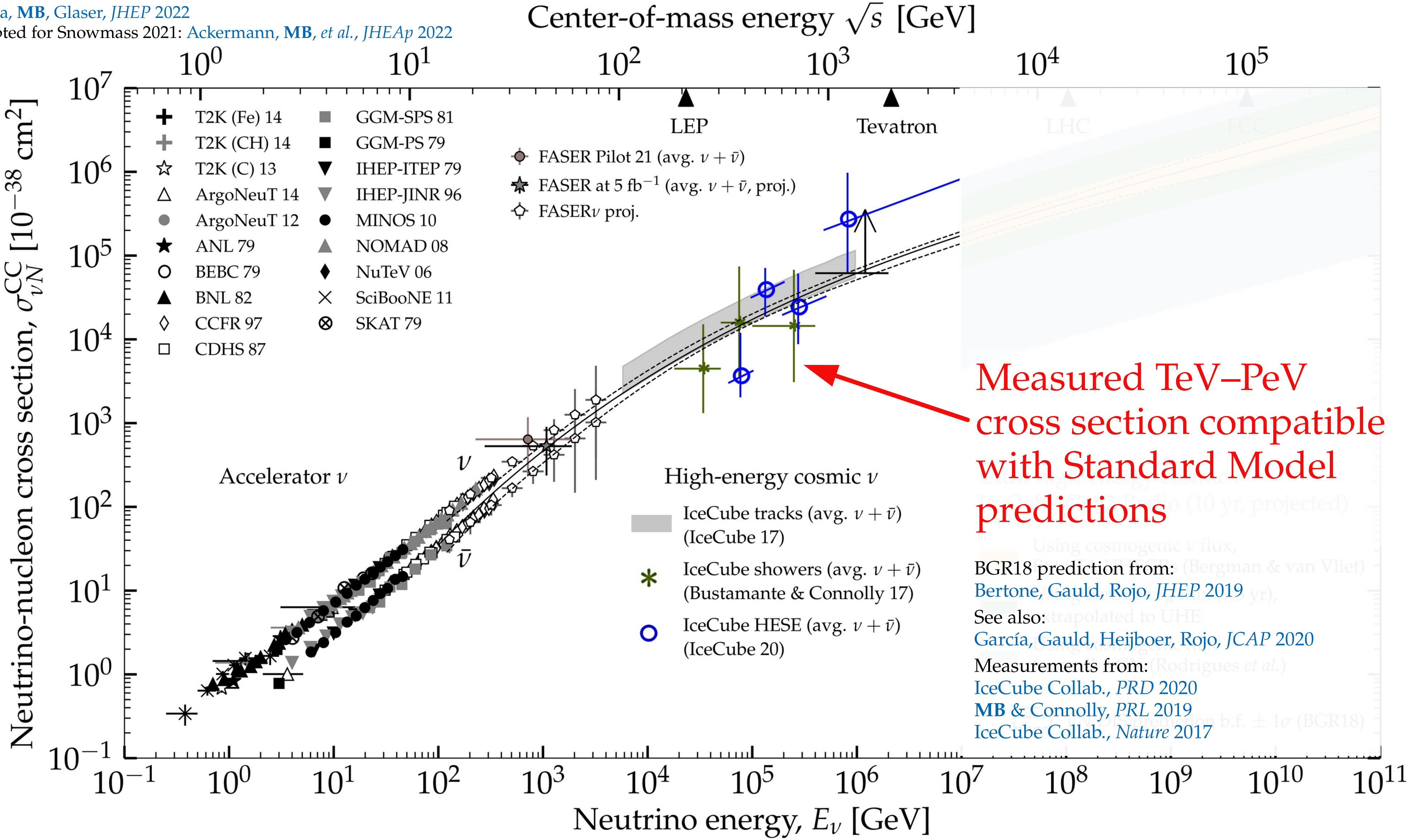
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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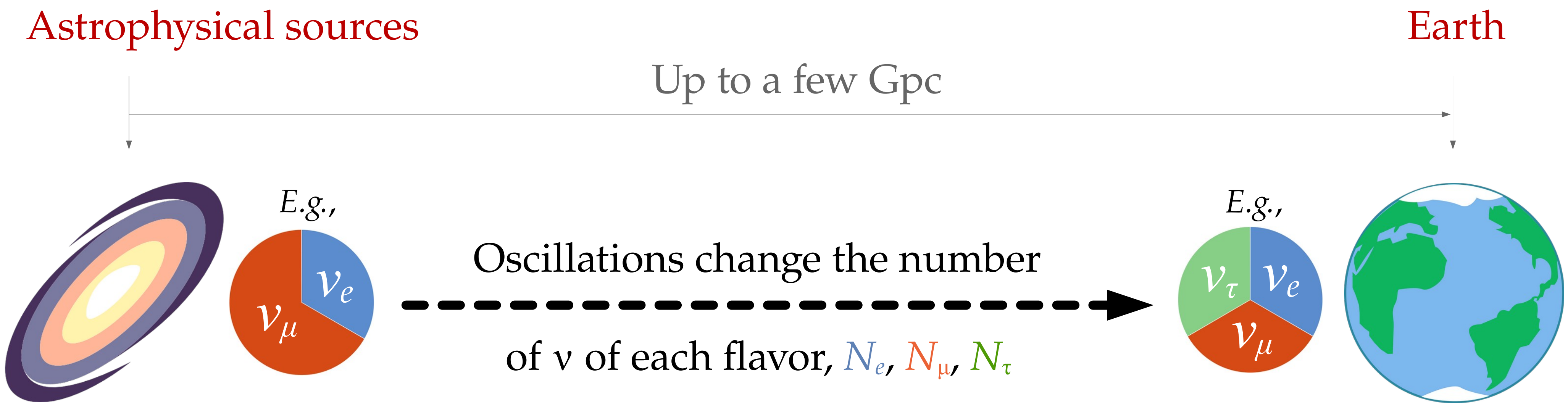
IceCube Collab., *Nature* 2017

Flavor composition

(with the help of lower-energy experiments)

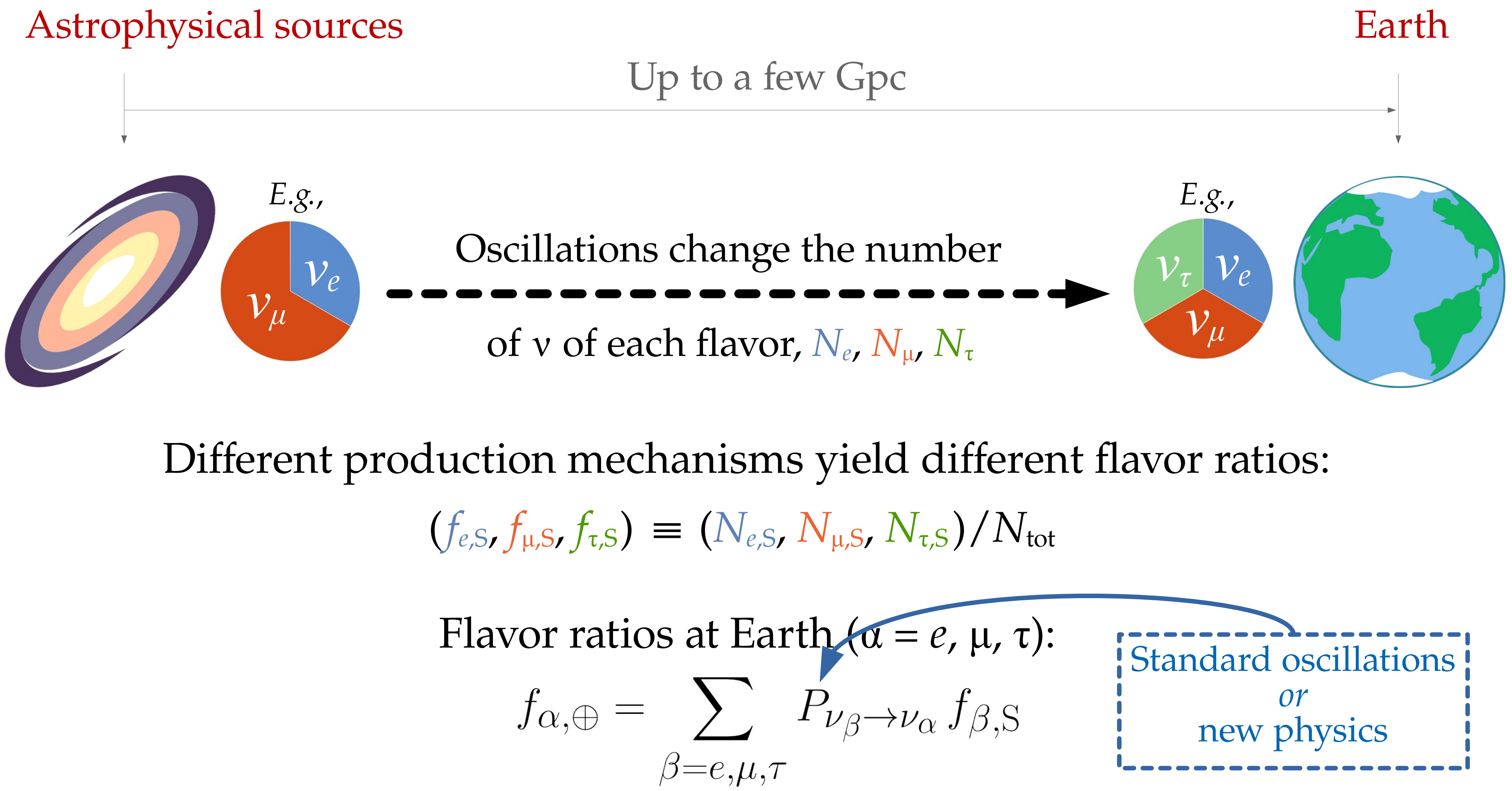


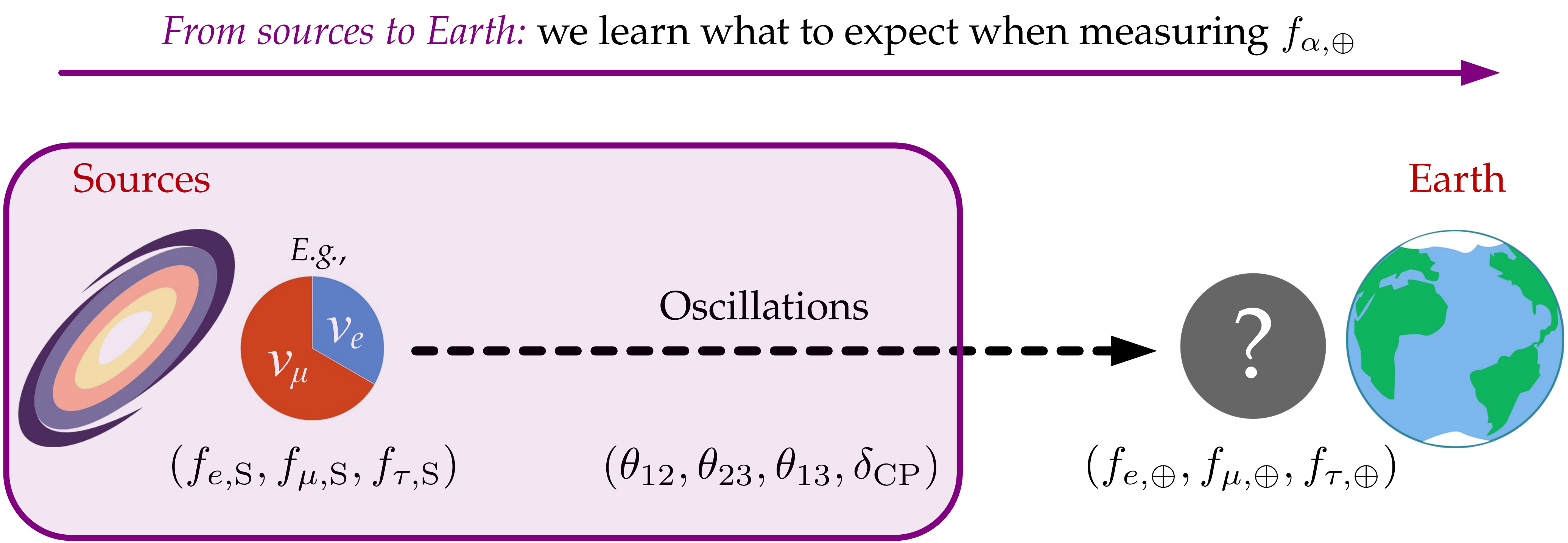
Different production mechanisms yield different flavor ratios:

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

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:
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$
Standard oscillations
or
new physics



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

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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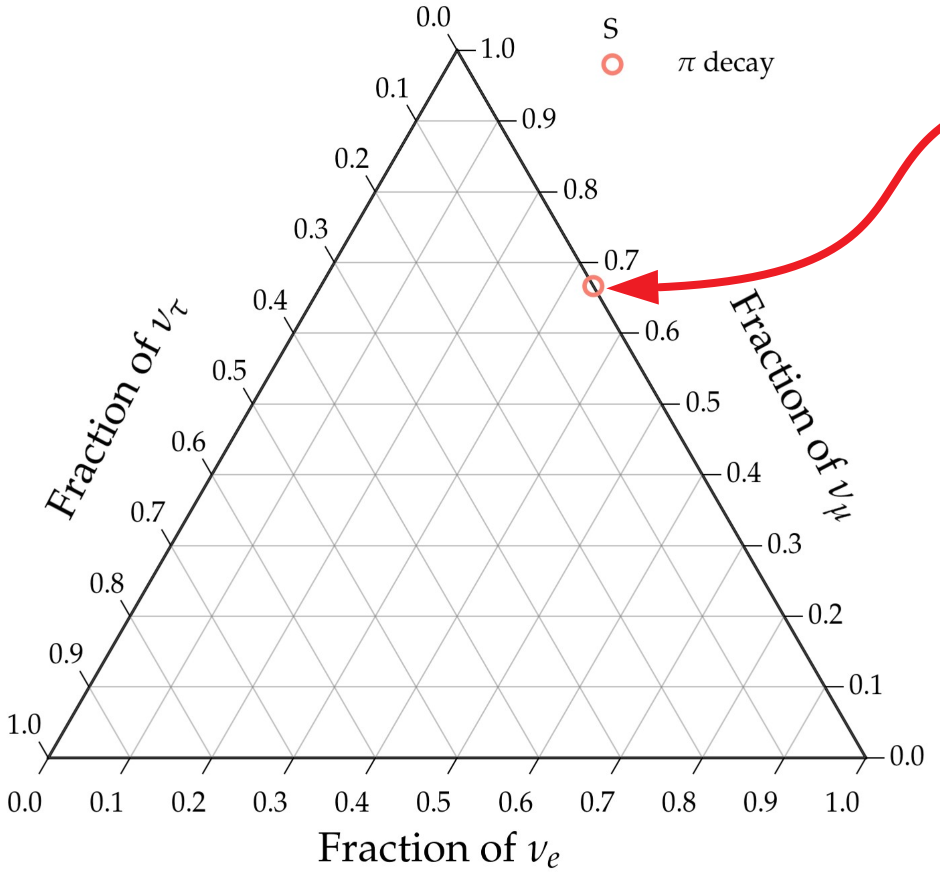

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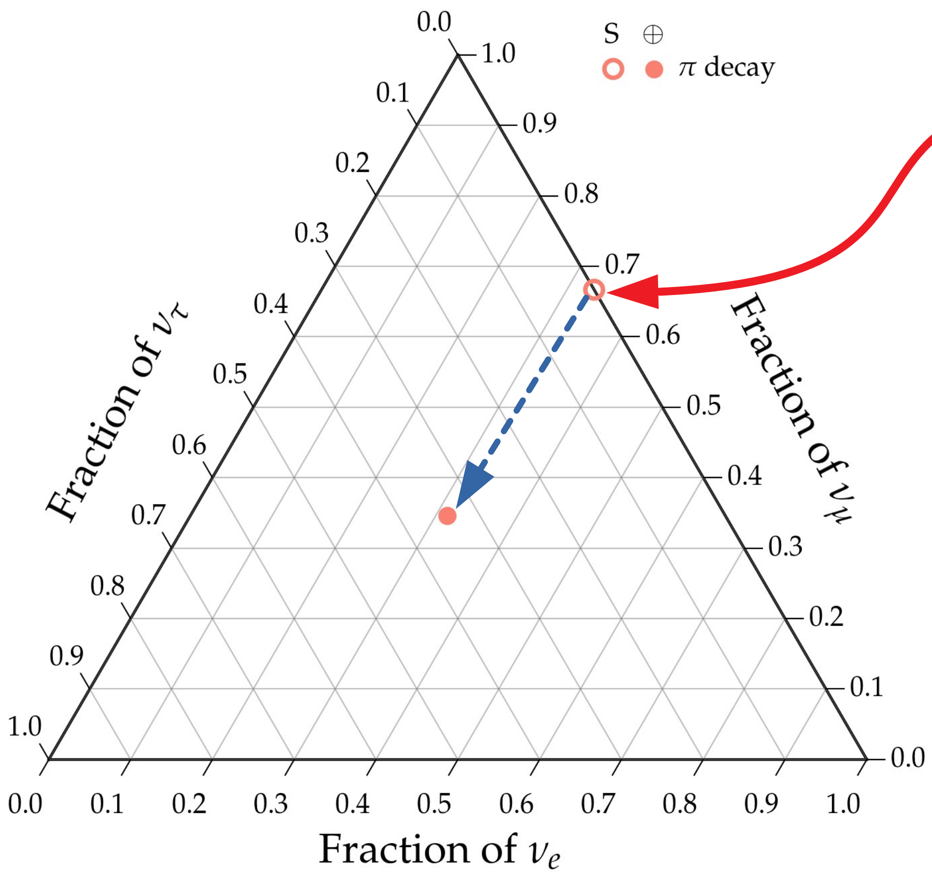

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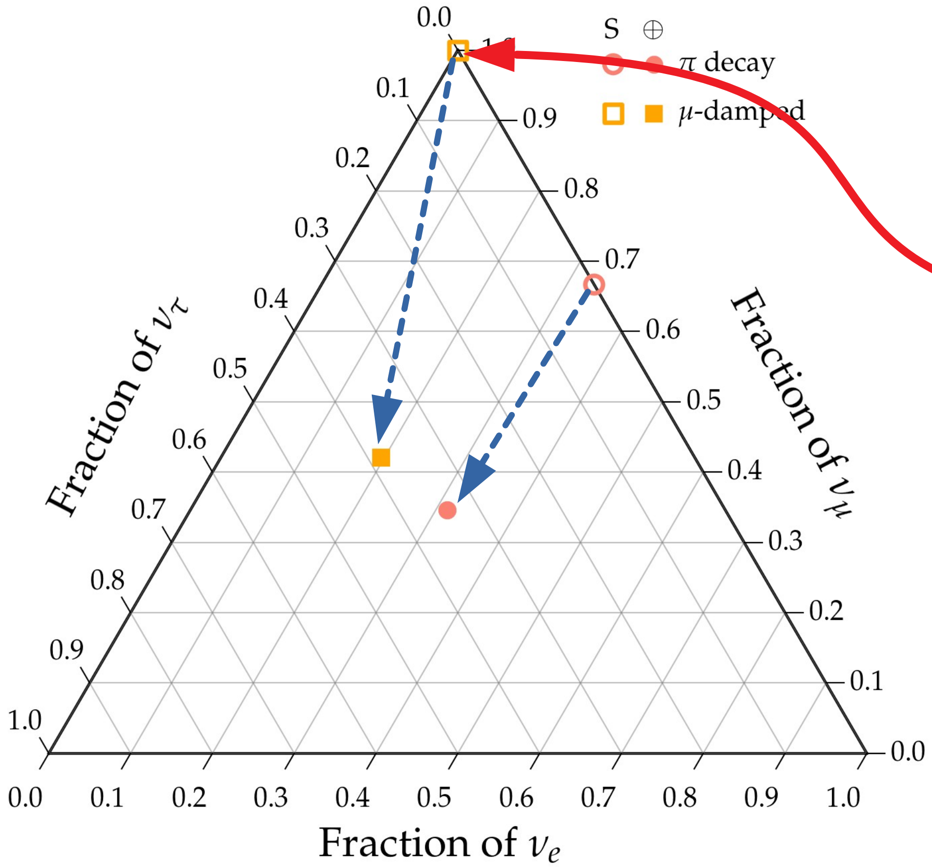

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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

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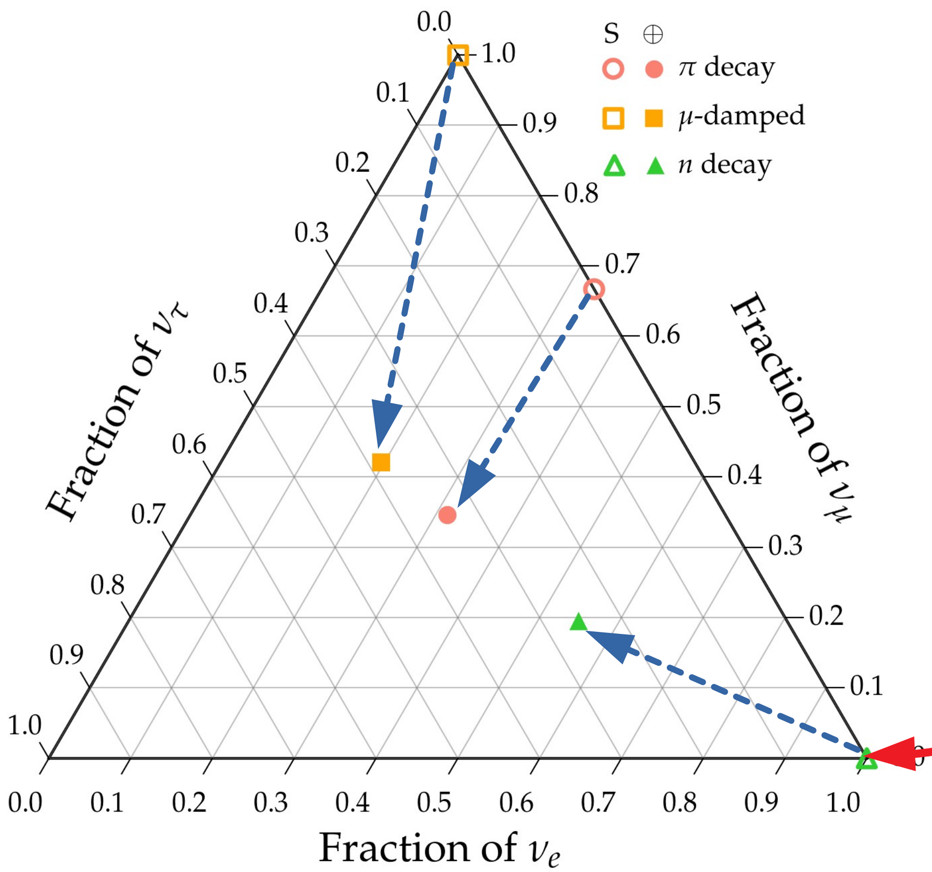


Full π decay chain

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

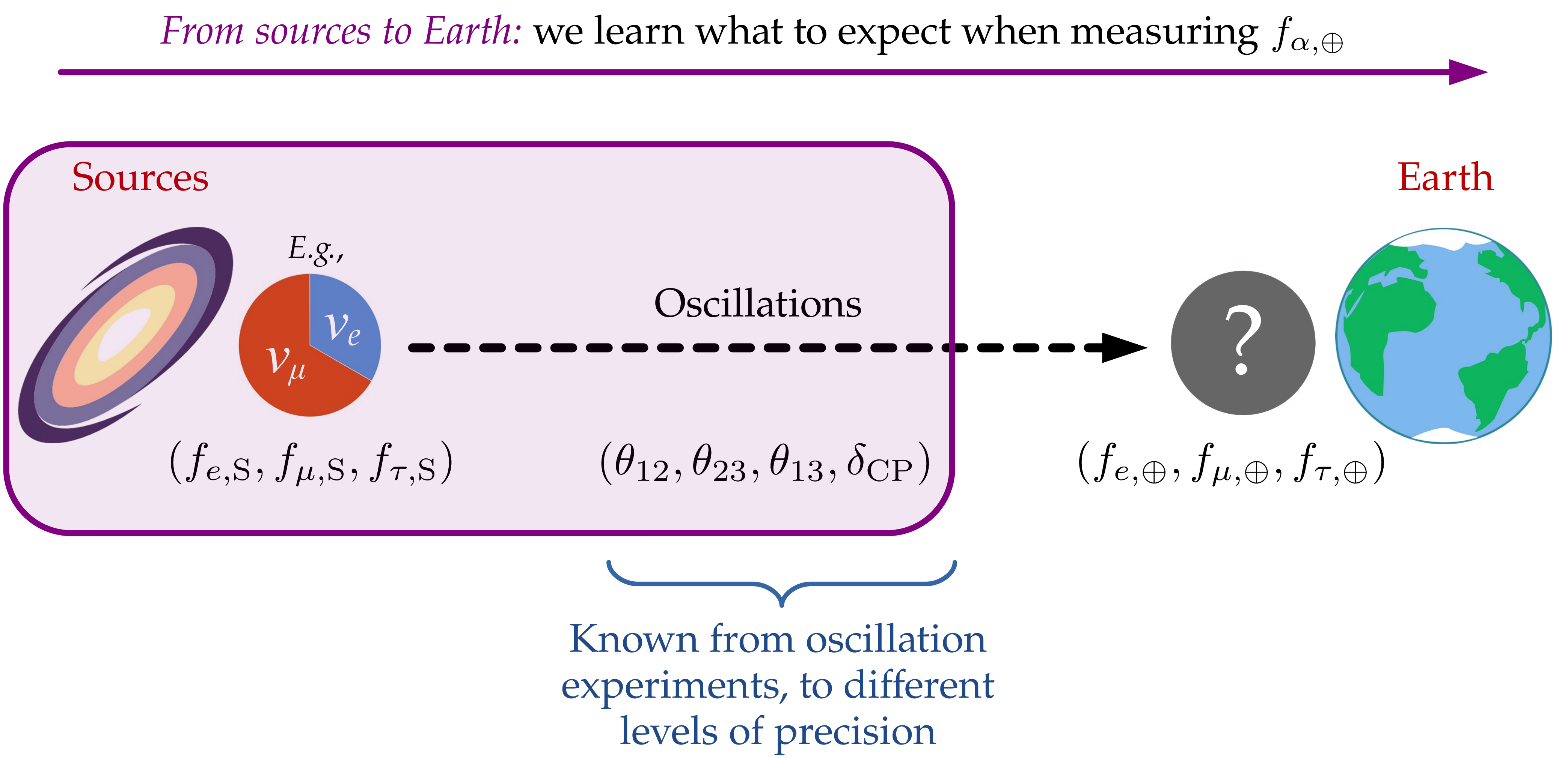
Muon damped

$(0:1:0)_S$

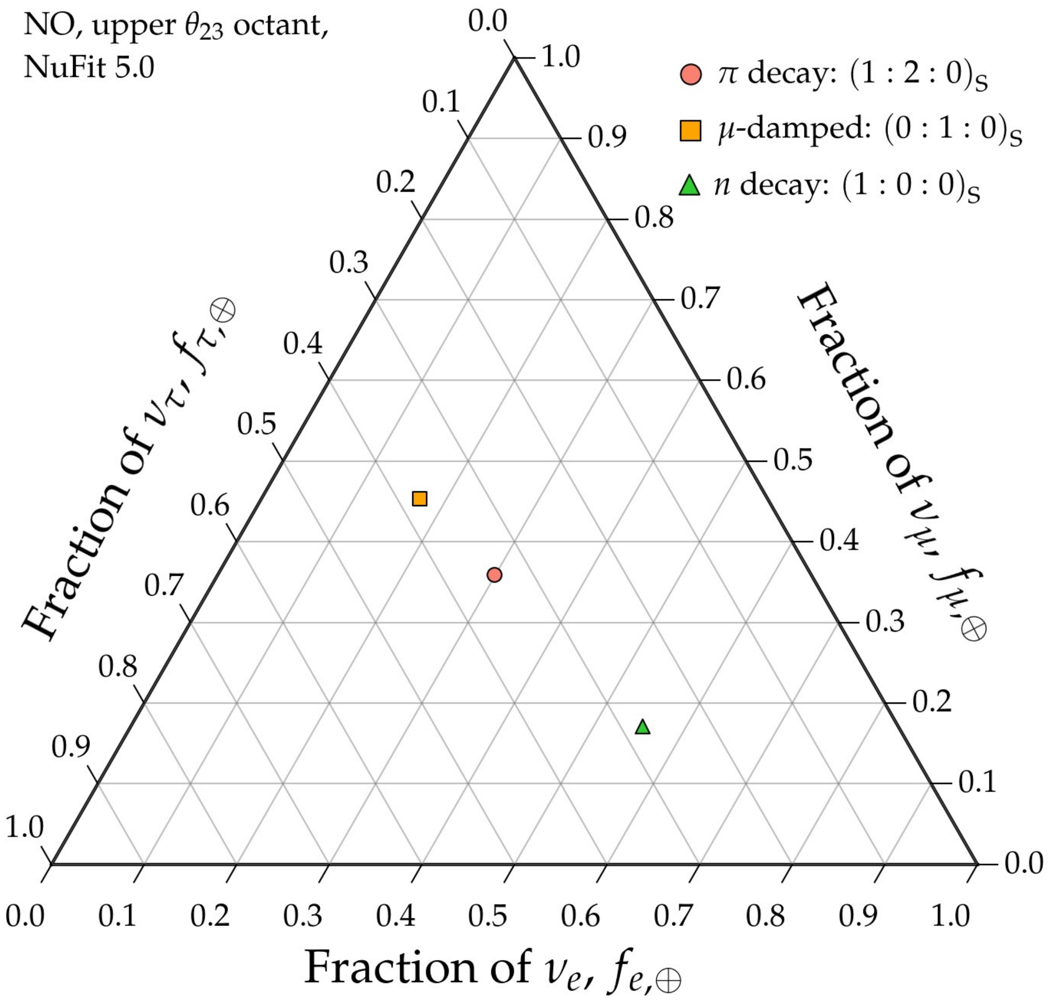
Neutron decay

$(1:0:0)_S$

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


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

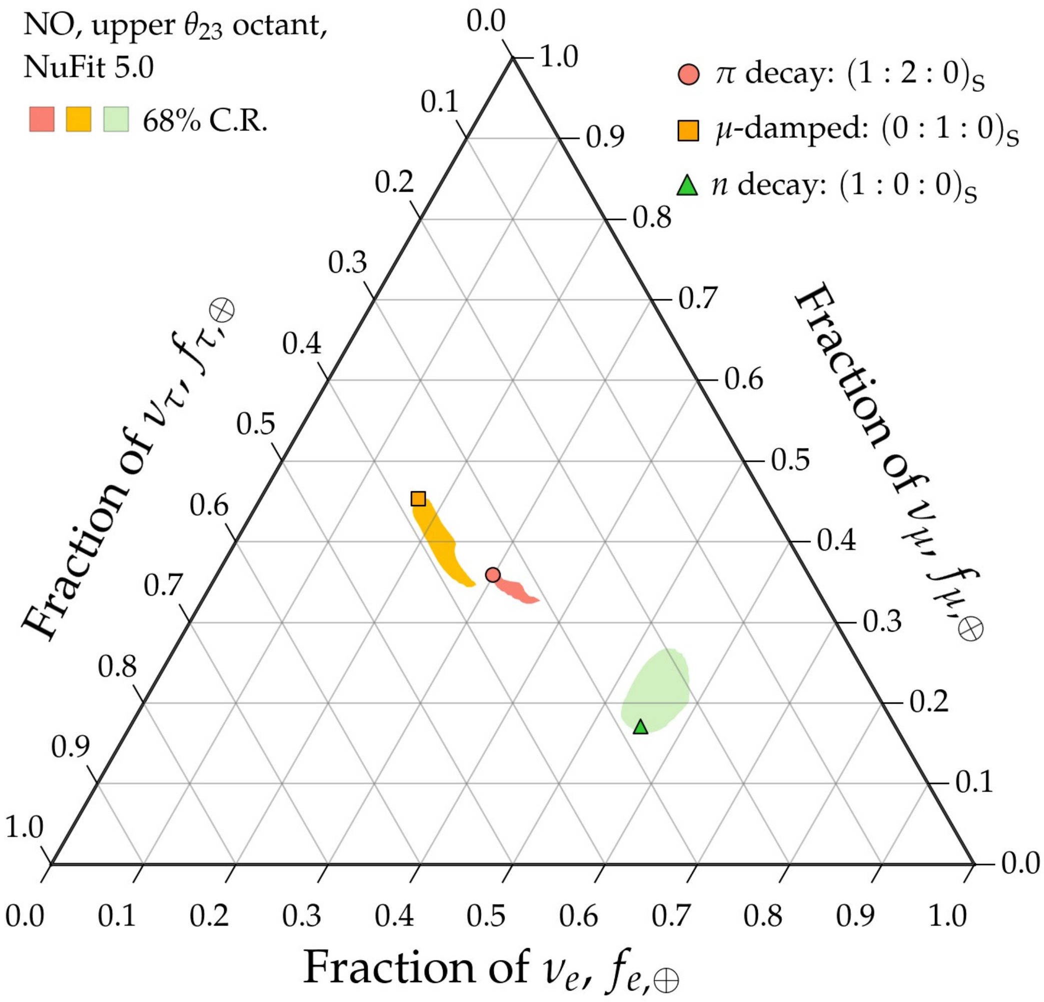
Theoretically palatable regions: today



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

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

Theoretically palatable regions: today



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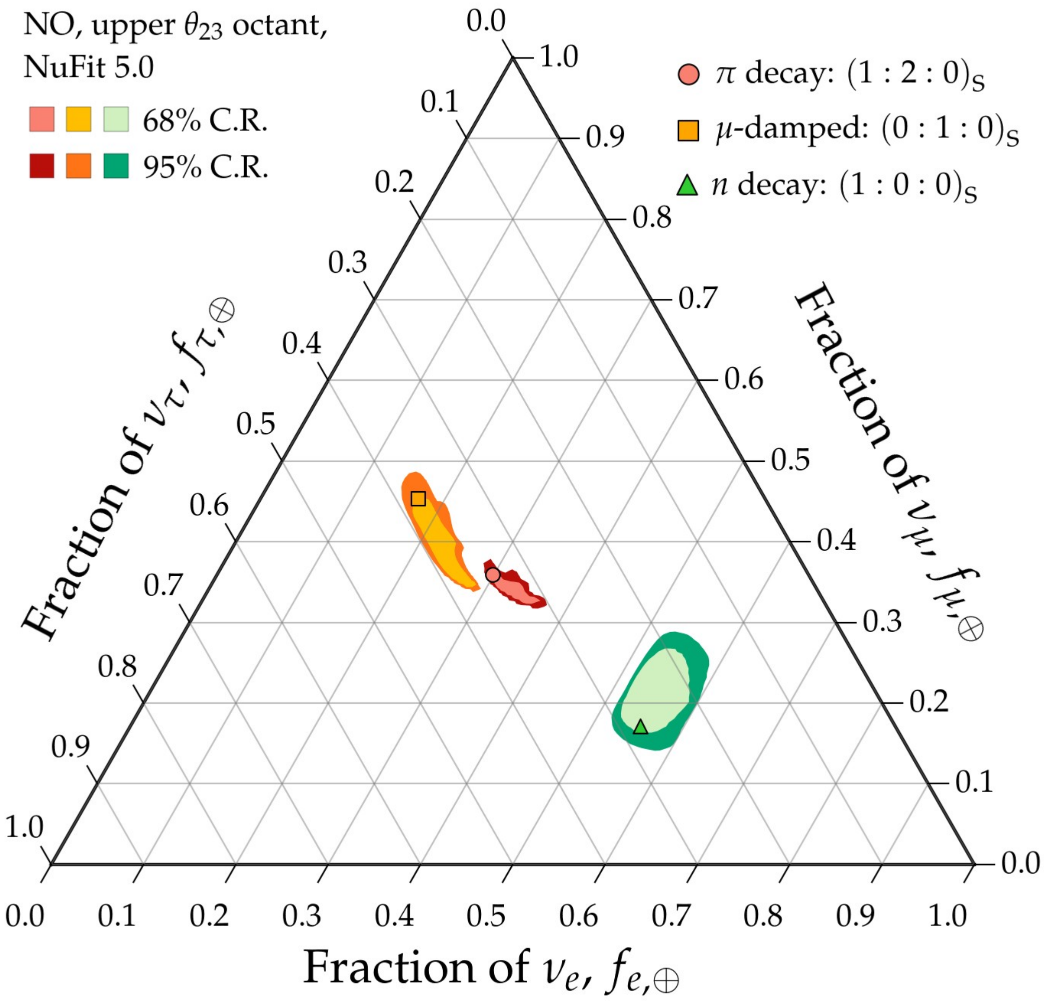

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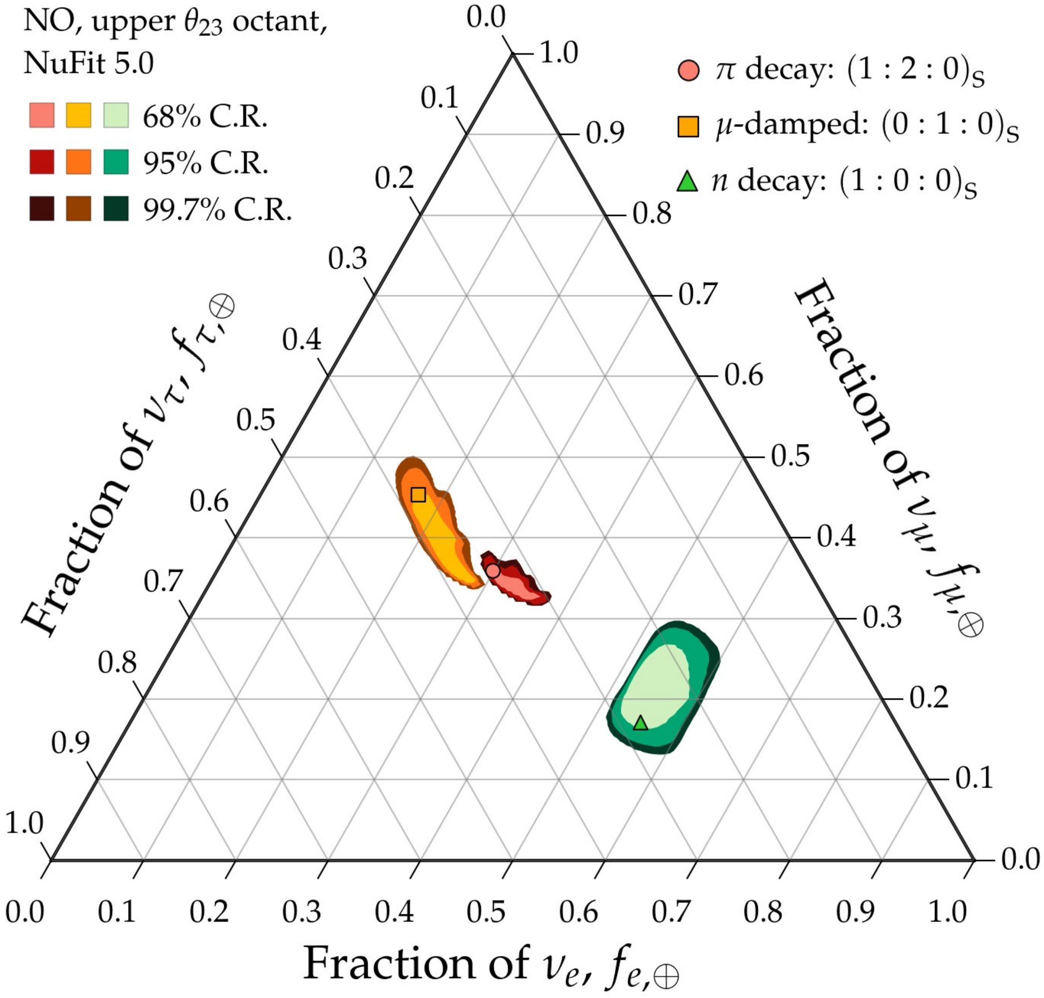

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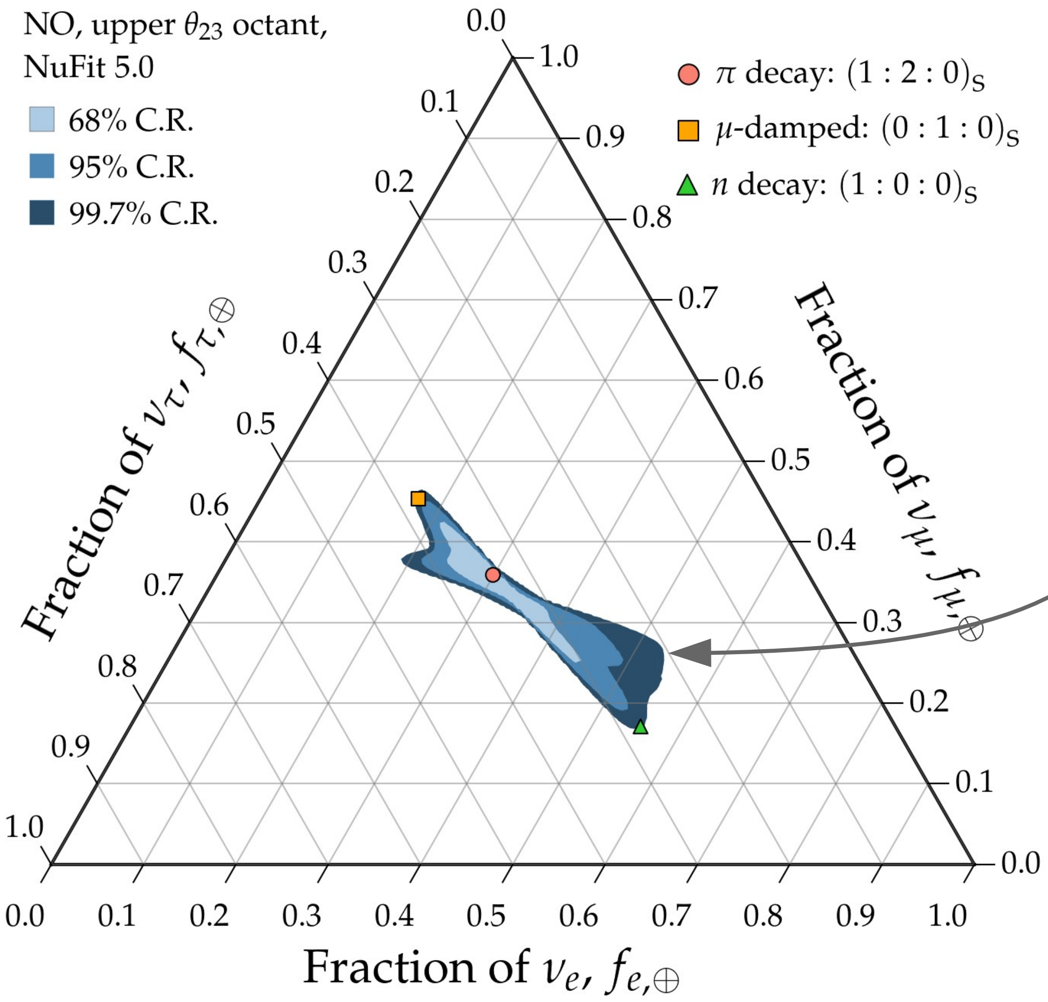

Varying over all possible flavor ratios at the source

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

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

Theoretically palatable regions: today

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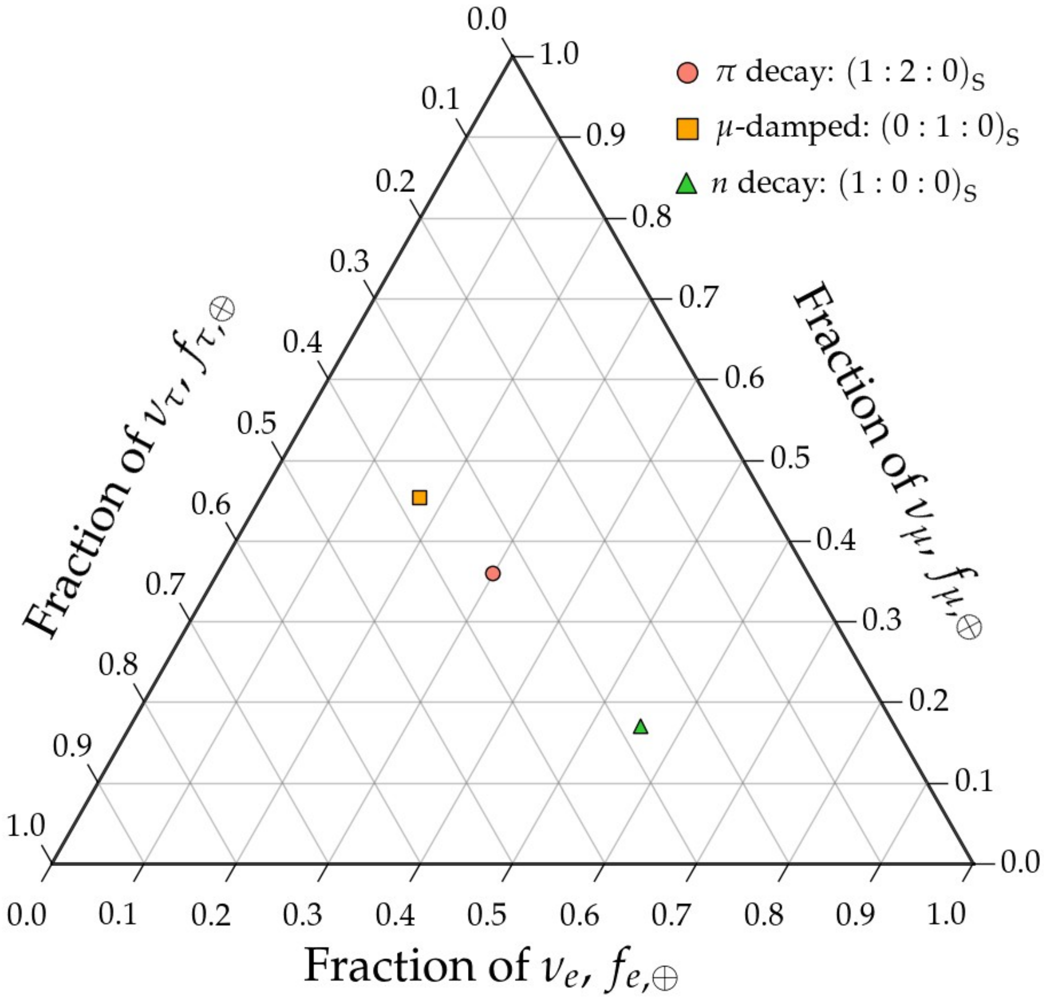
Measuring flavor composition: 2015–2020

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

Measuring flavor composition: 2015–2020



IceCube Collab., *EPJC* 2022
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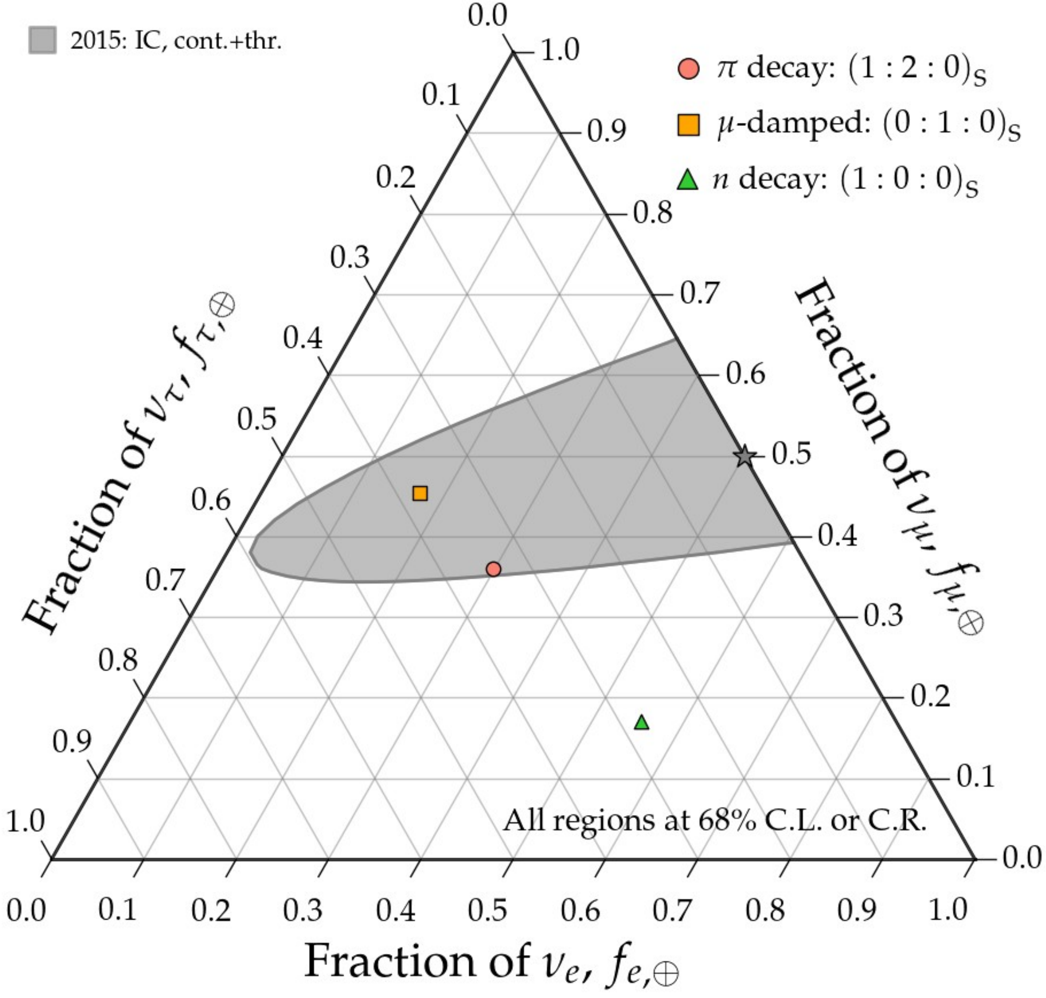
Measuring flavor composition: 2015–2020



IceCube Collab., *EPJC* 2022
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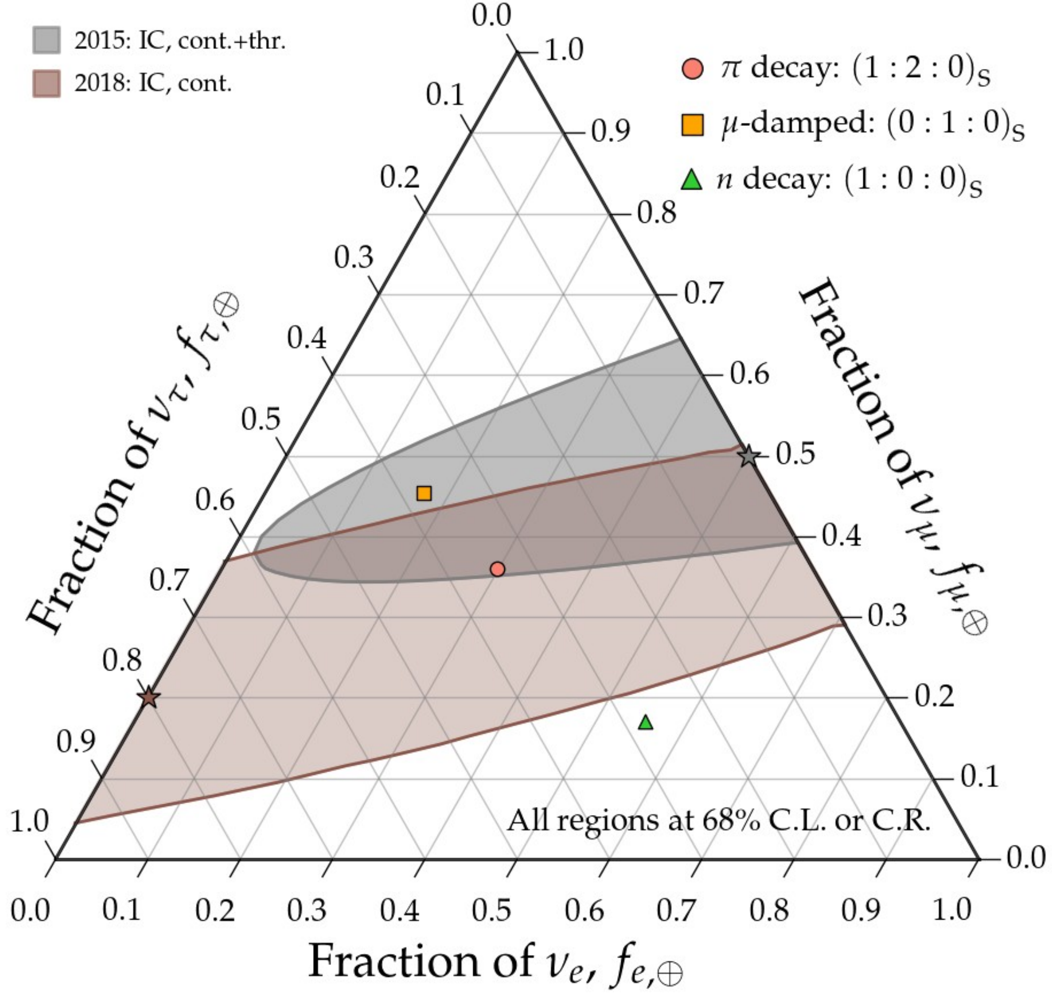

IceCube Collab., *EPJC* 2022
IceCube Collab., *PRD* 2019
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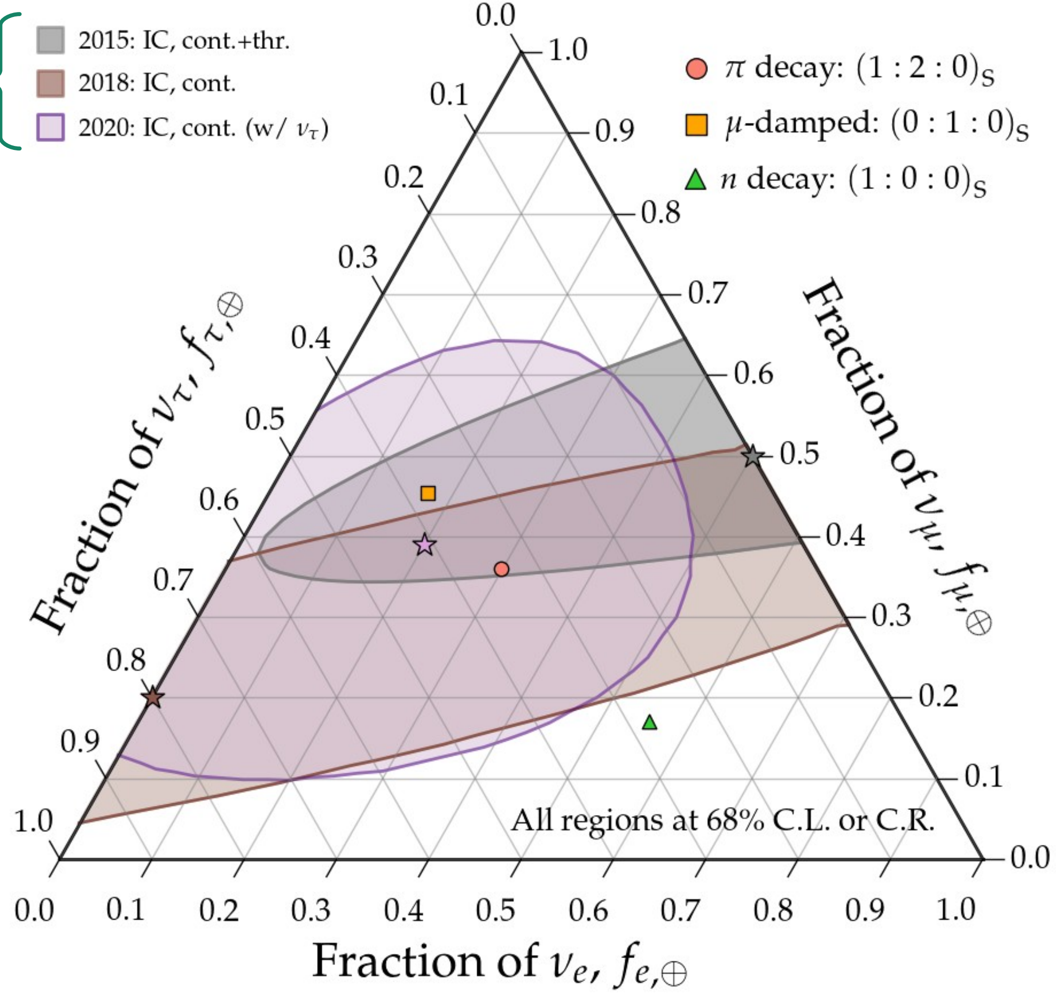
Measuring flavor composition: 2015–2020

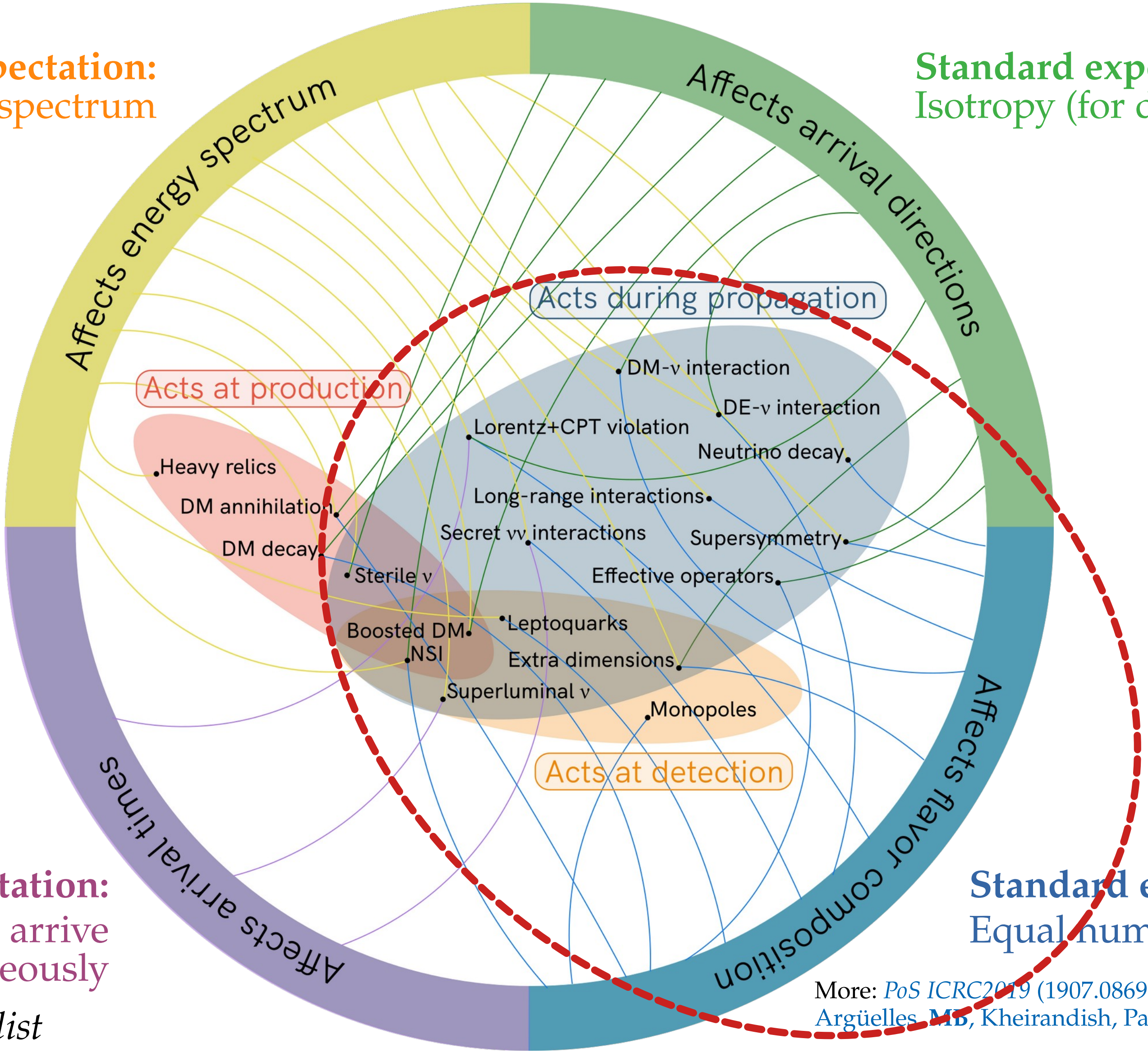
Based on real data



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

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

Use the flavor sensitivity to test new physics:

New physics in flavor composition

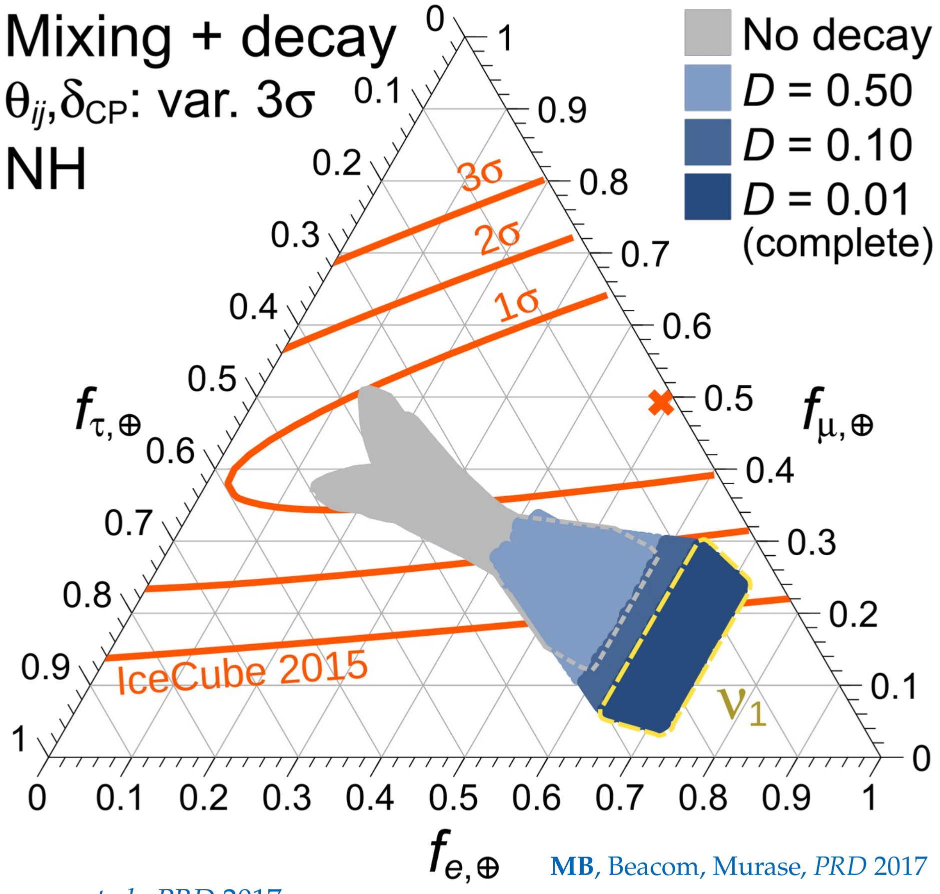
Use the flavor sensitivity to test new physics:

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

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



MB, Beacom, Murase, *PRD* 2017

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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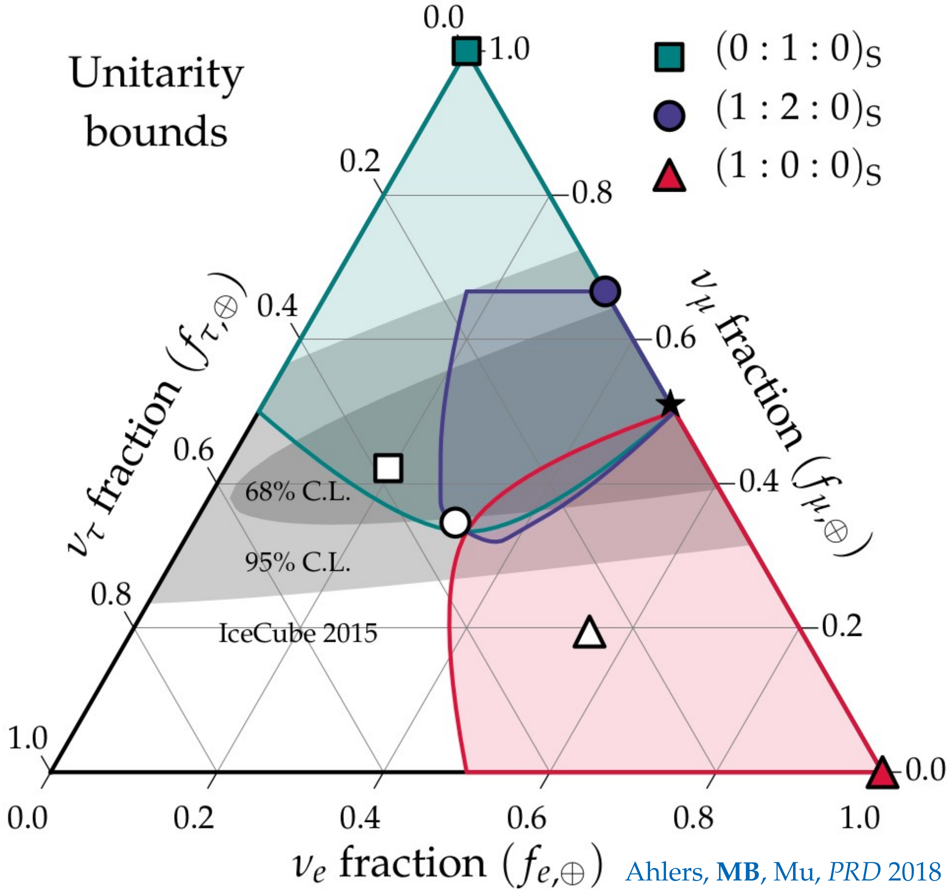
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]



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

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

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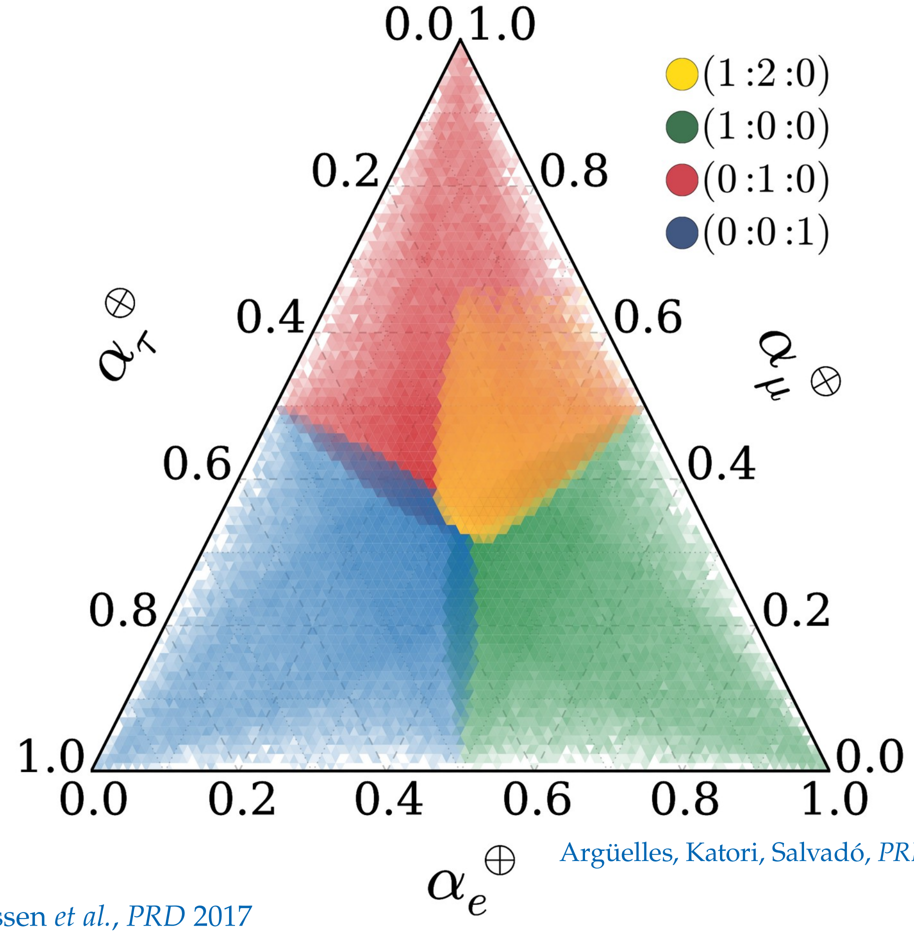
  Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
  Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]



Argüelles, Katori, Salvadó, *PRL* 2015

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Use the flavor sensitivity to test new physics:

- Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
- Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
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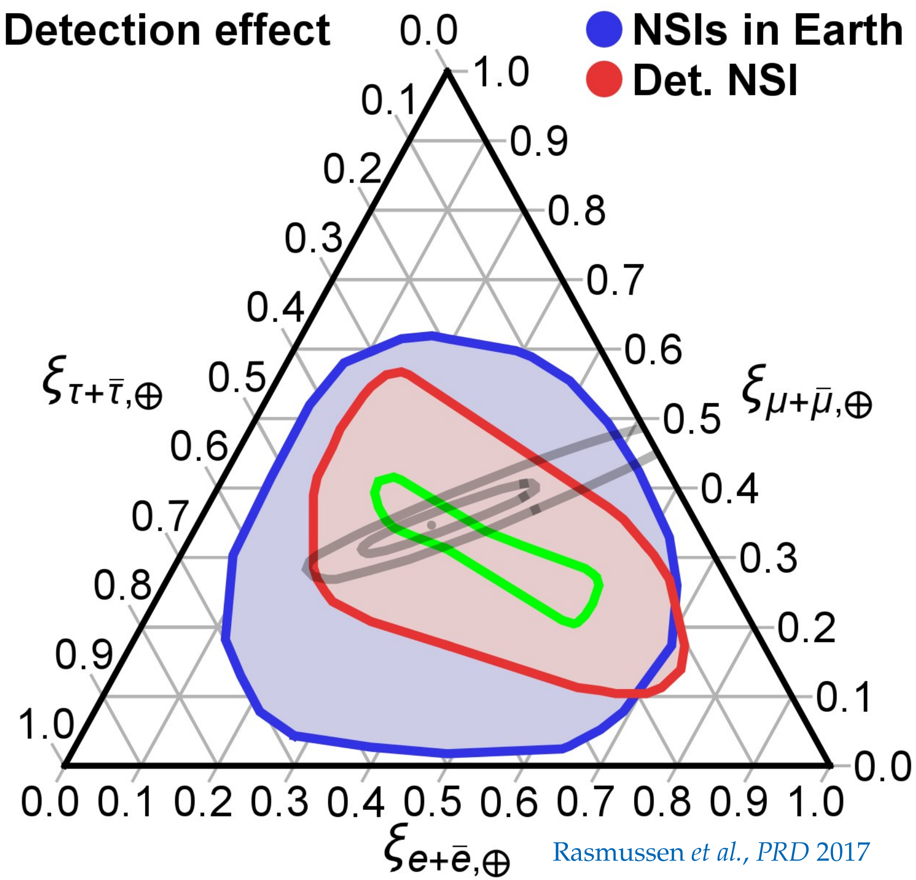

Rasmussen *et al.*, *PRD* 2017

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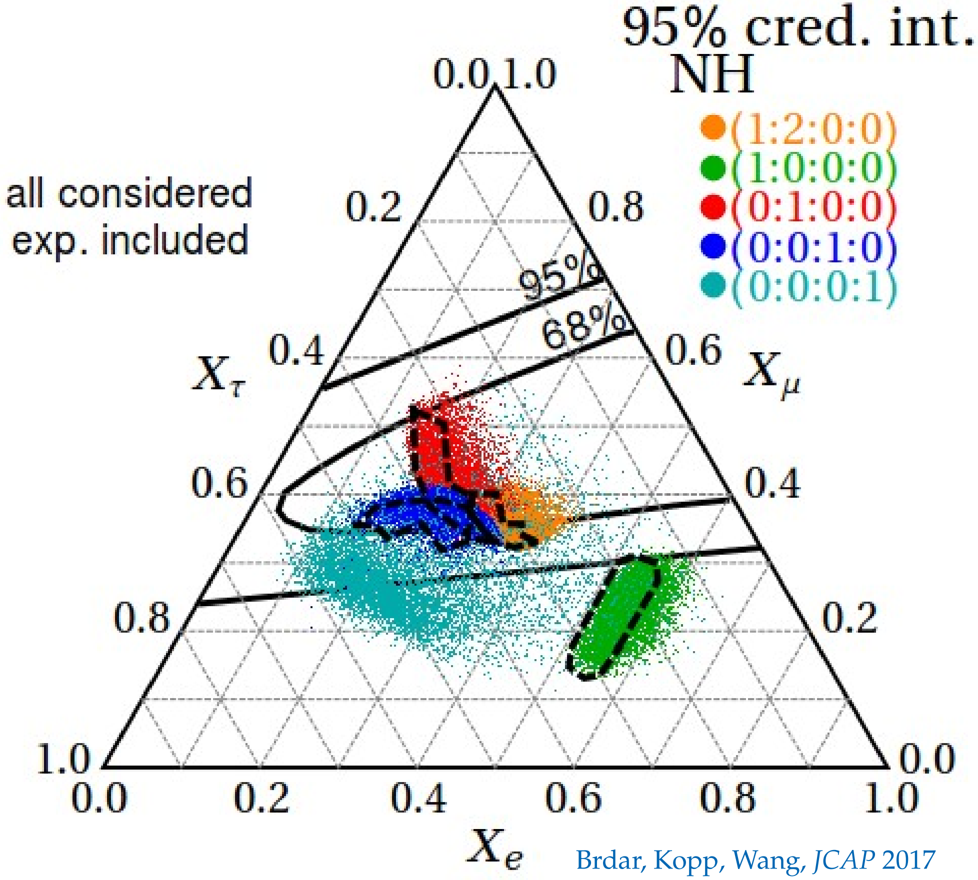
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

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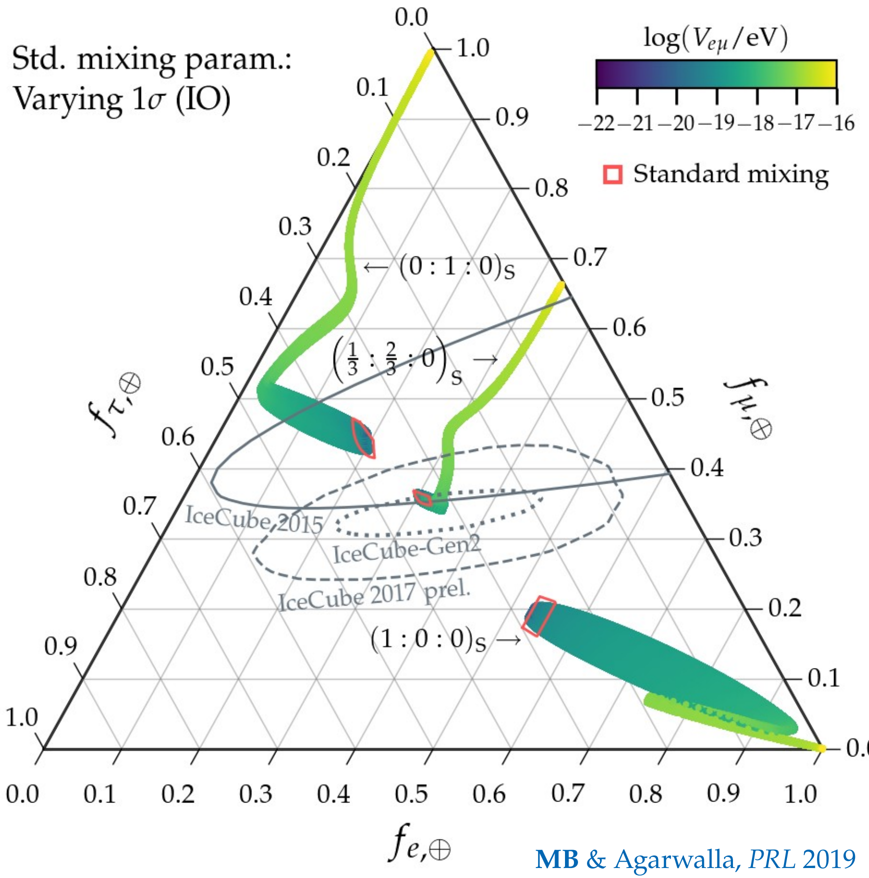
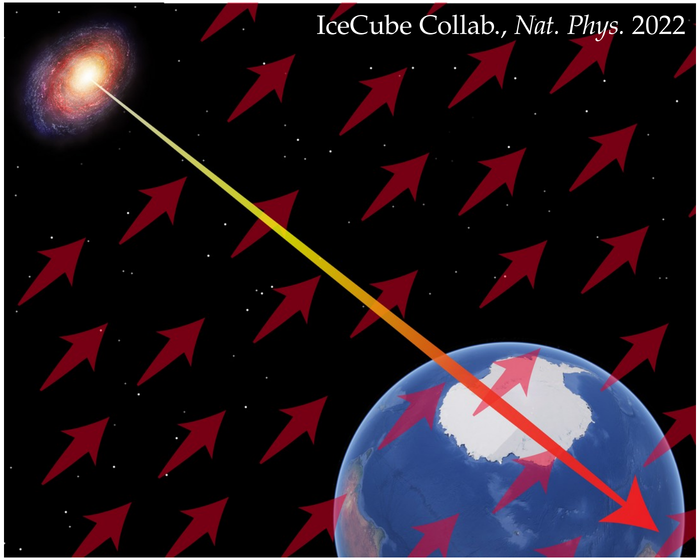
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]



MB & Agarwalla, *PRL* 2019

Reviews:
Argüelles *et al.* (inc. **MB**), *EPJC* 2023; Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

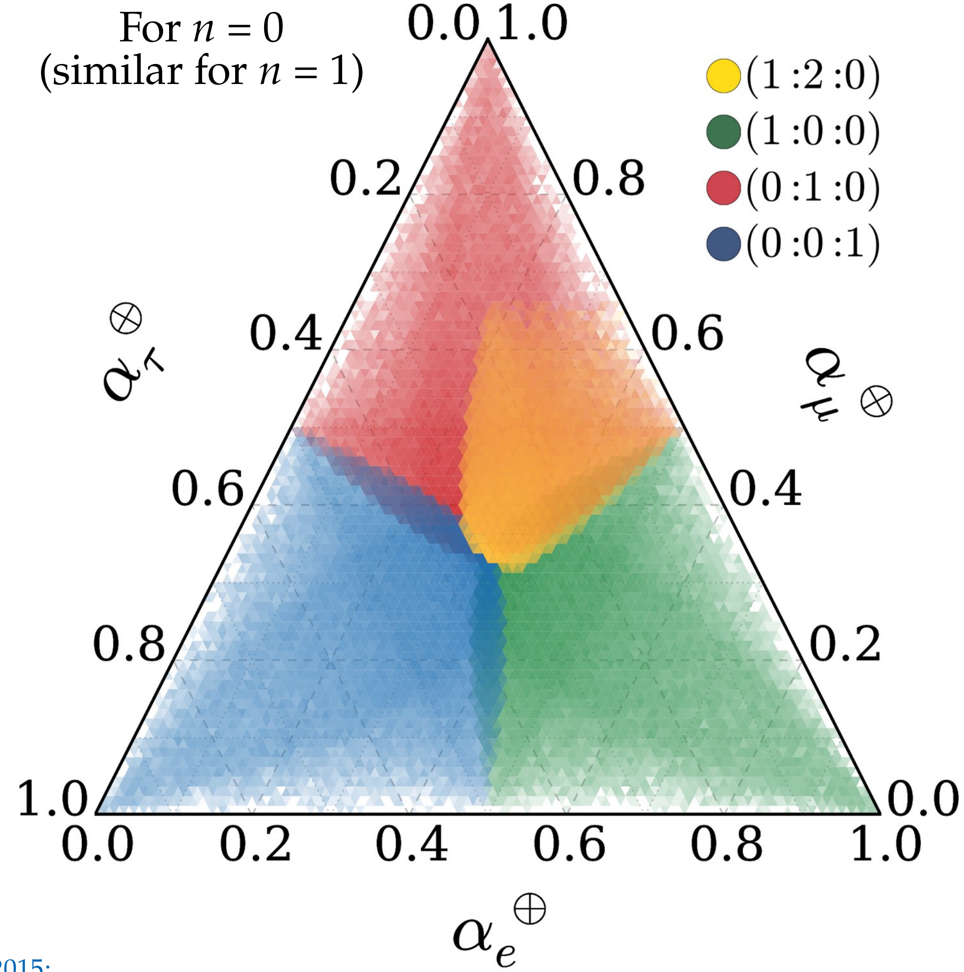
Lorentz-invariance violation can fill up the flavor triangle



$$H_{\rm tot} = H_{\rm std} + H_{\rm NP}$$

$$H_{\rm std} = \frac{1}{2E} U^\dagger_{\rm PMNS}\,{\rm diag}\left(0, \Delta m^2_{21}, \Delta m^2_{31}\right) U_{\rm PMNS}$$

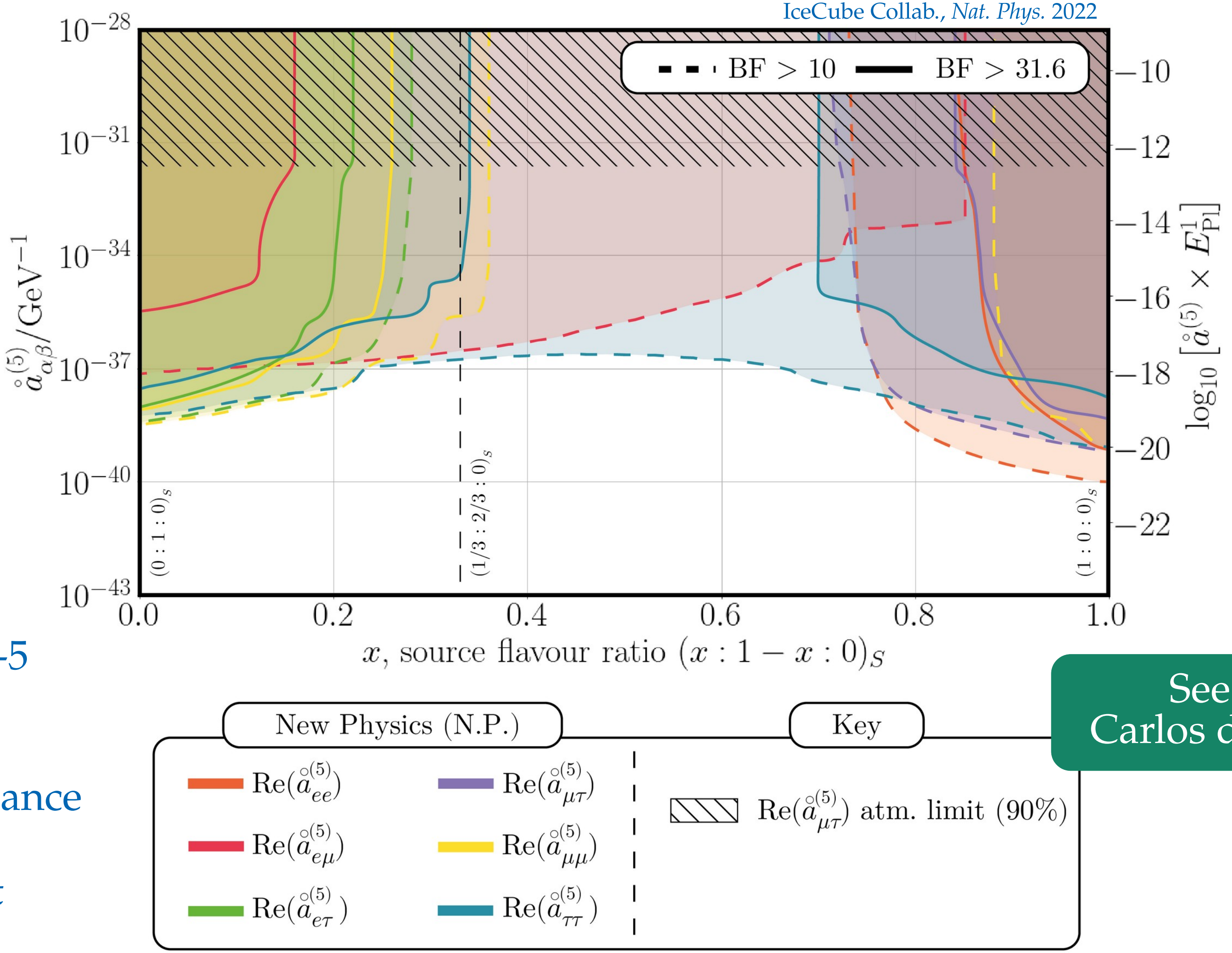
$$H_{\rm NP} = \sum_n \left(\frac{E}{\Lambda_n}\right)^n U^\dagger_n\,{\rm diag}\left(O_{n,1}, O_{n,2}, O_{n,3}\right) U_n$$



See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

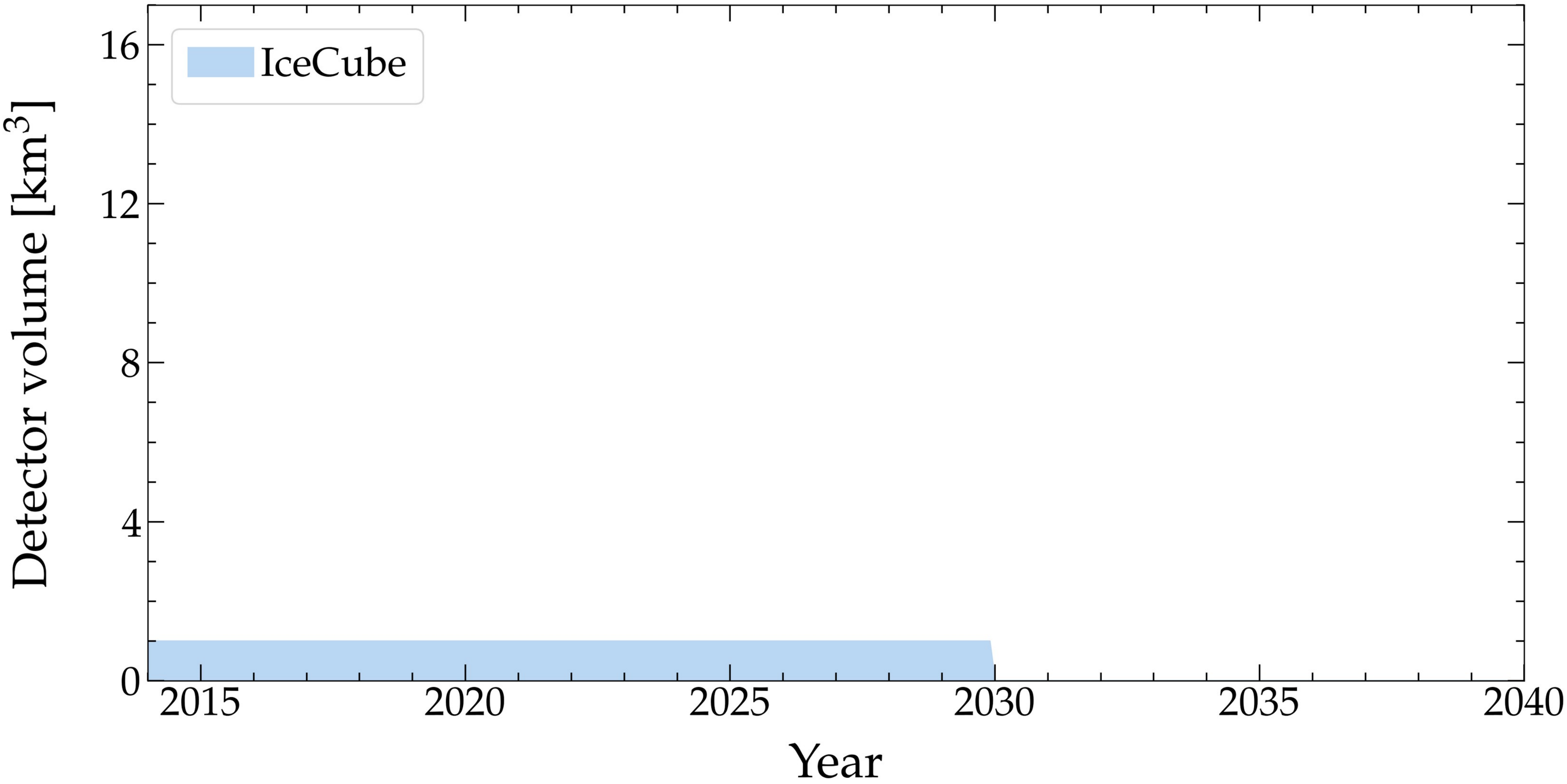
Argüelles, Katori, Salvadó, *PRL* 2015

IceCube Collab., *Nat. Phys.* 2022

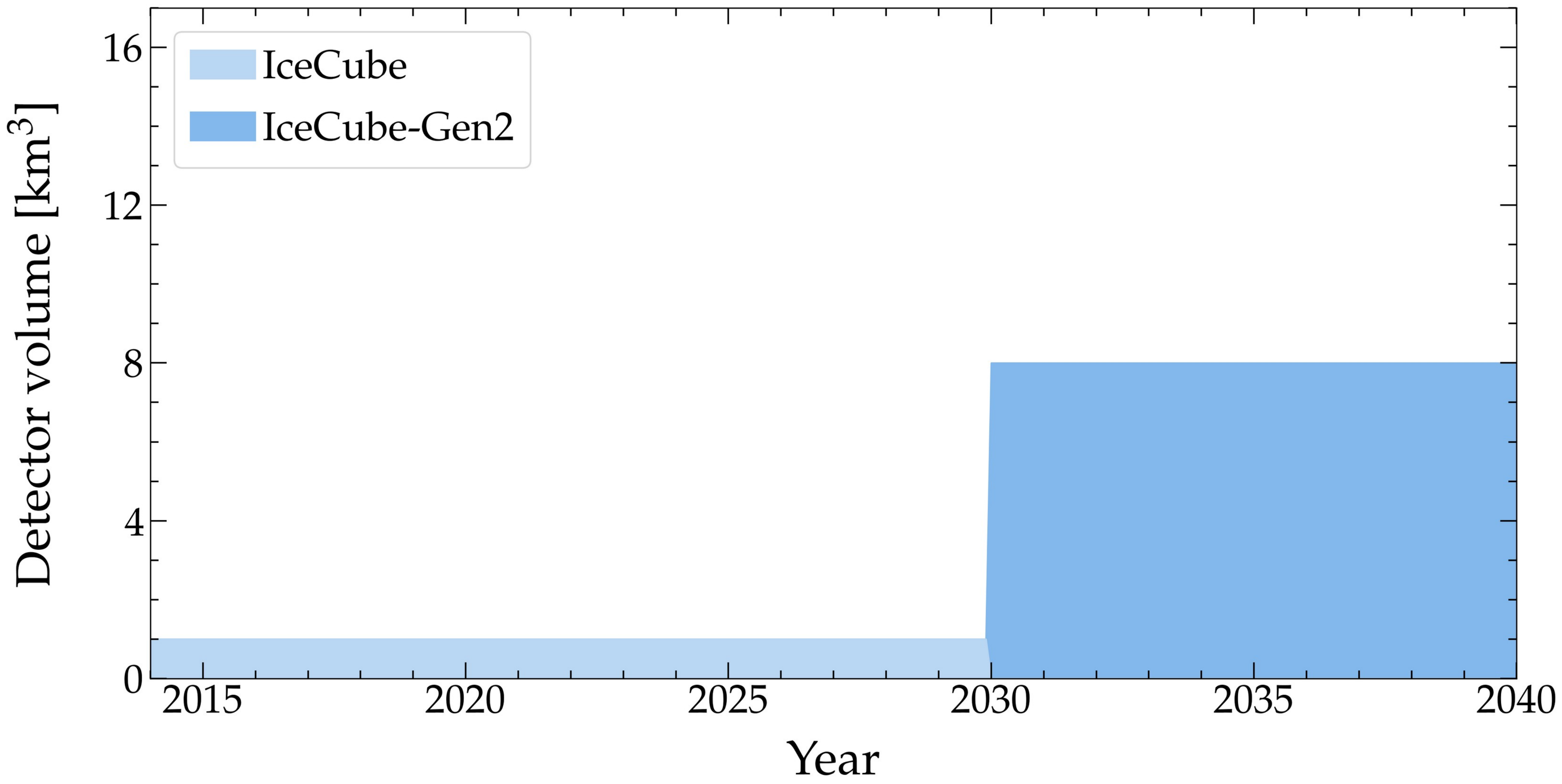


Dimension-5
CPT-odd
Isotropic
Lorentz-invariance
-violating
coefficient

See talk by
Carlos de los Heros



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



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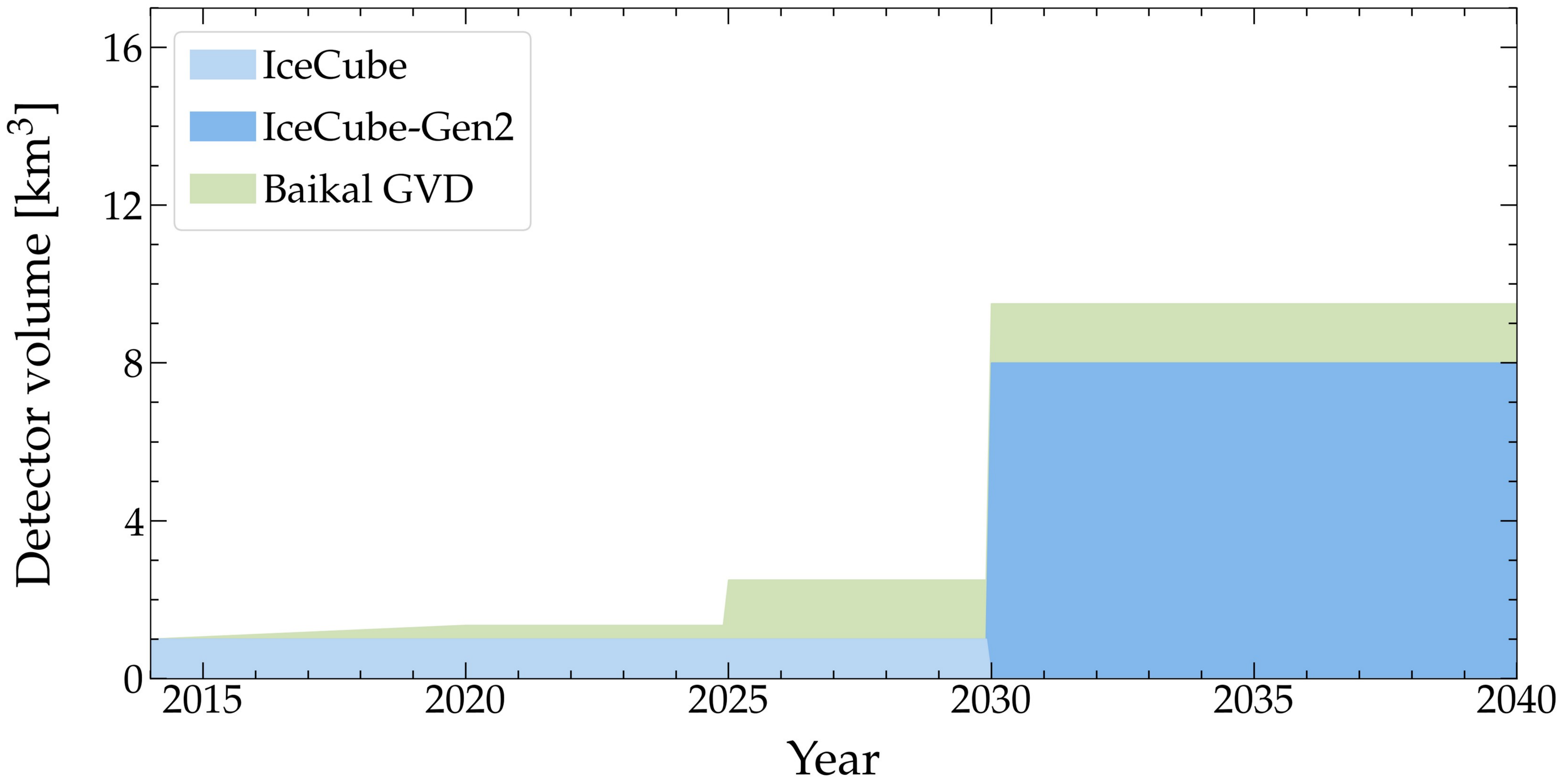

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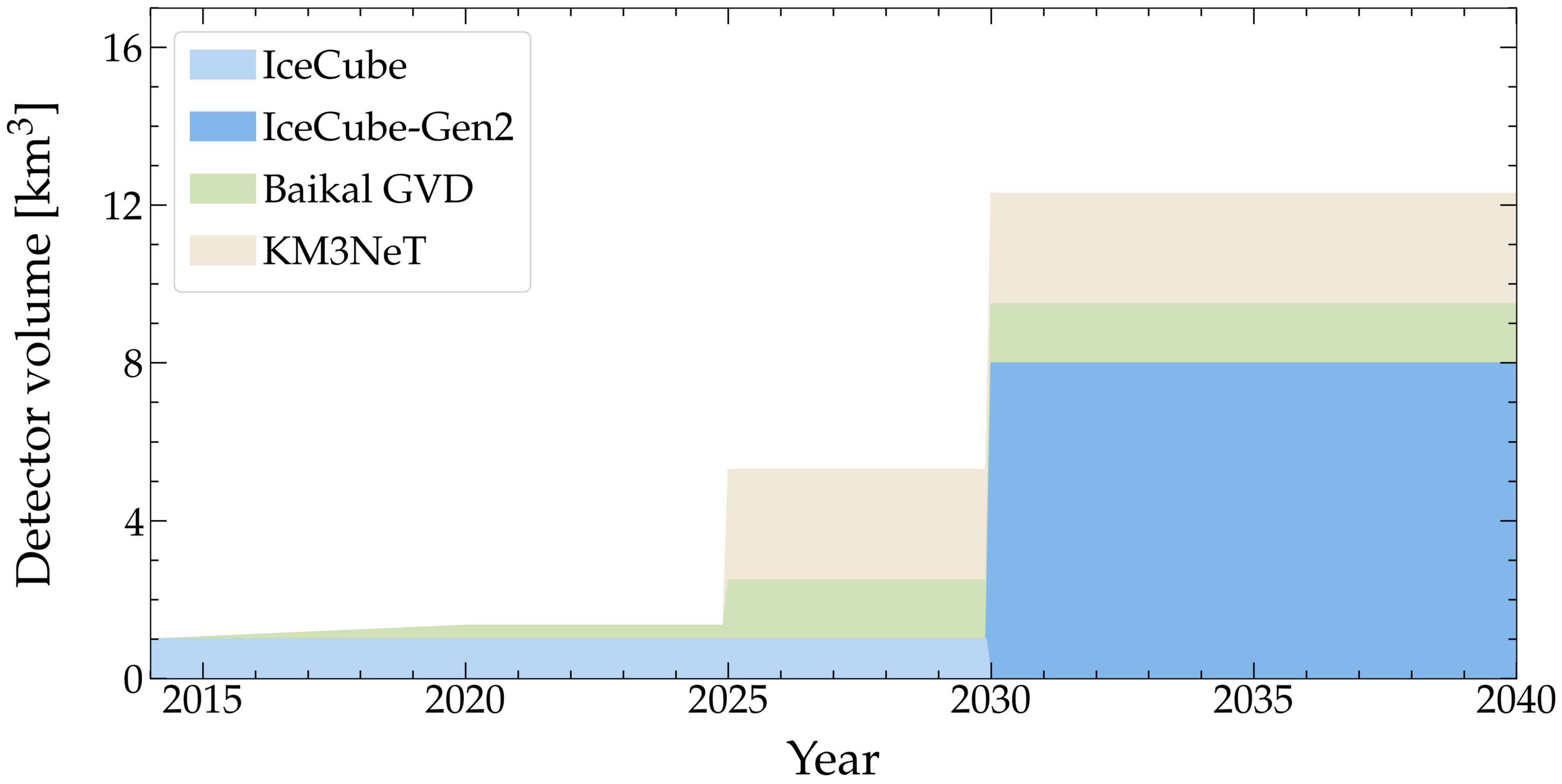

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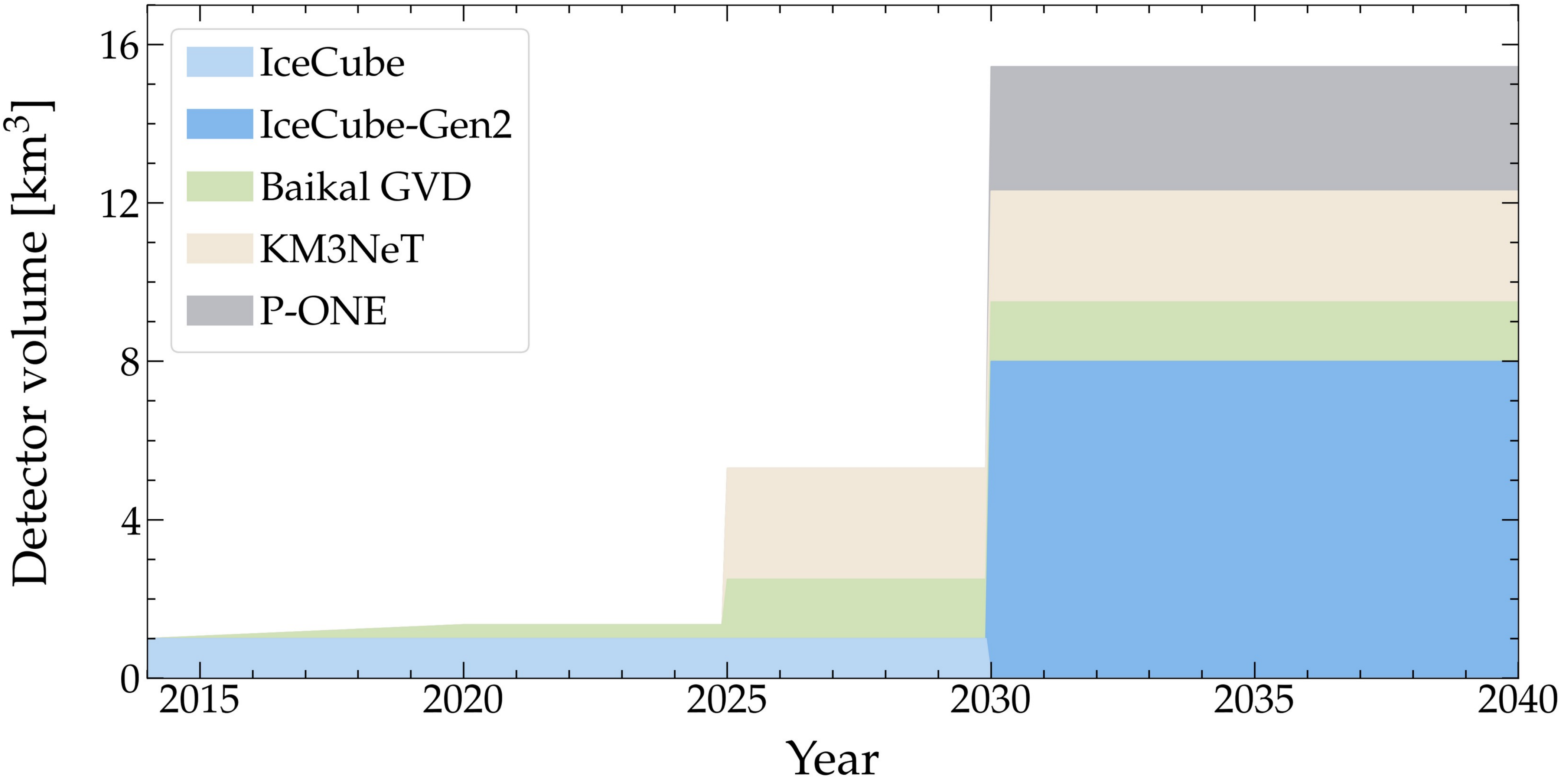
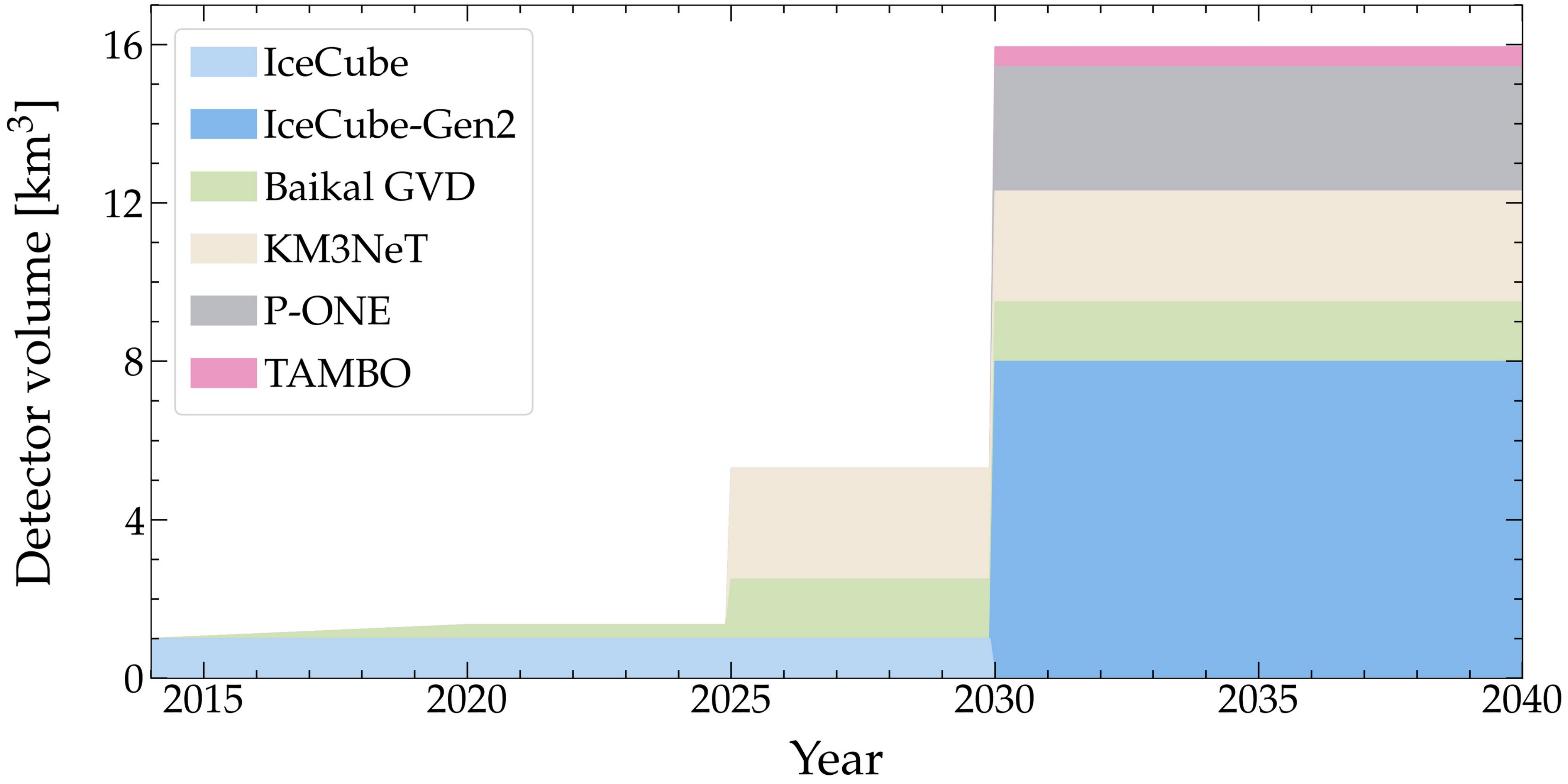
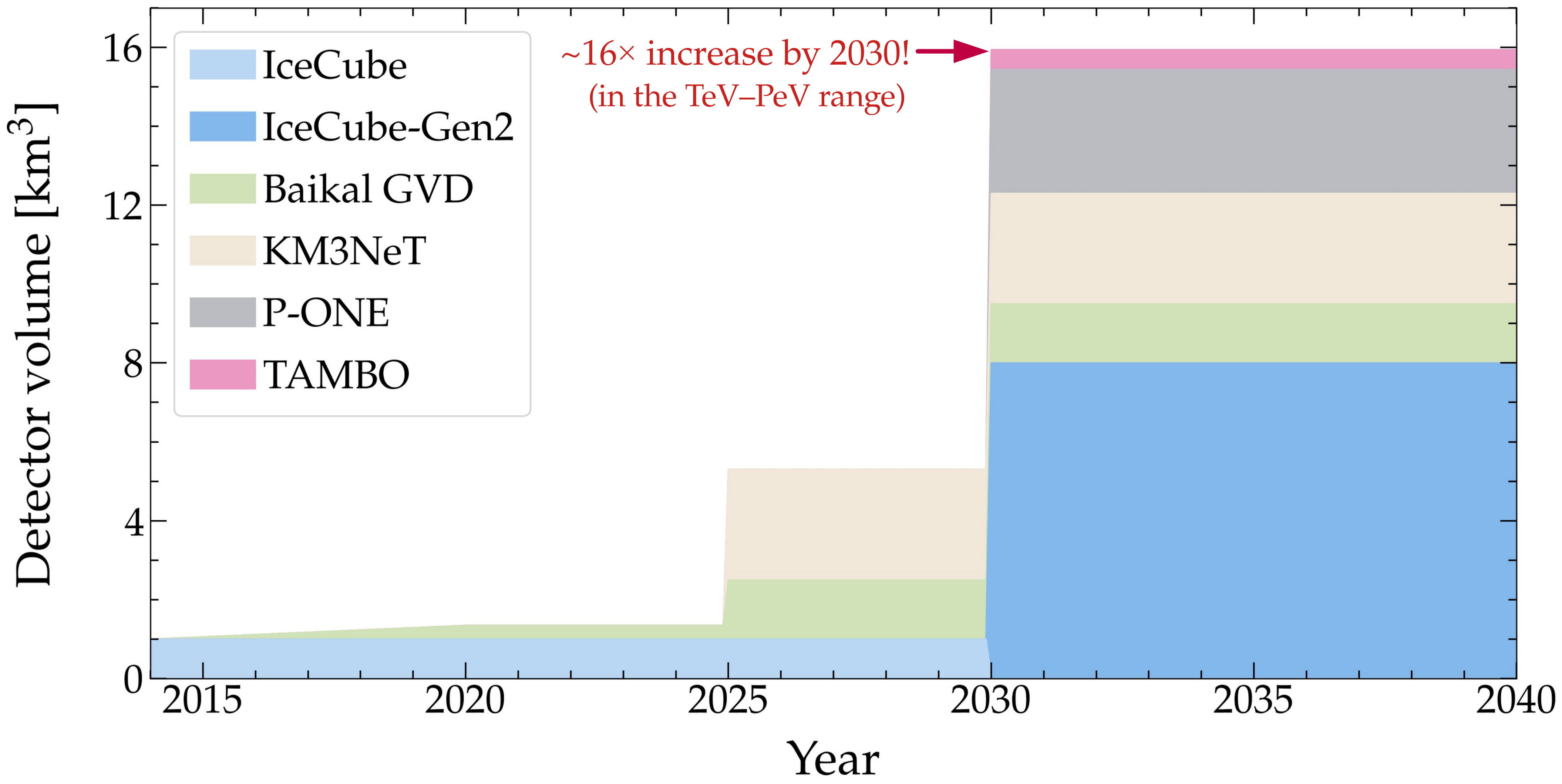


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



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

Measuring flavor composition: 2015–2040

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

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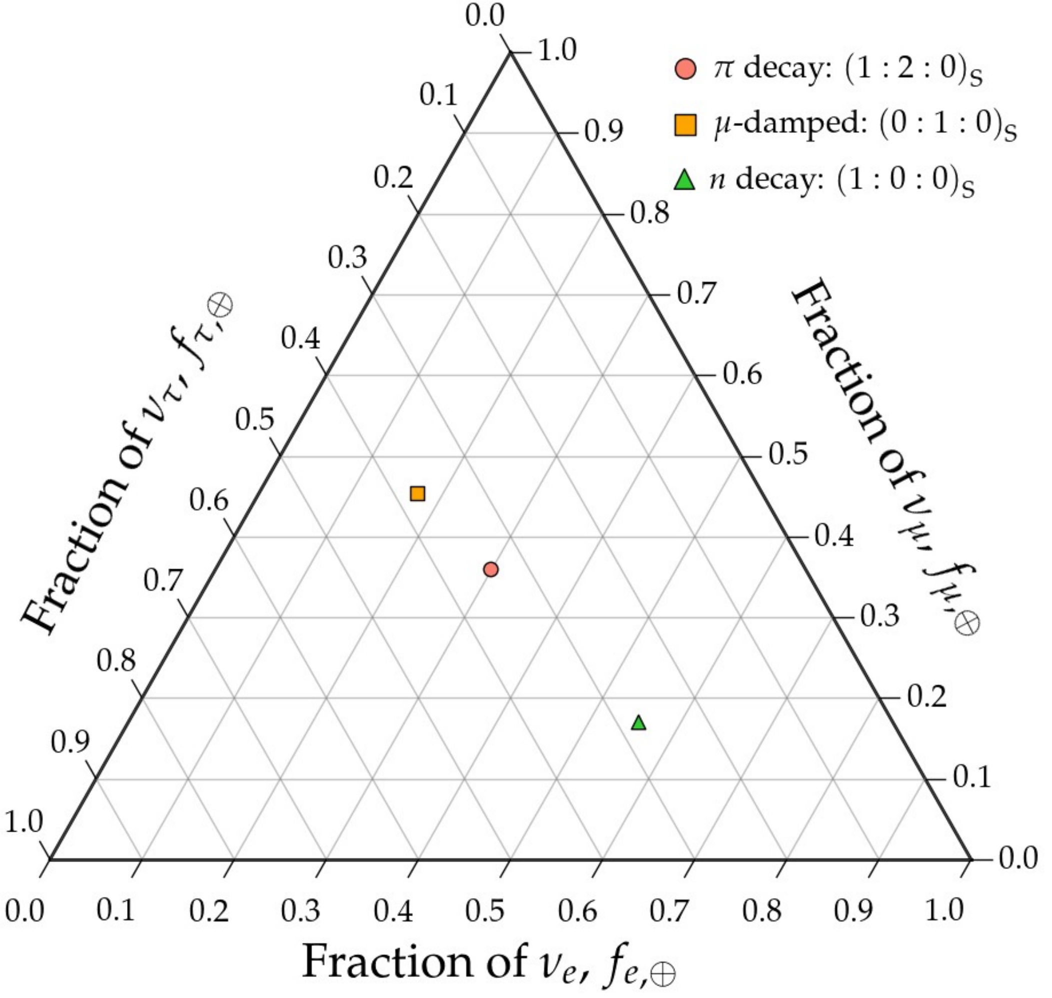

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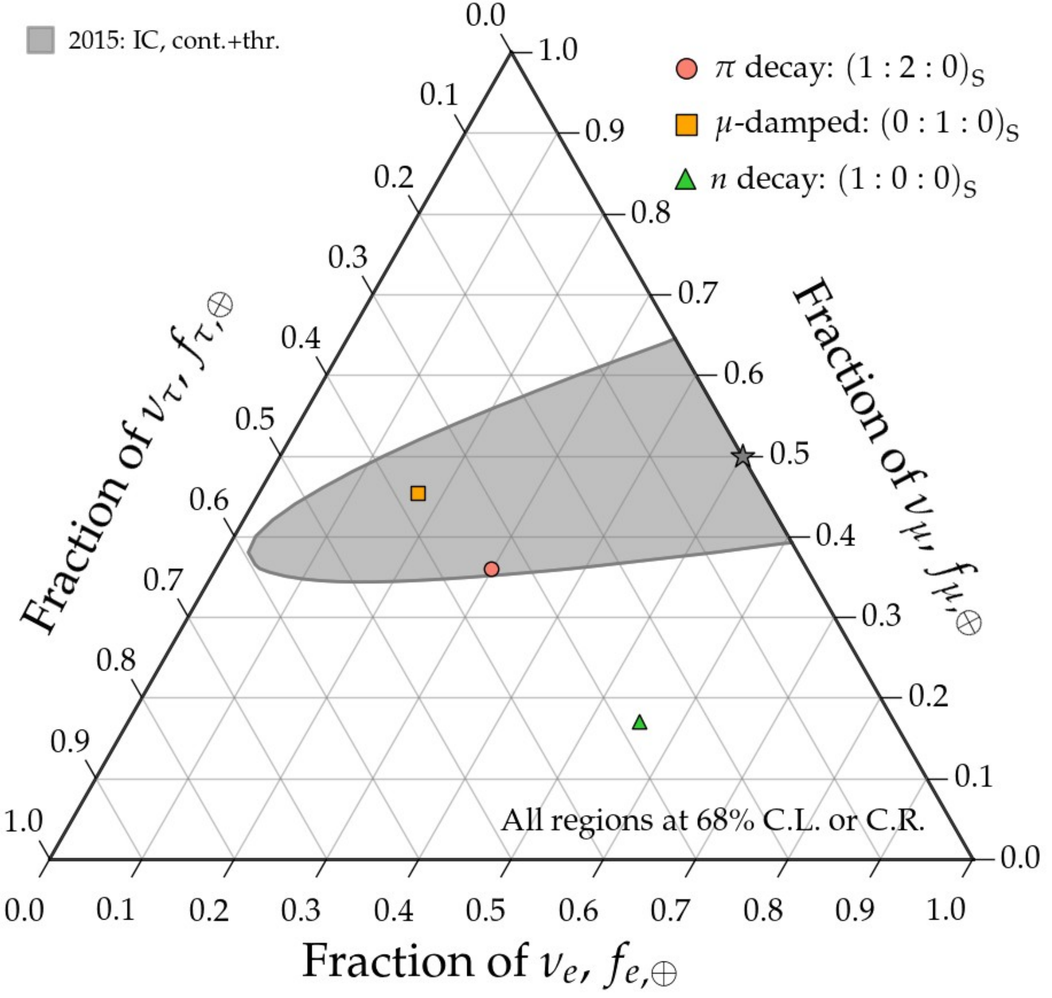

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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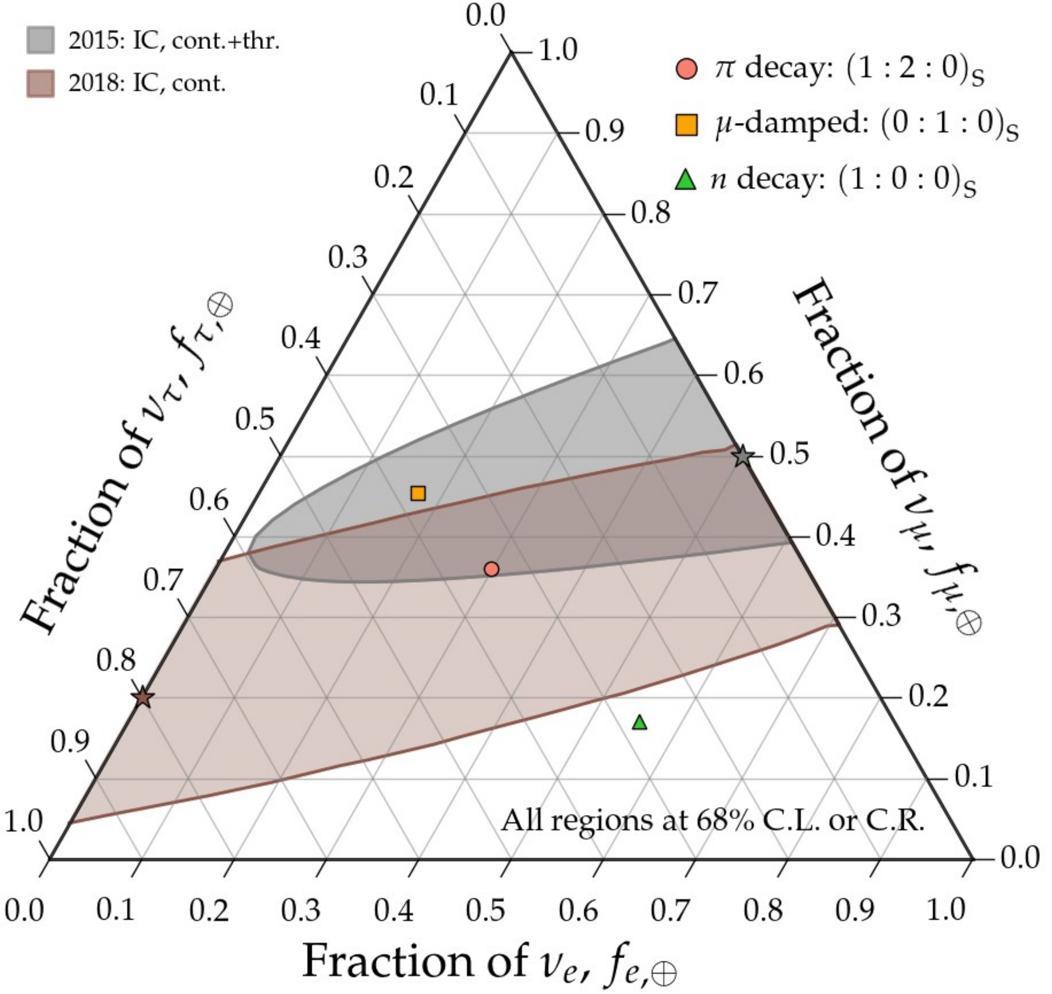

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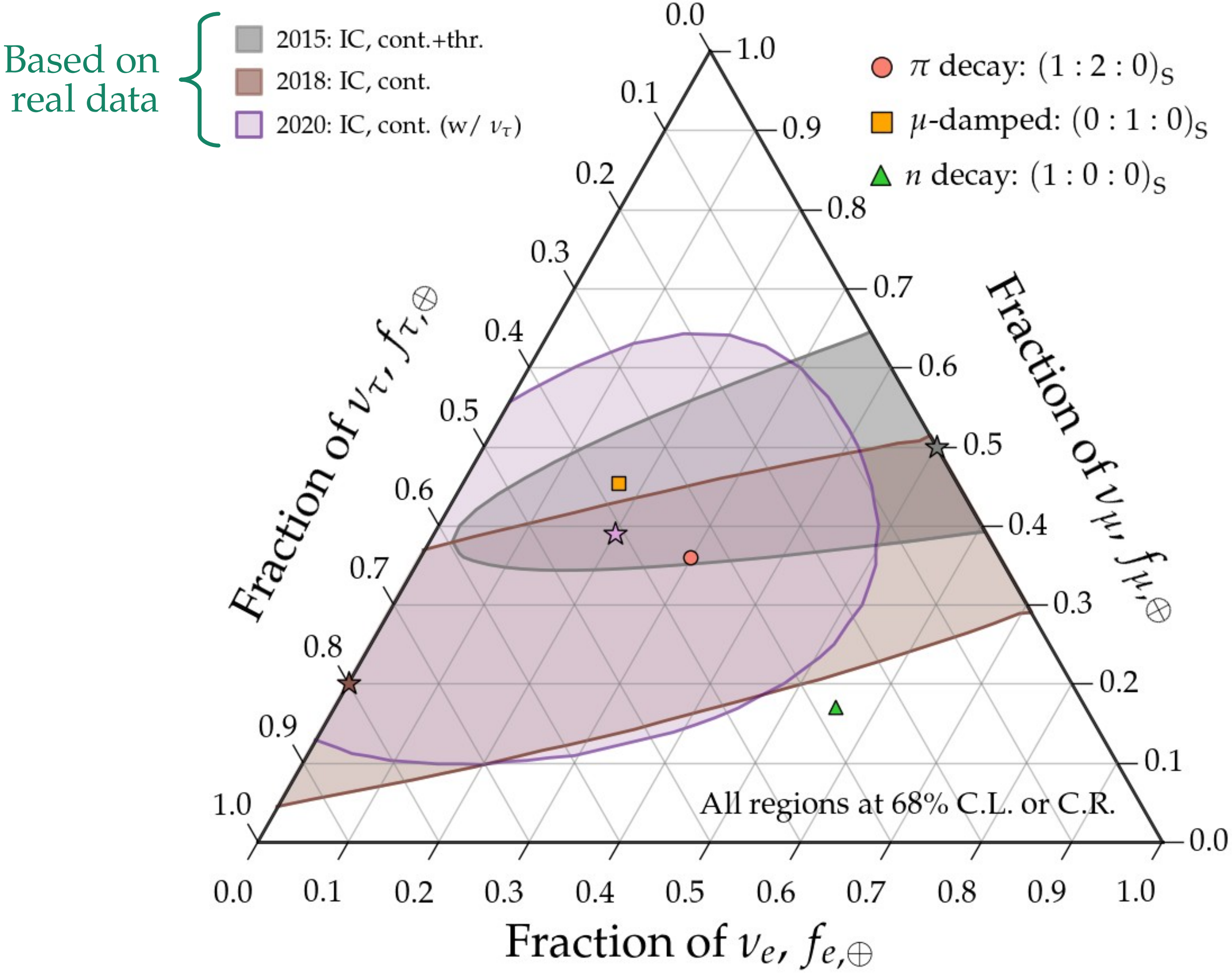

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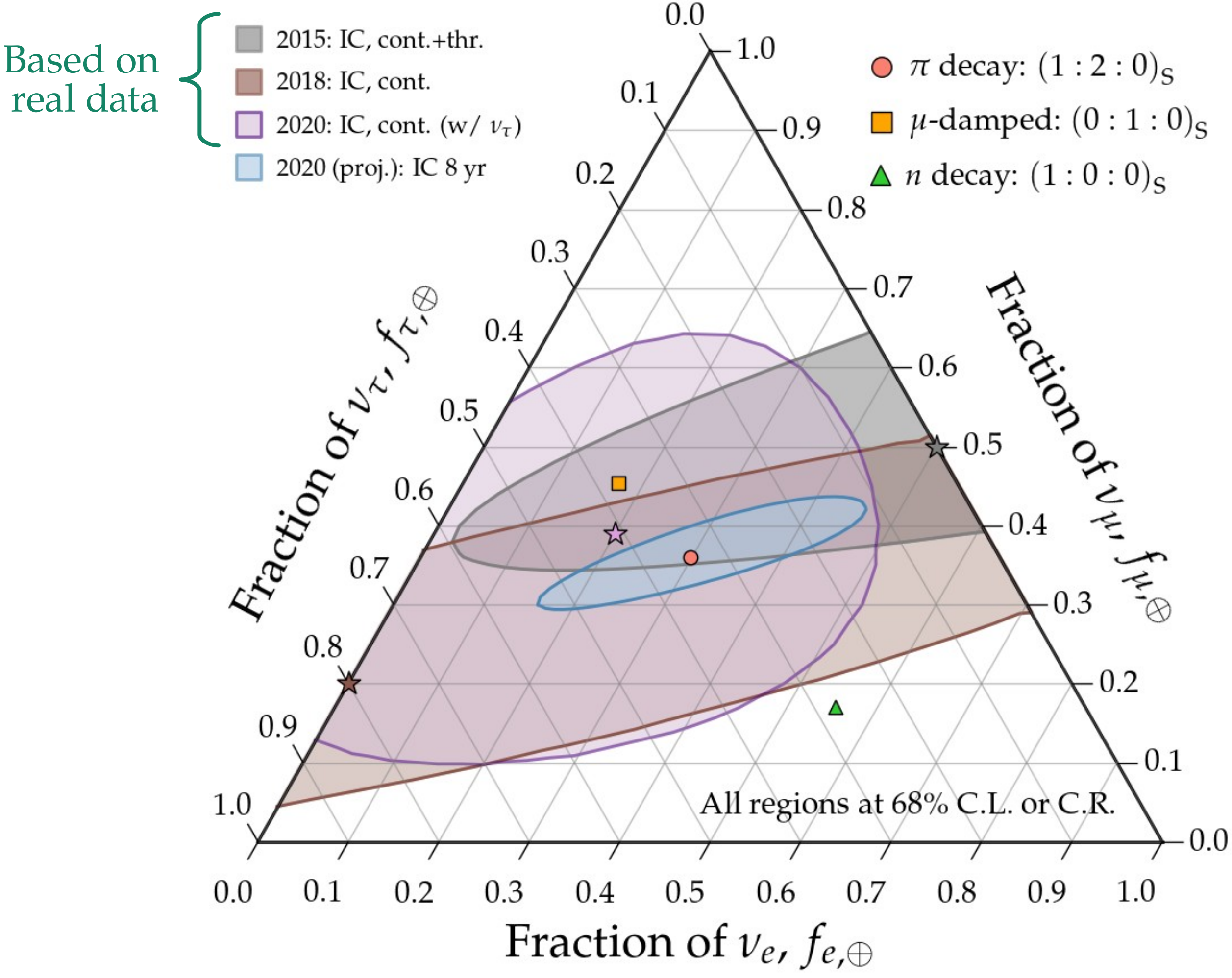

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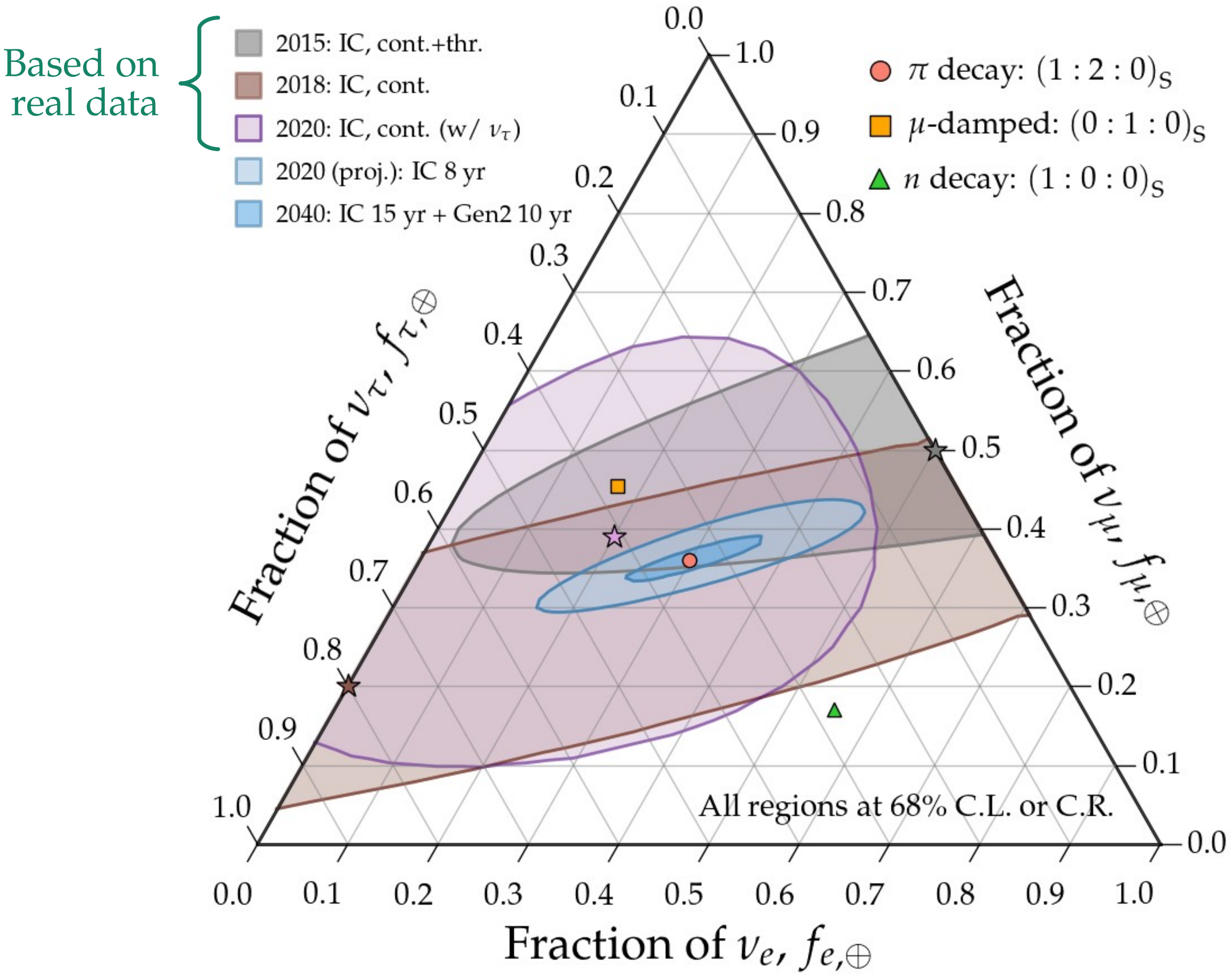

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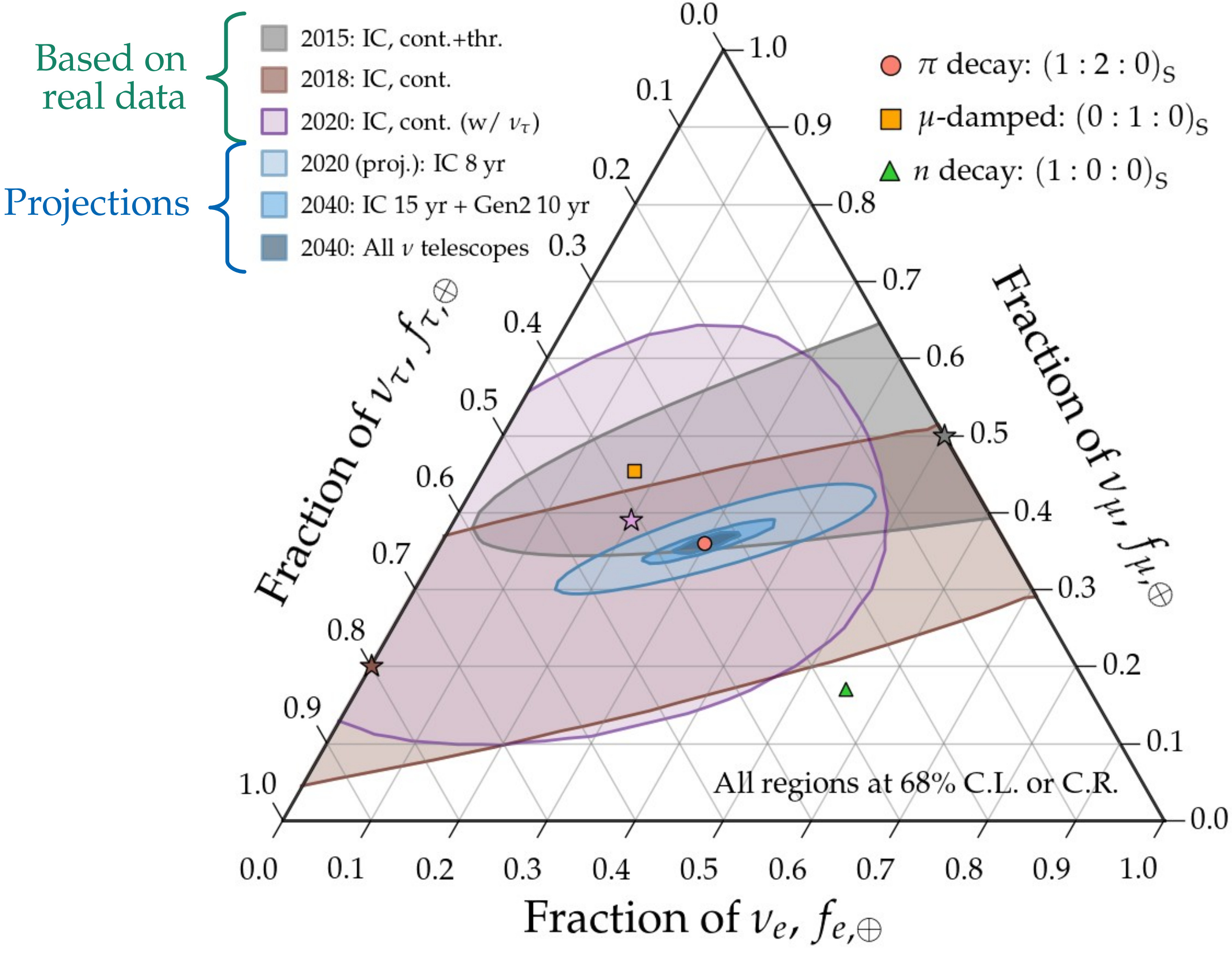
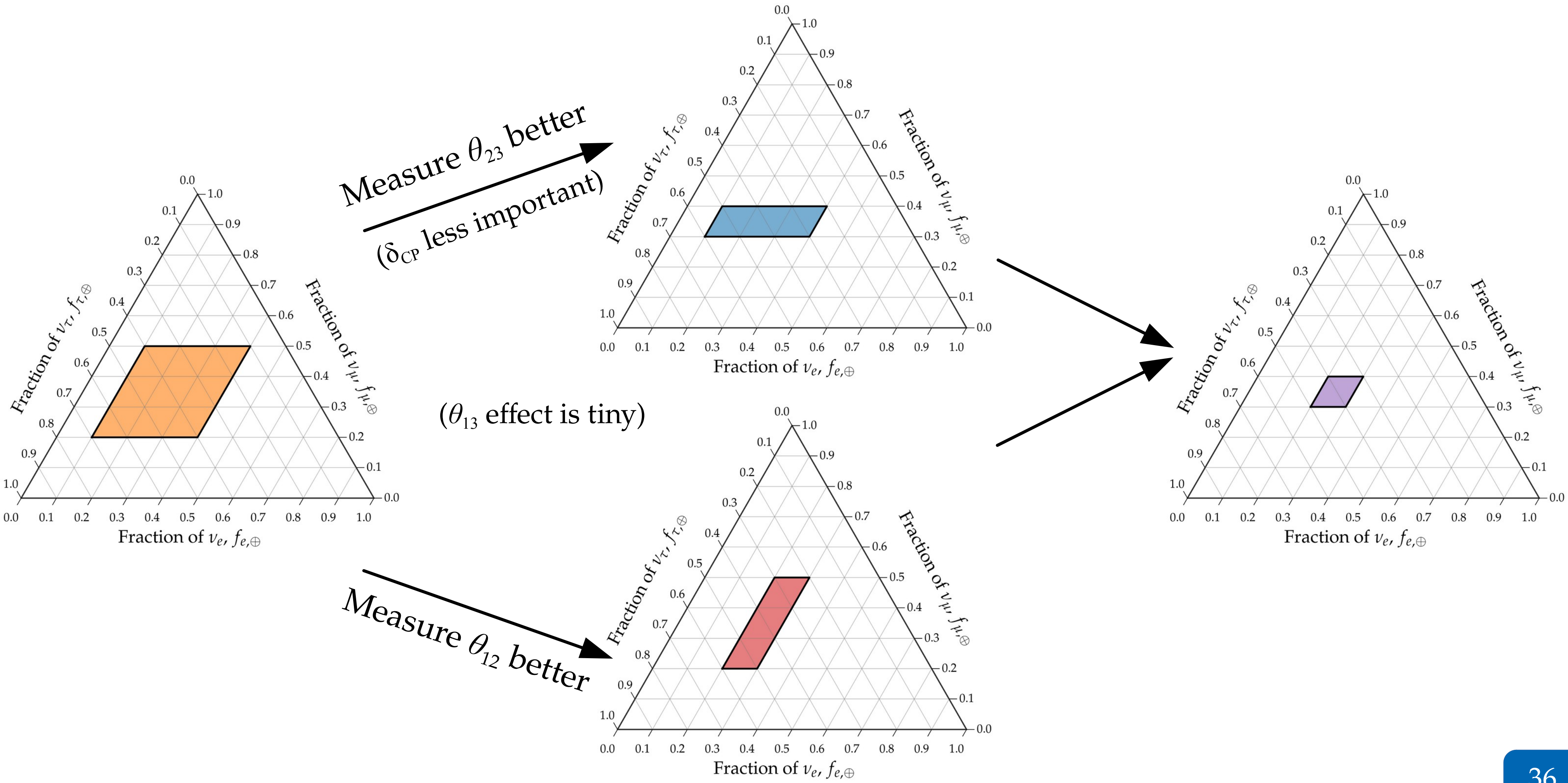


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

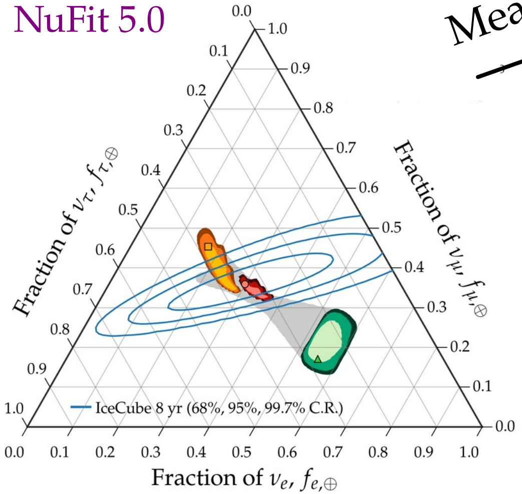
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

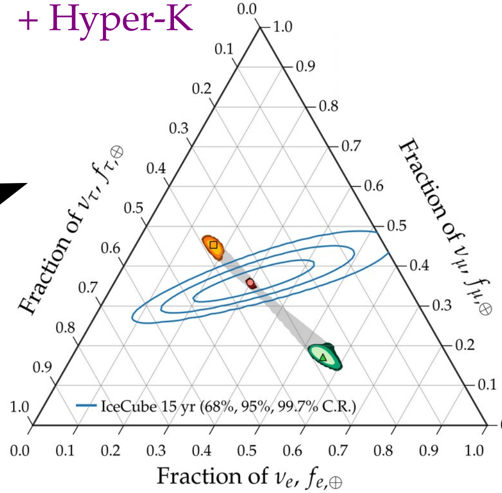
2020

NuFit 5.0

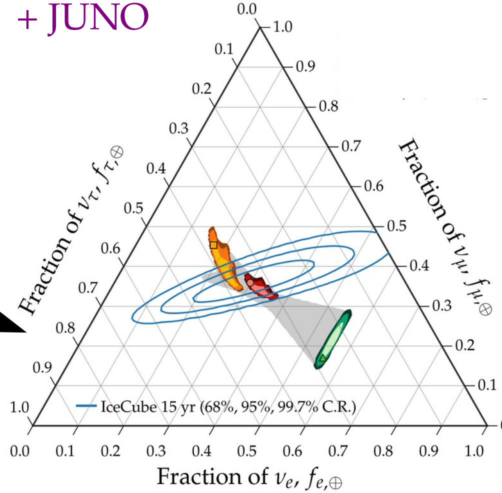


Measure θ_{23} better

+ Hyper-K



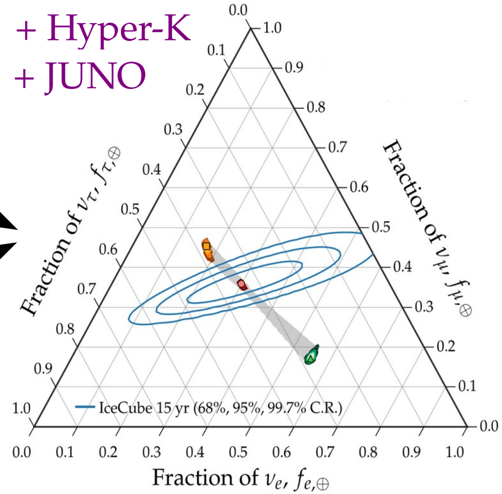
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

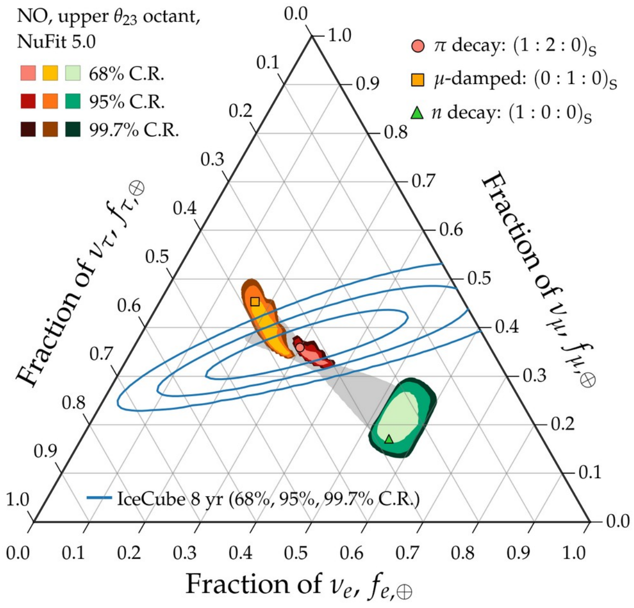
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: 2020 → 2030 → 2040

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



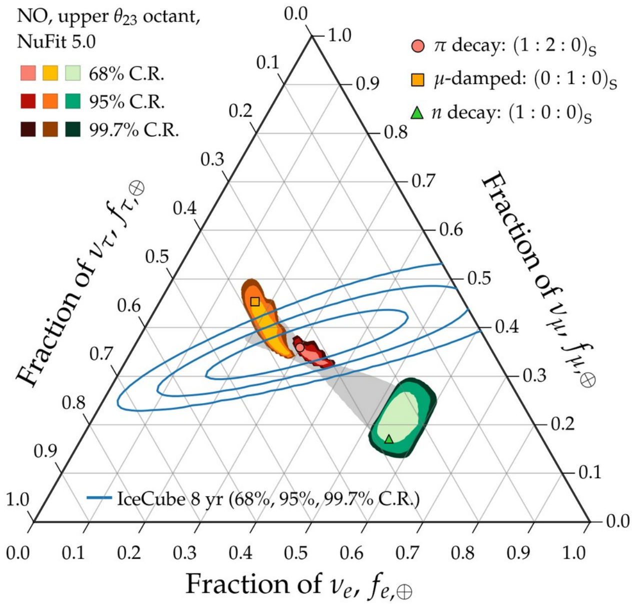
Allowed regions: overlapping

Measurement: imprecise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

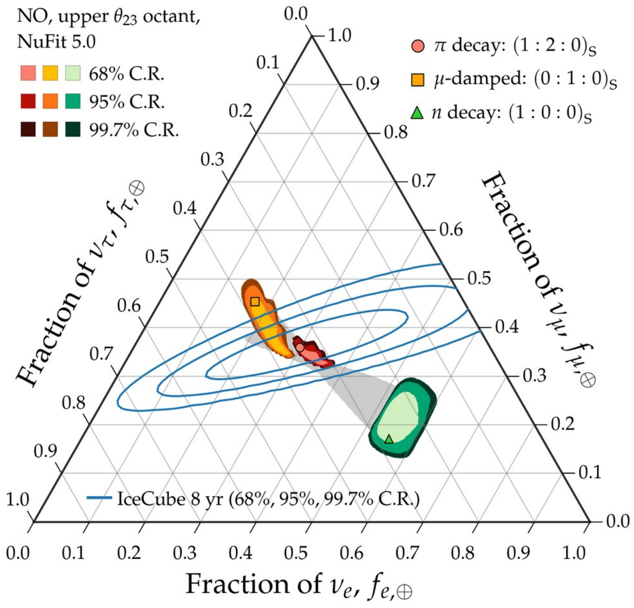
Measurement: imprecise

Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

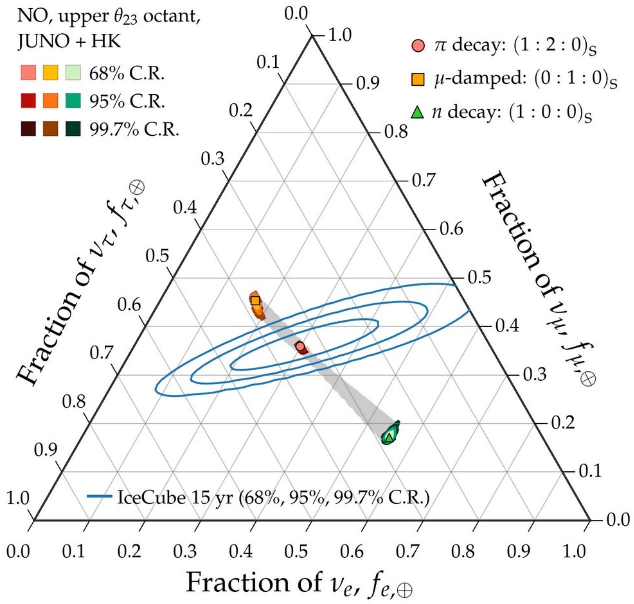


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



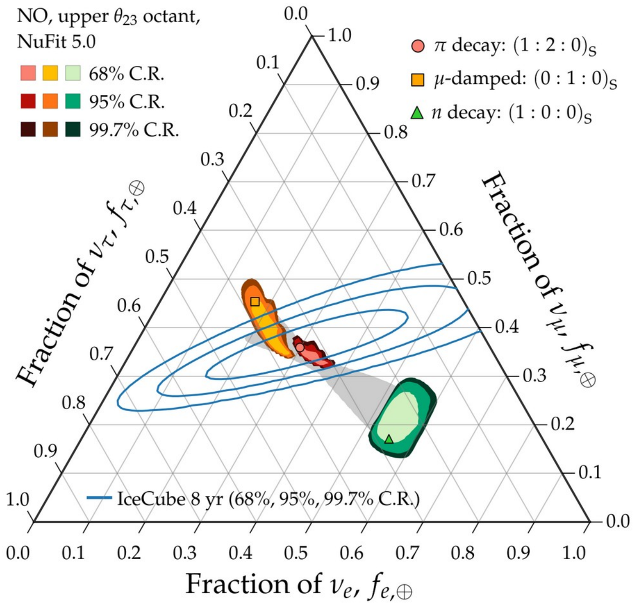
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

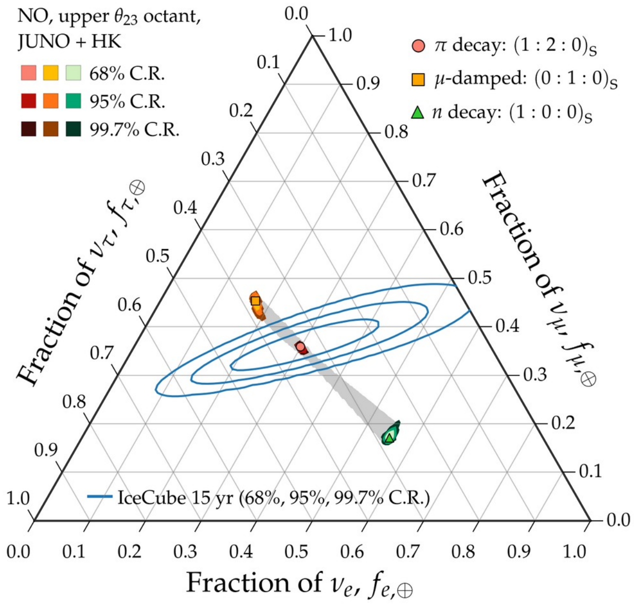


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

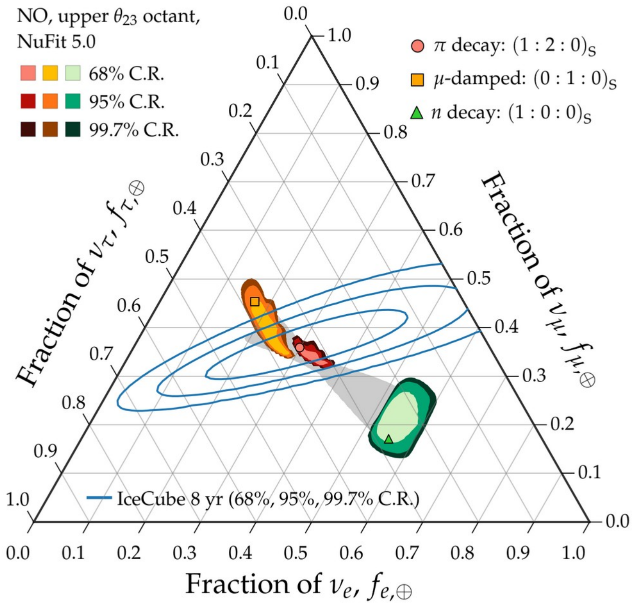
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

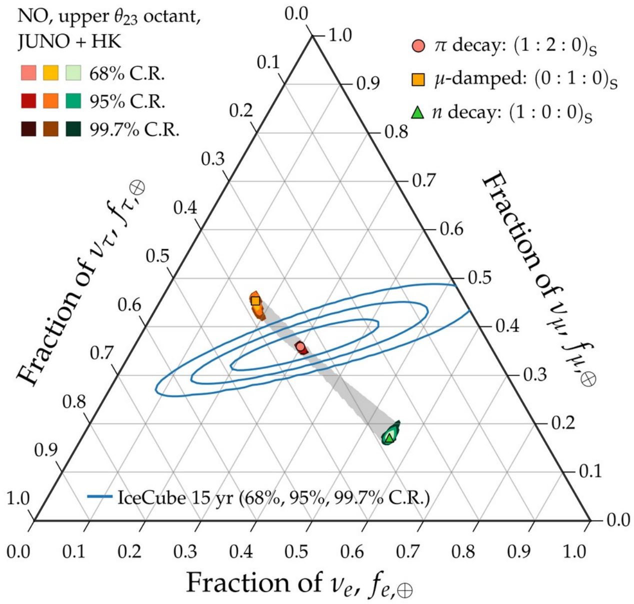


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

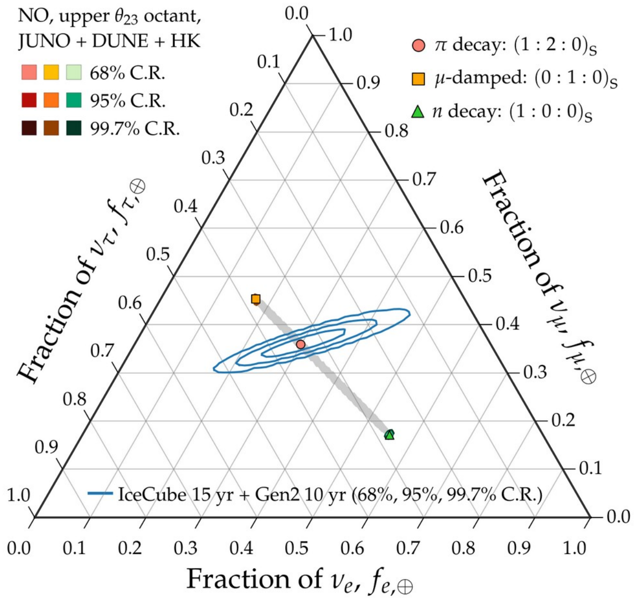


Allowed regions: well separated

Measurement: improving

Nice

2040



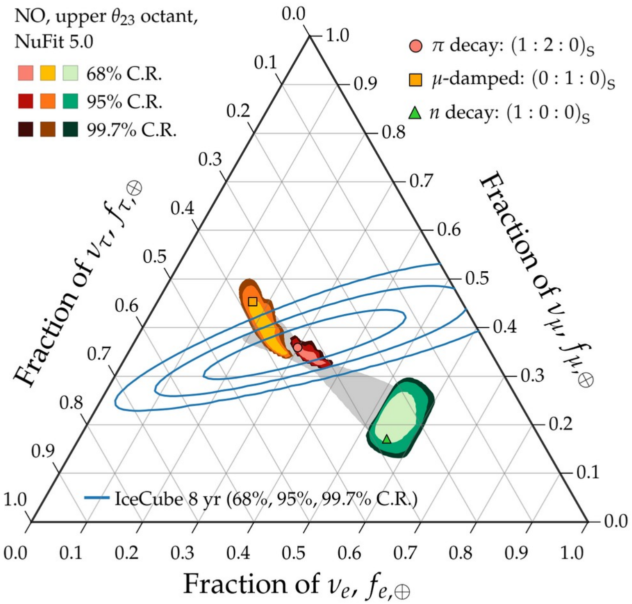
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

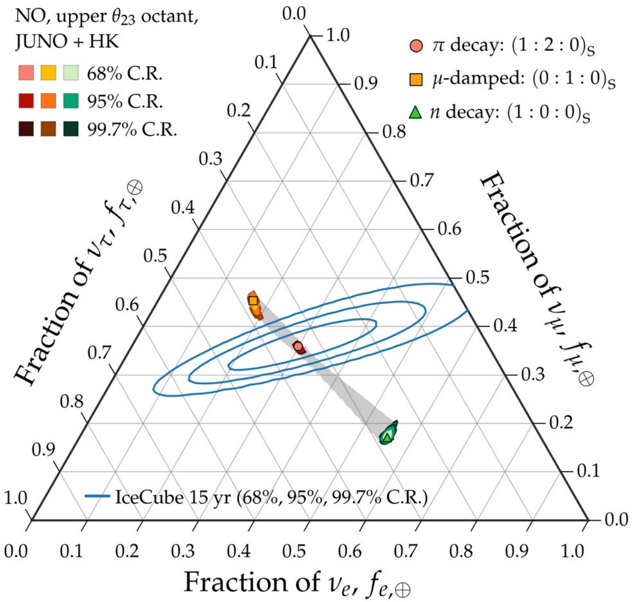
2020



Allowed regions: overlapping
Measurement: imprecise

Not ideal

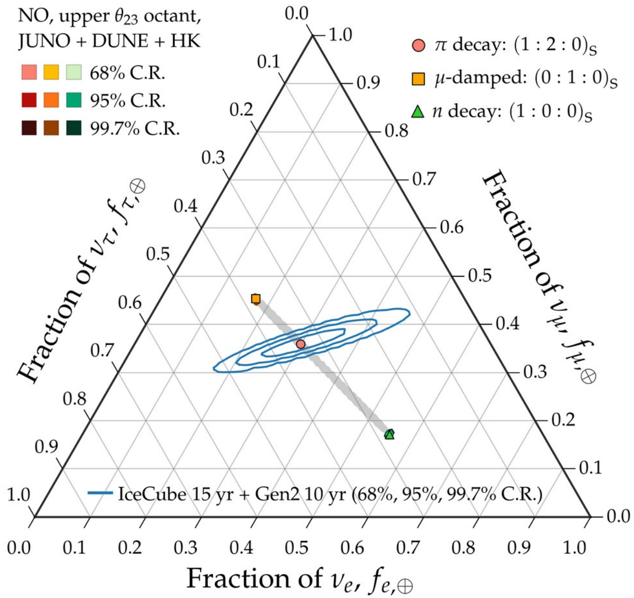
2030



Allowed regions: well separated
Measurement: improving

Nice

2040



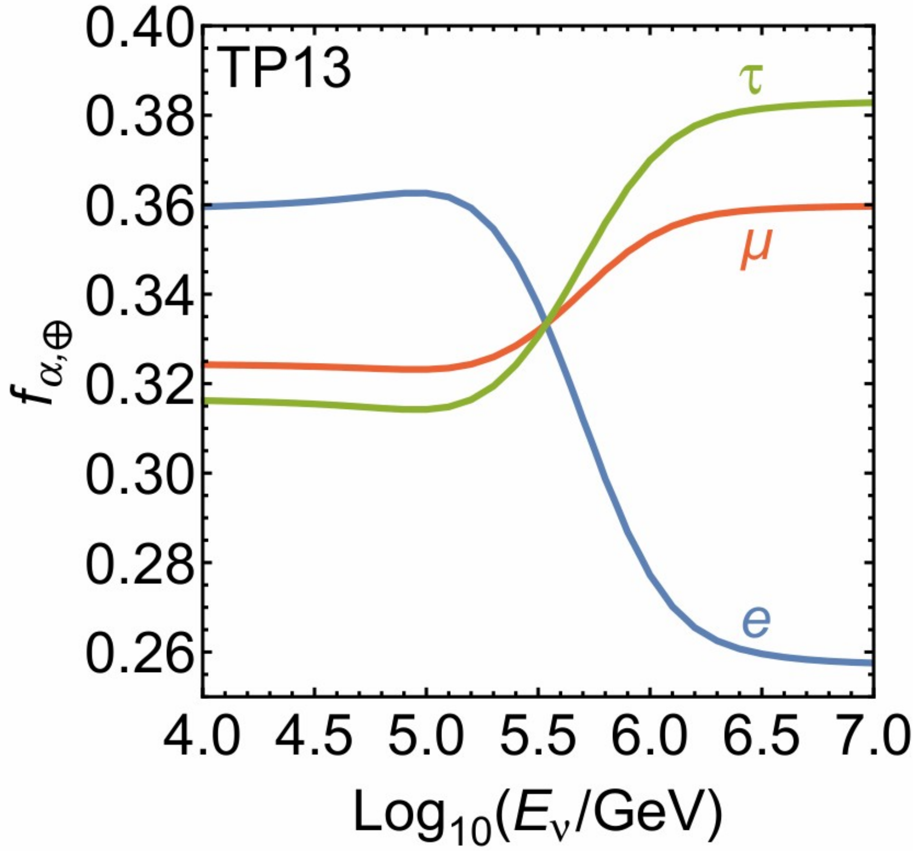
Allowed regions: well separated
Measurement: precise

Success

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

Flavor composition: measuring the energy dependence

Expected from astrophysical processes



MB, Beacom, Winter *PRL* 2015

Flavor composition: measuring the energy dependence

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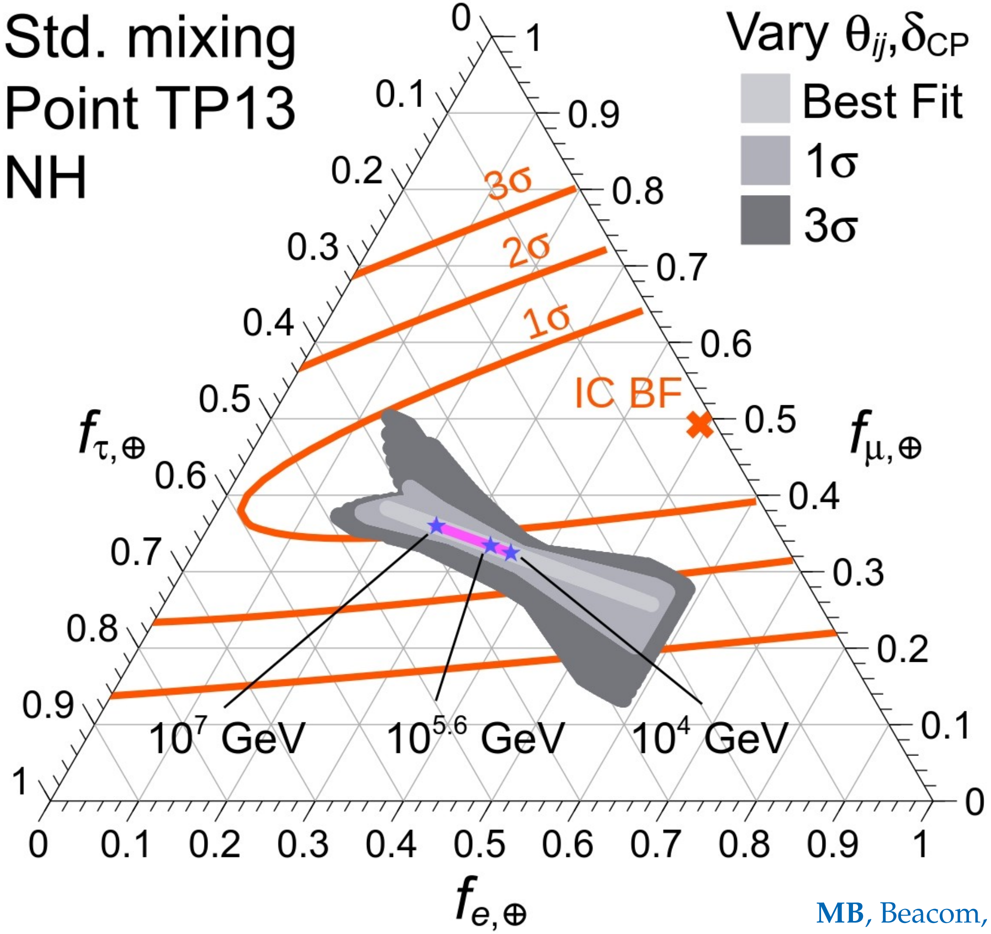

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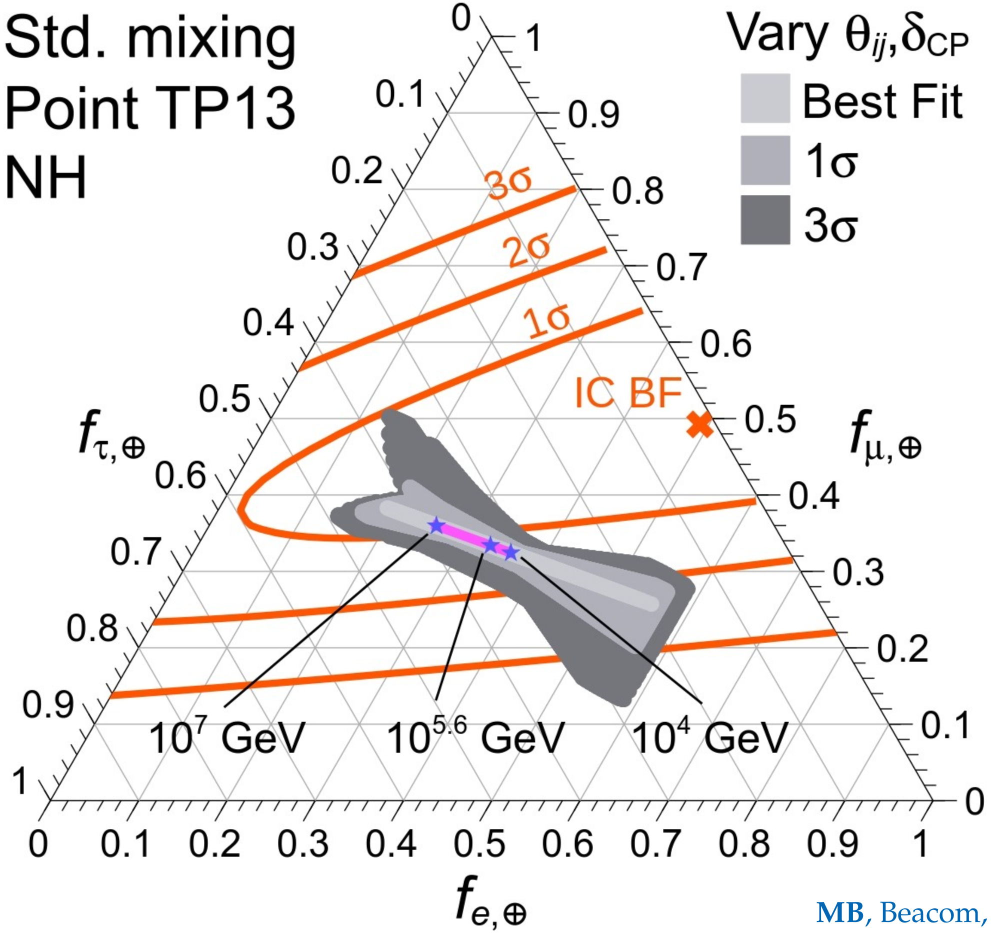
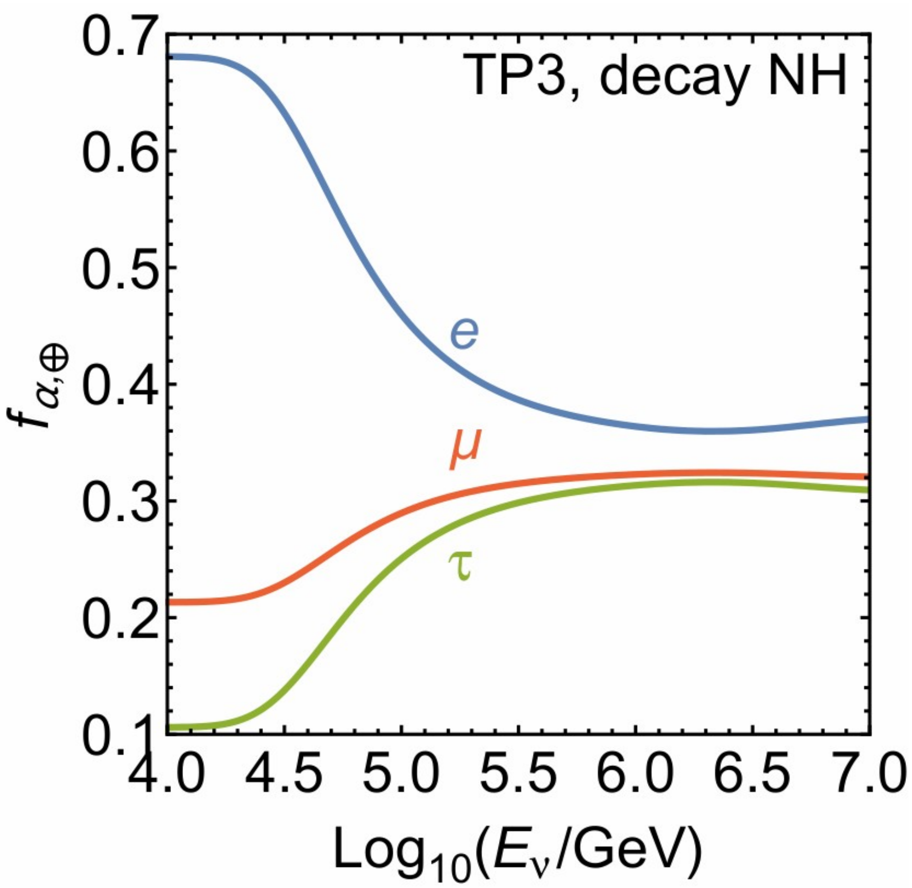


Expected from new physics (*e.g.*, ν decay)



MB, Beacom, Winter *PRL* 2015

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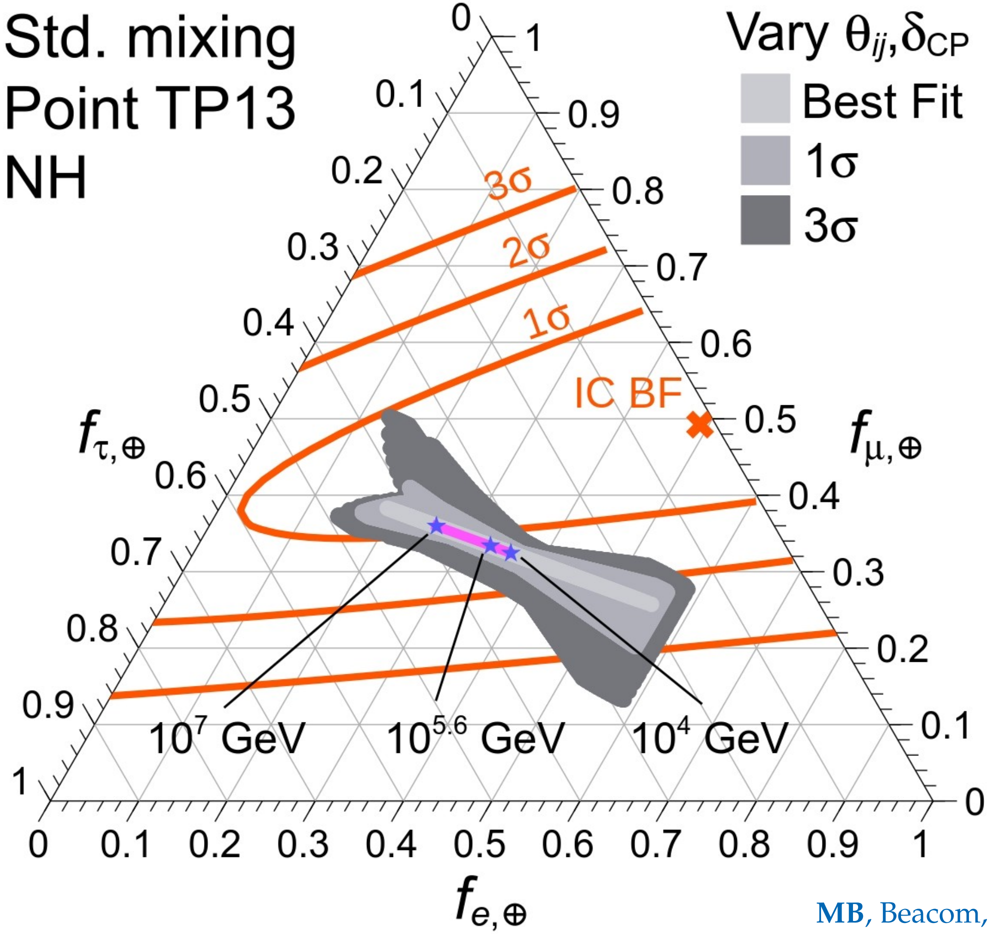
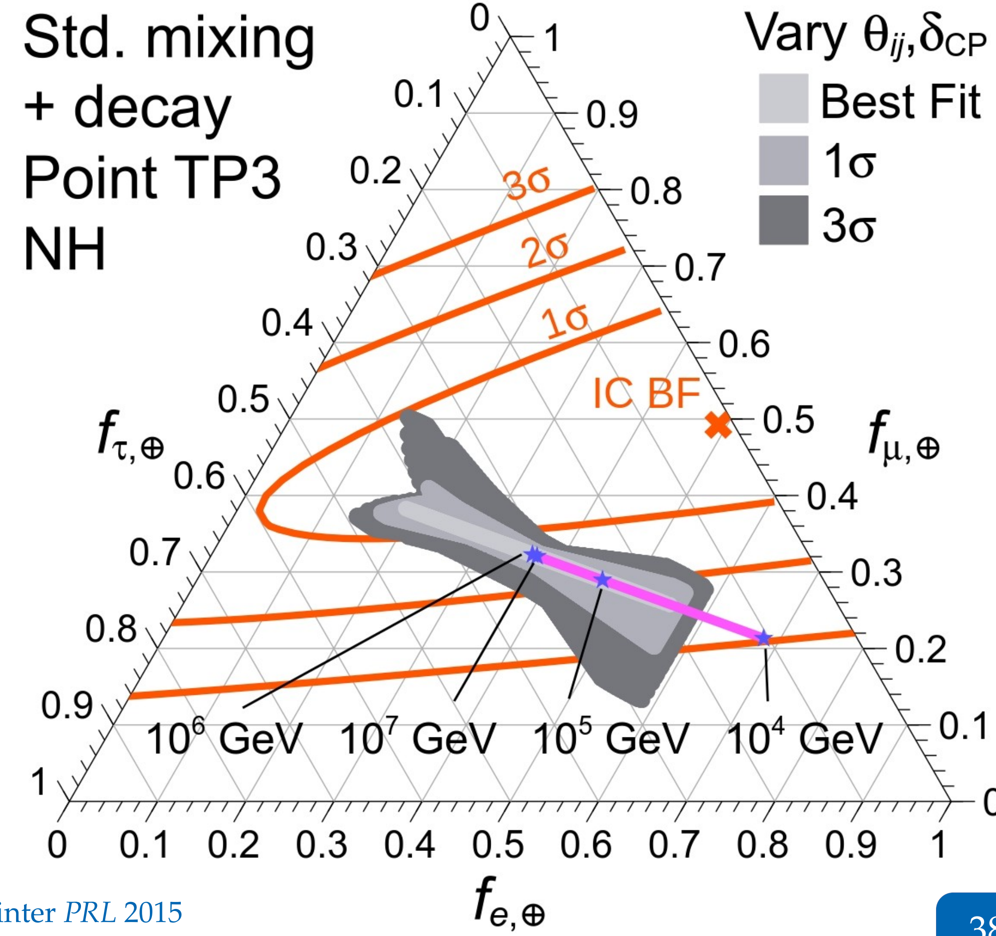
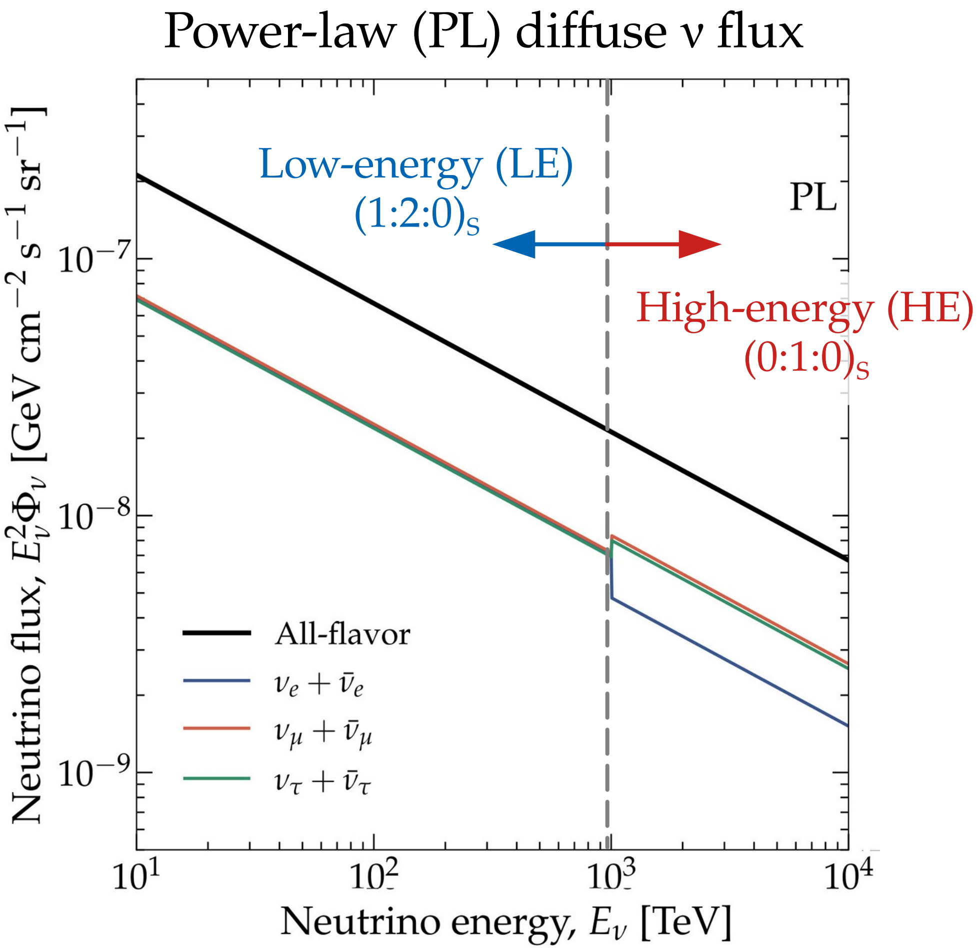


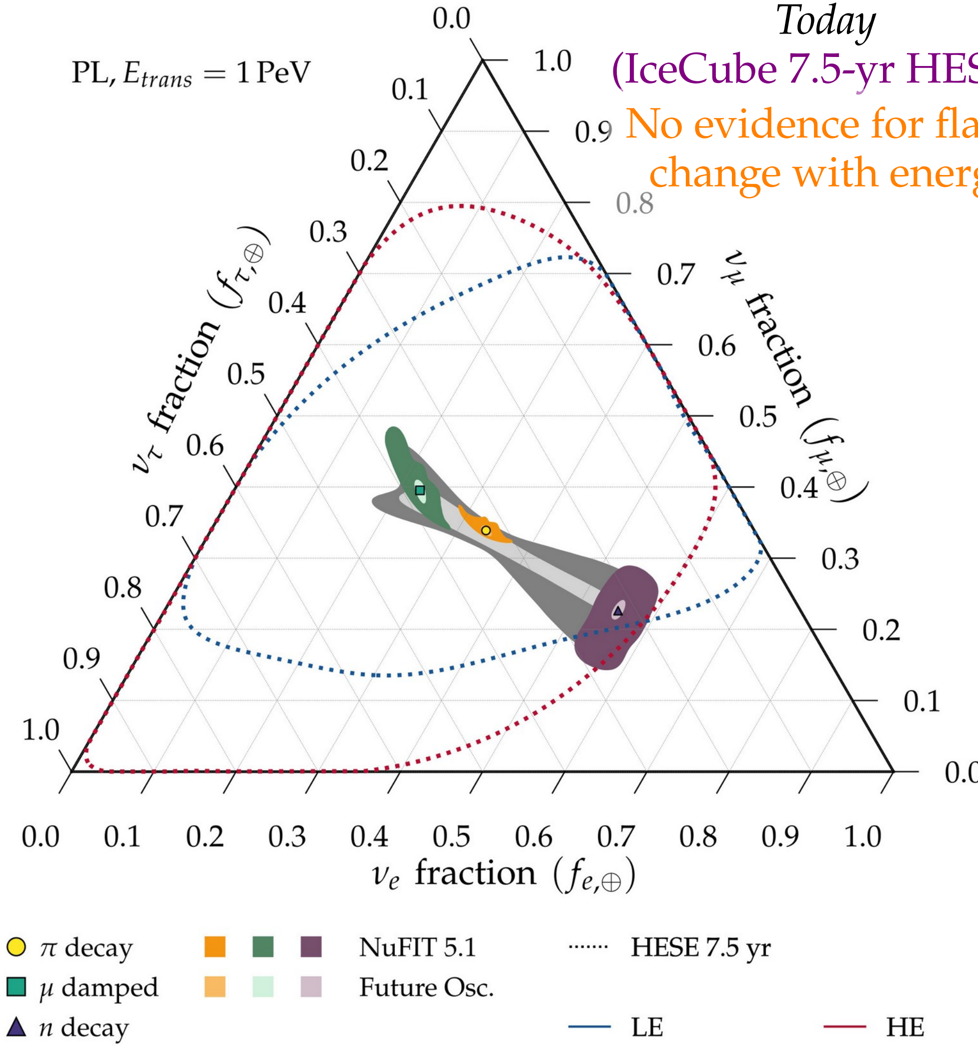
Expected from new physics (*e.g.*, ν decay)



MB, Beacom, Winter *PRL* 2015

Flavor composition: measuring the energy dependence

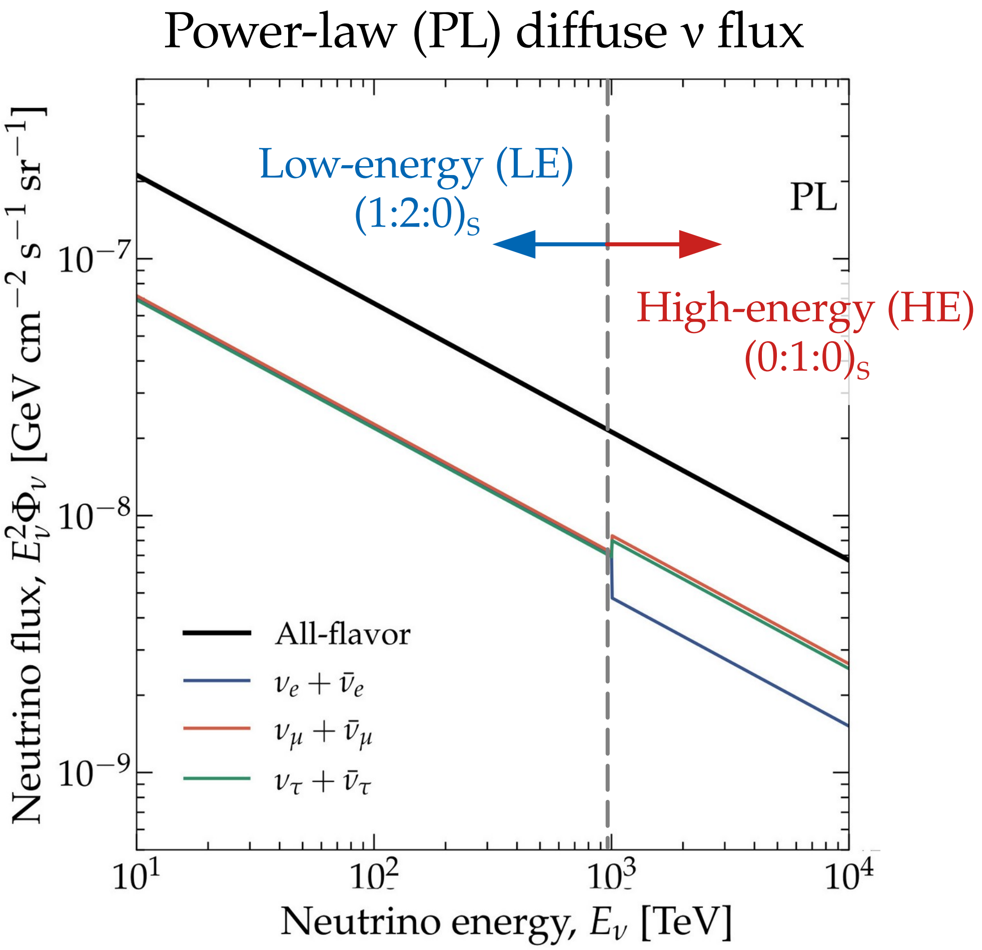


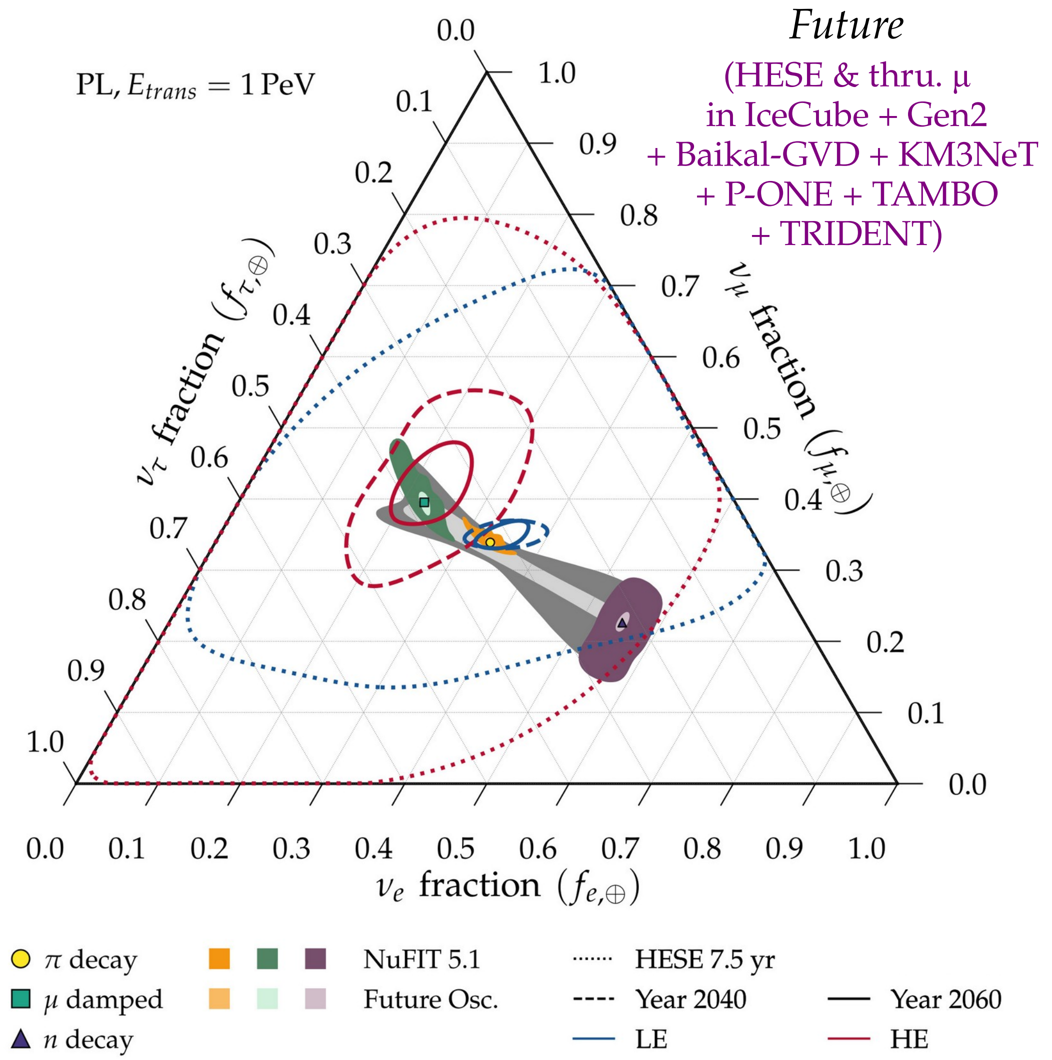


Today
(IceCube 7.5-yr HESE):
No evidence for flavor change with energy

Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, *In prep.*

Flavor composition: measuring the energy dependence





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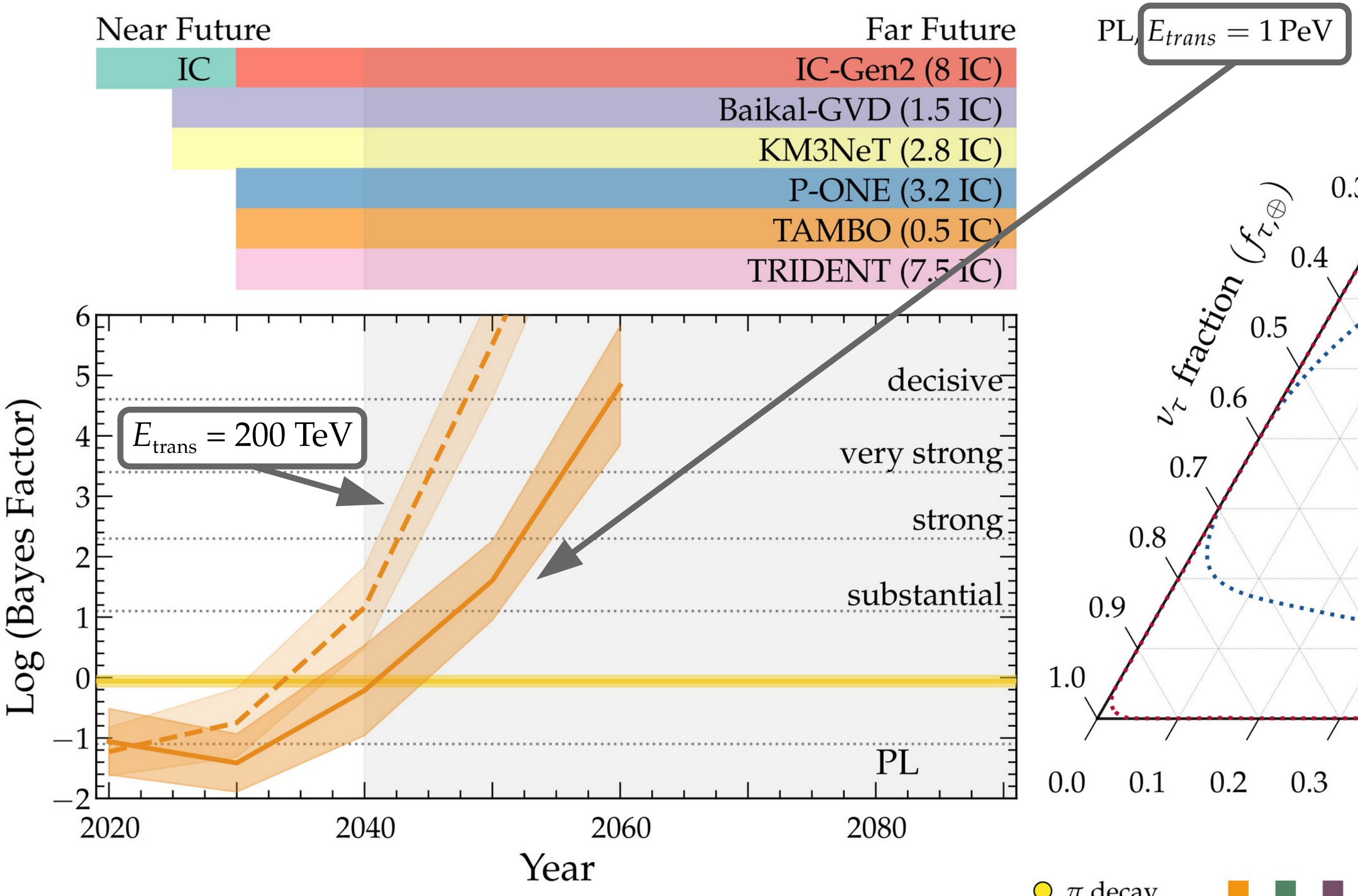
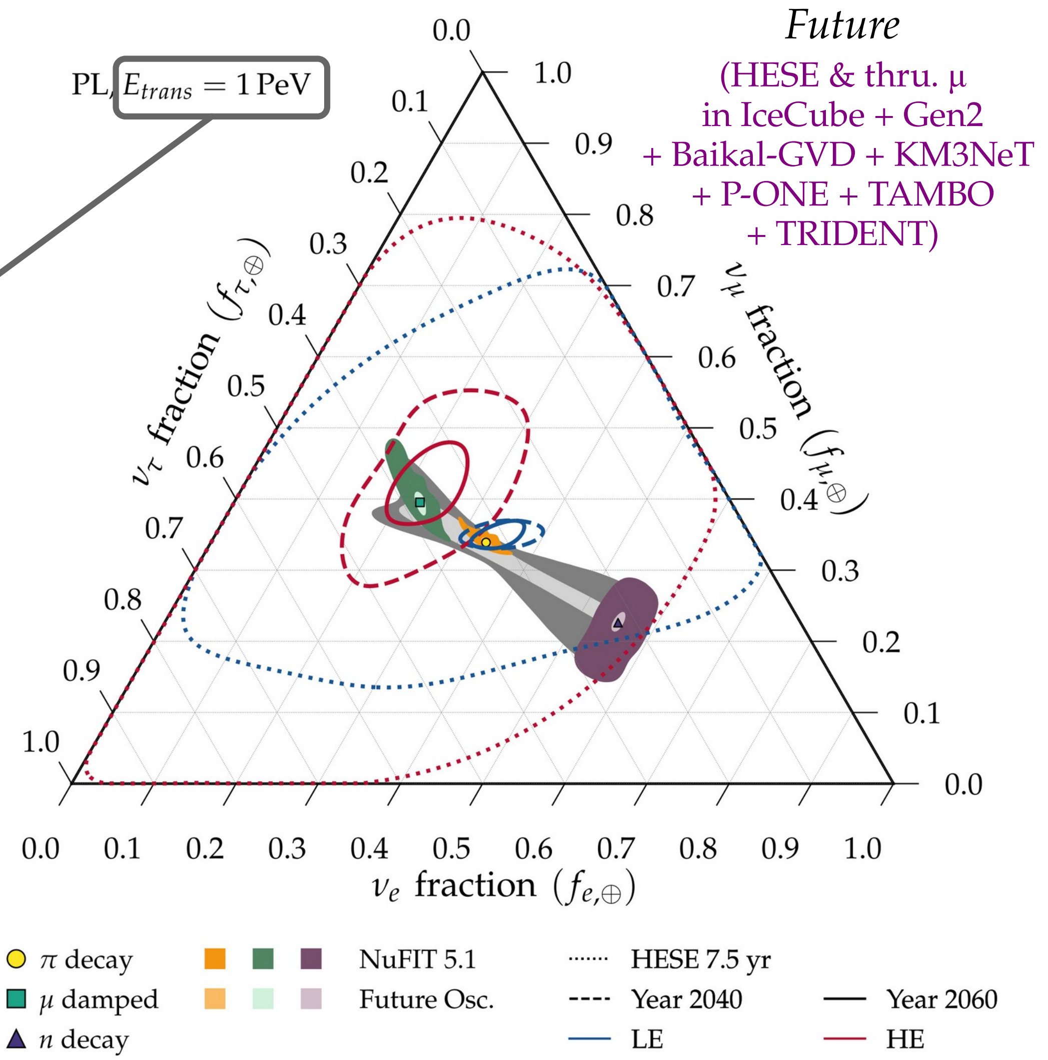
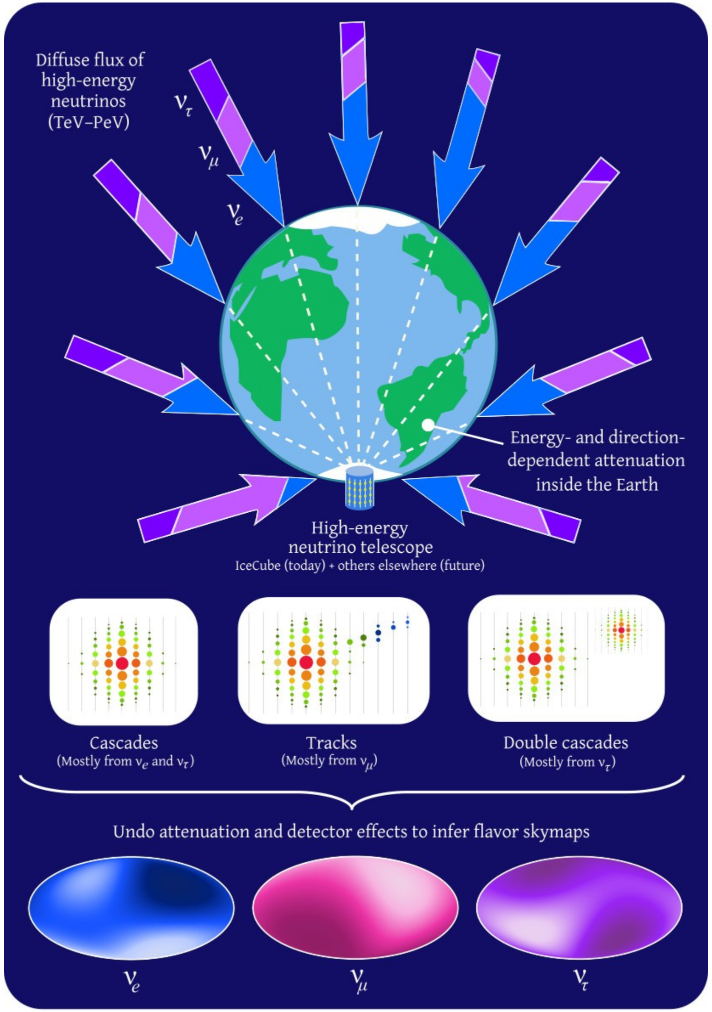




Liu, Fiorillo, Argüelles, **MB**, Song, Vincent, *In prep.*

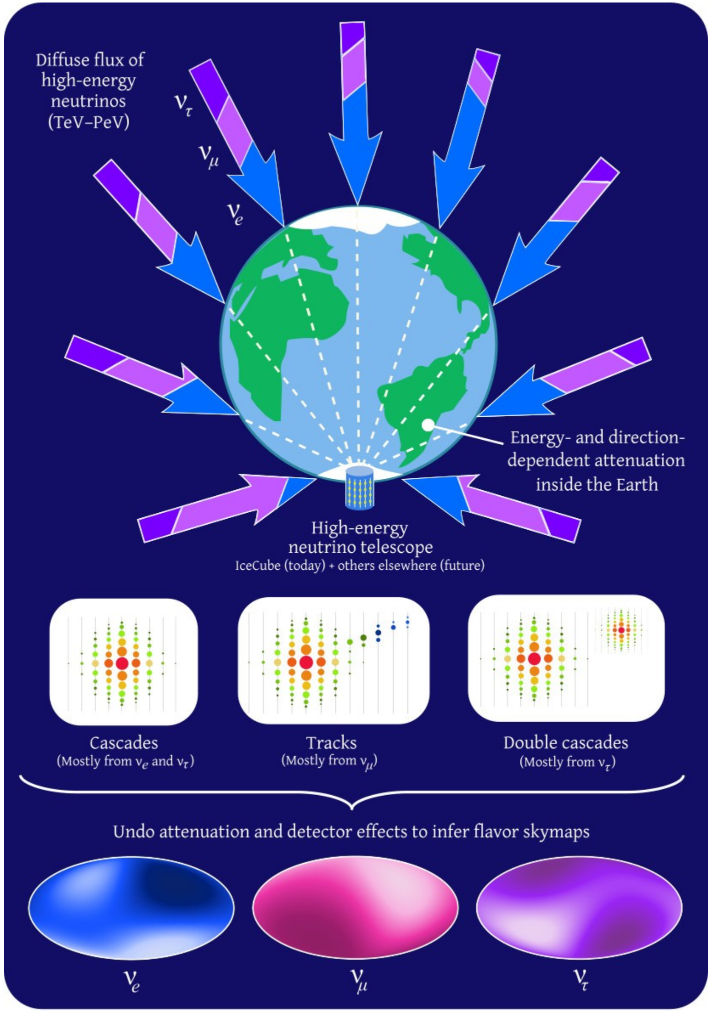
Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

Telalovic, **MB**, 2310.15224

Flavor anisotropy in the high-energy neutrino sky



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From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

Telalovic, **MB**, 2310.15224

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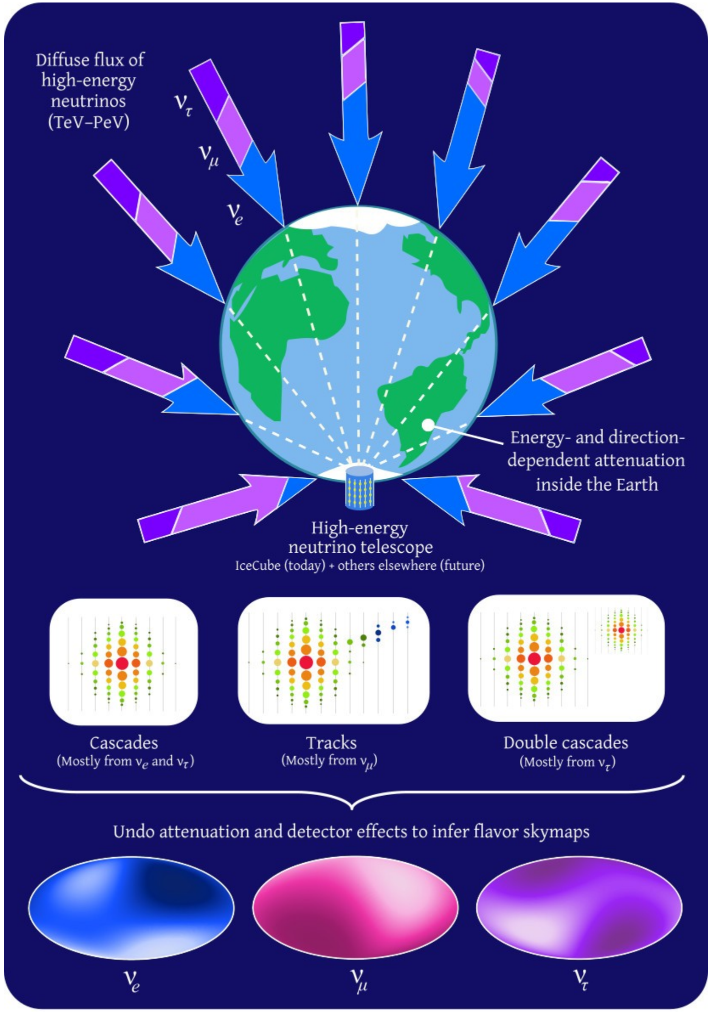

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… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

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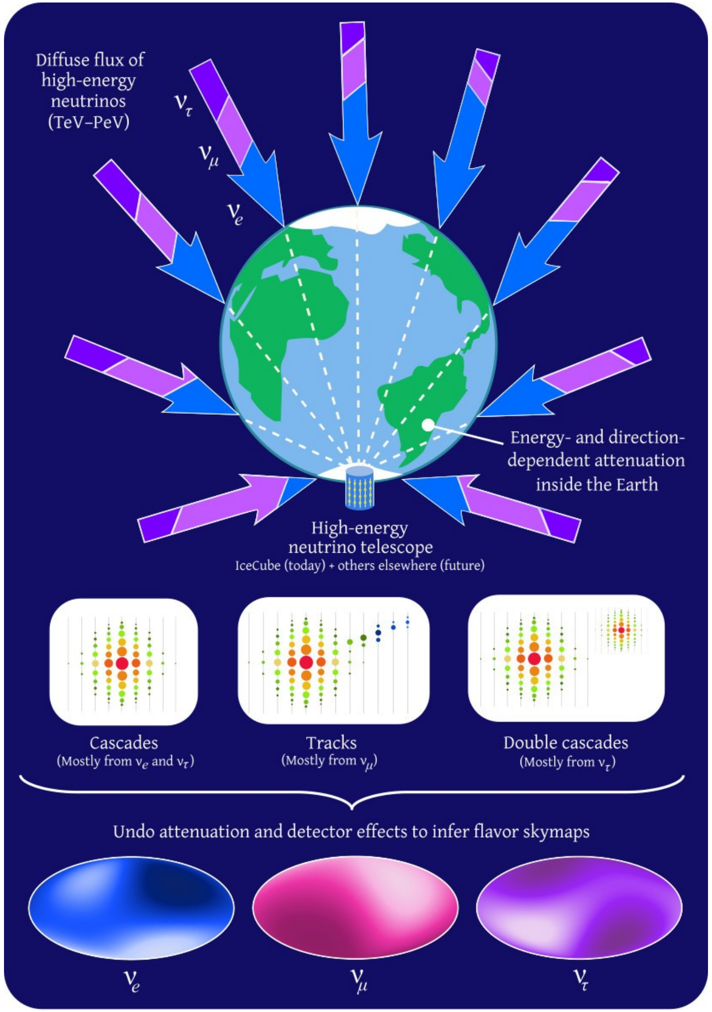
Flavor anisotropy in the high-energy neutrino sky



Does the high-energy sky shine equally brightly
In neutrinos of all flavors?

From the angular distribution of detected events in neutrino telescopes (HESE cascades, tracks, double cascades) …

How? Undo detection effects (use public IceCube HESE Monte Carlo)

… we infer the directional dependence of the diffuse fluxes of ν_e, ν_μ, ν_τ

Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

Real, public data

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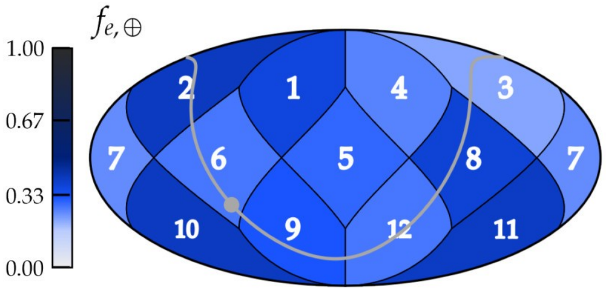

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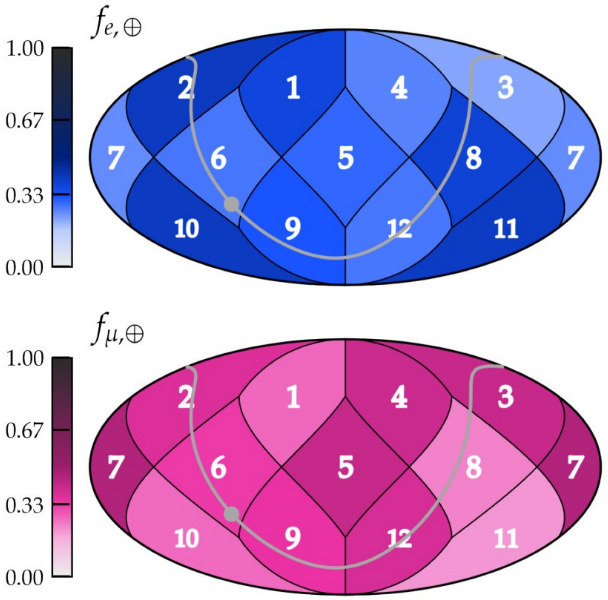

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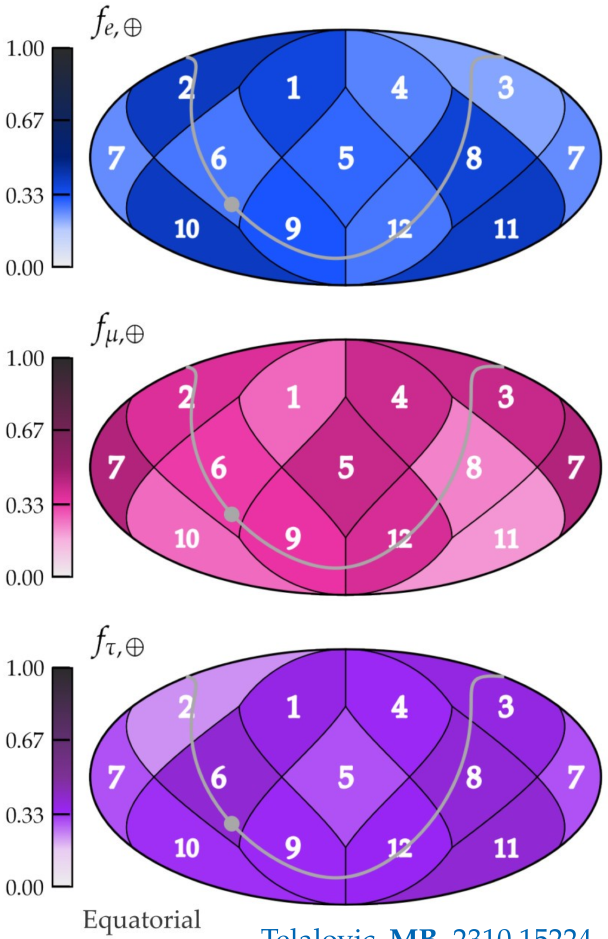
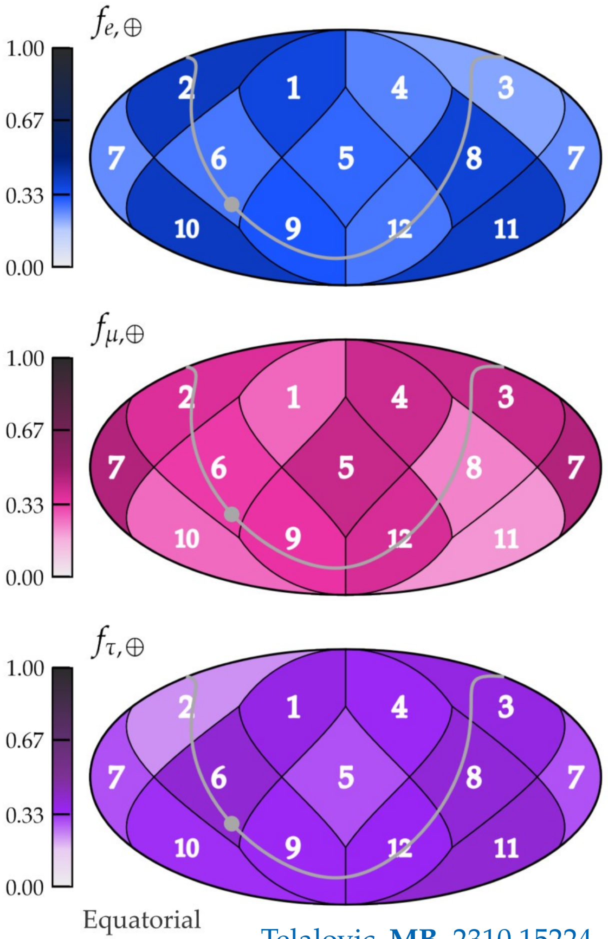
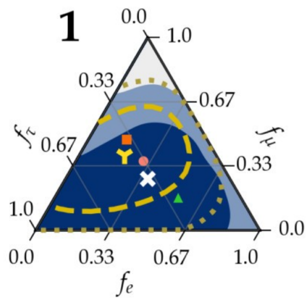


Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: ✕ Best fit ■ 1σ ■ 2σ ■ 3σ — IceCube 2020 all-sky: Y Best fit - - 1σ ··· 2σ — Benchmarks: ● $\pi^{\pm}$ decay: $(1:2:0)_{\rm S}$ ■ μ-damped: $(0:1:0)_{\rm S}$ ▲ n decay: $(1:0:0)_{\rm S}$





Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: Best fit | 1σ | 2σ | 3σ

IceCube 2020 all-sky: Best fit | 1σ | 2σ

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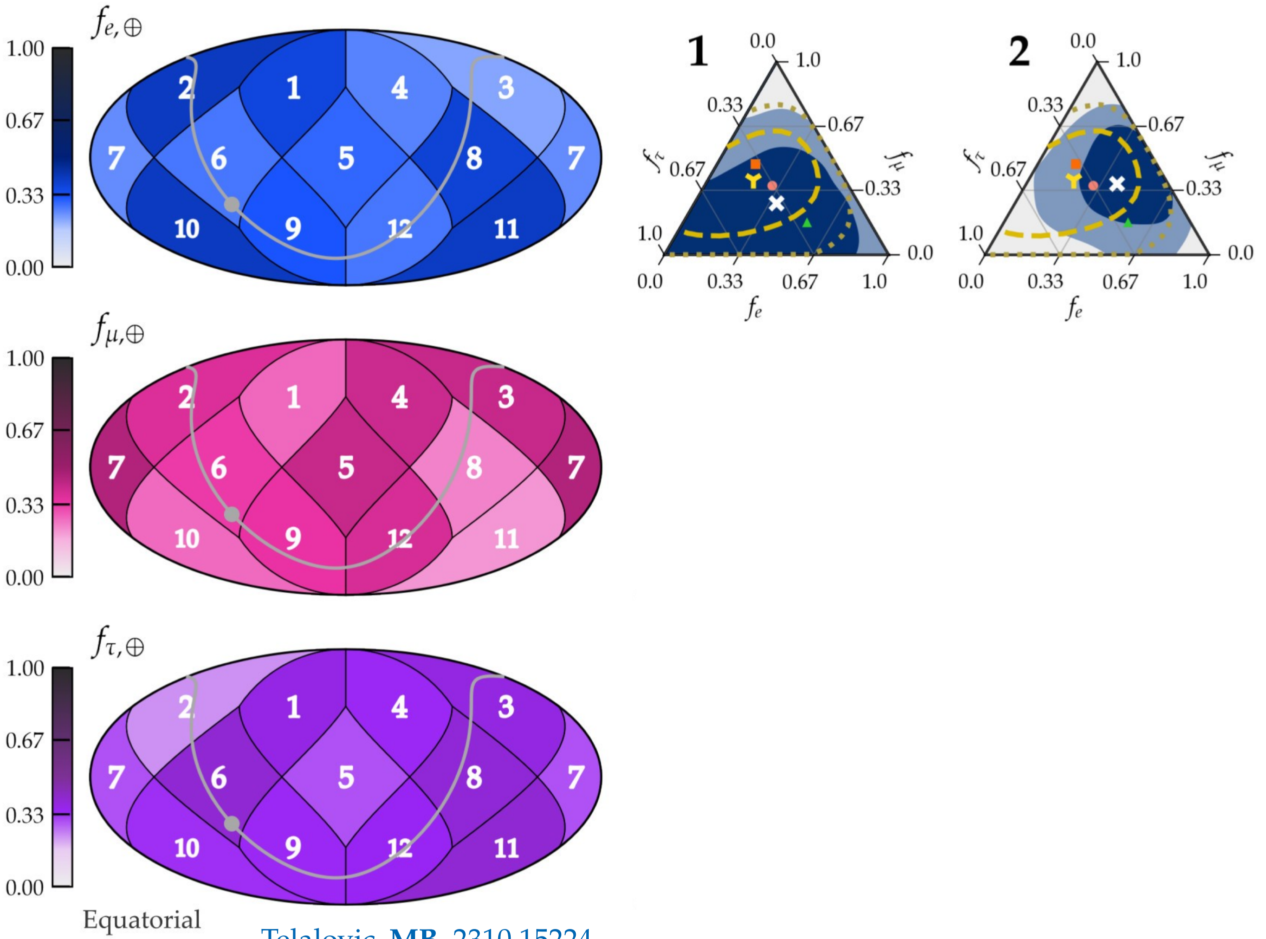
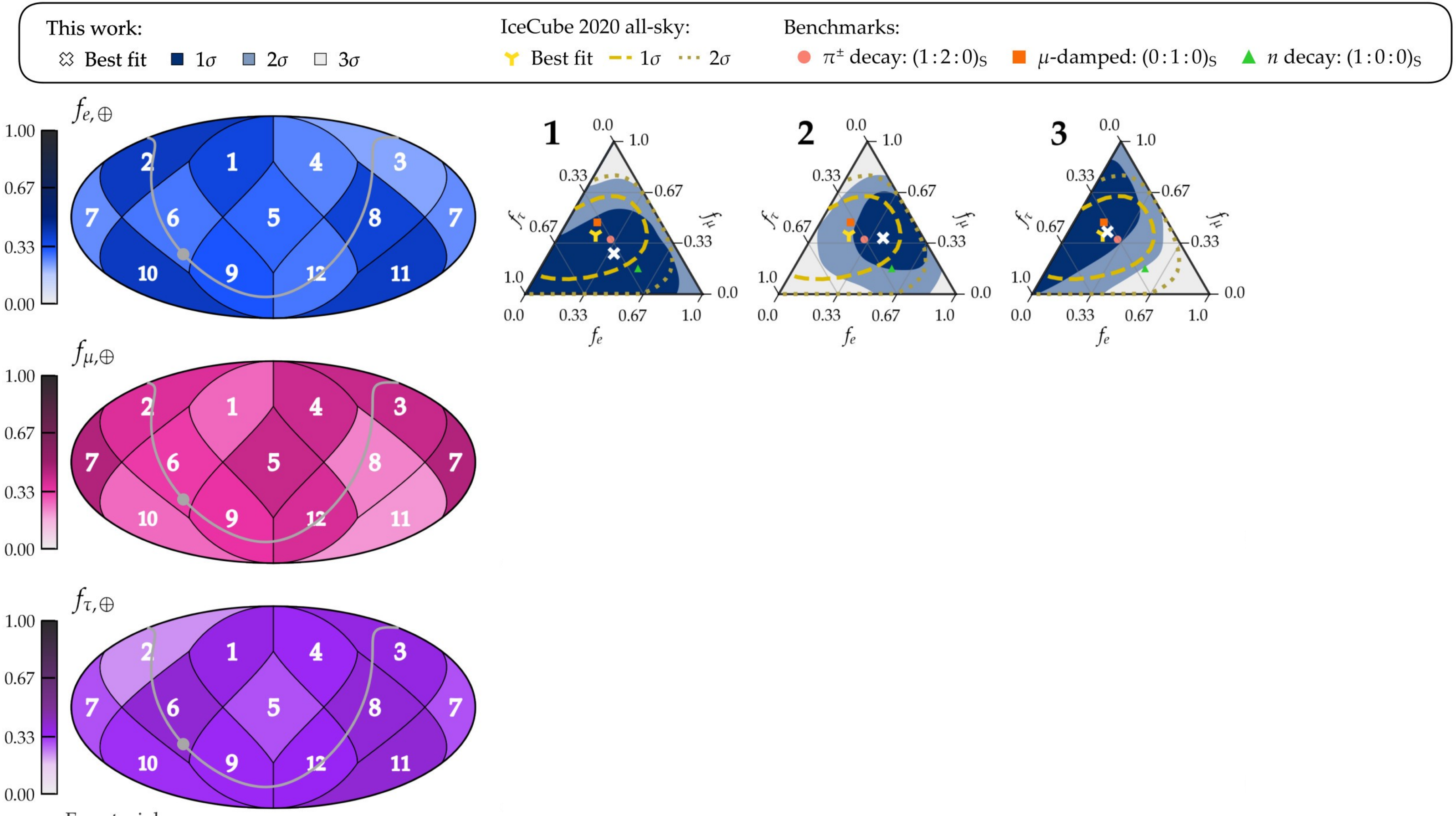


Telalovic, **MB**, 2310.15224

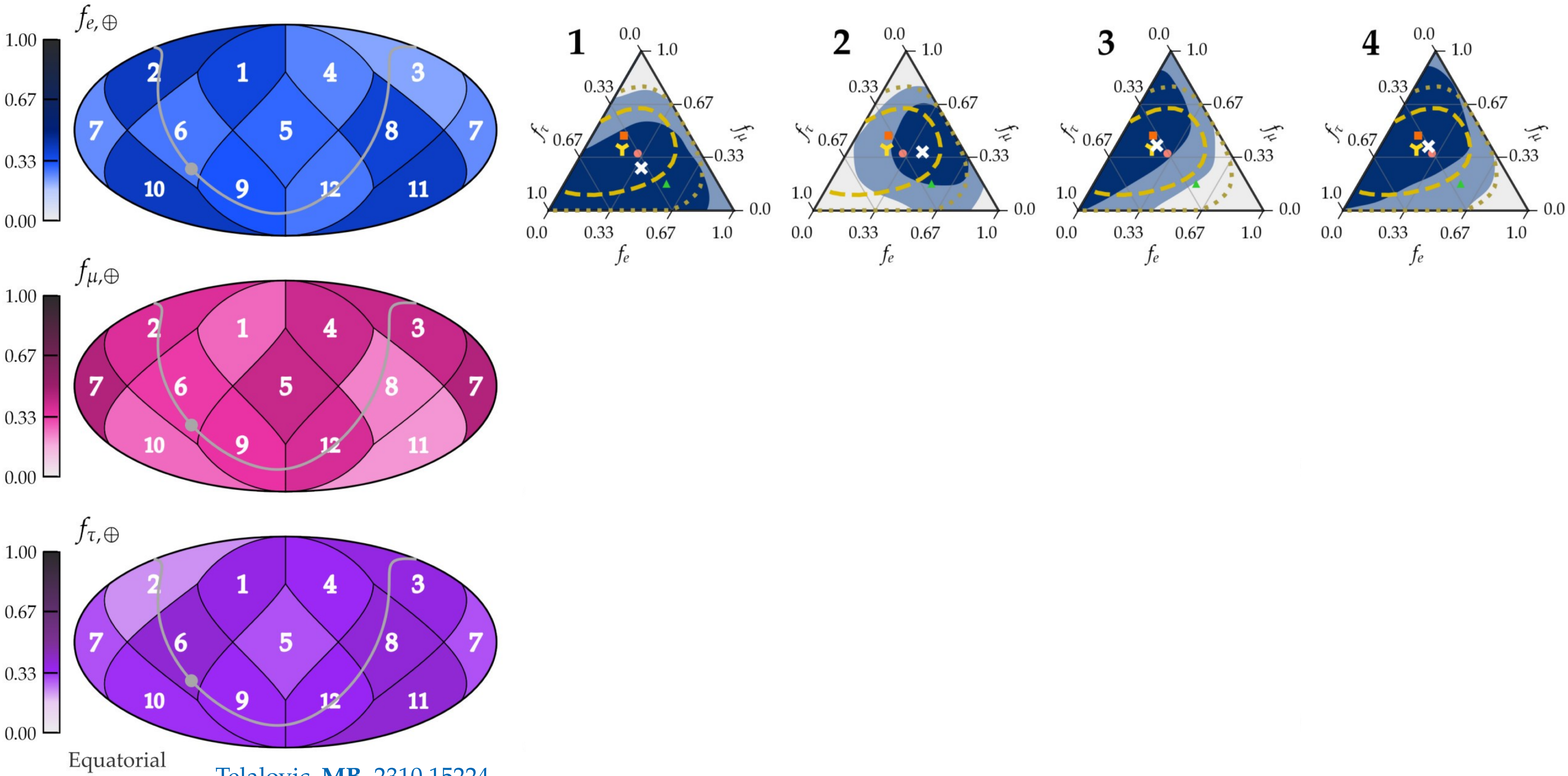
Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: Best fit, 1σ, 2σ, 3σ | IceCube 2020 all-sky: Best fit, 1σ, 2σ | Benchmarks: $\pi^\pm$ decay: $(1:2:0)_S$, μ-damped: $(0:1:0)_S$, n decay: $(1:0:0)_S$



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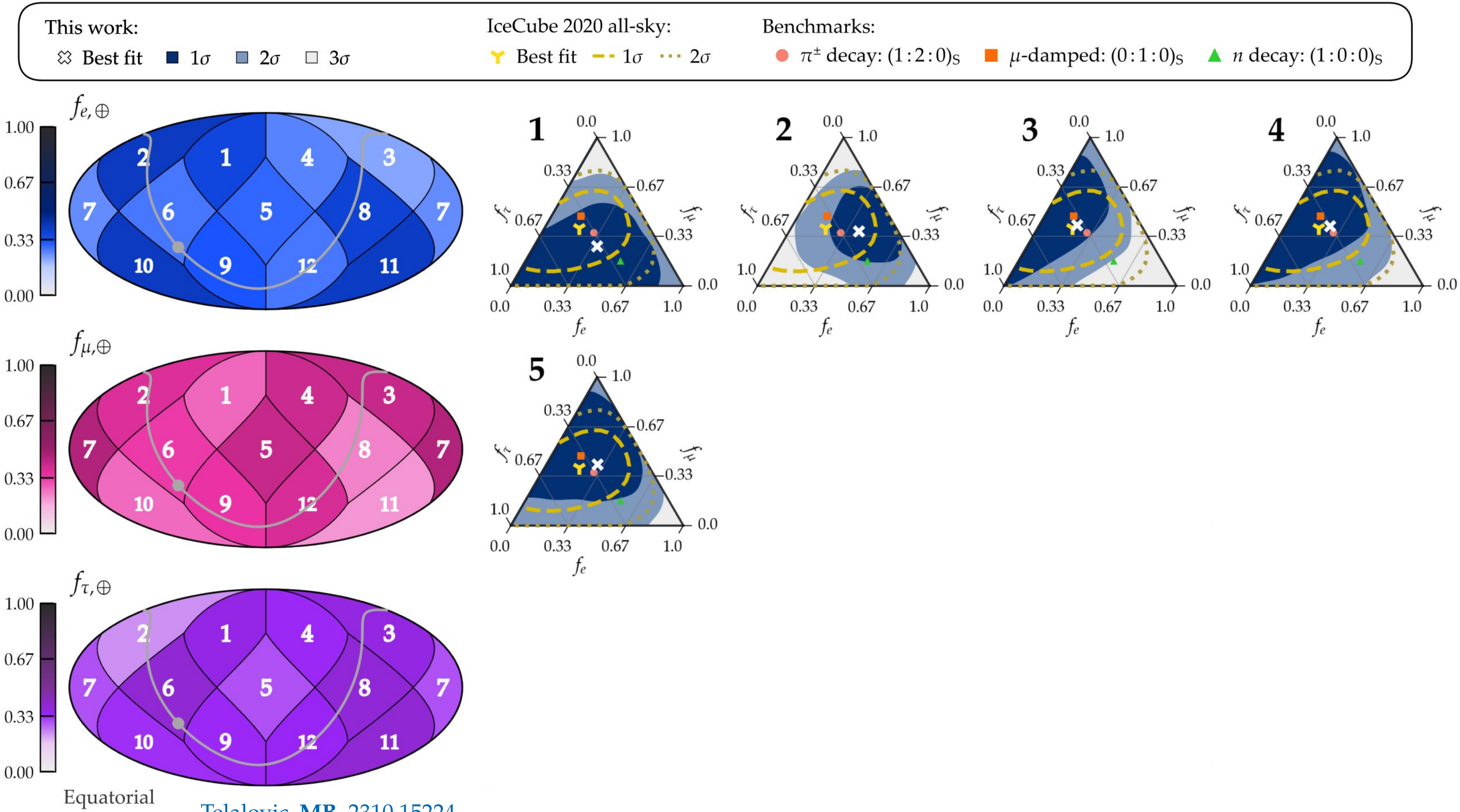
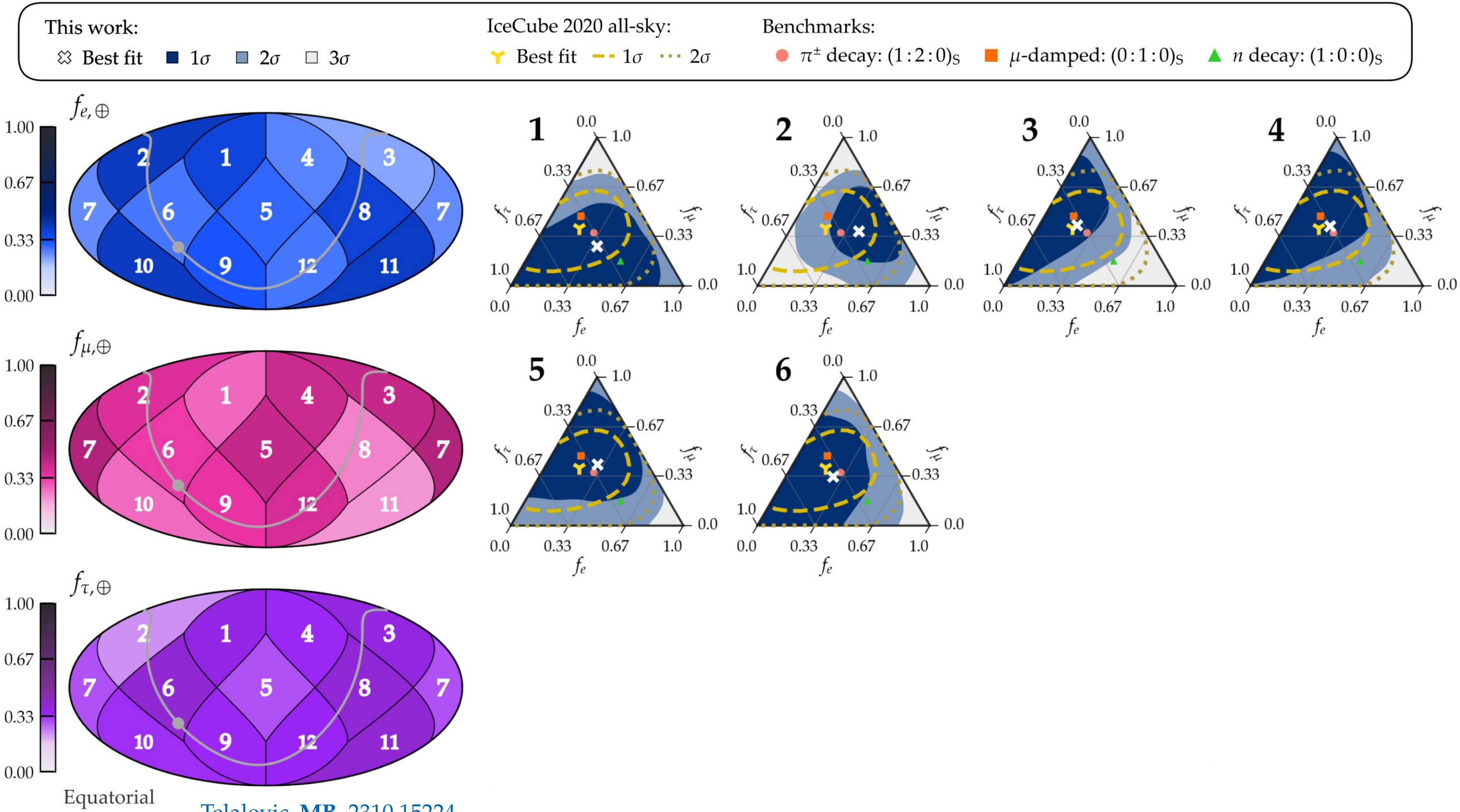


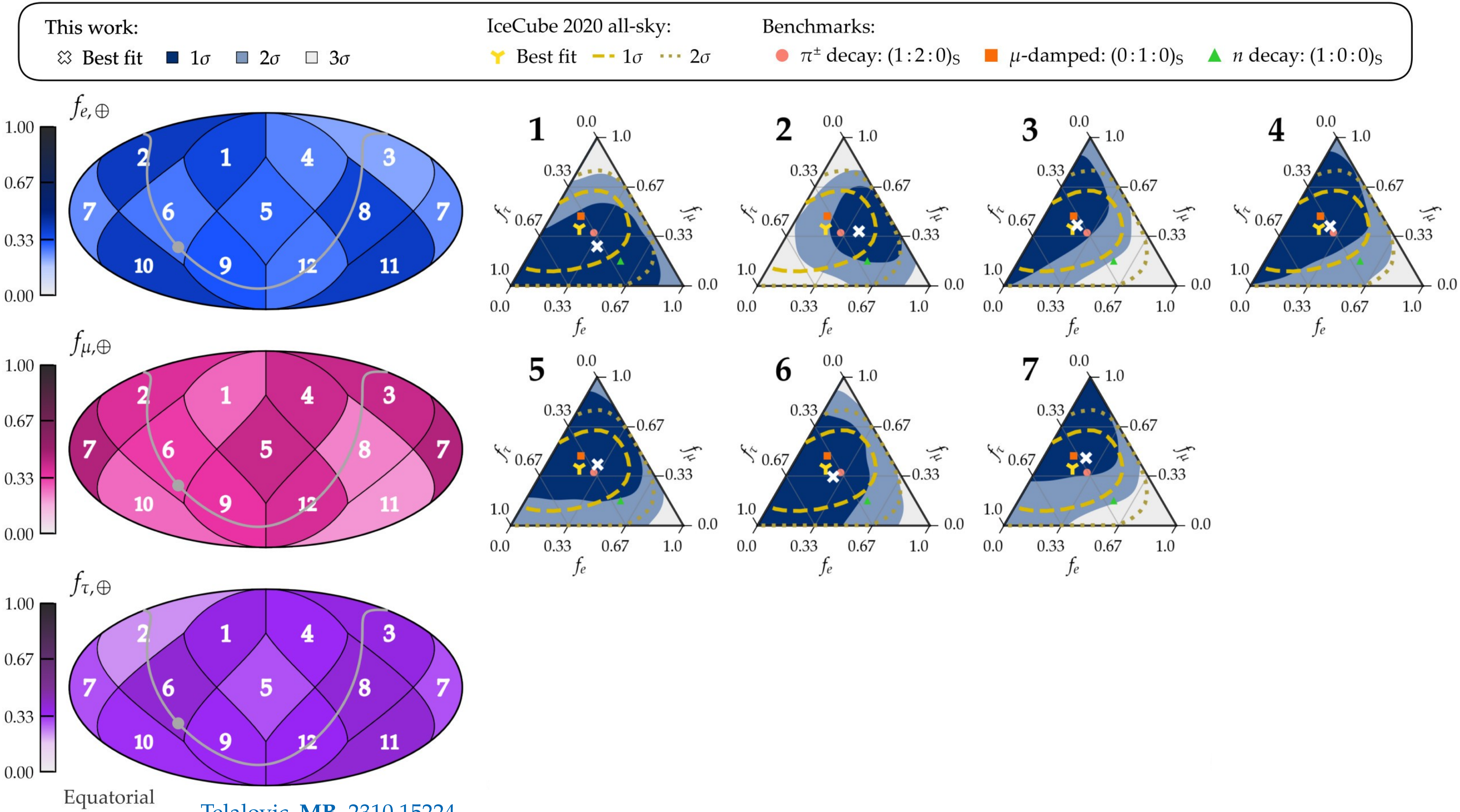
Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



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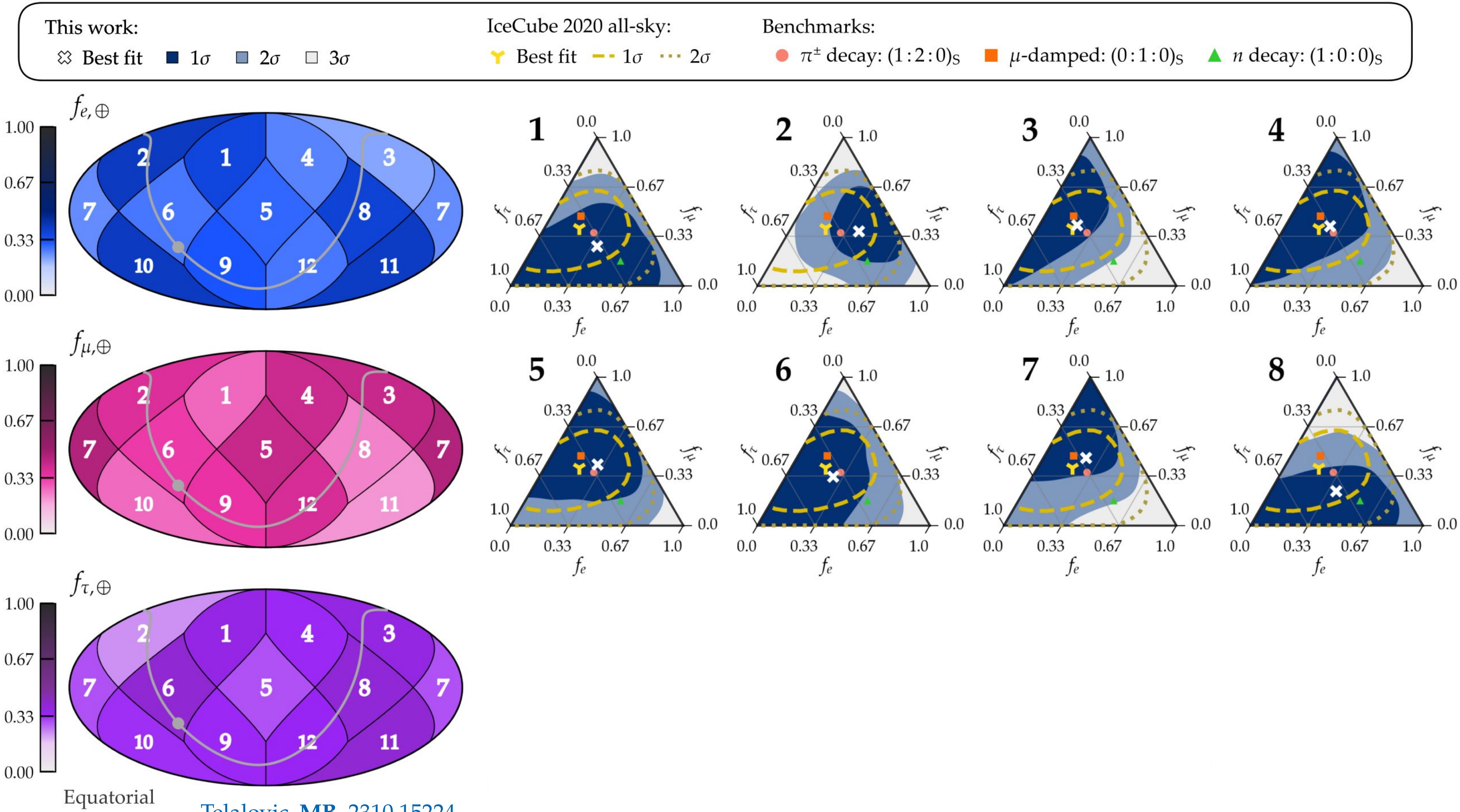
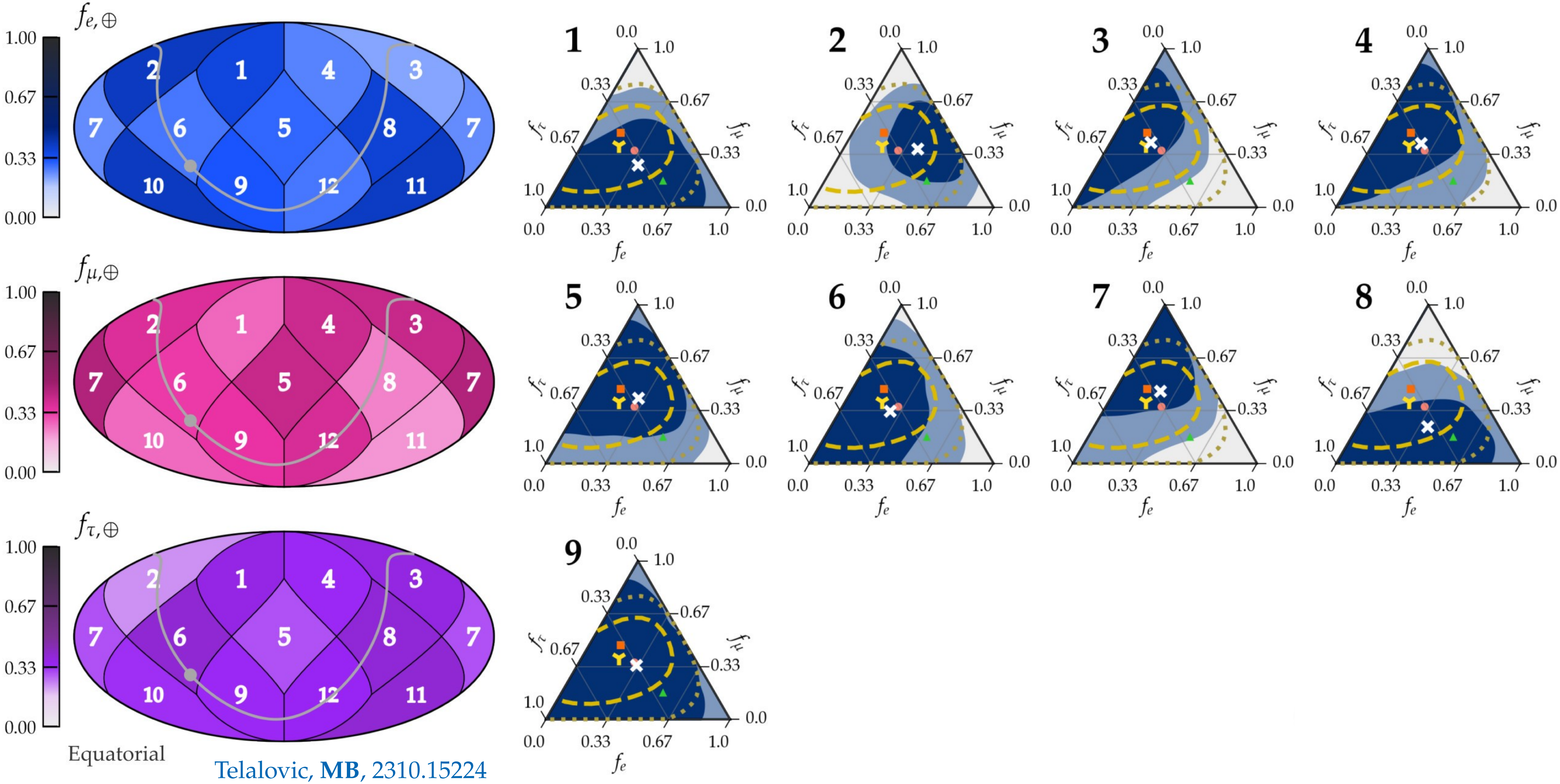


Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)

This work: Best fit 1σ 2σ 3σ
IceCube 2020 all-sky: Best fit 1σ 2σ
Benchmarks: $\pi^\pm$ decay: $(1:2:0)_S$ μ-damped: $(0:1:0)_S$ n decay: $(1:0:0)_S$



Telalovic, **MB**, 2310.15224

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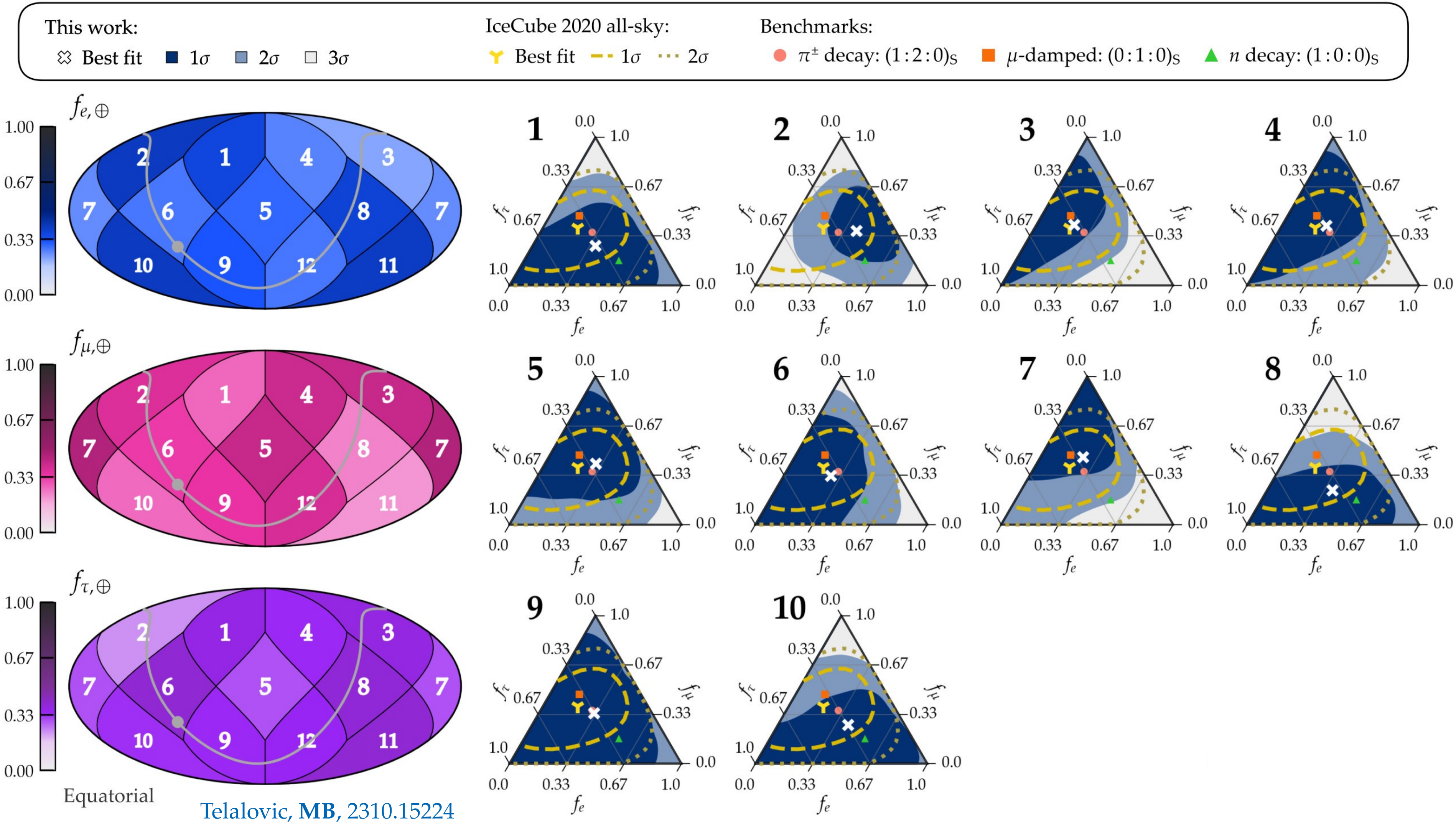
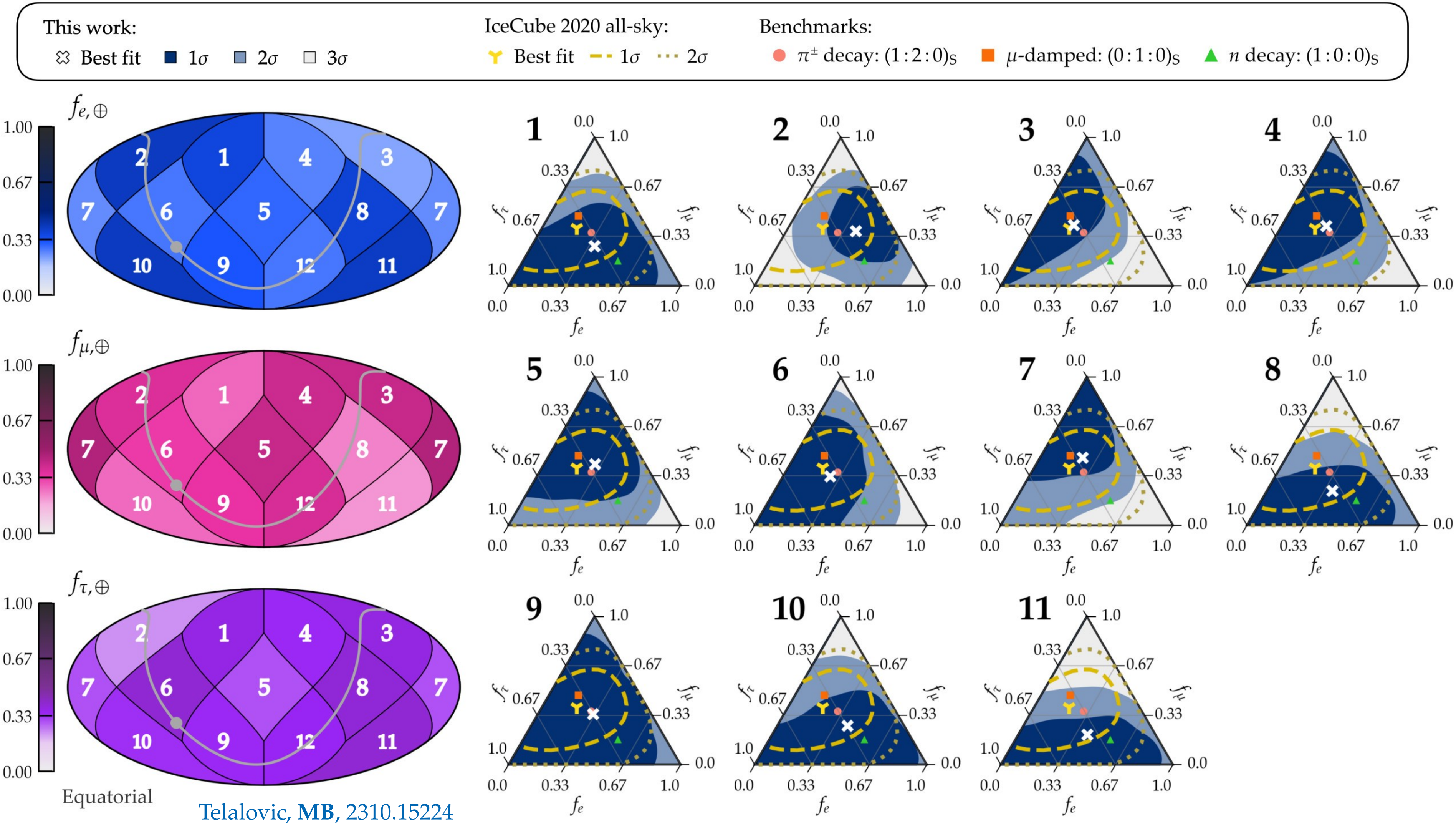


Telalovic, **MB**, 2310.15224

Directional high-energy astrophysical neutrino flavor composition: IceCube HESE (7.5 yr)



Telalovic, **MB**, 2310.15224

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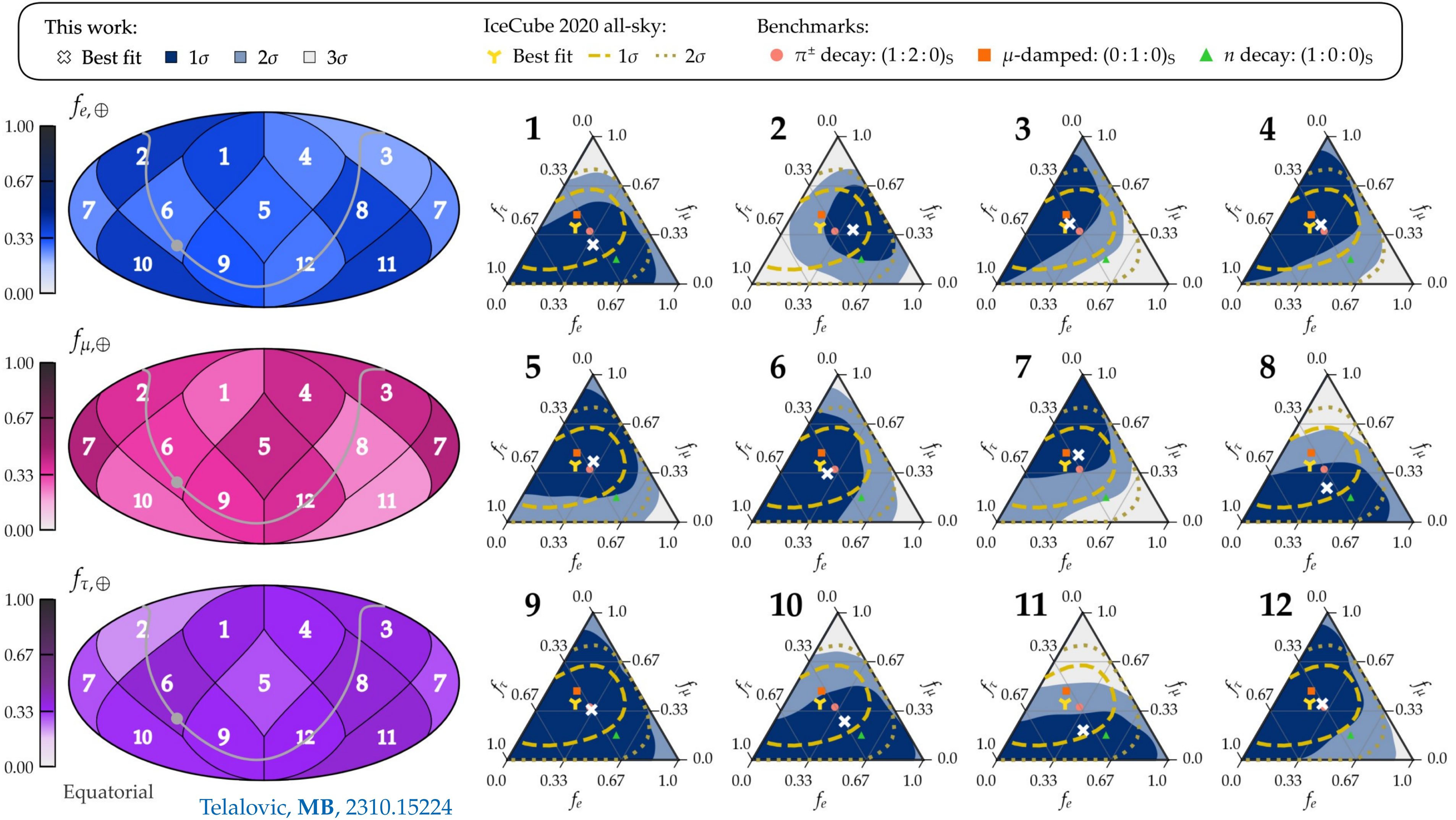

Telalovic, **MB**, 2310.15224

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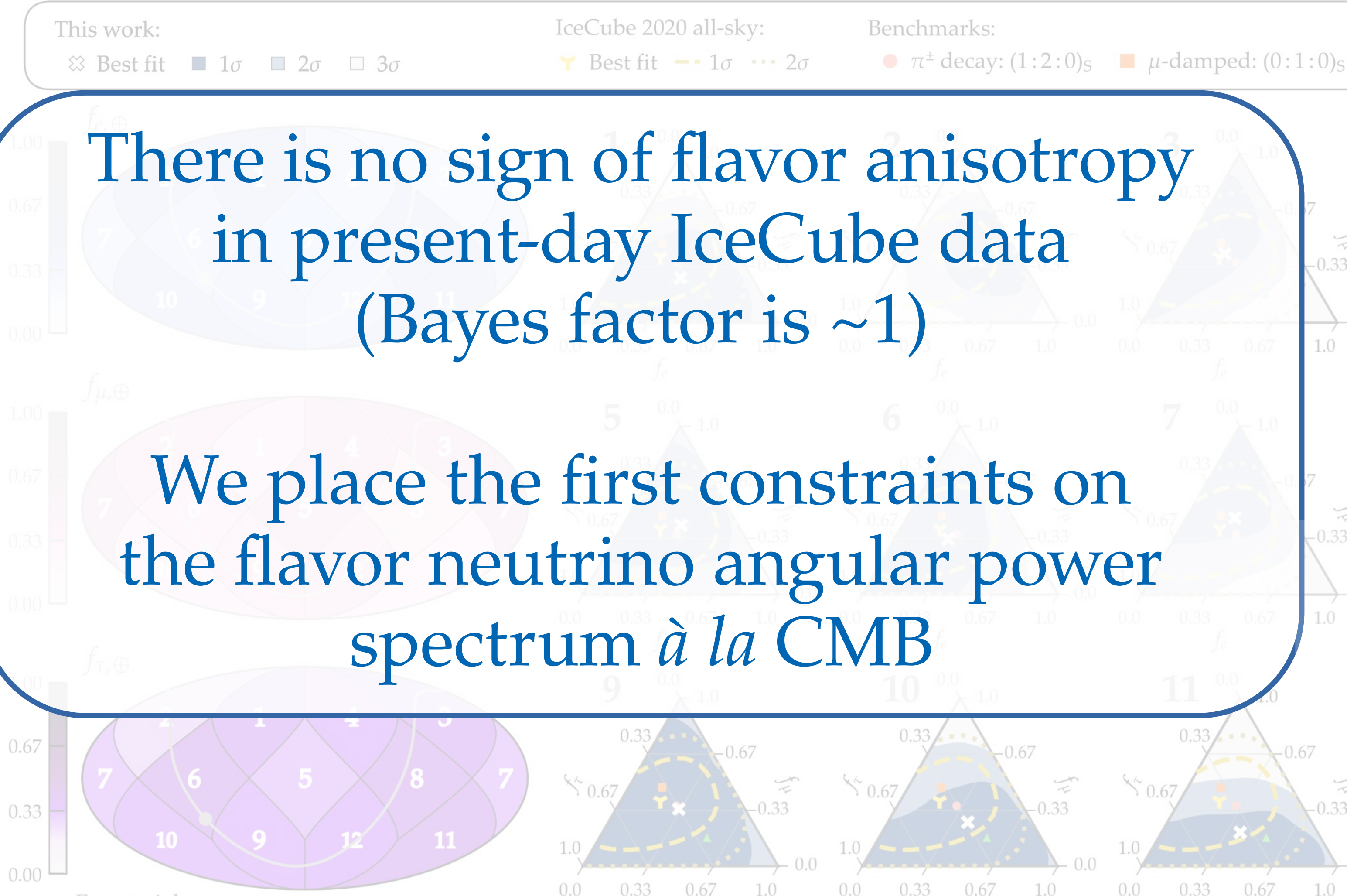


There is no sign of flavor anisotropy in present-day IceCube data (Bayes factor is ~1)

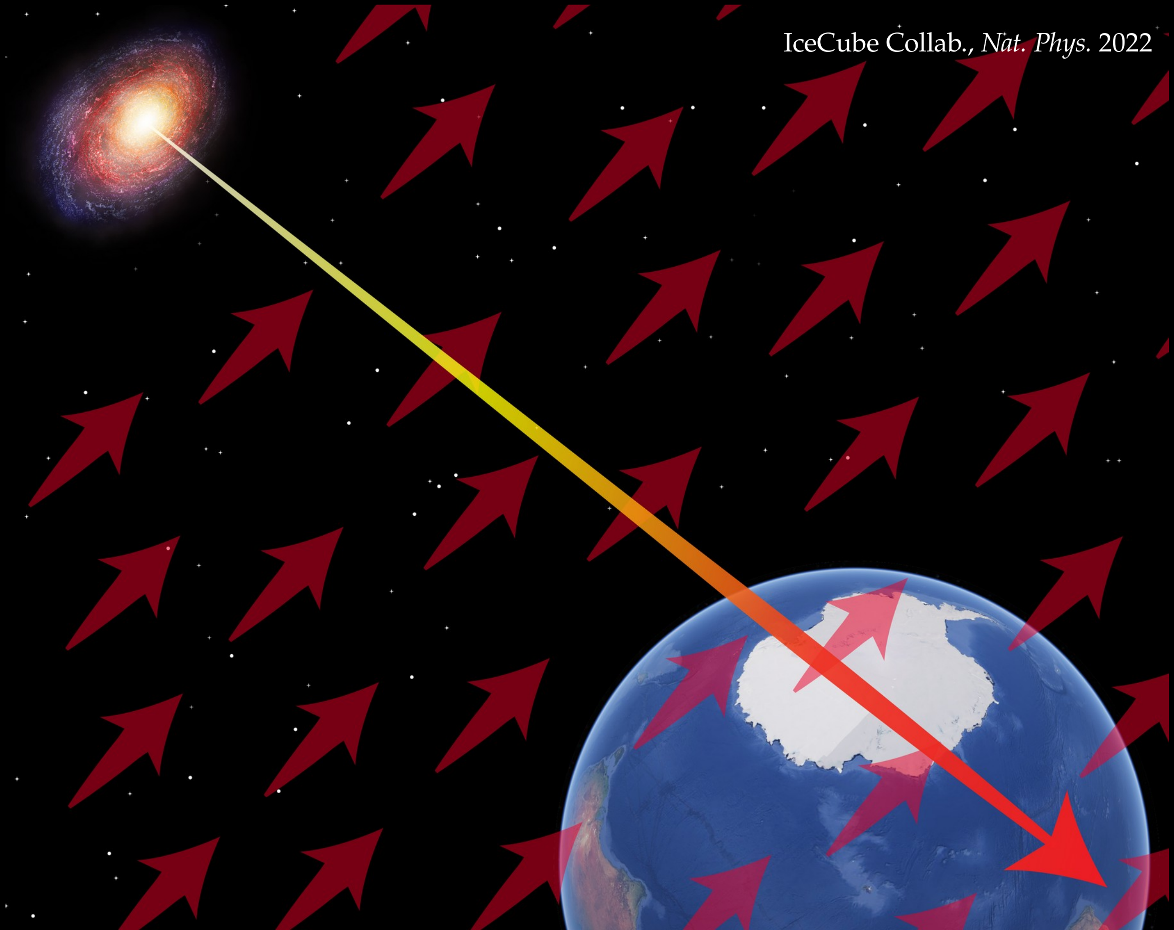
We place the first constraints on the flavor neutrino angular power spectrum *à la* CMB

Work led by Bernanda Telalovic

Telalovic, **MB**, 2310.15224

Why is this interesting for neutrino physics?

Because new physics can introduce preferred directions for different flavors



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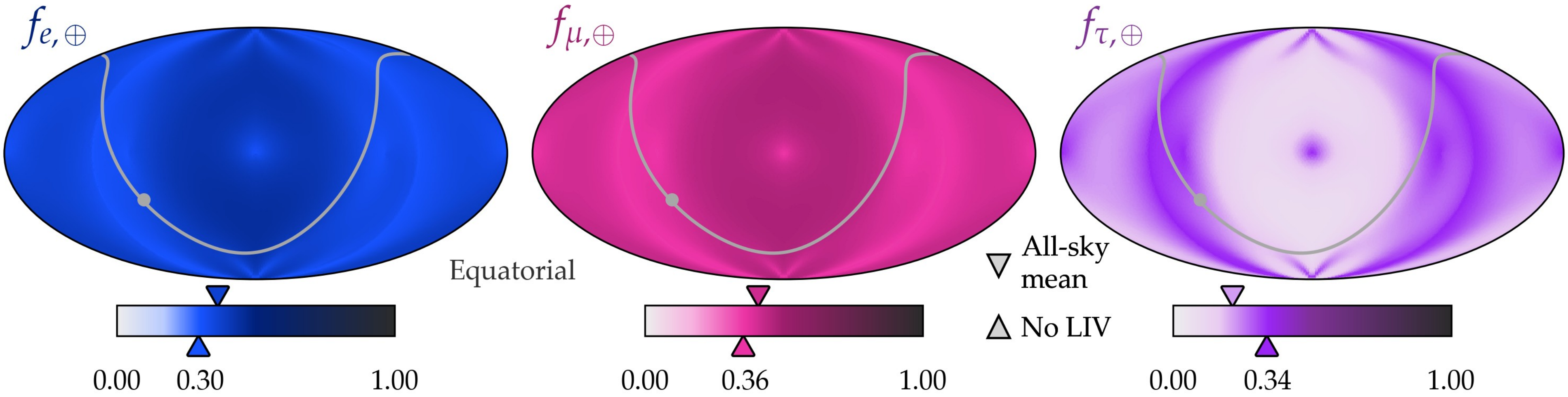
E.g., compass asymmetries from Lorentz-invariance violation



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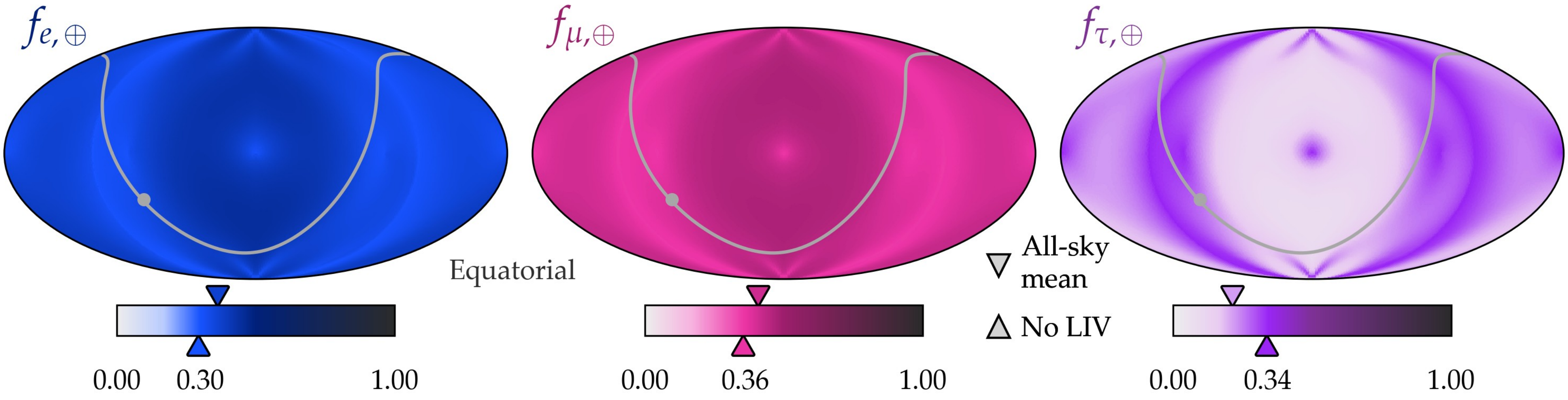

For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

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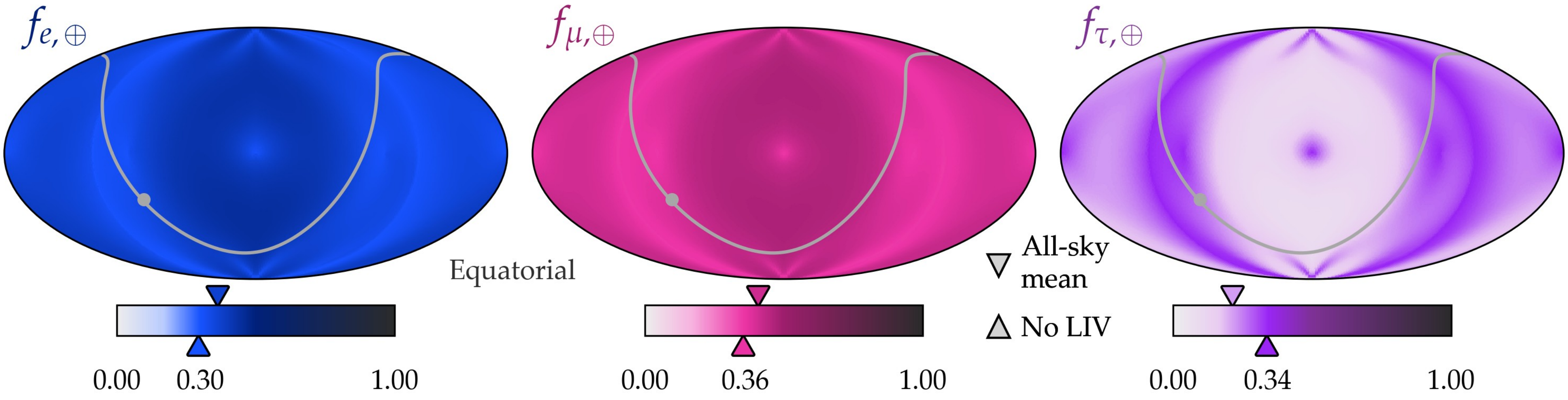


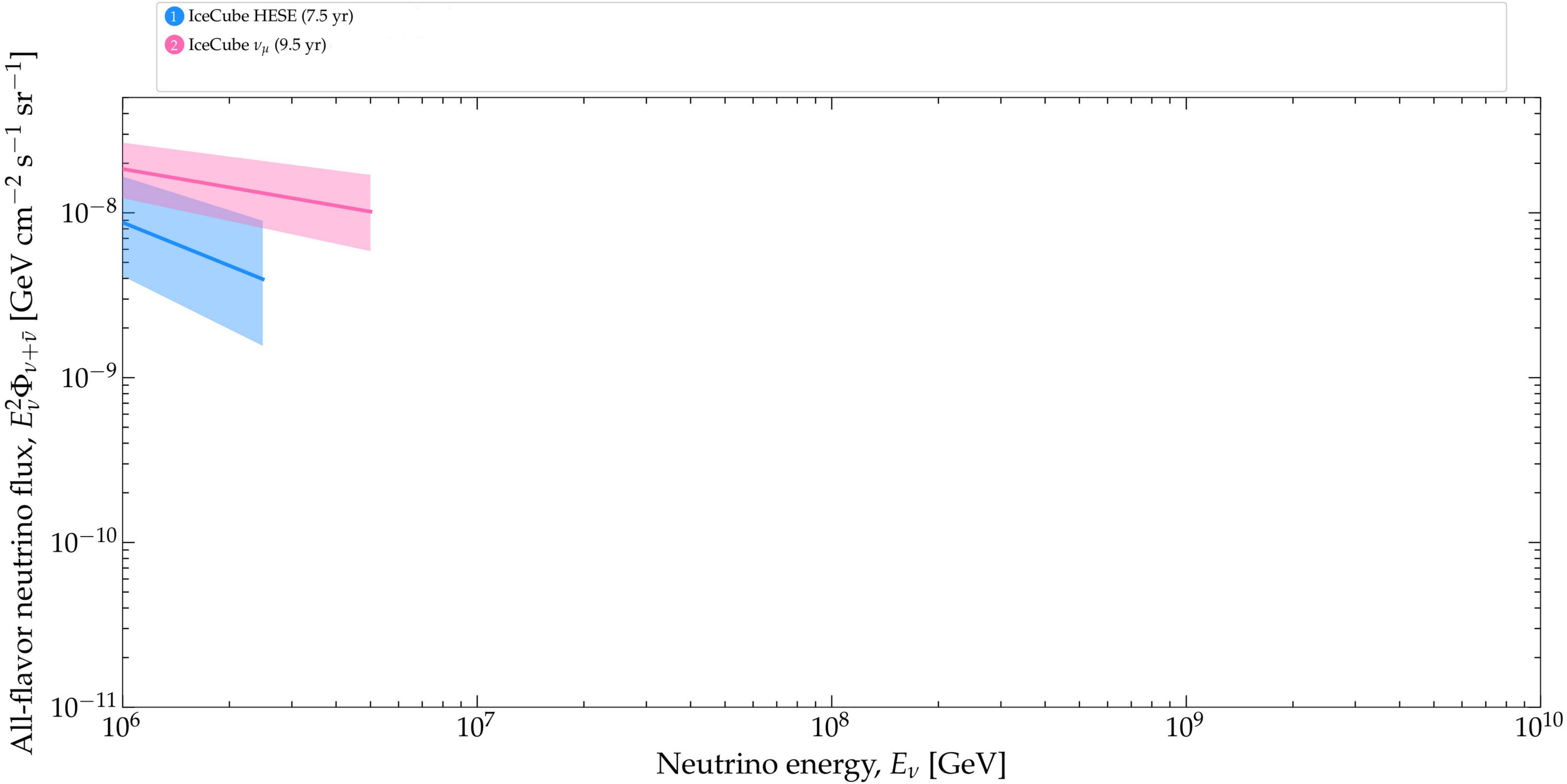
For dimension-5 CPT-odd LIV coefficient

Upper limits from accelerator ν (MINOS): $< 10^{-20}$–10^{-15} GeV^{-1}

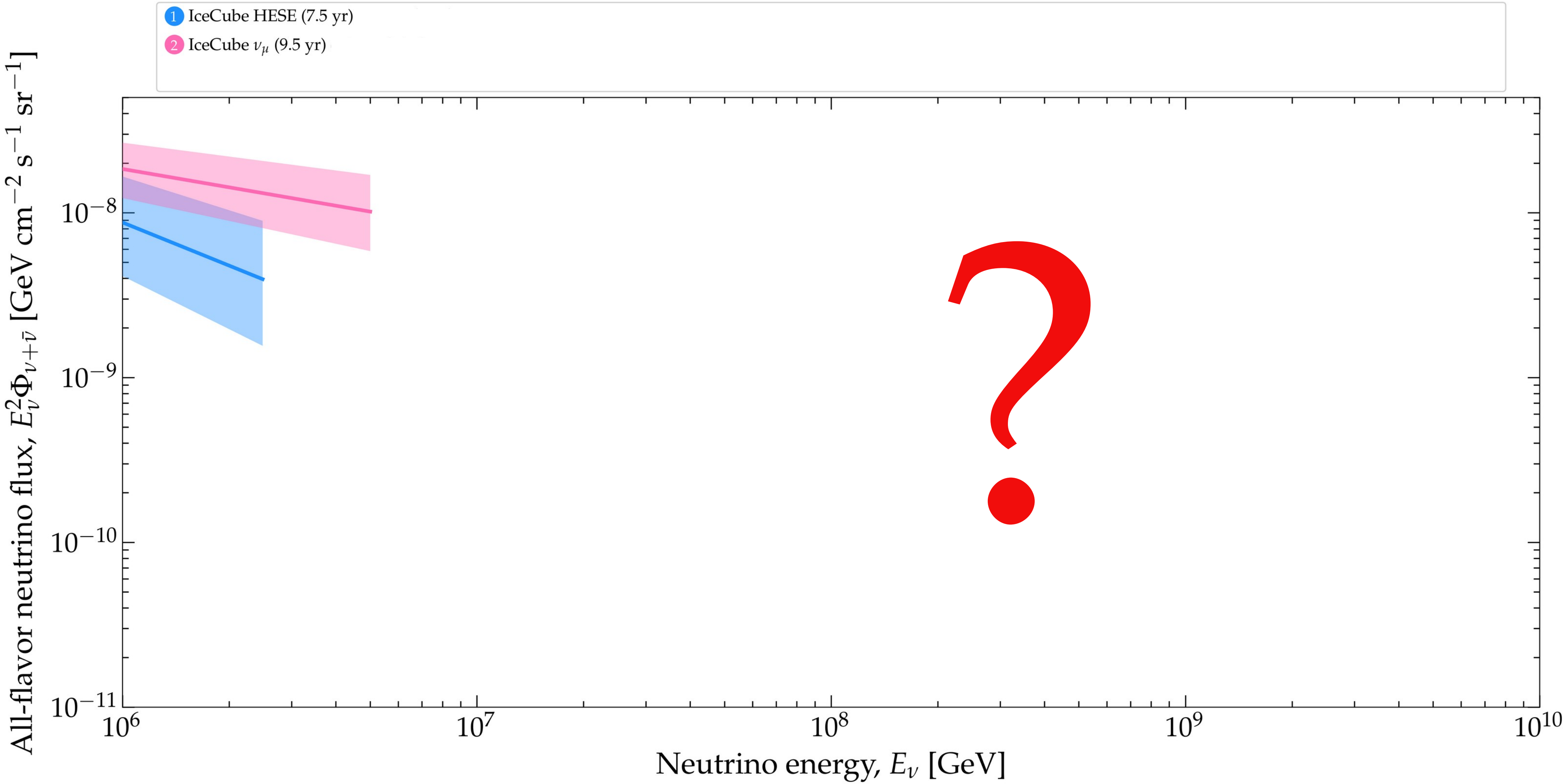
Upper limits from 7.5-year HESE: $< 10^{-34}$ GeV^{-1}

Telalovic, **MB**, 2310.15224

Prospects at ultra-high energies



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



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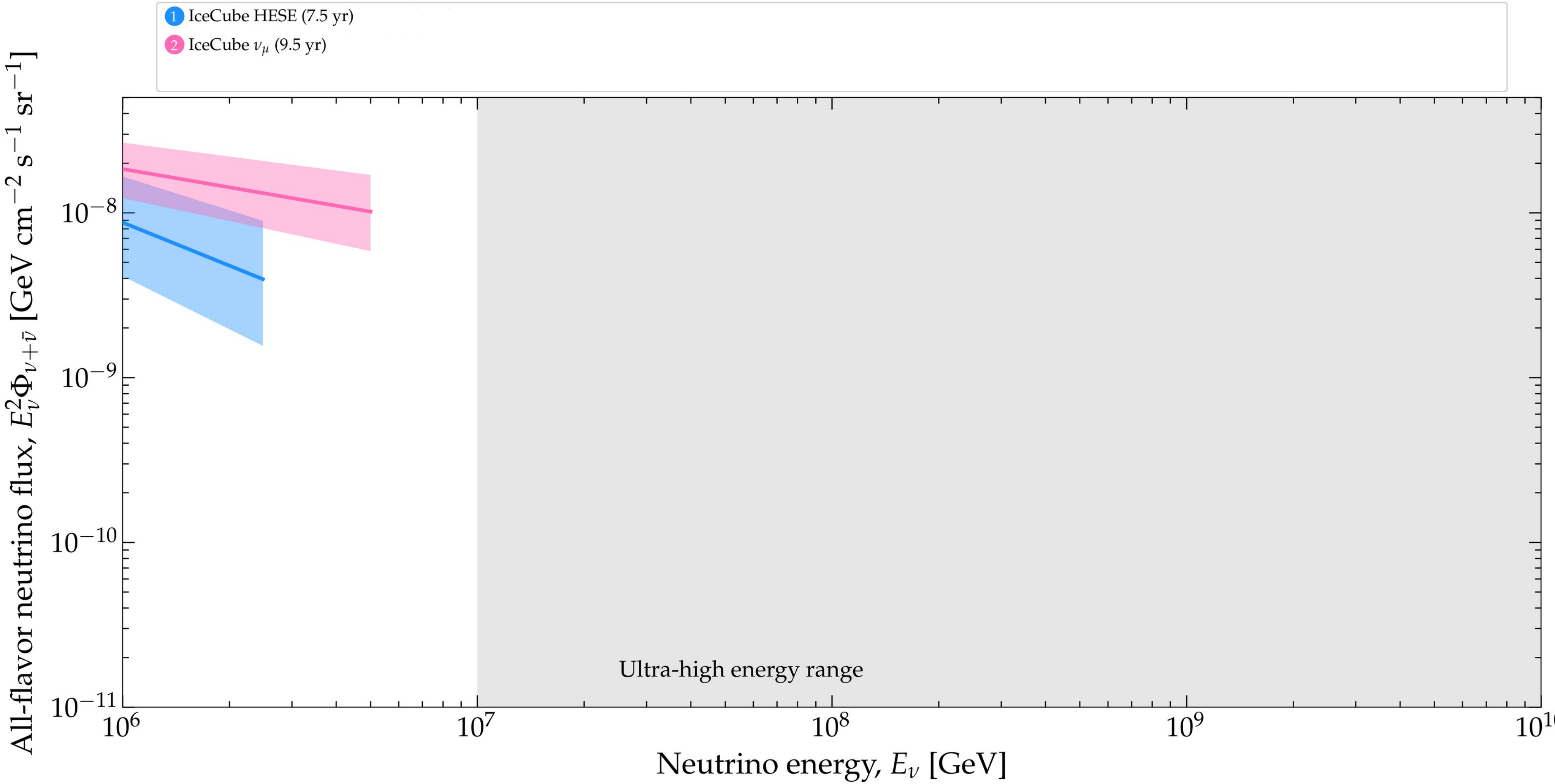
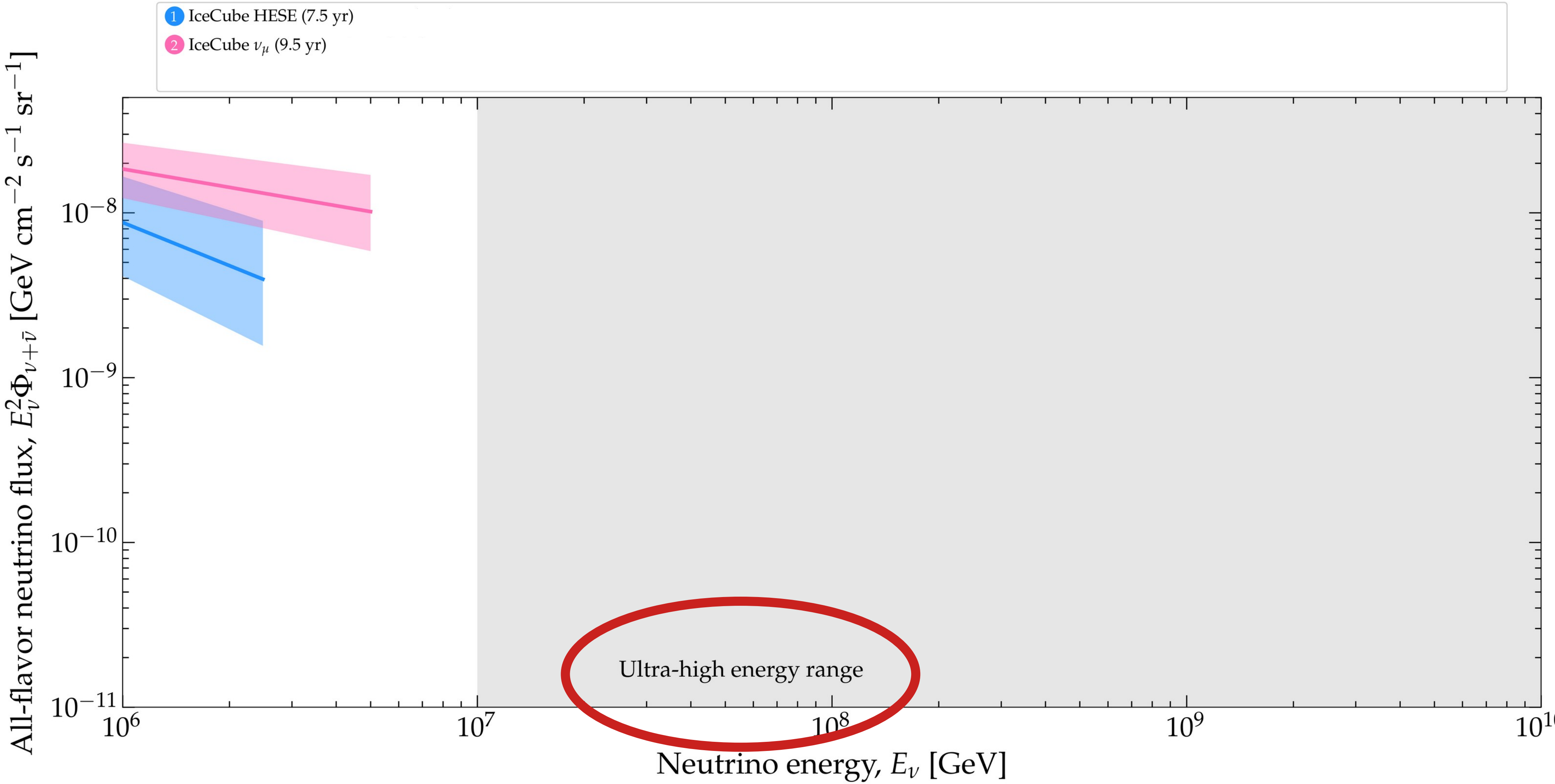
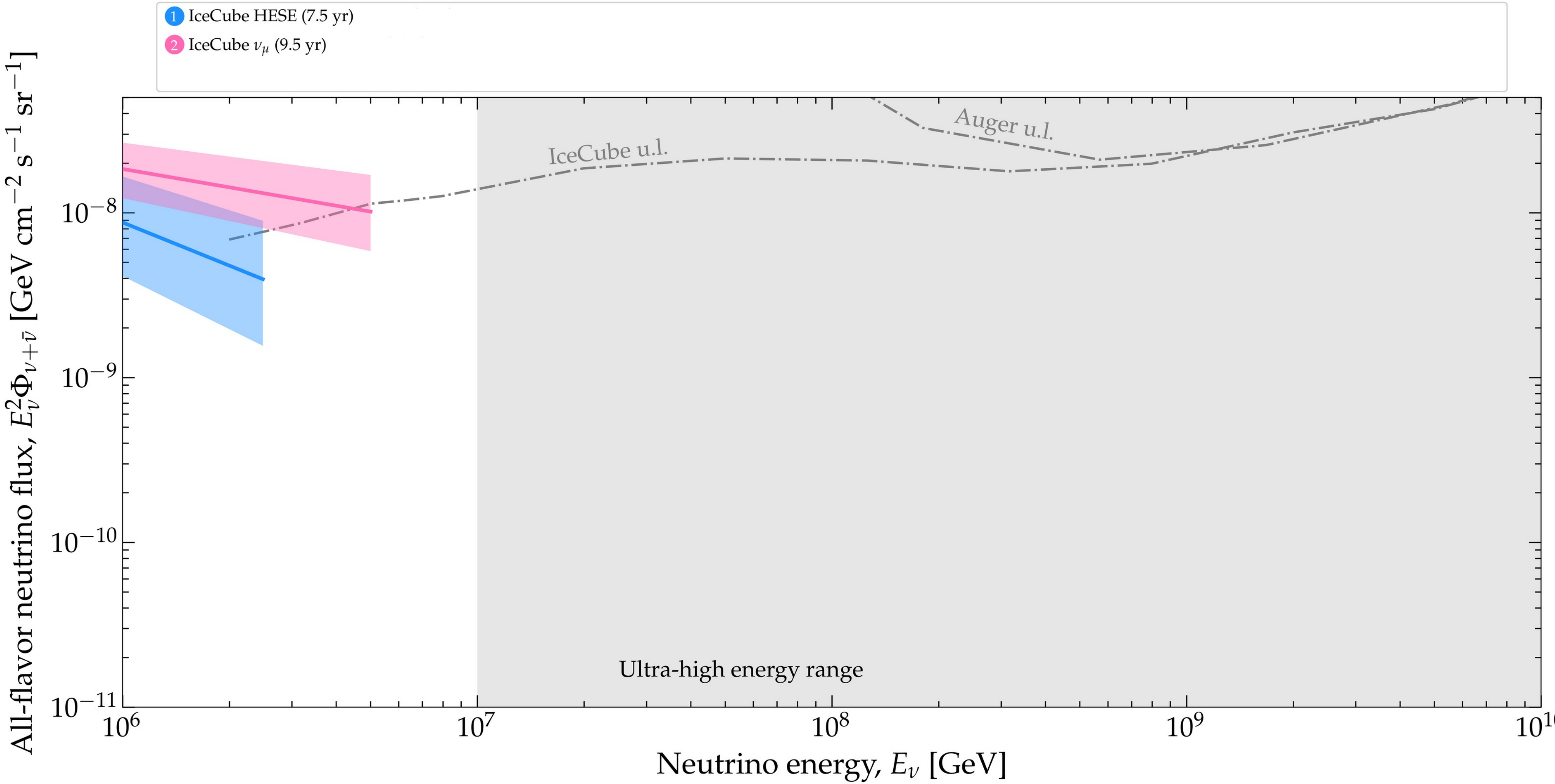
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?

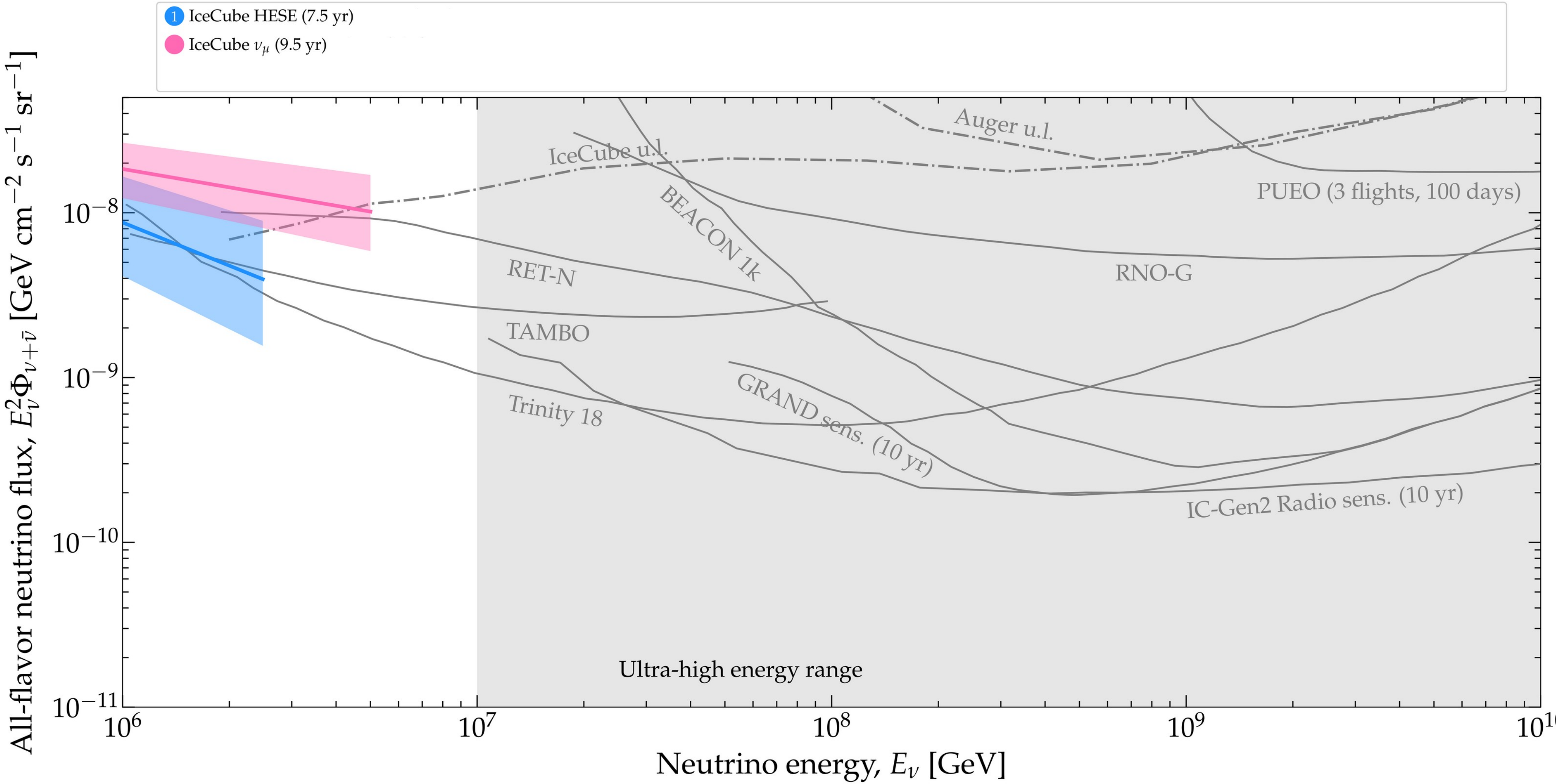


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Ultra-high energy range
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]


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



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



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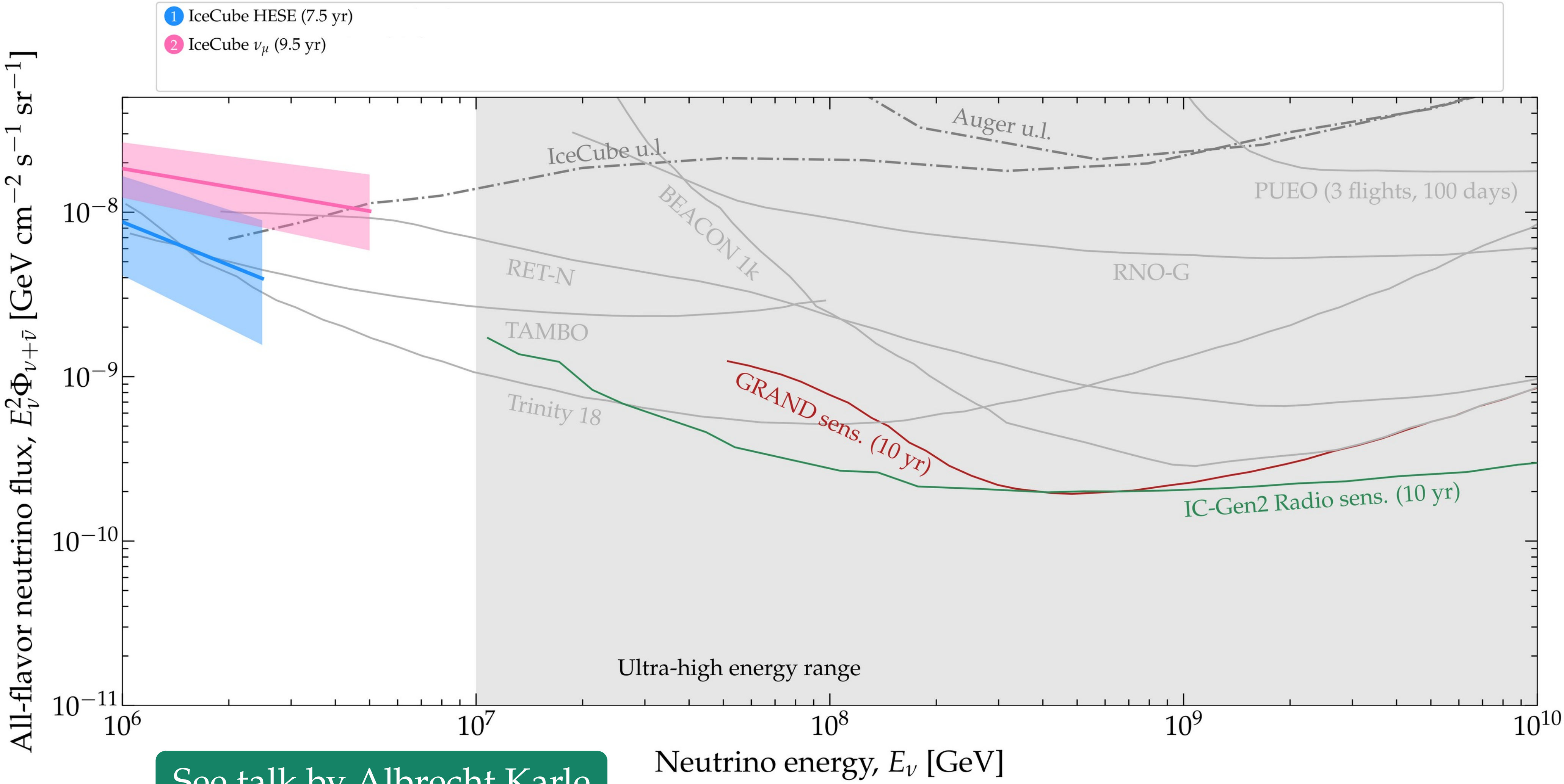
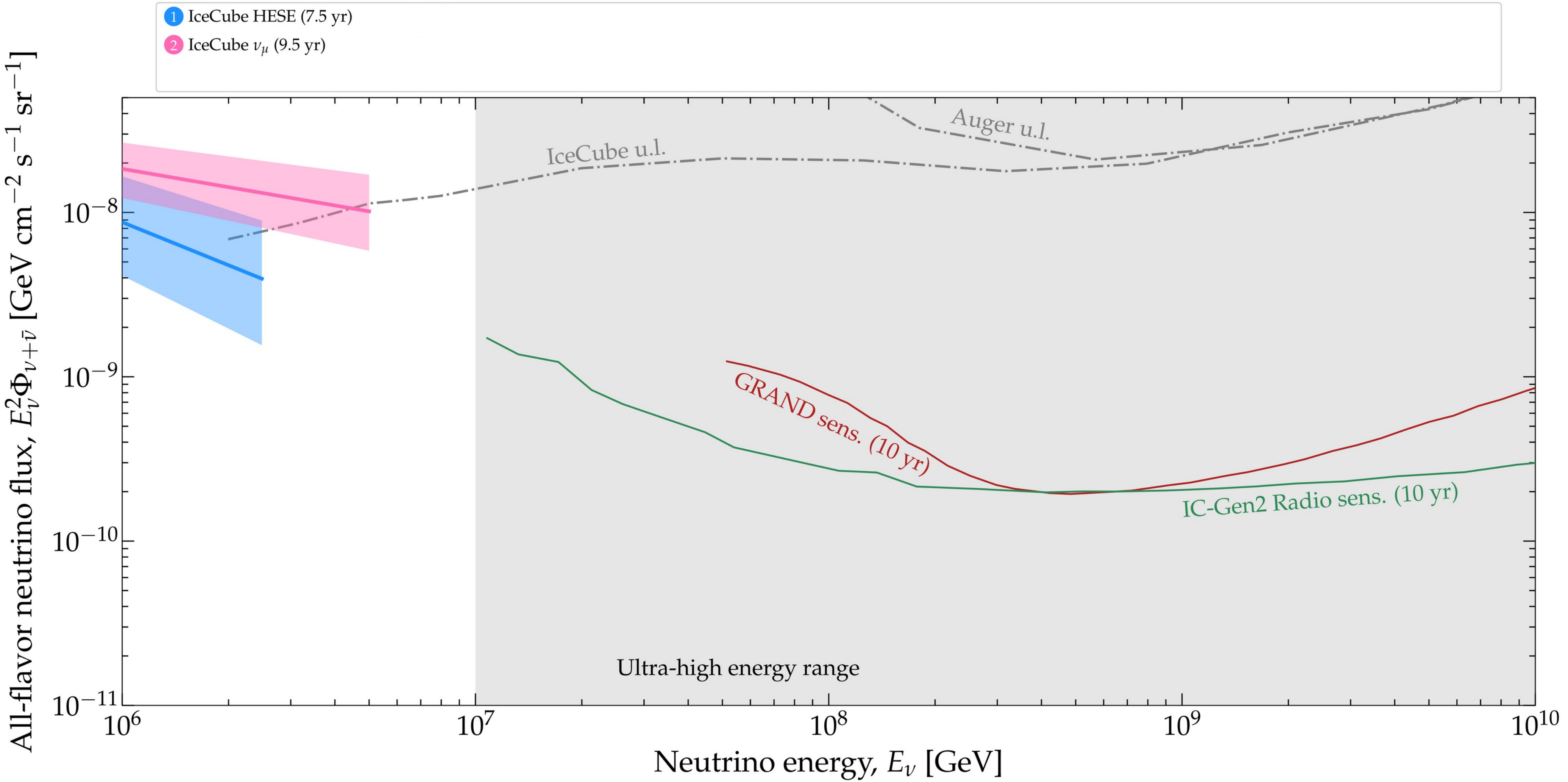
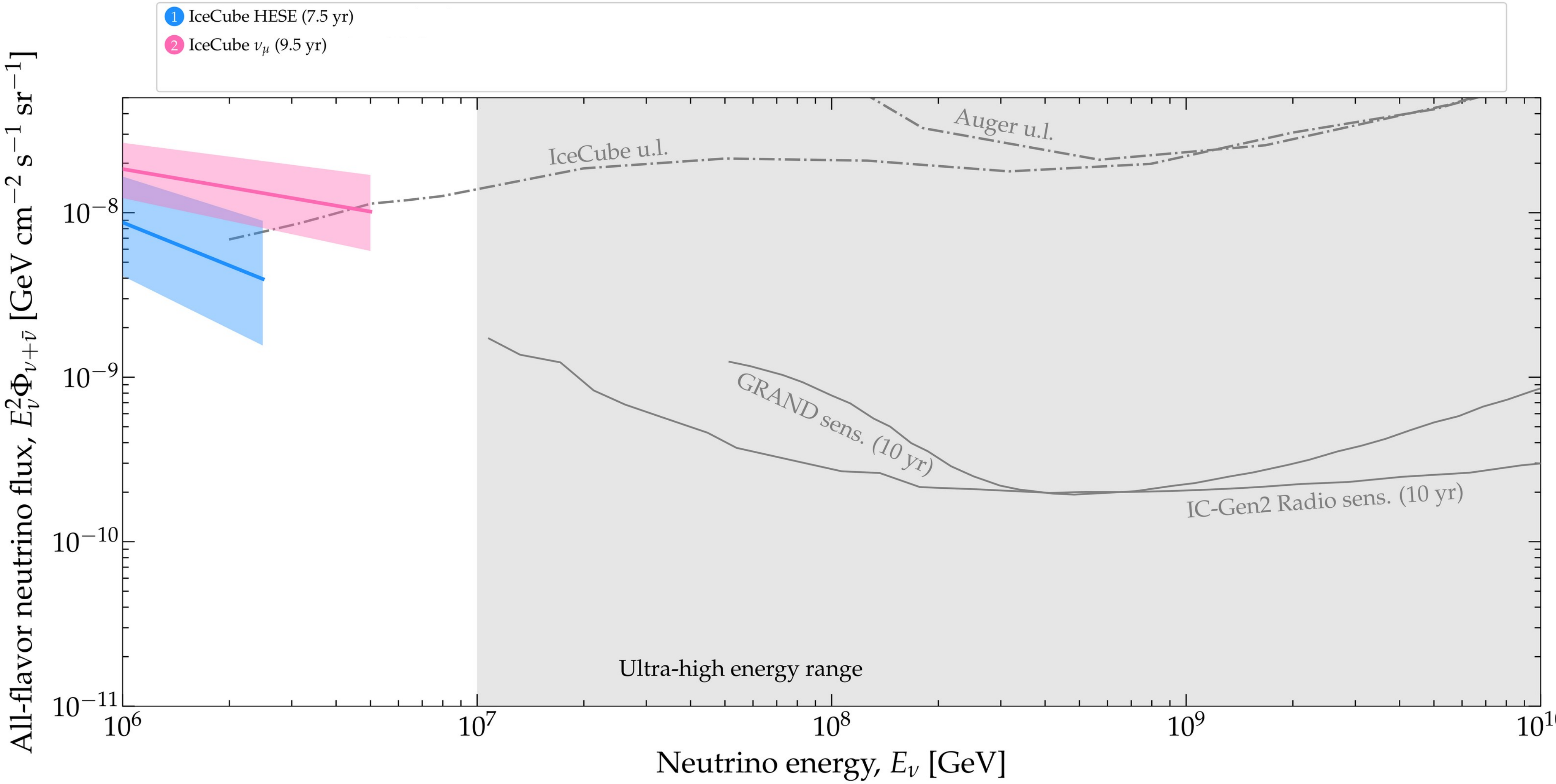
IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity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



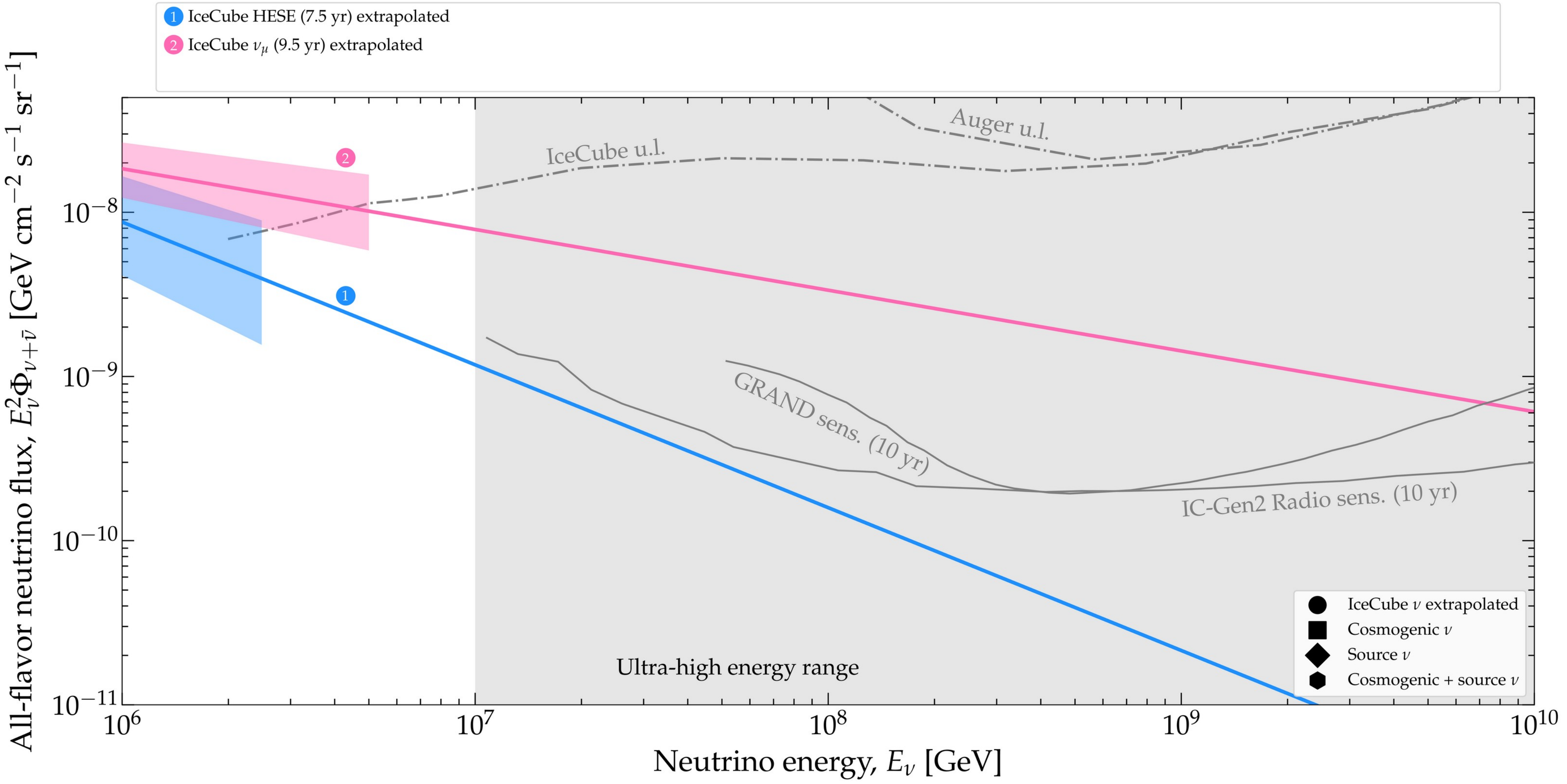
See talk by Albrecht Karle



1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

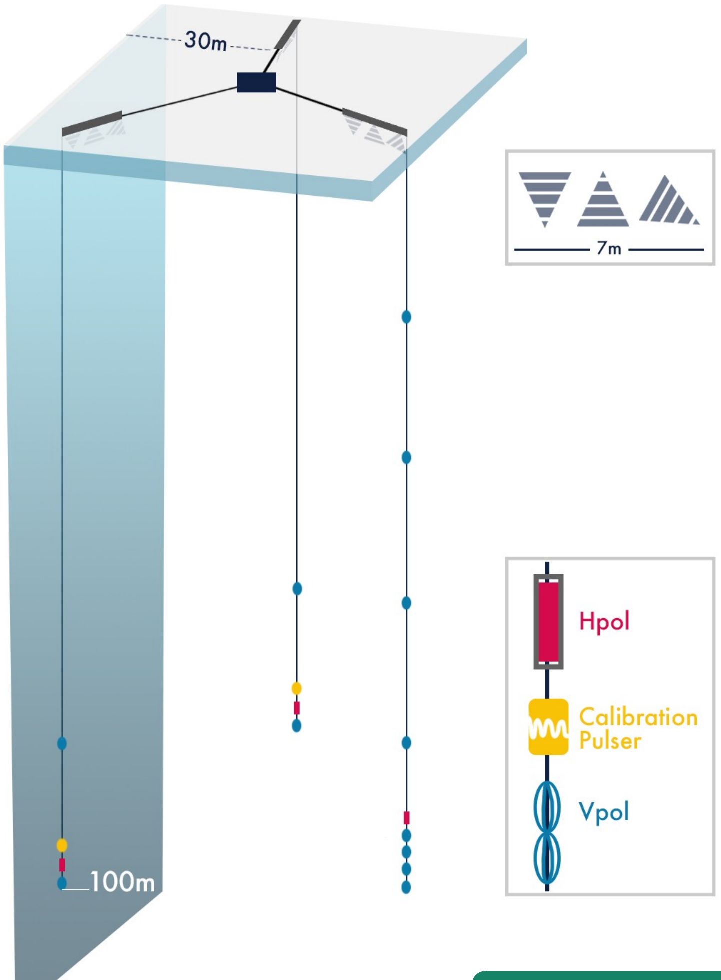


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range

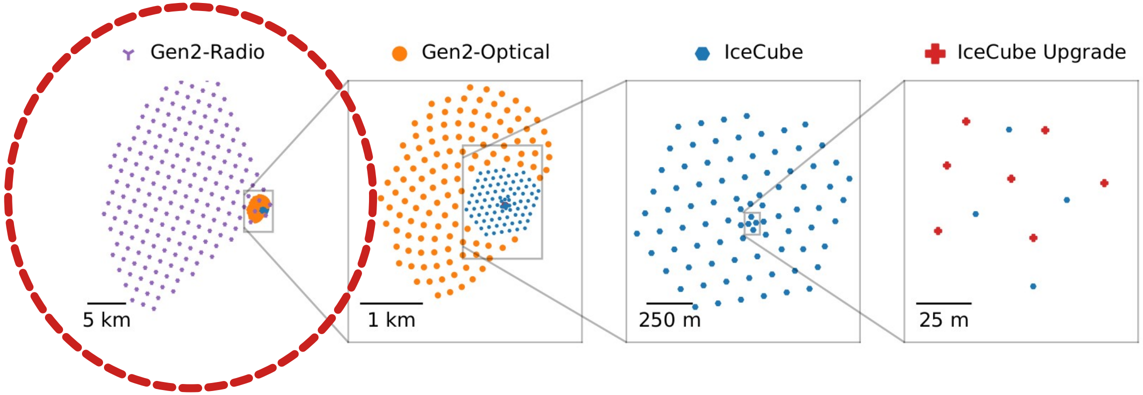


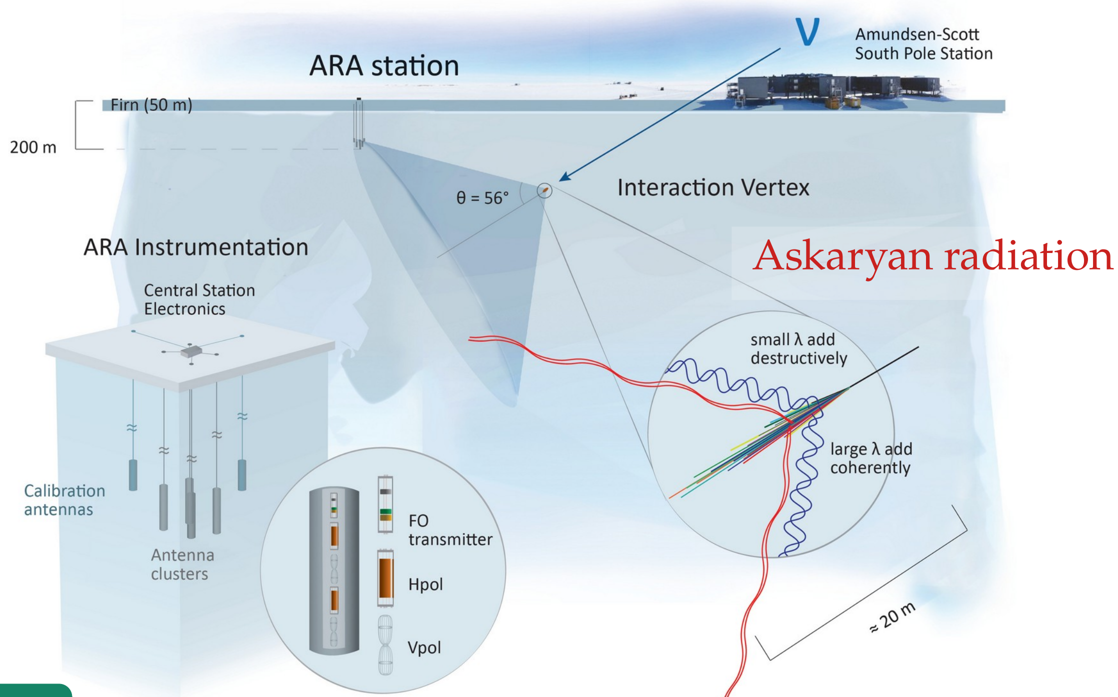
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

IceCube-Gen2 Radio



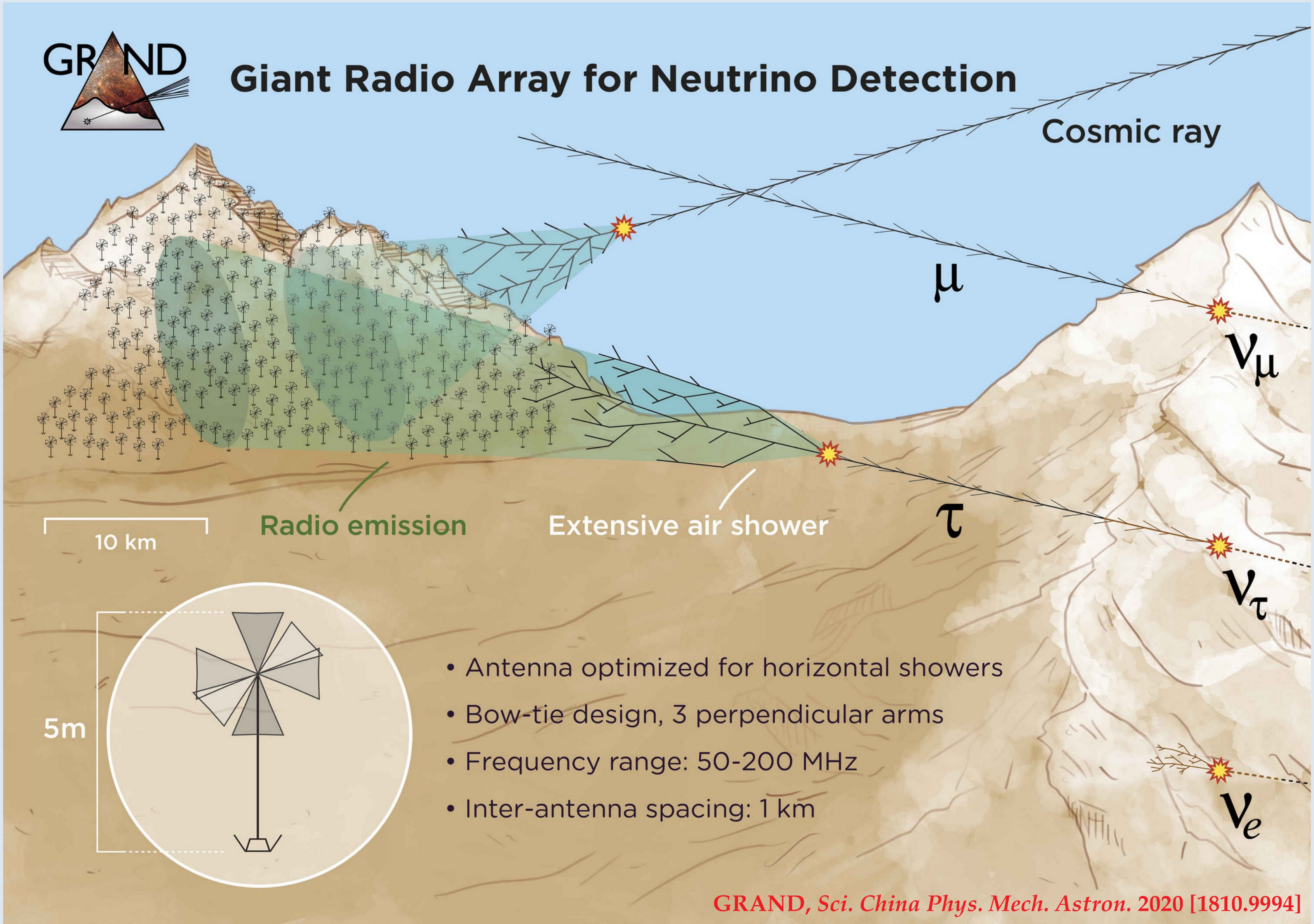
IceCube-Gen2, *J. Phys. G* 2021





ARA / WIPAC

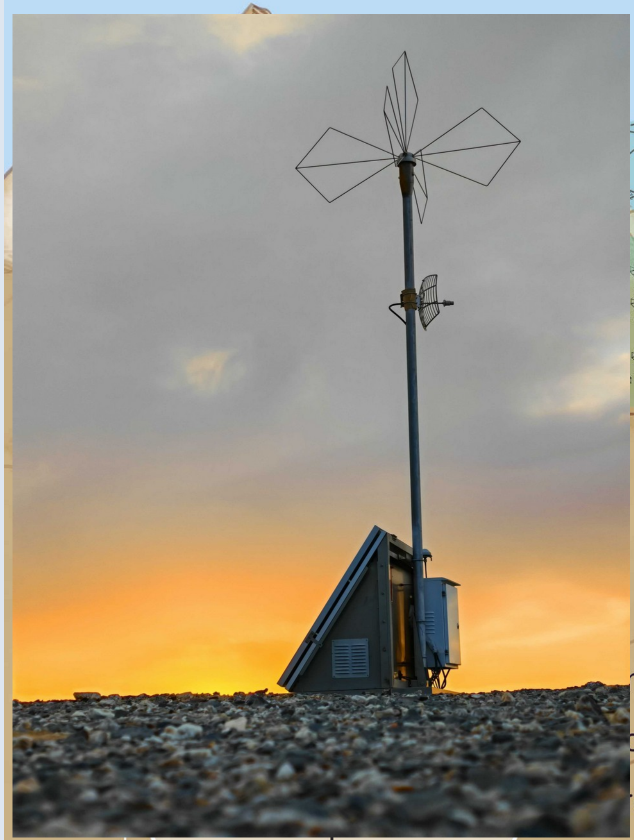
See talk by Delia Tosi



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

Giant Radio Array for Neutrino Detection

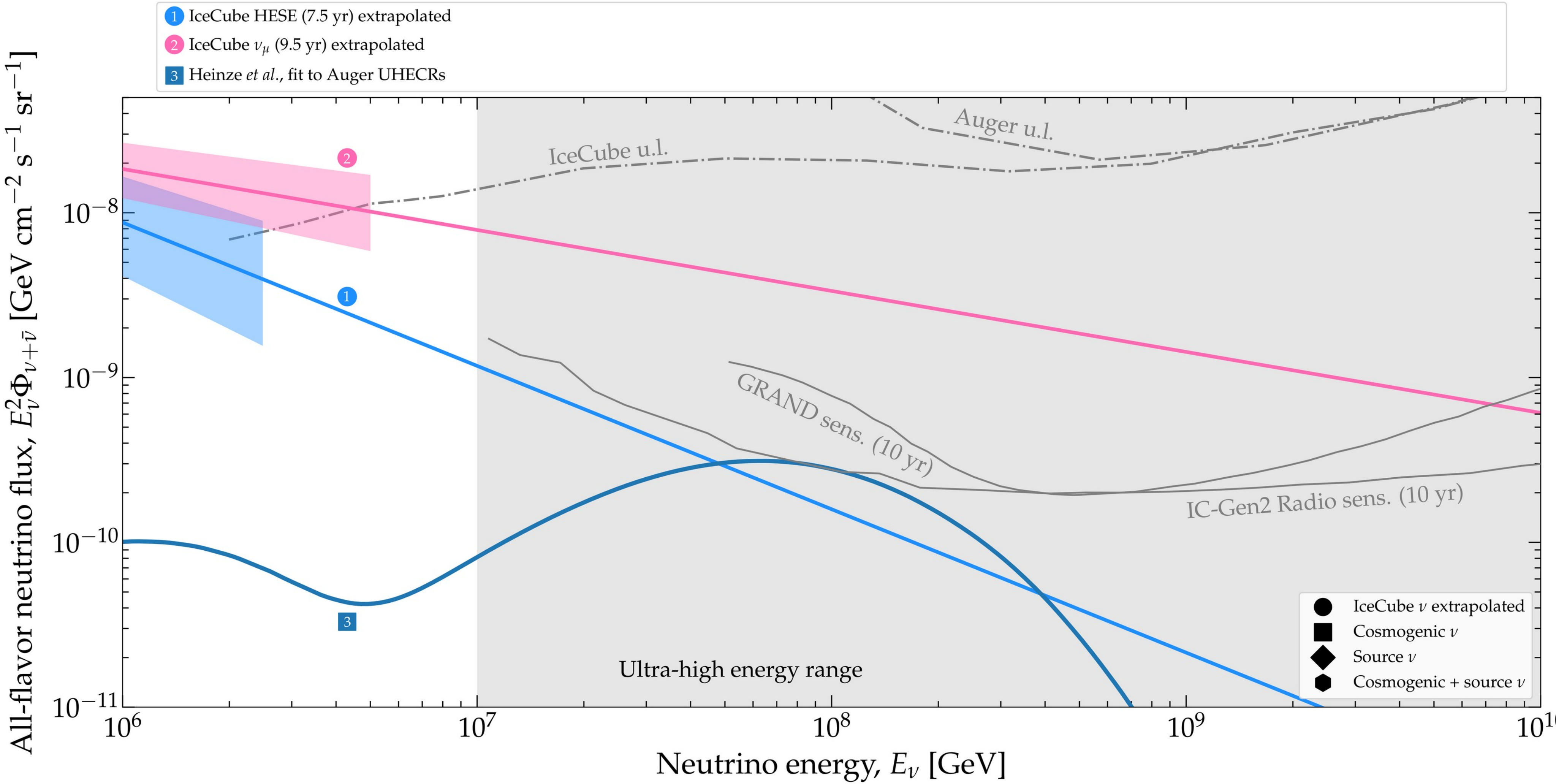
Cosmic ray



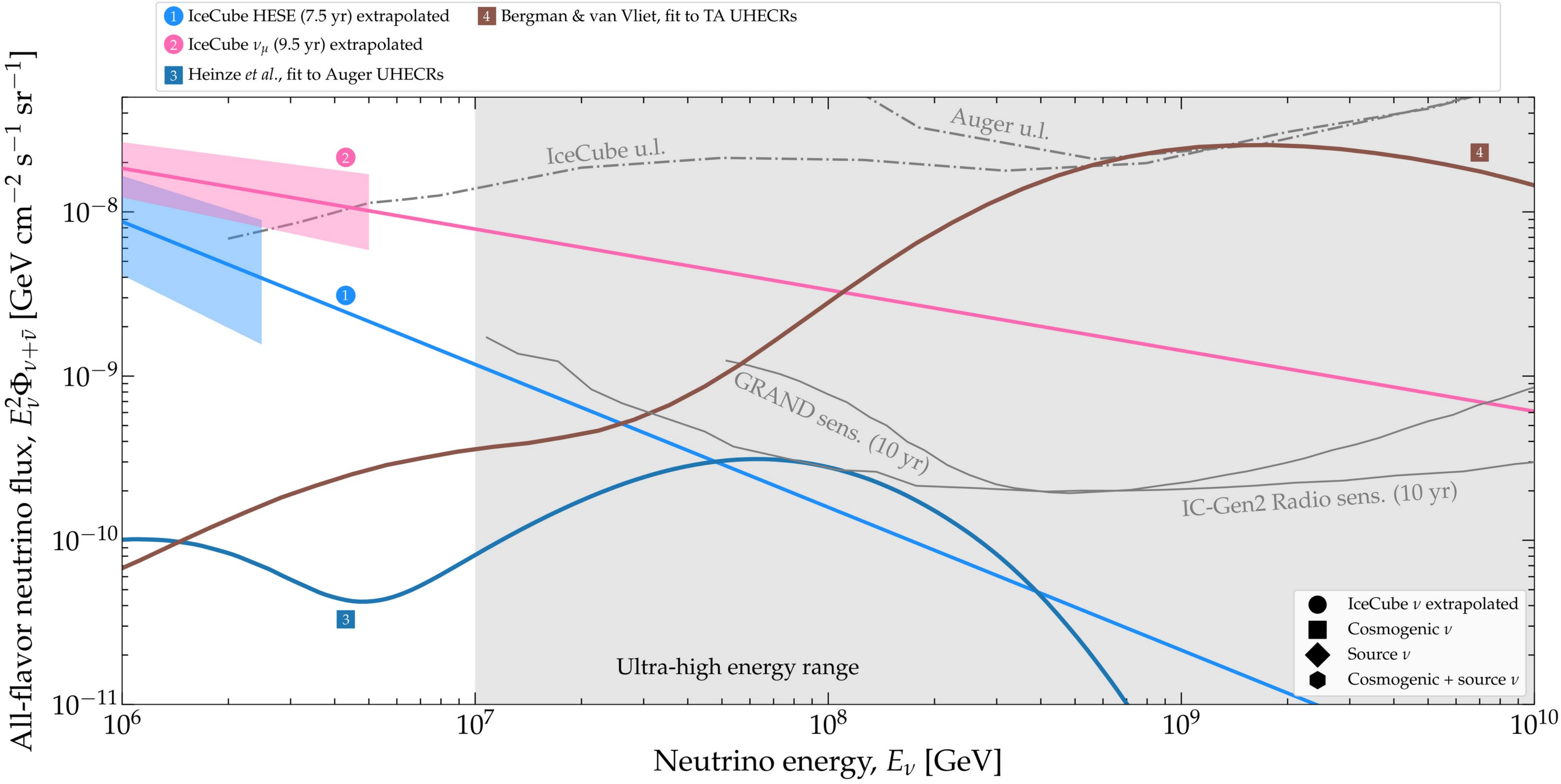
• Inter-antenna spacing: 1 km

ν_e

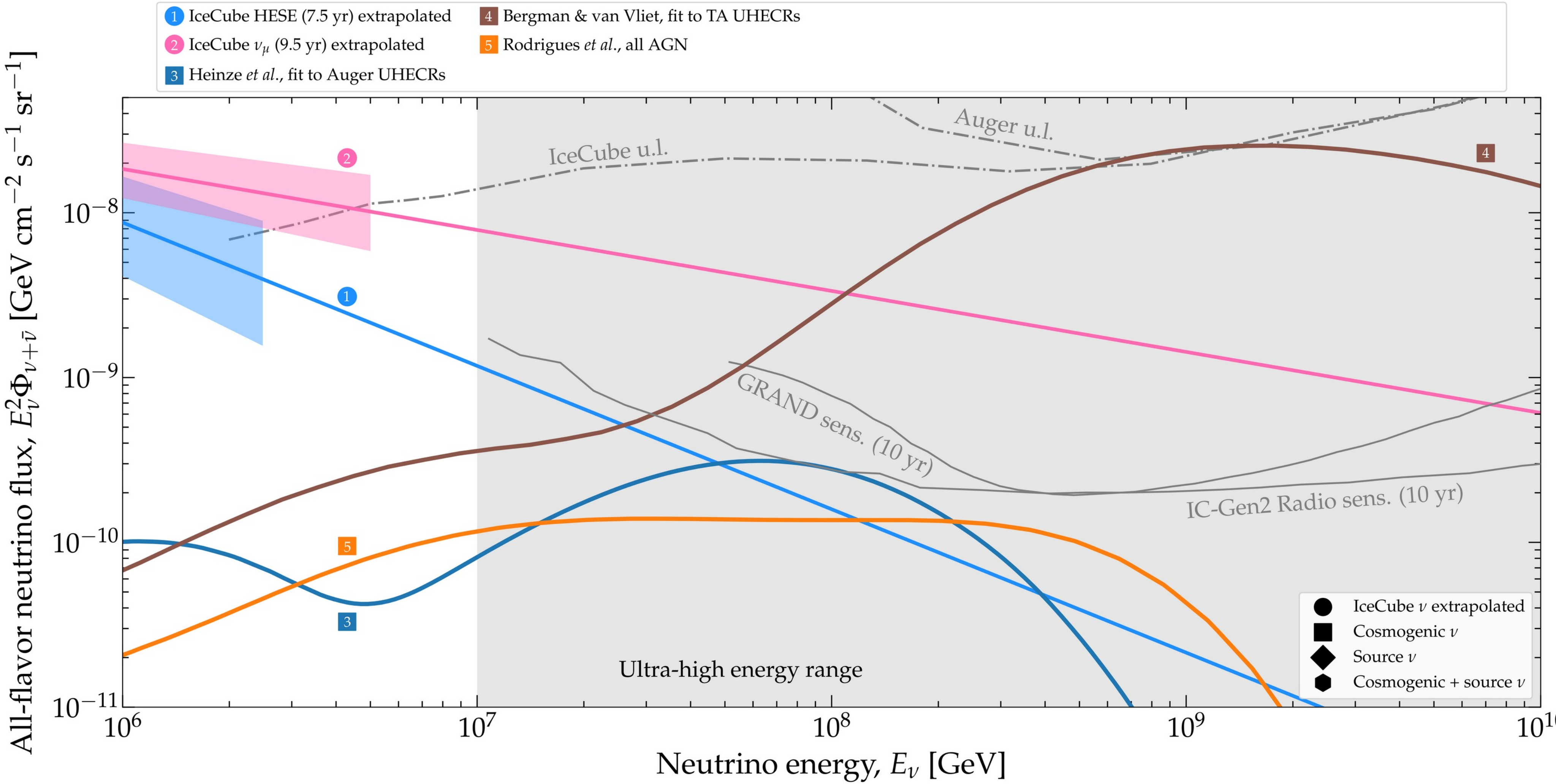
GRAND, *Sci. China Phys. Mech. Astron.* 2020 [1810.9994]



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



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze *et al.*, fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



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Source ν
Cosmogenic + source ν
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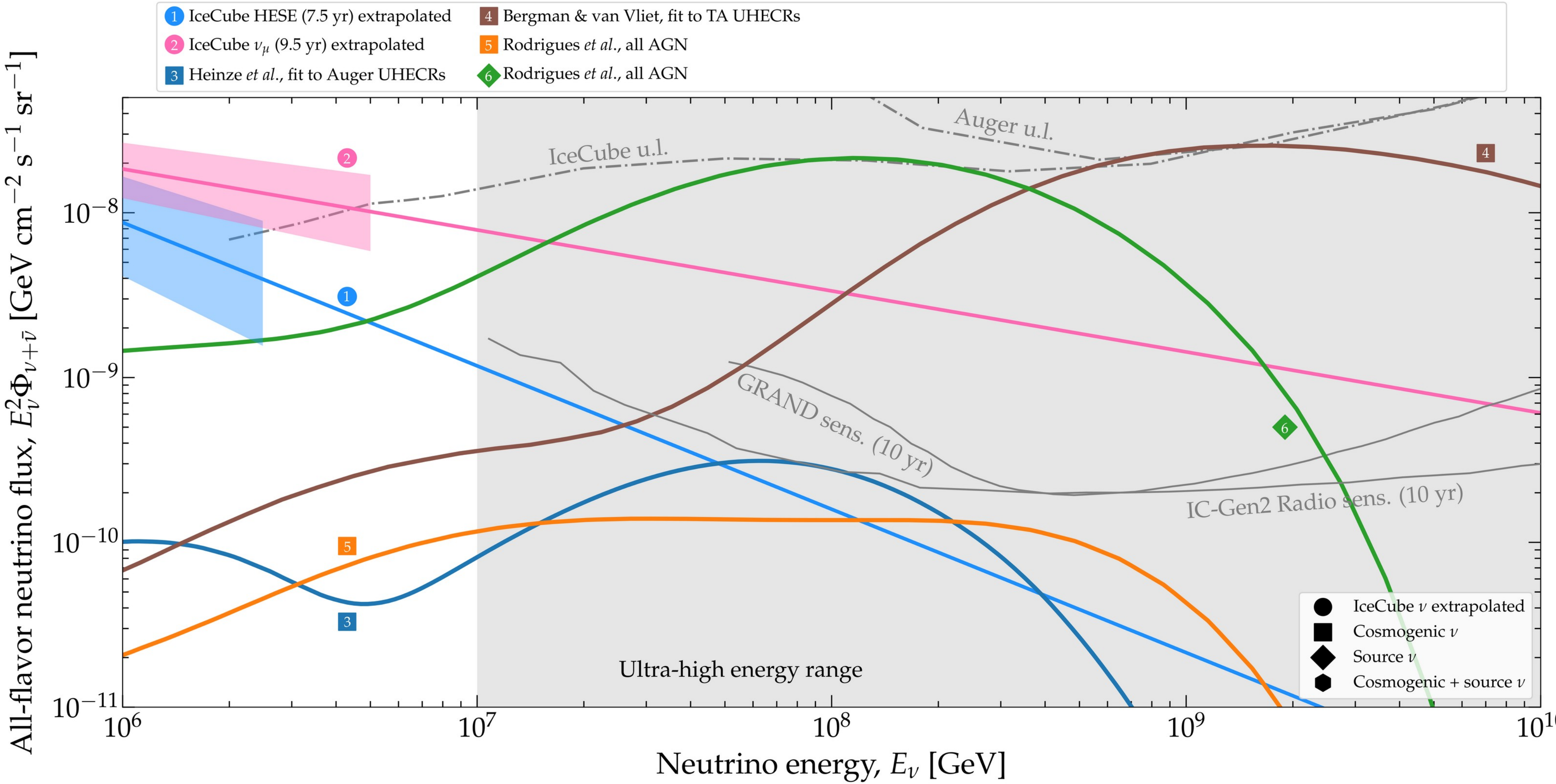

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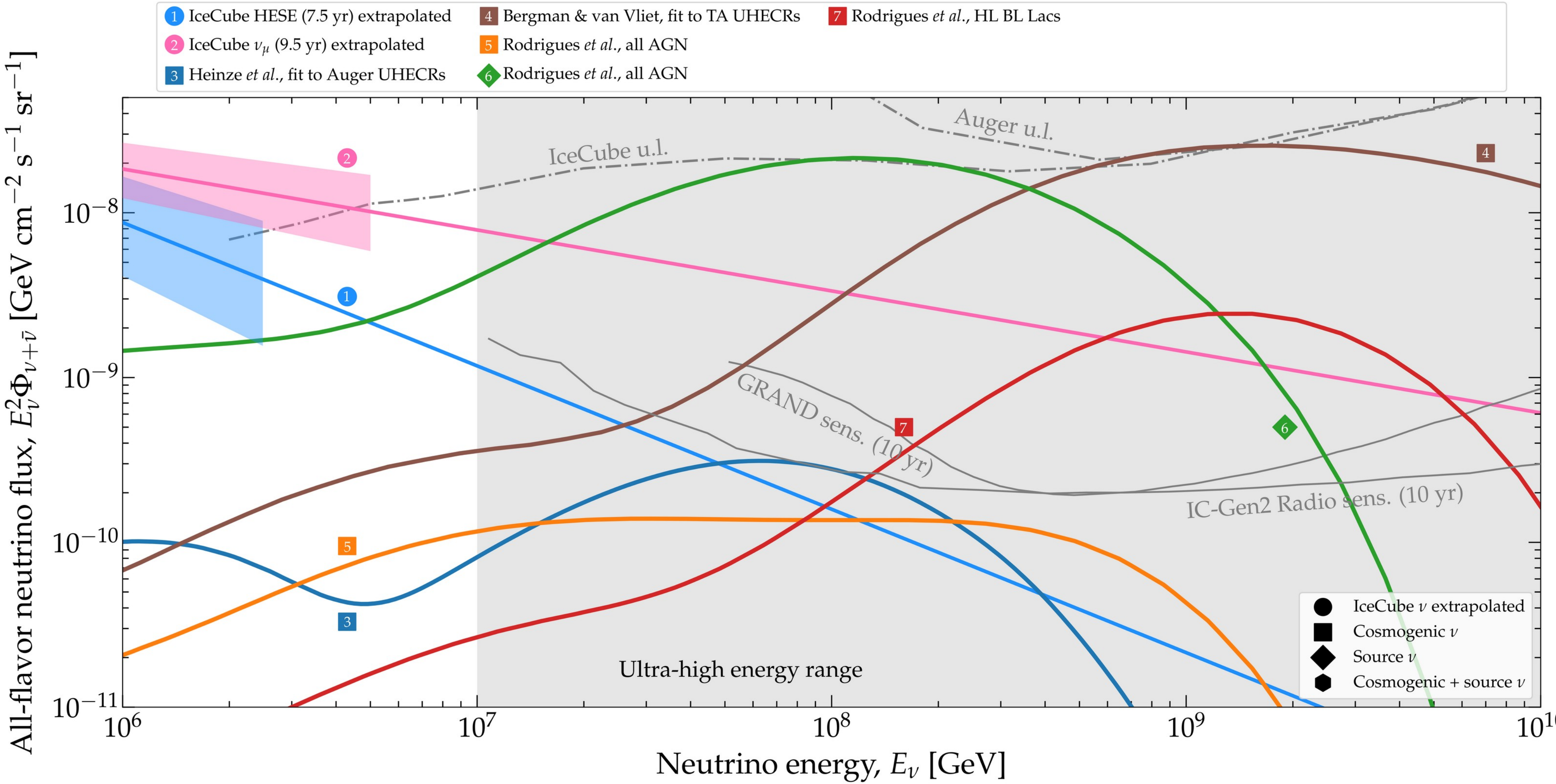

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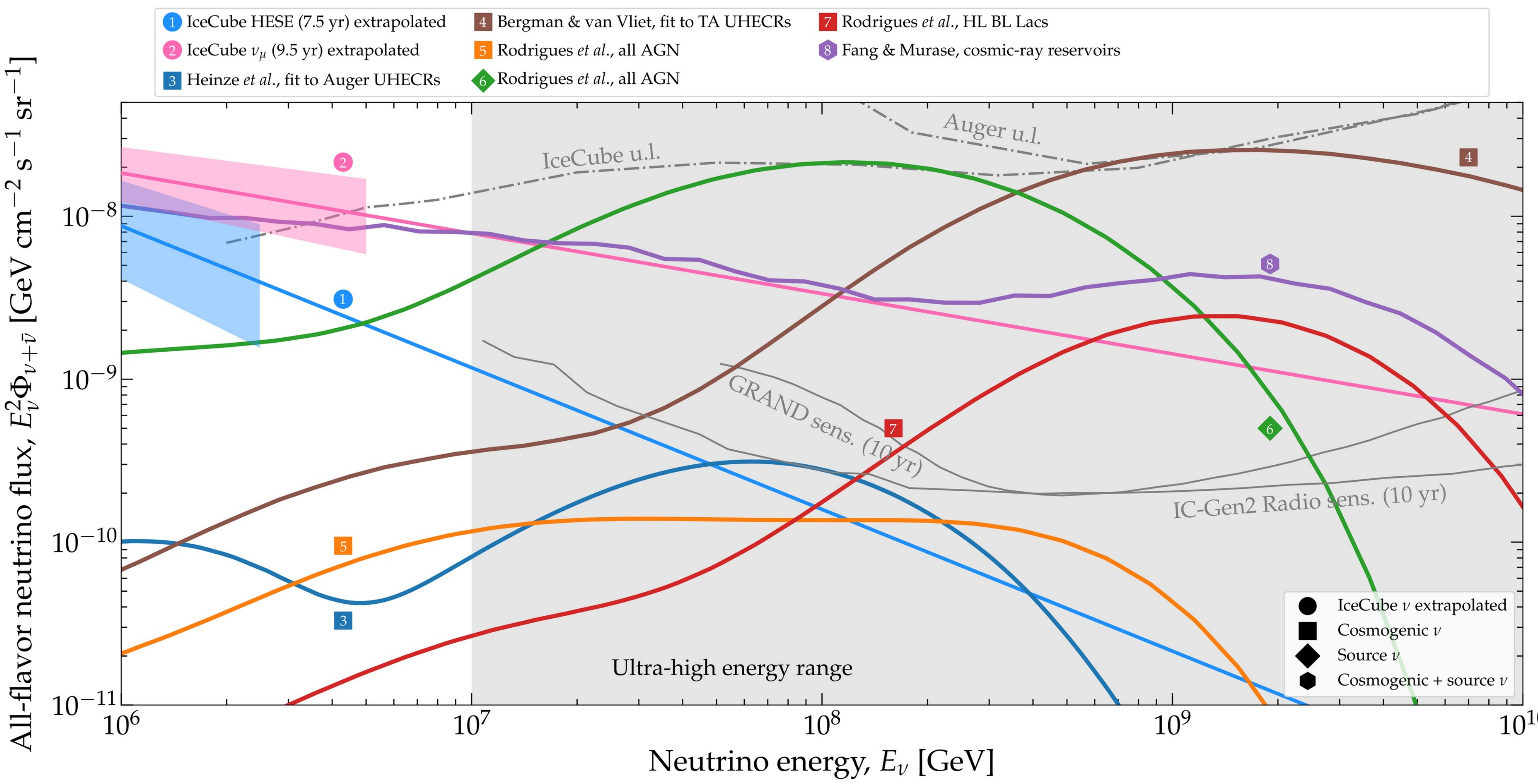
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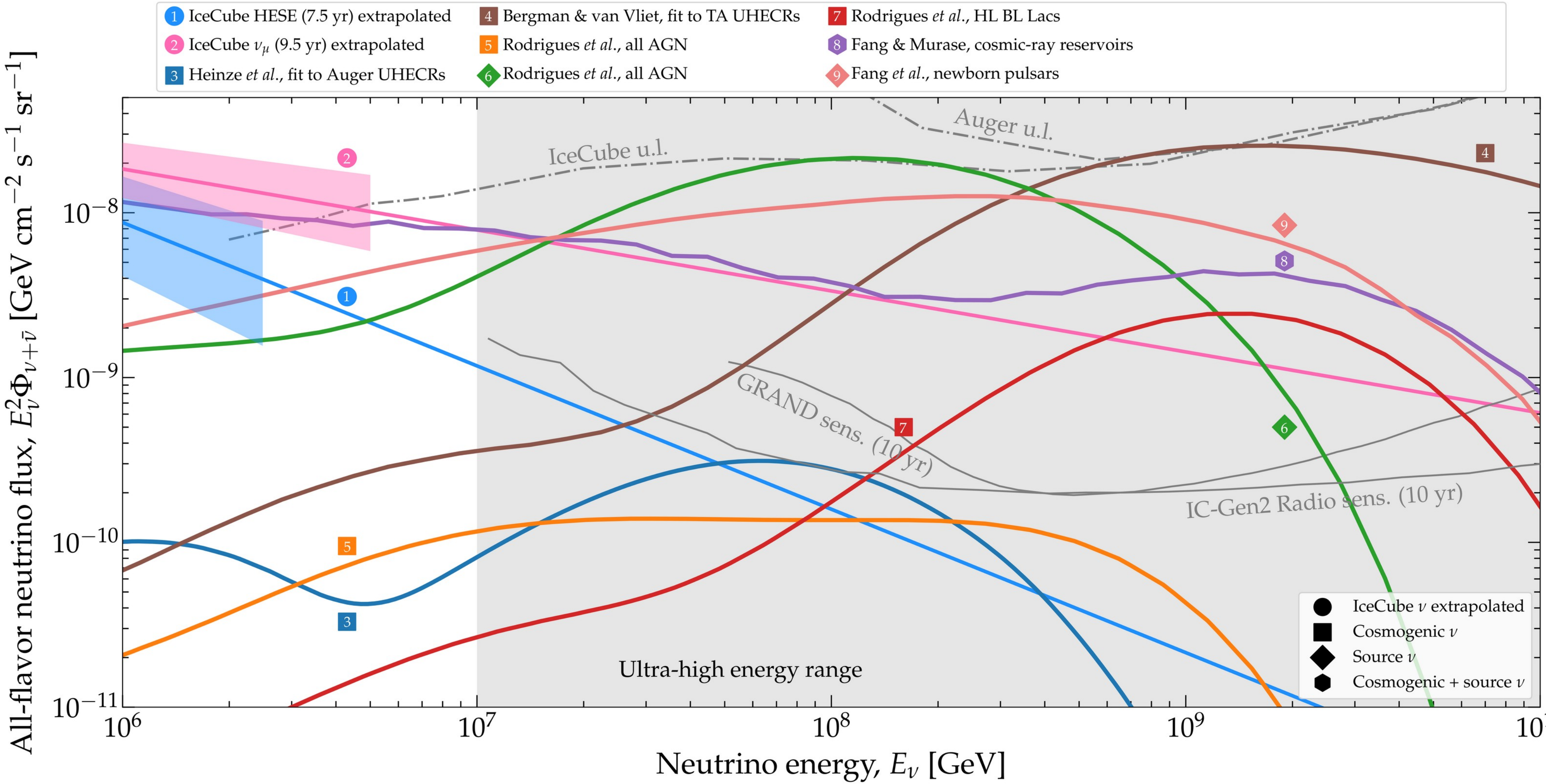

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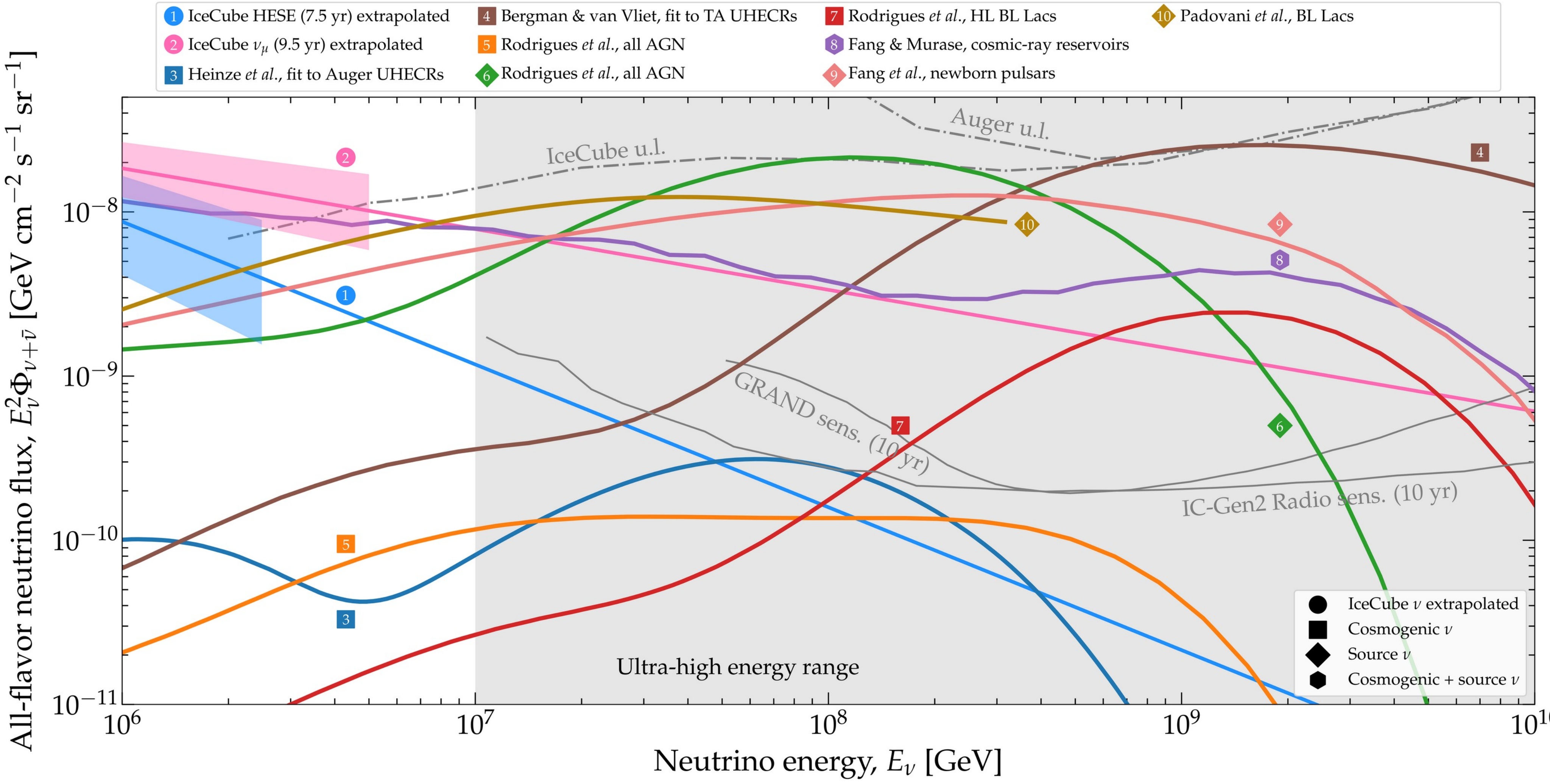

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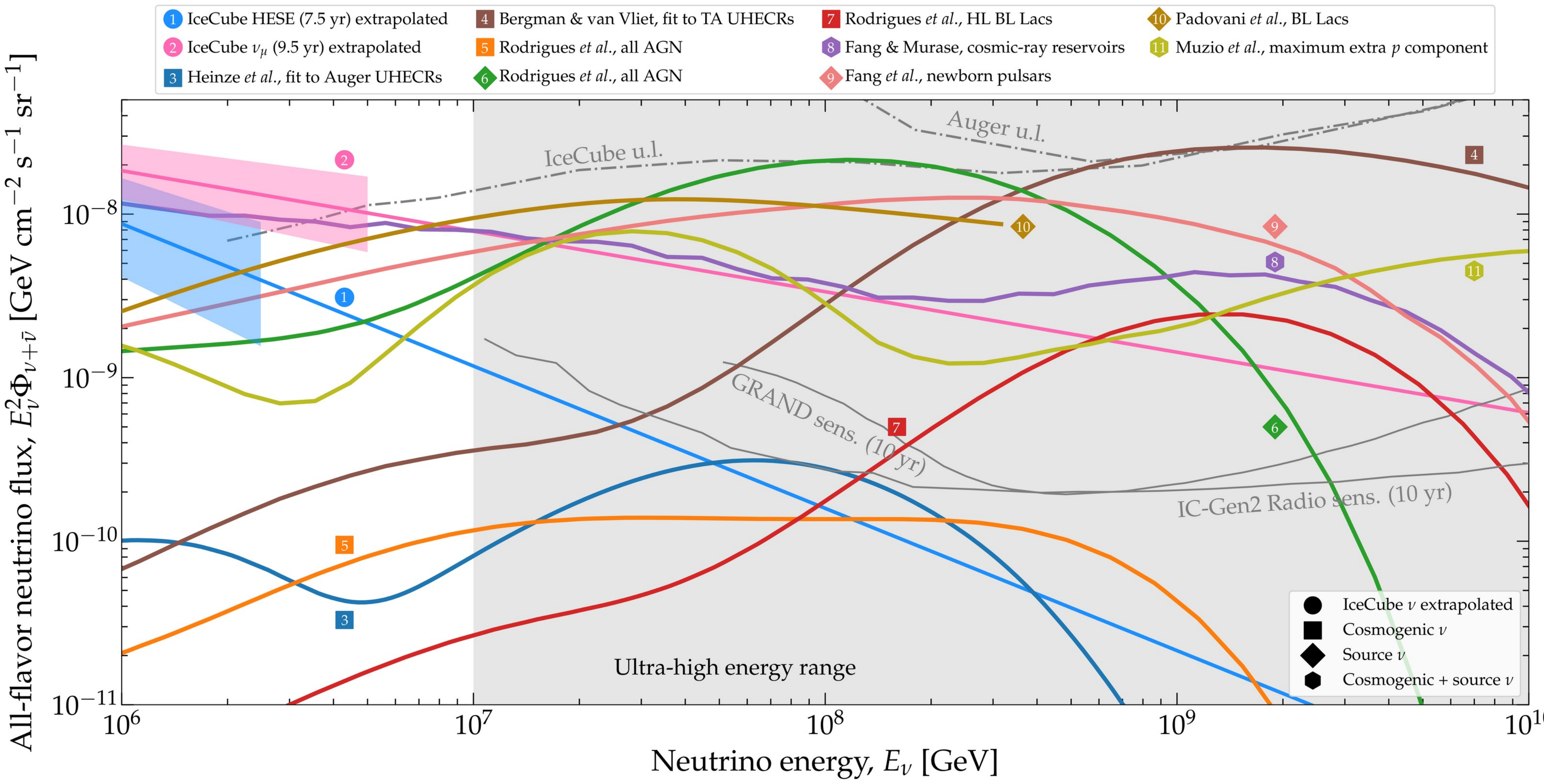

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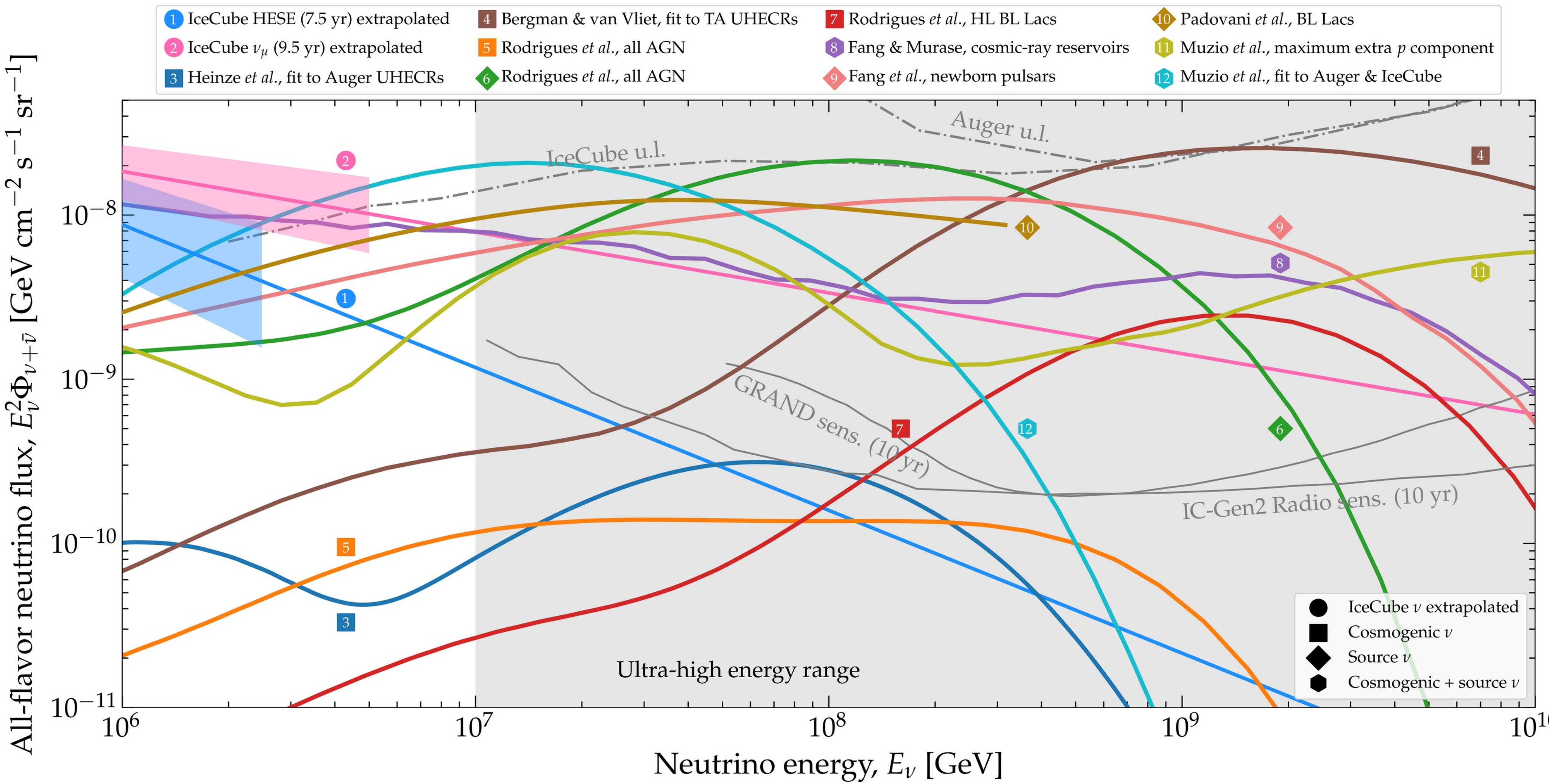

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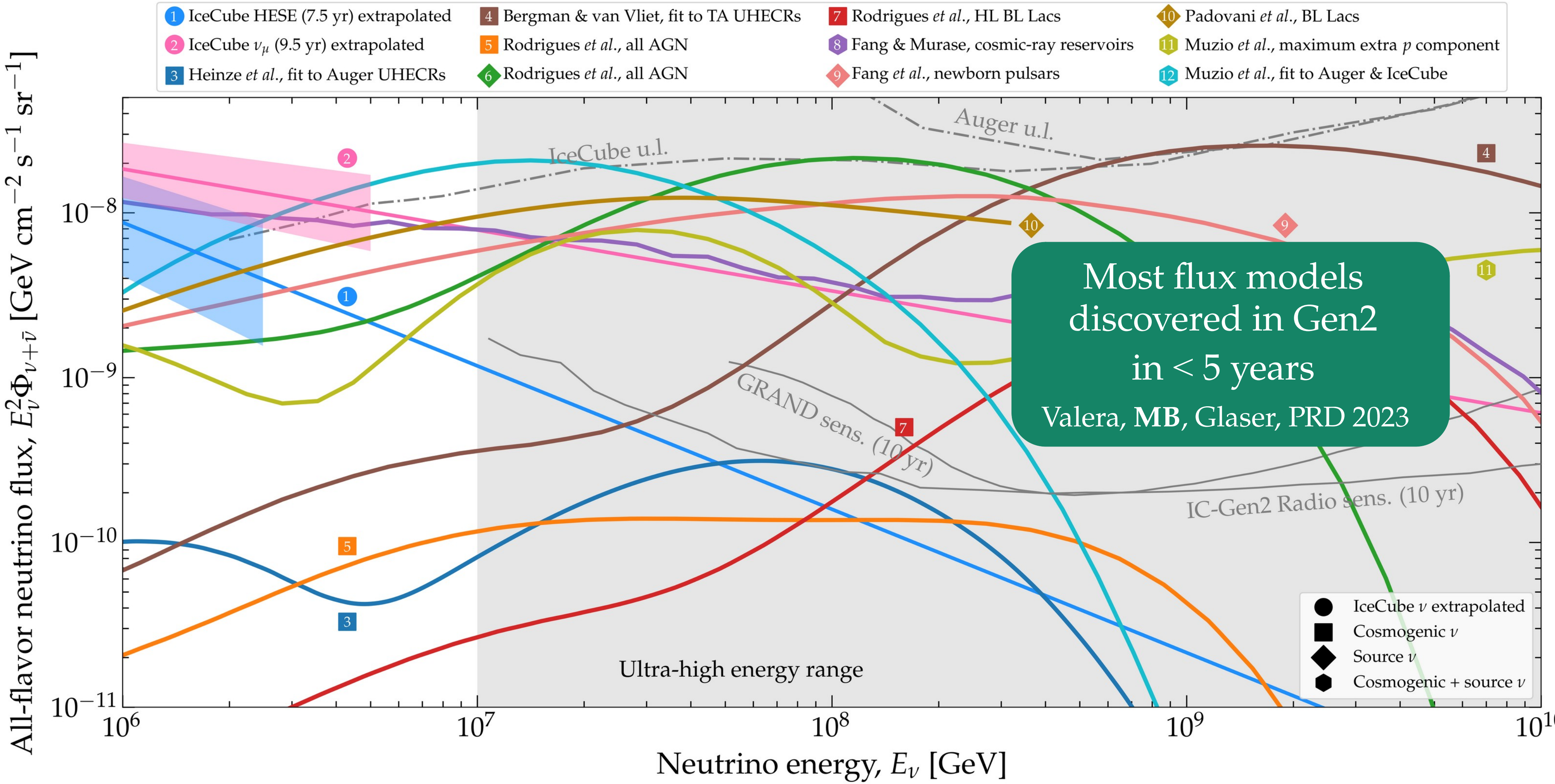
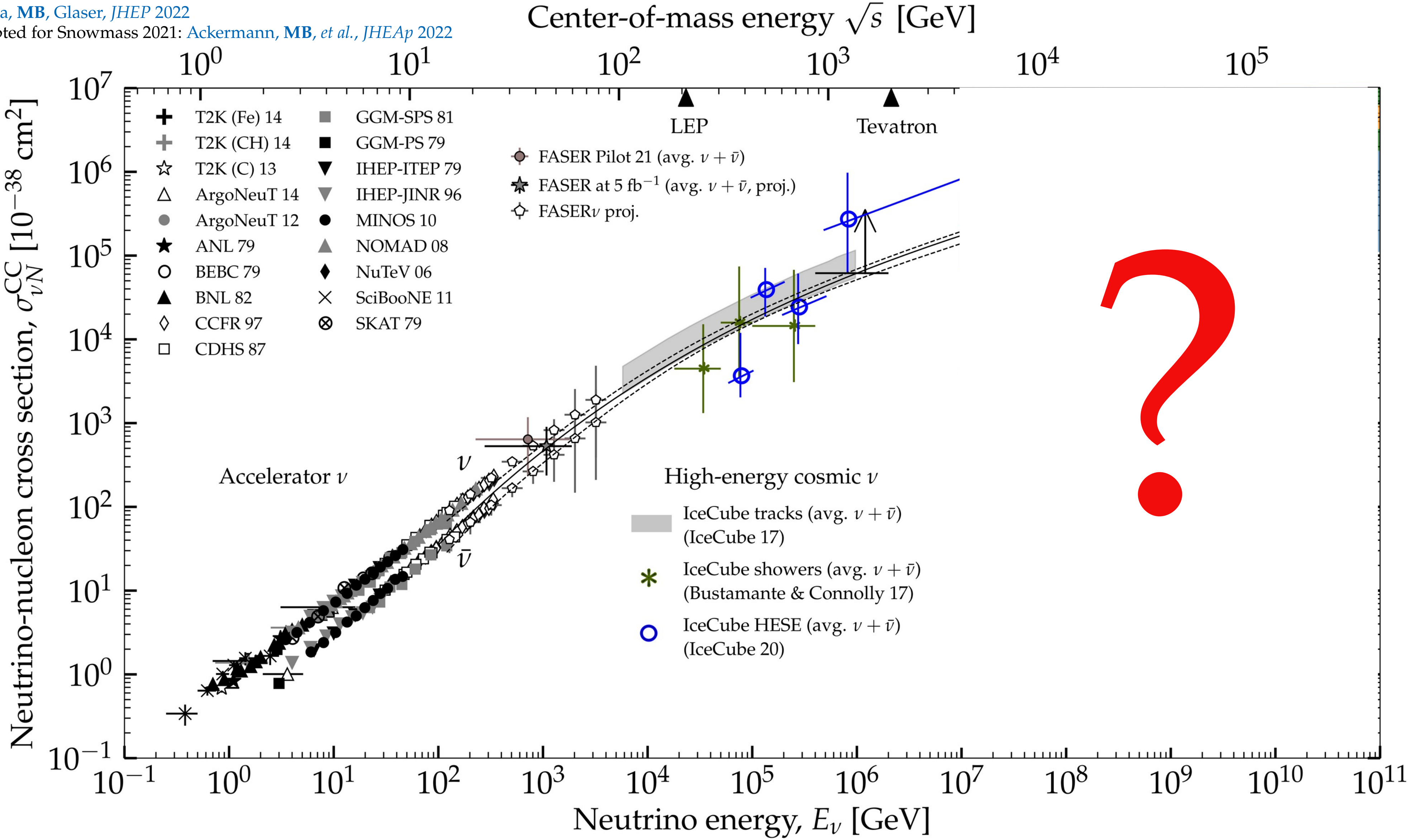


Most flux models discovered in Gen2 in < 5 years

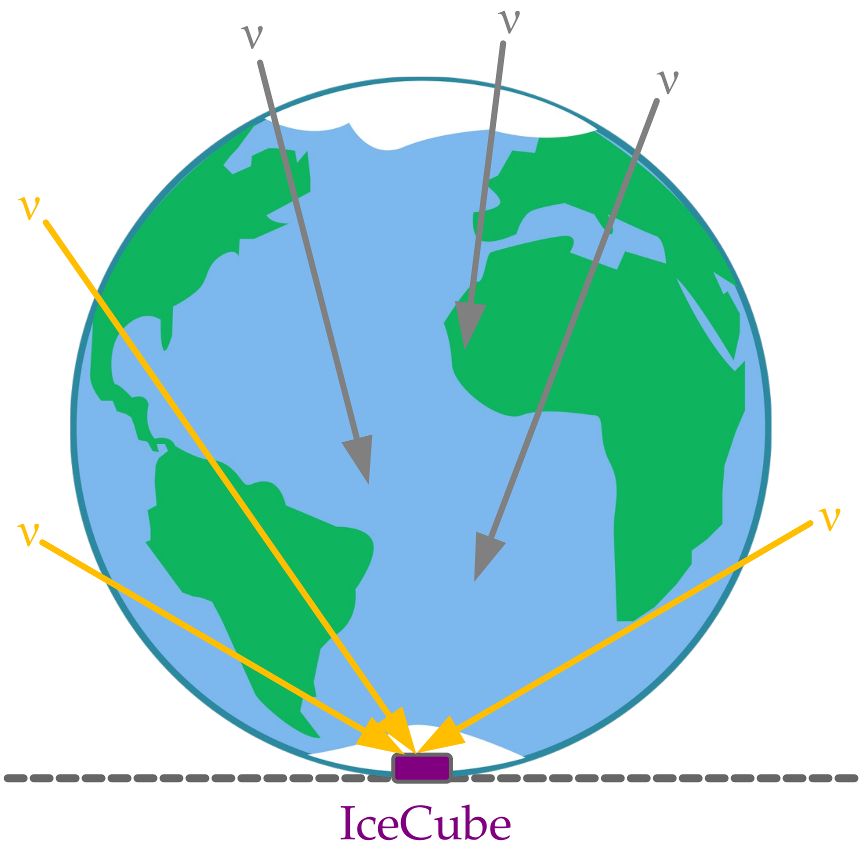
Valera, **MB**, Glaser, PRD 2023

Neutrino cross section at ultra-high energies

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

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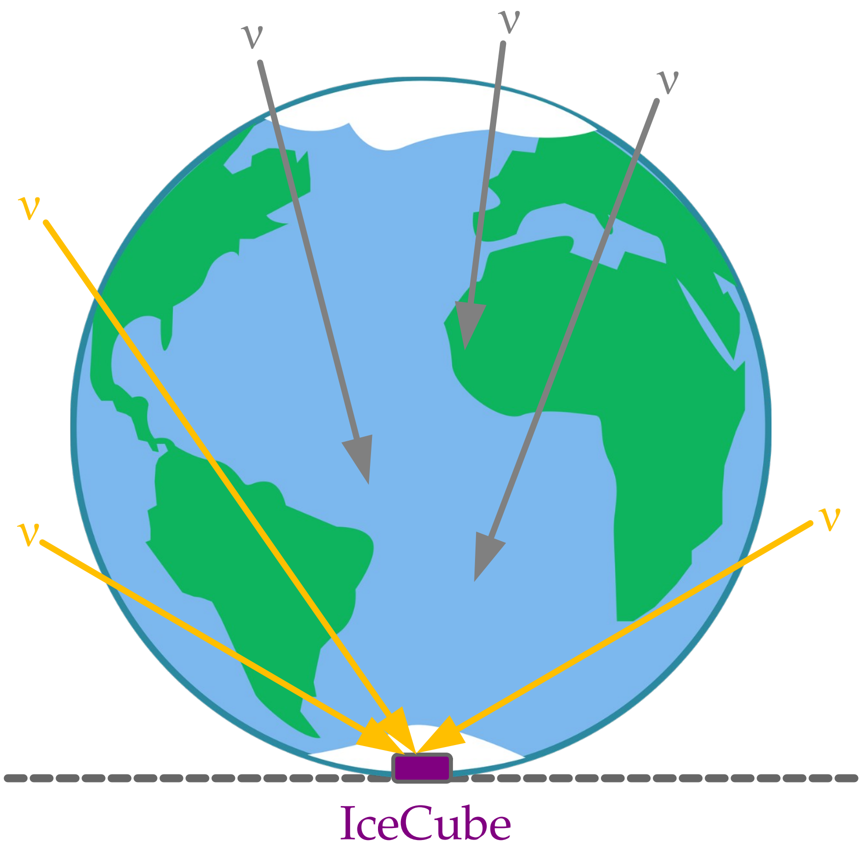

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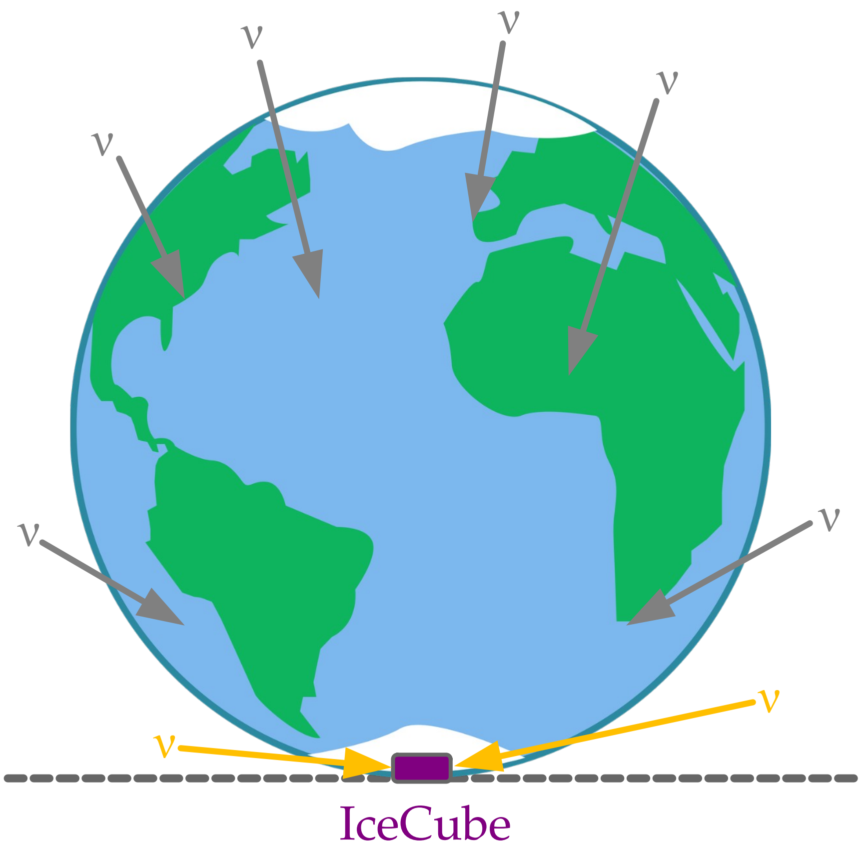
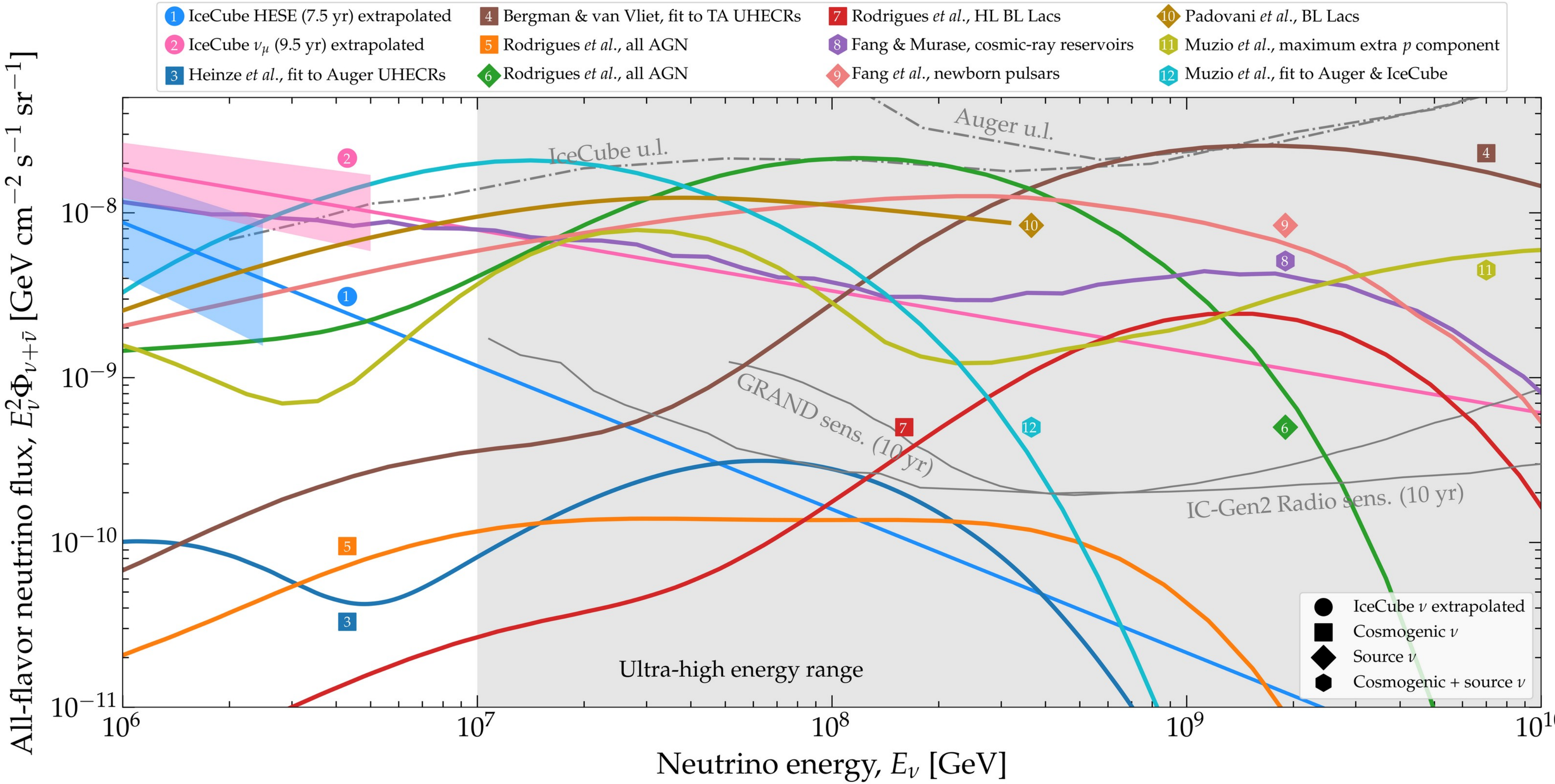
>100 PeV:



Earth is *completely* opaque,
but horizontal ν still make it through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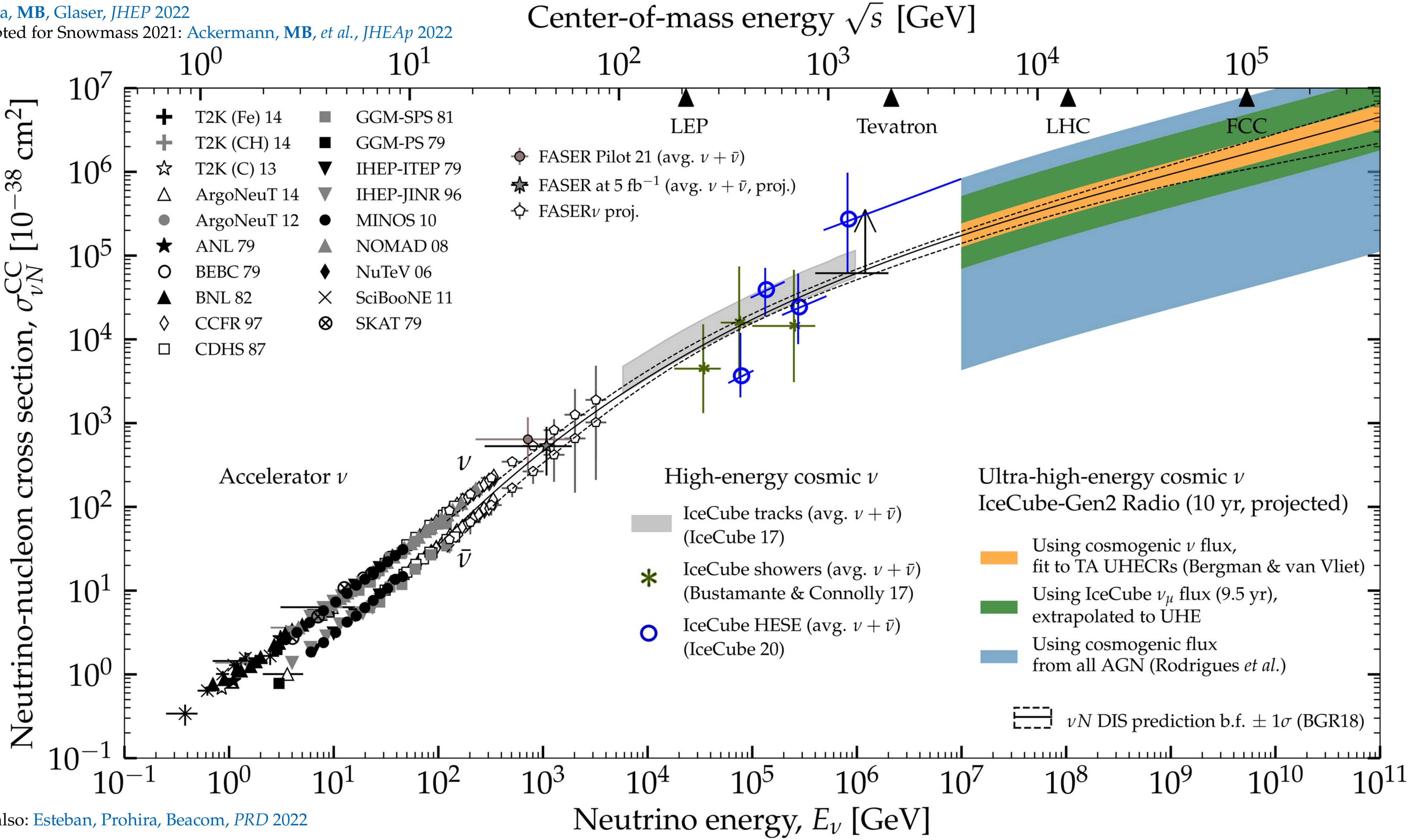
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

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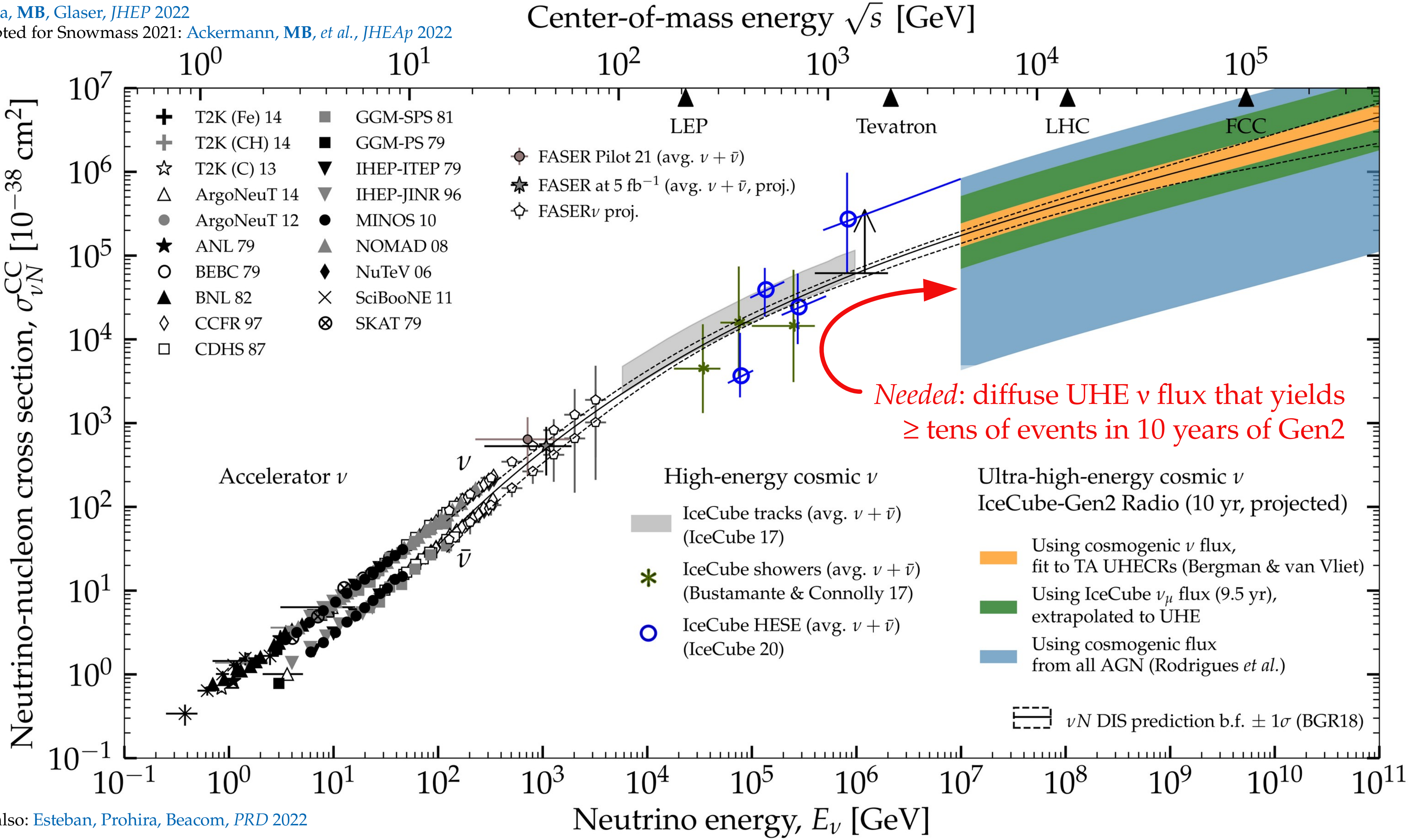

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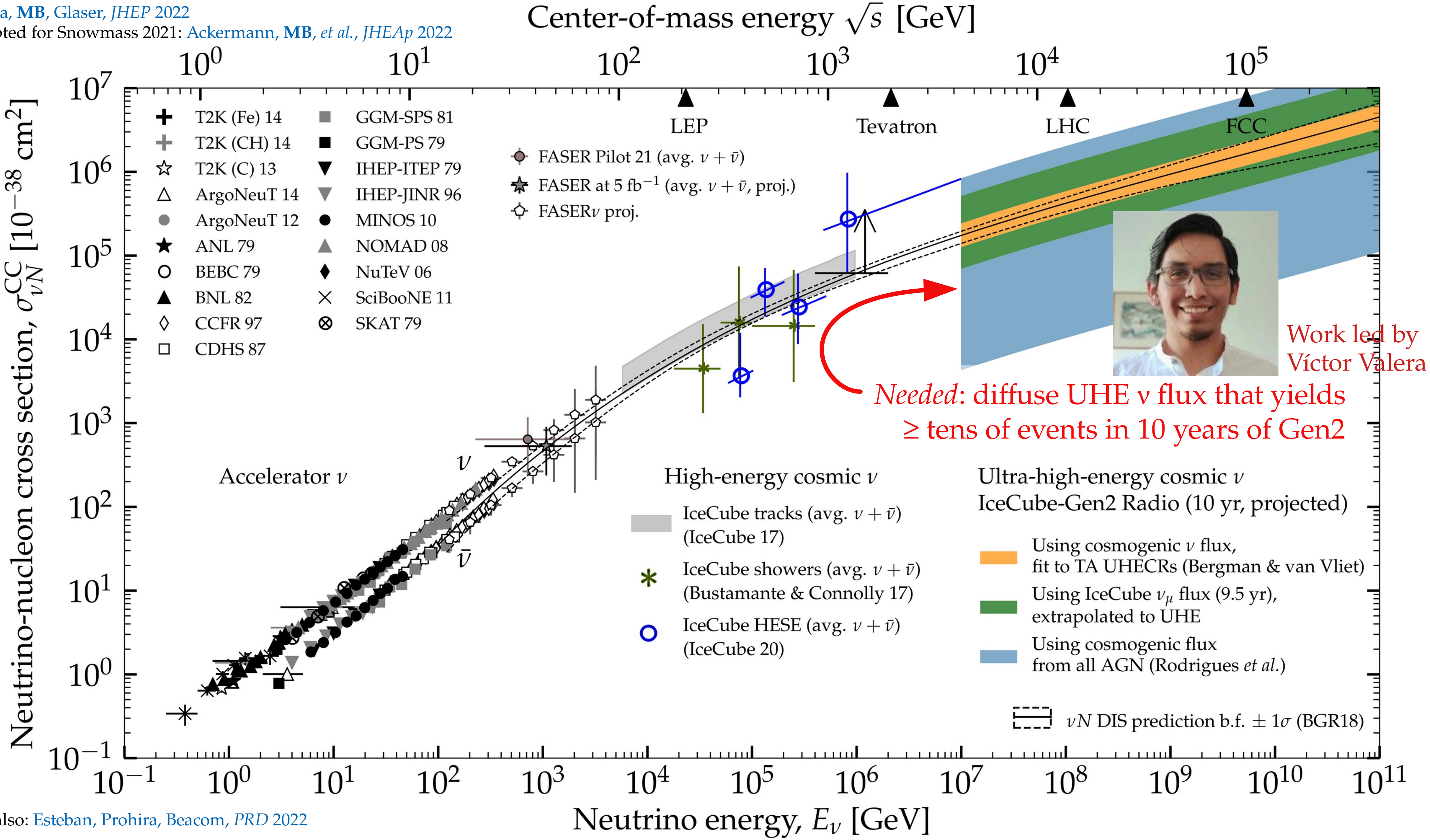

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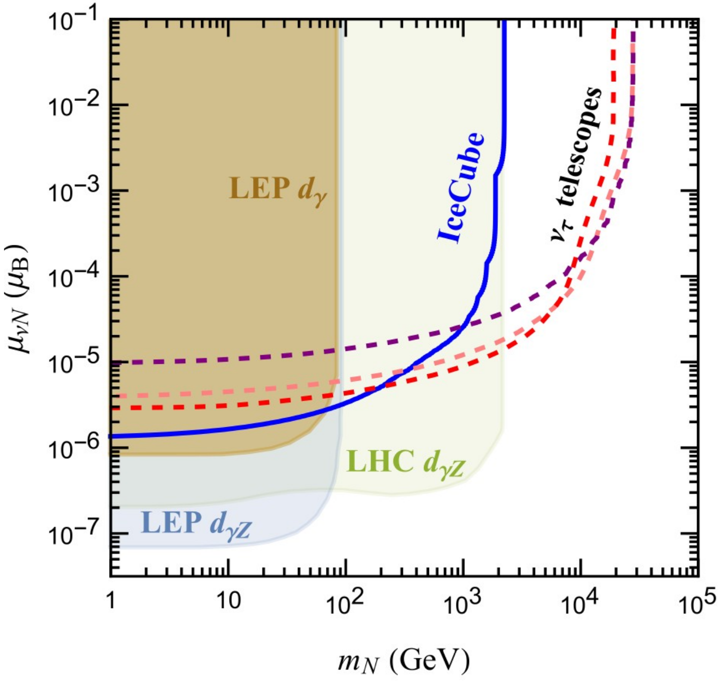
New physics in the UHE νN cross section

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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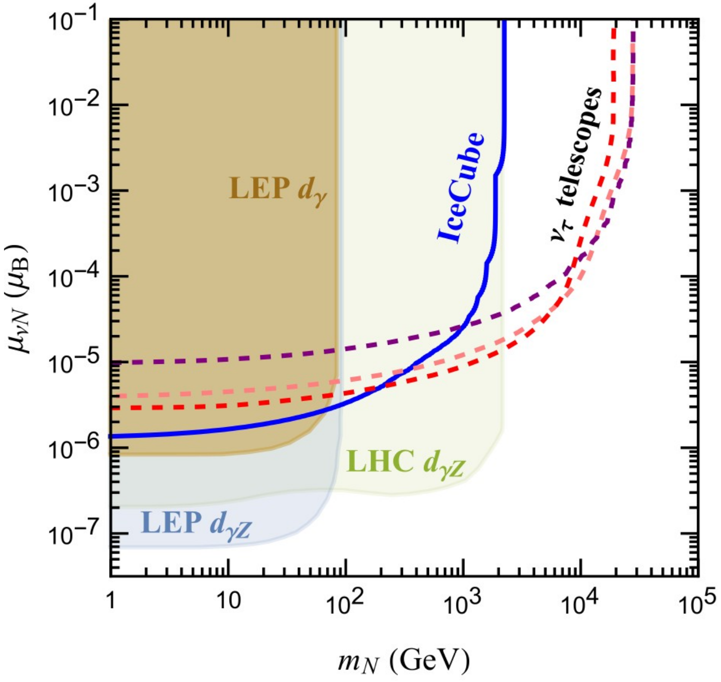
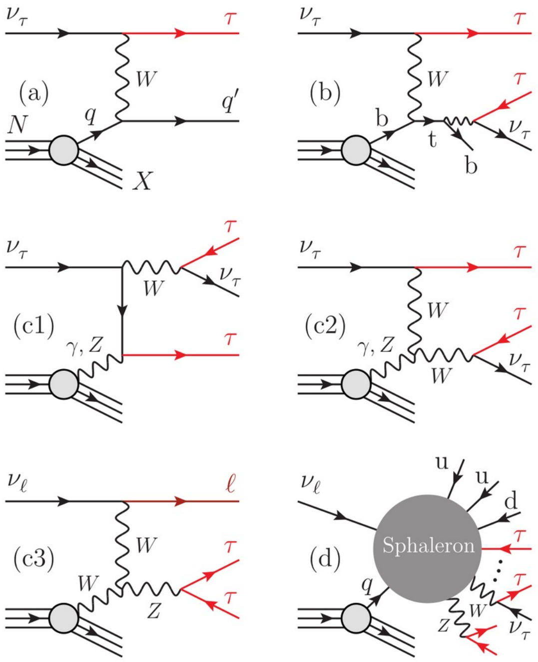


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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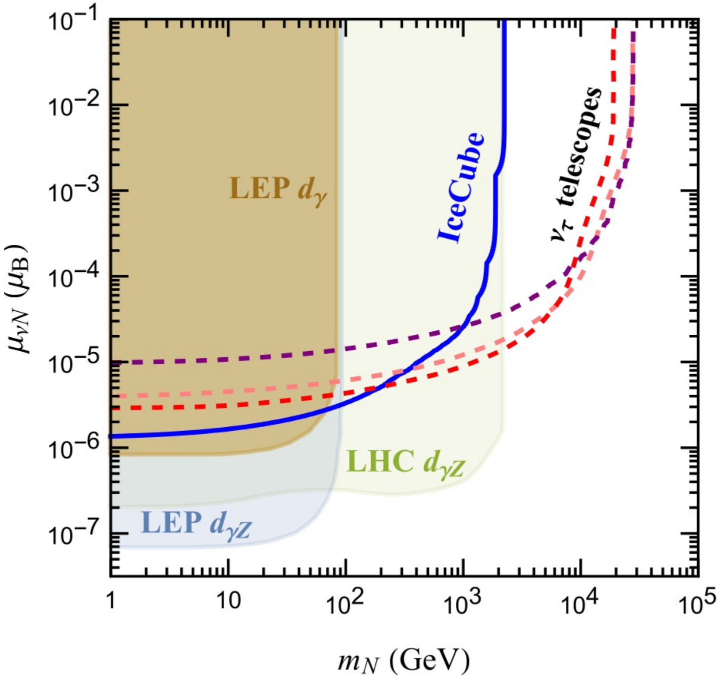

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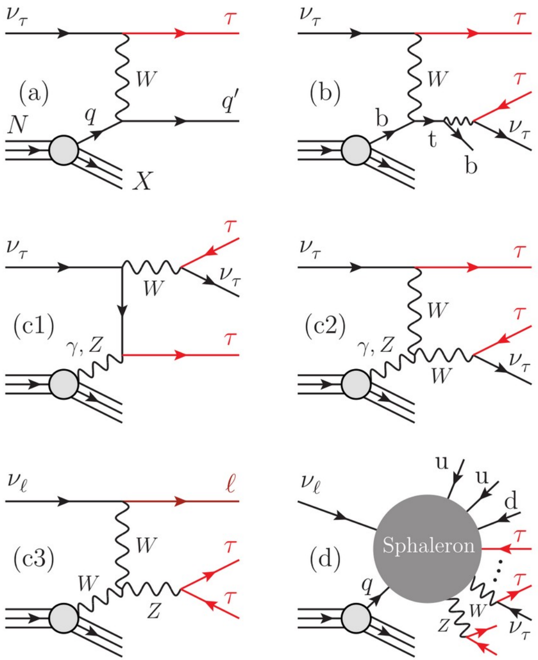
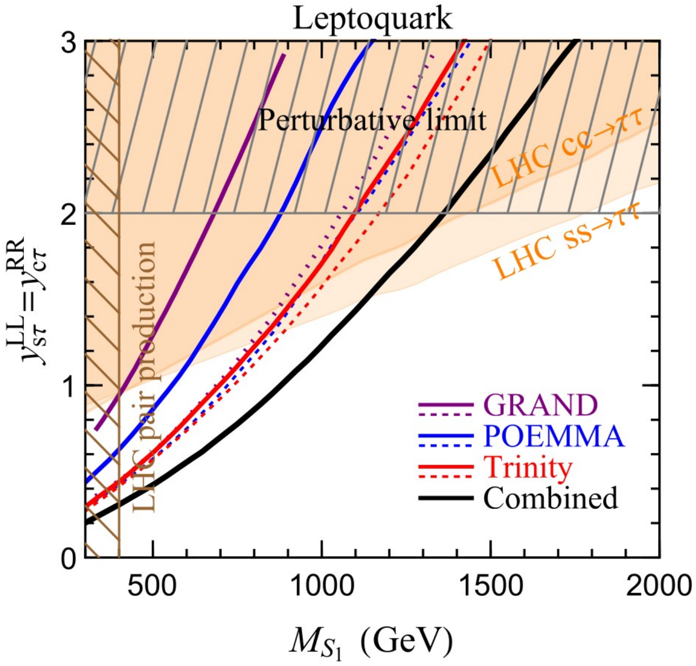


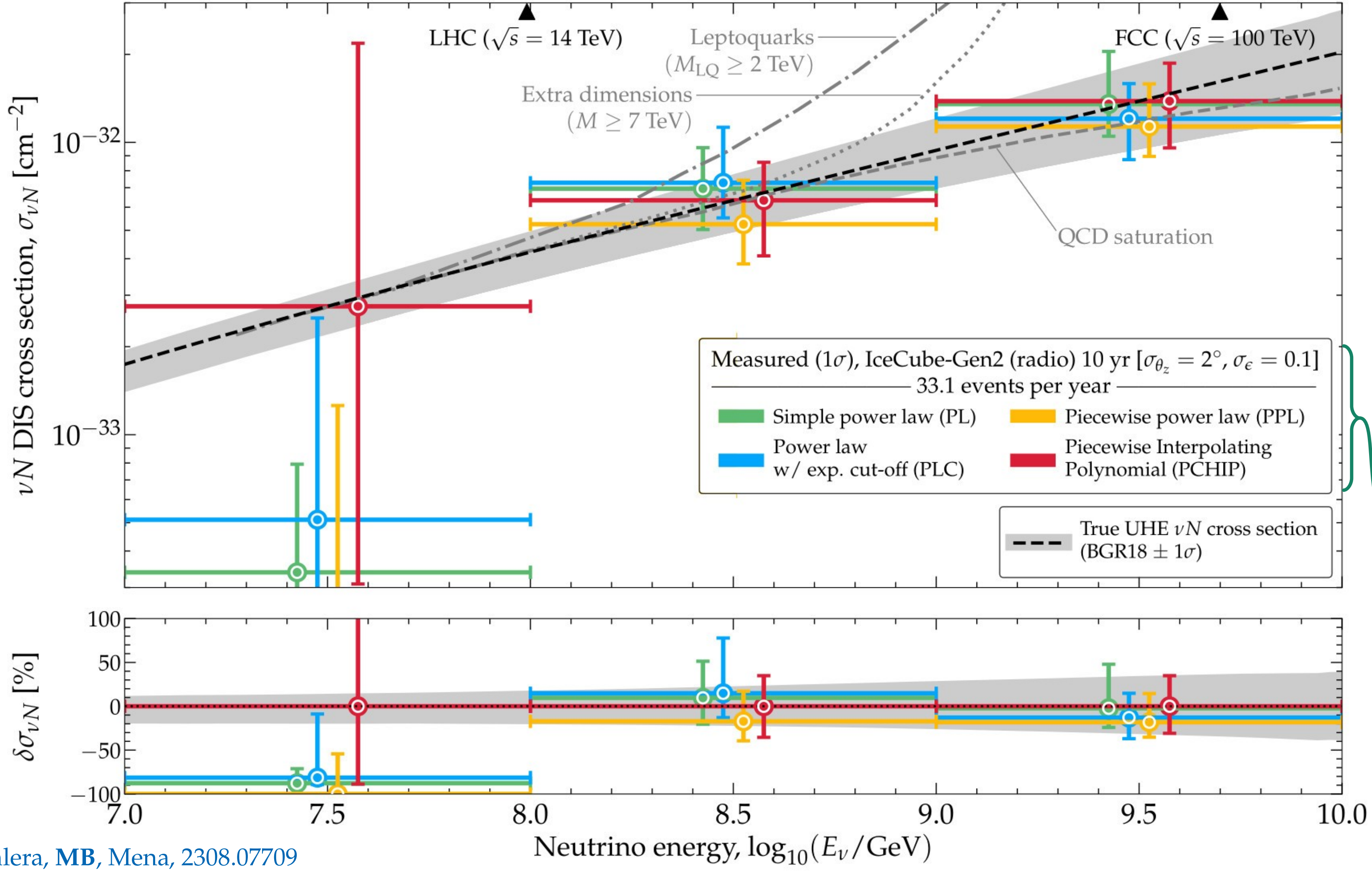
Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc*.



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

Measuring the energy dependence of the cross section



10-year forecasts, IceCube-Gen2:

Measure the UHE νN in three energy bins

Simultaneously measure the ν energy spectrum

Different spectrum fit models

Key: need a flexible spectrum parametrization

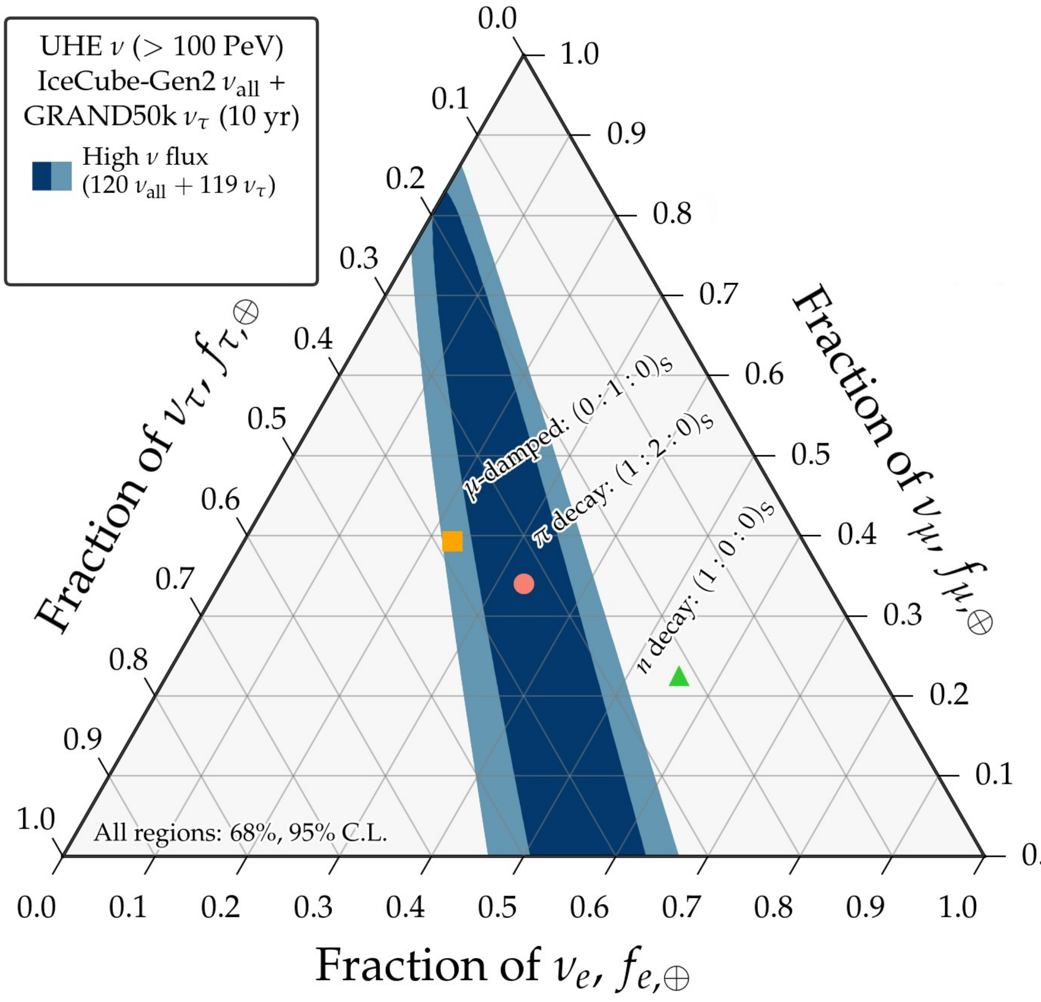
Valera, **MB**, Mena, 2308.07709

Flavor
at ultra-high energies

Manufacturing UHE flavor sensitivity with two detectors

What if future UHE radio-detection neutrino telescopes cannot see flavor?

Then we combine two of detectors:



Testagrossa, Fiorillo, **MB**, 2310.12215

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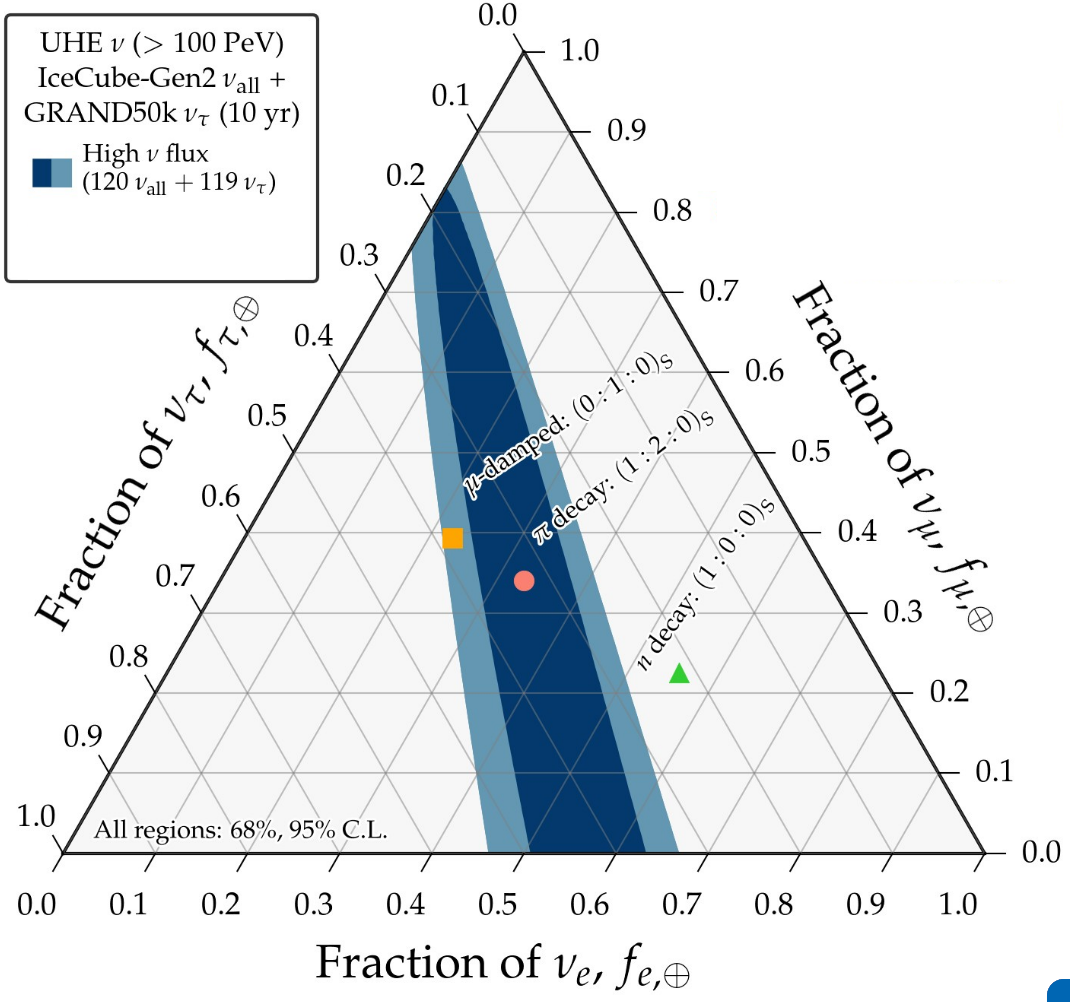

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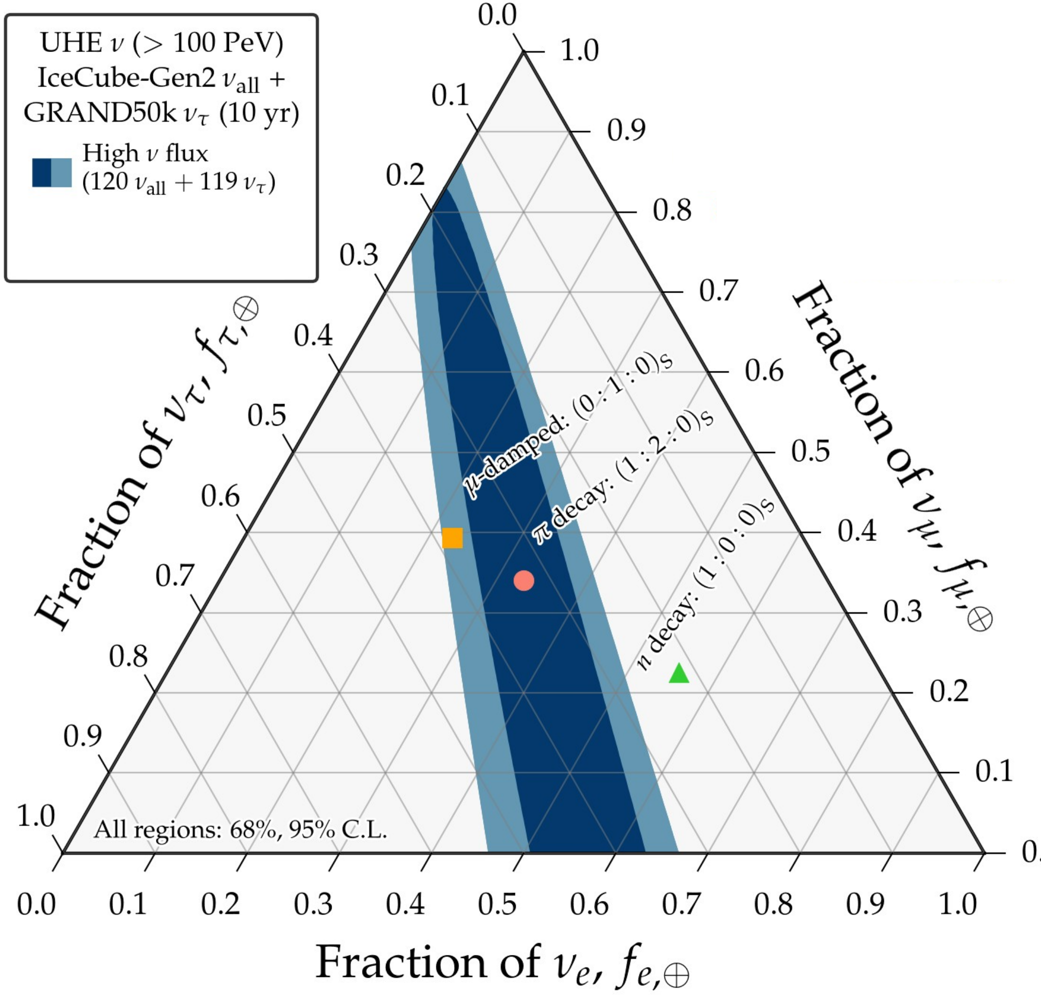

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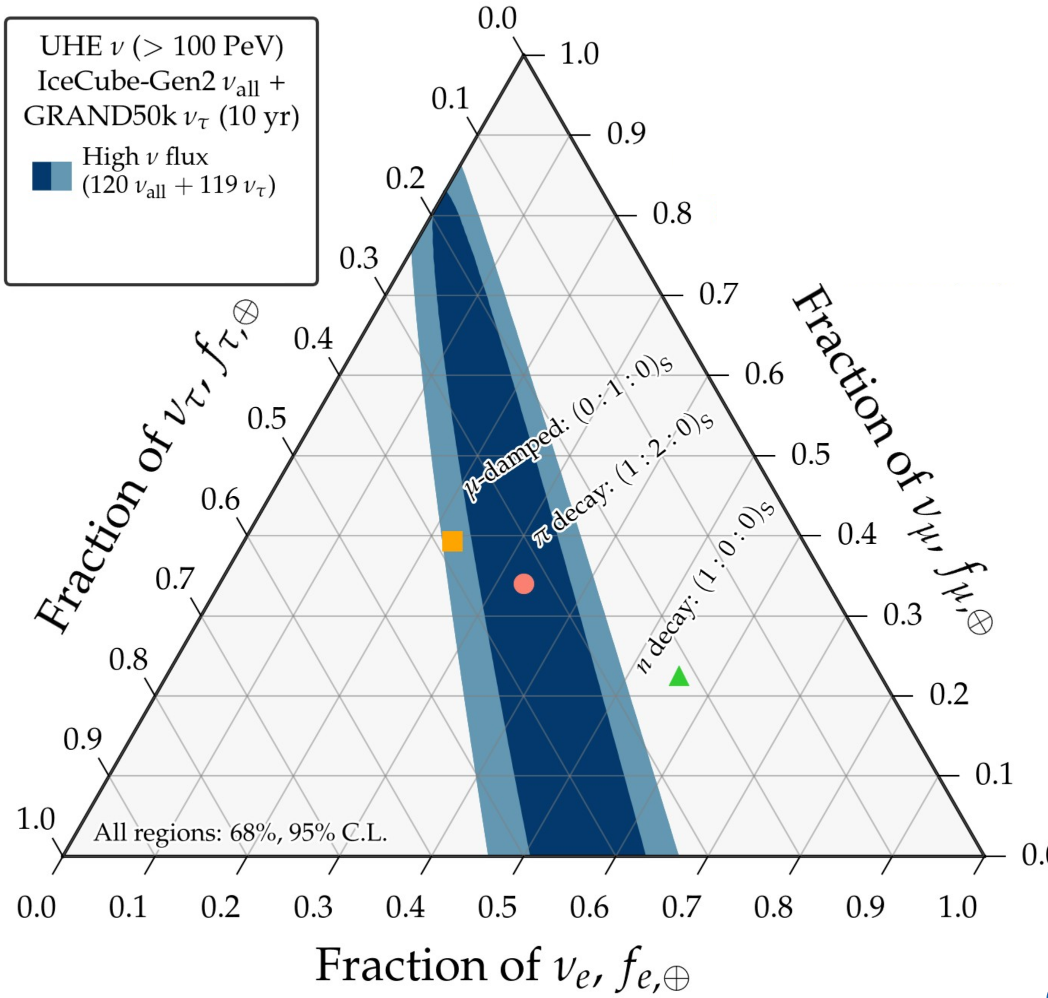

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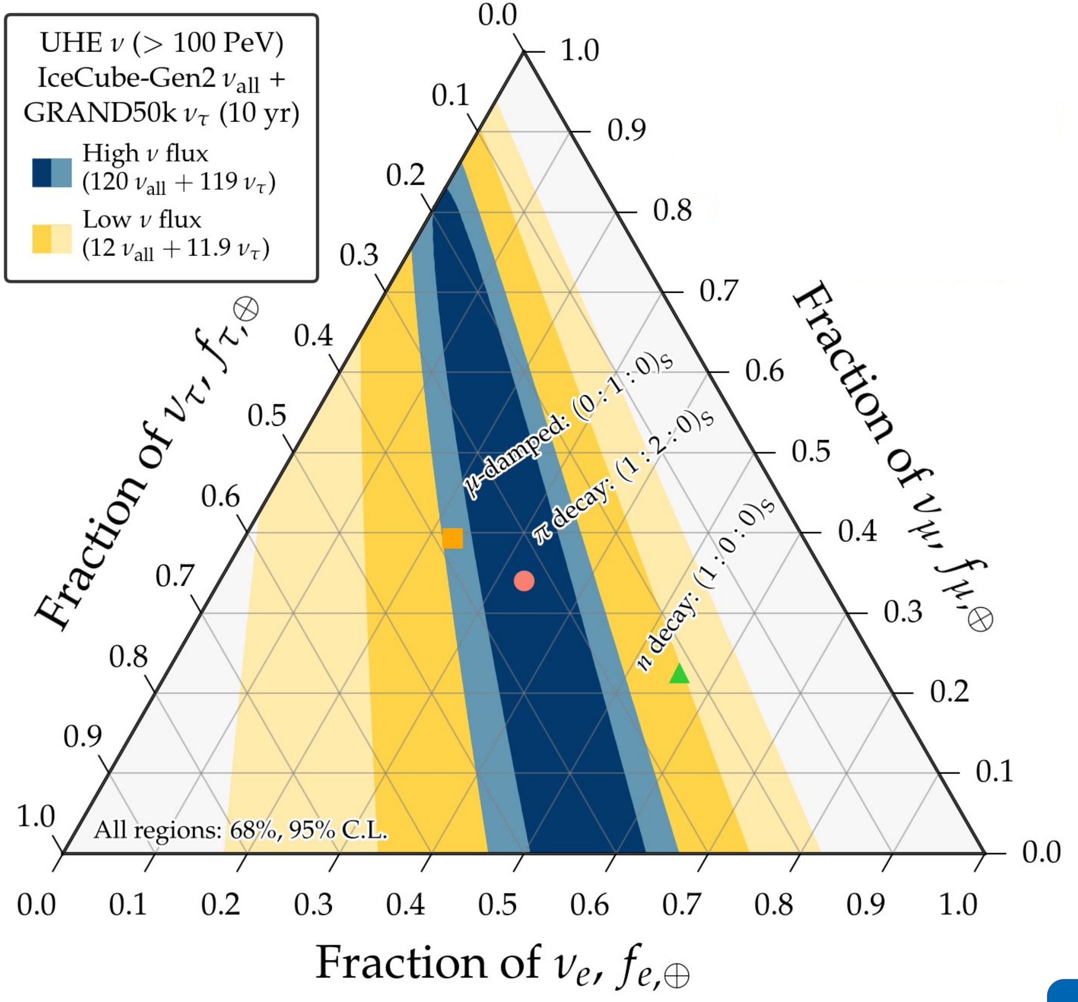

Testagrossa, Fiorillo, **MB**, 2310.12215

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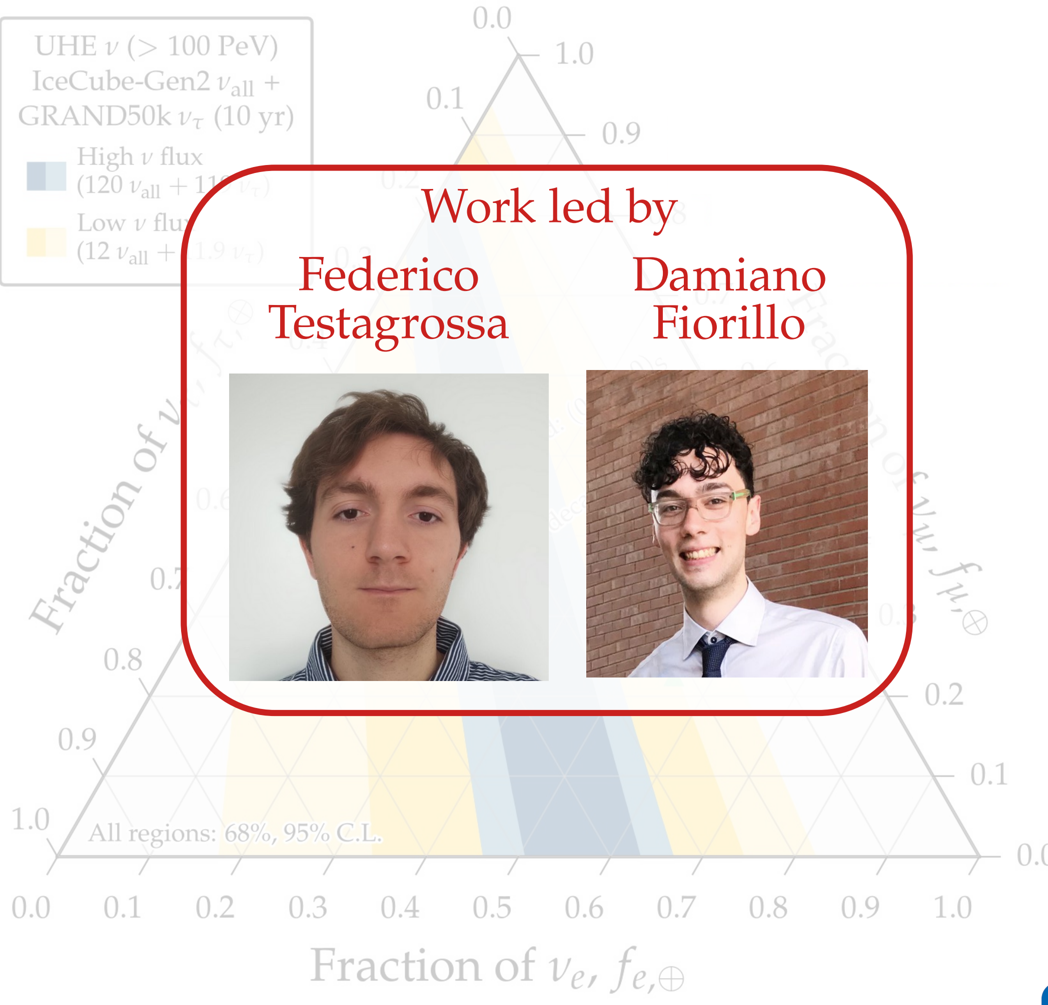

Work led by

Federico Testagrossa

Damiano Fiorillo

Testagrossa, Fiorillo, **MB**, 2310.12215

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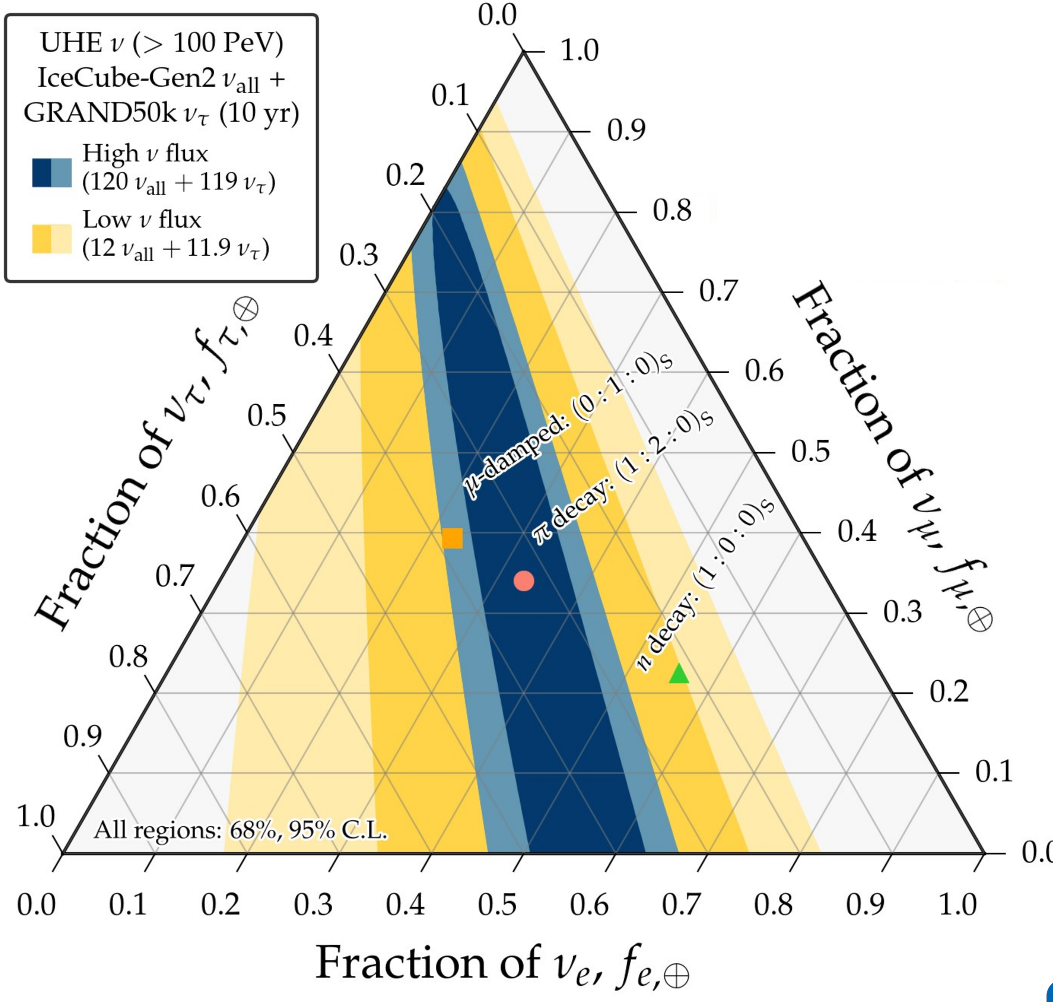

Testagrossa, Fiorillo, **MB**, 2310.12215

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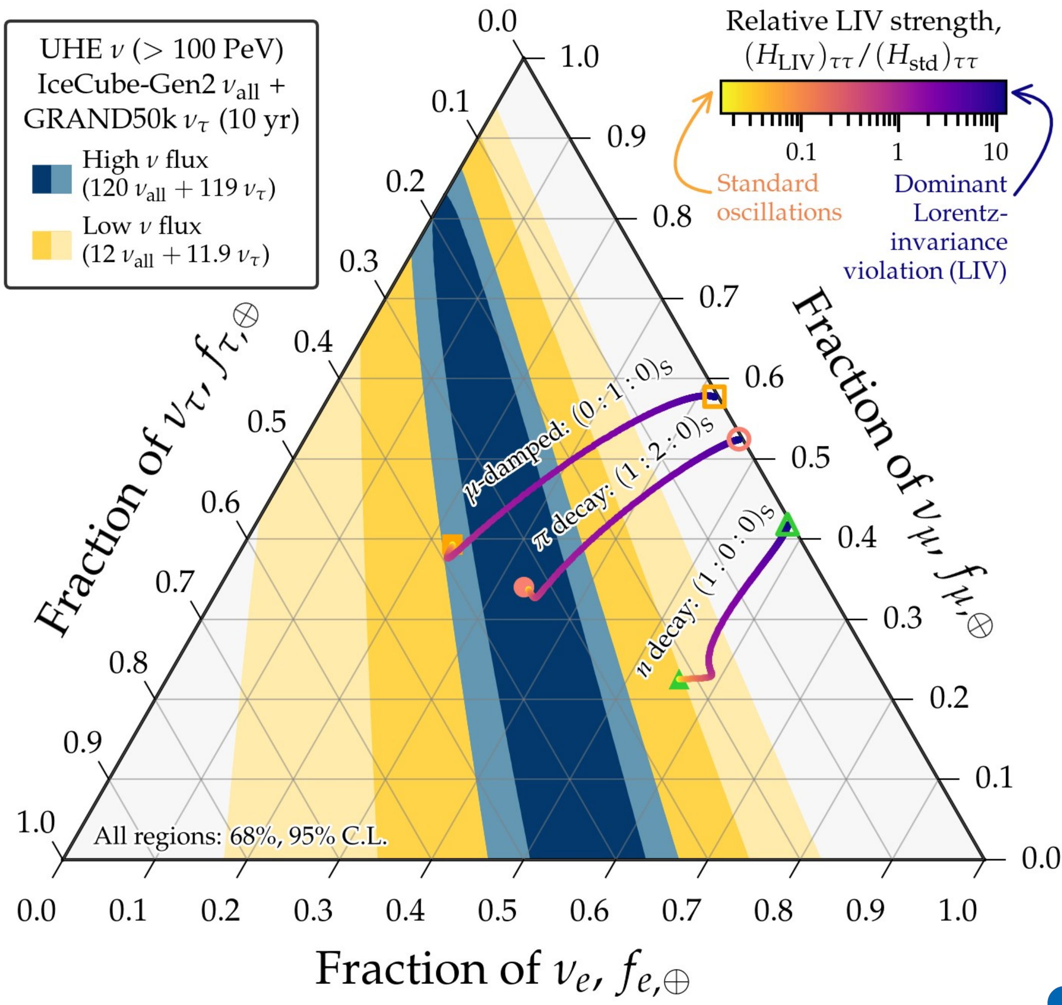
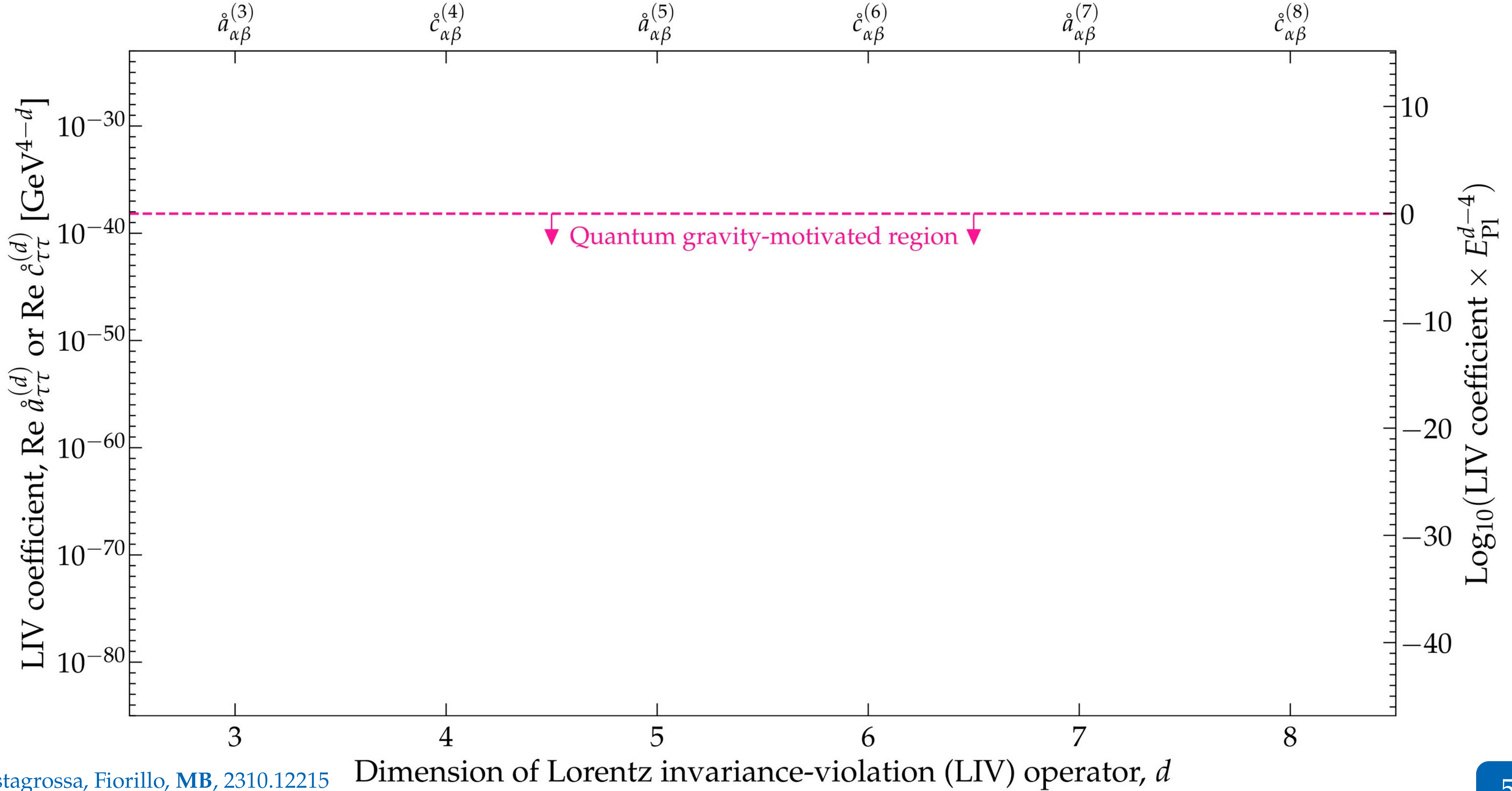


Testagrossa, Fiorillo, **MB**, 2310.12215

Lorentz-invariance violation at ultra-high energies



Testagrossa, Fiorillo, **MB**, 2310.12215

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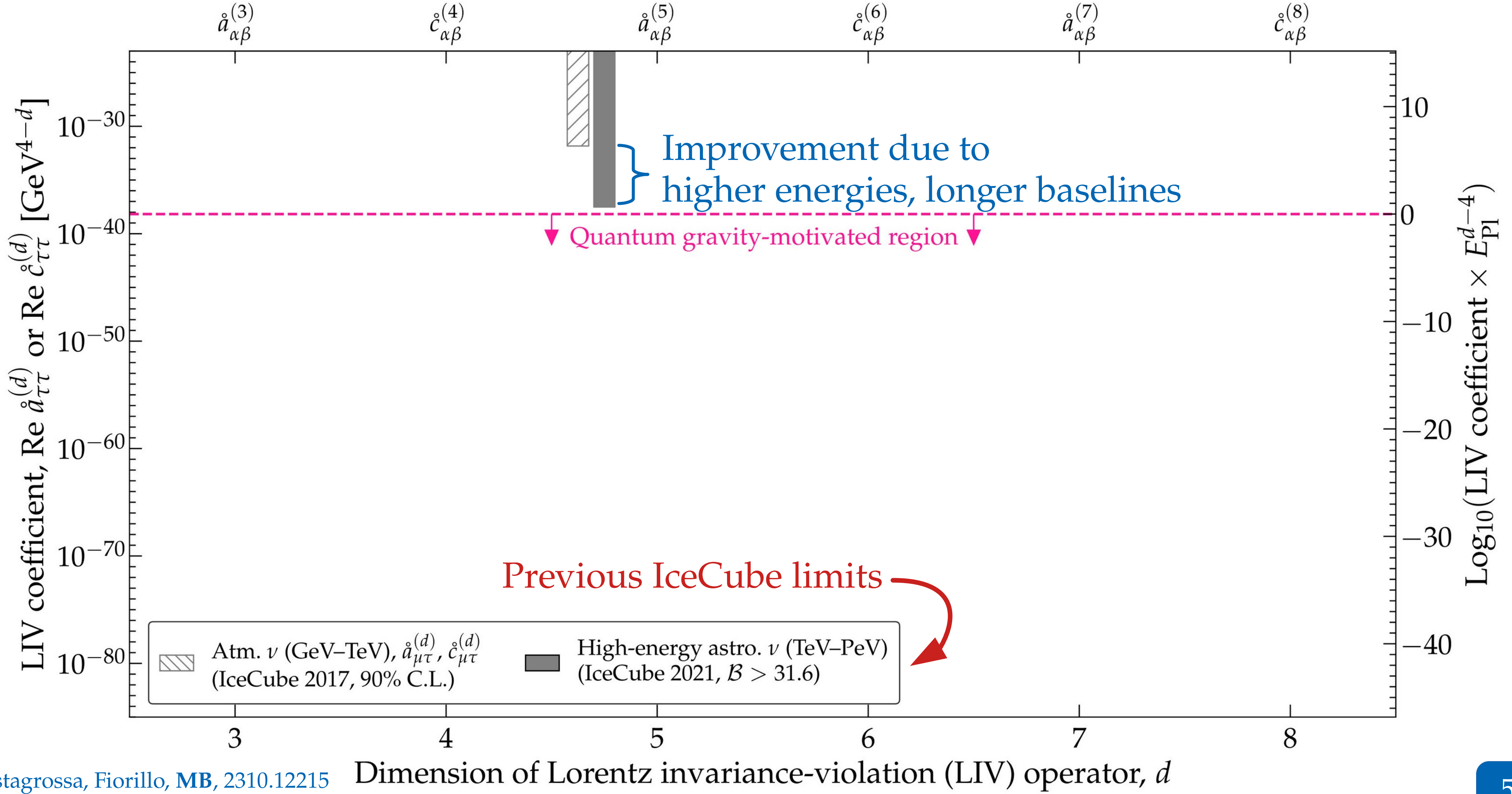

Testagrossa, Fiorillo, **MB**, 2310.12215

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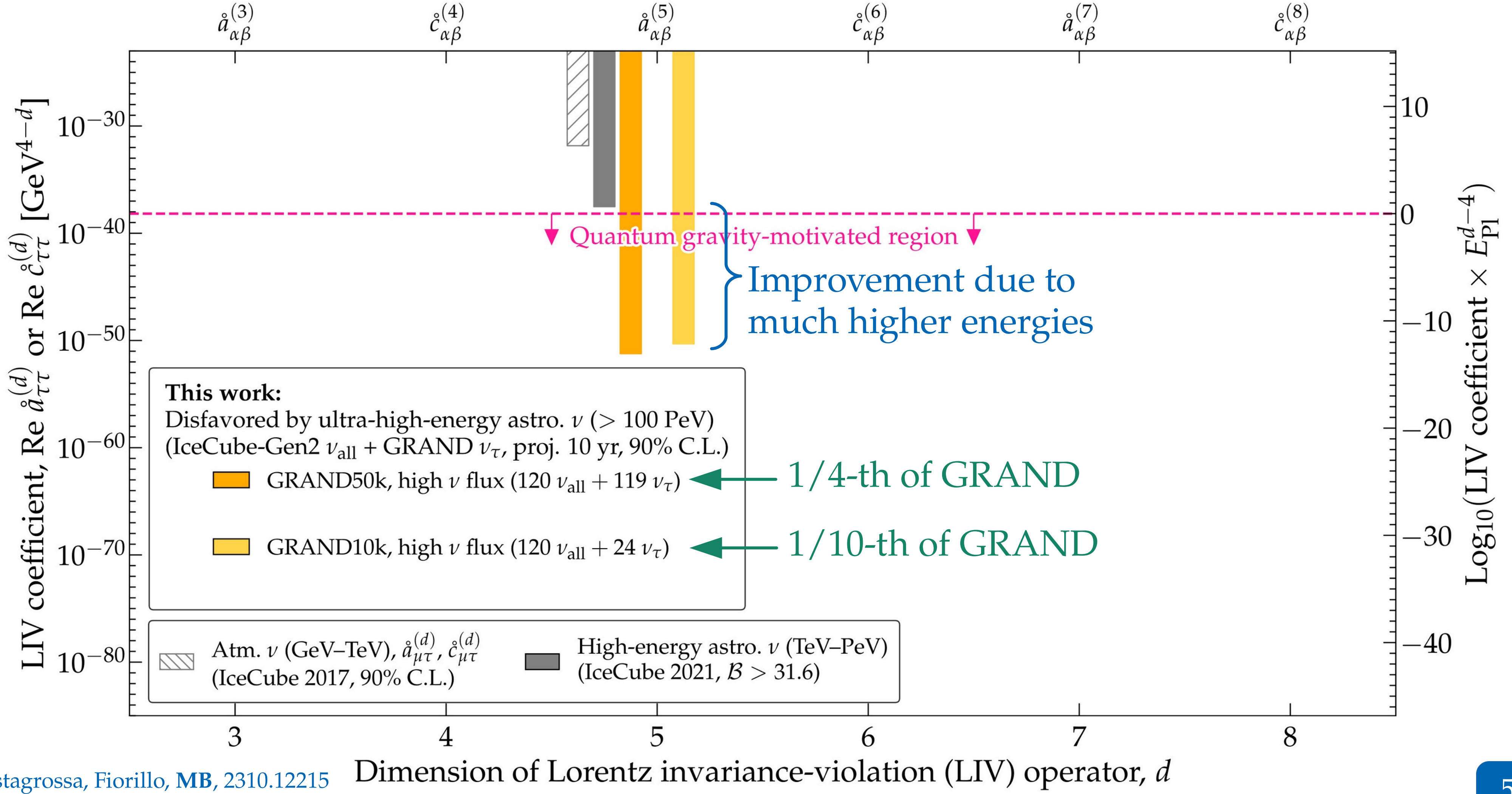

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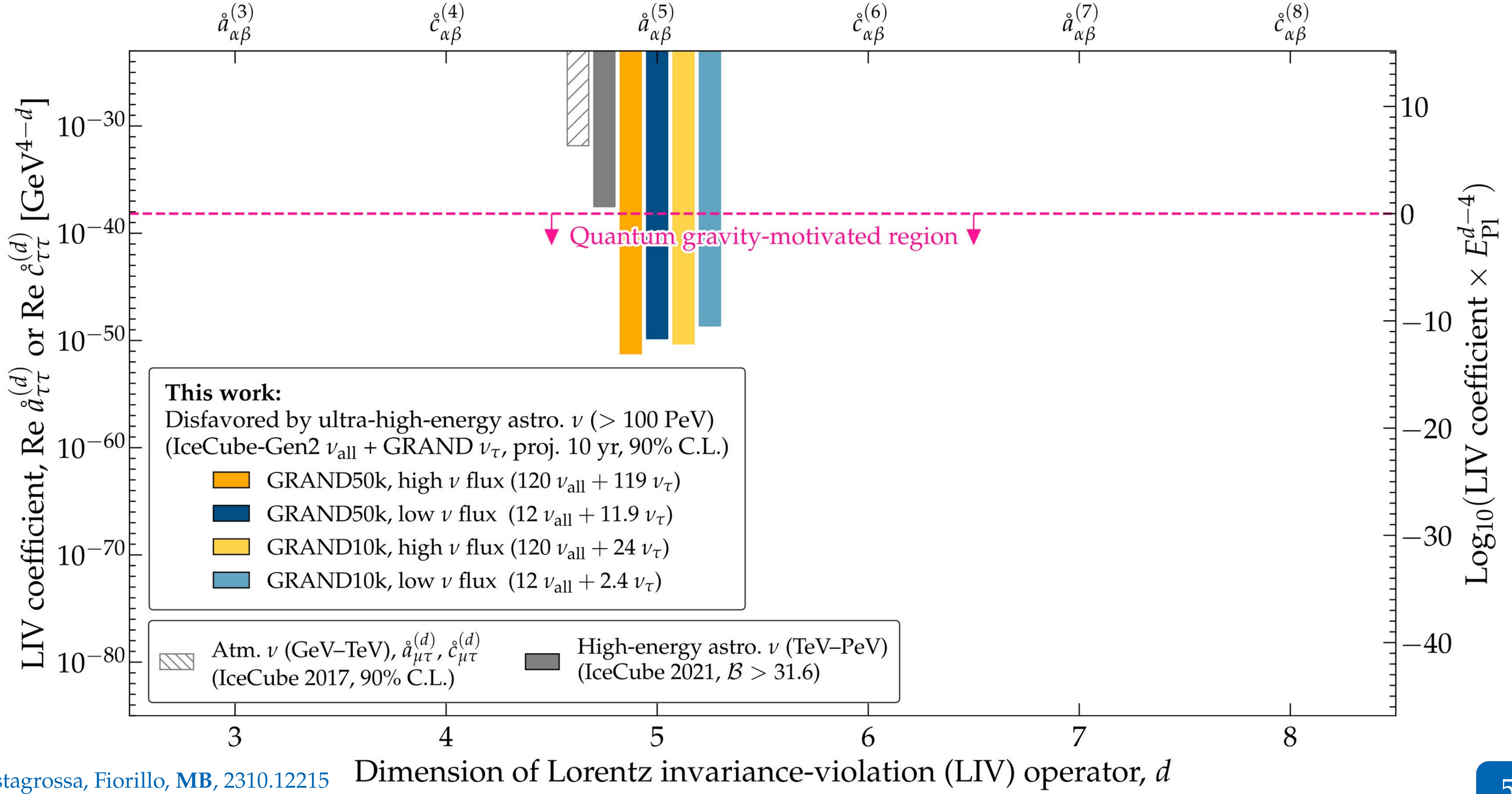

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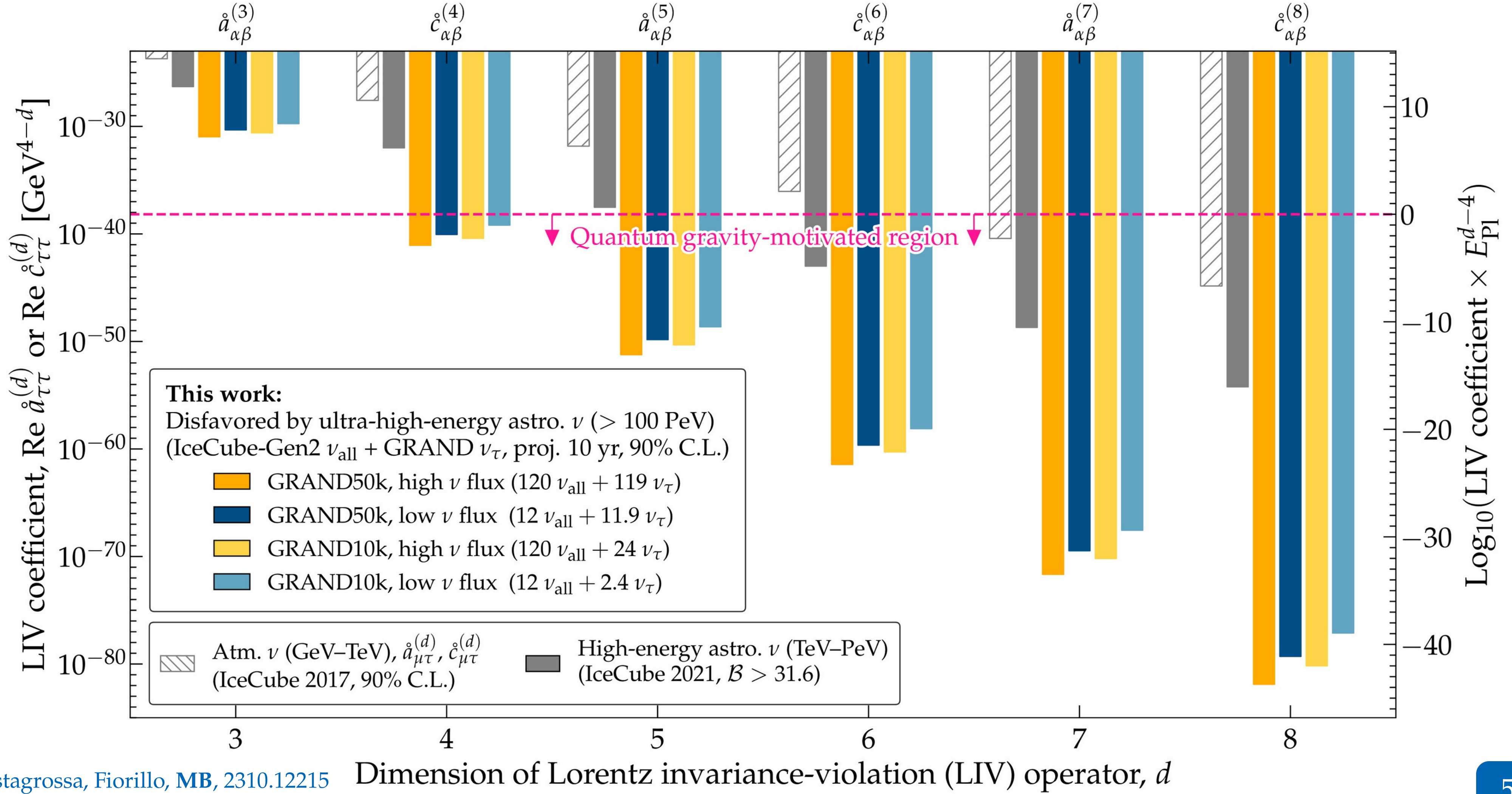
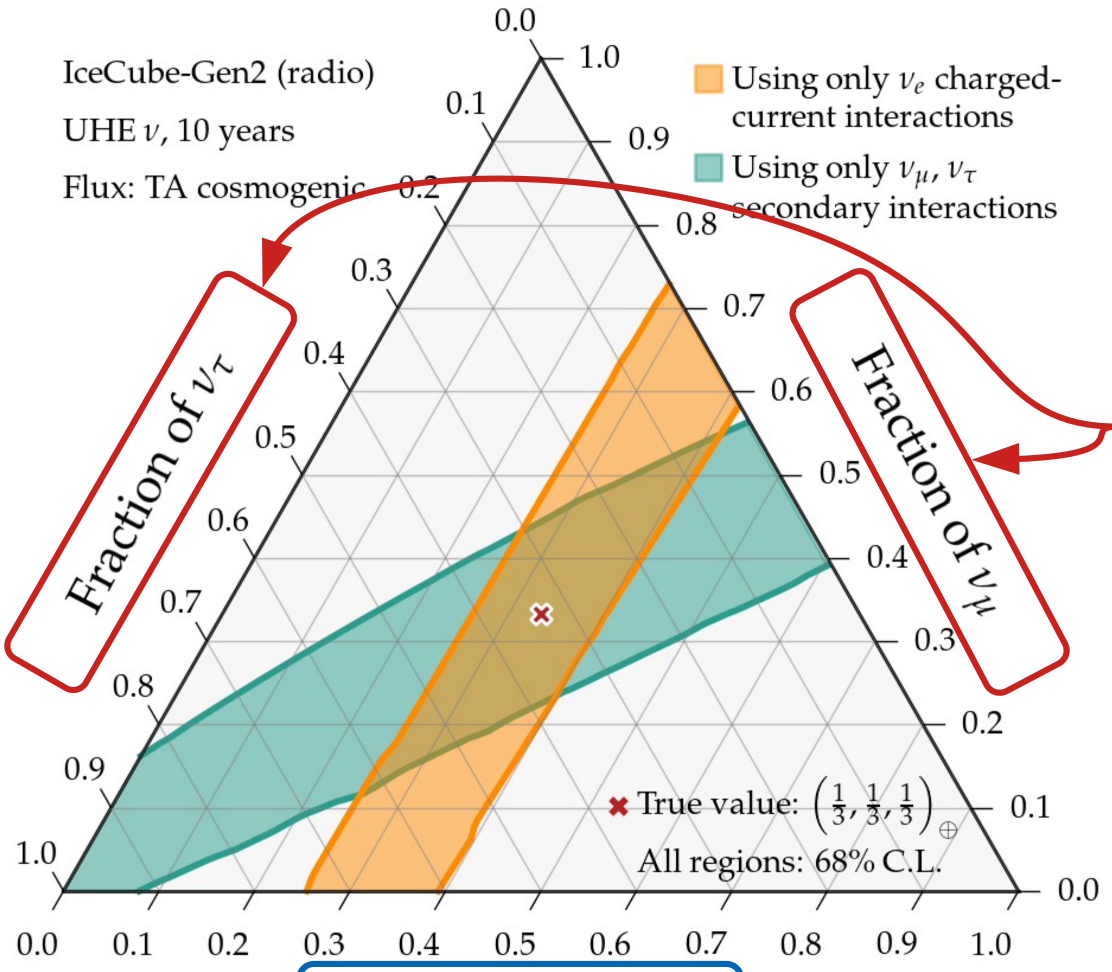


Testagrossa, Fiorillo, **MB**, 2310.12215

IceCube-Gen2 (radio) alone might measure flavor



Fraction of ν_e

Showers are elongated due to the LPM effect

Fraction of $\nu_\mu + \nu_\tau$

Secondary muons and tauons create showers that hit >1 radio station

Coleman, Ericsson, **MB**, Glaser, *In prep.*

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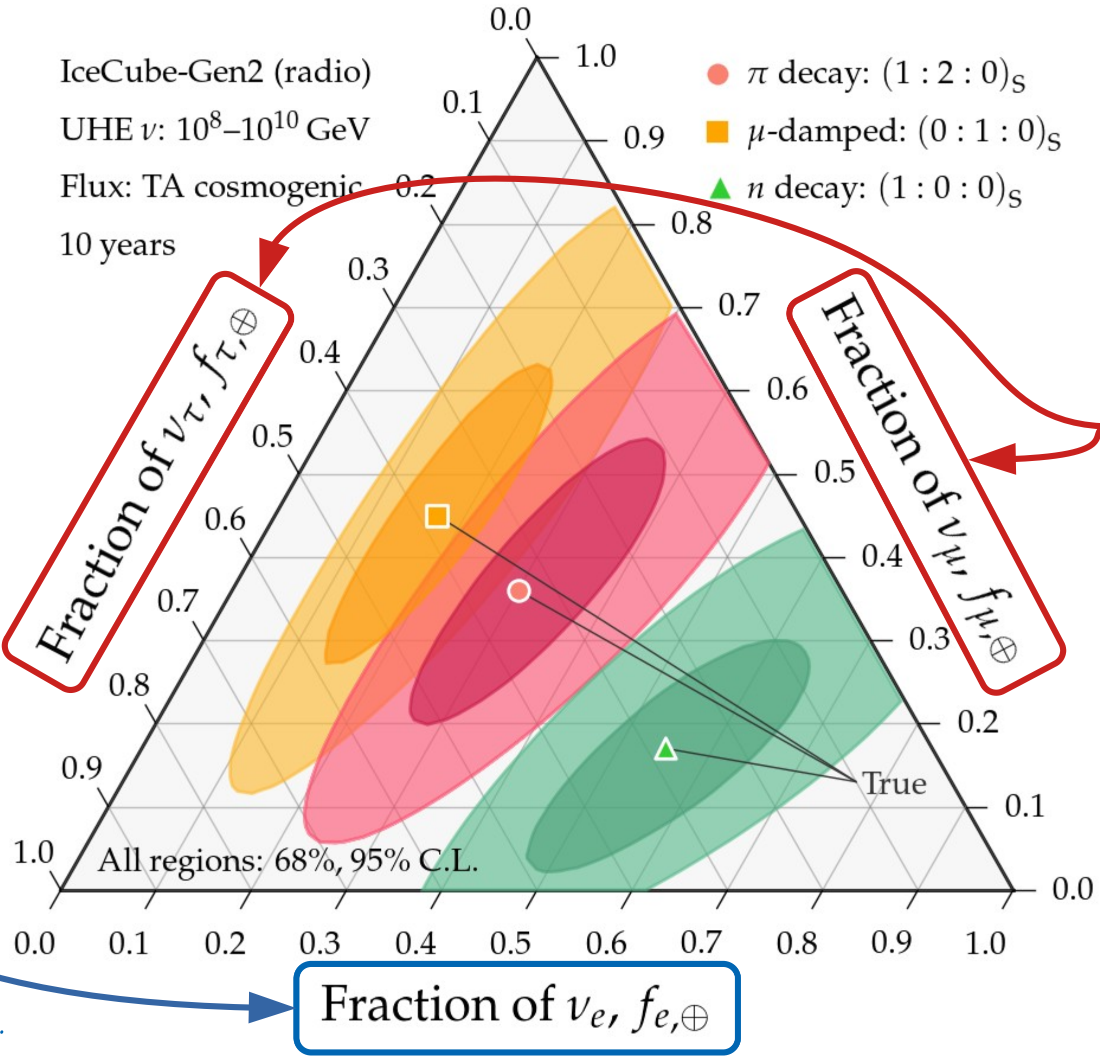

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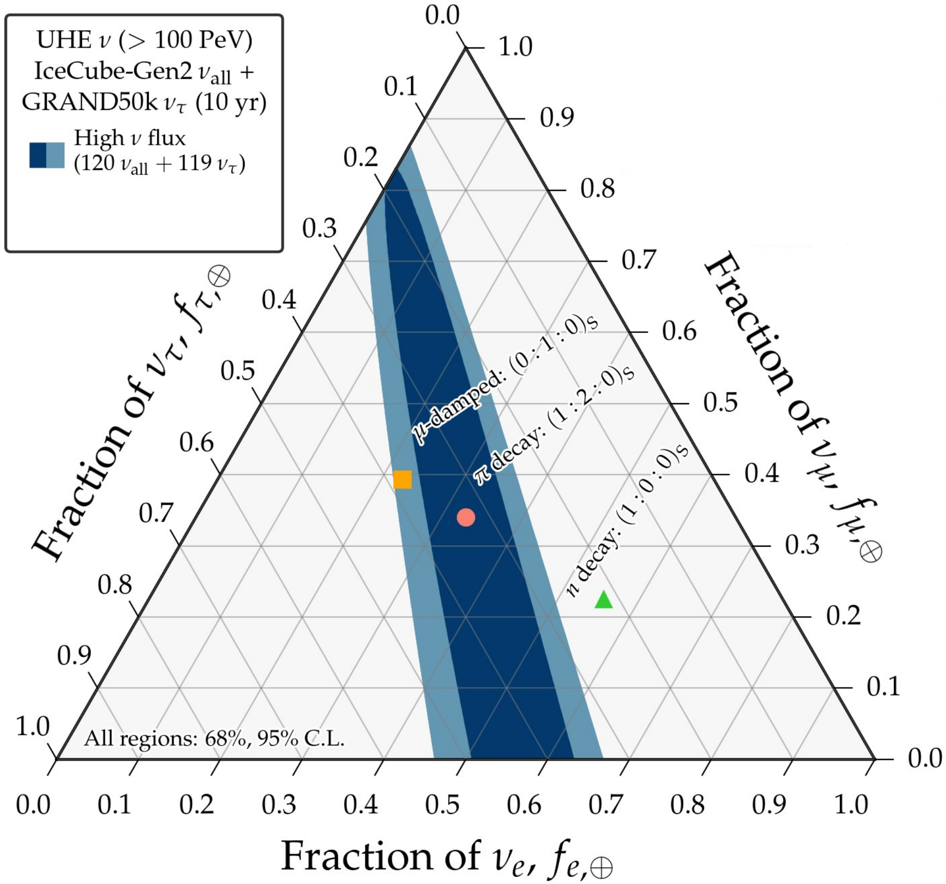
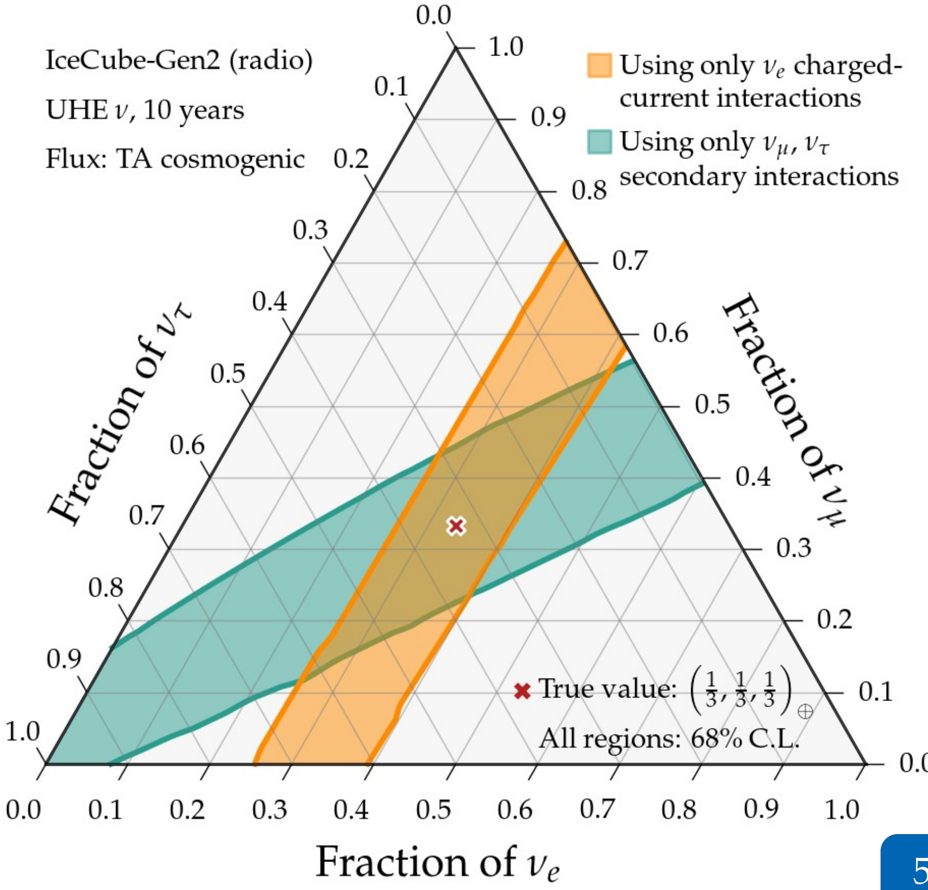
Coleman, Ericsson, **MB**, Glaser, *In prep.*

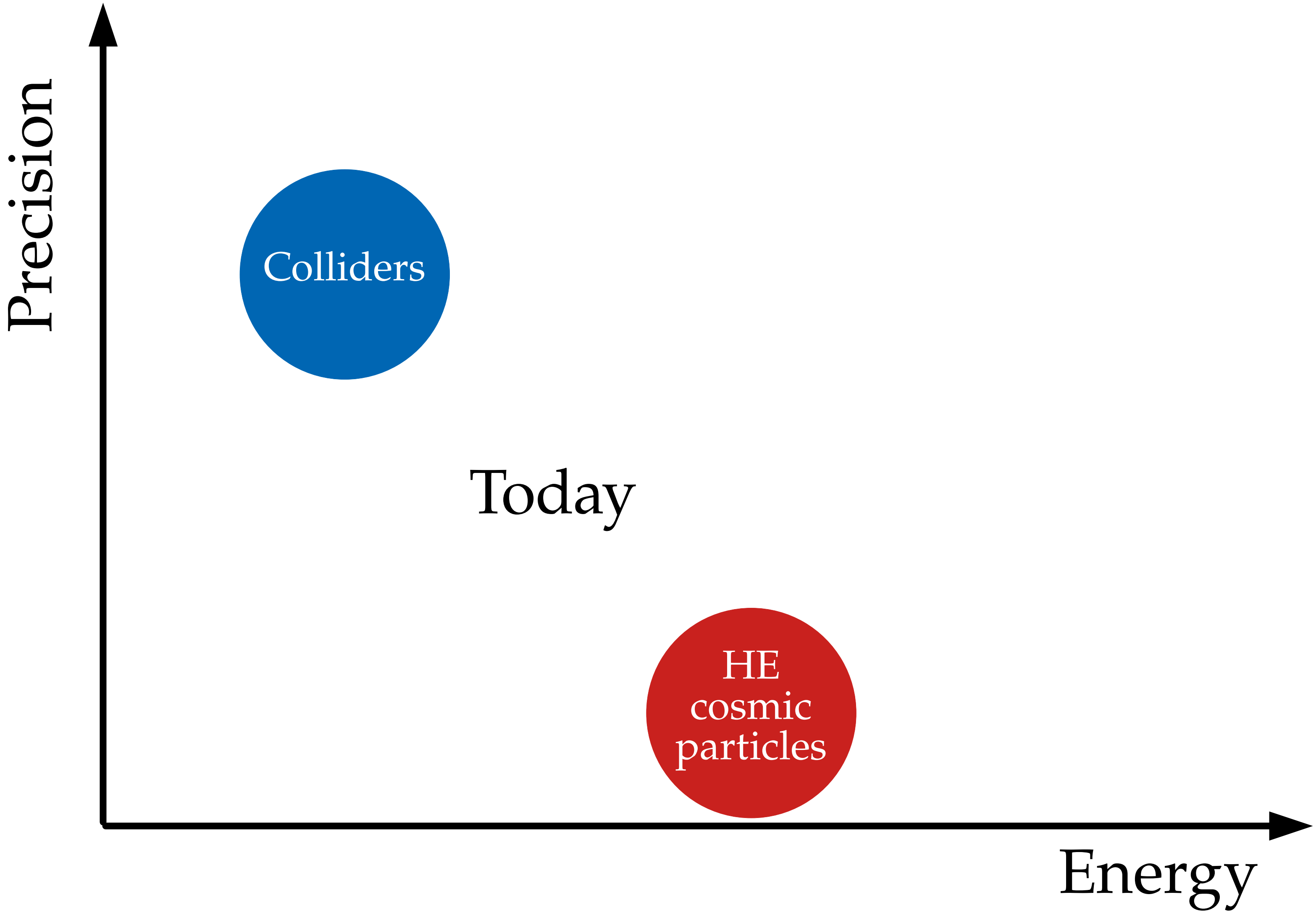
Accessing the full UHE flavor information

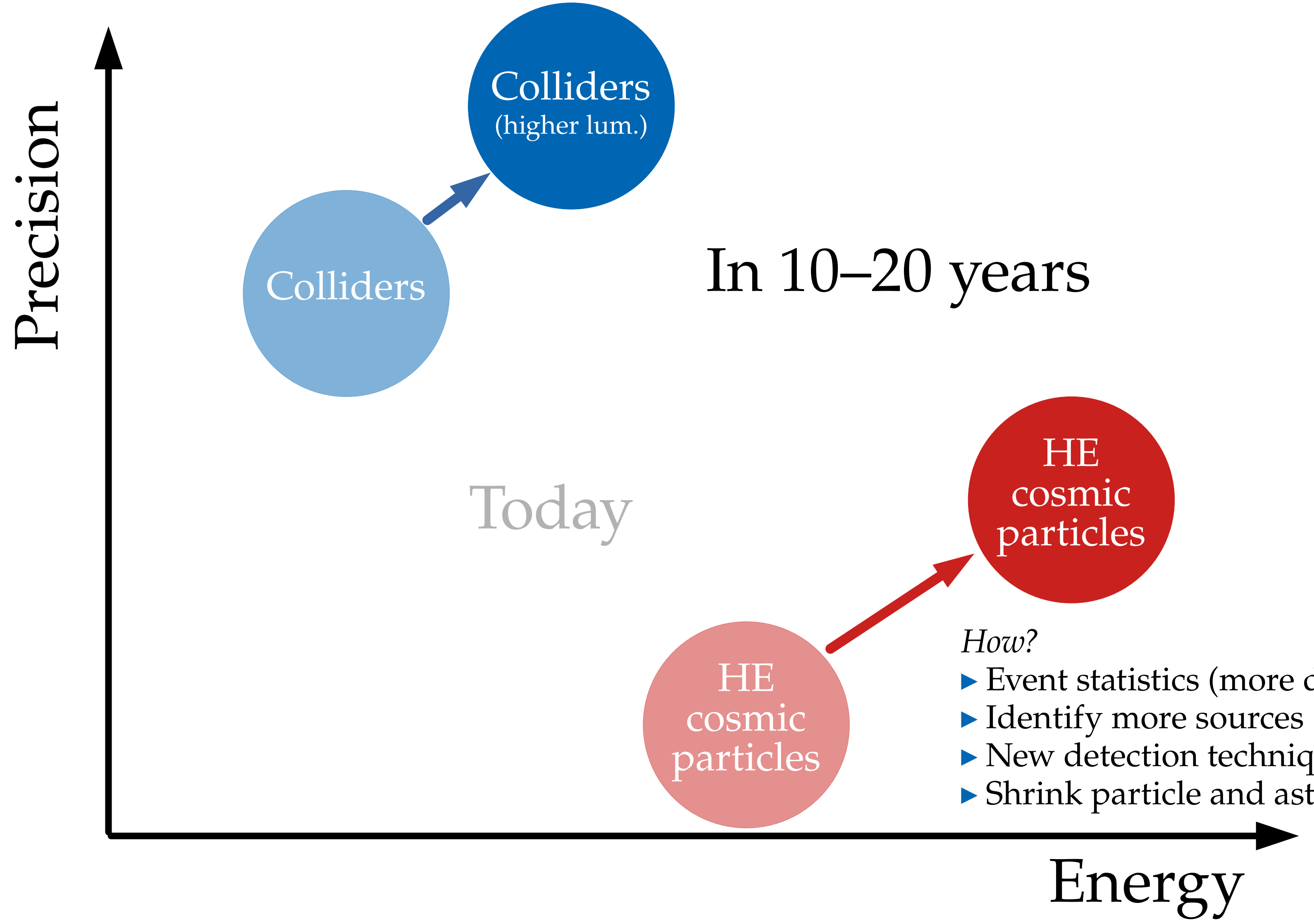
IceCube-Gen2 (no flavor-id) + GRAND:
Access to ν_τ fraction



IceCube-Gen2 (with flavor-id):
Access to ν_e fraction and ν_μ+ν_τ fraction

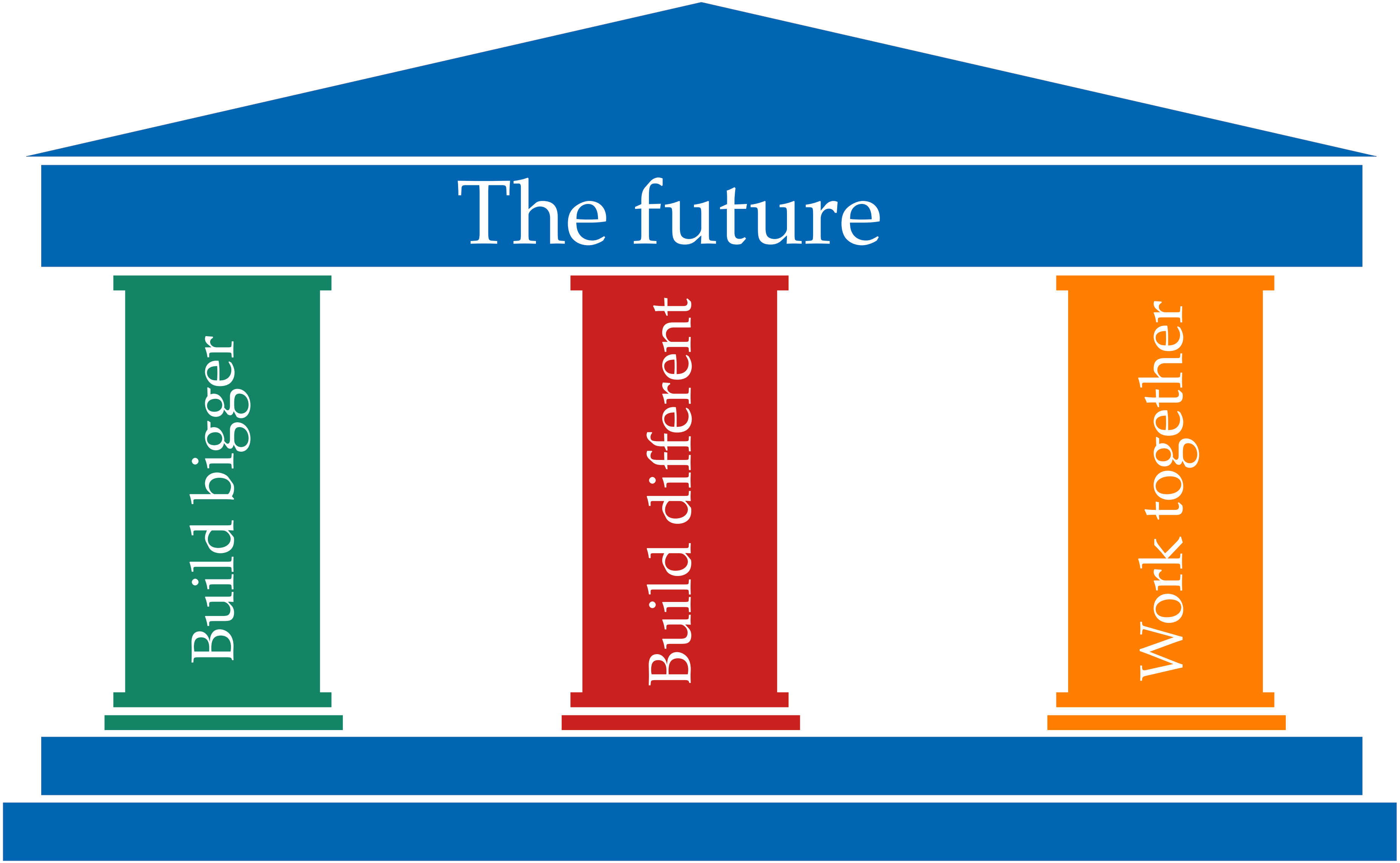


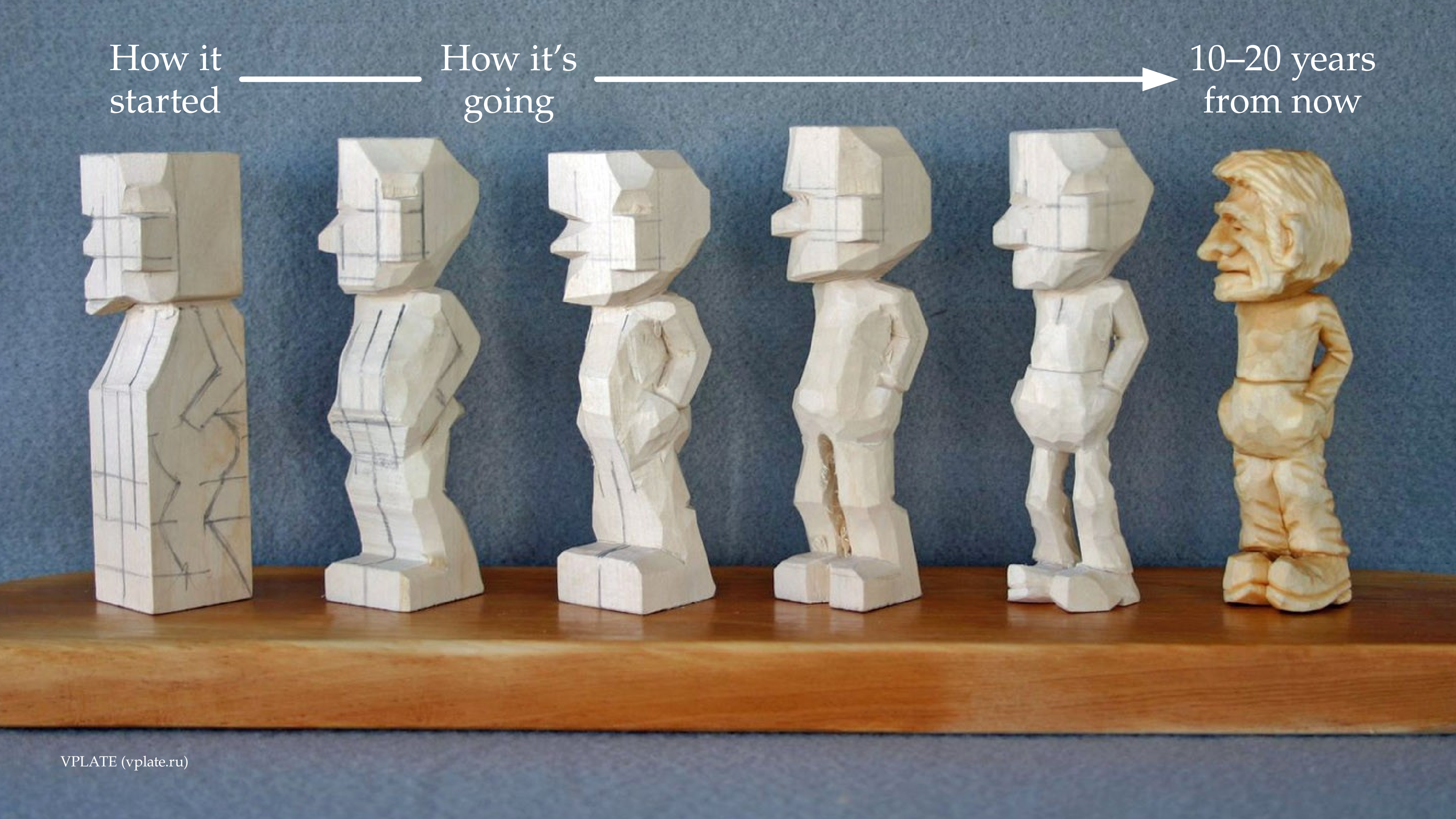

Precision
Colliders
Today
HE
cosmic
particles
Energy



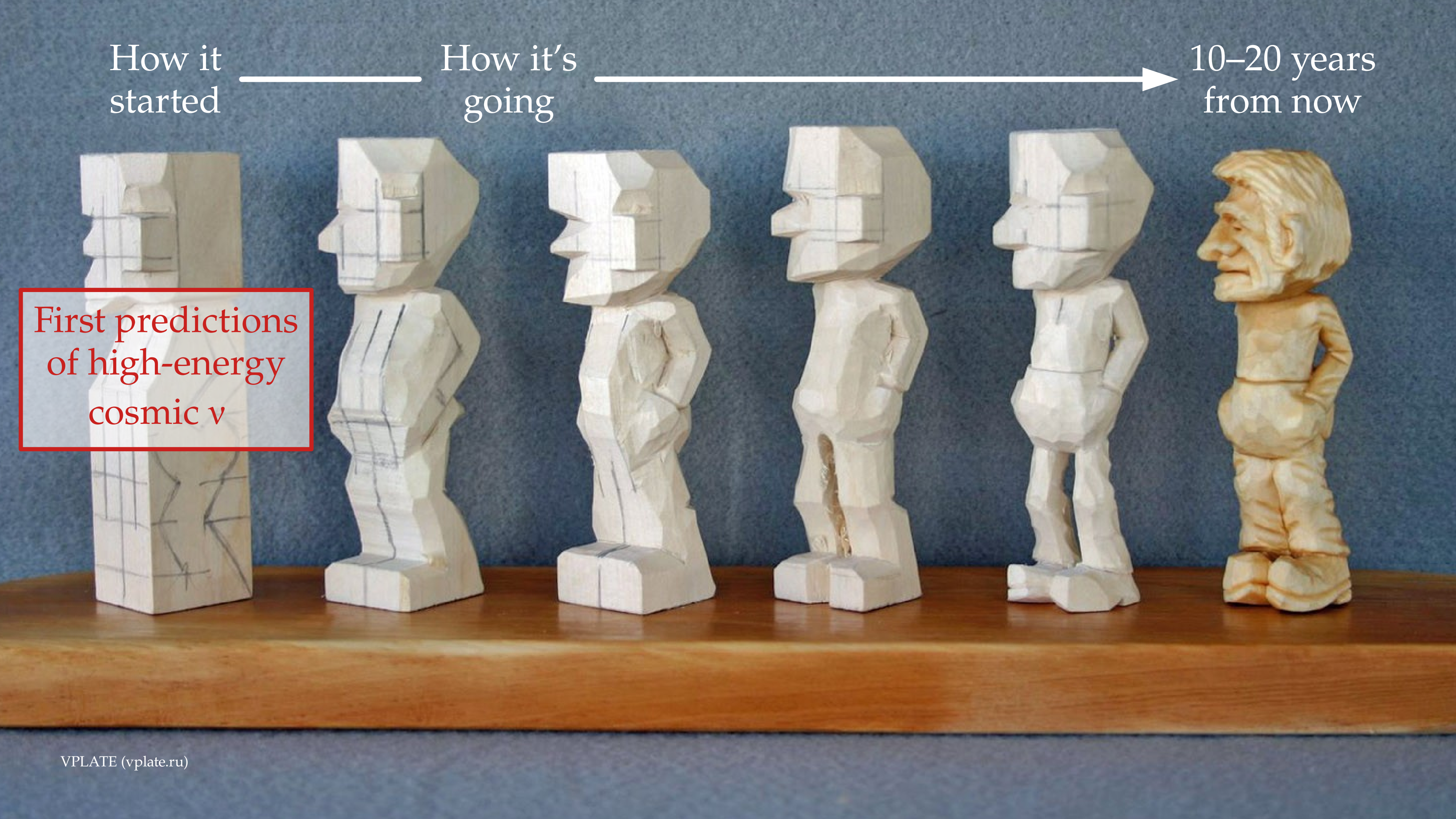
How?

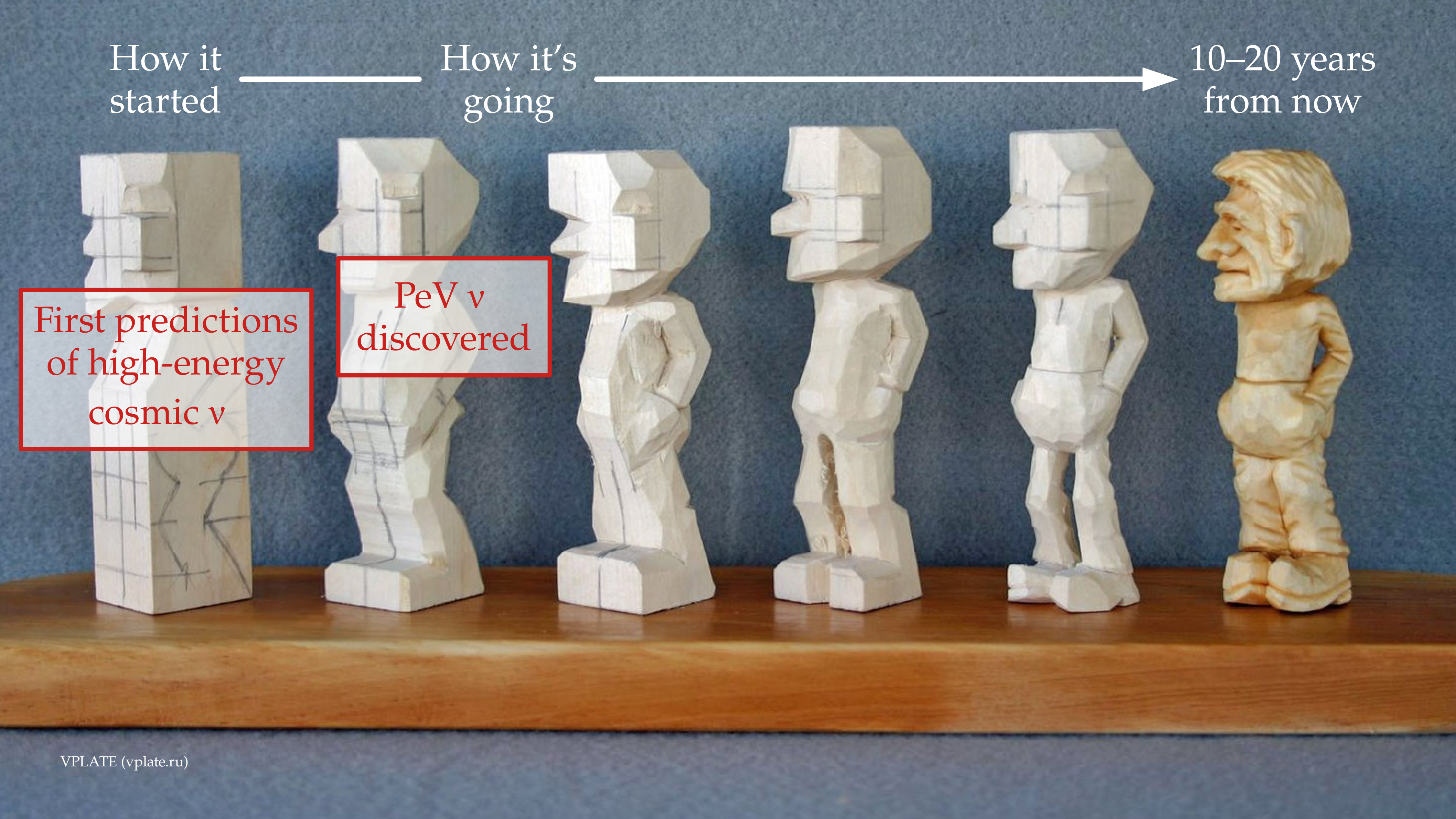
- Event statistics (more detectors)
- Identify more sources
- New detection techniques
- Shrink particle and astro systematics


The future
Build bigger
Build different
Work together



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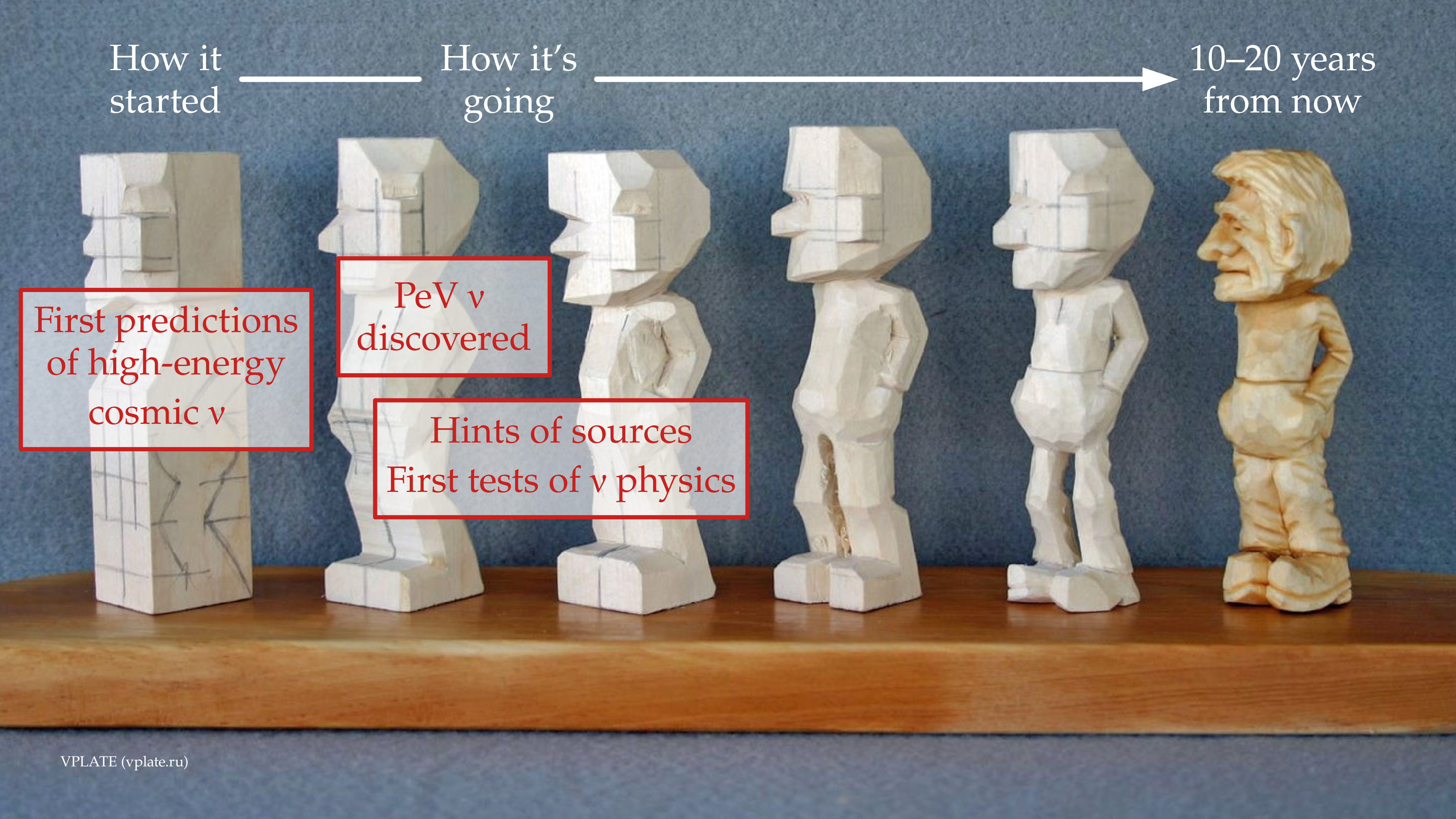
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Hints of sources
First tests of ν physics
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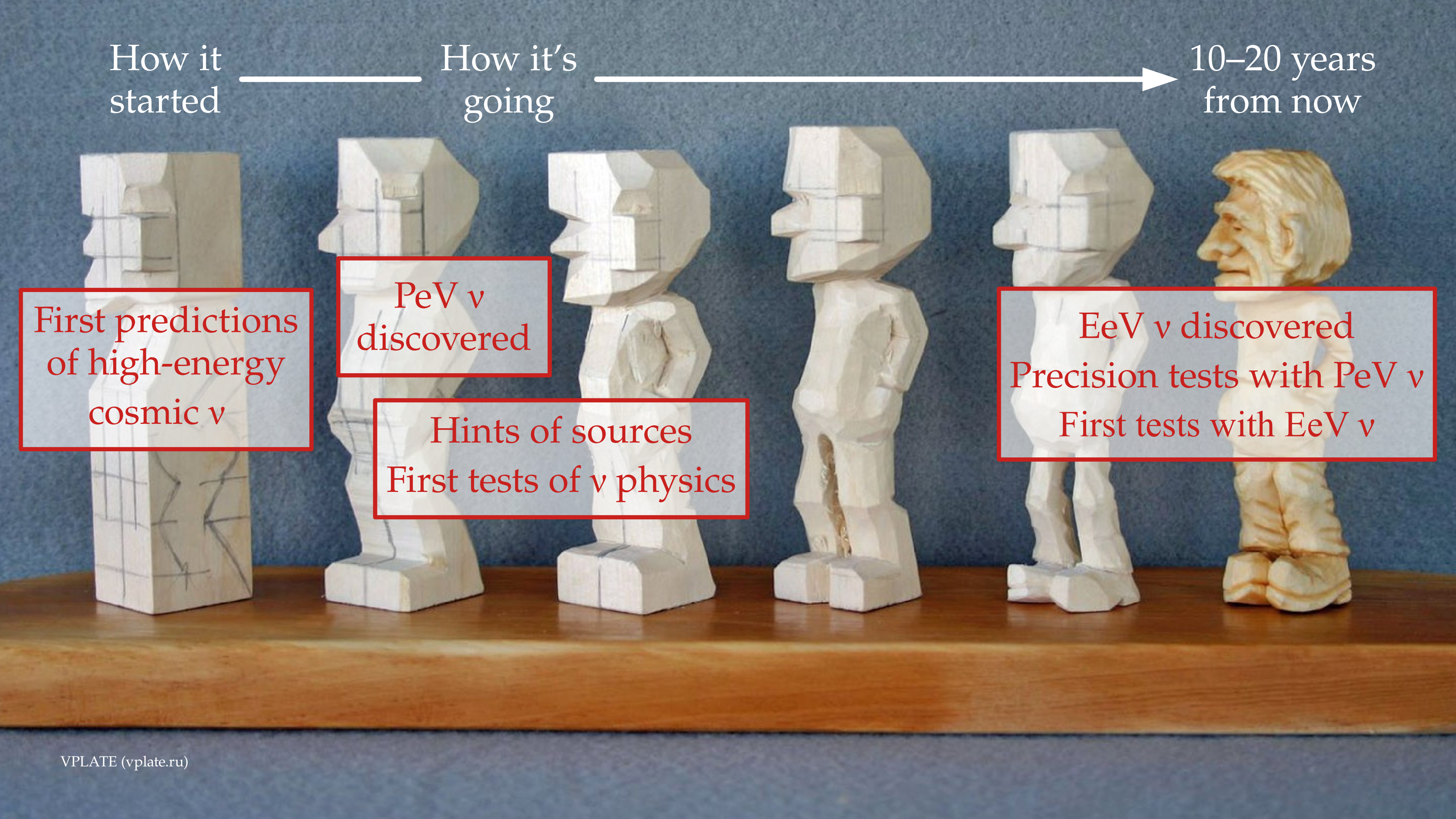
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10–20 years from now
First predictions of high-energy cosmic ν
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EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
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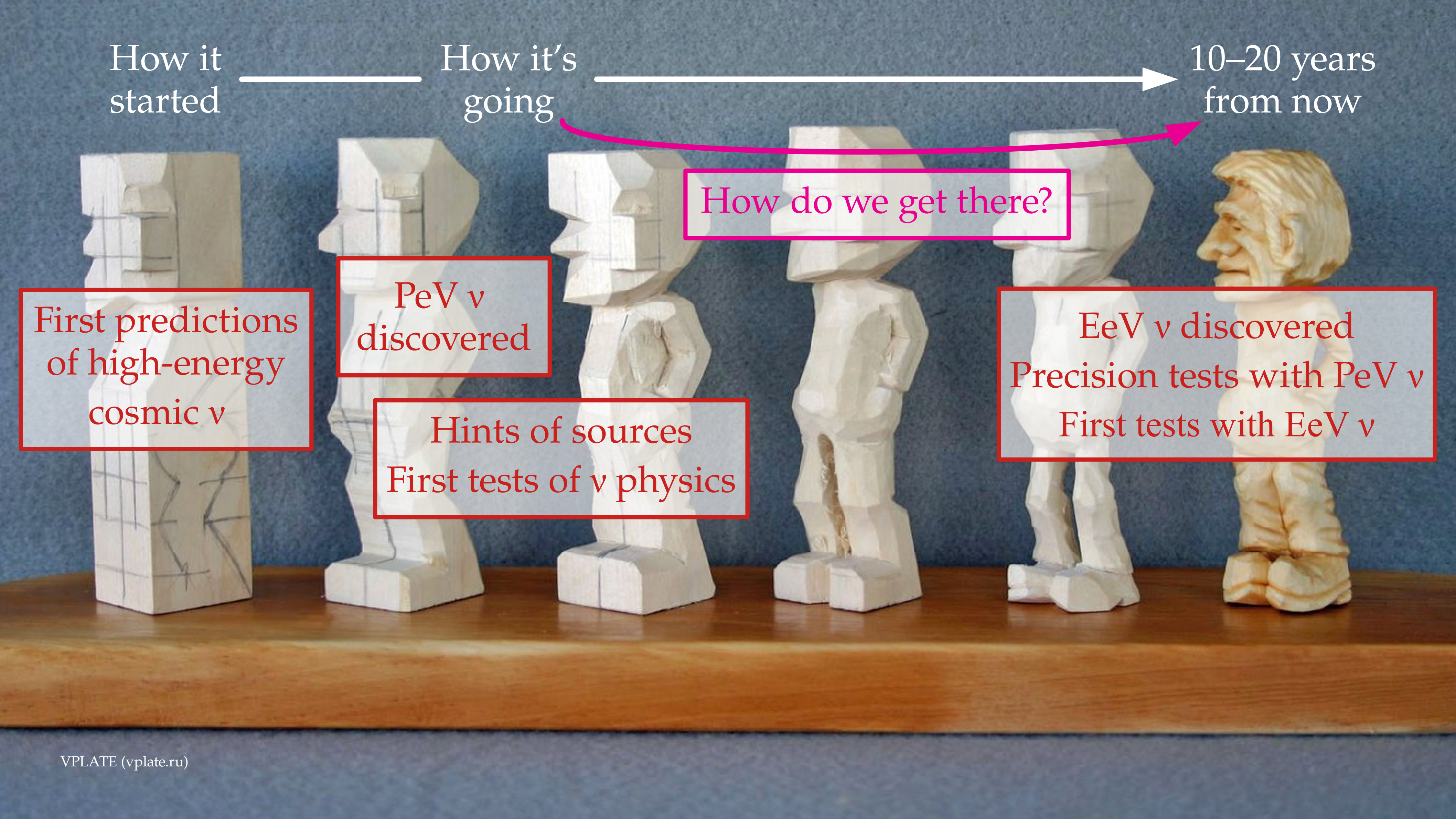
How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
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EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
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Backup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

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)

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(L long → lots of matter)

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

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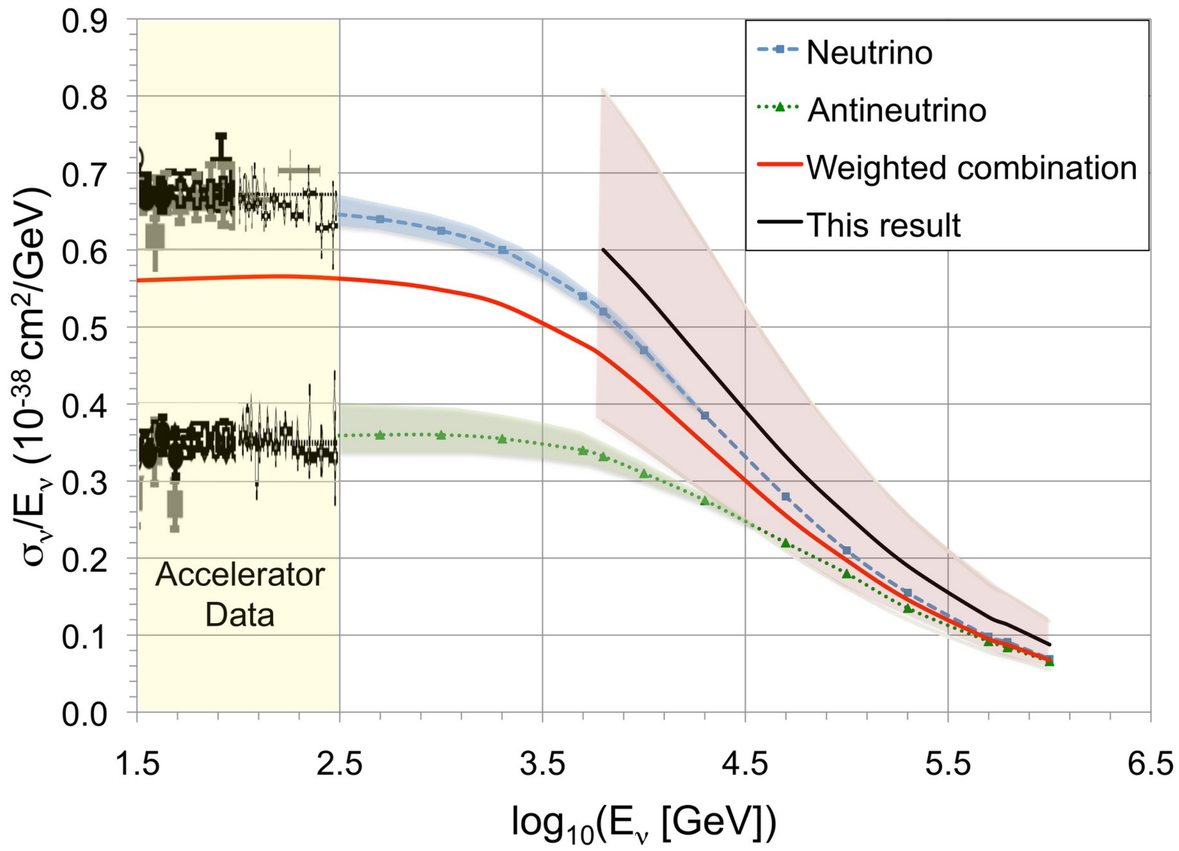
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

Using through-going muons instead

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



IceCube, *Nature* 2017

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

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

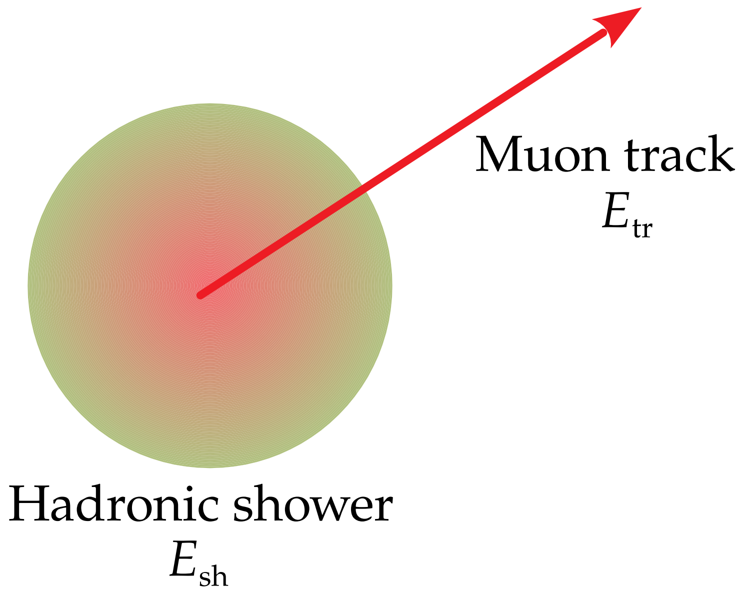
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \;\Rightarrow\; y = (1 + E_\mu/E_X)^{-1}$

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

- In a HESE starting track:

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

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



IceCube Collab., *PRD* 2019

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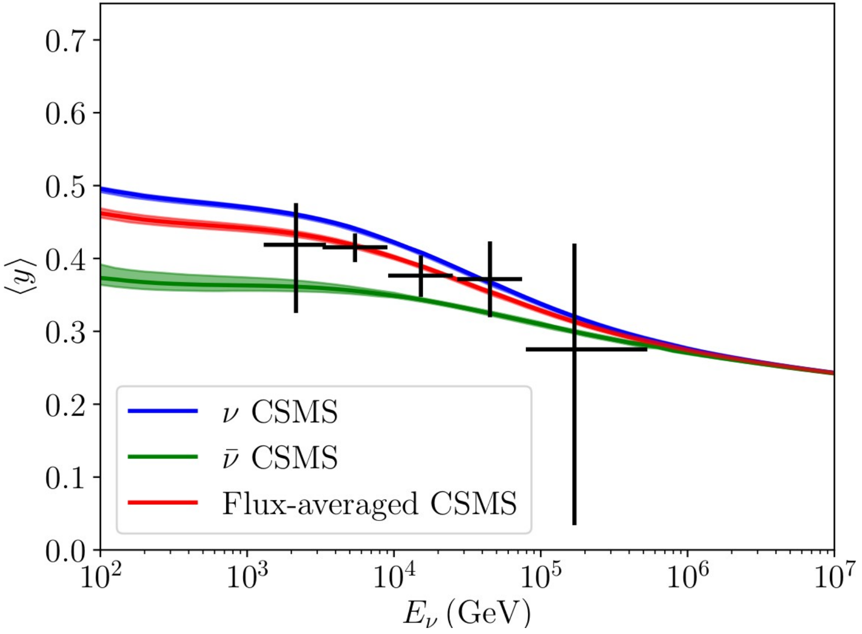


IceCube Collab., *PRD* 2019

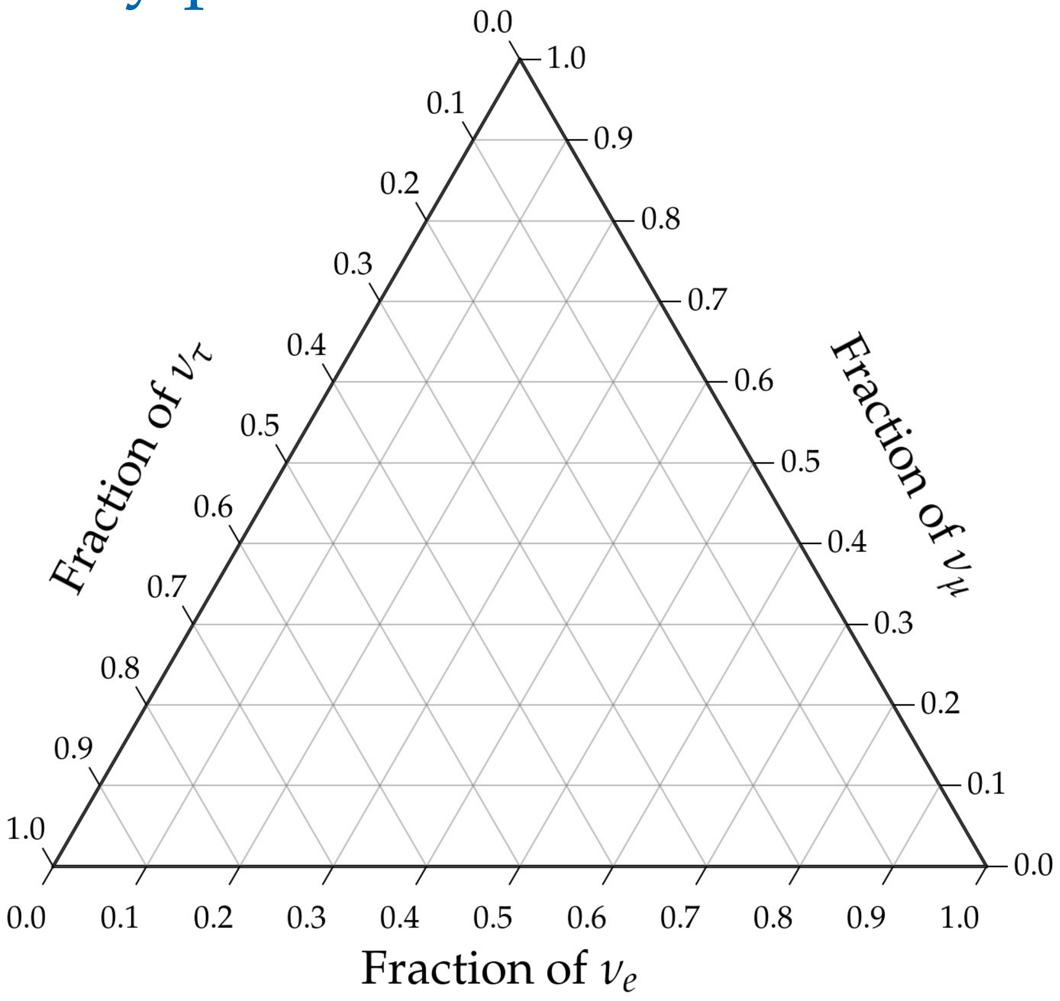
Quick aside: how to read a ternary plot

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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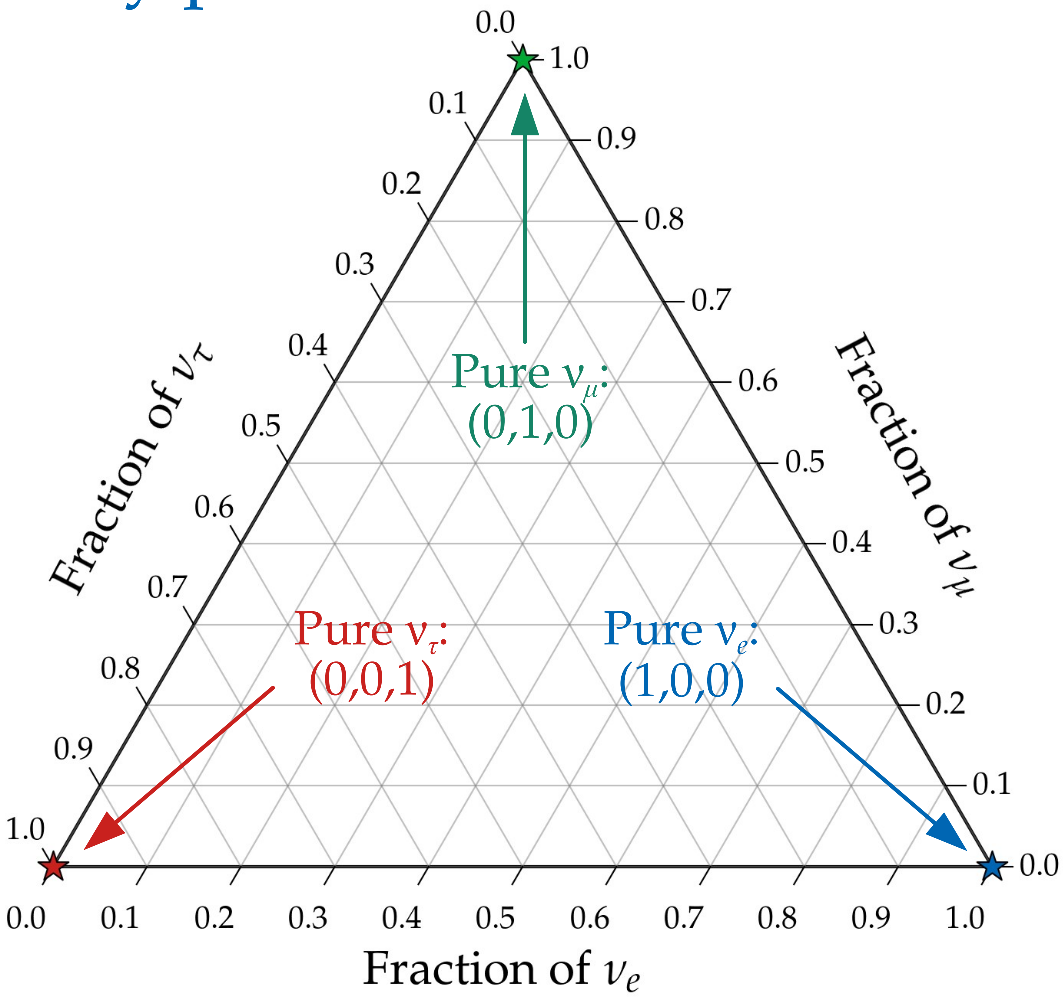

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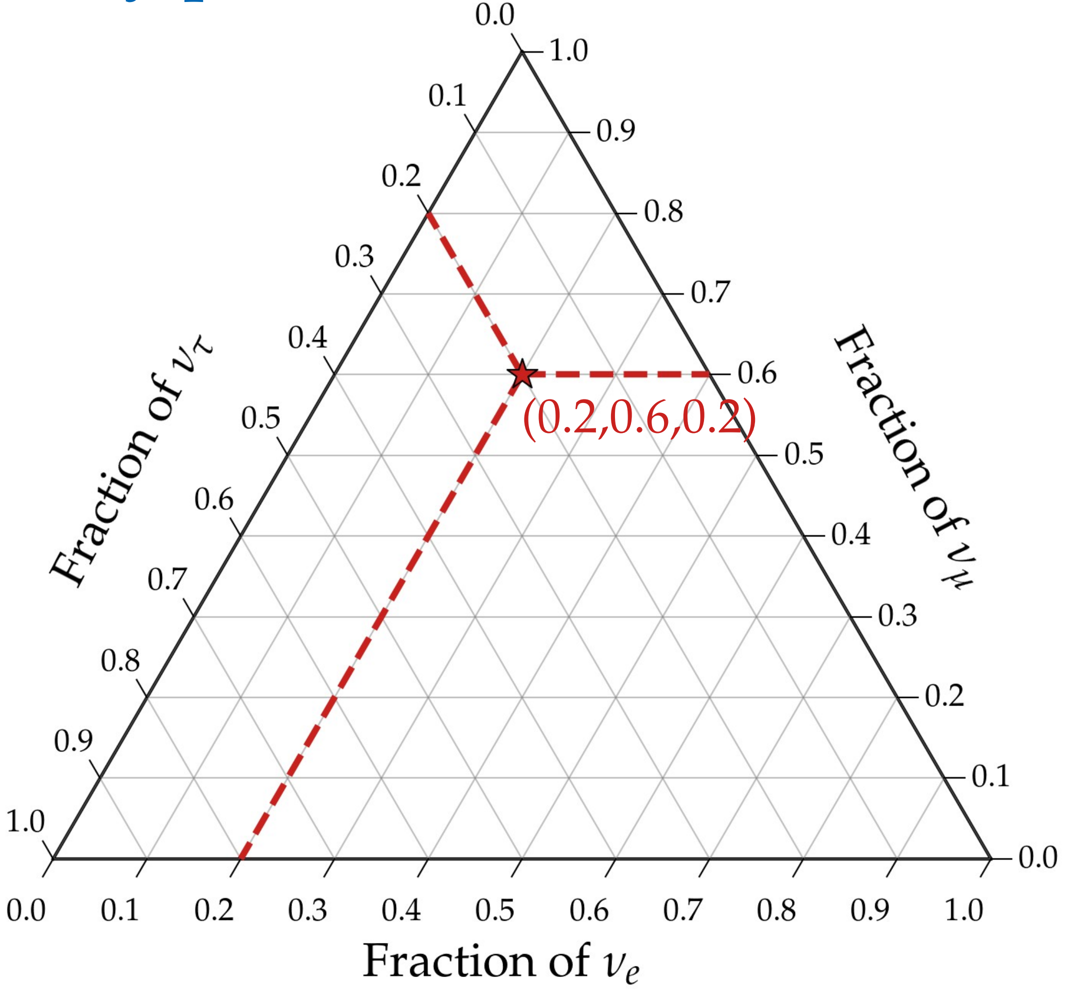

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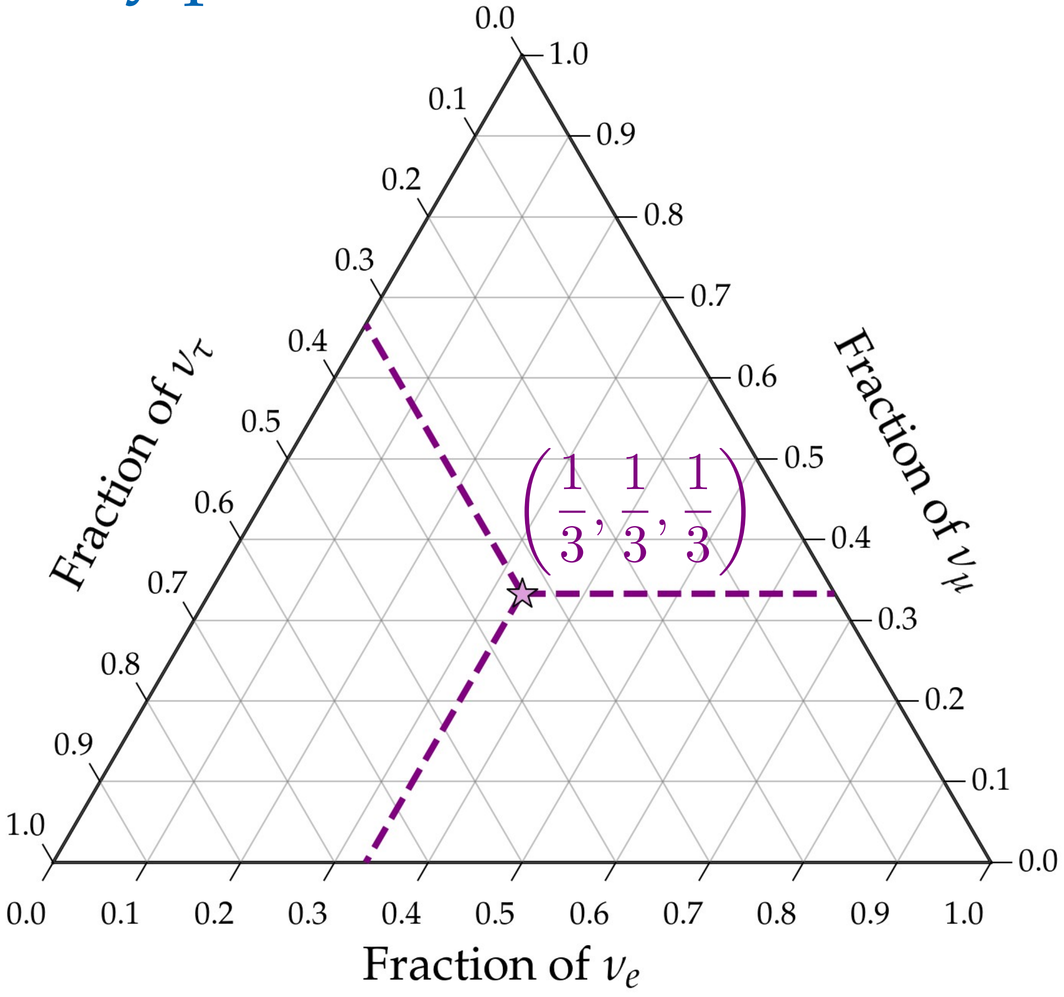

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

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Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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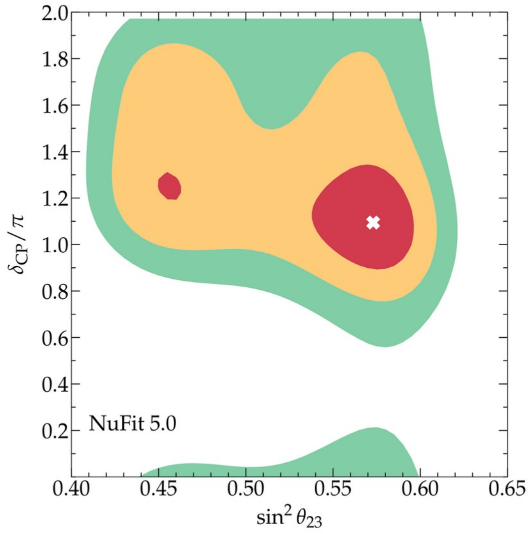
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org



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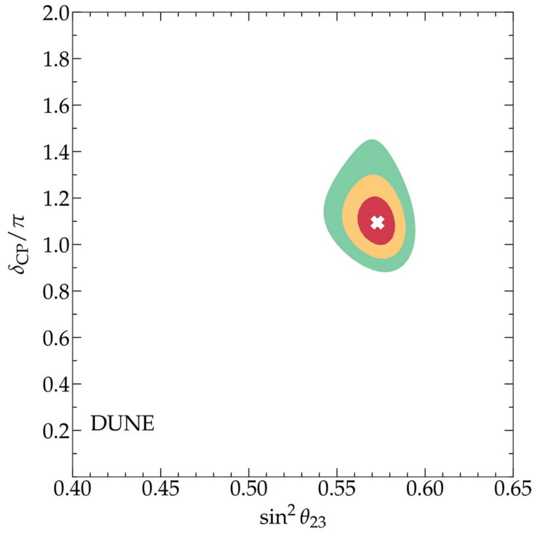
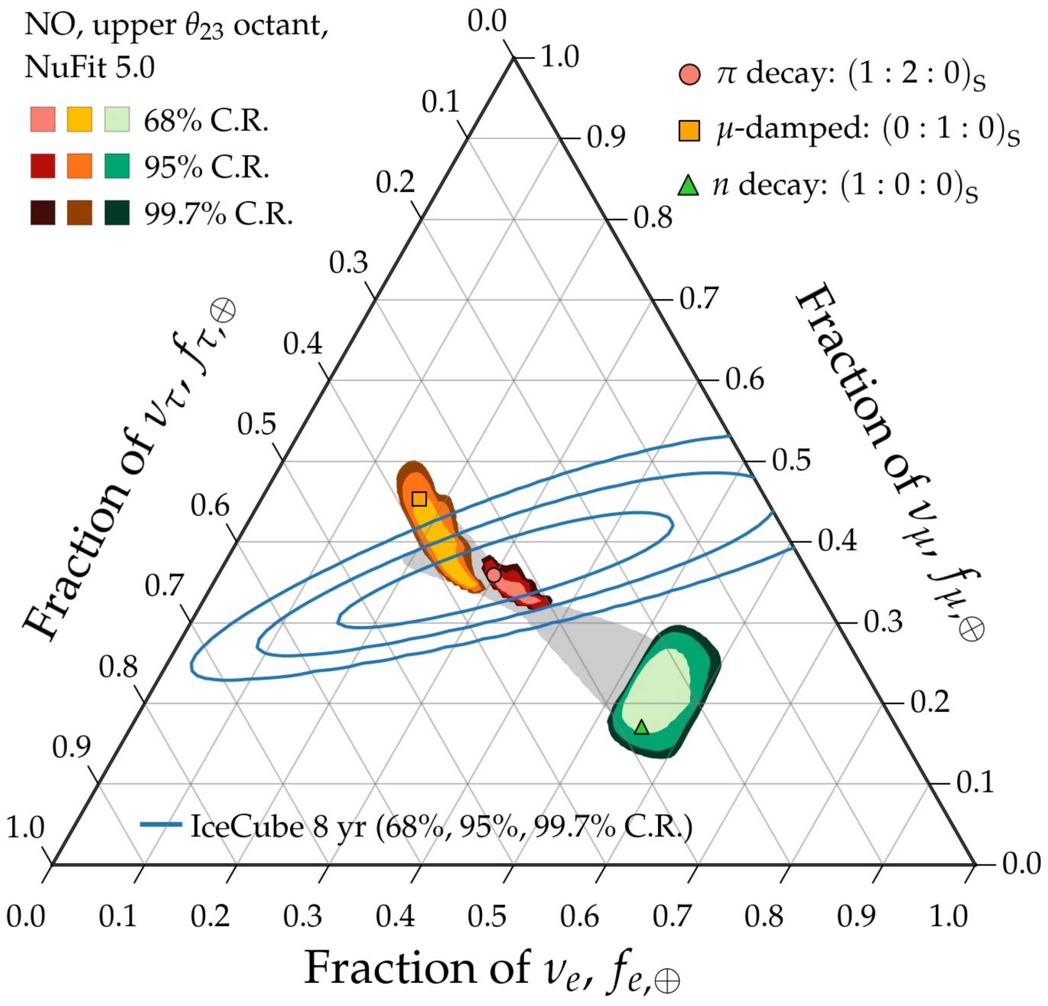
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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



Theoretically palatable regions: today



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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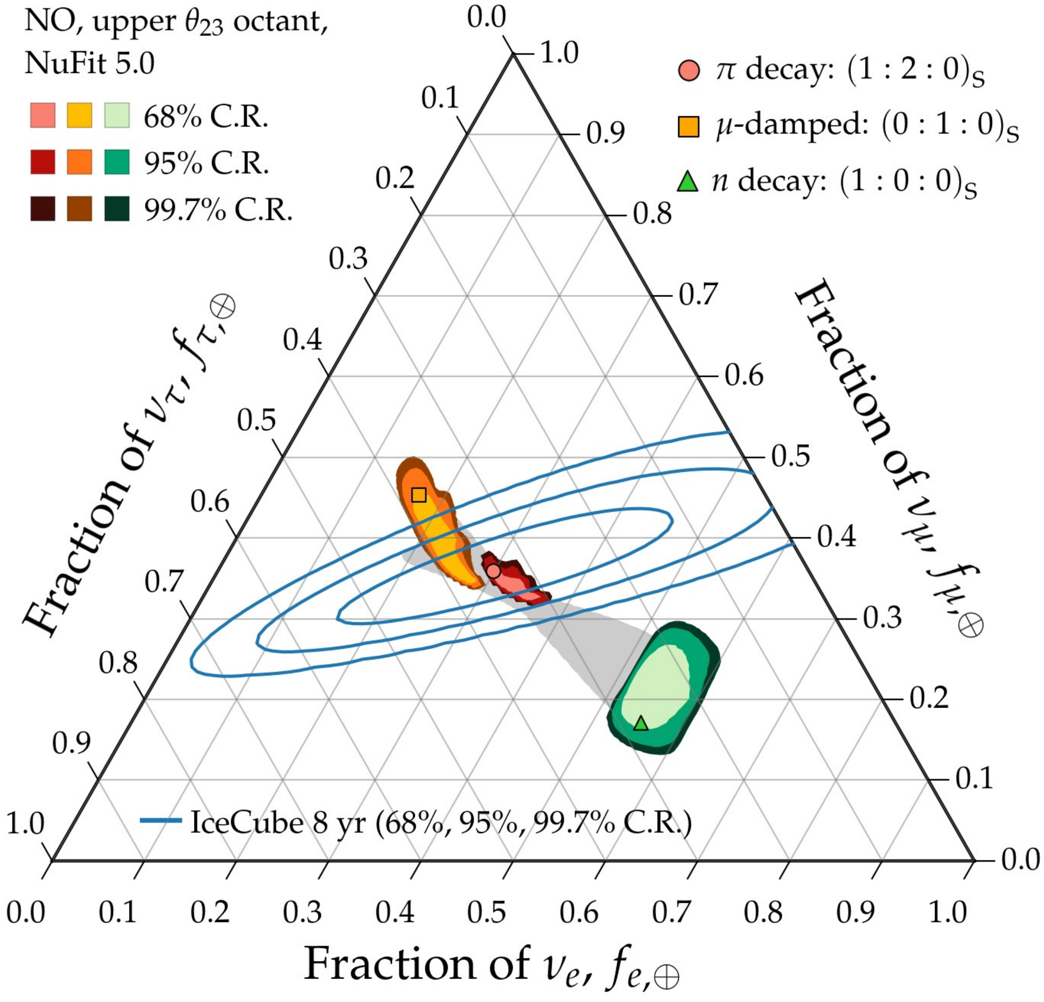

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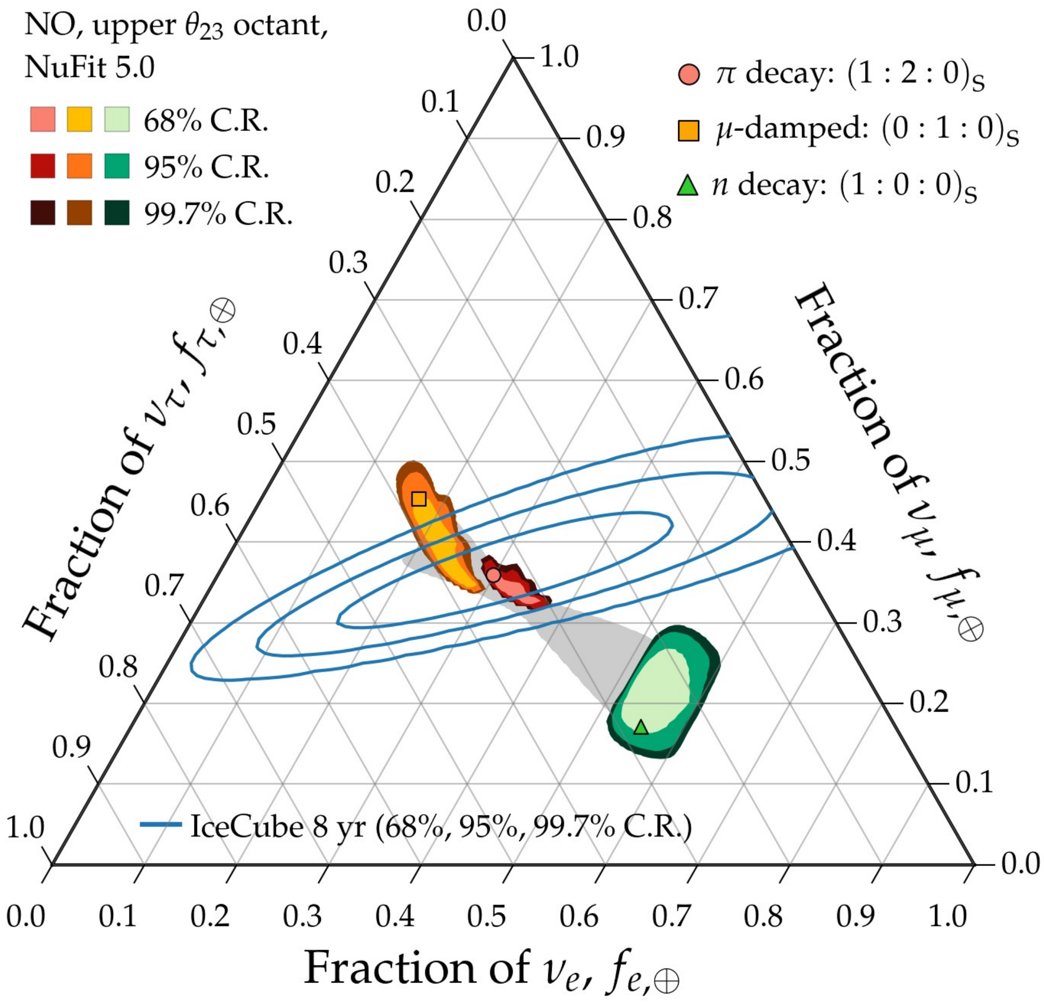

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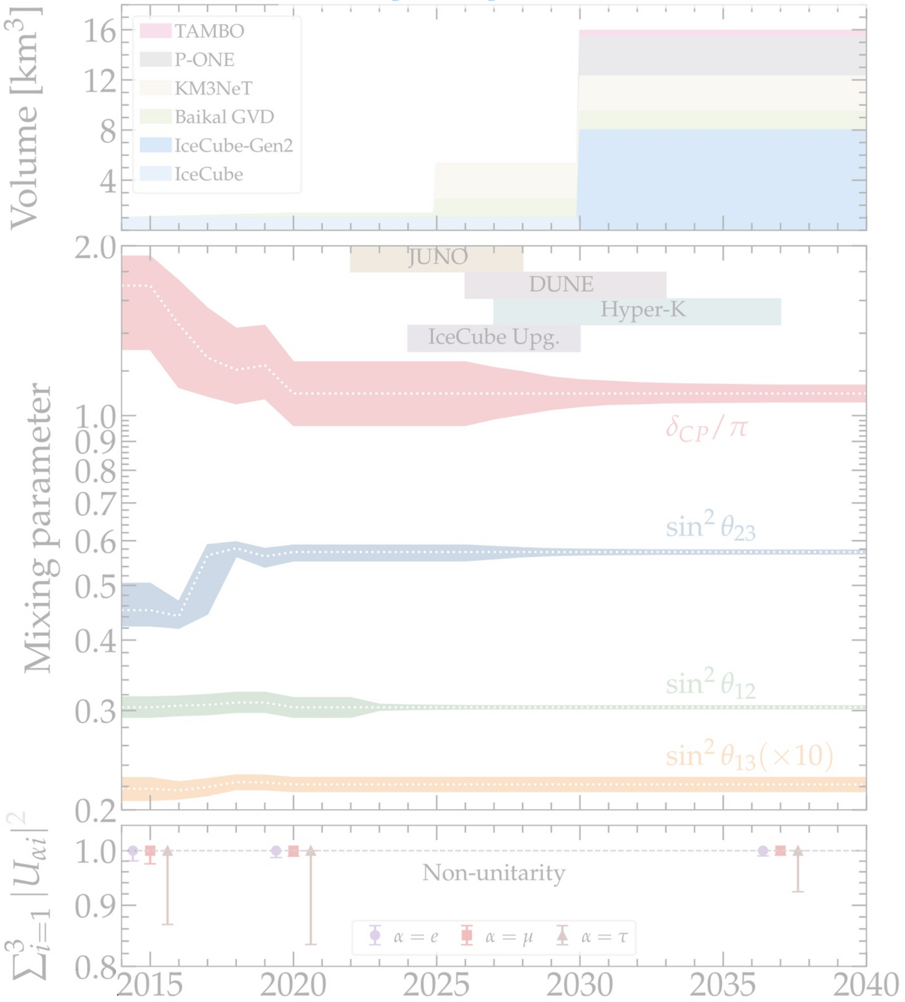
Will be overcome by 2040

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

Three reasons to be excited

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



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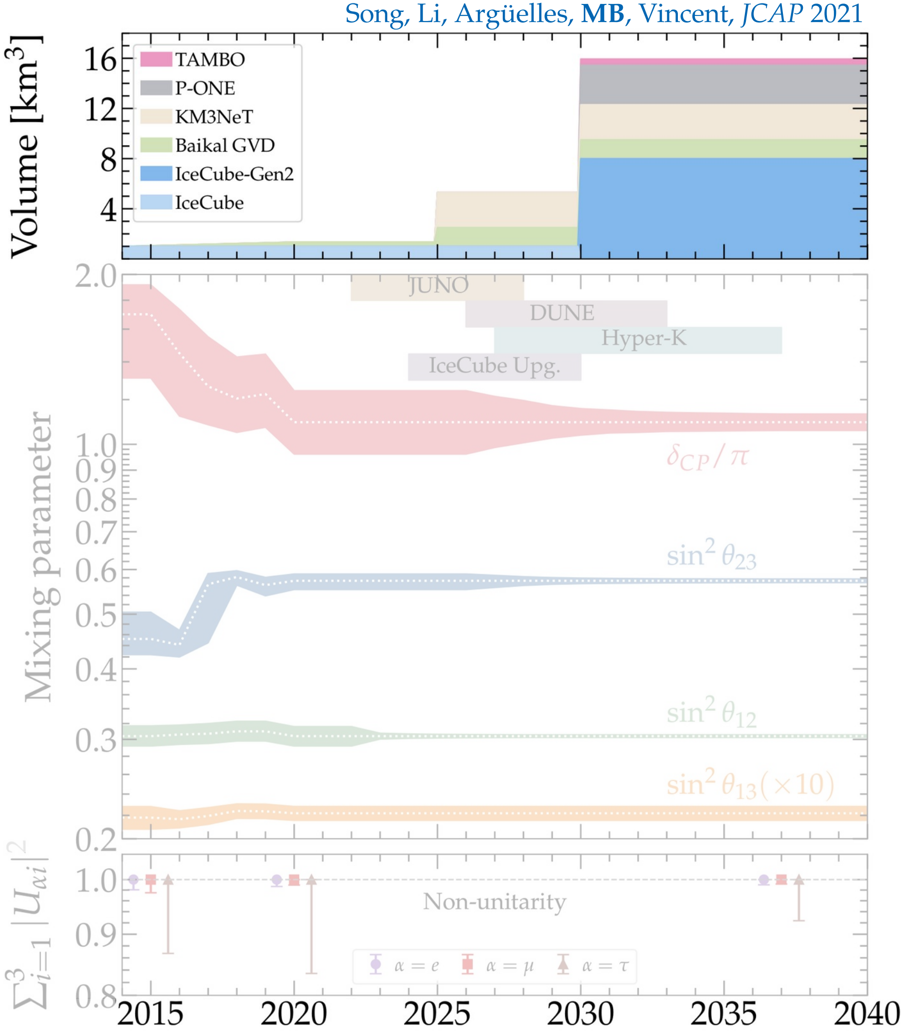

Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

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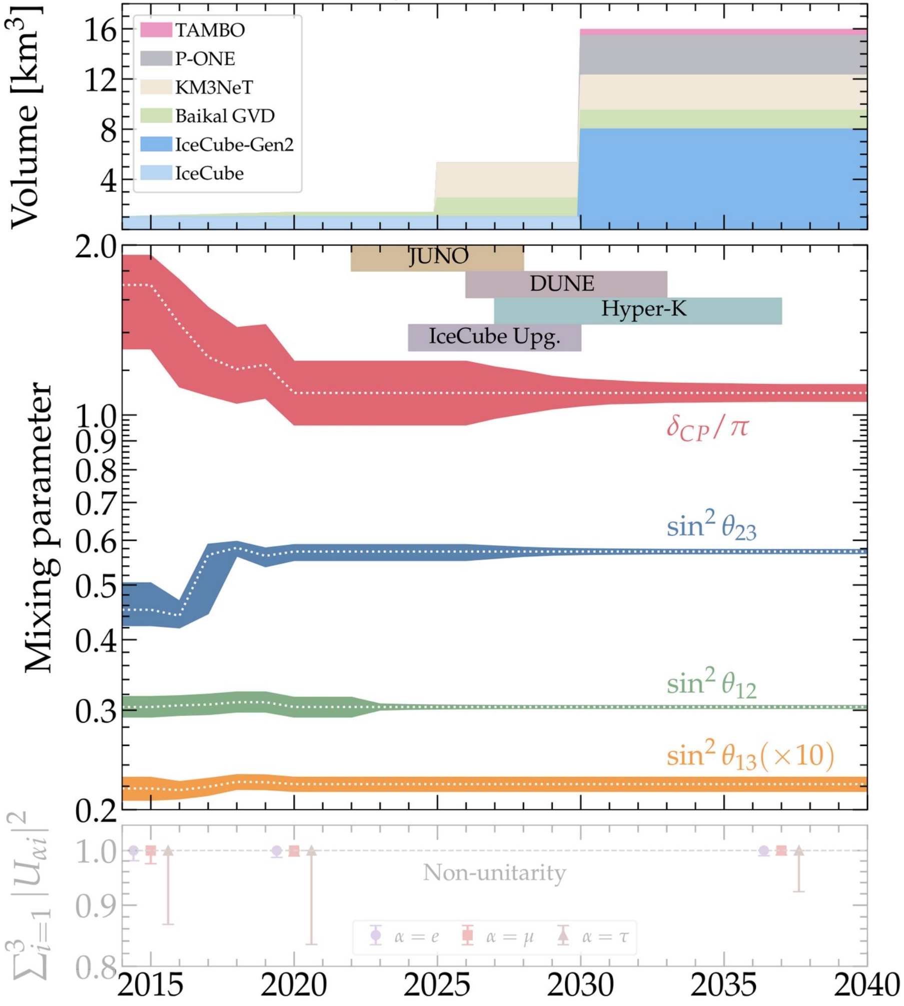

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We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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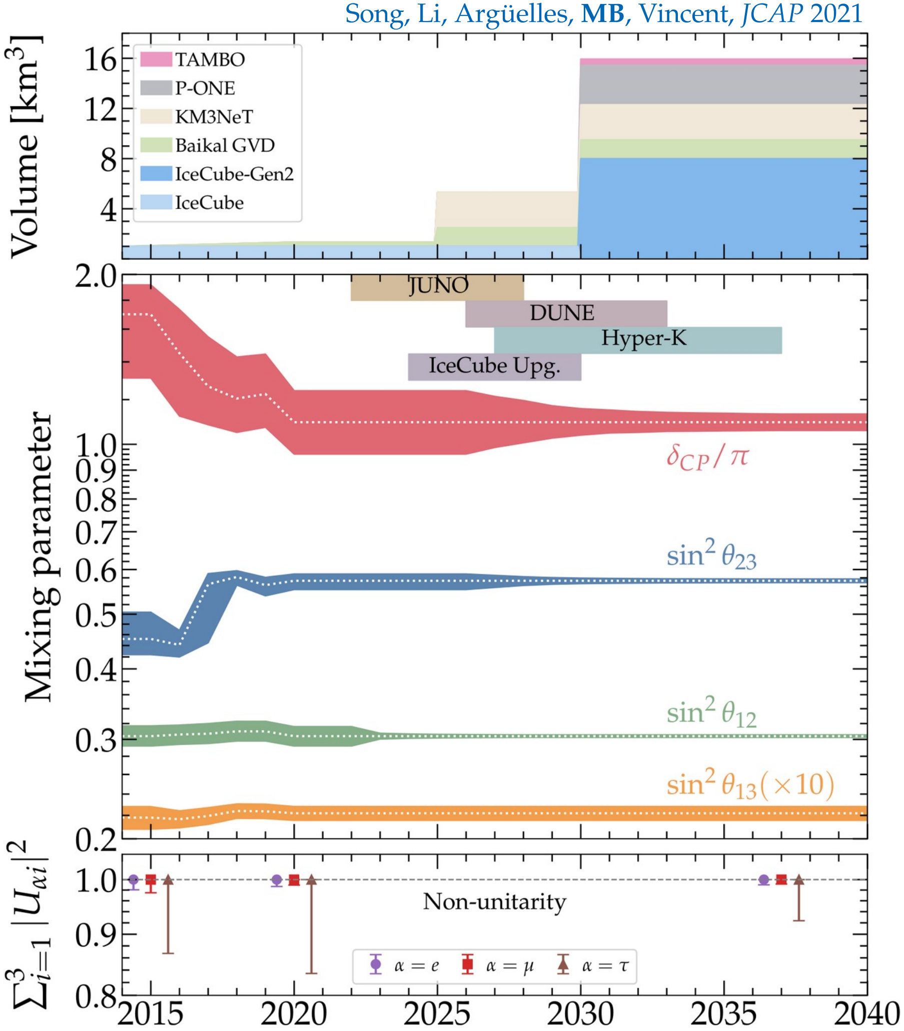

Flavor measurements:
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Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

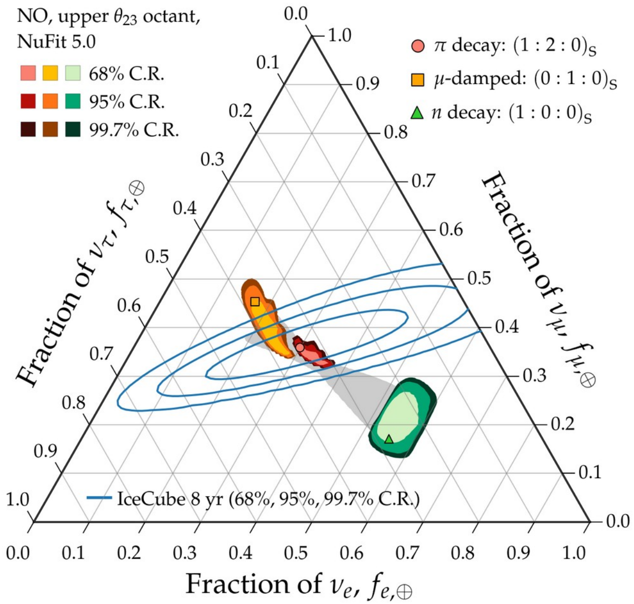
Test of the oscillation framework:
We will be able to do what we want even if oscillations are non-unitary

Theoretically palatable regions: 2020 → 2030 → 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

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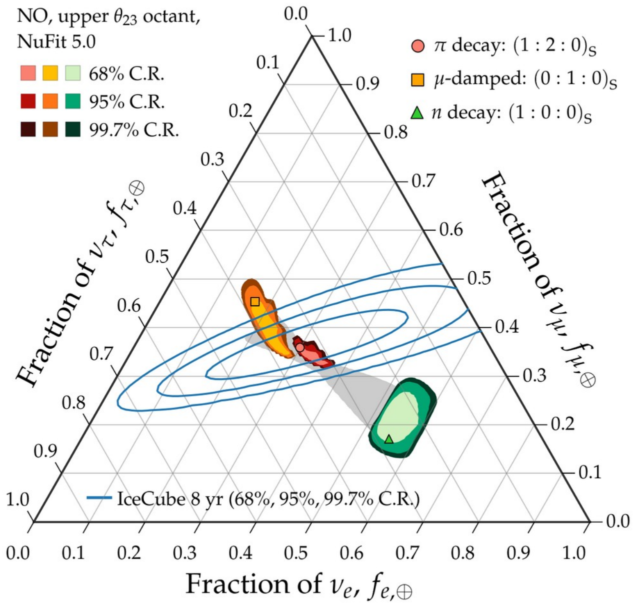

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Not ideal

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

Theoretically palatable regions: 2020 → 2030 → 2040

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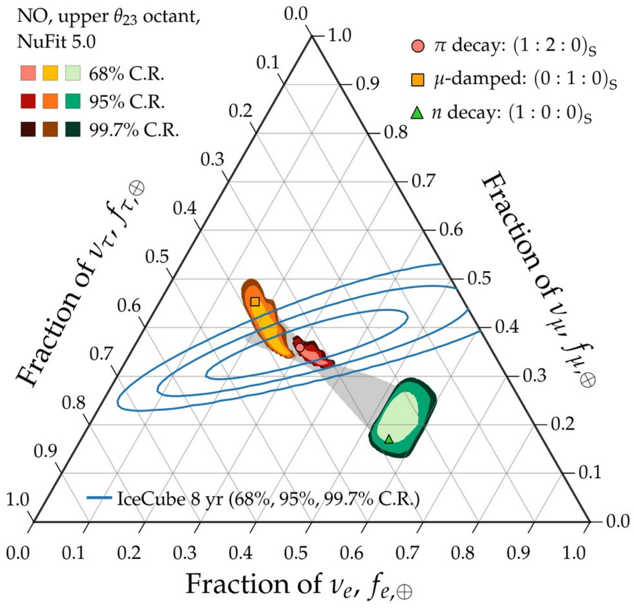

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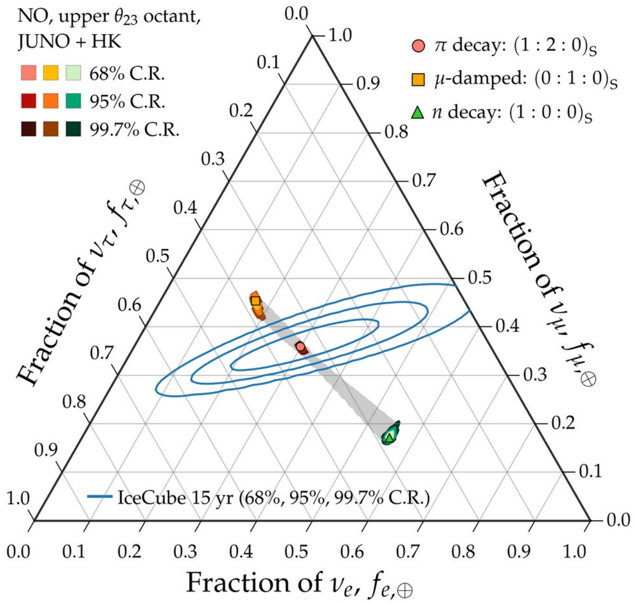
2030



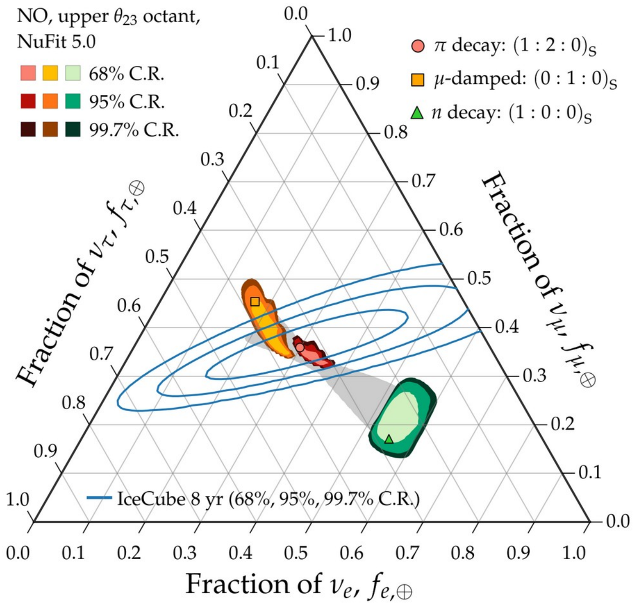
Allowed regions: well separated

Measurement: improving

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

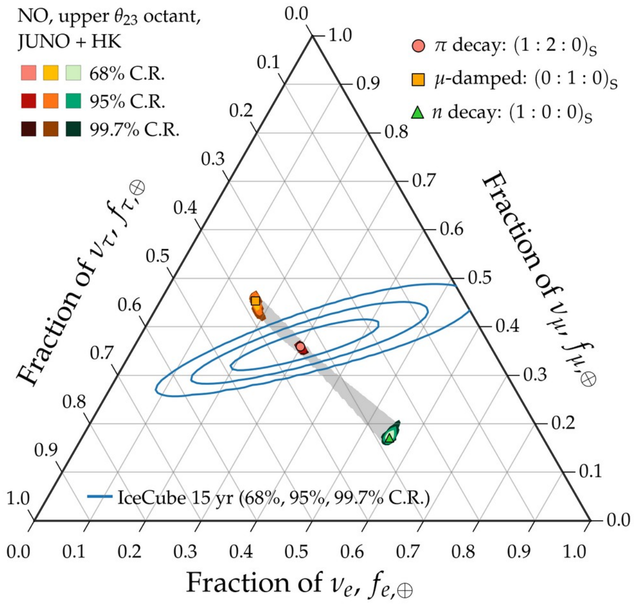


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



Allowed regions: well separated

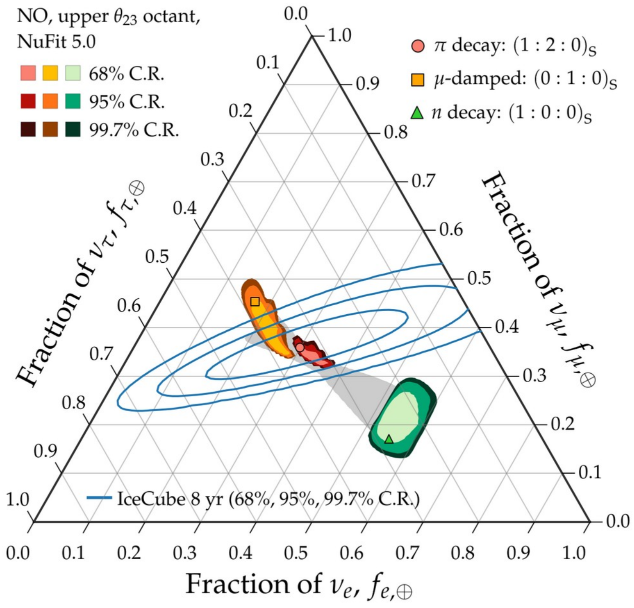
Measurement: improving

Nice

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020

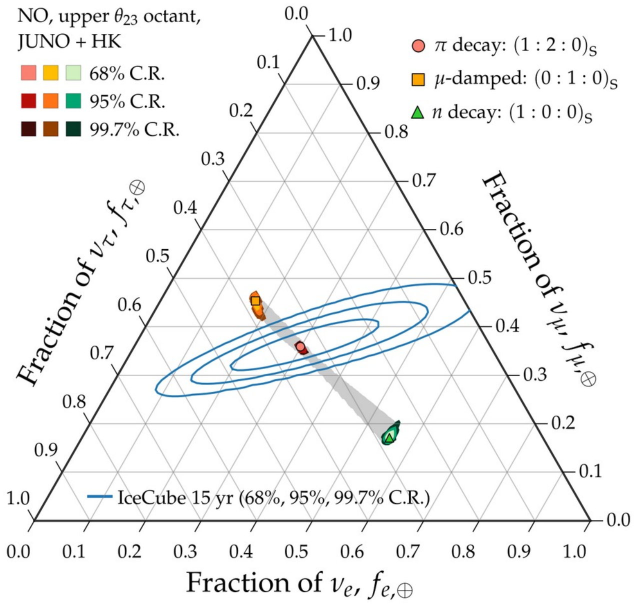


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

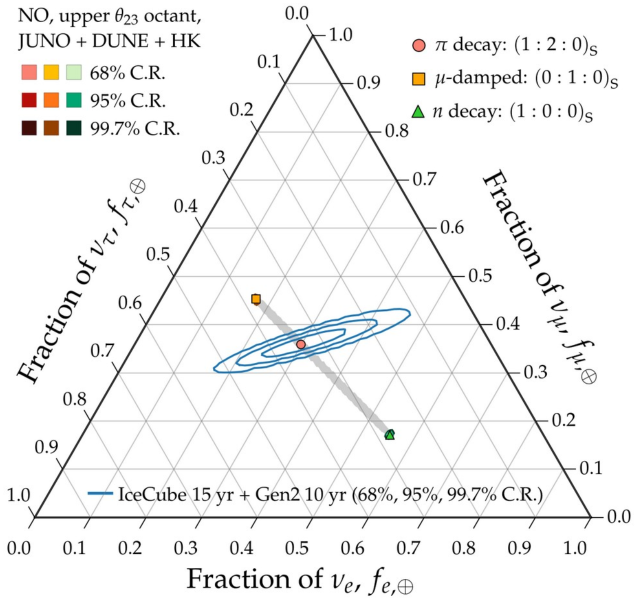


Allowed regions: well separated

Measurement: improving

Nice

2040



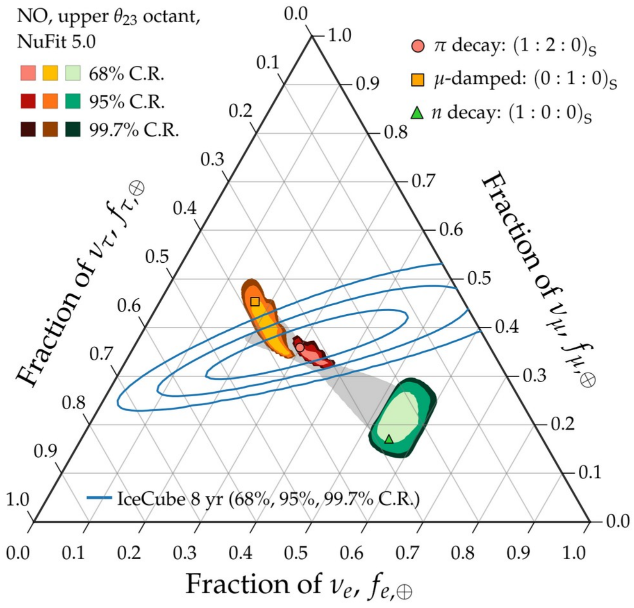
Allowed regions: well separated

Measurement: precise

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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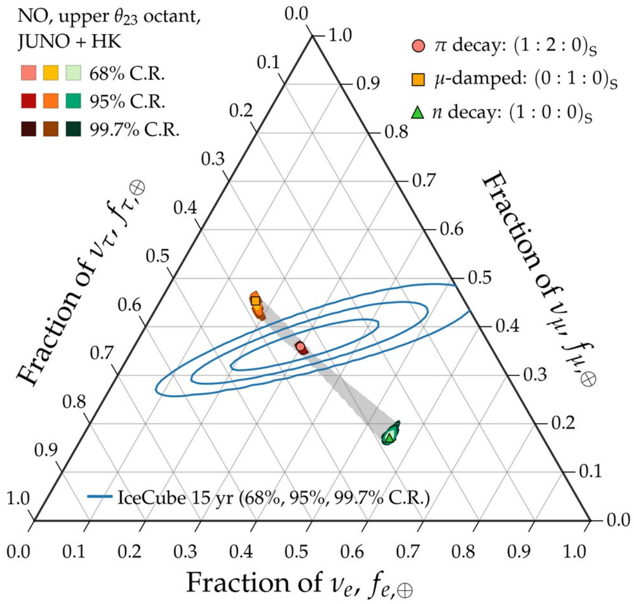
Not ideal

2030

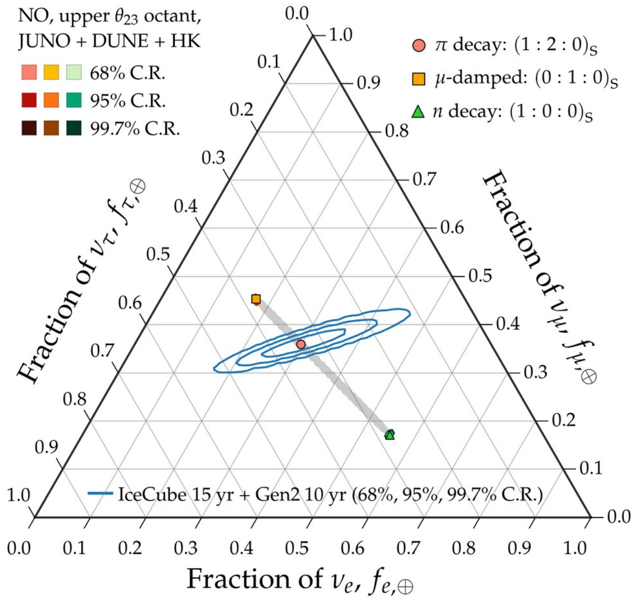


Allowed regions: well separated

Measurement: improving

Nice

2040



Allowed regions: well separated

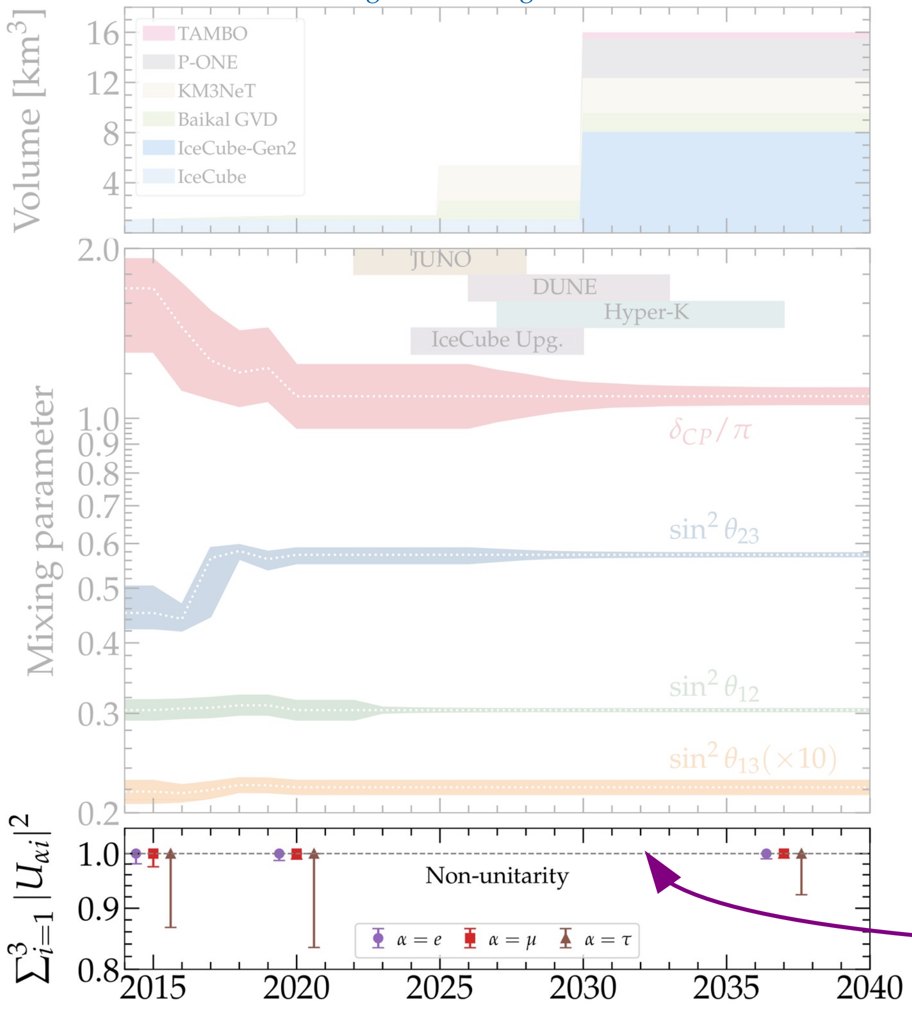
Measurement: precise

Success

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

No unitarity? *No problem*

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



The 3×3 active mixing matrix is a non-unitary sub-matrix of a bigger one:

Active flavors

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \cdots & \cdots & \cdots & \ddots \end{pmatrix}$$

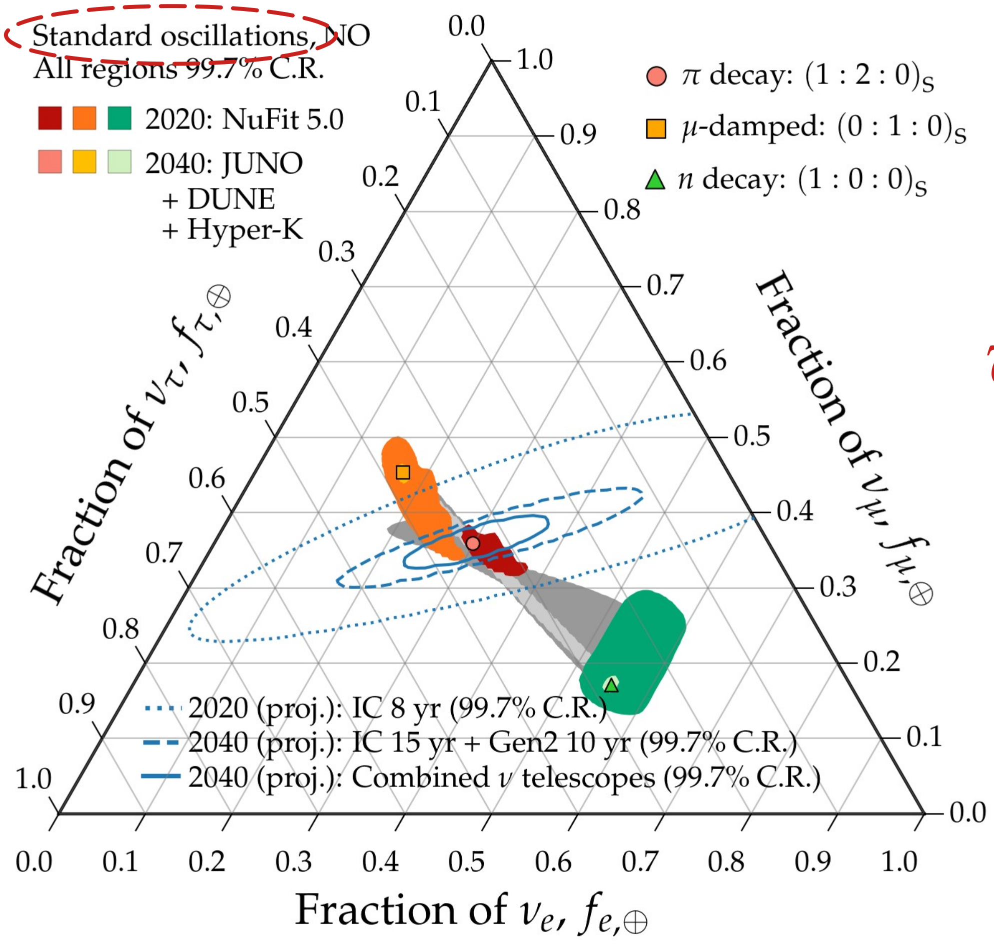
Additional sterile flavors

The elements $|U_{\alpha i}|^2$ for active flavors can be measured *without* assuming unitarity

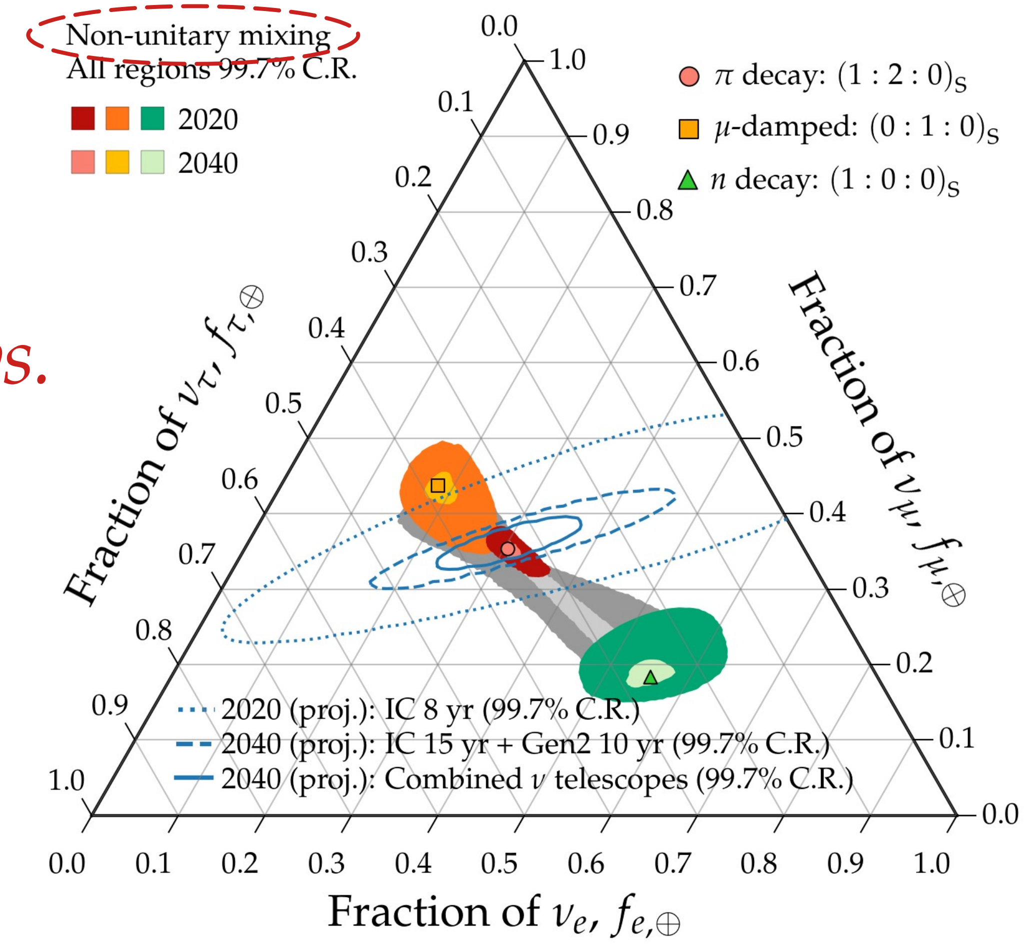
Because the sub-matrix is not-unitary ($U_{3\nu}^\dagger U_{3\nu} \neq 1$), the "row sum" may be < 1

Ellis, Kelly, Li, 2008.01088
Parke & Ross-Lonergan, *PRD* 2016

No unitarity? *No problem*

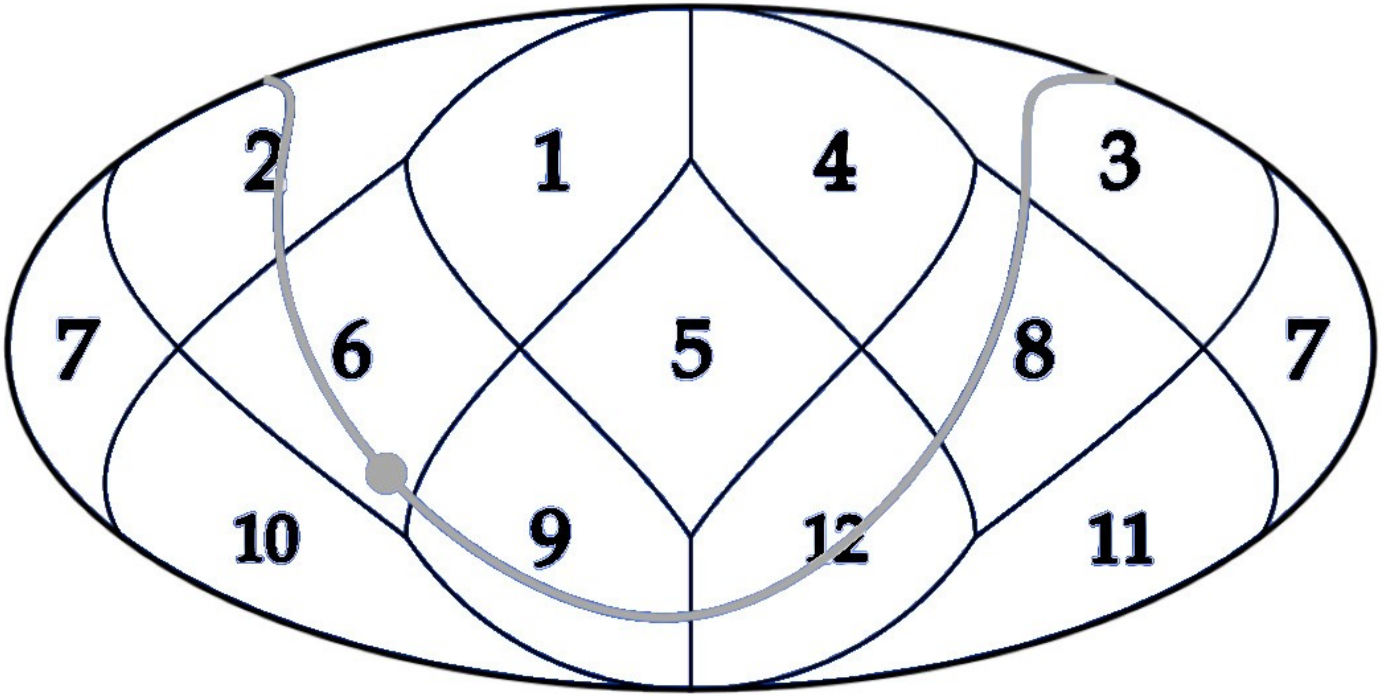


vs.



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

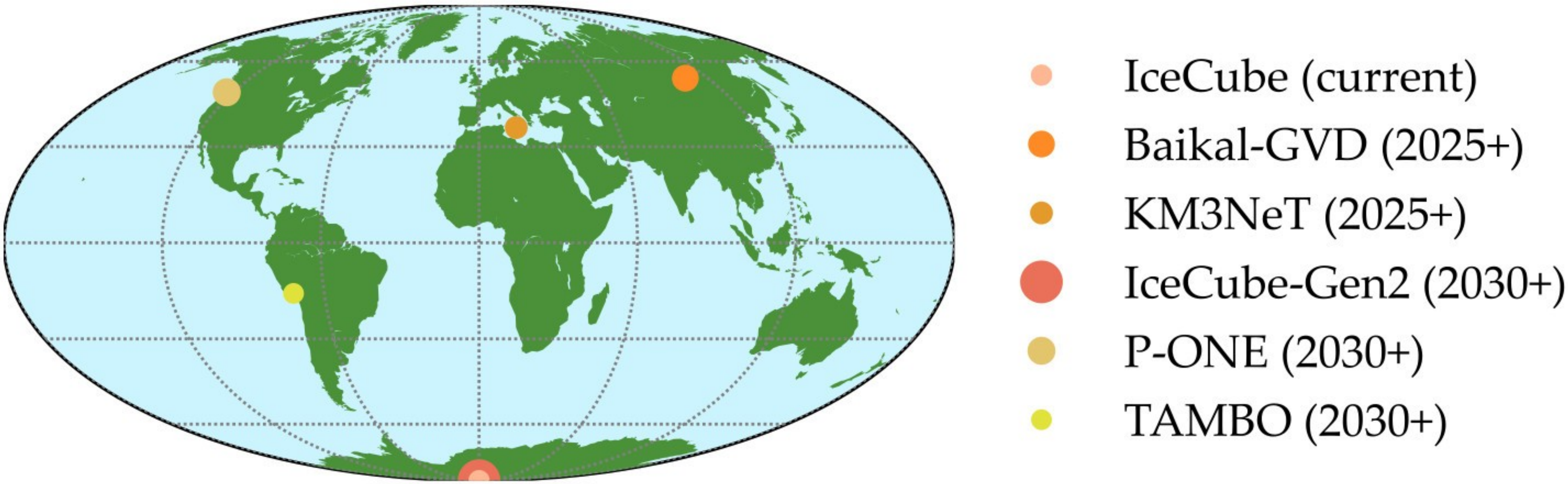
We tessellate the sky into 12 large pixels (HEALPix)—



Large pixels due to limited data + large angular uncertainty

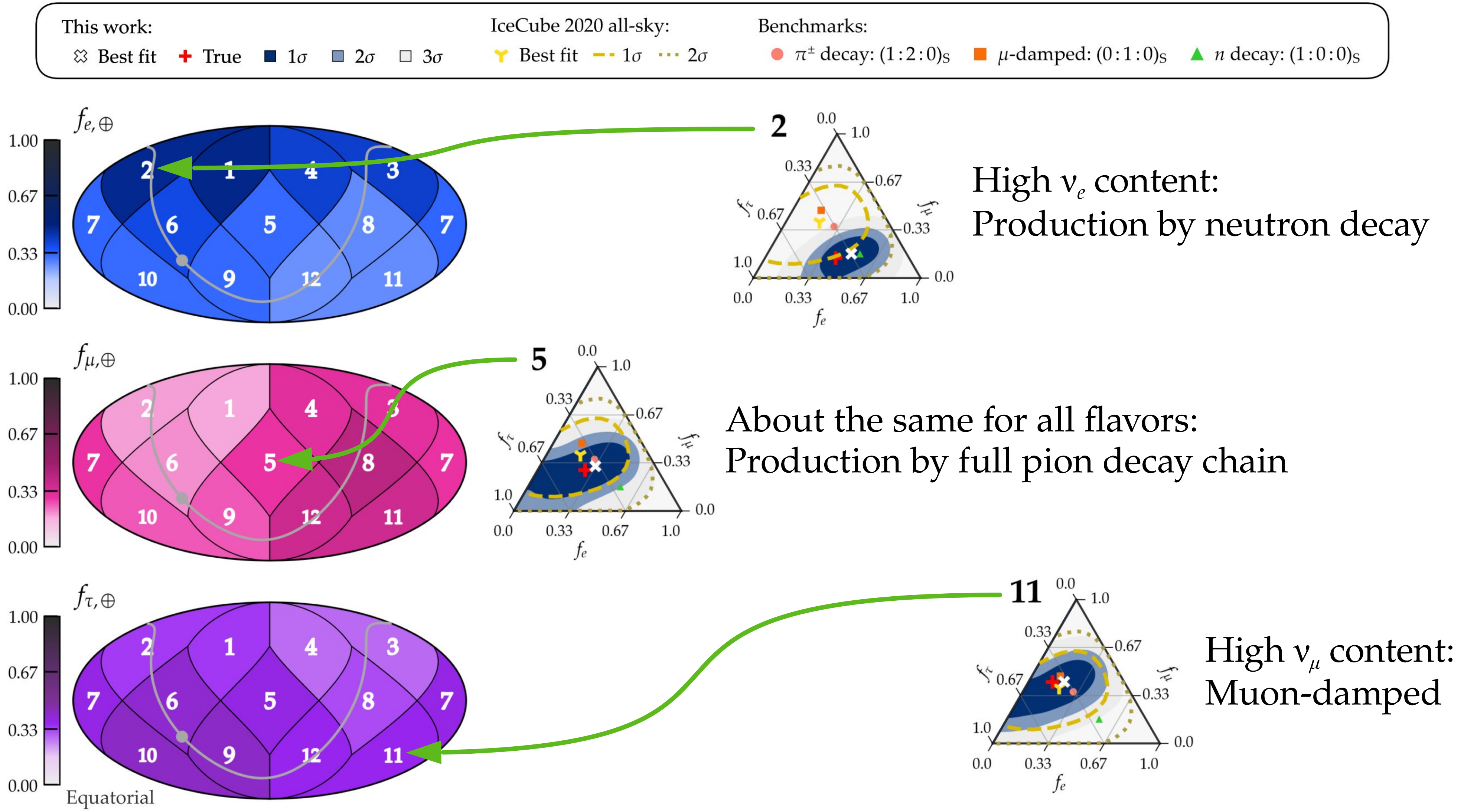
Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)

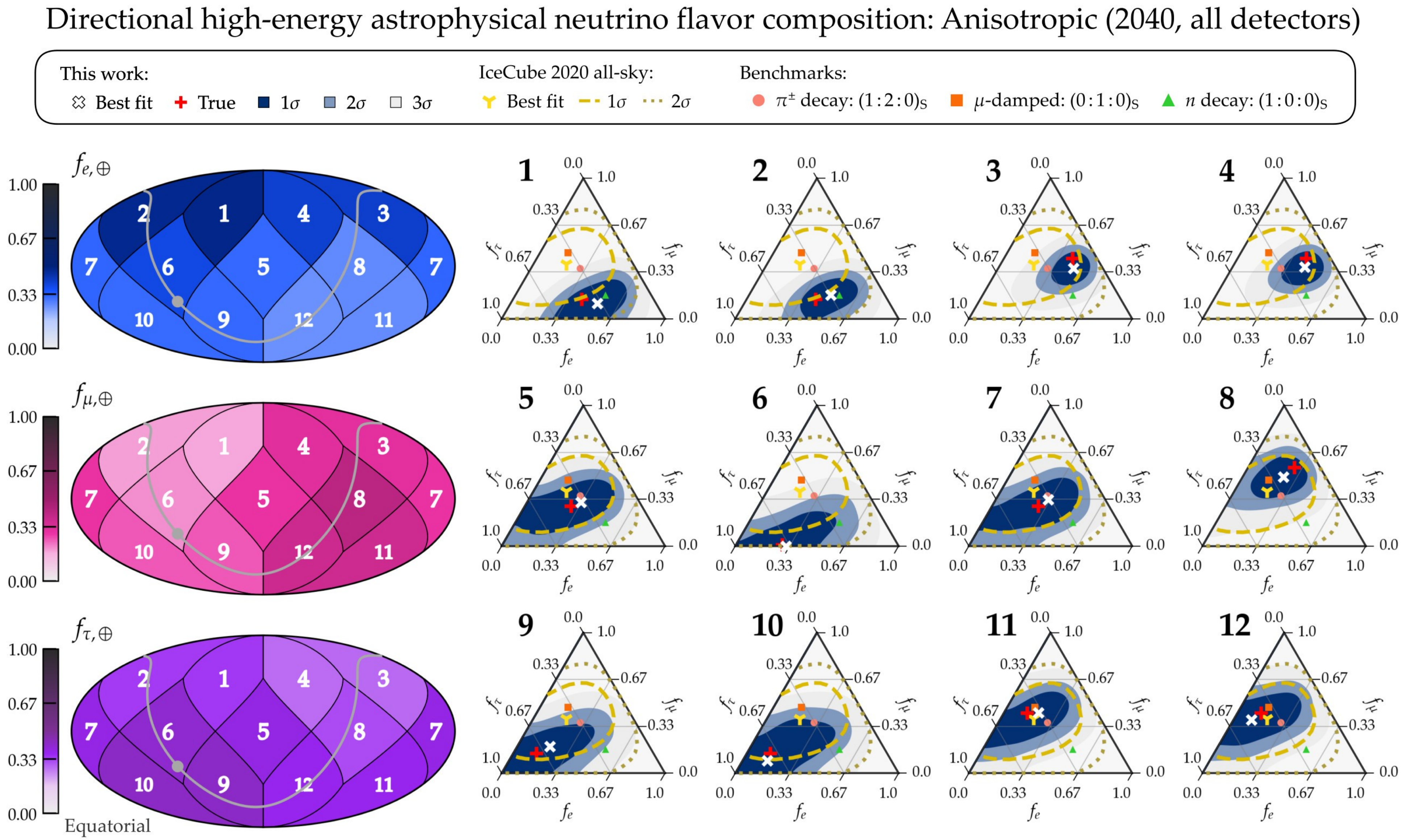
Forecast

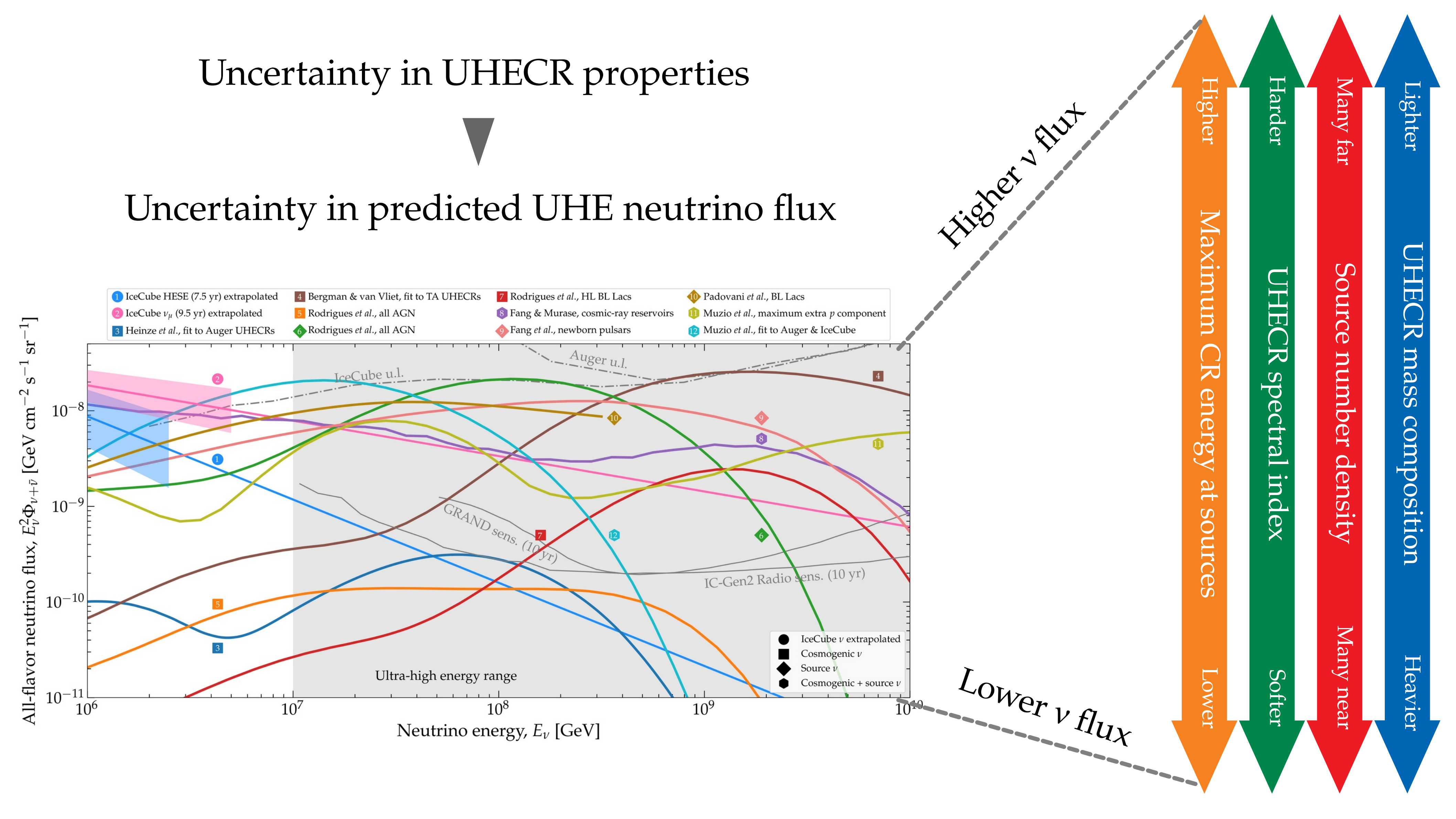


The different detector positions matter

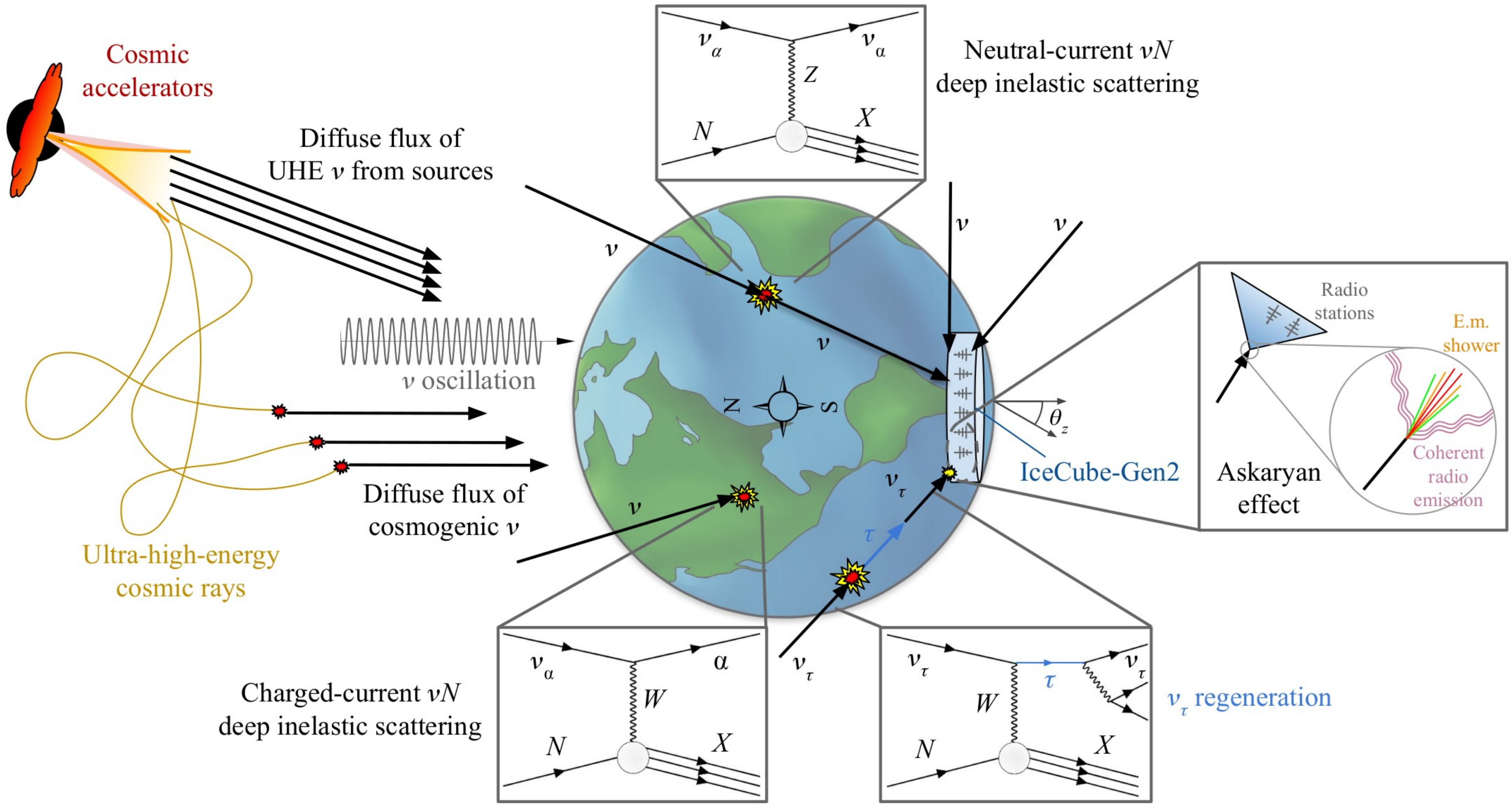
Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)



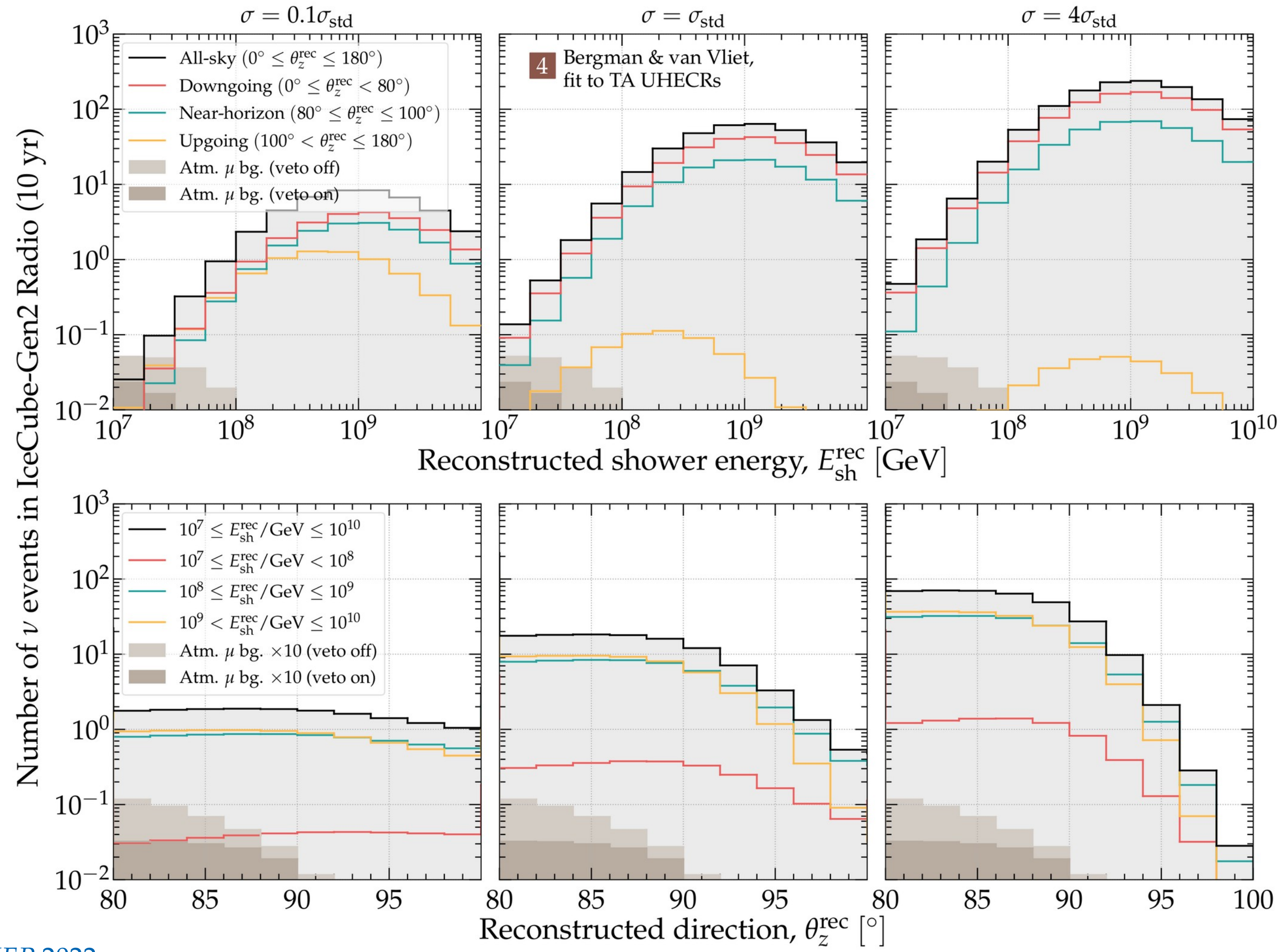

Directional high-energy astrophysical neutrino flavor composition: Anisotropic (2040, all detectors)
This work:
Best fit
True
1σ
2σ
3σ
IceCube 2020 all-sky:
Best fit
1σ
2σ
Benchmarks:
π± decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
fe,⊕
fμ,⊕
fτ,⊕
1.00
0.67
0.33
0.00
Equatorial
fe
fμ
fτ
0.0
0.33
0.67
1.0
1
2
3
4
5
6
7
8
9
10
11
12



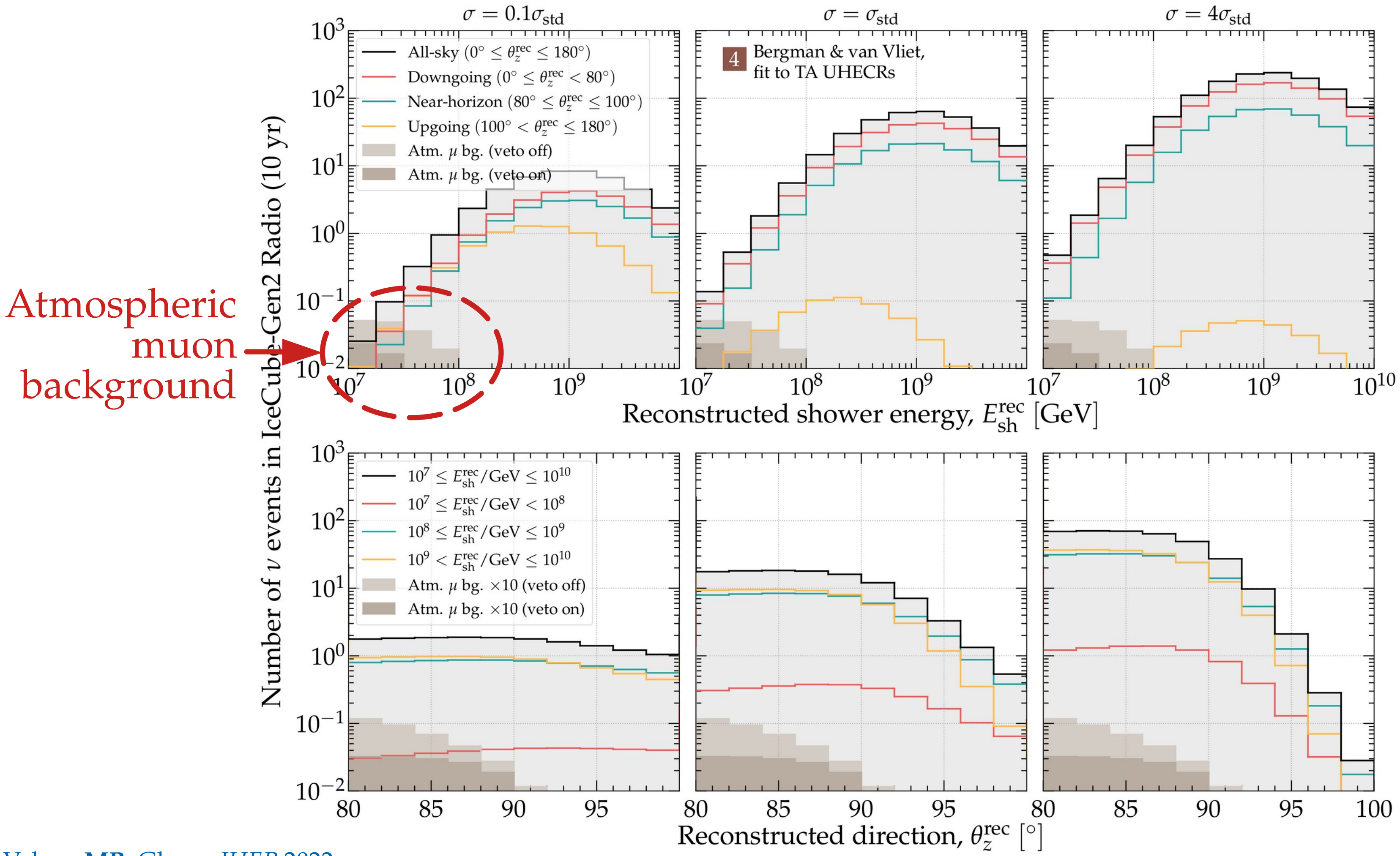
Uncertainty in UHECR properties
Uncertainty in predicted UHE neutrino flux
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., 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}]
Neutrino energy, E_ν [GeV]
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Higher ν flux
Lower ν flux
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier



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

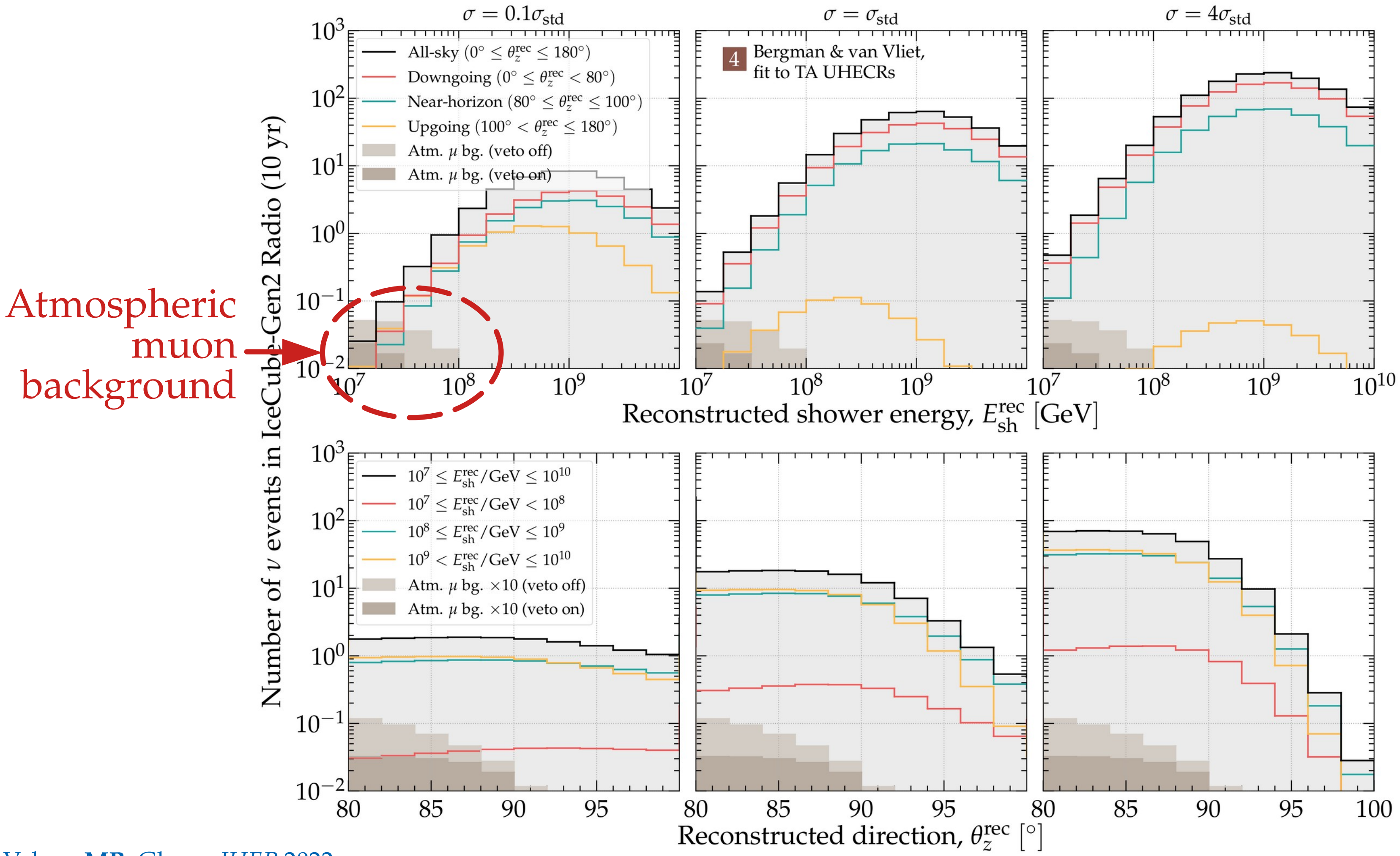


Valera, **MB**, Glaser, *JHEP* 2022



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

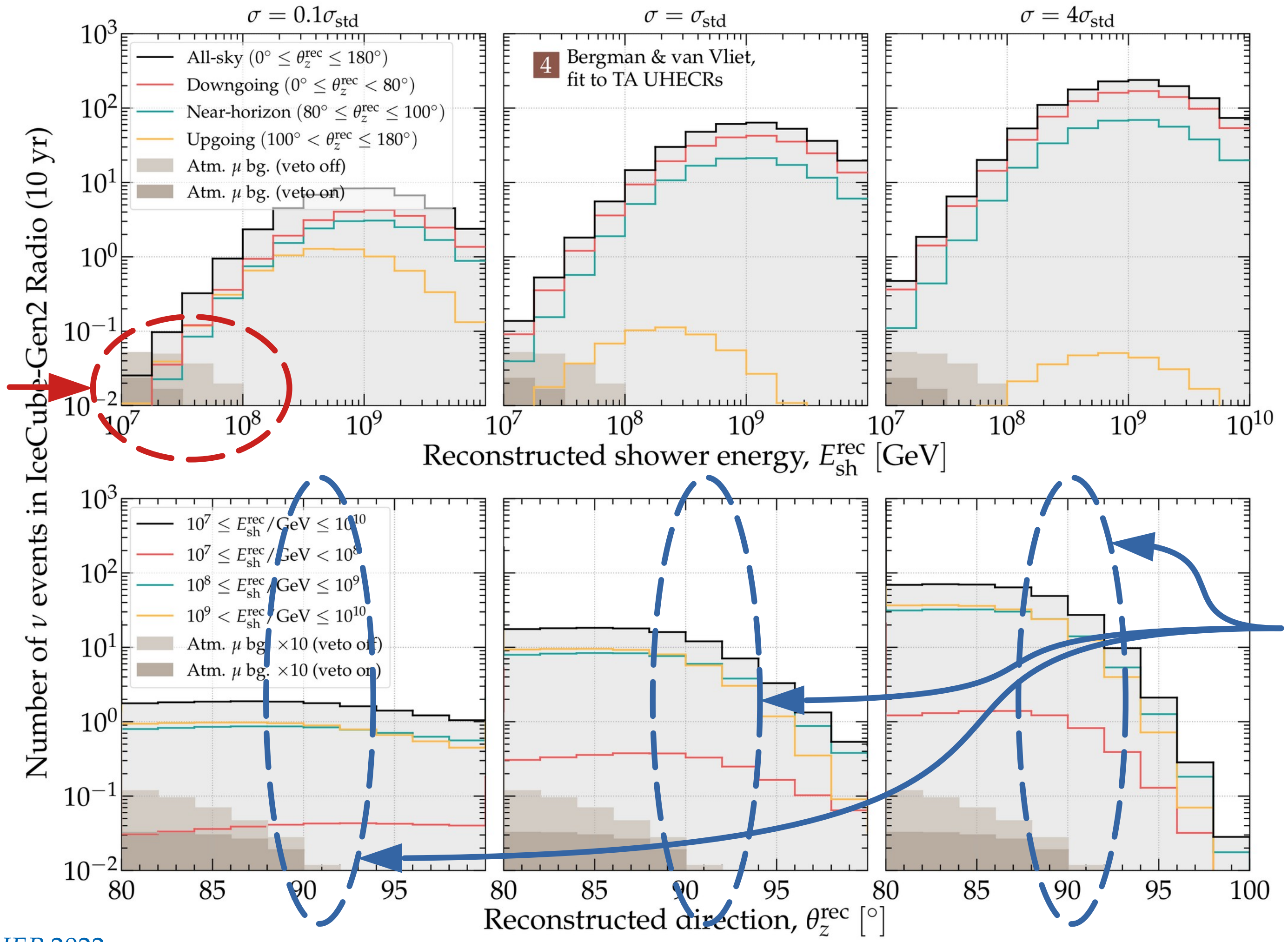
Larger neutrino-nucleon cross section



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

Larger neutrino-nucleon cross section

Atmospheric muon background

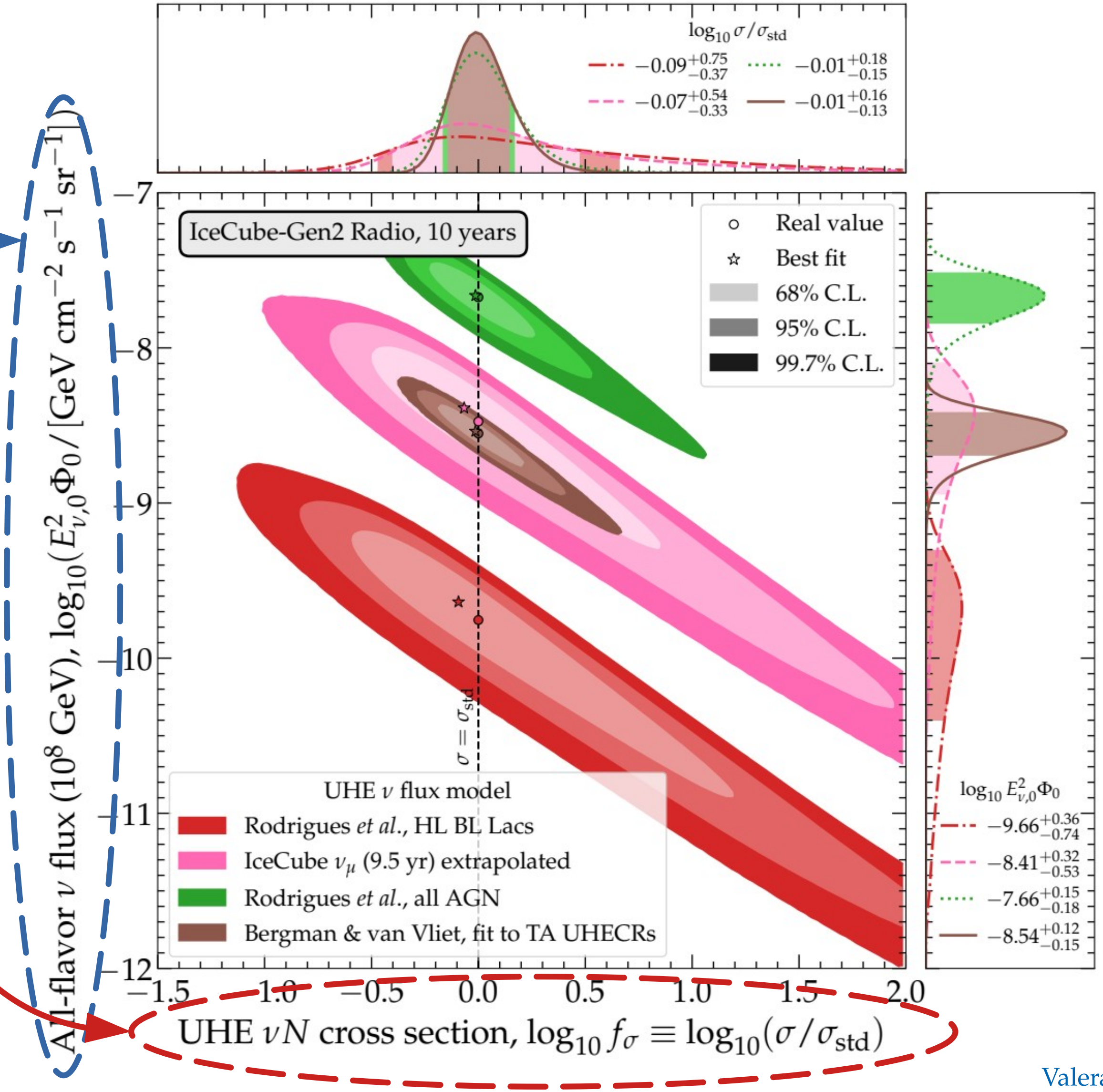


Sensitivity to cross section comes from horizontal neutrinos

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

Flux normalization

Cross section



Needed to measure the cross section?

~30–300 events

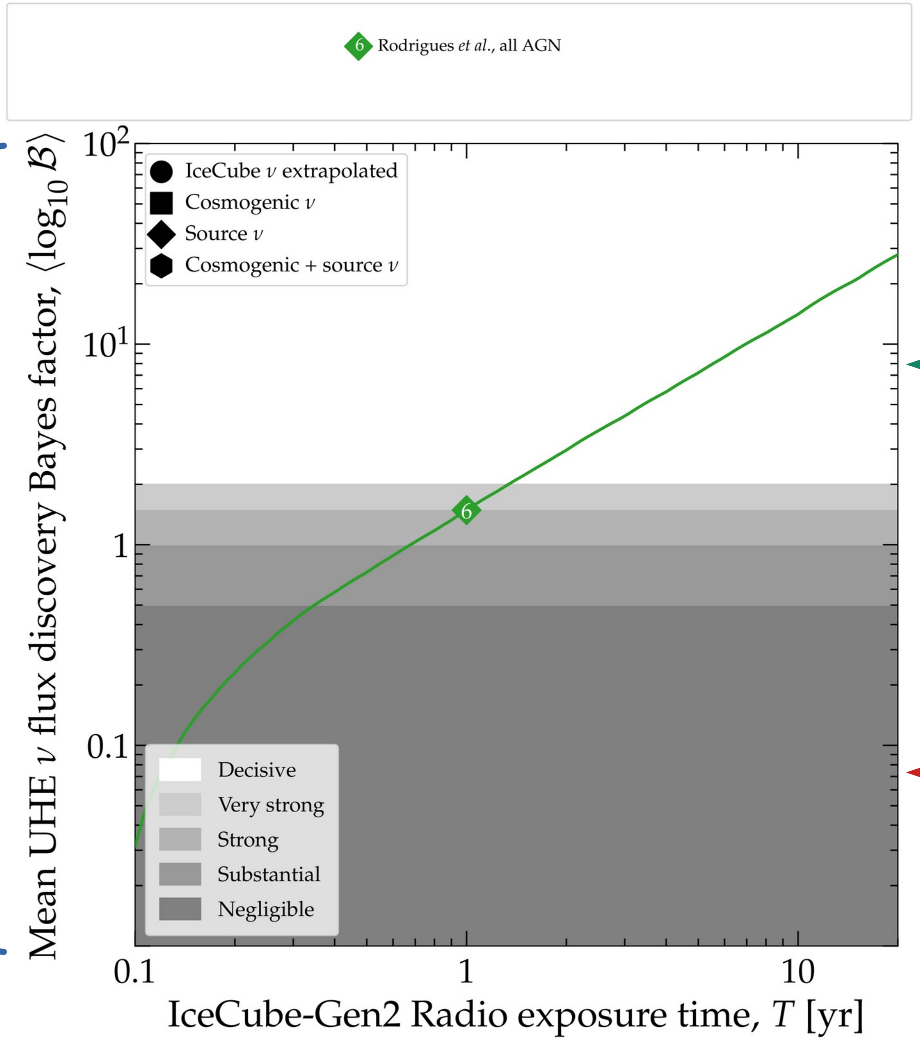
In this work:
We fix the energy dependence of flux and cross section (but explore many alternatives)

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

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

Discovering the diffuse flux of UHE neutrinos

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



High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

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

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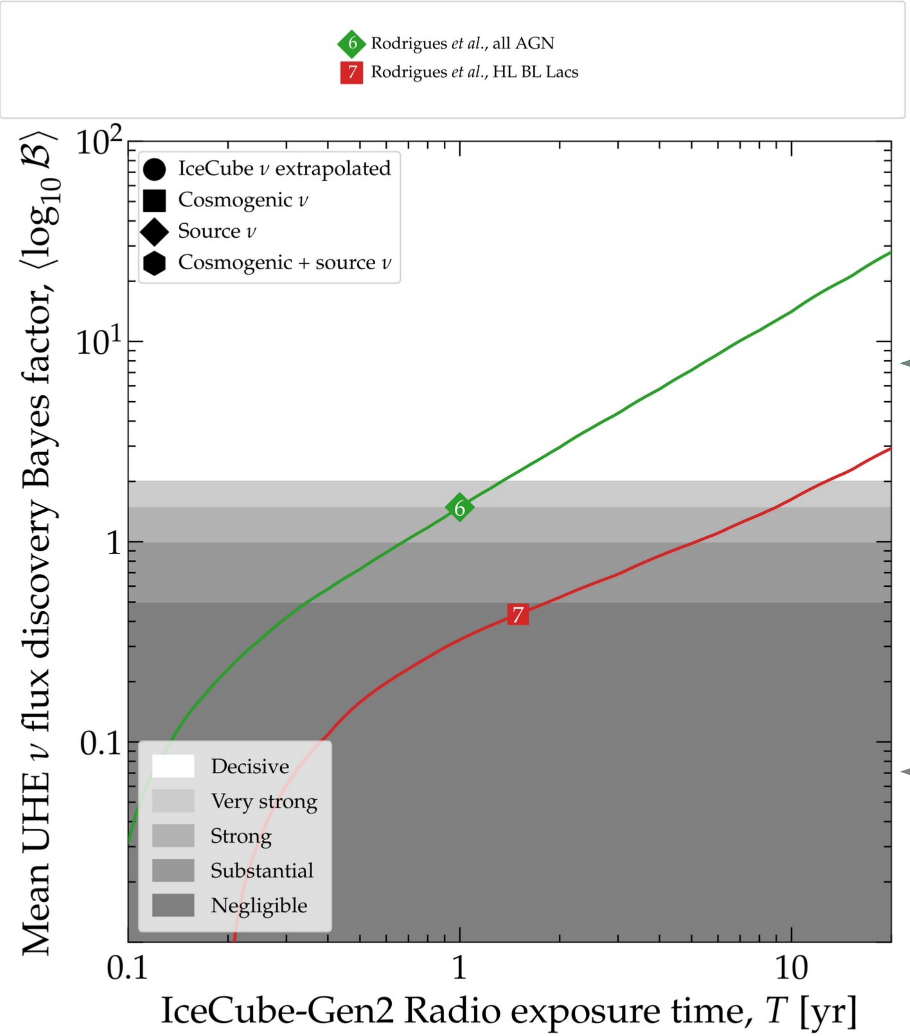

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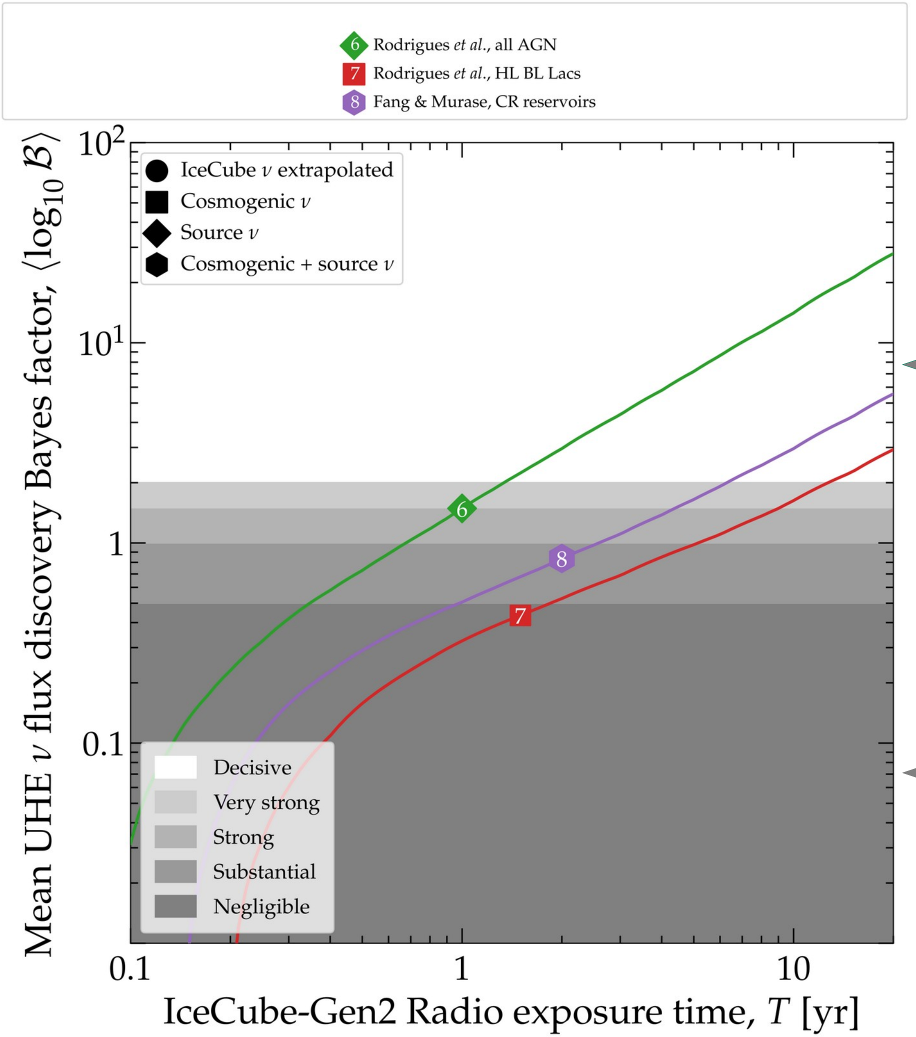

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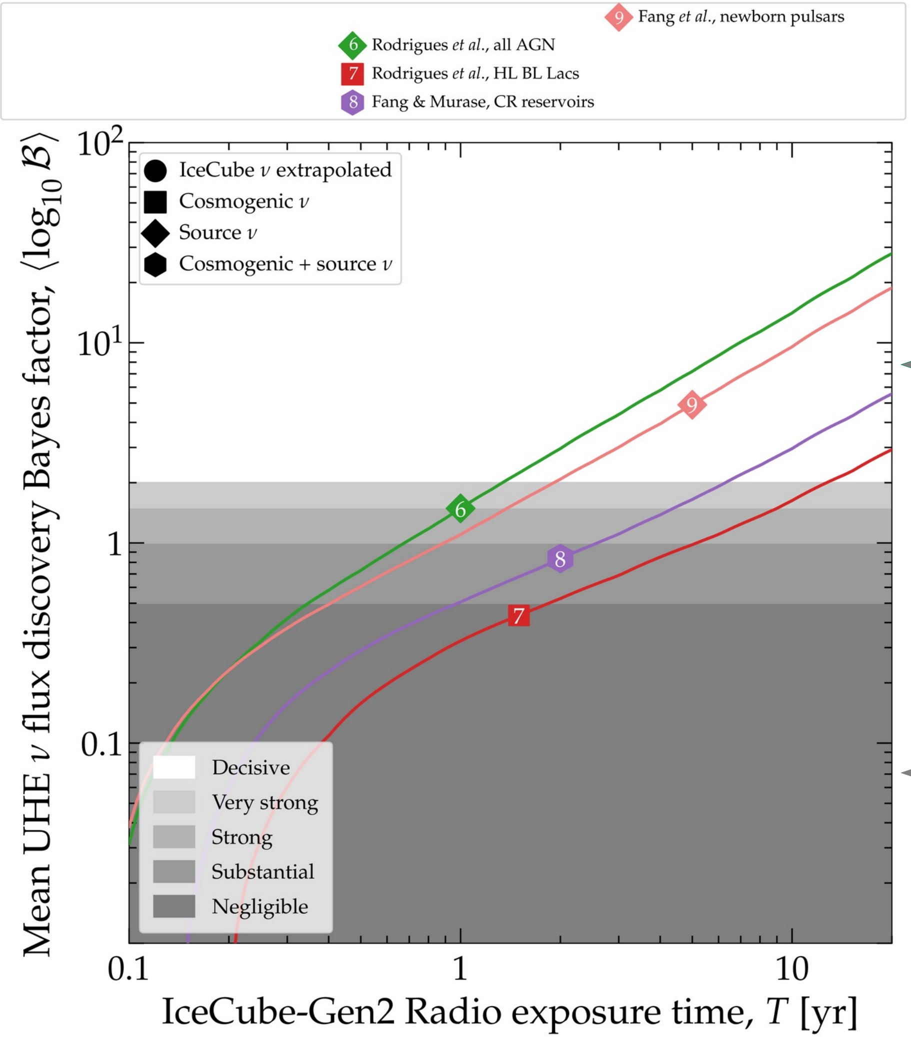

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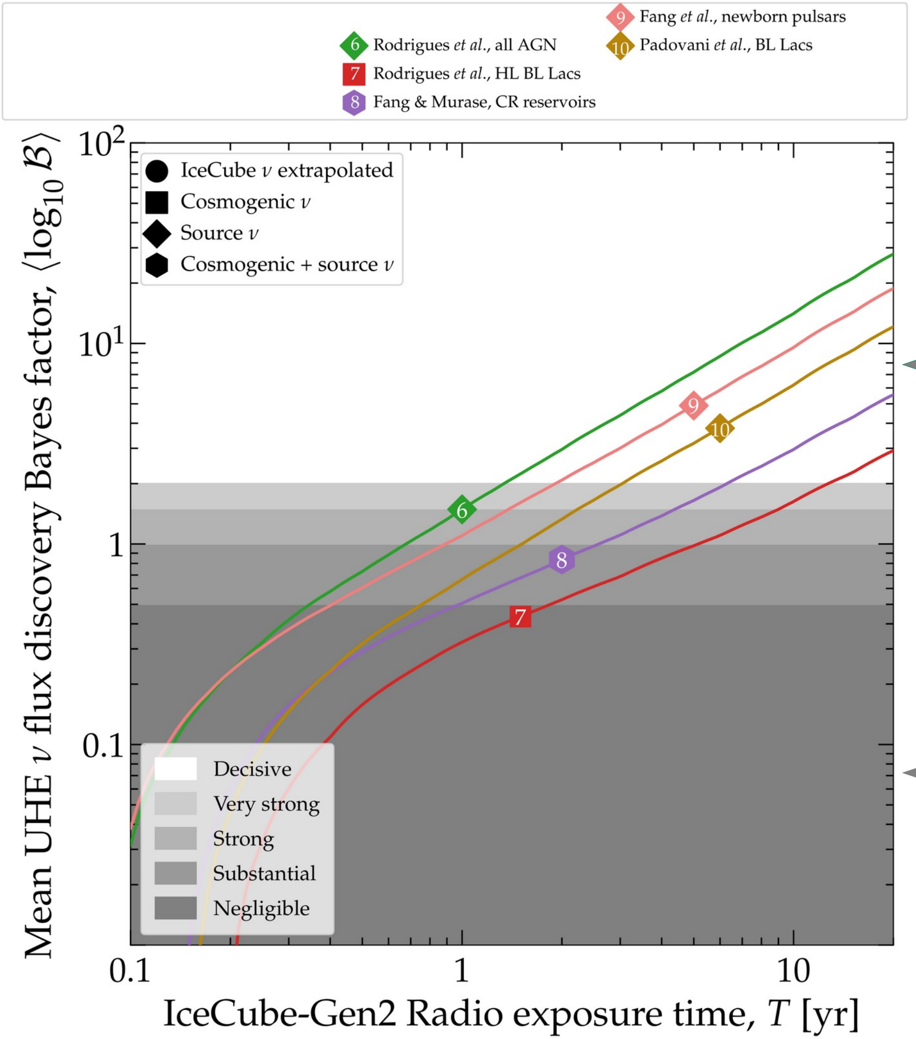

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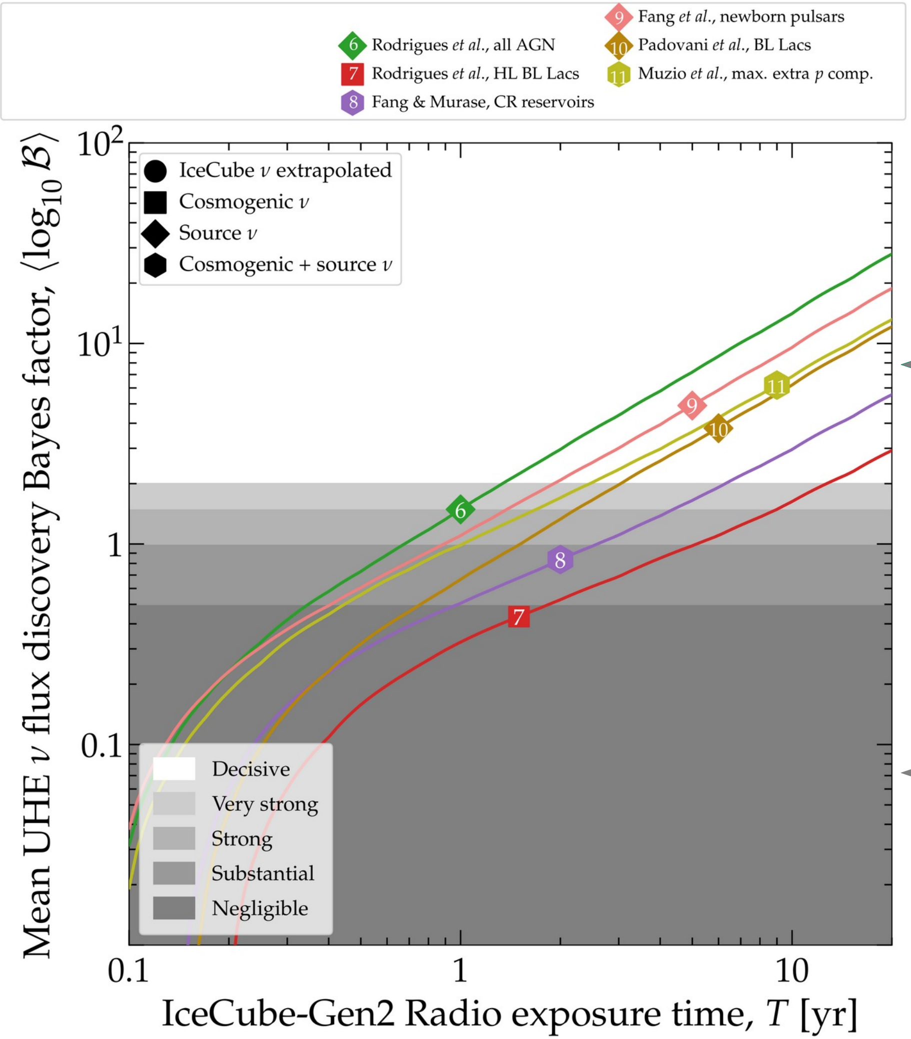

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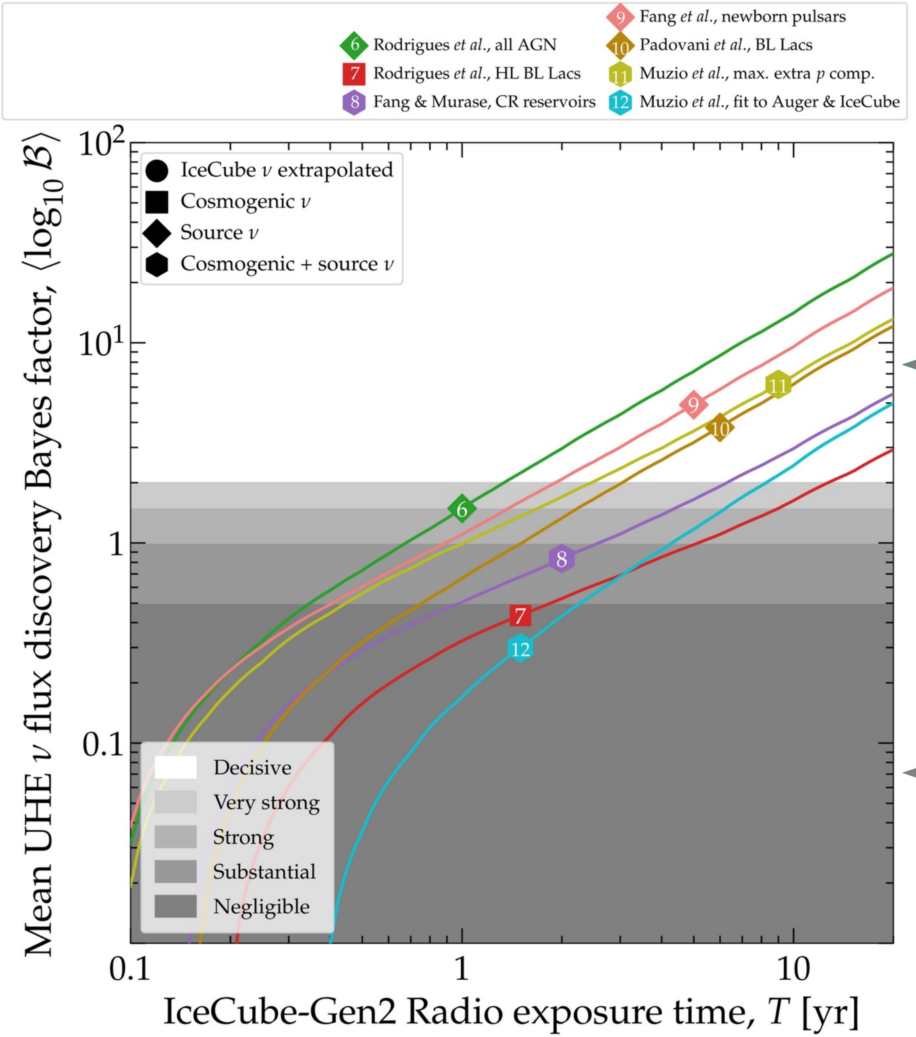

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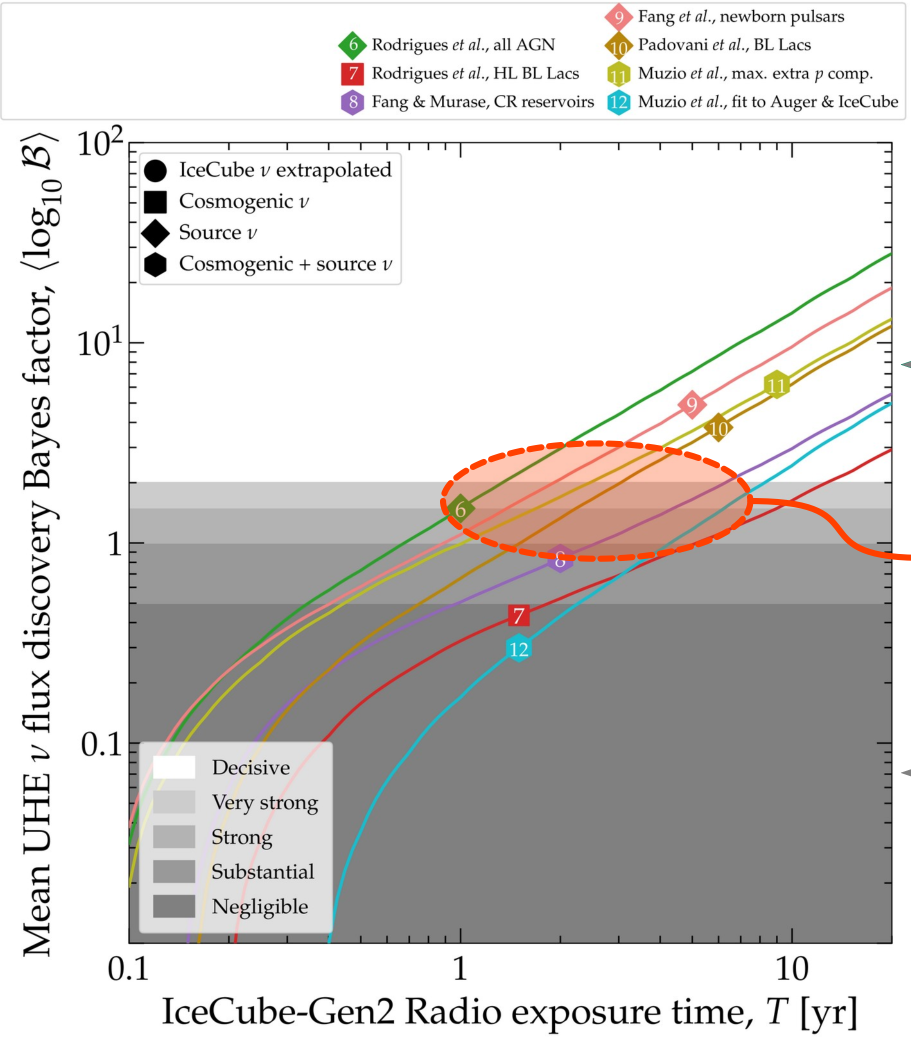

High Bayes factor
→ Decisive flux discovery

Most flux models are discoverable within a few years

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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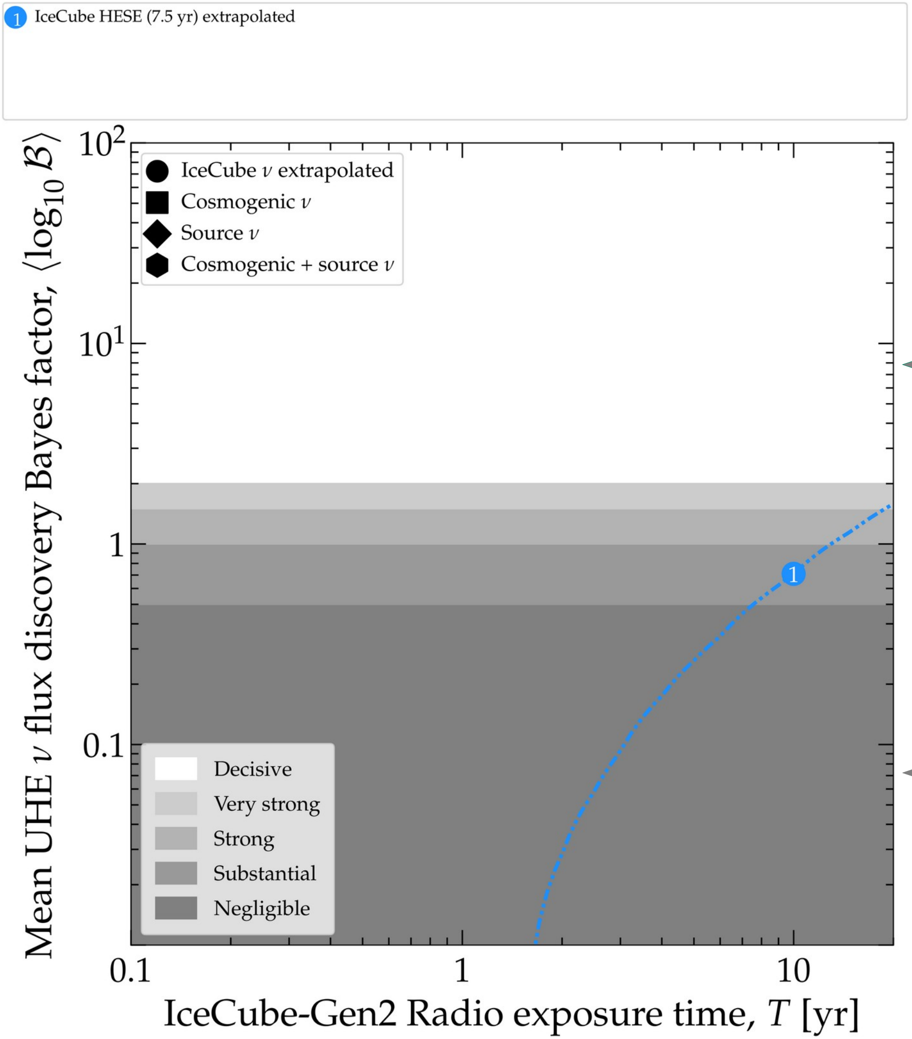

High Bayes factor → Decisive flux discovery

Low Bayes factor → No flux discovered

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

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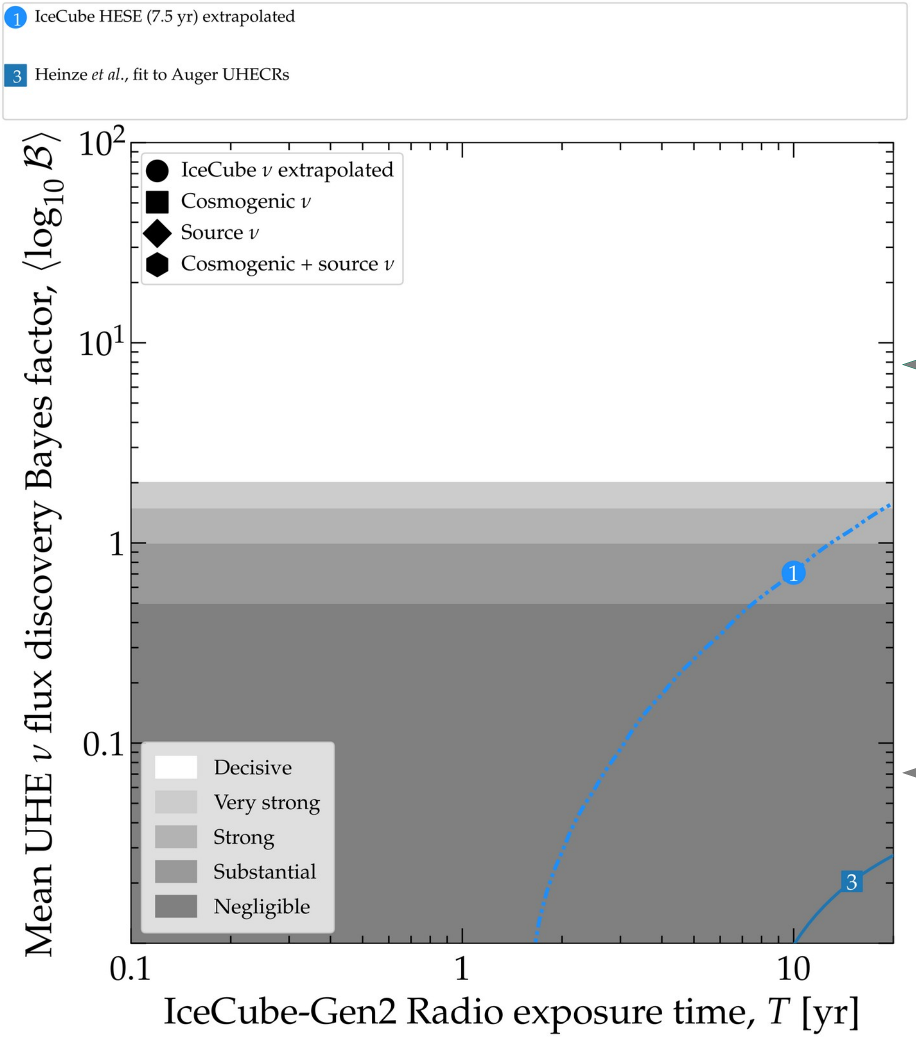

Bayes factor compares signal+bkg. *vs.* bkg.-only

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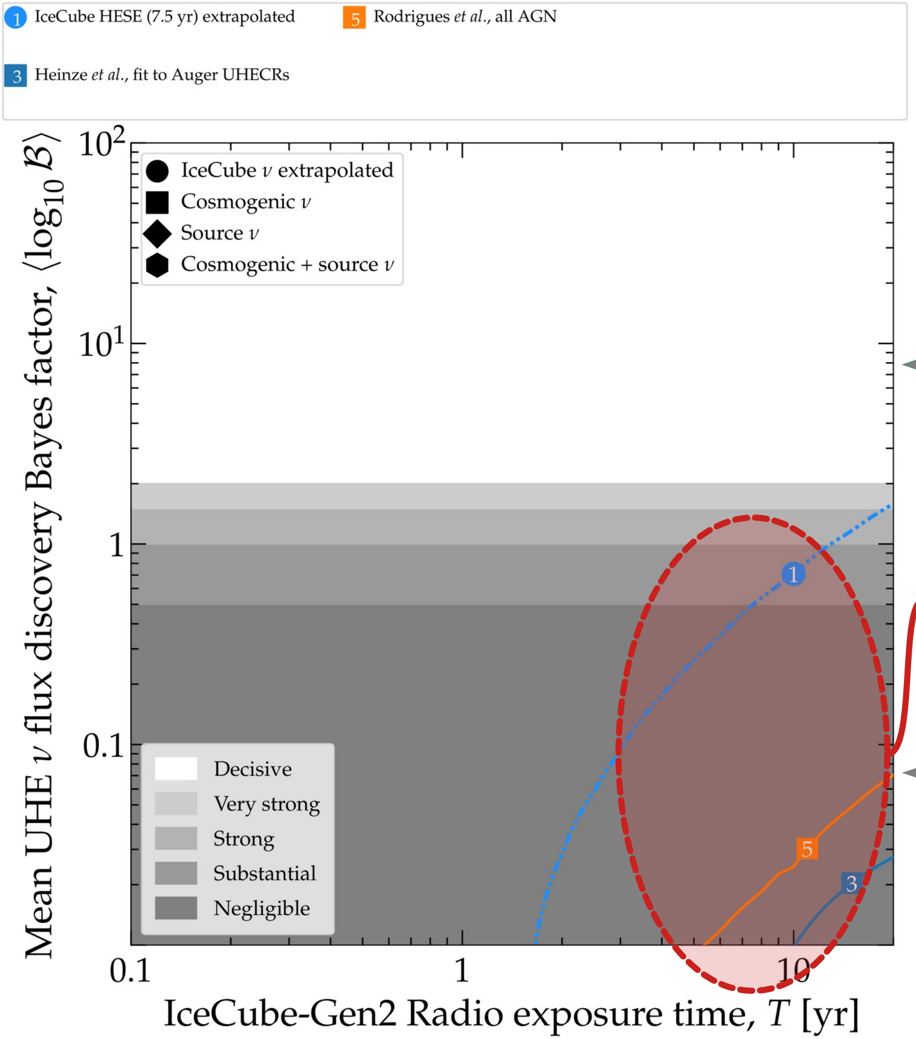


High Bayes factor
→ Decisive flux discovery

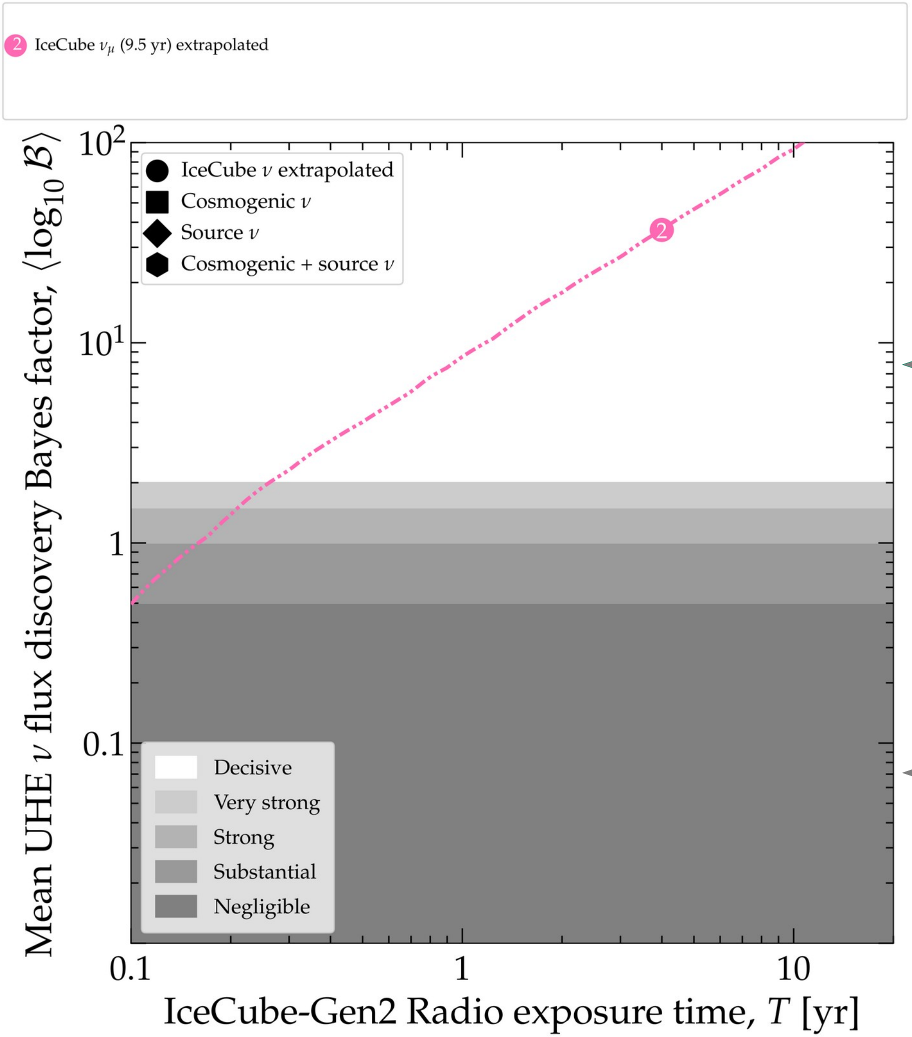
Some models will *not* be discovered

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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



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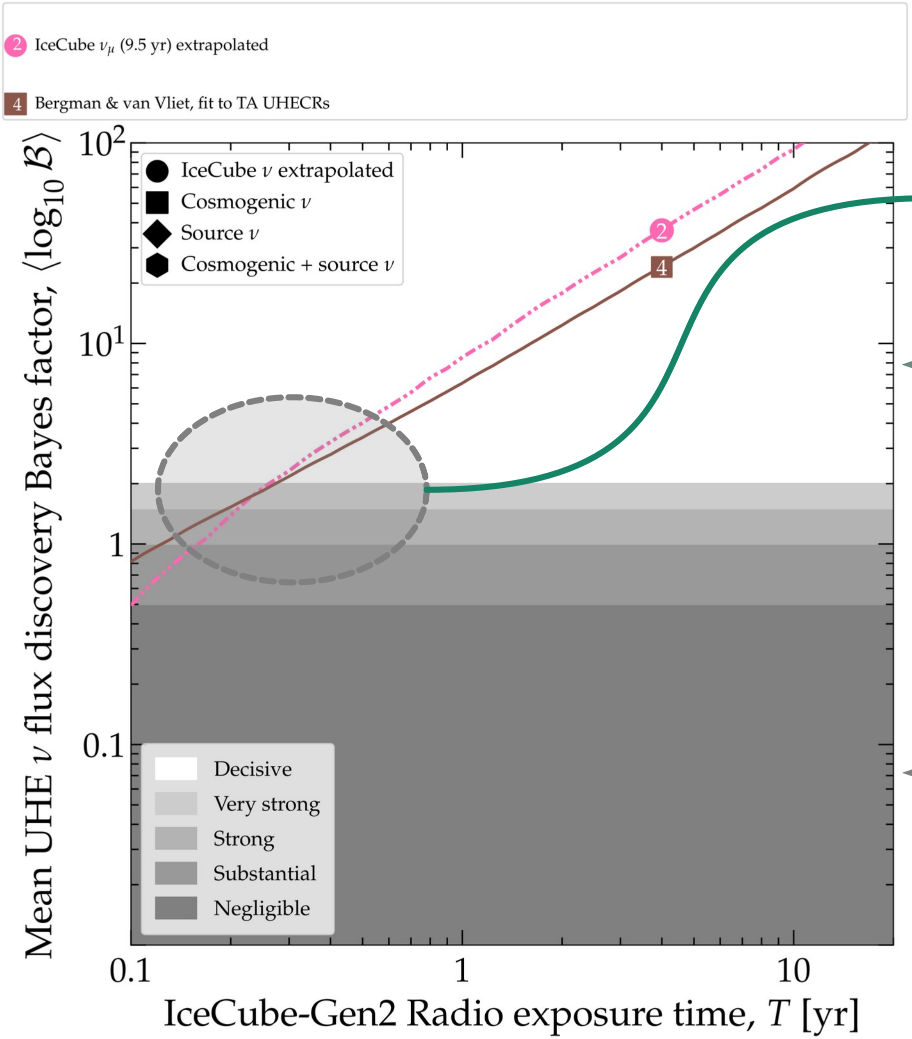

Some models will be discovered right away

High Bayes factor
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Low Bayes factor
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Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

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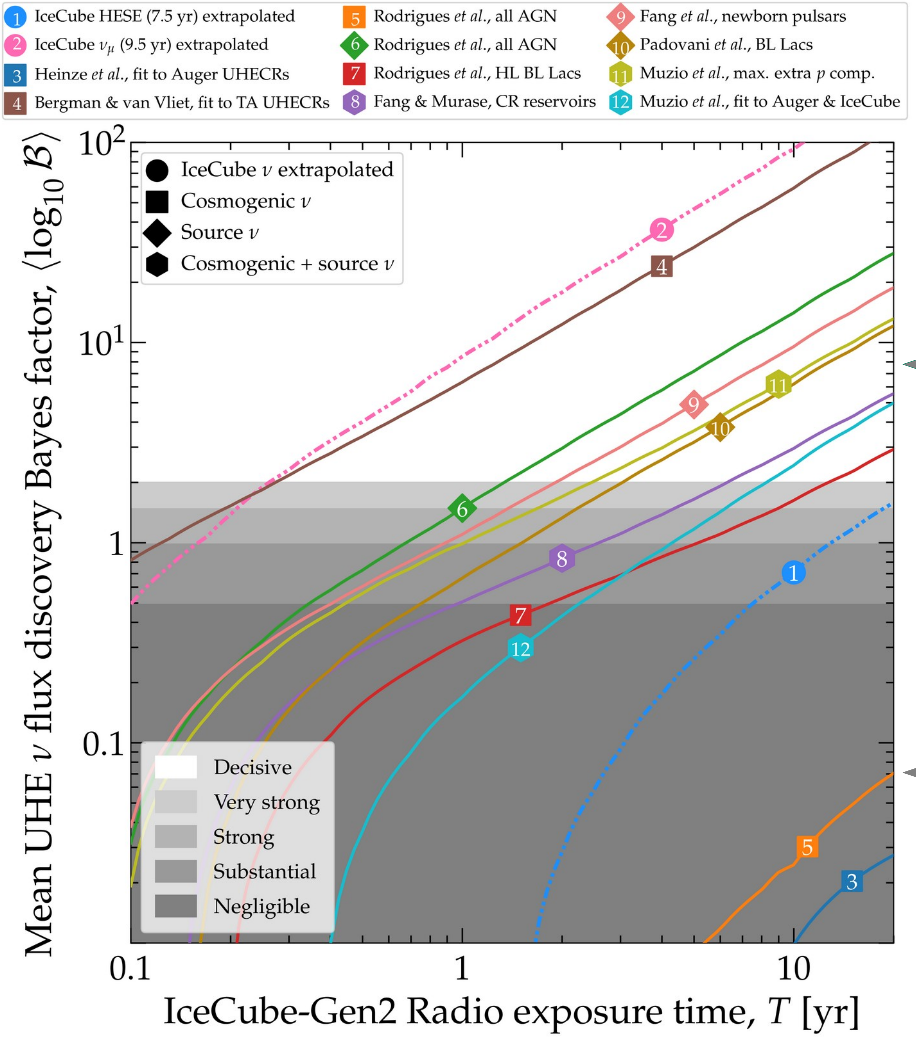

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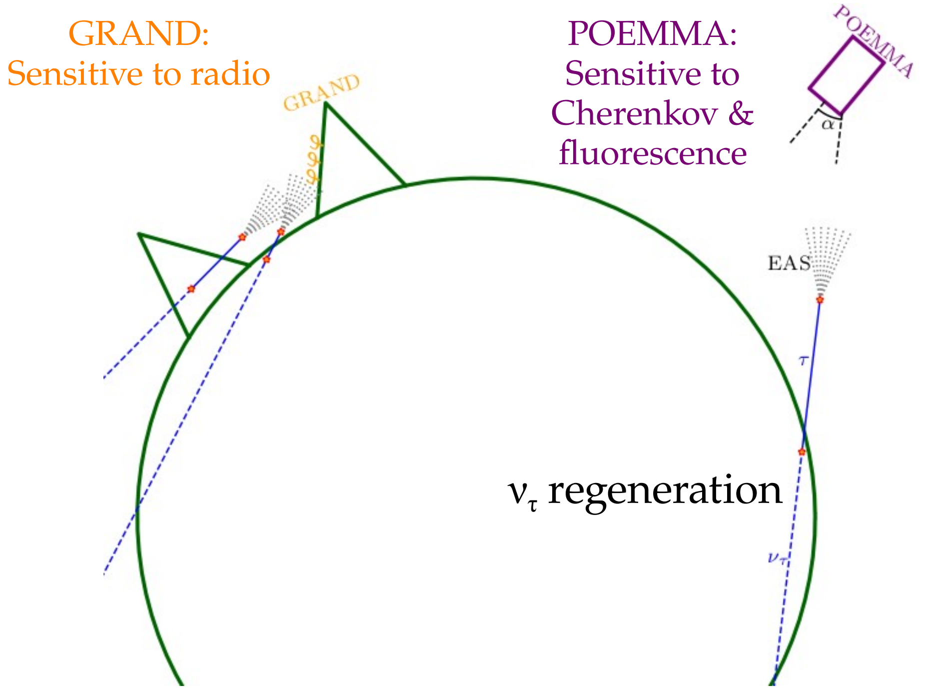
Work led by Víctor Valera

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

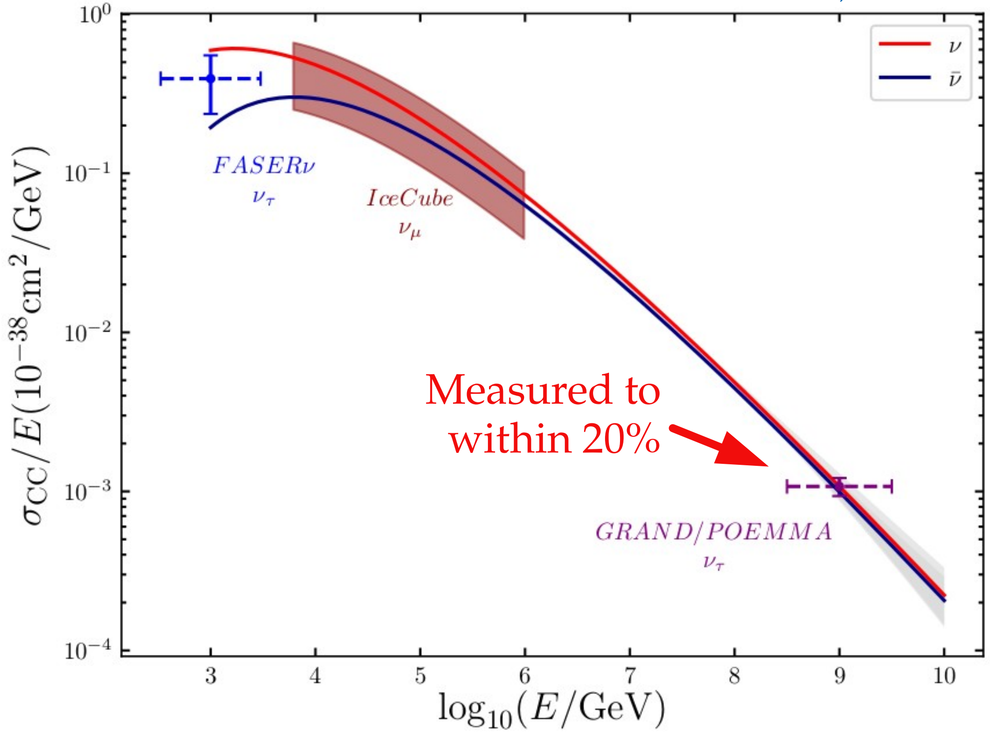
GRAND & POEMMA

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



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 → 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

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

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Downgoing neutrinos

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

Upgoing neutrinos

(L long → lots of matter)

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

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Measuring the high-energy νN cross section

Number of detected neutrinos (simplified for presentation):

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

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

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

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

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

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

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

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

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

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

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 ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\text{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\text{eV})^{-9}$ yr
  - Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$): $\tau > 10^{55}\,(m_i/\text{eV})^{-5}$ yr

  » Age of Universe (~ 14.5 Gyr)

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

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

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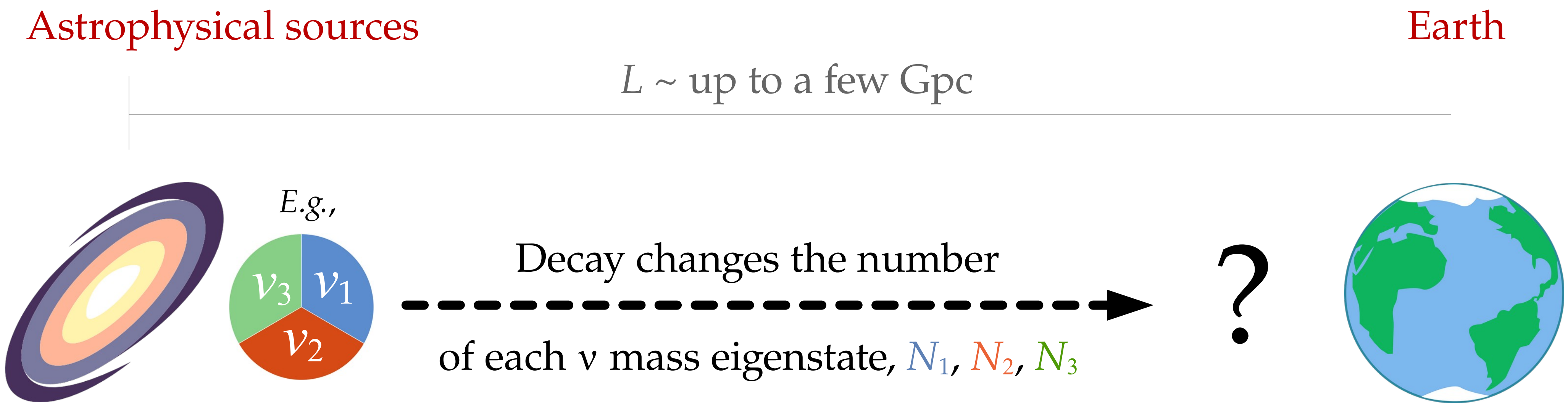
  Nambu-Goldstone boson of a broken symmetry

- We work in a model-independent way:

  the nature of φ is unimportant if it is invisible to neutrino detectors



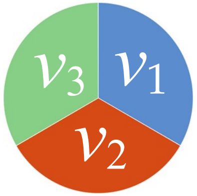
The flux of ν_i is attenuated by $\exp[-\ (L/E)\cdot(\underbrace{m_i}_{\text{Mass of } \nu_i}/\underbrace{\tau_i}_{\text{Lifetime of } \nu_i})]$

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

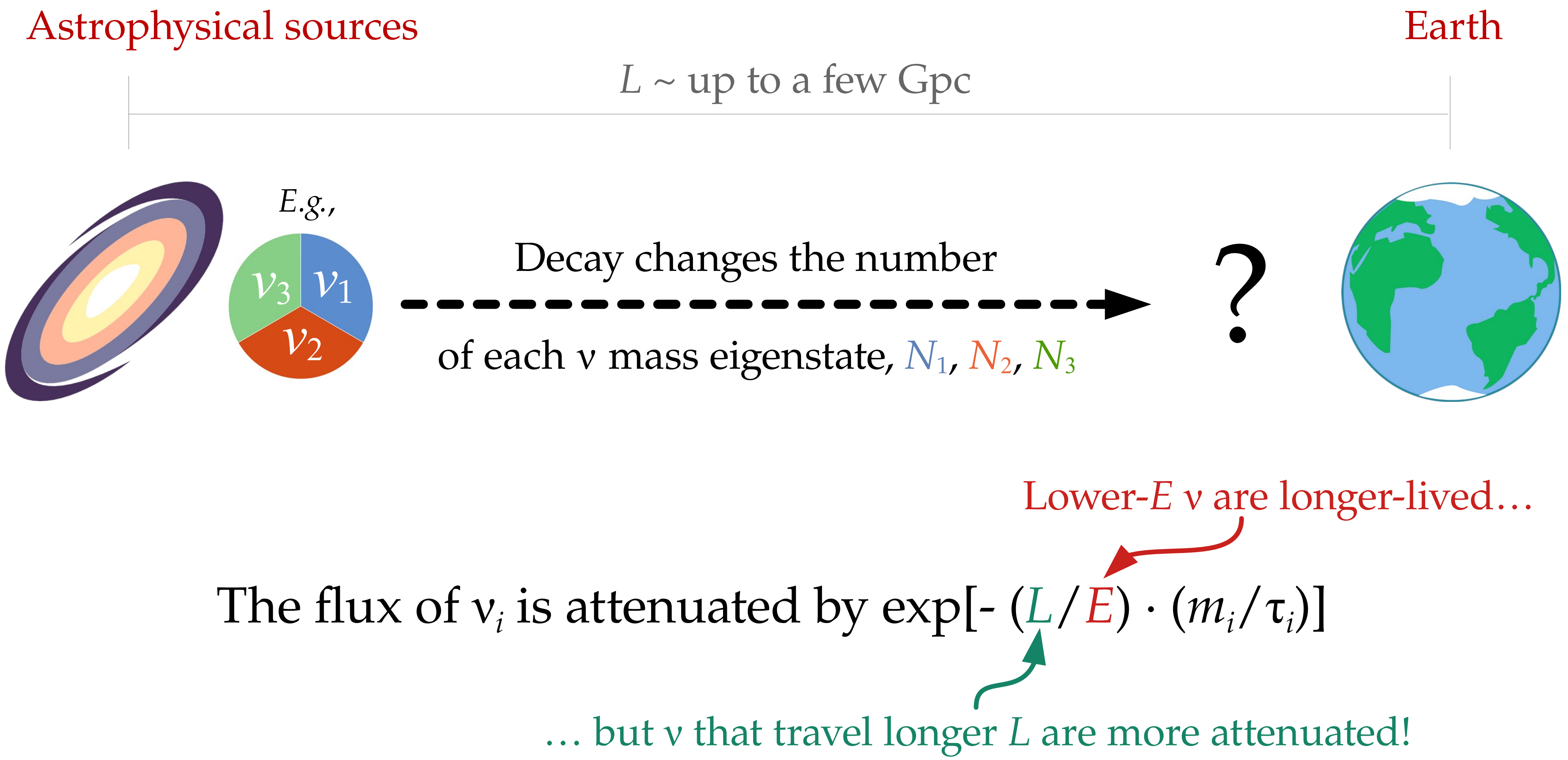


Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot\overbrace{(\underbrace{m_i}_{\text{Mass of }\nu_i}/\underbrace{\tau_i}_{\text{Lifetime of }\nu_i})}^{\text{Only sensitive to their ratio}}]$

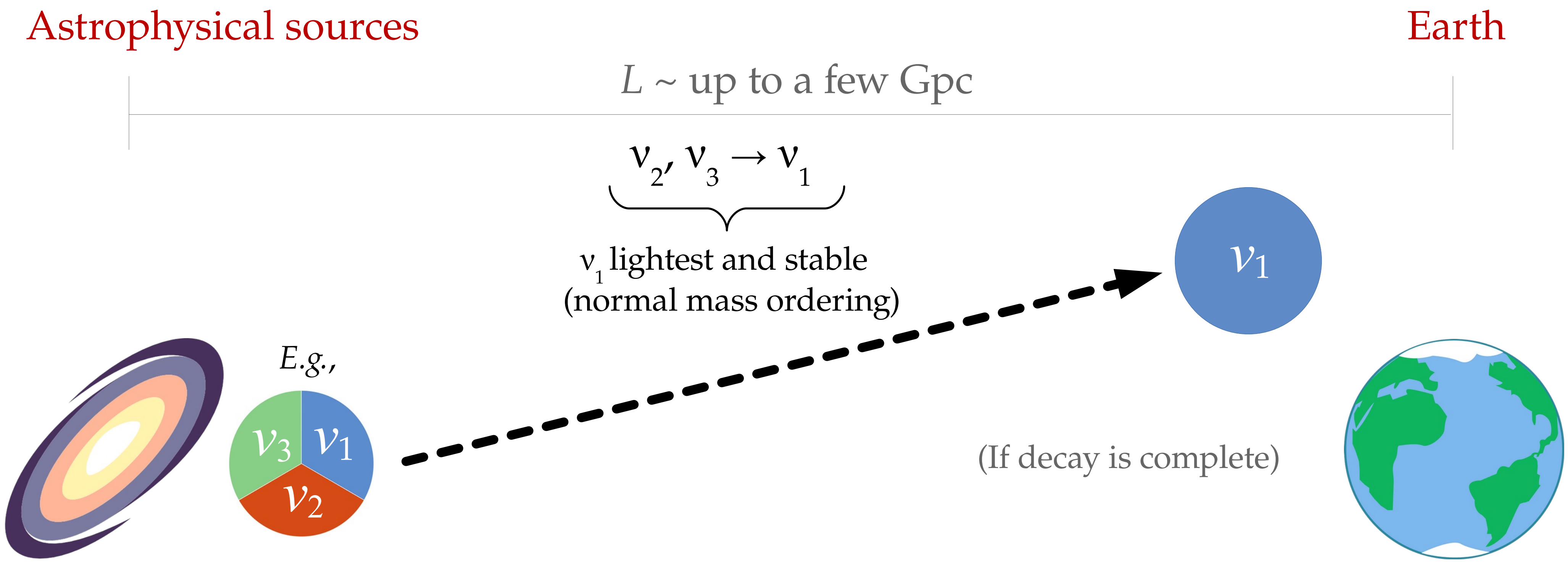

Astrophysical sources
Earth
L ~ up to a few Gpc
E.g.,
ν_3 ν_1 ν_2
Decay changes the number
of each ν mass eigenstate, N_1, N_2, N_3
?
Lower-E ν are longer-lived…
The flux of ν_i is attenuated by $\exp[-\,(L/E)\cdot(m_i/\tau_i)]$
… but ν that travel longer L are more attenuated!

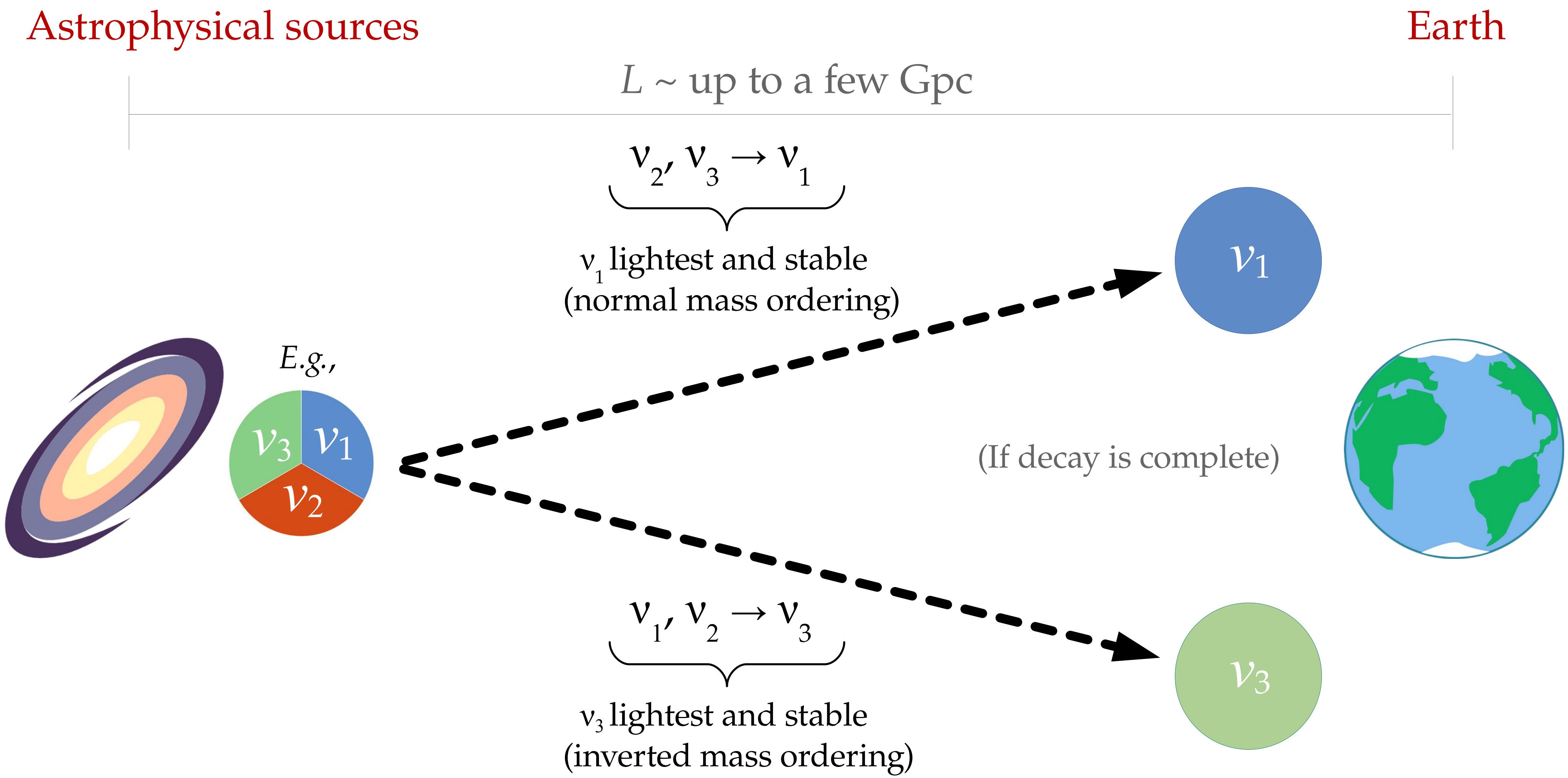
Astrophysical sources

Earth

$L \sim$ up to a few Gpc

E.g.,


Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \rightarrow \nu_1$
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3
ν_1
ν_2
ν_1
(If decay is complete)



Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \to \nu_1$
ν_1 lightest and stable
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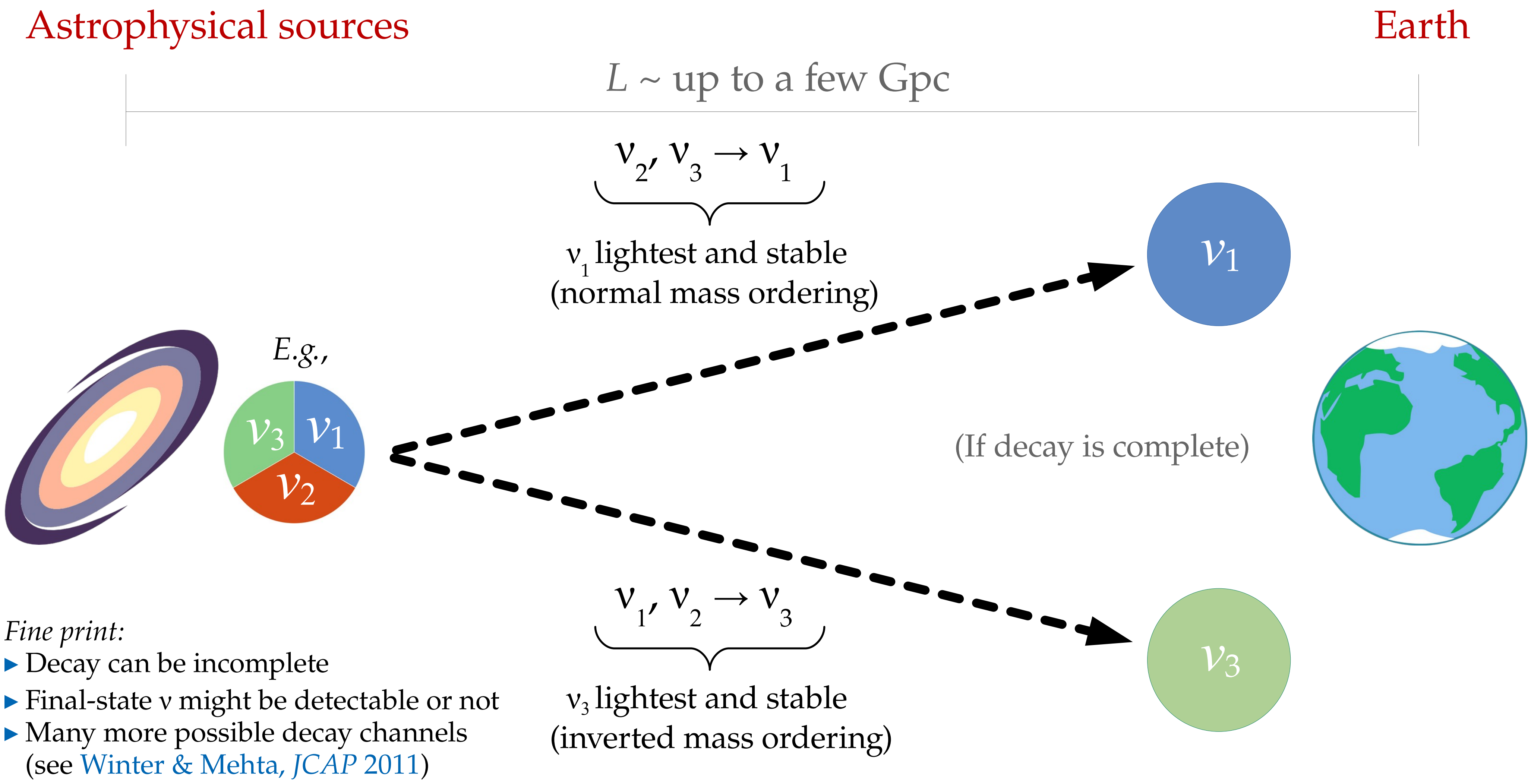
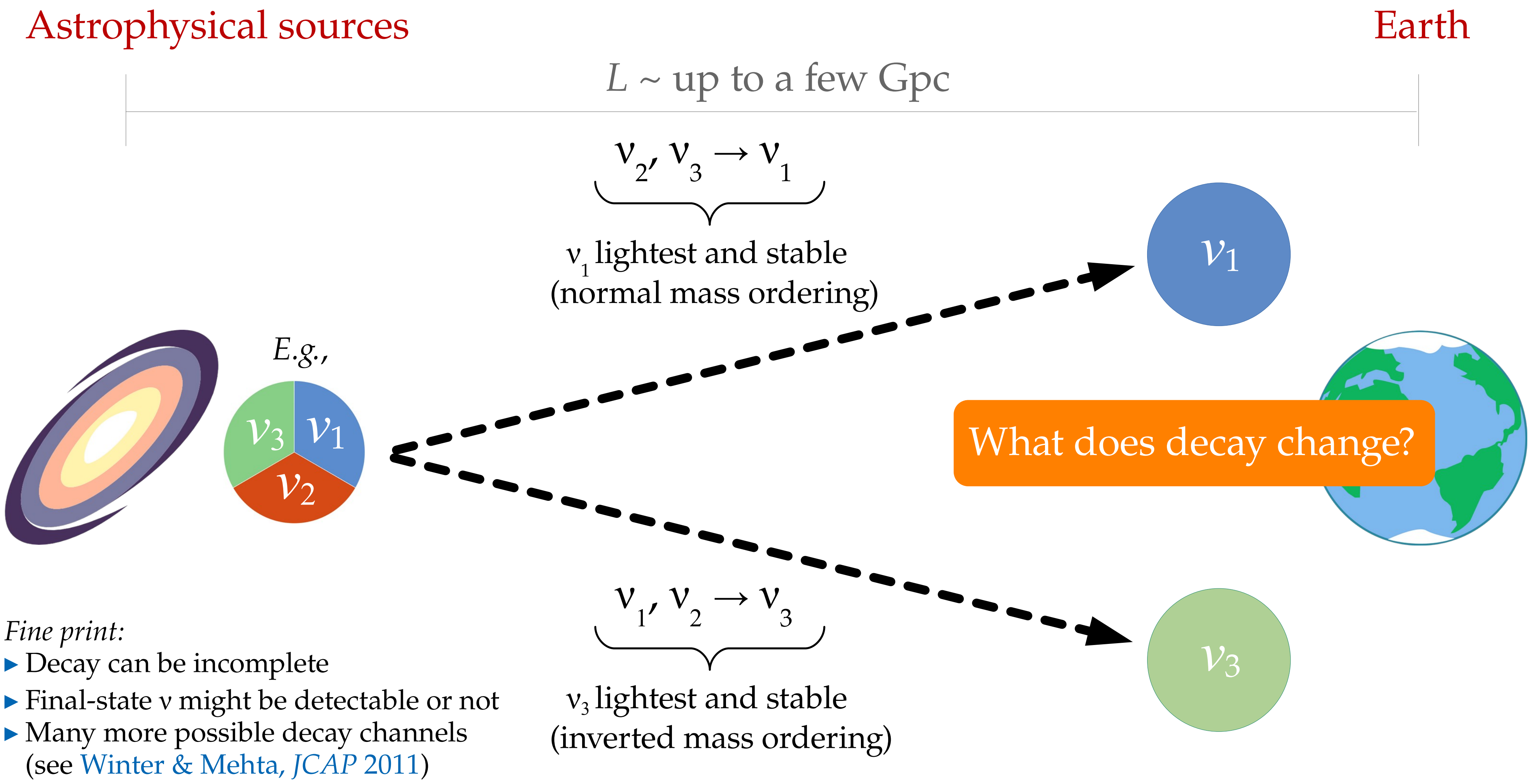
E.g.,
ν_1
ν_2
ν_3
(If decay is complete)
$\nu_1, \nu_2 \to \nu_3$
ν_3 lightest and stable
(inverted mass ordering)



Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)
ν1, ν2 → ν3
ν3 lightest and stable
(inverted mass ordering)
ν3
Fine print:
Decay can be incomplete
Final-state ν might be detectable or not
Many more possible decay channels
(see Winter & Mehta, JCAP 2011)


Astrophysical sources
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$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$
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ν_1
E.g.,
ν_3 ν_1
ν_2
What does decay change?
$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}$
ν_3 lightest and stable
(inverted mass ordering)
ν_3
Fine print:
▸ Decay can be incomplete
▸ Final-state ν might be detectable or not
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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

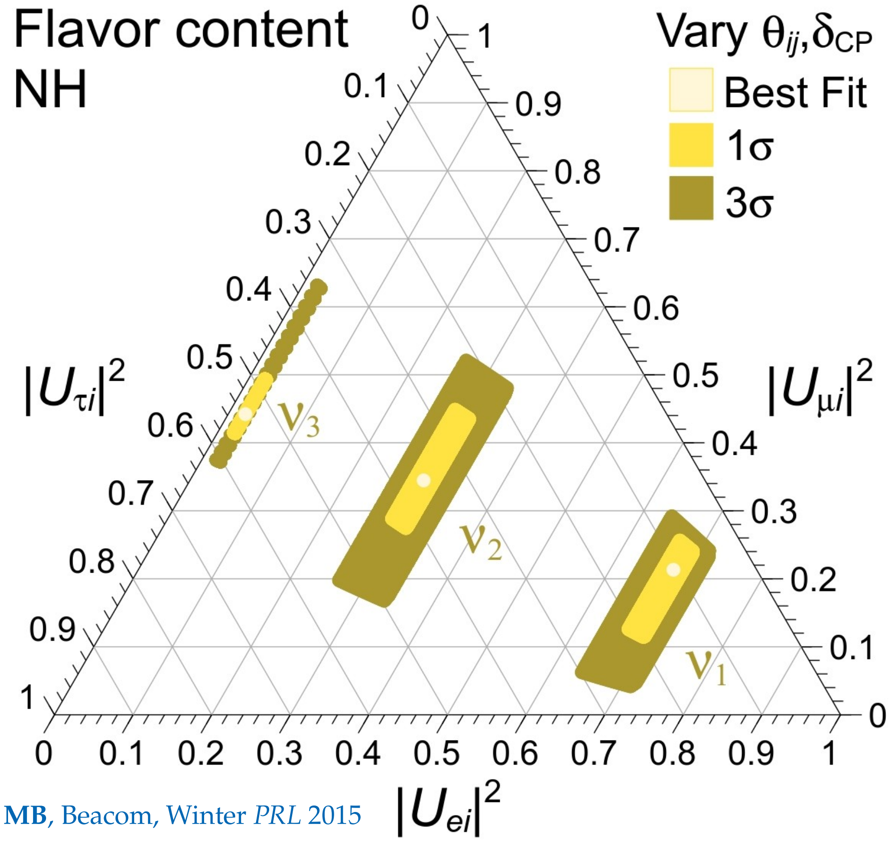
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

Known to within 20% (or worse)



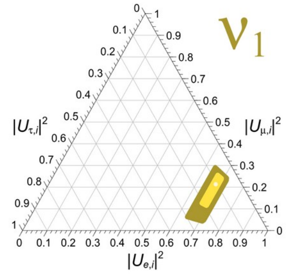
MB, Beacom, Winter *PRL* 2015

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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

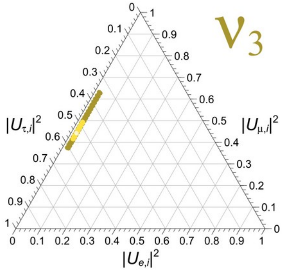
ν_1 lightest and stable
(normal mass ordering)



E.g.,

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

ν_3 lightest and stable
(inverted mass ordering)



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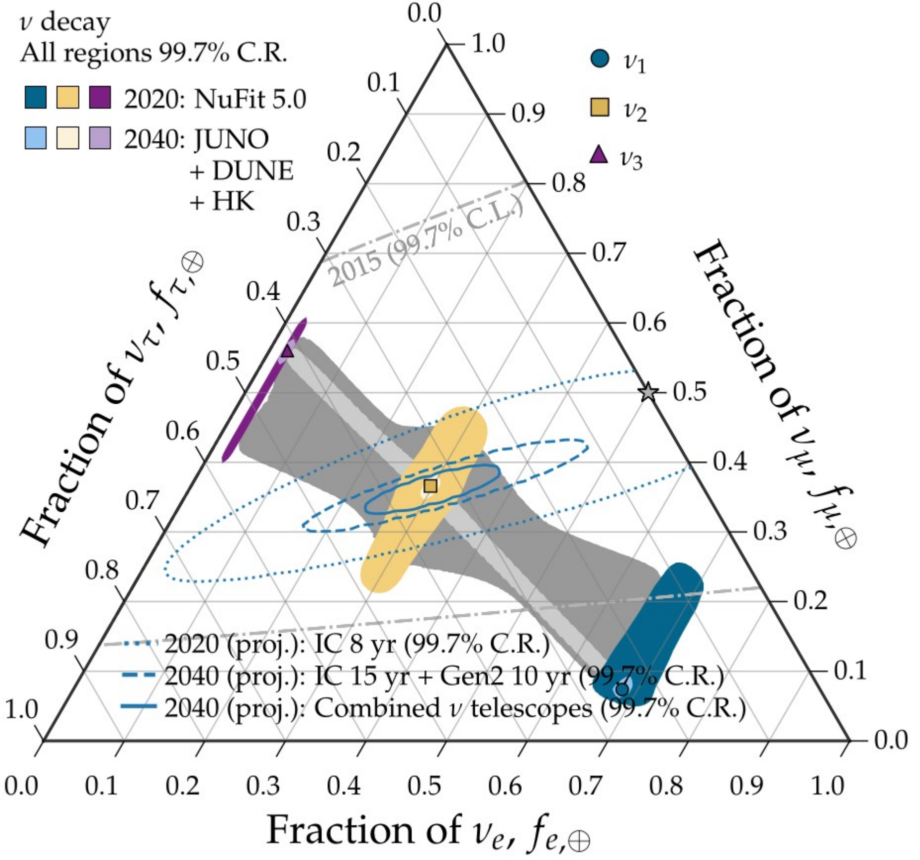
Flavor composition ⇔ Spectrum shape ⇔ Event rate



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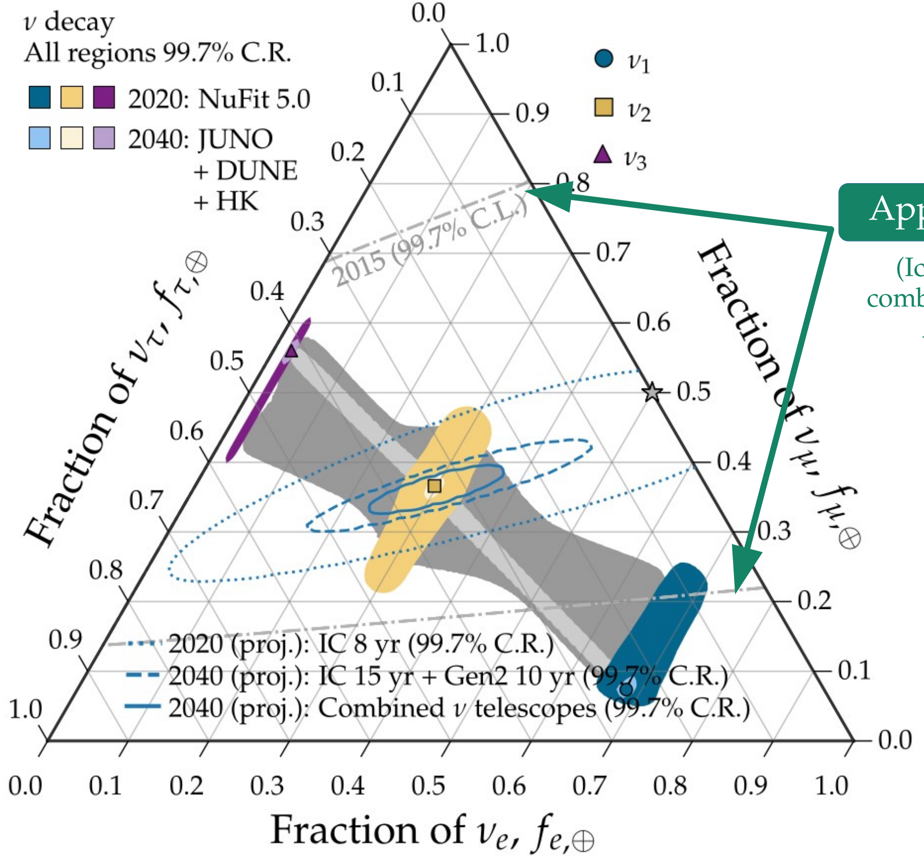
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

(IceCube 2015 combined analysis, *ApJ* 2015)

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

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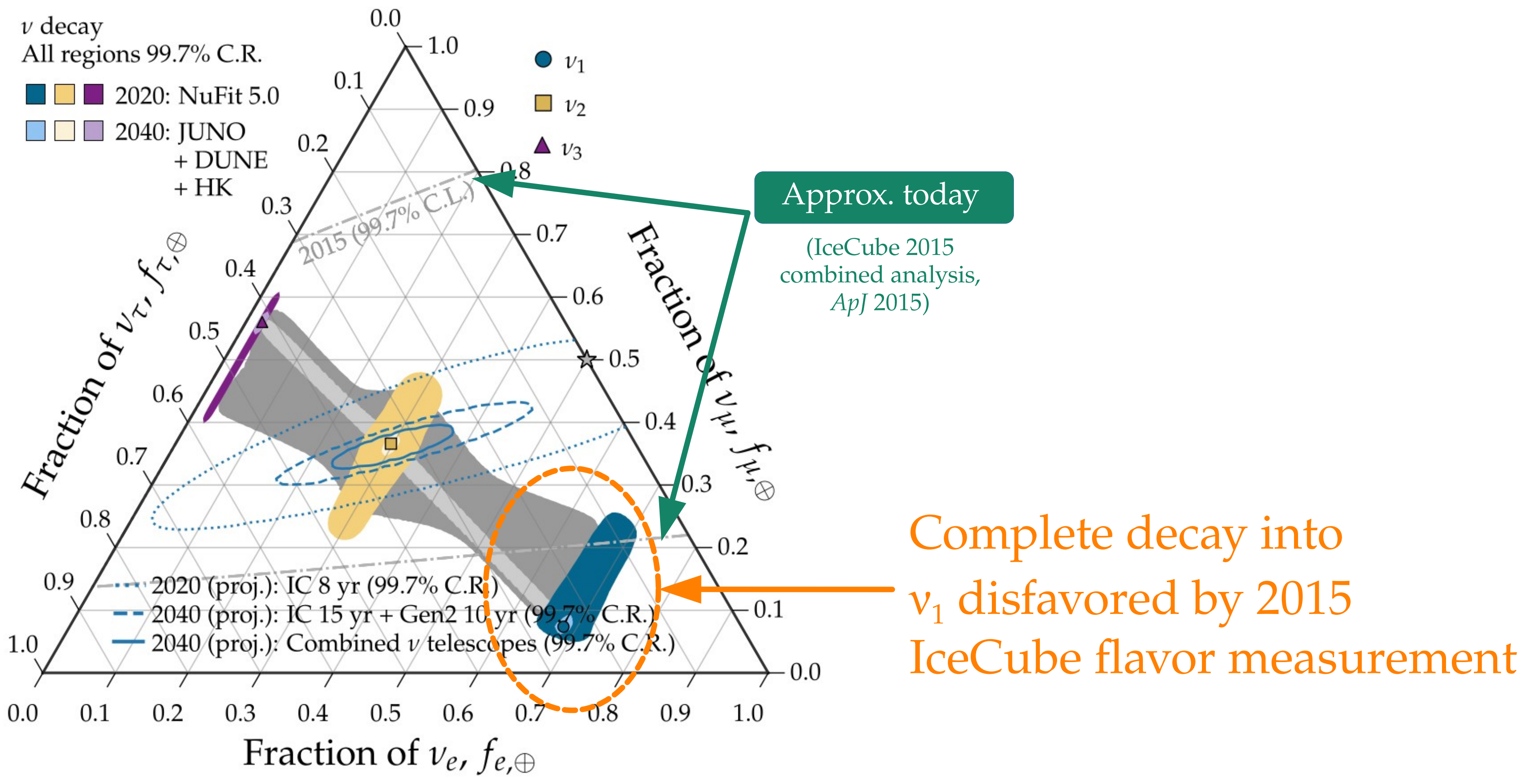

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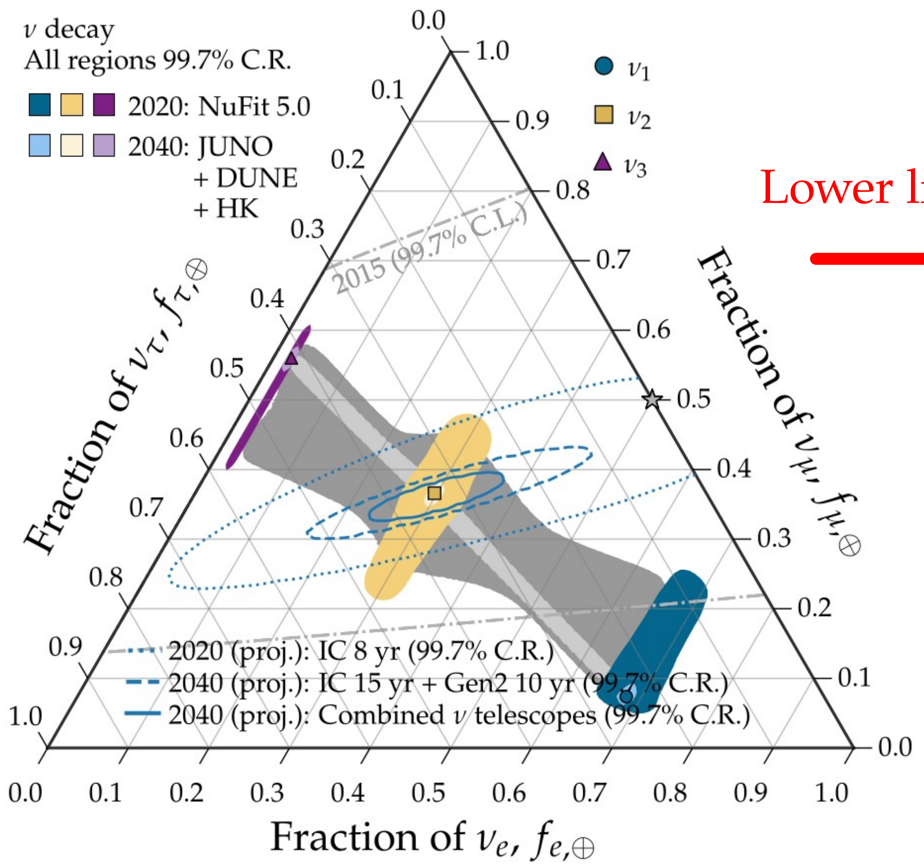

Lower limit on τ/m →

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

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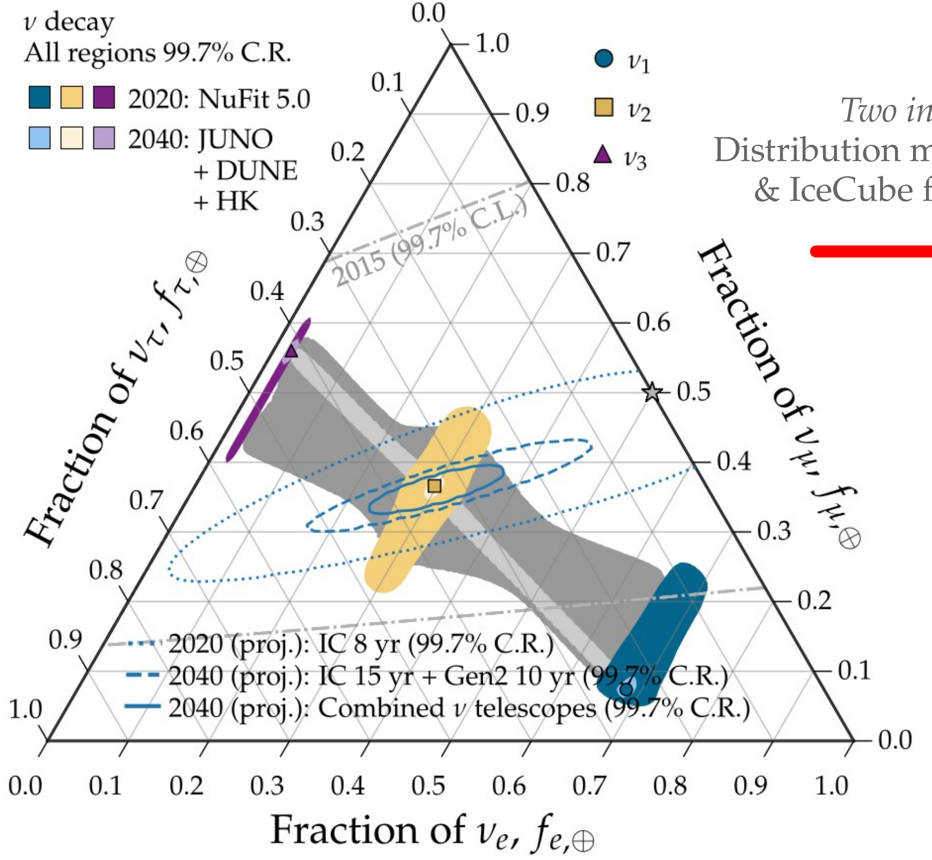

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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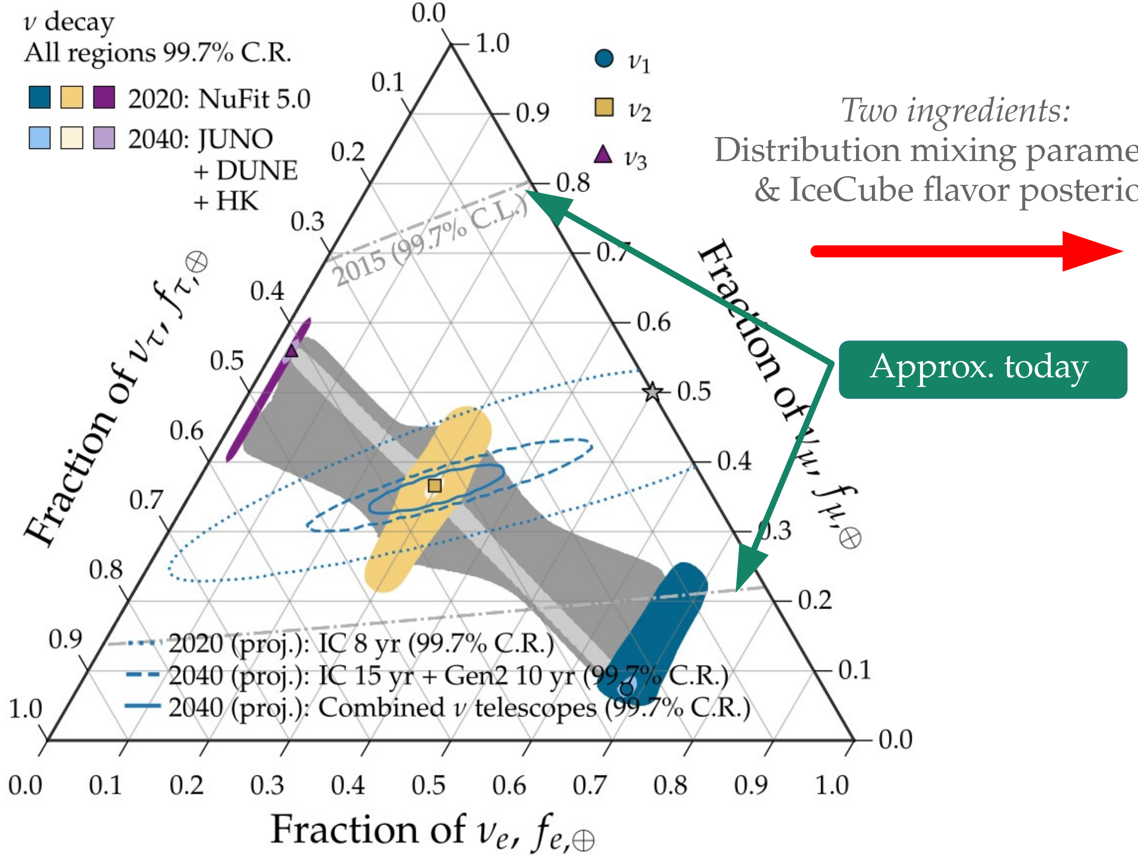

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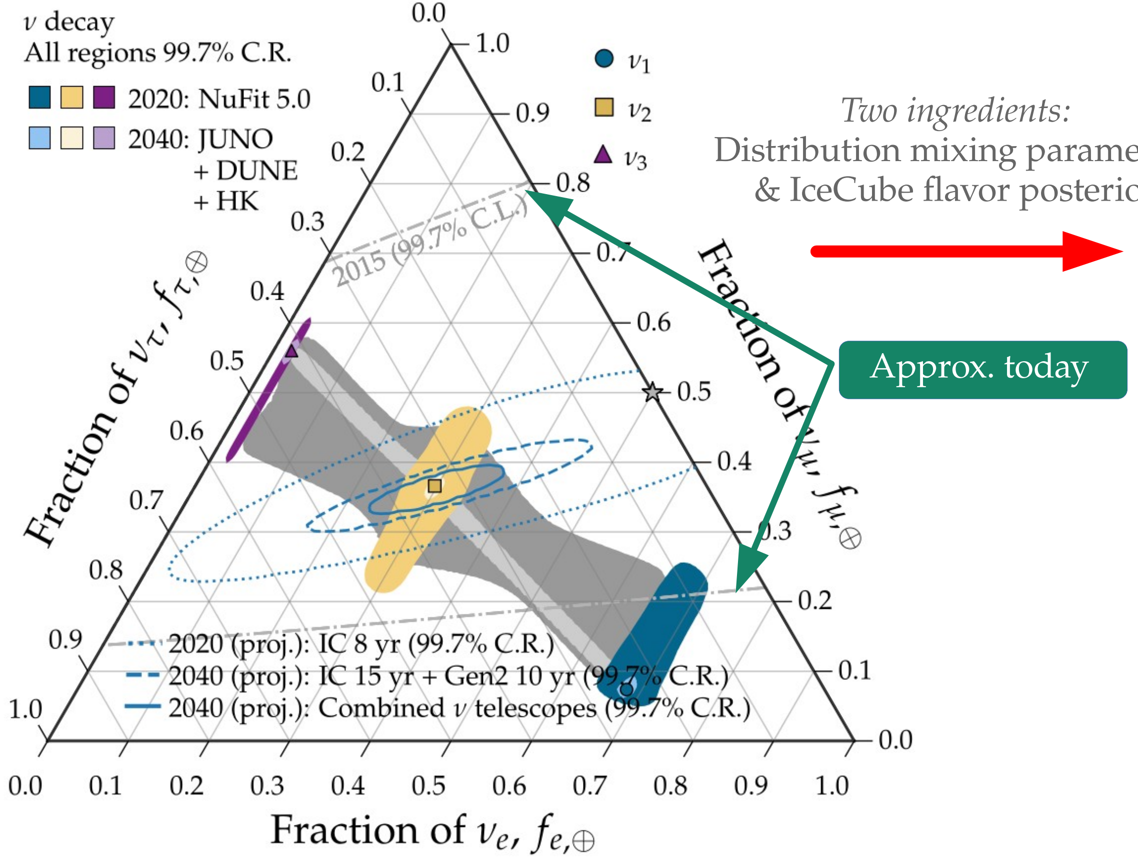

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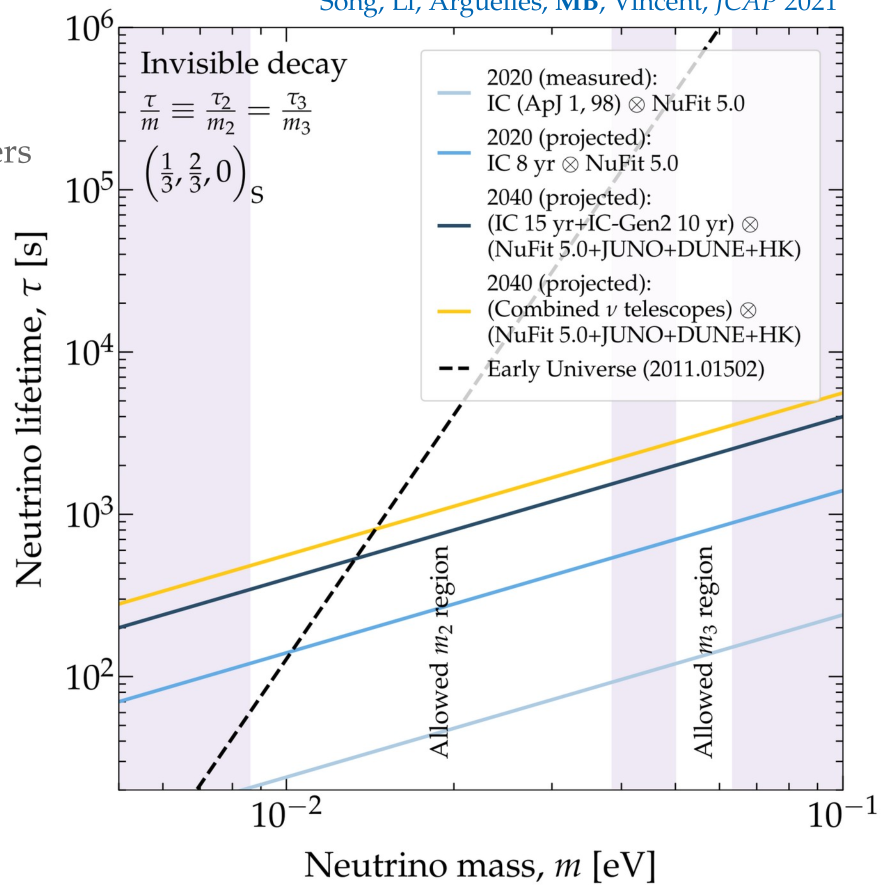
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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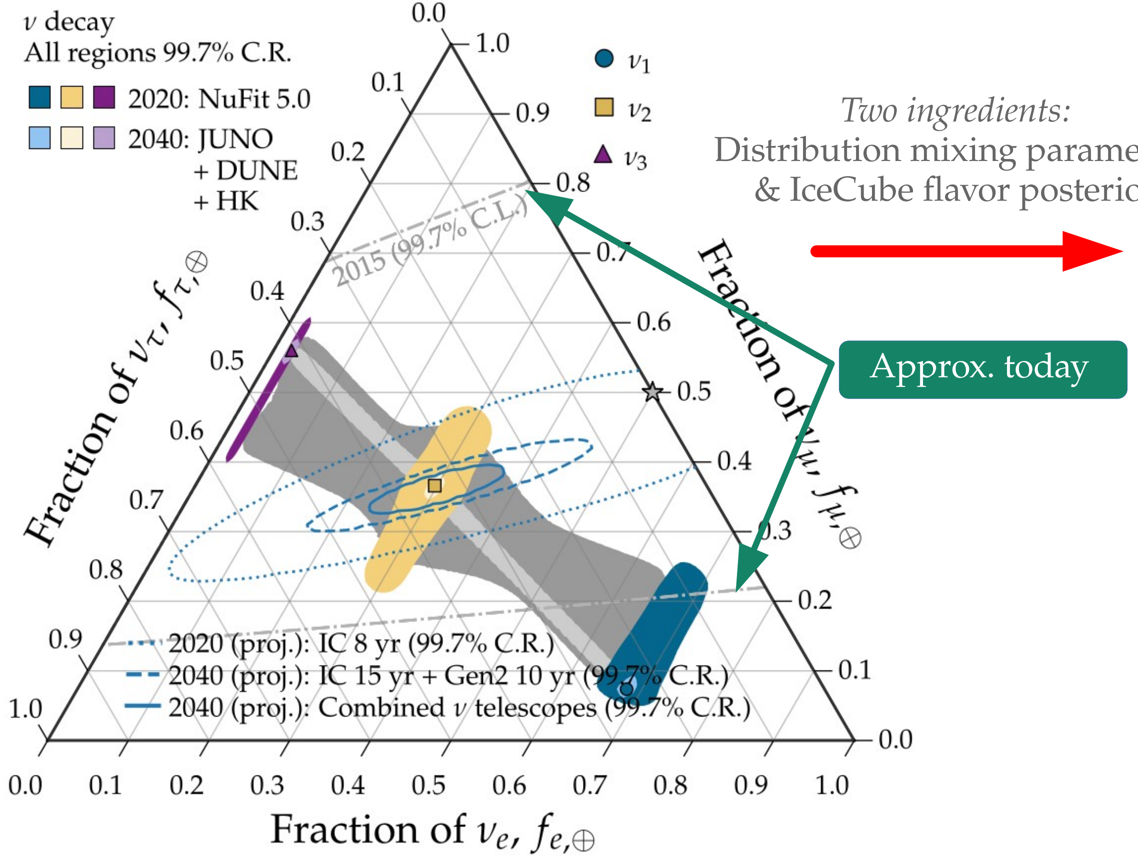

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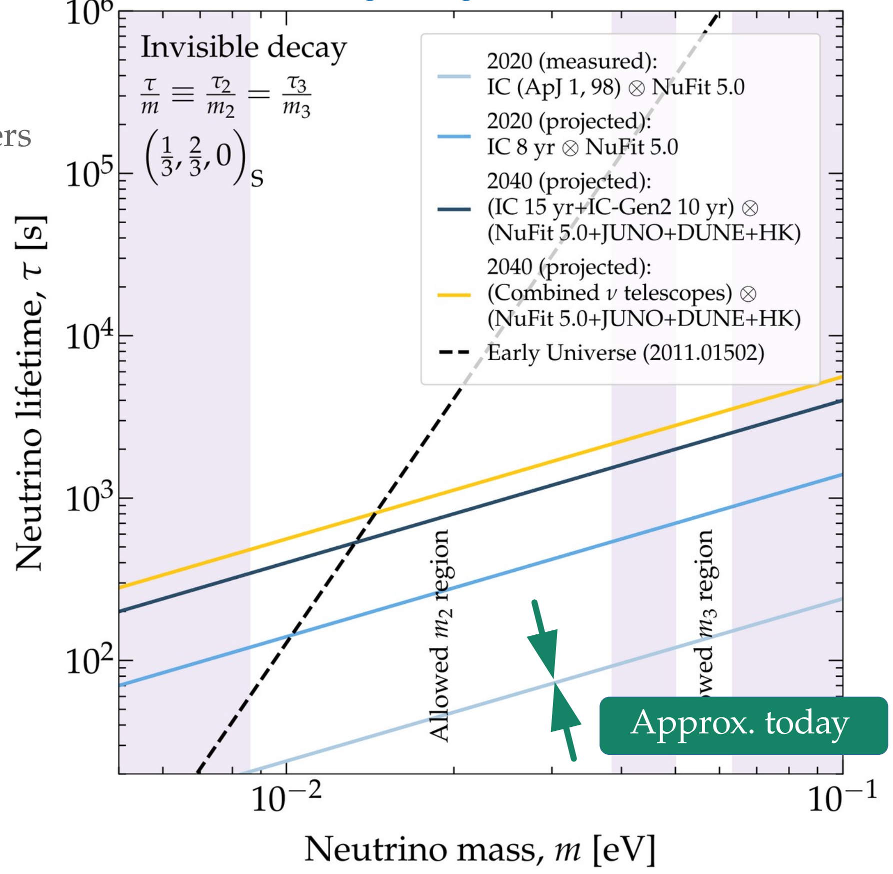

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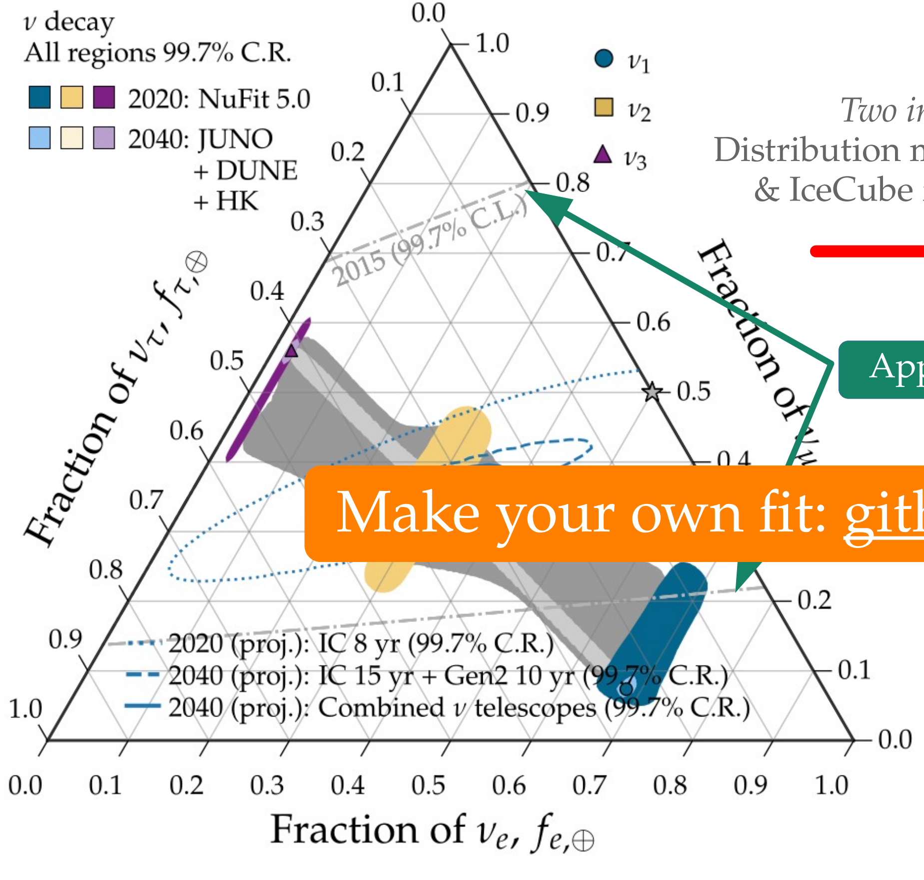

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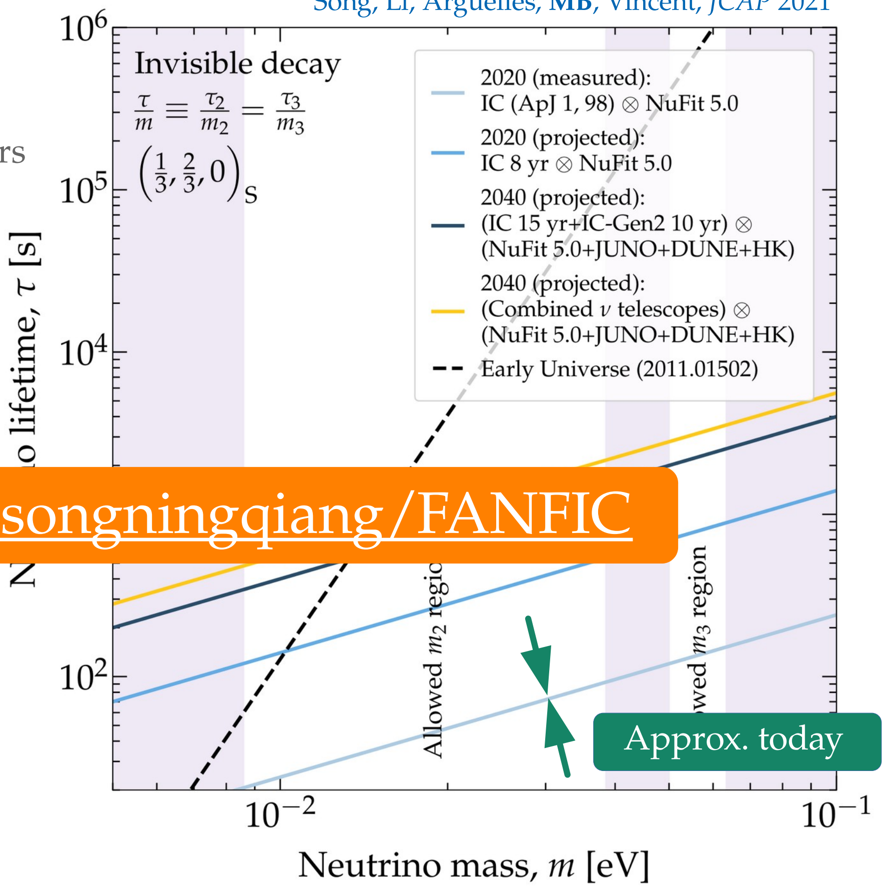
Distribution mixing parameters & IceCube flavor posterior

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



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

What does neutrino decay change?

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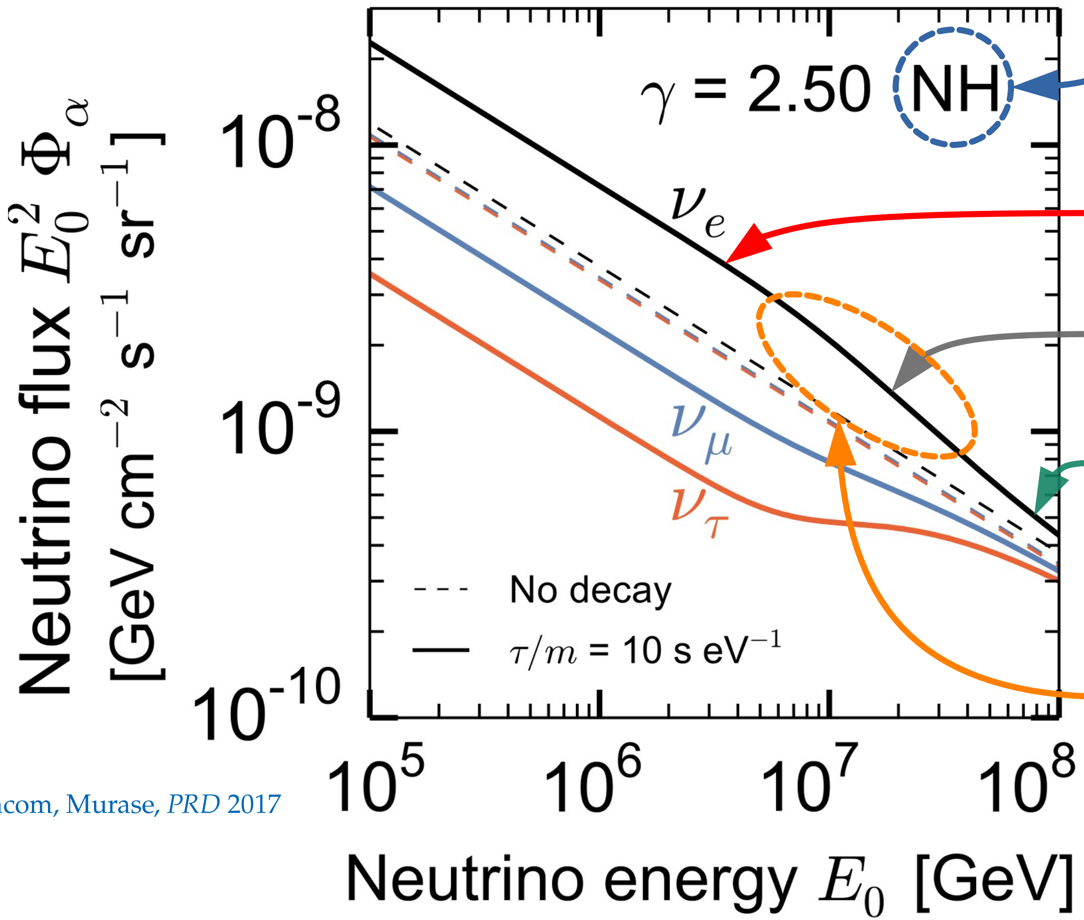
Flavor composition ⟺ Spectrum shape ⟺ Event rate



$\nu_2, \nu_3 \to \nu_1$

Low energy: decay evident

Transition region

High energy: no decay

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

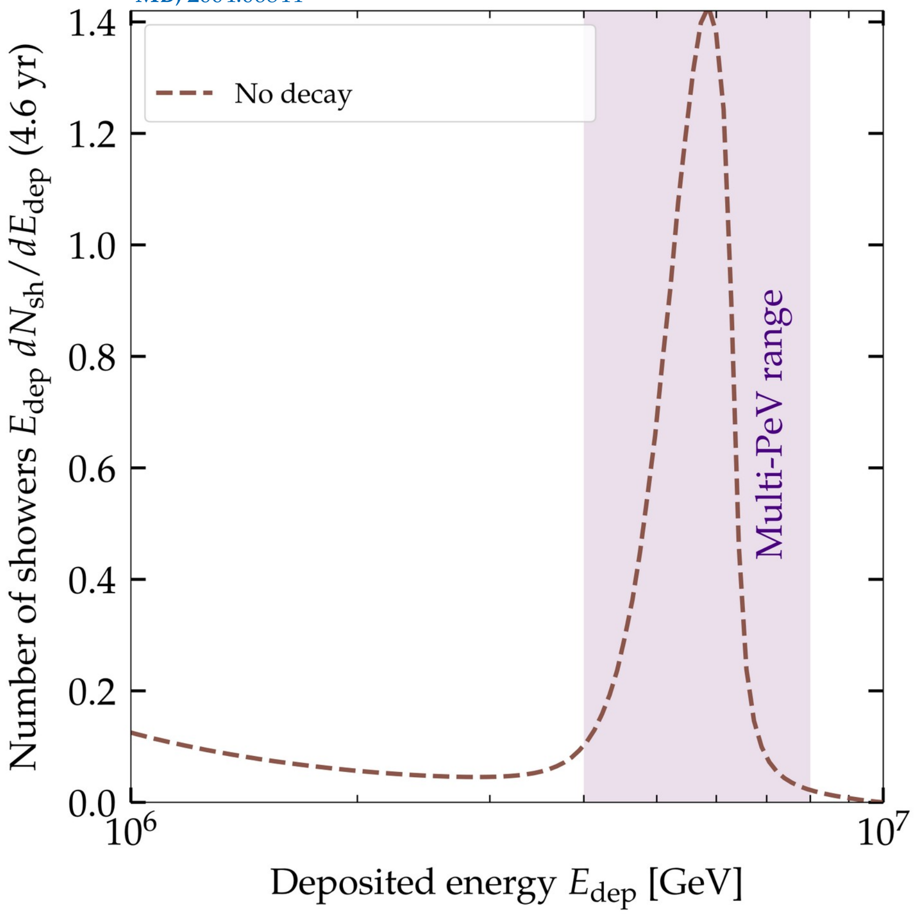
MB, Beacom, Murase, *PRD* 2017

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



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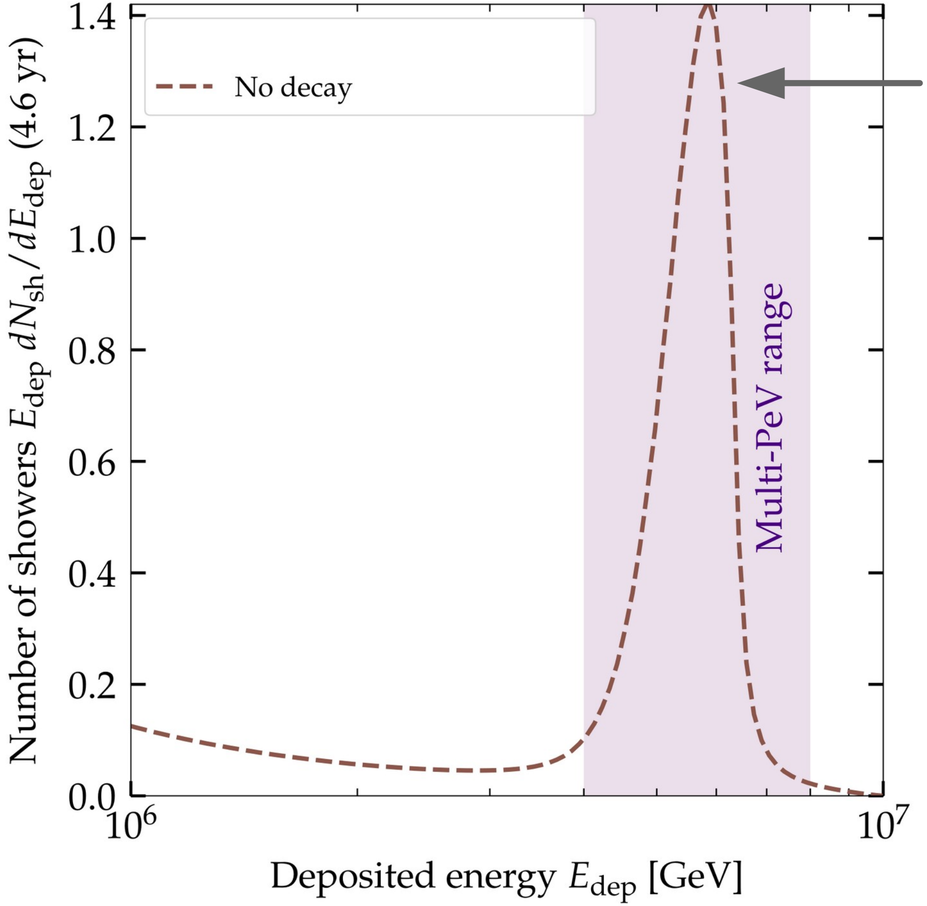
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



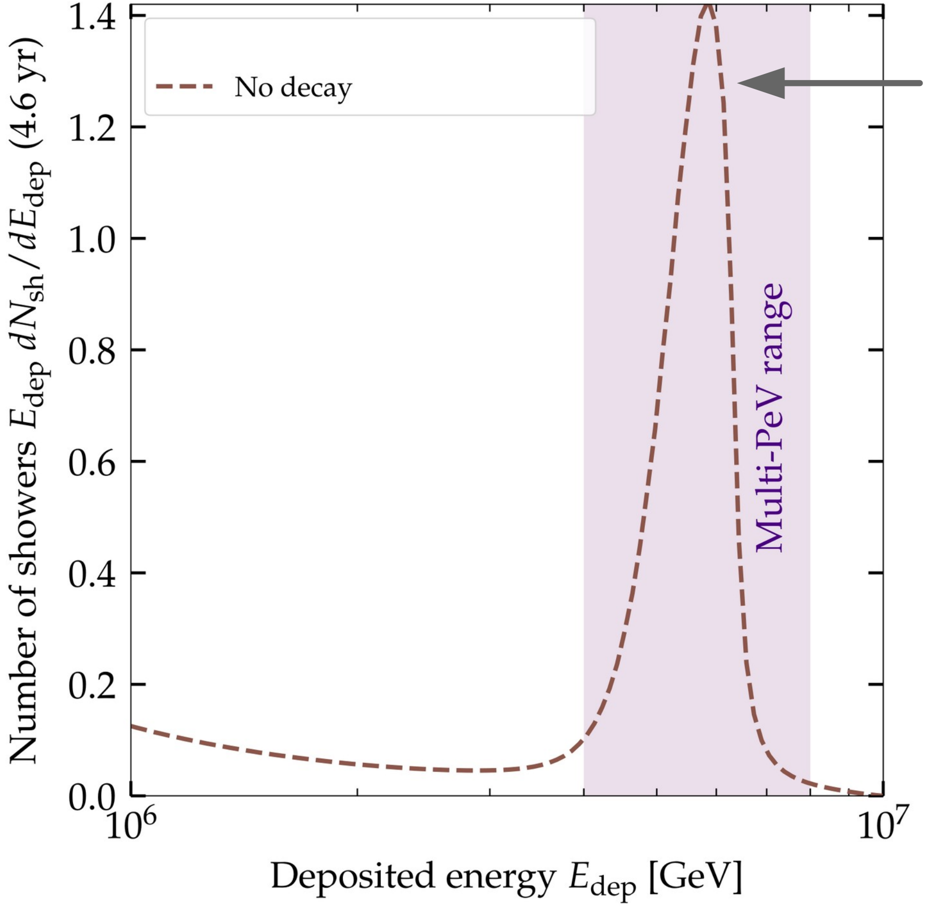
Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

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

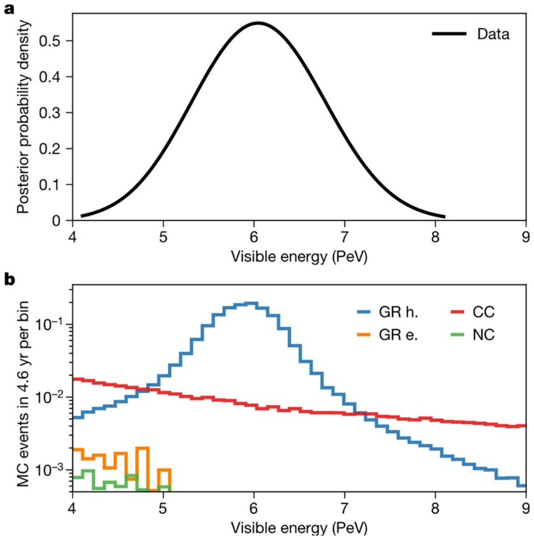
Flavor composition ⟺ Spectrum shape ⟺ Event rate

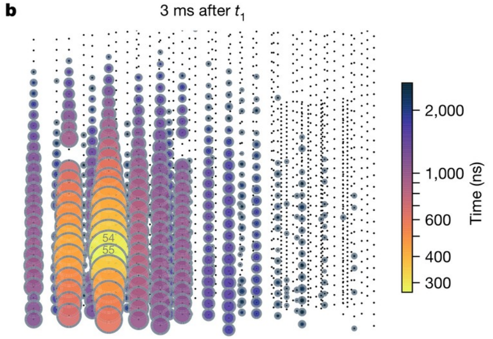
MB, 2004.06844



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

IceCube has seen one GR candidate in 4.6 years:





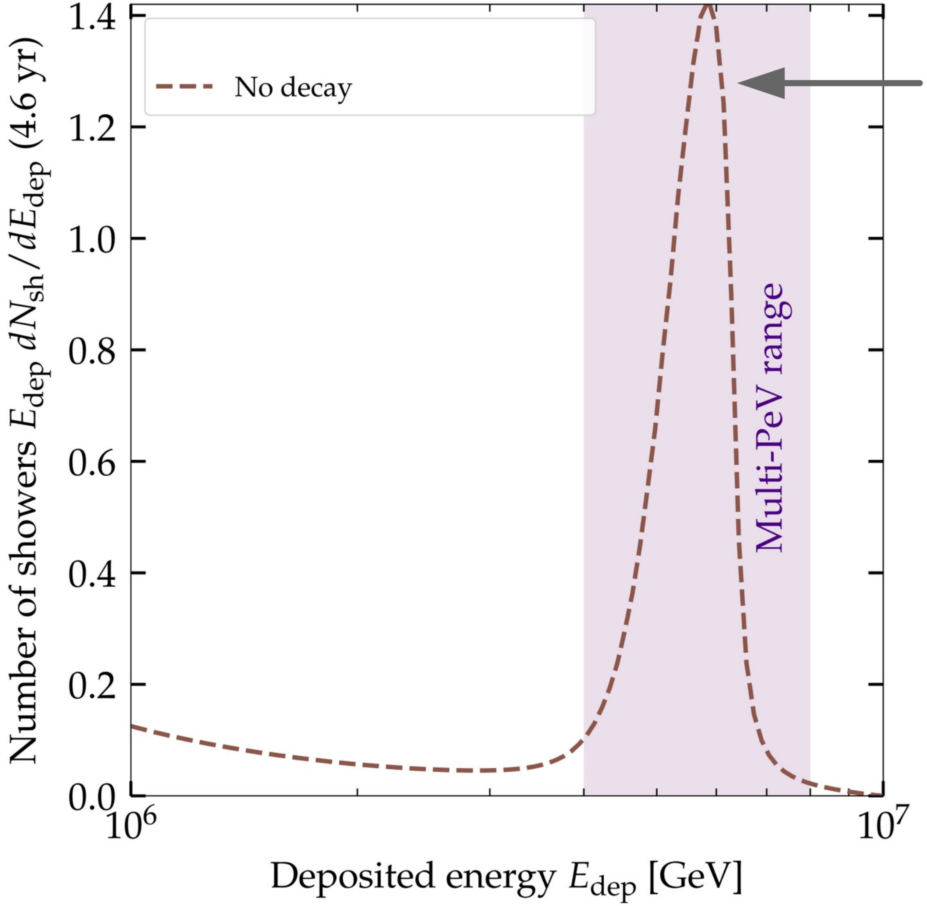
IceCube Collab., *Nature* 2021

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

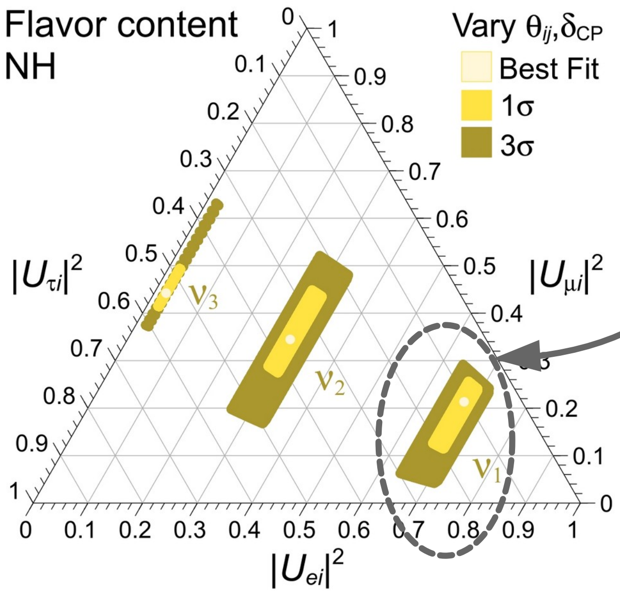
Flavor composition ⟺ Spectrum shape ⟺ Event rate

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

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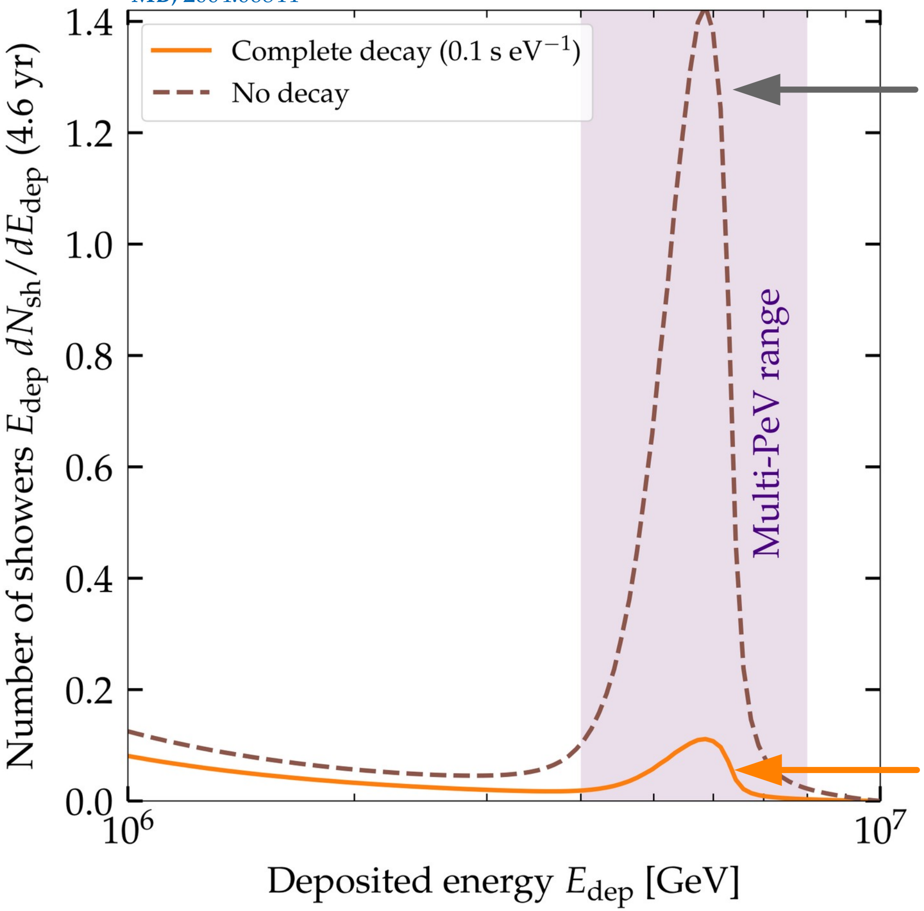

Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

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

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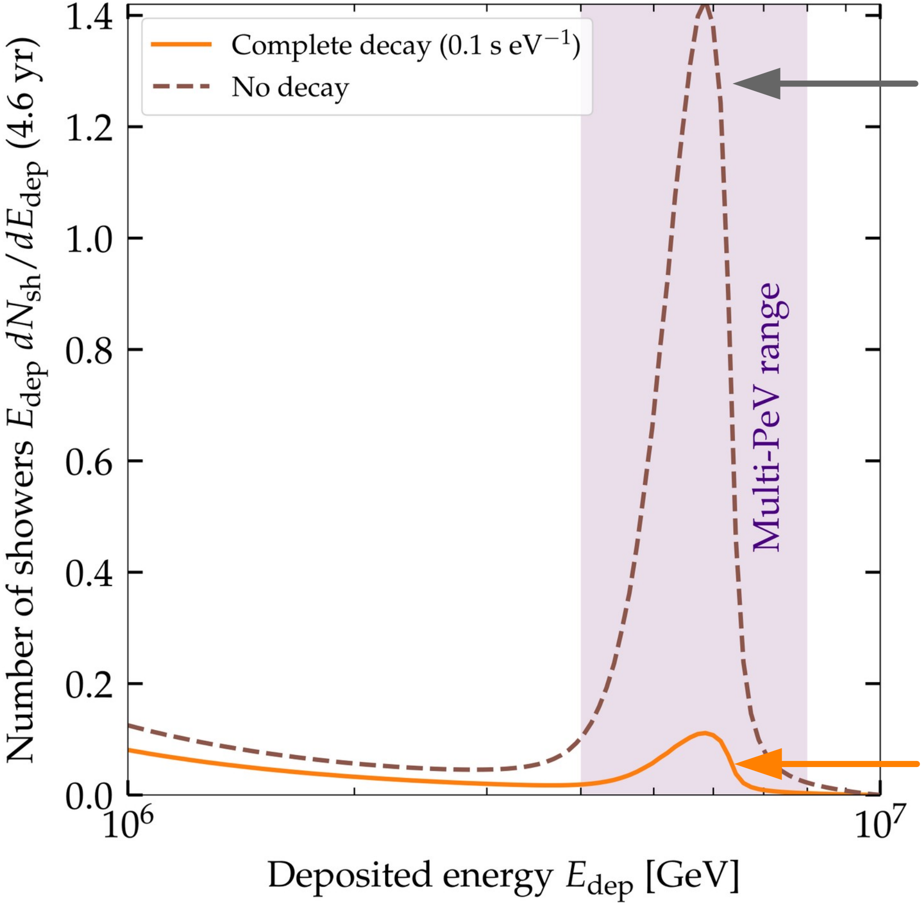


Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

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

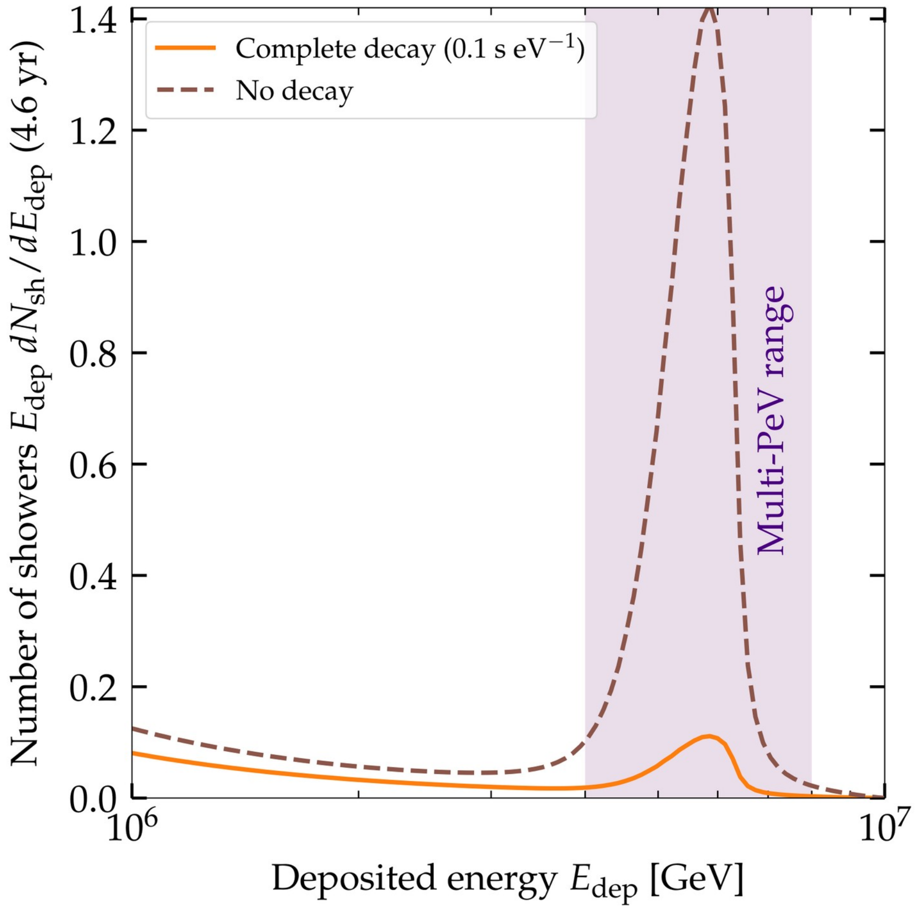
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

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



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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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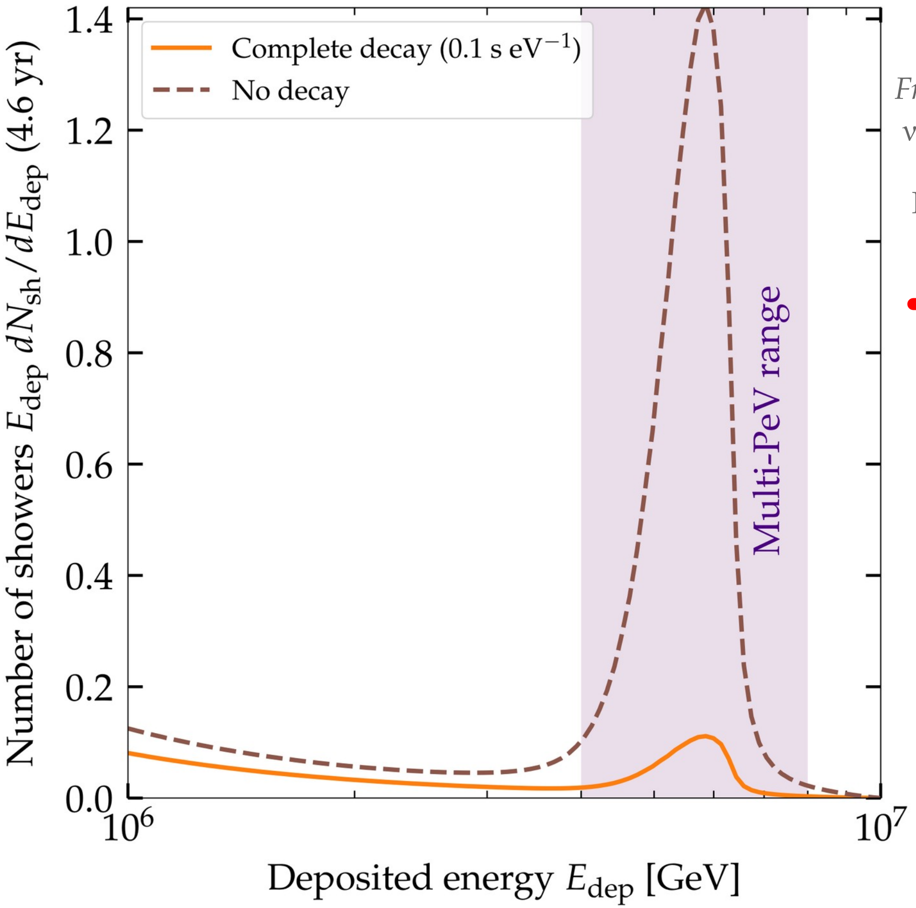

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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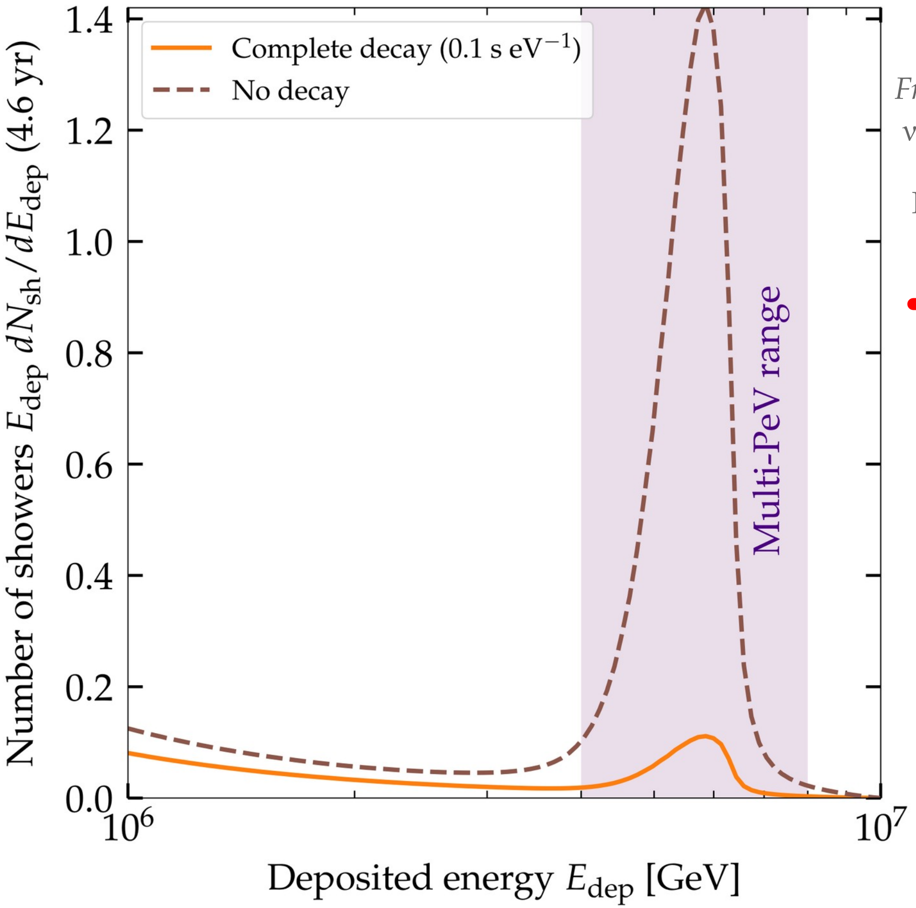
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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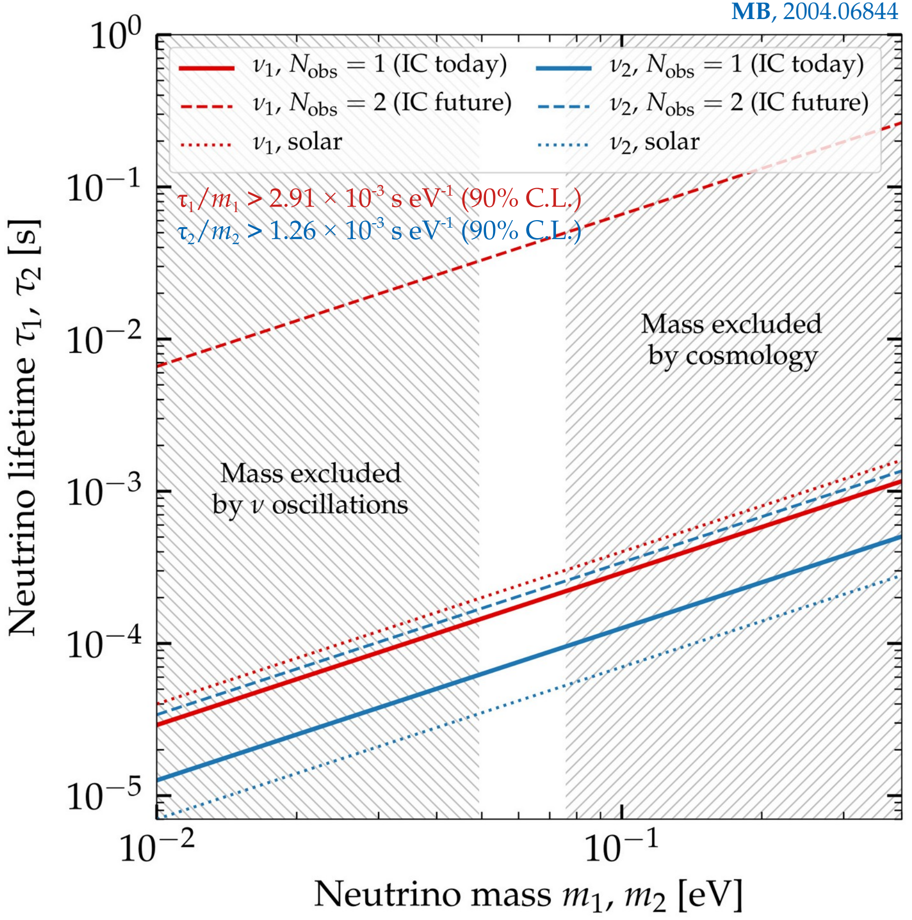
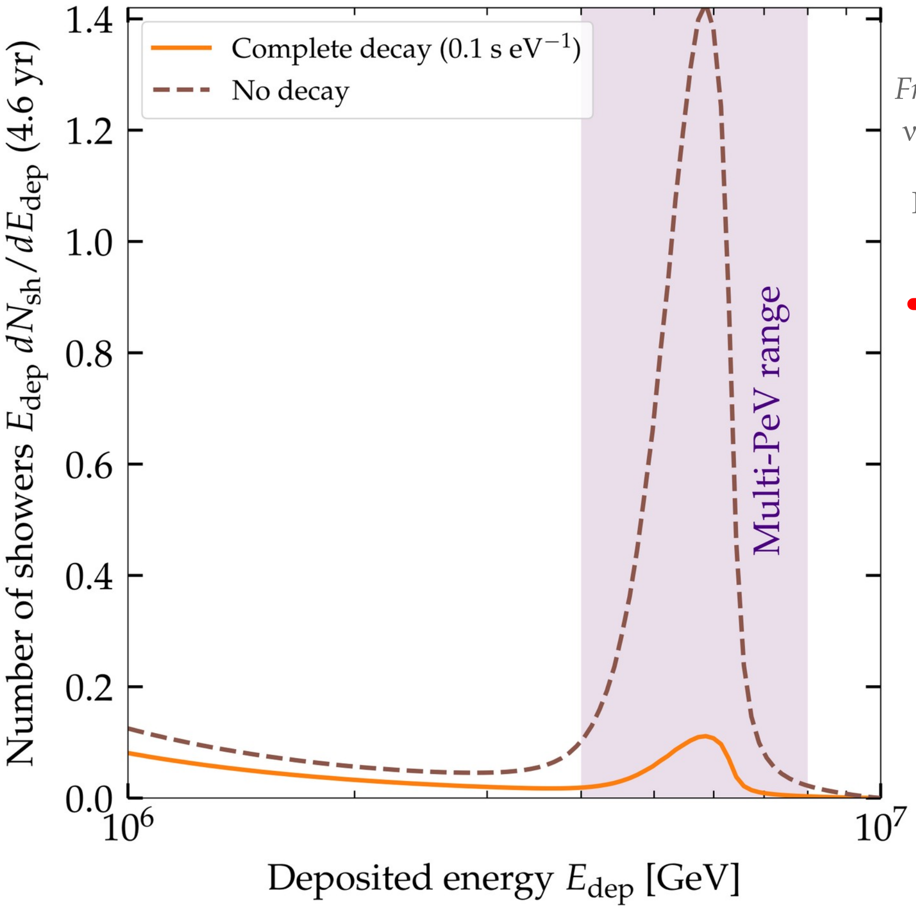


What does neutrino decay change?

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 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⇔ Spectrum shape ⇔ **Event rate**



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