Neutrino astronomy with high-energy neutrinos

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

TAMBO touch-base workshop
October 18, 2022

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

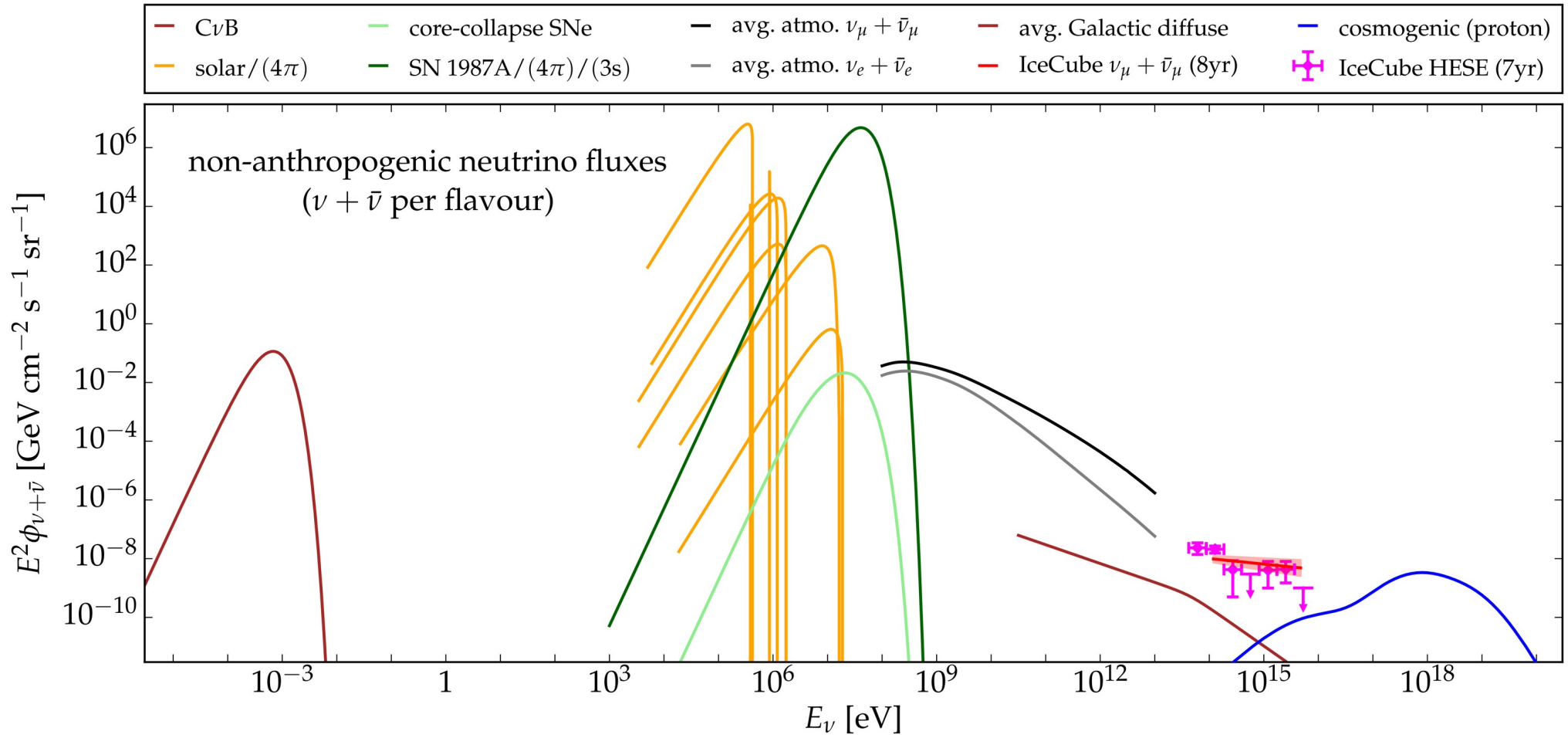


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

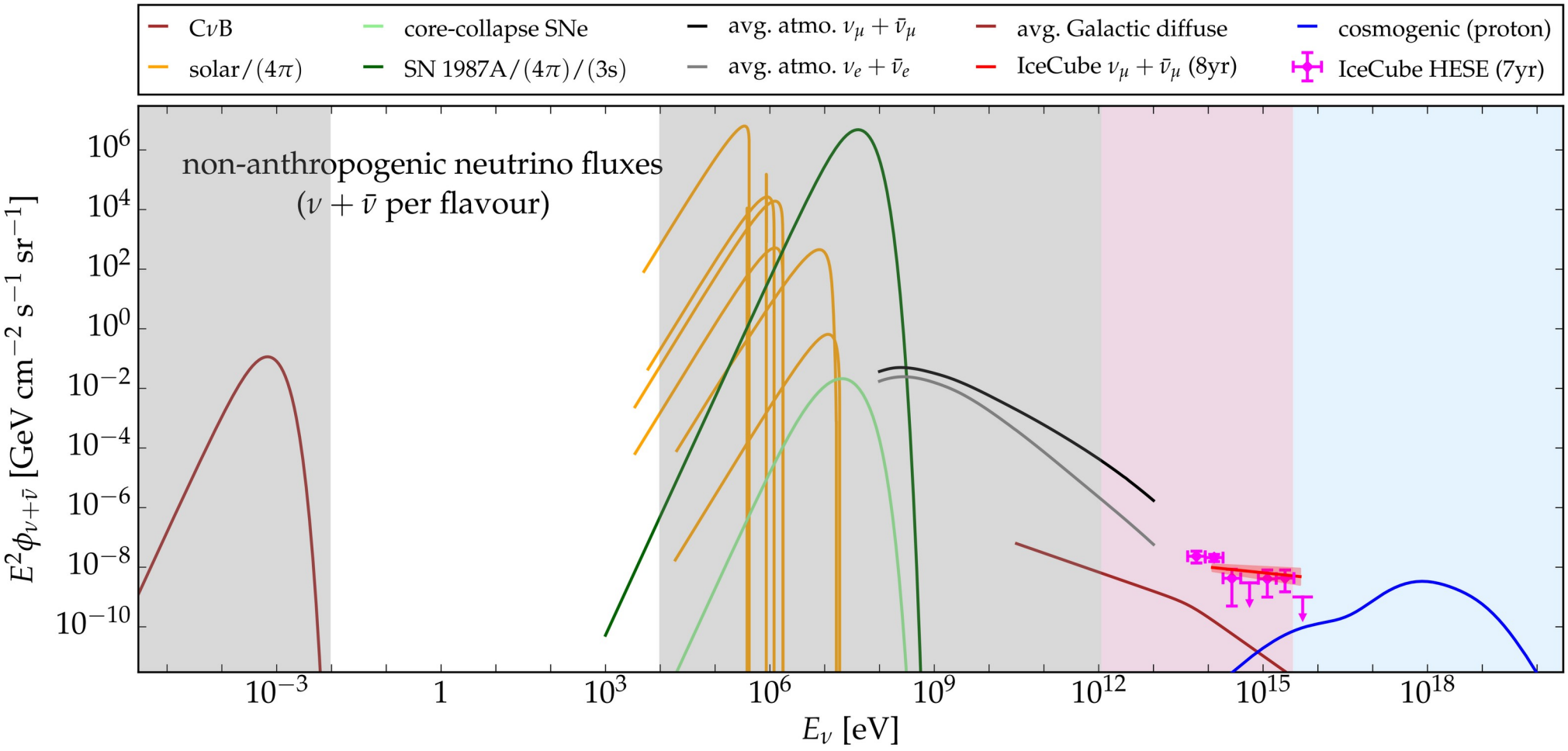


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

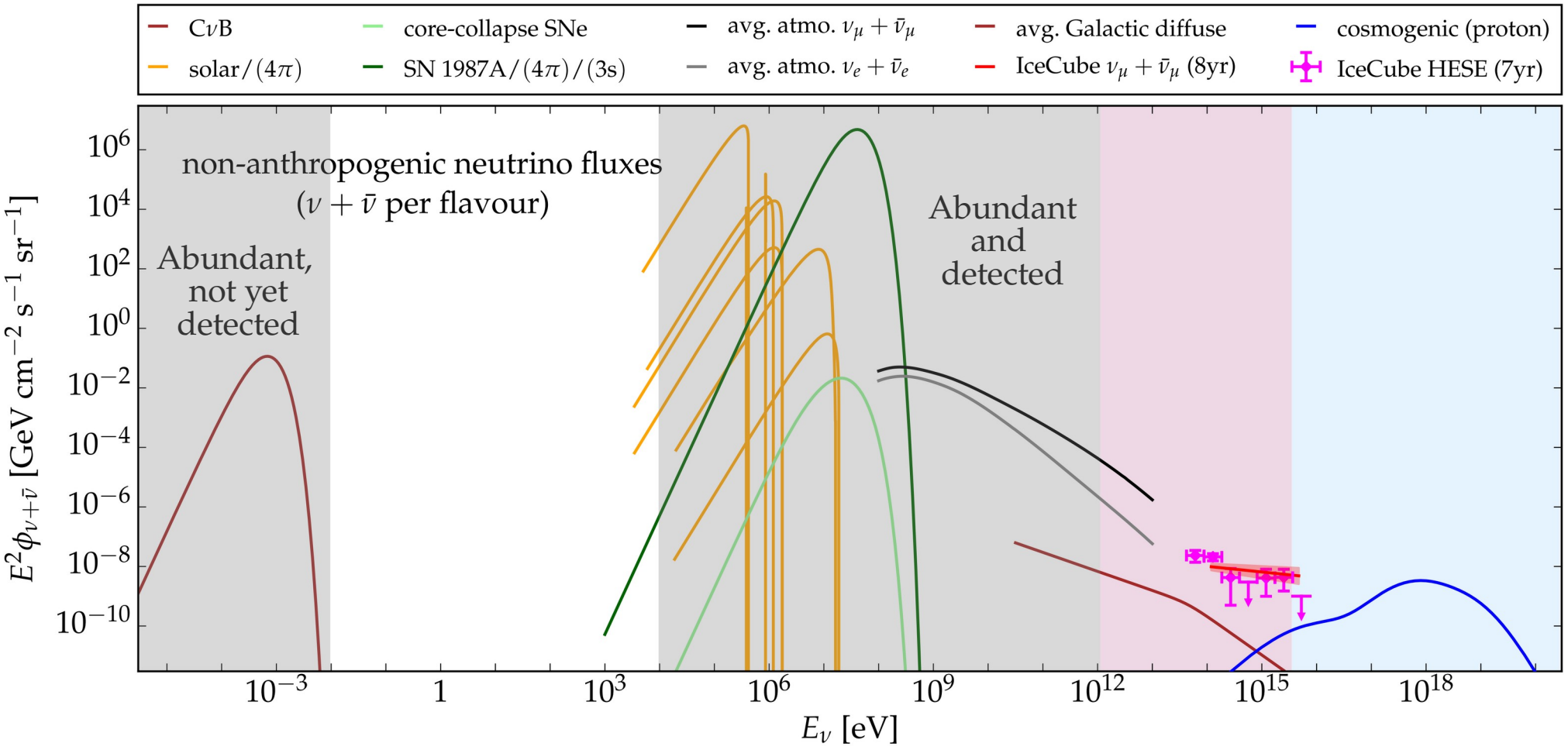


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

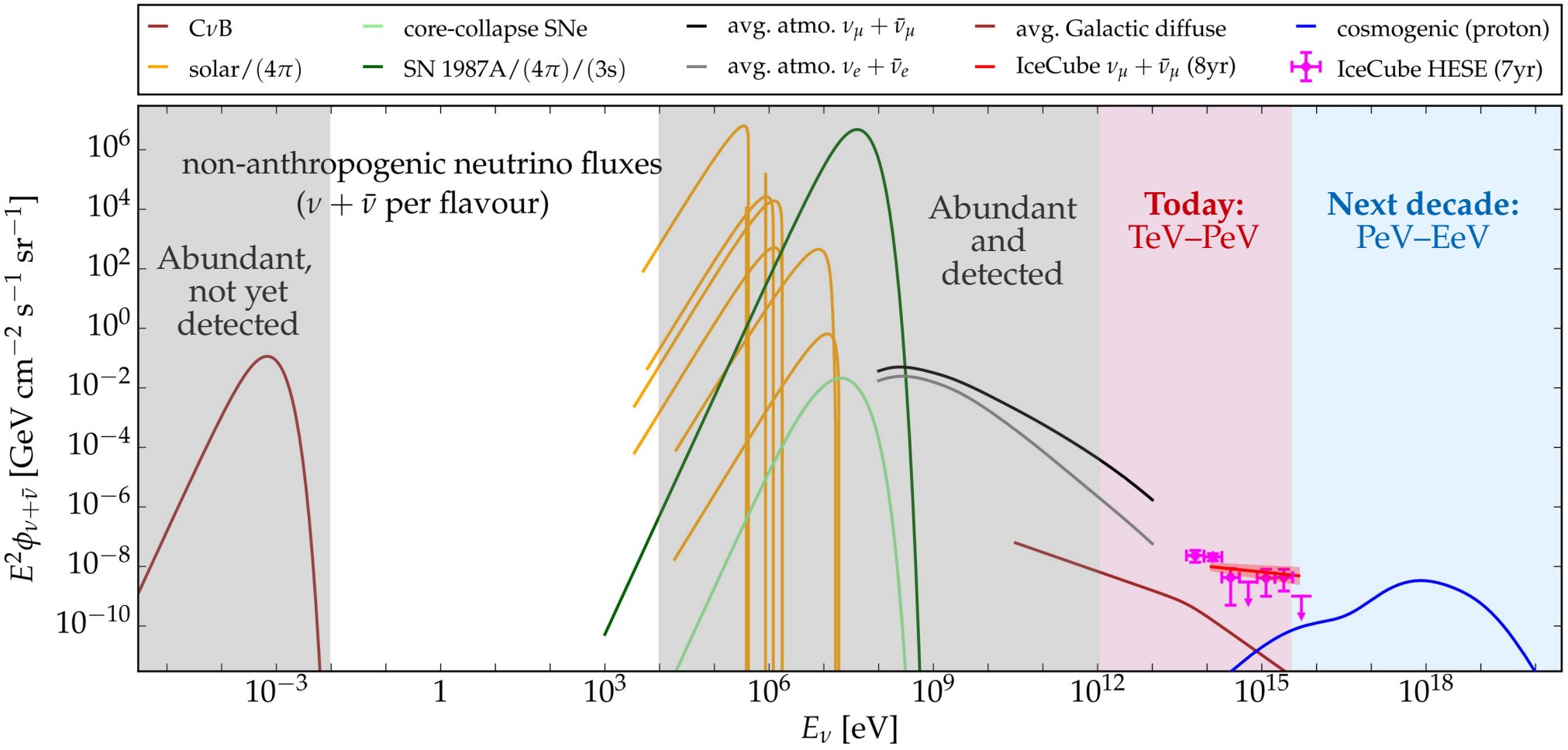


Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

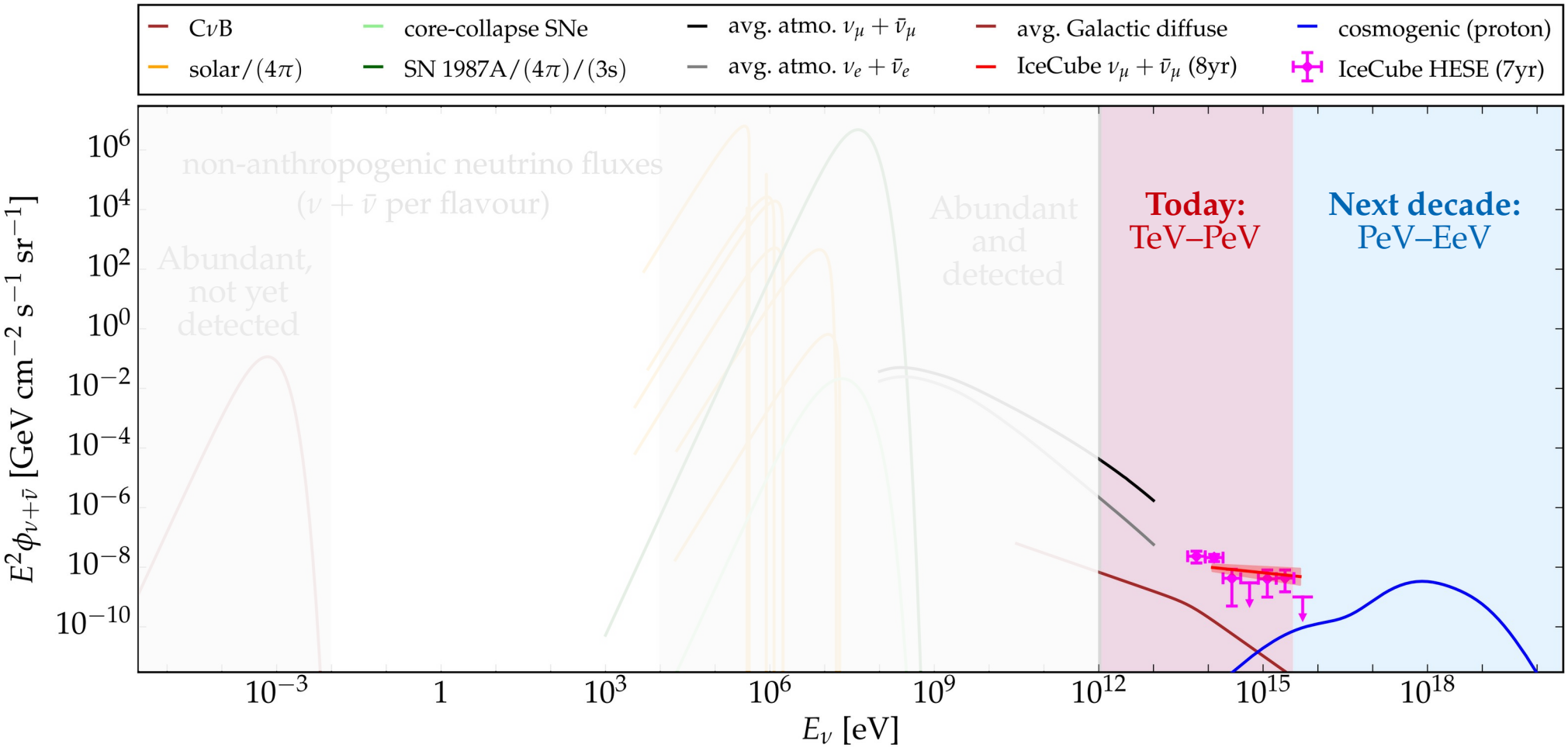
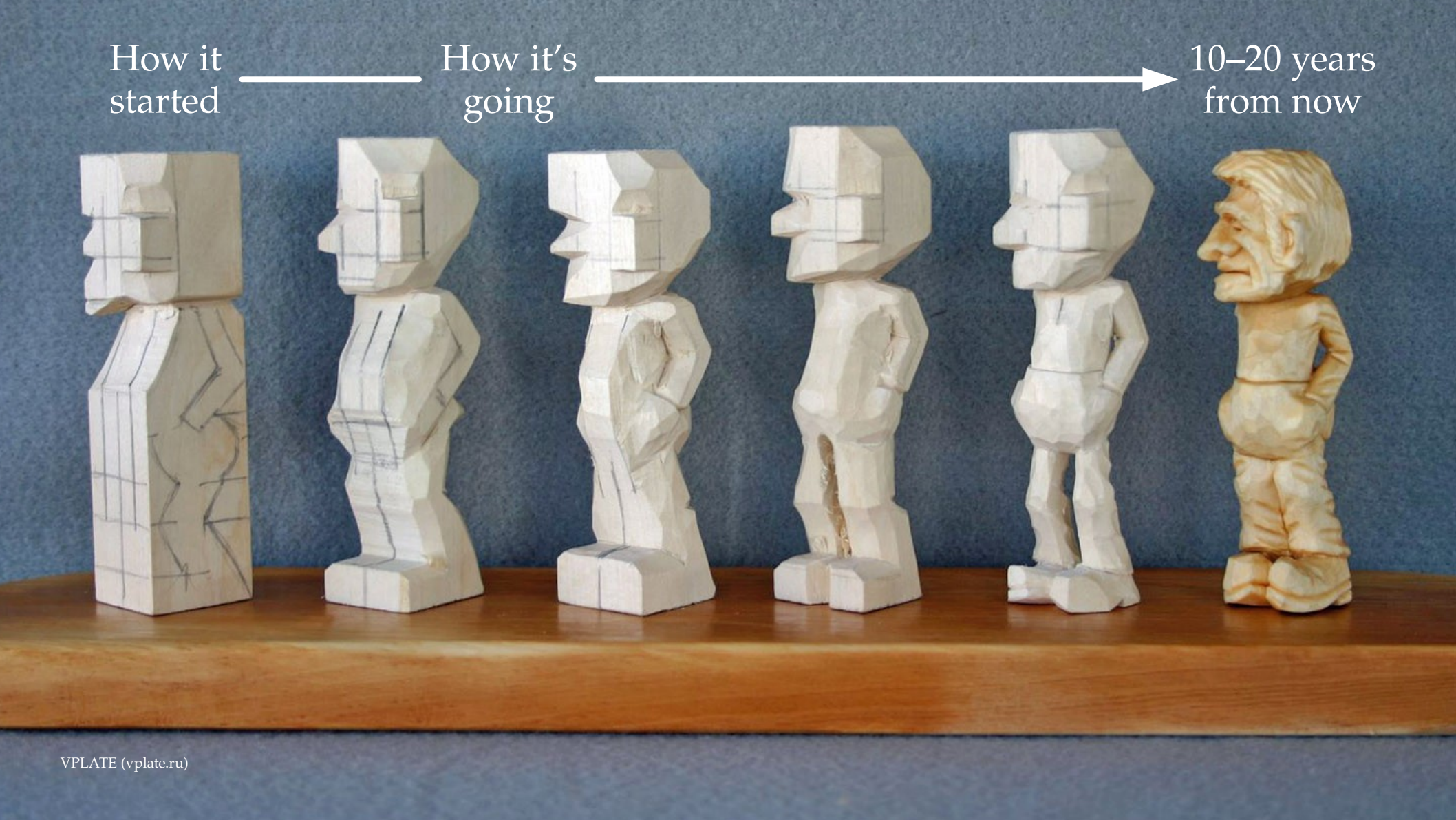
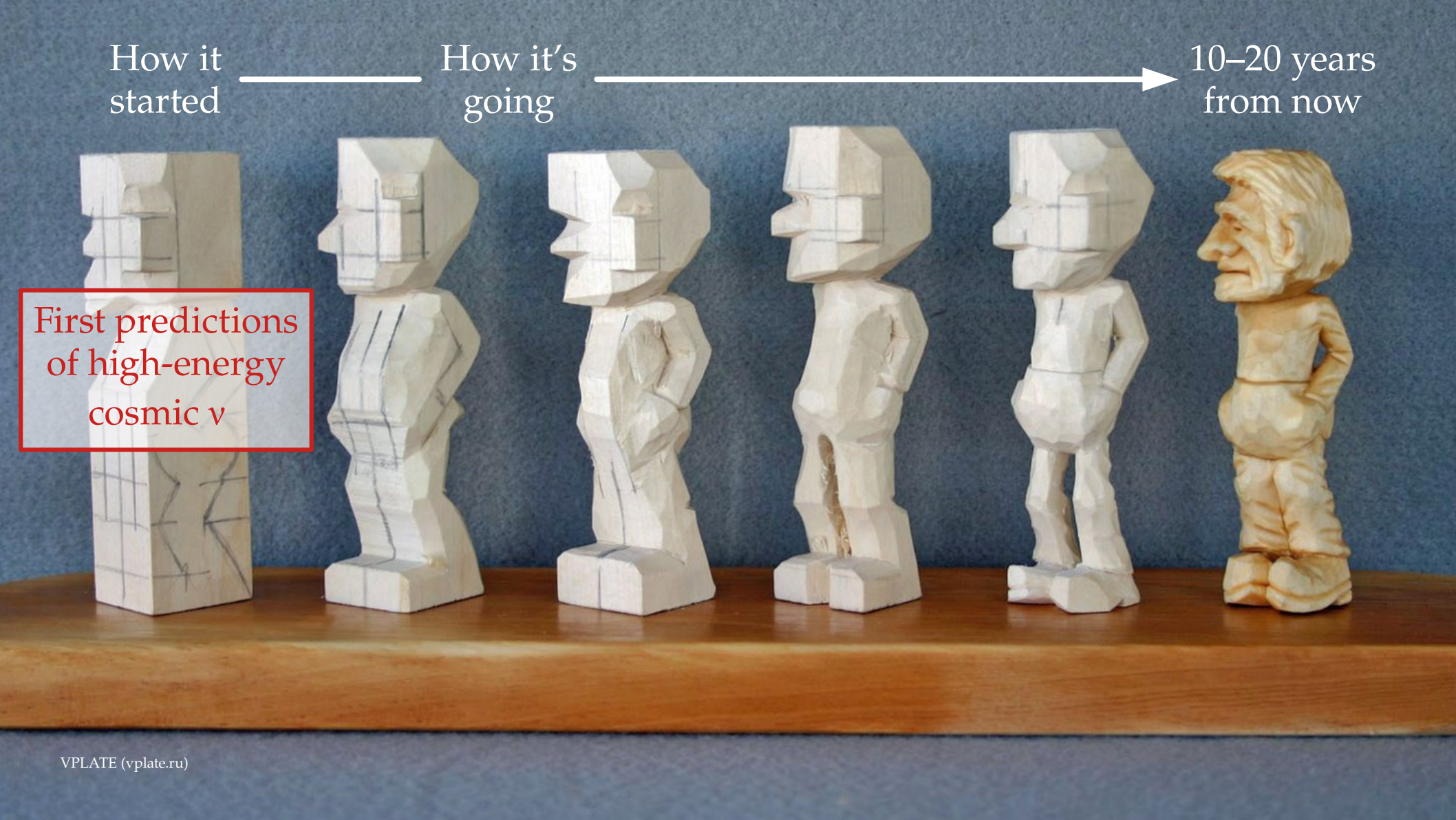
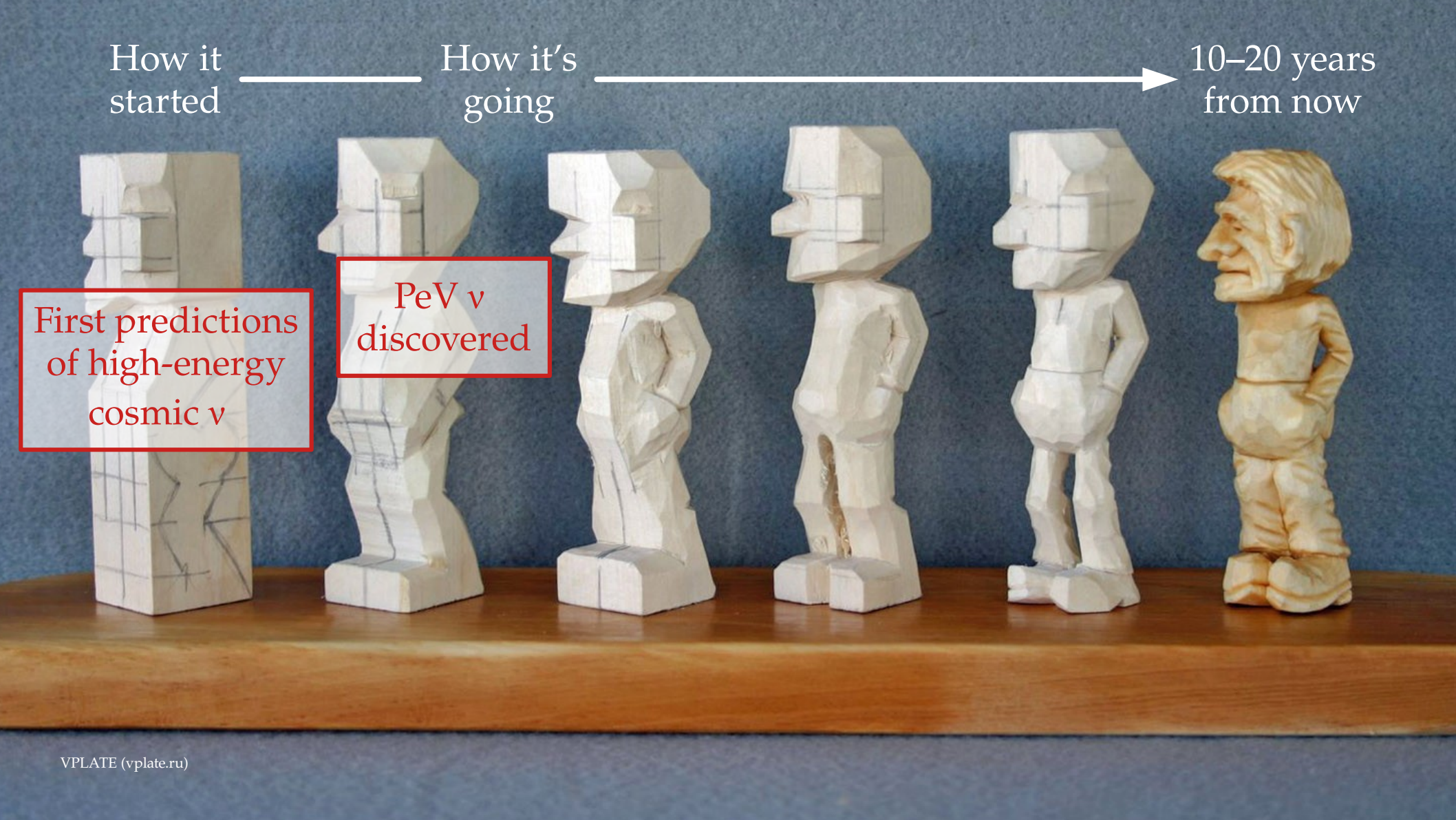
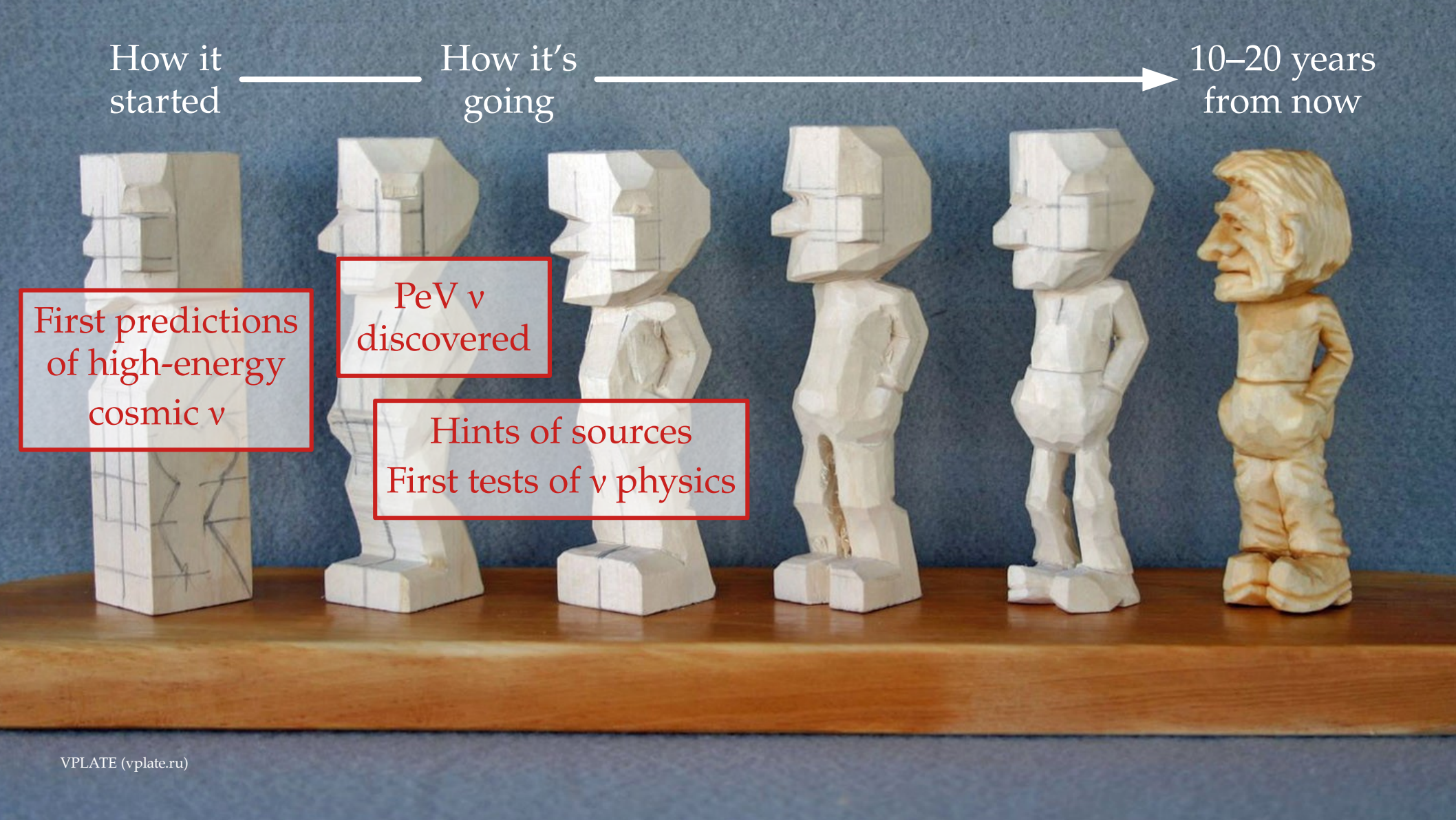


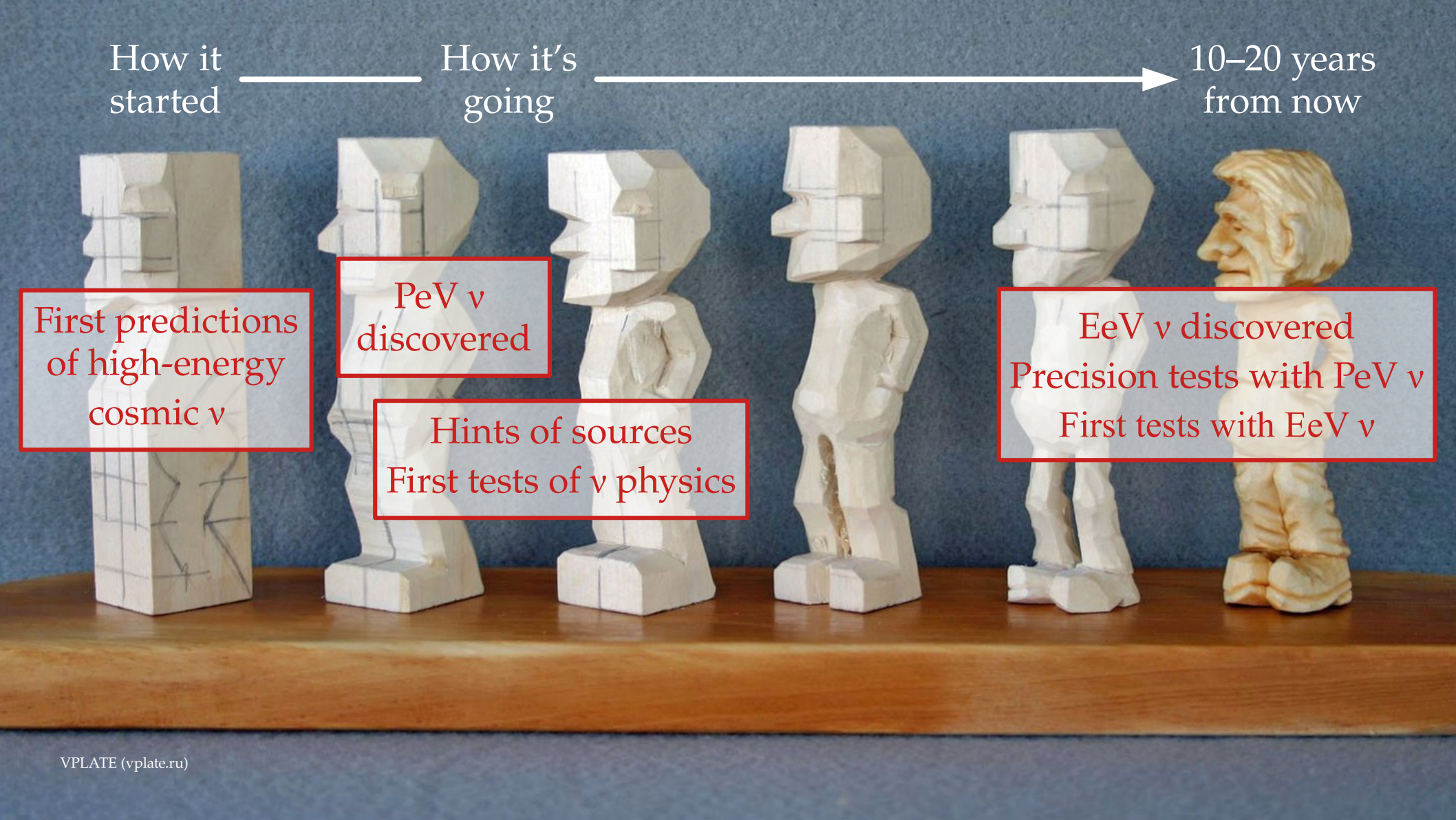
Figure courtesy of Markus Ahlers
Maoloud, De Wasseige, Ahlers, **MB**, Van Elewyck, PoS(ICRC2019), 1023

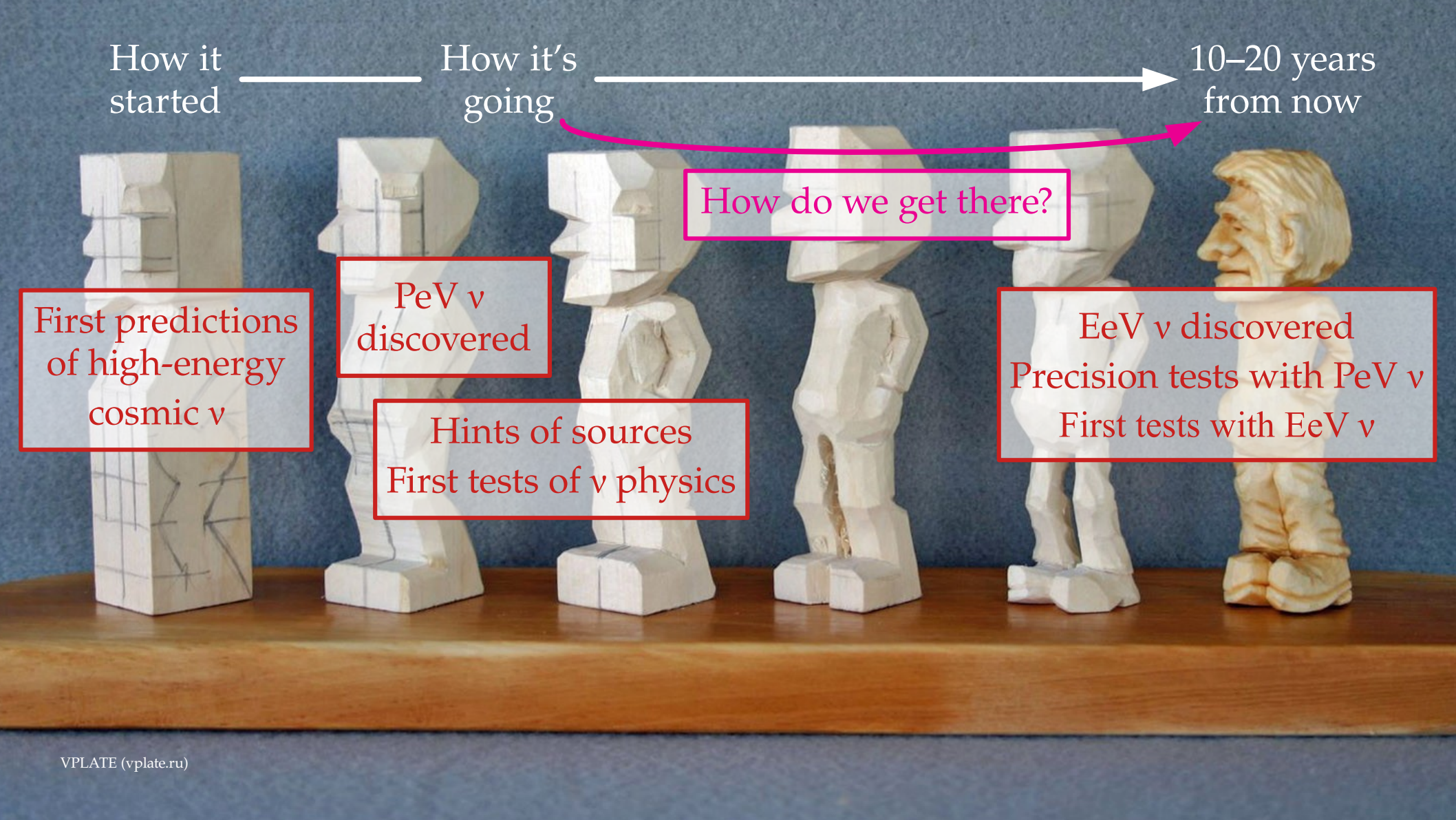

How it started
How it's going
10–20 years from now
VPLATE (vplate.ru)


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

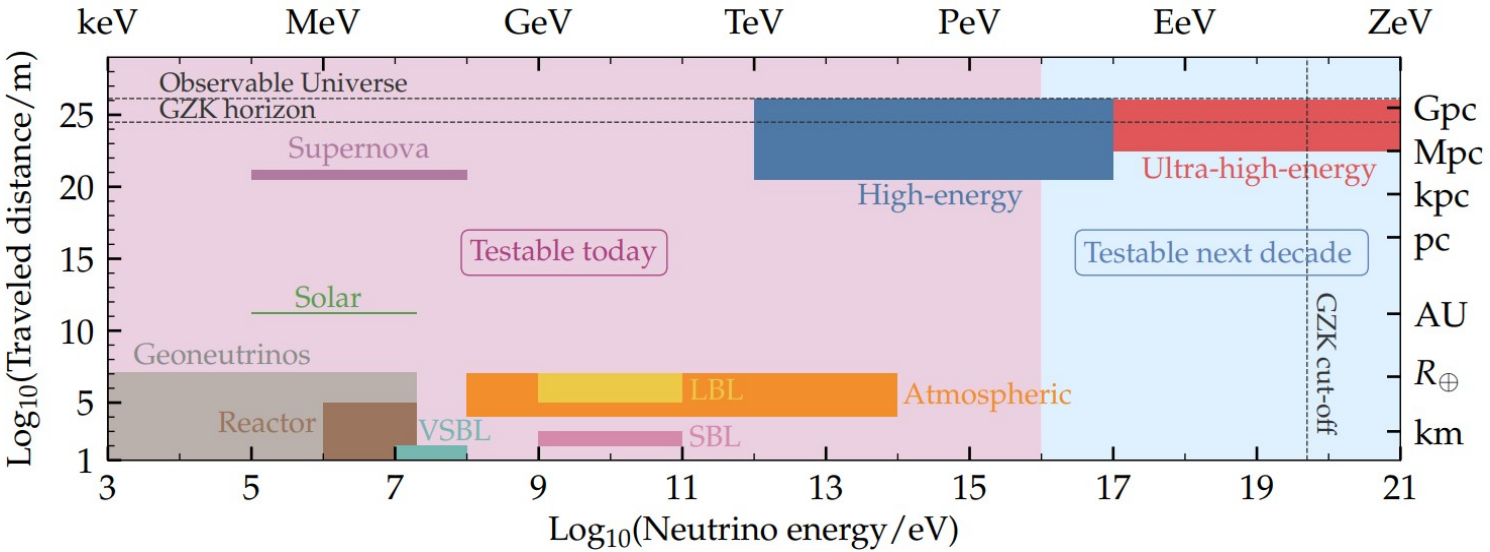

How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
VPLATE (vplate.ru)


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


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


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

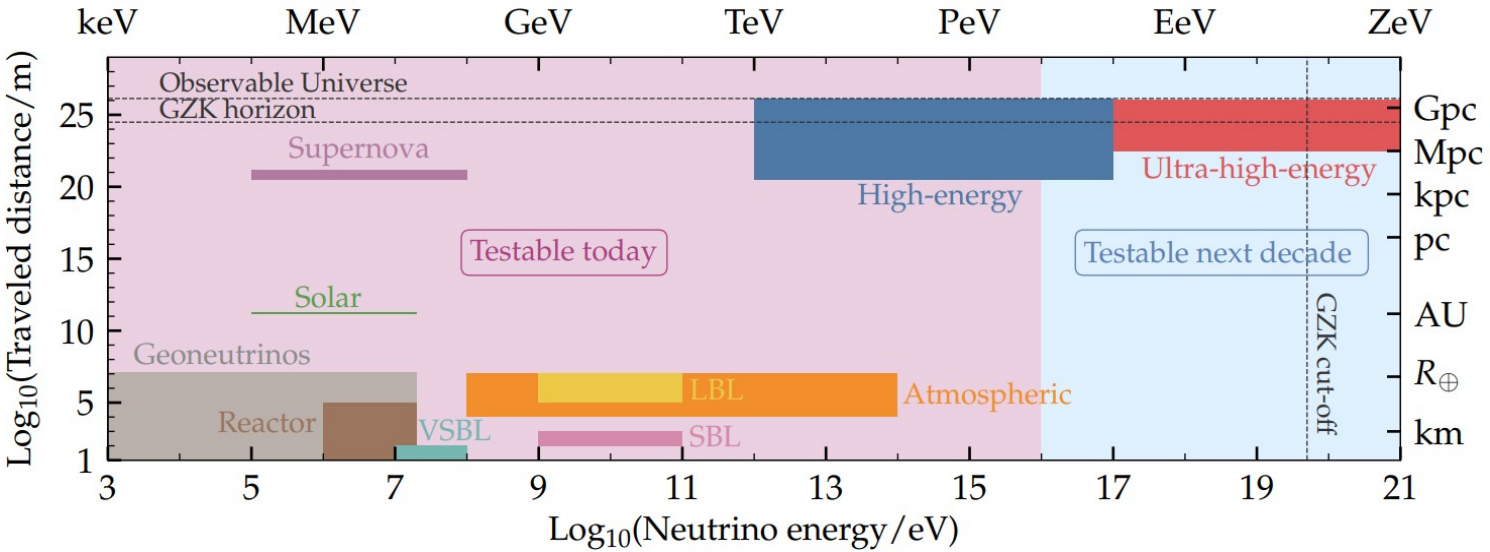
What makes high-energy cosmic ν exciting?



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

What makes high-energy cosmic ν exciting?

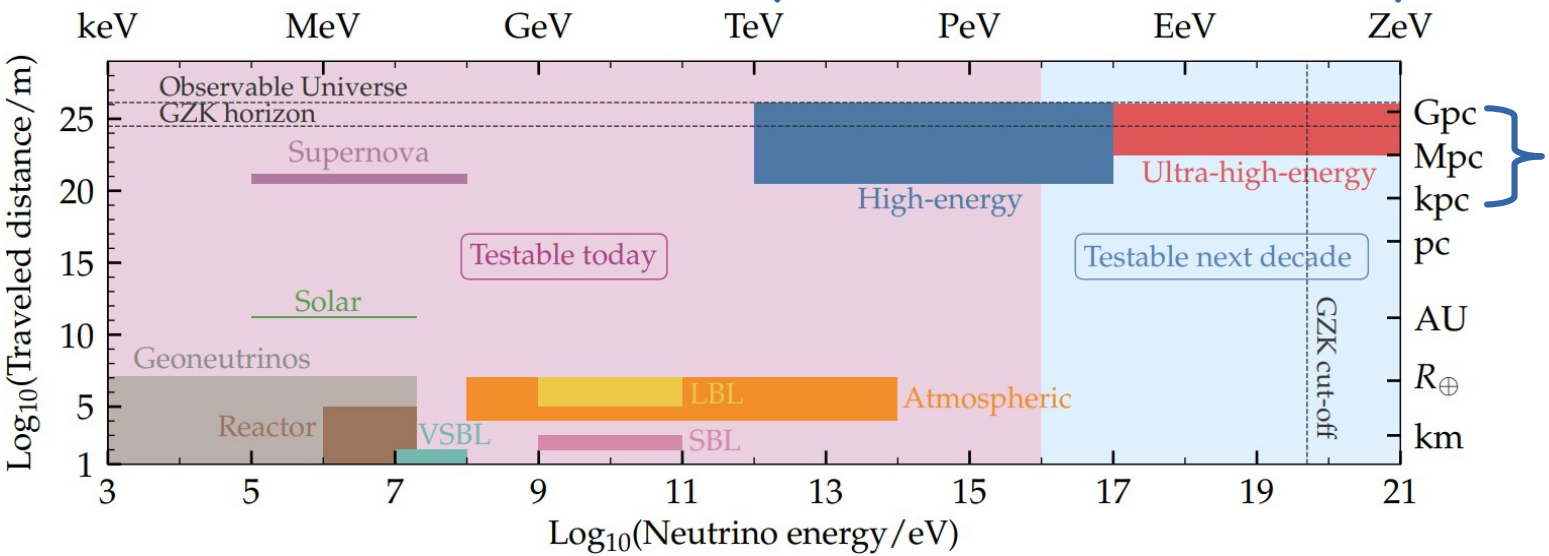
They have the highest energies



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

What makes high-energy cosmic ν exciting?

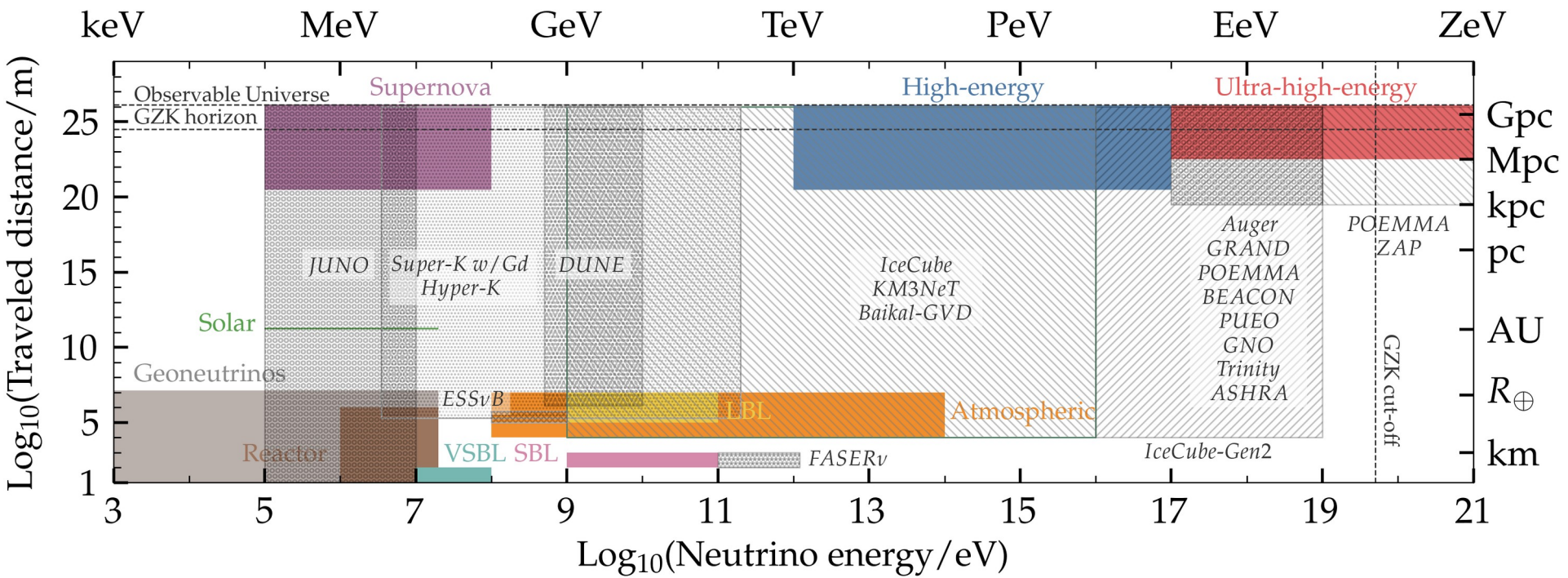
They have the highest energies



They travel the longest distances

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

Next decade: a host of planned neutrino detectors

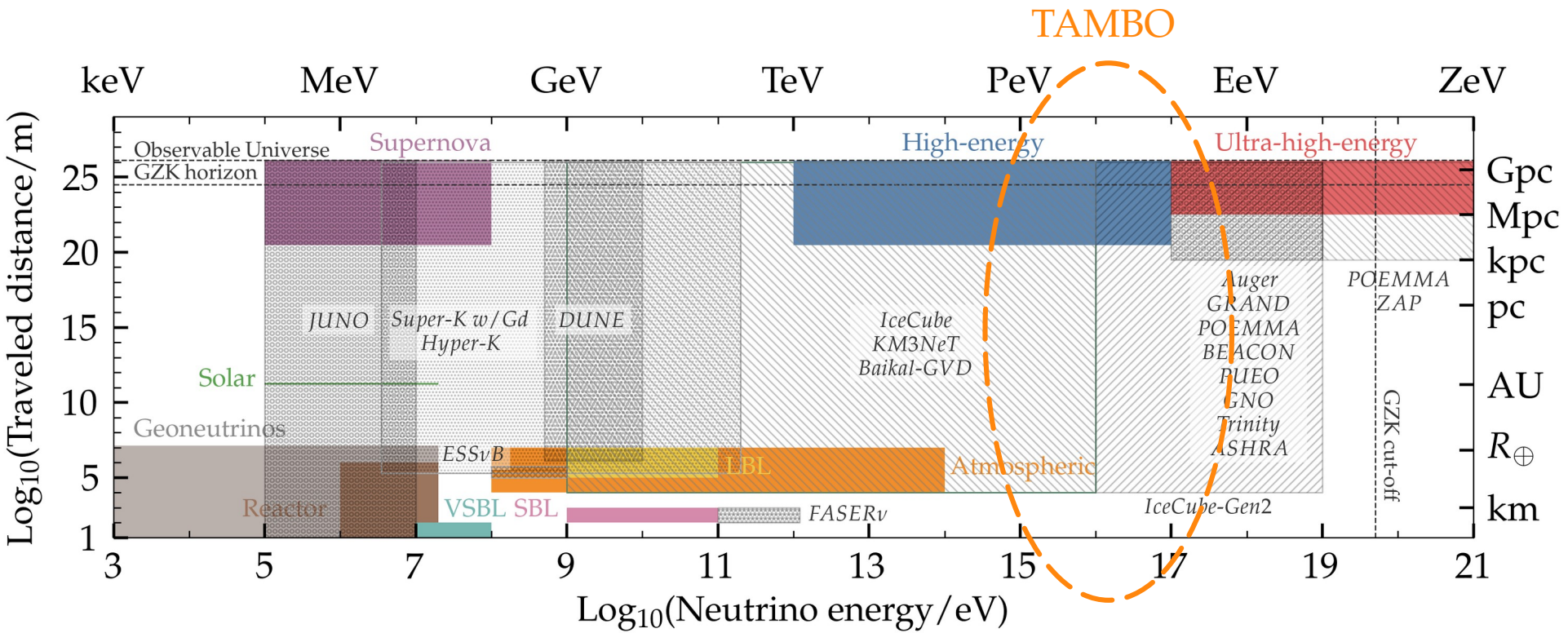


Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

Next decade: a host of planned neutrino detectors



High-energy neutrinos: TeV–PeV

(*Discovered*)

Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

High-energy neutrinos: TeV–PeV

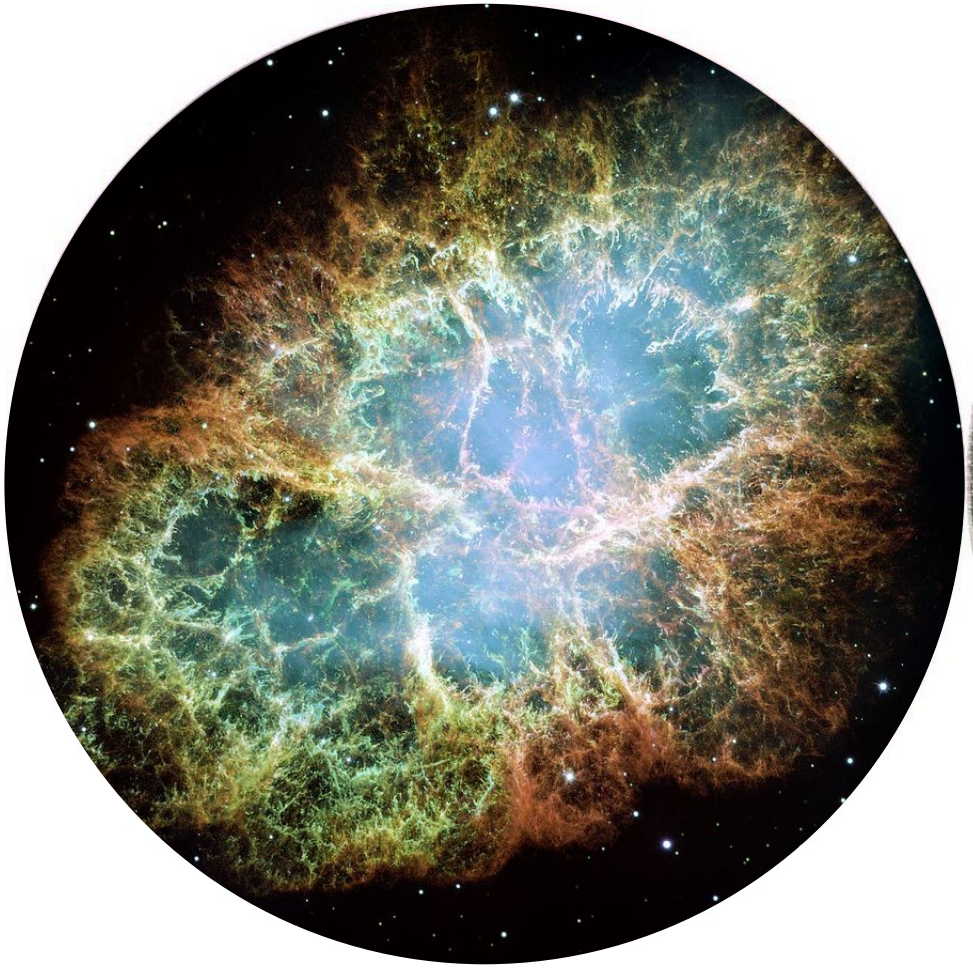
(*Discovered*)

TAMBO

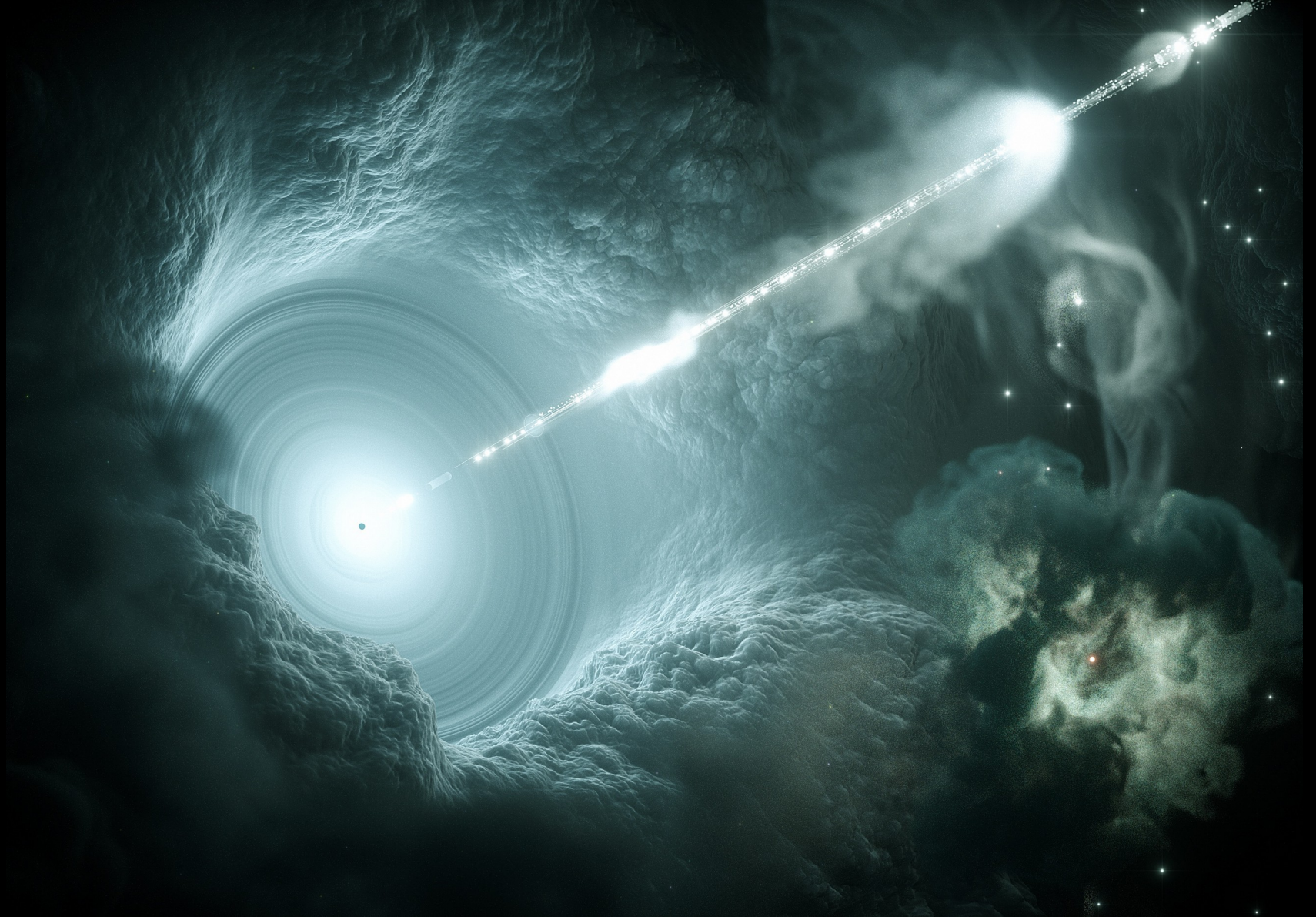
Ultra-high-energy neutrinos: > 100 PeV

(*Predicted but undiscovered*)

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

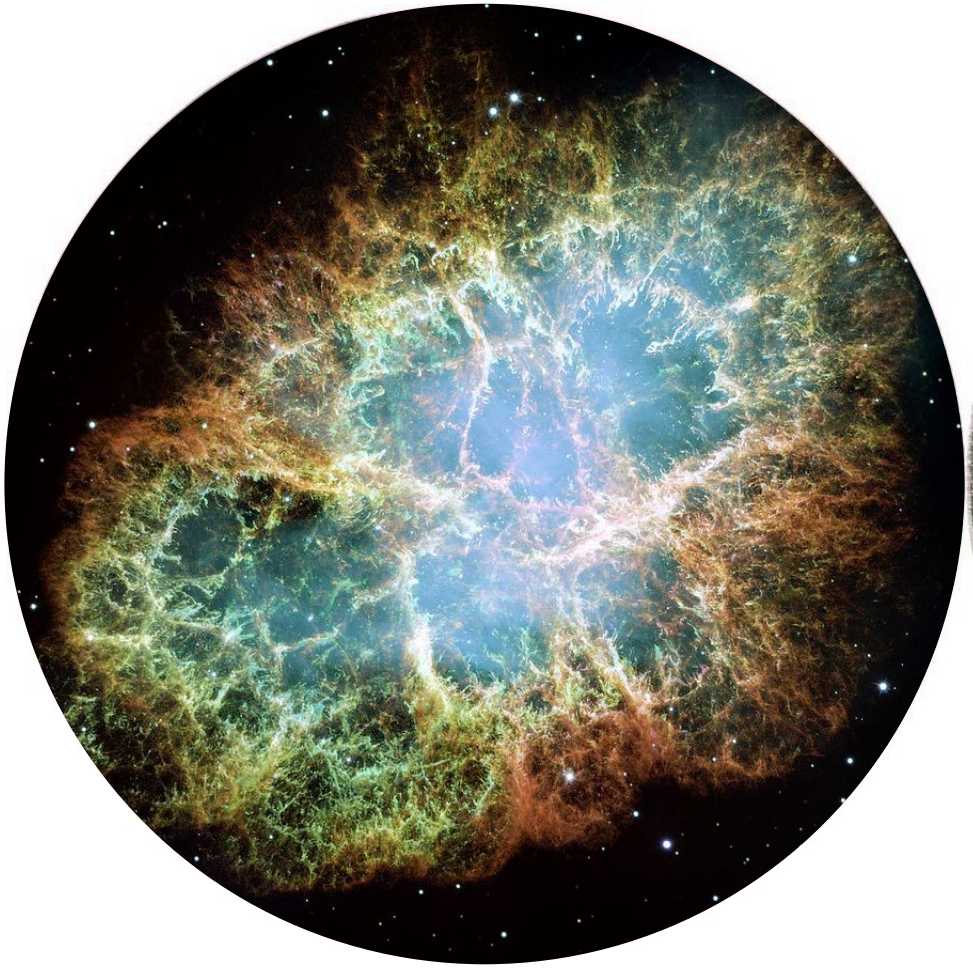


Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

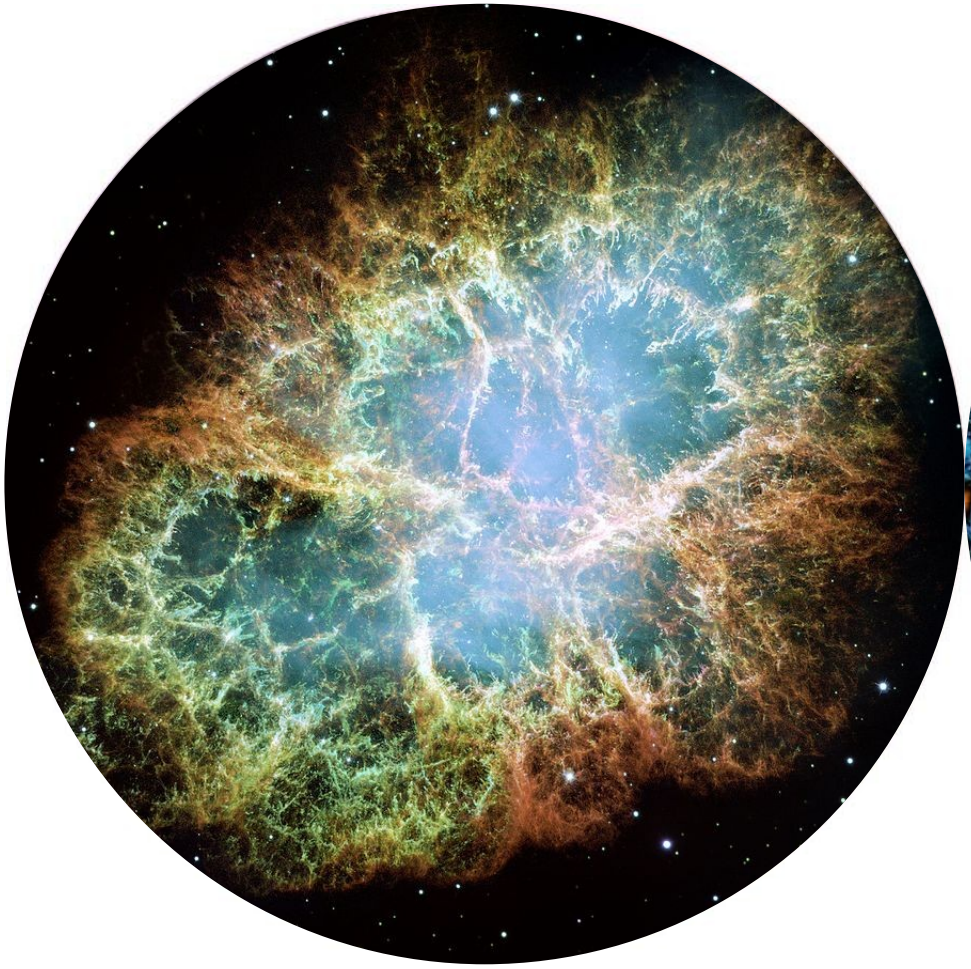


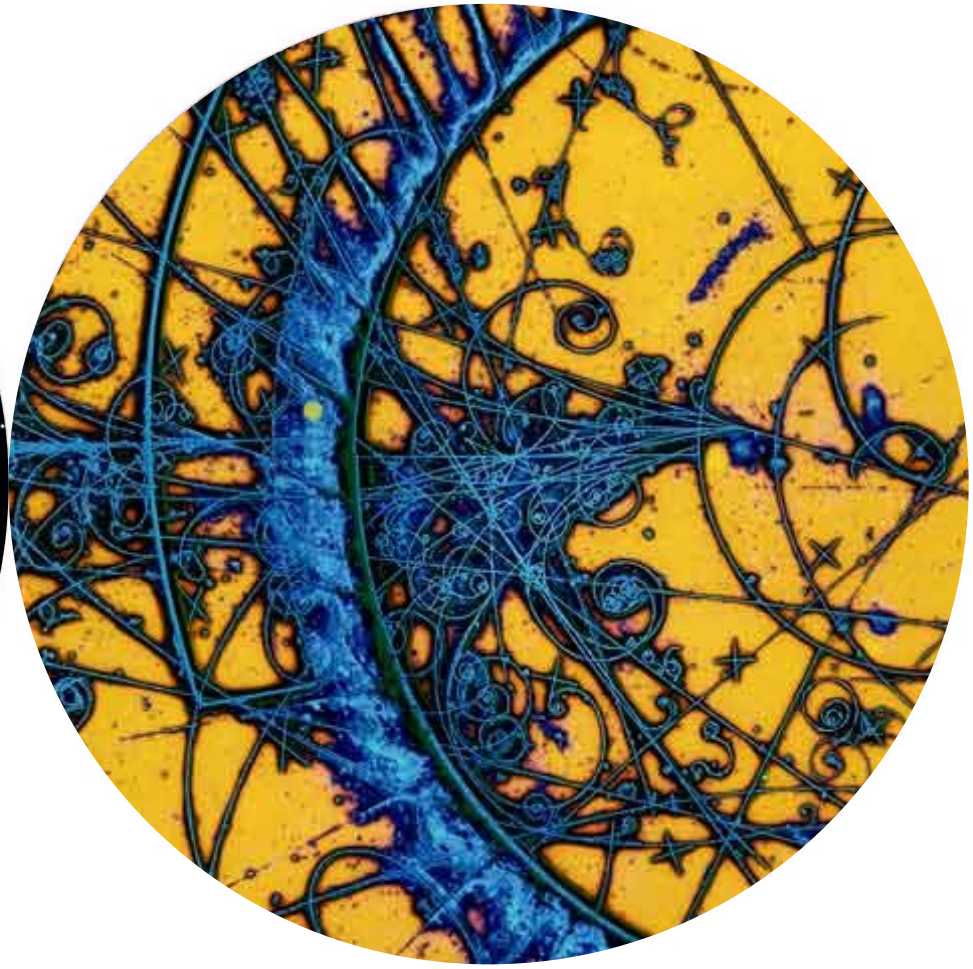
DESY

DESY



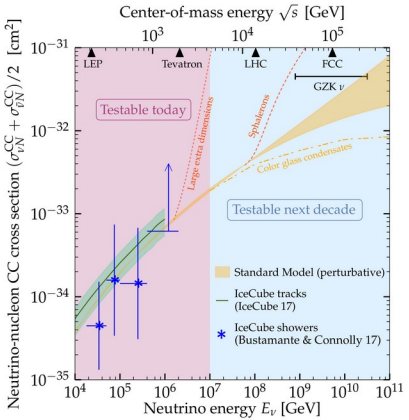
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine





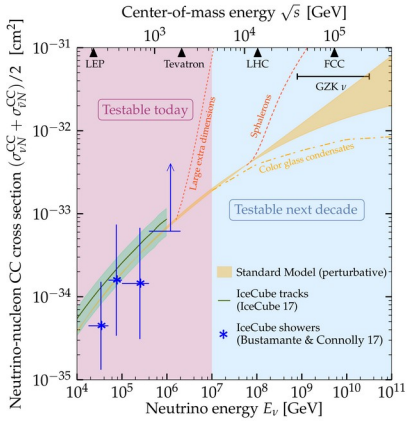
Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine

TeV–EeV ν cross sections



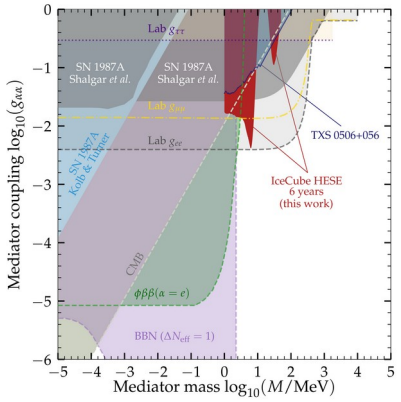
MB & Connolly, *PRL* 2019

TeV–EeV ν cross sections



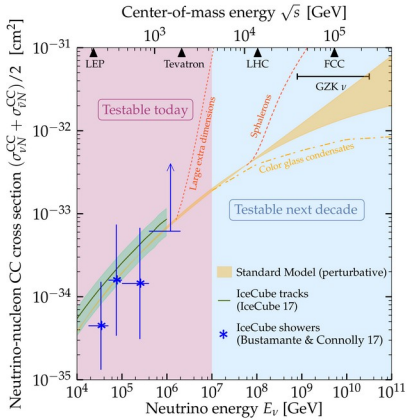
MB & Connolly, *PRL* 2019

ν self-interactions



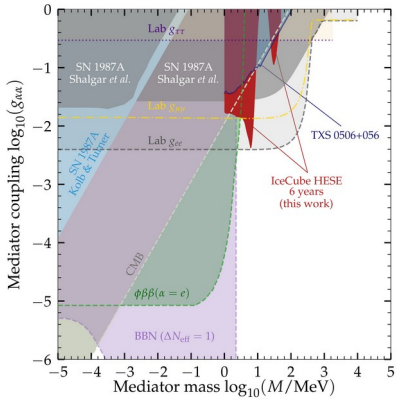
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

TeV–EeV ν cross sections



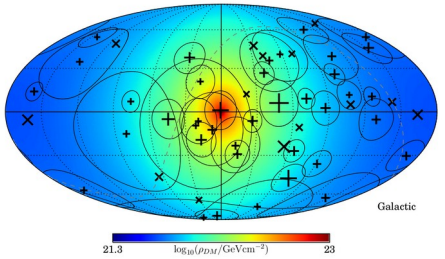
MB & Connolly, *PRL* 2019

ν self-interactions



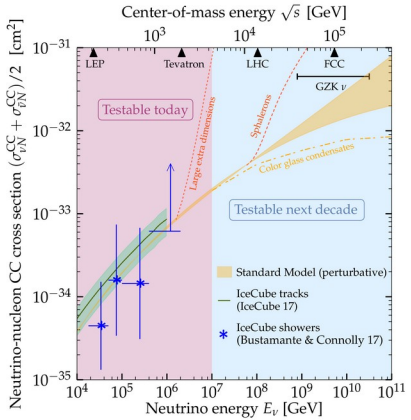
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



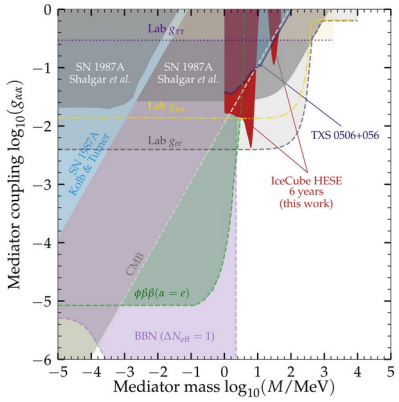
Argüelles, Kheirandish, Vincent, *PRL* 2017

TeV–EeV ν cross sections



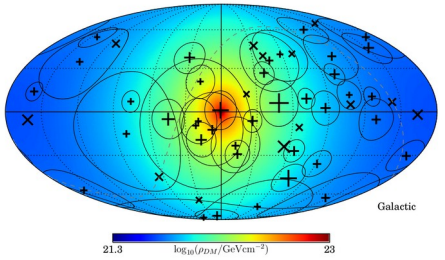
MB & Connolly, *PRL* 2019

ν self-interactions



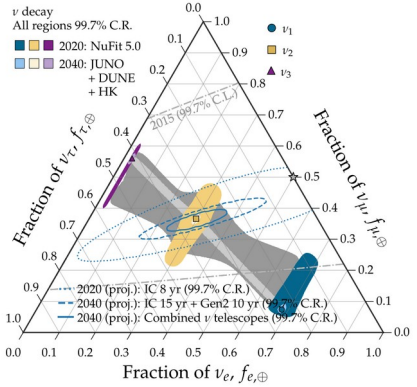
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



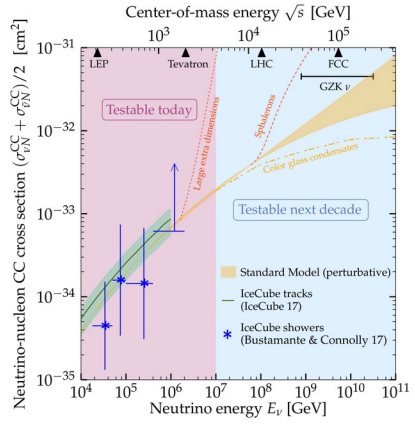
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



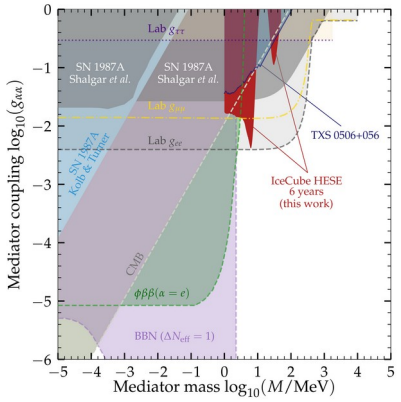
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

TeV–EeV ν cross sections



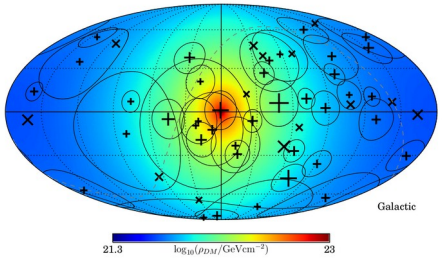
MB & Connolly, *PRL* 2019

ν self-interactions



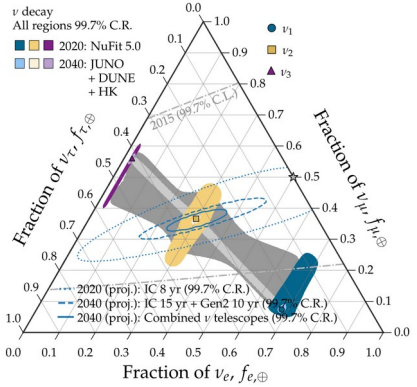
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



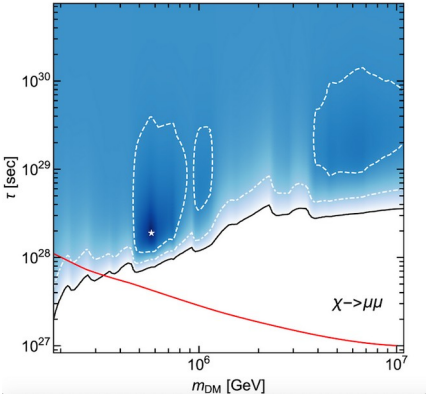
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



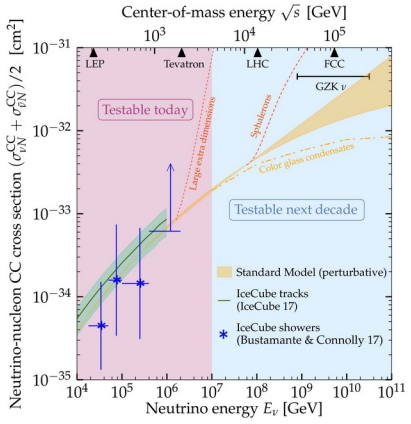
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



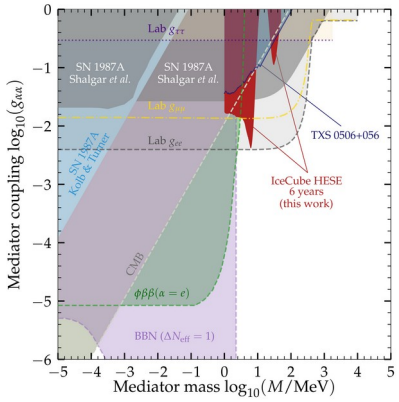
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

TeV–EeV ν cross sections



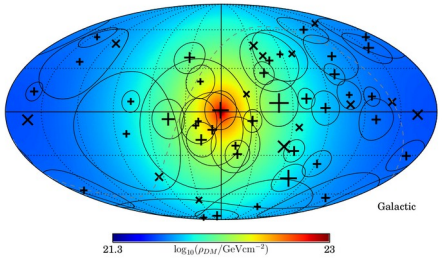
MB & Connolly, *PRL* 2019

ν self-interactions



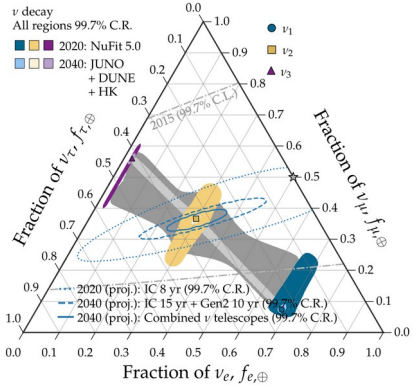
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



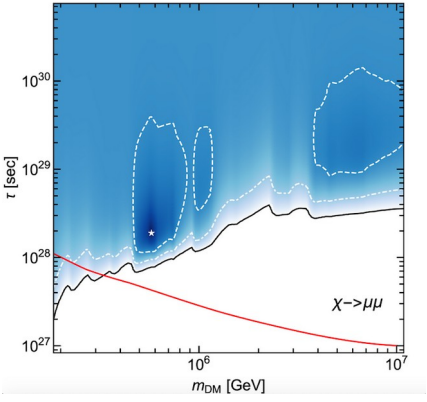
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



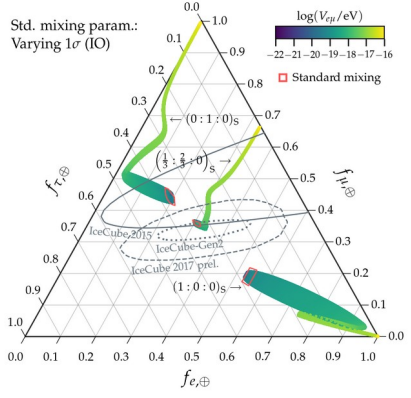
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



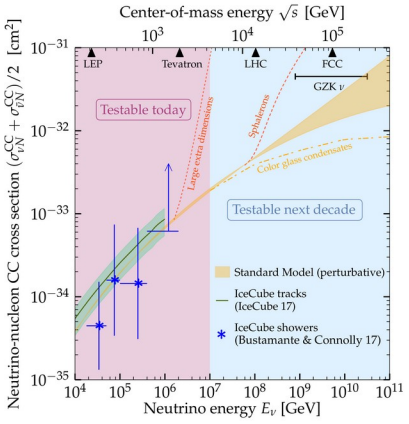
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



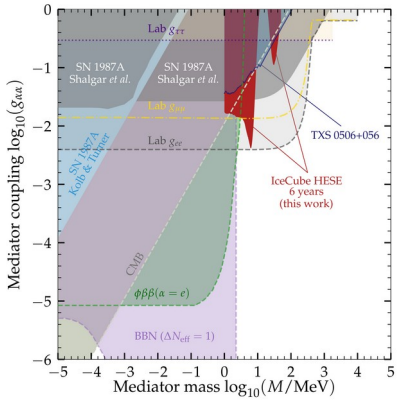
MB & Agarwalla, *PRL* 2019

TeV–EeV ν cross sections



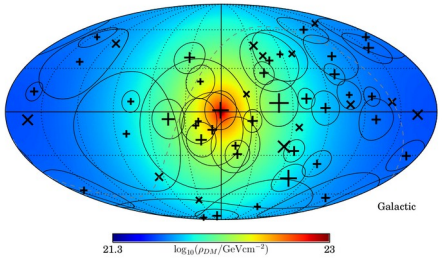
MB & Connolly, *PRL* 2019

ν self-interactions



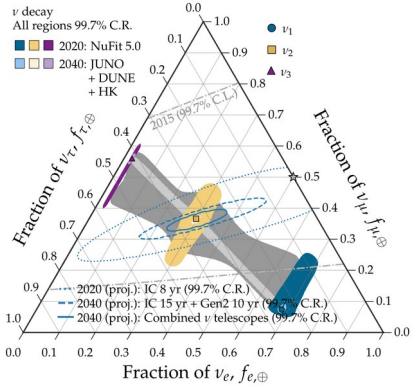
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



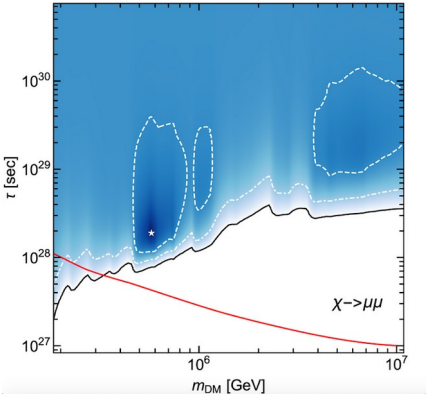
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



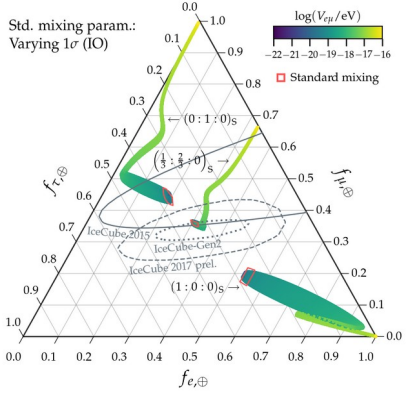
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



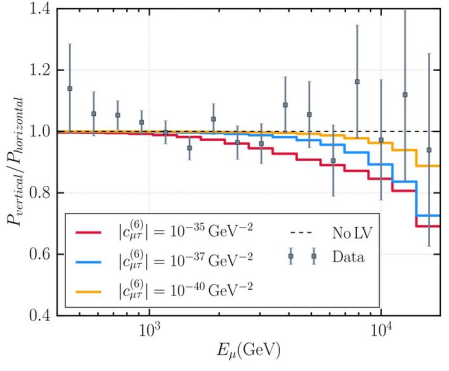
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



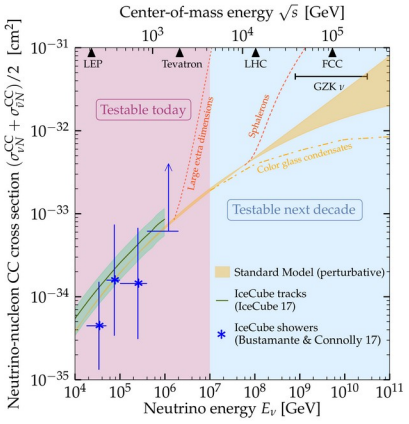
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



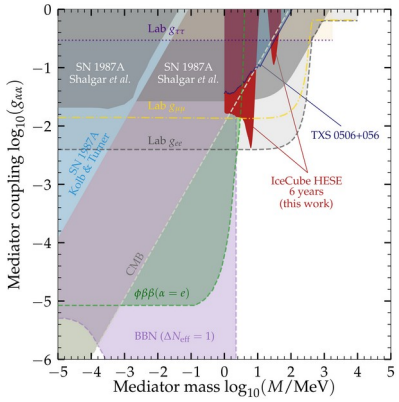
IceCube, *Nature Phys.* 2018

TeV–EeV ν cross sections



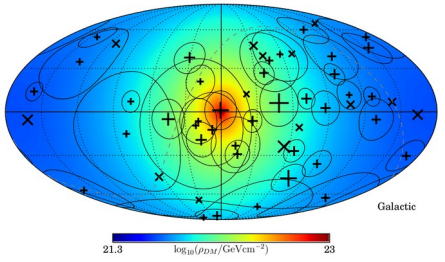
MB & Connolly, *PRL* 2019

ν self-interactions



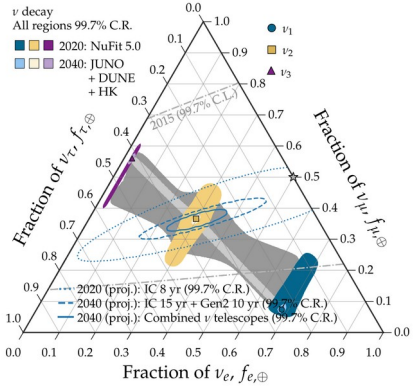
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



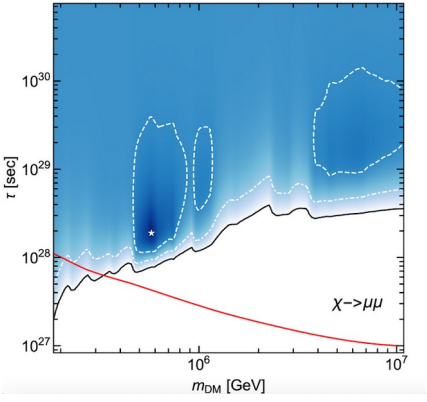
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



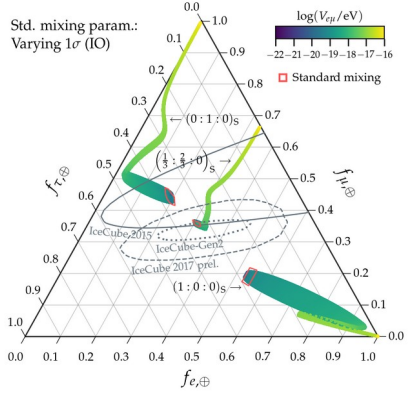
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



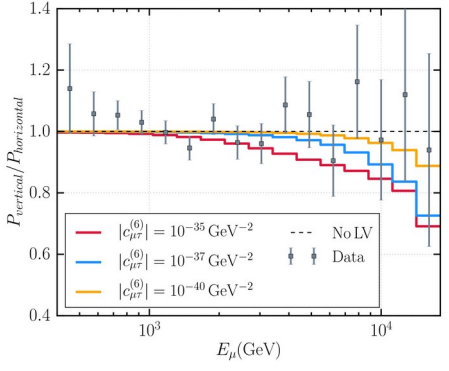
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



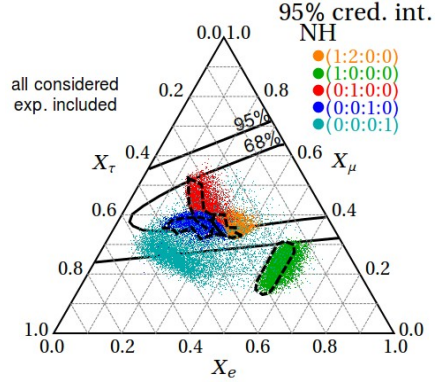
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



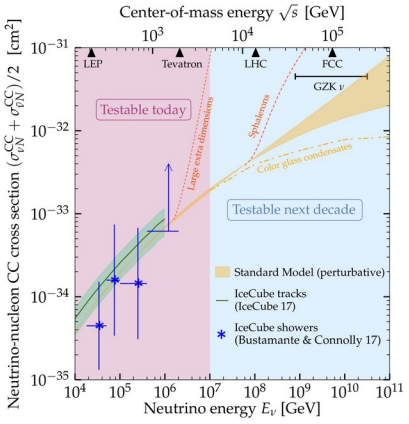
IceCube, *Nature Phys.* 2018

Sterile neutrinos



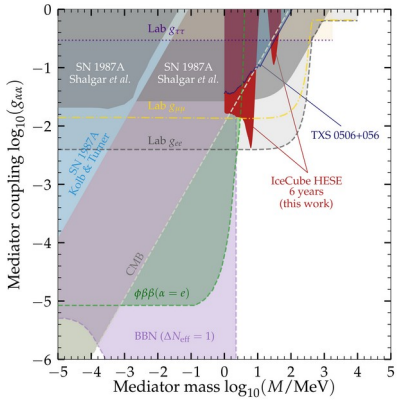
Brdar, Kopp, Wang, *JCAP* 2017

TeV–EeV ν cross sections



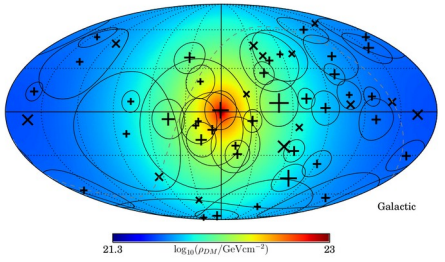
MB & Connolly, *PRL* 2019

ν self-interactions



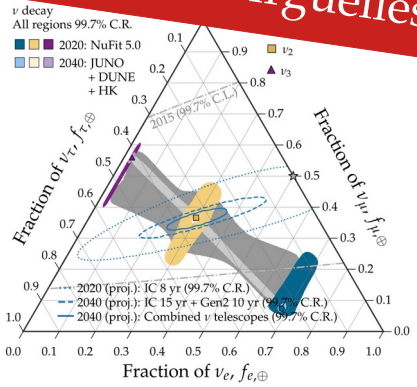
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galacti



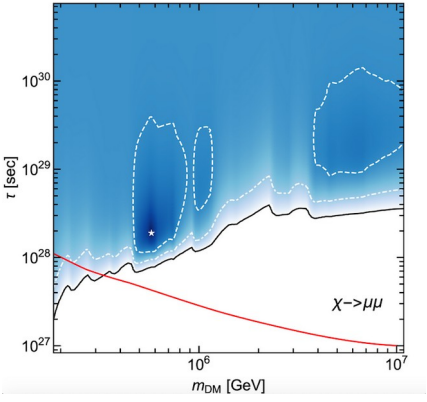
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



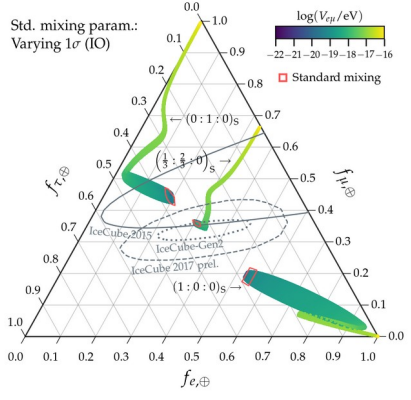
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



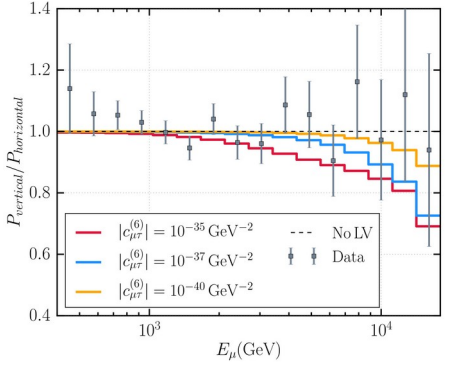
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



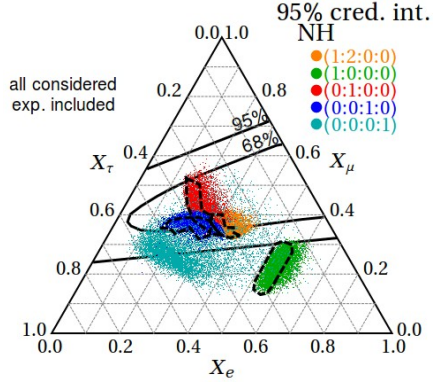
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017

Making high-energy astrophysical neutrinos

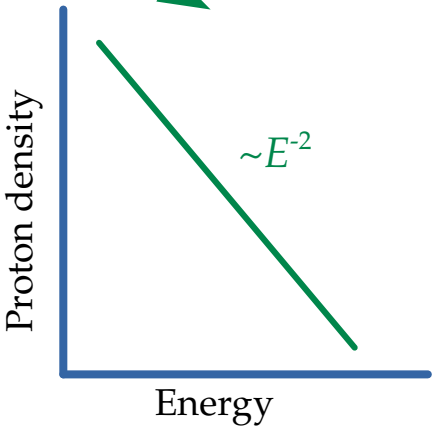
(or $p + p$)

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

Making high-energy astrophysical neutrinos

(or $p + p$)

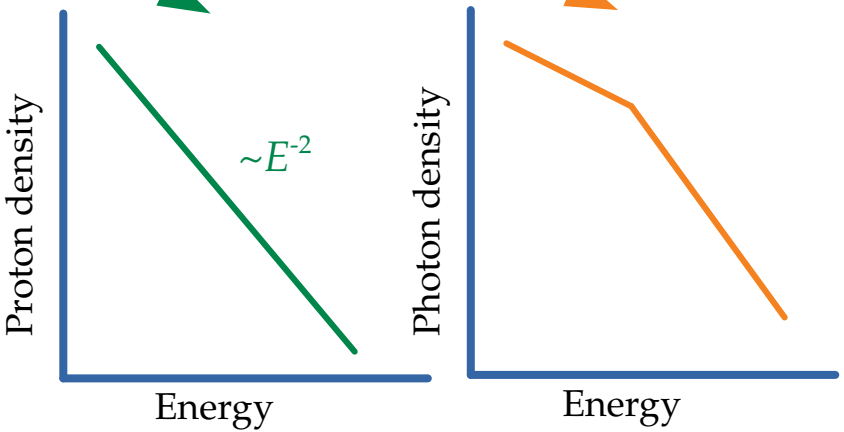
$$p + \gamma_{\text{target}} \rightarrow \Delta^{+} \rightarrow \begin{cases} p + \pi^{0}, & \text{Br} = 2/3 \\ n + \pi^{+}, & \text{Br} = 1/3 \end{cases}$$



Making high-energy astrophysical neutrinos

(or $p + p$)

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



Making high-energy astrophysical neutrinos

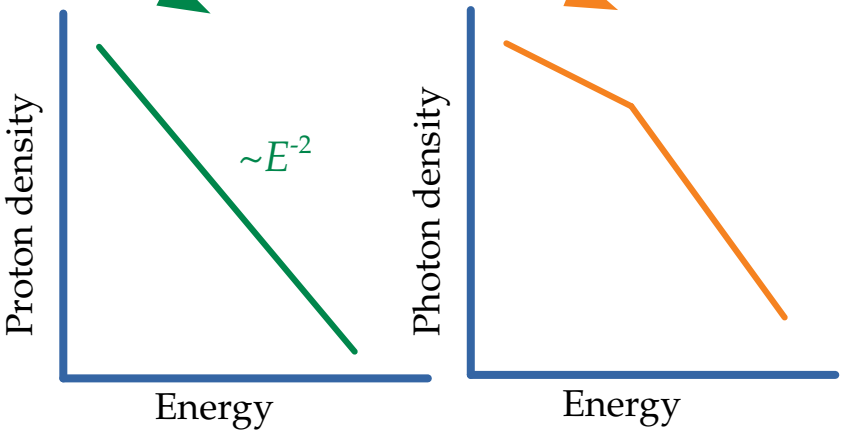
(or $p + p$)

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

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

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

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



Making high-energy astrophysical neutrinos

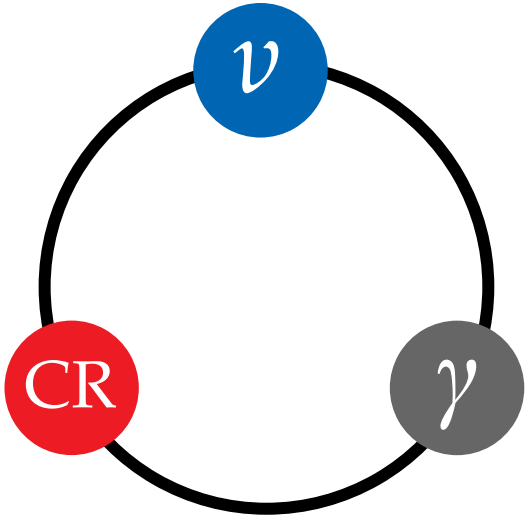
(or $p + p$)

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

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

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

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

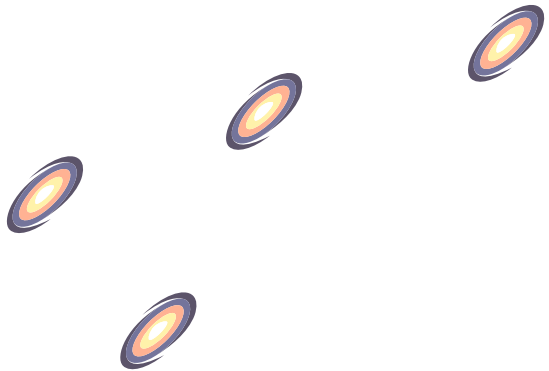


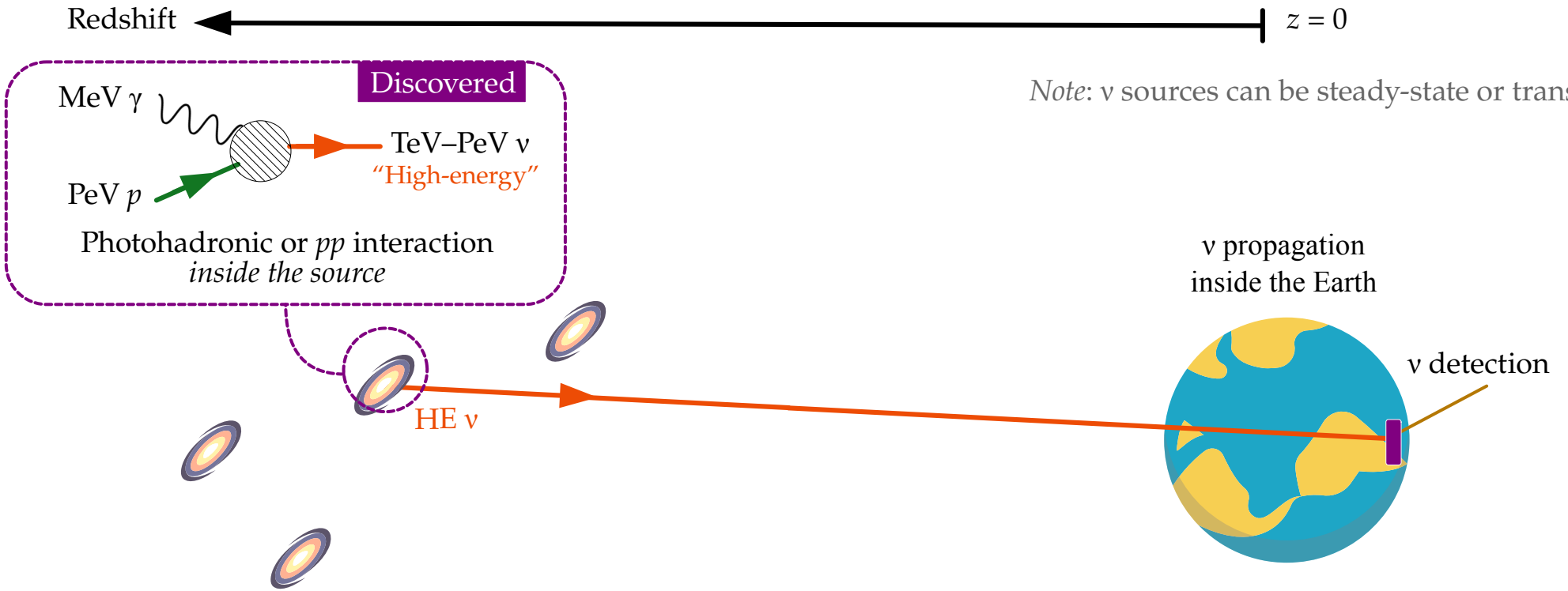
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

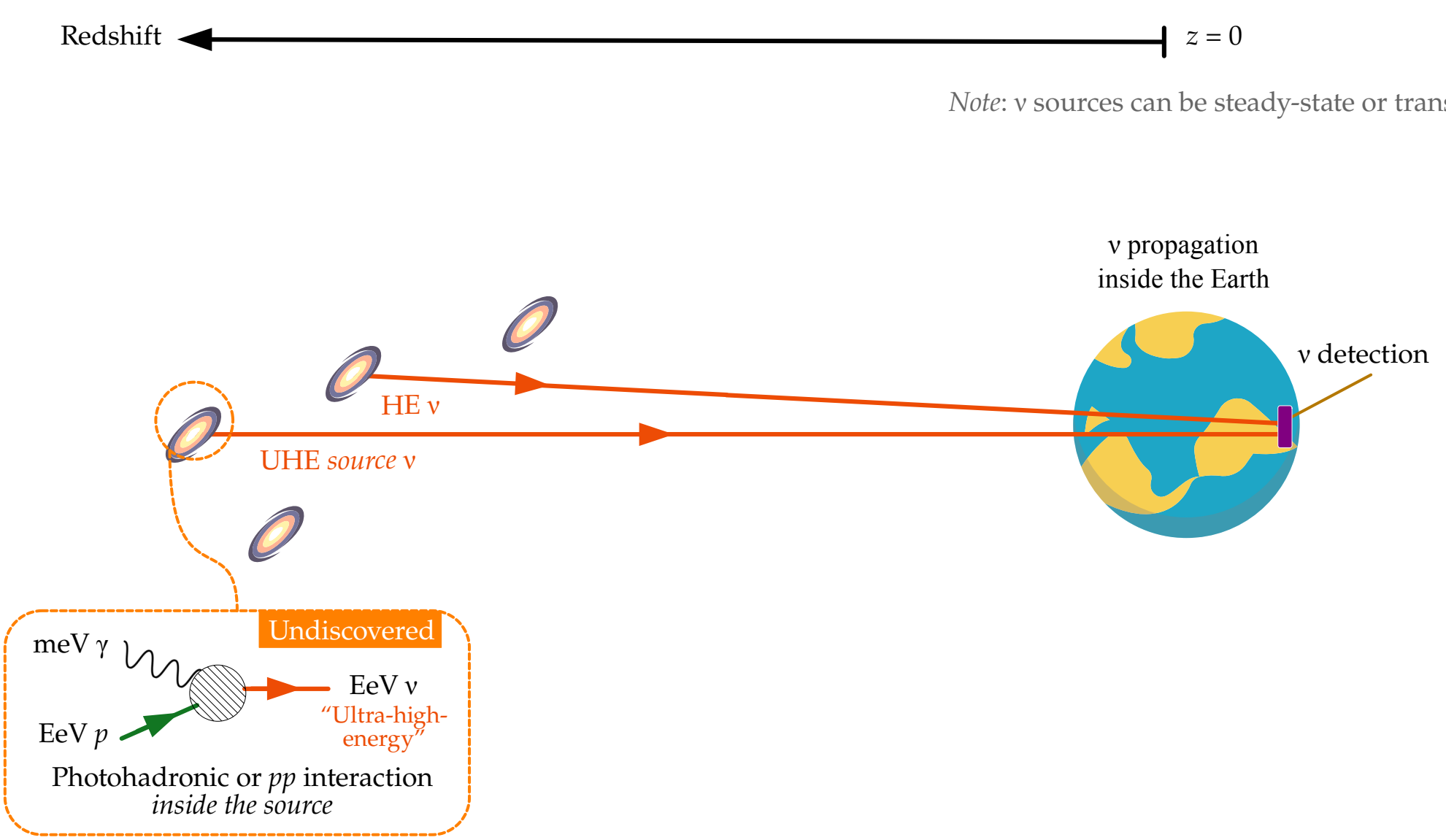
Redshift $z = 0$

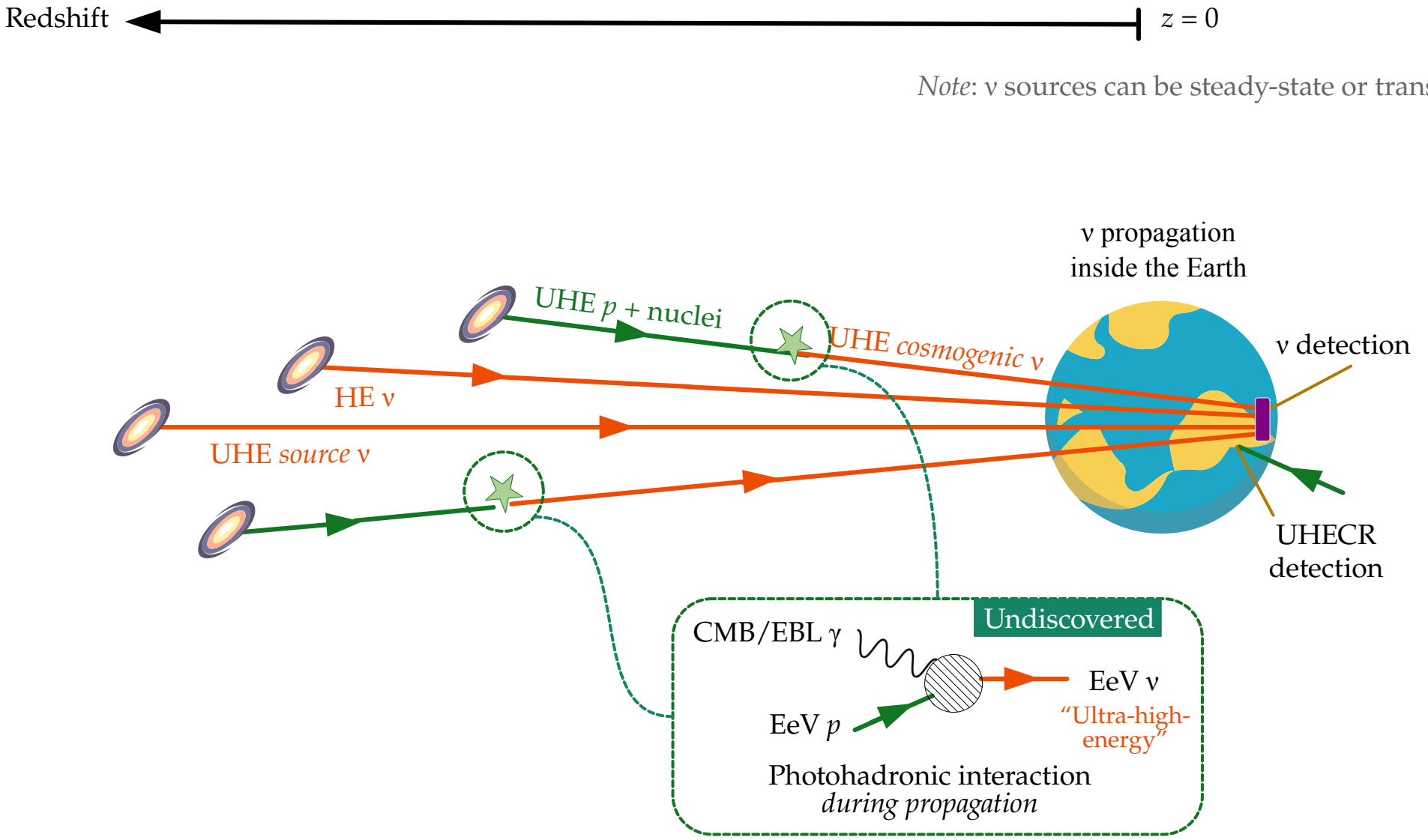
Note: ν sources can be steady-state or transient

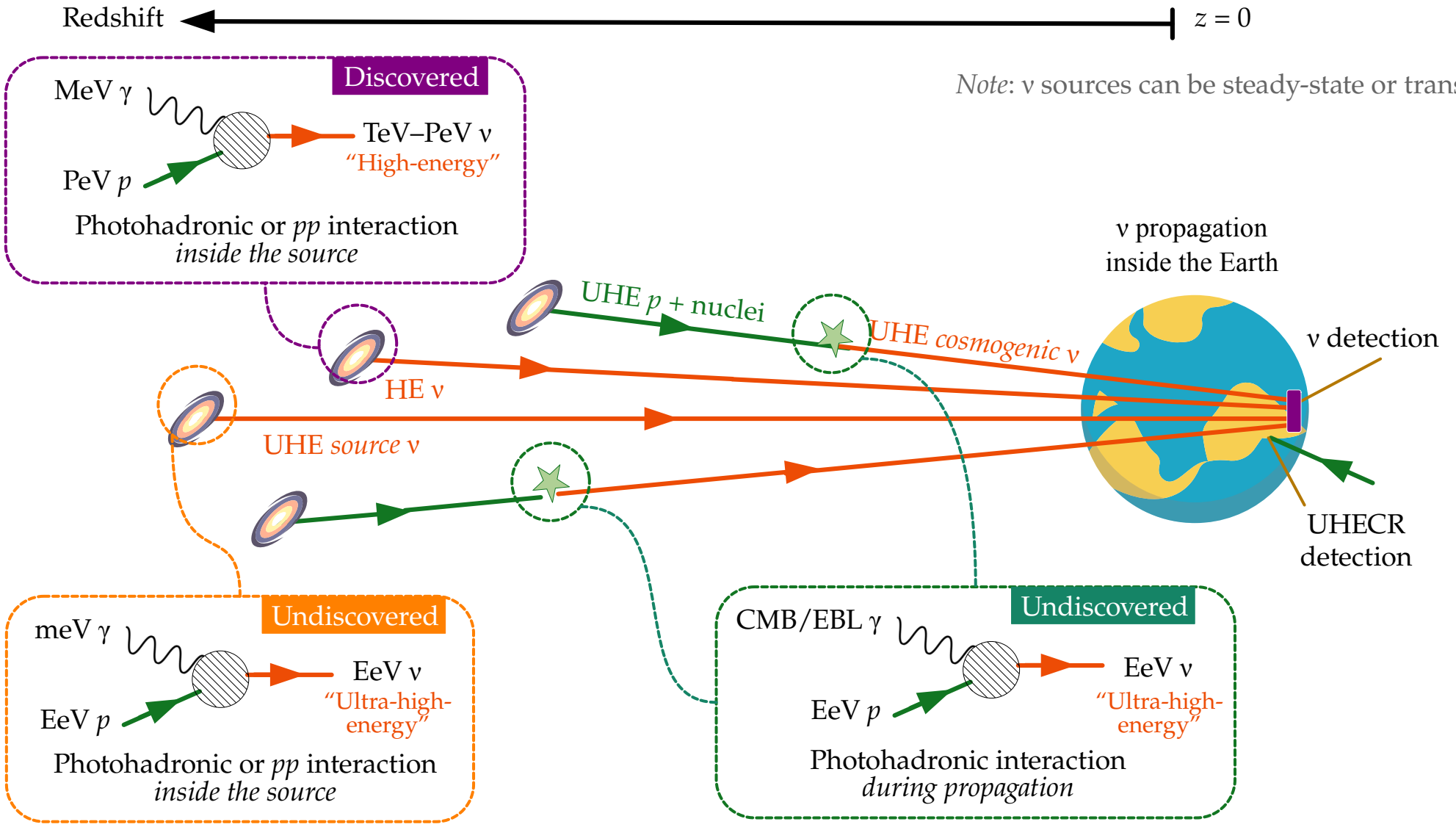




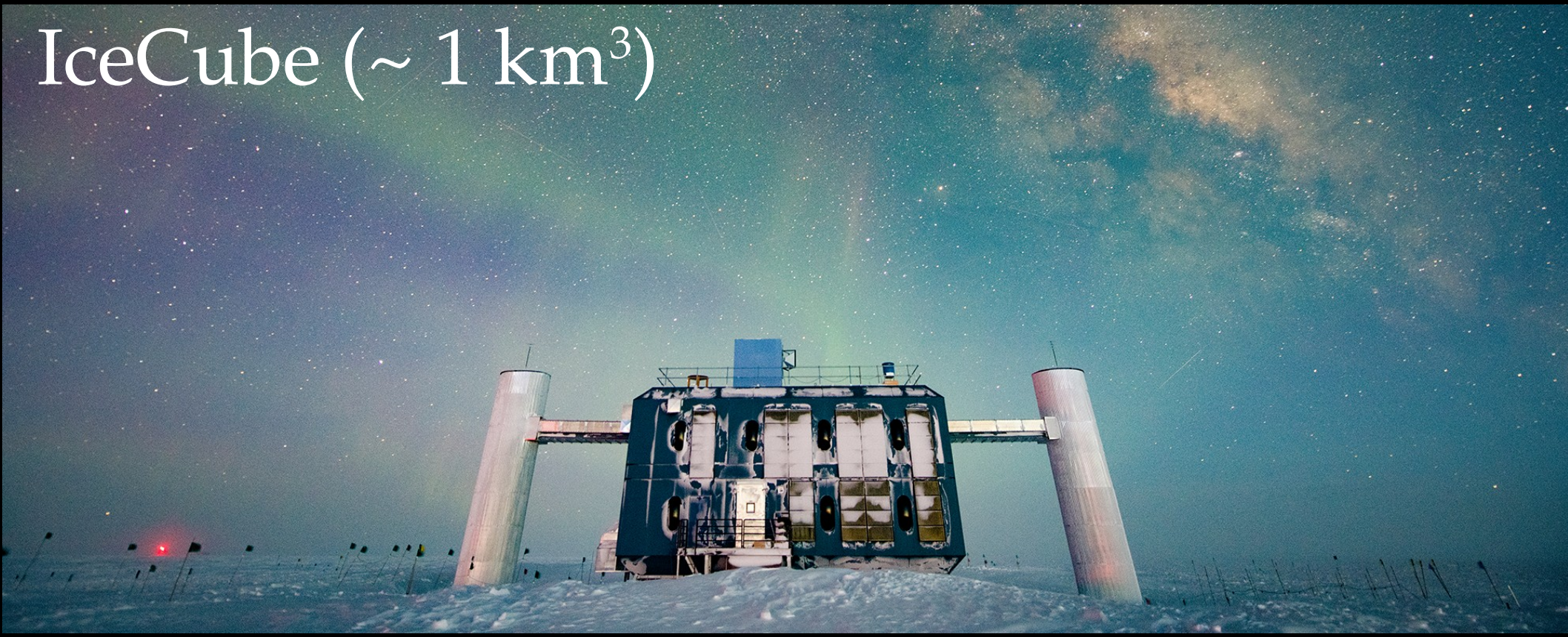
Note: ν sources can be steady-state or transient


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
"Ultra-high-
energy"
EeV p
Photohadronic interaction
during propagation

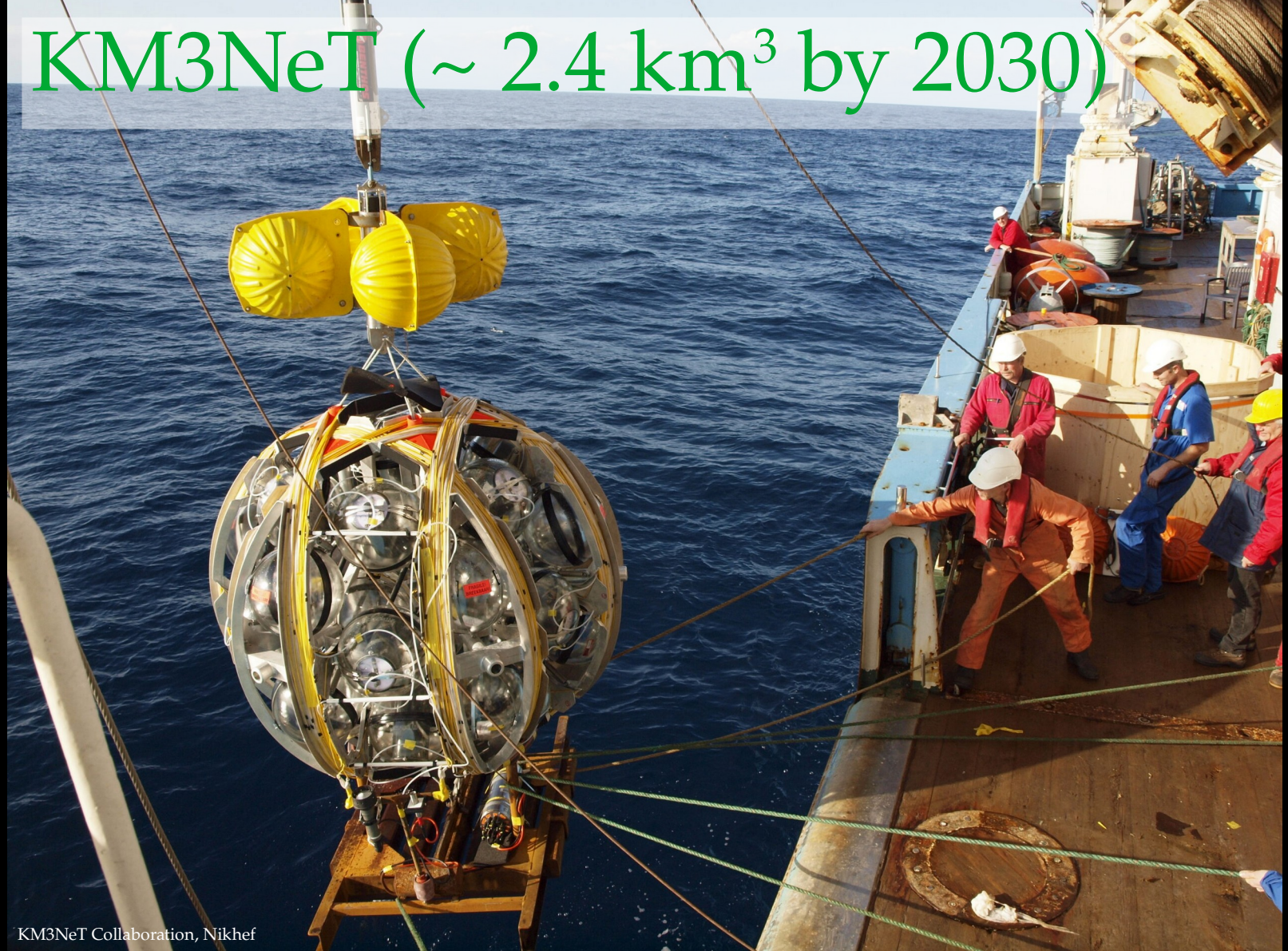

Redshift
z = 0
Note: ν sources can be steady-state or transient
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
meV γ
EeV ν
"Ultra-high-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

IceCube (~ 1 km^3)



Yuya Makino, IceCube/NSF

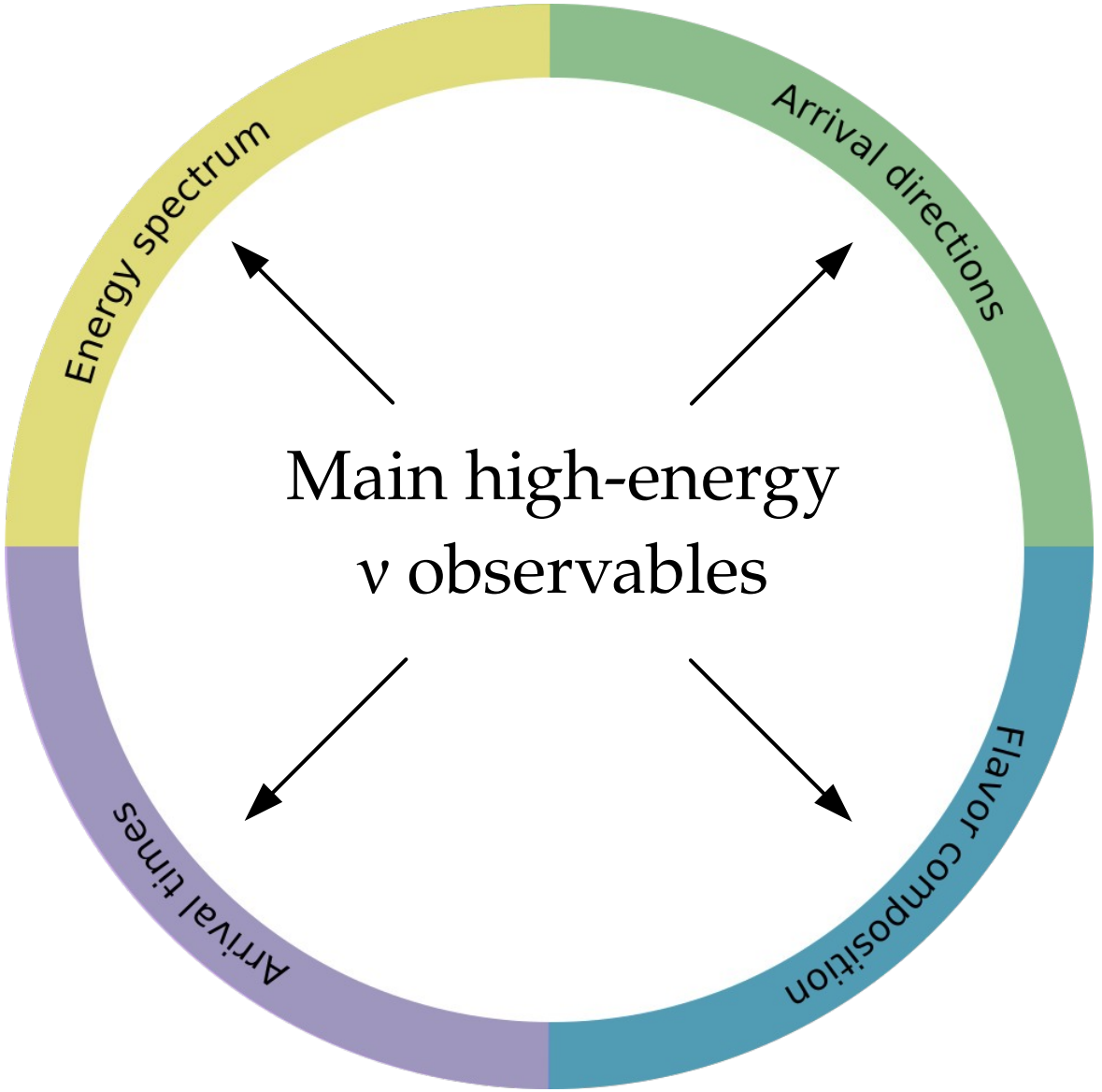
KM3NeT (~ 2.4 km^3 by 2030)



KM3NeT Collaboration, Nikhef

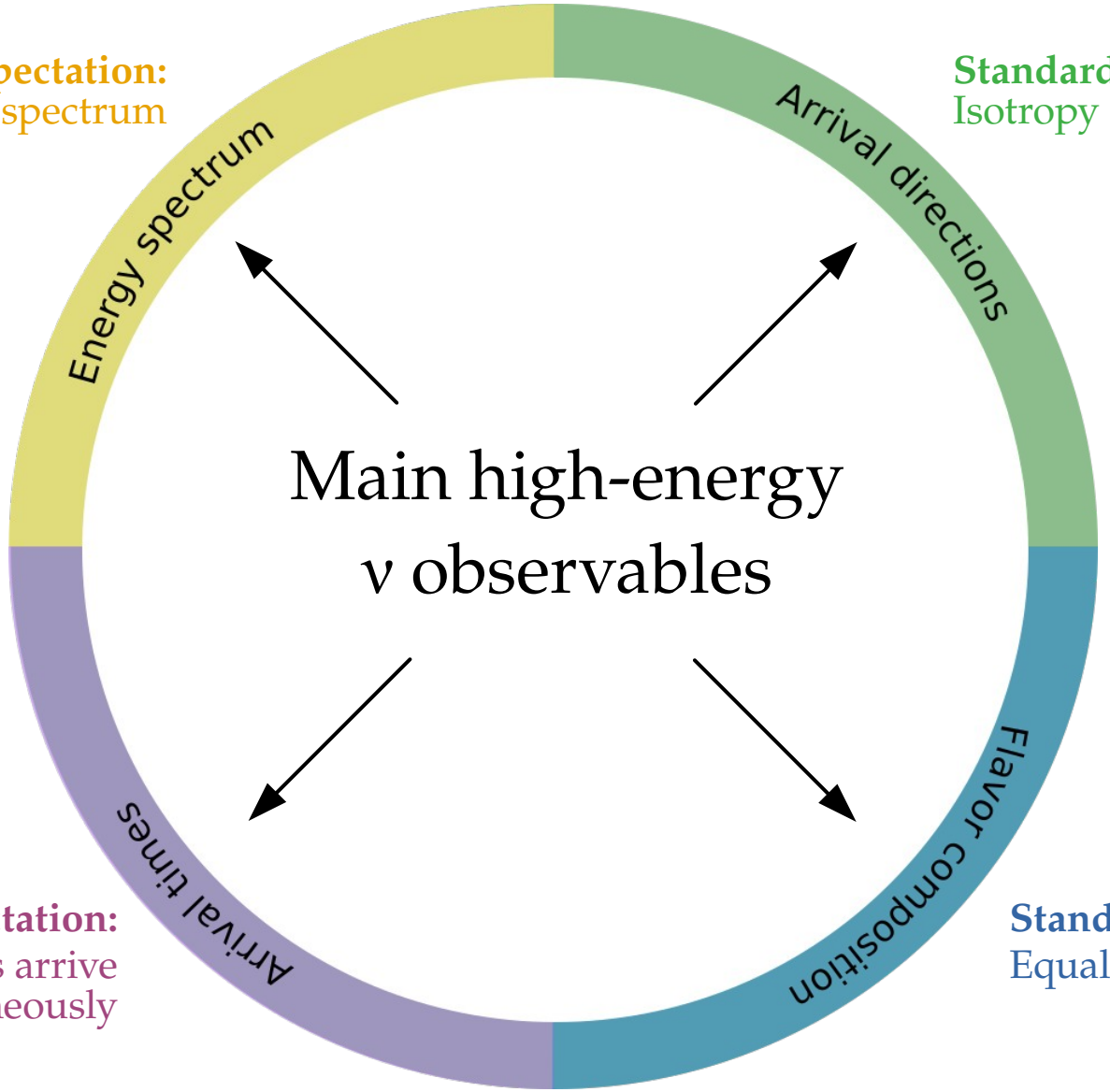
Baikal-GVD (~ 1.5 km^3 by 2025)

Baikal Collaboration, INR


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

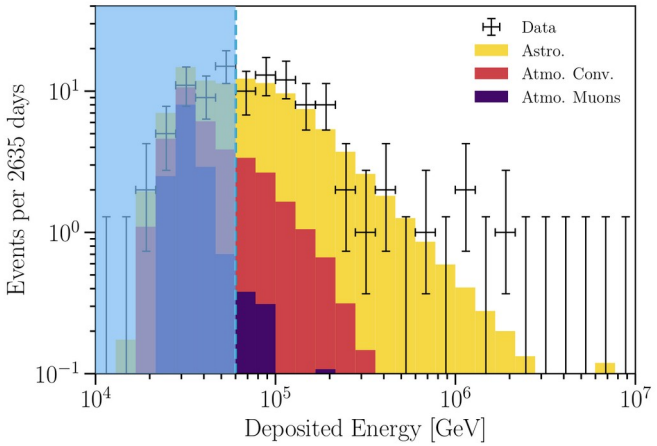


Standard expectation:
ν and γ from transients arrive simultaneously

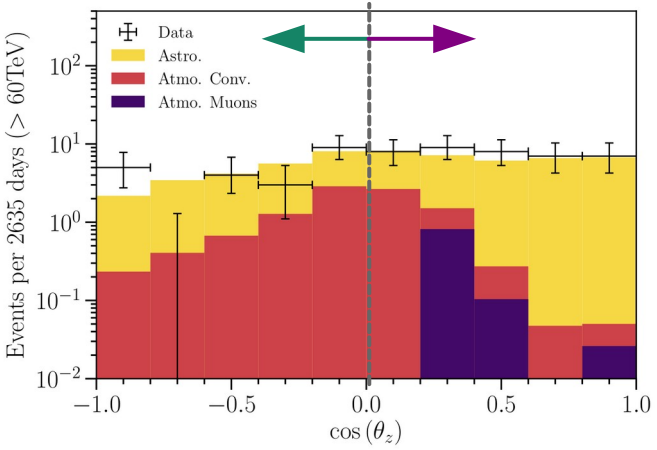
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

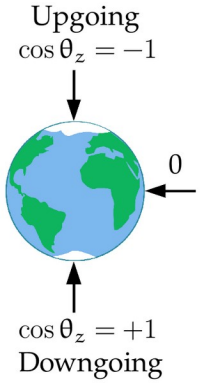
IceCube: Energy spectrum (~10 yr)

100+ contained events above 60 TeV:



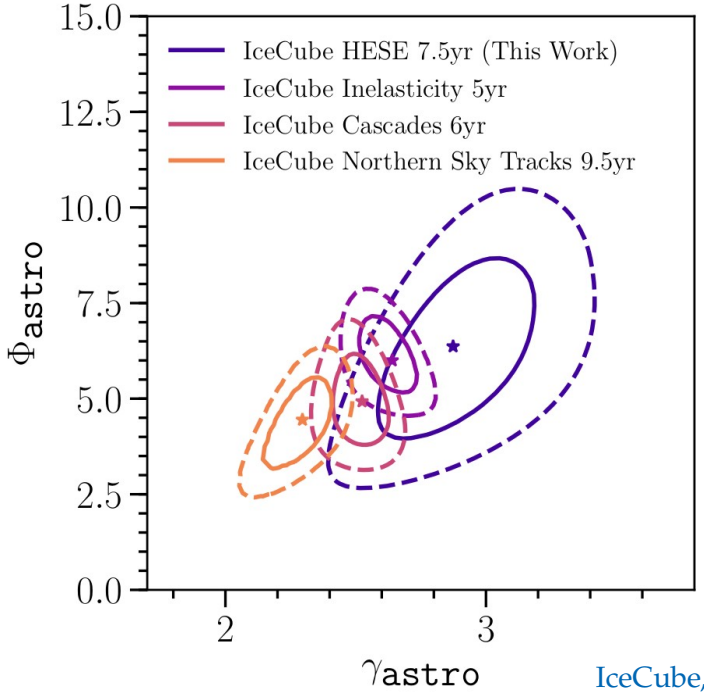
ν attenuated by Earth Atm. ν and μ vetoed





Data is fit well by a single power law:

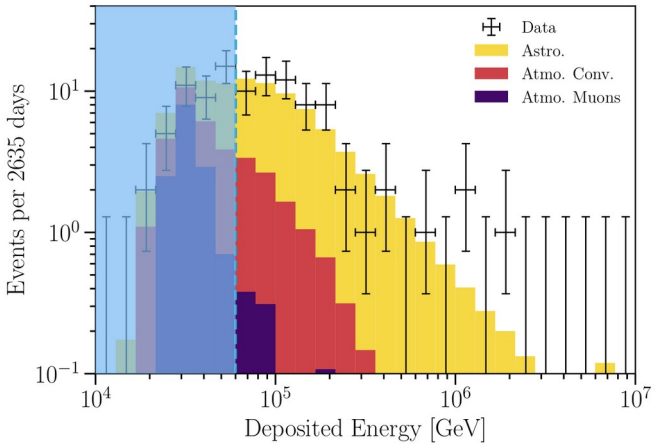
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



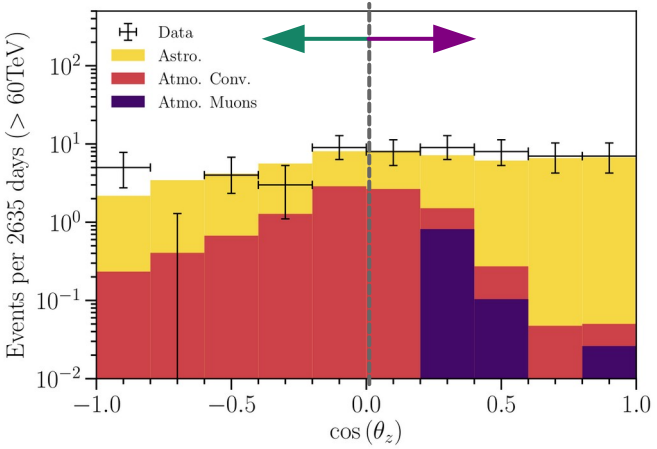
IceCube, 2011.03545

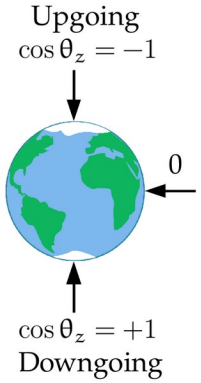
IceCube: Energy spectrum (~10 yr)

100+ contained events above 60 TeV:



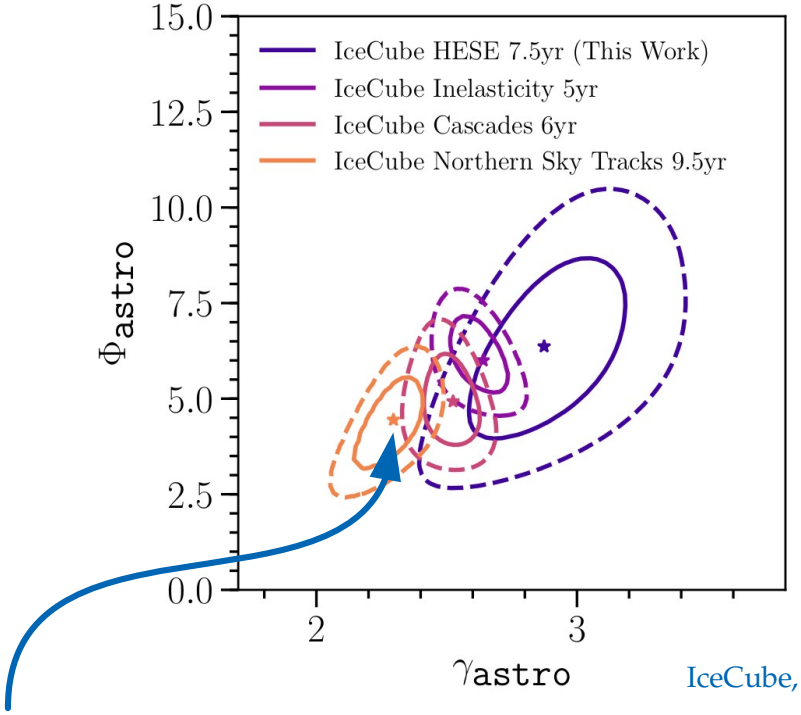
ν attenuated by Earth Atm. ν and μ vetoed





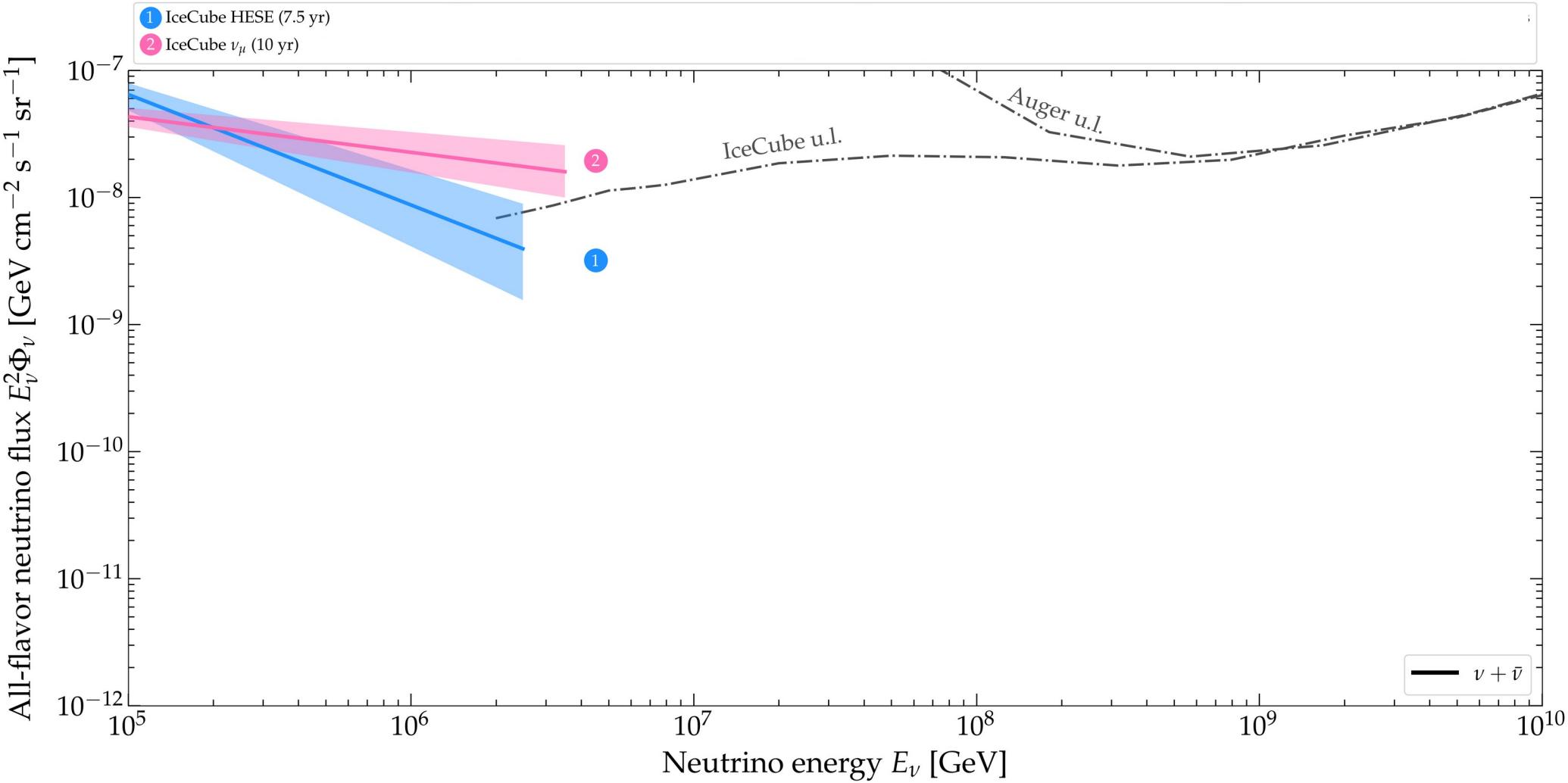
Data is fit well by a single power law:

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



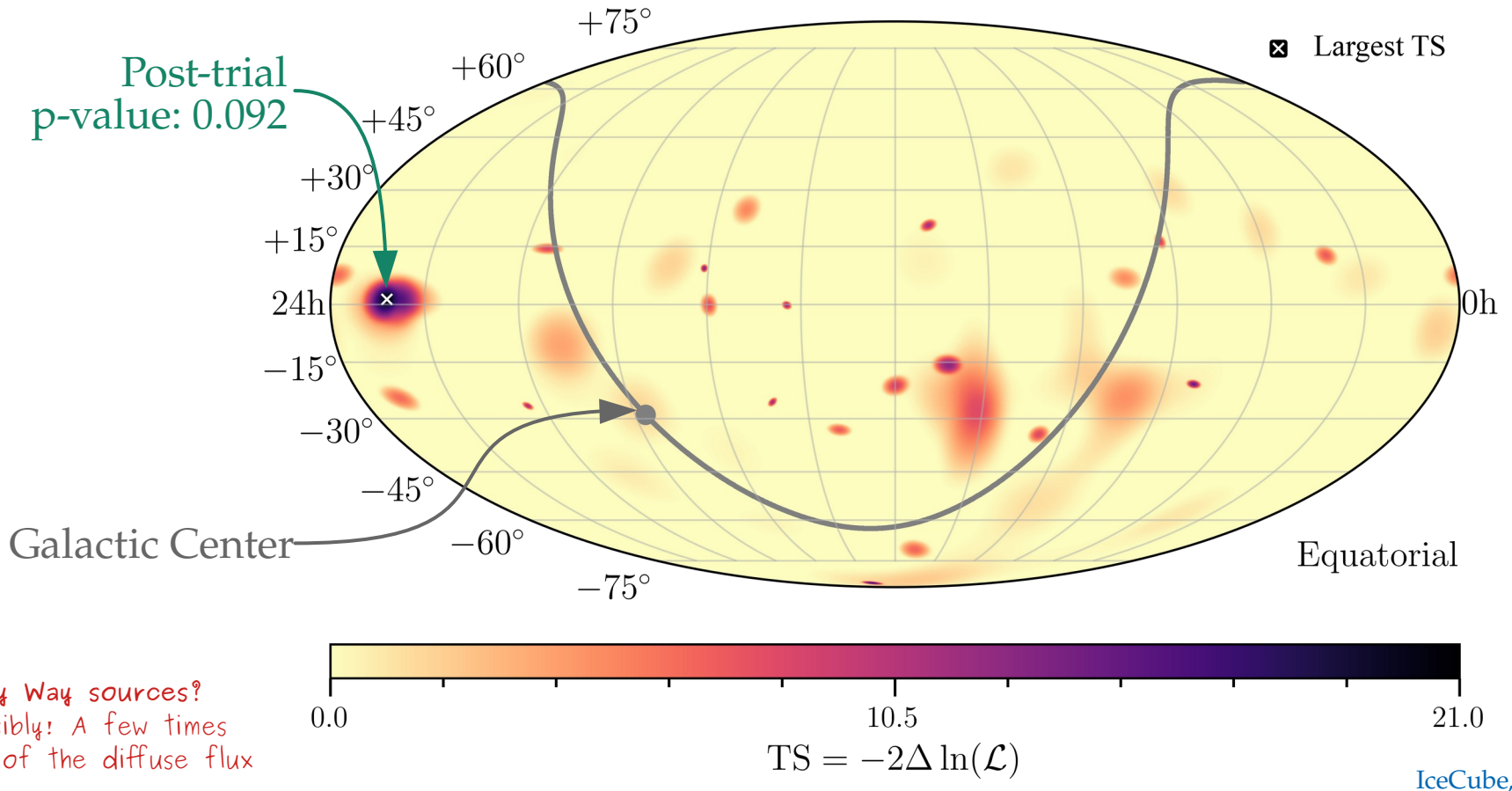
IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ


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

Arrival directions (HESE 7.5 yr)

No significant excess in the neutrino sky map:



Milky Way sources?
Possibly: A few times 10% of the diffuse flux

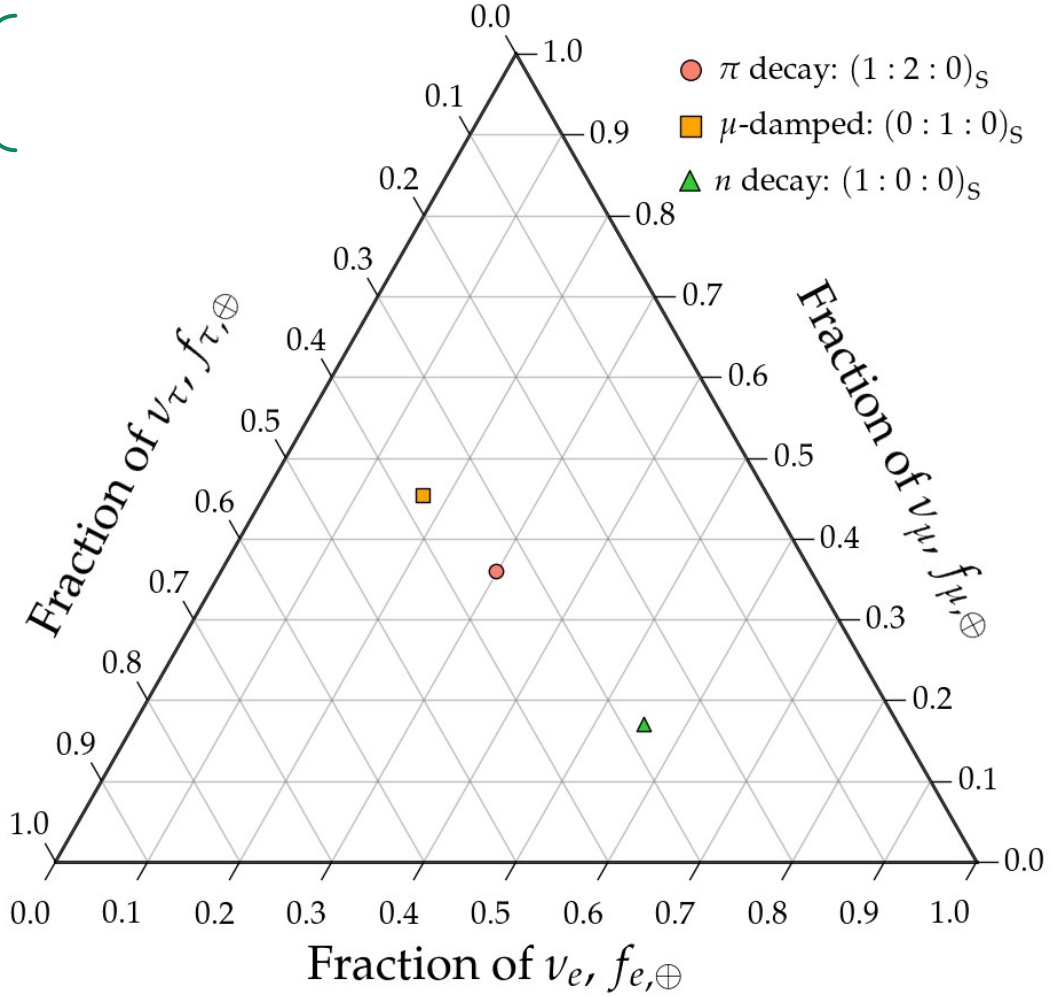
IceCube, 2011.03545

Flavor composition: 2015–2020

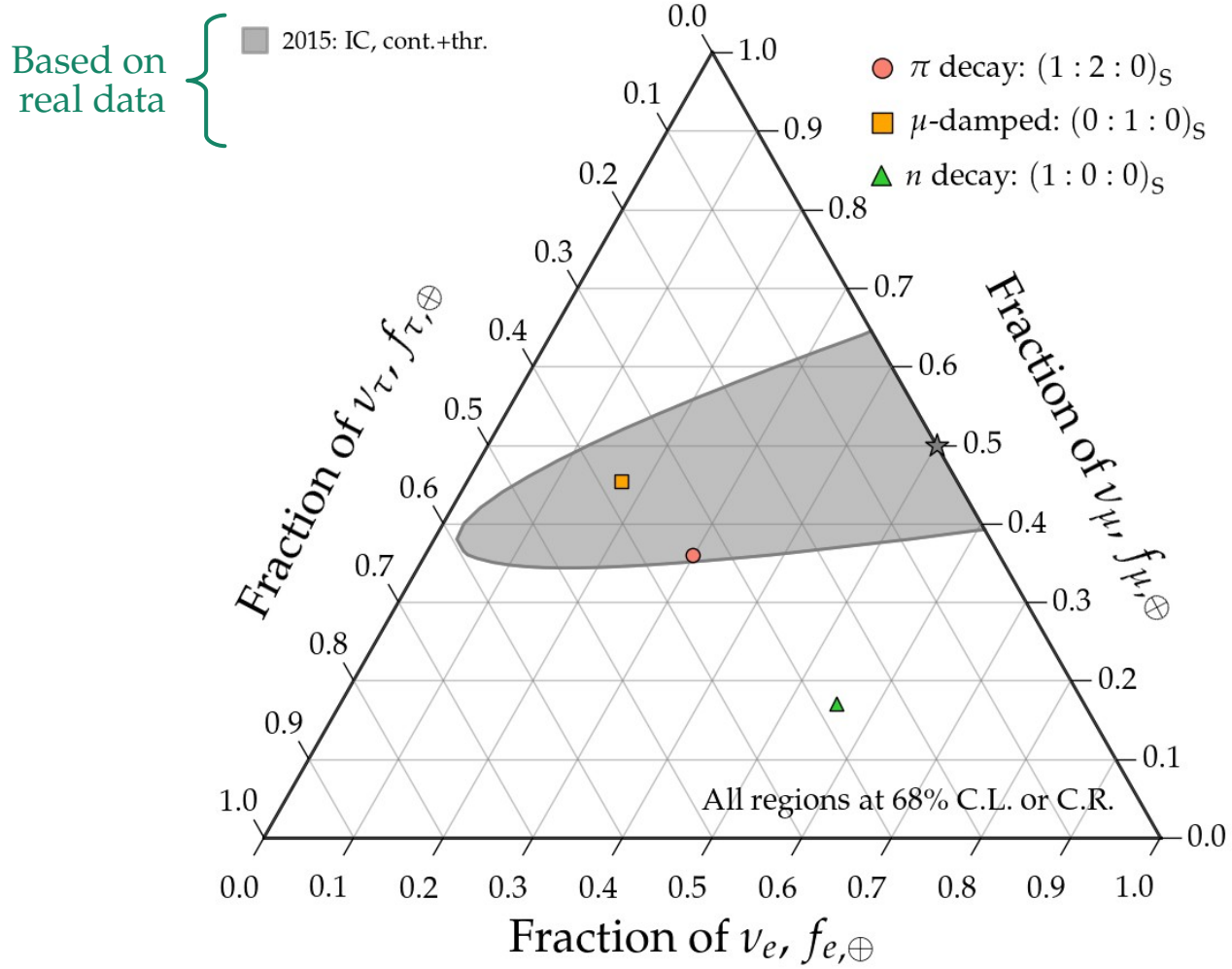
Based on real data

Flavor composition: 2015–2020

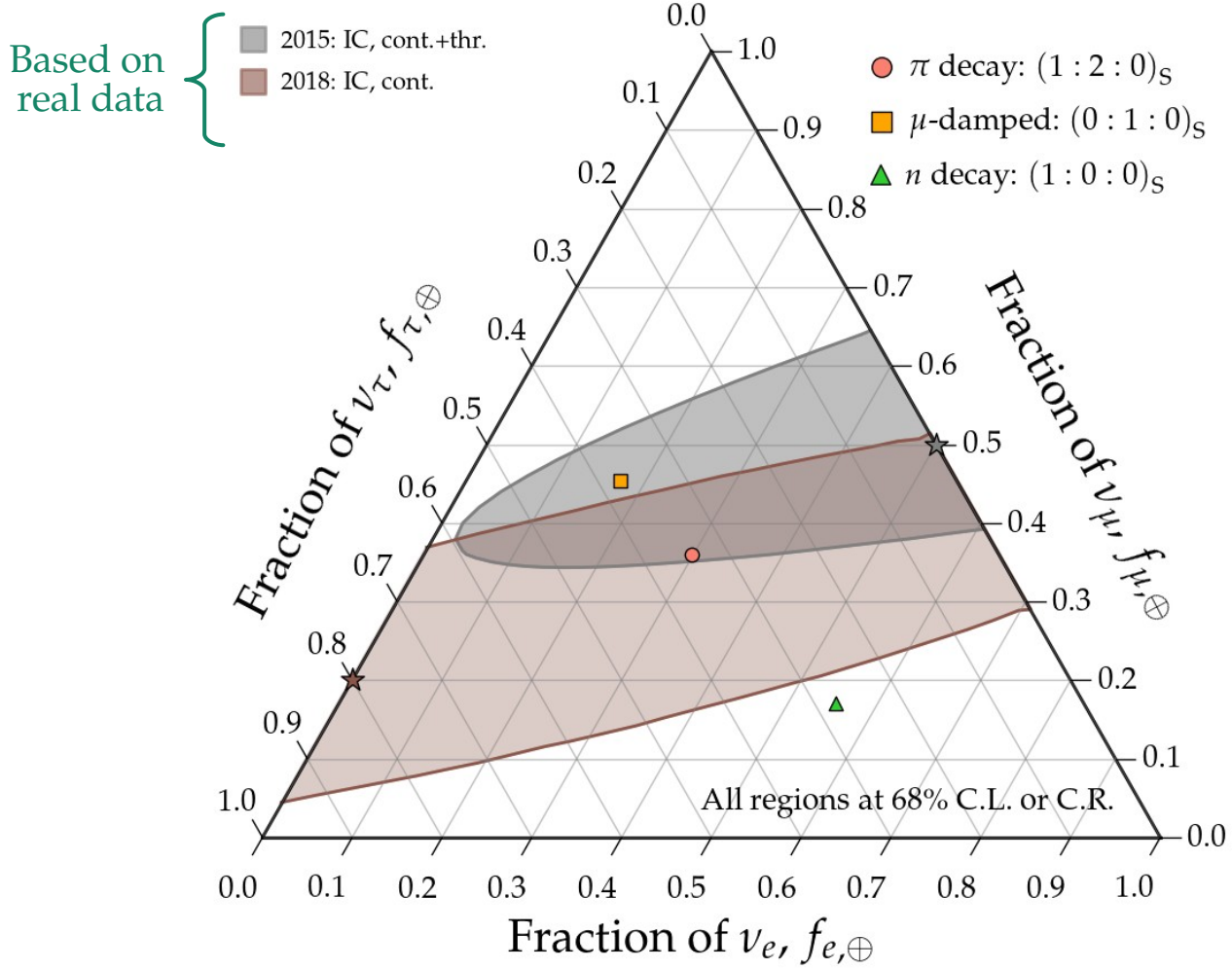
Based on real data



Flavor composition: 2015–2020



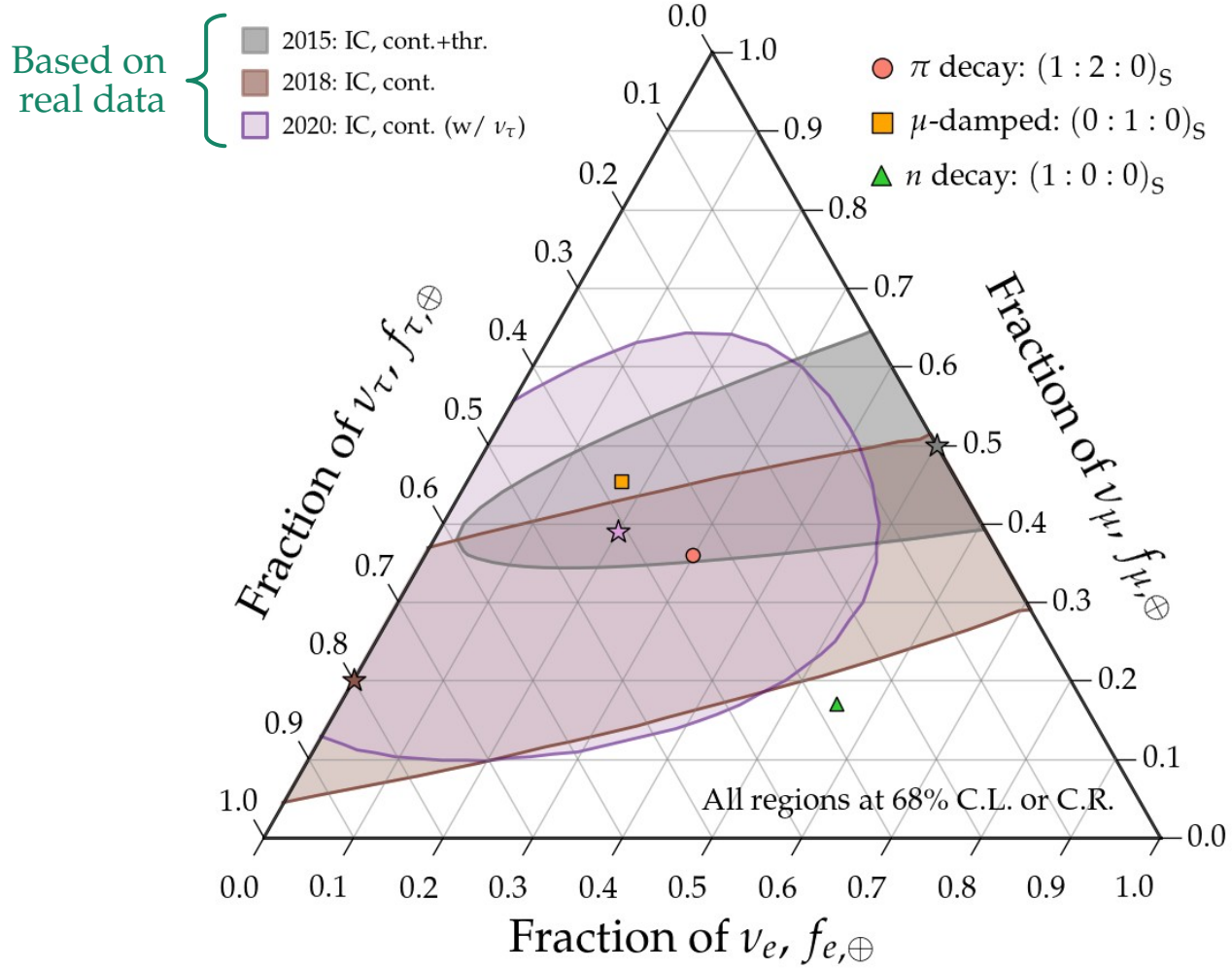
Flavor composition: 2015–2020



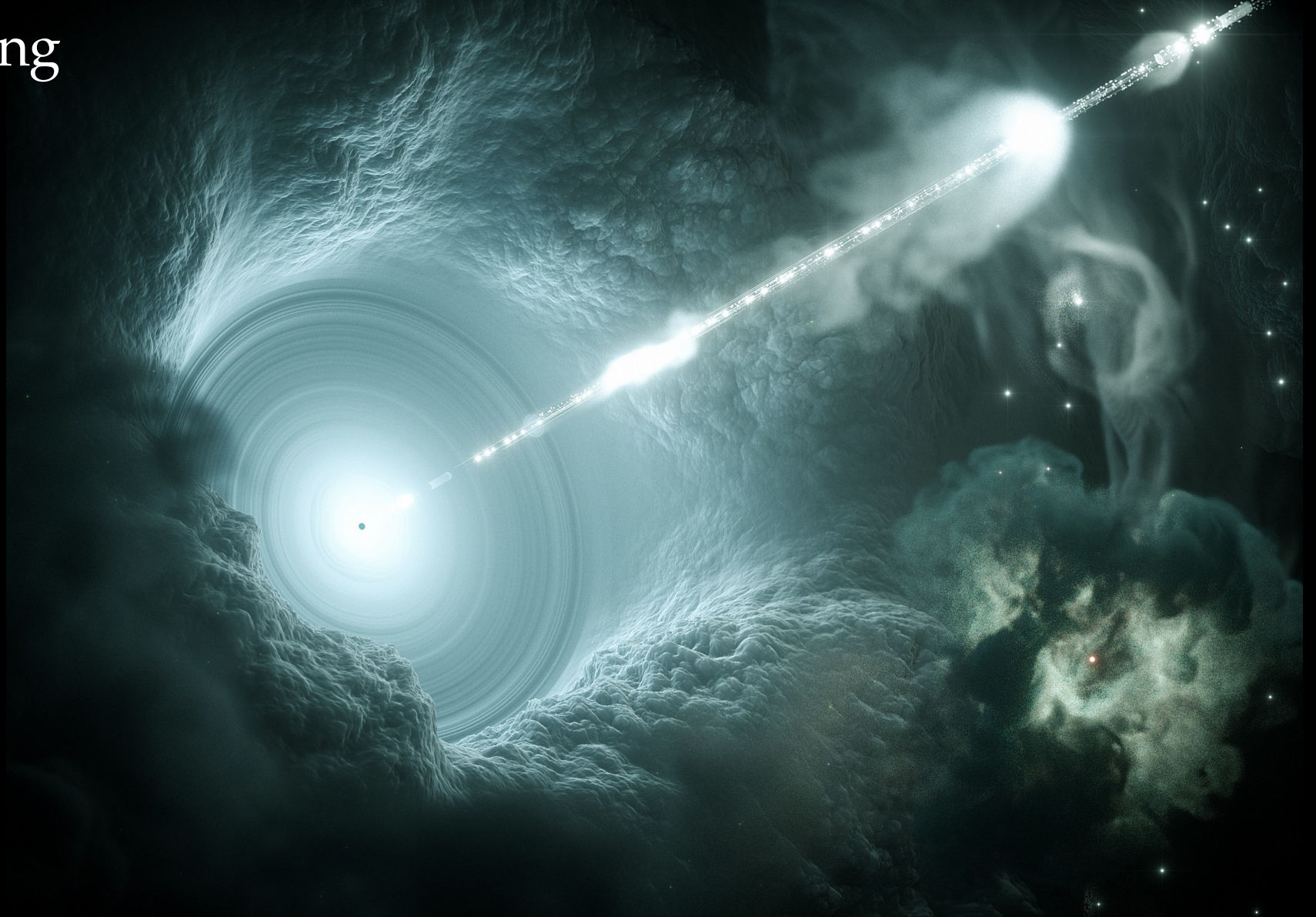
Flavor composition: 2015–2020

Based on real data

Flavor composition: 2015–2020



Timing

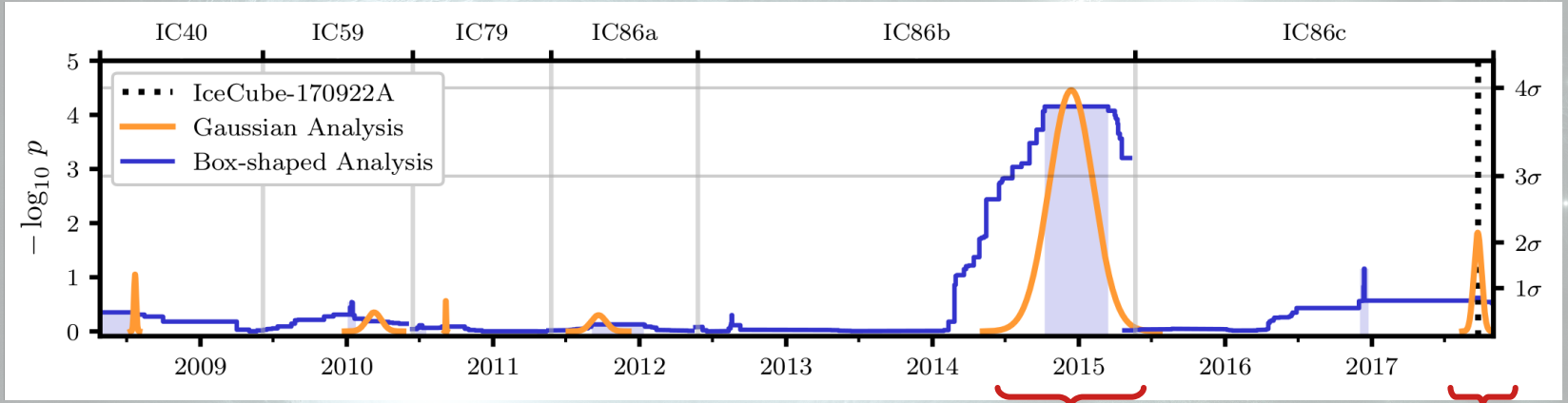


DESY

Timing

Blazar TXS 0506+056:

IceCube, *Science* 2018

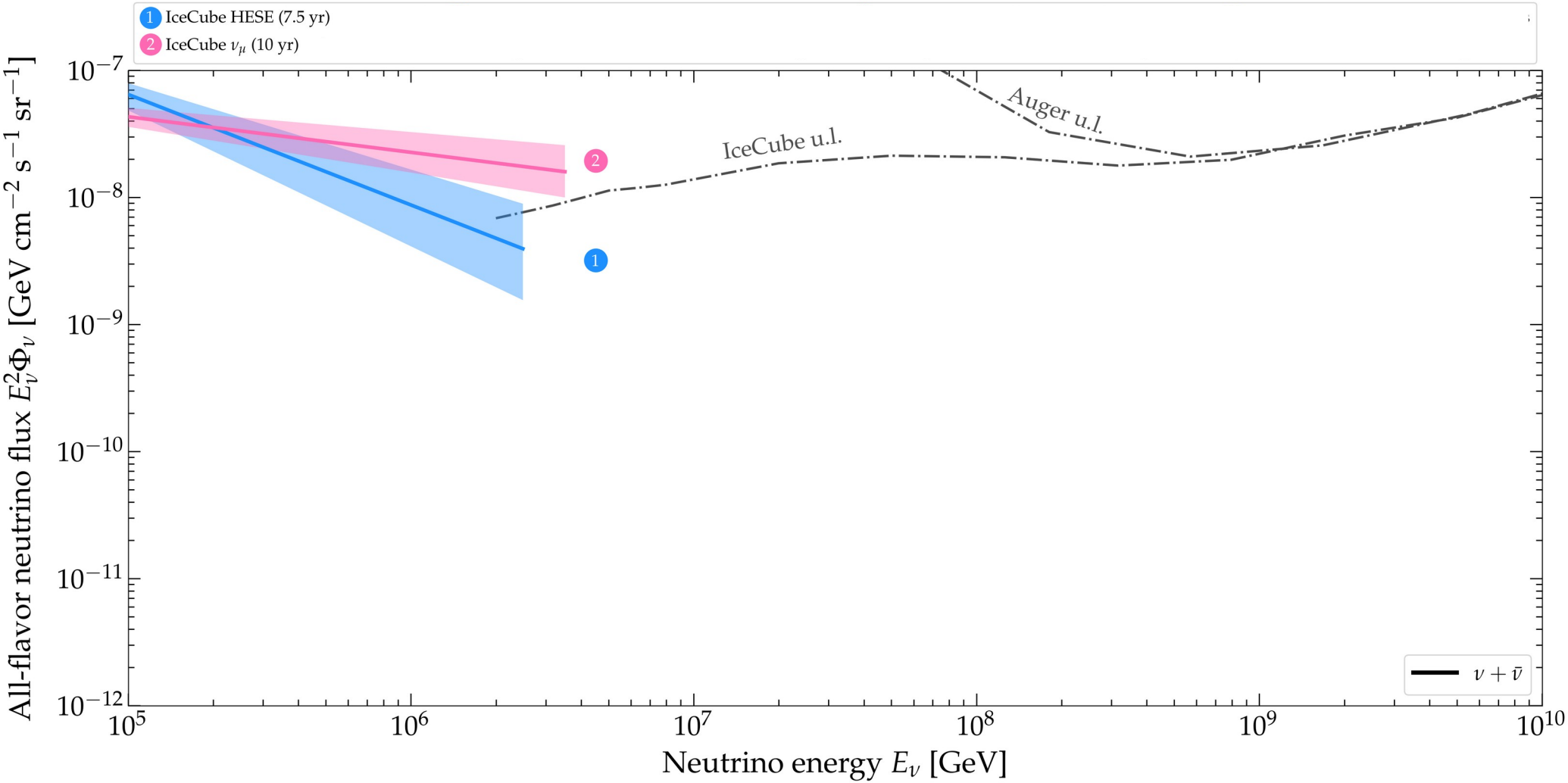


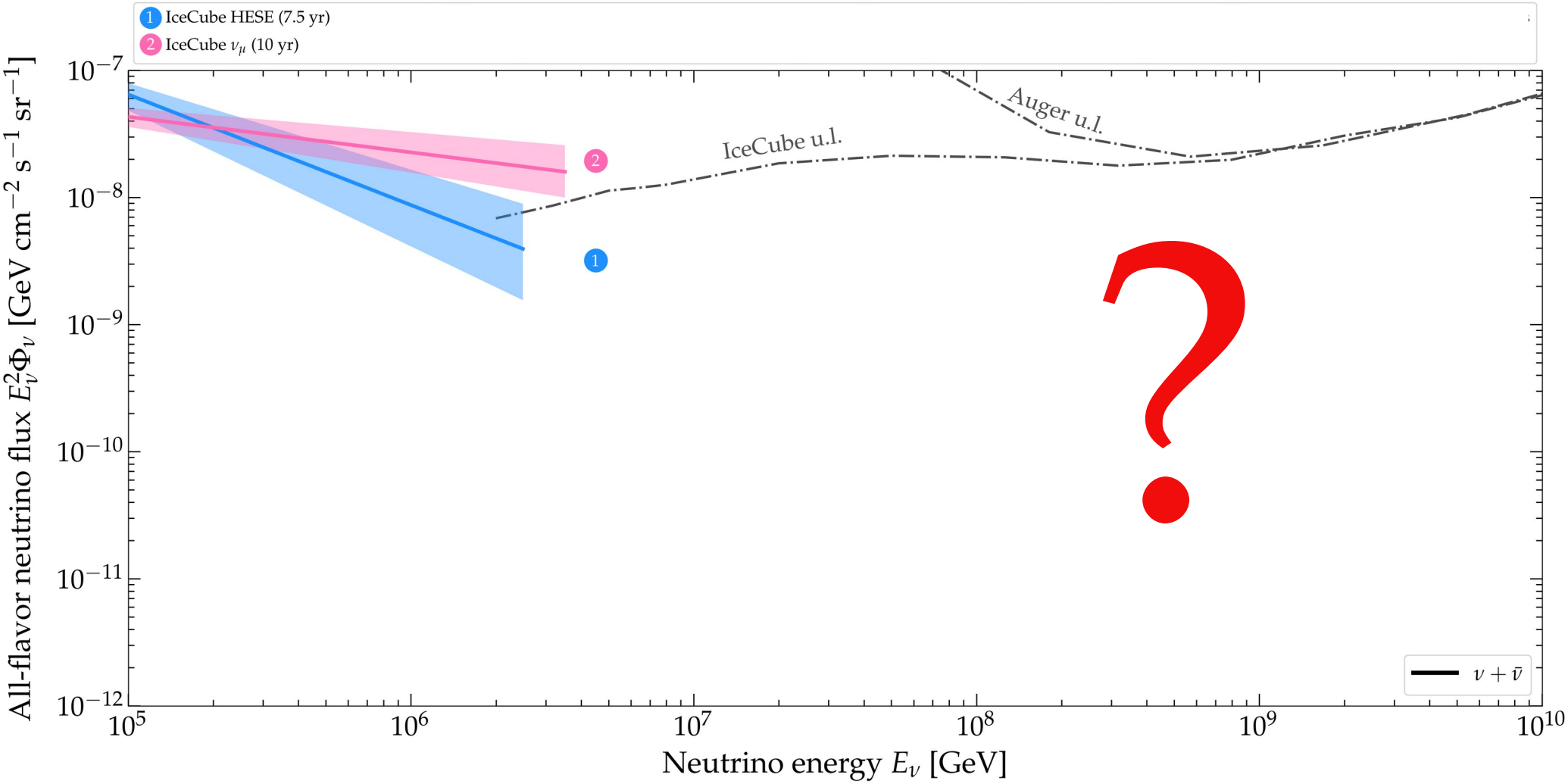
After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

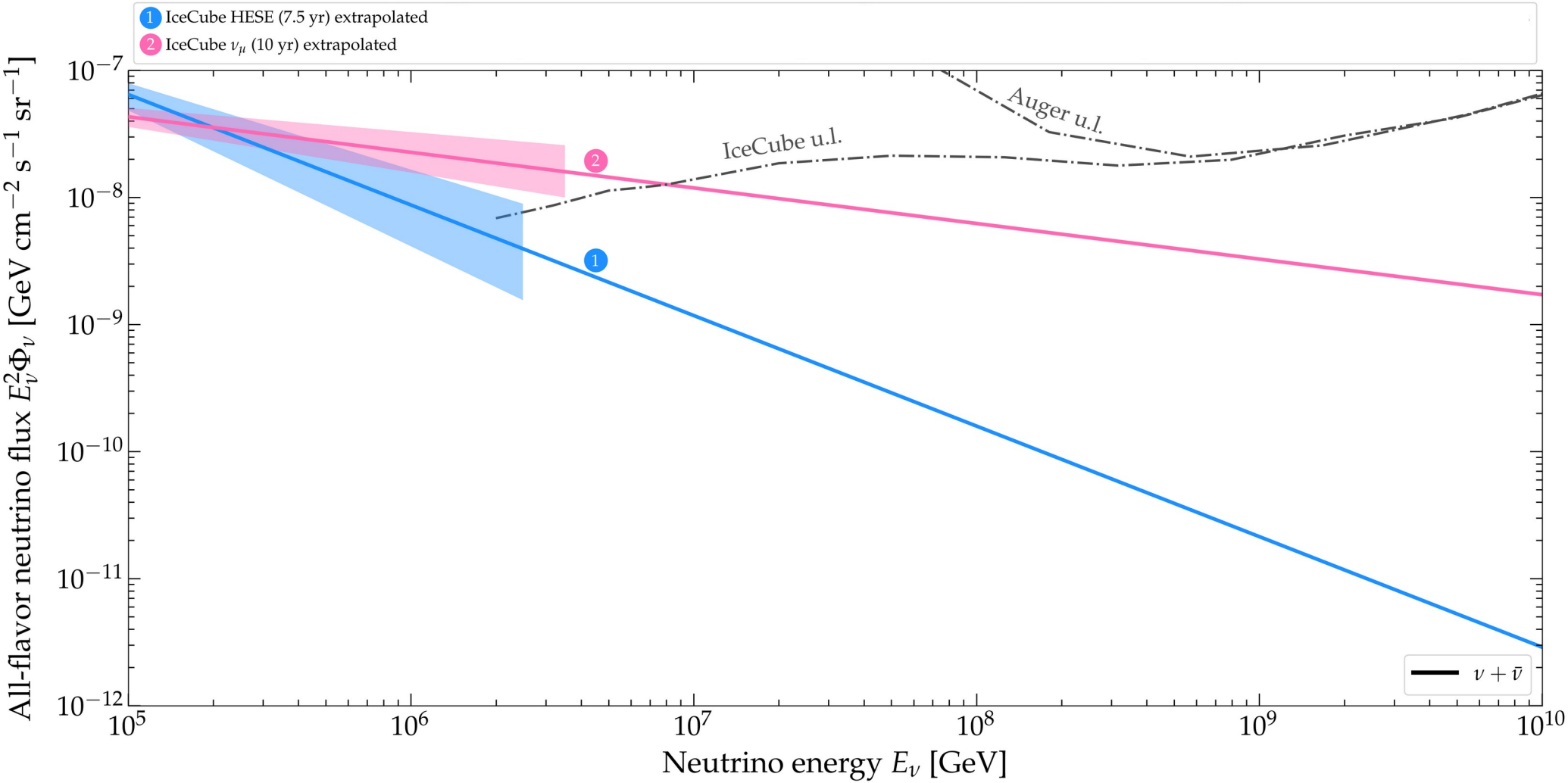
2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

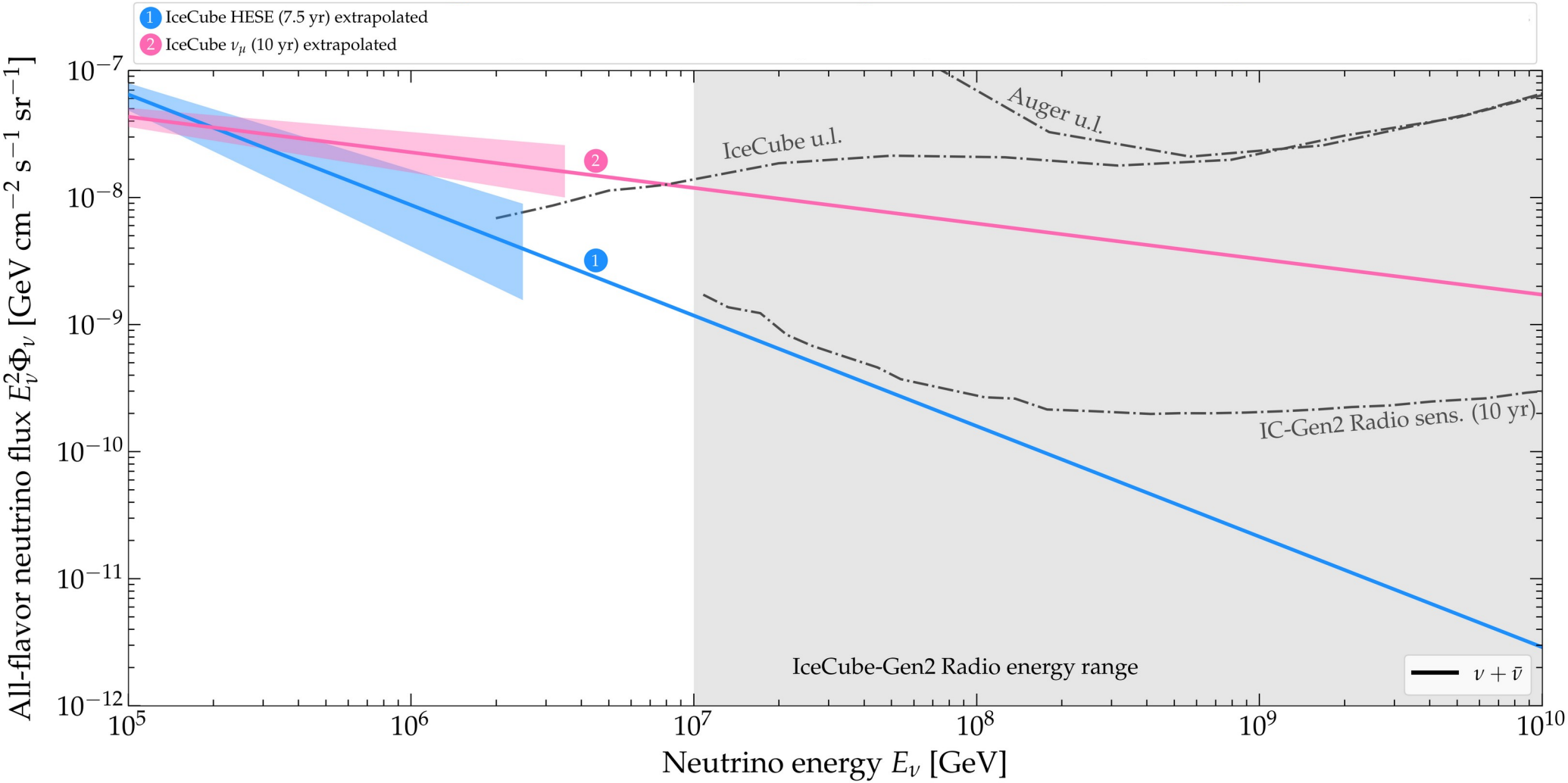
2017: one 290-TeV ν + X-ray flare
1.4σ significance of correlation

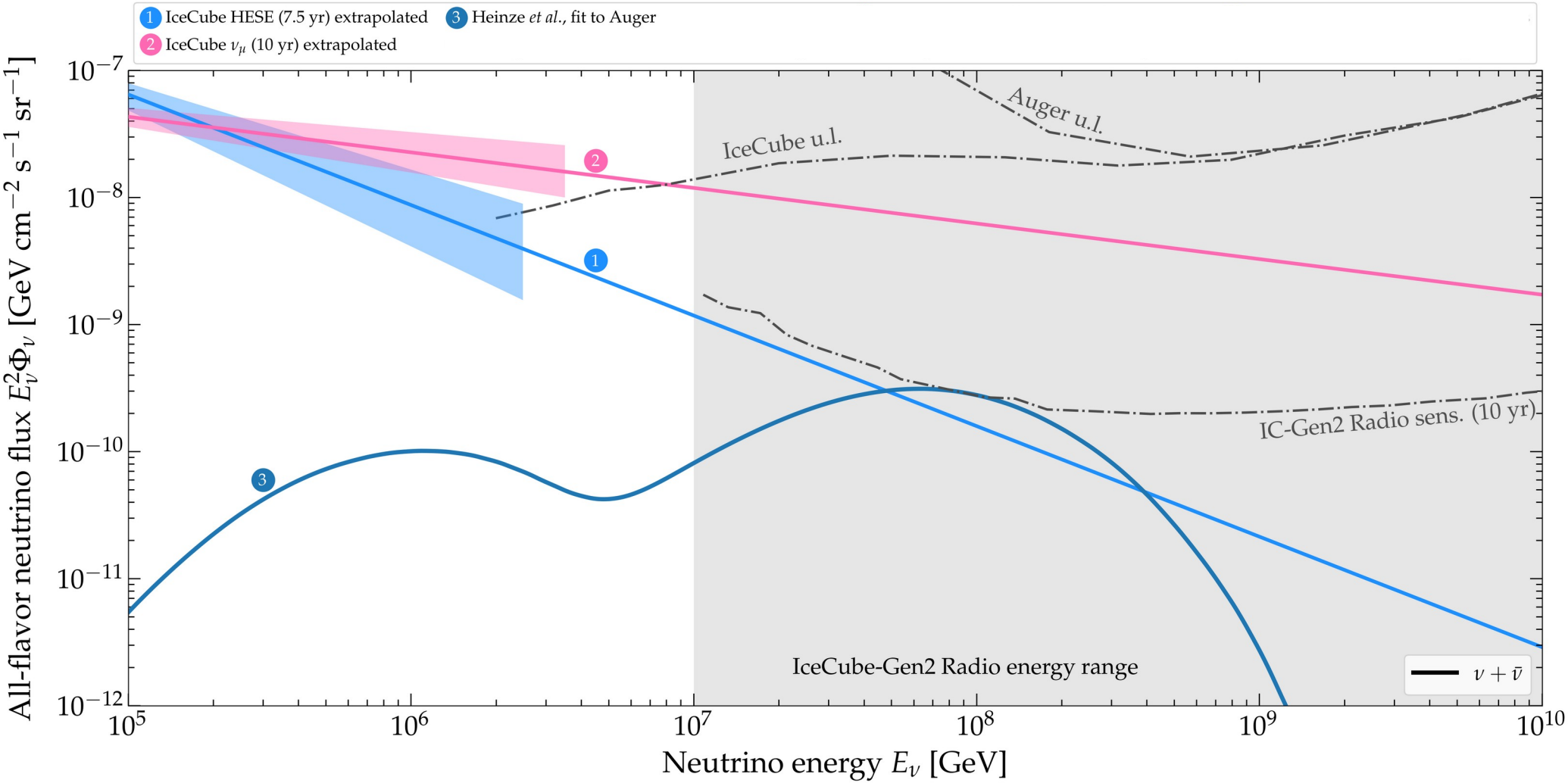
Combined (pre-trial): 4.1σ

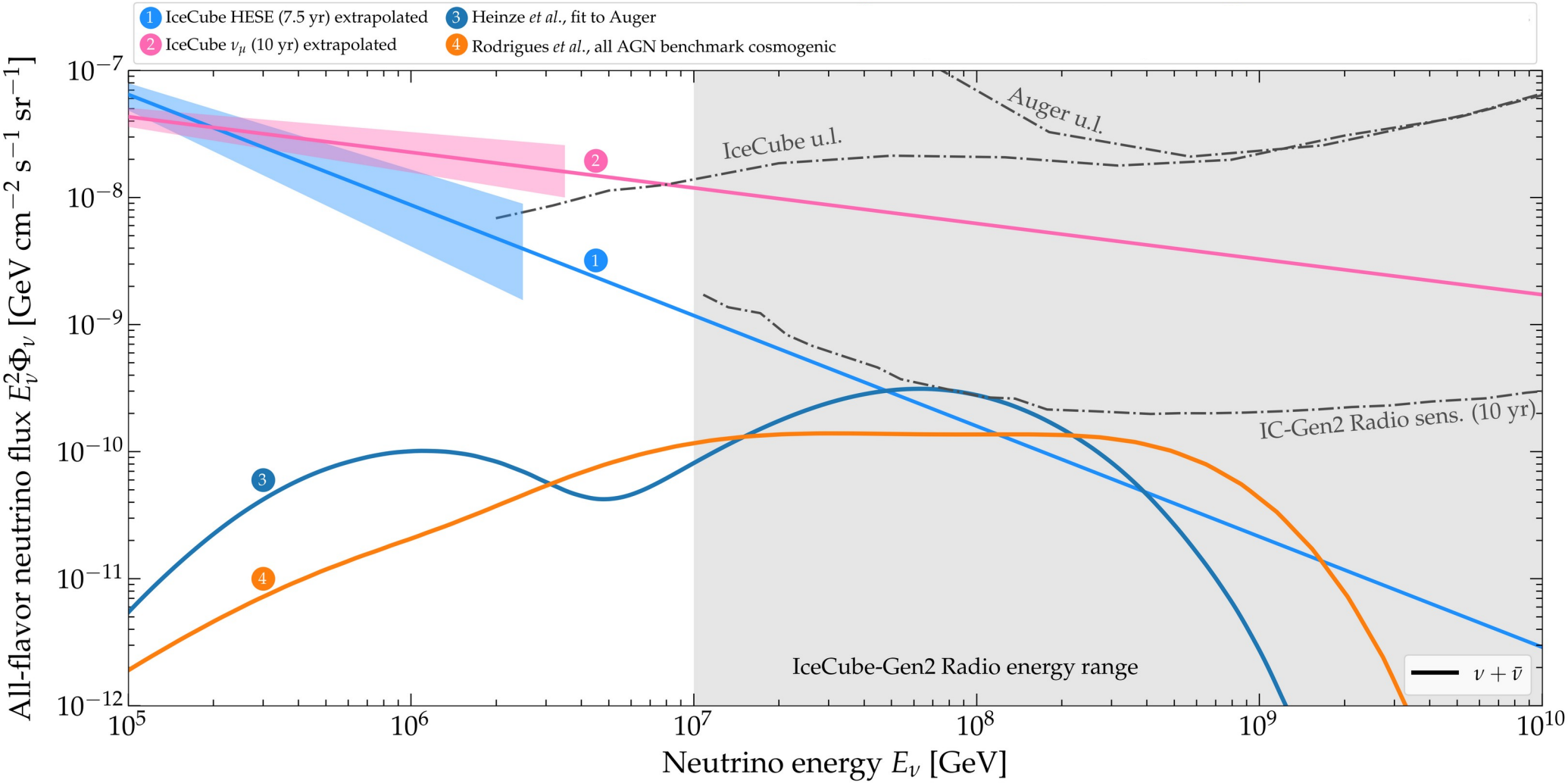

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
IceCube u.l.
Auger u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

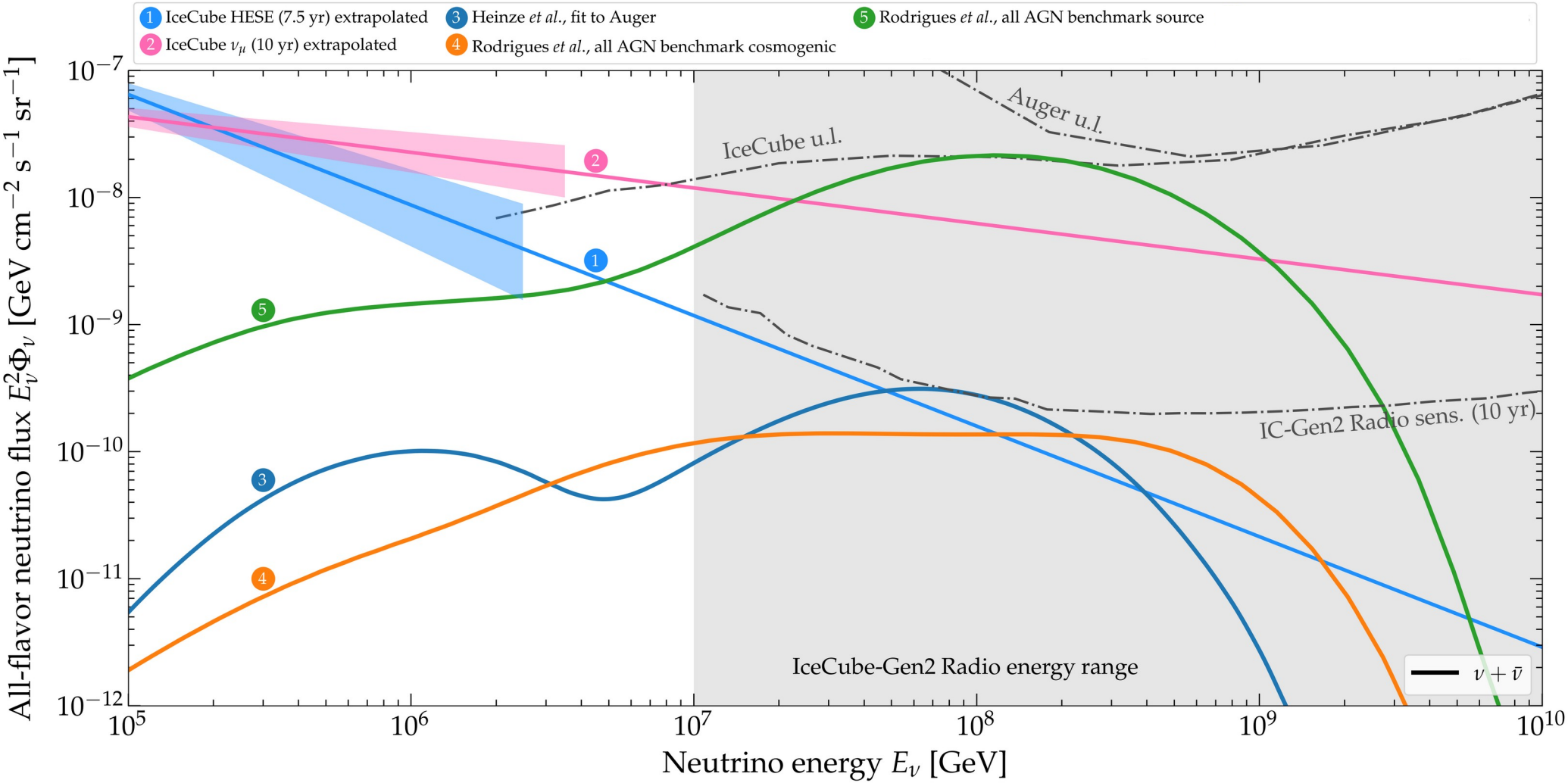

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
IceCube u.l.
Auger u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

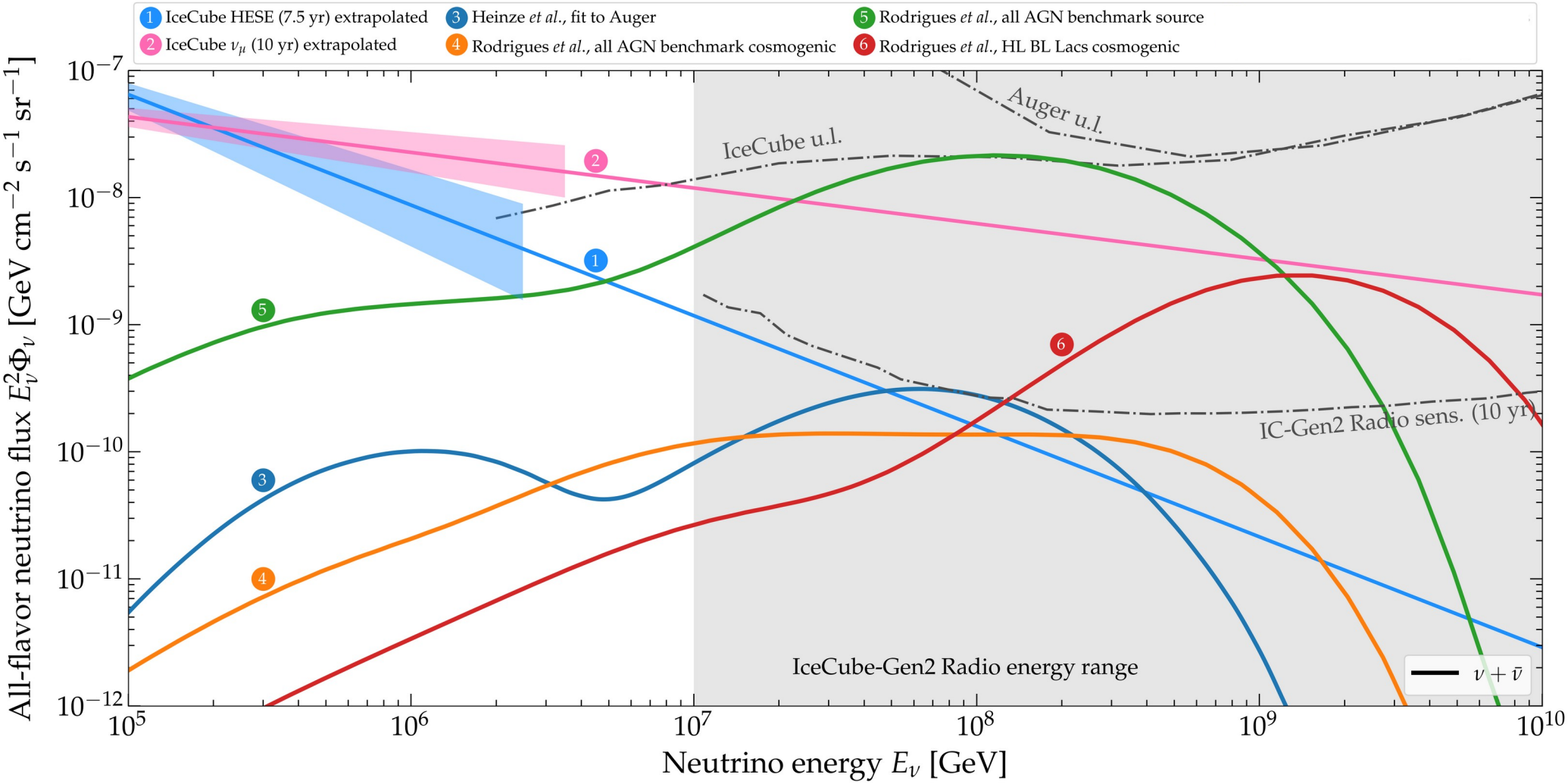

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
IceCube u.l.
Auger u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

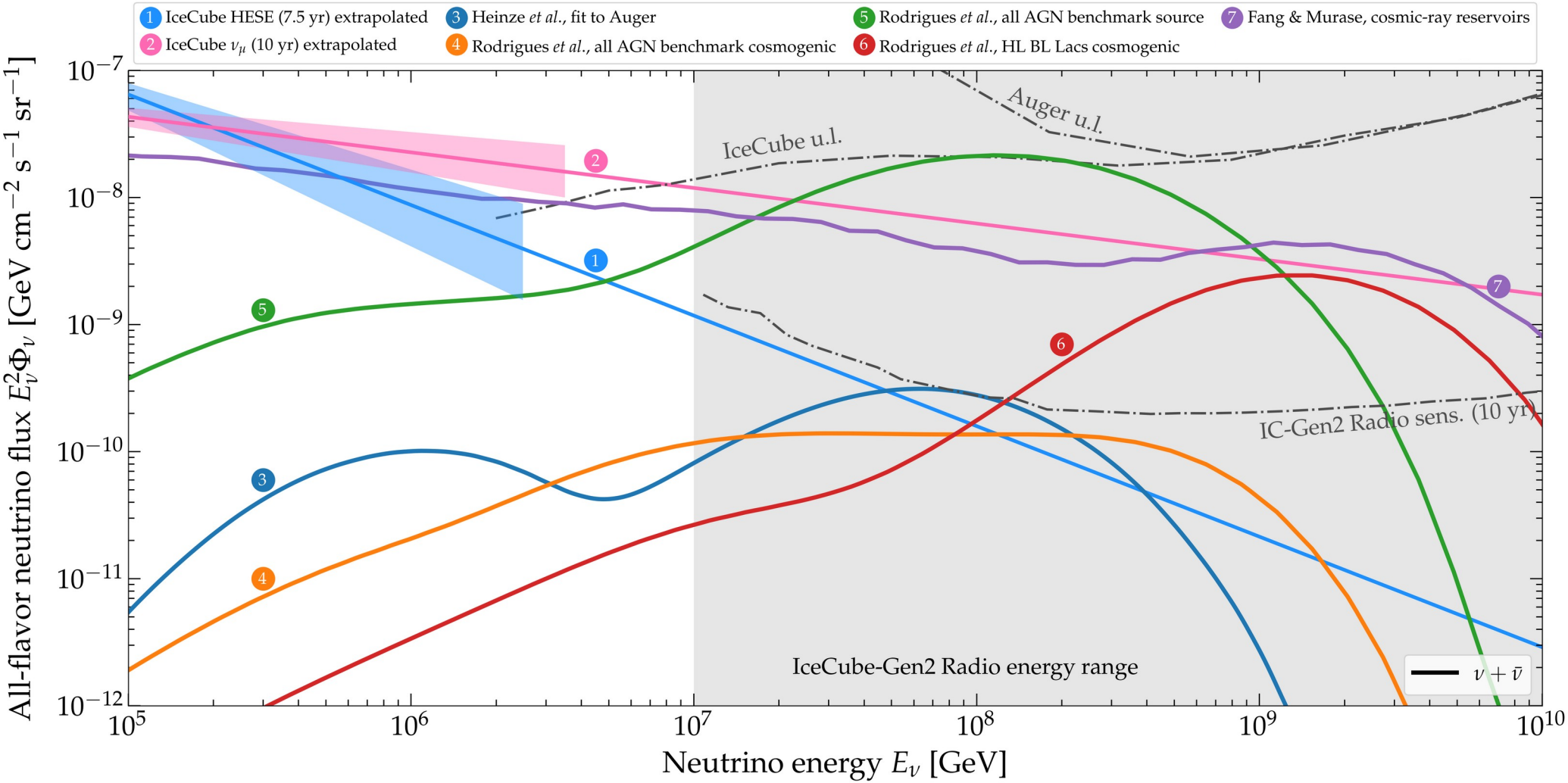

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}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

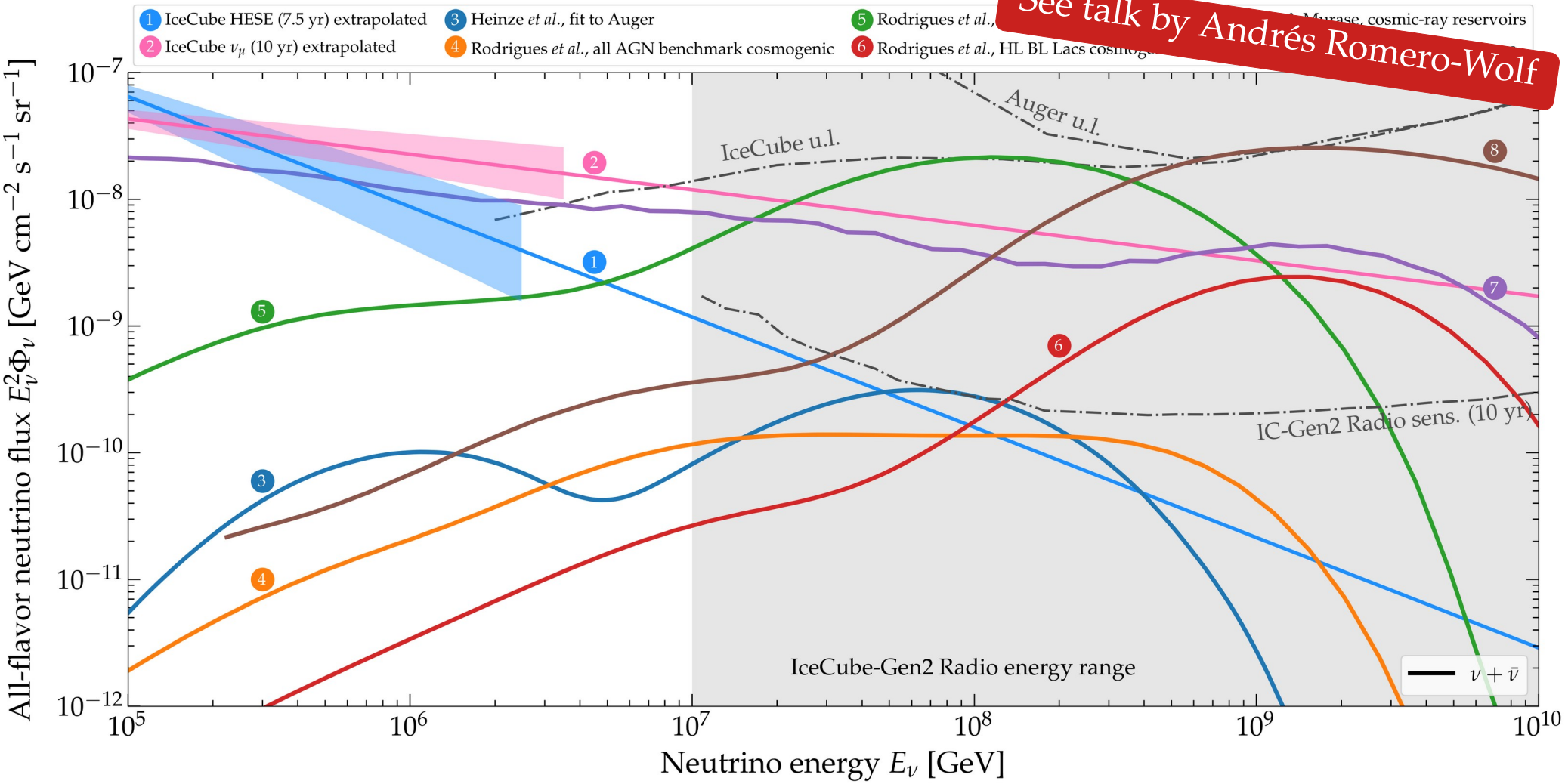

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]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


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
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}

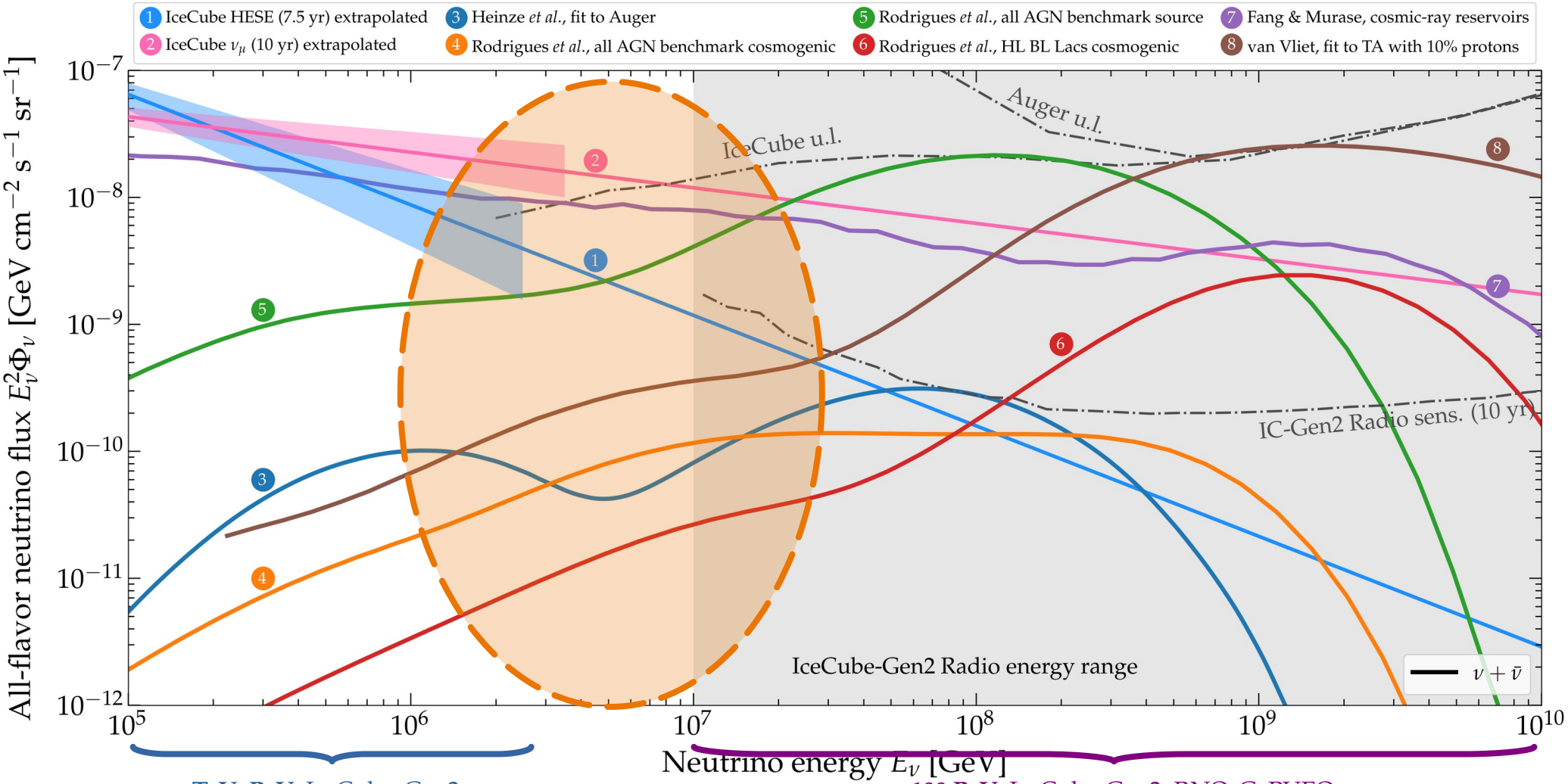

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
Auger u.l.
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$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


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
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
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
IceCube u.l.
Auger 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]

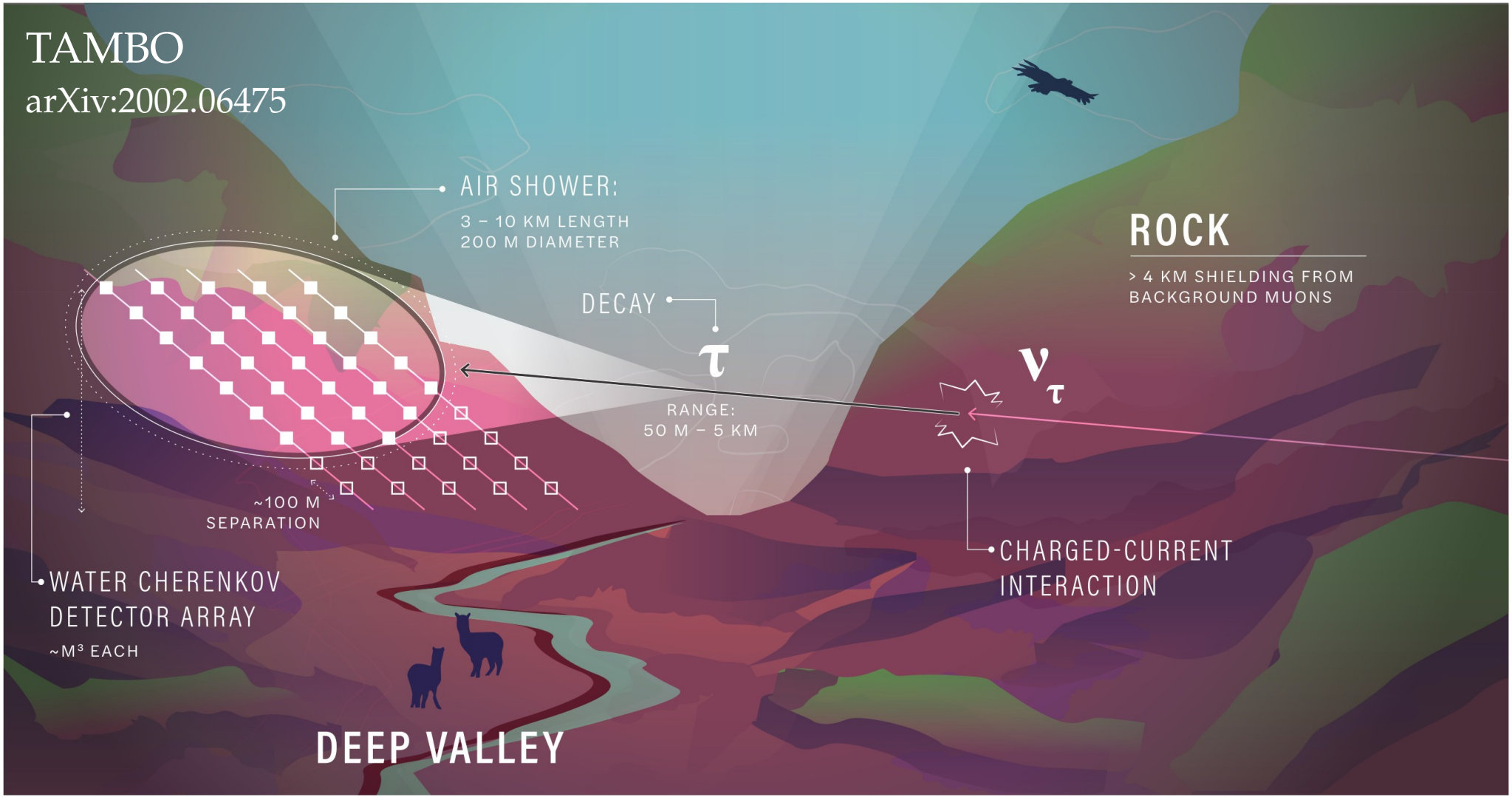

1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*,
6 Rodrigues *et al.*, HL BL Lacs cosmo
Murase, cosmic-ray reservoirs
See talk by Andrés Romero-Wolf
Auger u.l.
IceCube u.l.
8
7
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]

Valera, **MB**, Glaser, 2210.03756



TeV–PeV: IceCube, Gen2, KM3NeT, Baikal-GVD, P-ONE

> 100 PeV: IceCube-Gen2, RNO-G, PUEO, BEACON, GRAND, RET, *etc.*



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

What do we hope to learn in the next 10–20 years?

What do we hope to learn in the next 10–20 years?

TeV–PeV neutrinos: *sharpen*

1. What are the sources of the IceCube TeV–PeV neutrinos?
2. Relative contribution of steady-state *vs.* transient sources at TeV–PeV?
3. Is there a sizable component of TeV–PeV neutrinos of Galactic origin?
4. What is the precise flavor composition of TeV–PeV neutrinos?

What do we hope to learn in the next 10–20 years?

TeV–PeV neutrinos: *sharpen*

1. What are the sources of the IceCube TeV–PeV neutrinos?
2. Relative contribution of steady-state *vs.* transient sources at TeV–PeV?
3. Is there a sizable component of TeV–PeV neutrinos of Galactic origin?
4. What is the precise flavor composition of TeV–PeV neutrinos?

Need mainly statistics

What do we hope to learn in the next 10–20 years?

TeV–PeV neutrinos: *sharpen*

1. What are the sources of the IceCube TeV–PeV neutrinos?
2. Relative contribution of steady-state *vs.* transient sources at TeV–PeV?
3. Is there a sizable component of TeV–PeV neutrinos of Galactic origin?
4. What is the precise flavor composition of TeV–PeV neutrinos?

Need mainly statistics

EeV neutrinos: *discover*

5. What is the size of the diffuse flux of UHE neutrinos?
6. Relative contribution of cosmogenic *vs.* source UHE neutrinos?
7. *The big one*: what are the sources of UHECRs?

What do we hope to learn in the next 10–20 years?

TeV–PeV neutrinos: *sharpen*

1. What are the sources of the IceCube TeV–PeV neutrinos?
2. Relative contribution of steady-state *vs.* transient sources at TeV–PeV?
3. Is there a sizable component of TeV–PeV neutrinos of Galactic origin?
4. What is the precise flavor composition of TeV–PeV neutrinos?

Need mainly statistics

EeV neutrinos: *discover*

5. What is the size of the diffuse flux of UHE neutrinos?
6. Relative contribution of cosmogenic *vs.* source UHE neutrinos?
7. *The big one*: what are the sources of UHECRs?

Need mainly higher energies

What do we hope to learn in the next 10–20 years?

TeV–PeV neutrinos: *sharpen*

1. What are the sources of the IceCube TeV–PeV neutrinos?
2. Relative contribution of steady-state *vs.* transient sources at TeV–PeV?
3. Is there a sizable component of TeV–PeV neutrinos of Galactic origin?
4. What is the precise flavor composition of TeV–PeV neutrinos?

Need mainly statistics

Gap at few to tens of PeV

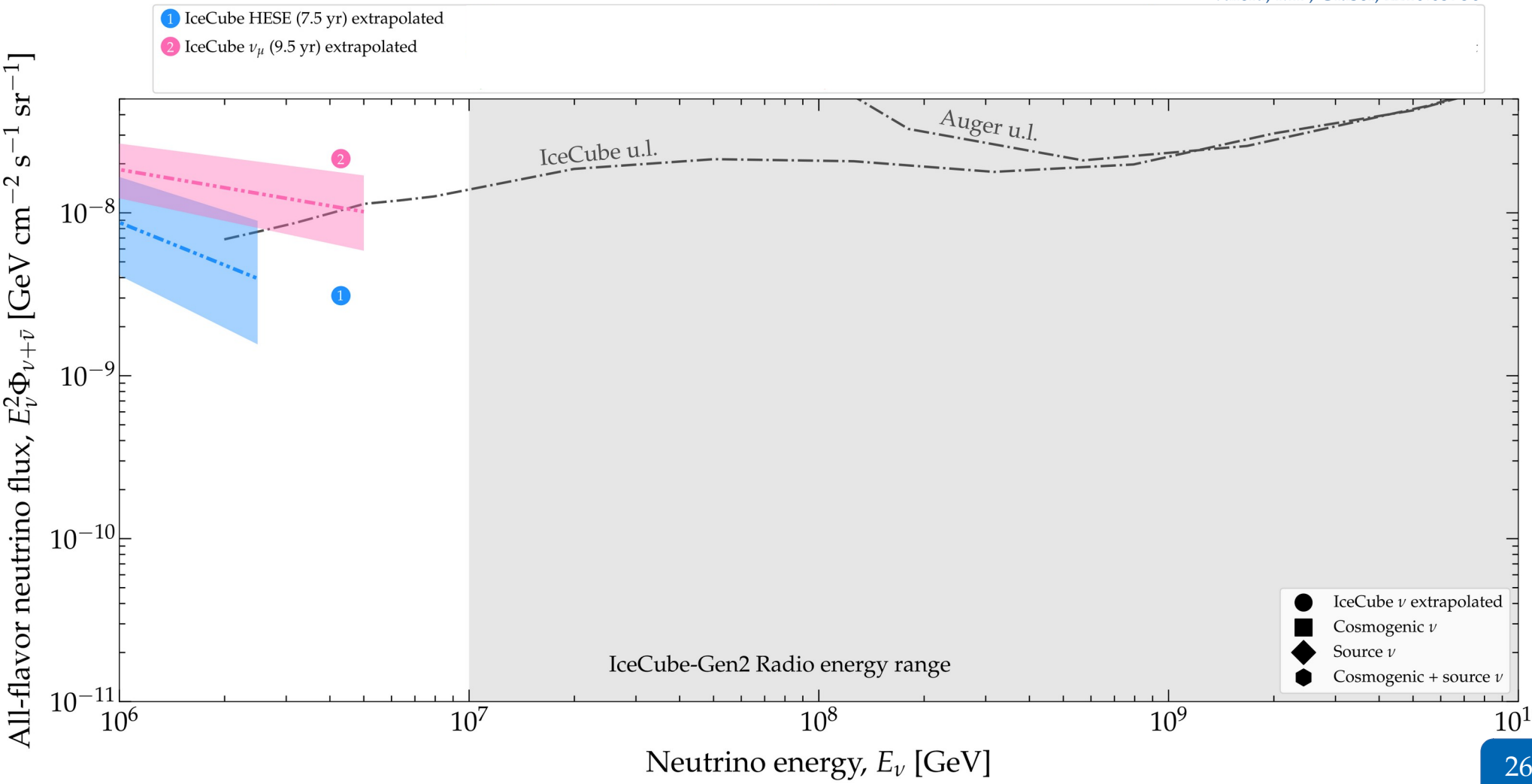
EeV neutrinos: *discover*

5. What is the size of the diffuse flux of UHE neutrinos?
6. Relative contribution of cosmogenic *vs.* source UHE neutrinos?
7. *The big one*: what are the sources of UHECRs?

Need mainly higher energies

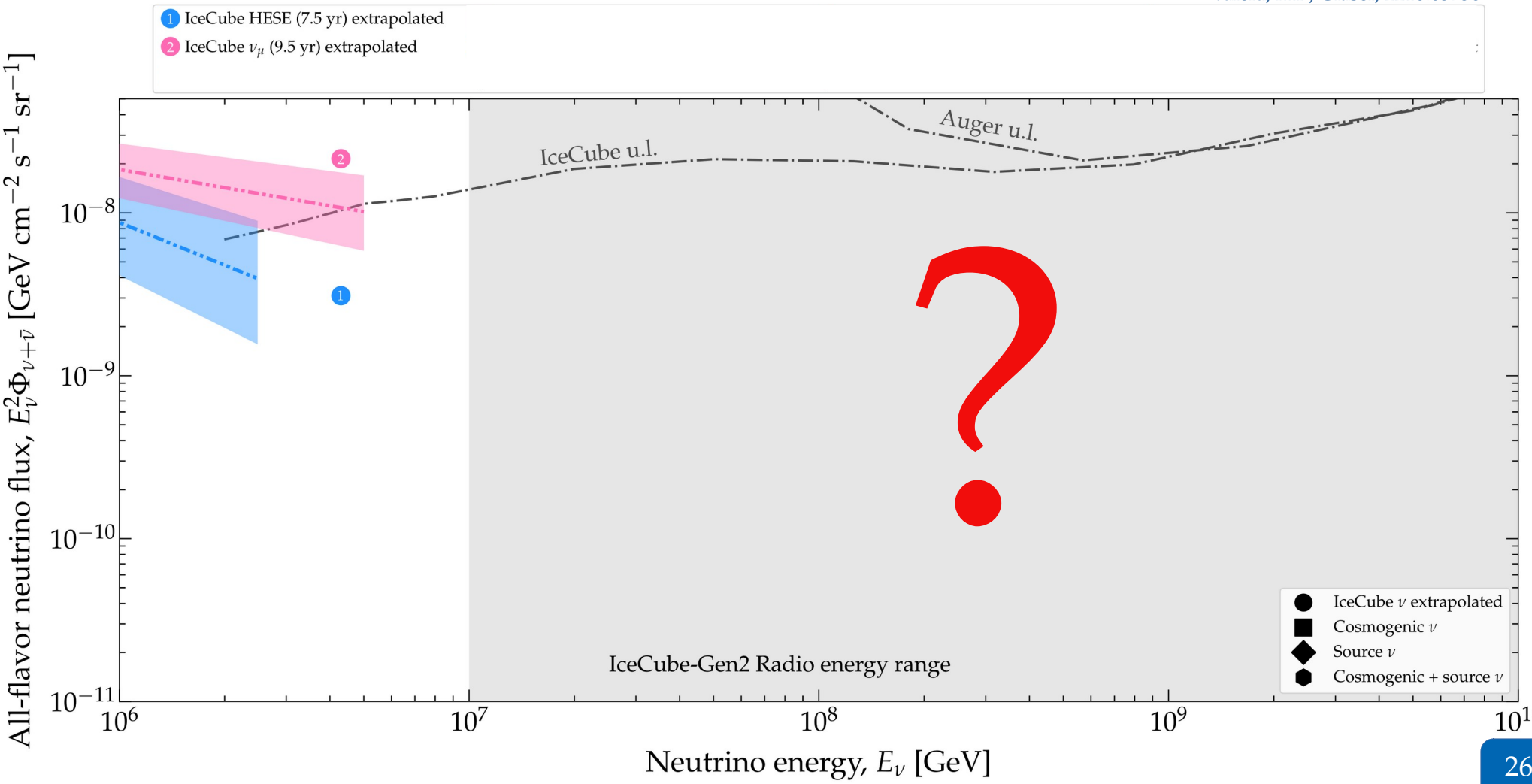
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



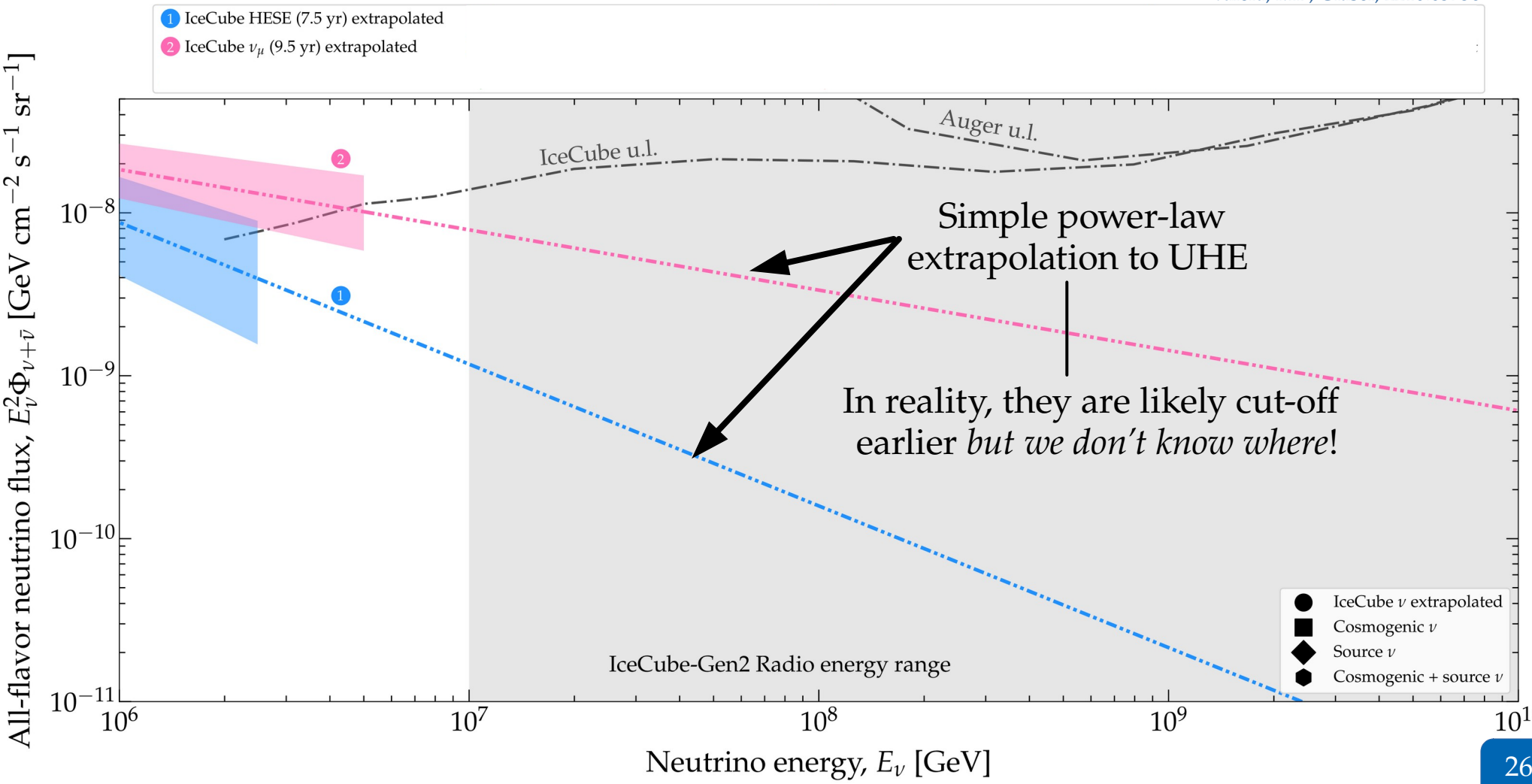
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



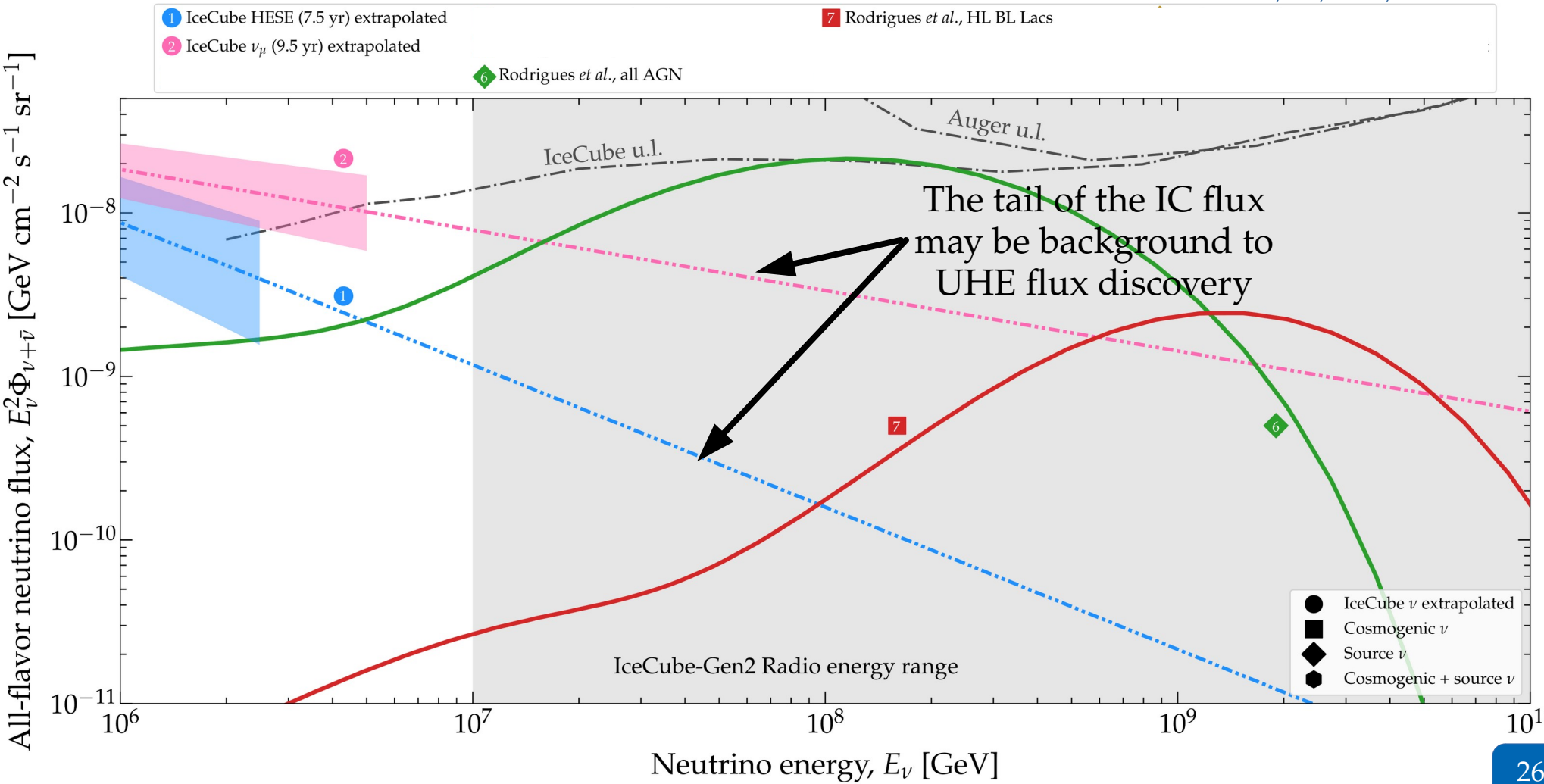
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756

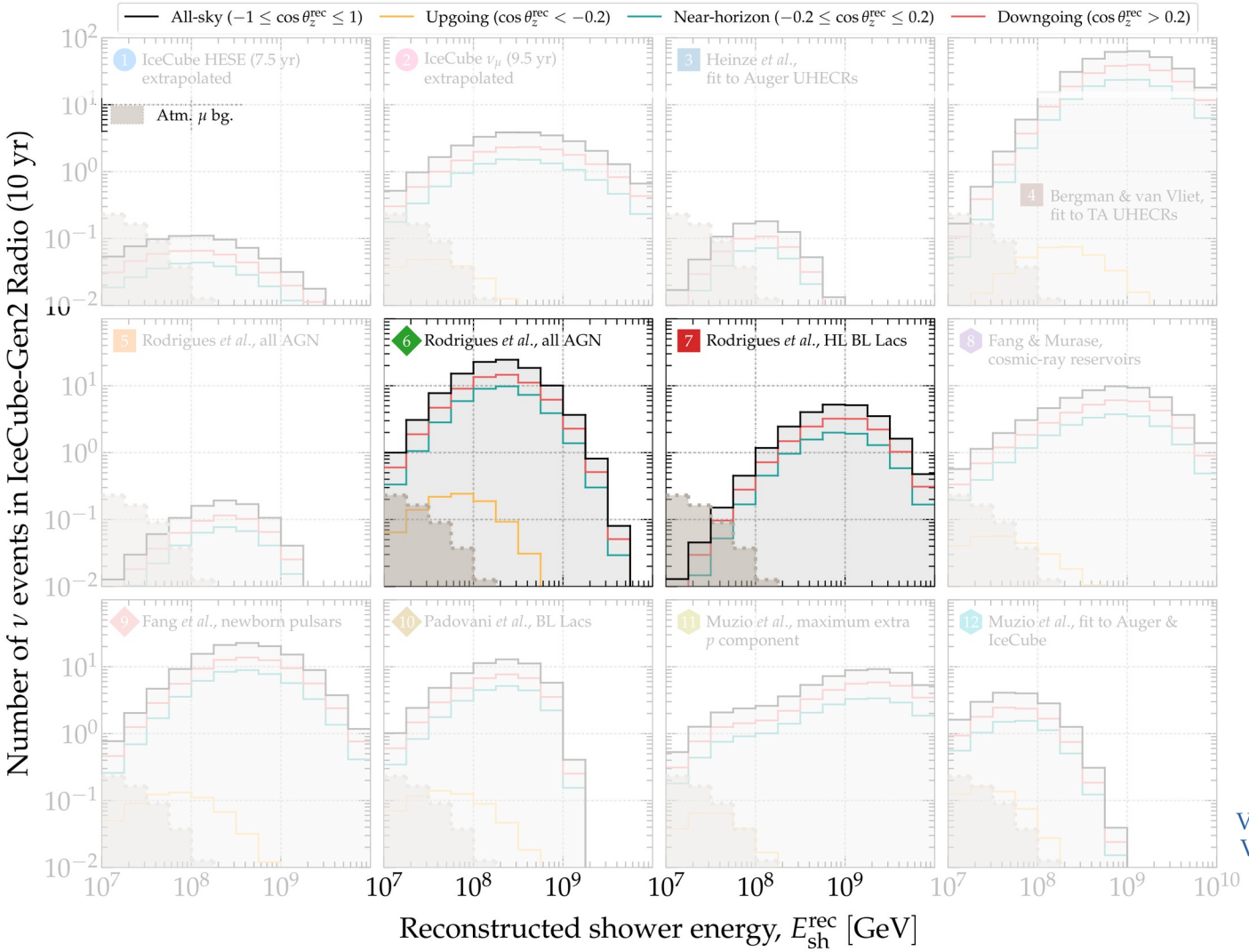


TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



TAMBO astro case #1: the tail of the IceCube flux



Valera, **MB**, Glaser, 2210.03756
Valera, **MB**, Glaser, *JHEP* 2022

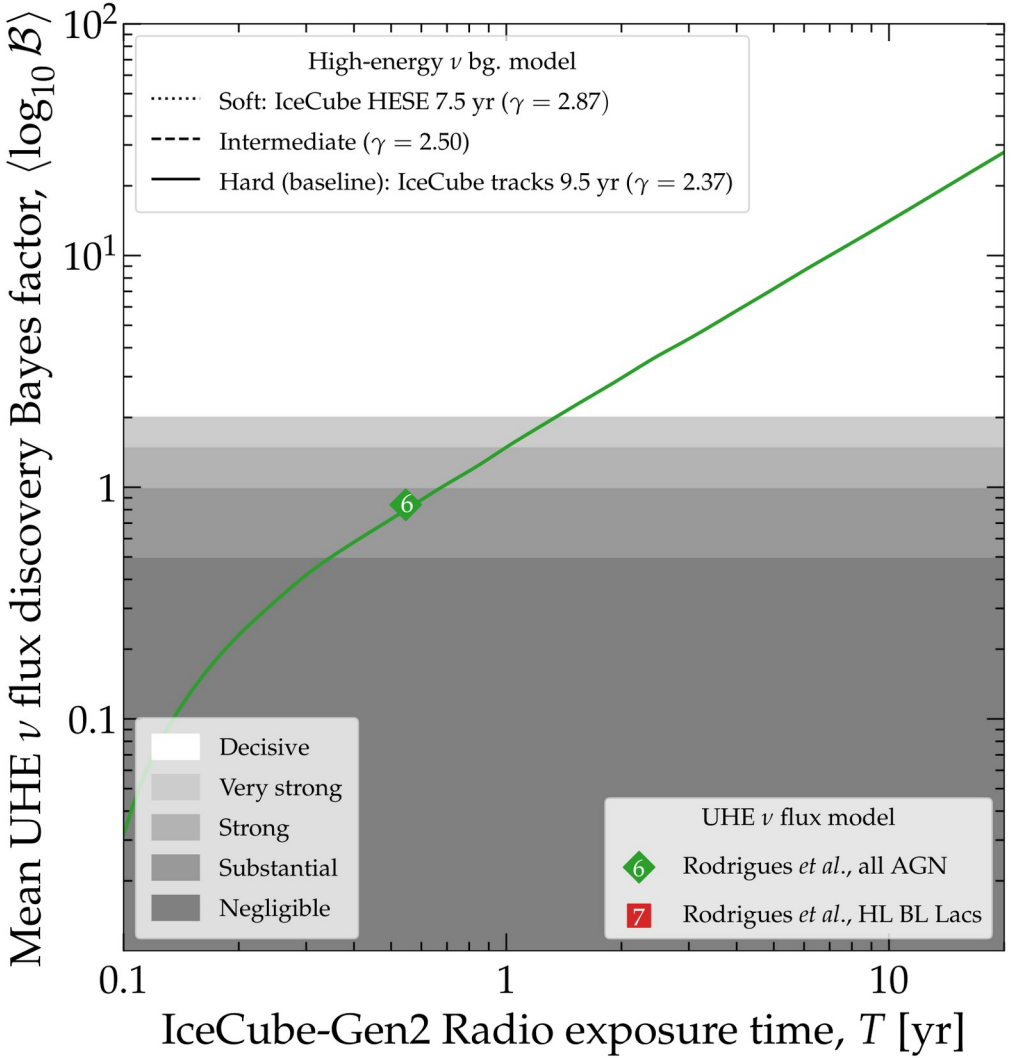
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

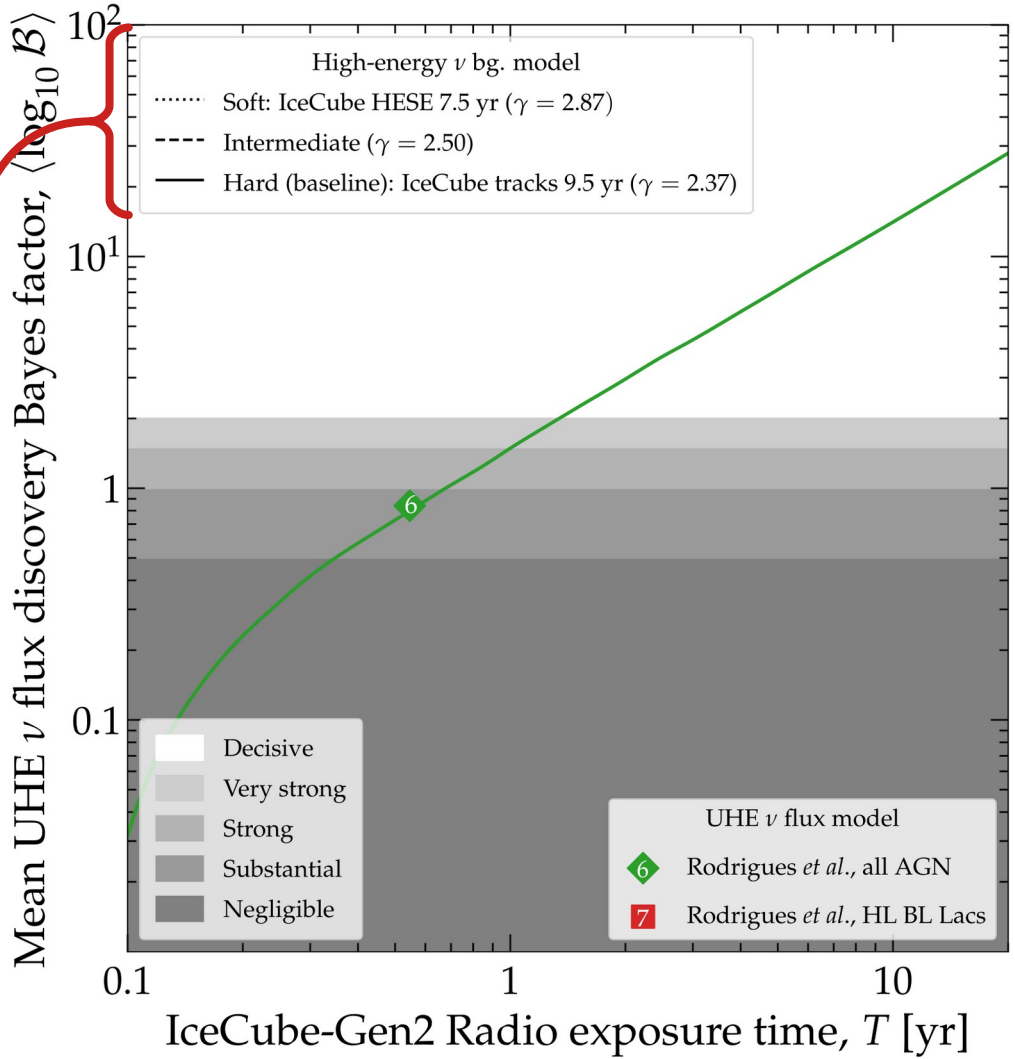
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

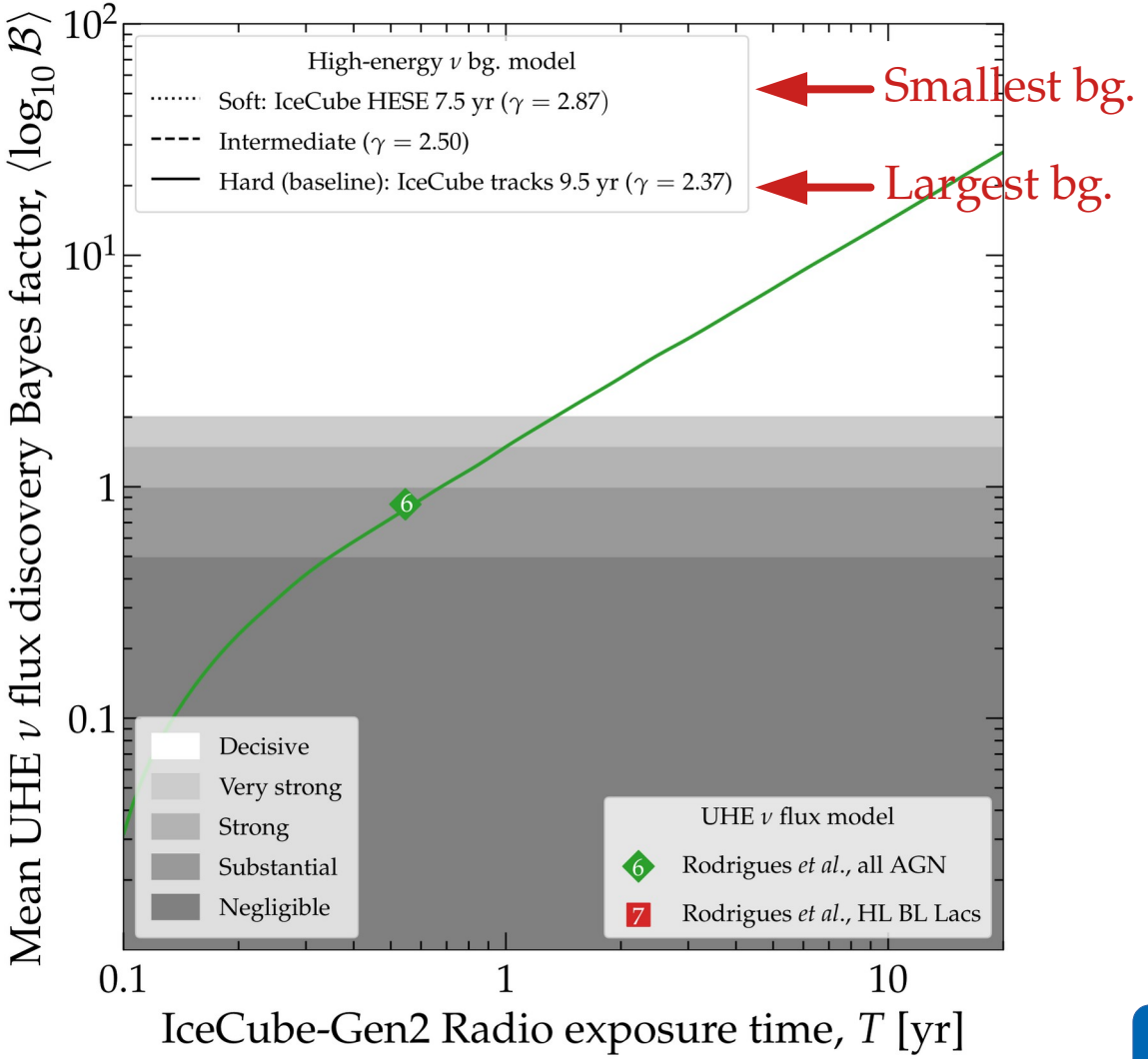
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

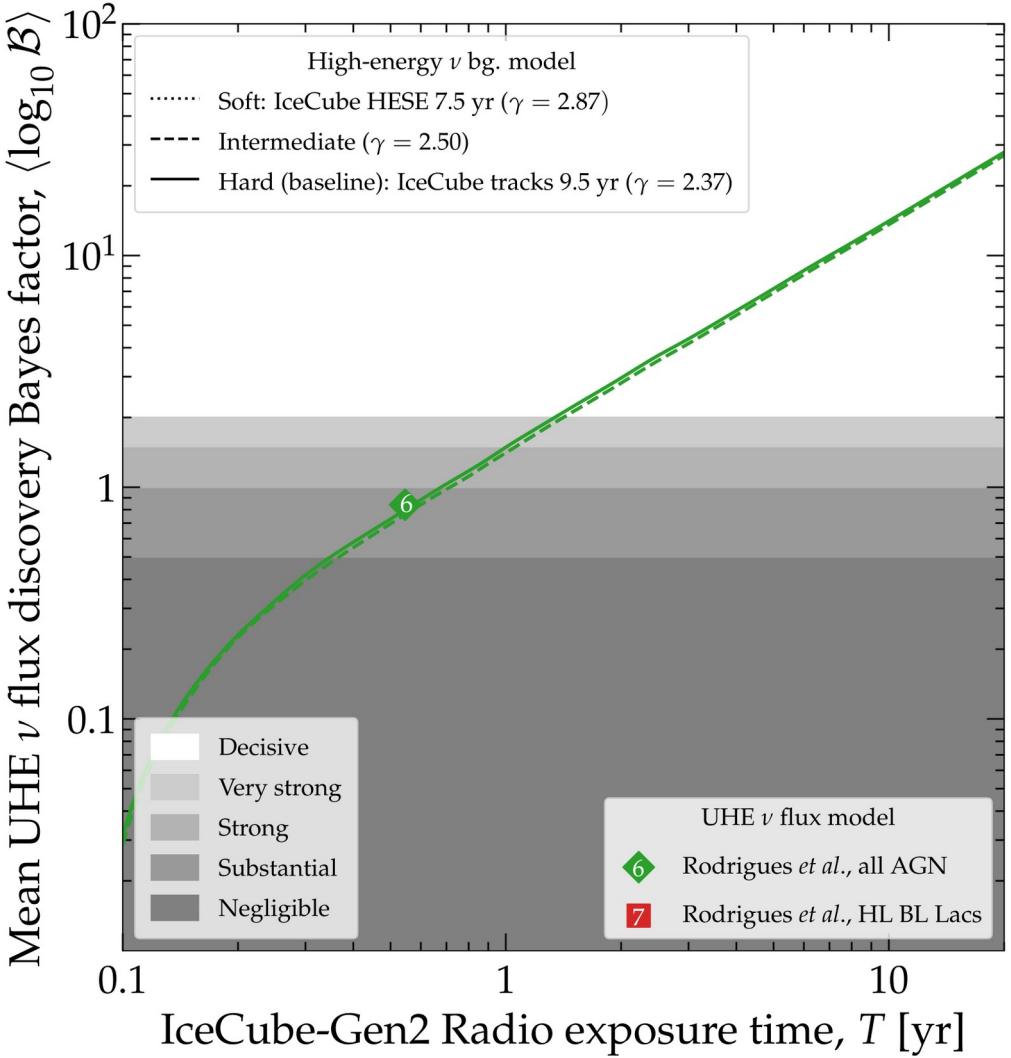
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

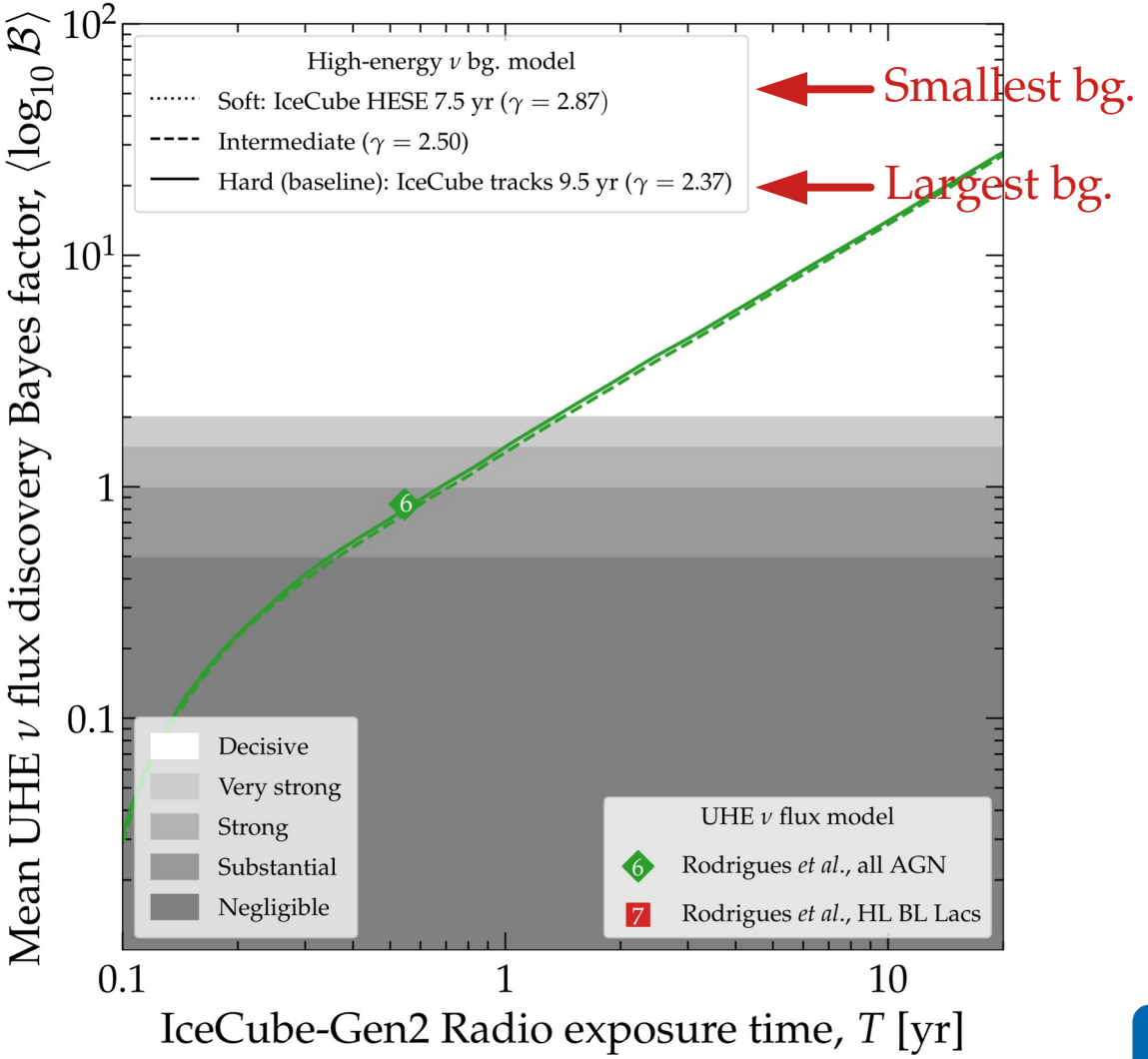
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

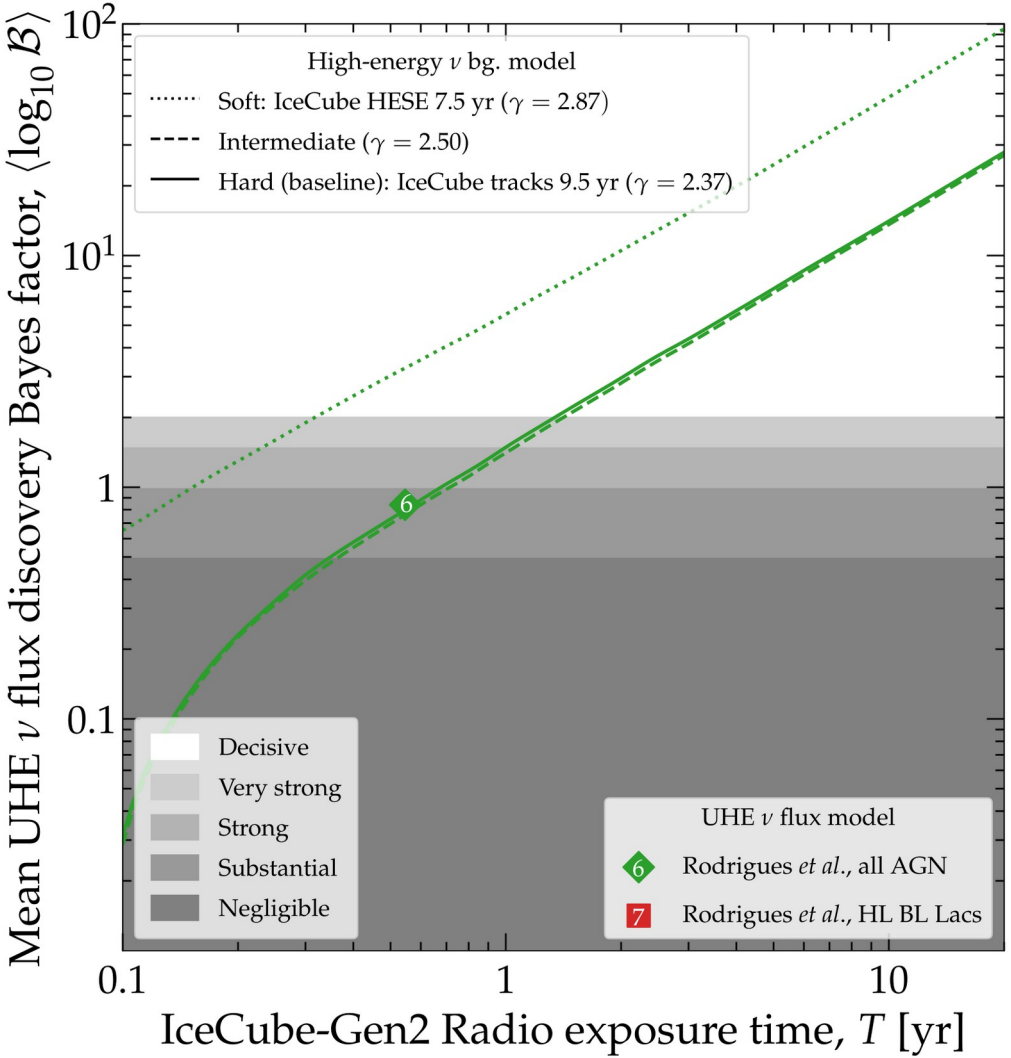
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

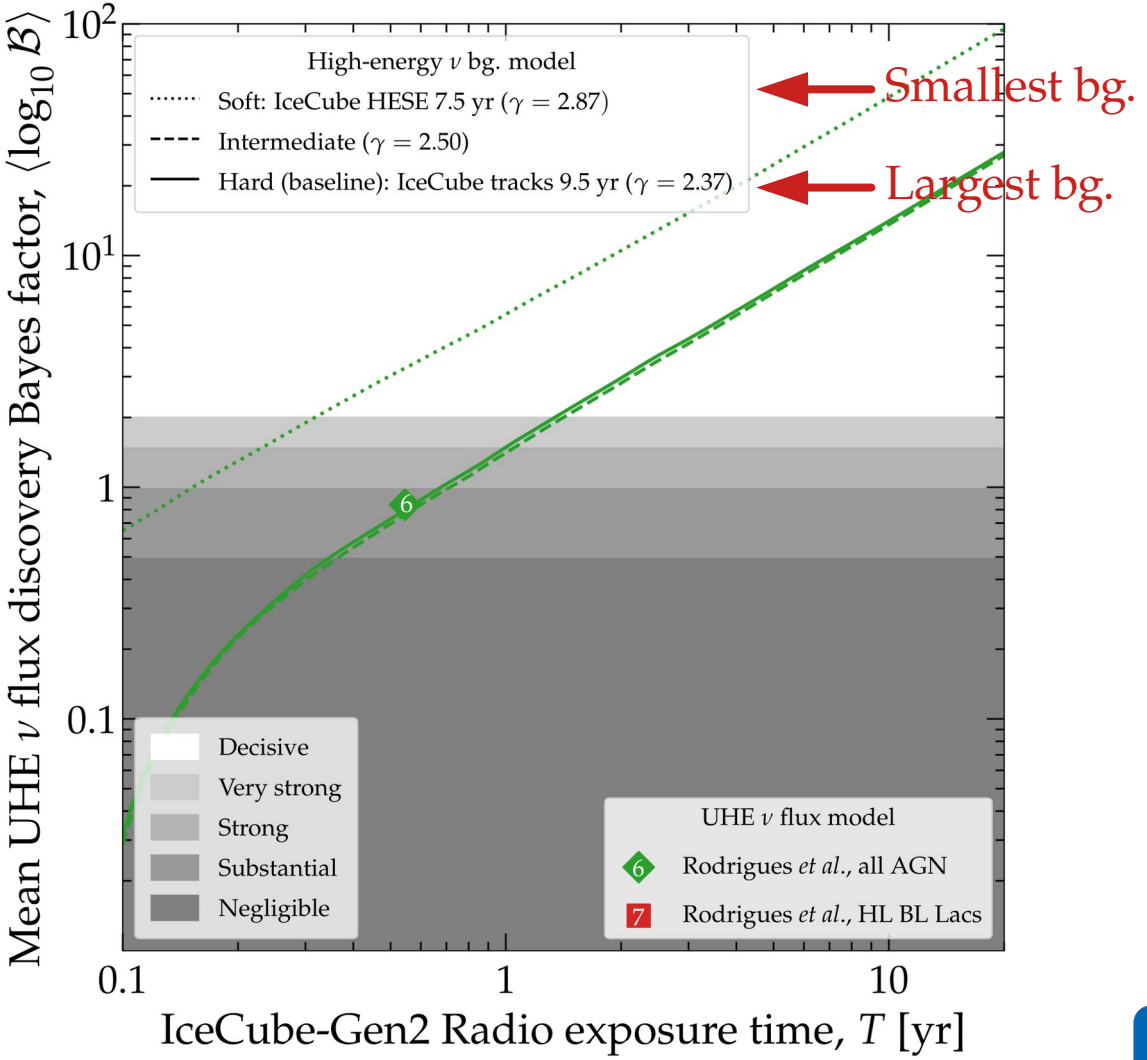
TAMBO astro case #1: the tail of the IceCube flux

To discover UHE flux model #6, compare its signal to background:

Atmospheric muons (small)

+

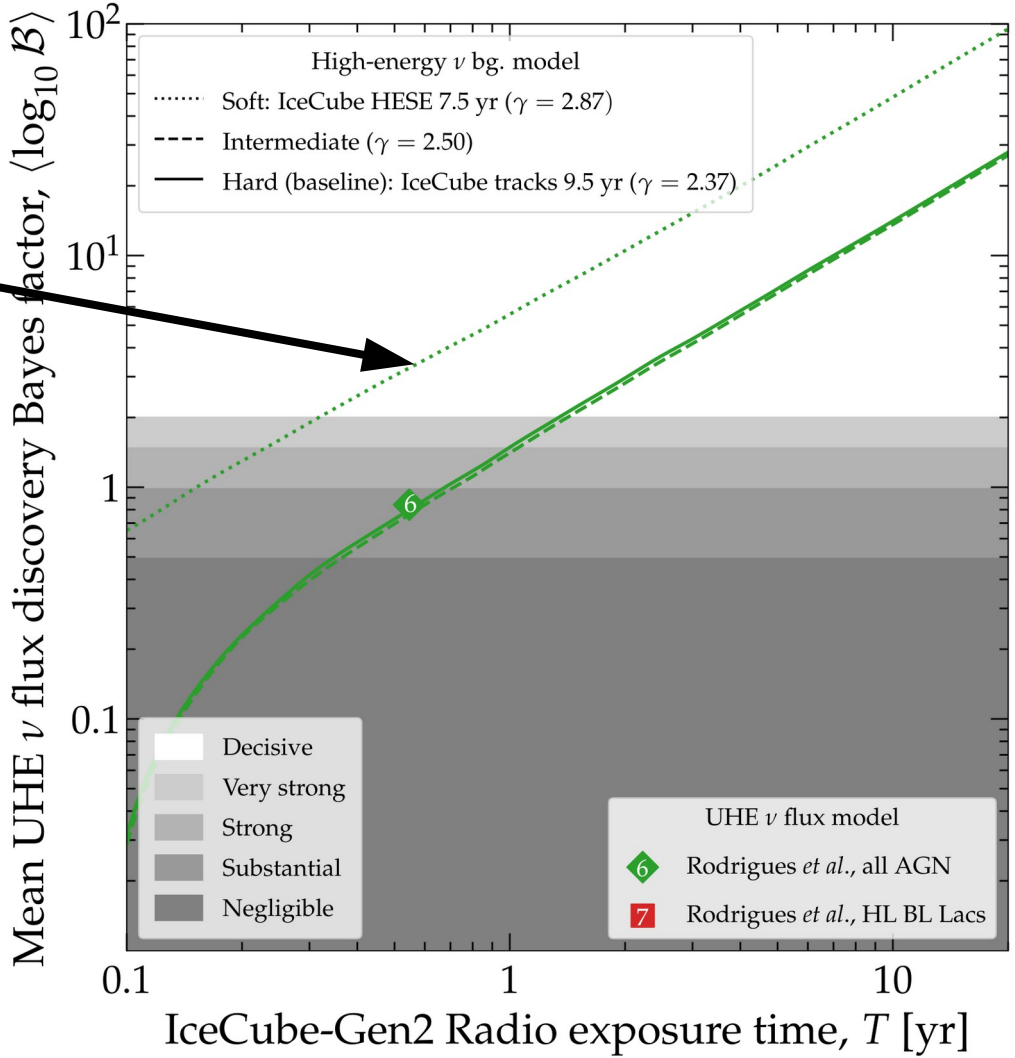
Tail of the IceCube flux (potentially dominant)



Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

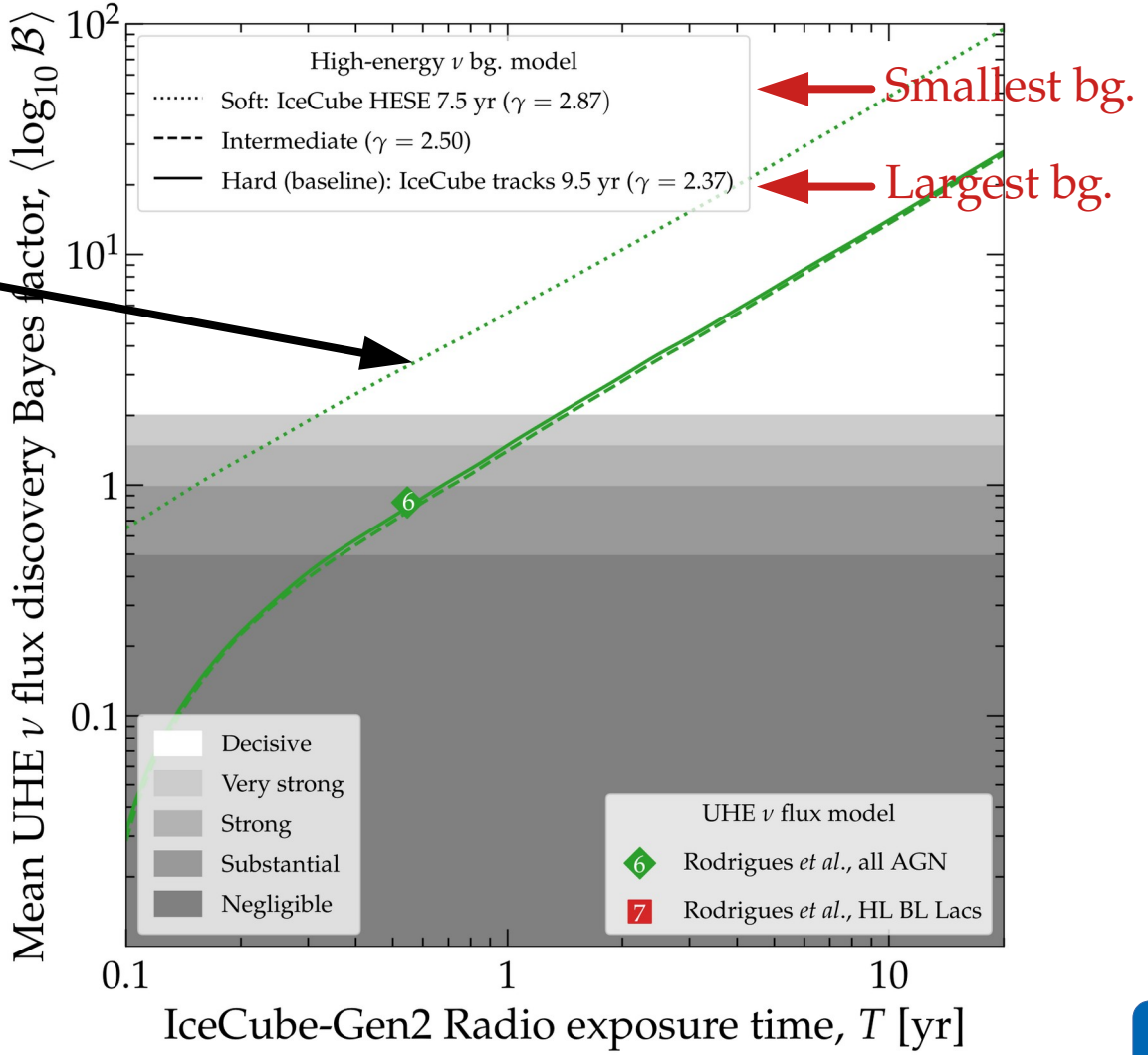
Knowing the slope
of the IceCube background
may hasten UHE flux discovery



Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

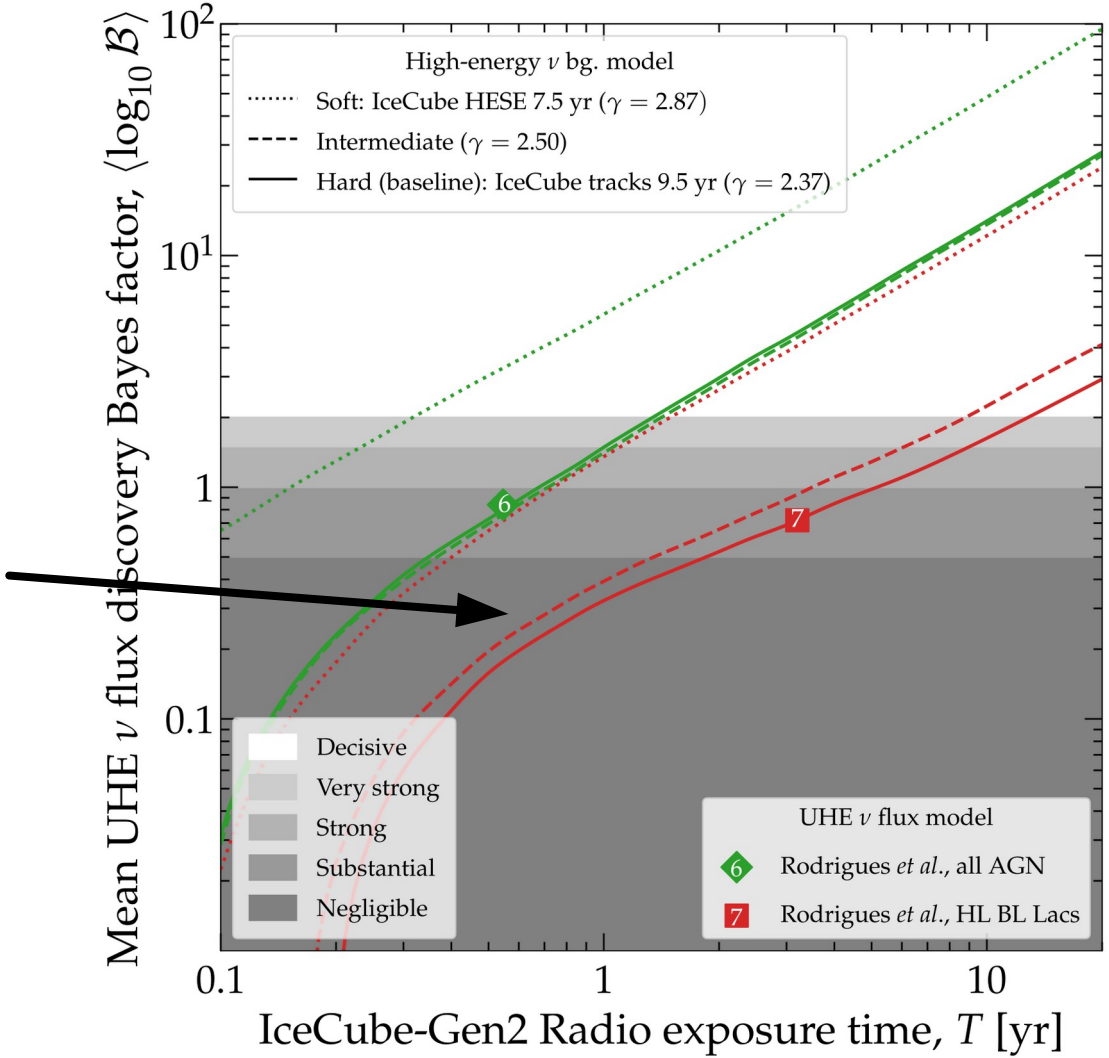
Knowing the slope
of the IceCube background
may hasten UHE flux discovery



Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

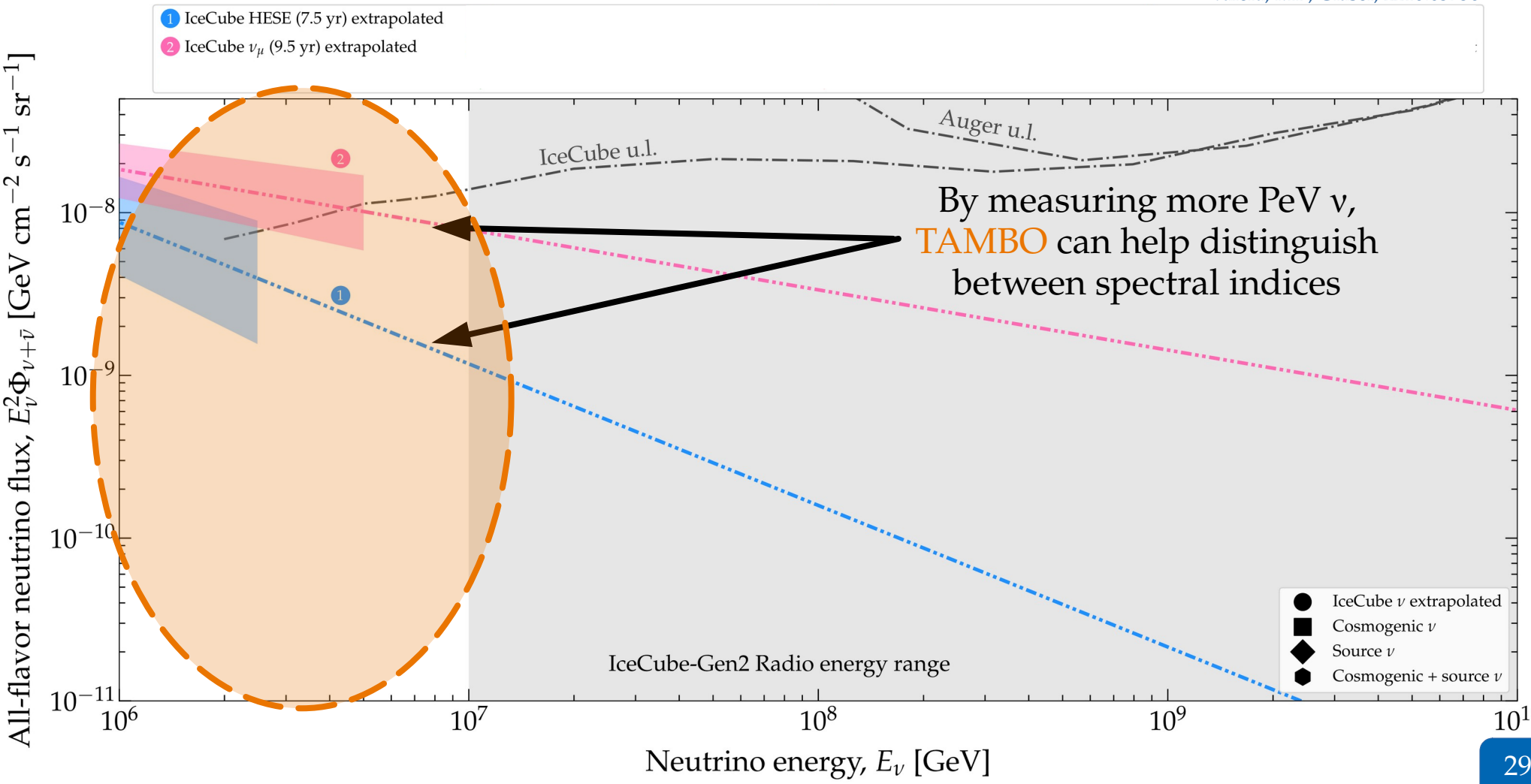
Similar improvements for other UHE flux models



Valera, **MB**, Glaser, 2210.03756

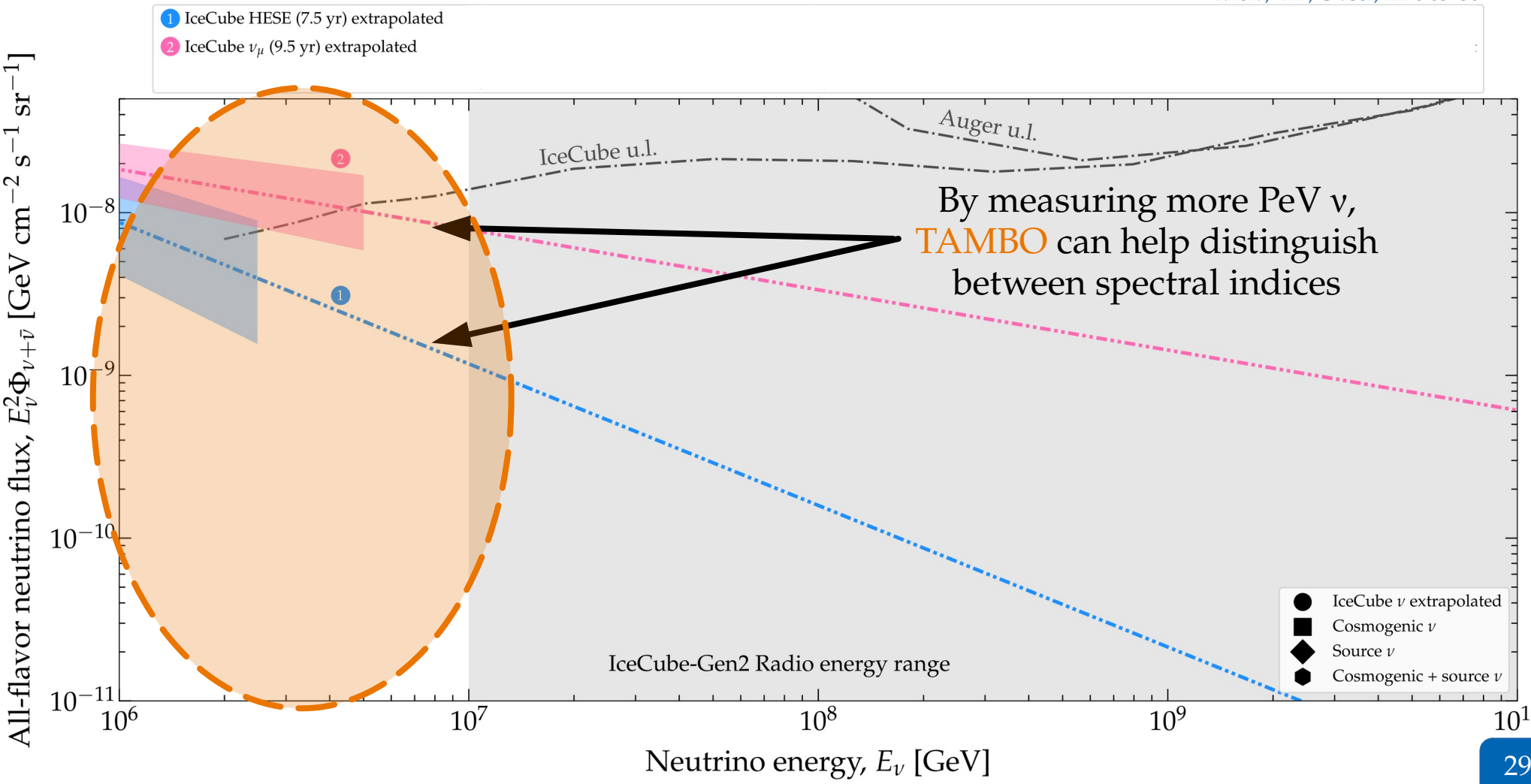
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



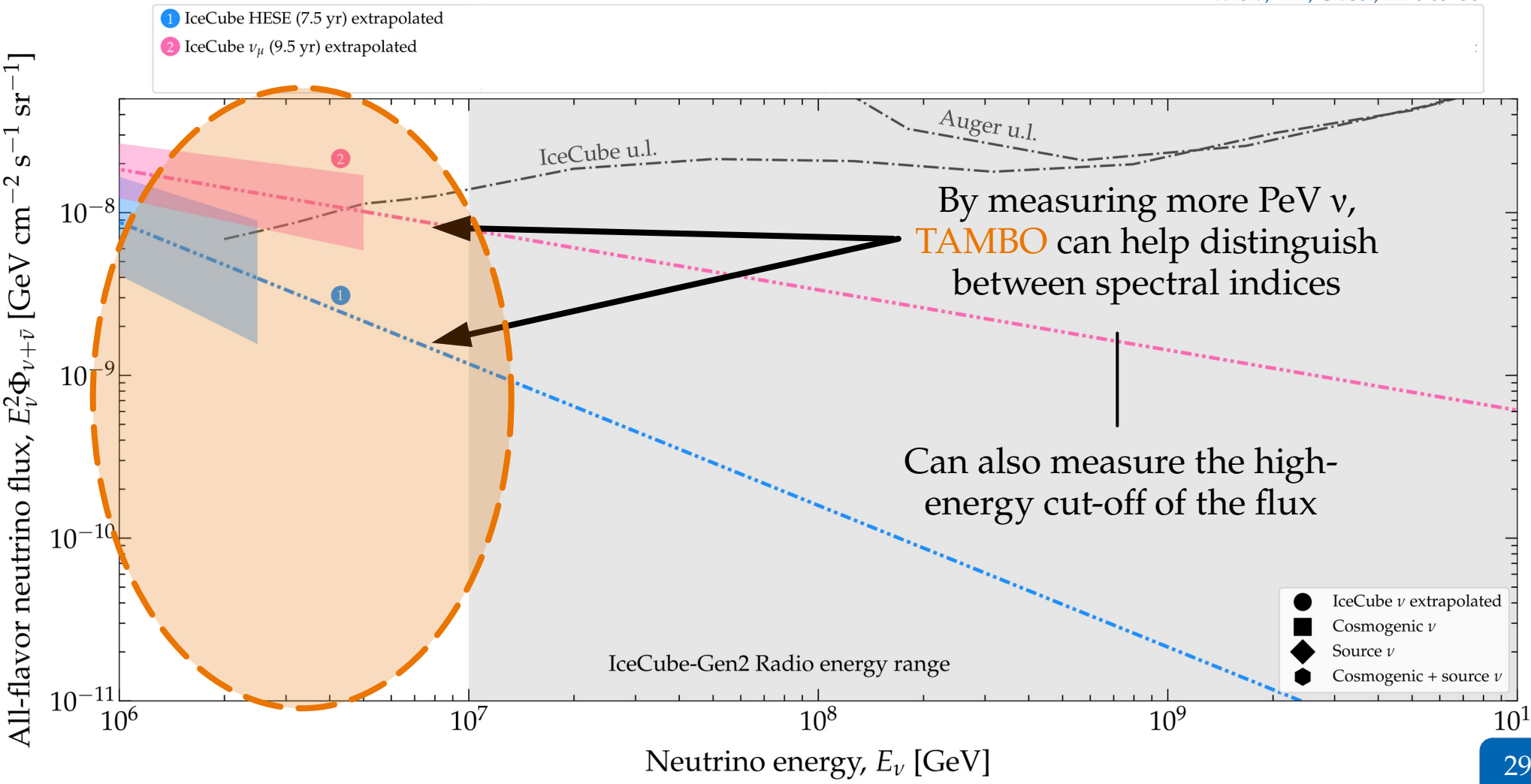
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



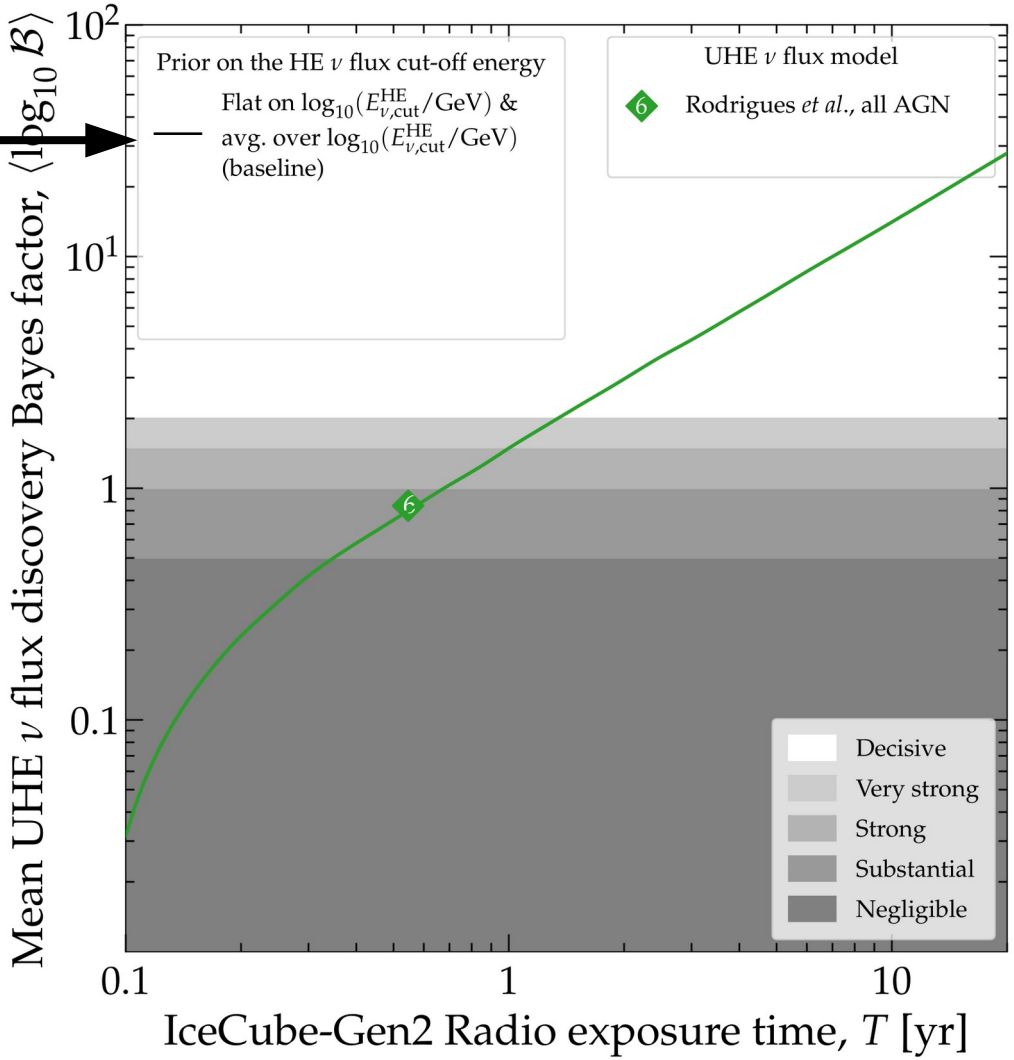
TAMBO astro case #1: the tail of the IceCube flux

Valera, **MB**, Glaser, 2210.03756



TAMBO astro case #1: the tail of the IceCube flux

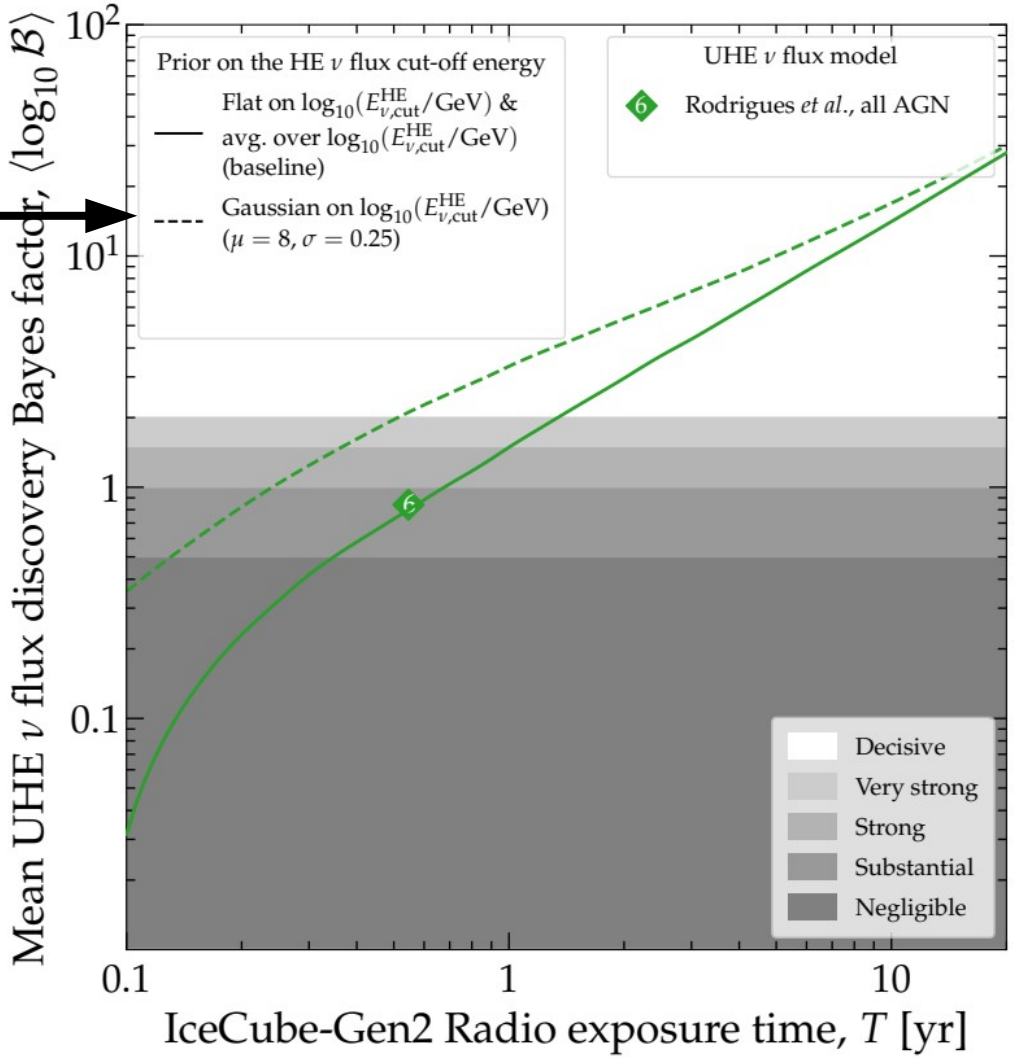
No knowledge
of the cut-off energy



Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

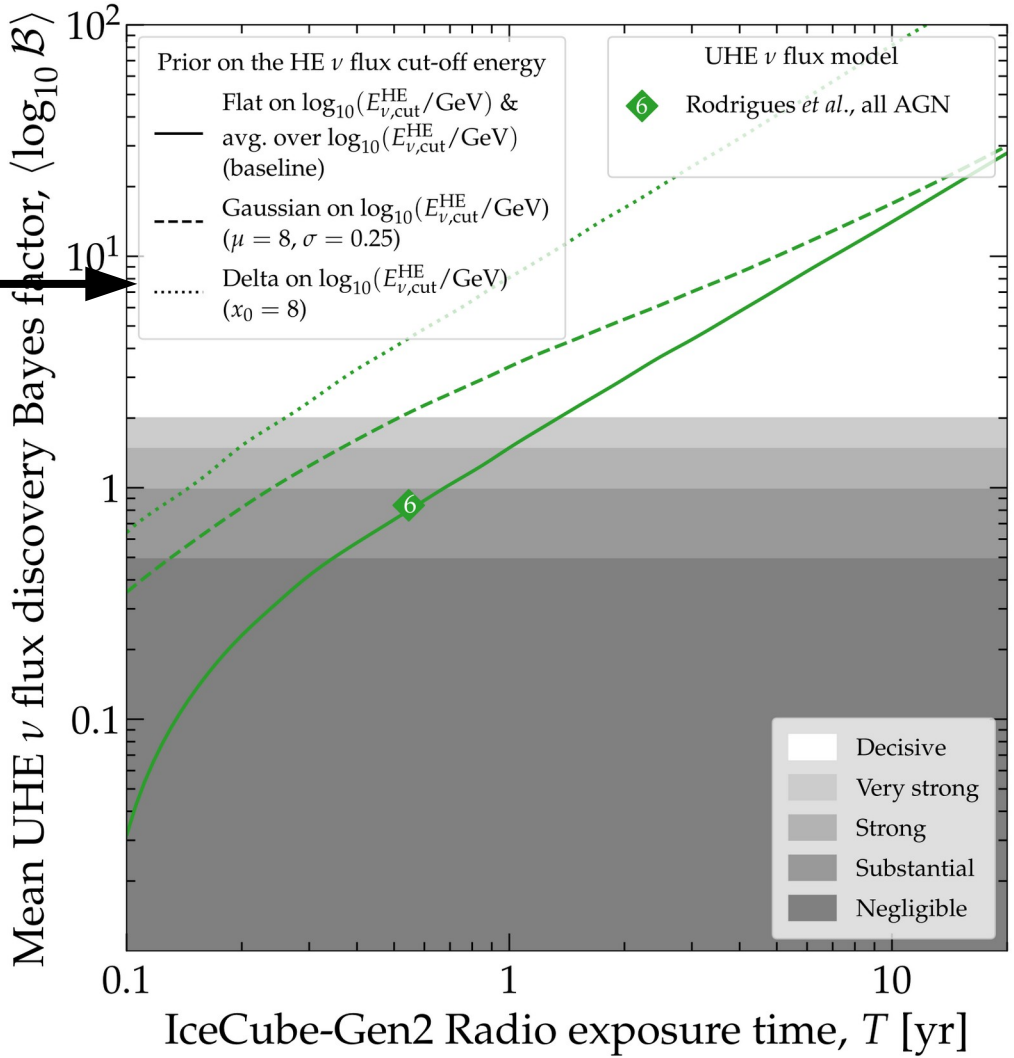
Some knowledge of the cut-off energy



Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

Perfect knowledge of the cut-off energy

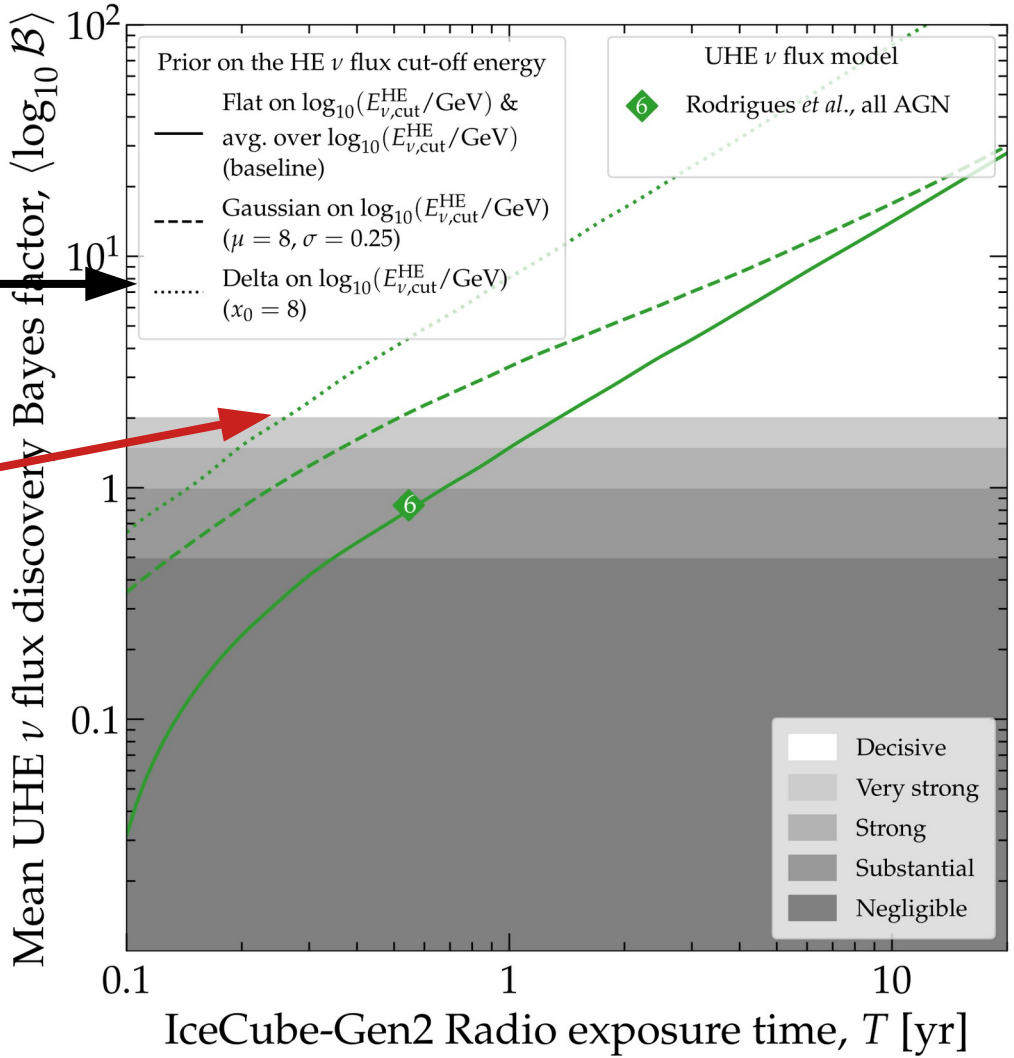


Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

Perfect knowledge of the cut-off energy

Expedites discovery of an UHE flux model



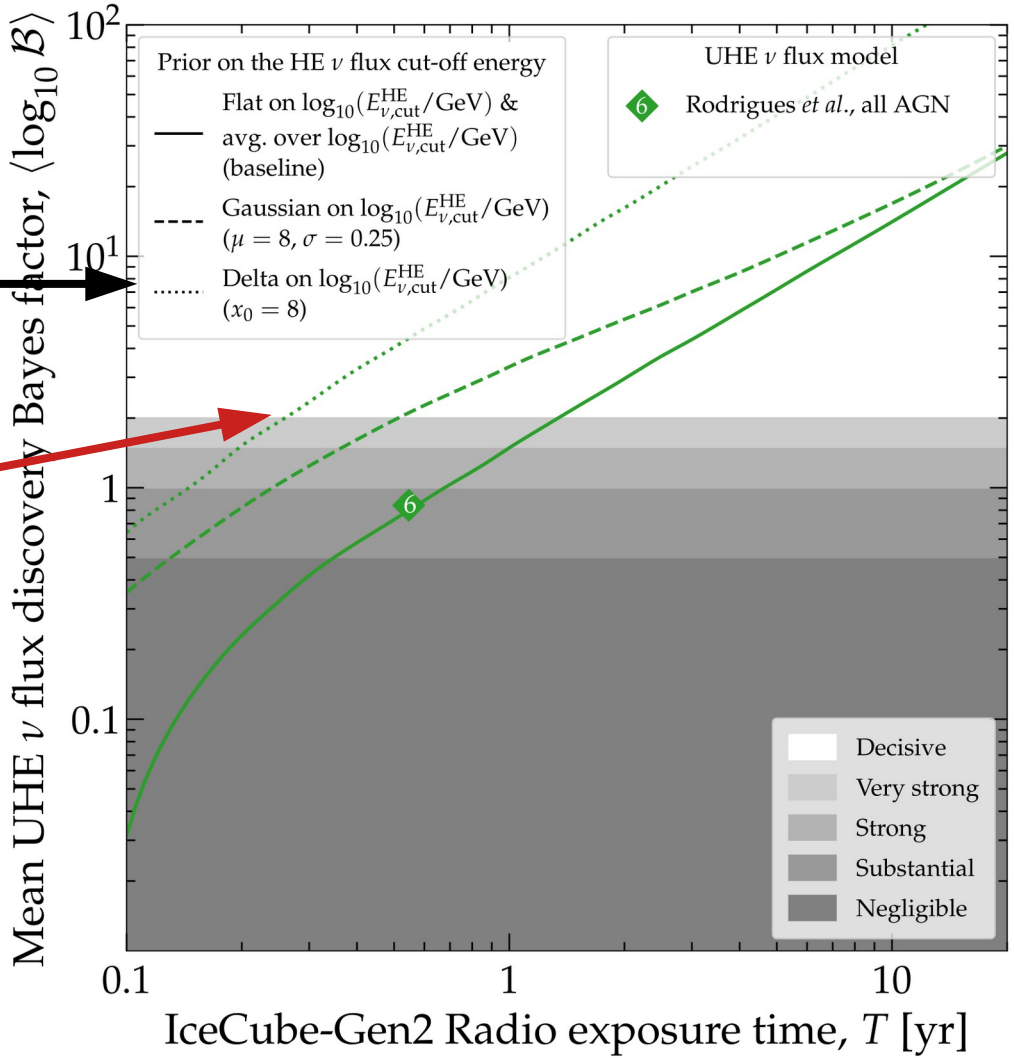
Valera, **MB**, Glaser, 2210.03756

TAMBO astro case #1: the tail of the IceCube flux

Perfect knowledge of the cut-off energy

Expedites discovery of an UHE flux model

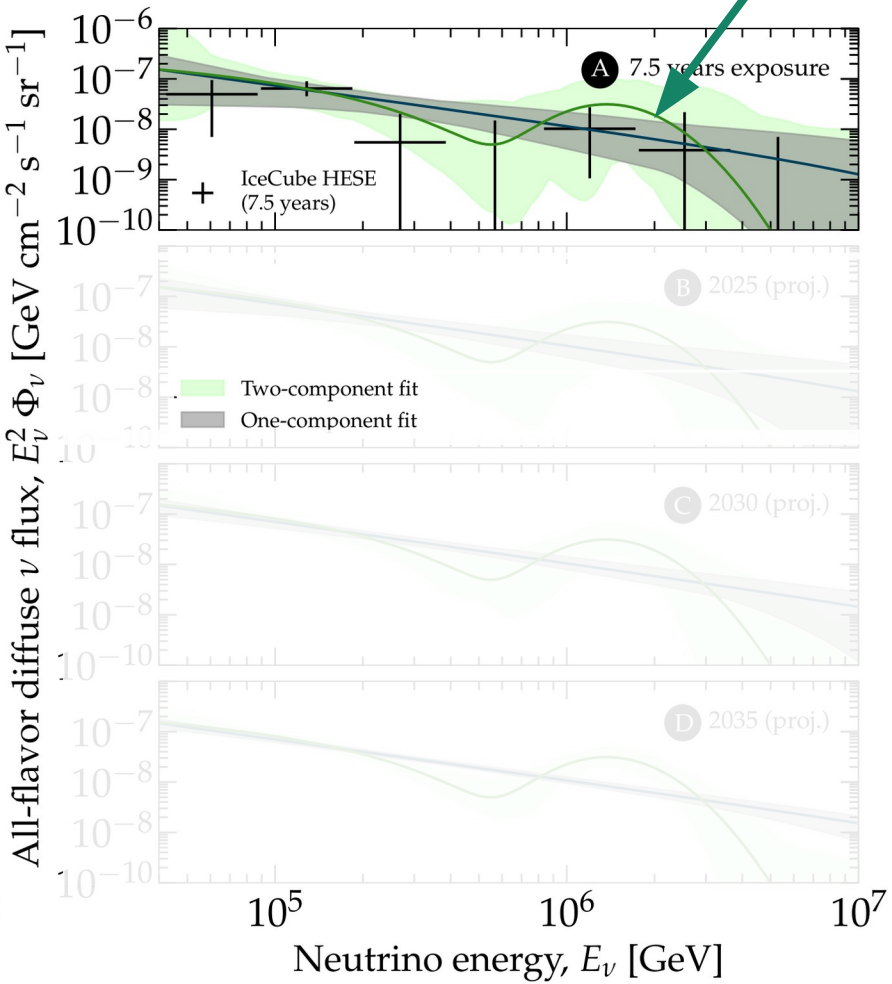
Also (not shown): knowing the tail of the IceCube flux helps distinguish between competing flux models



Valera, **MB**, Glaser, 2210.03756

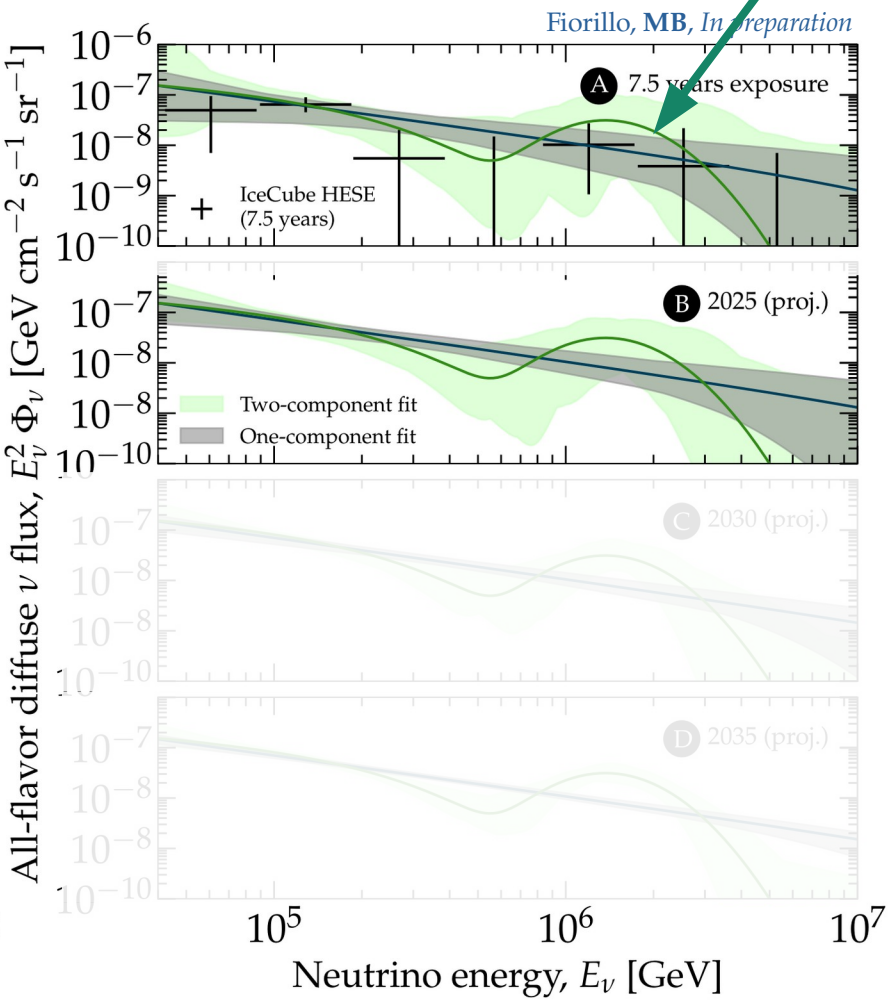
TAMBO astro case #2: finding PeV bumps

A bump can reveal a population of $p\gamma$ sources



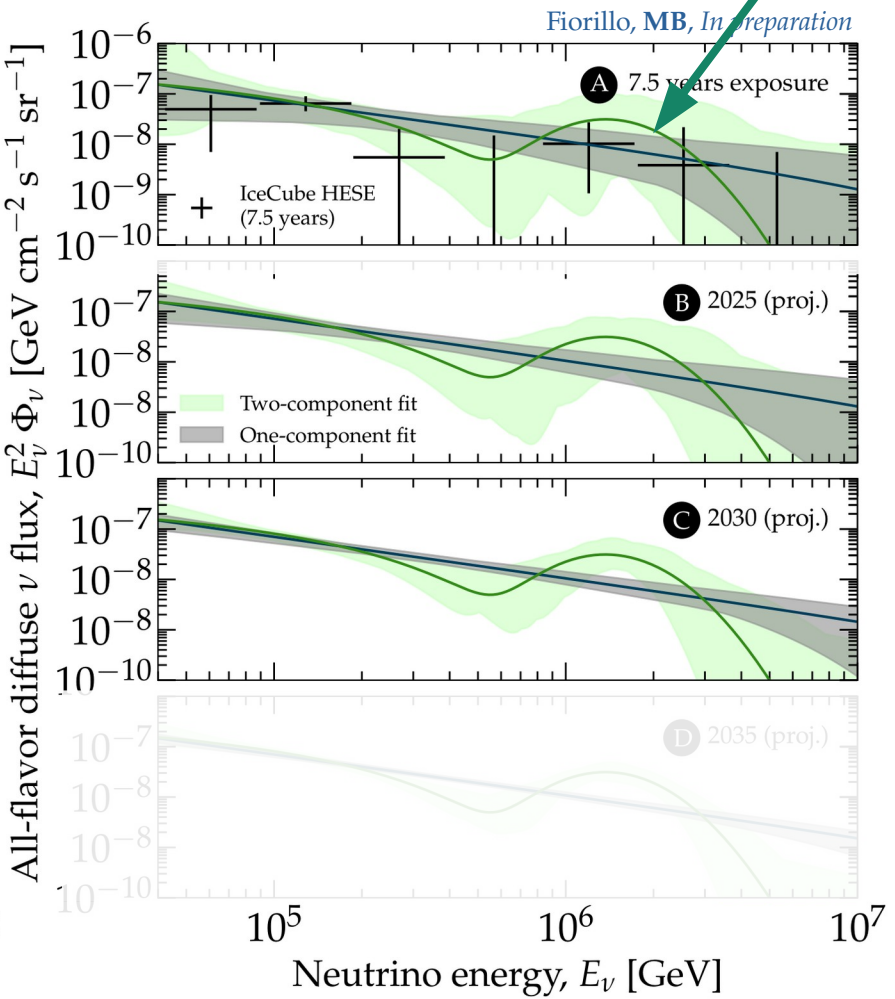
TAMBO astro case #2: finding PeV bumps

A bump can reveal a population of $p\gamma$ sources



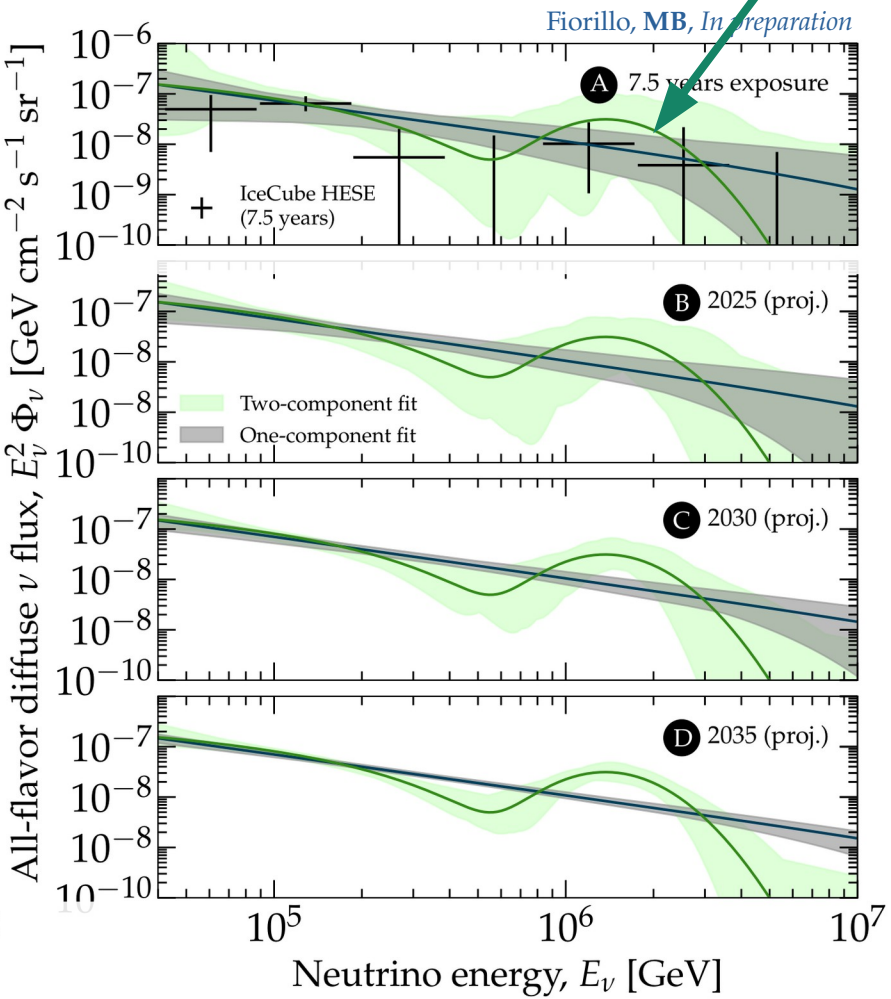
TAMBO astro case #2: finding PeV bumps

A bump can reveal a population of $p\gamma$ sources

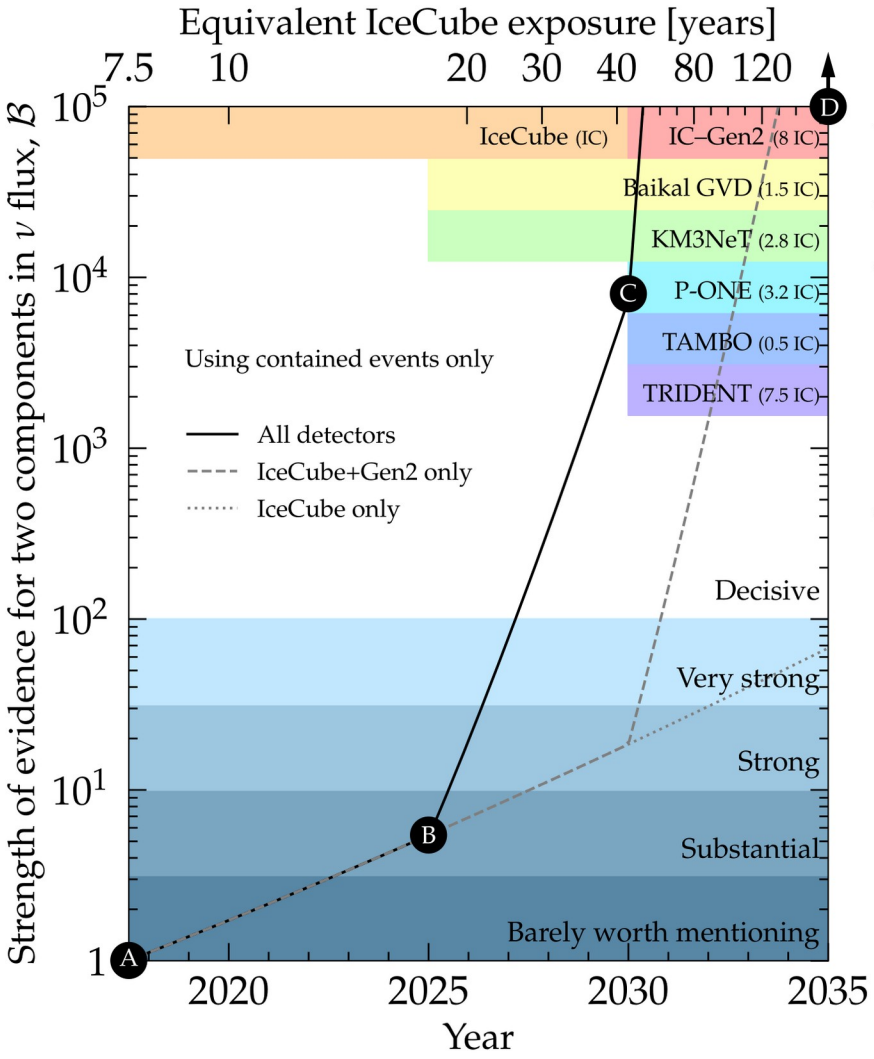


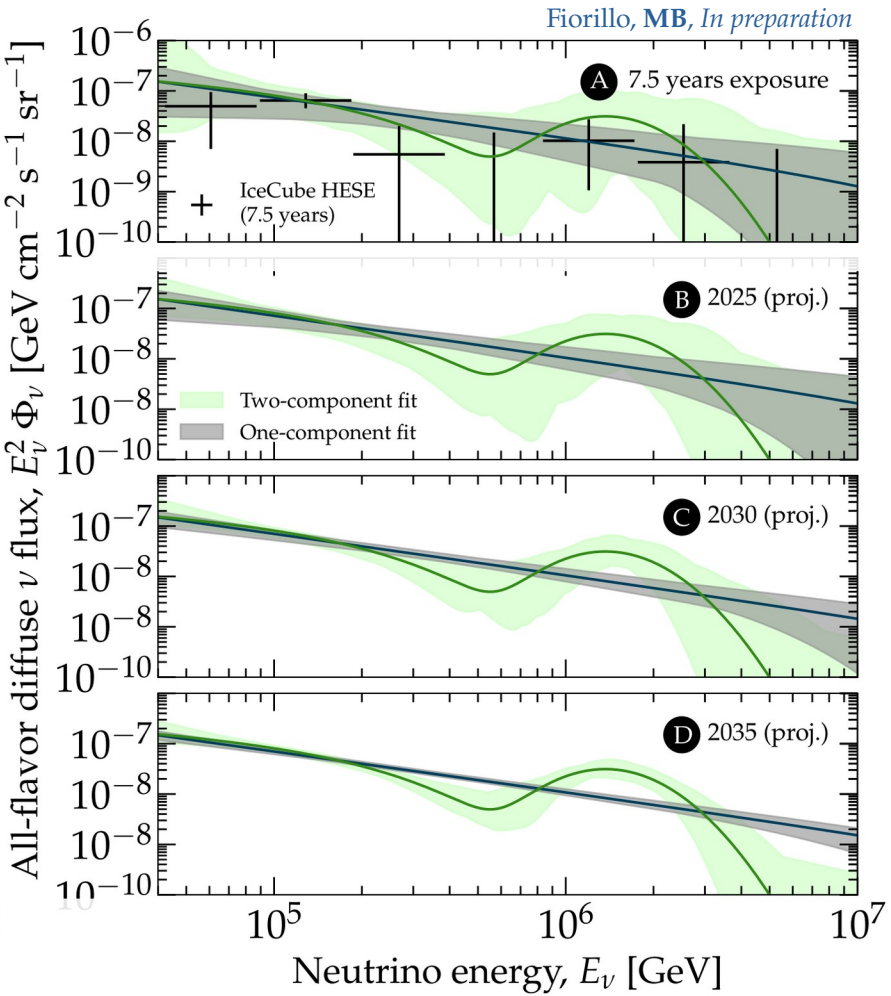
TAMBO astro case #2: finding PeV bumps

A bump can reveal a population of $p\gamma$ sources

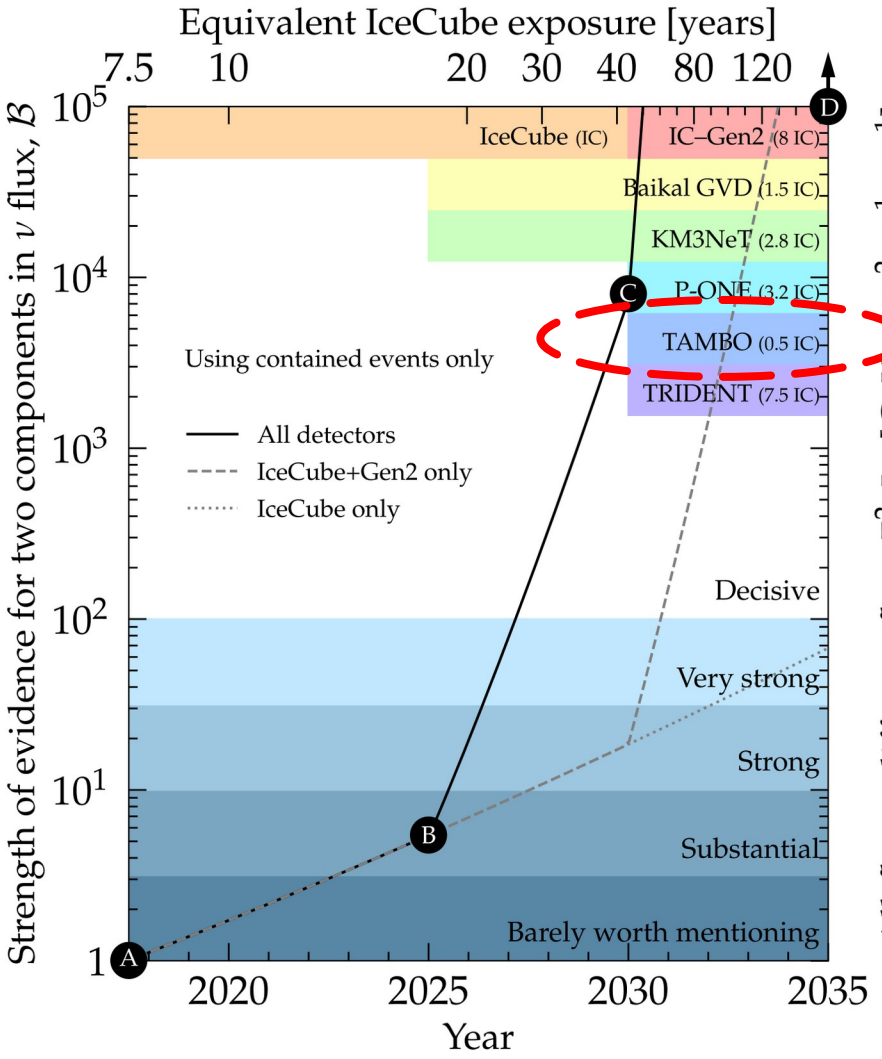


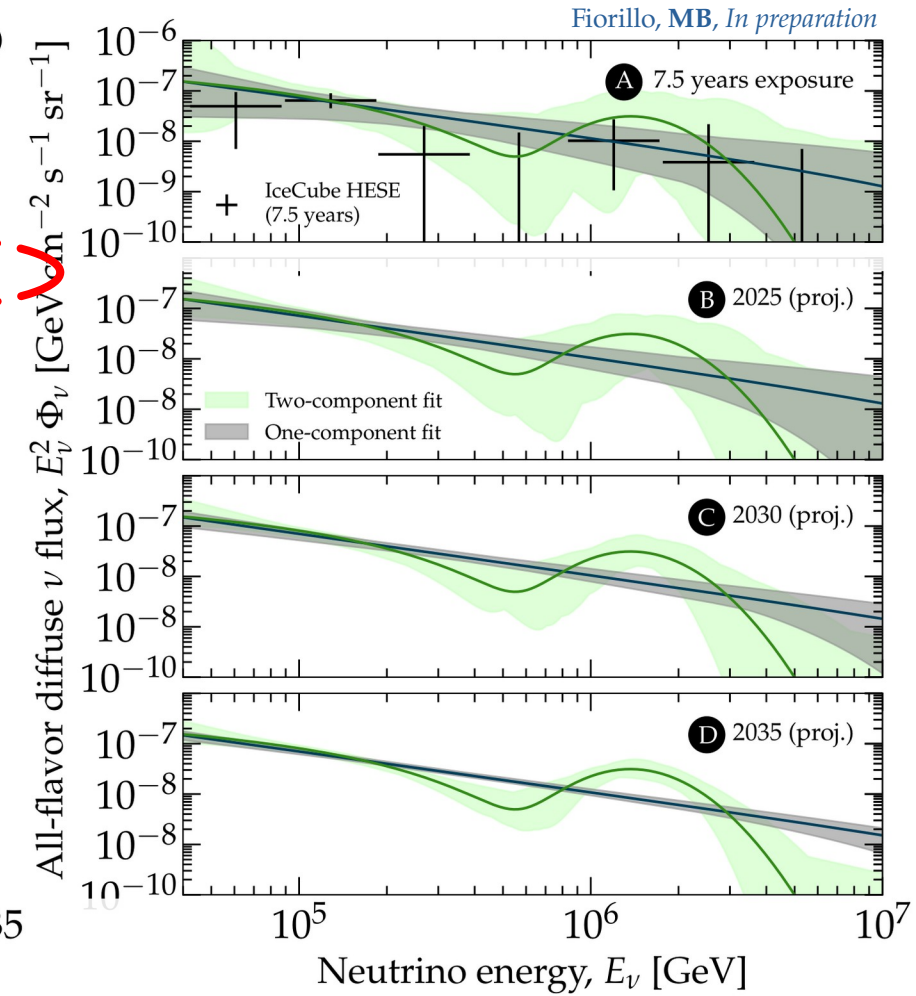
TAMBO astro case #2: finding PeV bumps



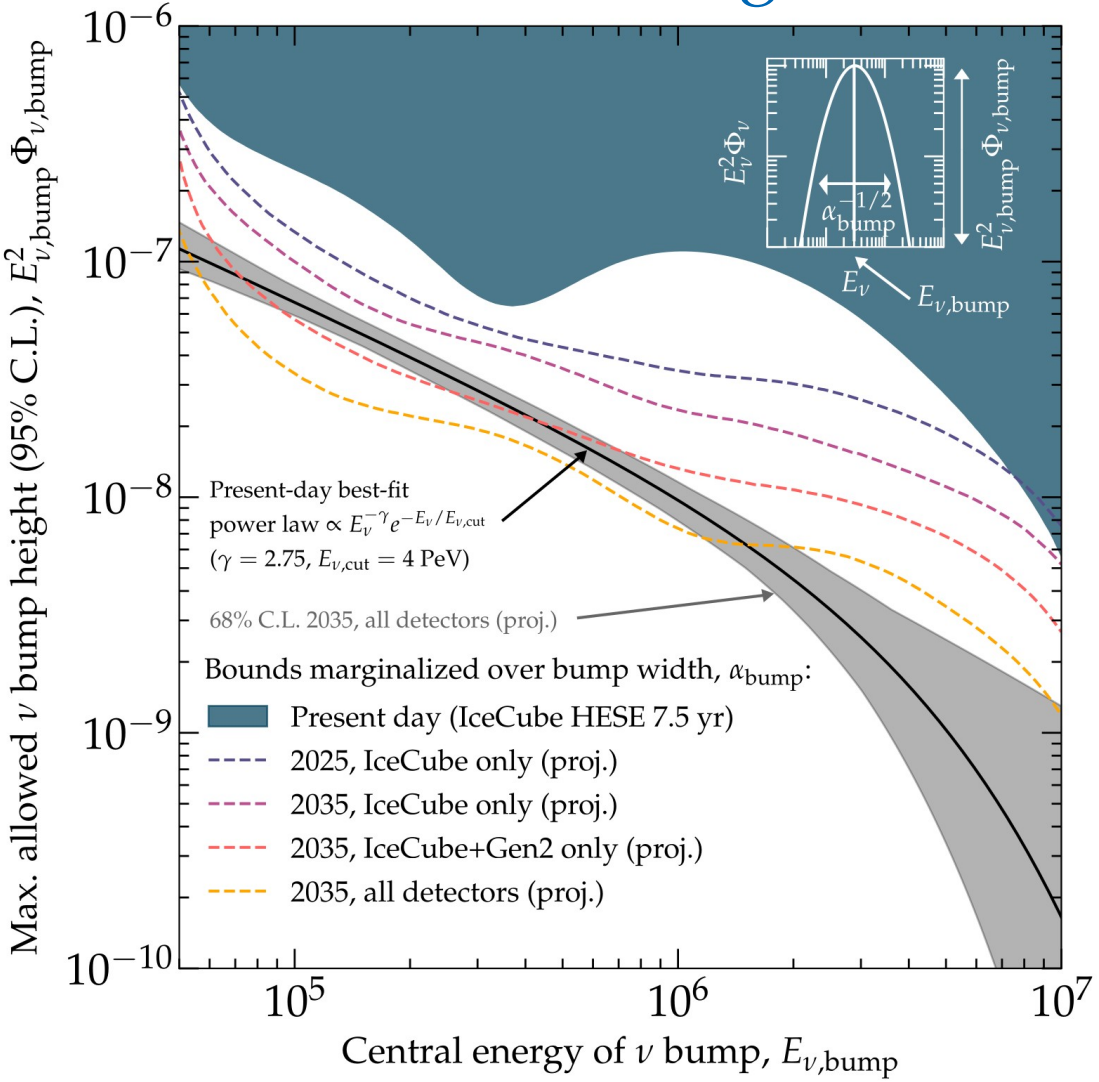


TAMBO astro case #2: finding PeV bumps



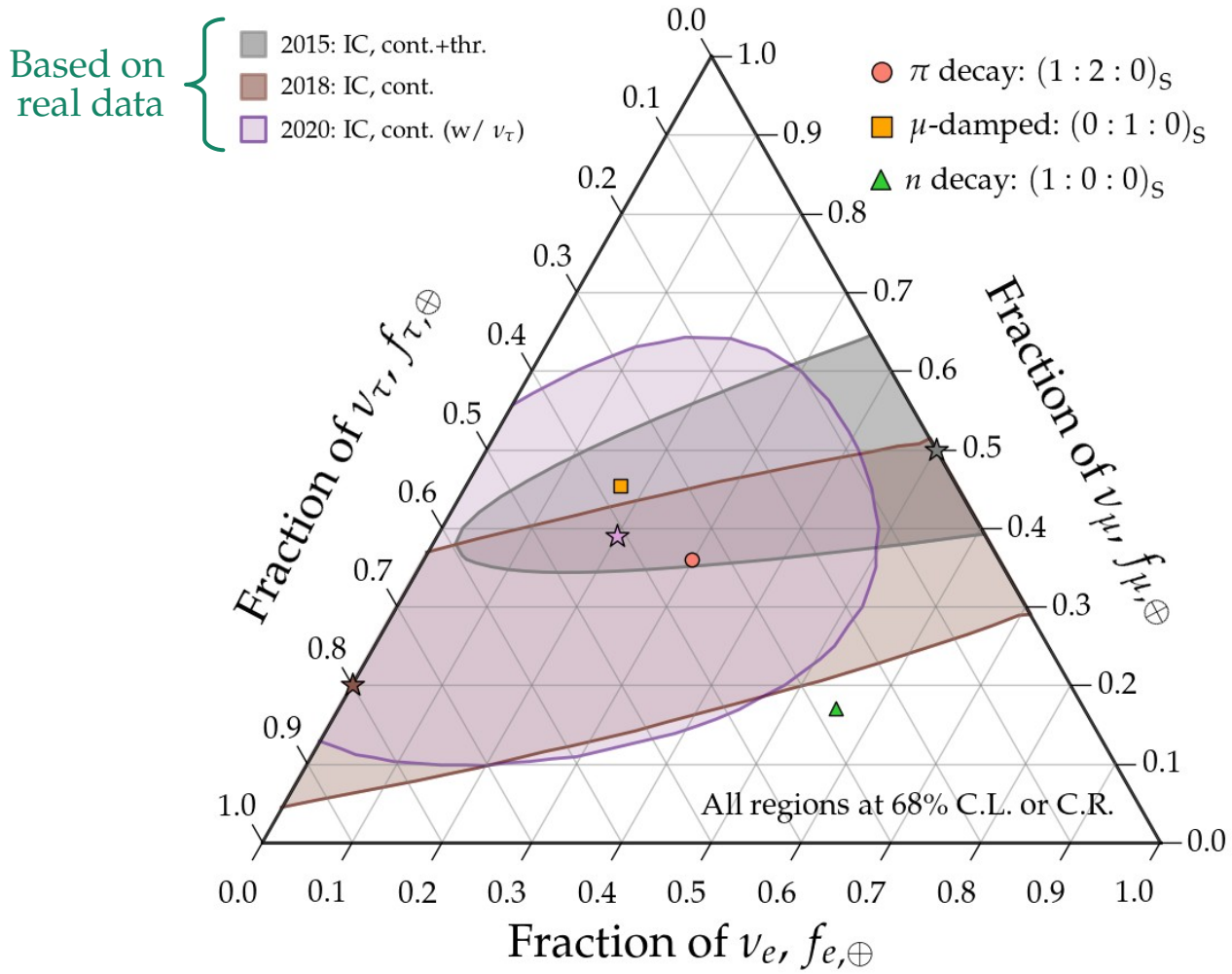


TAMBO astro case #2.5: constraining subdominant bumps

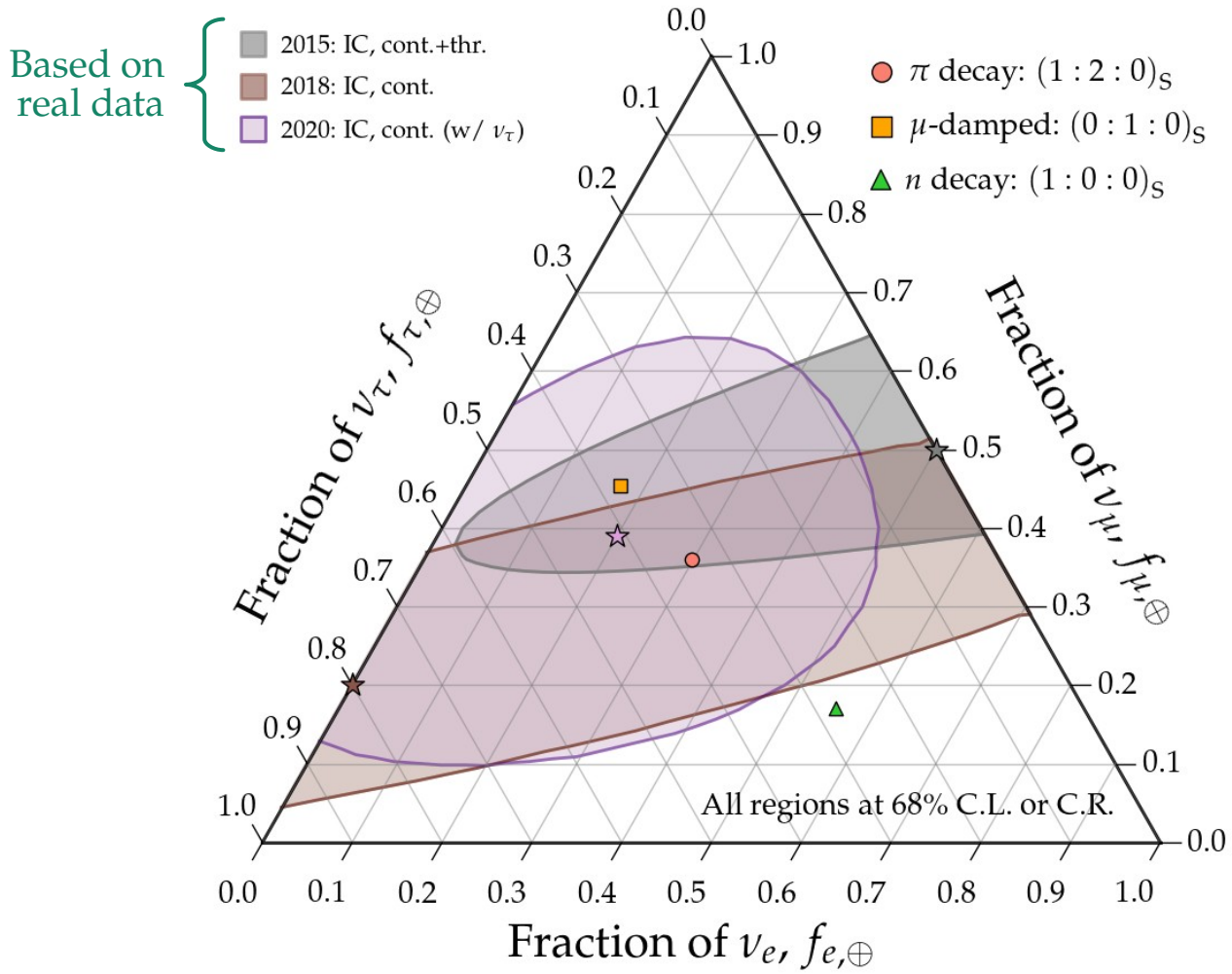


Fiorillo, **MB**, *In preparation*

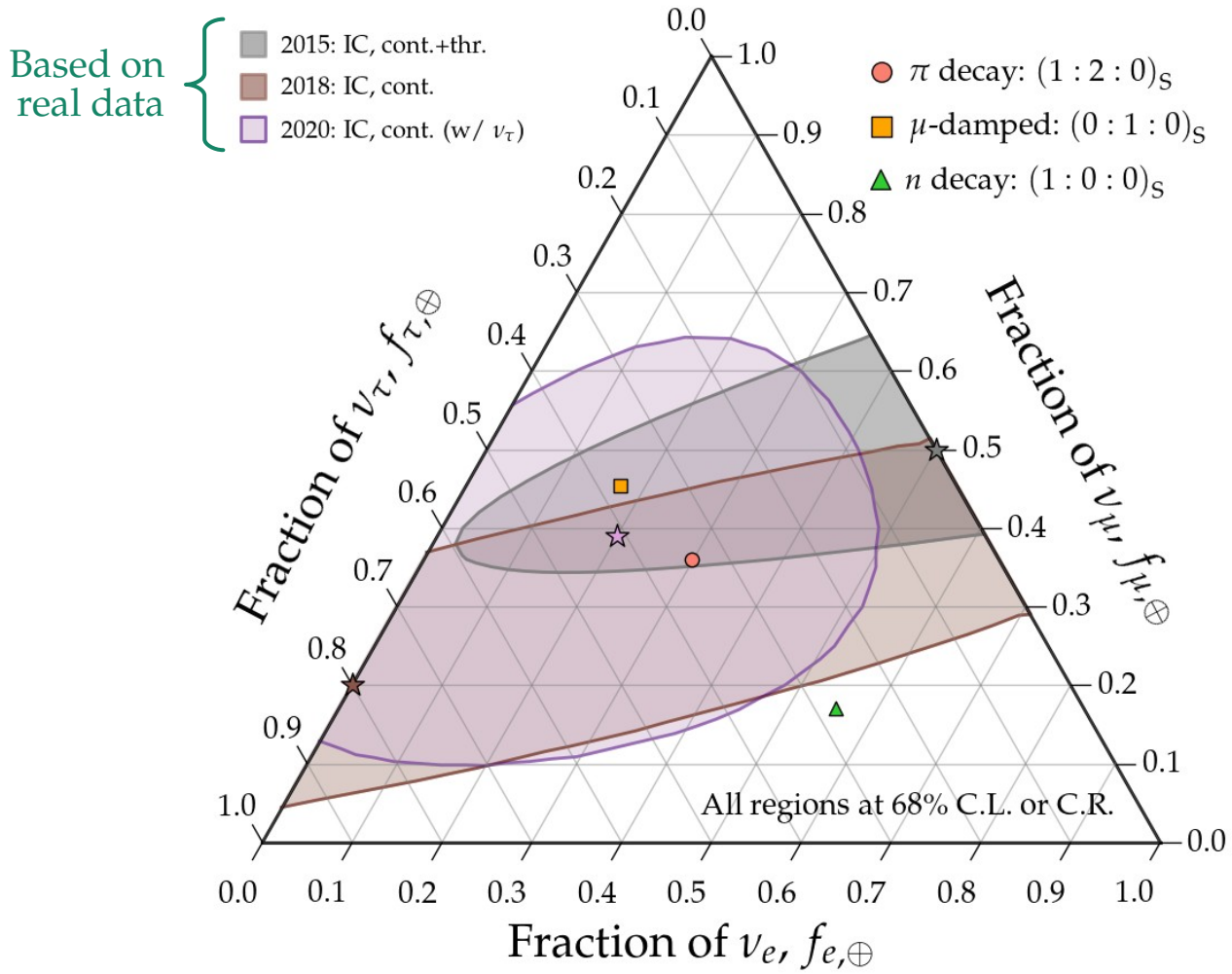
TAMBO astro case #3: flavor composition



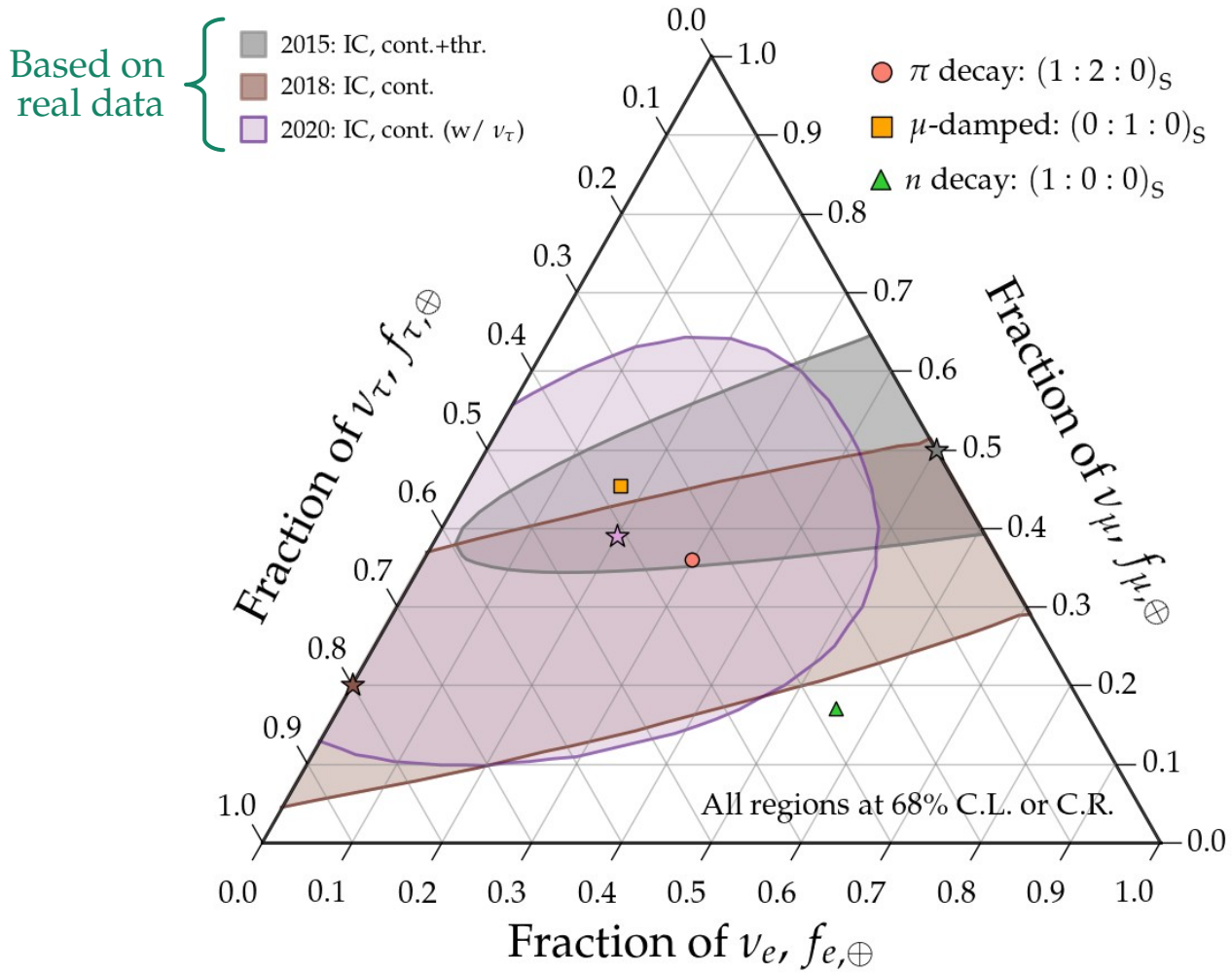
TAMBO astro case #3: flavor composition



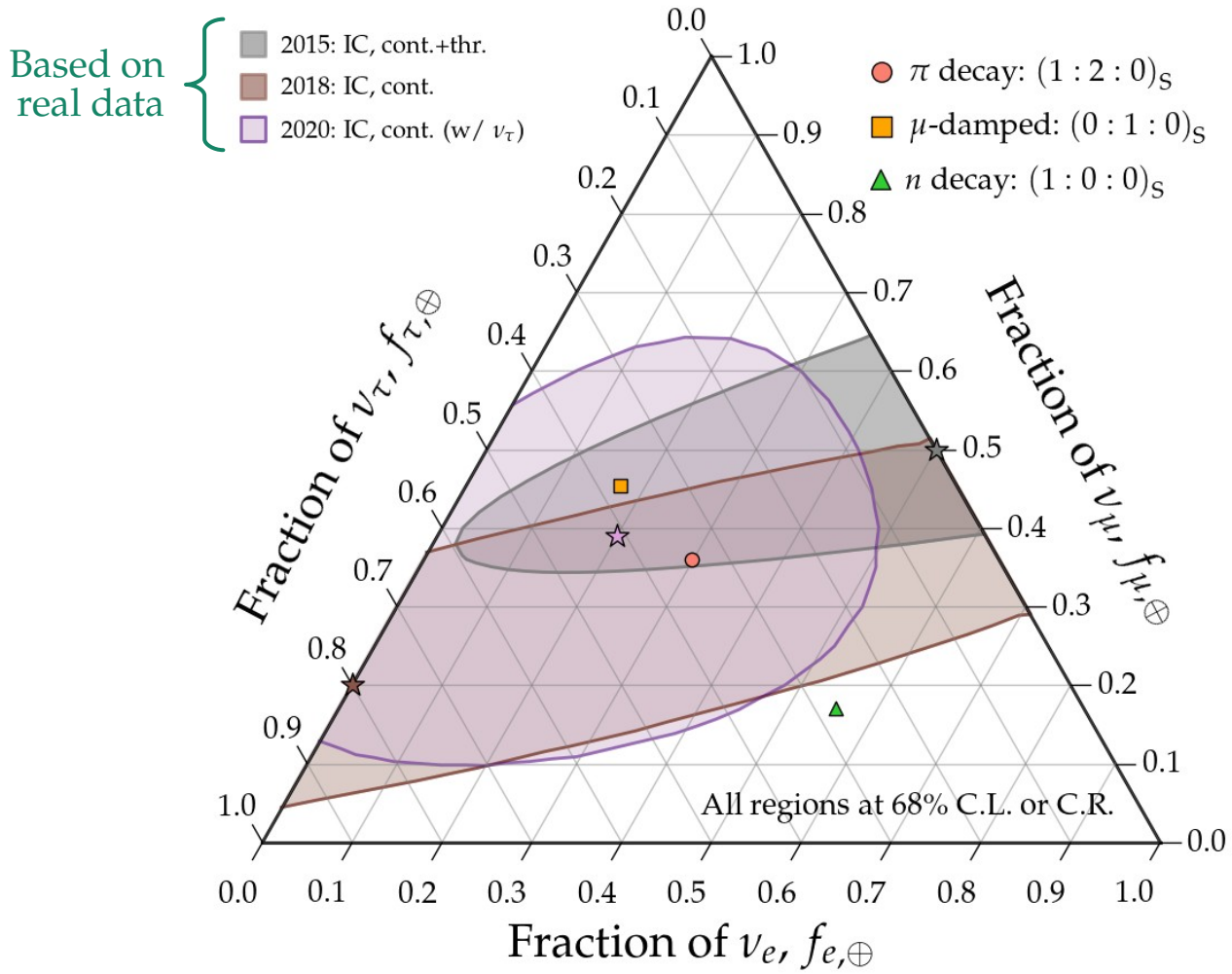
TAMBO astro case #3: flavor composition



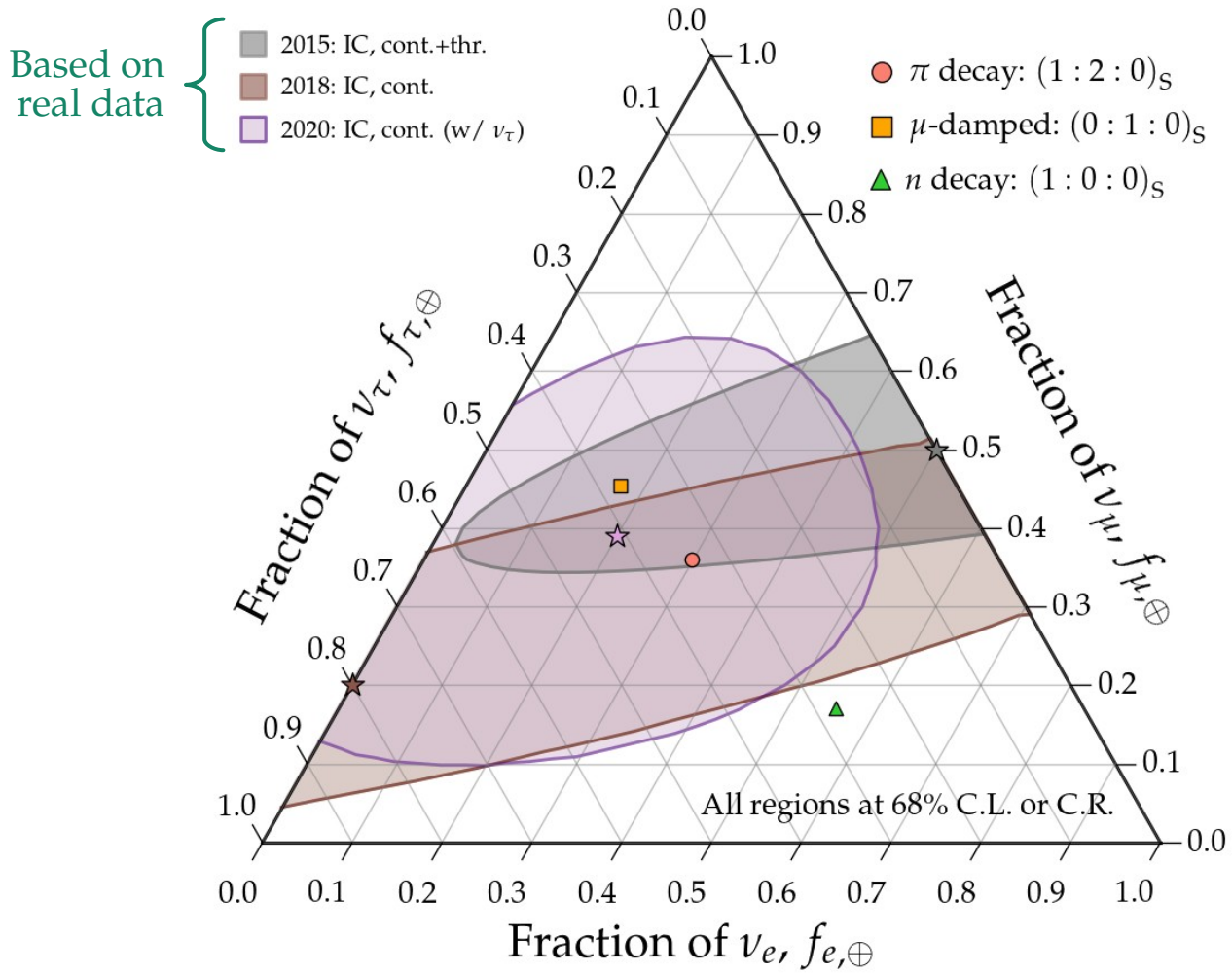
TAMBO astro case #3: flavor composition

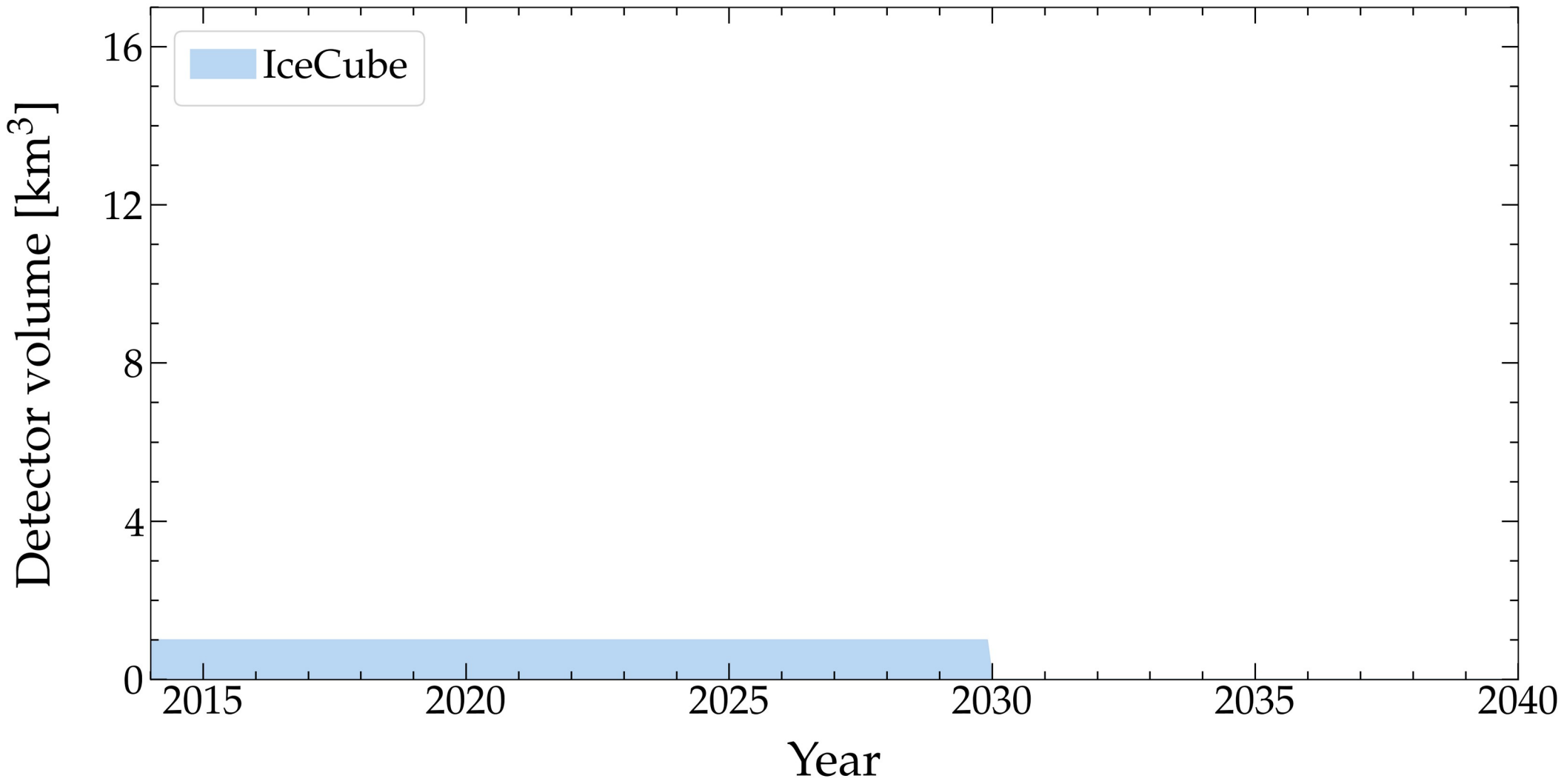


TAMBO astro case #3: flavor composition

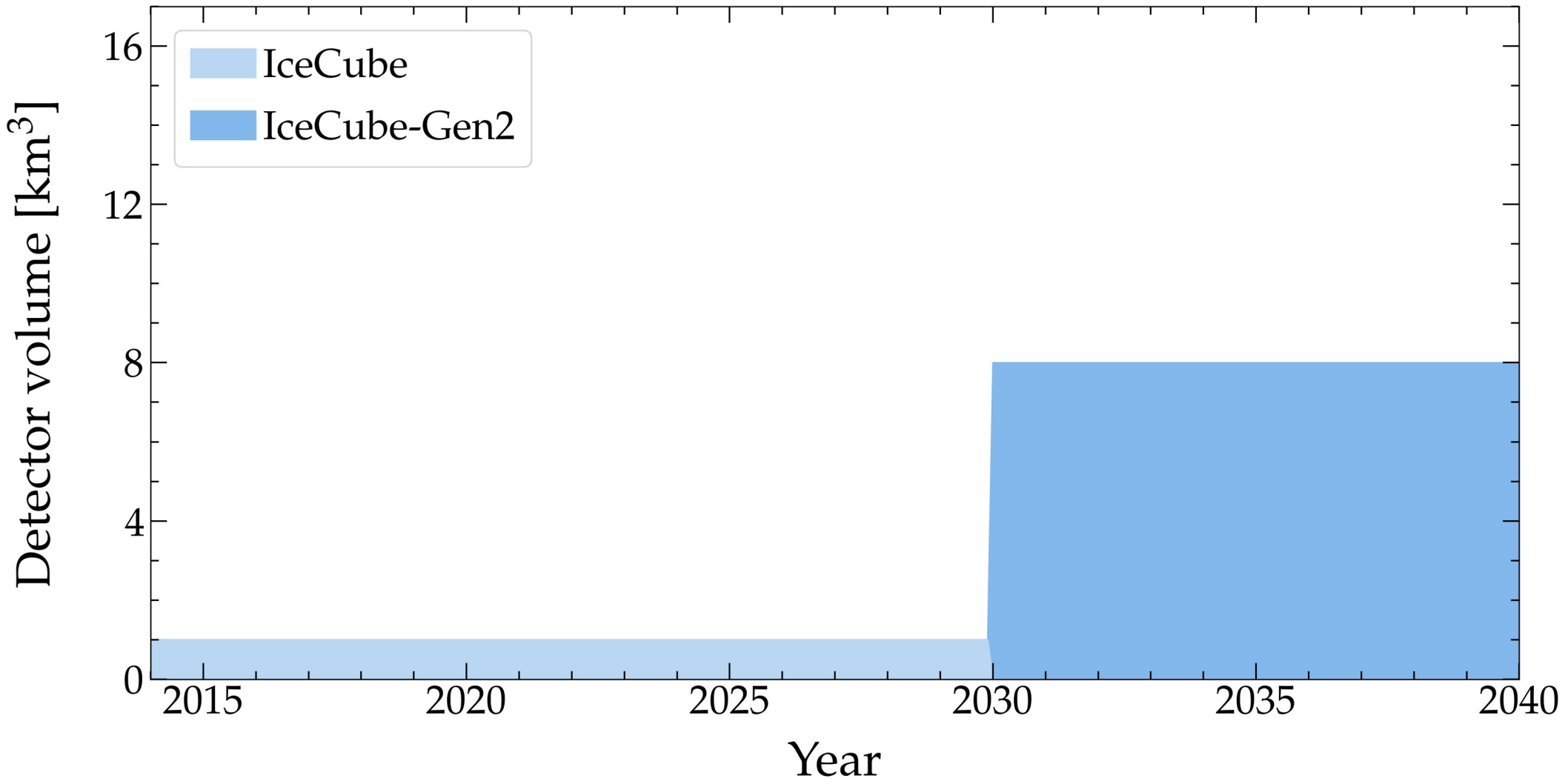


TAMBO astro case #3: flavor composition

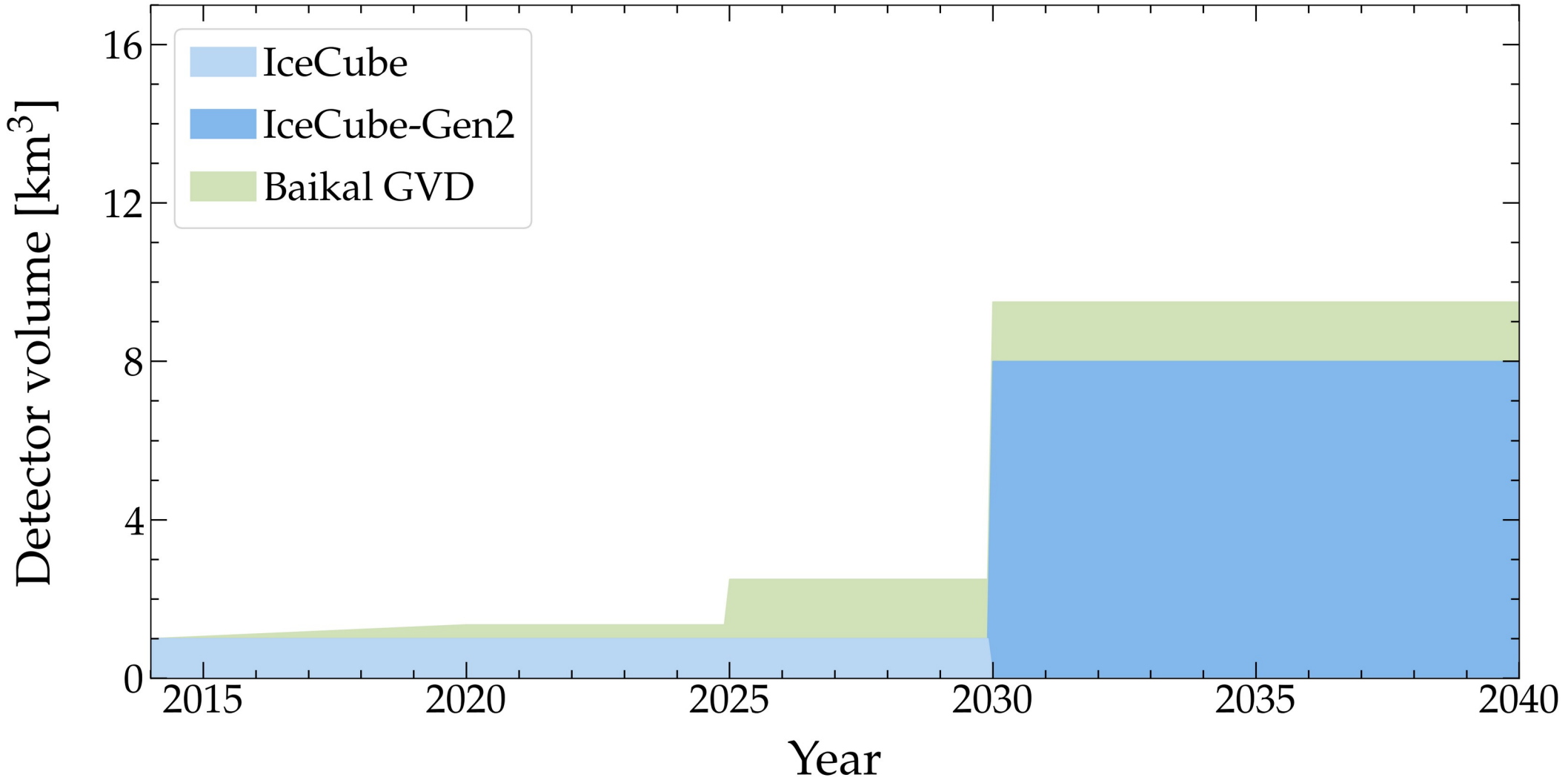




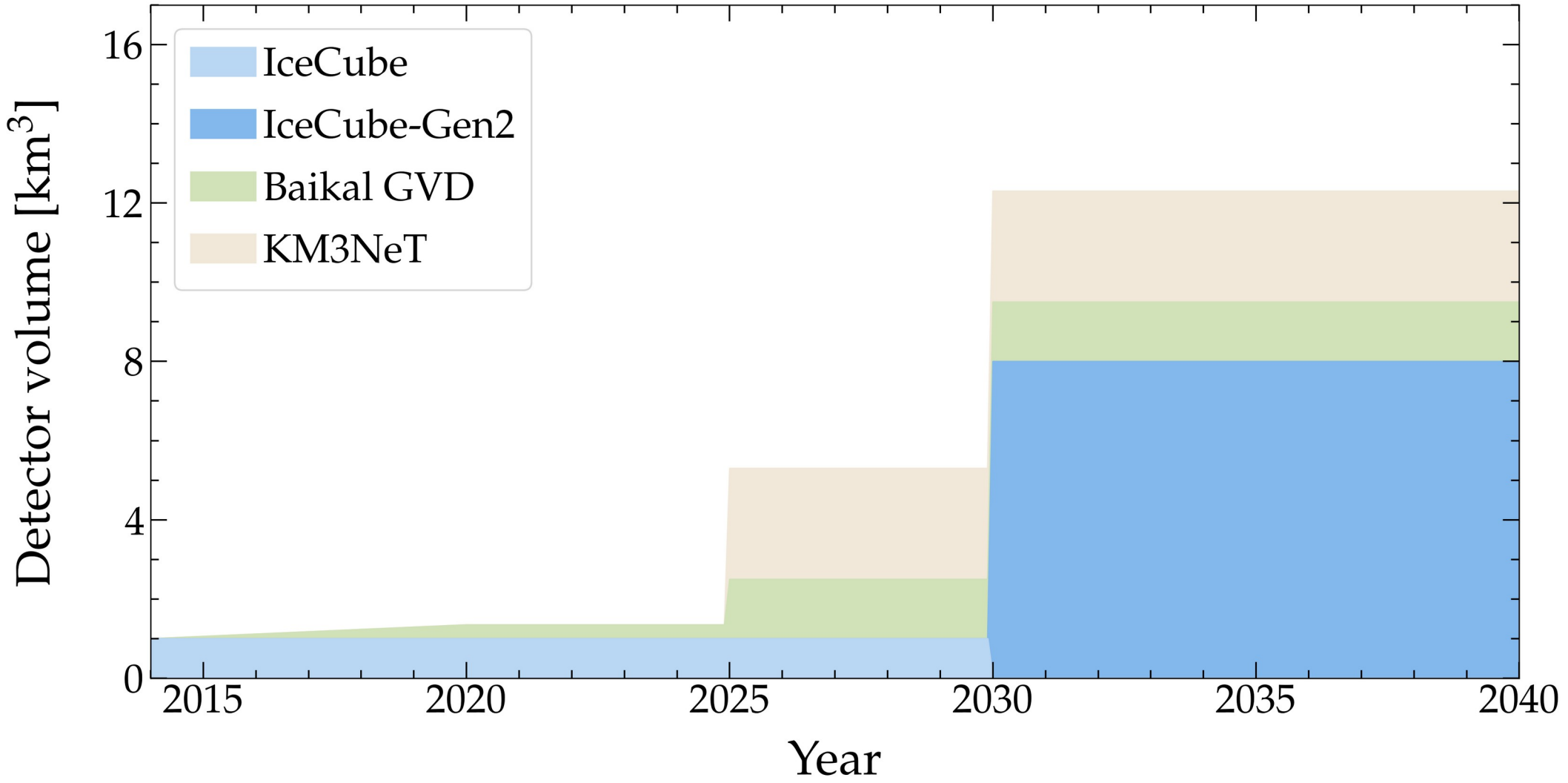
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



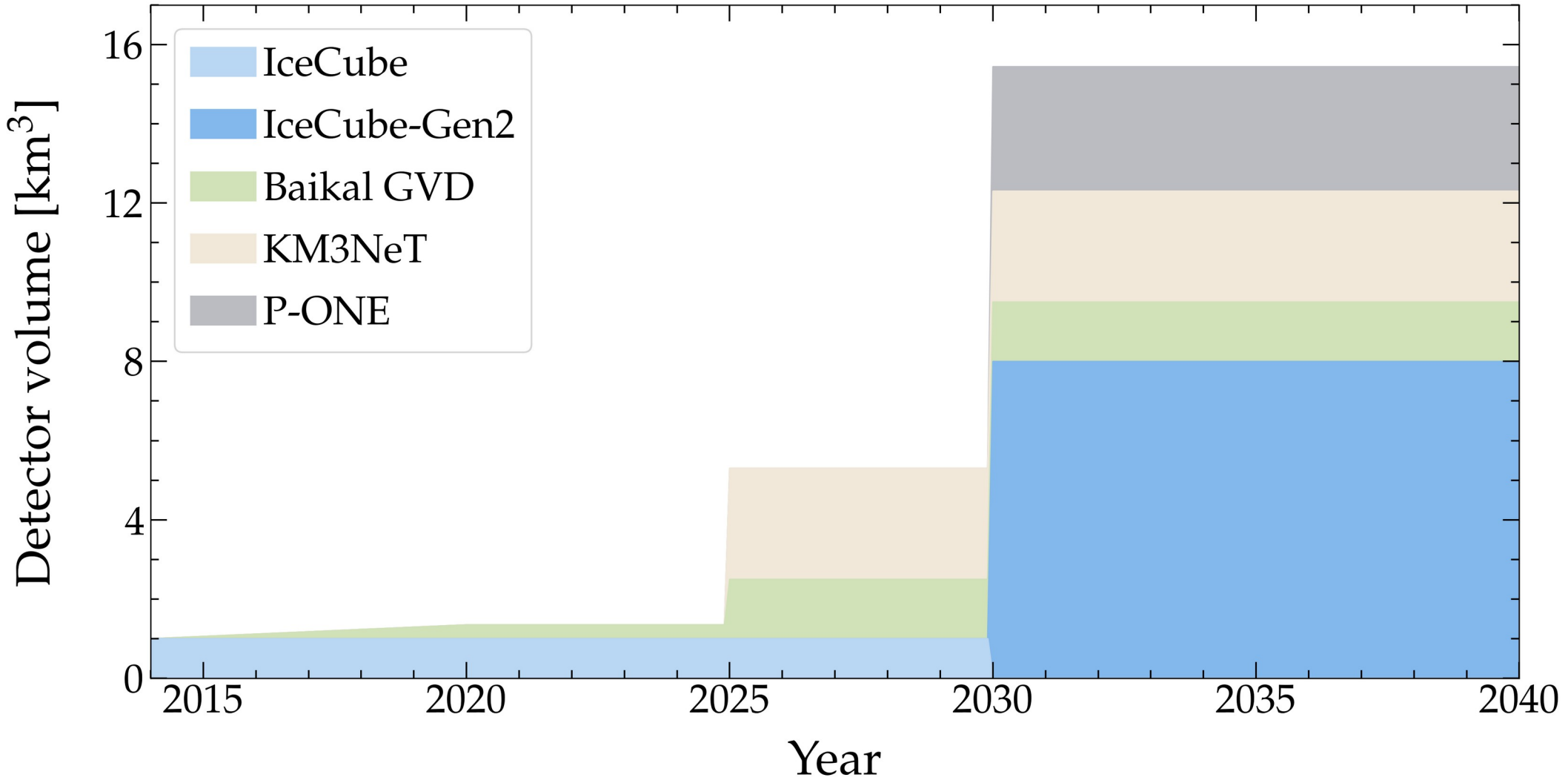
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



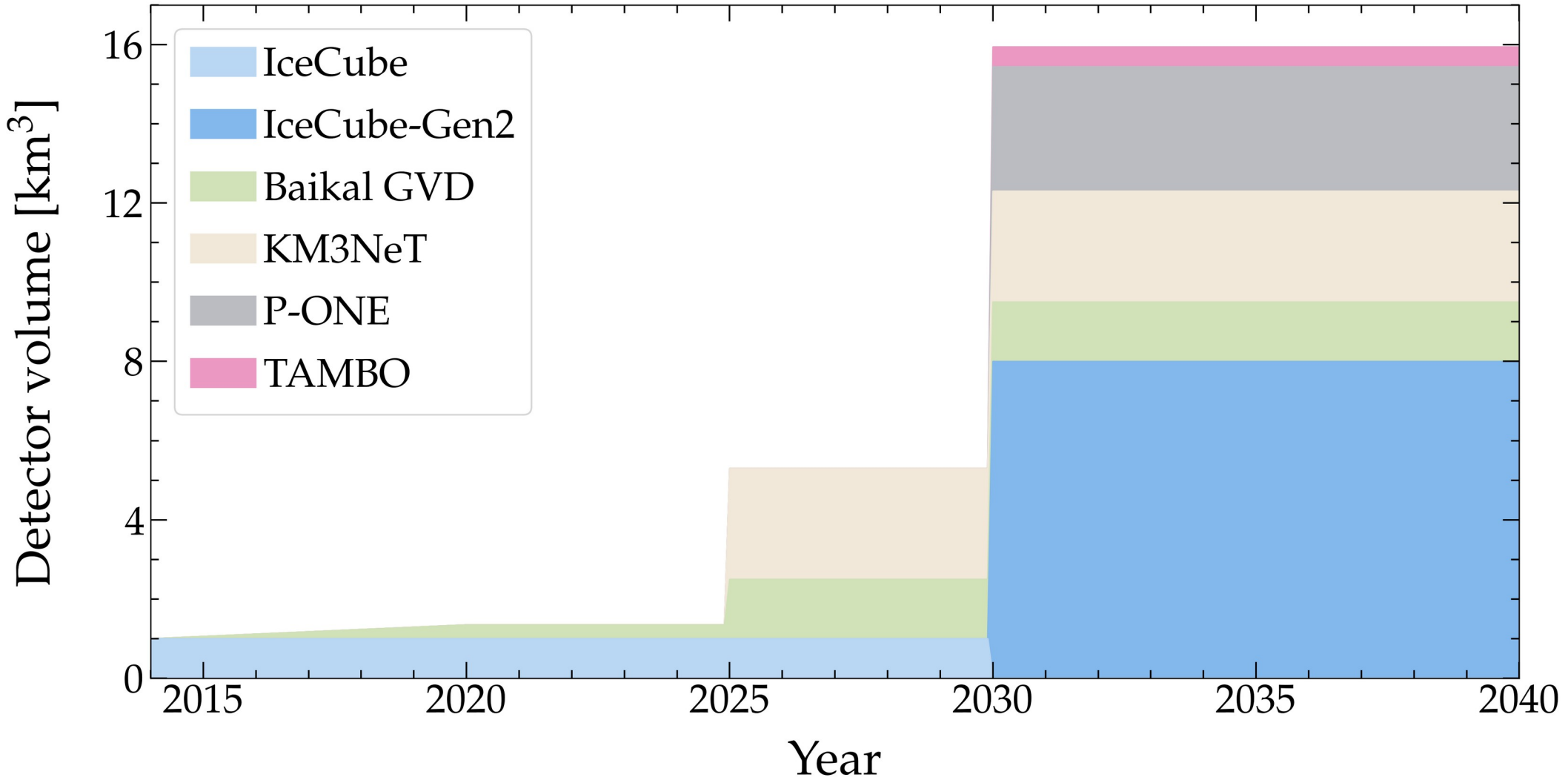
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



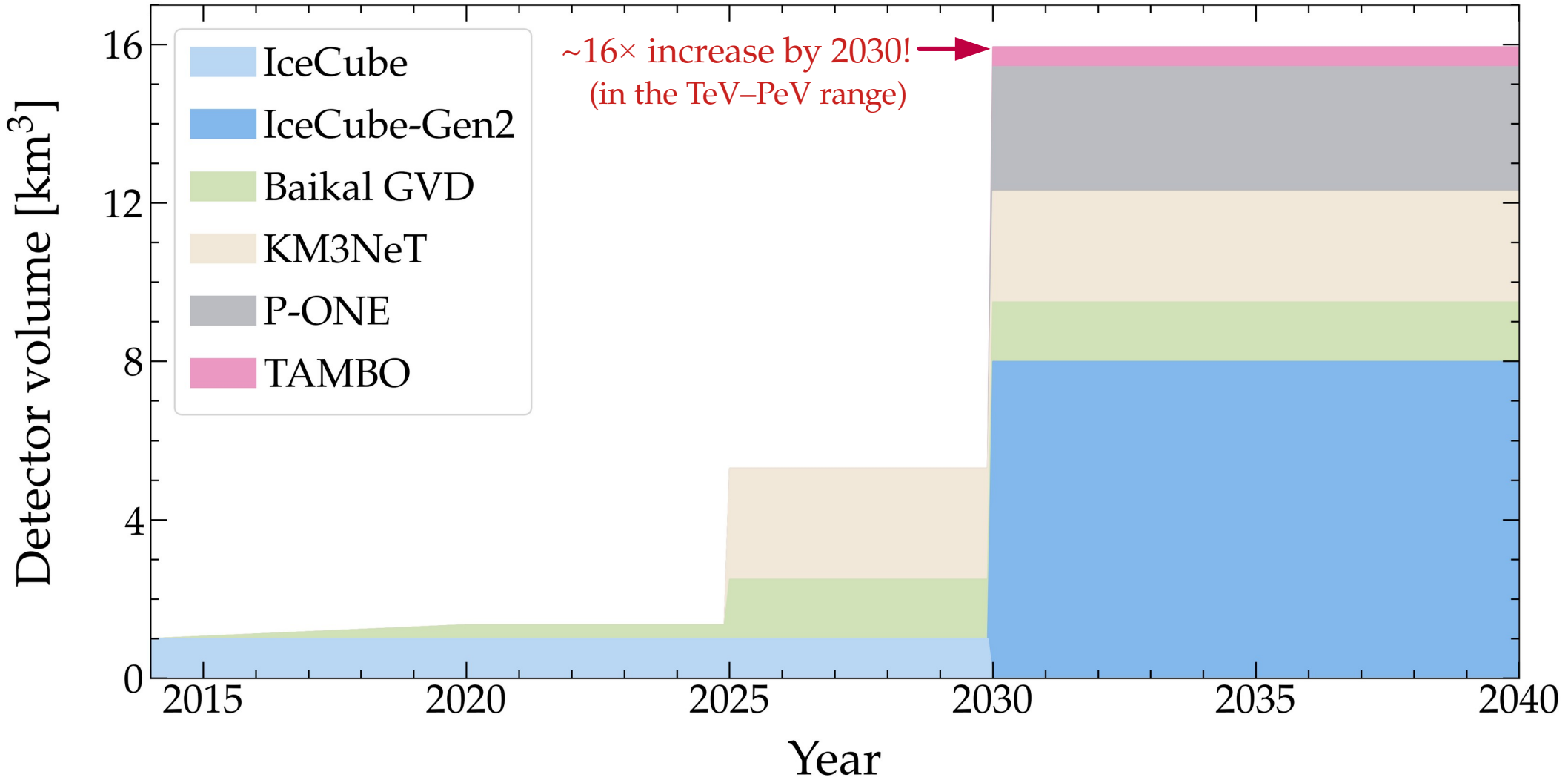
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



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



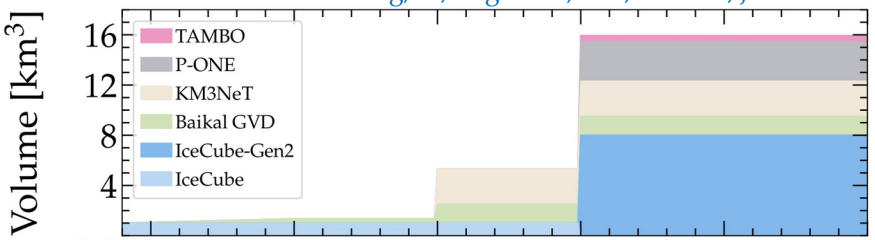
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

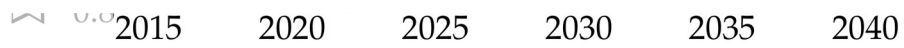


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

TAMBO astro case #3: flavor composition

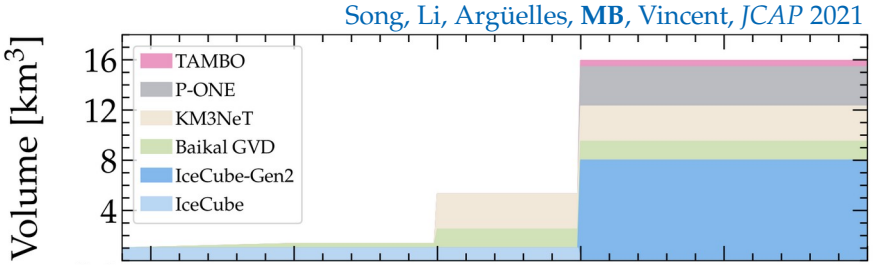
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

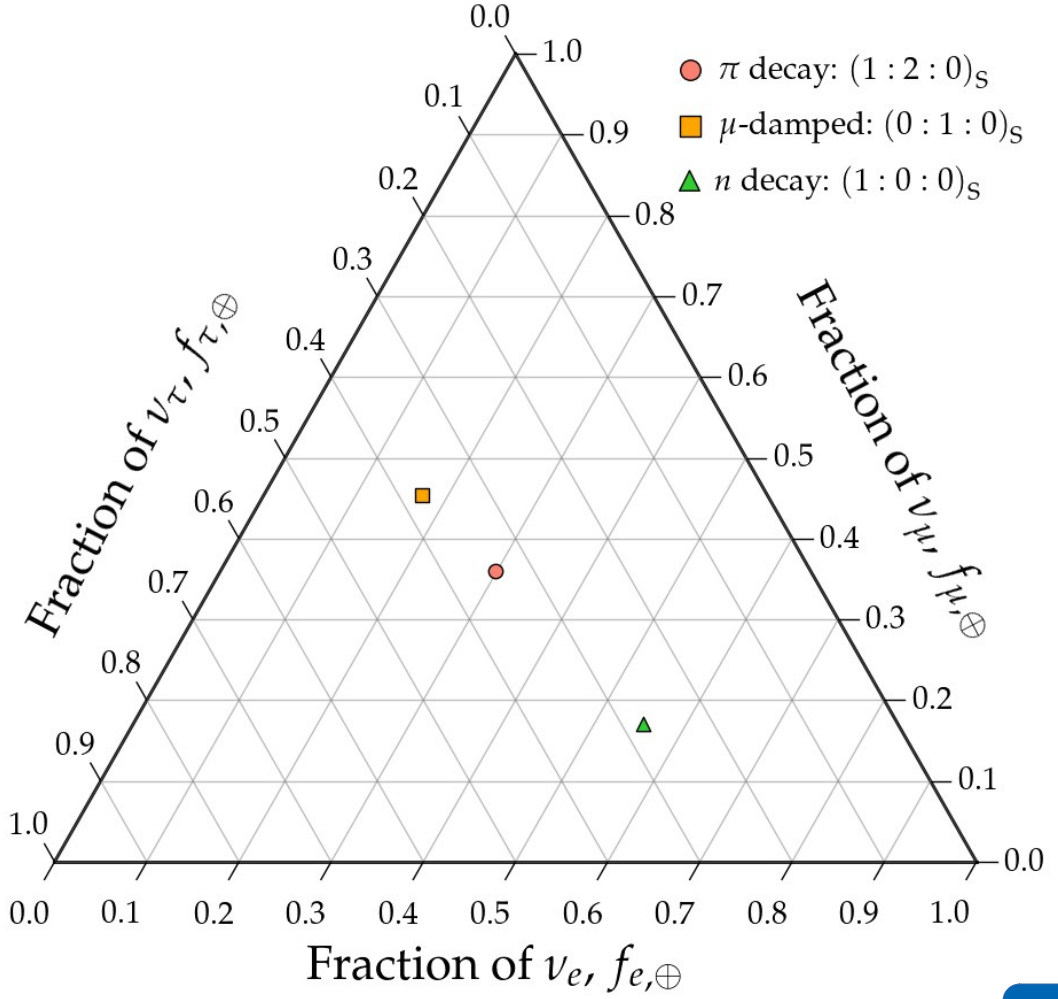




TAMBO astro case #3: flavor composition

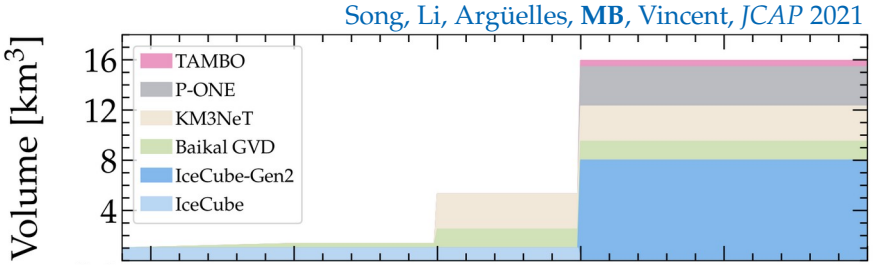
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

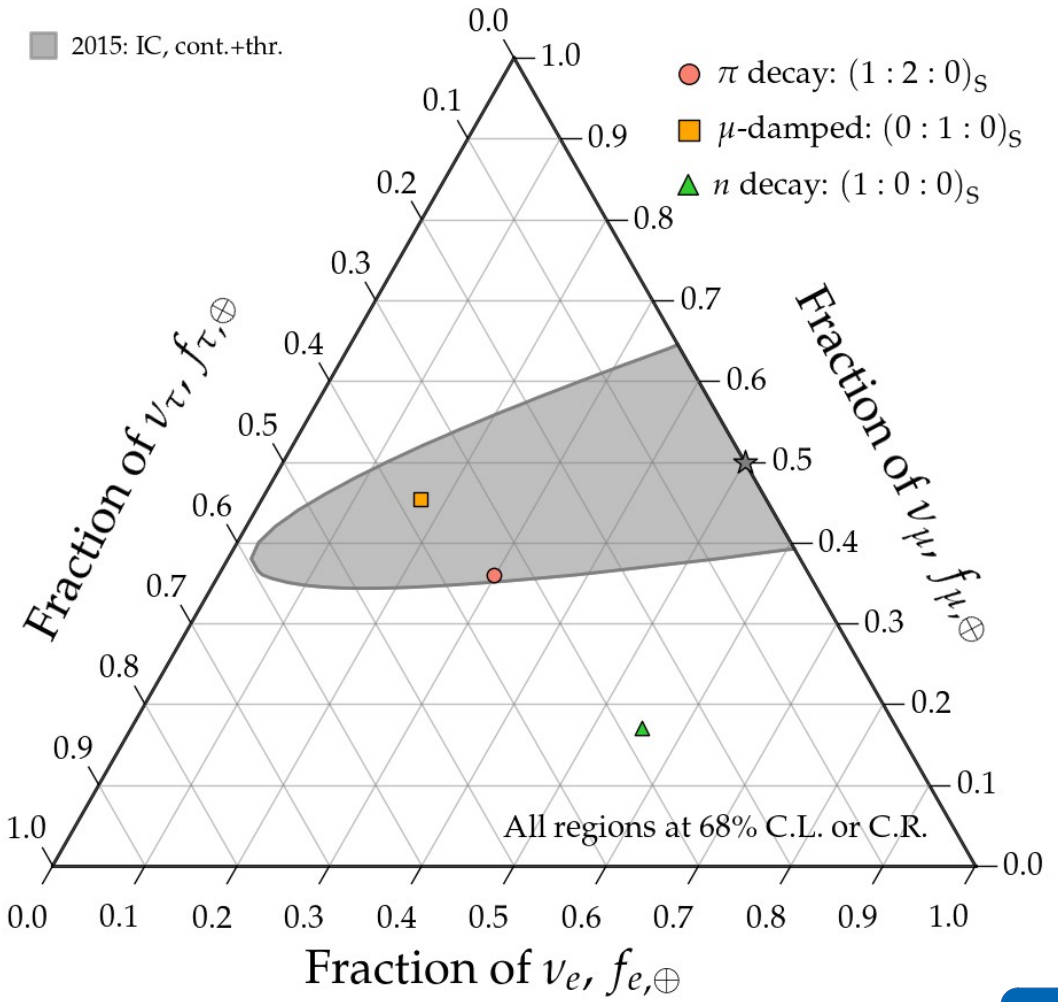




TAMBO astro case #3: flavor composition

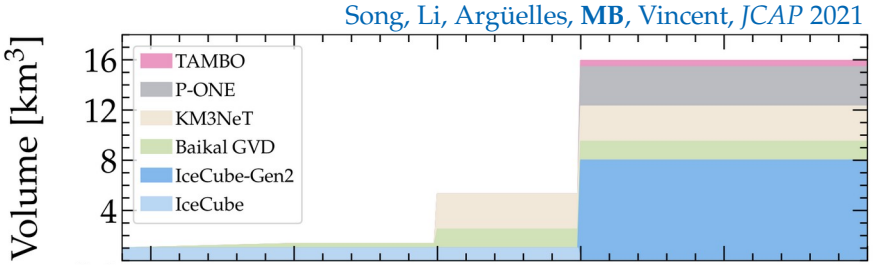
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

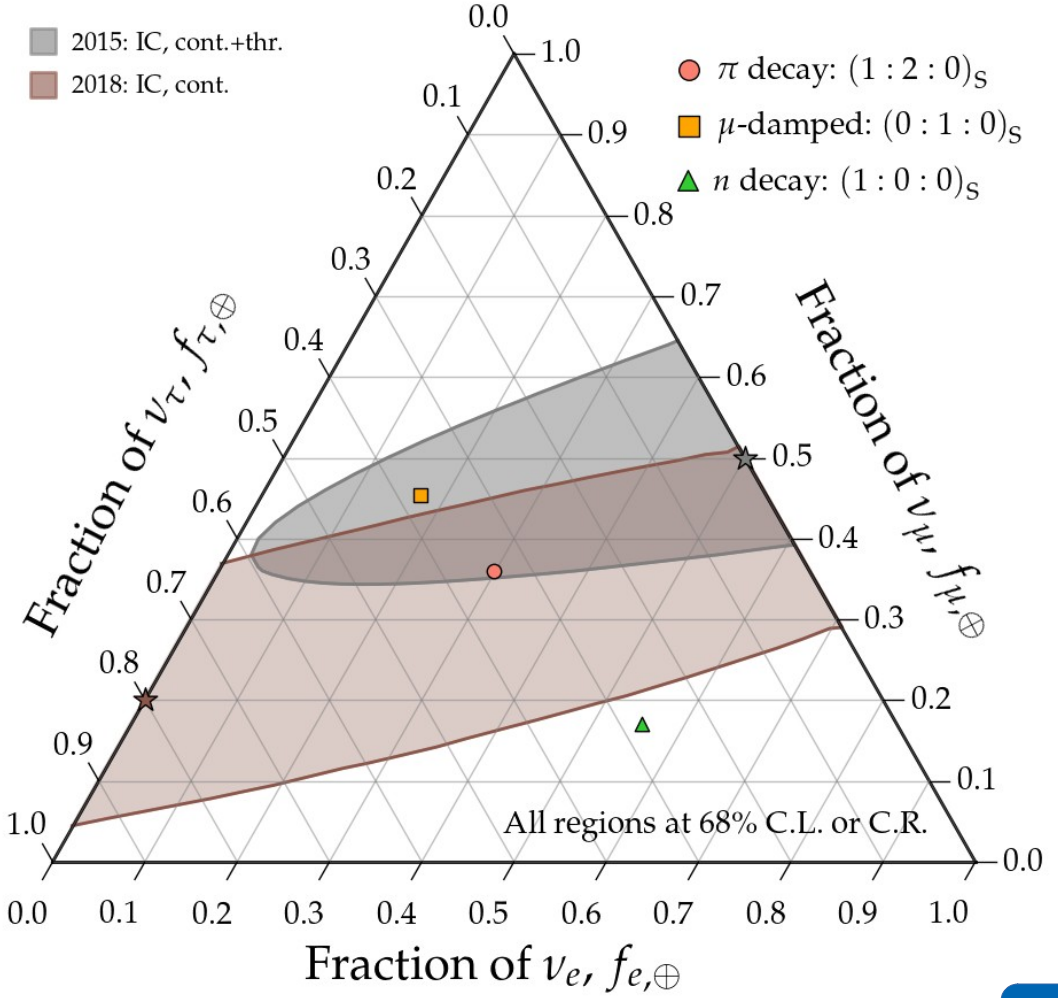




TAMBO astro case #3: flavor composition

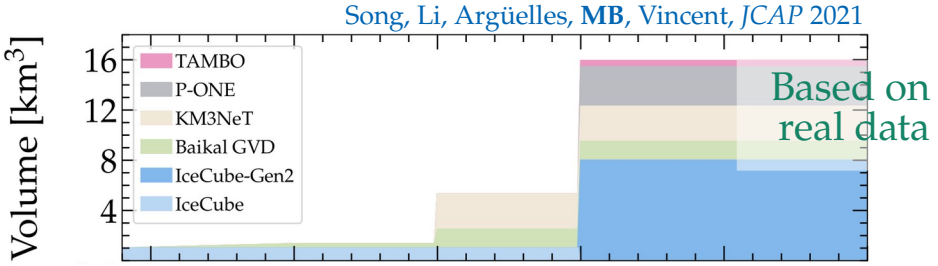
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

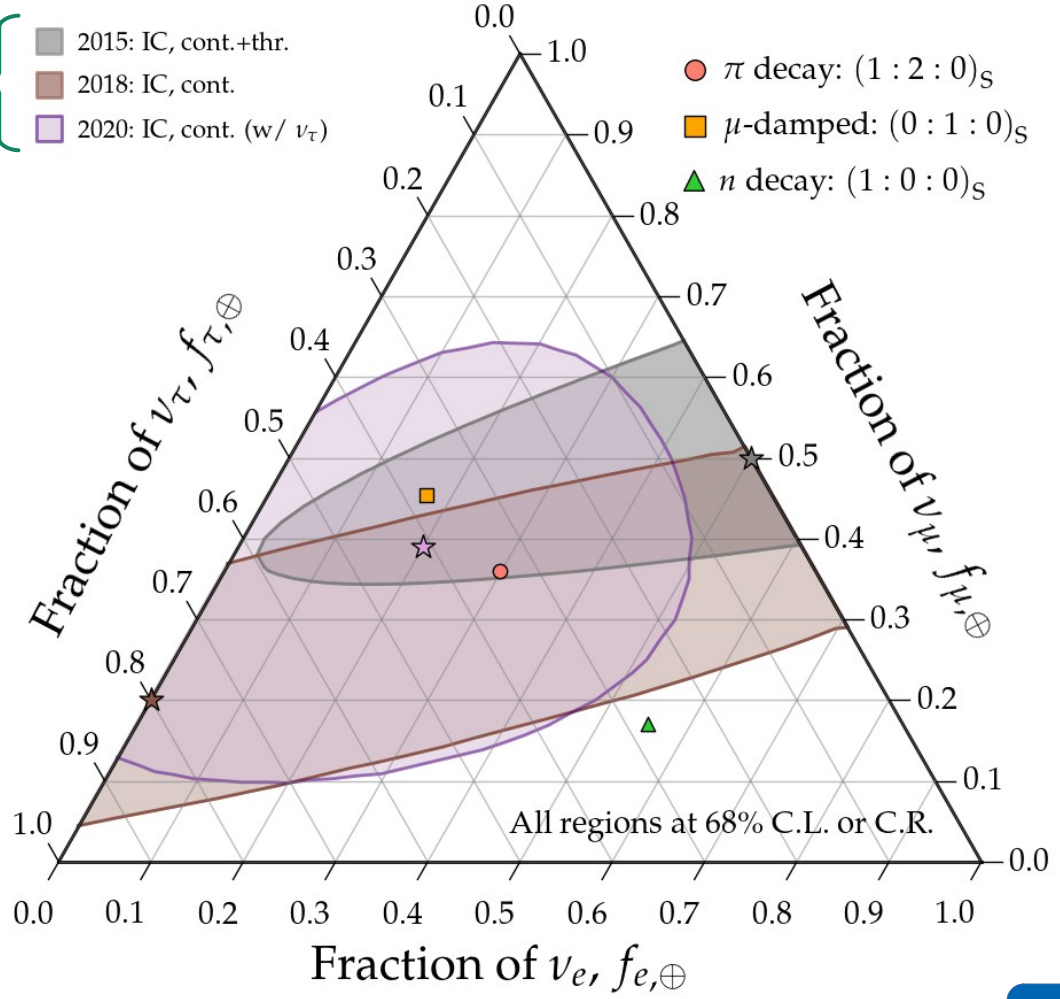




TAMBO astro case #3: flavor composition

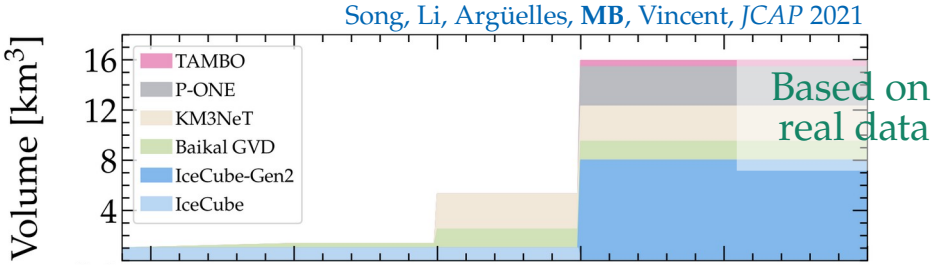
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

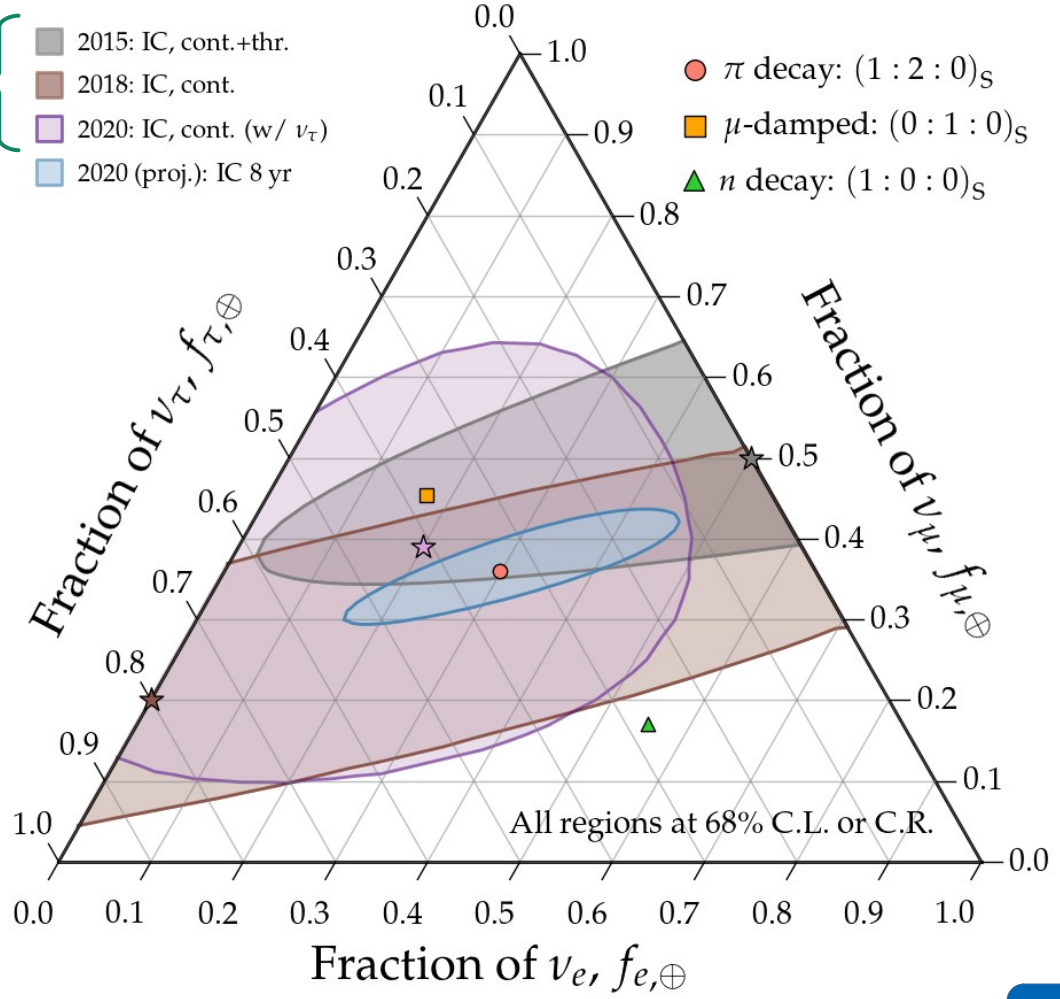




TAMBO astro case #3: flavor composition

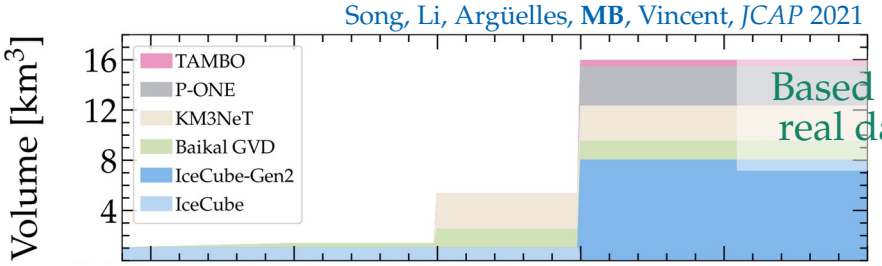
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

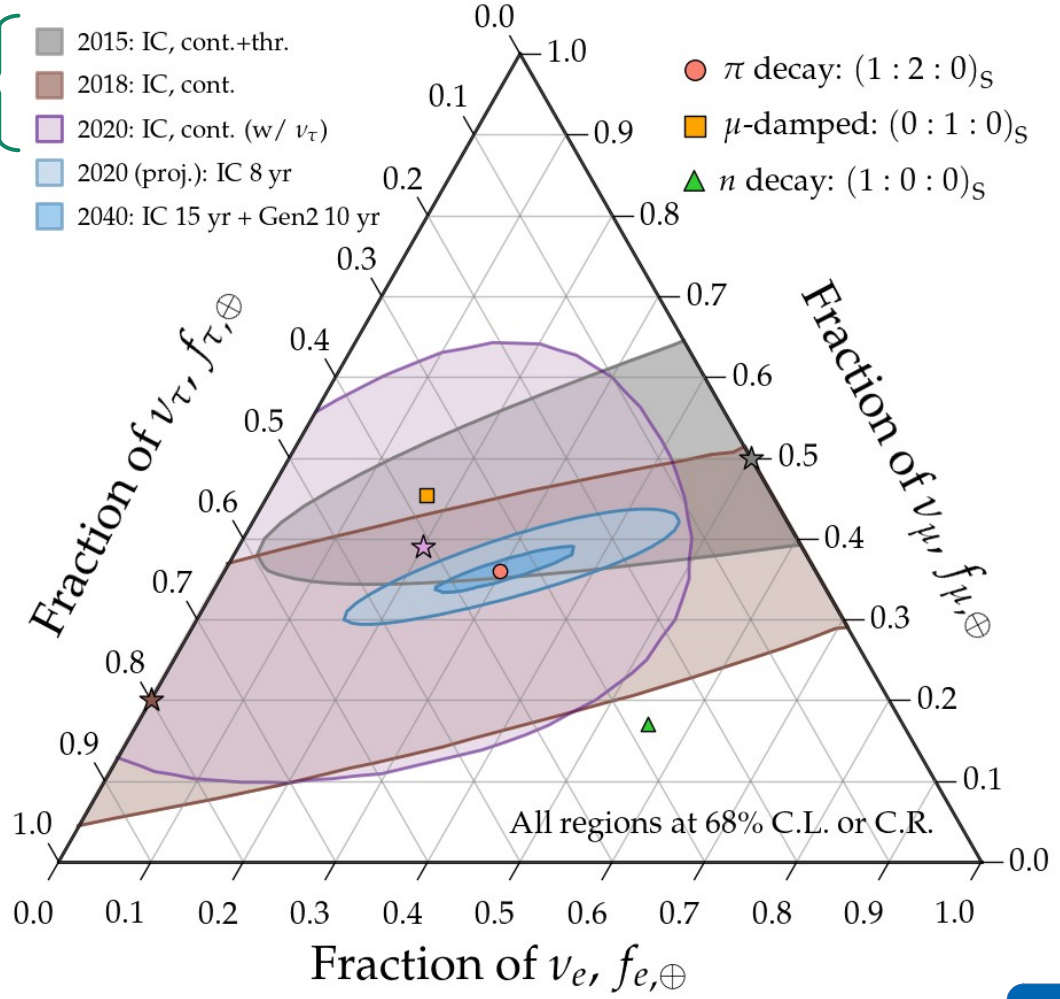




TAMBO astro case #3: flavor composition

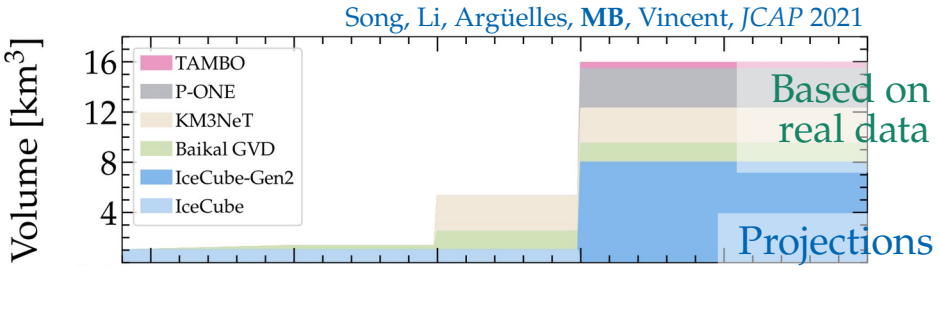
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

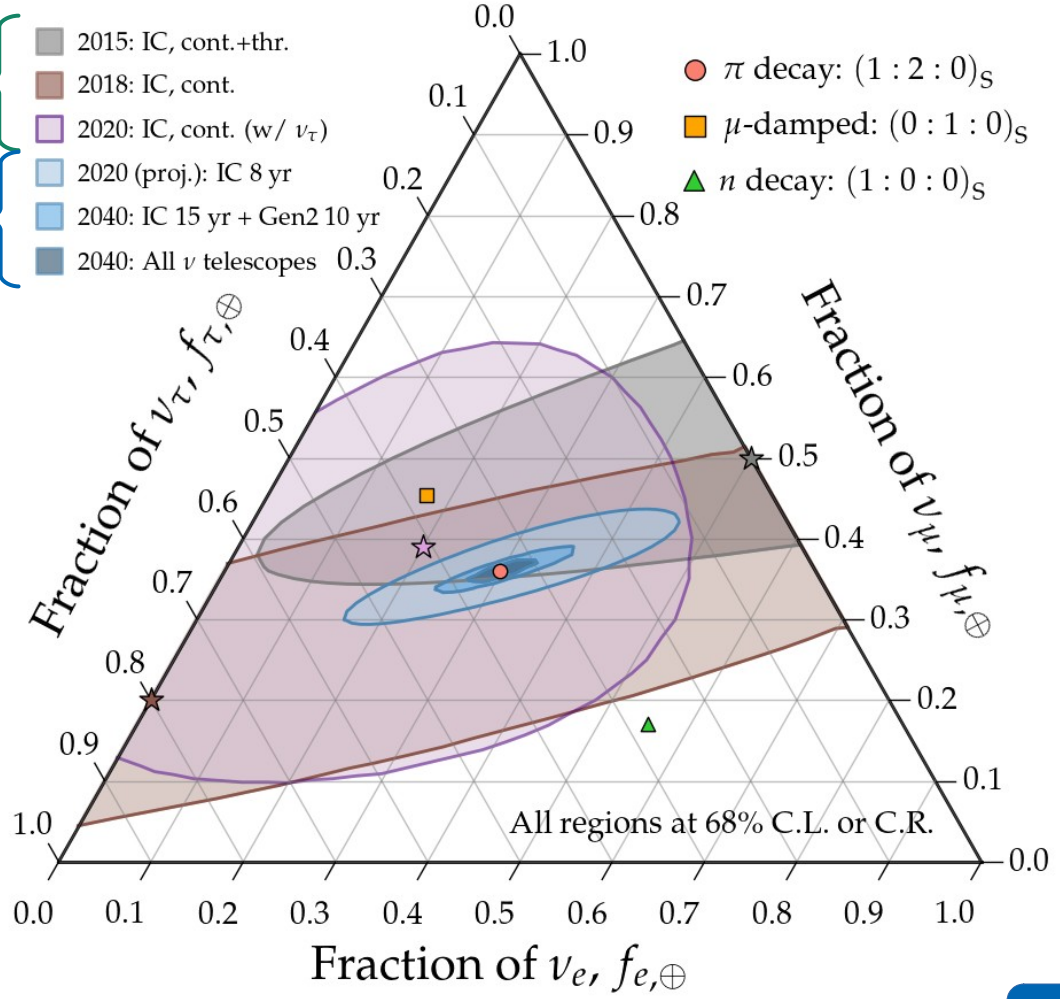




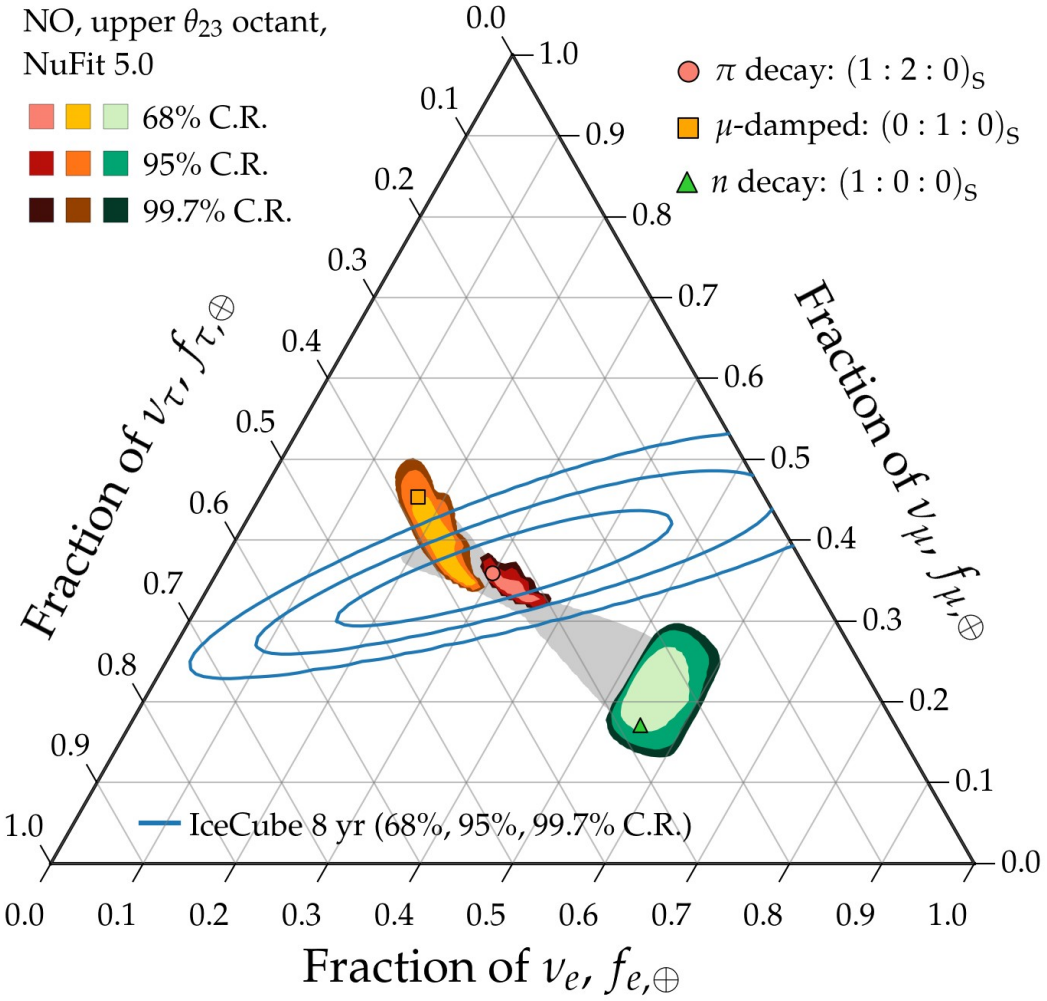
TAMBO astro case #3: flavor composition

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





TAMBO astro case #3: flavor composition



Two limitations:

Allowed flavor regions overlap – Insufficient precision in the mixing parameters

Will be overcome by 2030

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

Will be overcome by 2040

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

What do we need to define about TAMBO?

We need these to gear the preceding predictions to TAMBO:

- Energy range where it is sensitive
- Effective volume
- Benchmark energy and angular resolution
- Benchmark event rates

With them, we can assess the position of TAMBO as the bridge between PeV and EeV neutrinos

End

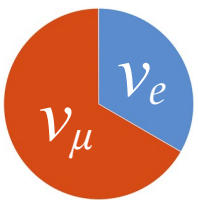
Backup slides

Astrophysical sources

Earth

Up to a few Gpc

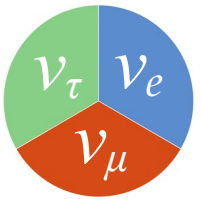
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



Different production mechanisms yield different flavor ratios:

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

Flavor ratios at Earth (α = e, μ, τ):

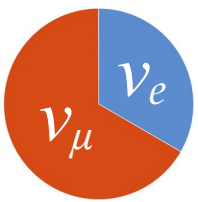
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$$

Astrophysical sources

Earth

Up to a few Gpc

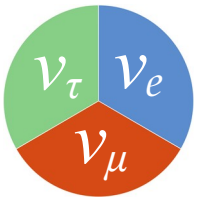
E.g.,



Oscillations change the number

of ν of each flavor, N_e, N_μ, N_τ

E.g.,



Different production mechanisms yield different flavor ratios:

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

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

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

Standard oscillations
or
new physics

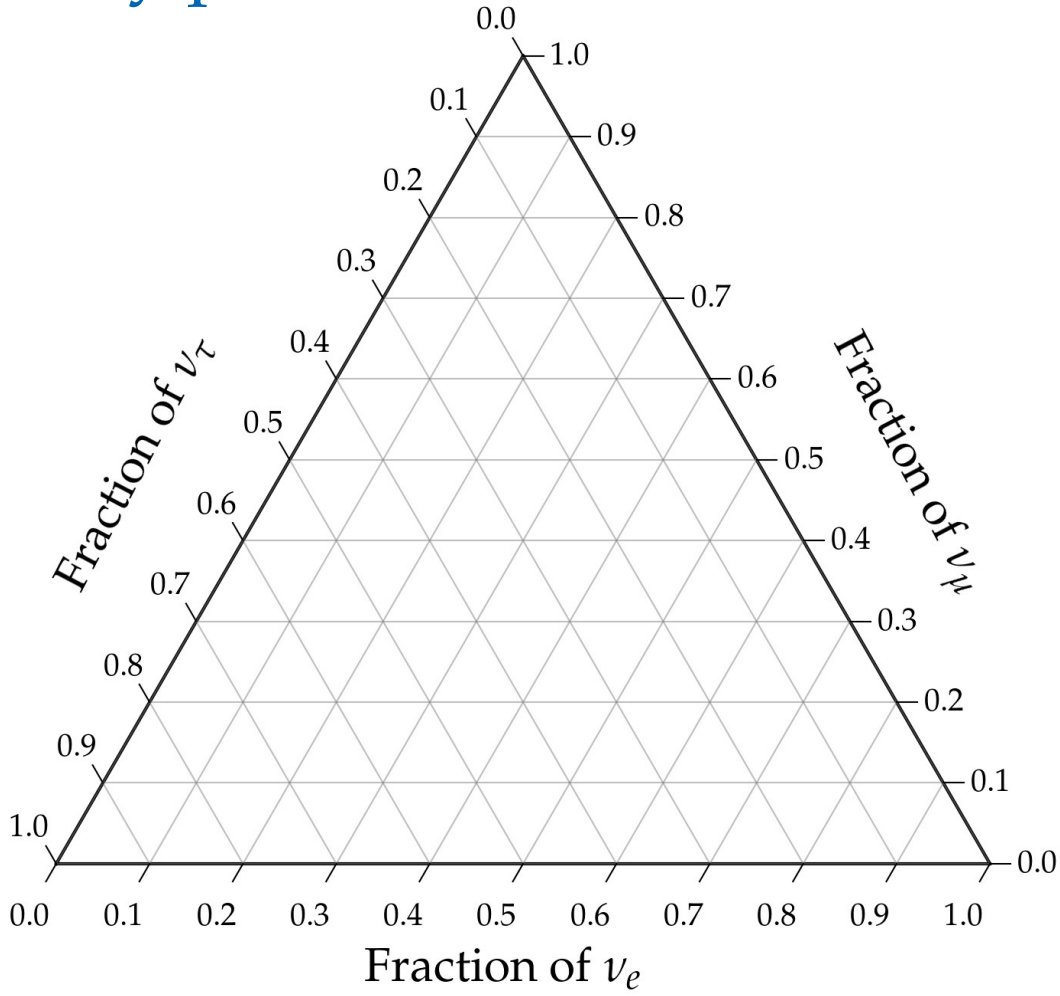
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



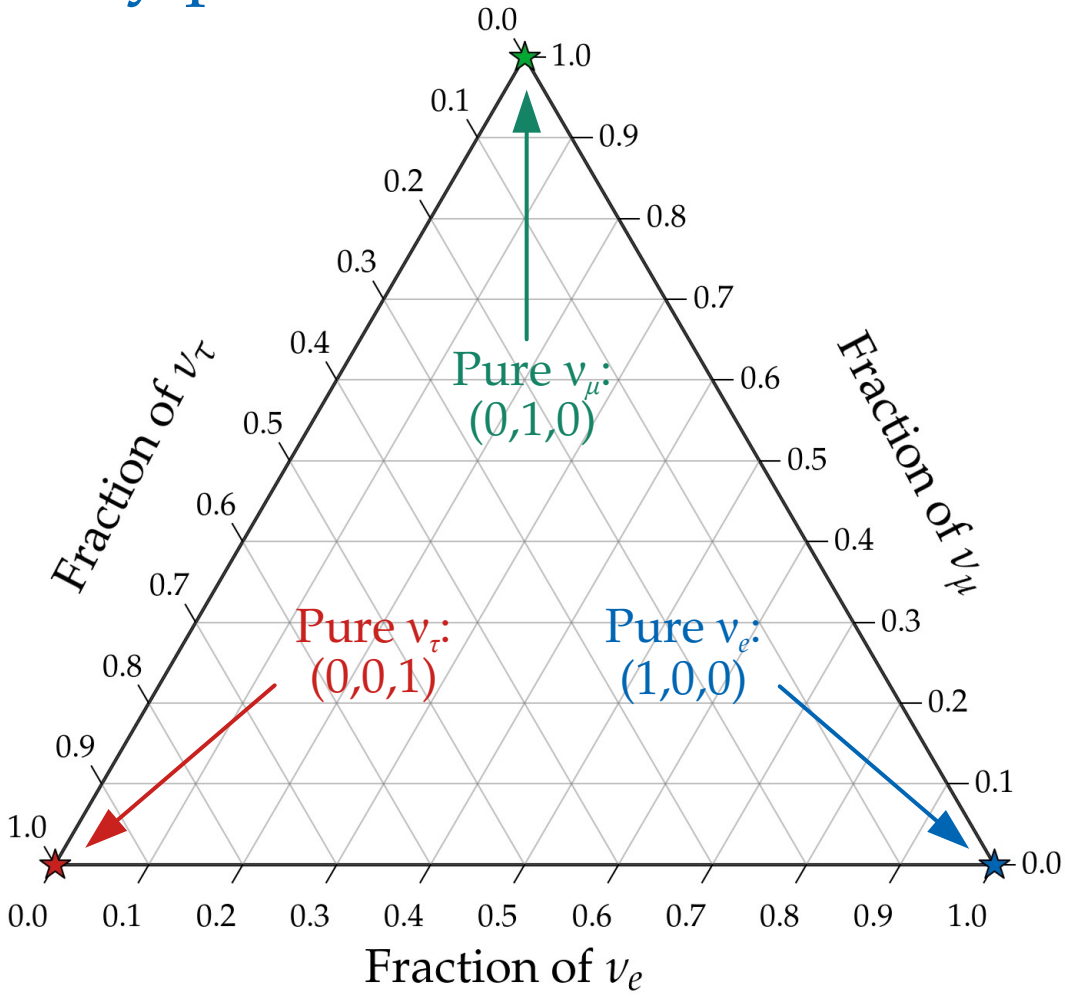
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



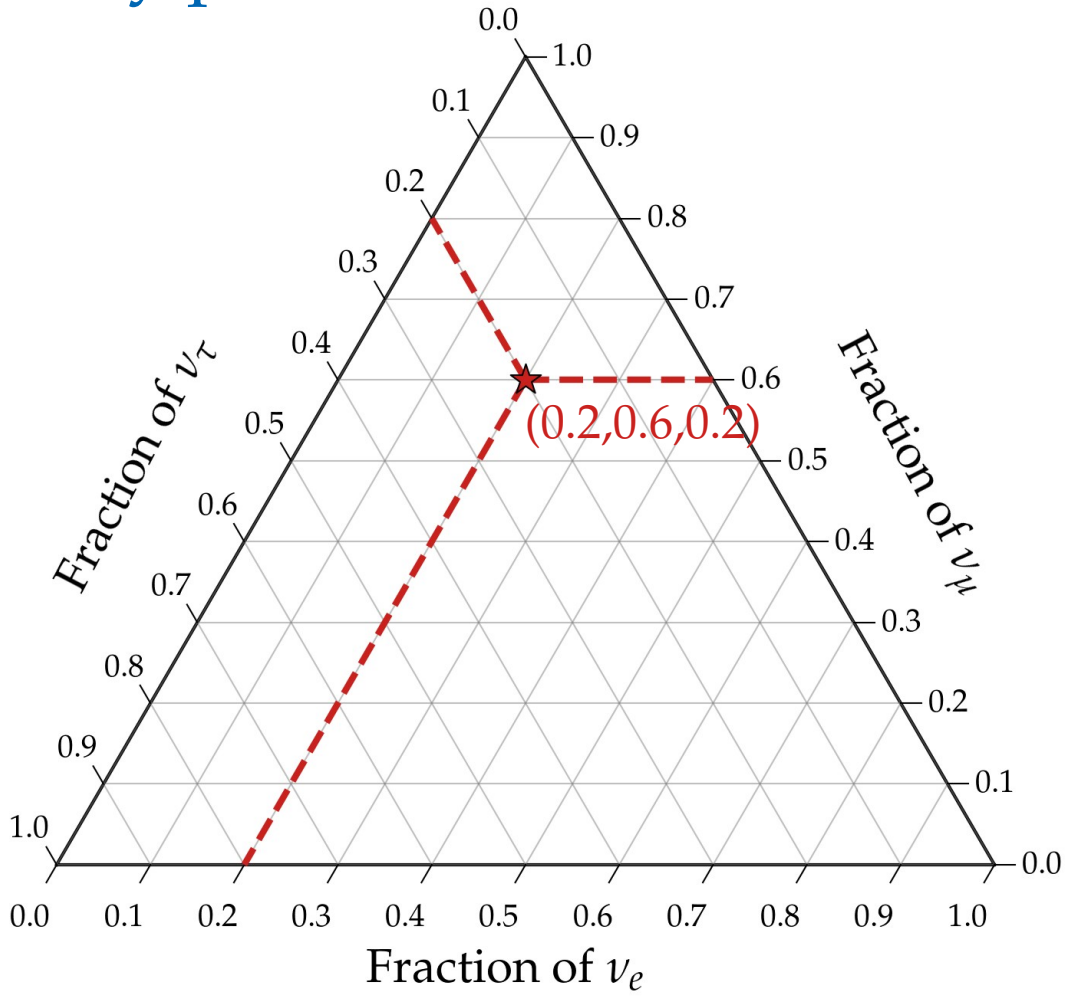
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



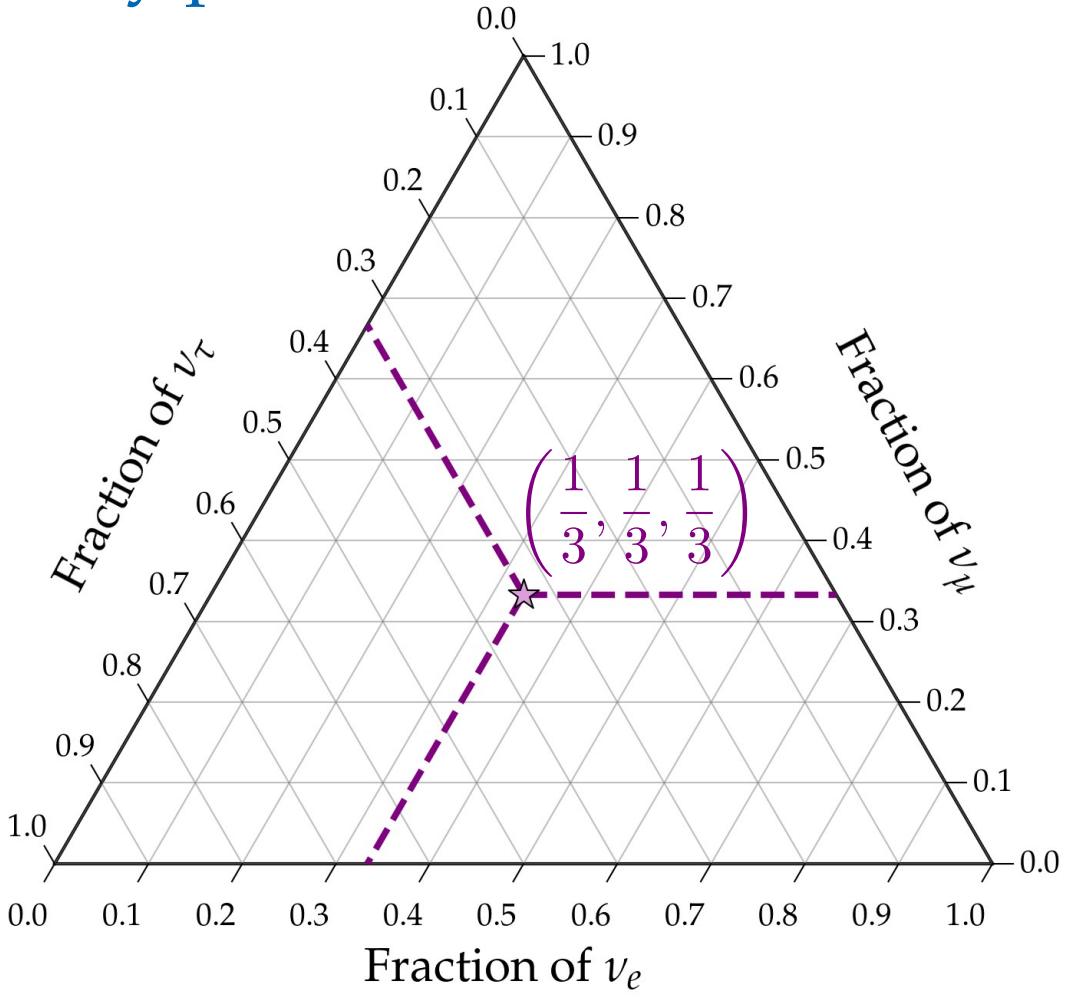
Quick aside: how to read a ternary plot

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

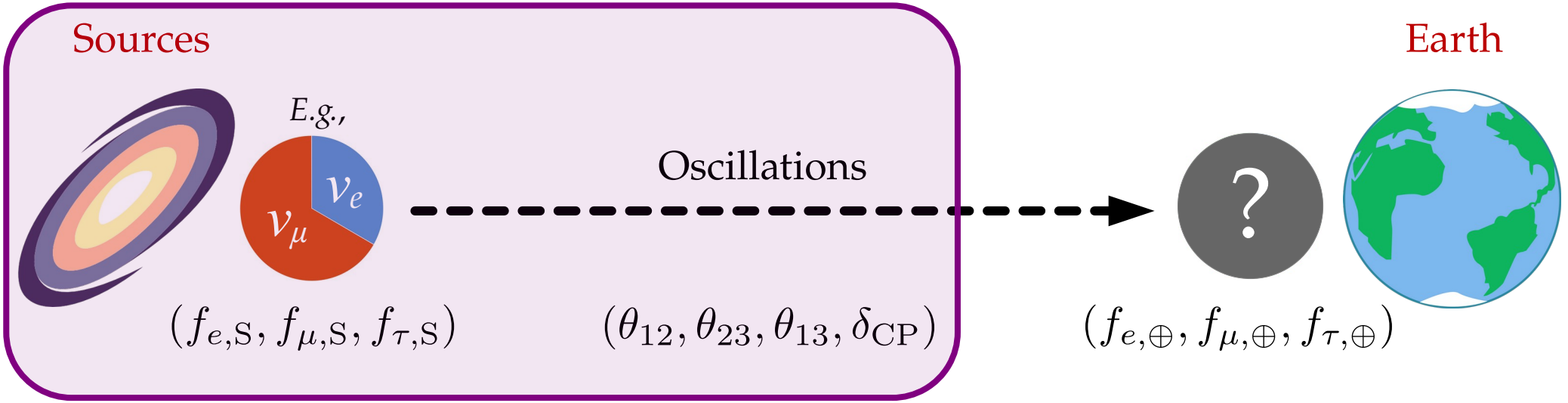
How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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



One likely TeV–PeV ν production scenario:

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

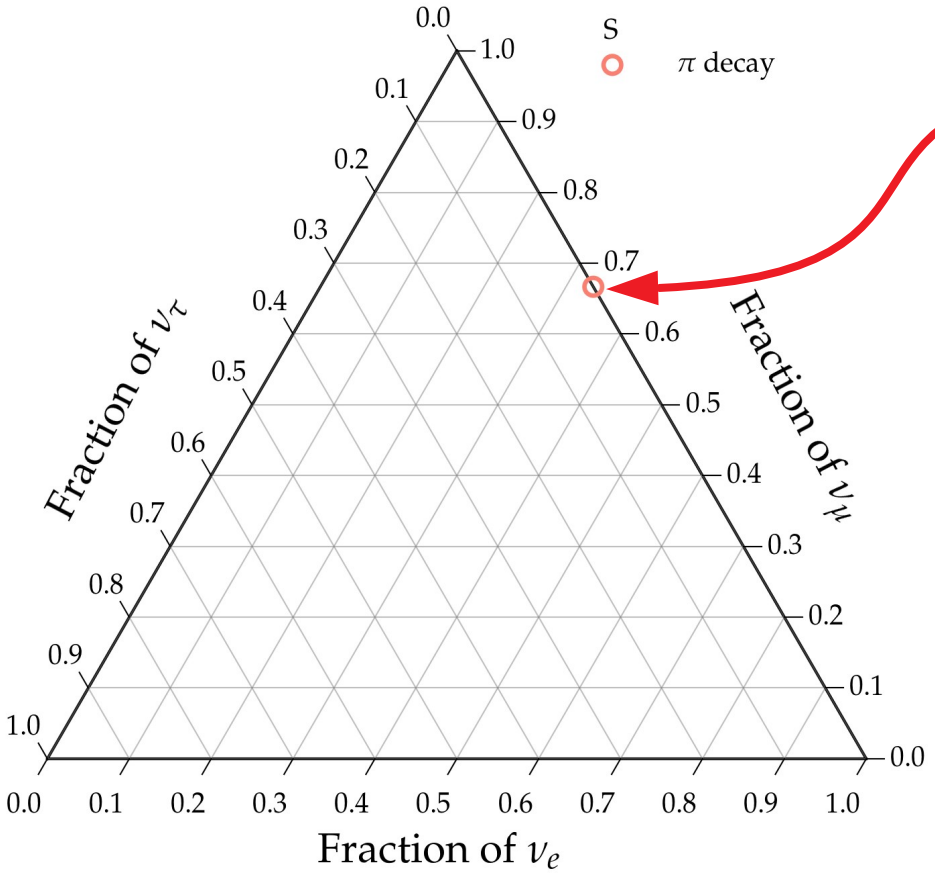
Full π decay chain

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

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



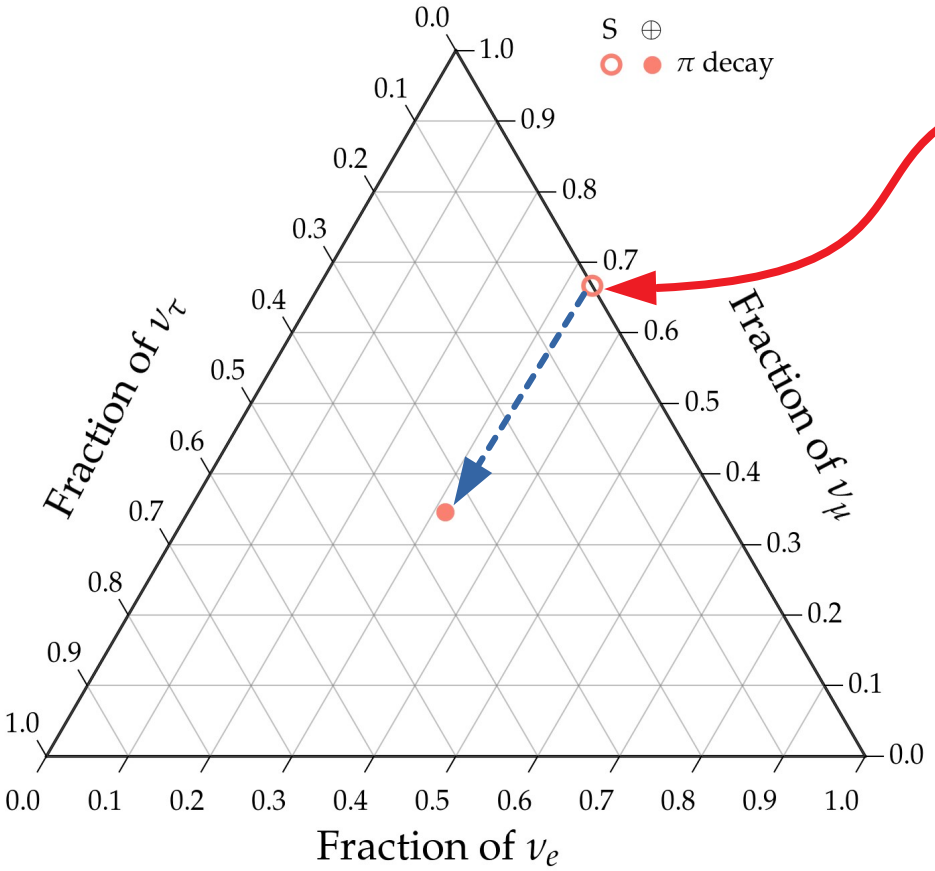
Full π decay chain

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

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



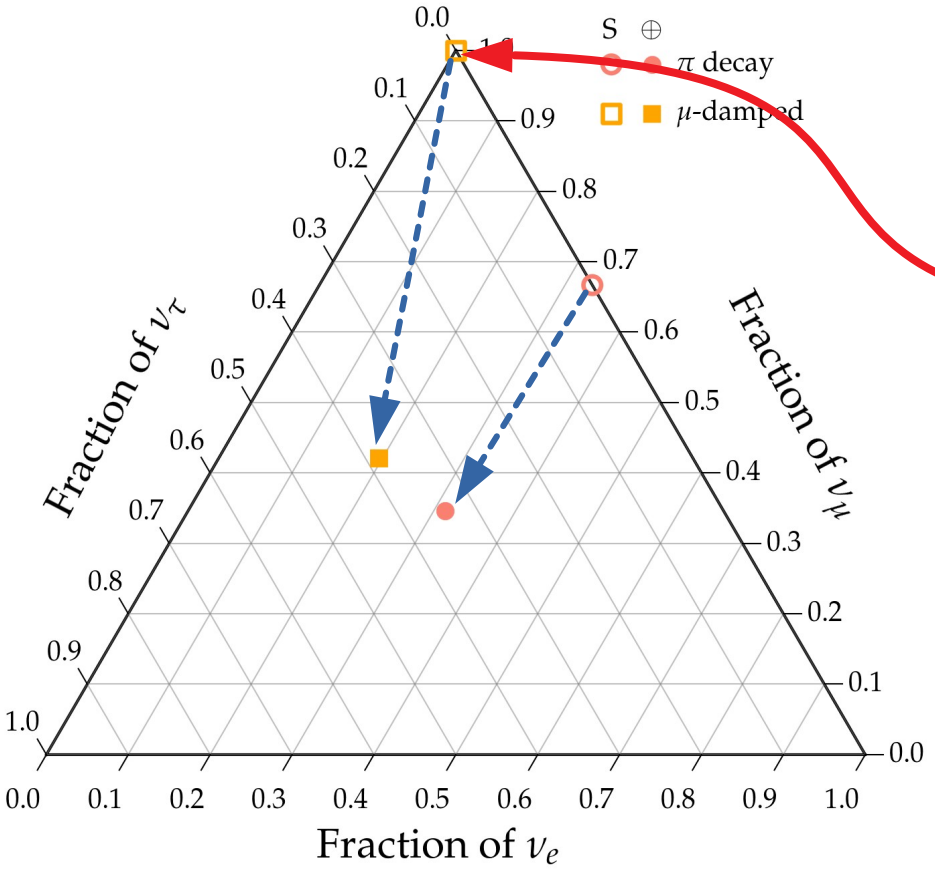
Full π decay chain

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

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



Full π decay chain

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

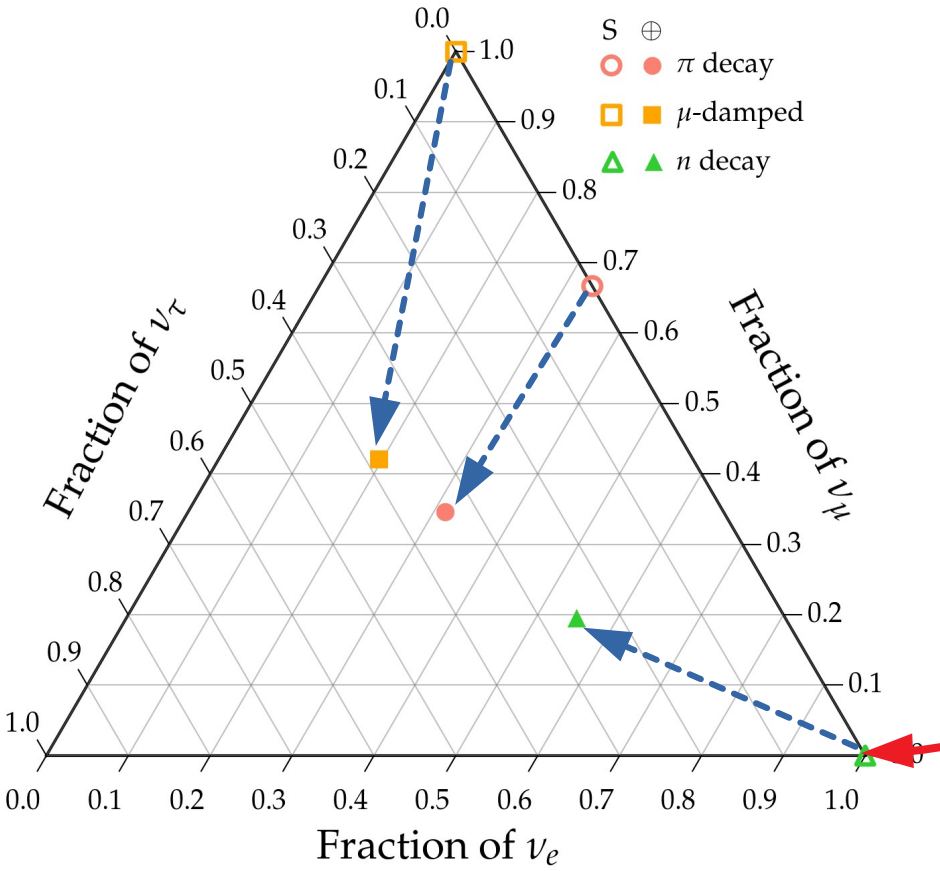
Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

Muon damped

$(0{:}1{:}0)_S$

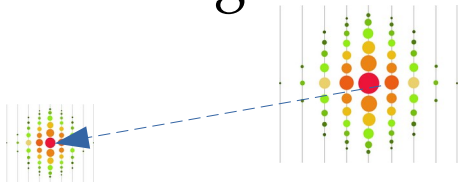
Neutron decay

$(1{:}0{:}0)_S$

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

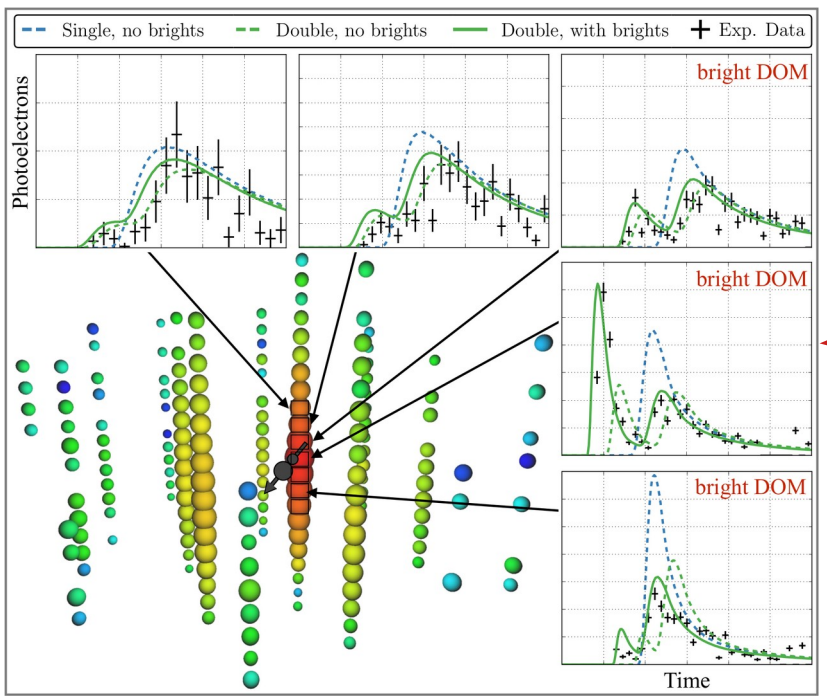
First identified high-energy astrophysical ν_τ

Double bang:

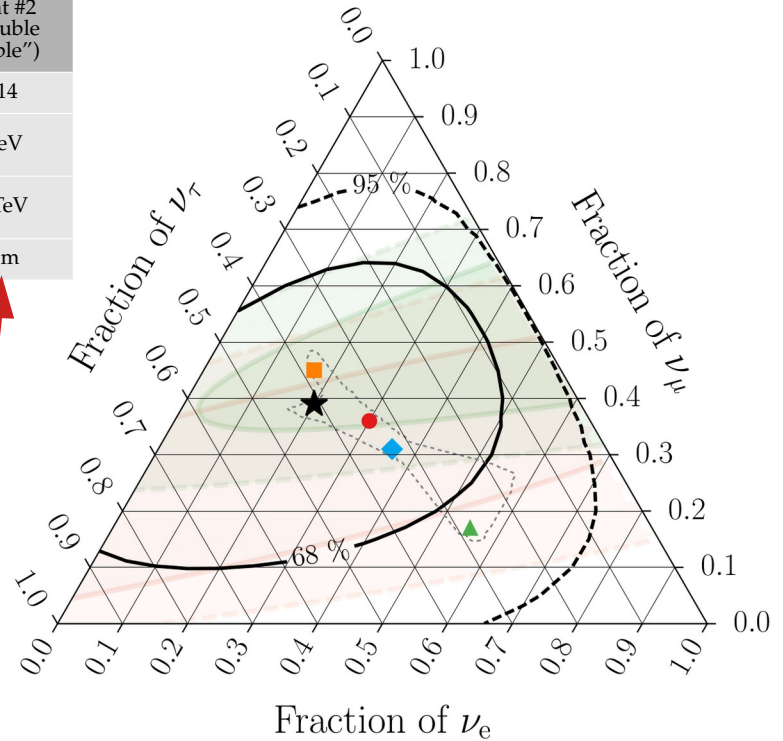


τ decay $\quad$ $\nu_\tau N$ scattering

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



Most likely to be a ν_τ



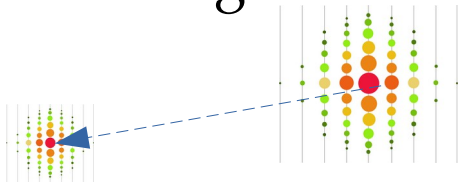
HESE with ternary topology ID
Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
Inelasticity (IceCube, PRD 2019)
3ν-mixing 3σ allowed region

$\nu_e : \nu_\mu : \nu_\tau$ at source $\rightarrow$ on Earth:
0:1:0 $\rightarrow$ 0.17 : 0.45 : 0.37
1:2:0 $\rightarrow$ 0.30 : 0.36 : 0.34
1:0:0 $\rightarrow$ 0.55 : 0.17 : 0.28
1:1:0 $\rightarrow$ 0.36 : 0.31 : 0.33

IceCube, 2011.03561

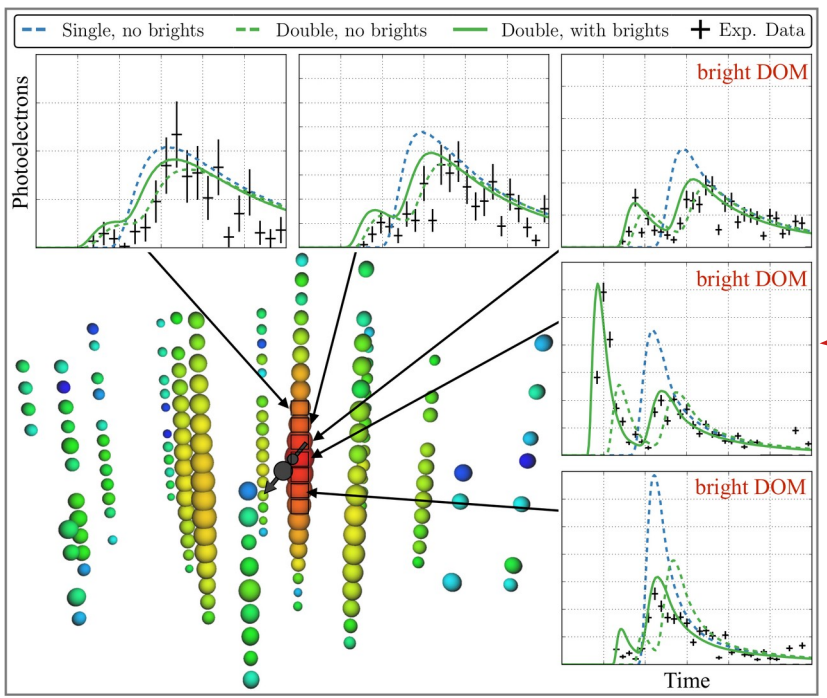
First identified high-energy astrophysical ν_τ

Double bang:

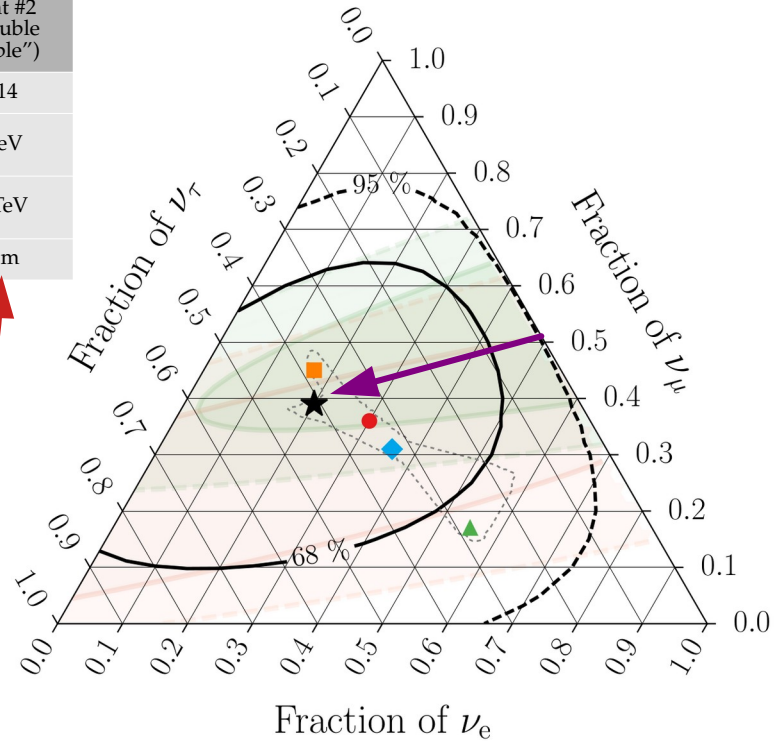


τ decay $\nu_\tau N$ scattering

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



Most likely to be a ν_τ



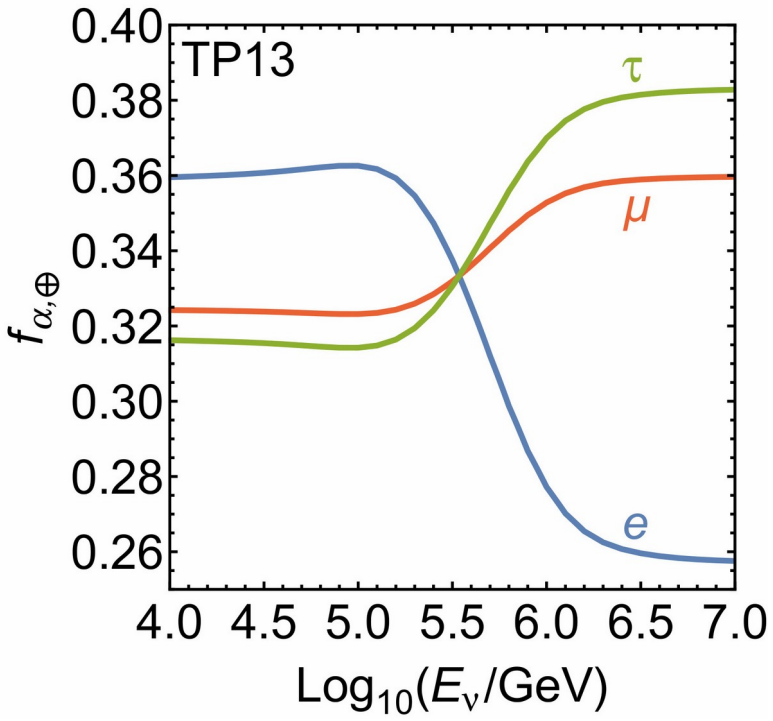
HESE with ternary topology ID
Best fit: 0.20 : 0.39 : 0.42
Global Fit (IceCube, APJ 2015)
Inelasticity (IceCube, PRD 2019)
3ν-mixing 3σ allowed region

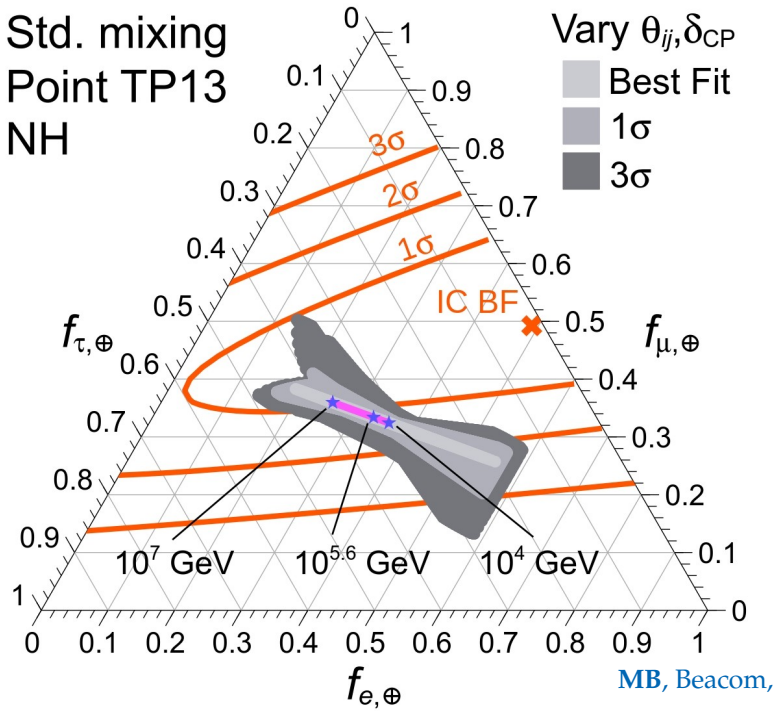
$\nu_e : \nu_\mu : \nu_\tau$ at source → on Earth:
0:1:0 → 0.17 : 0.45 : 0.37
1:2:0 → 0.30 : 0.36 : 0.34
1:0:0 → 0.55 : 0.17 : 0.28
1:1:0 → 0.36 : 0.31 : 0.33

IceCube, 2011.03561

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



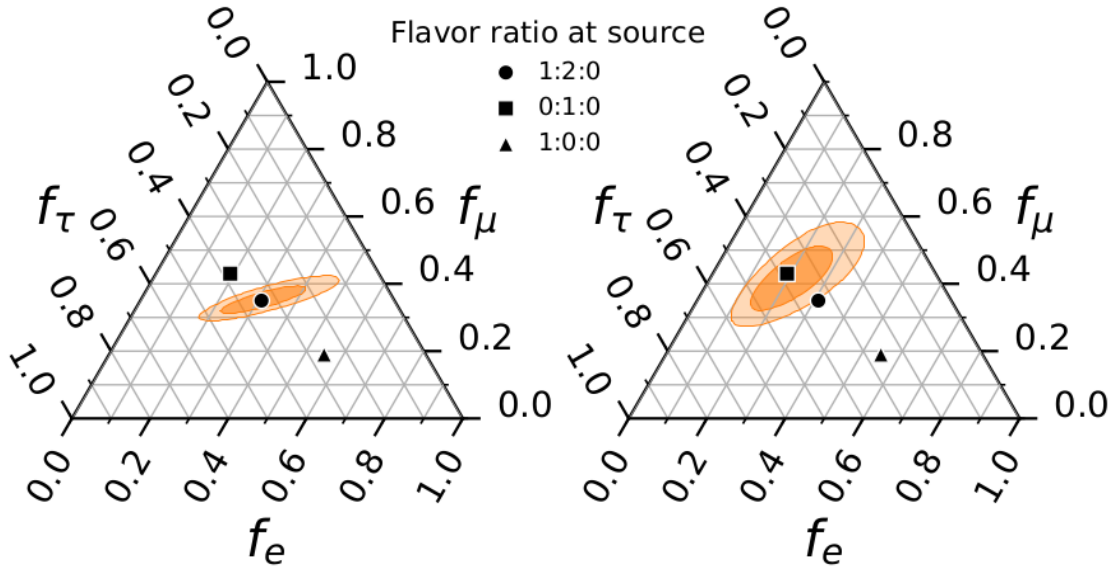


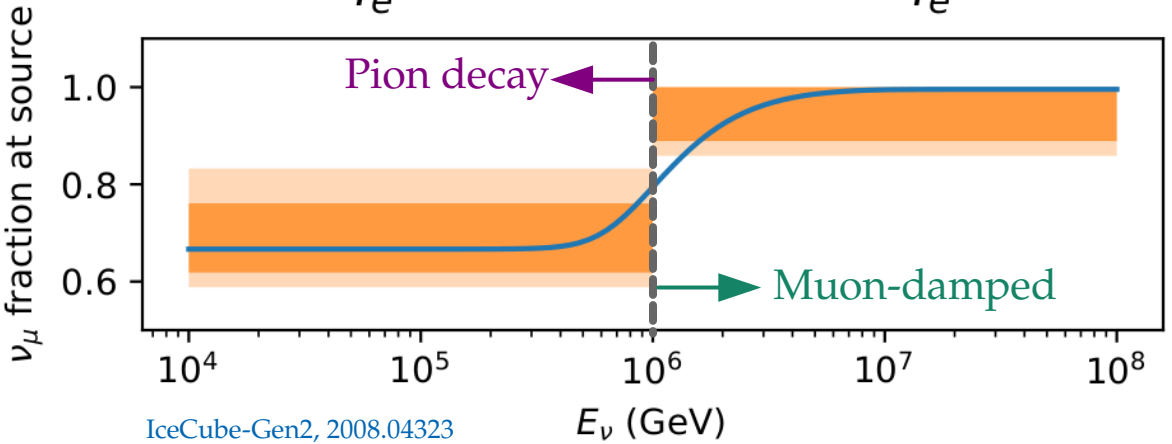
MB, Beacom, Winter, *PRL* 2015

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

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:

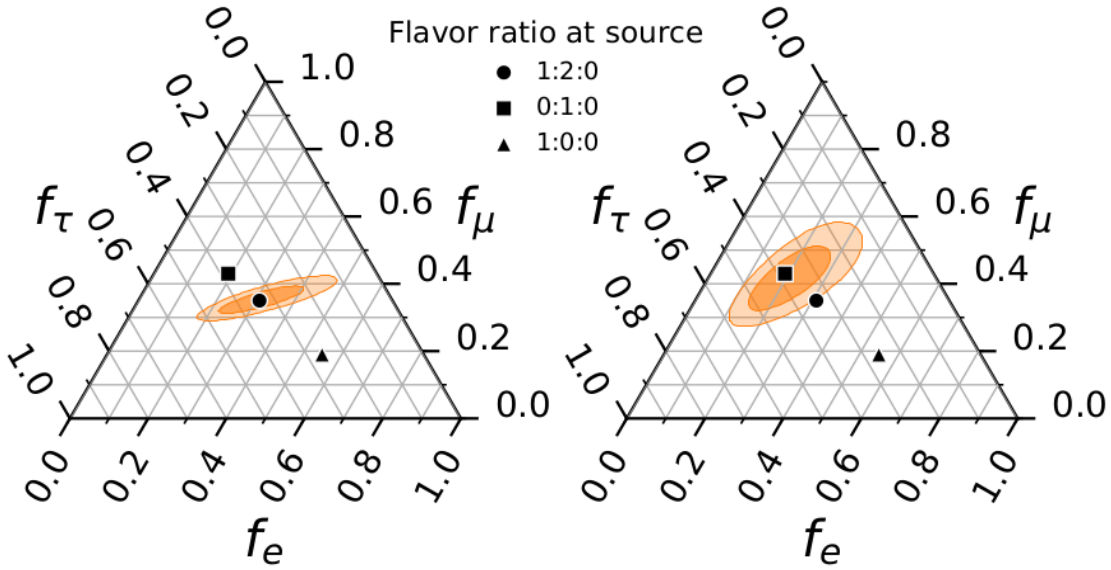


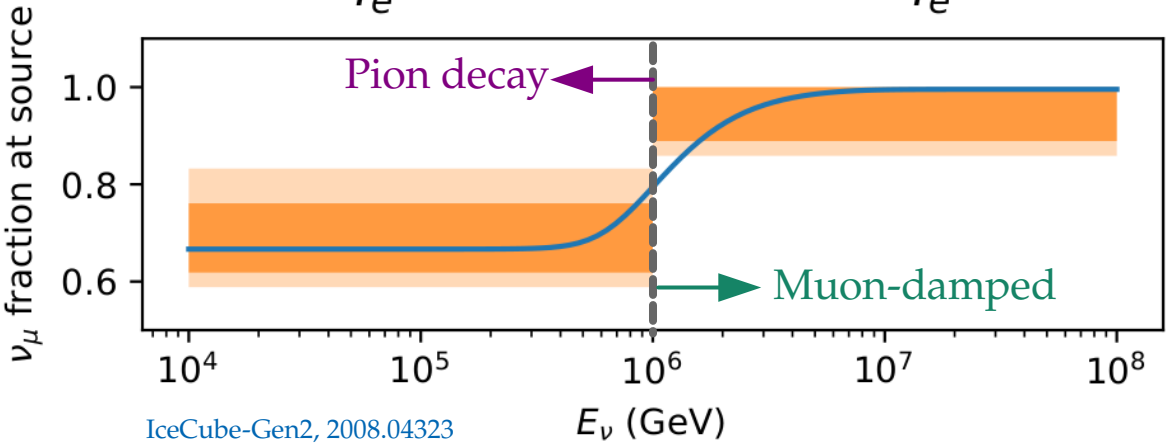


IceCube-Gen2, 2008.04323

Energy dependence of flavor ratios – in IceCube-Gen2

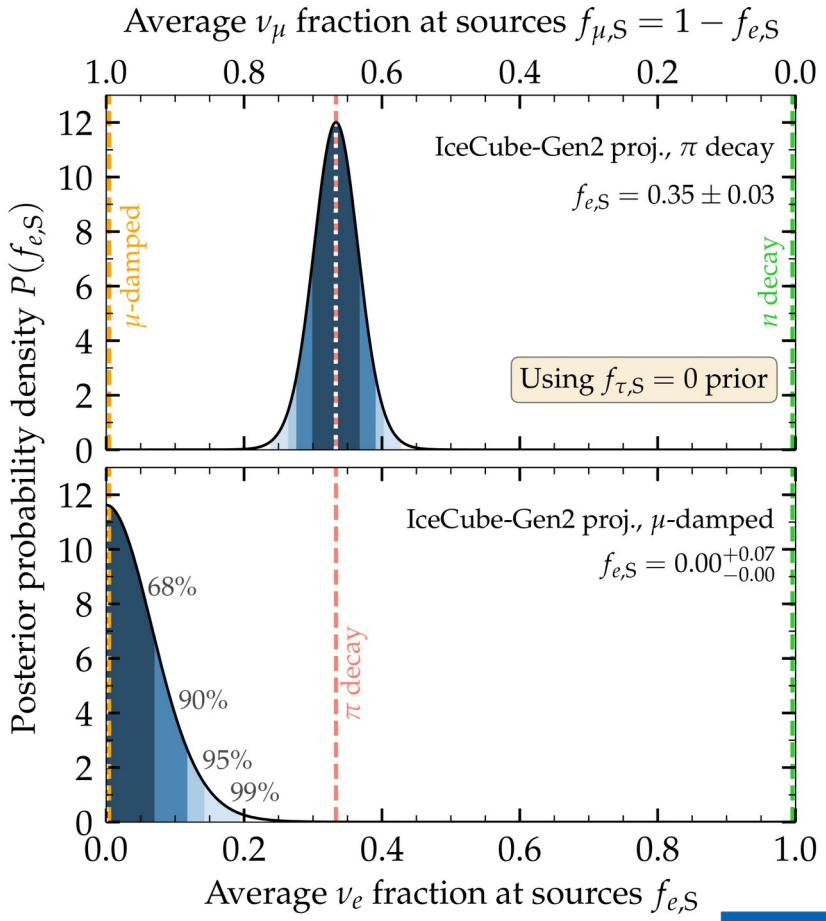
Measured:





IceCube-Gen2, 2008.04323

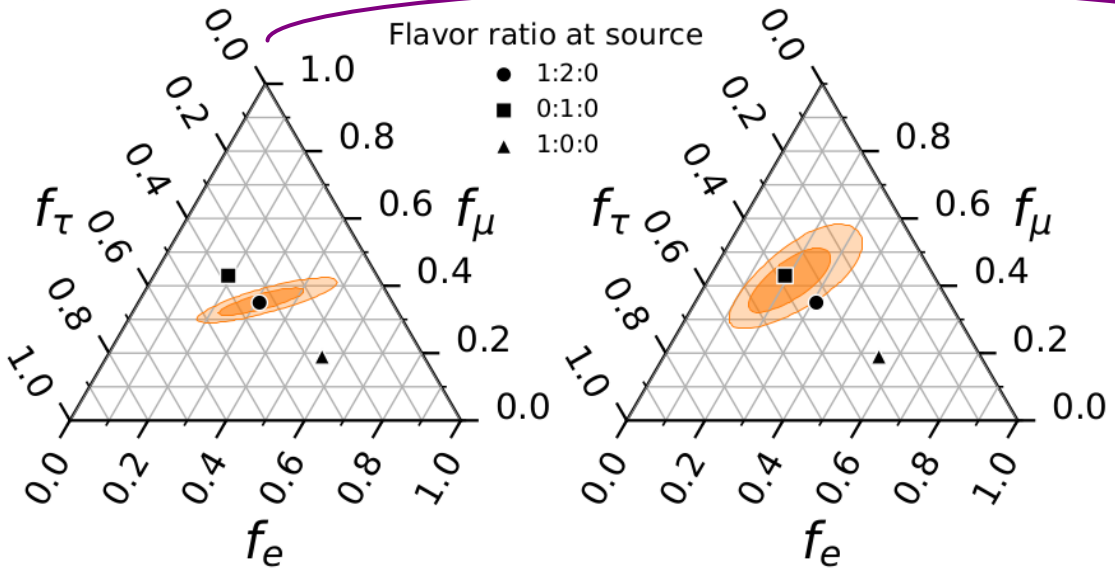
Inferred (at sources):

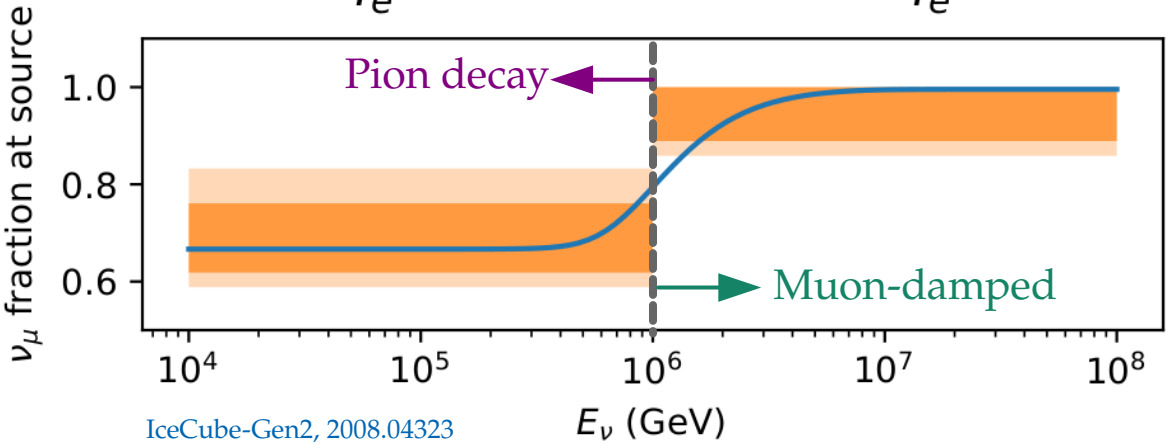


MB & Ahlers, *PRL* 2019

Energy dependence of flavor ratios – in IceCube-Gen2

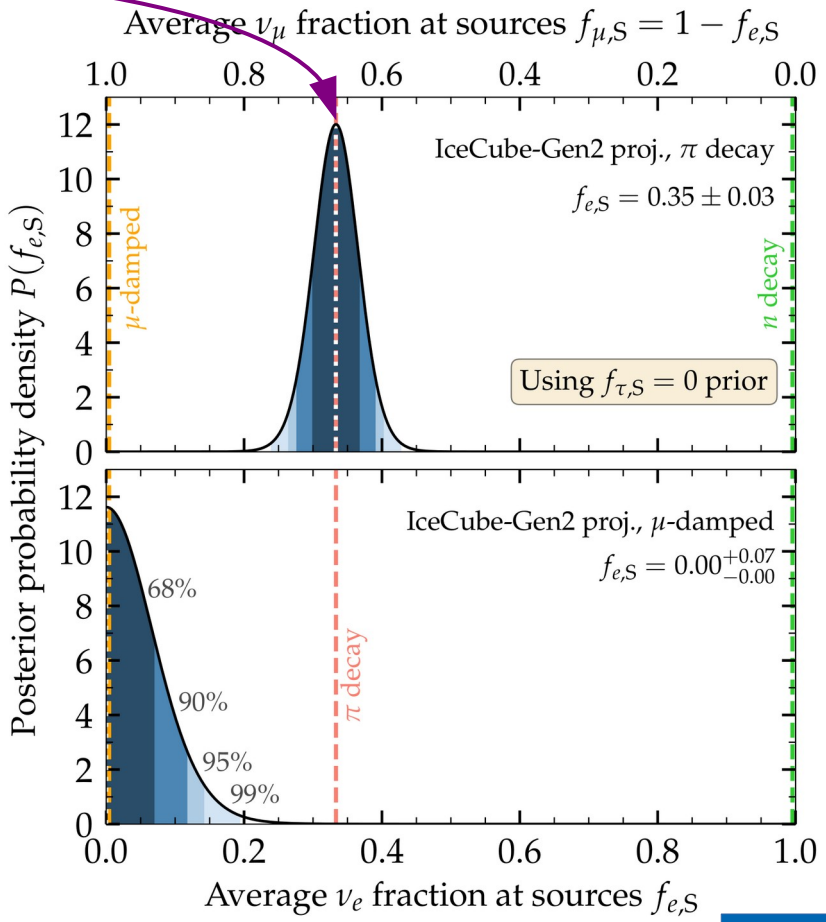
Measured:





IceCube-Gen2, 2008.04323

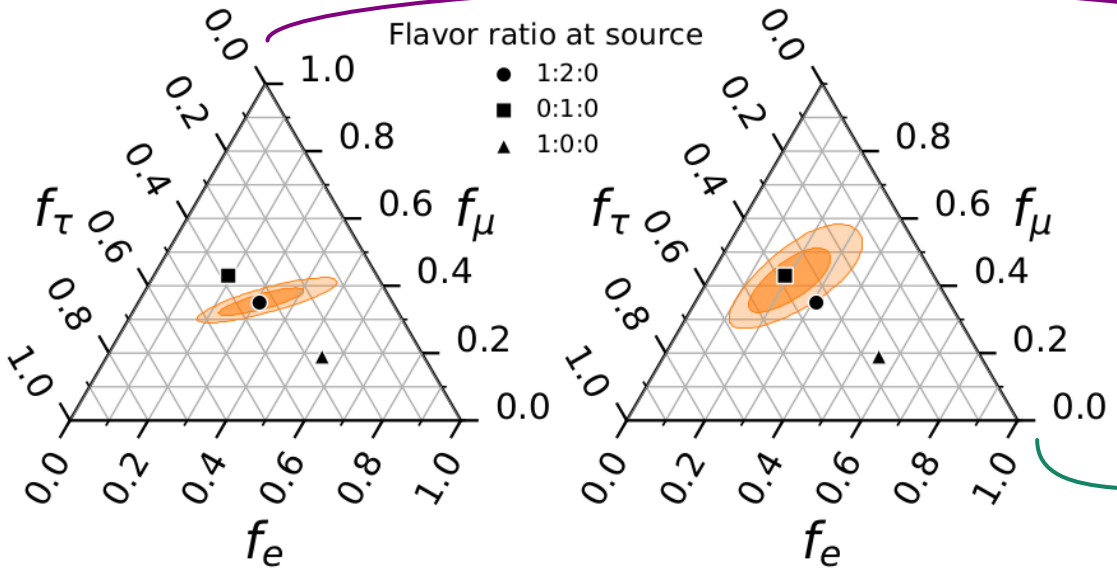
Inferred (at sources):

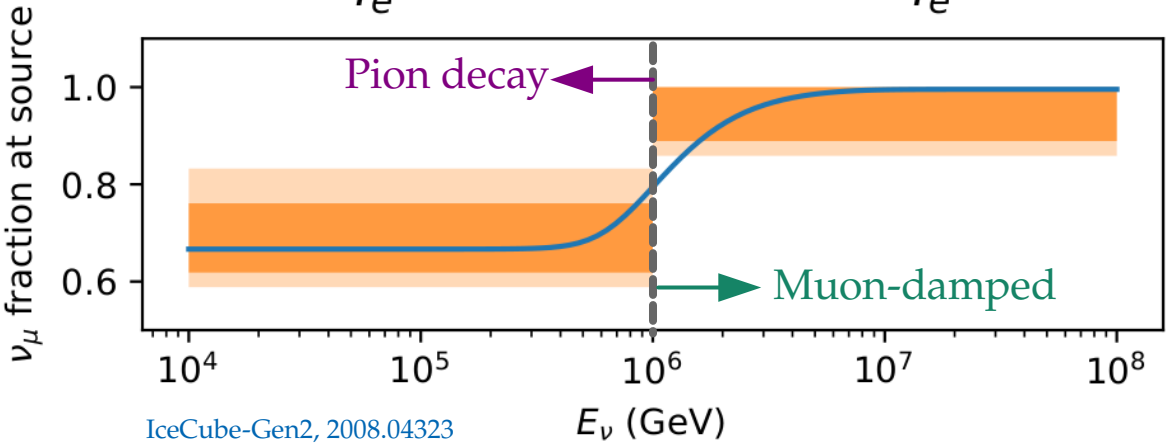


MB & Ahlers, *PRL* 2019

Energy dependence of flavor ratios – in IceCube-Gen2

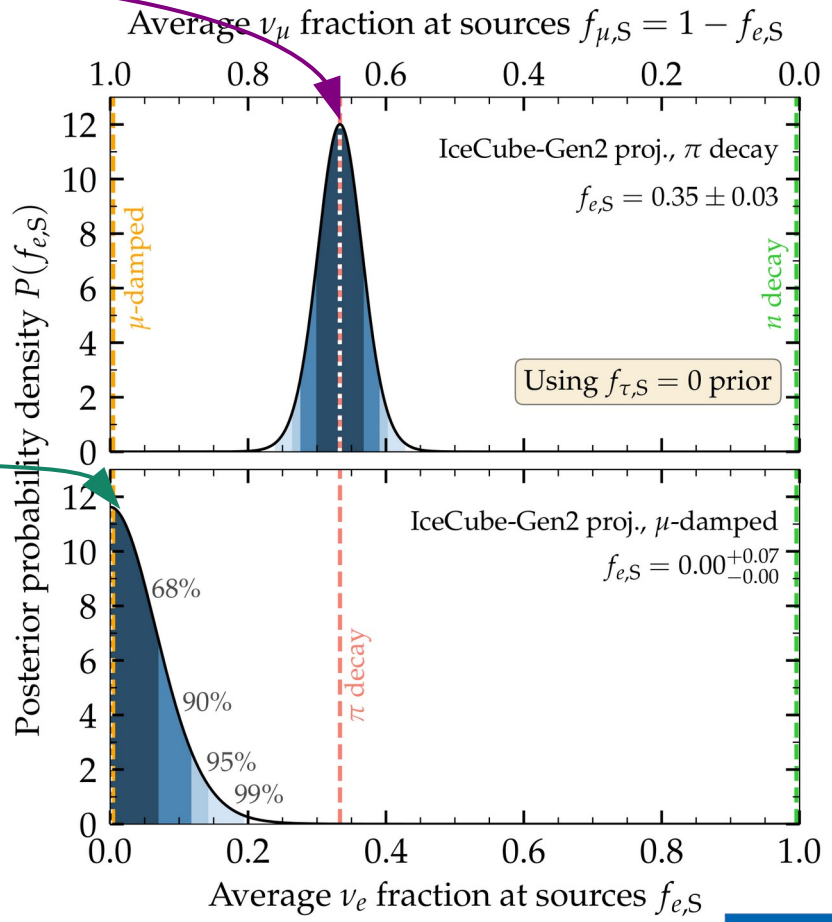
Measured:





IceCube-Gen2, 2008.04323

Inferred (at sources):

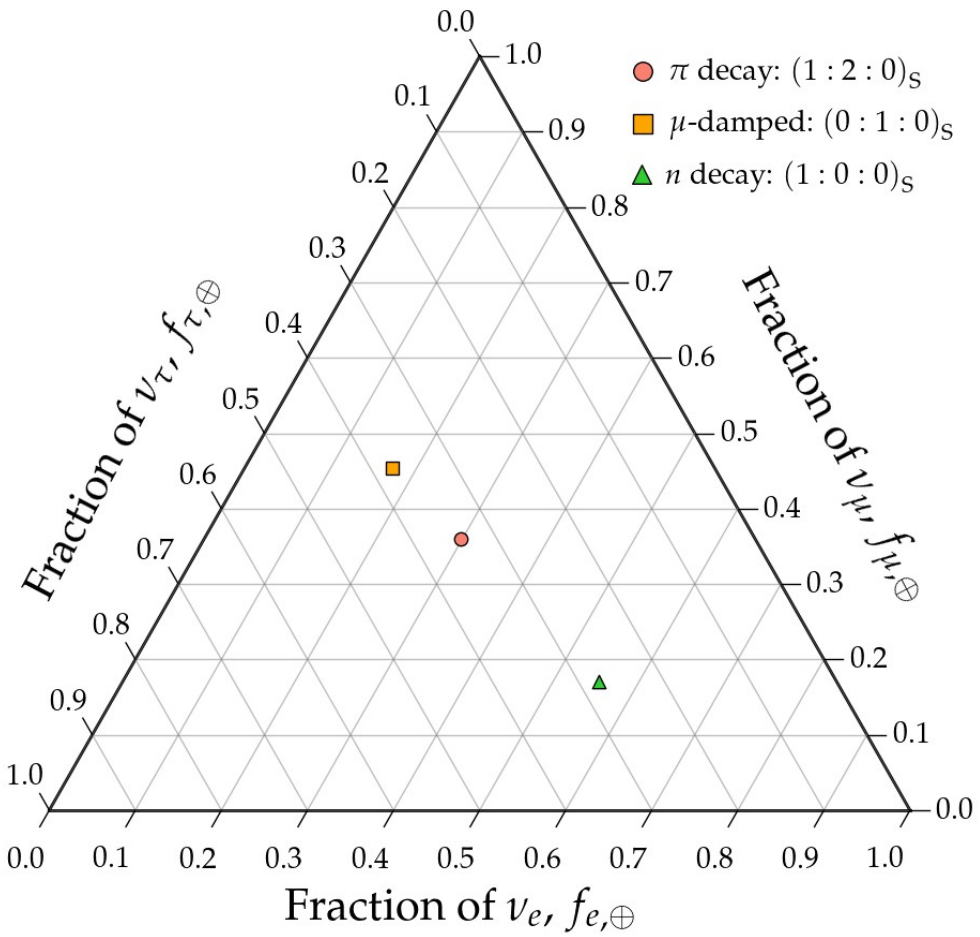


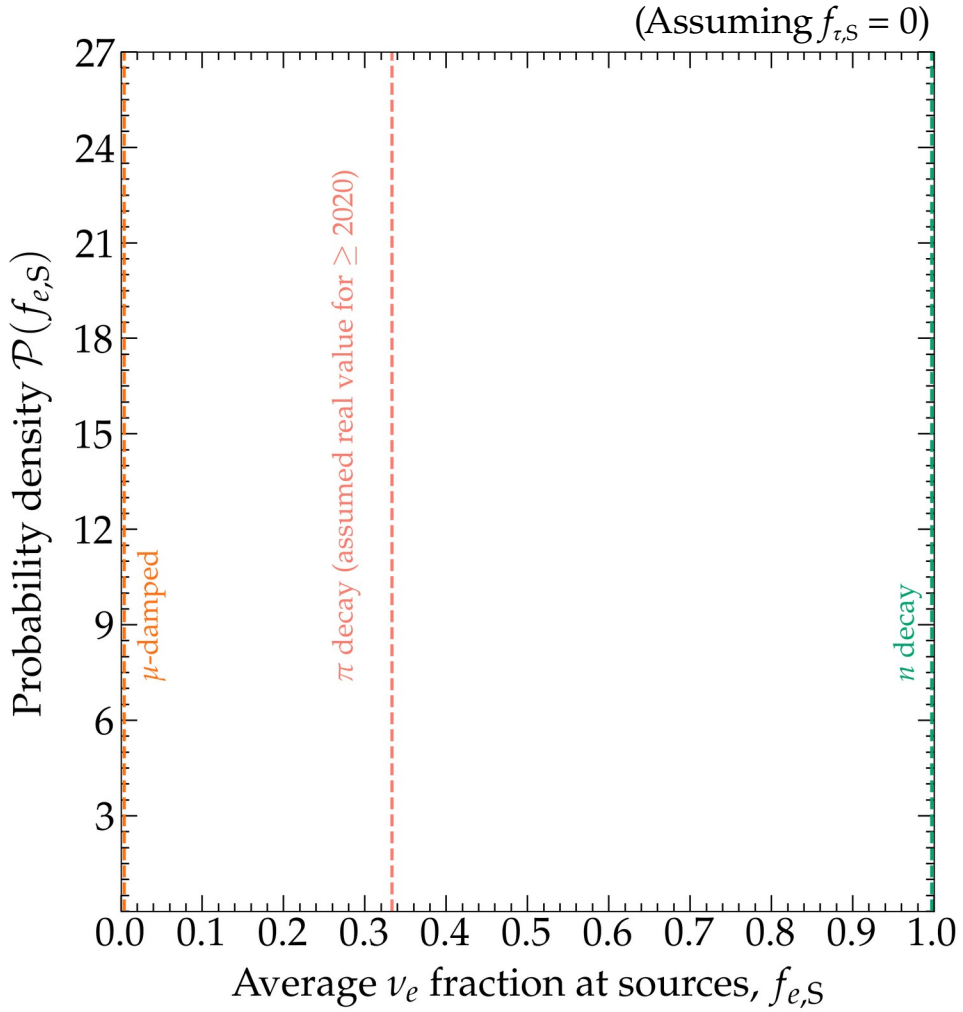
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

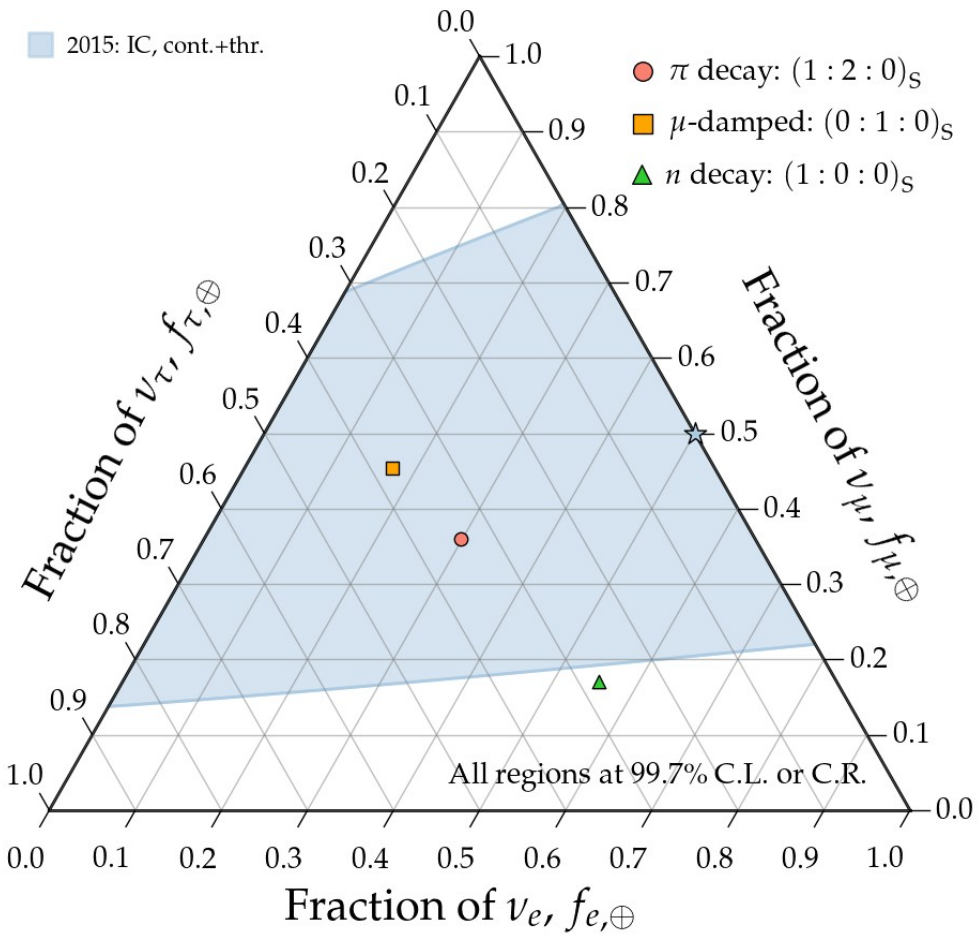
Inferring the flavor composition at the sources

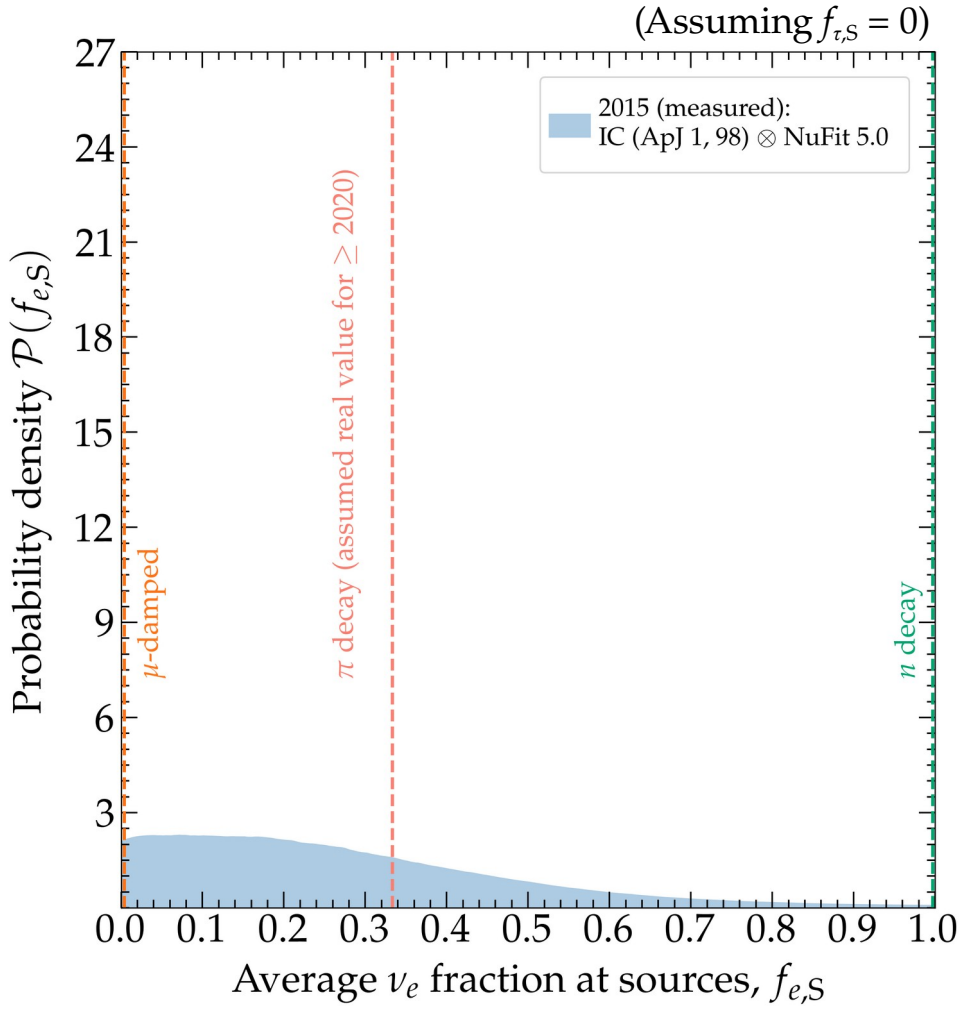




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

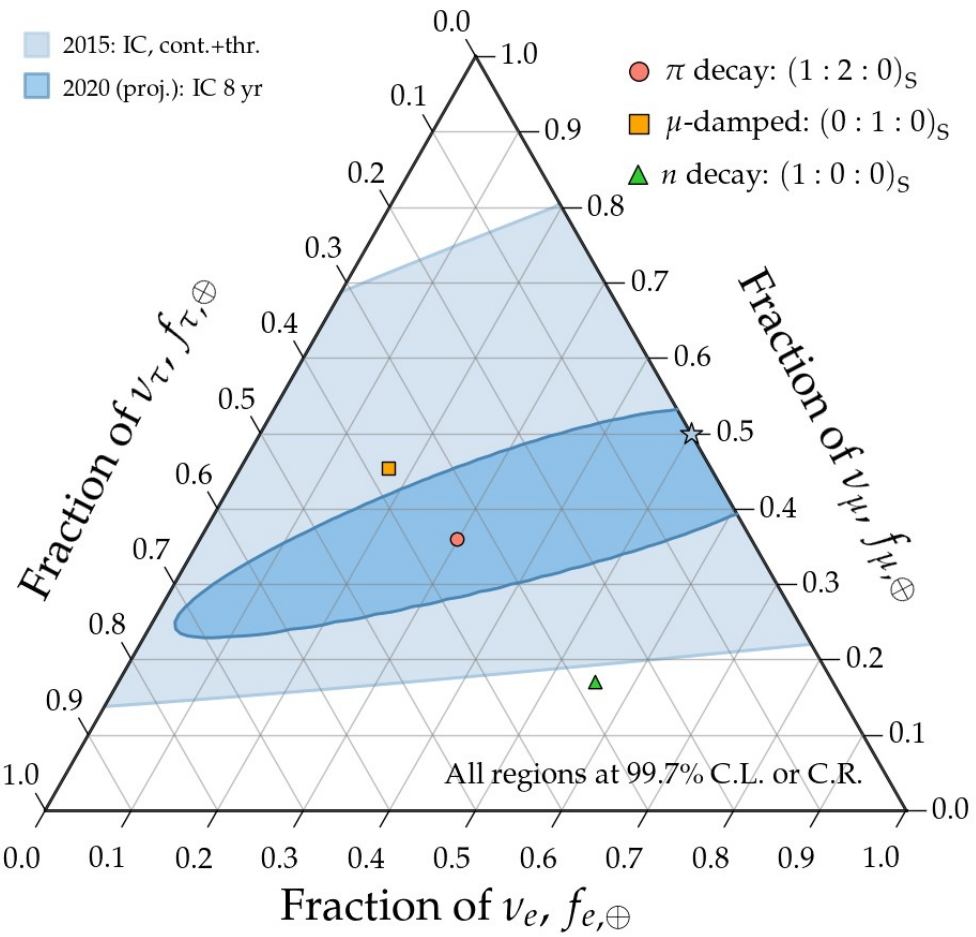
Inferring the flavor composition at the sources

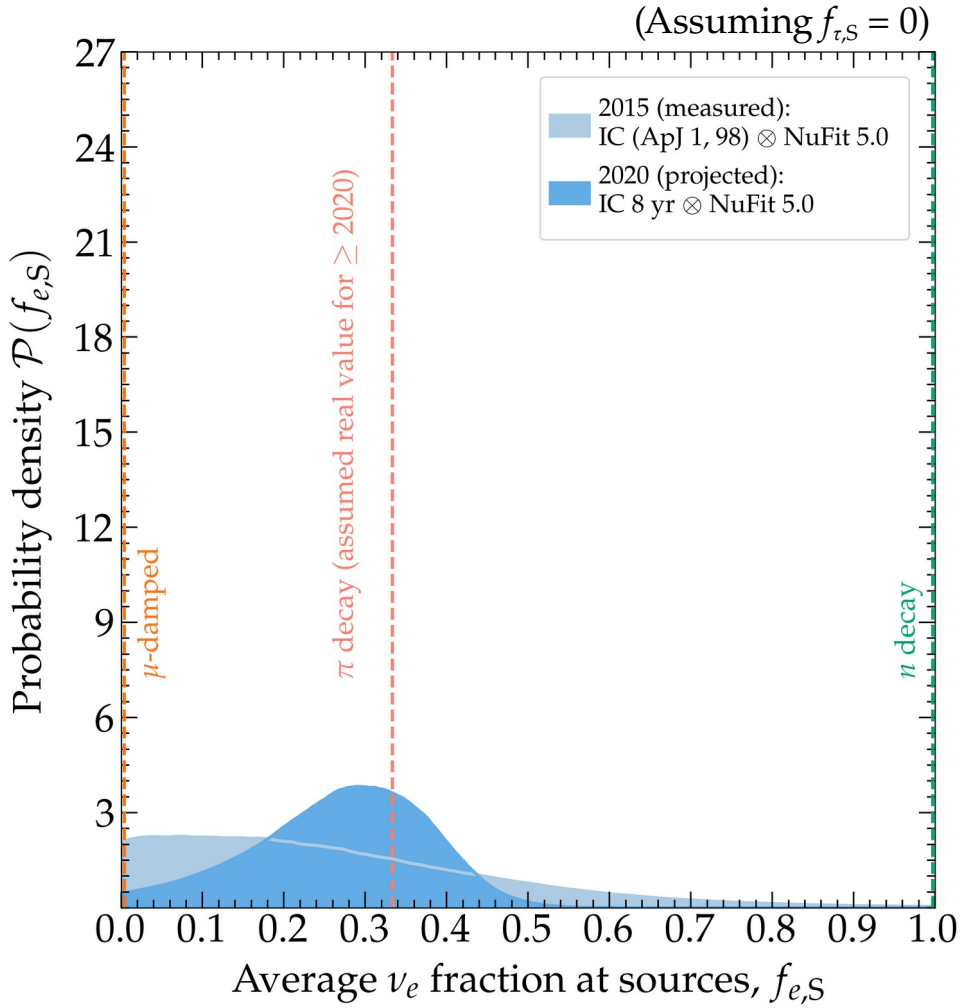




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

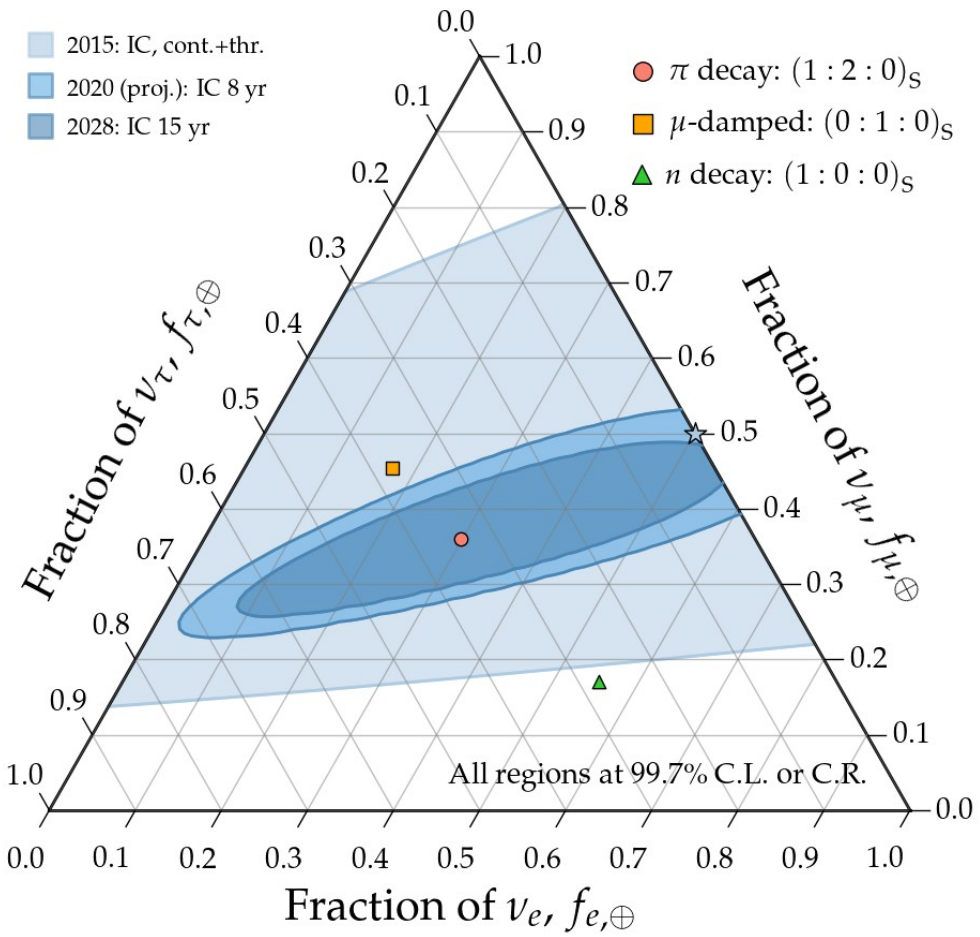
Inferring the flavor composition at the sources

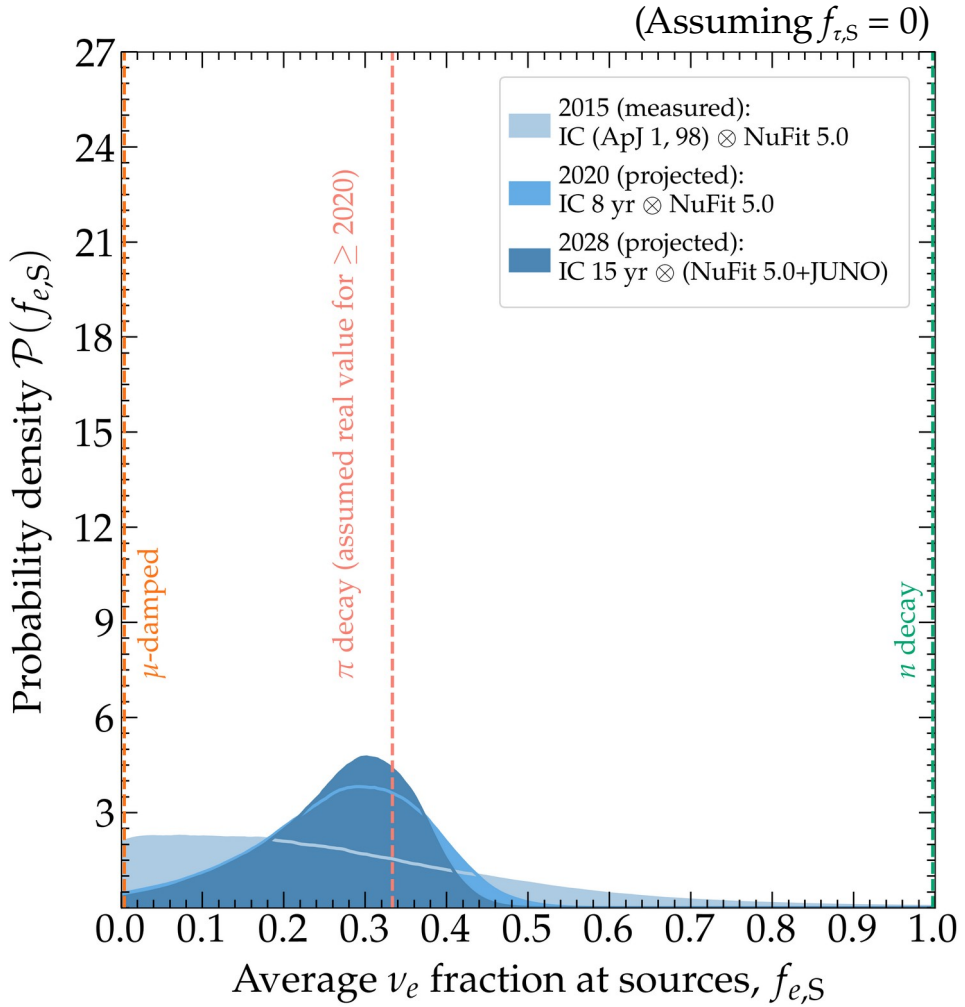




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

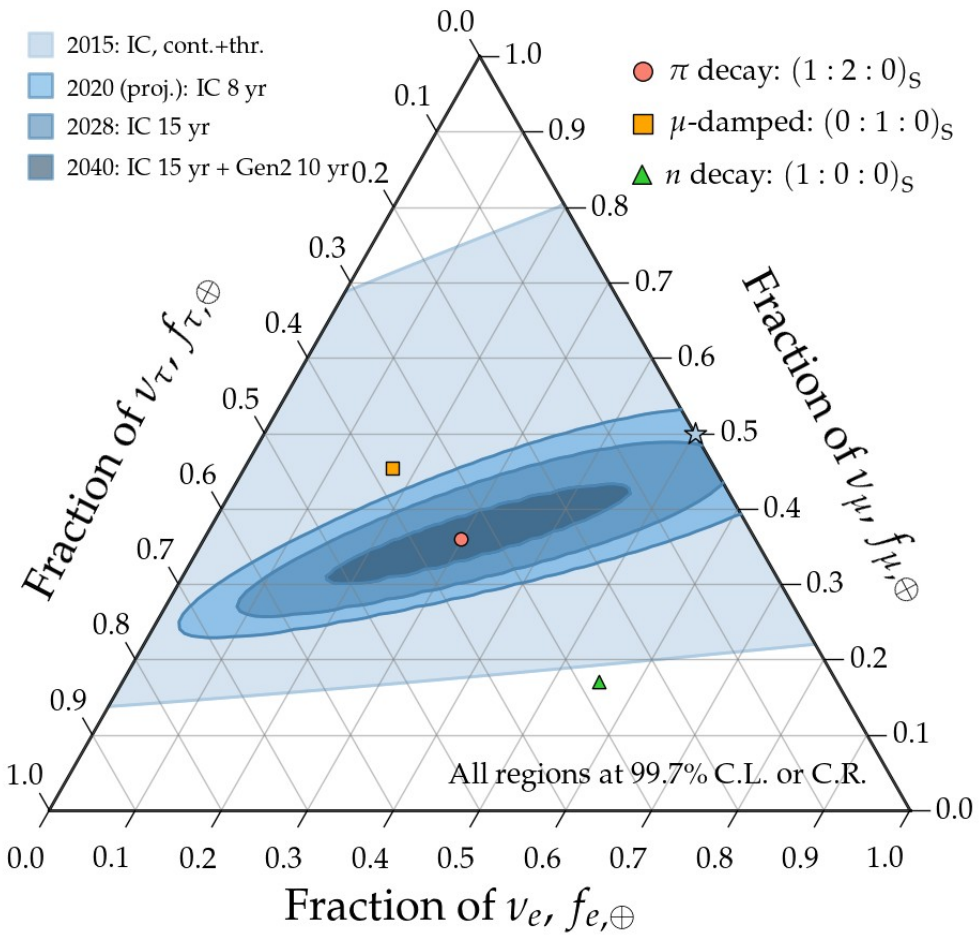
Inferring the flavor composition at the sources

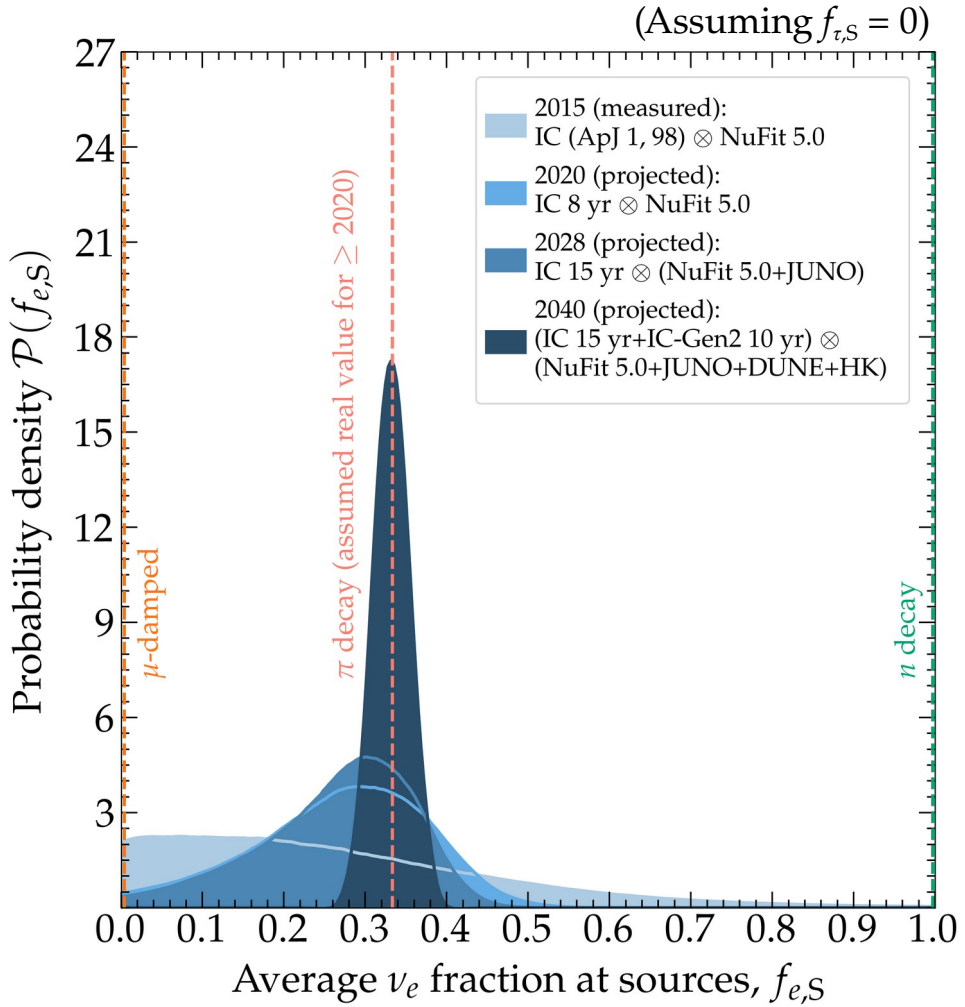




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

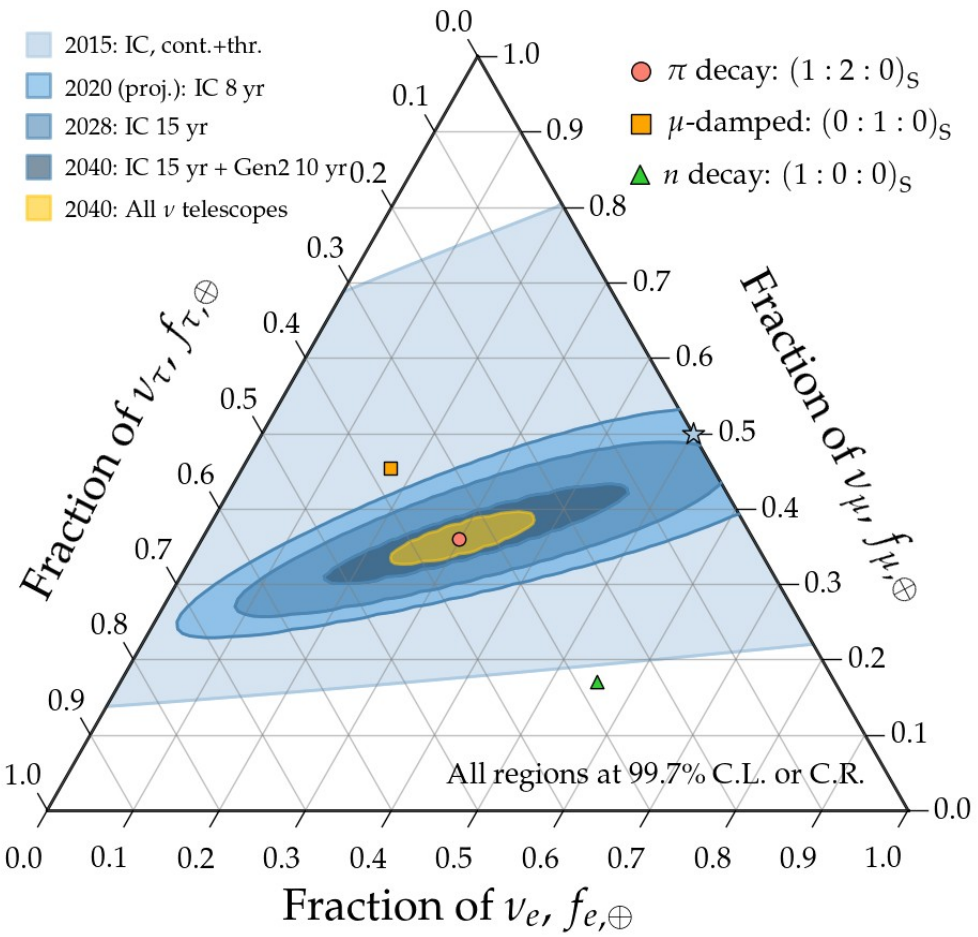
Inferring the flavor composition at the sources

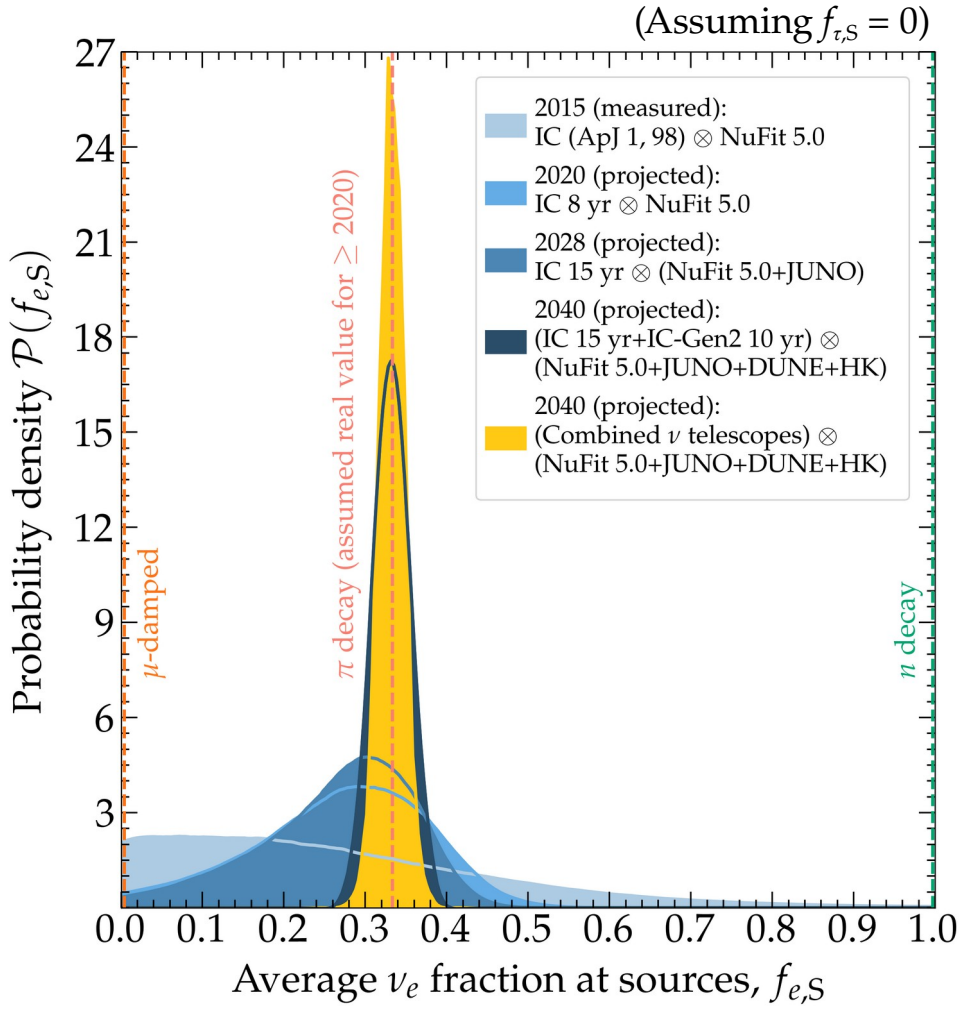




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources





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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

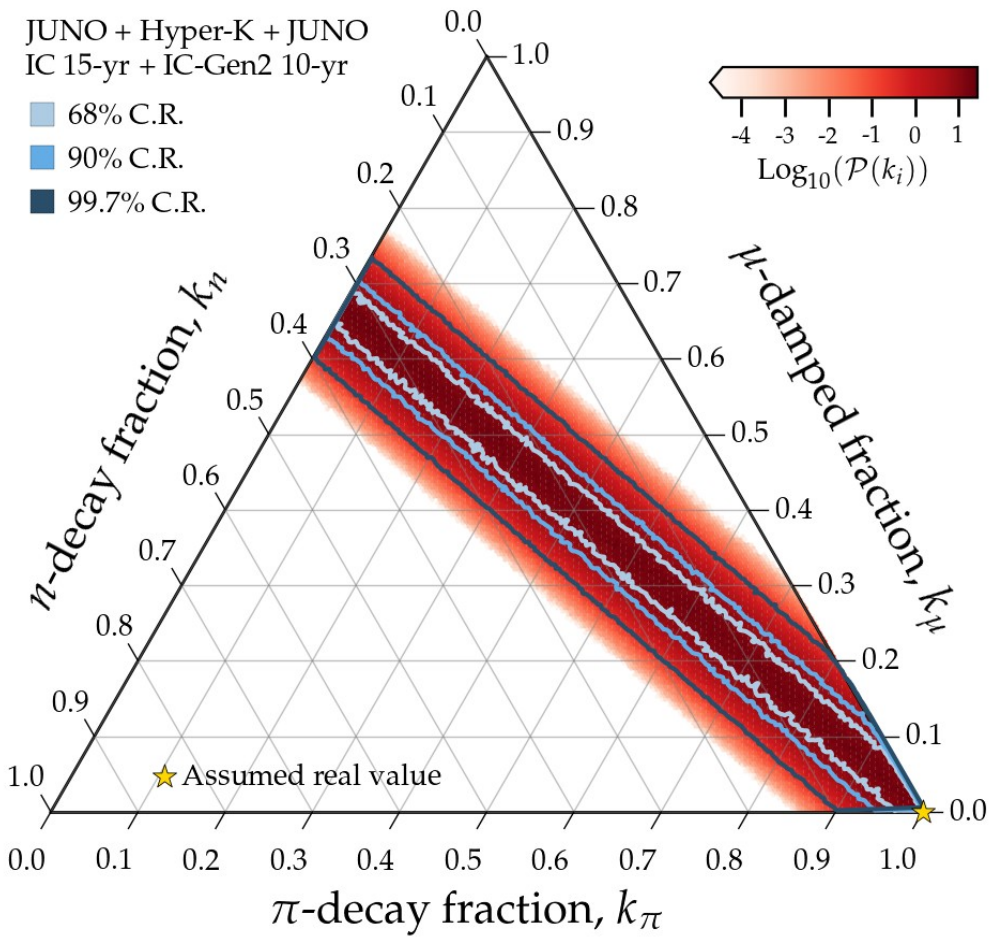
Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

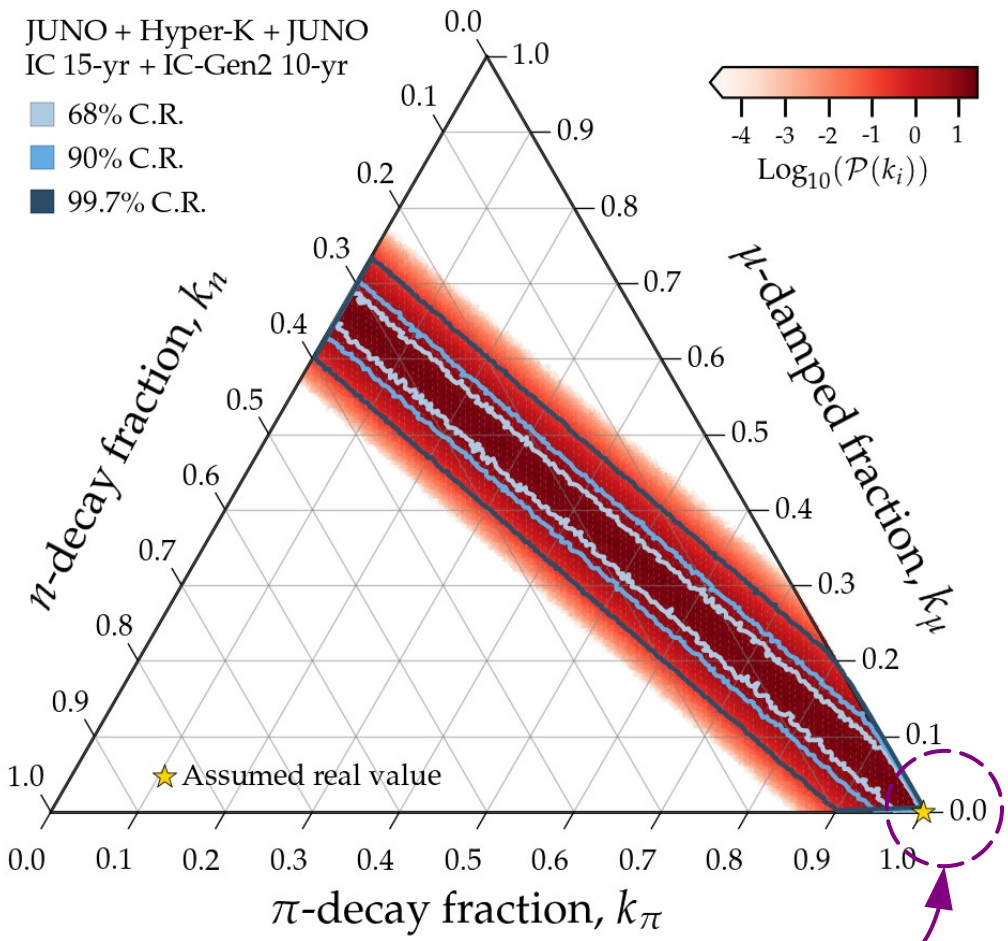
Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

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

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

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



We do recover the real value

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

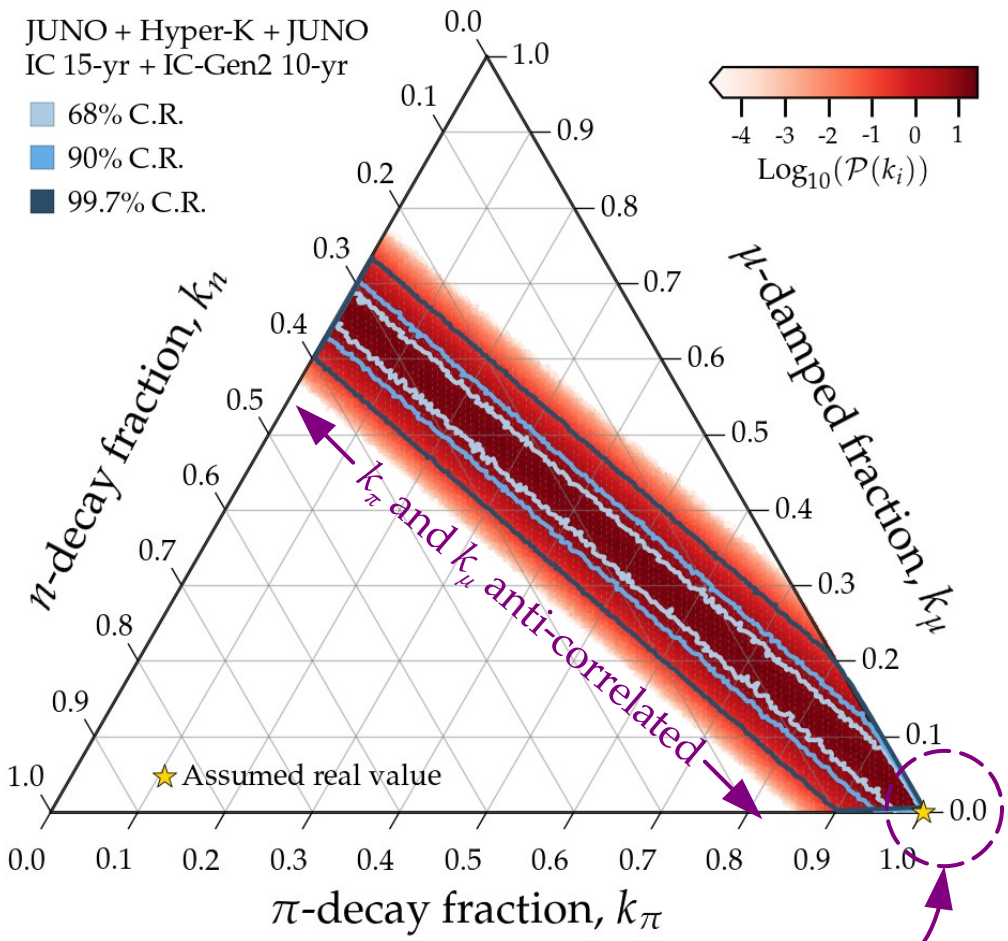
Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

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

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

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



We do recover the real value

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

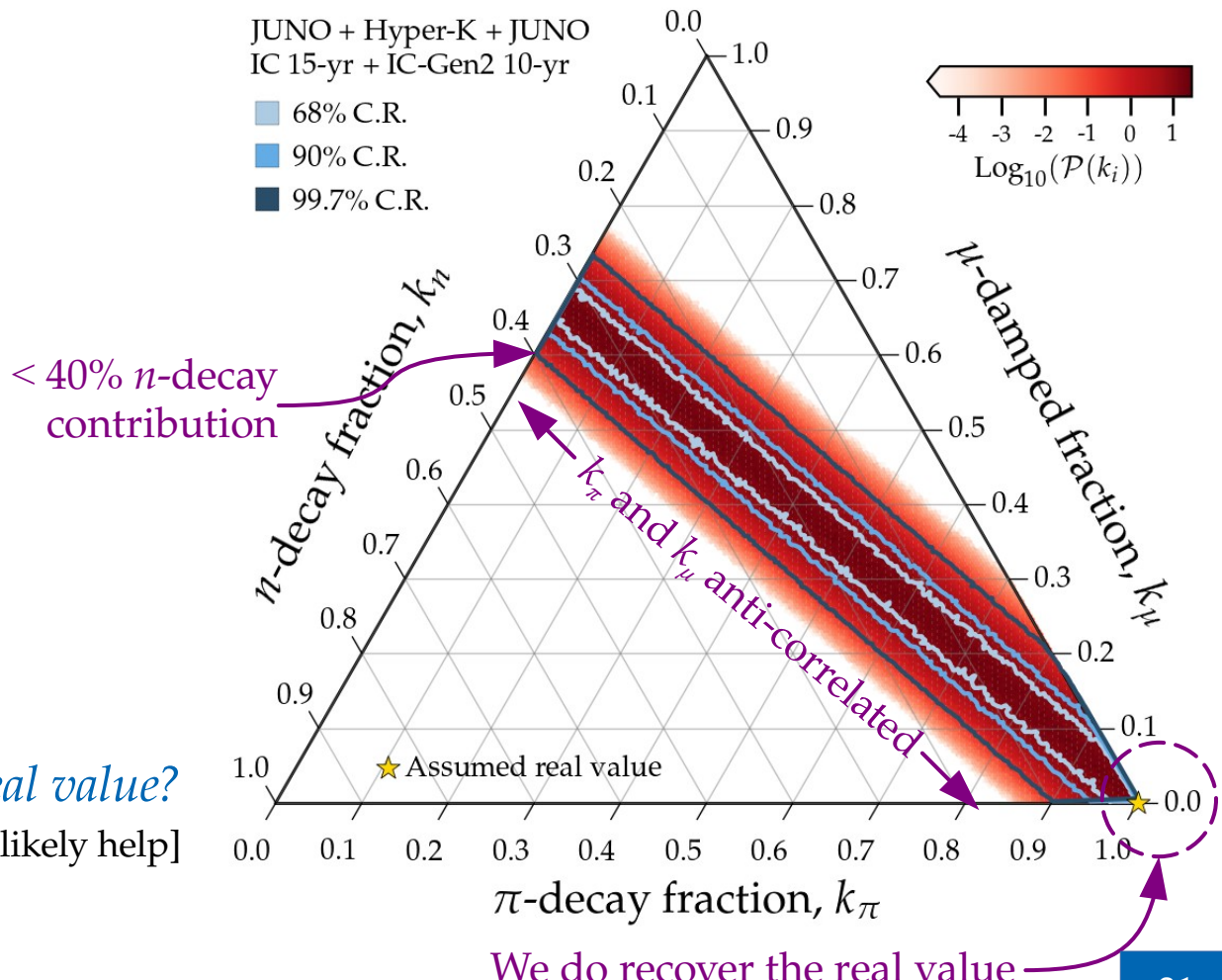
Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}^{\pi}_{\rm S}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}^{\mu}_{\rm S}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}^{n}_{\rm S}}_{n\text{ decay: }(1,\,0,\,0)}$$

Propagate to Earth ↓

$$\boldsymbol{f}_{\oplus}$$

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

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

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

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

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

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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

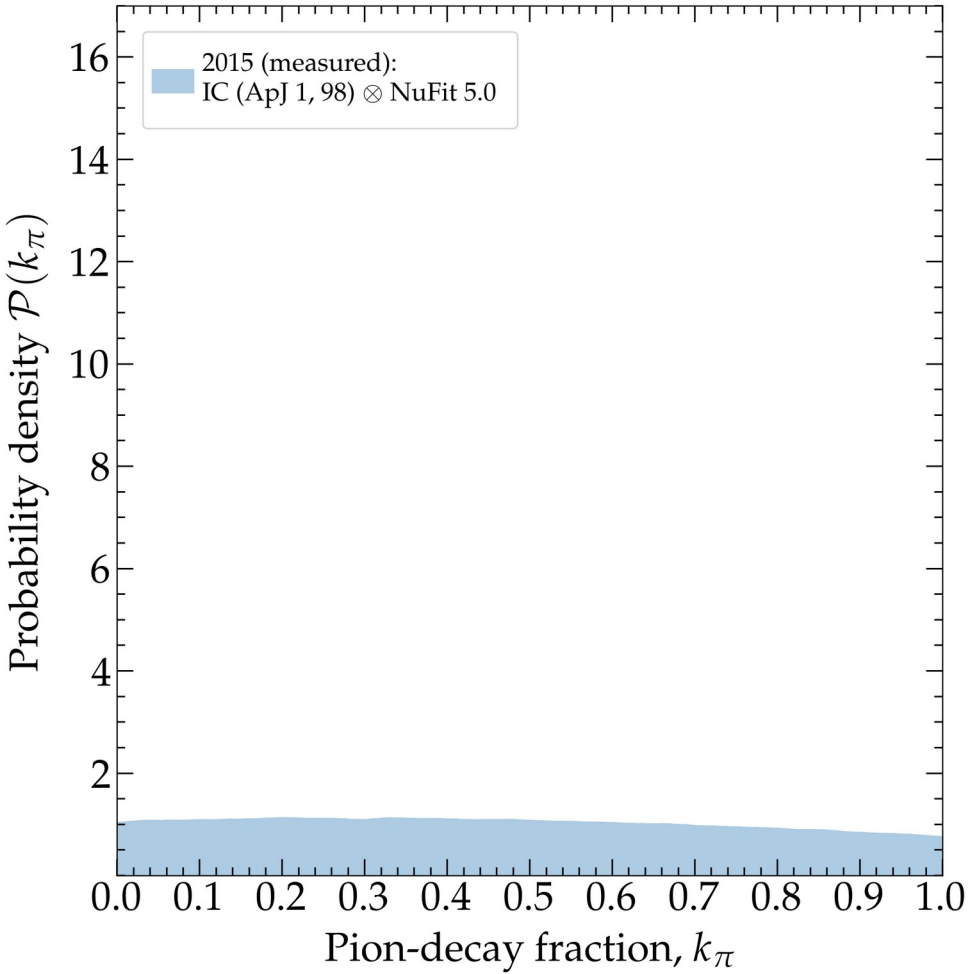
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

$$\boldsymbol{f}_{\rm S} = k_\pi \underbrace{\boldsymbol{f}_{\rm S}^{\pi}}_{\pi\text{ decay: }(1/3,\,2/3,\,0)} + k_\mu \underbrace{\boldsymbol{f}_{\rm S}^{\mu}}_{\mu\text{ damped: }(0,\,1,\,0)} + k_n \underbrace{\boldsymbol{f}_{\rm S}^{n}}_{n\text{ decay: }(1,\,0,\,0)}$$

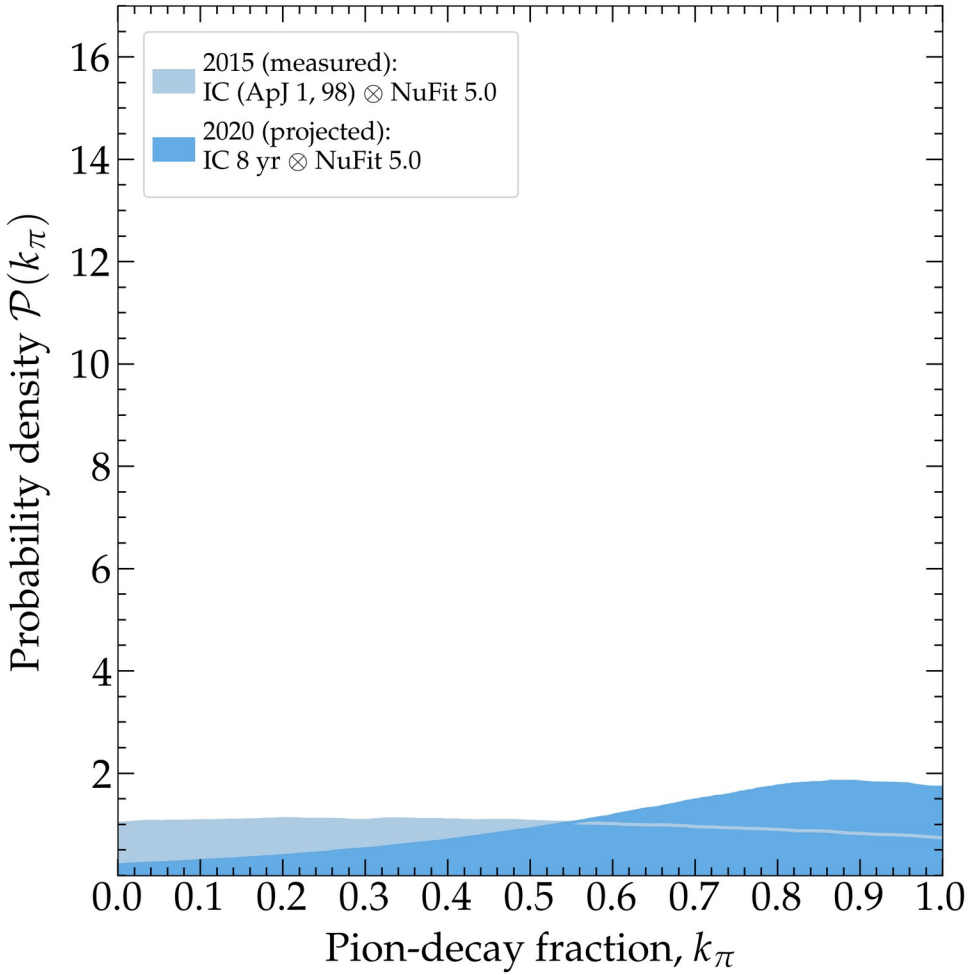
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

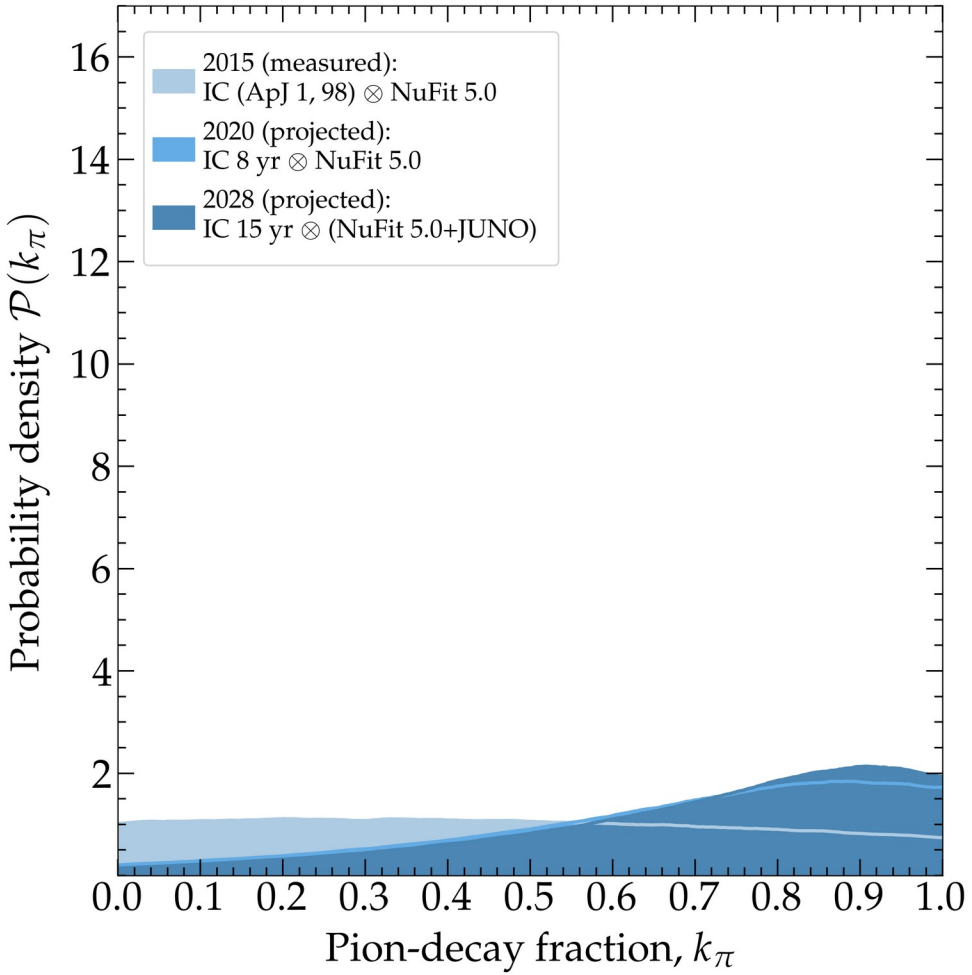
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

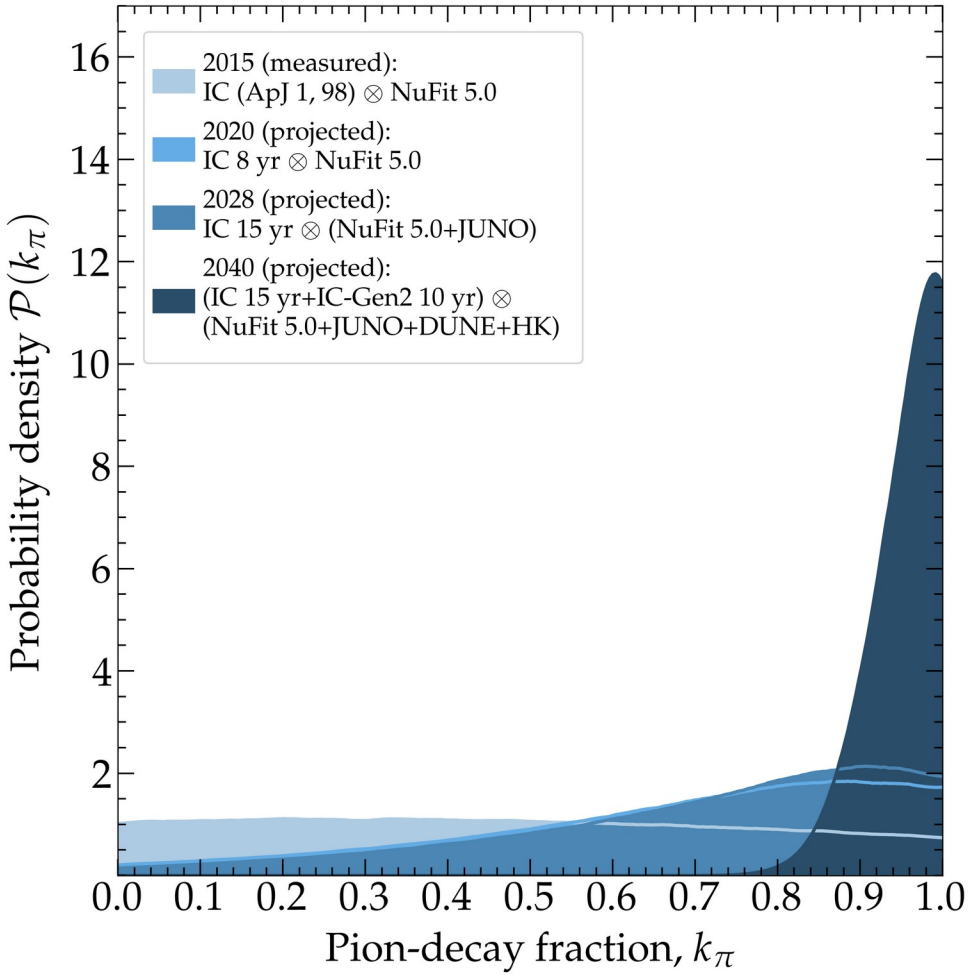
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

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



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

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0)

μ damped: (0, 1, 0)

n decay: (1, 0, 0)

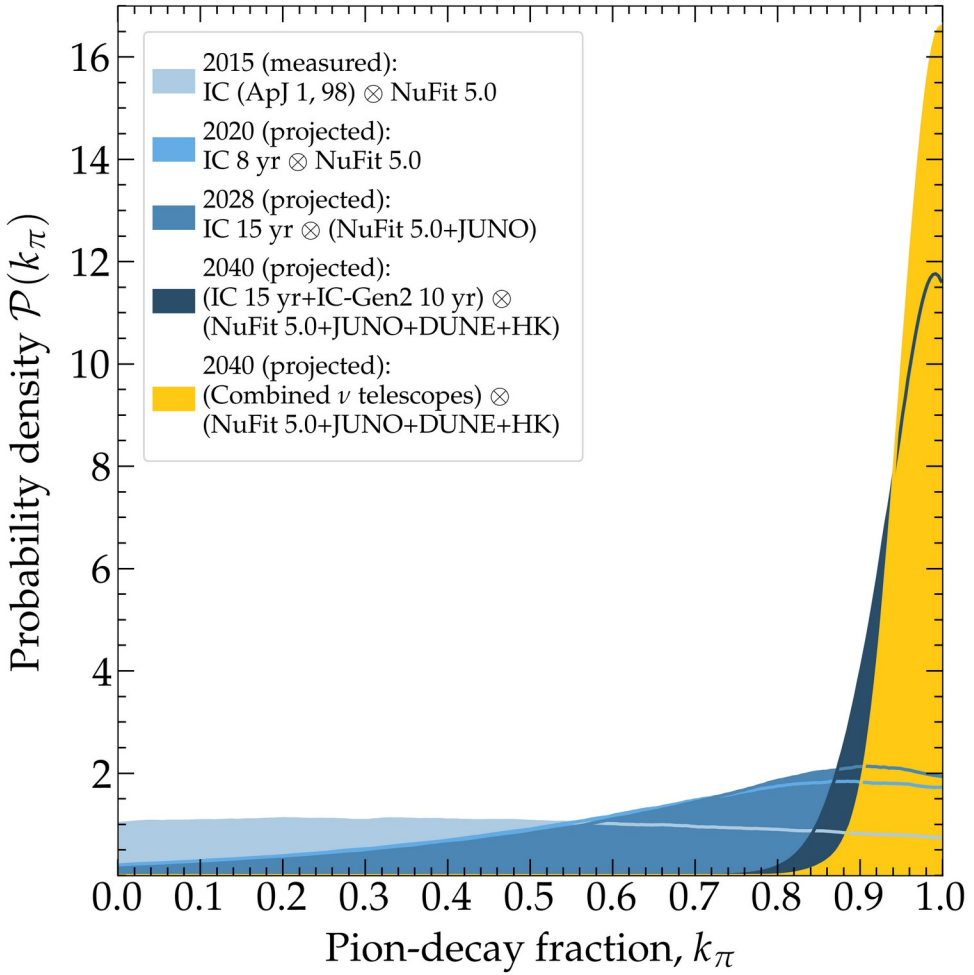
Propagate to Earth

$$\boldsymbol{f}_{\oplus}$$

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

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

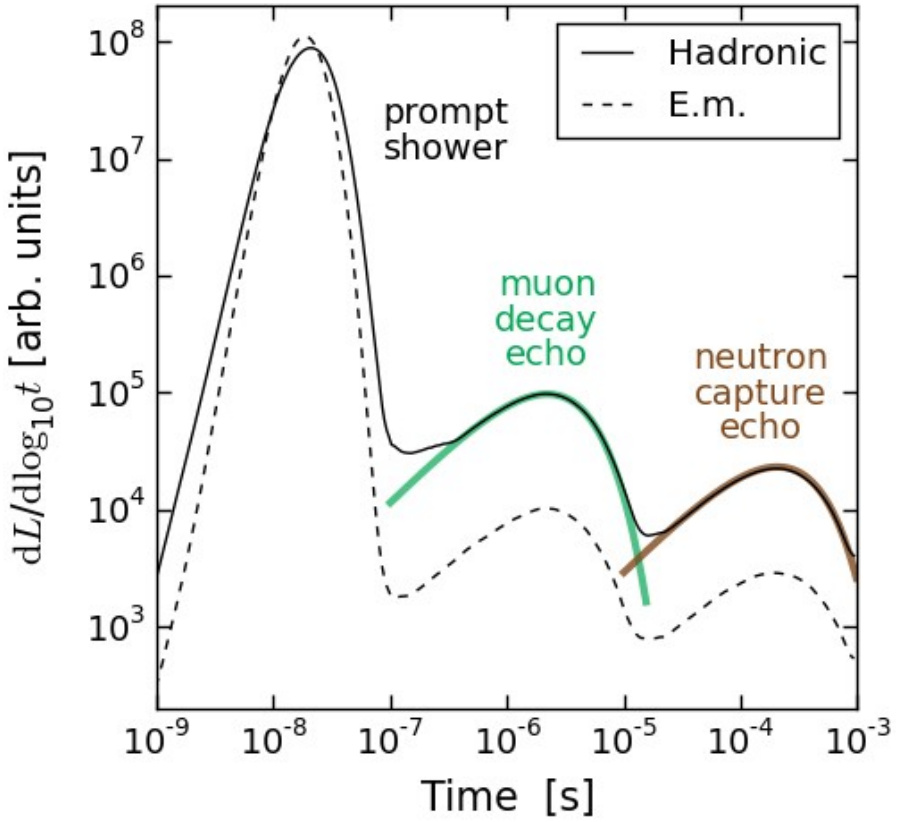
[Adding spectrum information (not shown) will likely help]

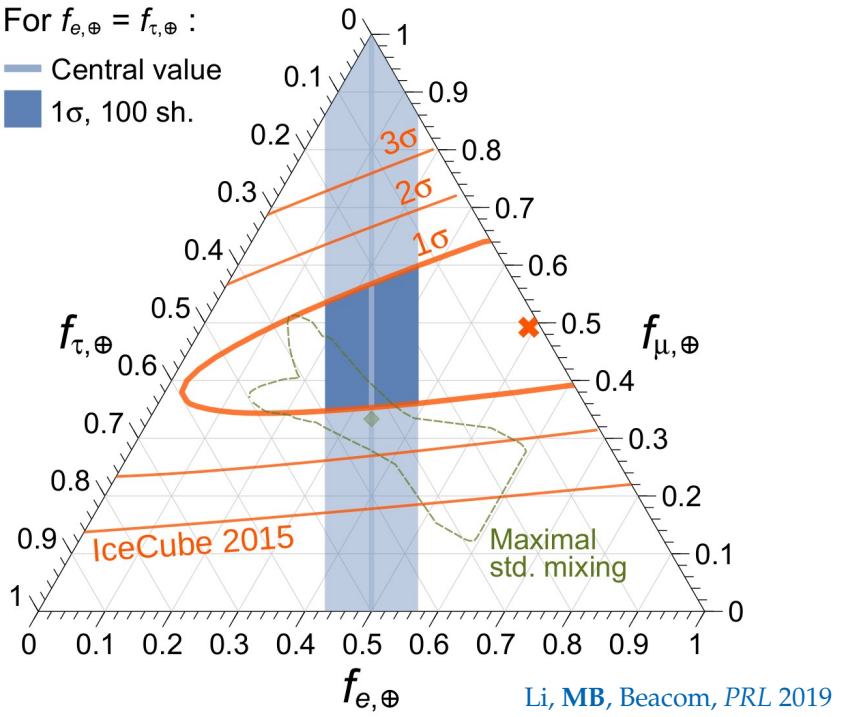


Song, Li, Argüelles, **MB**, Vincent, 2012.12893

Side note: Improving flavor-tagging using *echoes*

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

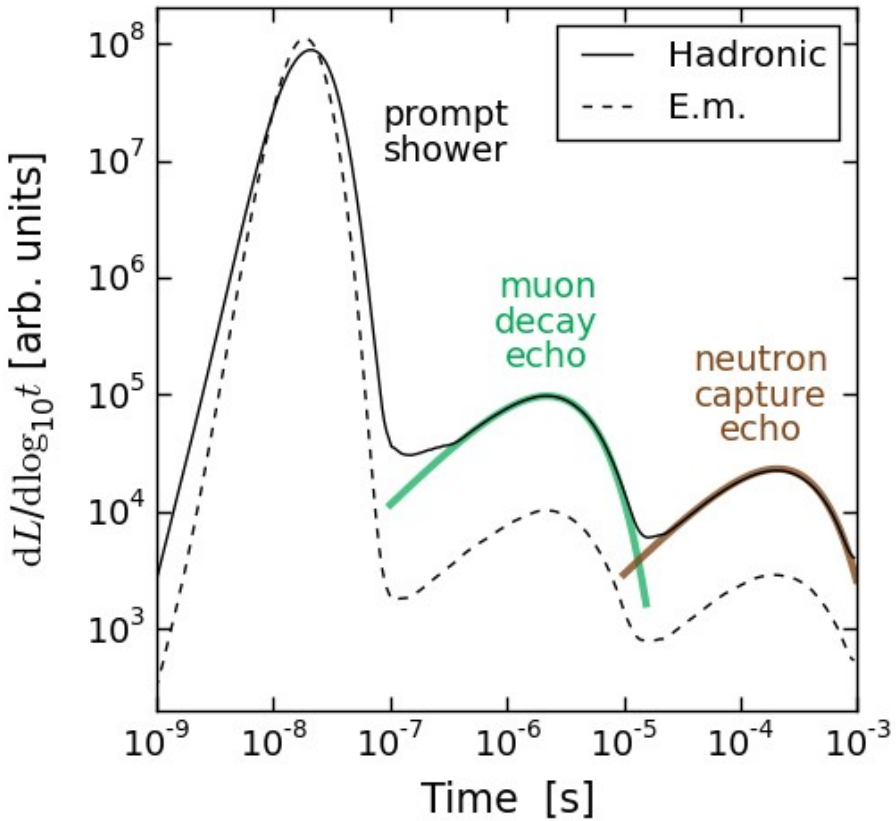




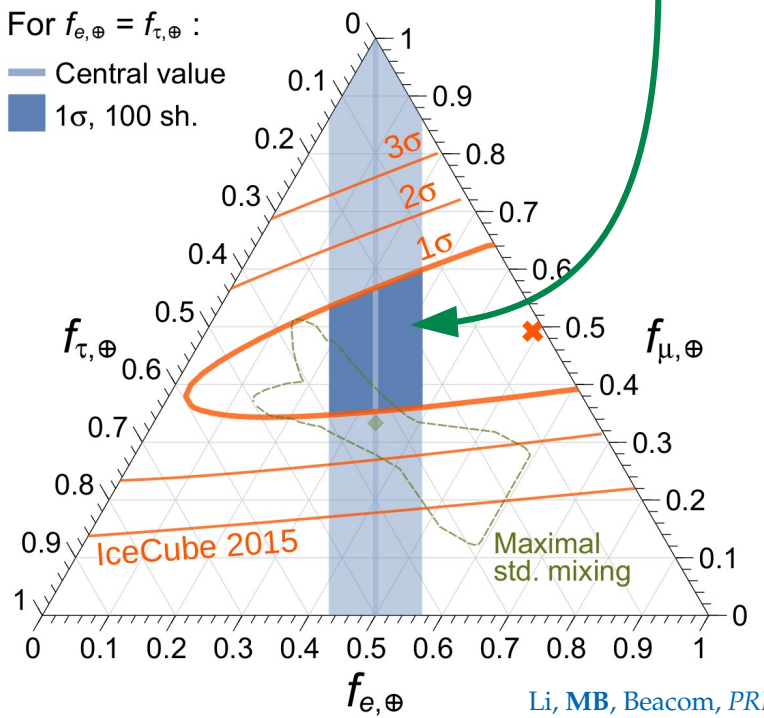
Li, **MB**, Beacom, *PRL* 2019

Side note: Improving flavor-tagging using *echoes*

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



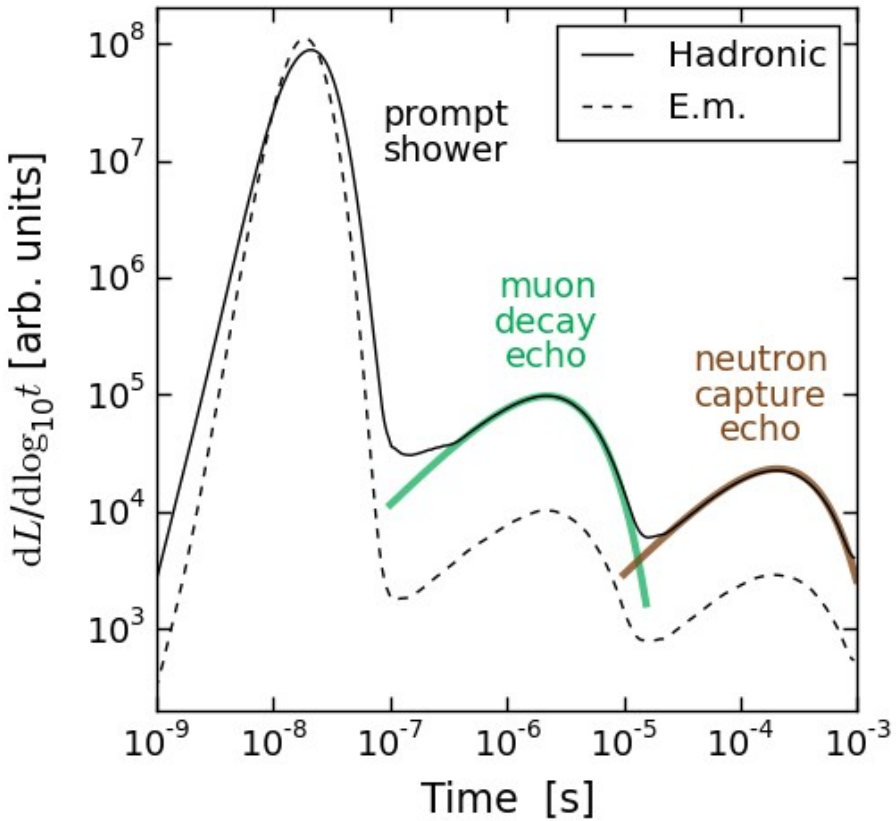
~10 × improvement over current measurement



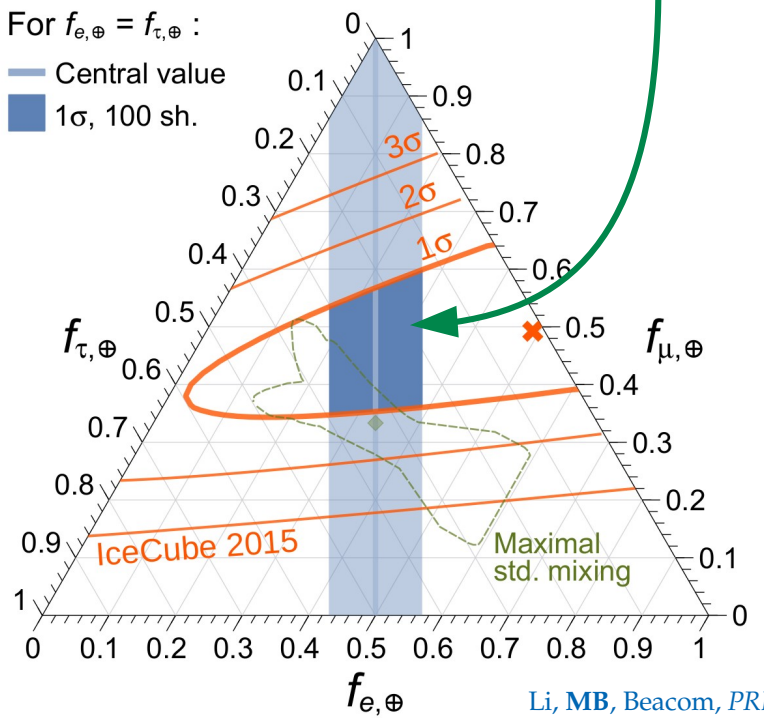
Li, **MB**, Beacom, *PRL* 2019

Side note: Improving flavor-tagging using *echoes*

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



~10 × improvement over current measurement



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