Higher, further, faster: high-energy cosmic neutrinos for particle physics and astrophysics

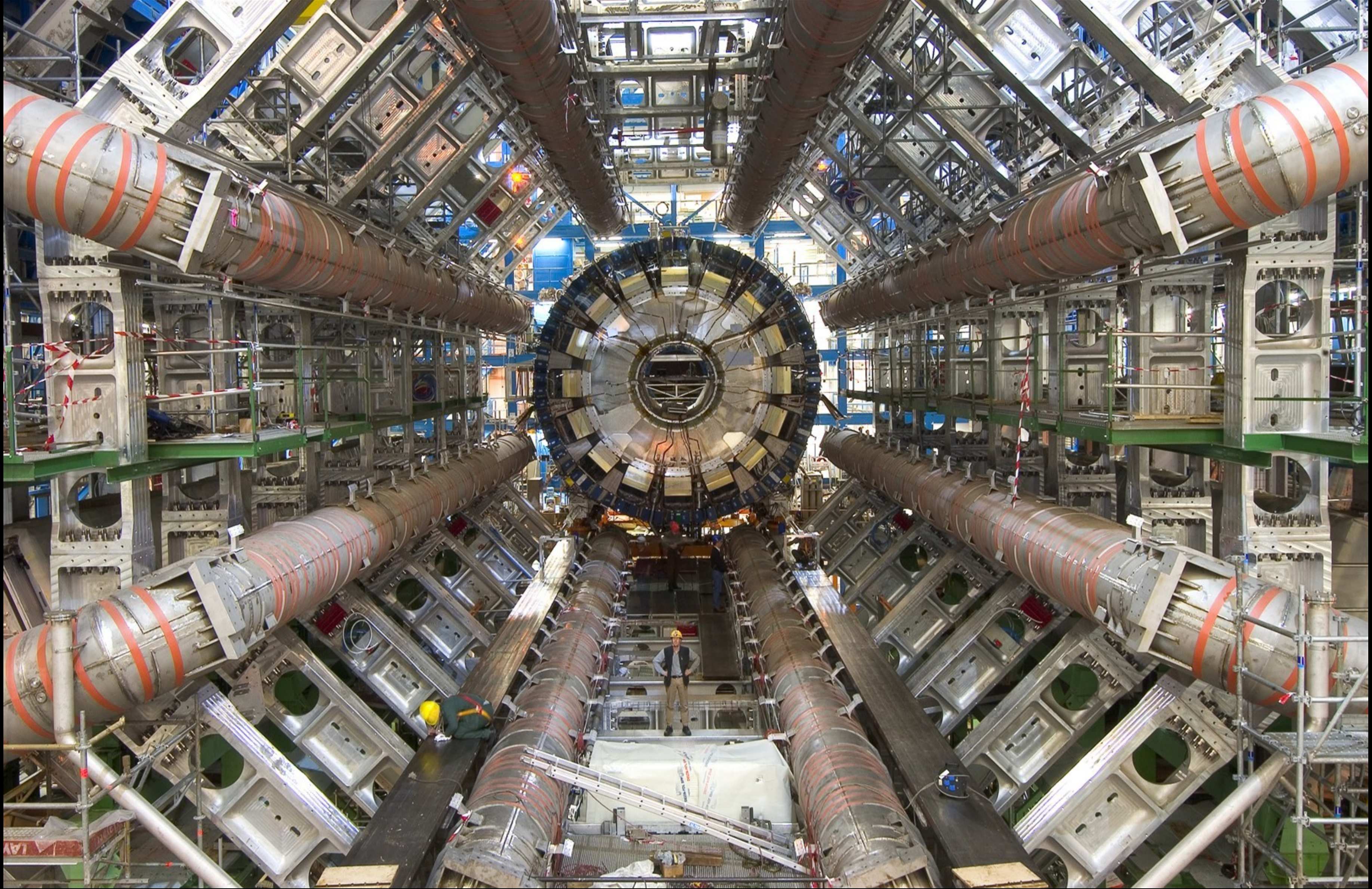
Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

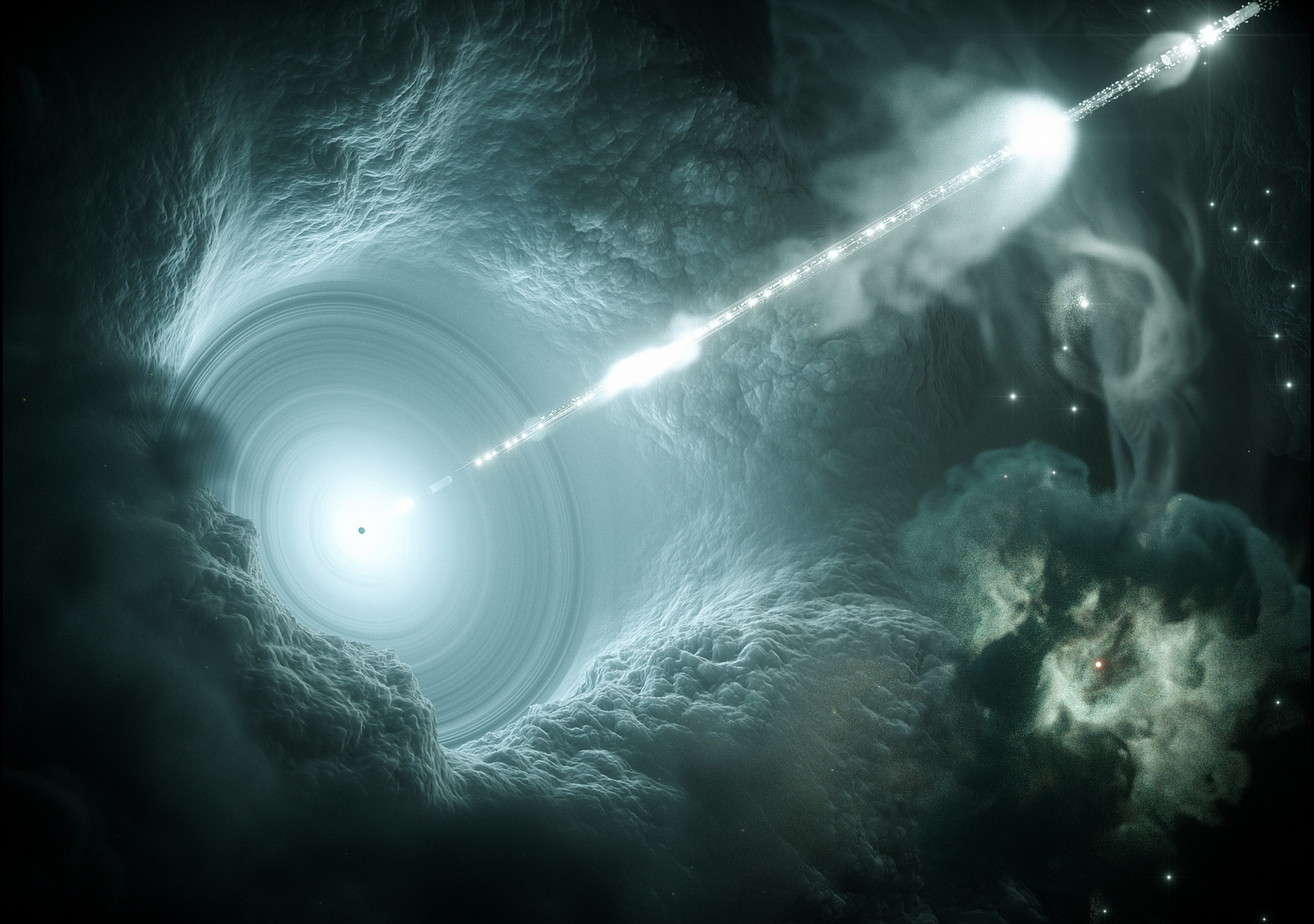
NBIA Junior Colloquium, February 21, 2025

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

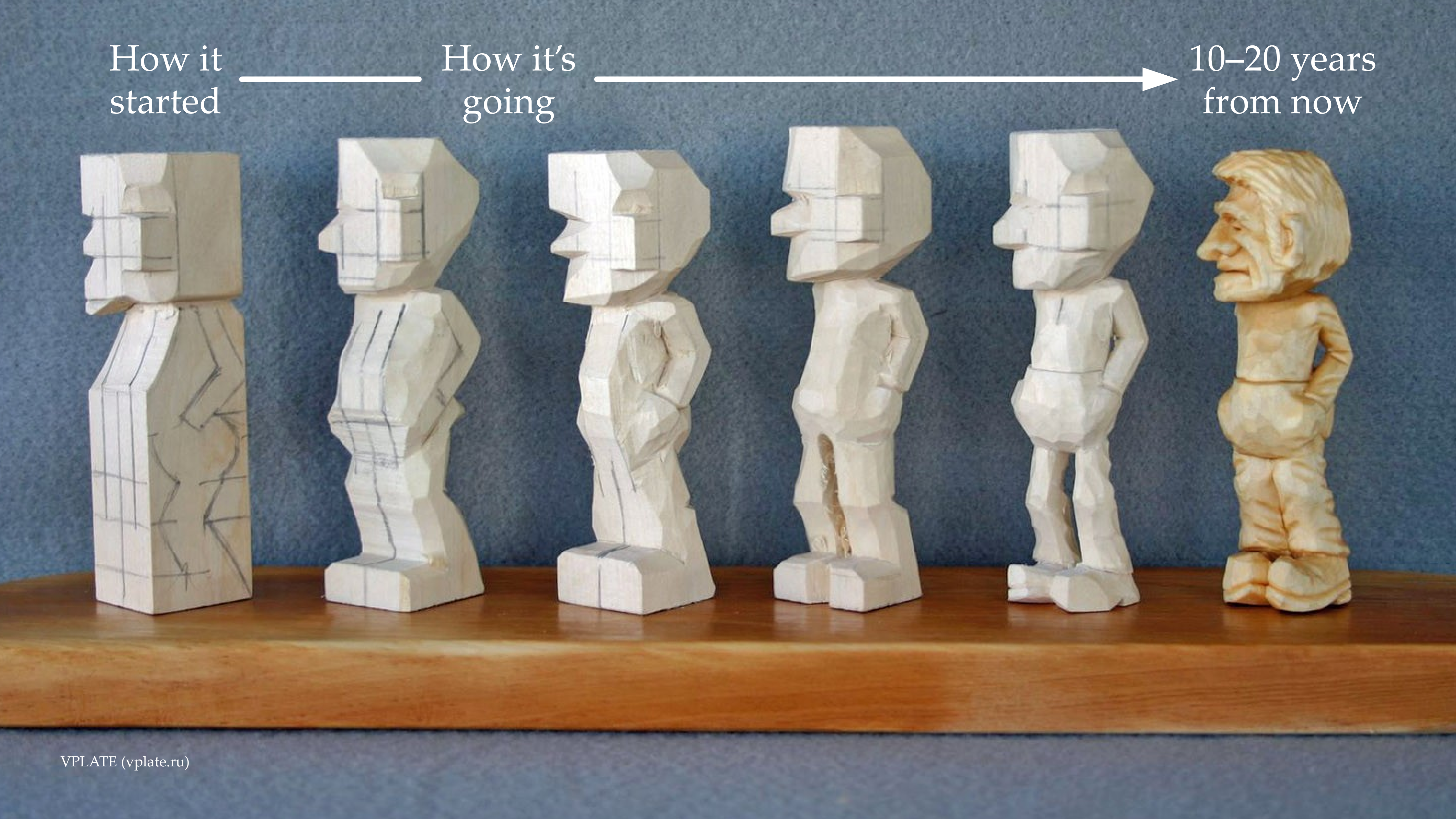


ATLAS

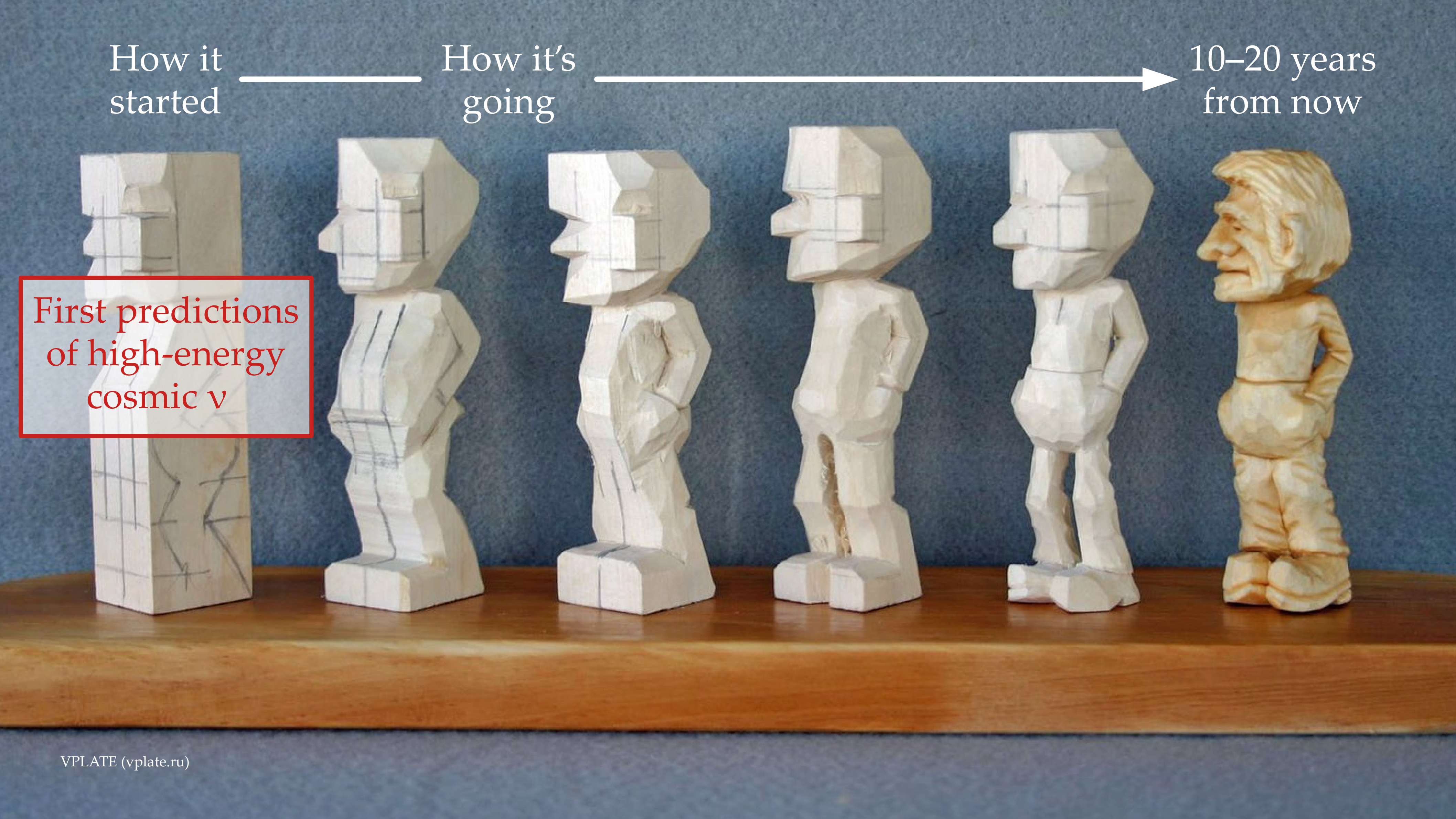


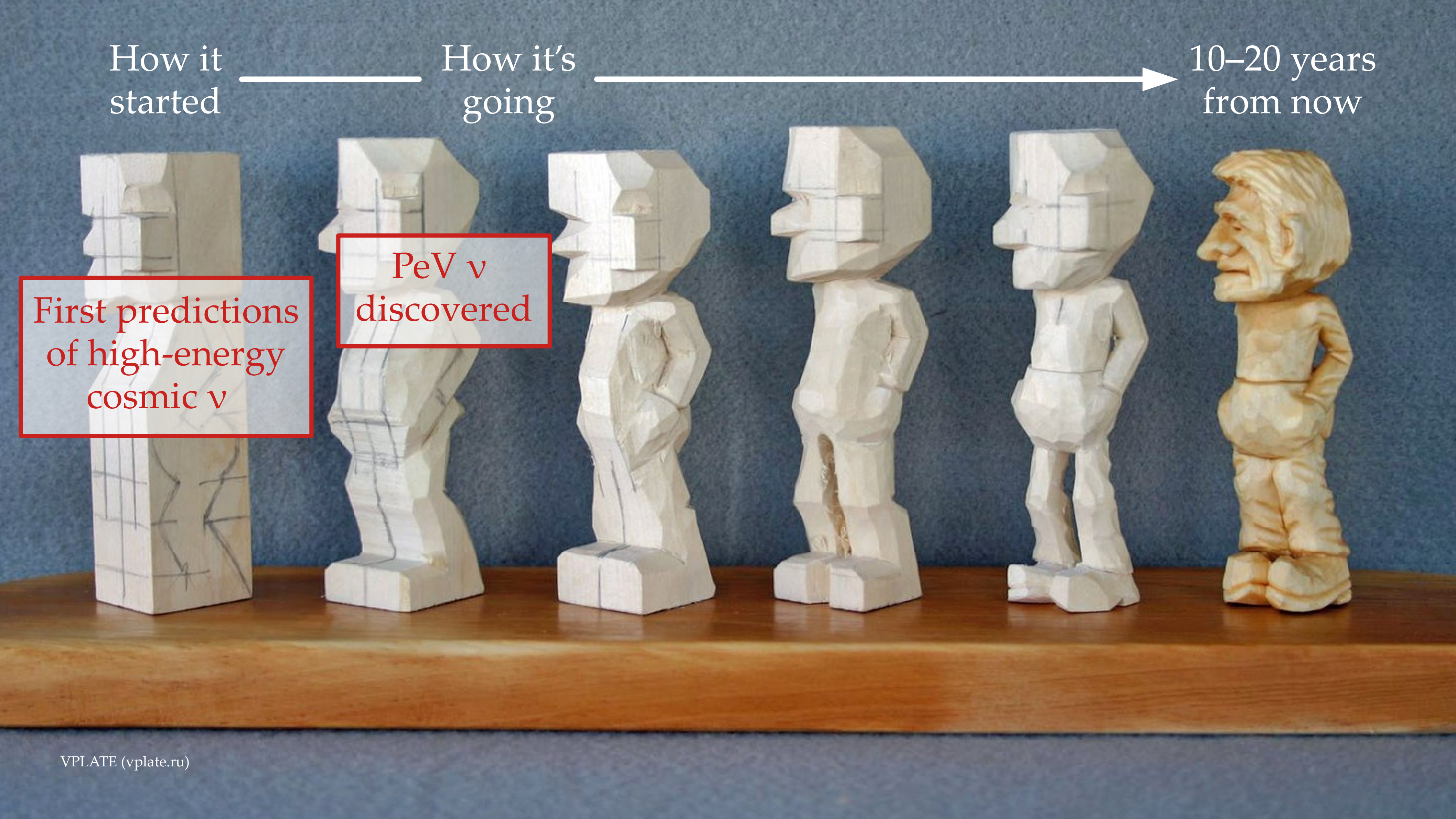
DESY

DESY

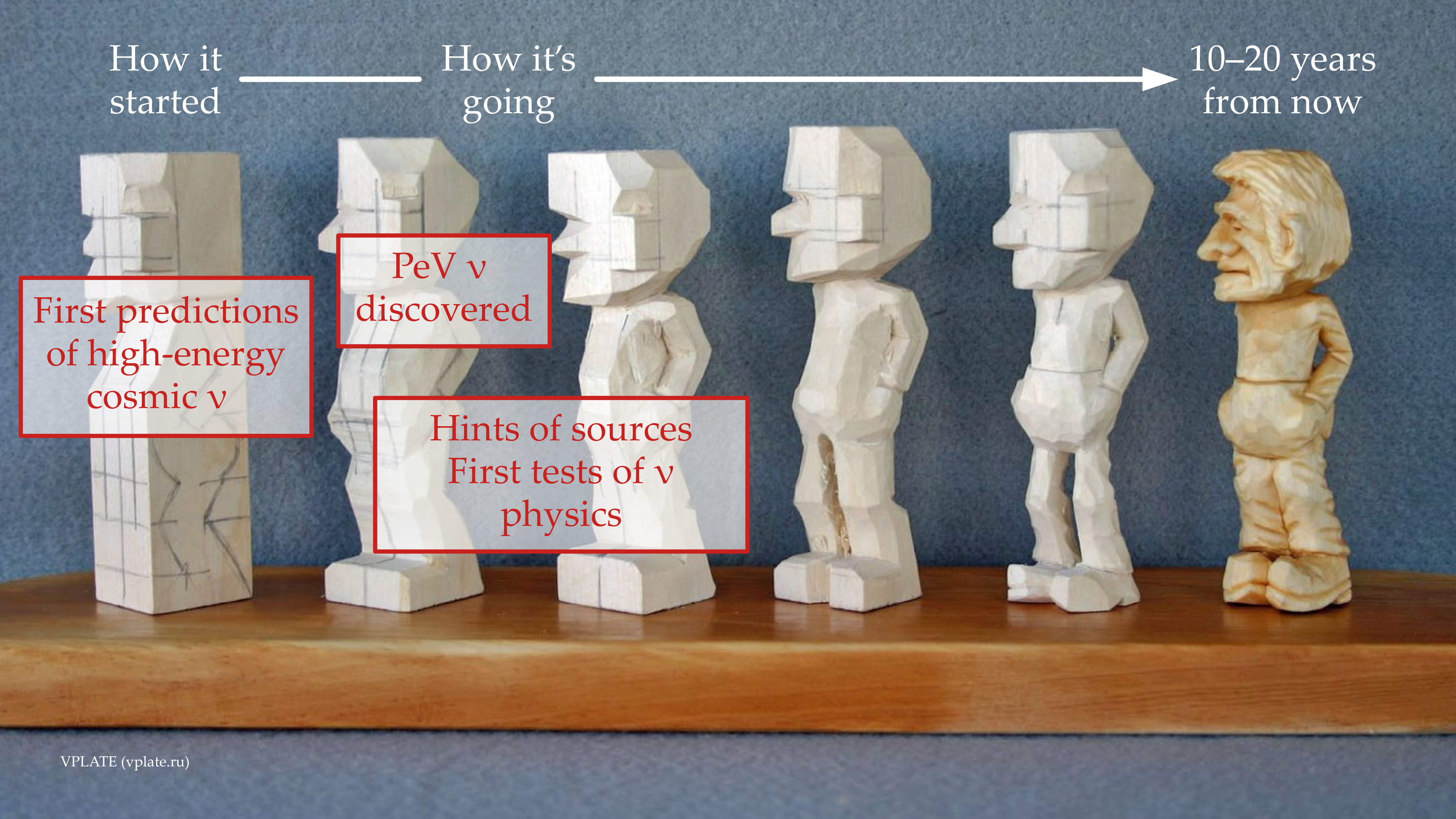


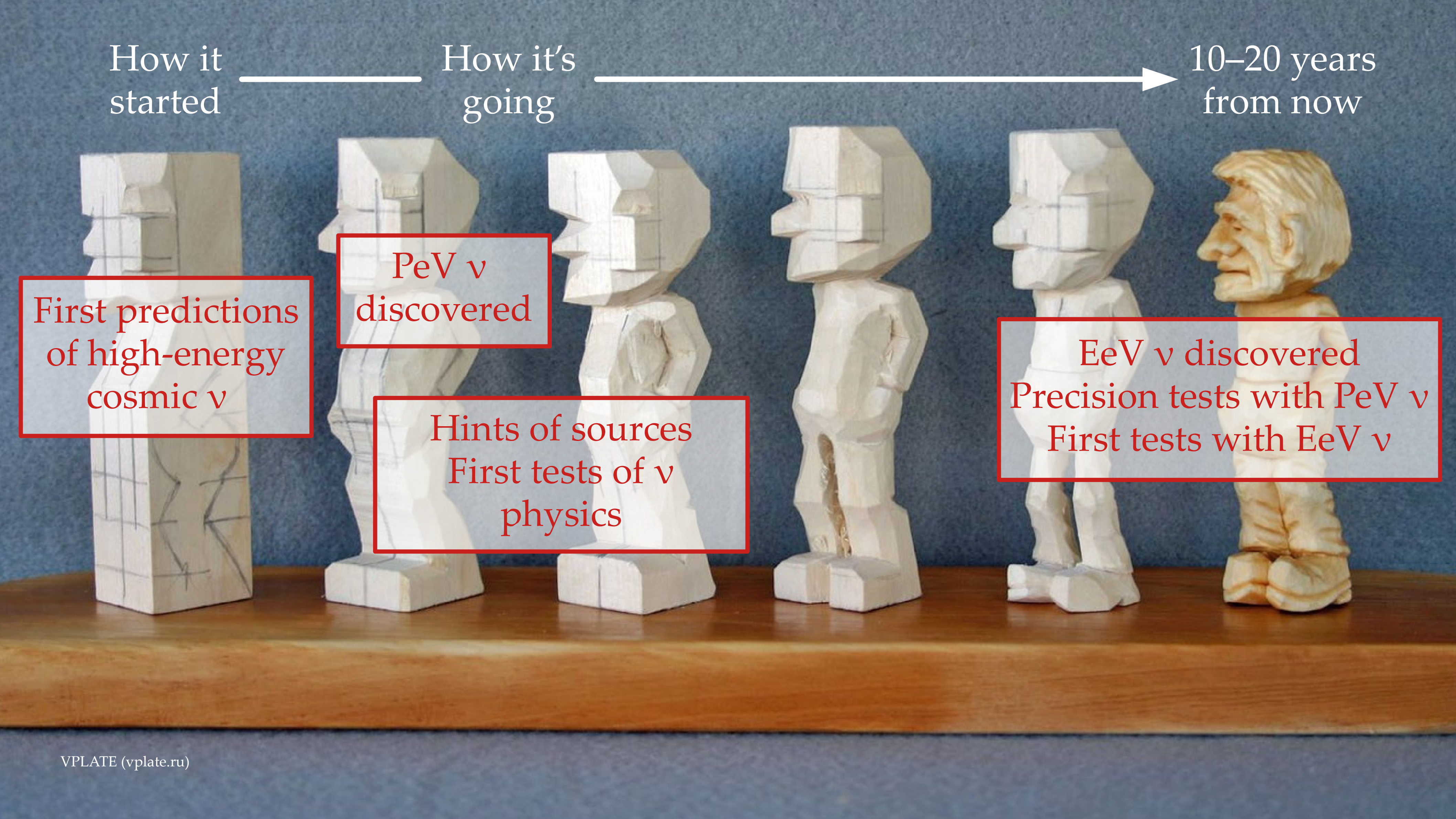
VPLATE (vplate.ru)

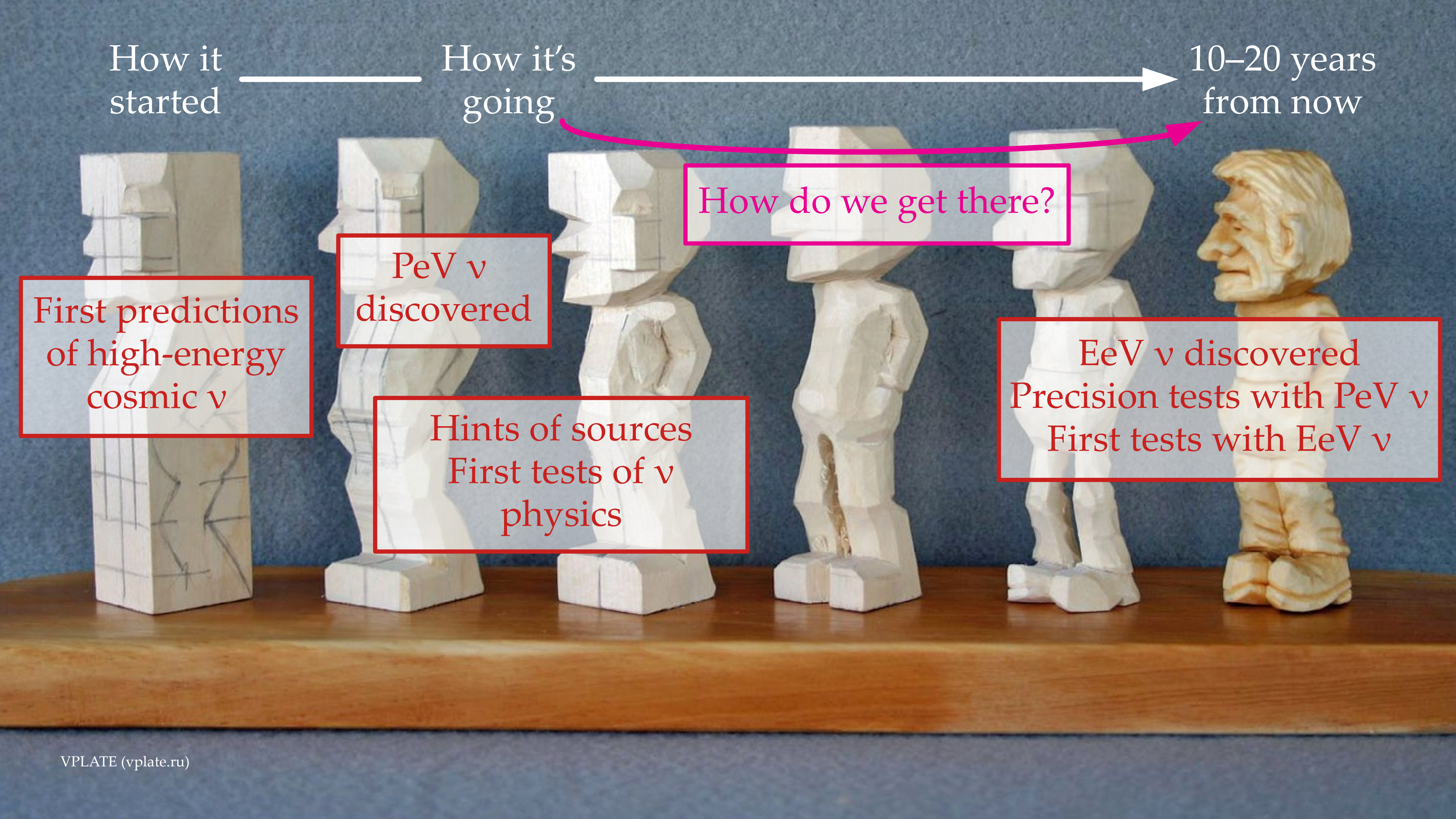

How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
VPLATE (vplate.ru)



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)

Neutrinos are elementary particles,

electrically neutral,

very light,

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

very light,

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

= *no electric charge*

very light,

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

= *no electric charge*

very light,

= *so light that we don't know their mass!*

and superbly antisocial

Neutrinos are elementary particles,

= *indivisible*

electrically neutral,

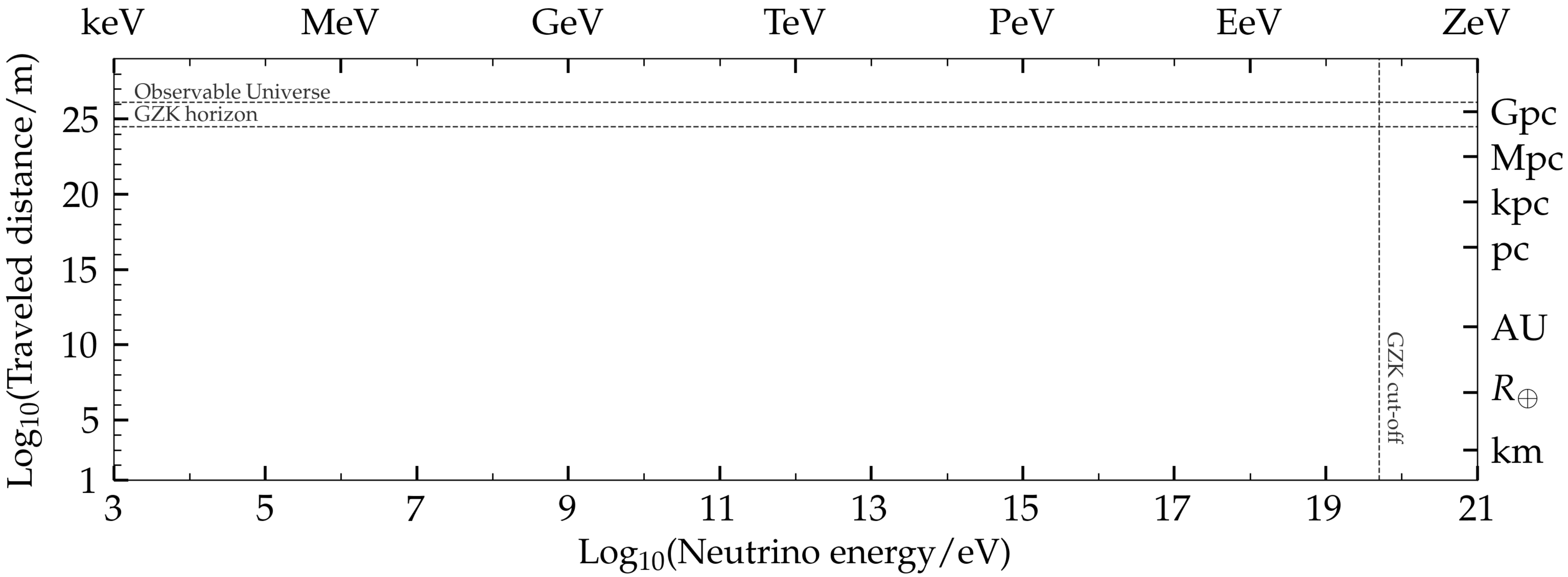
= *no electric charge*

very light,

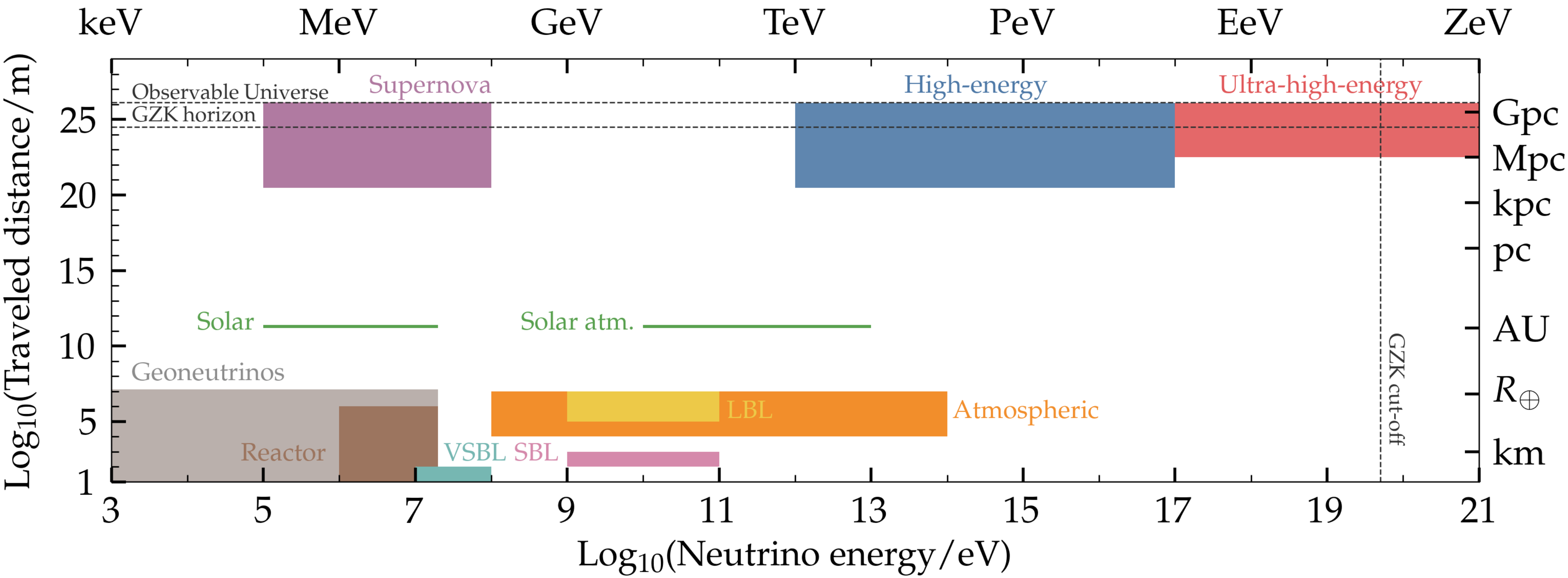
= *so light that we don't know their mass!*

and superbly antisocial

= *barely interact with matter*

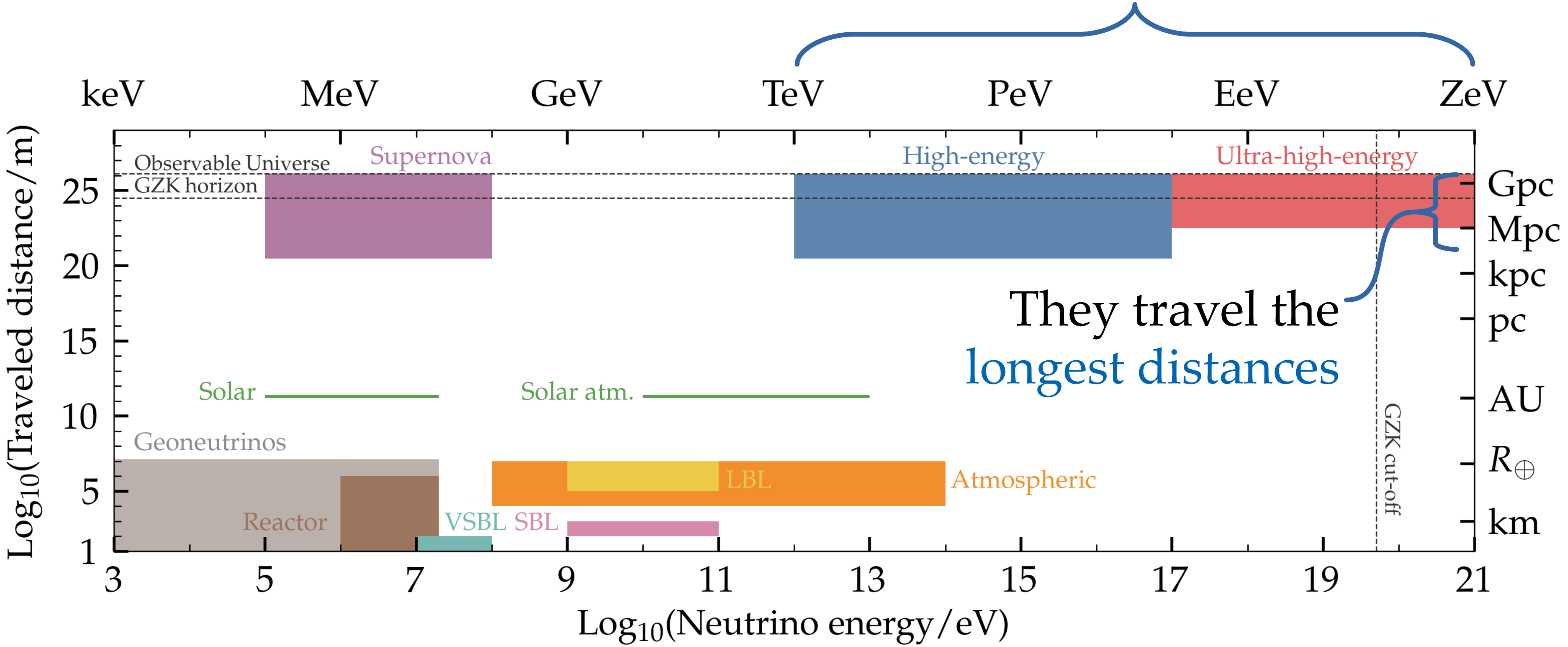


Ackermann, ***MB***, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

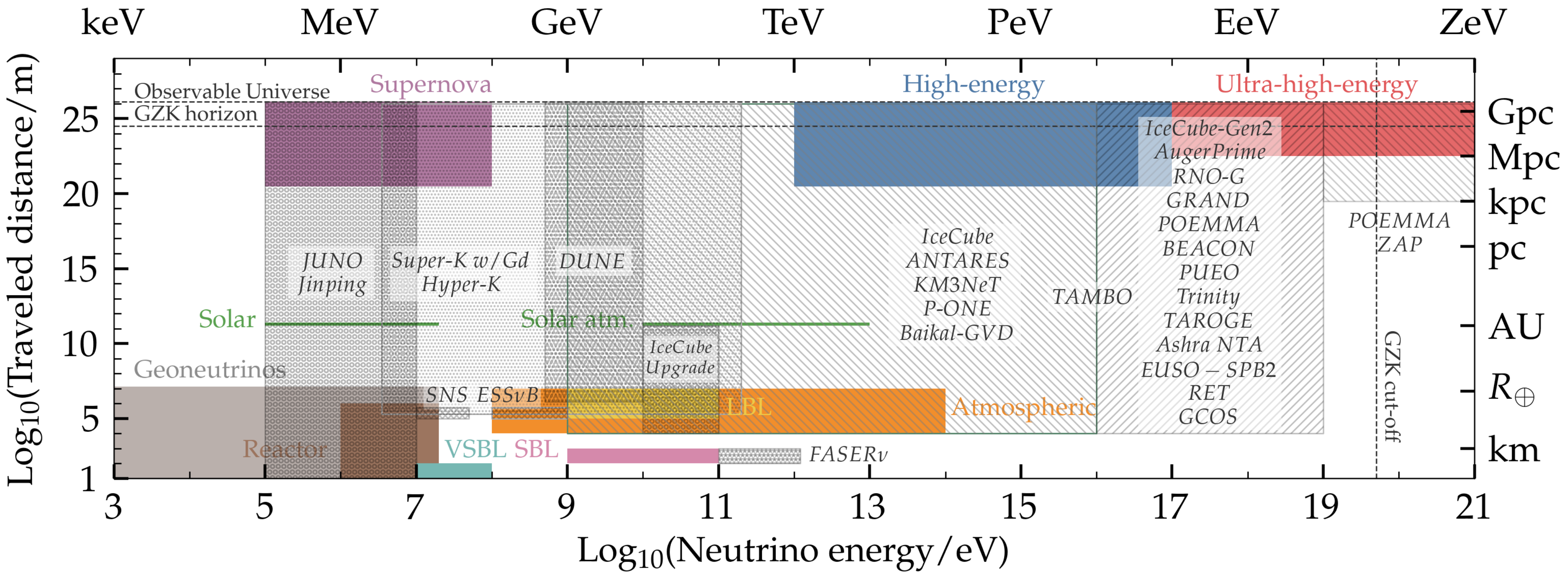


Ackermann, ***MB***, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

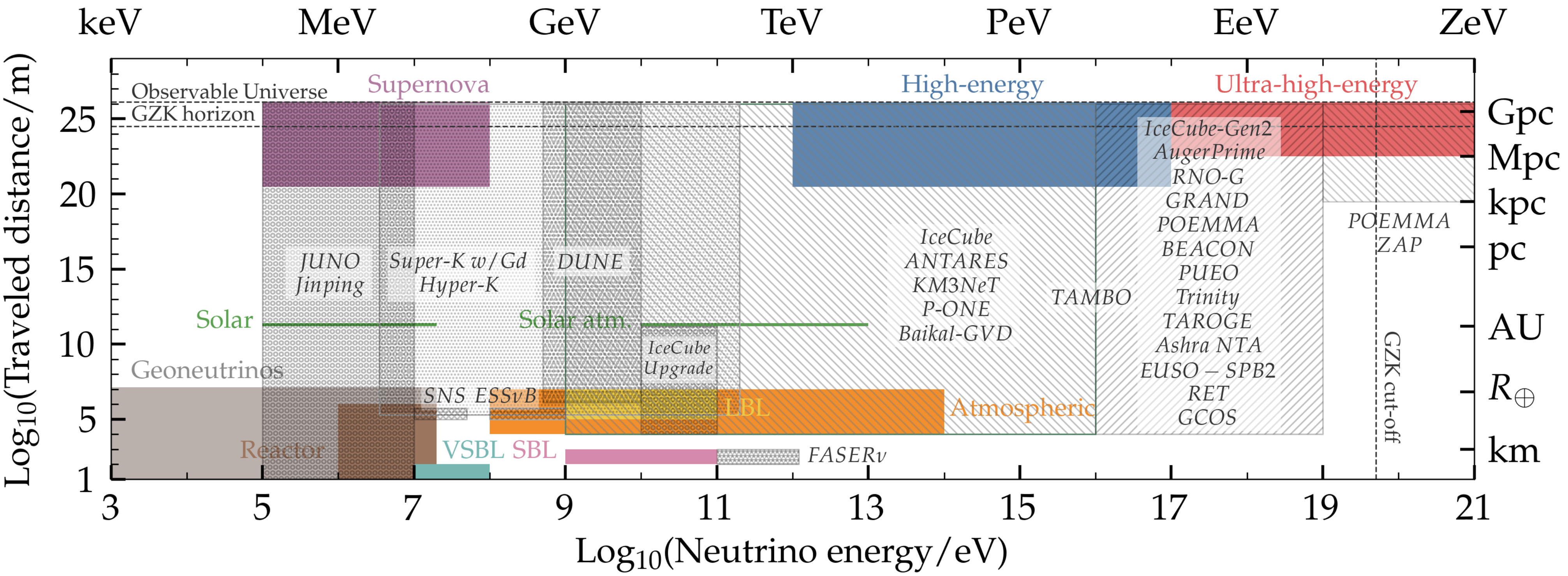
They have the highest energies



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

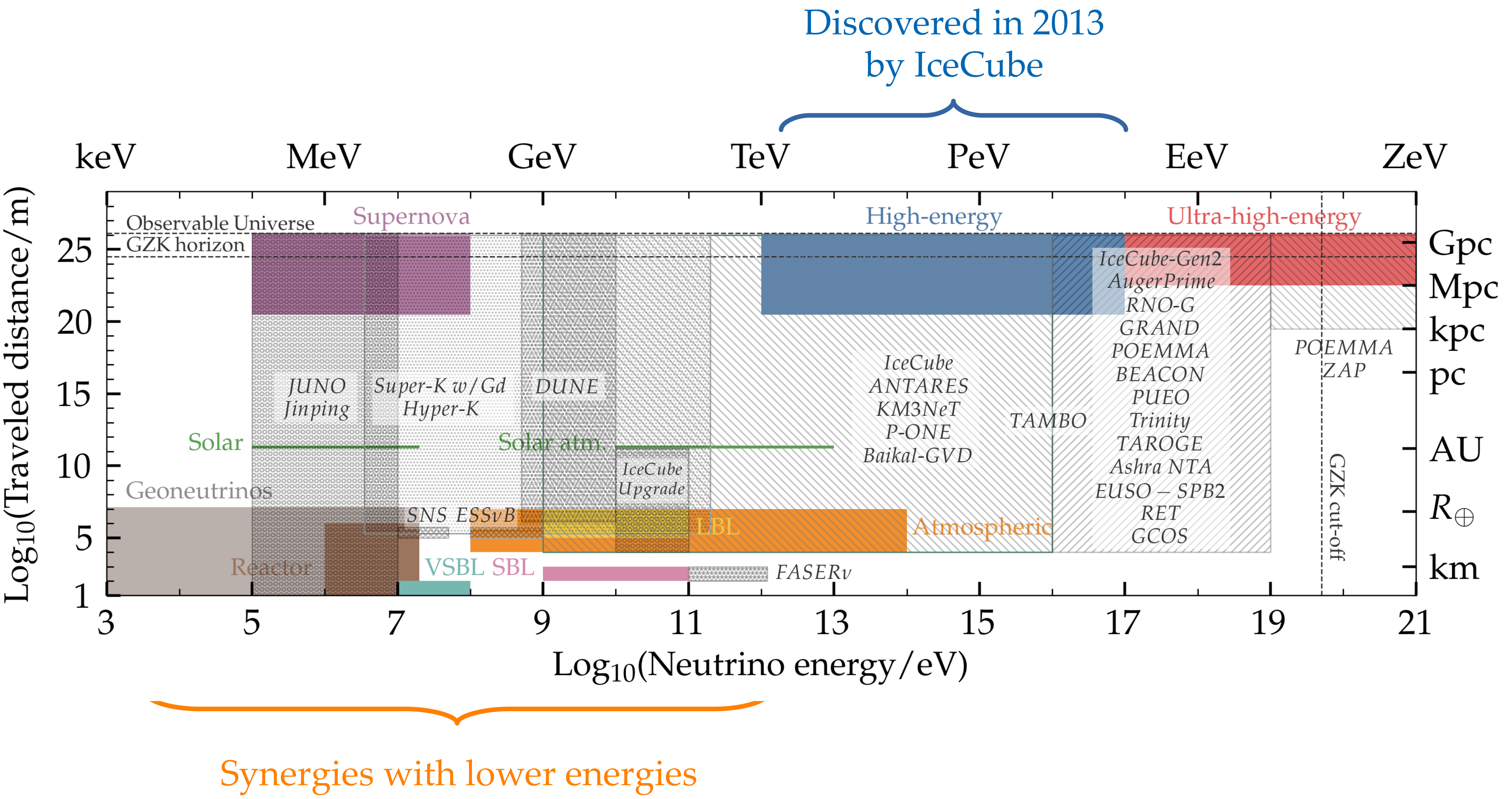


Ackermann, ***MB***, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



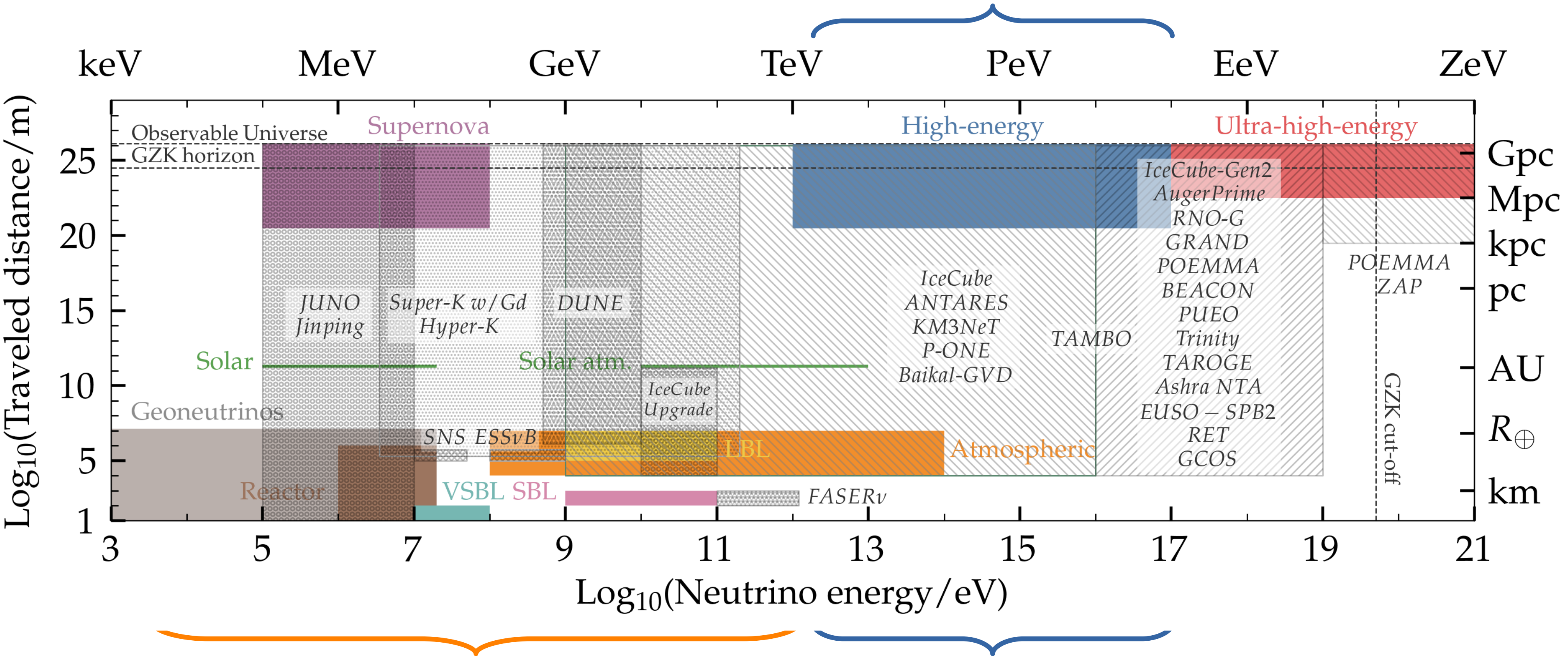
Synergies with lower energies

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



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

Discovered in 2013
by IceCube



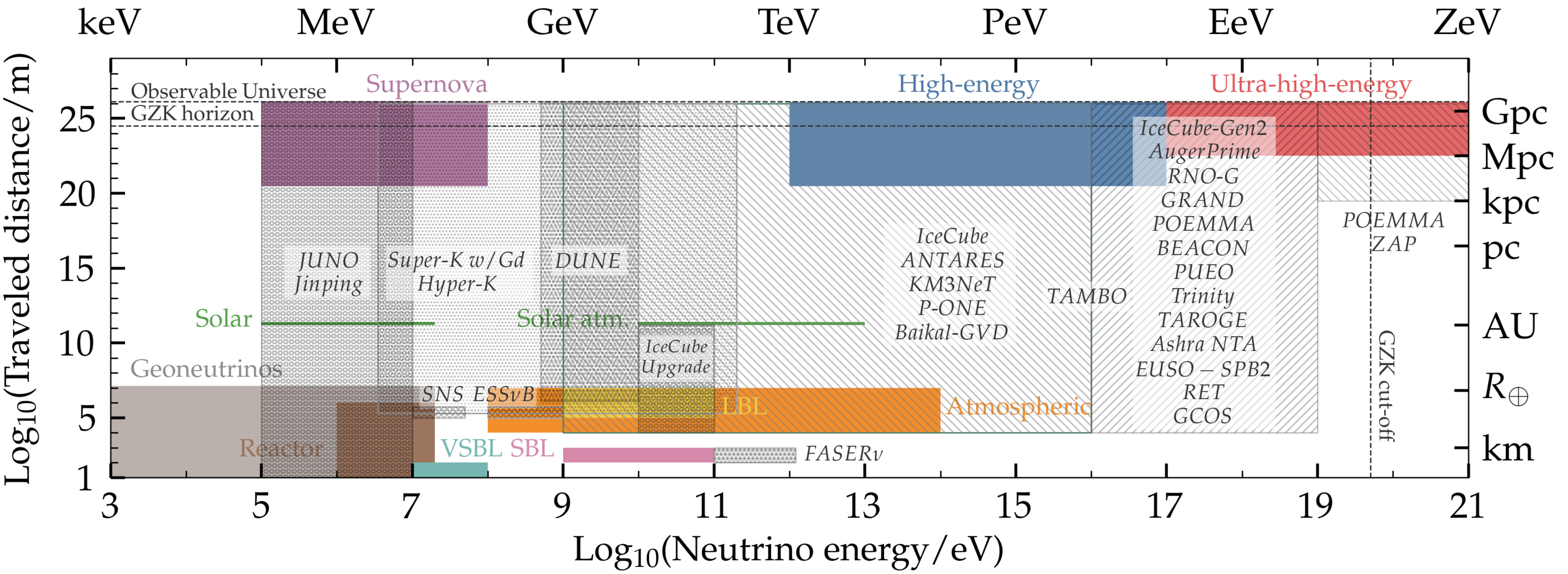
Synergies with lower energies

Increase TeV–PeV
ν statistics

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

Discovered in 2013 by IceCube

Predicted in 1969 by Berezinksy



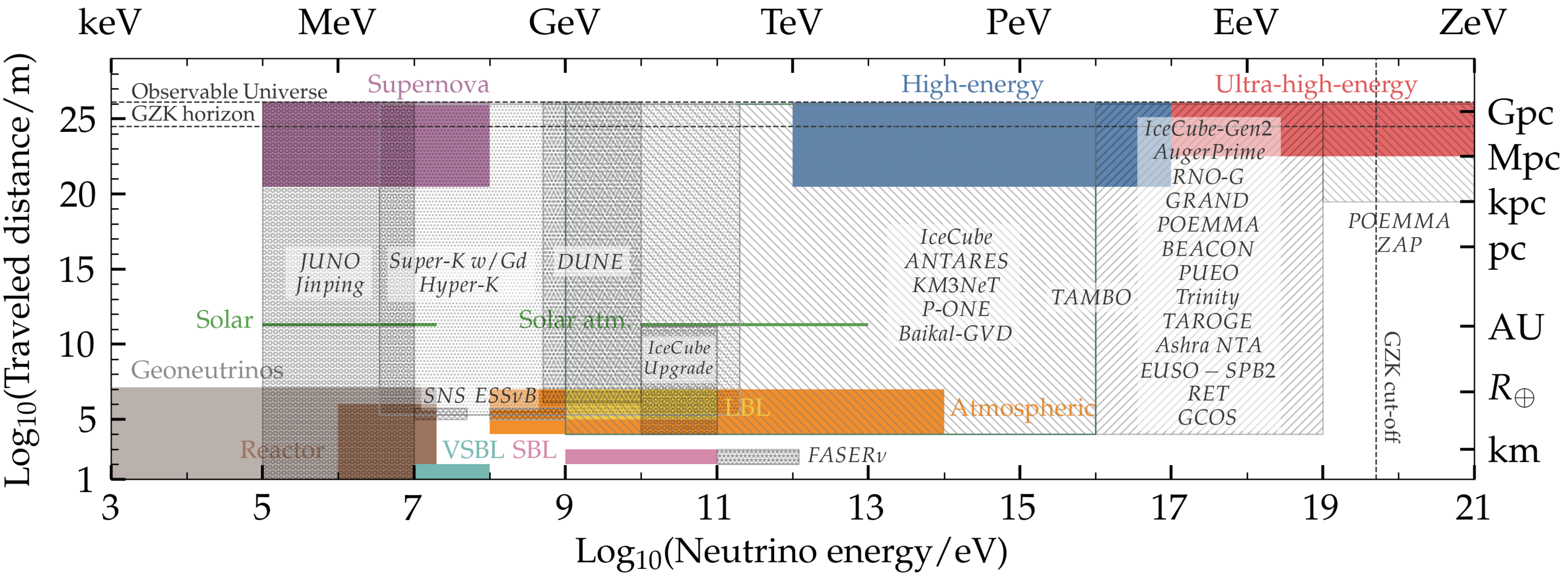
Synergies with lower energies

Increase TeV–PeV ν statistics

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

Discovered in 2013
by IceCube

Predicted in 1969
by Berezinksy



Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

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

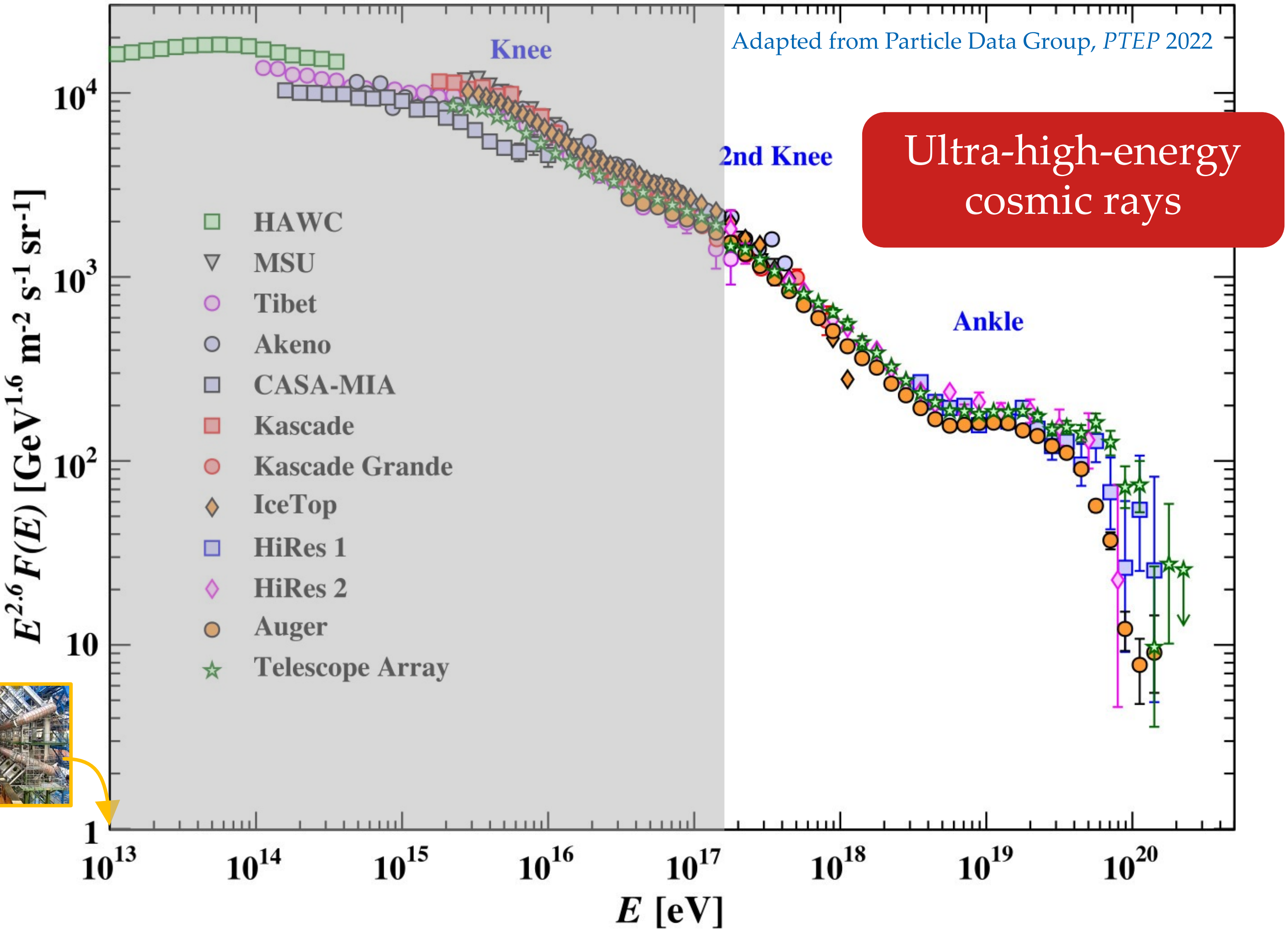
Today
TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

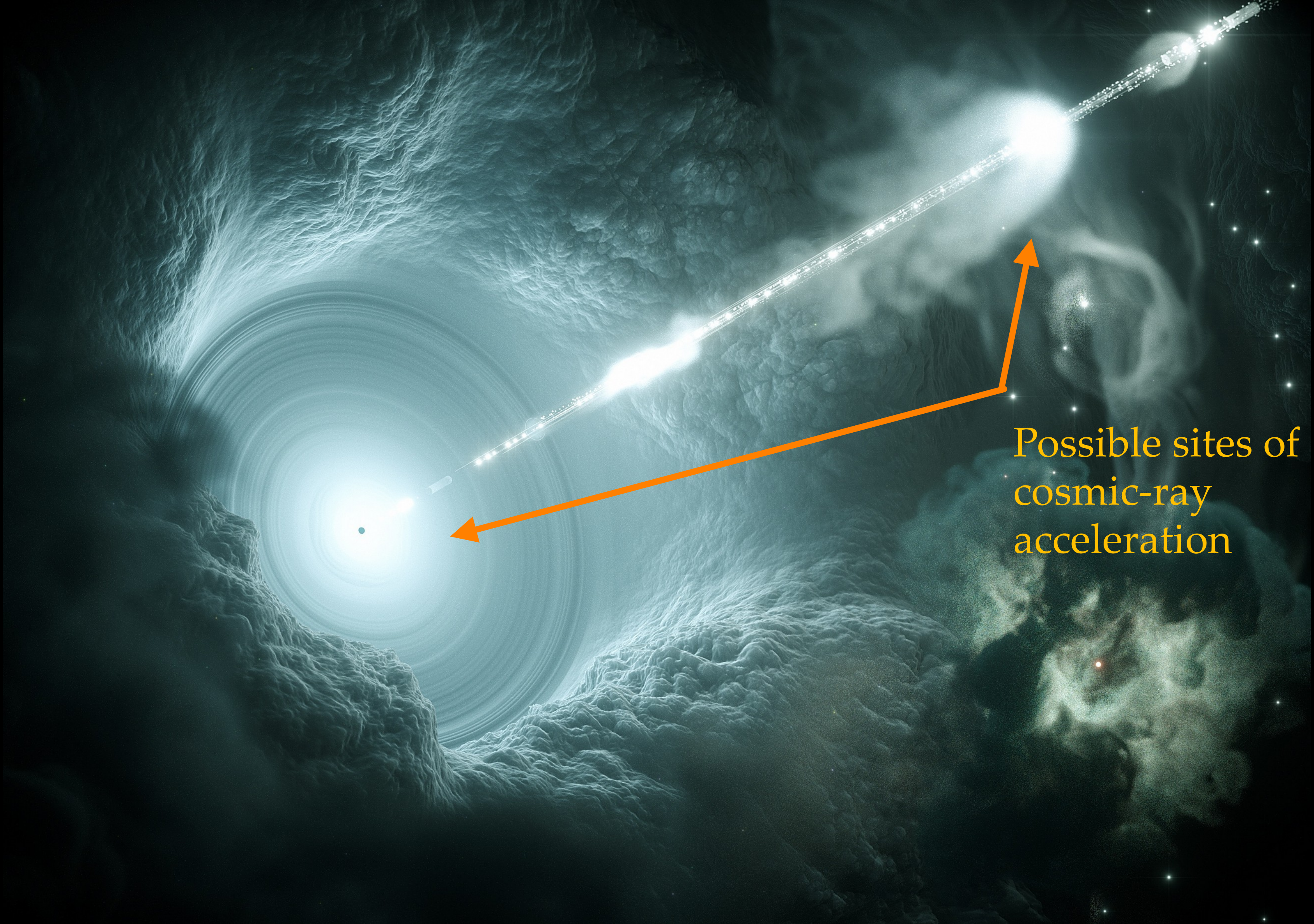
Next decade
> 100-PeV ν

Make predictions for a new energy regime



10^{12} eV

6×10^{20} eV



DESY

The multi-messenger connection: a simple picture

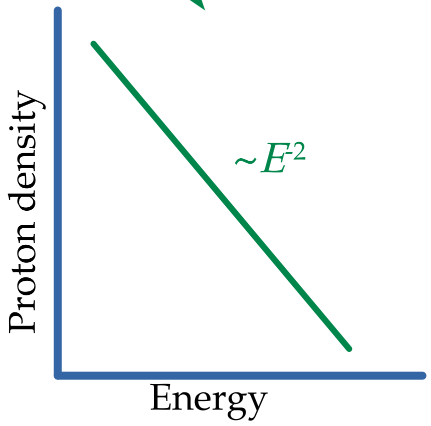
(or $p+p$)

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

The multi-messenger connection: a simple picture

(or $p + p$)

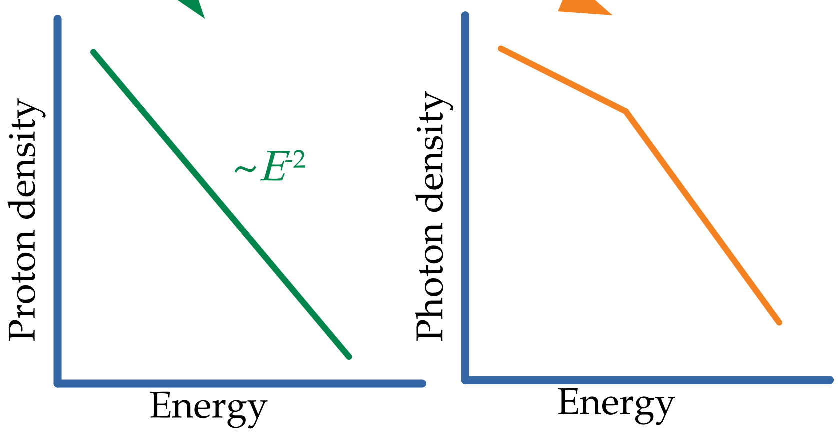
$$p + \gamma_{\mathrm{target}} \longrightarrow \Delta^{+} \longrightarrow \begin{cases} p + \pi^{0}, & \mathrm{Br} = 2/3 \\ n + \pi^{+}, & \mathrm{Br} = 1/3 \end{cases}$$



The multi-messenger connection: a simple picture

(or $p + p$)

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



The multi-messenger connection: a simple picture

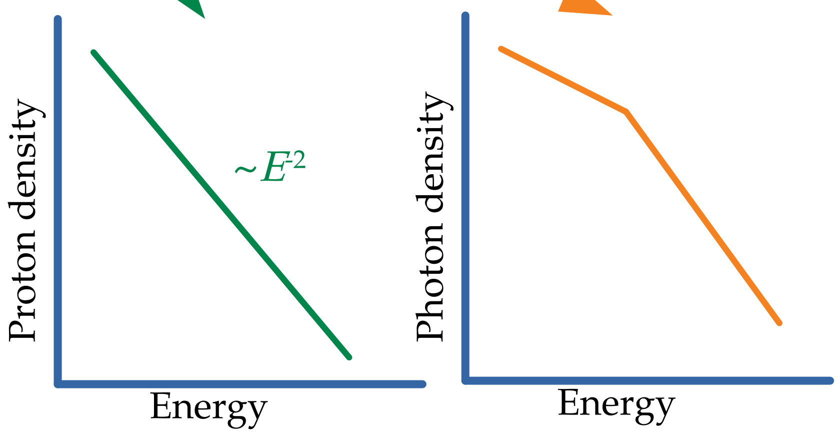
(or $p + p$)

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

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

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

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



The multi-messenger connection: a simple picture

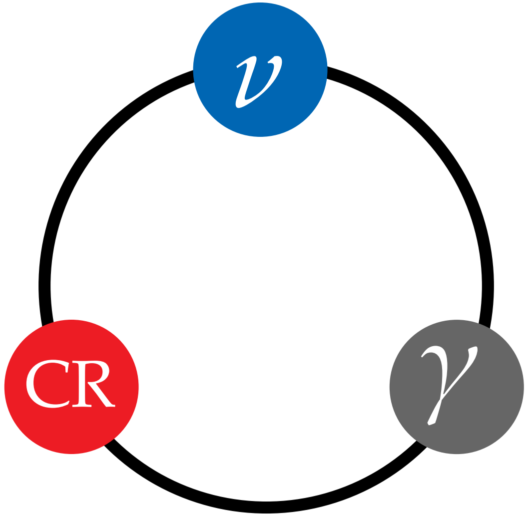
(or $p + p$)

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

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

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

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



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

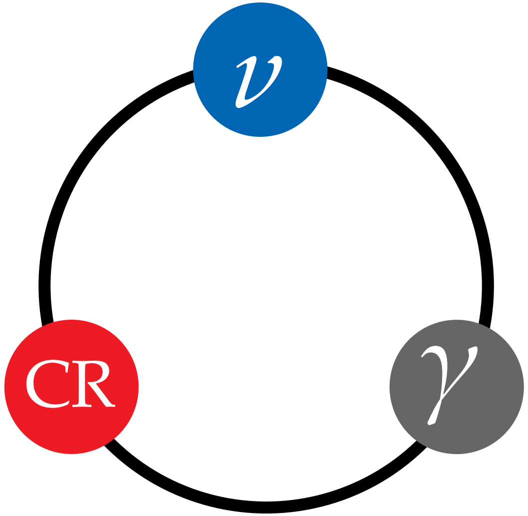
(or $p + p$)

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

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

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

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



1 PeV 20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

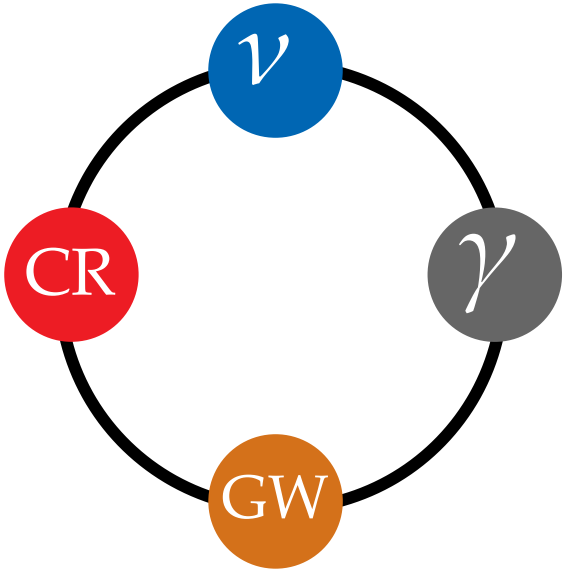
(or $p + p$)

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

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

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

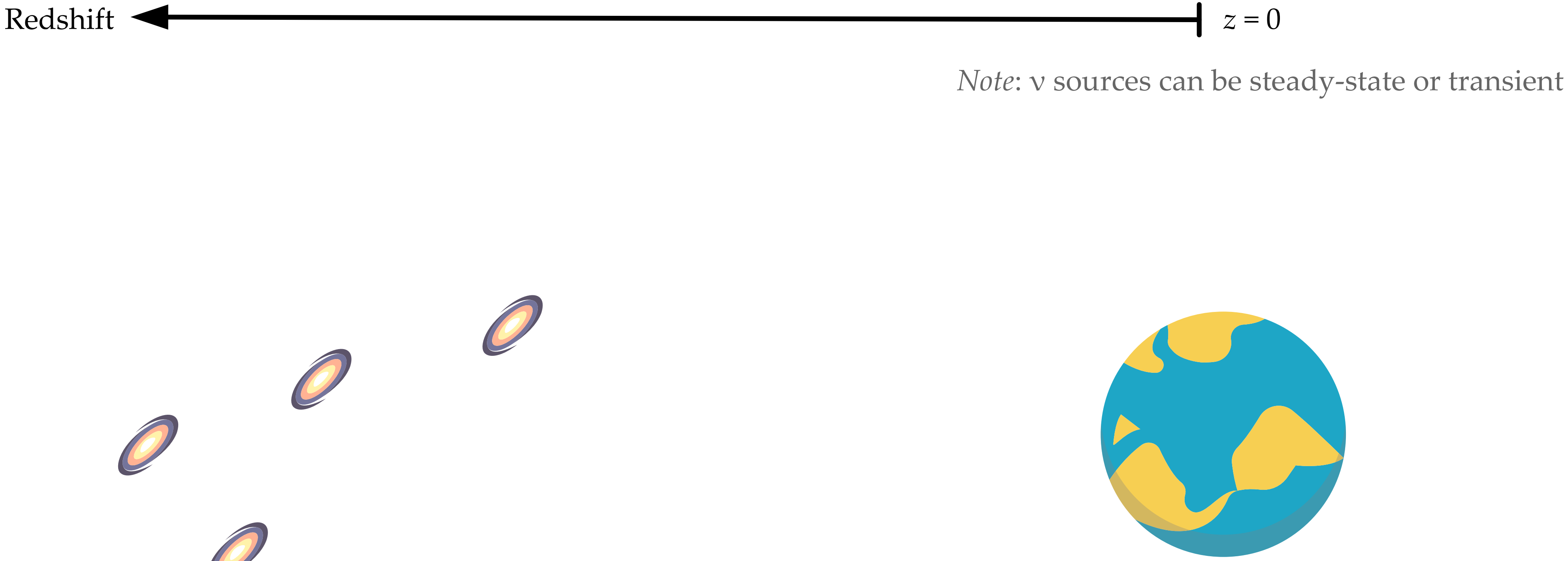
$$n \text{ (escapes)} \longrightarrow p + e^- + \bar{\nu}_e$$

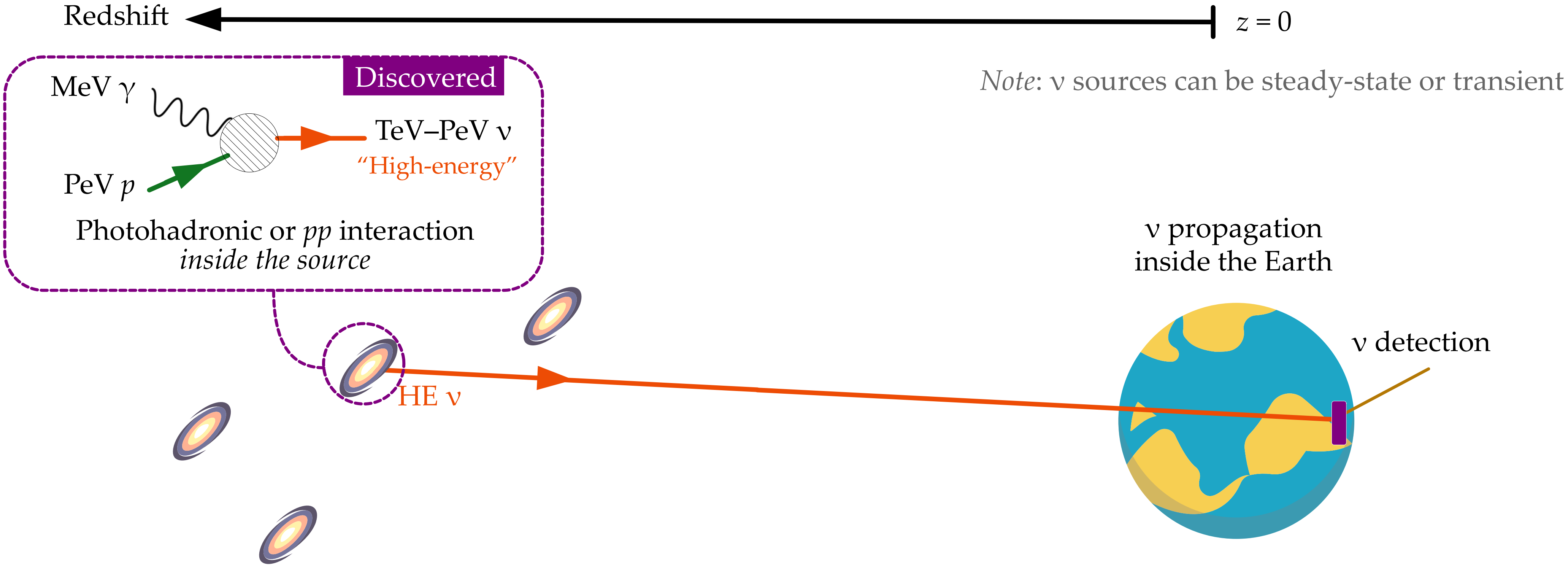


1 PeV 20 PeV

Neutrino energy = Proton energy / 20

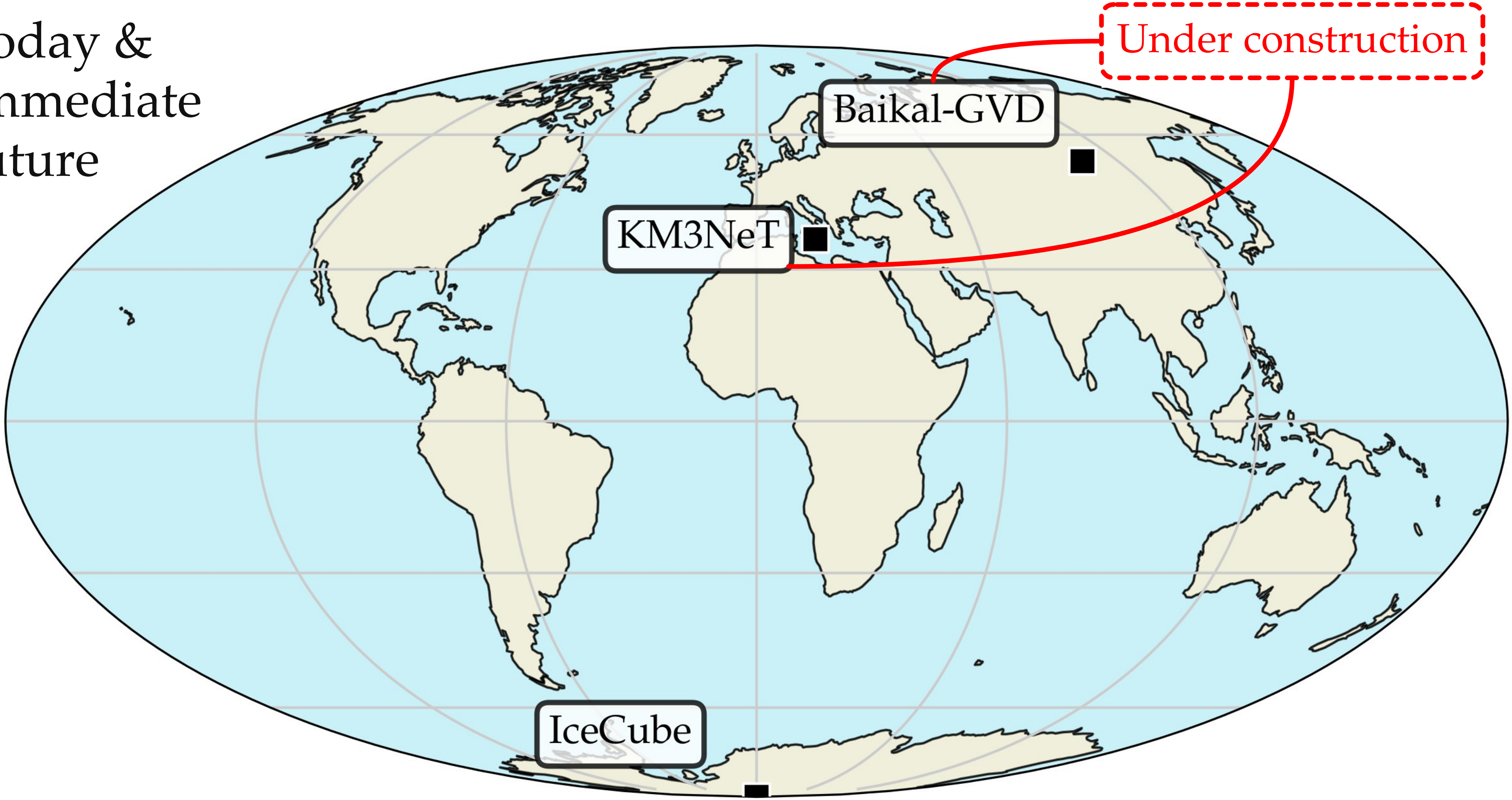
Gamma-ray energy = Proton energy / 10


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



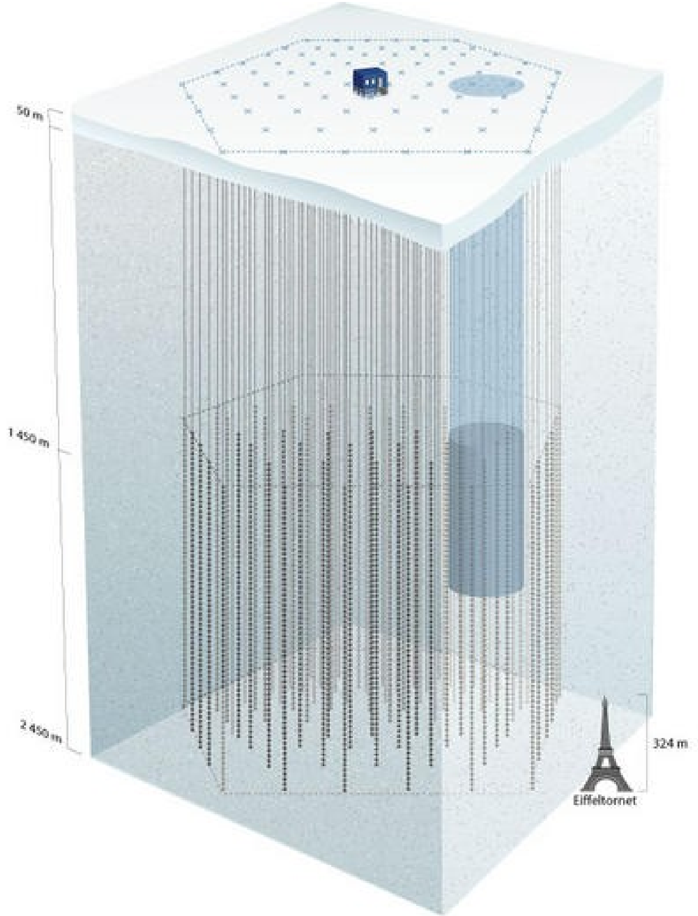
Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

Today &
immediate
future



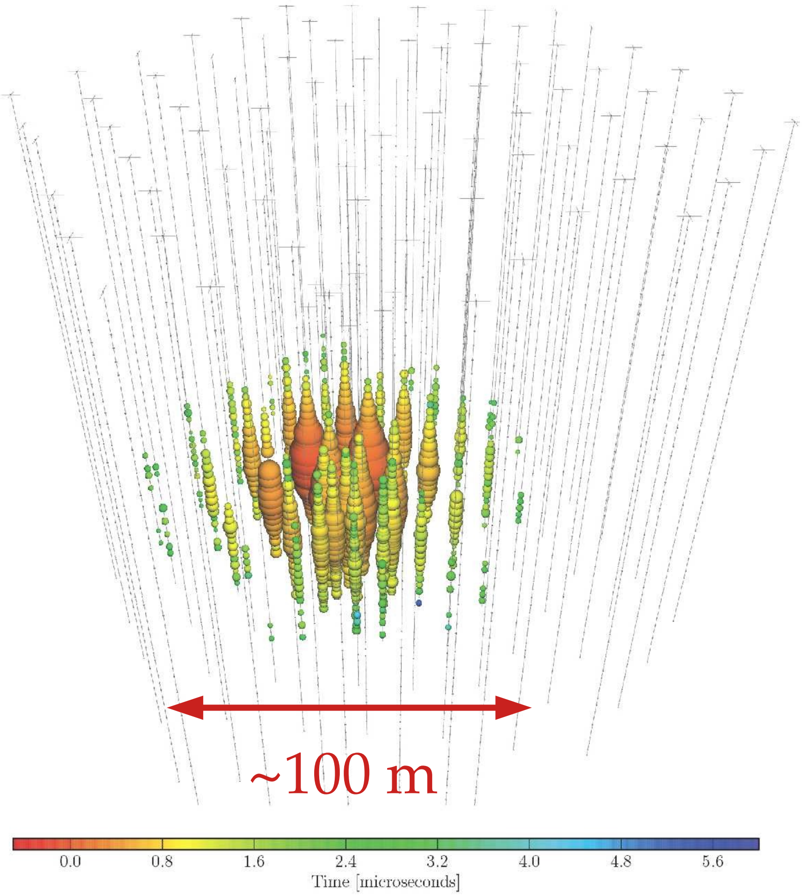
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

IceCube – What is it?



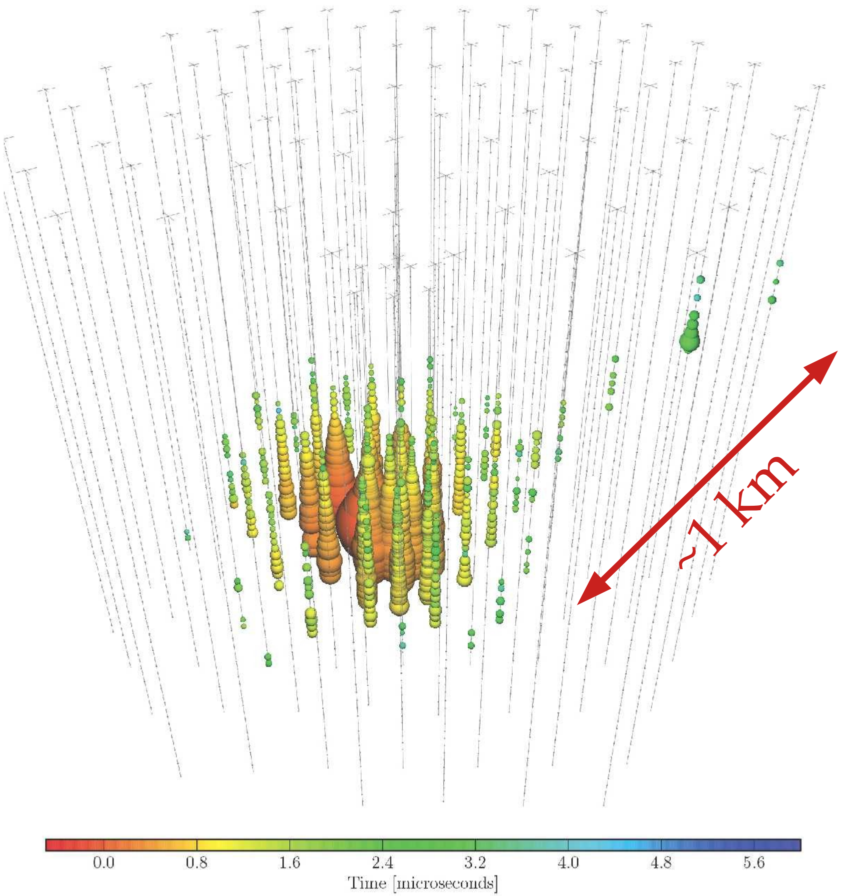
- Km³ in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

Shower
(mainly from ν_e and ν_τ)

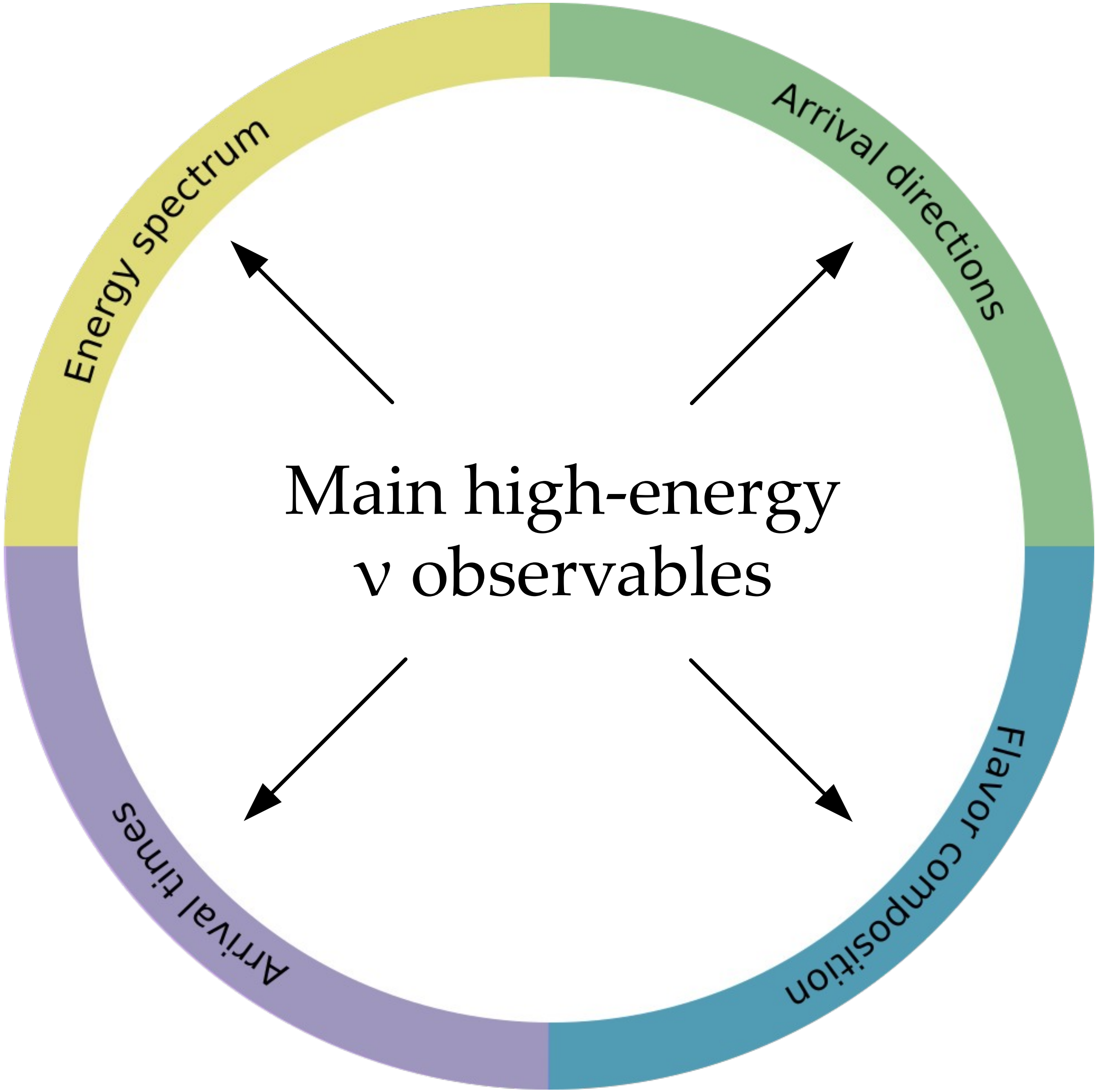


Poor angular resolution: < 5°

Track
(mainly from ν_μ)

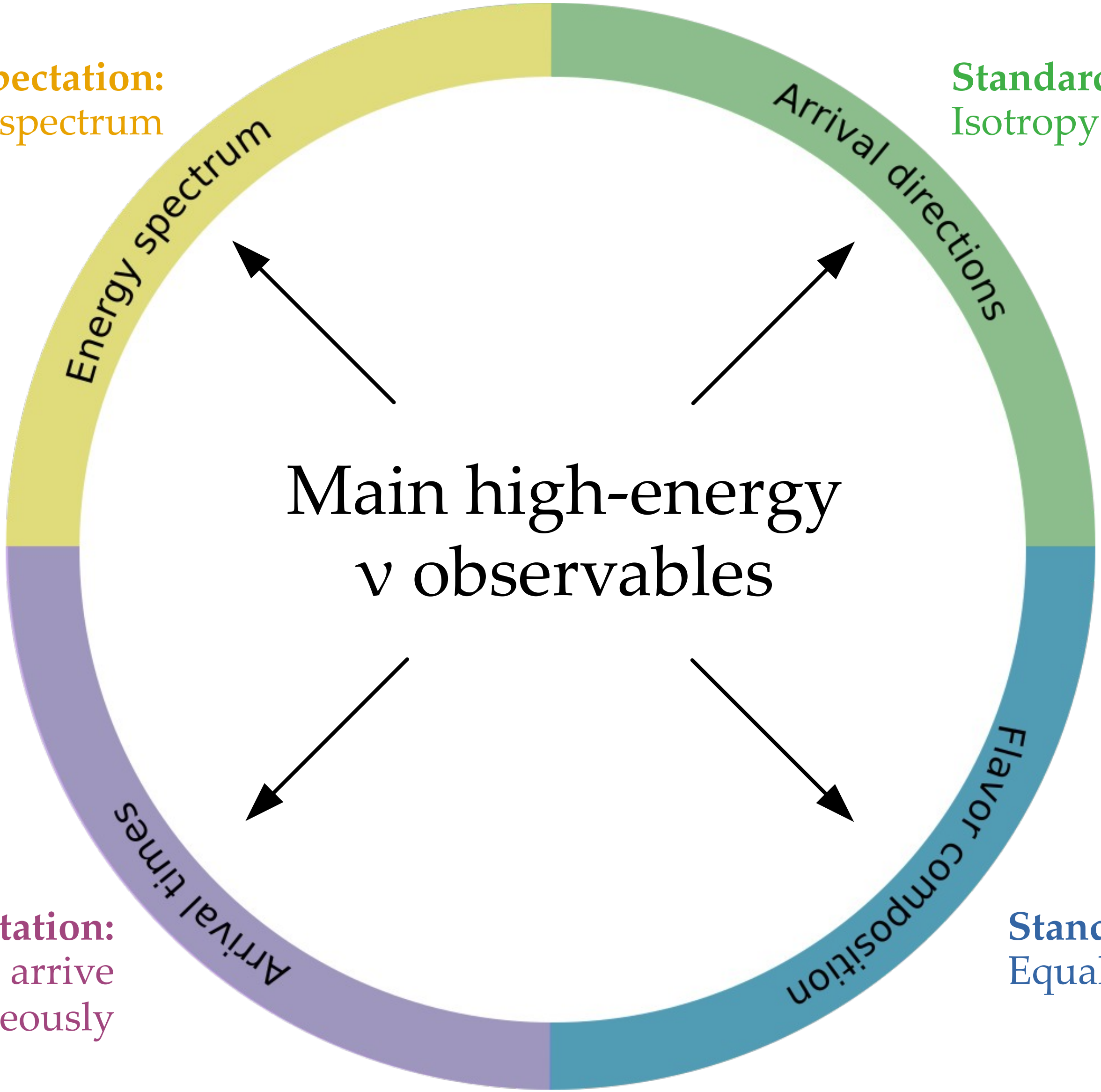


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

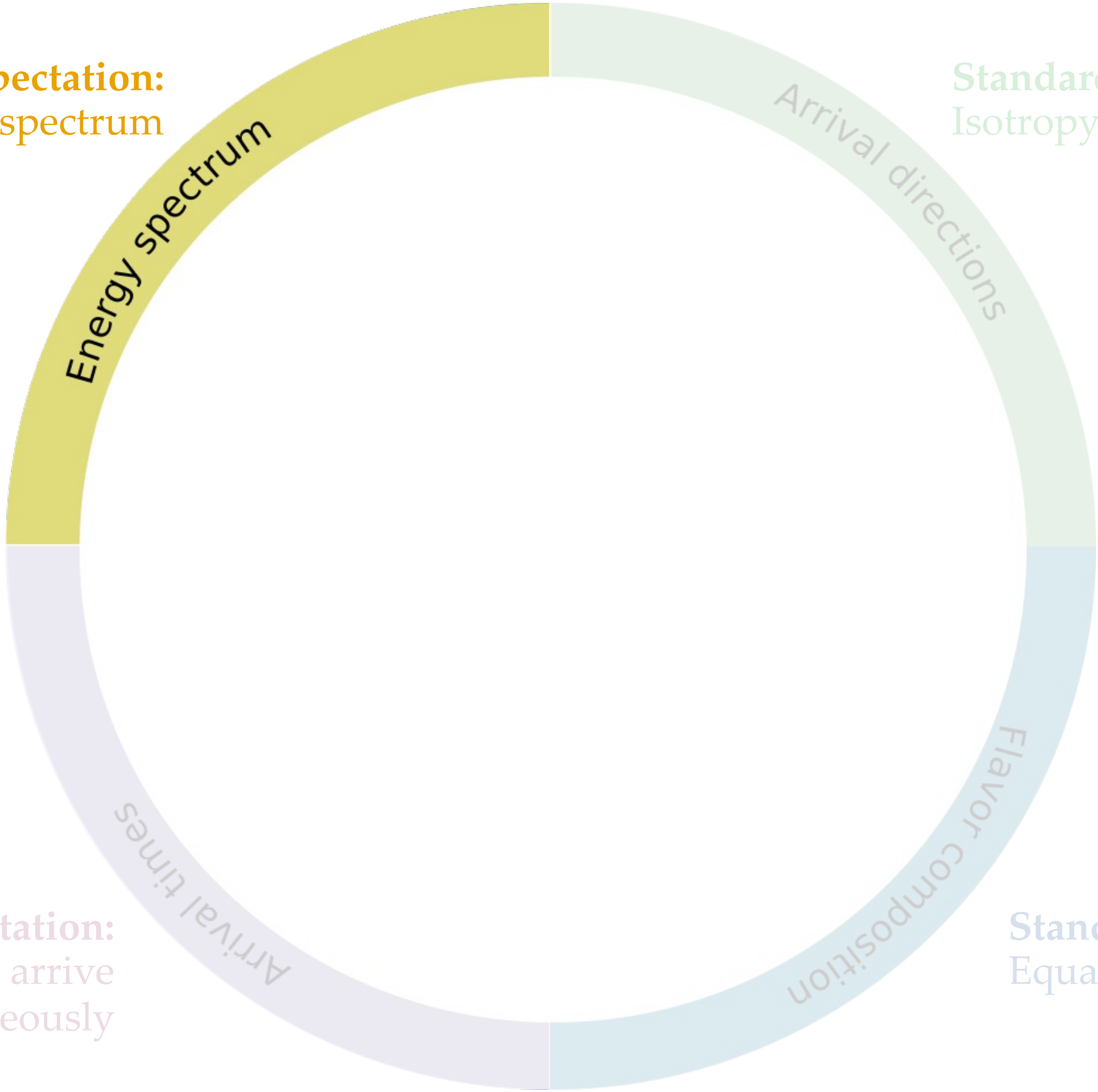


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

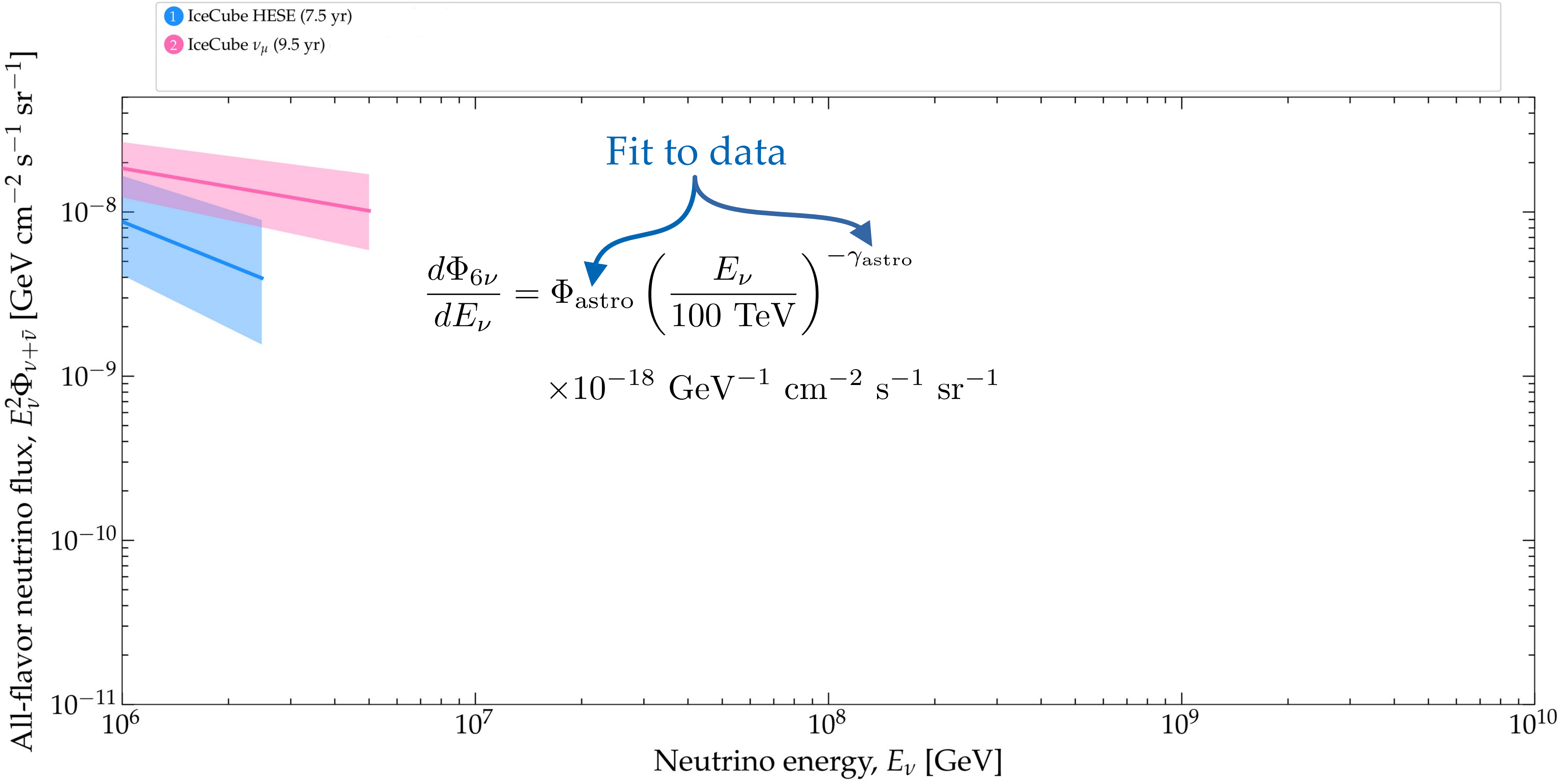
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

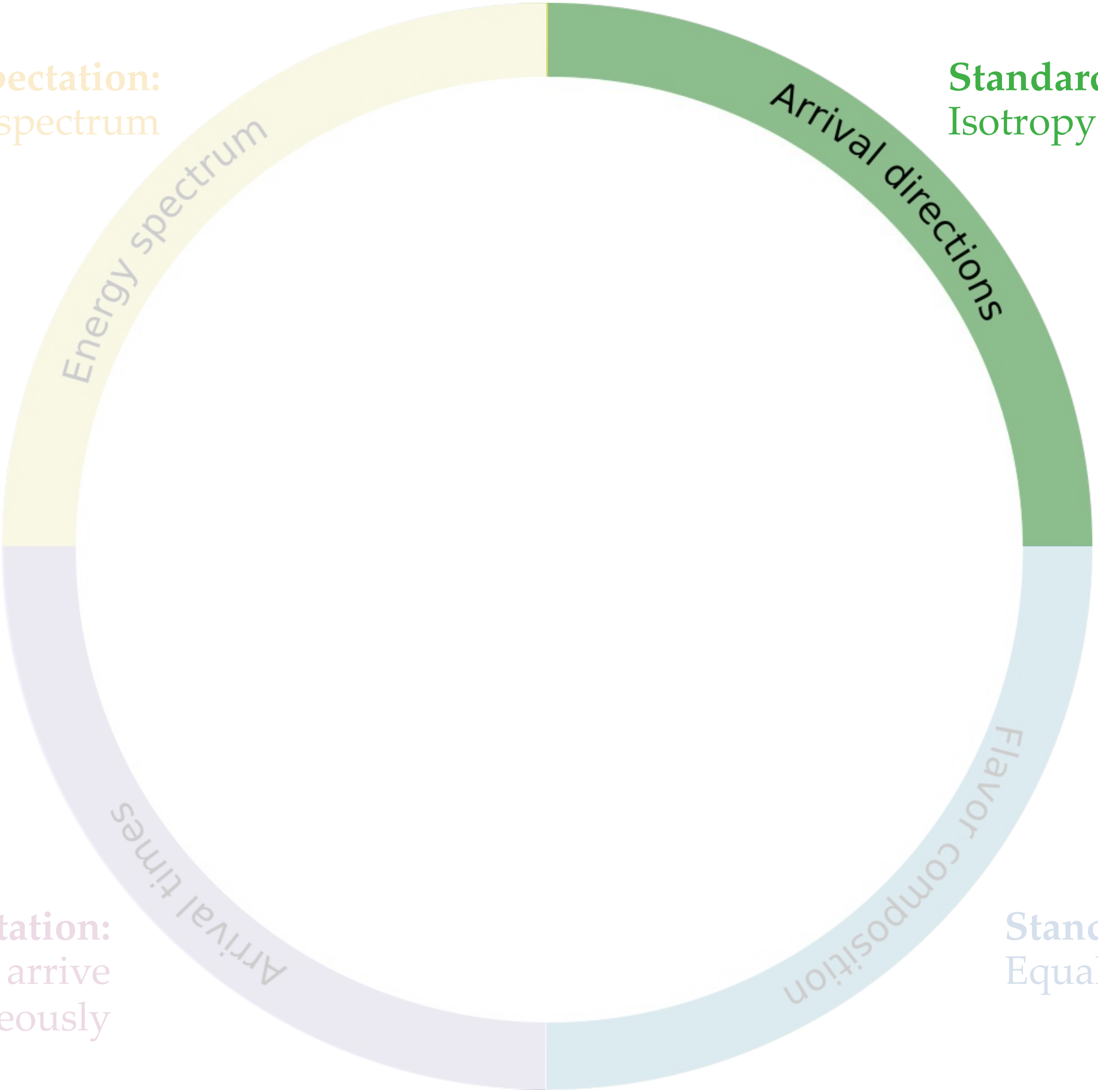
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ



$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro} \left(\frac{E_\nu}{100~\rm TeV} \right)^{-\gamma_{\rm astro}}$$

$$\times 10^{-18}~\rm GeV^{-1}~cm^{-2}~s^{-1}~sr^{-1}$$

Standard expectation:
Power-law energy spectrum



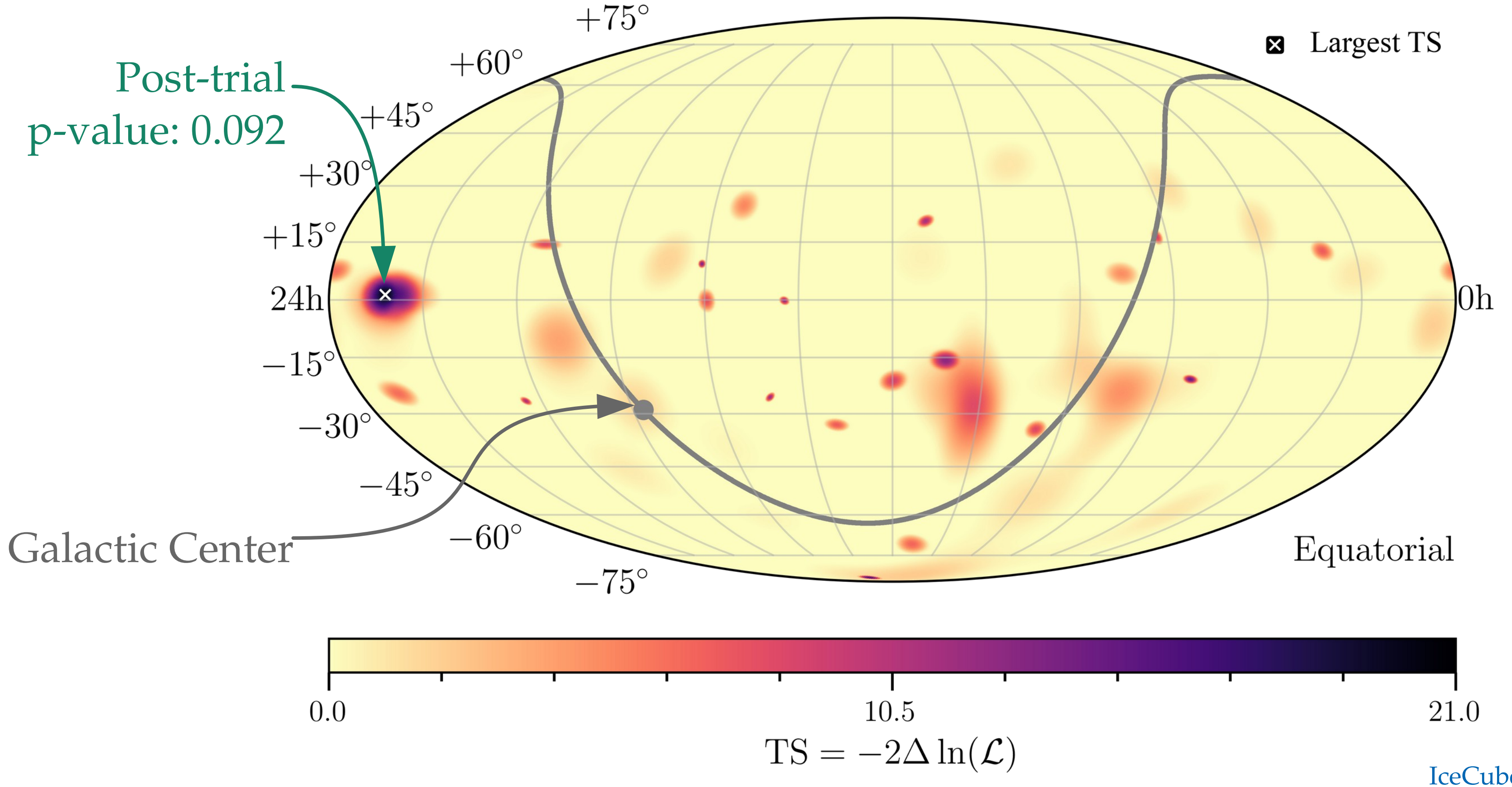
Standard expectation:
Isotropy (for diffuse flux)

Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

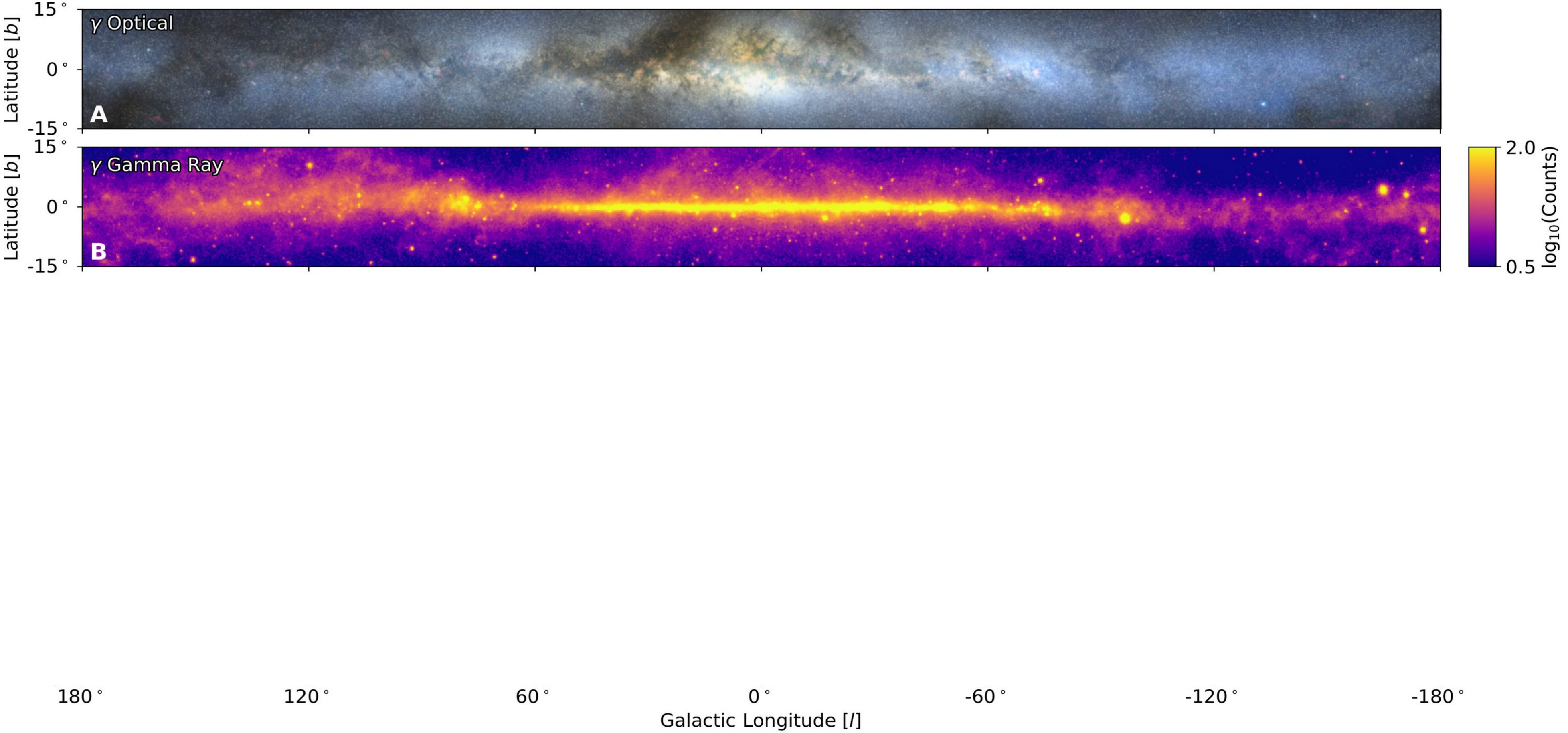
Arrival directions (7.5 yr)

No significant excess in the neutrino sky map:



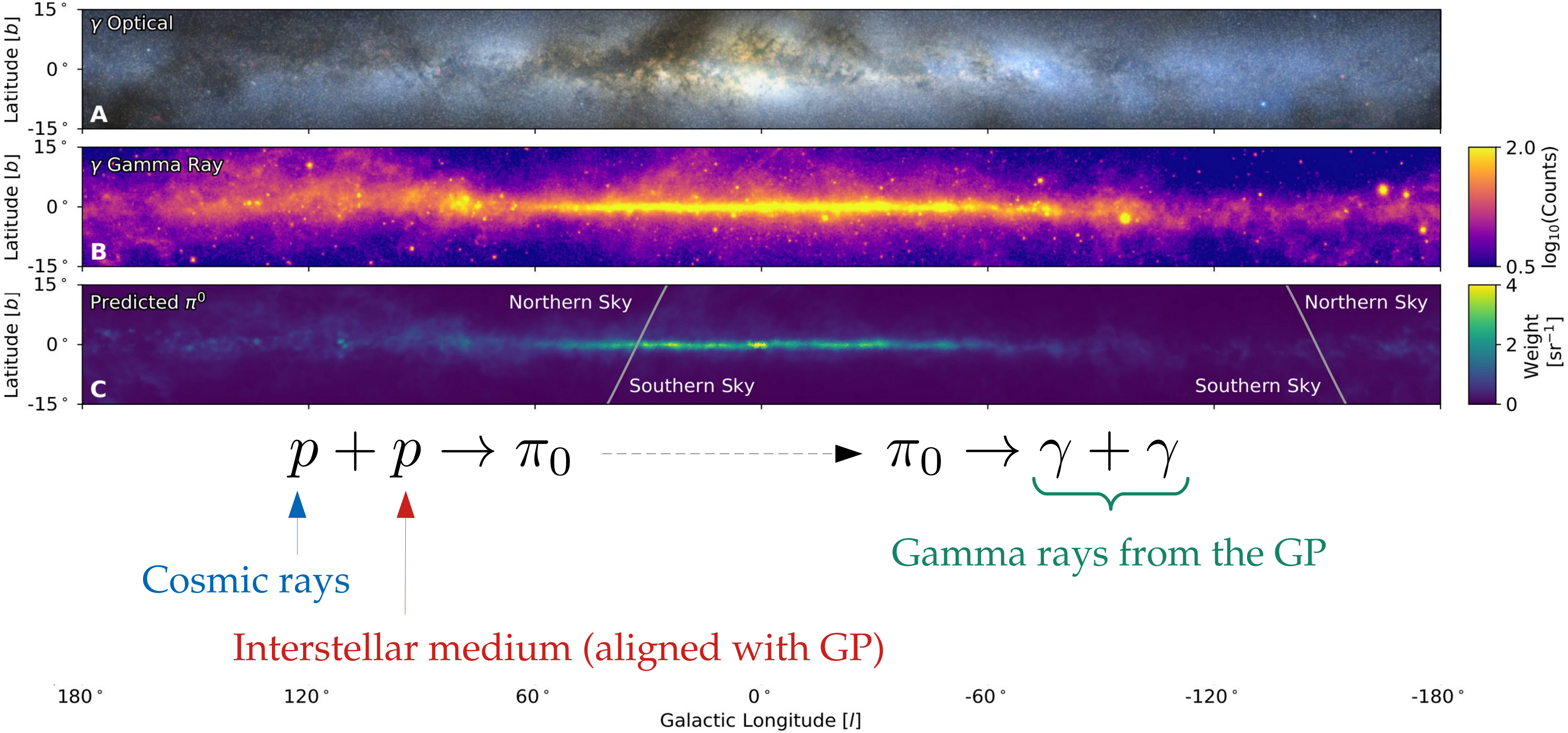
IceCube, *PRD* 2021

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023
MB, *Nature Rev. Phys.* 2024

High-energy neutrinos from the Galactic Plane



$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

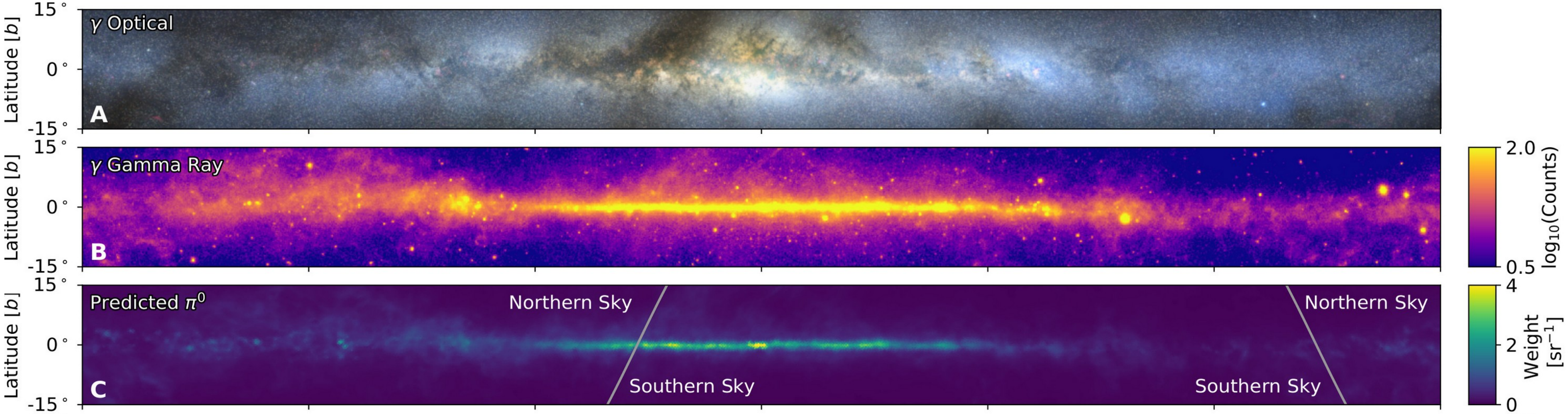
Cosmic rays

Interstellar medium (aligned with GP)

Gamma rays from the GP

IceCube Collab., *Science* 2023
MB, *Nature Rev. Phys.* 2024

High-energy neutrinos from the Galactic Plane

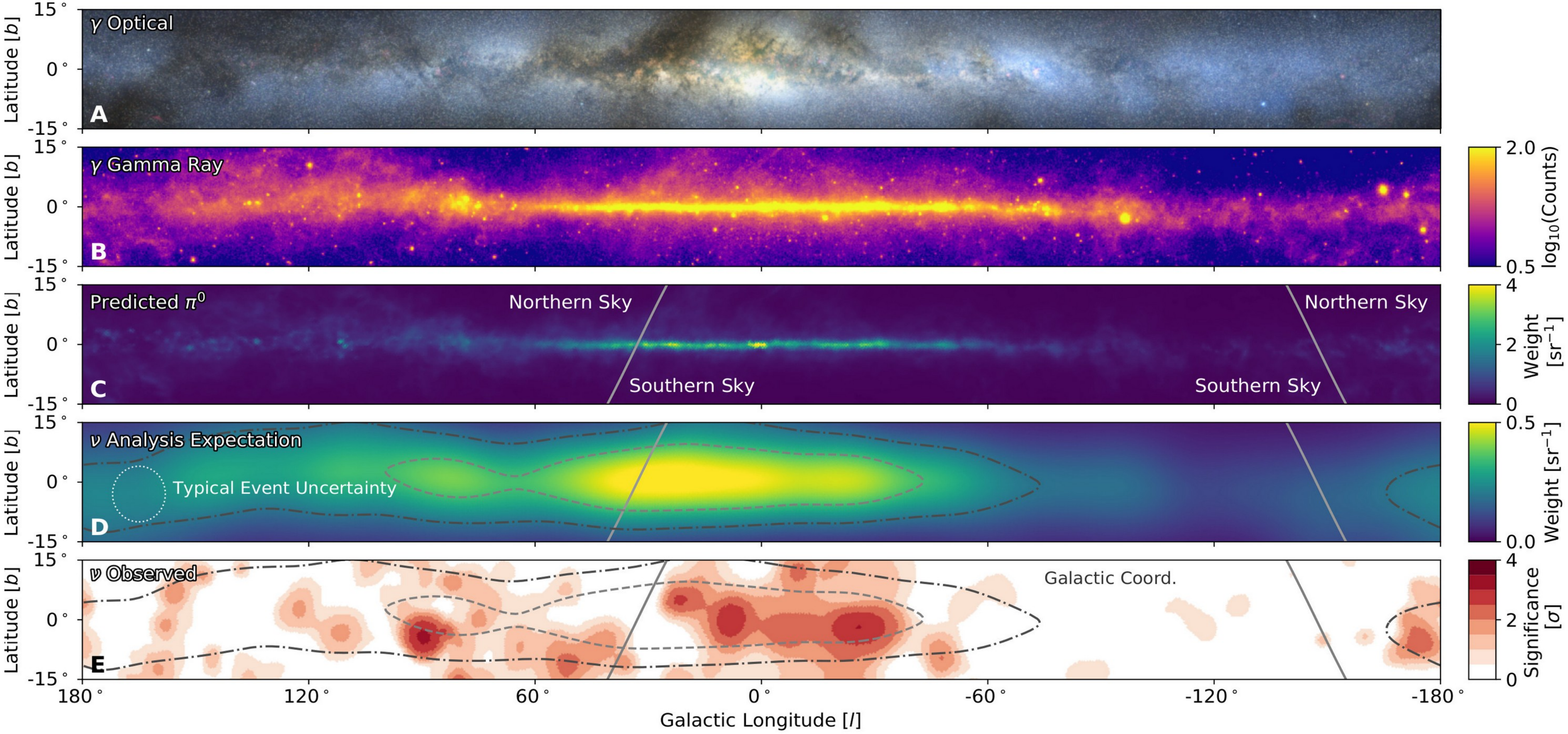


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

$$\pi^{\pm} \dashrightarrow \pi^{\pm} \rightarrow \nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$$

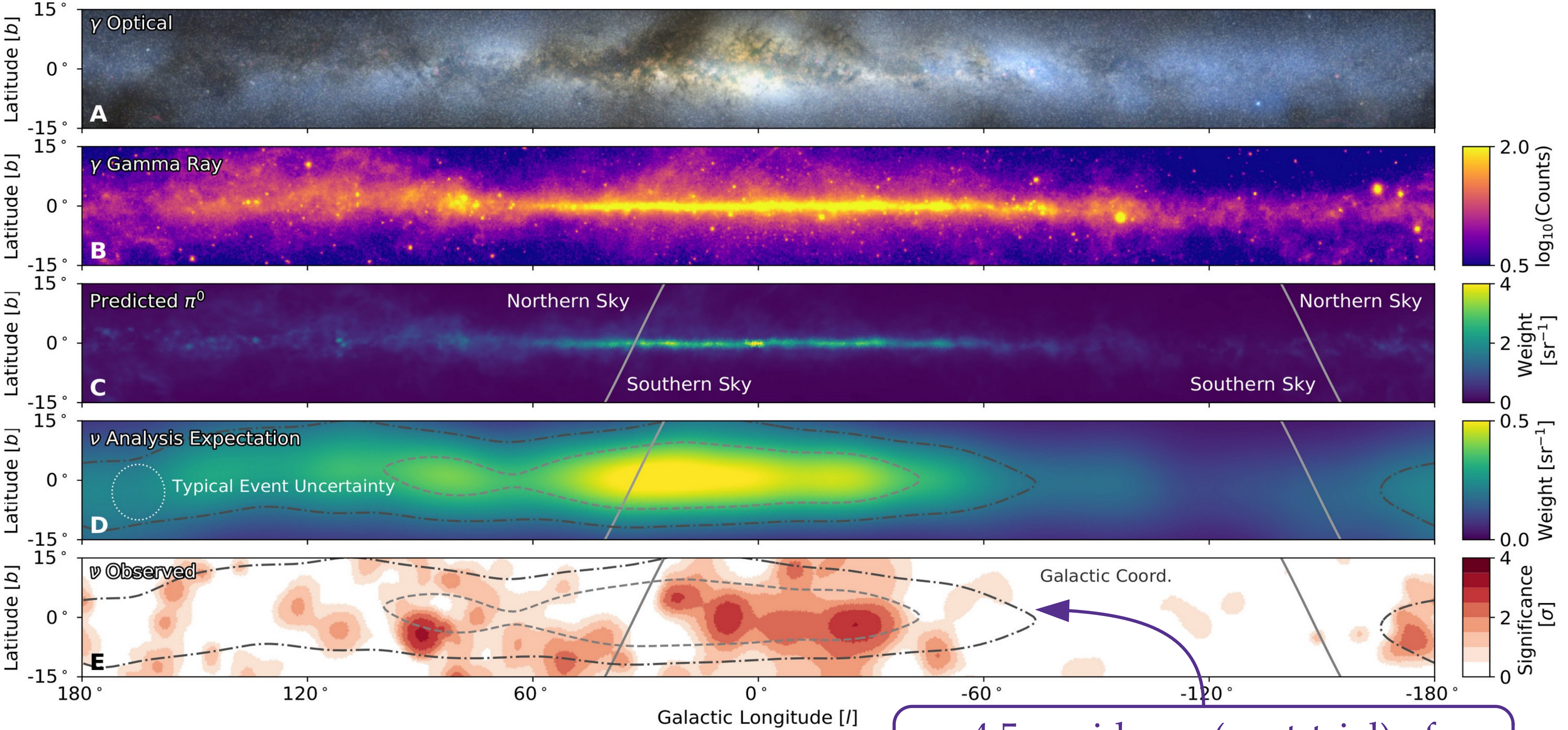
IceCube Collab., *Science* 2023
MB, *Nature Rev. Phys.* 2024

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023
MB, *Nature Rev. Phys.* 2024

High-energy neutrinos from the Galactic Plane

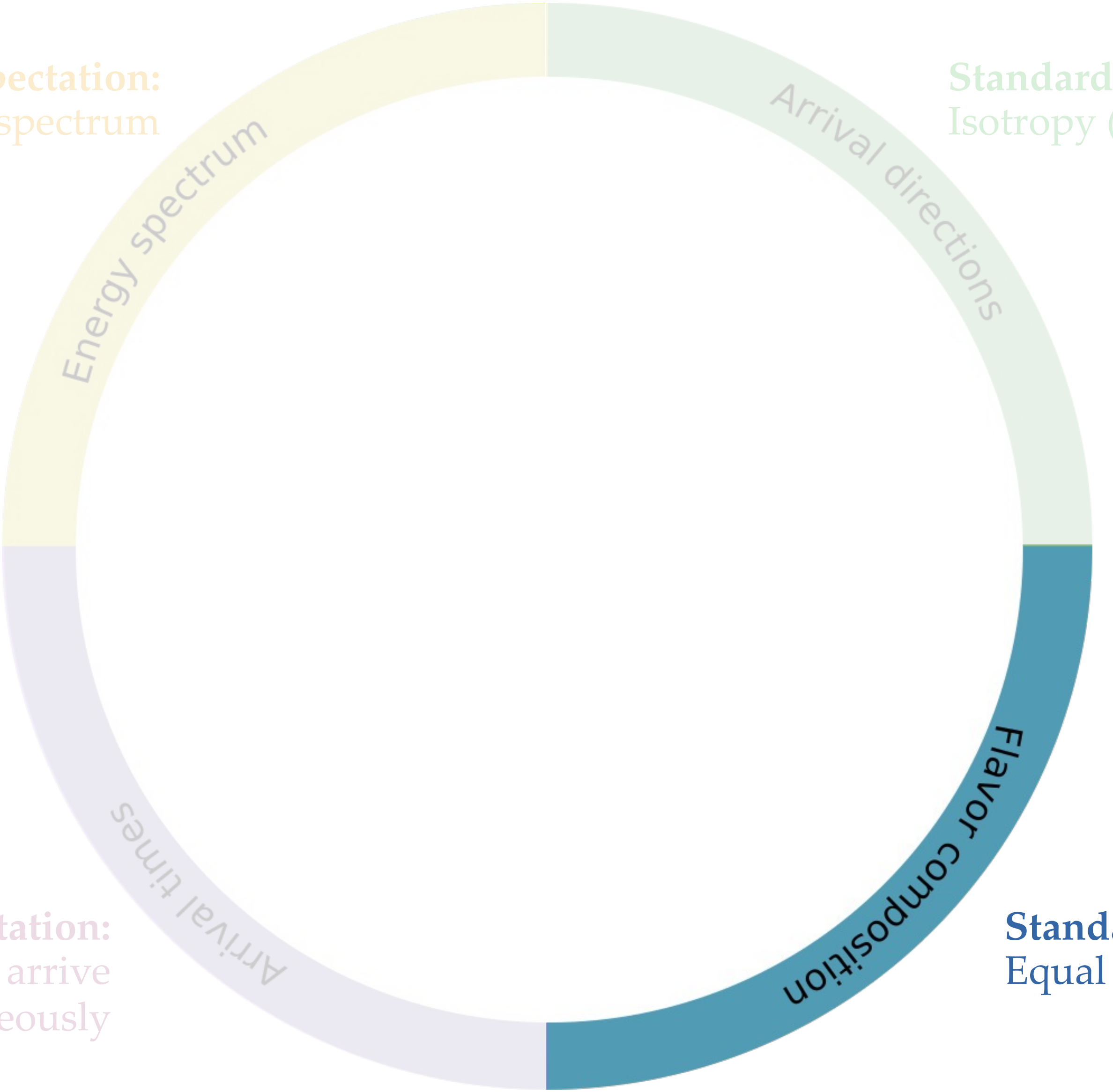


4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

IceCube Collab., *Science* 2023
MB, *Nature Rev. Phys.* 2024

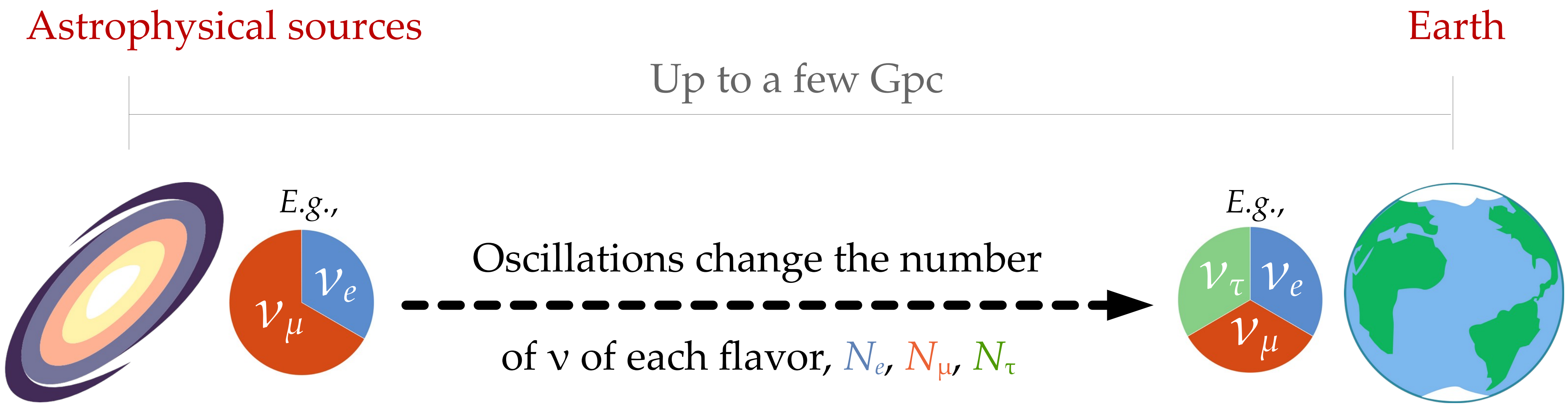
Standard expectation:
Power-law energy spectrum

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

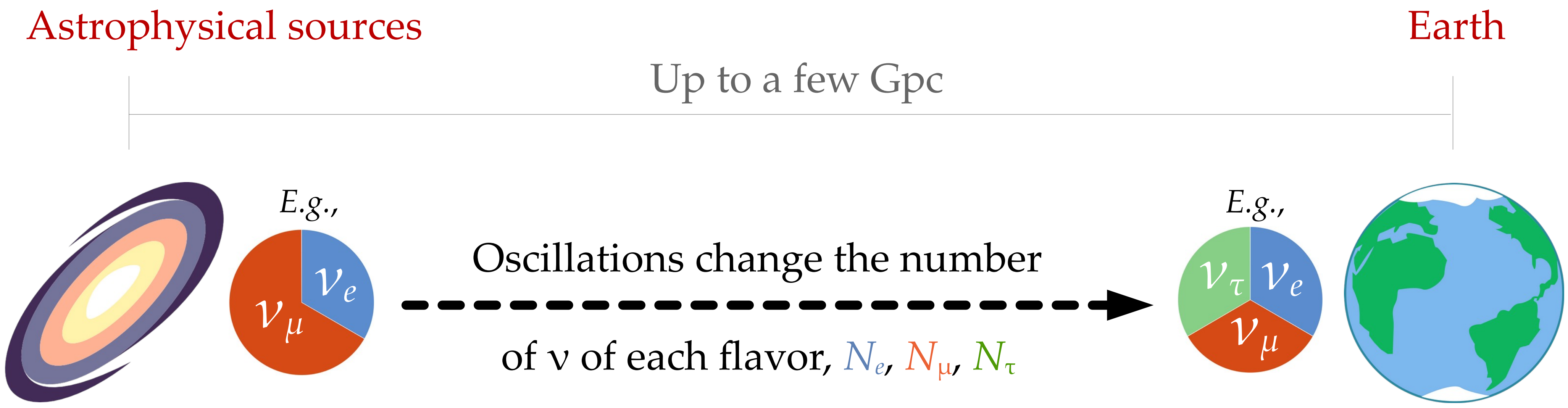


Different production mechanisms yield different flavor ratios:

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

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

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



Different production mechanisms yield different flavor ratios:

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

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

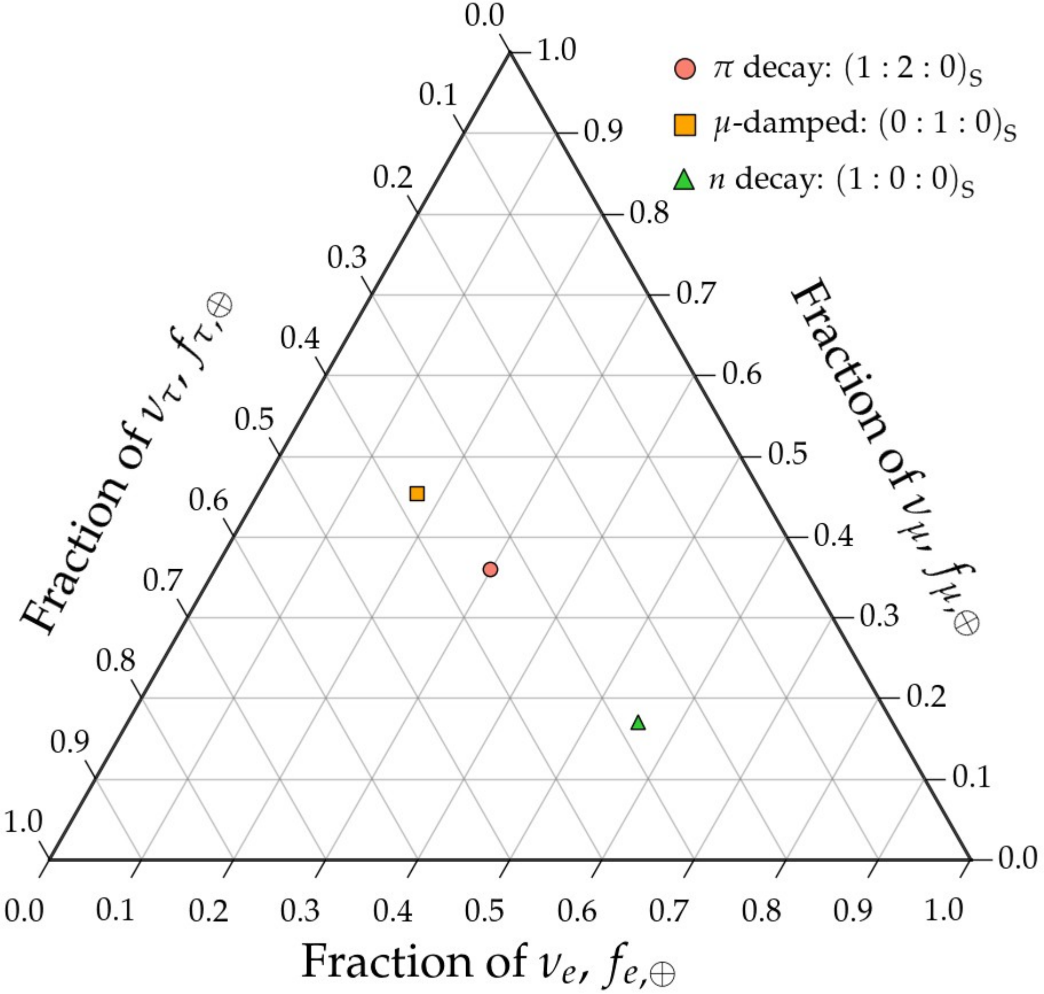
$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,\mathrm{S}}$$

Standard oscillations *or* new physics

Measuring flavor composition

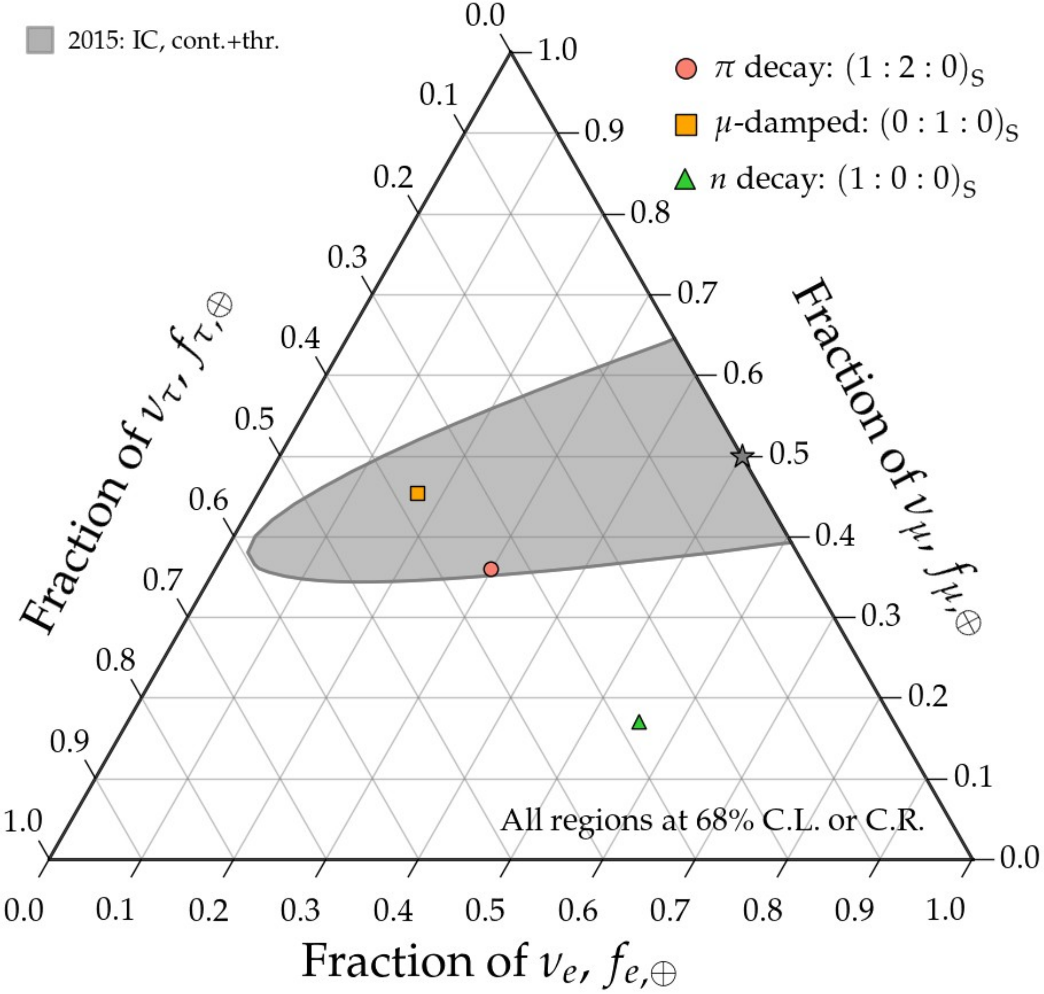
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition



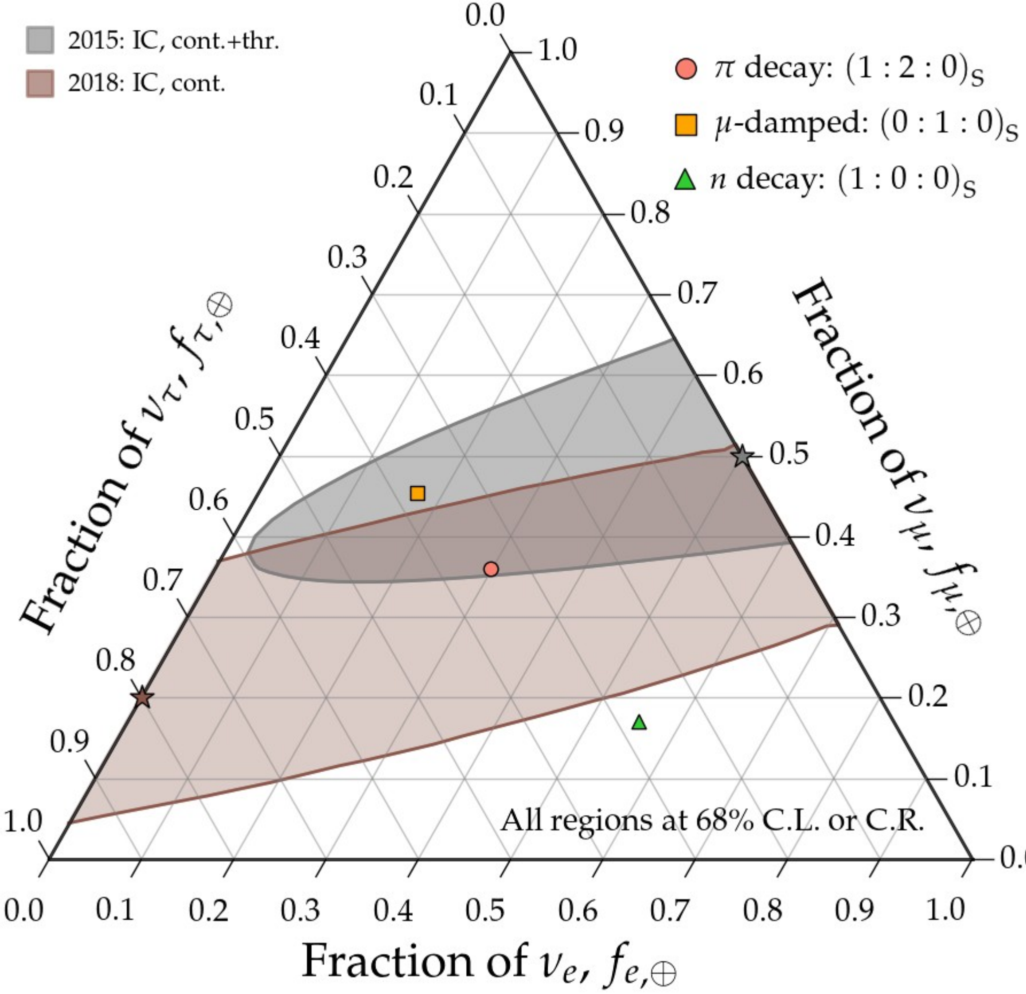
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition



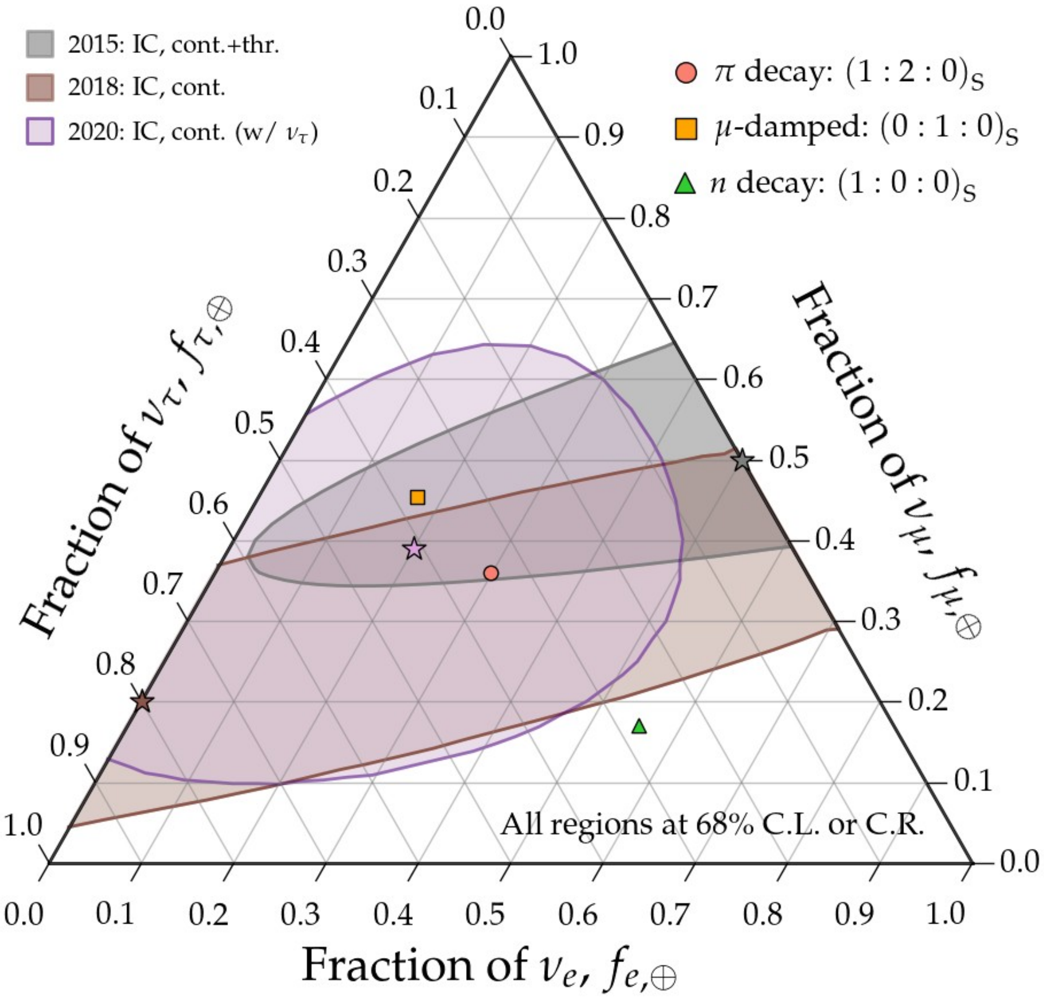
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition



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

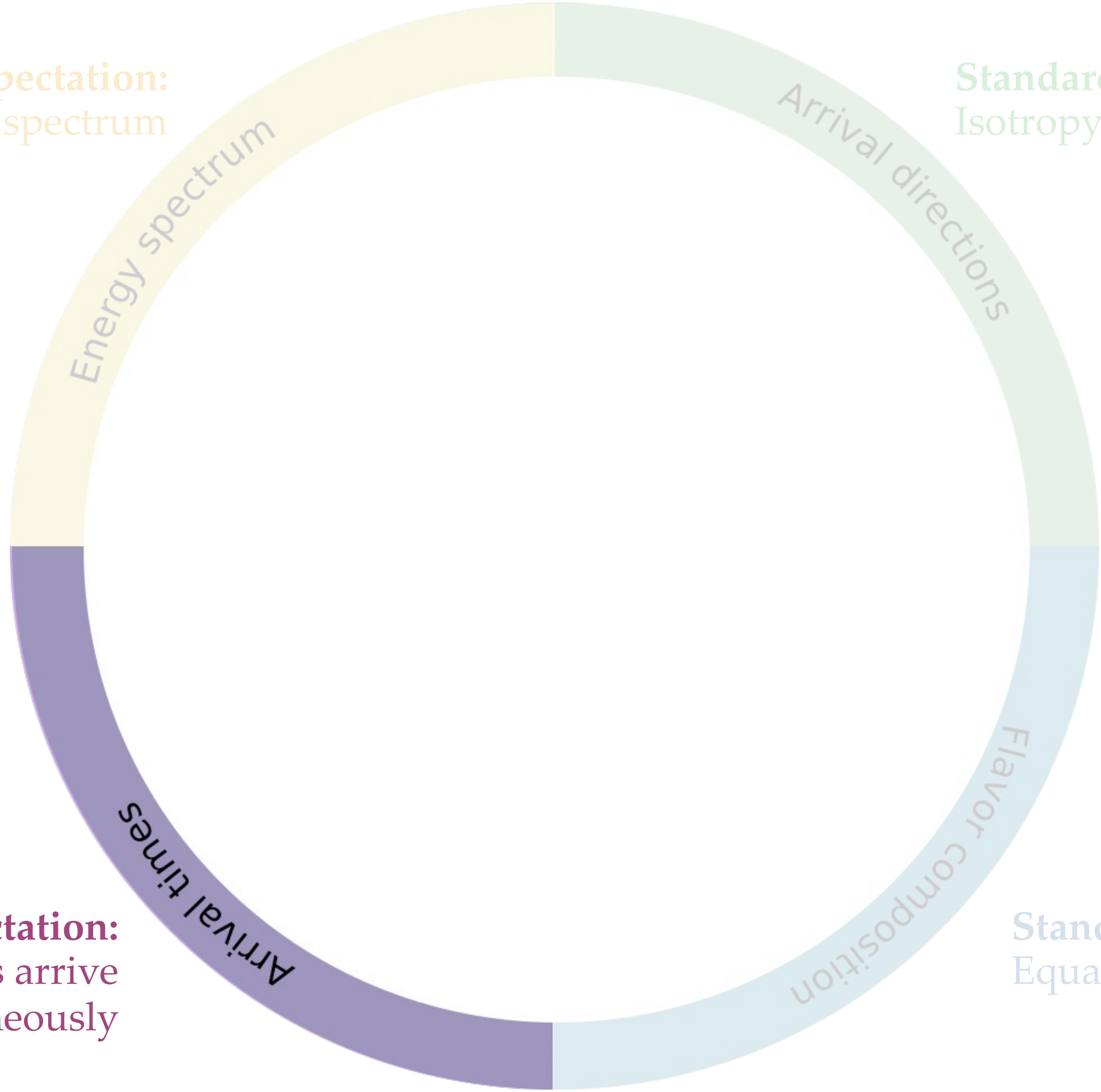
Measuring flavor composition



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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



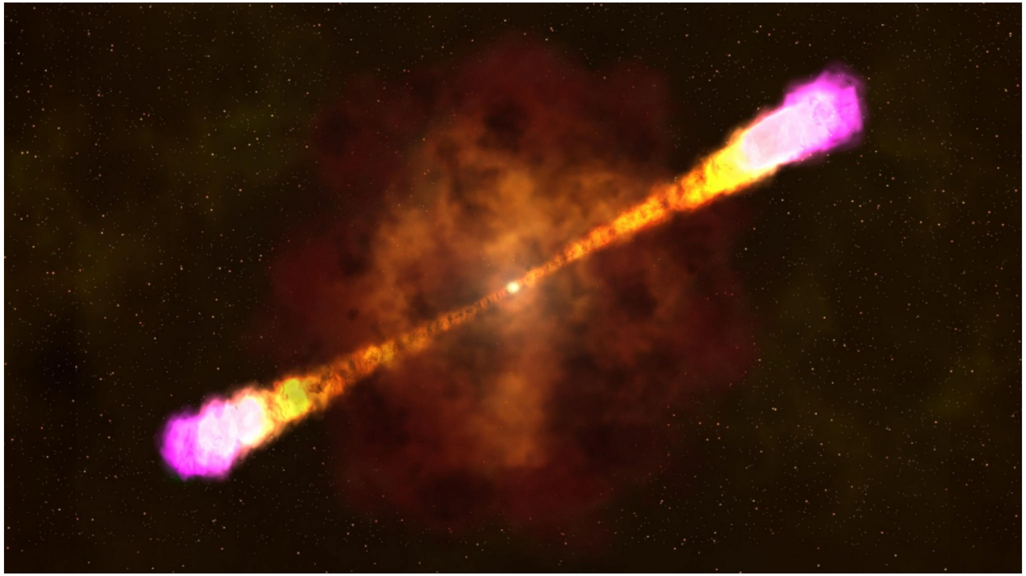
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

What have we learned about astrophysics?

Gamma-ray bursts and blazars – *not* dominant

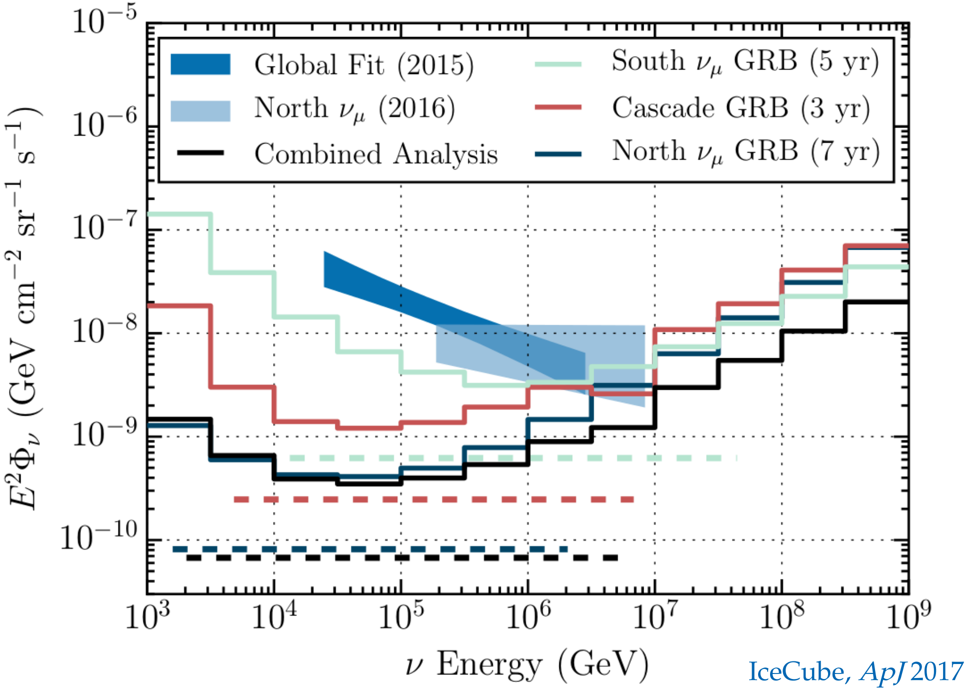
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

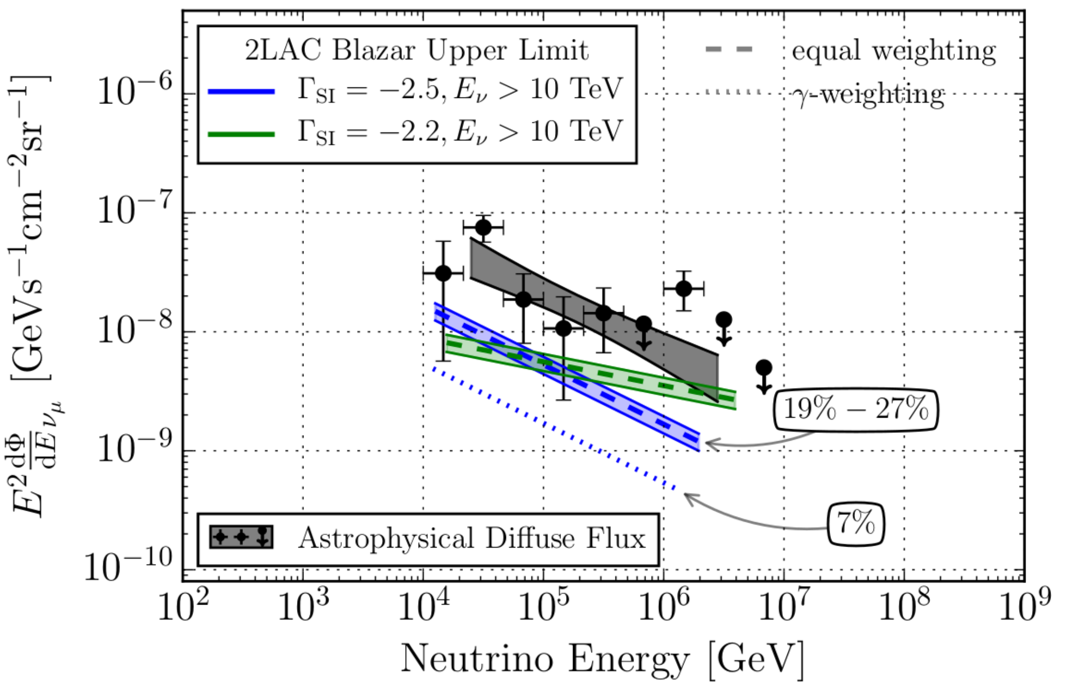


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

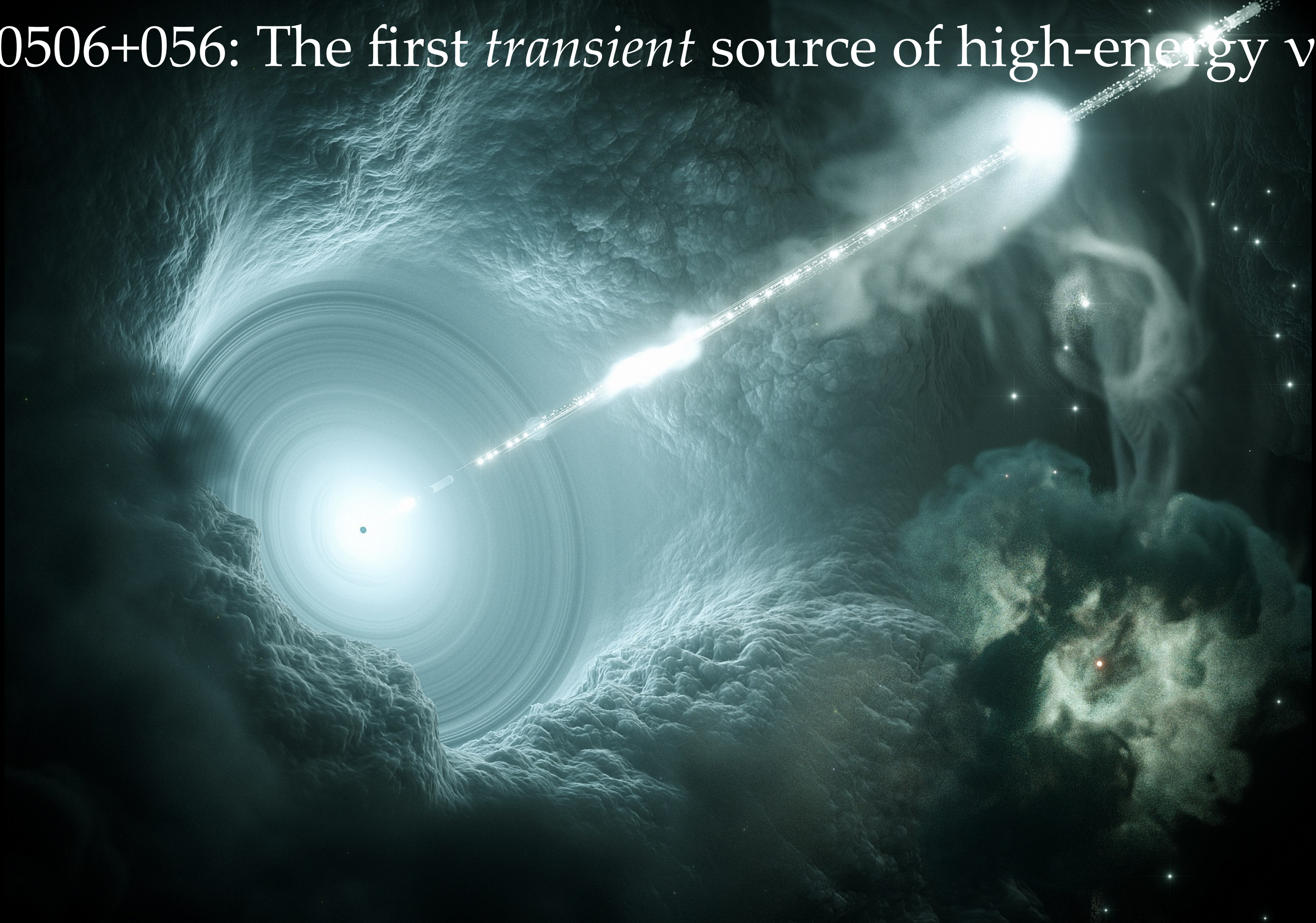
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

TXS 0506+056: The first *transient* source of high-energy ν

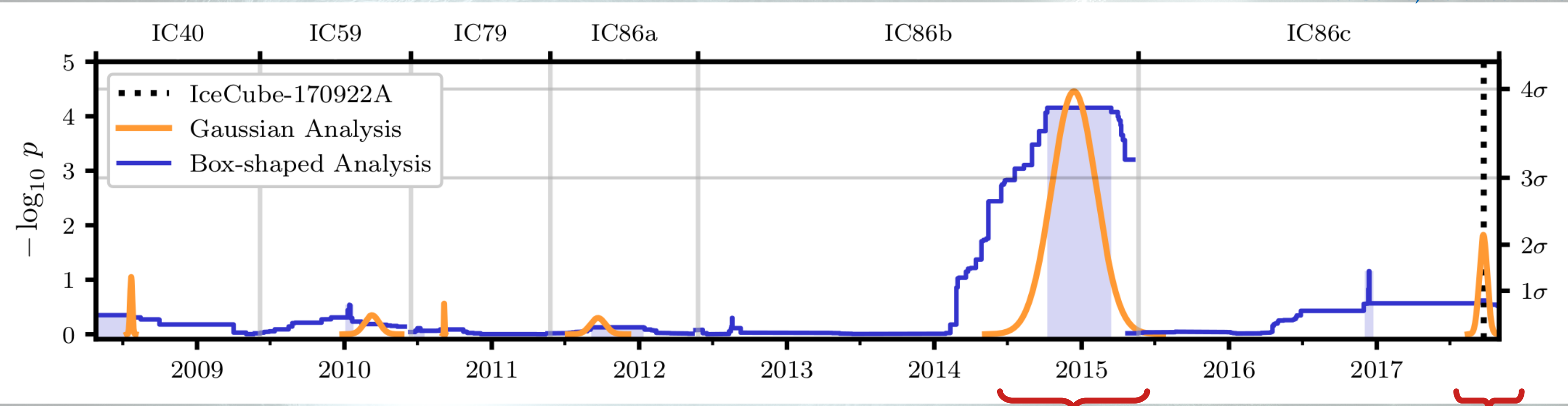


DESY

TXS 0506+056: The first *transient* source of high-energy ν

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

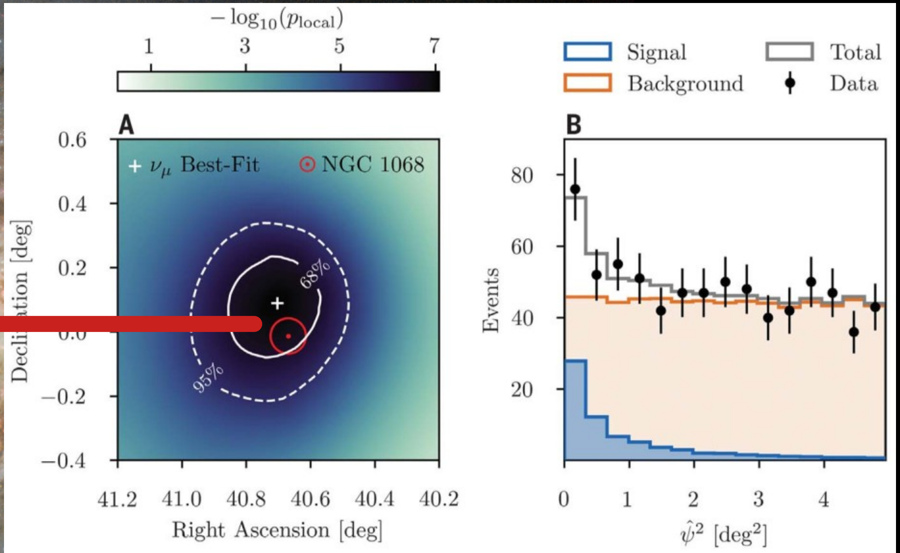
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

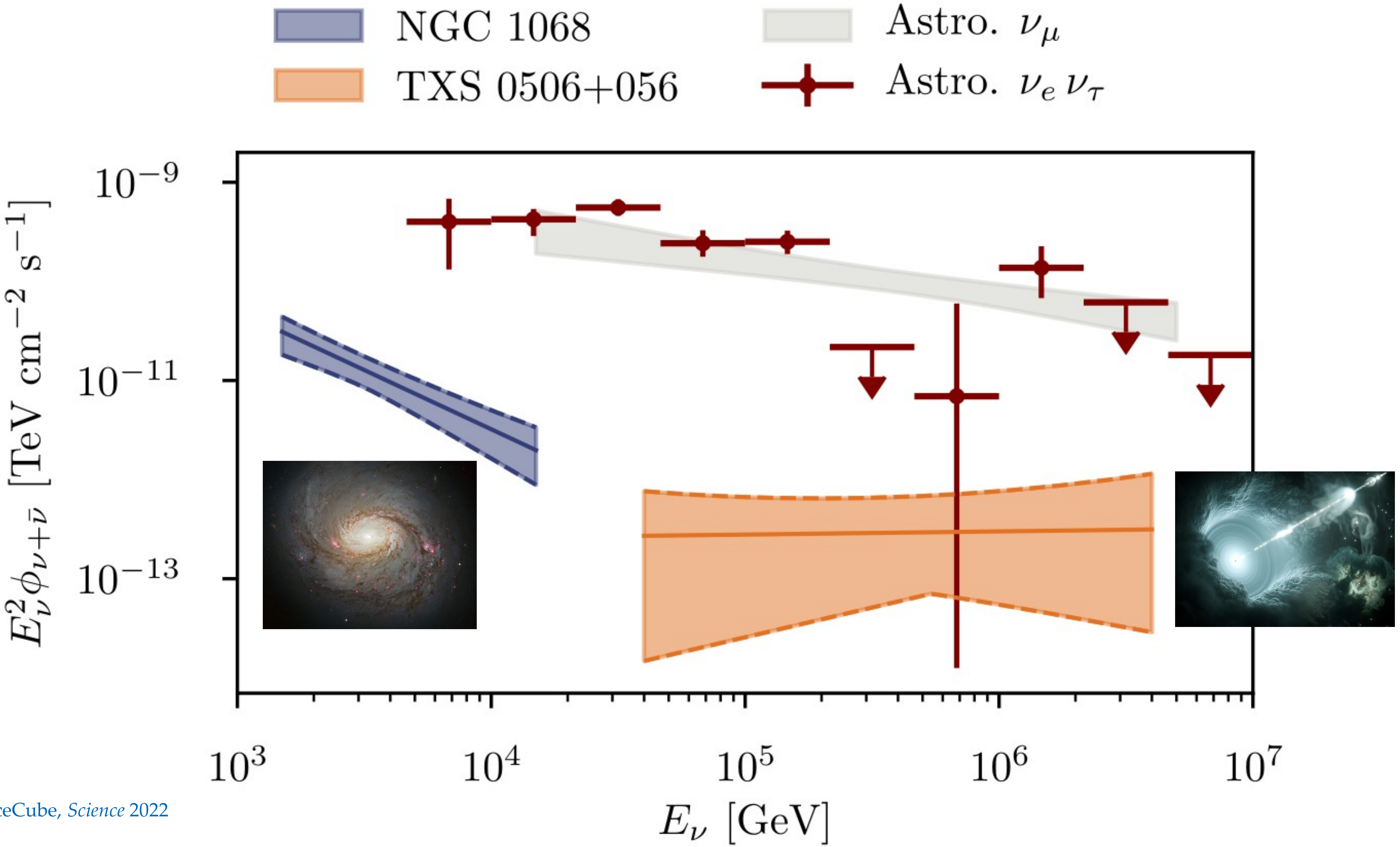
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



IceCube Collab., *Science* 378, 538 (2022)

Hubble Space Telescope,
NASA, ESA & A. van der Hoeven

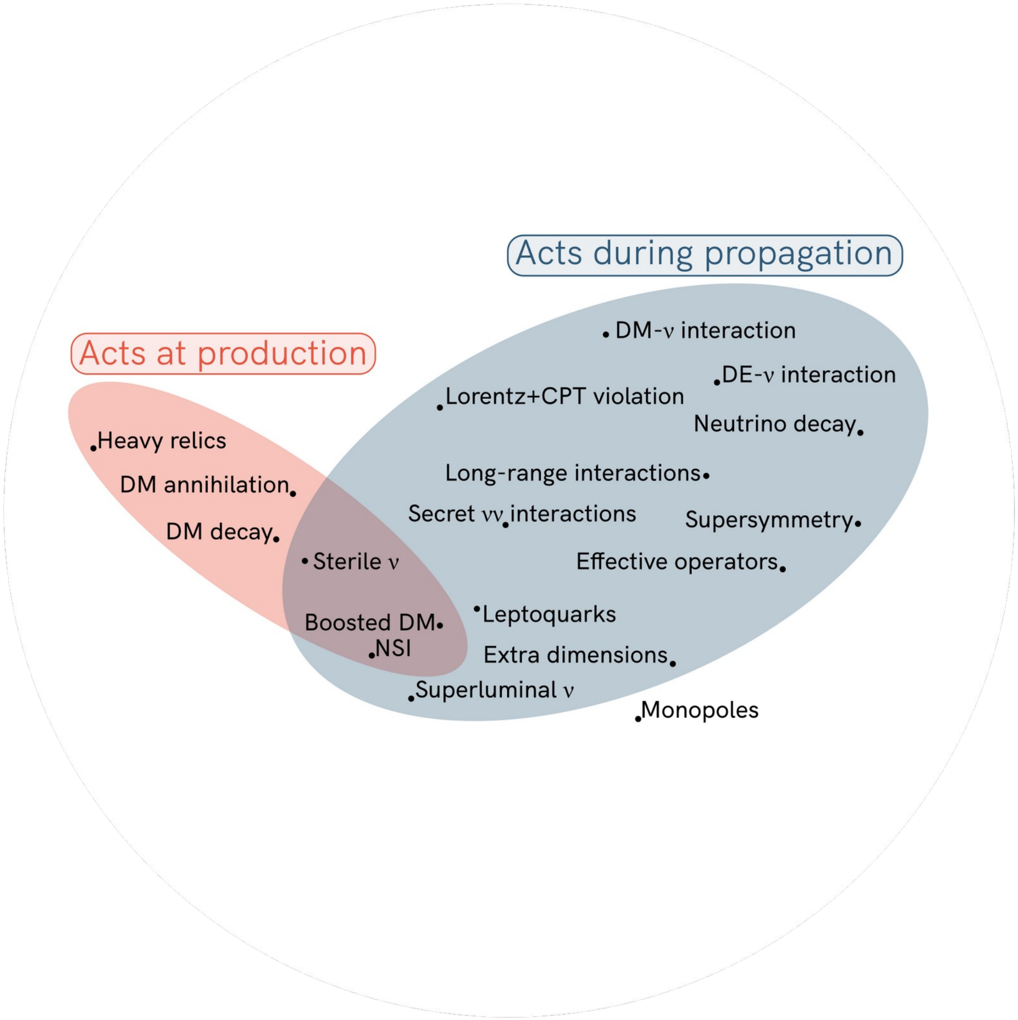


IceCube, *Science* 2022

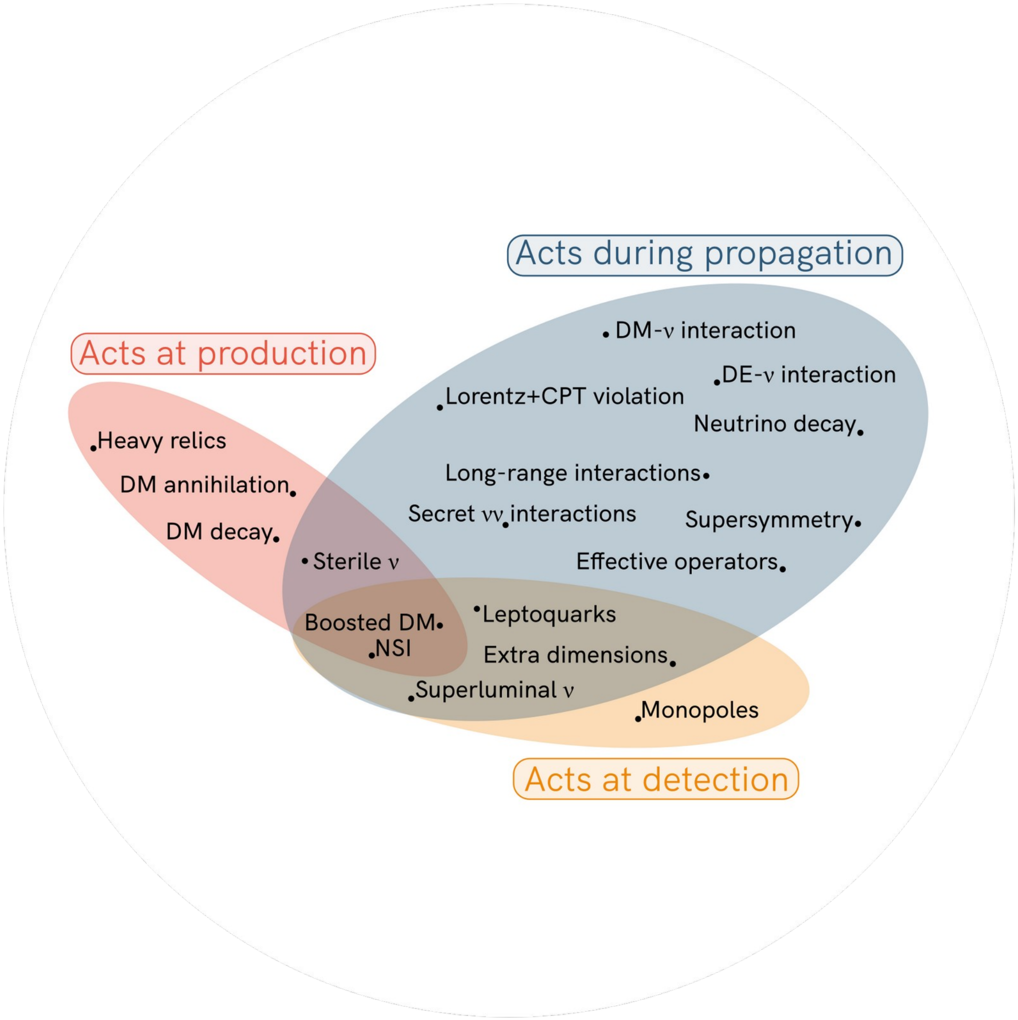
What have we learned about particle physics?

Note: Not an exhaustive list

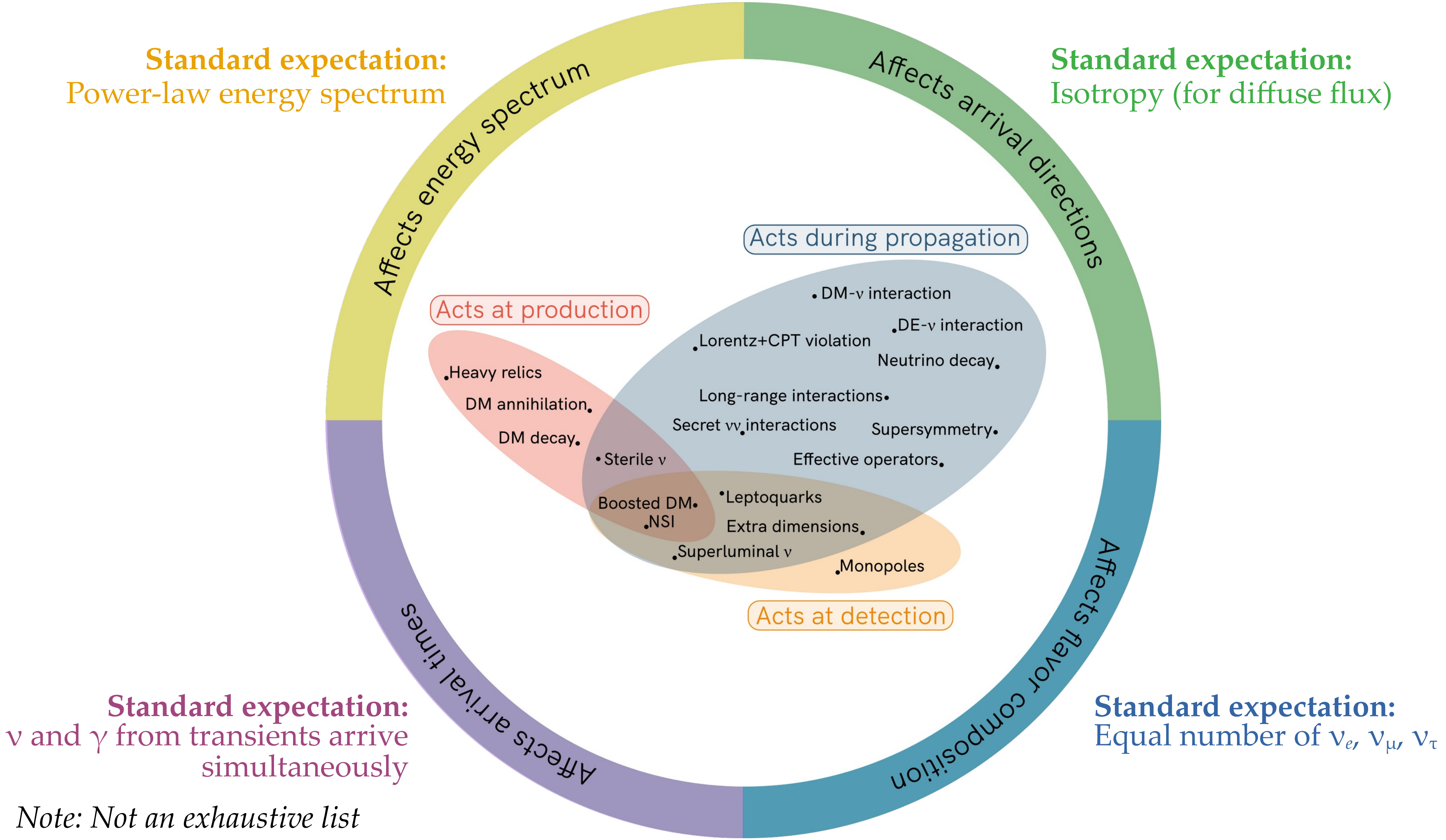
Note: Not an exhaustive list

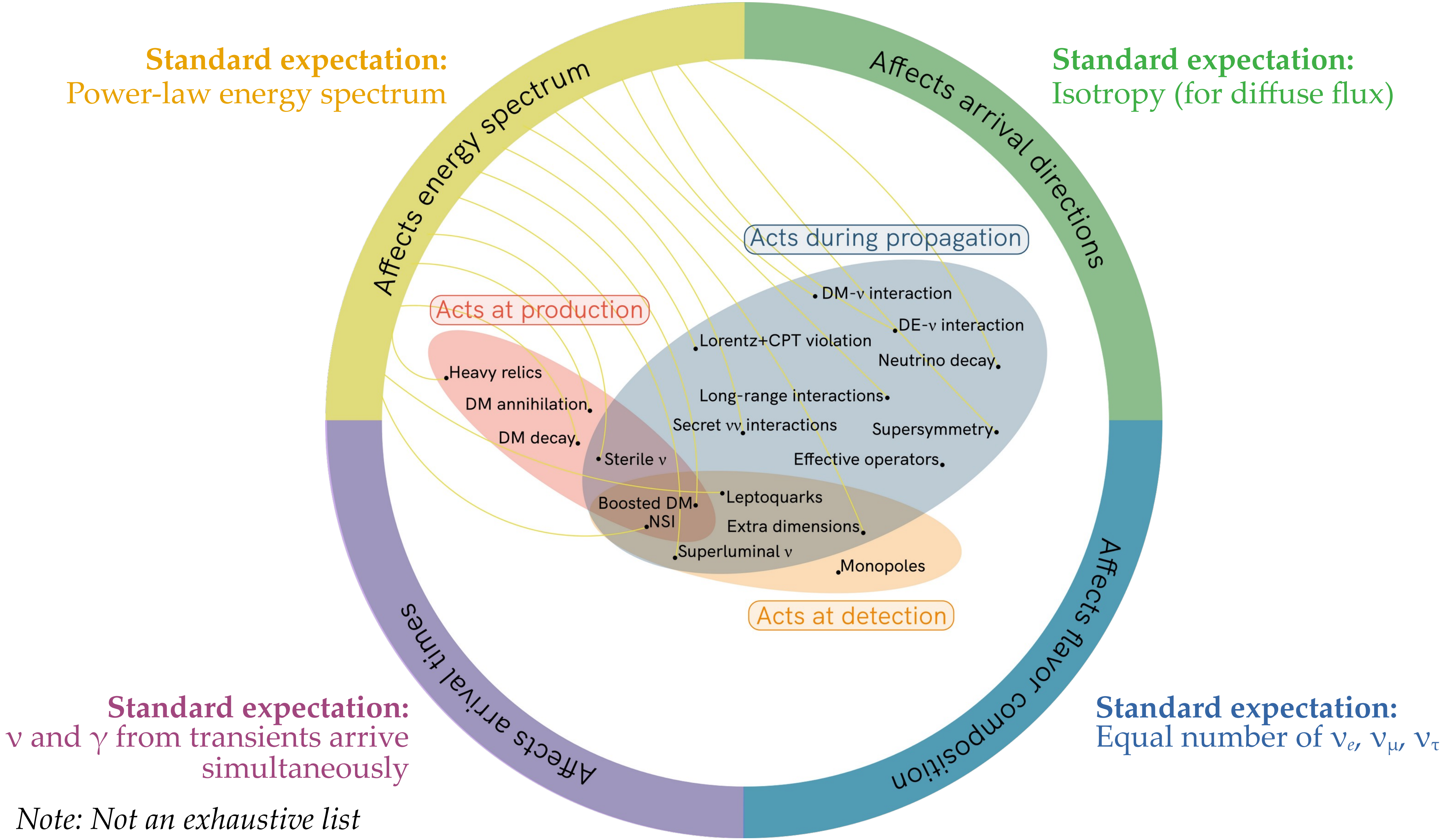


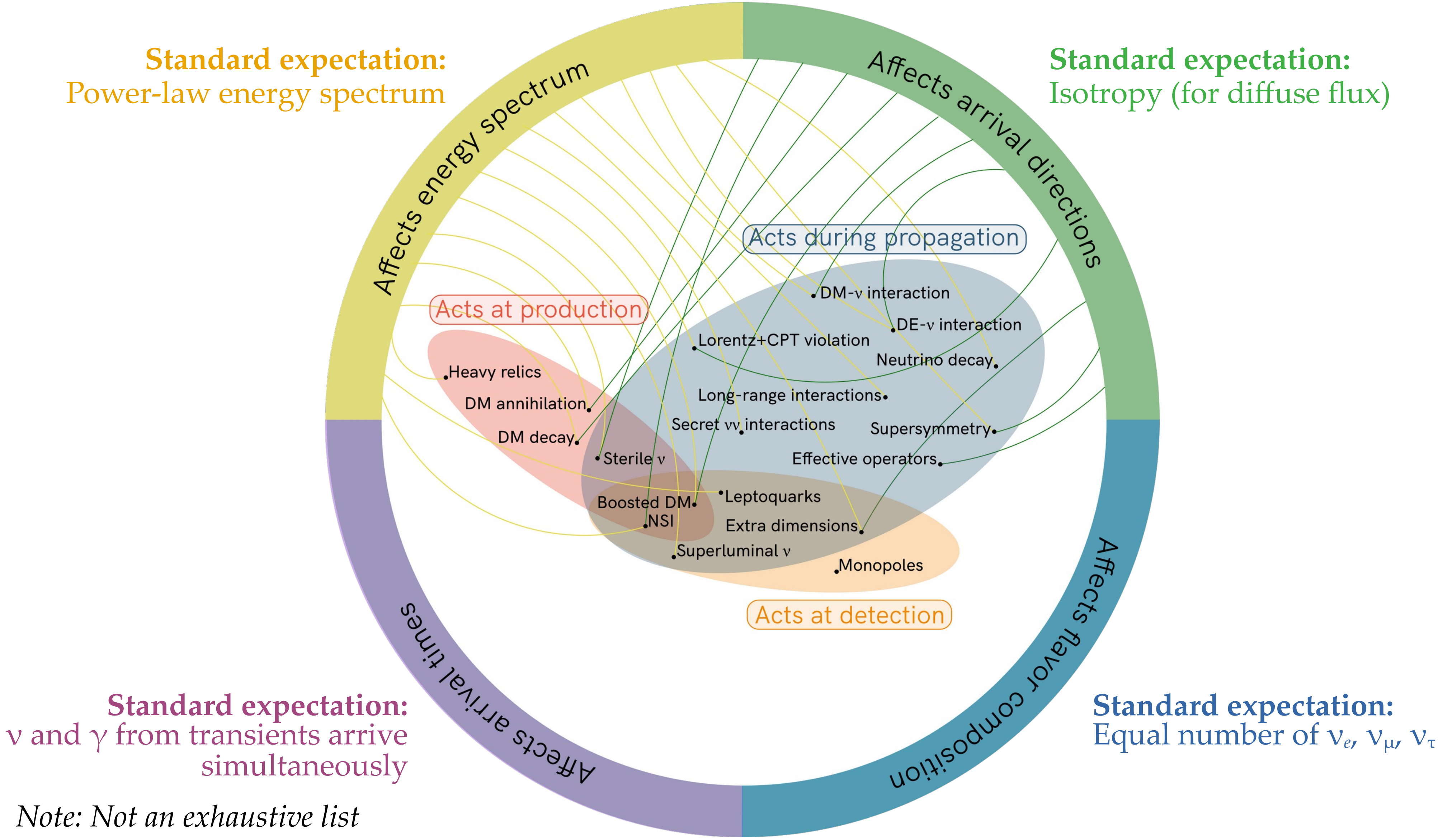
Note: Not an exhaustive list



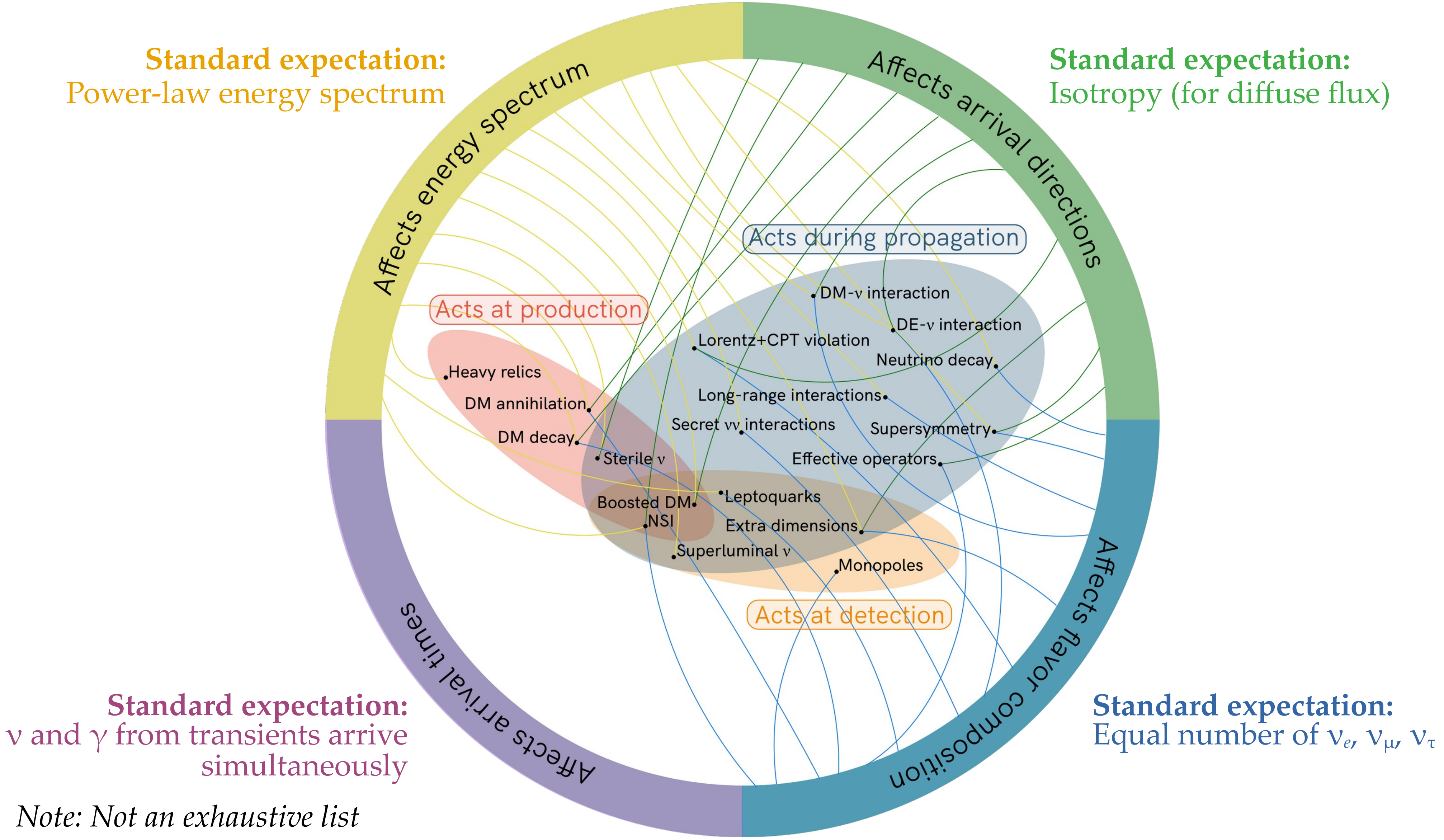
Note: Not an exhaustive list


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


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



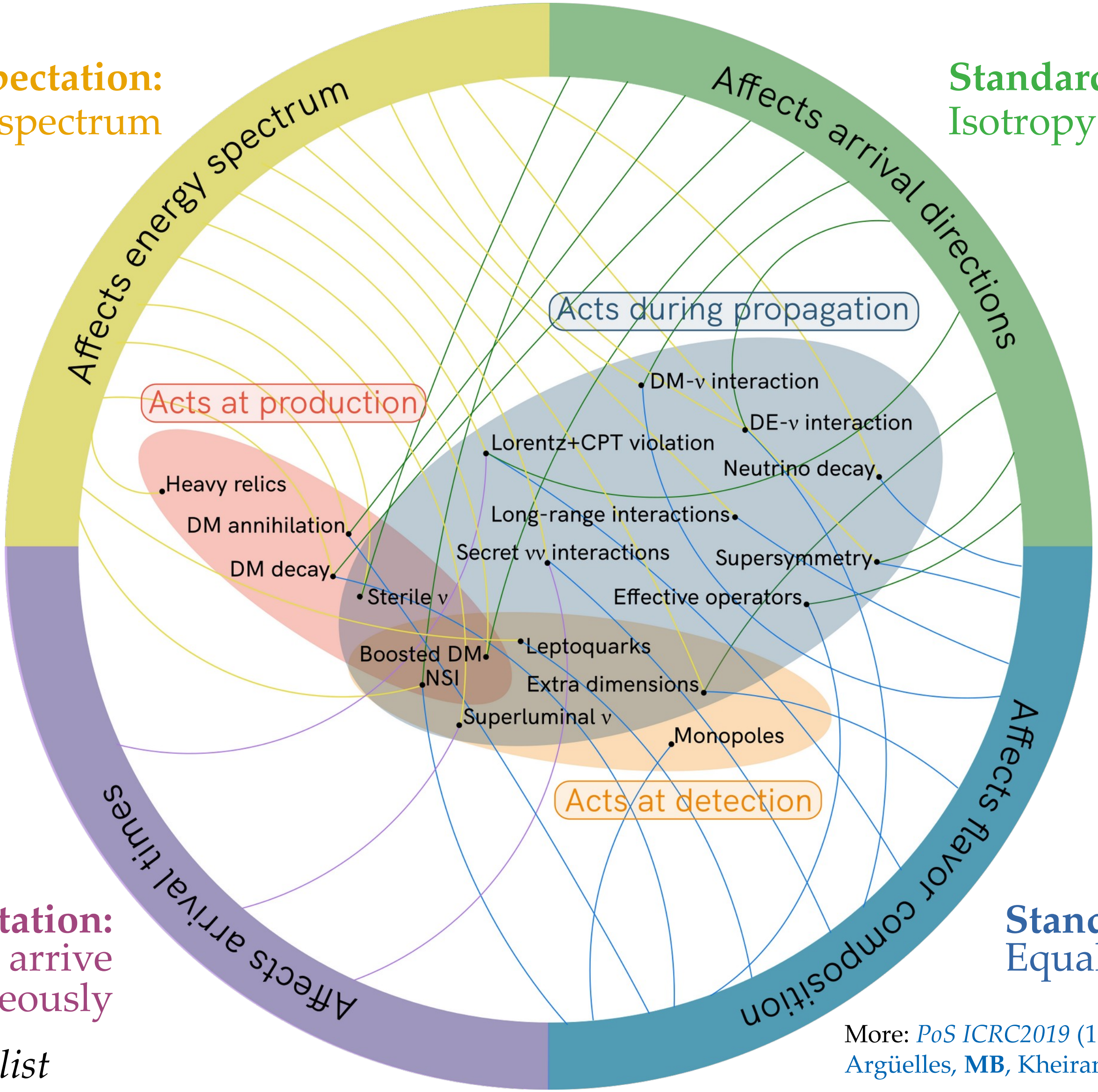
Note: Not an exhaustive list



Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

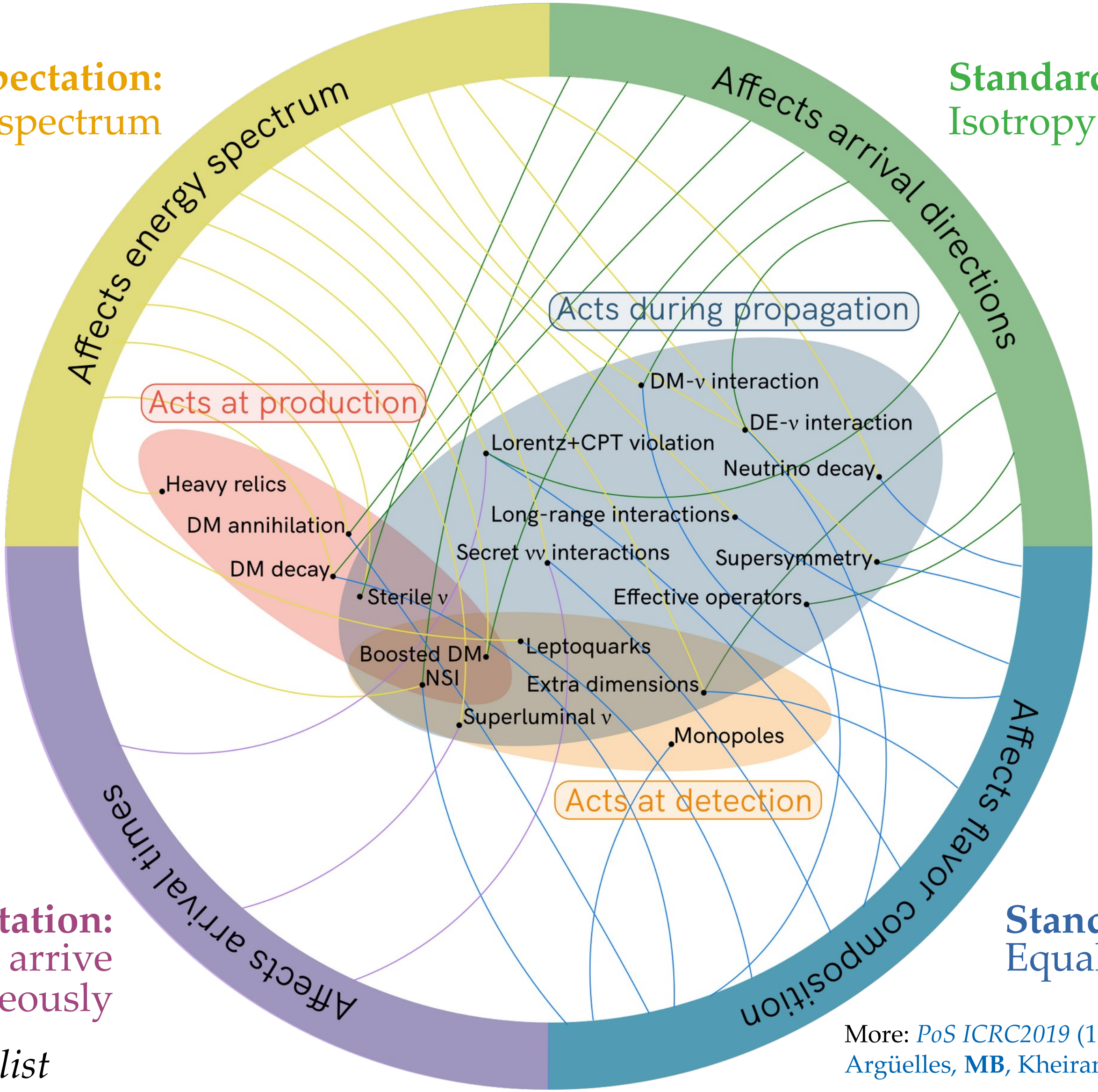
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

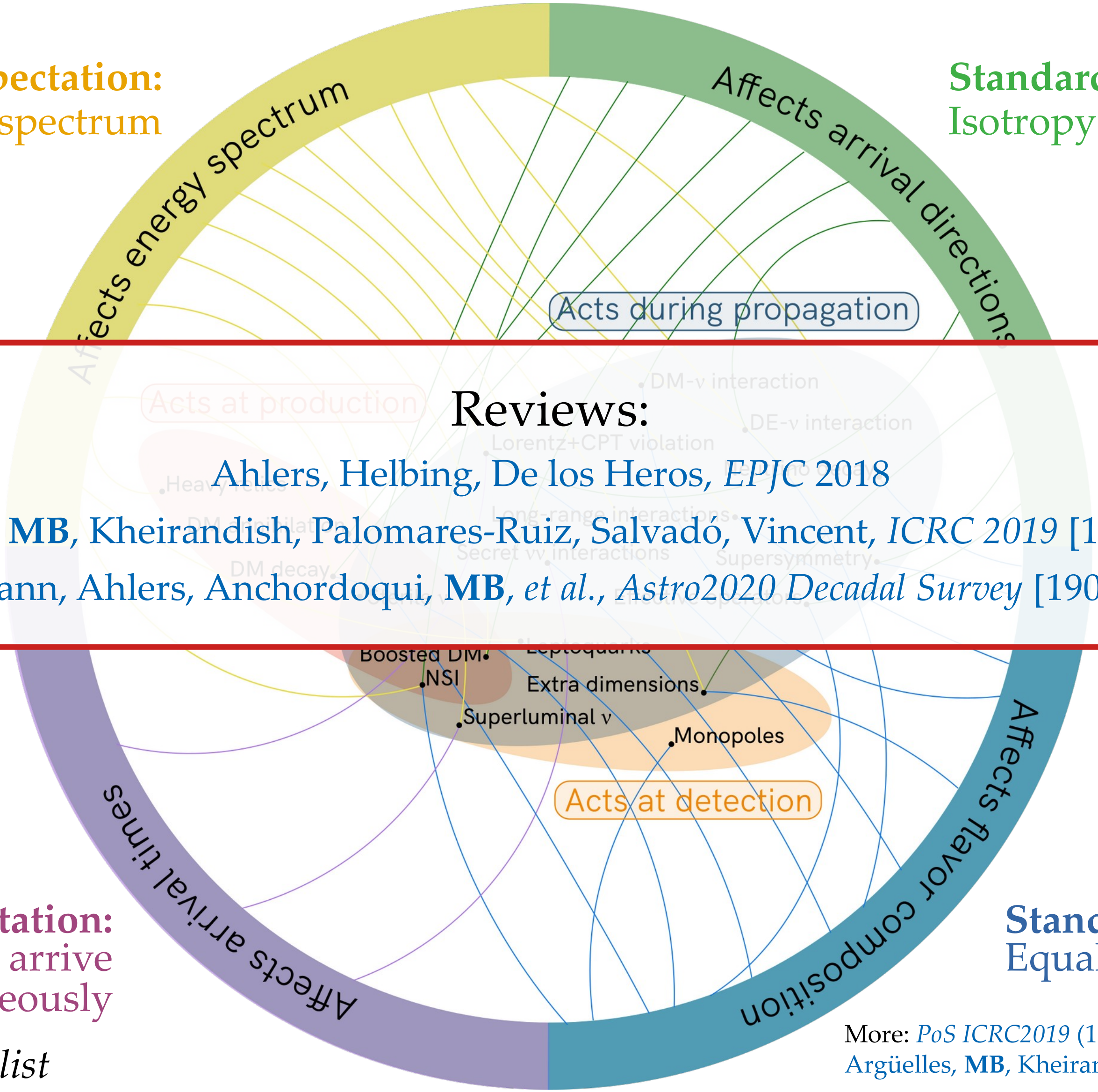
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Reviews:

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

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

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

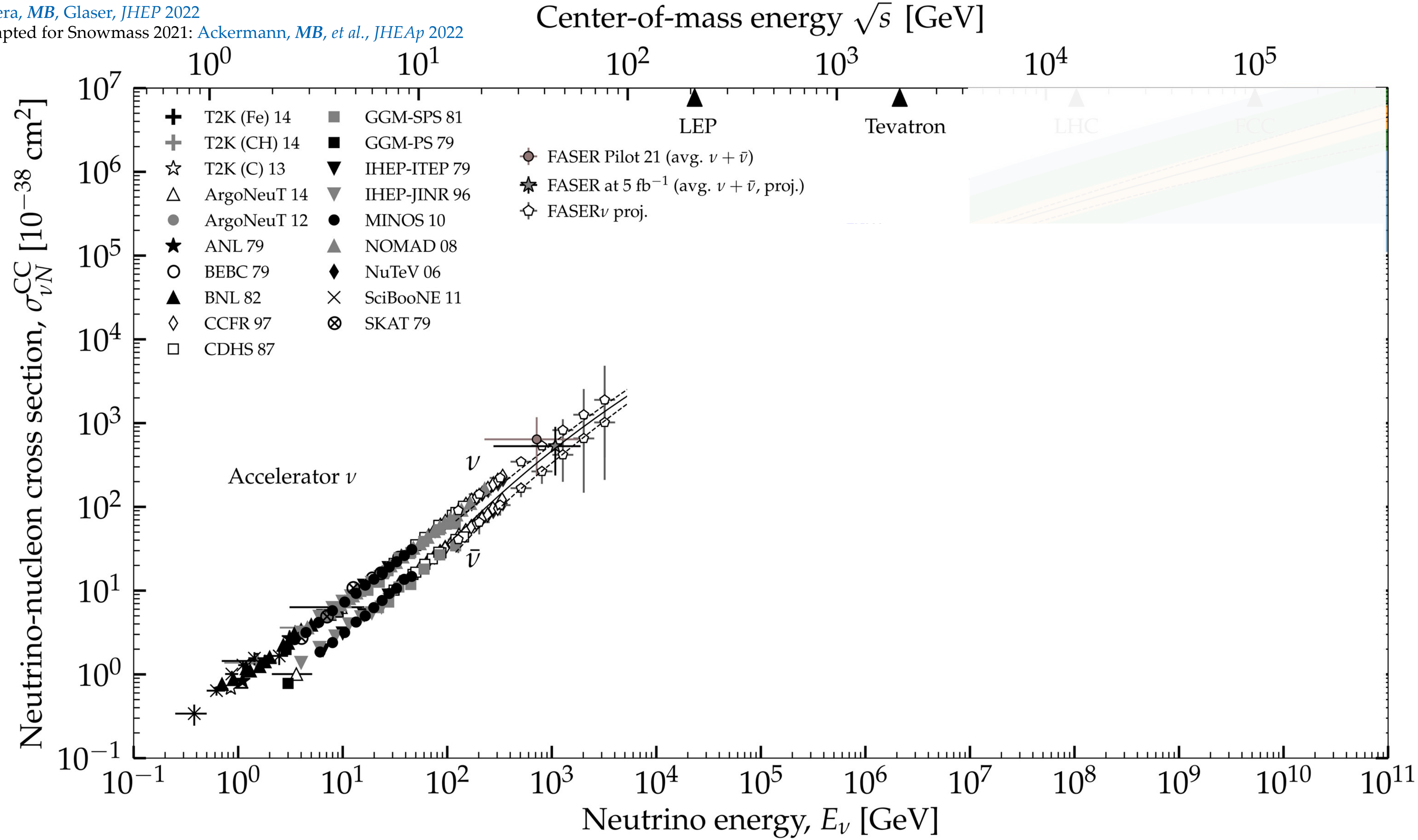
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

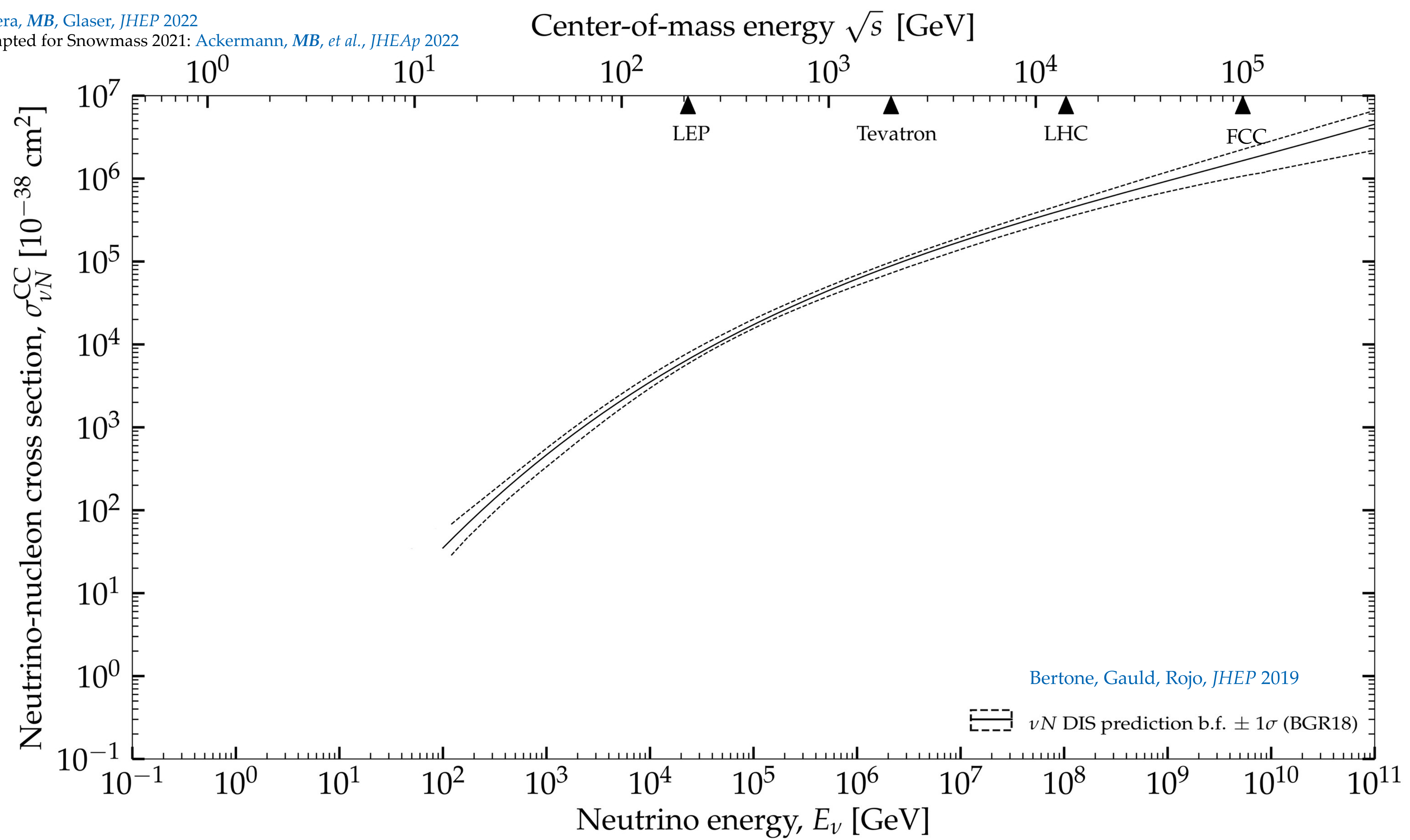
Note: Not an exhaustive list

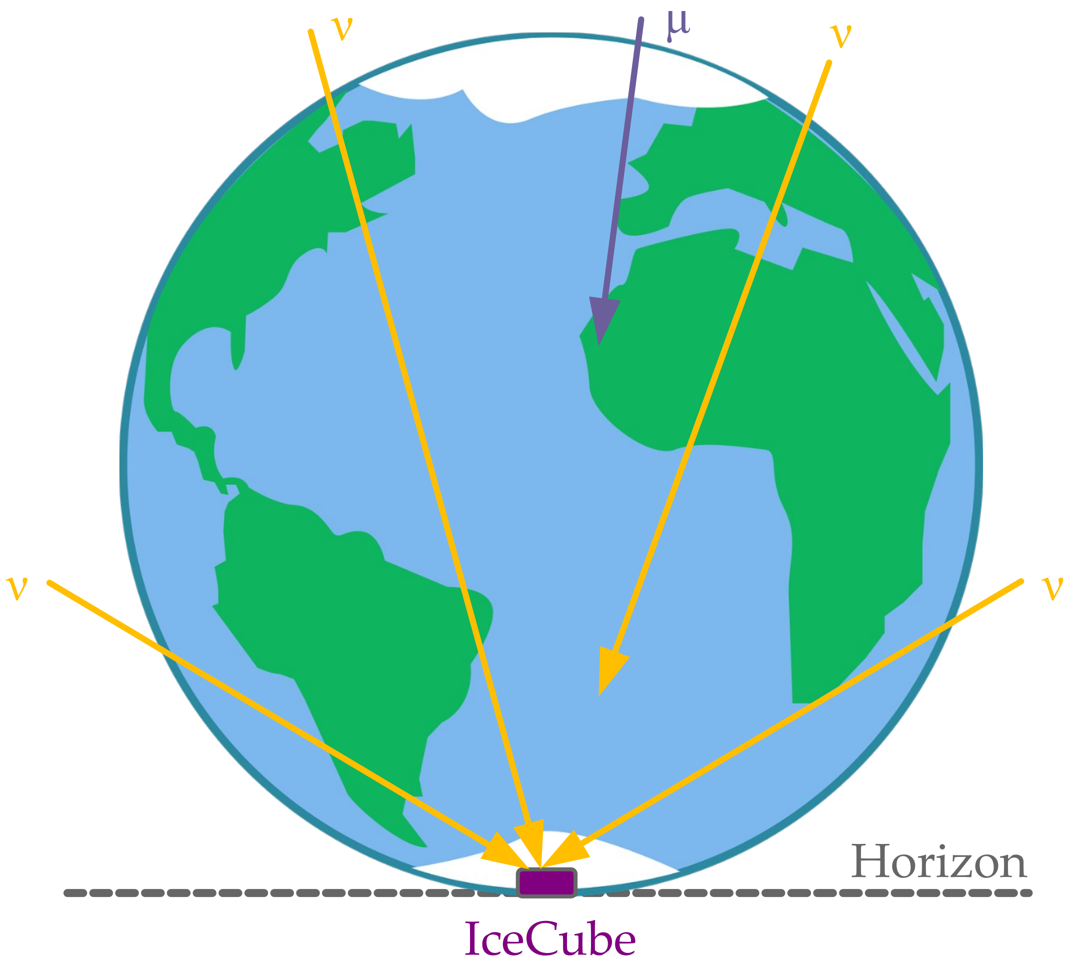
More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

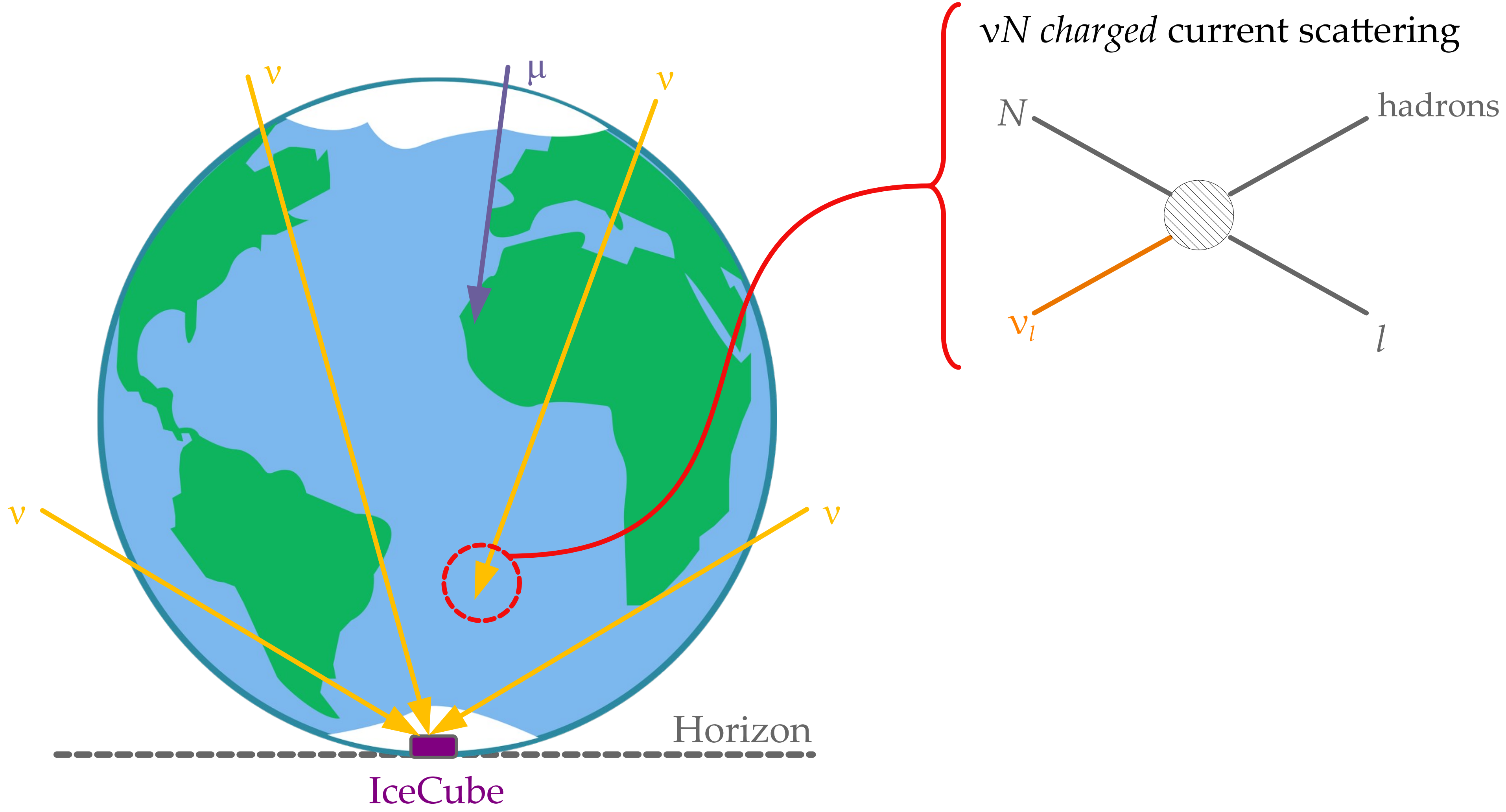
Valera, ***MB***, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, ***MB***, *et al.*, *JHEAp* 2022

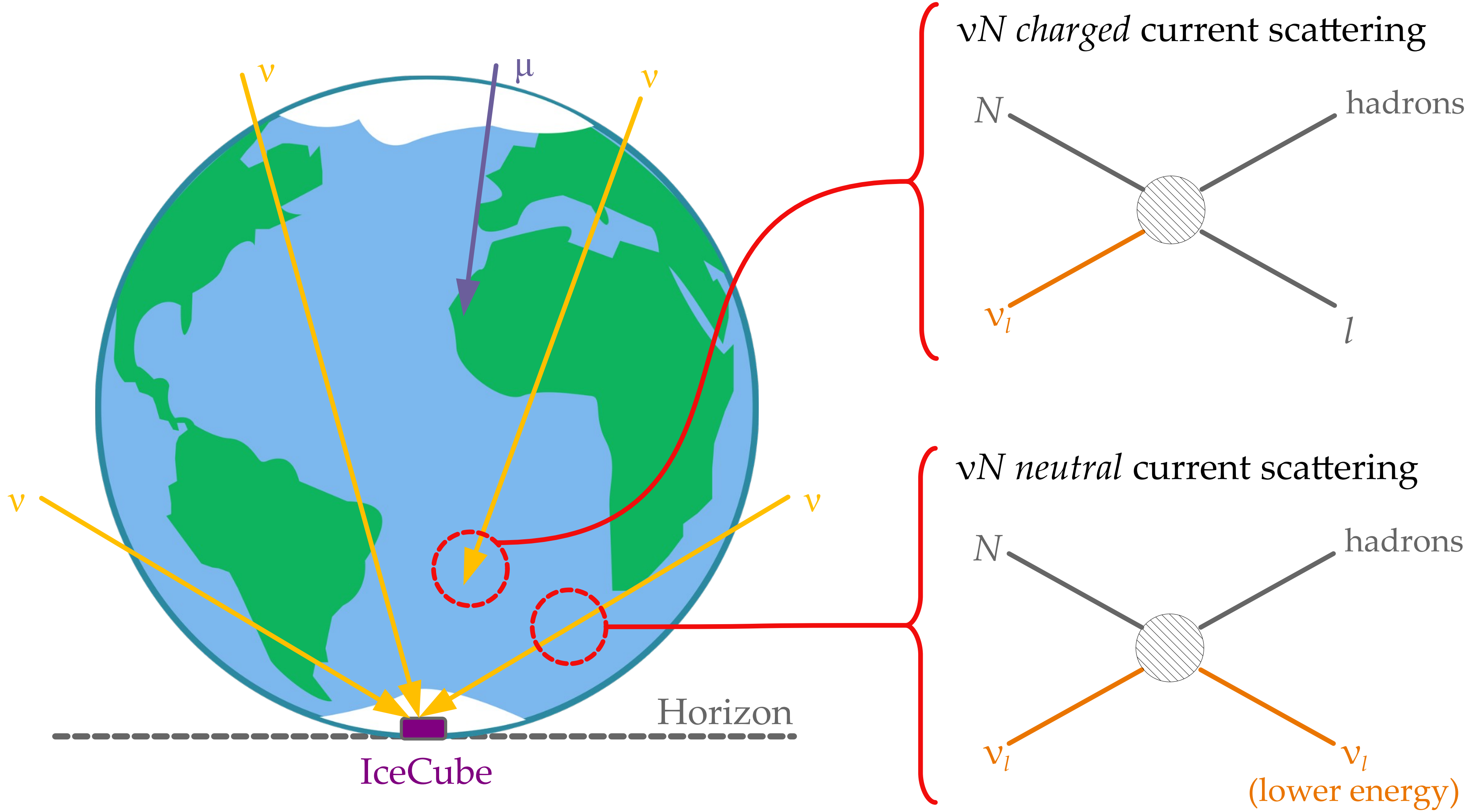


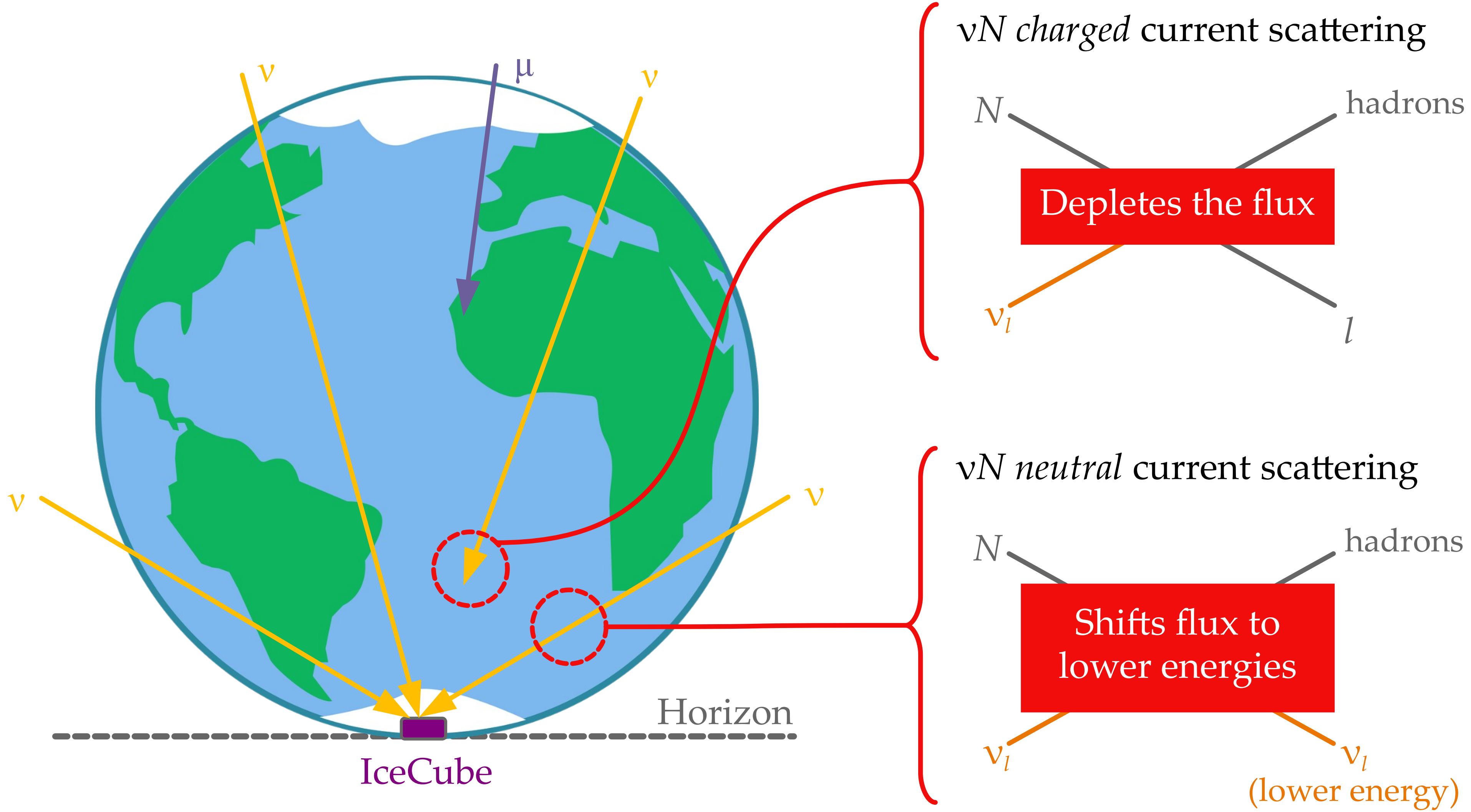
Valera, ***MB***, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, ***MB***, *et al.*, *JHEAp* 2022



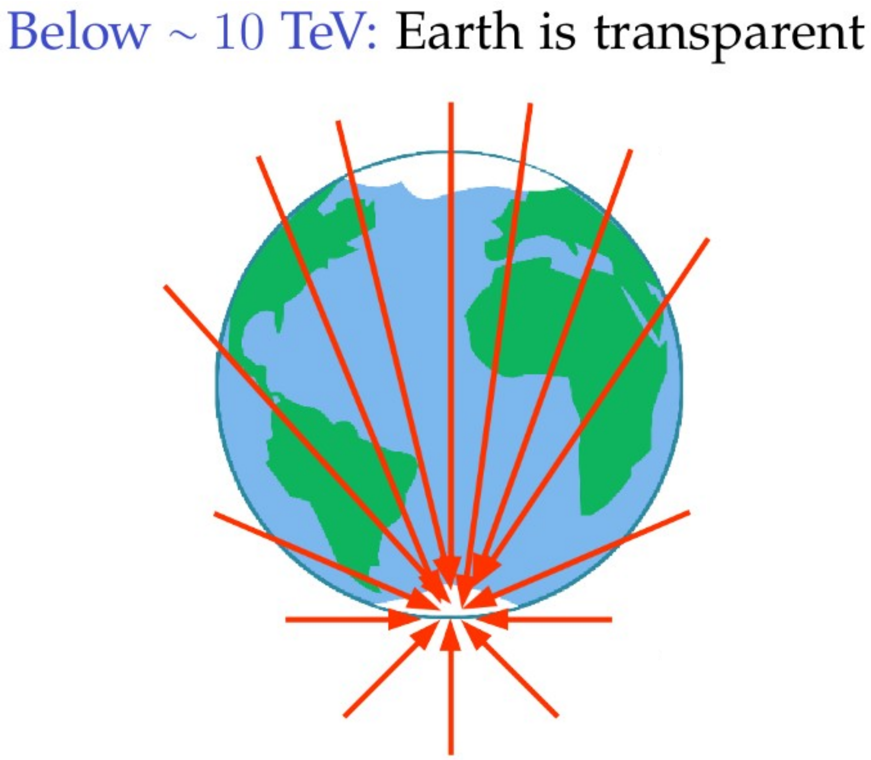

ν
μ
ν
ν
ν
Horizon
IceCube

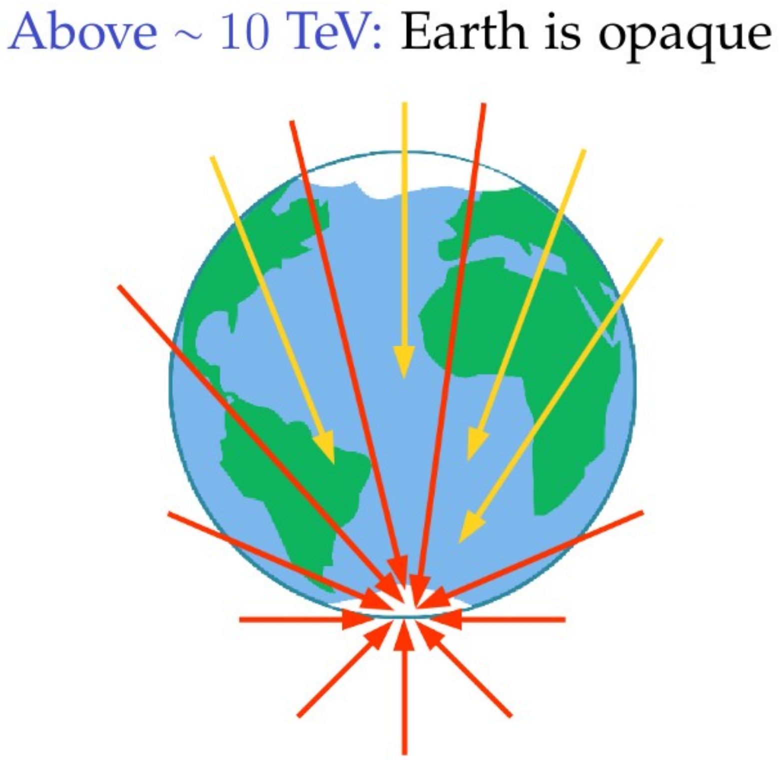

ν
μ
ν
ν
ν
Horizon
IceCube
νN *charged* current scattering
N
hadrons
ν_l
l


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


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

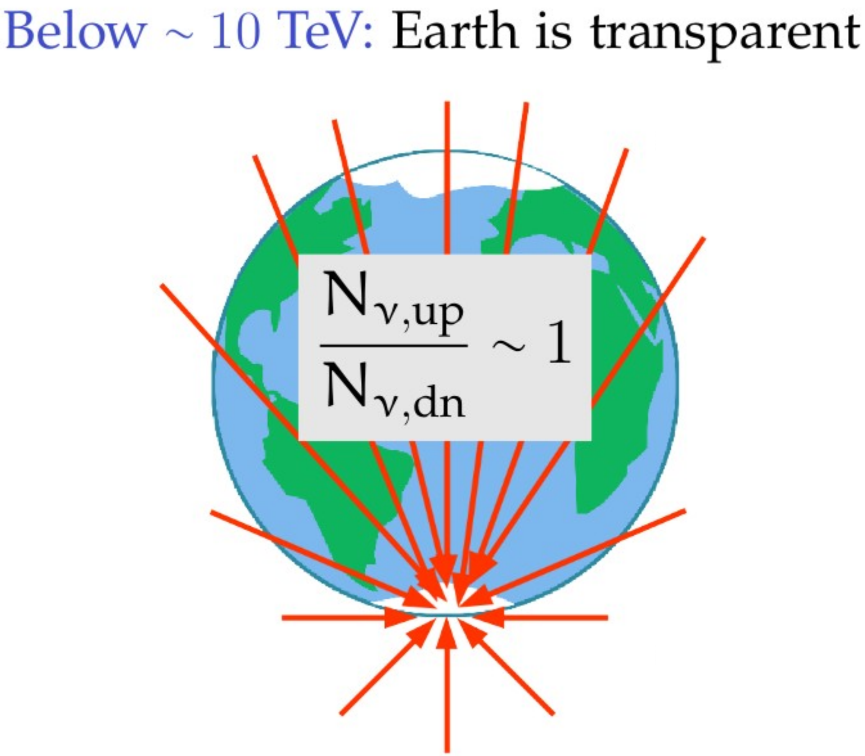
Measuring the high-energy νN cross section

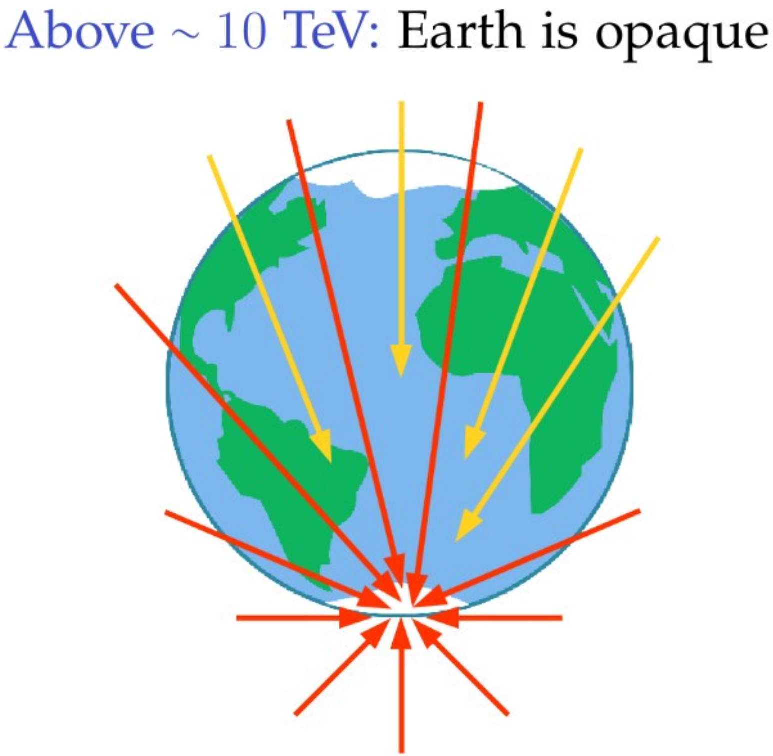




Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

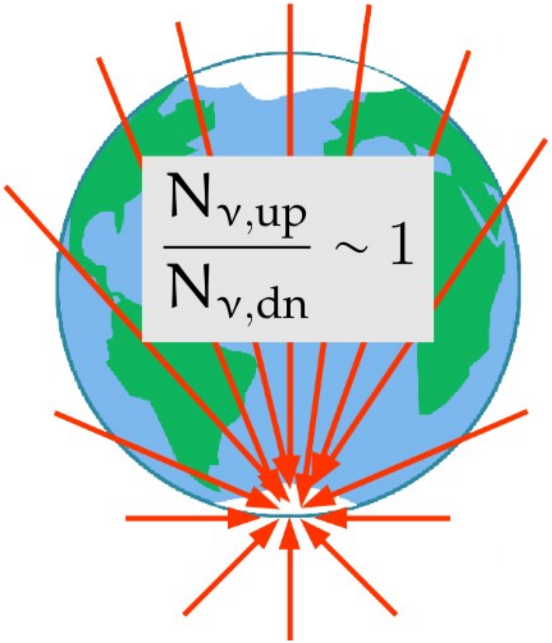




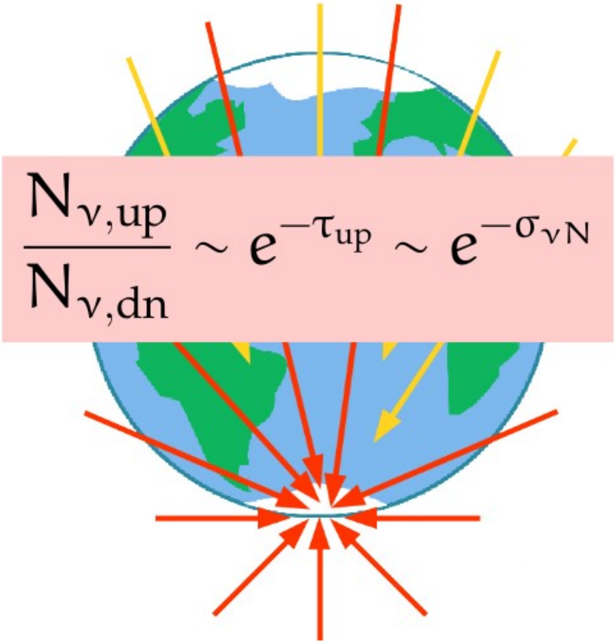
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

Measuring the high-energy νN cross section

Below ~ 10 TeV: Earth is transparent

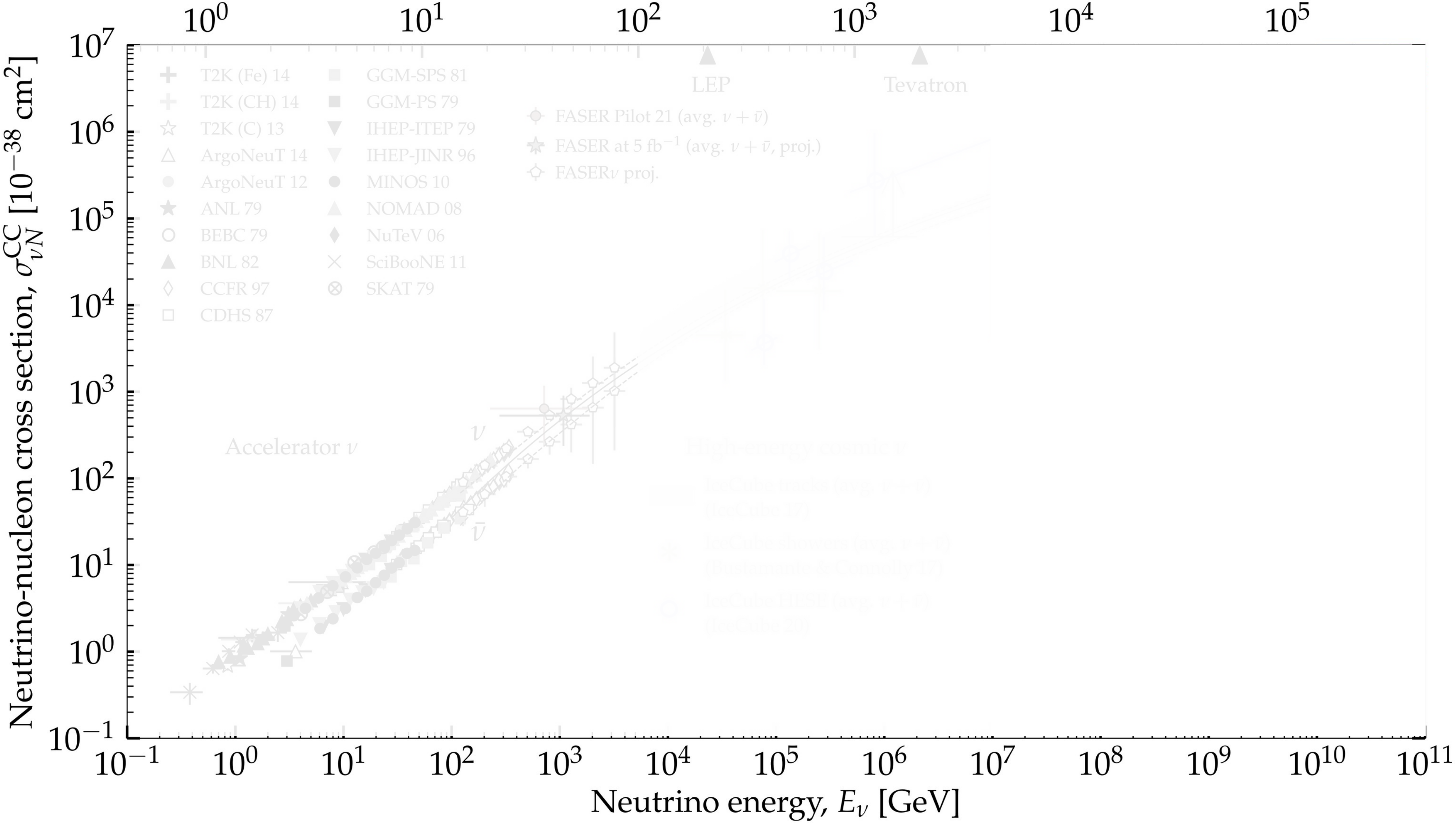


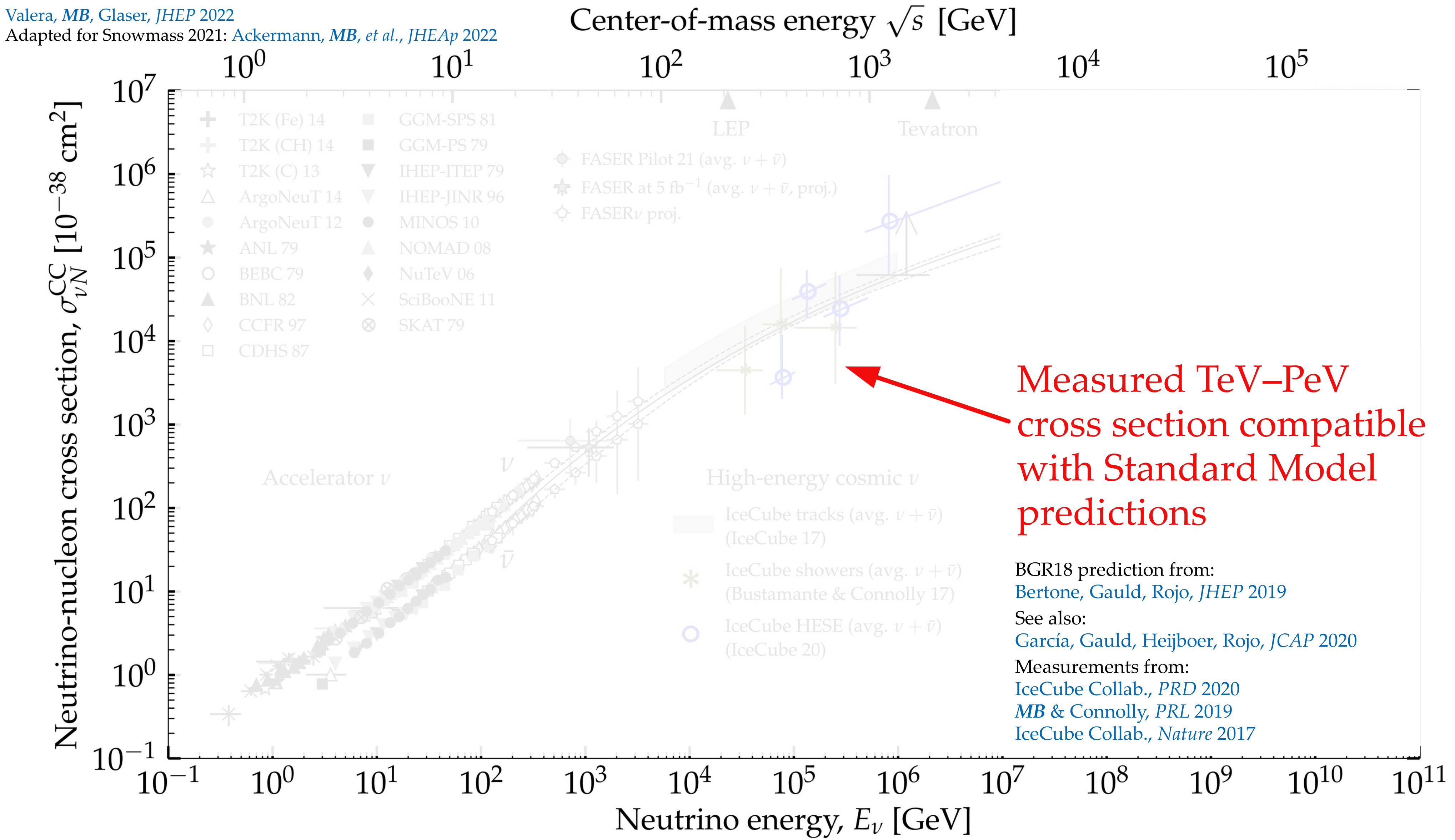
Above ~ 10 TeV: Earth is opaque



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

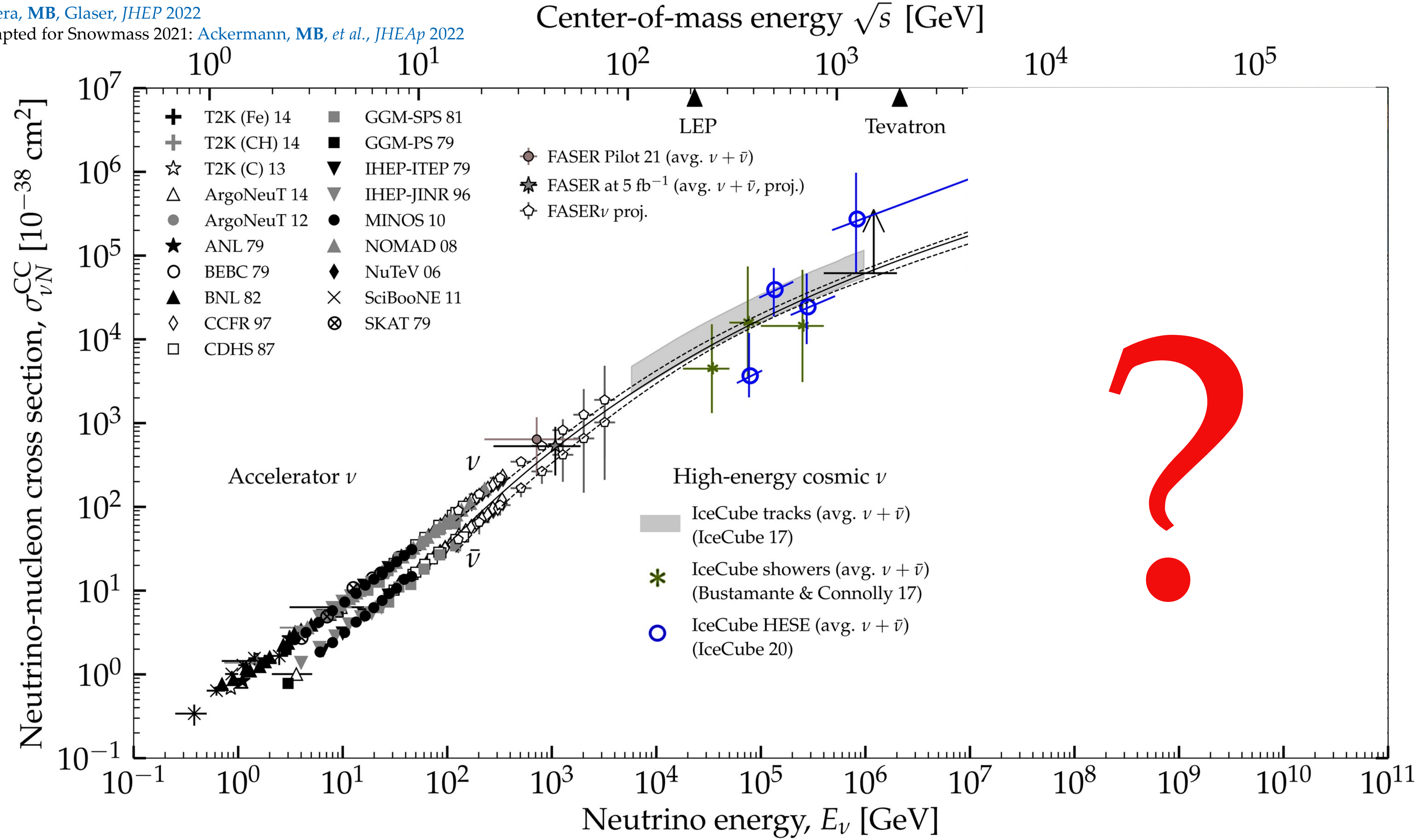
Valera, ***MB***, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, ***MB***, *et al.*, *JHEAp* 2022





Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy $\sqrt{s}$ [GeV]
10^0 10^1 10^2 10^3 10^4 10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7 10^6 10^5 10^4 10^3 10^2 10^1 10^0 10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
FASER Pilot 21 (avg. $\nu + \bar{\nu}$)
FASER at 5 fb^{-1} (avg. $\nu + \bar{\nu}$, proj.)
FASERν proj.
Accelerator ν
ν
$\bar{\nu}$
High-energy cosmic ν
IceCube tracks (avg. $\nu + \bar{\nu}$)
(IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$)
(Bustamante & Connolly 17)
IceCube HESE (avg. $\nu + \bar{\nu}$)
(IceCube 20)
Measured TeV–PeV cross section compatible with Standard Model predictions
BGR18 prediction from:
Bertone, Gauld, Rojo, JHEP 2019
See also:
García, Gauld, Heijboer, Rojo, JCAP 2020
Measurements from:
IceCube Collab., PRD 2020
MB & Connolly, PRL 2019
IceCube Collab., Nature 2017
10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11}
Neutrino energy, E_ν [GeV]

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



Today

TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

Key developments:

Larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today
TeV–PeV ν

Astro: Find & understand sources

Particle: Turn predictions into tests

Key developments:

Larger statistics

Better reconstruction

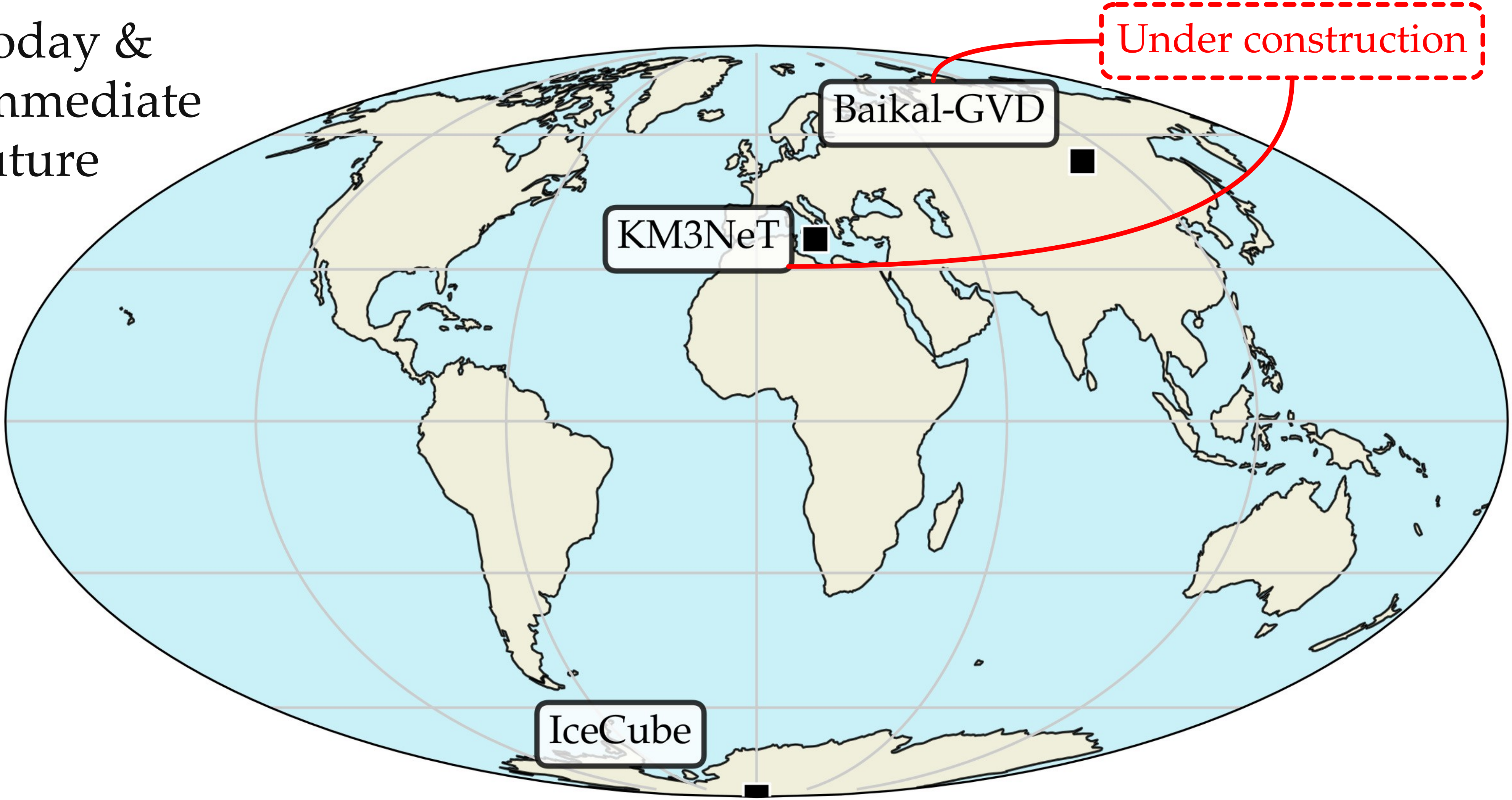
Smaller astrophysical uncertainties

Next decade
> 100-PeV ν

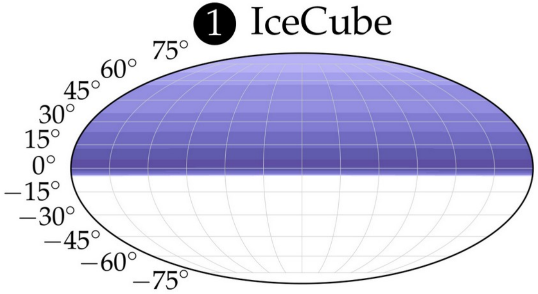
Make predictions for

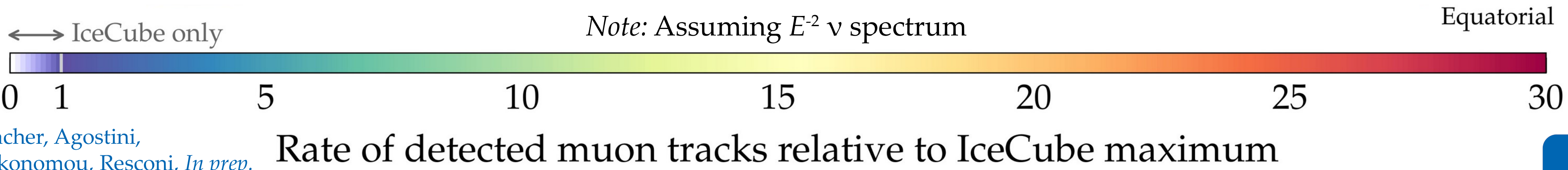
a new energy regime

Today & immediate future

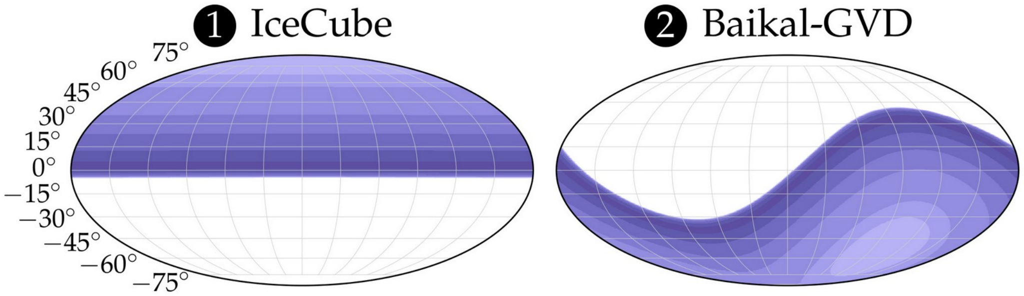


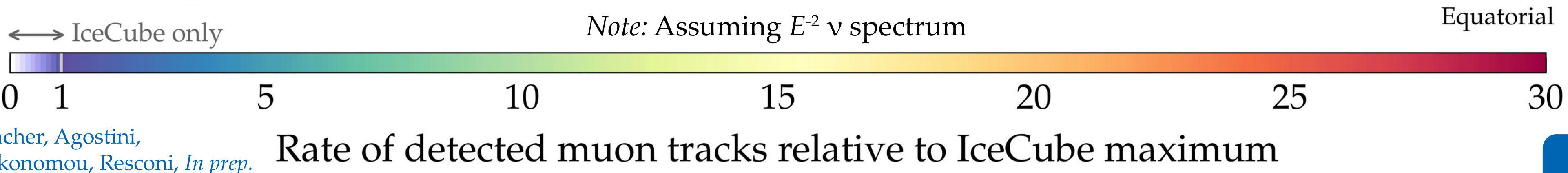
Schumacher, Agostini, ***MB***, Oikonomou, Resconi, *In prep.*



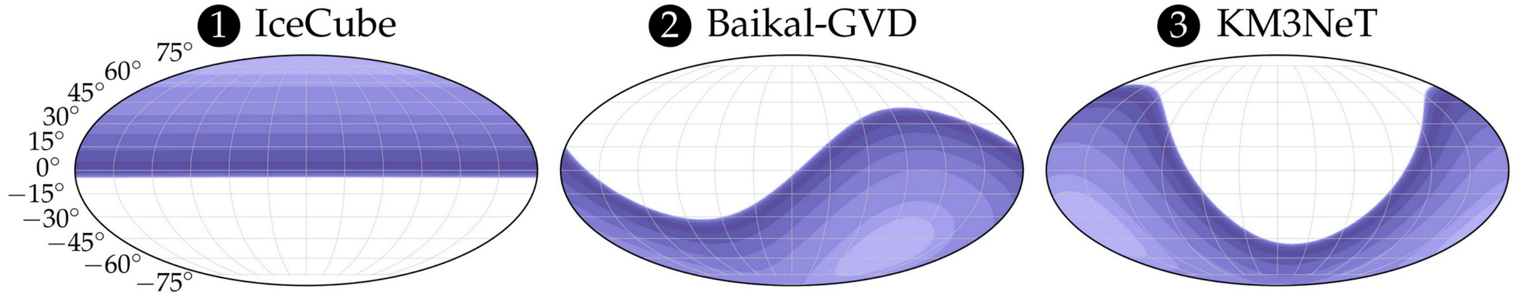


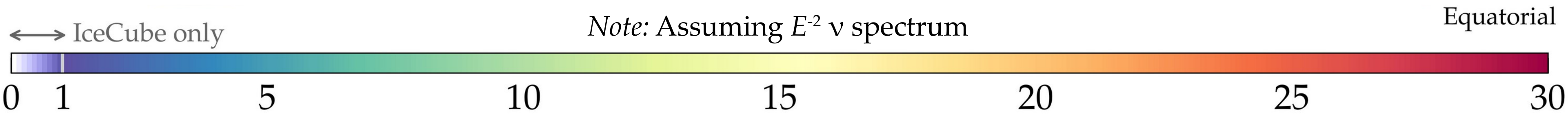
Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*





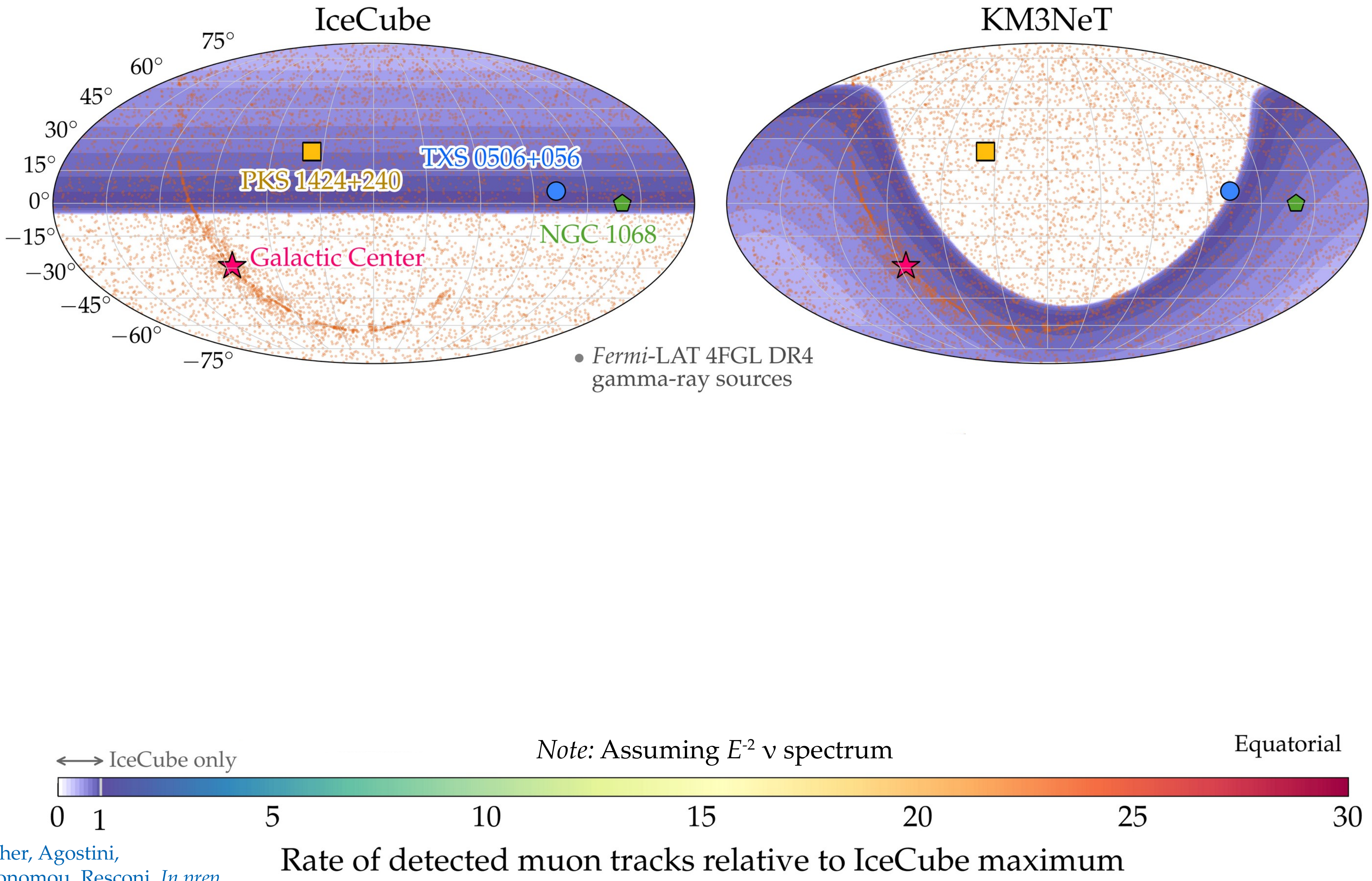
Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*





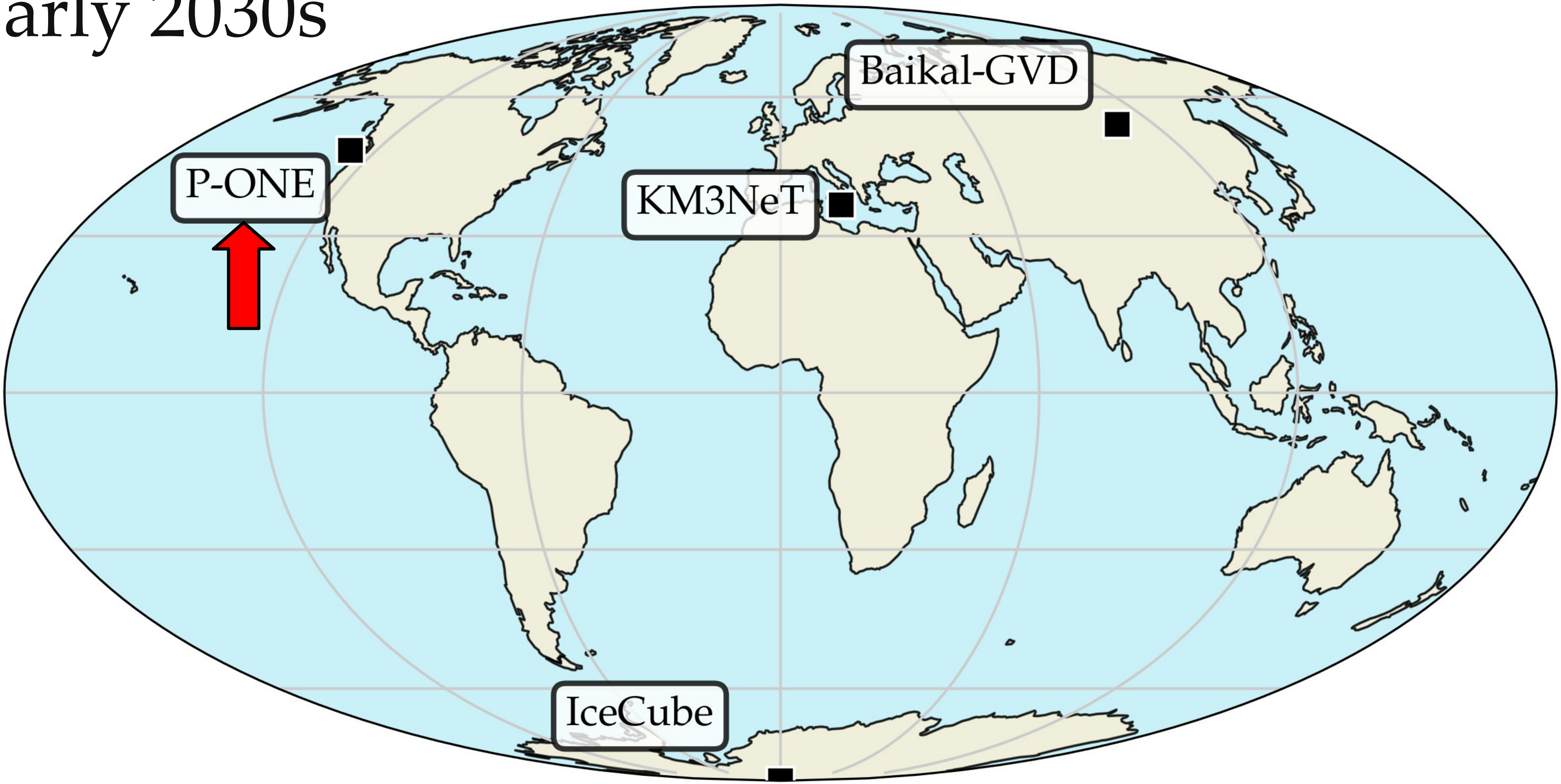
Rate of detected muon tracks relative to IceCube maximum

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

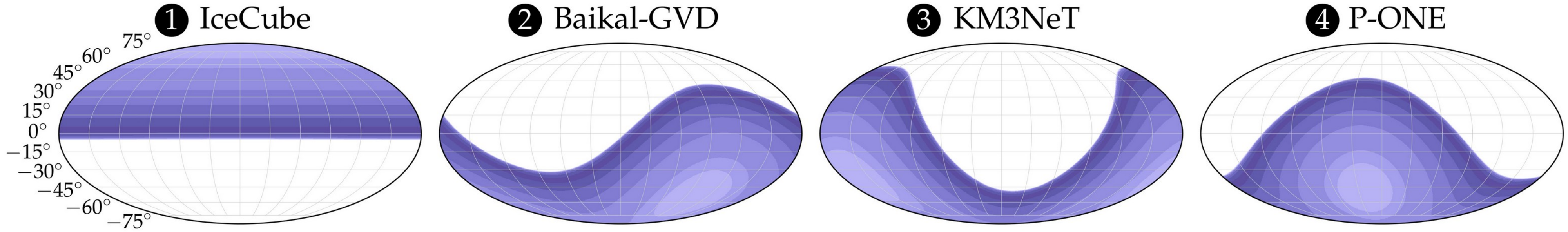


Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*

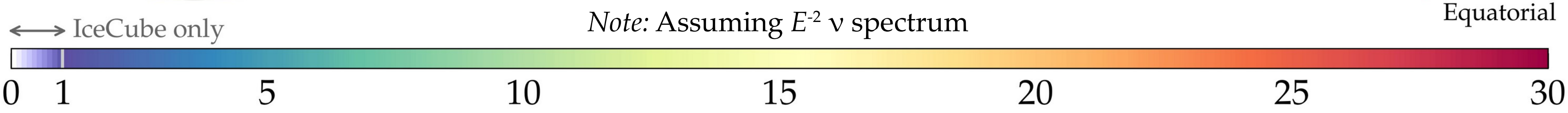
Early 2030s



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



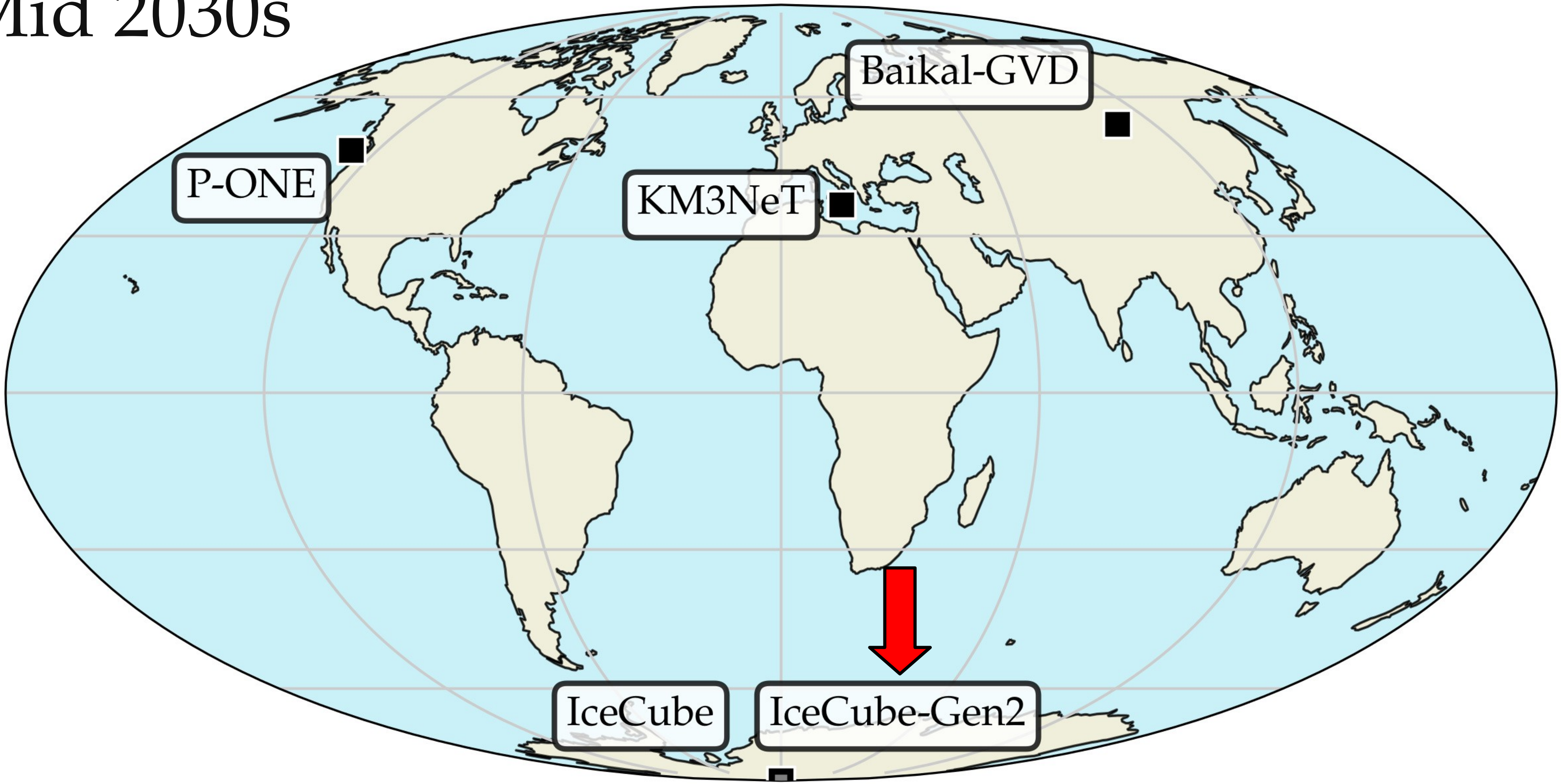
Note: Assuming E^{-2} ν spectrum



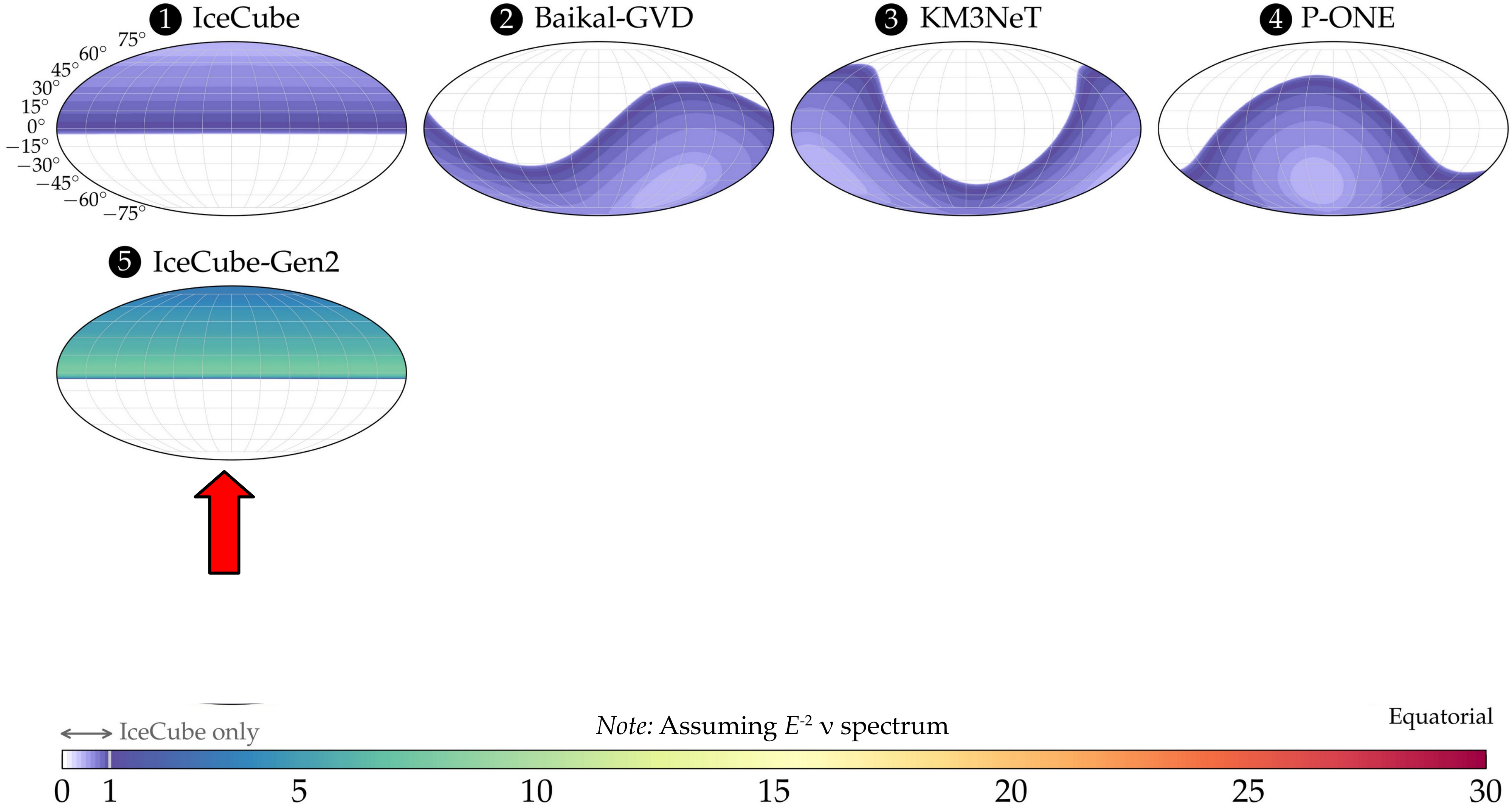
Rate of detected muon tracks relative to IceCube maximum

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

Mid 2030s



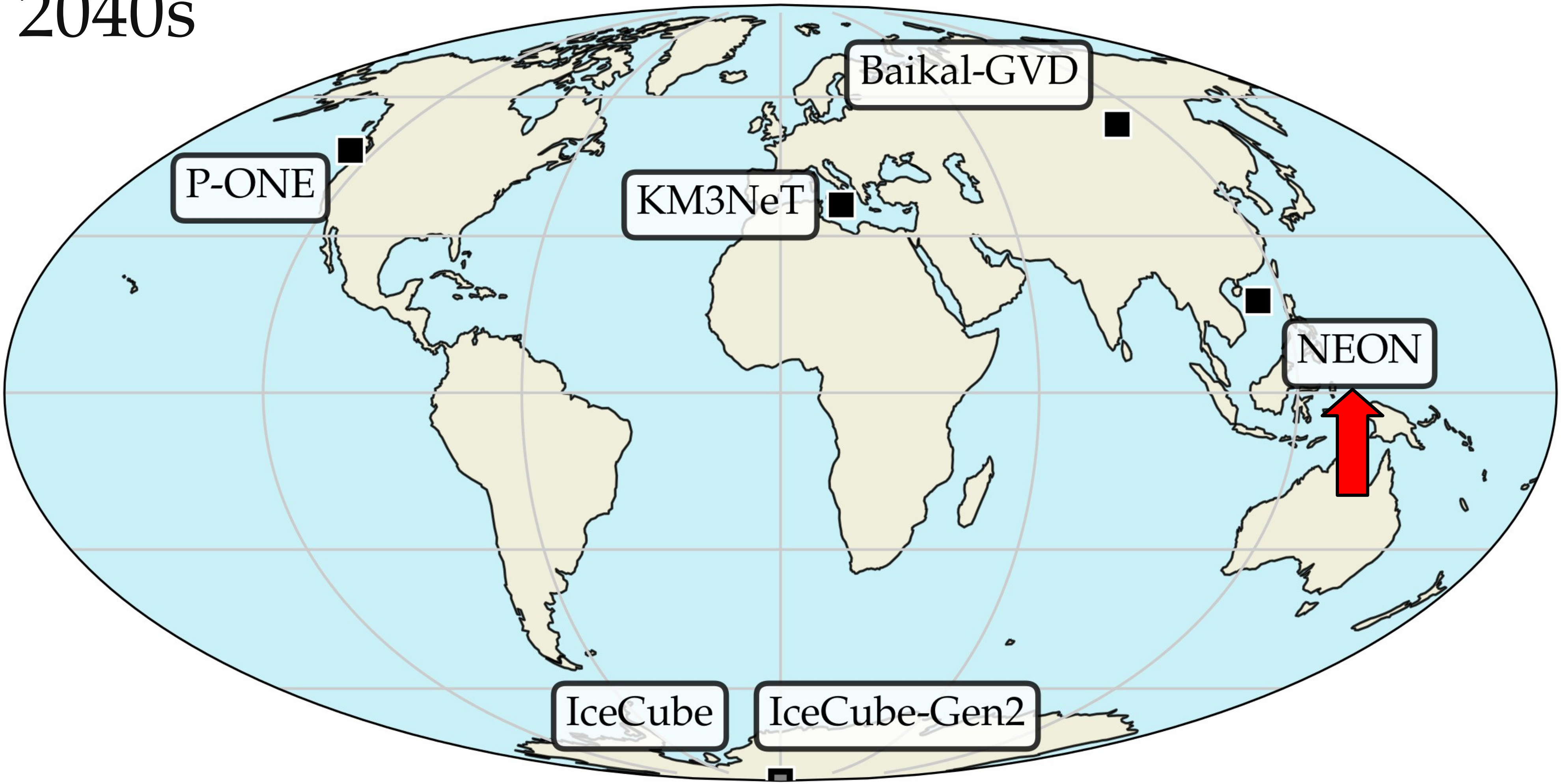
Schumacher, Agostini, ***MB***, Oikonomou, Resconi, *In prep.*



Rate of detected muon tracks relative to IceCube maximum

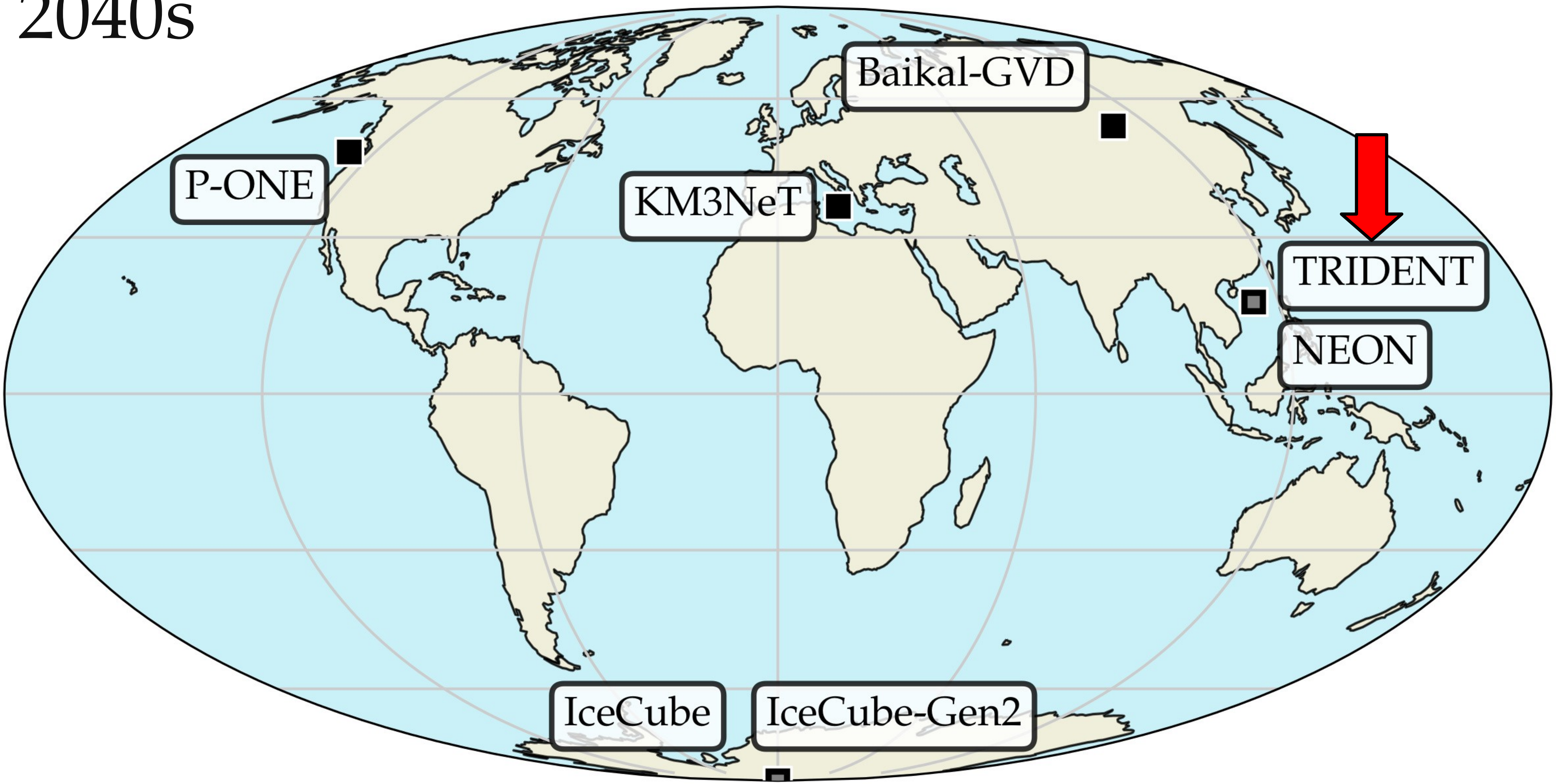
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

2040s

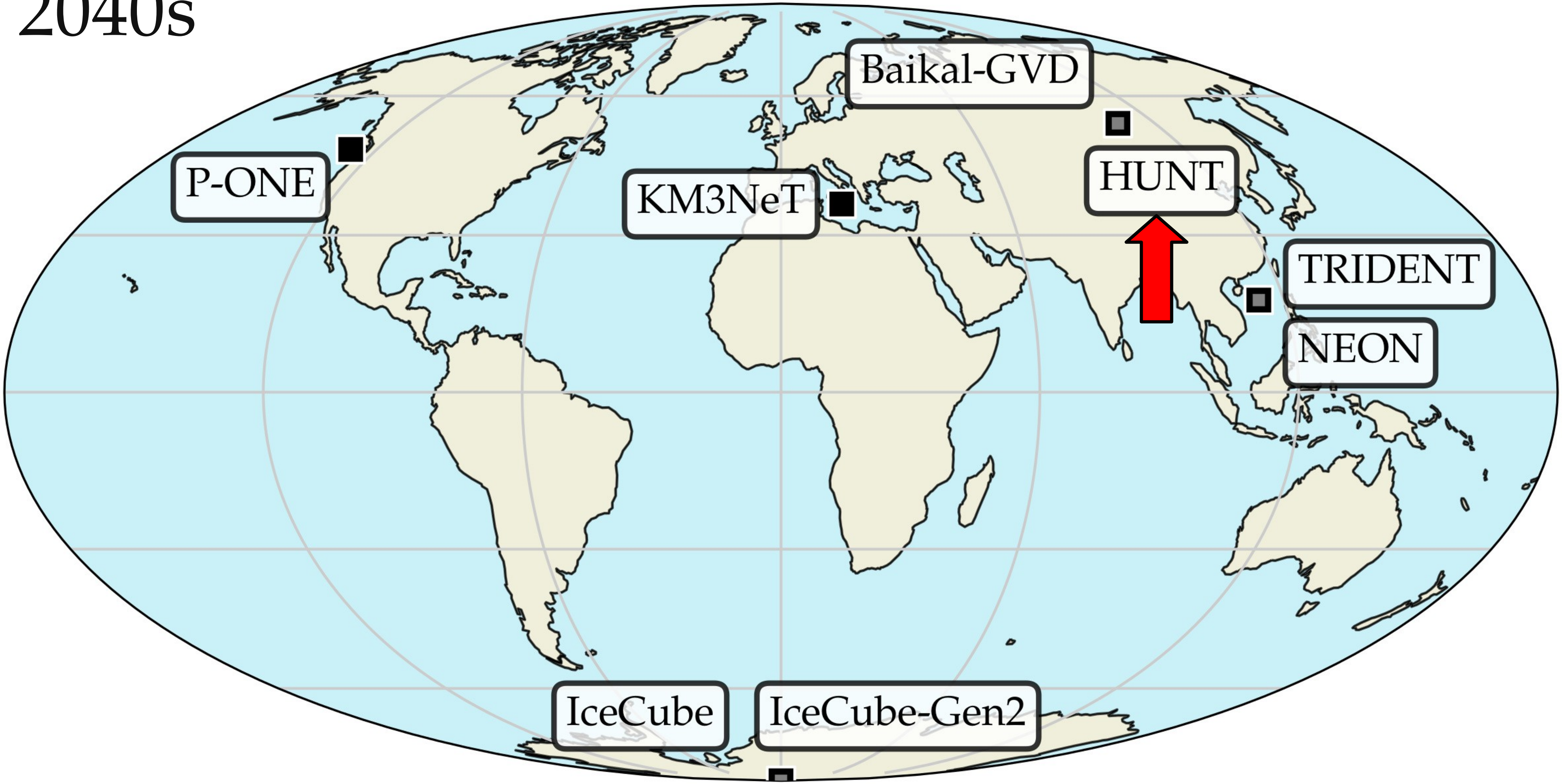


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

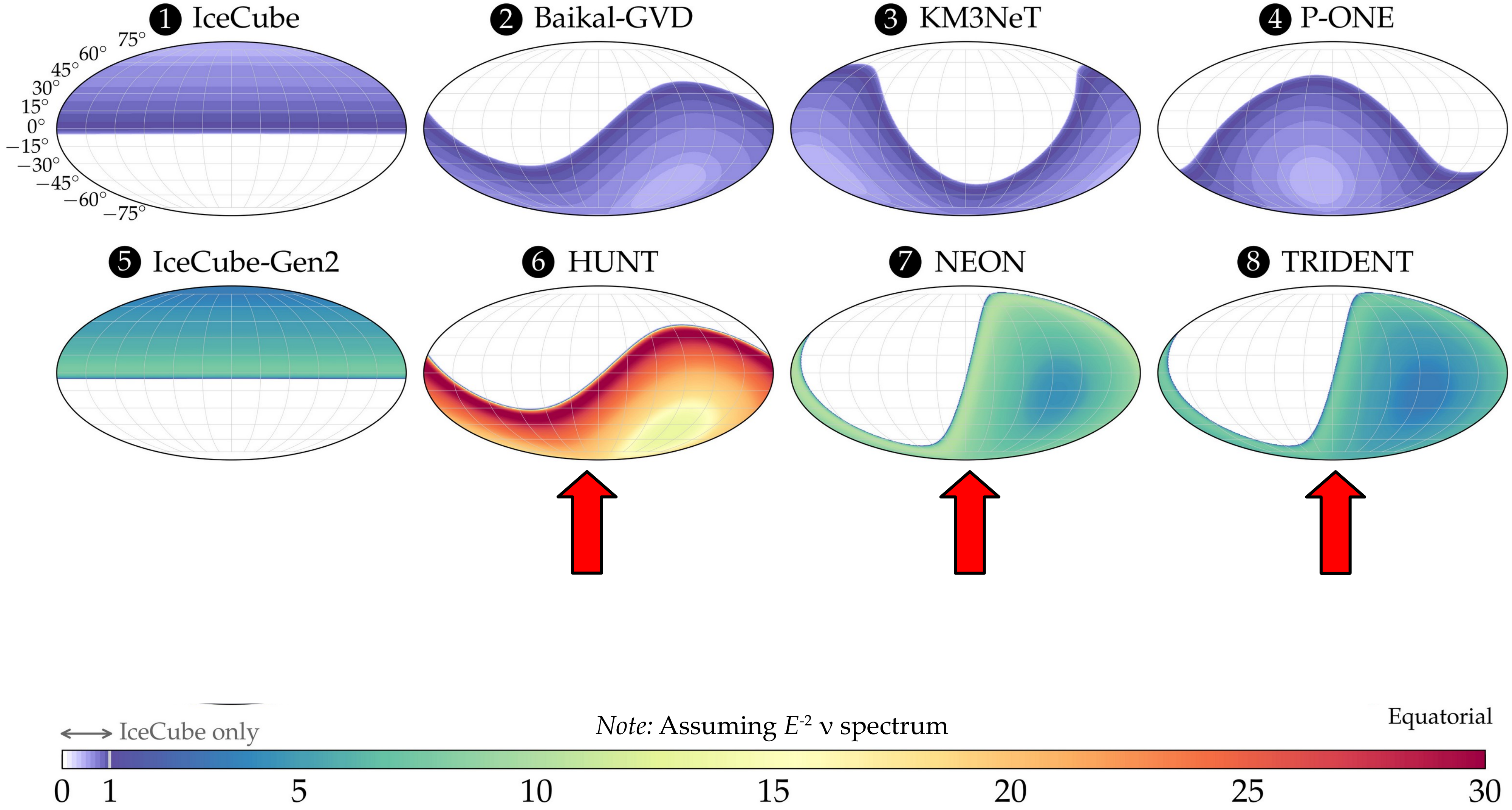
2040s



2040s

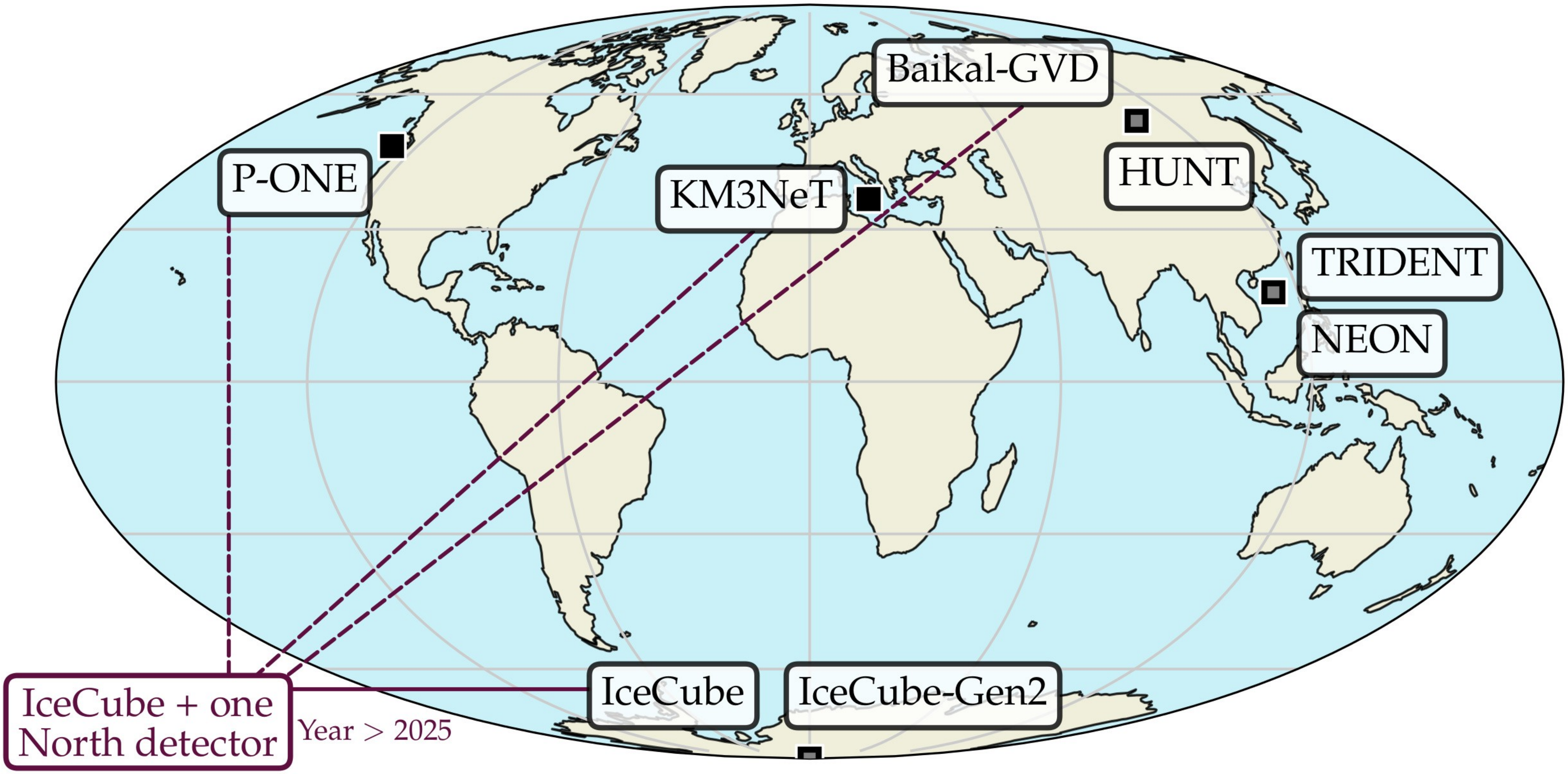


Schumacher, Agostini, ***MB***, Oikonomou, Resconi, *In prep.*

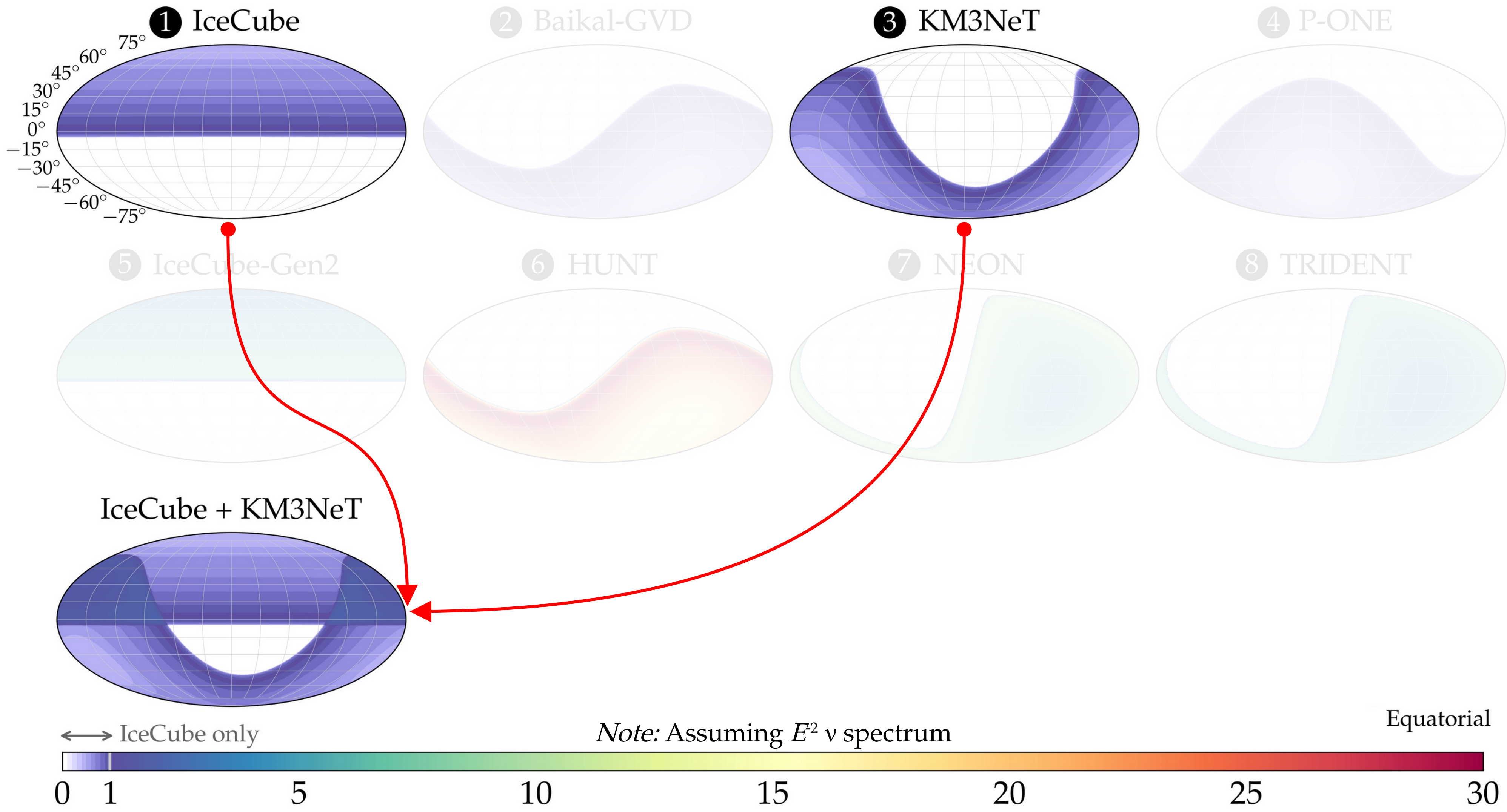


Rate of detected muon tracks relative to IceCube maximum

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

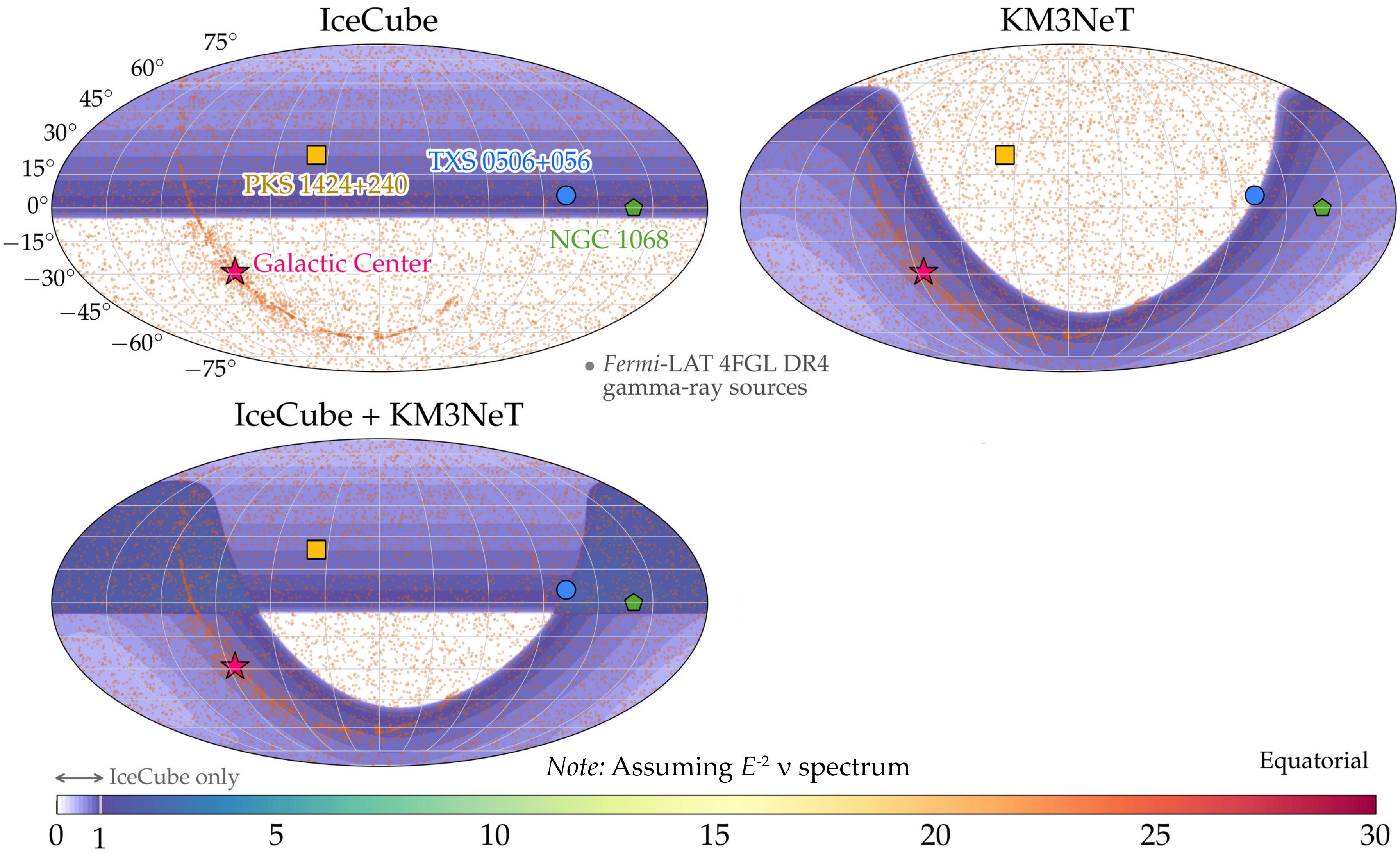


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

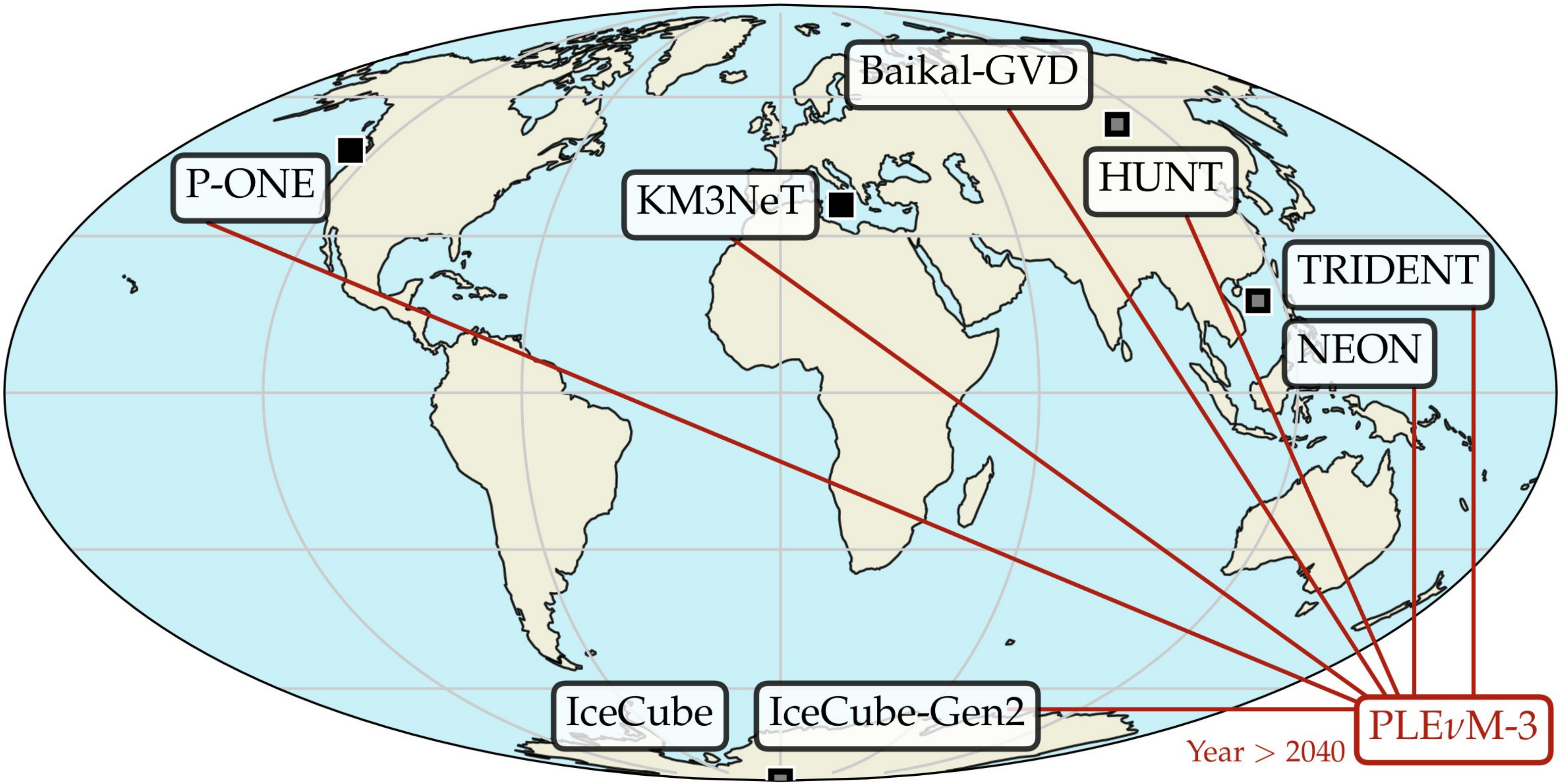


Rate of detected muon tracks relative to IceCube maximum

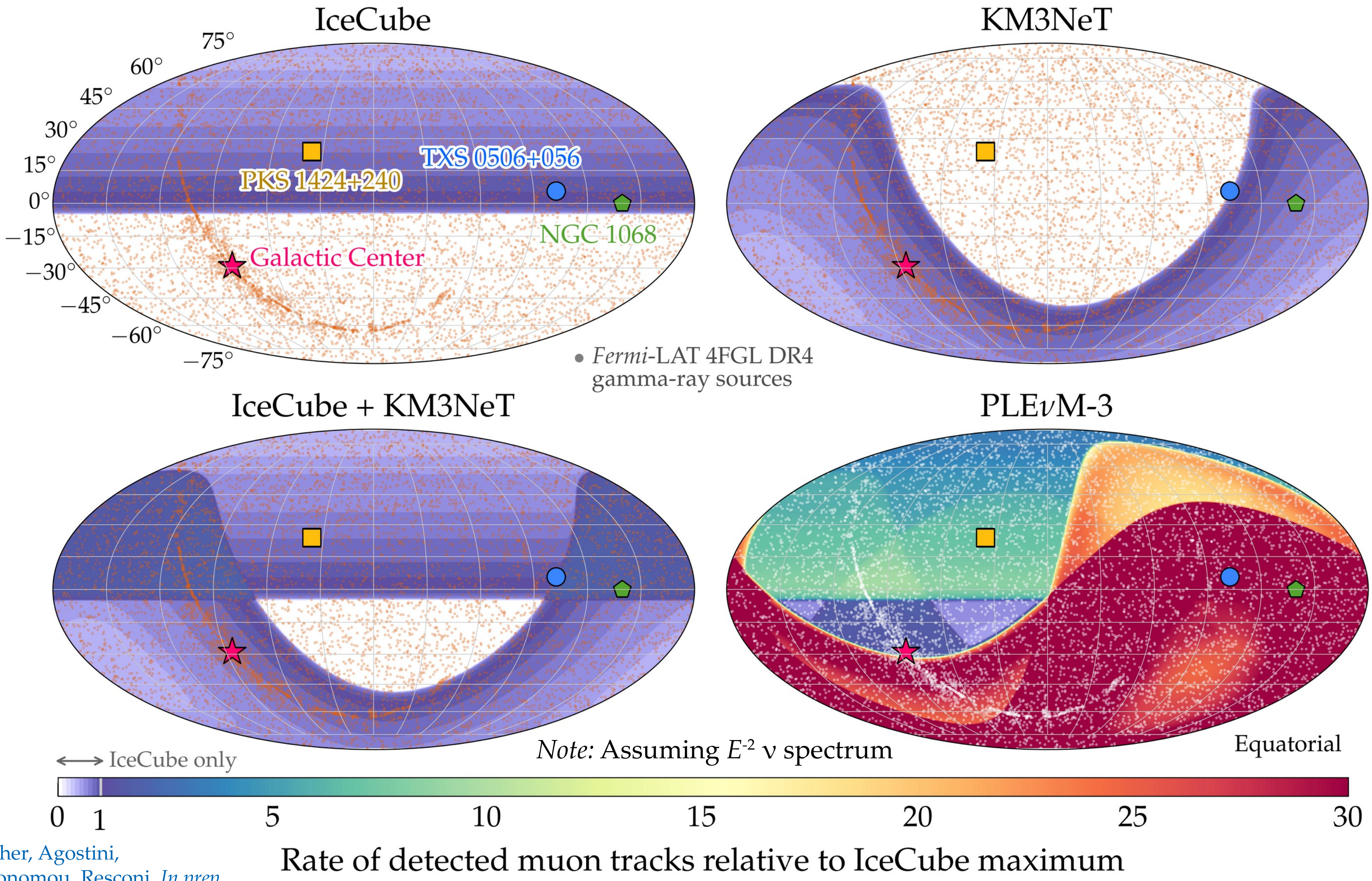
Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*



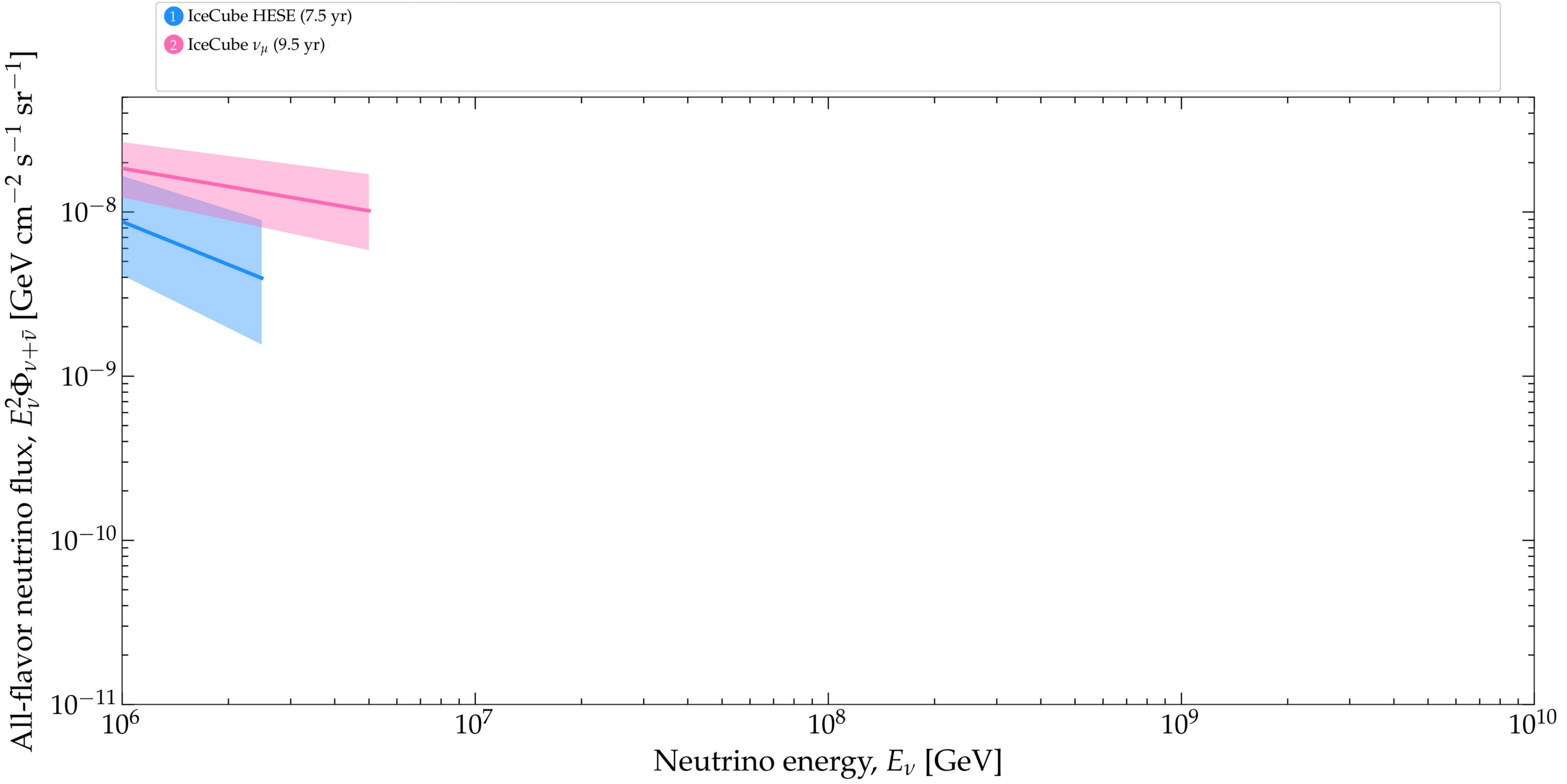
Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*



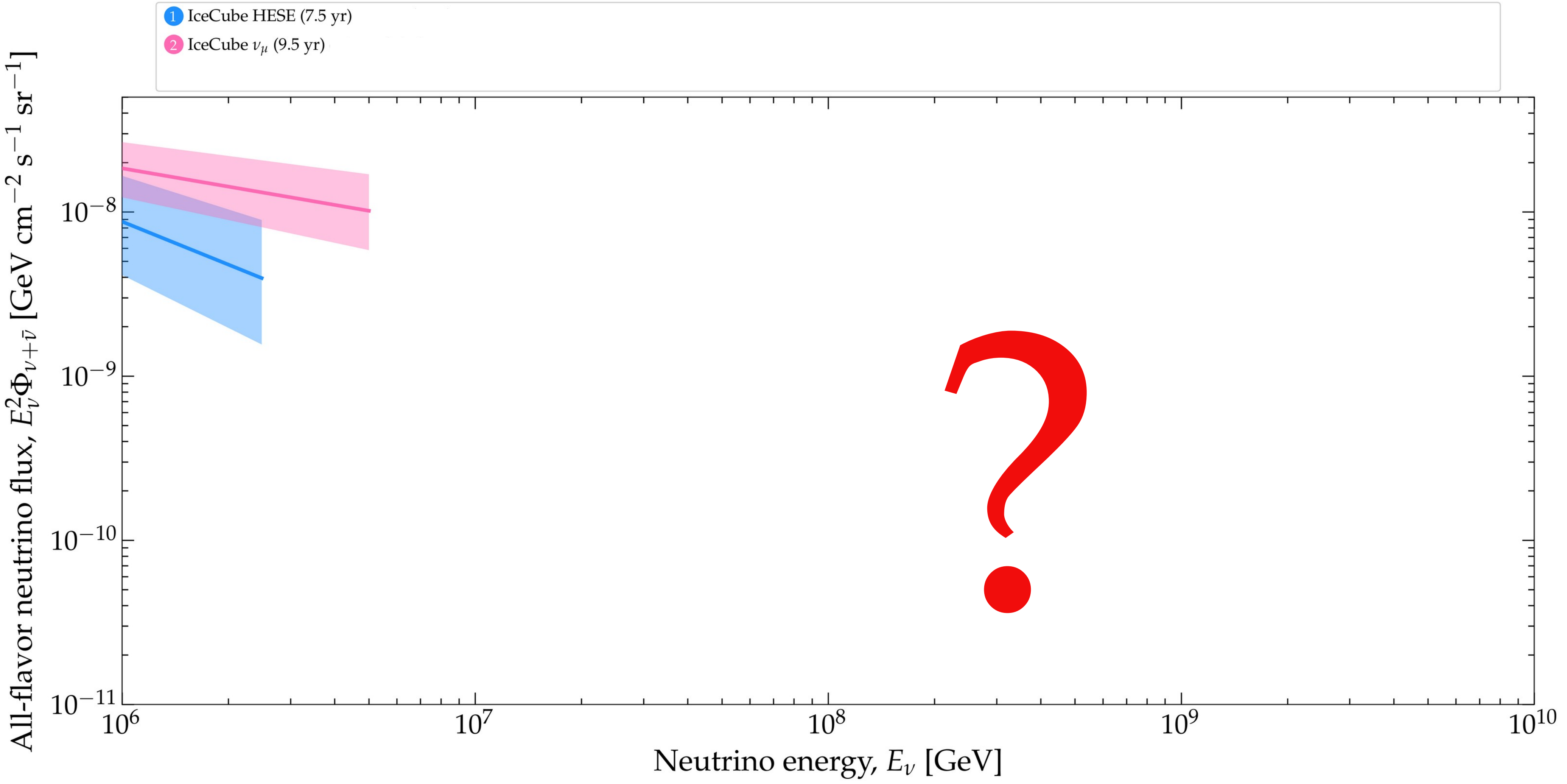
Schumacher, Agostini, ***MB***, Oikonomou, Resconi, *In prep.*



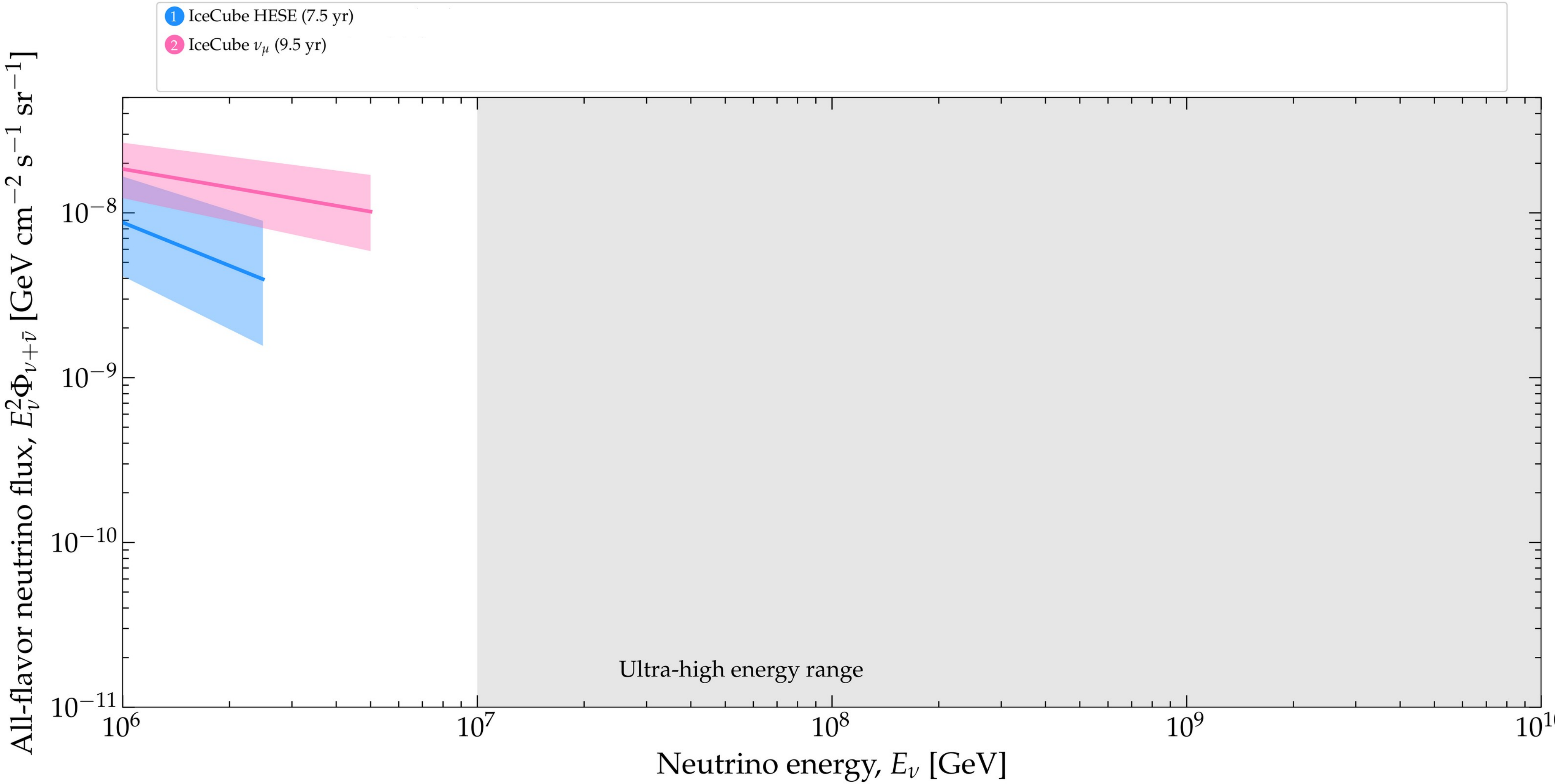
Schumacher, Agostini,
MB, Oikonomou, Resconi, *In prep.*

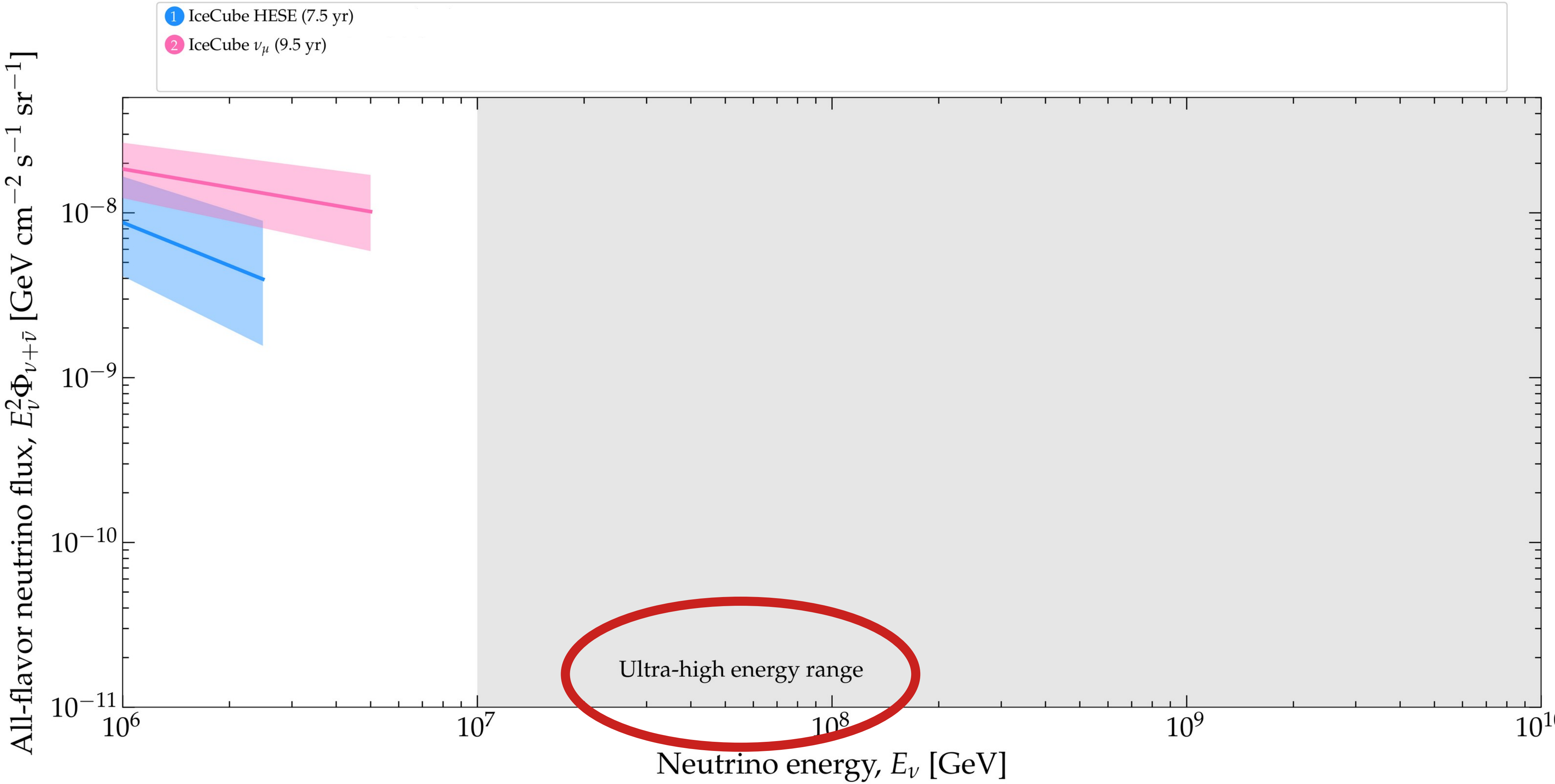


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]

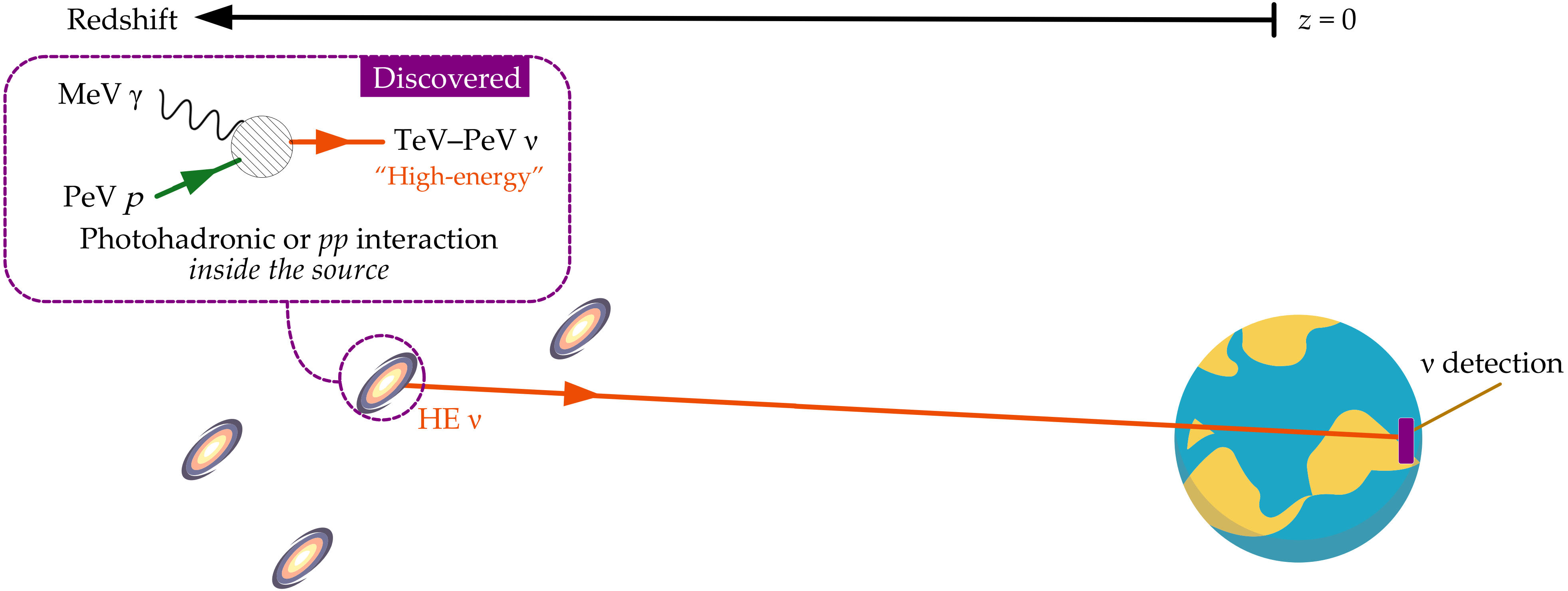


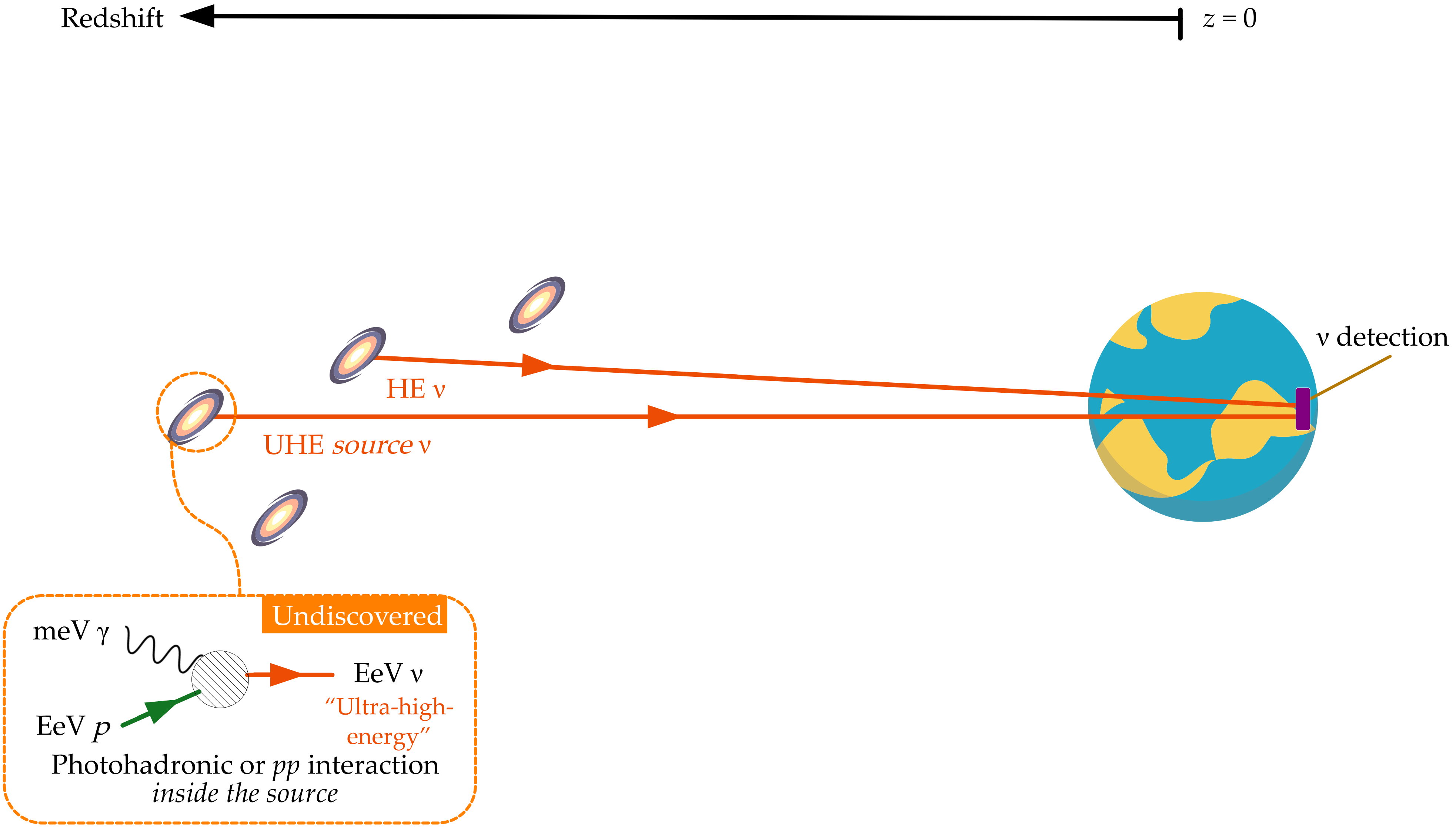
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
?


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

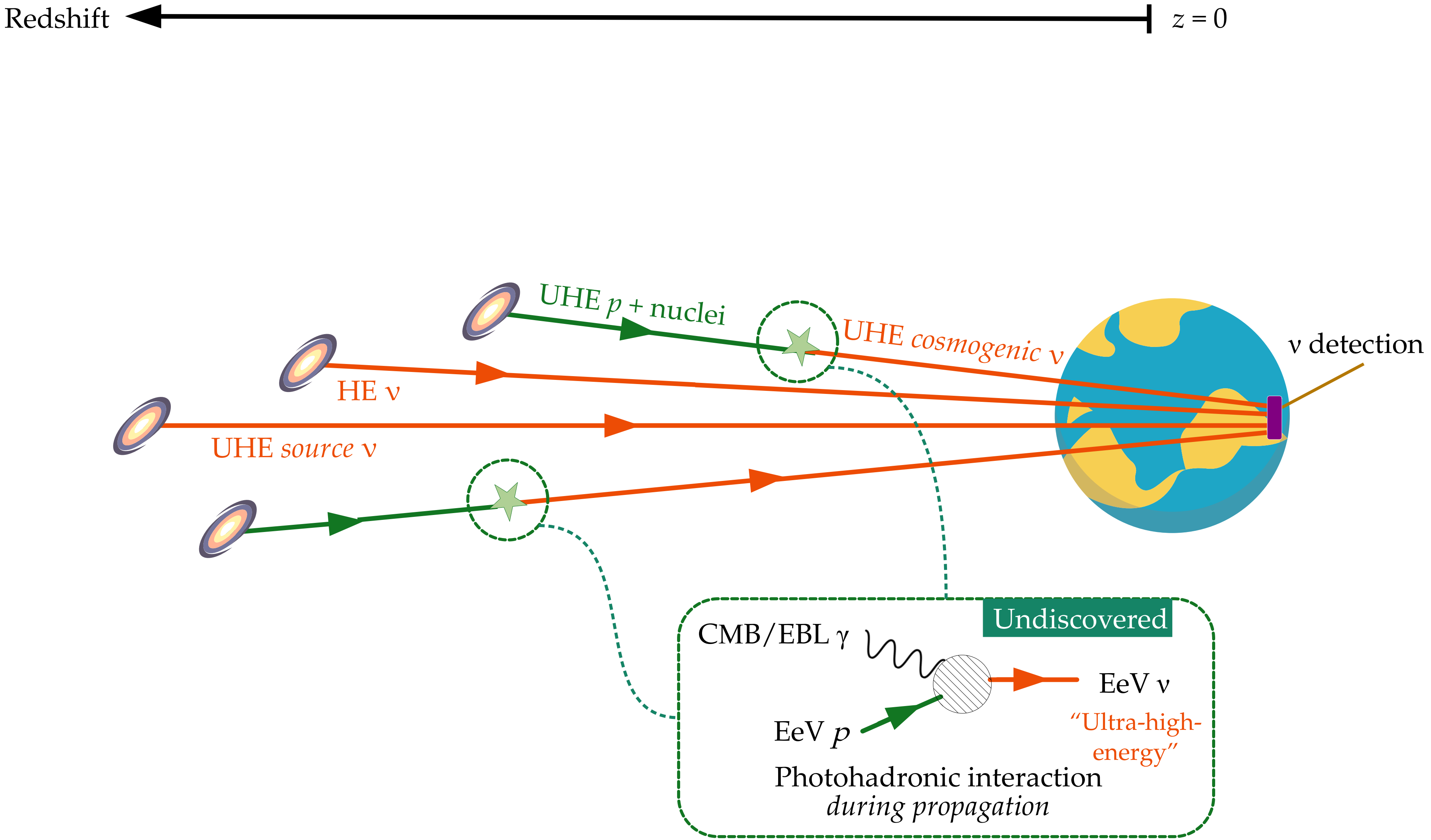


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
Ultra-high energy range

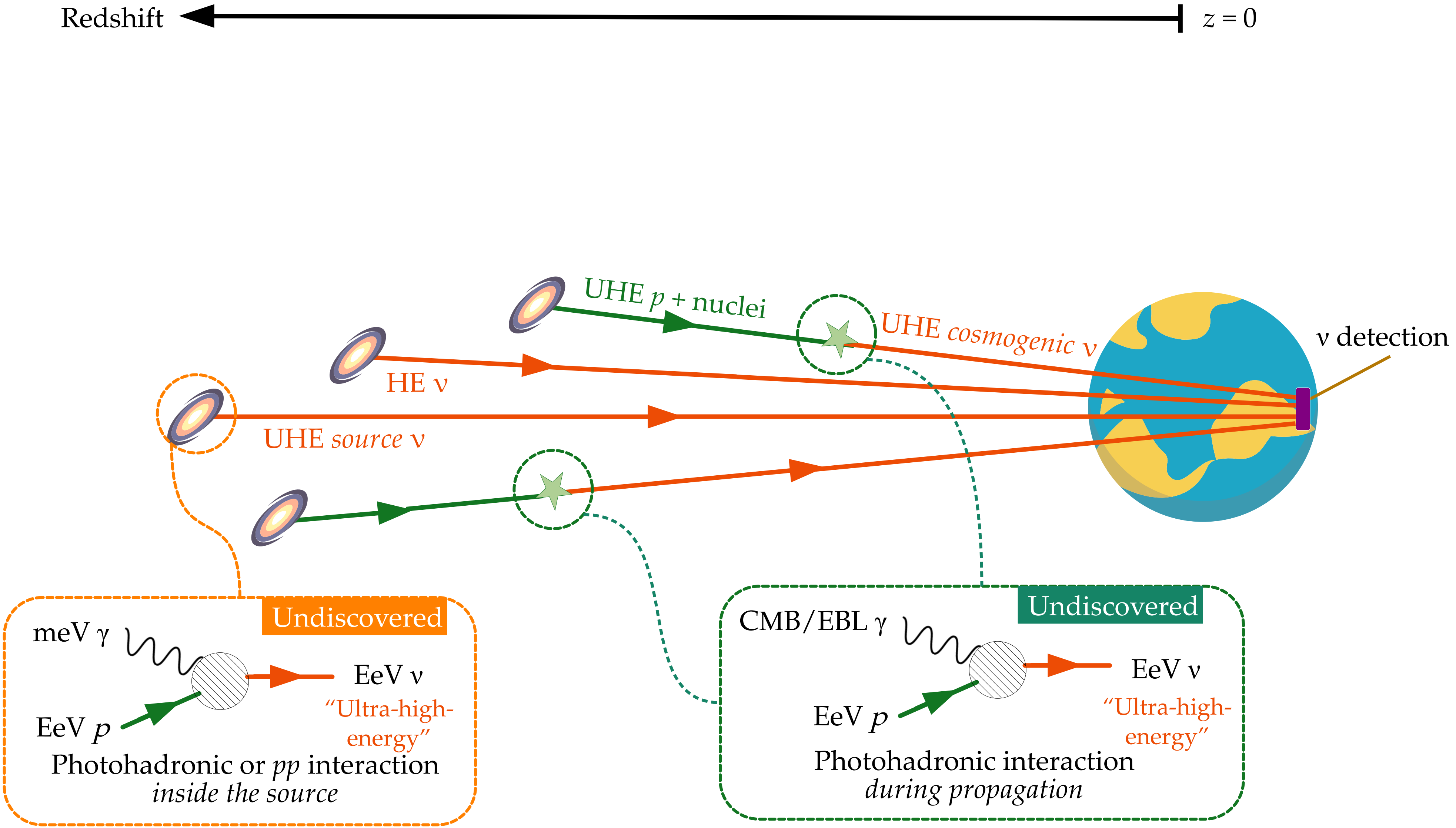

Redshift
z = 0
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
HE ν
ν detection

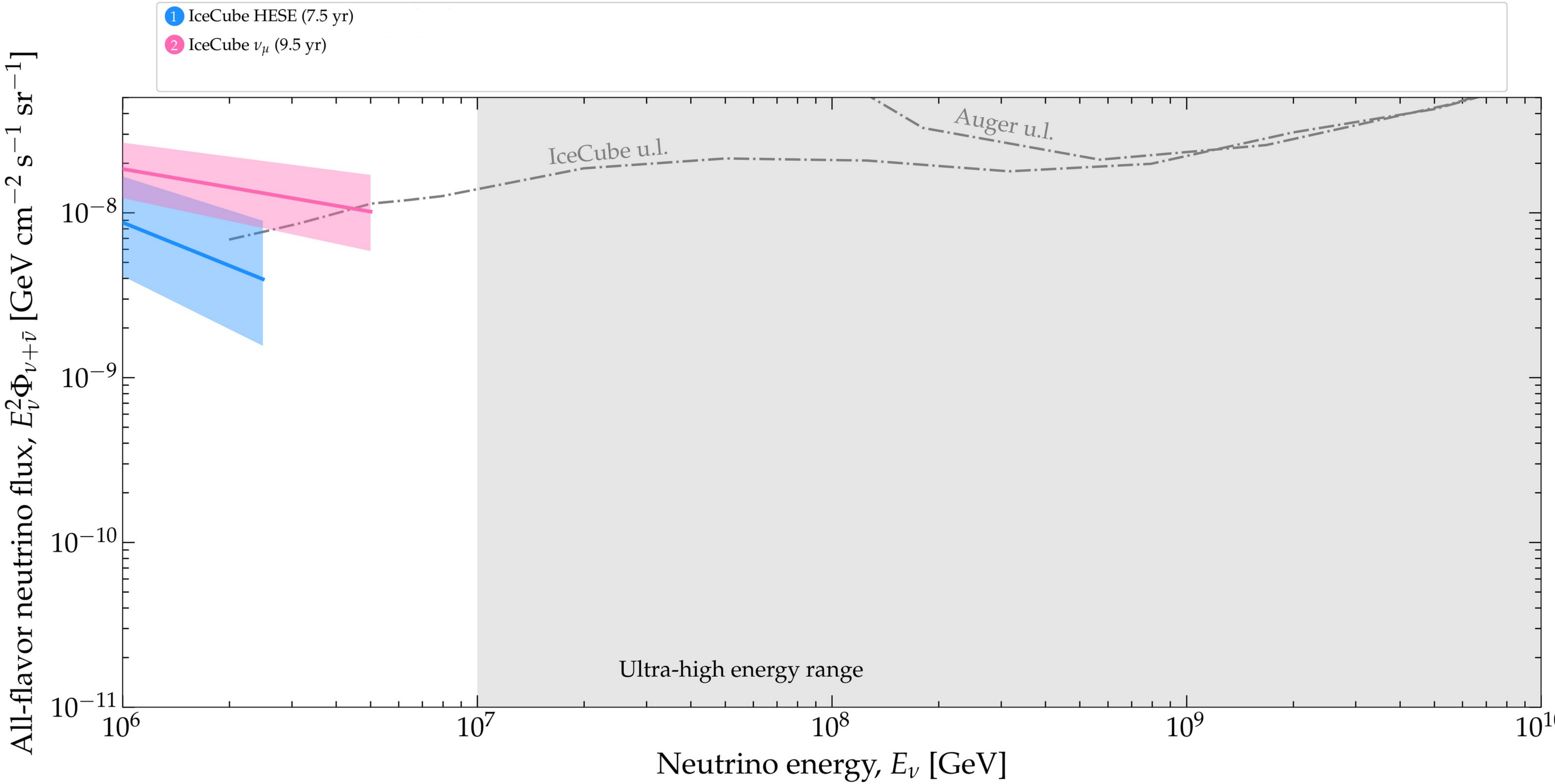


Redshift
z = 0
ν detection
HE ν
UHE source ν
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV p
Photohadronic or pp interaction
inside the source



Redshift
z = 0
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation


Redshift
z = 0
UHE p + nuclei
UHE cosmogenic ν
HE ν
UHE source ν
ν detection
Undiscovered
meV γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic or pp interaction
inside the source
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-energy"
Photohadronic interaction
during propagation



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

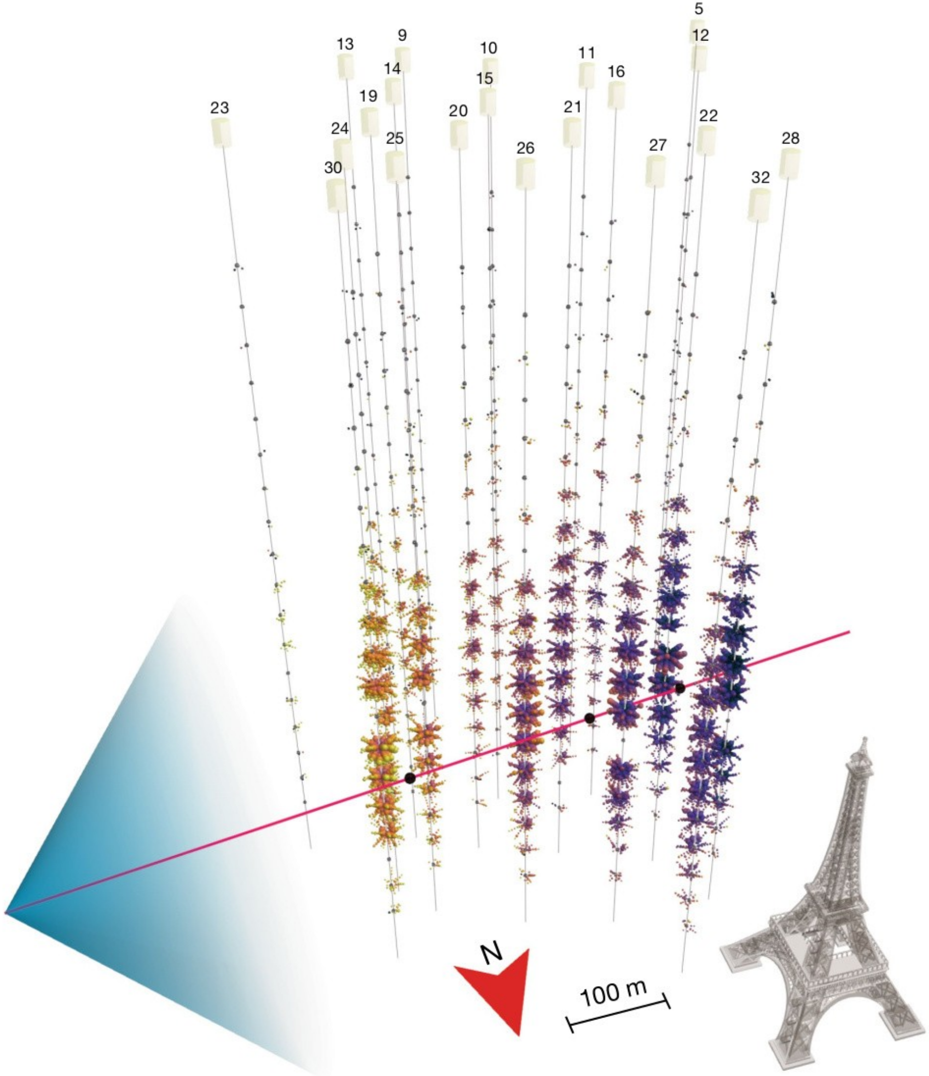
Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

One muon detected with 120^{+110}_{-60} PeV


The international journal of science / 13 February 2025
nature
COSMIC CATCHER
Deep-sea telescope detects neutrino with highest energy ever recorded


5
12
13
9
10
11
16
14
15
19
20
21
22
23
24
25
26
27
28
30
32
N
100 m

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

One muon detected with 120^{+110}_{-60} PeV

But is it due to a neutrino?

Yes! Direction points underground, after traveling 150 km through Earth

Inferred neutrino energy: 220^{+570}_{-110} PeV

Article

Observation of an ultra-high-energy cosmic neutrino with KM3NeT

KM3NeT Collab. *Nature* 638, 376 (2025)

One muon detected with 120^{+110}_{-60} PeV

But is it due to a neutrino?

Yes! Direction points underground, after traveling 150 km through Earth

Inferred neutrino energy: 220^{+570}_{-110} PeV

RECORD BREAKER

The New York Times

'Ultrahigh Energy' Neutrino Found With a Telescope Under the Sea

It's the most energetic particle of its kind ever discovered, and scientists have no idea where it came from.

EL MUNDO

El potente telescopio KM3NeT, sumergido en el Mediterráneo, 'atrapa' el neutrino de mayor energía jamás observado

Este hallazgo "abre un nuevo capítulo en la astronomía de neutrinos y una nueva ventana de observación al universo"

Le Monde

'Ultra-high energy' neutrino detected in Mediterranean

CNN Science

Scientists detect record-breaking 'ghost particle' in the Mediterranean Sea

LA NACION

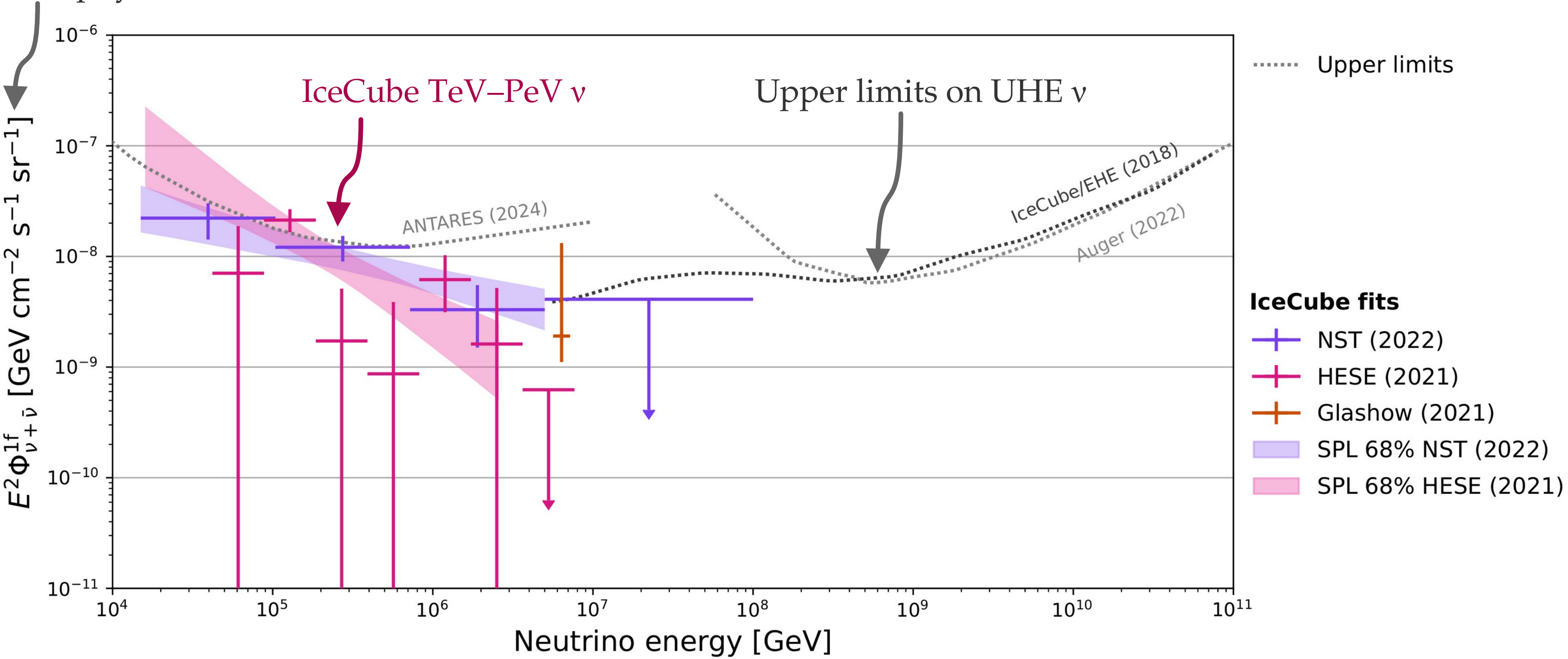
Sorpresa y enigma: un telescopio submarino detectó una extraordinaria partícula que desconcierta a los científicos

Reuters

High-energy cosmic neutrino detected under Mediterranean Sea

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

Diffuse flux of high-energy astrophysical ν

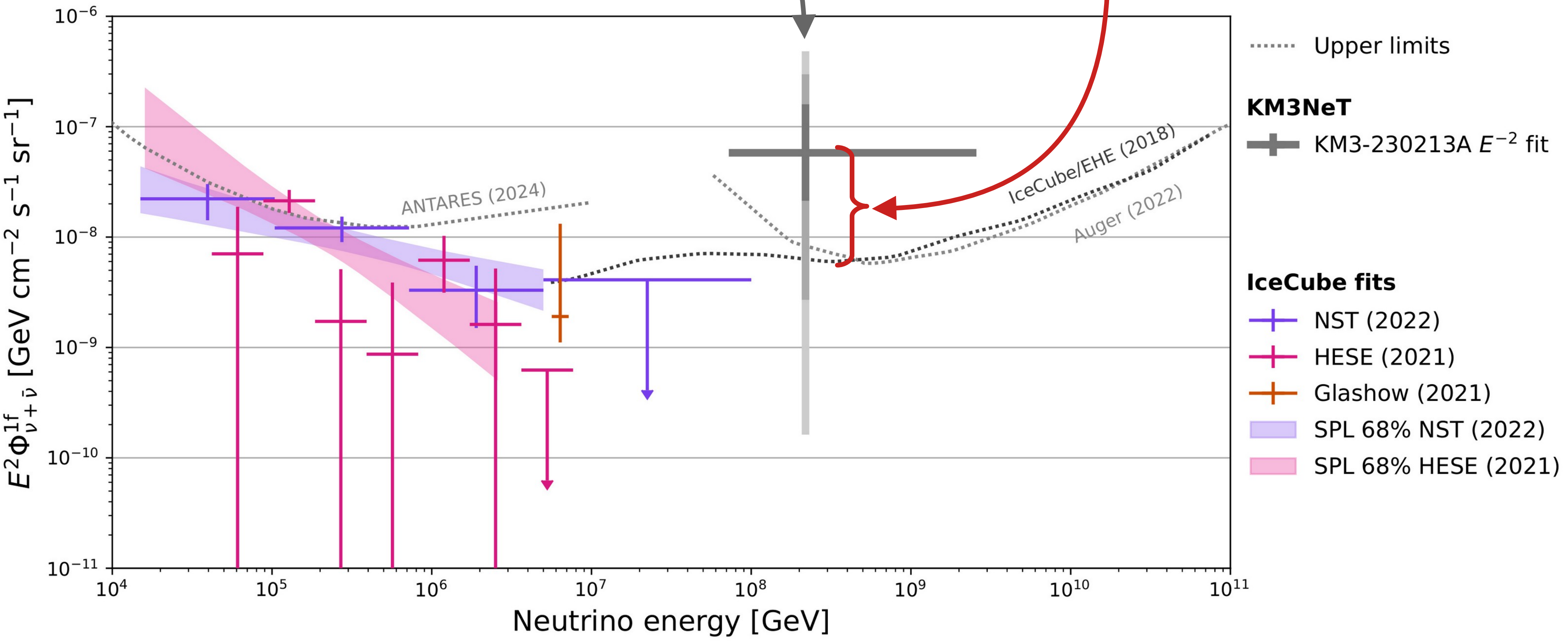


KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

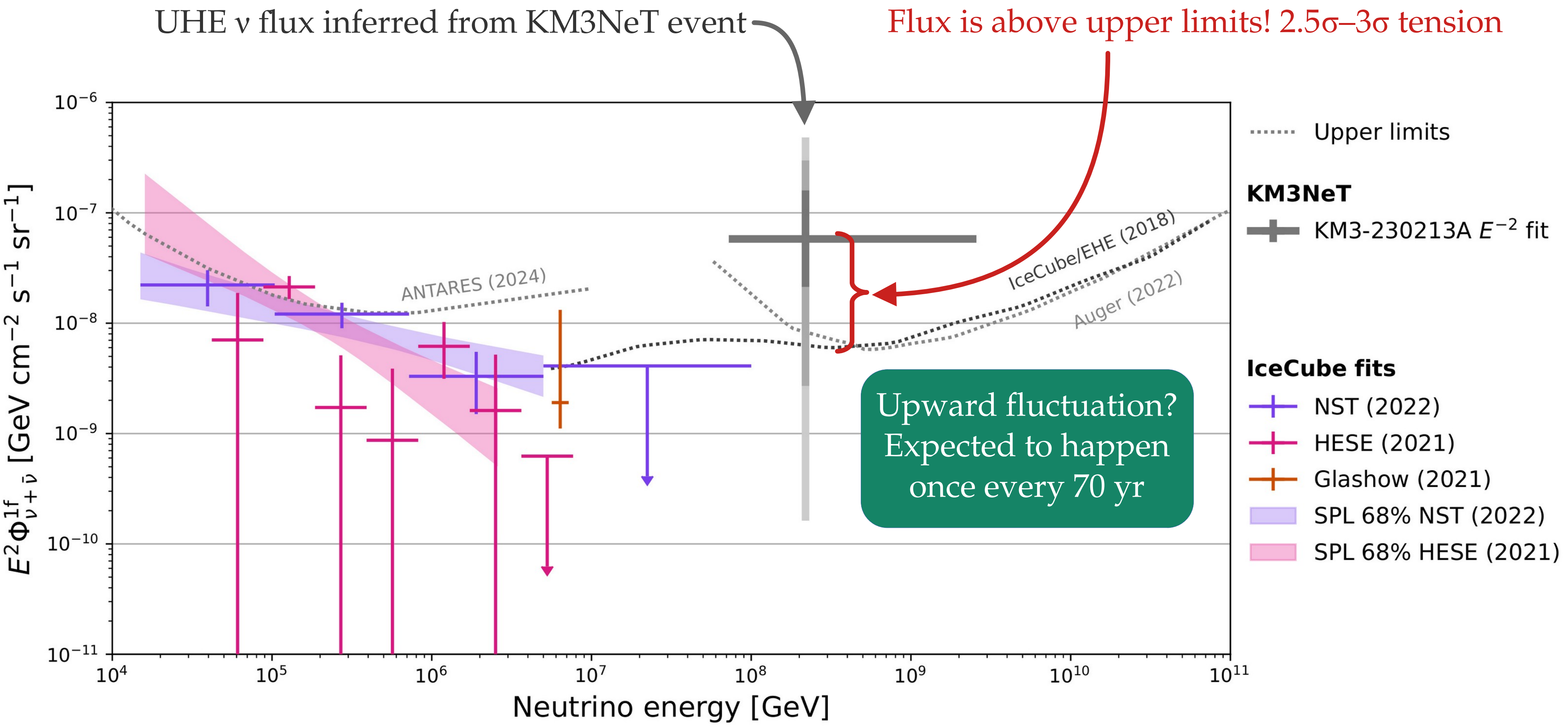
UHE ν flux inferred from KM3NeT event

Flux is above upper limits! 2.5σ–3σ tension



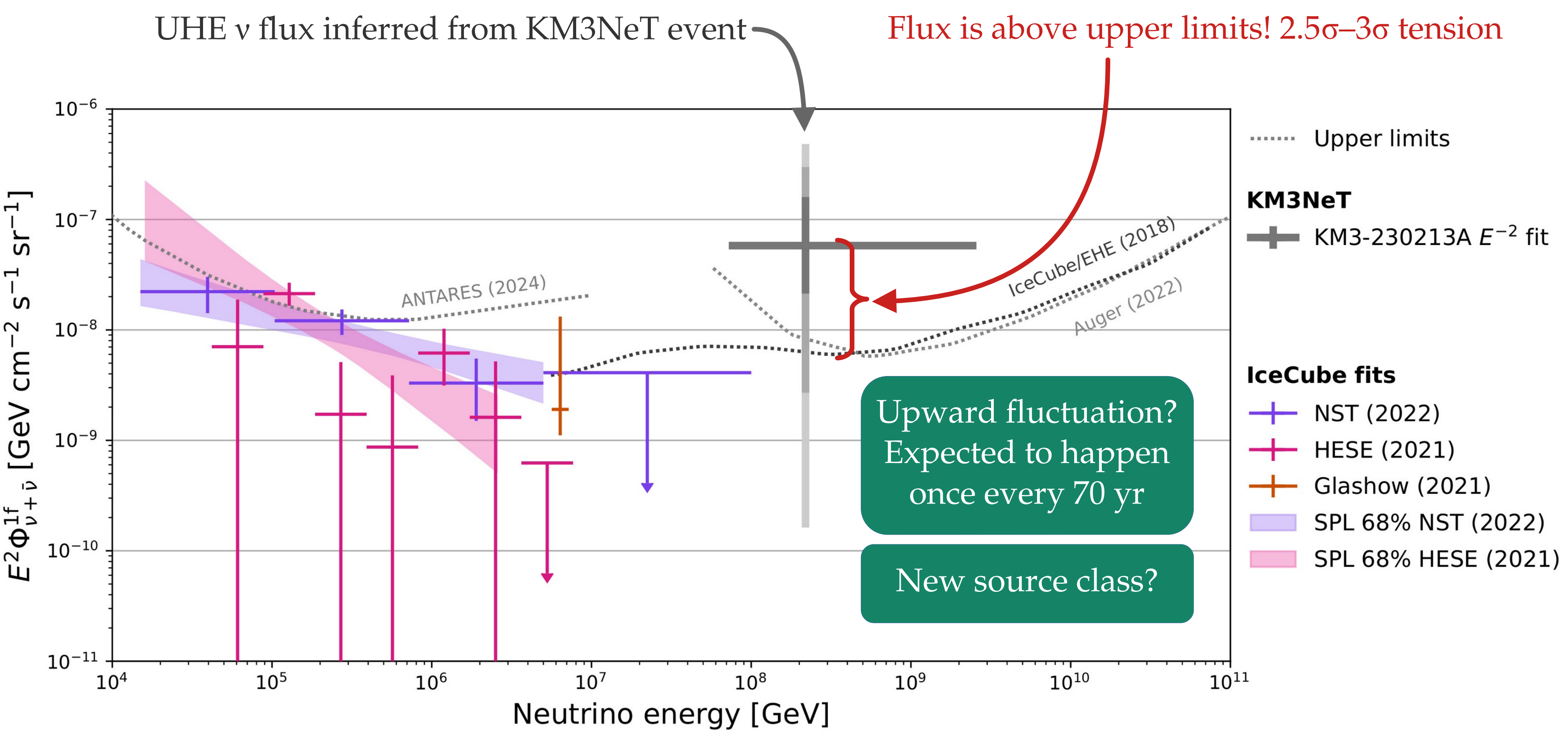
KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

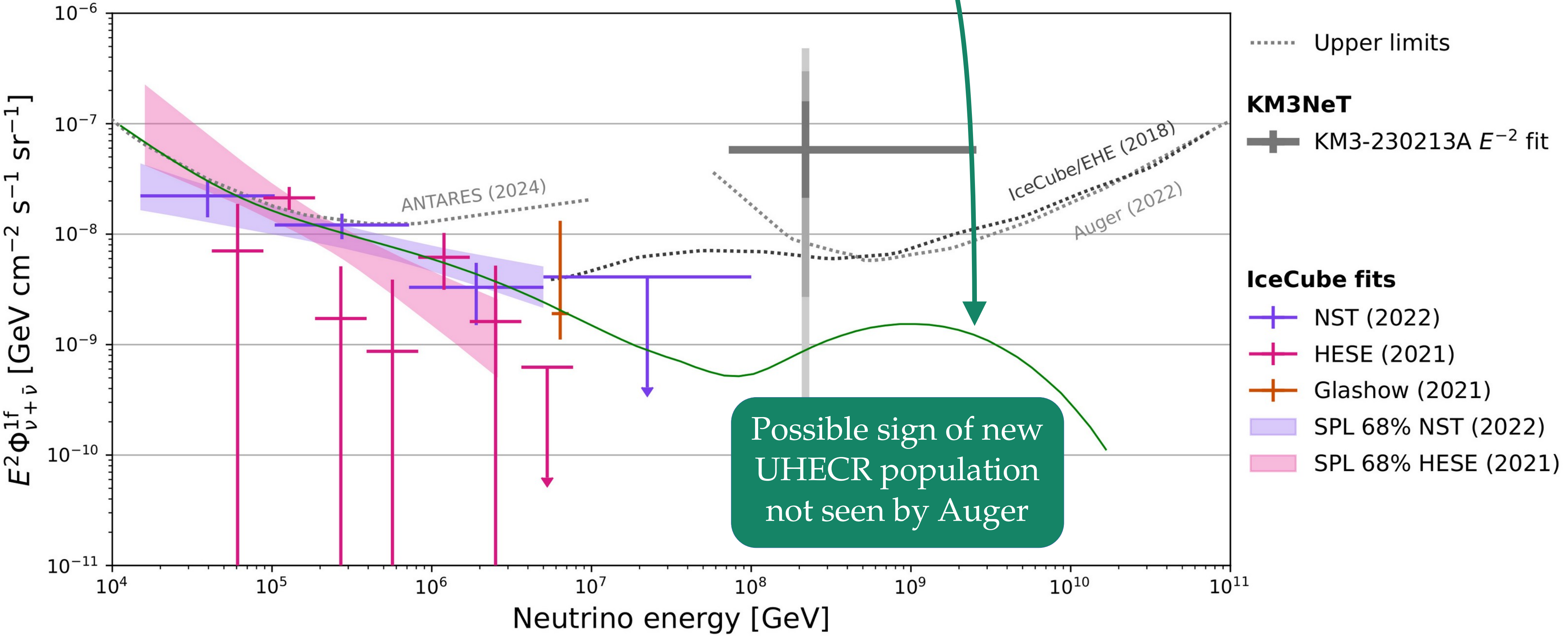


KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

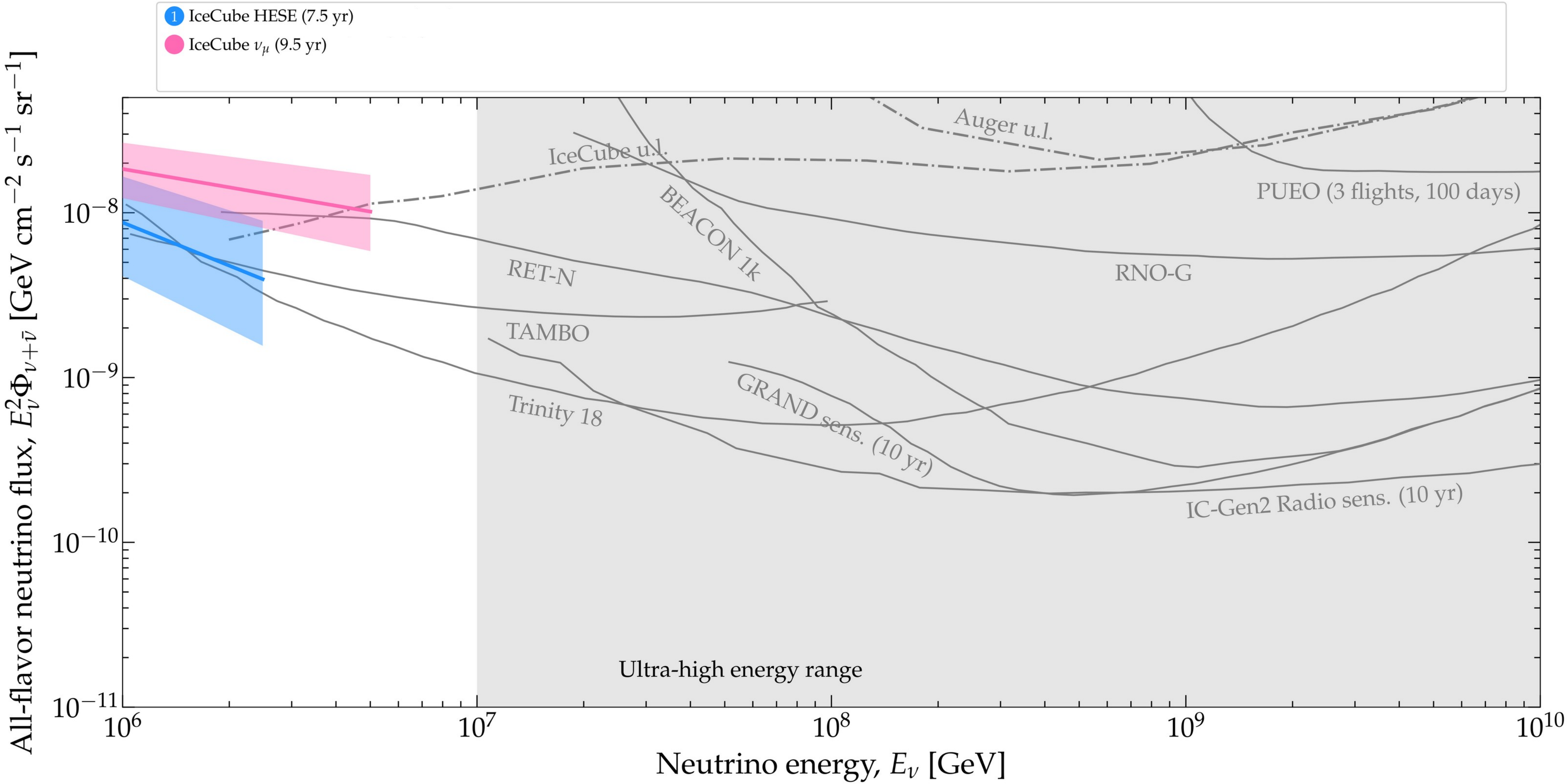
Was it a *cosmogenic* neutrino? KM3NeT *vs.* IceCube

Joint fit to IceCube and KM3NeT ν data + Auger UHECR data

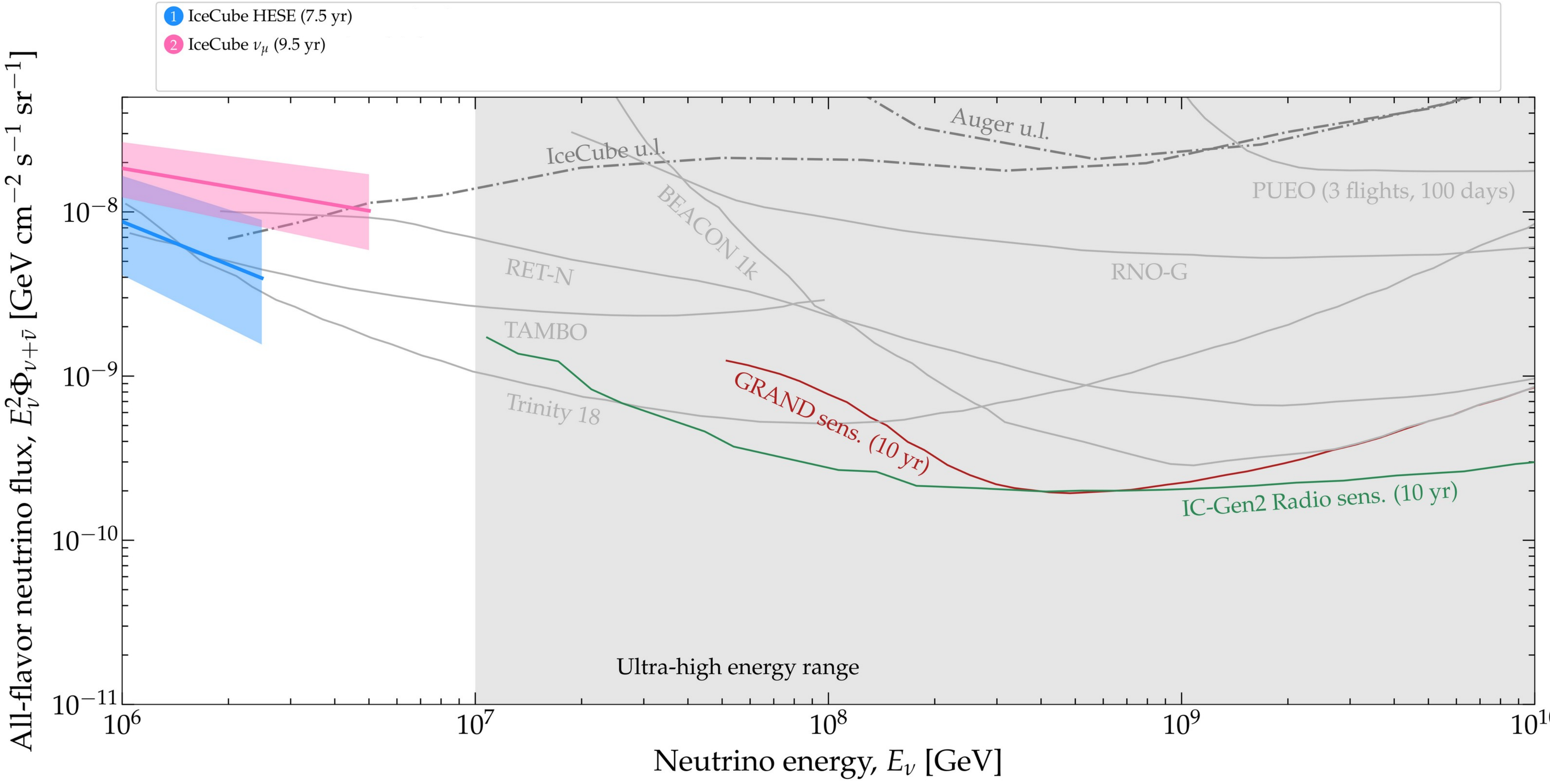
Muzio, Yuan, Lu, arXiv:2502.06944



KM3NeT Collab., arXiv:2502.08173 (adapted)
KM3NeT Collab. *Nature* 638, 376 (2025)

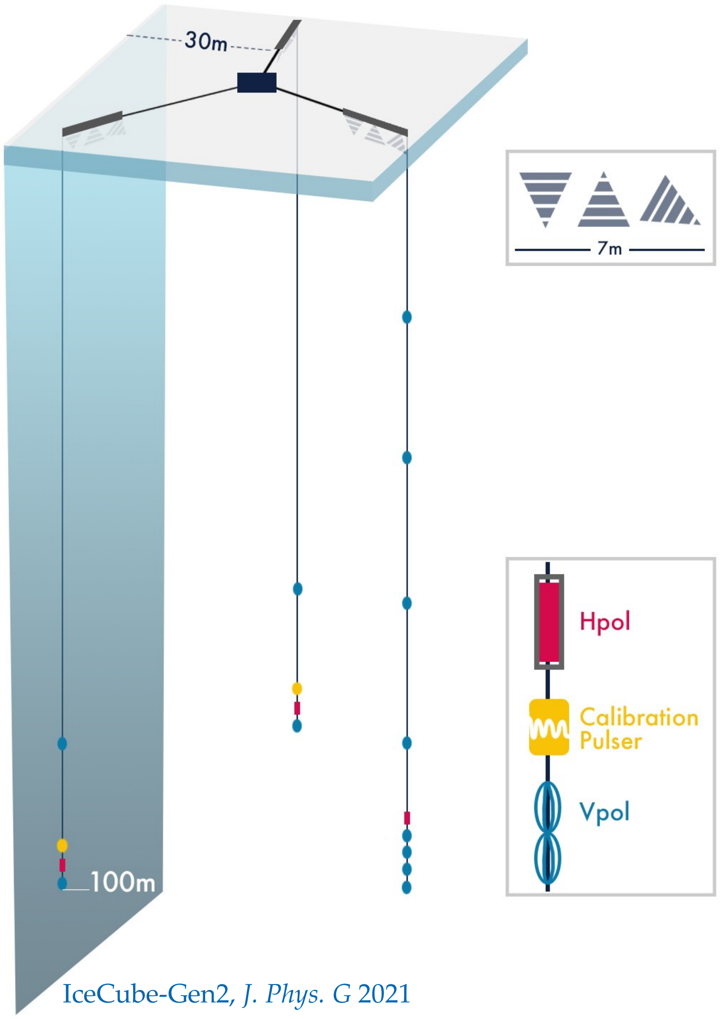


1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}

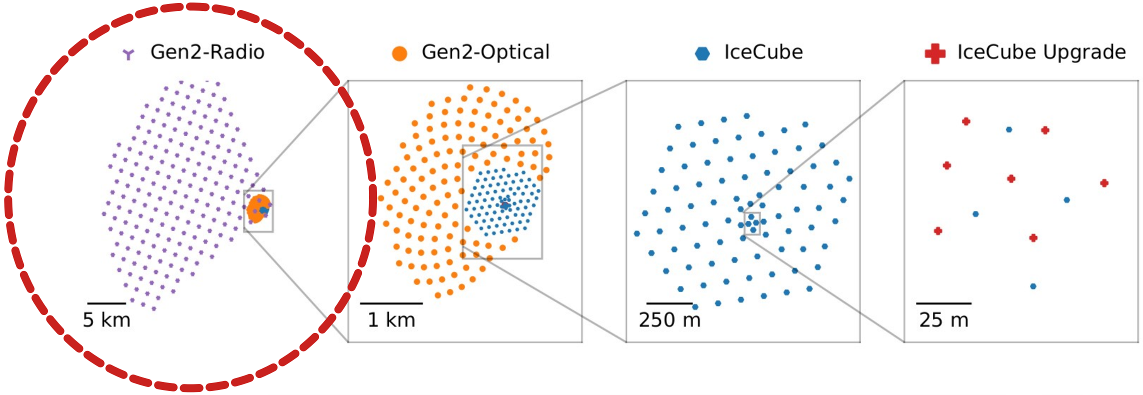


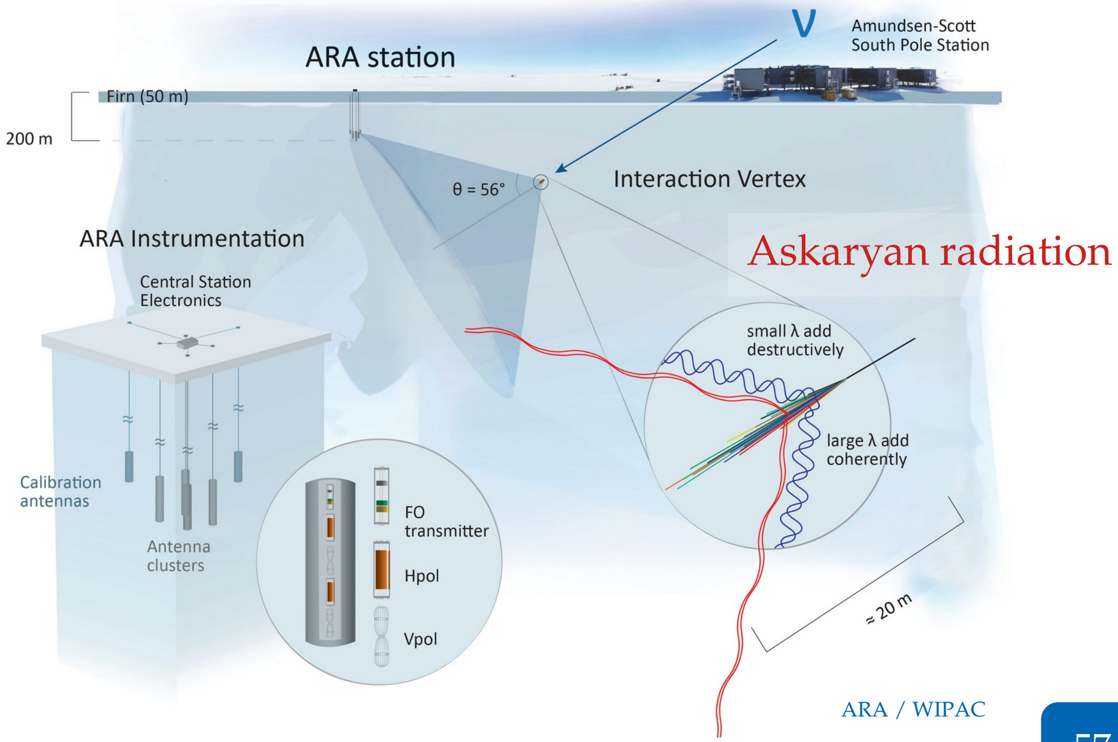
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
BEACON 1k
PUEO (3 flights, 100 days)
RET-N
RNO-G
TAMBO
Trinity 18
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

IceCube-Gen2 Radio

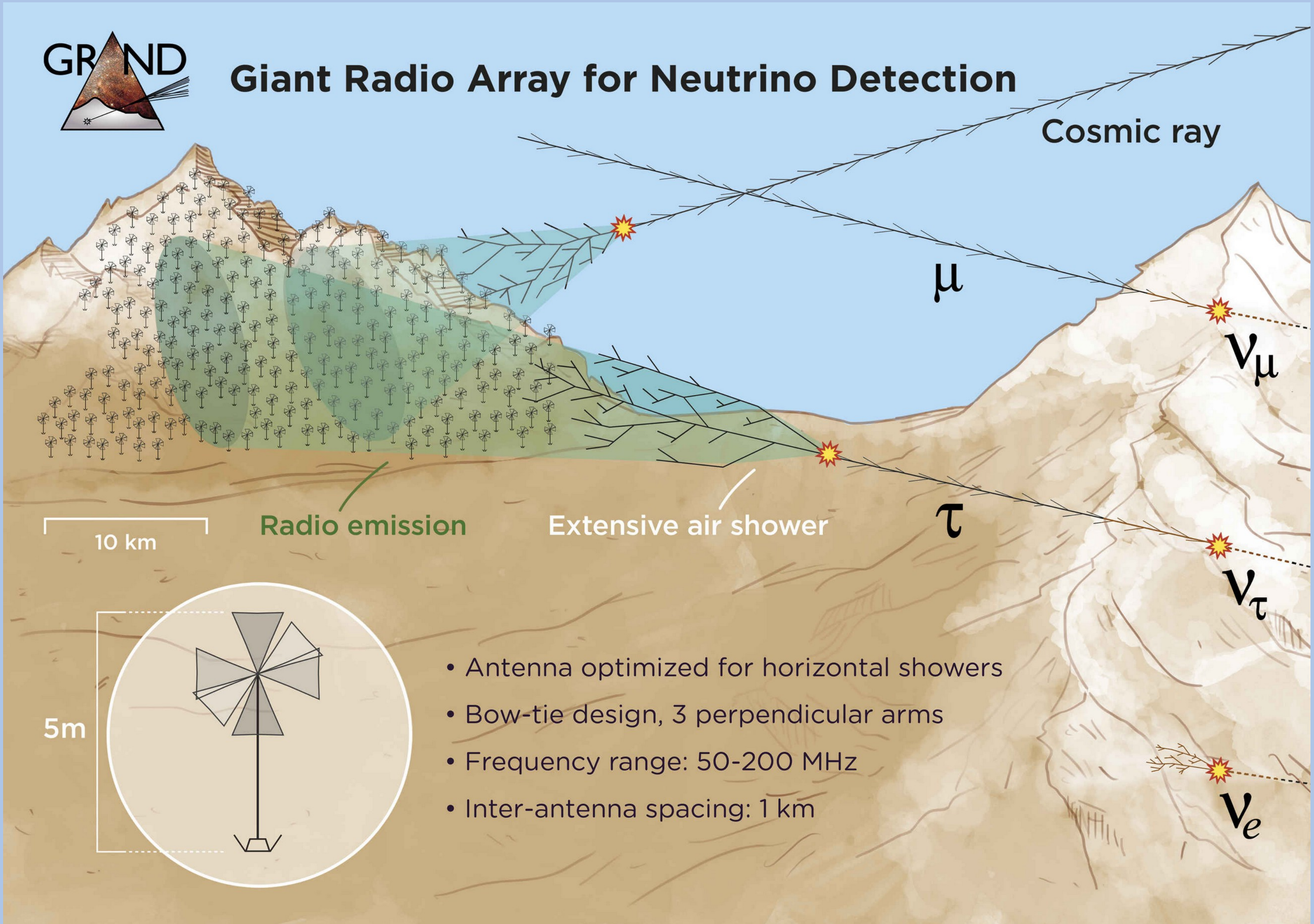


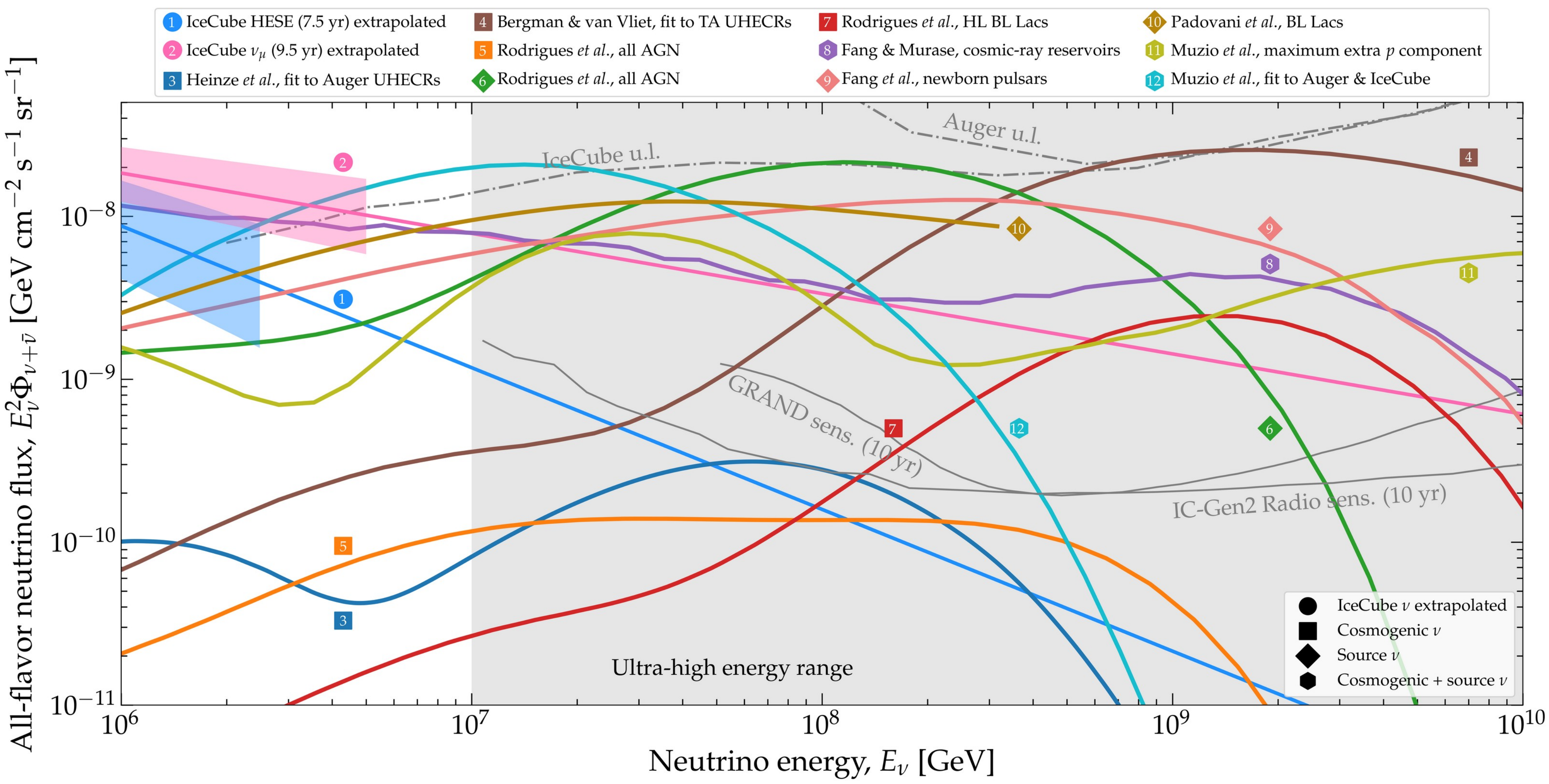
IceCube-Gen2, *J. Phys. G* 2021



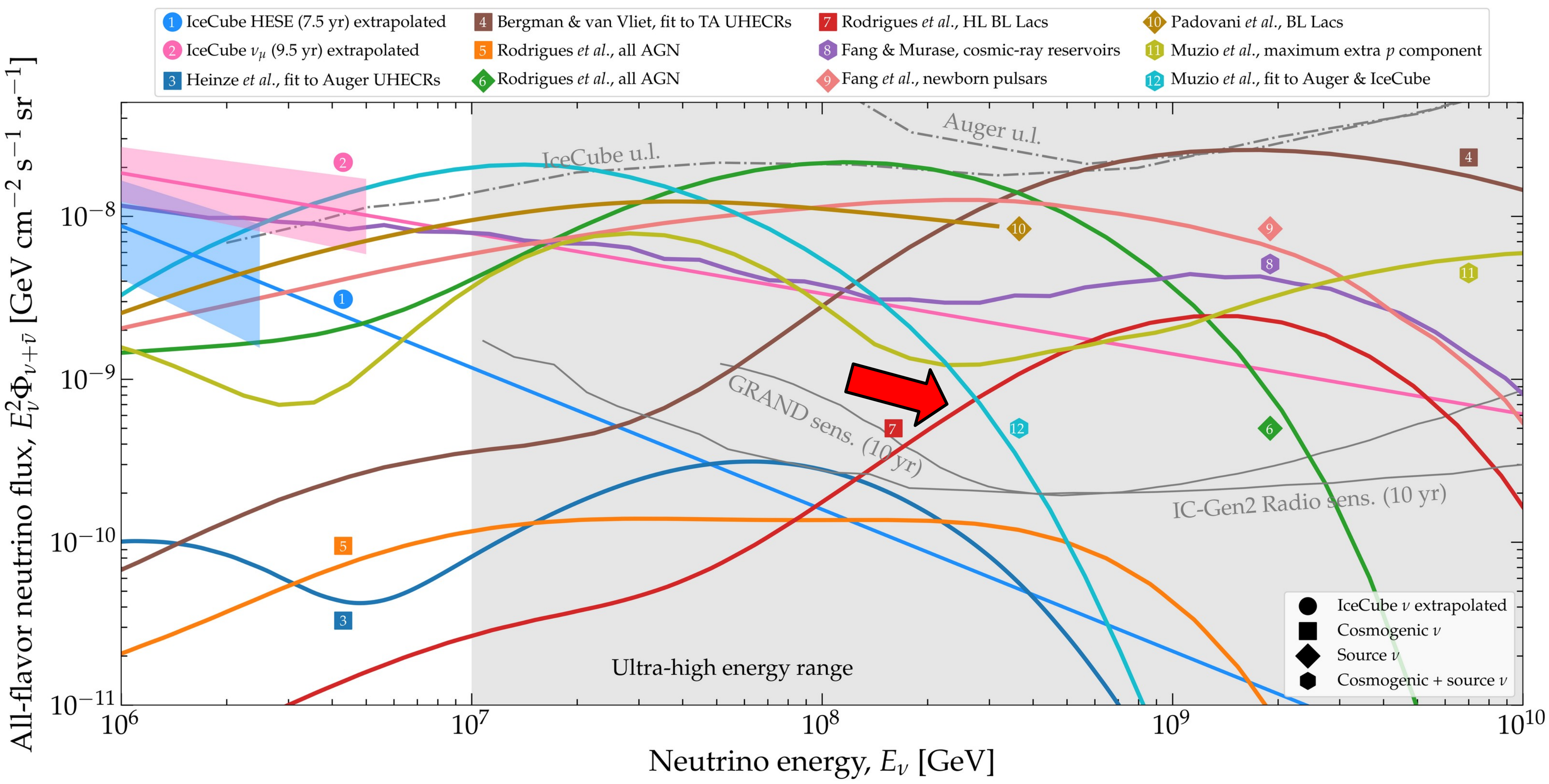


ARA / WIPAC

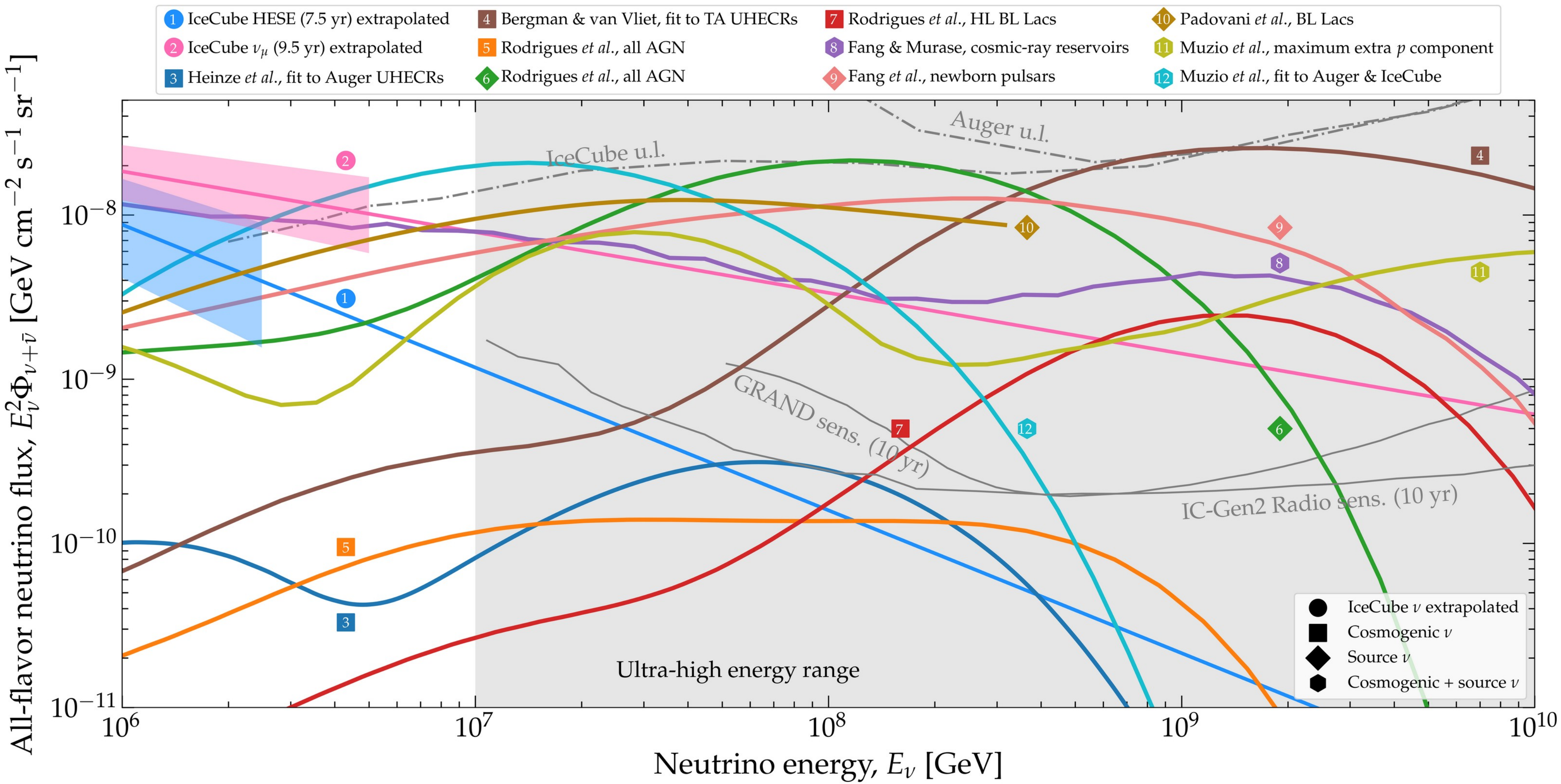

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
νμ
τ
ντ
νe
Radio emission
Extensive air shower
10 km
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km



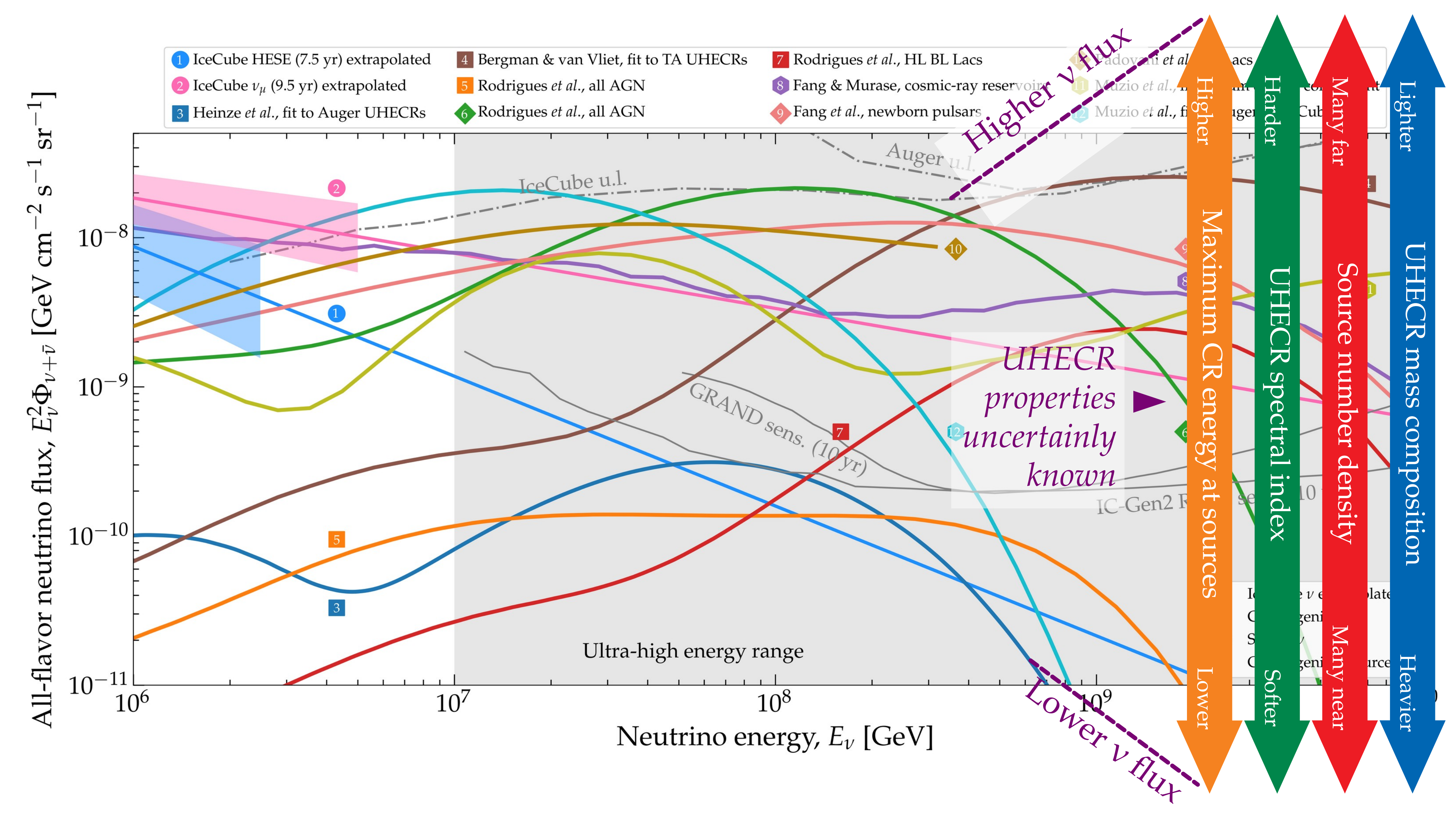
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars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



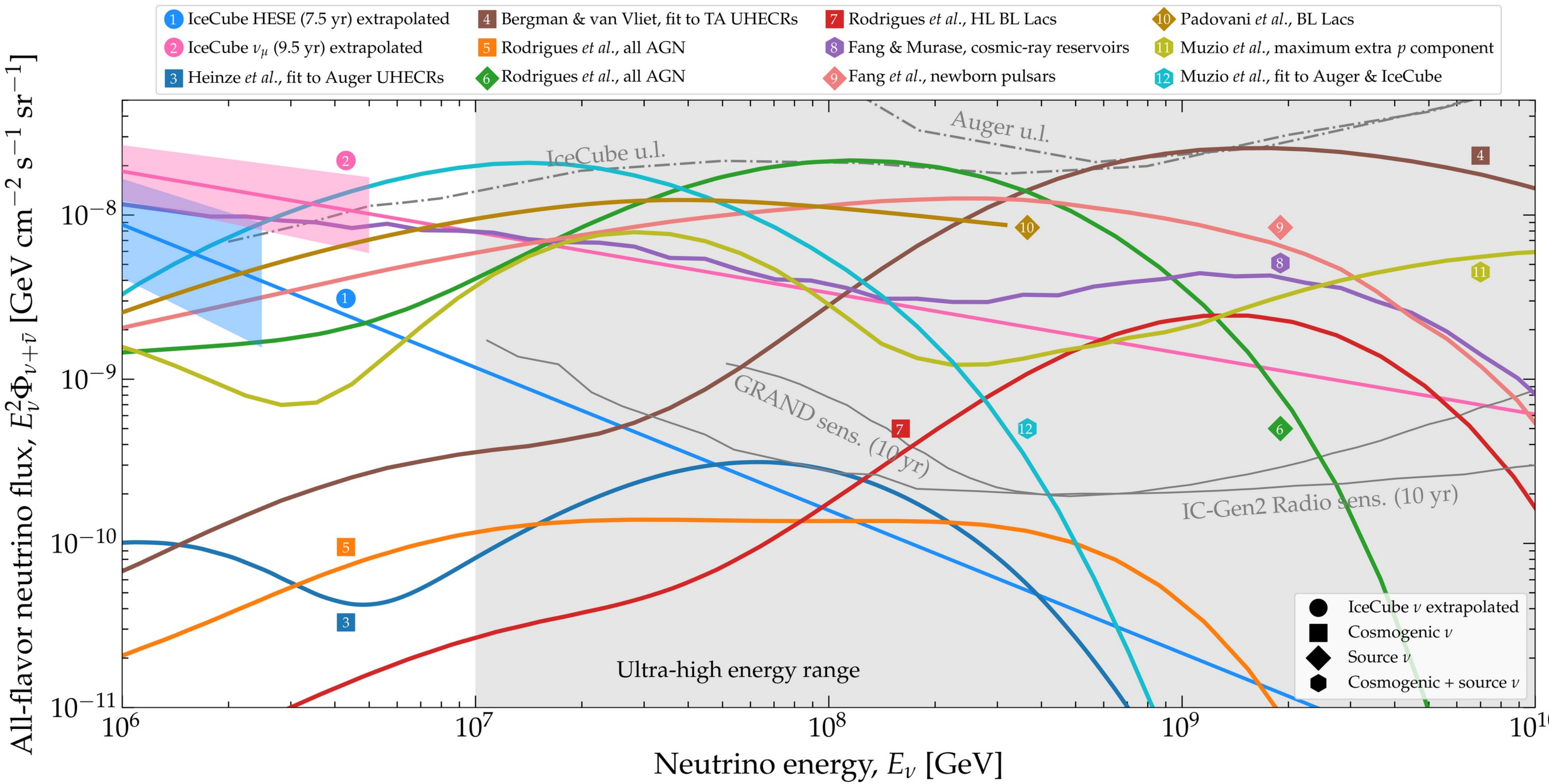
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars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

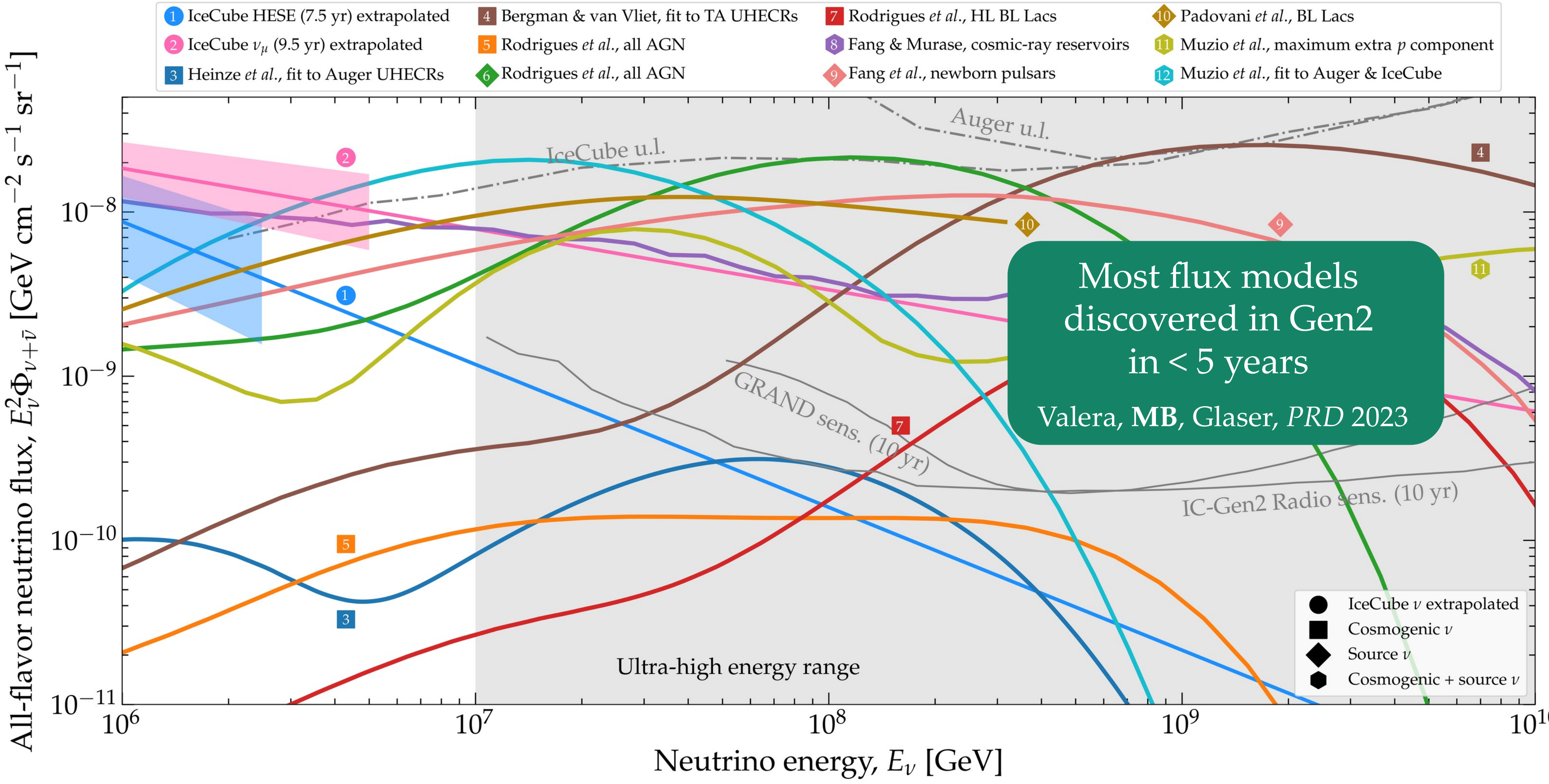


1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars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



IceCube HESE (7.5 yr) extrapolated
IceCube ν_μ (9.5 yr) extrapolated
Heinze et al., fit to Auger UHECRs
Bergman & van Vliet, fit to TA UHECRs
Rodrigues et al., all AGN
Rodrigues et al., all AGN
Rodrigues et al., HL BL Lacs
Fang & Murase, cosmic-ray reservoirs
Fang et al., newborn pulsars
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
Ultra-high energy range
UHECR properties uncertainly known
Higher ν flux
Lower ν flux
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9


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



Most flux models discovered in Gen2 in < 5 years

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

Today

TeV–PeV ν

Turn predictions

into data-driven tests

<u>Key developments</u>:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Today

TeV–PeV ν

Turn predictions
into data-driven tests

<u>Key developments</u>:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Key developments:

Discovery

New detection techniques

Better UHE ν flux predictions

Today
TeV–PeV ν

Turn predictions
into data-driven tests

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

Next decade
> 100-PeV ν

Make predictions for
a new energy regime

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

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

Today

TeV–PeV ν

Turn predictions
into data-driven tests

Key developments:

Bigger detectors → larger statistics

Better reconstruction

Smaller astrophysical uncertainties

Next decade

> 100-PeV ν

Make predictions for
a new energy regime

Key developments:

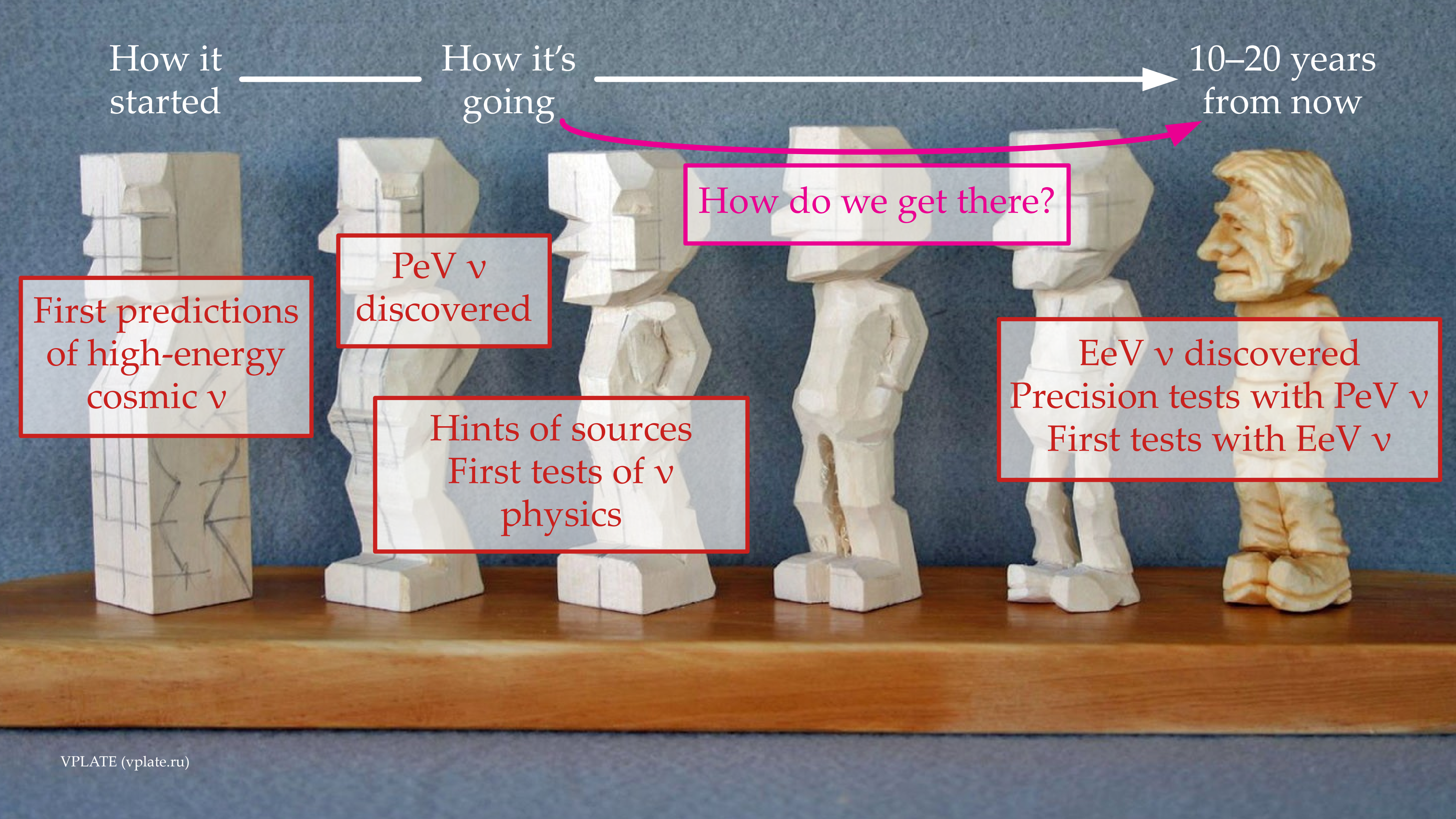
Discovery

New detection techniques

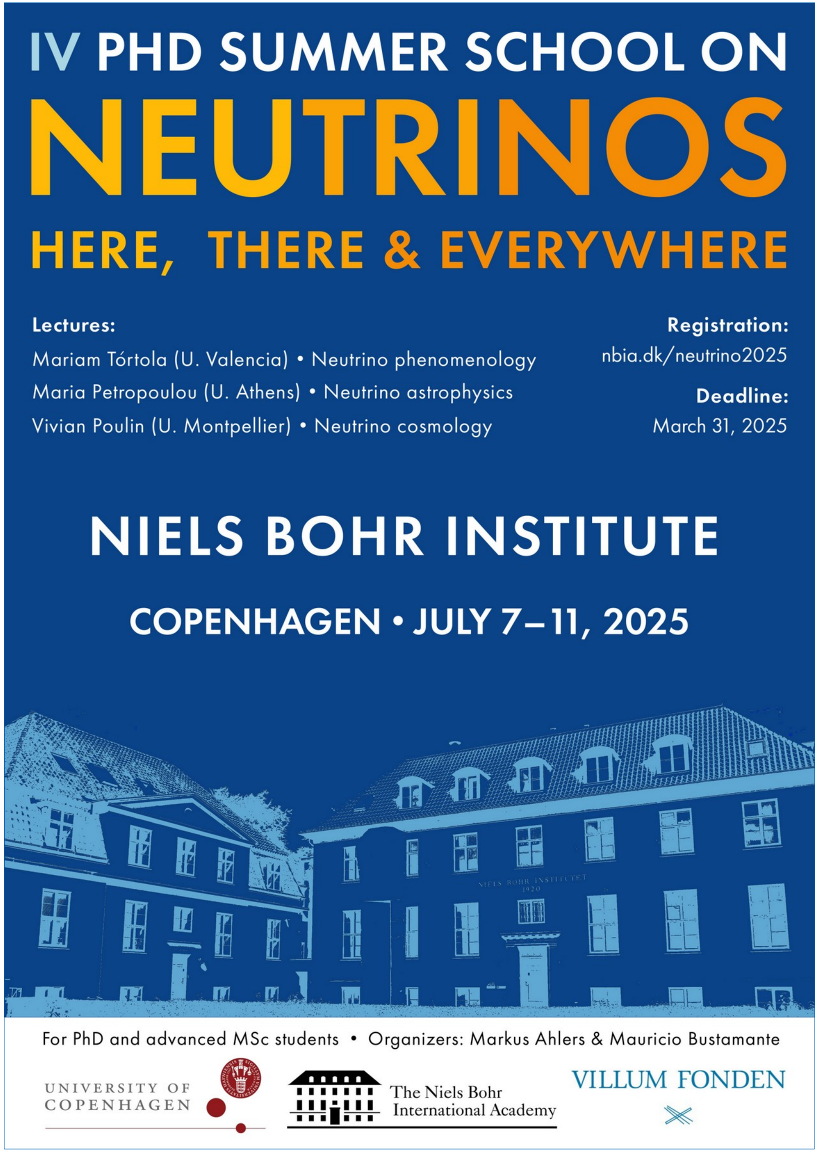
Better UHE ν flux predictions

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

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


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

Thanks!

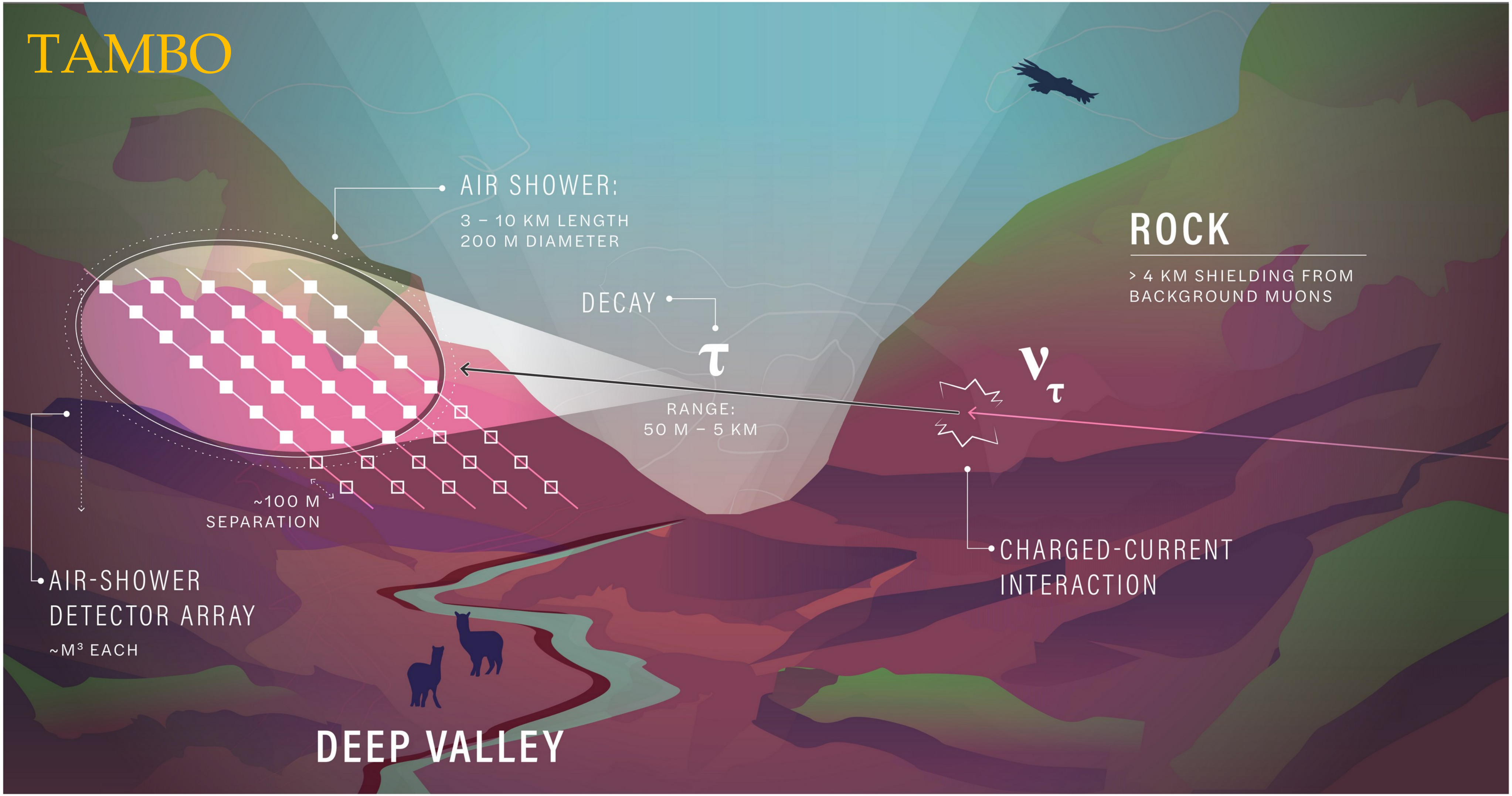


- Three tracks:
  - Neutrino phenomenology: Mariam Tórtola (Valencia)
  - Neutrino astrophysics: Maria Petropoulou (Athens)
  - Neutrino cosmology: Vivian Poulin (Montpellier)
- Plus topical seminars & student talks
- Registration open (deadline: March 31)

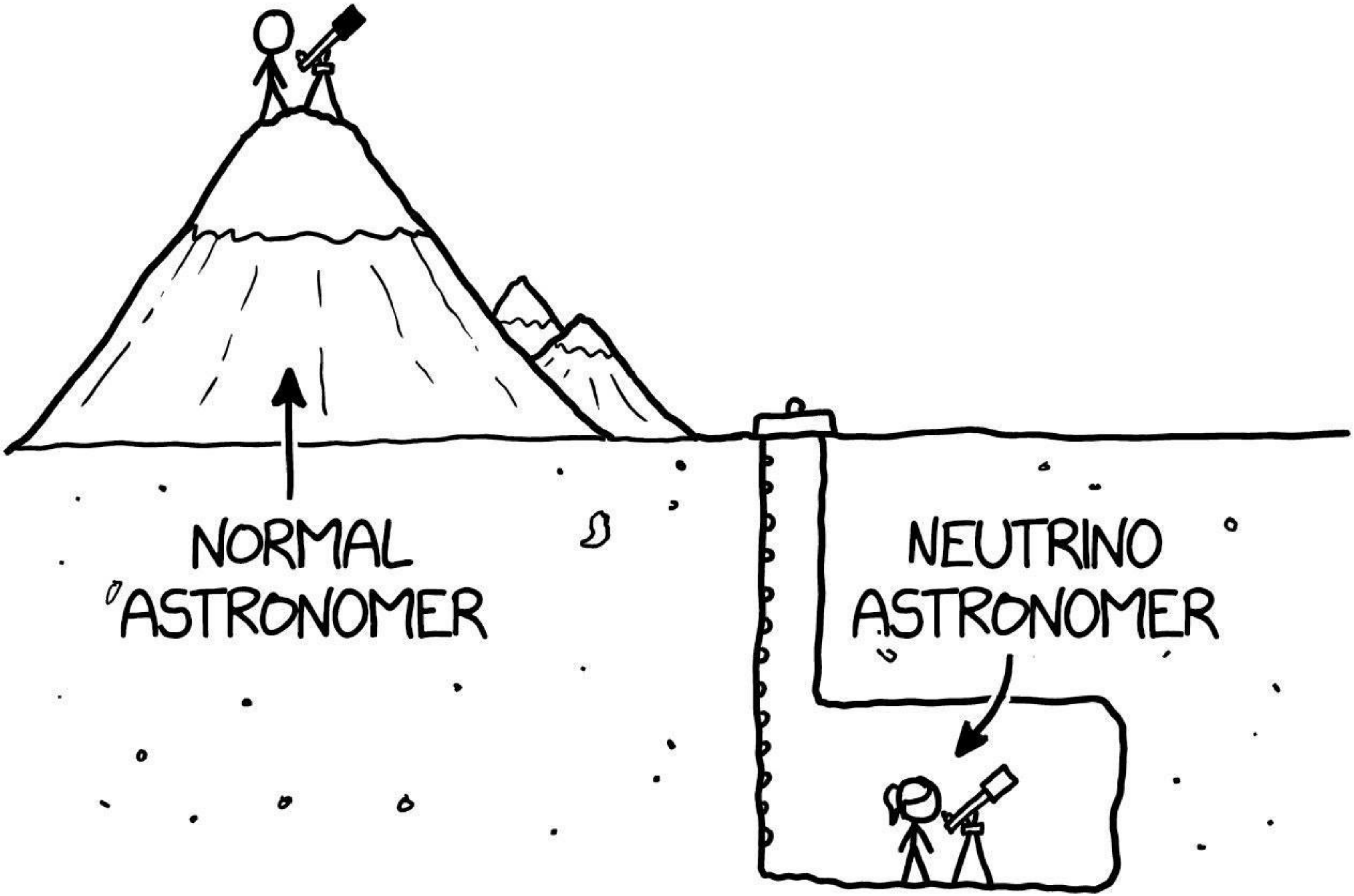
nbia.dk/neutrino2025

Thanks!

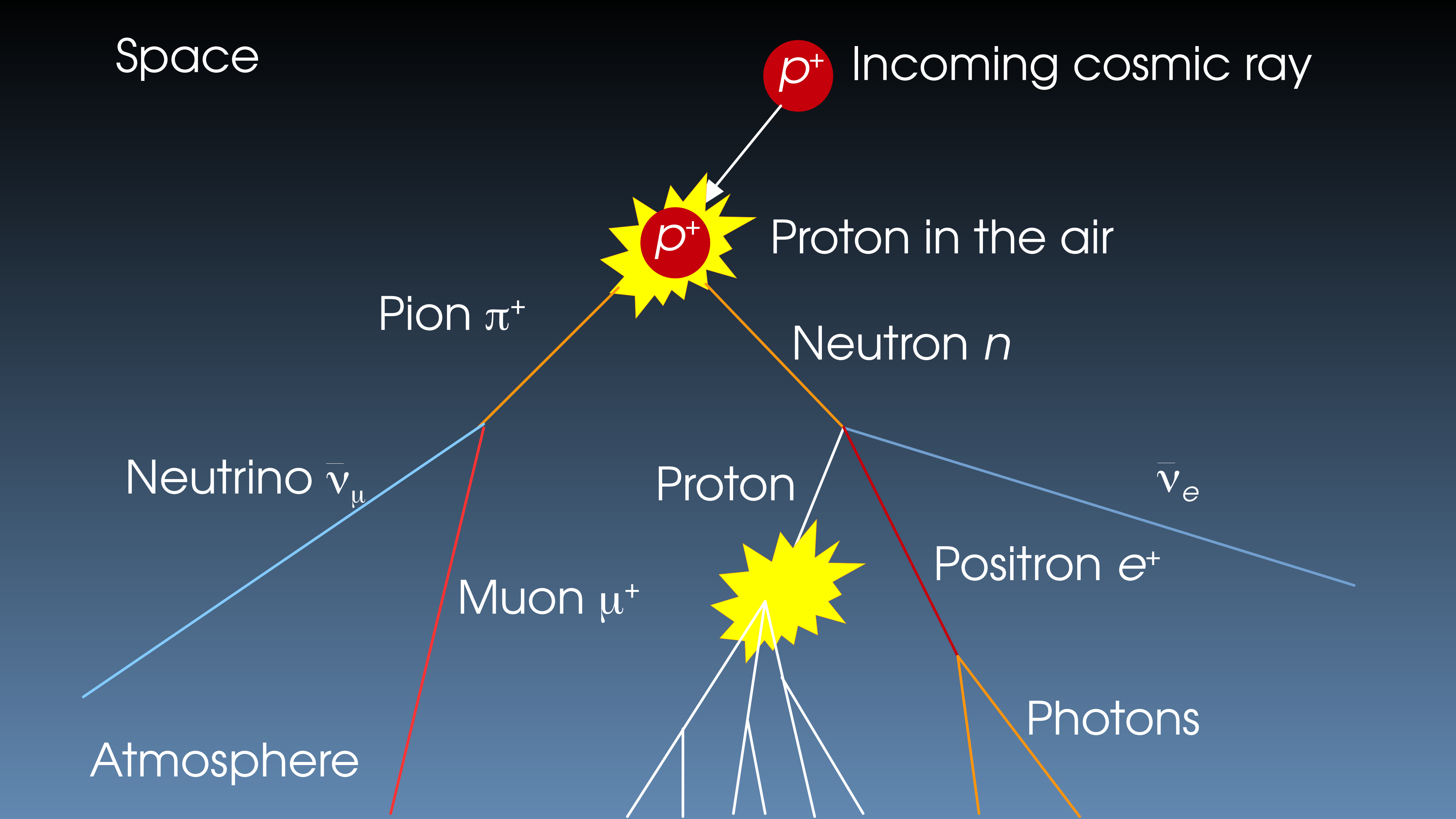
Backup slides



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



xkcd


Space
p^+ Incoming cosmic ray
p^+ Proton in the air
Pion π^+
Neutron n
Neutrino $\bar{\nu}_\mu$
Proton
$\bar{\nu}_e$
Positron e^+
Muon μ^+
Photons
Atmosphere

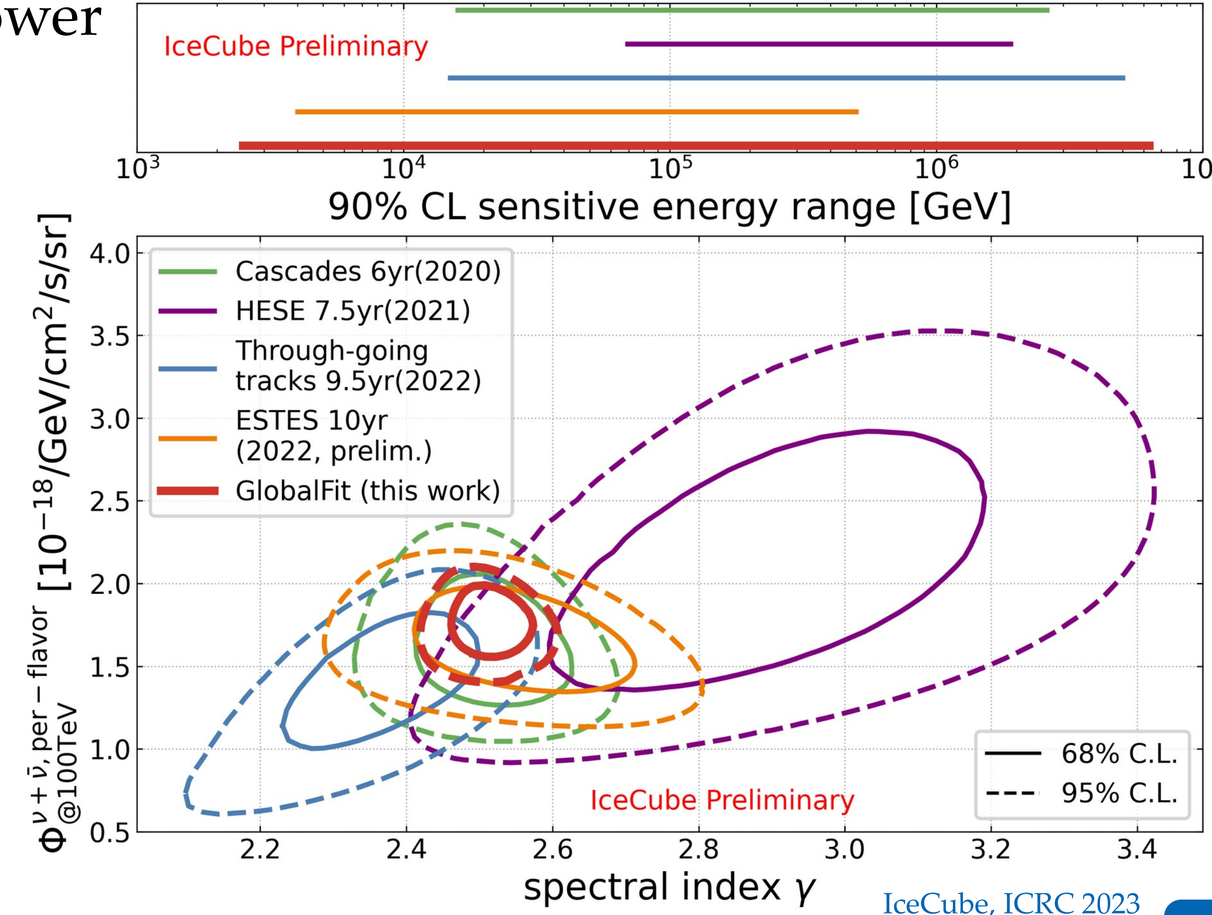
Neutrino energy spectrum

IceCube data is fit well by a power law in neutrino energy:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma_{\rm astro}}$$

$$\times 10^{-18}\ \rm GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$$

The power law is inherited from the parent protons



IceCube, ICRC 2023

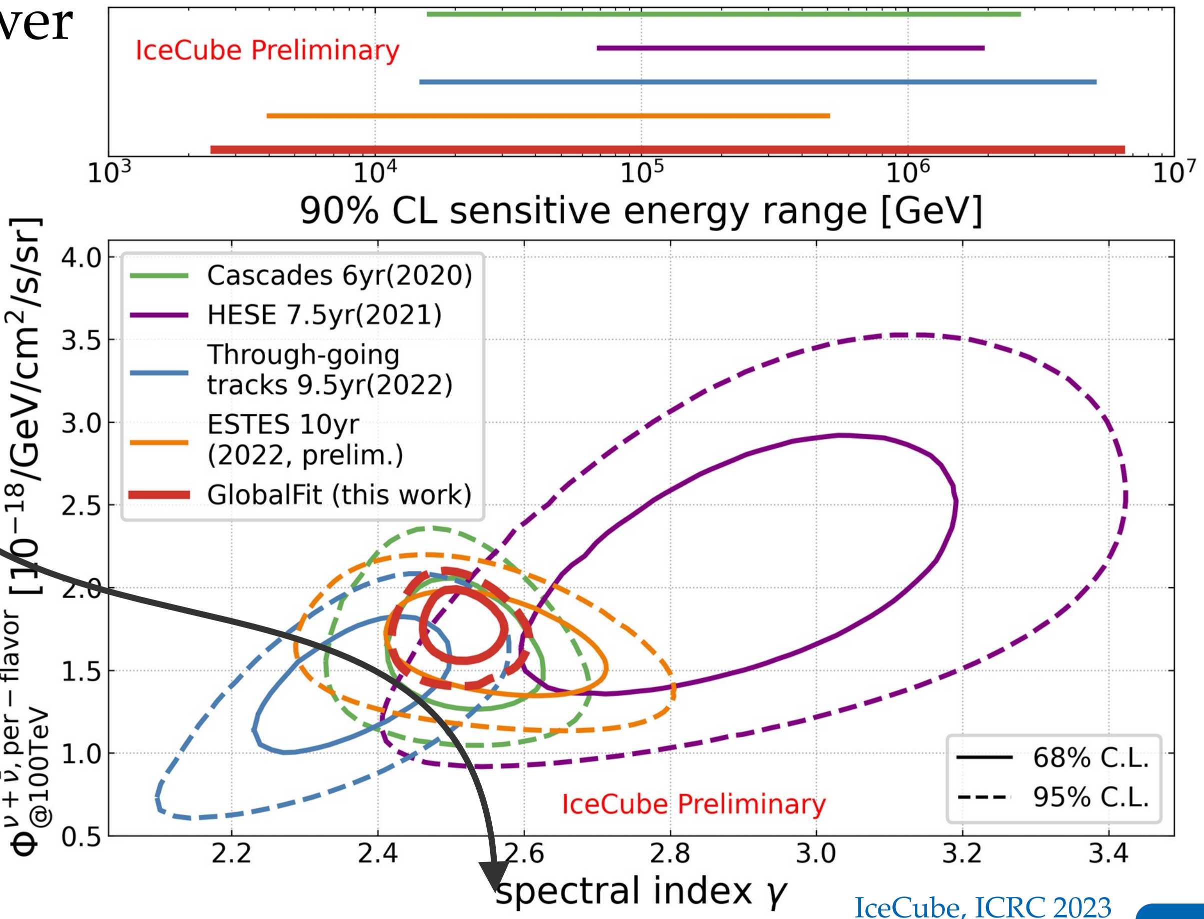
Neutrino energy spectrum

IceCube data is fit well by a power law in neutrino energy:

$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\rm astro}\left(\frac{E_\nu}{100\ {\rm TeV}}\right)^{-\gamma_{\rm astro}}$$

$$\times 10^{-18}\ {\rm GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

The power law is inherited from the parent protons



IceCube, ICRC 2023

One likely TeV–PeV ν production scenario:

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

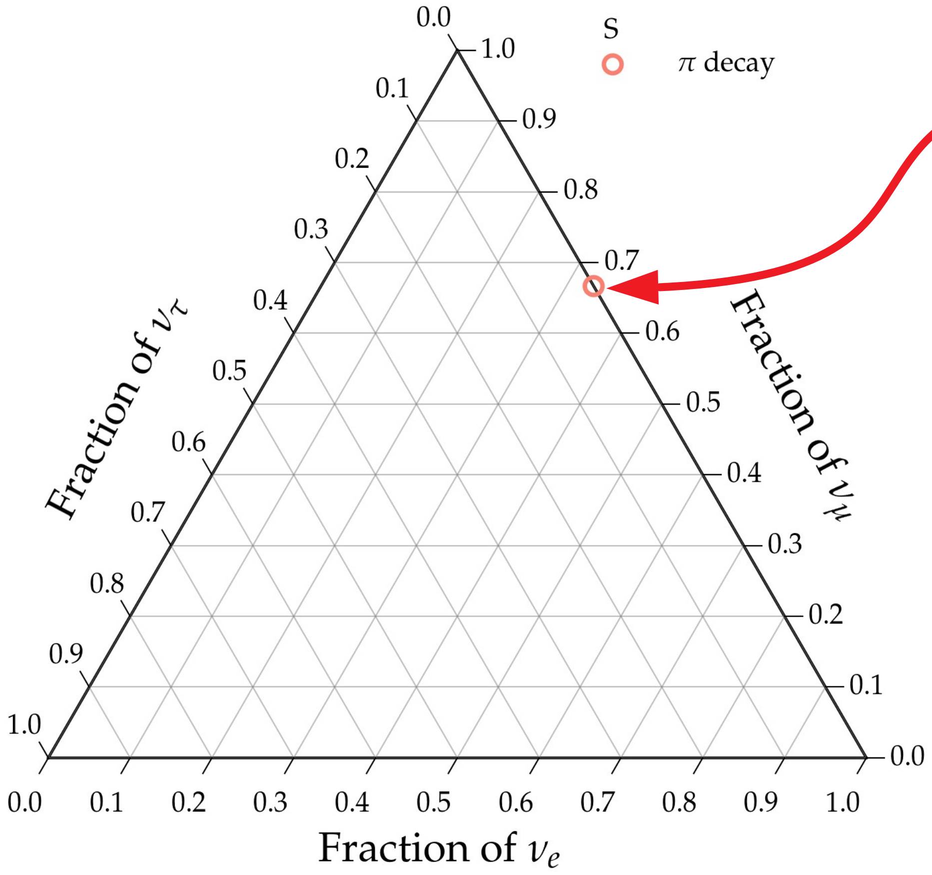
Full π decay chain

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

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



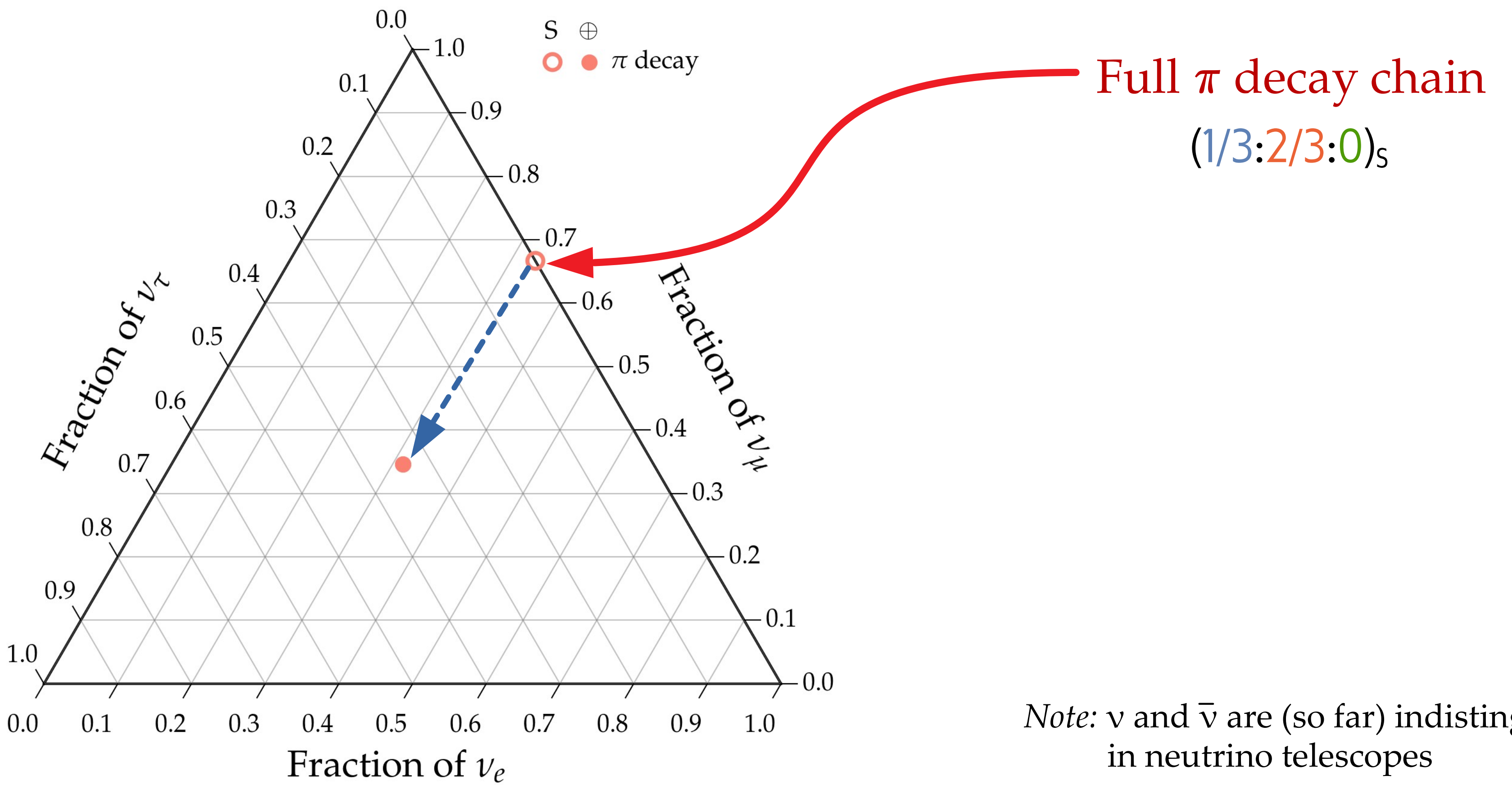
Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

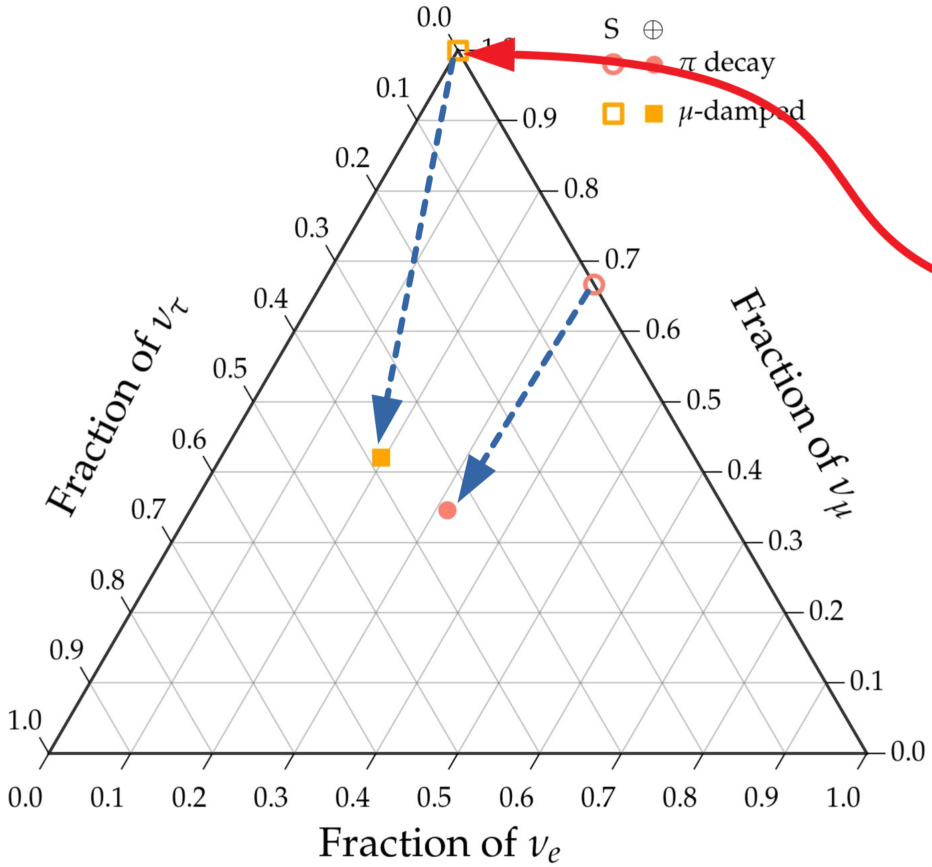
$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu$ followed by $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$



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

One likely TeV–PeV ν production scenario:

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



Full π decay chain

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

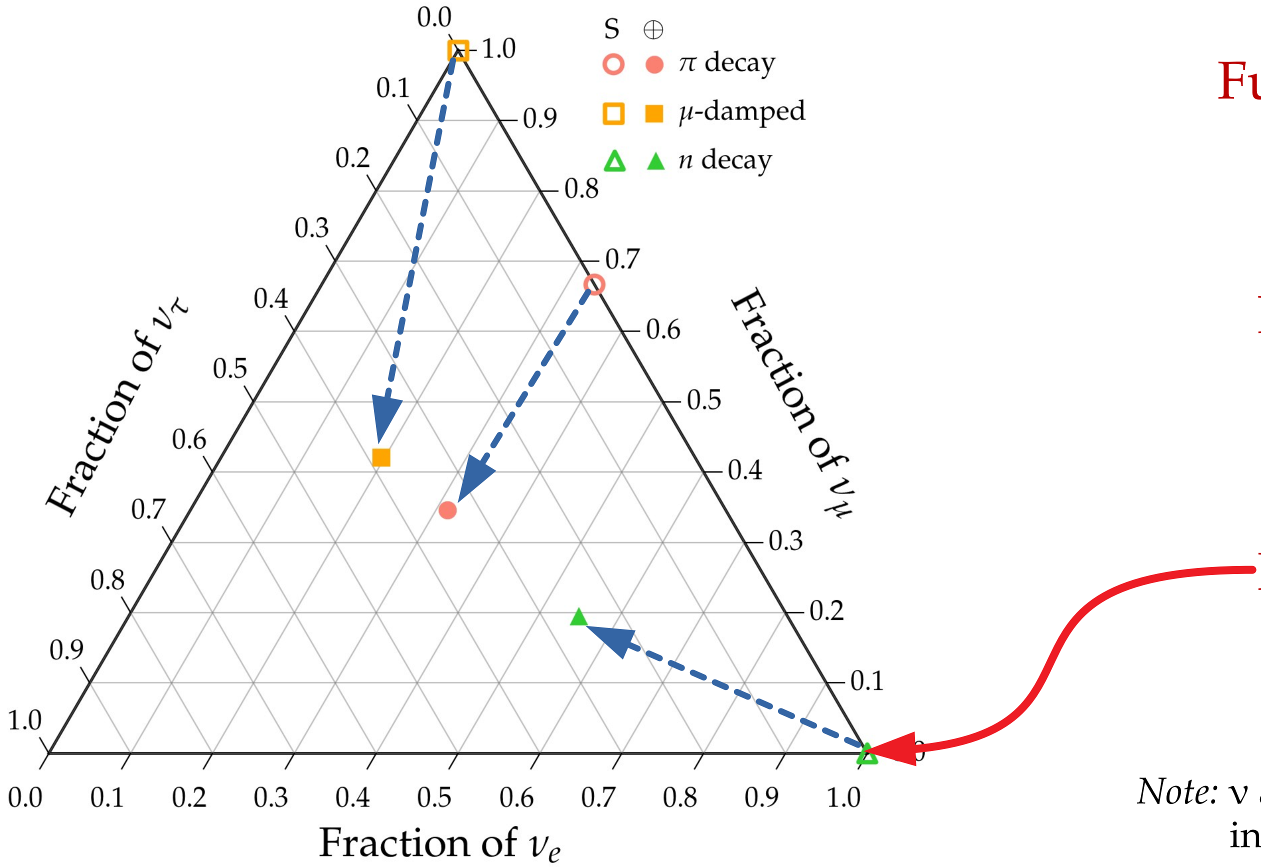
Muon damped

$(0 : 1 : 0)_S$

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

One likely TeV–PeV ν production scenario:

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



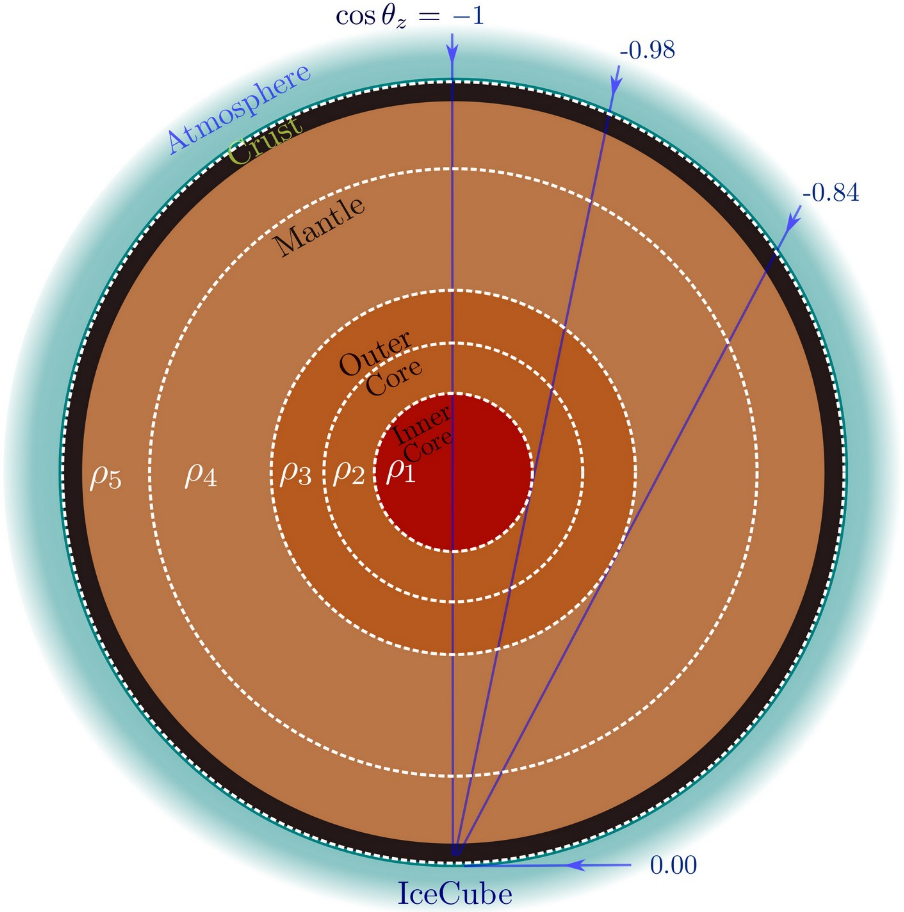
Full π decay chain
$(1/3:2/3:0)_S$

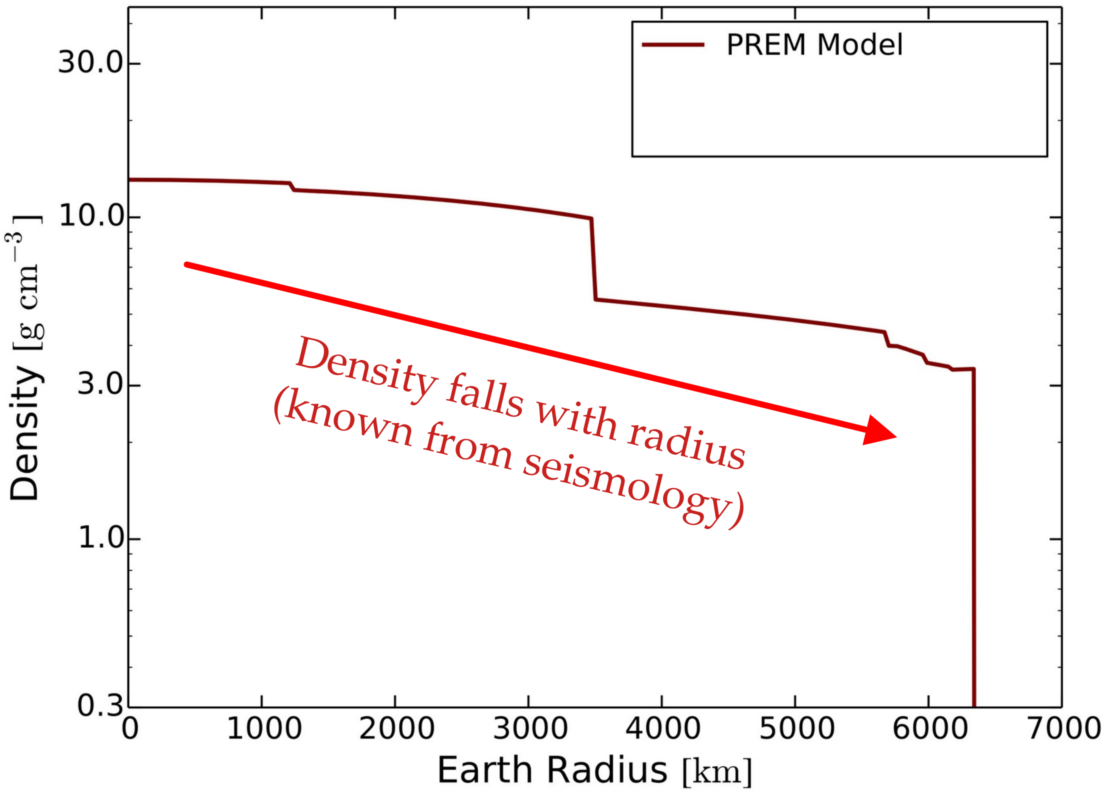
Muon damped
$(0:1:0)_S$

Neutron decay
$(1:0:0)_S$

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

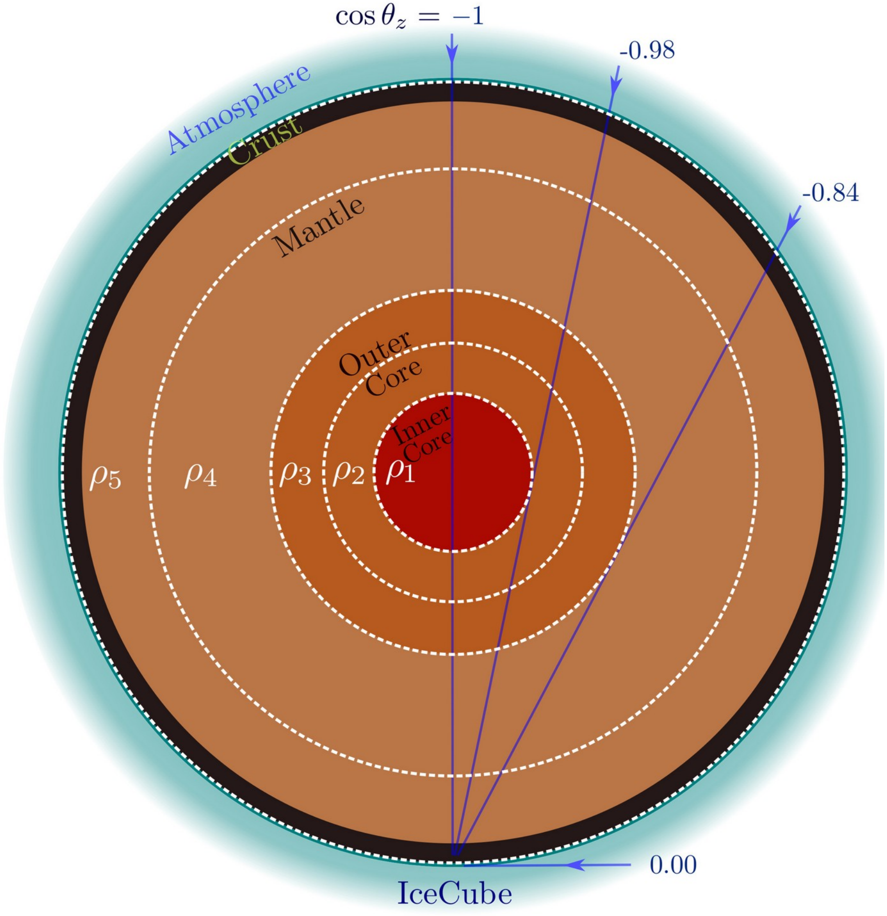
Weighing the Earth with neutrinos



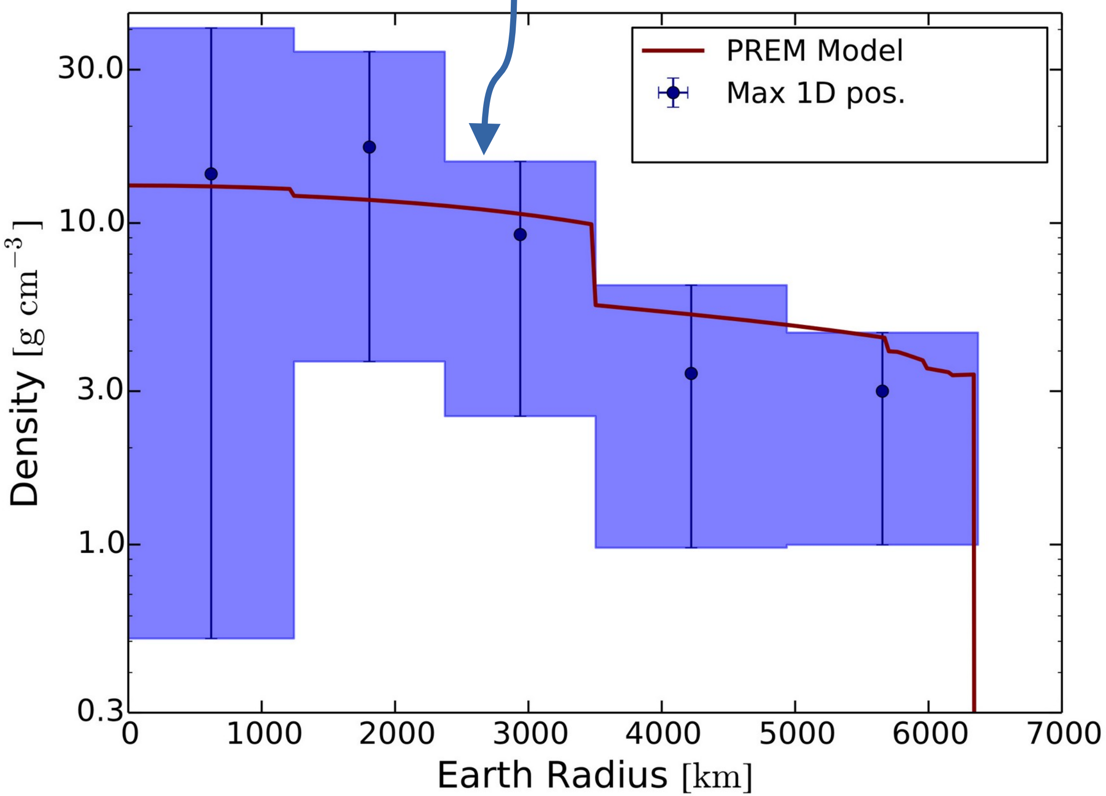


Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Weighing the Earth with neutrinos



With 1 yr of IceCube (atmospheric) TeV ν

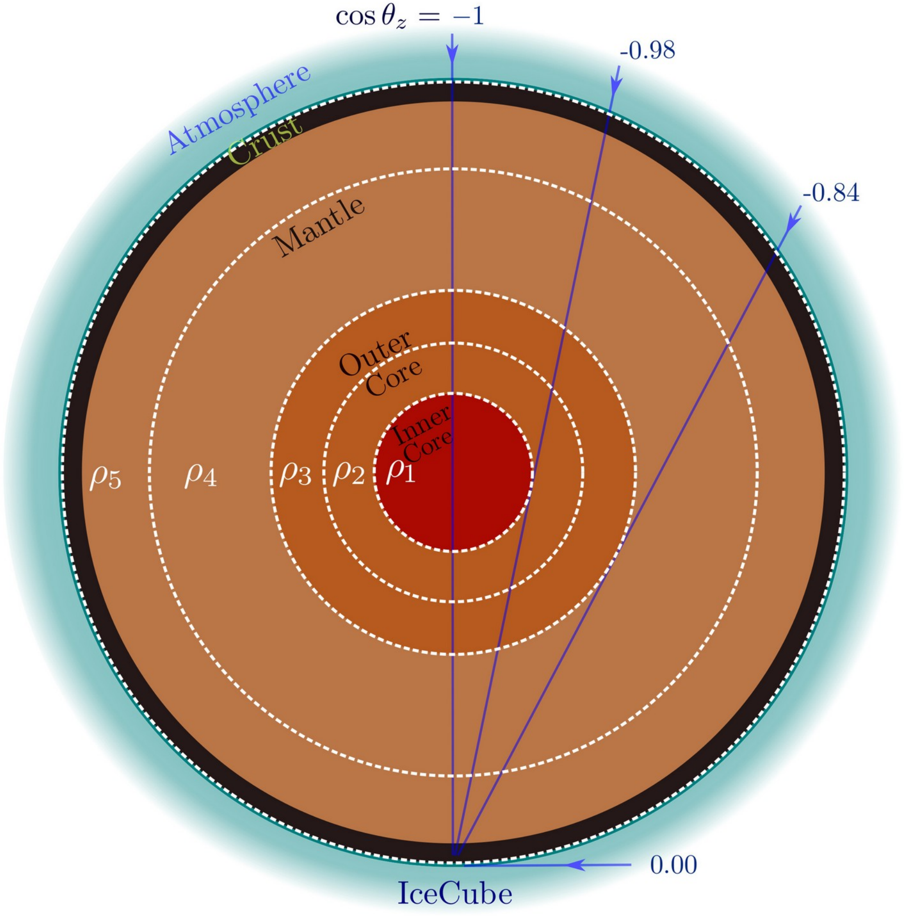


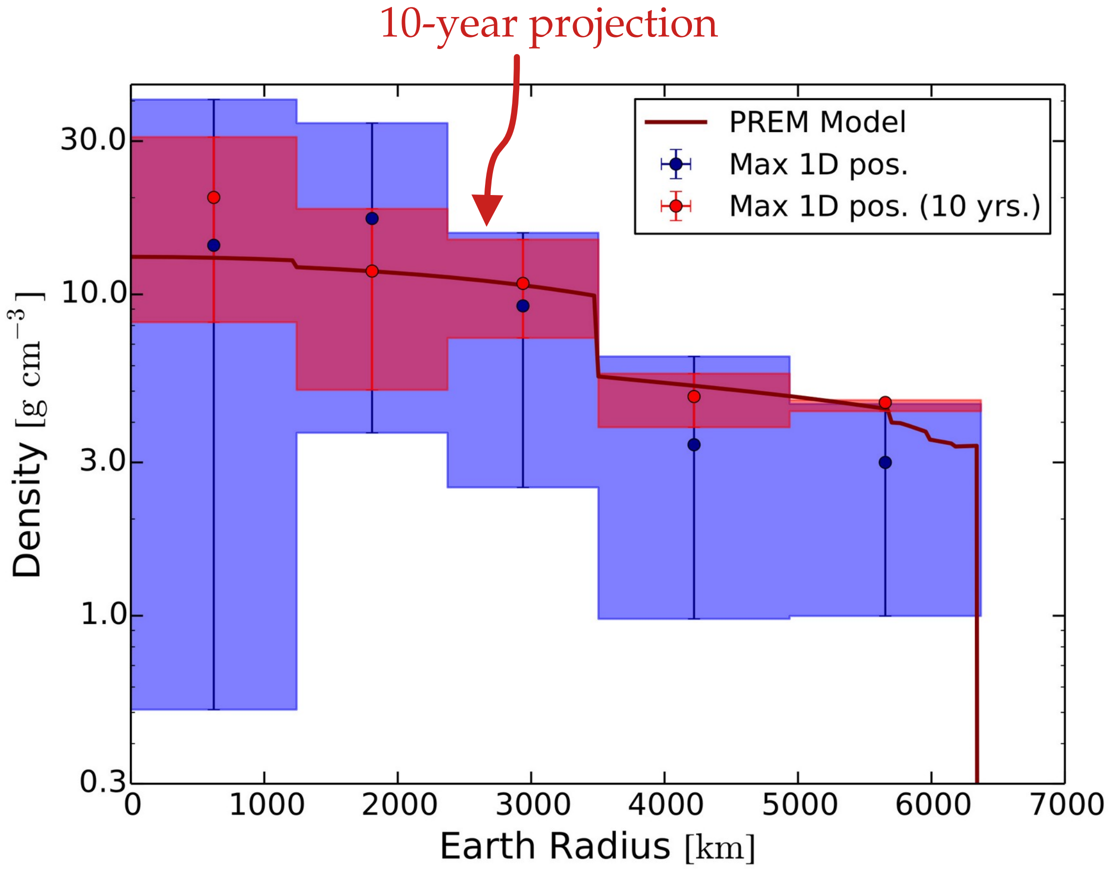
Mass of the Earth using ν: $6.0^{+1.6}_{-1.3} \times 10^{24}$ kg

From gravitational measurements: $(5.9722 \pm 0.0006) \times 10^{24}$

Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Weighing the Earth with neutrinos

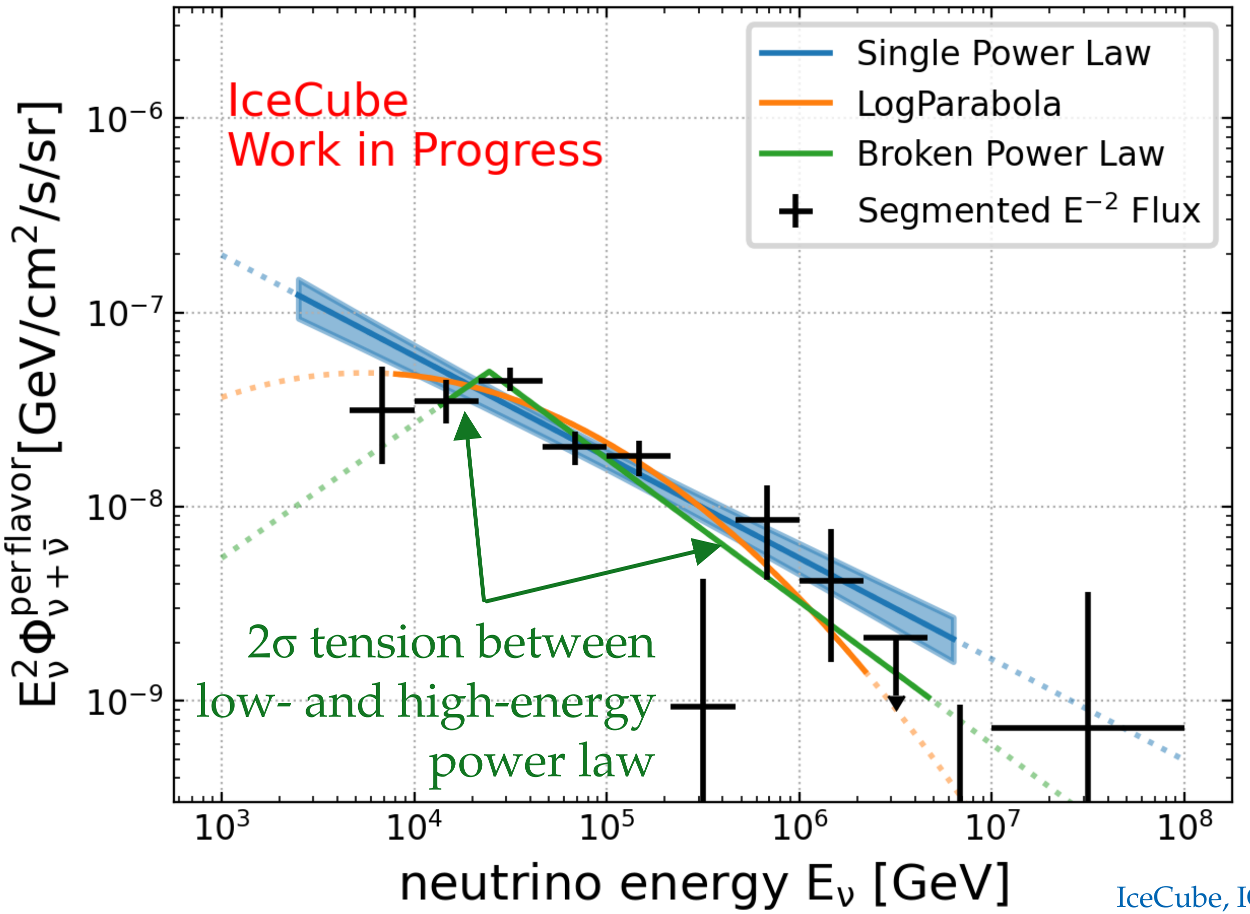




Donini, Palomares-Ruiz, Salvadó, *Nature Phys.* 2019

Neutrino energy spectrum

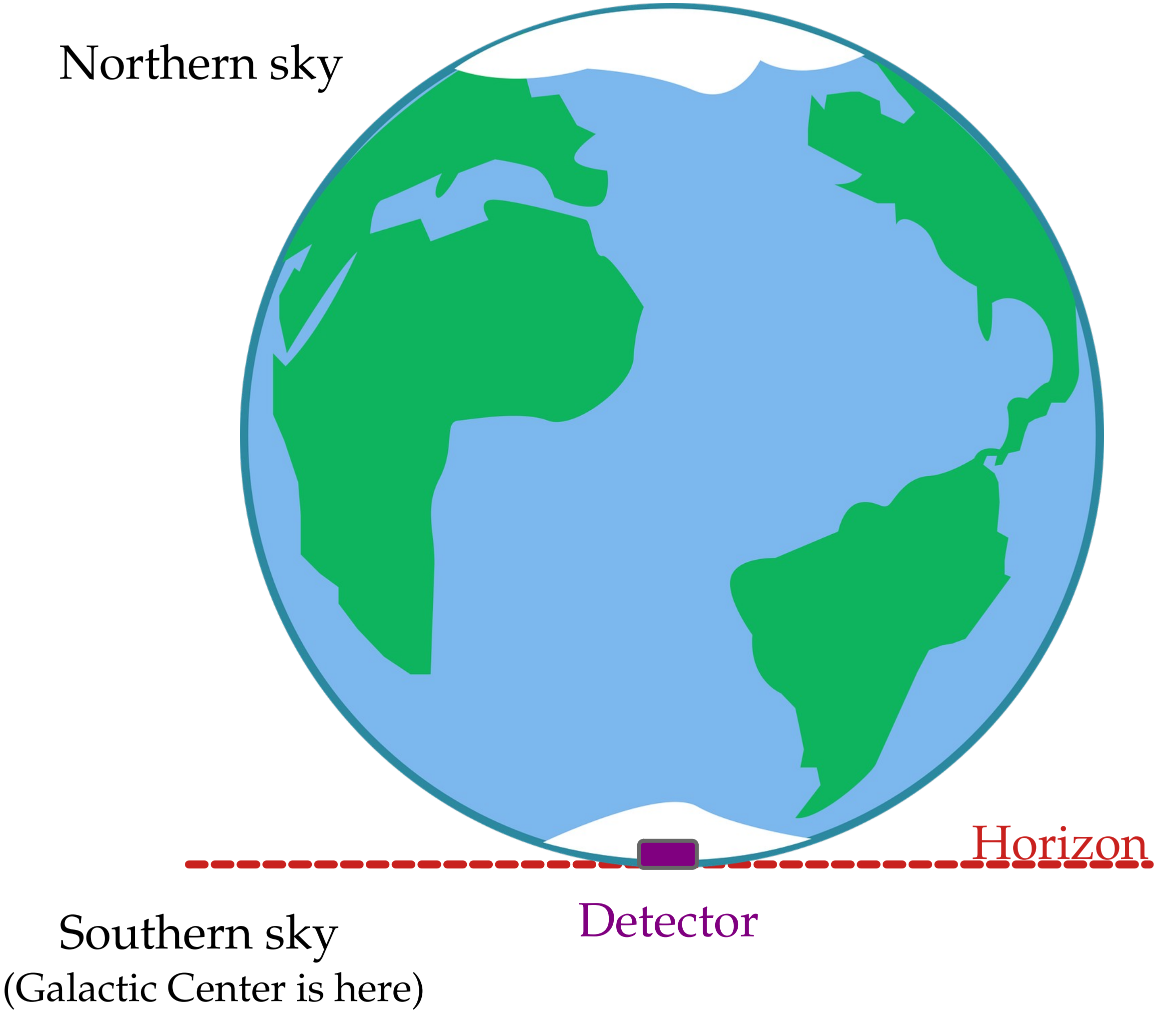
With > 10 years of data, deviations from a power law start to be testable:



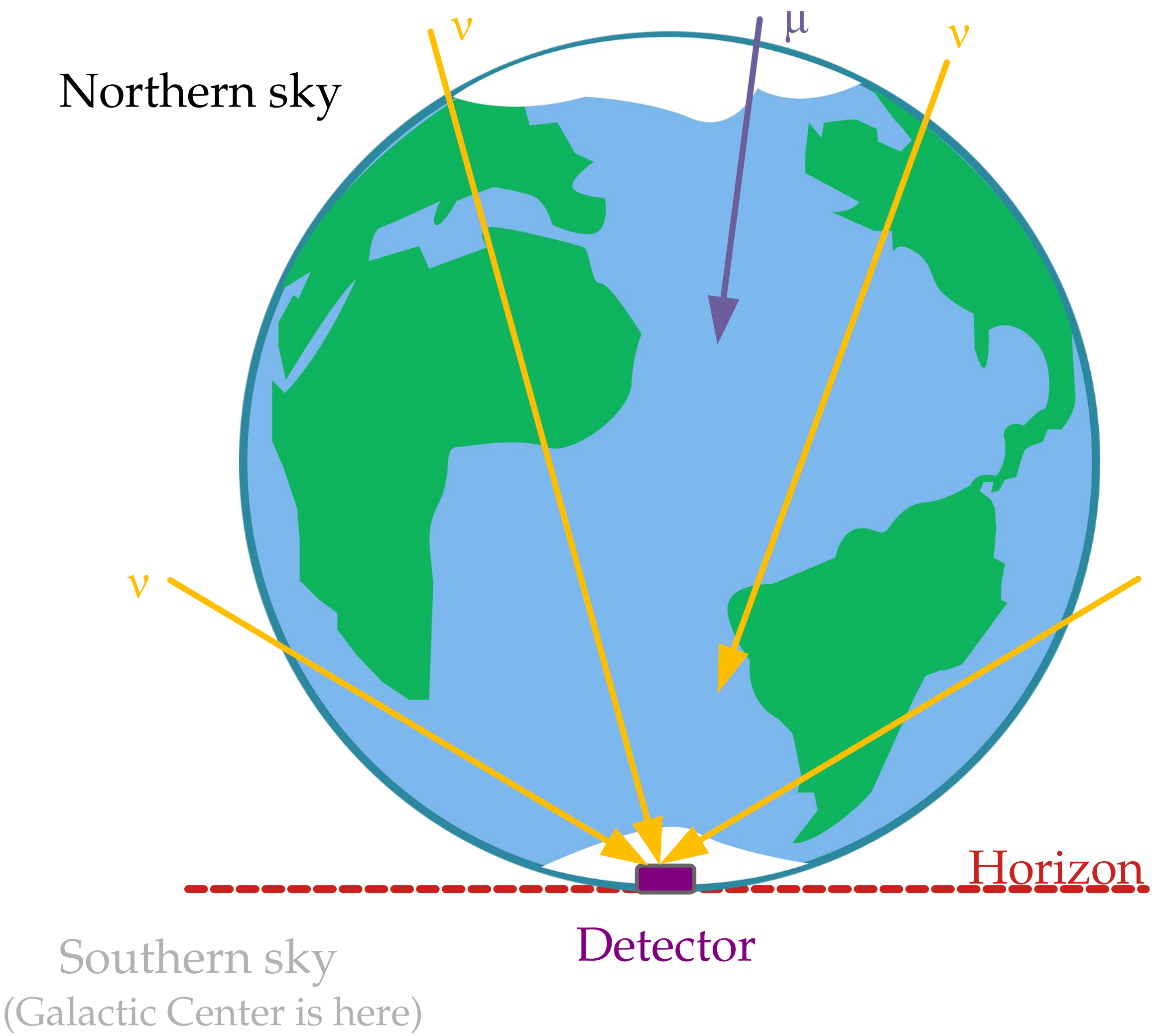
Different spectra might reflect different source populations

IceCube, ICRC 2023

Upgoing *vs.* downgoing neutrinos



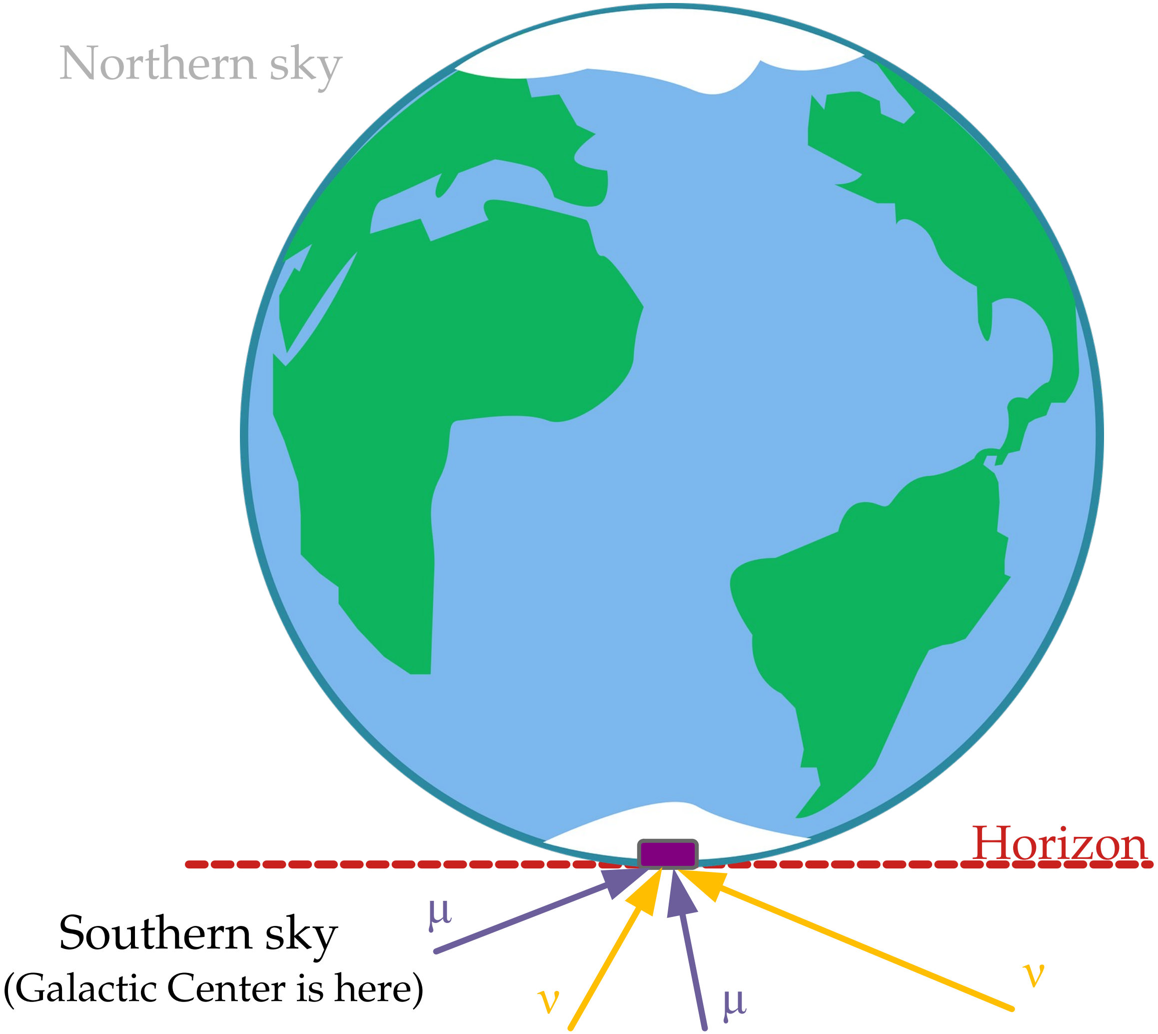
Upgoing *vs.* downgoing neutrinos



Neutrinos from the Northern sky
≡
Upgoing neutrinos

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

Upgoing *vs.* downgoing neutrinos



Neutrinos from the Southern sky

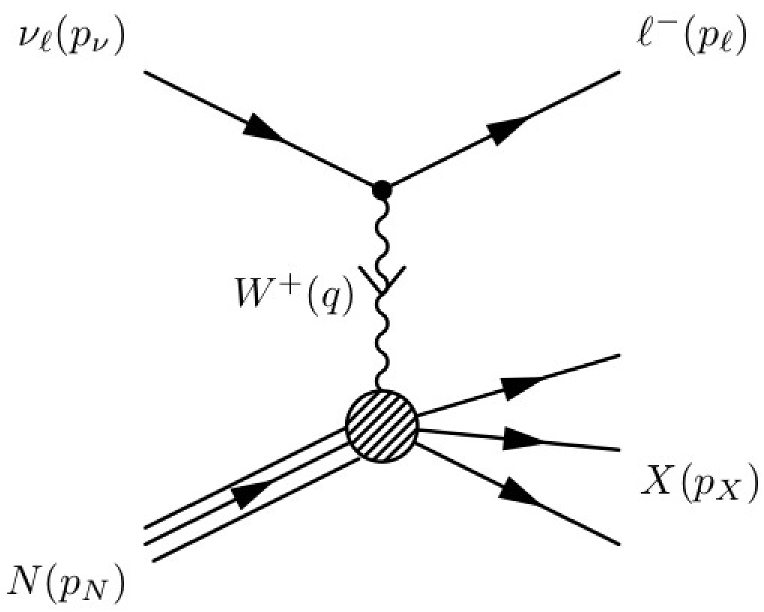
≡

Downgoing neutrinos

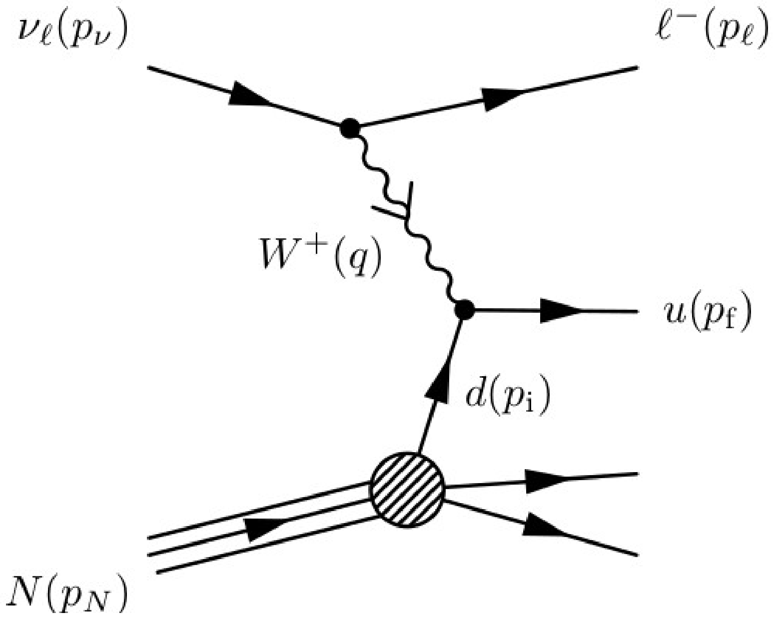
- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

Deep inelastic scattering

What you see



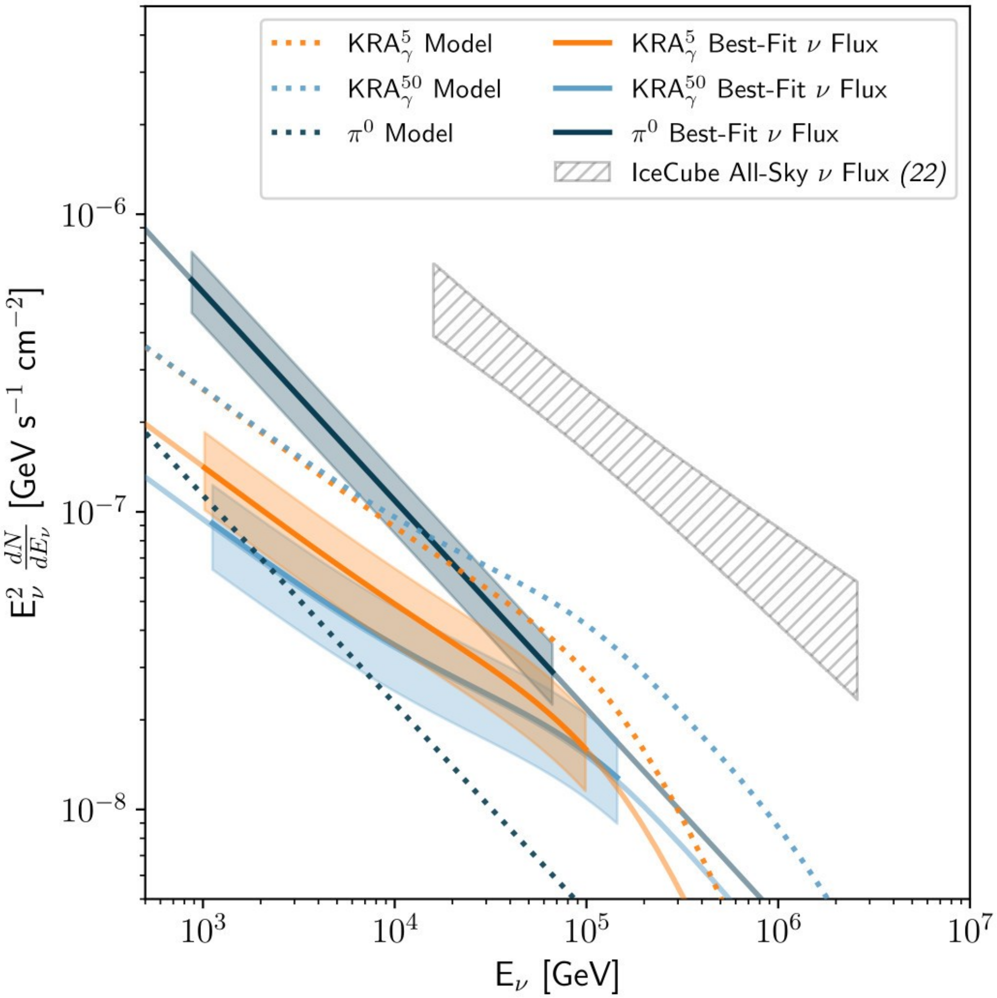
Beneath the hood



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

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

High-energy neutrinos from the Galactic Plane



Three models of Galactic diffuse ν:

π^0: MeV–GeV π^0 template inferred from gamma rays extrapolated to TeV

KRA_γ^5: Spectrum varies spatially, harder ν spectrum, cut-off at 5 PeV in CR energy

KRA_γ^{50}: Cut-off at 50 PeV in CR energy

None of the models matched data

(caveat: there are relatively simple models)

No Galactic ν source identified

(likely diffuse + source: Fang & Murase, 2307.02905)

GP flux is 6–13% of all-sky at 30 TeV

IceCube Collab., *Science* 2023

Fundamental physics with high-energy cosmic neutrinos

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

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

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

Fundamental physics with high-energy cosmic neutrinos

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

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

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

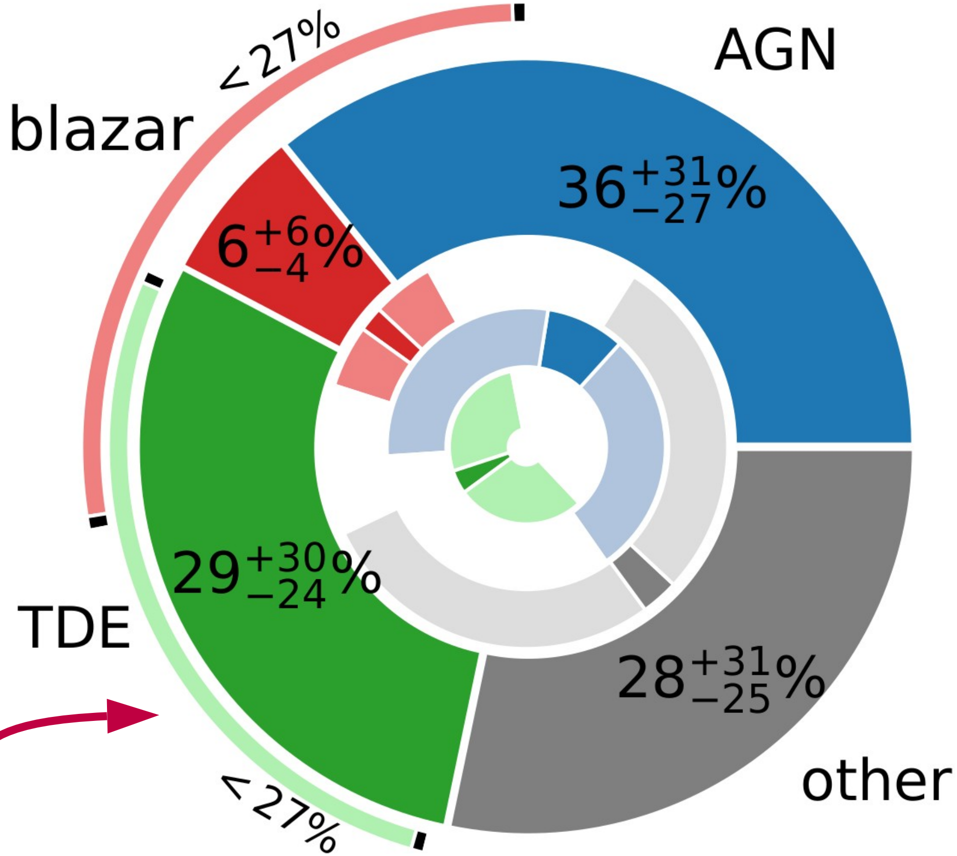
- Improvement over limits using atmospheric ν: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$

The IceCube pie chart

Sources with associated ν emission:

Name	Type	p
NGC 1068	AGN	0.008
TXS 0506+056	blazar	0.001
PKS 1502+106	blazar	0.01
PKS 1424-41	blazar	0.05
AT2019dsg	TDE	0.002

Fractional contribution of each source population to total diffuse flux (Bayesian analysis)

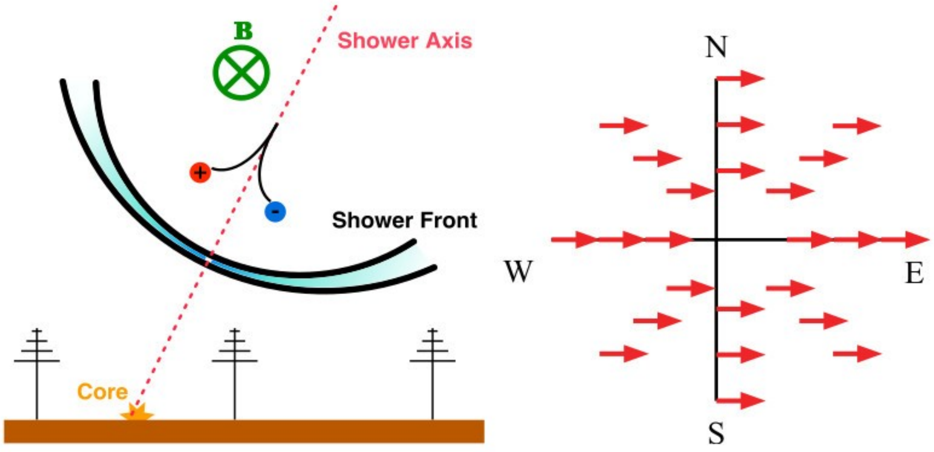


I. Bartos *et al.*, *ApJ* 2021 [2105.03792]

Note: Outer rings are from separate stacking analyses

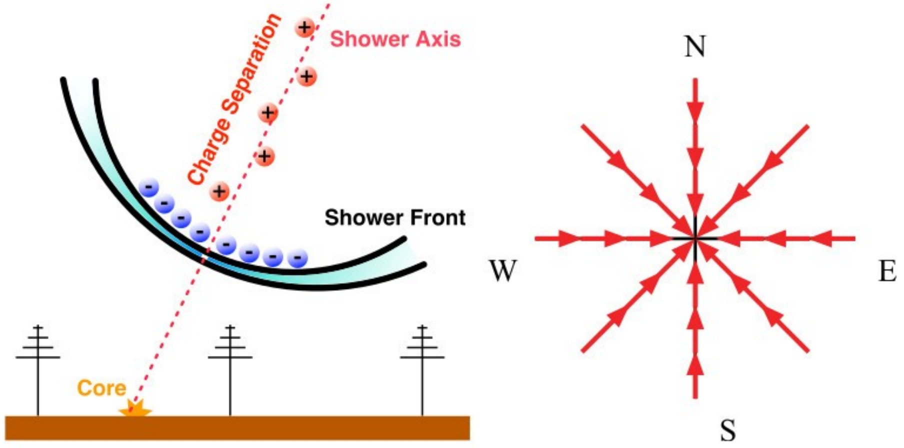
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

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

Radio emission: geomagnetic and Askaryan

Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

But likely not of Milky-Way origin

KM3NeT Collab. arXiv:2502.08387

Likely extragalactic origin

Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

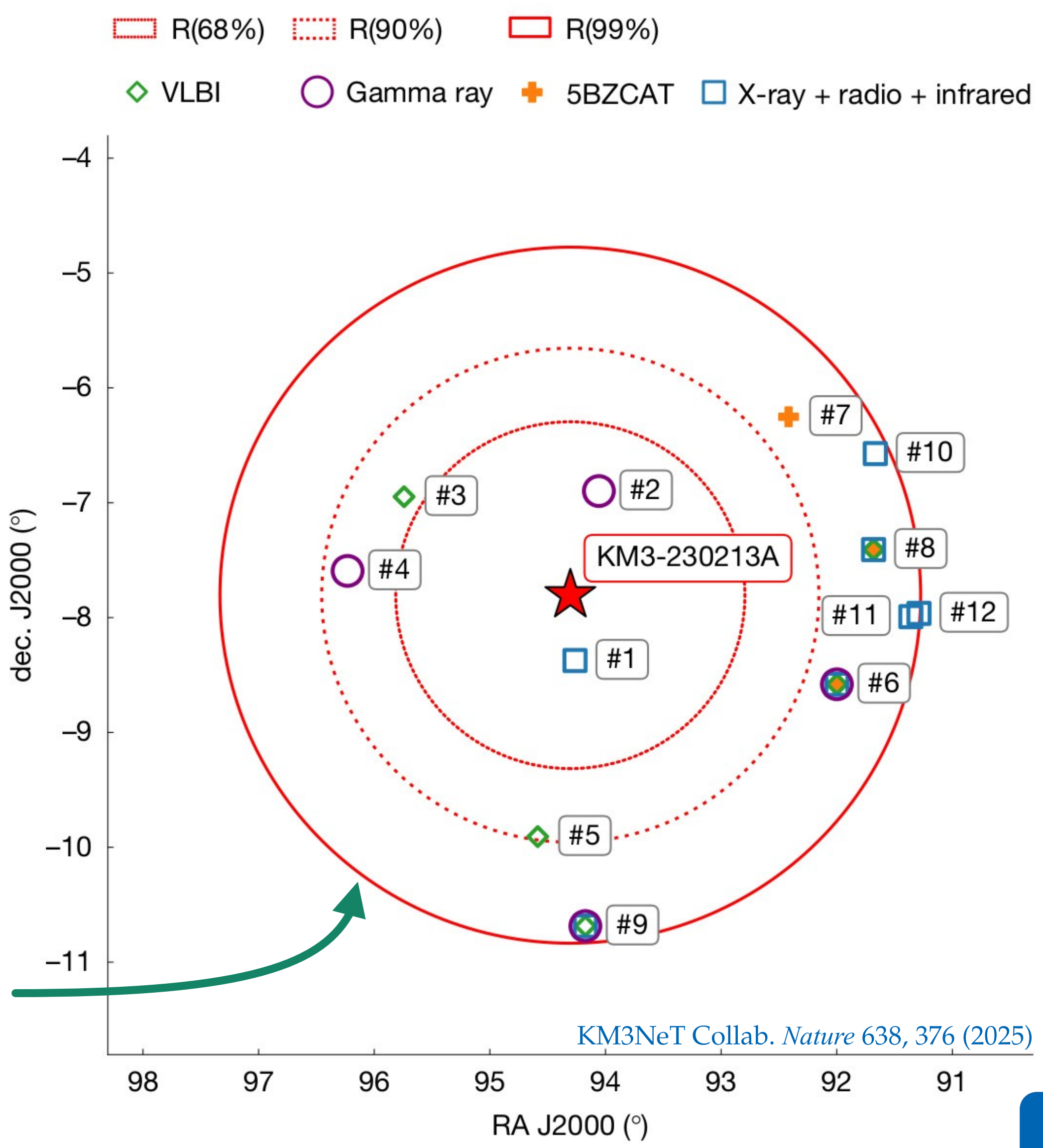
But likely not of Milky-Way origin

KM3NeT Collab. arXiv:2502.08387

Likely extragalactic origin

Few extragalactic sources (blazars) near event position, but no strong association

KM3NeT Collab. arXiv:2502.08484



KM3NeT Collab. *Nature* 638, 376 (2025)

Where did it come from?

From the Southern Hemisphere

(RA = 94.3°, dec = -7.8°)

Not far from Milky Way plane

But likely not of Milky-Way origin

KM3NeT Collab. arXiv:2502.08387

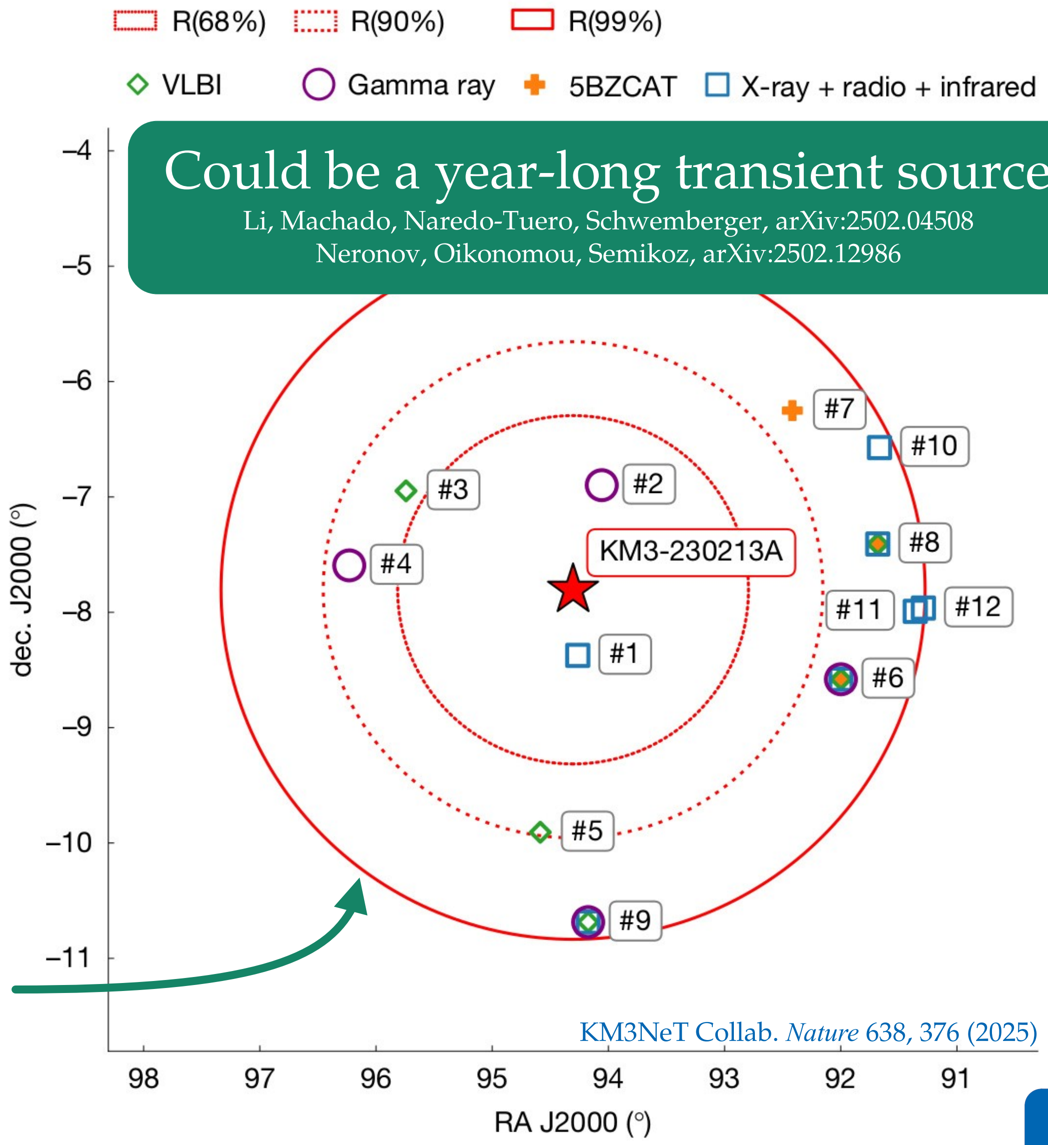
Likely extragalactic origin

Few extragalactic sources (blazars) near event position, but no strong association

KM3NeT Collab. arXiv:2502.08484

Could be a year-long transient source

Li, Machado, Naredo-Tuero, Schwemberger, arXiv:2502.04508
Neronov, Oikonomou, Semikoz, arXiv:2502.12986



KM3NeT Collab. *Nature* 638, 376 (2025)

Glashow resonance:
Long-sought, finally seen

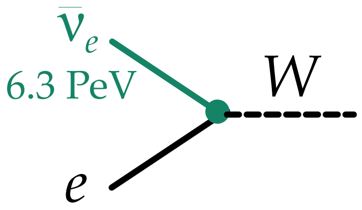
First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

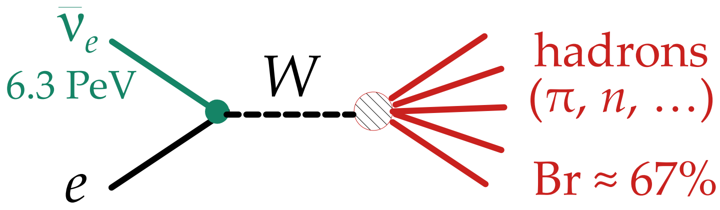
Predicted in 1960:



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

First observation of a Glashow resonance

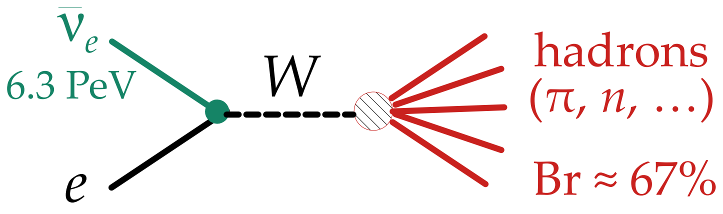
Predicted in 1960:

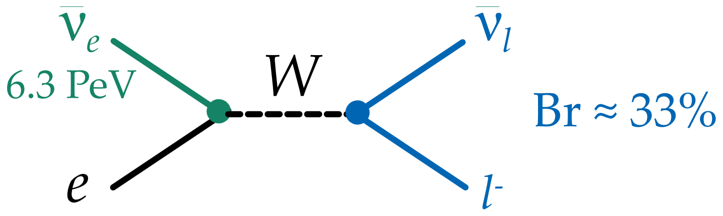


IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:

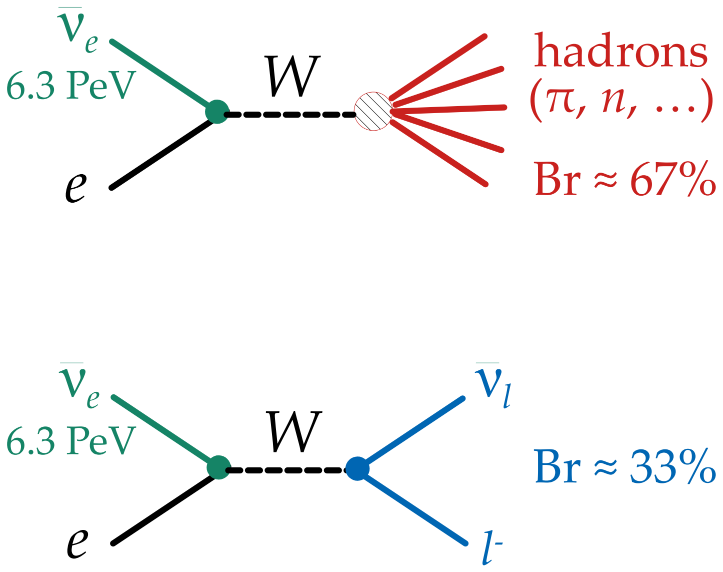




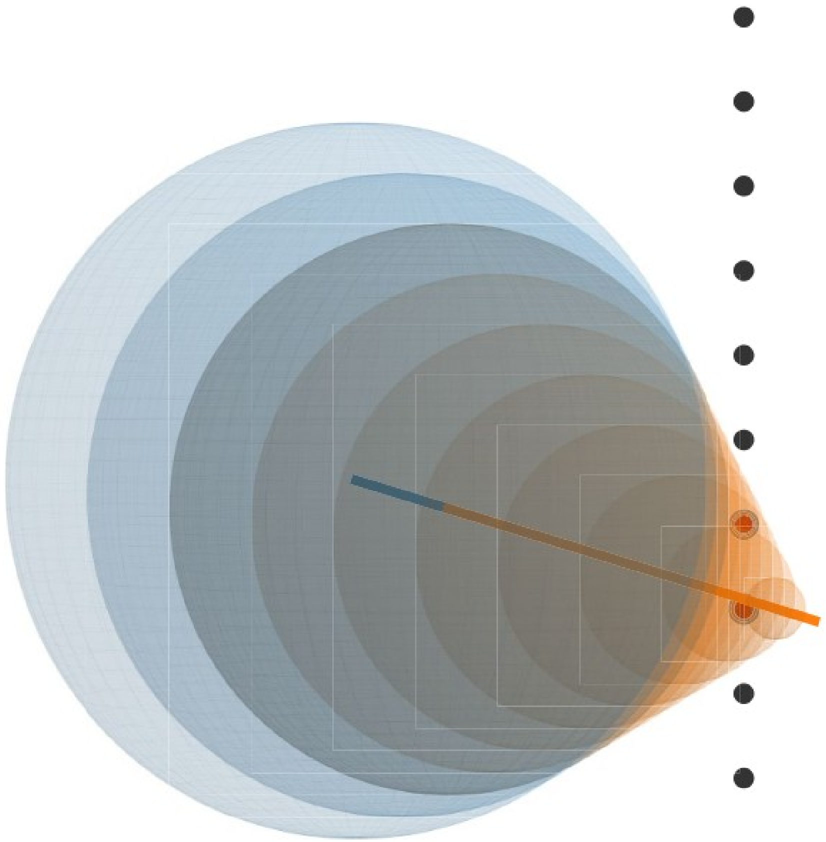
IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



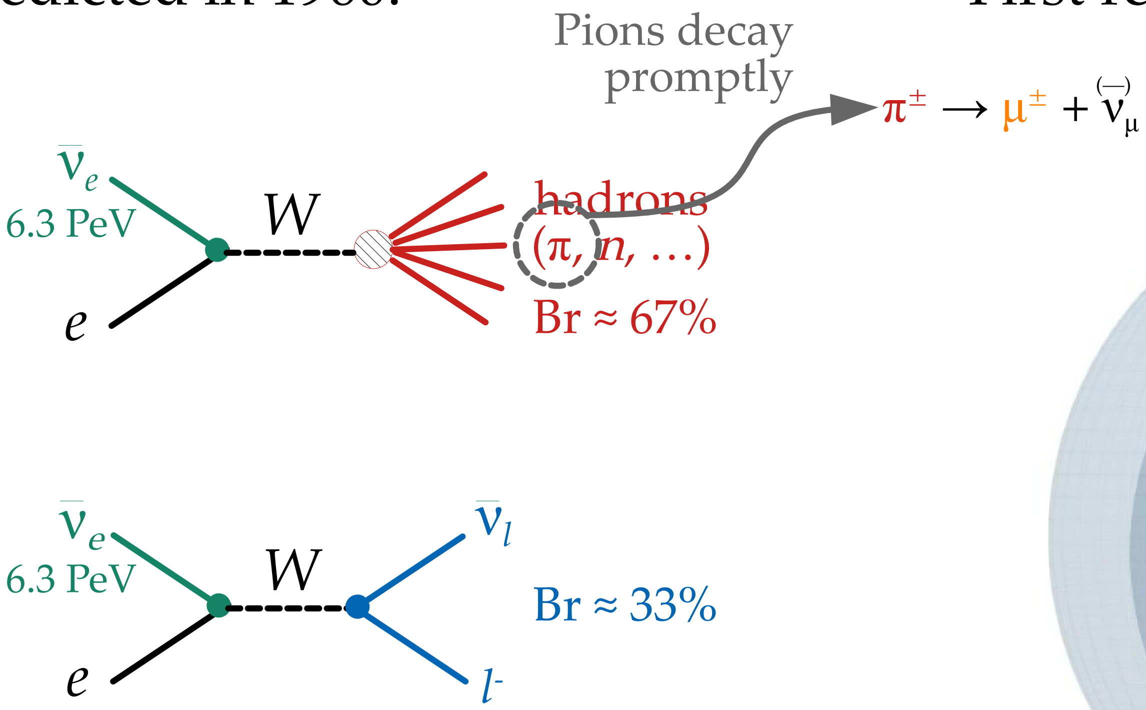
First reported by IceCube in 2021:



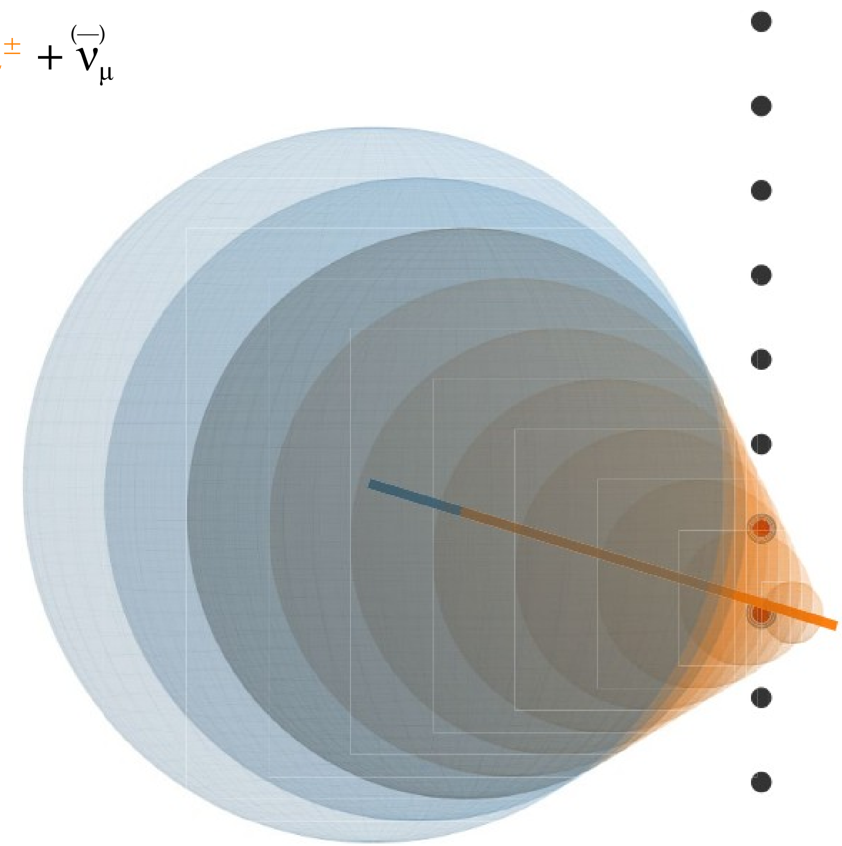
IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:



First reported by IceCube in 2021:

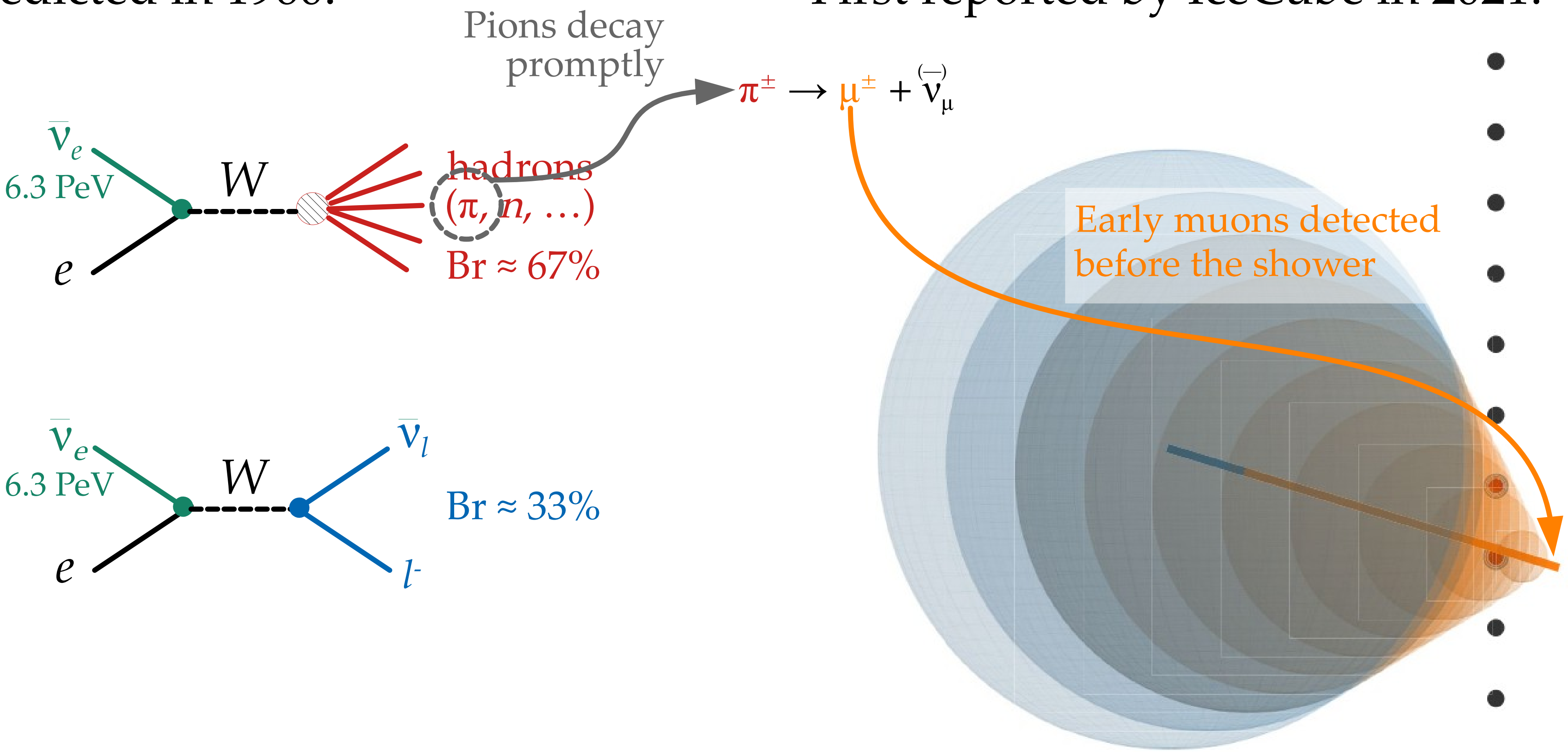


IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:

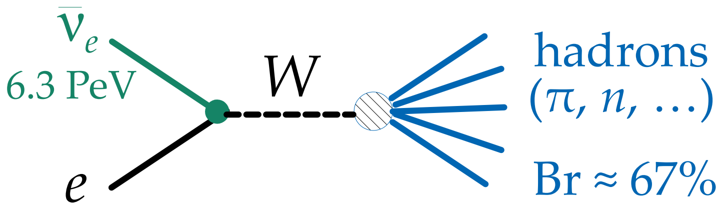
First reported by IceCube in 2021:

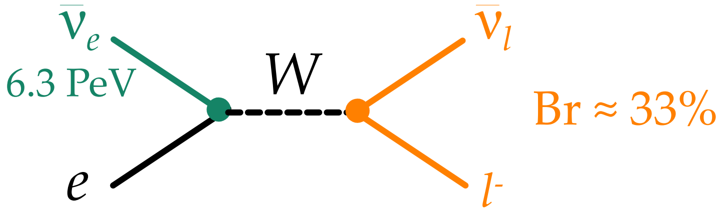


IceCube, *Nature* 2021
Glashow, *PR* 1960

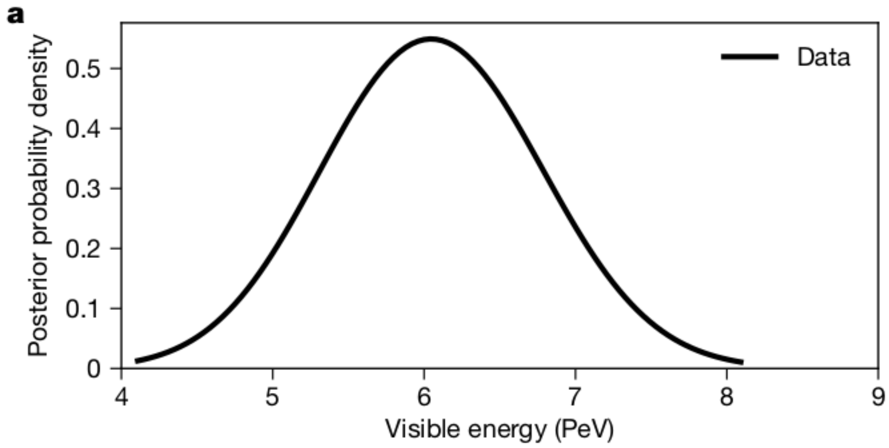
First observation of a Glashow resonance

Predicted in 1960:





First reported by IceCube in 2021:

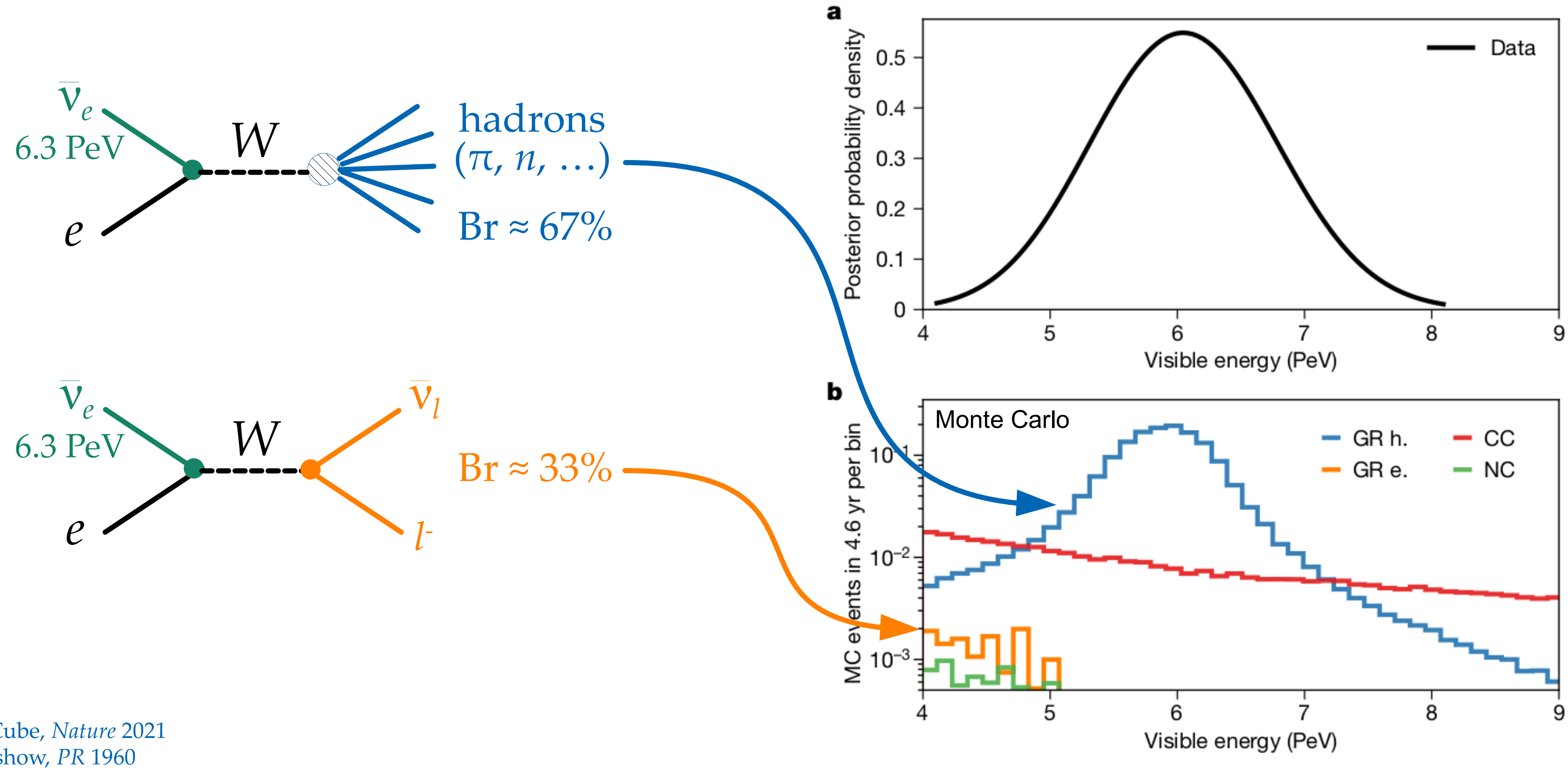


IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

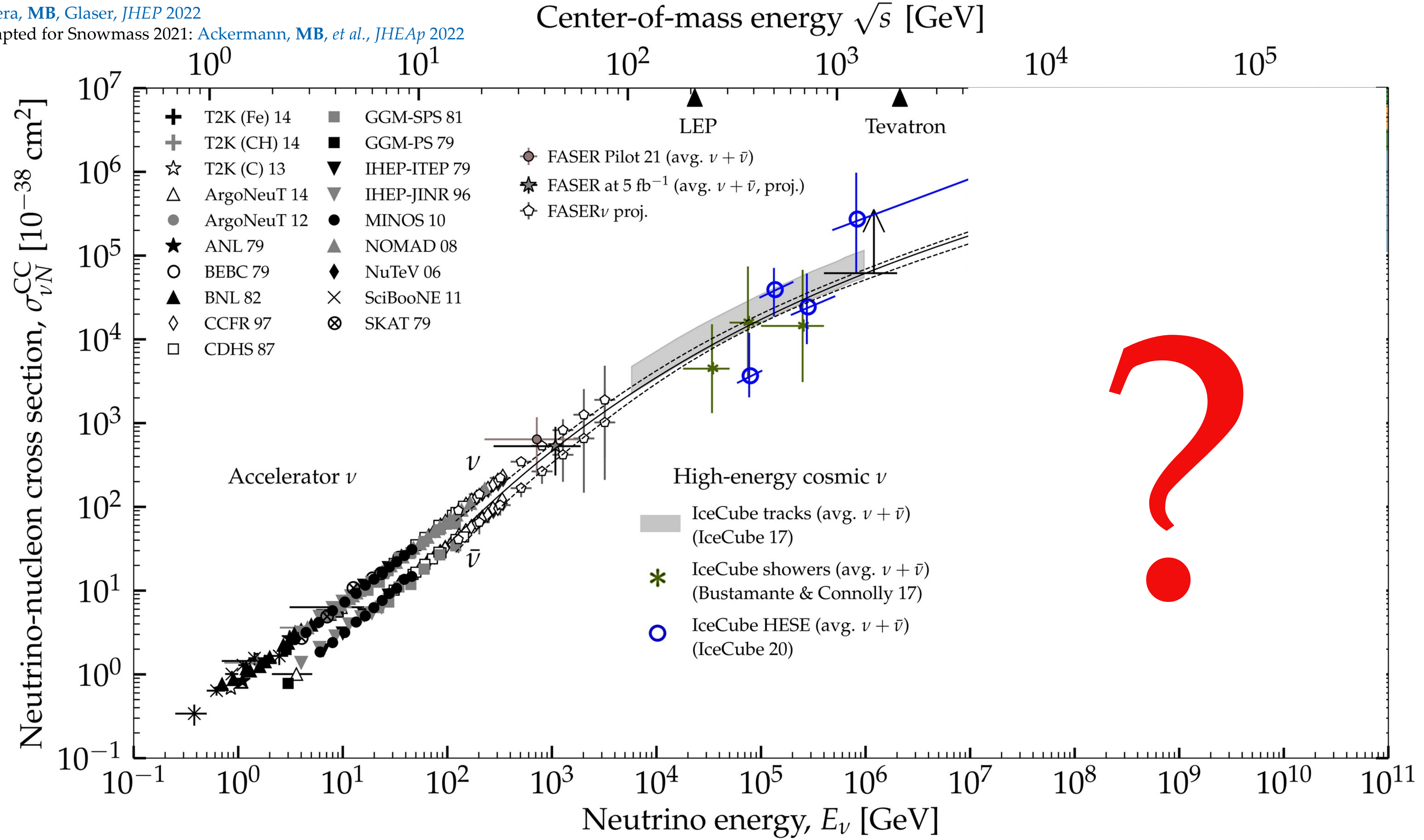
Predicted in 1960:

First reported by IceCube in 2021:

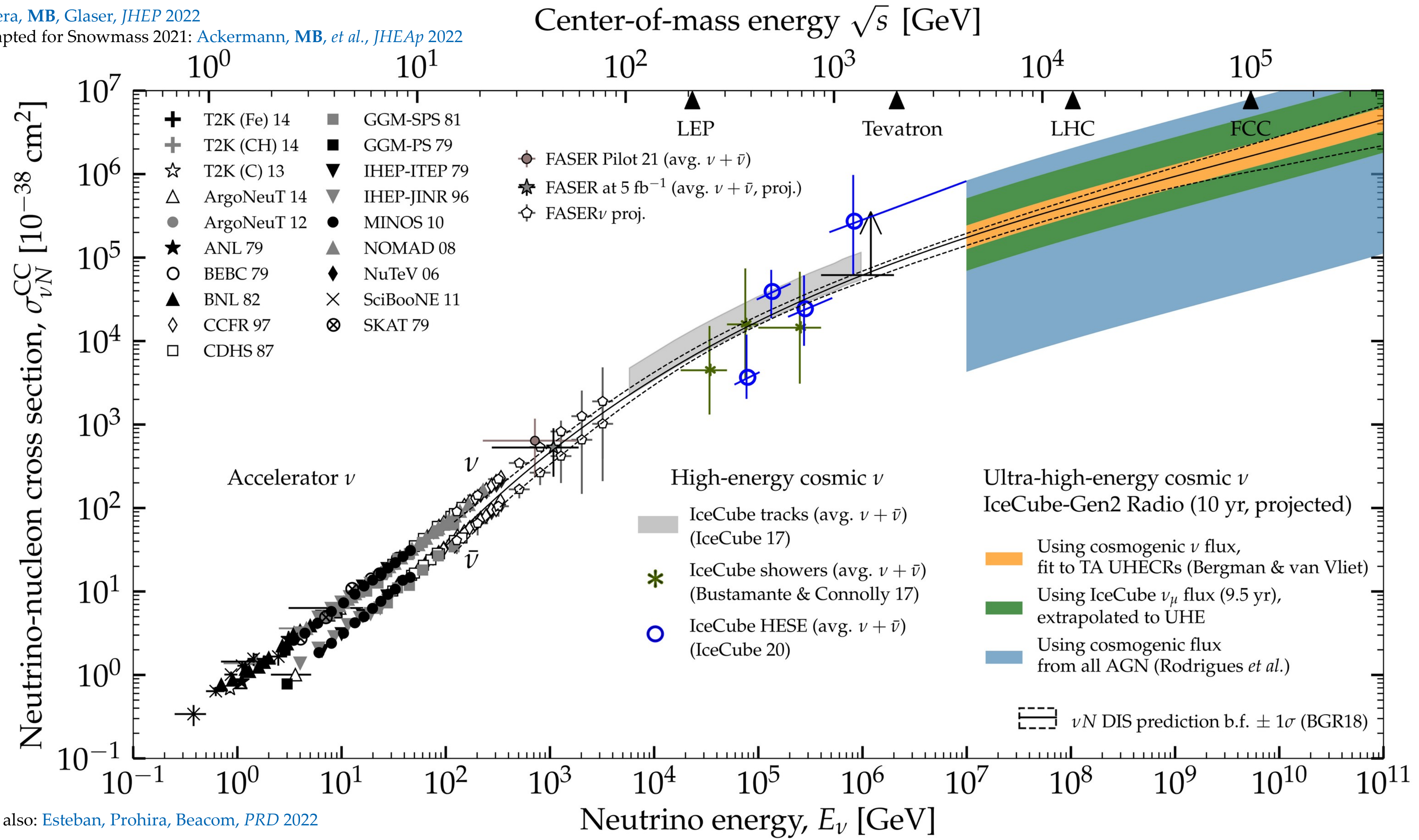


IceCube, *Nature* 2021
Glashow, *PR* 1960

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

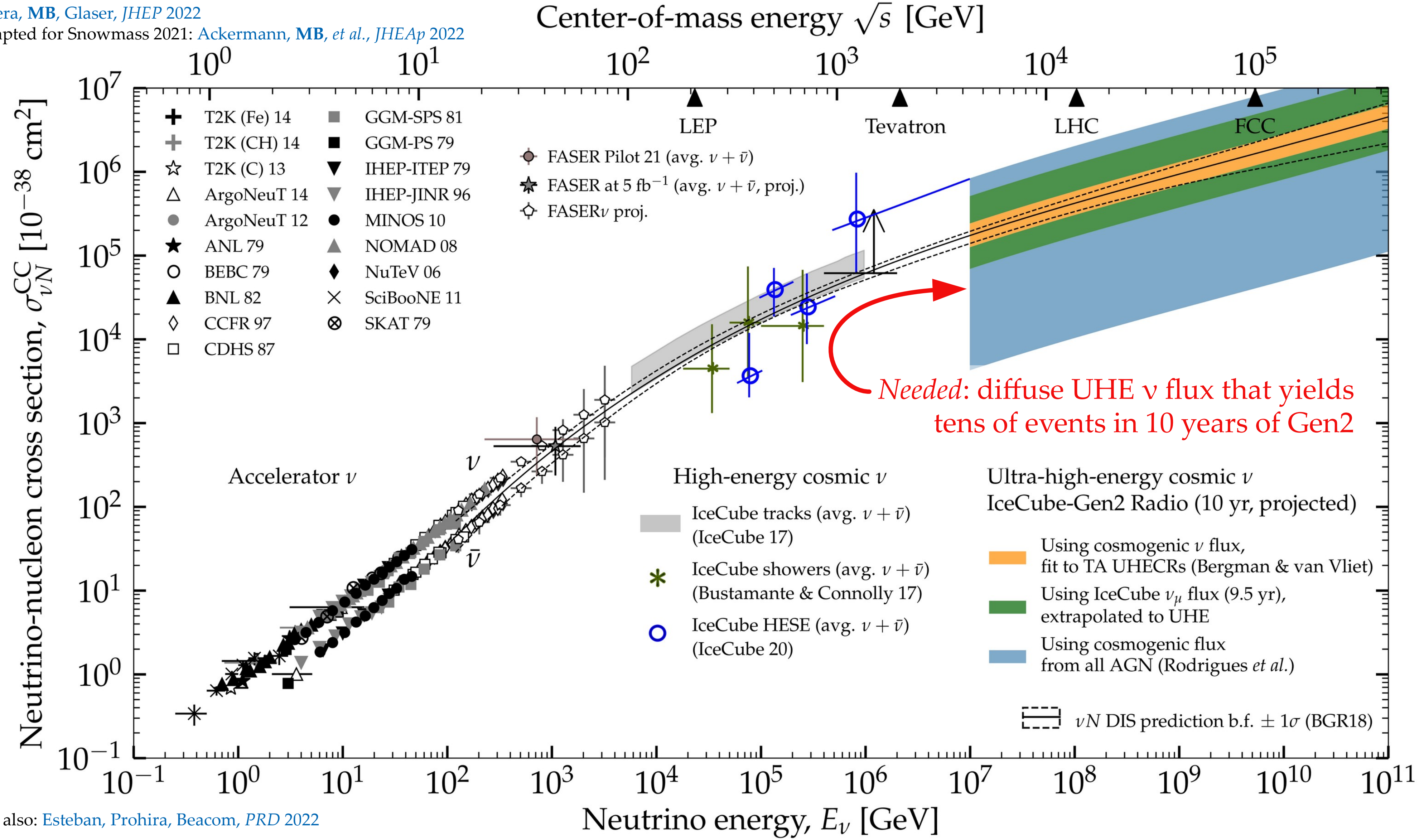


Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022



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

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



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

4. Dark matter:

Annihilation and decay into ν

High-energy neutrinos from dark matter

Dark matter co-annihilation:

$\chi + \chi \to \nu + \bar{\nu}$

$\chi + \chi \to \ldots \to \nu + \bar{\nu} + \ldots$

$E_{\mathrm{max}} = m_\chi$

Dark matter decay:

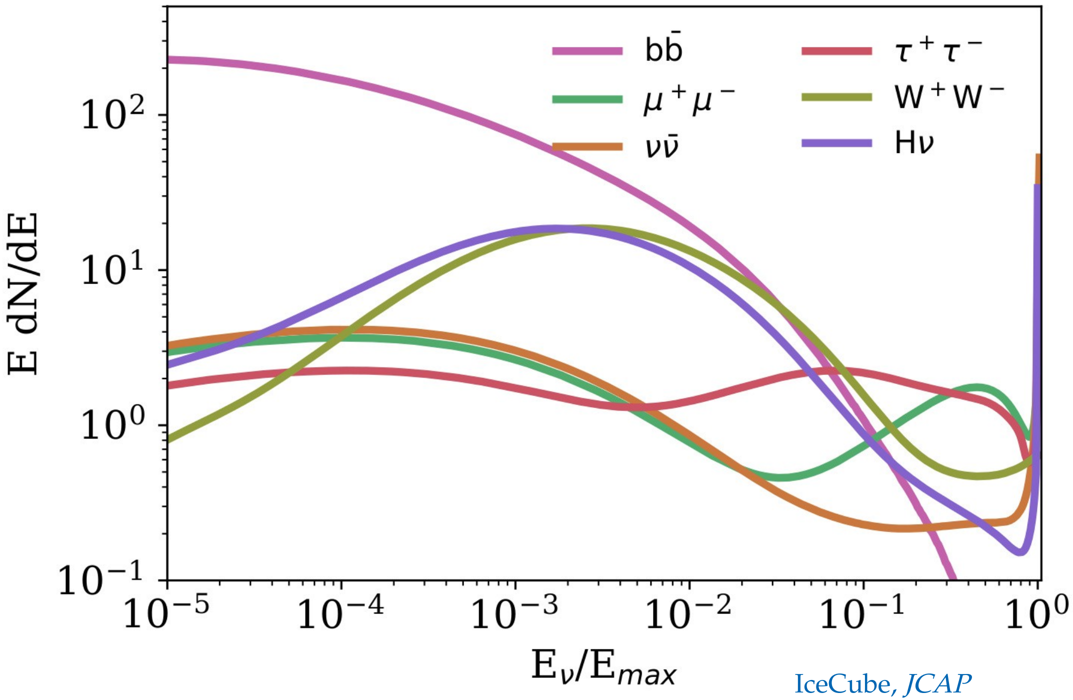
$\chi \to \nu + \bar{\nu}$

$\chi \to \ldots \to \nu + \bar{\nu} + \ldots$

$E_{\mathrm{max}} = m_\chi / 2$

Electroweak corrections (off-shell W and Z emission) broaden the ν spectrum

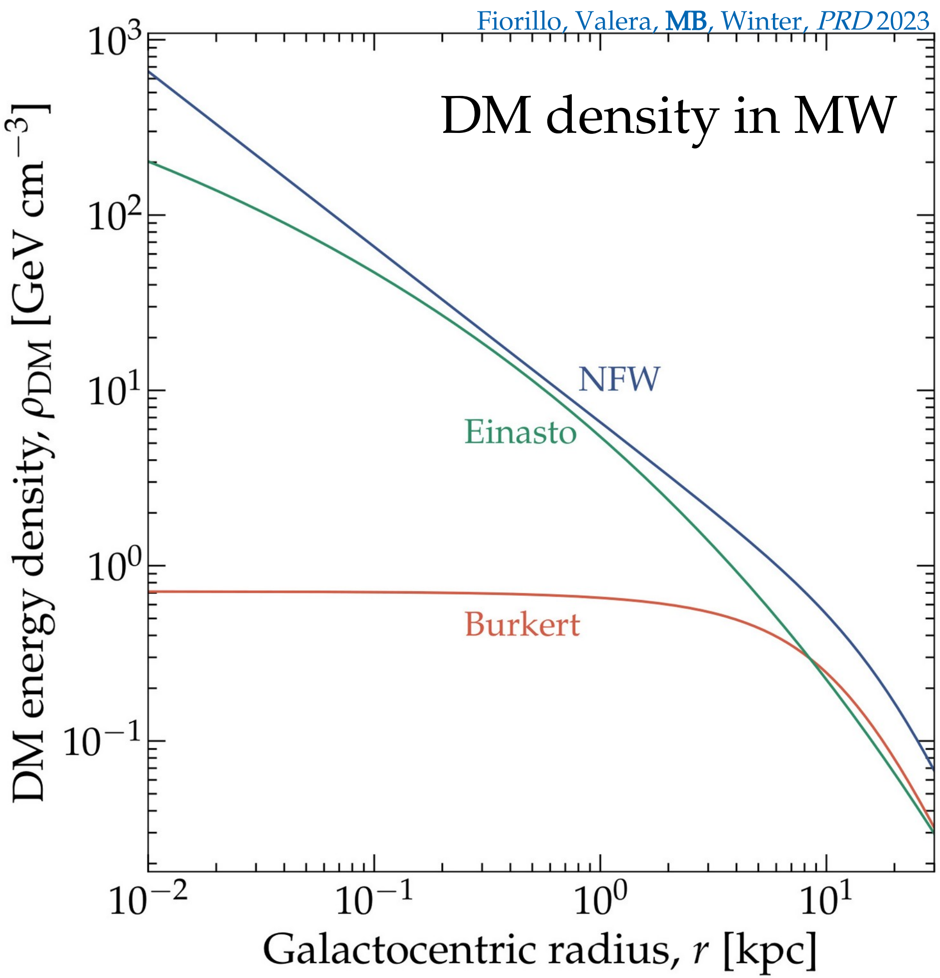
ν + ν̄ yield from DM (at source)



IceCube, *JCAP* 2023

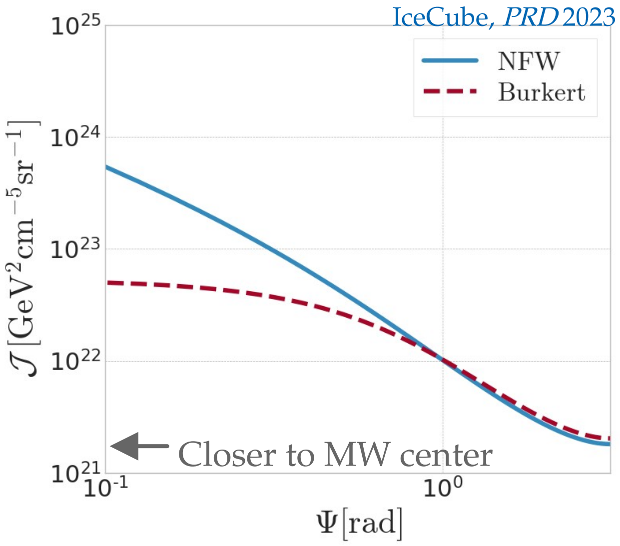
Approximate independence on m_χ valid for $m_\chi \approx$ 100 TeV–10 PeV

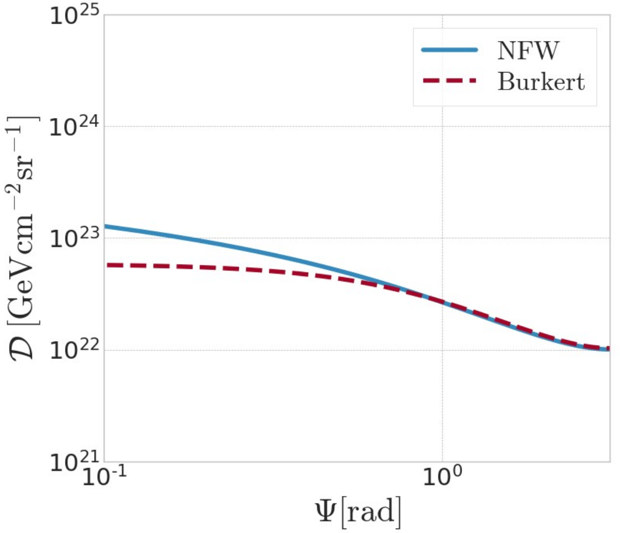
Dark matter in the Milky Way



DM annihilation
$\Phi_\nu \propto \mathcal{J} \propto \rho_{\rm DM}^2$

DM decay
$\Phi_\nu \propto \mathcal{D} \propto \rho_{DM}$

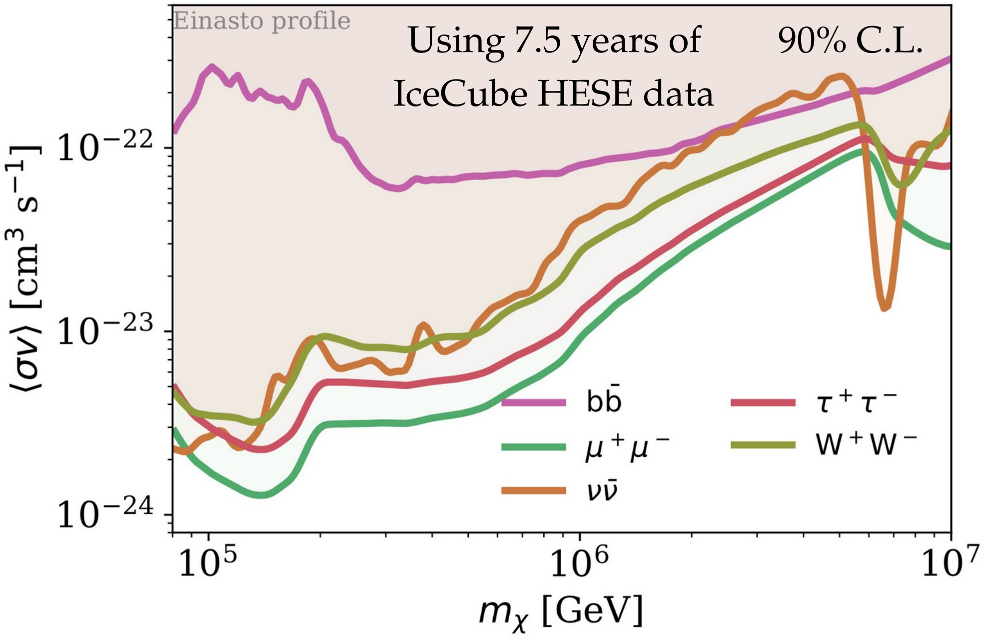




Limits on dark matter annihilation

Per annihilation channel

(assuming 100% branching ratio)



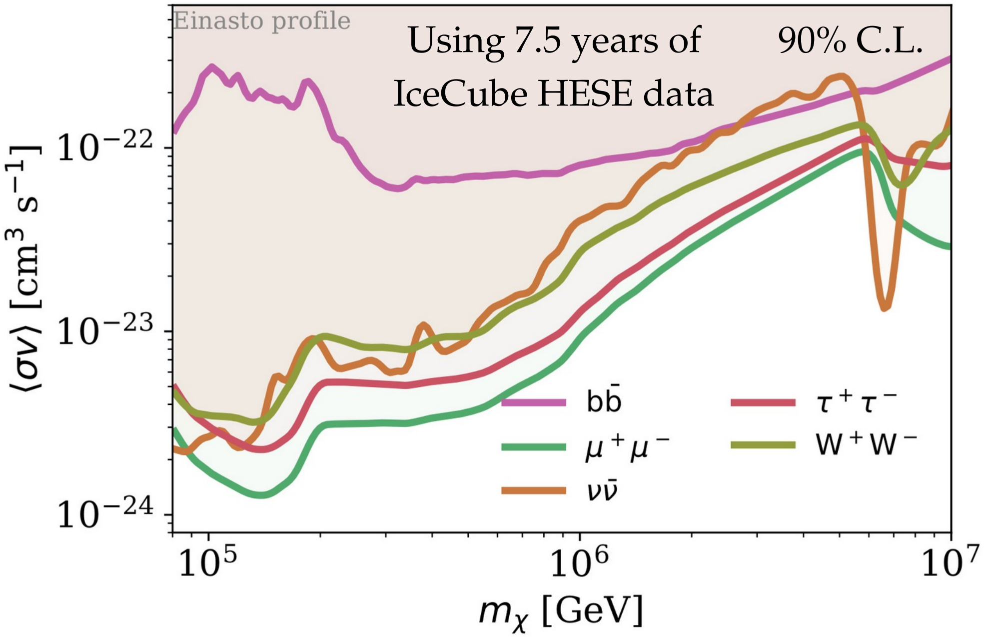
Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter annihilation

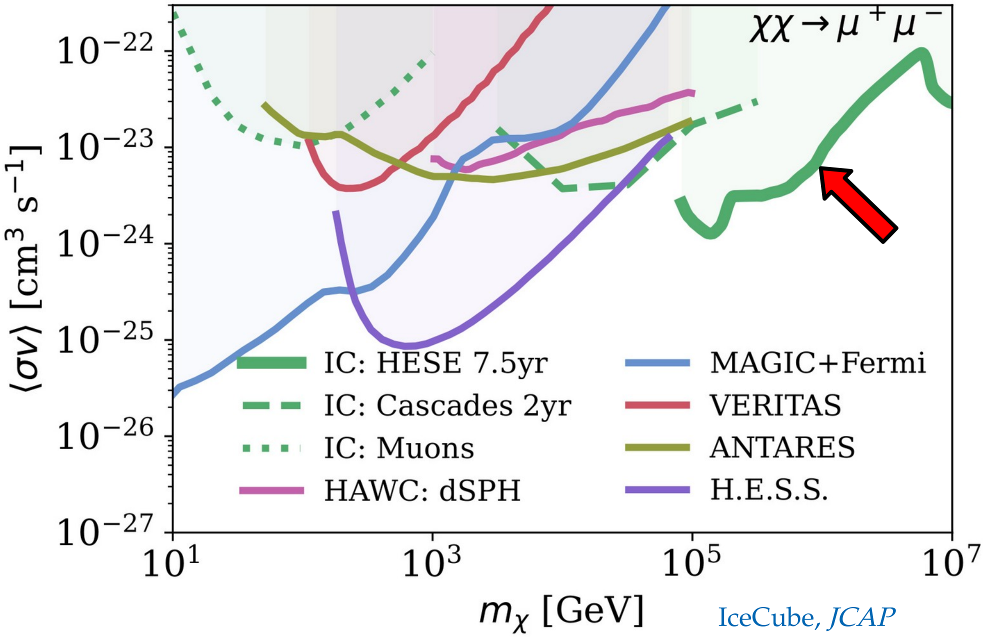
Per annihilation channel

(assuming 100% branching ratio)



Compared to other limits

(assuming annihilation to muons)



IceCube, *JCAP* 2023

Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

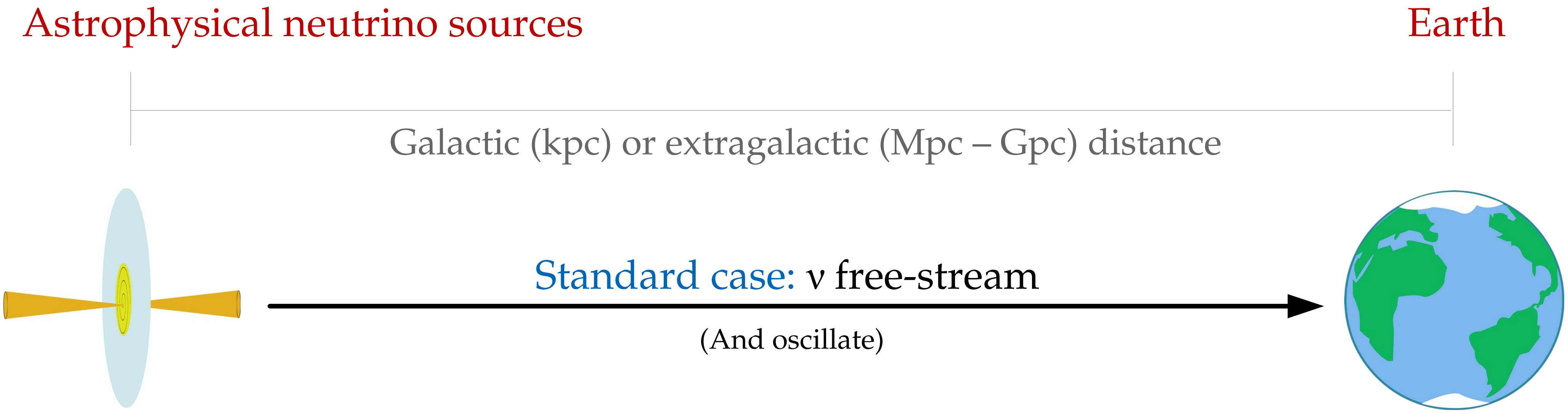
5. New neutrino interactions:

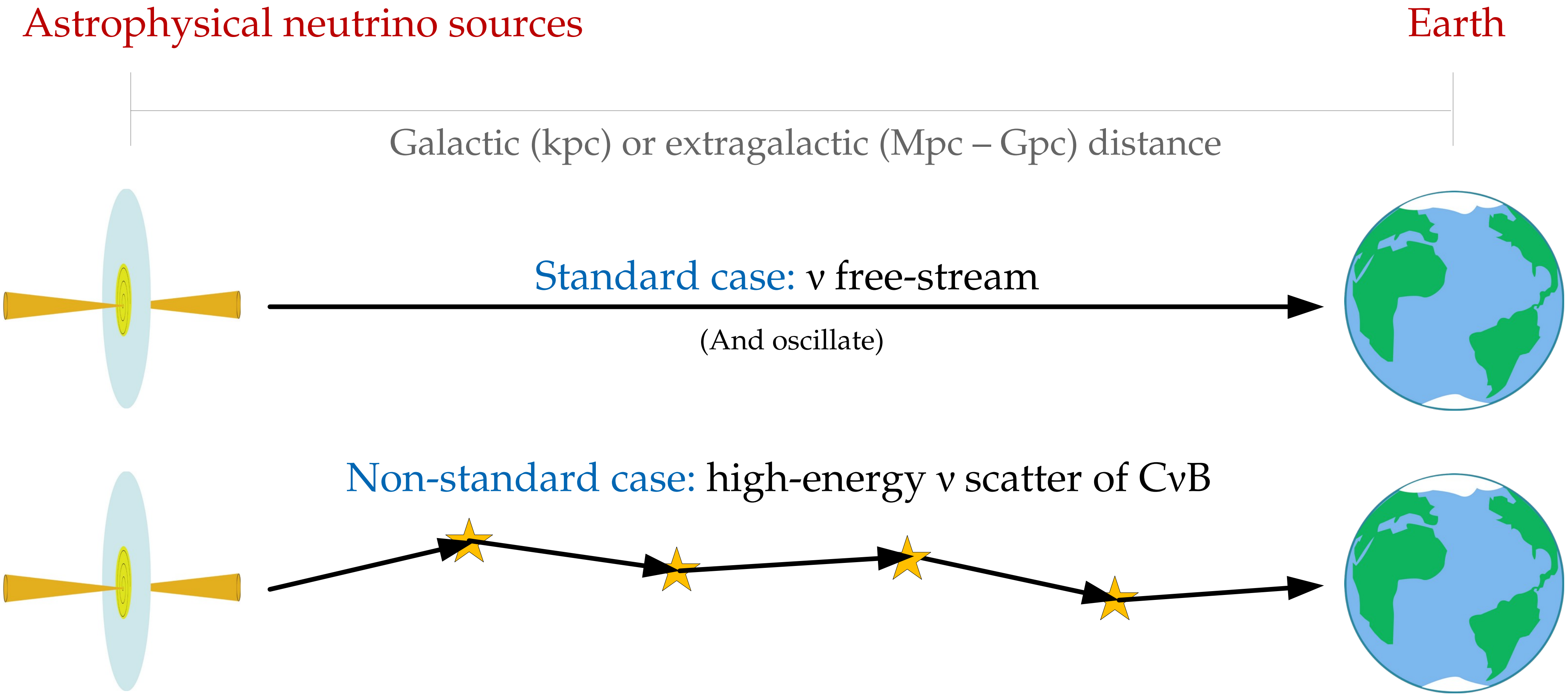
Are there secret νν interactions?

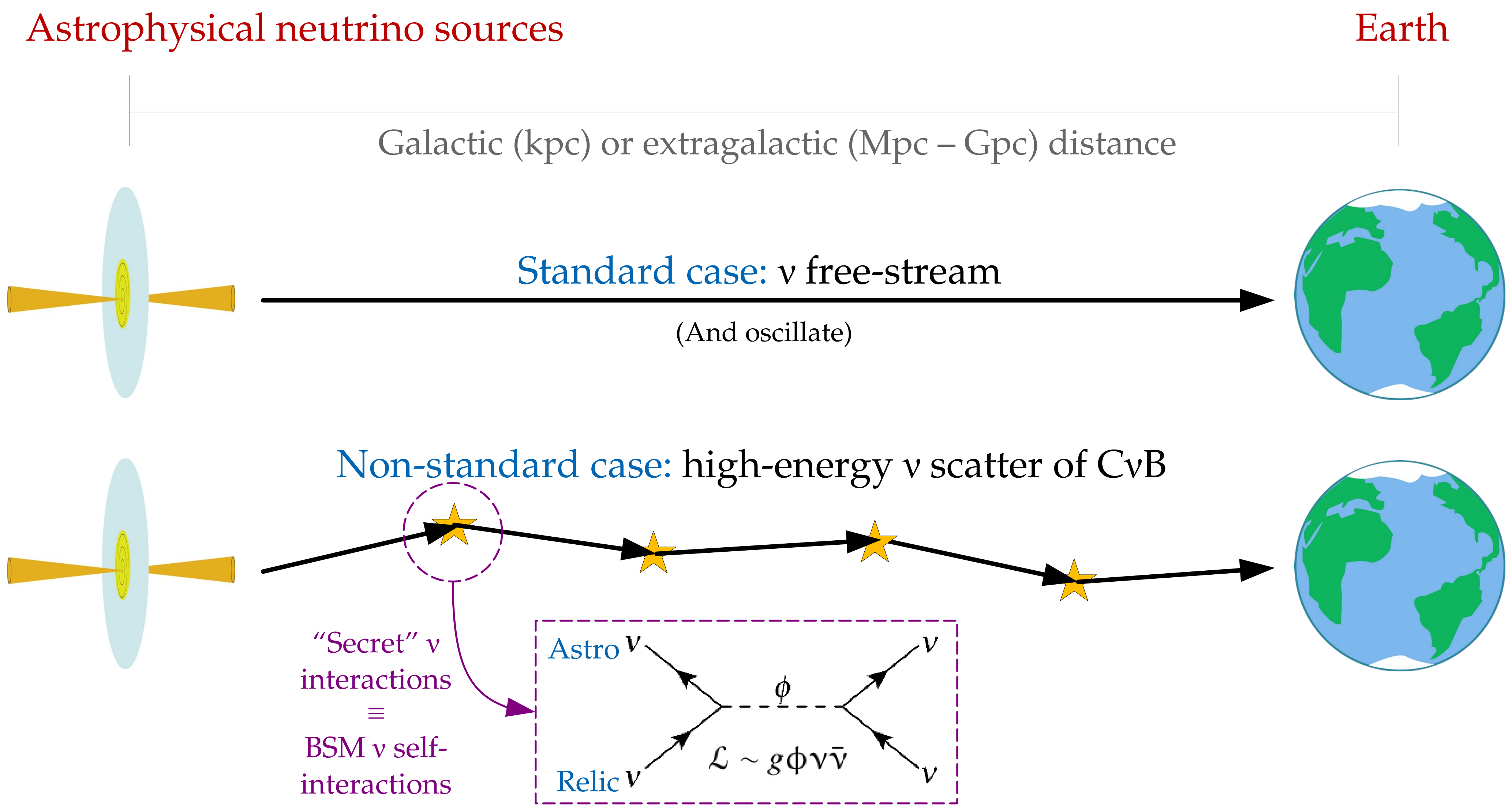
Astrophysical neutrino sources

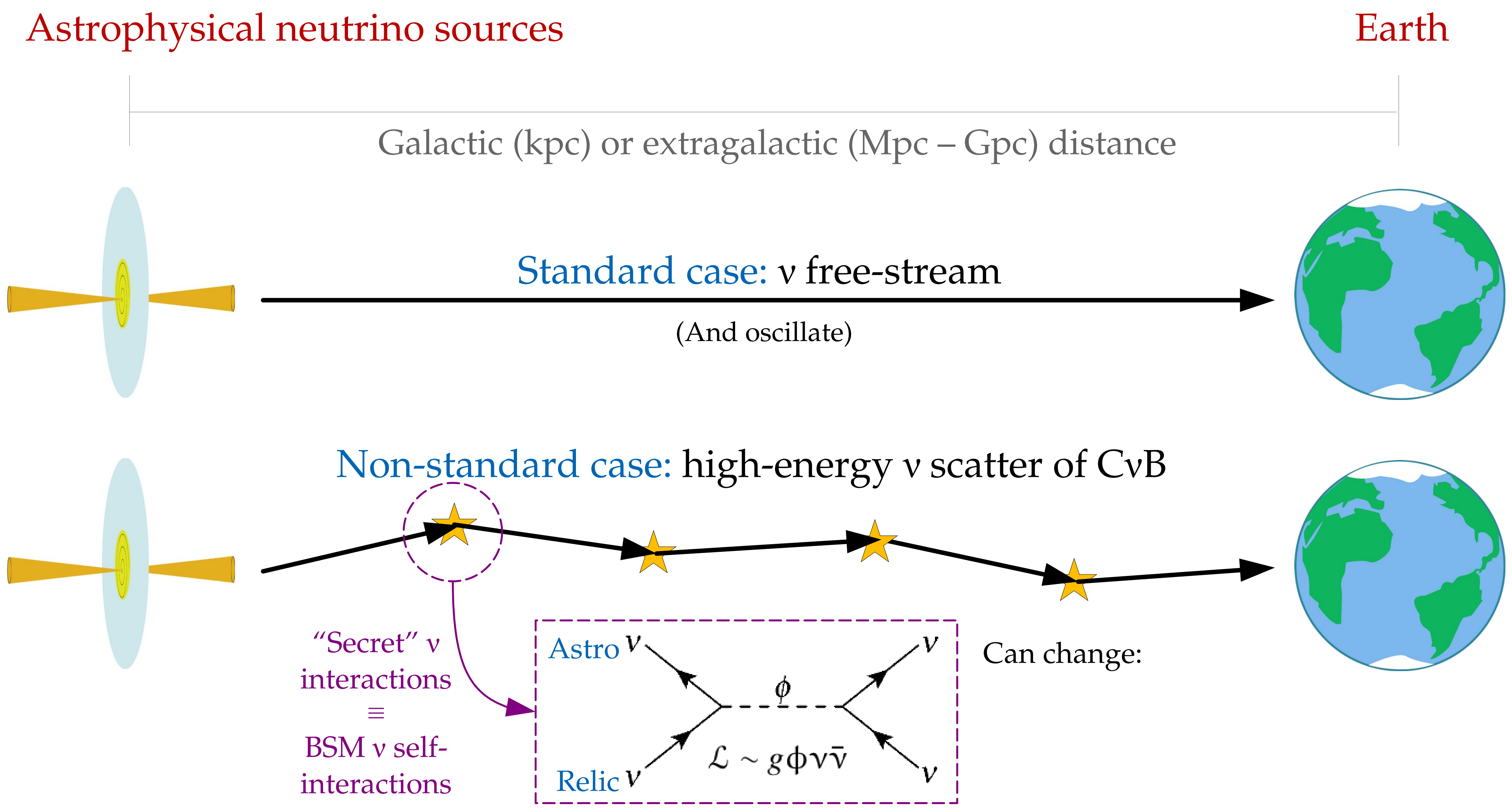
Earth

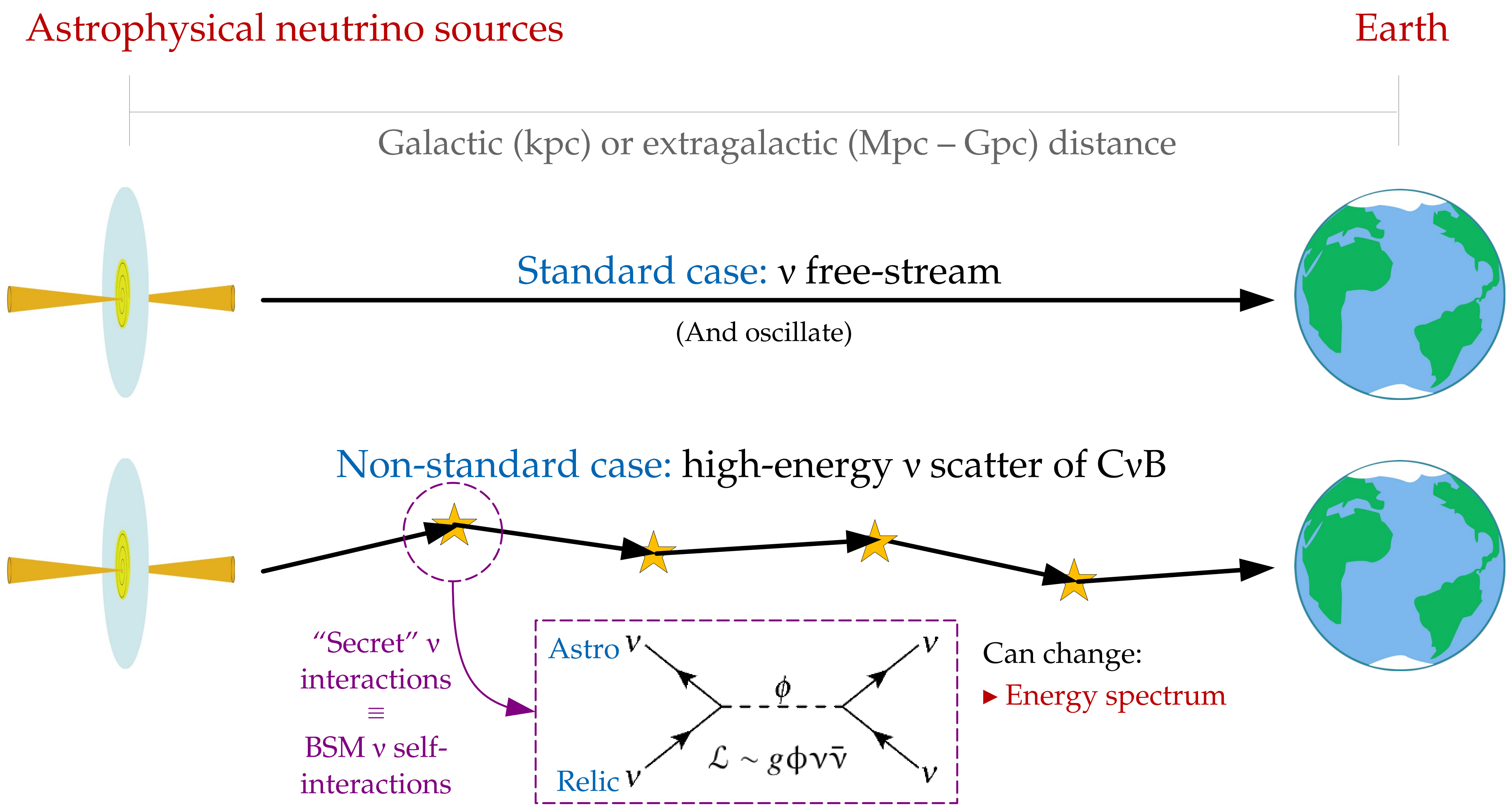
Galactic (kpc) or extragalactic (Mpc – Gpc) distance

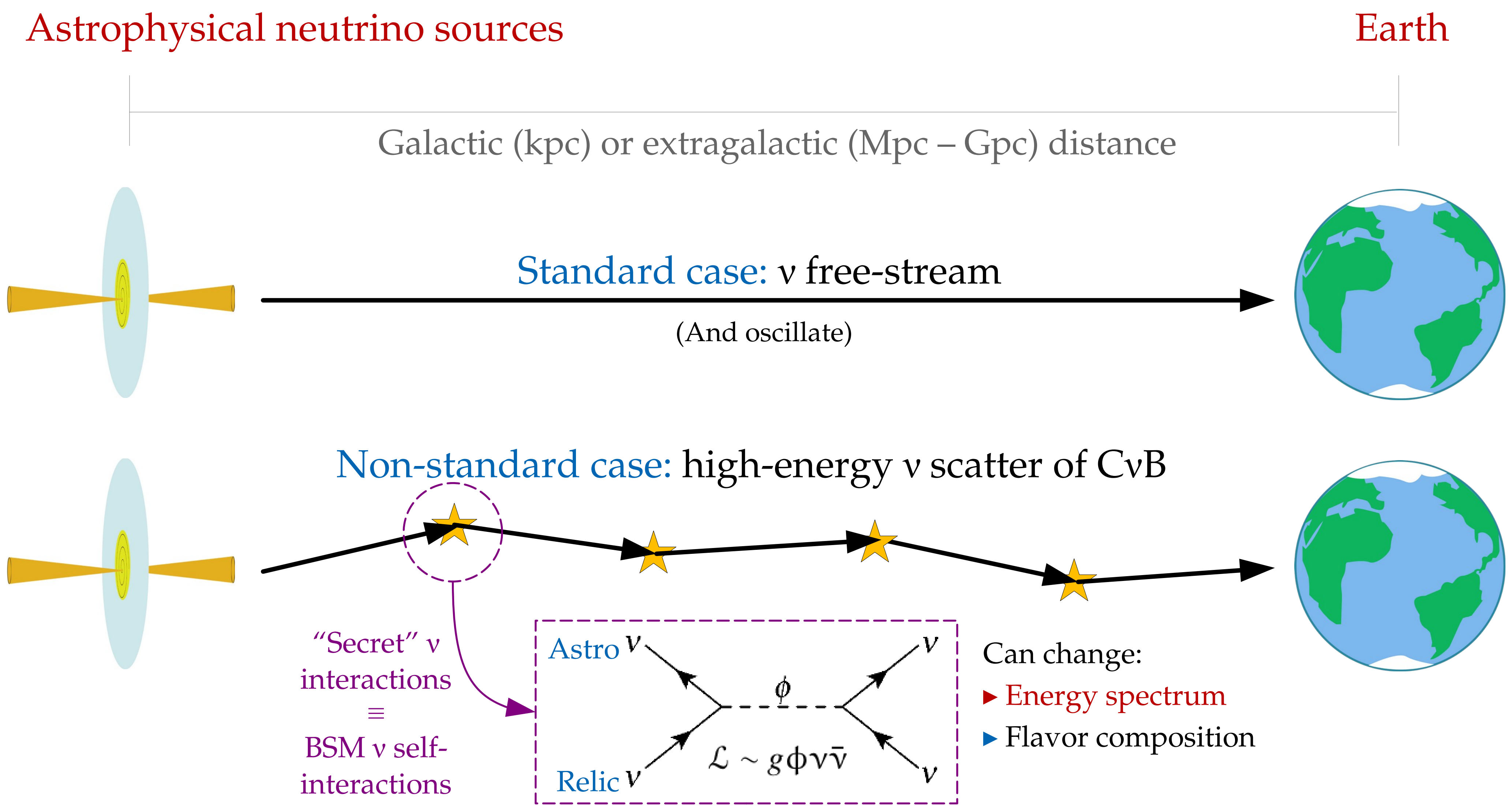

Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)


Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB

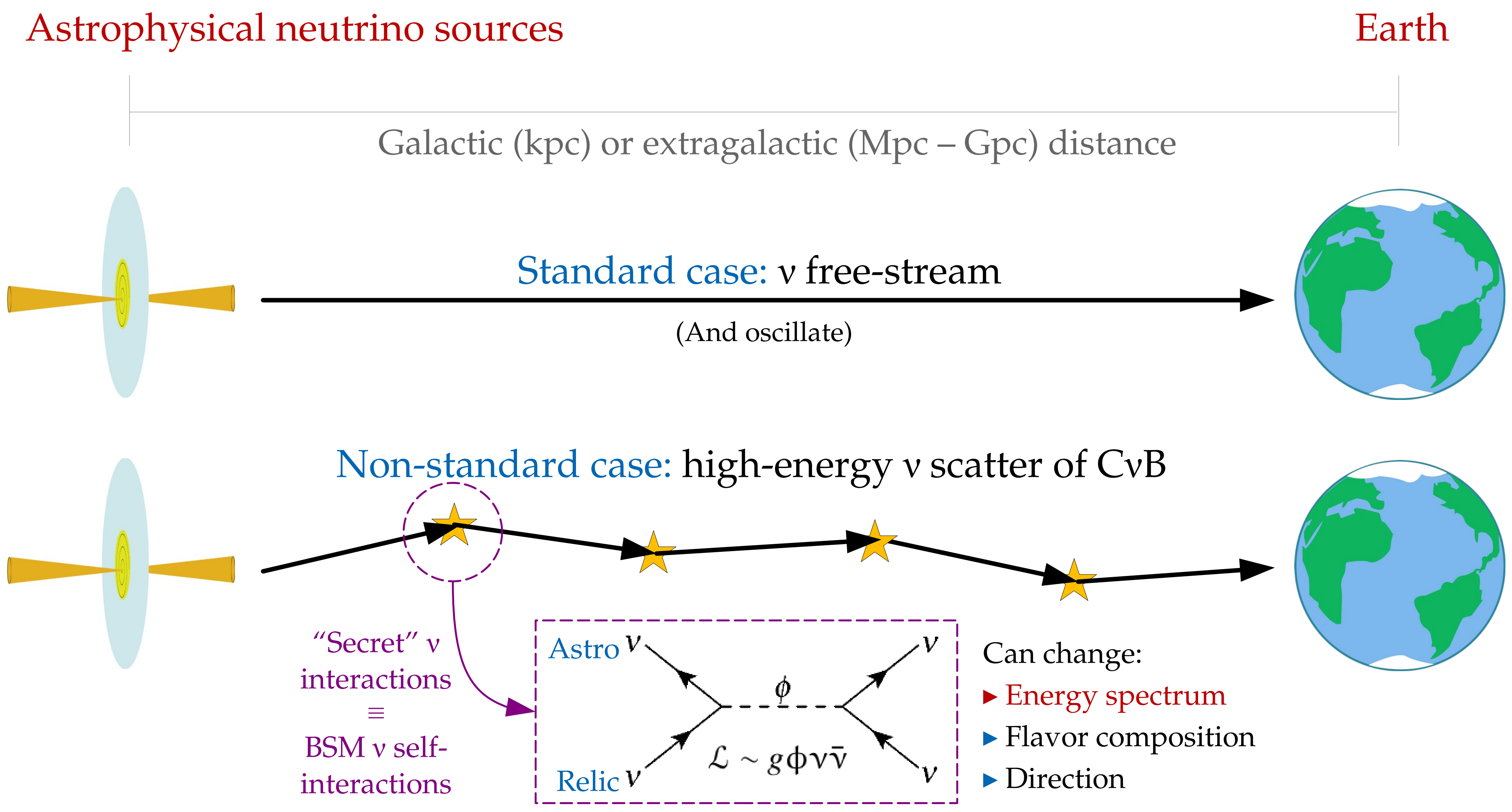

Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$

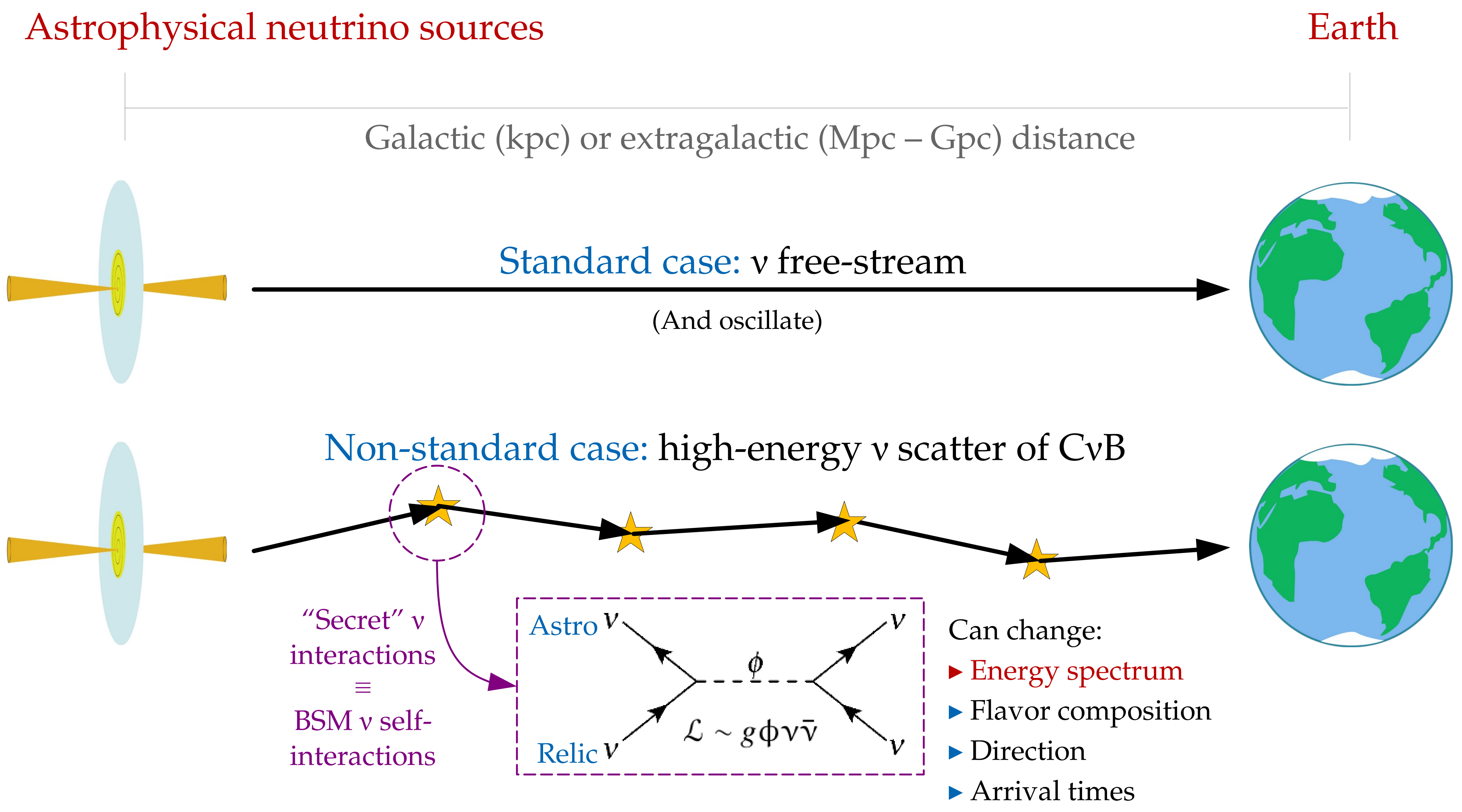

Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:


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



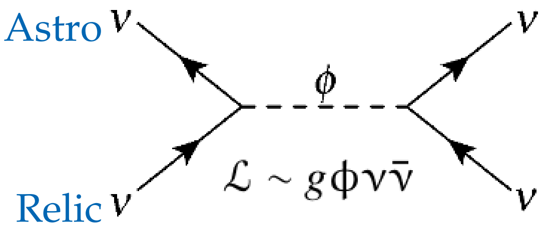
Astrophysical neutrino sources
Earth
Galactic (kpc) or extragalactic (Mpc – Gpc) distance
Standard case: ν free-stream
(And oscillate)
Non-standard case: high-energy ν scatter of CνB
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change: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


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


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

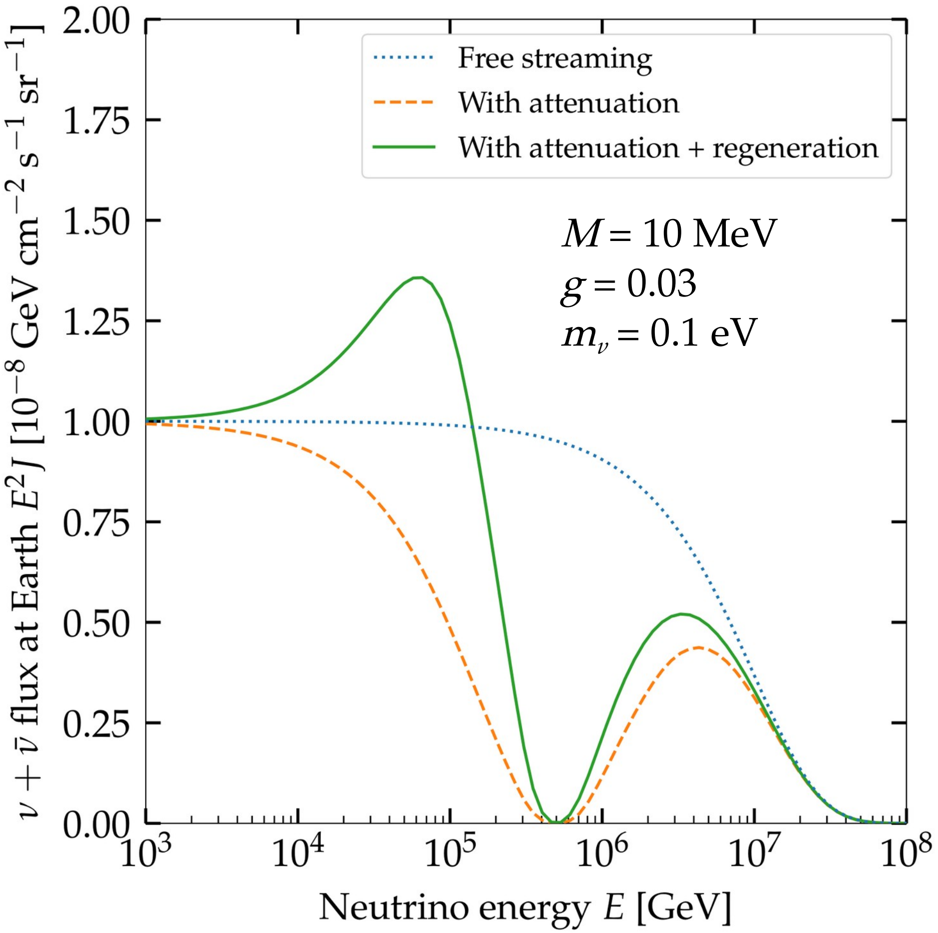
Secret interactions of high-energy astrophysical neutrinos

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



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

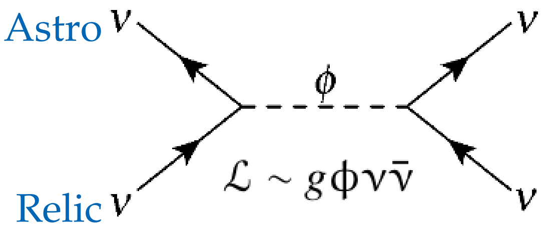
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

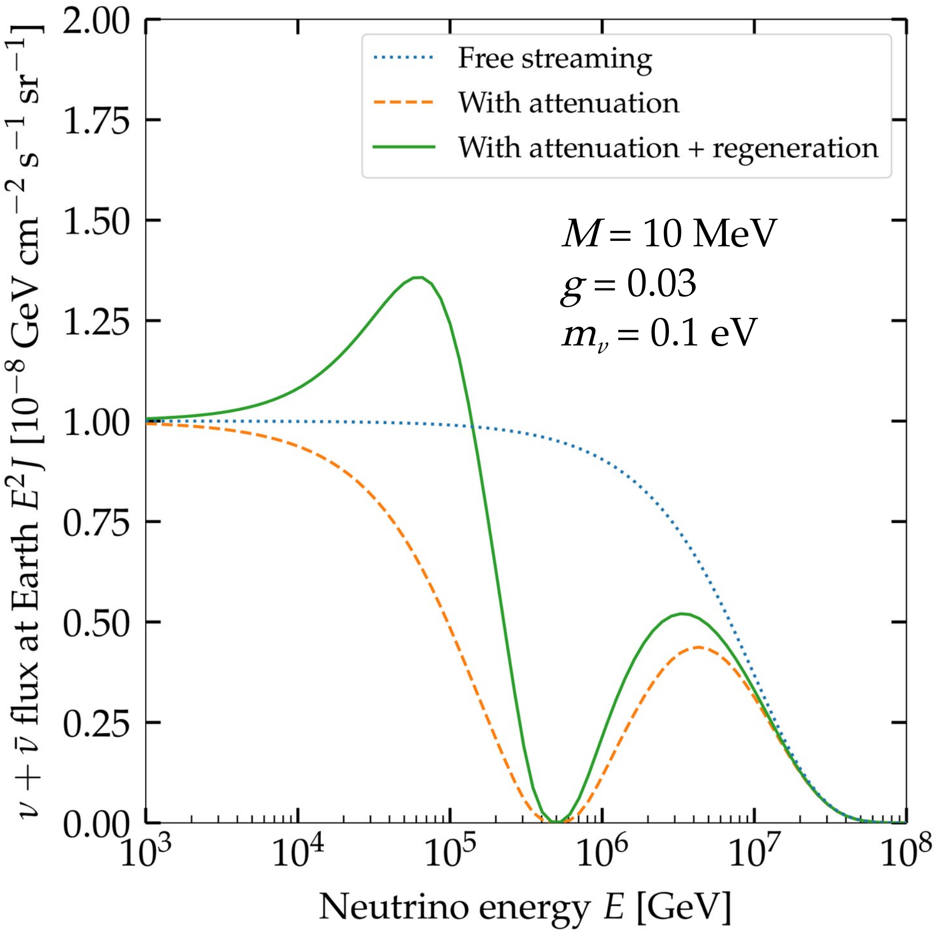


New coupling

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

Mediator mass

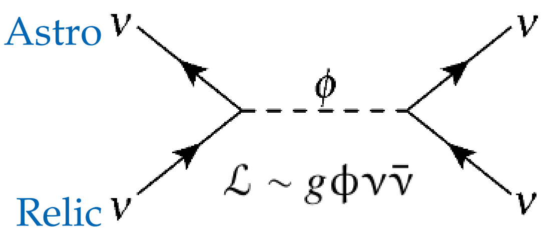
Resonance energy: $$E_{\mathrm{res}} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

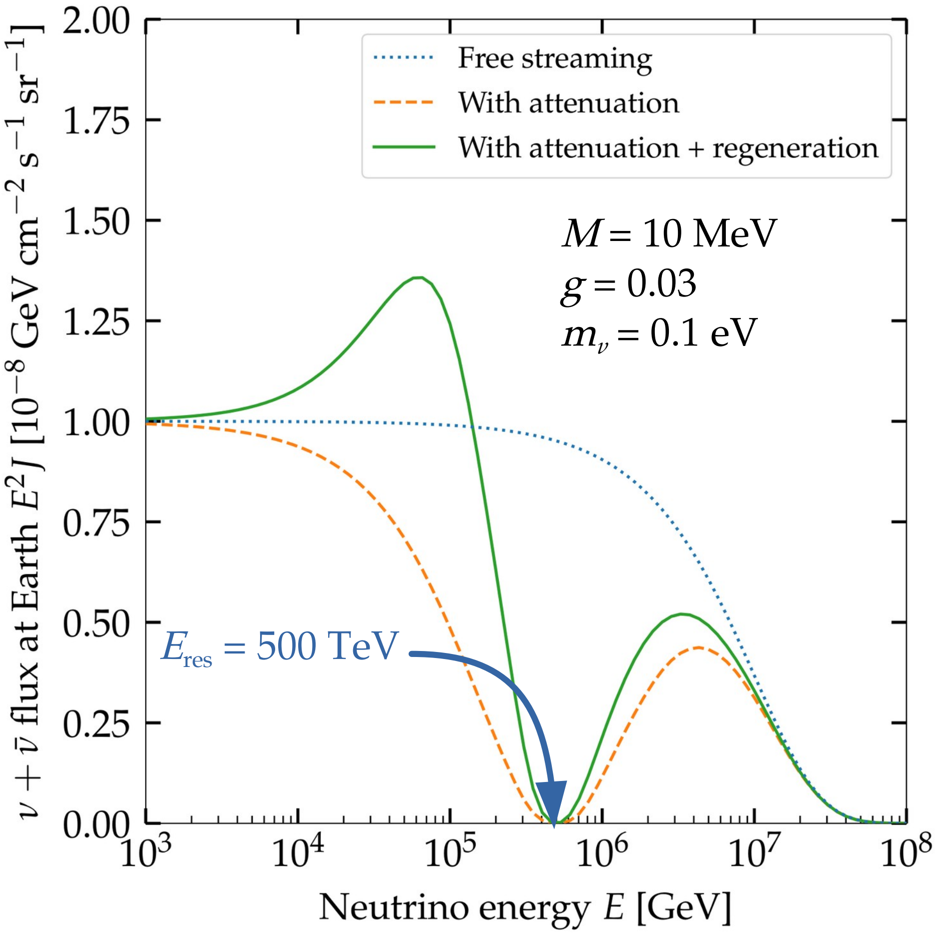


New coupling

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

Mediator mass

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

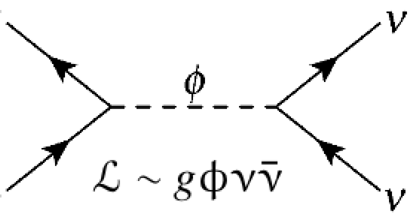


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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

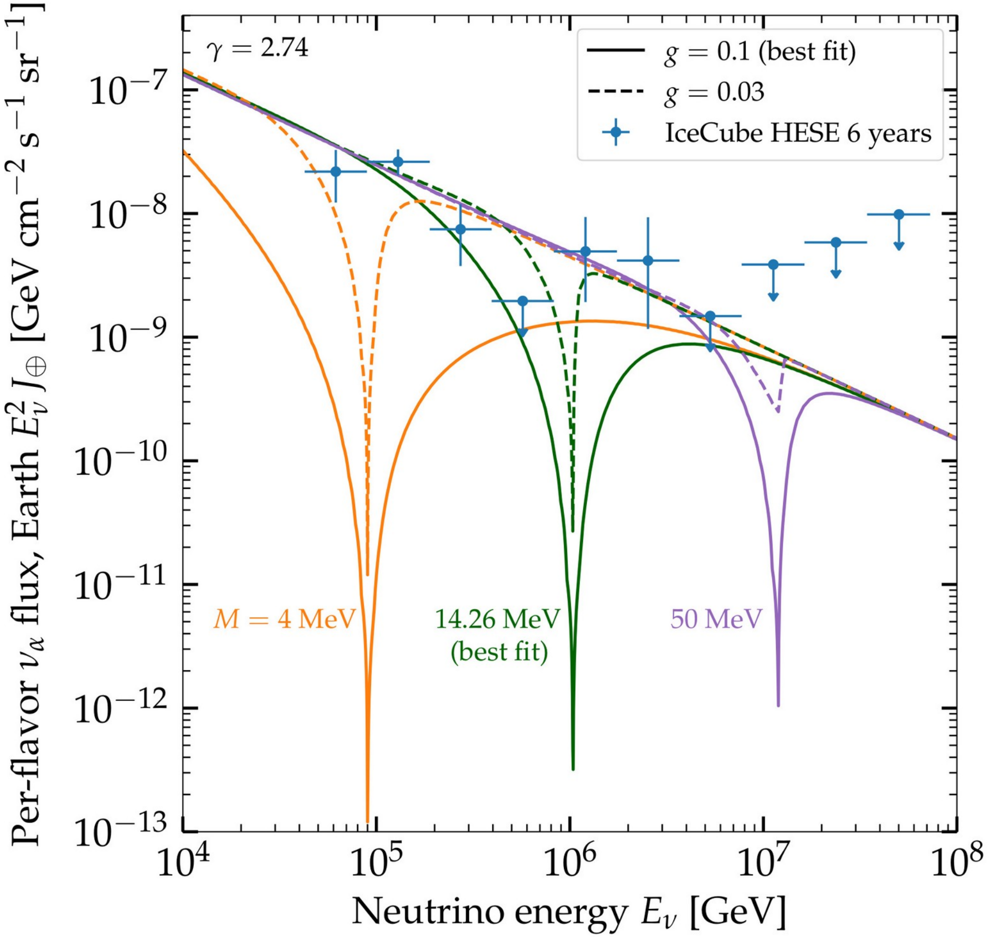


New coupling

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

Mediator mass

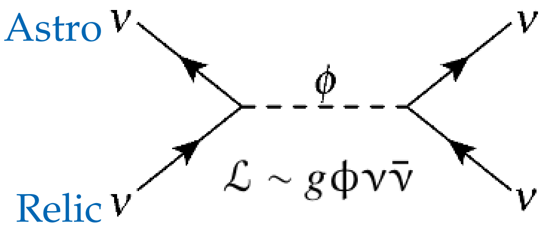
Resonance energy: $E_{\rm res} = \frac{M^2}{2m_\nu}$



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Secret interactions of high-energy astrophysical neutrinos

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



New coupling

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

Mediator mass

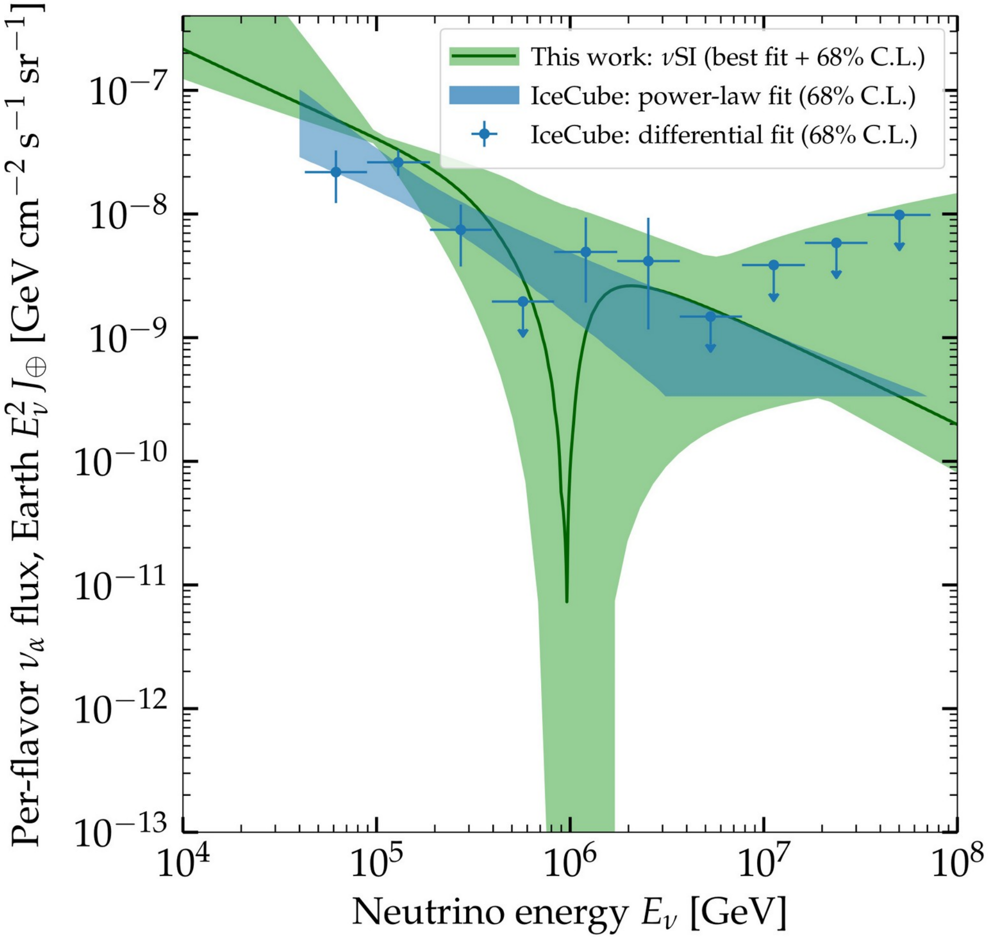
Resonance energy: $$E_{\rm res} = \frac{M^2}{2m_\nu}$$

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Esteban, Pandey, Brdar, Beacom, *PRD* 2021
Creque-Sarbinowski, Hyde, Kamionkowski, *PRD* 2021
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

Looking for evidence of νSI

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

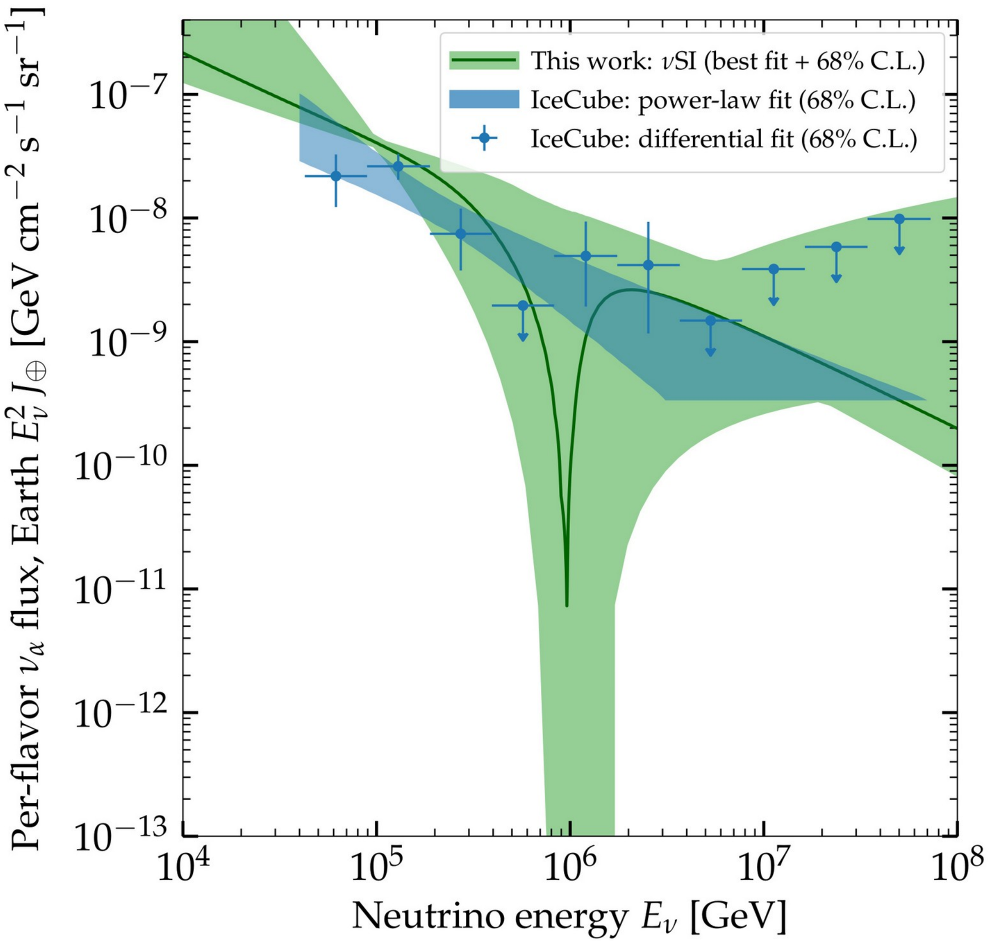
No significant (> 3σ) evidence for a spectral dip …



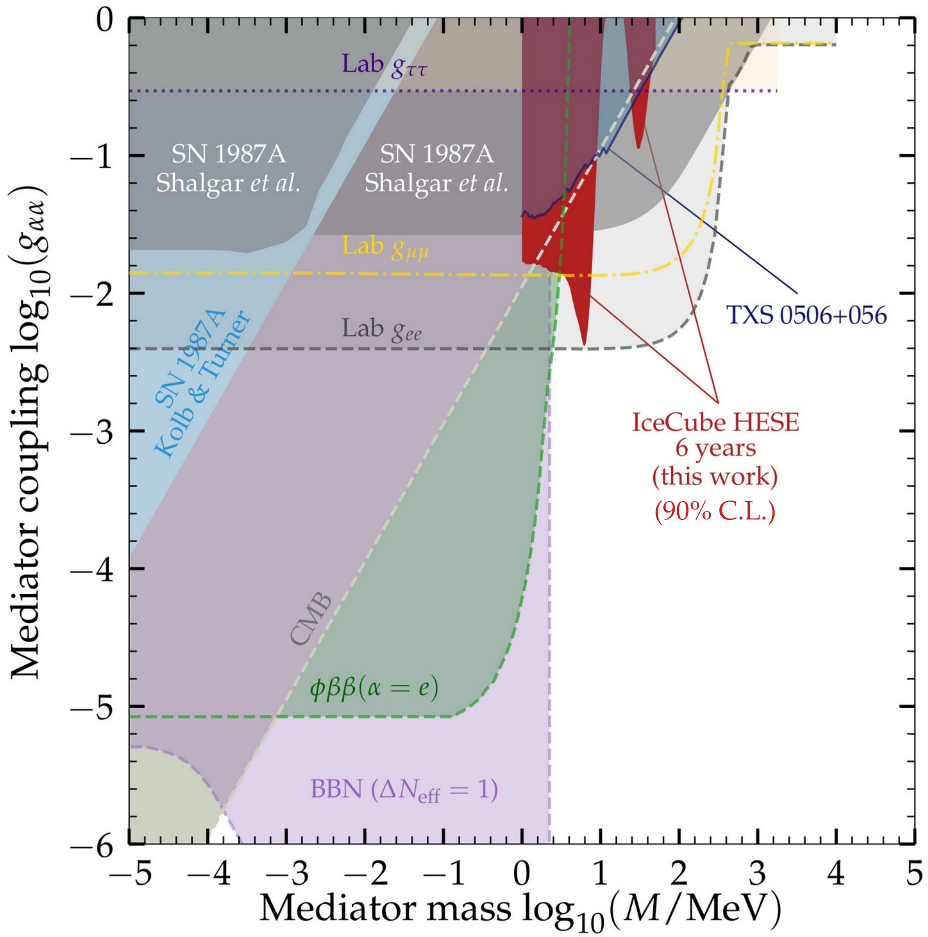
MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

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

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



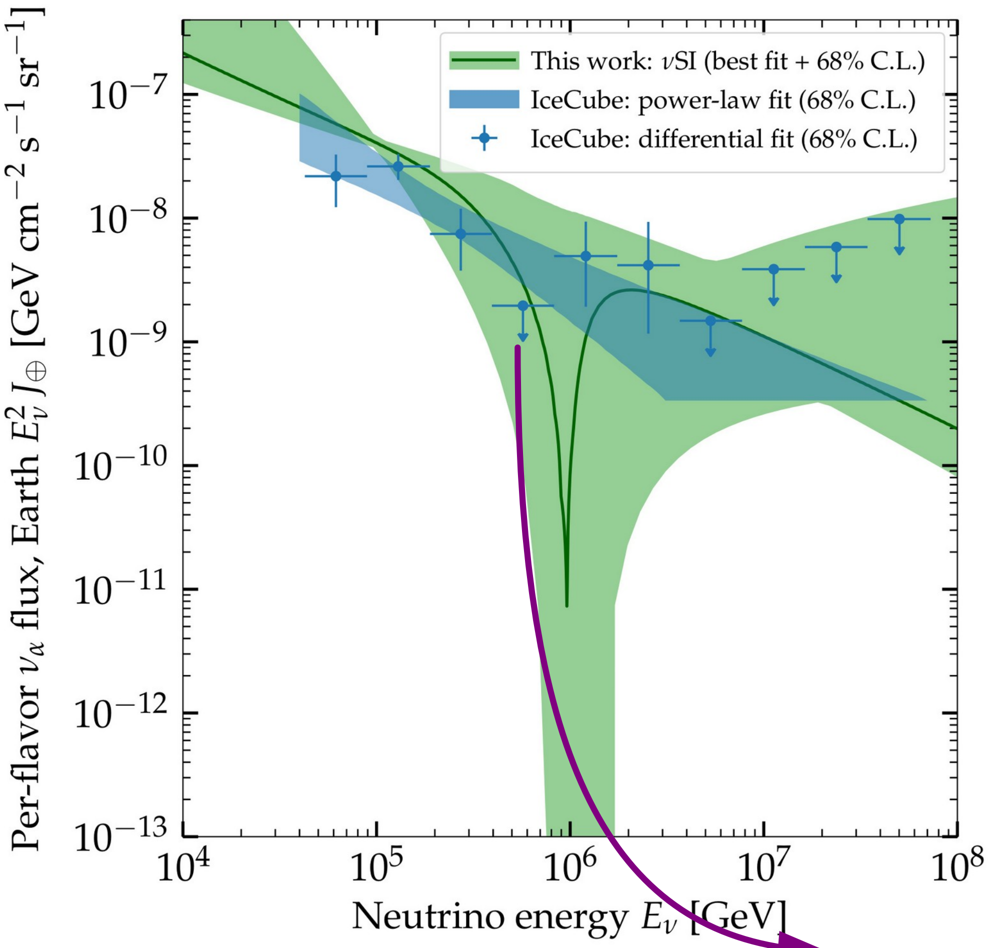
… so we set upper limits on the coupling g

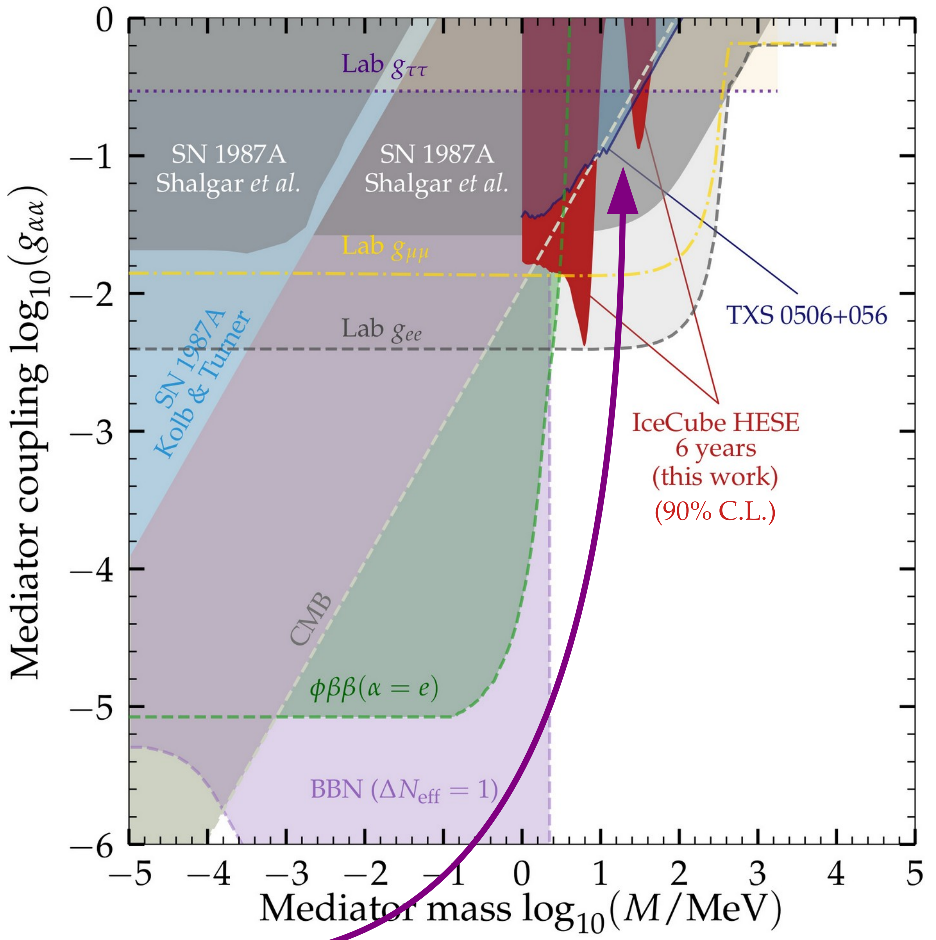


MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020

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

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





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

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

6. Unstable neutrinos:

Are neutrinos for ever?

Are neutrinos forever?

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

  » Age of Universe (~ 14.5 Gyr)

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

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

Are neutrinos forever?

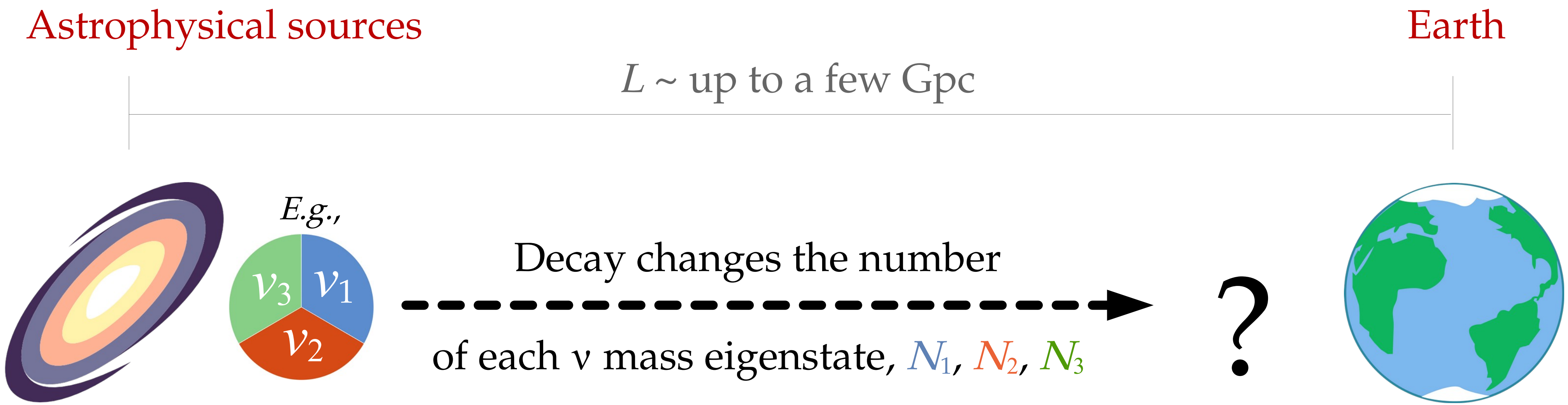
- In the Standard Model (νSM), neutrinos are essentially stable ($\tau > 10^{36}$ yr):
  - One-photon decay ($\nu_i \rightarrow \nu_j + \gamma$): $\tau > 10^{36}\,(m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \rightarrow \nu_j + \gamma + \gamma$): $\tau > 10^{57}\,(m_i/\mathrm{eV})^{-9}$ yr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

  » Age of Universe (~ 14.5 Gyr)

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

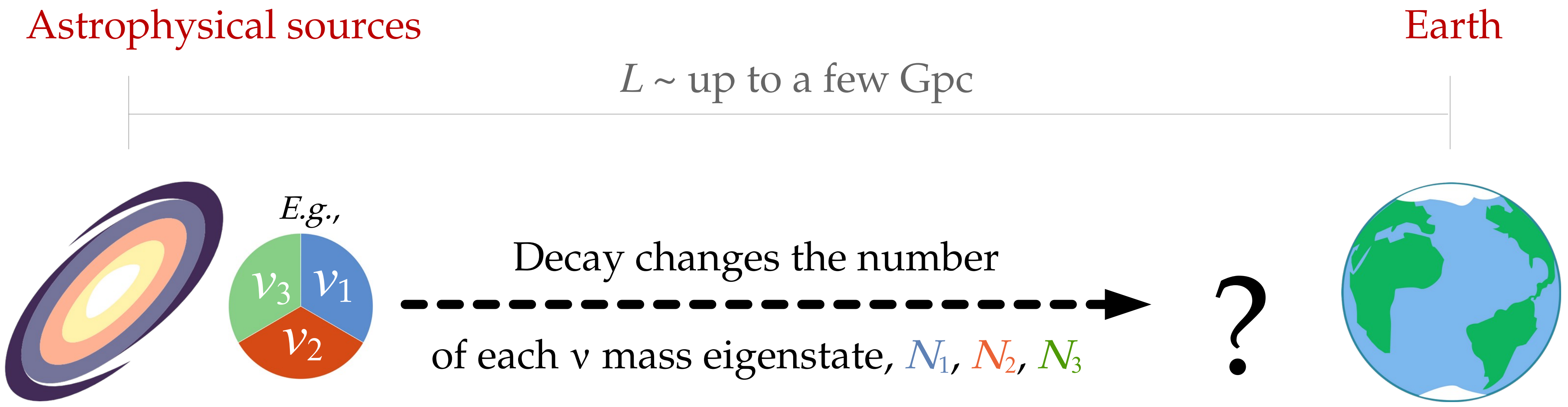
  Nambu-Goldstone boson of a broken symmetry

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



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

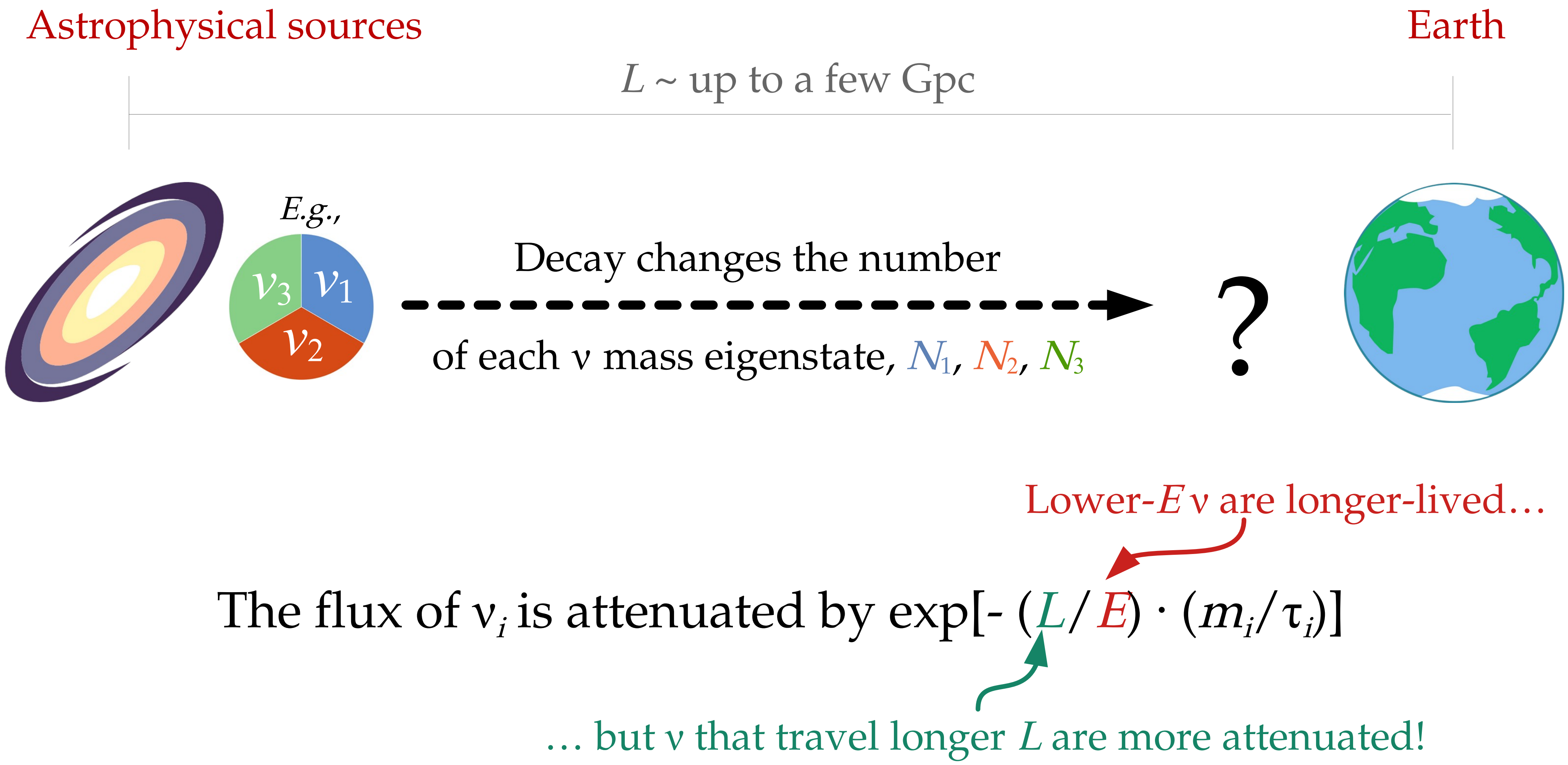
Mass of ν_i Lifetime of ν_i



Only sensitive to their ratio

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

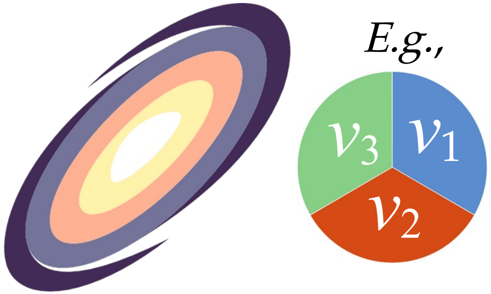
Mass of ν_i Lifetime of ν_i

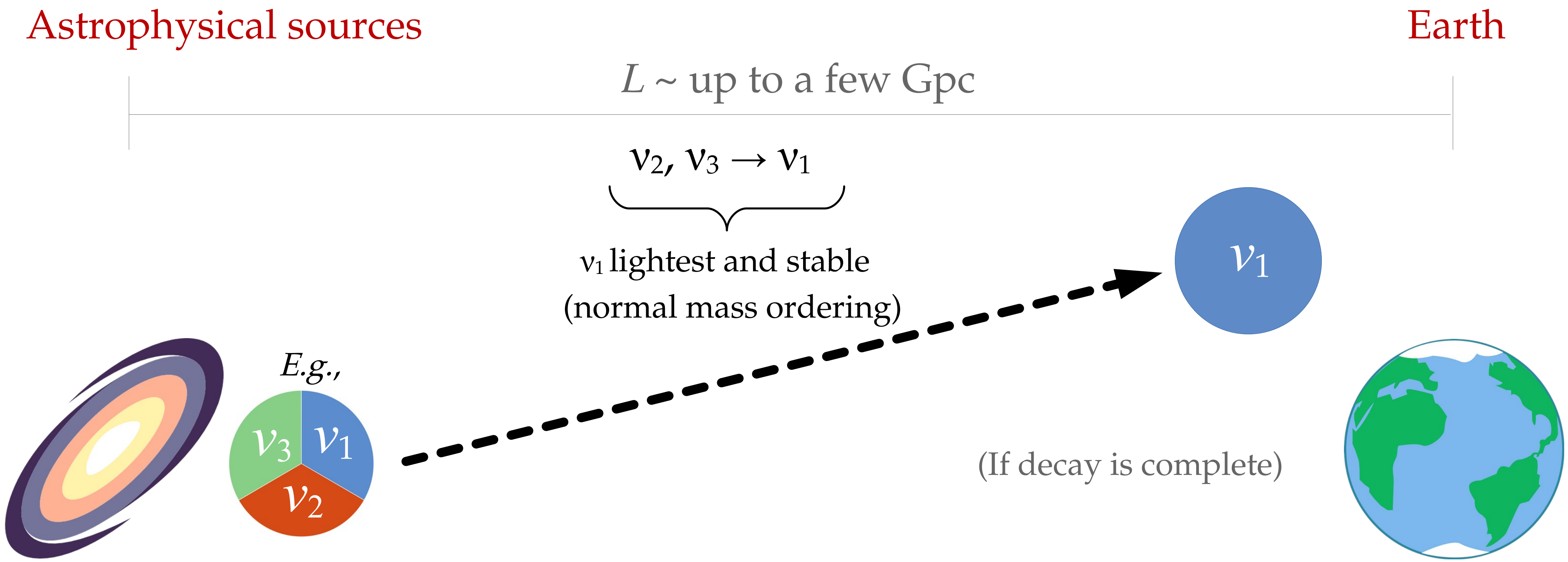

Astrophysical sources
Earth
L ~ up to a few Gpc
E.g.,
ν3
ν1
ν2
Decay changes the number
of each ν mass eigenstate, N1, N2, N3
?
Lower-E ν are longer-lived…
The flux of νi is attenuated by exp[- (L/E) · (mi/τi)]
… but ν that travel longer L are more attenuated!

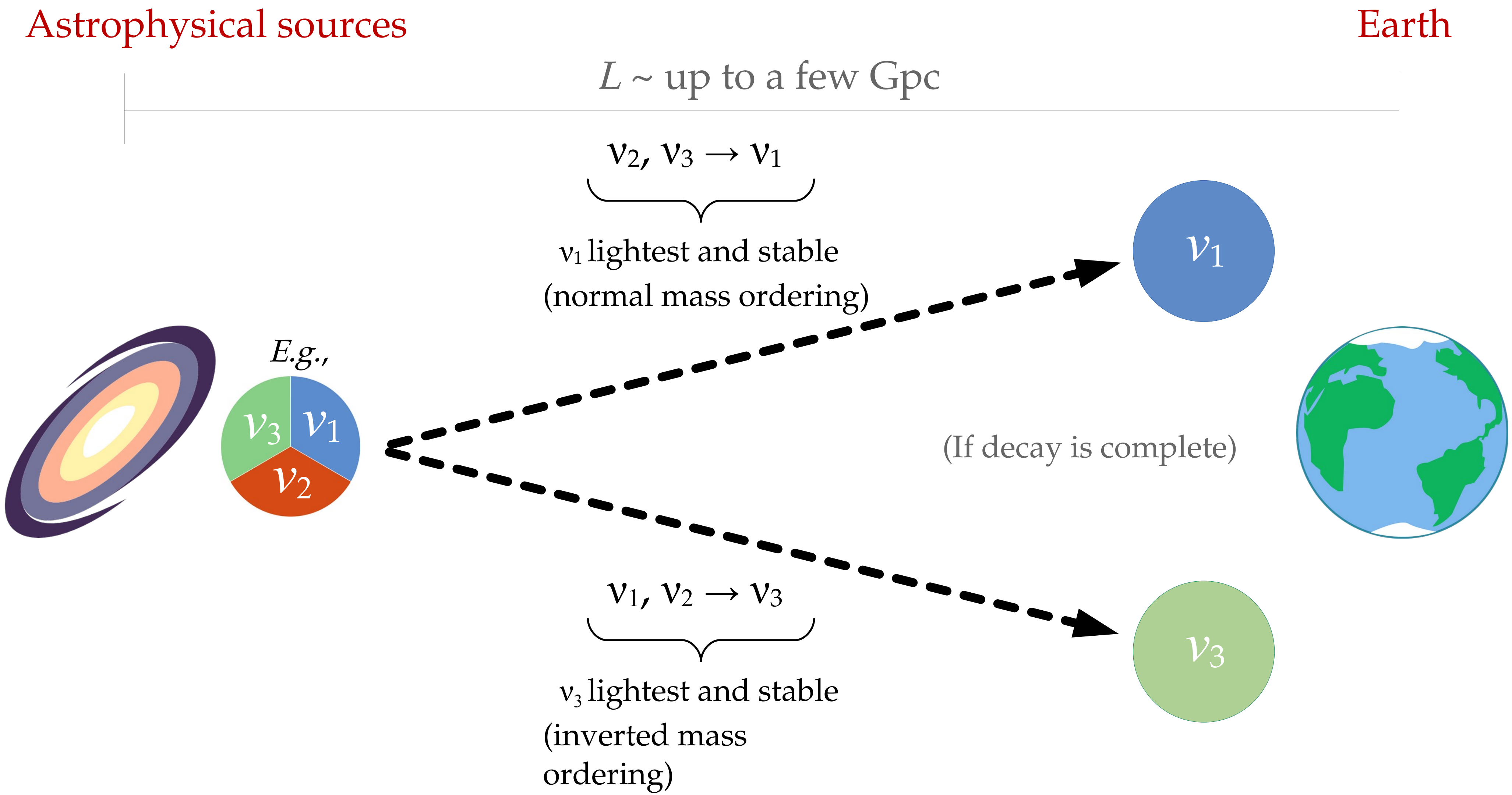
Astrophysical sources

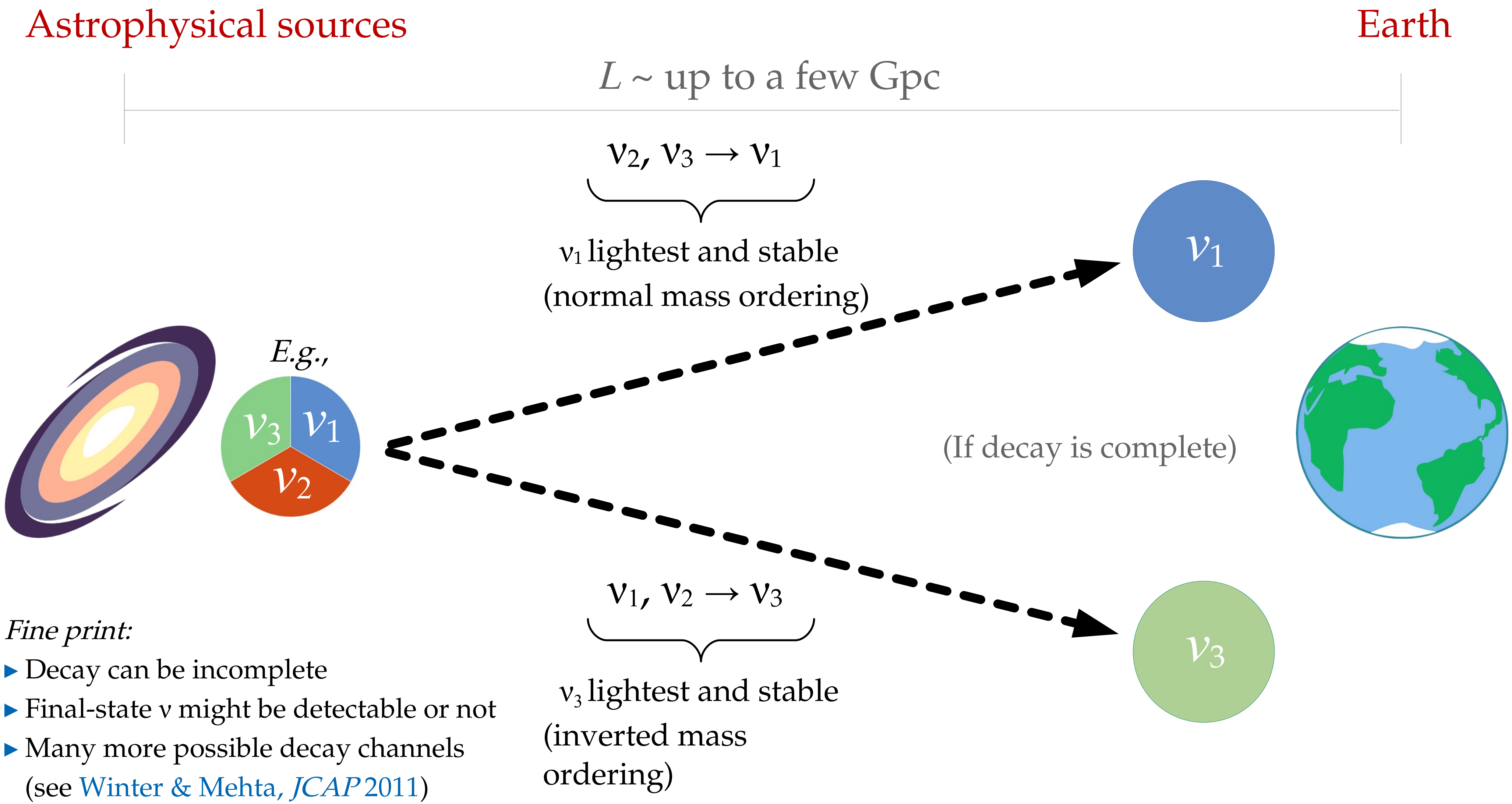
Earth

L ~ up to a few Gpc



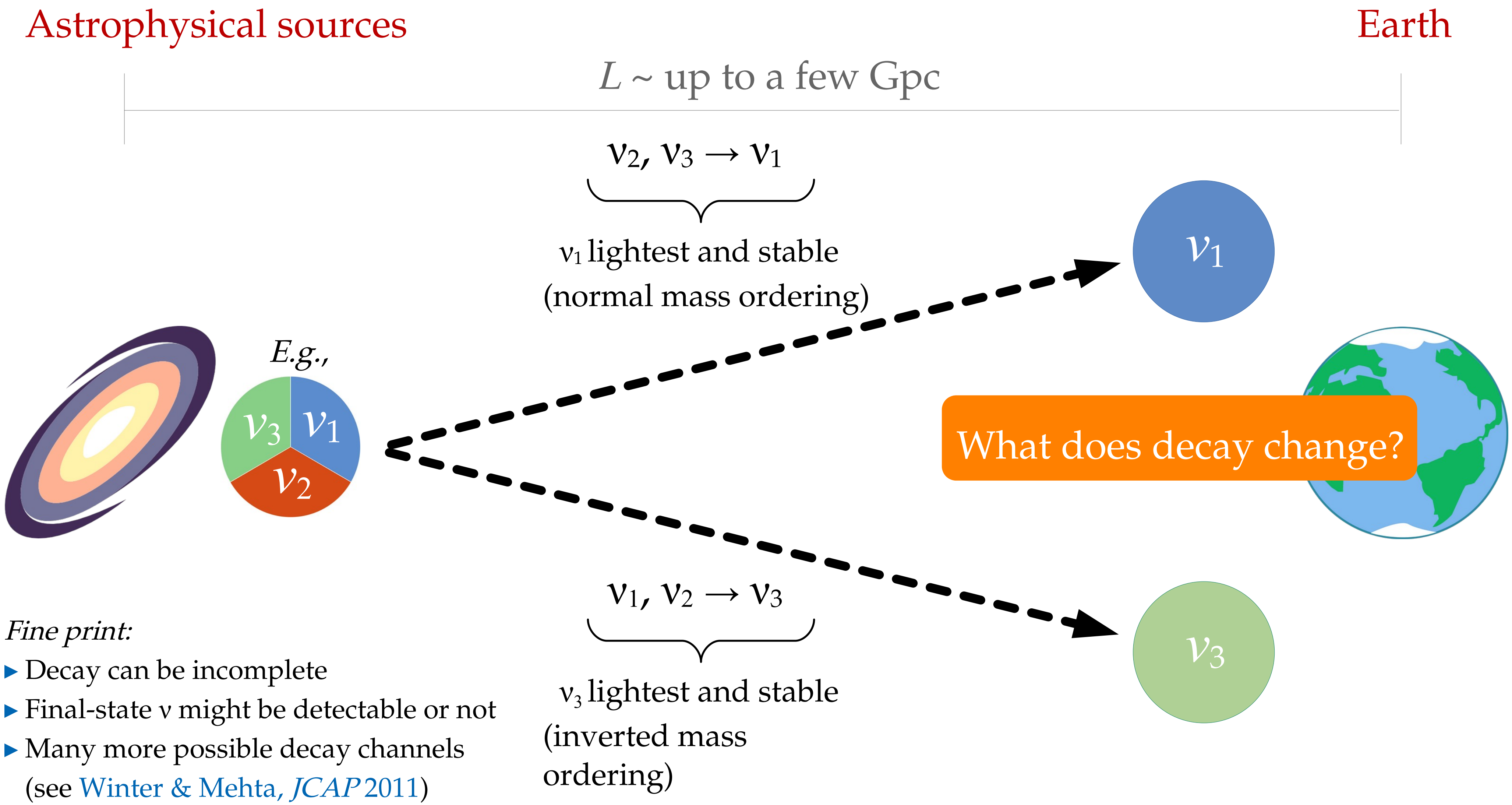

Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)


Astrophysical sources
Earth
L ~ up to a few Gpc
ν2, ν3 → ν1
ν1 lightest and stable
(normal mass ordering)
E.g.,
ν3
ν1
ν2
ν1
(If decay is complete)
ν1, ν2 → ν3
ν3 lightest and stable
(inverted mass
ordering)
ν3



Fine print:

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


Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \to \nu_1$
ν_1 lightest and stable
(normal mass ordering)
E.g.,
ν_3
ν_1
ν_2
ν_1
What does decay change?
$\nu_1, \nu_2 \to \nu_3$
ν_3 lightest and stable
(inverted mass ordering)
ν_3
Fine print:
▸ Decay can be incomplete
▸ Final-state ν might be detectable or not
▸ Many more possible decay channels
(see Winter & Mehta, *JCAP* 2011)

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

What does neutrino decay change?

Flavor composition ⟺ Spectrum shape ⟺ Event rate

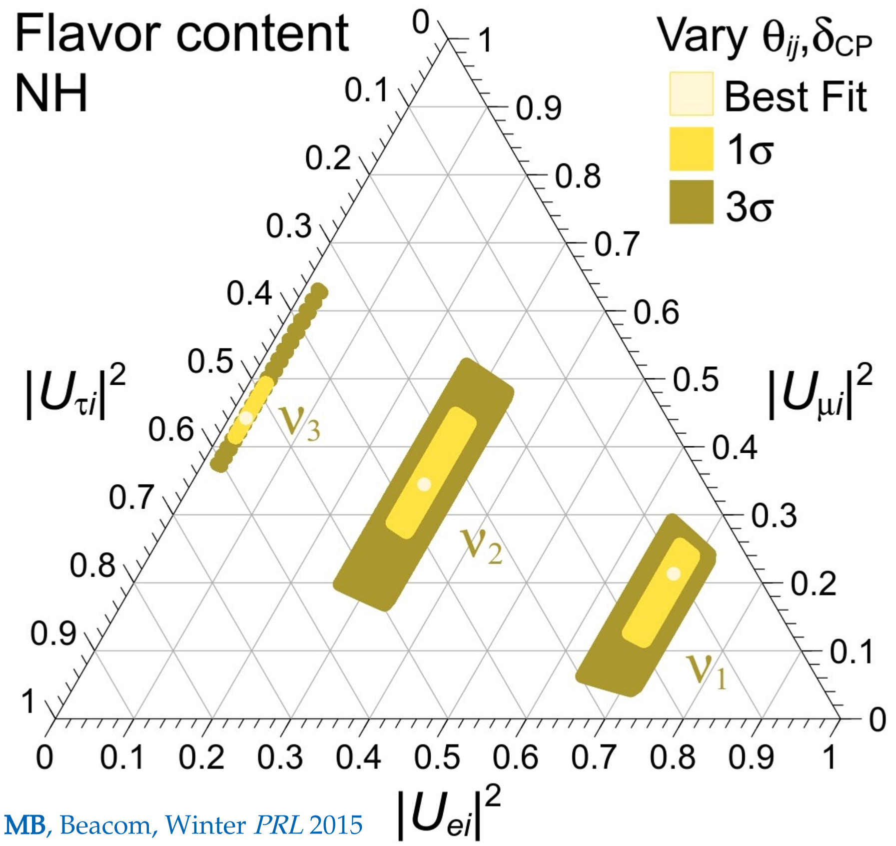
Flavor content of mass eigenstates:

Known to within 2%

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

Known to within 8%

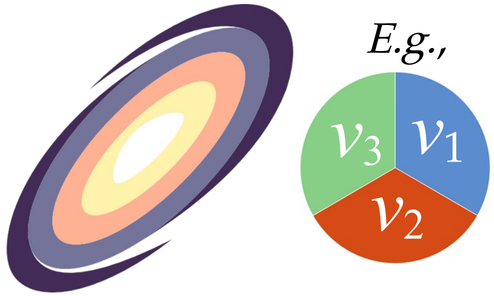
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

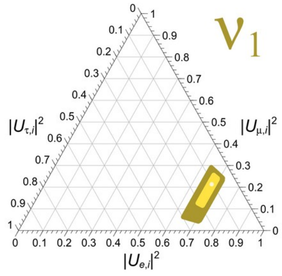
What does neutrino decay change?

Flavor composition ⇔ Spectrum shape ⇔ Event rate



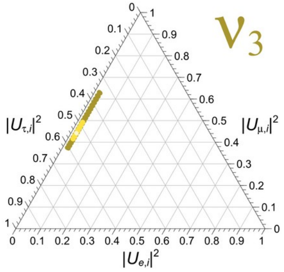
$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)



$\nu_1, \nu_2 \rightarrow \nu_3$

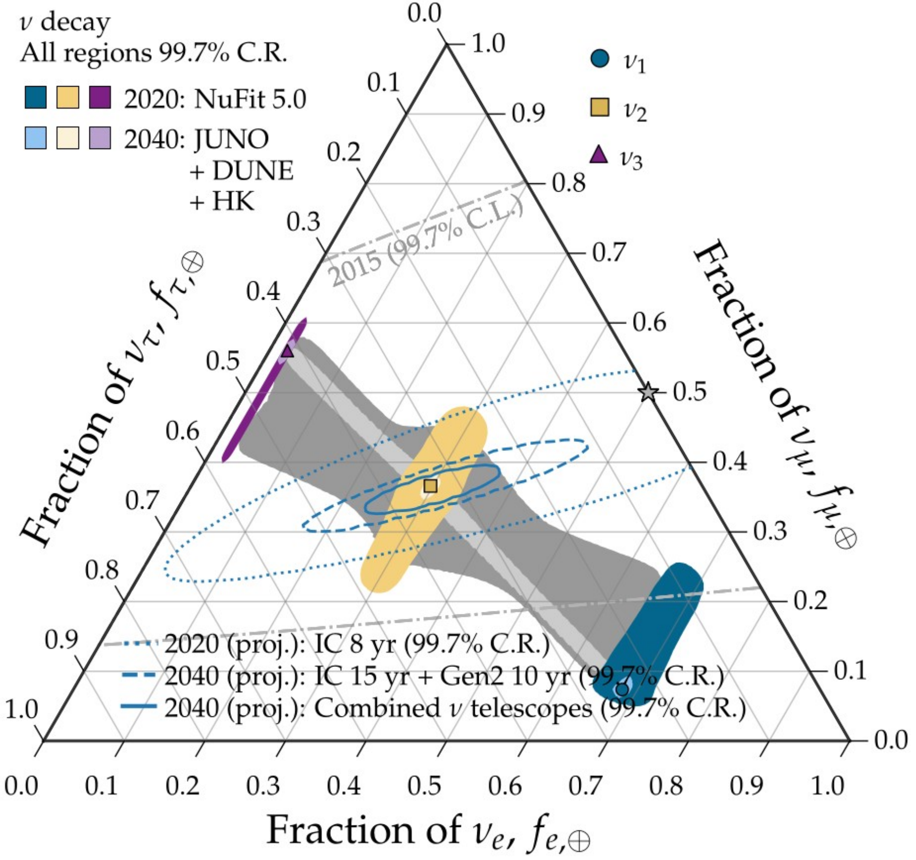
ν_3 lightest and stable
(inverted mass ordering)



What does neutrino decay change?

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

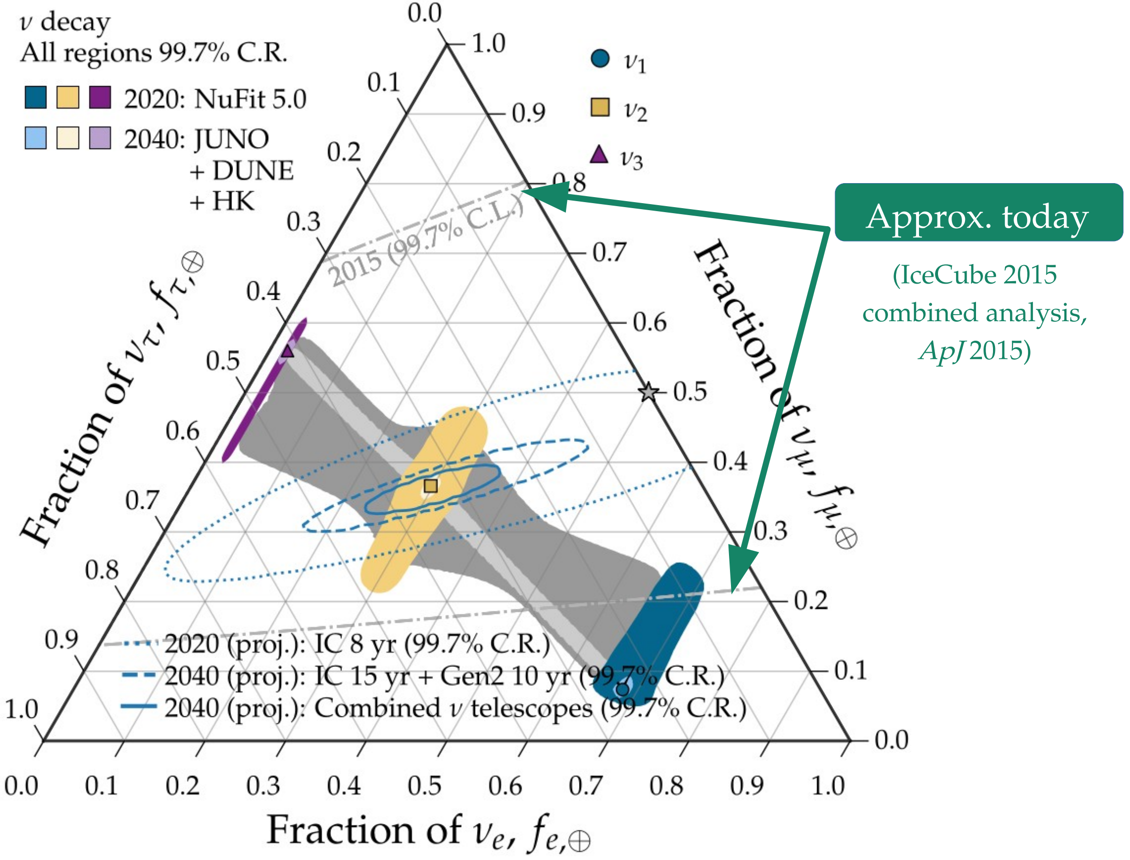
Flavor composition ⟺ Spectrum shape ⟺ Event rate



What does neutrino decay change?

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

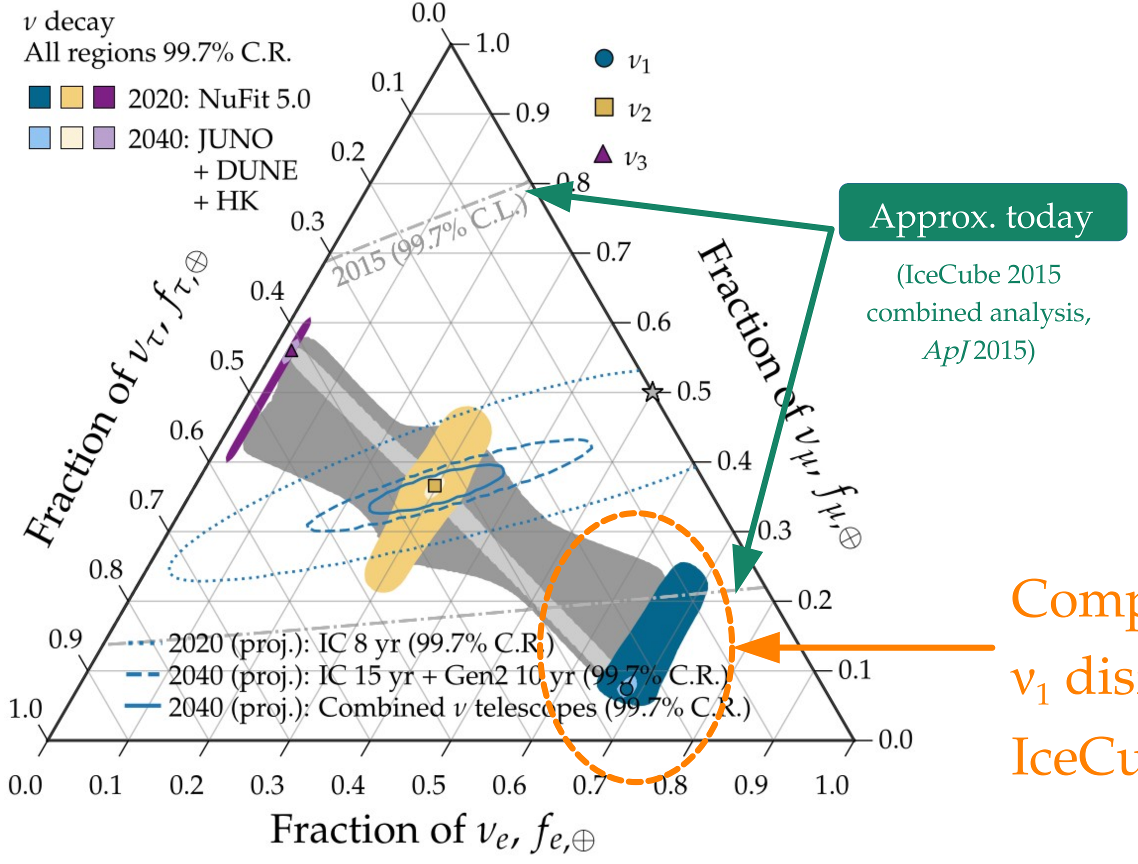
Flavor composition ⟺ Spectrum shape ⟺ Event rate



What does neutrino decay change?

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

Flavor composition ⇔ Spectrum shape ⇔ Event rate

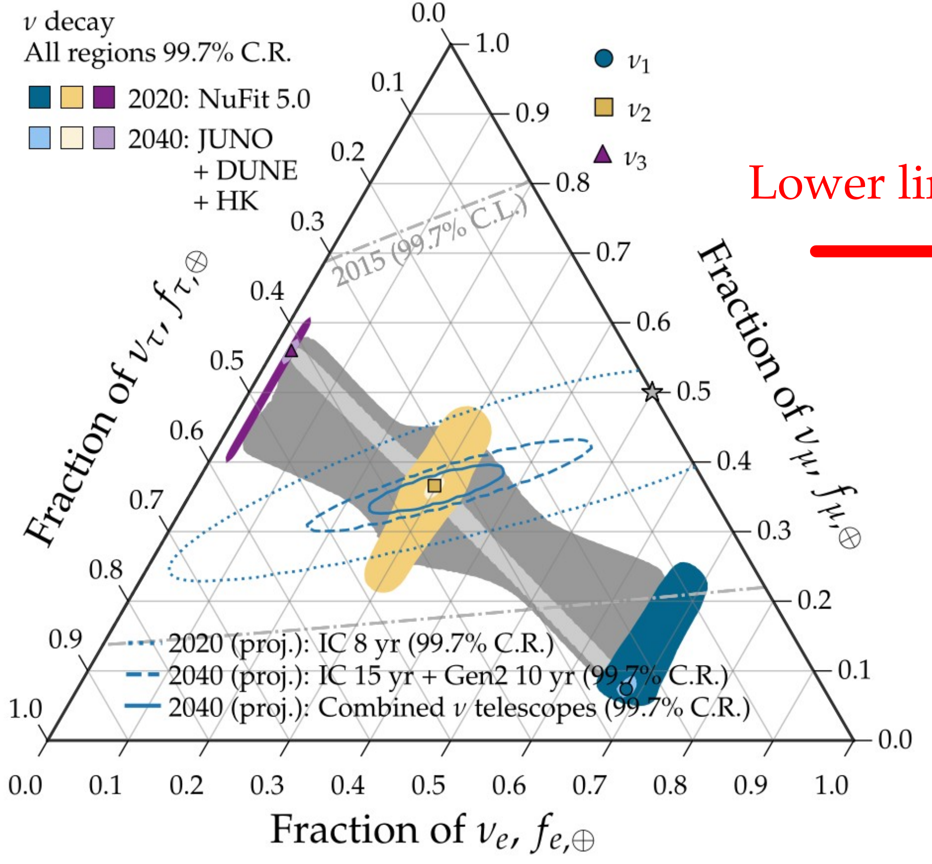


Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

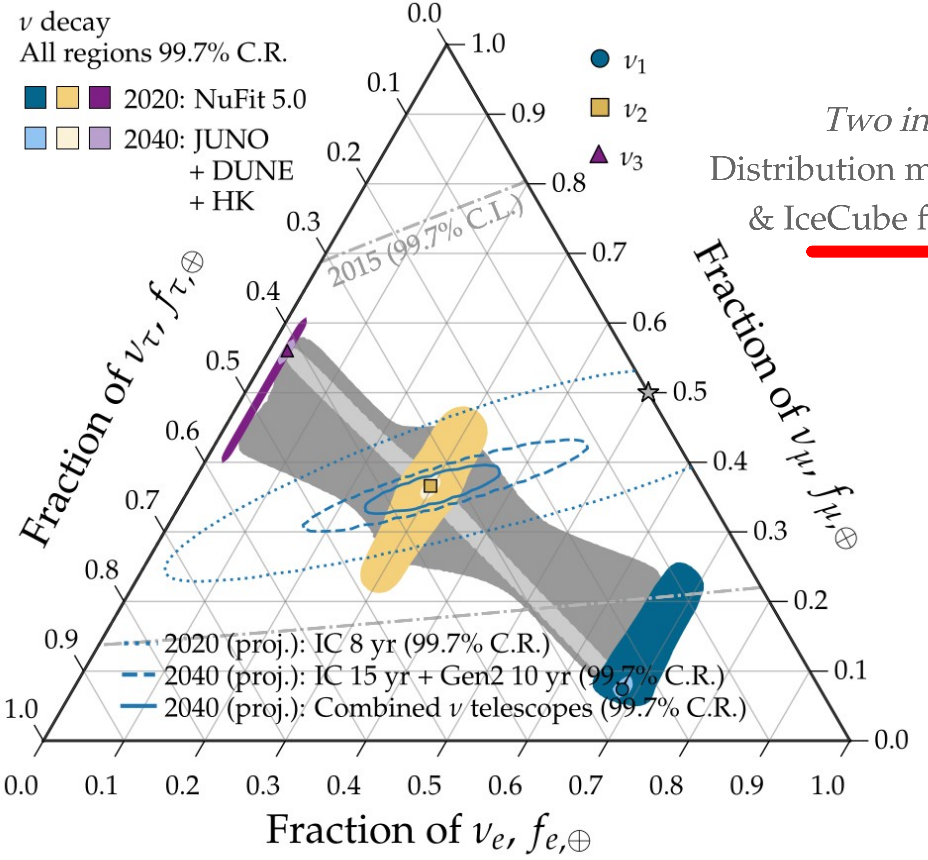


Lower limit on τ/m →

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

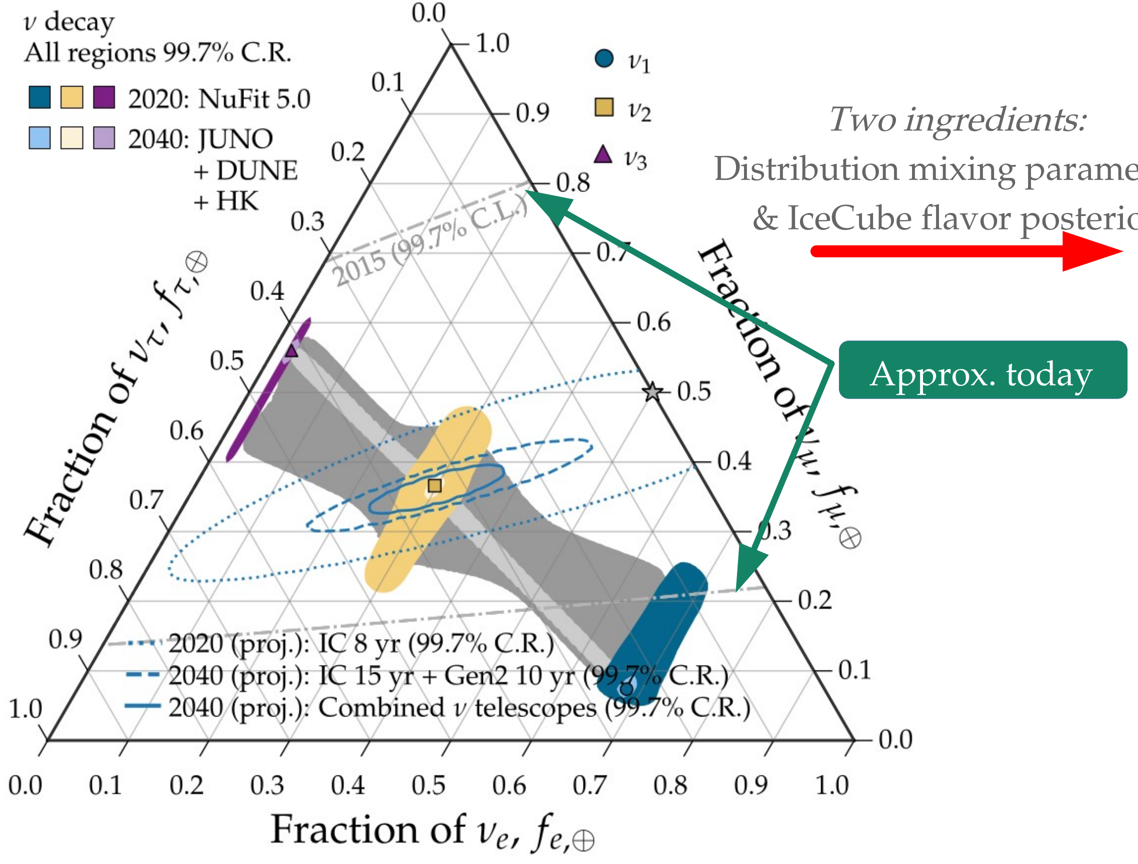


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

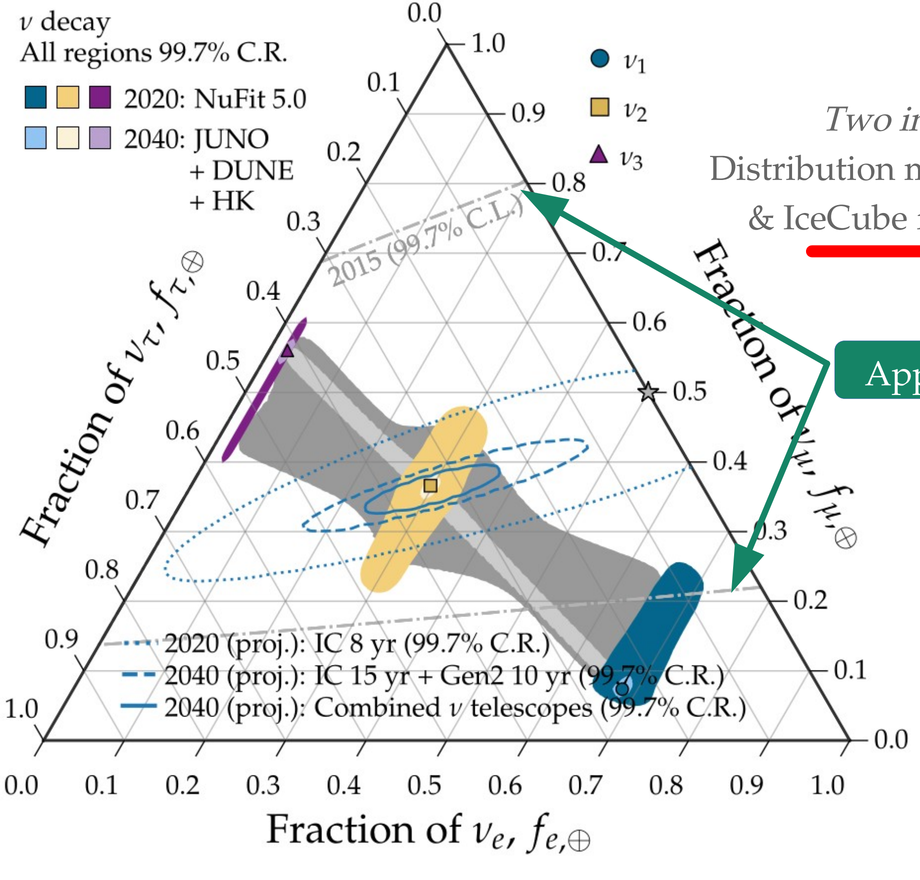


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

What does neutrino decay change?

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

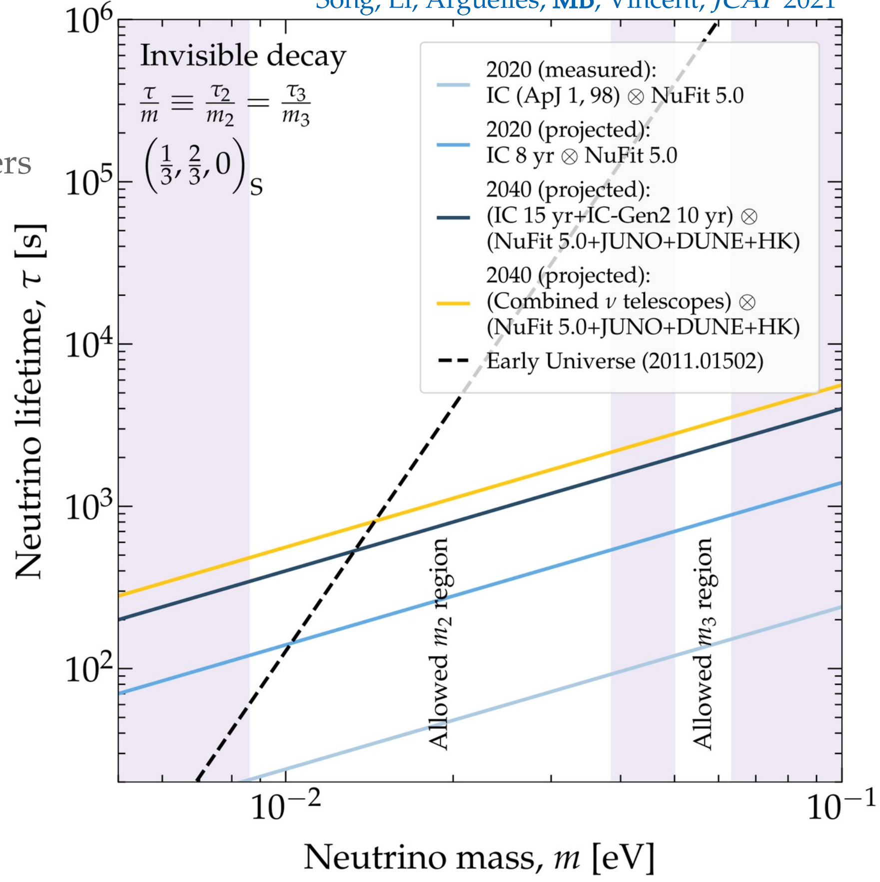
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

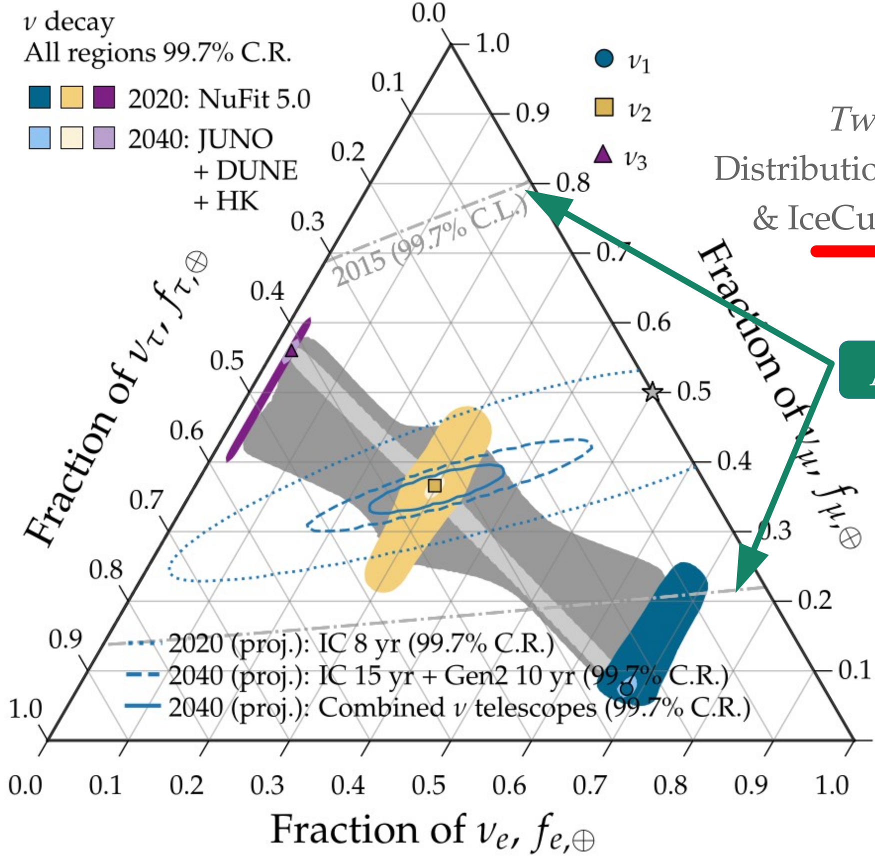
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

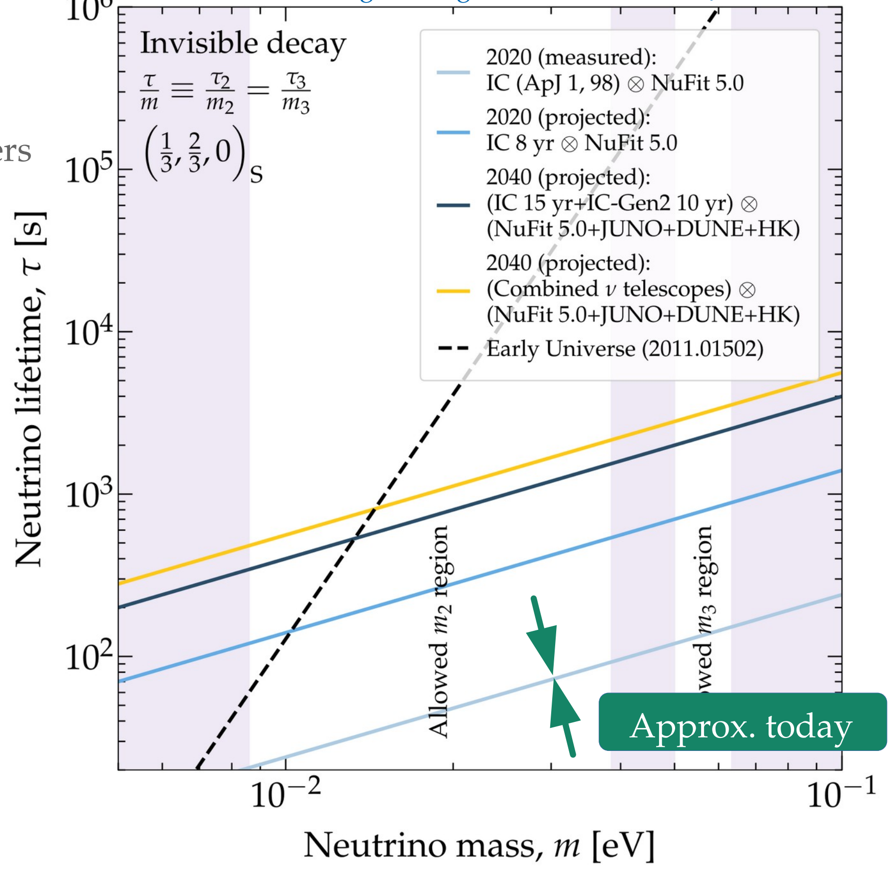
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

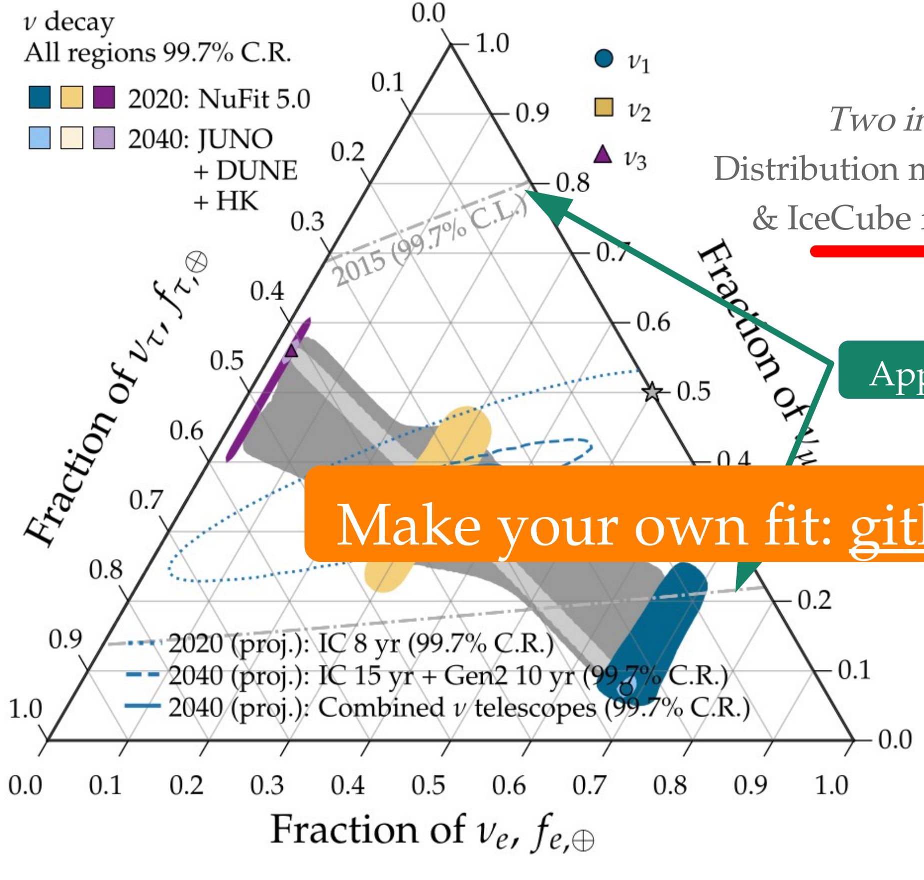
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

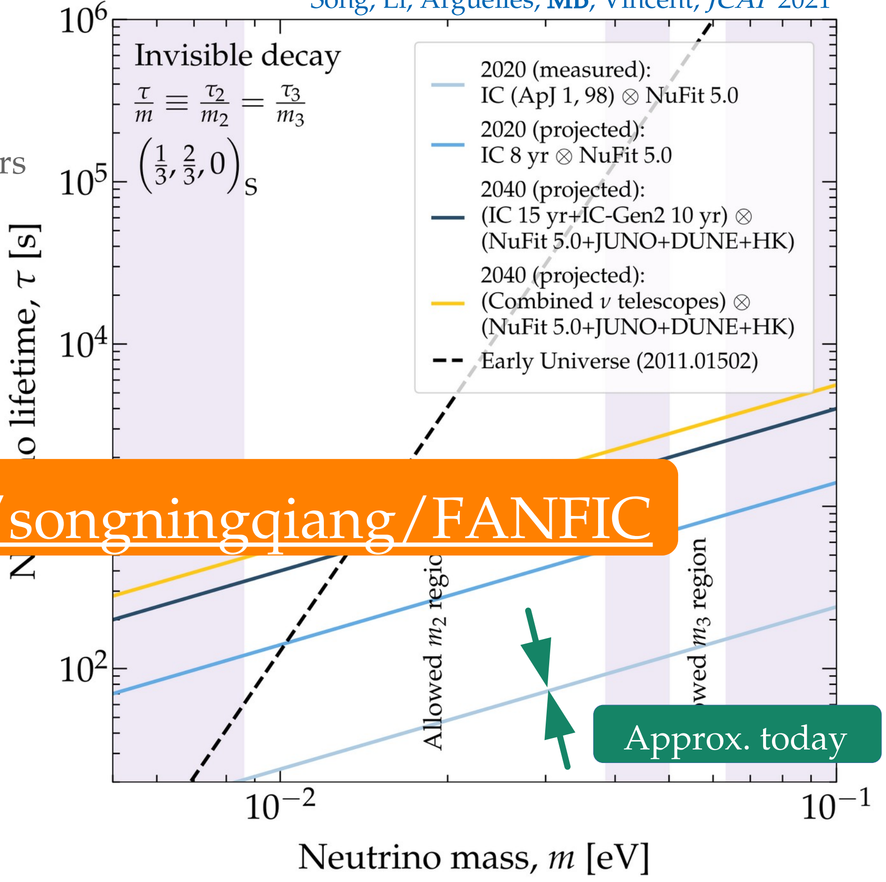
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

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

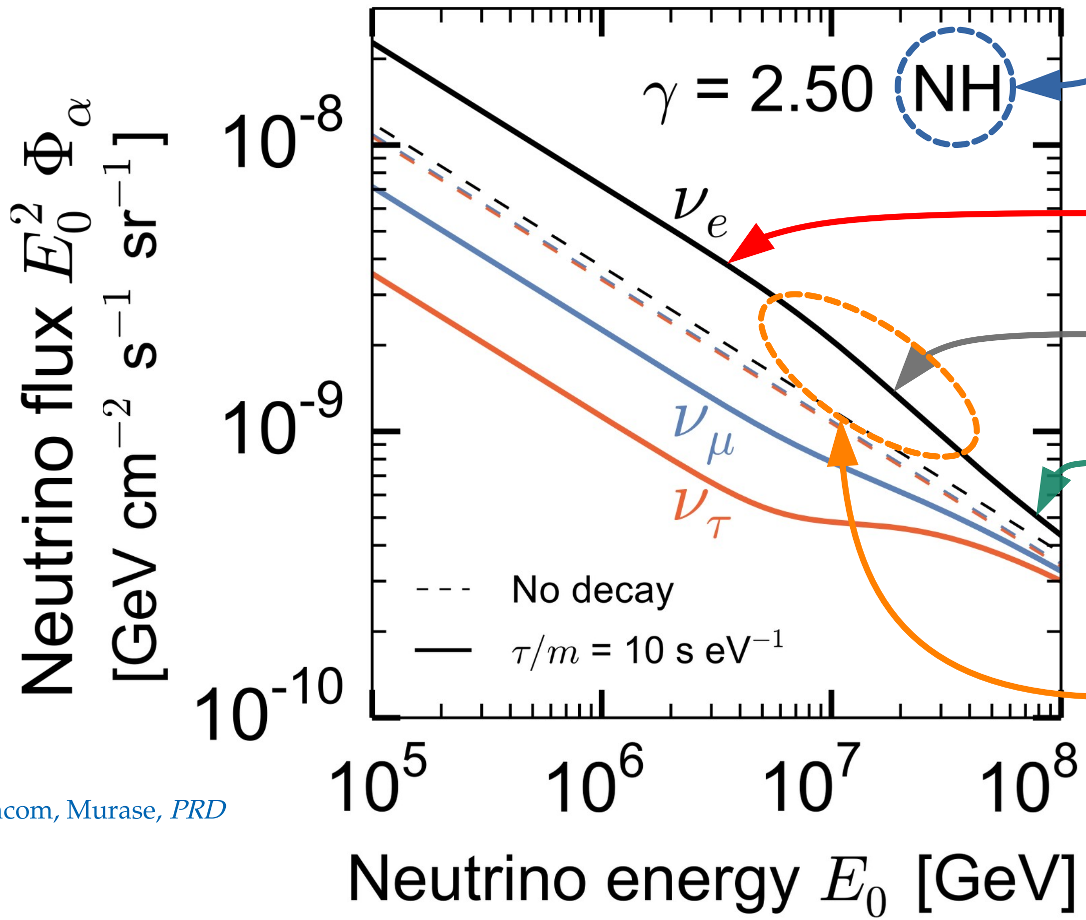


Make your own fit: github.com/songningqiang/FANFIC

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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

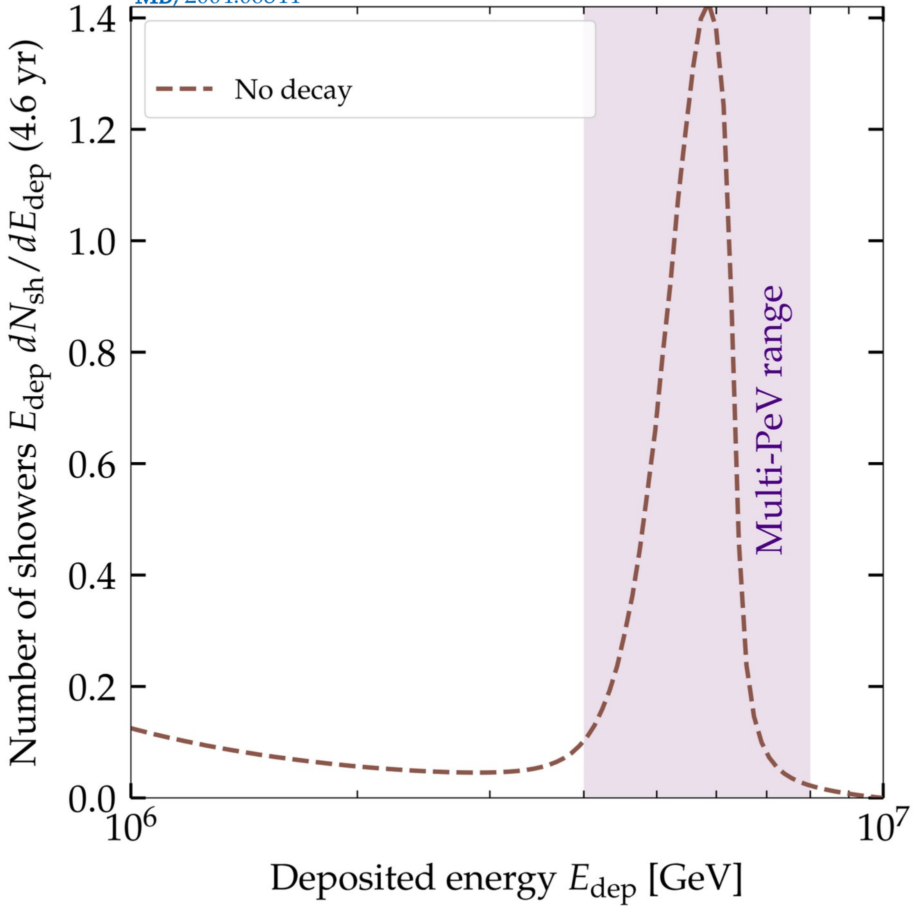
MB, Beacom, Murase, *PRD* 2017

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

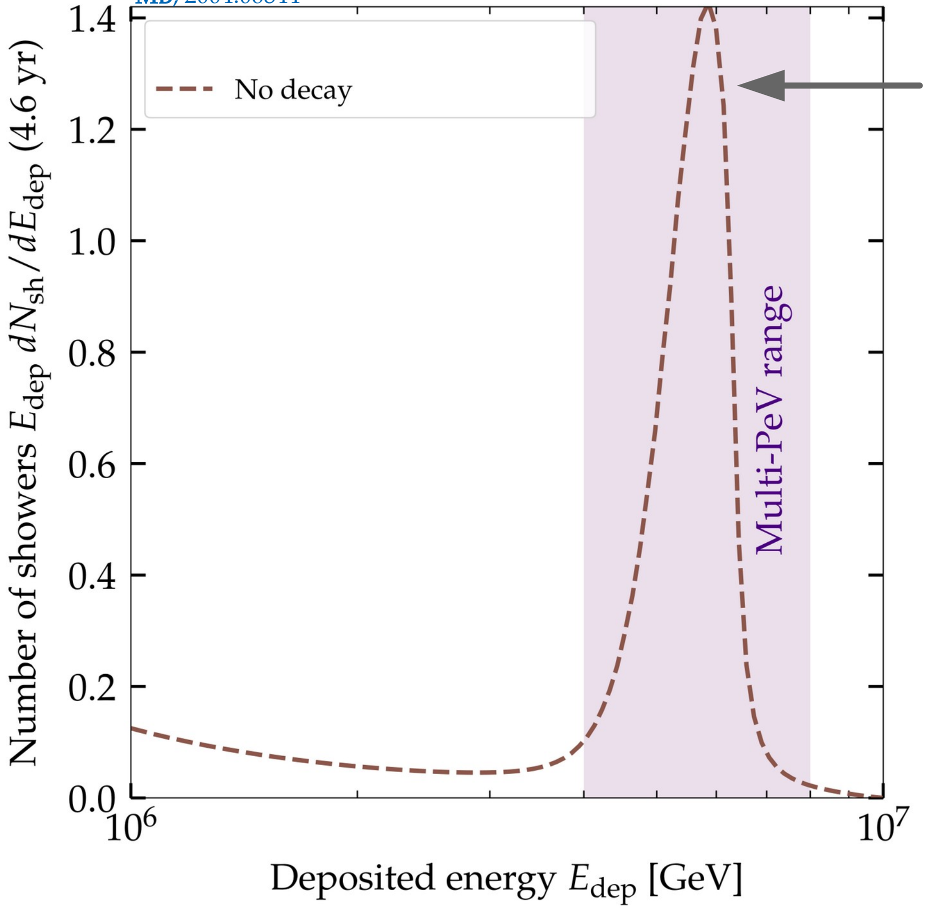


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



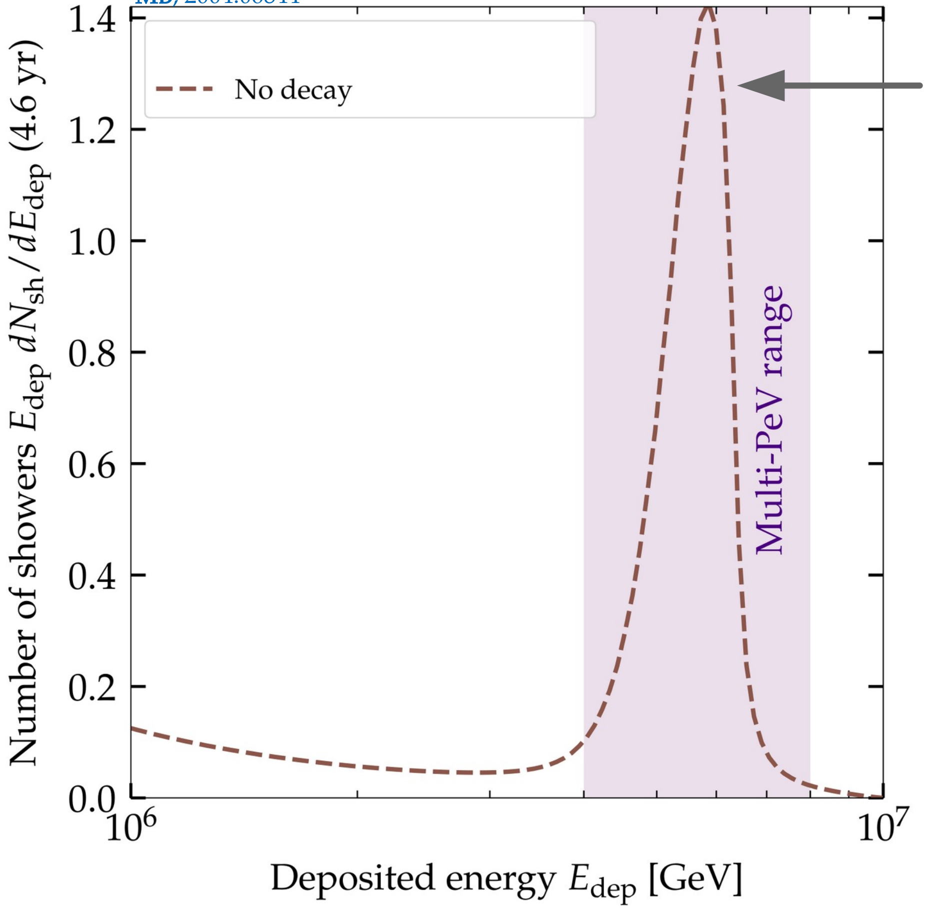
Glashow resonance (GR):
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

What does neutrino decay change?

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

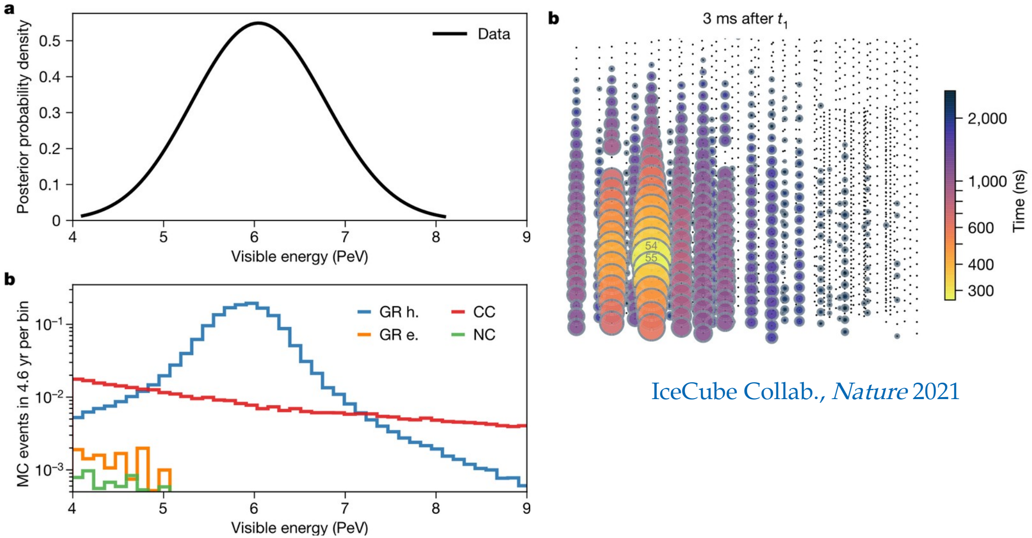
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

IceCube has seen one GR candidate in 4.6 years:



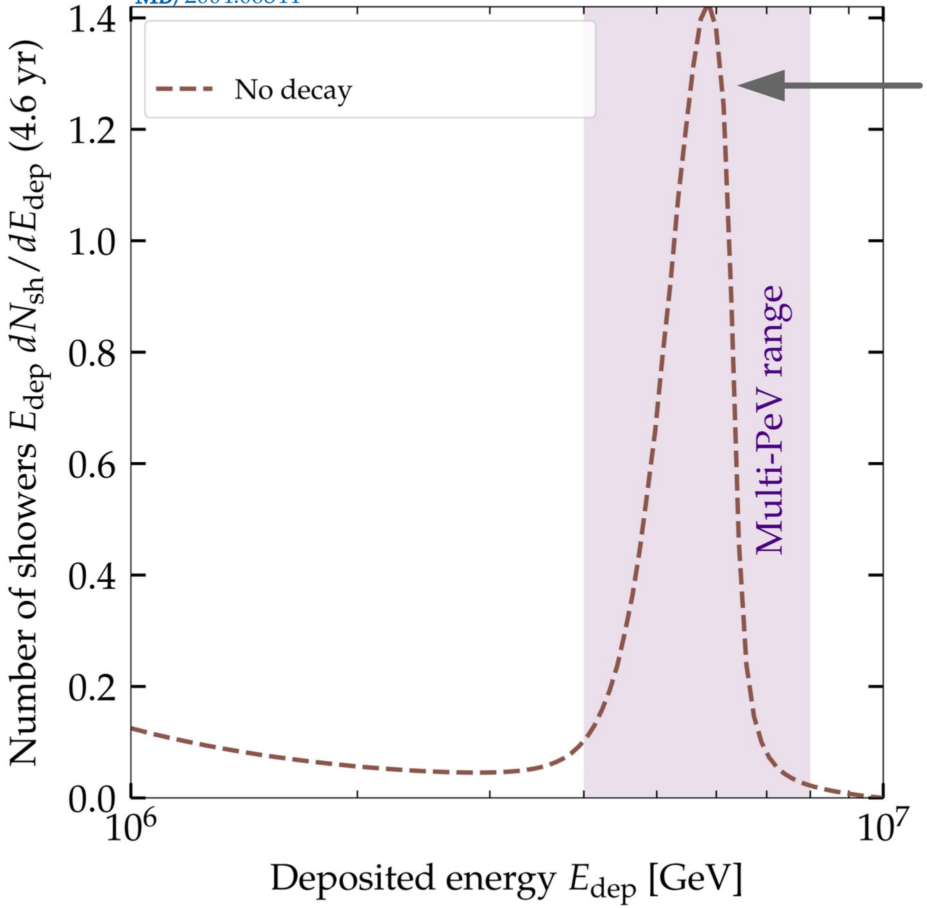
IceCube Collab., *Nature* 2021

What does neutrino decay change?

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

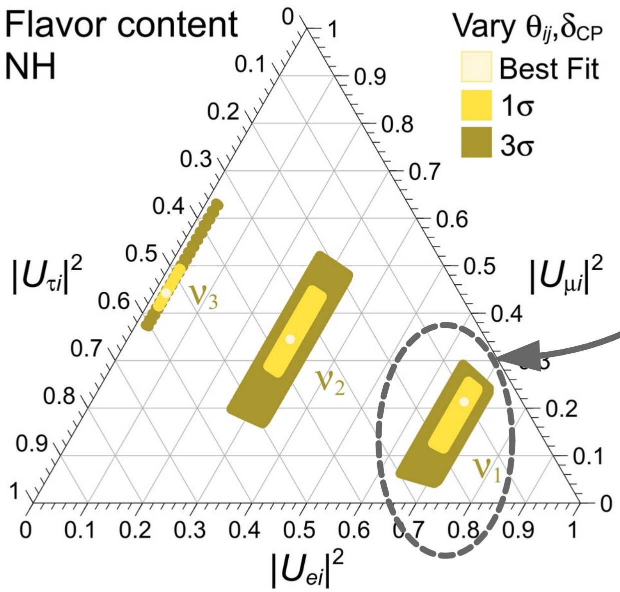
Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

ν_1 is the mass eigenstate with the most e flavor

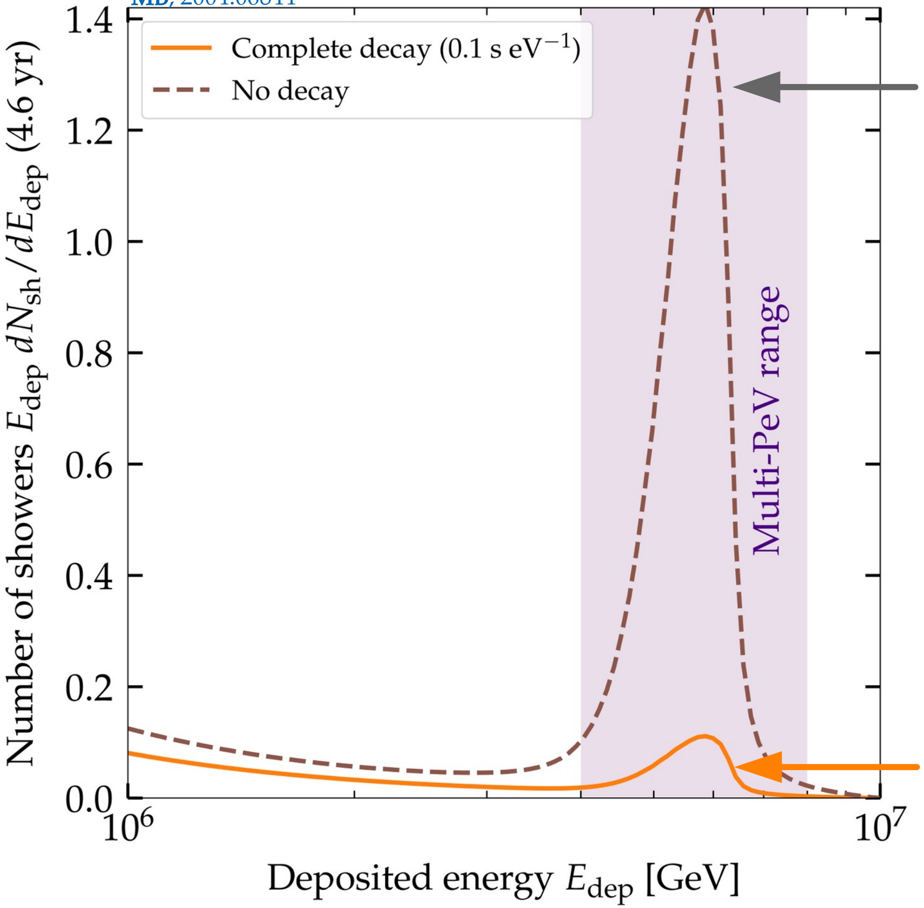


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

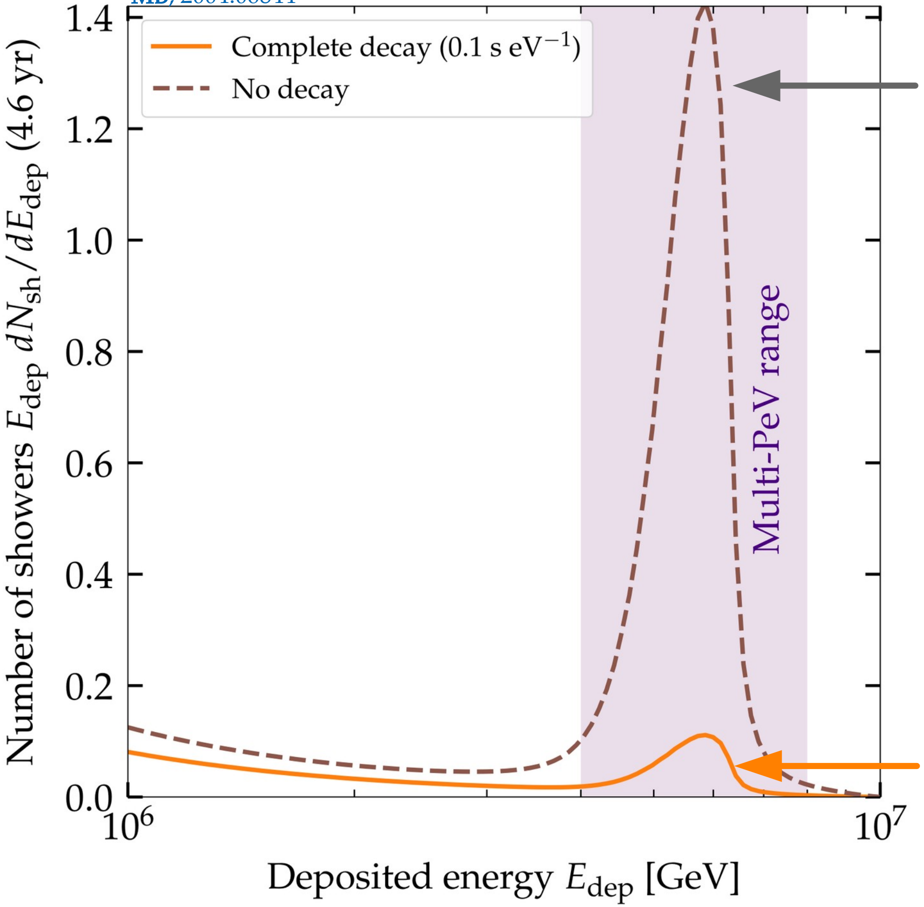
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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

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

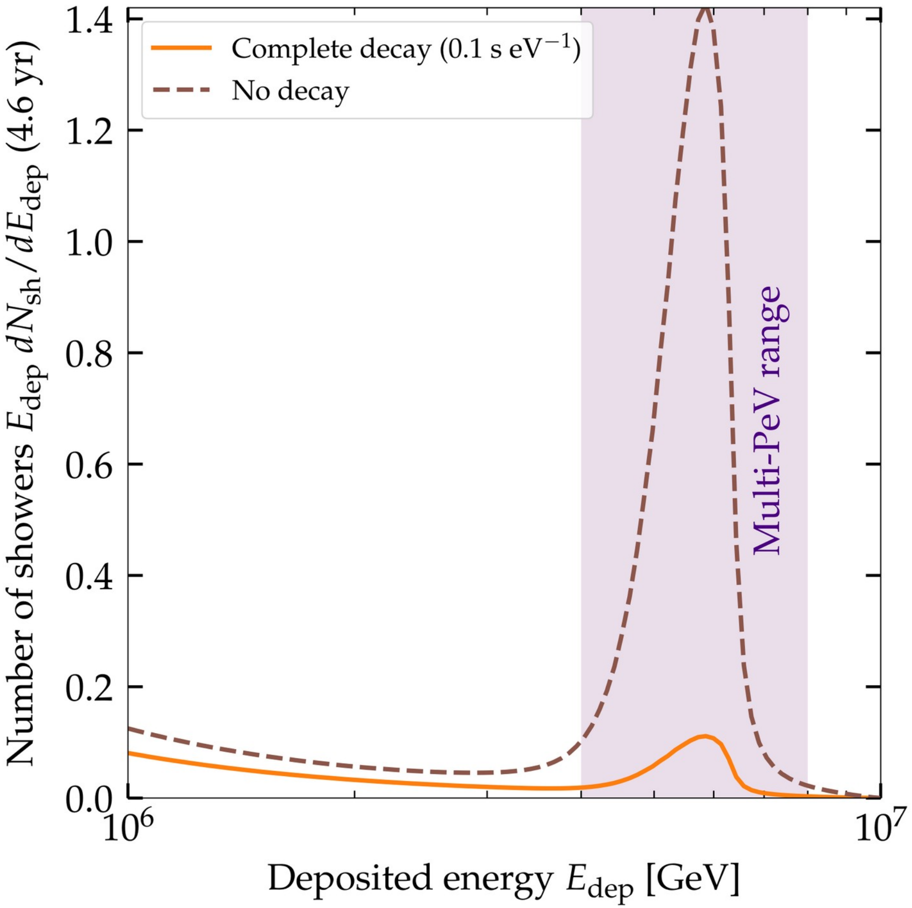
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

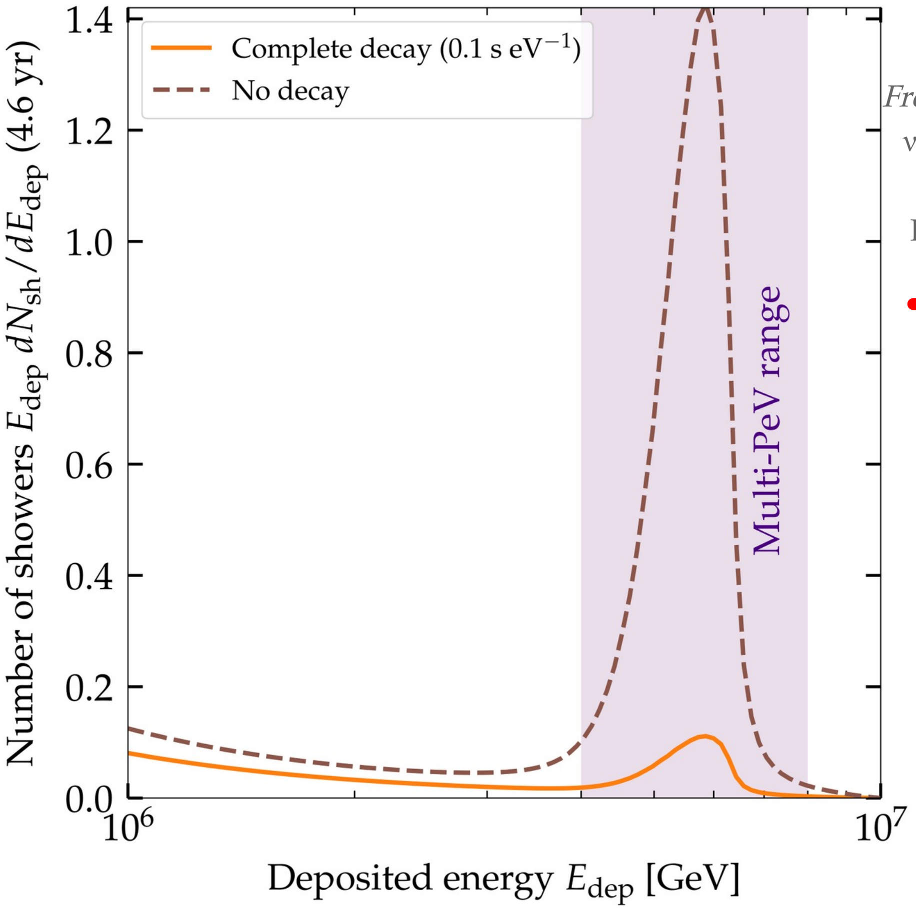


What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844

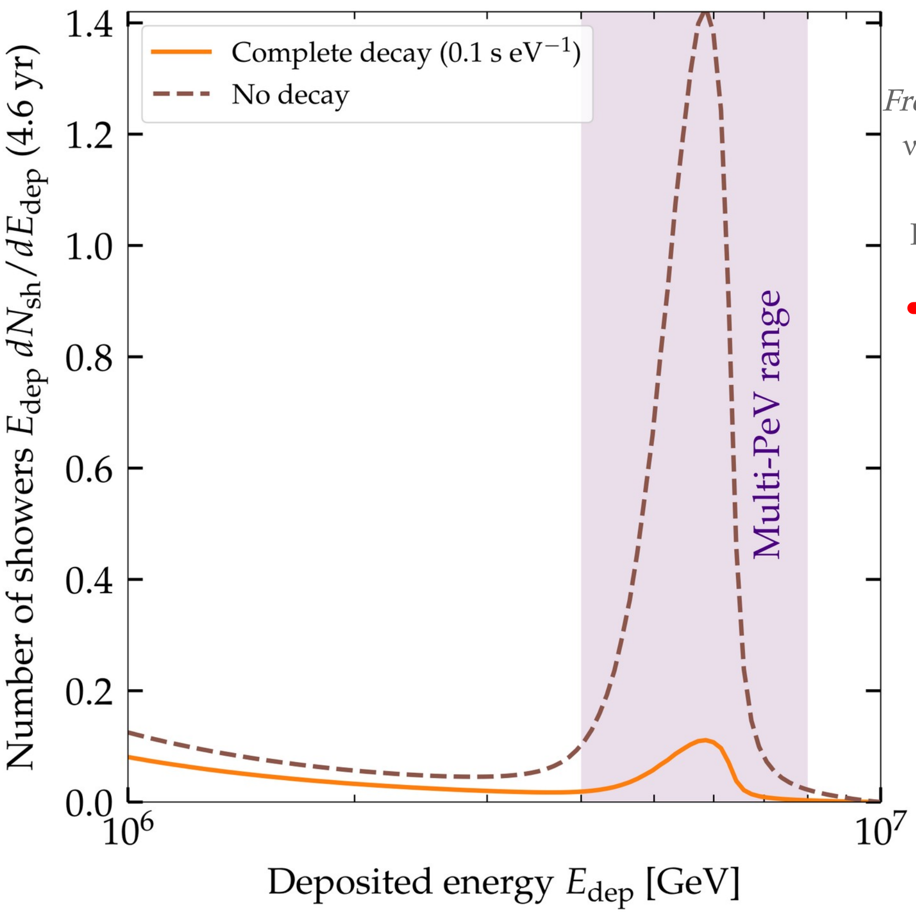


Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\nu/\bar{\nu}$ ratio

What does neutrino decay change?

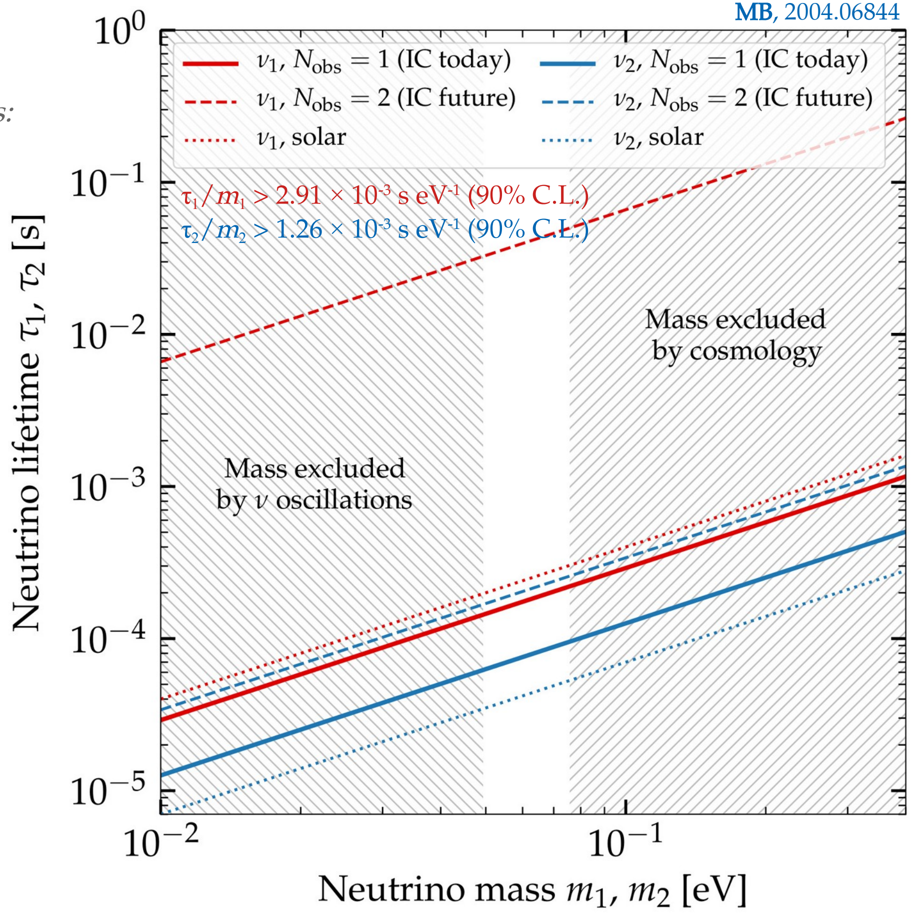
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⇔ Spectrum shape ⇔ Event rate



Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
ν/ν ratio

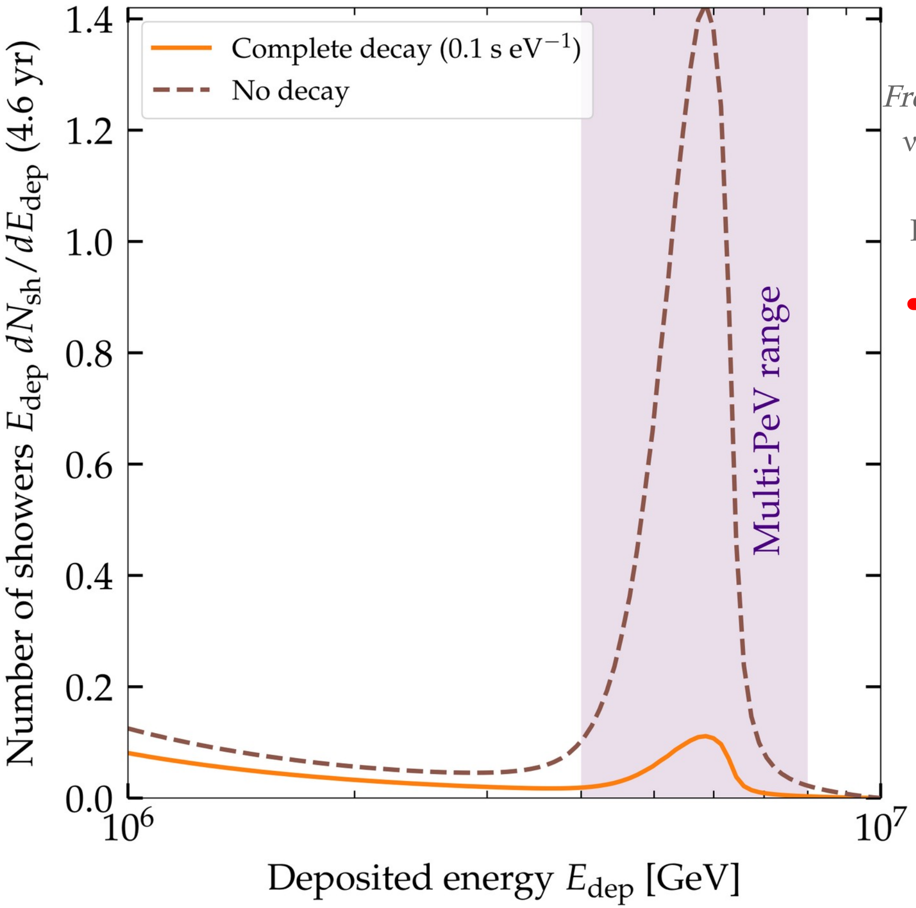
MB, 2004.06844



What does neutrino decay change?

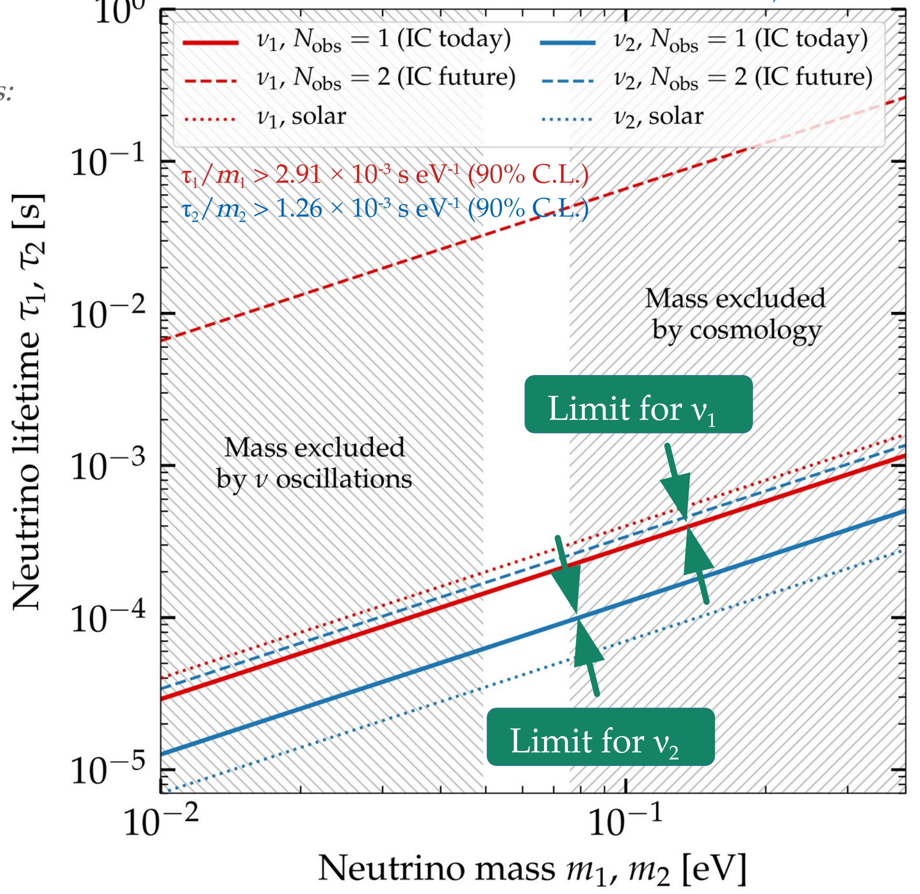
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2020

Flavor composition ⟺ Spectrum shape ⟺ Event rate



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

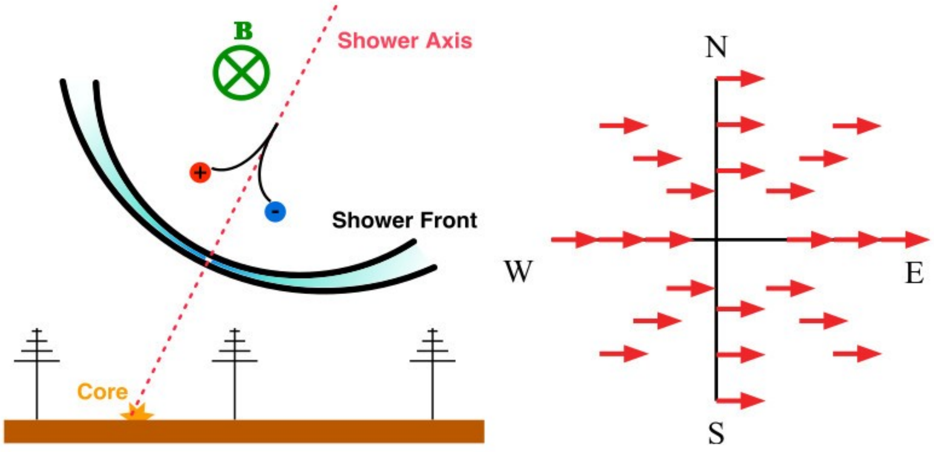
MB, 2004.06844



Neutrino radio-detection

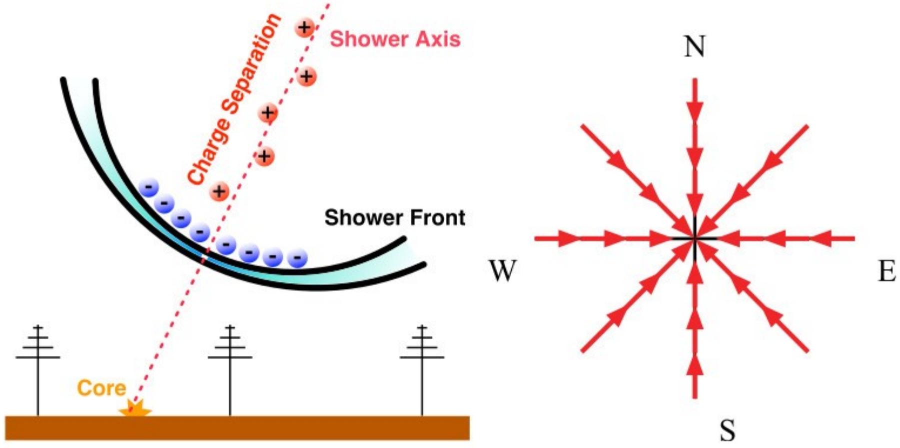
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

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

Radio emission: geomagnetic and Askaryan