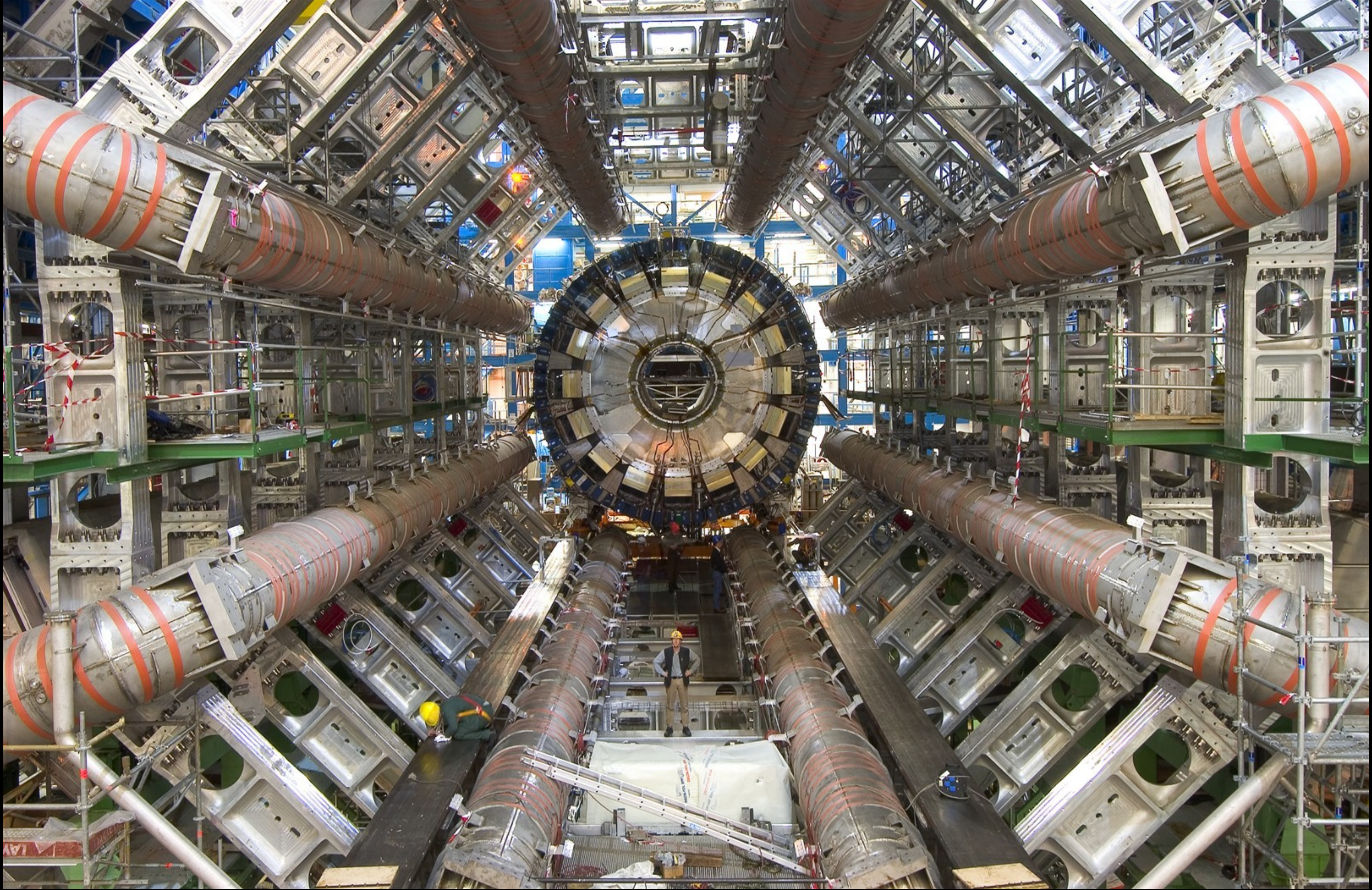
New physics from high-energy cosmic messengers

Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

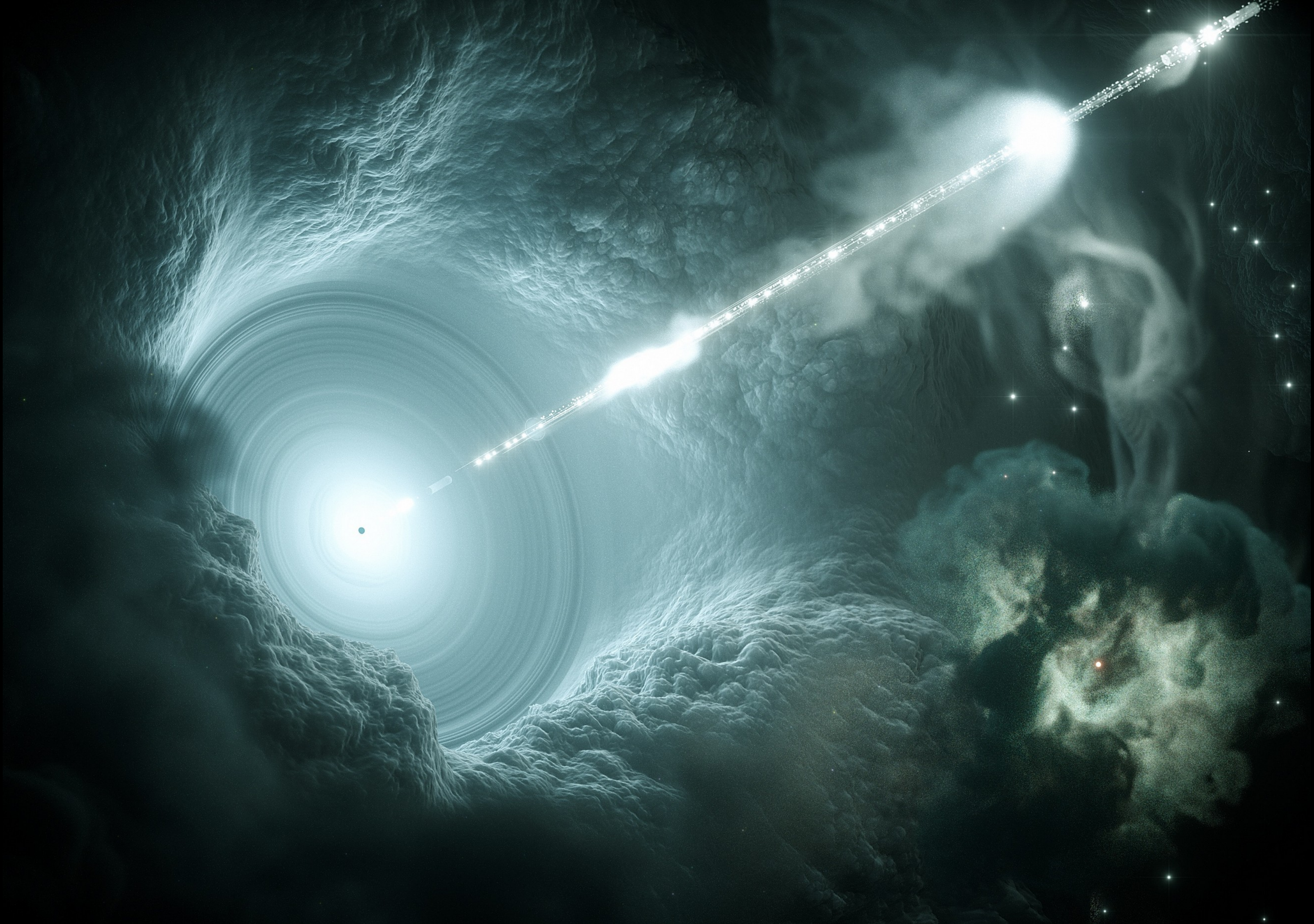
Quantum gravity phenomenology
in the multi-messenger approach
July 13, 2023

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



ATLAS



DESY

DESY

New physics from high-energy cosmic ~~messengers~~ neutrinos

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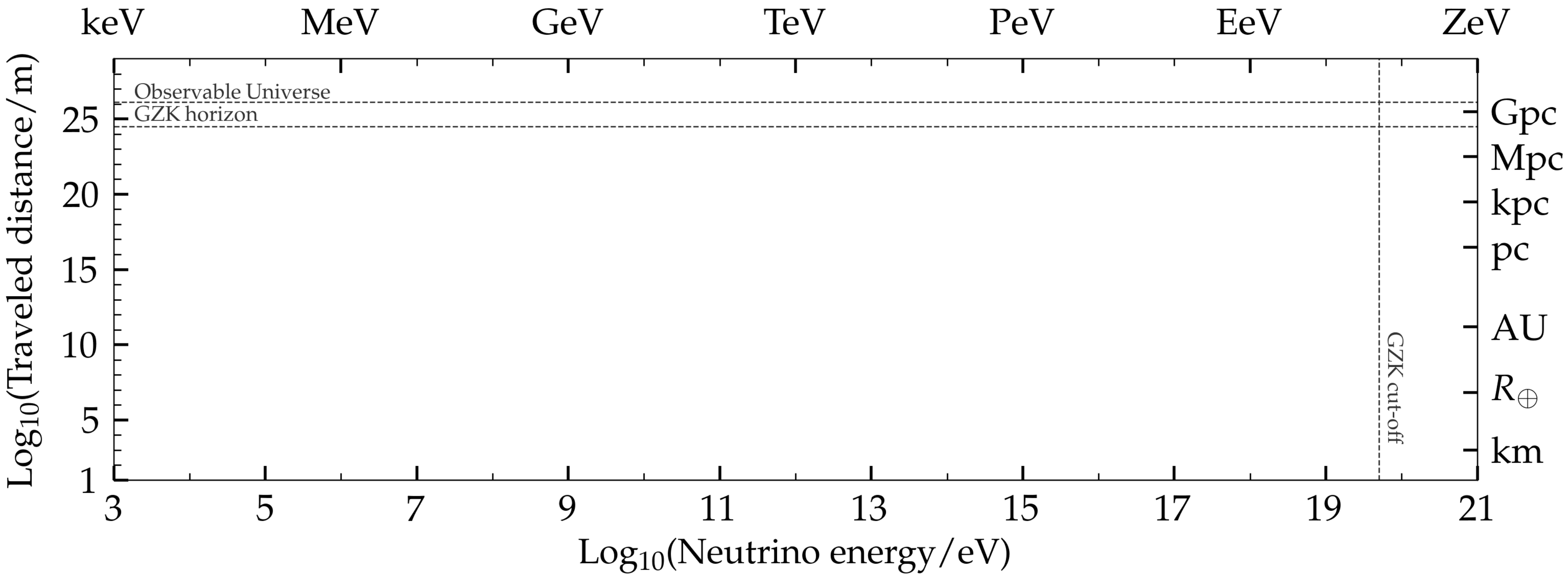
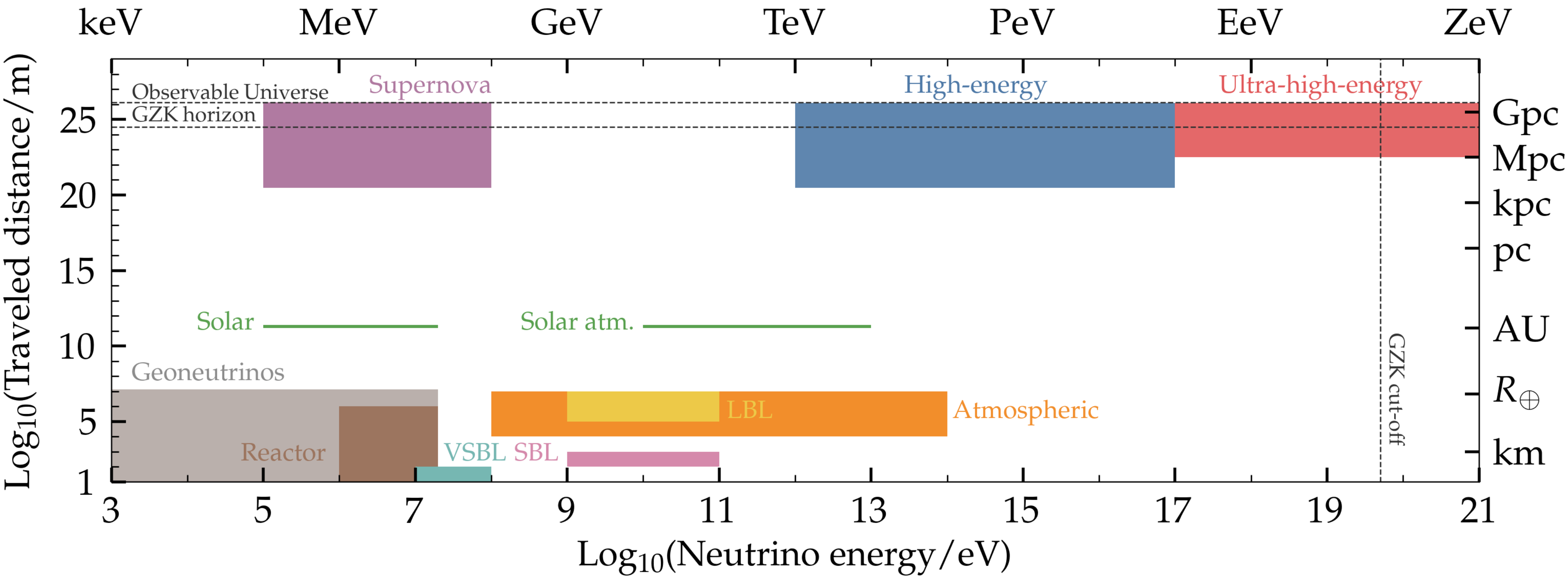


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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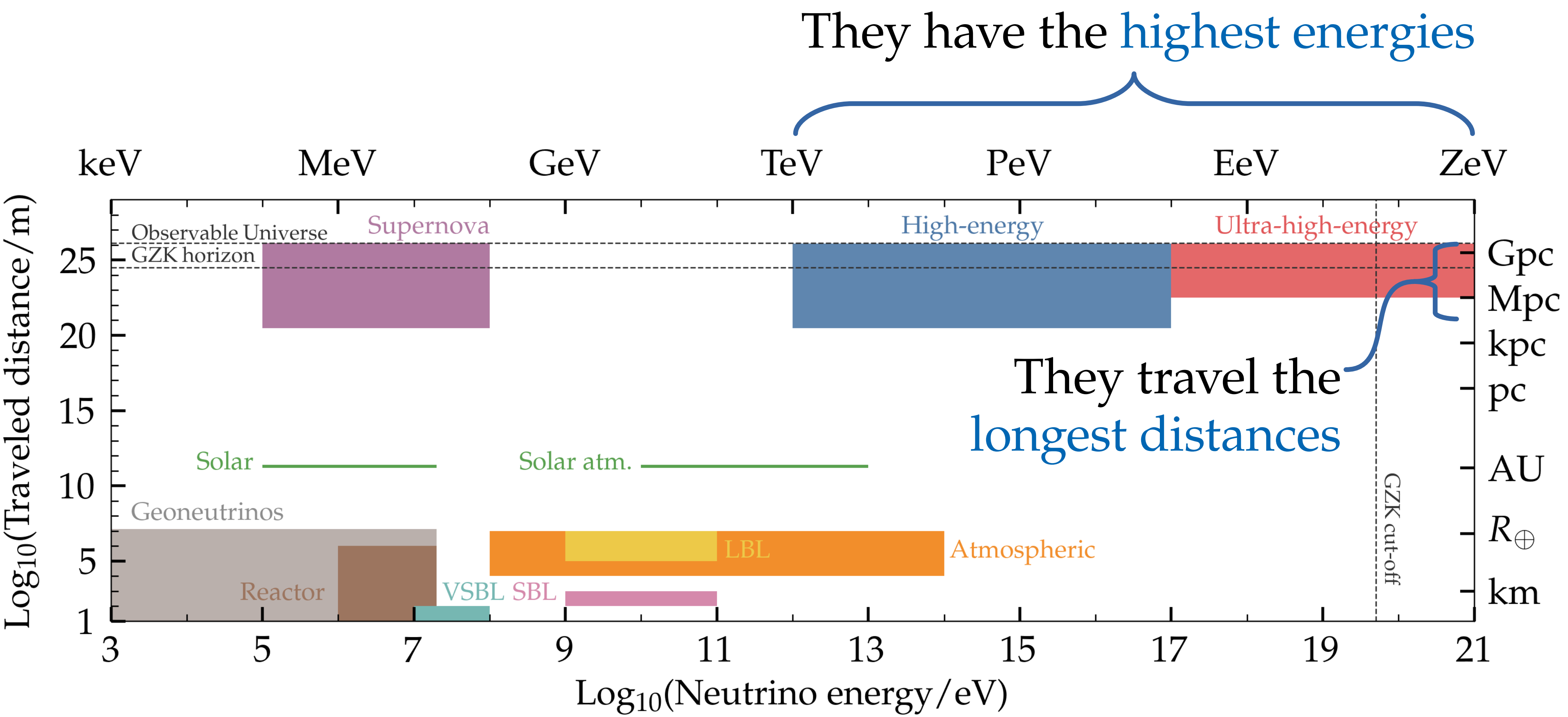

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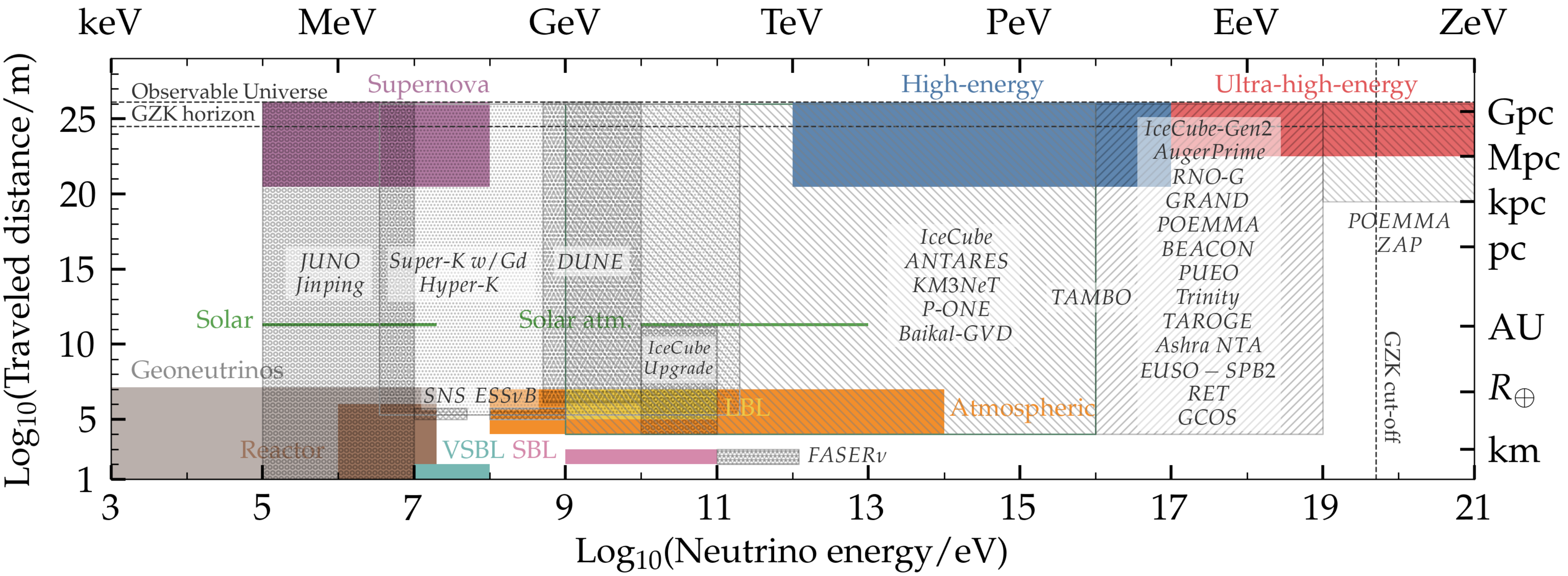

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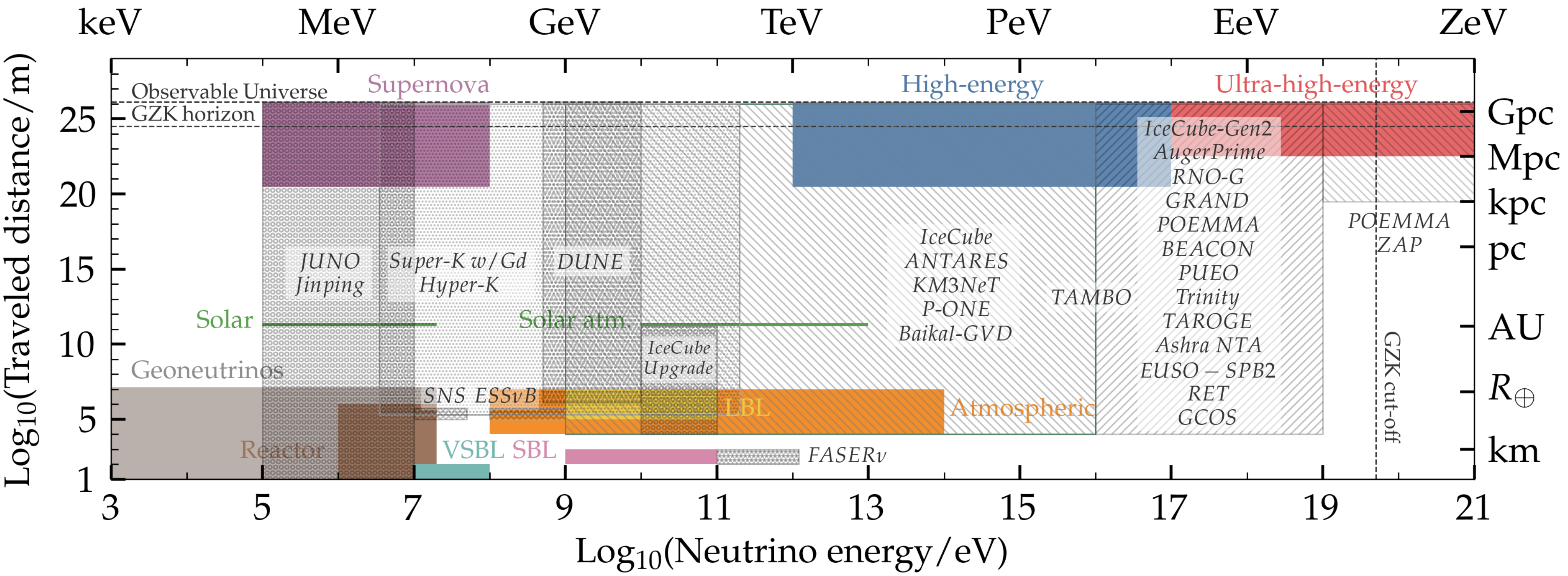
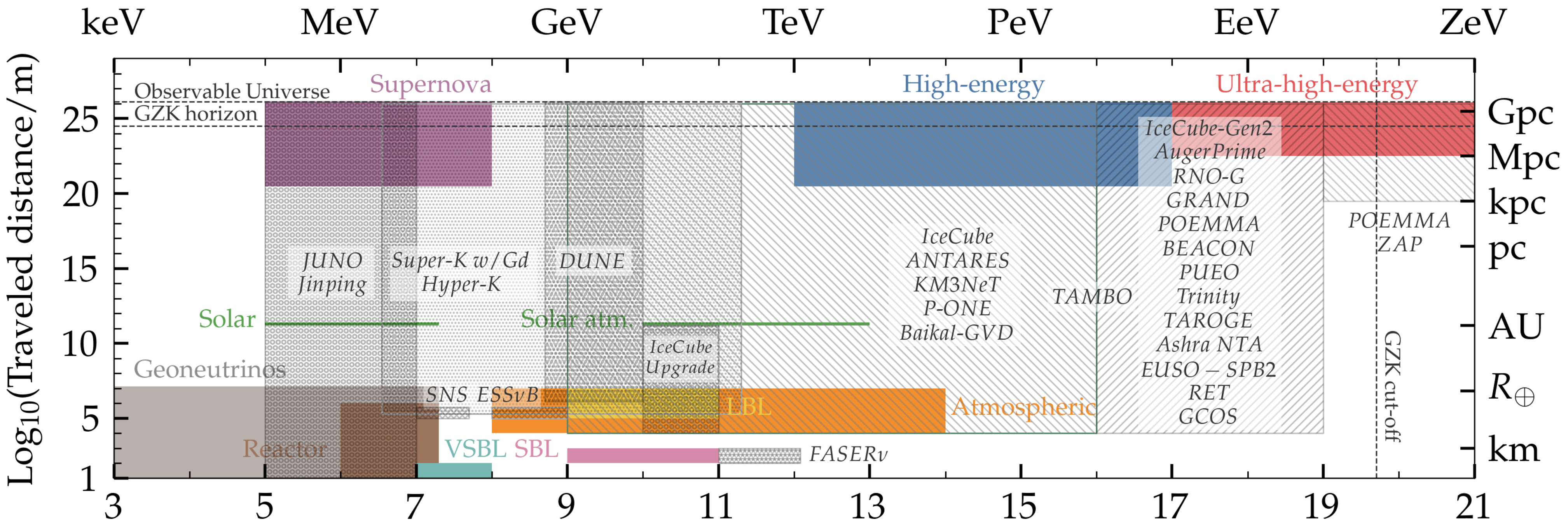


Synergies with lower energies

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

Discovered in 2013
by IceCube



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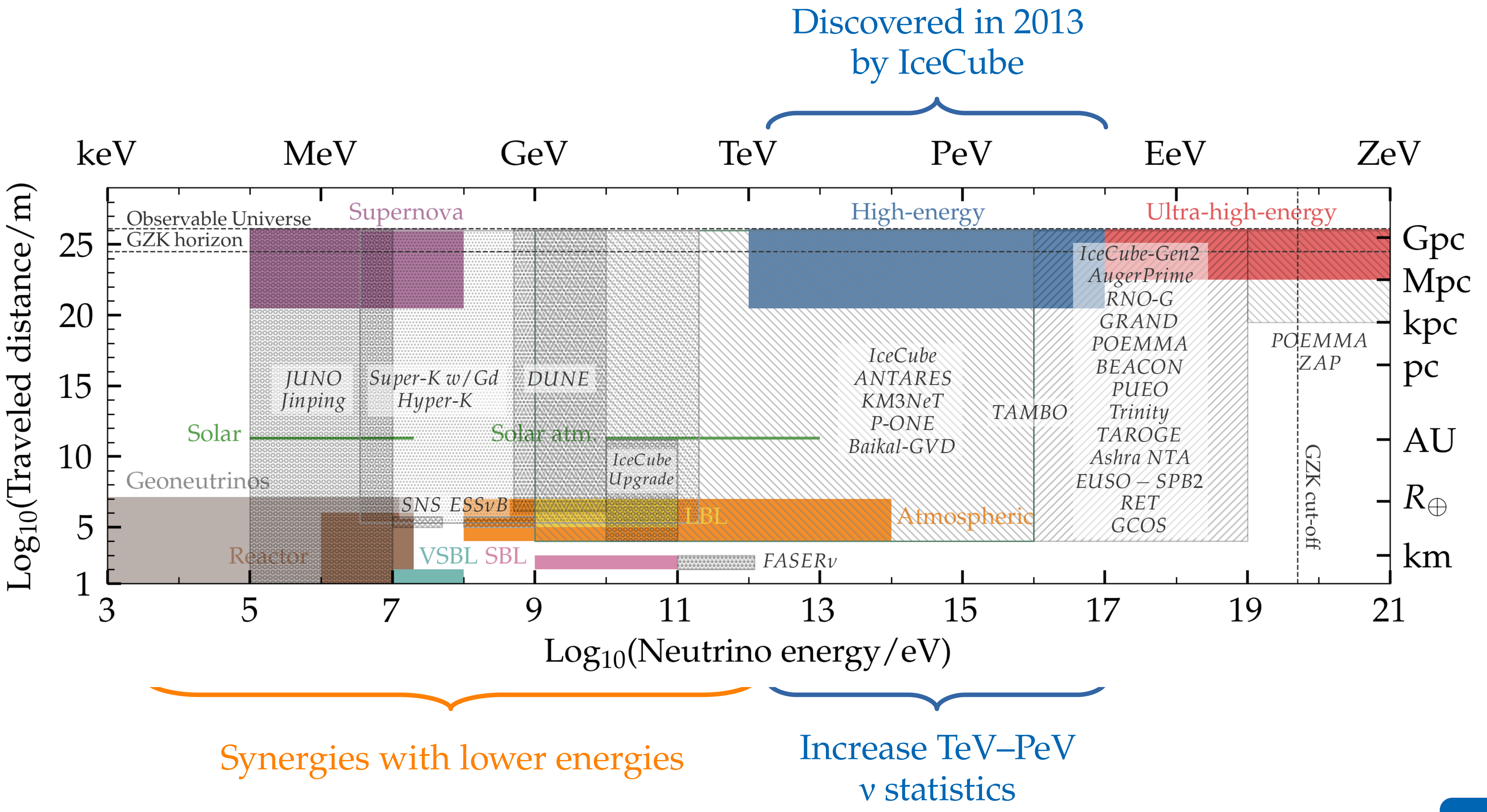
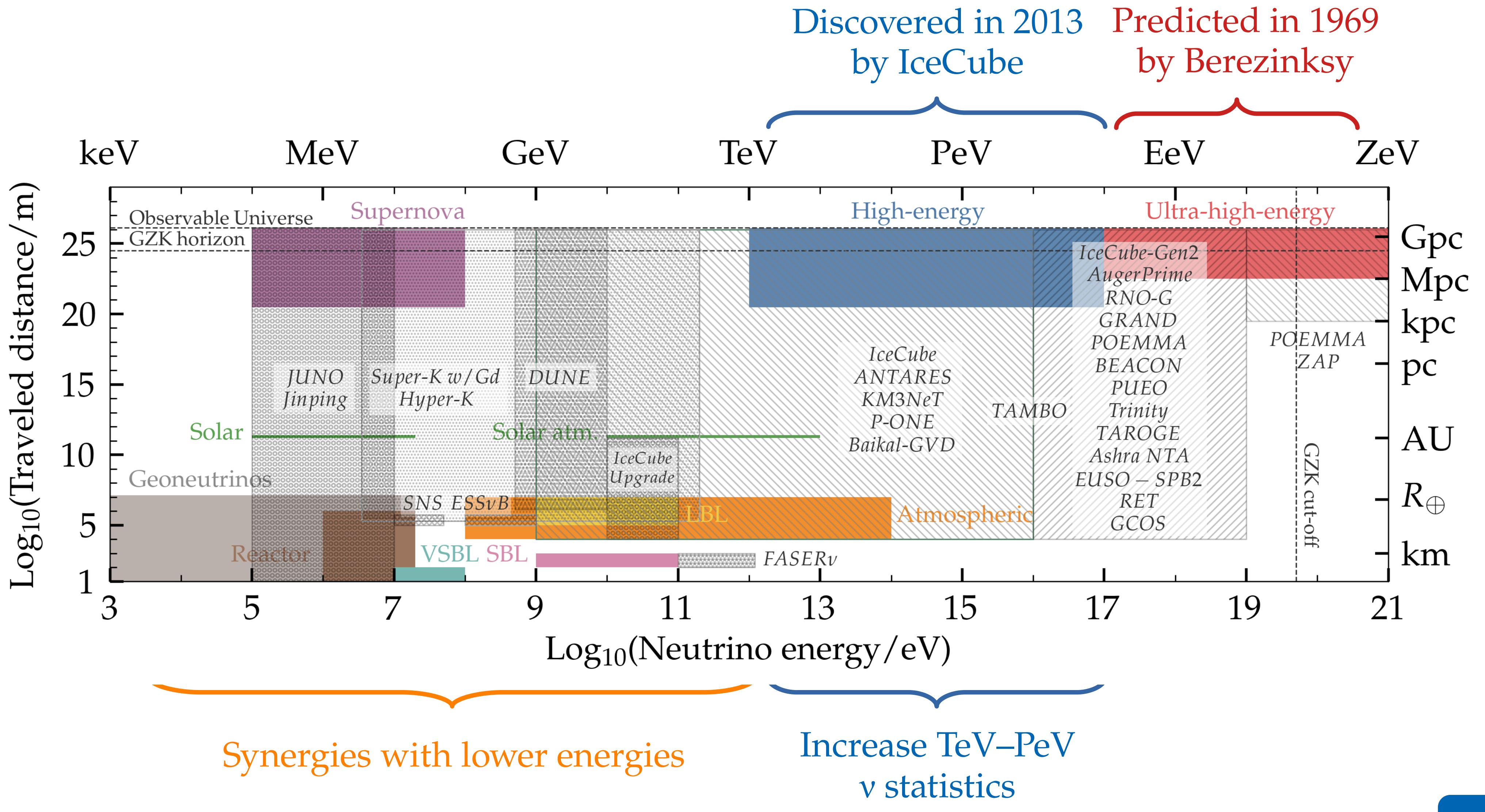
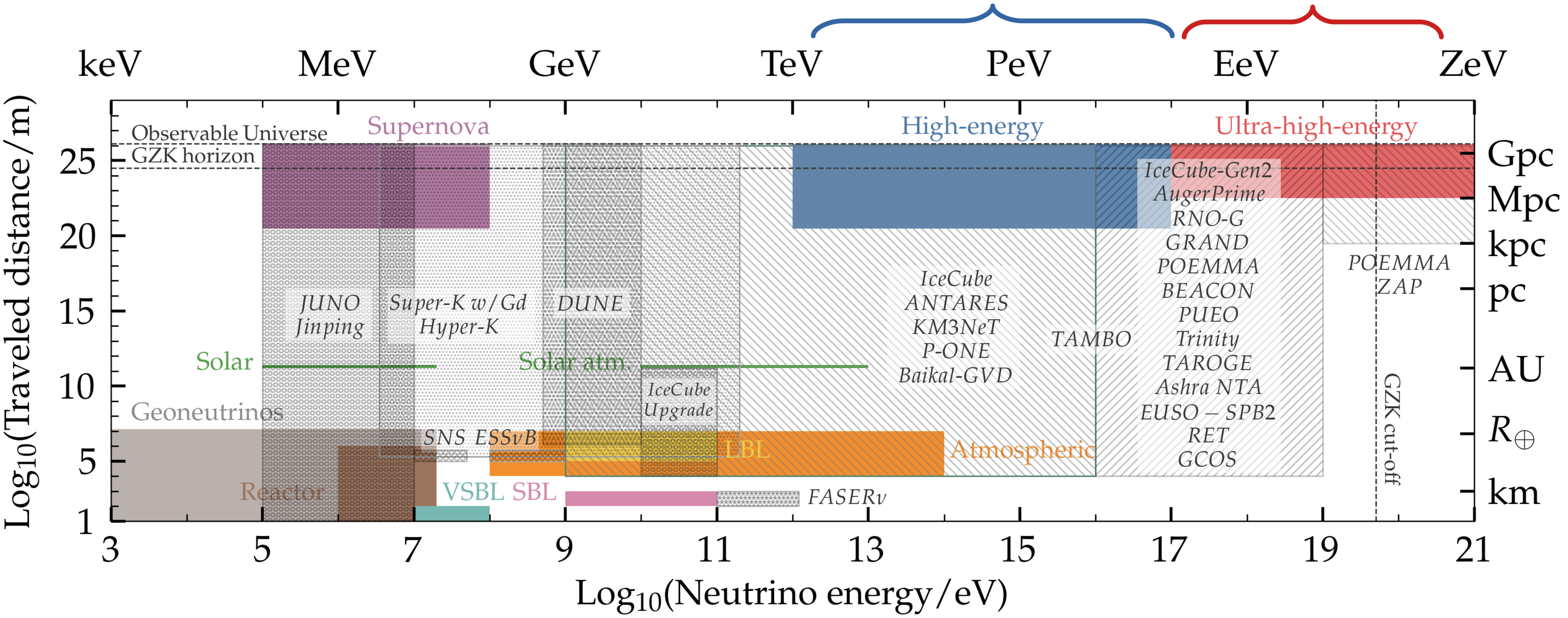


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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

Discovered in 2013 by IceCube — Predicted in 1969 by Berezinksy



Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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

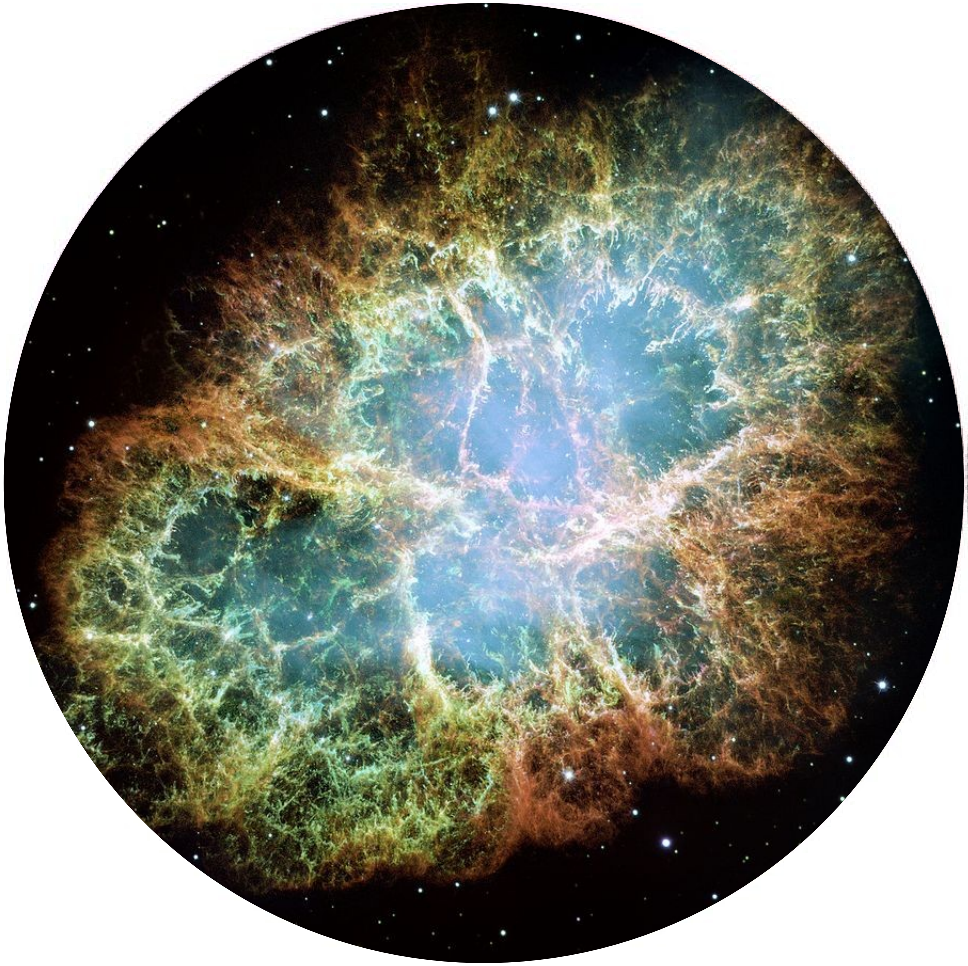
Today

TeV–PeV ν

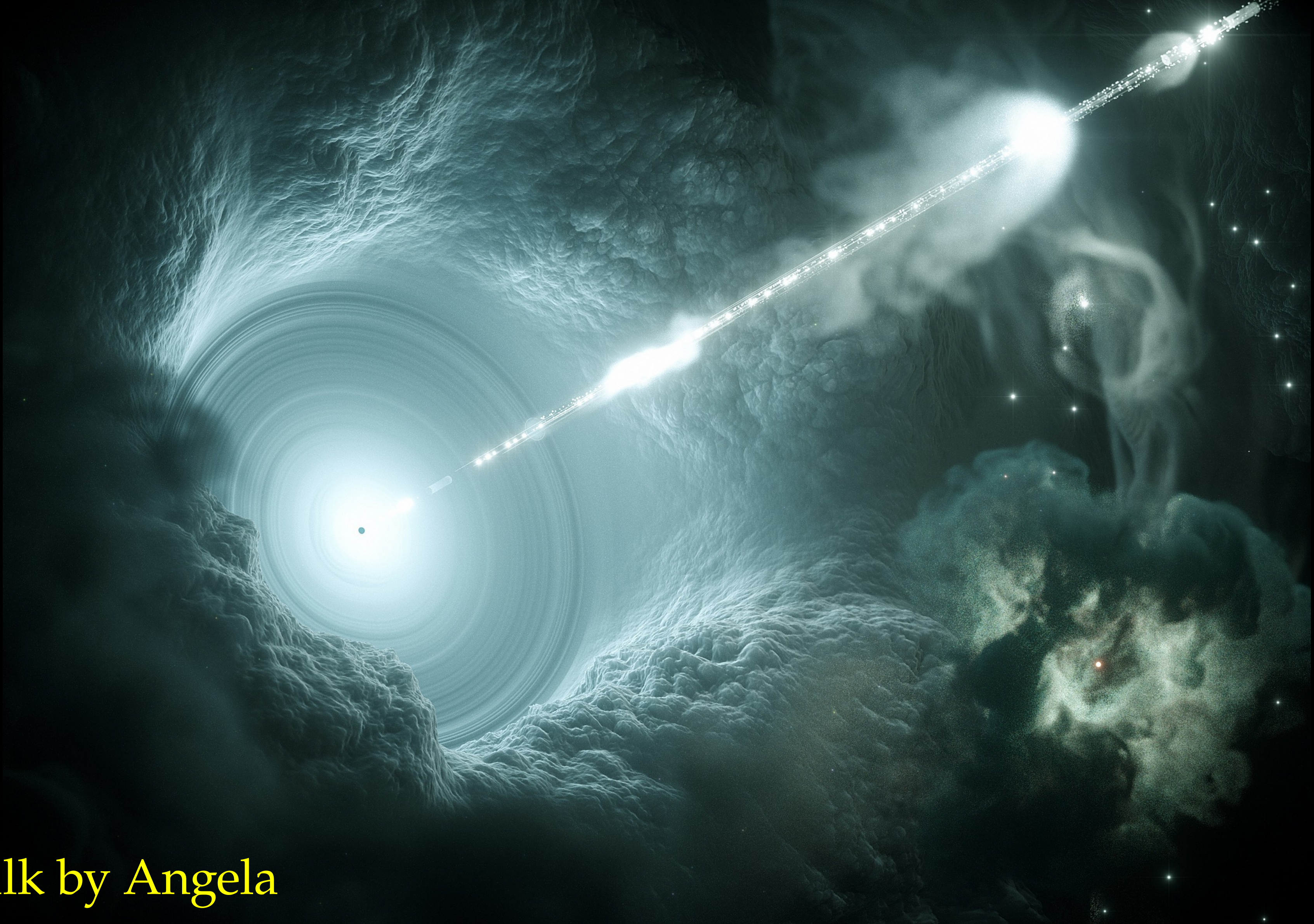
Next decade

> 100-PeV ν

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



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



See talk by Angela

DESY

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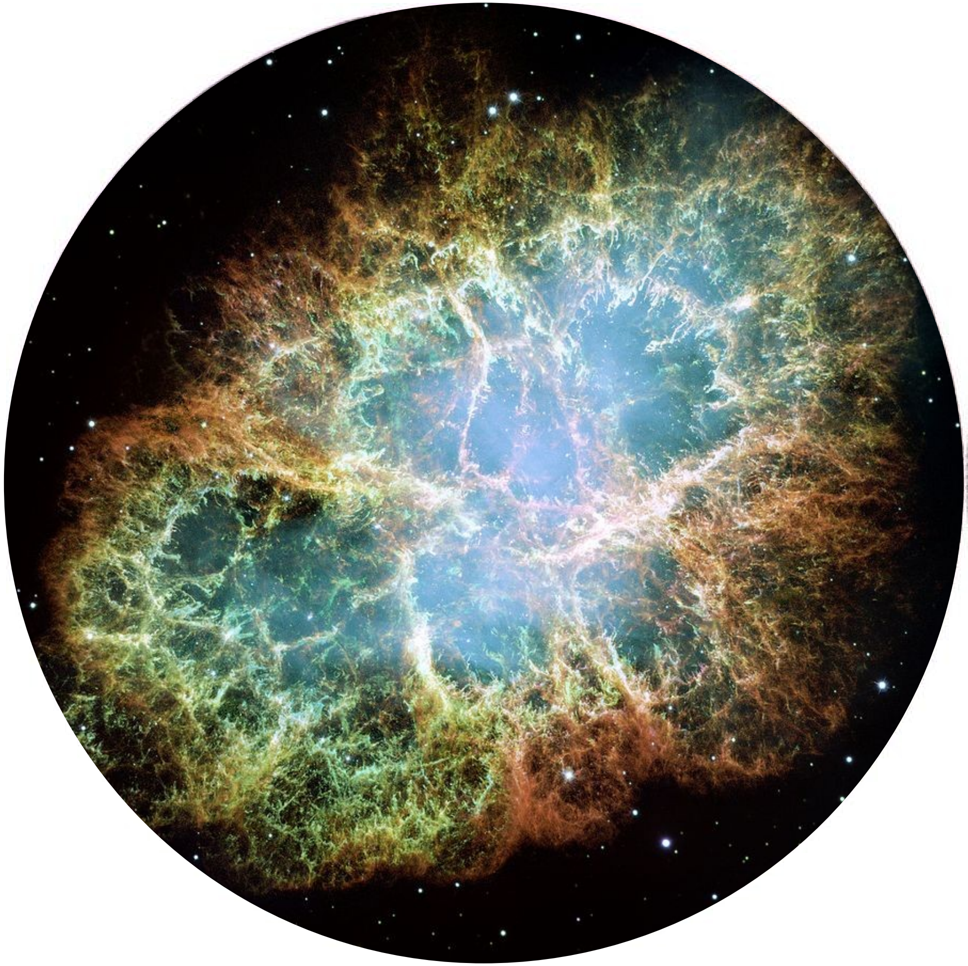

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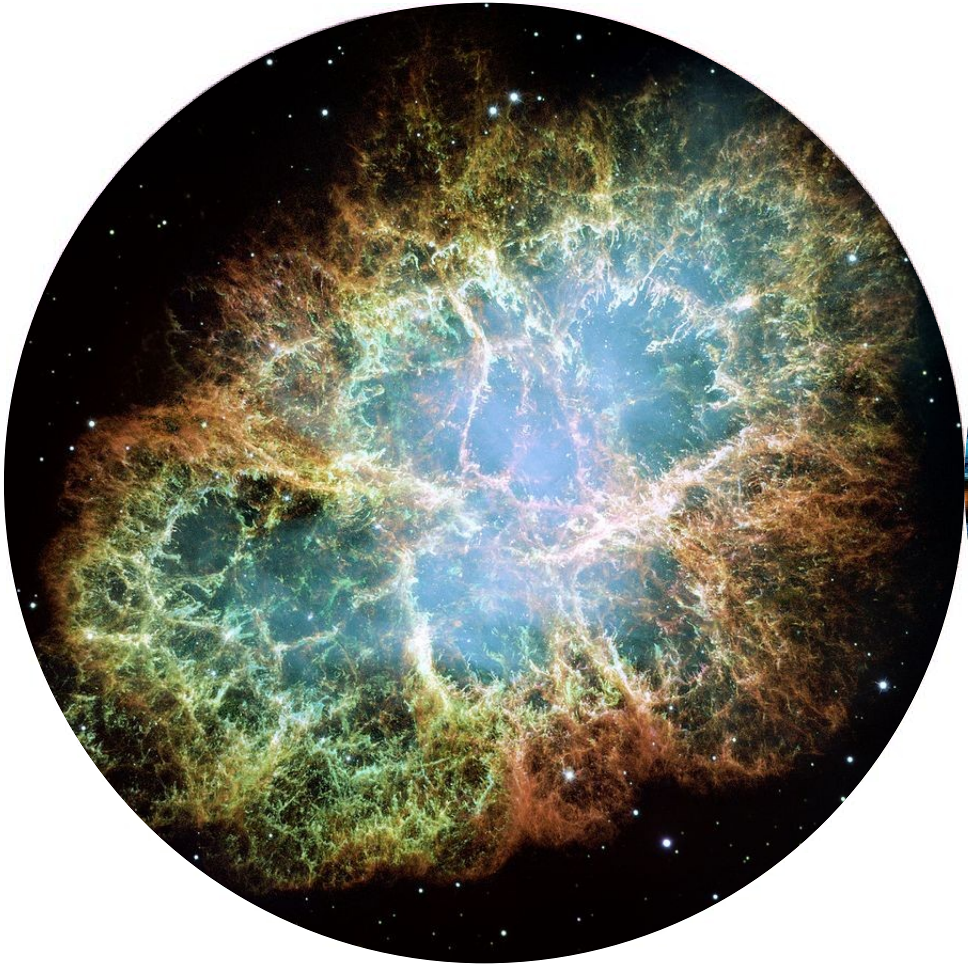

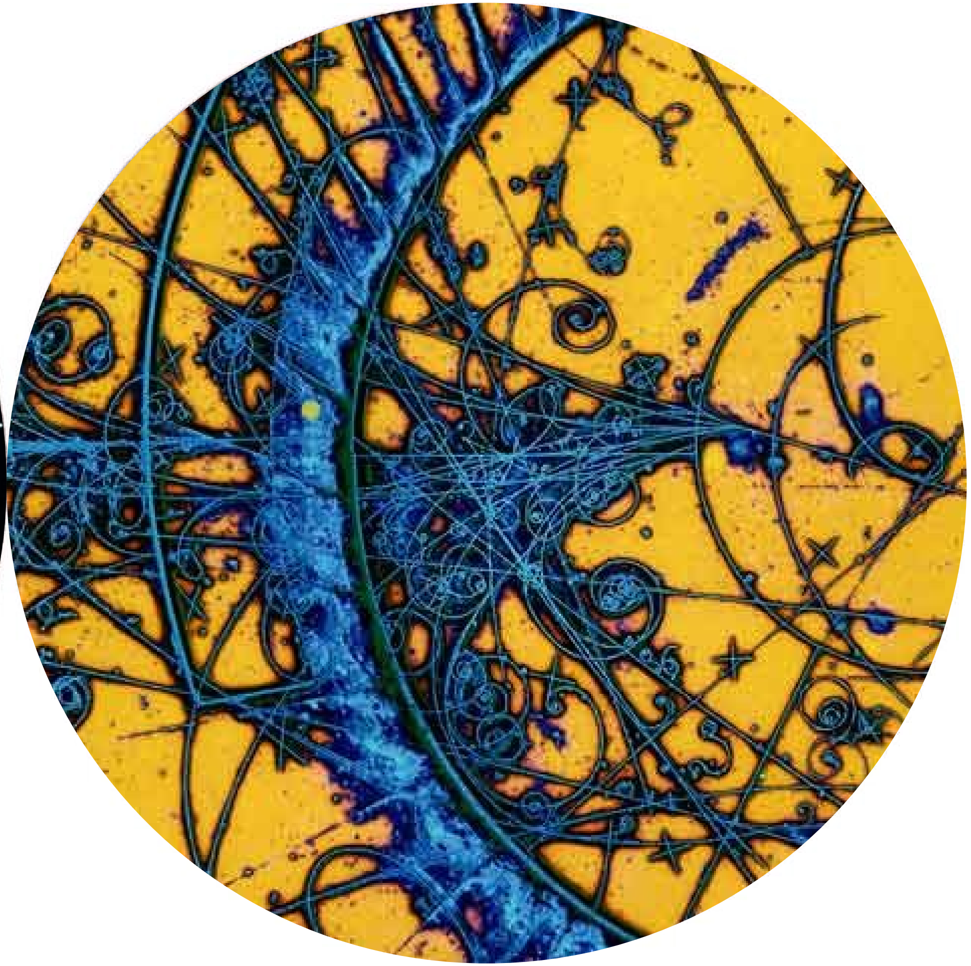

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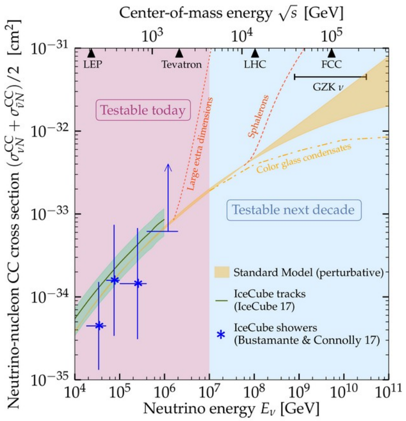
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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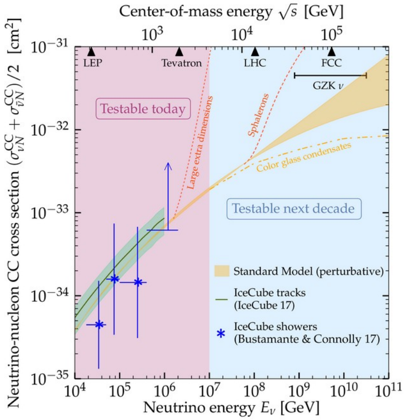
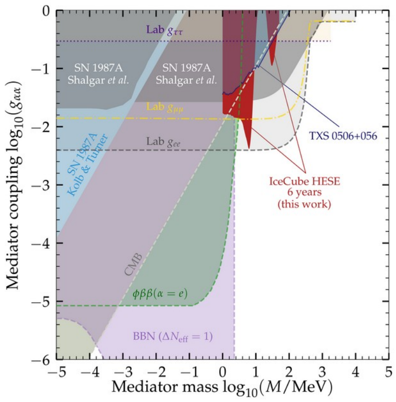


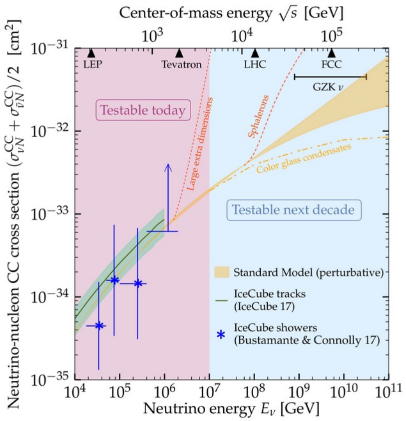
MB & Connolly, *PRL* 2019

ν self-interactions



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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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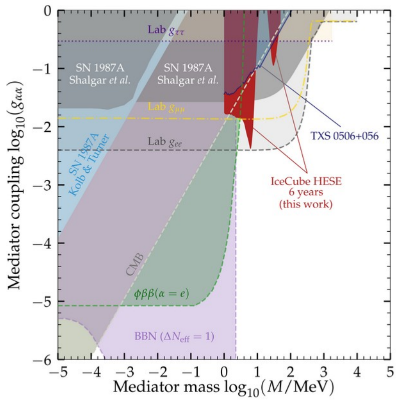
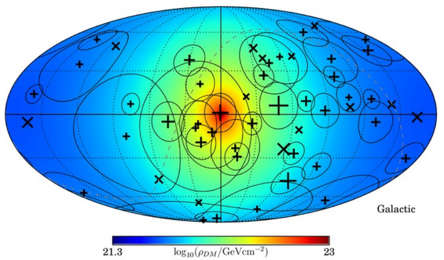


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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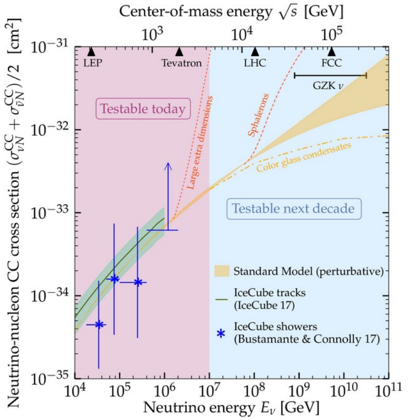

MB & Connolly, *PRL* 2019

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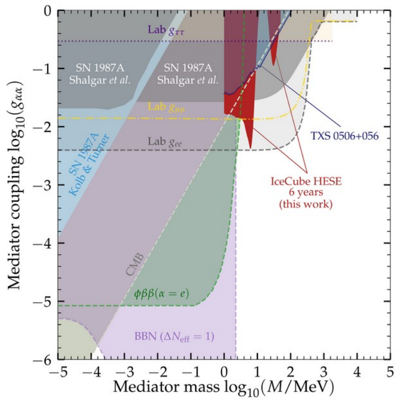

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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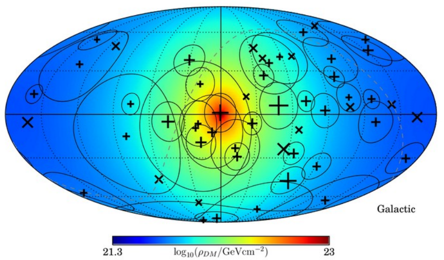
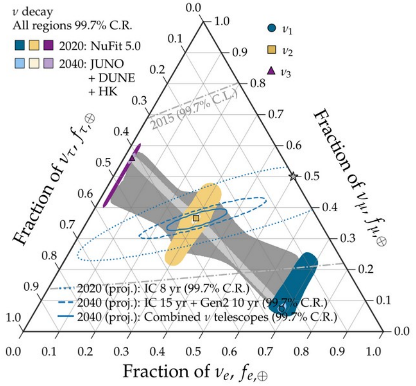


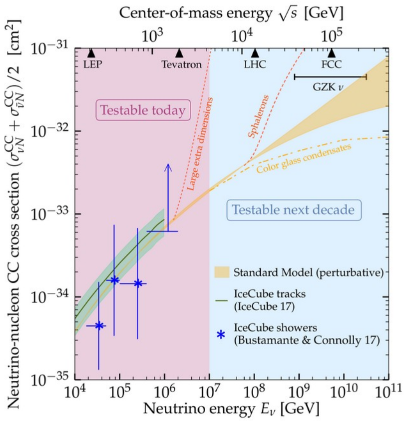
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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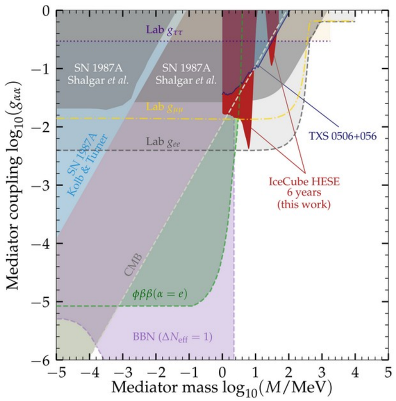

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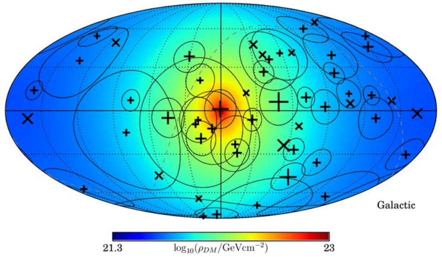

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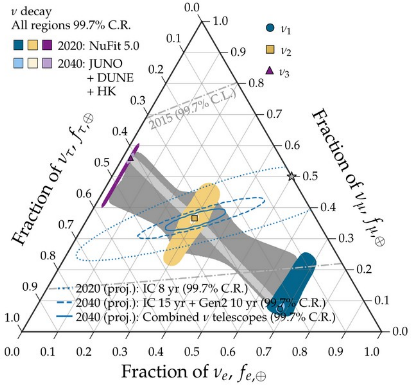
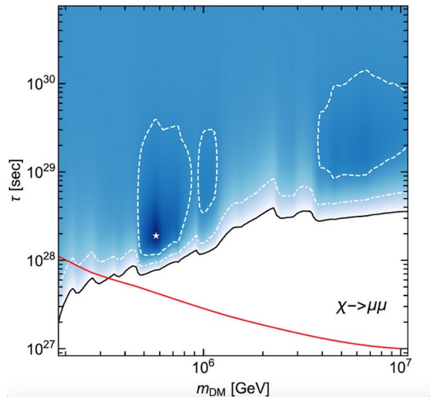


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

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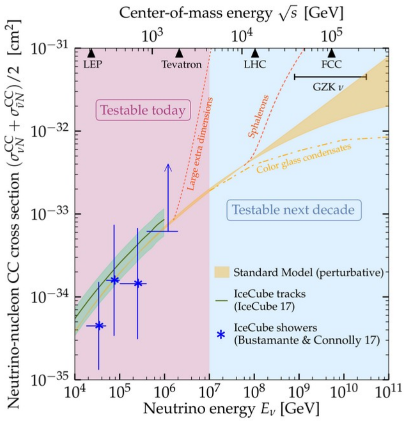

MB & Connolly, *PRL* 2019

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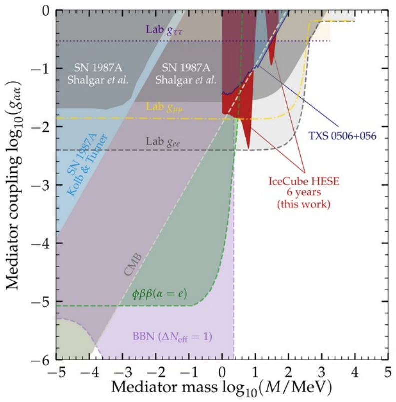
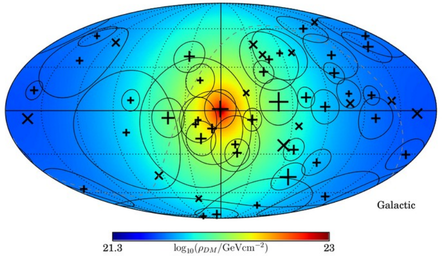


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



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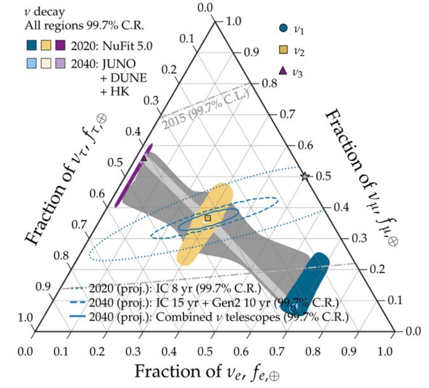

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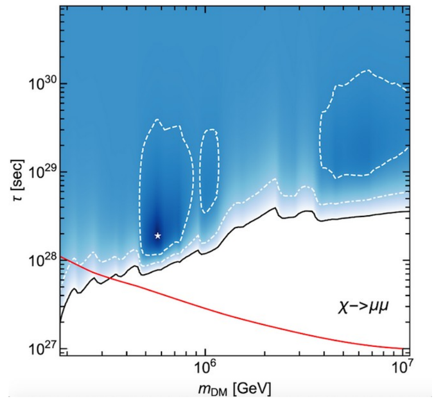
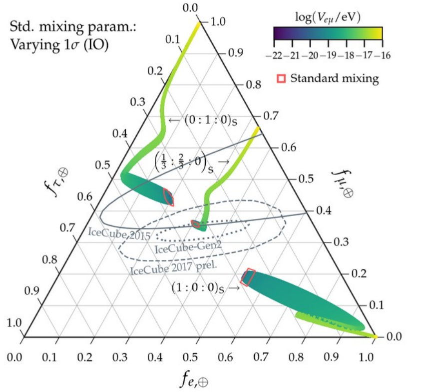


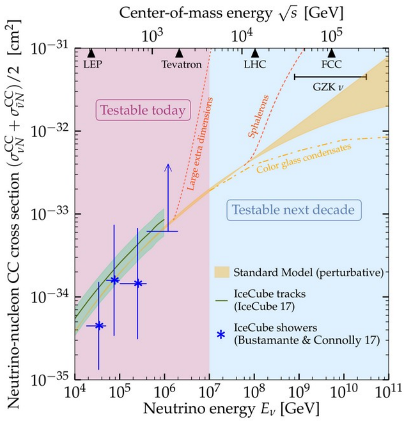
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



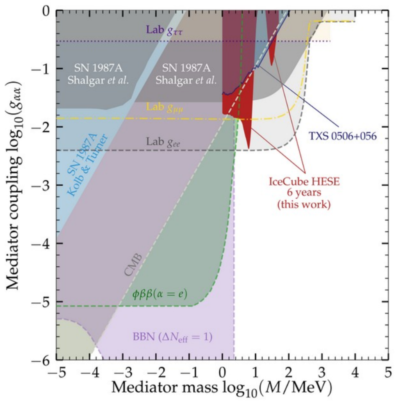
MB & Agarwalla, *PRL* 2019

ν TeV–EeV cross sections



MB & Connolly, *PRL* 2019

ν self-interactions



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

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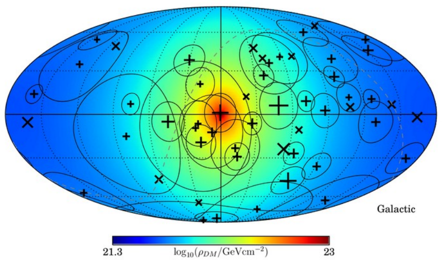

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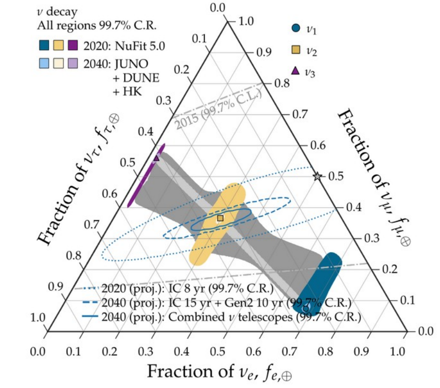

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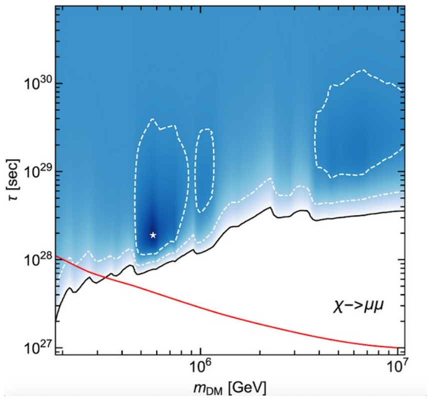

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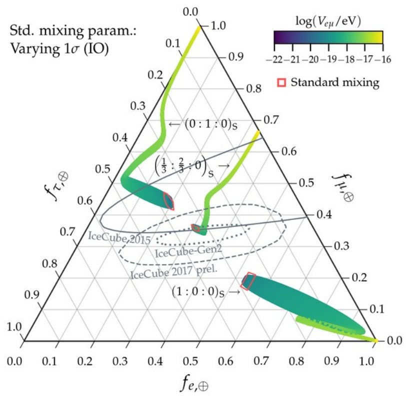
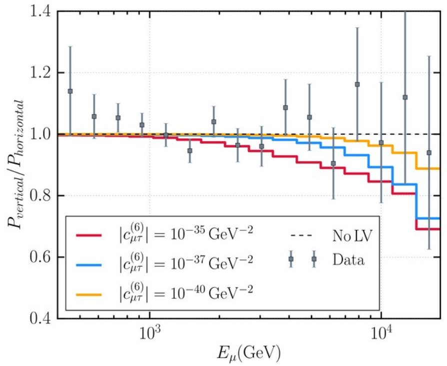


MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

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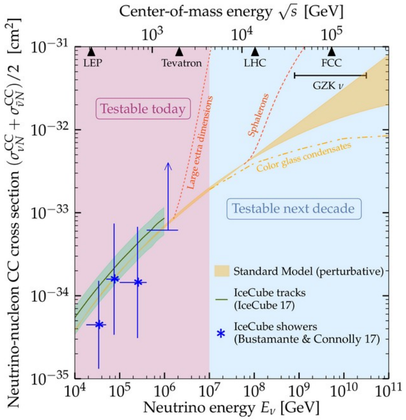
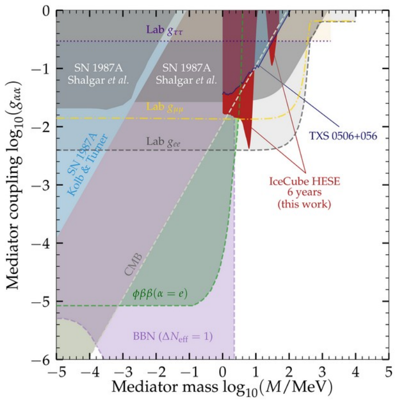


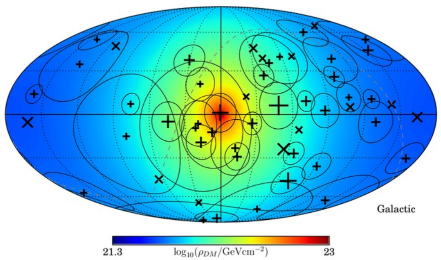
MB & Connolly, *PRL* 2019

ν self-interactions



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

ν scattering on Galactic DM



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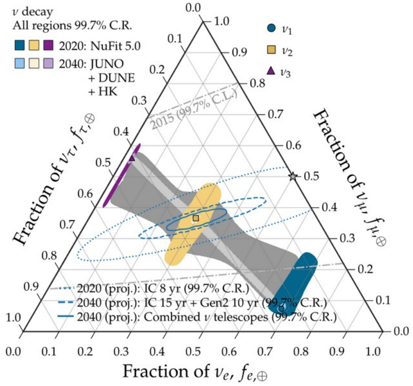
ν decay



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

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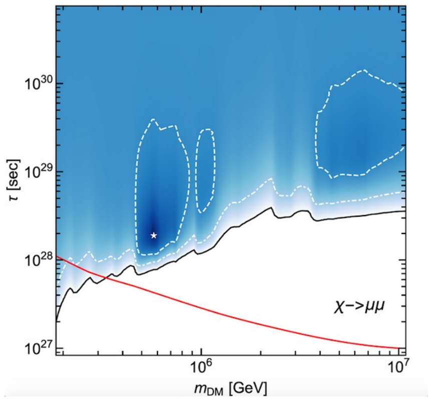

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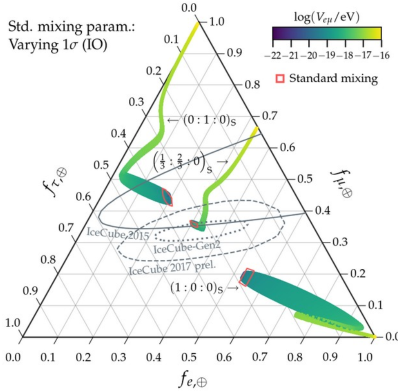

MB & Agarwalla, *PRL* 2019

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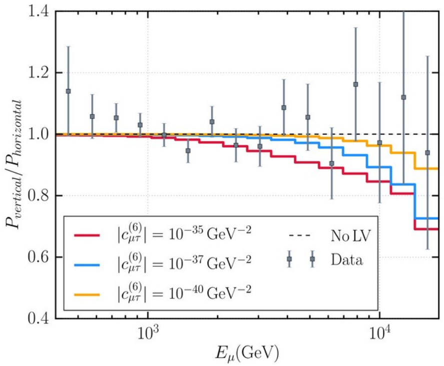
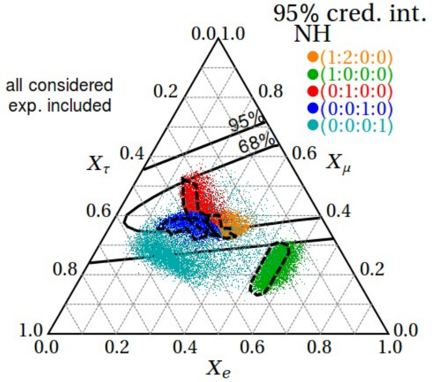


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Fundamental physics with high-energy cosmic neutrinos

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

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

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

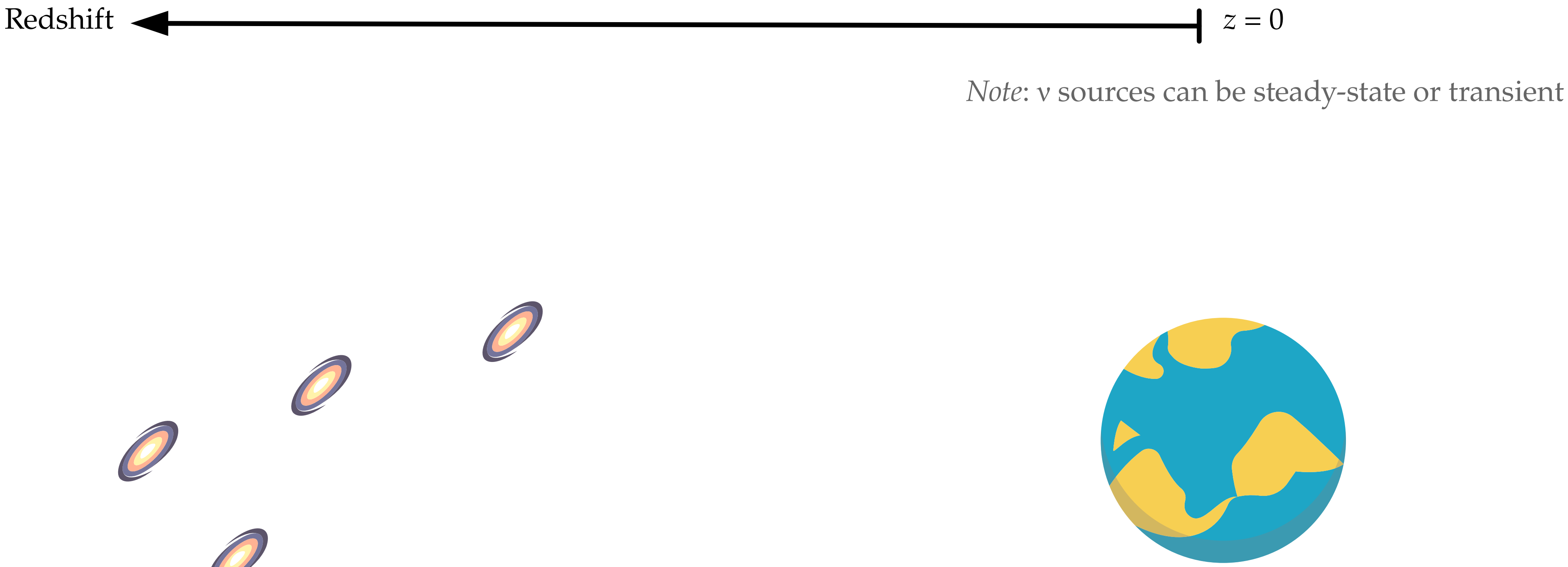
Fundamental physics with high-energy cosmic neutrinos

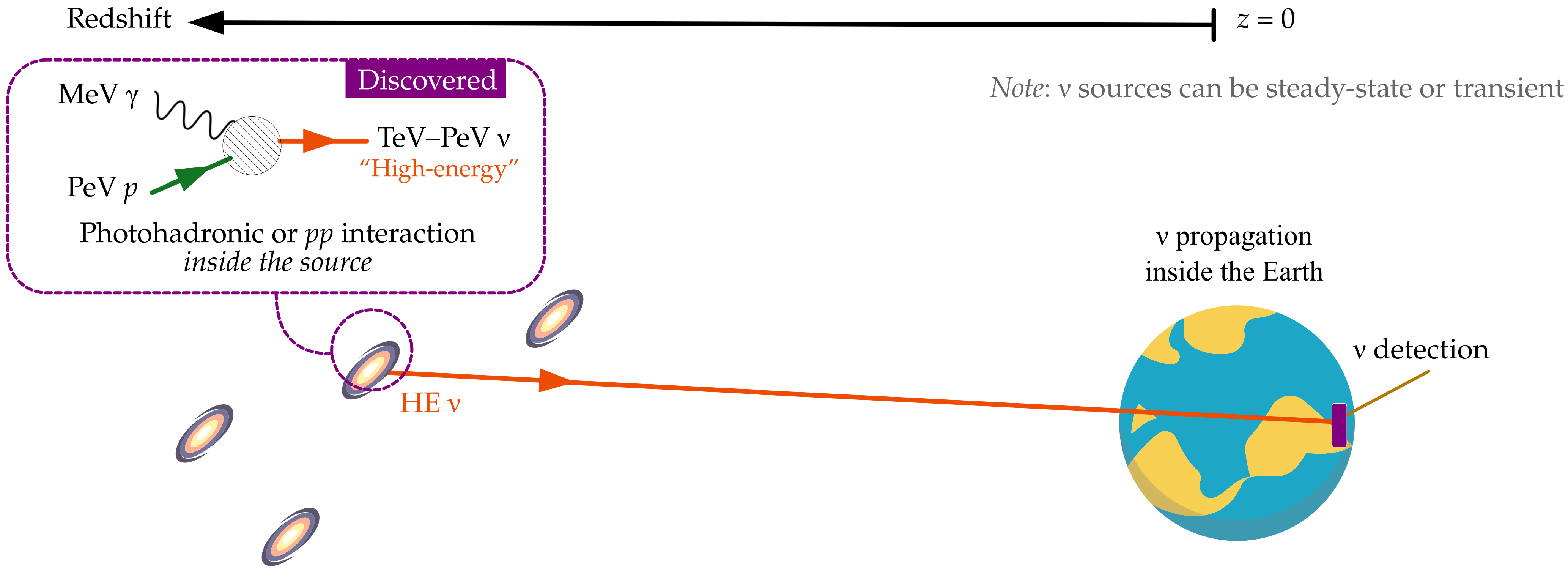
- Numerous new ν physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$

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

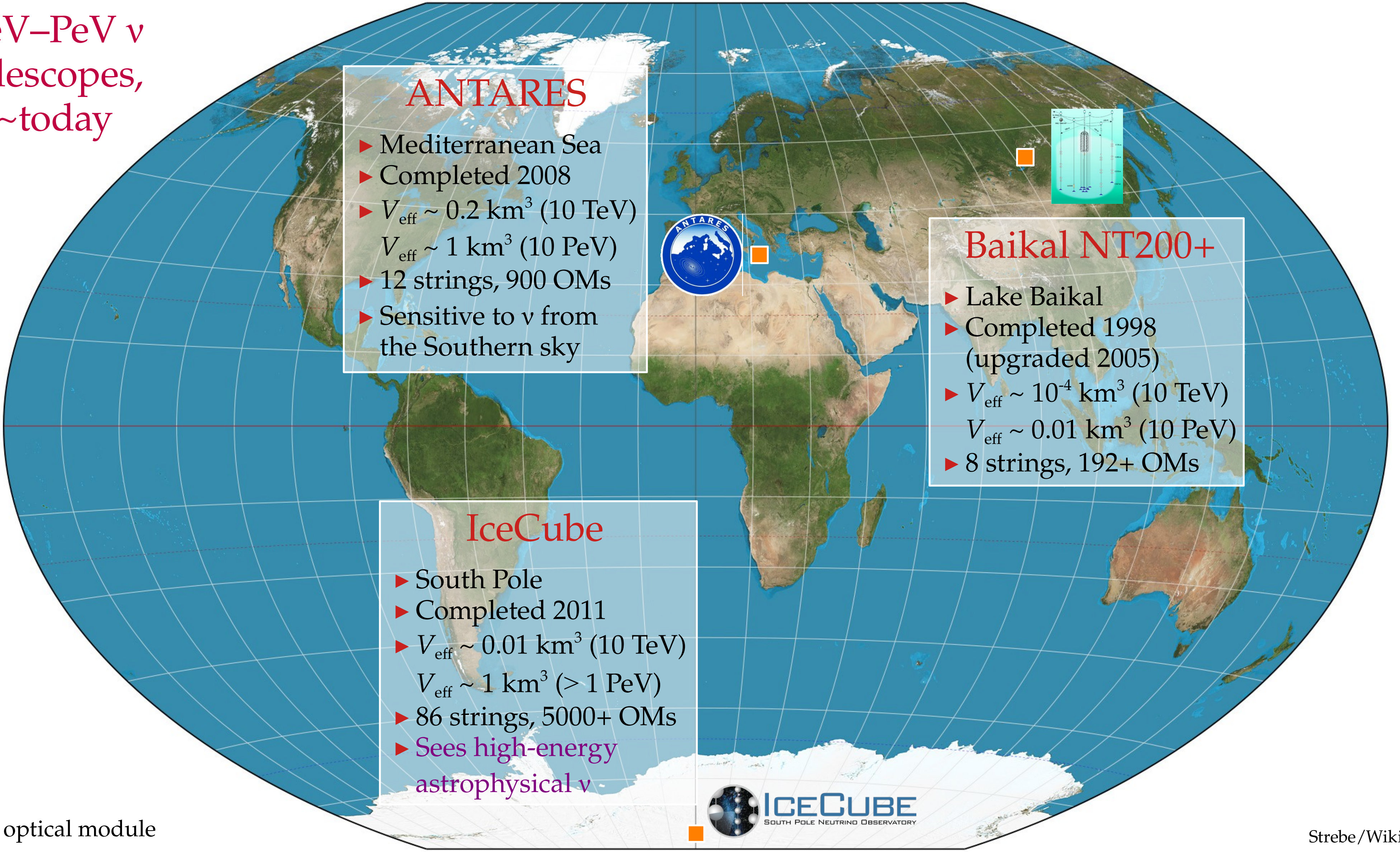
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\mathrm{PeV})^{-n} (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$

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


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


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

TeV–PeV ν telescopes, ~today



ANTARES

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

Baikal NT200+

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

IceCube

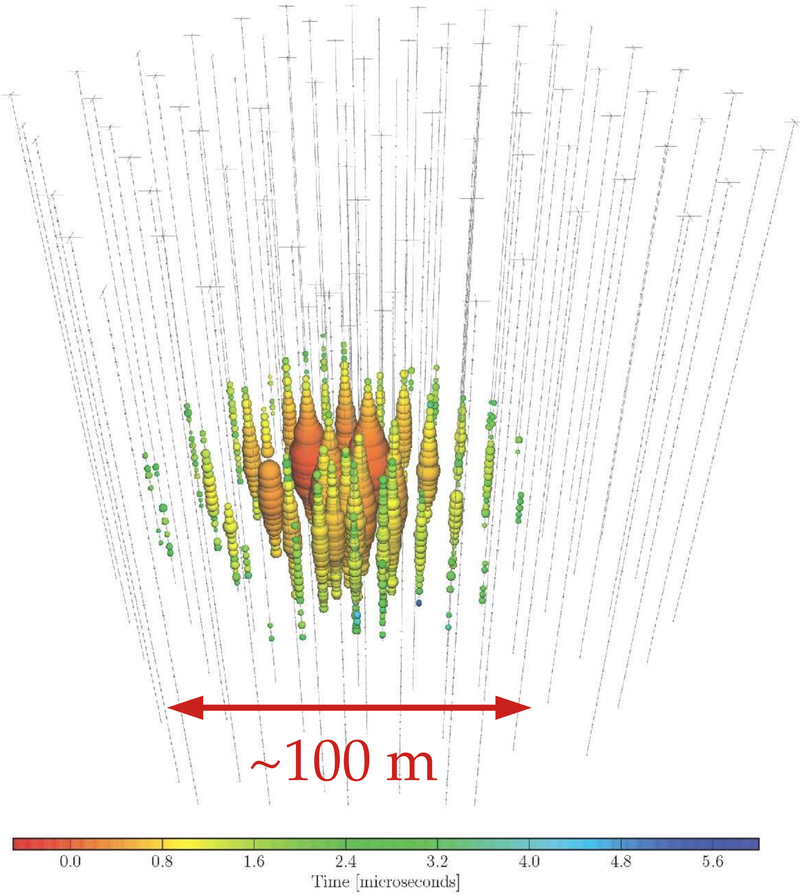
- South Pole
- Completed 2011
- $V_{\mathrm{eff}} \sim 0.01\ \mathrm{km}^3$ (10 TeV)
  $V_{\mathrm{eff}} \sim 1\ \mathrm{km}^3$ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

OM: optical module

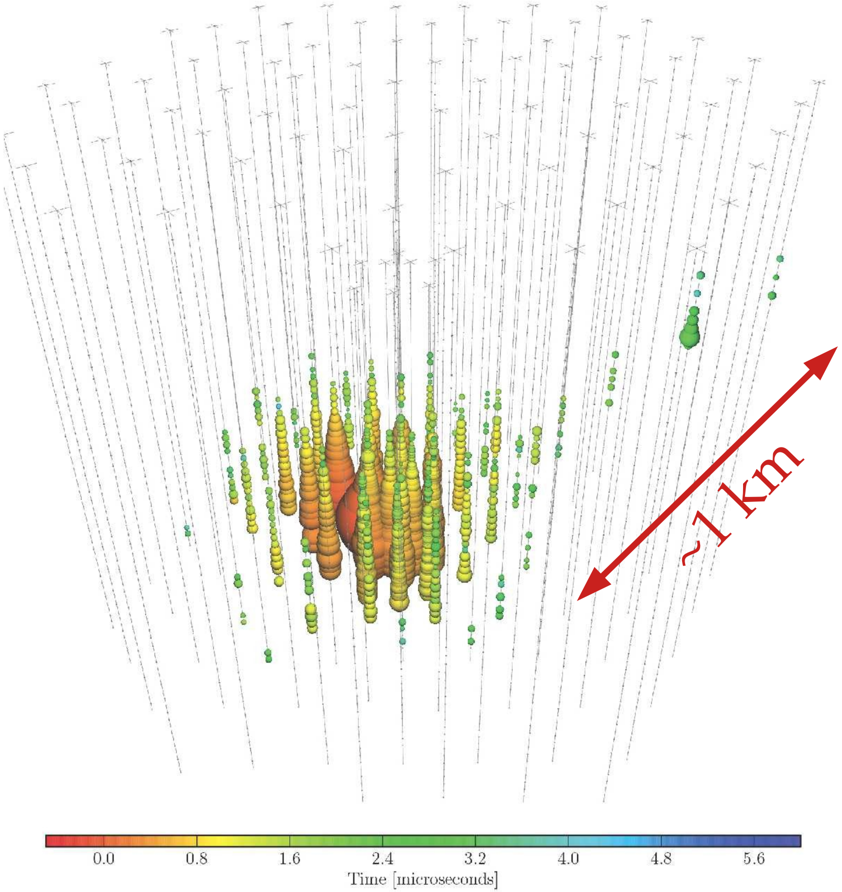
Strebe/Wikipedia

Shower
(mainly from ν_e and ν_τ)

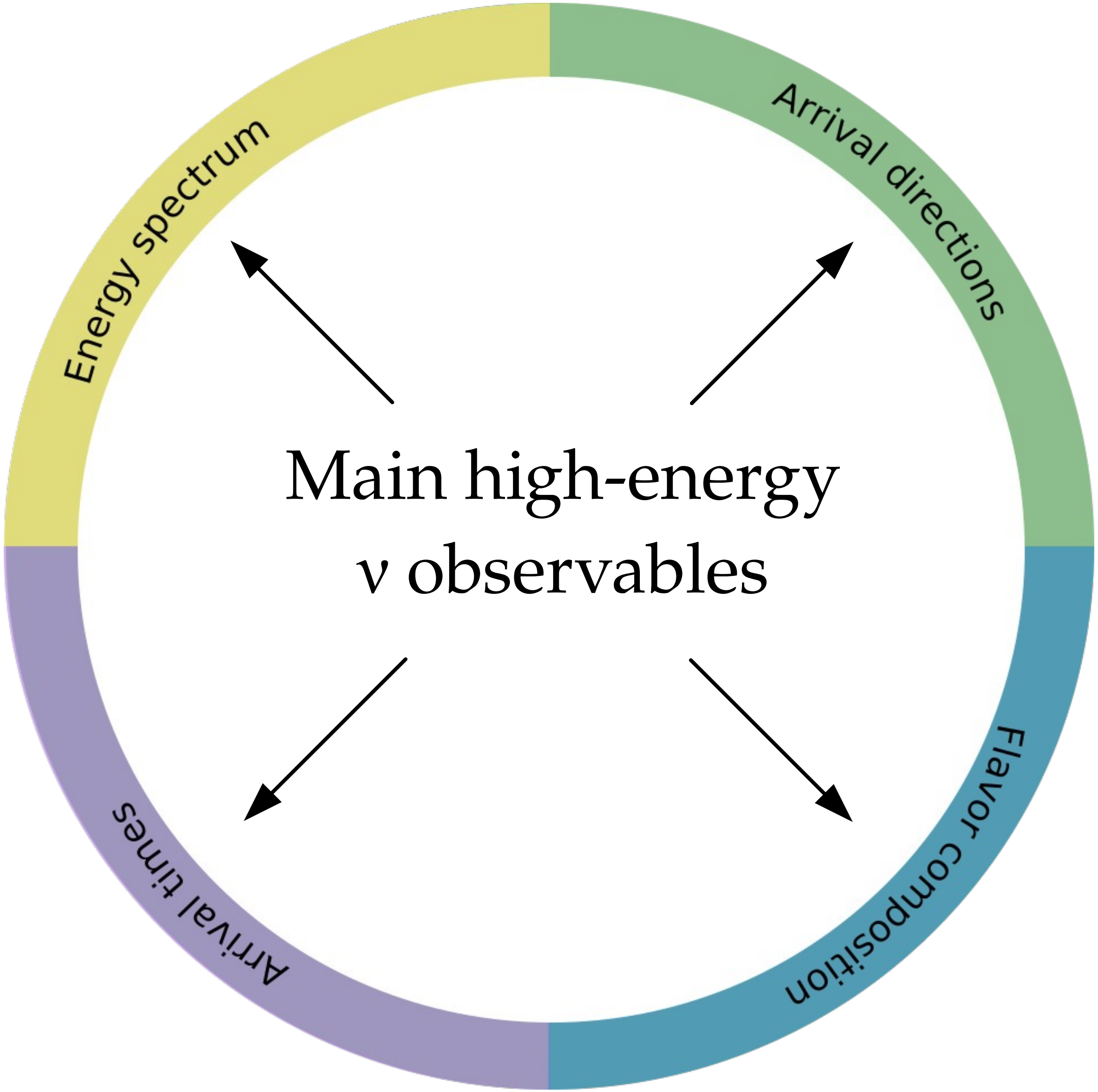


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

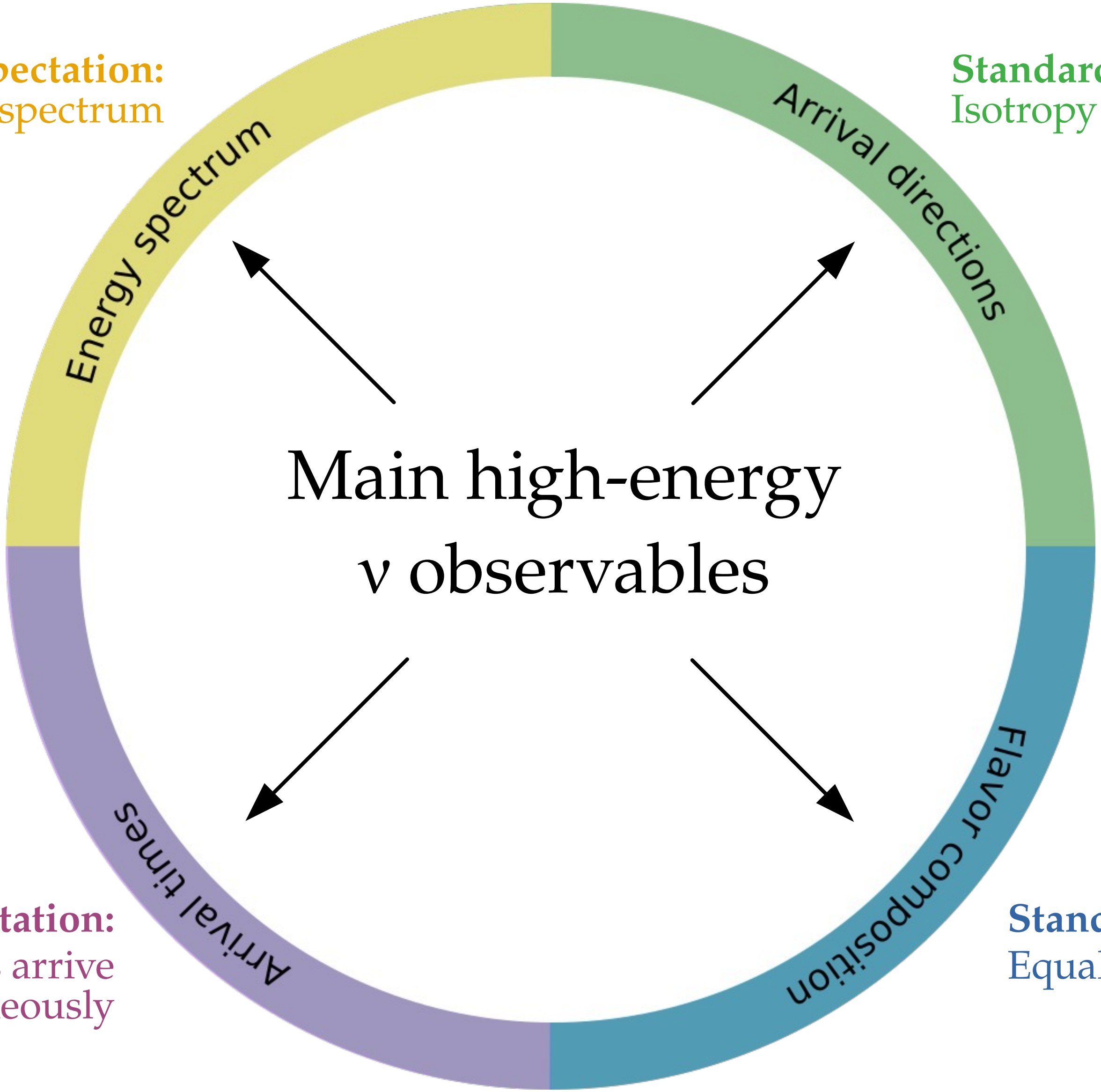


Angular resolution: < 1°


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

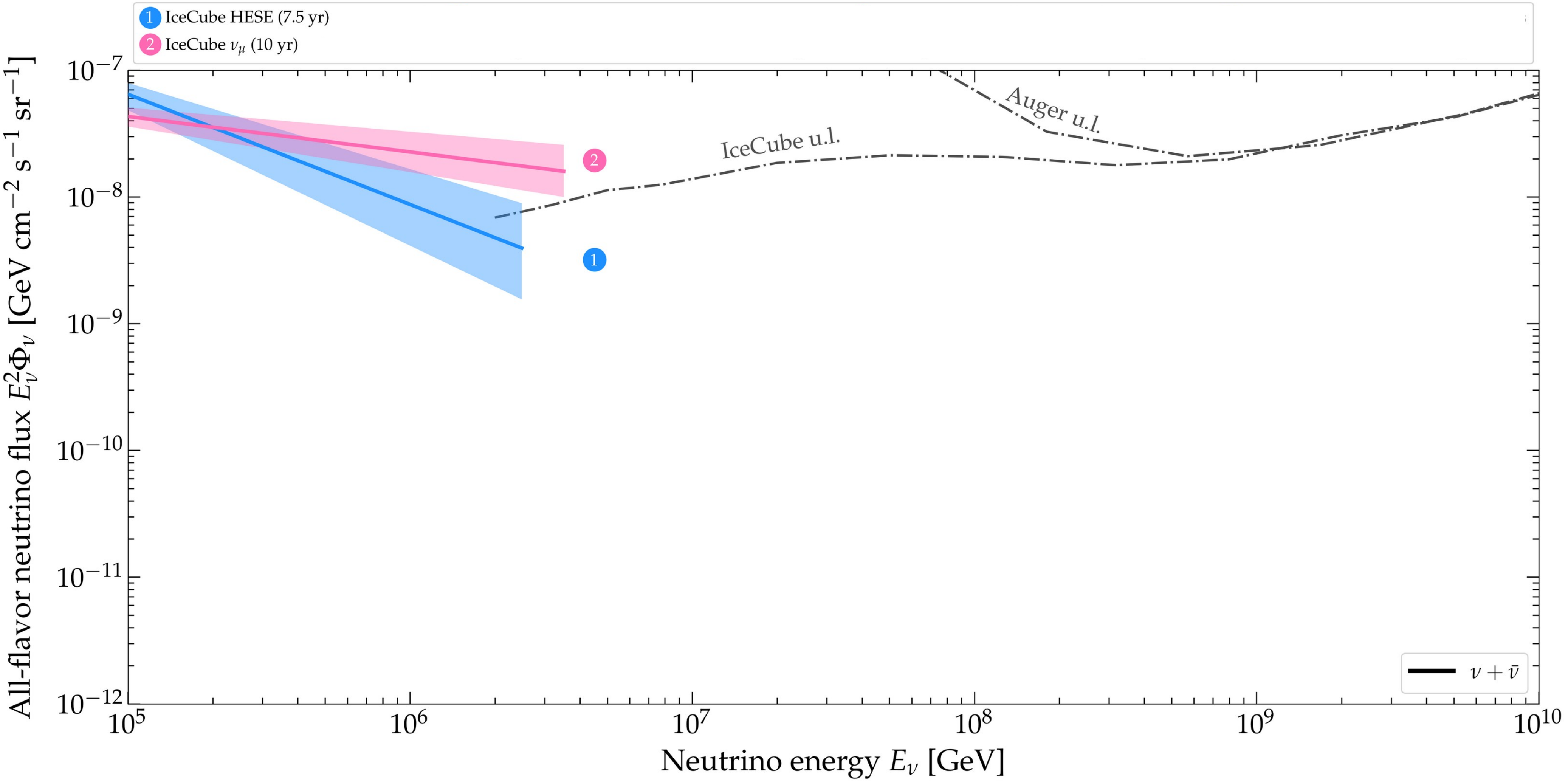
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ


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

Today

TeV–PeV ν

Today

TeV–PeV ν

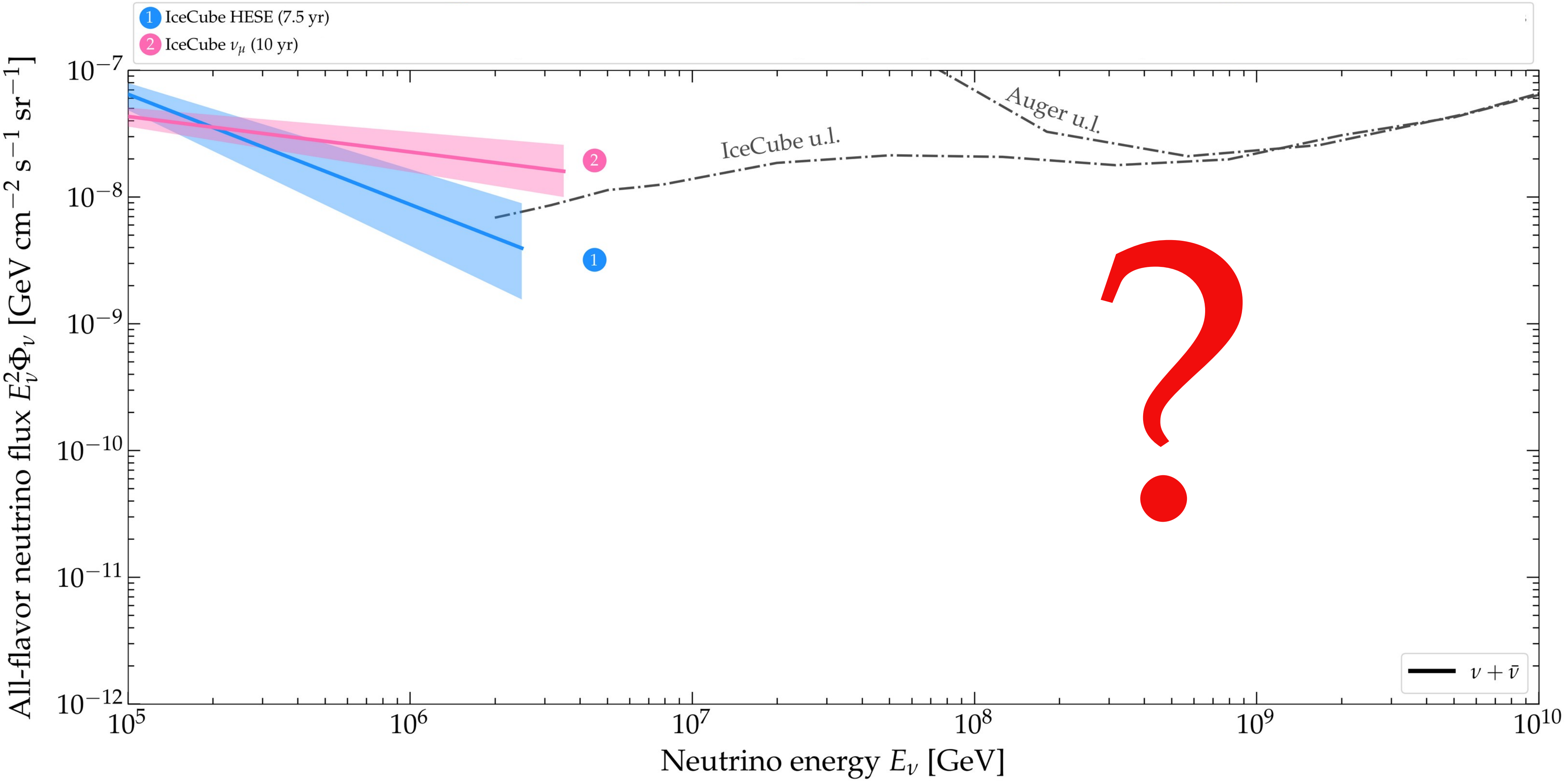
Turn predictions
into data-driven tests

Today

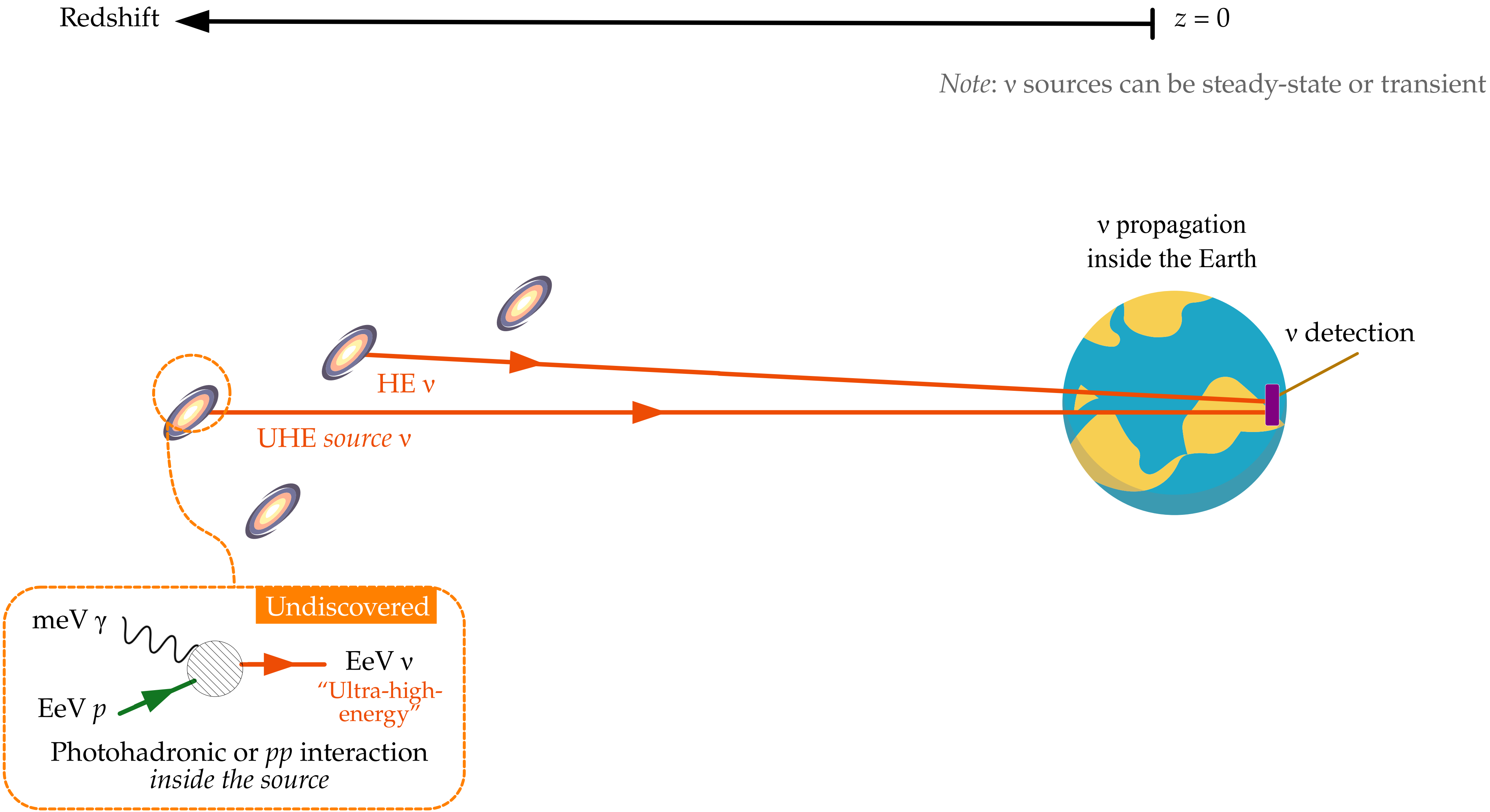
TeV–PeV ν

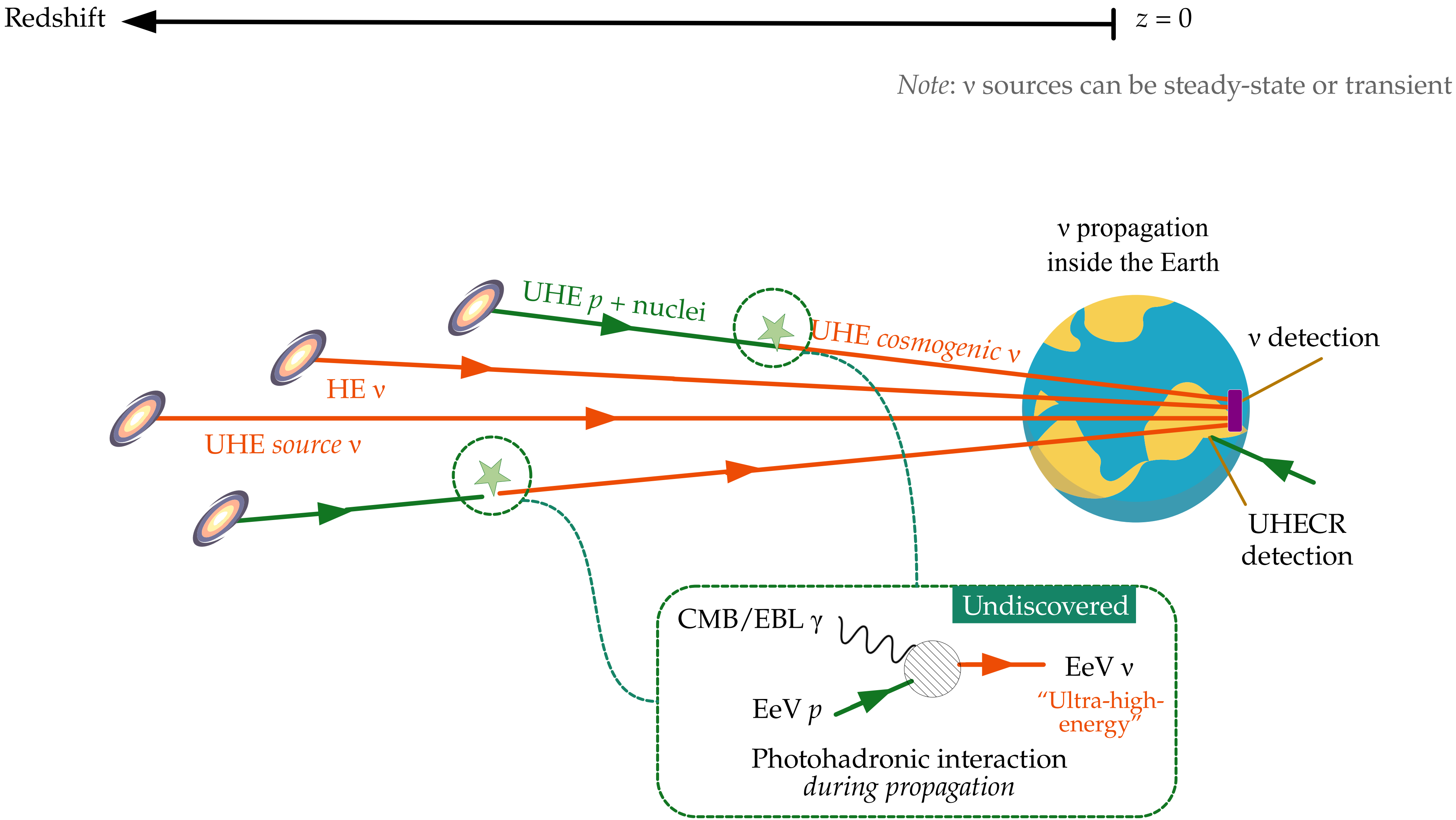
Turn predictions
into data-driven tests

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

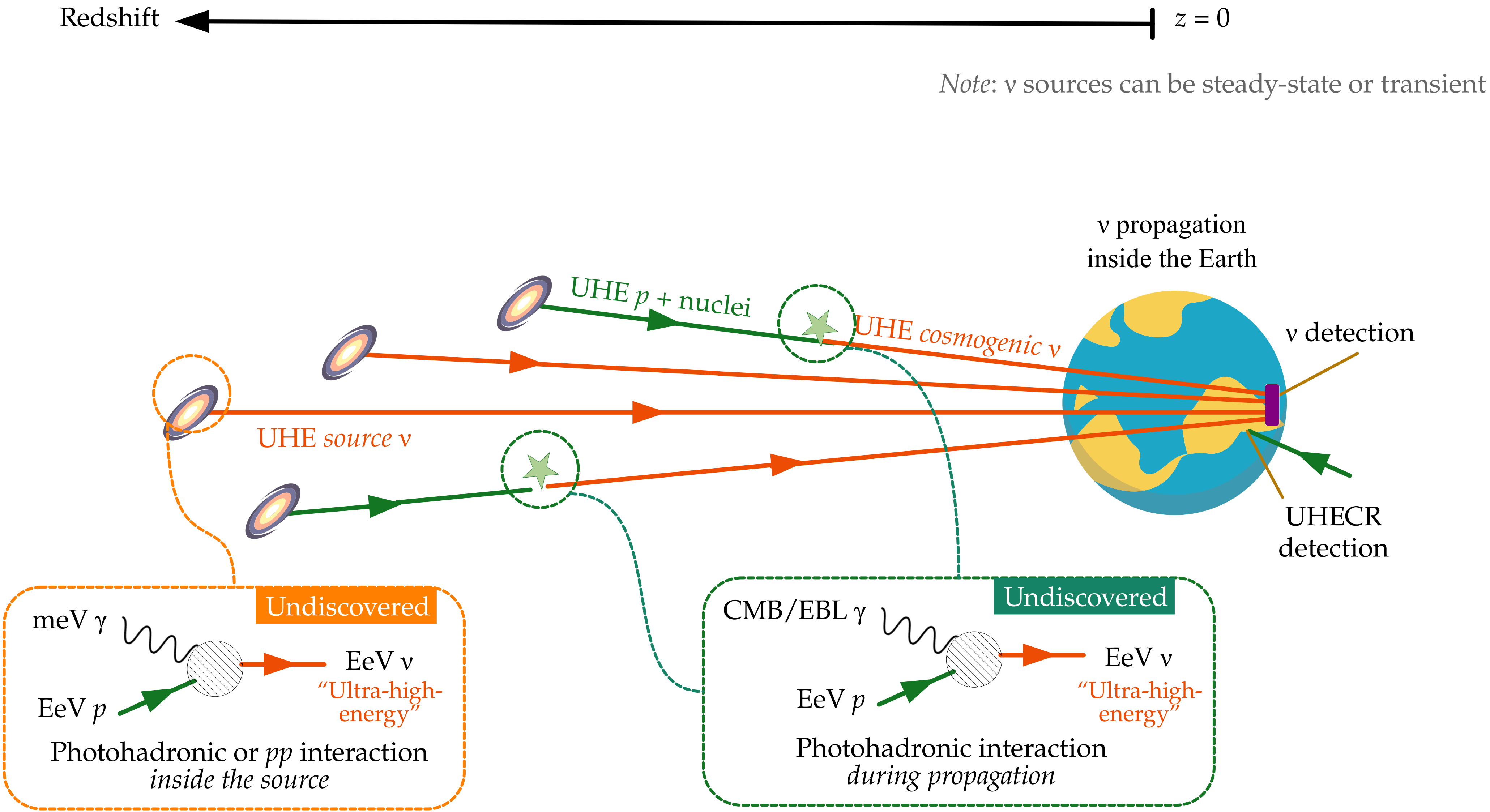


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
1
2
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]


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



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


Redshift
$z = 0$
Note: ν sources can be steady-state or transient
UHE p + nuclei
UHE *cosmogenic* ν
UHE *source* ν
ν propagation inside the Earth
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meV γ
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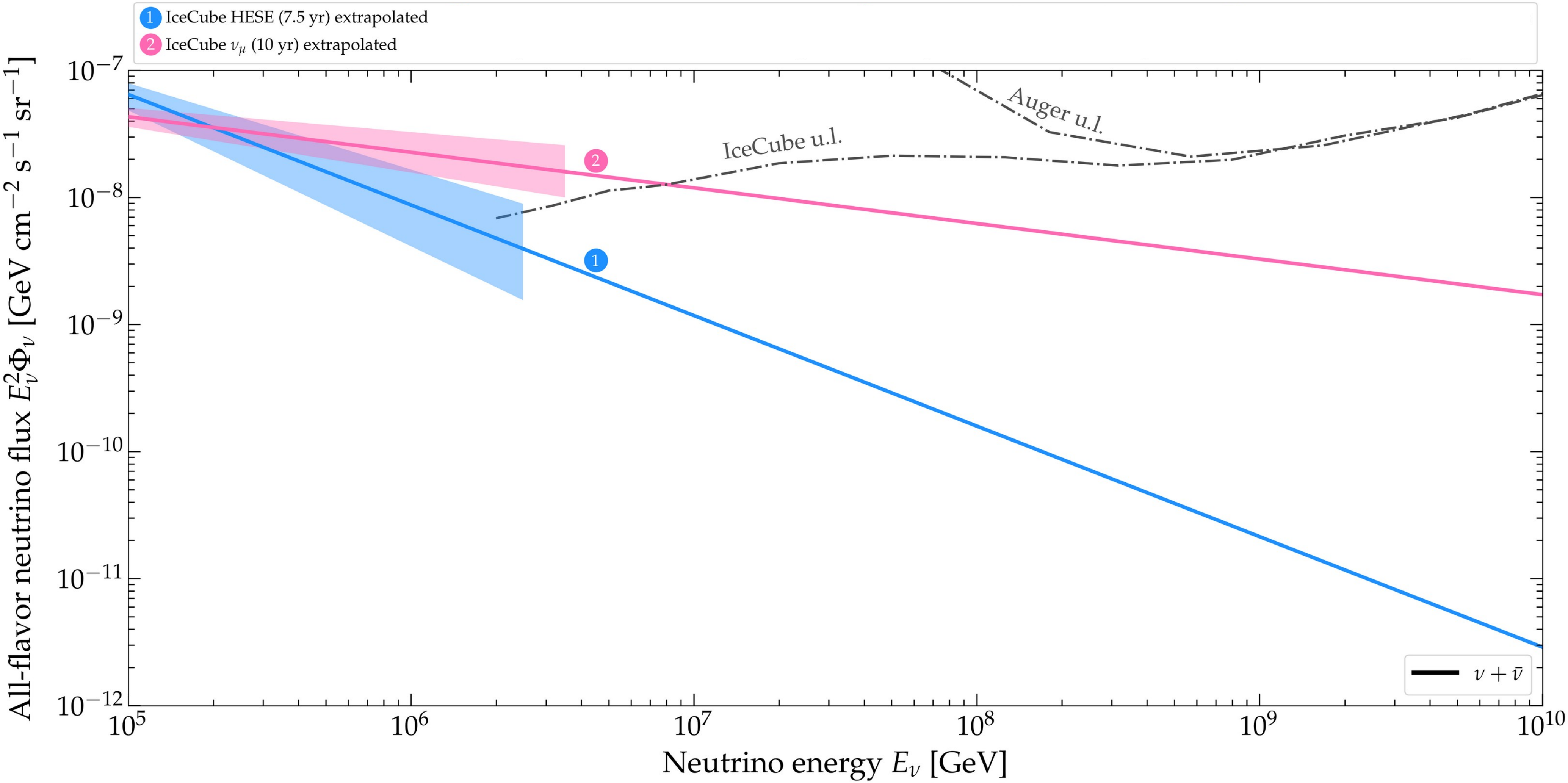

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
1
2
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
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10^{-9}
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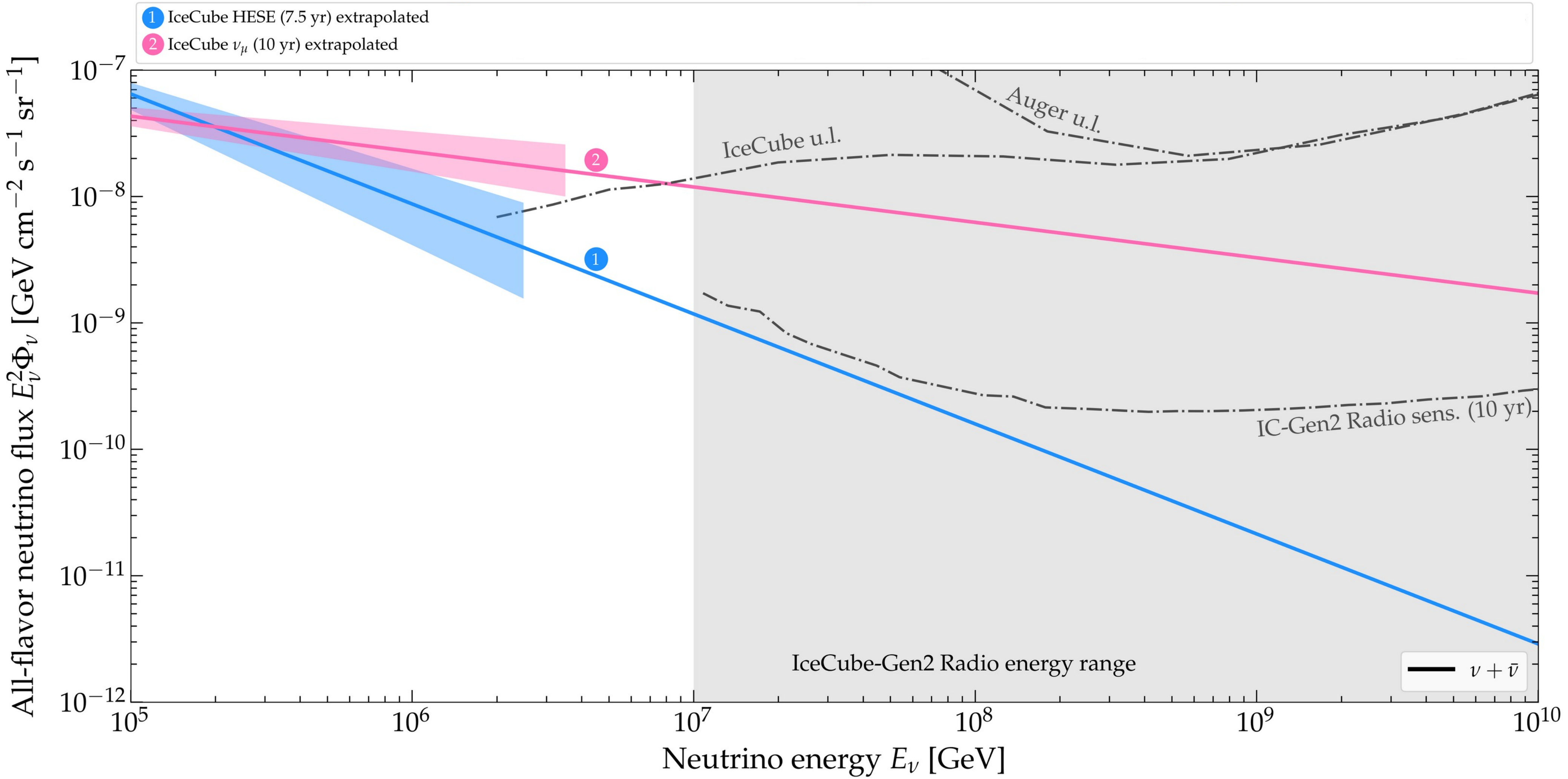
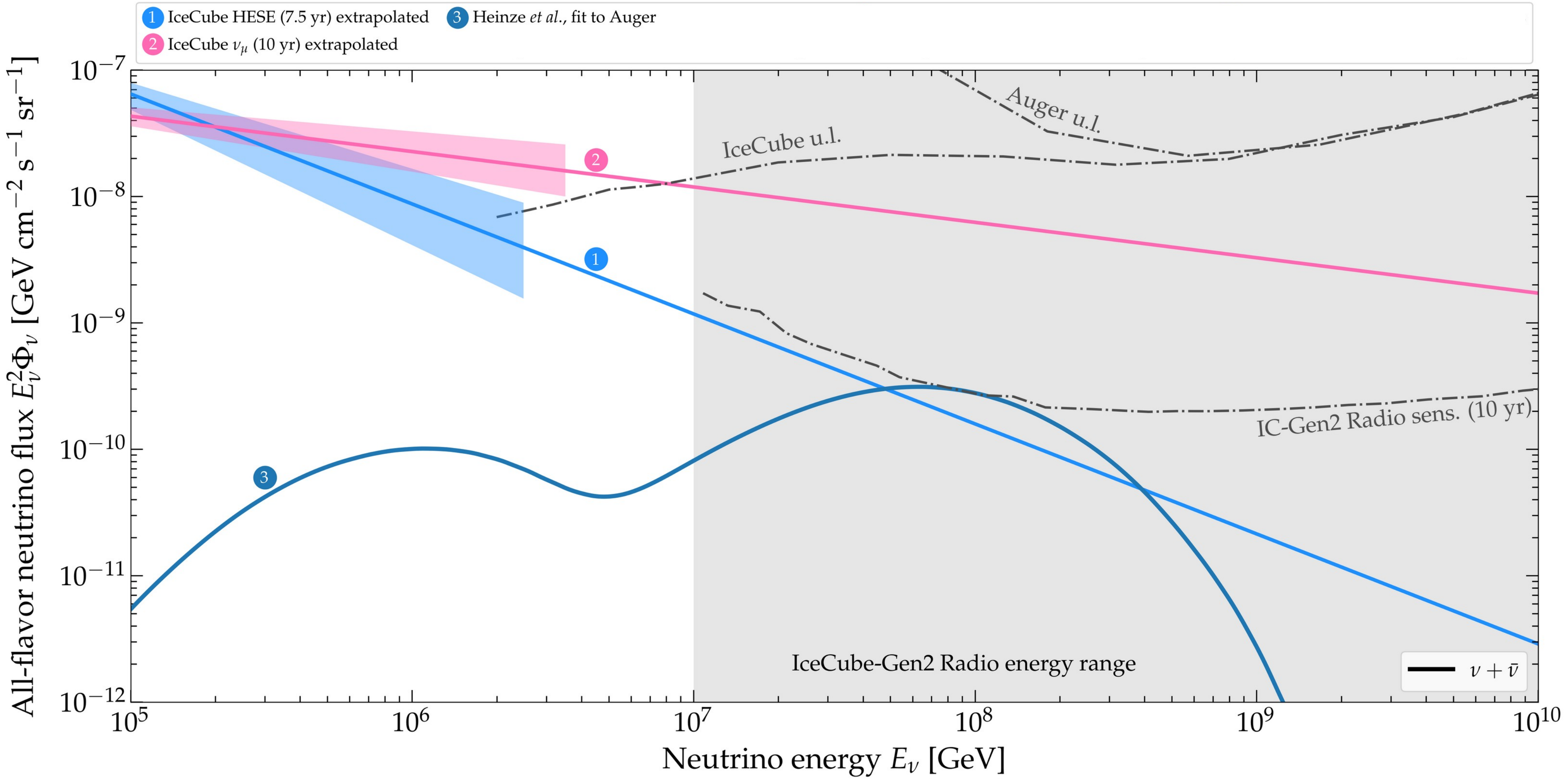
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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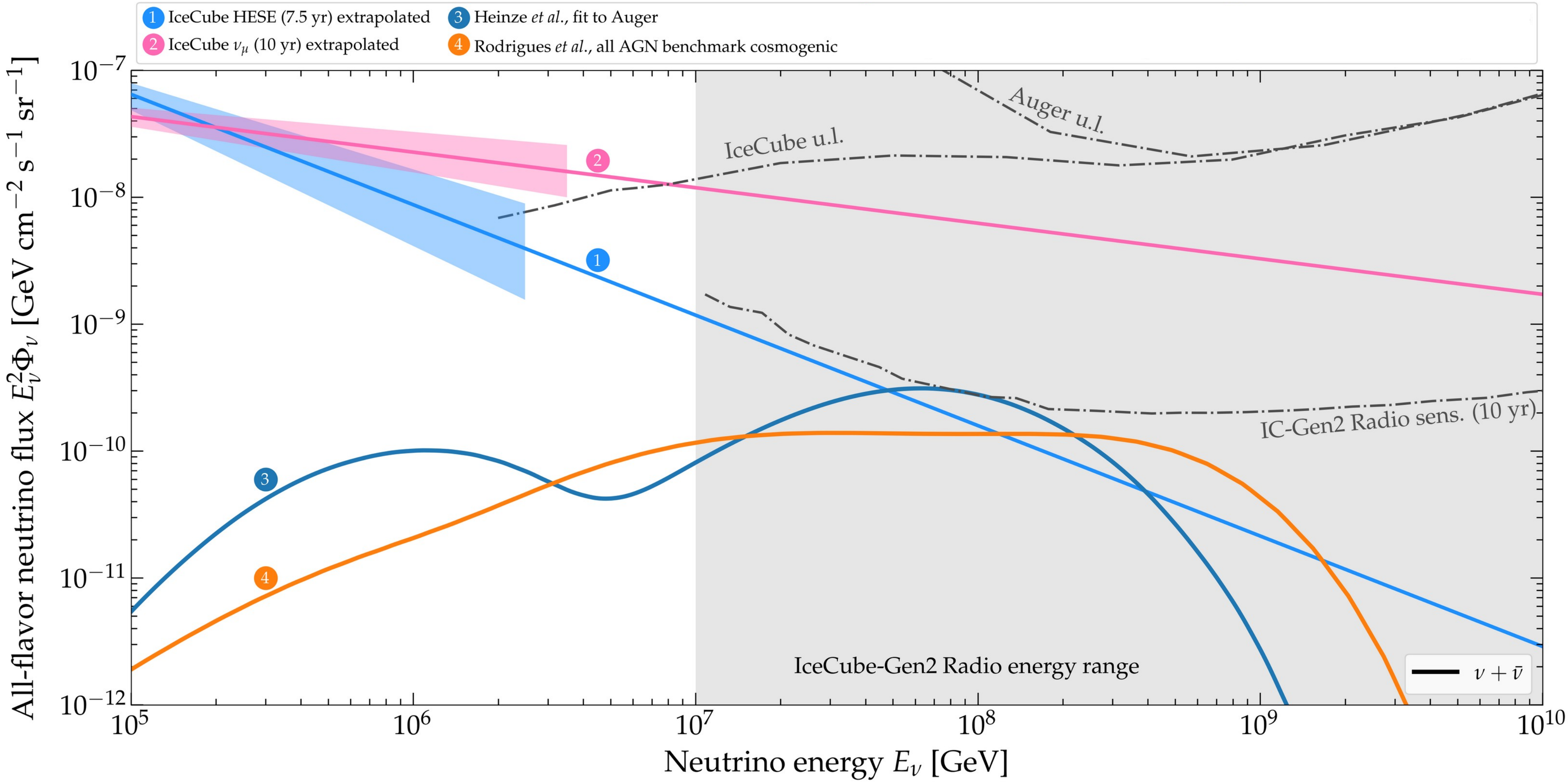
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^5
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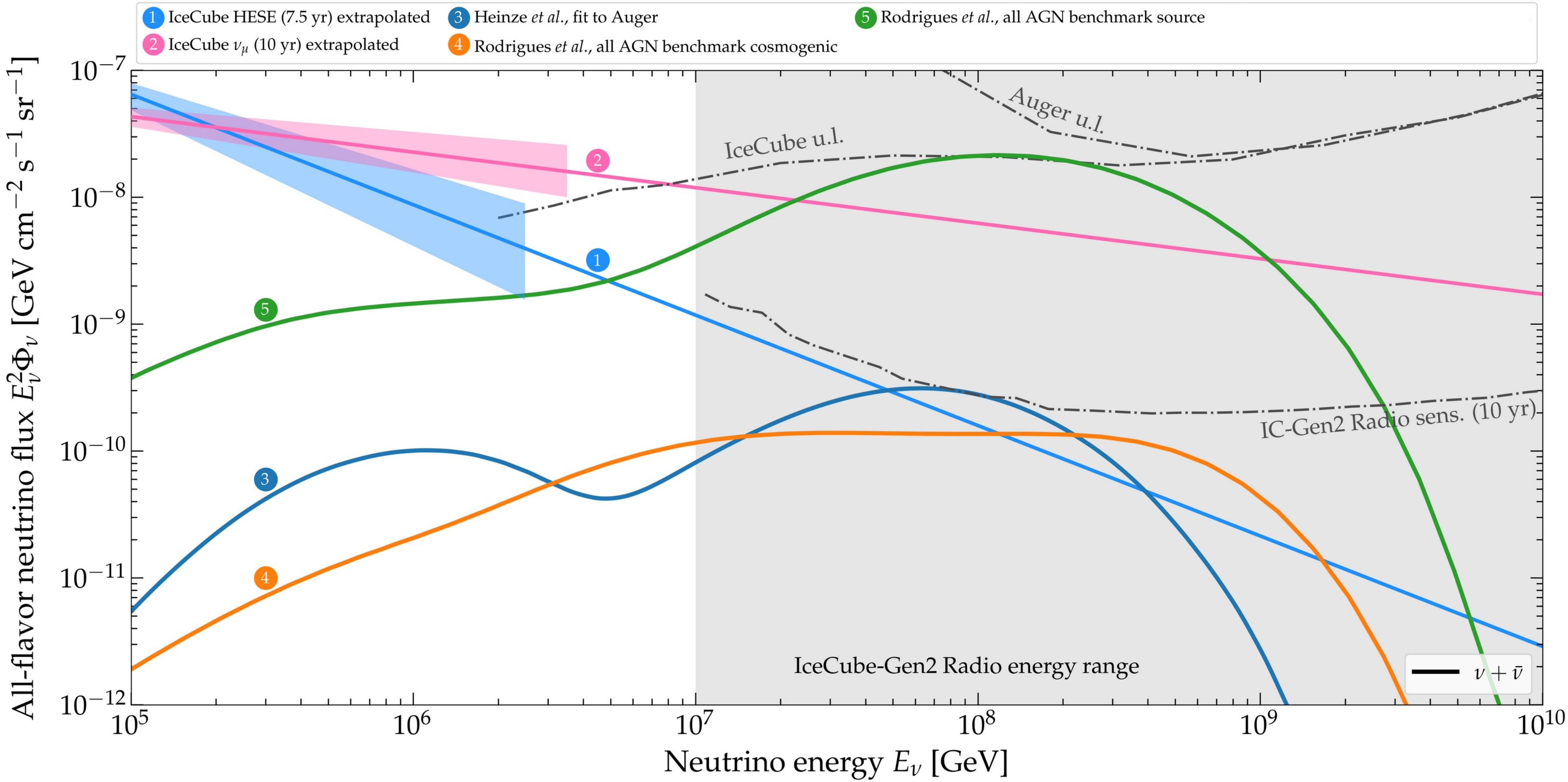

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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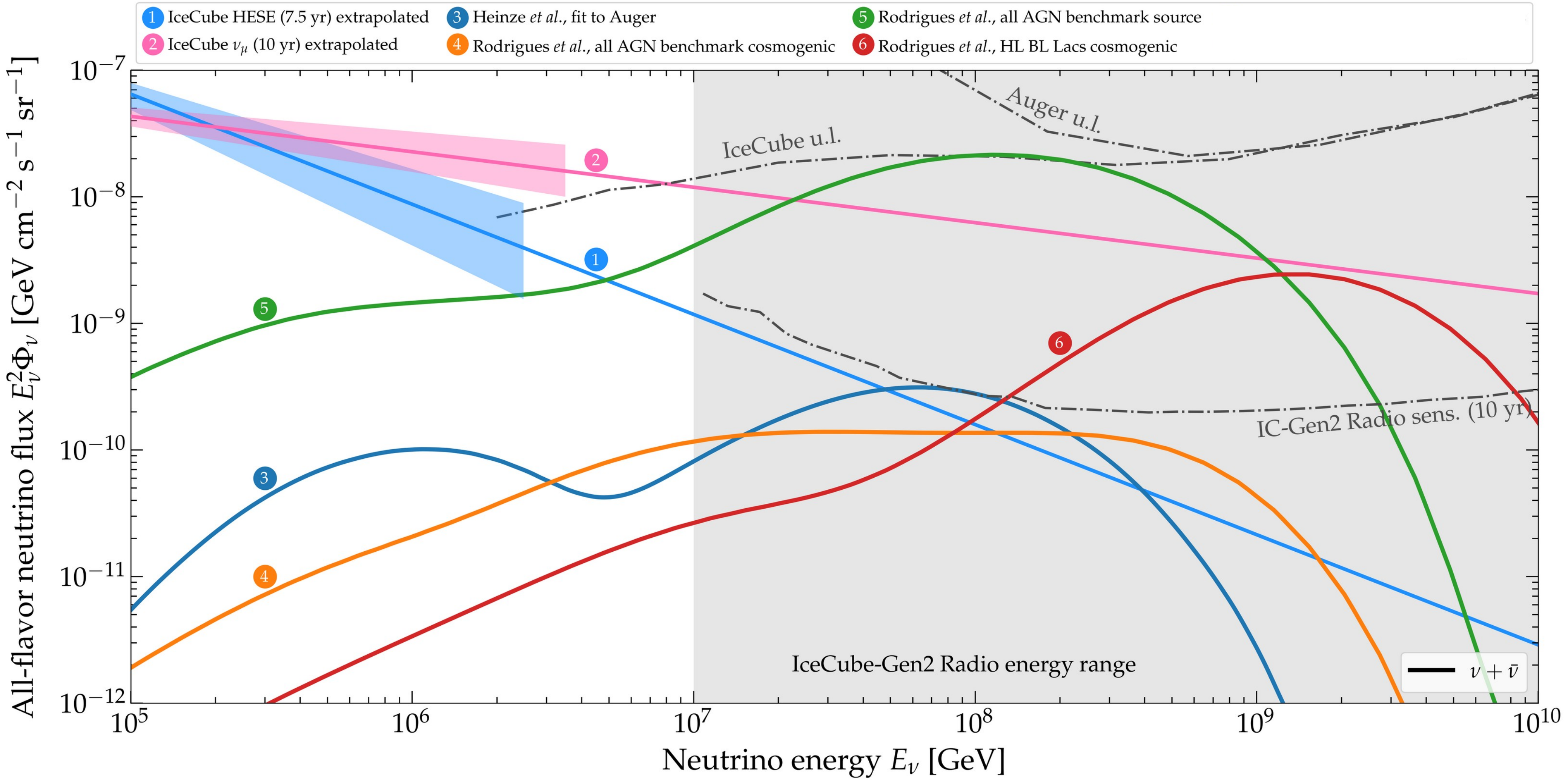
10^7
10^8
10^9
10^{10}



1 IceCube HESE (7.5 yr) extrapolated
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3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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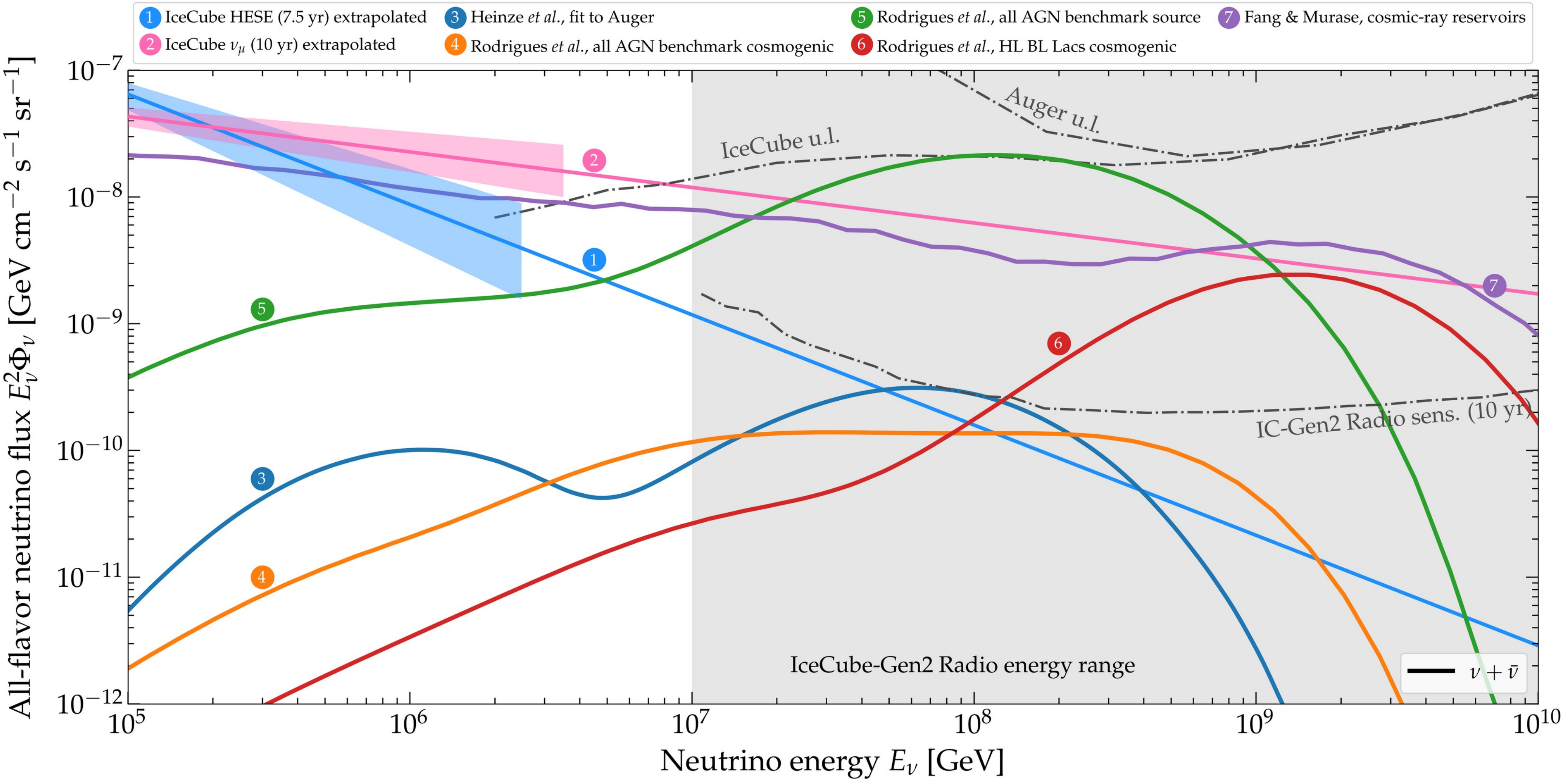

1 IceCube HESE (7.5 yr) extrapolated
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3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
Auger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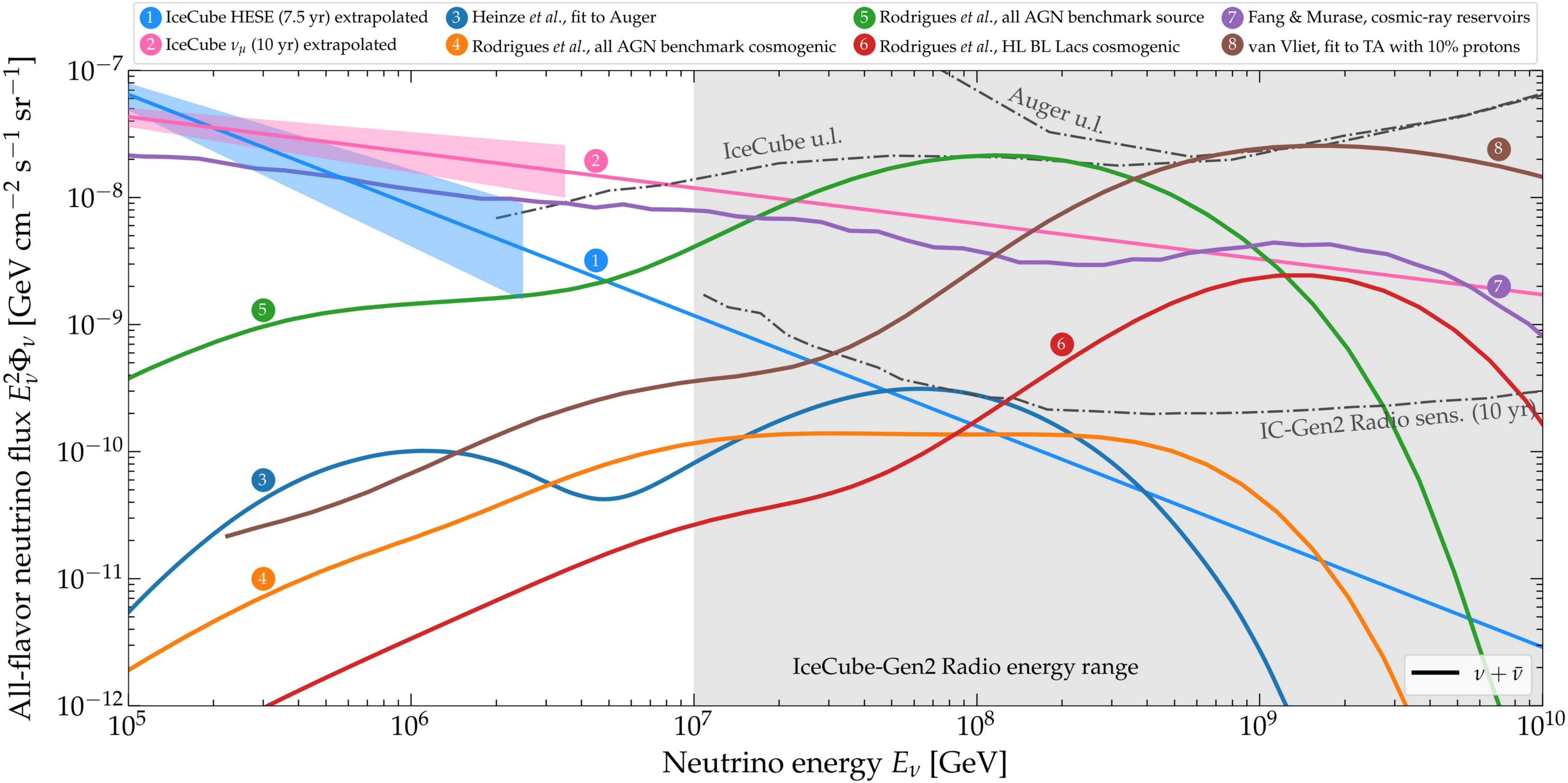
1 IceCube HESE (7.5 yr) extrapolated
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3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van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

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today

TeV–PeV ν

Turn predictions
into data-driven tests

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

Next decade

> 100-PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:
Bigger detectors $\rightarrow$ larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

$>$ 100-PeV ν

Make predictions for
a new energy regime

Key developments:
Discovery
New detection techniques
Better UHE ν flux predictions

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:
Bigger detectors → larger statistics
Better reconstruction
Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

<u>Key developments</u>:
Discovery
New detection techniques
Better UHE ν flux predictions

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

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

Note: Not an exhaustive list

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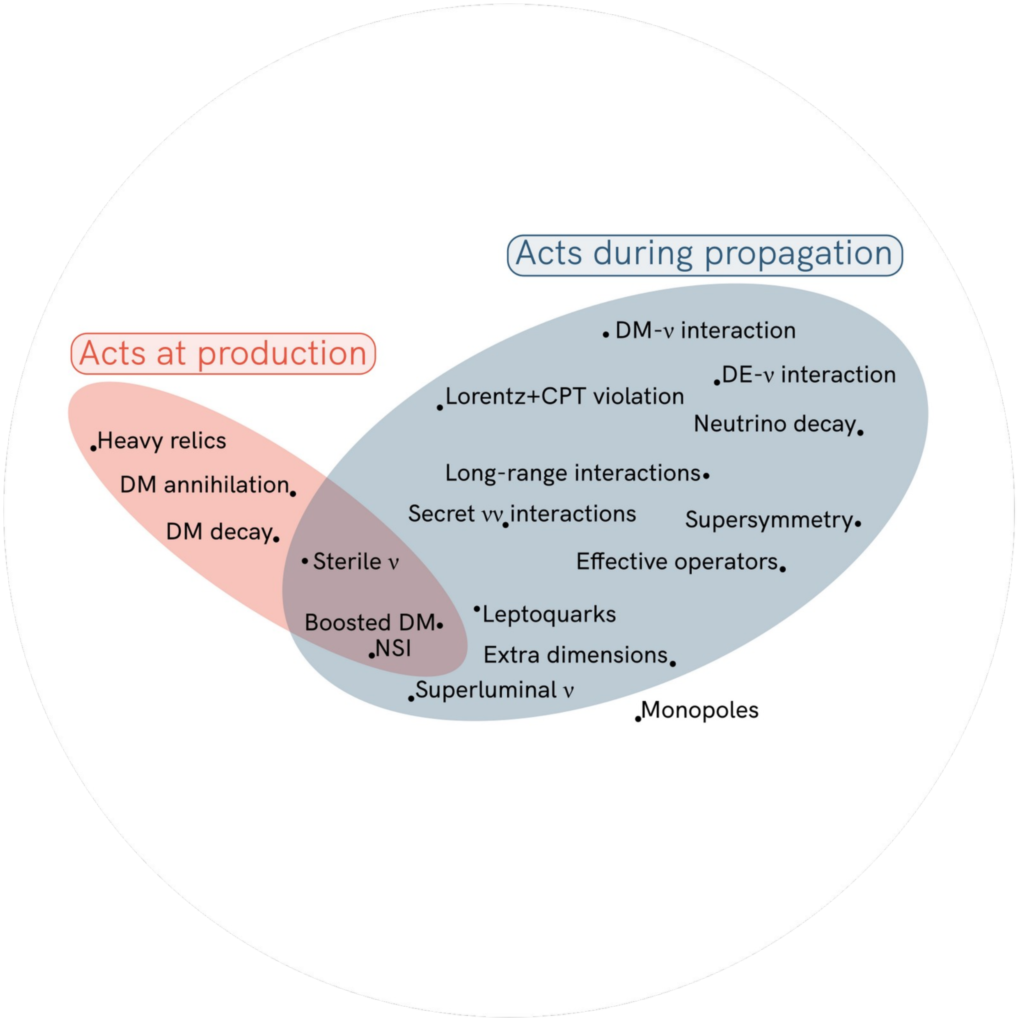
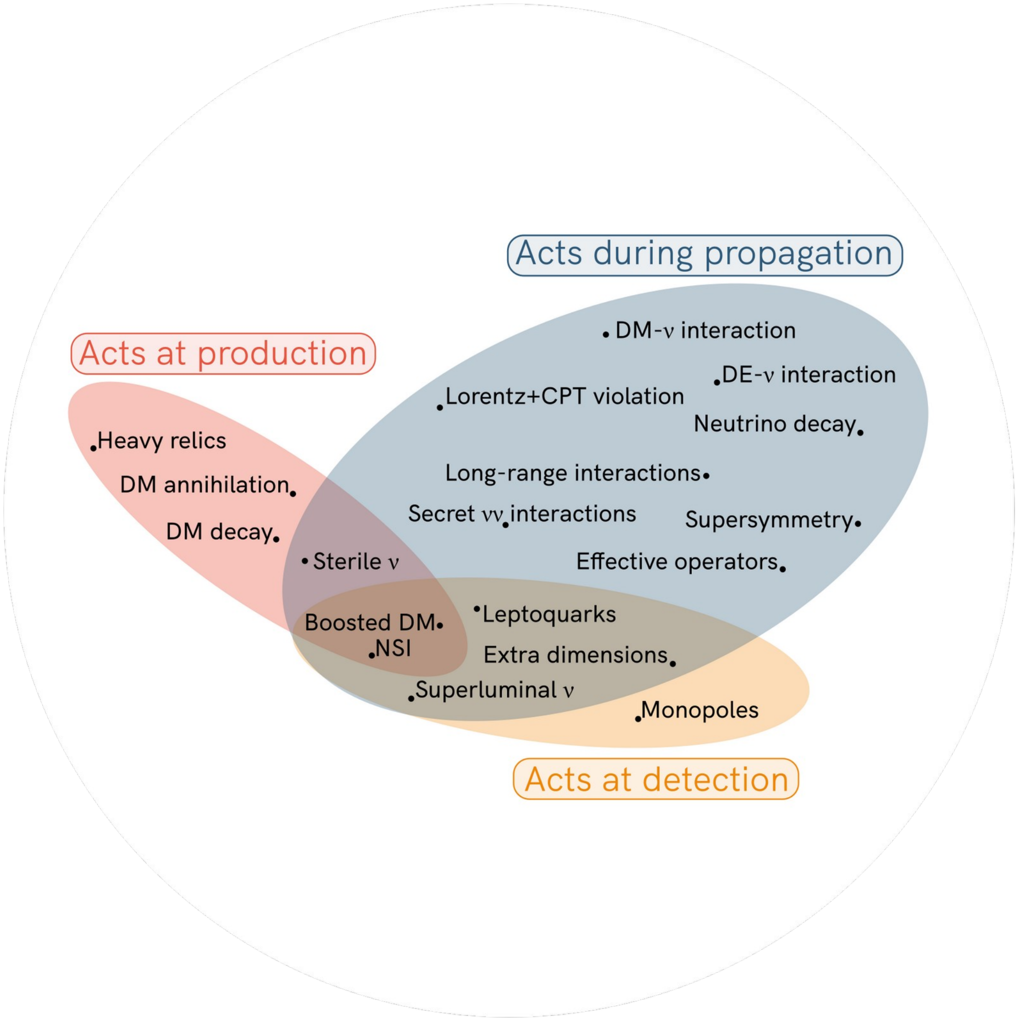


Note: Not an exhaustive list



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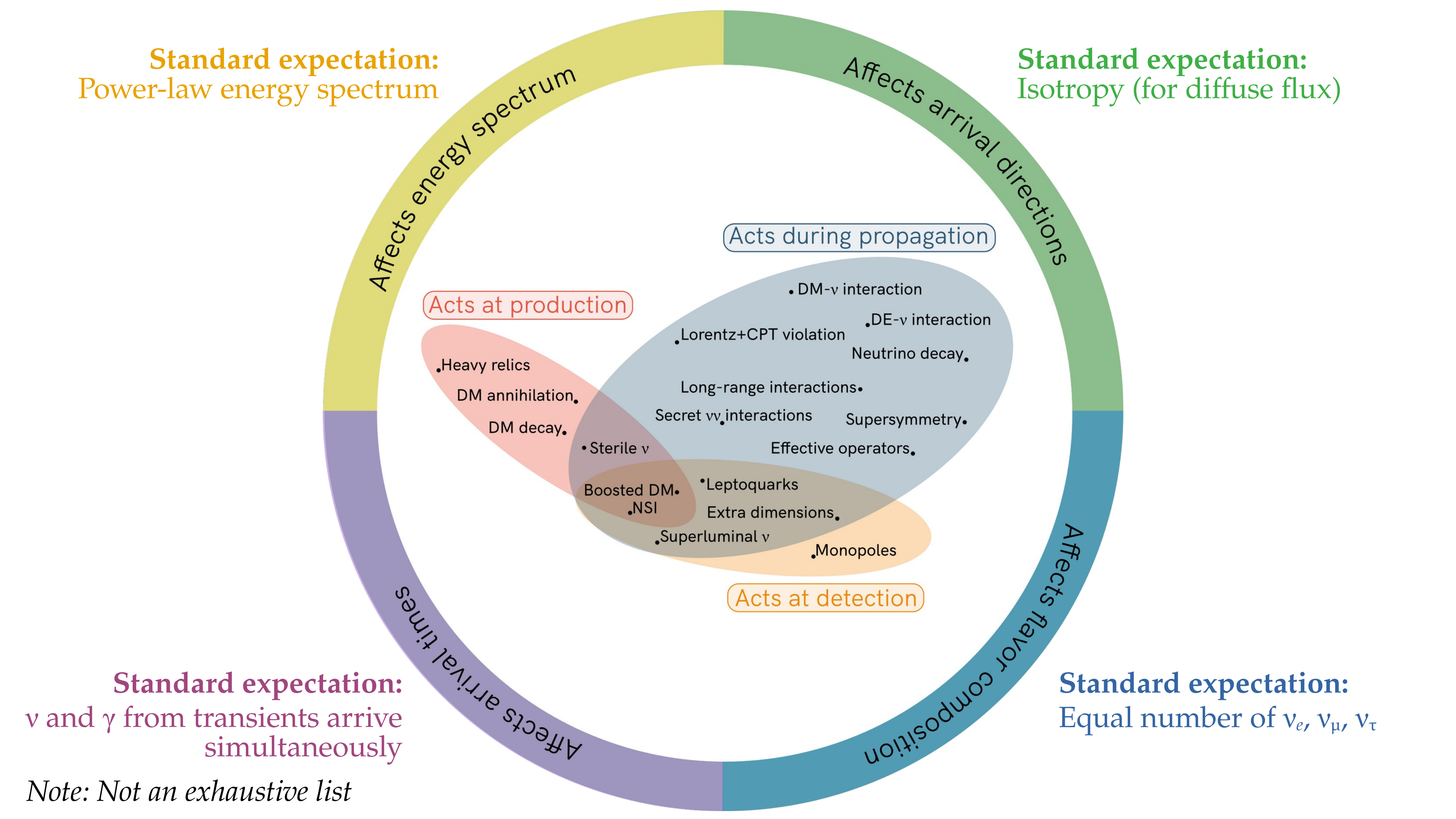
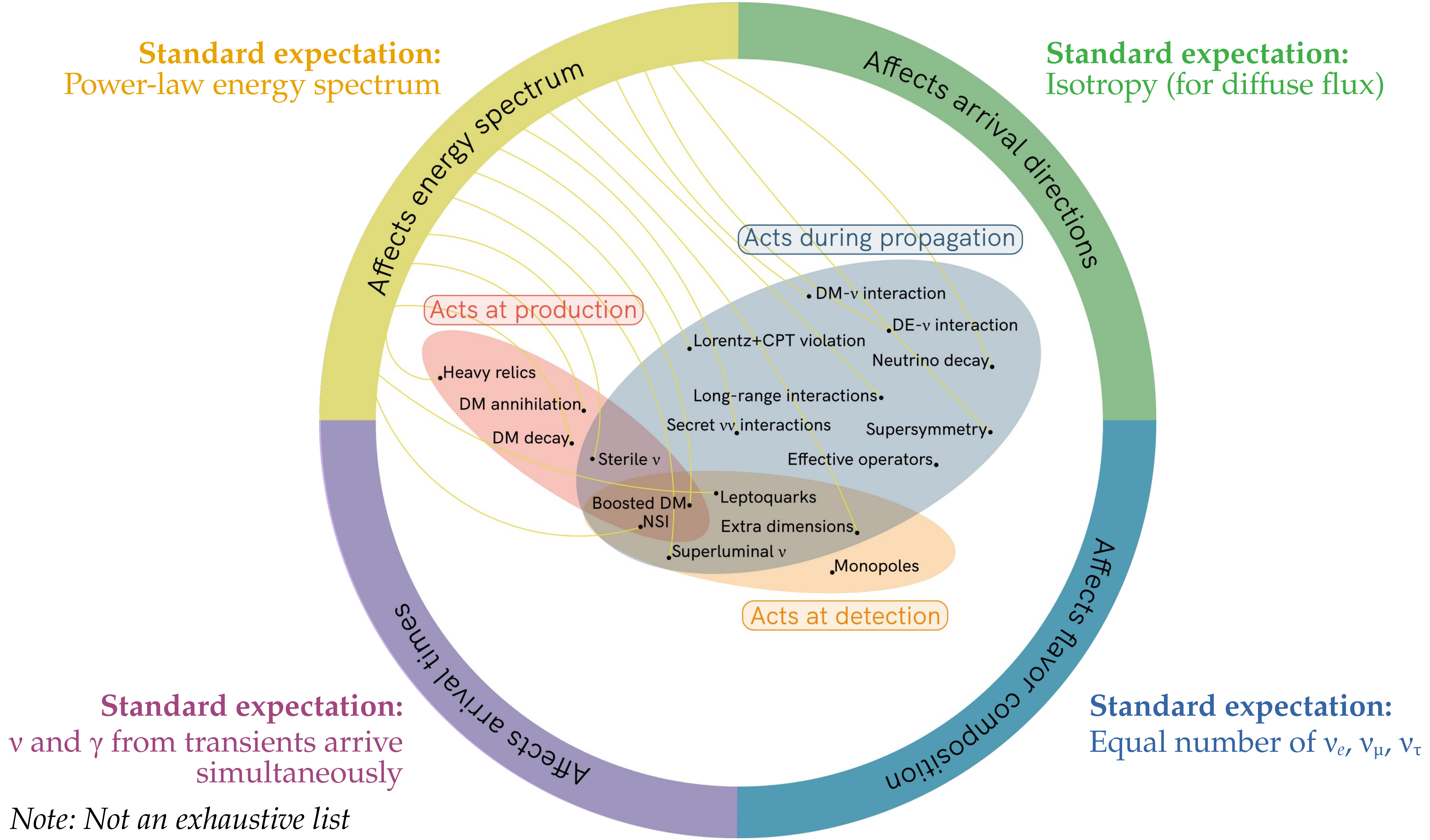

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ
Note: Not an exhaustive list
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
Heavy relics
DM annihilation
DM decay
Sterile ν
Boosted DM
NSI
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Long-range interactions
Secret νν interactions
Supersymmetry
Effective operators
Leptoquarks
Extra dimensions
Superluminal ν
Monopoles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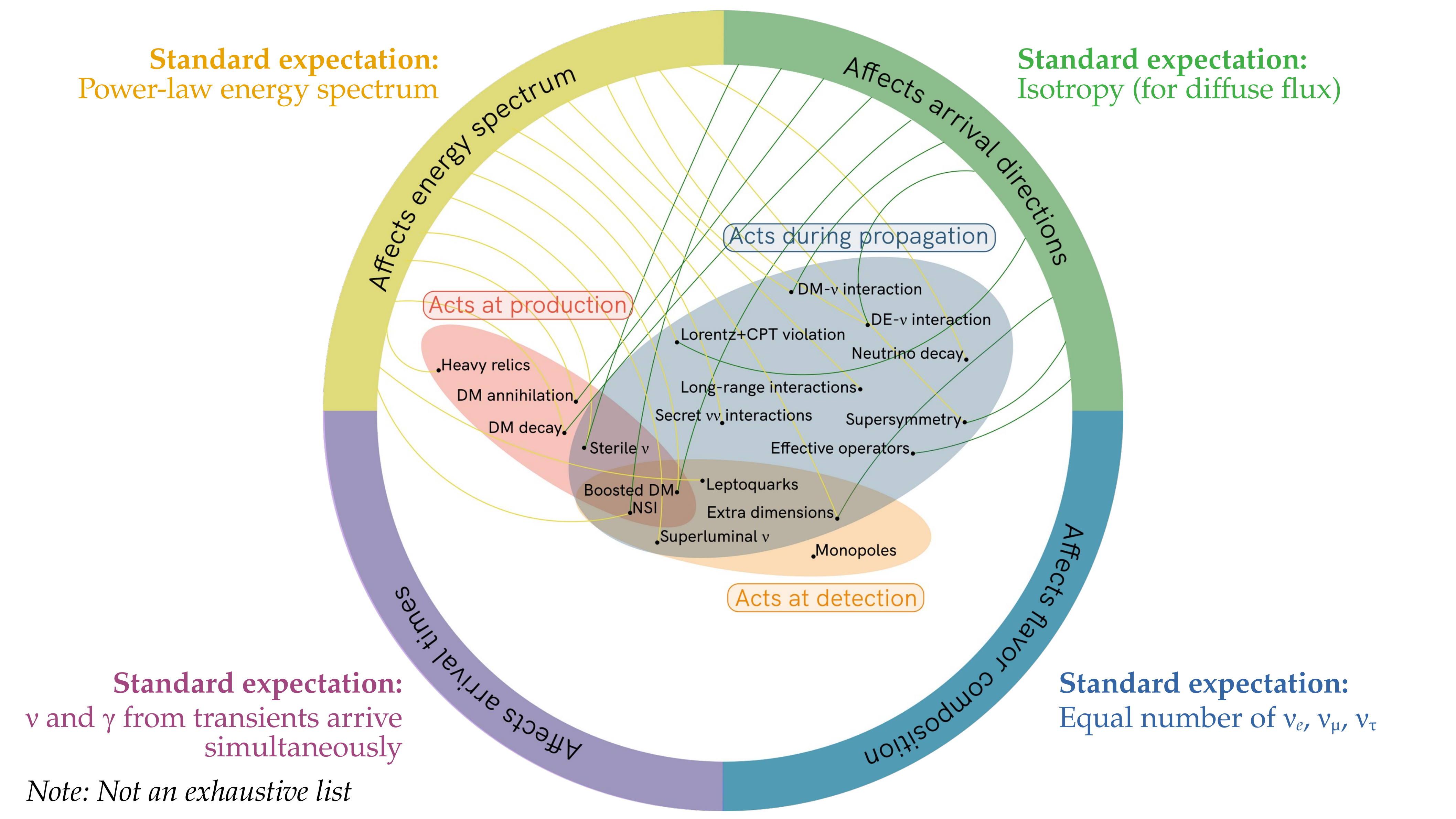

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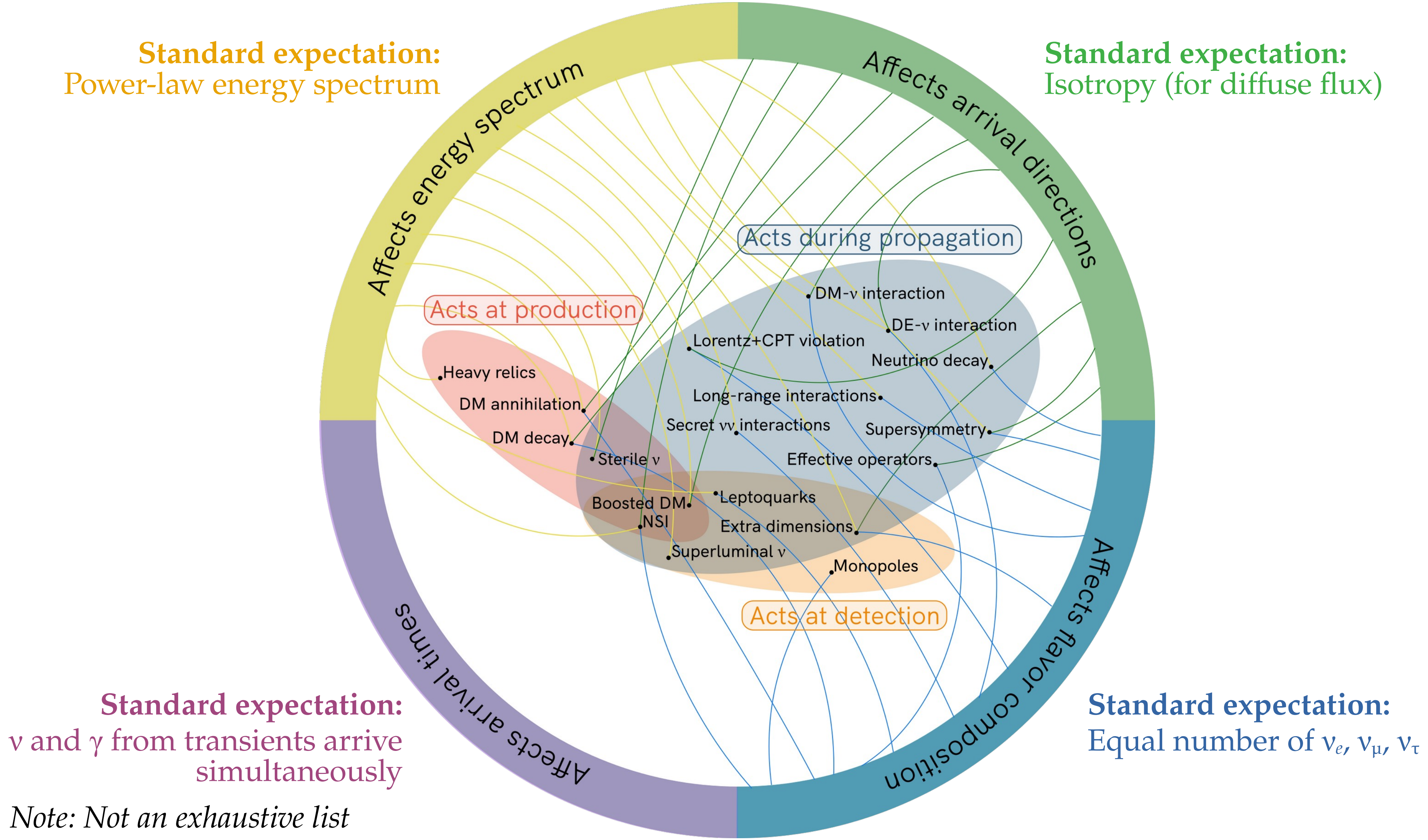
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Monopoles
Note: Not an exhaustive list

Standard expectation:
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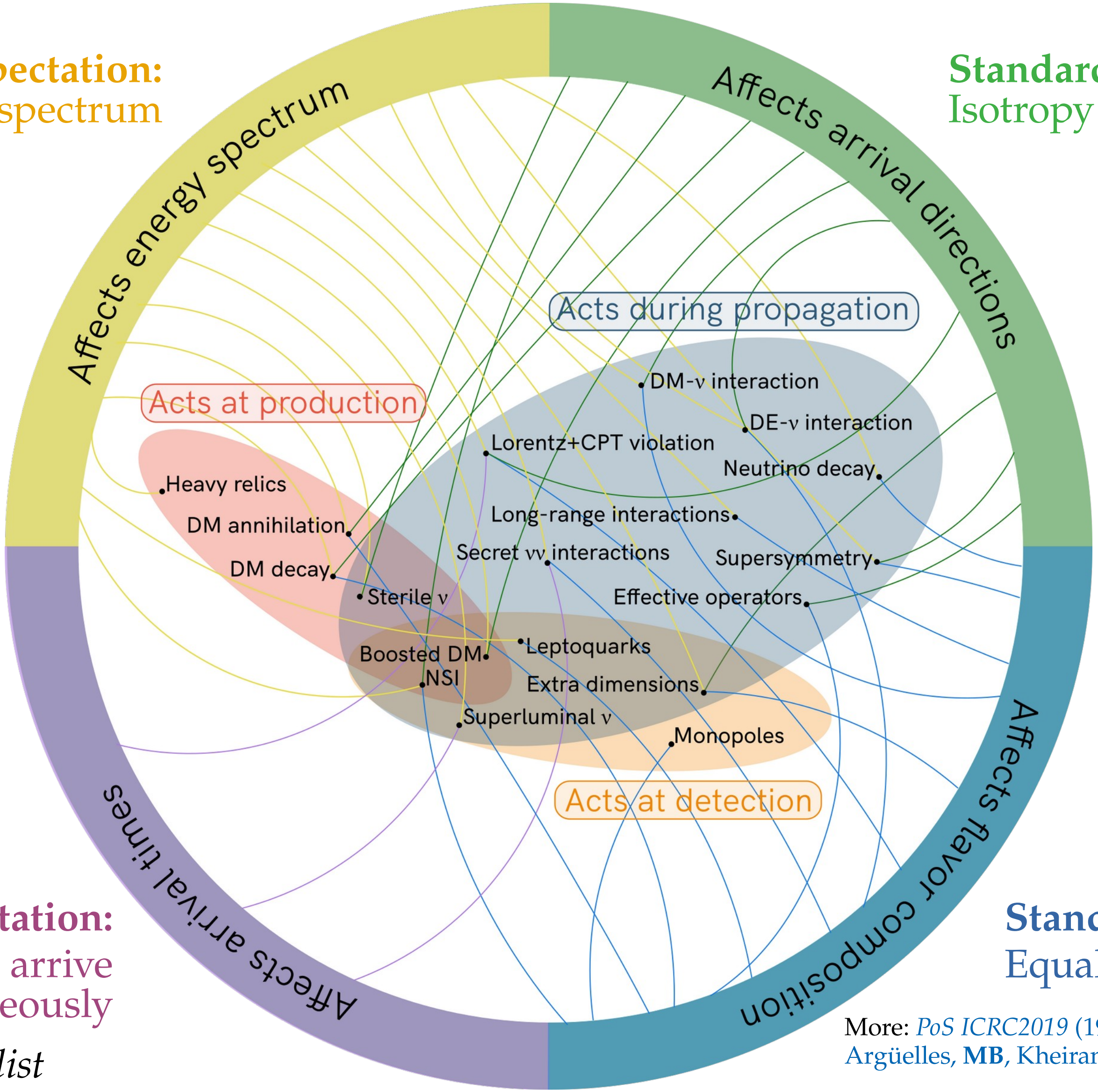
Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
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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

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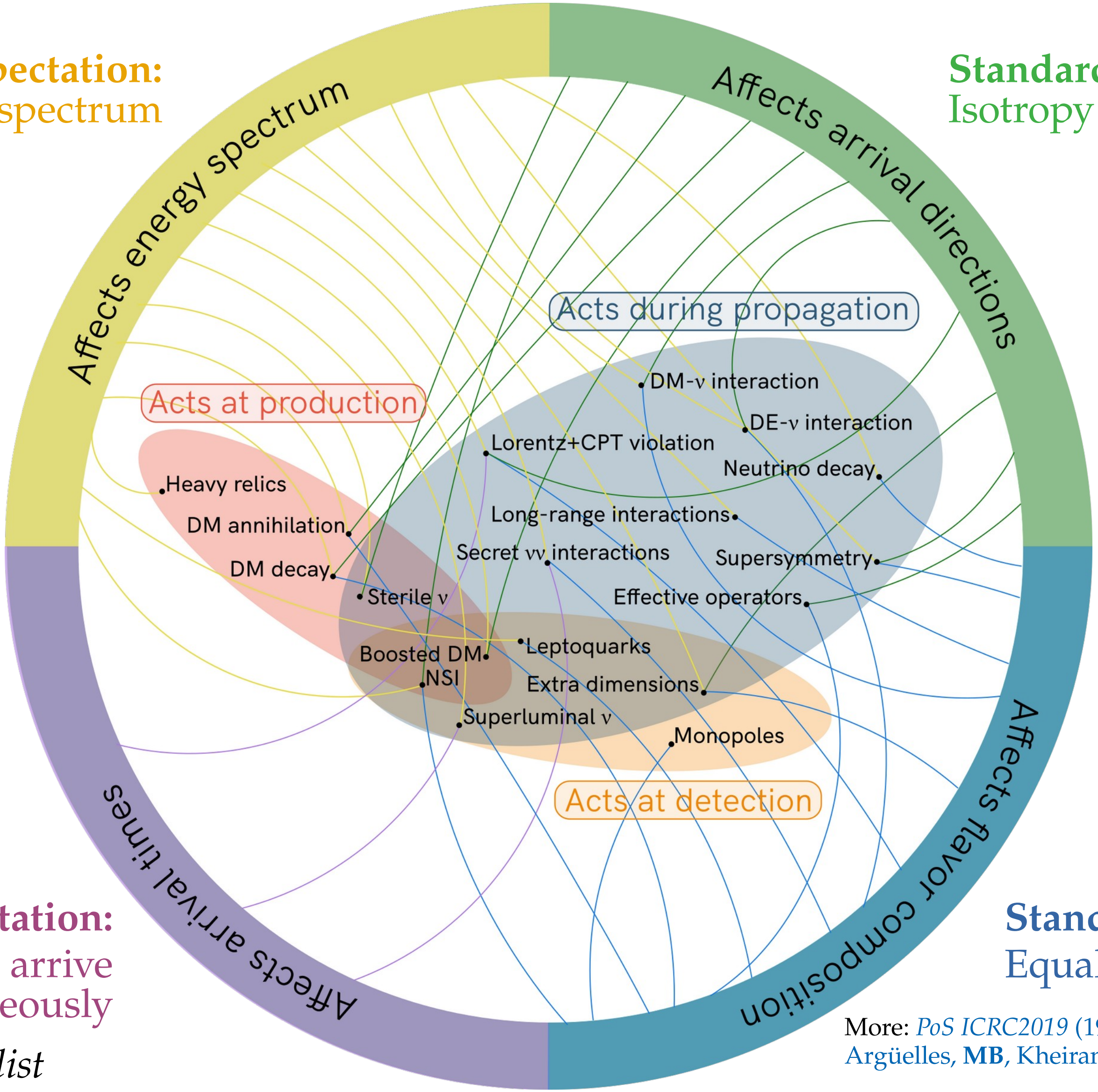
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



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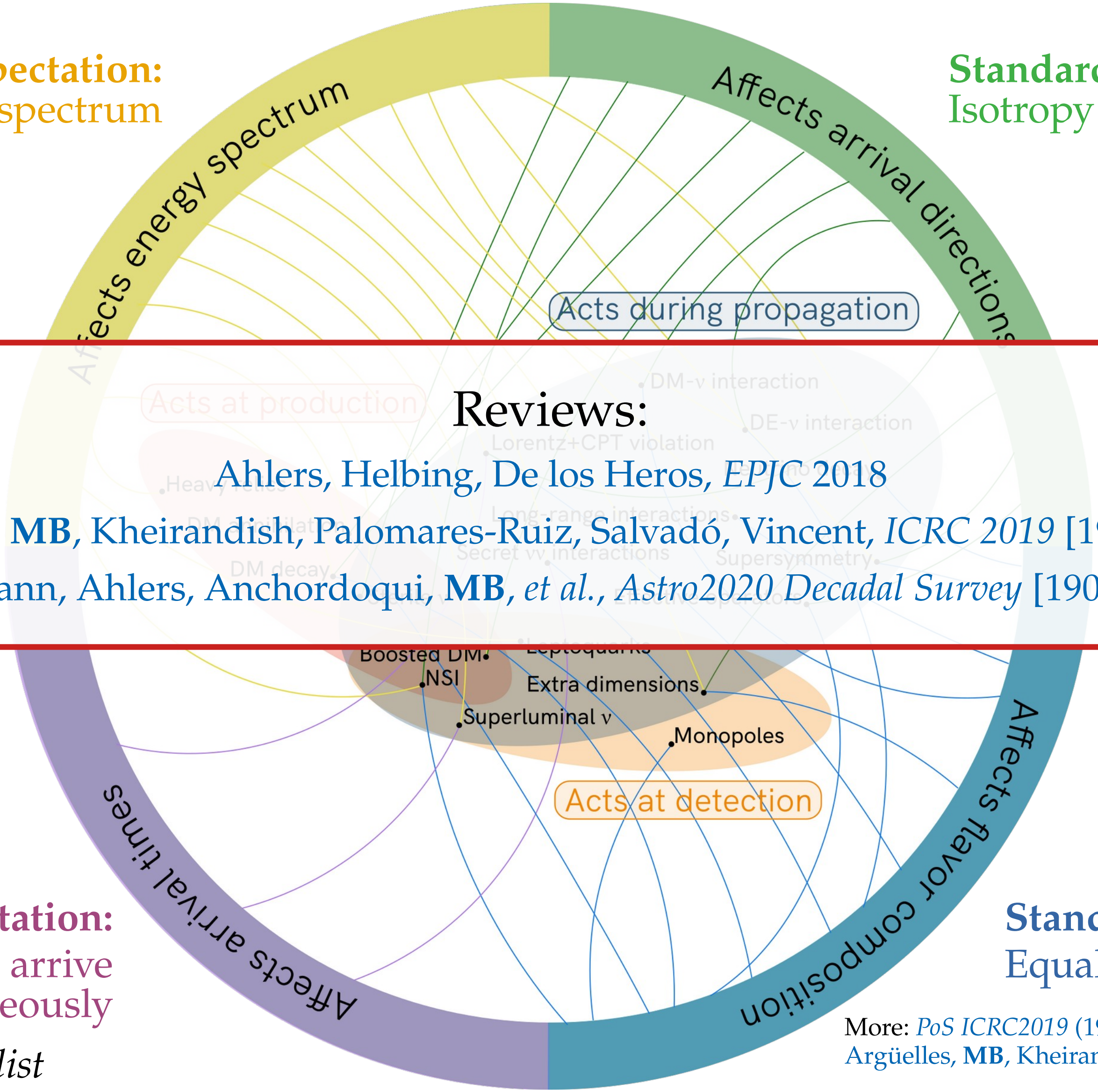

Reviews:

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

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

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

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A selection of neutrino physics

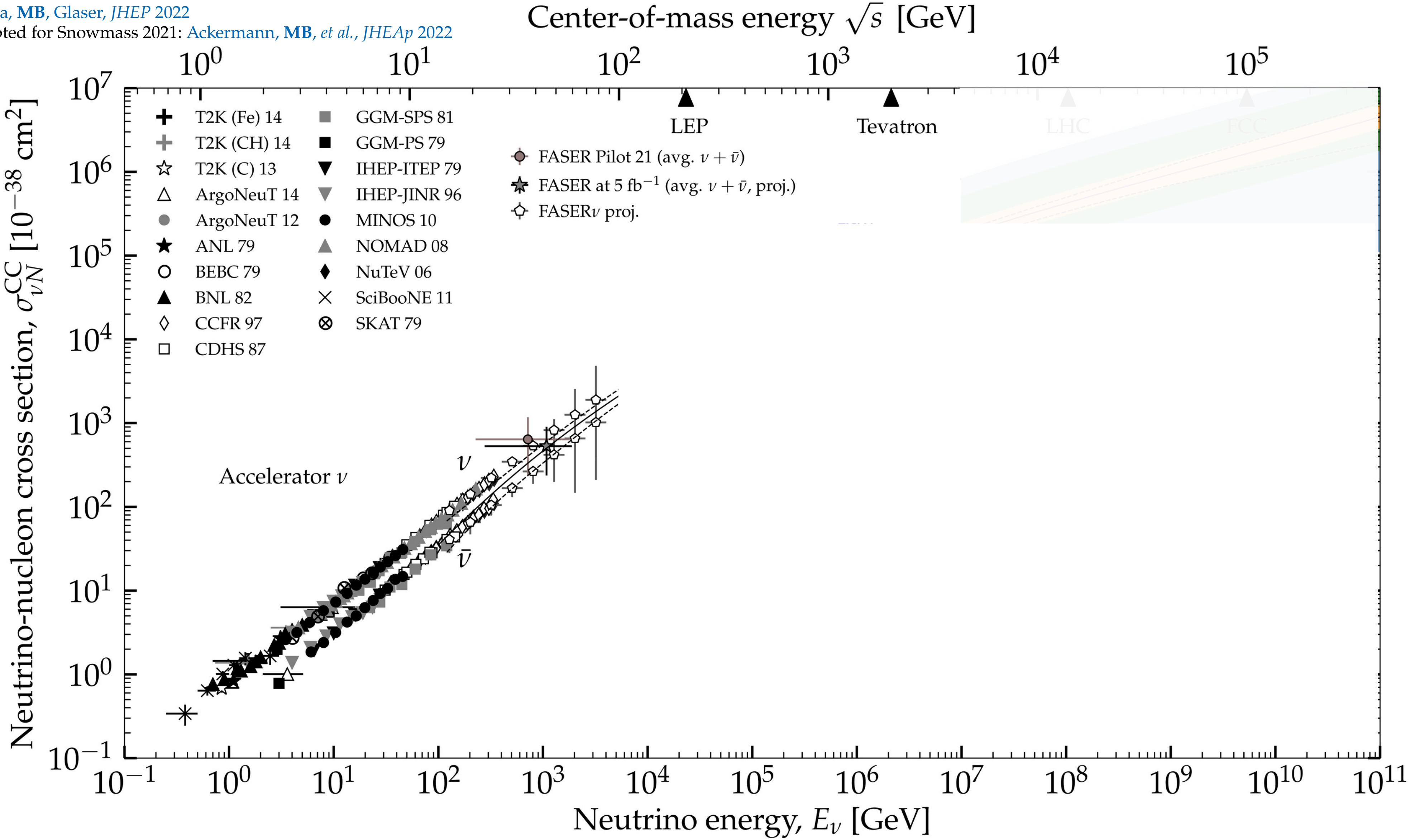
1. Neutrino-matter cross section

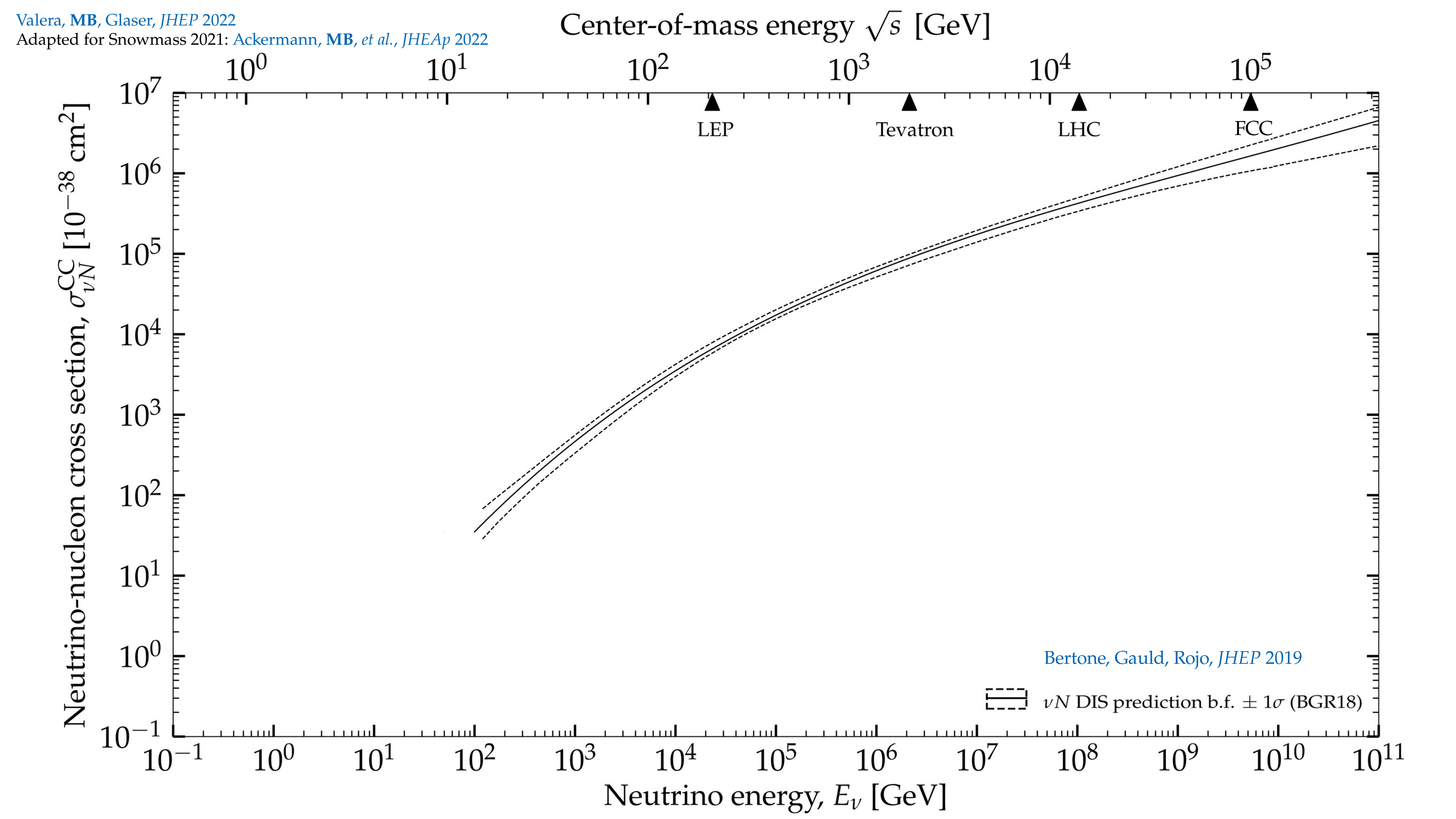
2. Flavor

3. New tests of Lorentz invariance

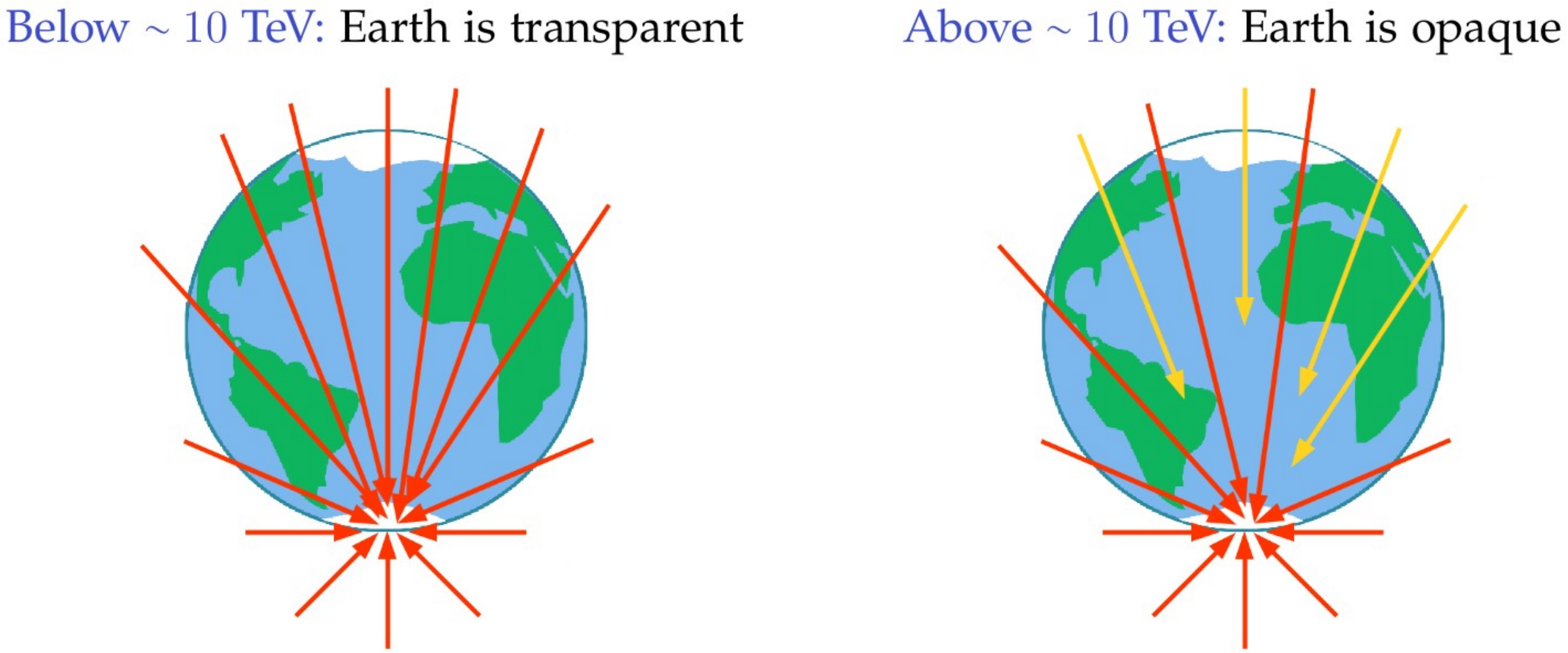
1. Neutrino-matter cross section:
From TeV to EeV

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
Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
Bertone, Gauld, Rojo, JHEP 2019
νN DIS prediction b.f. $\pm$ 1σ (BGR18)

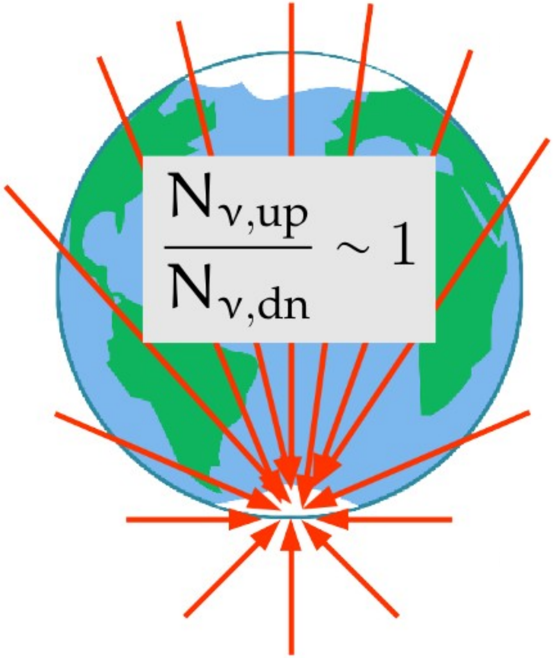
Measuring the high-energy νN cross section



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

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent



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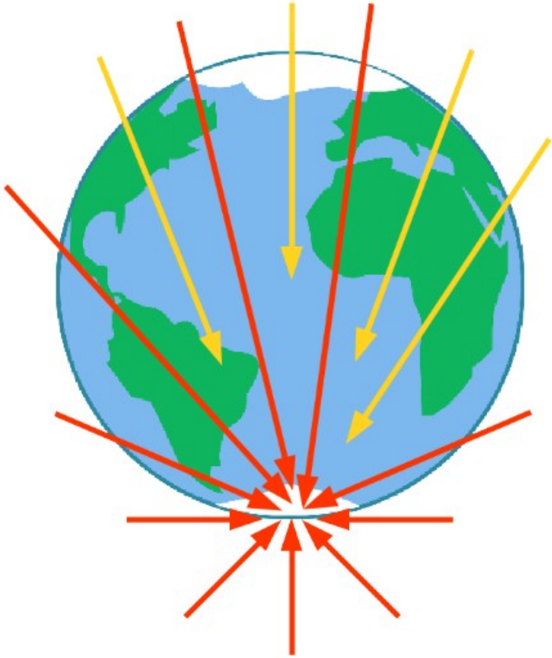
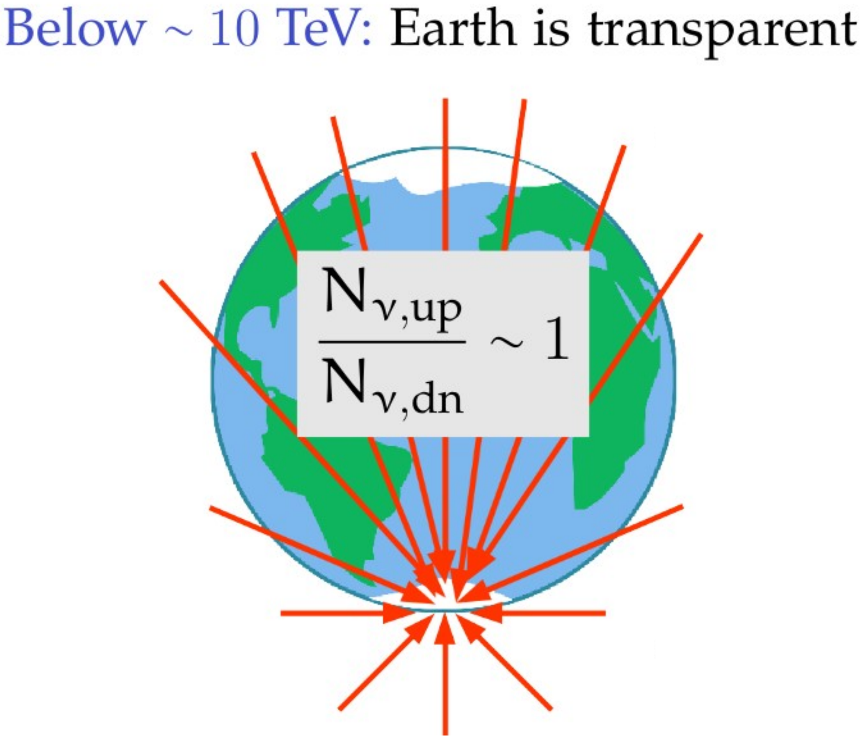
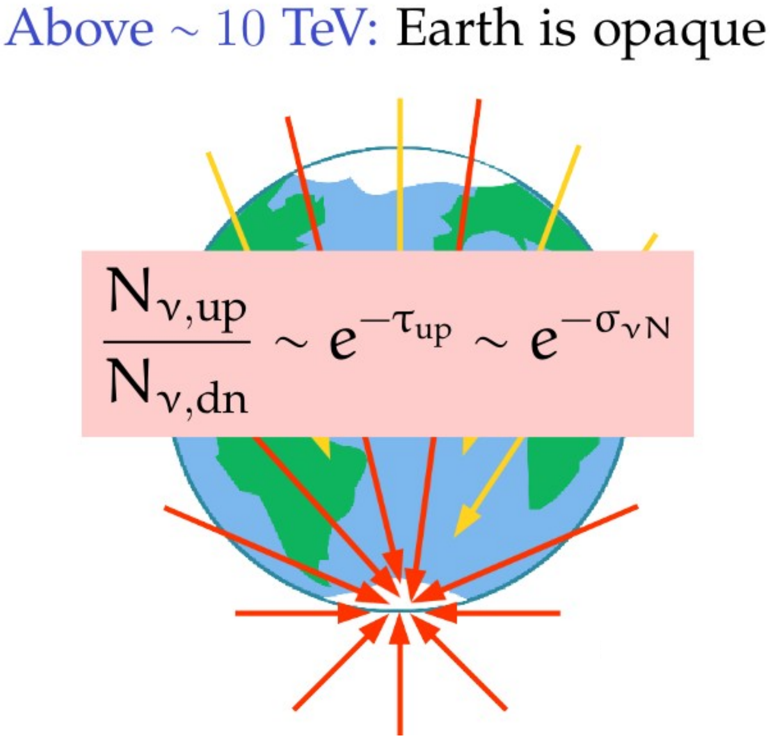


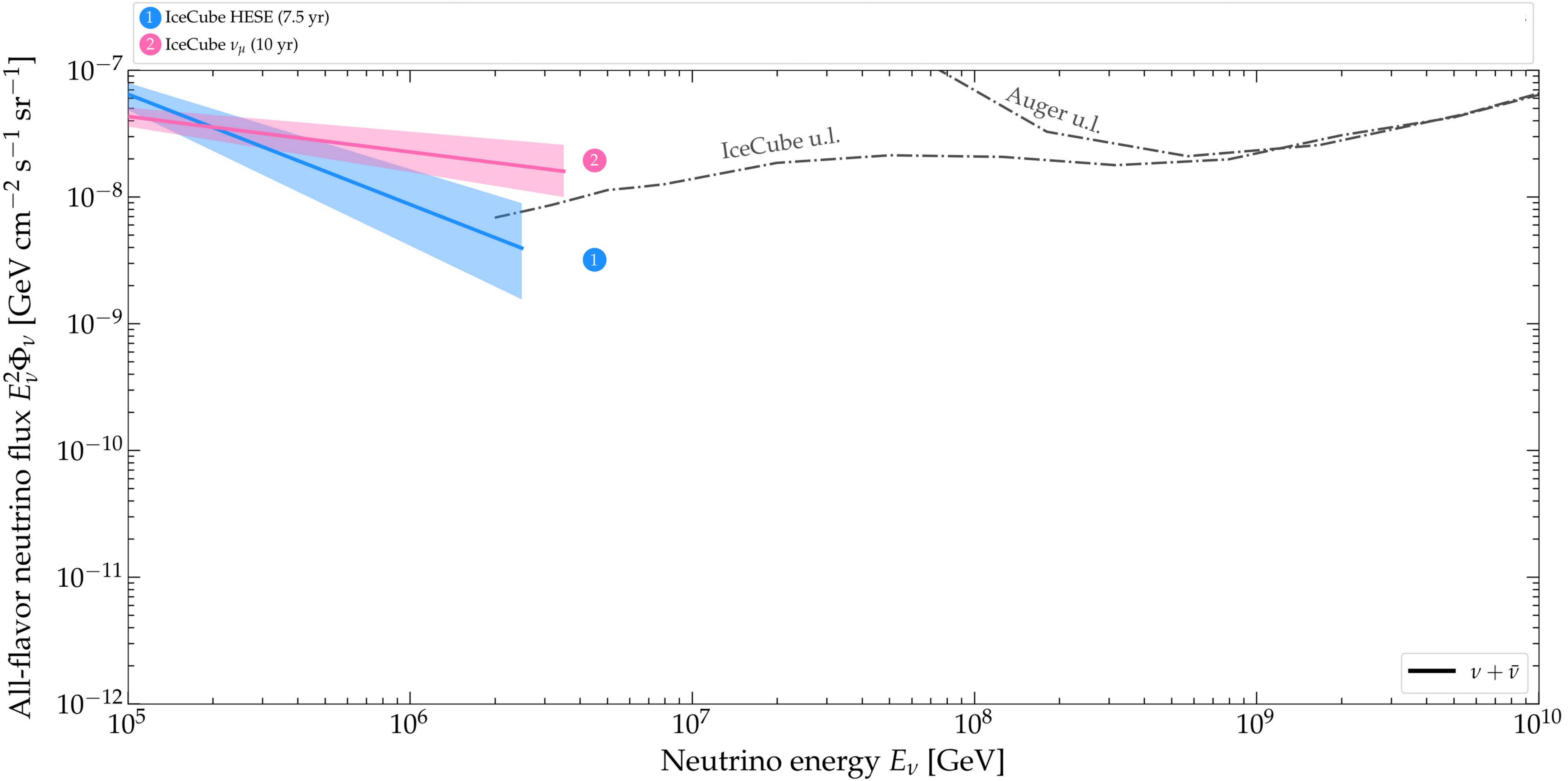
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section



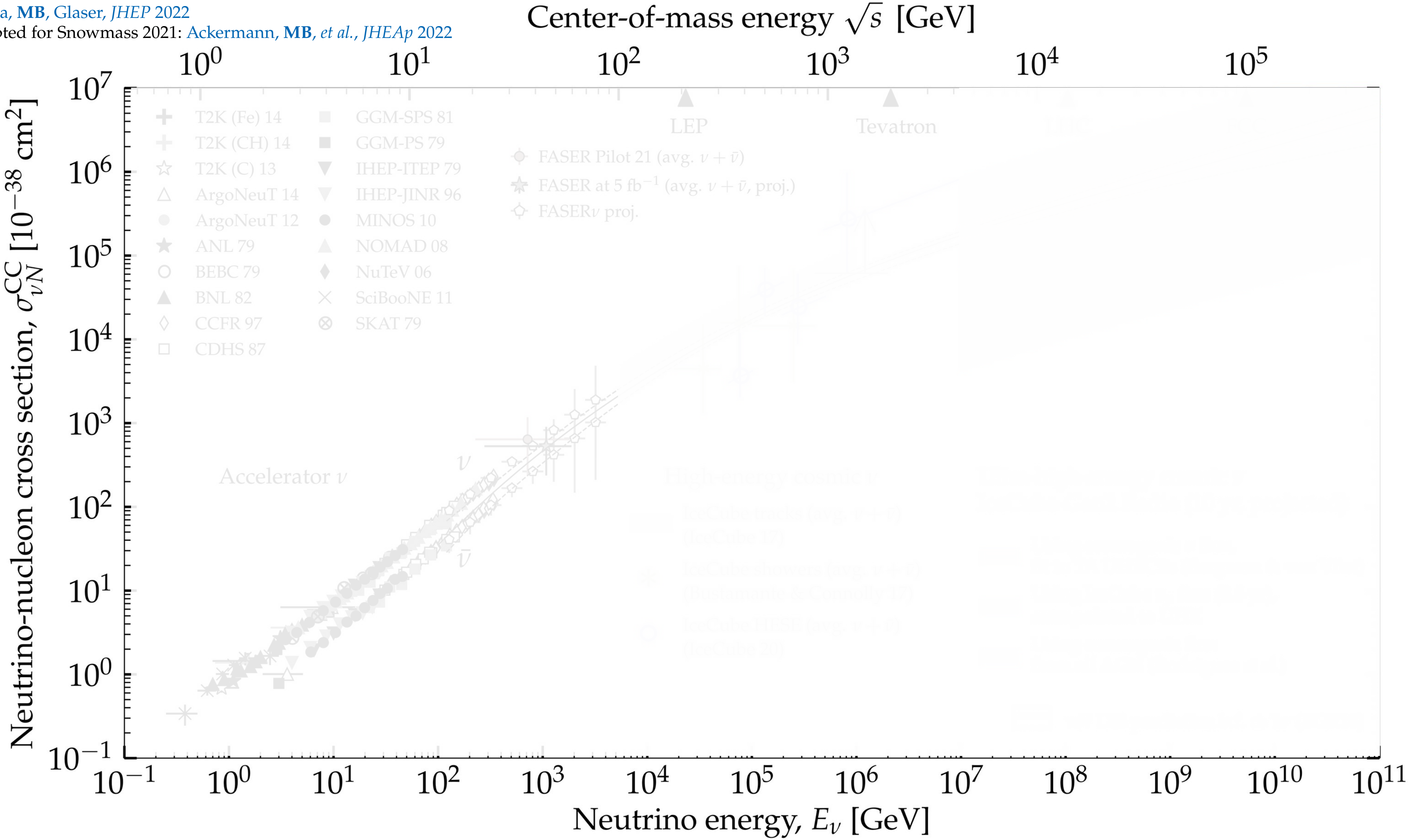


Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

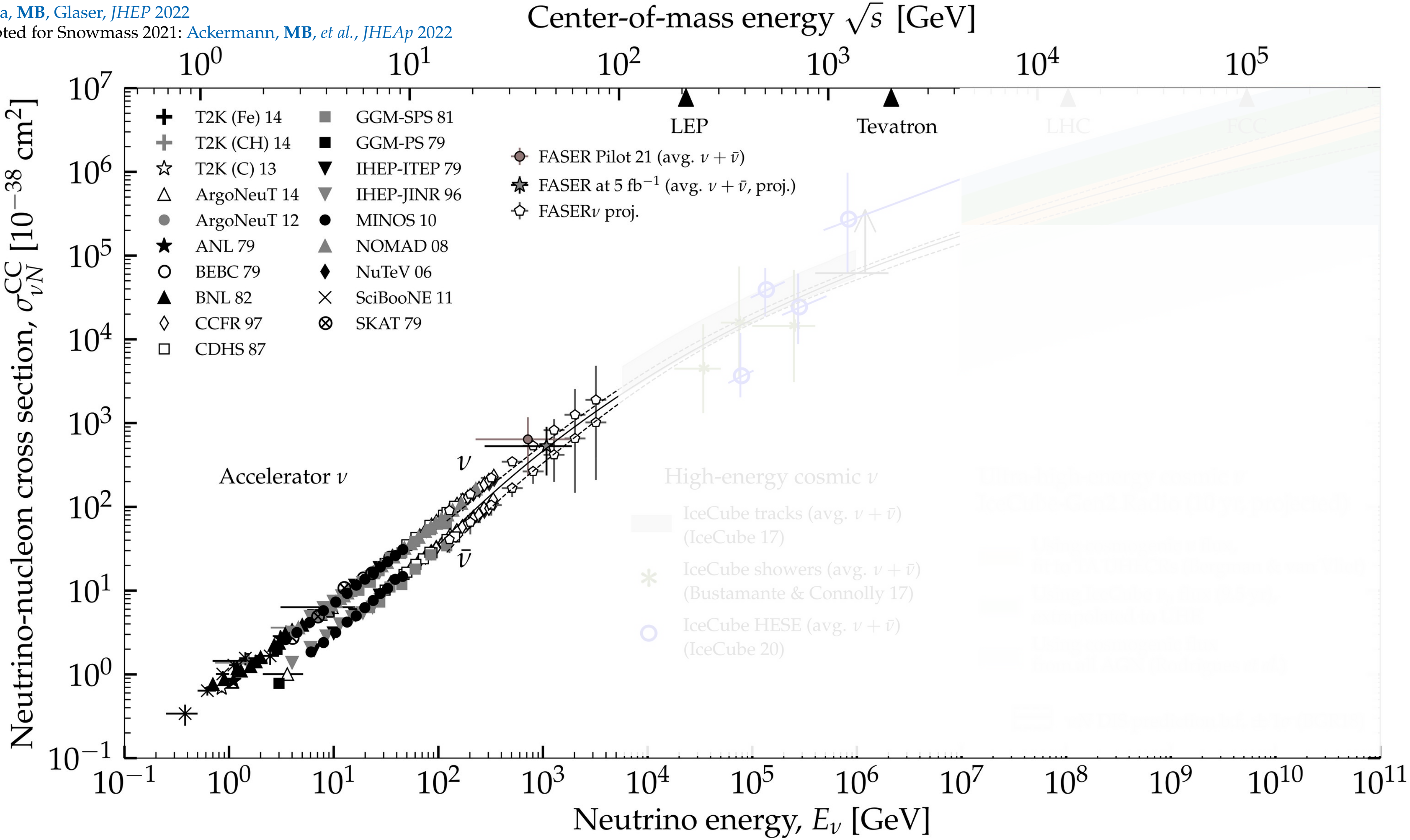


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

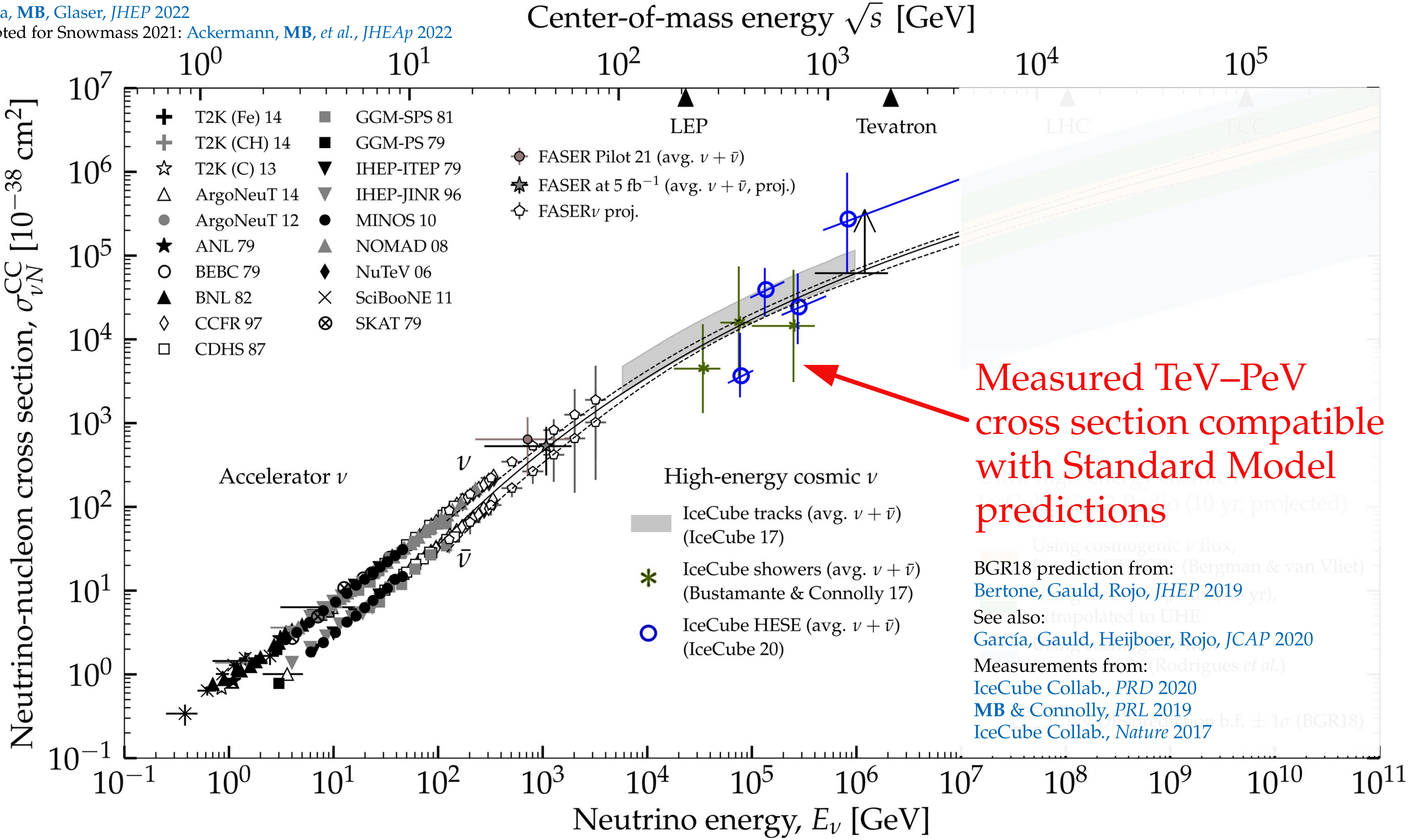
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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



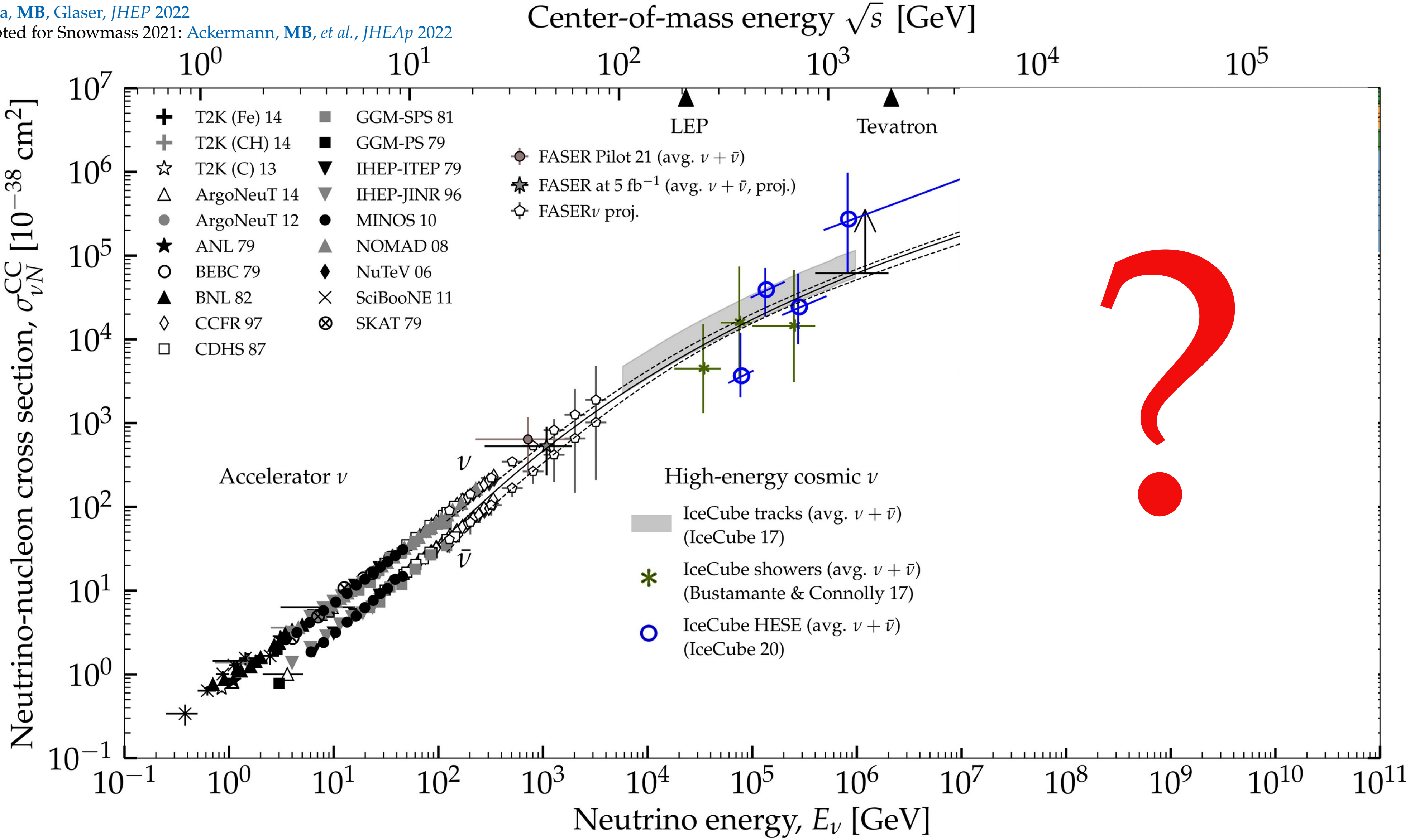
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



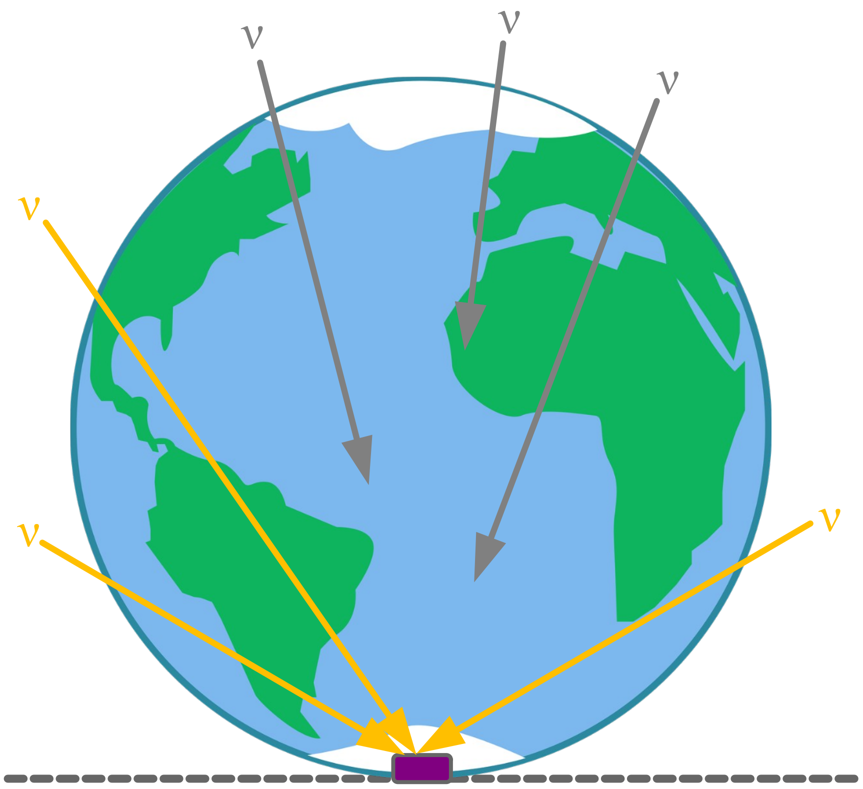
Measured TeV–PeV cross section compatible with Standard Model predictions

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

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

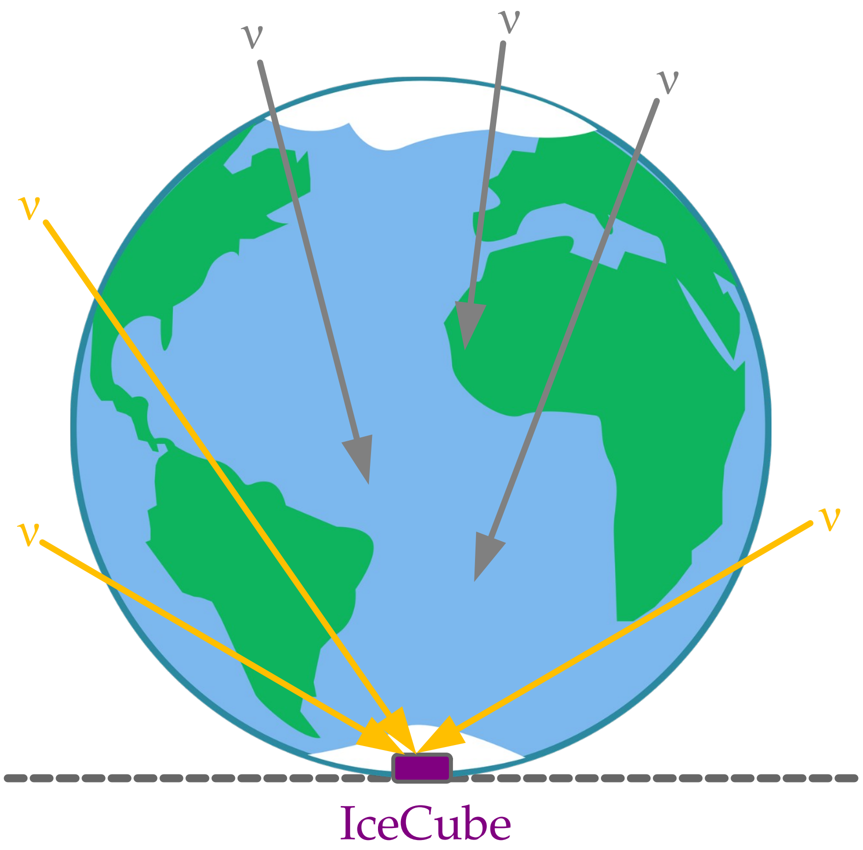


TeV–PeV:



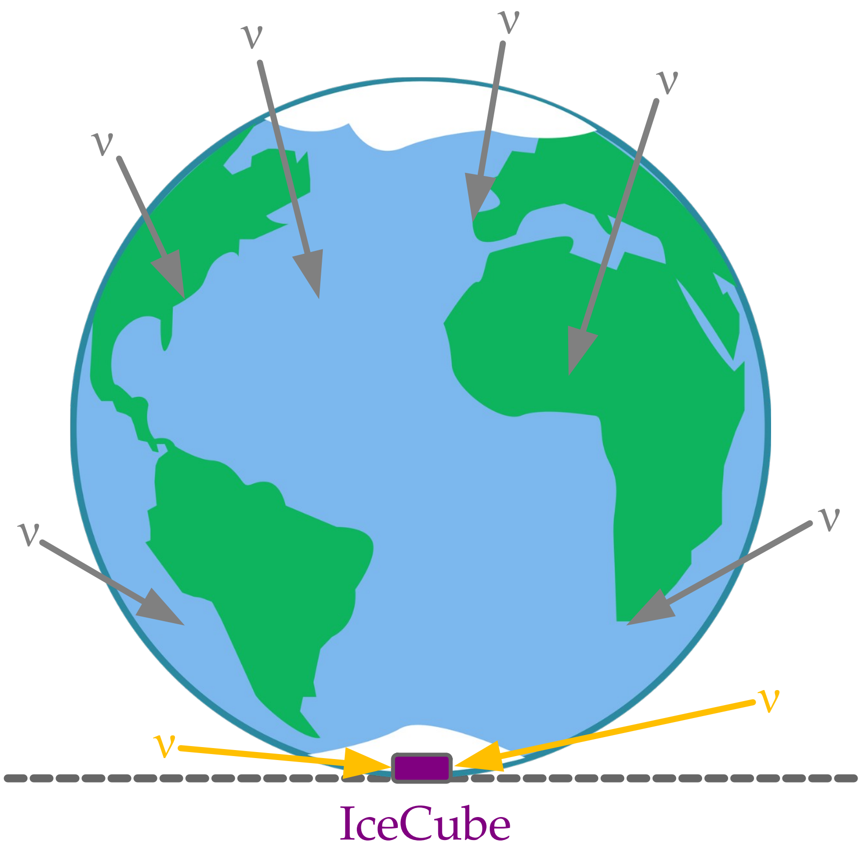
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:

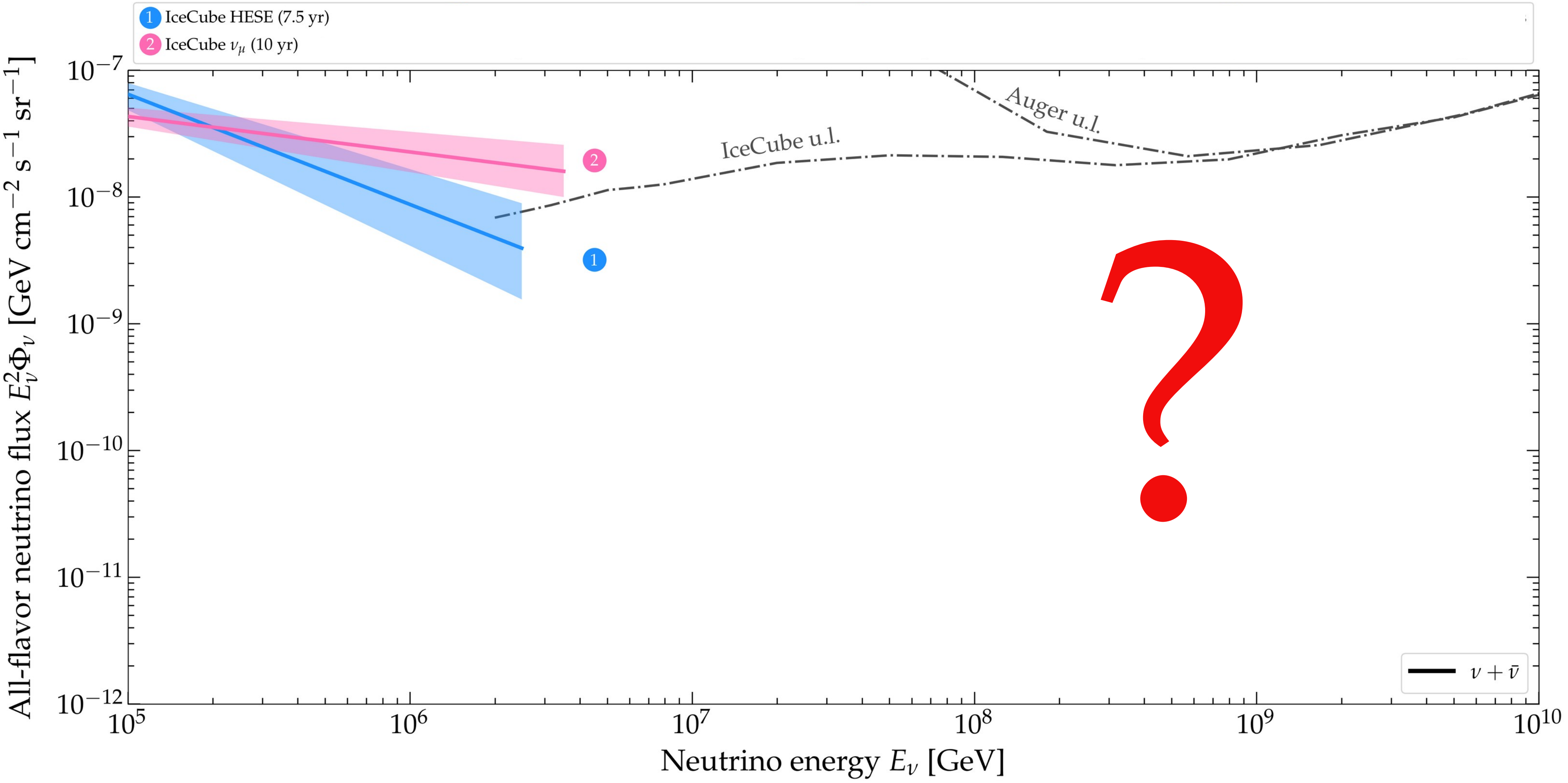


Earth is *almost fully* opaque,
some upgoing ν still make it through

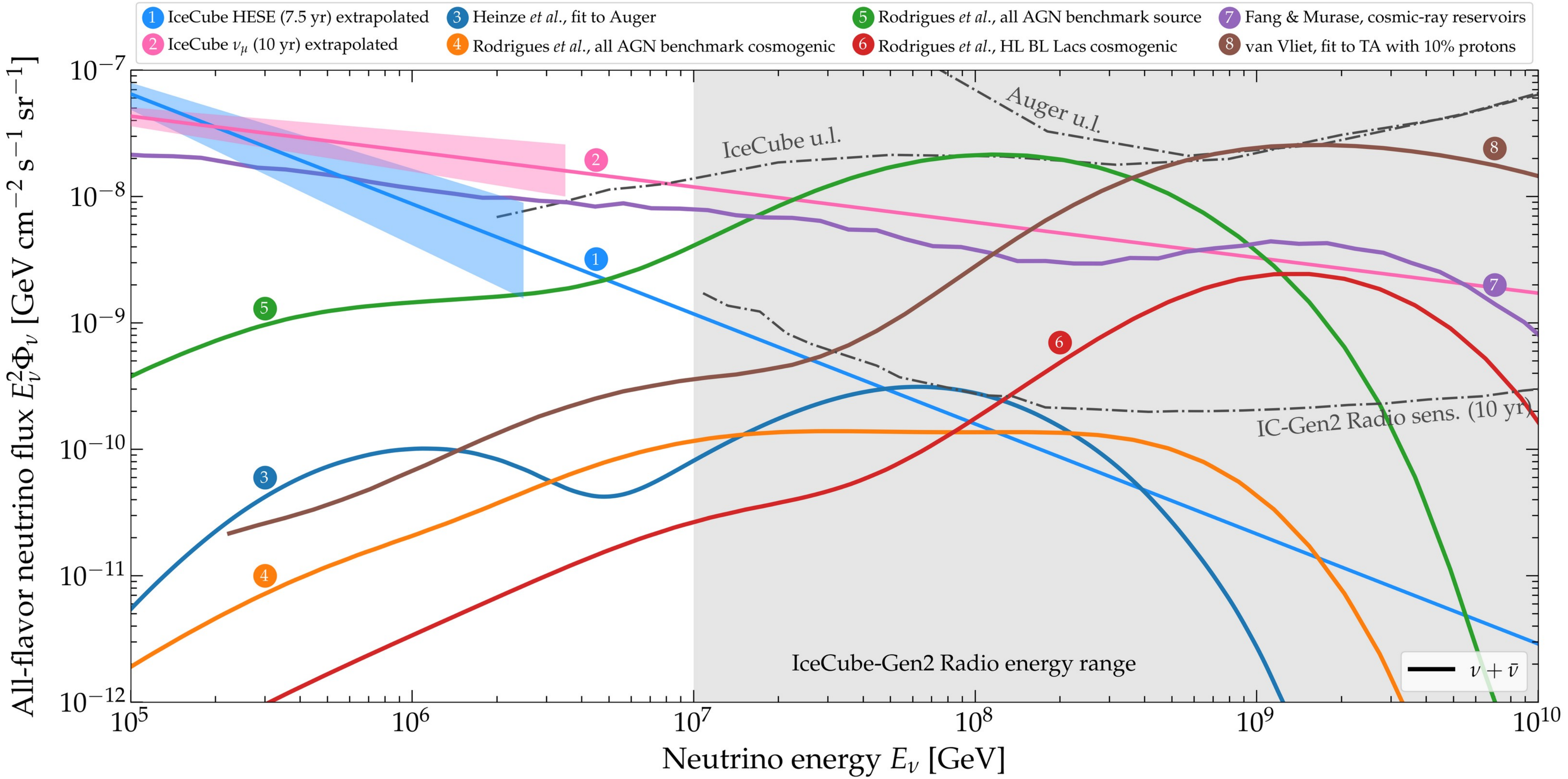
$>$ 100 PeV:



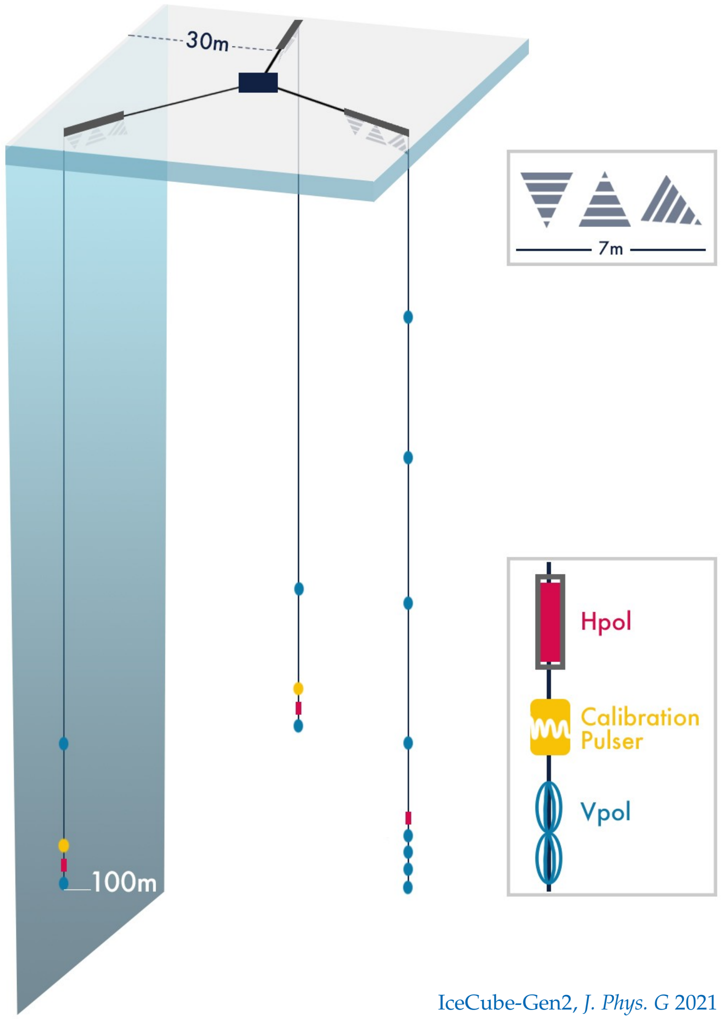
Earth is *completely* opaque,
but horizontal ν still make it through



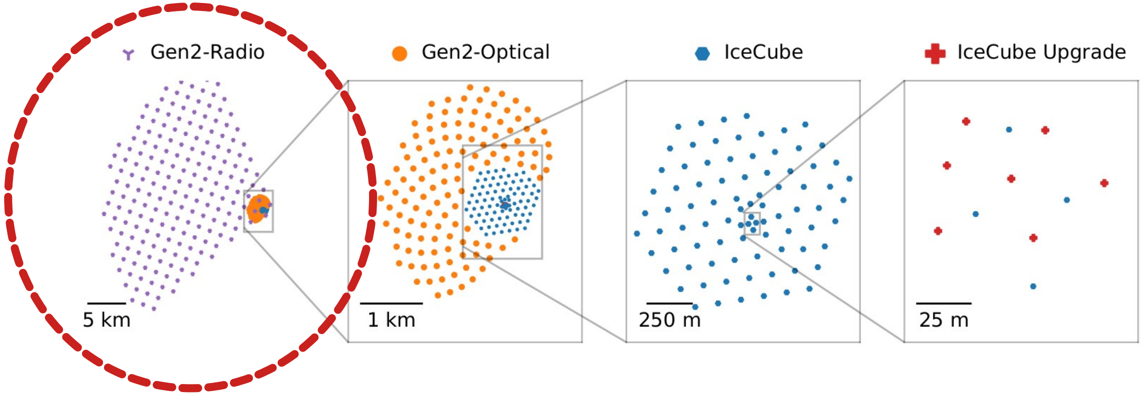
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
?
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]

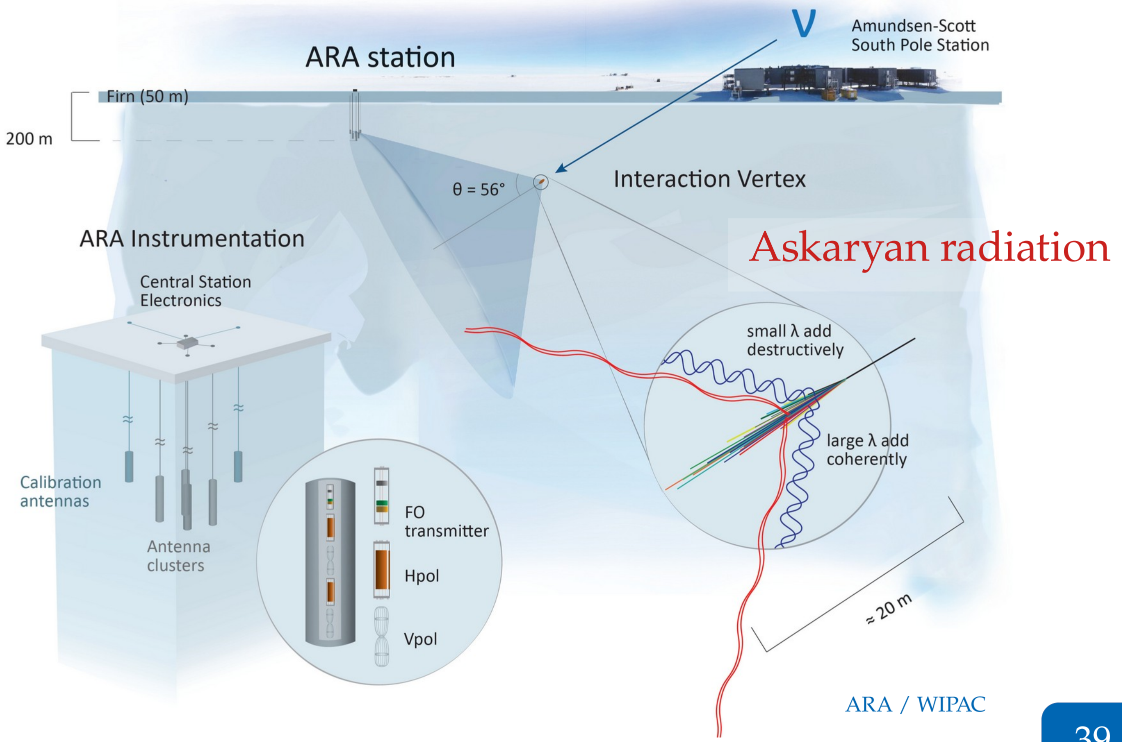

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA with 10% protons
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

IceCube-Gen2 Radio



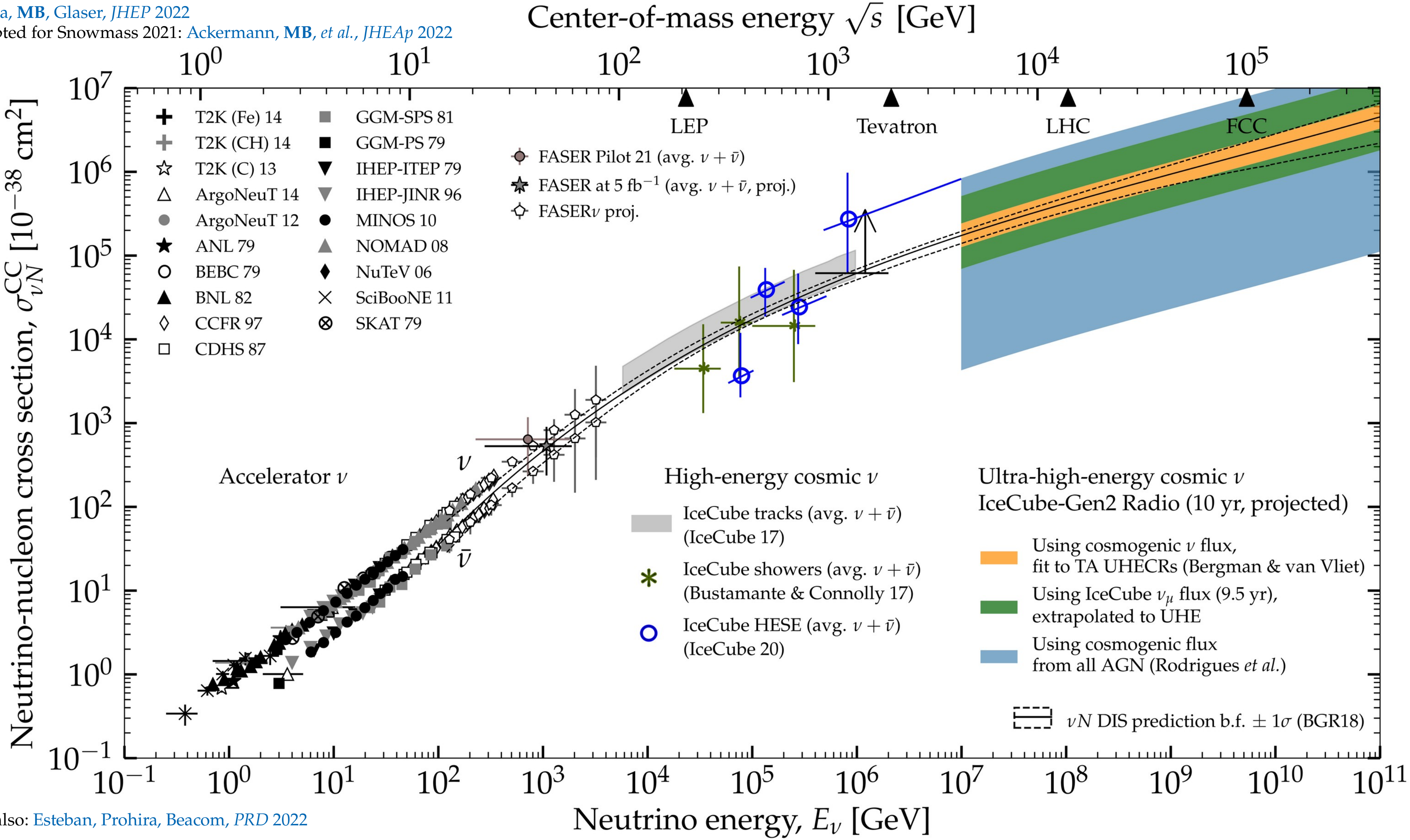
IceCube-Gen2, *J. Phys. G* 2021





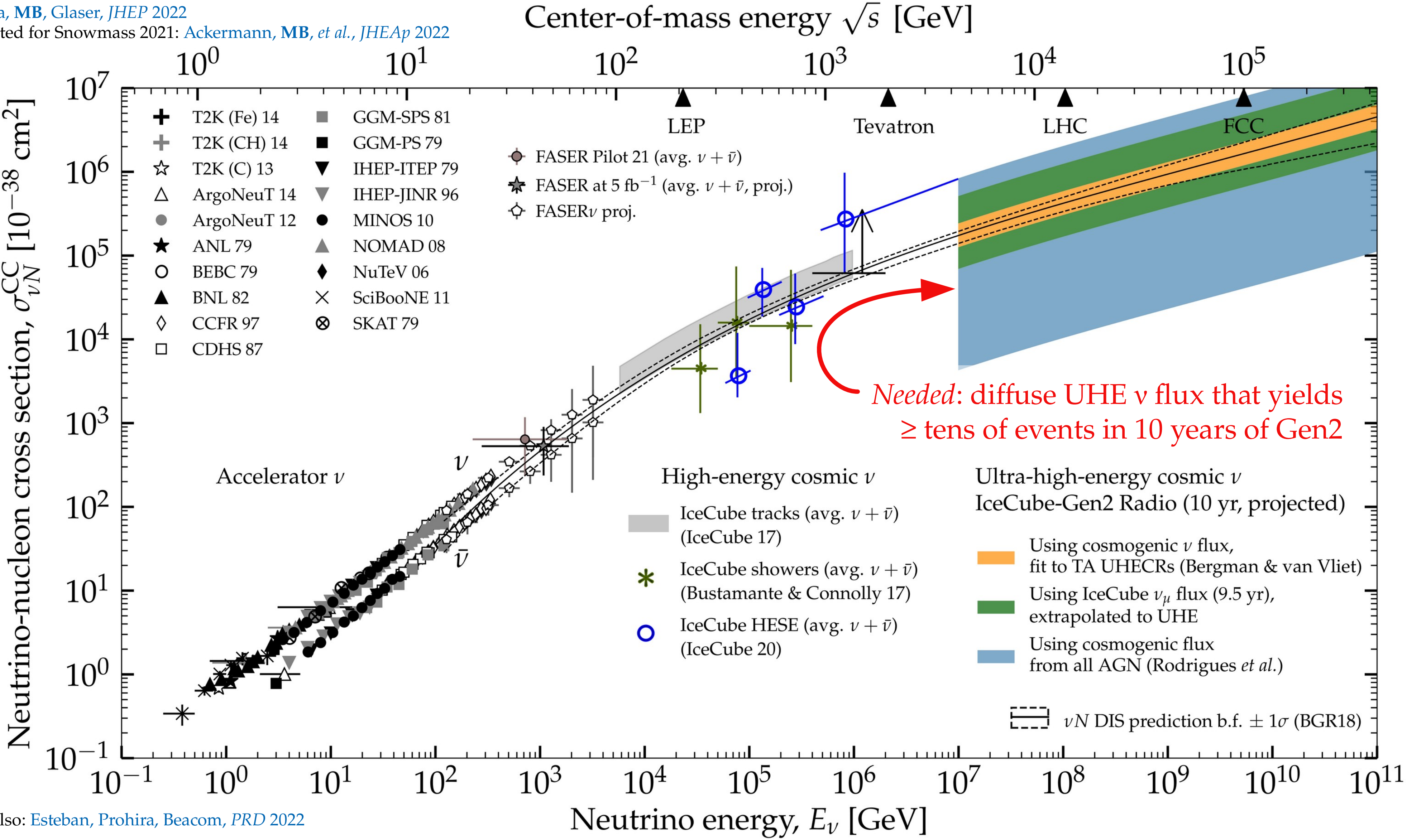
ARA / WIPAC

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



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

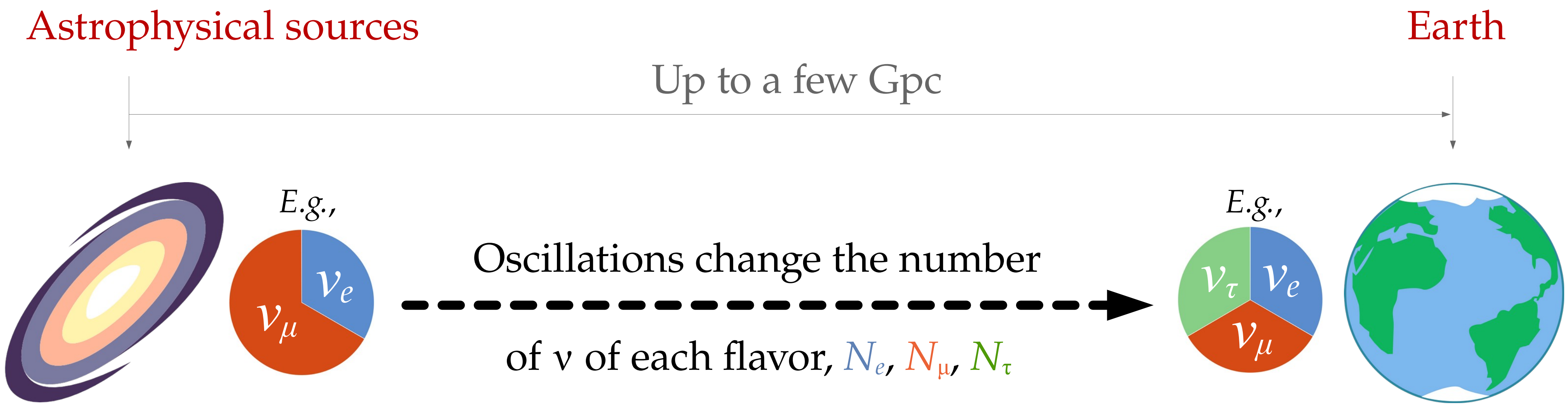
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

2. Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

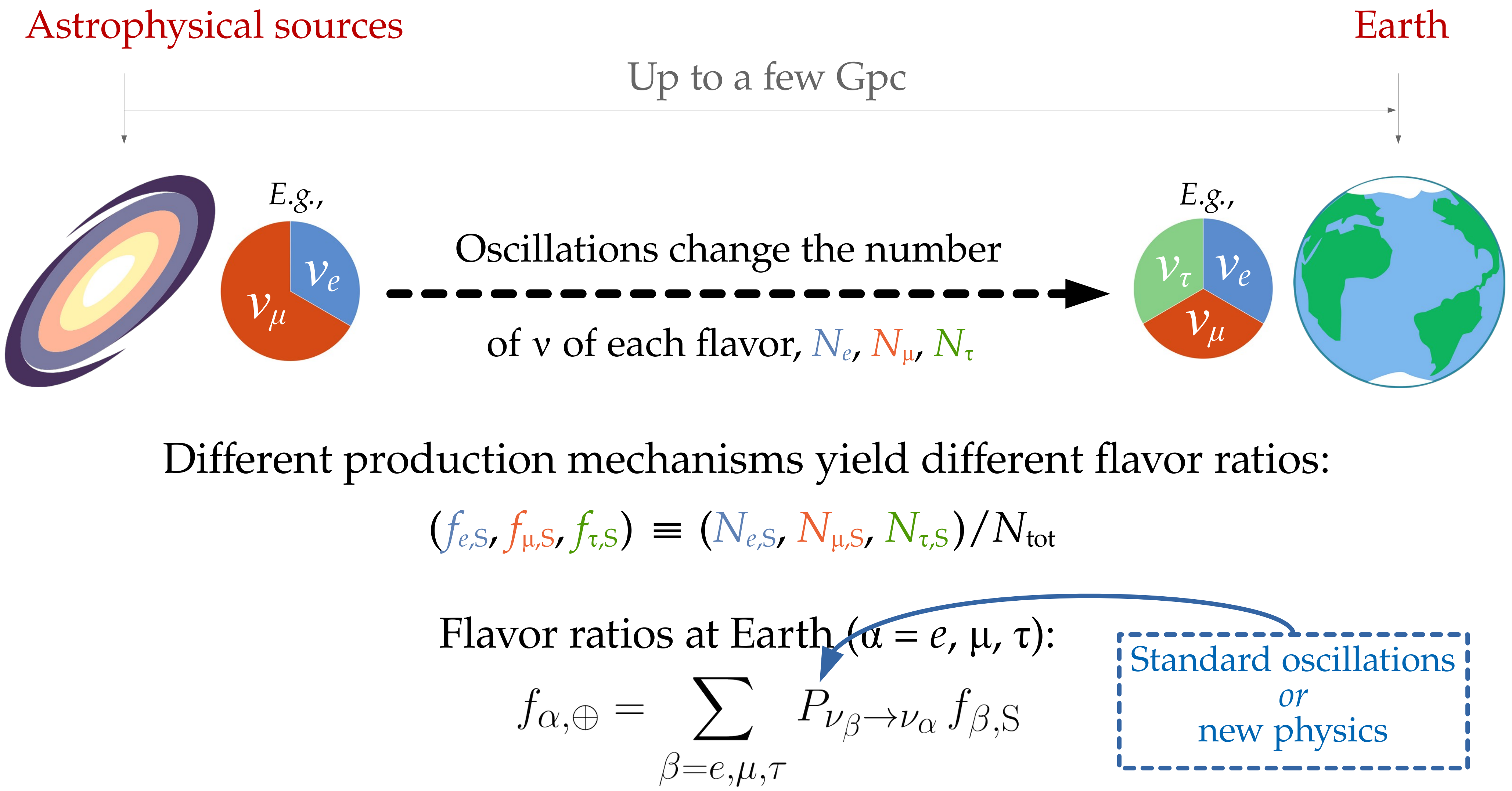


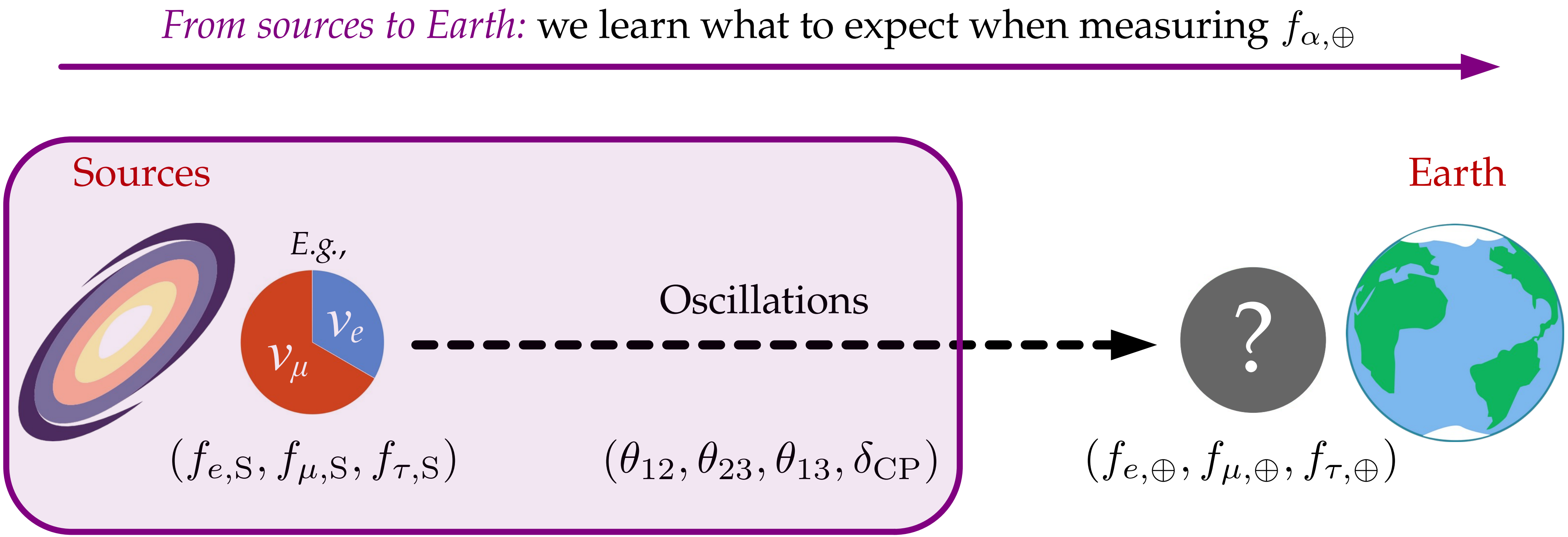
Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$
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:

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

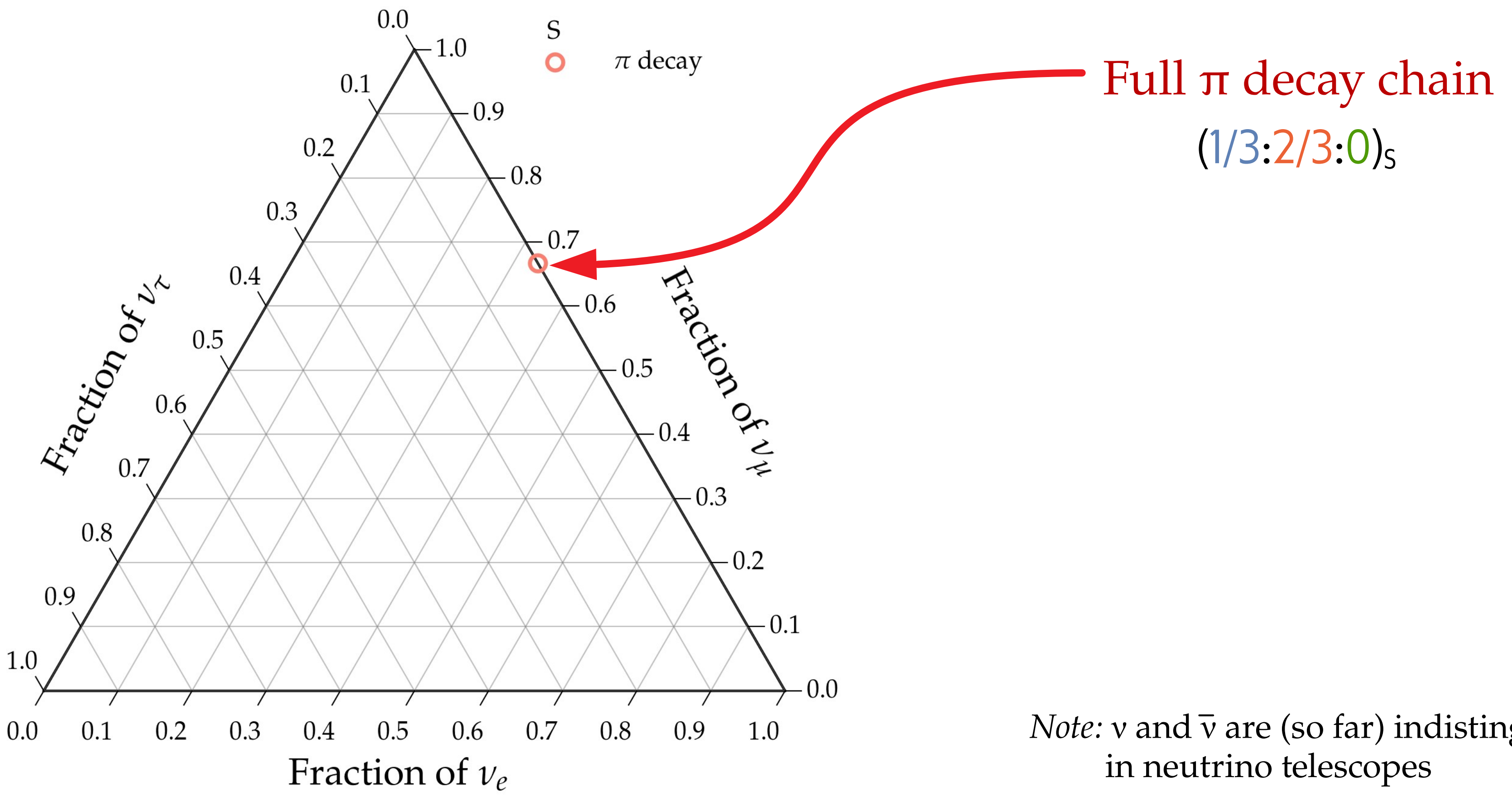
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

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



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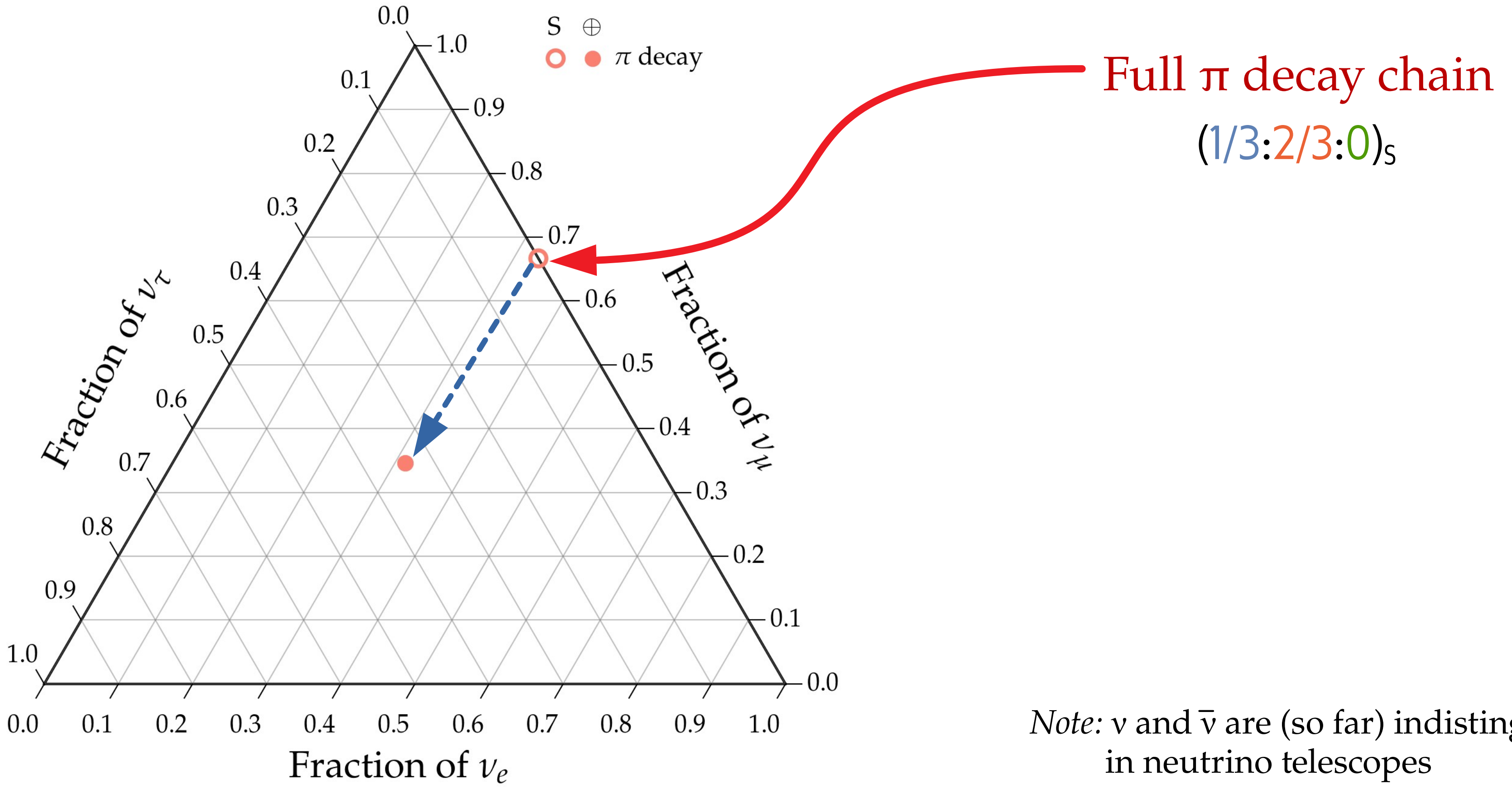

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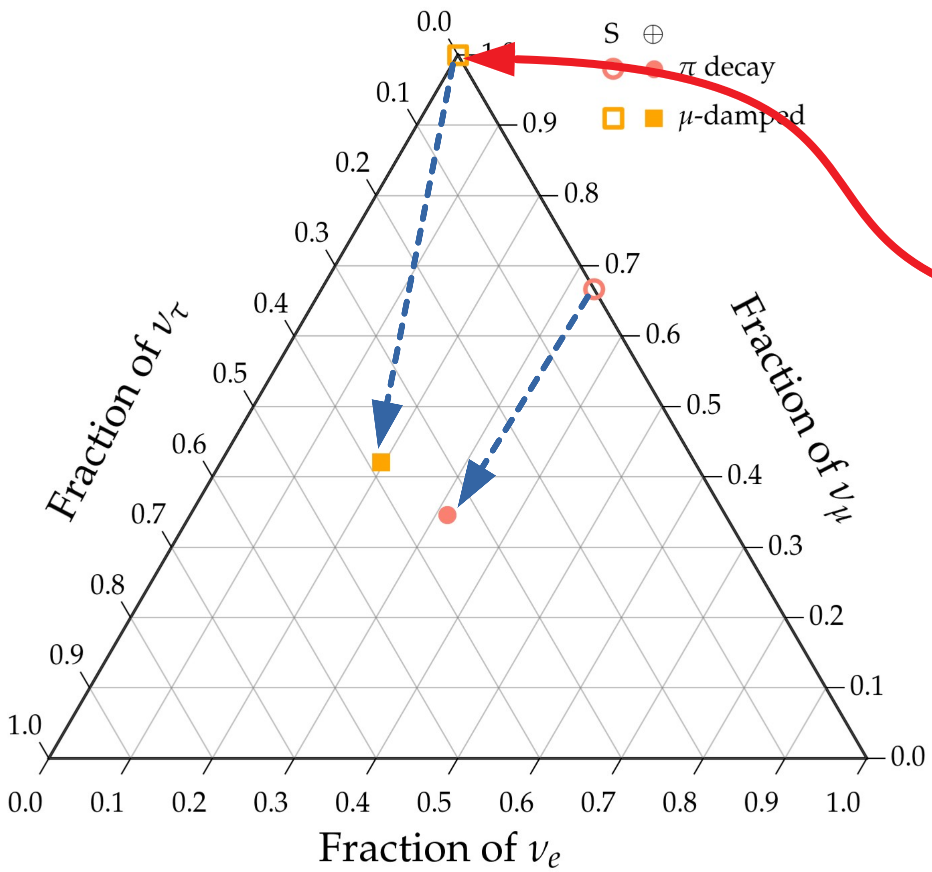

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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

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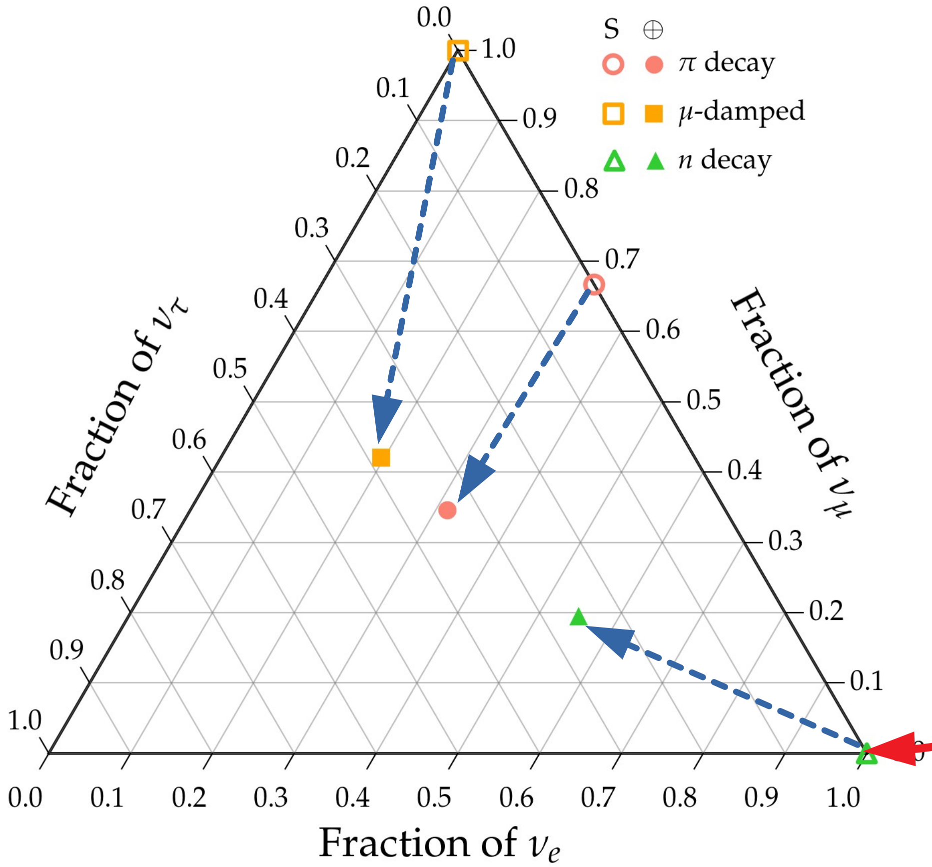


Full π decay chain

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

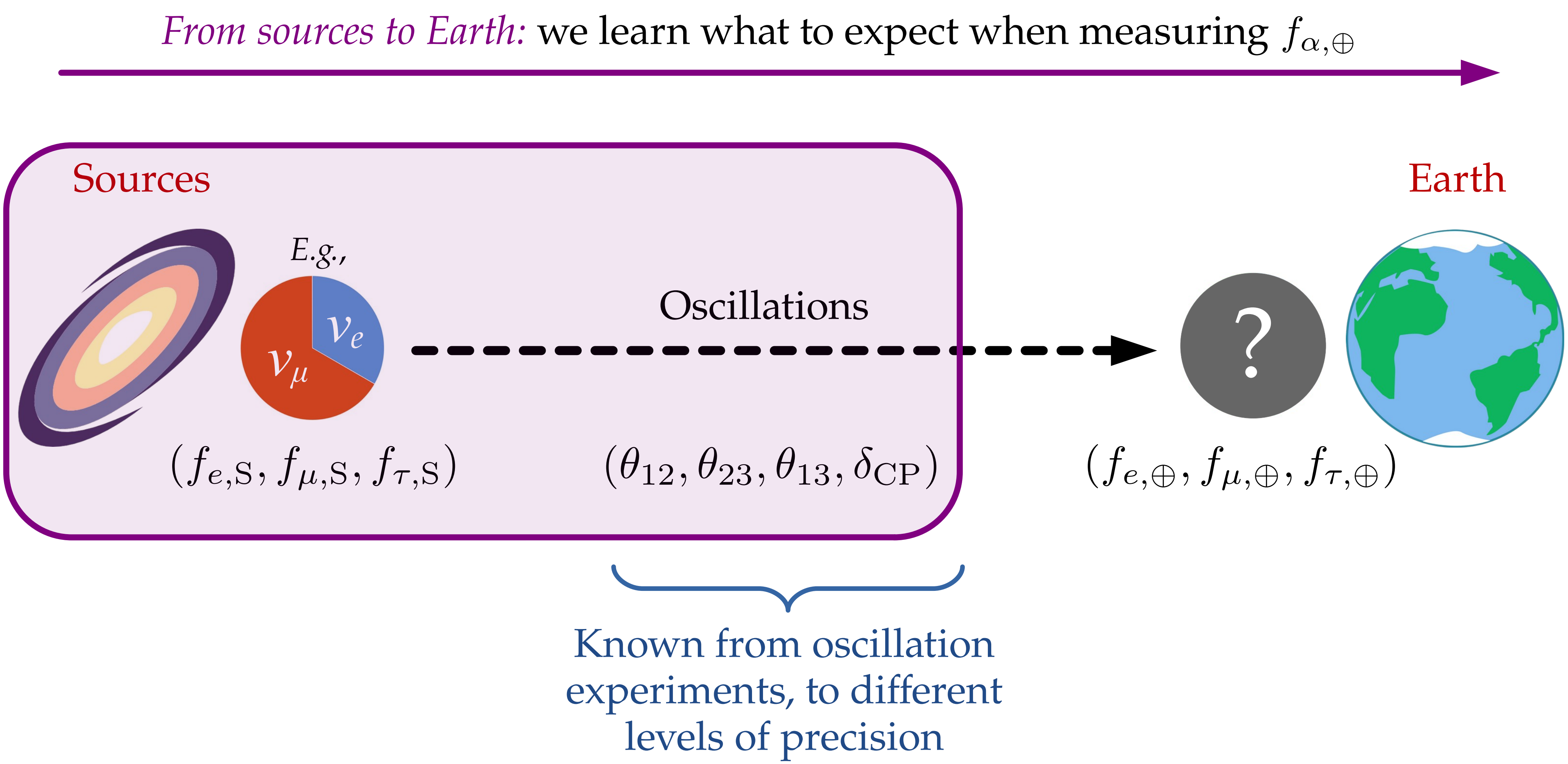
Muon damped

$(0:1:0)_S$

Neutron decay

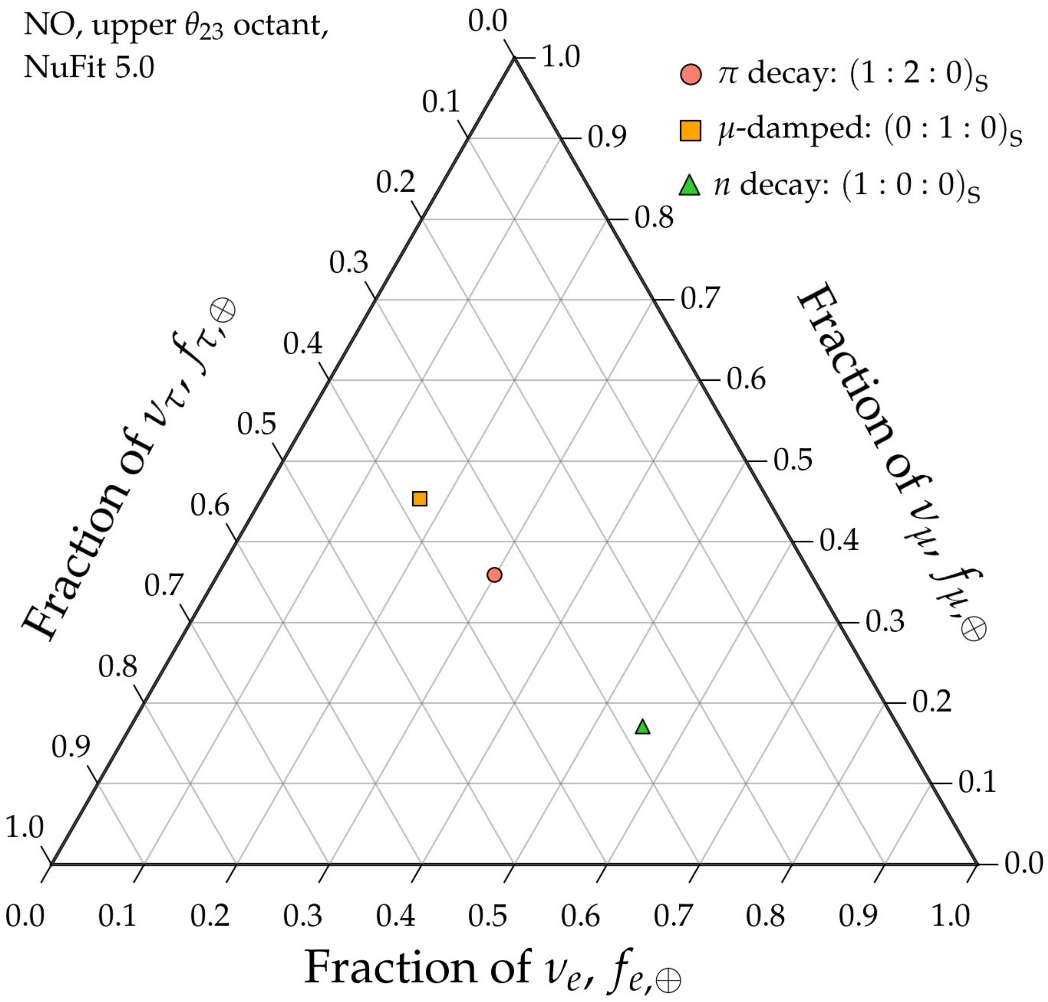
$(1:0:0)_S$

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
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
?
Earth
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$
Known from oscillation experiments, to different levels of precision

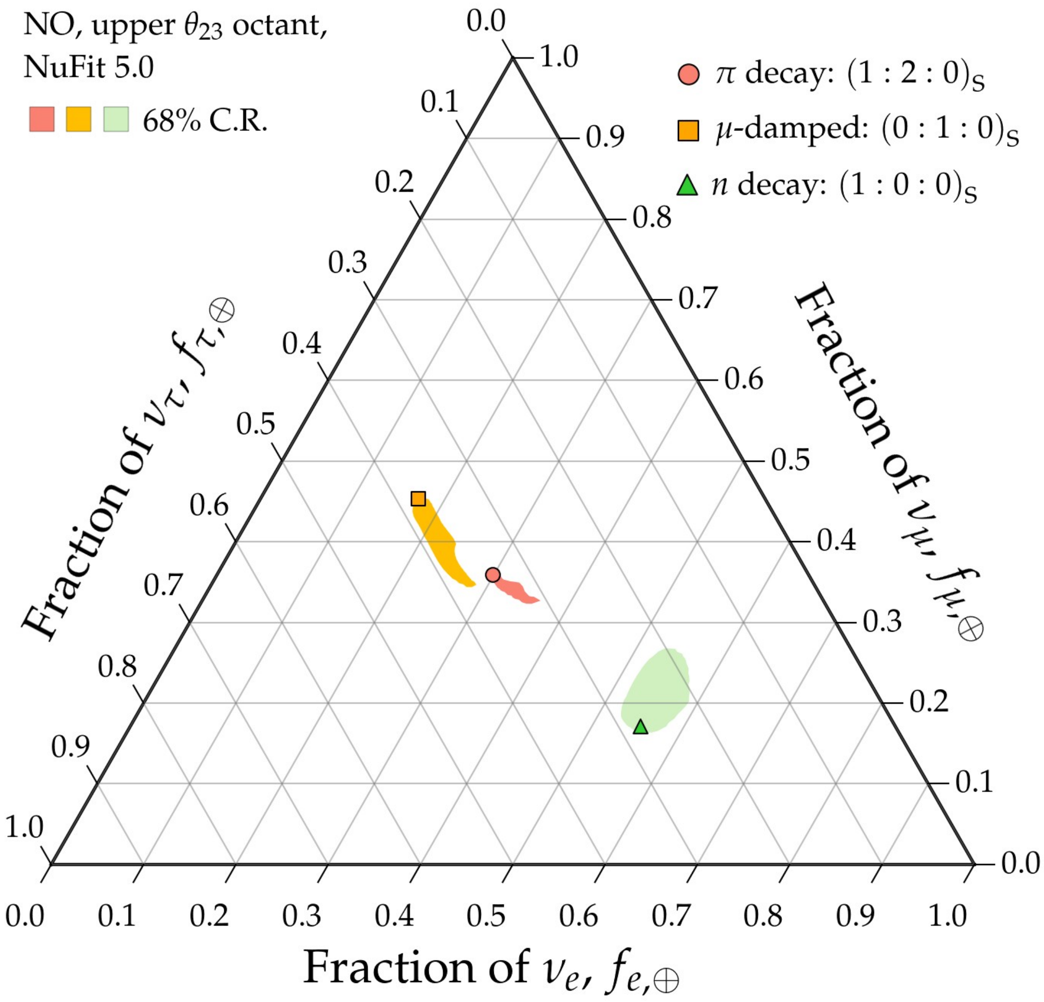
Theoretically palatable regions: today



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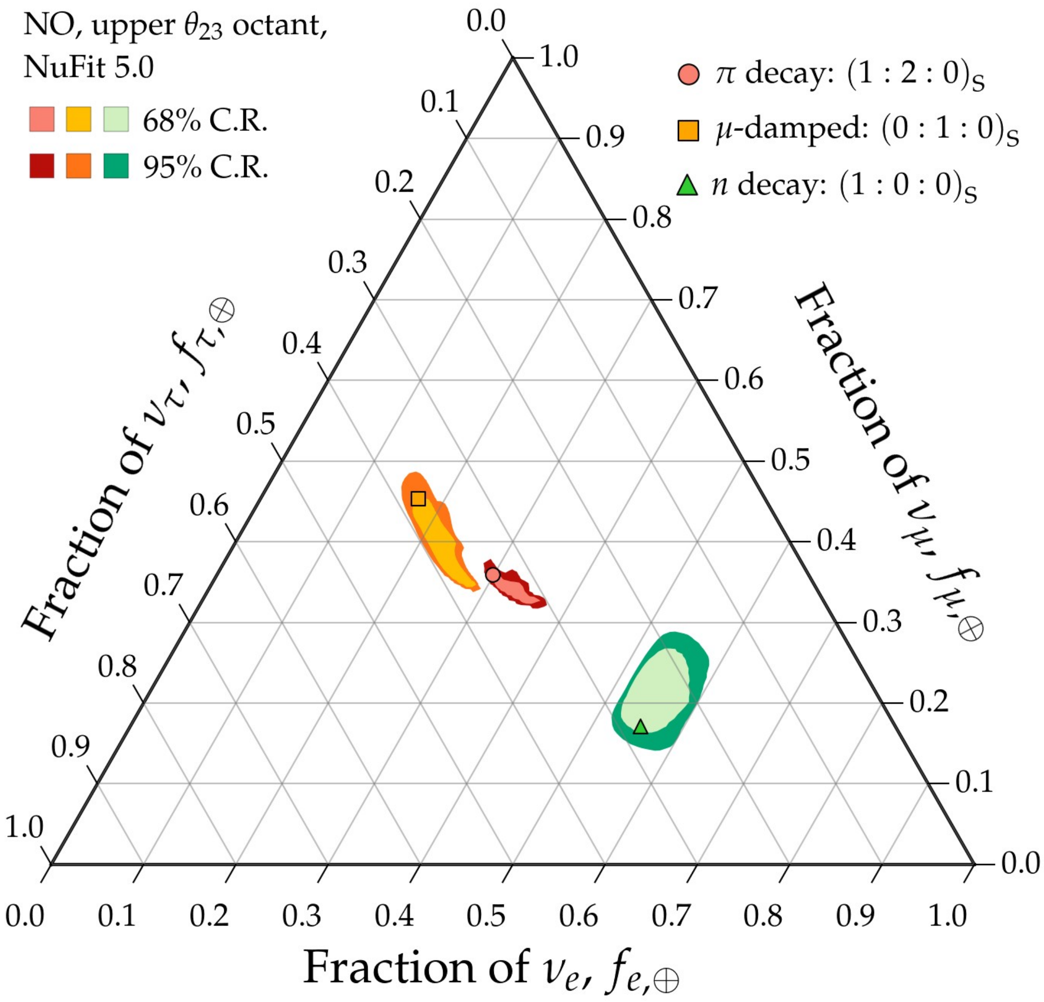
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today



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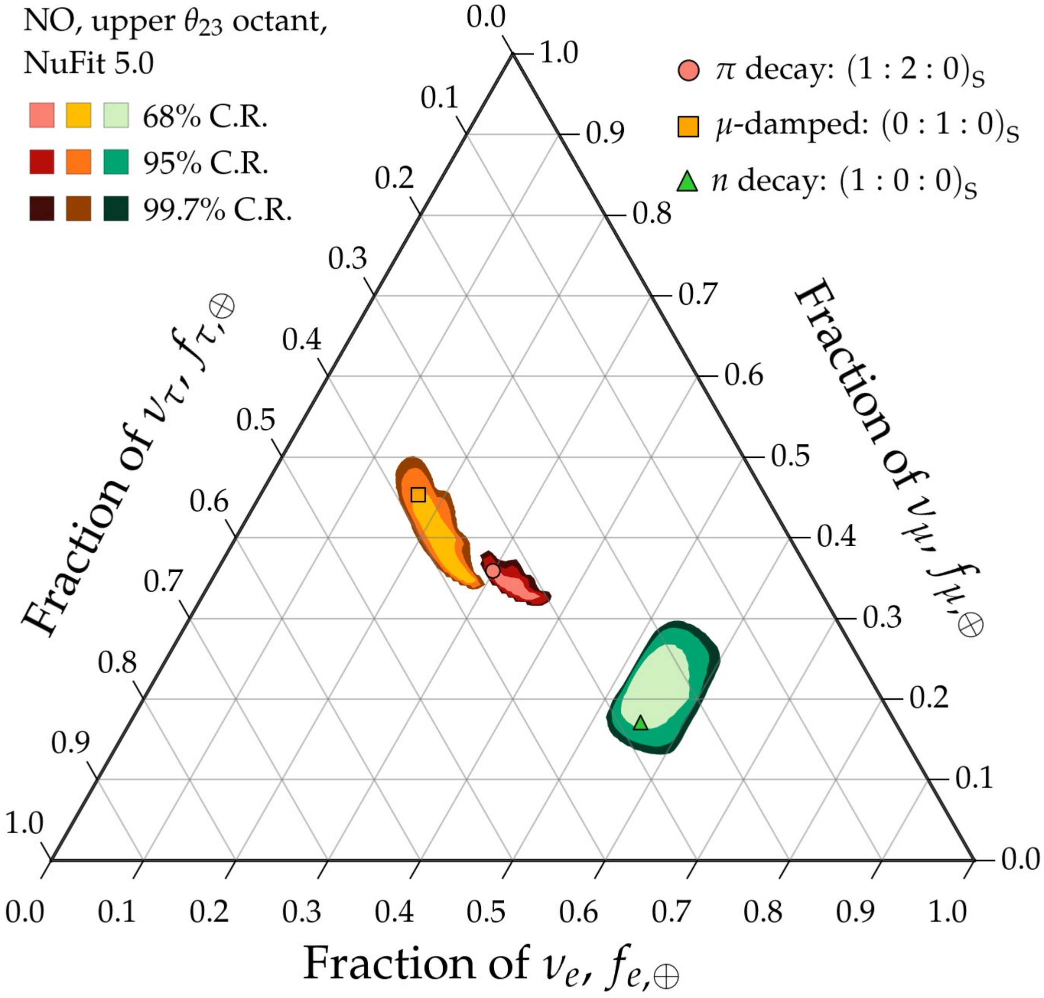
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today



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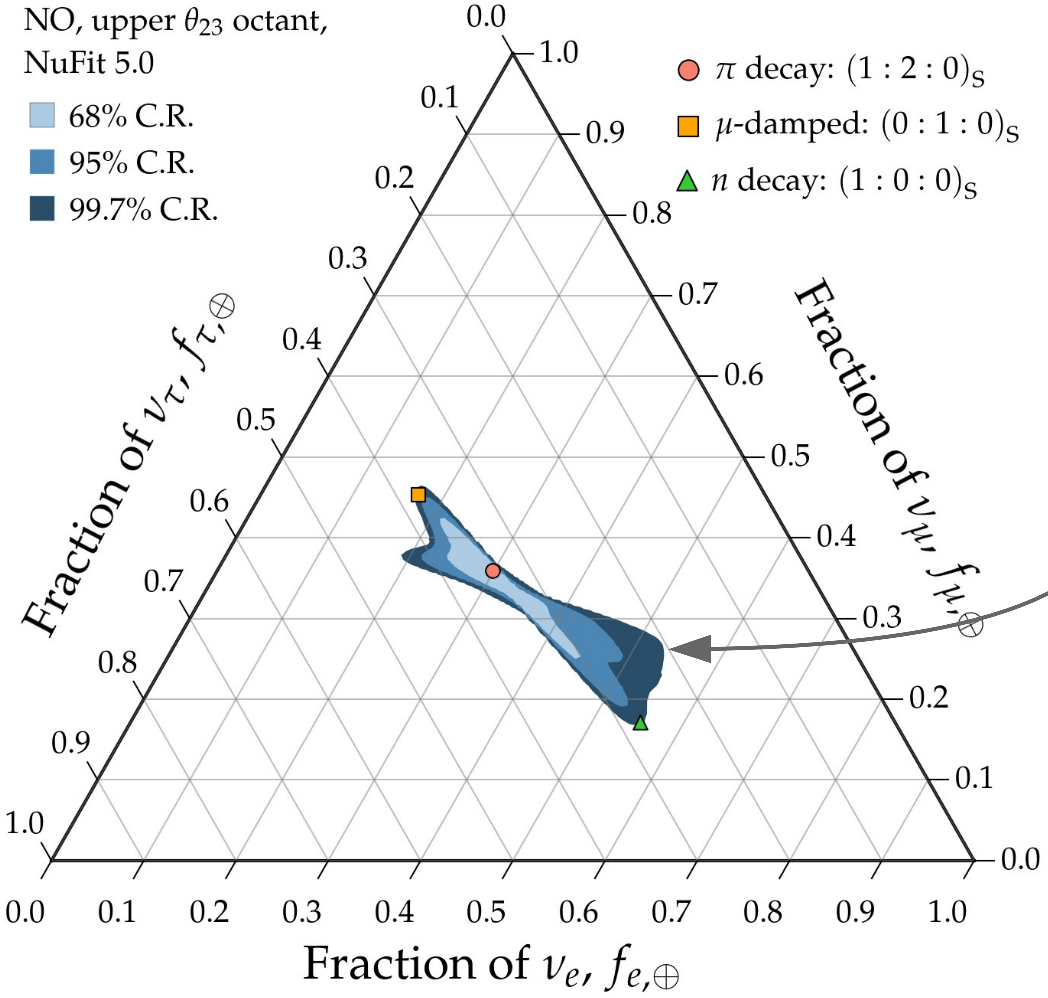
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today

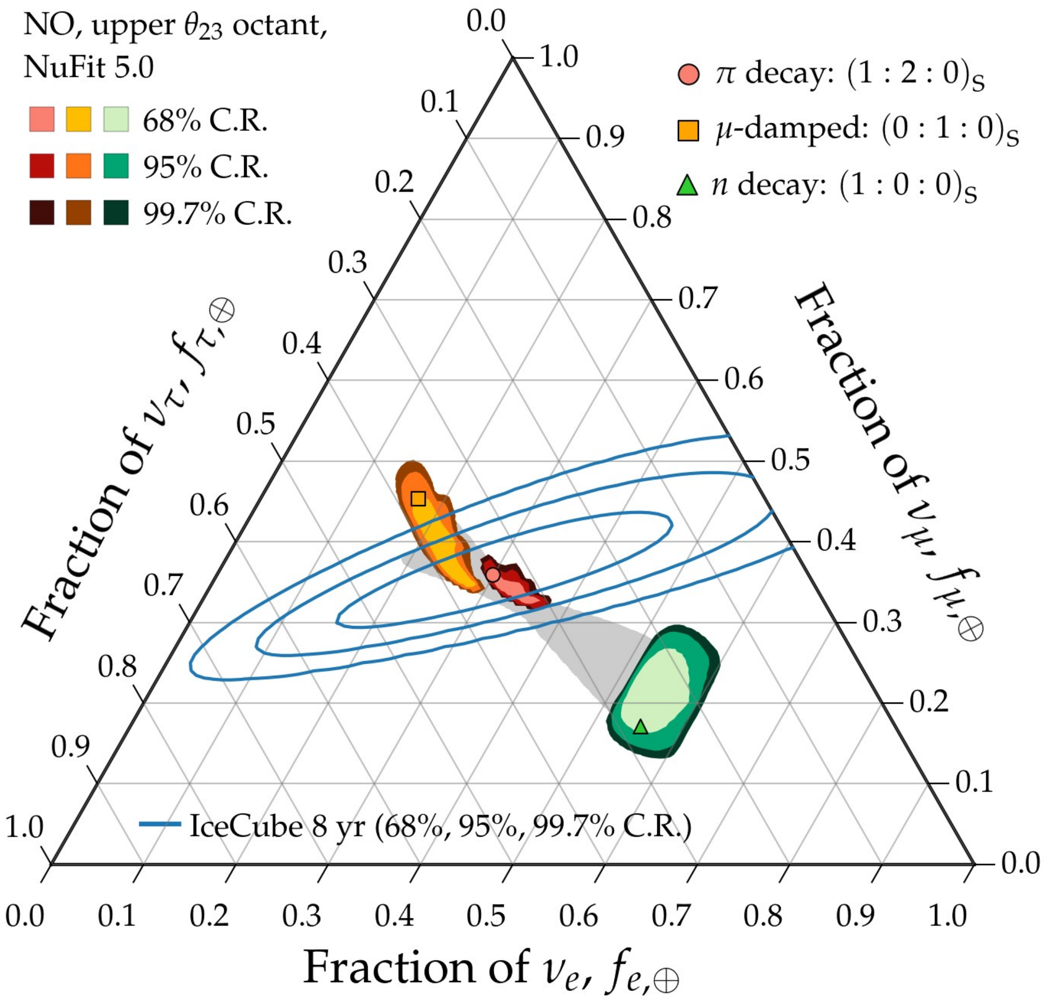


Varying over all possible flavor ratios at the source

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

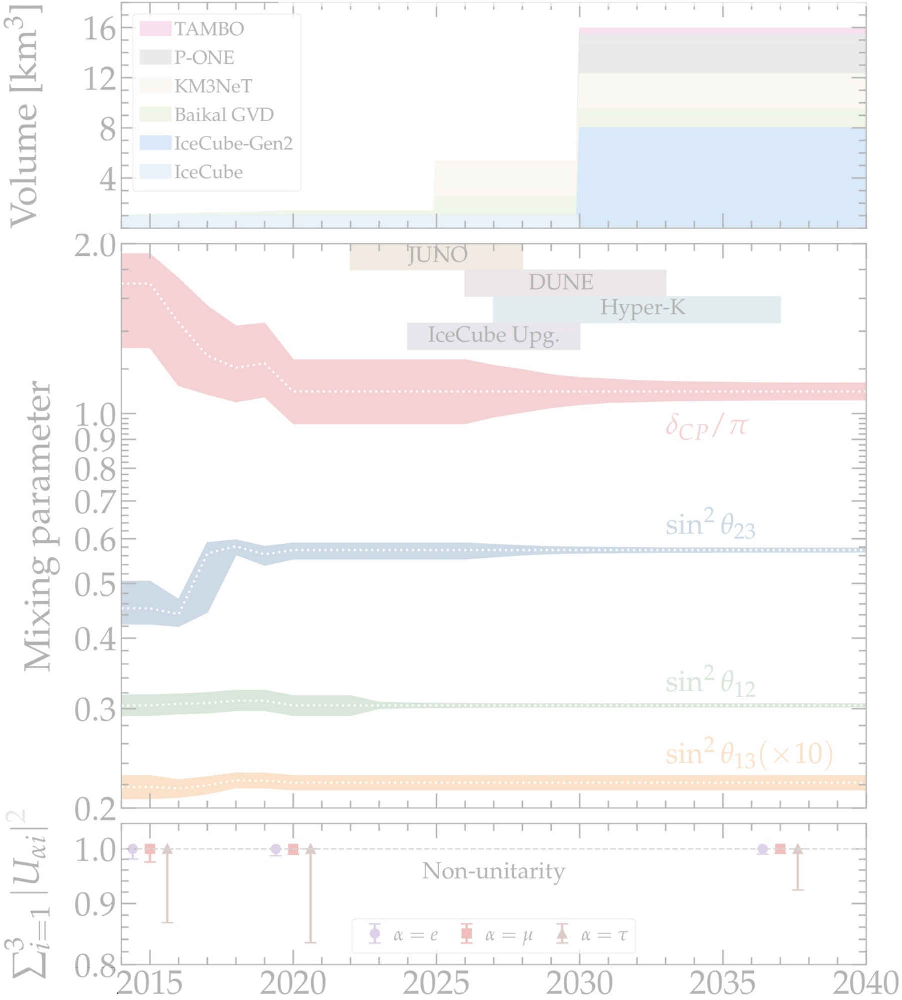


Note:
All plots shown are for normal neutrino mass ordering (NO); inverted ordering looks similar

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

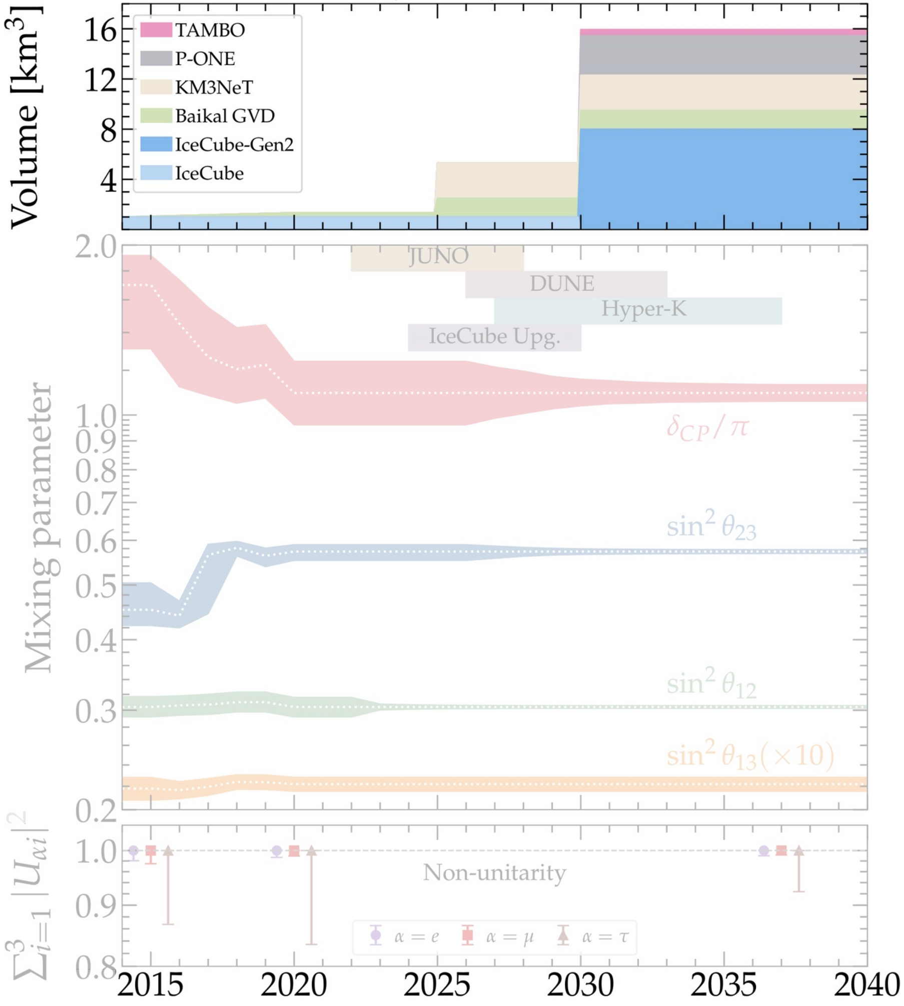
Three reasons to be excited

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



Three reasons to be excited

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

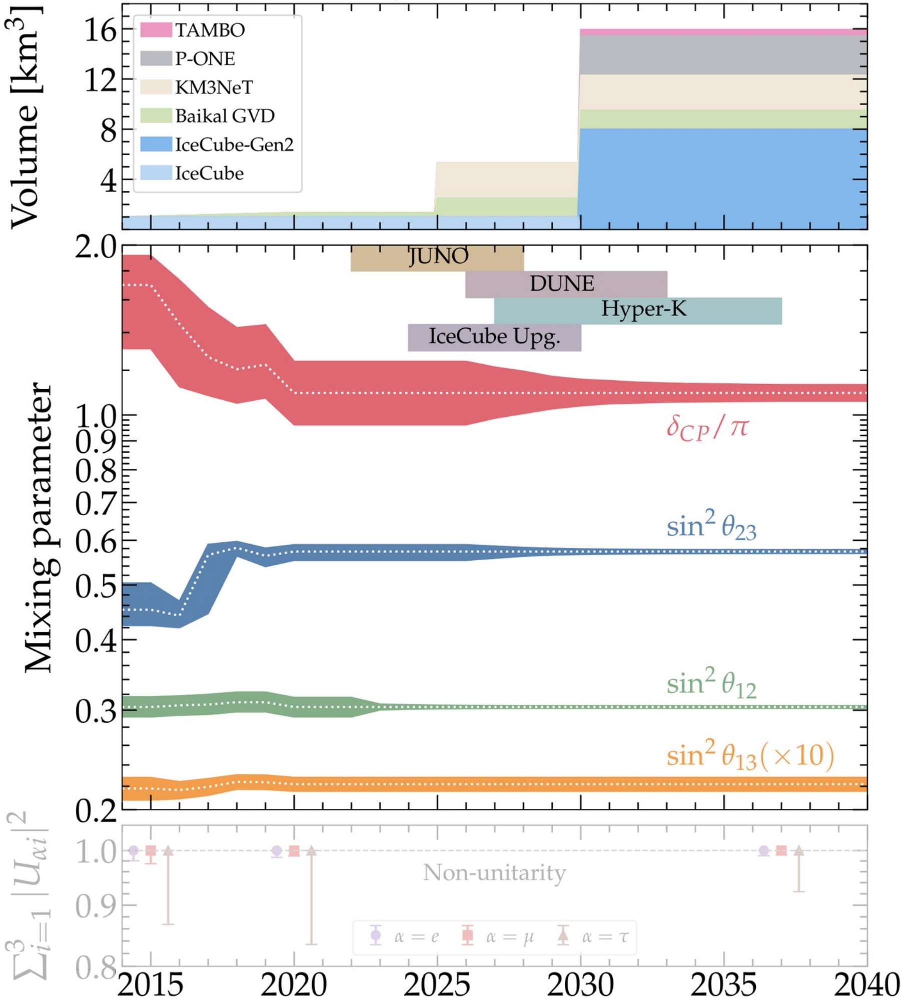


Flavor measurements:

New neutrino telescopes = more events, better flavor measurement

Three reasons to be excited

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



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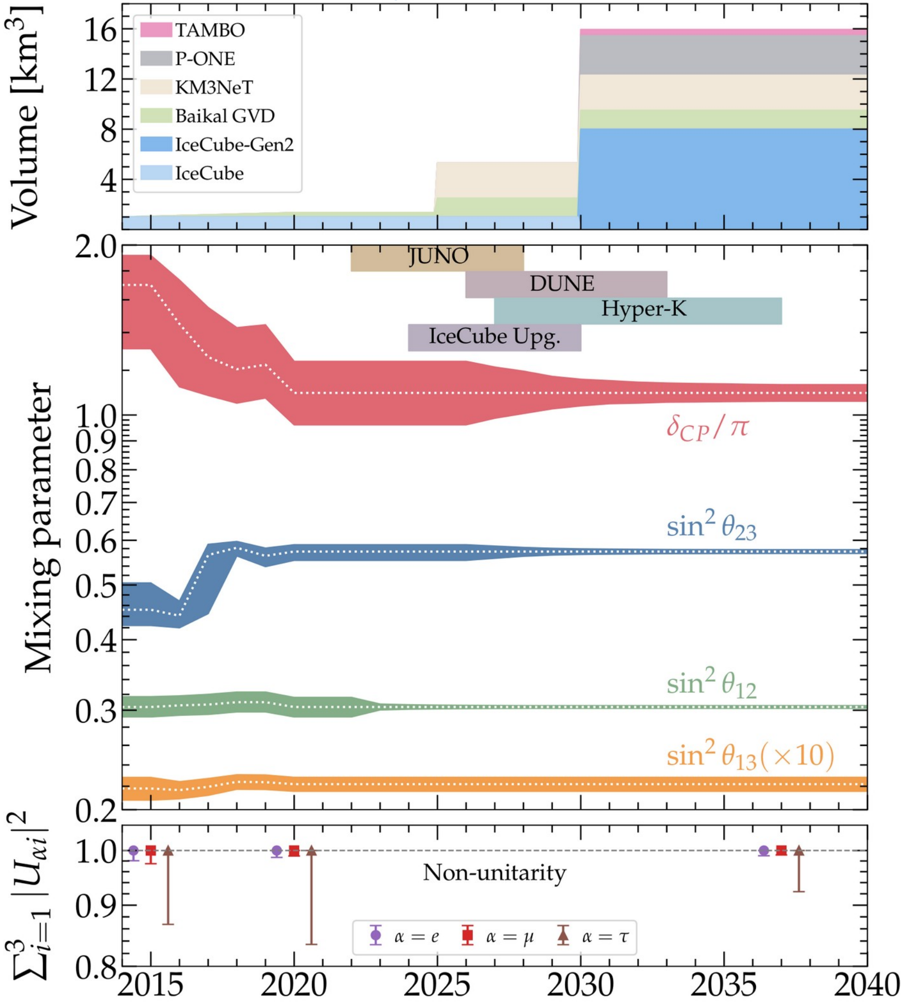
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

Three reasons to be excited

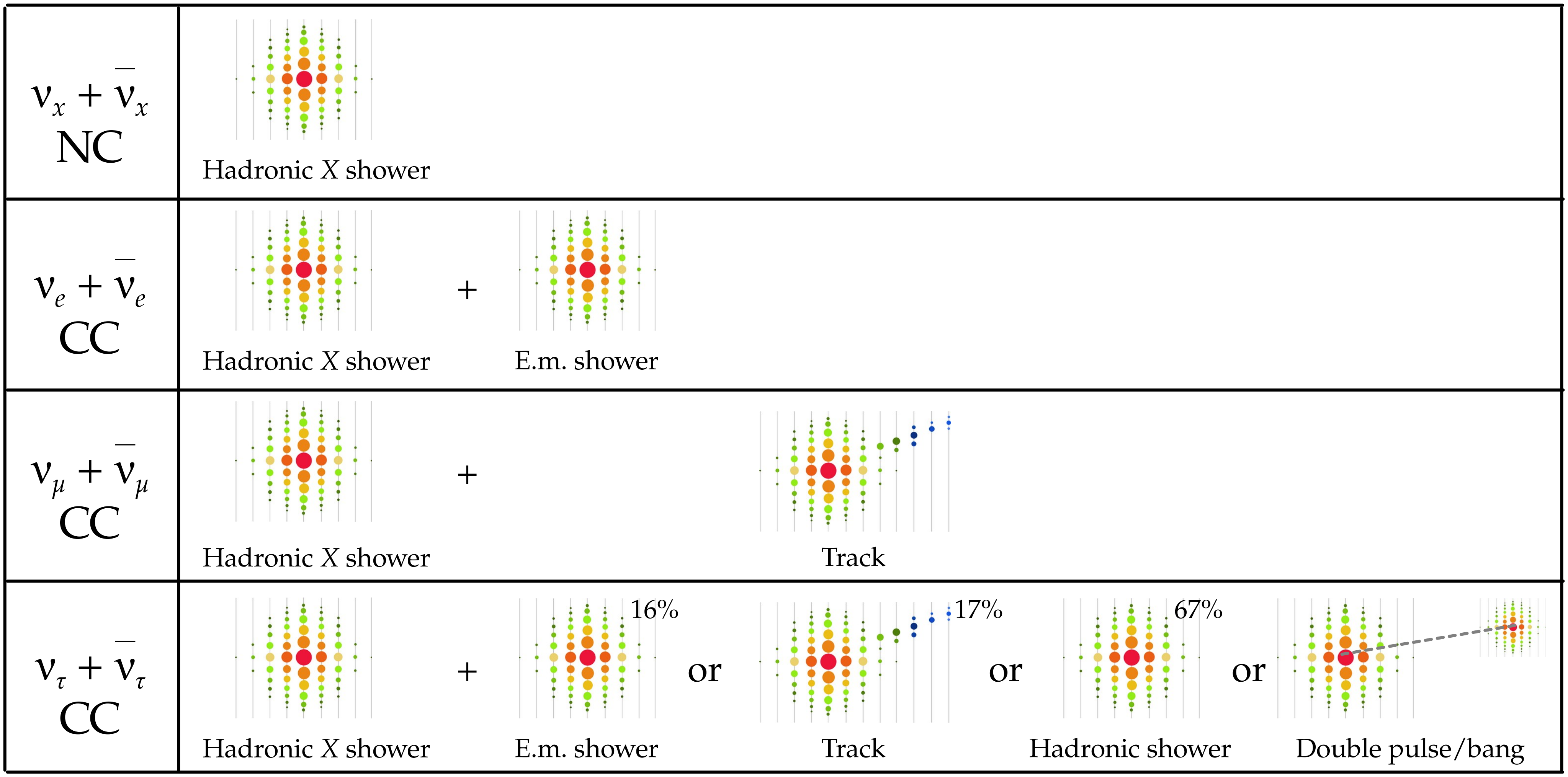
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

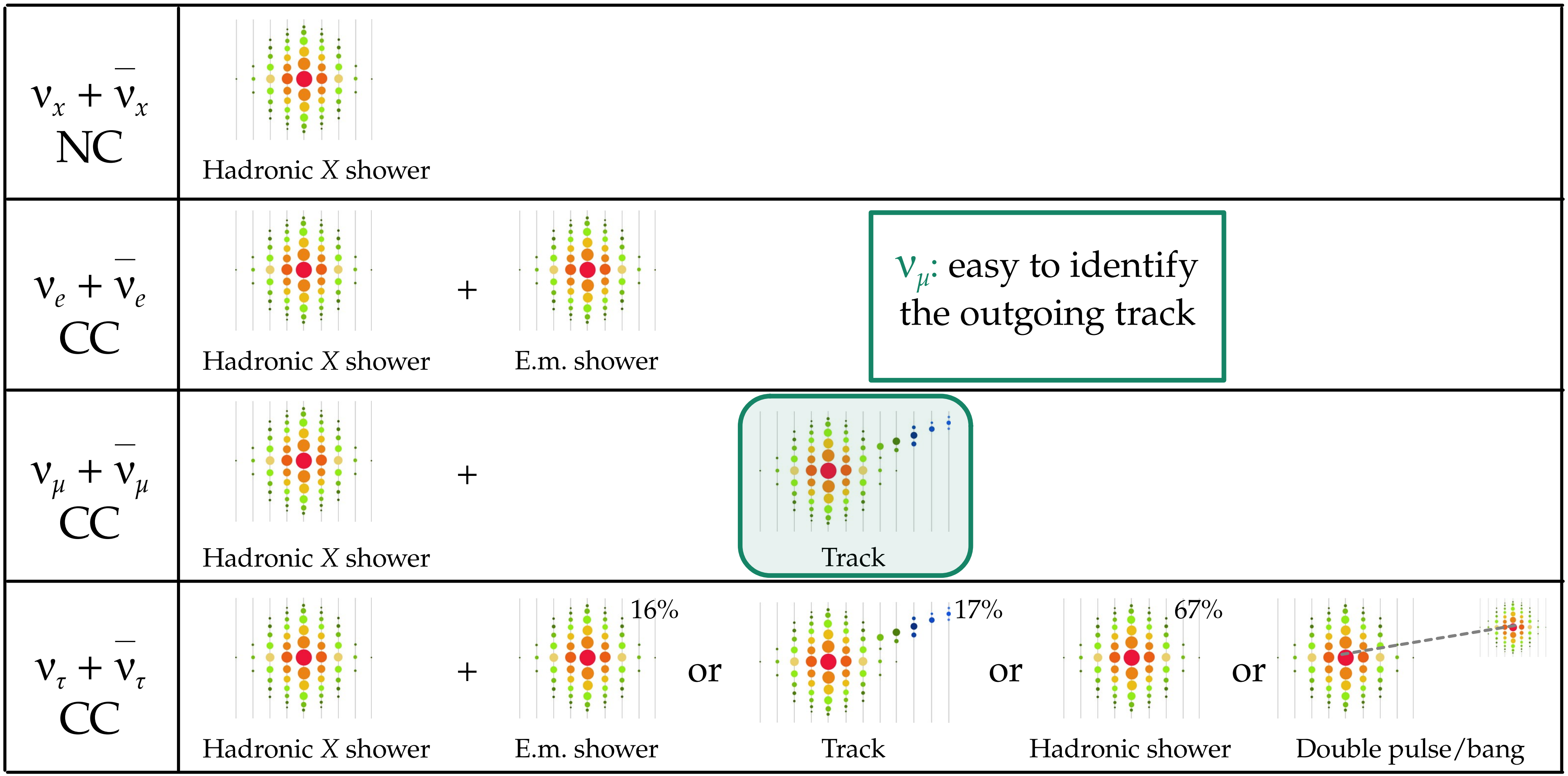


Flavor measurements:
New neutrino telescopes = more events, better flavor measurement

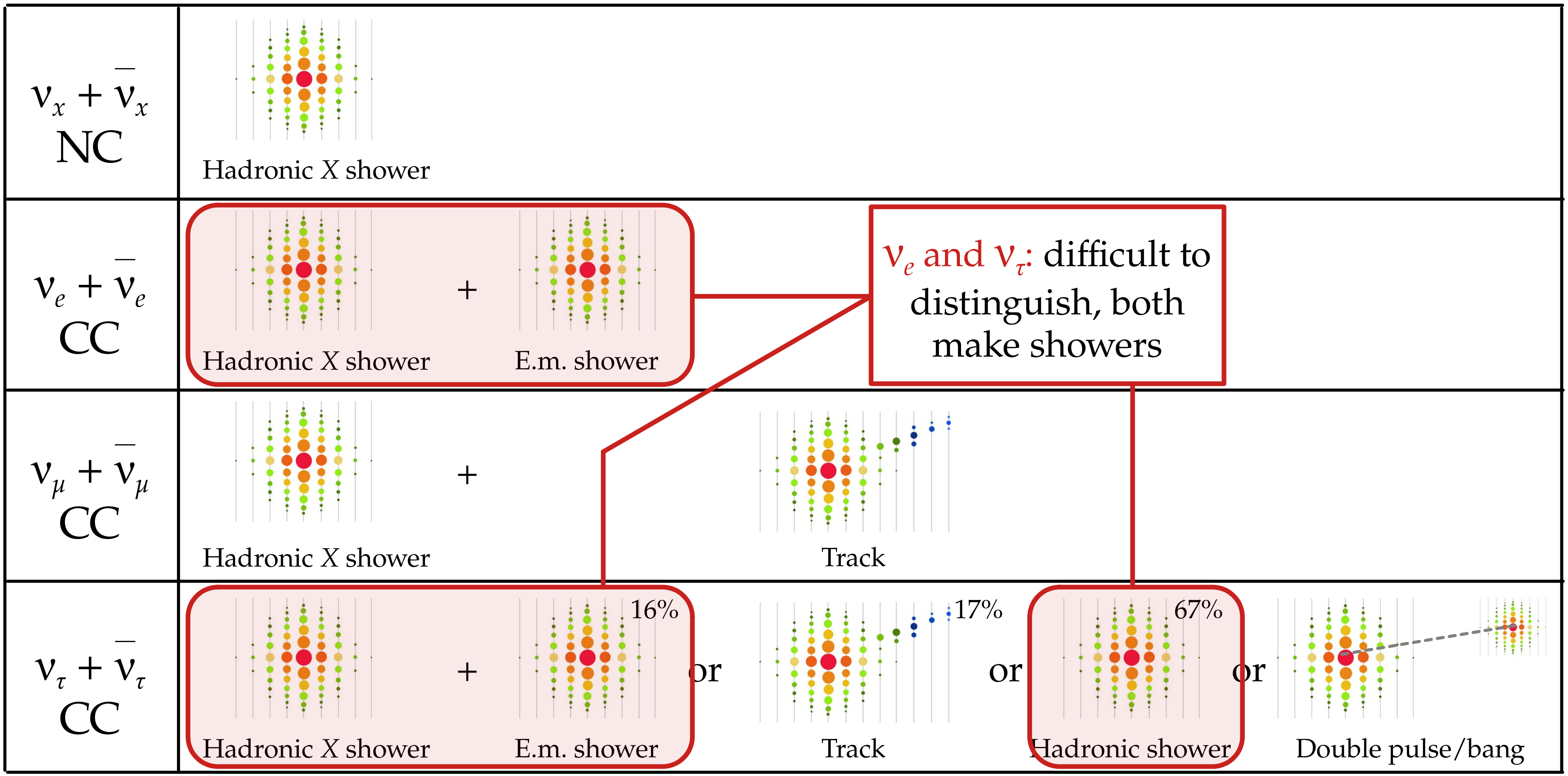
Oscillation physics:
We will know the mixing parameters better (JUNO, DUNE, Hyper-K, IceCube Upgrade)

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

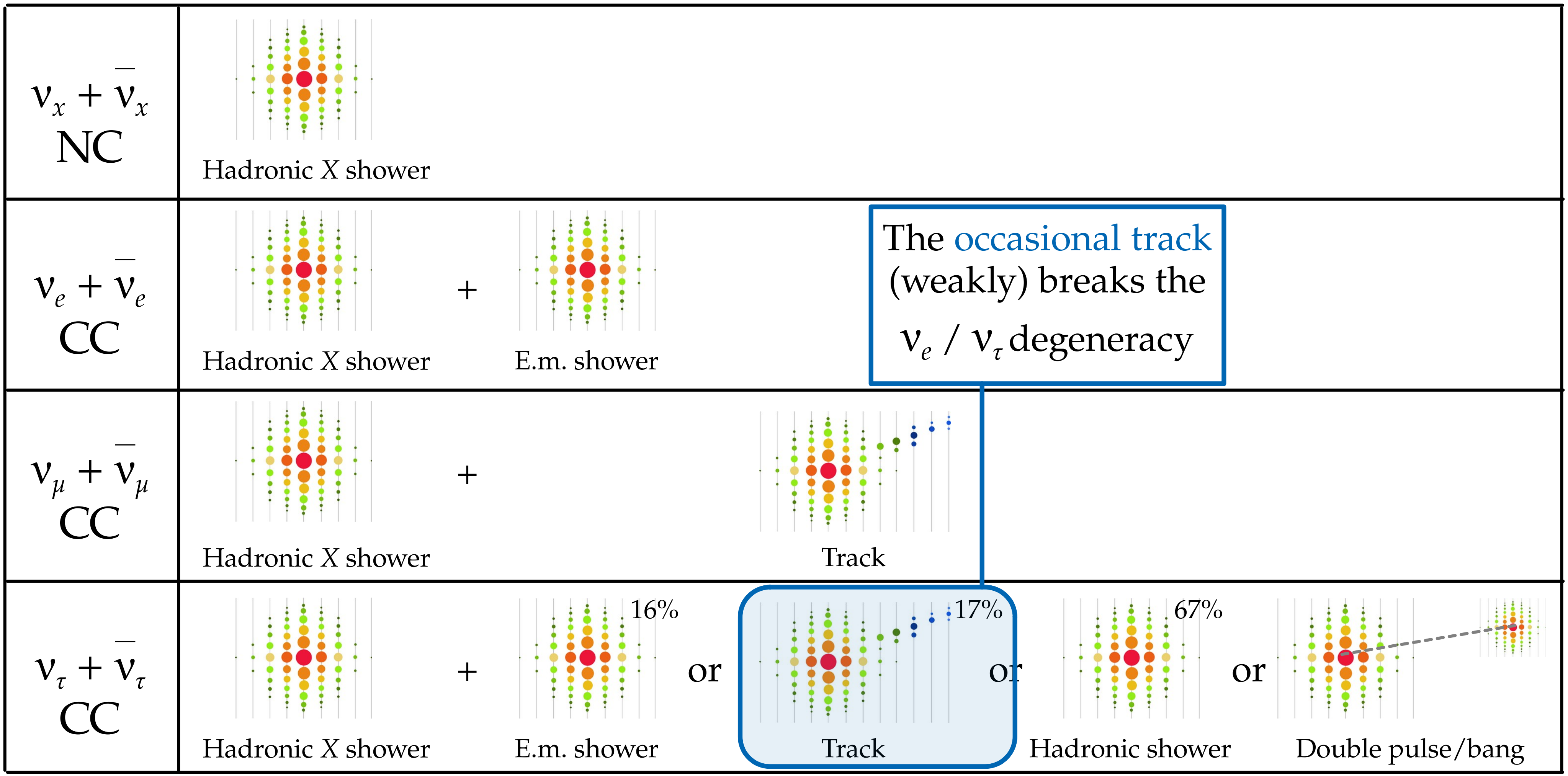

$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang



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



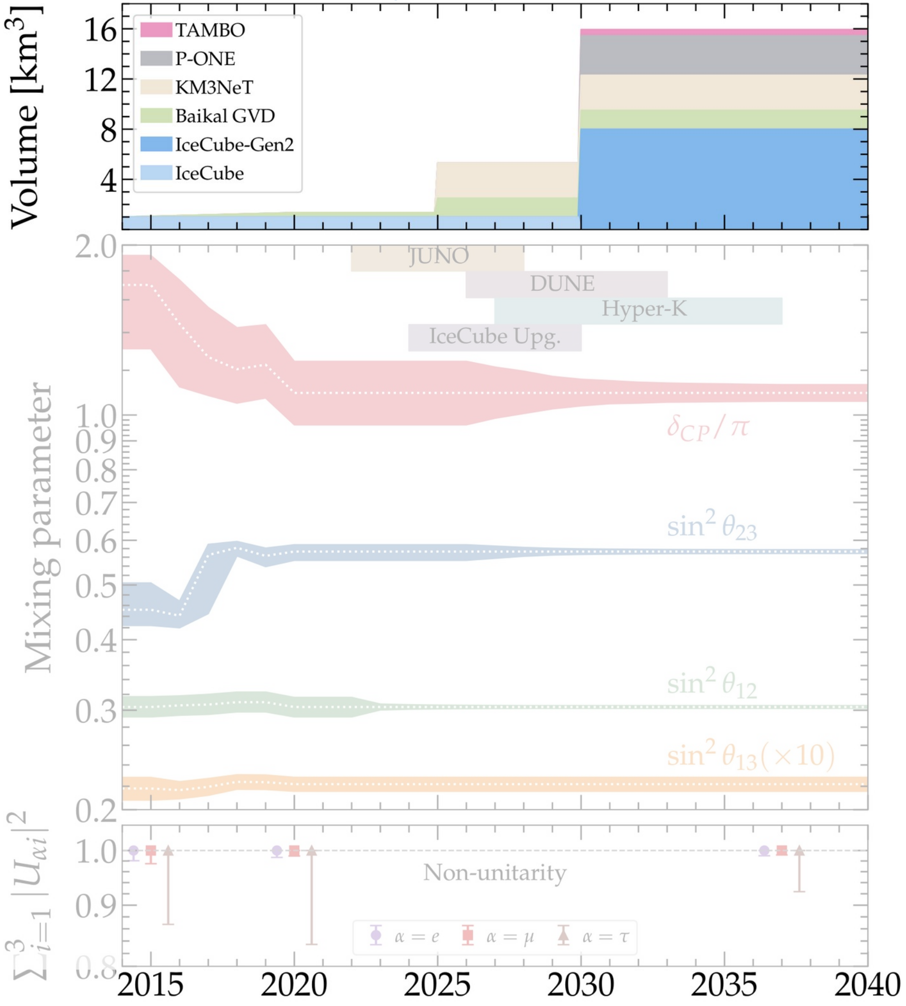
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$
CC
Hadronic X shower
+
E.m. shower
16%
or
Track
17%
or
Hadronic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



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

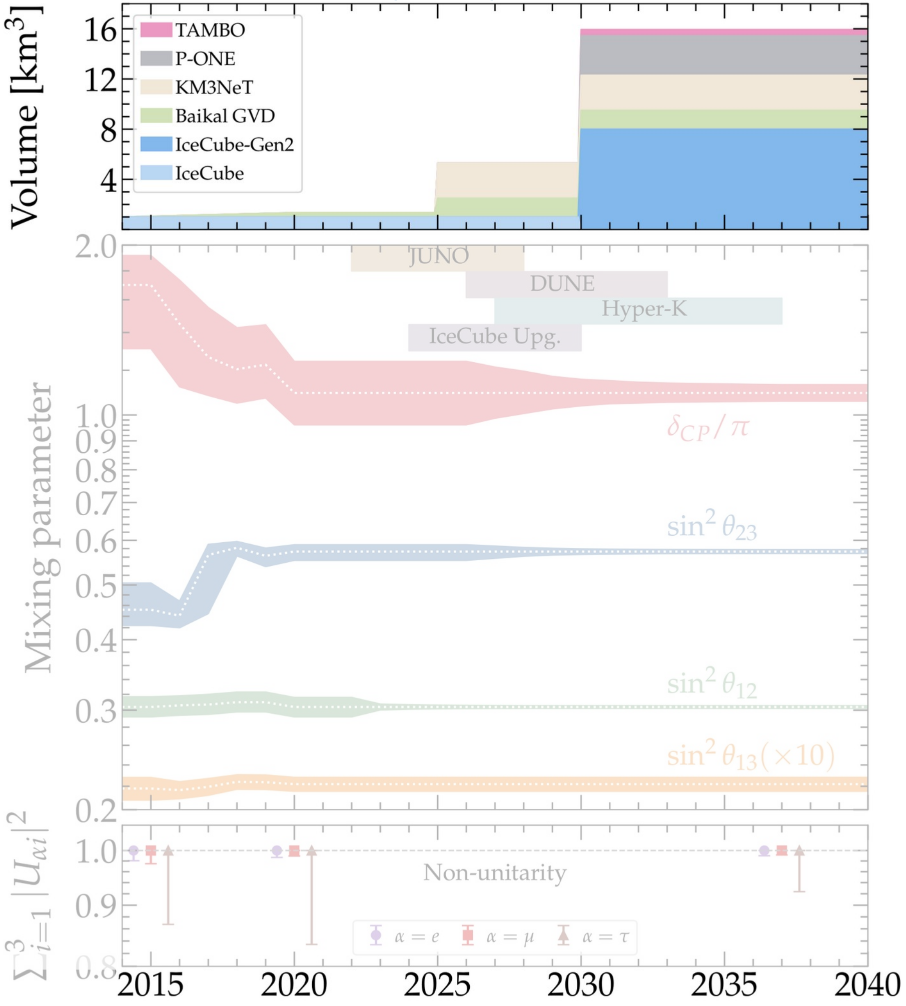
Measuring flavor composition: 2015–2040

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



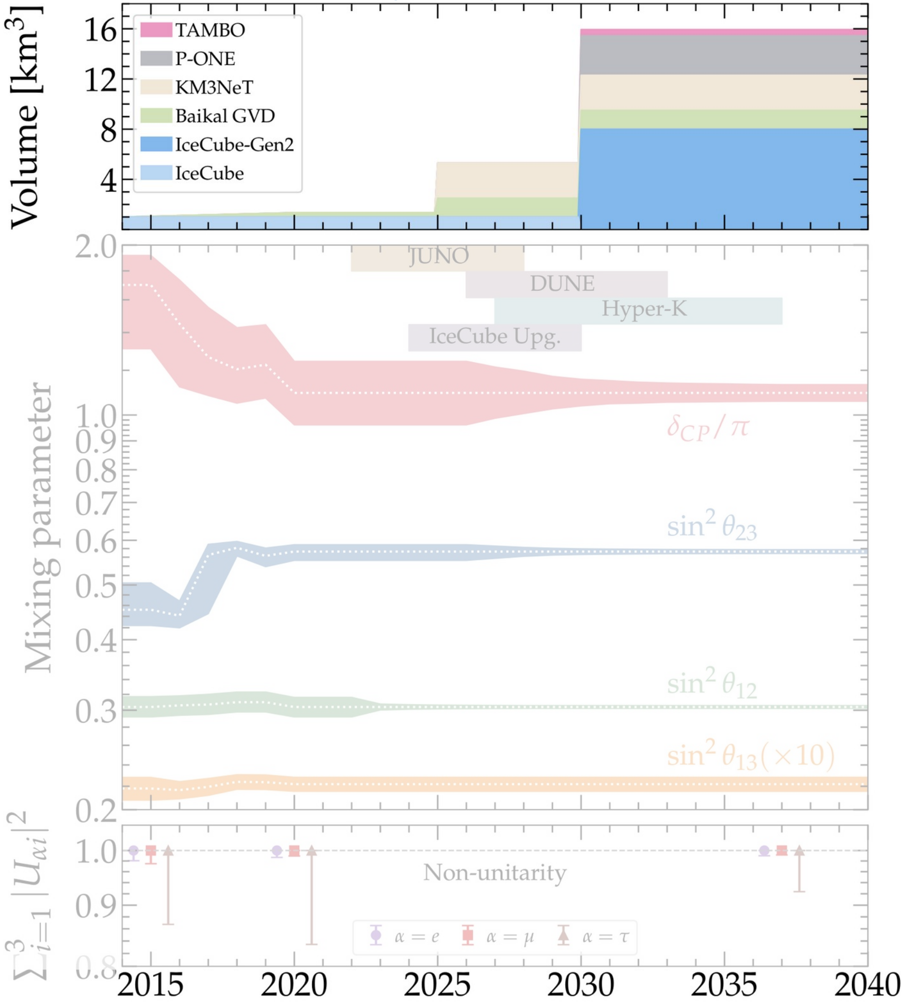
Measuring flavor composition: 2015–2040

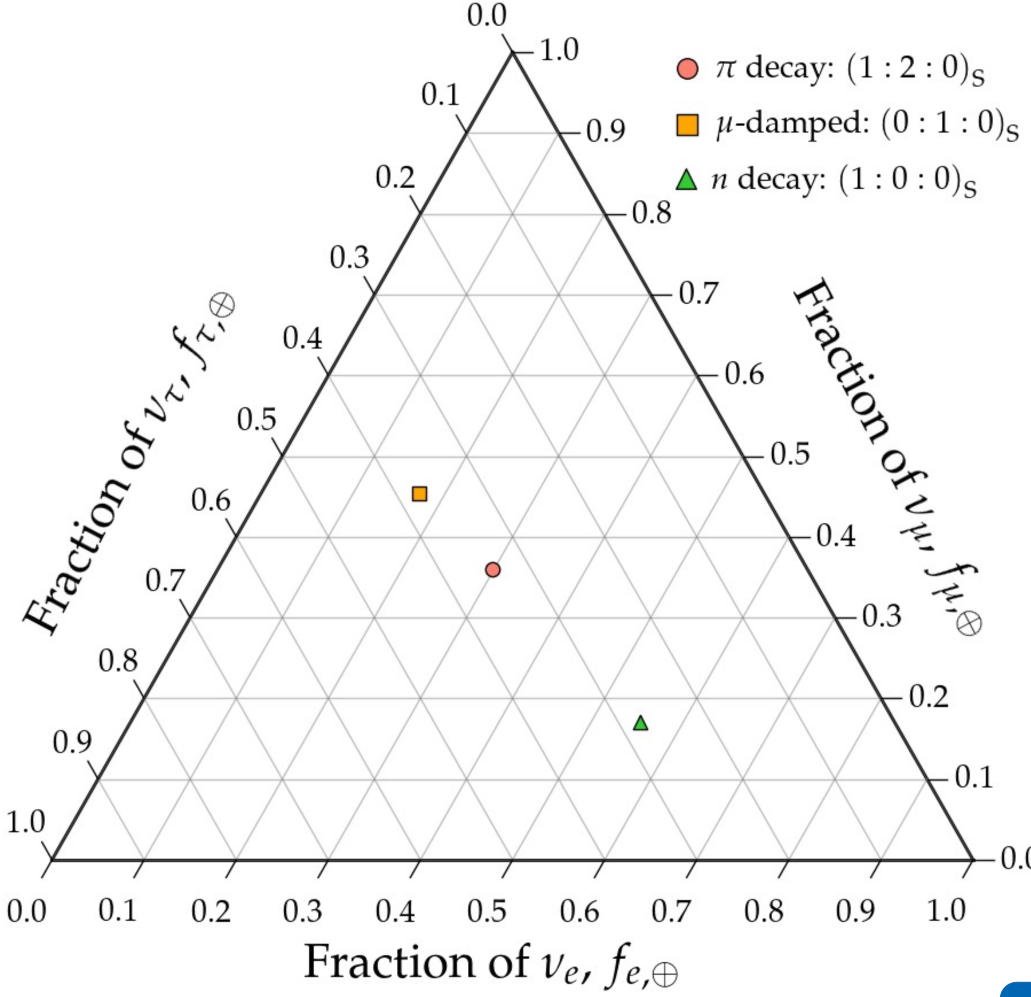
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



Measuring flavor composition: 2015–2040

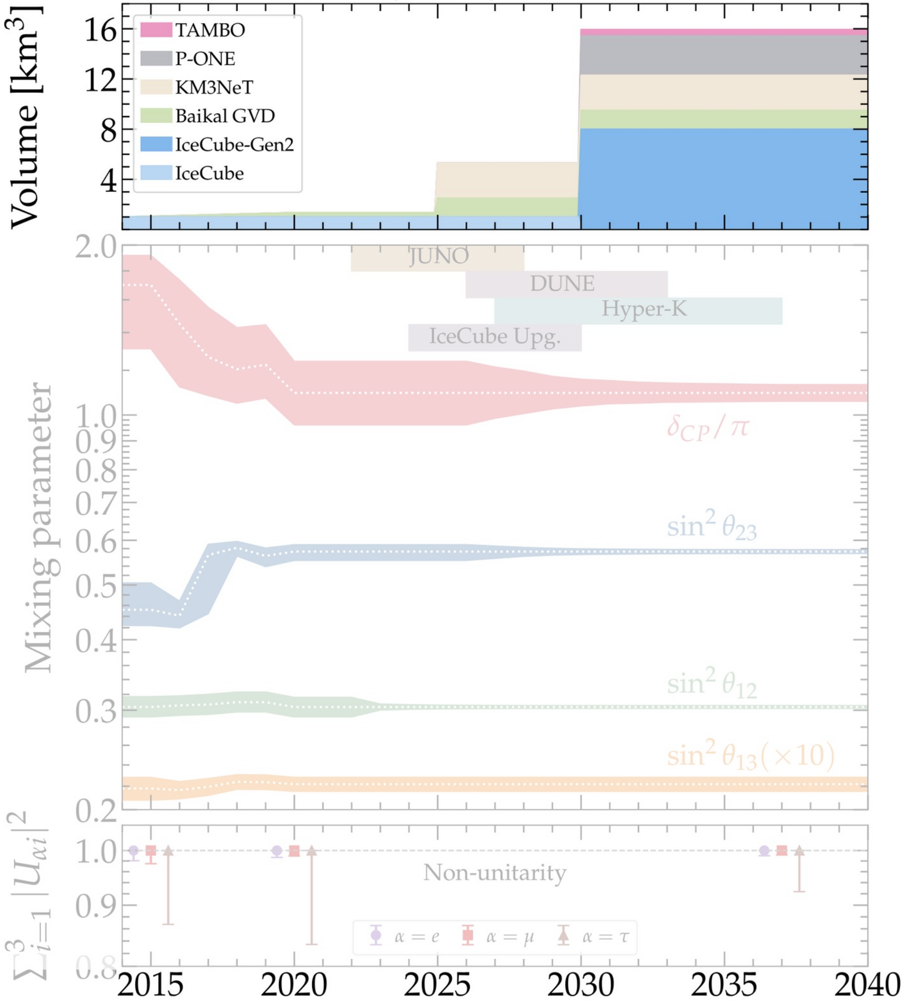
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

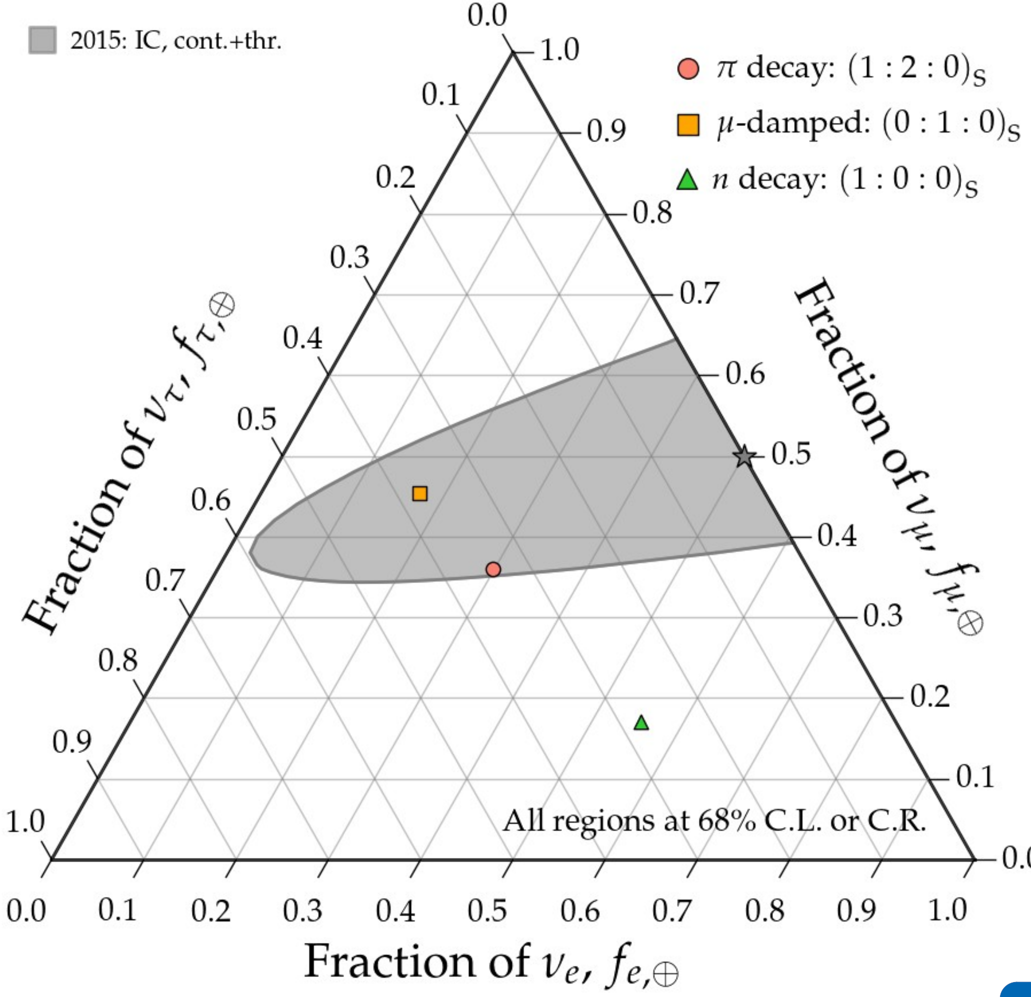




Measuring flavor composition: 2015–2040

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





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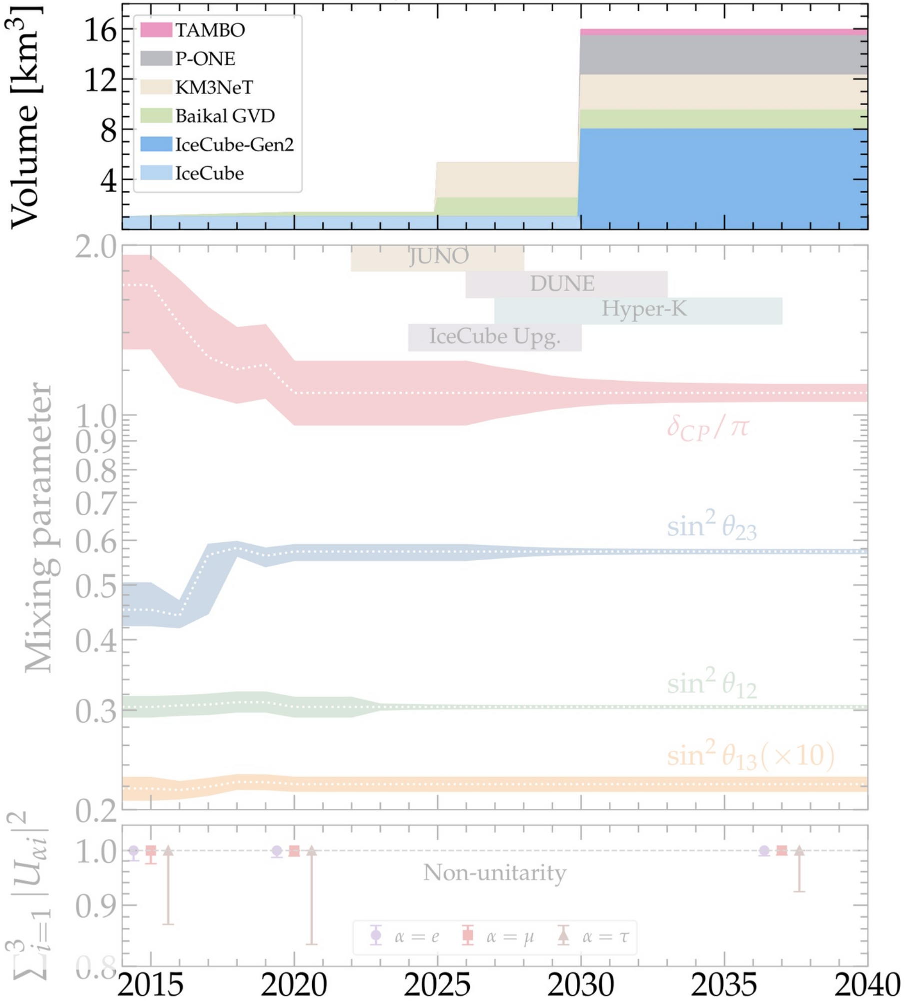

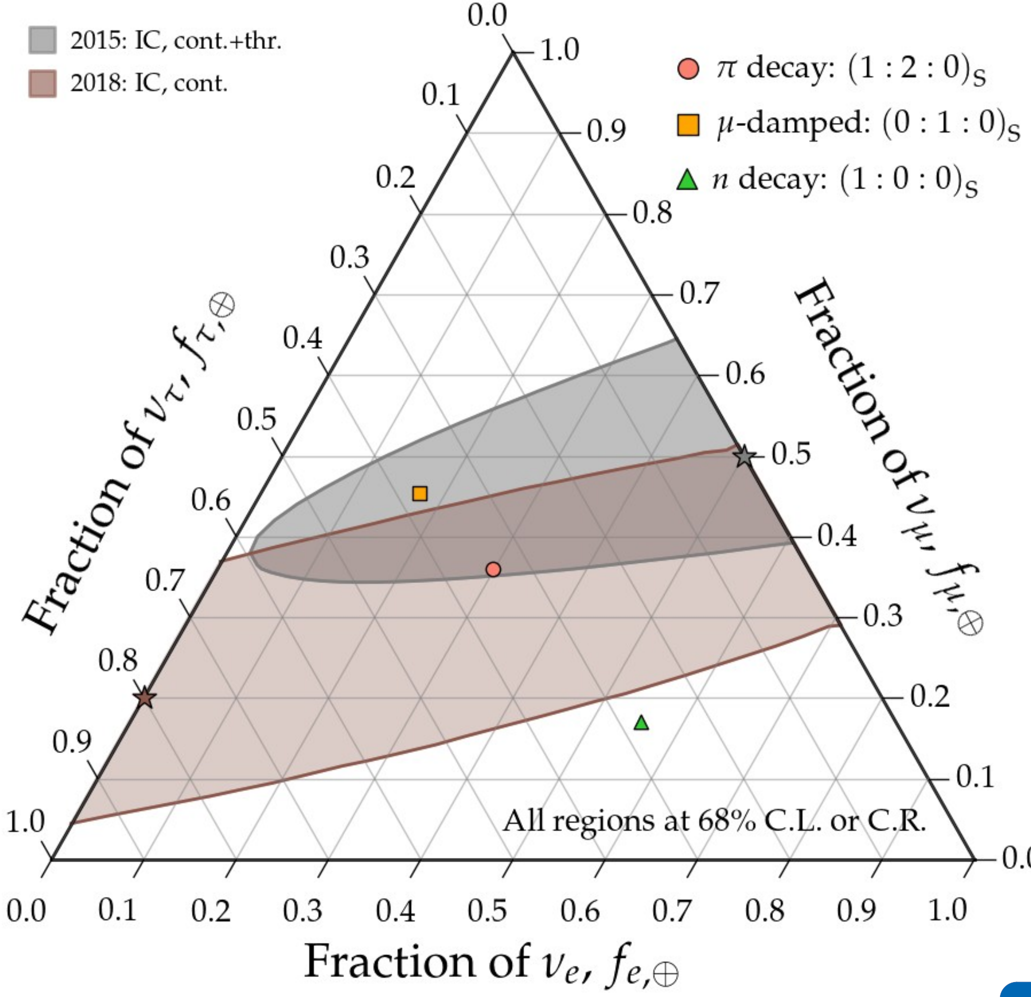

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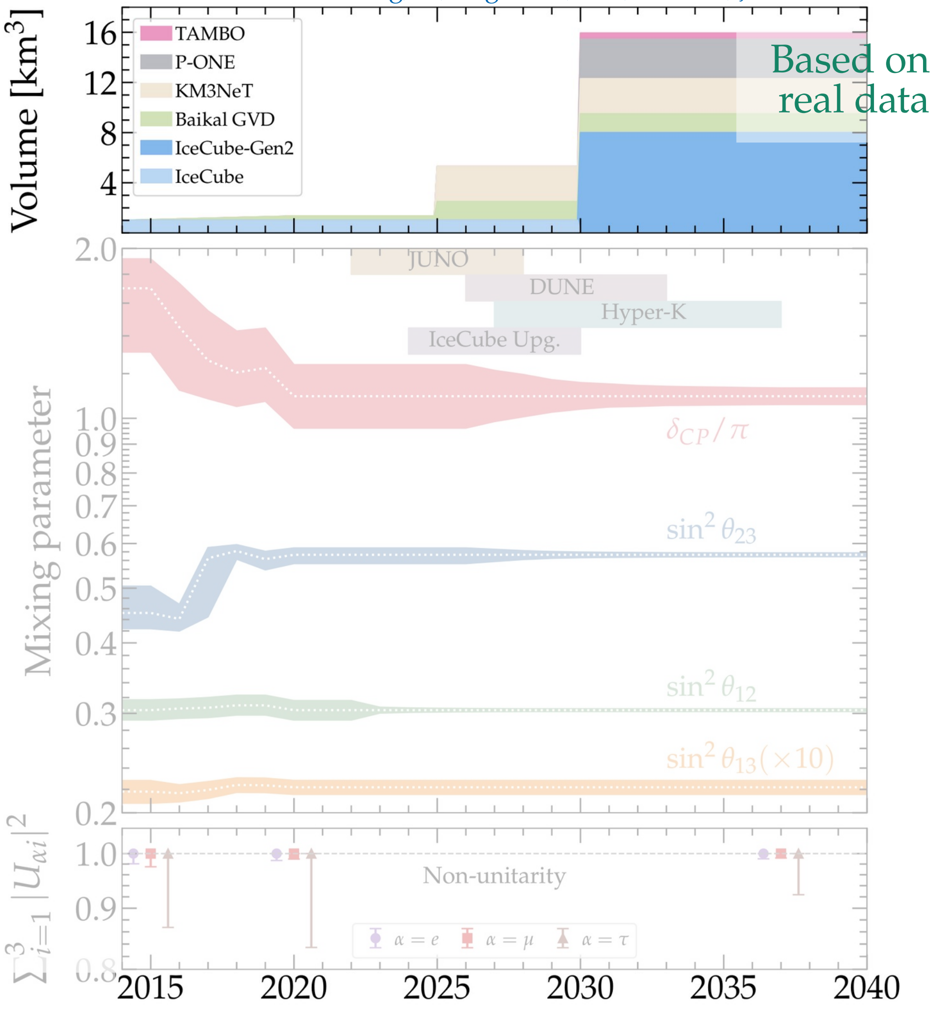

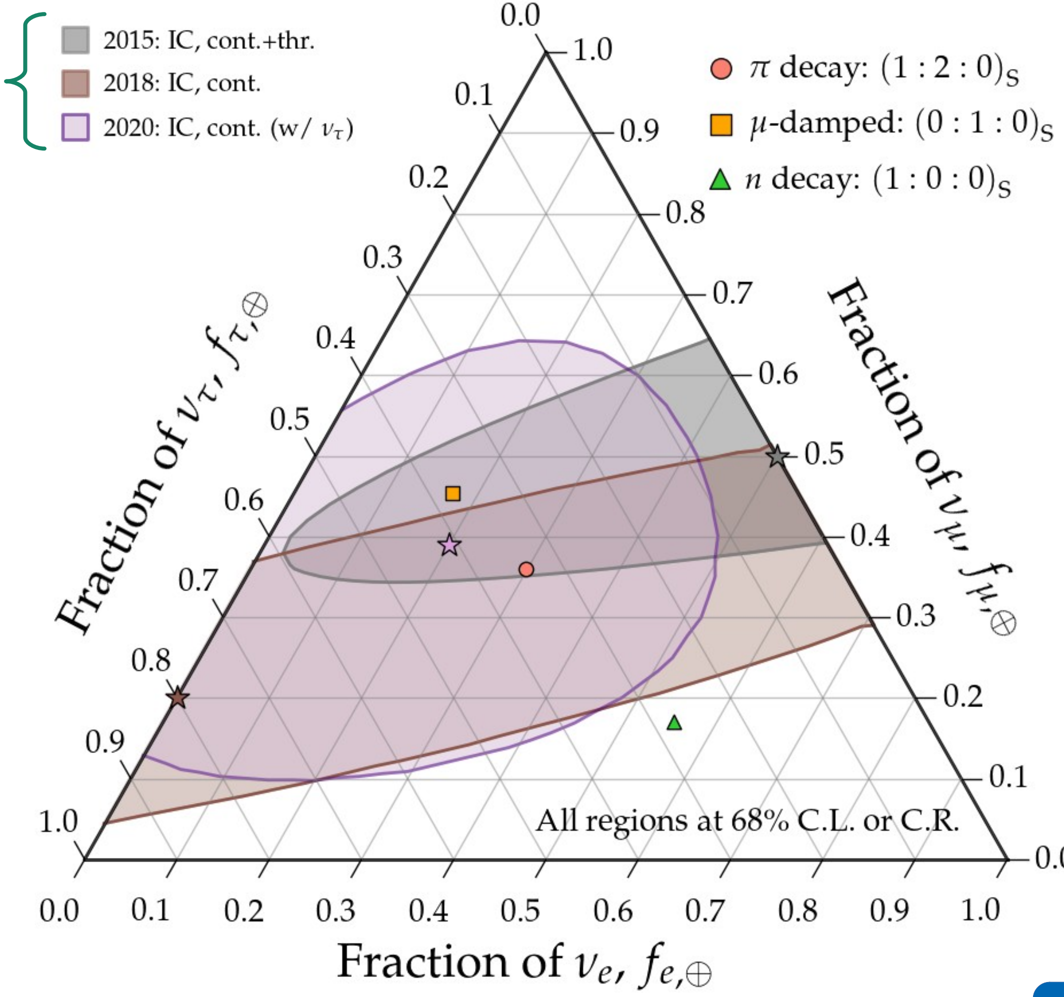

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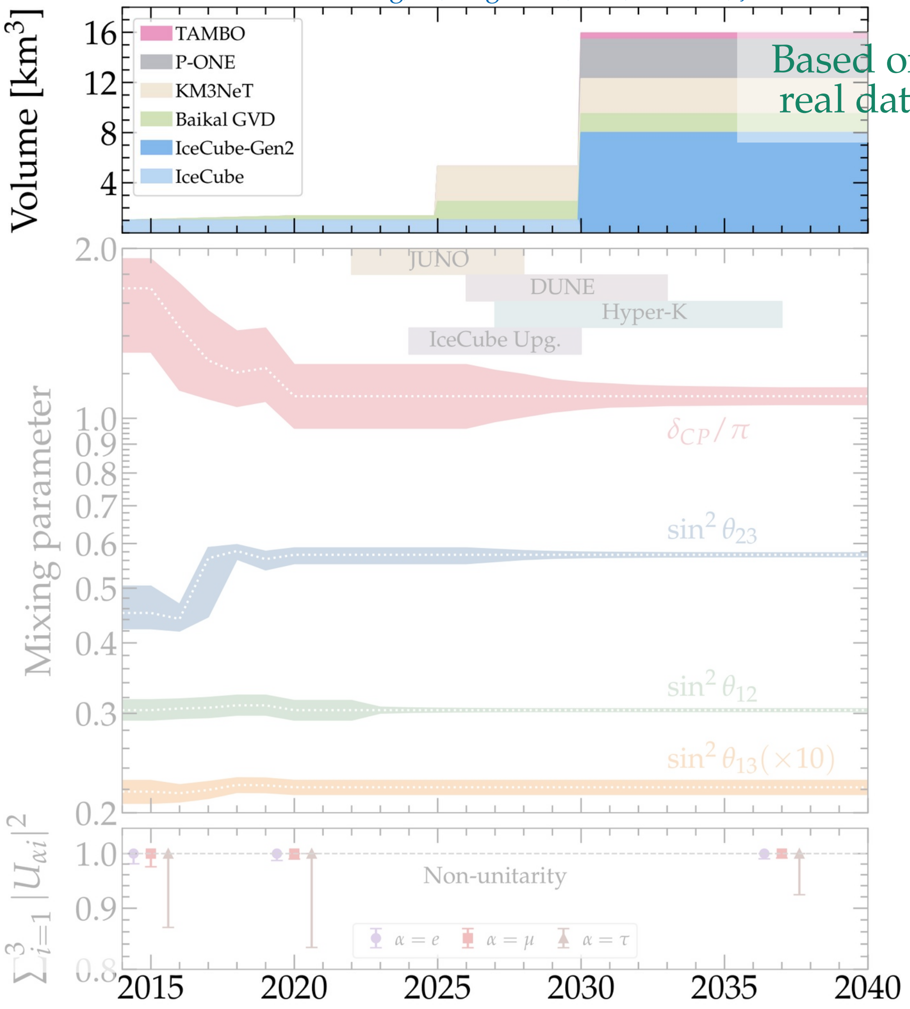
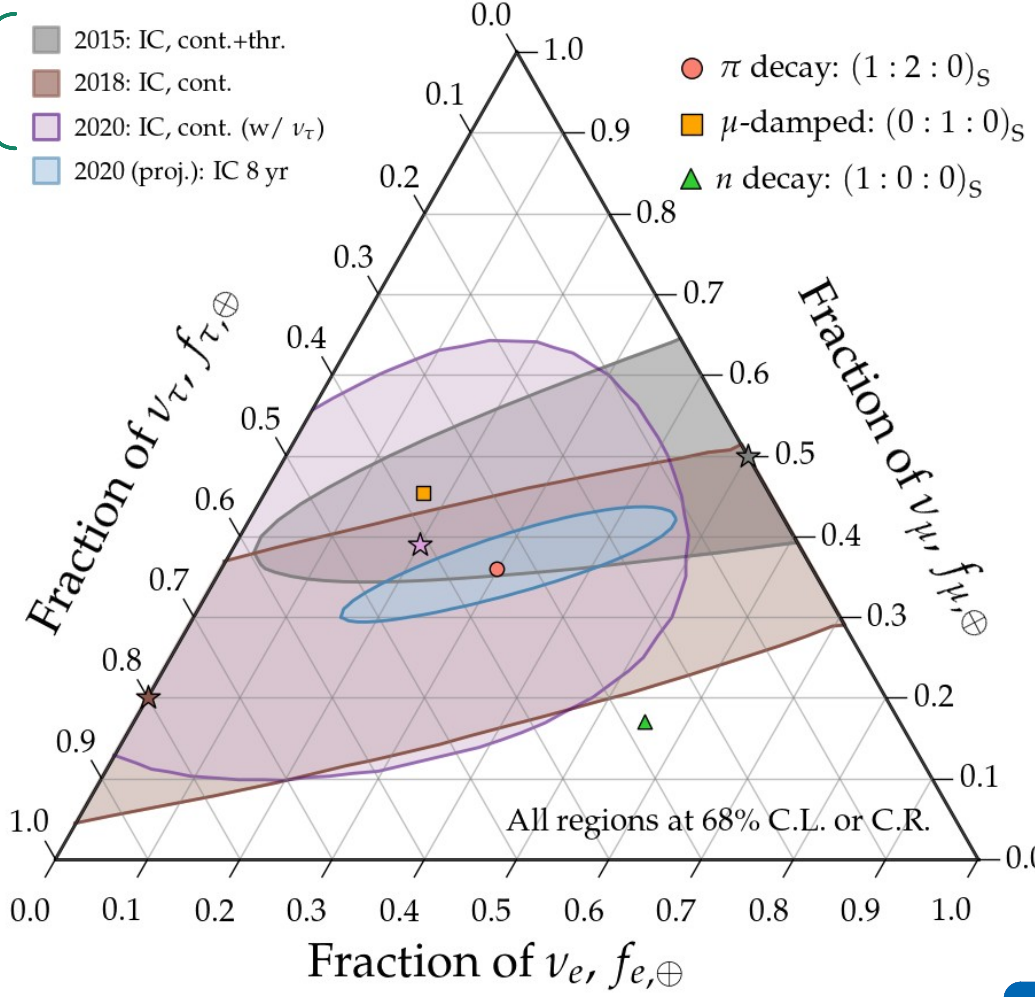


Based on real data



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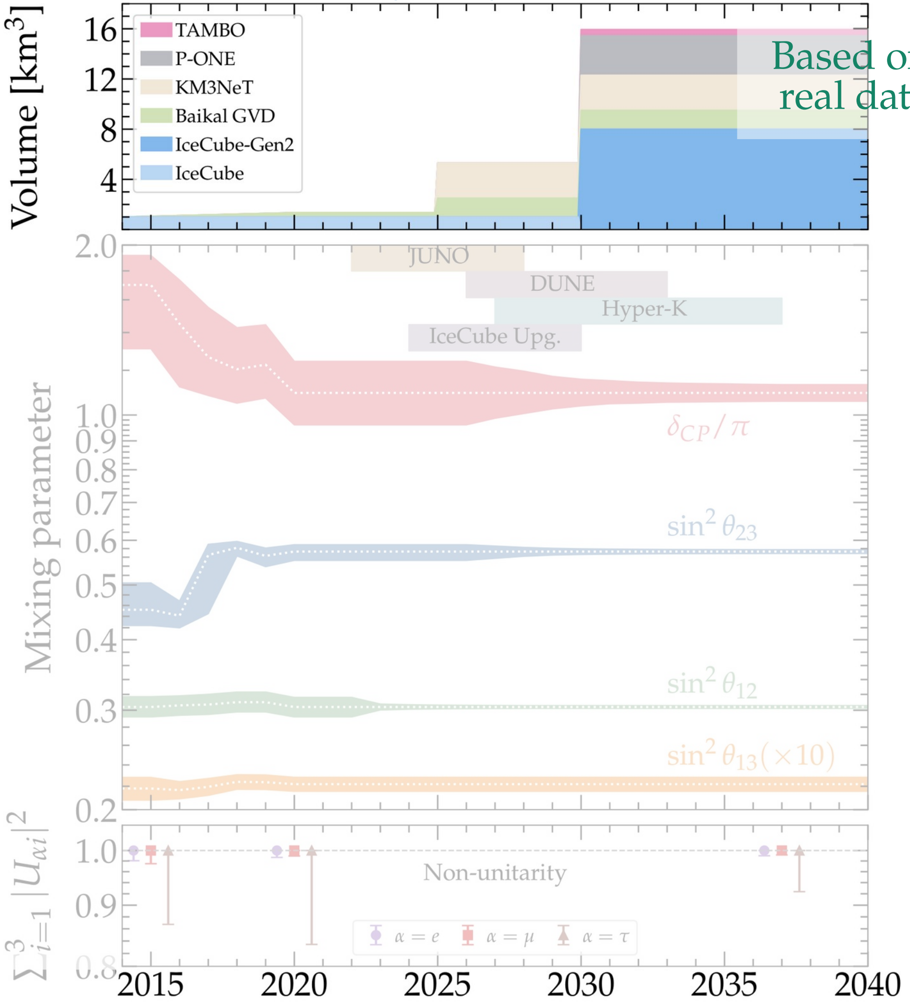

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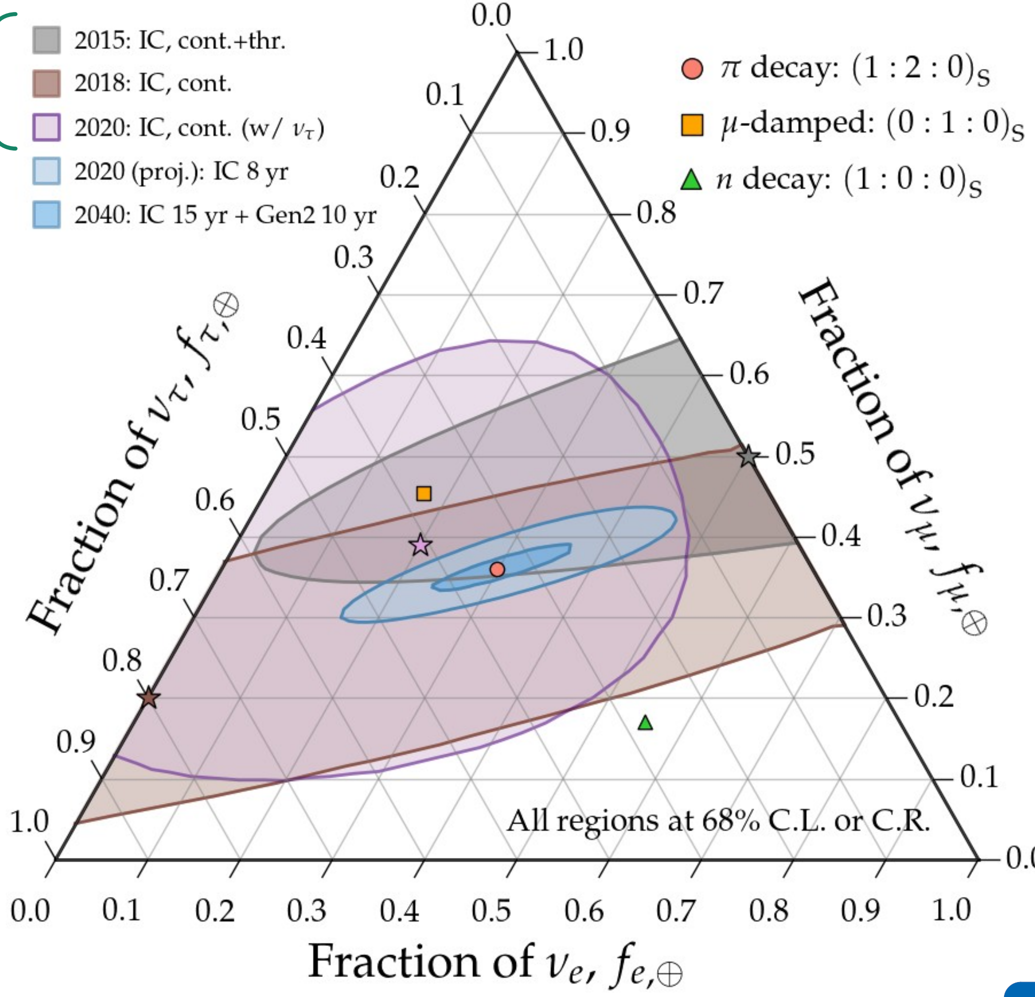

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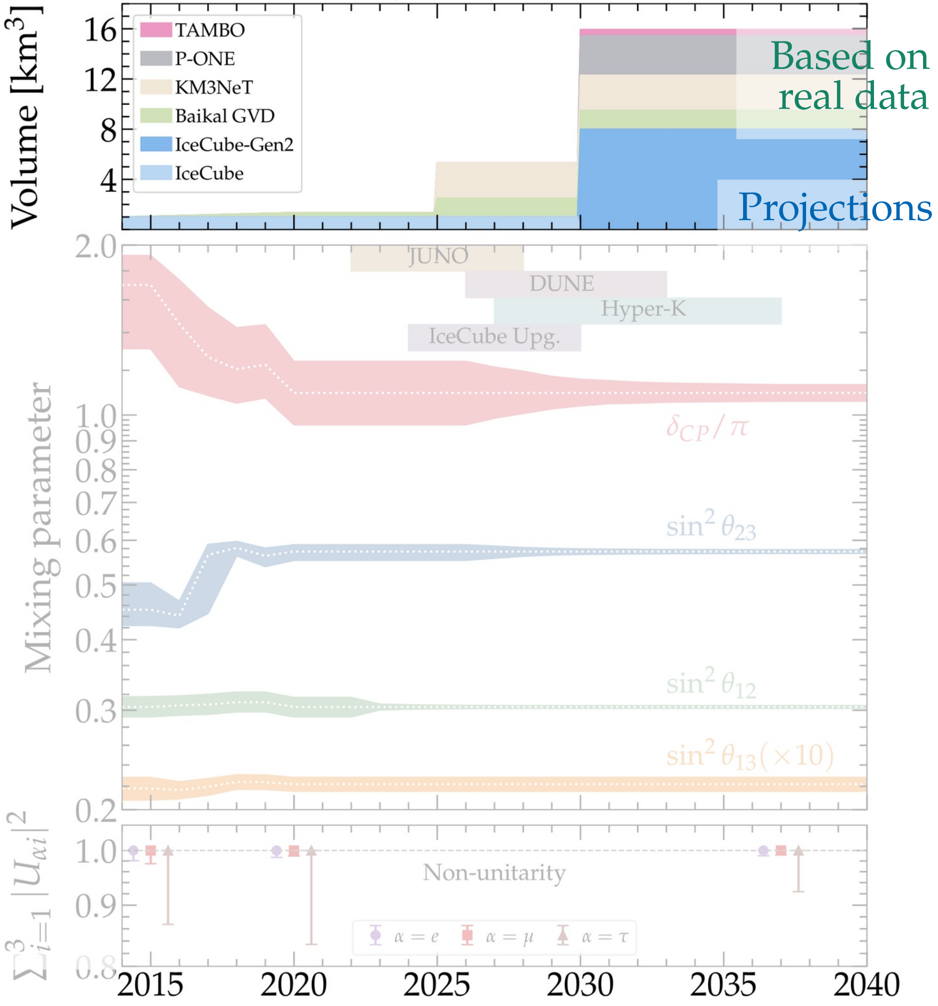
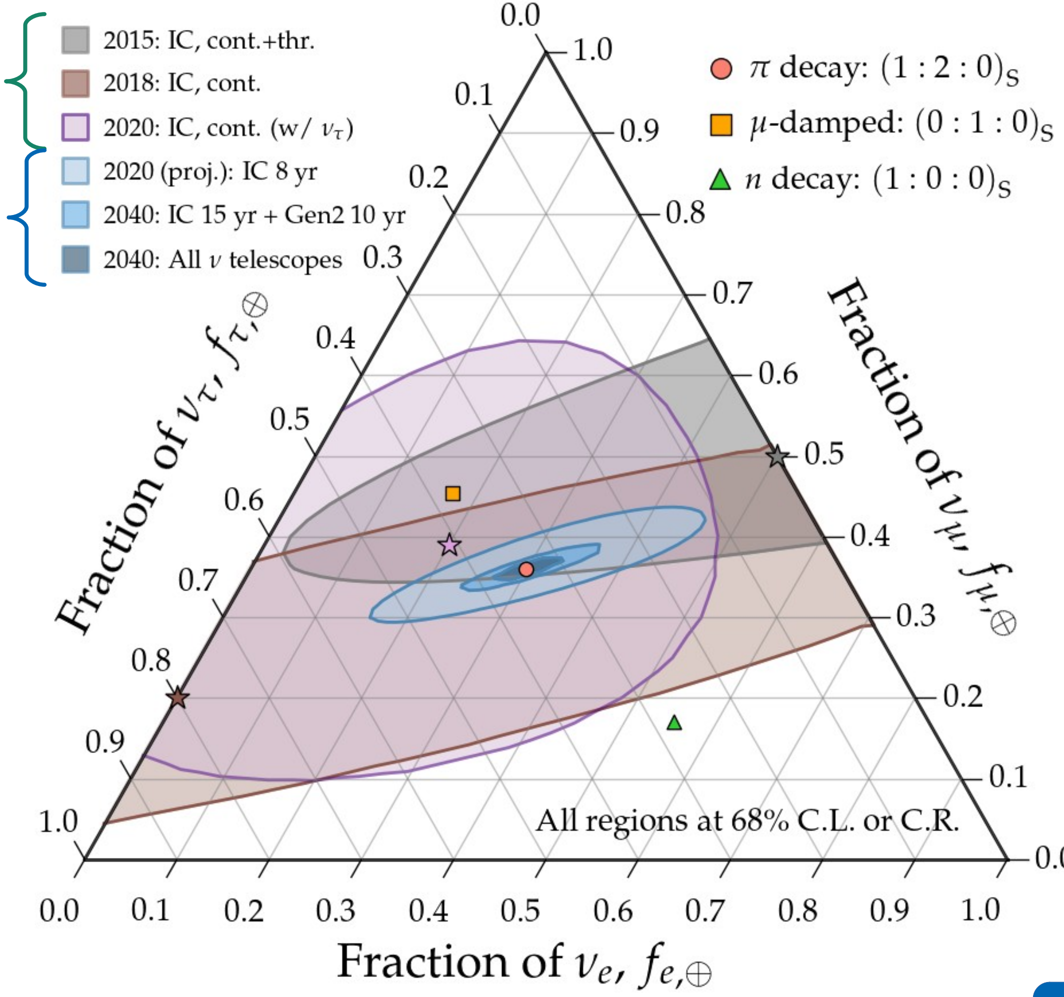
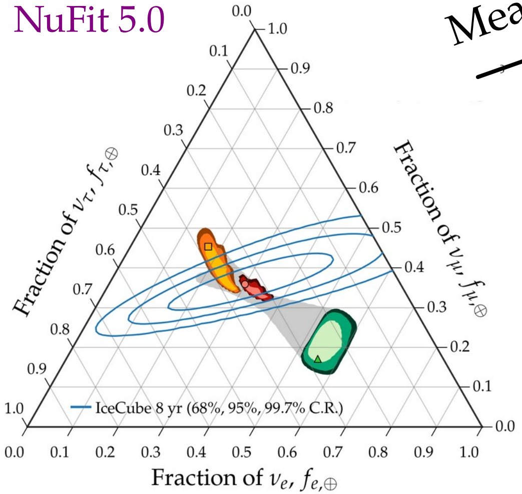




How knowing the mixing parameters better helps

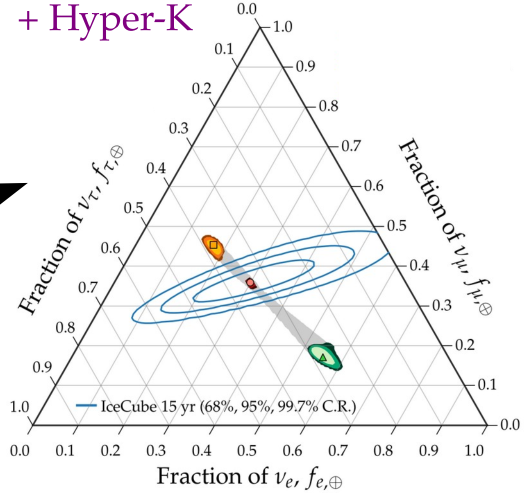
2020

NuFit 5.0



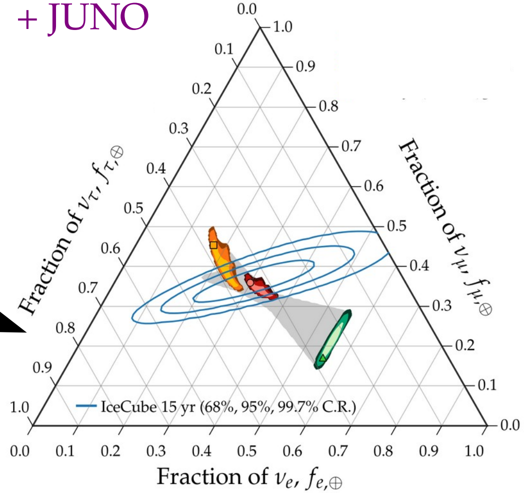
Measure θ_{23} better

+ Hyper-K



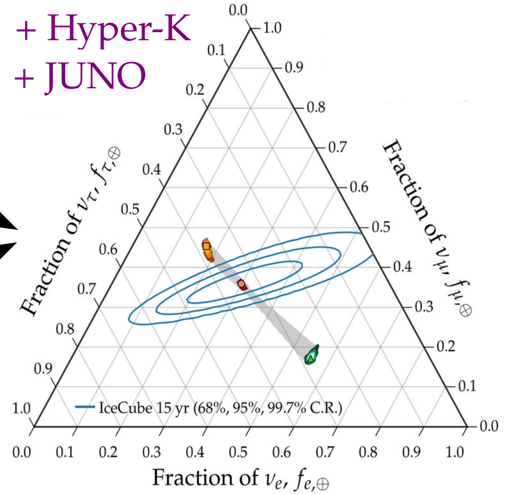
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO

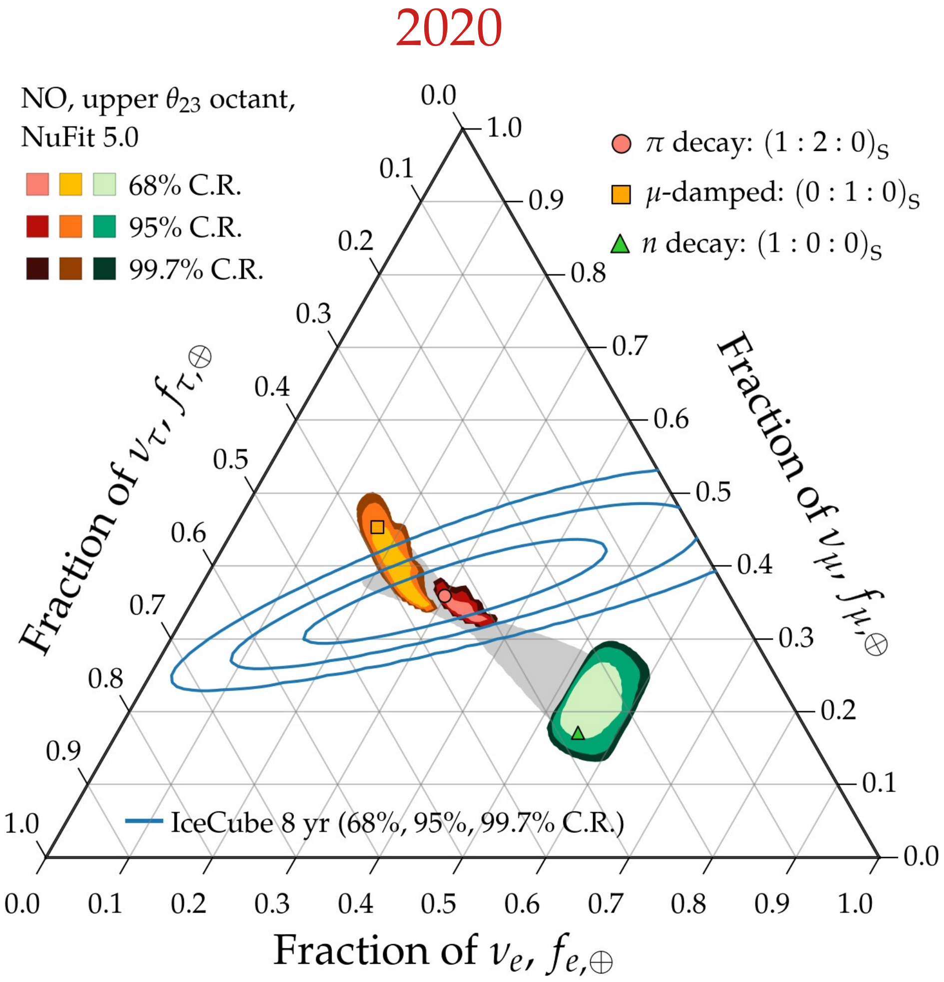


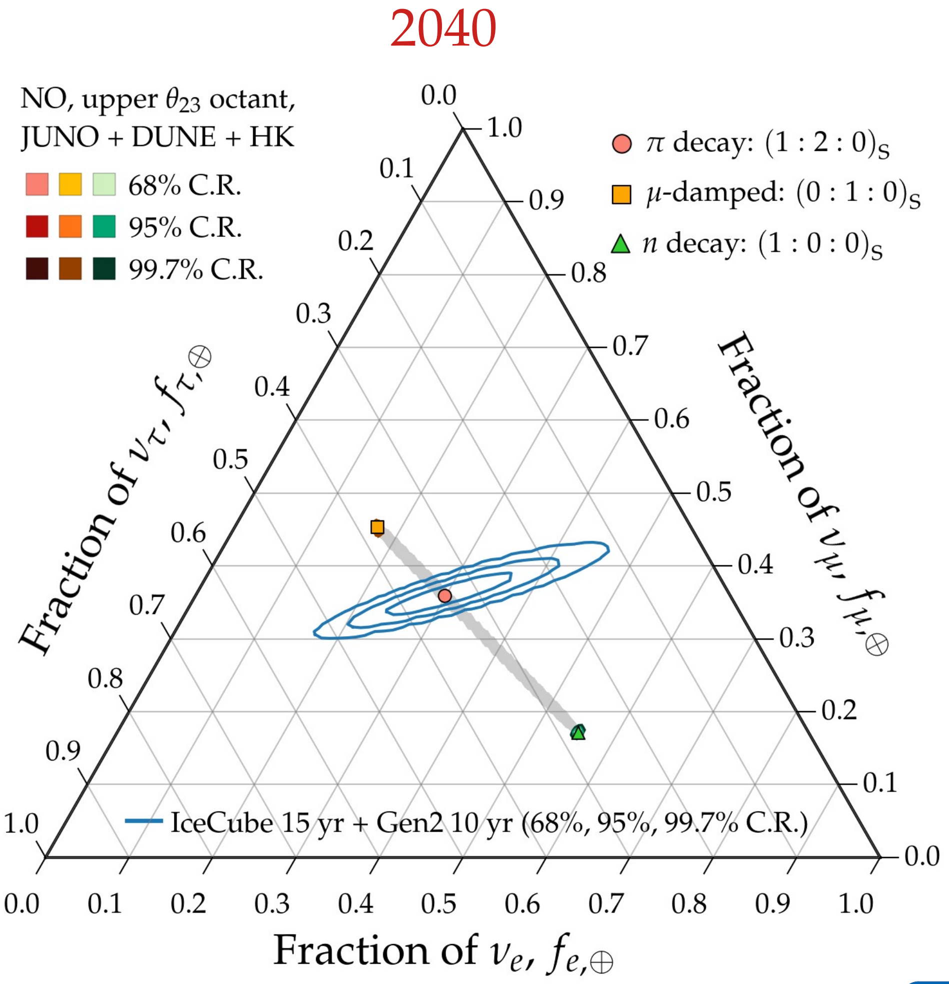
In our results:
JUNO + Hyper-K + DUNE

Marginal improvement til 2040

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

Theoretically palatable regions: 2020 → 2040

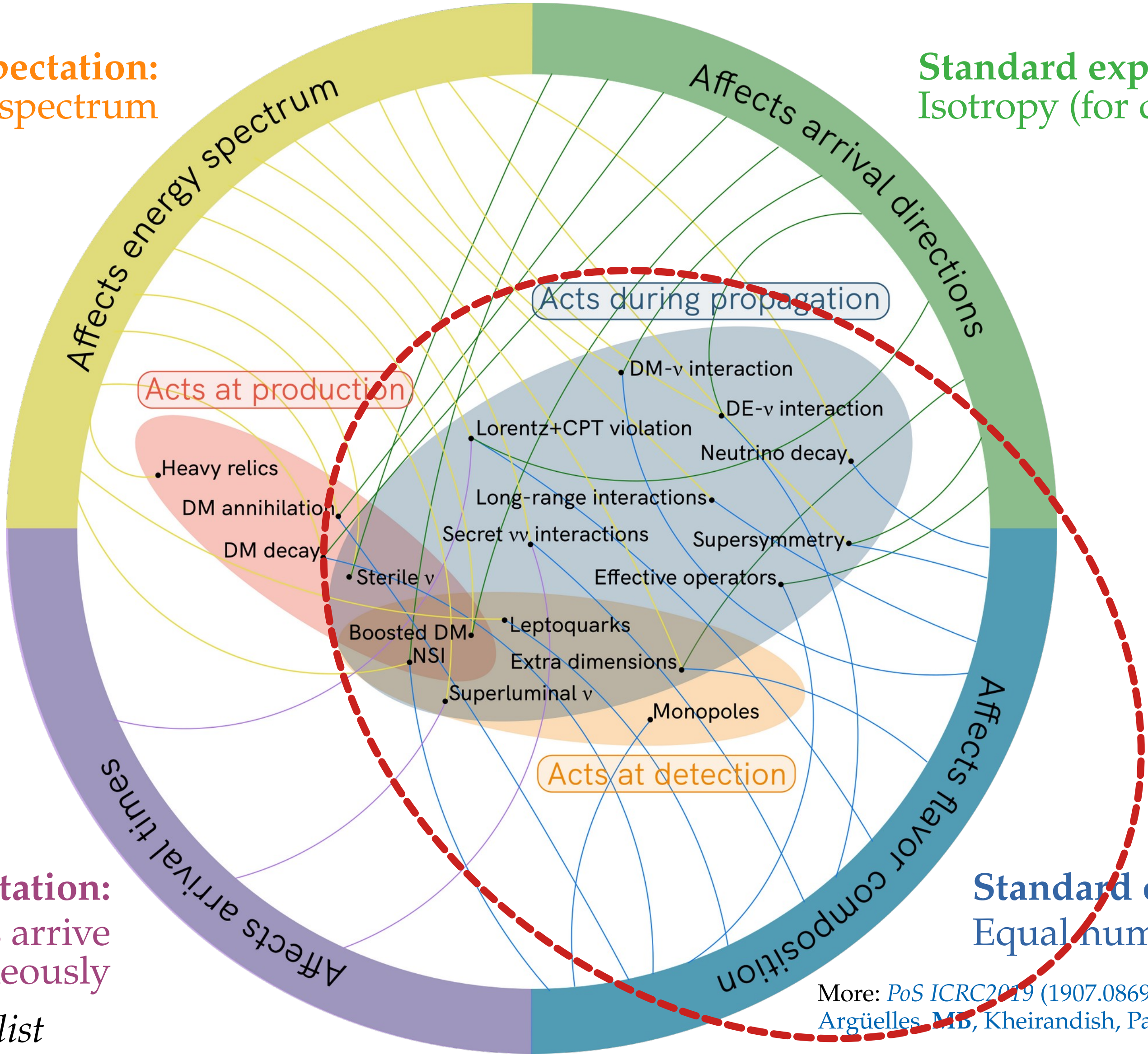




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
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Note: Not an exhaustive list

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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Reviews:
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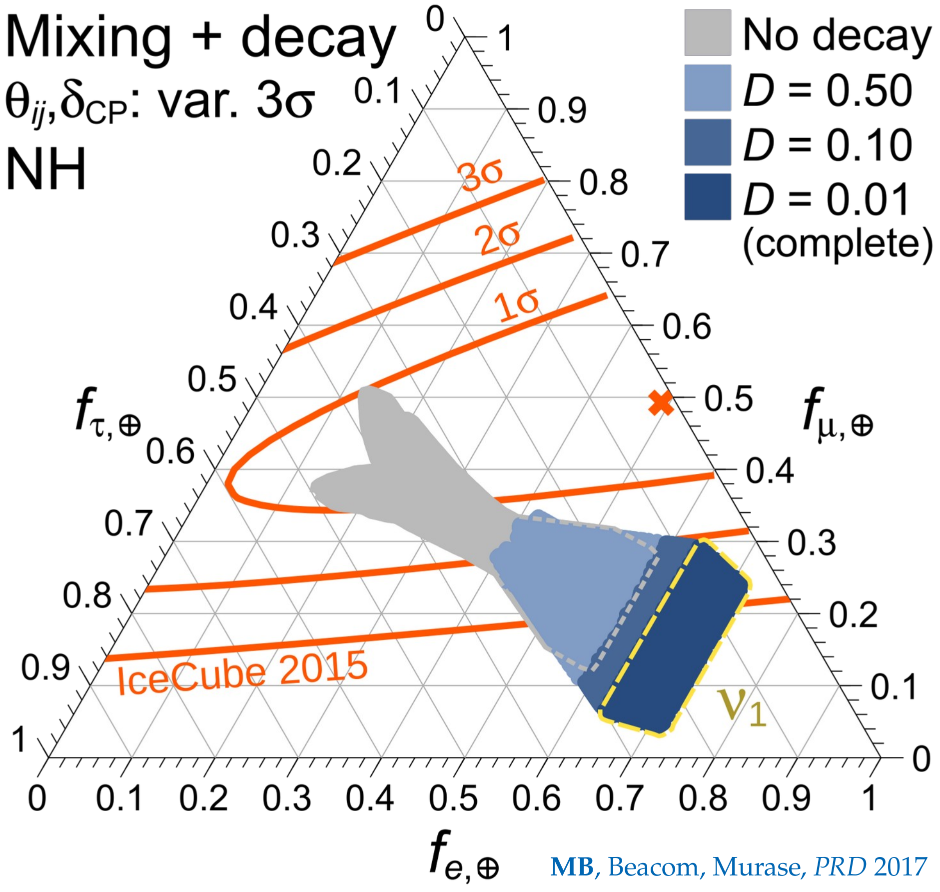

MB, Beacom, Murase, *PRD* 2017

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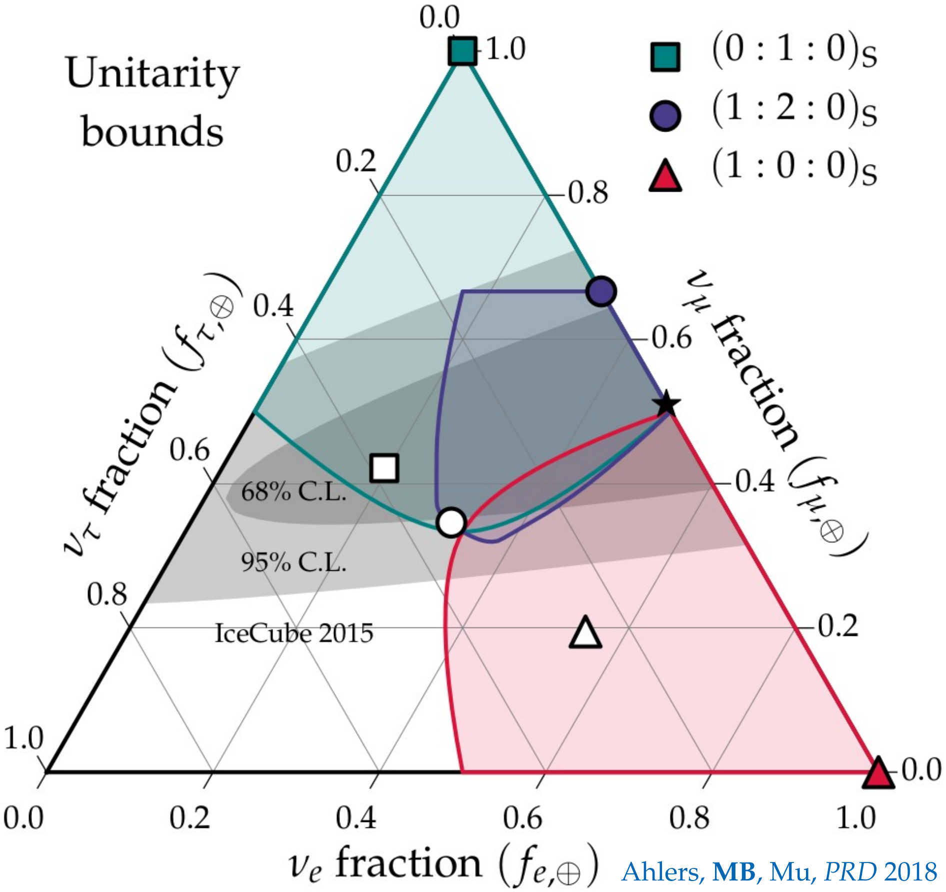

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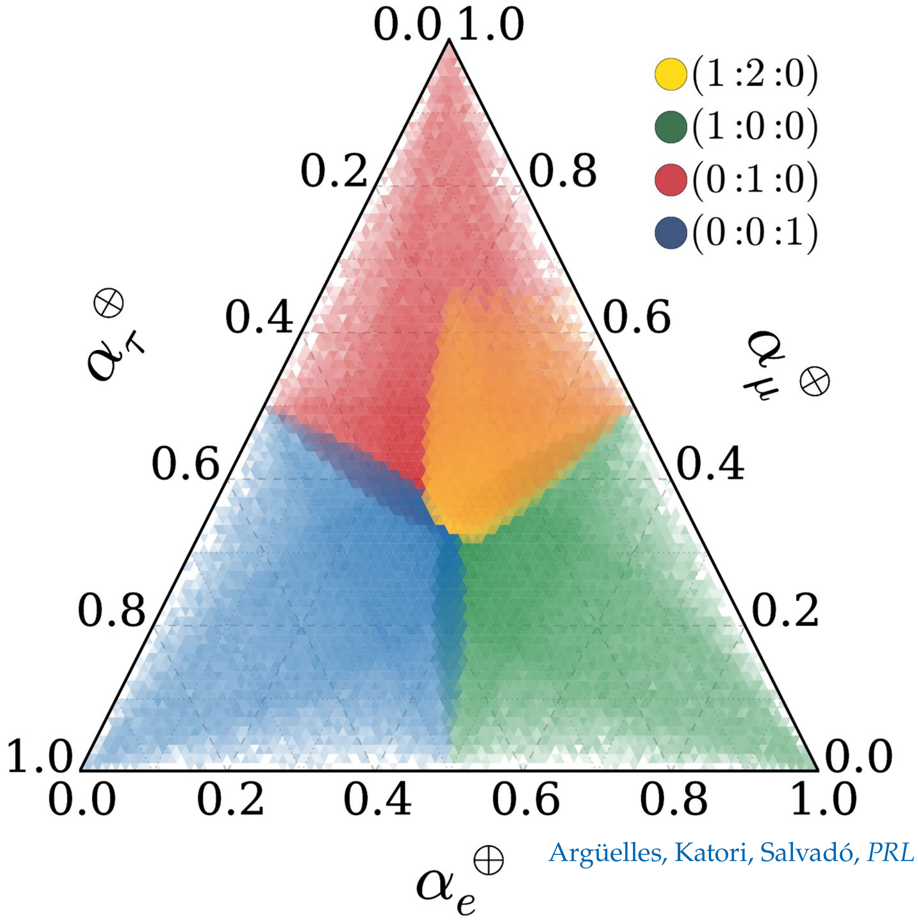

Argüelles, Katori, Salvadó, *PRL* 2015

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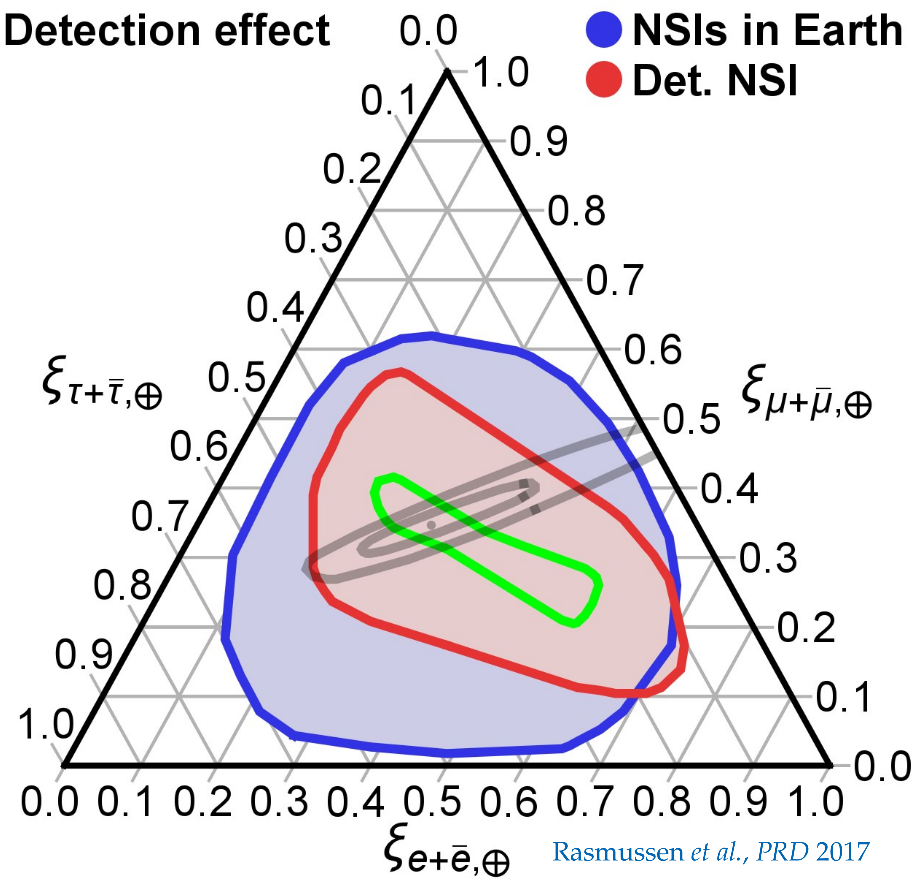

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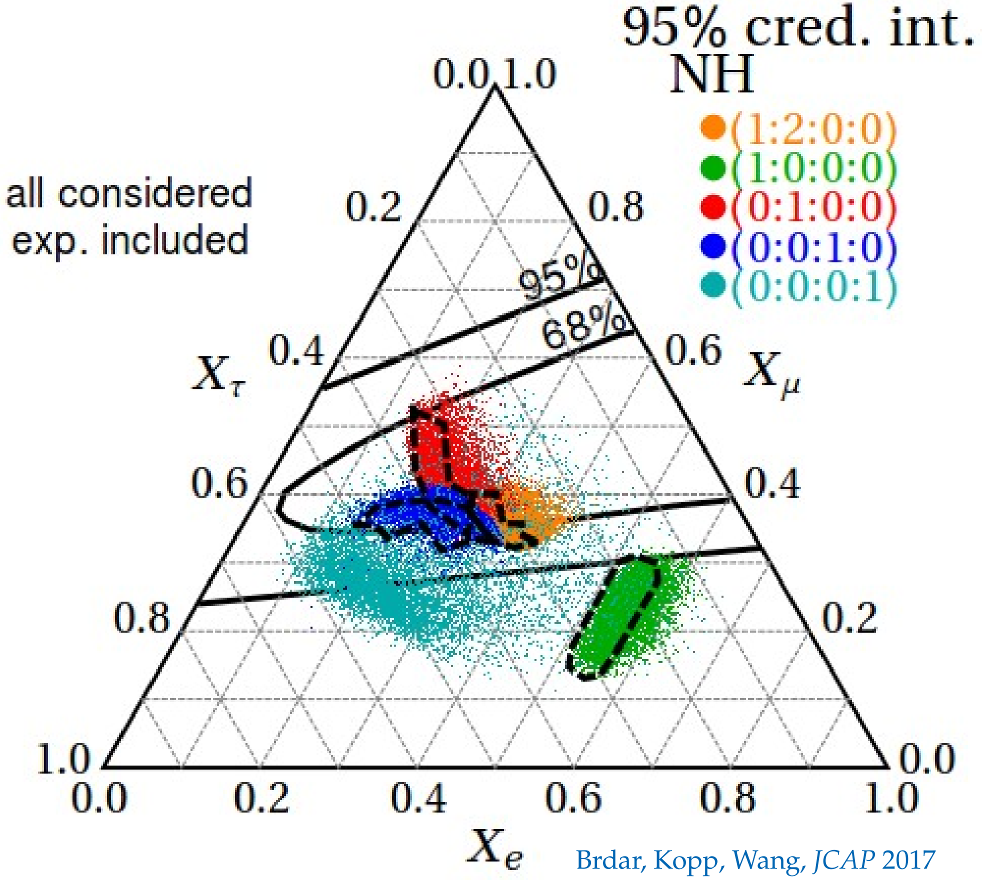

Brdar, Kopp, Wang, *JCAP* 2017

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Reviews:
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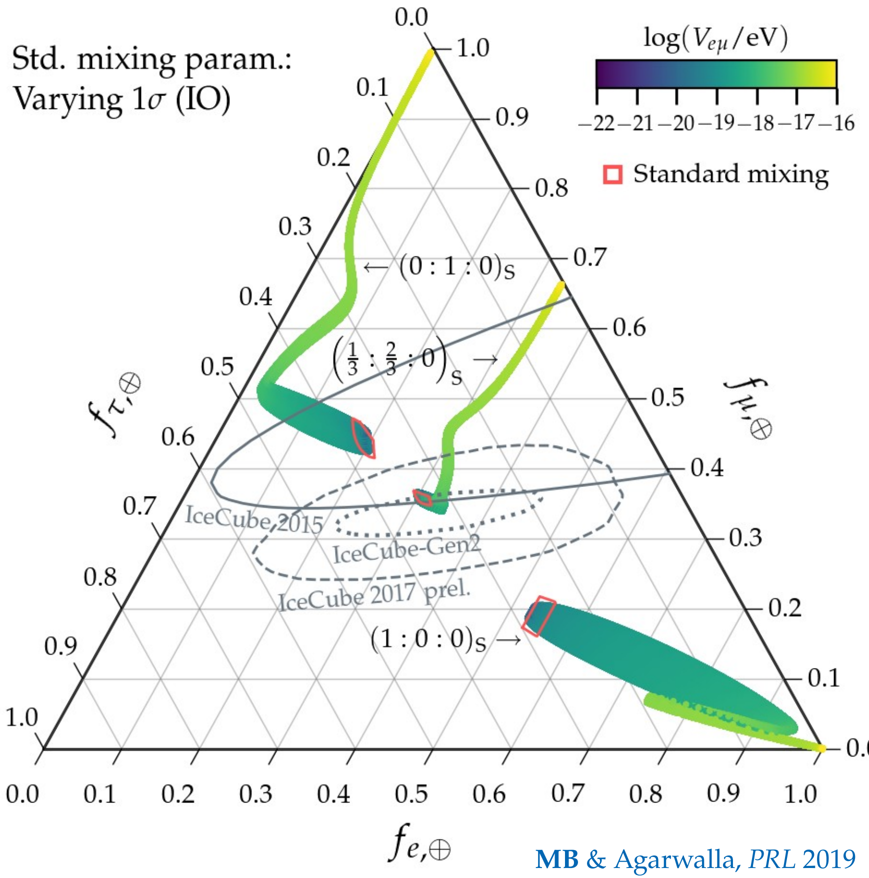

MB & Agarwalla, *PRL* 2019

3. New tests of Lorentz invariance

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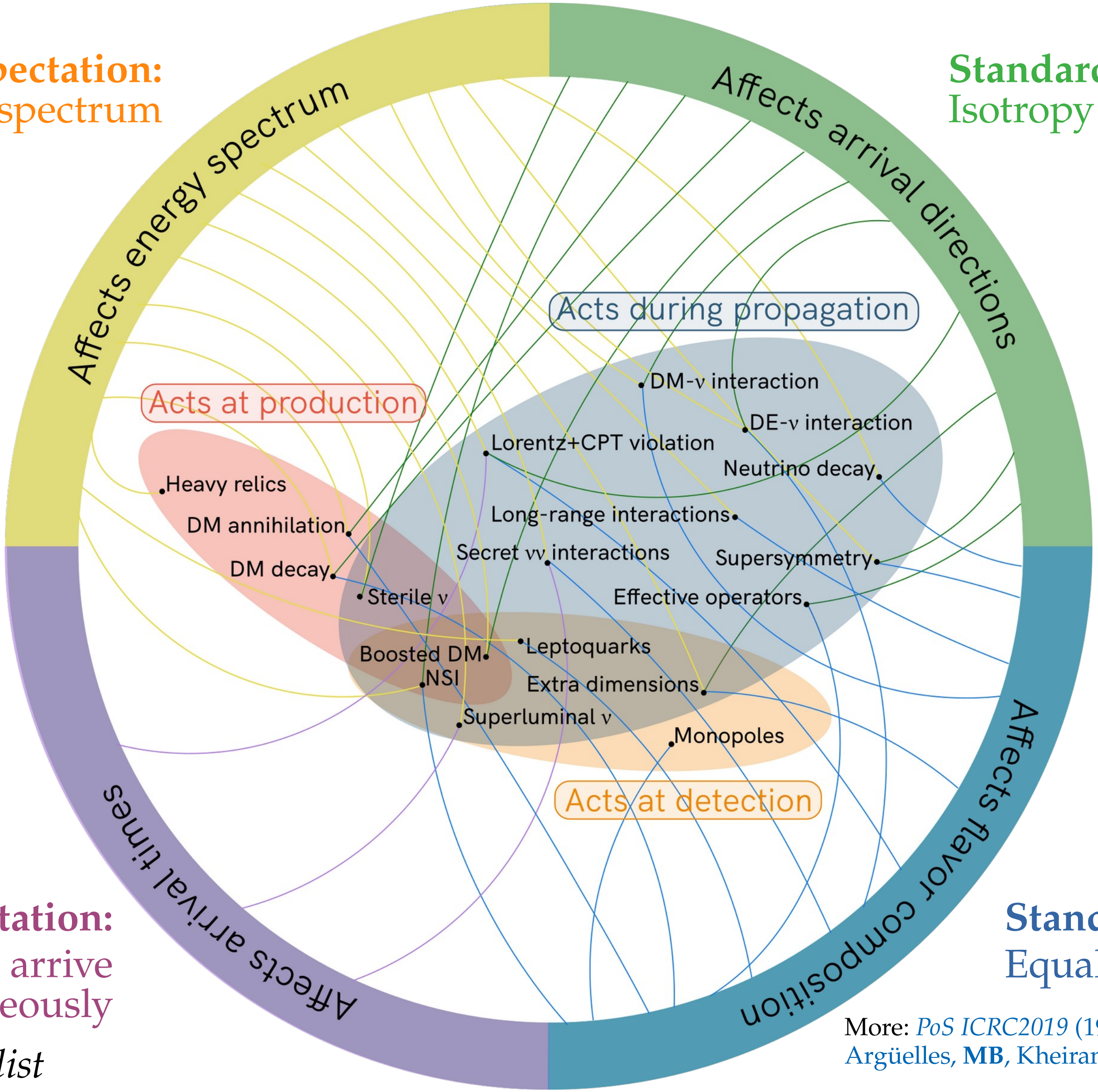

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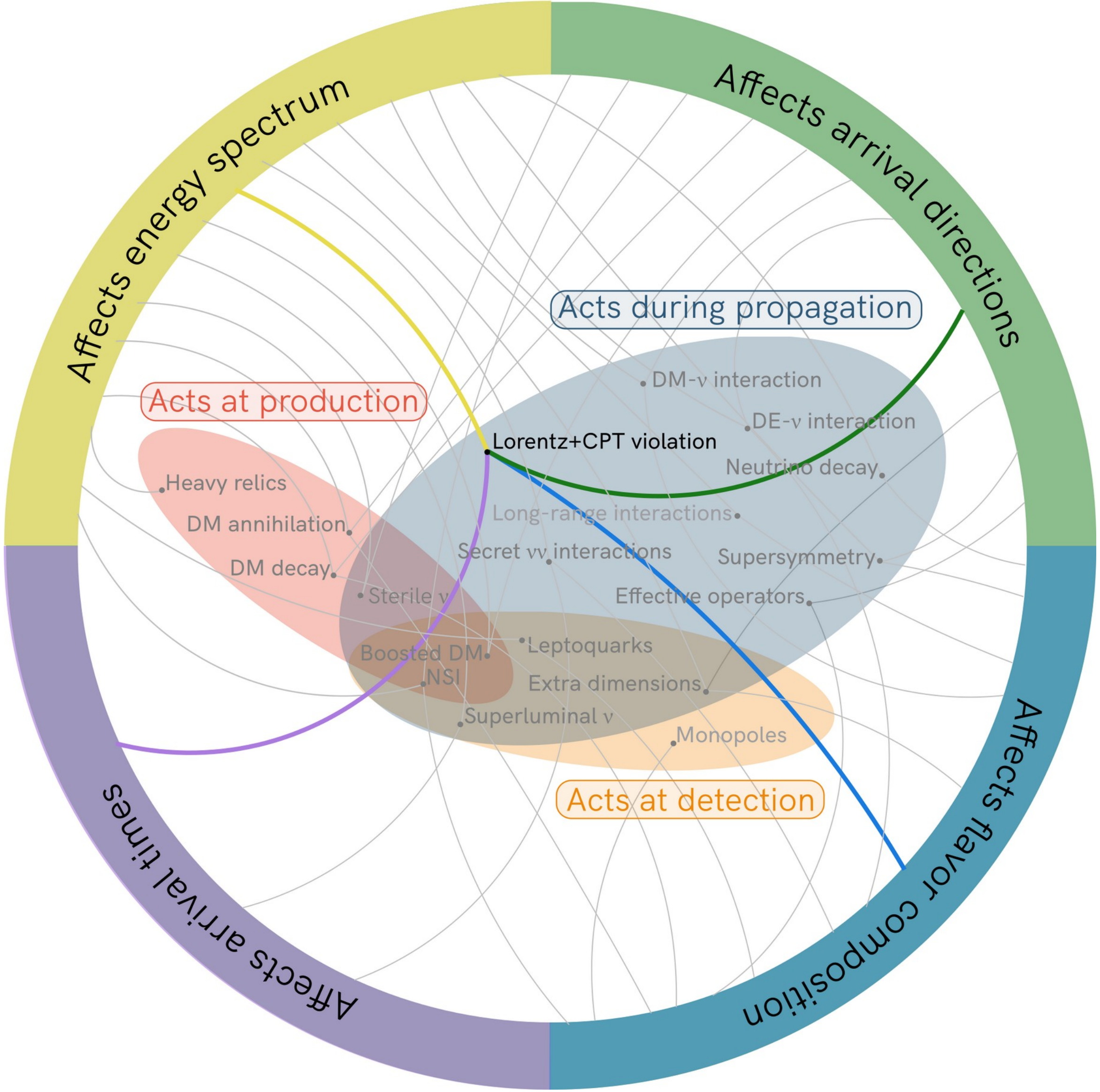
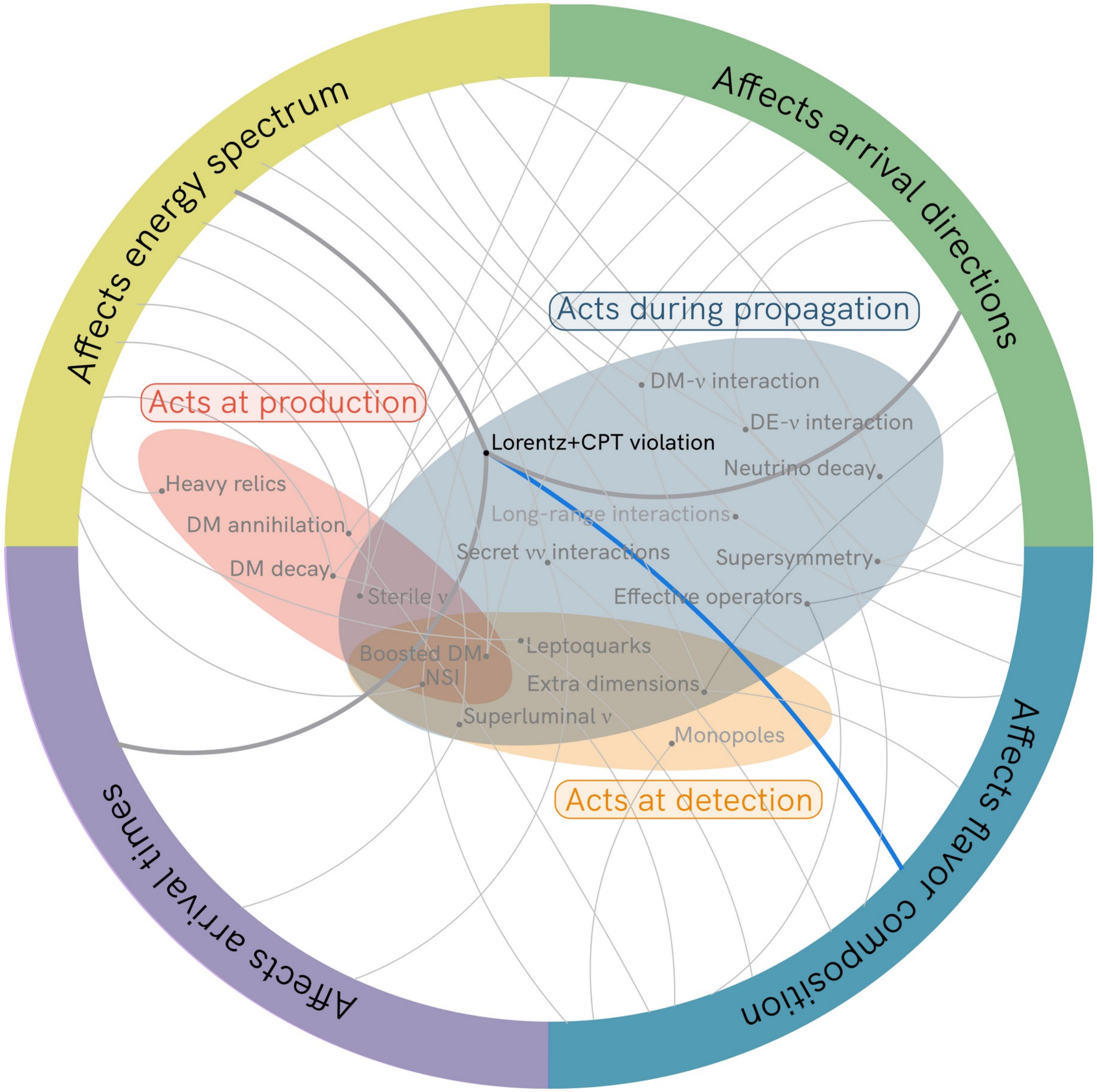

Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
DM decay
Long-range interactions
Secret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



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Boosted DM
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Superluminal ν
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How to fill out the flavor triangle?

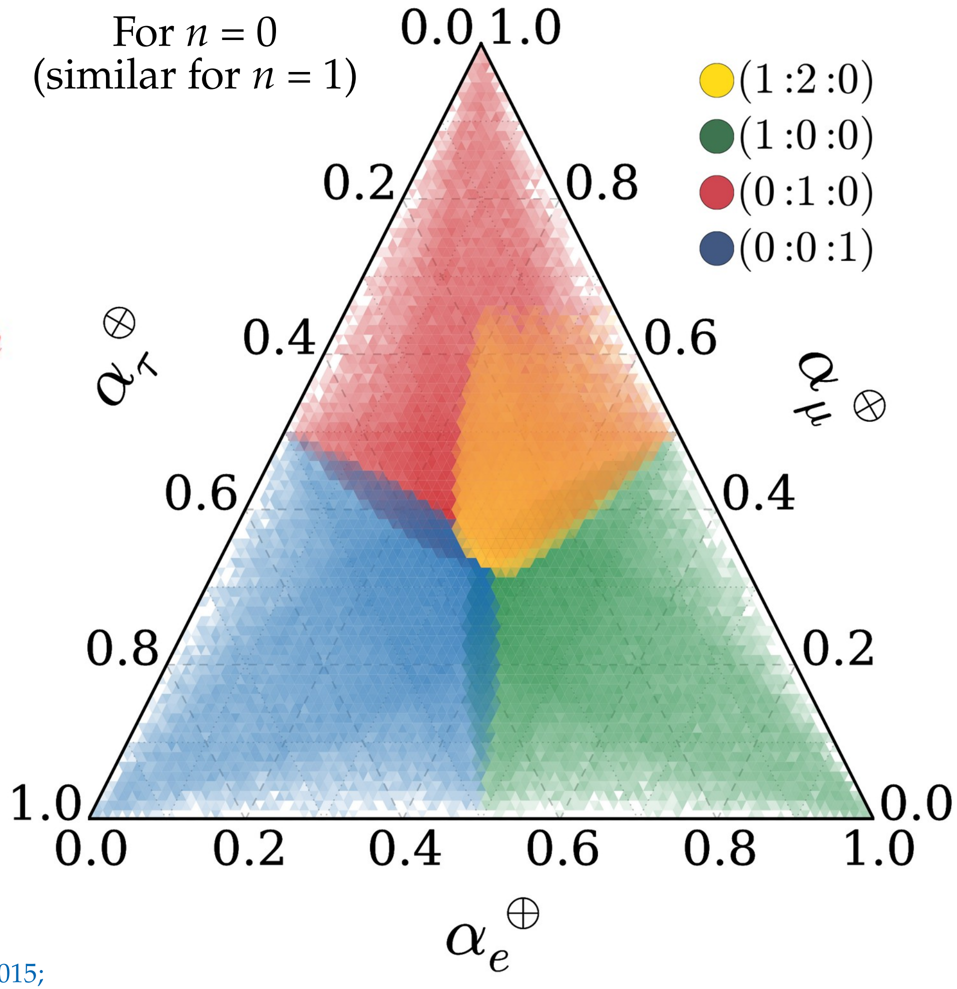
$$H_{\mathrm{tot}} = H_{\mathrm{std}} + H_{\mathrm{NP}}$$

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

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

This can populate *all* of the triangle –

- Use current atmospheric bounds on $O_{n,i}$:
  $O_0 < 10^{-23}$ GeV, $O_1/\Lambda_1 < 10^{-27}$ GeV
- Sample the unknown new mixing angles



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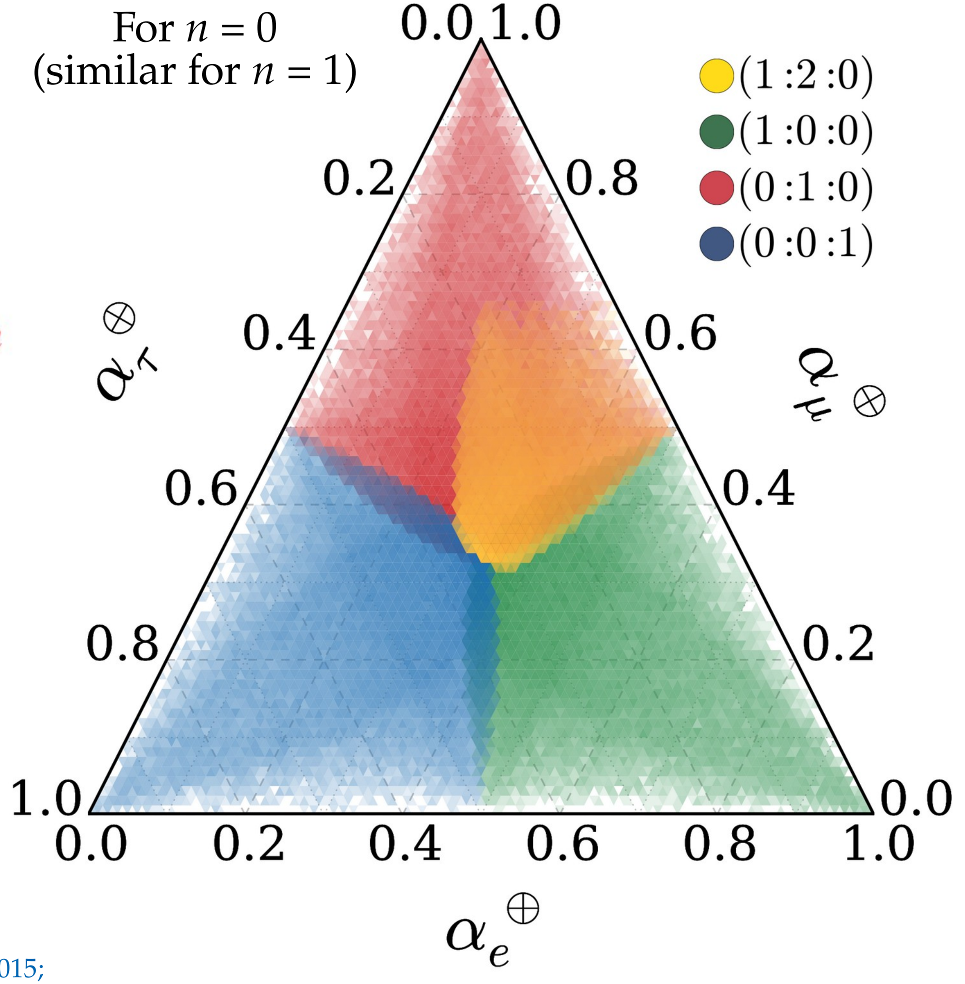

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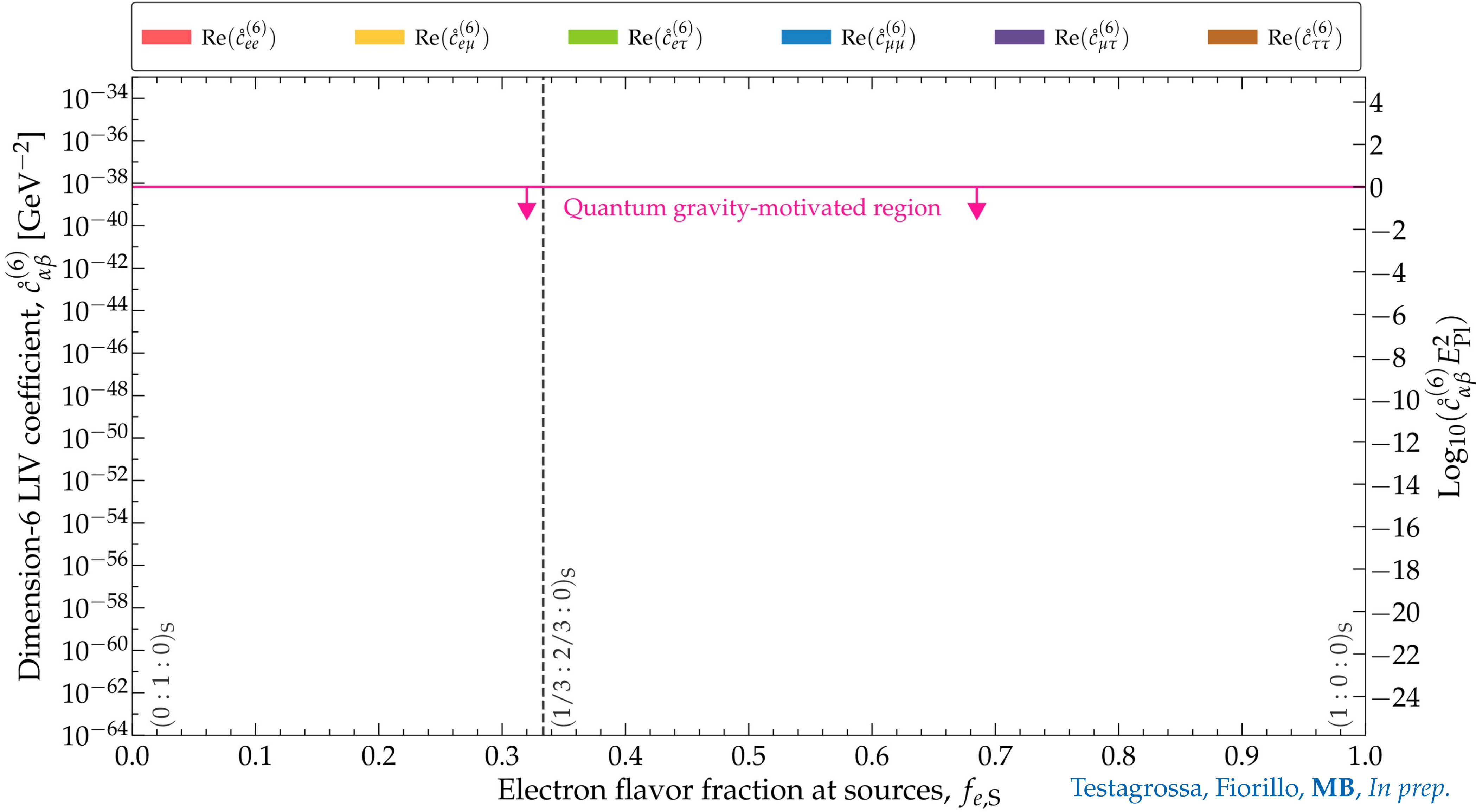
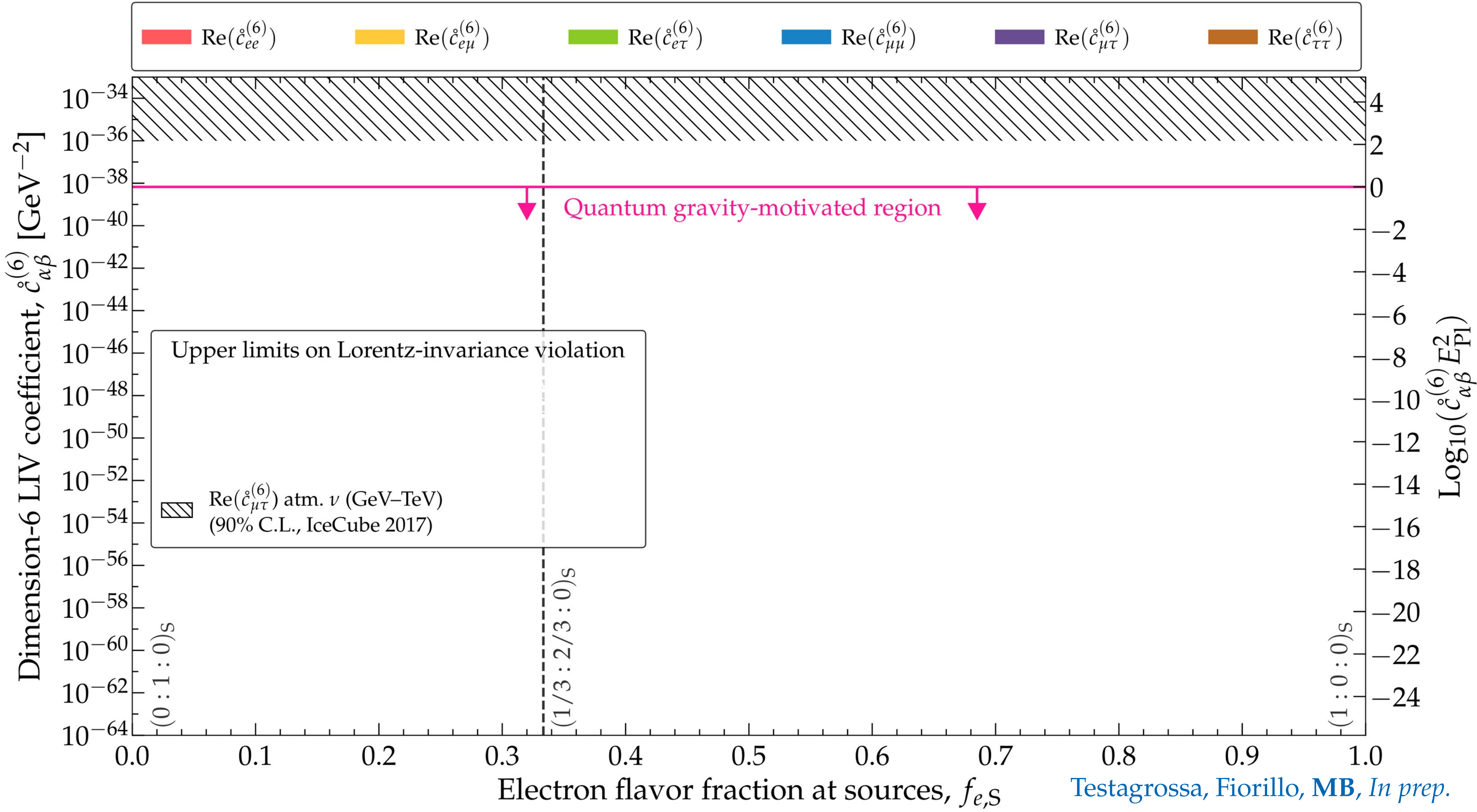


Testagrossa, Fiorillo, **MB**, *In prep.*



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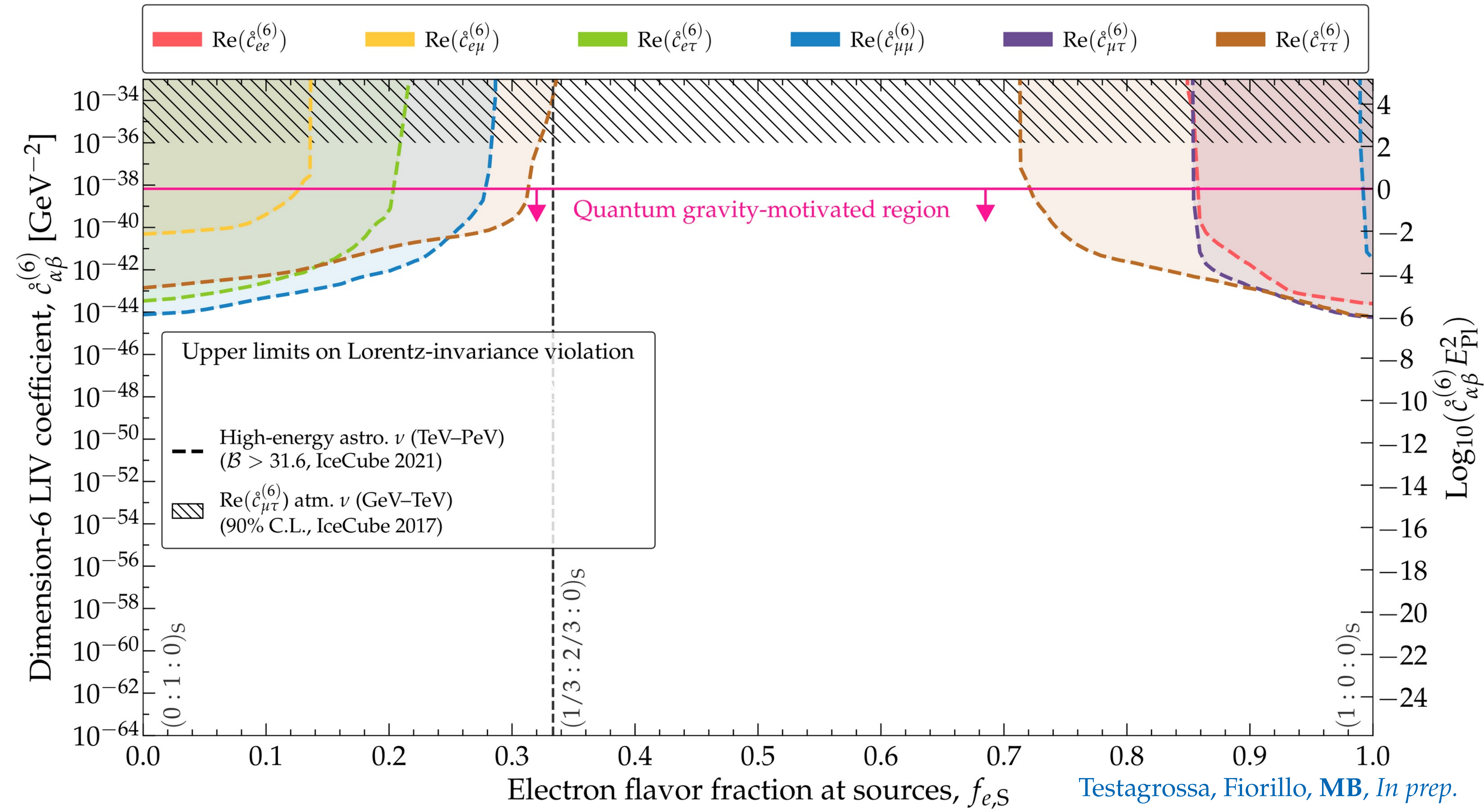
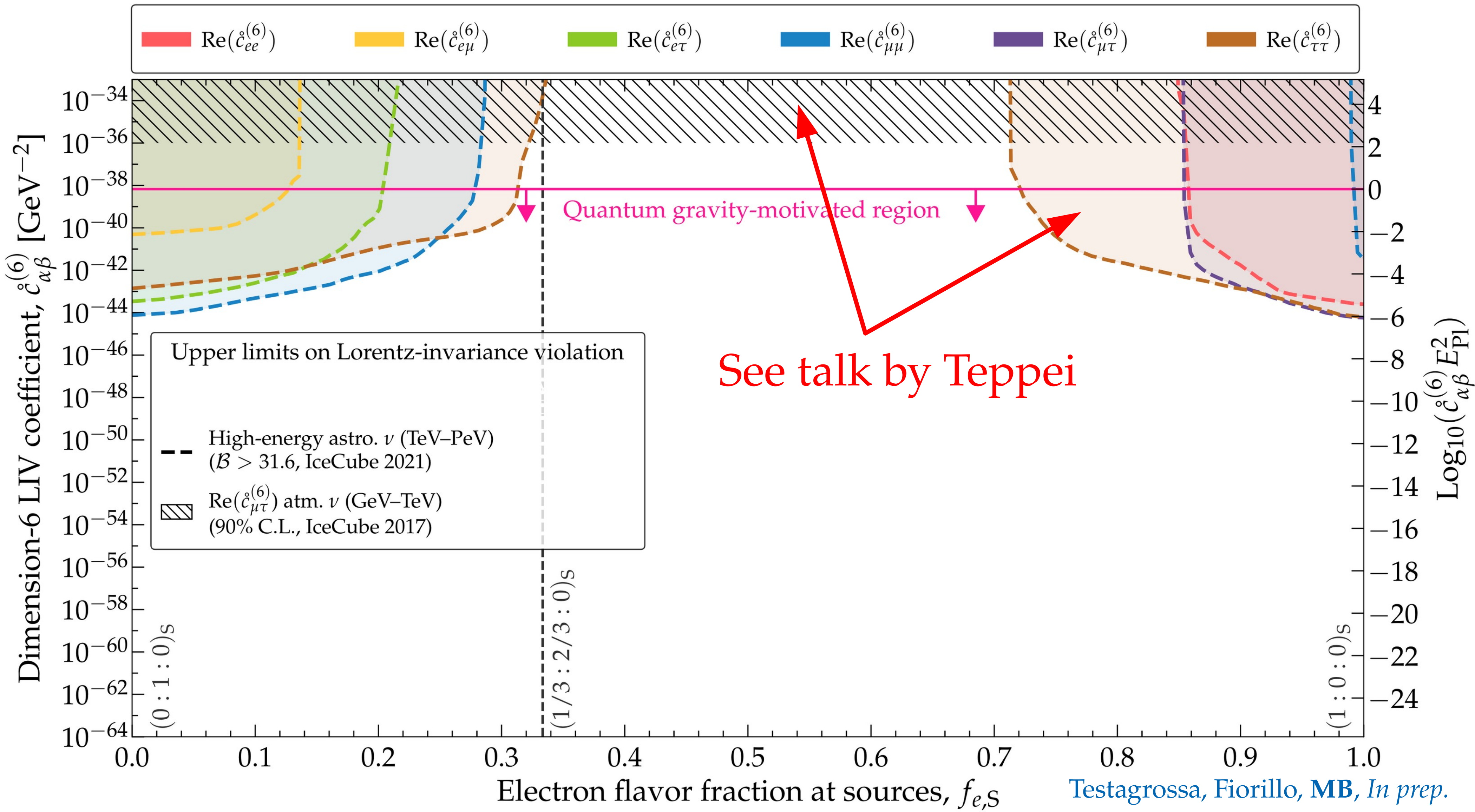


Re($\mathring{c}_{ee}^{(6)}$)
Re($\mathring{c}_{e\mu}^{(6)}$)
Re($\mathring{c}_{e\tau}^{(6)}$)
Re($\mathring{c}_{\mu\mu}^{(6)}$)
Re($\mathring{c}_{\mu\tau}^{(6)}$)
Re($\mathring{c}_{\tau\tau}^{(6)}$)
Quantum gravity-motivated region
Upper limits on Lorentz-invariance violation
High-energy astro. ν (TeV–PeV)
($\mathcal{B} > 31.6$, IceCube 2021)
Re($\mathring{c}_{\mu\tau}^{(6)}$) atm. ν (GeV–TeV)
(90% C.L., IceCube 2017)
$(0:1:0)_S$
$(1/3:2/3:0)_S$
$(1:0:0)_S$
Dimension-6 LIV coefficient, $\mathring{c}_{\alpha\beta}^{(6)}$ [GeV^{-2}]
$\mathrm{Log}_{10}(\mathring{c}_{\alpha\beta}^{(6)} E_{\mathrm{Pl}}^2)$
Electron flavor fraction at sources, $f_{e,S}$
10^{-34}
10^{-36}
10^{-38}
10^{-40}
10^{-42}
10^{-44}
10^{-46}
10^{-48}
10^{-50}
10^{-52}
10^{-54}
10^{-56}
10^{-58}
10^{-60}
10^{-62}
10^{-64}
4
2
0
−2
−4
−6
−8
−10
−12
−14
−16
−18
−20
−22
−24
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Testagrossa, Fiorillo, **MB**, *In prep.*



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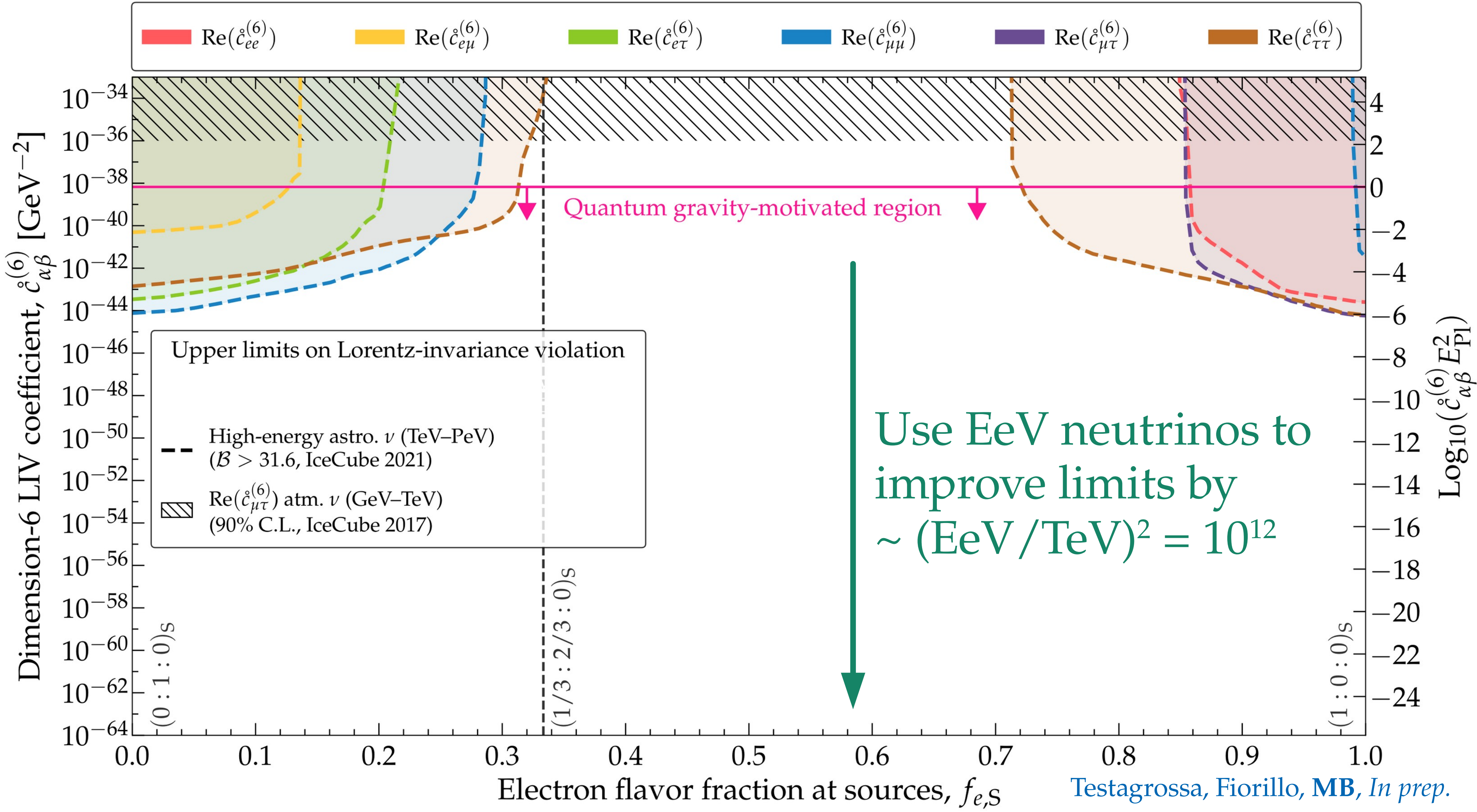

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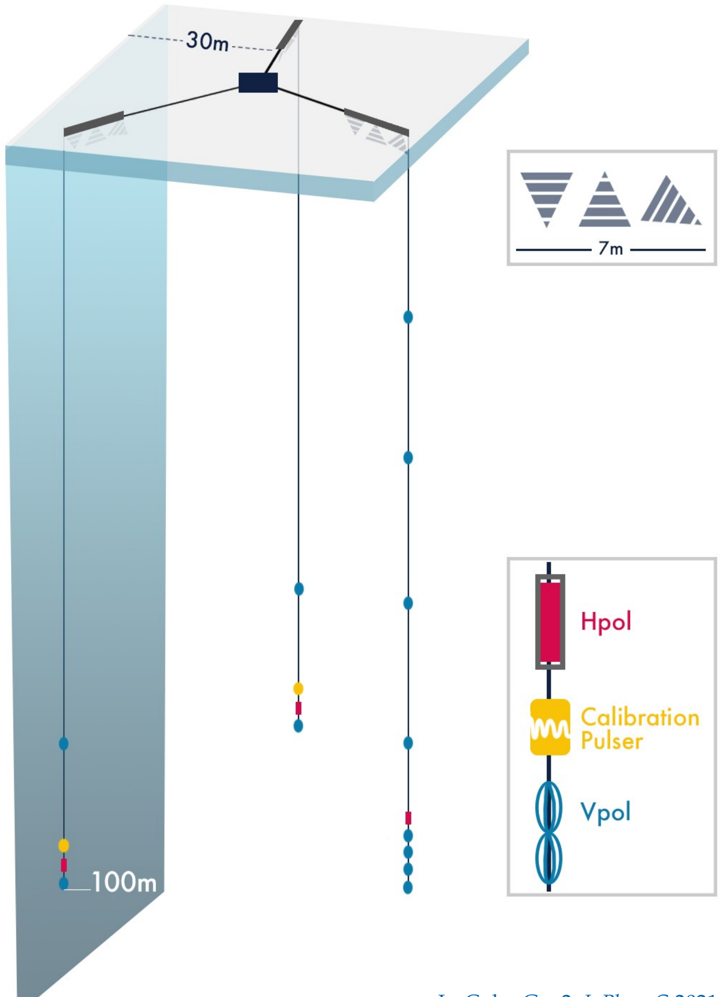
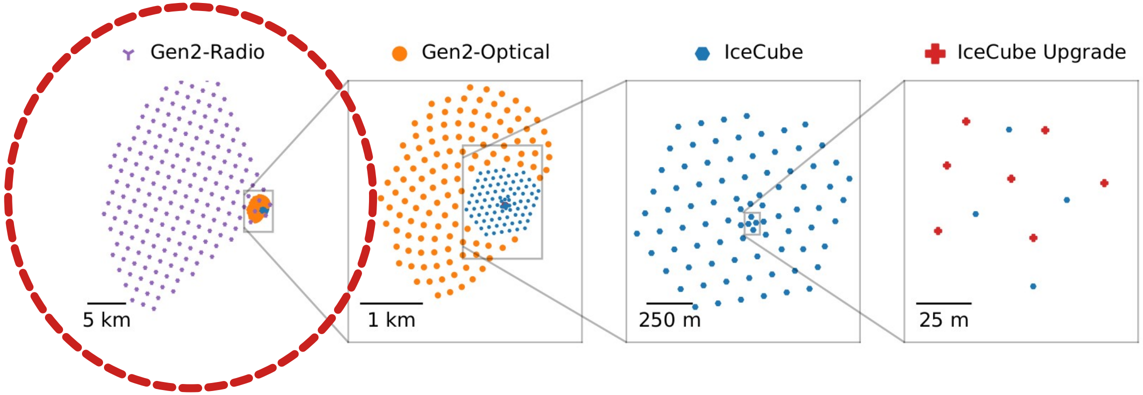
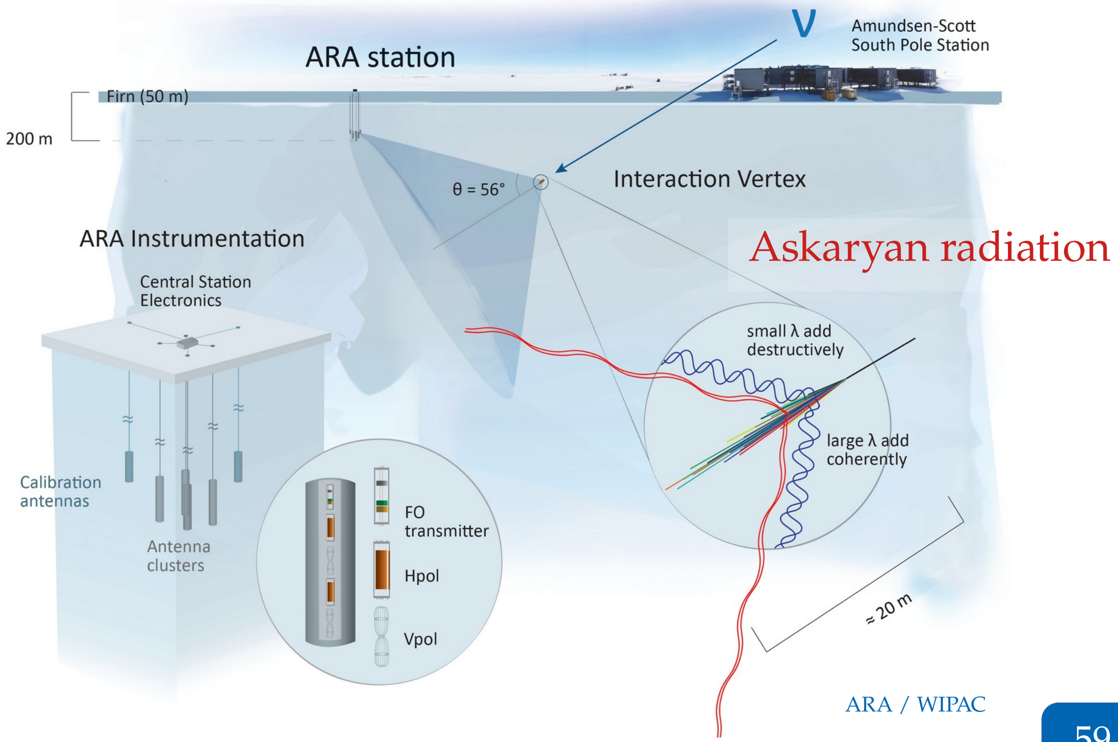
IceCube-Gen2 Radio



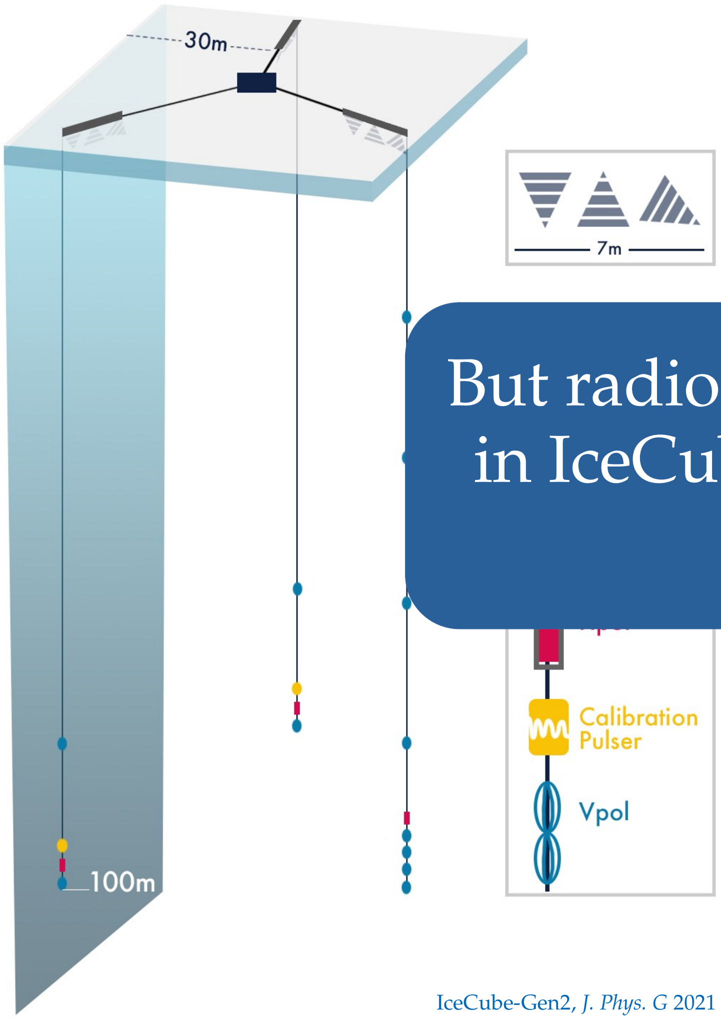
IceCube-Gen2, *J. Phys. G* 2021

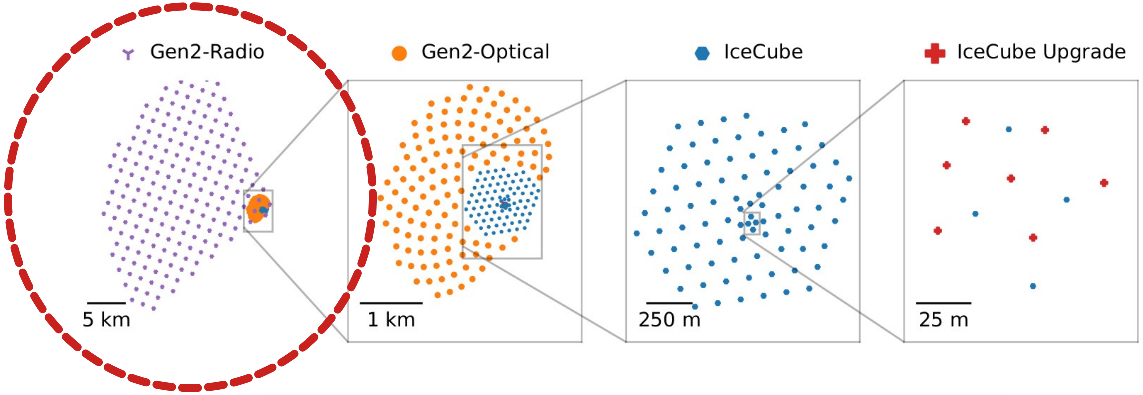




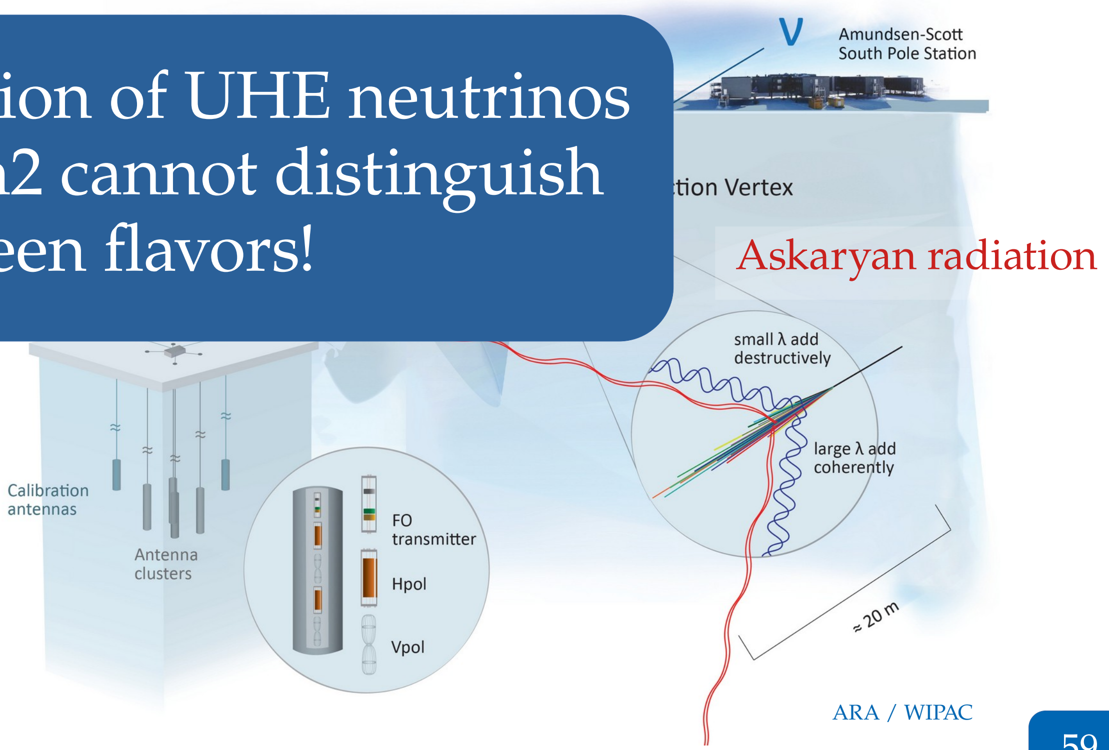
ARA / WIPAC

IceCube-Gen2 Radio



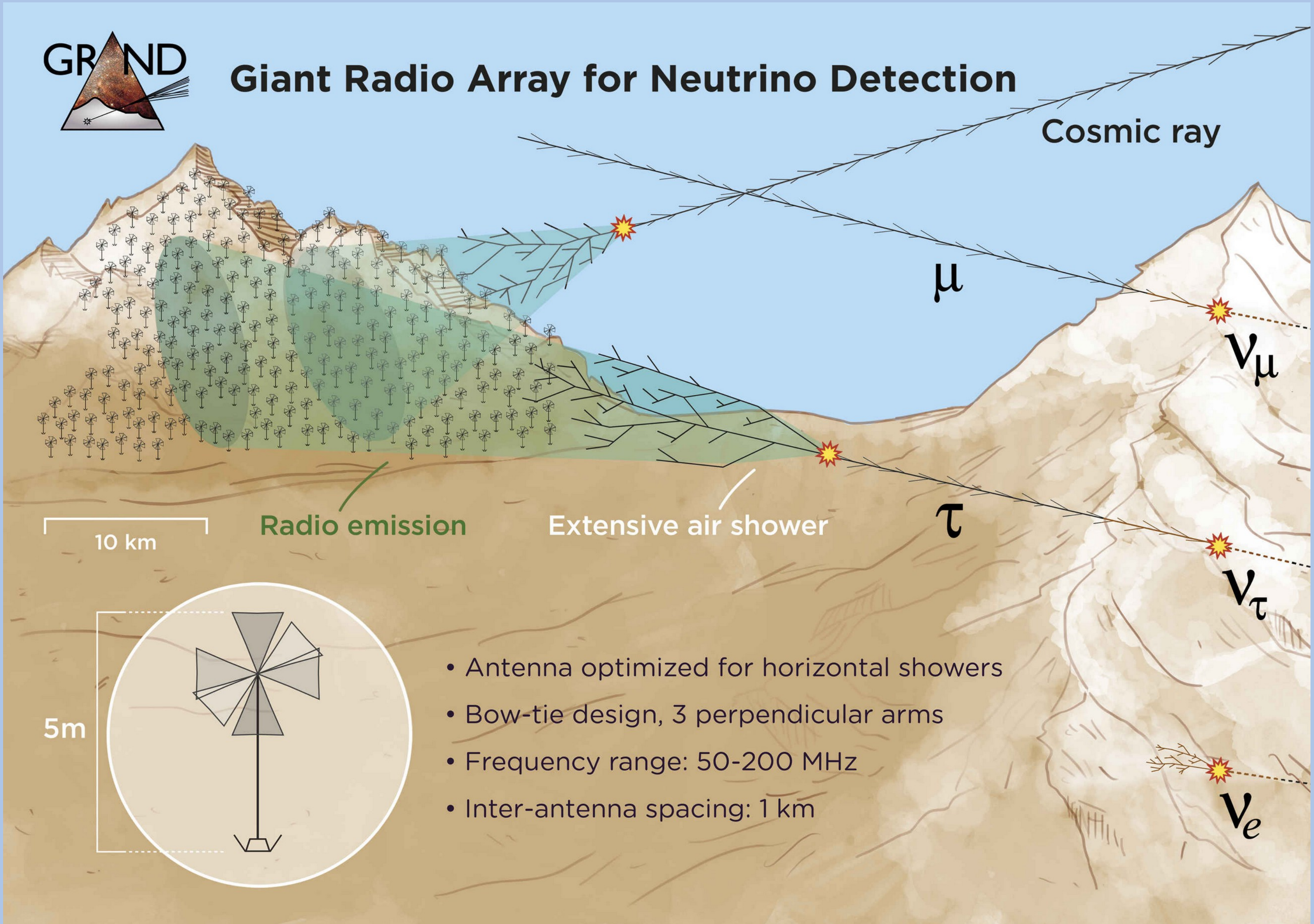


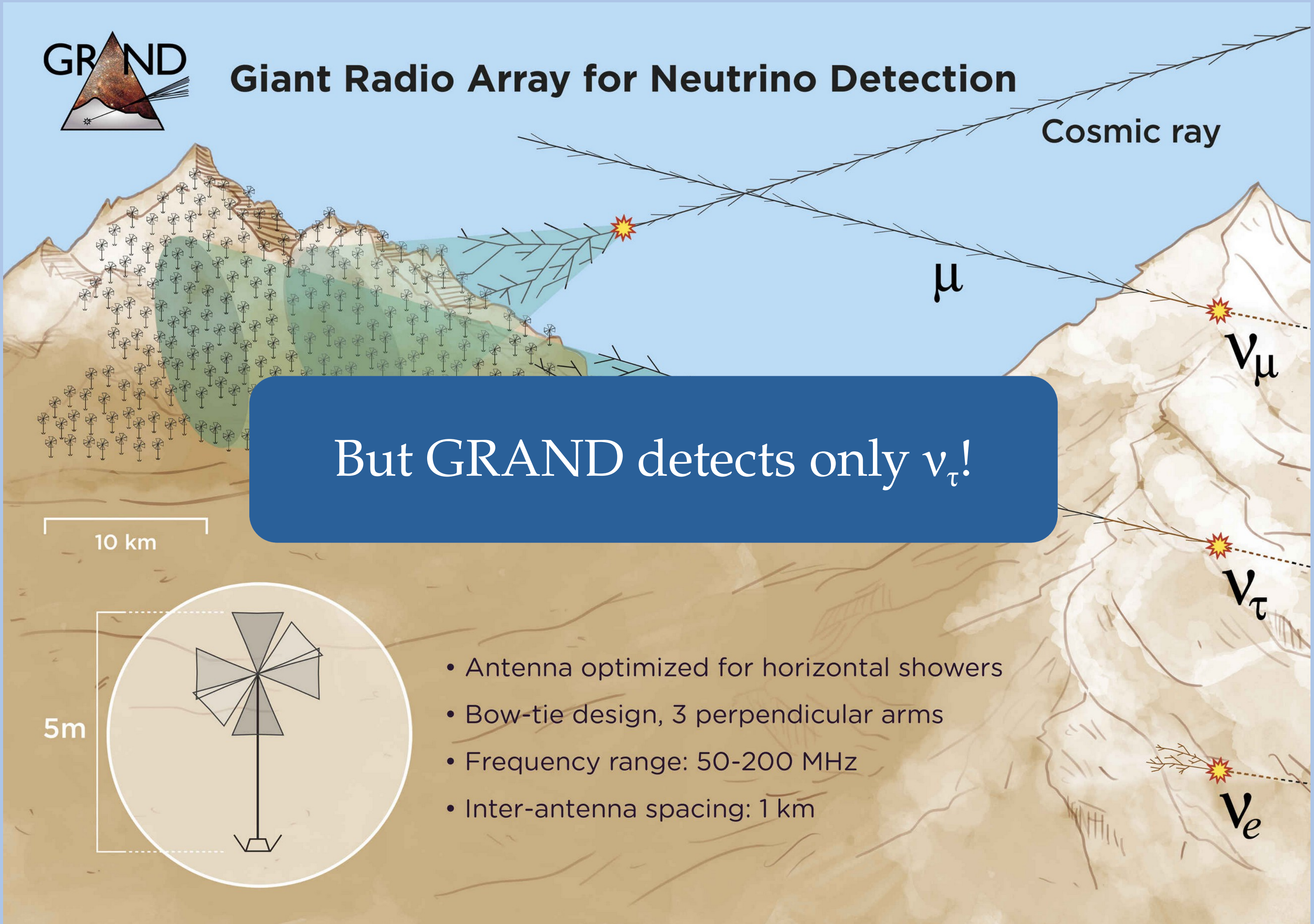
But radio-detection of UHE neutrinos in IceCube-Gen2 cannot distinguish between flavors!



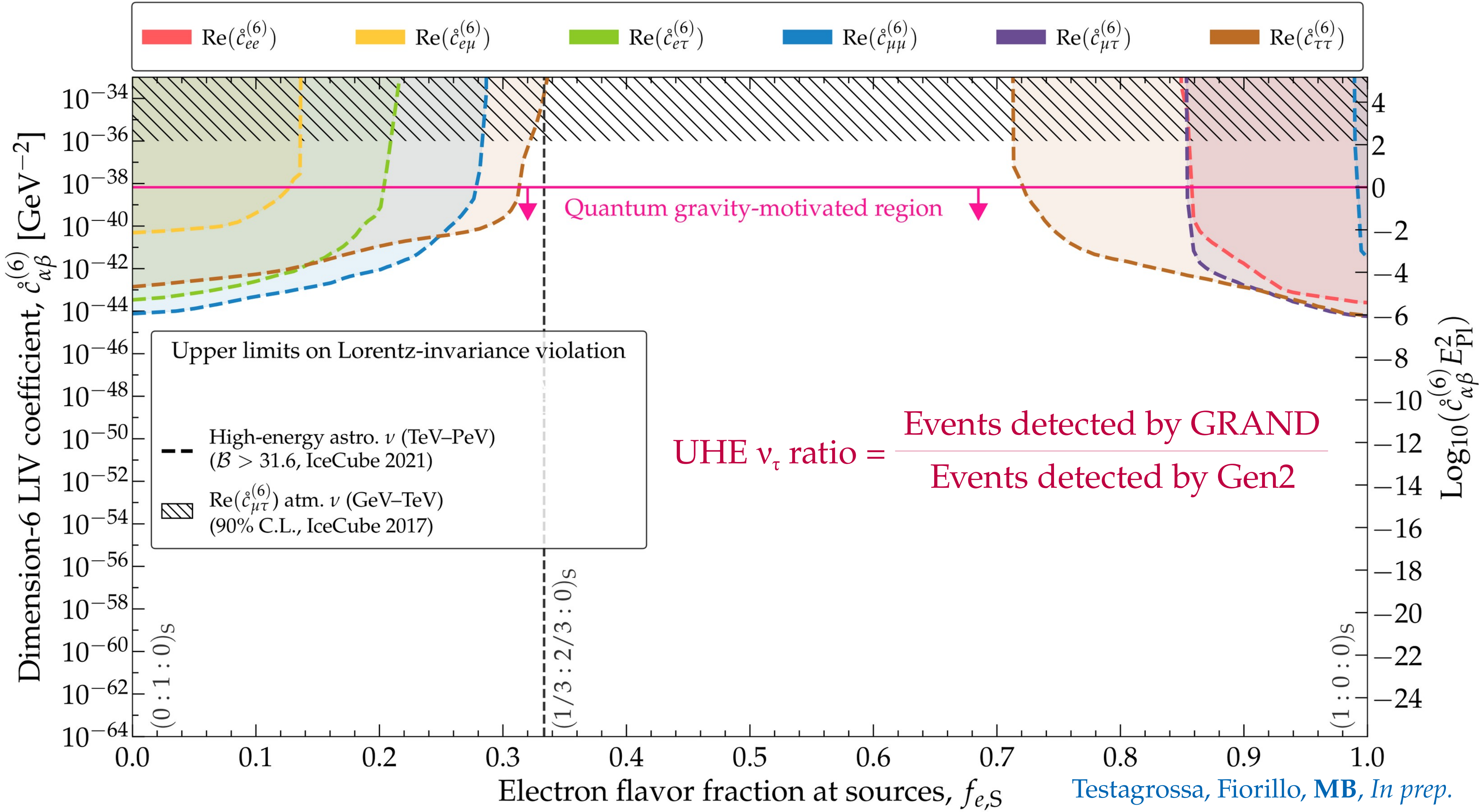
IceCube-Gen2, *J. Phys. G* 2021

ARA / WIPAC

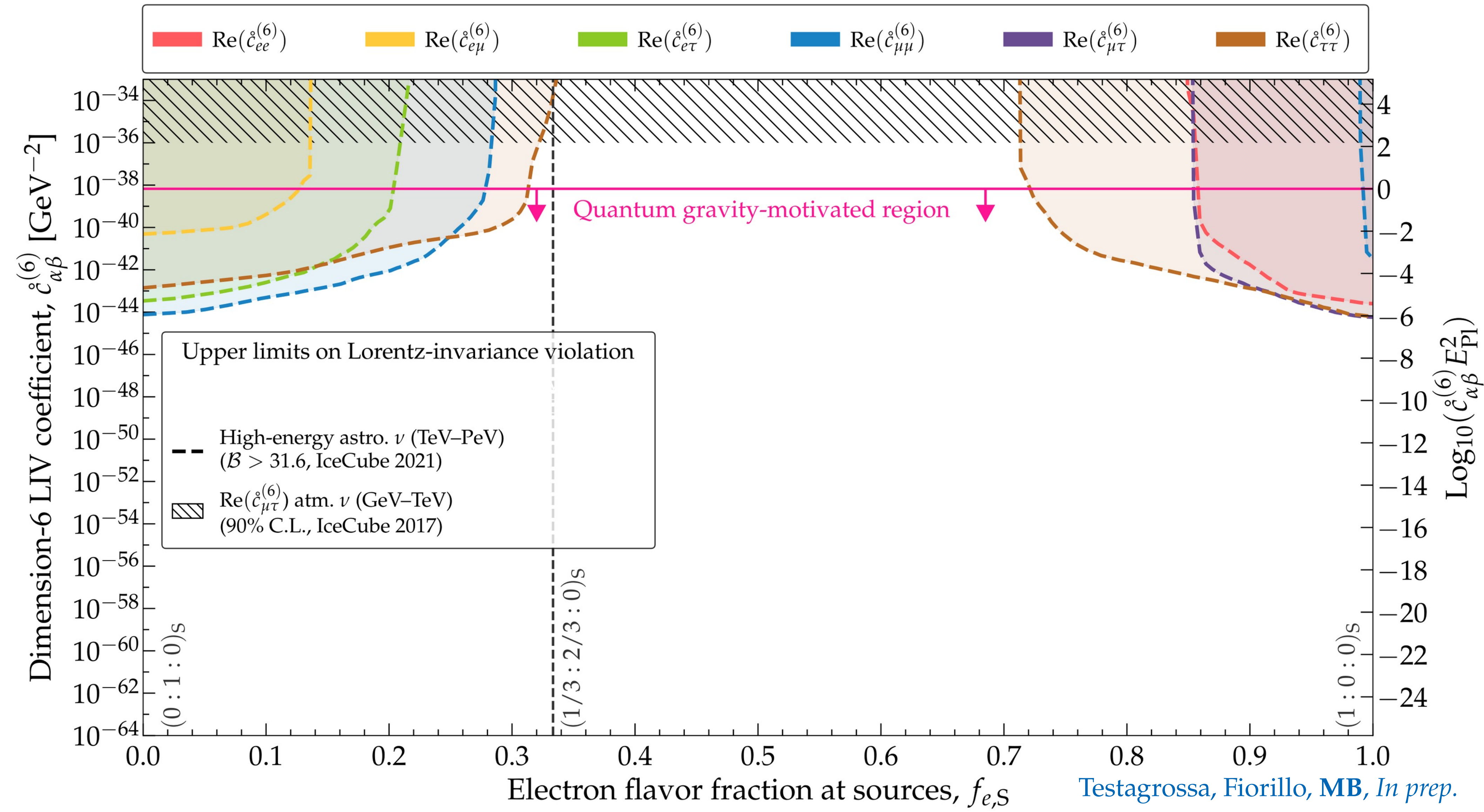

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
νμ
τ
ντ
νe
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km



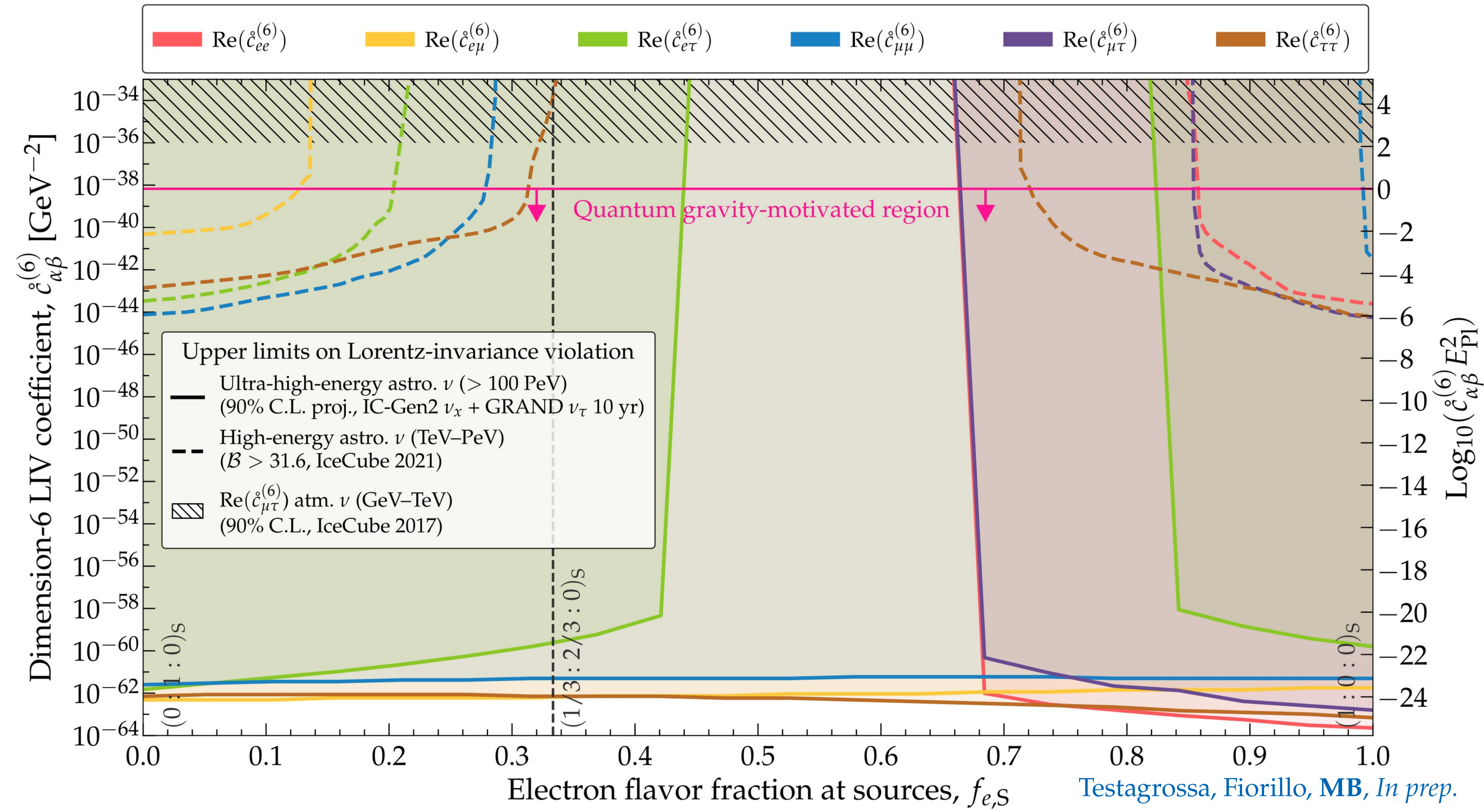
But GRAND detects only ν_τ!



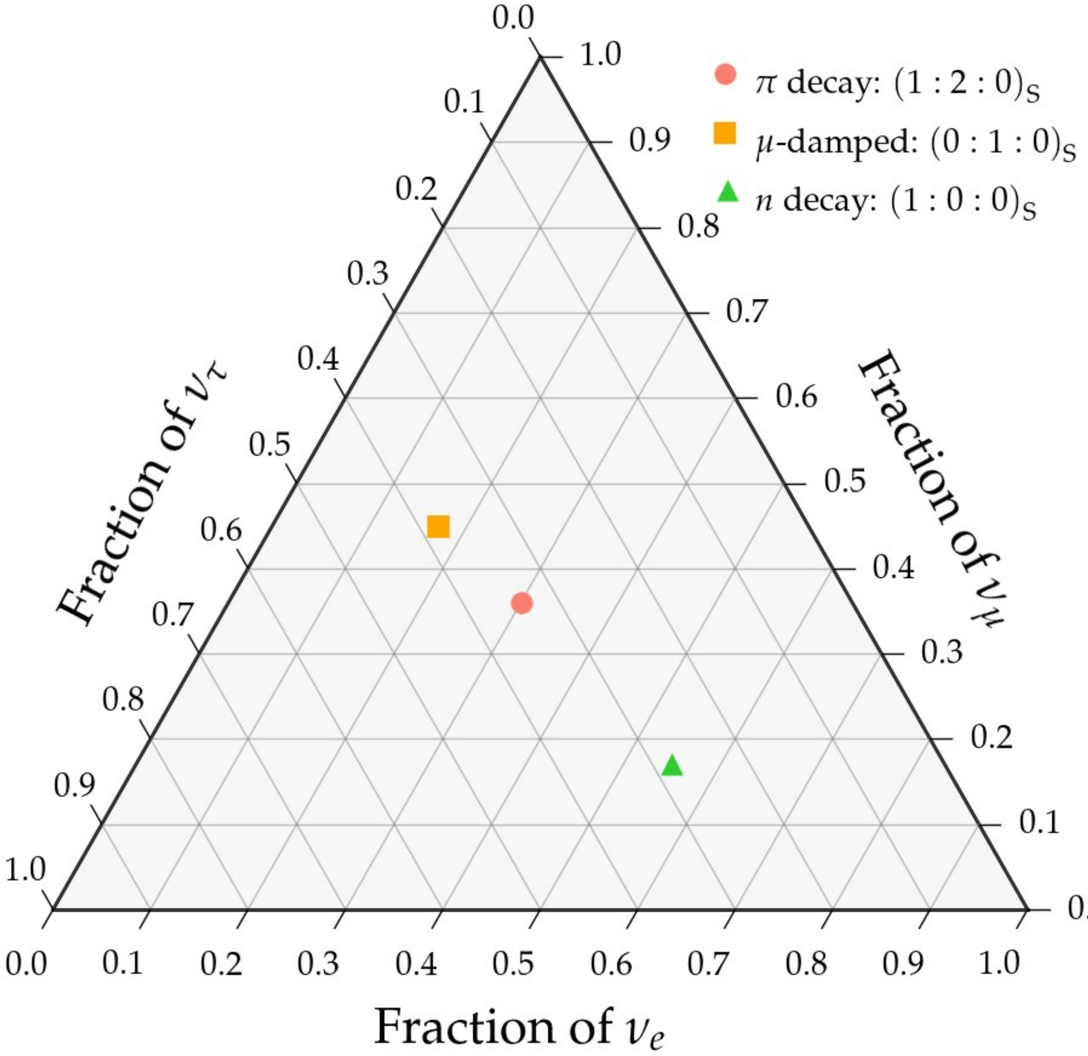
Testagrossa, Fiorillo, **MB**, *In prep.*

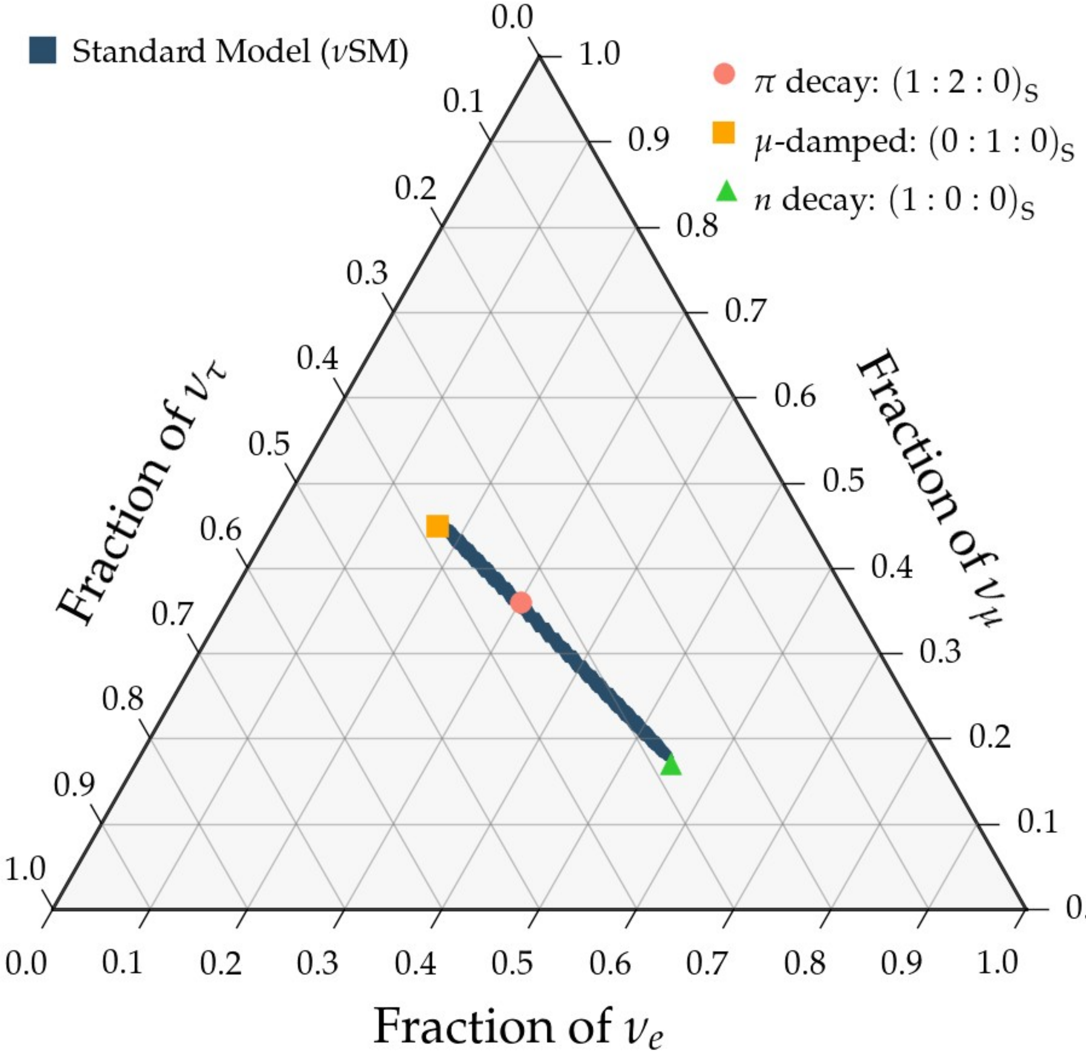


Re($\mathring{c}_{ee}^{(6)}$)
Re($\mathring{c}_{e\mu}^{(6)}$)
Re($\mathring{c}_{e\tau}^{(6)}$)
Re($\mathring{c}_{\mu\mu}^{(6)}$)
Re($\mathring{c}_{\mu\tau}^{(6)}$)
Re($\mathring{c}_{\tau\tau}^{(6)}$)
Quantum gravity-motivated region
Upper limits on Lorentz-invariance violation
High-energy astro. ν (TeV–PeV)
($\mathcal{B} > 31.6$, IceCube 2021)
Re($\mathring{c}_{\mu\tau}^{(6)}$) atm. ν (GeV–TeV)
(90% C.L., IceCube 2017)
$(0:1:0)_\mathrm{S}$
$(1/3:2/3:0)_\mathrm{S}$
$(1:0:0)_\mathrm{S}$
Dimension-6 LIV coefficient, $\mathring{c}_{\alpha\beta}^{(6)}$ [GeV^{-2}]
$\mathrm{Log}_{10}(\mathring{c}_{\alpha\beta}^{(6)} E_\mathrm{Pl}^2)$
Electron flavor fraction at sources, $f_{e,\mathrm{S}}$
Testagrossa, Fiorillo, **MB**, *In prep.*

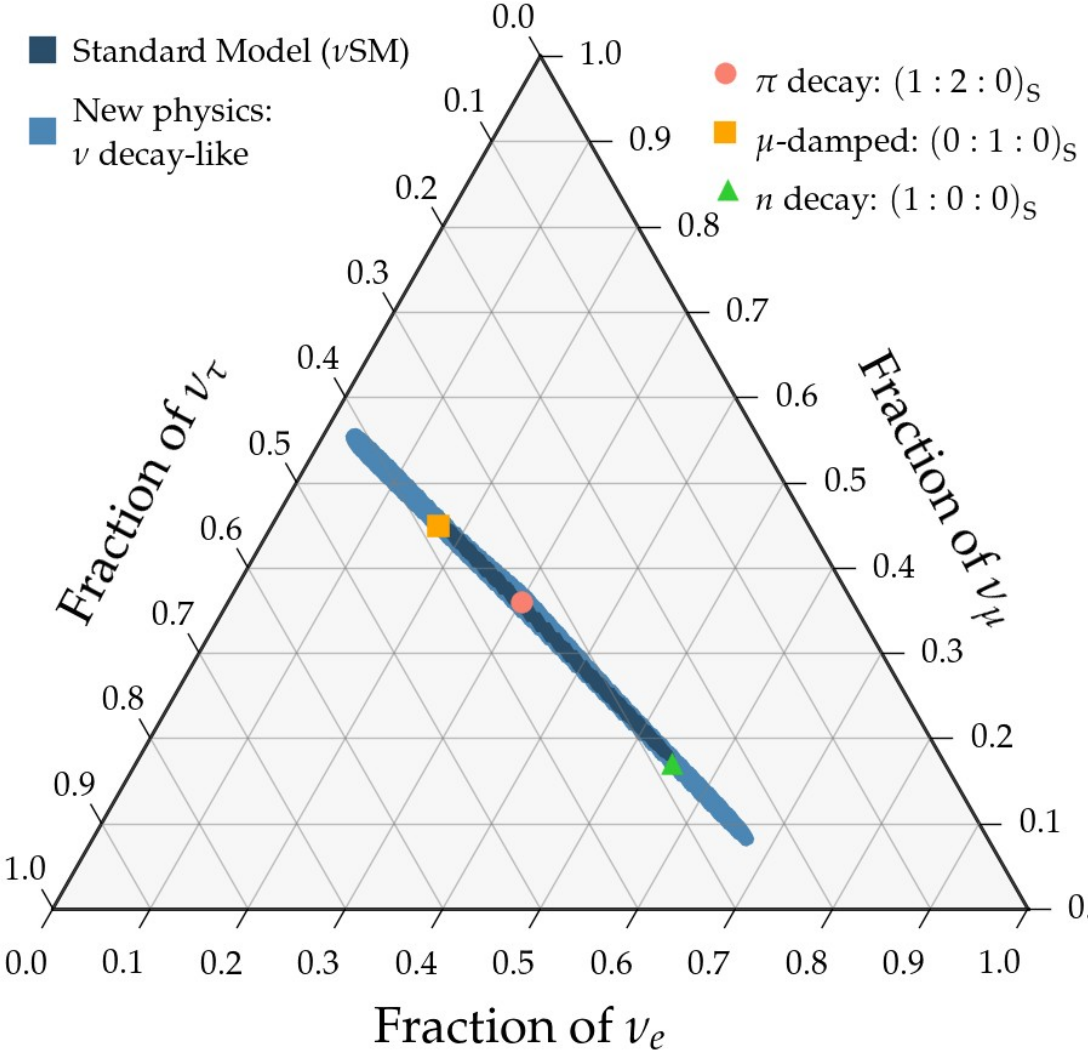


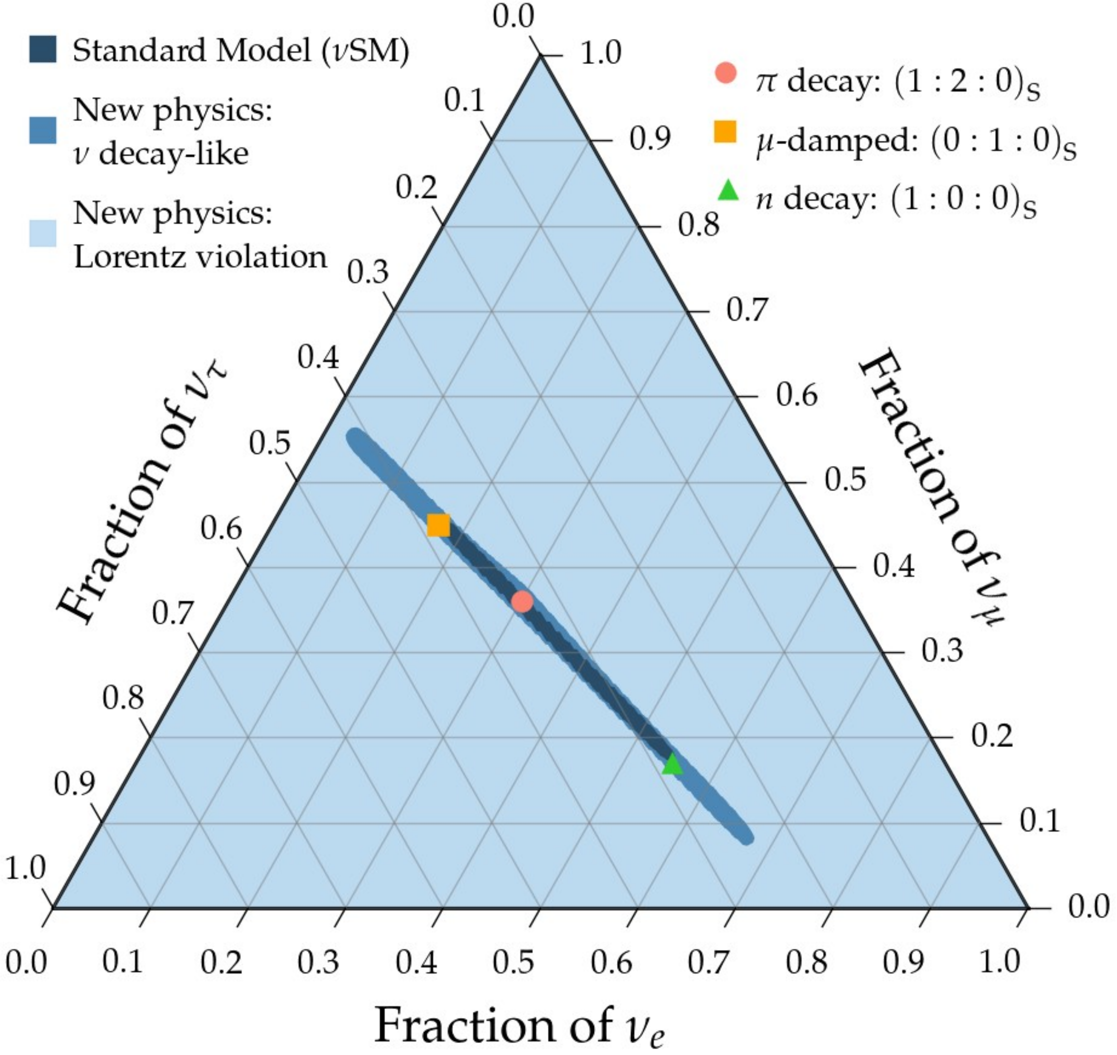
$\mathrm{Re}(\mathring{c}^{(6)}_{ee})$
$\mathrm{Re}(\mathring{c}^{(6)}_{e\mu})$
$\mathrm{Re}(\mathring{c}^{(6)}_{e\tau})$
$\mathrm{Re}(\mathring{c}^{(6)}_{\mu\mu})$
$\mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})$
$\mathrm{Re}(\mathring{c}^{(6)}_{\tau\tau})$
Quantum gravity-motivated region
Upper limits on Lorentz-invariance violation
Ultra-high-energy astro. ν (> 100 PeV)
(90% C.L. proj., IC-Gen2 ν_x + GRAND ν_τ 10 yr)
High-energy astro. ν (TeV–PeV)
($\mathcal{B}$ > 31.6, IceCube 2021)
$\mathrm{Re}(\mathring{c}^{(6)}_{\mu\tau})$ atm. ν (GeV–TeV)
(90% C.L., IceCube 2017)
$(0:1:0)_\mathrm{S}$
$(1/3:2/3:0)_\mathrm{S}$
$(1:0:0)_\mathrm{S}$
Dimension-6 LIV coefficient, $\mathring{c}^{(6)}_{\alpha\beta}$ [GeV^{-2}]
$\mathrm{Log}_{10}(\mathring{c}^{(6)}_{\alpha\beta} E^2_{\mathrm{Pl}})$
Electron flavor fraction at sources, $f_{e,\mathrm{S}}$
Testagrossa, Fiorillo, **MB**, *In prep.*

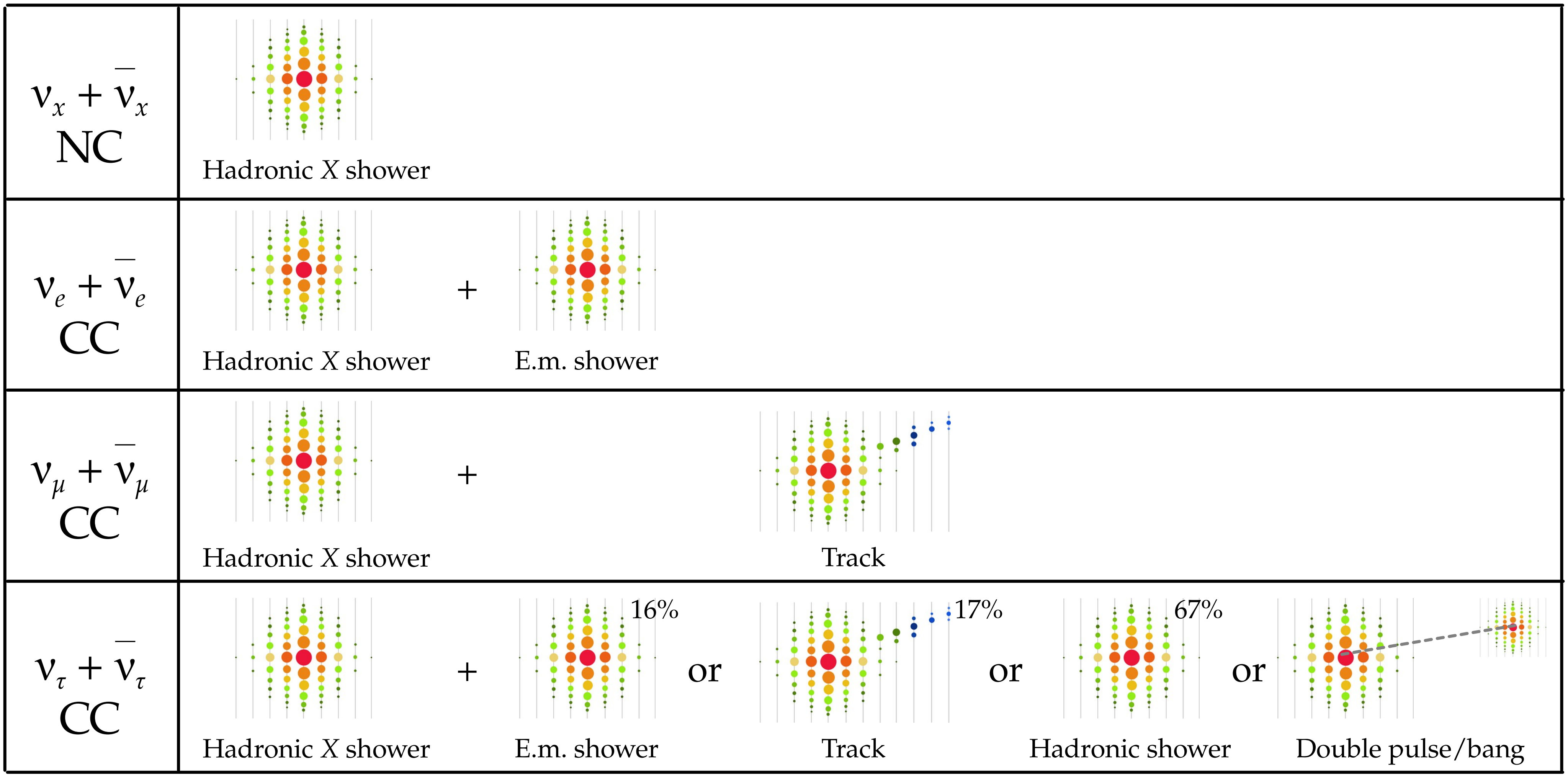

π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

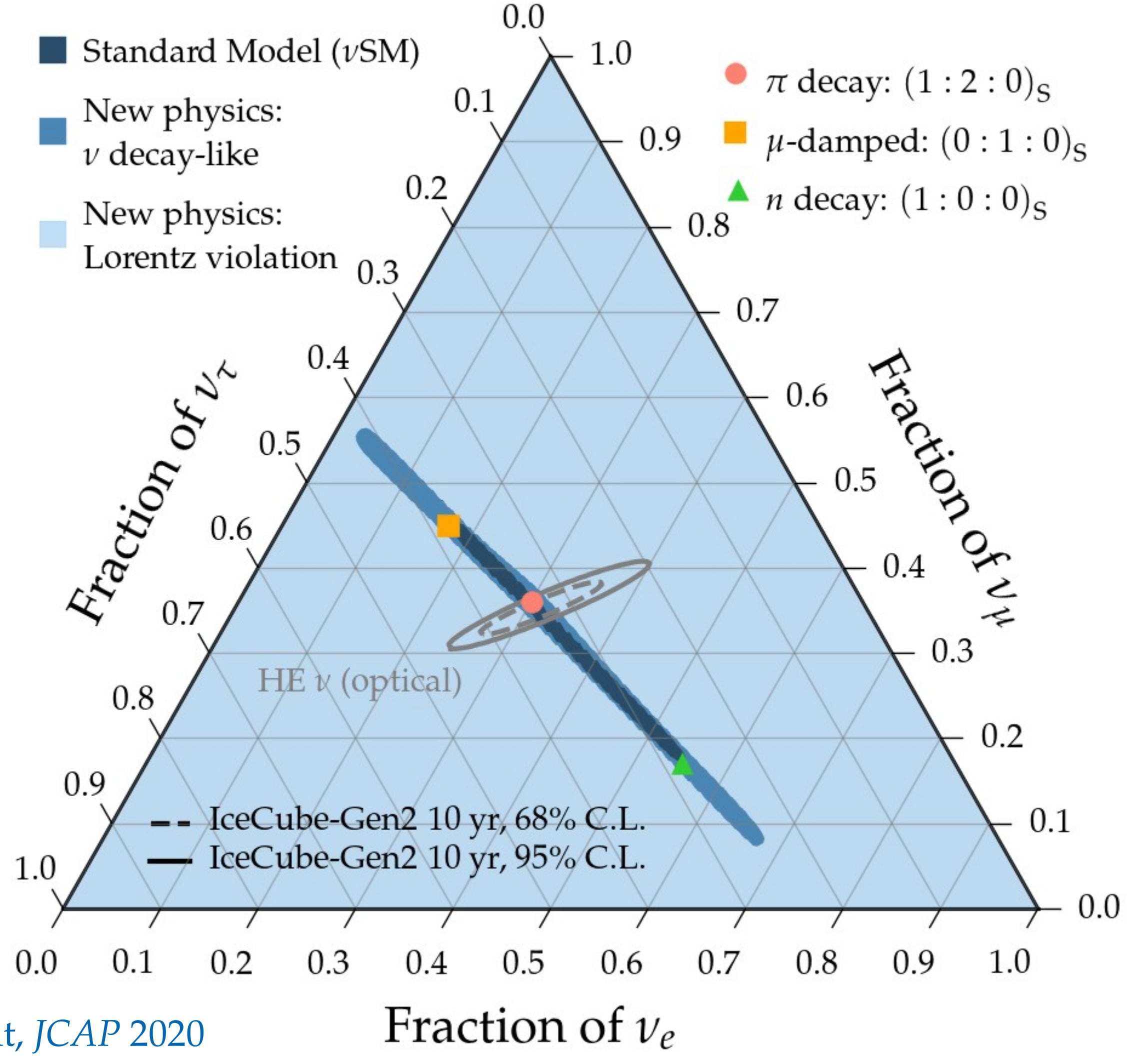


Standard Model (νSM)
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

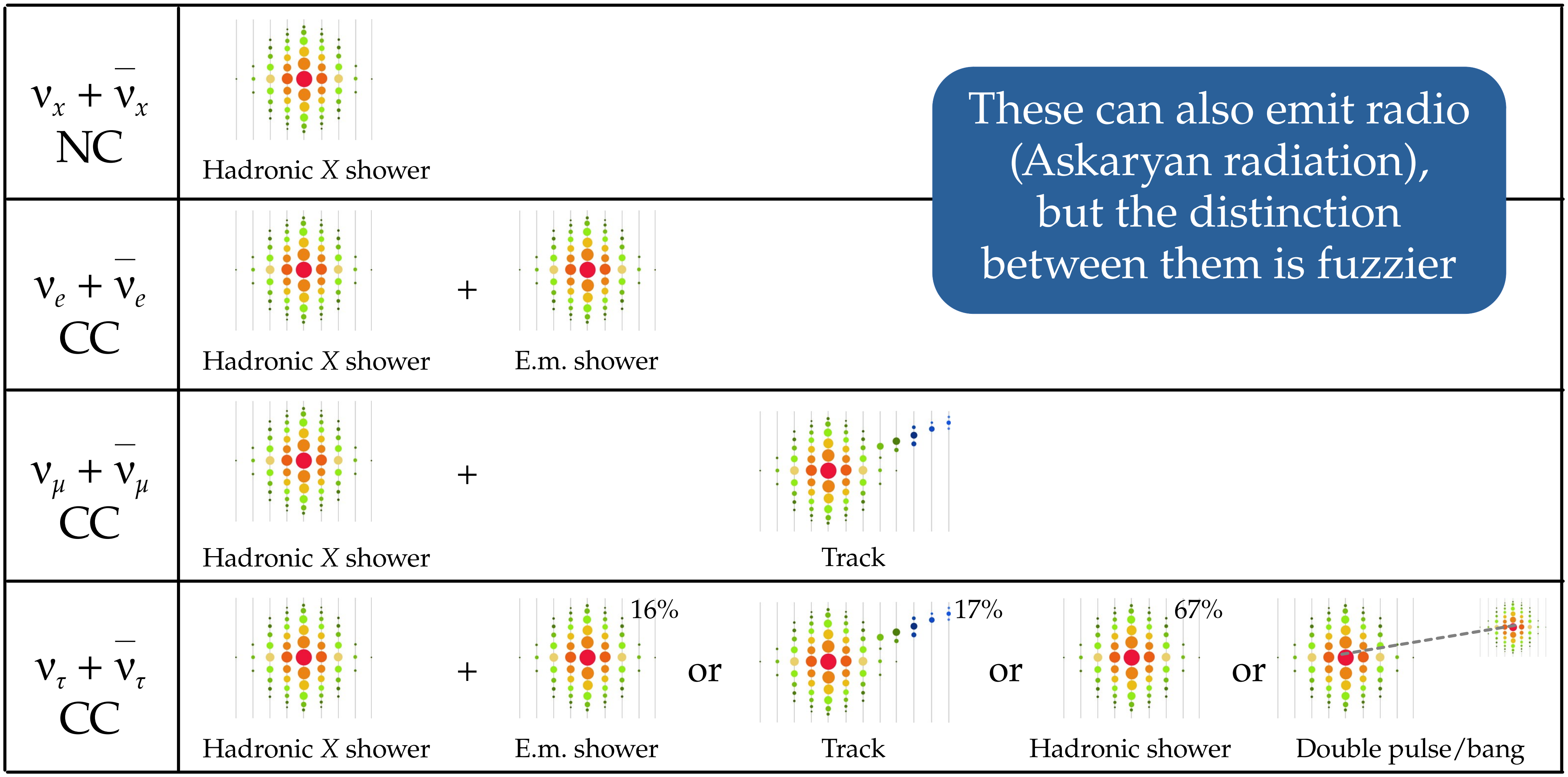

Standard Model (νSM)
New physics:
ν decay-like
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0


Standard Model (νSM)
New physics: ν decay-like
New physics: Lorentz violation
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
Fraction of ν_τ
Fraction of ν_μ
Fraction of ν_e
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

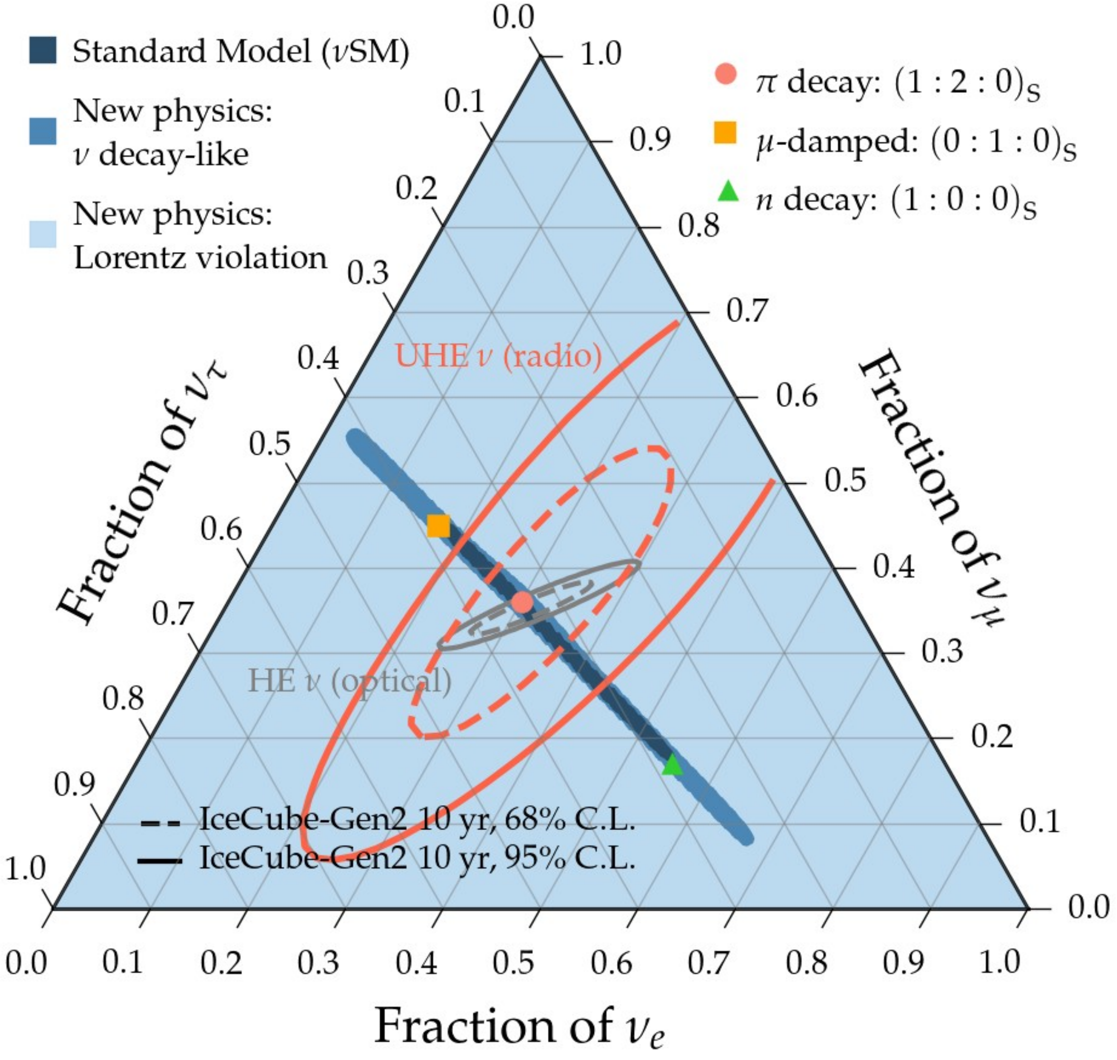

$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang

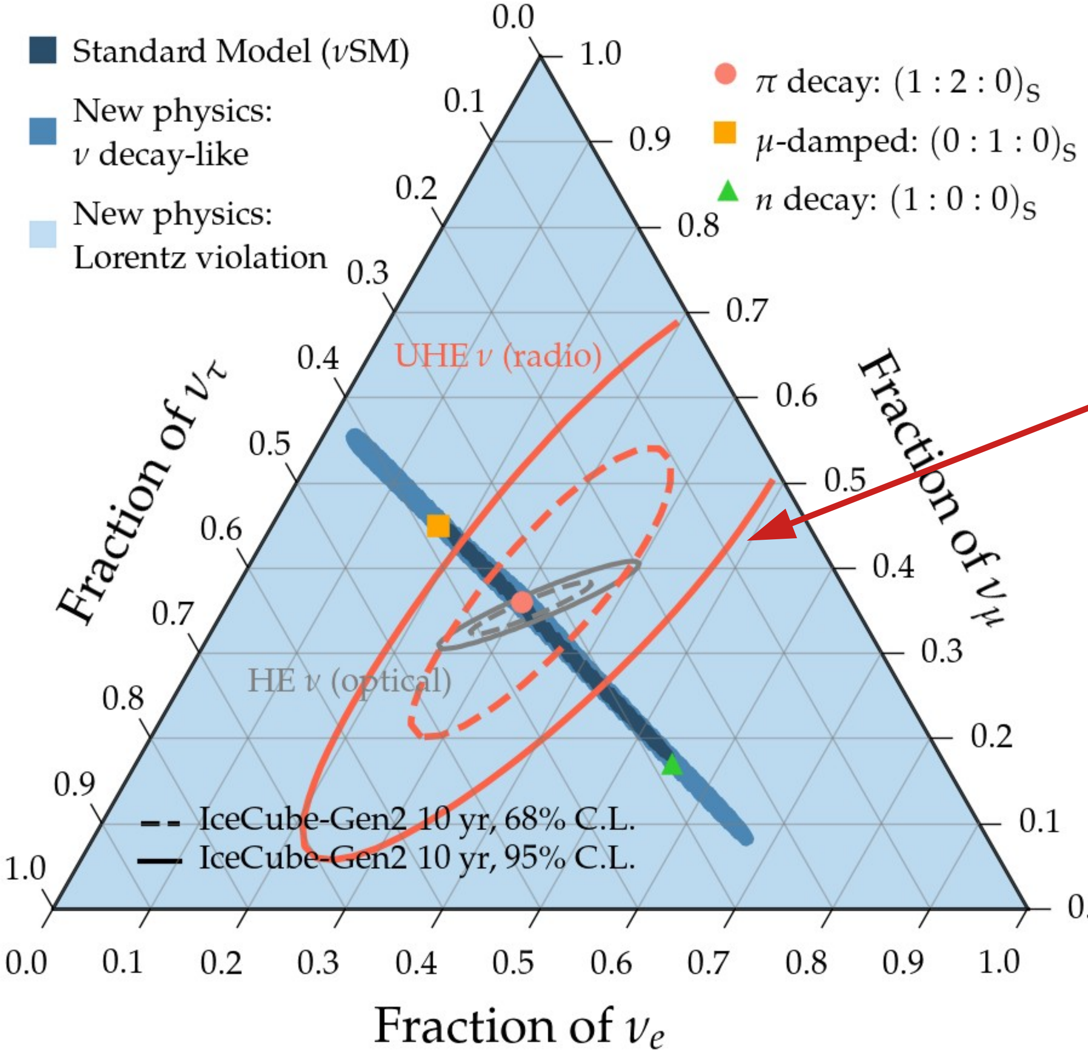


Song, Li, Argüelles, MB, Vincent, *JCAP* 2020
MB, Beacom, Winter, *PRL* 2015



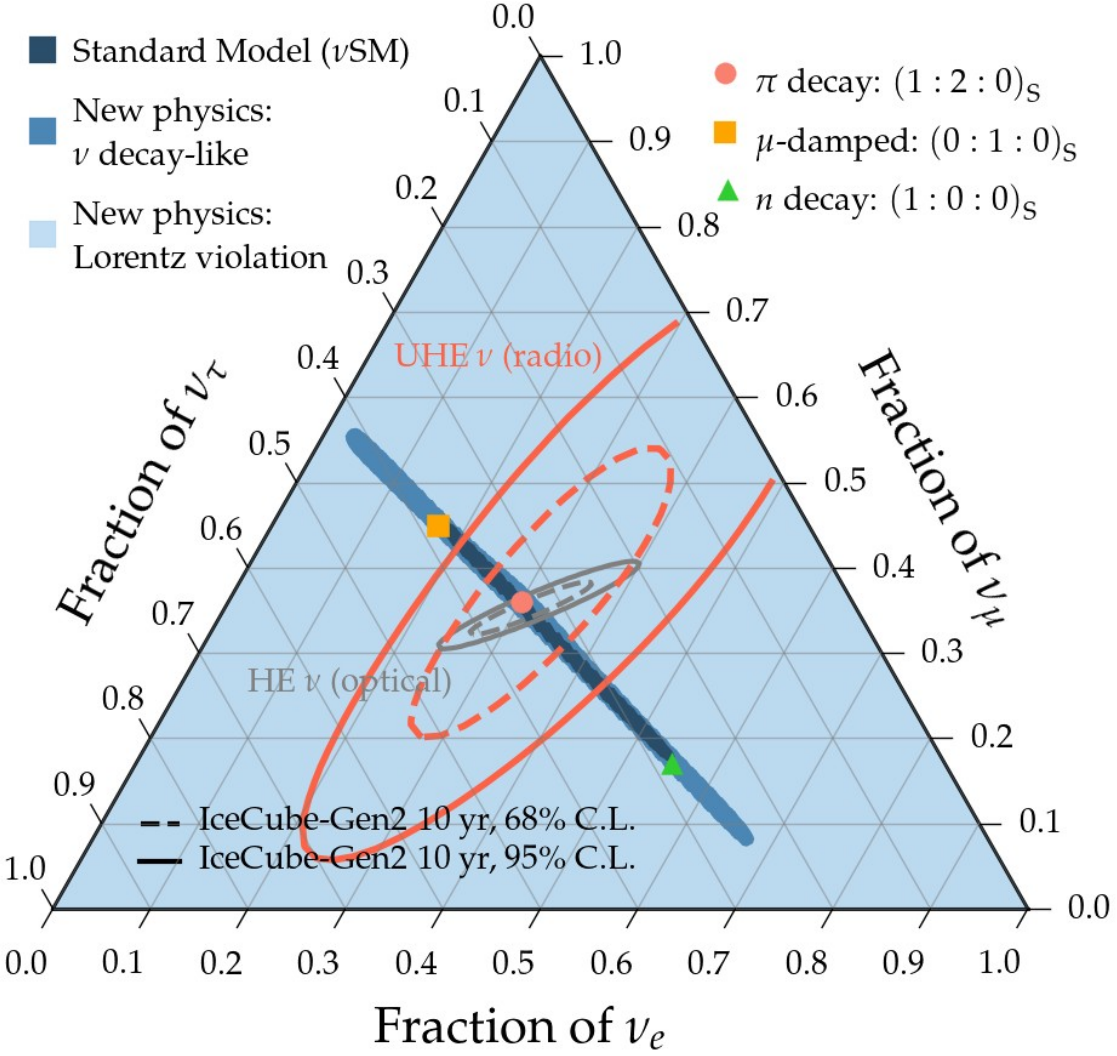
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang
These can also emit radio (Askaryan radiation), but the distinction between them is fuzzier

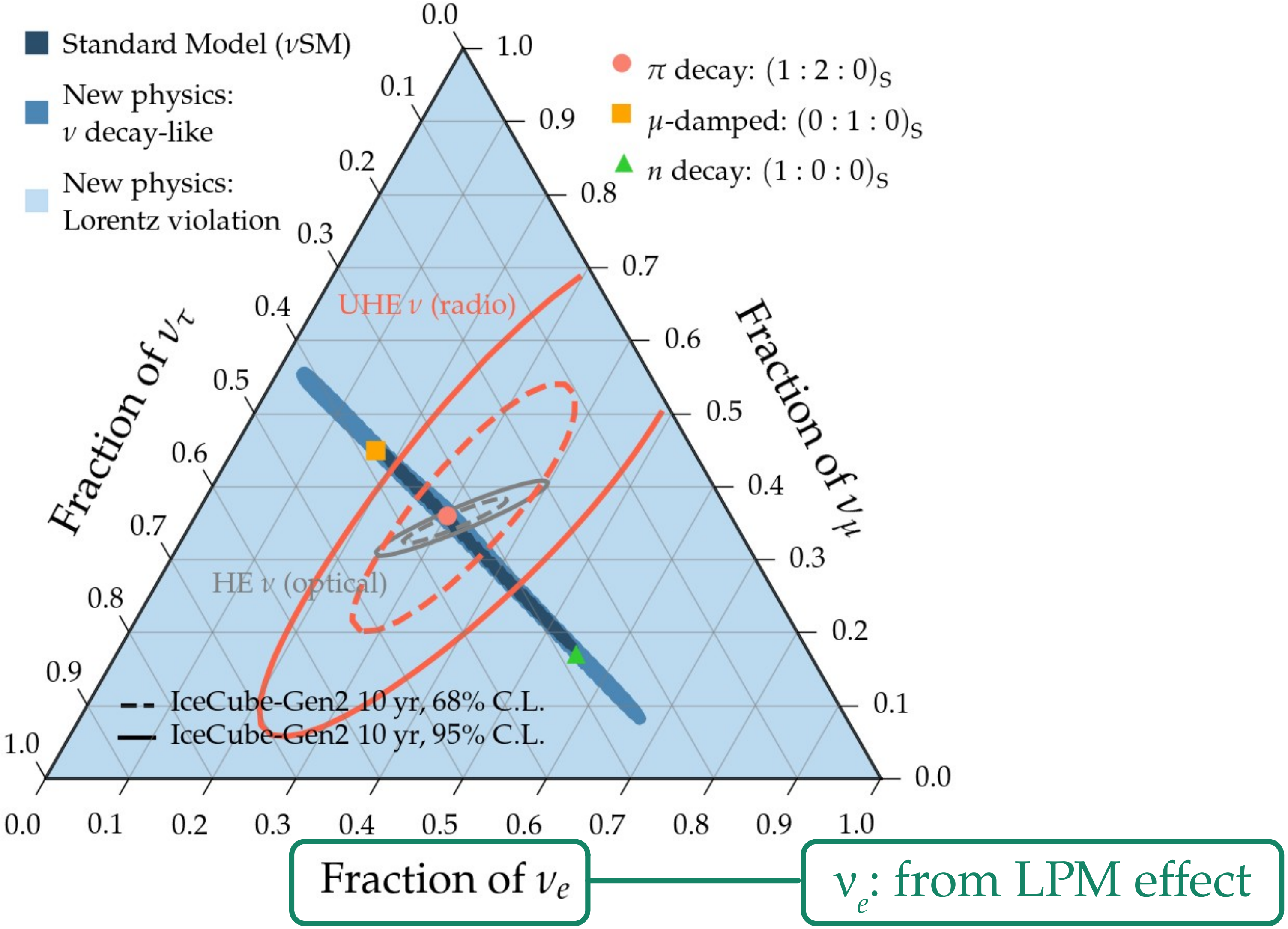

Standard Model (νSM)
New physics: ν decay-like
New physics: Lorentz violation
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
UHE ν (radio)
HE ν (optical)
IceCube-Gen2 10 yr, 68% C.L.
IceCube-Gen2 10 yr, 95% C.L.
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



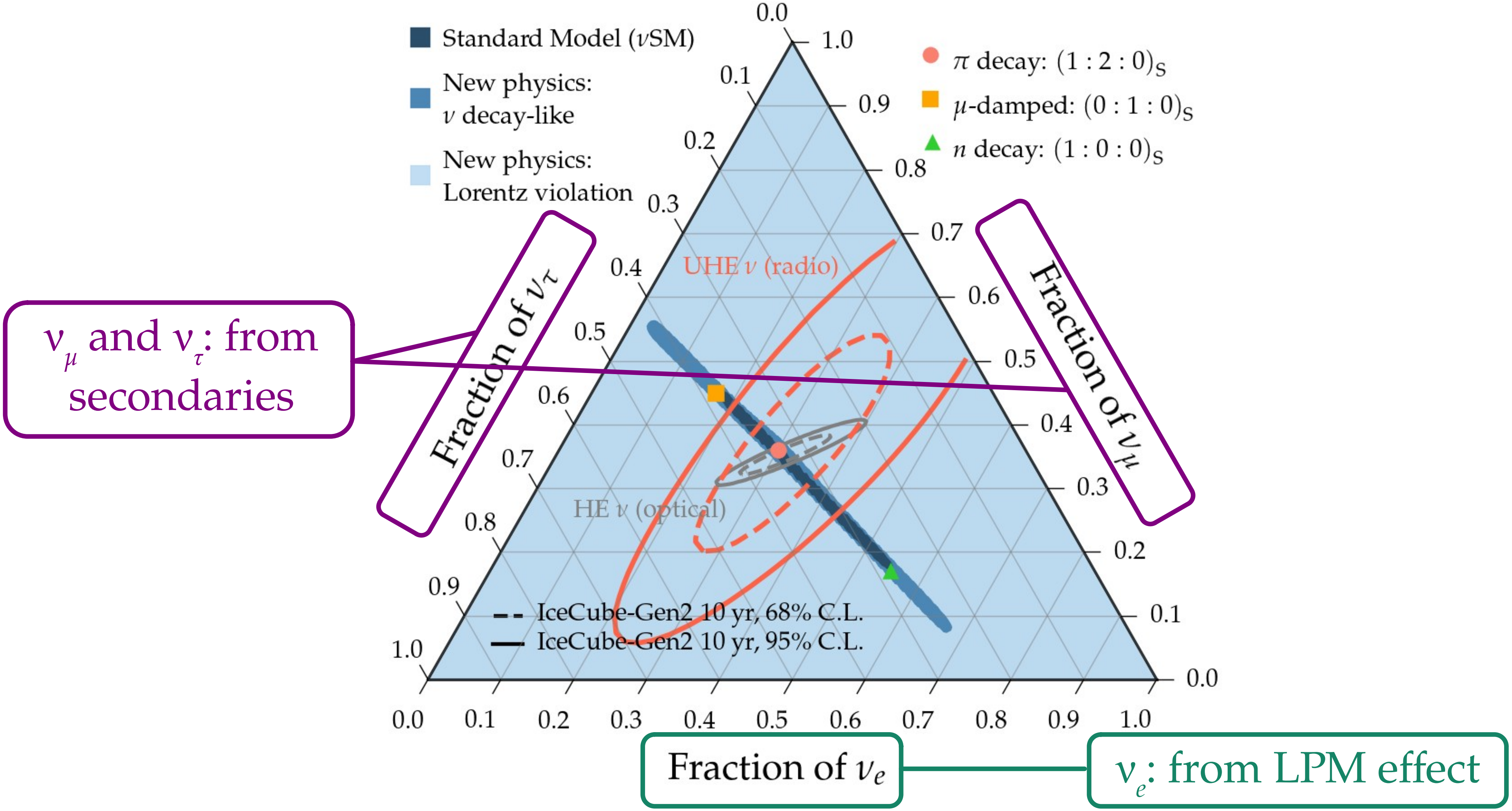
First realistic forecast of UHE ν flavor composition measurement

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

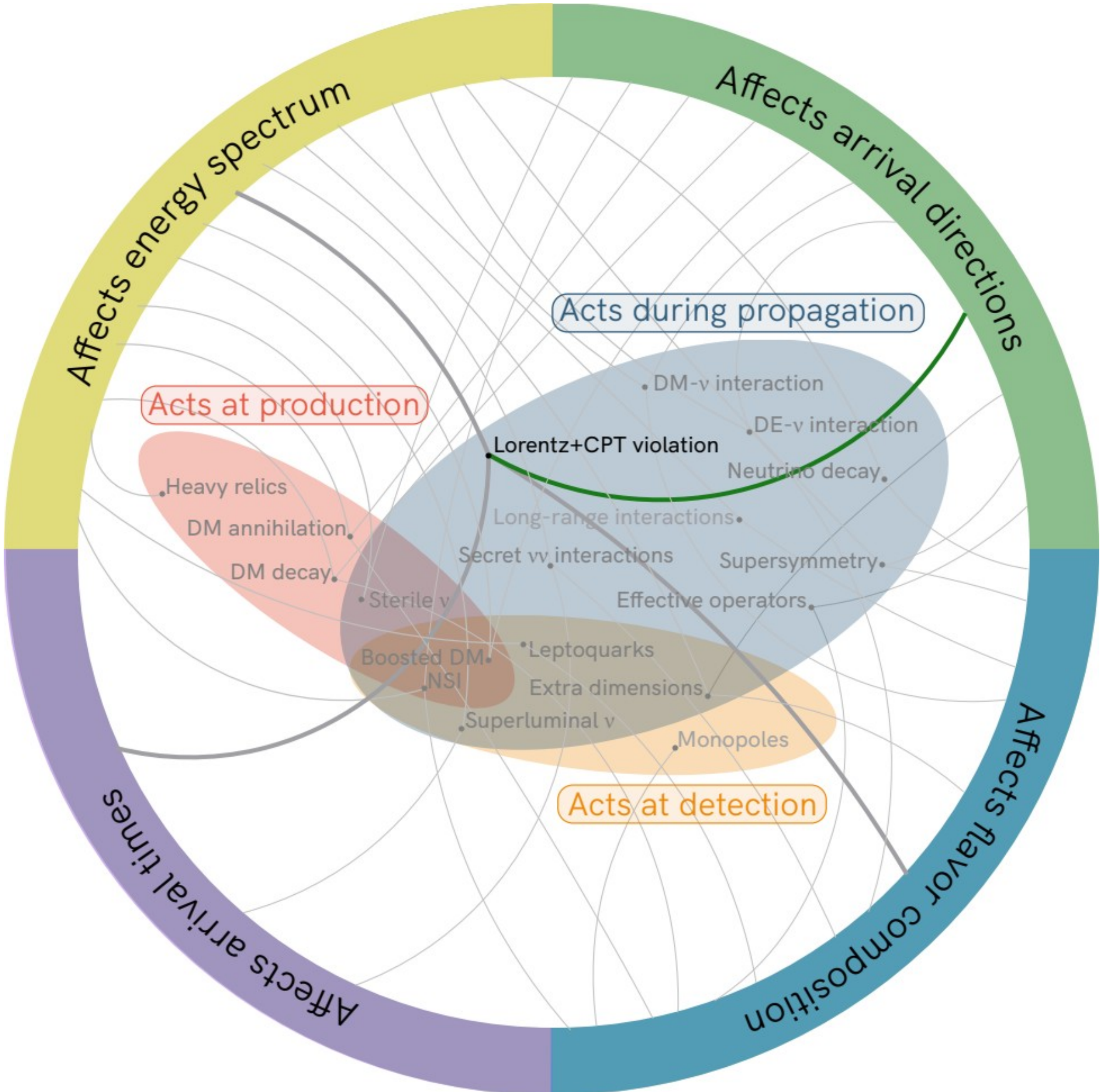

Standard Model (νSM)
New physics: ν decay-like
New physics: Lorentz violation
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
UHE ν (radio)
HE ν (optical)
IceCube-Gen2 10 yr, 68% C.L.
IceCube-Gen2 10 yr, 95% C.L.
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



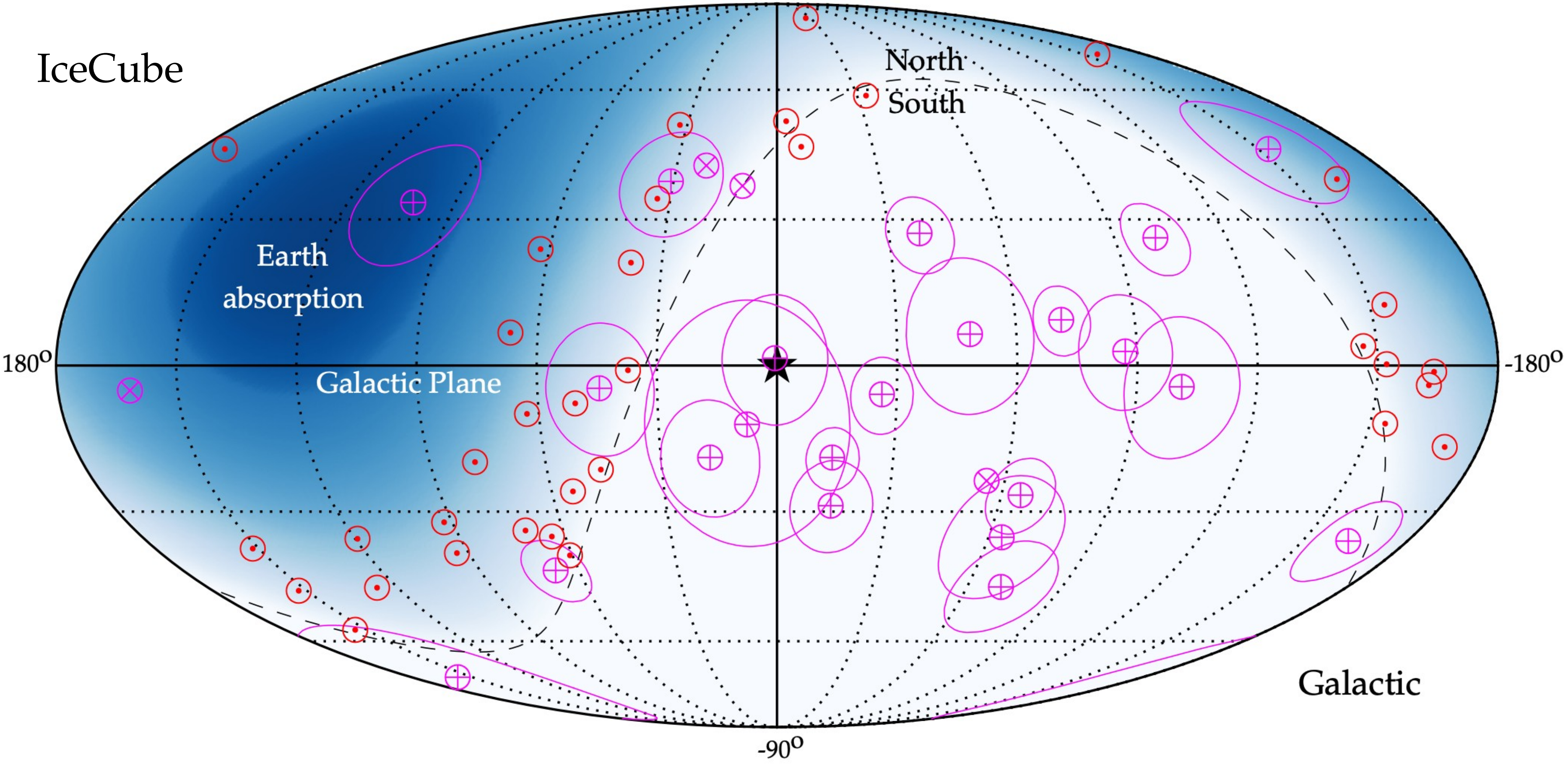
Standard Model (νSM)
New physics: ν decay-like
New physics: Lorentz violation
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
UHE ν (radio)
HE ν (optical)
IceCube-Gen2 10 yr, 68% C.L.
IceCube-Gen2 10 yr, 95% C.L.
Fraction of ντ
Fraction of νμ
Fraction of νe
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
νe: from LPM effect



Standard Model (νSM)
New physics: ν decay-like
New physics: Lorentz violation
π decay: (1 : 2 : 0)S
μ-damped: (0 : 1 : 0)S
n decay: (1 : 0 : 0)S
UHE ν (radio)
HE ν (optical)
IceCube-Gen2 10 yr, 68% C.L.
IceCube-Gen2 10 yr, 95% C.L.
Fraction of ντ
Fraction of νμ
Fraction of νe
νμ and ντ: from secondaries
νe: from LPM effect



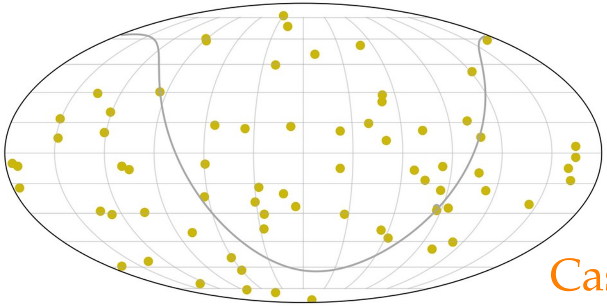
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
Long-range interactions
Secret νν interactions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


IceCube
North
South
Earth
absorption
180°
Galactic Plane
-180°
-90°
Galactic

Neutrino flavors → Event topologies (HESE)

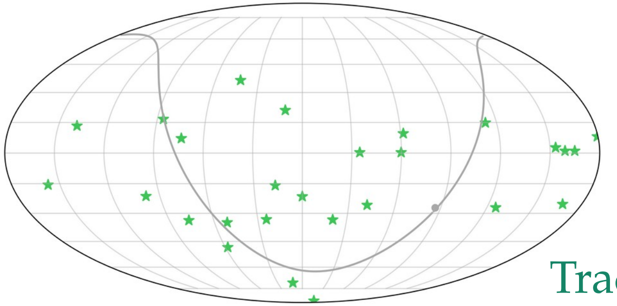
Attenuation inside Earth
Detector response

ν_e



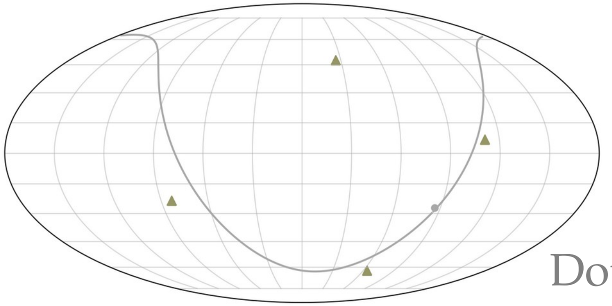
Cascades

ν_μ

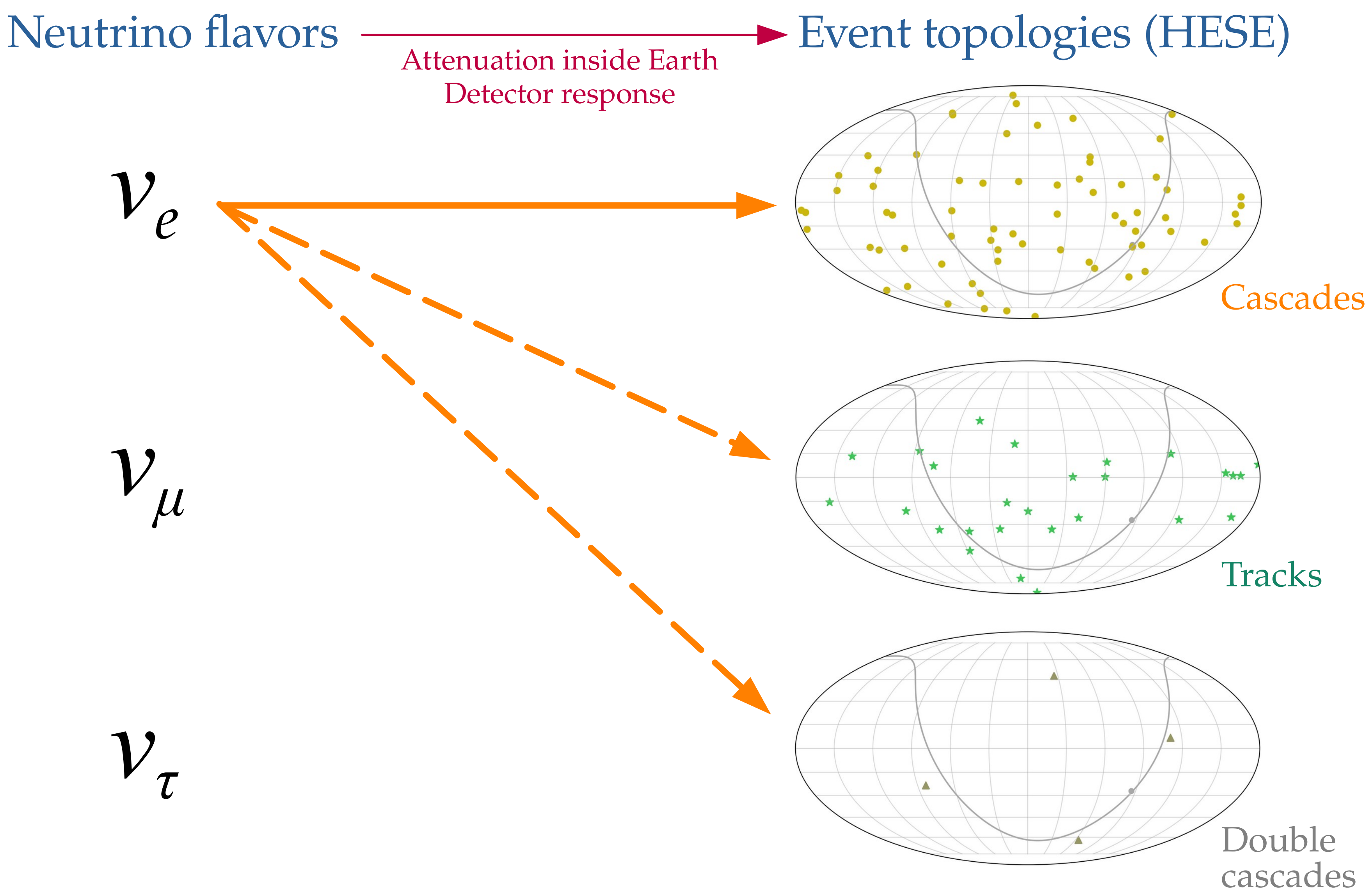


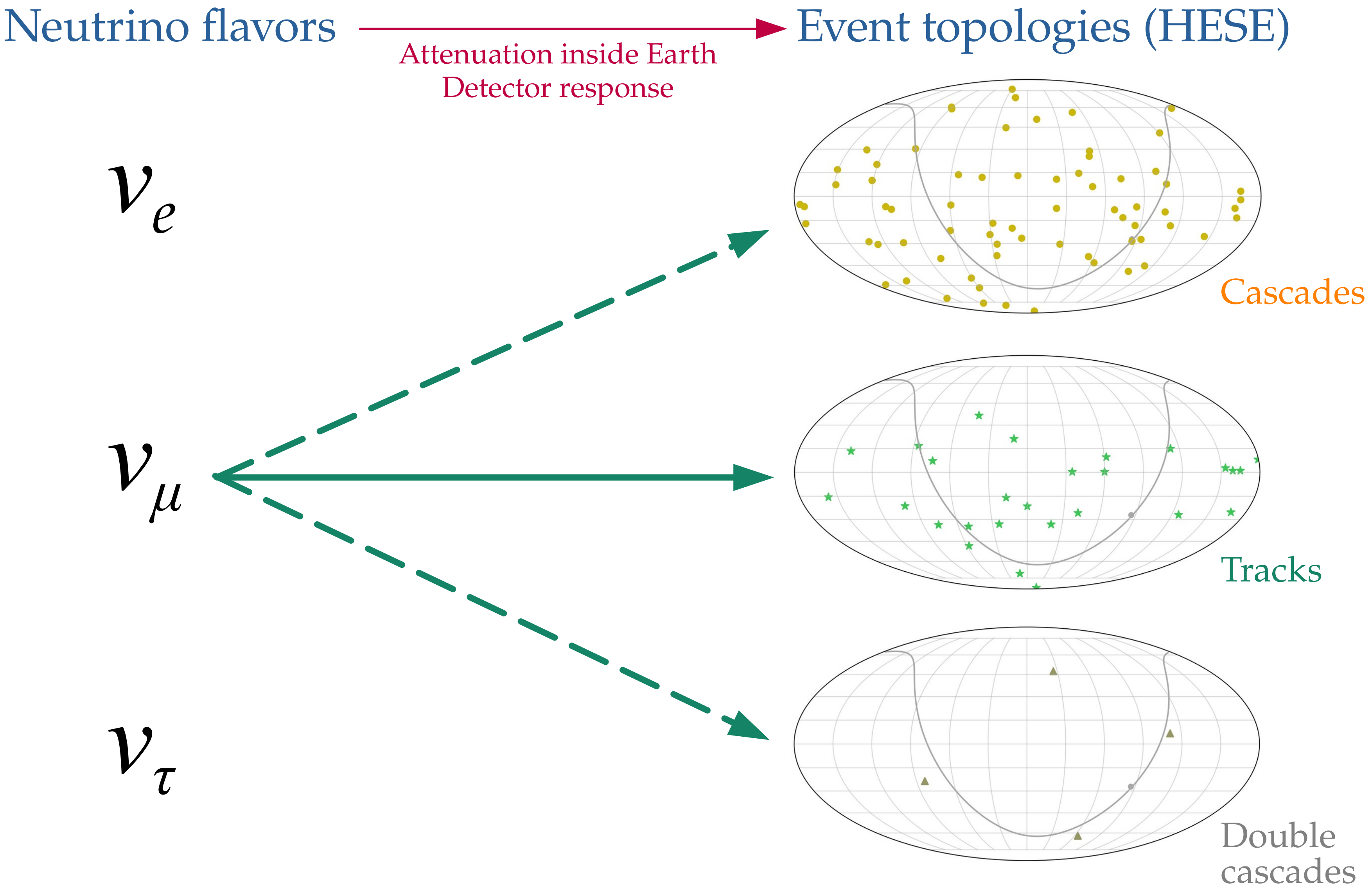
Tracks

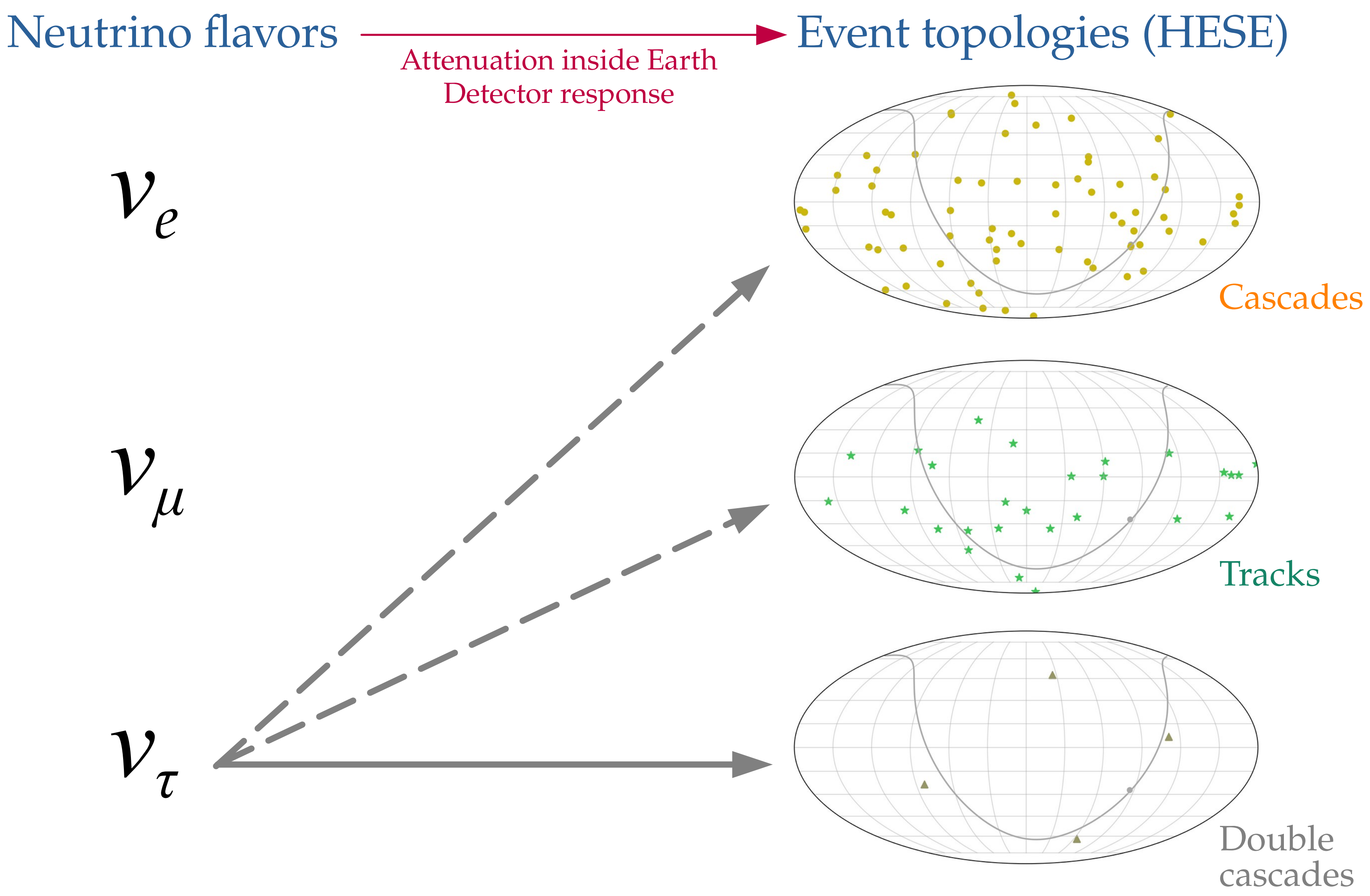
ν_τ



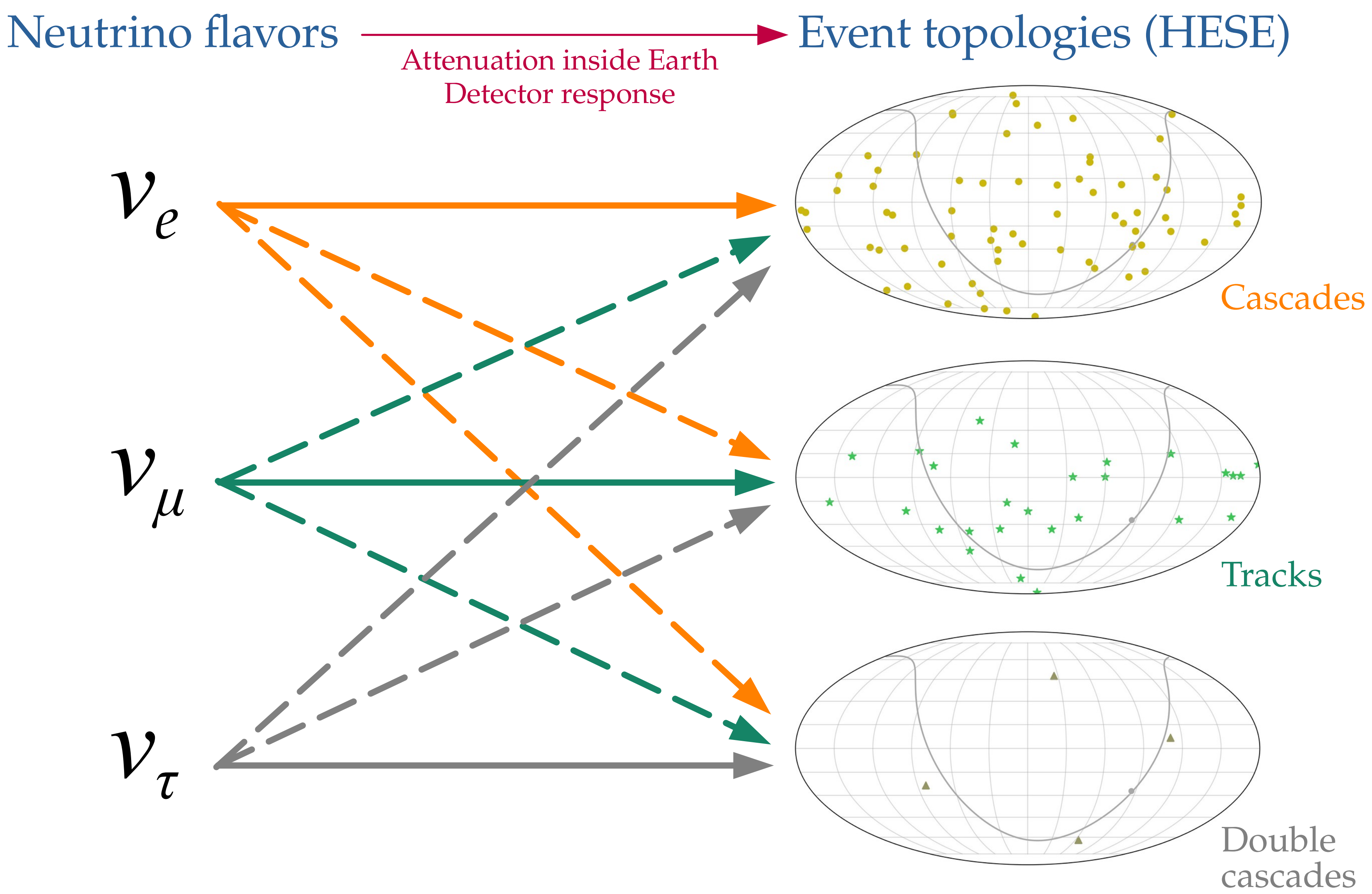
Double cascades


Neutrino flavors
Event topologies (HESE)
Attenuation inside Earth
Detector response
ν_e
ν_μ
ν_τ
Cascades
Tracks
Double cascades

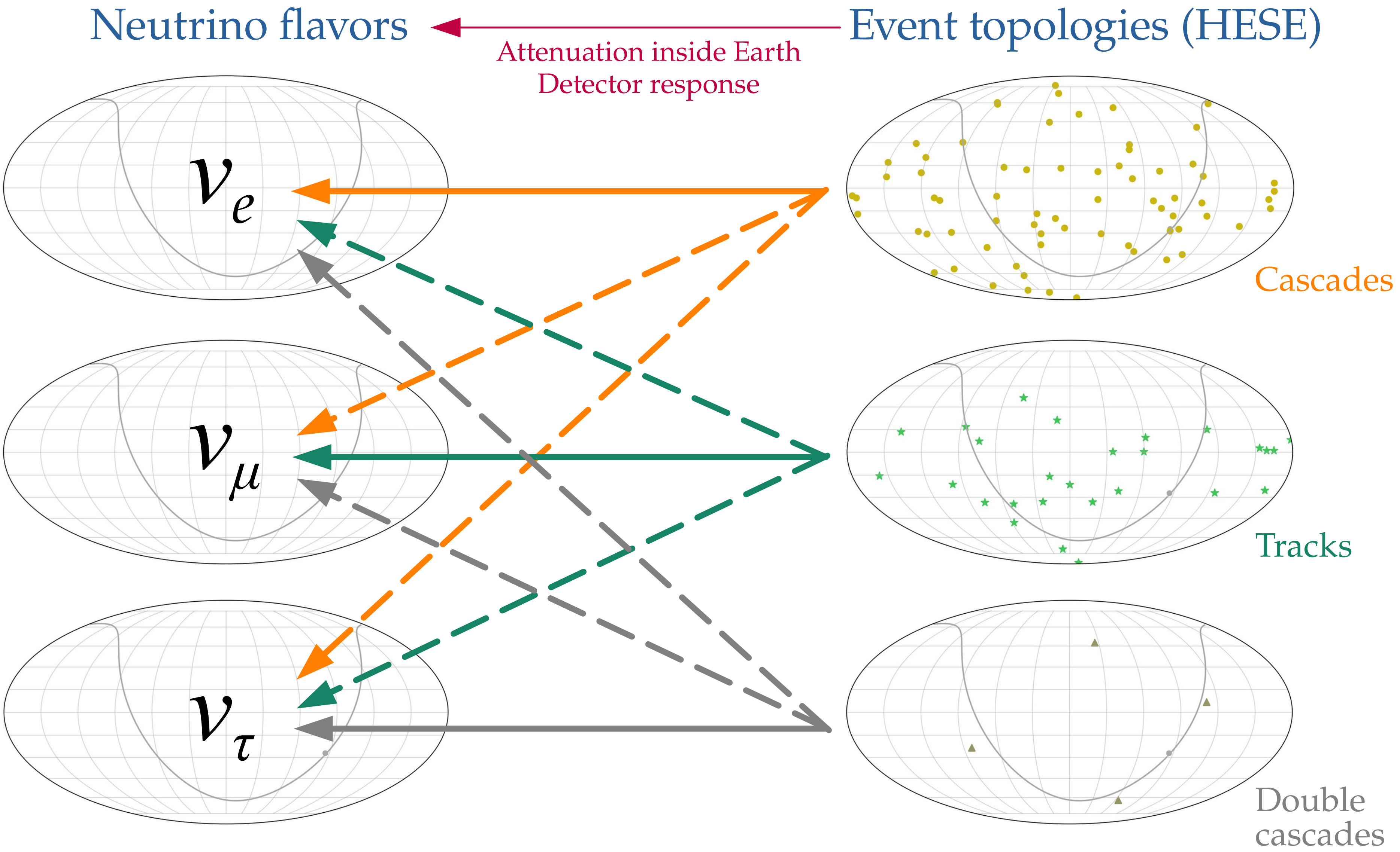

Neutrino flavors
Event topologies (HESE)
Attenuation inside Earth
Detector response
ν_e
ν_μ
ν_τ
Cascades
Tracks
Double cascades



Neutrino flavors
Event topologies (HESE)
Attenuation inside Earth
Detector response
ν_e
ν_μ
ν_τ
Cascades
Tracks
Double cascades



Neutrino flavors
Event topologies (HESE)
Attenuation inside Earth
Detector response
ν_e
ν_μ
ν_τ
Cascades
Tracks
Double cascades



Neutrino flavors
Event topologies (HESE)
Attenuation inside Earth
Detector response
ν_e
ν_μ
ν_τ
Cascades
Tracks
Double cascades

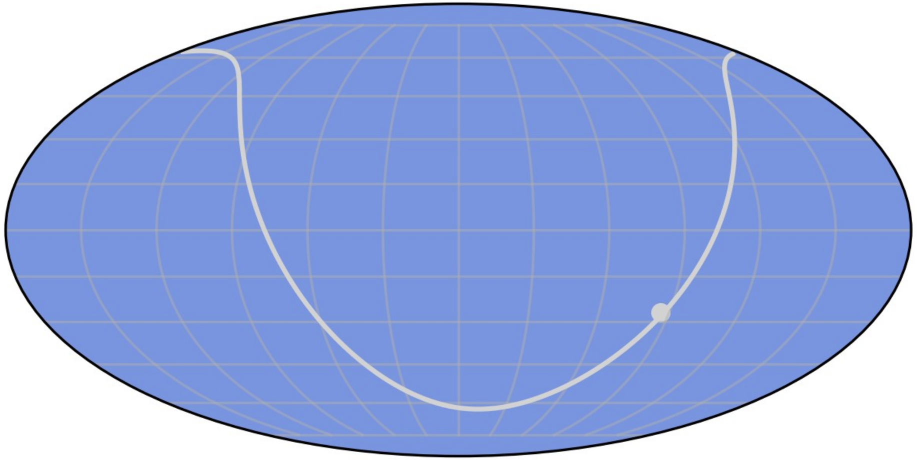
$$\Delta\Phi^{\alpha} \equiv \text{Relative variation of flux of } \nu_{\alpha} = \frac{\Phi^{\alpha} - \langle\Phi^{\alpha}\rangle}{\langle\Phi^{\alpha}\rangle}$$

$$\Delta\Phi^\alpha \equiv \text{Relative variation of flux of } \nu_\alpha = \frac{\Phi^\alpha - \langle\Phi^\alpha\rangle}{\langle\Phi^\alpha\rangle}$$

If the fluxes of all flavors were isotropic—

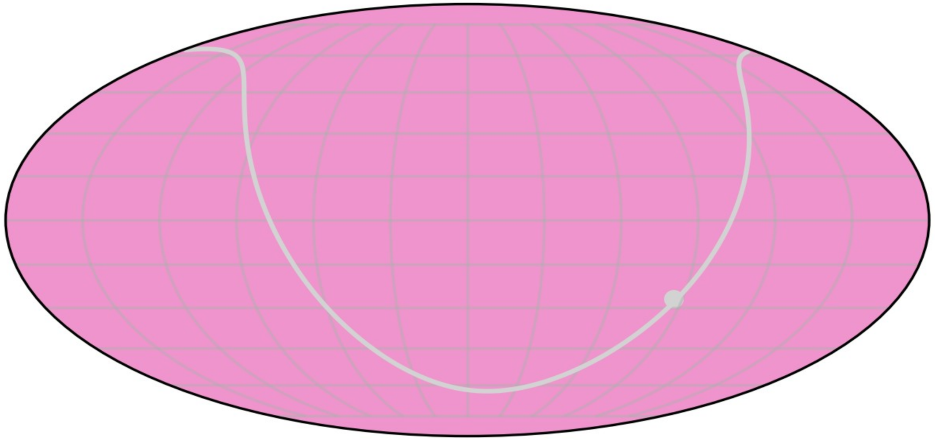
ν_e flux skymap ($= \nu_\tau$)

$\Delta\Phi^e = \Delta\Phi^\tau$

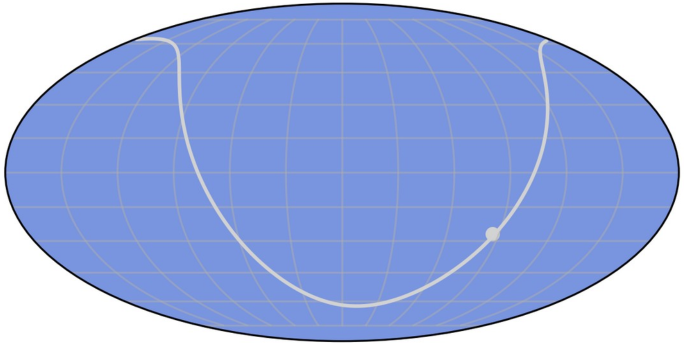


ν_μ flux skymap

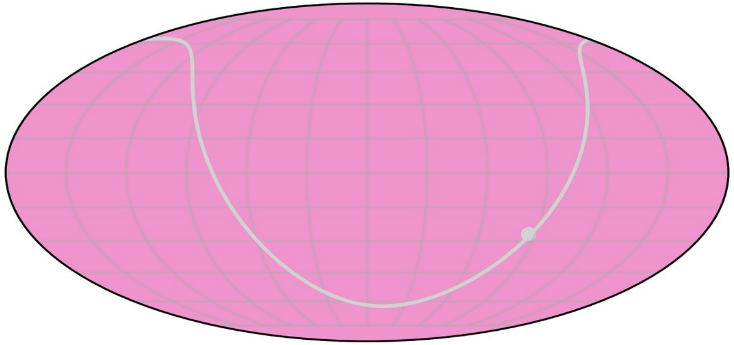
$\Delta\Phi^\mu$



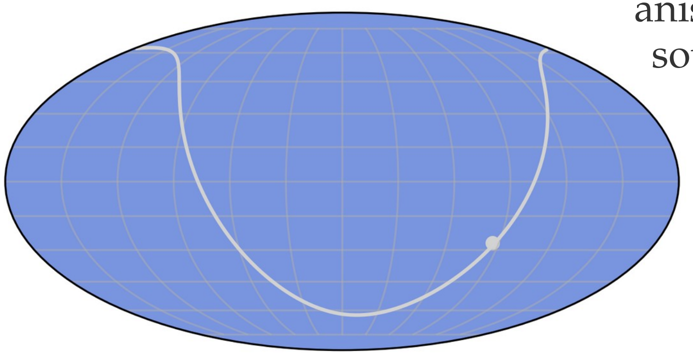
$\Delta\Phi^e = \Delta\Phi^\tau$



$\Delta\Phi^\mu$



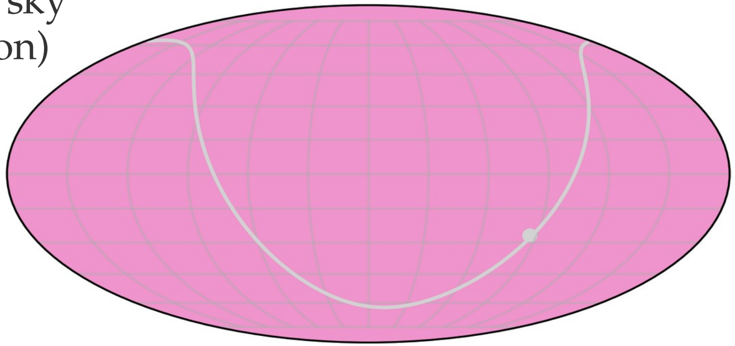
$\Delta\Phi^e = \Delta\Phi^\tau$



(Subtract skymaps to remove common anisotropies from sky source distribution)

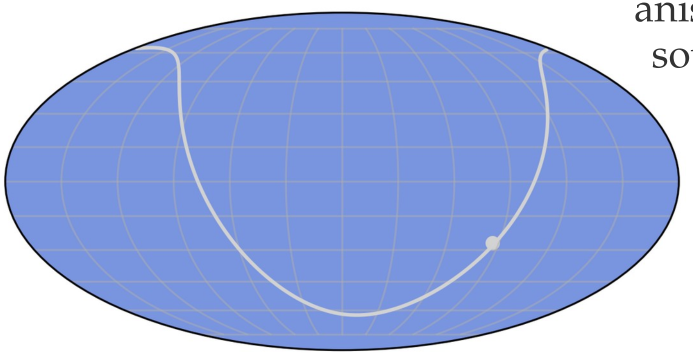
$-$

$\Delta\Phi^\mu$



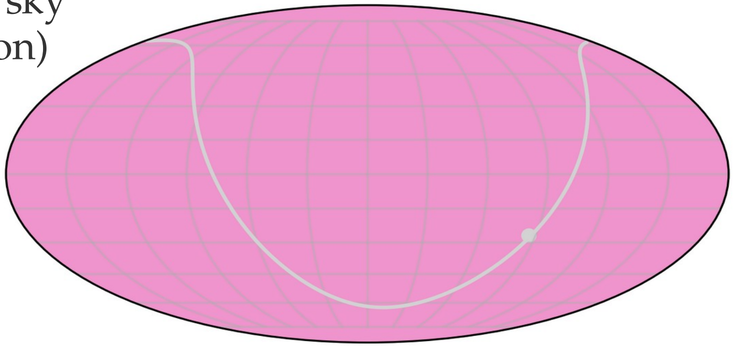
(Subtract skymaps to remove common anisotropies from sky source distribution)

$\Delta\Phi^{e} = \Delta\Phi^{\tau}$



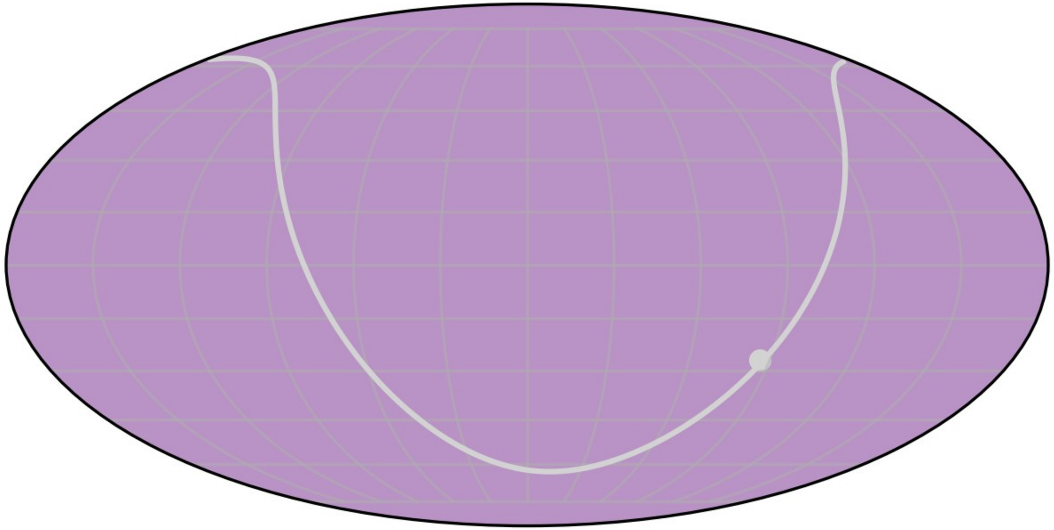
$-$

$\Delta\Phi^{\mu}$



$=$

$\Delta\Phi^{e} - \Delta\Phi^{\mu}$



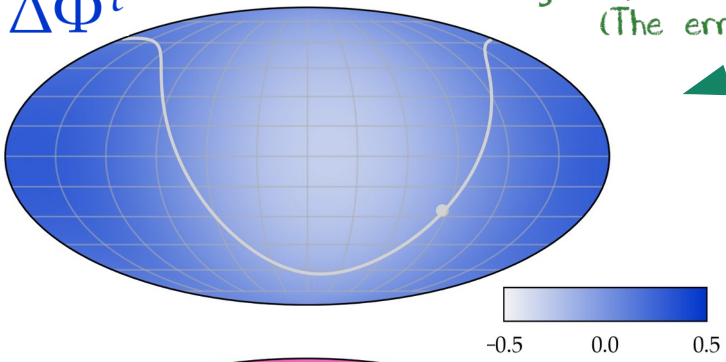
Any remaining anisotropy in the difference map is due to propagation effects

Inferred: neutrino flavor fluxes

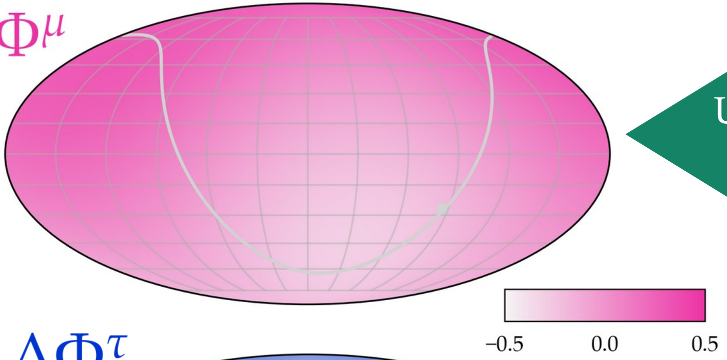
Detected: events (IC HESE 7.5 yr)

Showing only the best-fit maps
(The errors are large!)

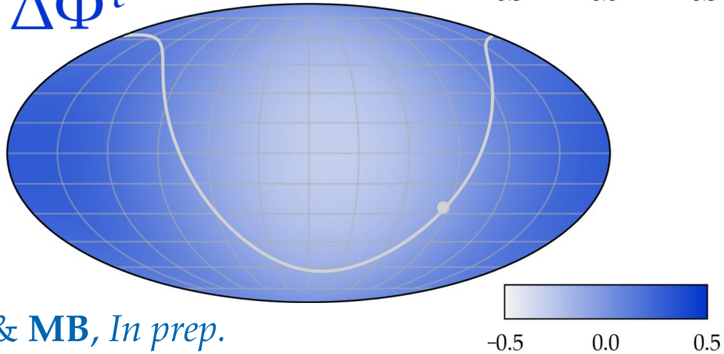
$\Delta\Phi^e = \Delta\Phi^\tau$



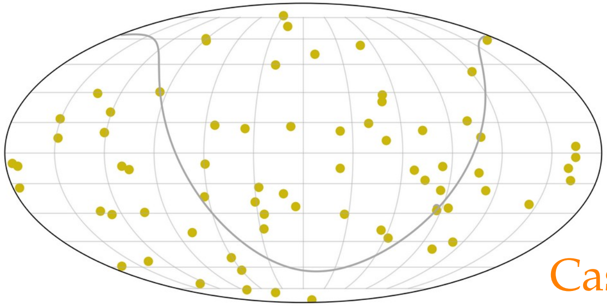
$\Delta\Phi^\mu$



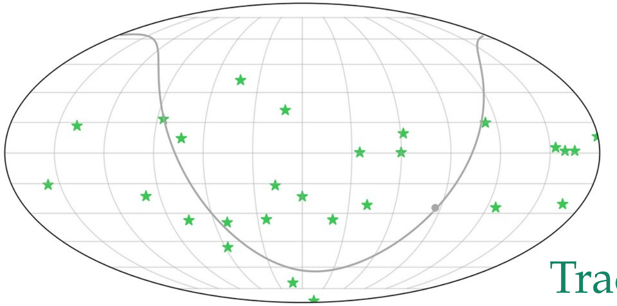
$\Delta\Phi^e = \Delta\Phi^\tau$



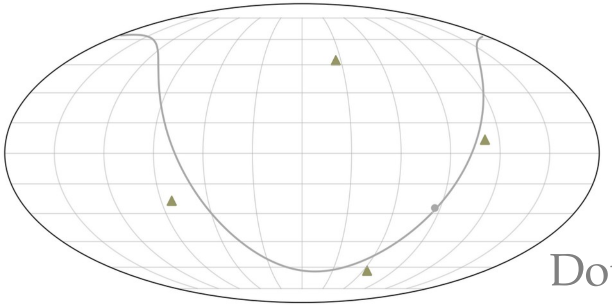
Undo Earth absorption & detector effects



Cascades



Tracks

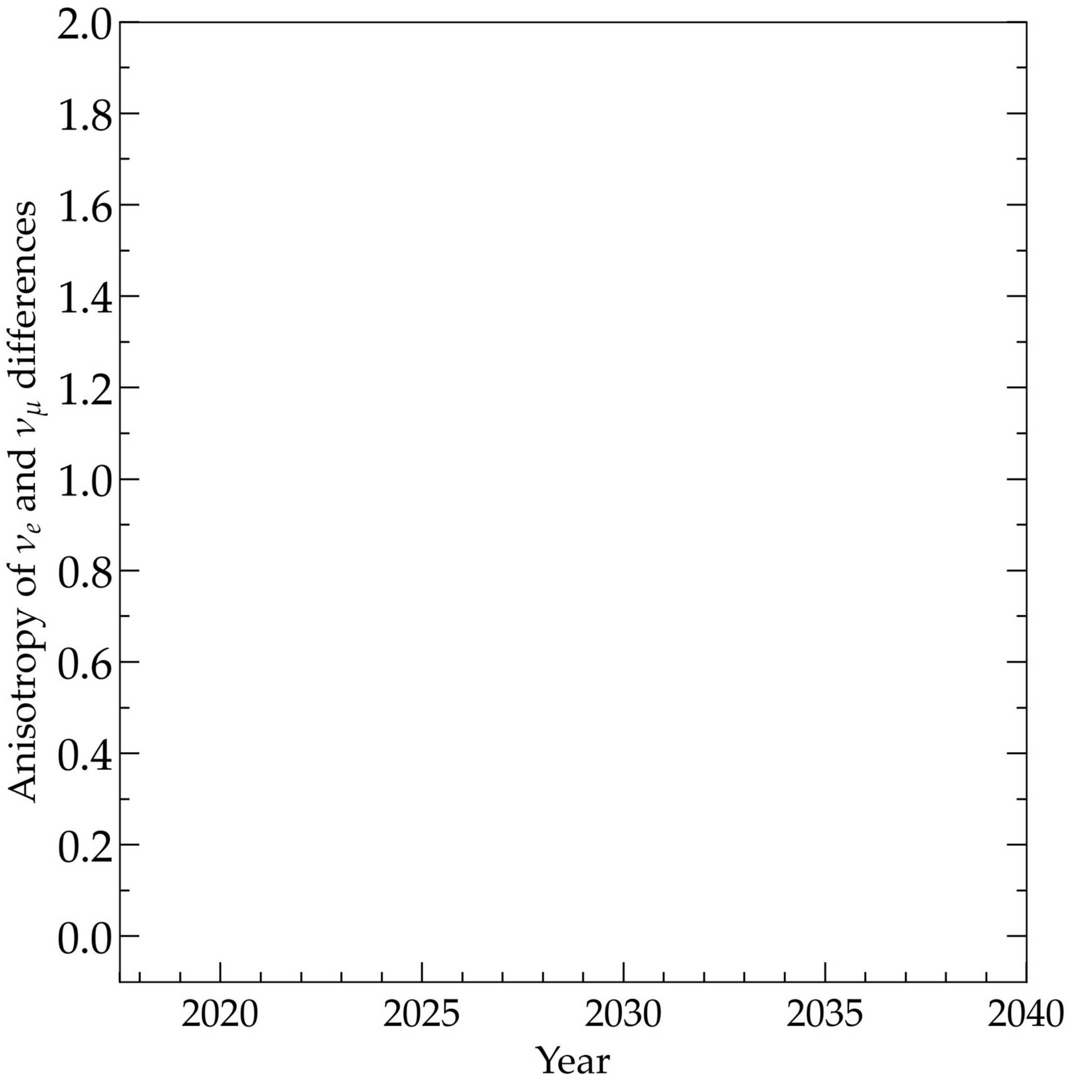


Double cascades

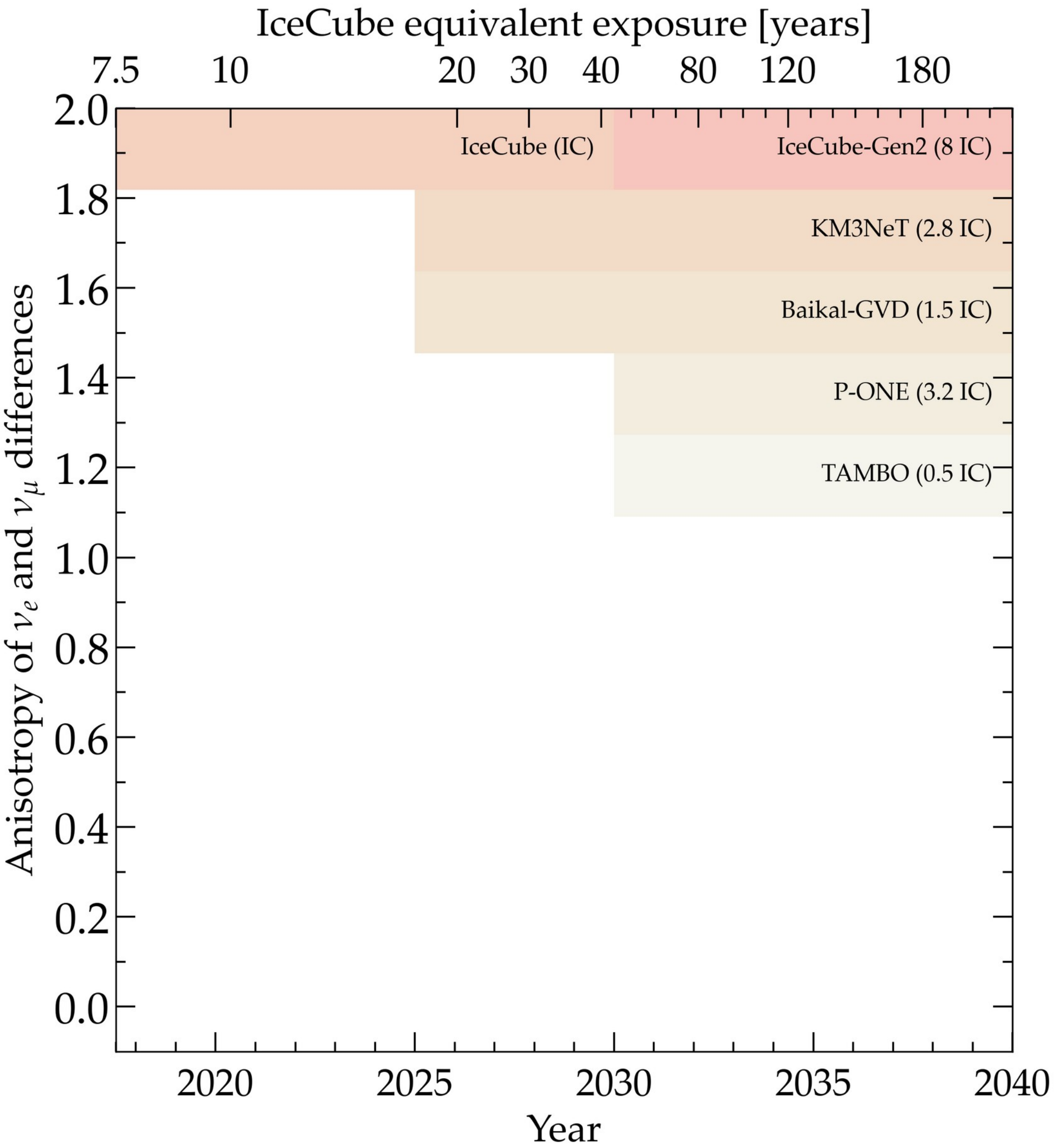
Telalovic & **MB**, *In prep.*

Spherical harmonics spectrum decomposition (à la CMB), up to dipole (l = 1):

$$C_1 = \frac{1}{2} \sum_m^{-1,0,1} |a_{1m}|^2$$

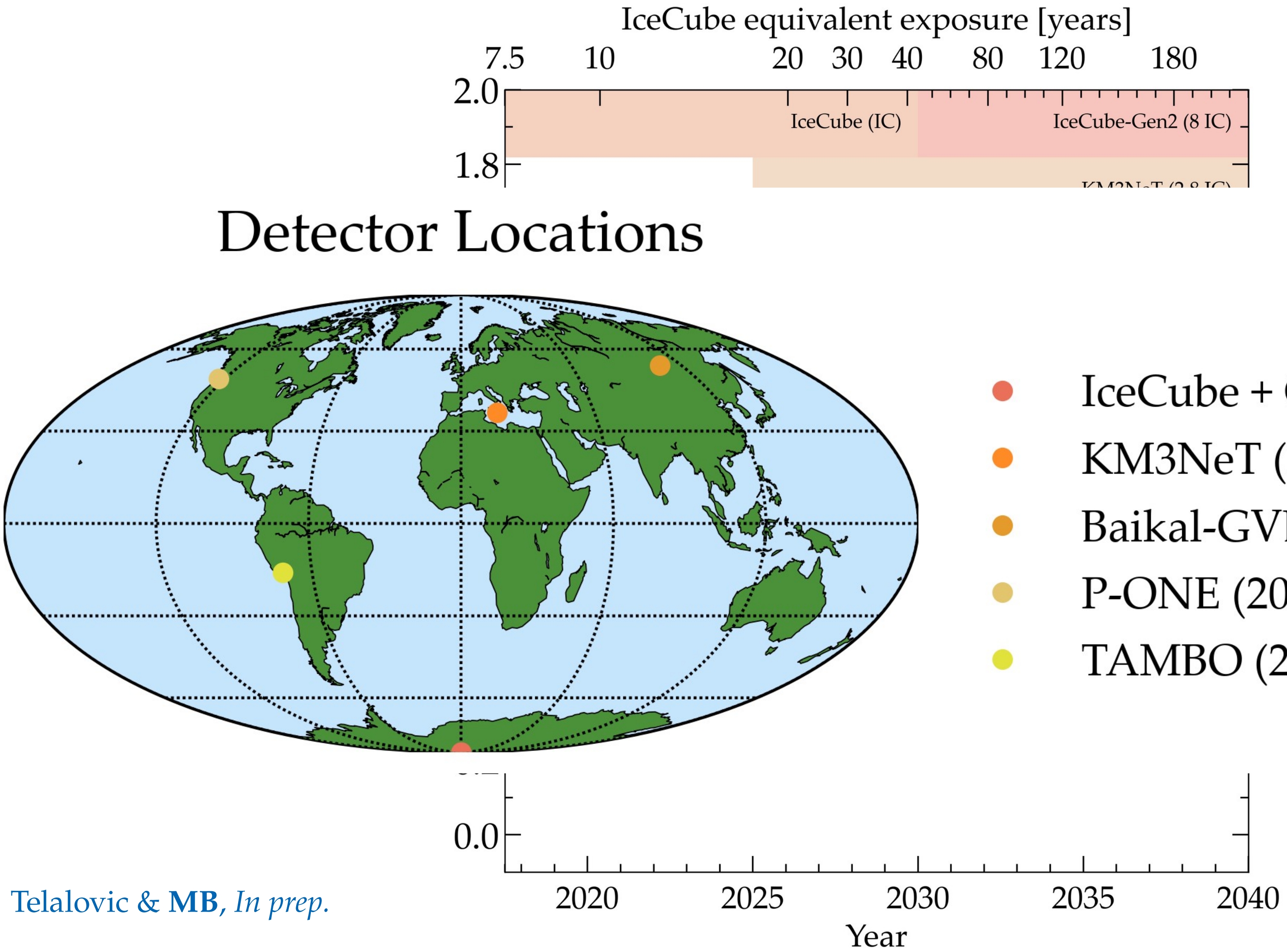


Telalovic & **MB**, *In prep.*

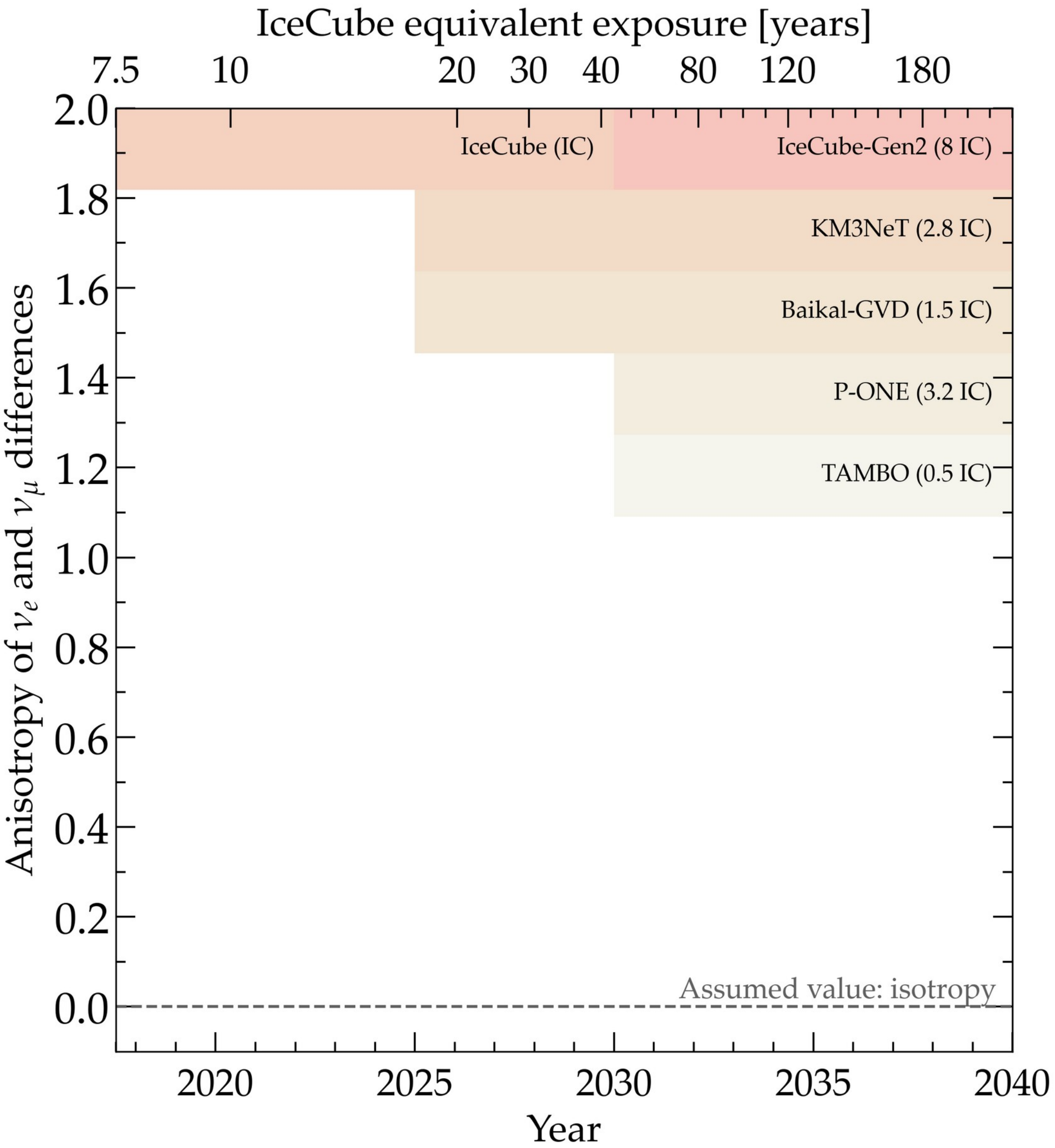


Telalovic & **MB**, *In prep.*

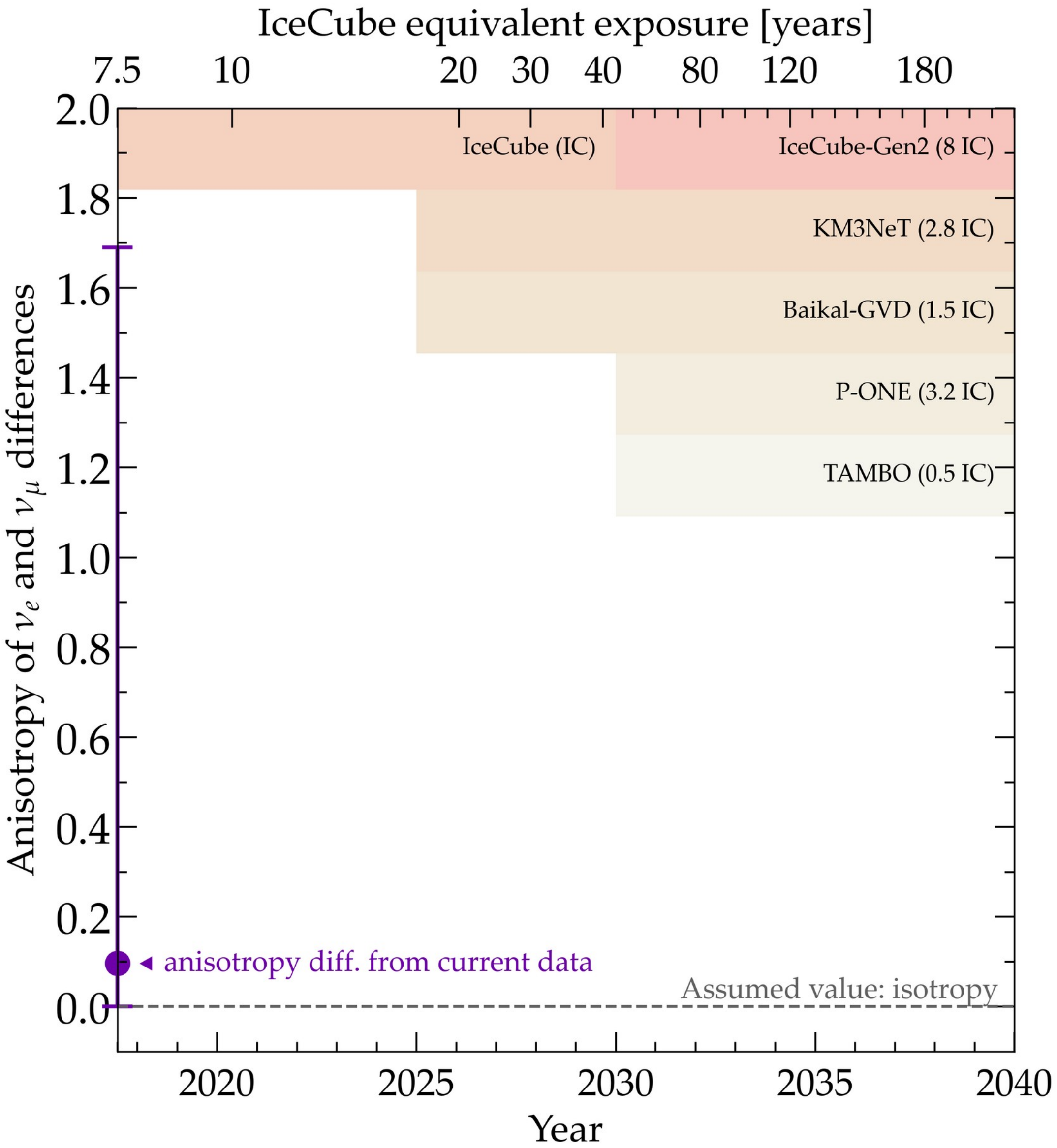
Detector Locations



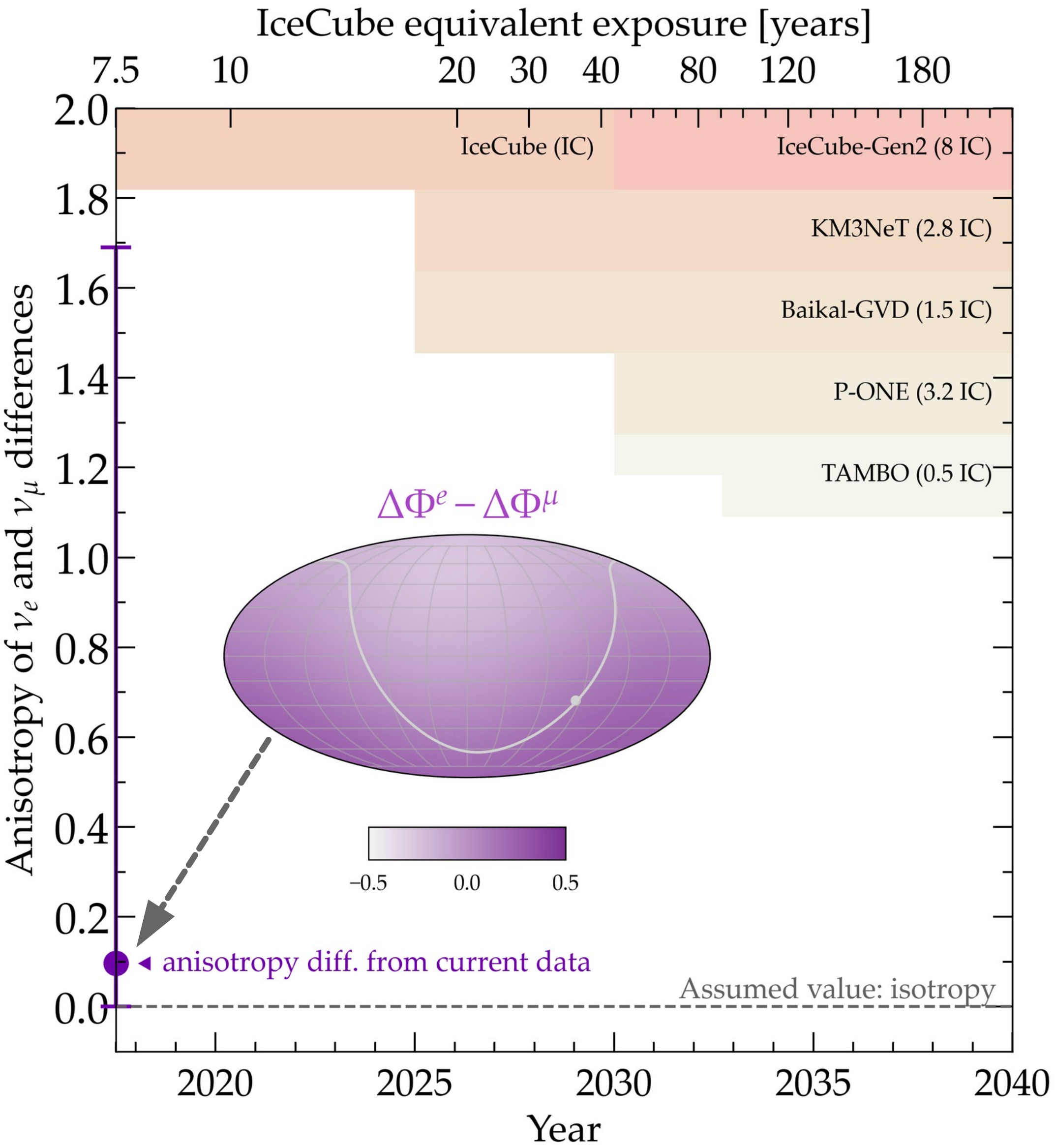
Telalovic & **MB**, *In prep.*



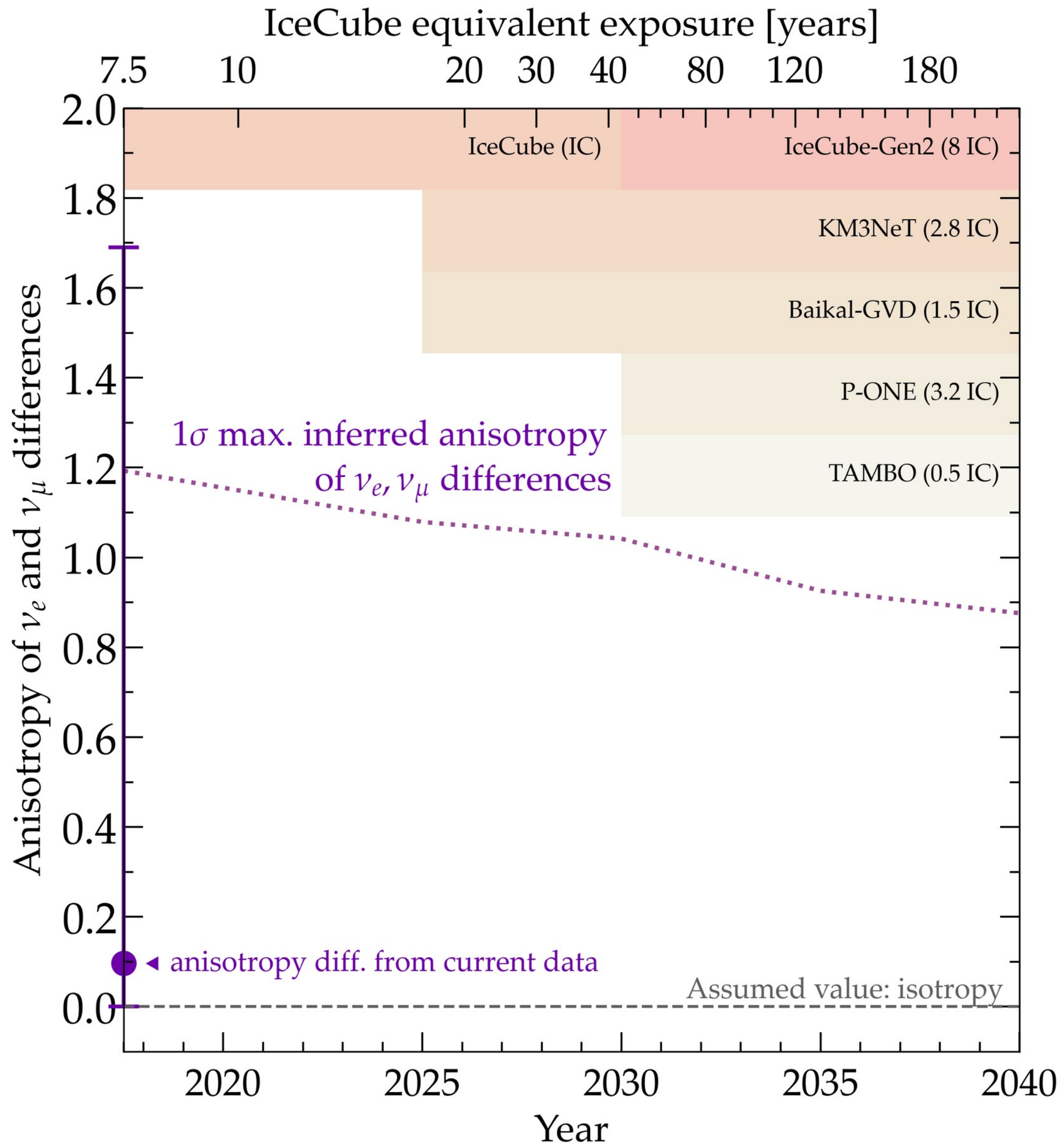
Telalovic & **MB**, *In prep.*



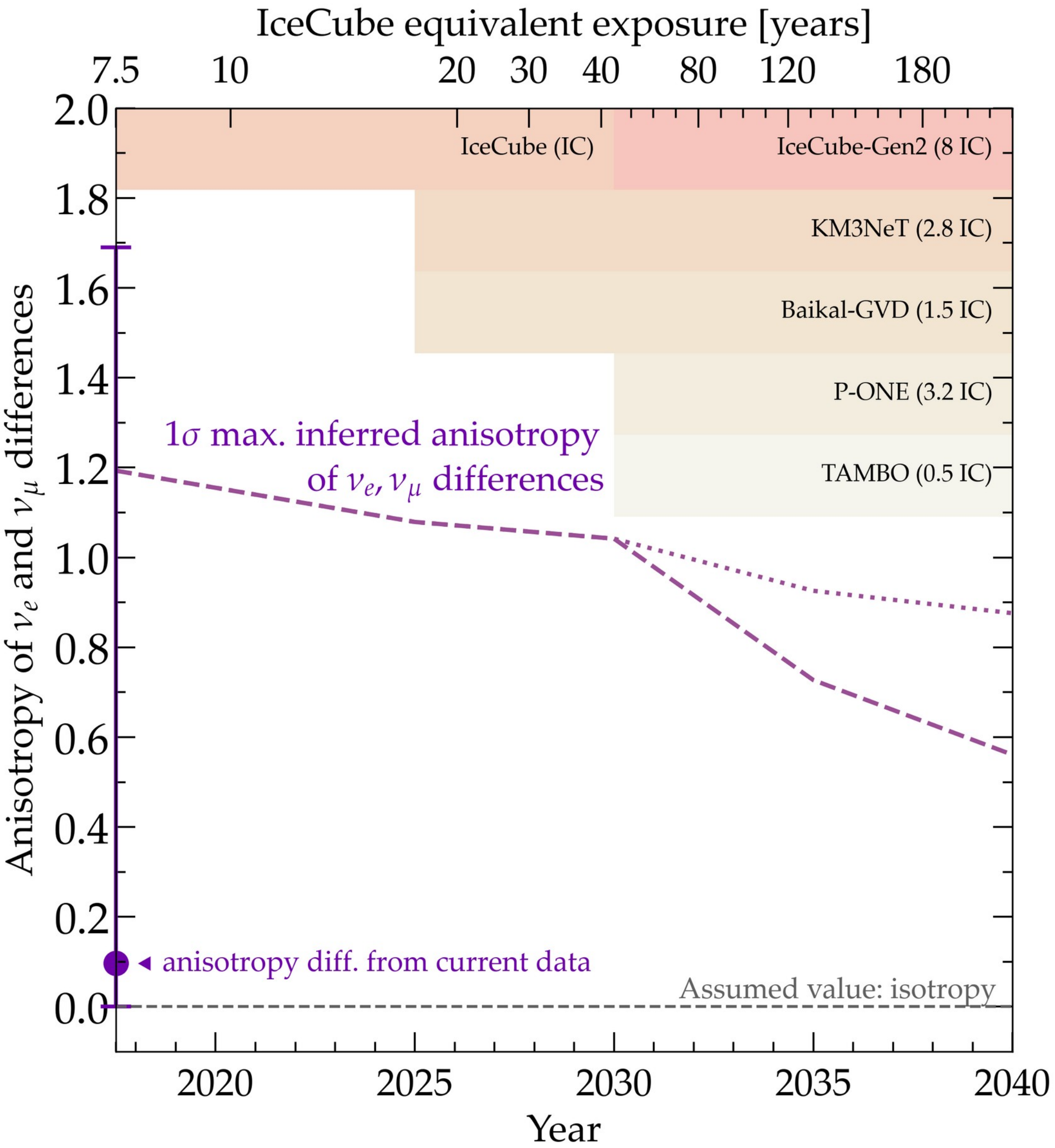
Telalovic & **MB**, *In prep.*



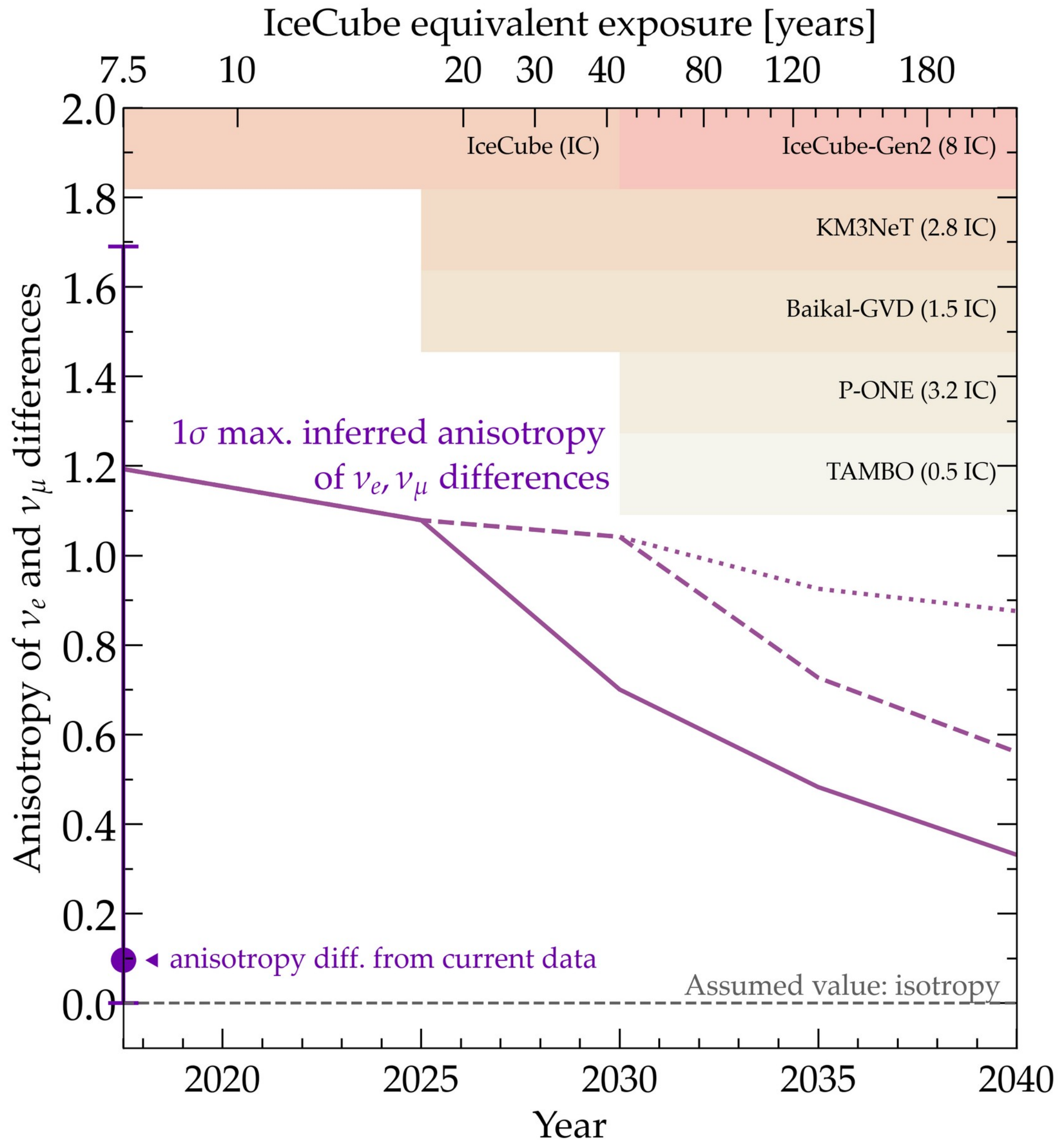
Telalovic & **MB**, *In prep.*



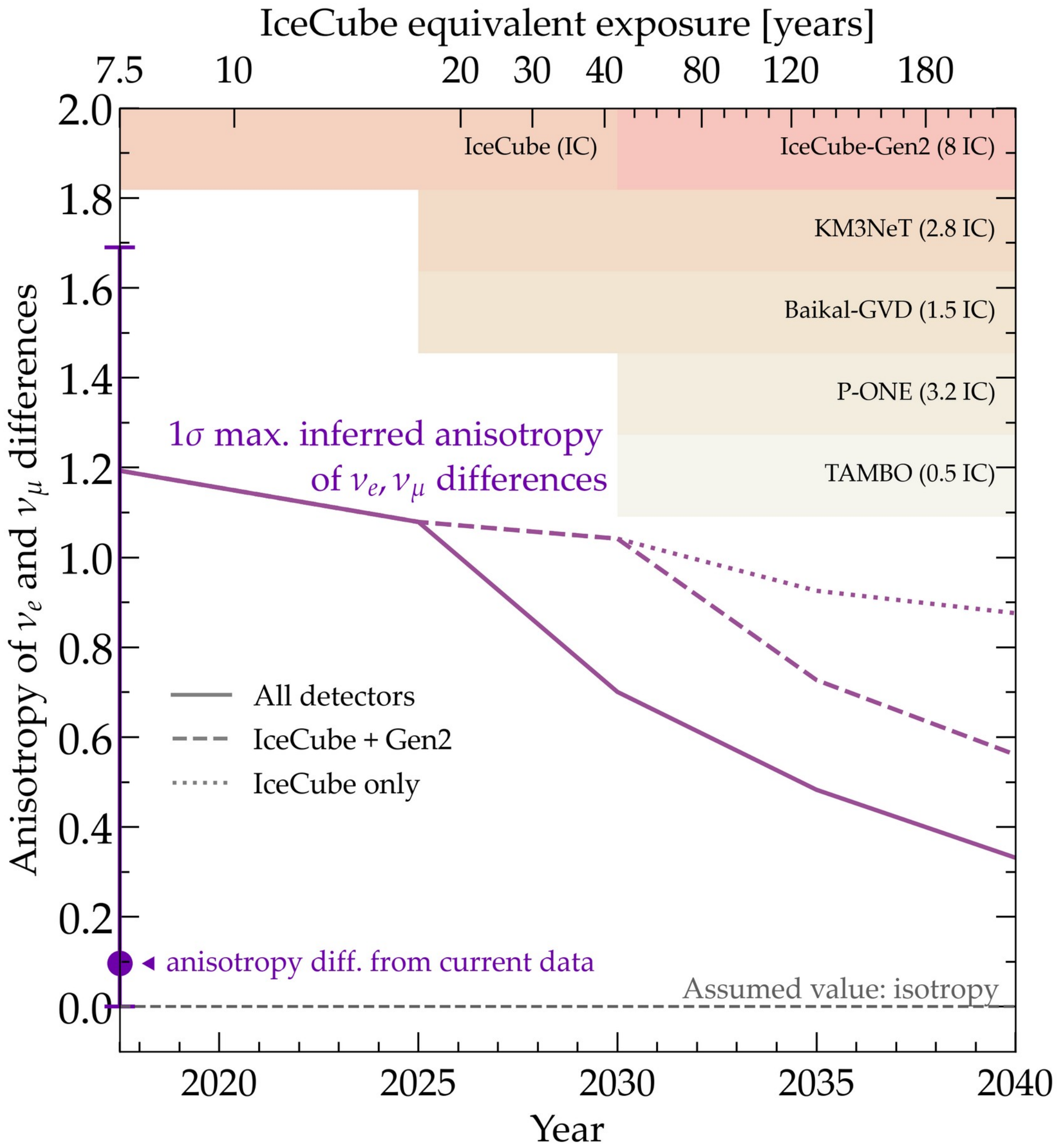
Telalovic & **MB**, *In prep.*



Telalovic & **MB**, *In prep.*



Telalovic & **MB**, *In prep.*



Telalovic & **MB**, *In prep.*

What's next?

Will likely happen: Larger detectors, higher energies

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

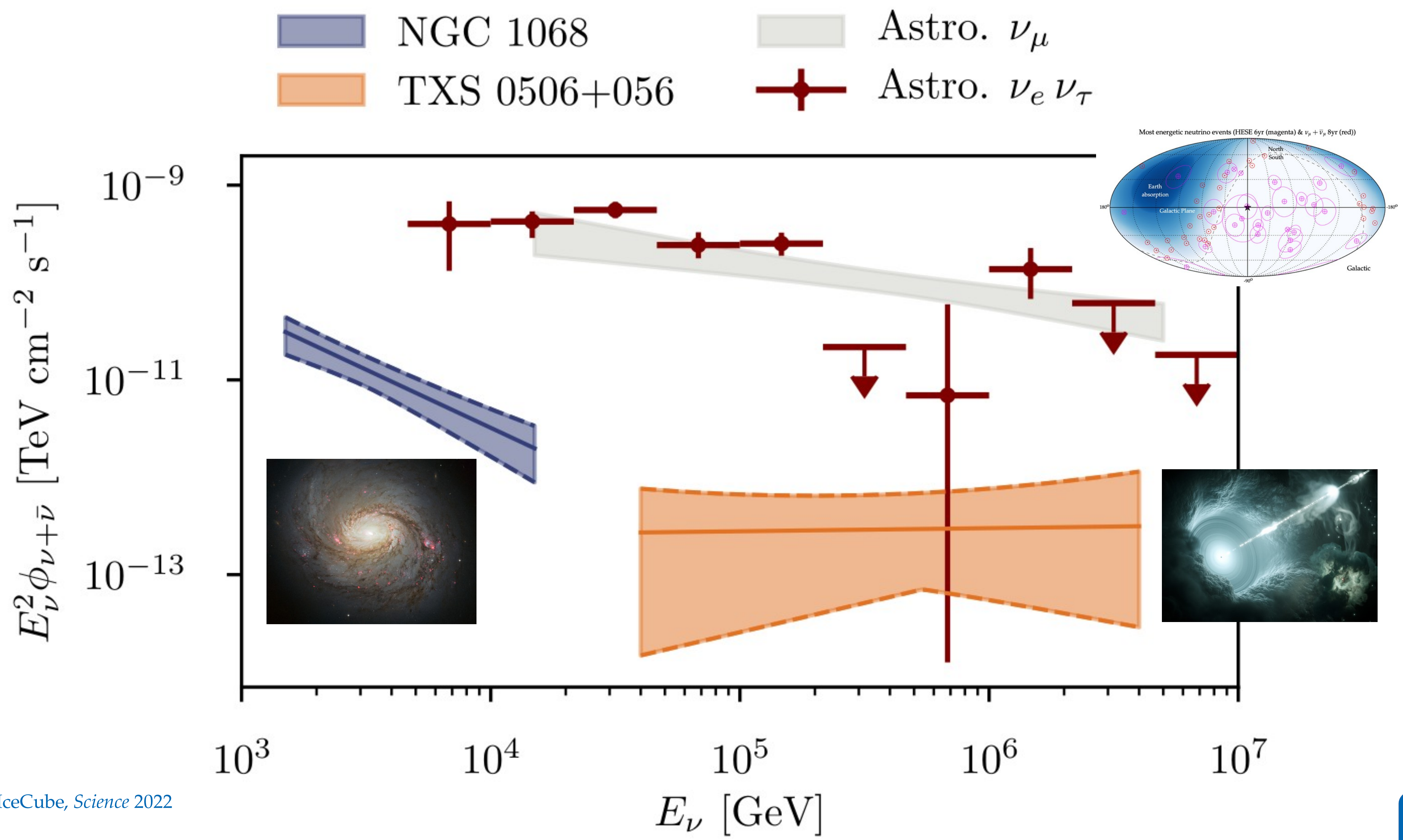
				Flavor		Technique			Neutrino Target					Geometry					
Experiments	Phase & Online Date	Energy Range	Site	Tau	All Flavor	Optical / UV	Radio	Showers	H_2O	Atmosphere	Earth's limb	Topography	Lunar Regolith	Embedded	Planar Arrays	Valley	Mountains	Balloon	Satellite
IceCube	2010	TeV-EeV	South Pole		✓	✓			✓					✓					
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]

Will likely happen: Larger detectors, higher energies

Is happening: Using many neutrino sources *vs*. one source



IceCube, *Science* 2022

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Must happen: Astrophysical unknowns <u>cannot</u> be ignored

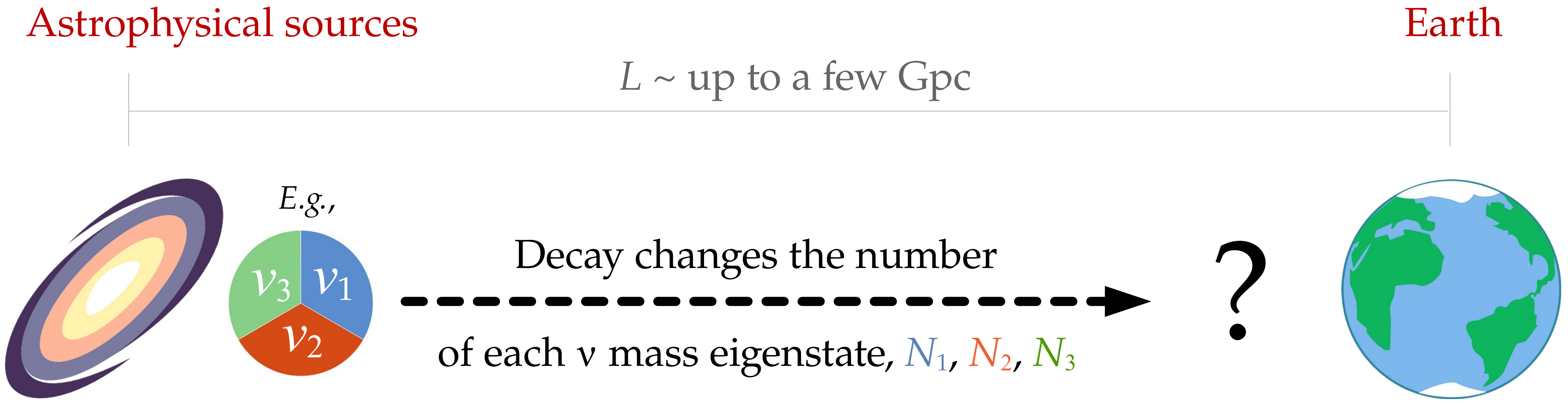
Will likely happen: Larger detectors, higher energies

Is happening: Using many neutrino sources *vs*. one source

Must happen: Astrophysical unknowns <u>cannot</u> be ignored

Example: neutrino decay ▶

See also (pseudo-Dirac ν): Rink & Sen 2211.16520, Carloni *et al.* 2212.00737



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

?

Only sensitive to their ratio

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

Mass of ν_i Lifetime of ν_i

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

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?

Lower-E ν are longer-lived…

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

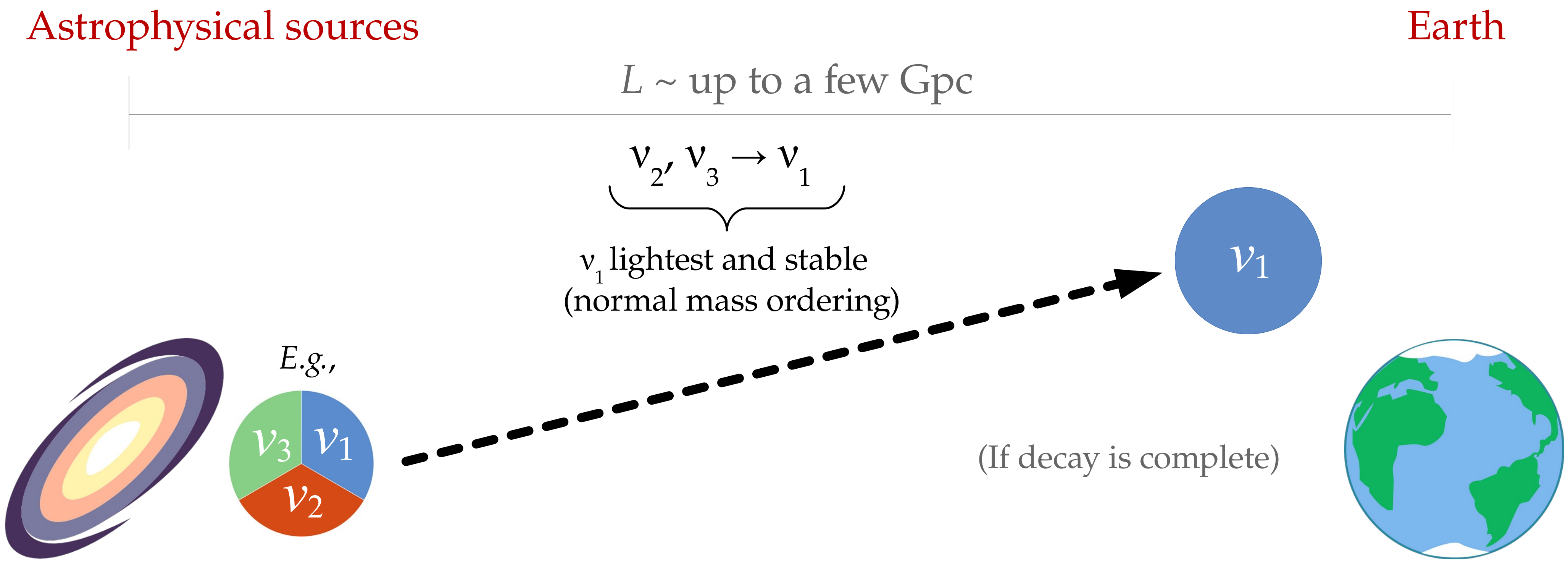
… but ν that travel longer L are more attenuated!

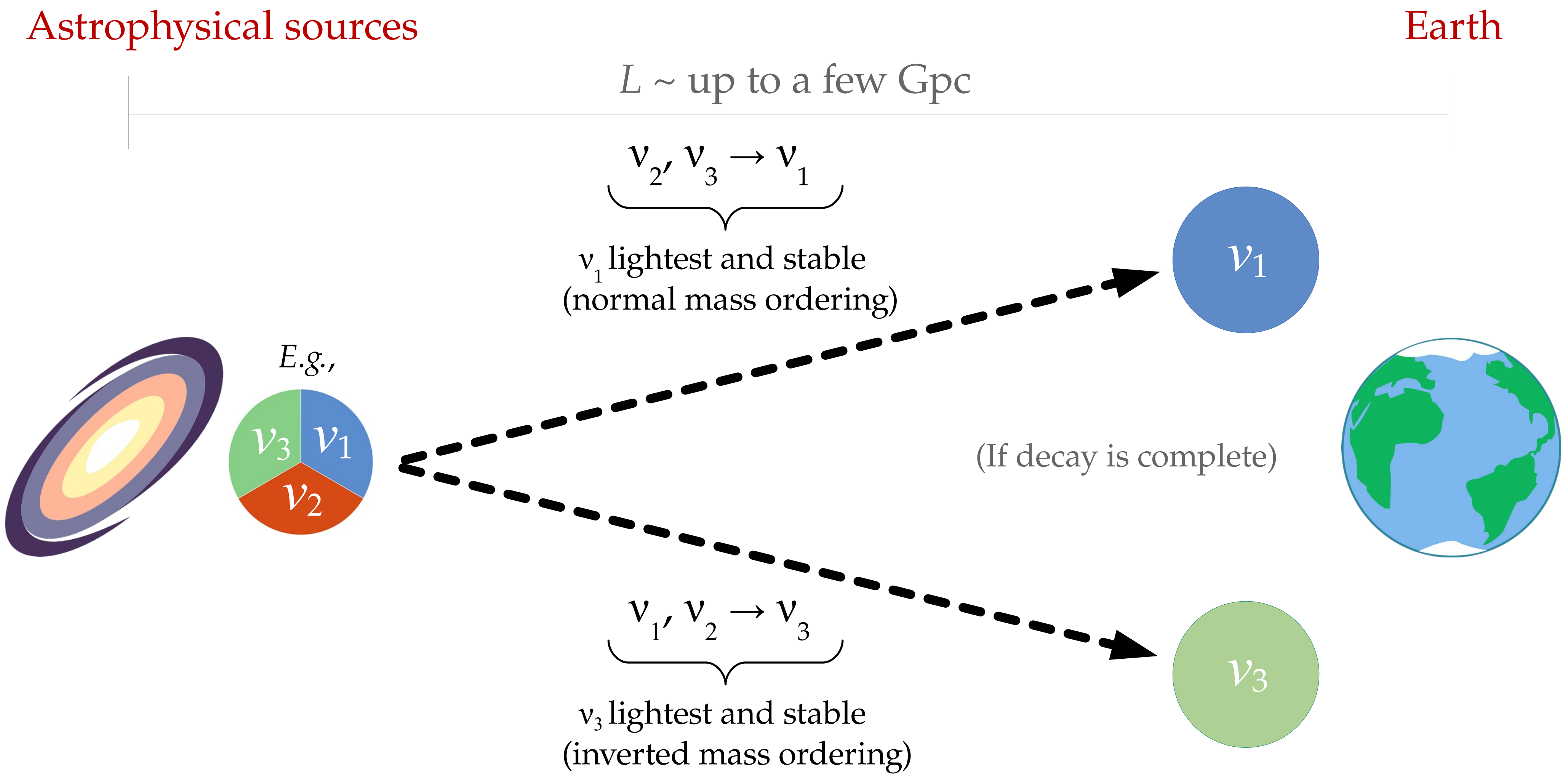
Astrophysical sources

Earth

L ~ up to a few Gpc

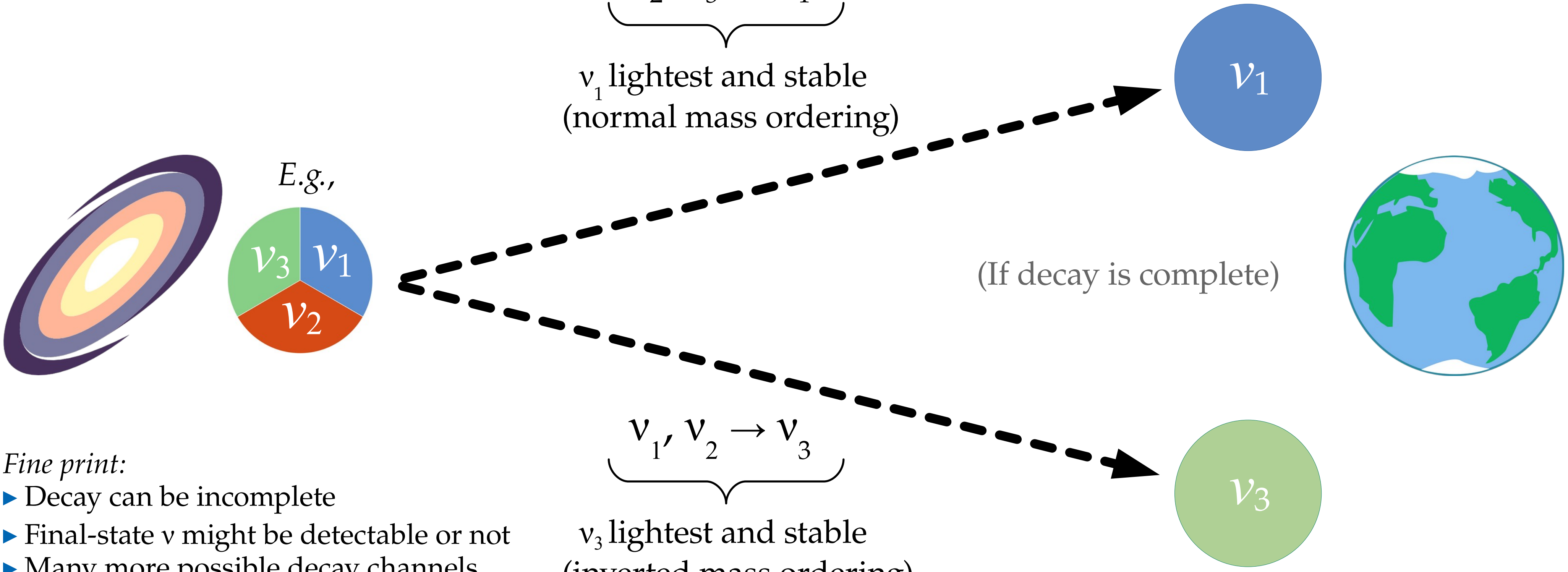
E.g.,


Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \to \nu_1$
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
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

Astrophysical sources — Earth

L ~ up to a few Gpc

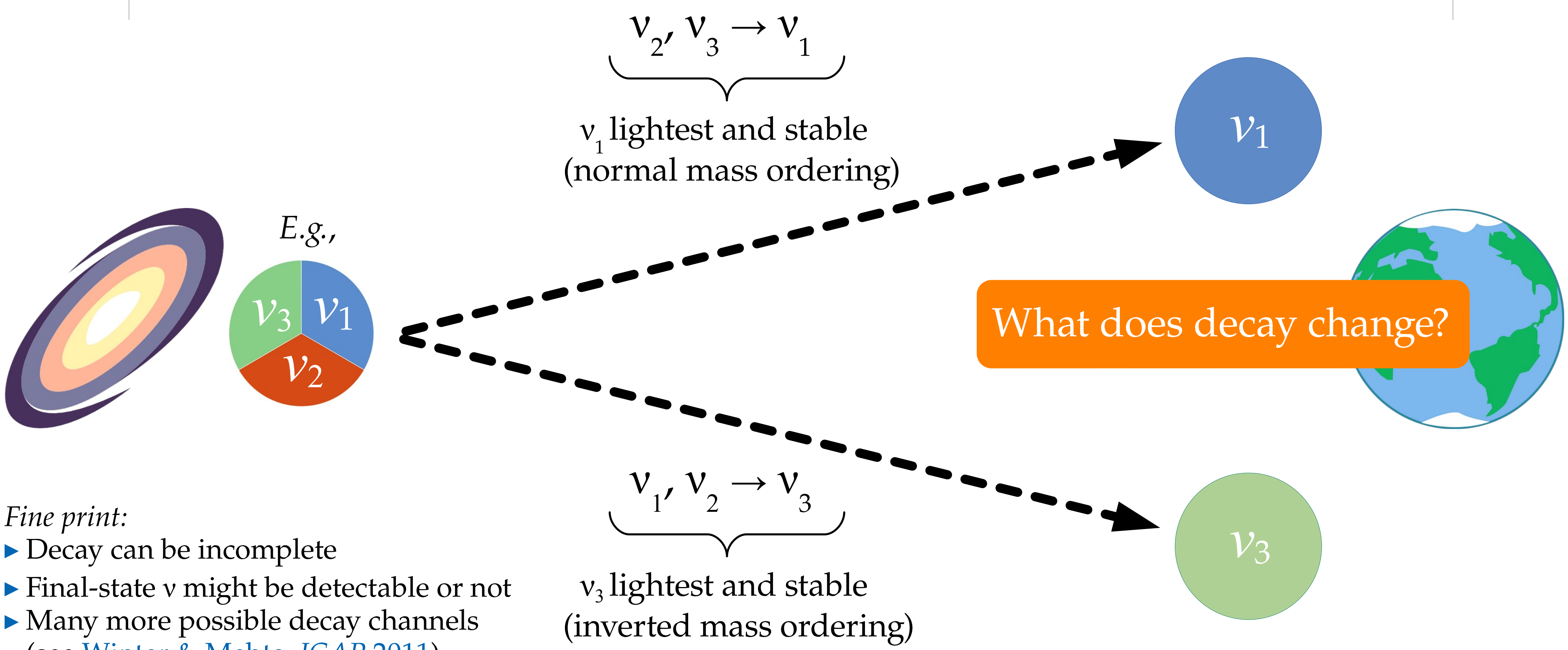


Fine print:

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

Astrophysical sources — Earth

L ~ up to a few Gpc



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What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

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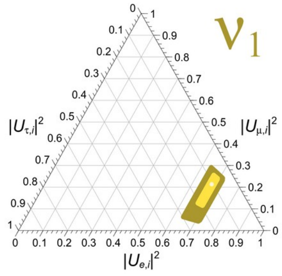
Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,

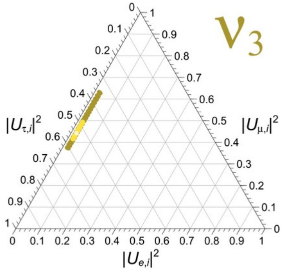
$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable
(normal mass ordering)



$\nu_1, \nu_2 \to \nu_3$

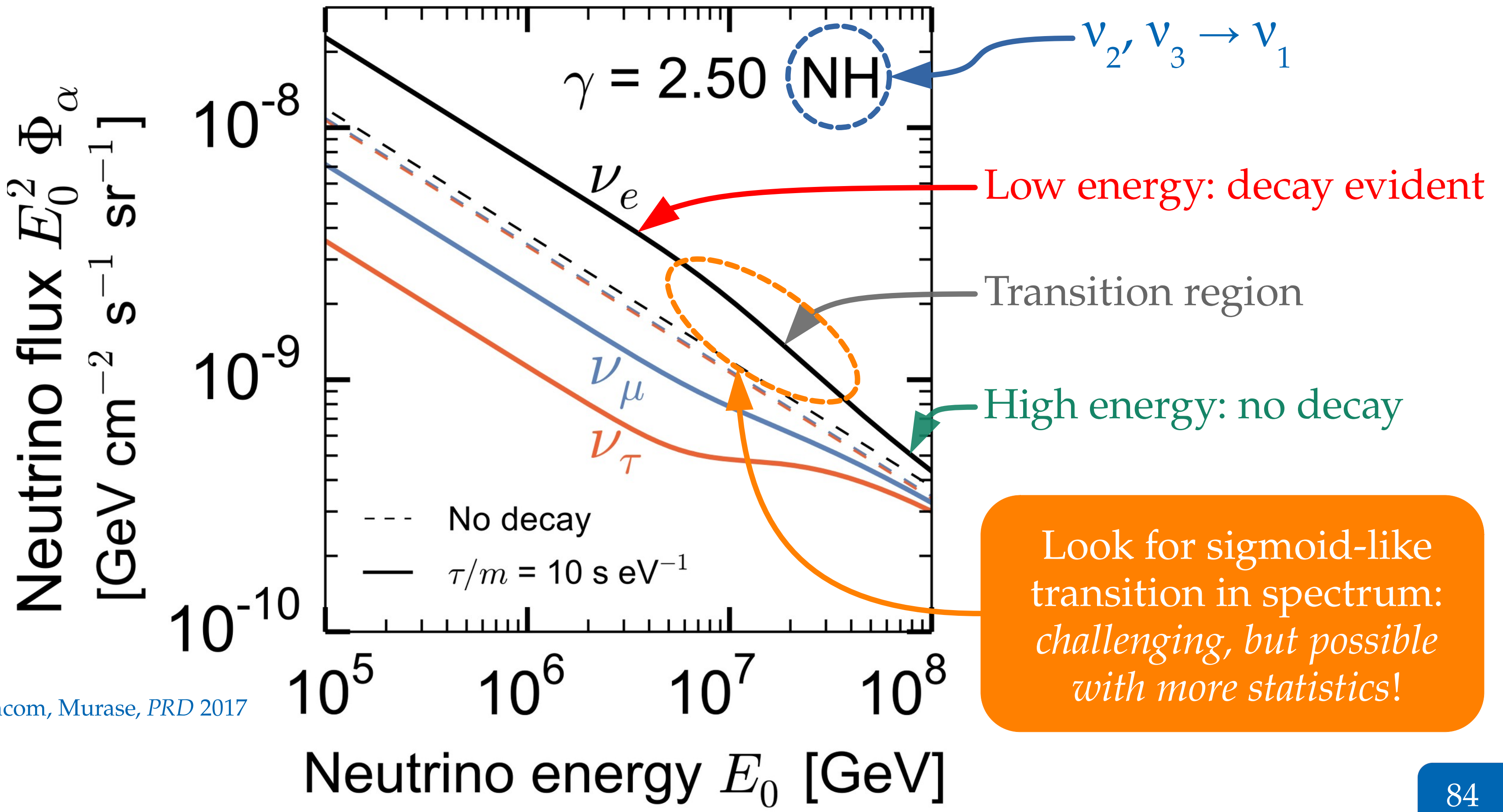
ν_3 lightest and stable
(inverted mass ordering)



What does neutrino decay change?

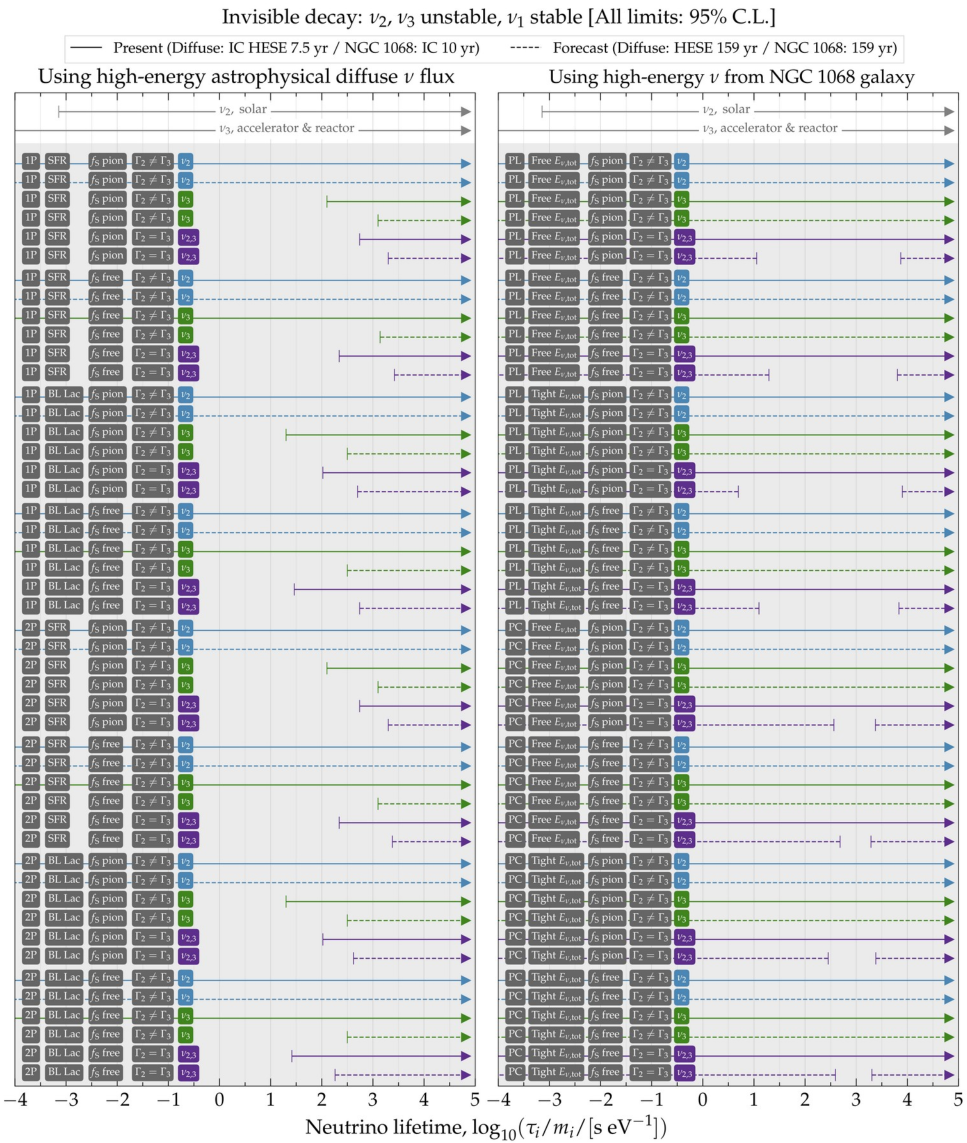
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ **Spectrum shape** ⟺ Event rate

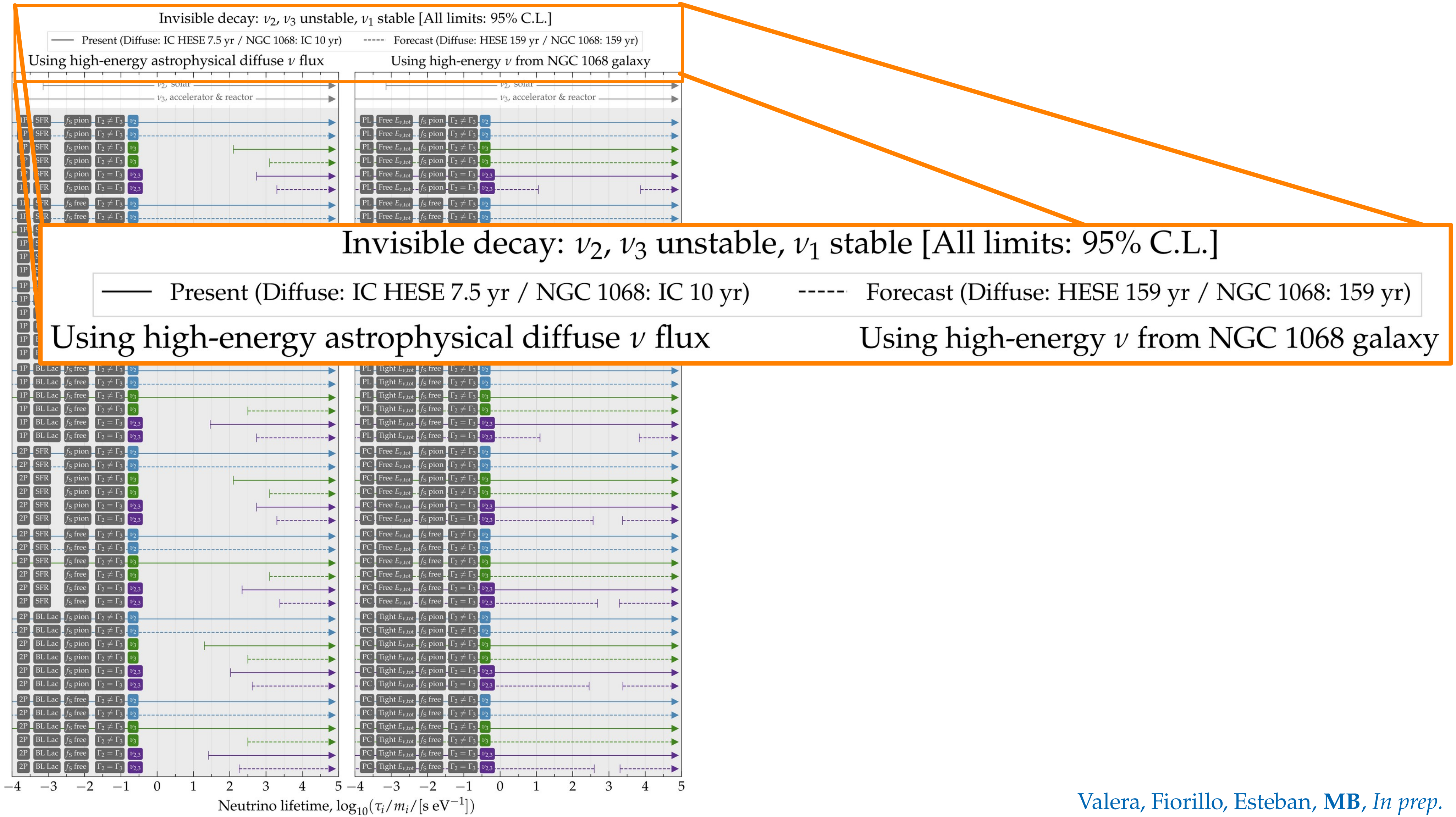


MB, Beacom, Murase, *PRD* 2017

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



Valera, Fiorillo, Esteban, **MB**, *In prep.*



Valera, Fiorillo, Esteban, **MB**, *In prep.*

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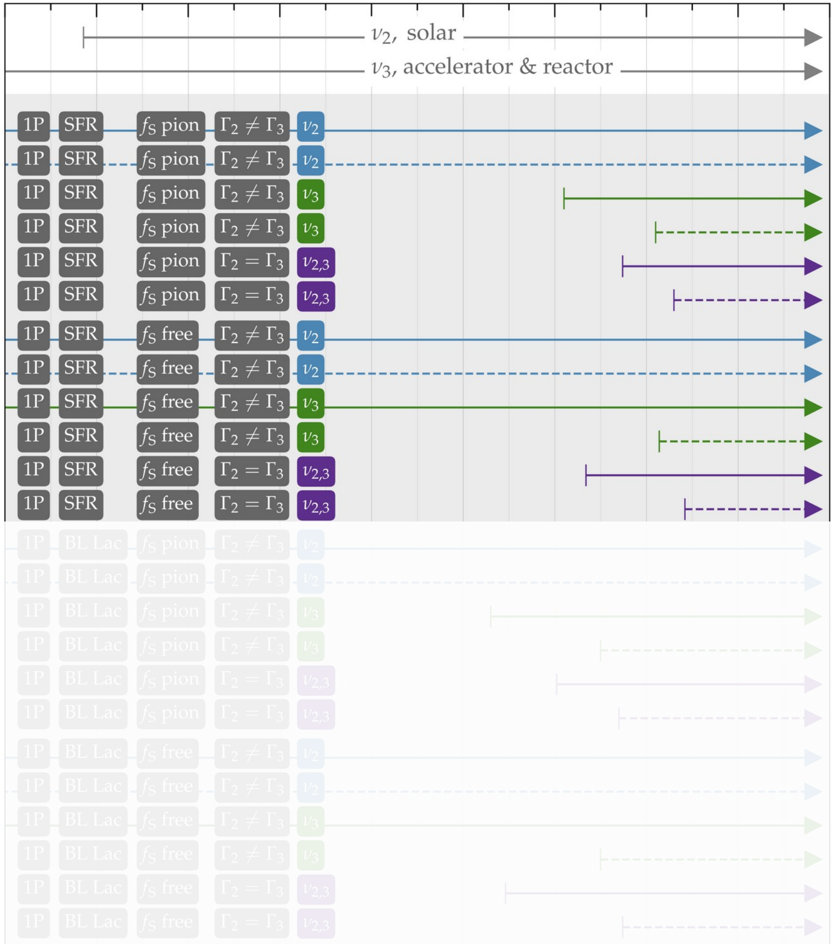
Using high-energy astrophysical diffuse ν flux

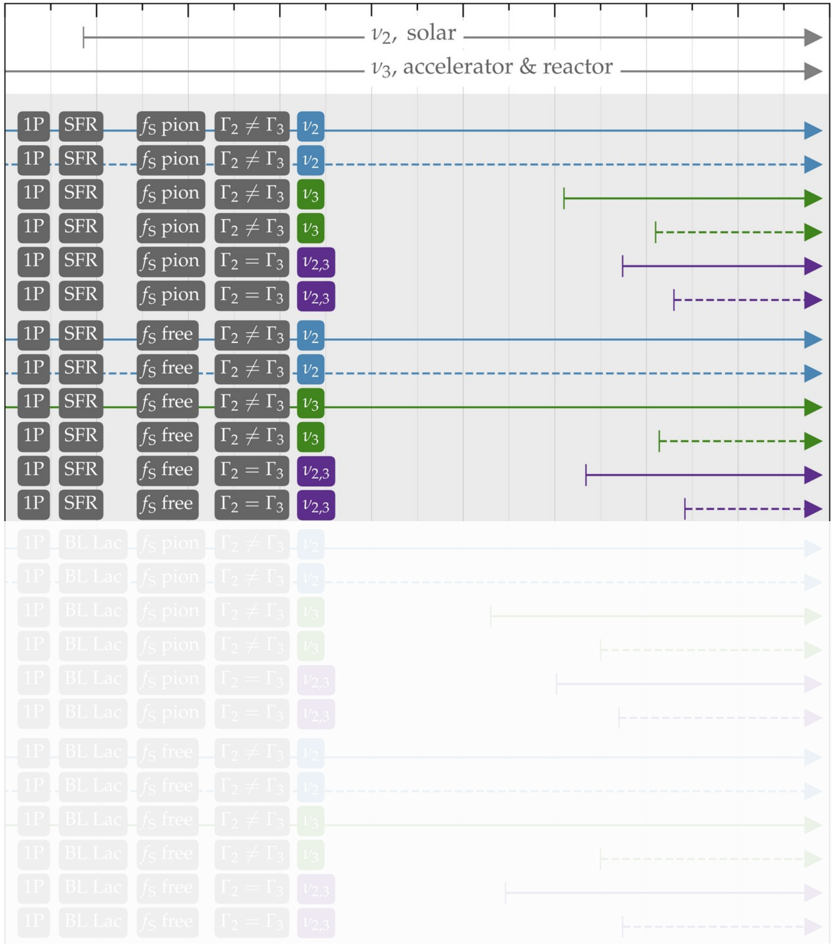


Valera, Fiorillo, Esteban, **MB**, *In prep.*

Assuming that the flavor composition at the sources *is known*

***Not** assuming it is known*

Using high-energy astrophysical diffuse ν flux



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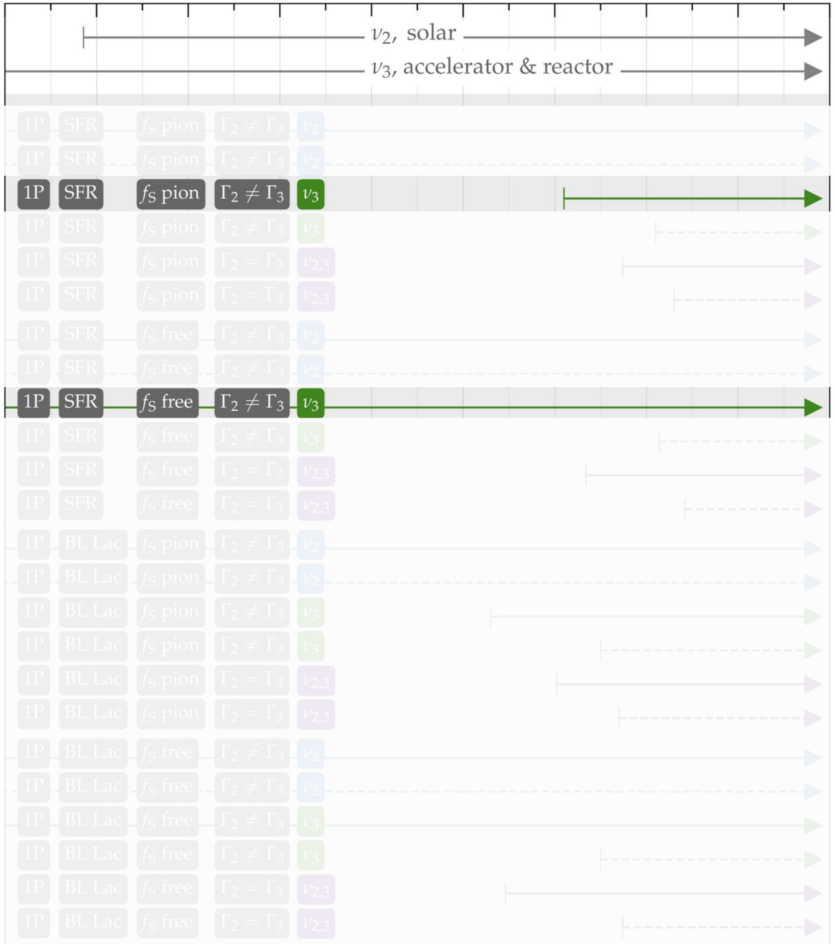

Valera, Fiorillo, Esteban, **MB**, *In prep.*

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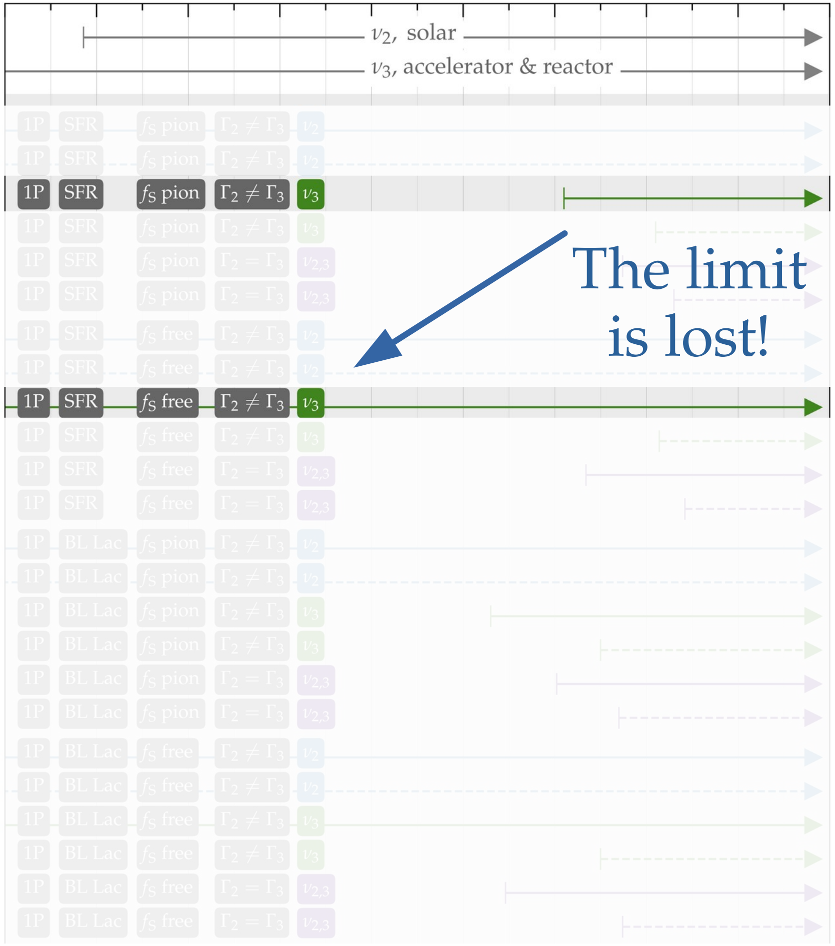
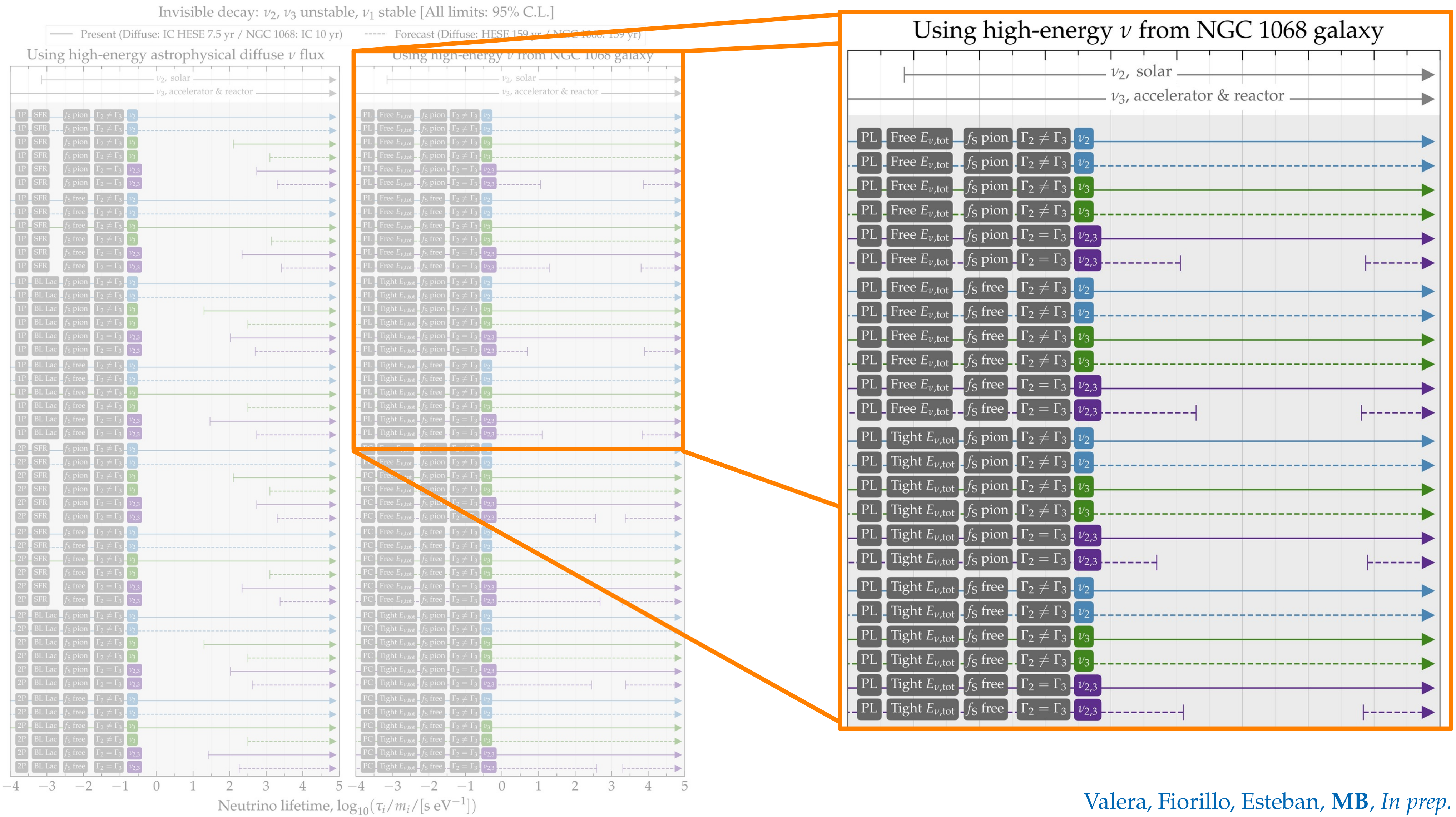


Valera, Fiorillo, Esteban, **MB**, *In prep.*



Valera, Fiorillo, Esteban, **MB**, *In prep.*

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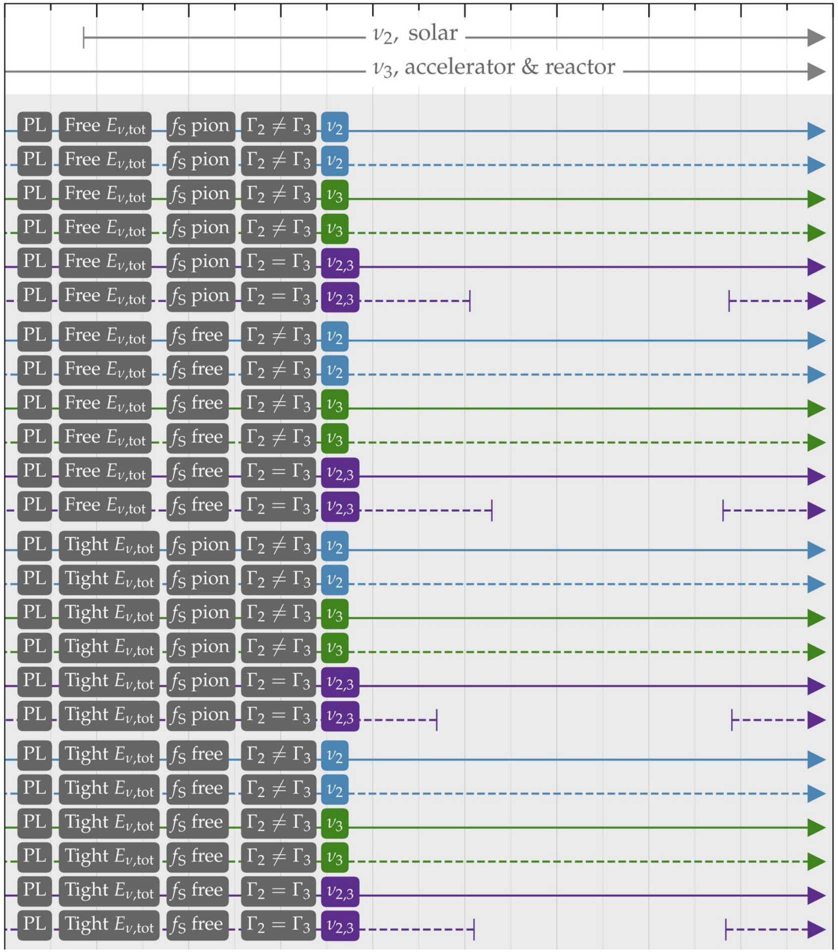
Using high-energy ν from NGC 1068 galaxy

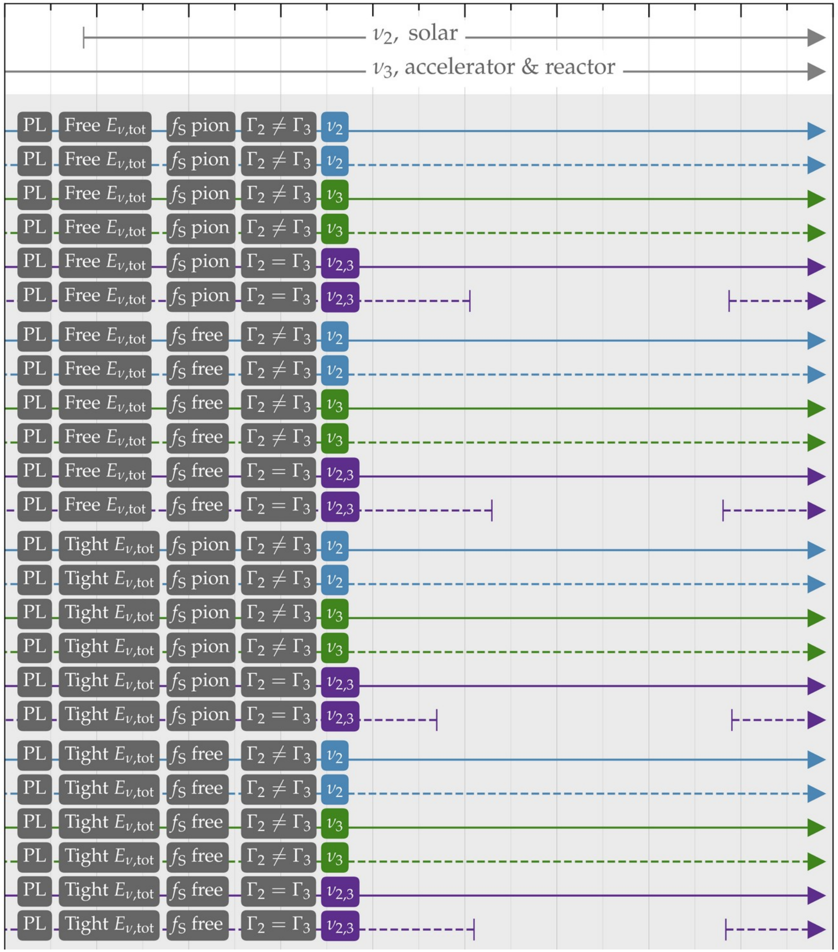


Valera, Fiorillo, Esteban, **MB**, *In prep.*

No prior on the energy emitted in neutrinos

Tight prior from X-ray observations

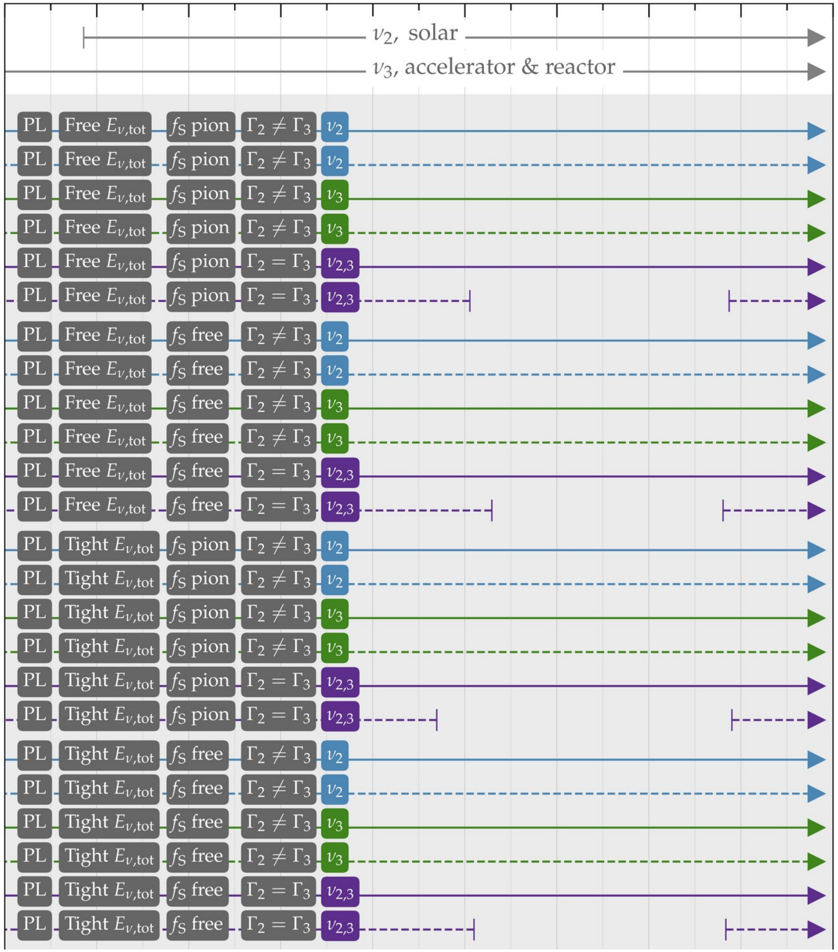
Using high-energy ν from NGC 1068 galaxy



Valera, Fiorillo, Esteban, **MB**, *In prep.*

No limits on neutrino lifetime from a point source if we acknowledge unknowns!

Using high-energy ν from NGC 1068 galaxy



Valera, Fiorillo, Esteban, **MB**, *In prep.*

When you have eliminated all which is impossible then whatever remains, however improbable, must be the truth.

—Sherlock Holmes
(*The Case-Book of Sherlock Holmes*, Arthur Conan Doyle)

Standard Model explanations

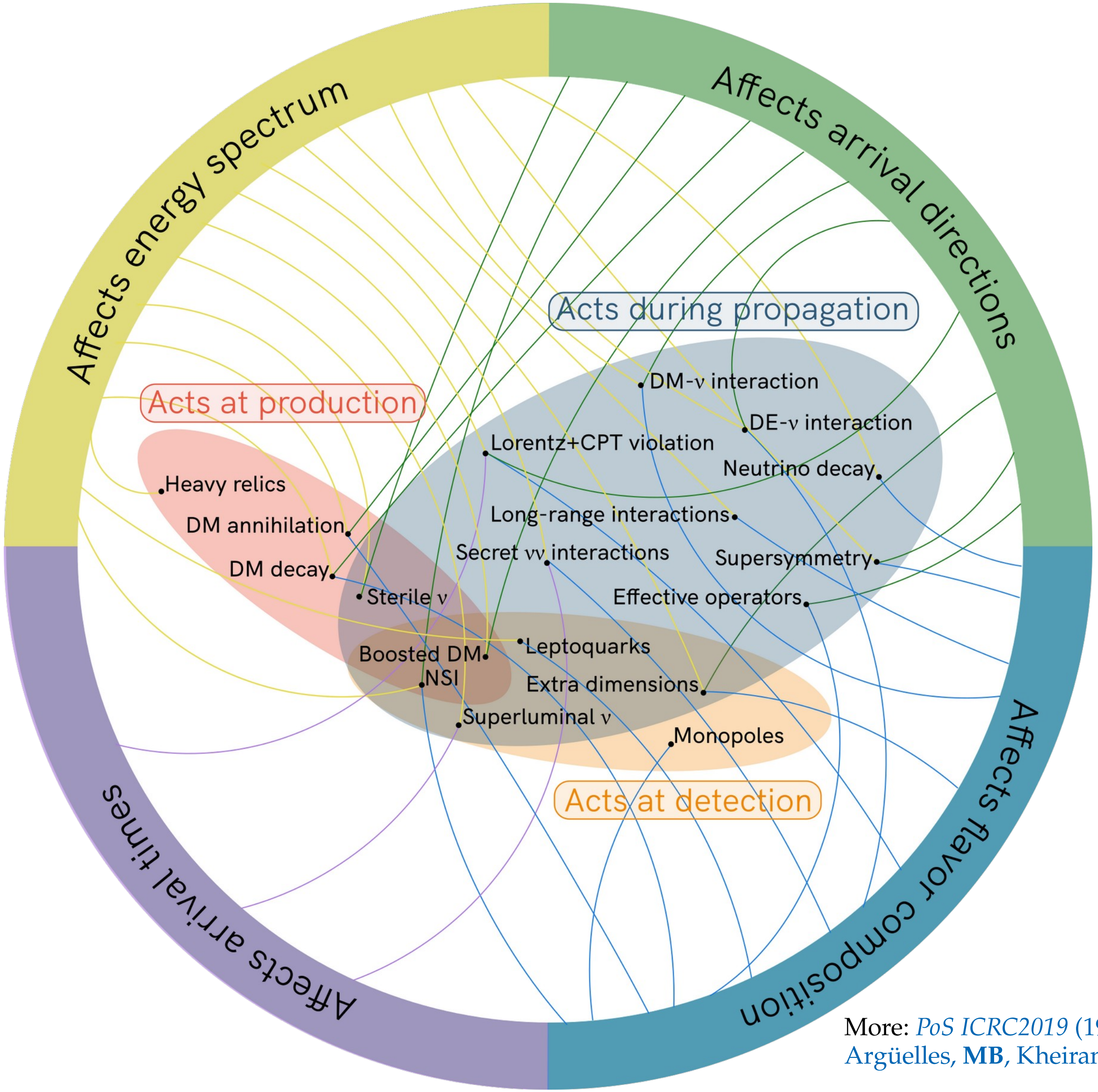
When you have eliminated all ~~which is impossible~~

then whatever remains, however improbable,

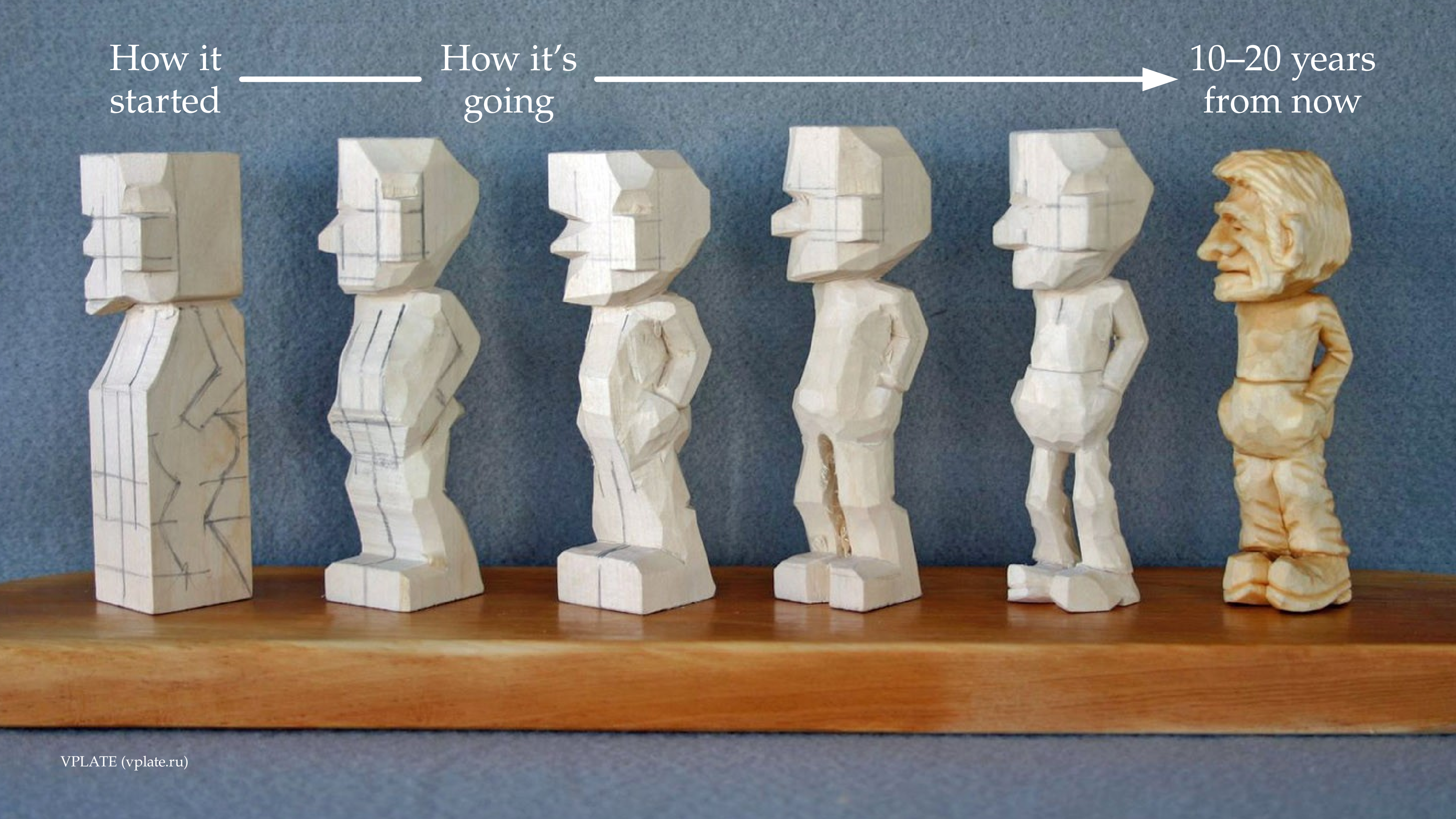
must be ~~the truth~~.

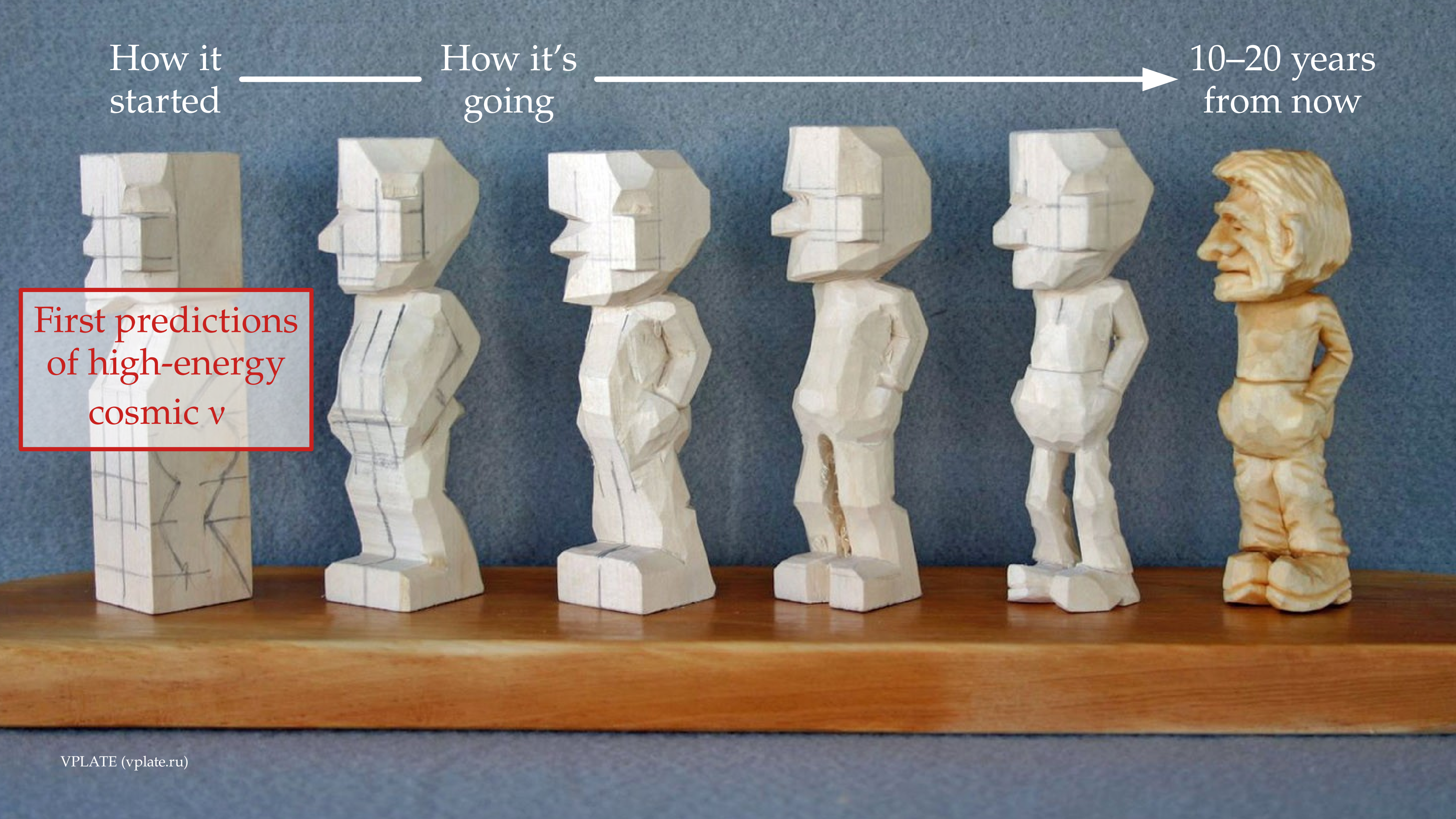
new Physics

—Sherlock Holmes
(*The Case-Book of Sherlock Holmes*, Arthur Conan Doyle)



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


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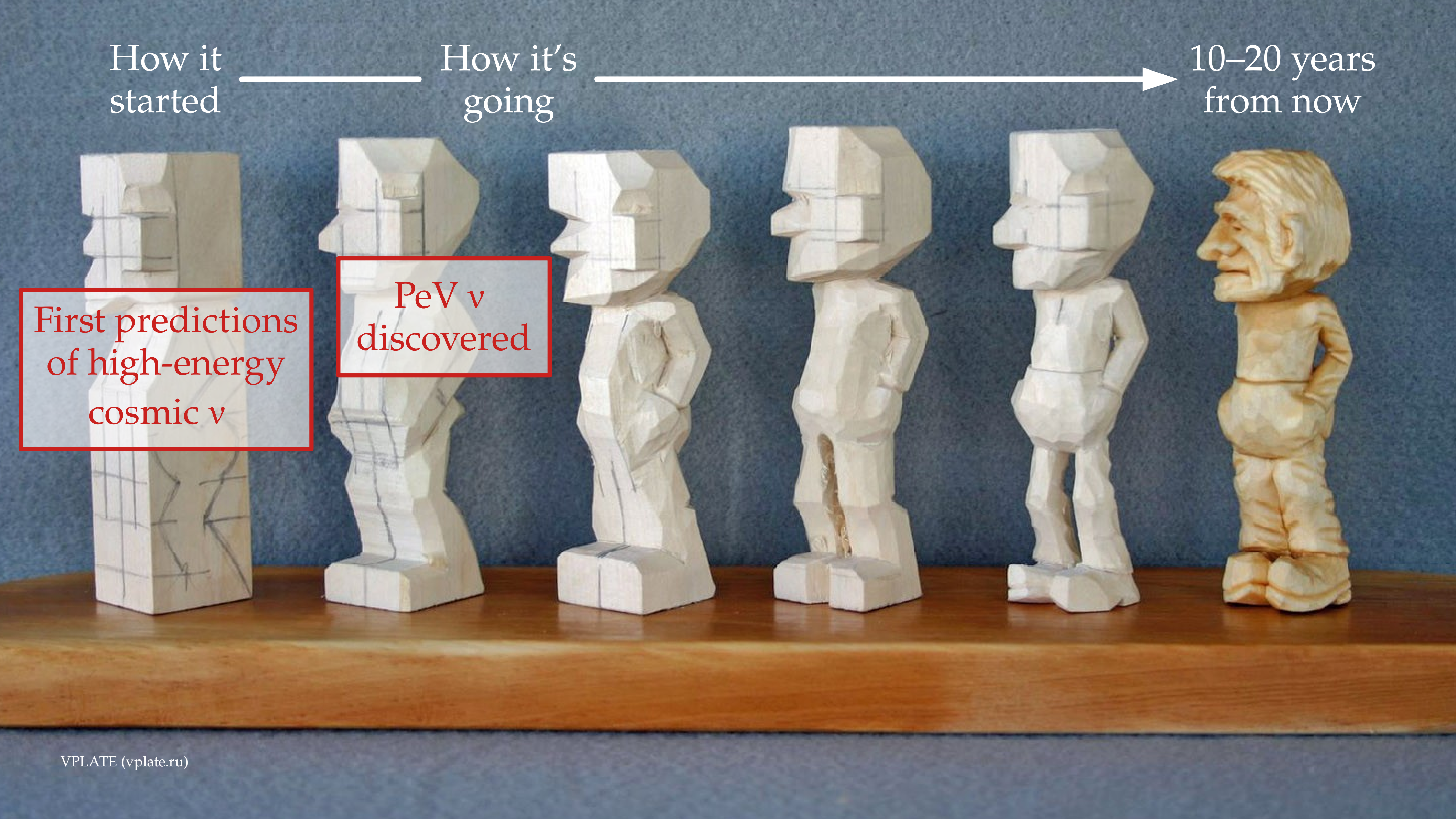
First predictions of high-energy cosmic ν
VPLATE (vplate.ru)



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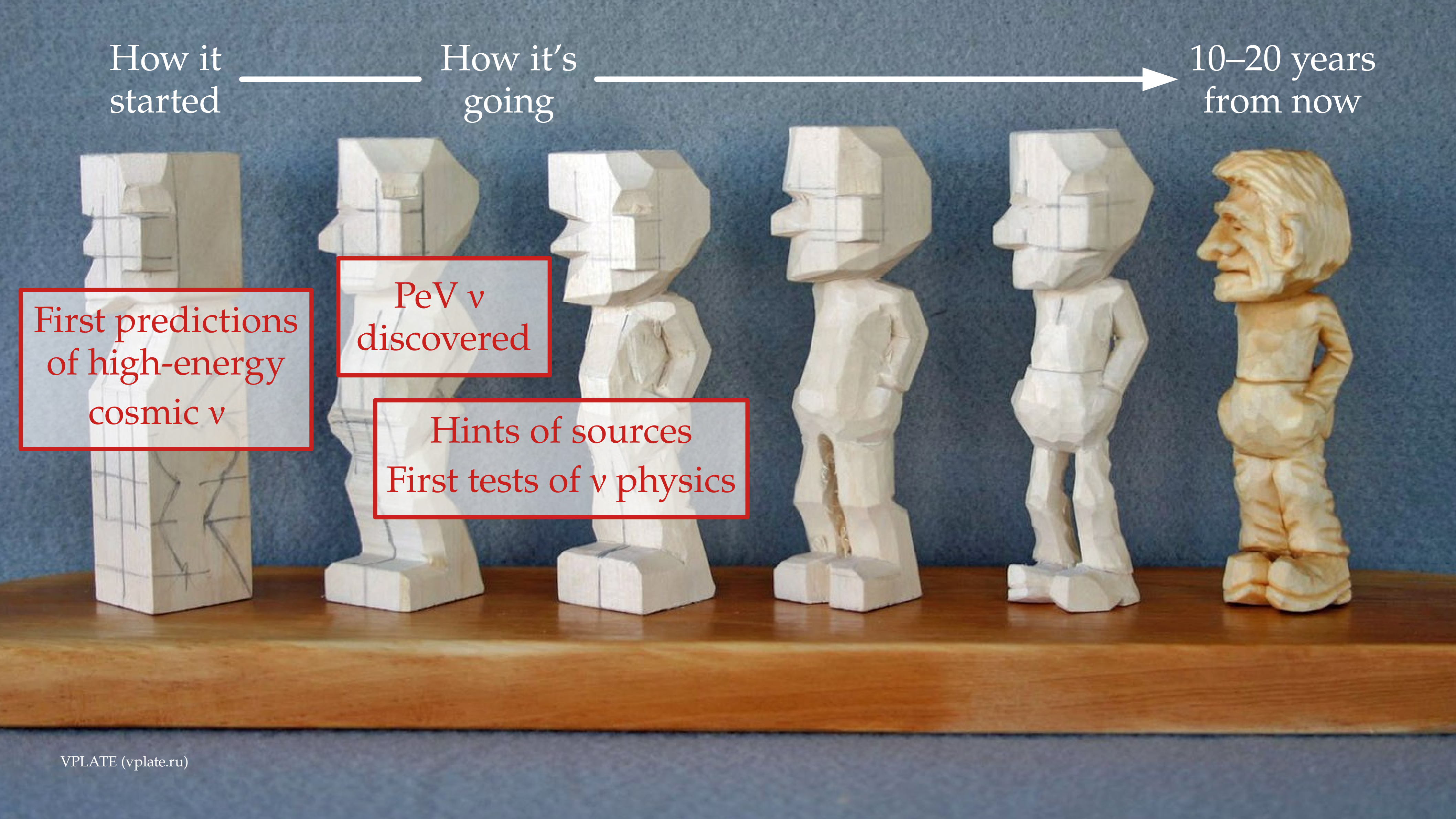
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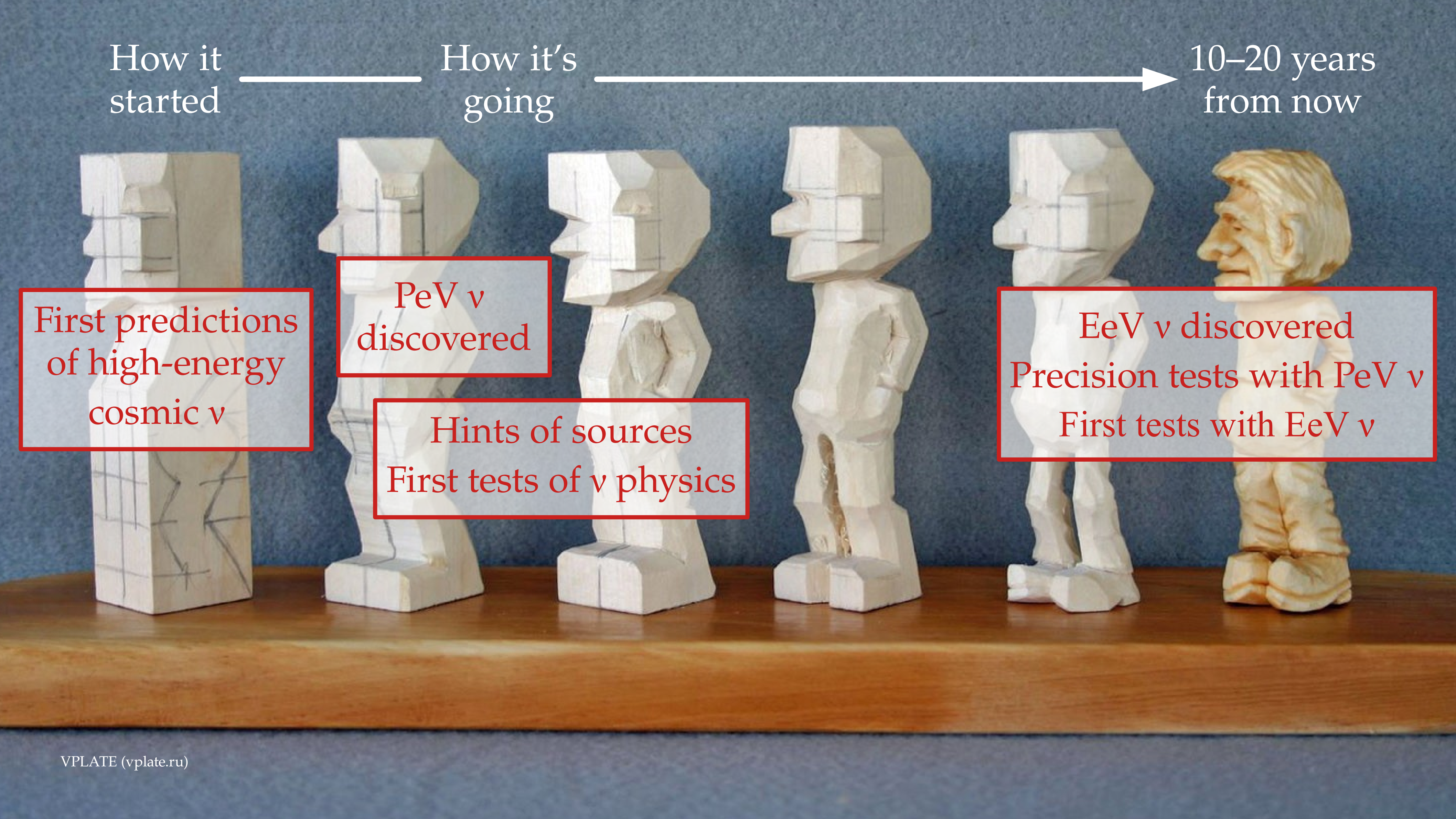
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Precision tests with PeV ν
First tests with EeV ν
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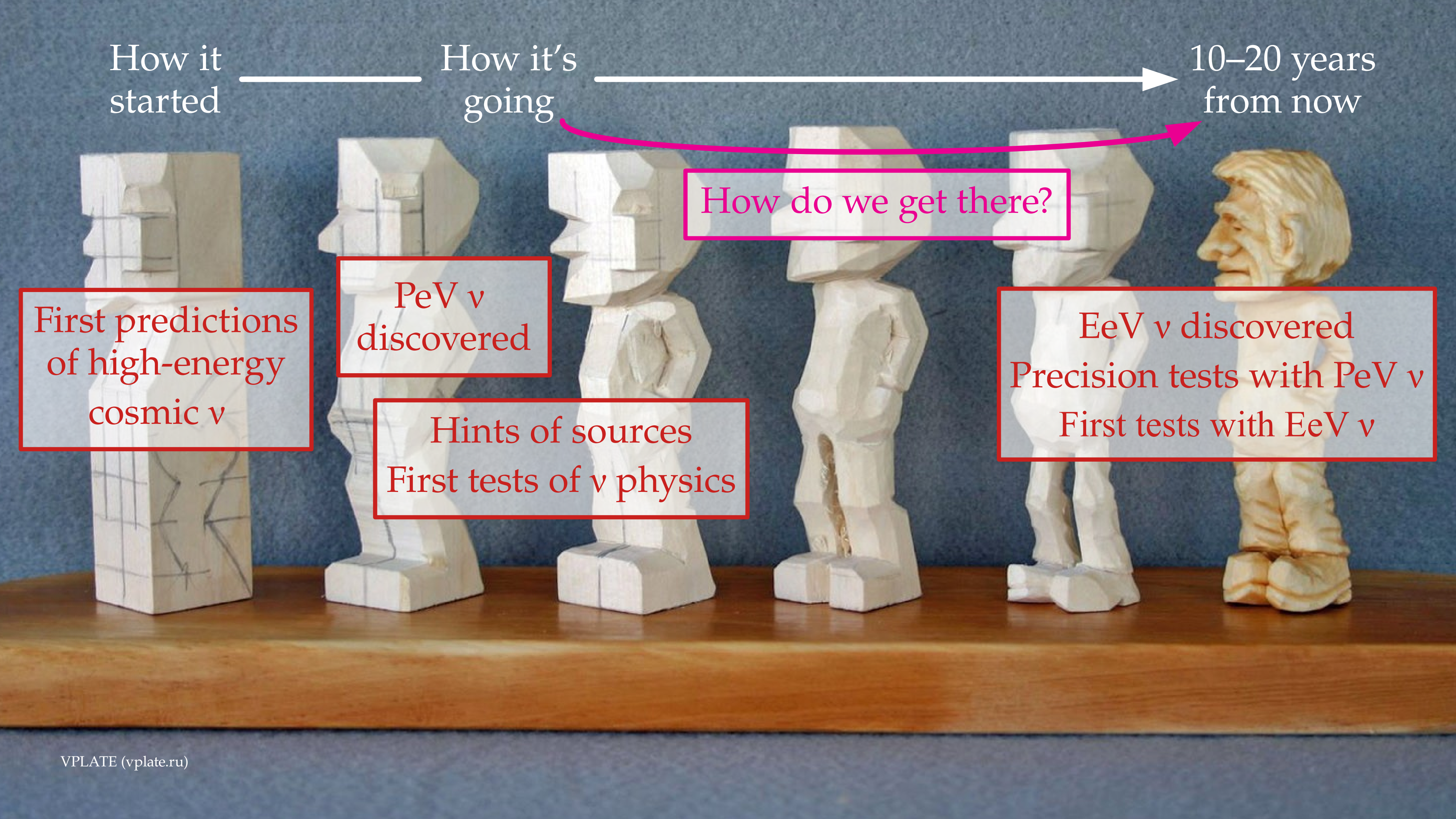
How it started
How it's going
10–20 years from now
How do we get there?
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)

Thanks!

- In-person school with remote participation
- No registration fee
- Neutrino theory & phenomenology
  Neutrino cosmology
  Neutrino astrophysics & astronomy
- Sign up here:

  nbia.nbi.ku.dk/neutrino2023

Backup slides

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

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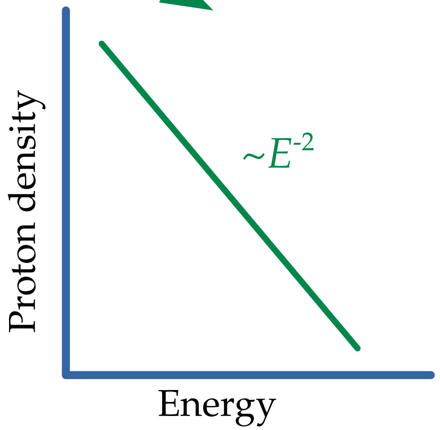

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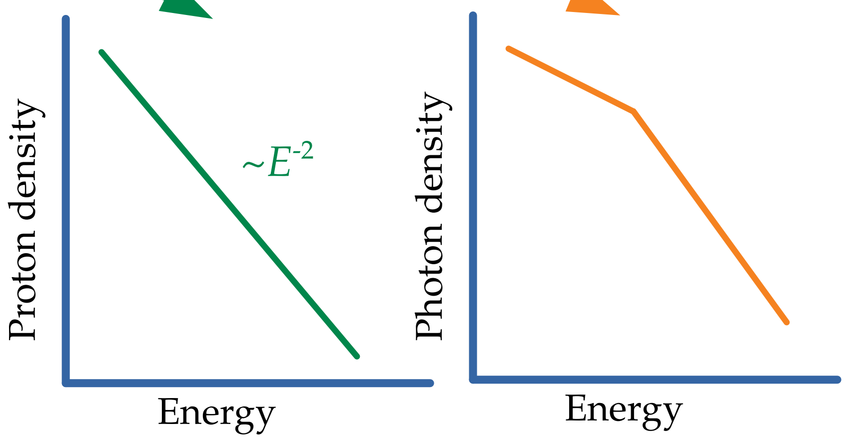

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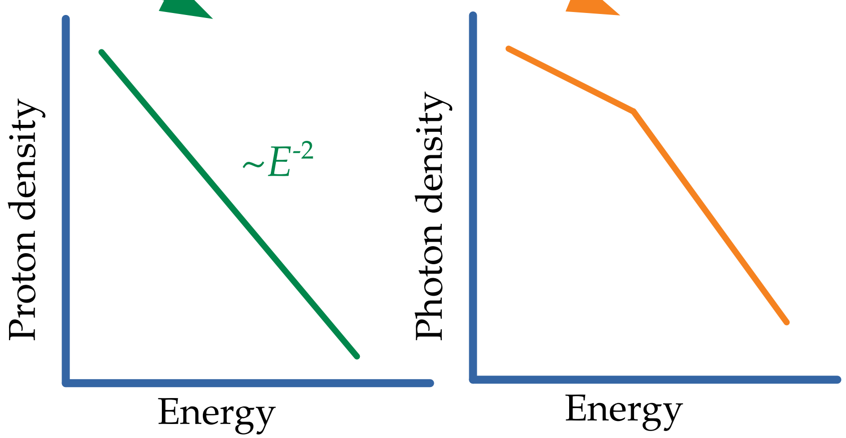
$$\pi^0 \longrightarrow \gamma + \gamma$$

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

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



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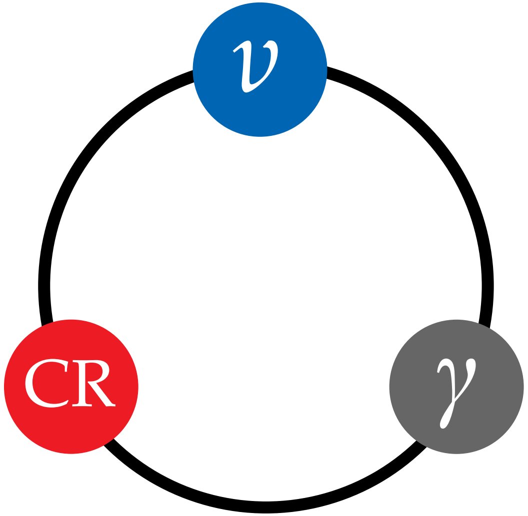
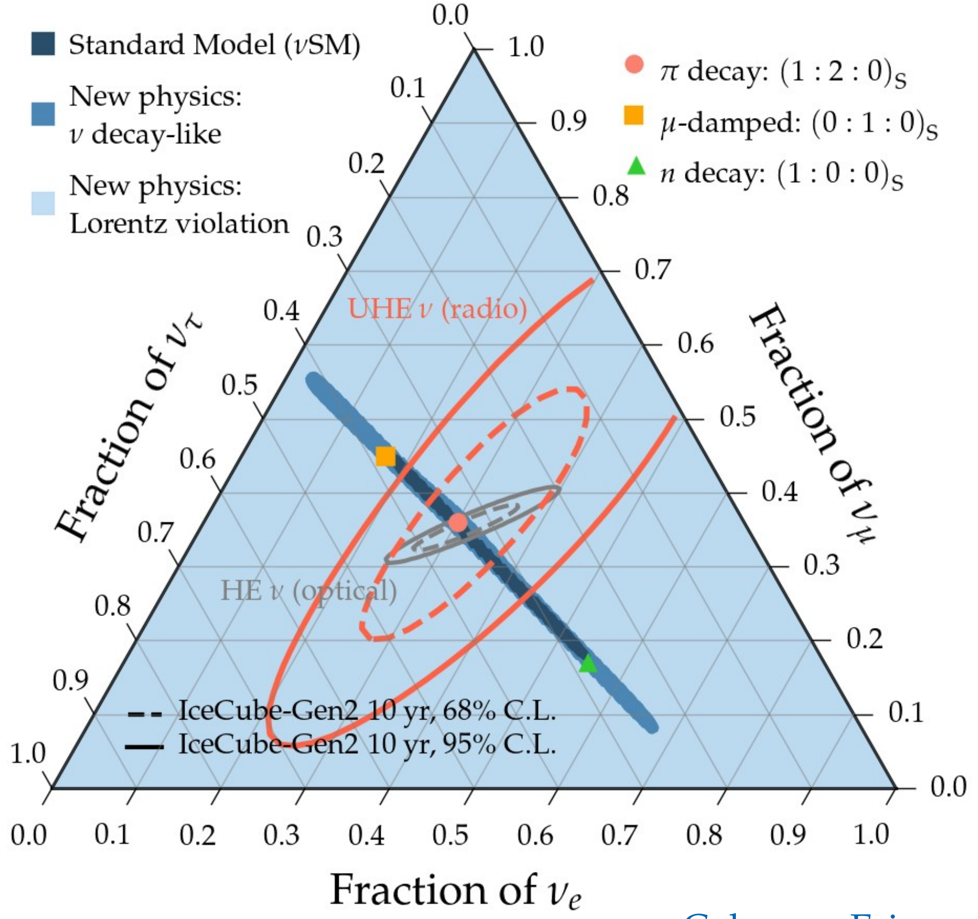


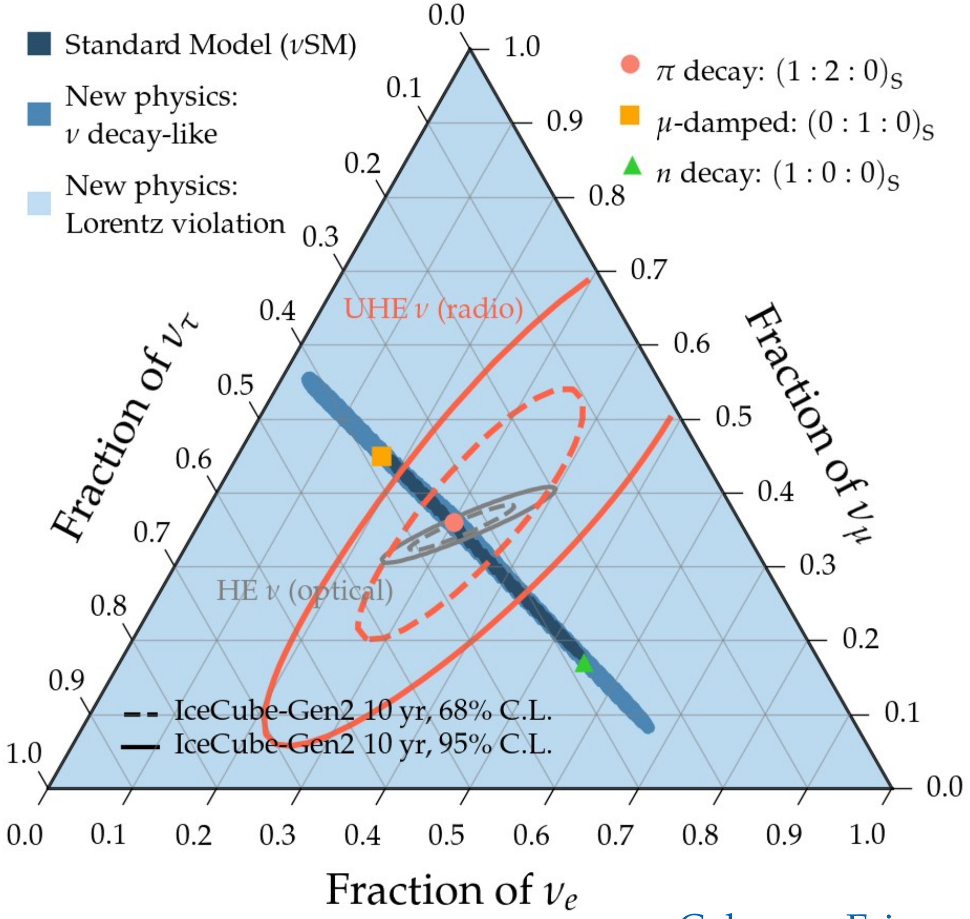
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10



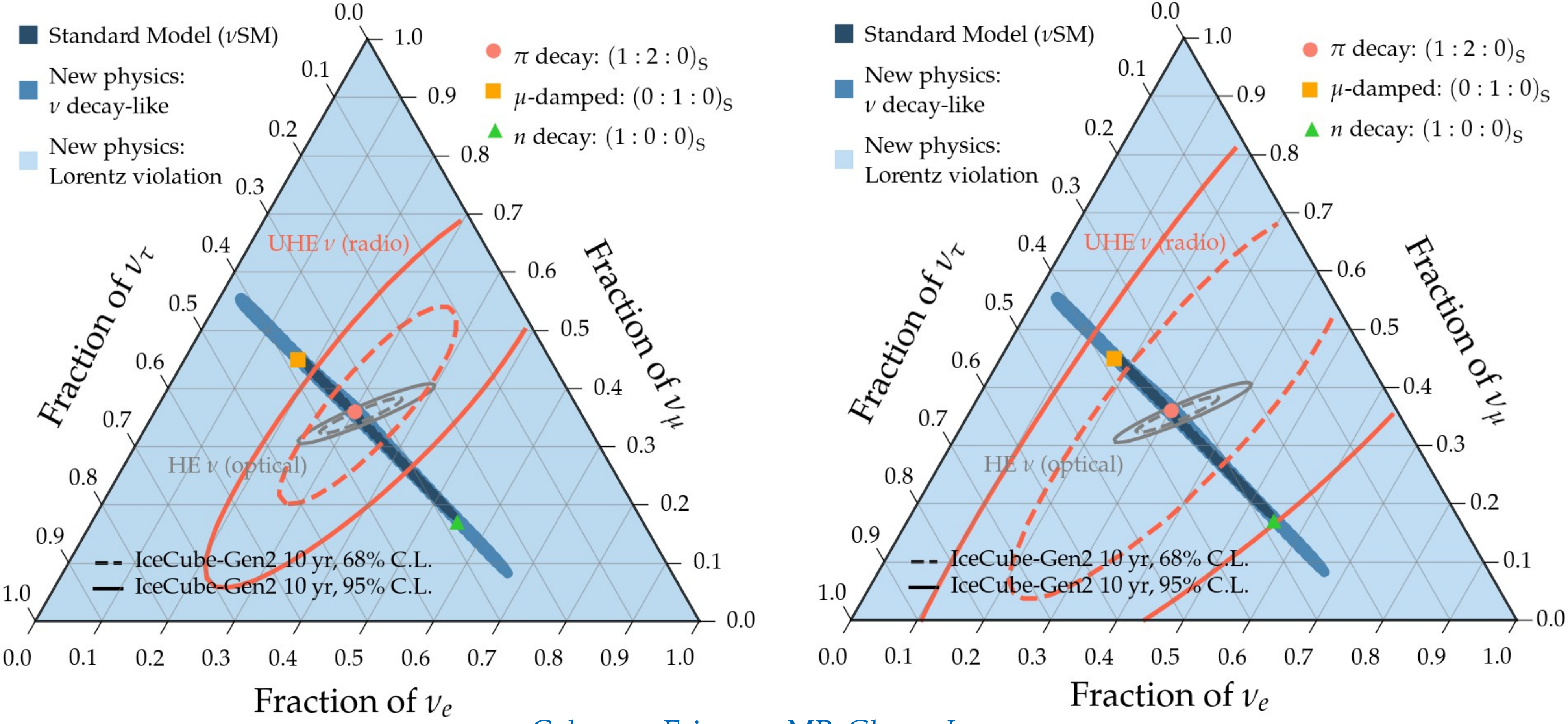
Coleman, Ericsson, MB, Glaser, *In prep.*

Large UHE ν flux



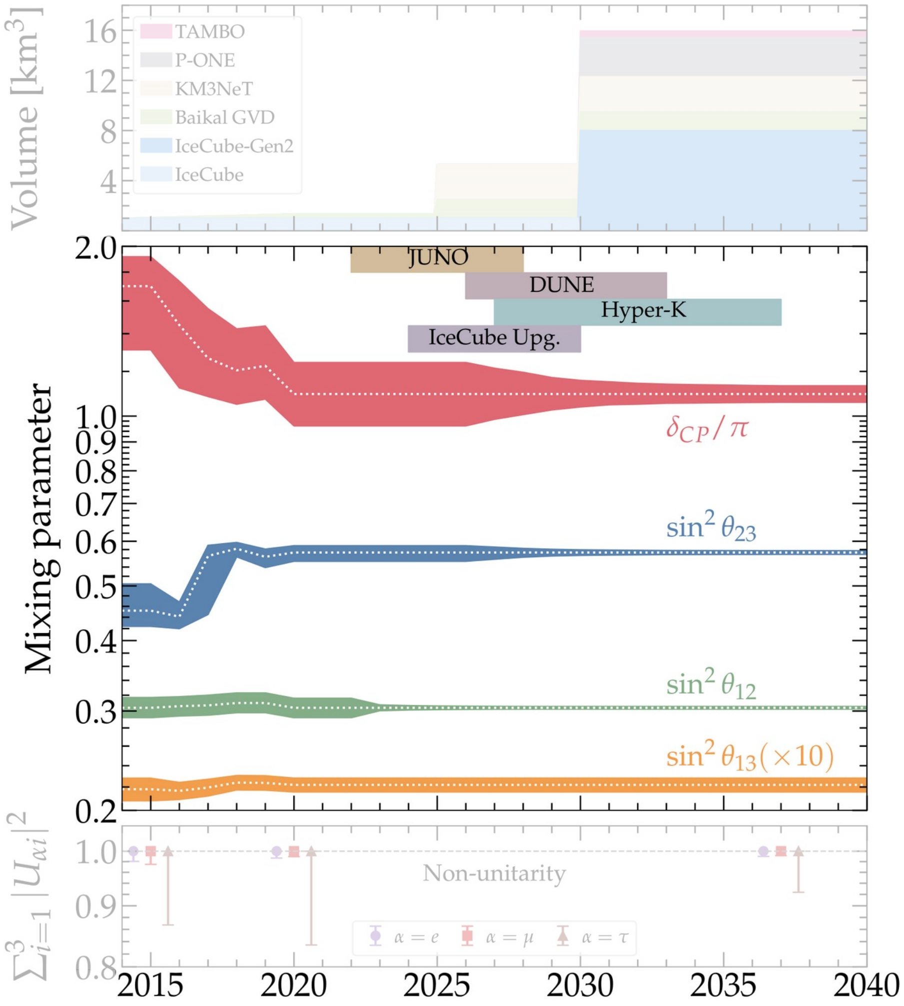
Coleman, Ericsson, MB, Glaser, *In prep.*

Large UHE ν flux | Small UHE ν flux



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

How knowing the mixing parameters better helps



We can compute the oscillation probability more precisely:

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

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

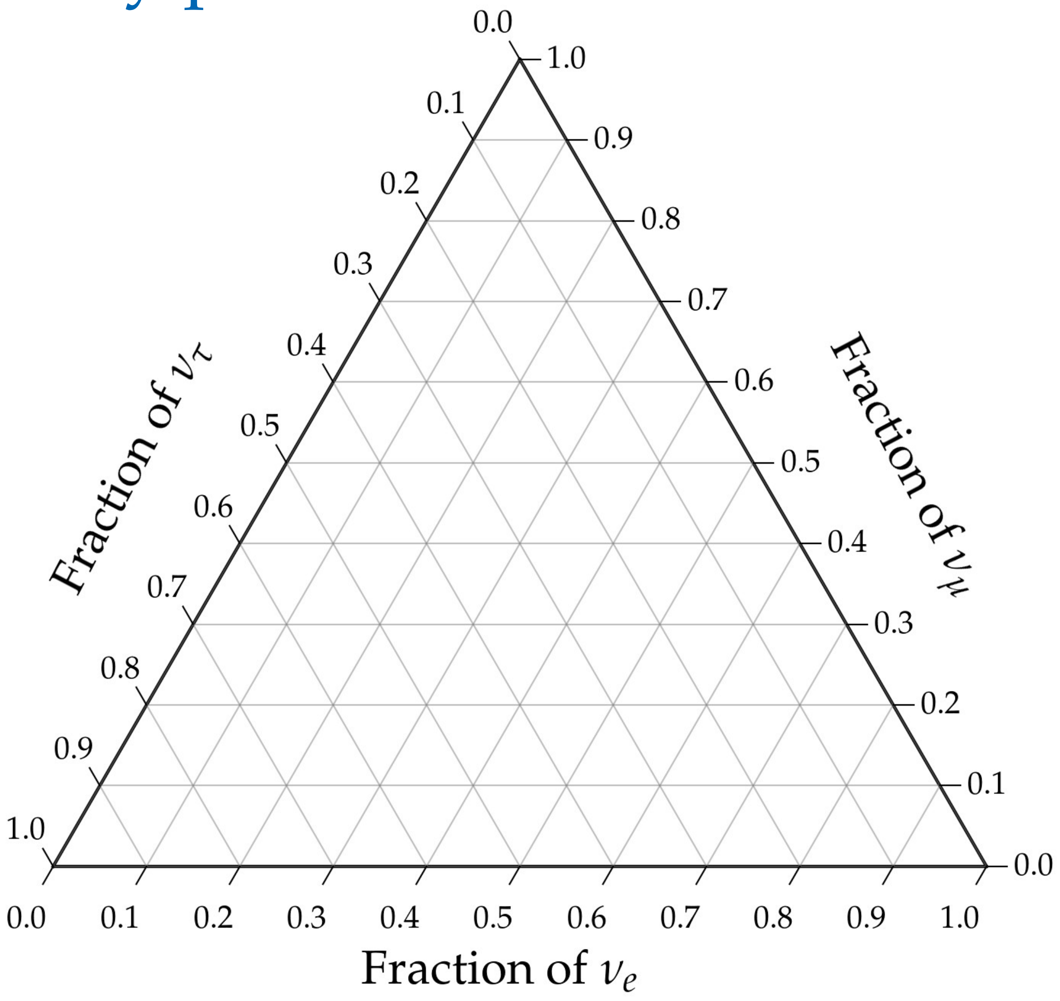
Quick aside: how to read a ternary plot

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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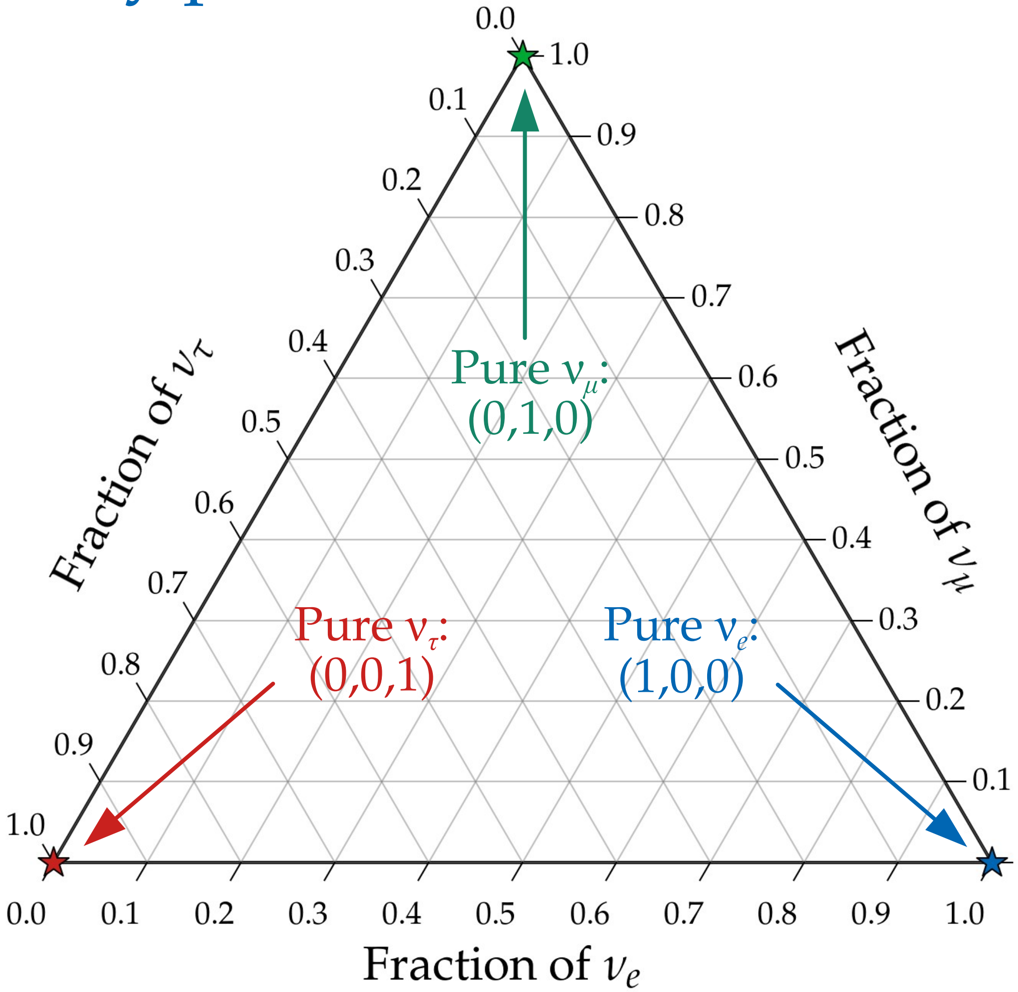

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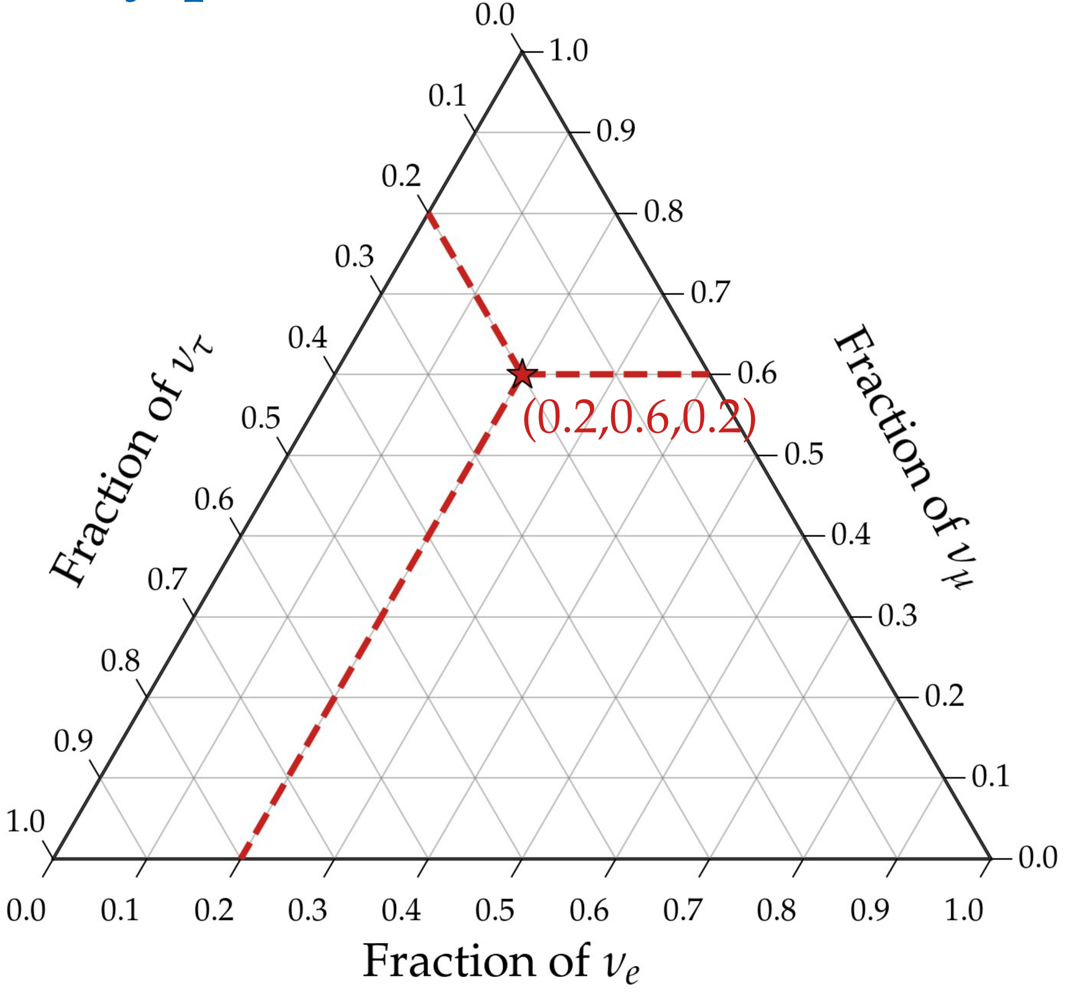

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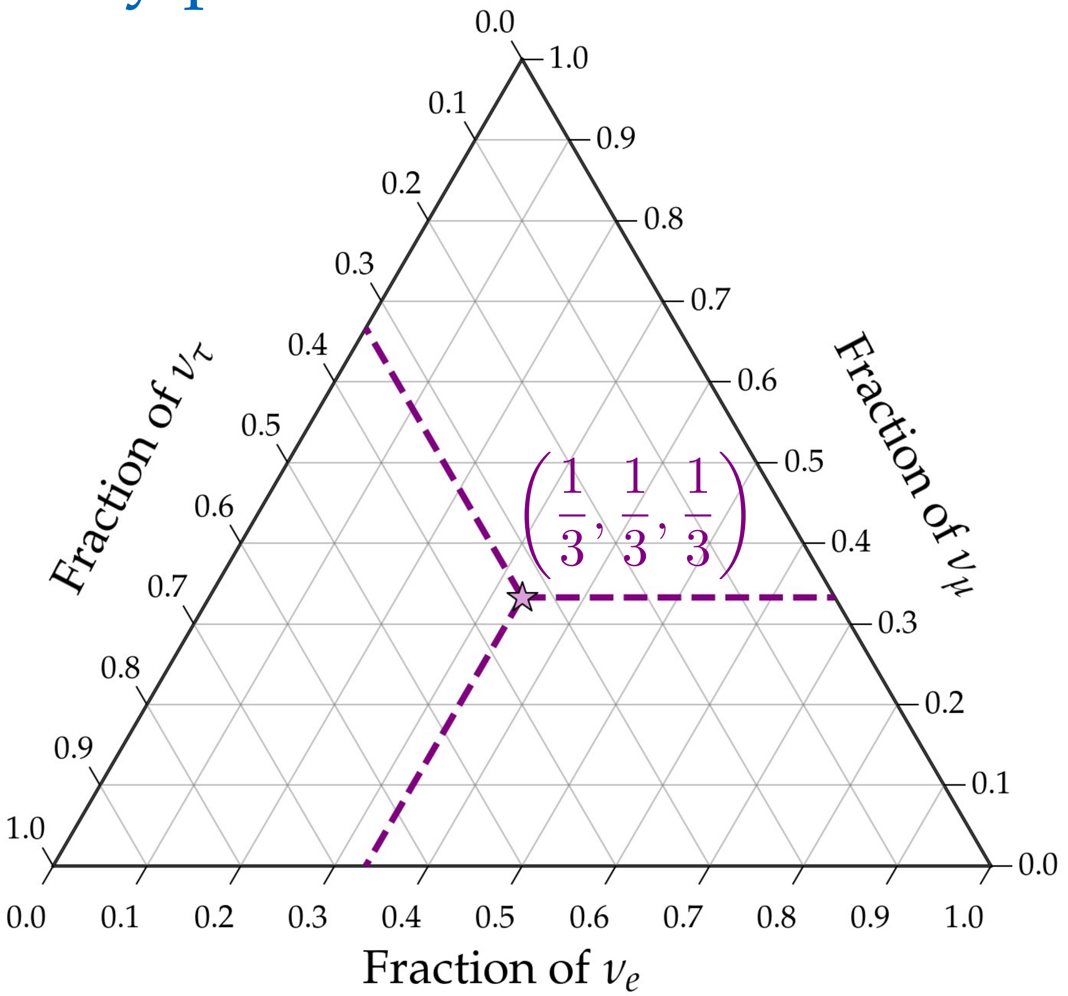

First observation of a Glashow resonance

Predicted in 1960:

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

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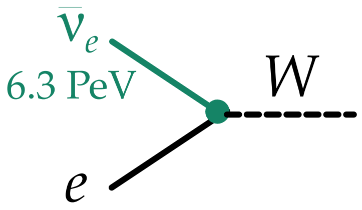

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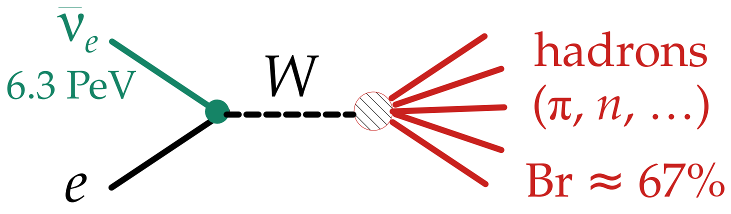

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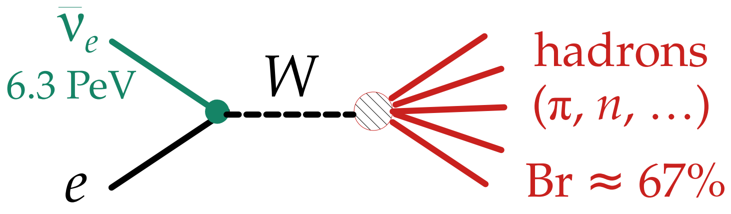

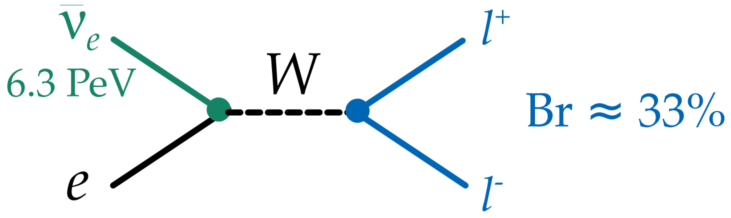

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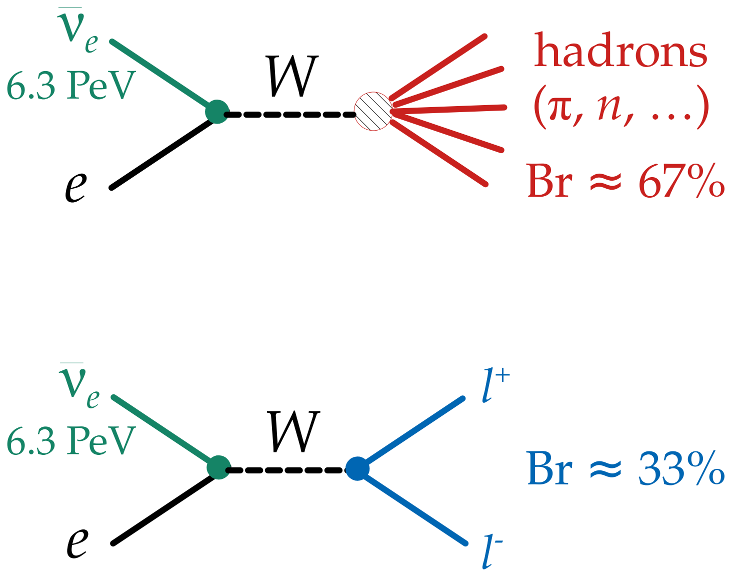

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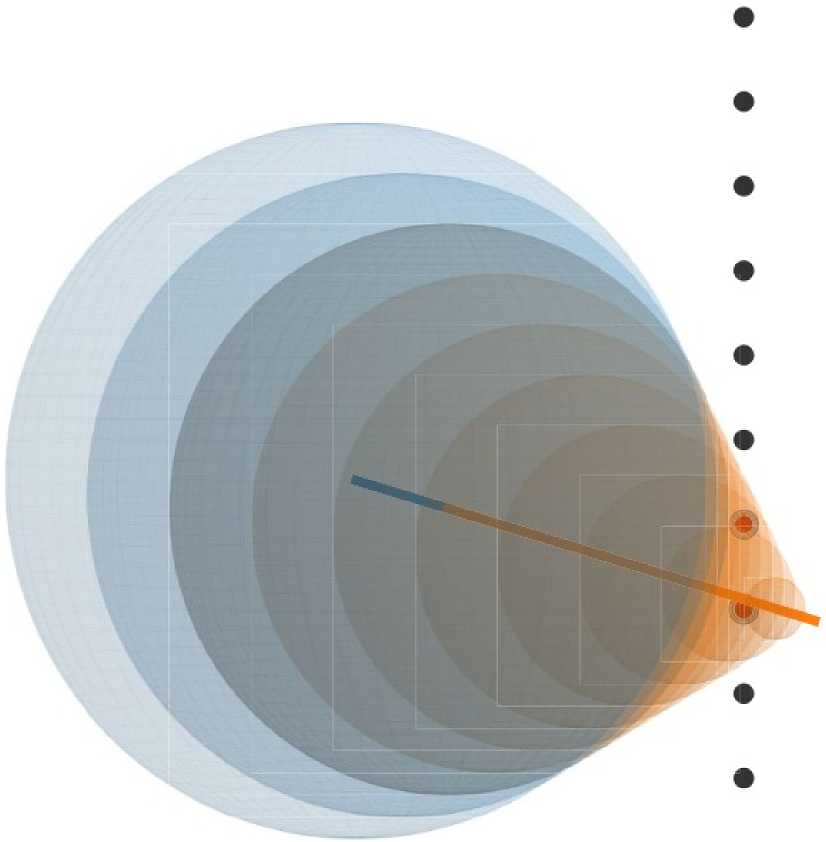

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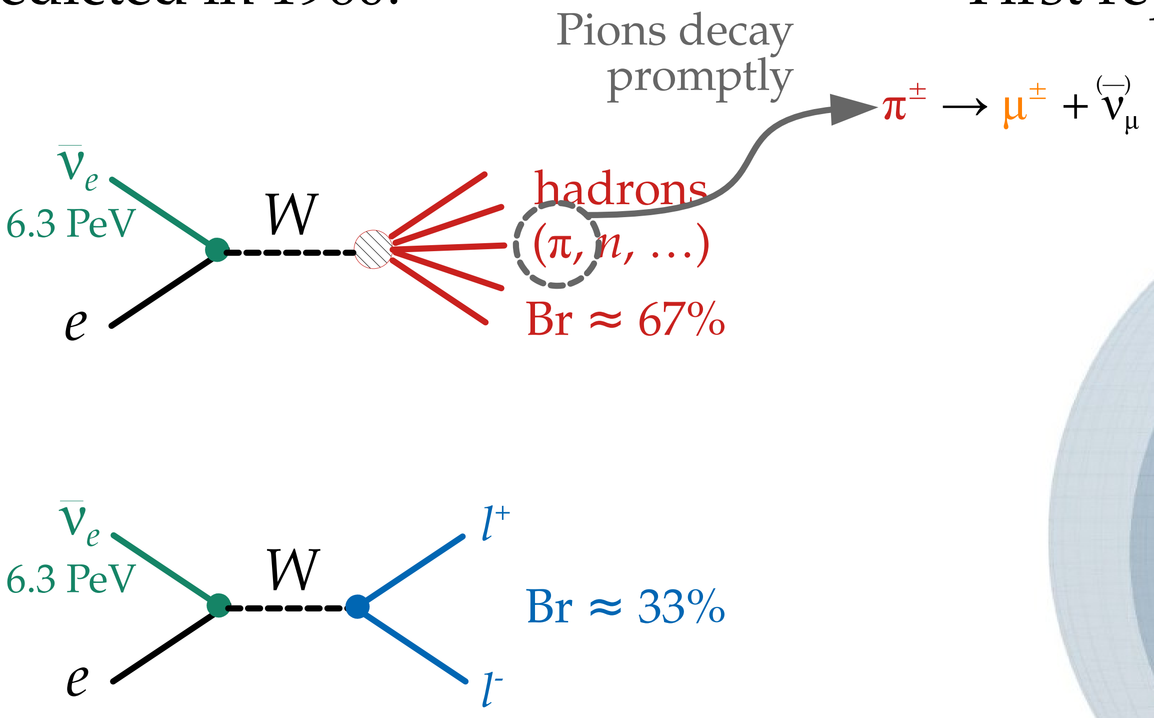

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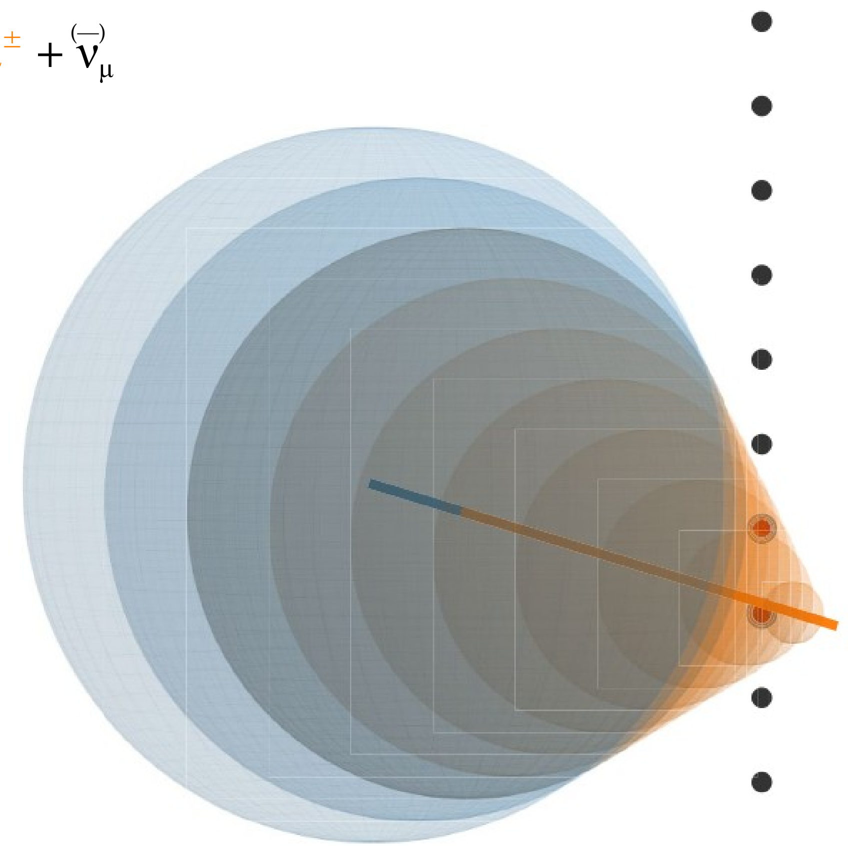

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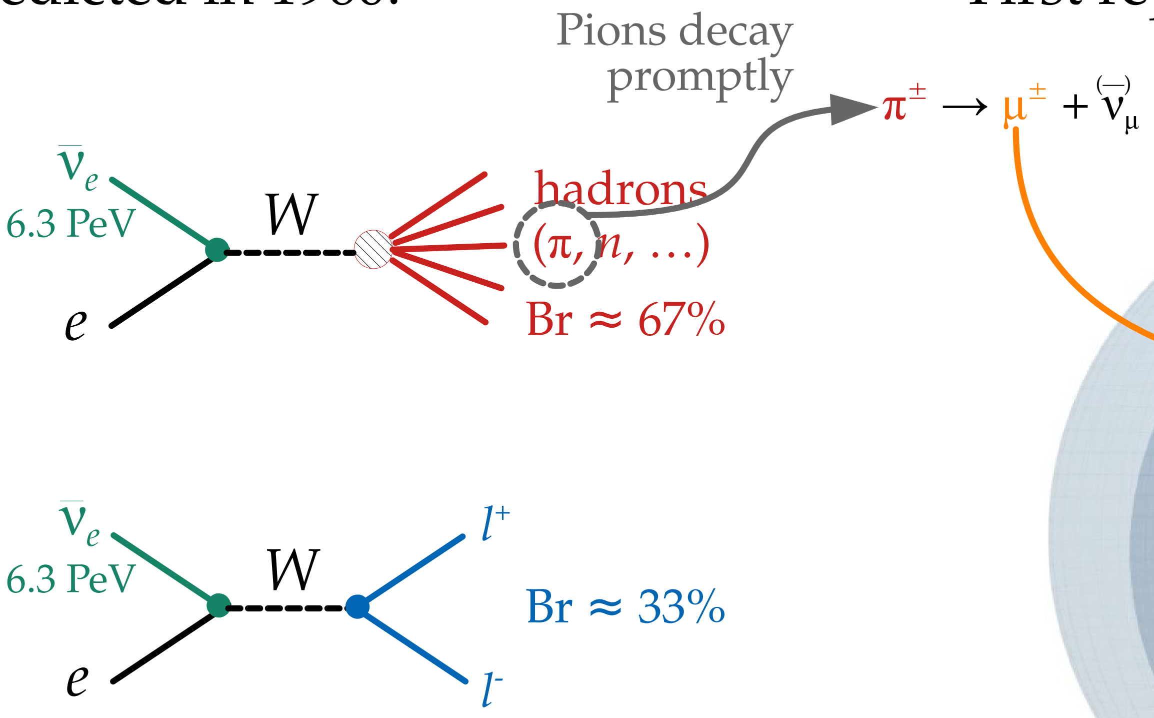

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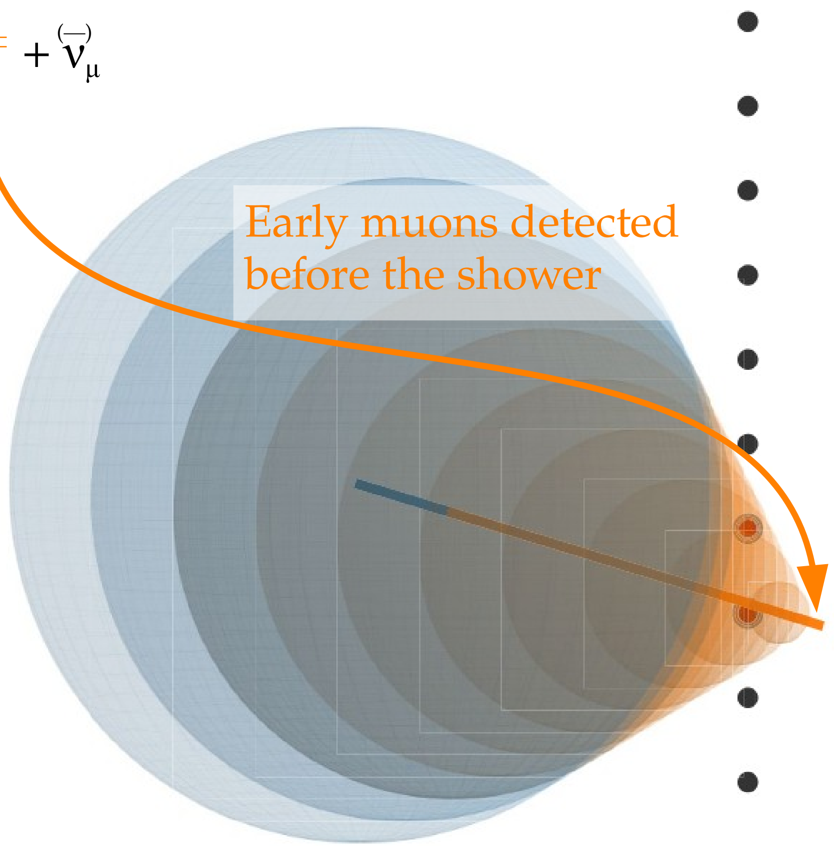

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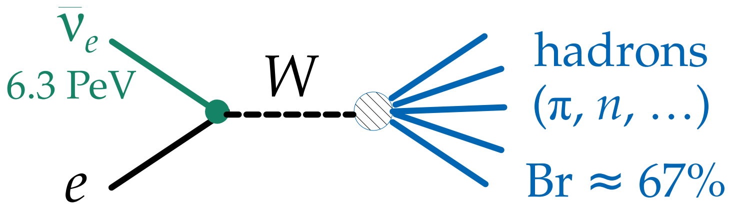

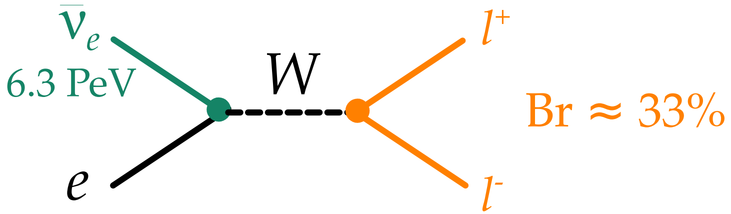

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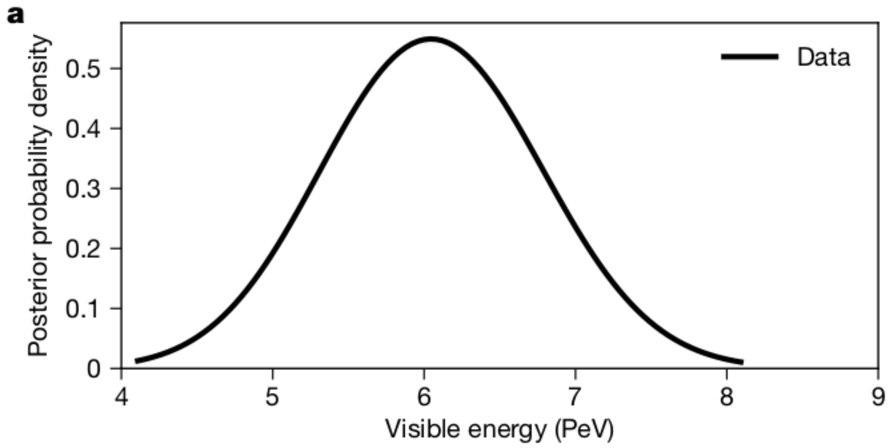

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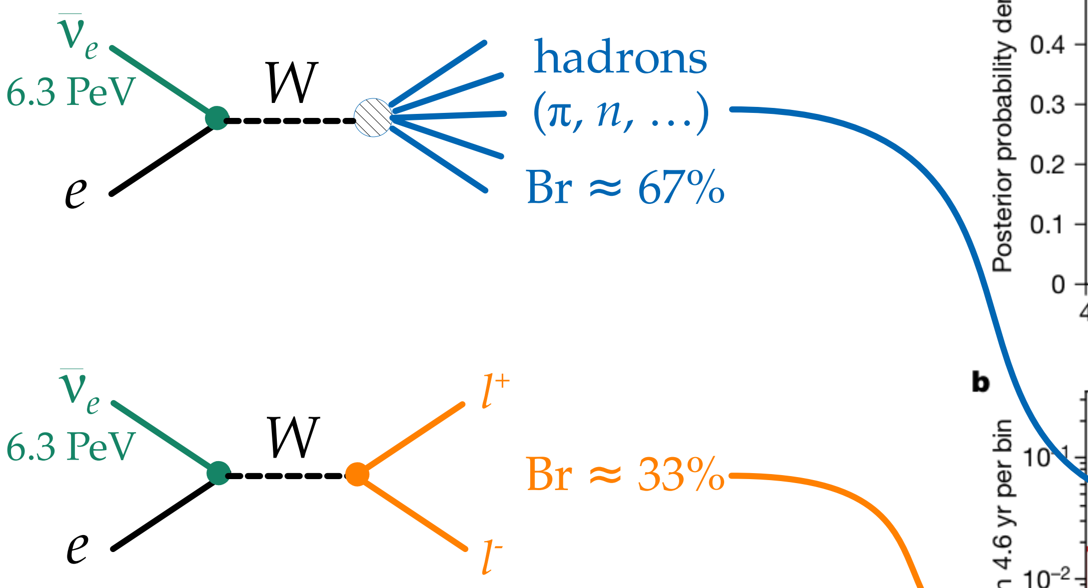

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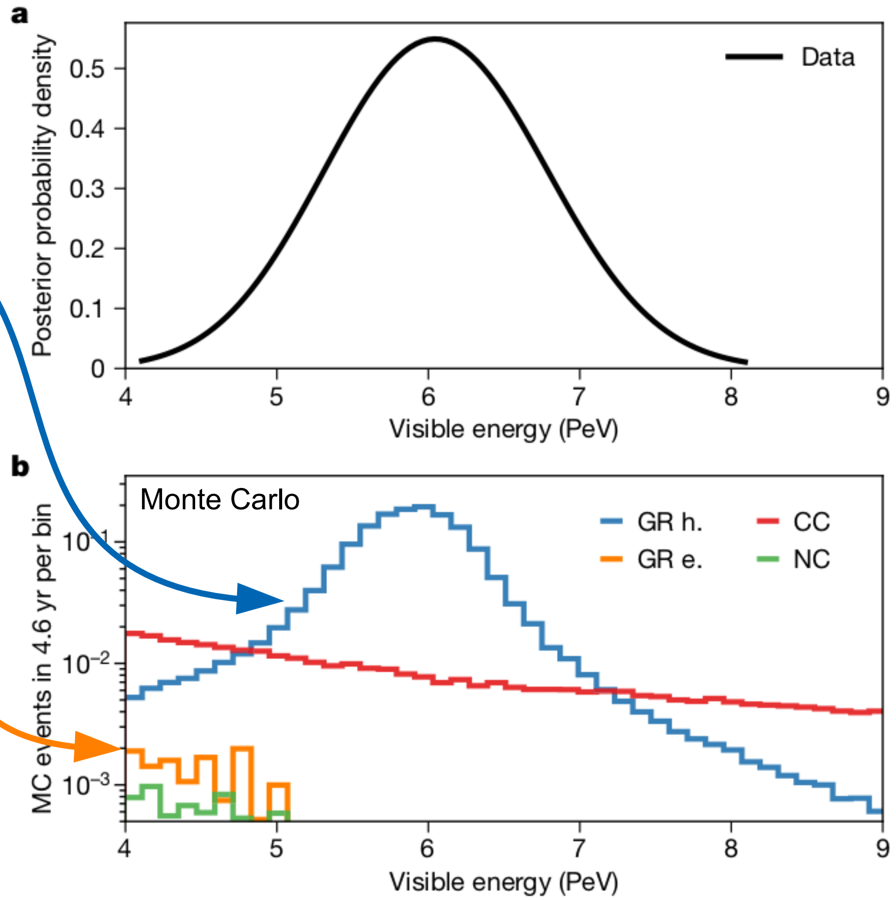

IceCube, *Nature* 2021
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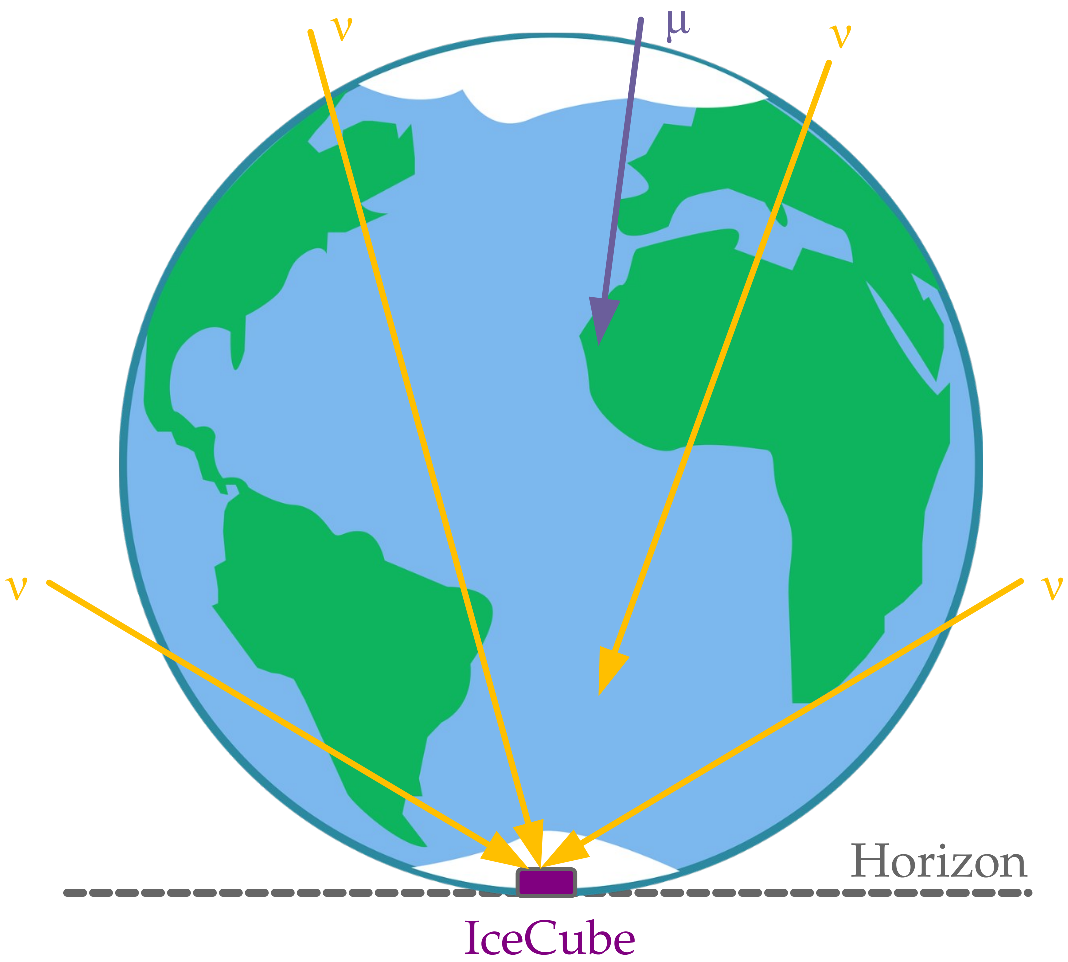
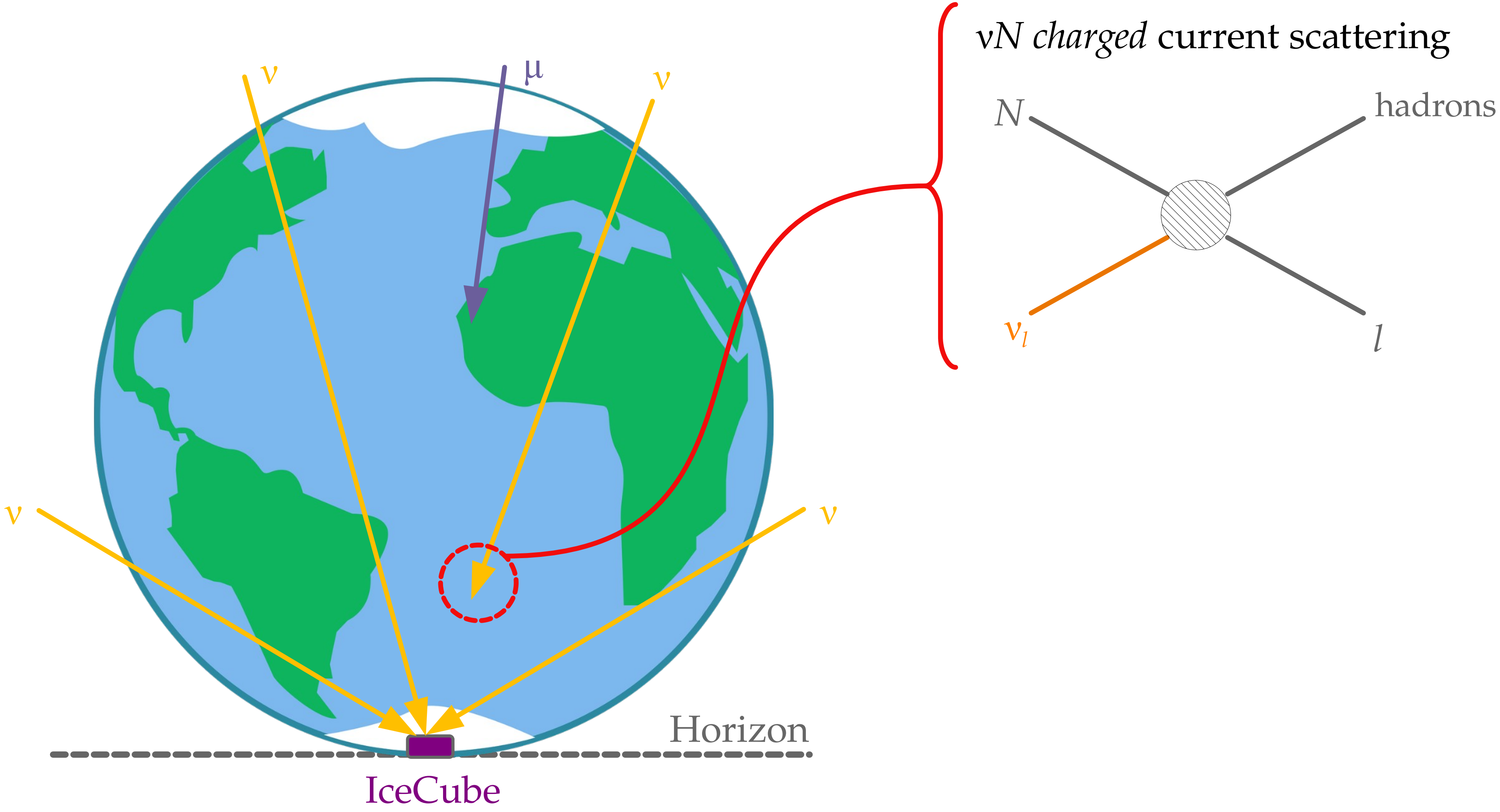
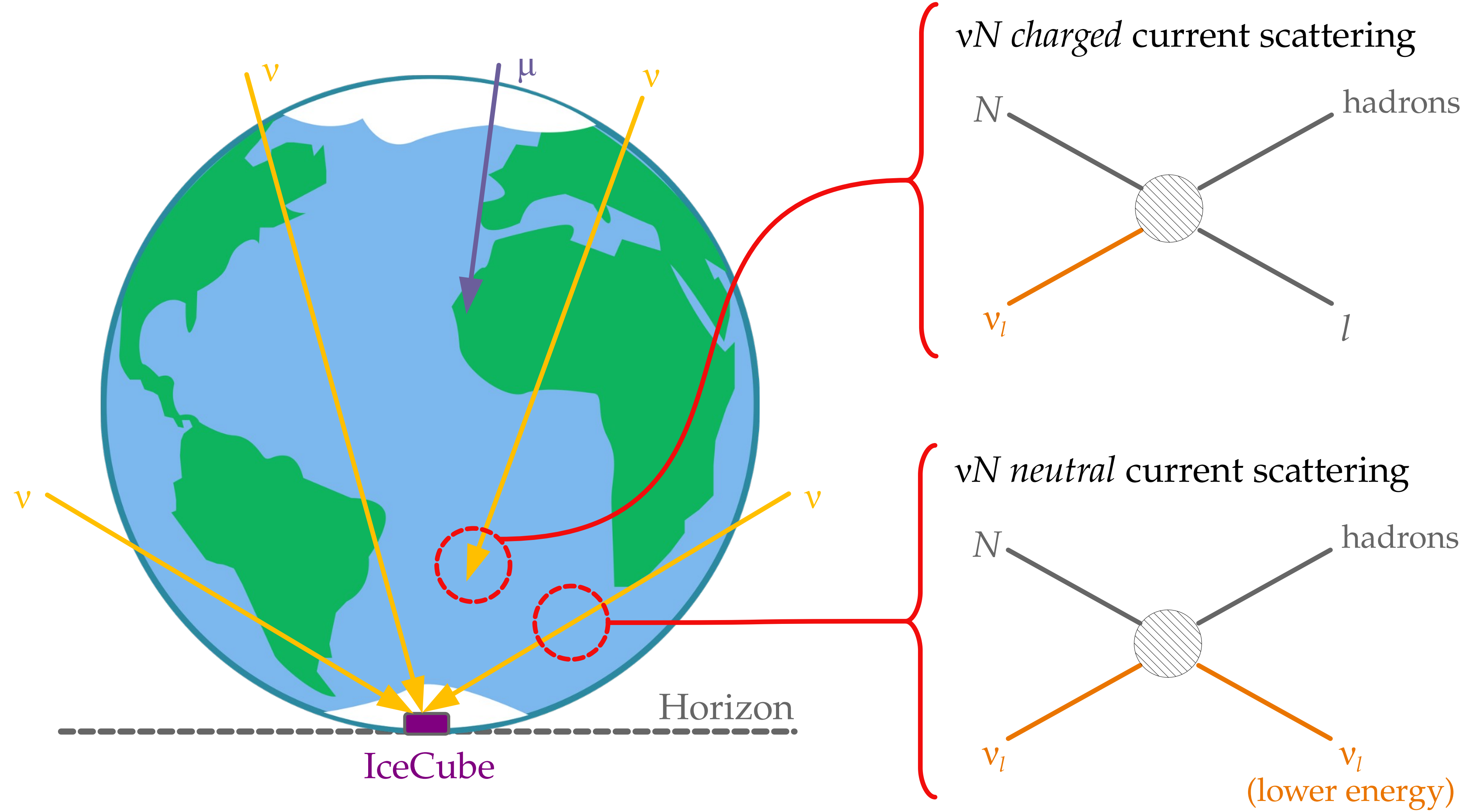
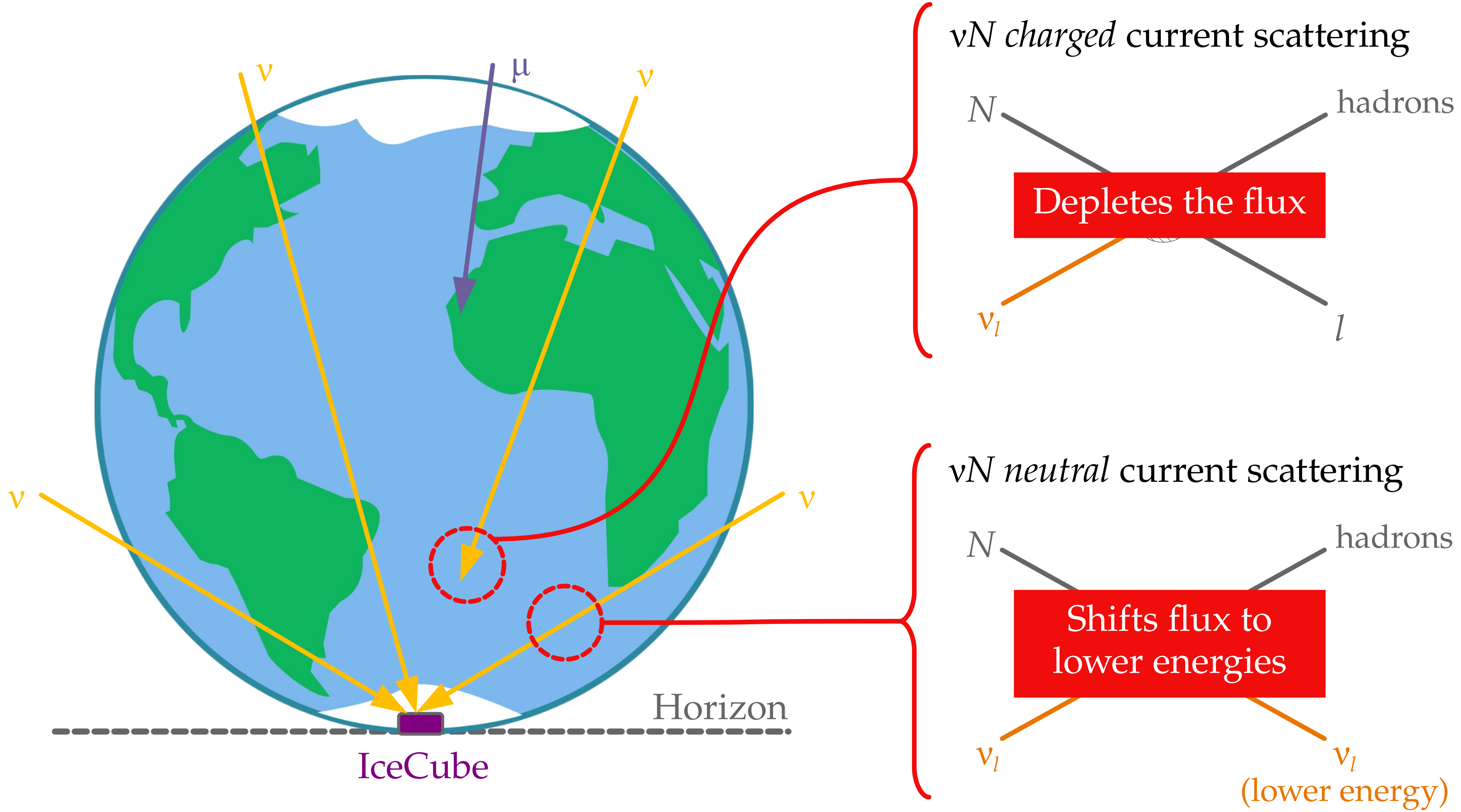

ν
μ
ν
ν
ν
Horizon
IceCube



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

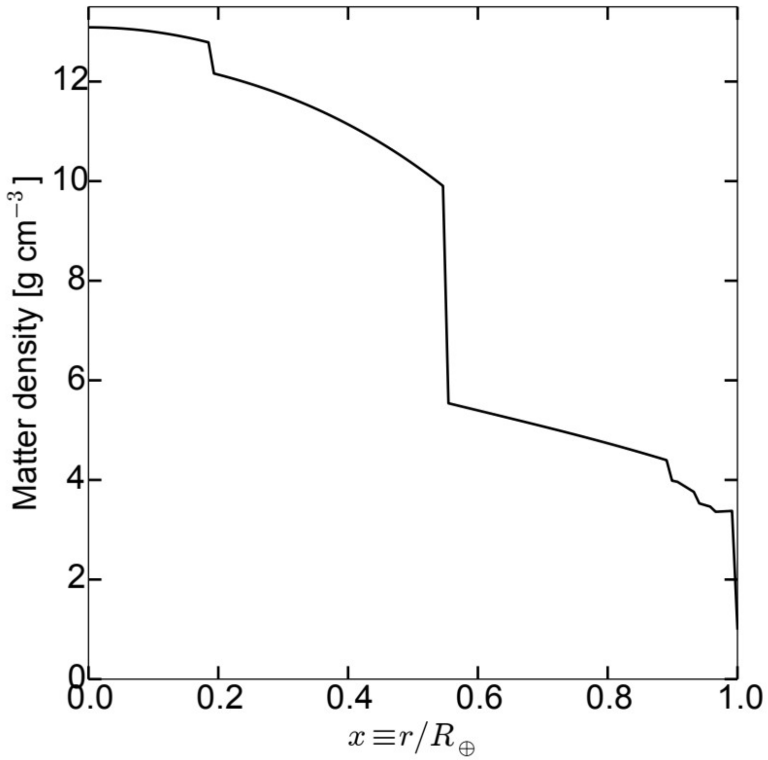


ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
Depletes the flux
ν_l
l
νN *neutral* current scattering
N
hadrons
Shifts flux to lower energies
ν_l
ν_l
(lower energy)

A feel for the in-Earth attenuation

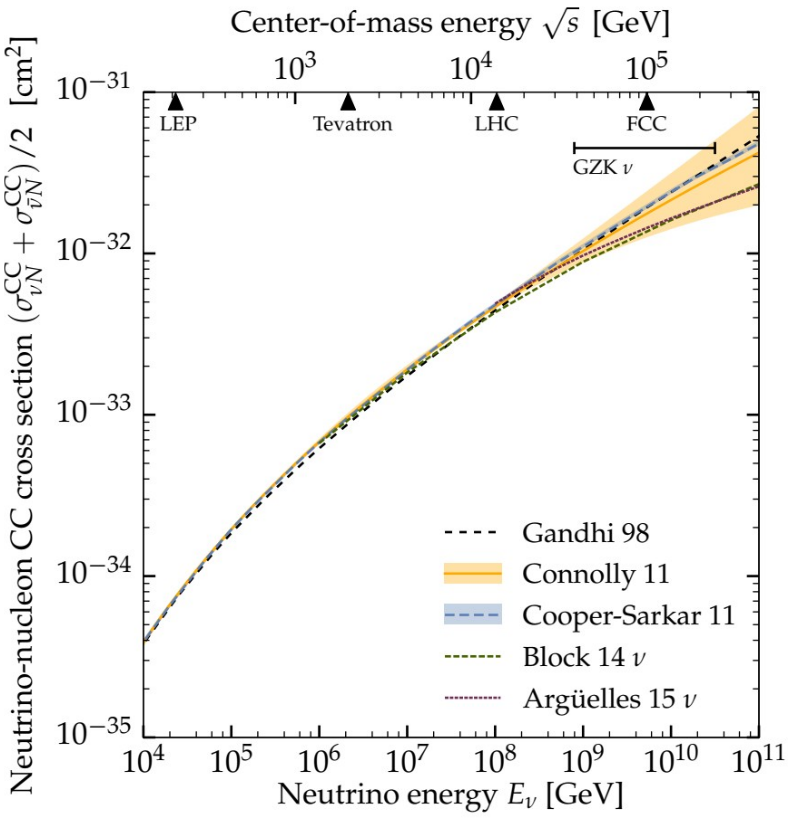
Earth matter density

(Preliminary Reference Earth Model)



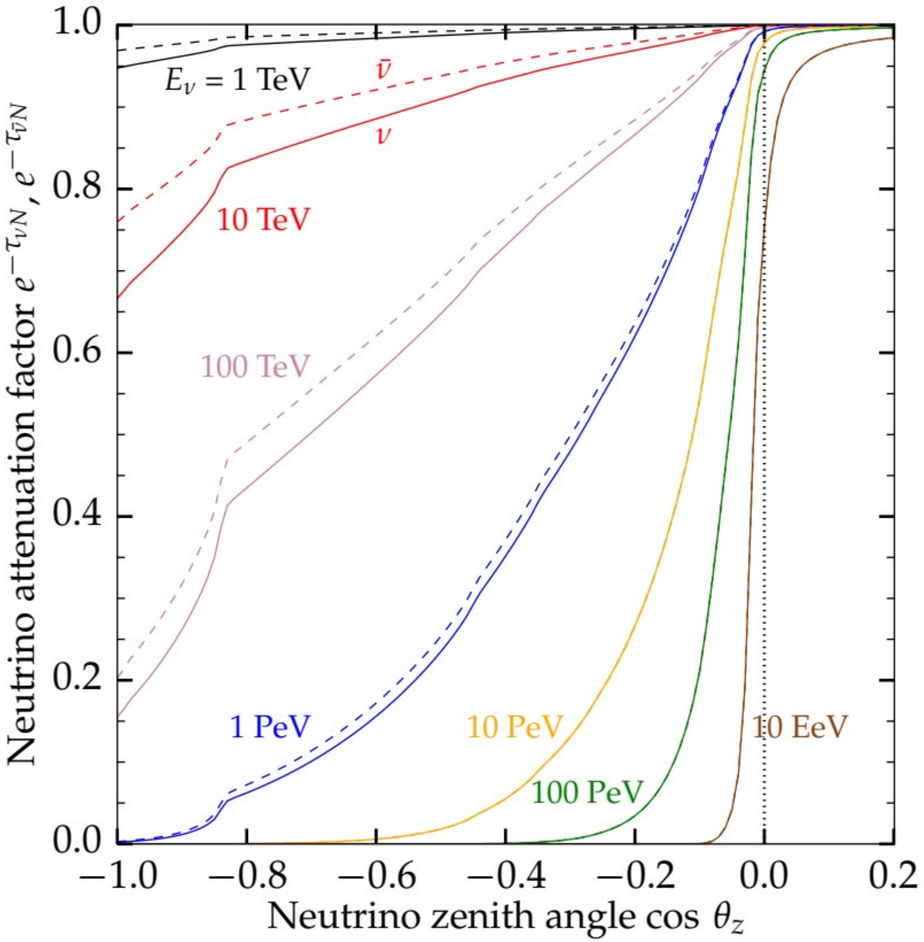
+

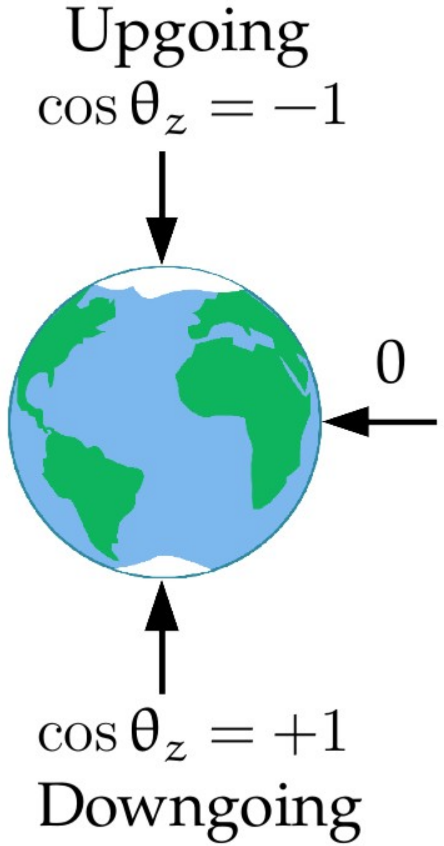
Neutrino-nucleon cross section

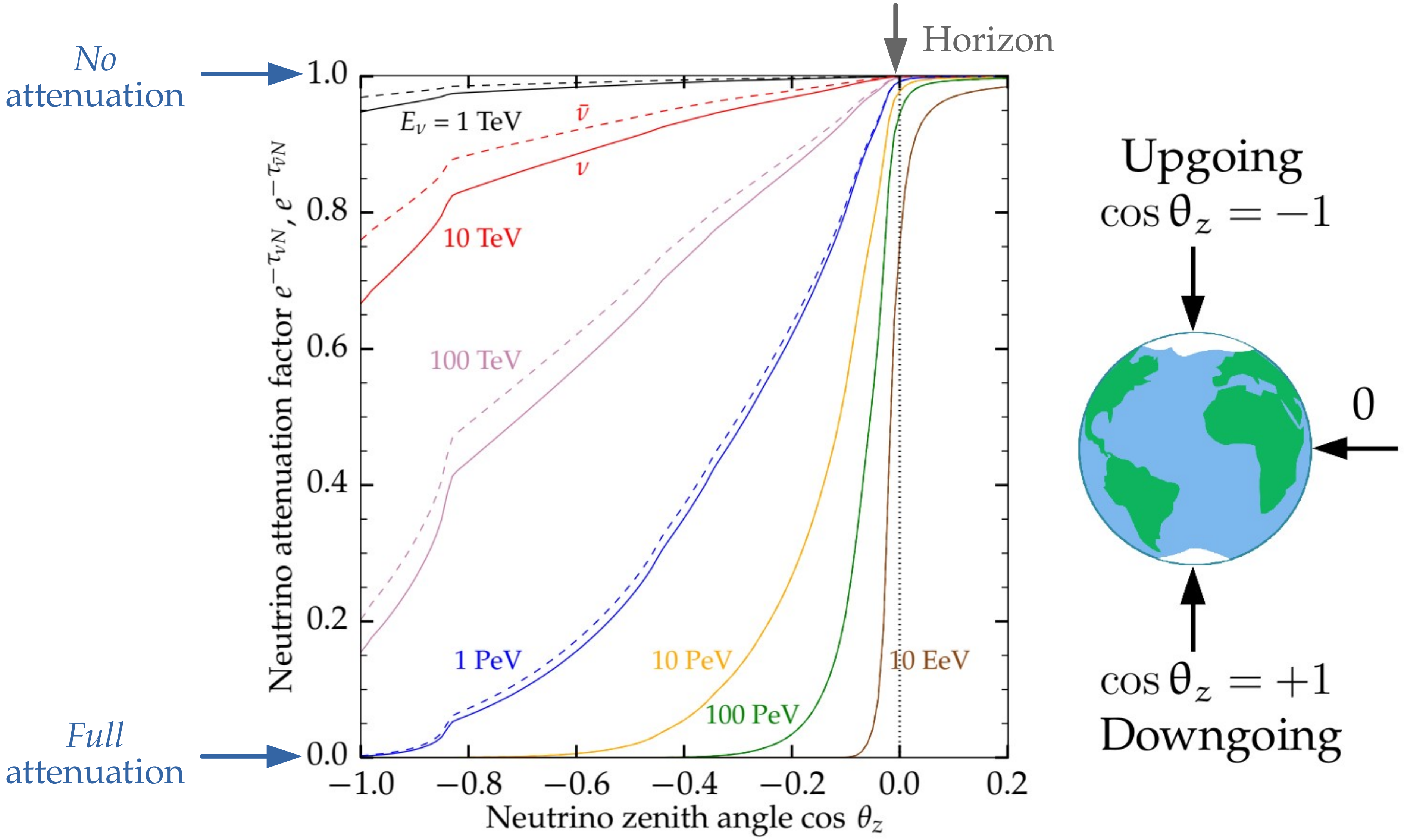


A feel for the in-Earth attenuation

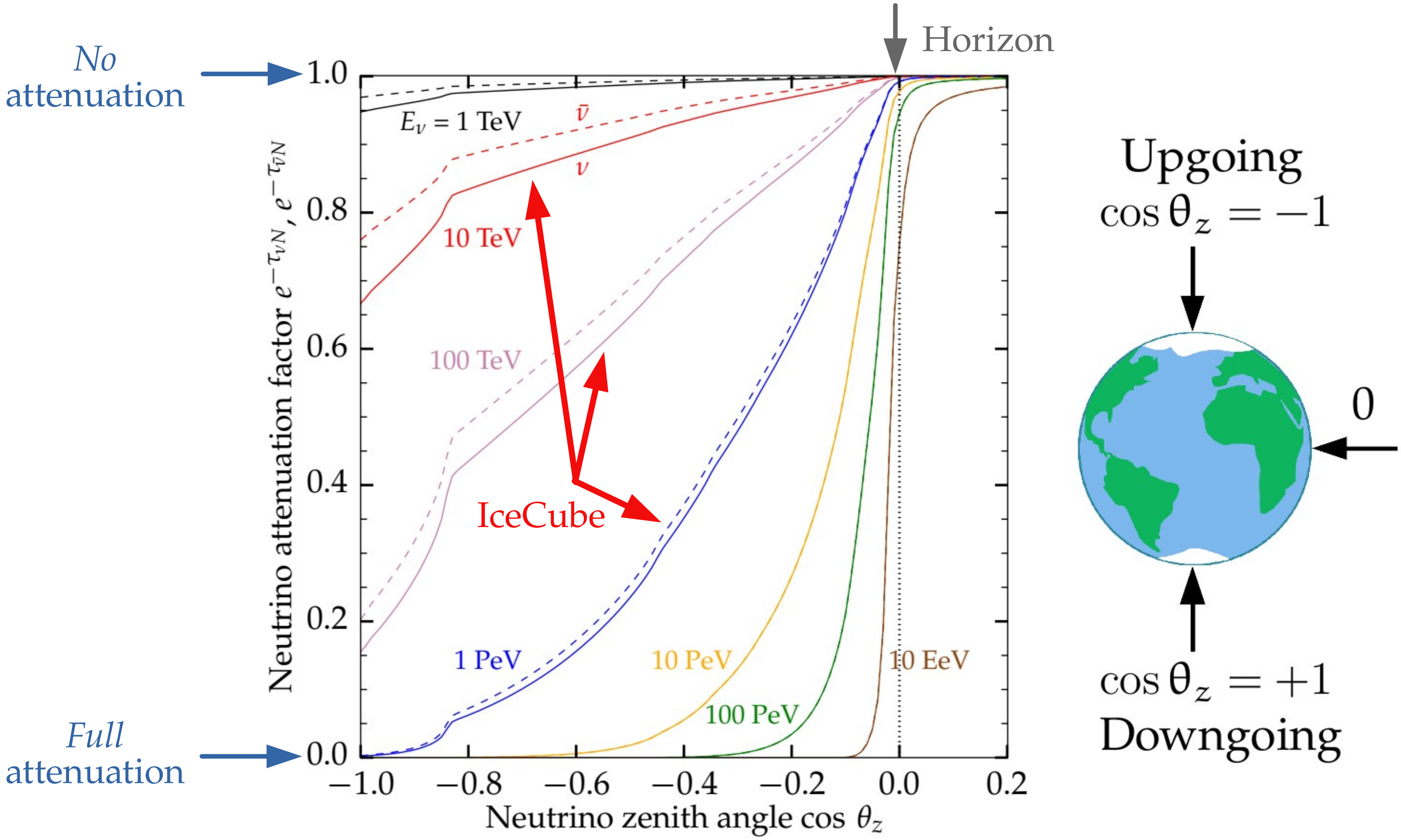
=



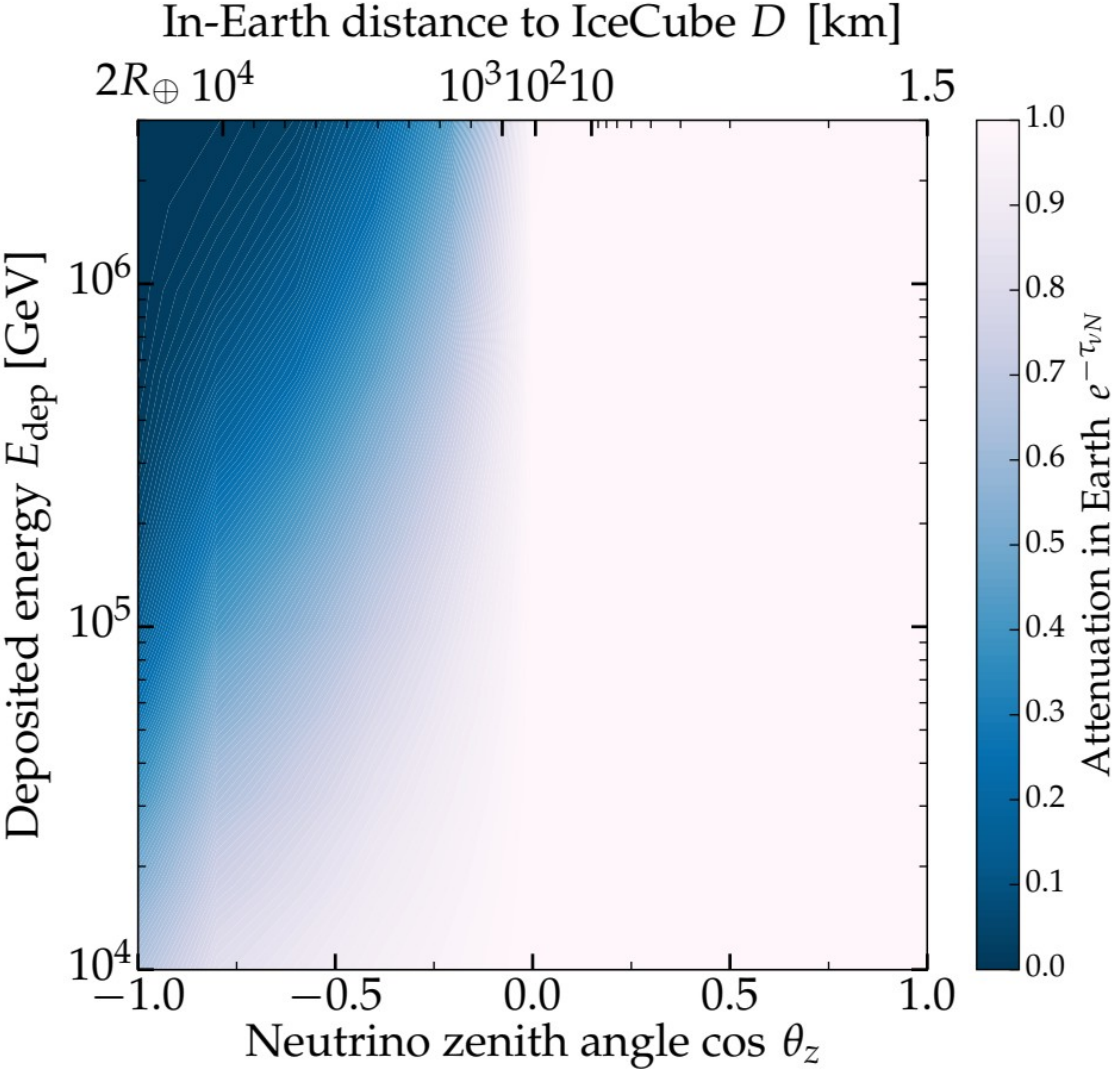


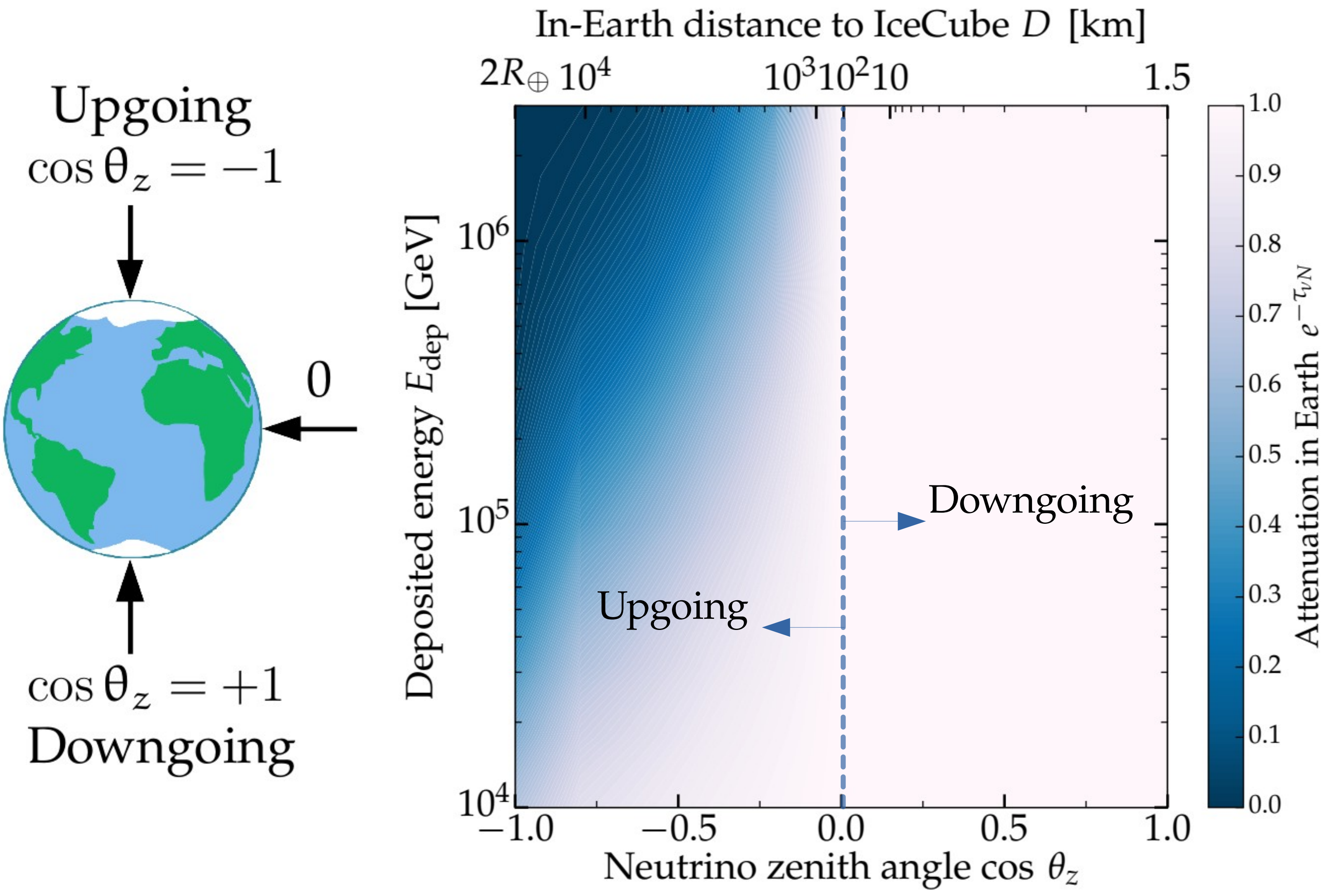


MB & Connolly, *PRL* 2019

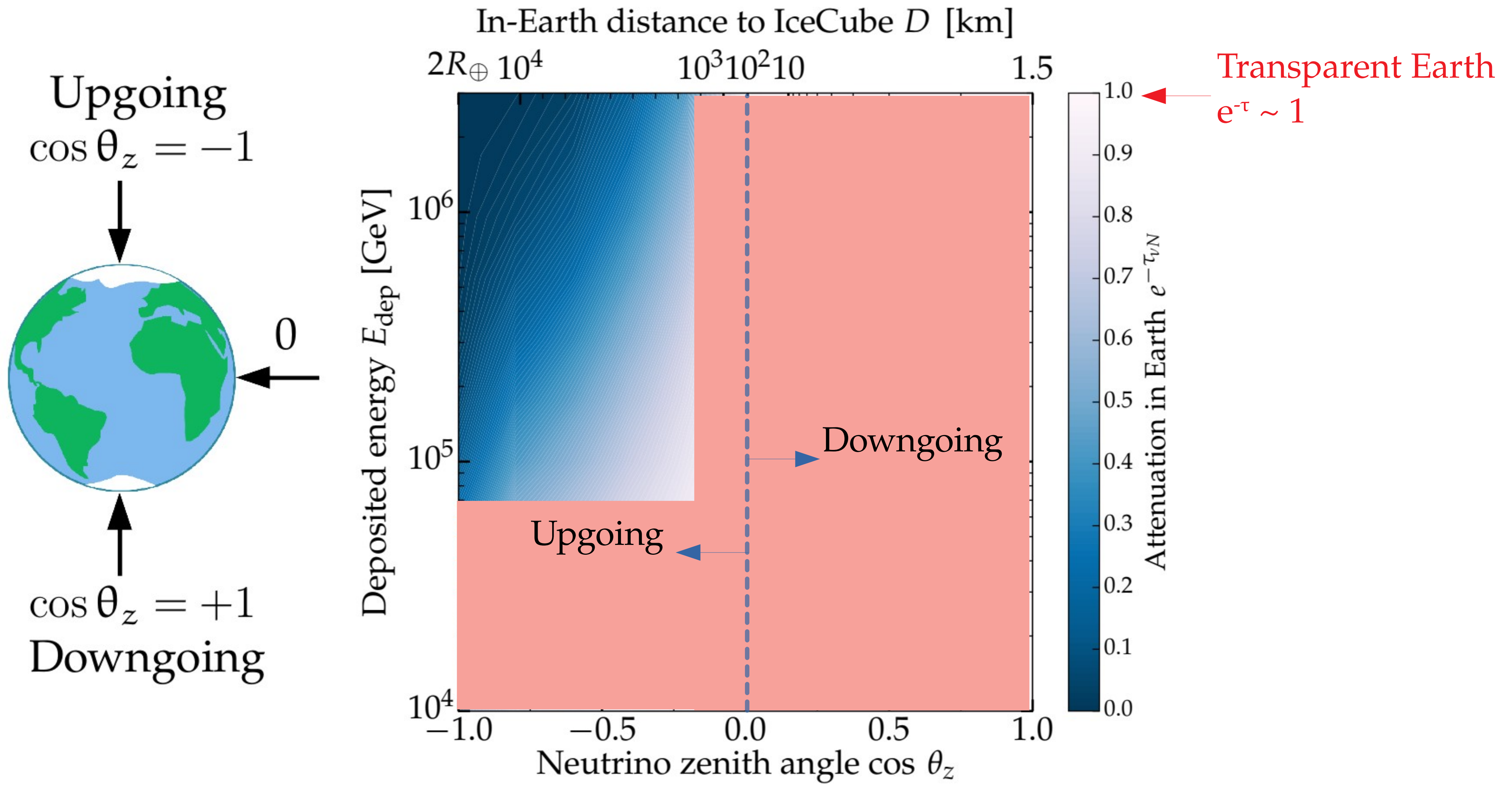


MB & Connolly, *PRL* 2019


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



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



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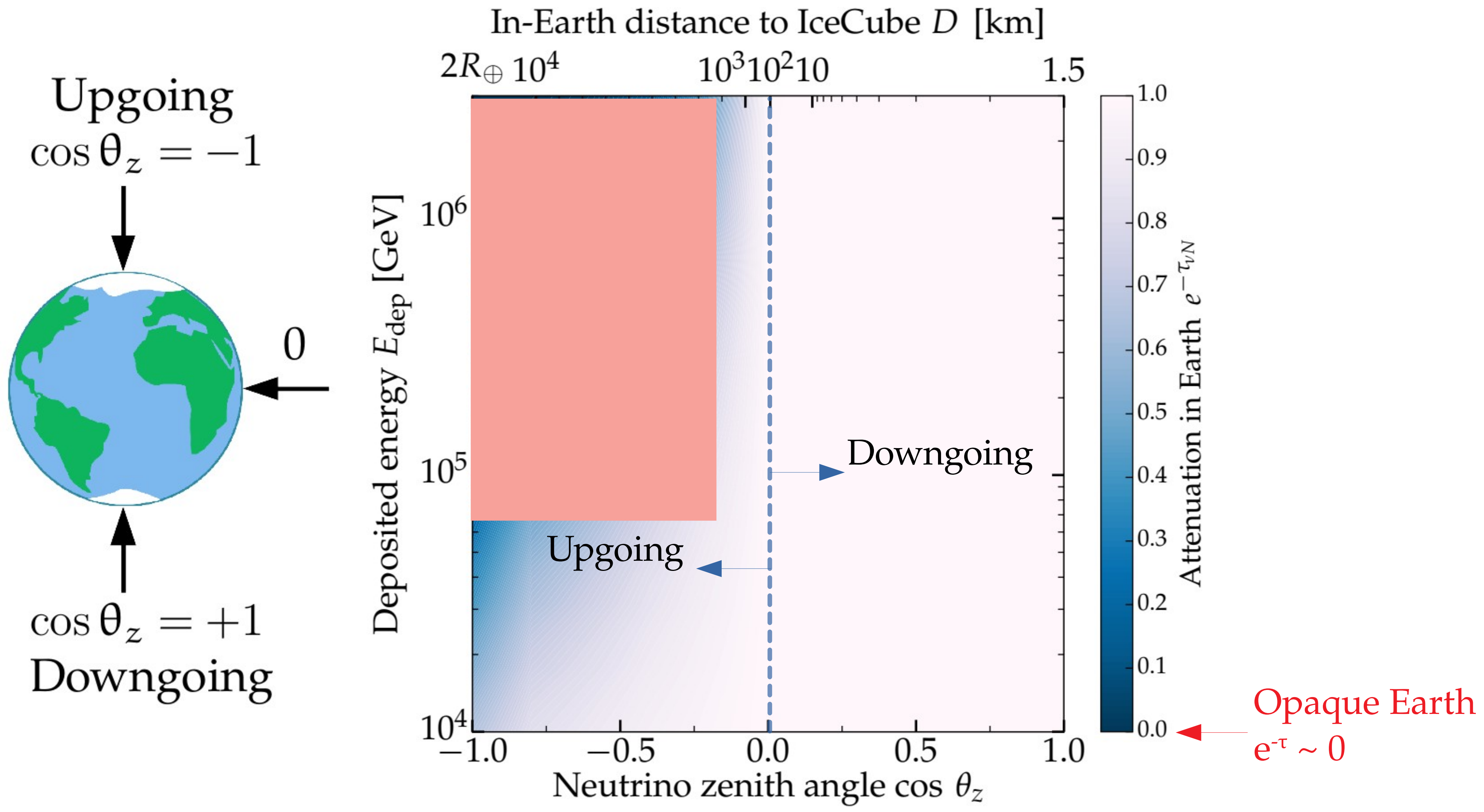
0
$\cos\theta_z = +1$
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2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



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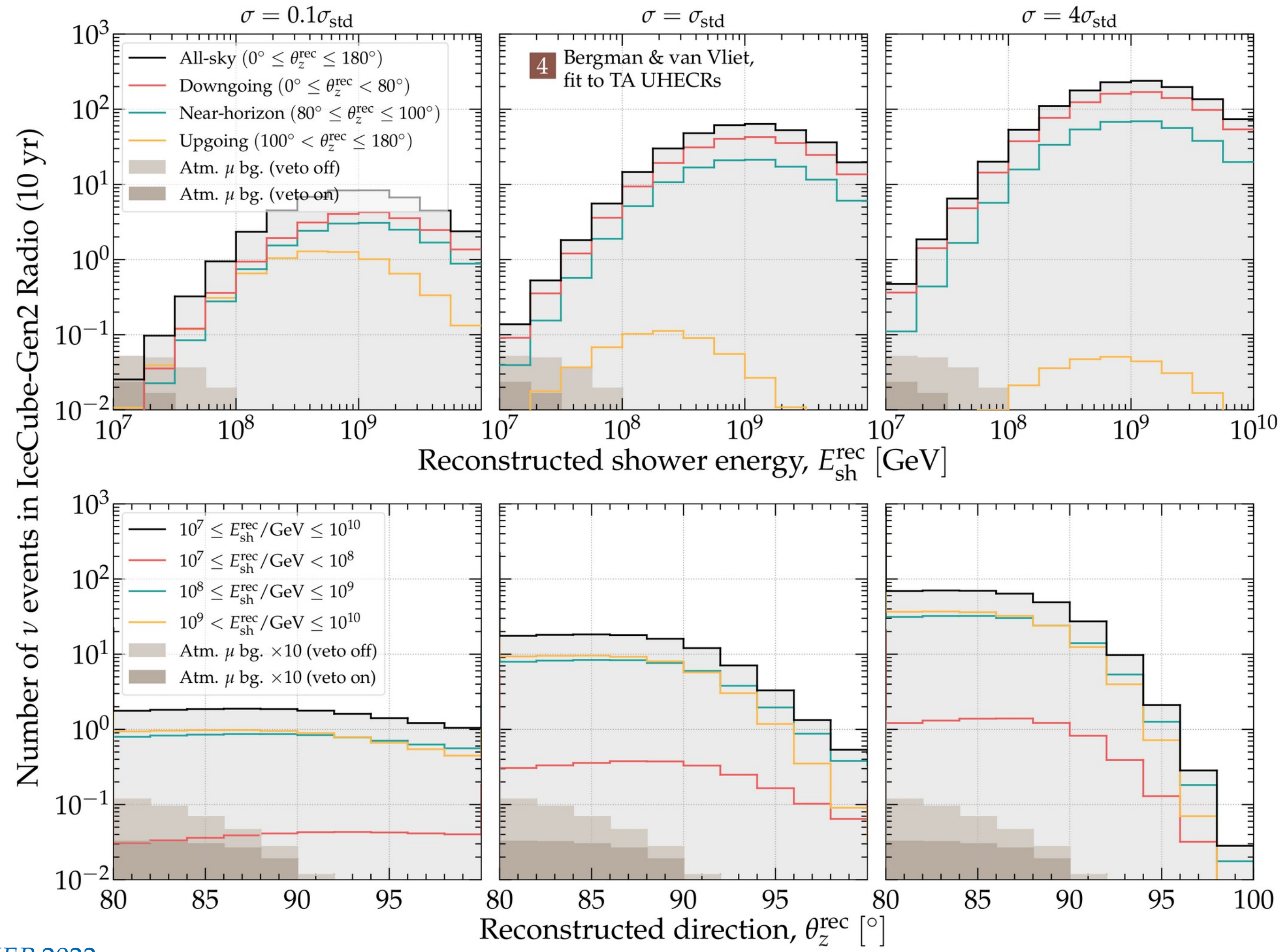
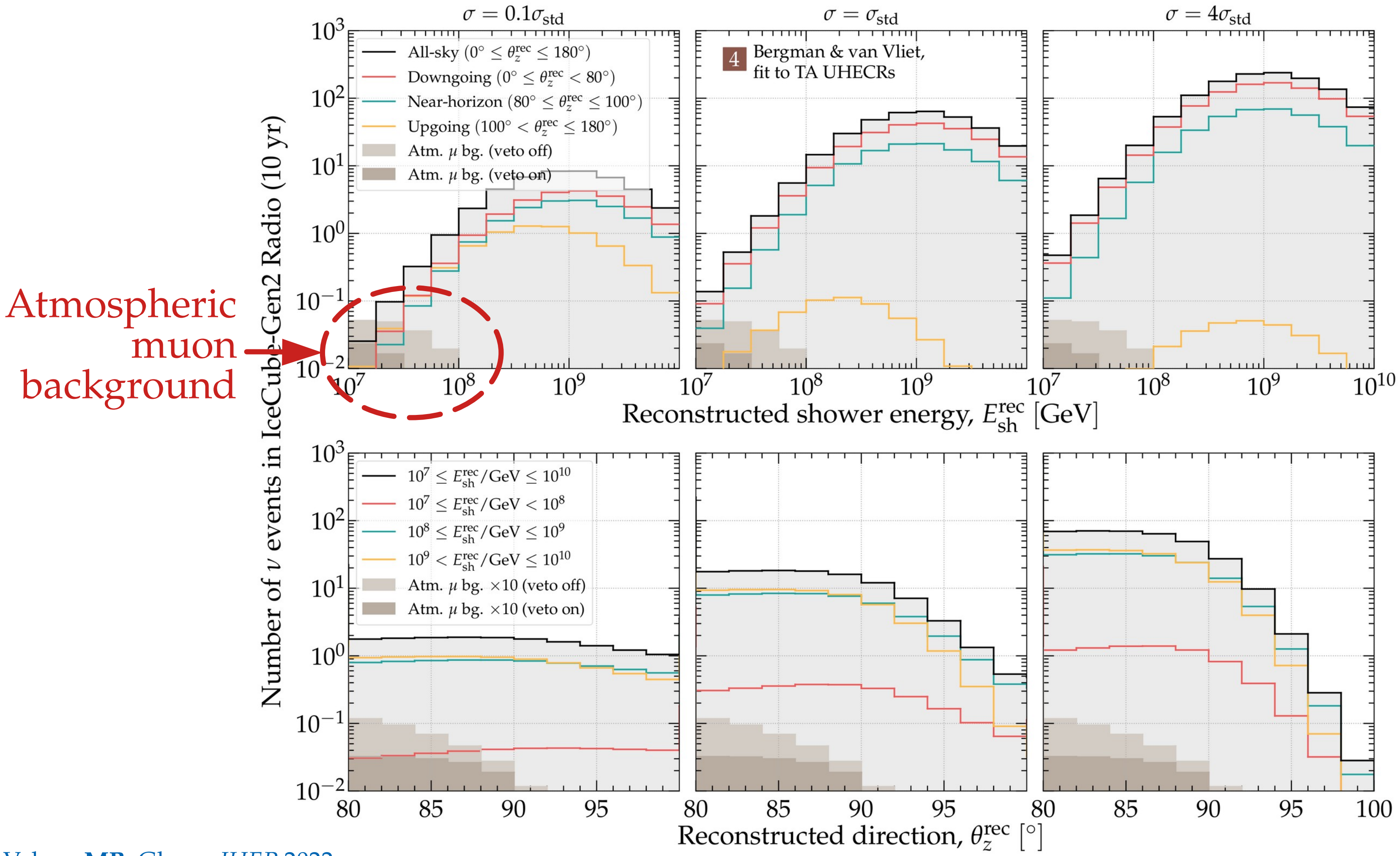
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Attenuation in Earth $e^{-\tau_{\nu N}}$
Opaque Earth
$e^{-\tau}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

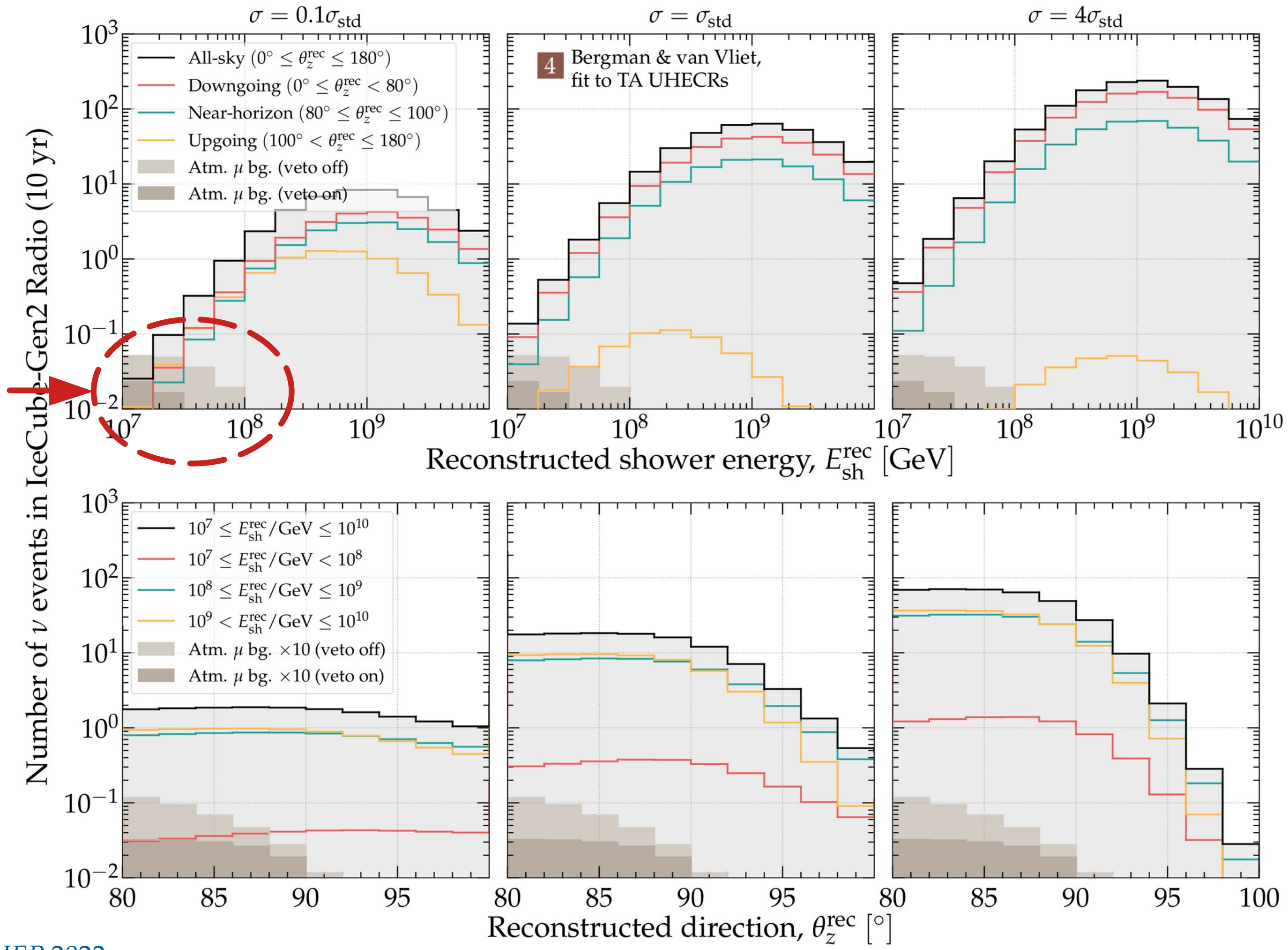


Valera, **MB**, Glaser, *JHEP* 2022



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

Larger neutrino-nucleon cross section



Atmospheric muon background

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

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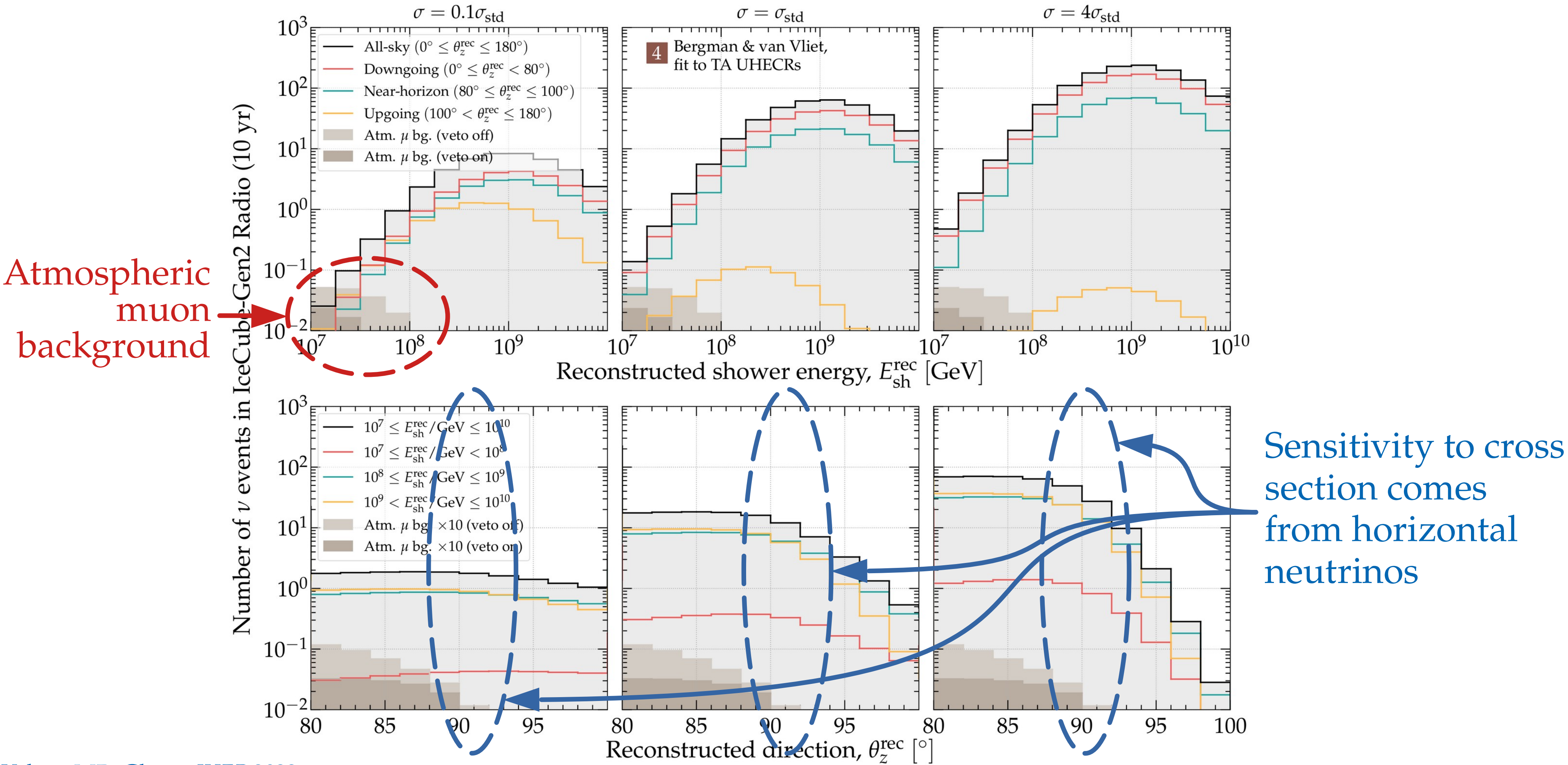

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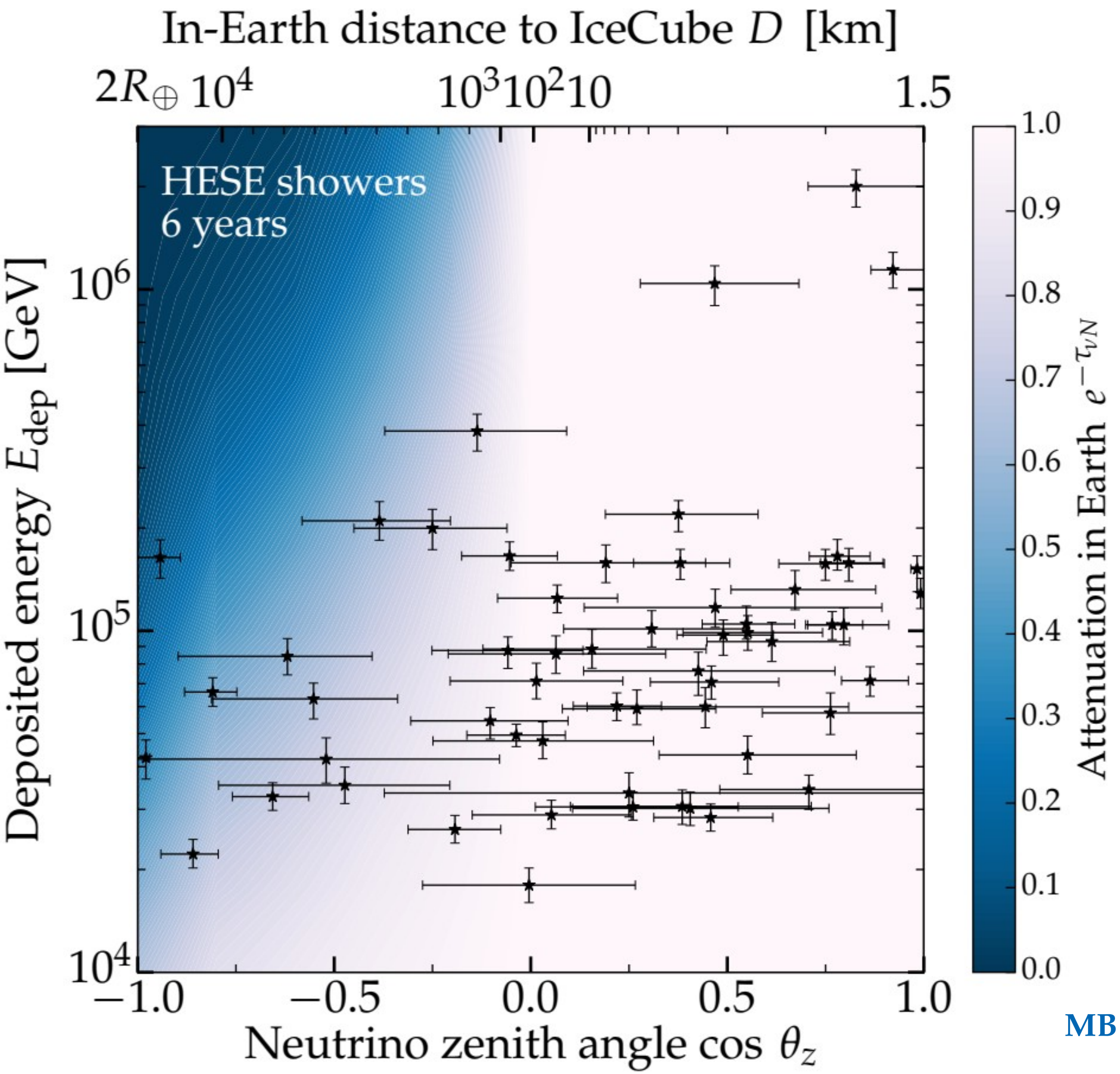
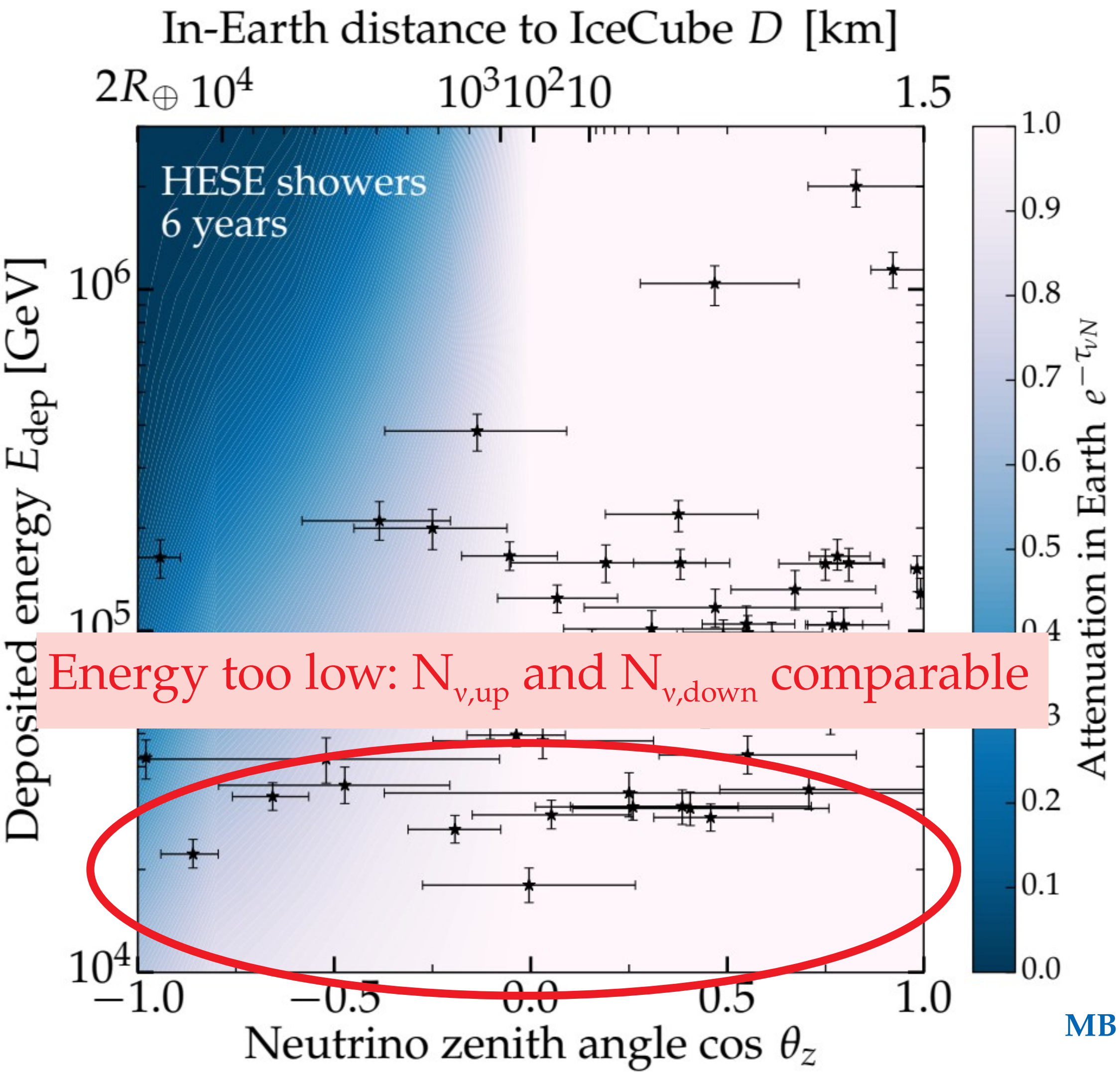


MB & Connolly, *PRL* 2019



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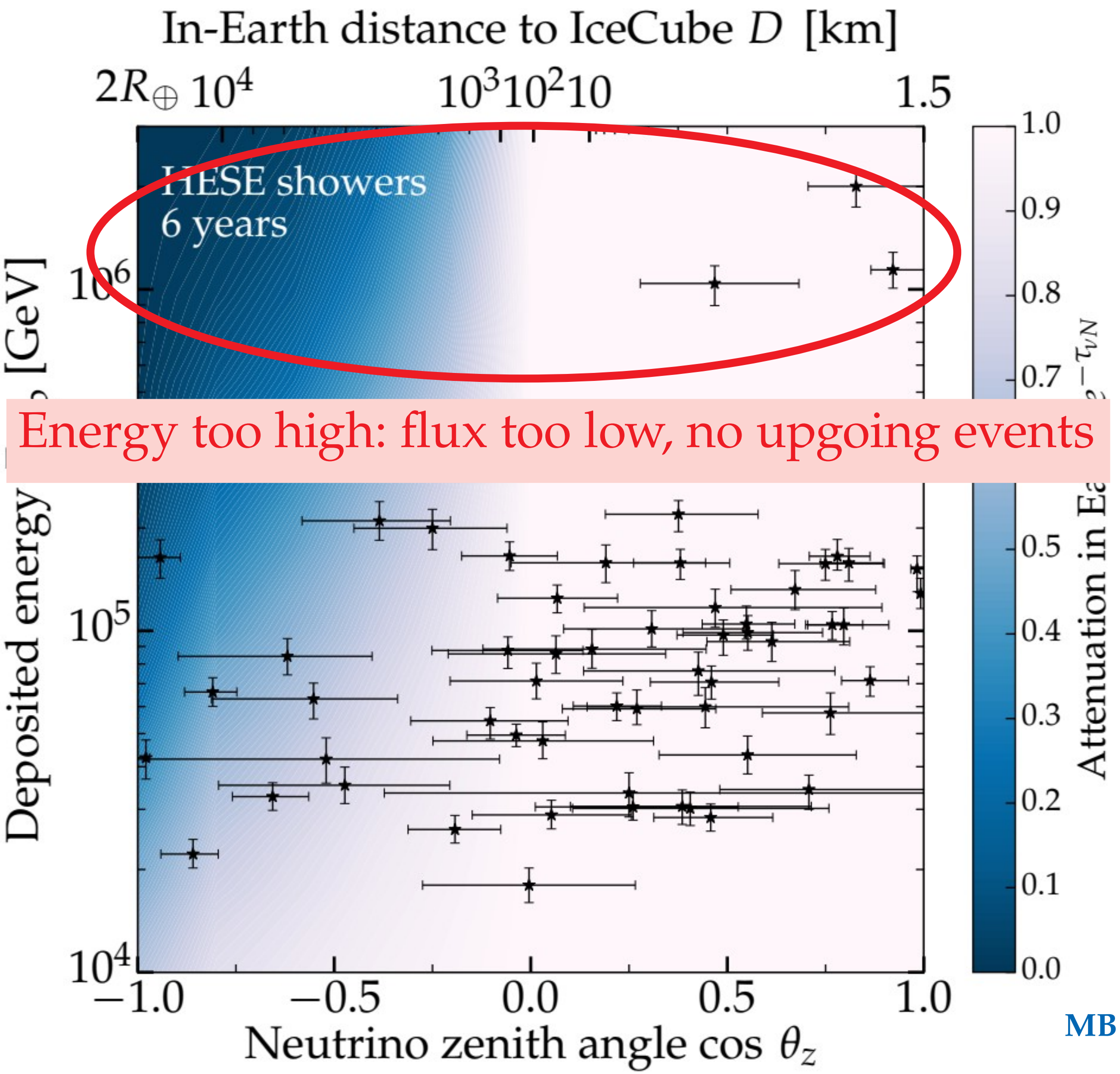

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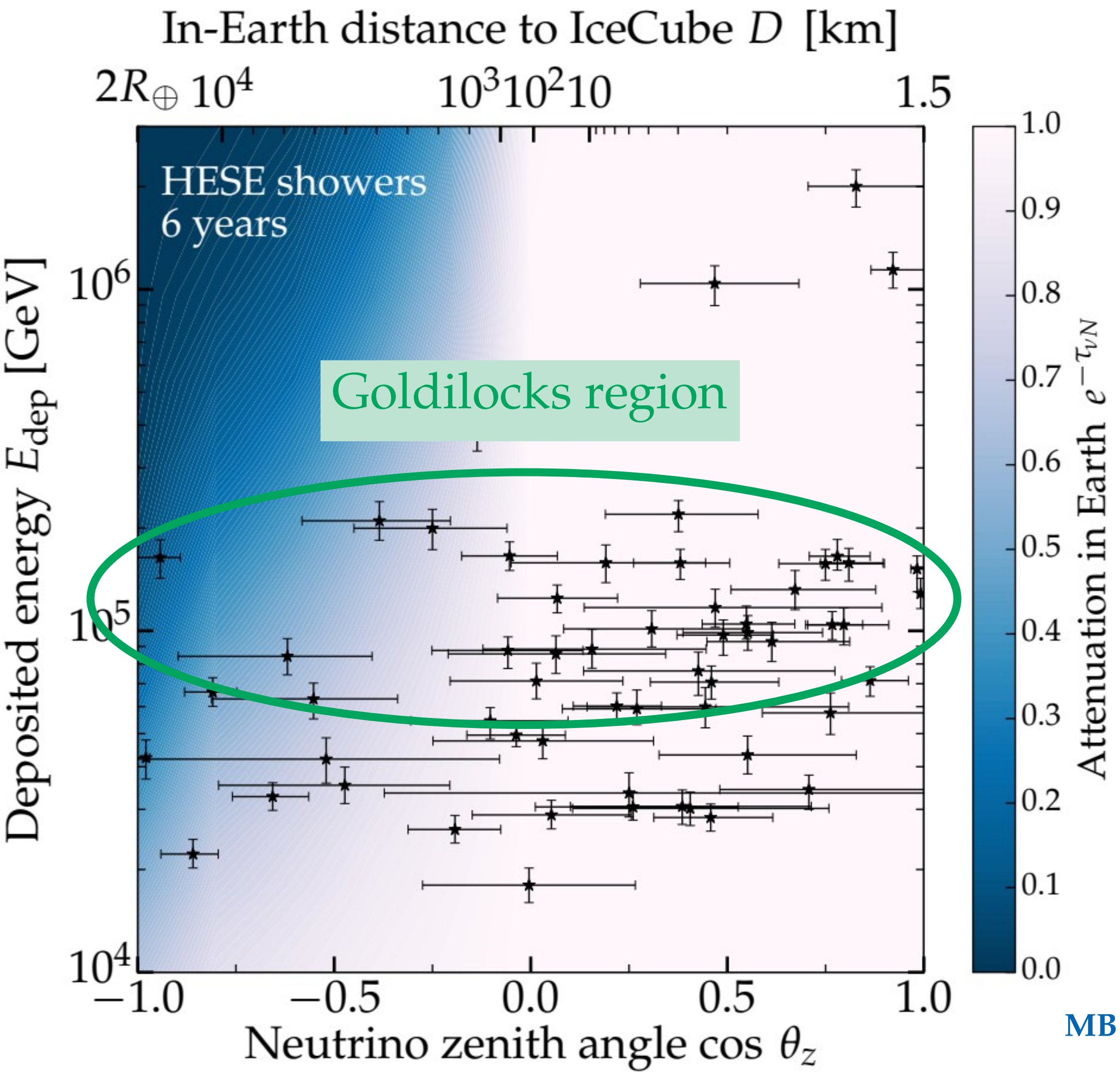

MB & Connolly, *PRL* 2019

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,

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

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

or

Explore all possible combinations

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

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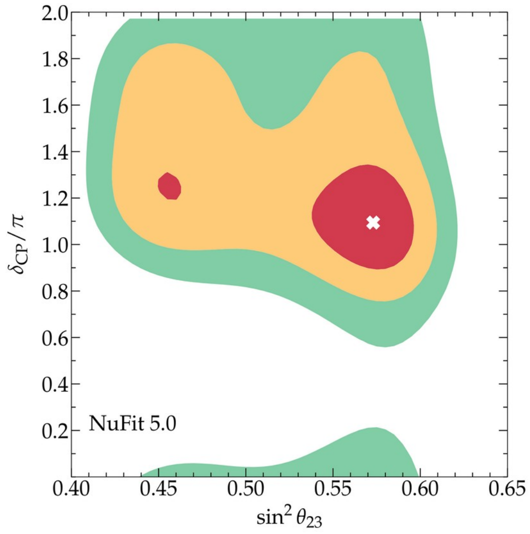
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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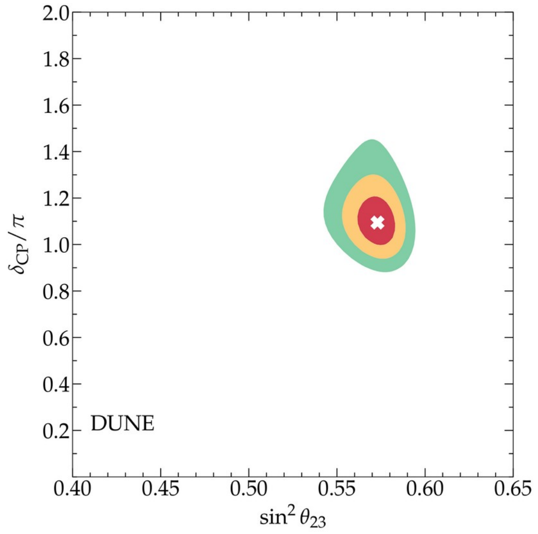
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



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

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 → no matter)

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

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(L short → no matter)

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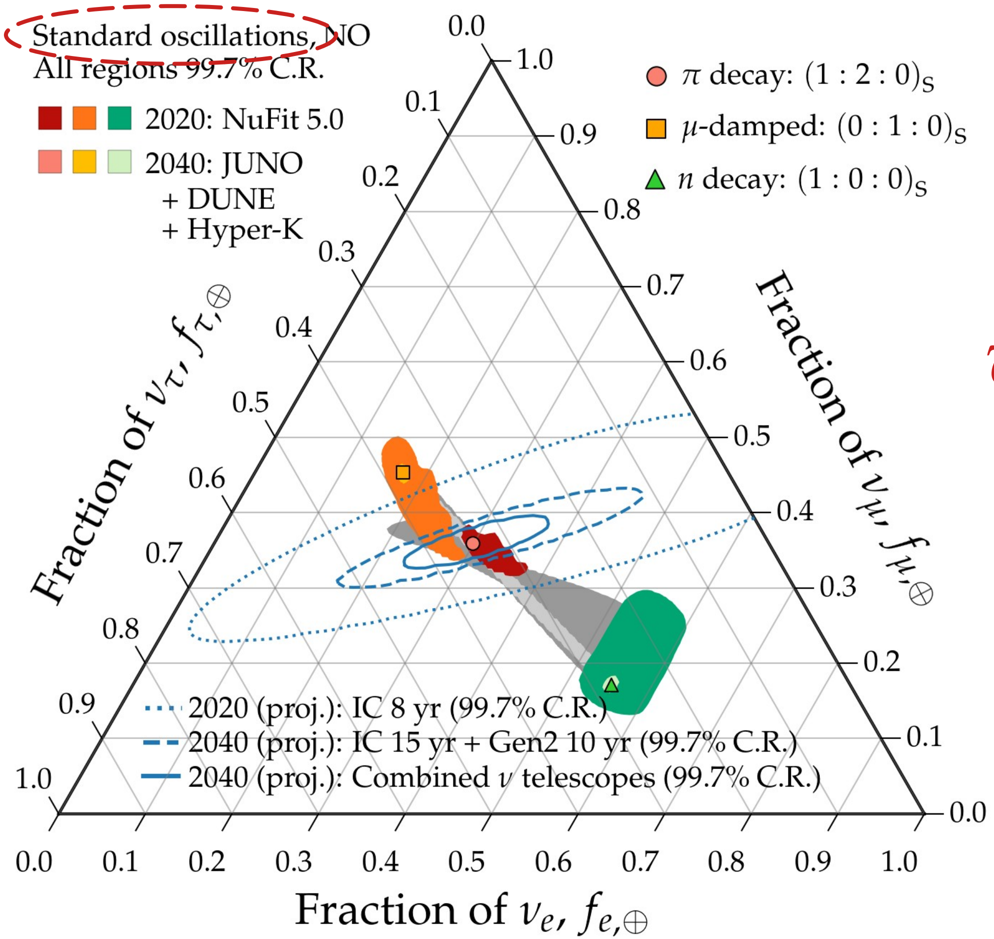
Upgoing neutrinos
(L long → lots of matter)

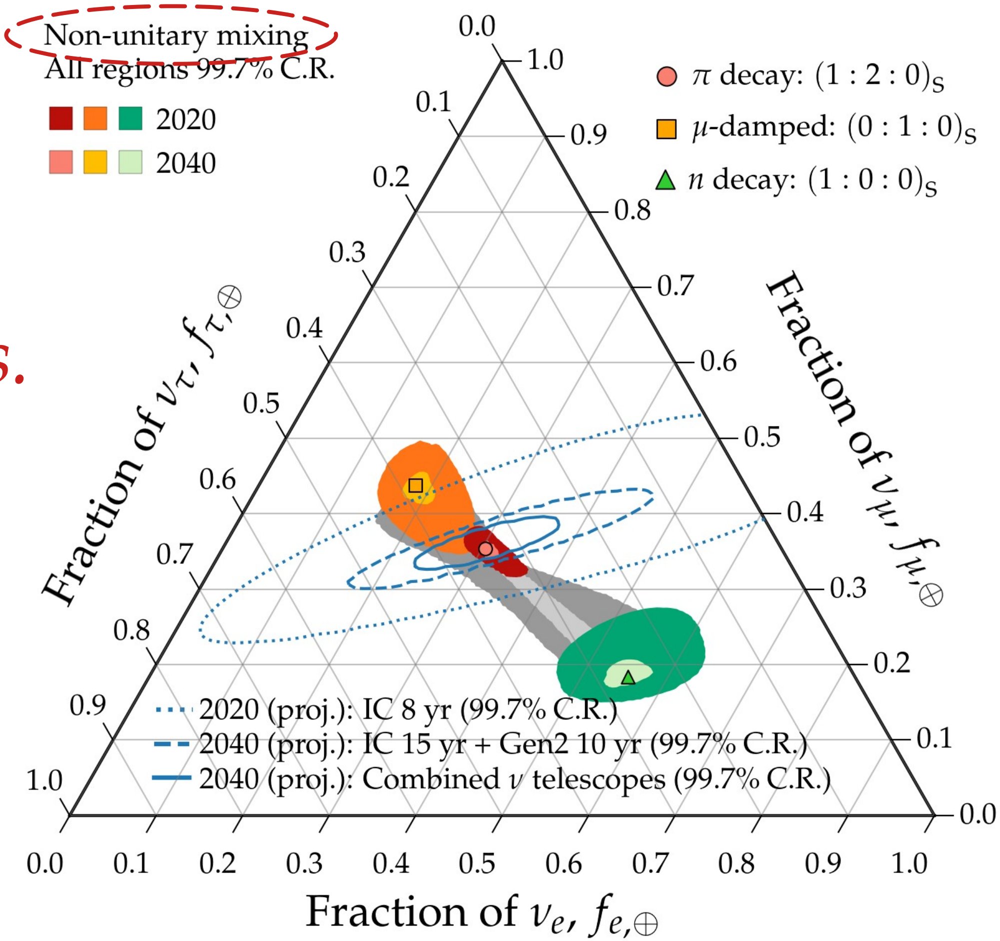
$$N \propto \Phi_\nu \sigma_{\nu N} \underbrace{e^{-L \sigma_{\nu N} n_N}}_{\text{Breaks the degeneracy}}$$

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

No unitarity? *No problem*



vs.



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

What does neutrino decay change?

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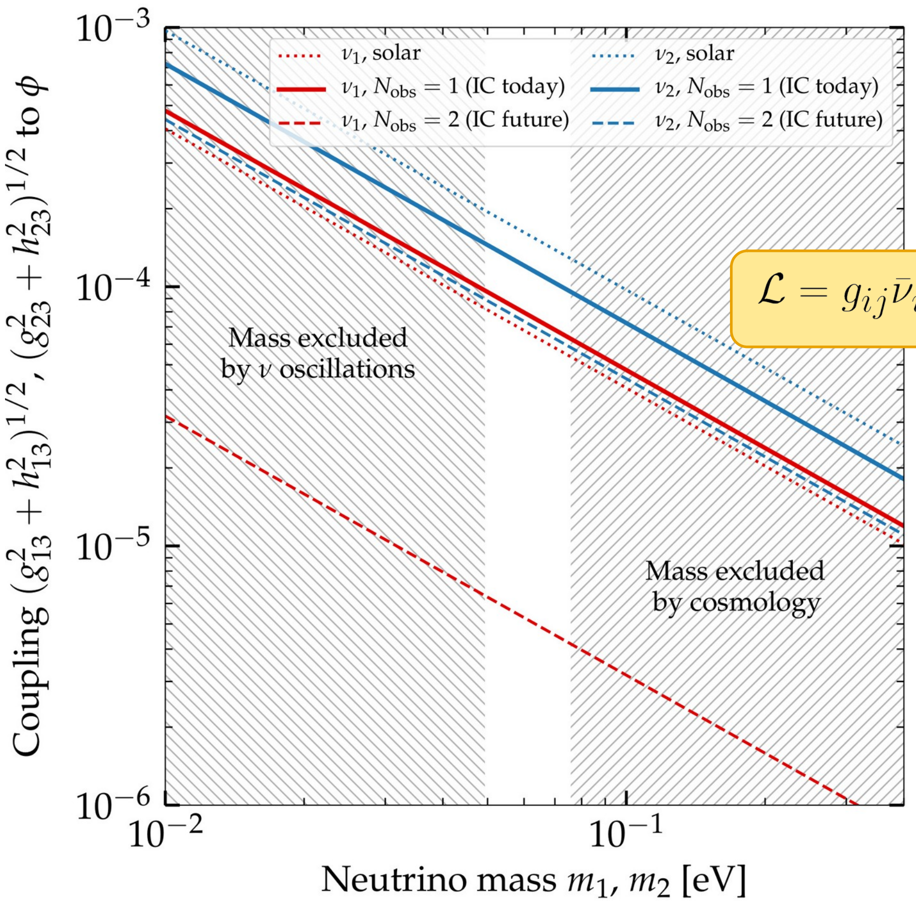
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

Lower limits on couplings

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Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

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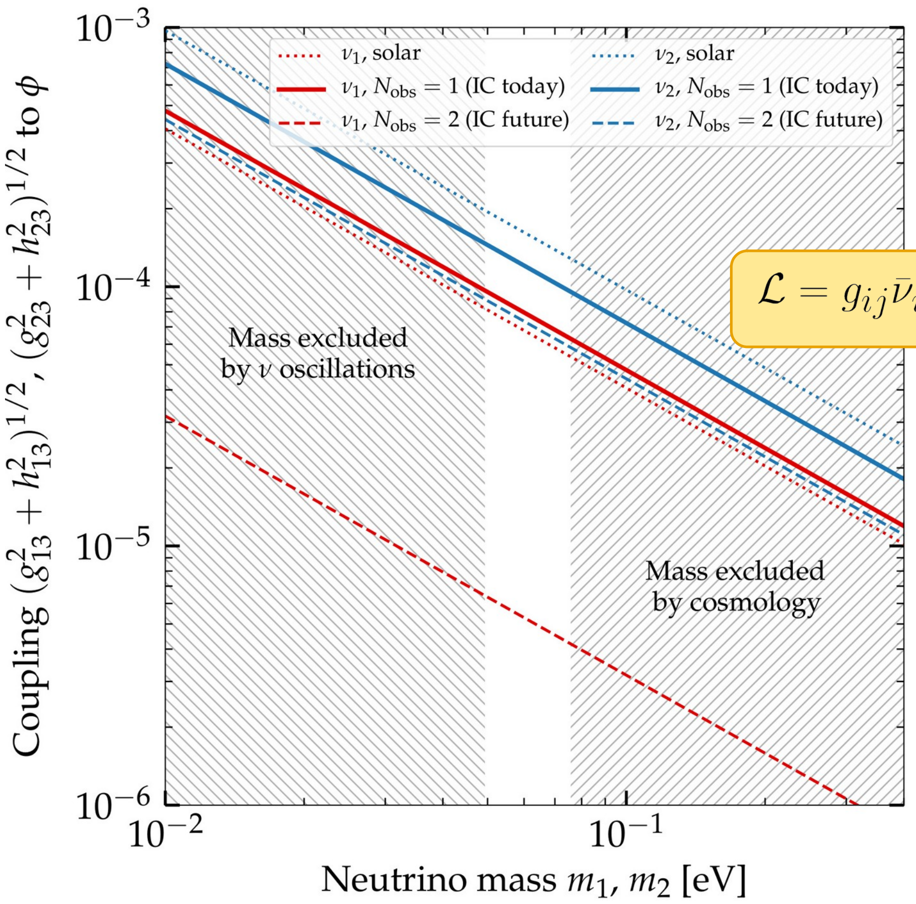

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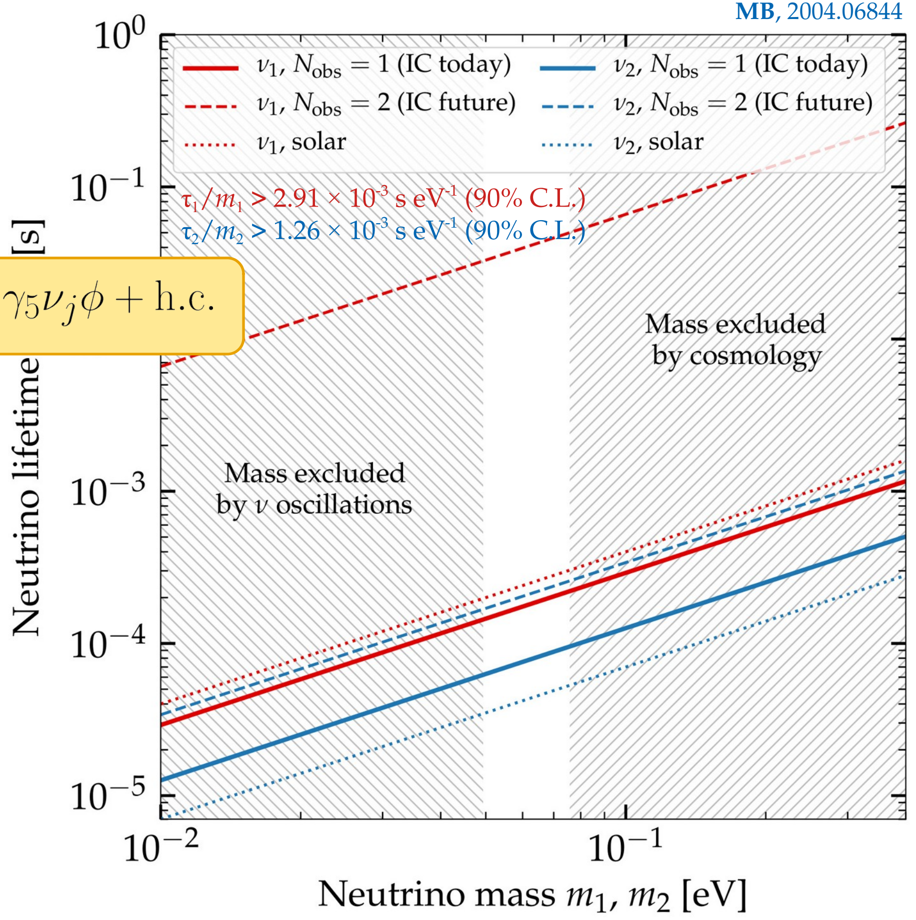

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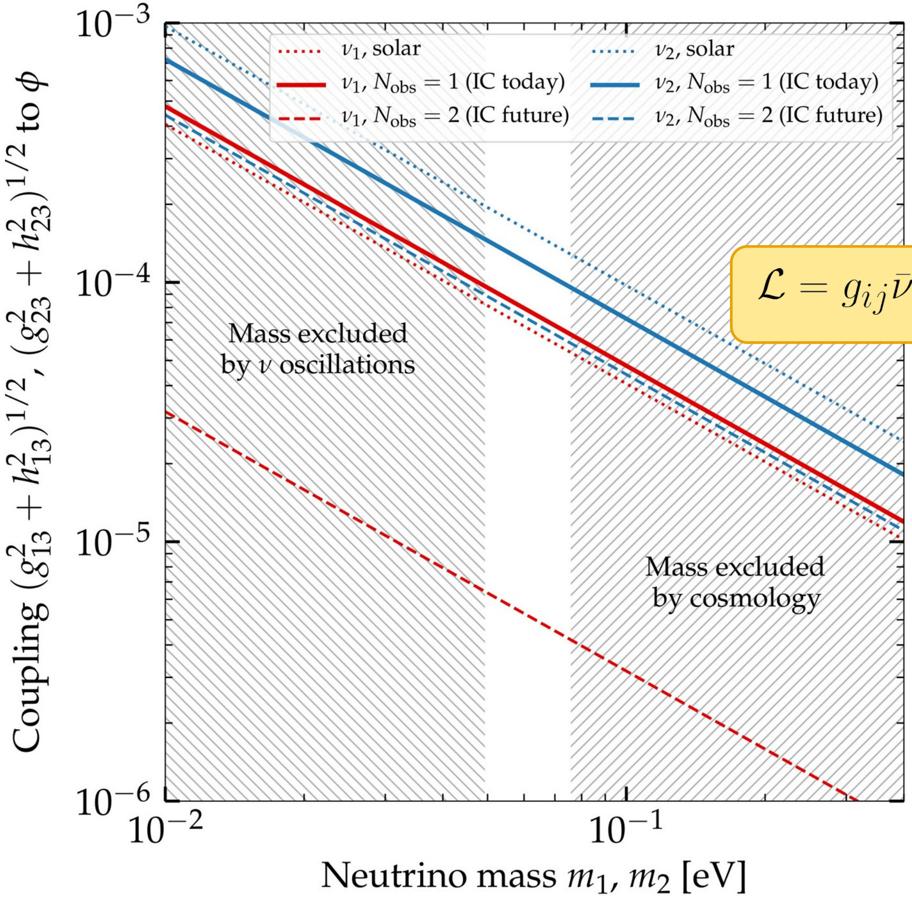

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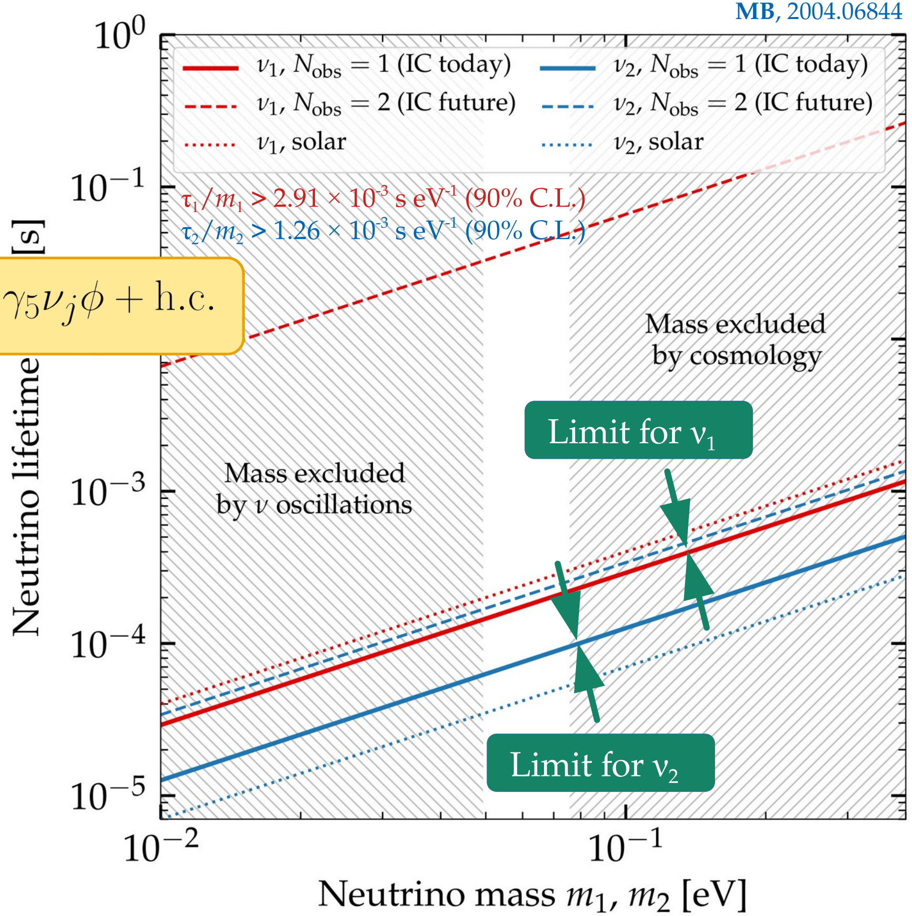
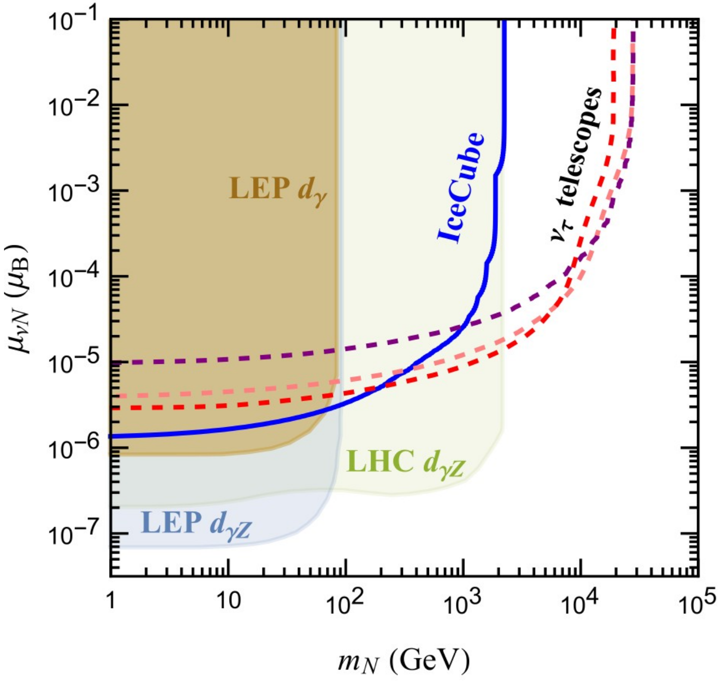


New physics in the UHE νN cross section

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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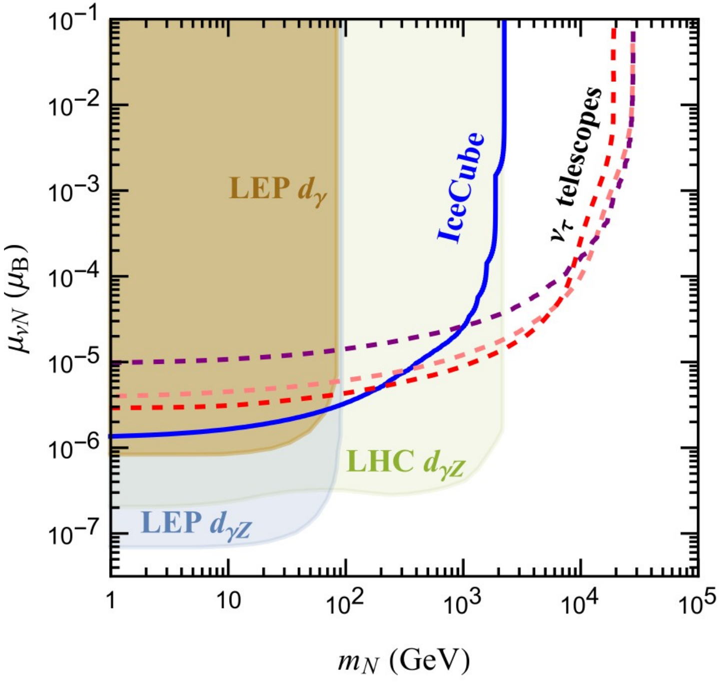
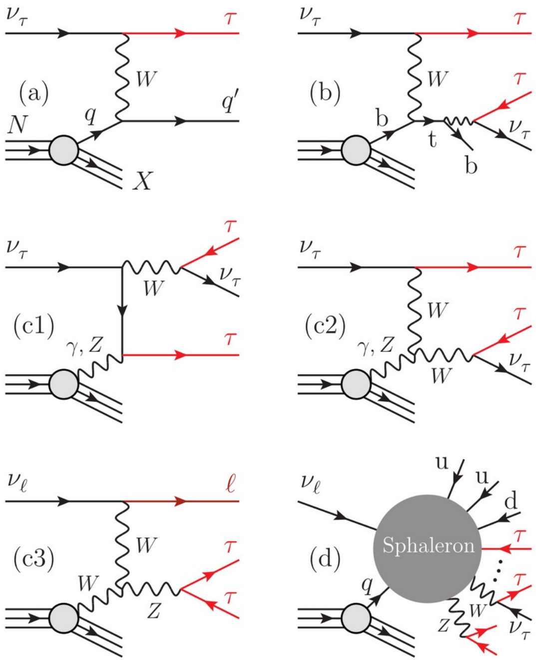


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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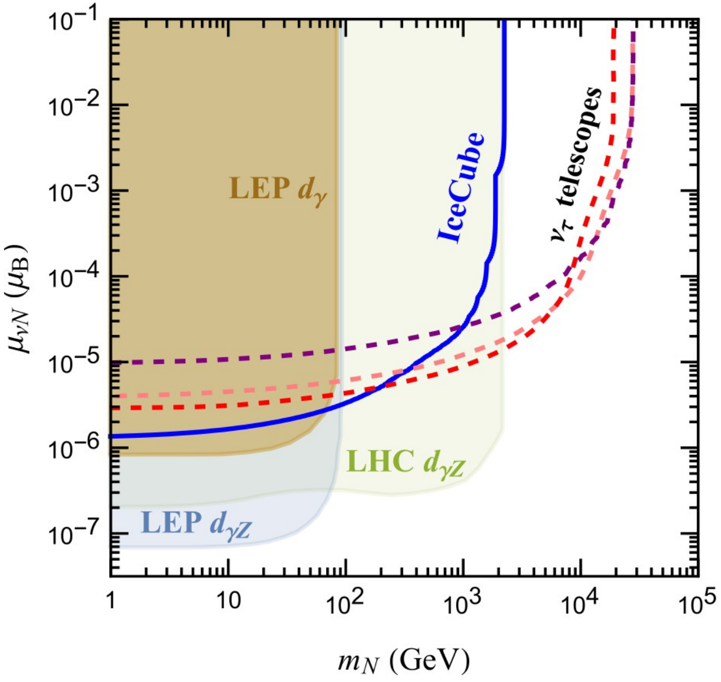

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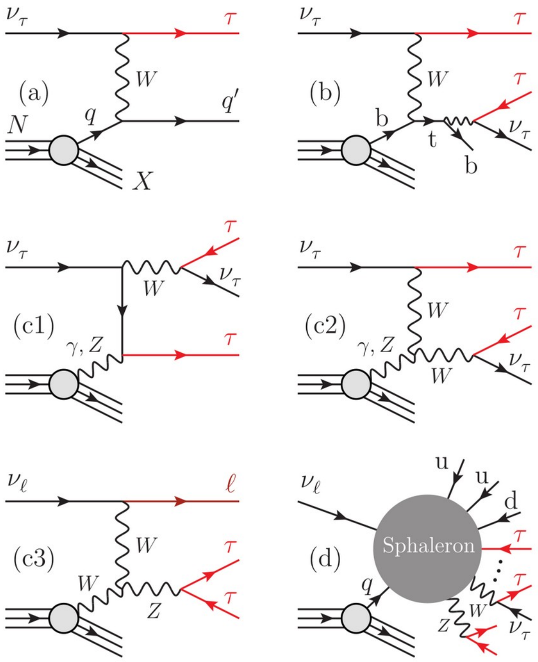
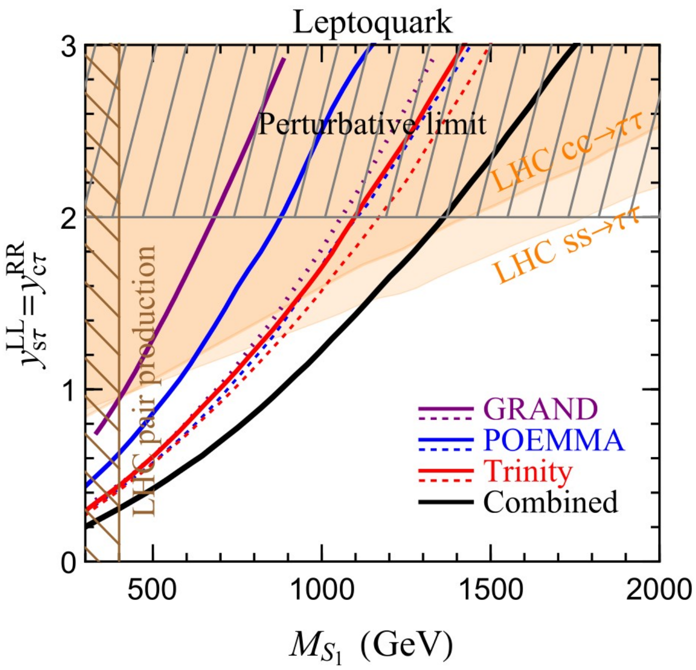


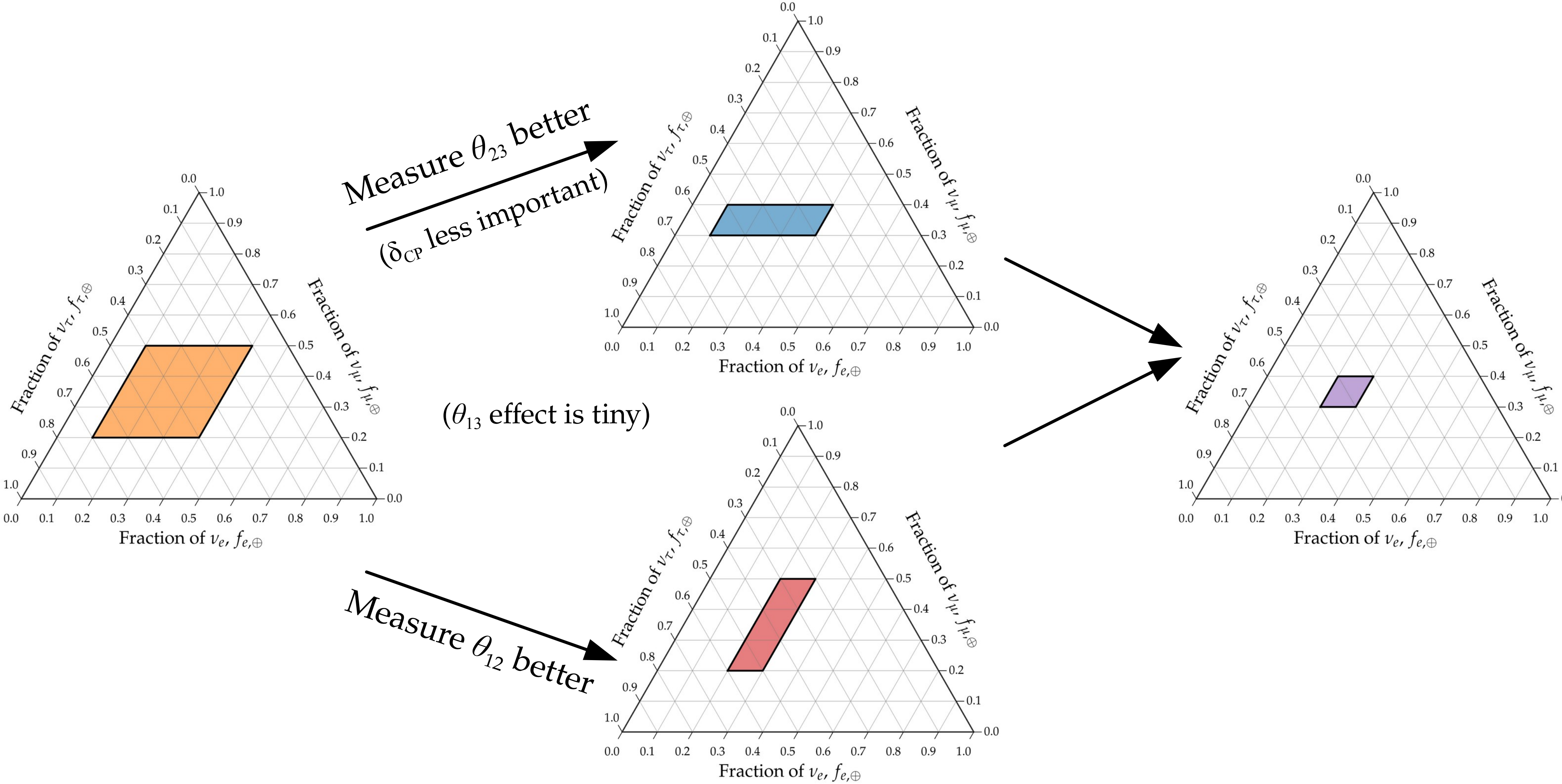
Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc.*



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

How knowing the mixing parameters better helps



What does neutrino decay change?

Flavor composition ⇔ Spectrum shape ⇔ Event rate

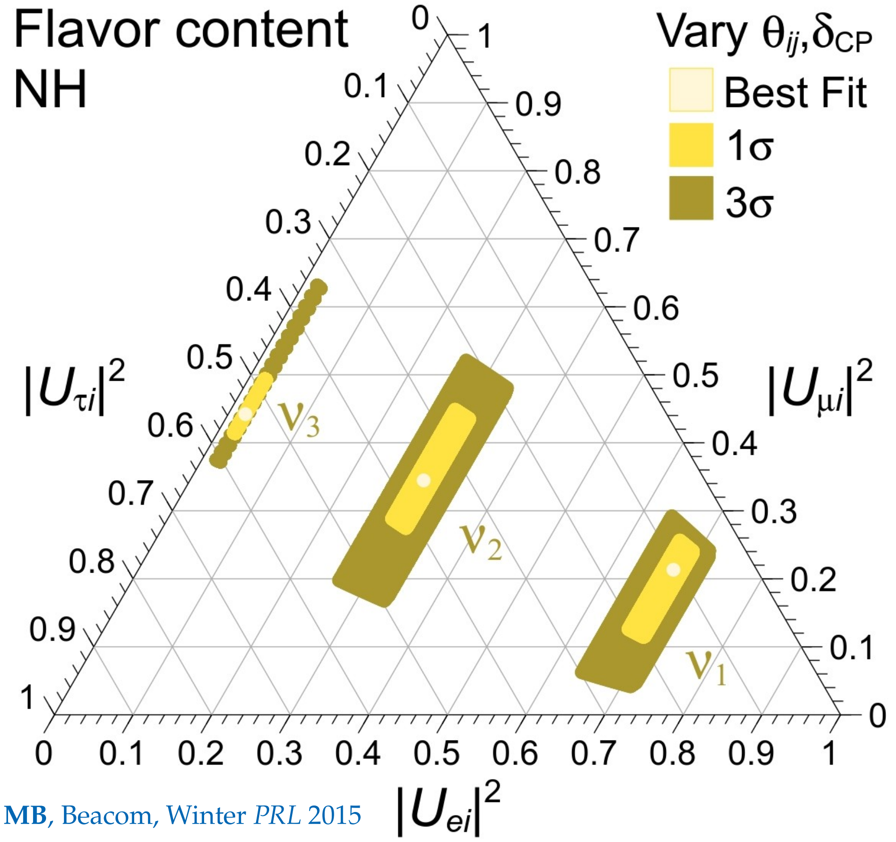
Flavor content of mass eigenstates:

Known to within 2%

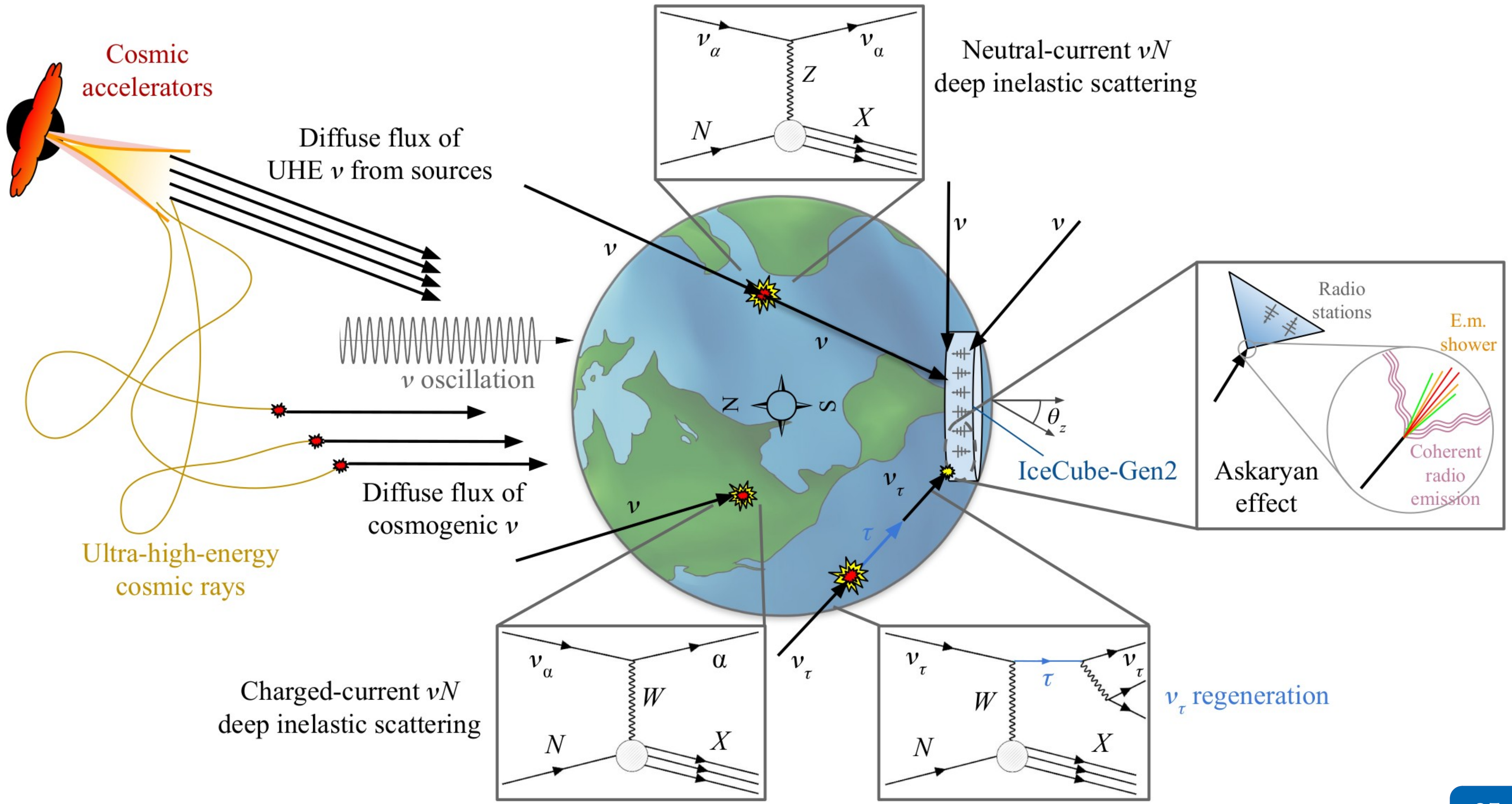
$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})|^2$$

Known to within 8%

Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015



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

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

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

- 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

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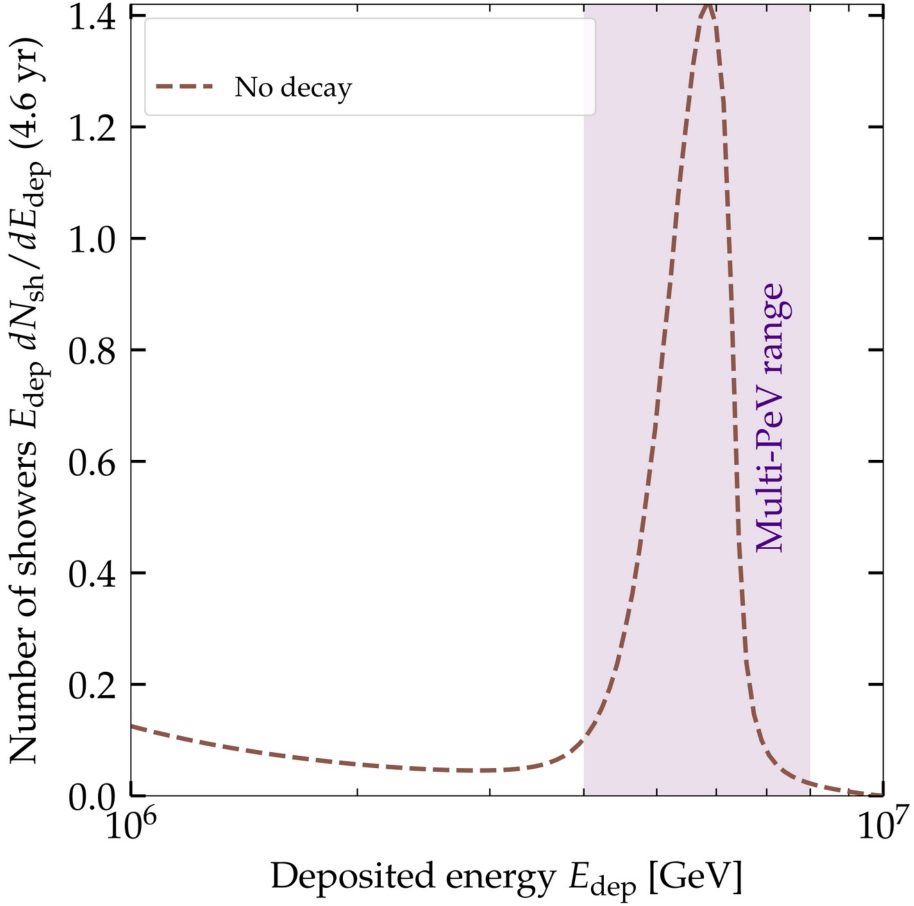
What does neutrino decay change?

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

MB, 2004.06844



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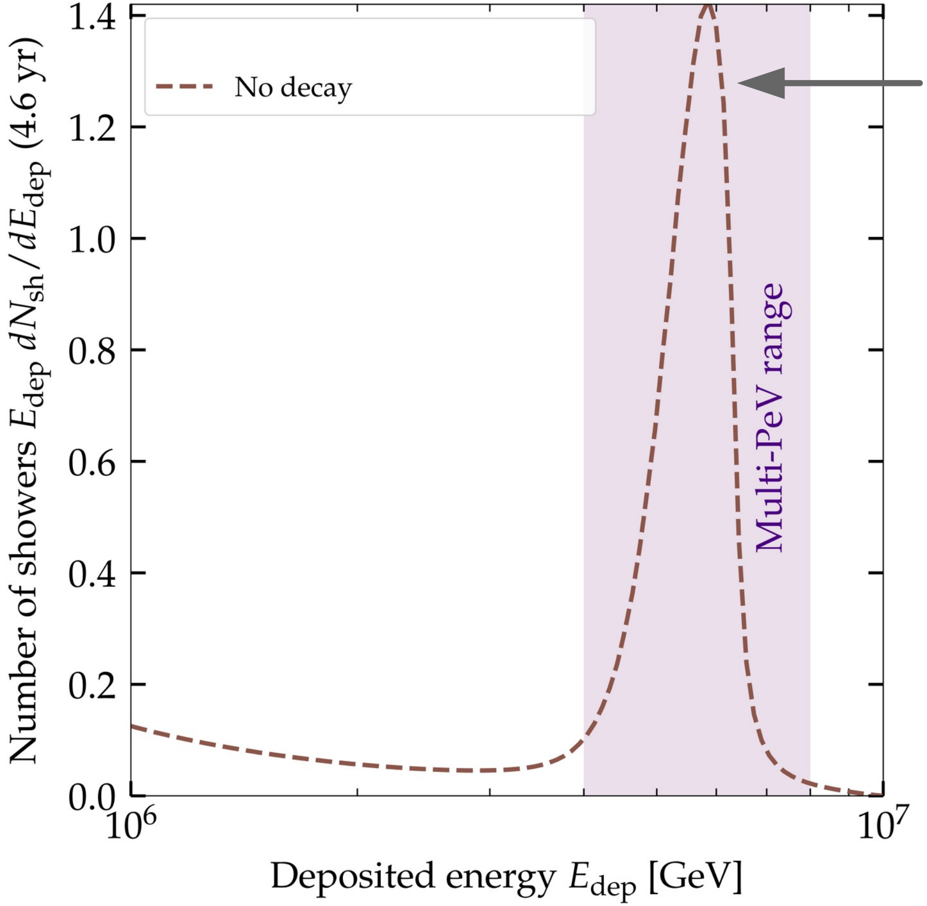

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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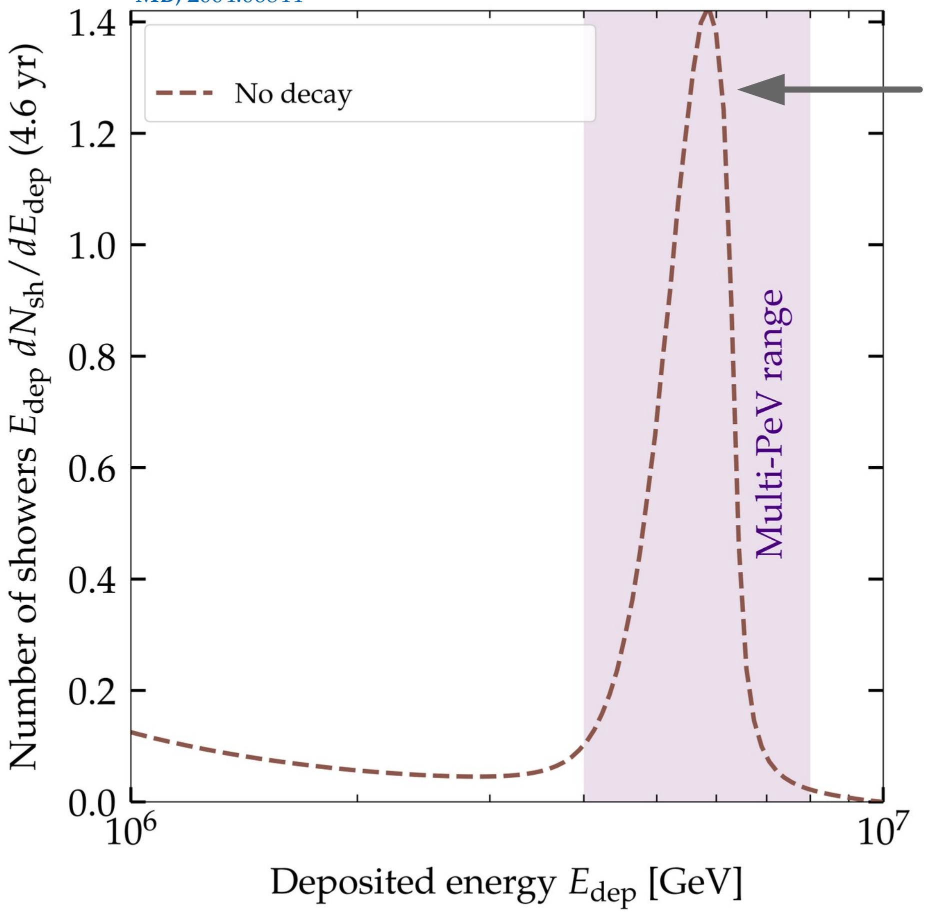

Glashow resonance (GR):
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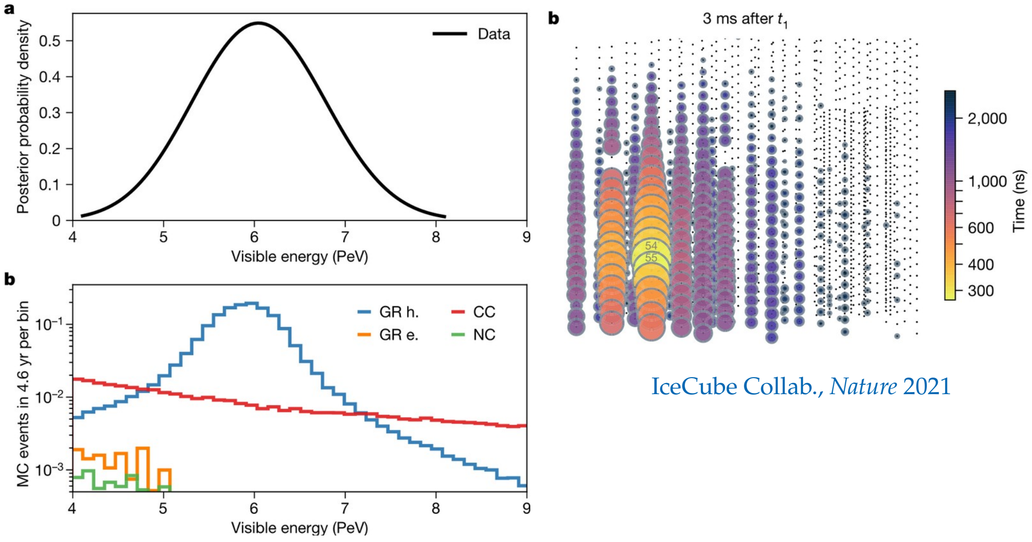
IceCube has seen one GR candidate in 4.6 years:



IceCube Collab., *Nature* 2021

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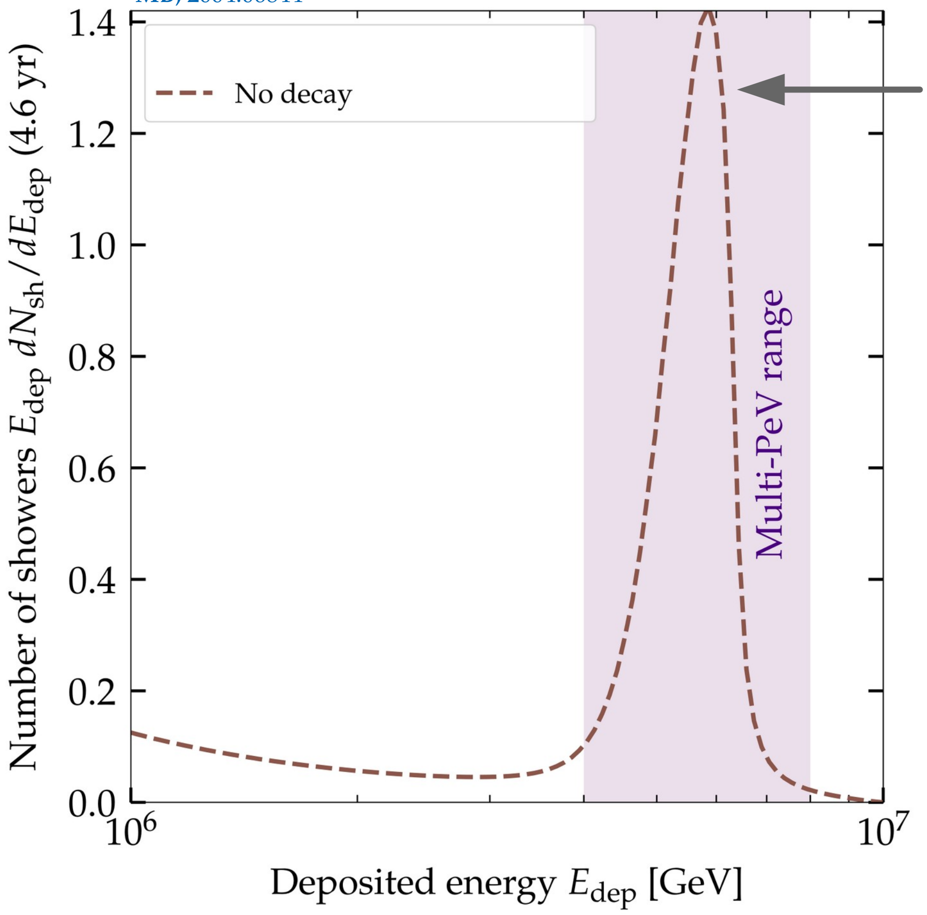
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844



Glashow resonance (GR):
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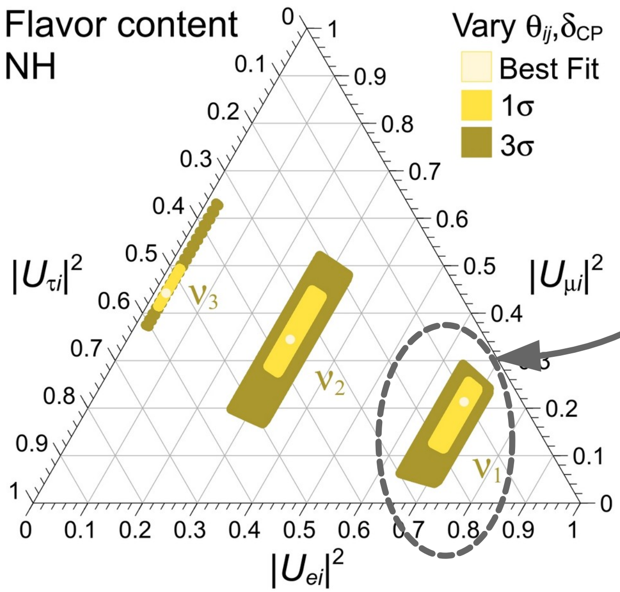
ν_1 is the mass eigenstate with the most e flavor



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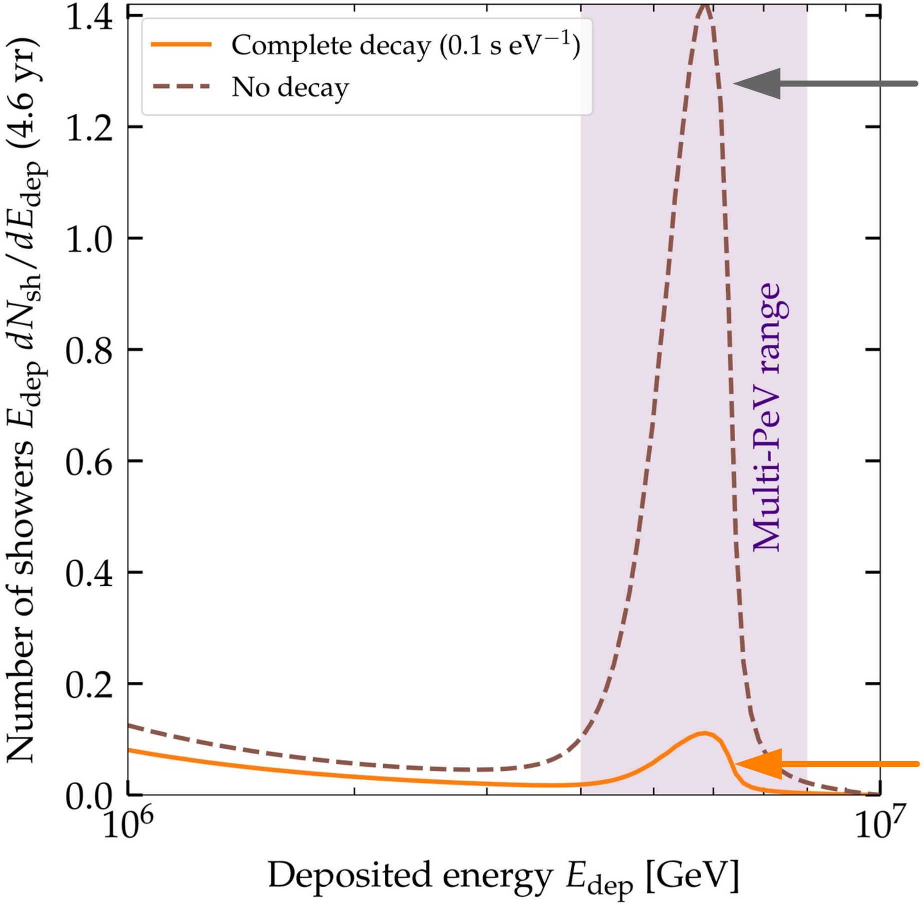

Glashow resonance (GR):
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If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

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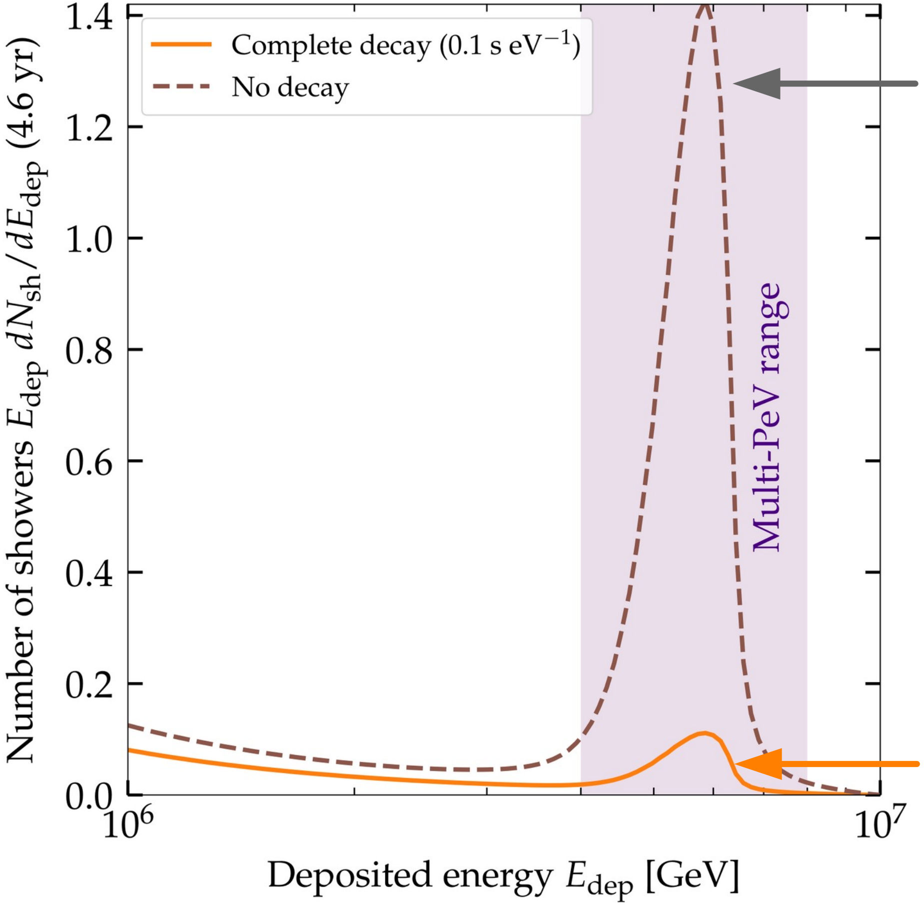

Glashow resonance (GR):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

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Flavor composition ⟺ Spectrum shape ⟺ Event rate

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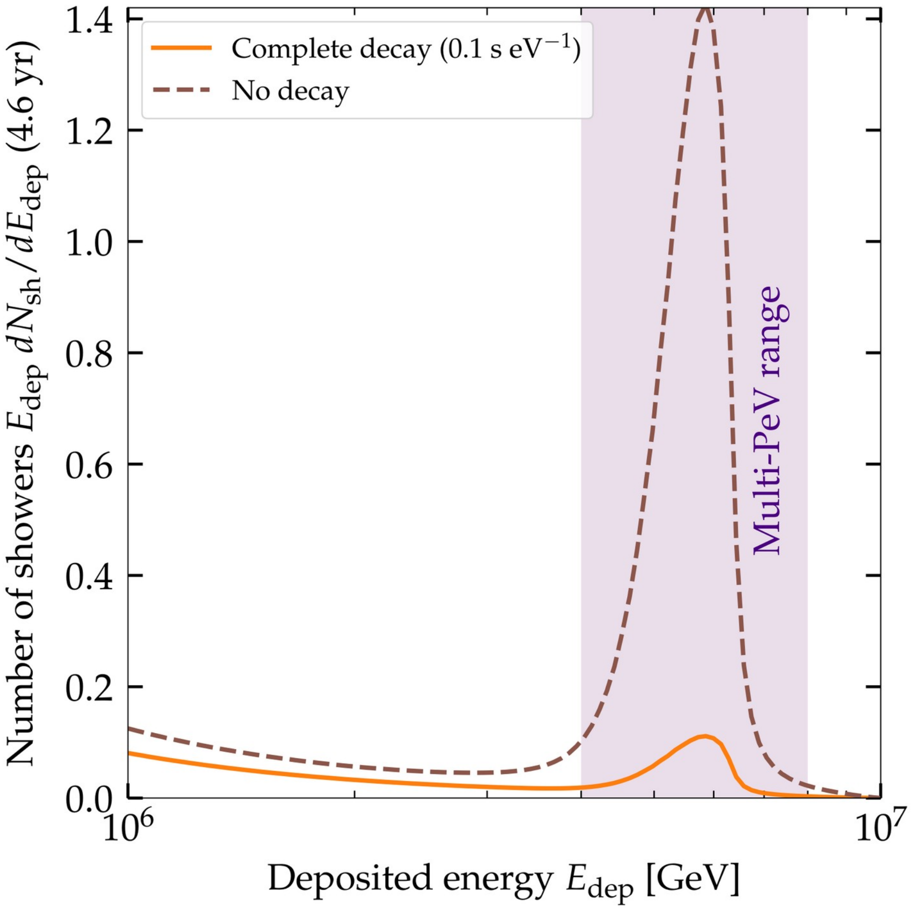

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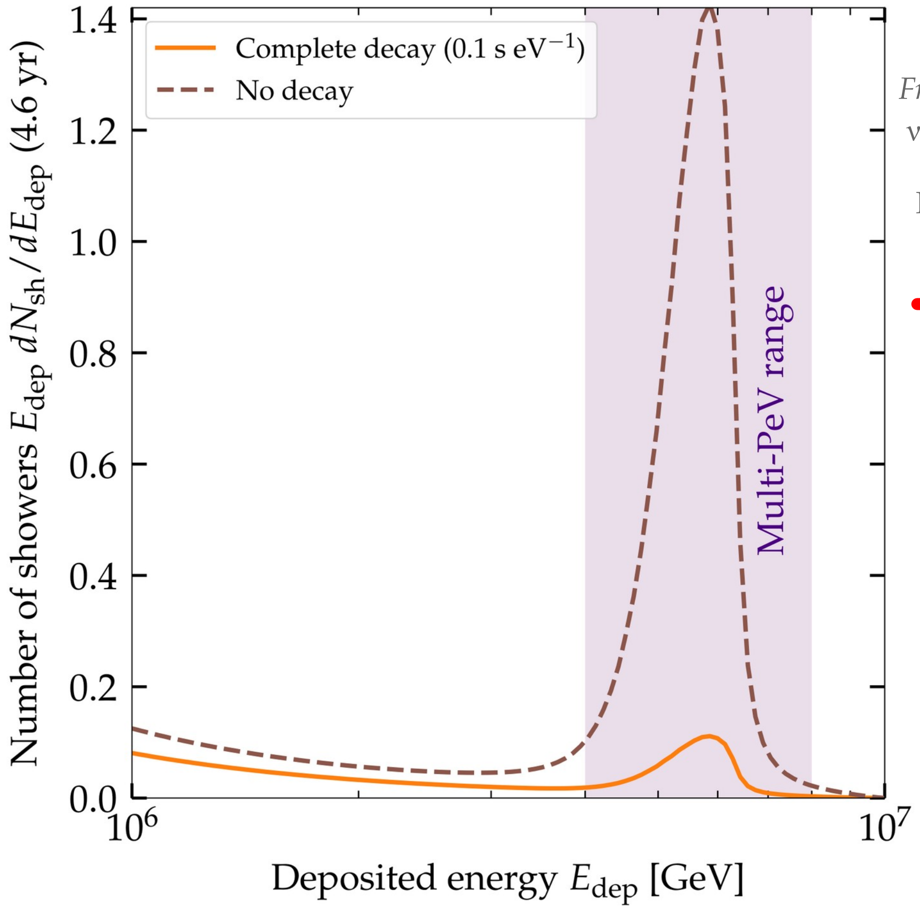

Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

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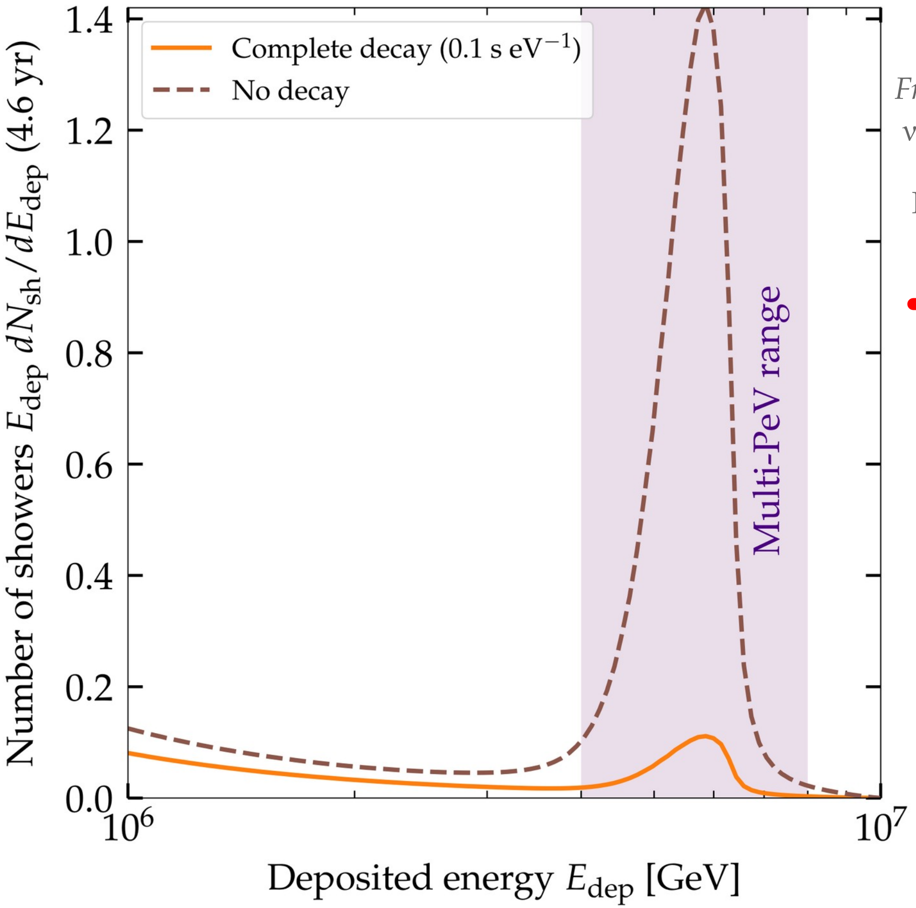
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**



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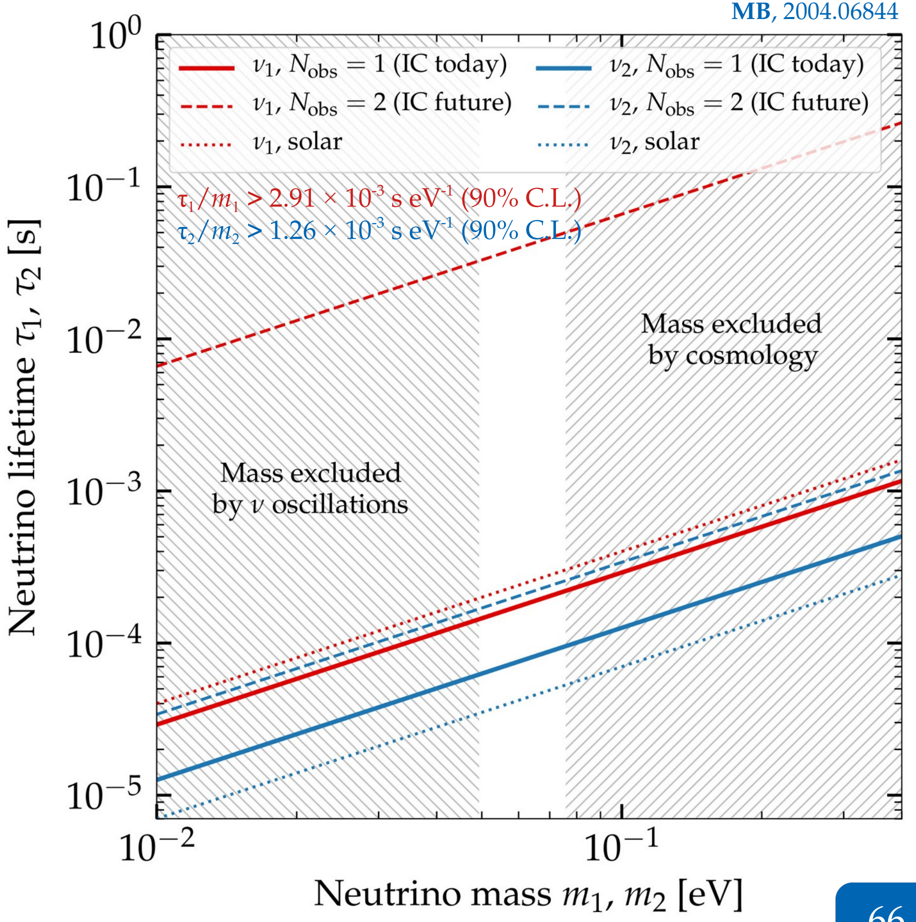

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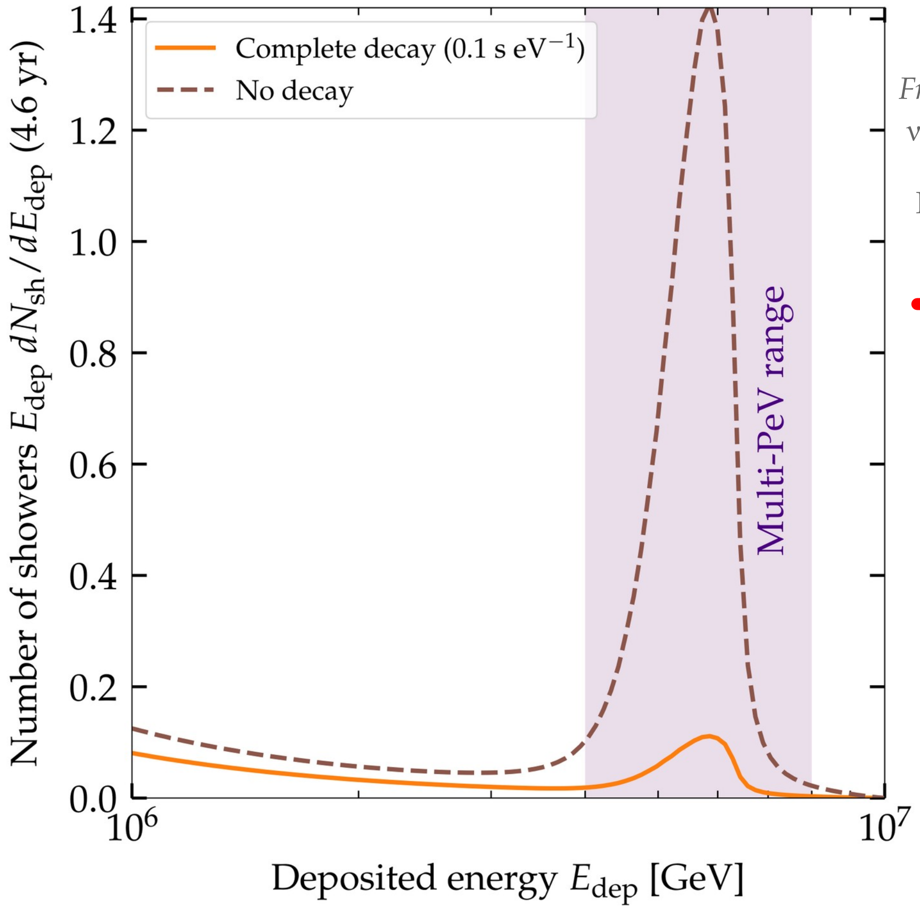

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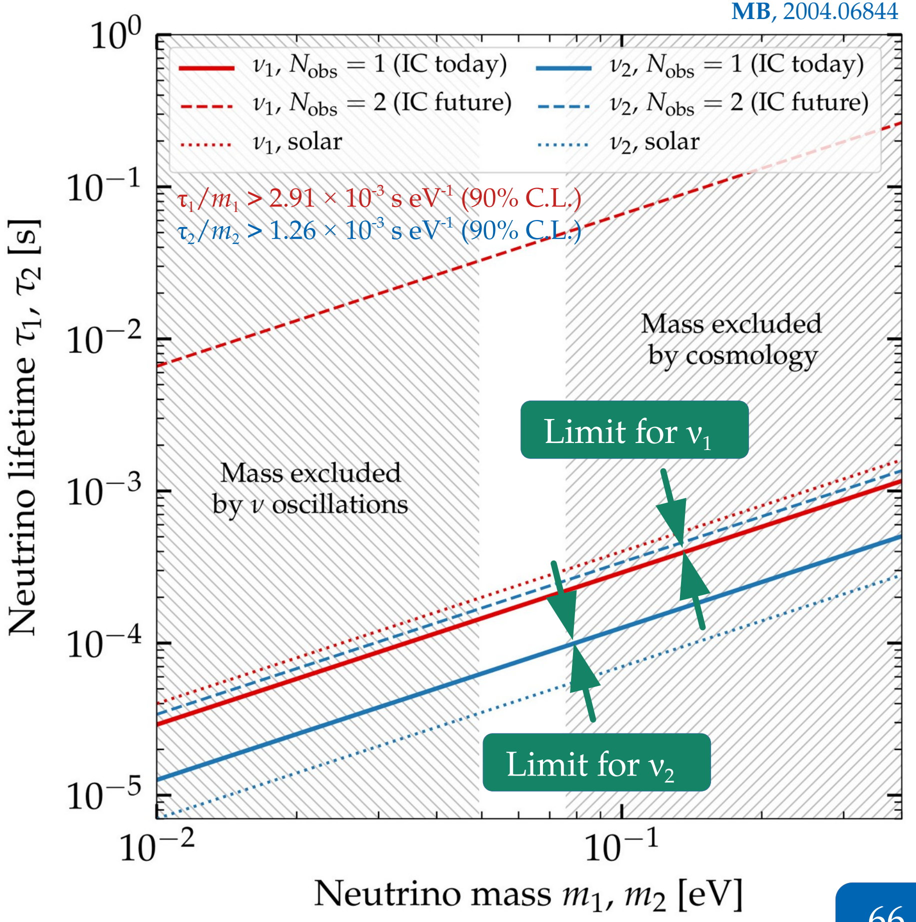

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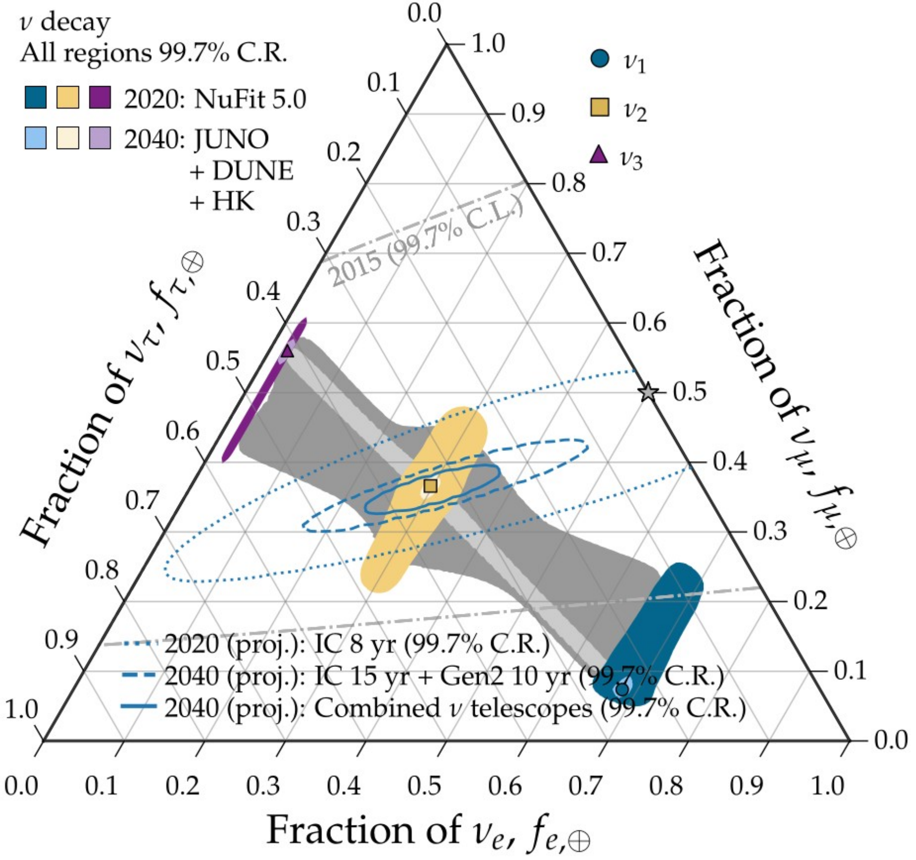

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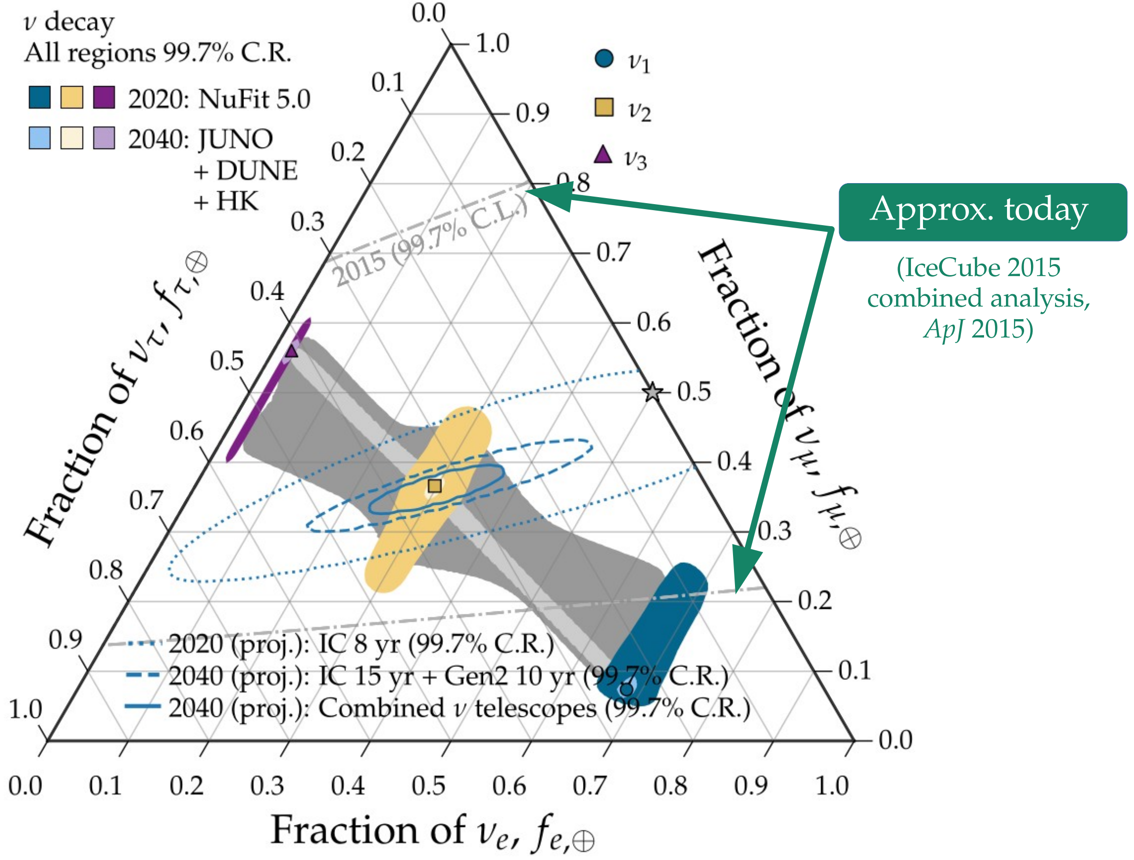

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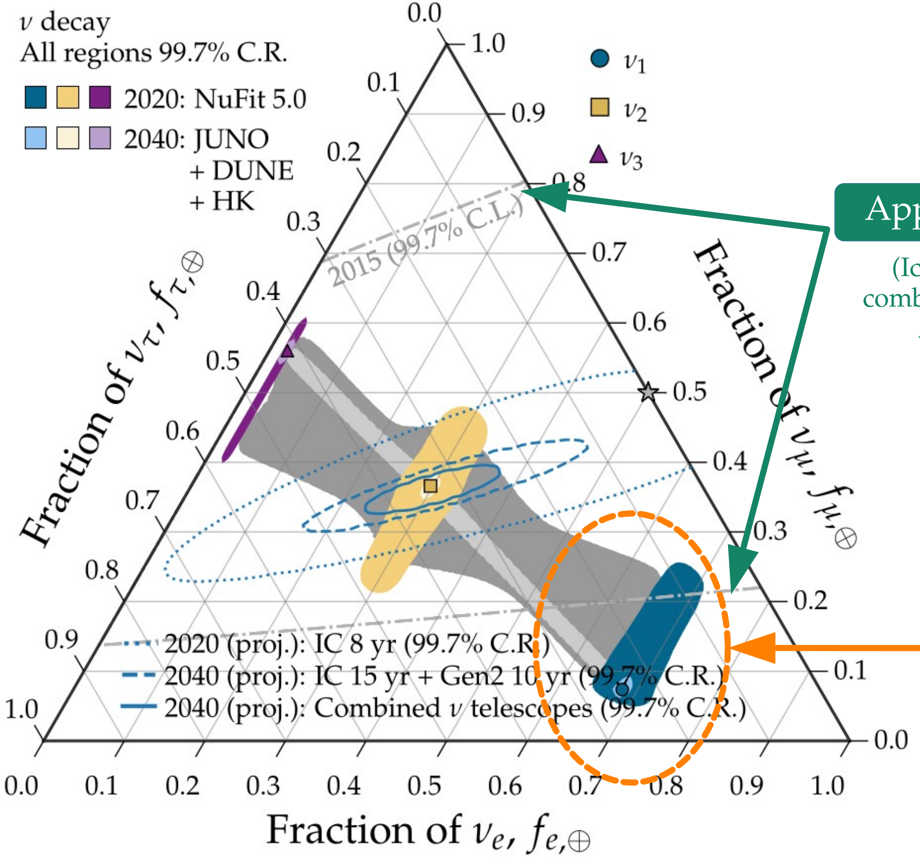


Approx. today

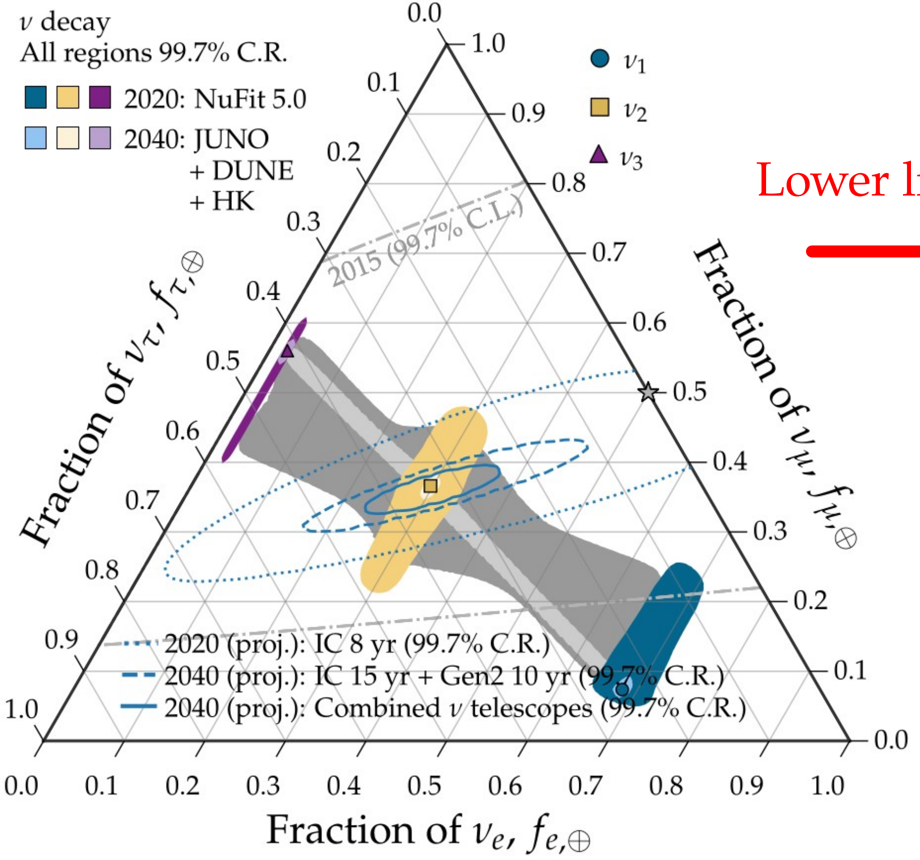
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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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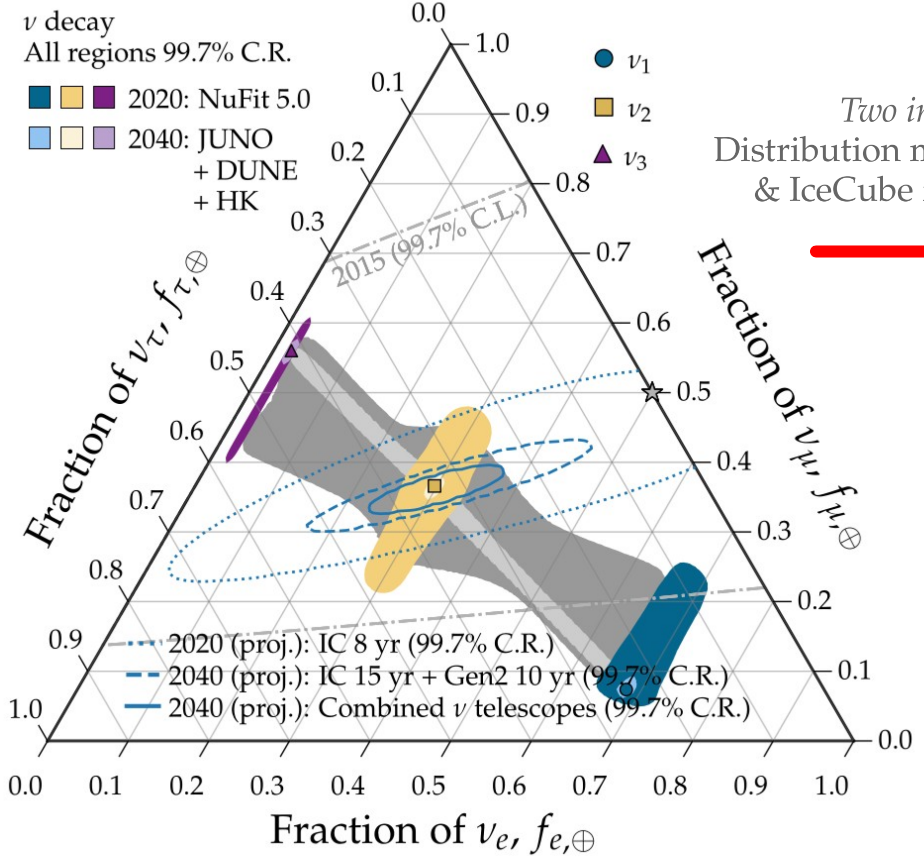

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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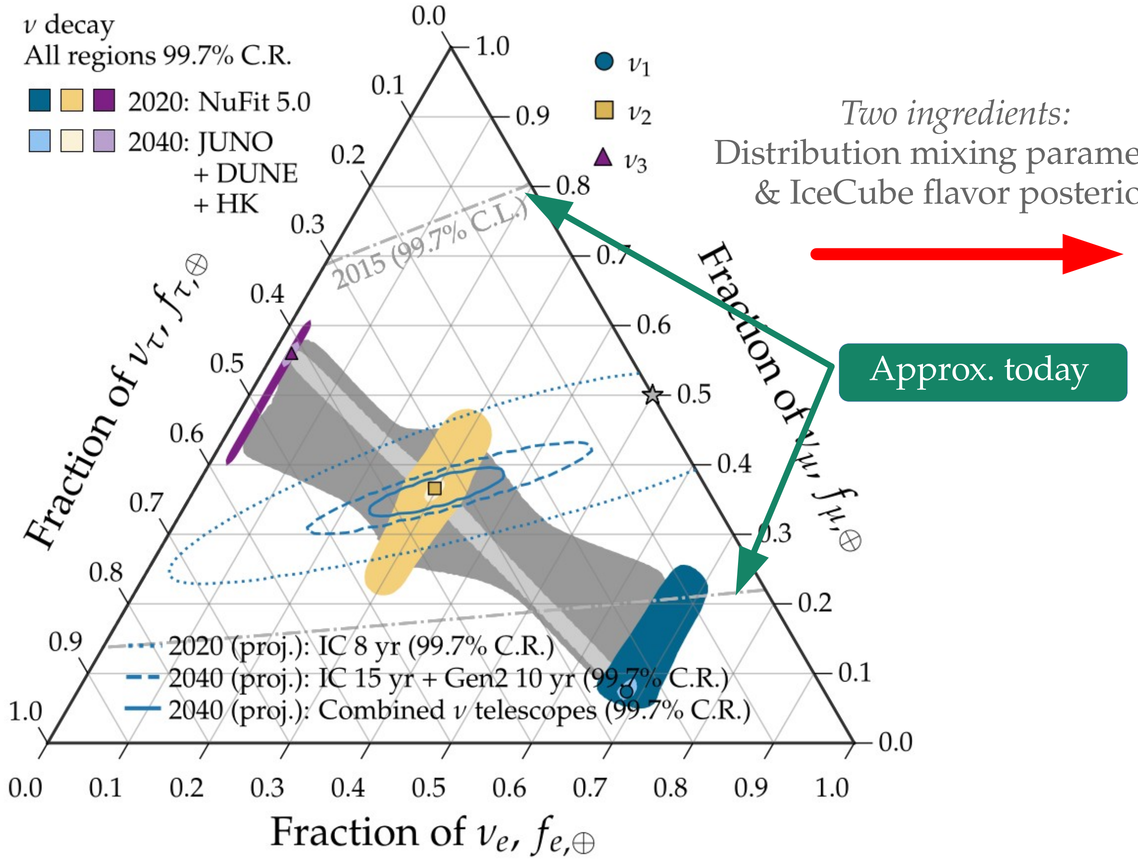

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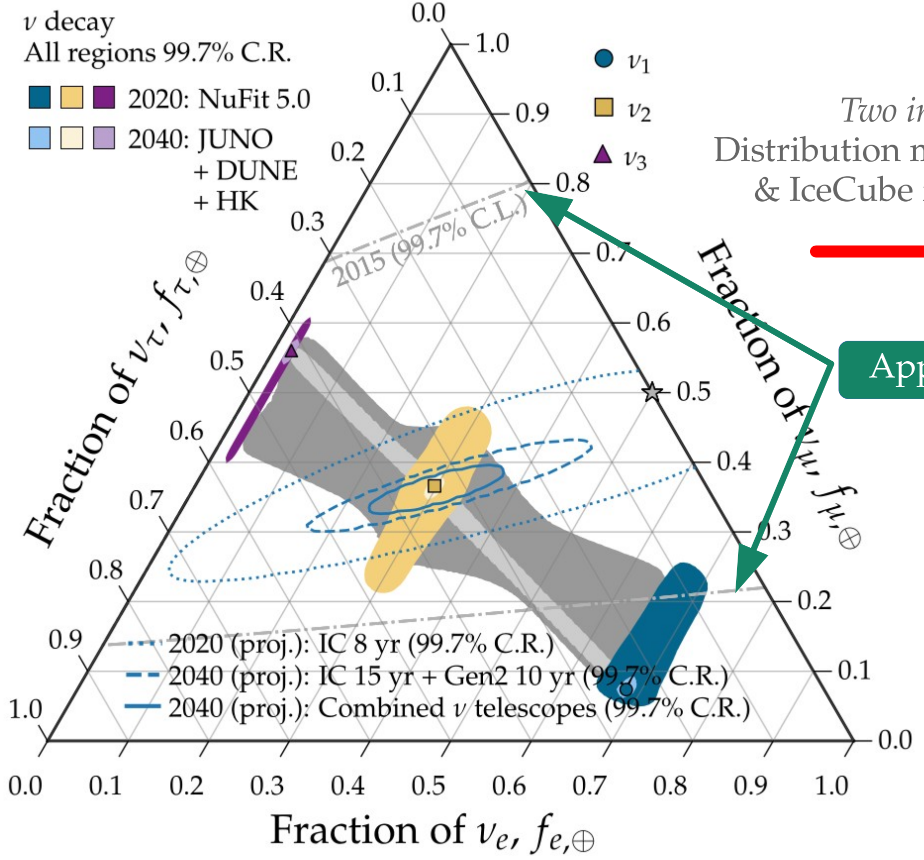

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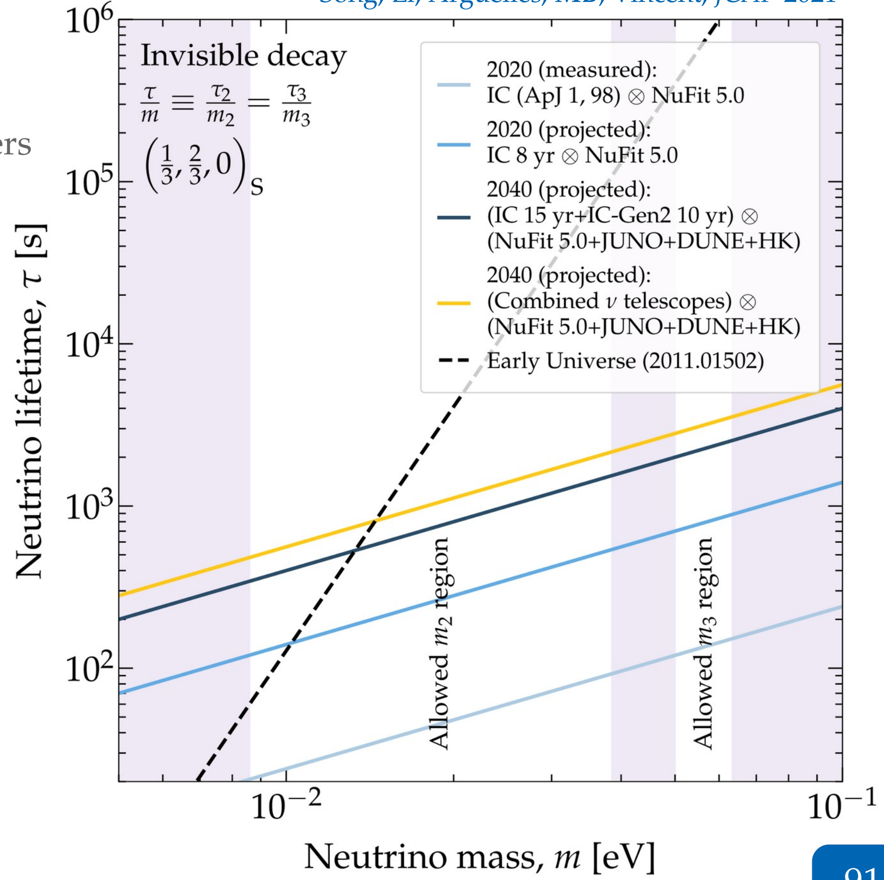
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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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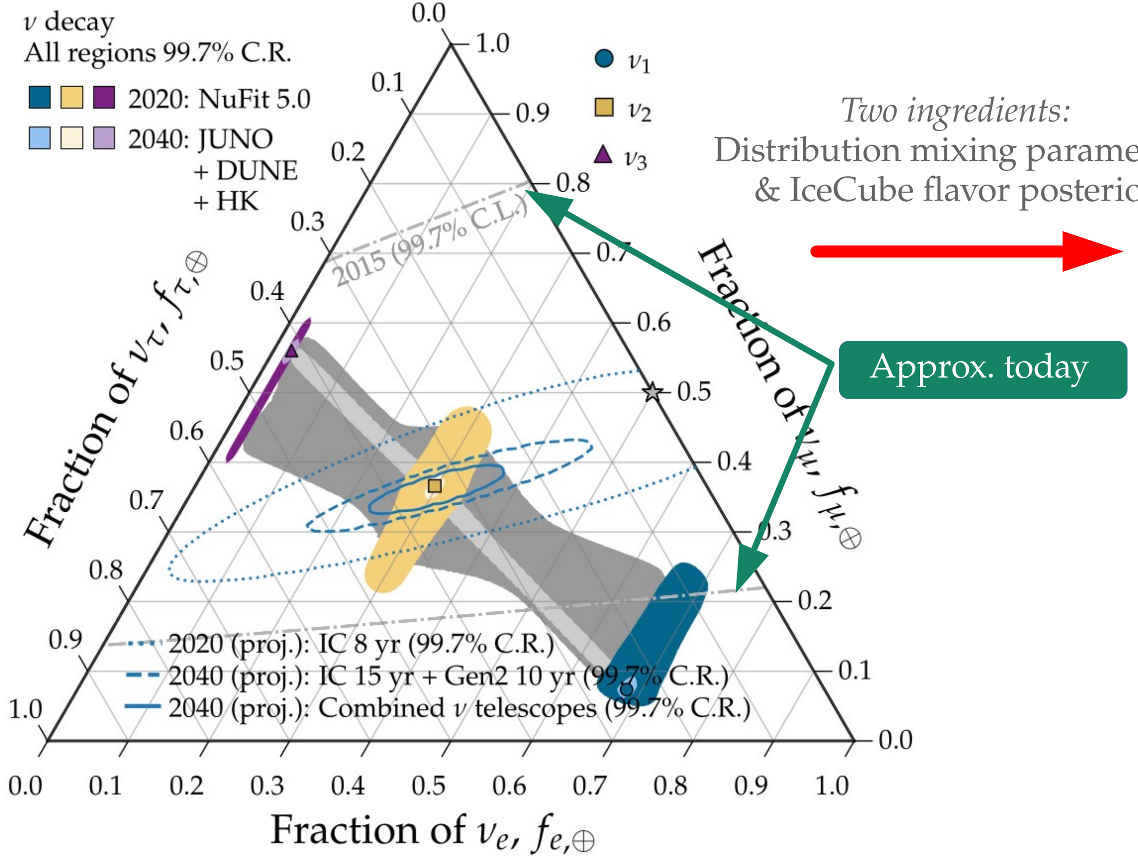

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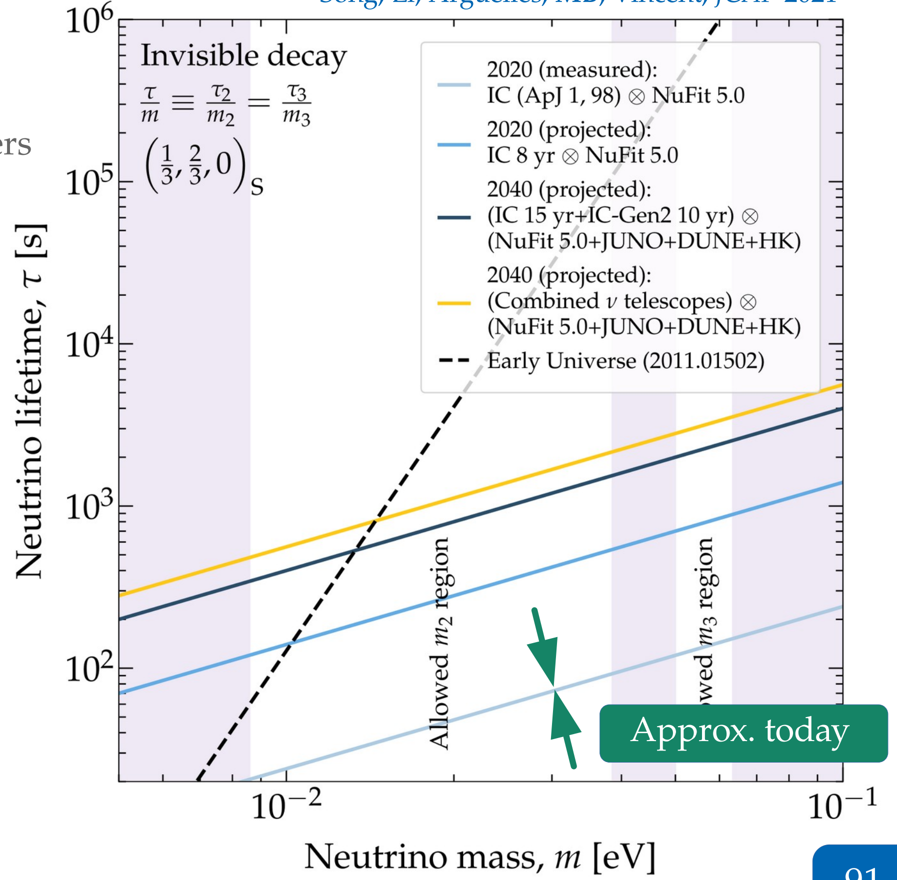

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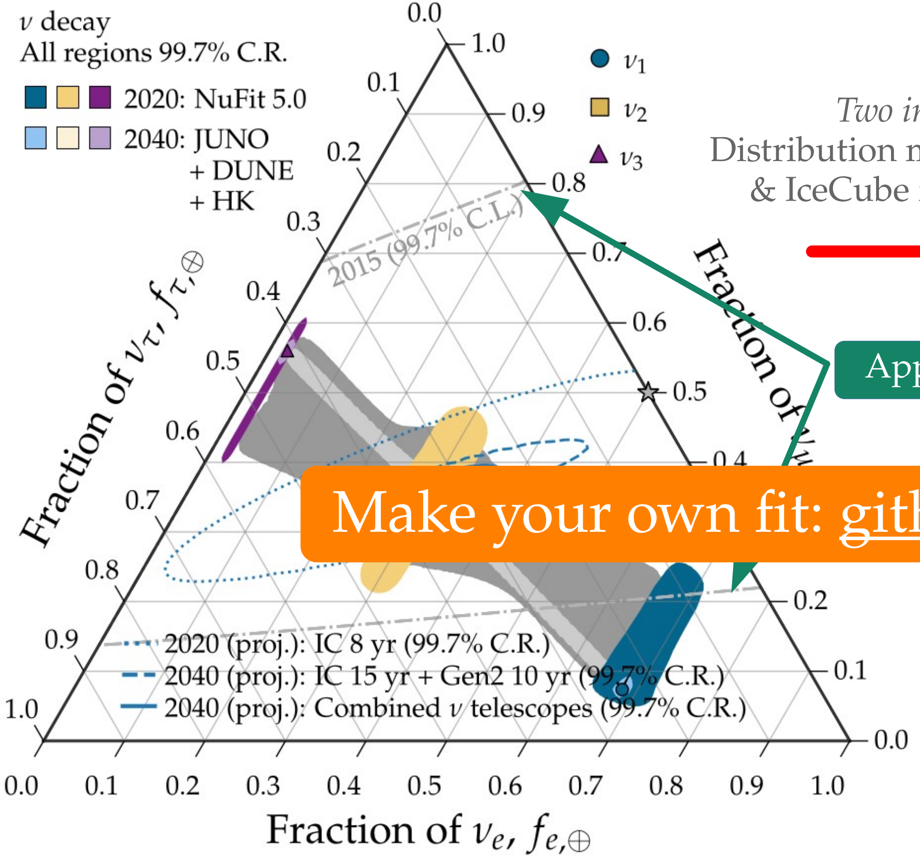

Two ingredients:
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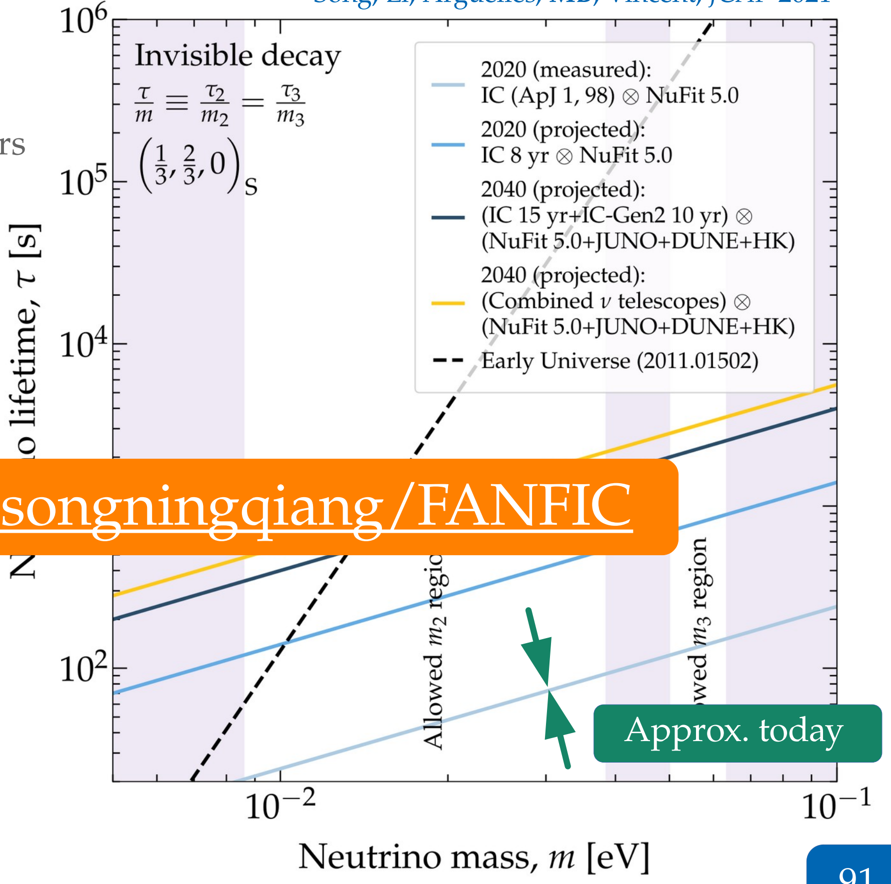
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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

New neutrino interactions:

Are there secret $\nu\nu$ interactions?

Astrophysical neutrino sources

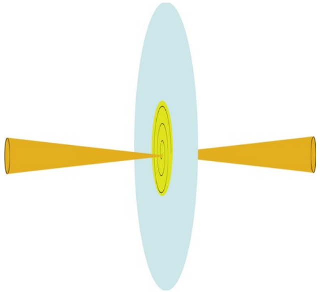
Earth

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

Astrophysical neutrino sources

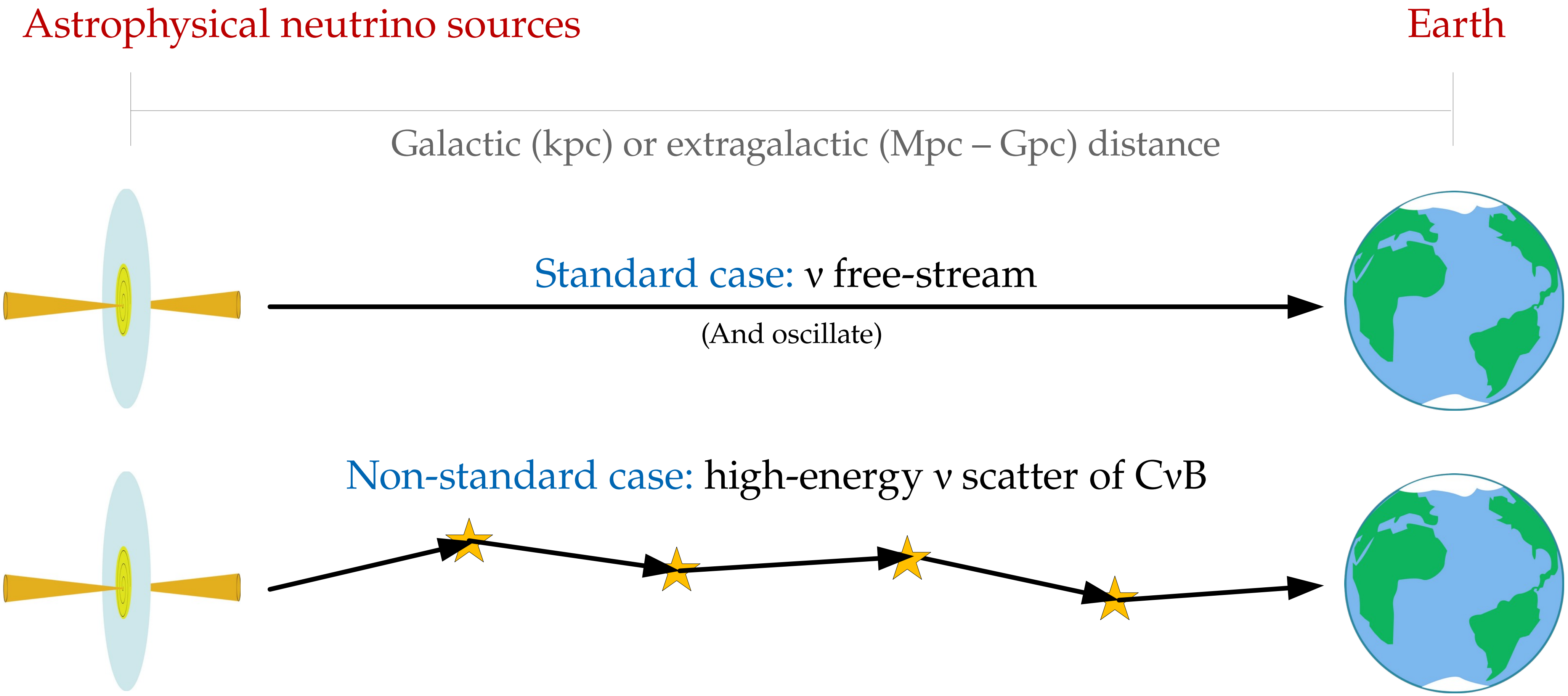
Earth

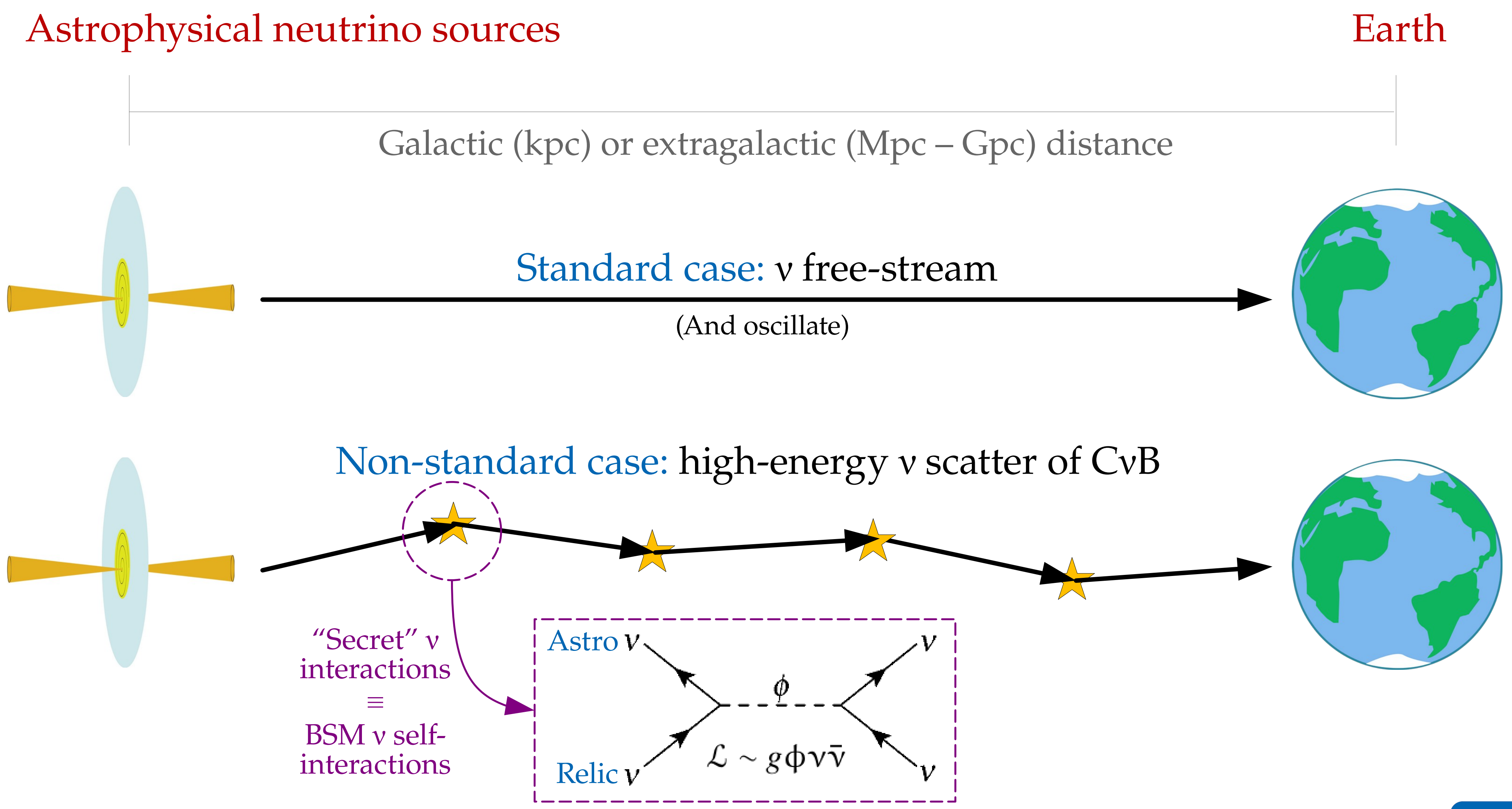
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB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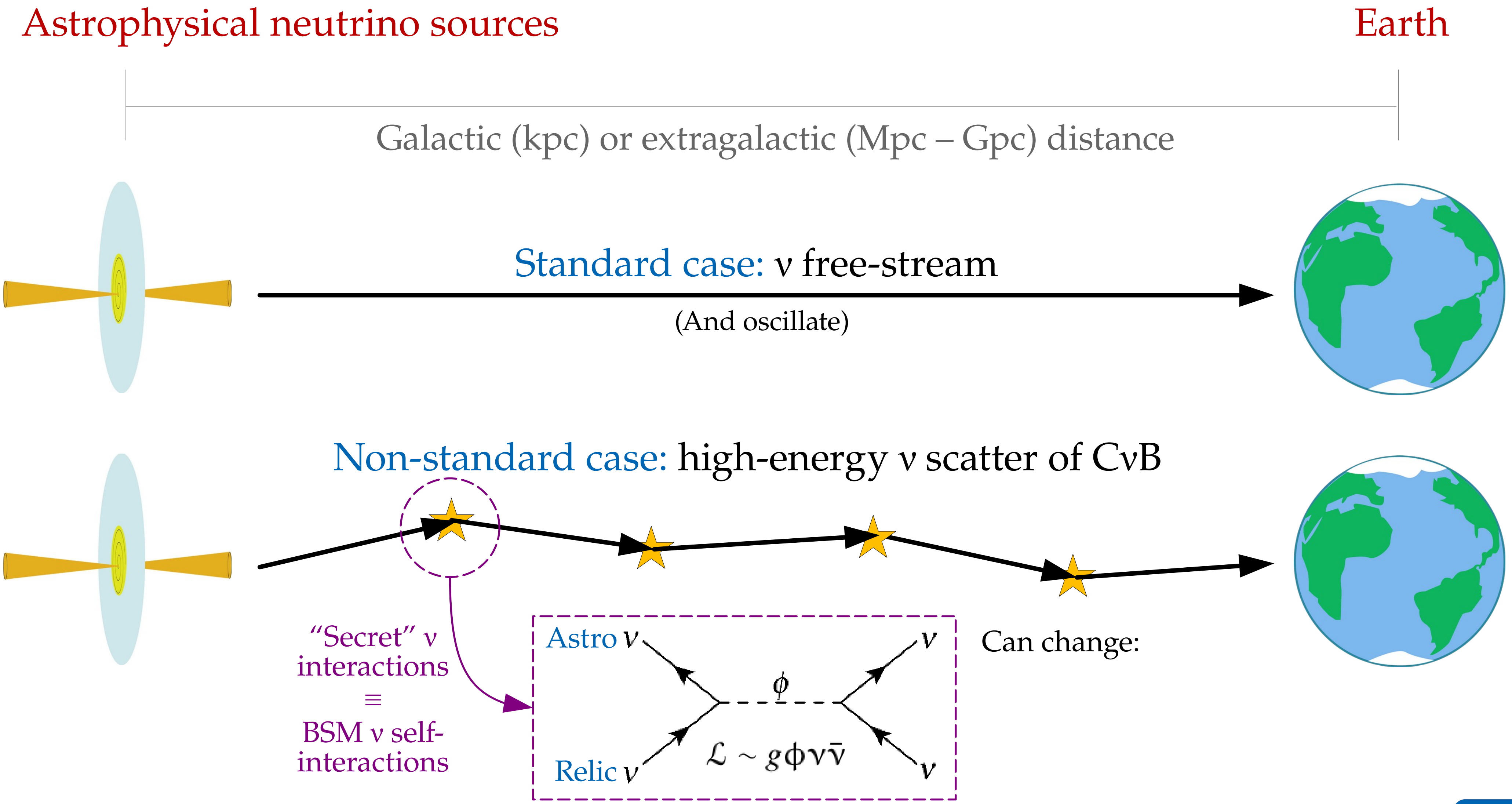
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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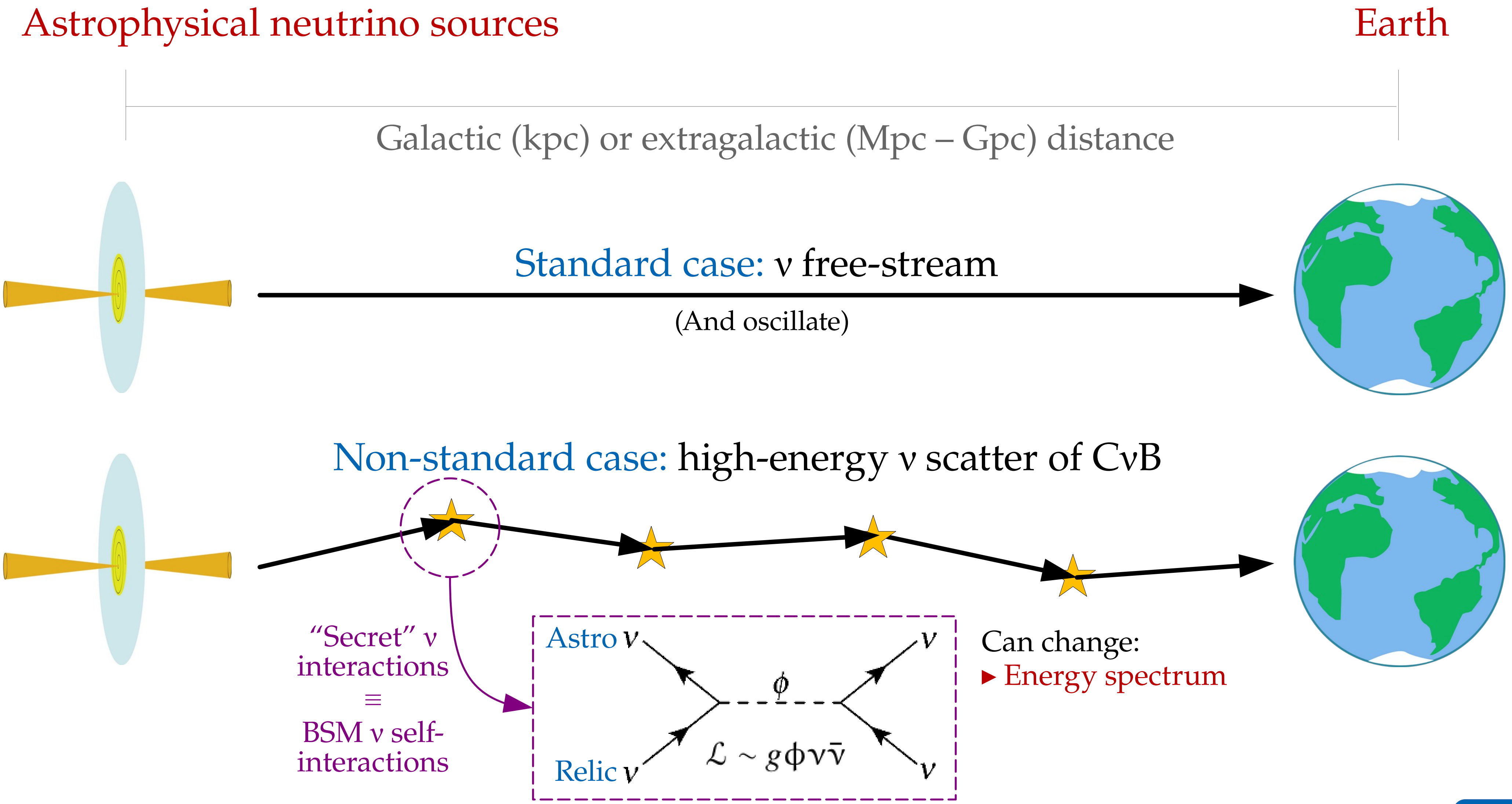
ℒ ~ gϕνν̄
Can change: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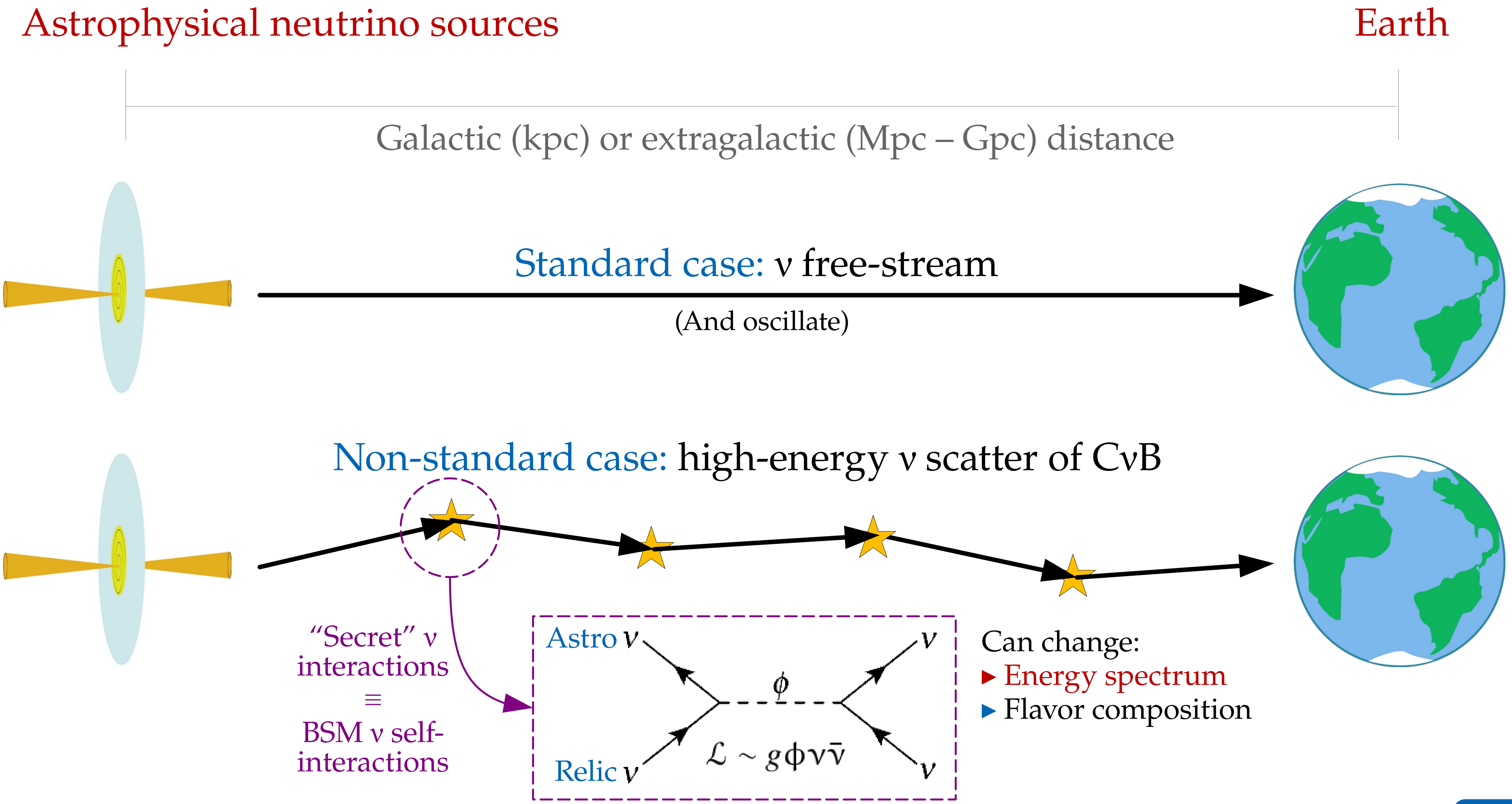
Can change:
▸ Energy spectrum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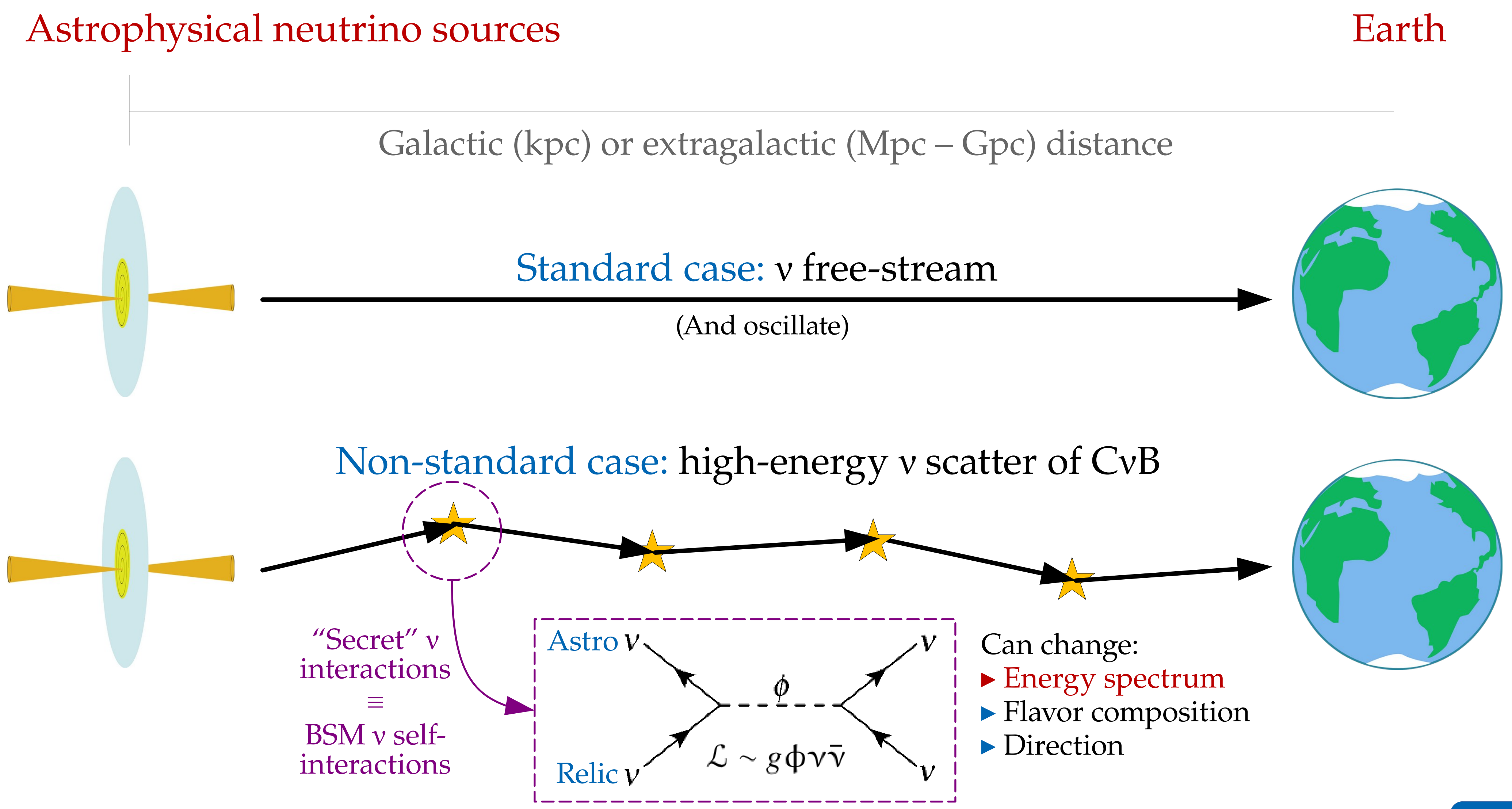
Can change:
▸ Energy spectrum
▸ Flavor composition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Energy spectrum
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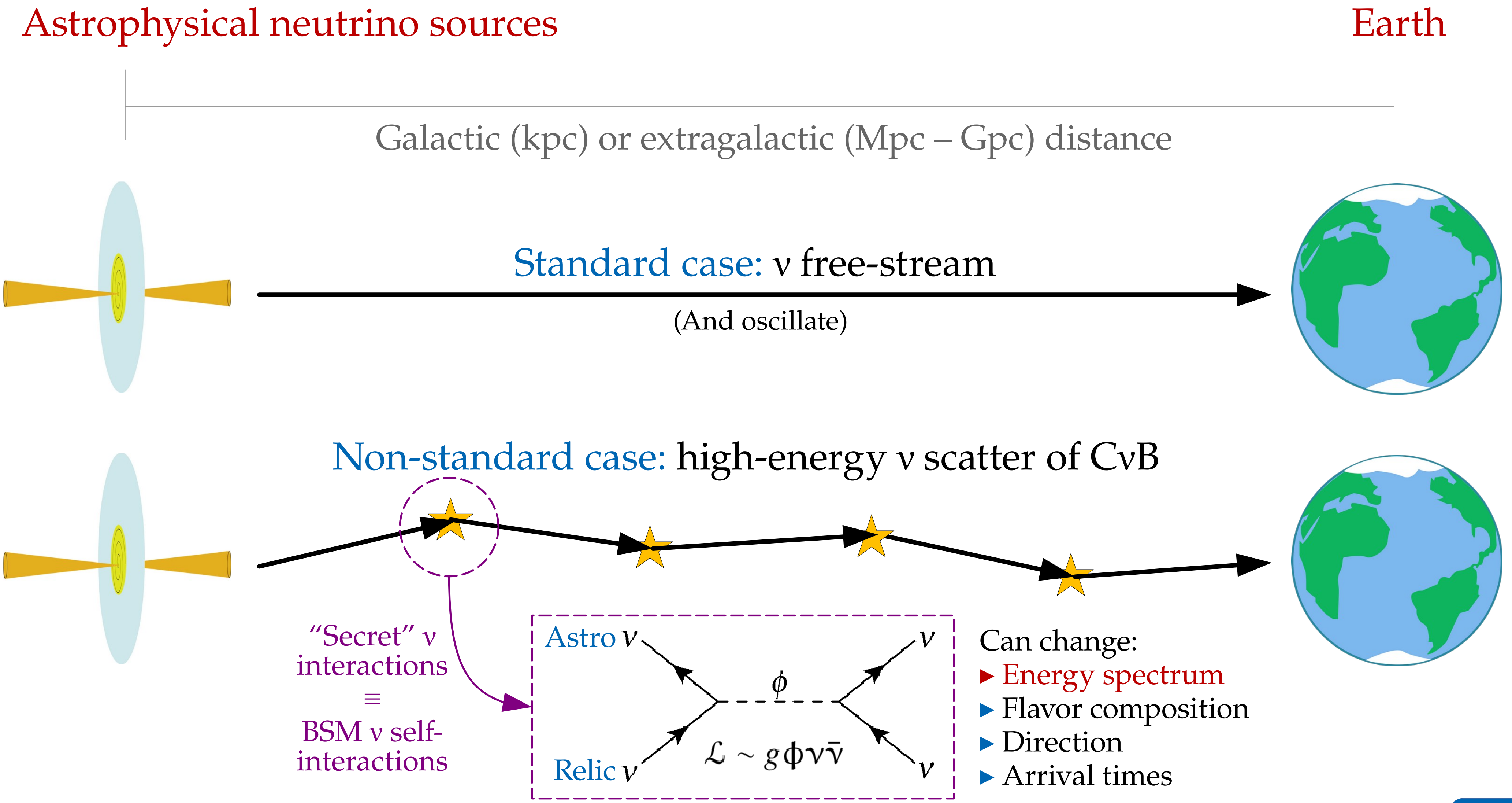
Direction



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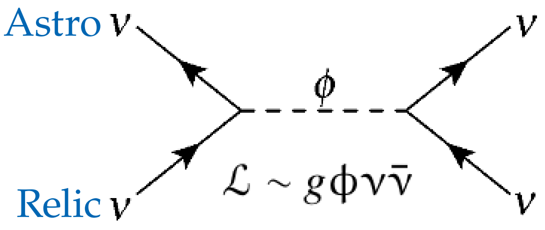
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

Secret interactions of high-energy astrophysical neutrinos

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



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

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

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
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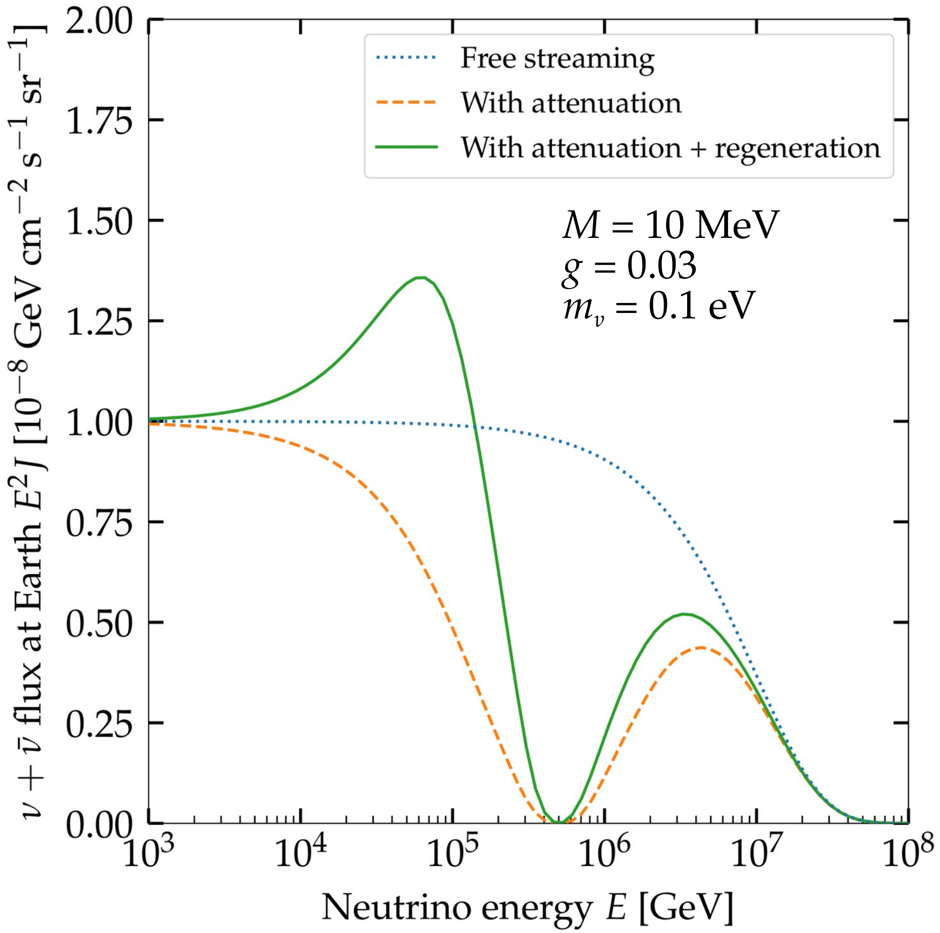
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799



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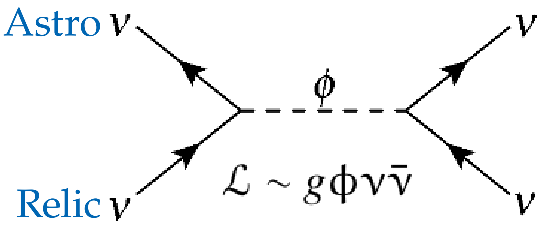

New coupling

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Mediator mass

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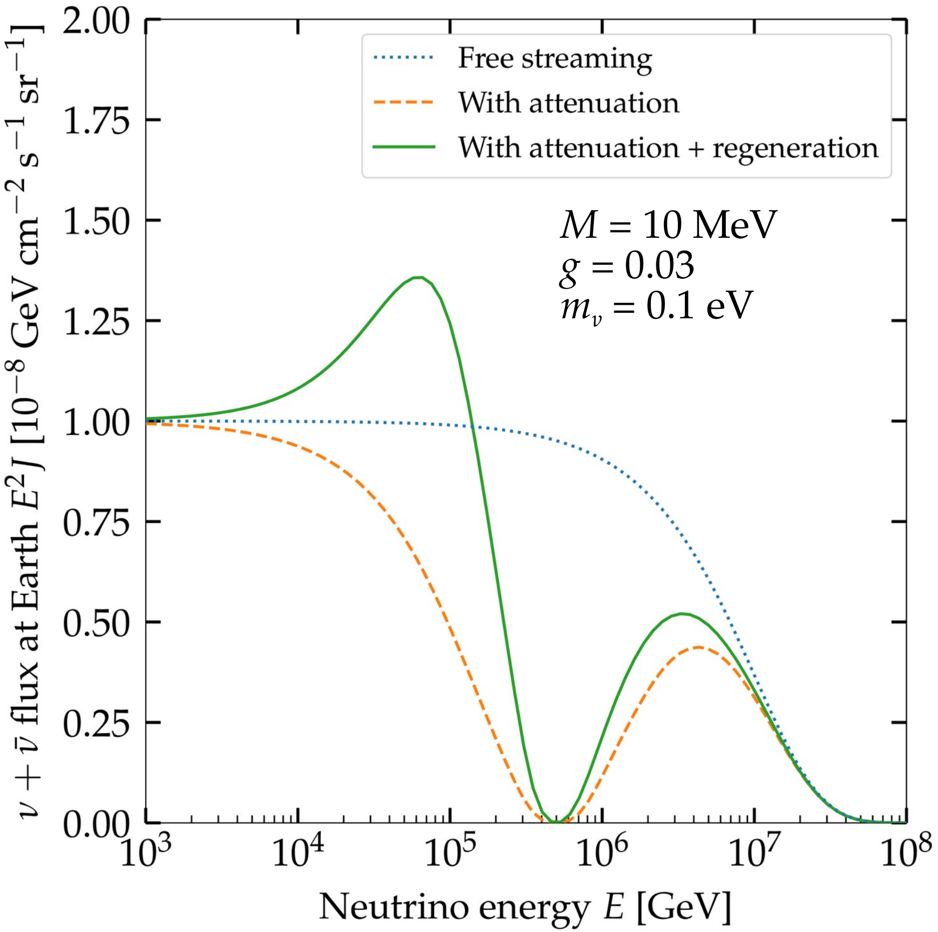

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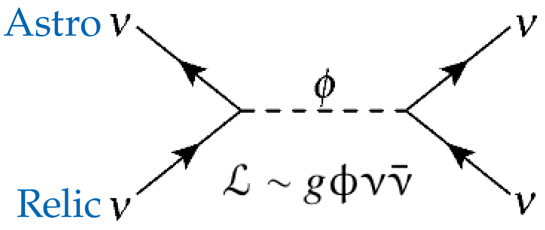

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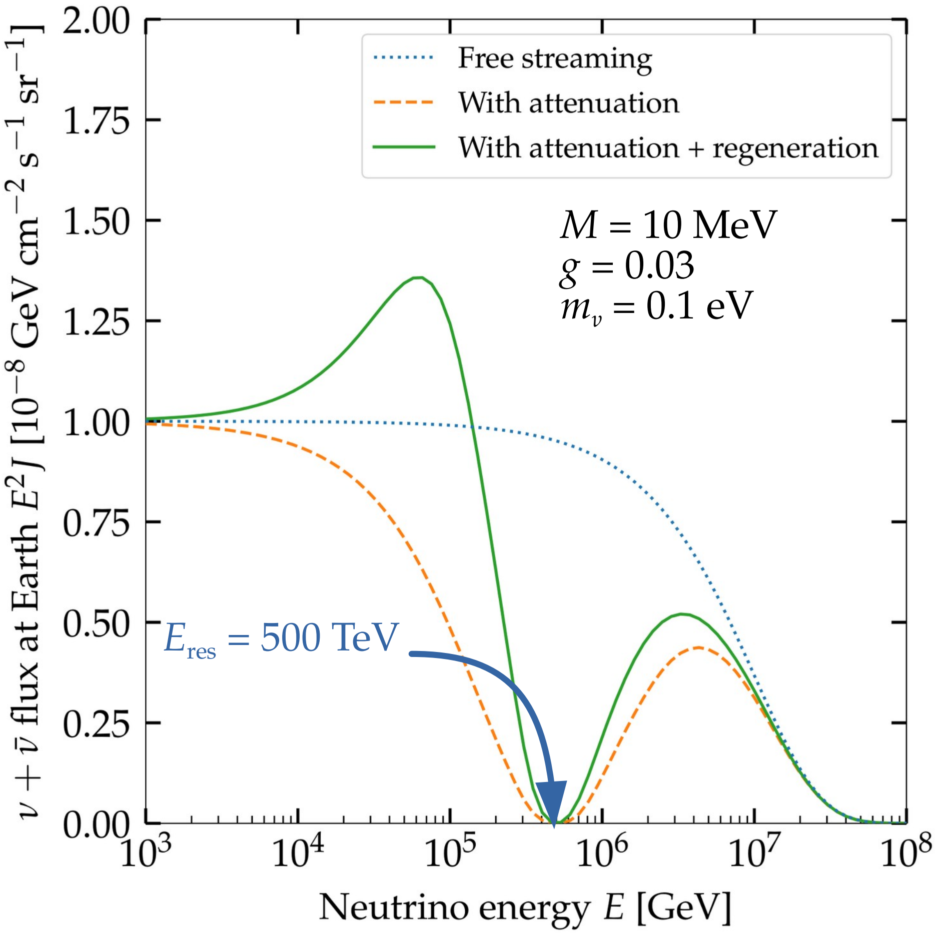

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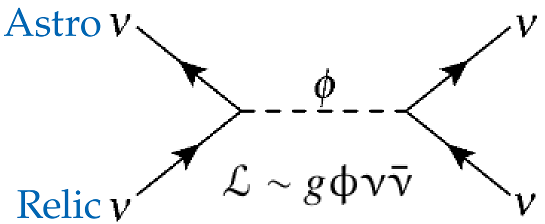

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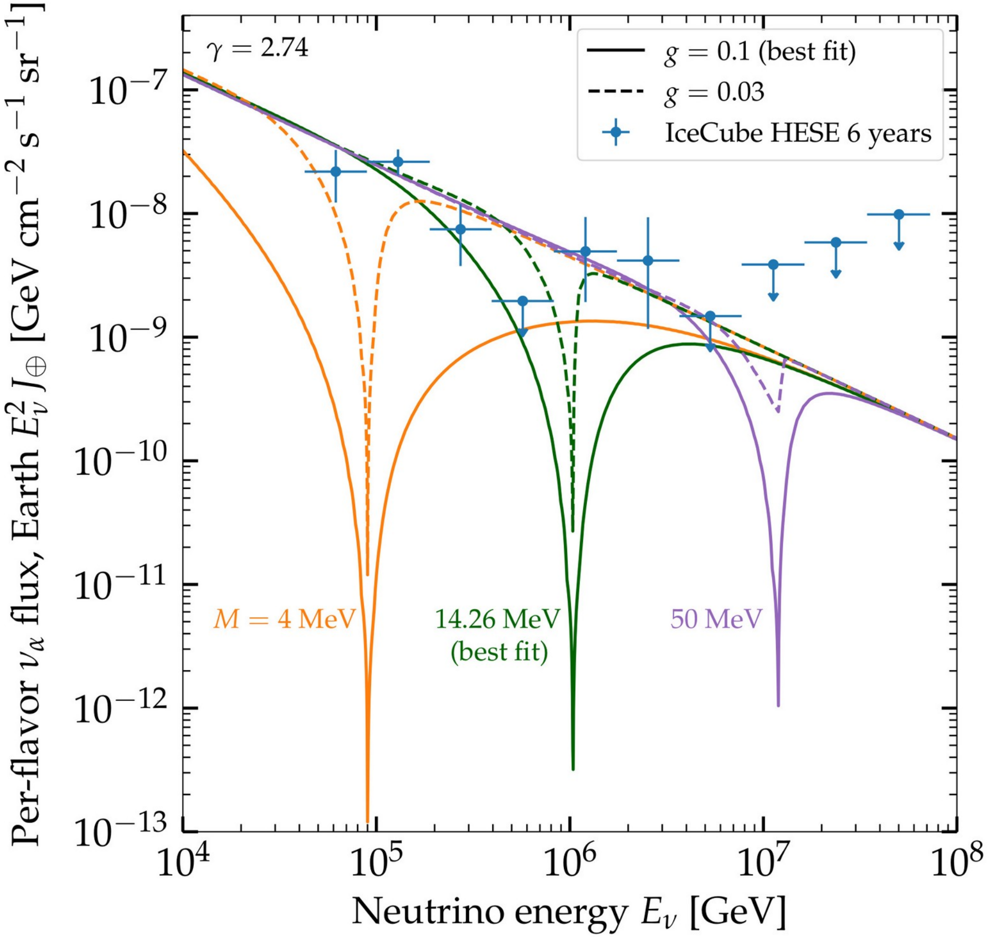

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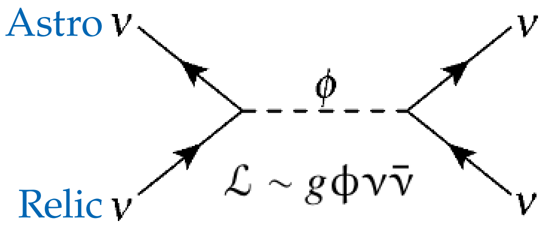

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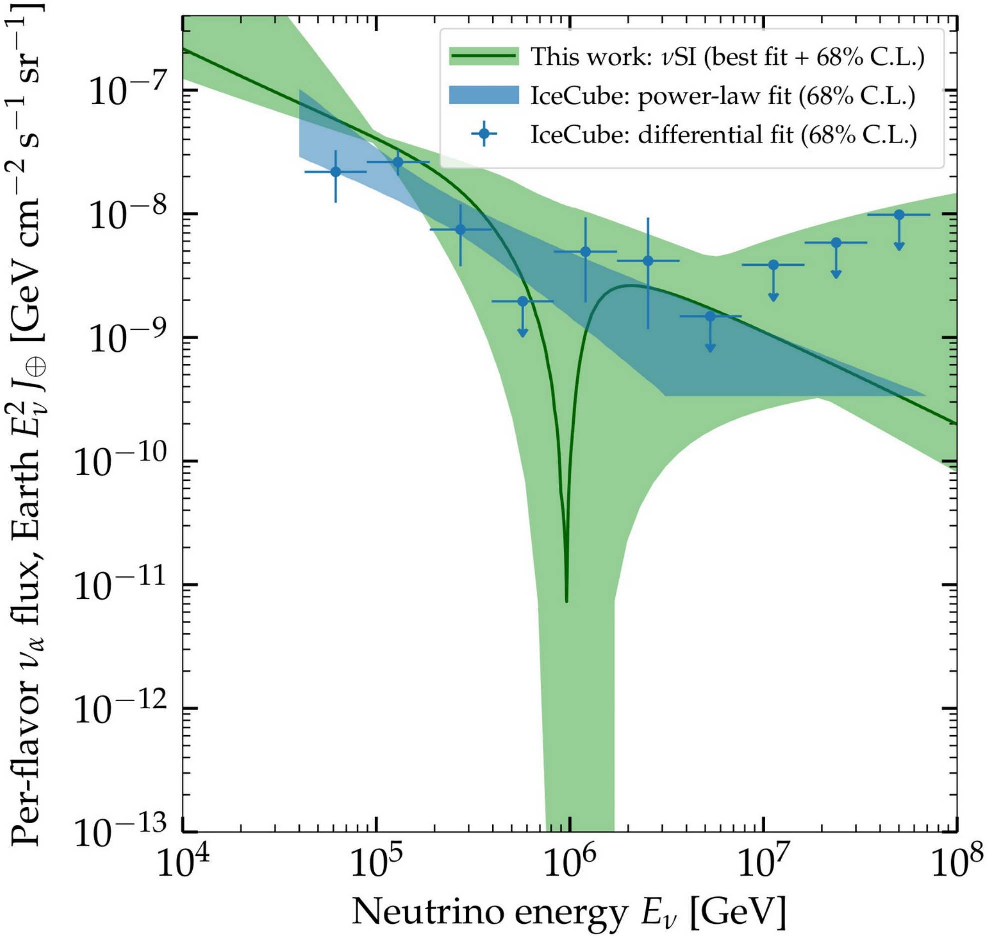
Looking for evidence of νSI

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

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



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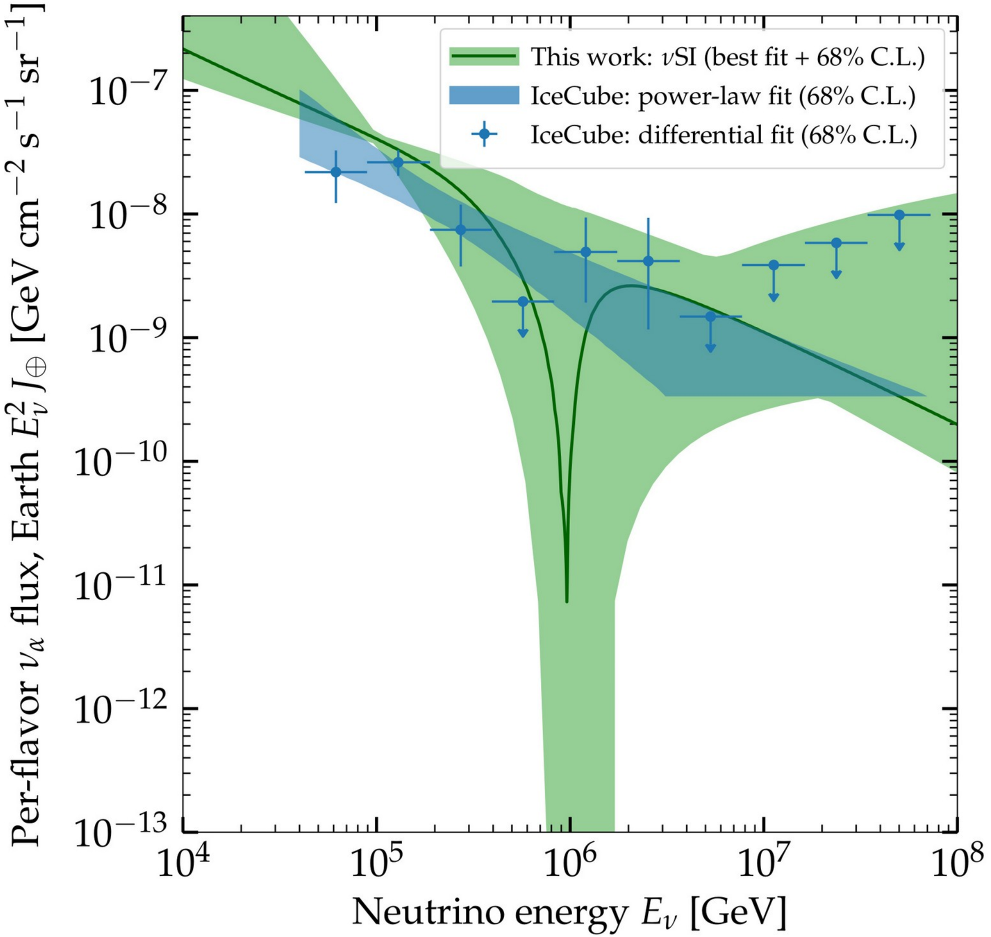
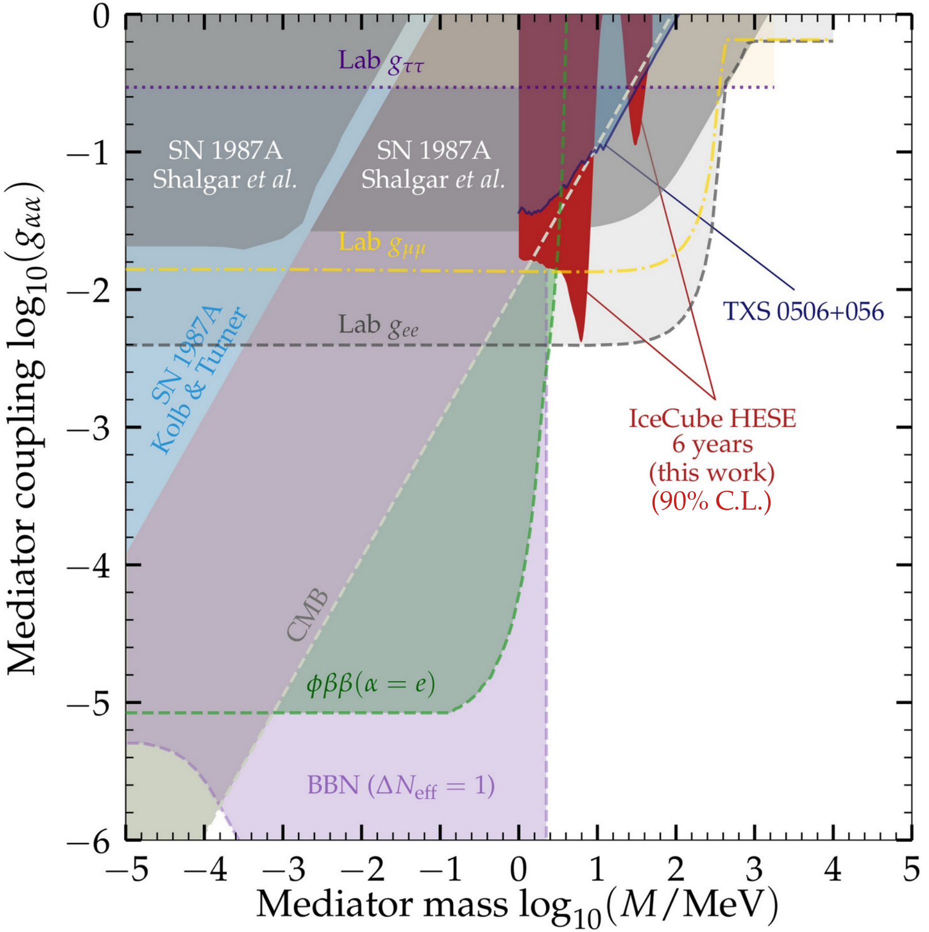
See also: Shalgar, **MB**, Tamborra, *PRD* 2020

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





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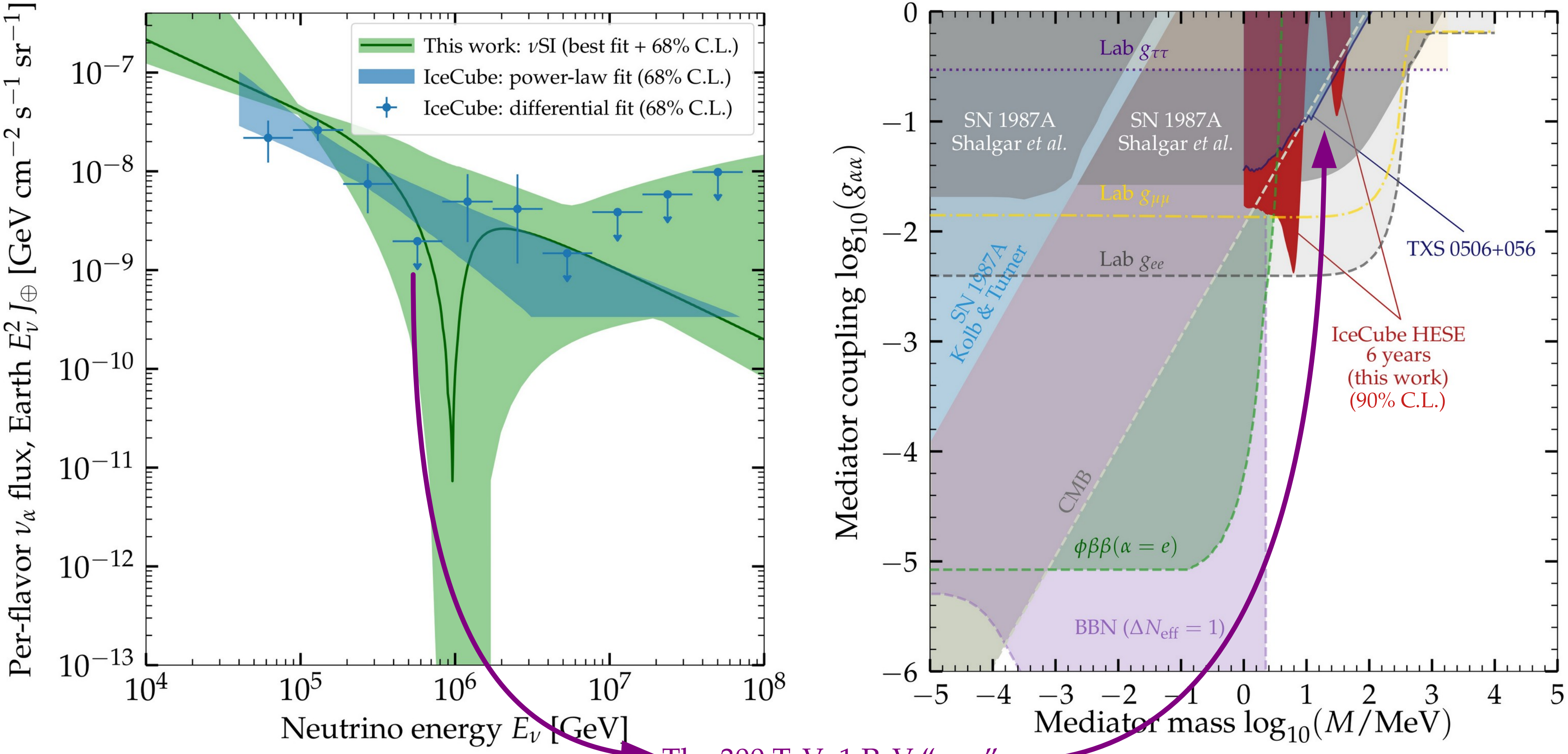

The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

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