High-energy cosmic neutrinos in particle physics and astrophysics: *present and future*

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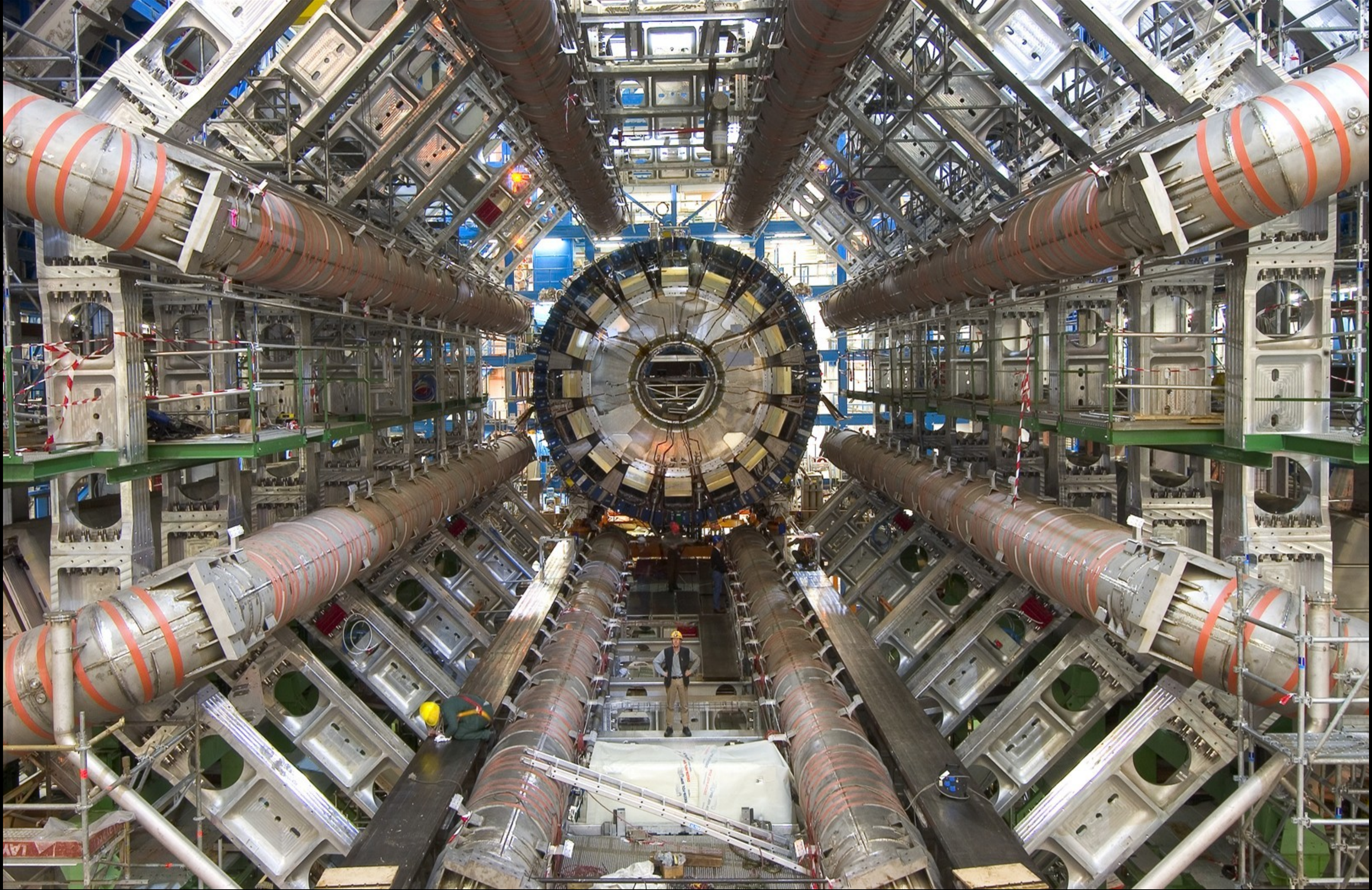
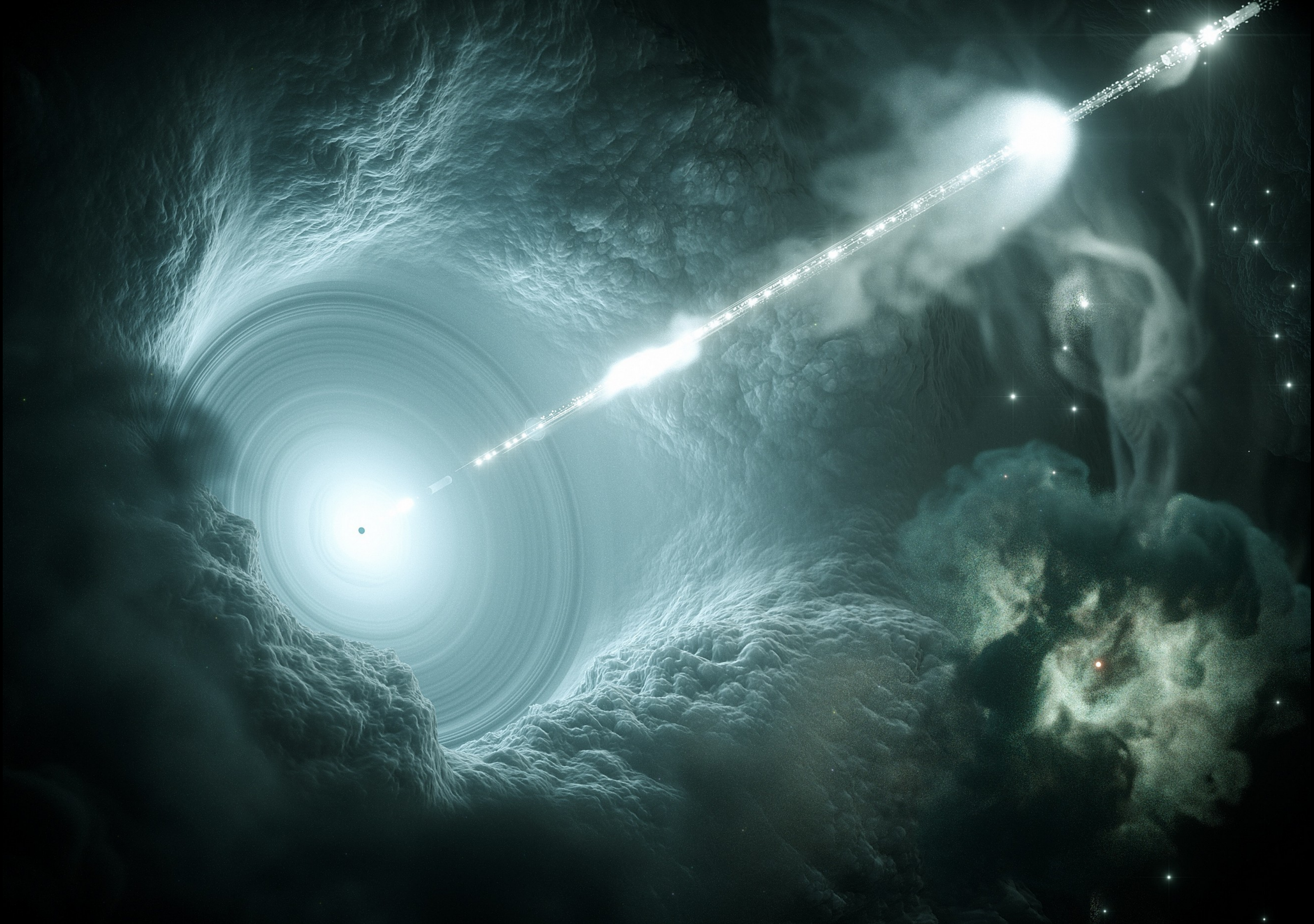
Partikeldagarna 2024
Uppsala, October 21, 2024

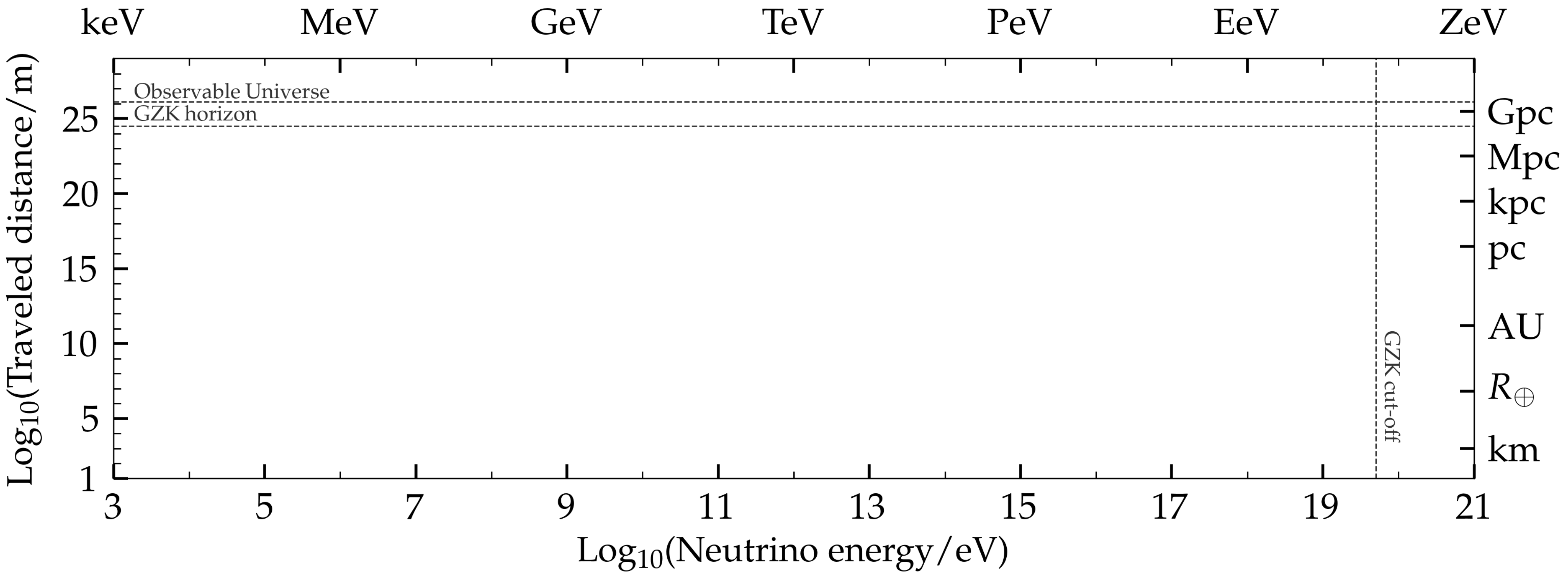
UNIVERSITY OF COPENHAGEN
VILLUM FONDEN



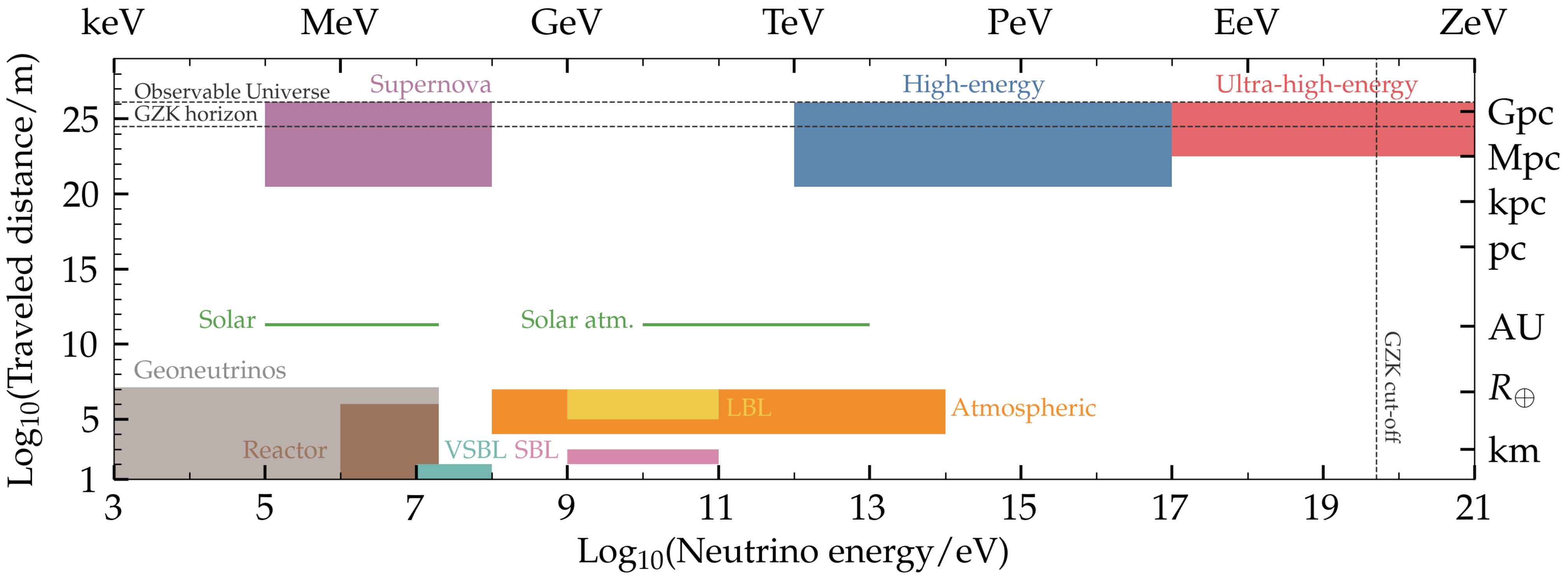
ATLAS



DESY

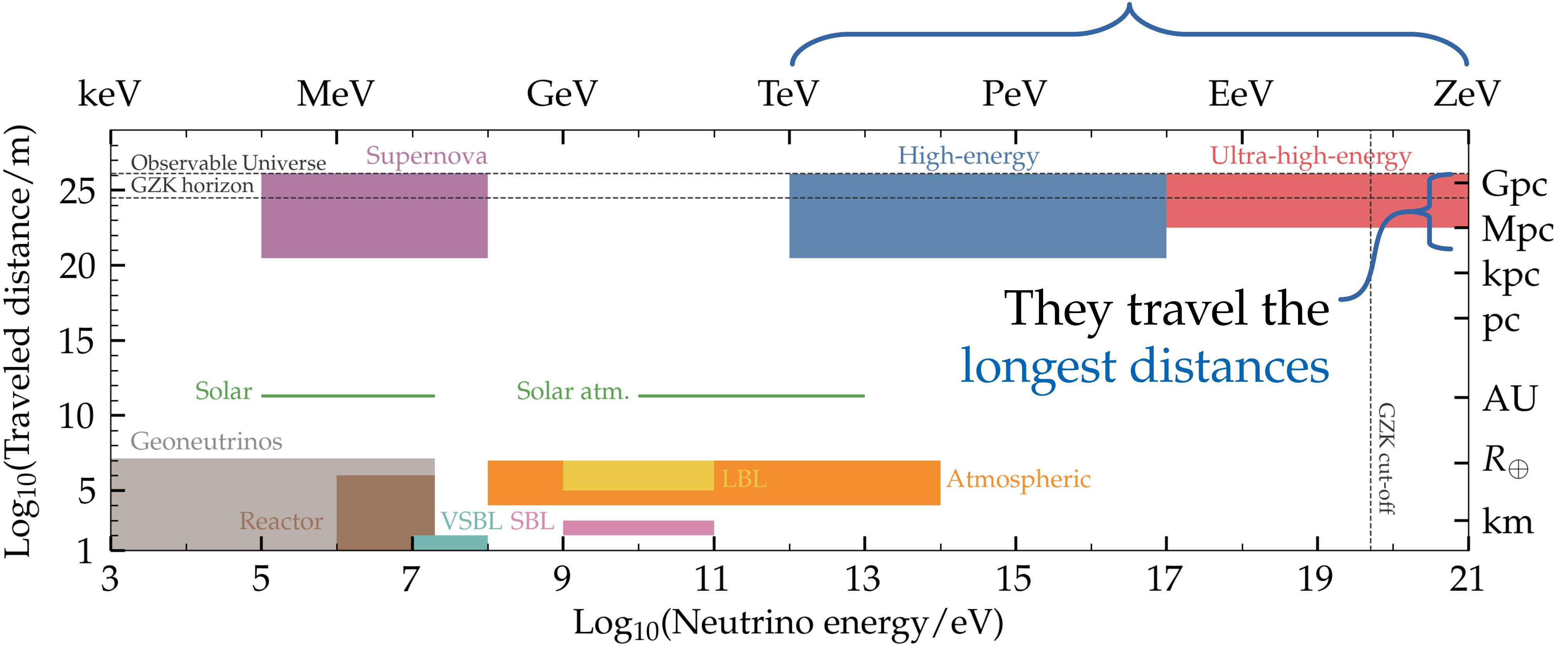


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted



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

They have the highest energies



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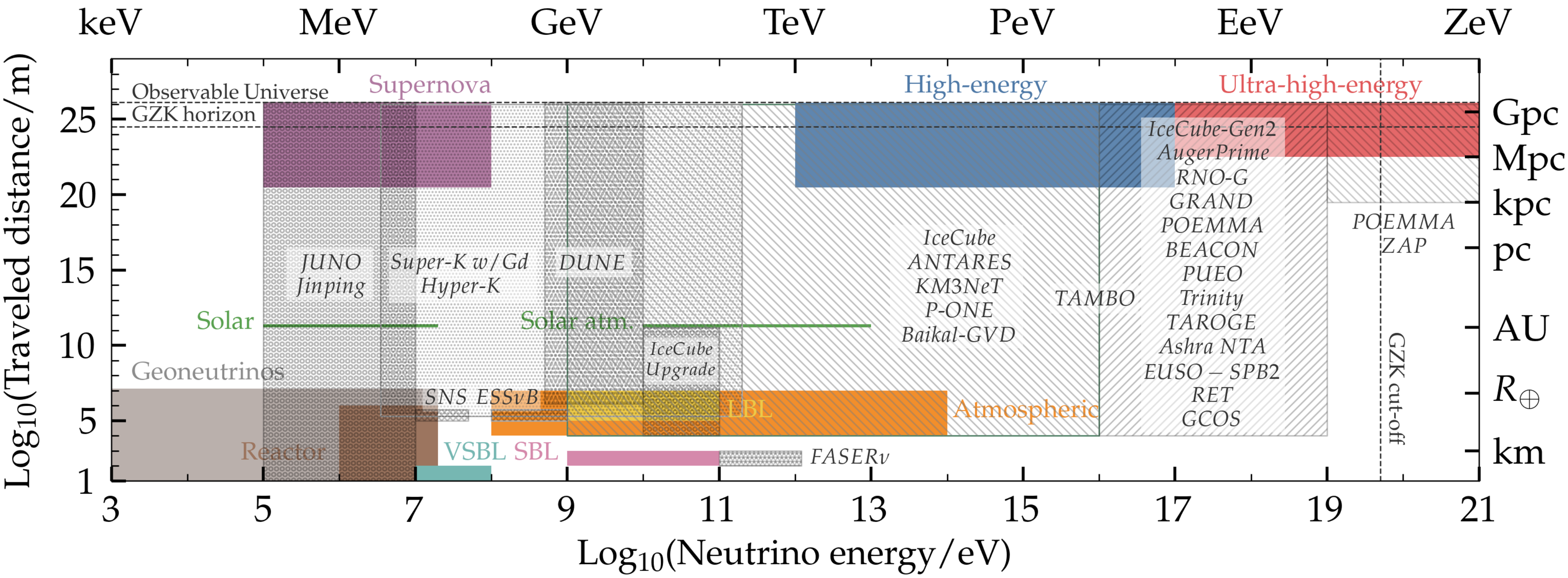

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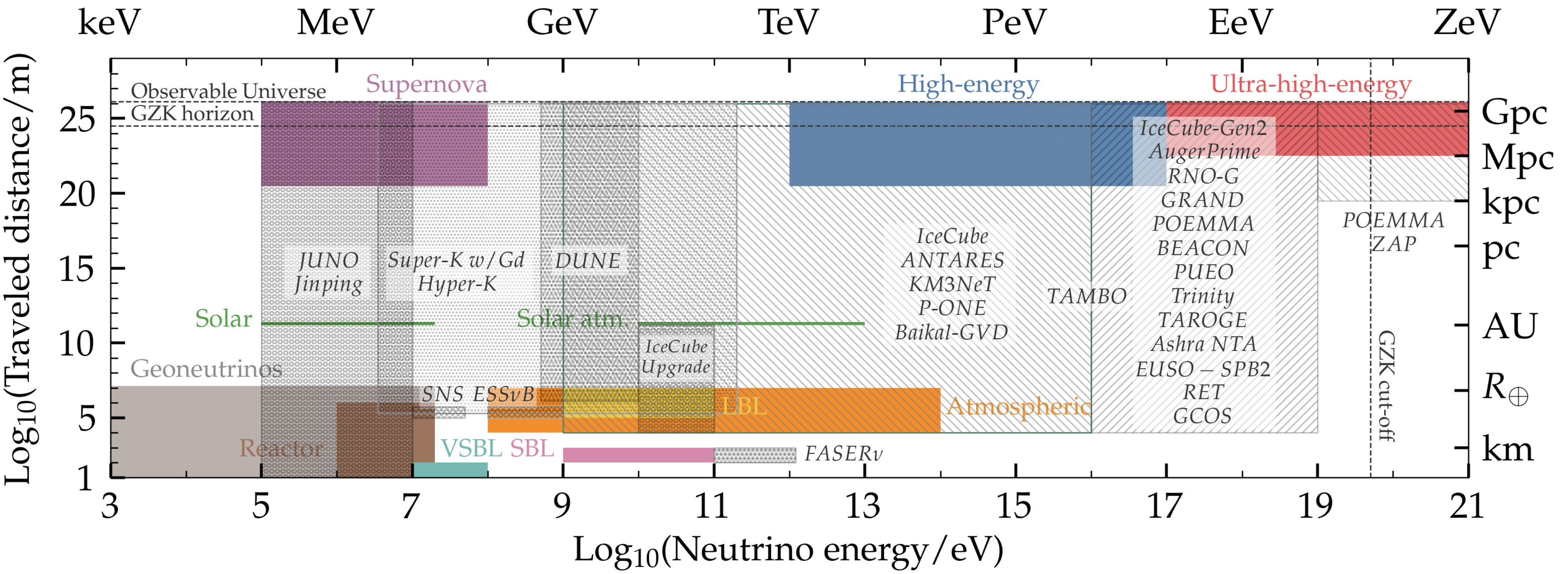
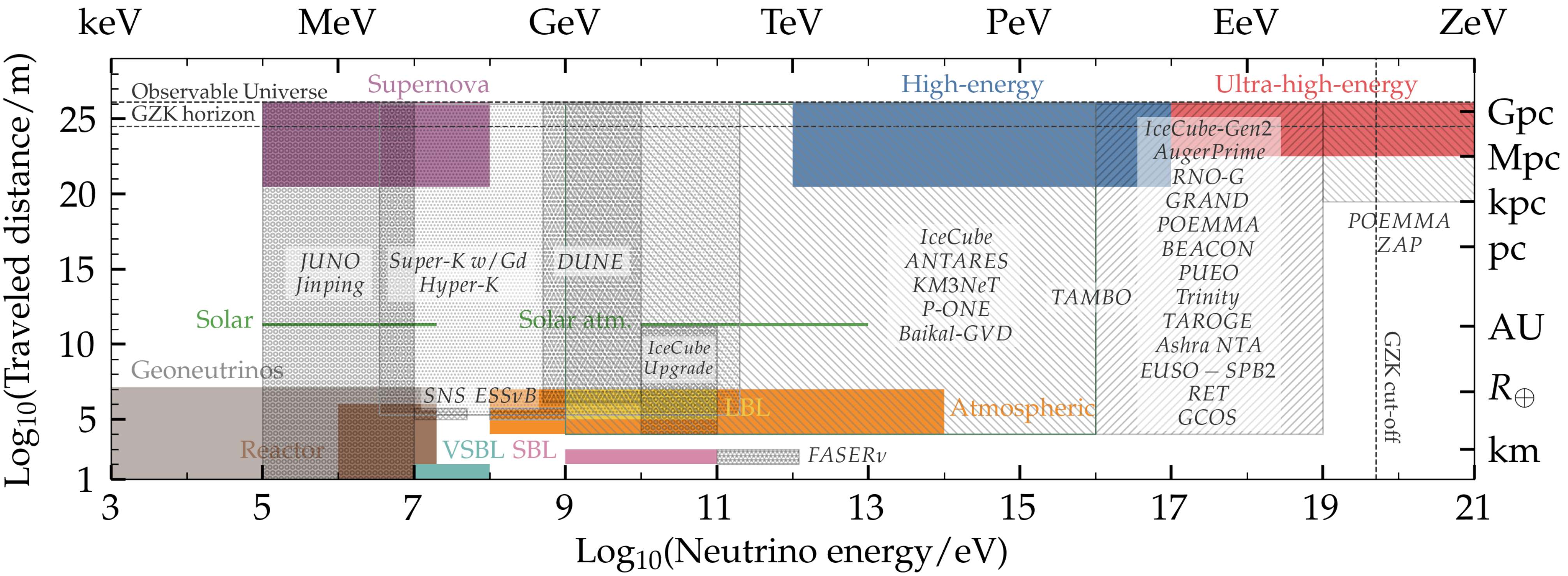


Synergies with lower energies

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

Discovered in 2013
by IceCube



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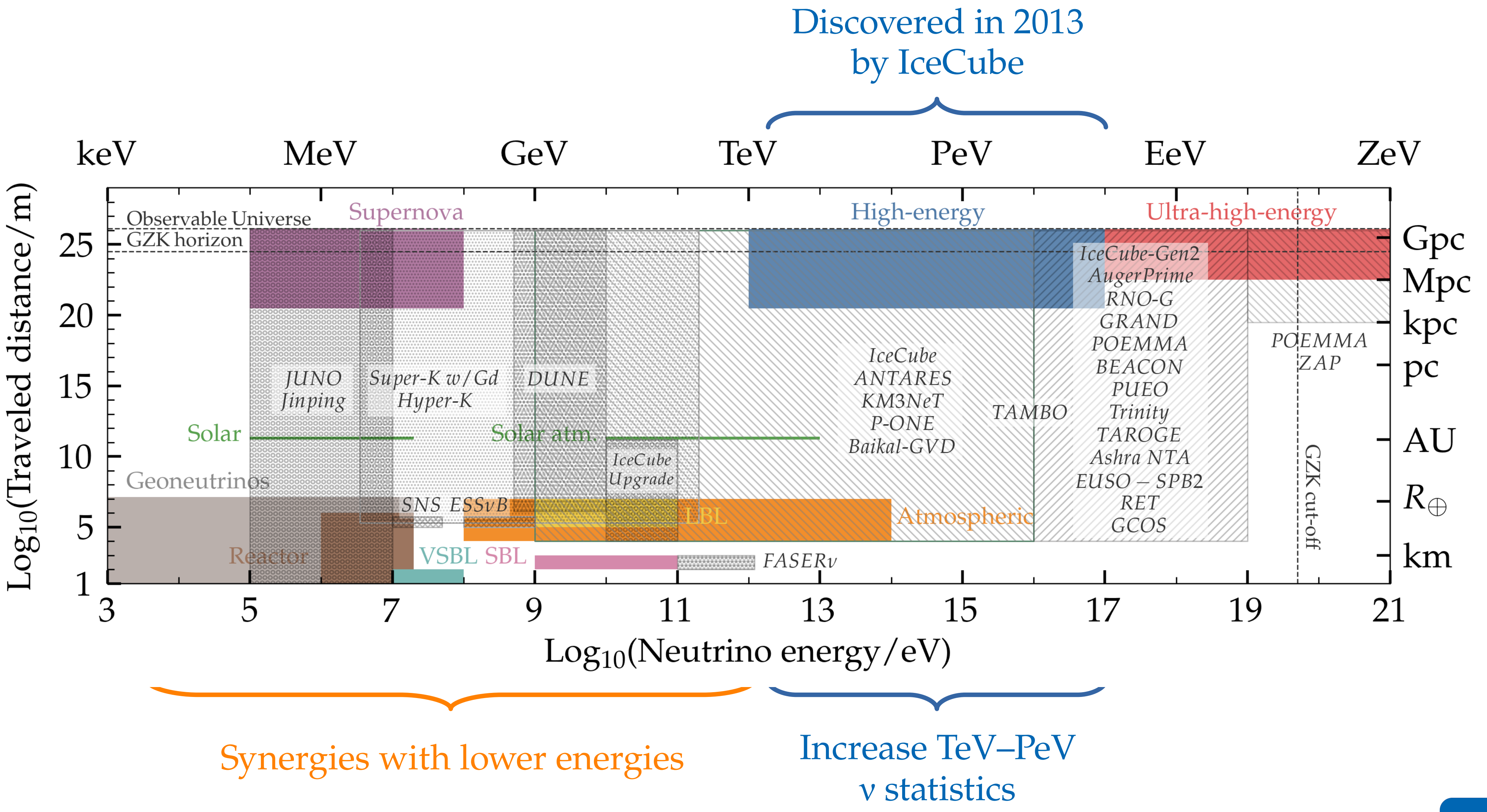

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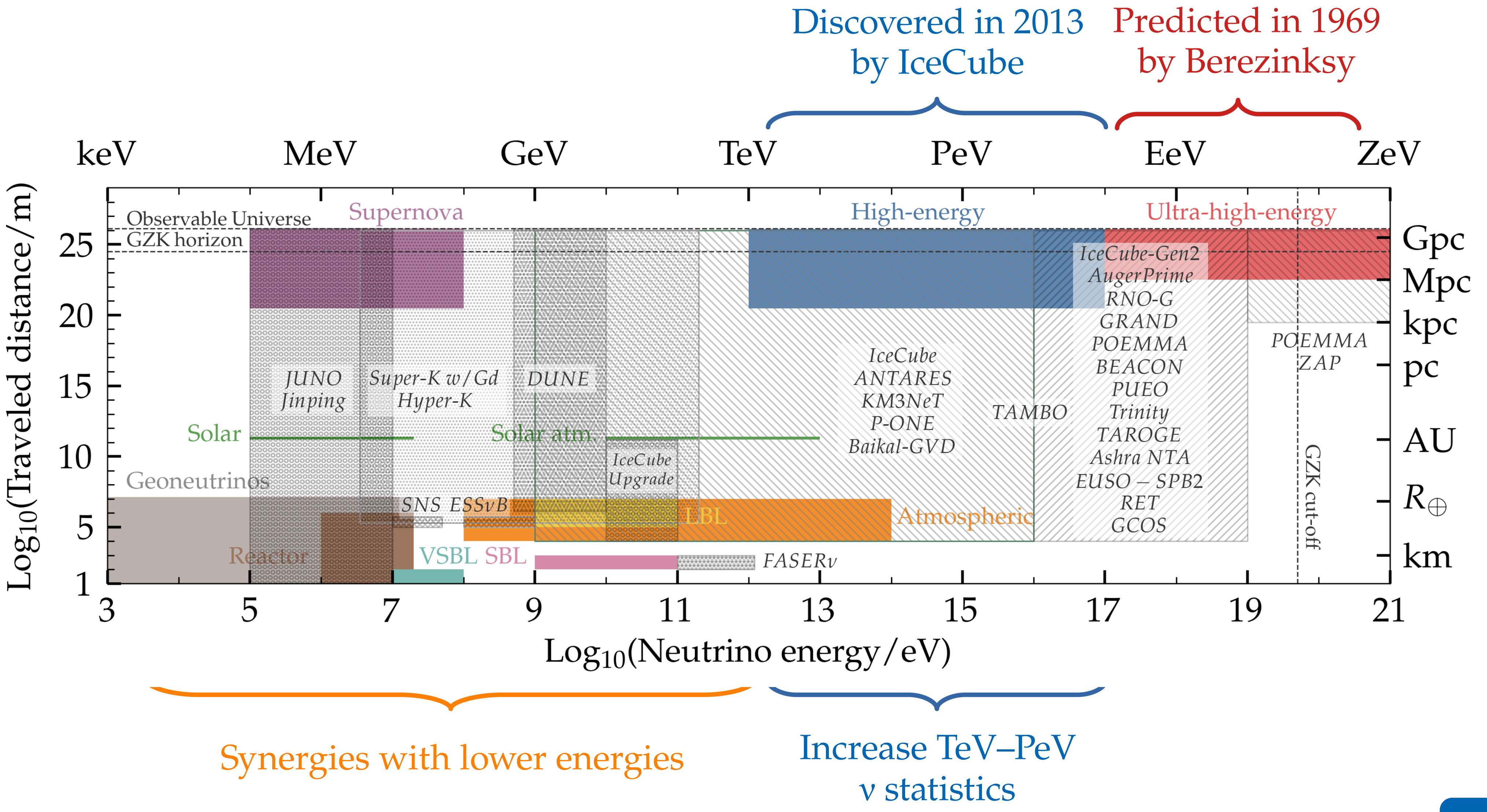
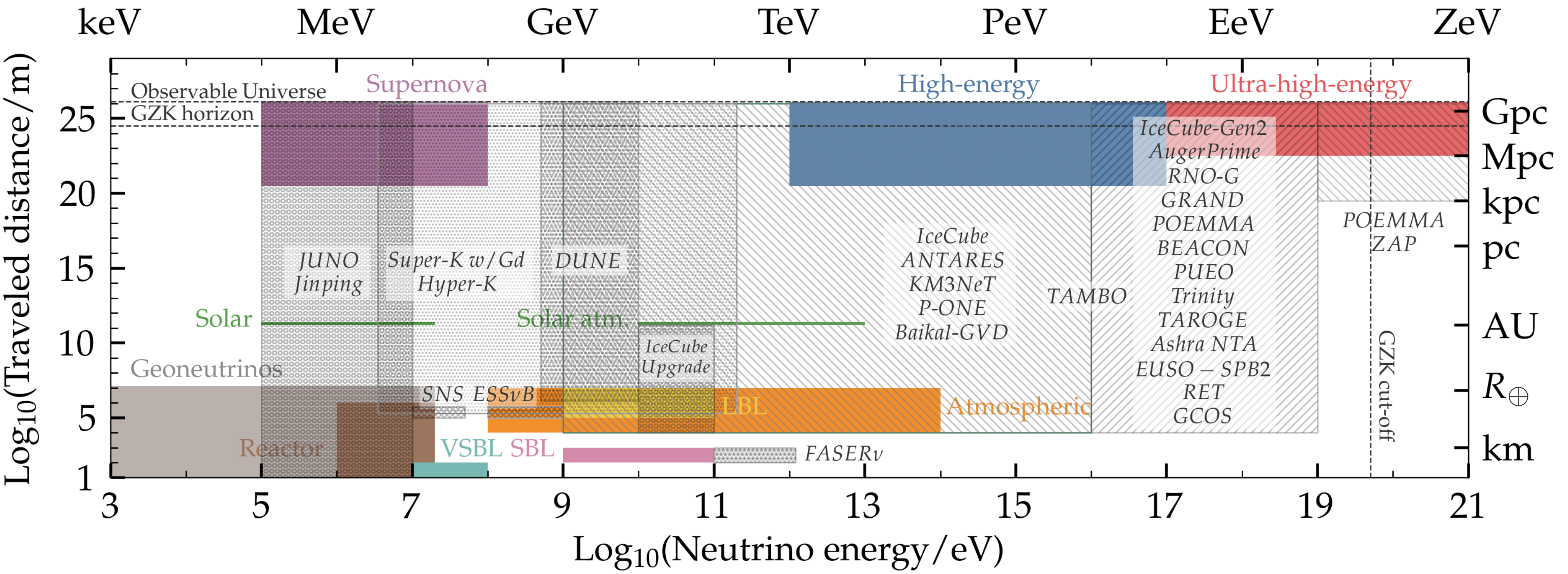


Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333), adapted

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

High-energy cosmic neutrinos:
Basics and current status

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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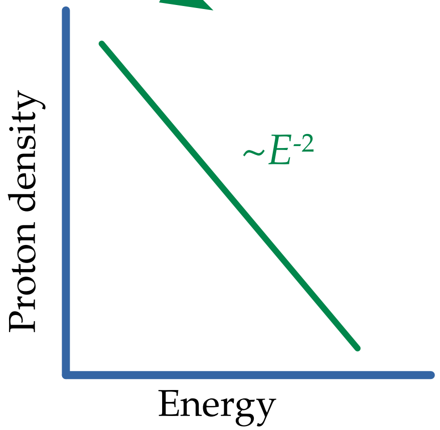

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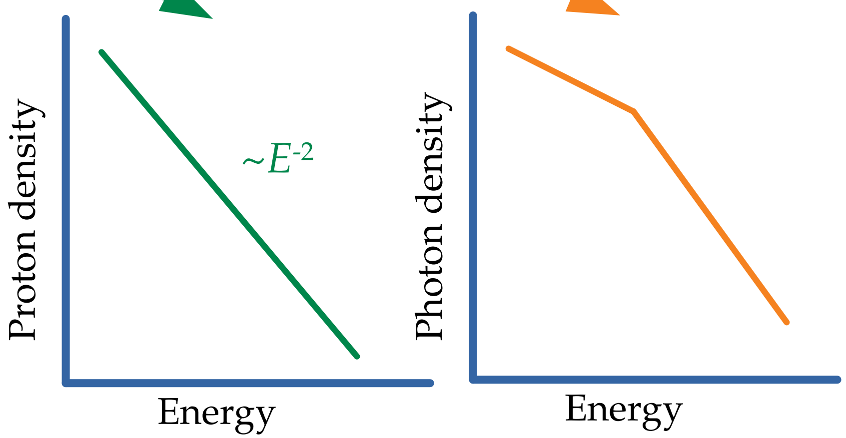

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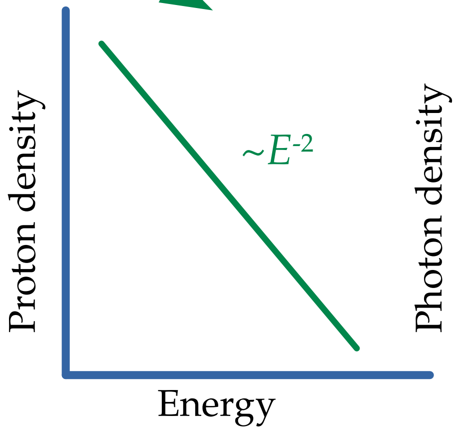
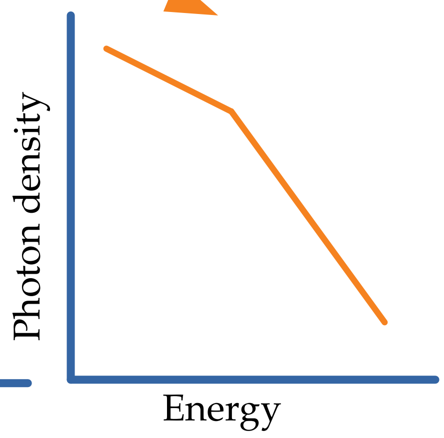
$$p + \gamma_{\text{target}} \longrightarrow \Delta^+ \longrightarrow \begin{cases} p + \pi^0, & \text{Br} = 2/3 \\ n + \pi^+, & \text{Br} = 1/3 \end{cases}$$

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

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

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





Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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

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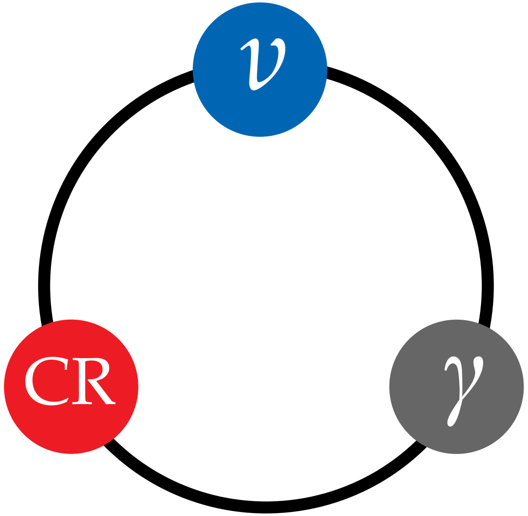
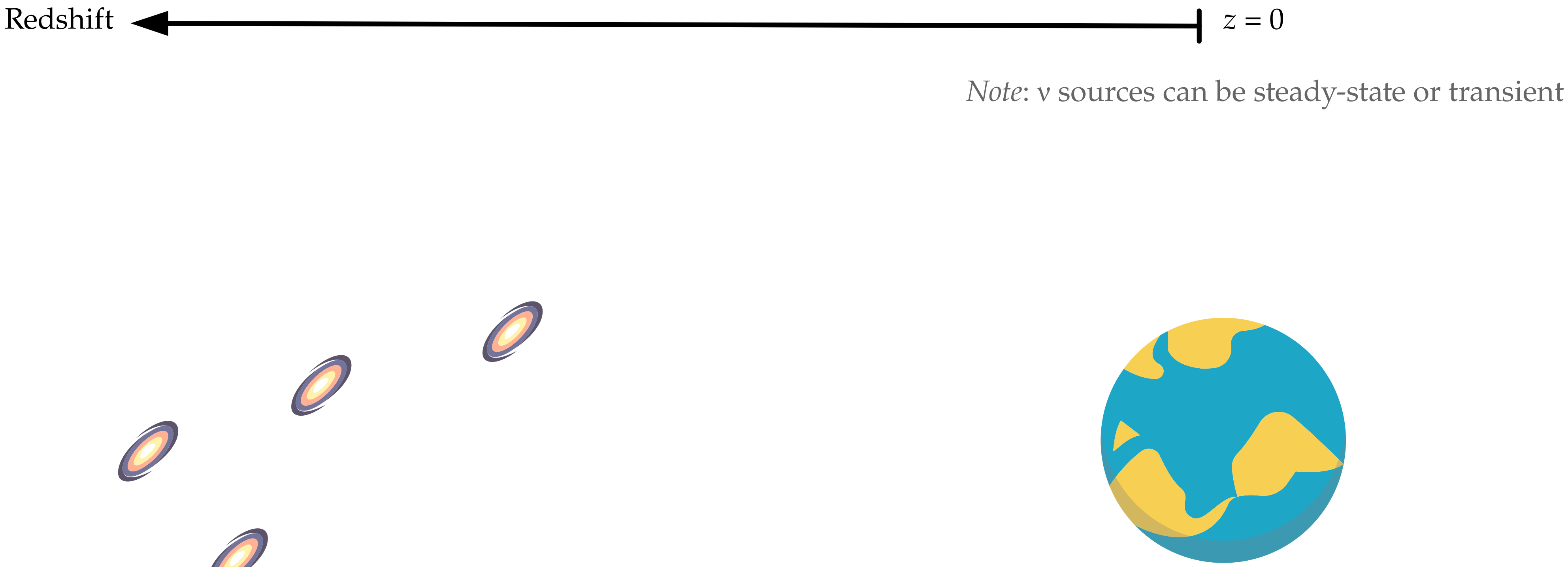
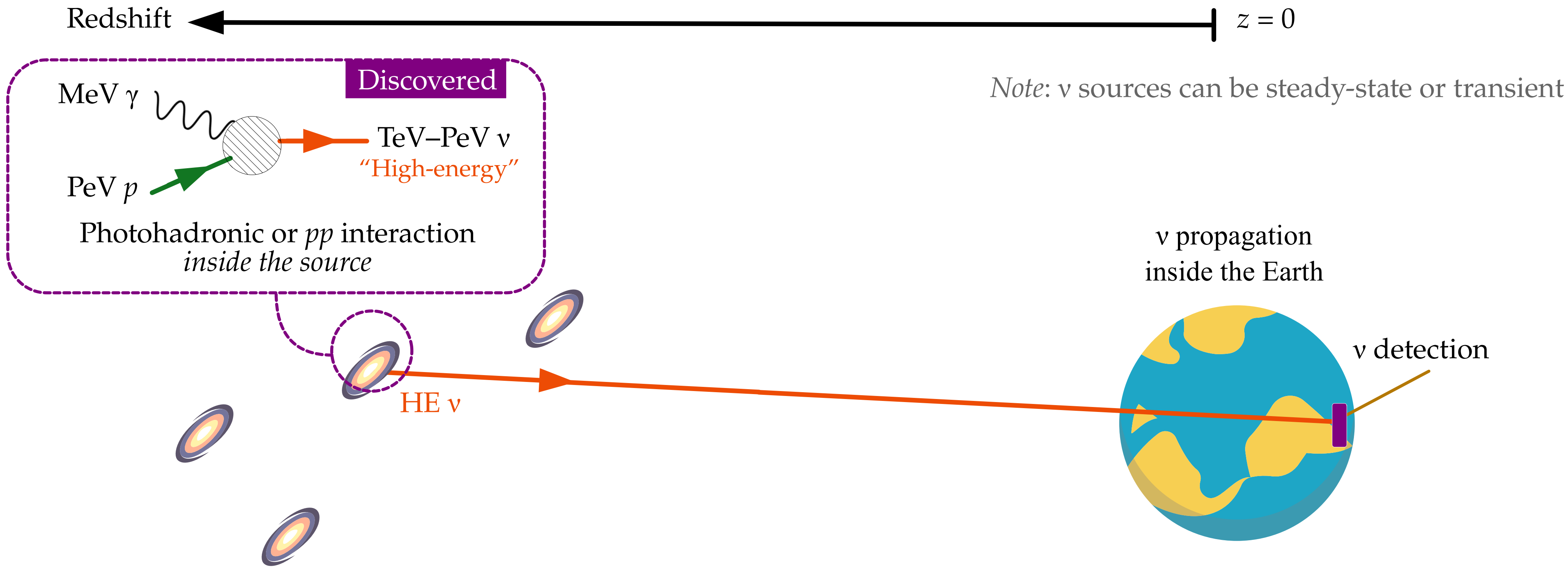


Neutrino energy = Proton energy / 20

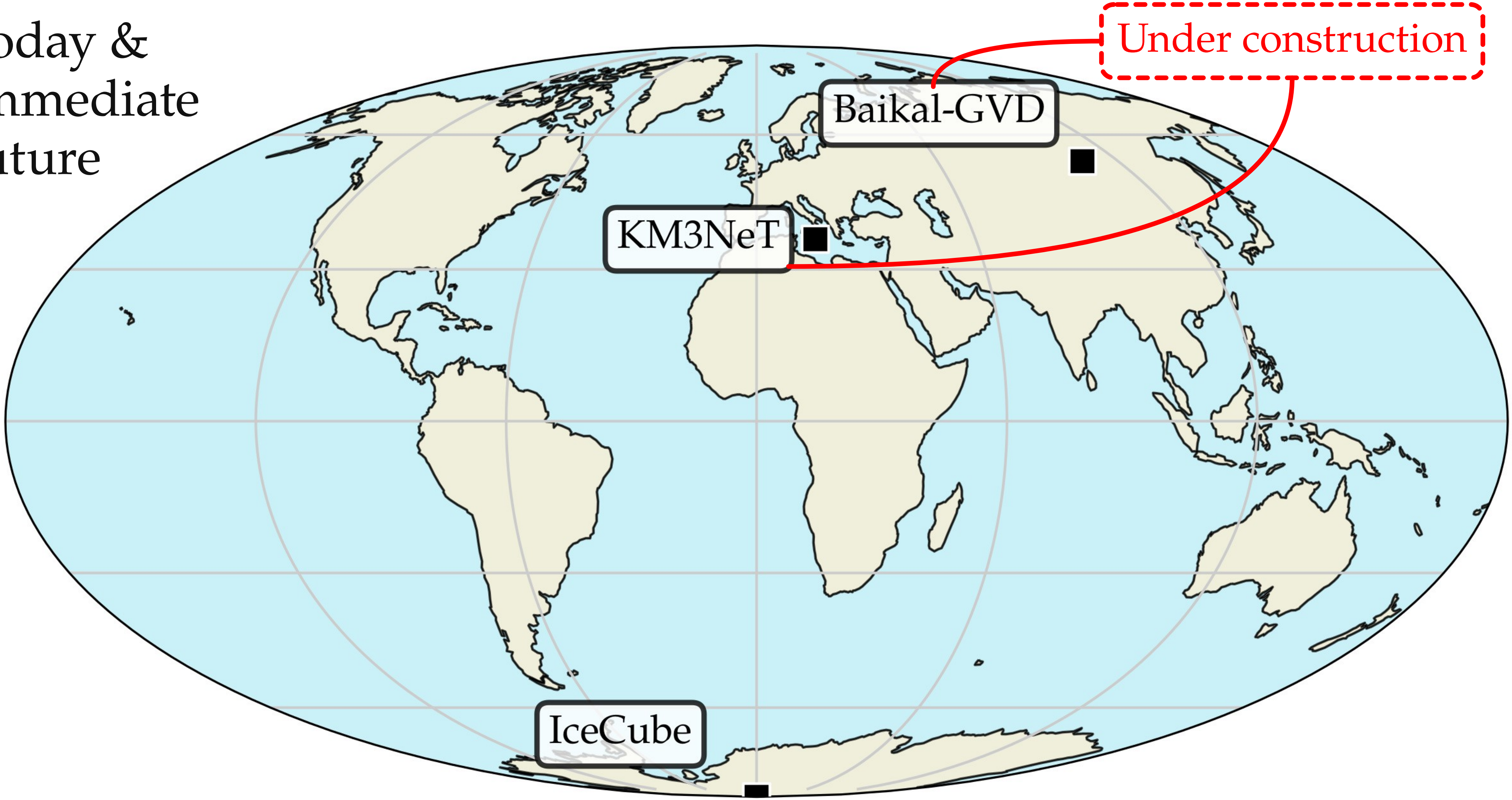
Gamma-ray energy = Proton energy / 10


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

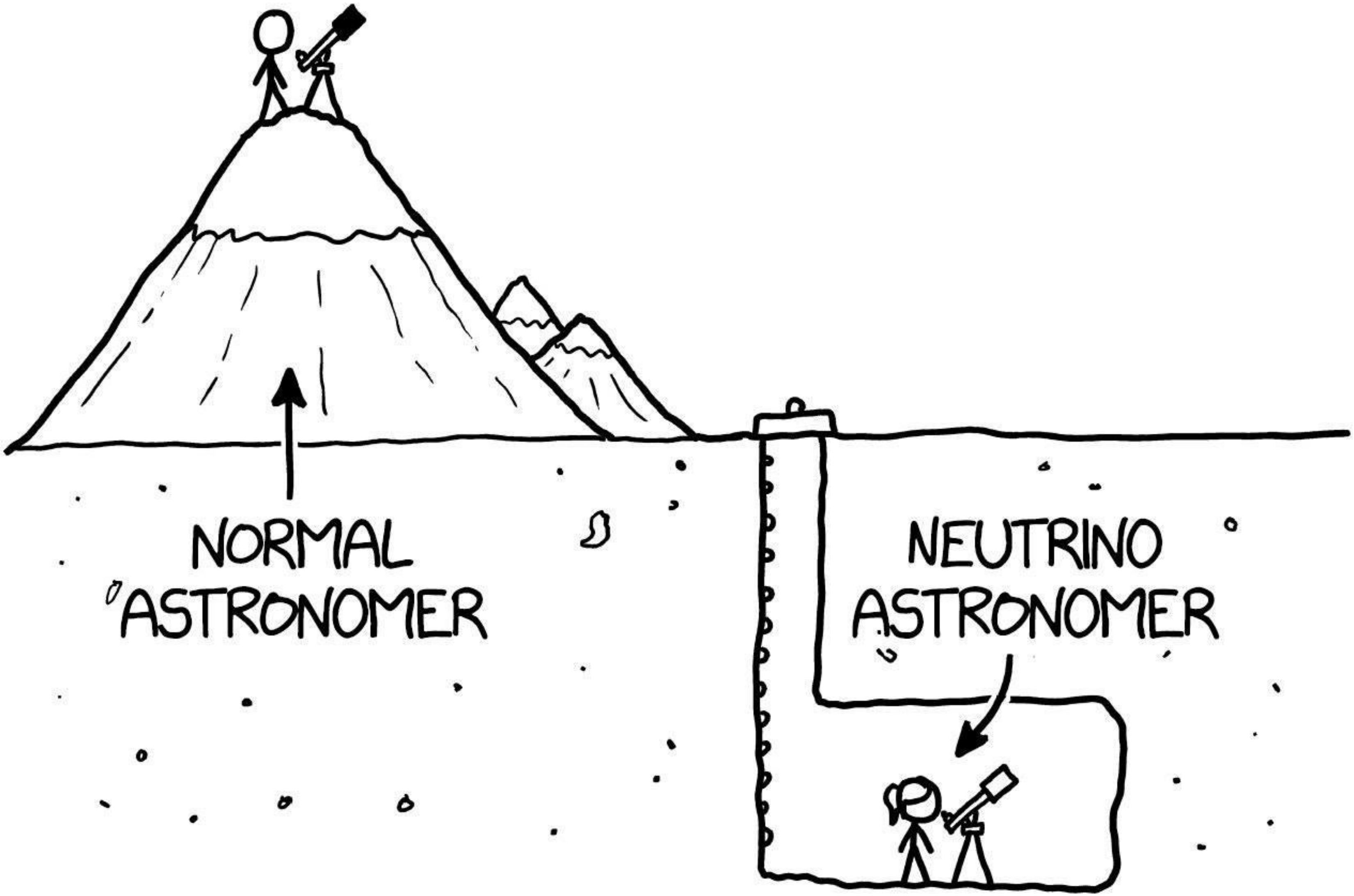


Redshift
$z = 0$
Discovered
MeV γ
TeV–PeV ν
"High-energy"
PeV p
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν

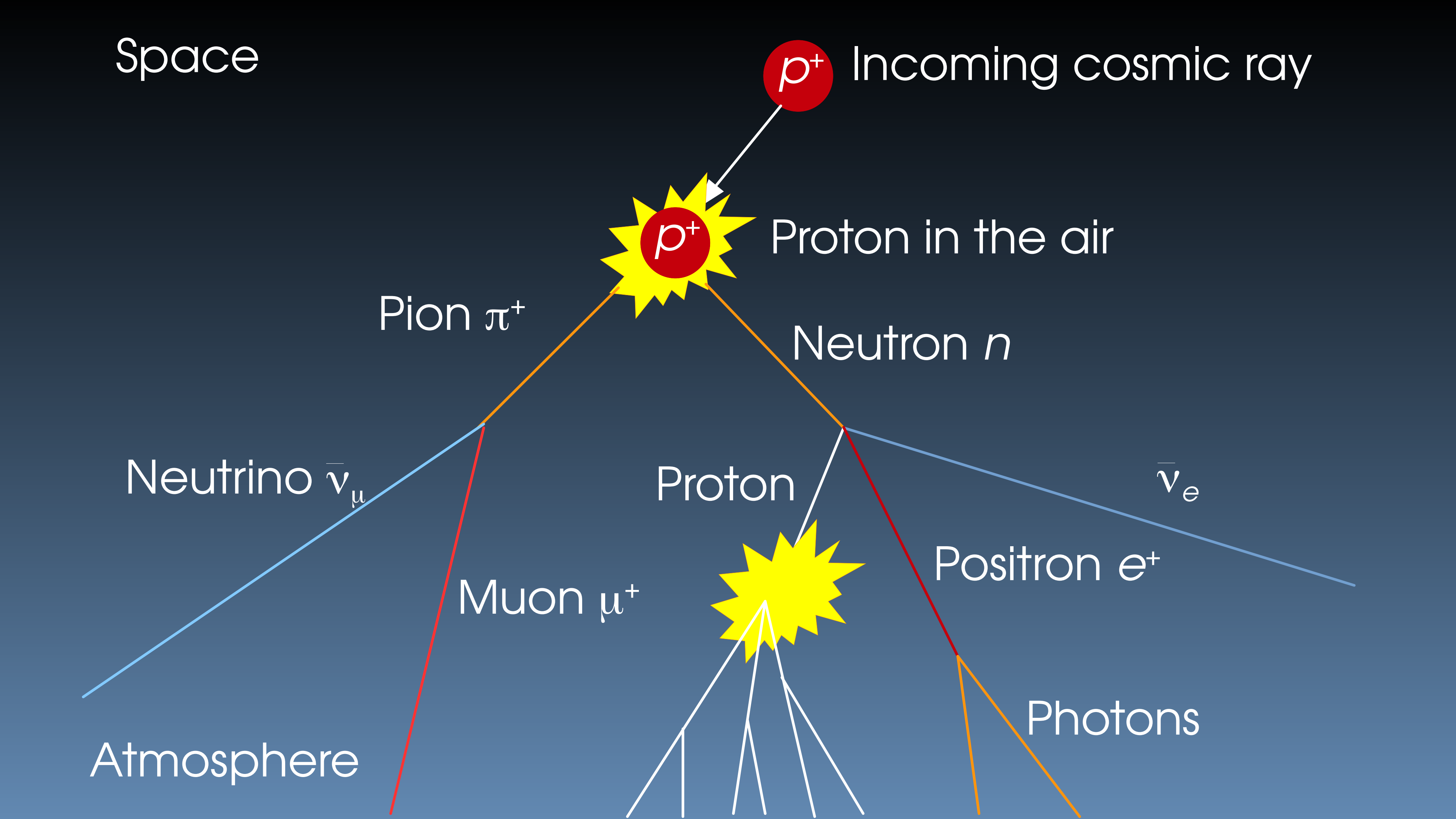
Today & immediate future



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

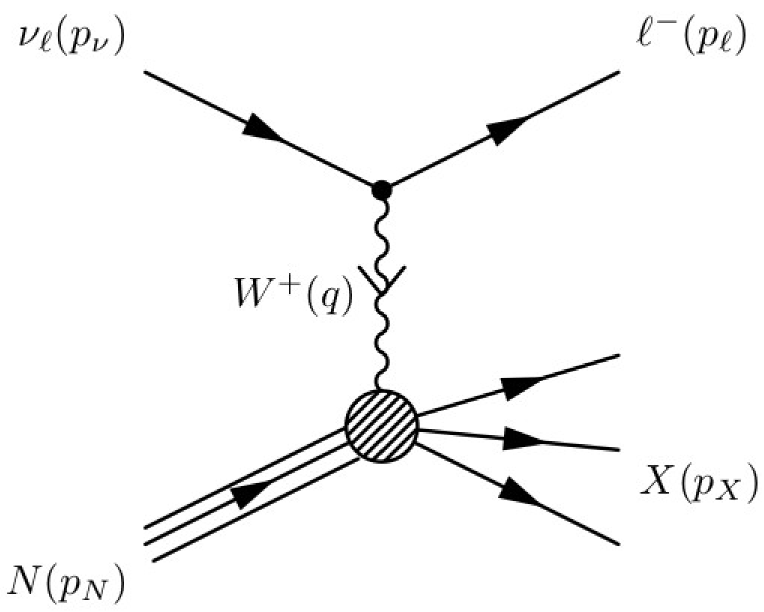


xkcd

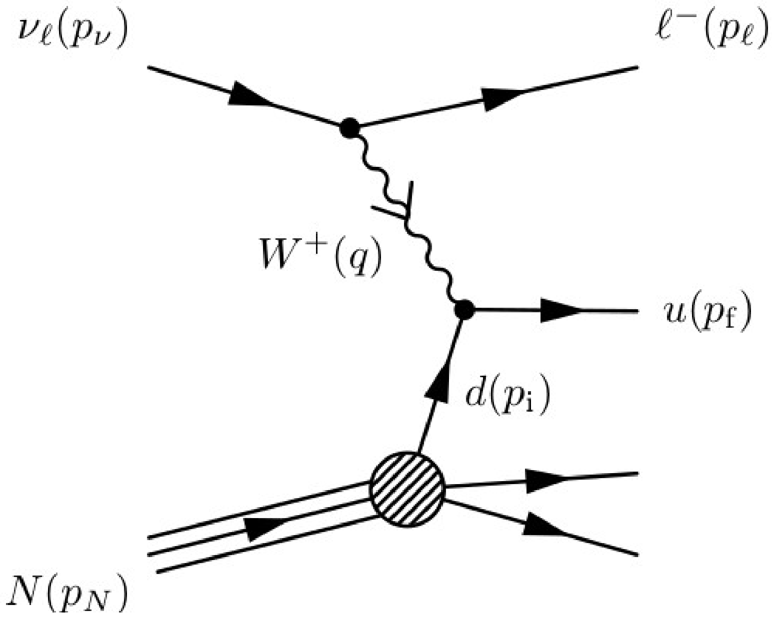

Space
p+
Incoming cosmic ray
p+
Proton in the air
Pion π+
Neutron n
Neutrino ν̄μ
Proton
ν̄e
Positron e+
Muon μ+
Photons
Atmosphere

Neutrino-nucleon deep inelastic scattering

What you see

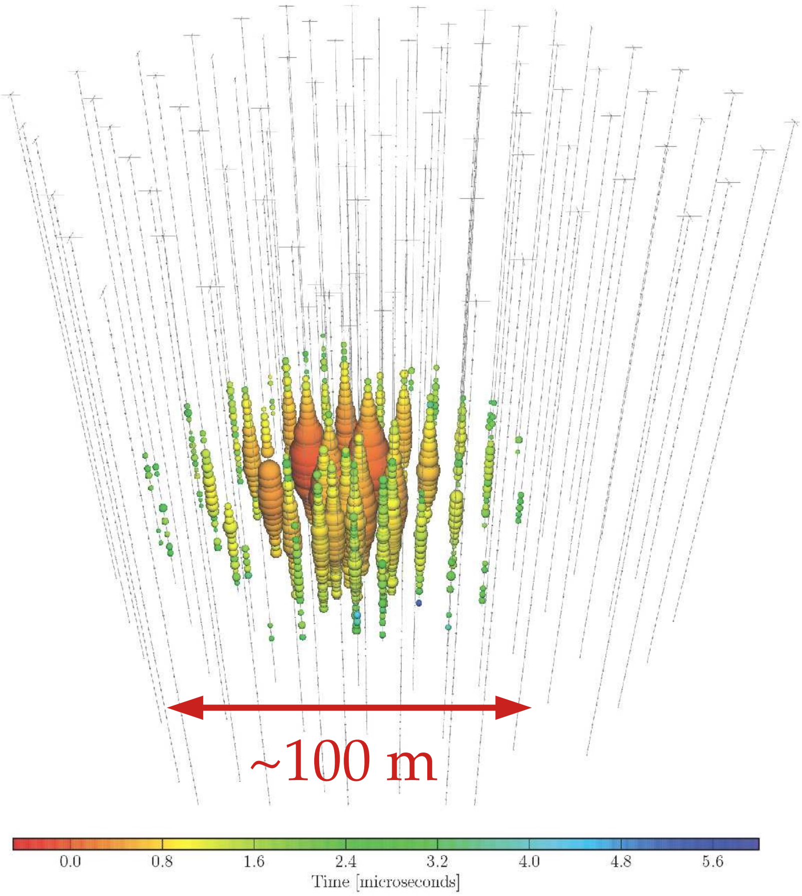


Beneath the hood



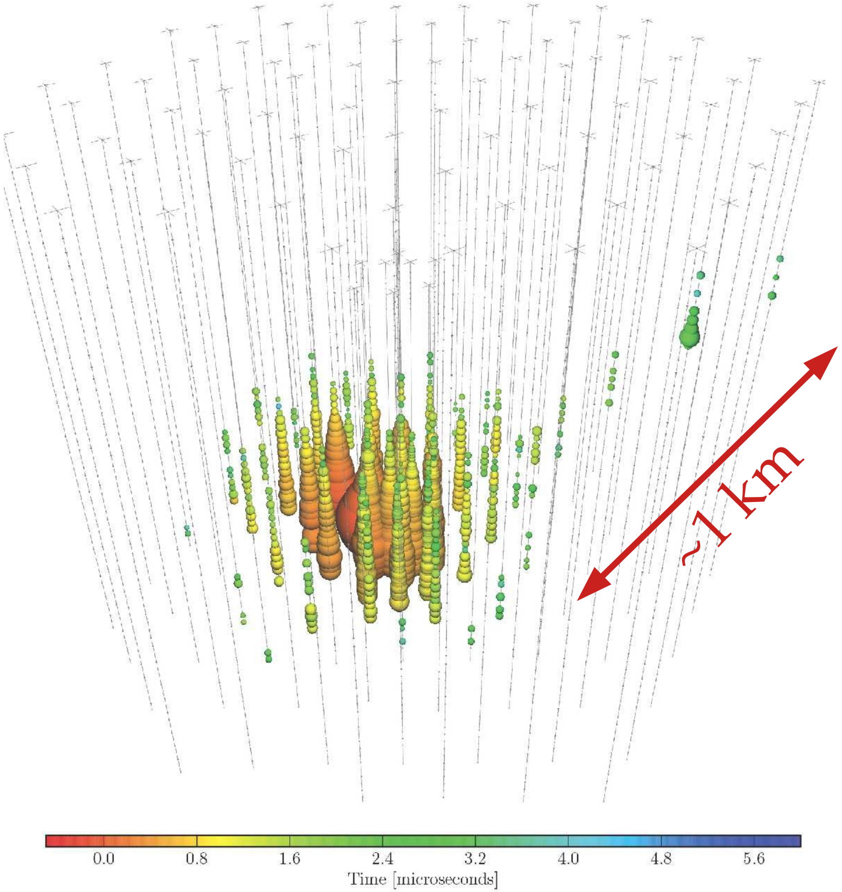
(Plus the equivalent neutral-current process (Z-exchange))

Shower
(mainly from ν_e and ν_τ)

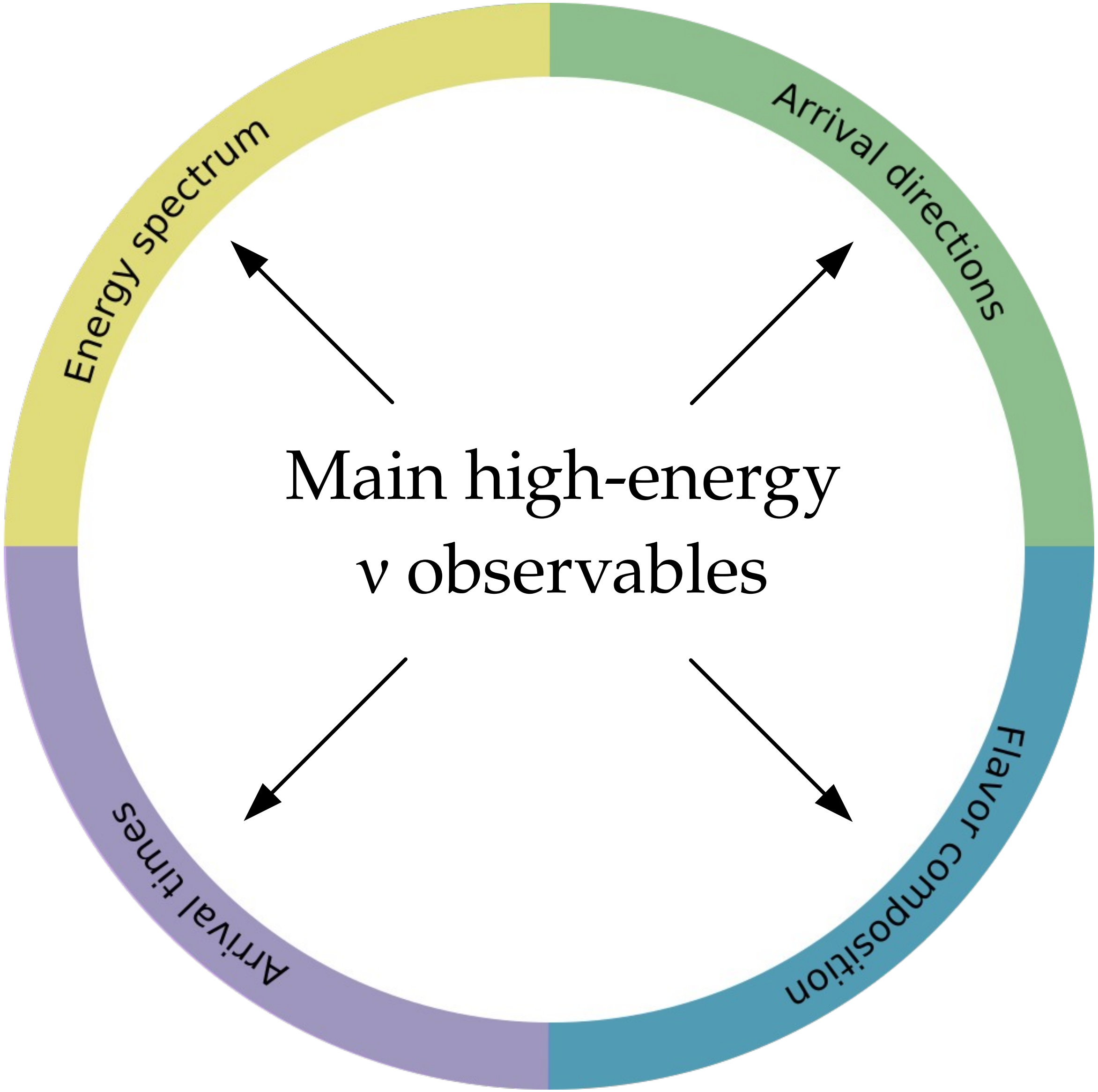


Poor angular resolution: ~10°

Track
(mainly from ν_μ)



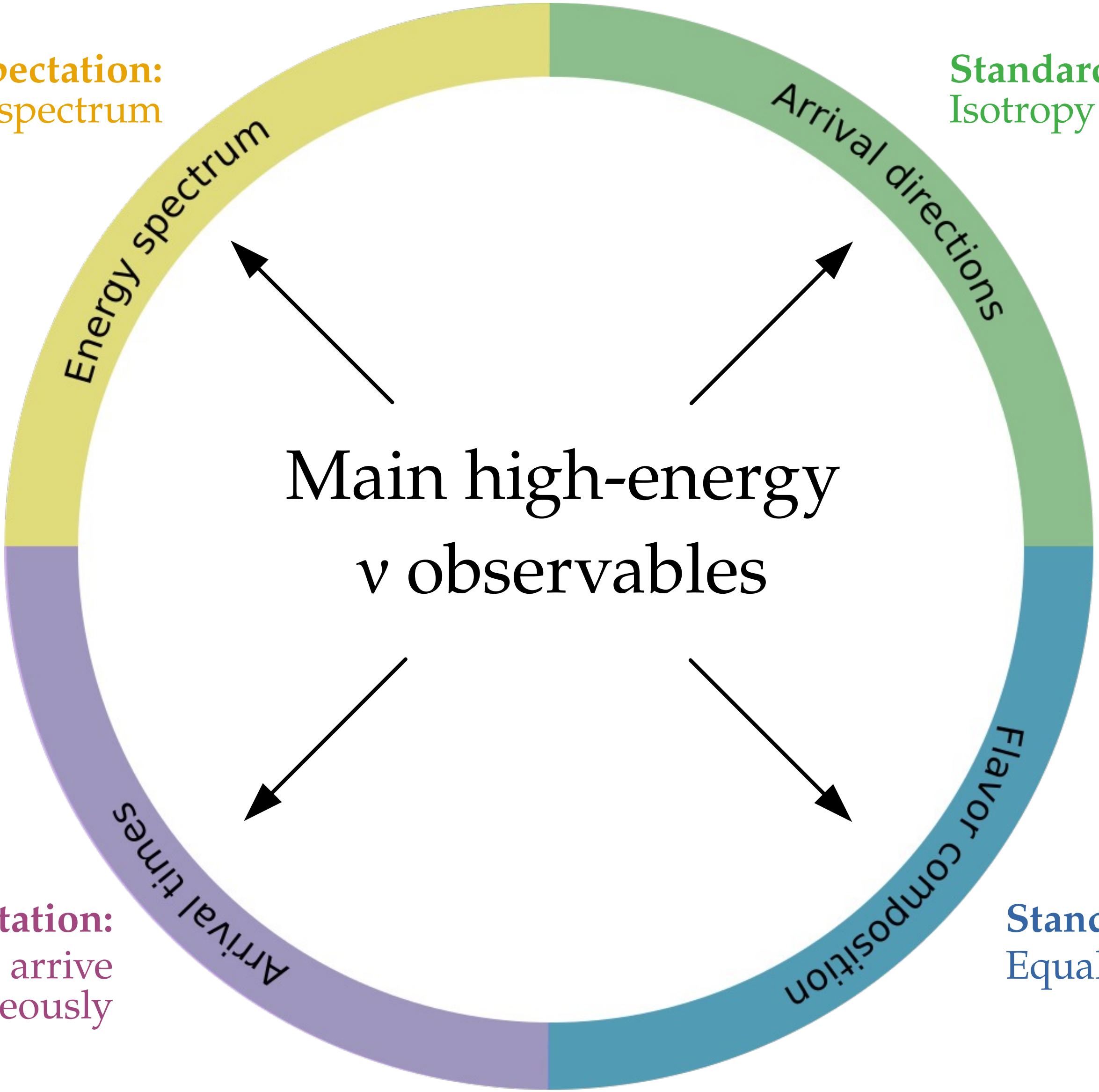
Angular resolution: < 1°



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

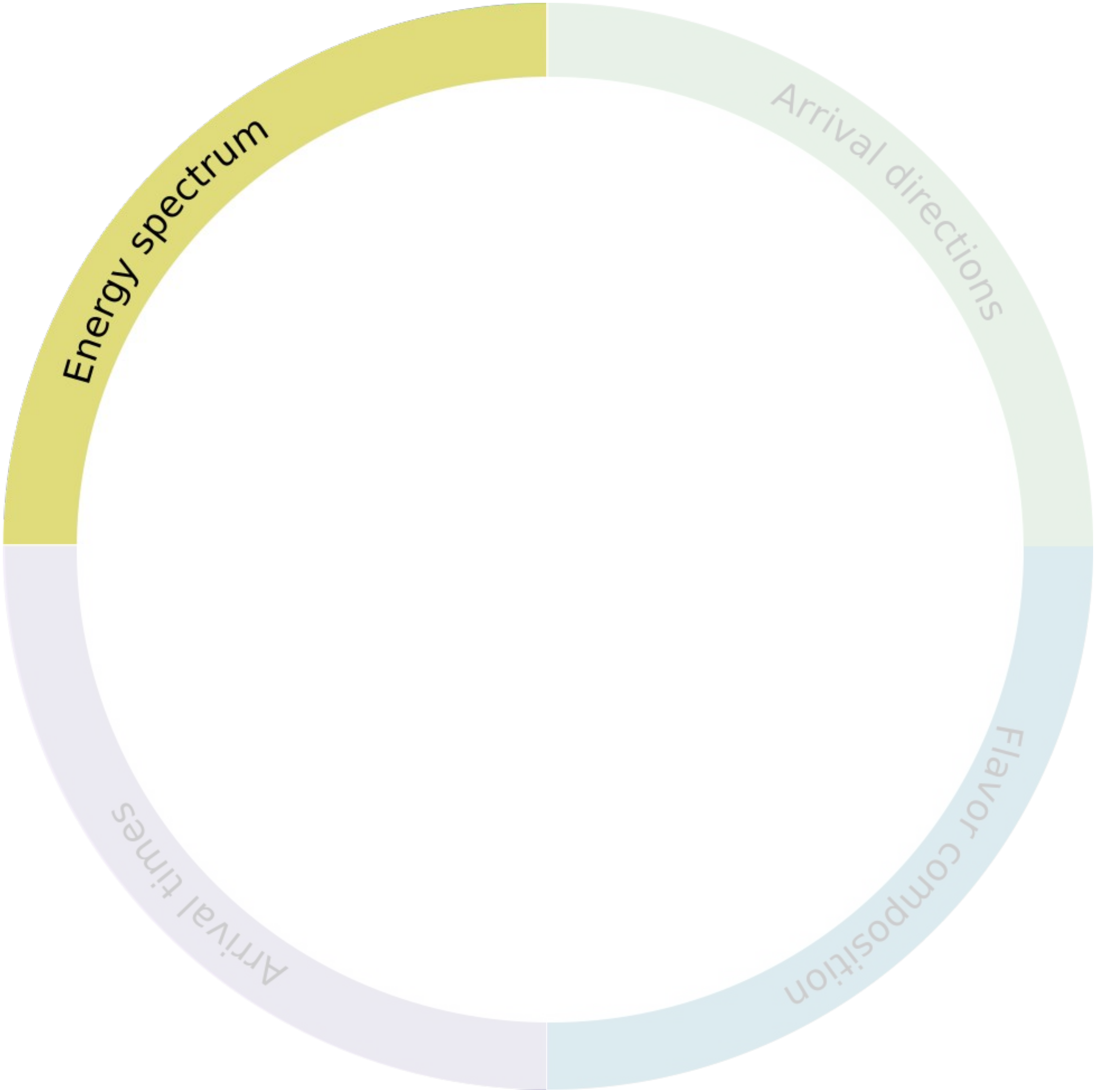
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ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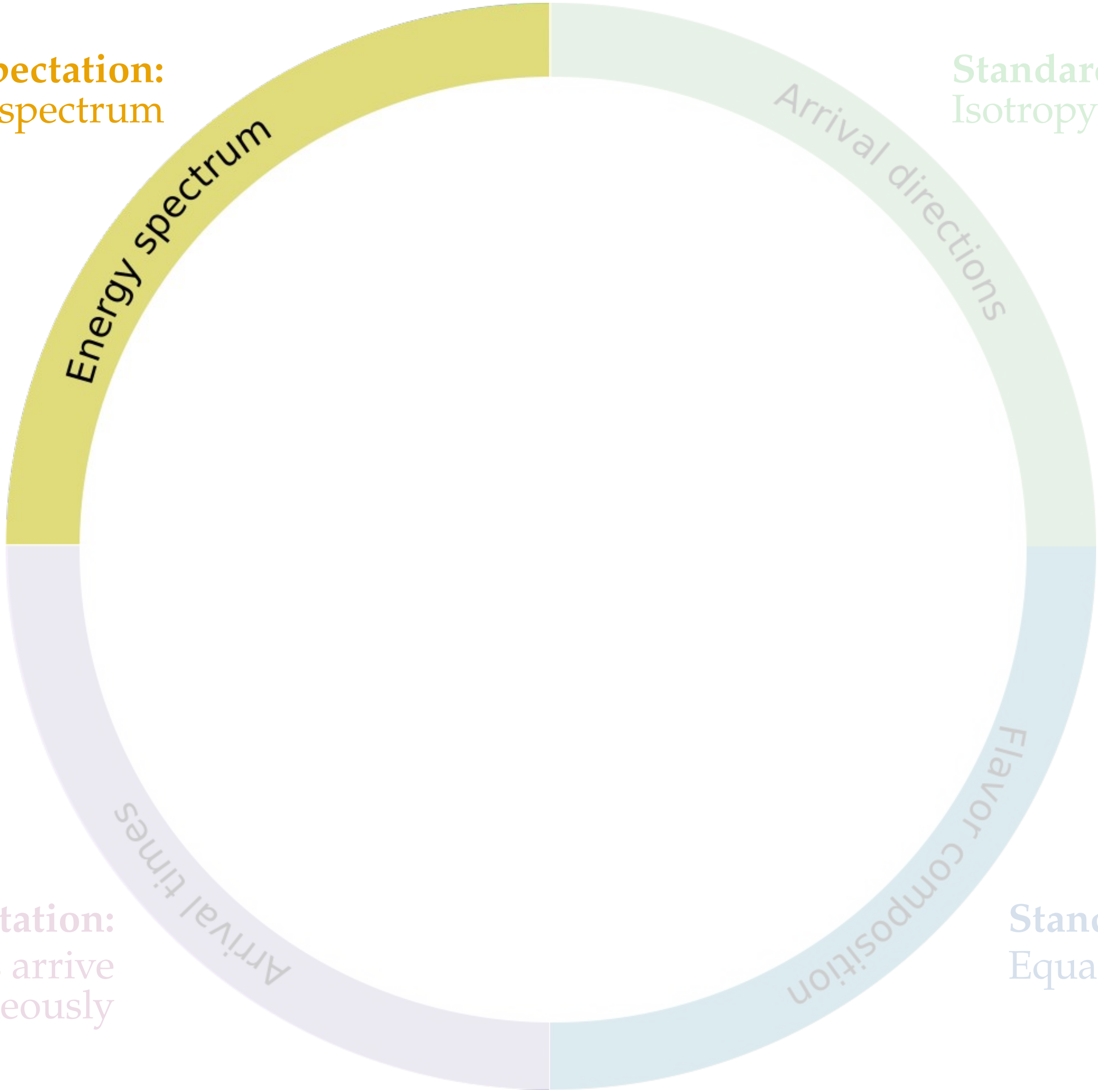
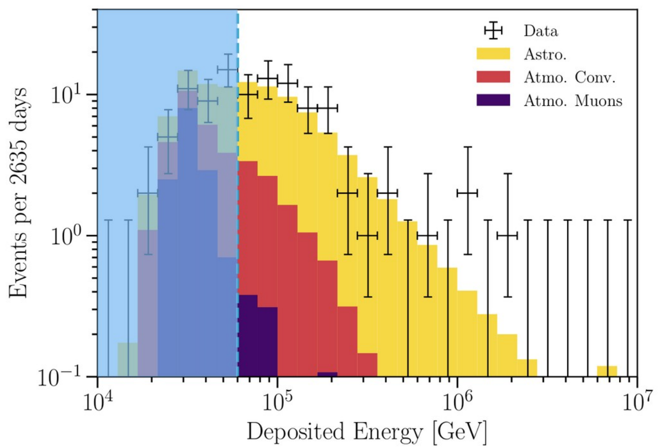


Standard expectation:
ν and γ from transients arrive simultaneously

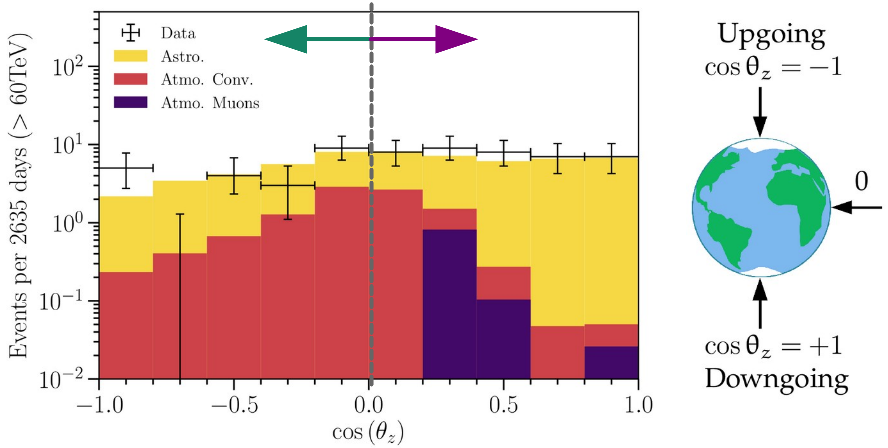
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Neutrino energy spectrum

7.5 yr: 100+ contained events > 60 TeV:

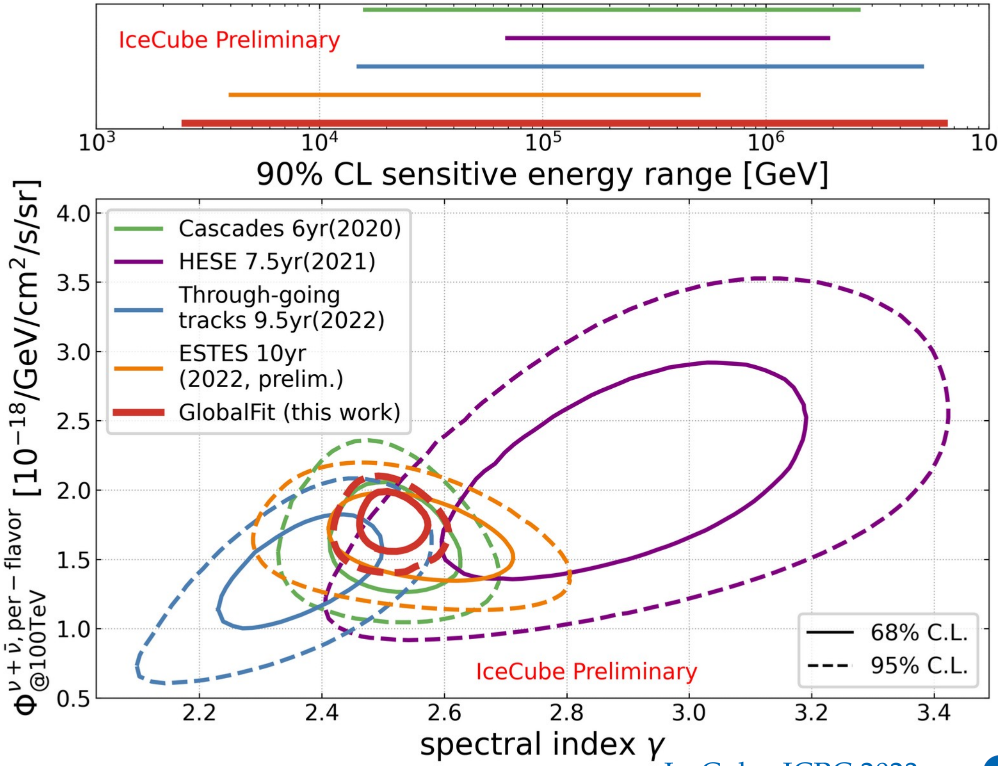


ν attenuated by Earth   Atm. ν and μ vetoed

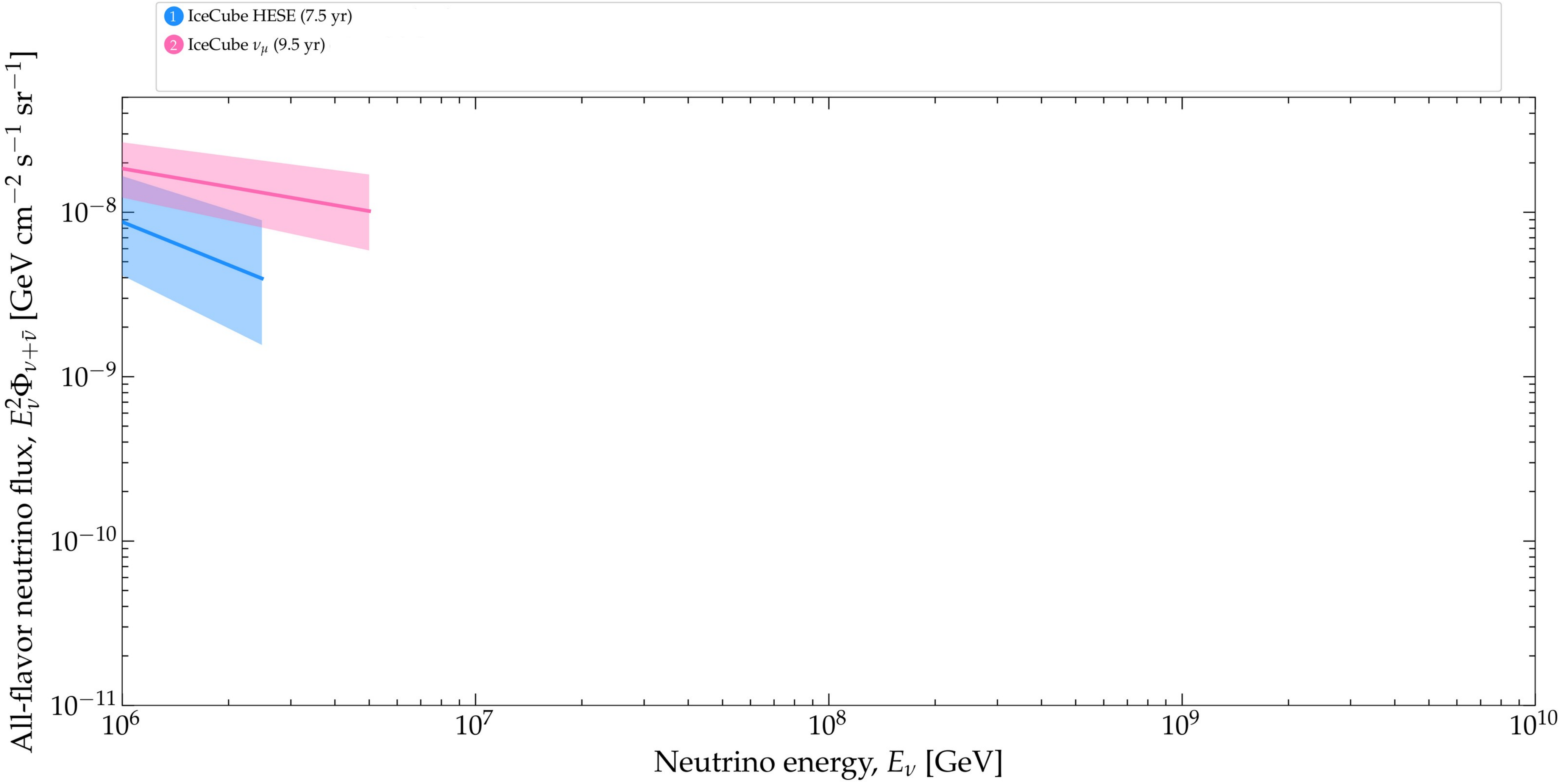


Data is fit well by a single power law:

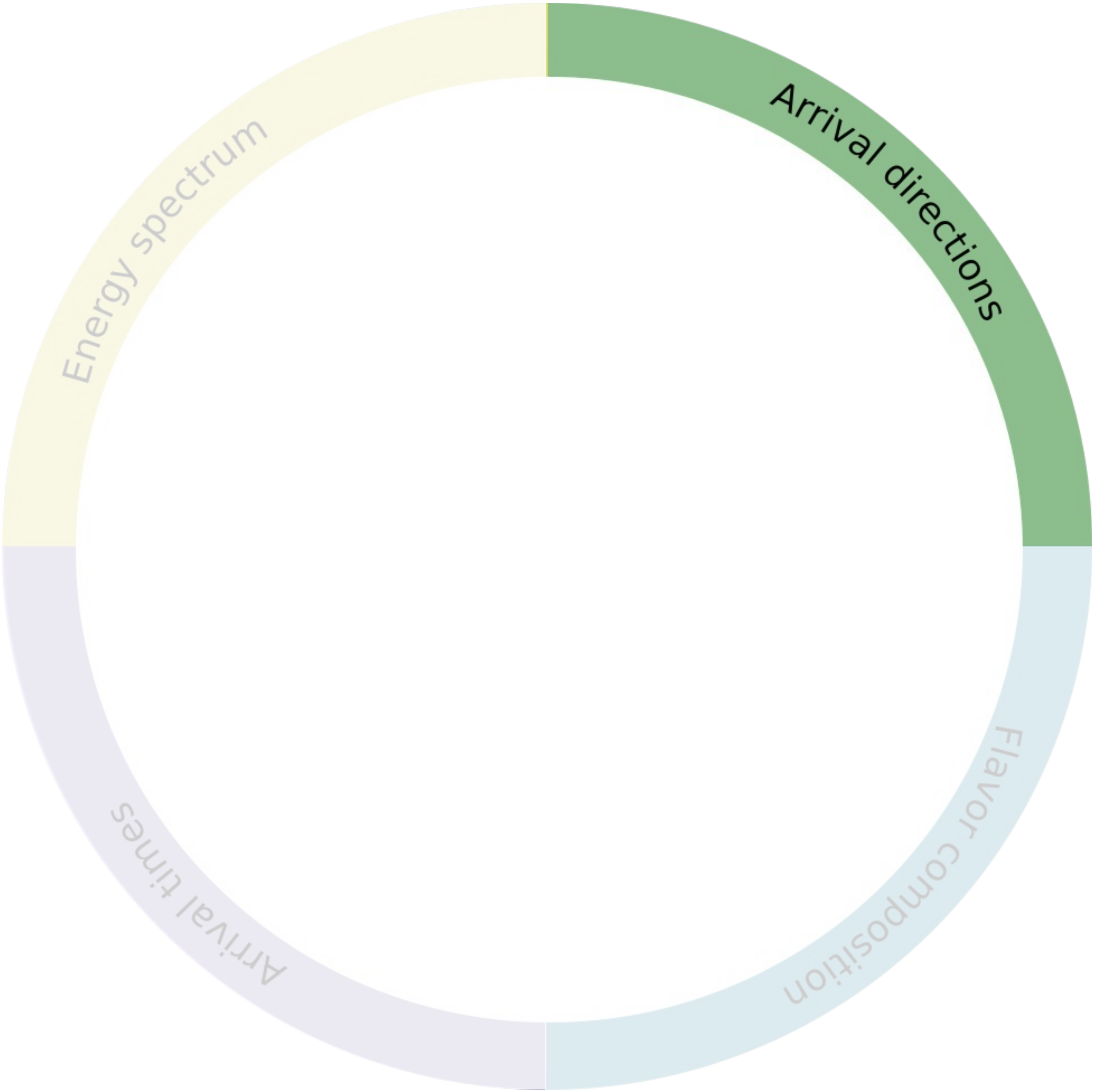
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\ \mathrm{TeV}}\right)^{-\gamma_{\mathrm{astro}}} \cdot 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$



IceCube, ICRC 2023



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]


Energy spectrum
Arrival directions
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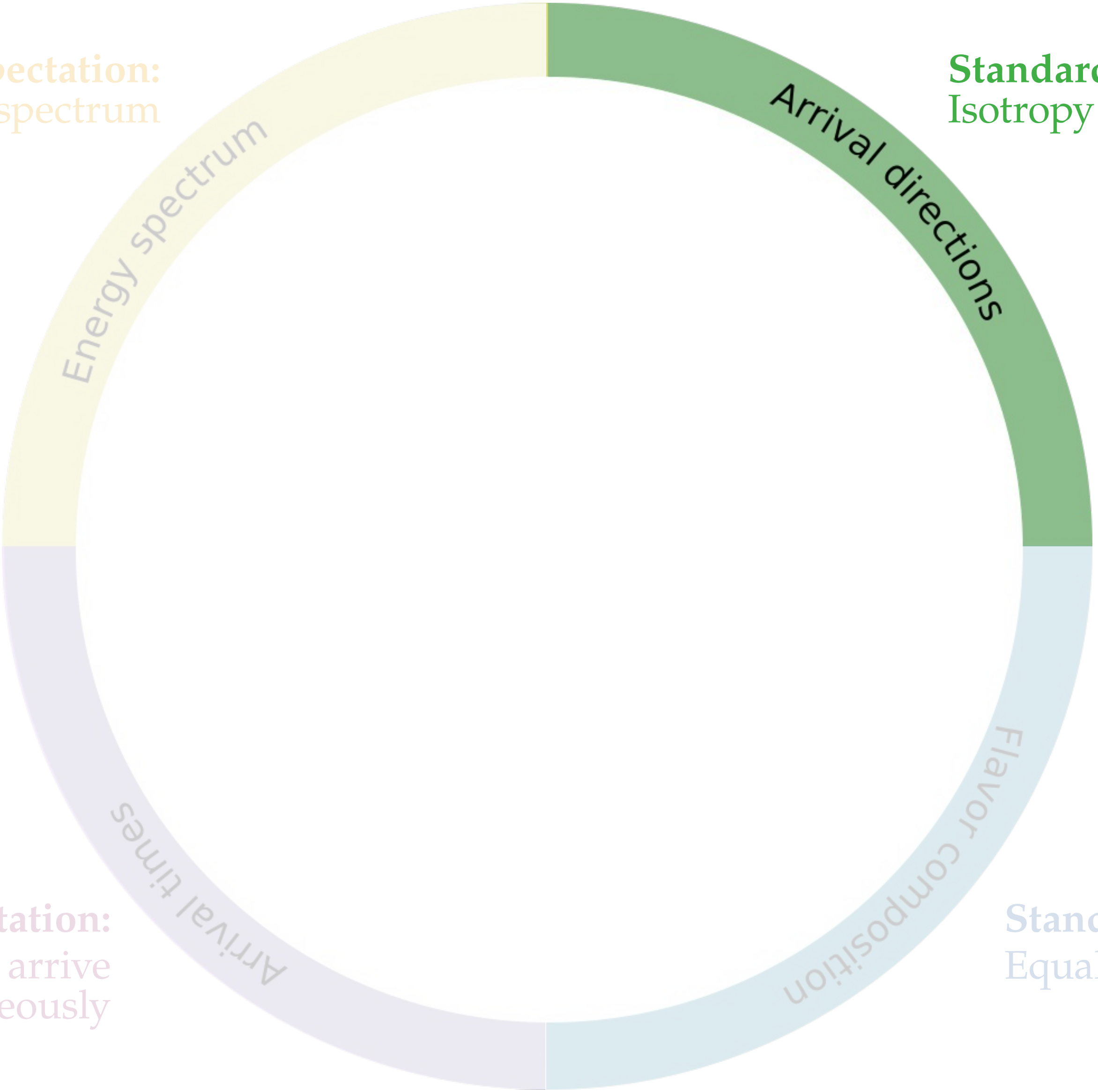
Standard expectation:
Isotropy (for diffuse flux)

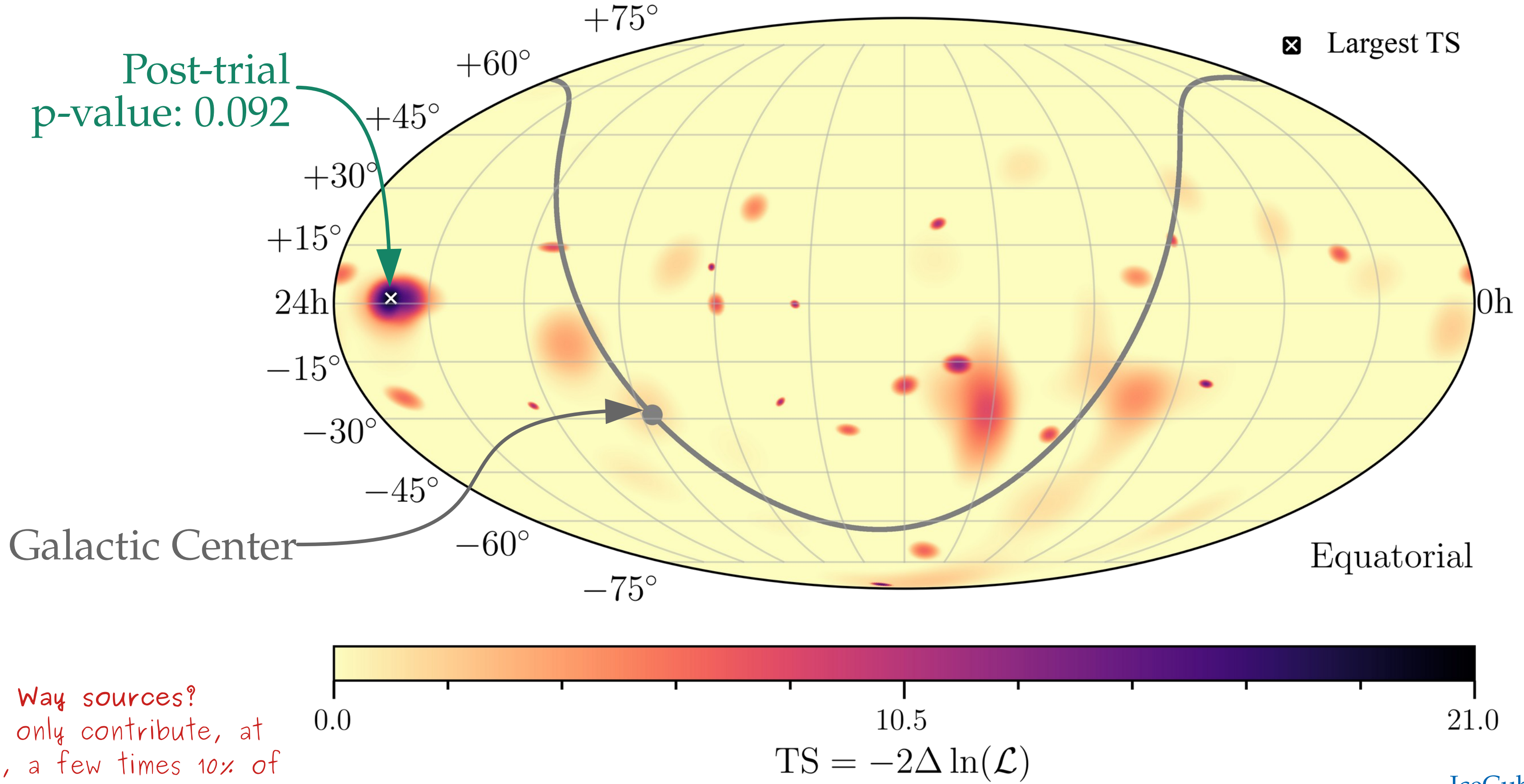


Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Arrival directions (7.5 yr)

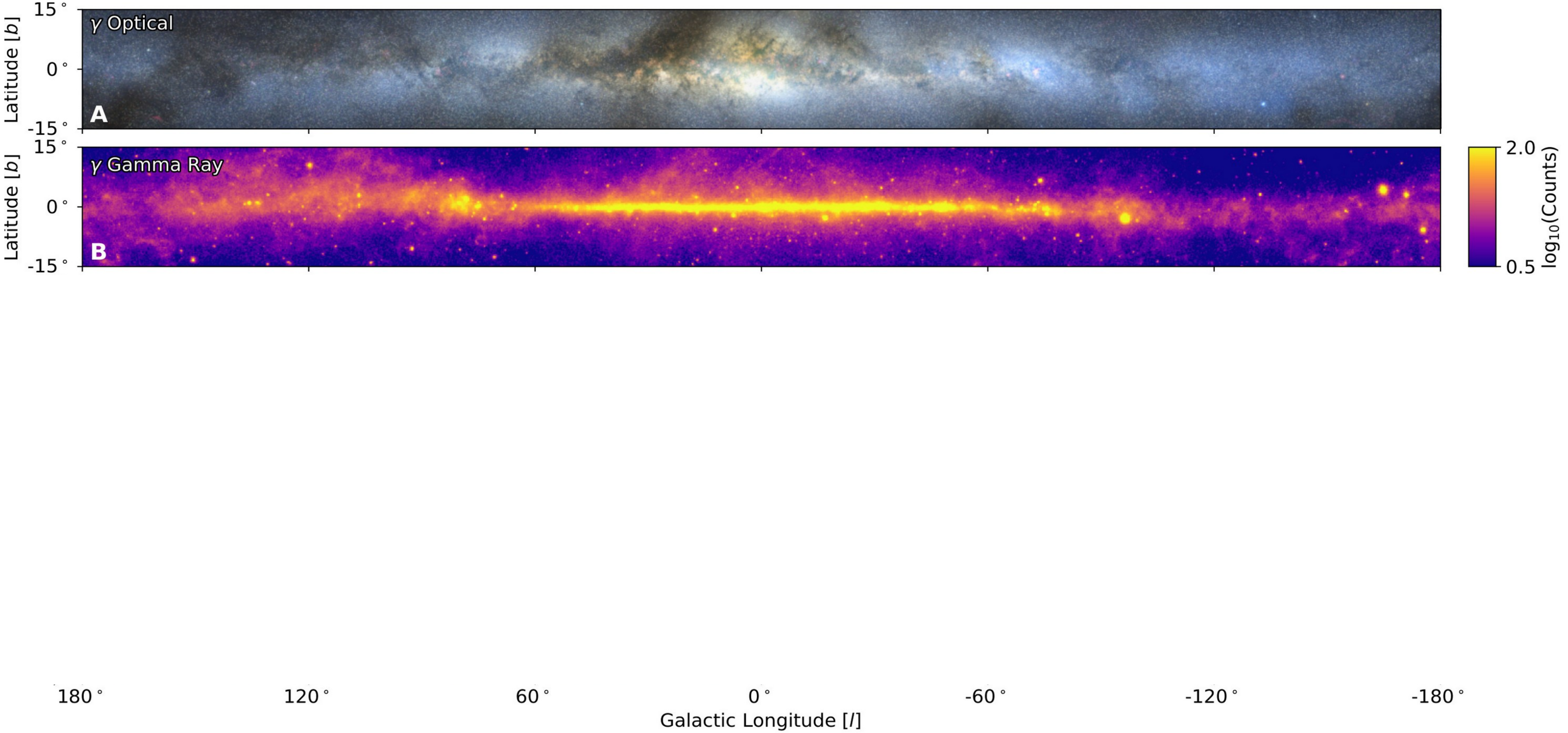
No significant excess in the neutrino sky map:



Milky Way sources?
They only contribute, at most, a few times 10% of the total diffuse flux

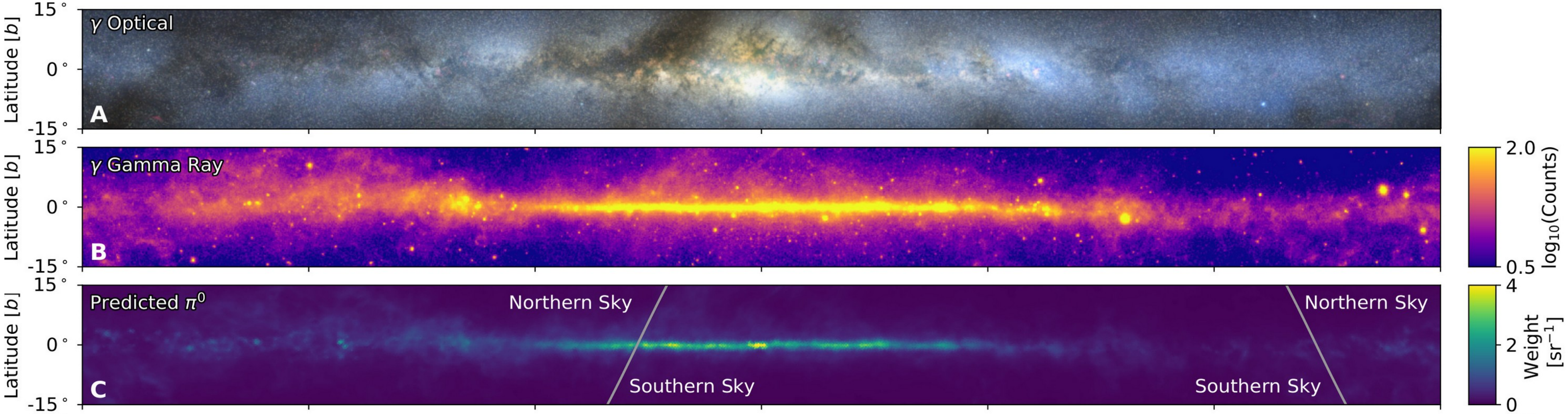
IceCube, *PRD* 2021

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \underbrace{\gamma + \gamma}$$

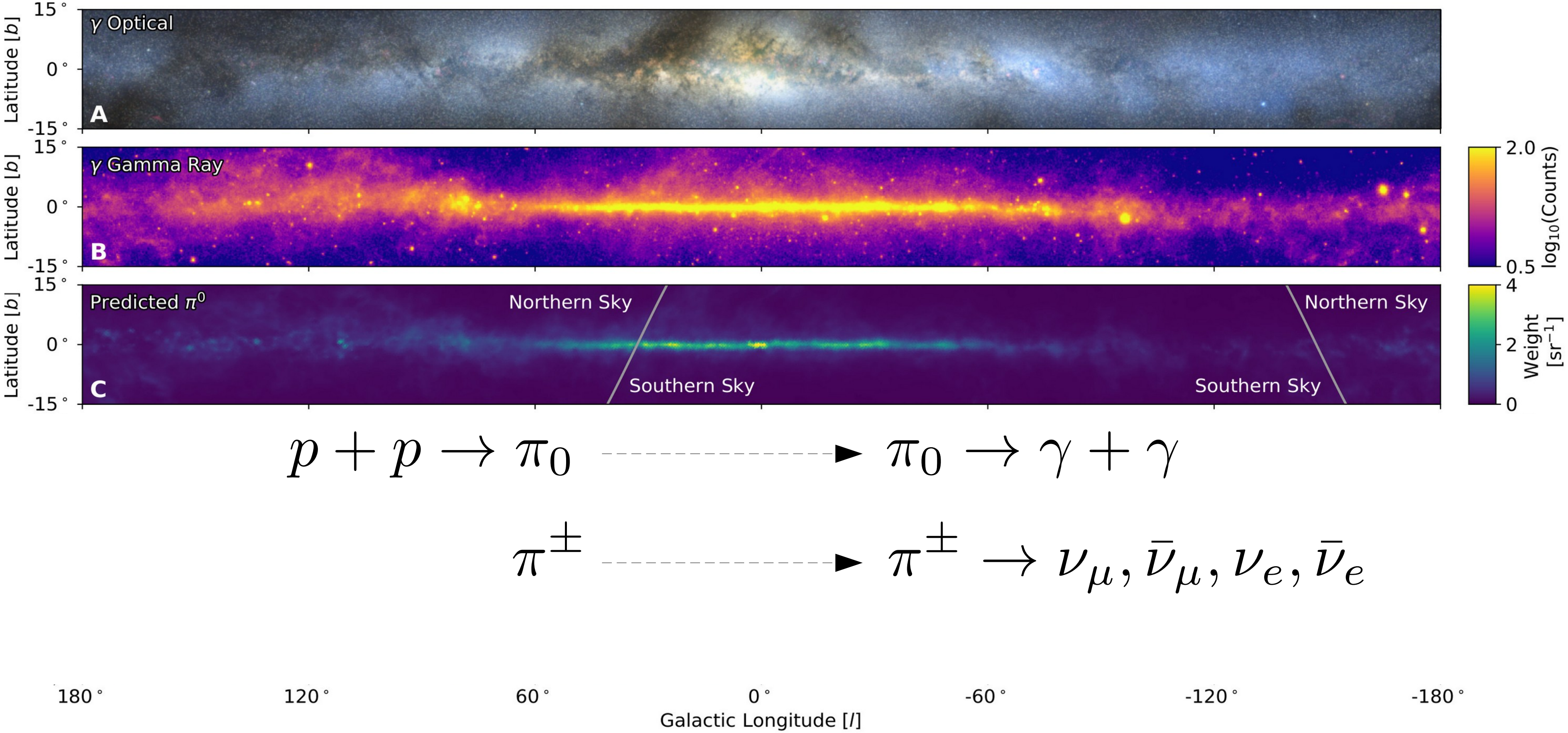
Gamma rays from the GP

Cosmic rays

Interstellar medium (aligned with GP)

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane

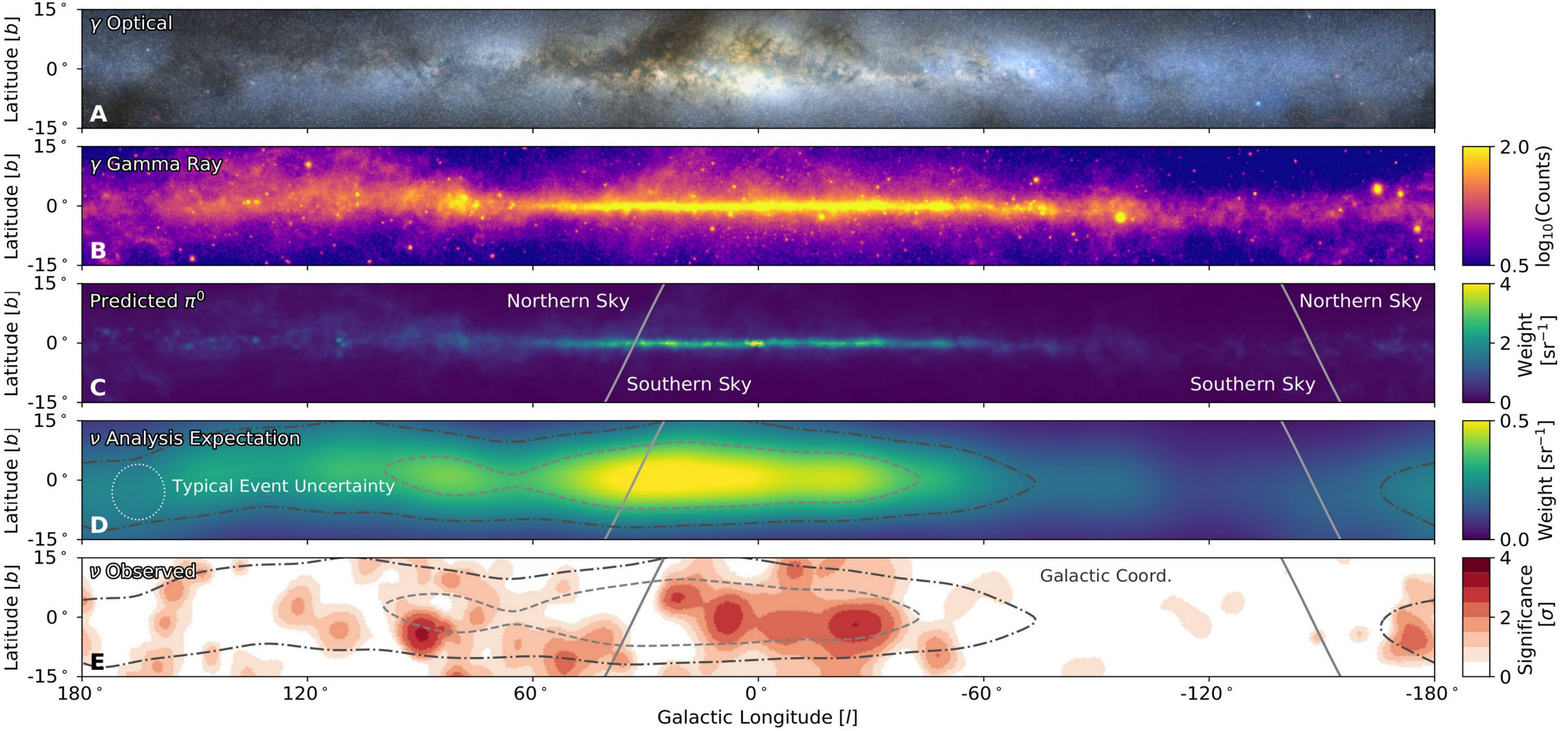


$$p + p \rightarrow \pi_0 \dashrightarrow \pi_0 \rightarrow \gamma + \gamma$$

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

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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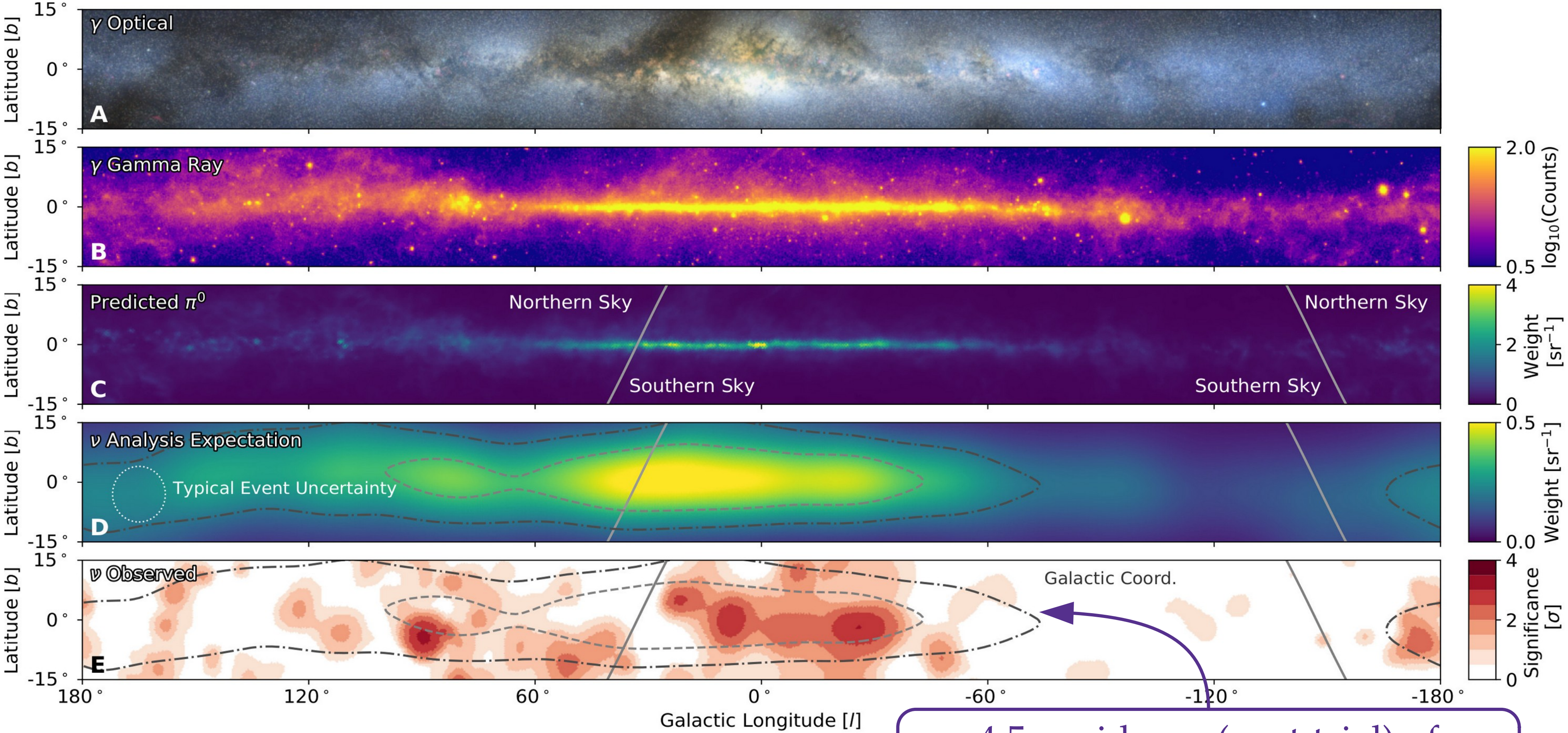
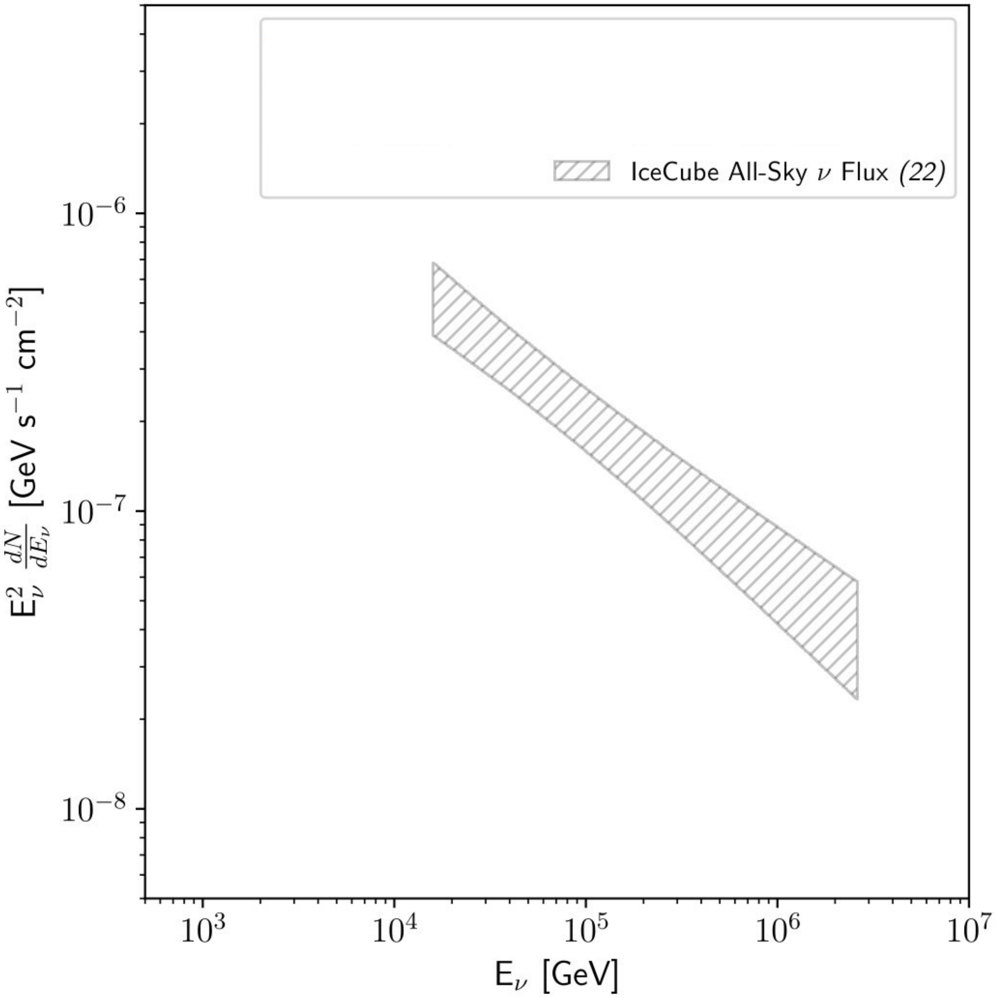


4.5σ evidence (post-trial) of diffuse flux of > TeV ν from the GP

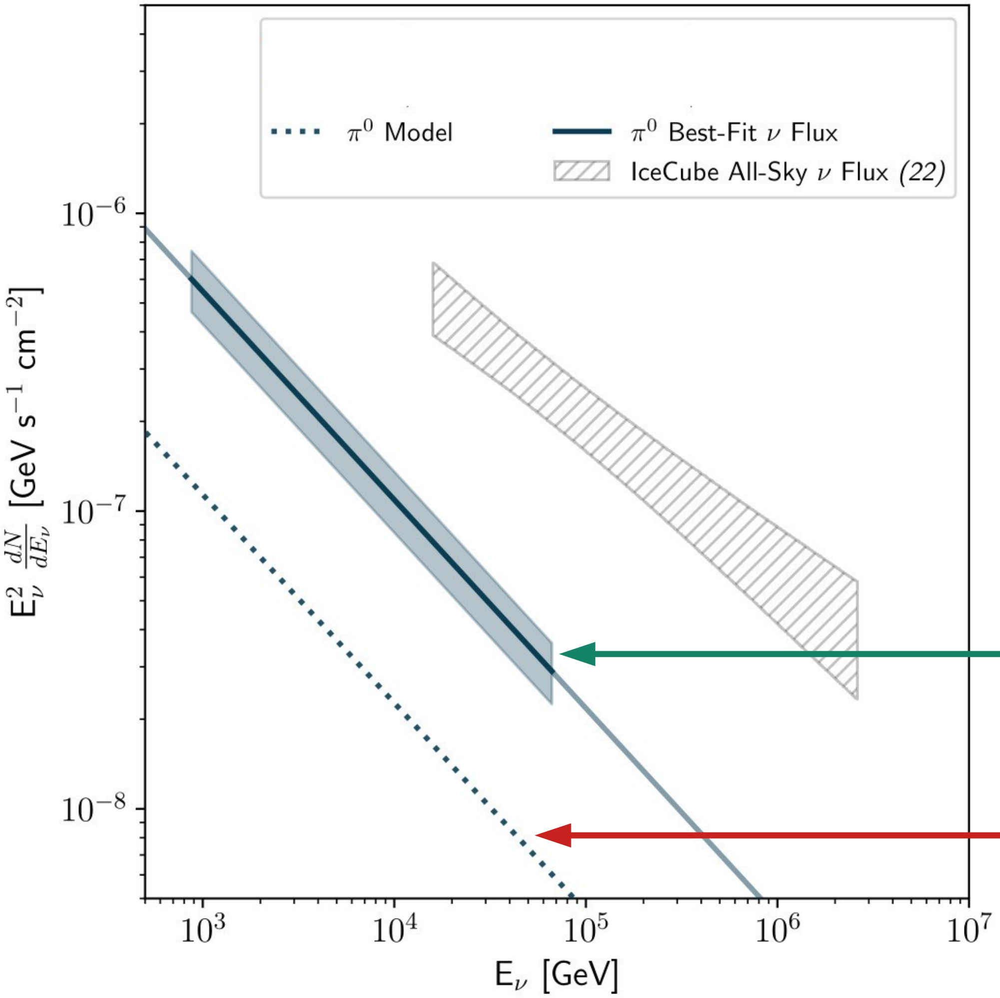
IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

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

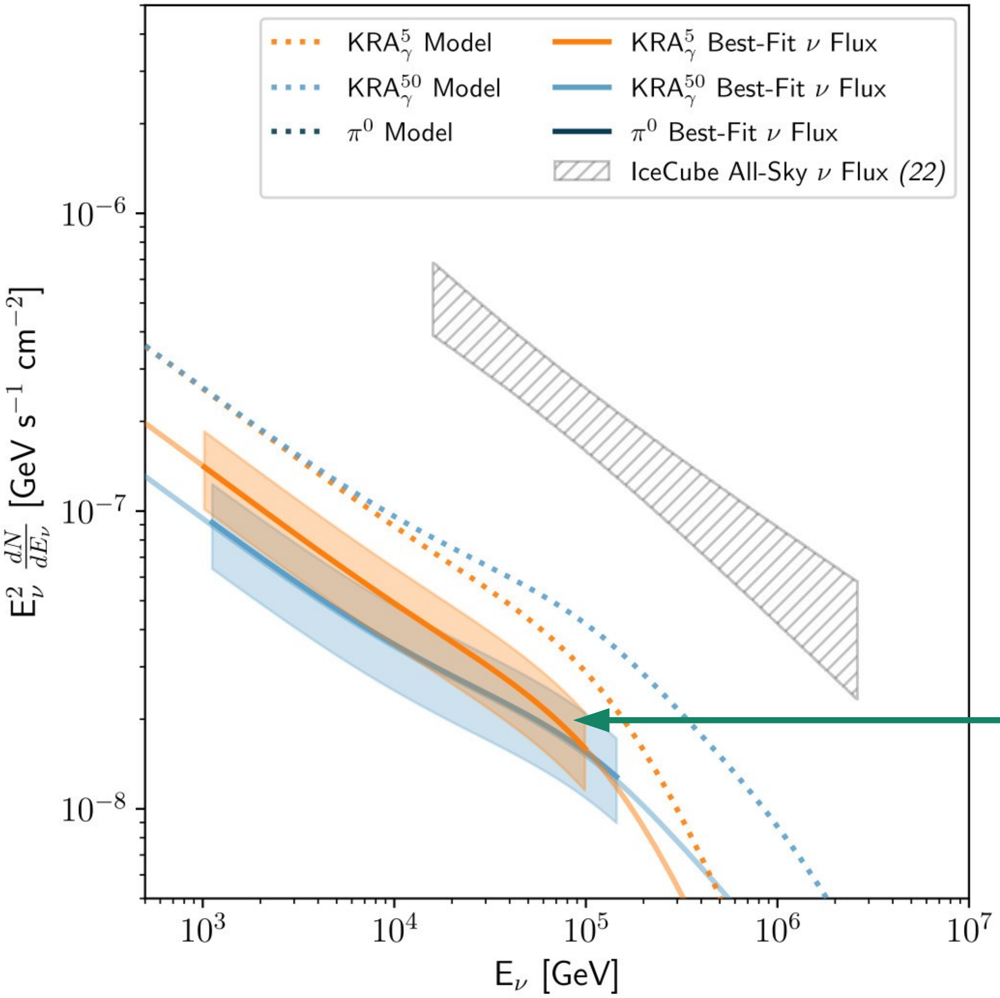
Observed (× 5 model)

Consistent with 100-TeV observations by Tibet Air Shower Array

Model

IceCube Collab., *Science* 2023

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

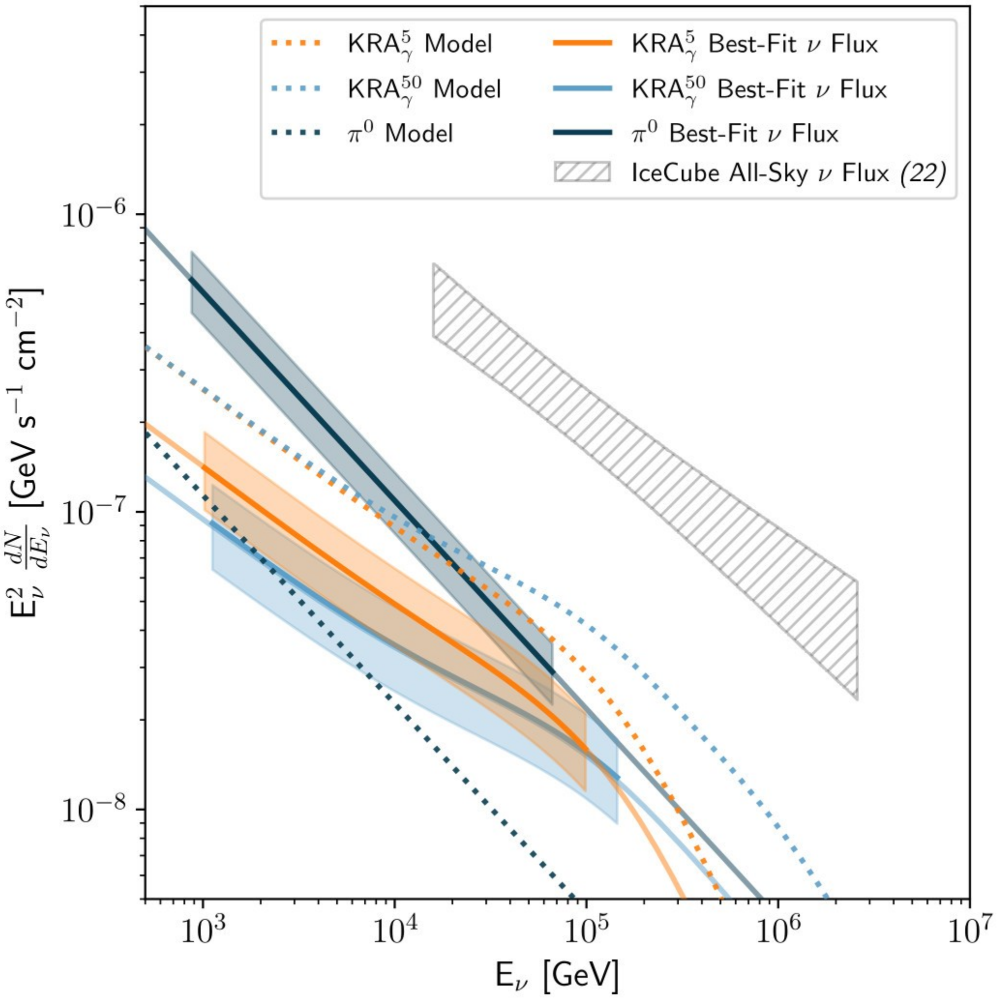
KRA_γ^{50}: Cut-off at 50 PeV in CR energy

Observed ($\times$ 0.5 model)

Cut-off energy could be different from the 5 and 50 PeV tested

IceCube Collab., *Science* 2023

High-energy neutrinos from the Galactic Plane



IceCube Collab., *Science* 2023

Three models of Galactic diffuse ν:

π^0: MeV–GeV π⁰ 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

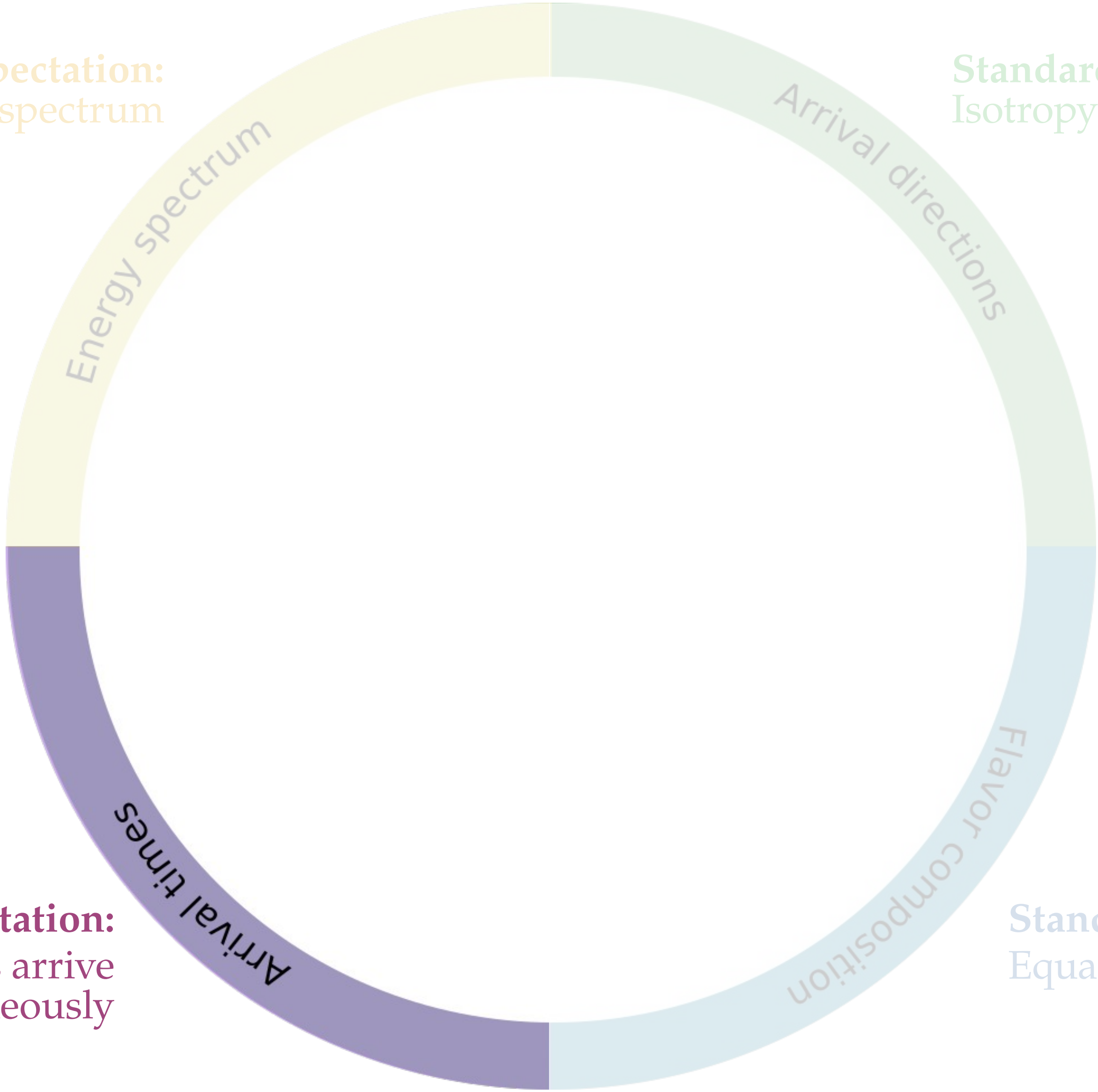
(likely diffuse + source: Fang & Murase, 2307.02905)

GP flux is 6–13% of all-sky at 30 TeV

Energy spectrum
Arrival directions
Flavor composition
Arrival times

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



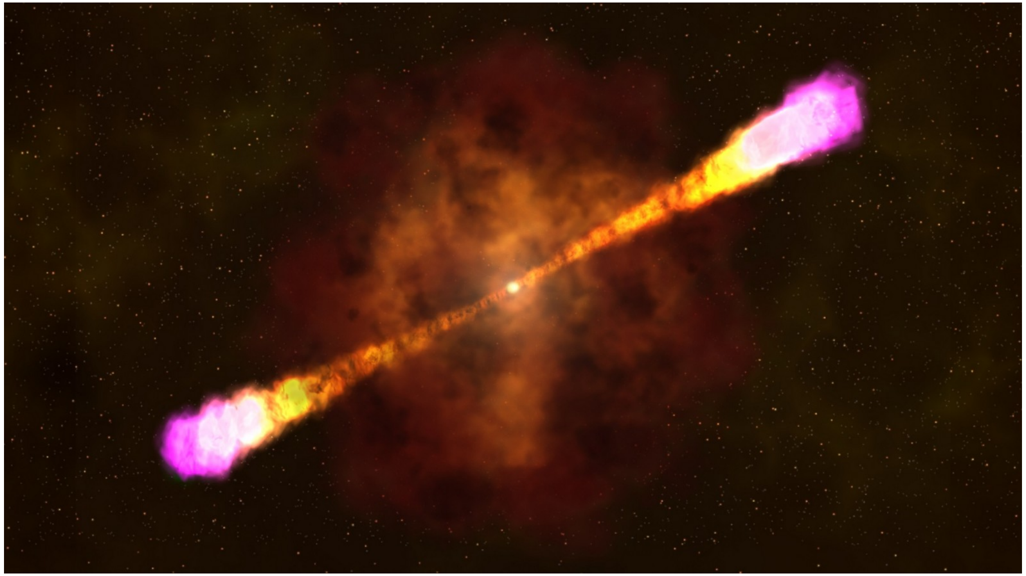
Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Gamma-ray bursts and blazars – *not* dominant

Energy in neutrinos $\propto$ energy in gamma rays

Gamma-ray bursts

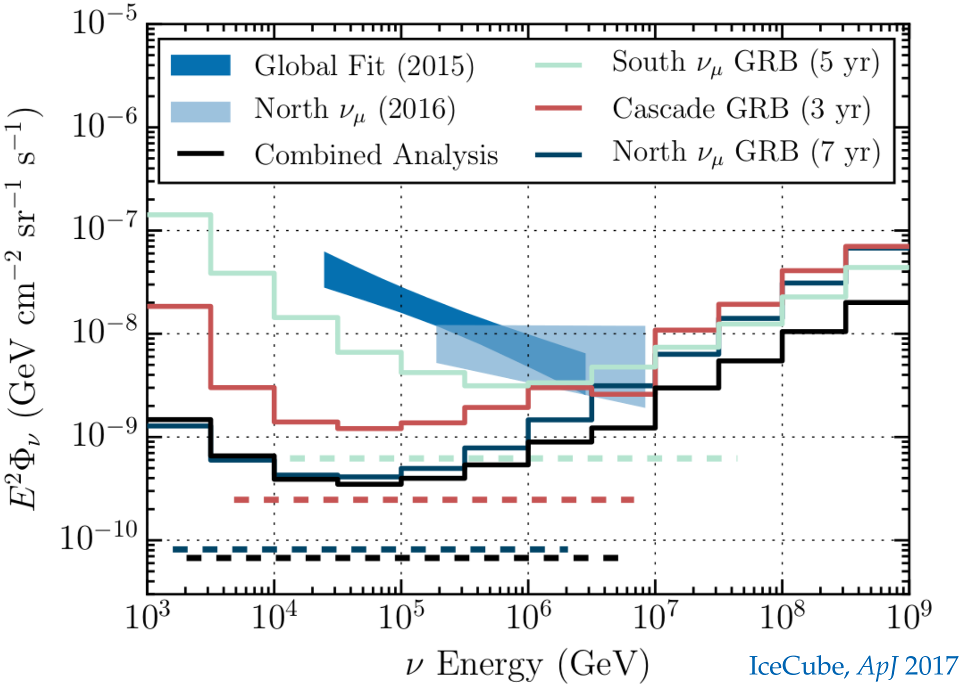


Blazars

Gamma-ray bursts and blazars – *not* dominant

Energy in neutrinos ∝ energy in gamma rays

Gamma-ray bursts

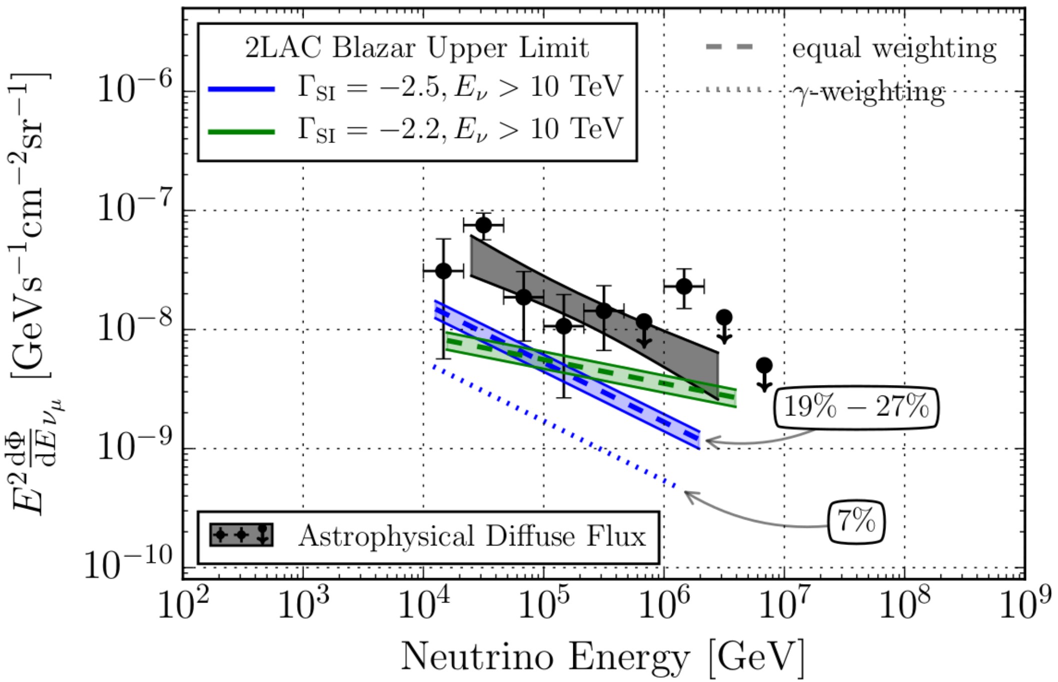


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

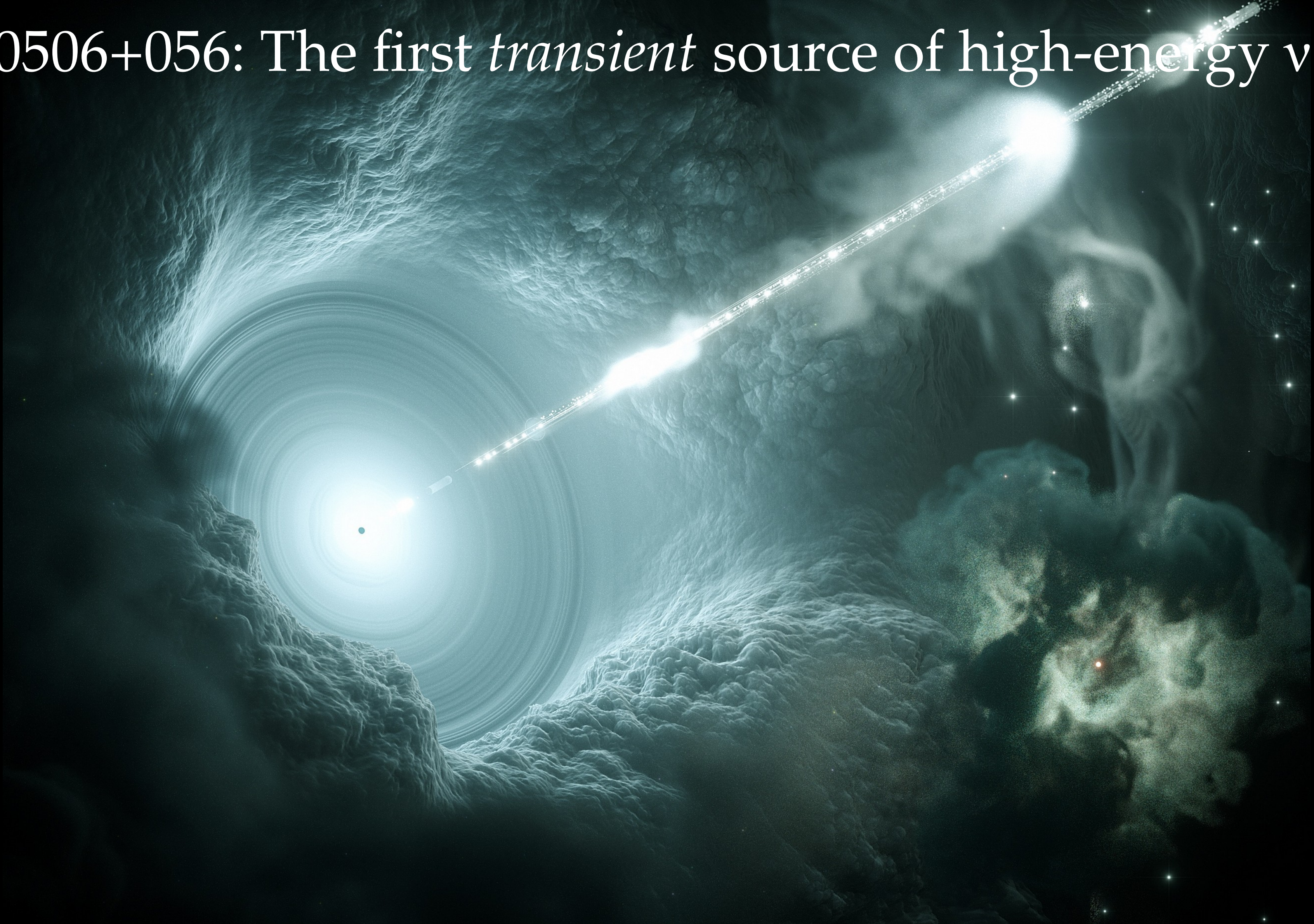
Blazars



862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

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

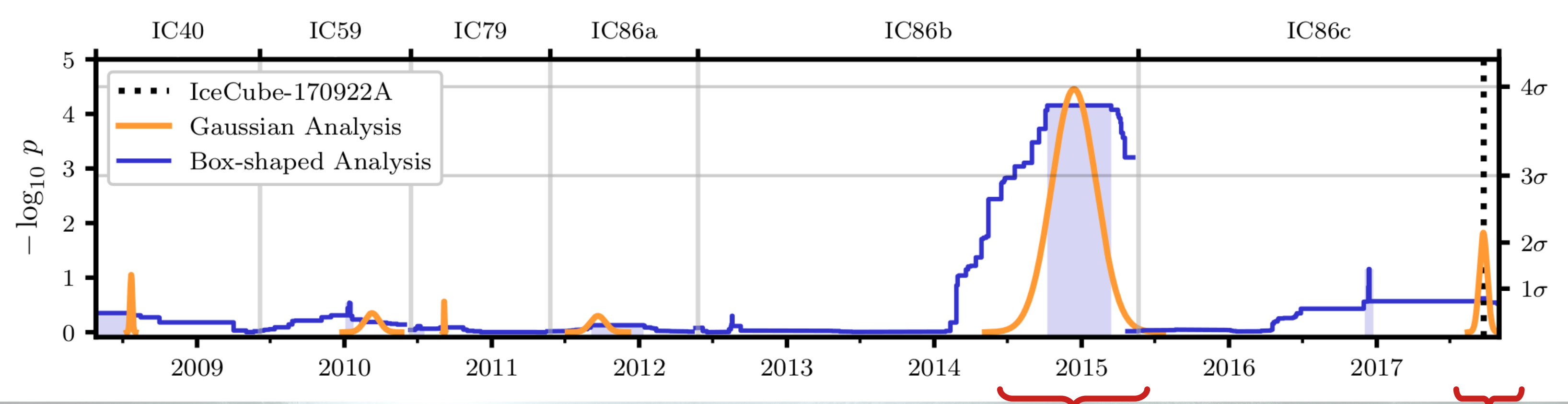


DESY

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

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

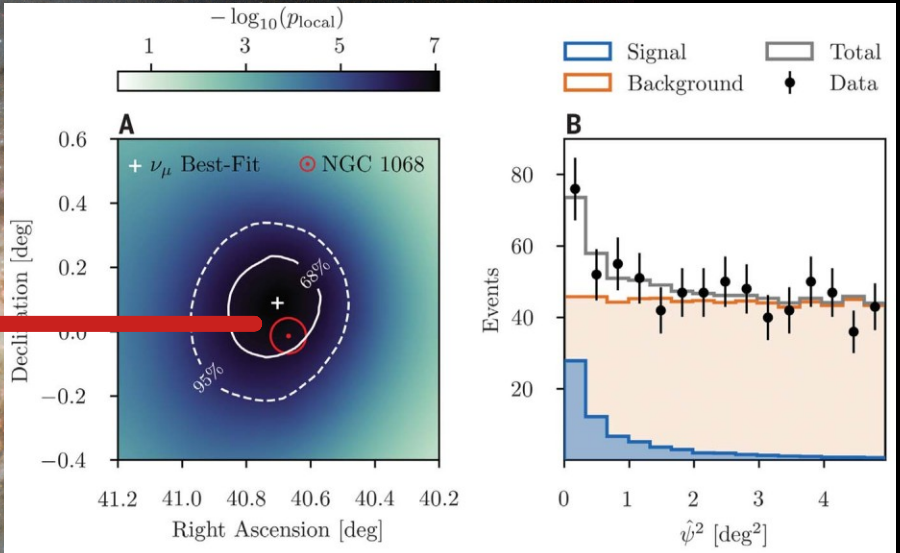
NGC1068: The first *steady-state* source of high-energy ν

Active galactic nucleus

Brightest type-2 Seyfert

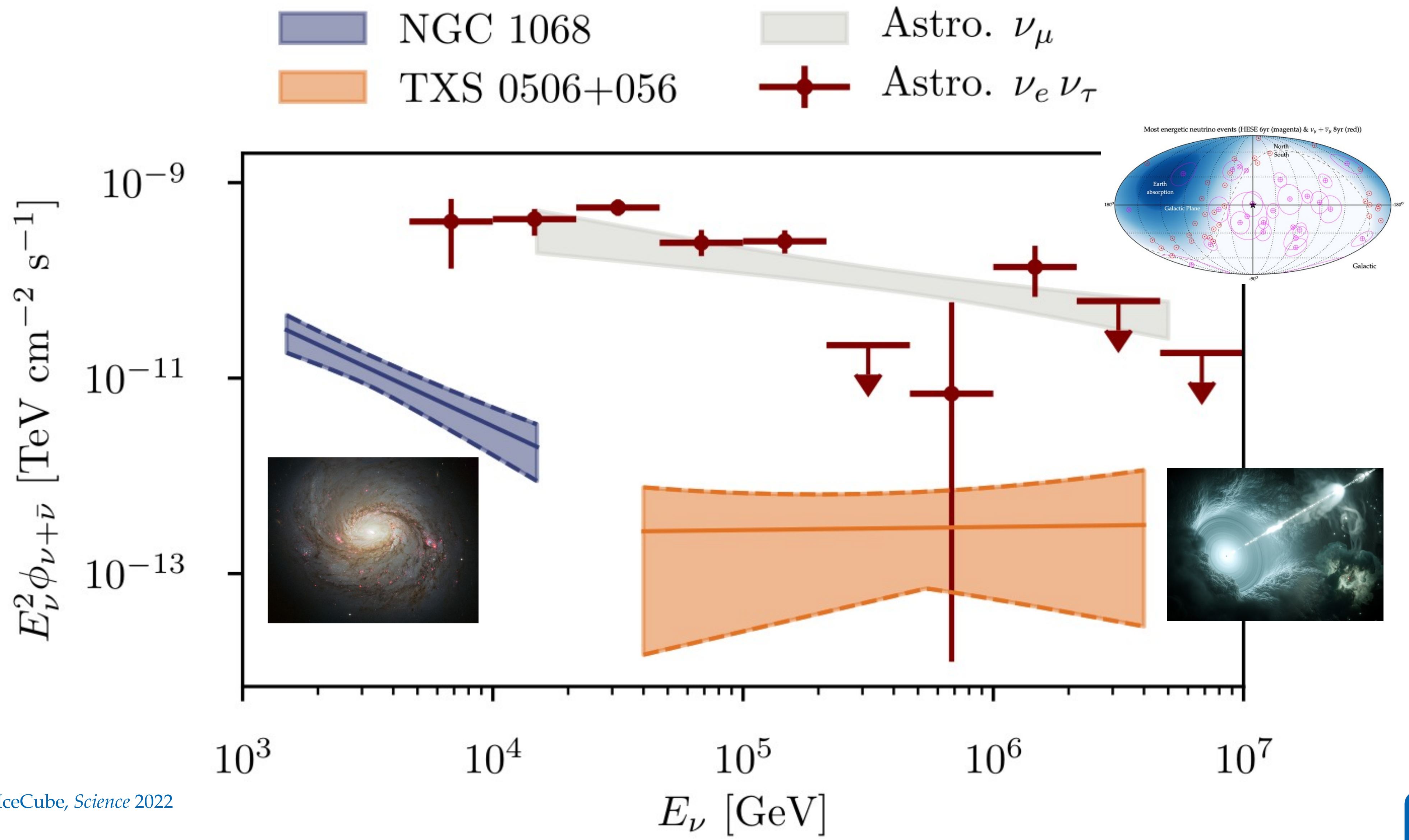
79^{+22}_{-20} ν of TeV energy

Significance: 4.2σ (global)



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

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

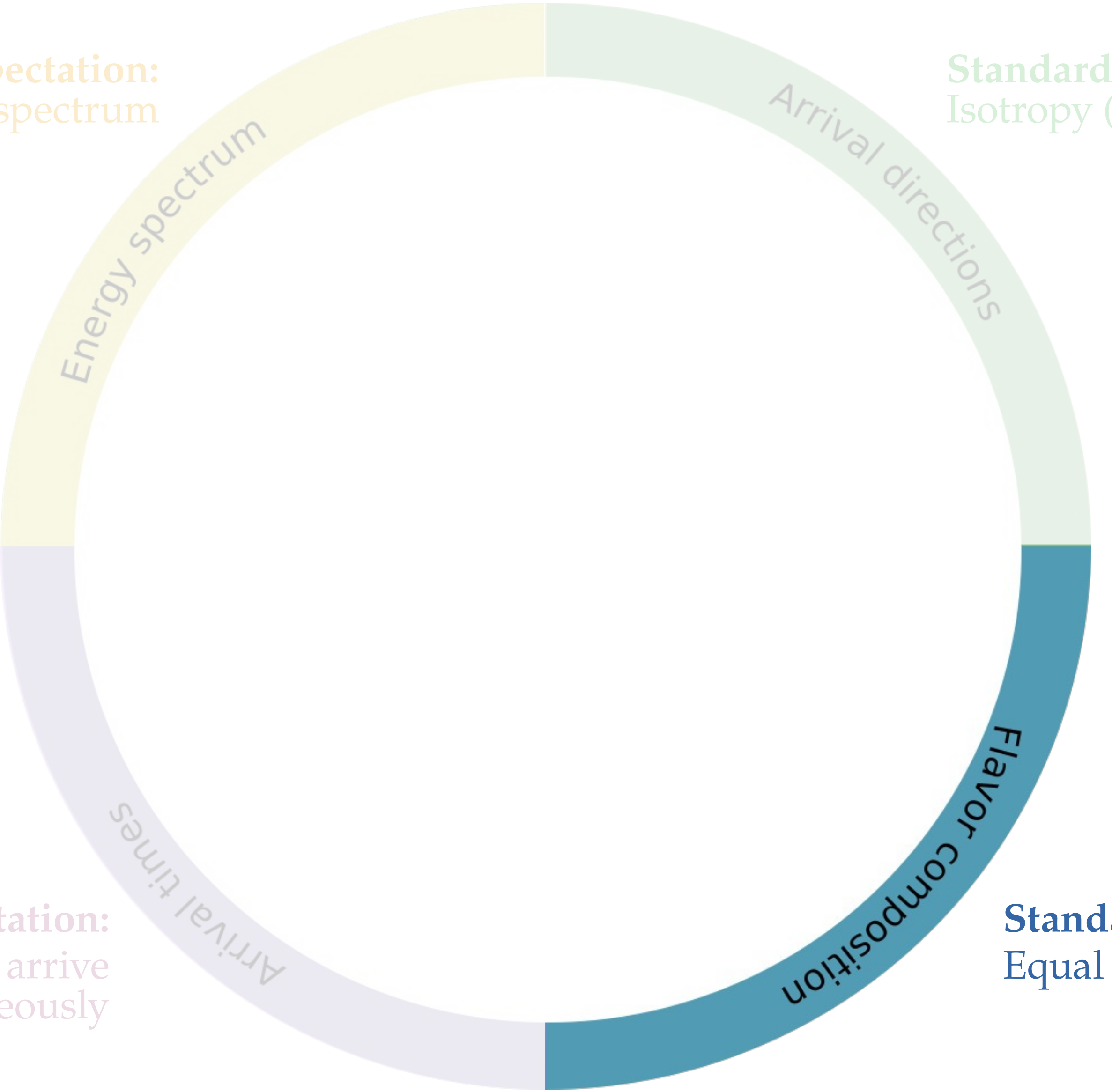


IceCube, *Science* 2022


Energy spectrum
Arrival directions
Arrival times
Flavor composition

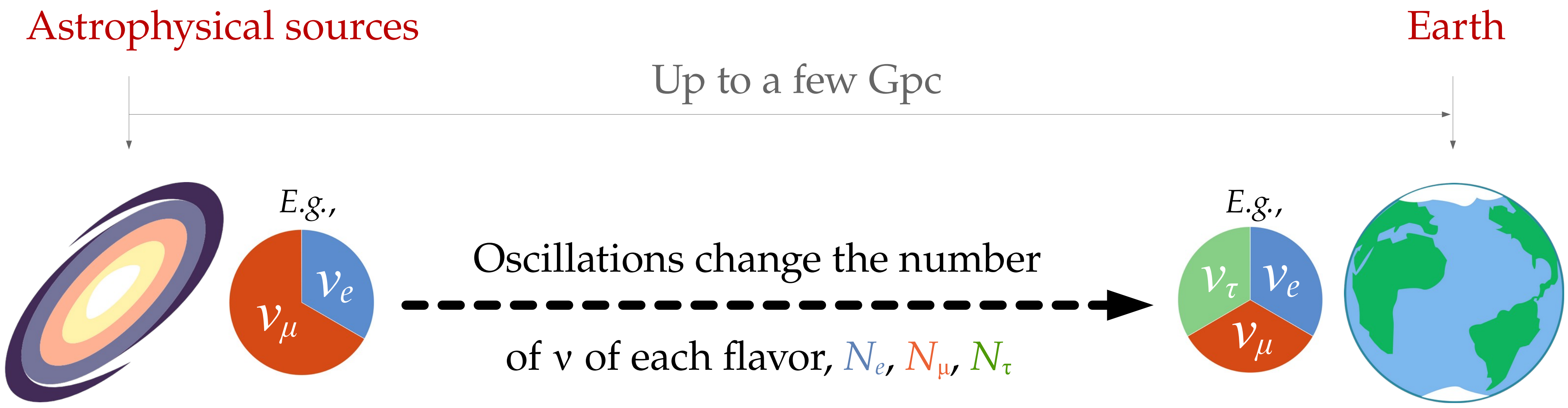
Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

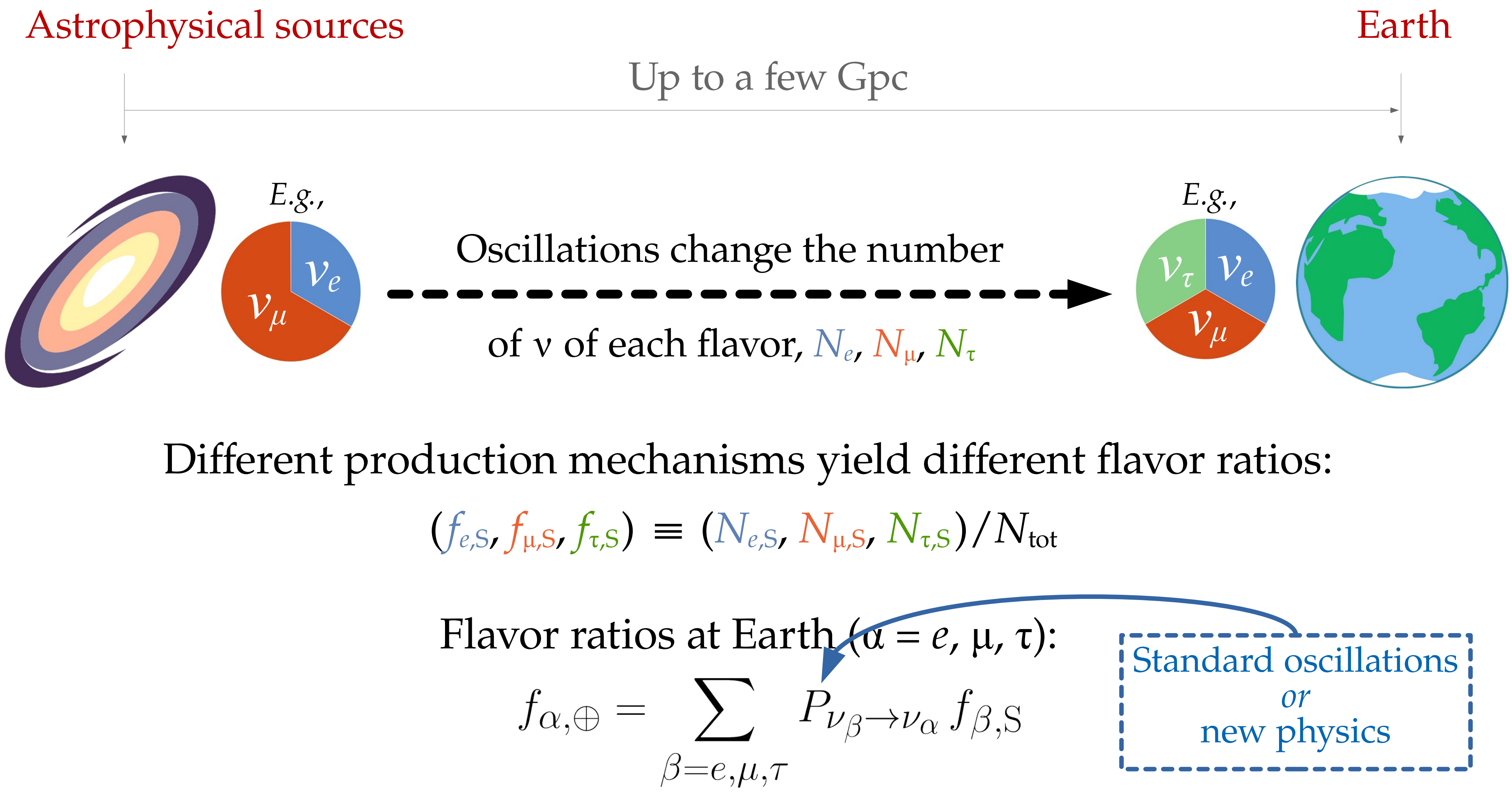


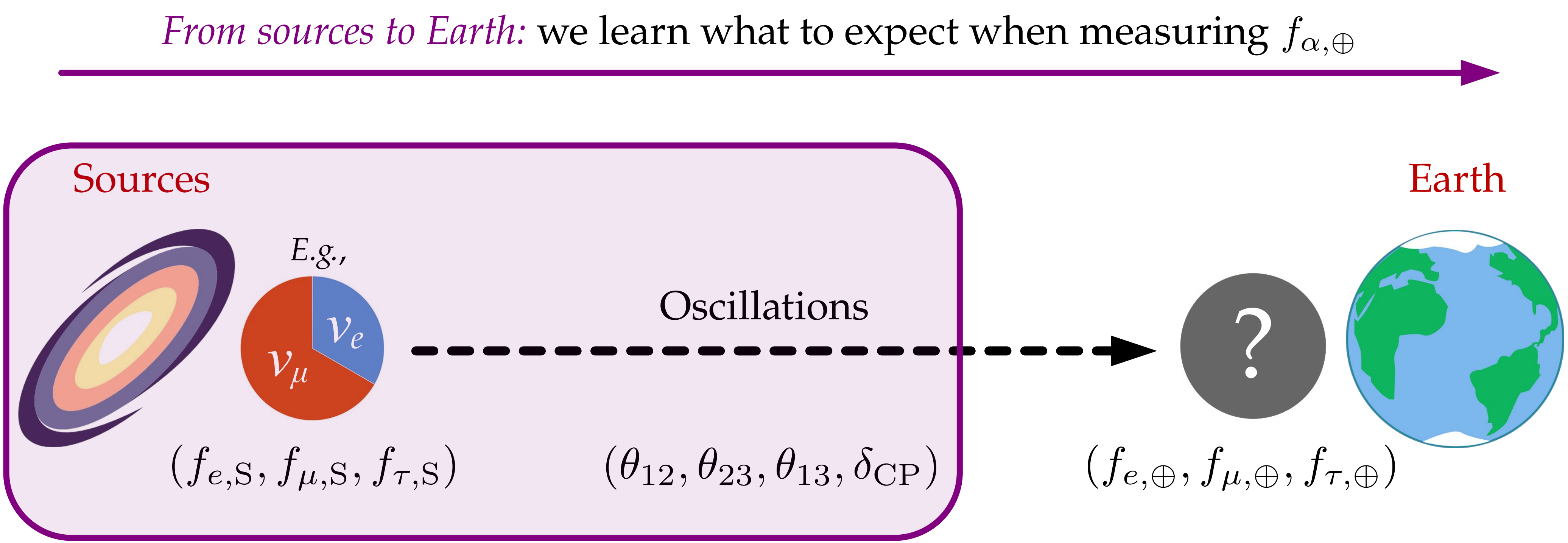
Different production mechanisms yield different flavor ratios:

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

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

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


Astrophysical sources
Earth
Up to a few Gpc
E.g.,
ν_e
ν_μ
Oscillations change the number
of ν of each flavor, N_e, N_μ, N_τ
E.g.,
ν_τ
ν_e
ν_μ
Different production mechanisms yield different flavor ratios:
$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$
Flavor ratios at Earth ($\alpha = e, \mu, \tau$):
$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$
Standard oscillations
or
new physics


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

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

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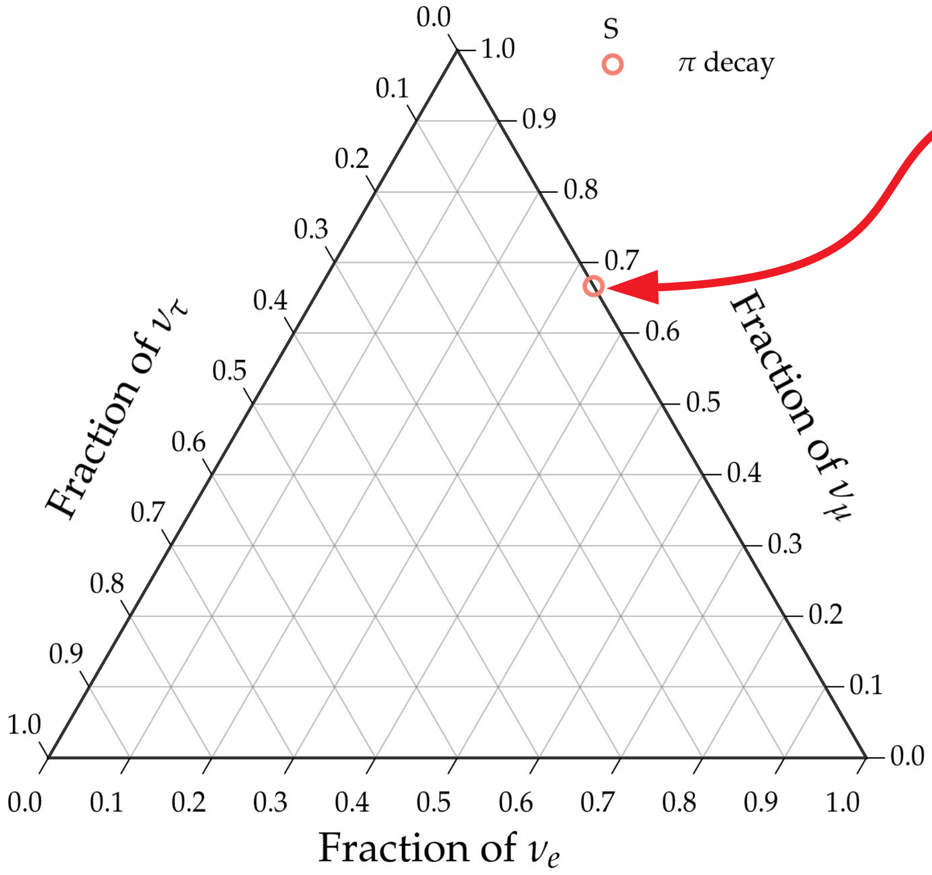

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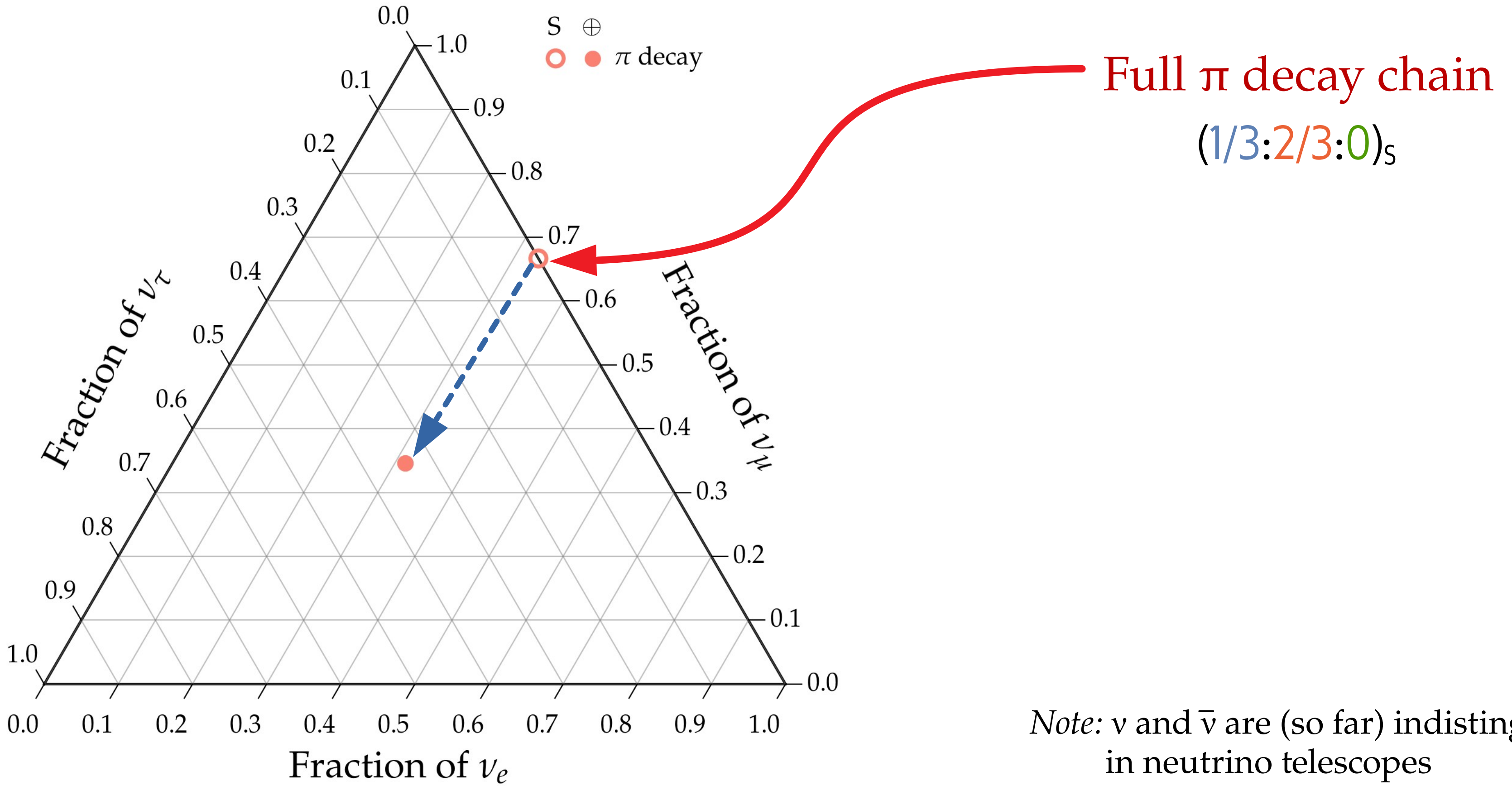

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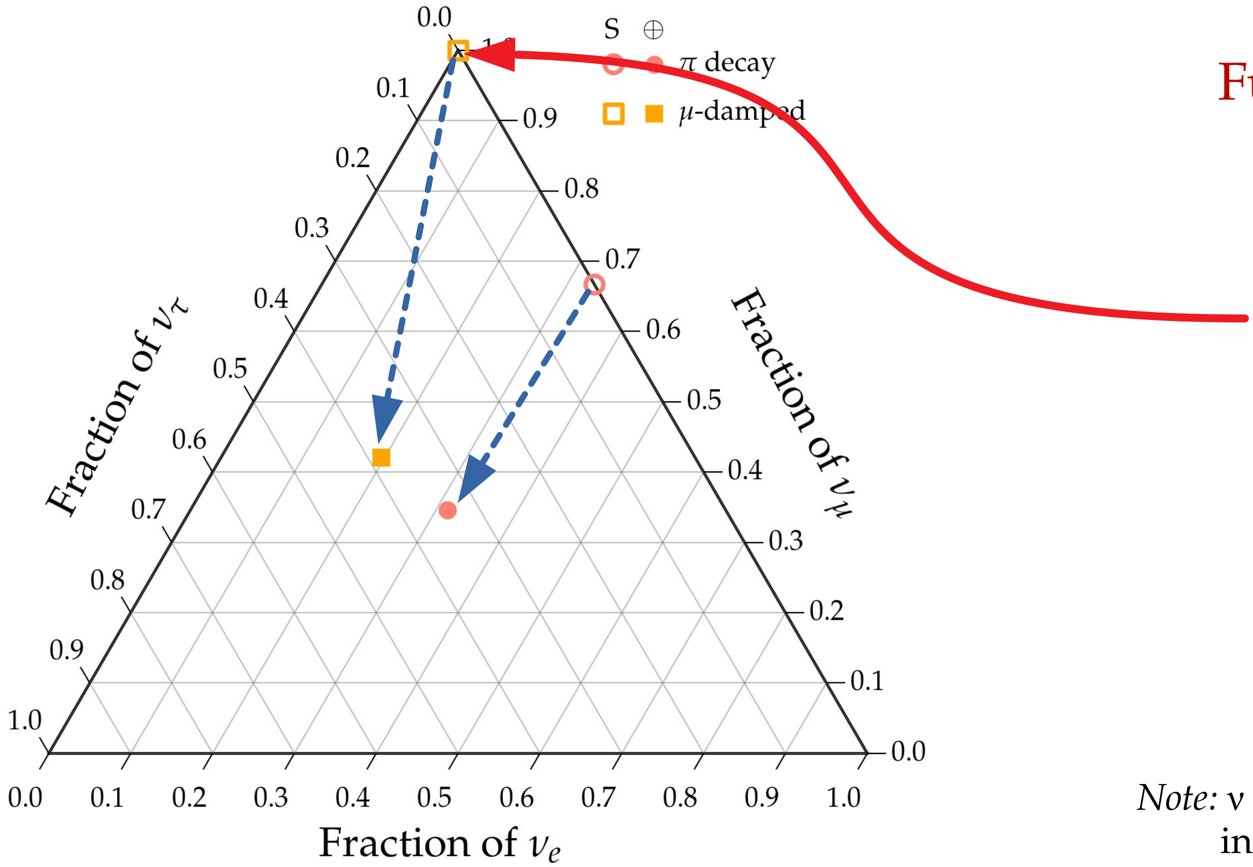

Full π decay chain

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

Muon damped

$(0 : 1 : 0)_S$

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

One likely TeV–PeV ν production scenario:

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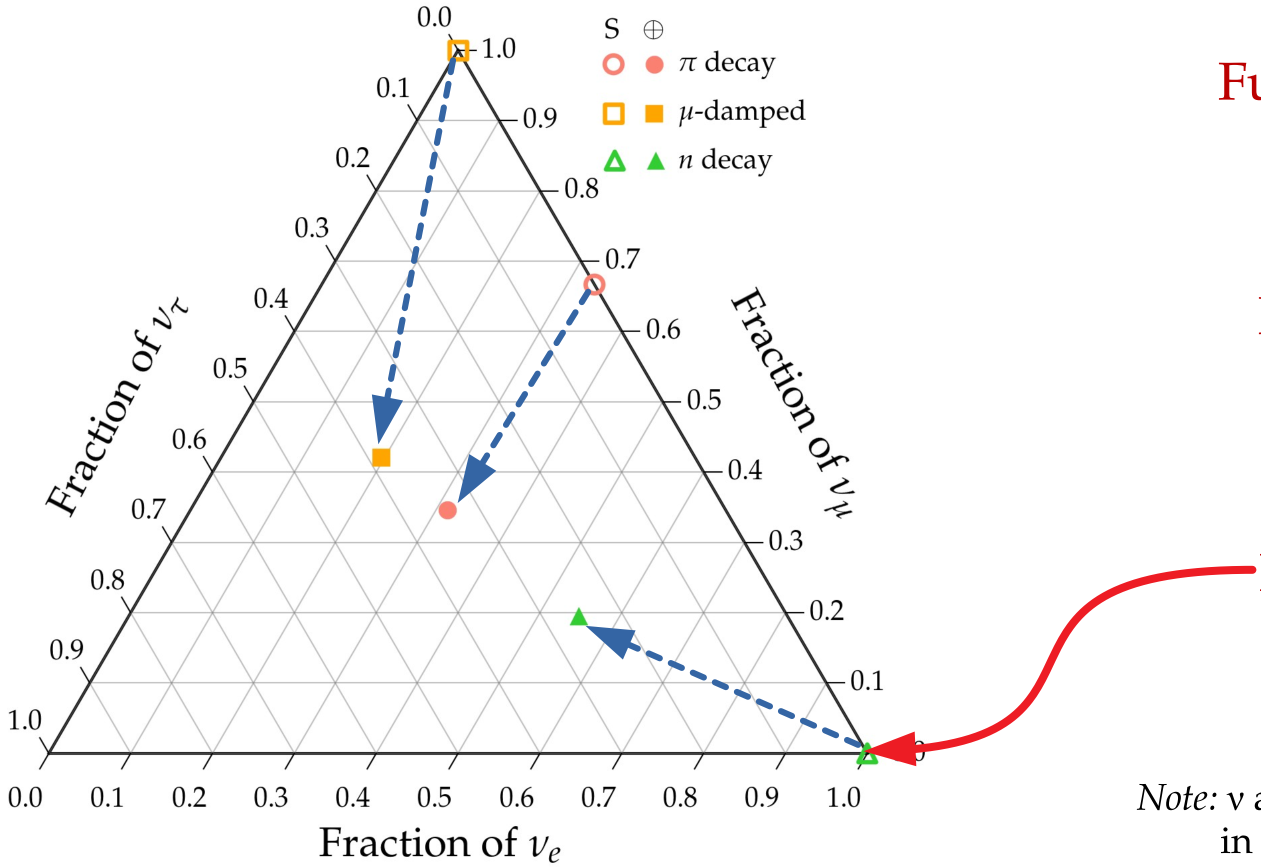


Full π decay chain

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

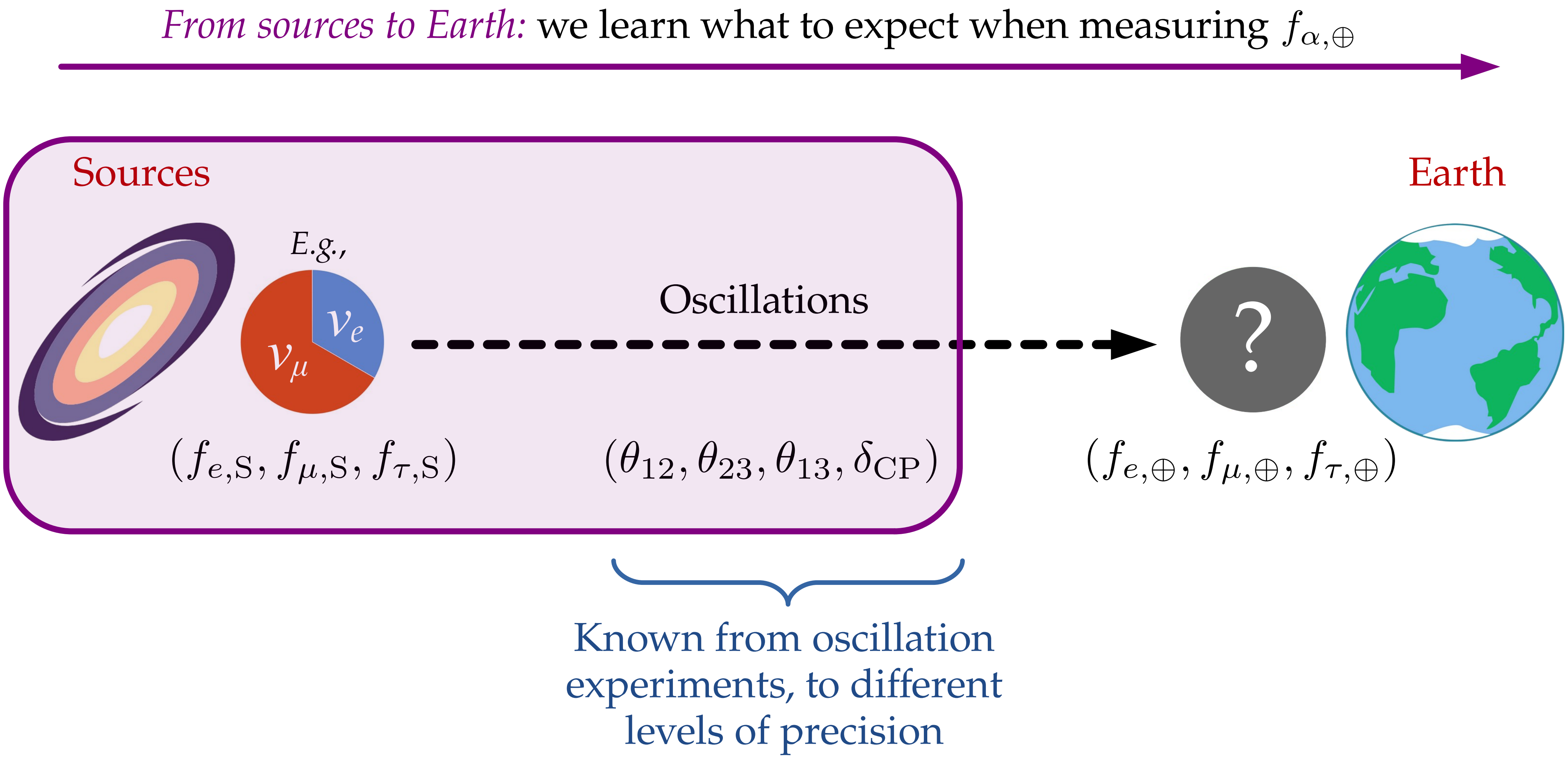
Muon damped

$(0:1:0)_S$

Neutron decay

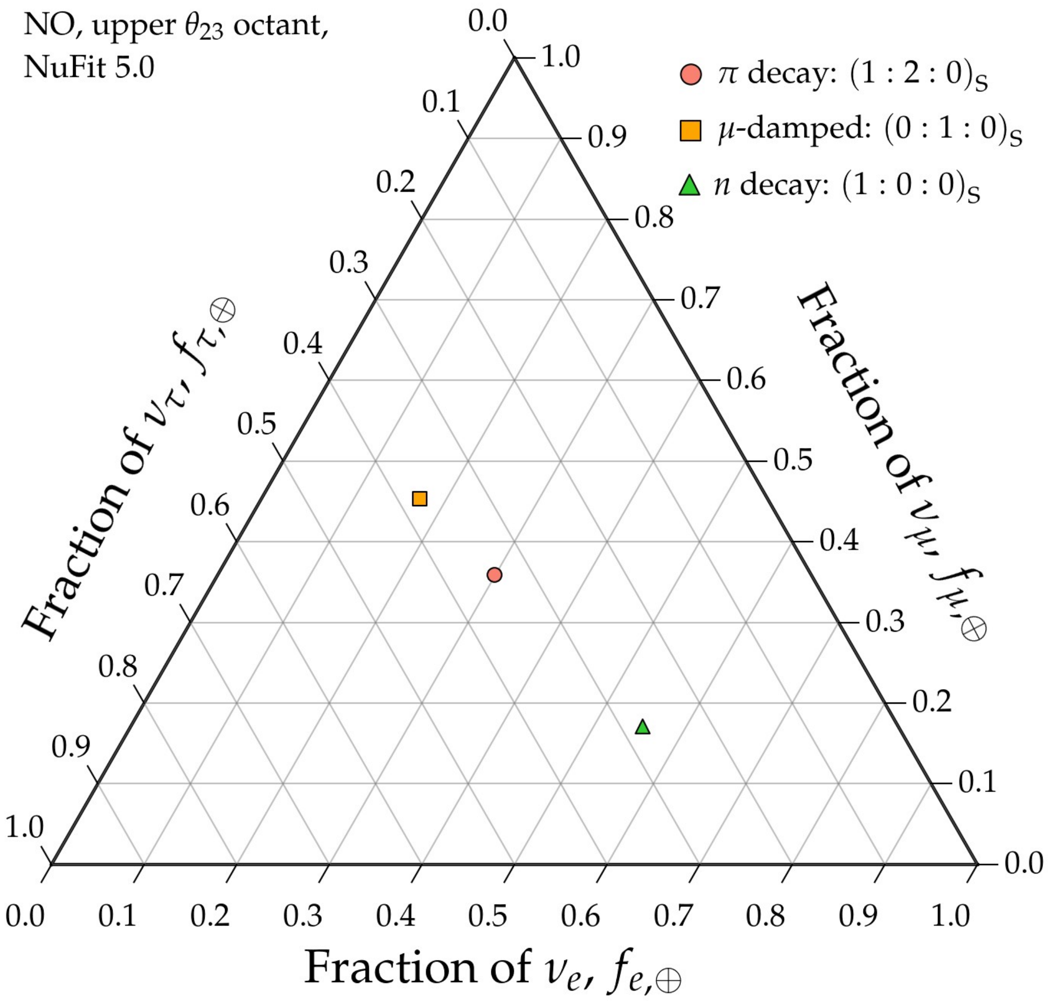
$(1:0:0)_S$

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



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

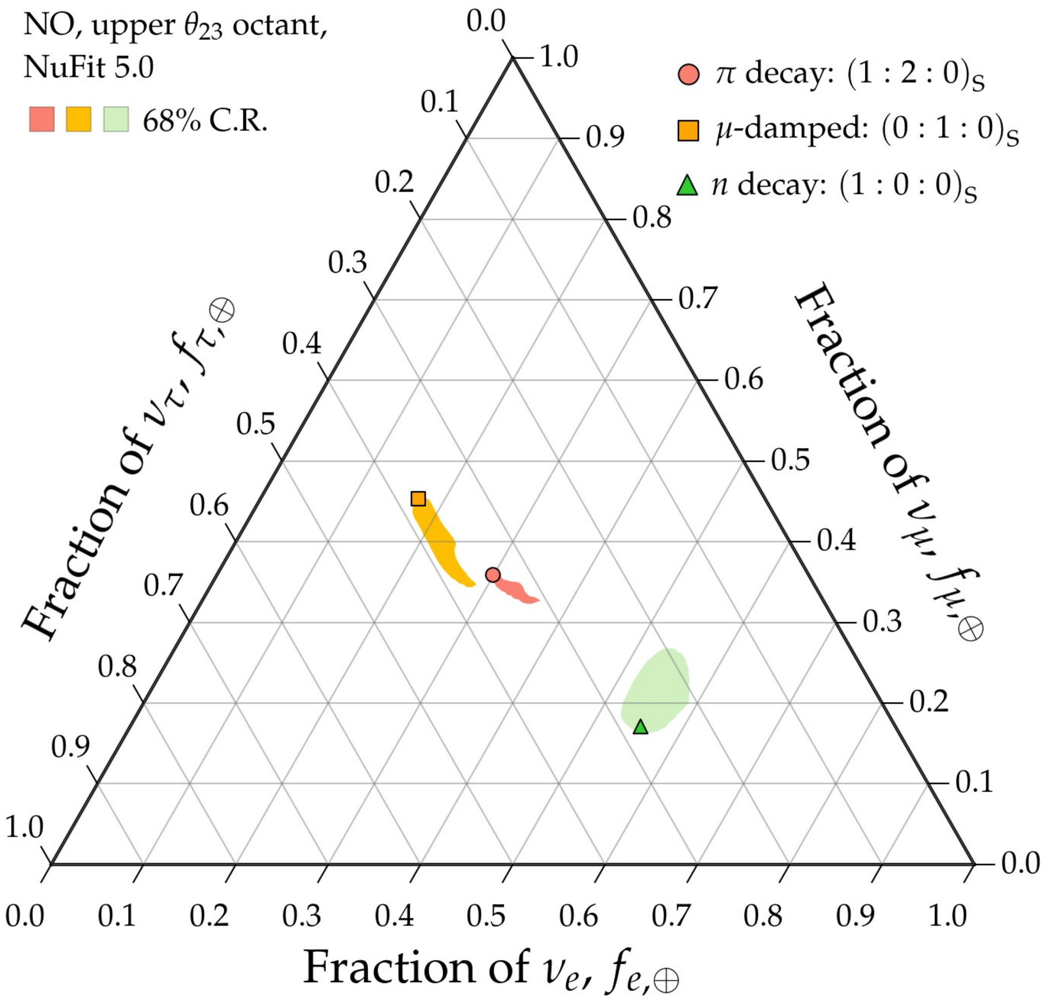
Theoretically palatable regions: today



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

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today



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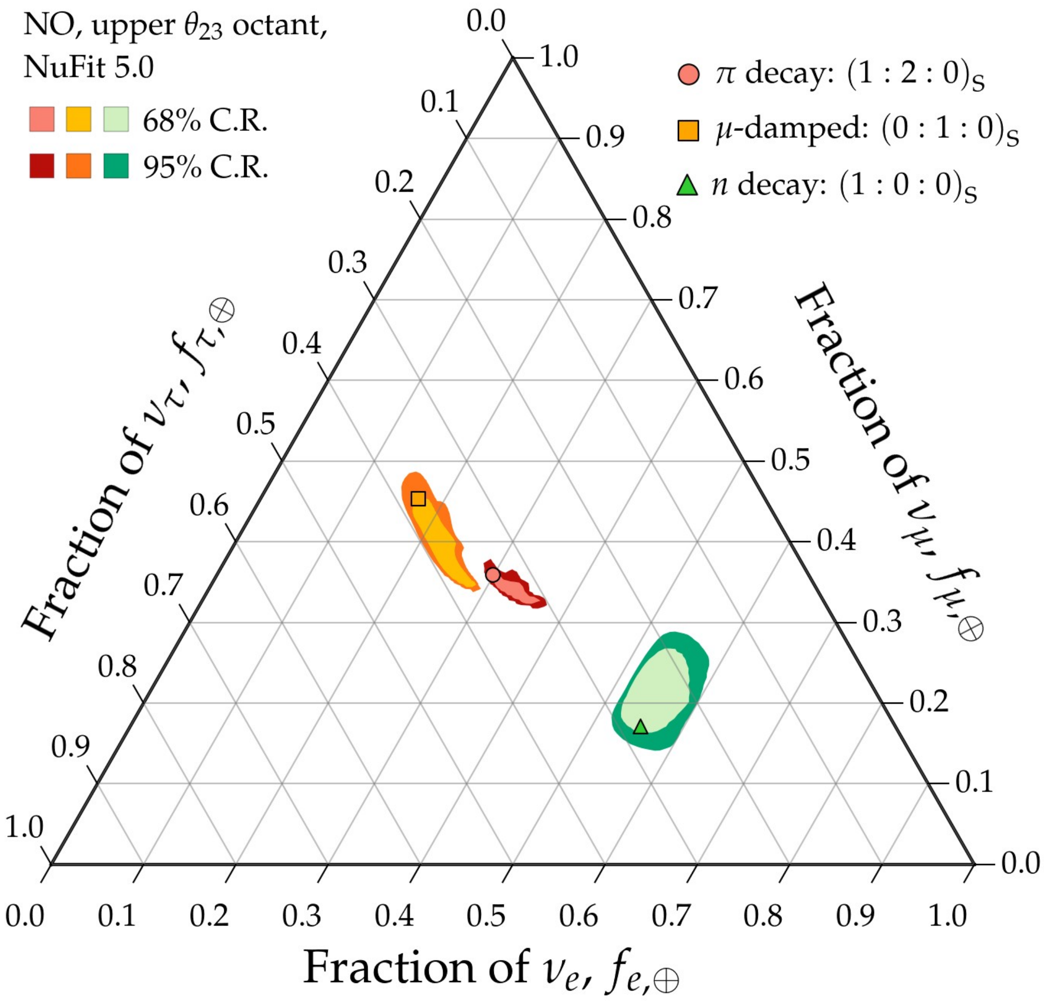

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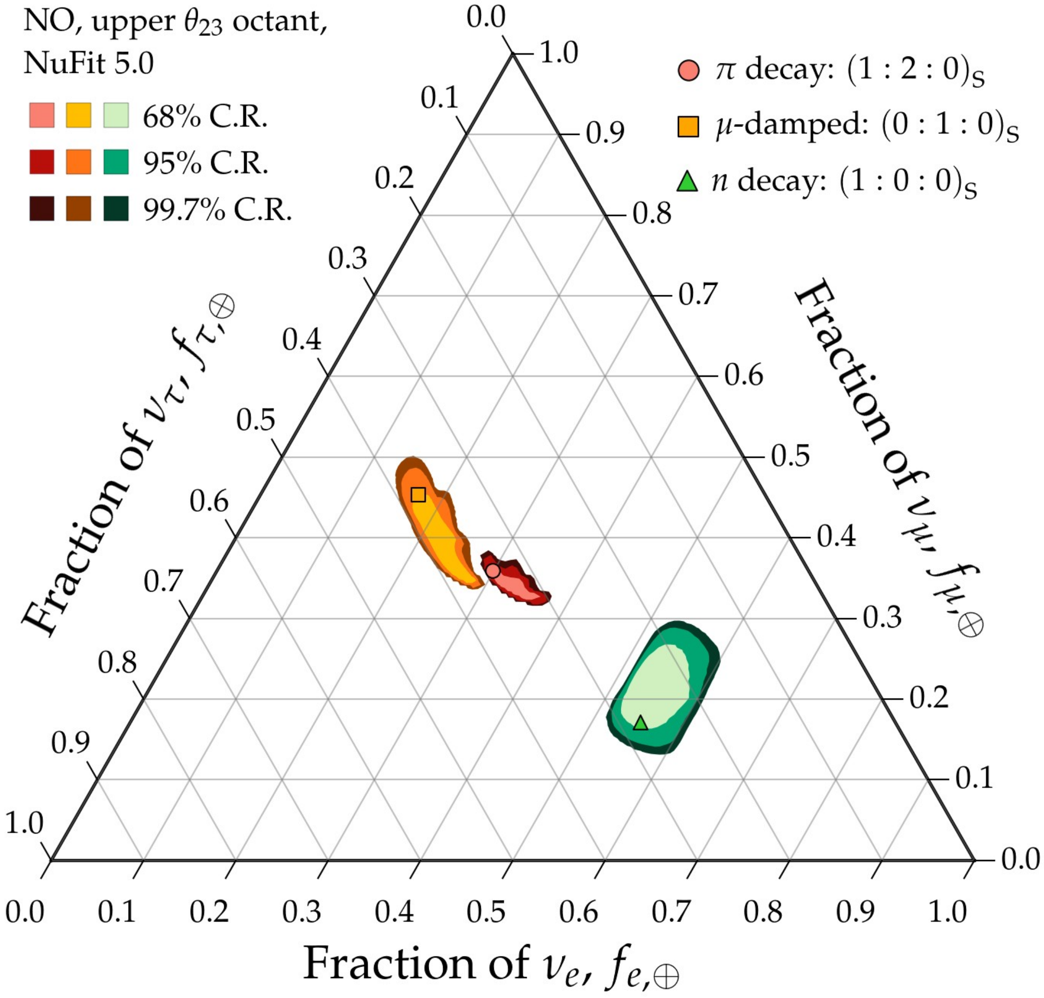

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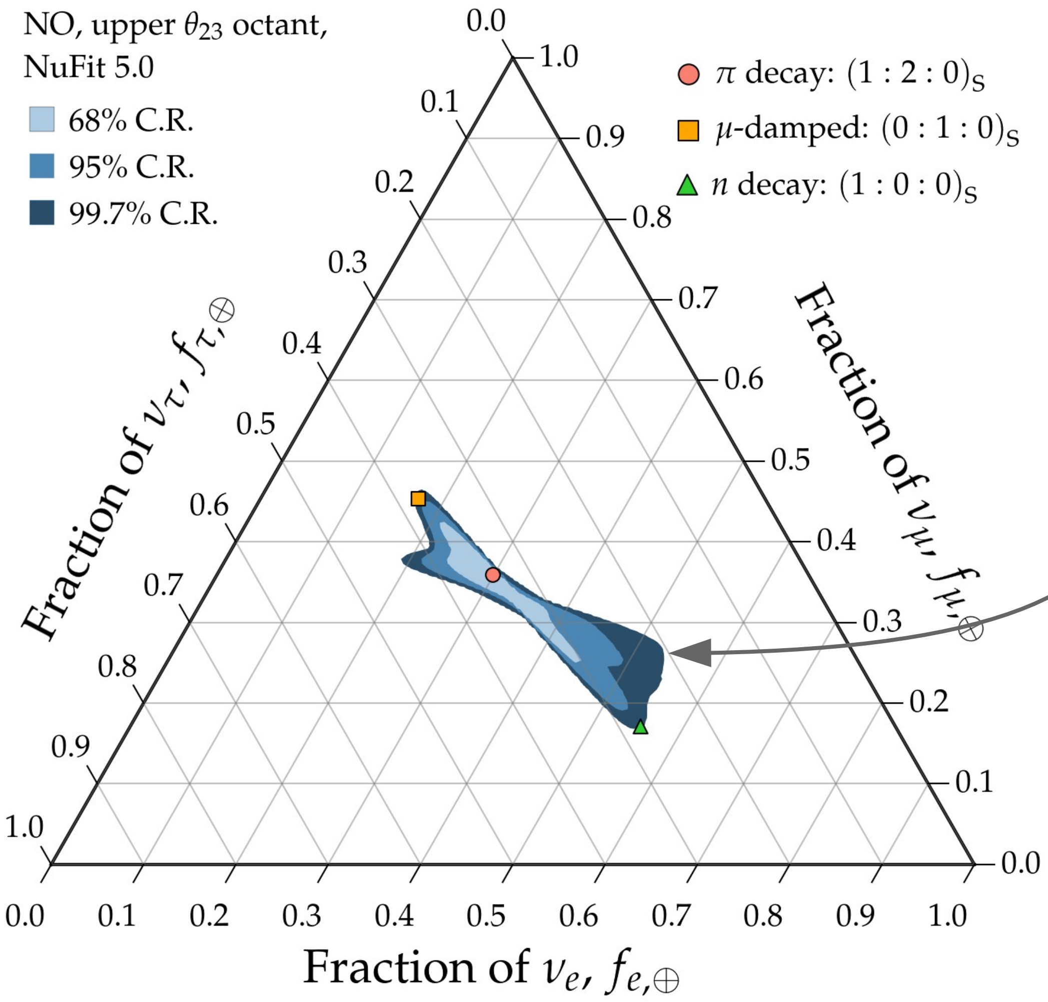
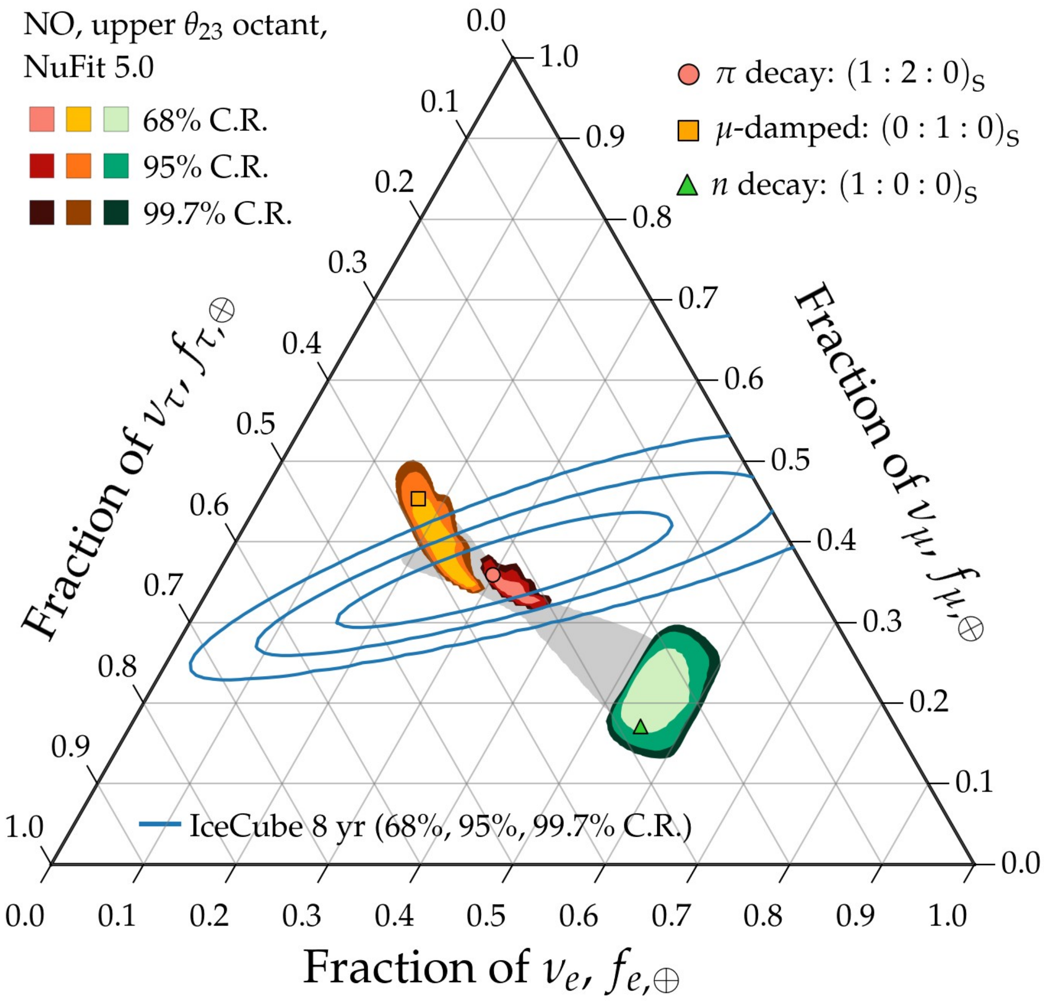


Varying over all possible flavor ratios at the source

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

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today



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

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
See also: **MB**, Beacom, Winter, *PRL* 2015

Measuring flavor composition: 2015–2040

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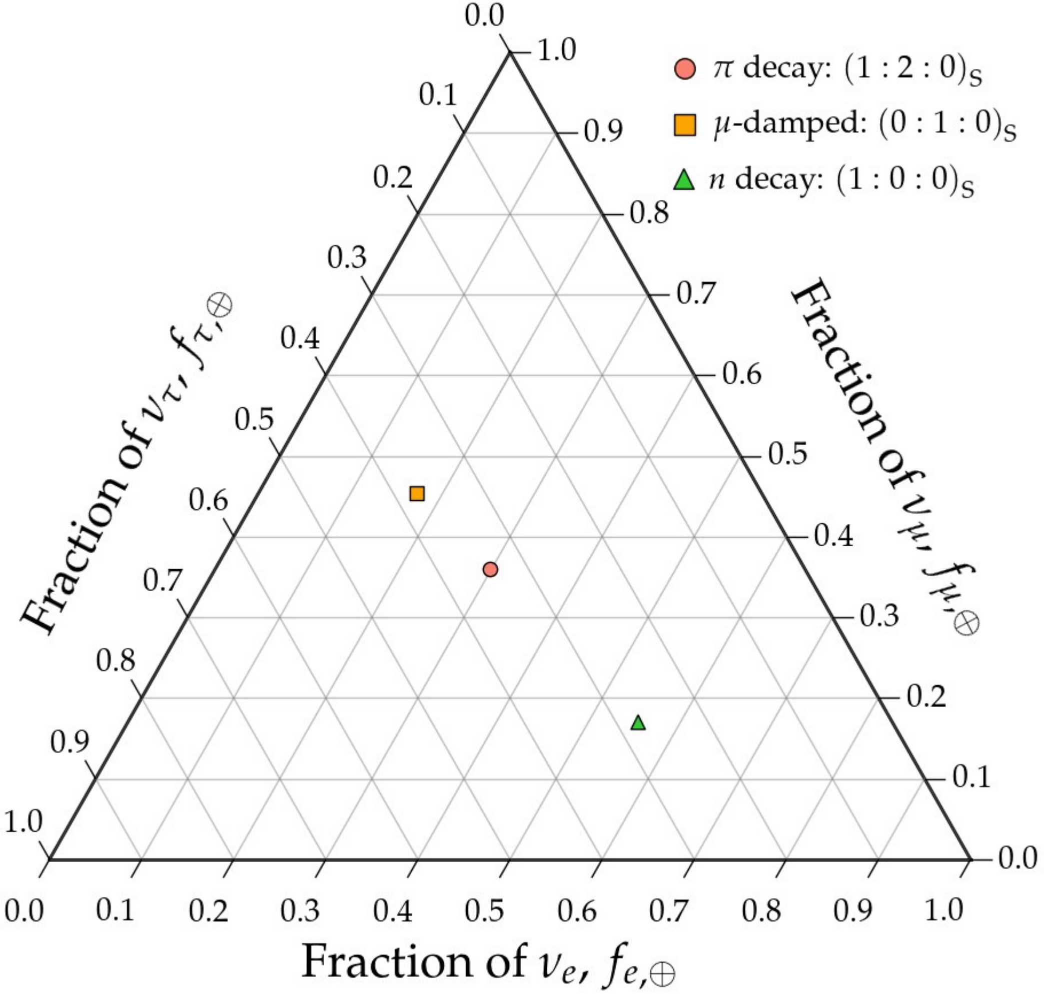

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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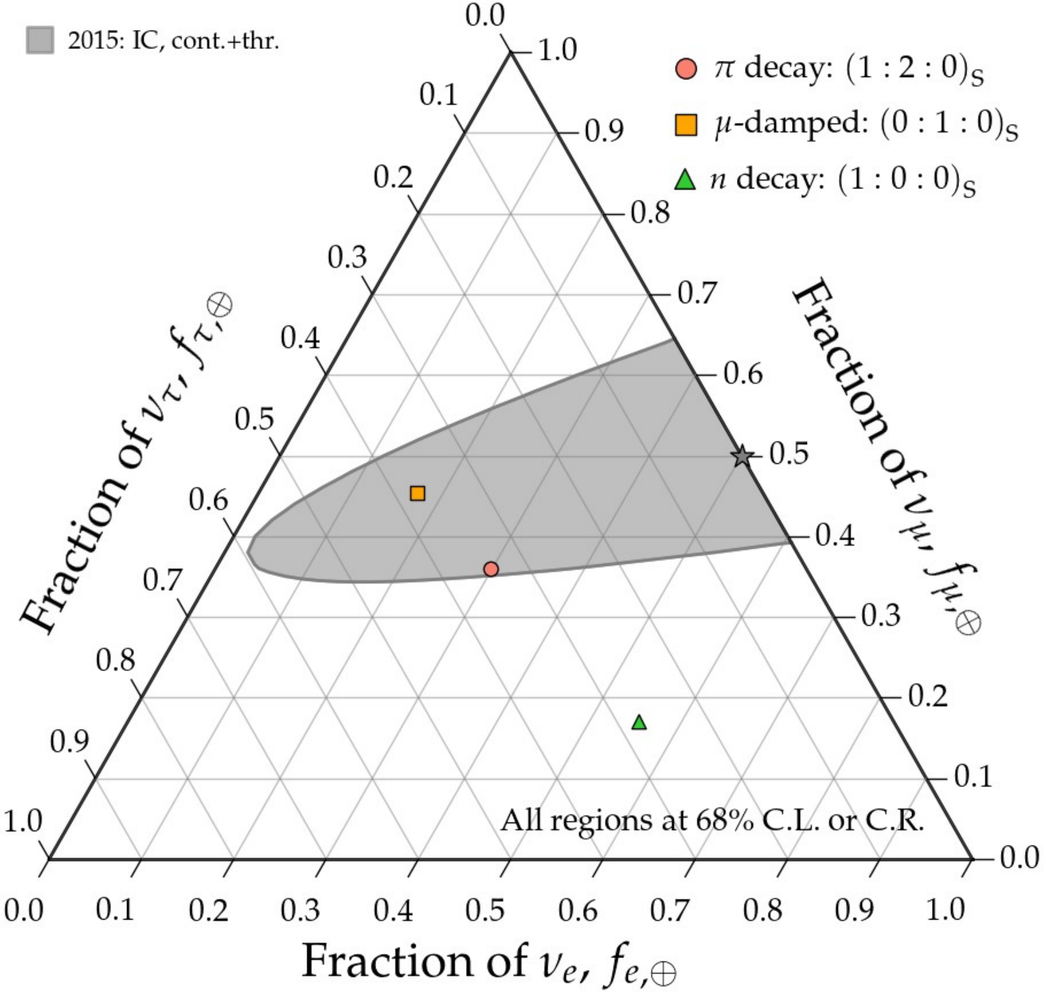

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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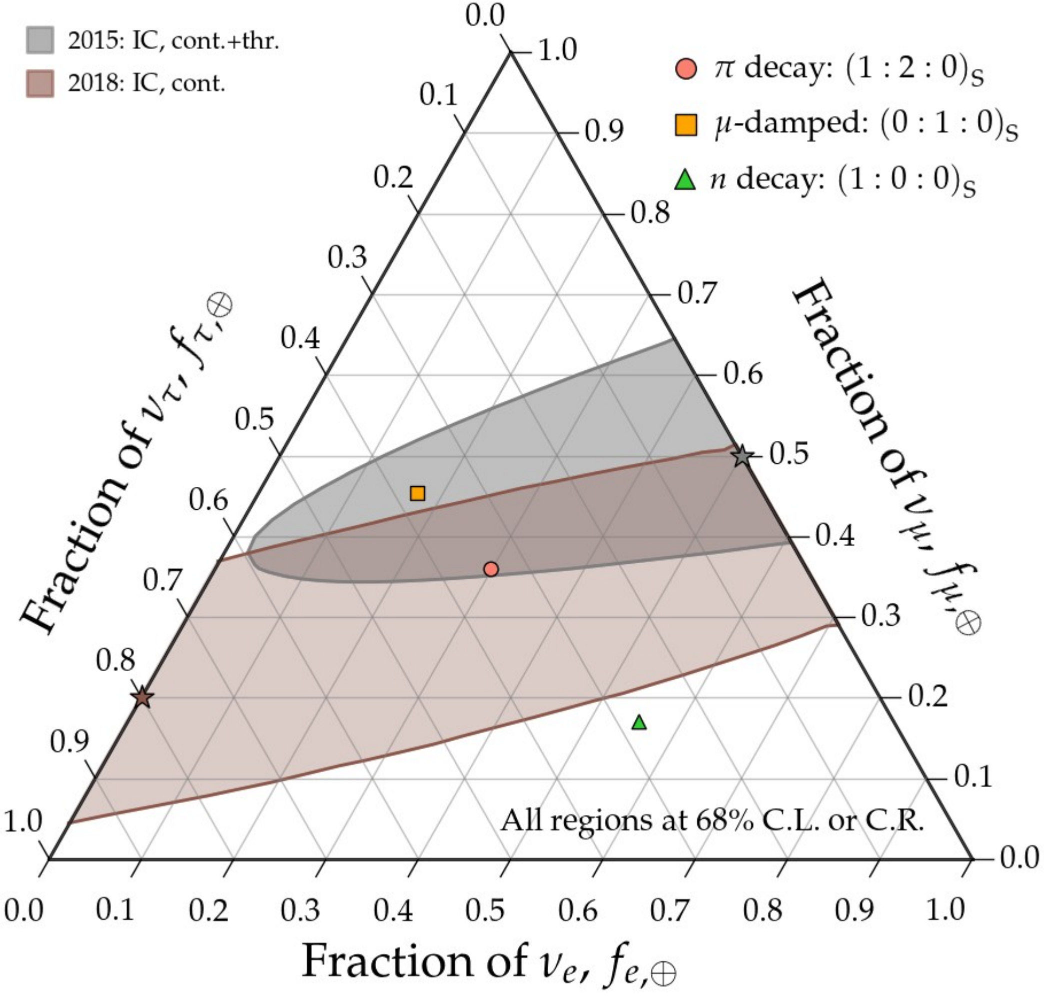
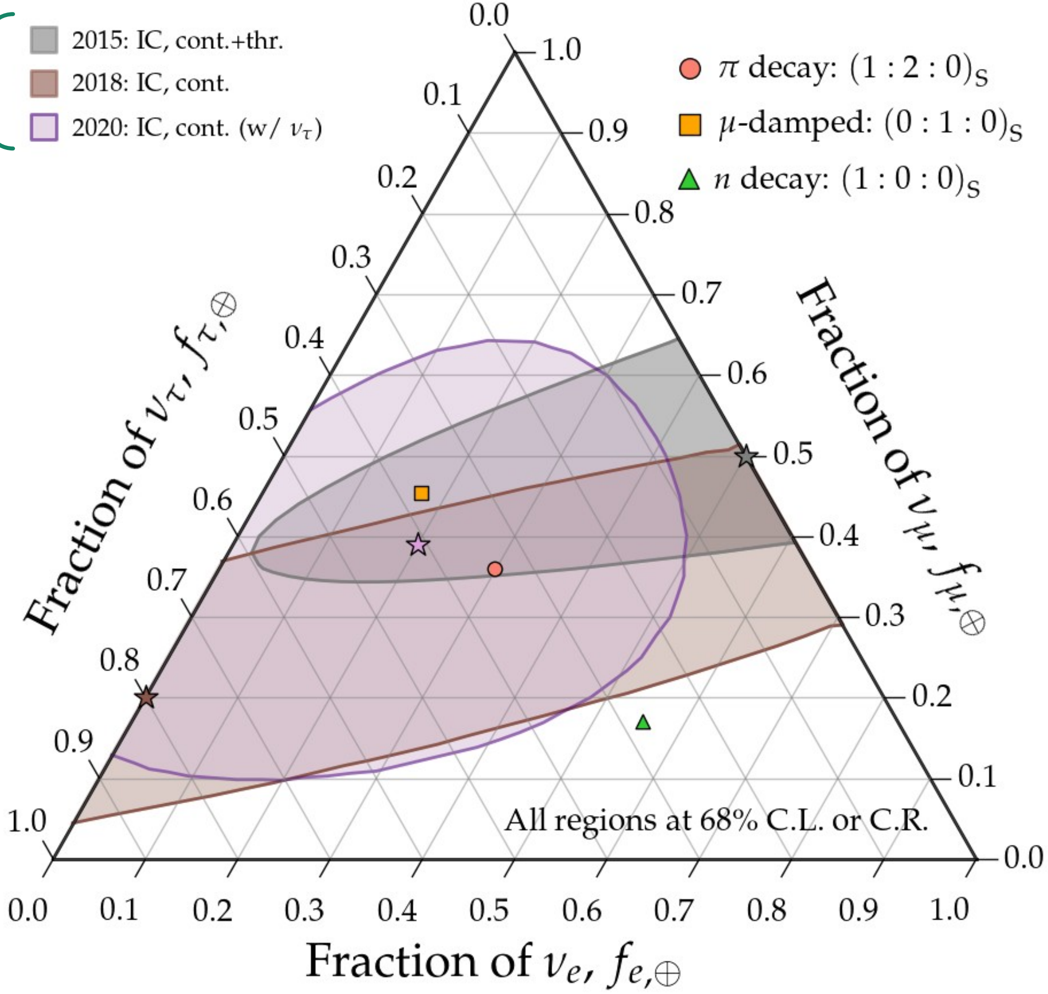


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Measuring flavor composition: 2015–2040

Based on real data



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

High-energy neutrino physics

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

Note: Not an exhaustive list

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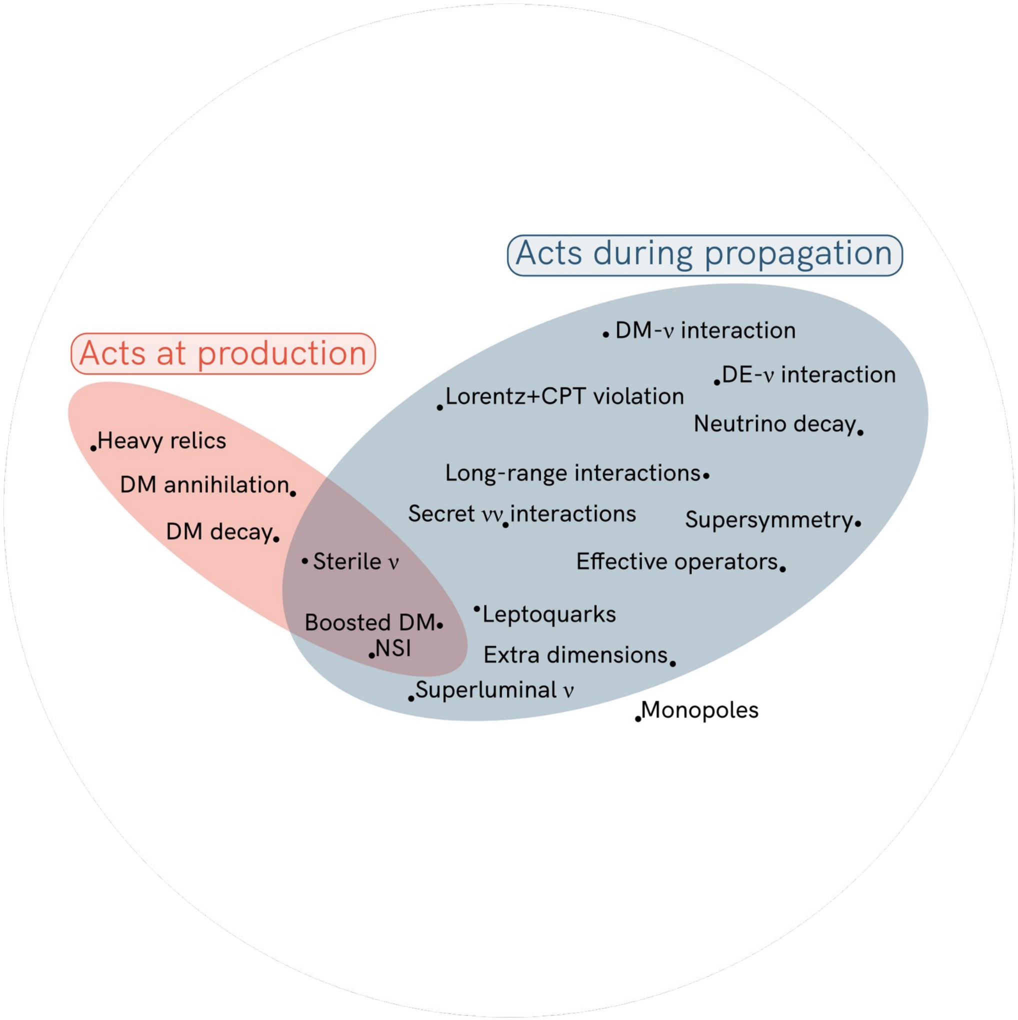

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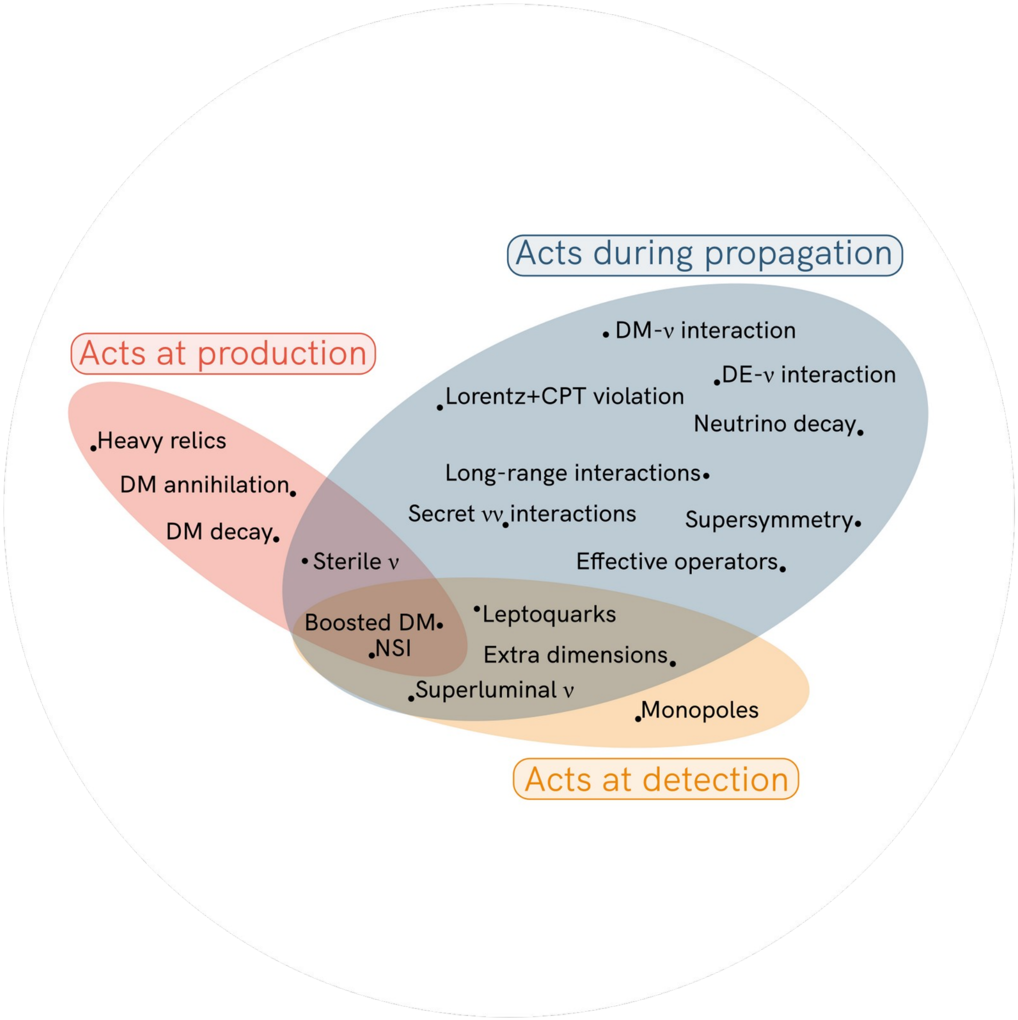

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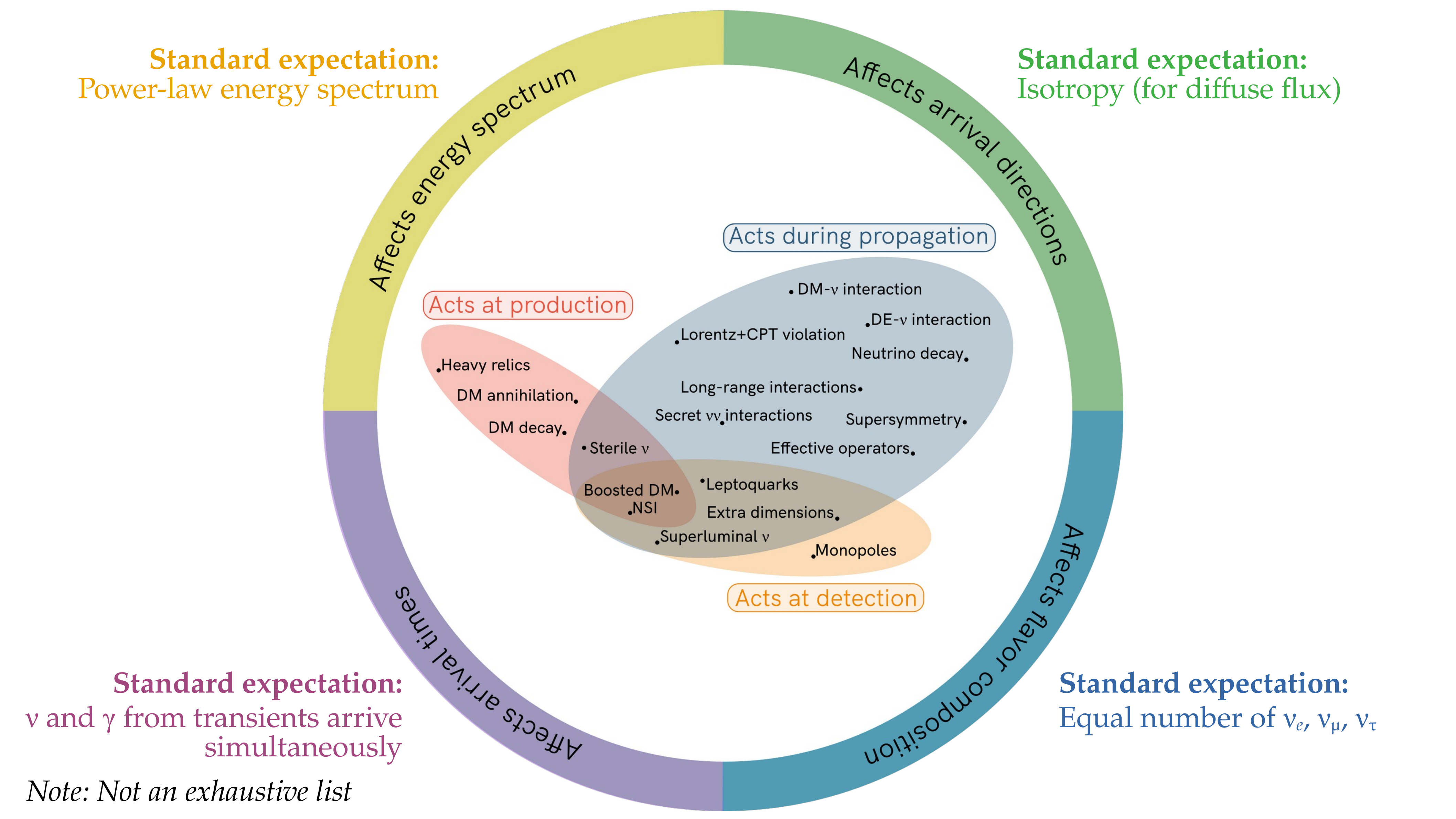
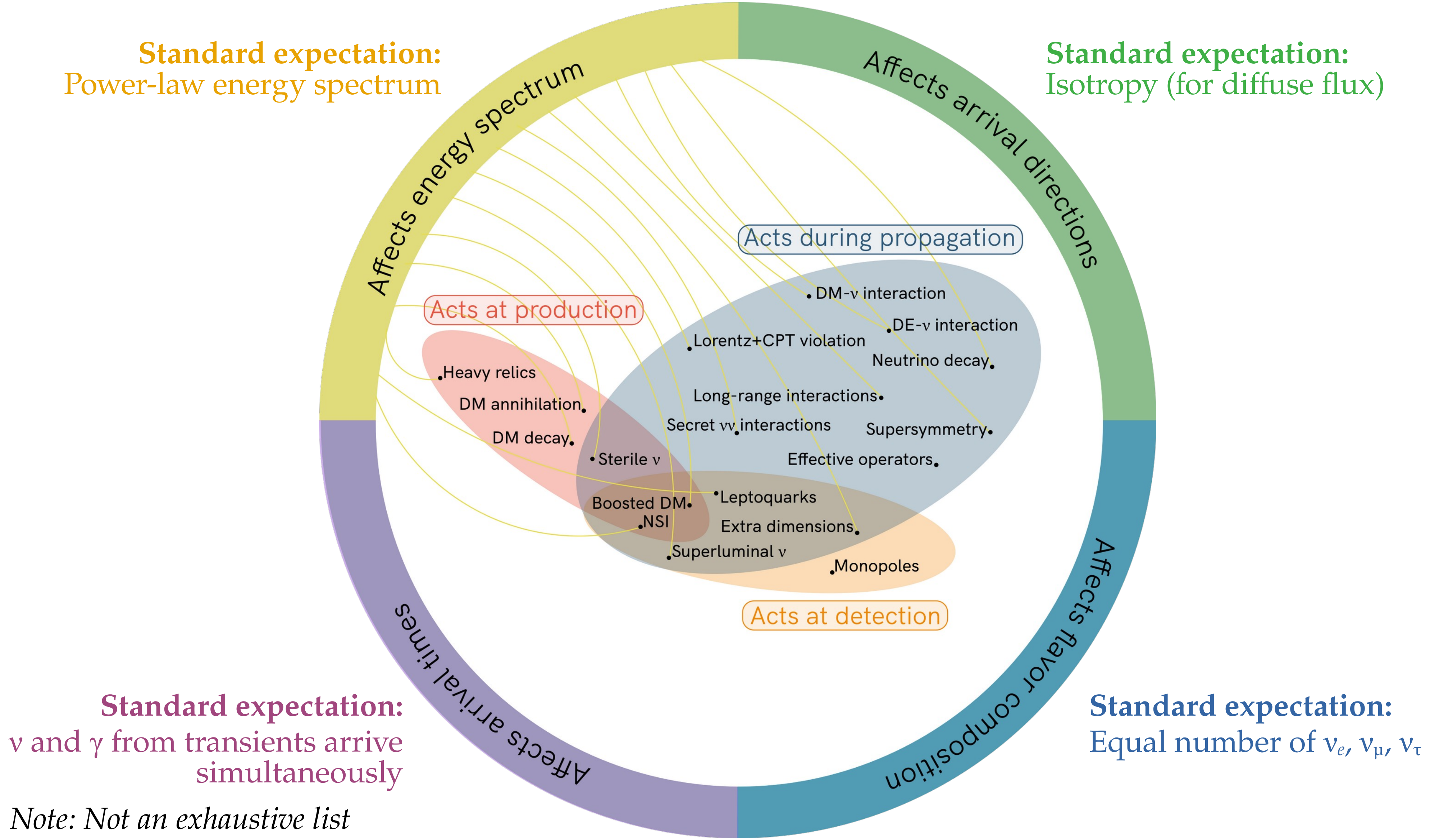


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT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



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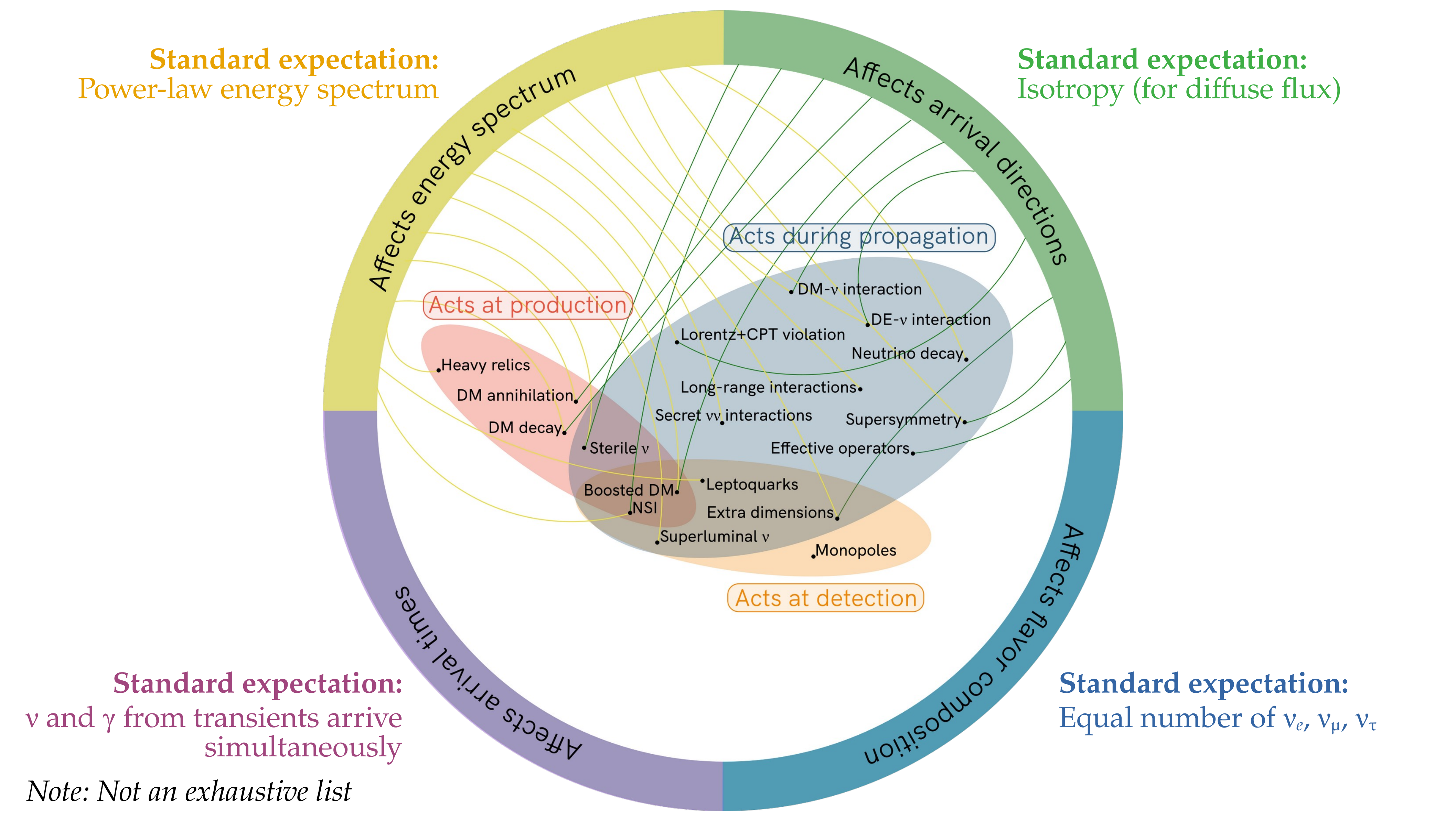

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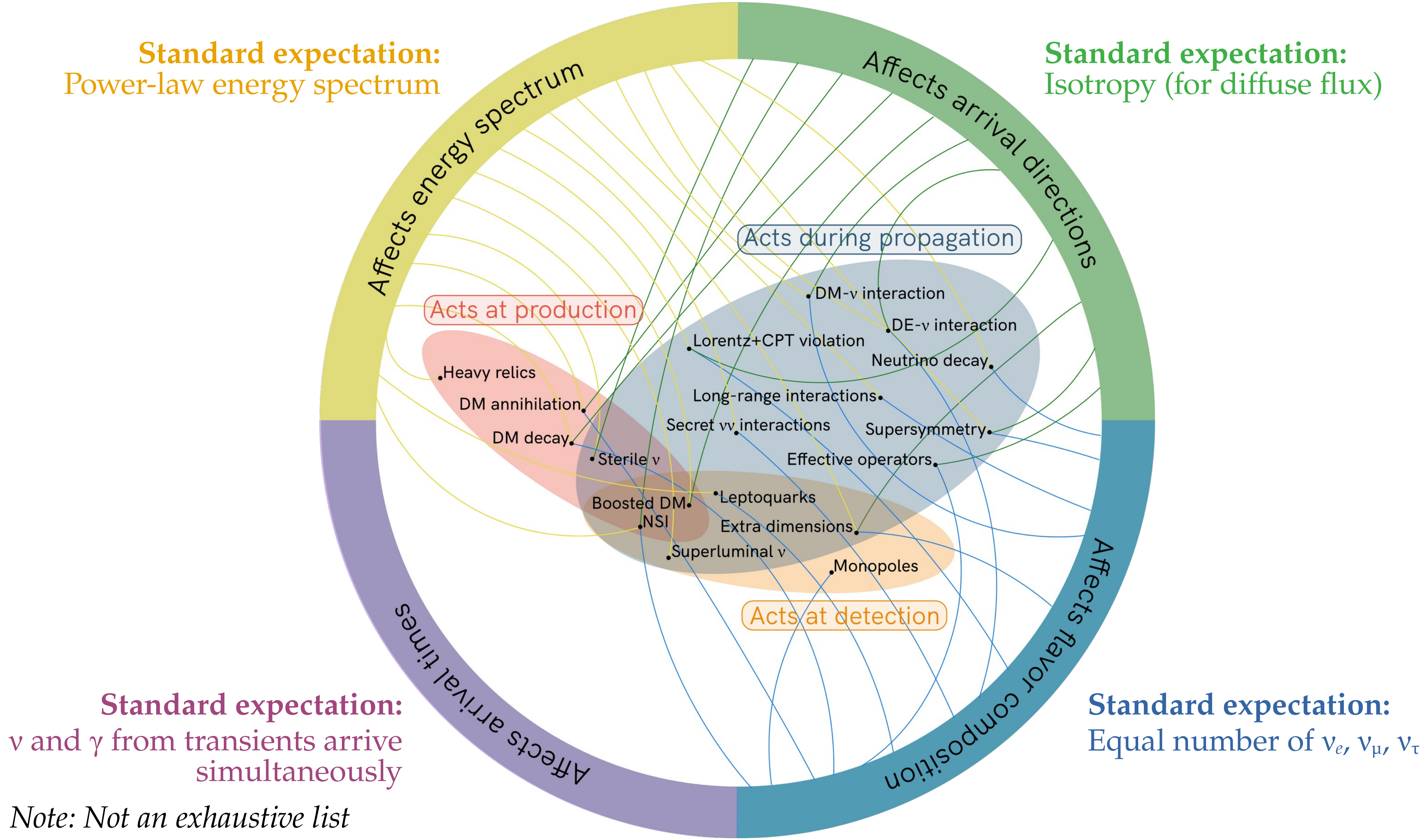

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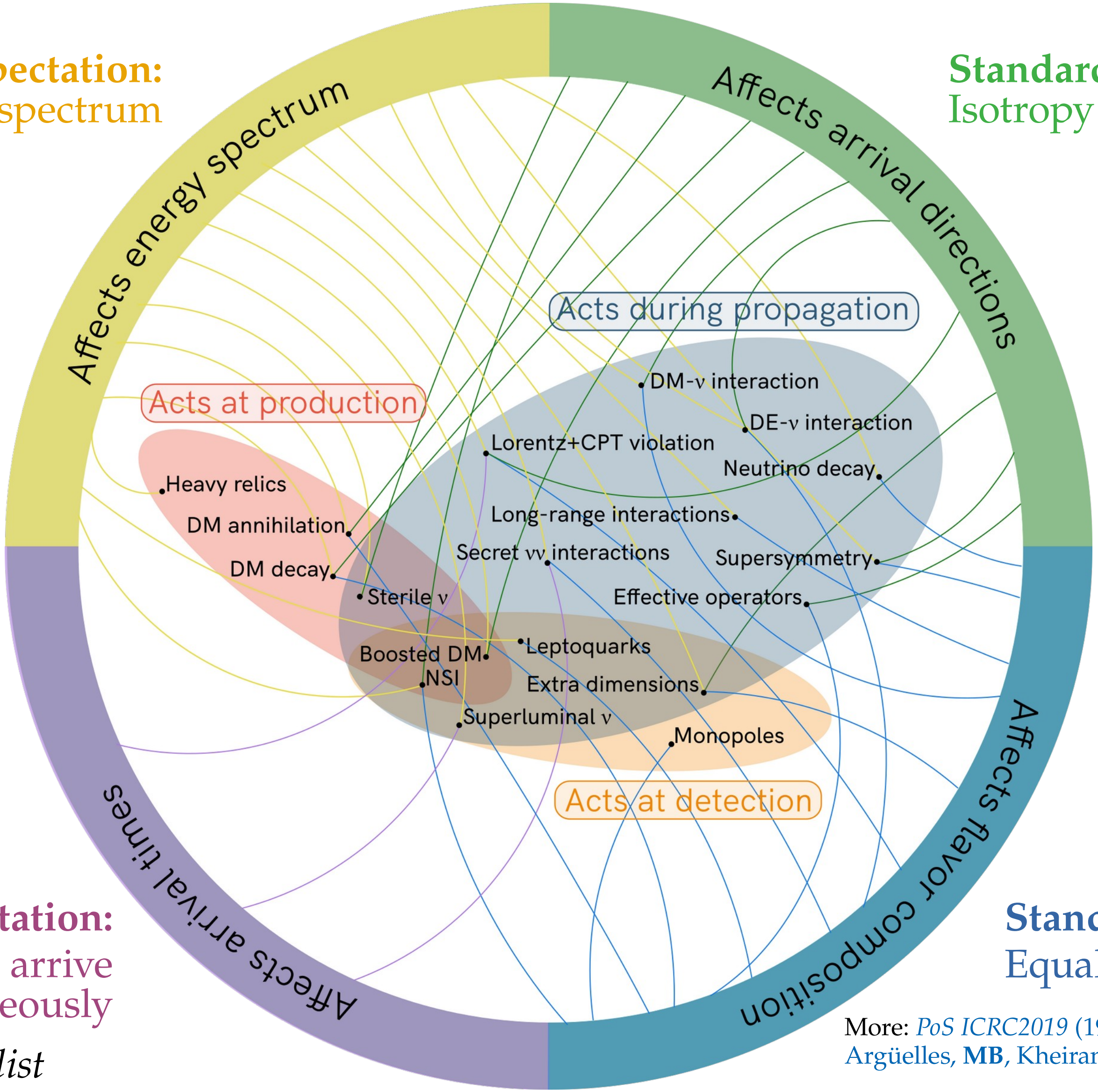

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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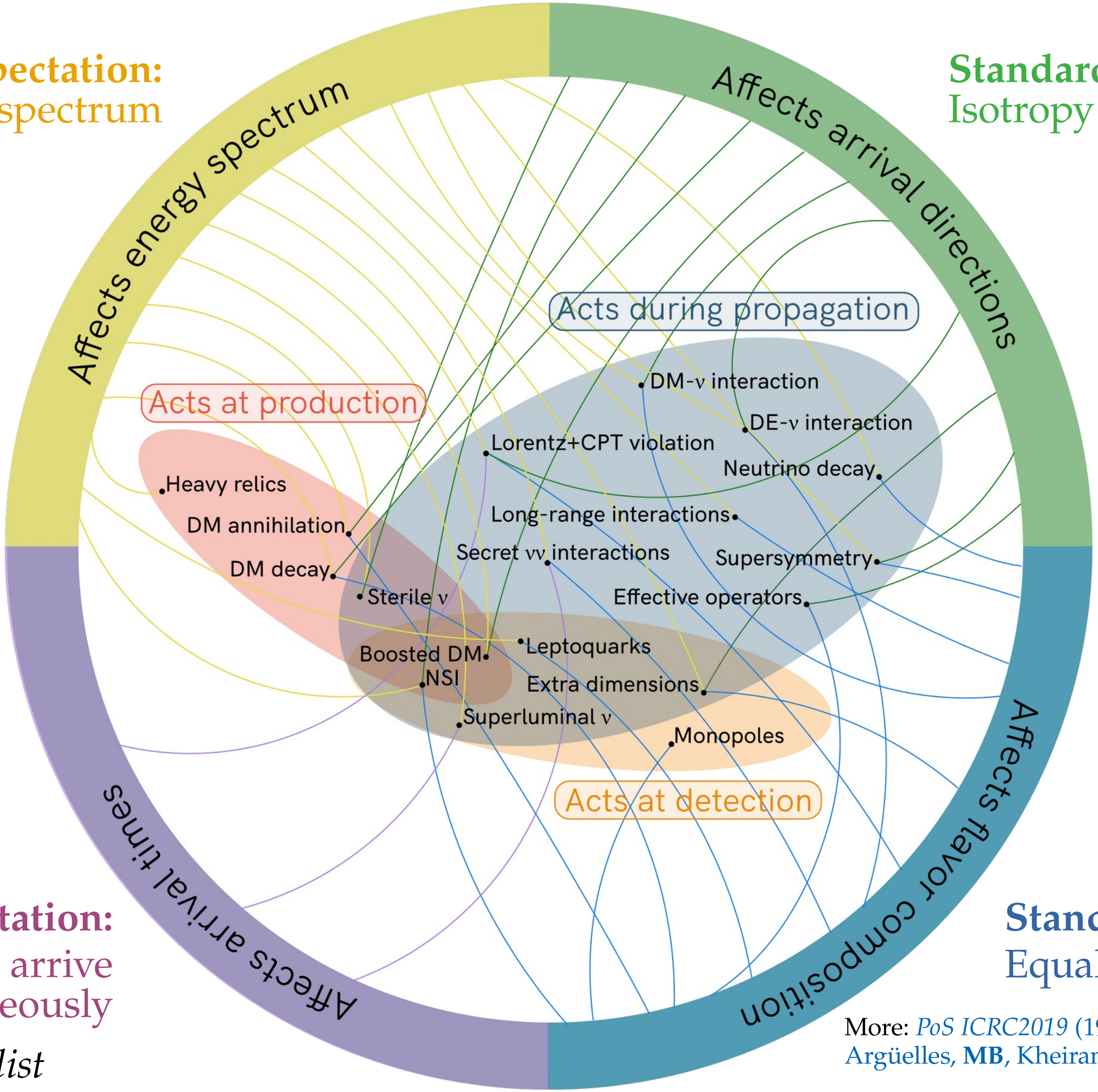

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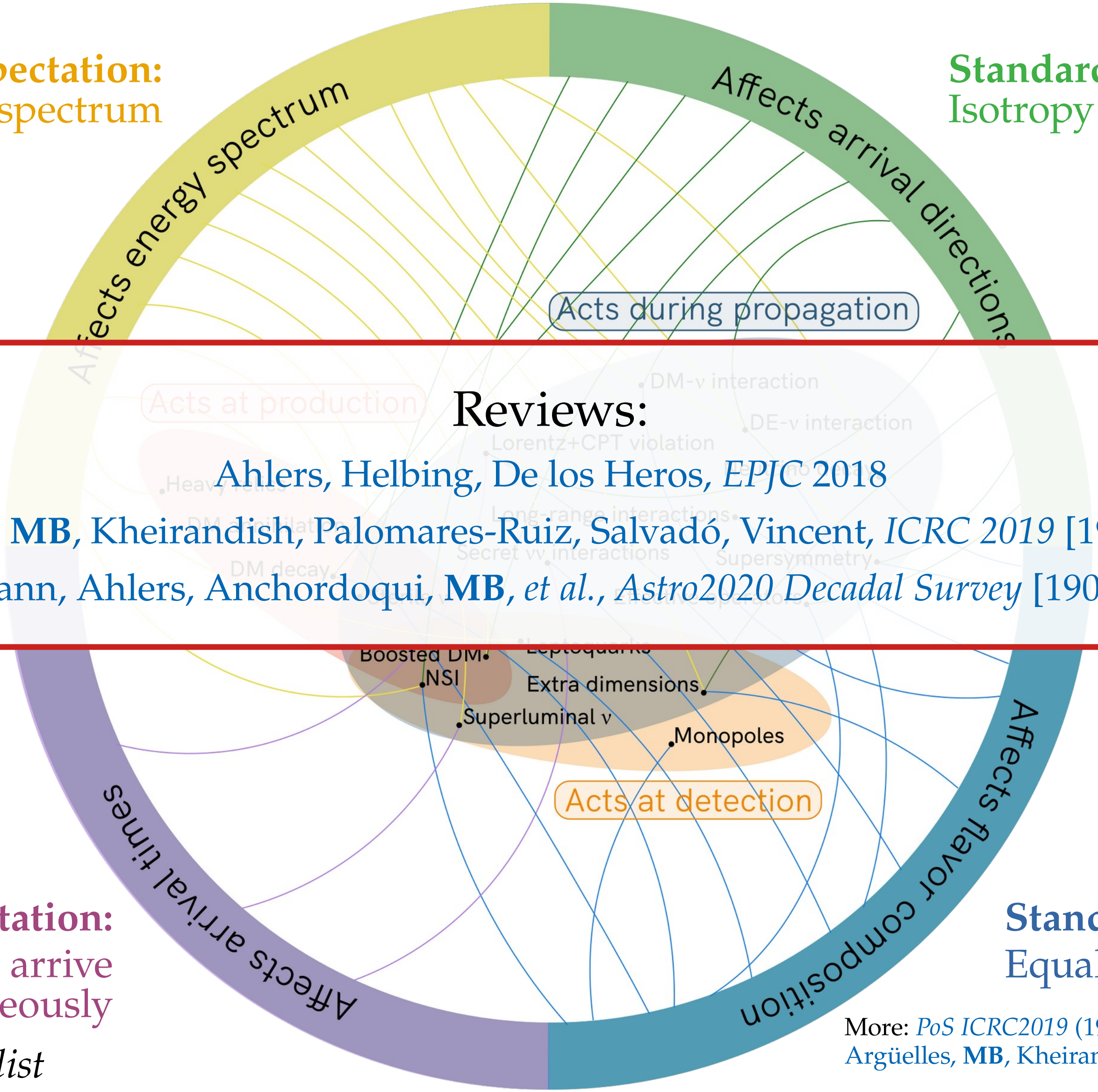

Reviews:

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

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

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

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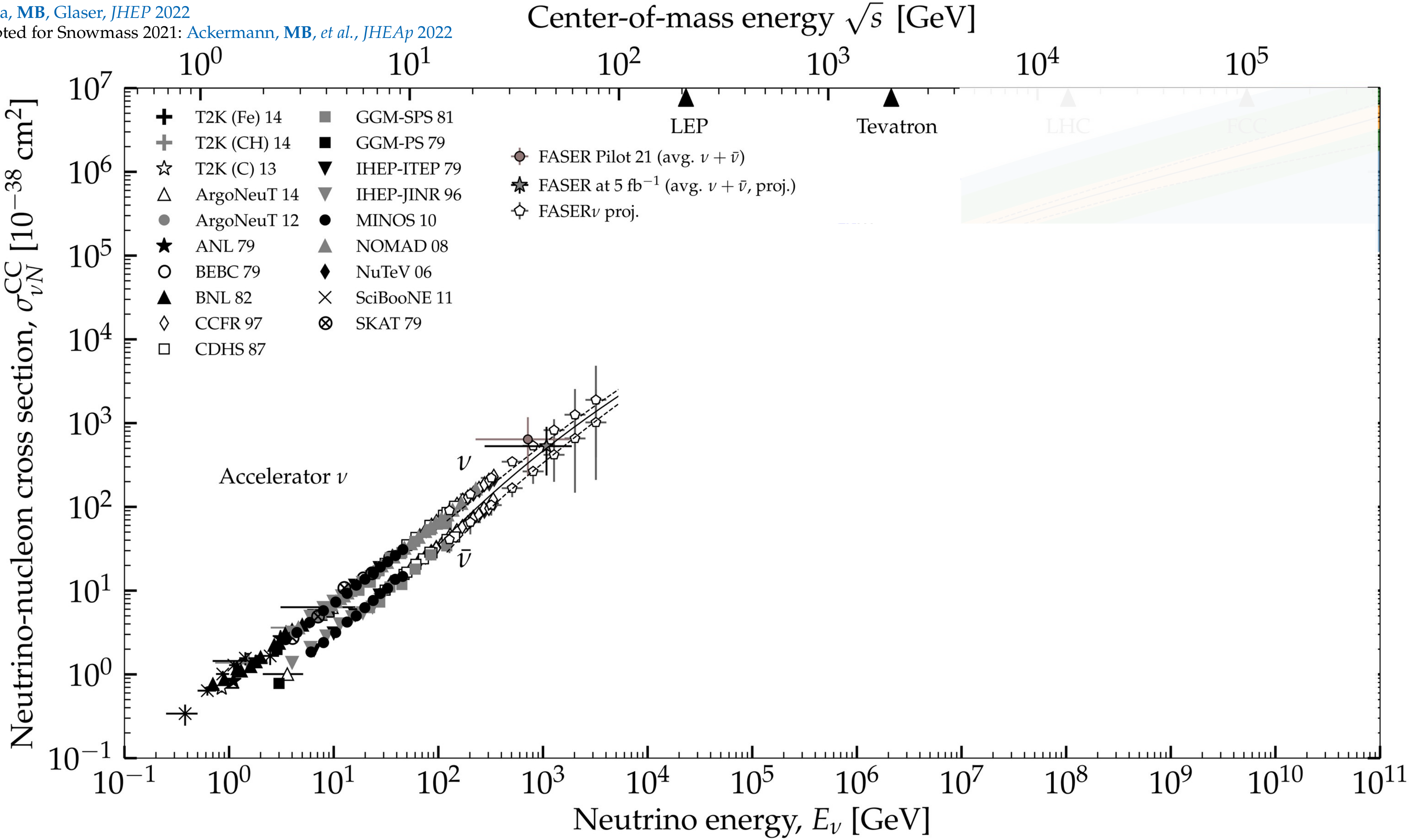
A selection of neutrino physics

1. Neutrino-matter cross section
2. Dark matter
3. Discovering the Glashow resonance
4. Secret neutrino interactions
5. Flavor physics
6. Neutrino decay

Backup slides (items 3–6)

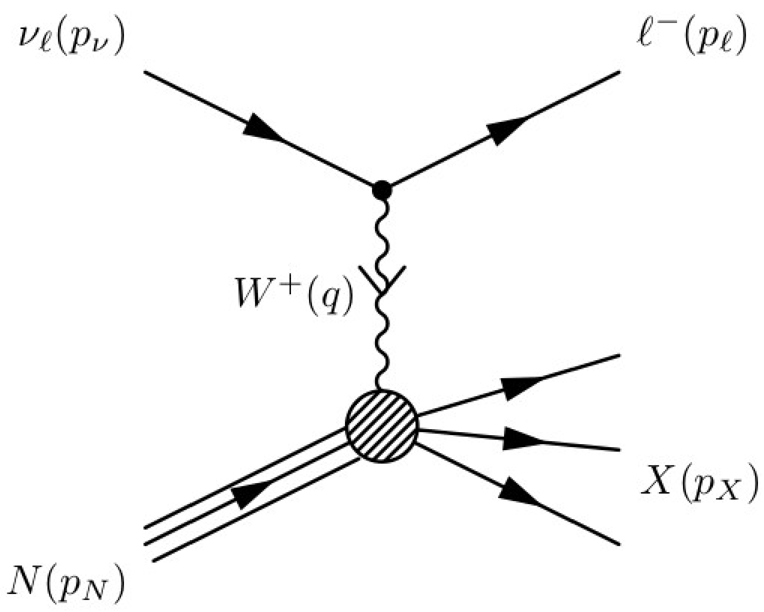
1. Neutrino-matter cross section:
Beyond TeV scale

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

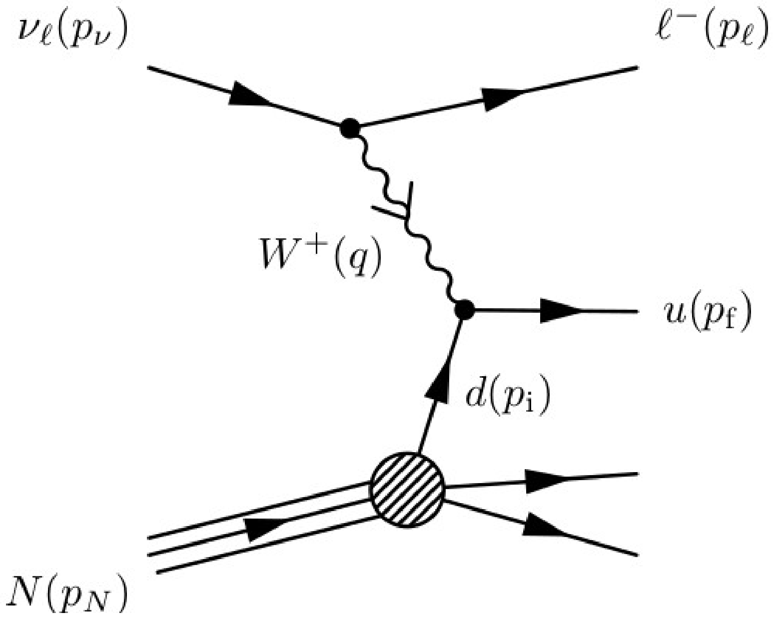


How does DIS probe nucleon structure?

What you see



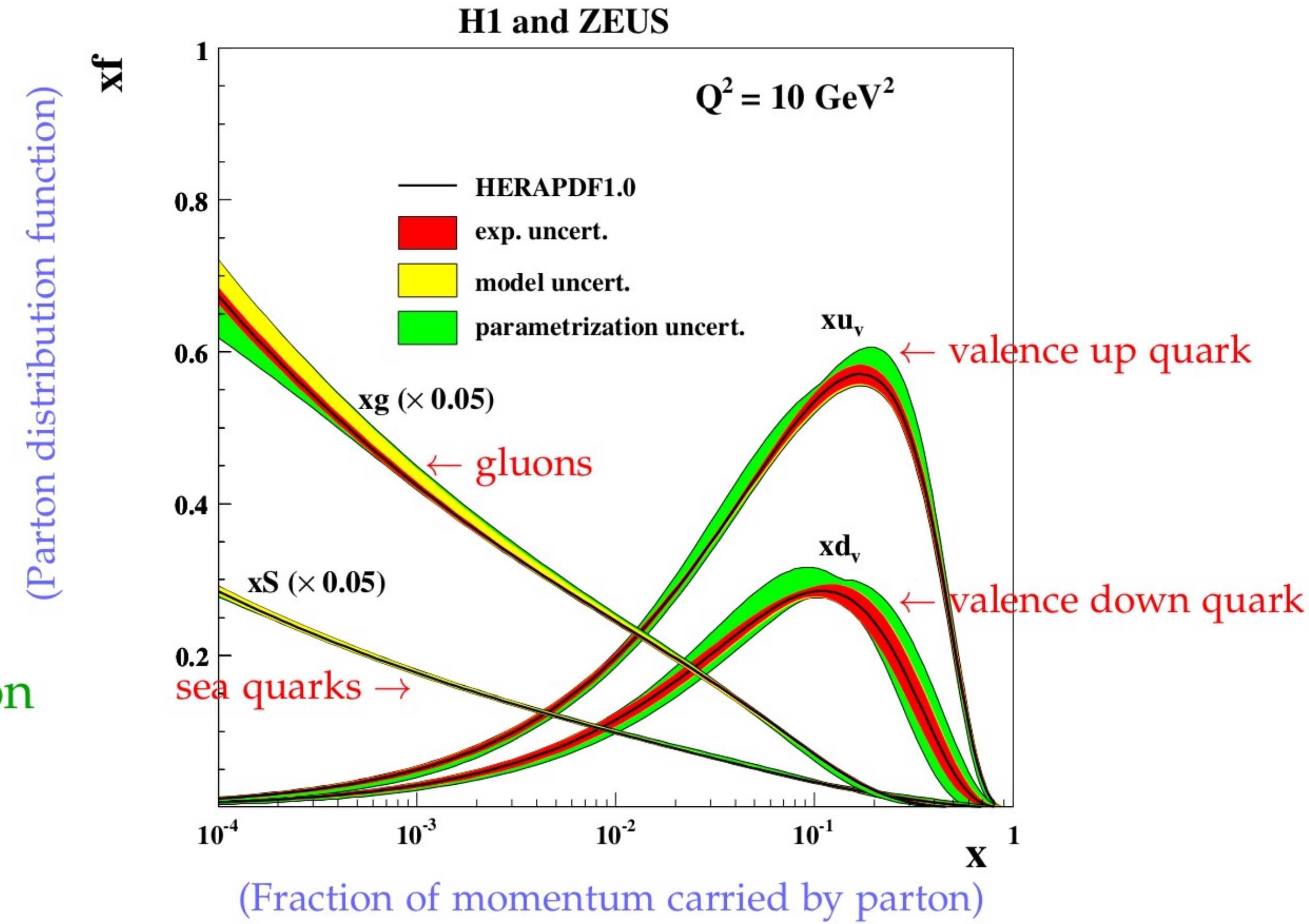
Beneath the hood



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

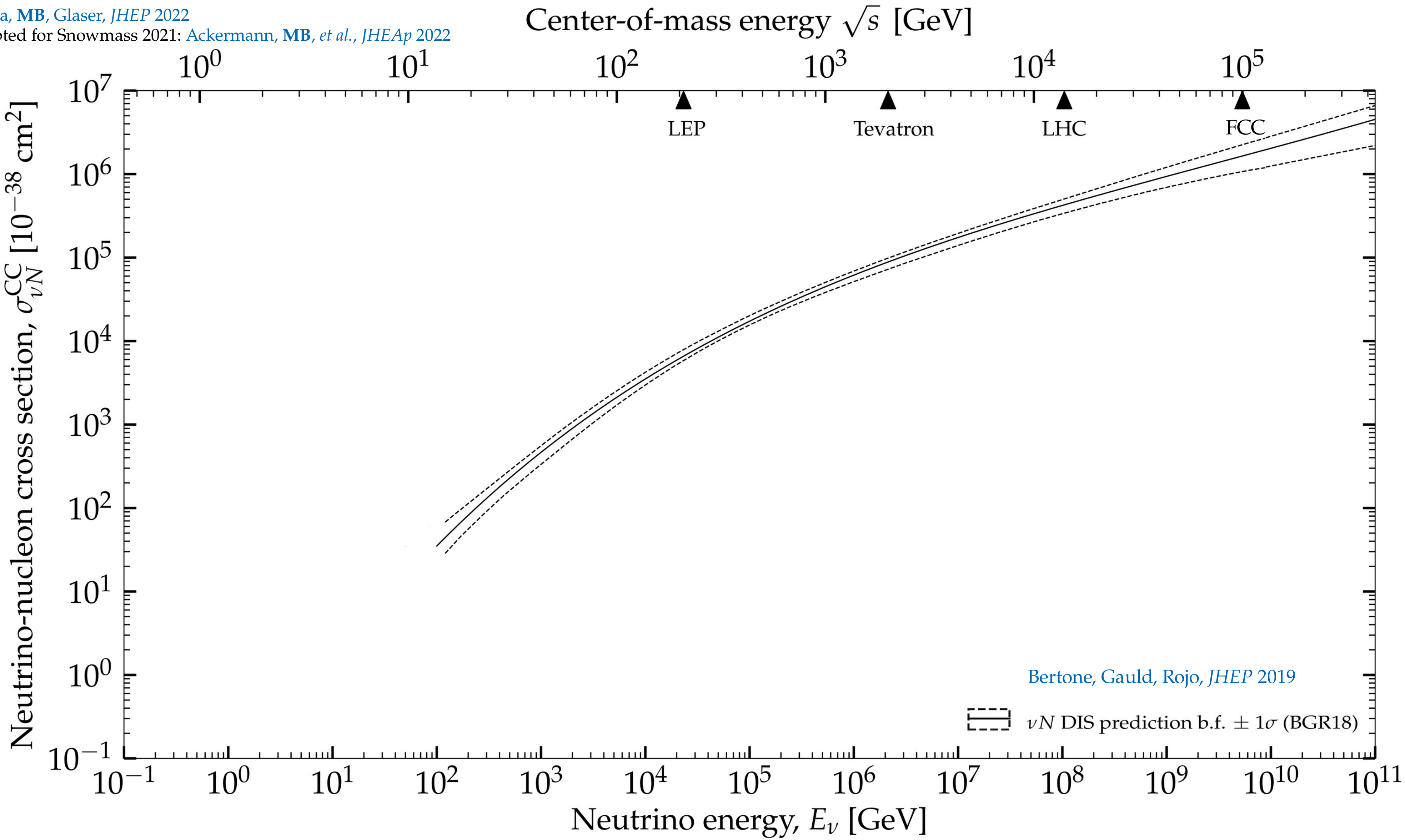
Giunti & Kim, *Fundamentals of Neutrino Physics & Astrophysics*

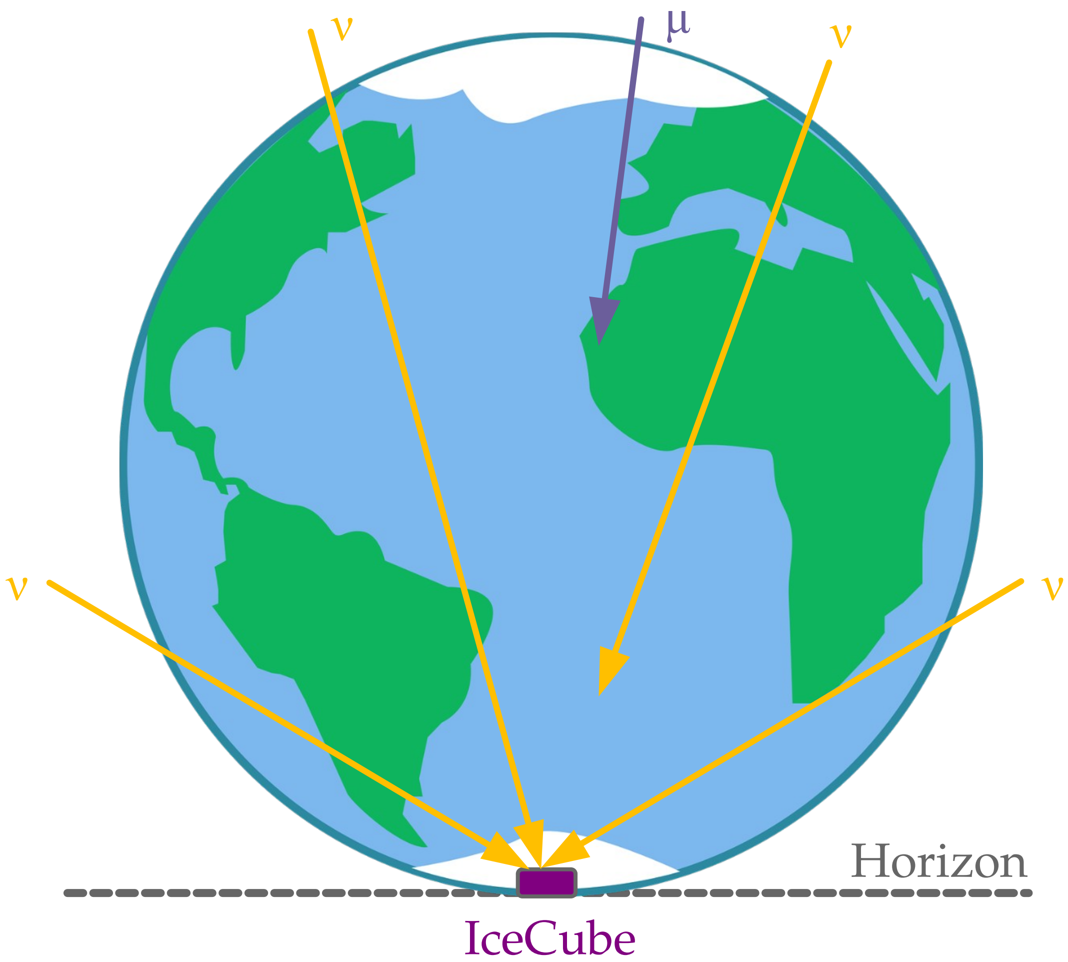
Peeking inside a proton

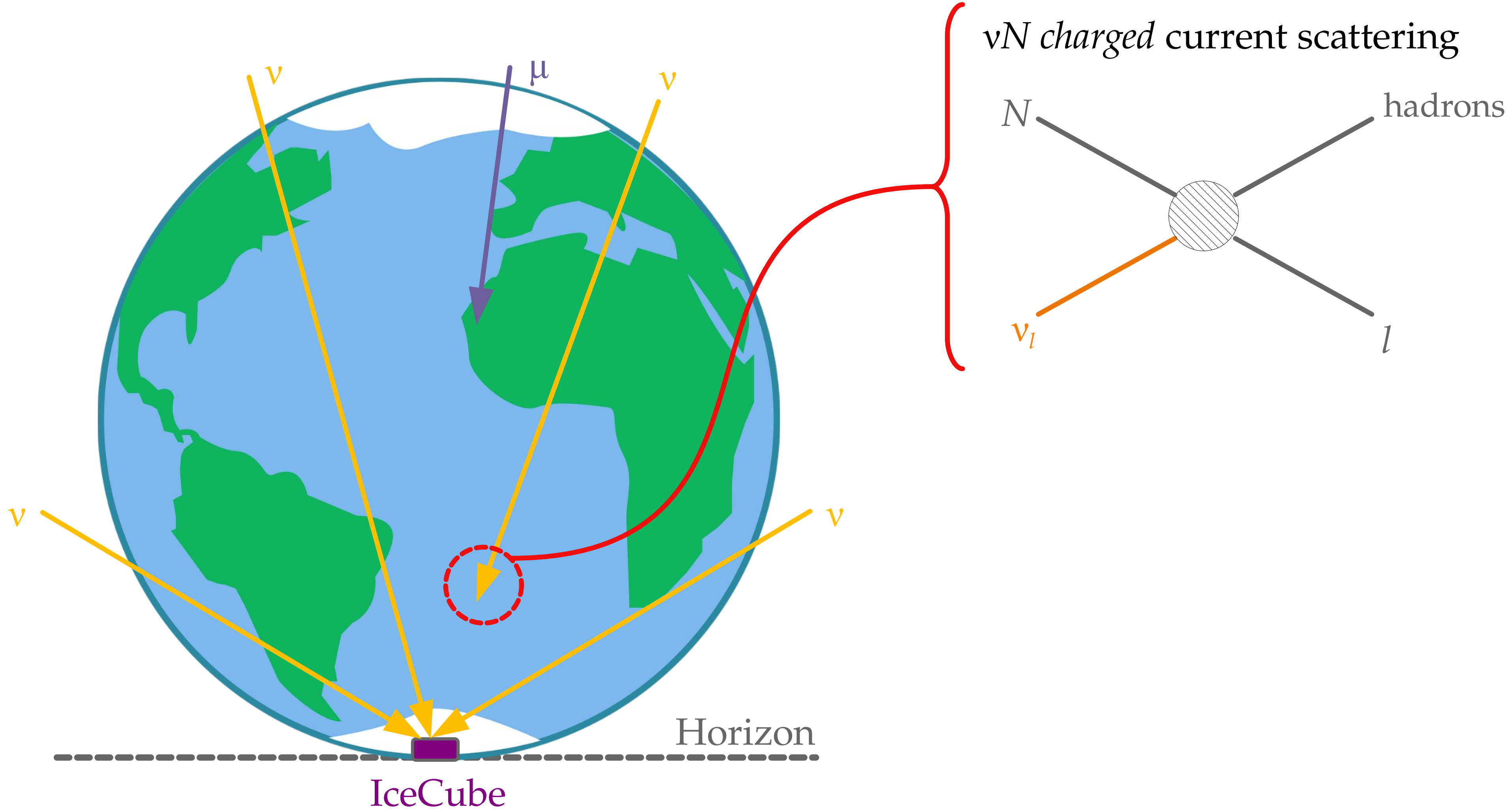


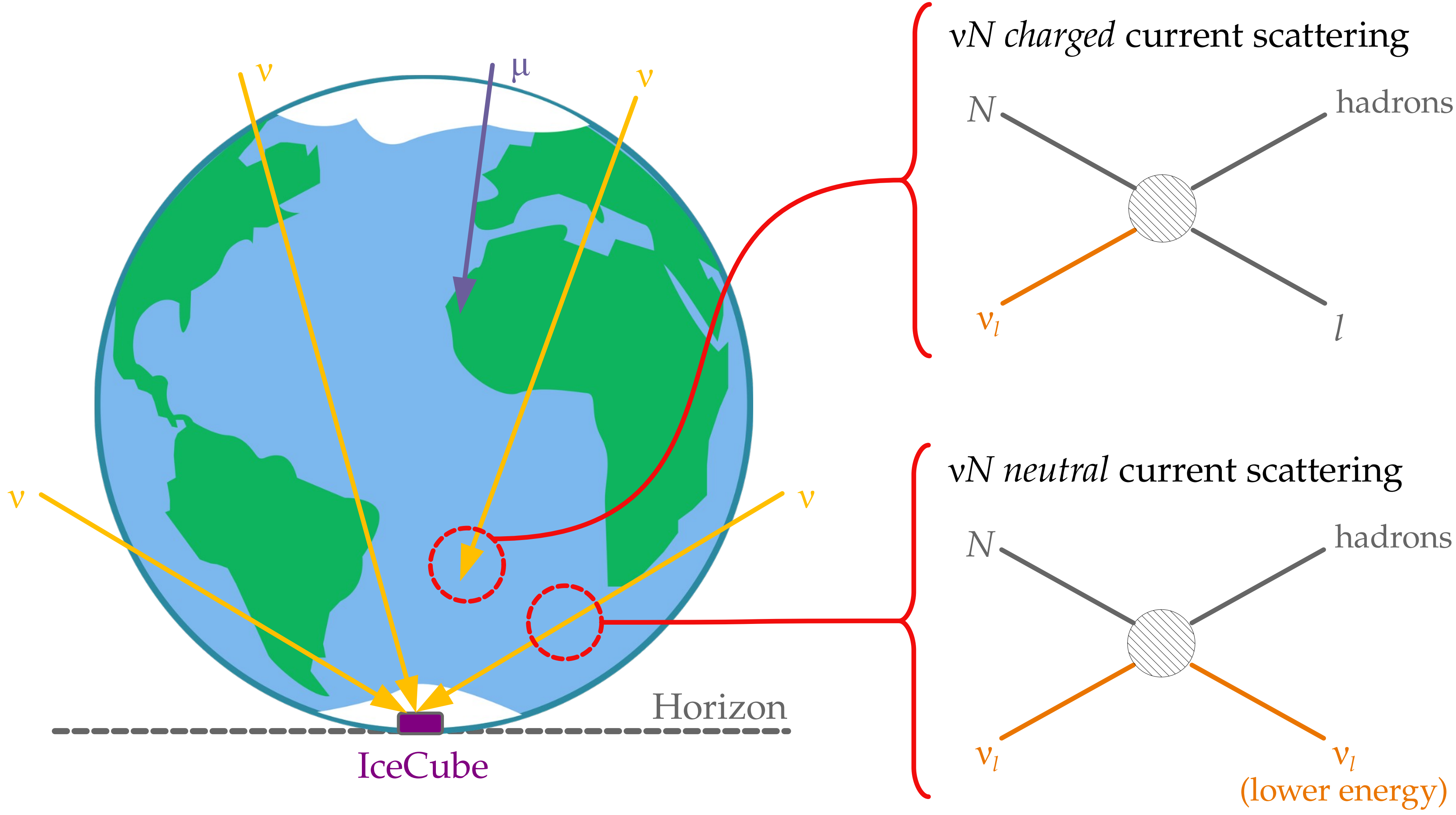
← Extrapolation

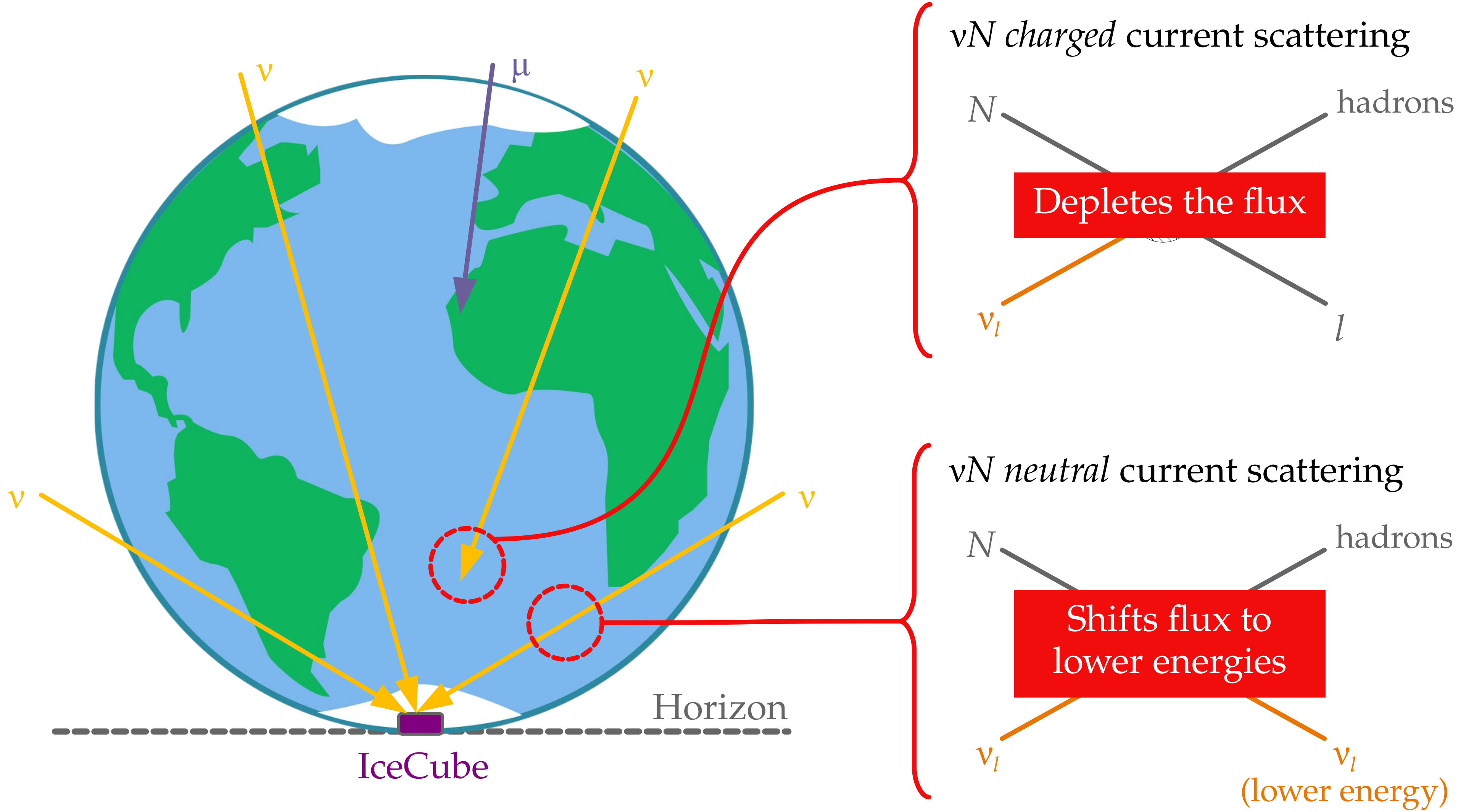
Valera, **MB**, Glaser, *JHEP* 2022
Adapted for Snowmass 2021: Ackermann, **MB**, *et al.*, *JHEAp* 2022




ν
μ
ν
ν
ν
Horizon
IceCube

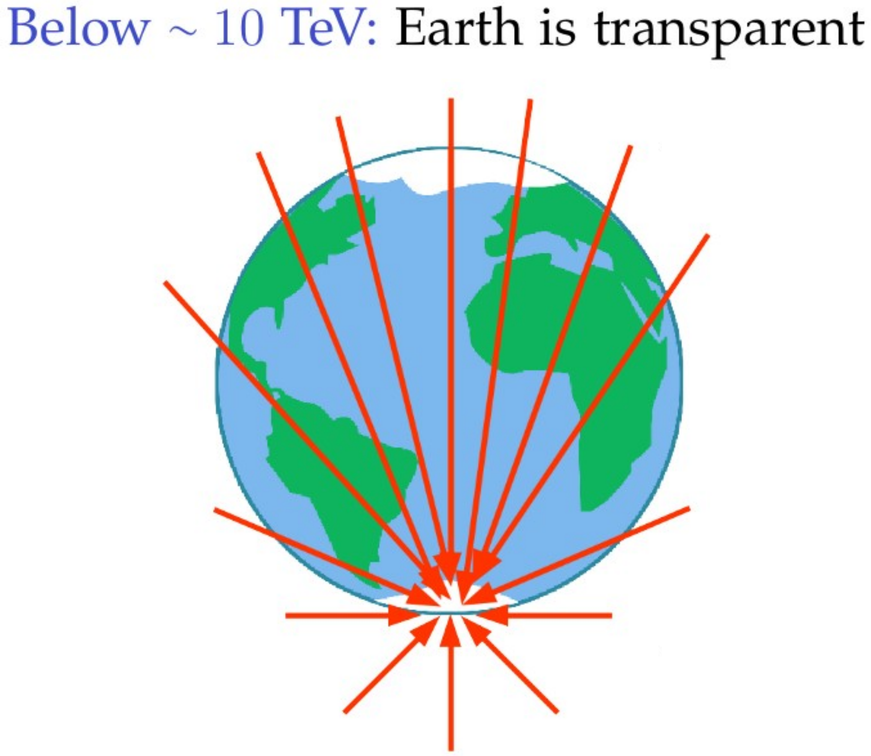

νN *charged* current scattering
N
hadrons
ν_l
l
ν
μ
ν
ν
ν
Horizon
IceCube

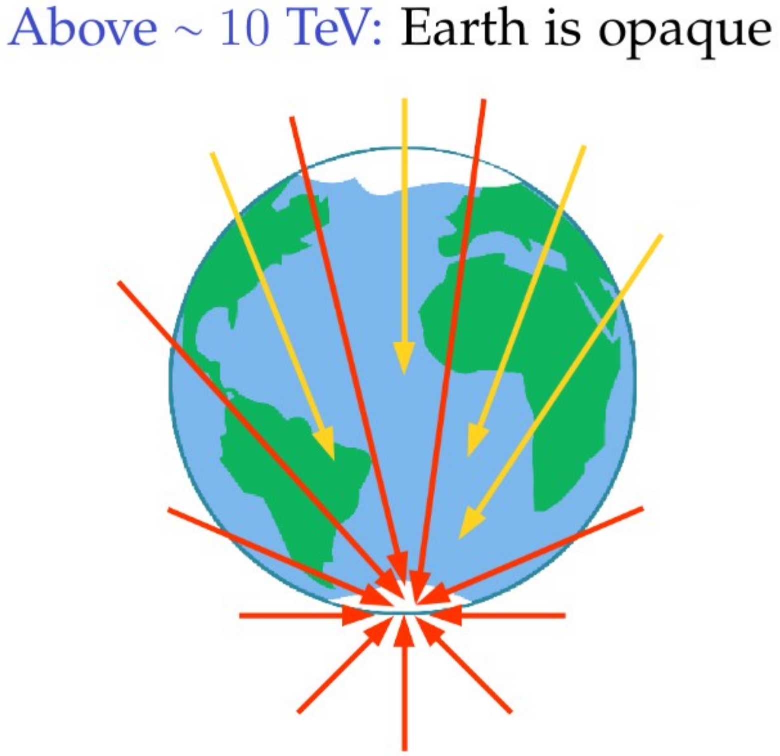

ν
μ
ν
ν
ν
Horizon
IceCube
νN charged current scattering
N
hadrons
ν_l
l
νN neutral current scattering
N
hadrons
ν_l
ν_l
(lower energy)



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

Measuring the high-energy νN cross section

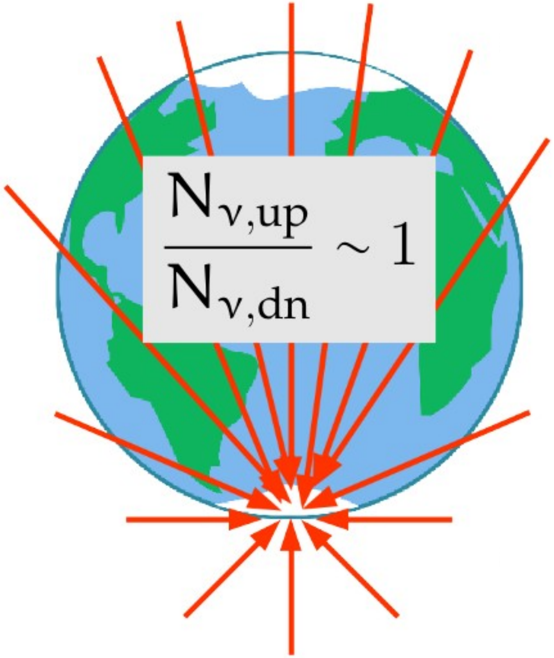




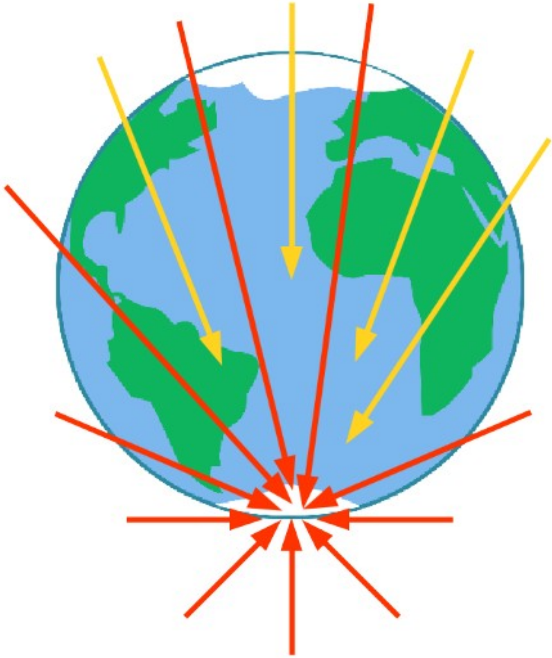
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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

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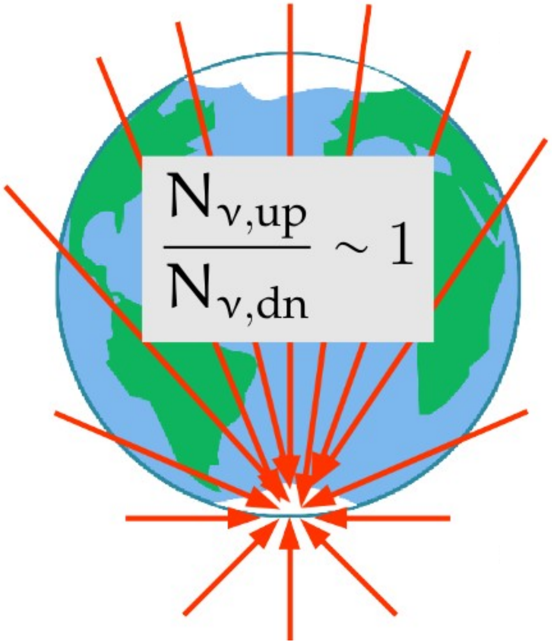
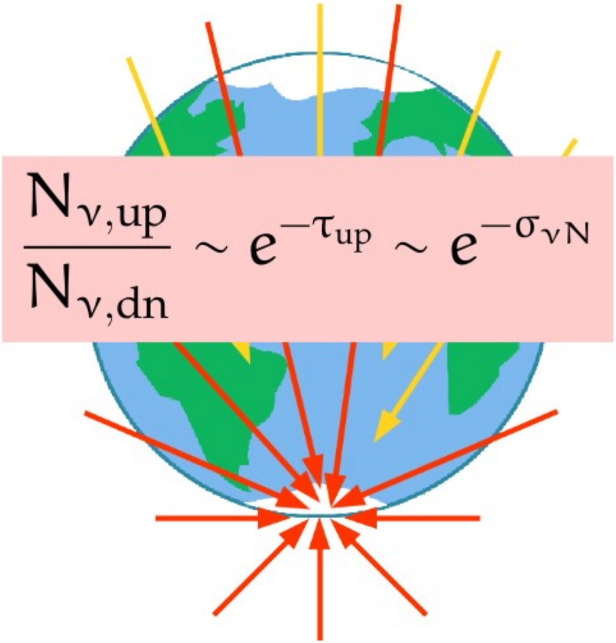
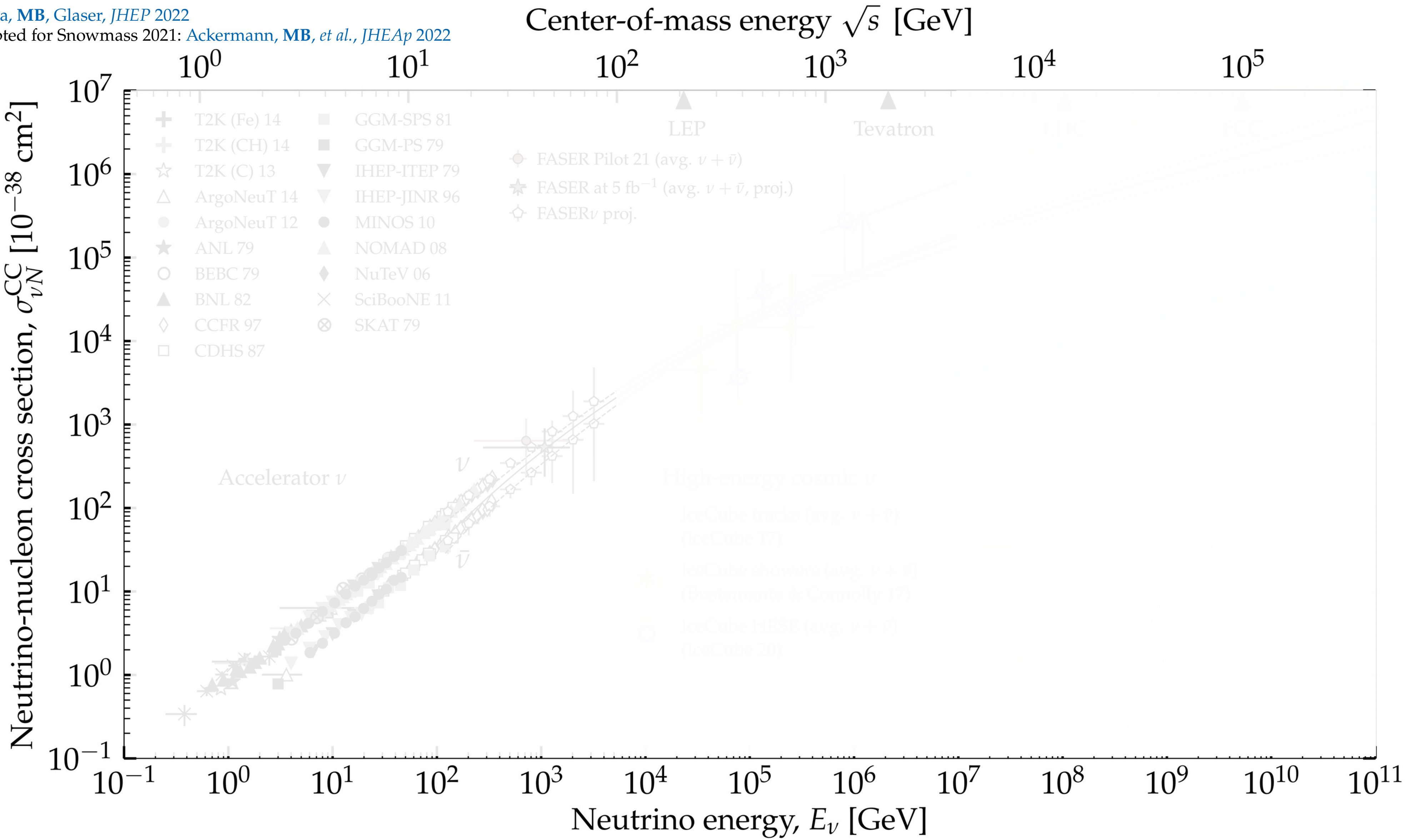


Above ~ 10 TeV: Earth is opaque



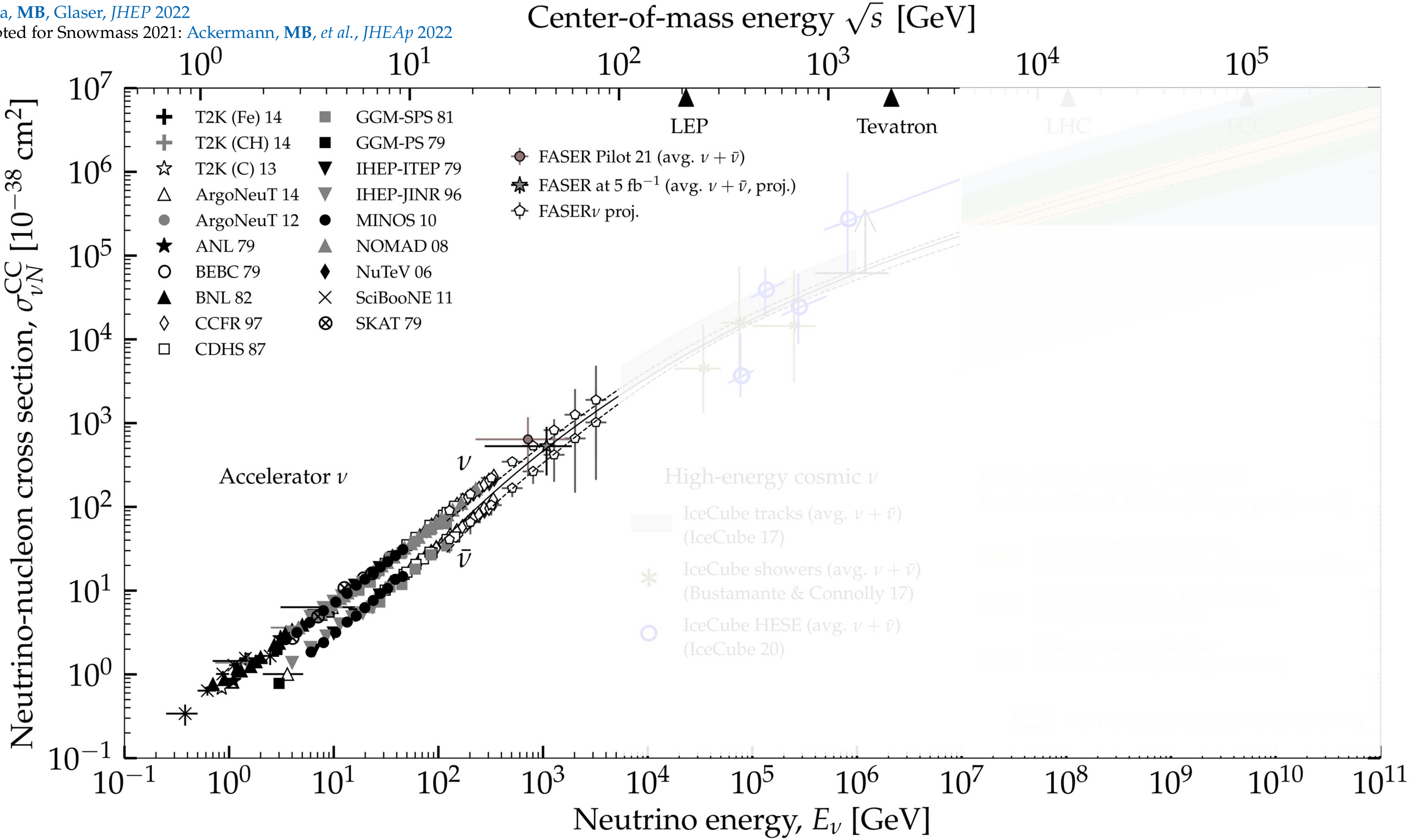
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008; Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015

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

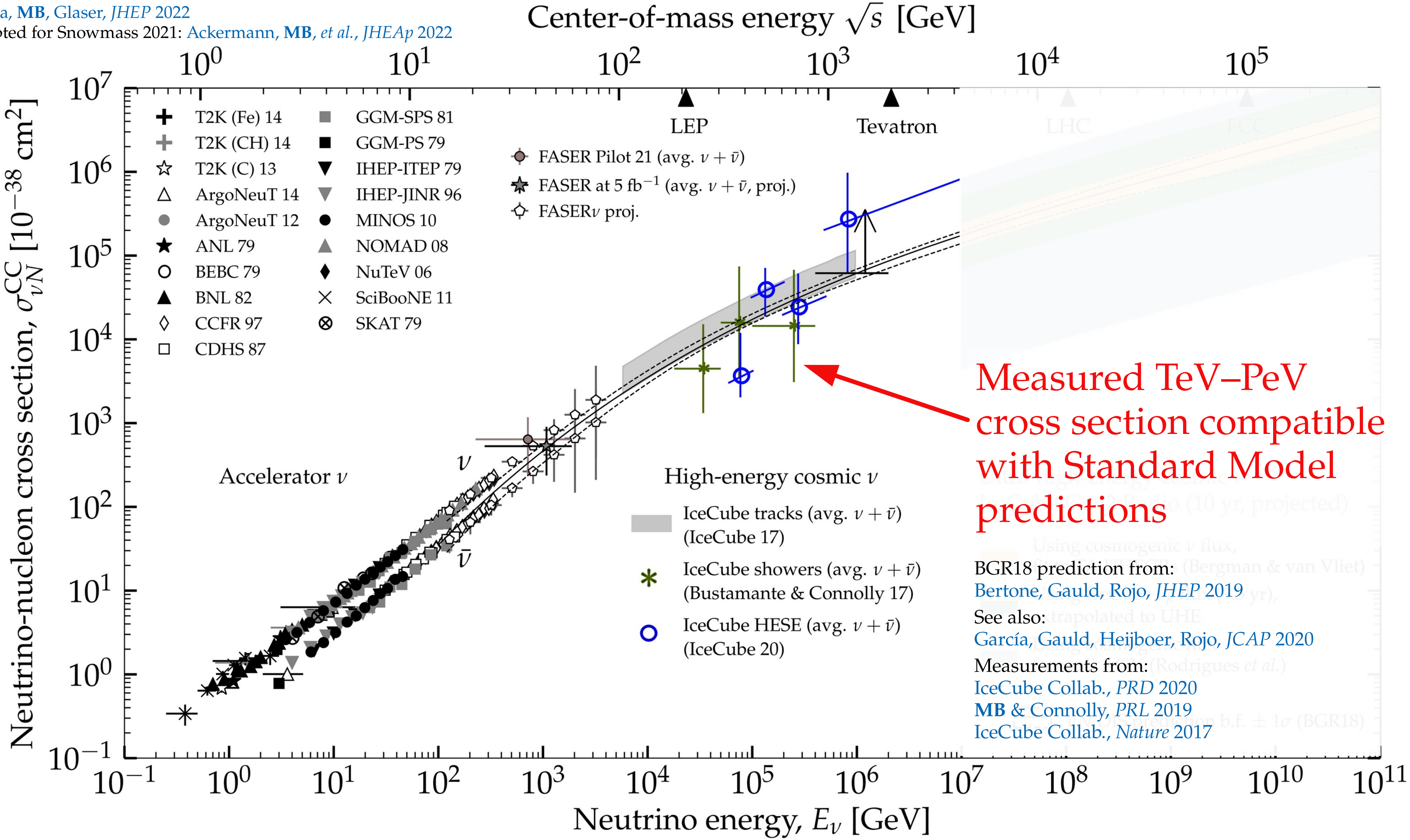


Valera, **MB**, Glaser, *JHEP* 2022

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



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



2. Dark matter:
Annihilation and decay

High-energy neutrinos from dark matter

Dark matter co-annihilation:

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

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

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

Dark matter decay:

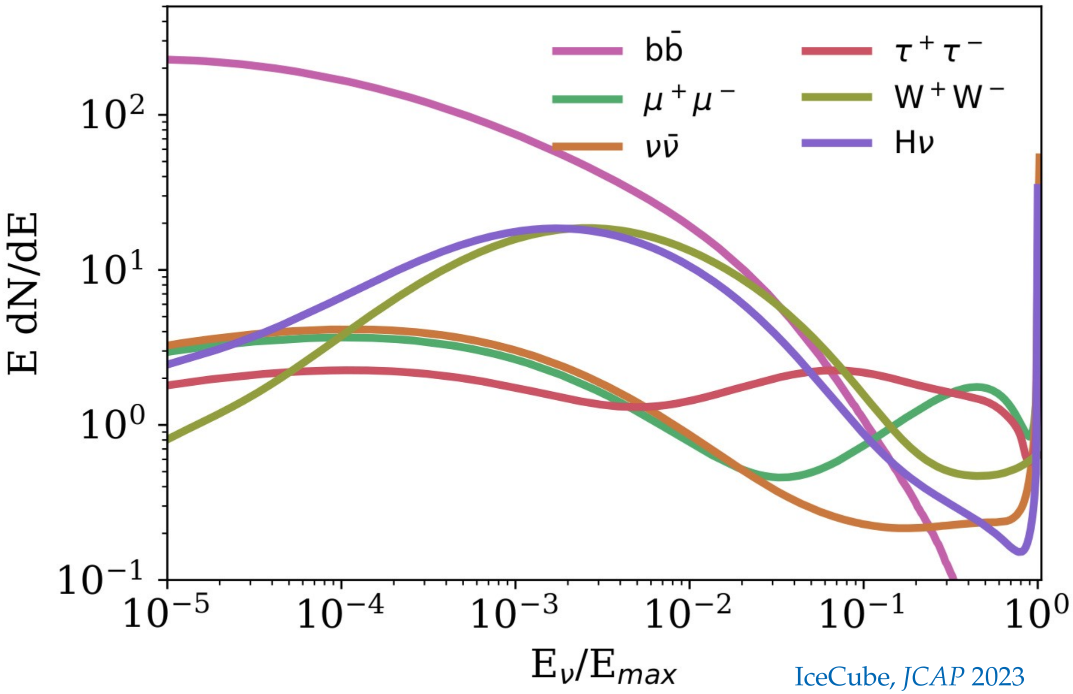
$$\chi \rightarrow \nu + \bar{\nu}$$

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

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

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

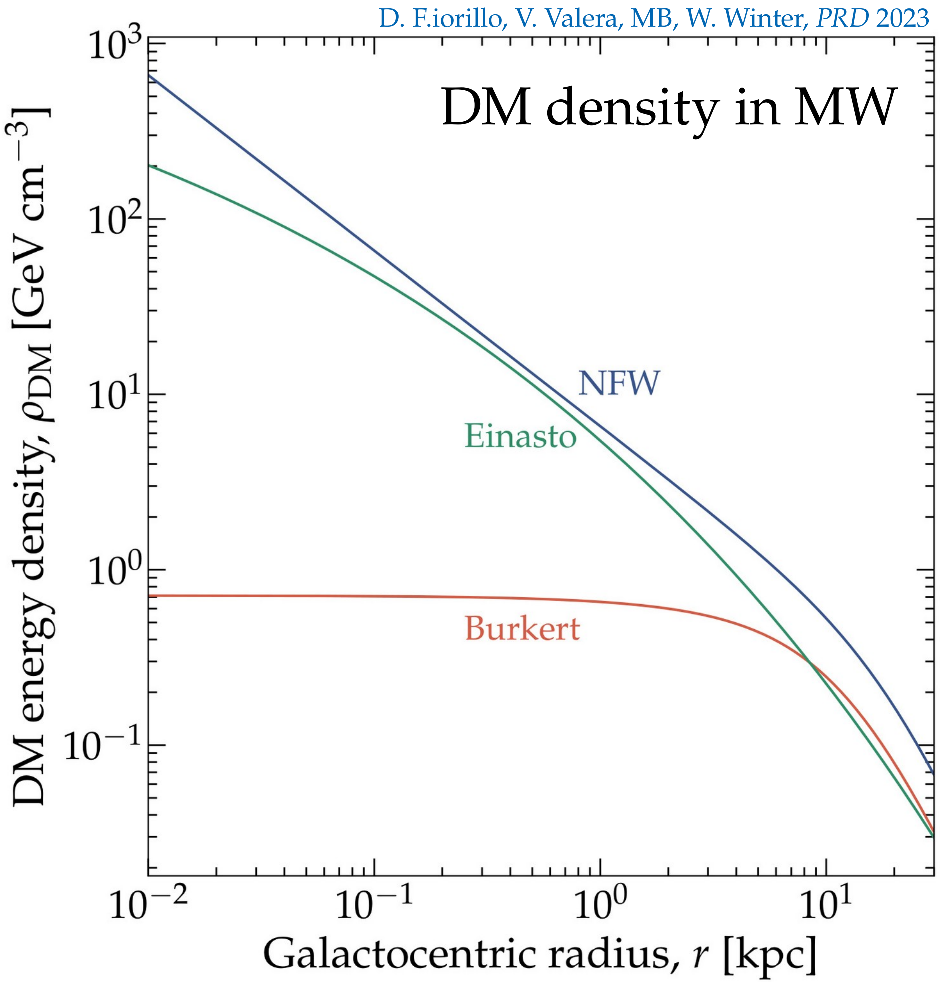
ν + ν̄ yield from DM (at source)



IceCube, *JCAP* 2023

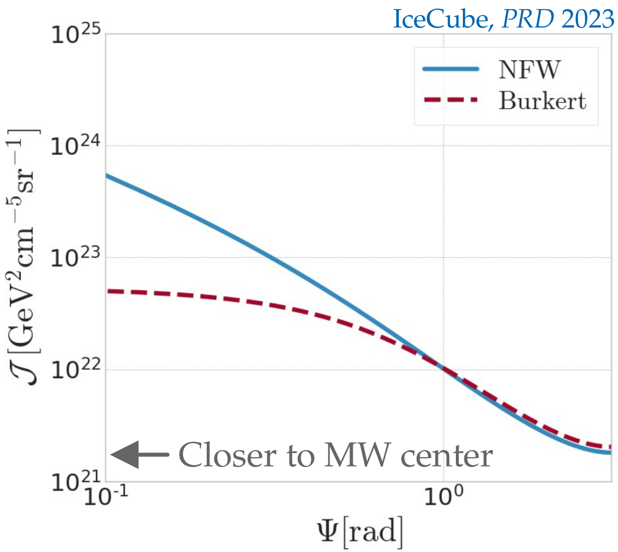
Approximate independence on m_χ valid for $m_\chi \approx$ 100 TeV–10 PeV

Dark matter in the Milky Way



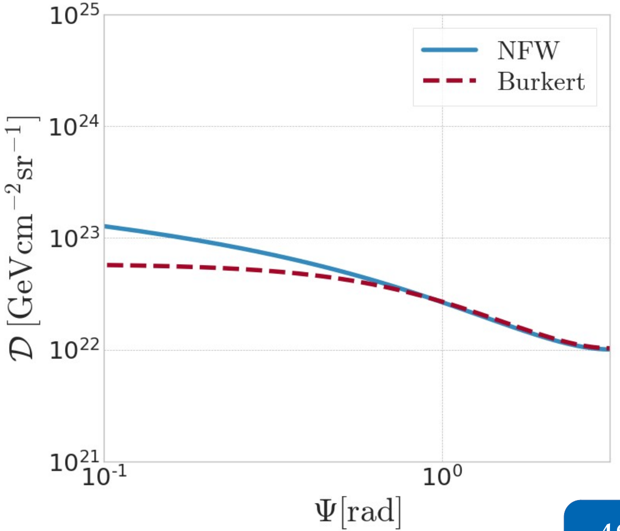
DM annihilation

$\Phi_\nu \propto \mathcal{I} \propto \rho^2_{\rm DM}$



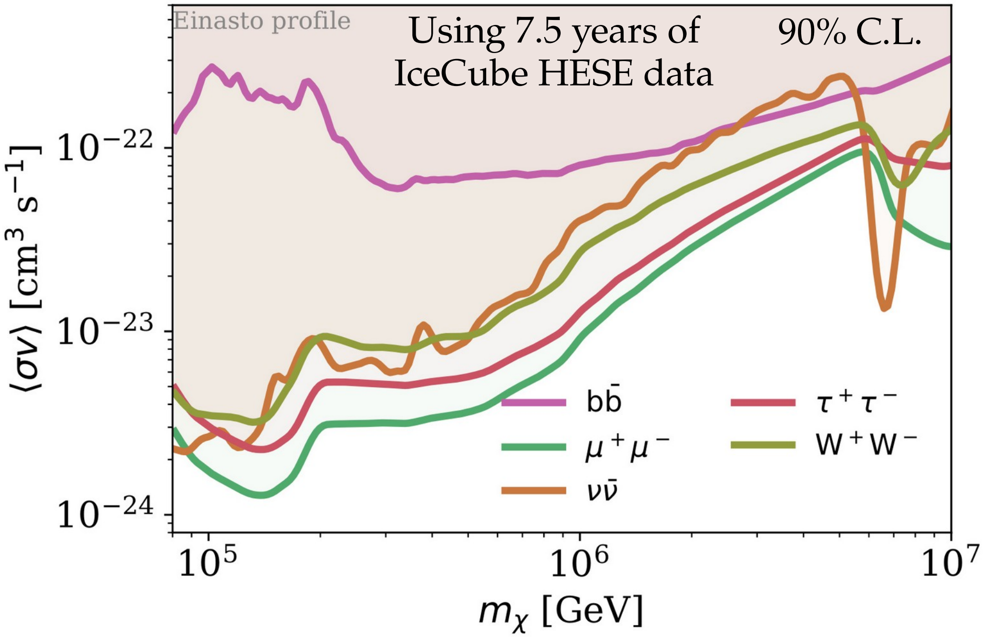
DM decay

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

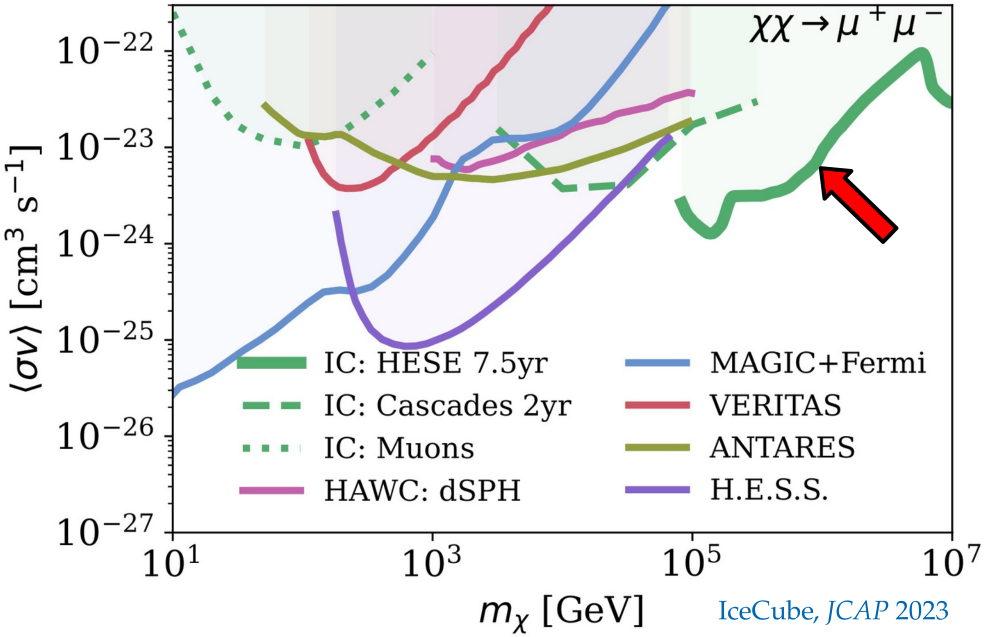


Limits on dark matter annihilation

Per annihilation channel
(assuming 100% branching ratio)



Compared to other limits
(assuming annihilation to muons)



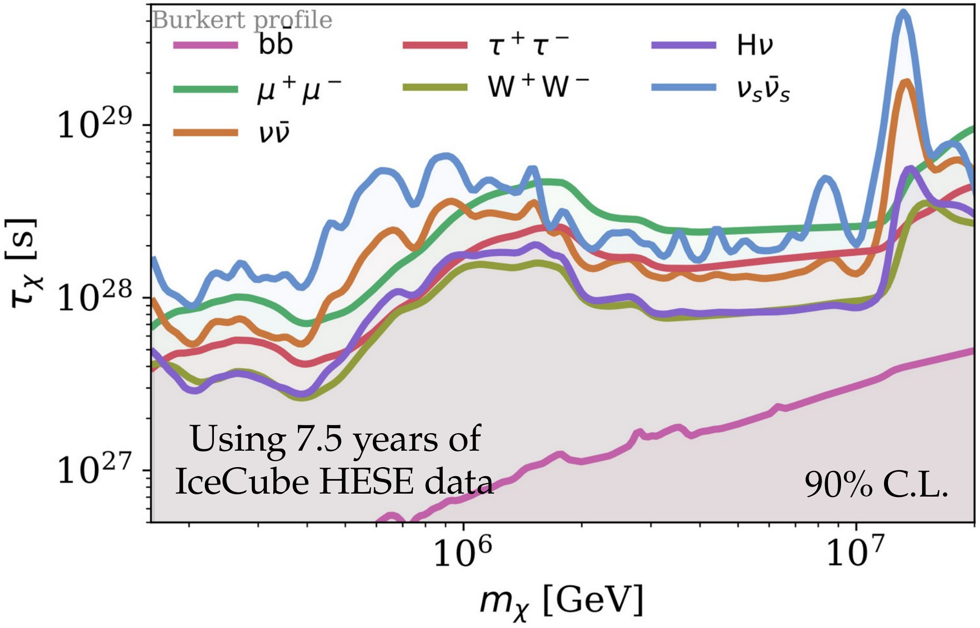
IceCube, *JCAP* 2023

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

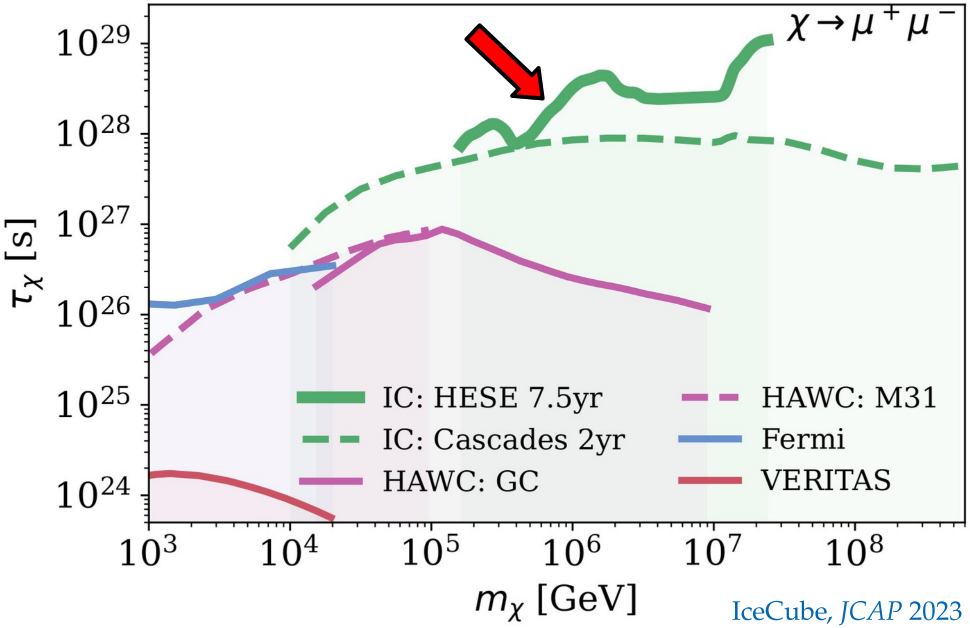
Plus background of atmospheric neutrinos (anisotropic, but different)

Limits on dark matter decay

Per annihilation channel
(assuming 100% branching ratio)



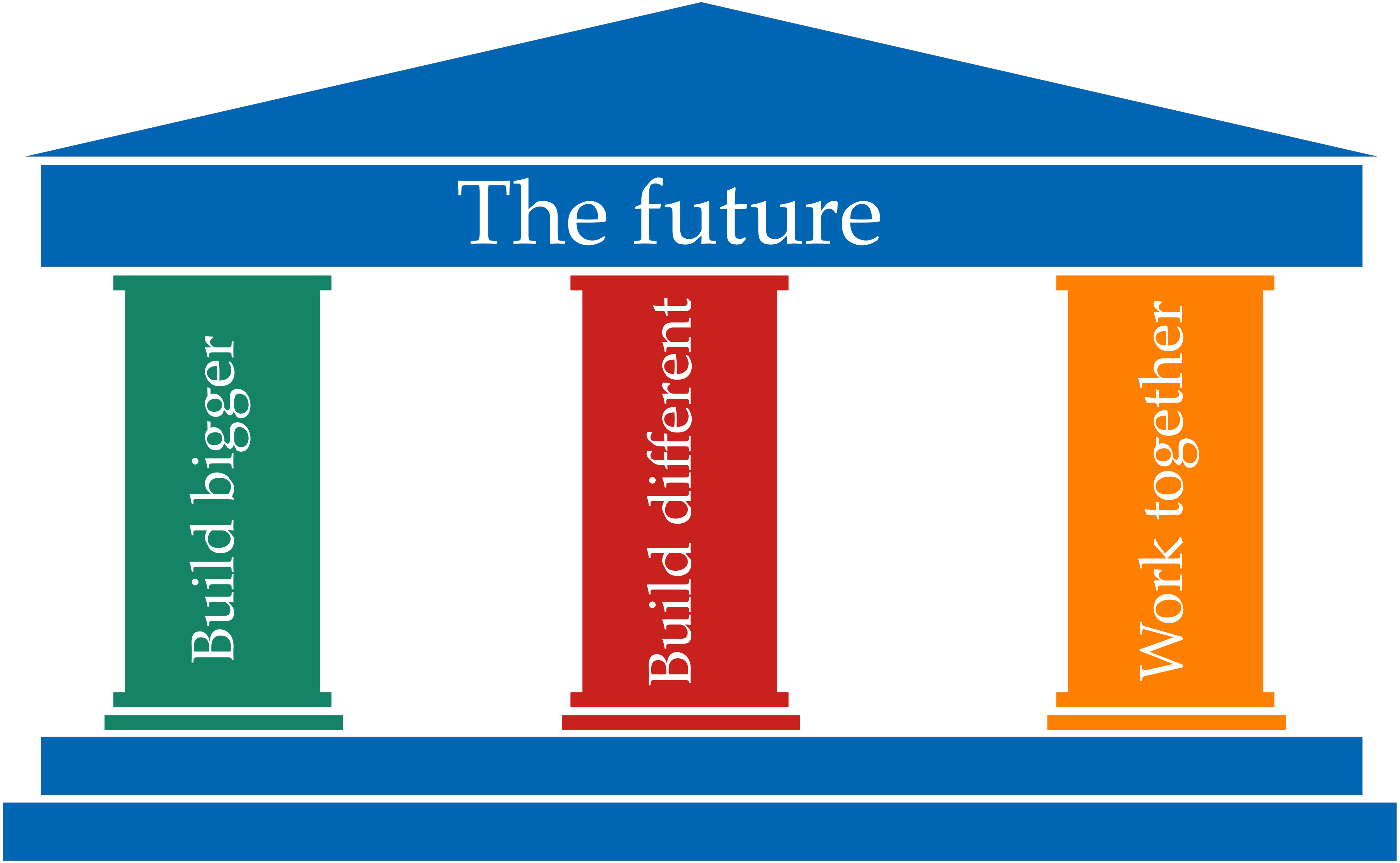
Compared to other limits
(assuming decay into muons)

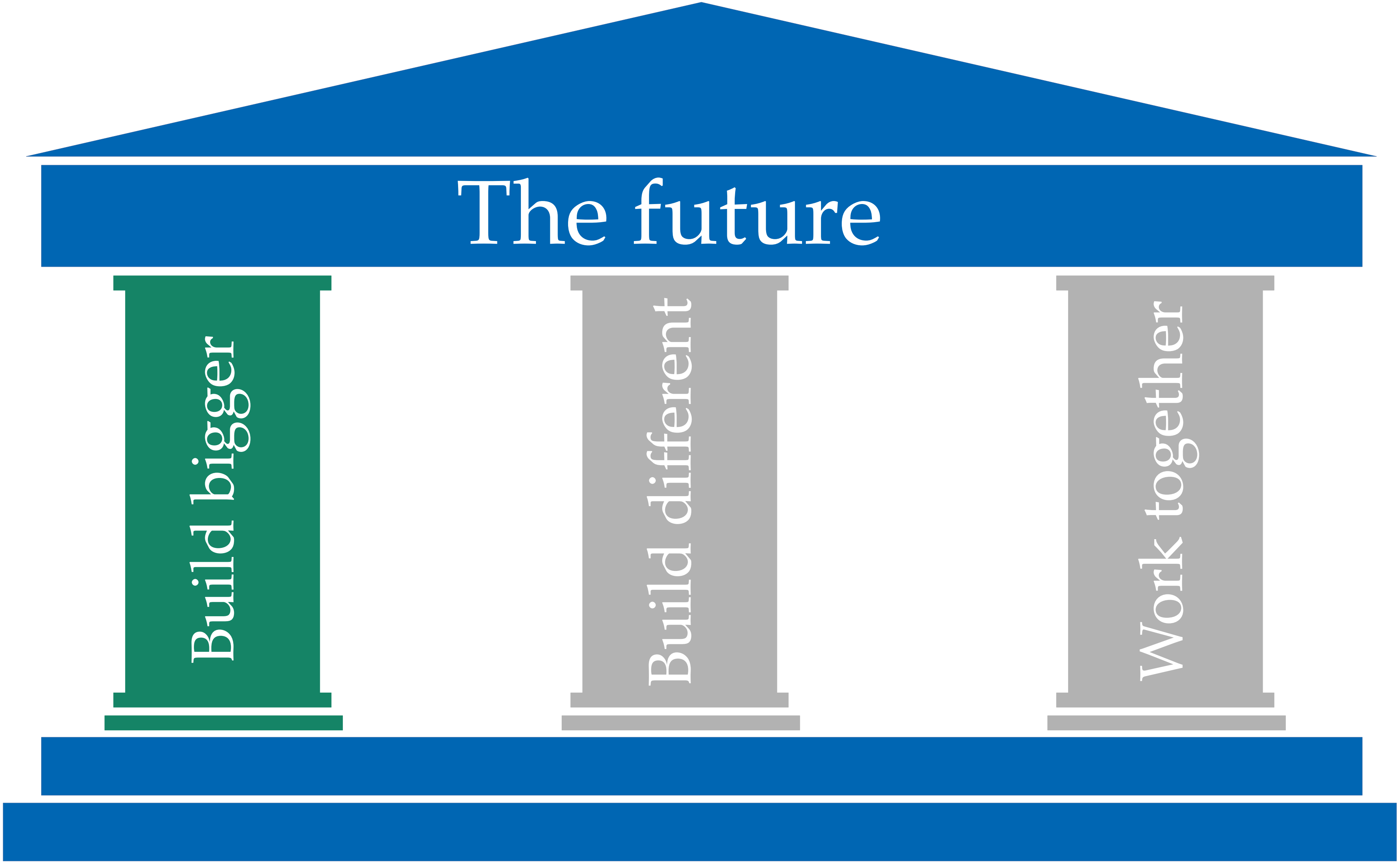


IceCube, *JCAP* 2023

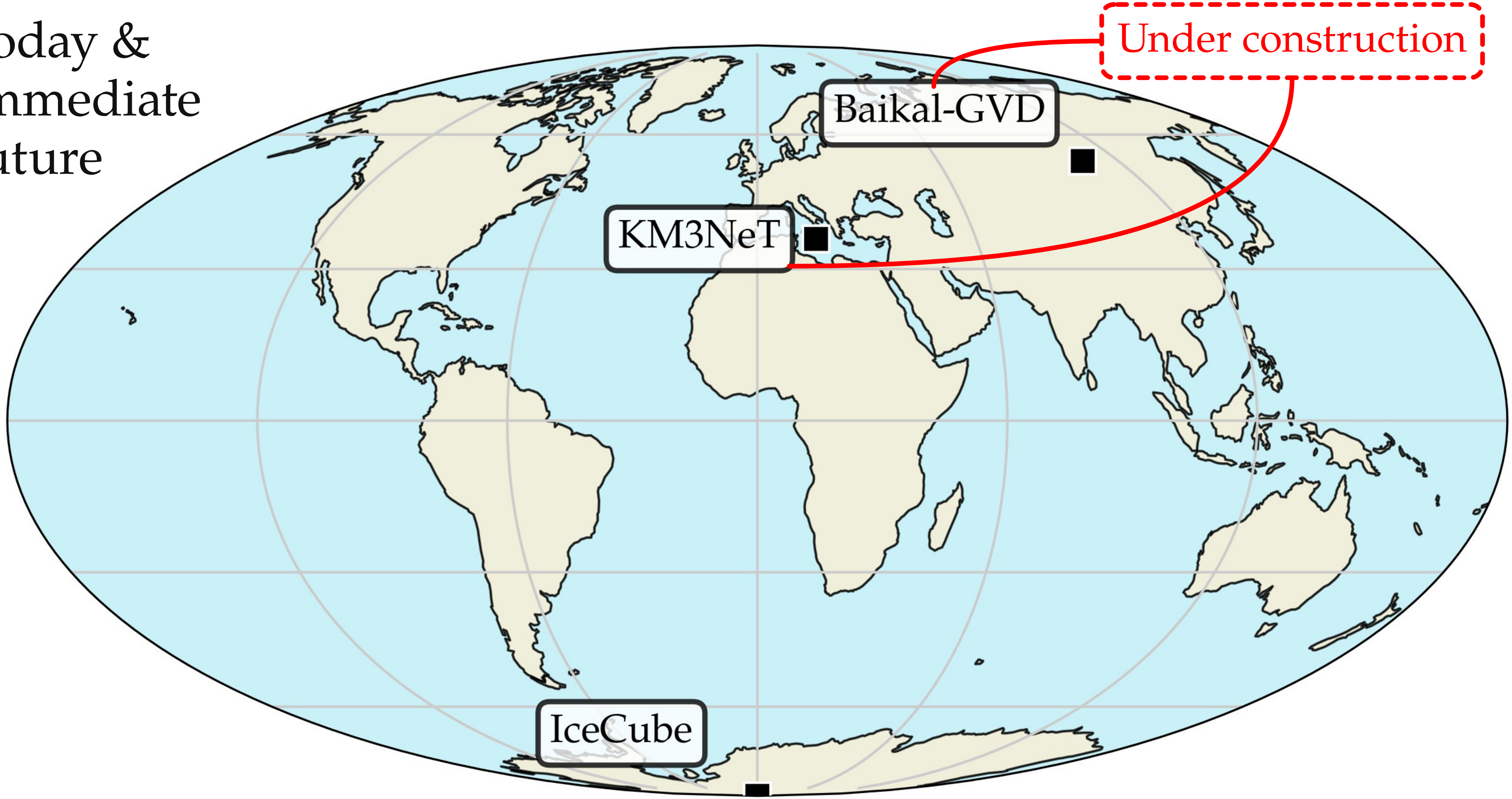
Two DM contributions: Galactic (anisotropic) + extragalactic (isotropic)

Plus background of atmospheric neutrinos (anisotropic, but different)

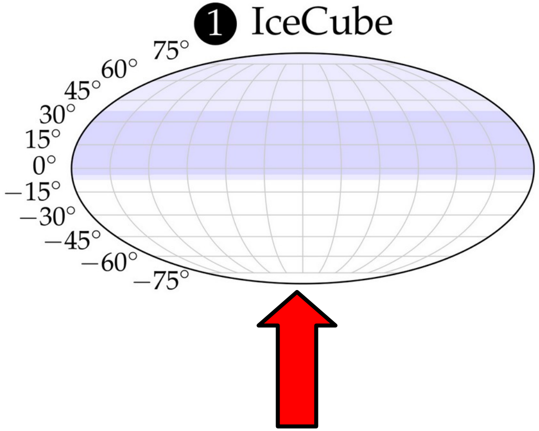

The future
Build bigger
Build different
Work together

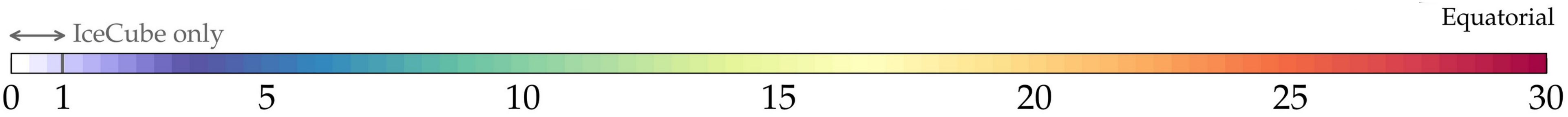

The future
Build bigger
Build different
Work together

Today & immediate future



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

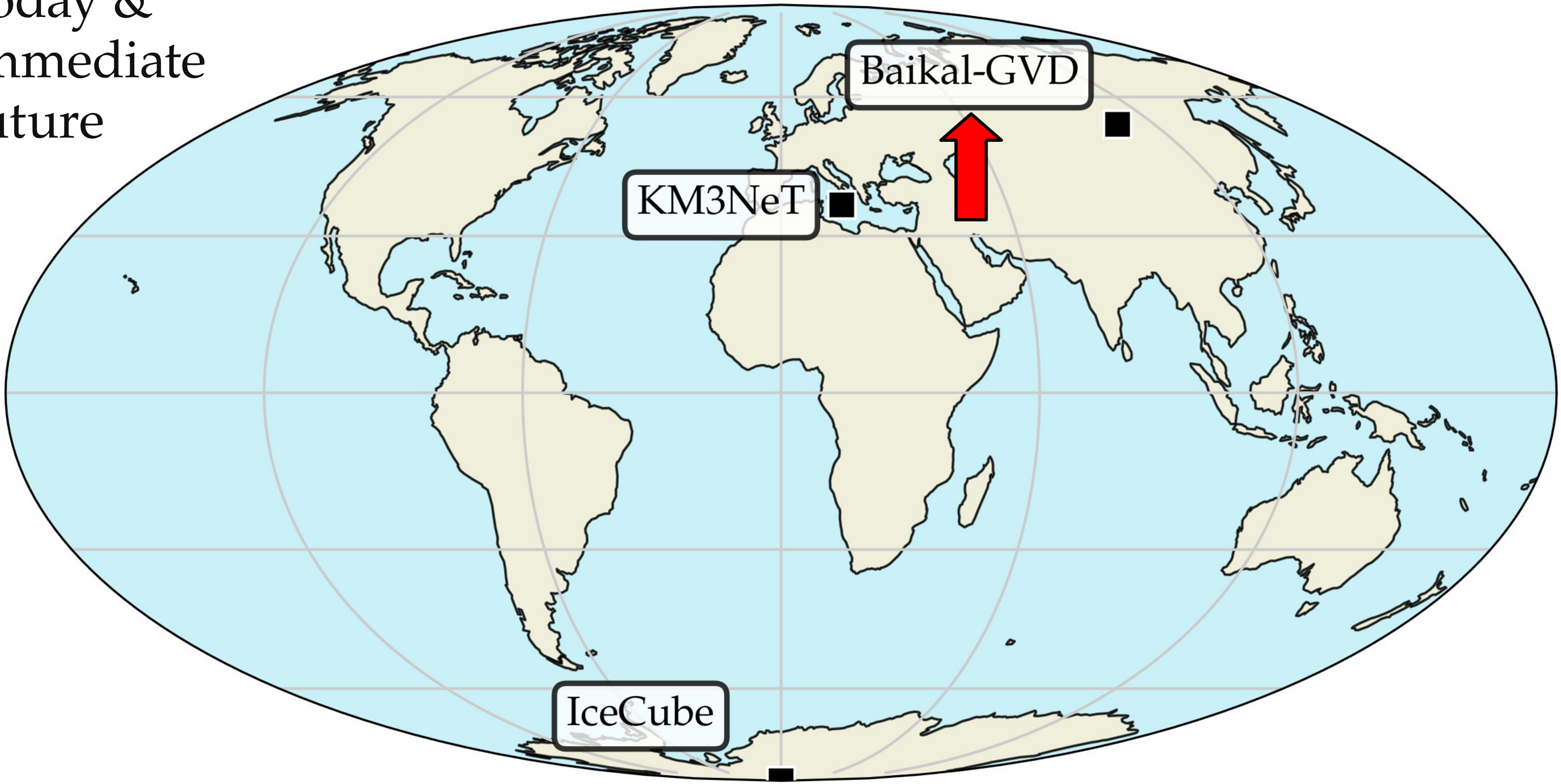




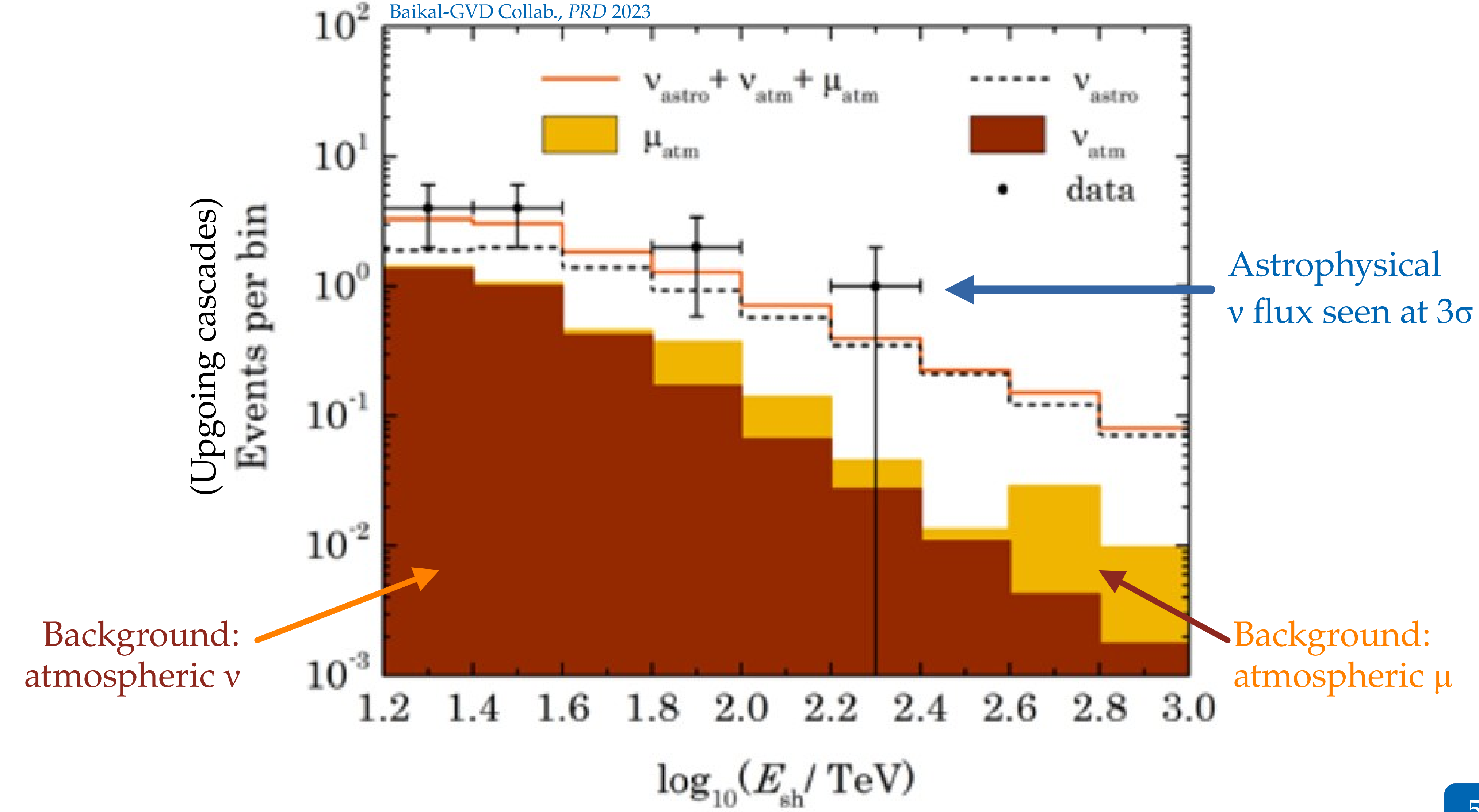
Rate of detected muon tracks relative to IceCube maximum

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

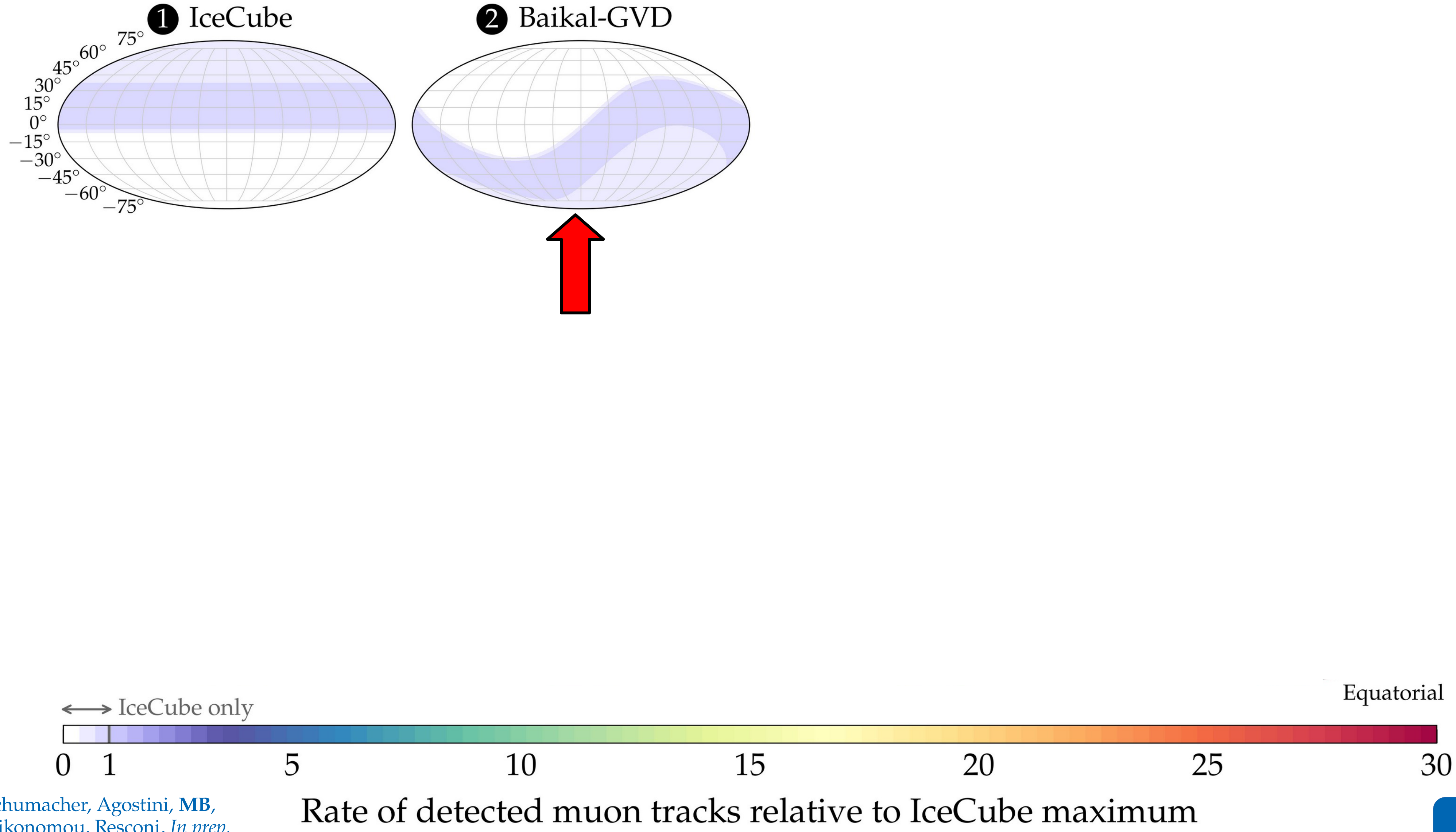
Today & immediate future



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

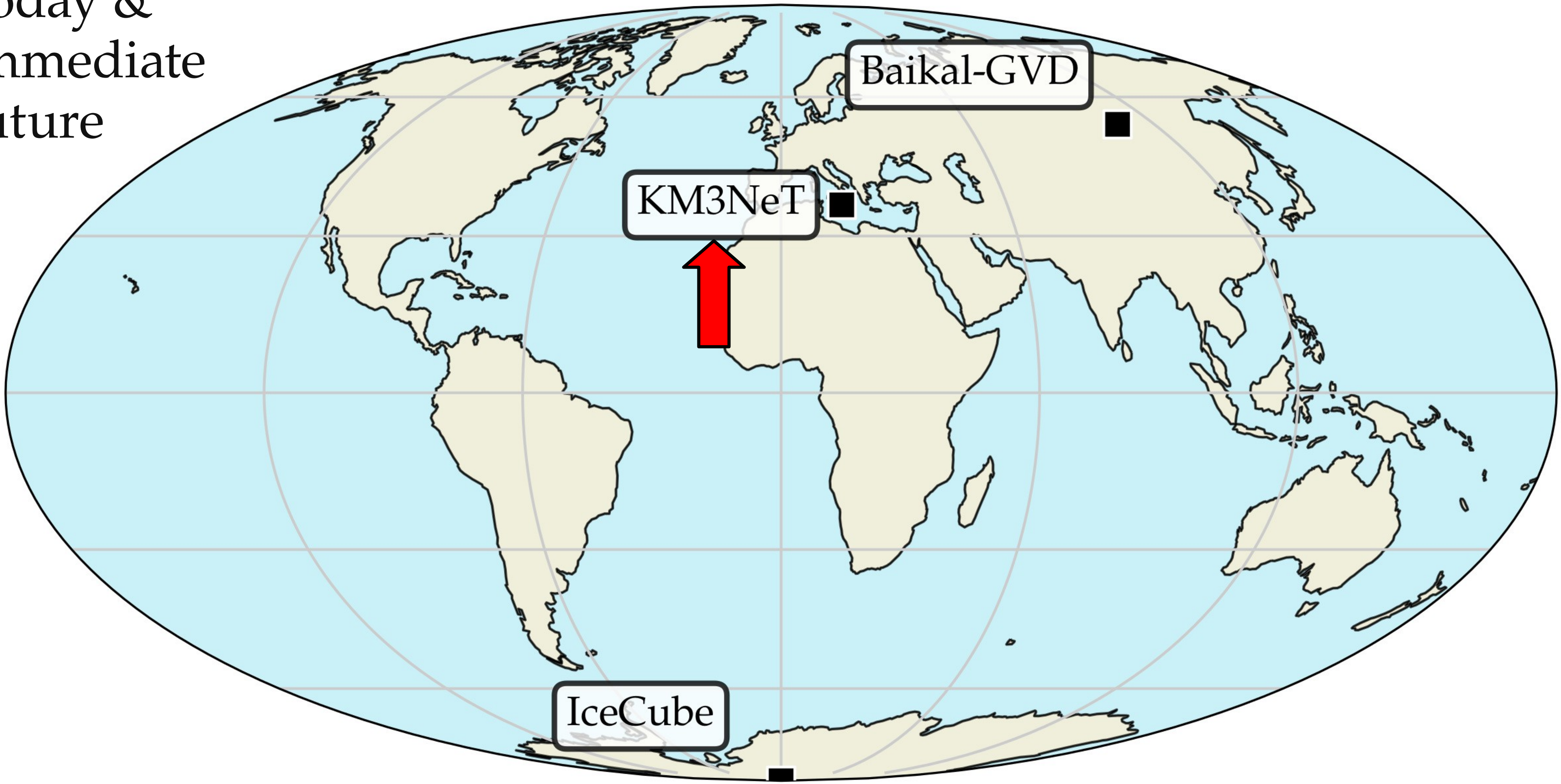


Baikal-GVD Collab., PRD 2023
ν astro + ν atm + μ atm
ν astro
μ atm
ν atm
data
(Upgoing cascades)
Events per bin
log10(E sh / TeV)
Astrophysical ν flux seen at 3σ
Background: atmospheric ν
Background: atmospheric μ



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

Today & immediate future

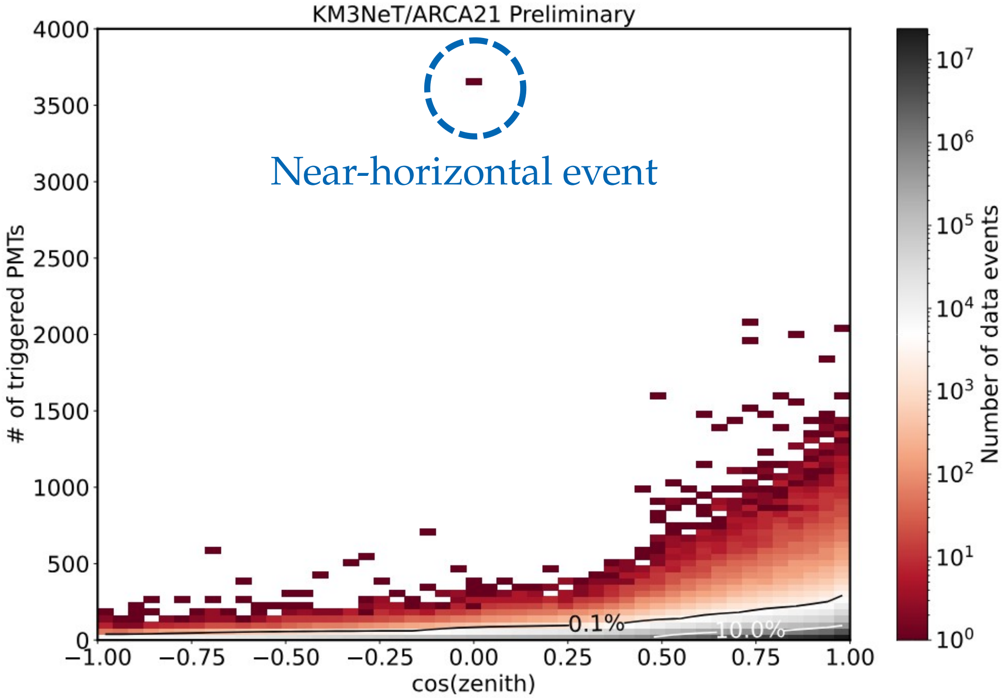


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

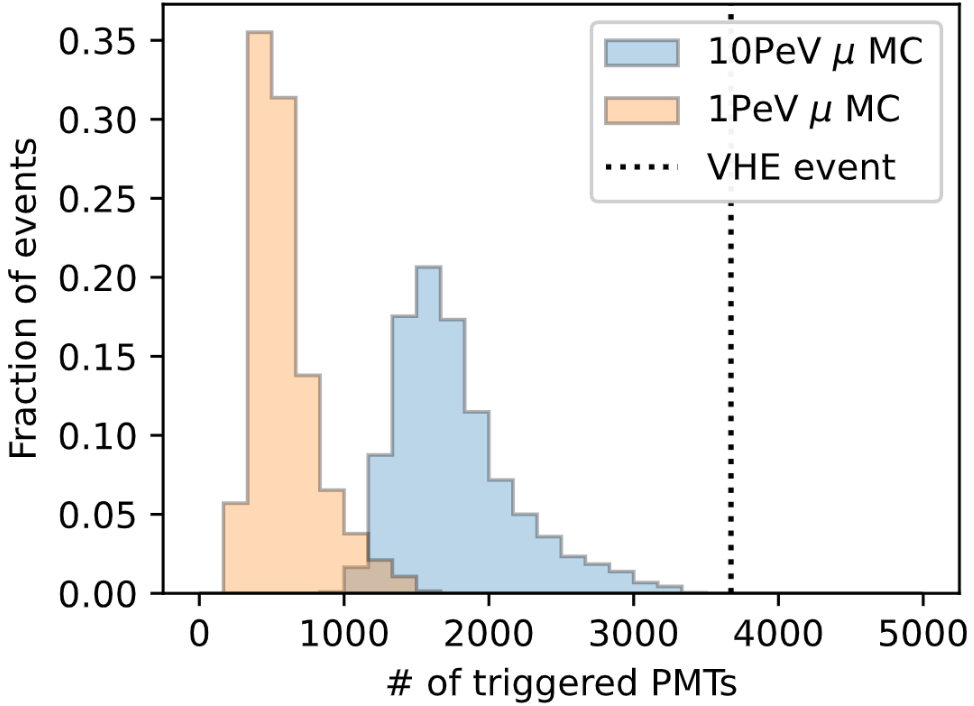
A 100-PeV neutrino detected?

Partially constructed KM3NeT detected an event with possibly tens of PeV:

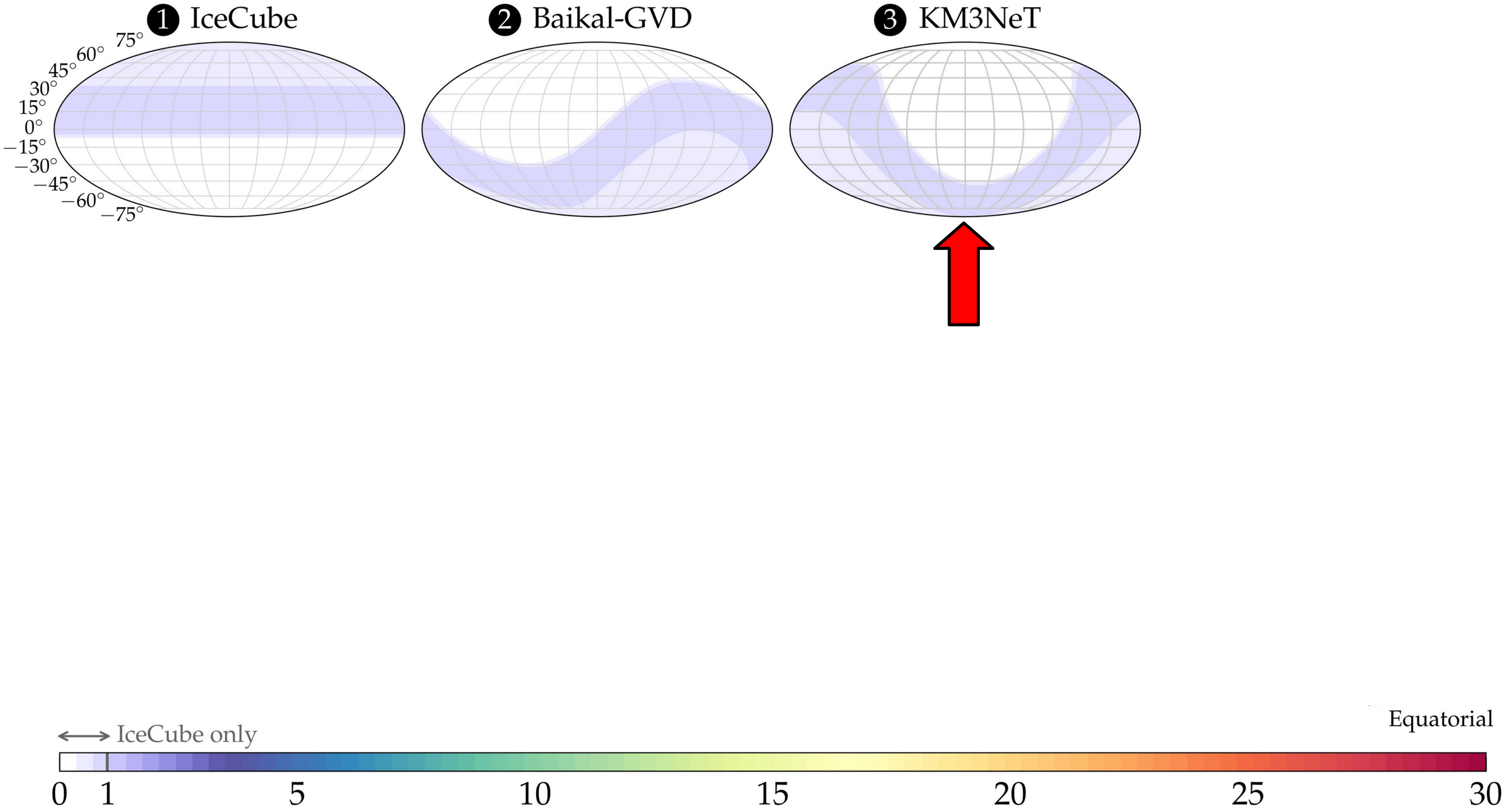
1 in 100 million events



3672 PMTs triggered
(35% of detector)

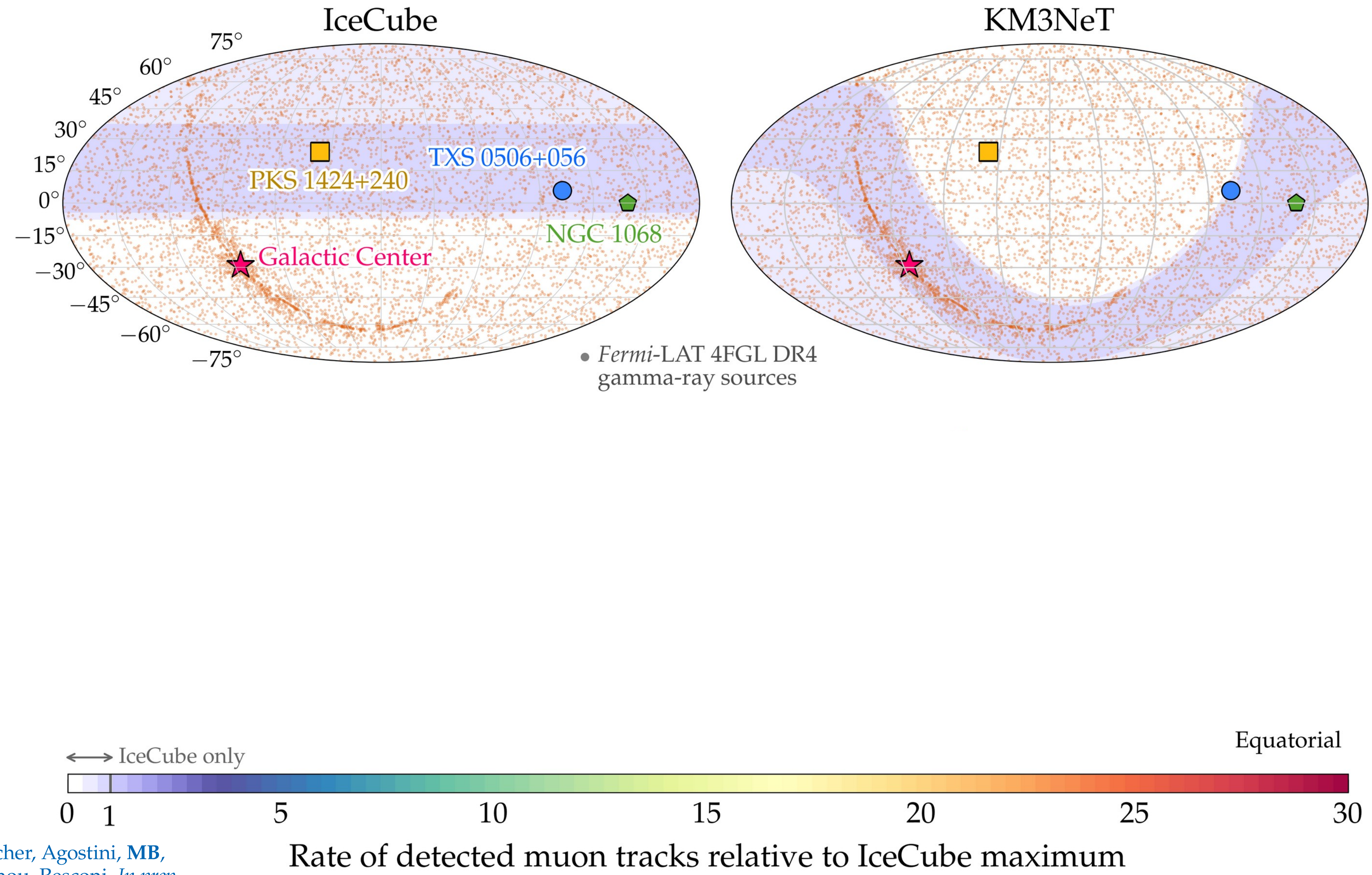


Is this from a diffuse ν flux or a transient event?



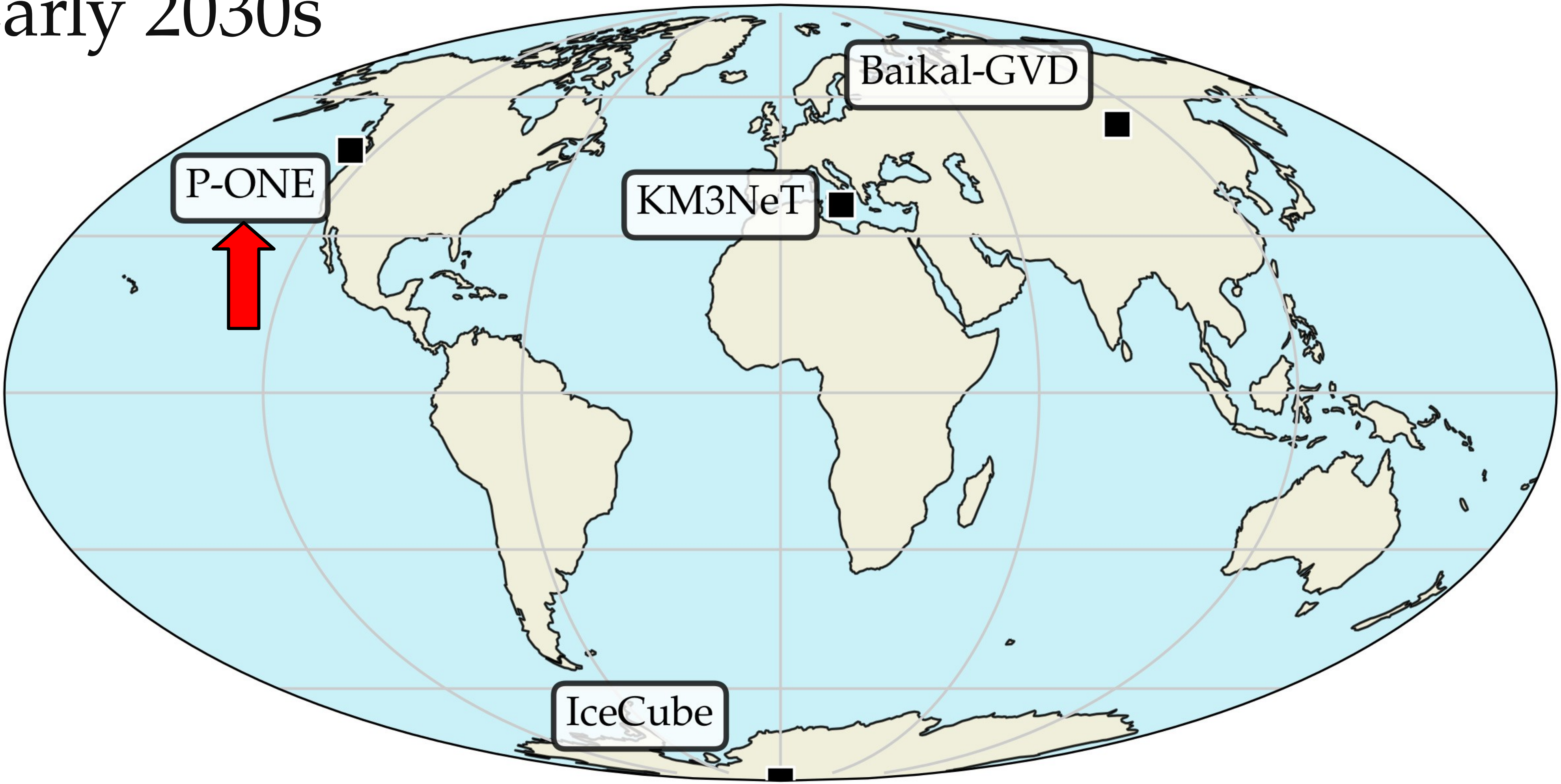
Rate of detected muon tracks relative to IceCube maximum

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

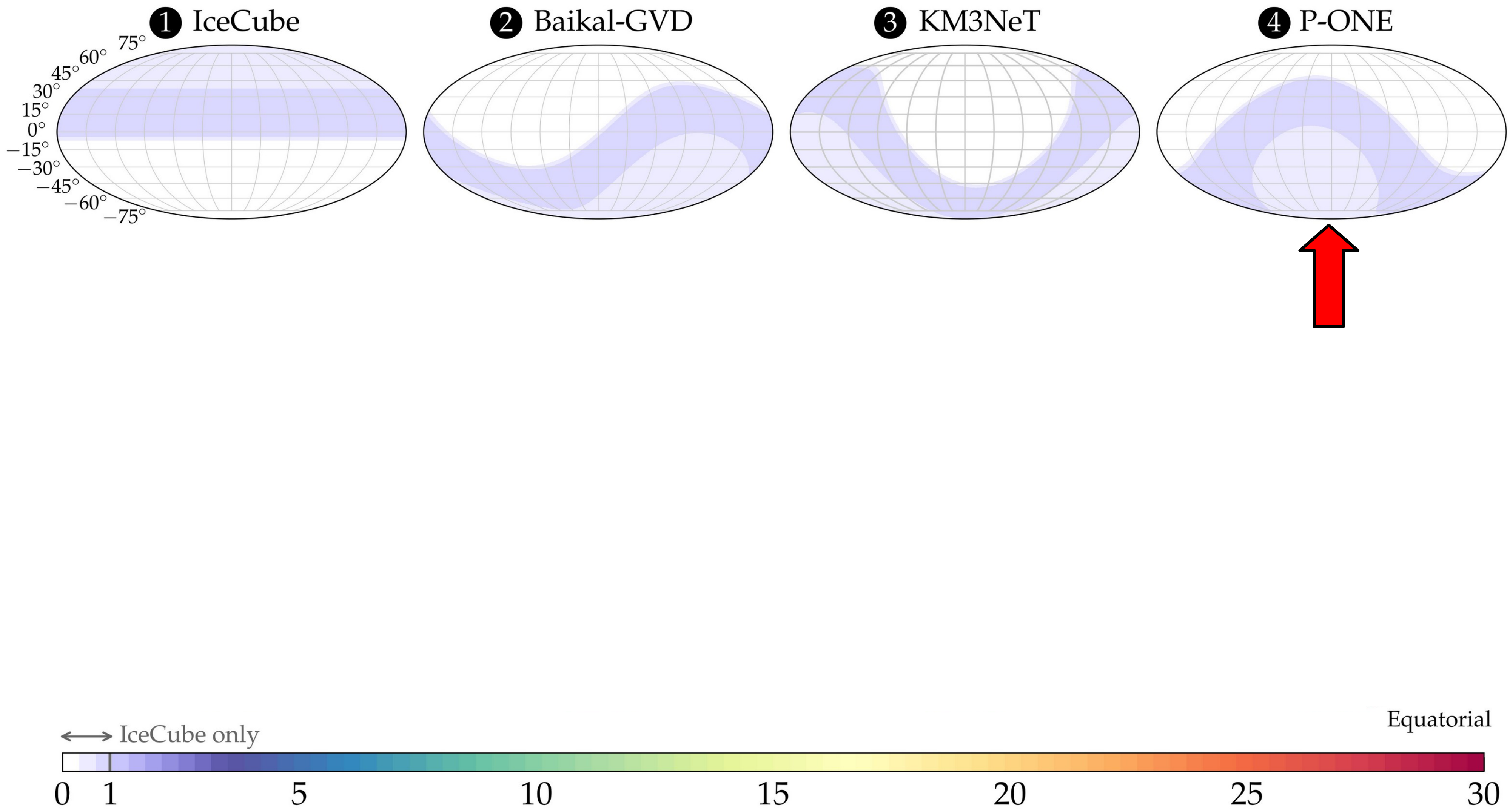


Schumacher, Agostini, **MB**,
Oikonomou, Resconi, *In prep.*

Early 2030s



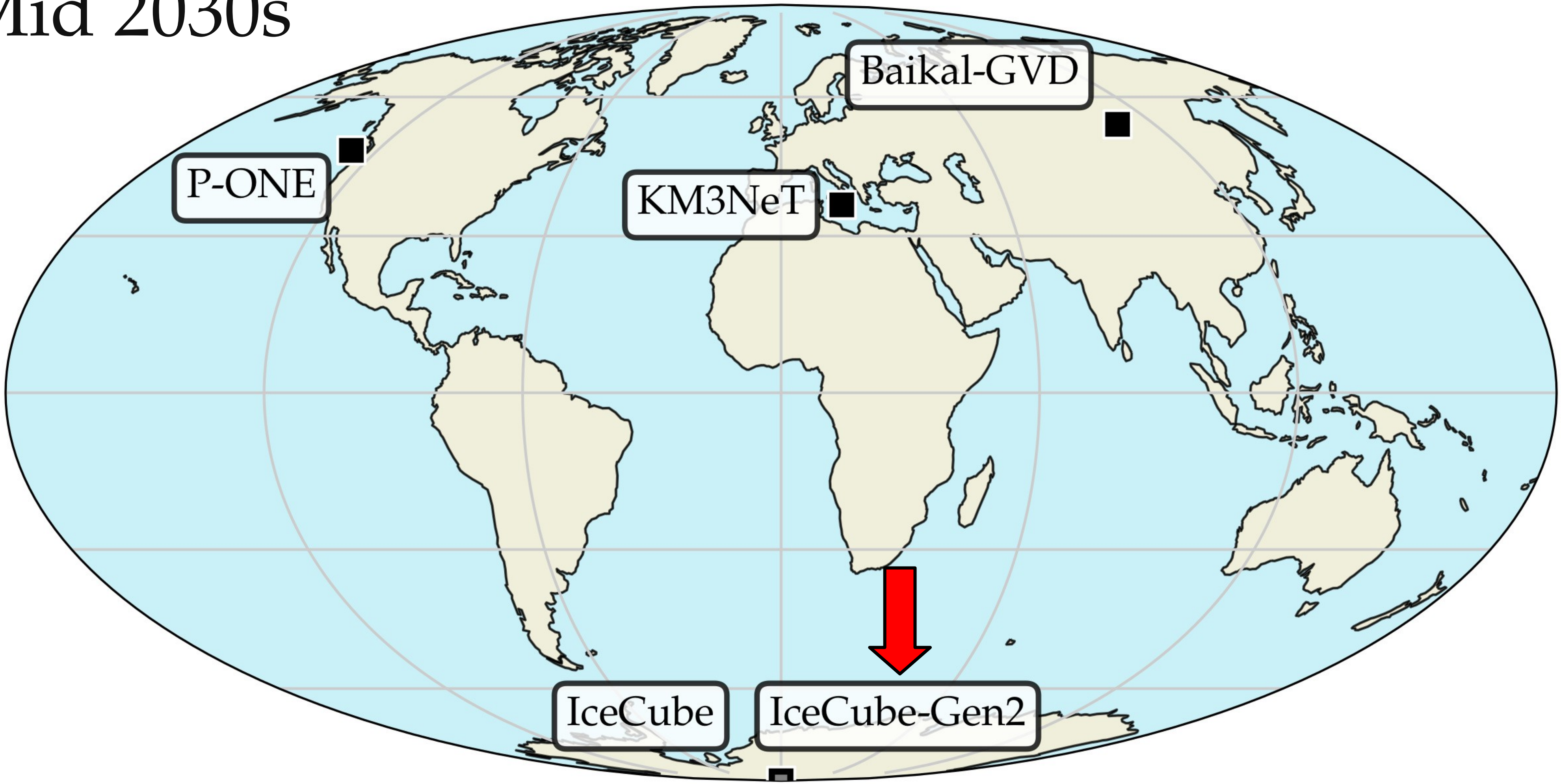
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



Rate of detected muon tracks relative to IceCube maximum

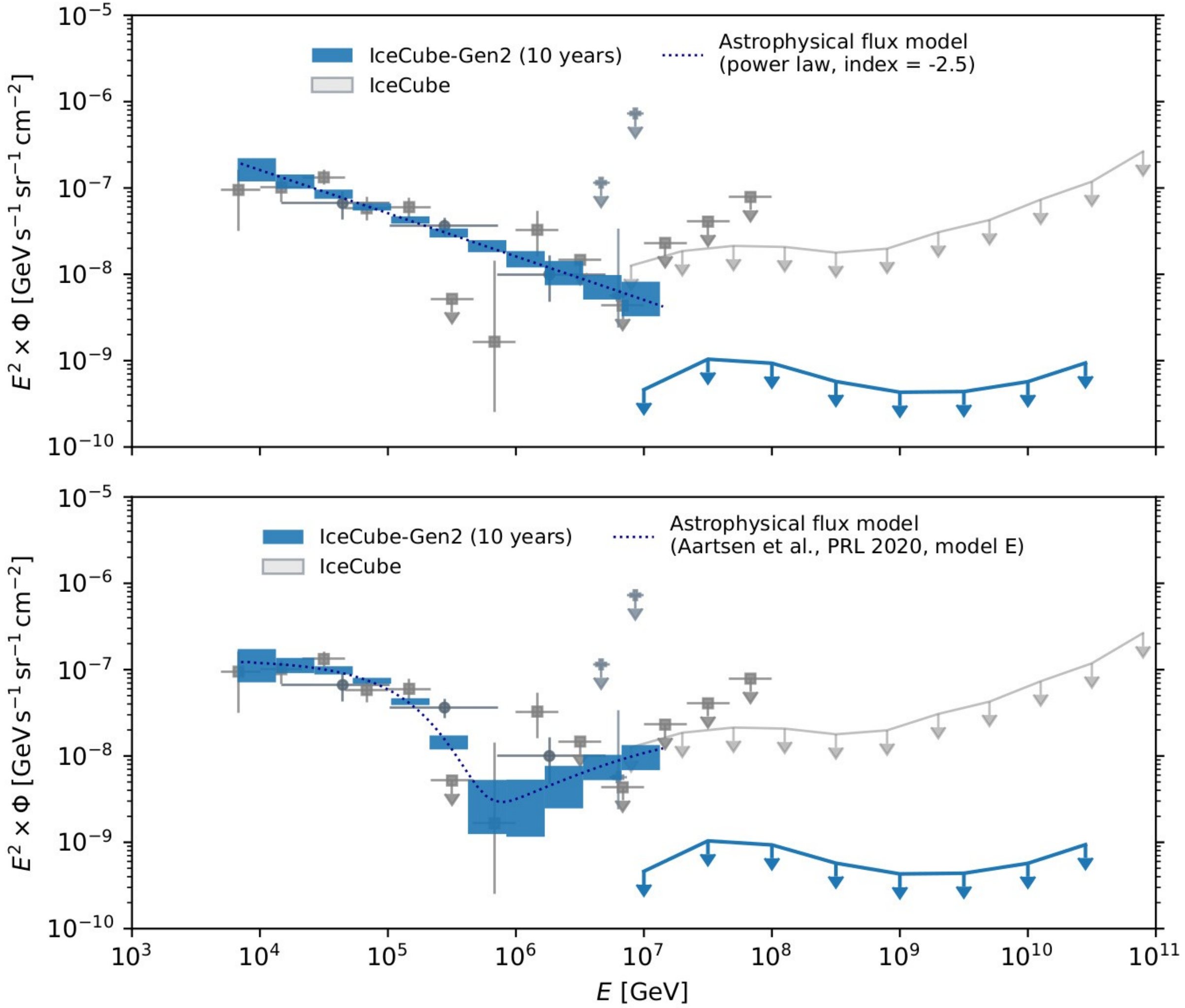
Schumacher, Agostini, **MB**,
Oikonomou, Resconi, *In prep.*

Mid 2030s



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

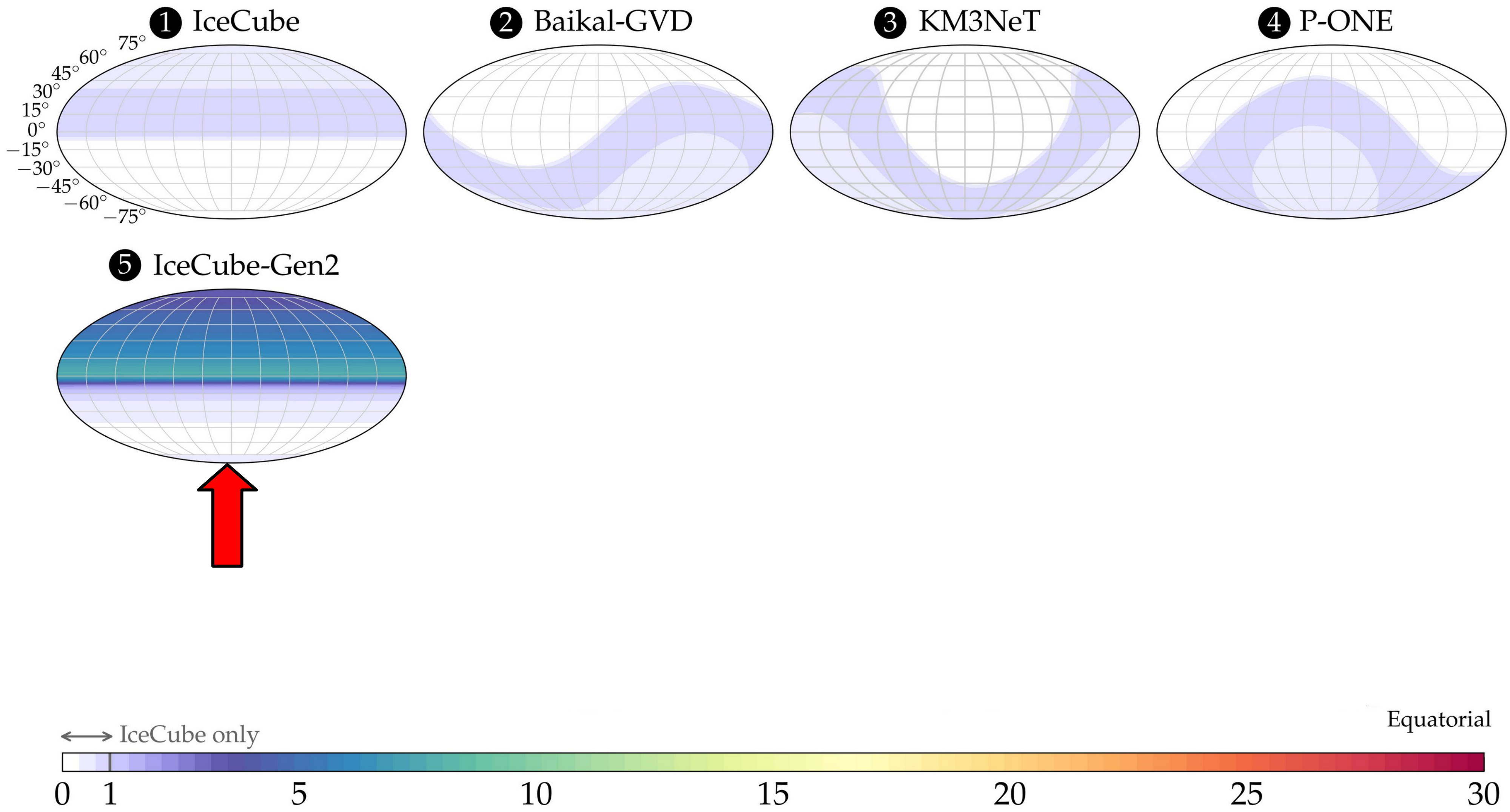
Measuring the diffuse flux *precisely*



Assuming a power-law ν flux ∝ $E^{-2.5}$

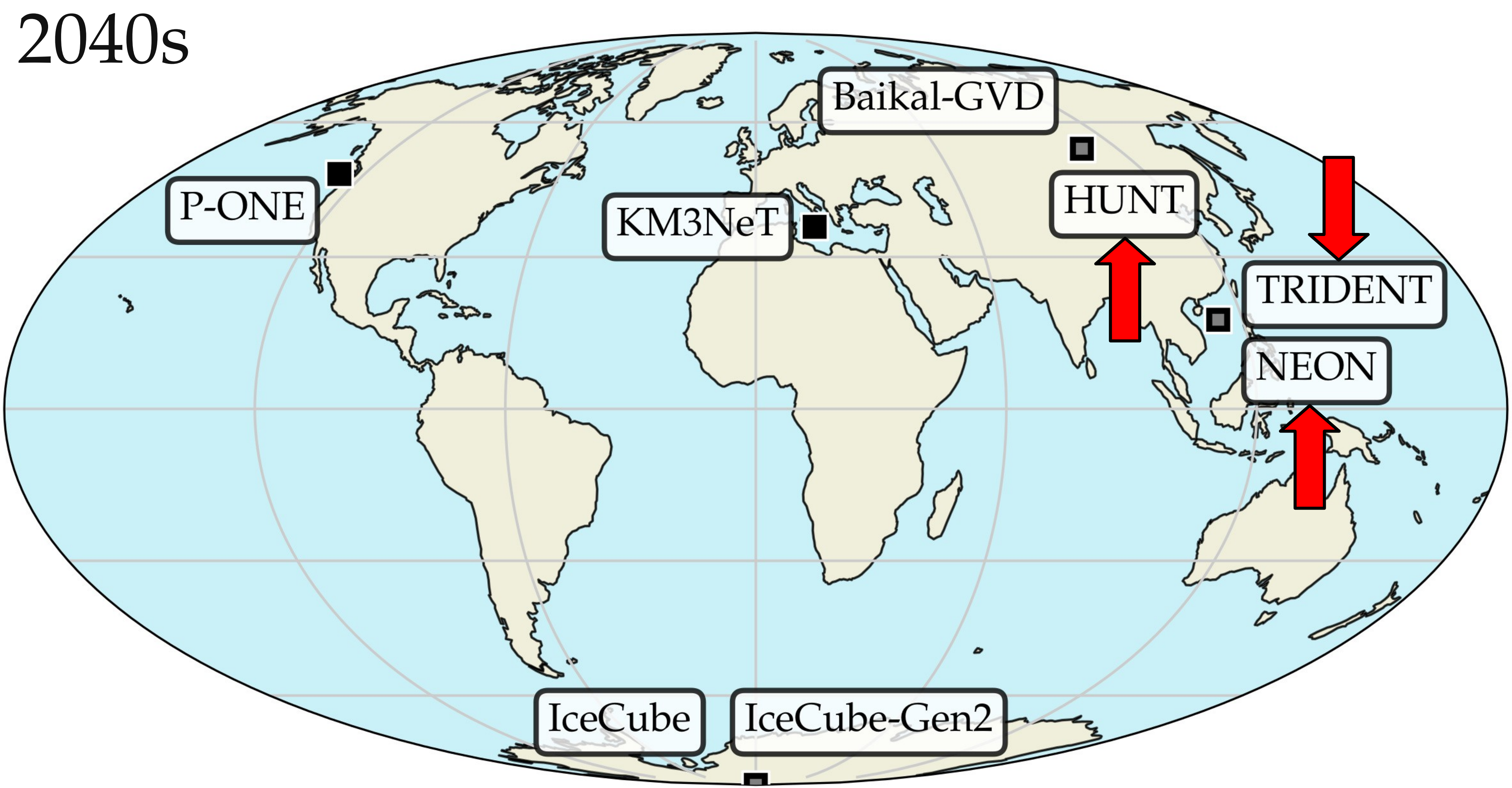
Assuming a power-law ν flux with 100-TeV cut-off + *pγ* bump at tens of TeV

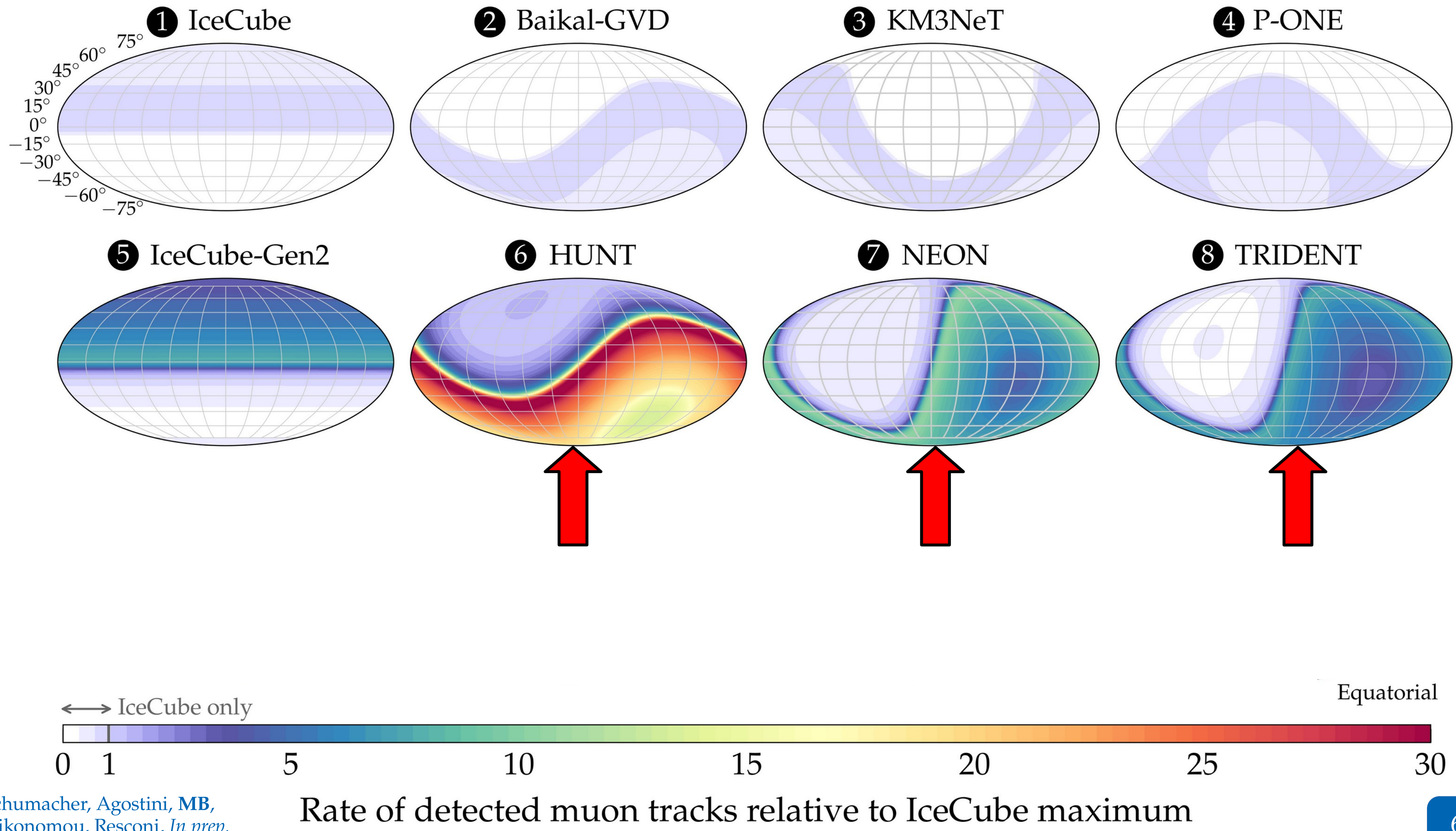
Ackermann, **MB** *et al.*, *JHEAp* 2022



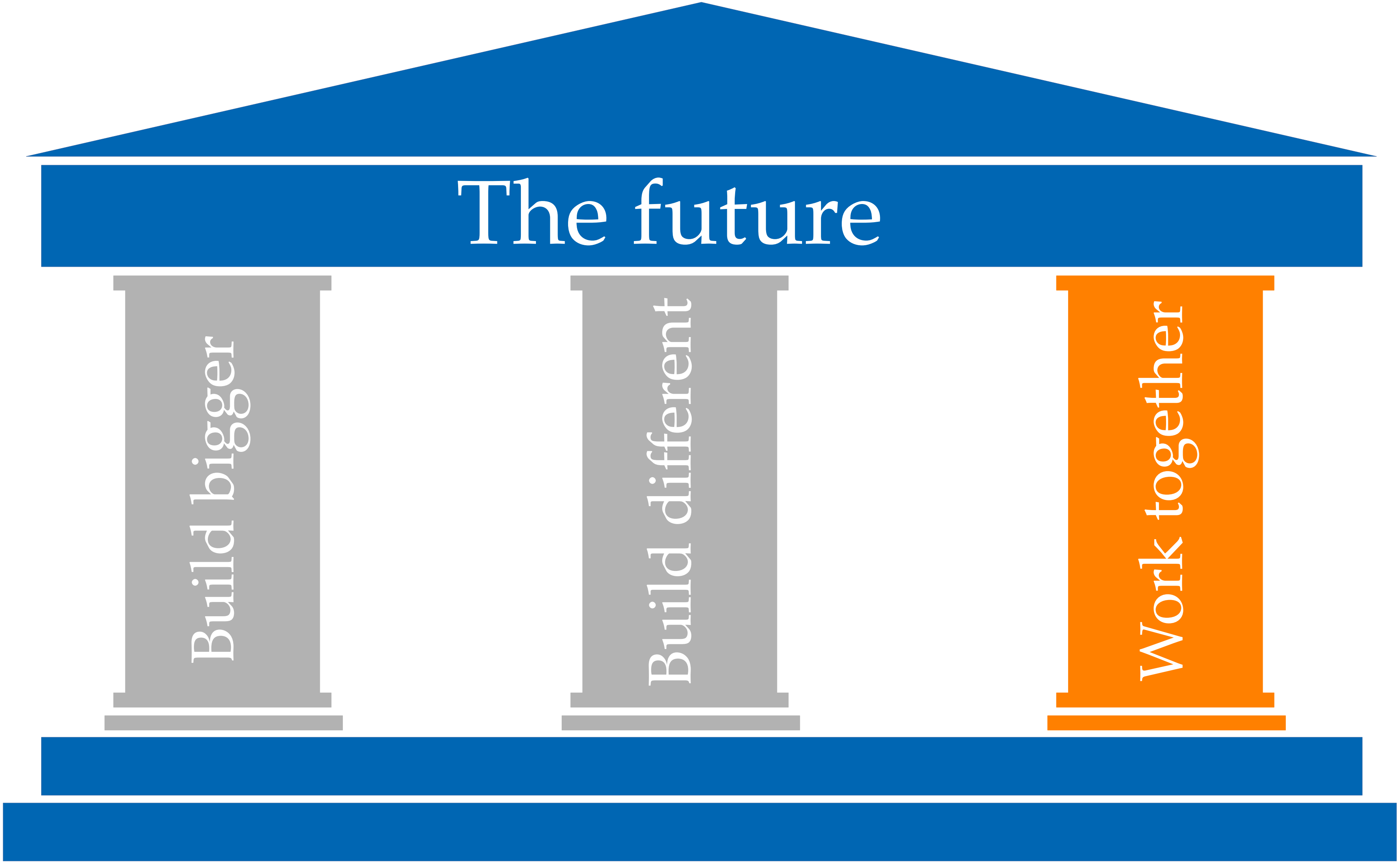
Rate of detected muon tracks relative to IceCube maximum

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

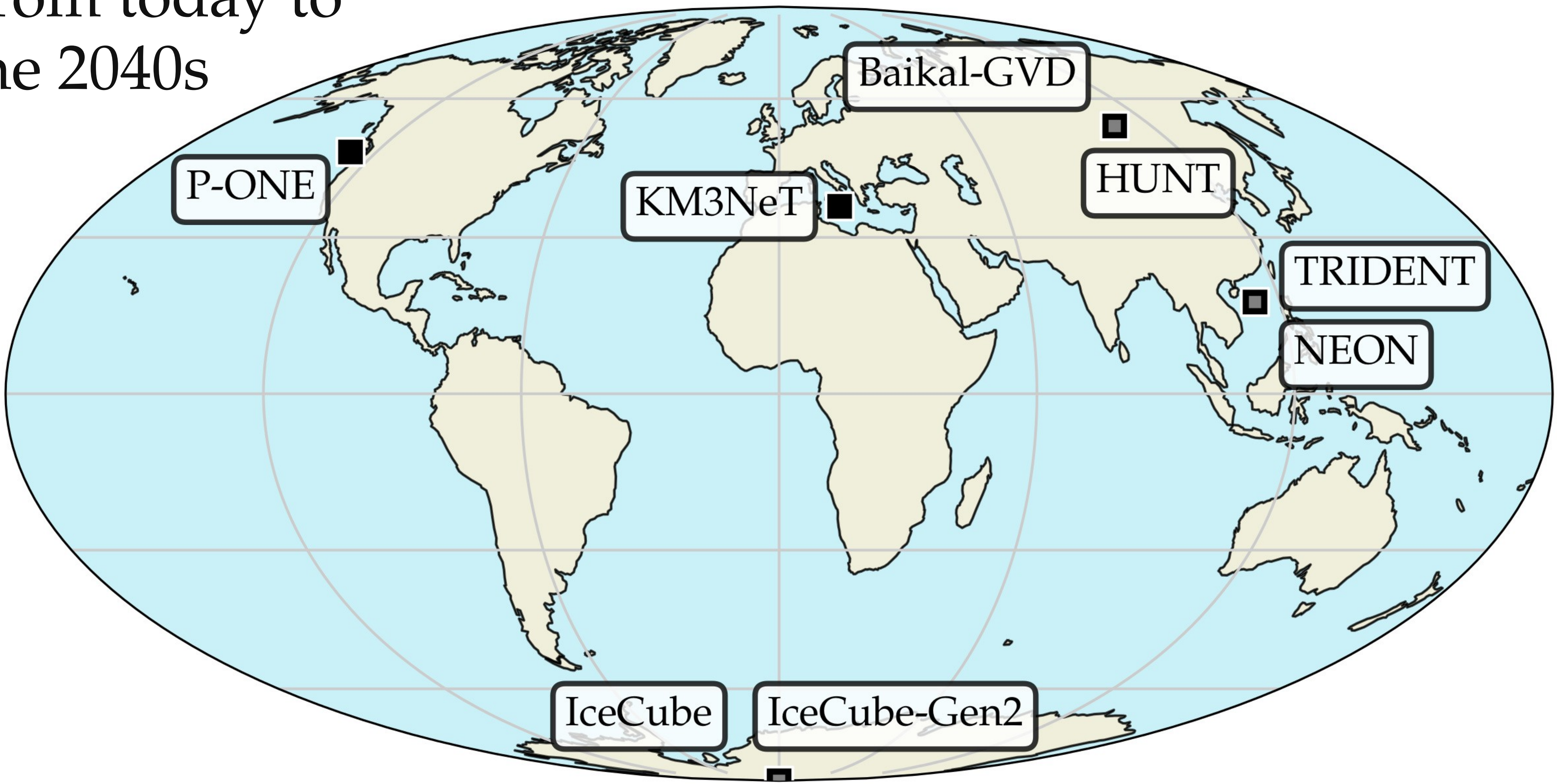

2040s
Baikal-GVD
P-ONE
KM3NeT
HUNT
TRIDENT
NEON
IceCube
IceCube-Gen2

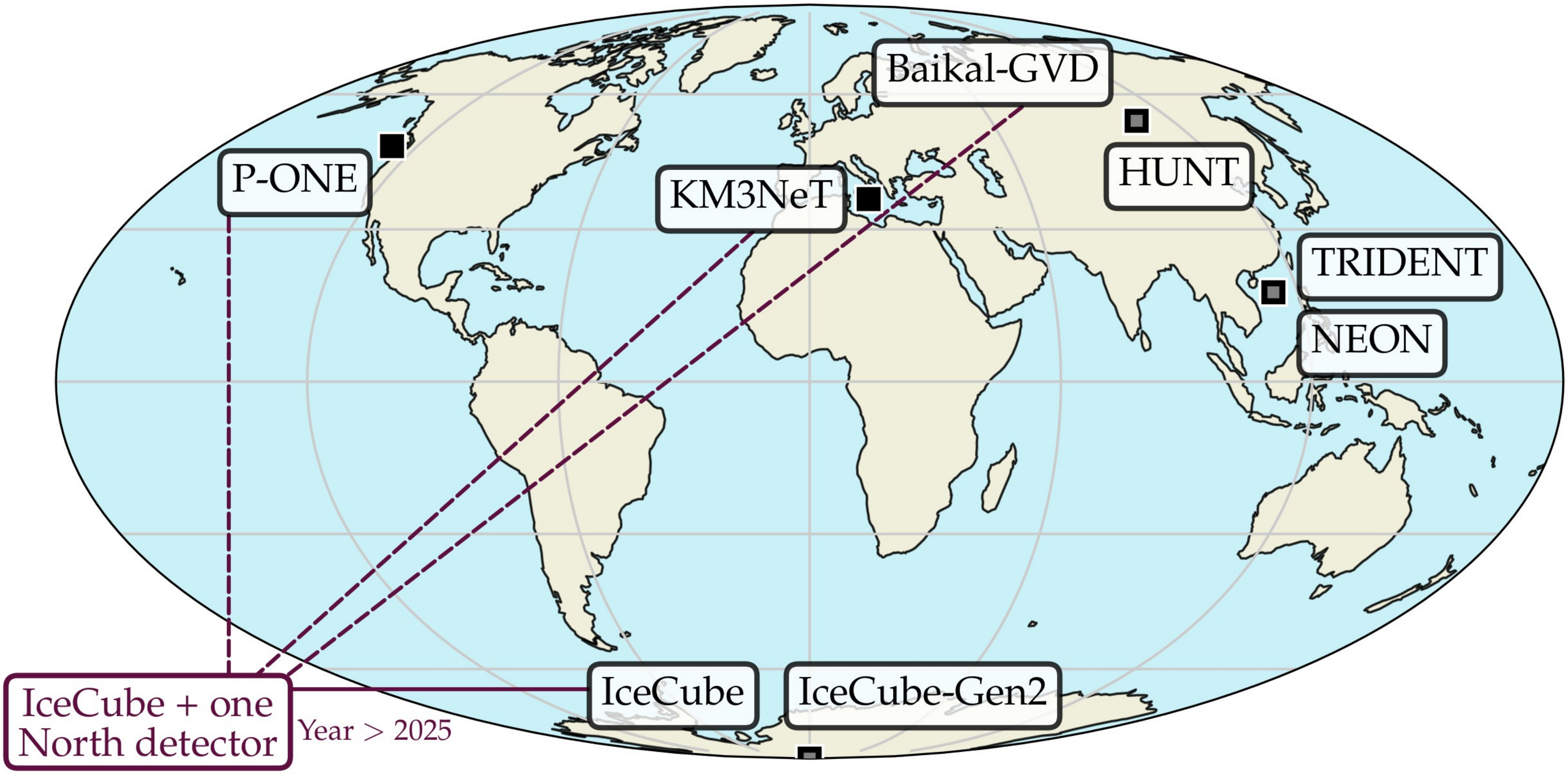


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

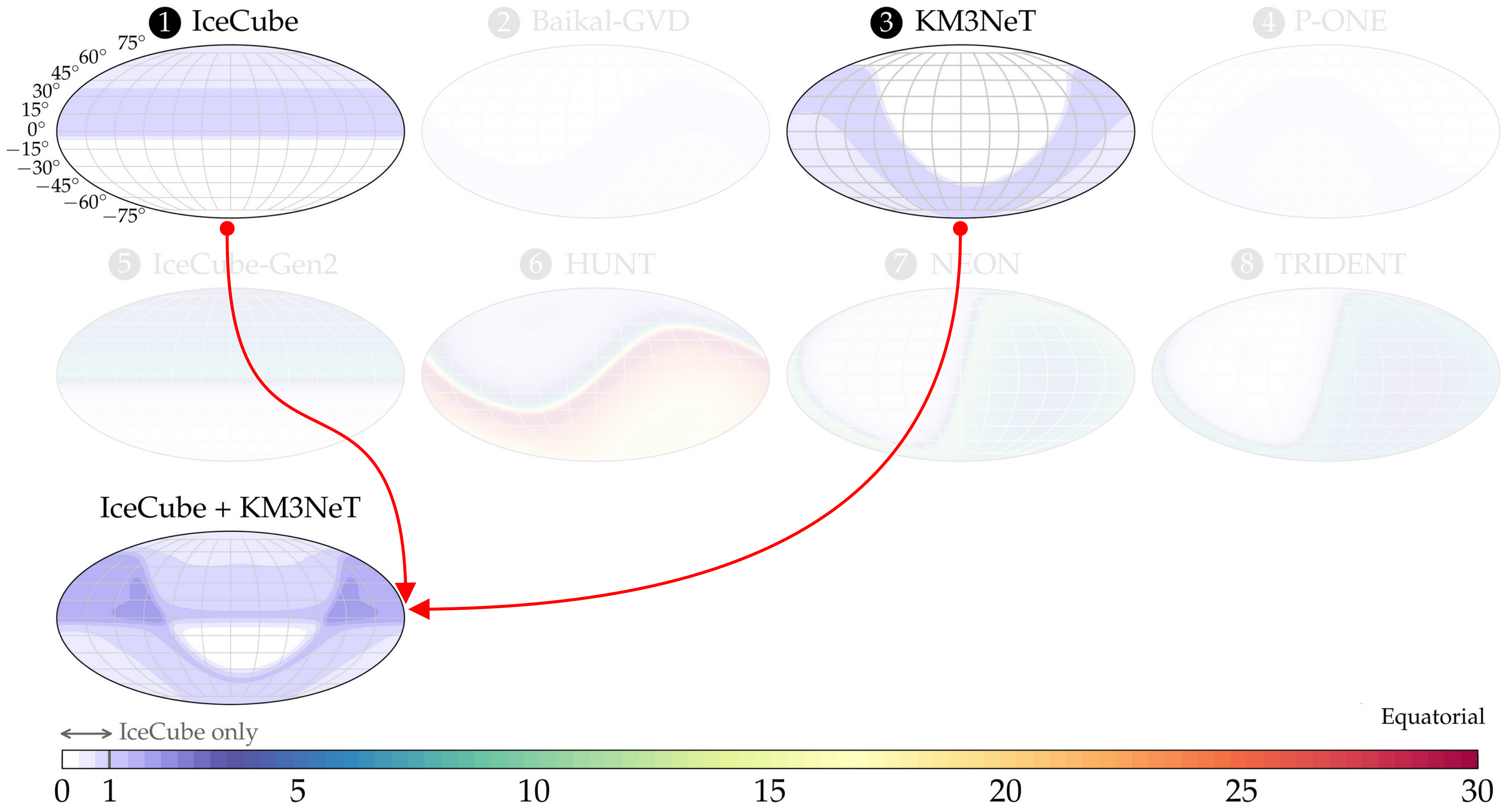

The future
Build bigger
Build different
Work together

From today to the 2040s

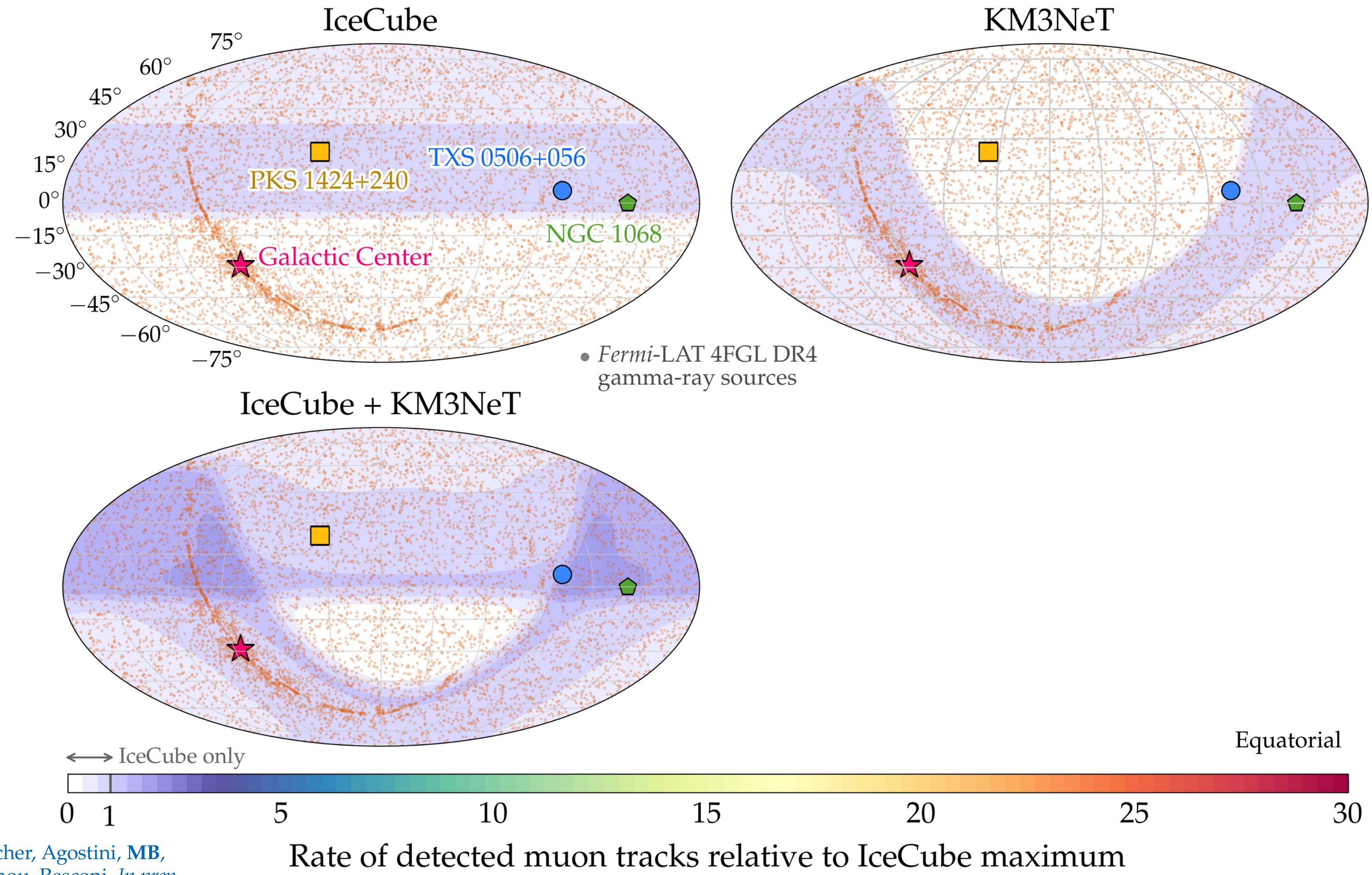




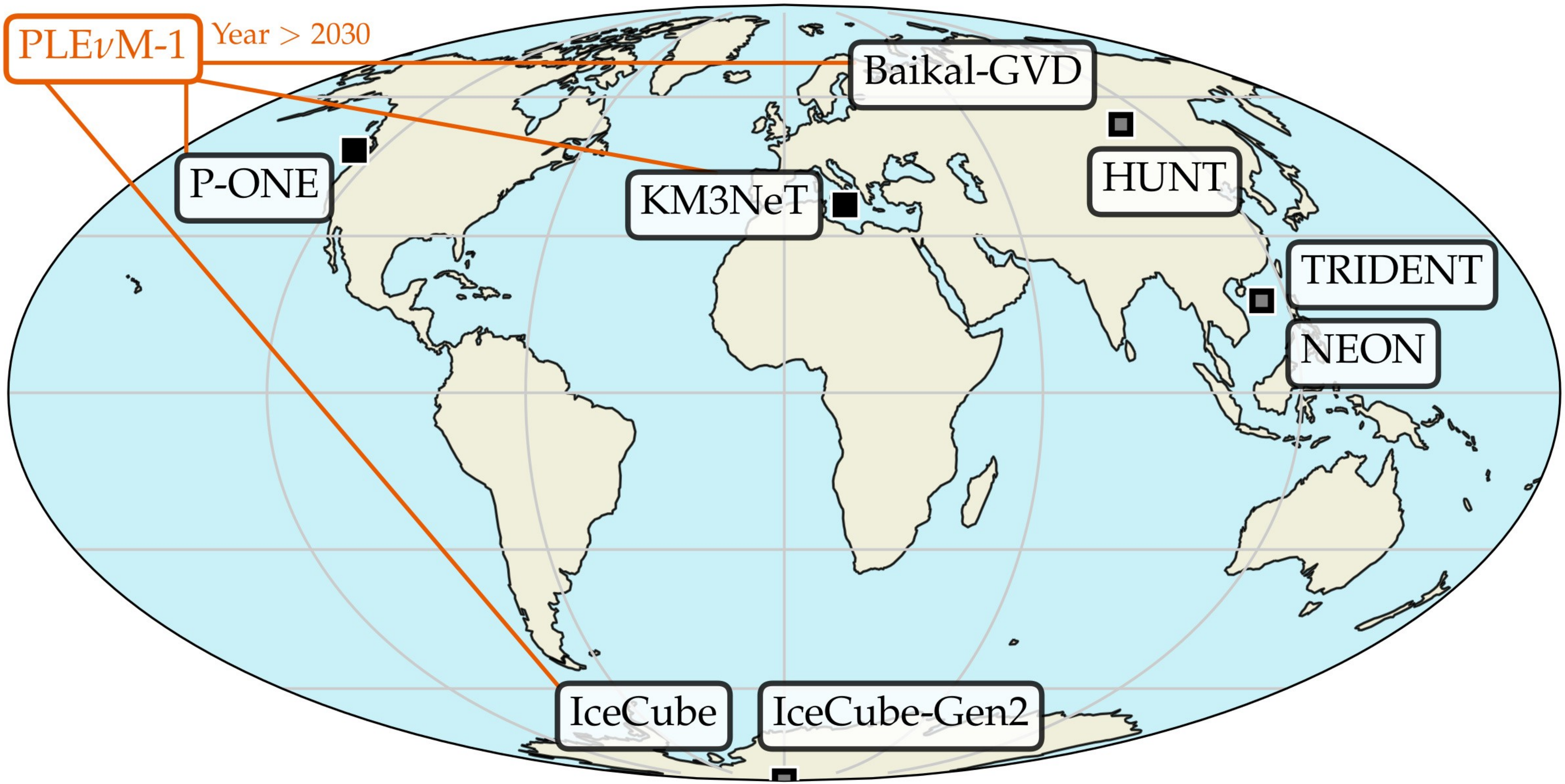
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



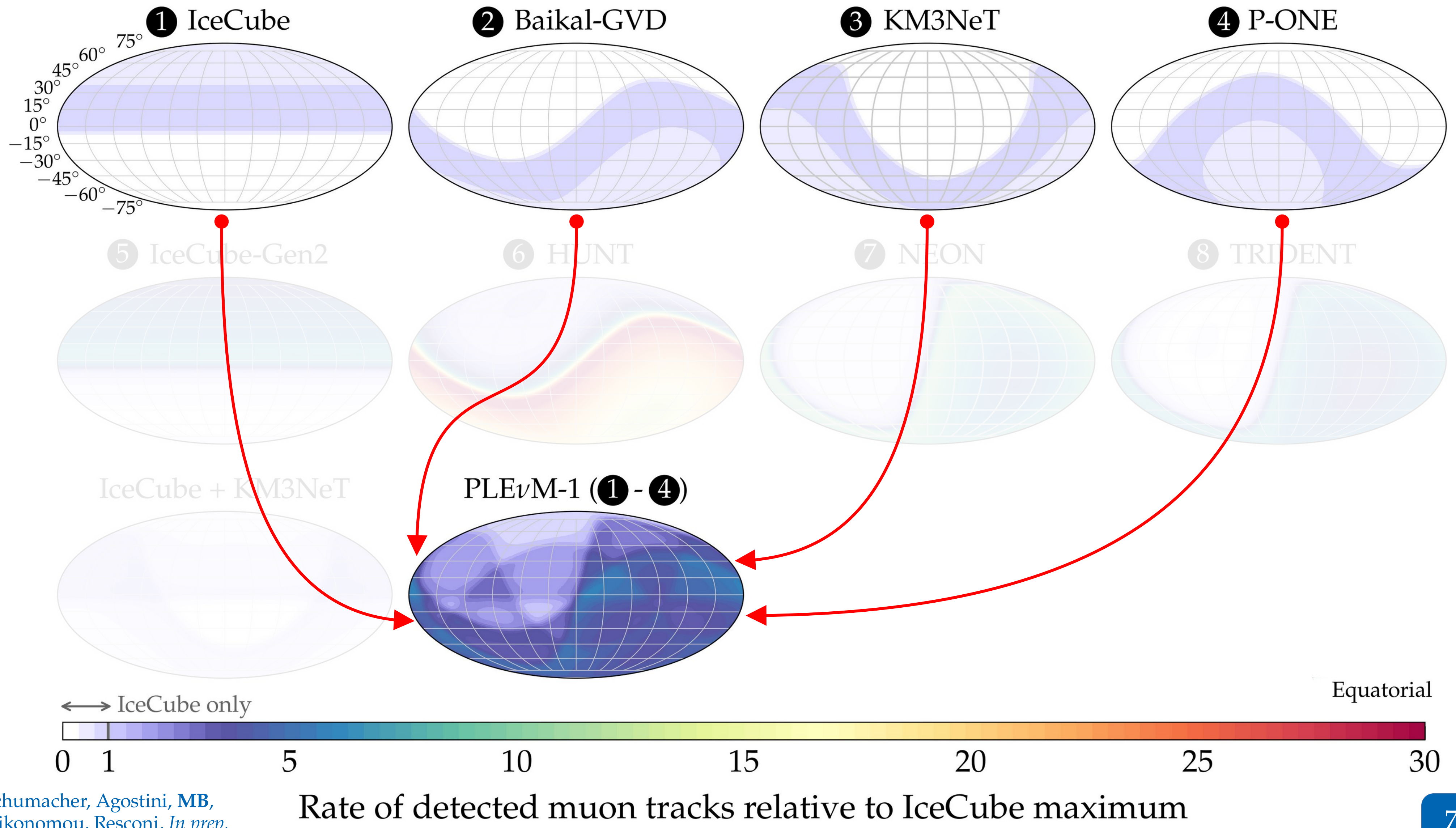
Schumacher, Agostini, **MB**,
Oikonomou, Resconi, *In prep.*



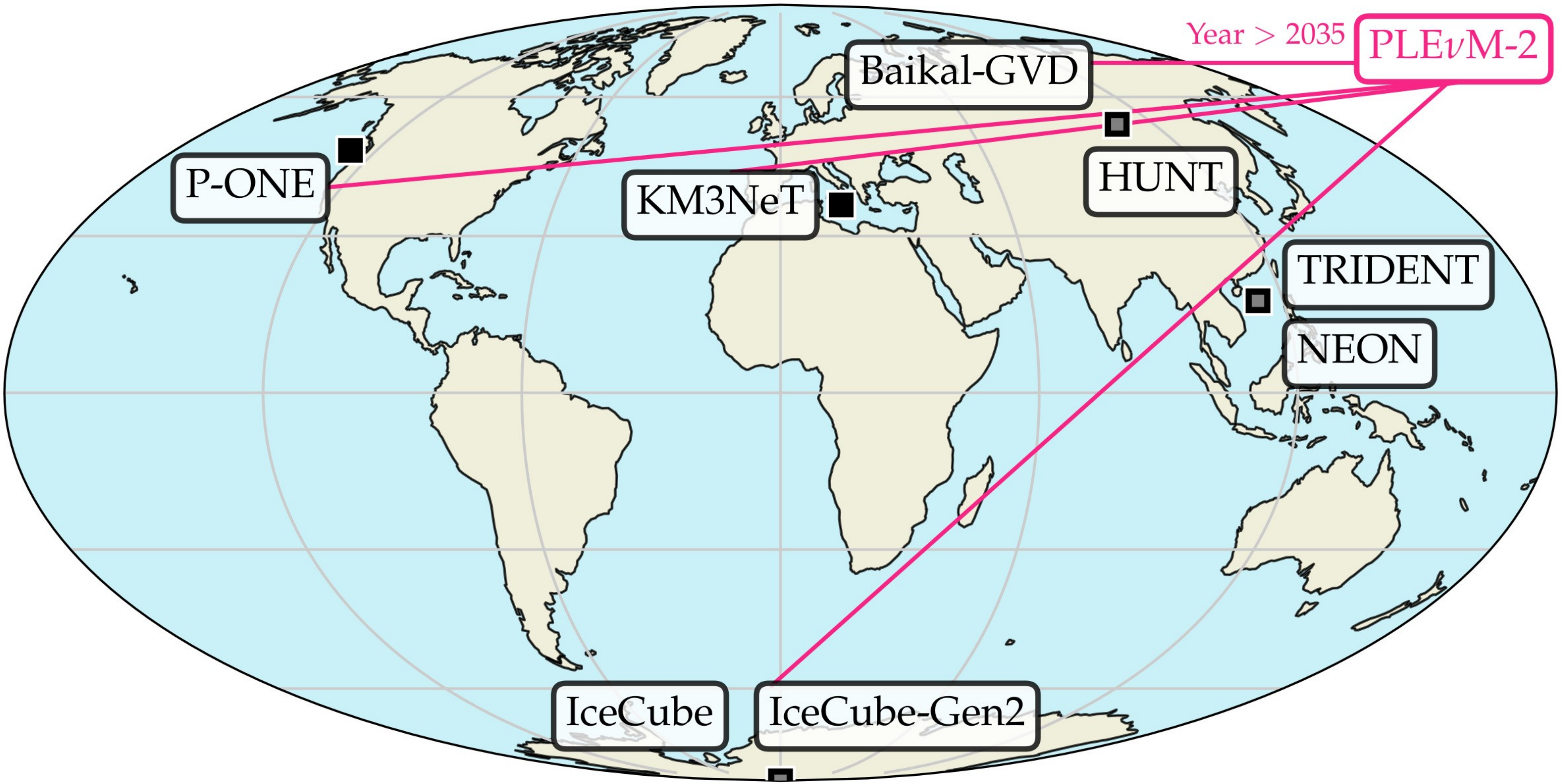
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



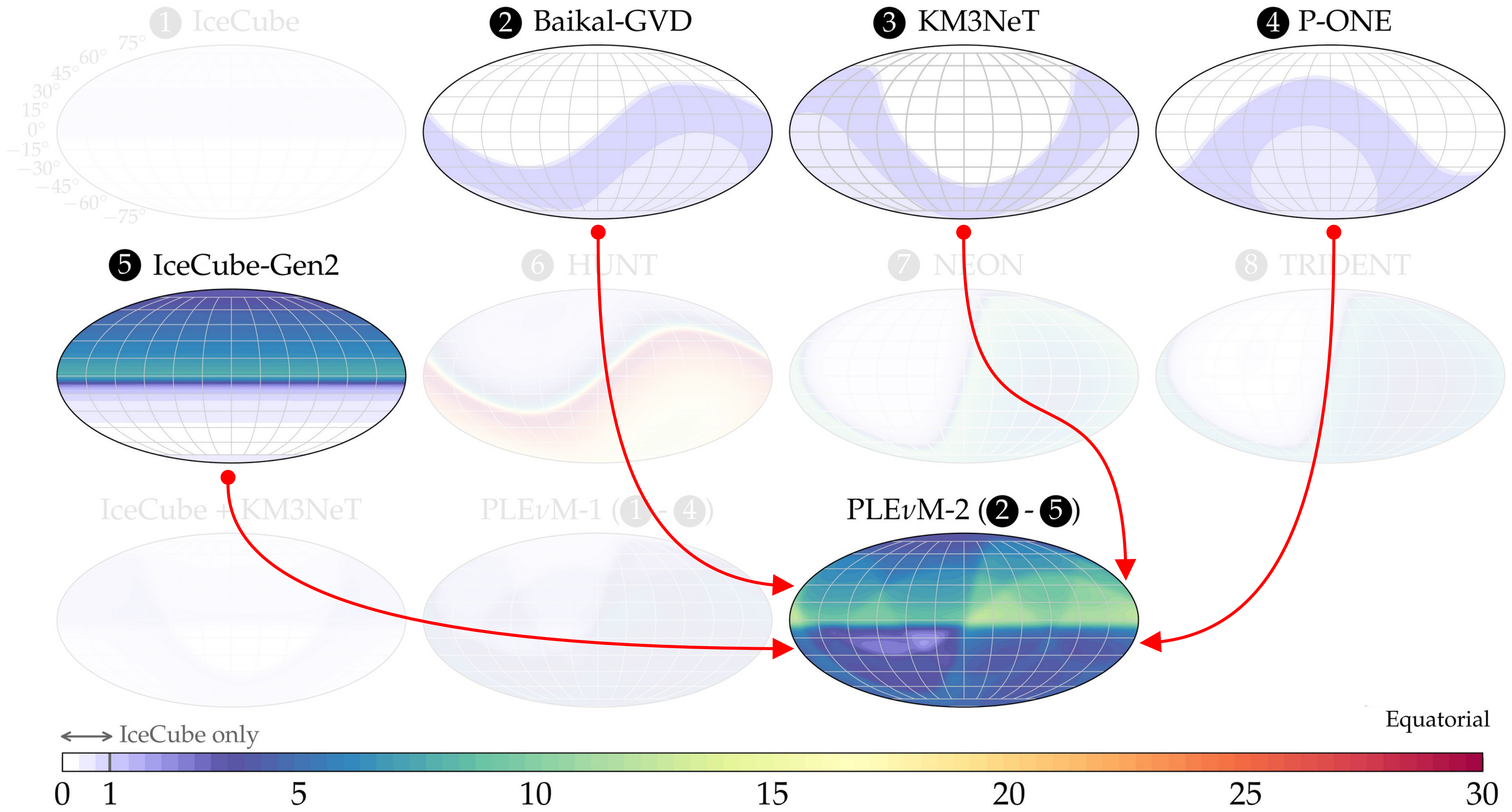
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*



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

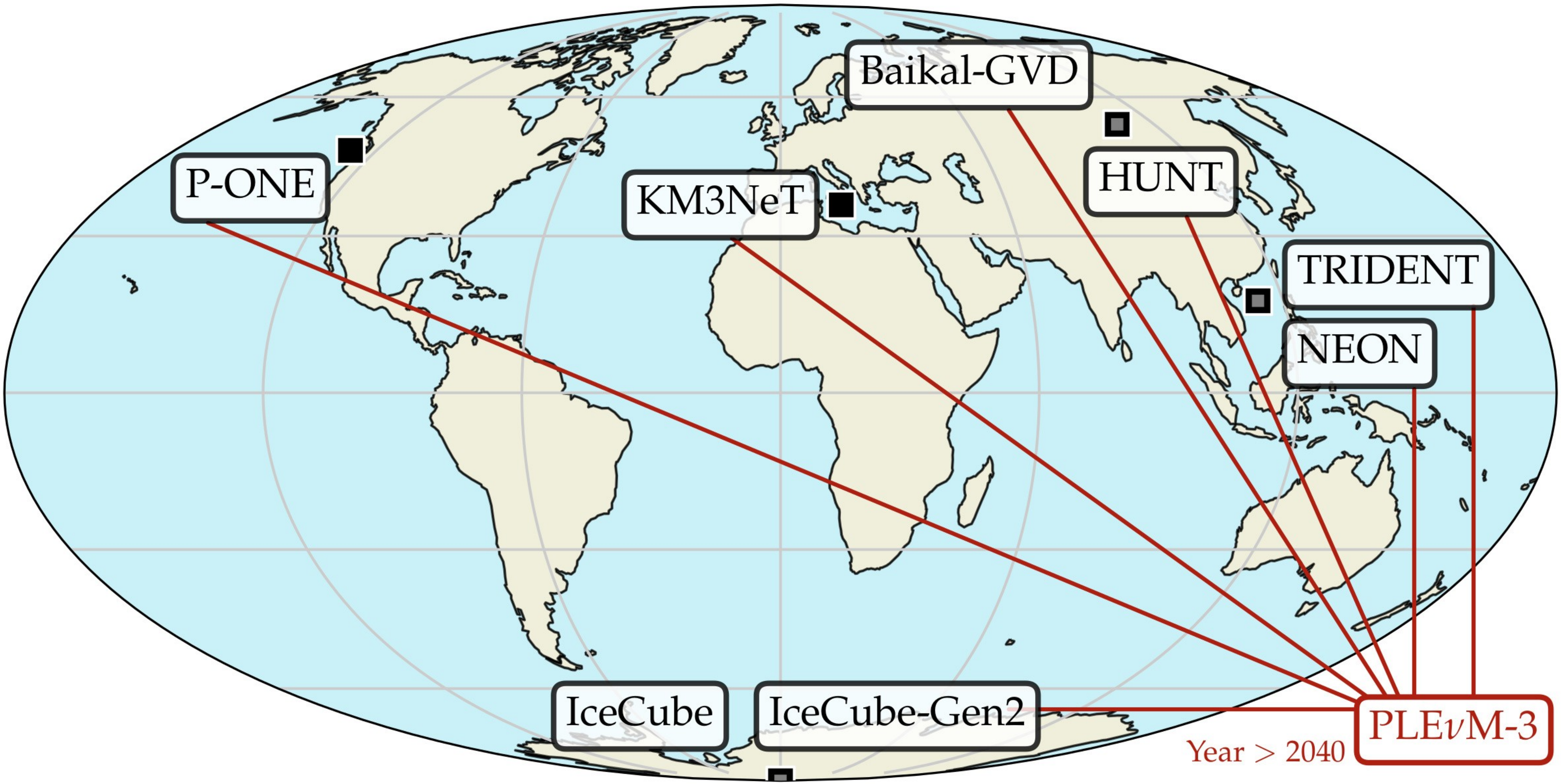


Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

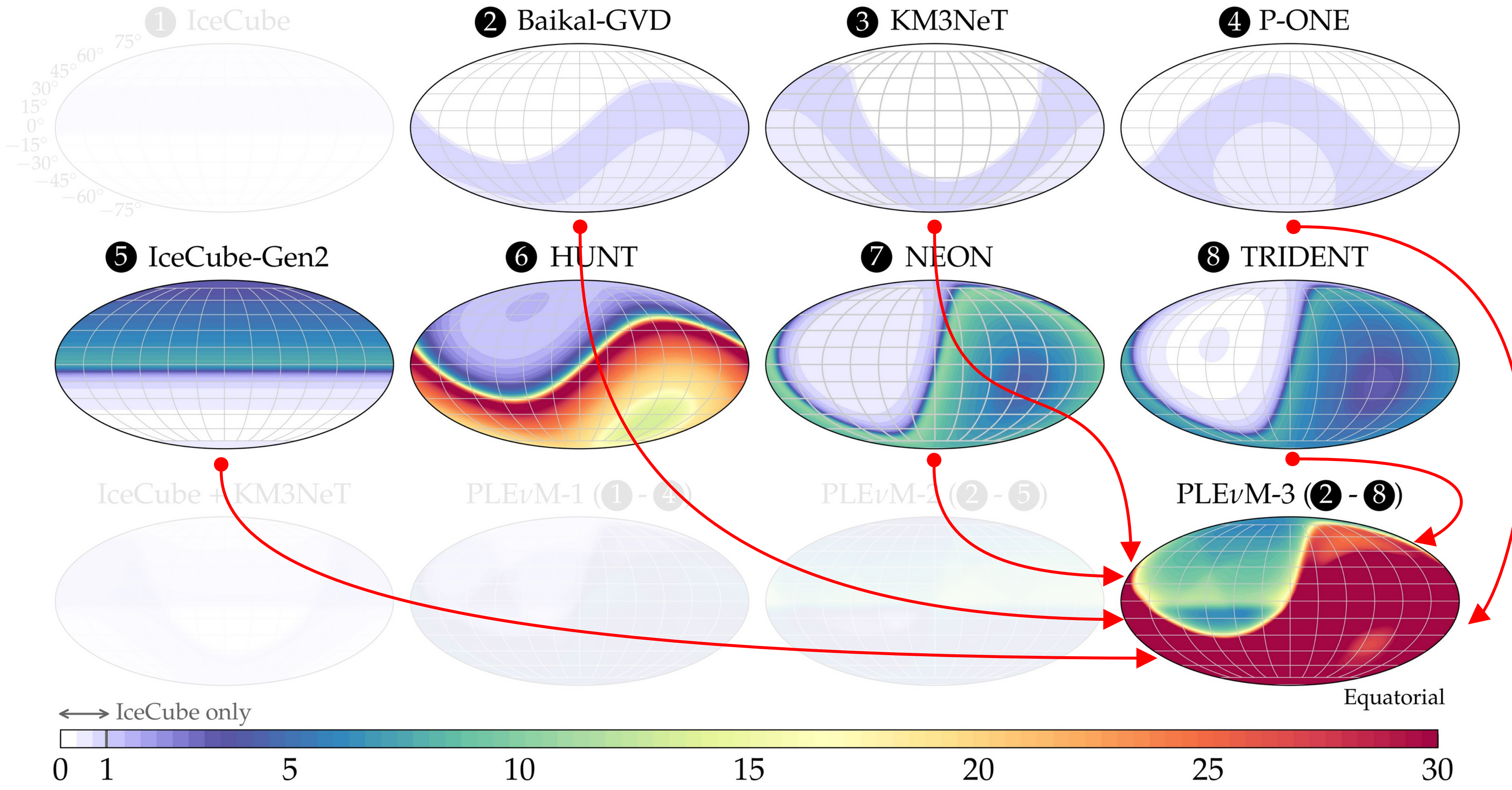


Rate of detected muon tracks relative to IceCube maximum

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



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



Rate of detected muon tracks relative to IceCube maximum

Schumacher, Agostini, **MB**,
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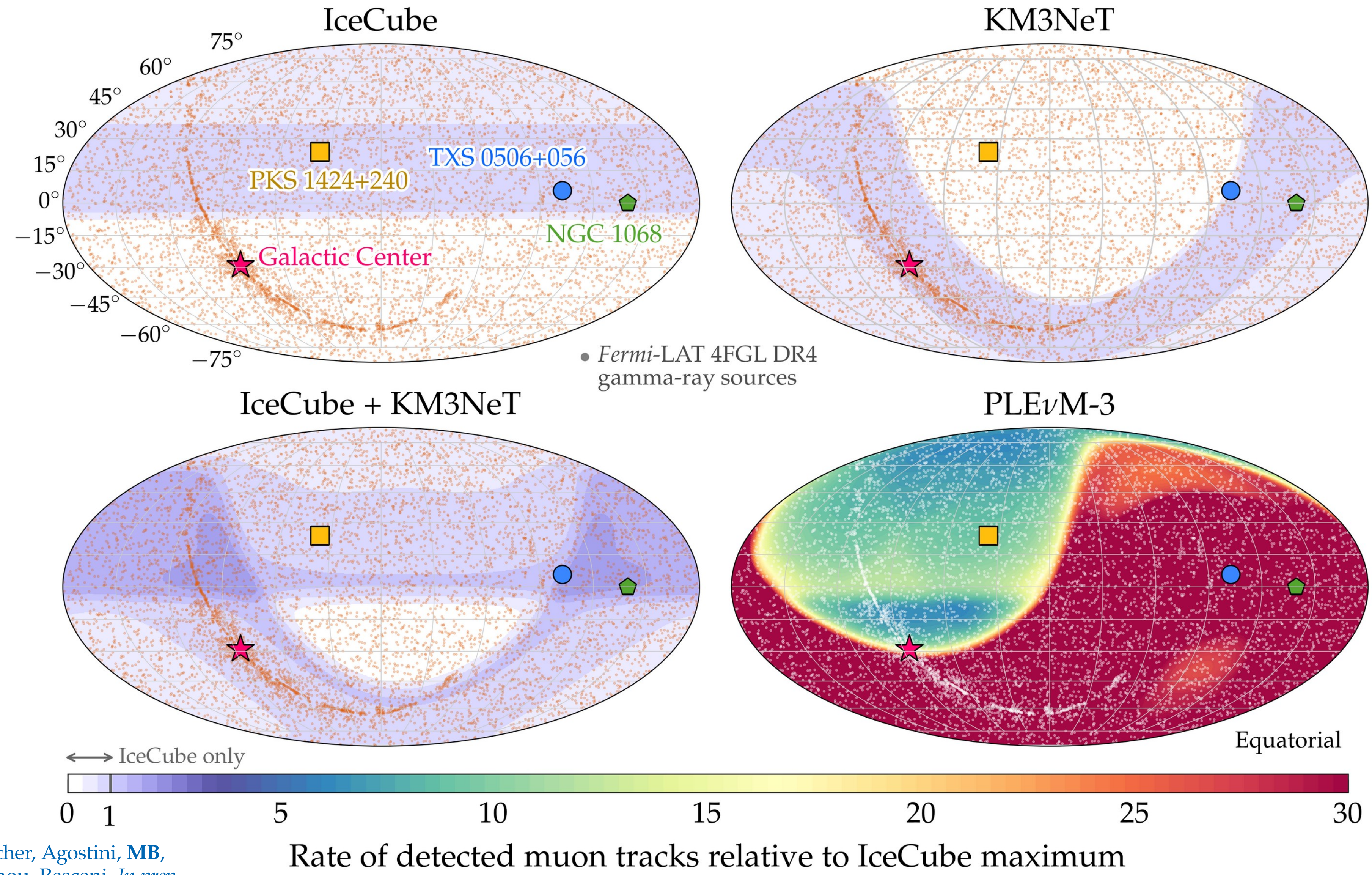
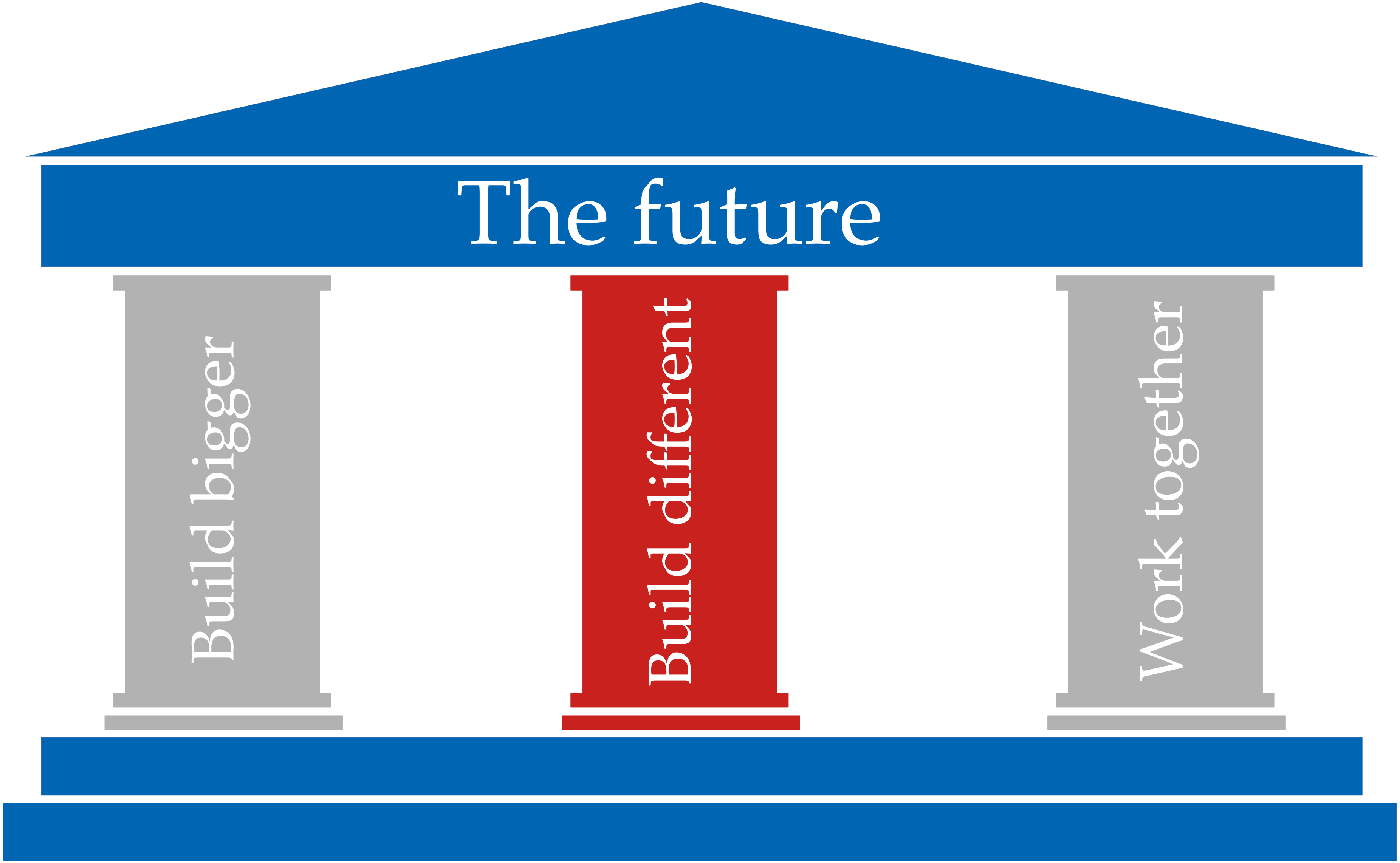
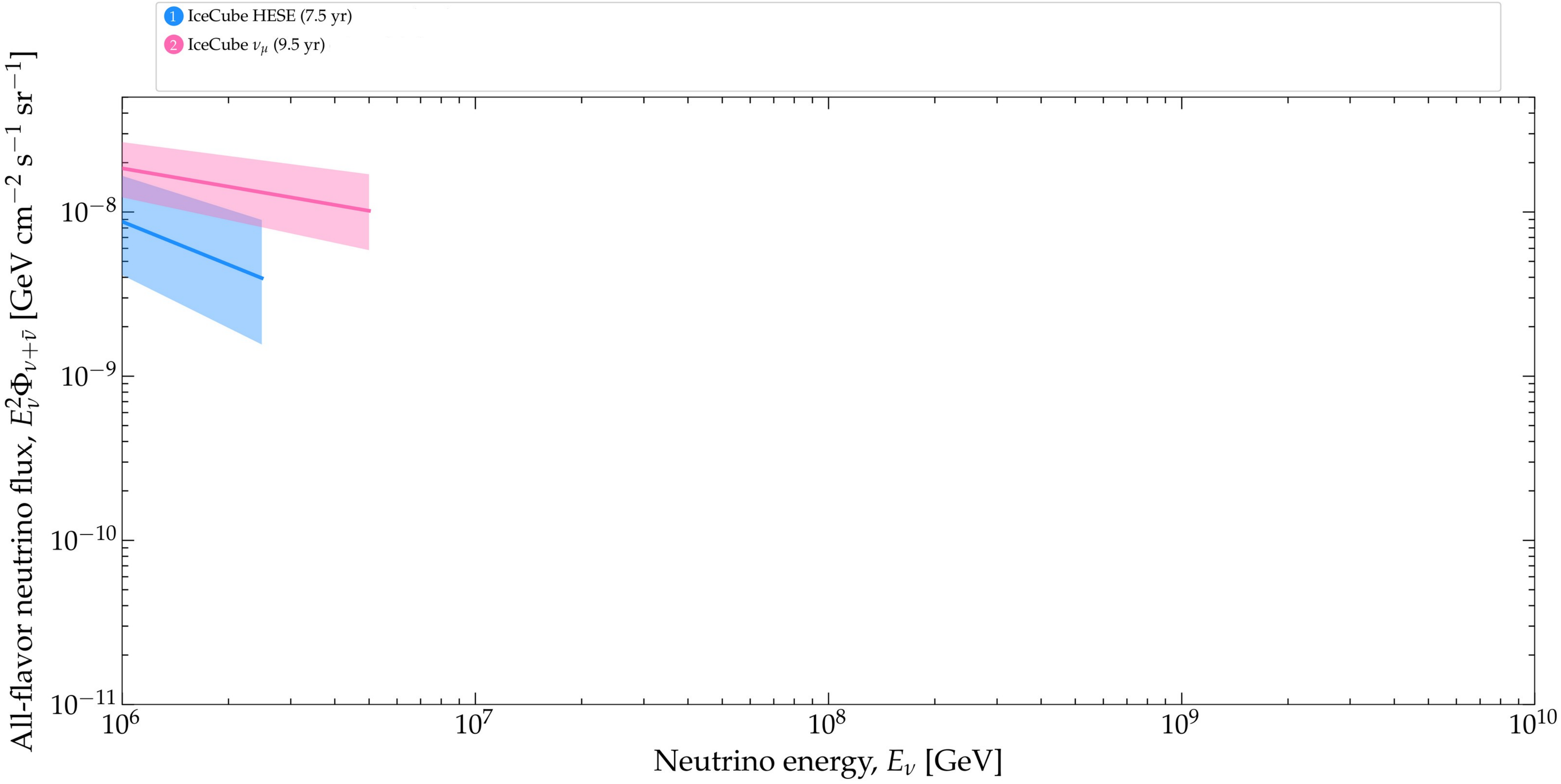
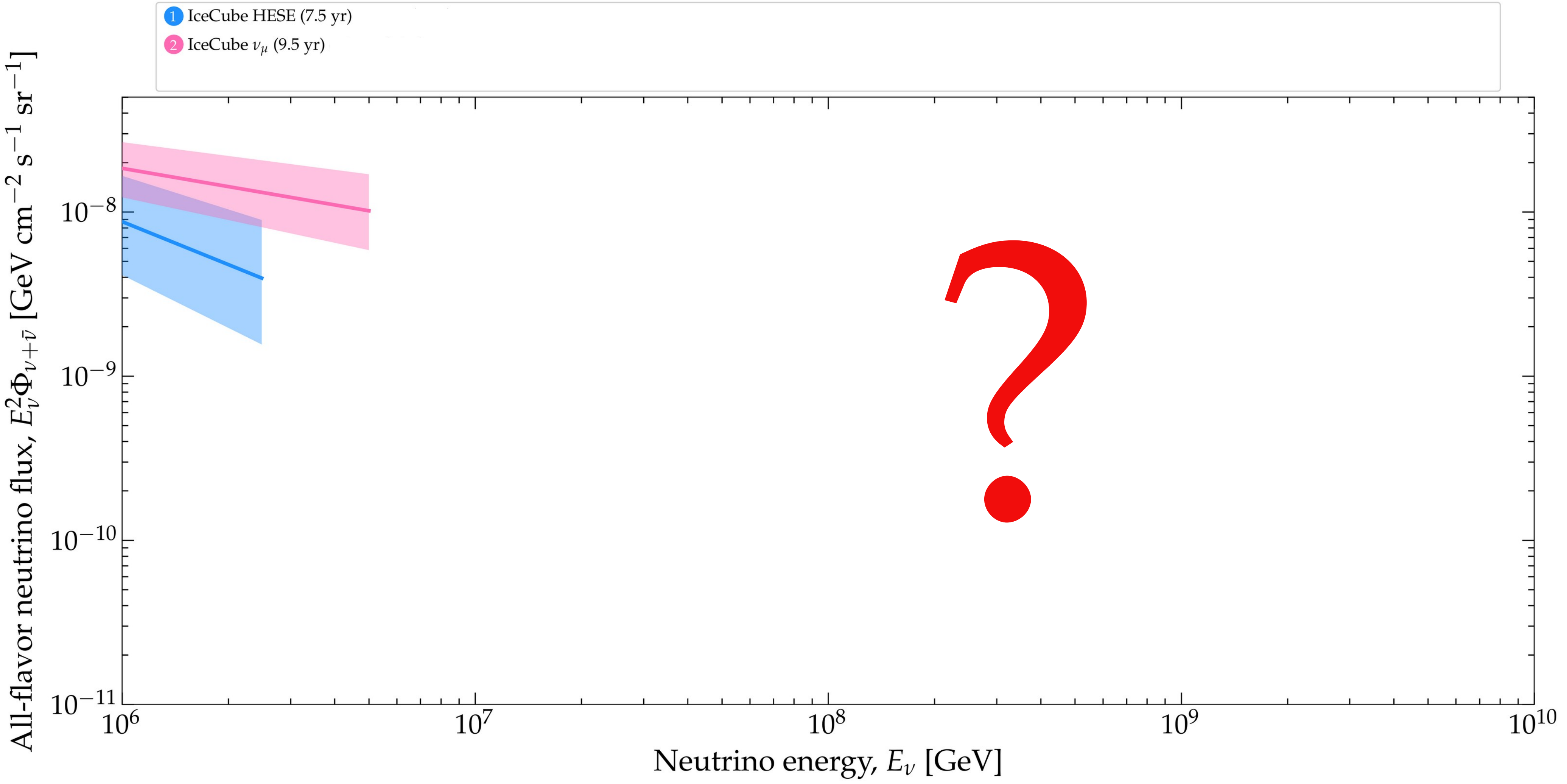


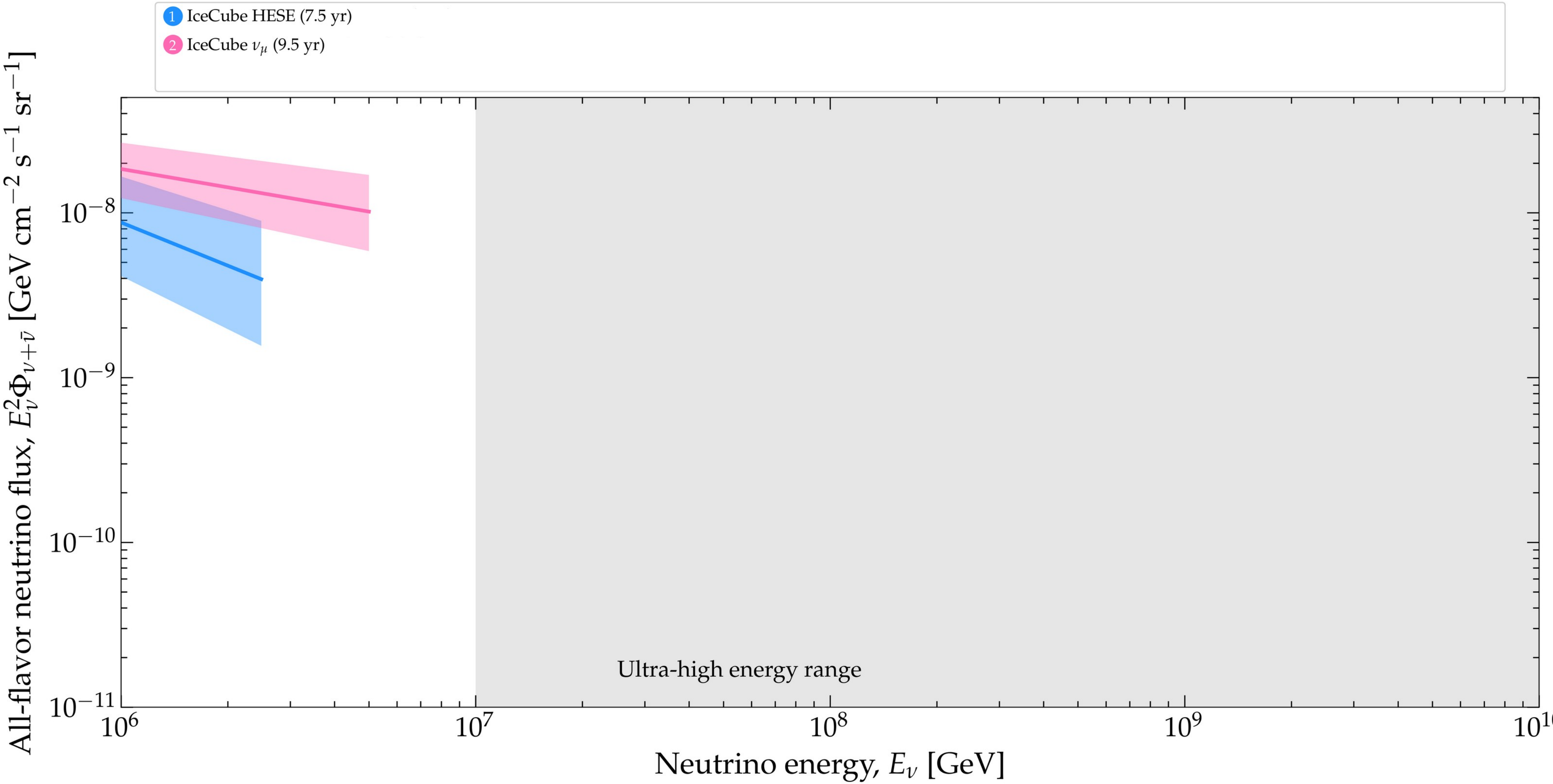
Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

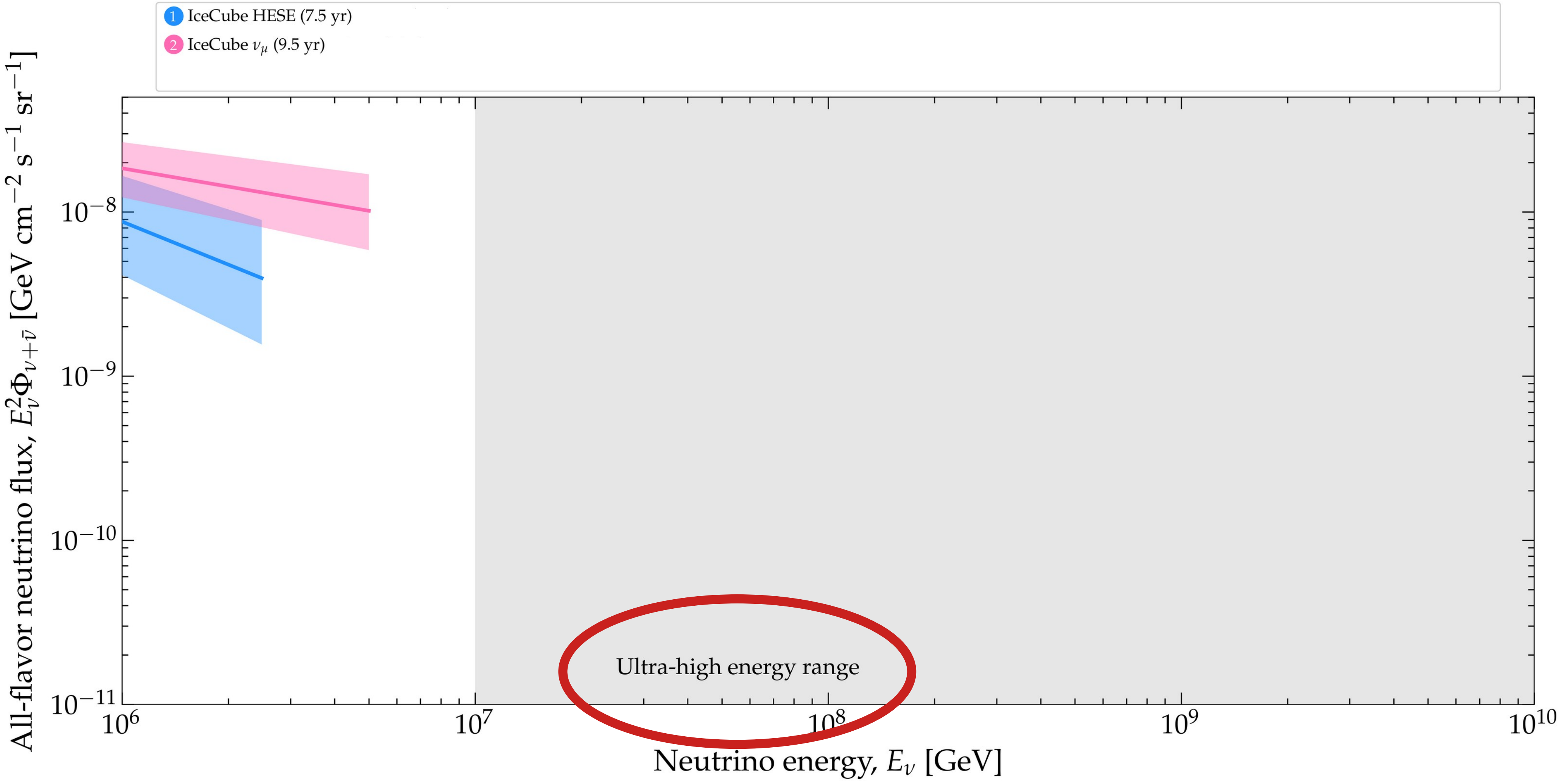

The future
Build bigger
Build different
Work together



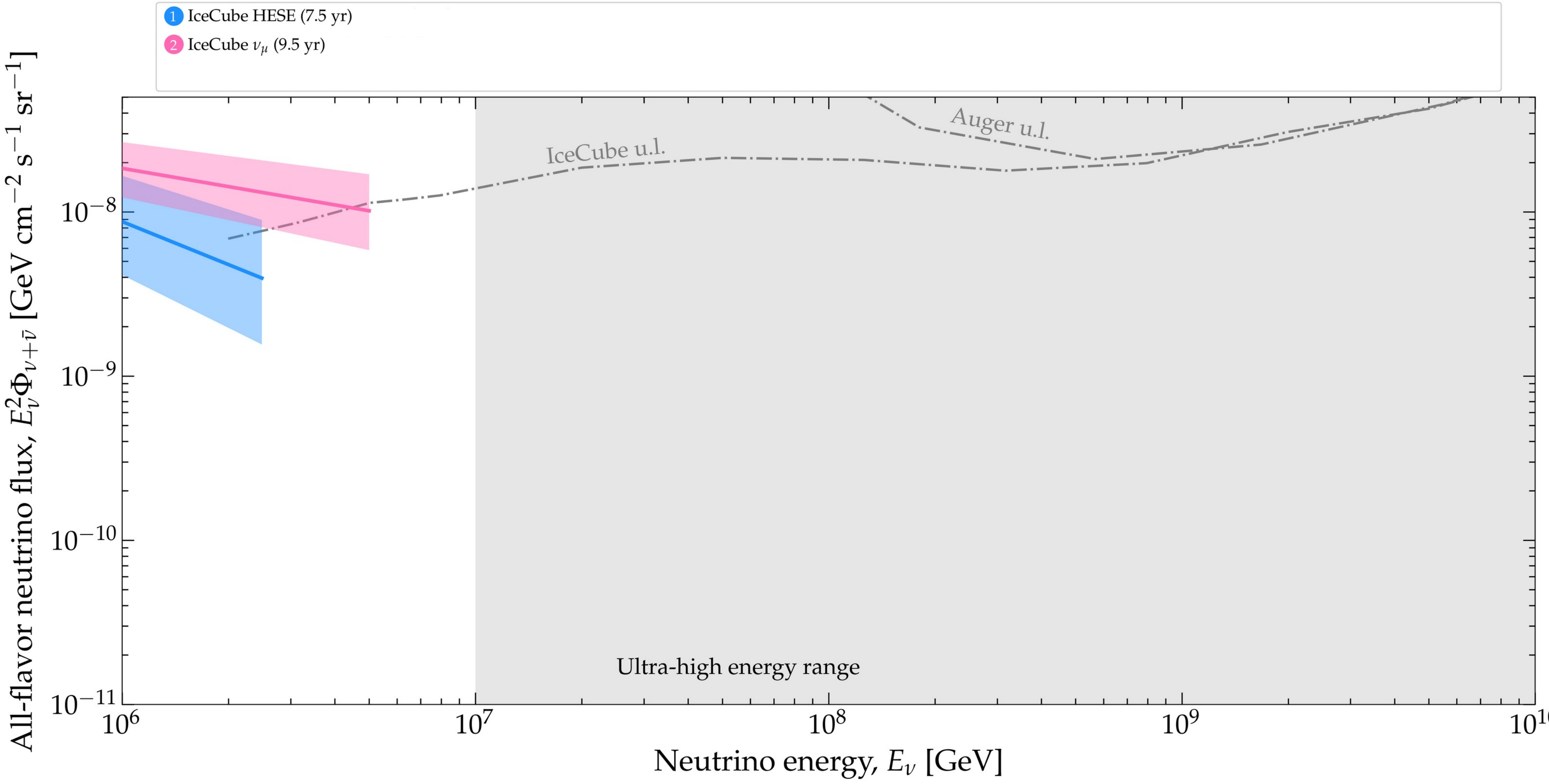
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

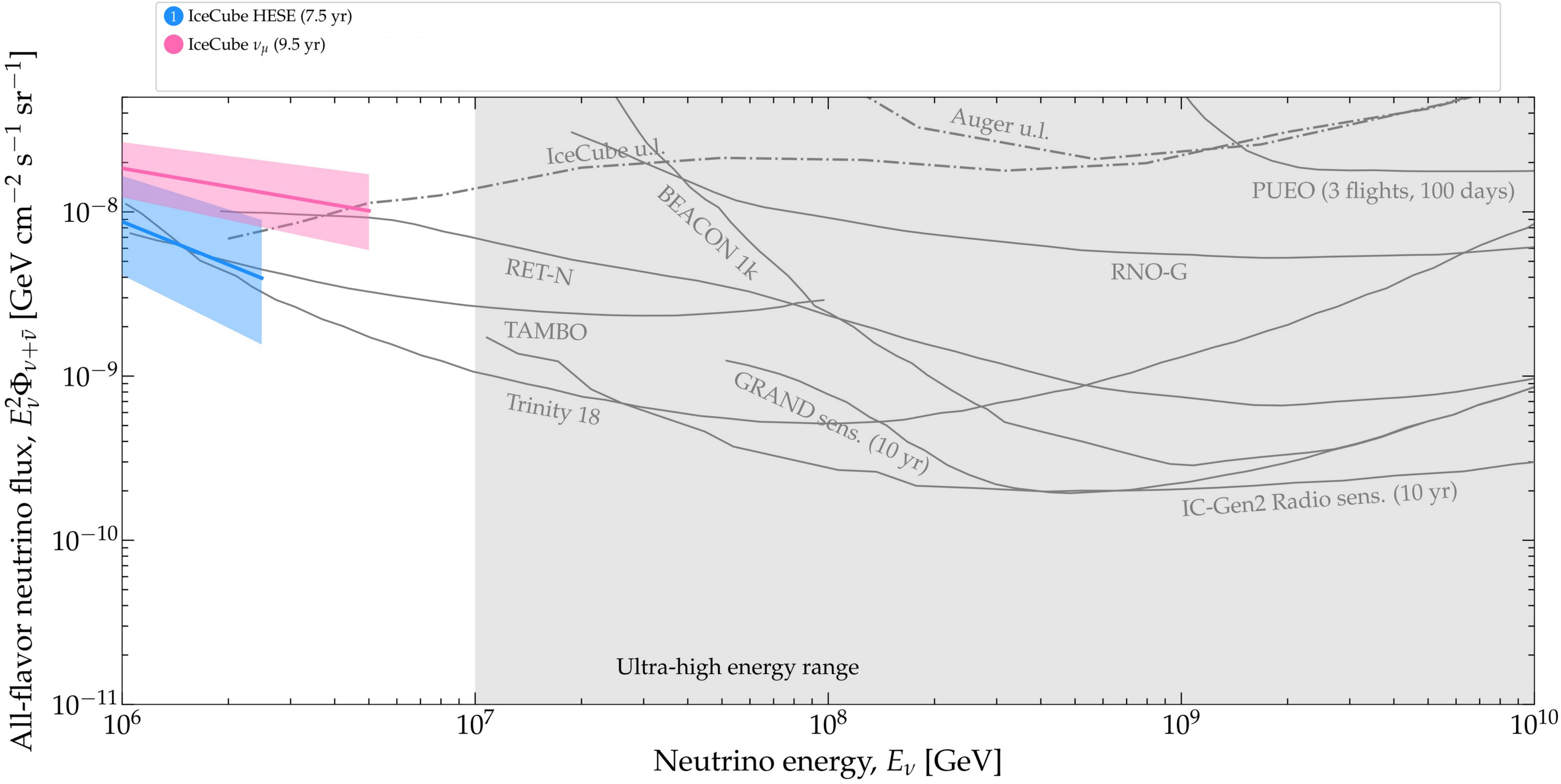

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]
?


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

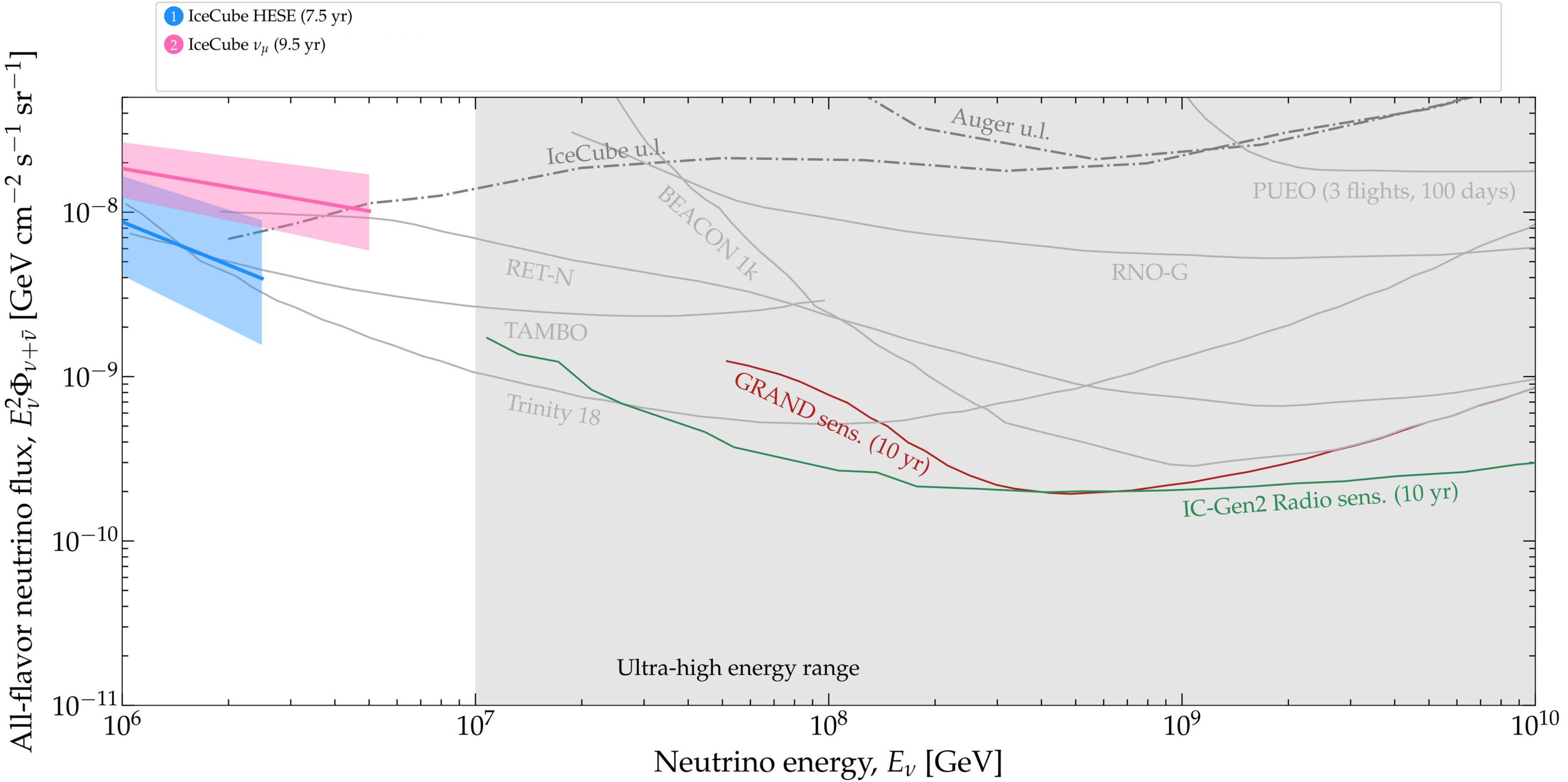


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Ultra-high energy range
Neutrino energy, E_ν [GeV]

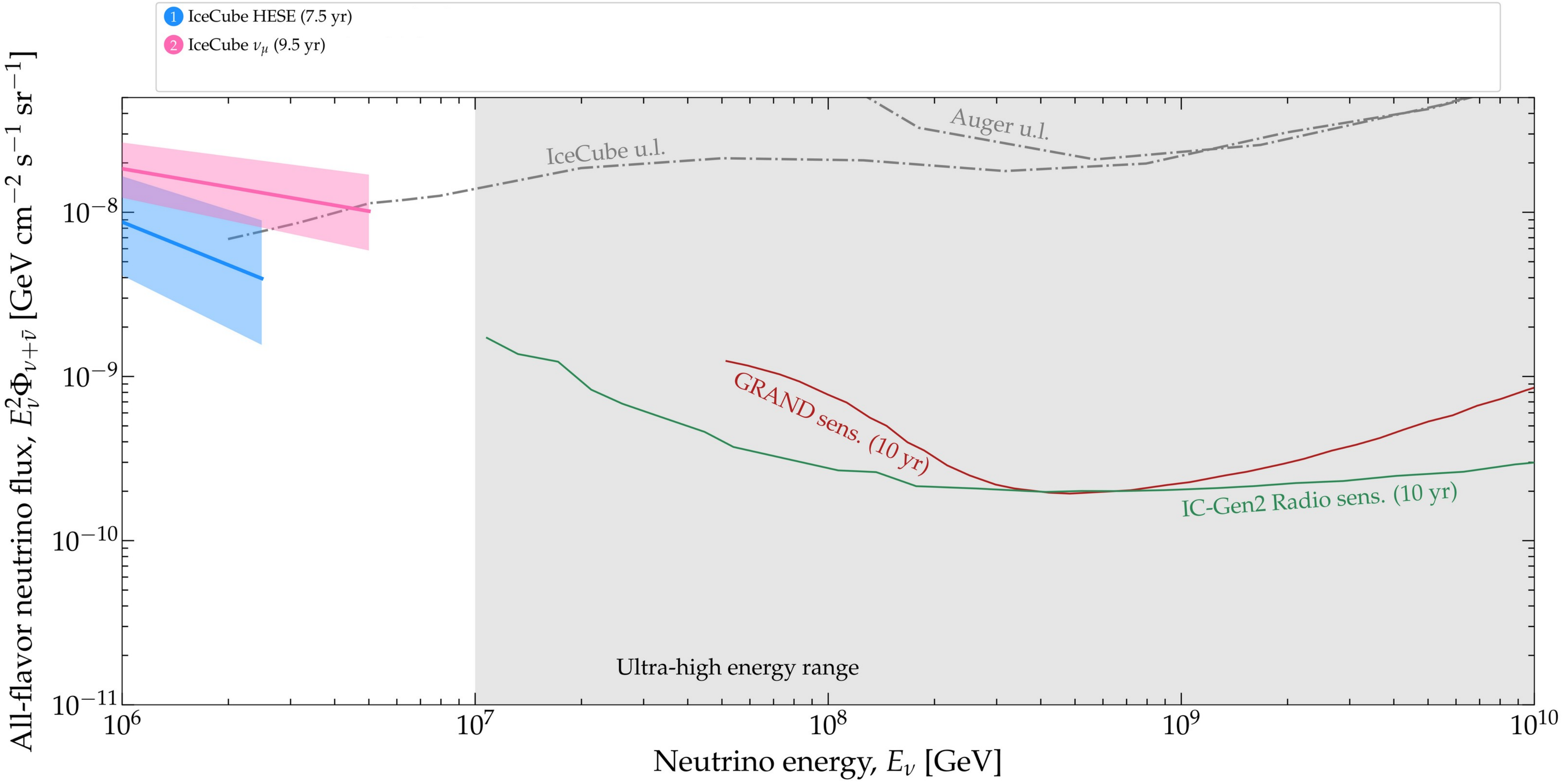

1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
IceCube u.l.
Auger u.l.
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]



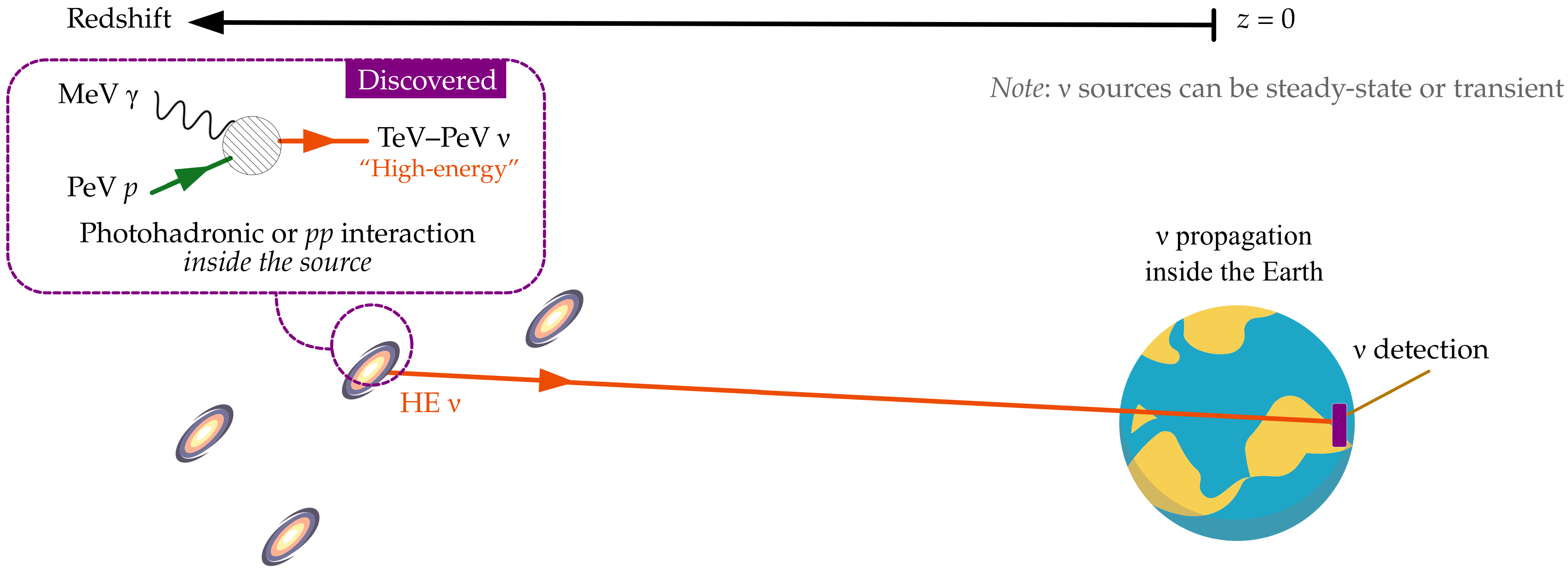
1 IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RNO-G
RET-N
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino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

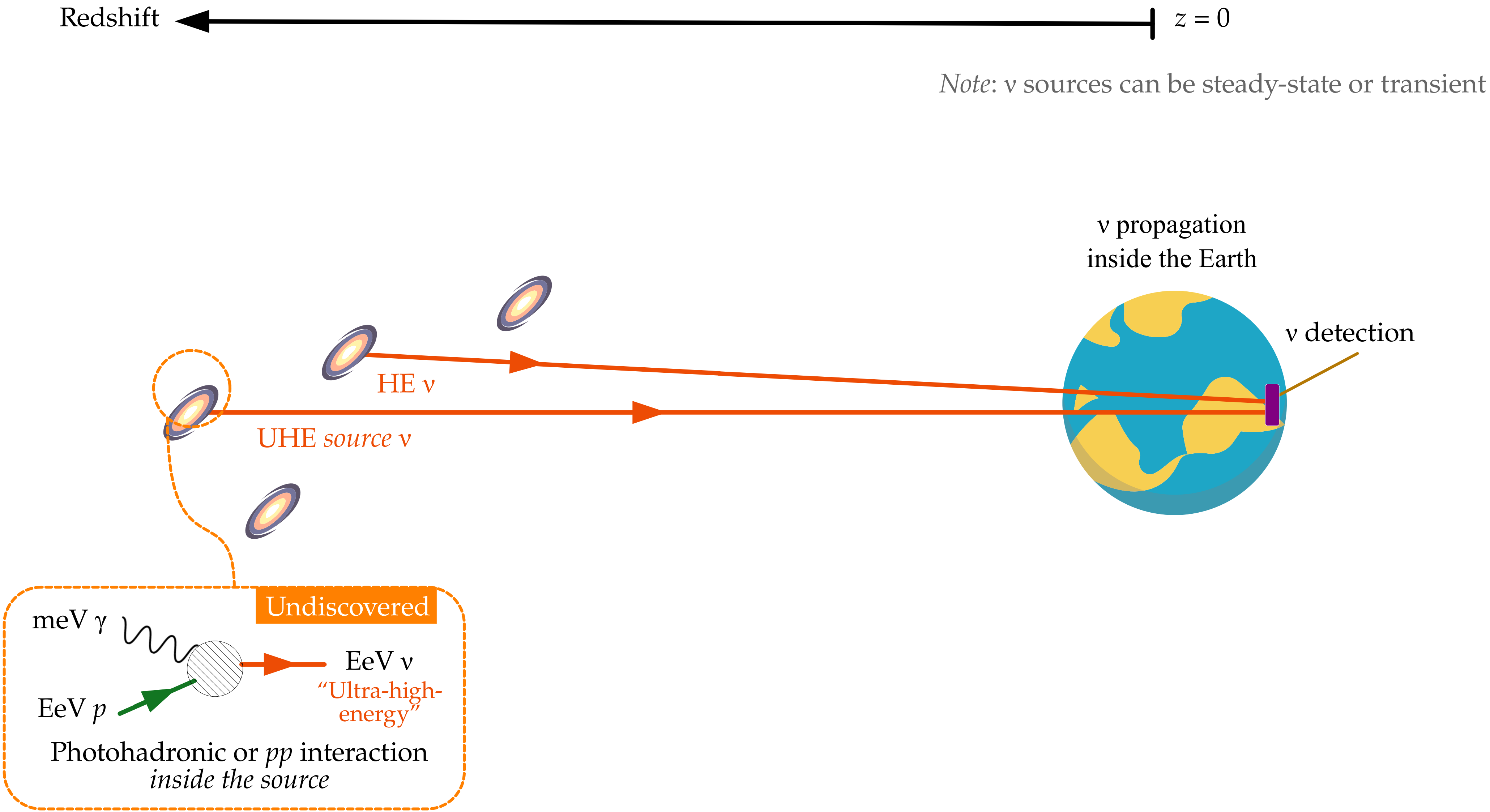


IceCube HESE (7.5 yr)
IceCube ν_μ (9.5 yr)
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
Auger u.l.
IceCube u.l.
PUEO (3 flights, 100 days)
BEACON 1k
RET-N
RNO-G
TAMBO
GRAND sens. (10 yr)
Trinity 18
IC-Gen2 Radio sens. (10 yr)
Ultra-high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

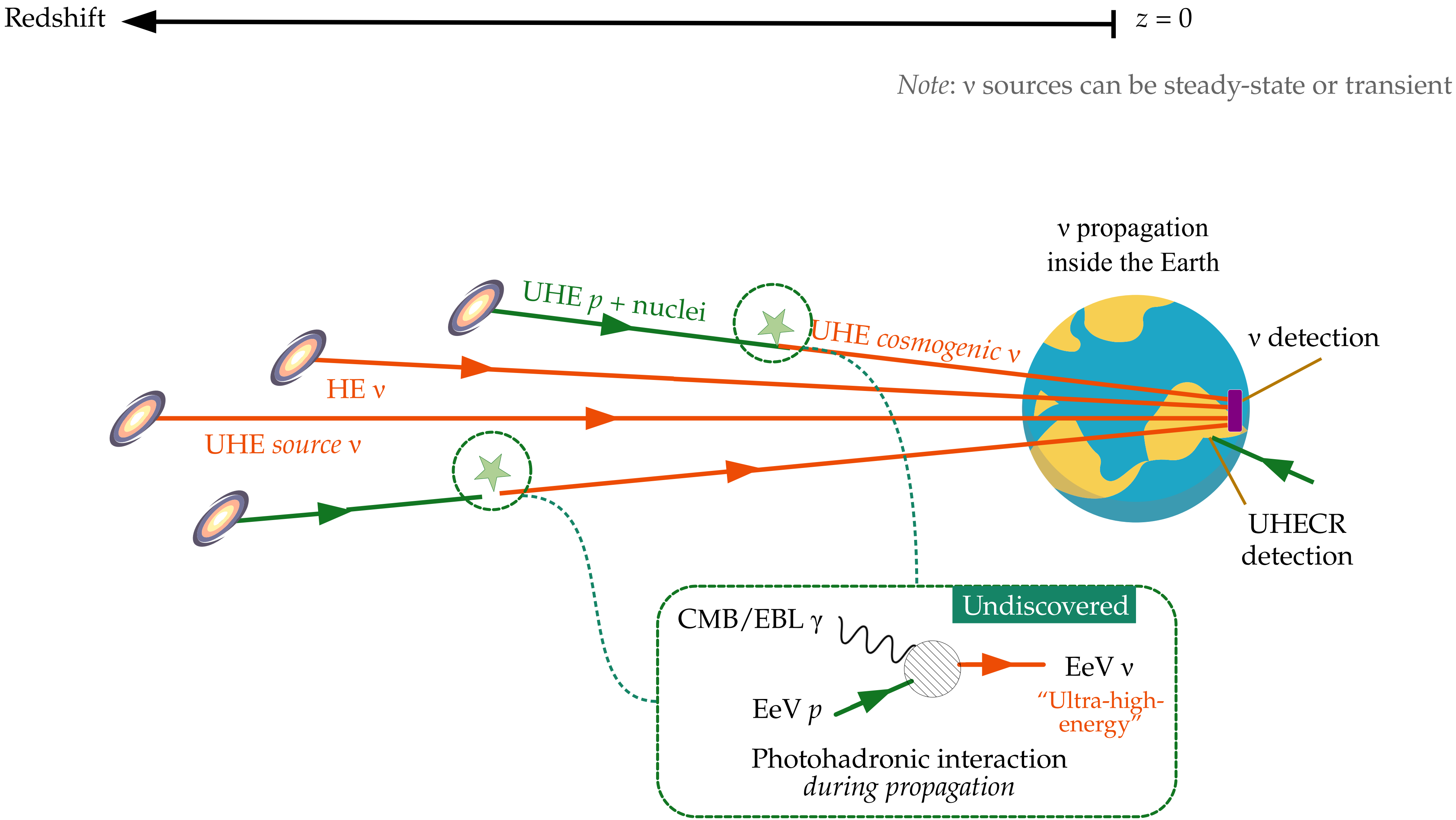


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (9.5 yr)
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8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

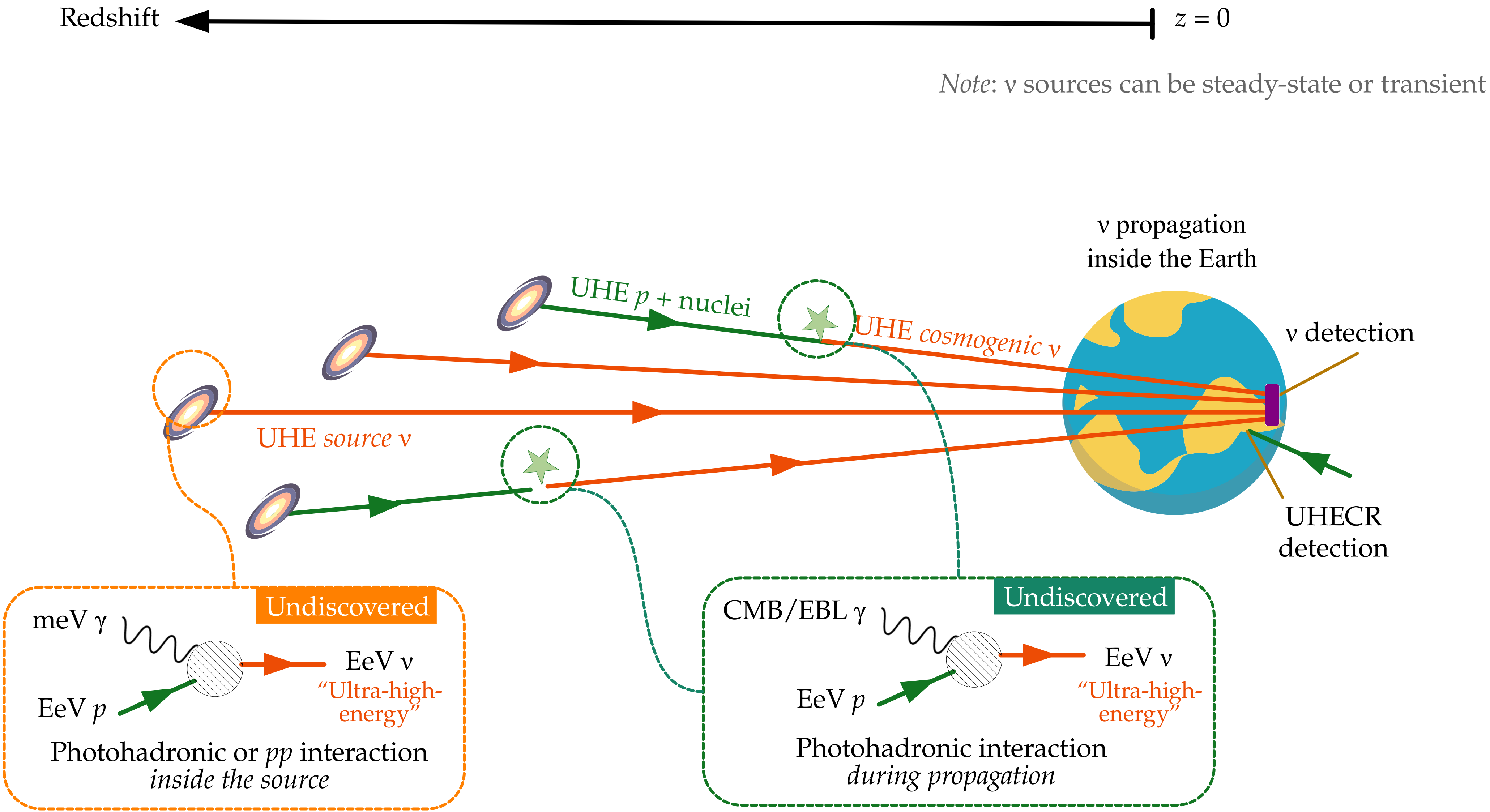

Redshift
$z = 0$
Discovered
MeV γ
PeV p
TeV–PeV ν
"High-energy"
Photohadronic or pp interaction
inside the source
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν



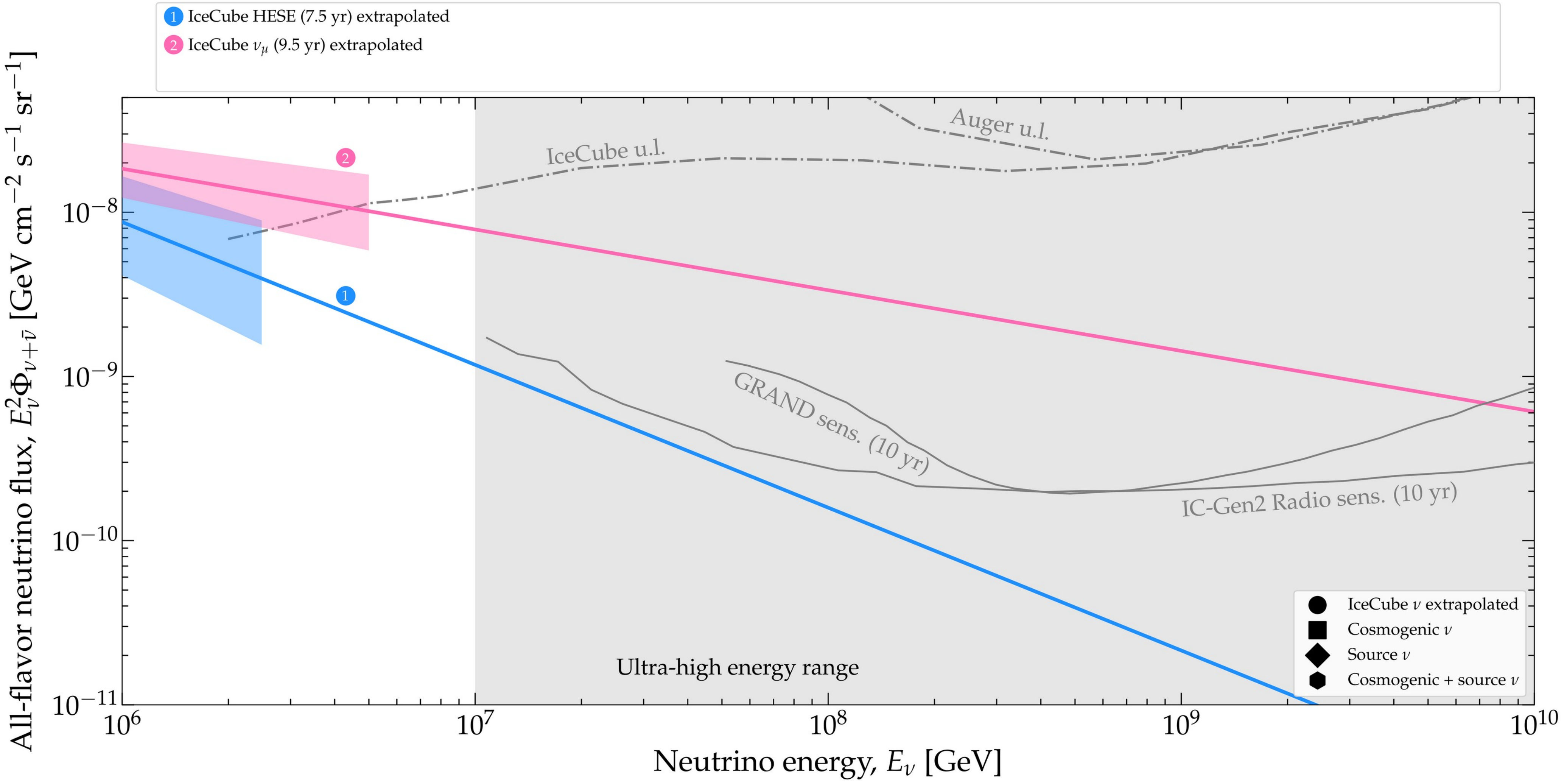
Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
ν detection
HE ν
UHE *source* ν
Undiscovered
meV γ
EeV ν
“Ultra-high-
energy”
EeV *p*
Photohadronic or *pp* interaction
inside the source



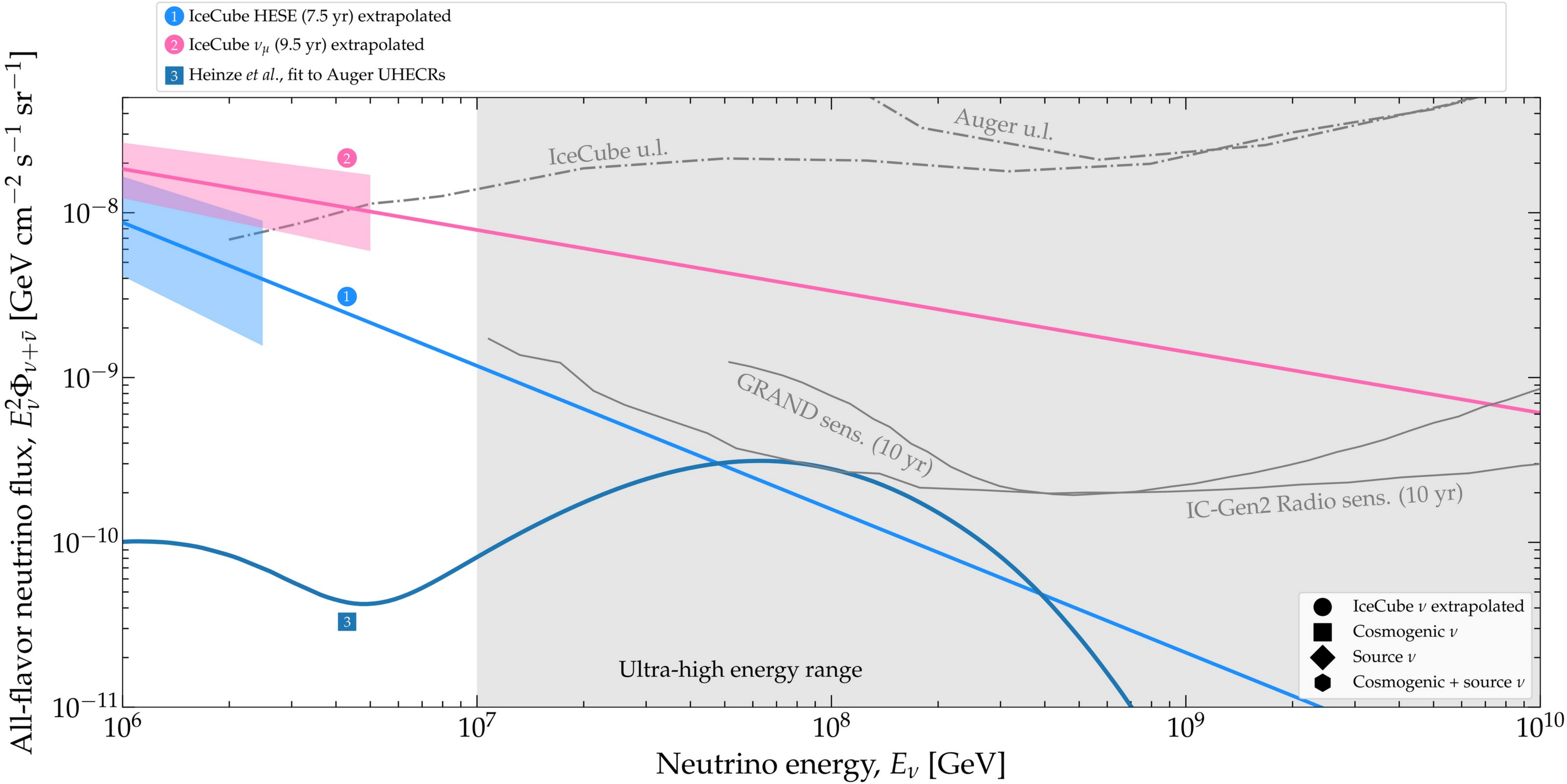
Redshift
z = 0
Note: ν sources can be steady-state or transient
ν propagation
inside the Earth
UHE p + nuclei
UHE cosmogenic ν
ν detection
HE ν
UHE source ν
UHECR
detection
Undiscovered
CMB/EBL γ
EeV ν
EeV p
"Ultra-high-
energy"
Photohadronic interaction
during propagation



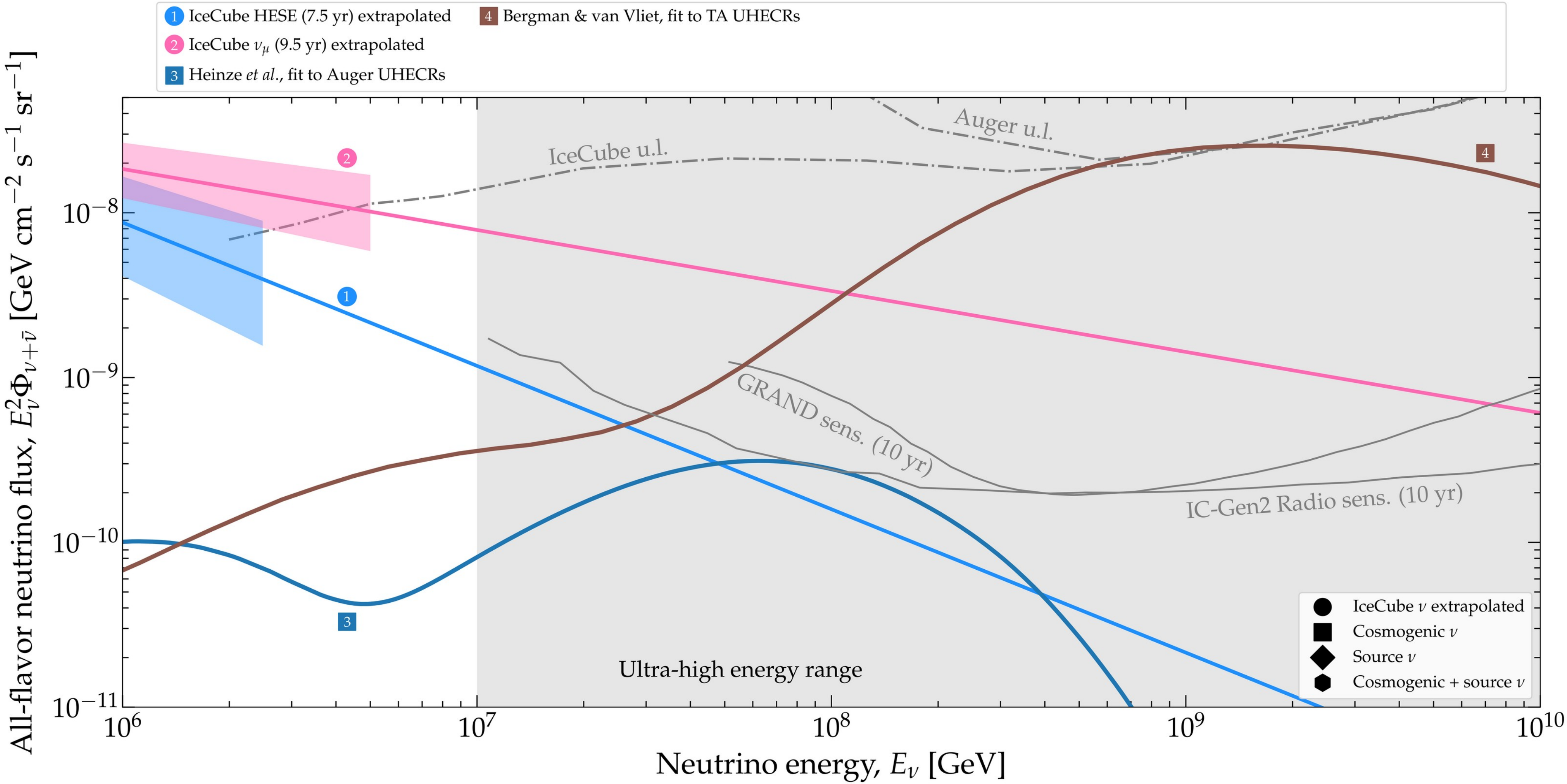
Redshift
$z = 0$
Note: ν sources can be steady-state or transient
ν propagation inside the Earth
UHE *p* + nuclei
UHE *cosmogenic* ν
ν detection
UHE *source* ν
UHECR detection
Undiscovered
meV γ
EeV ν
"Ultra-high-energy"
EeV *p*
Photohadronic or *pp* interaction
inside the source
Undiscovered
CMB/EBL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



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



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



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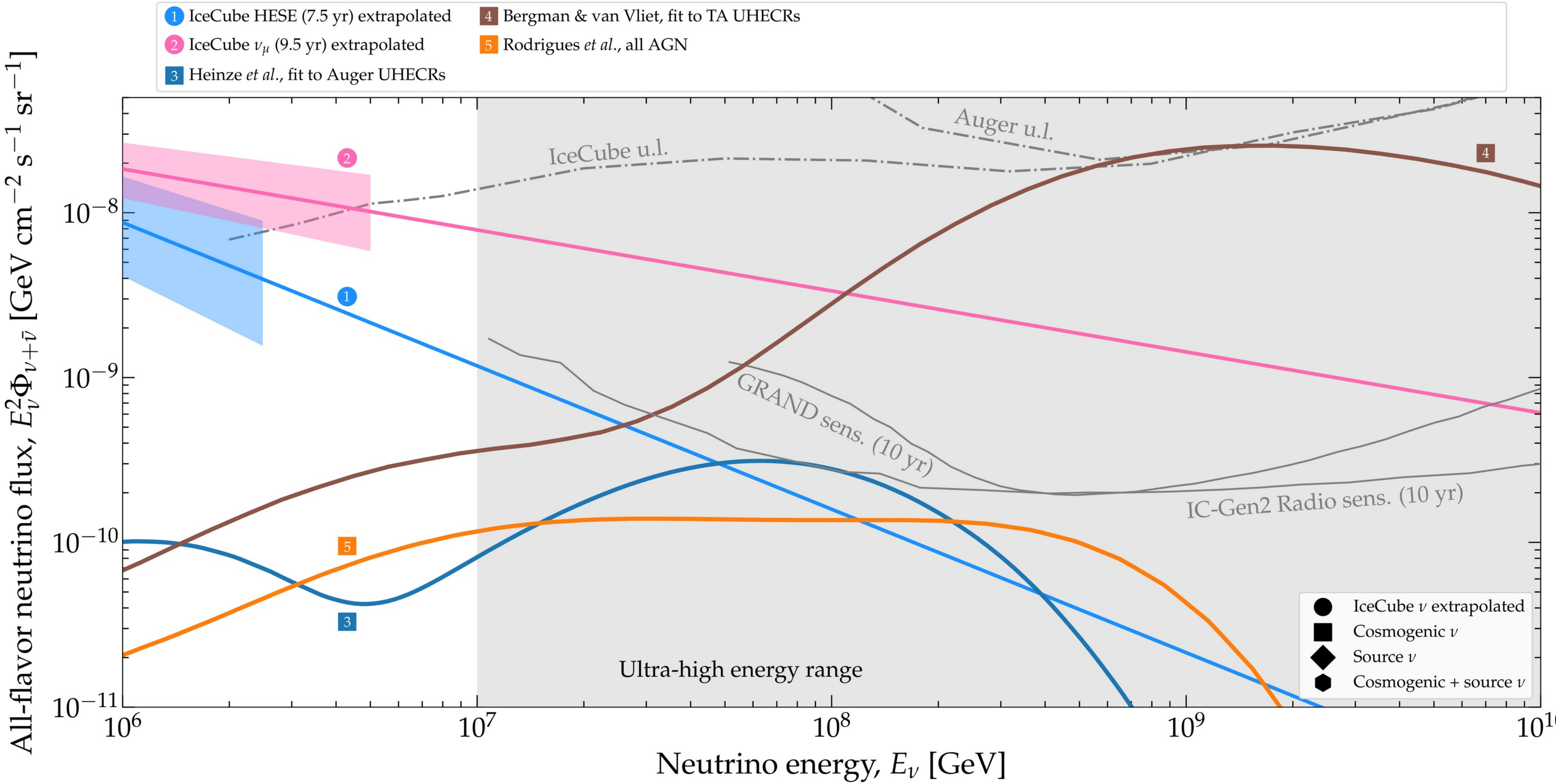
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}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



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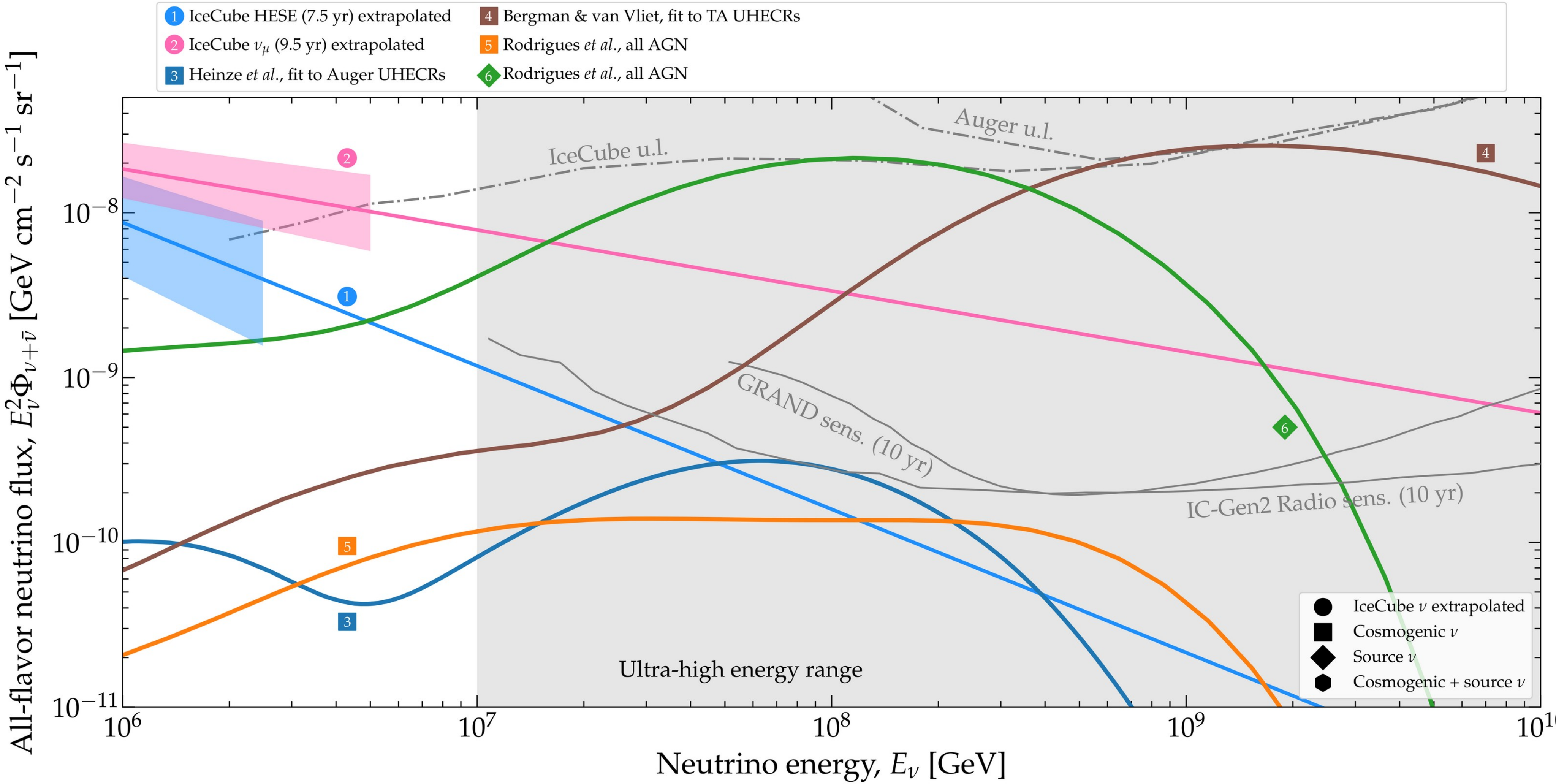
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues *et al.*, all AGN
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2}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



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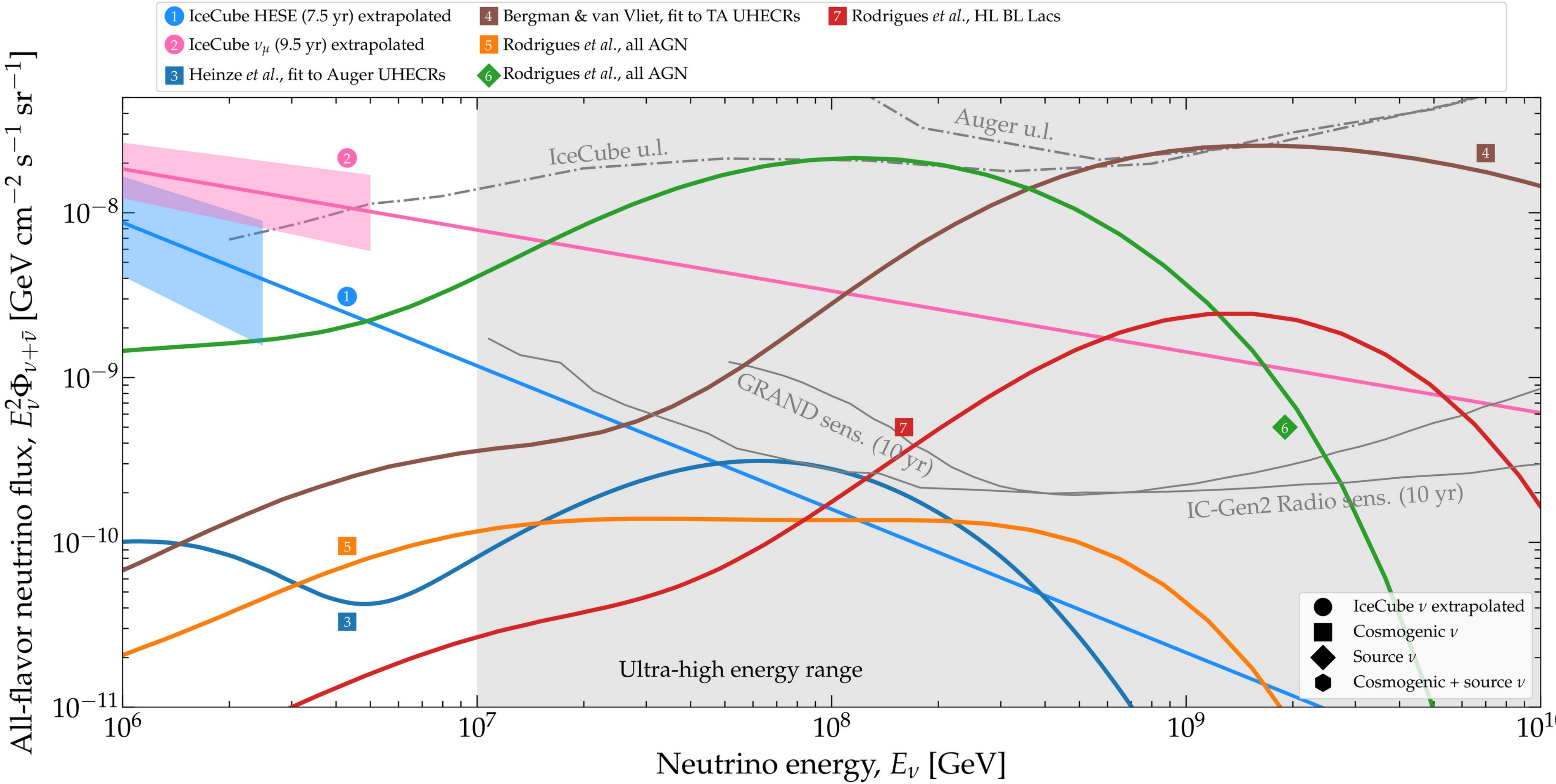
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2\Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9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



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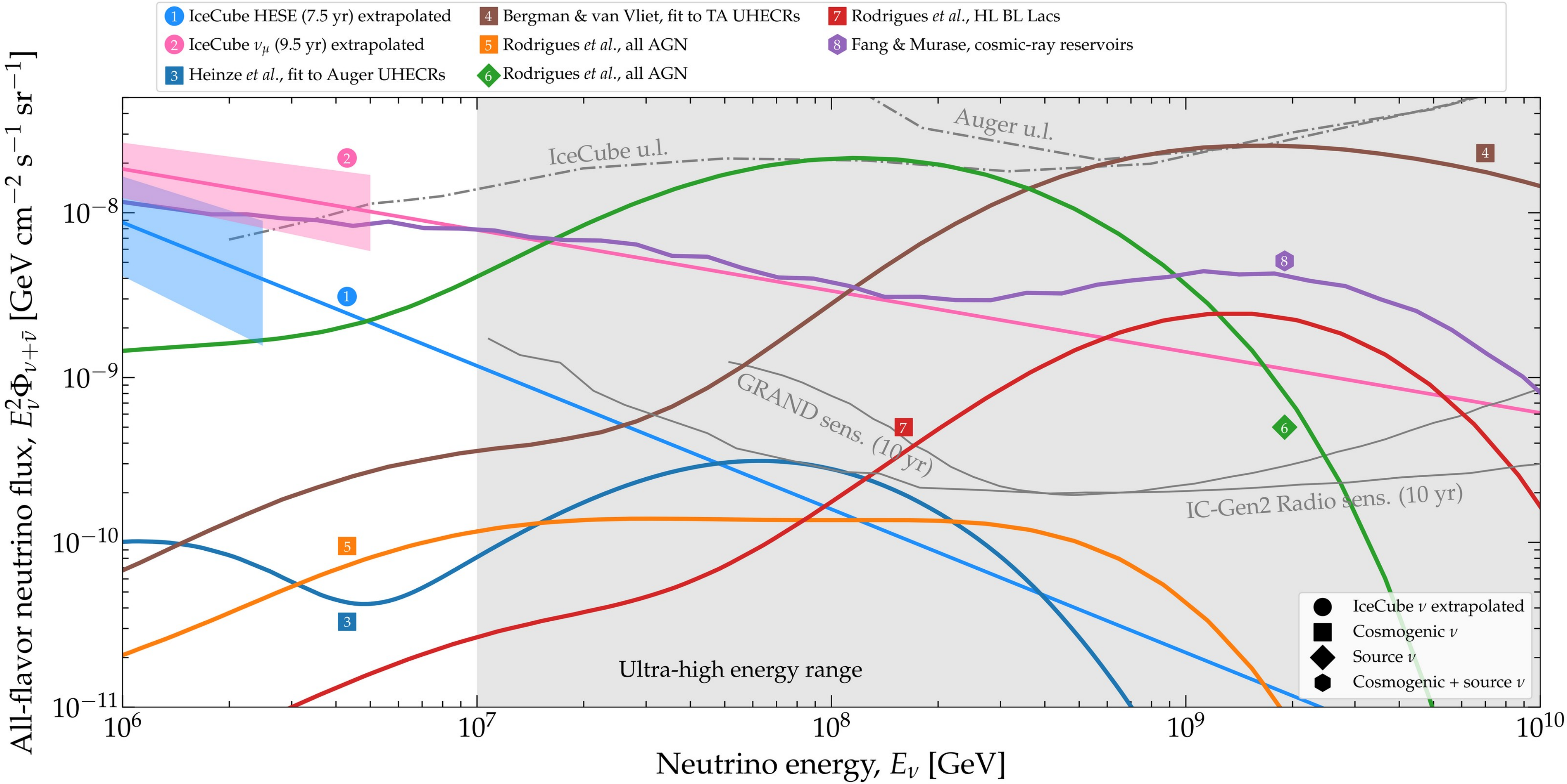
7 Rodrigues *et al.*, HL BL Lacs
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}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



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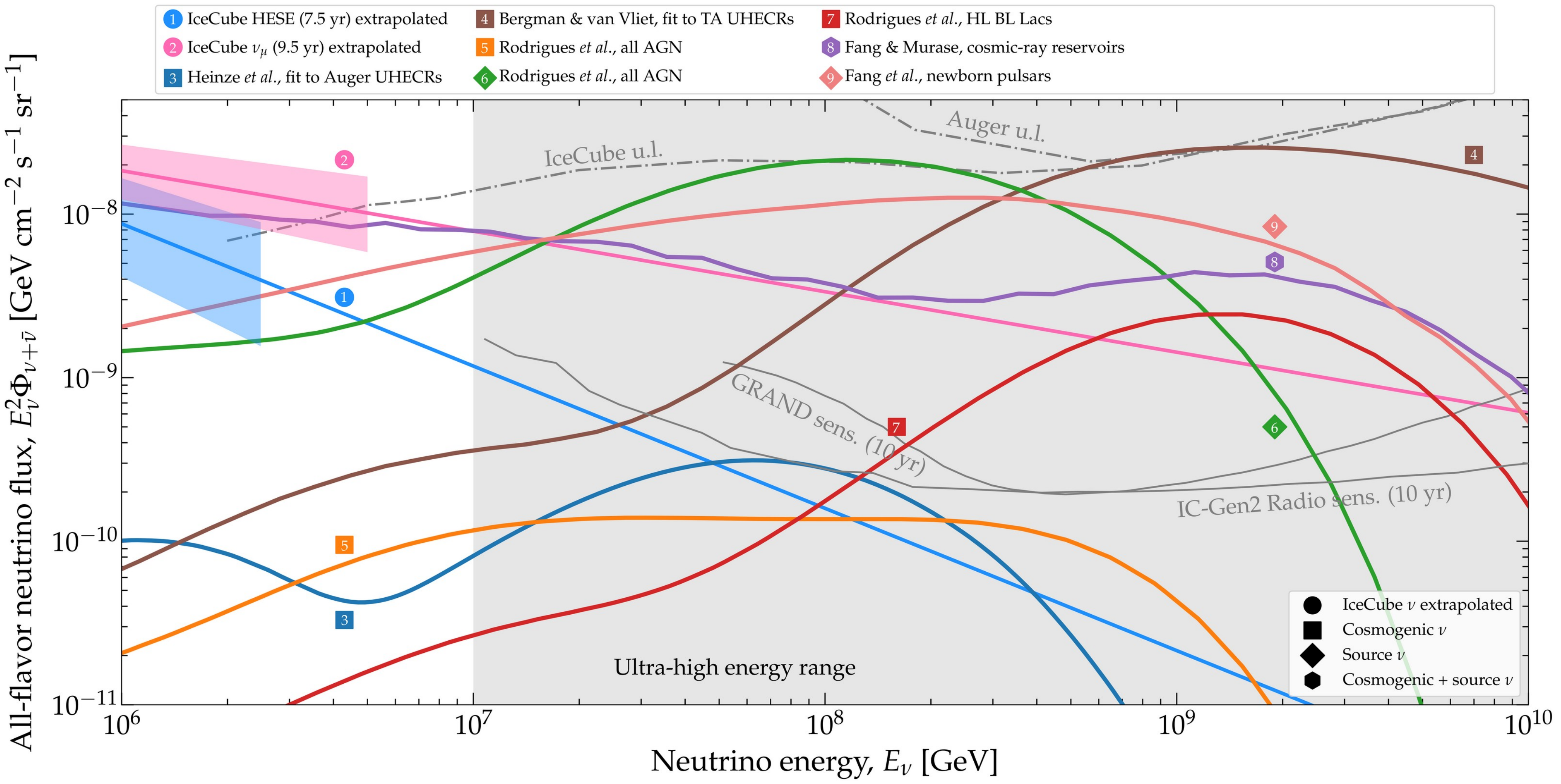
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}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



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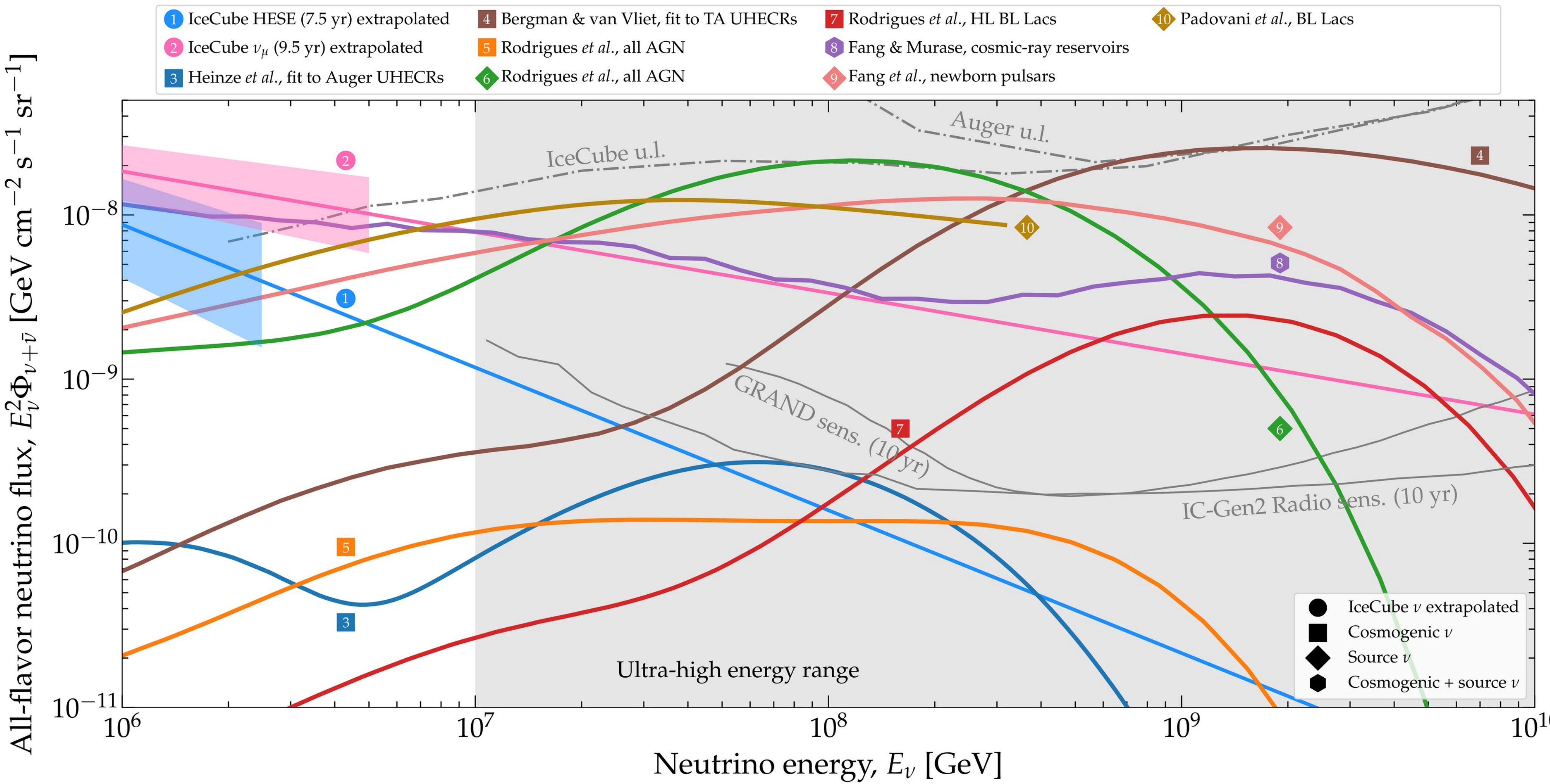
8 Fang & Murase, cosmic-ray reservoirs
9 Fang *et al.*, newborn pulsars
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]



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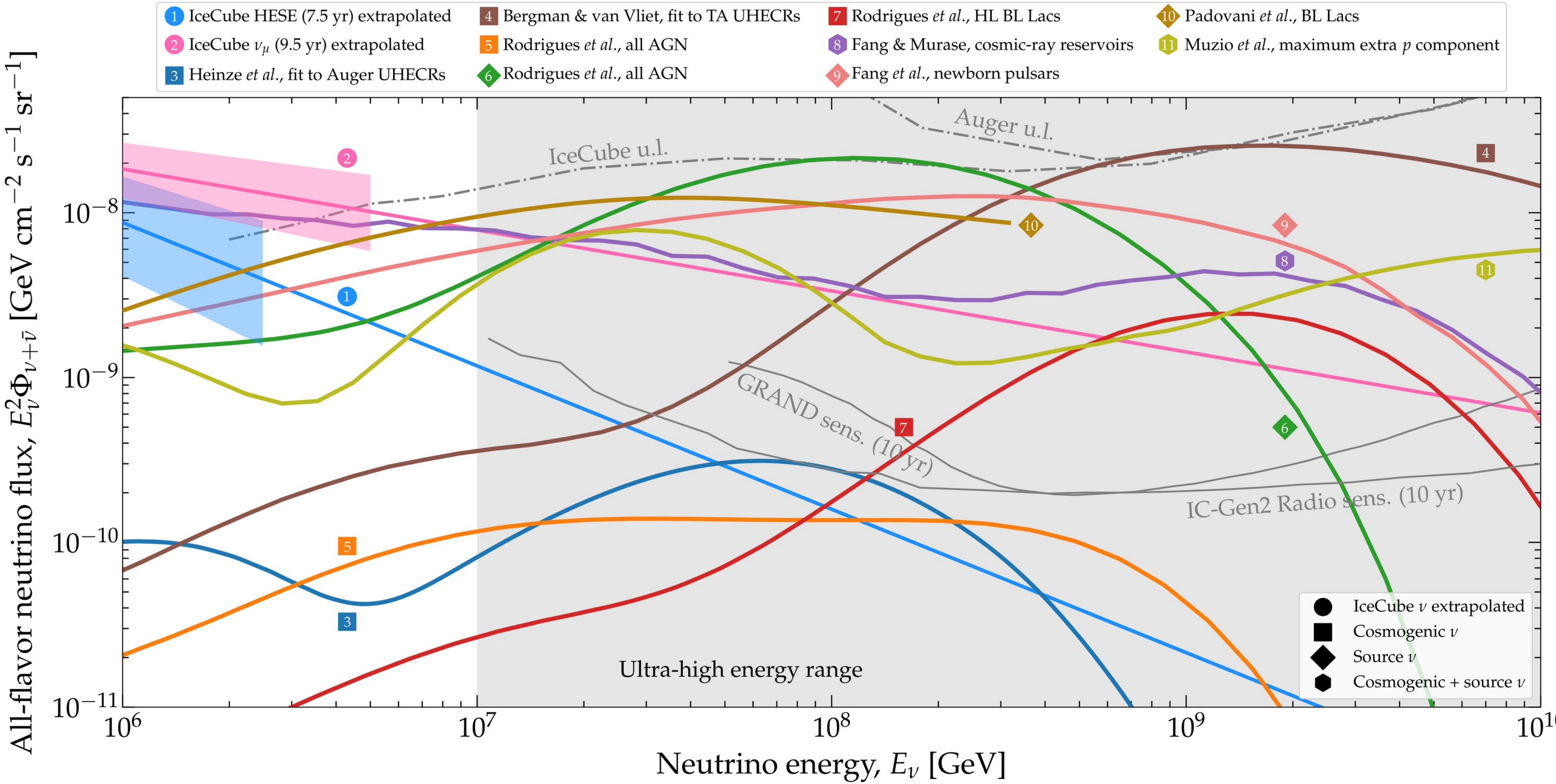
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated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



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8 Fang & Murase, cosmic-ray reservoirs
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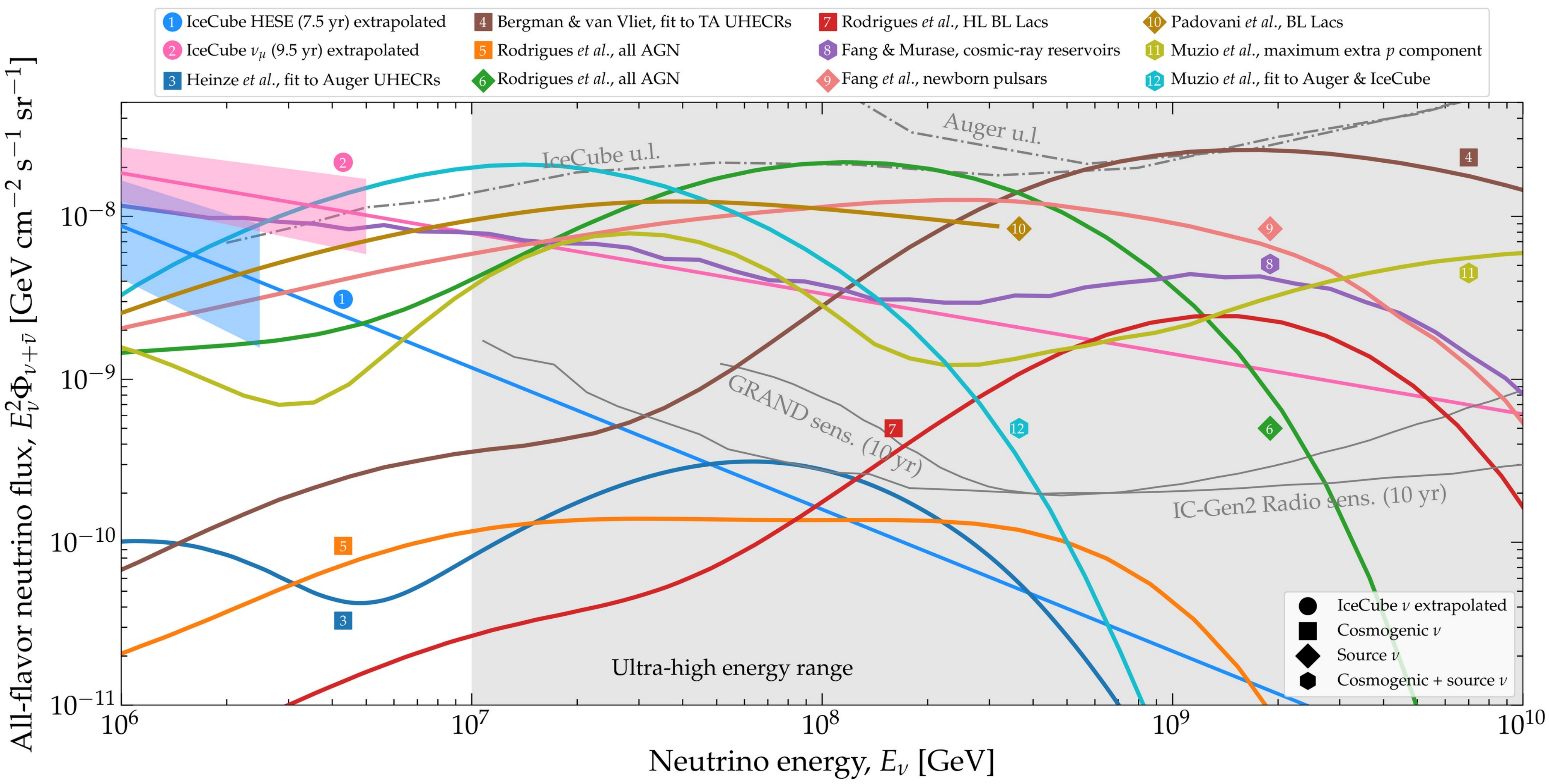
10 Padovani *et al.*, BL Lacs
11 Muzio *et al.*, maximum extra p component
Auger u.l.
IceCube u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy, E_ν [GeV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}



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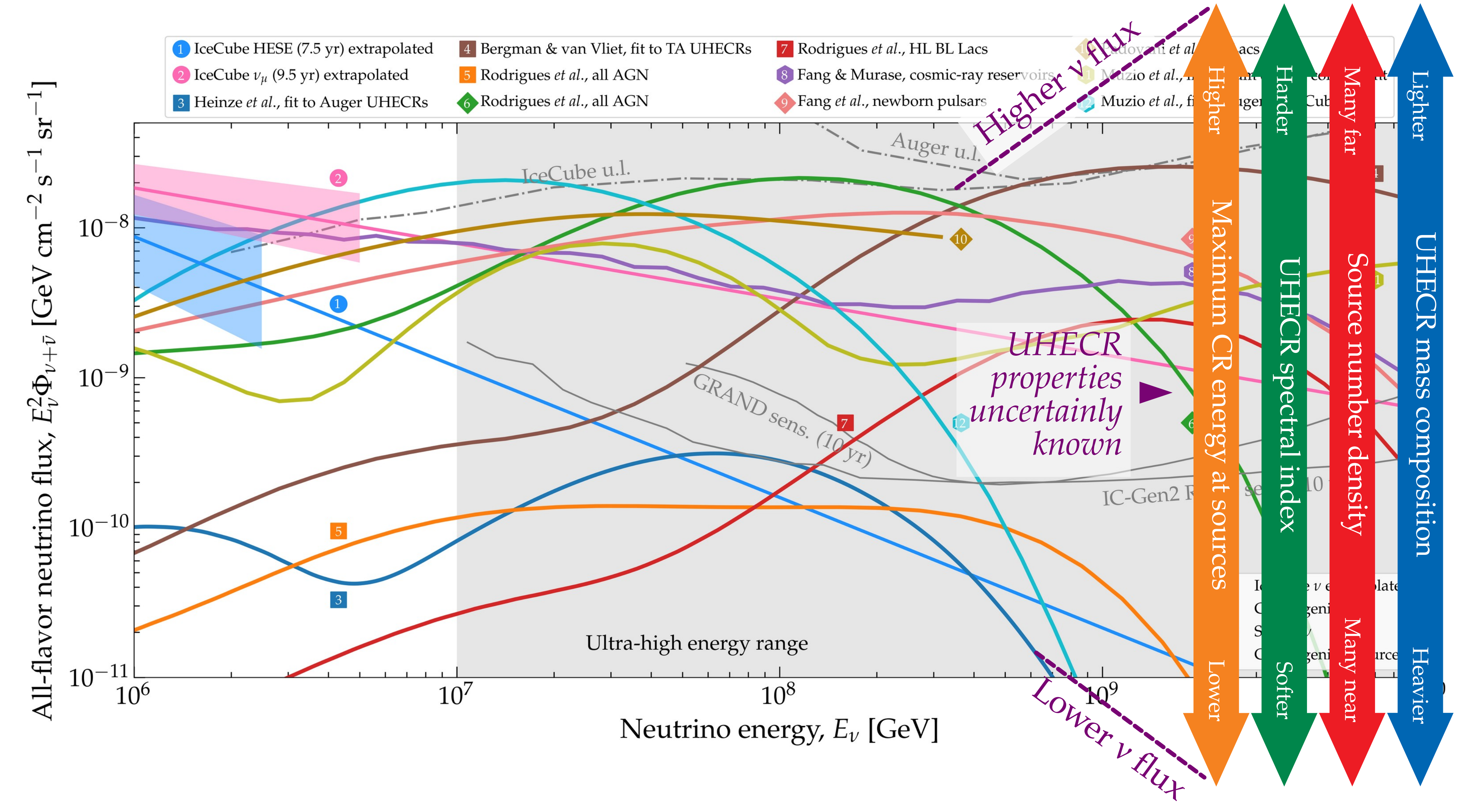
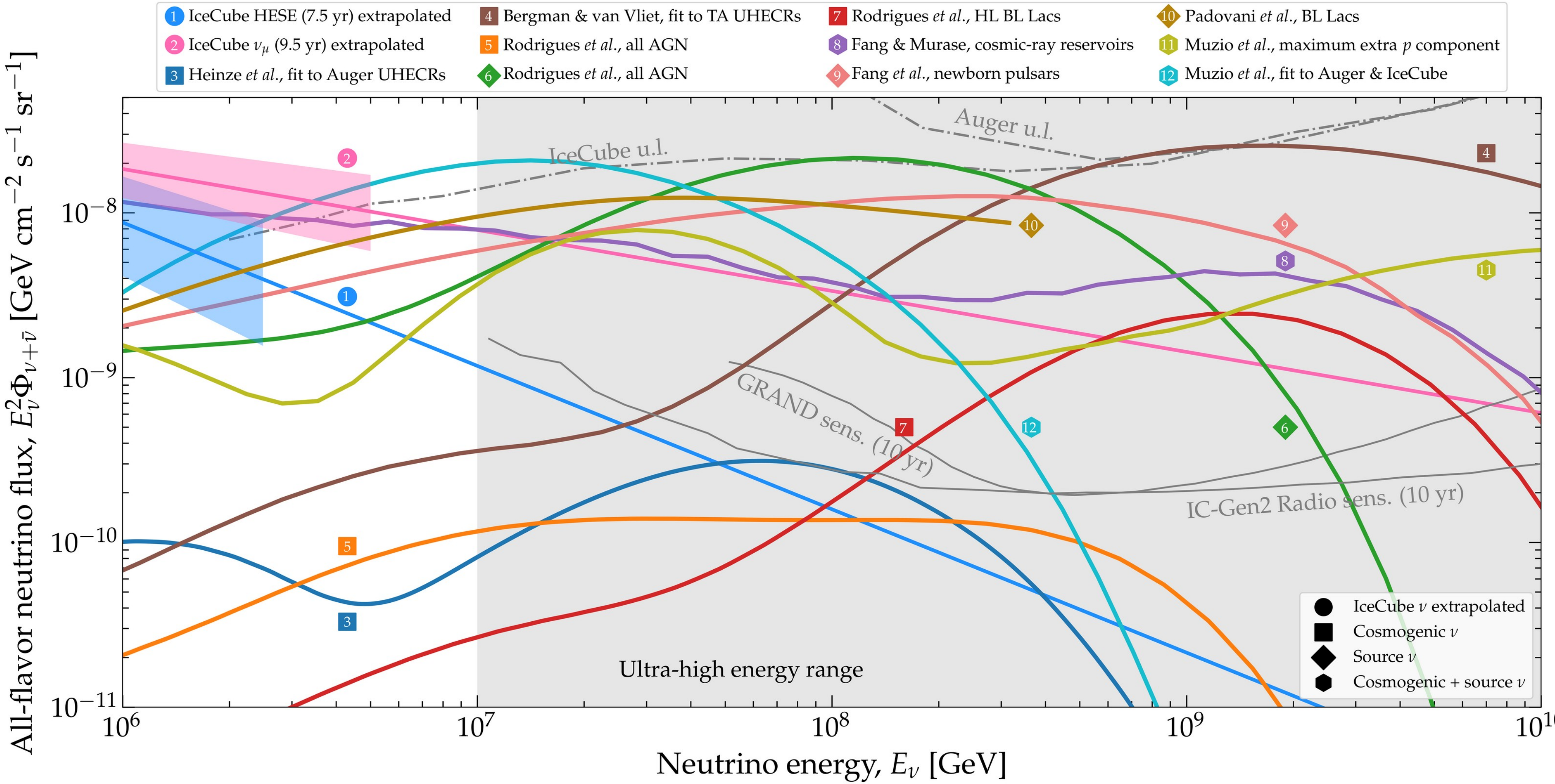
11 Muzio et al., maximum extra p component
12 Muzio et al., fit to Auger & IceCube
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [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
Higher ν flux
Lower ν flux
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
UHECR properties uncertainly known
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]
Higher
Maximum CR energy at sources
Lower
Harder
UHECR spectral index
Softer
Many far
Source number density
Many near
Lighter
UHECR mass composition
Heavier



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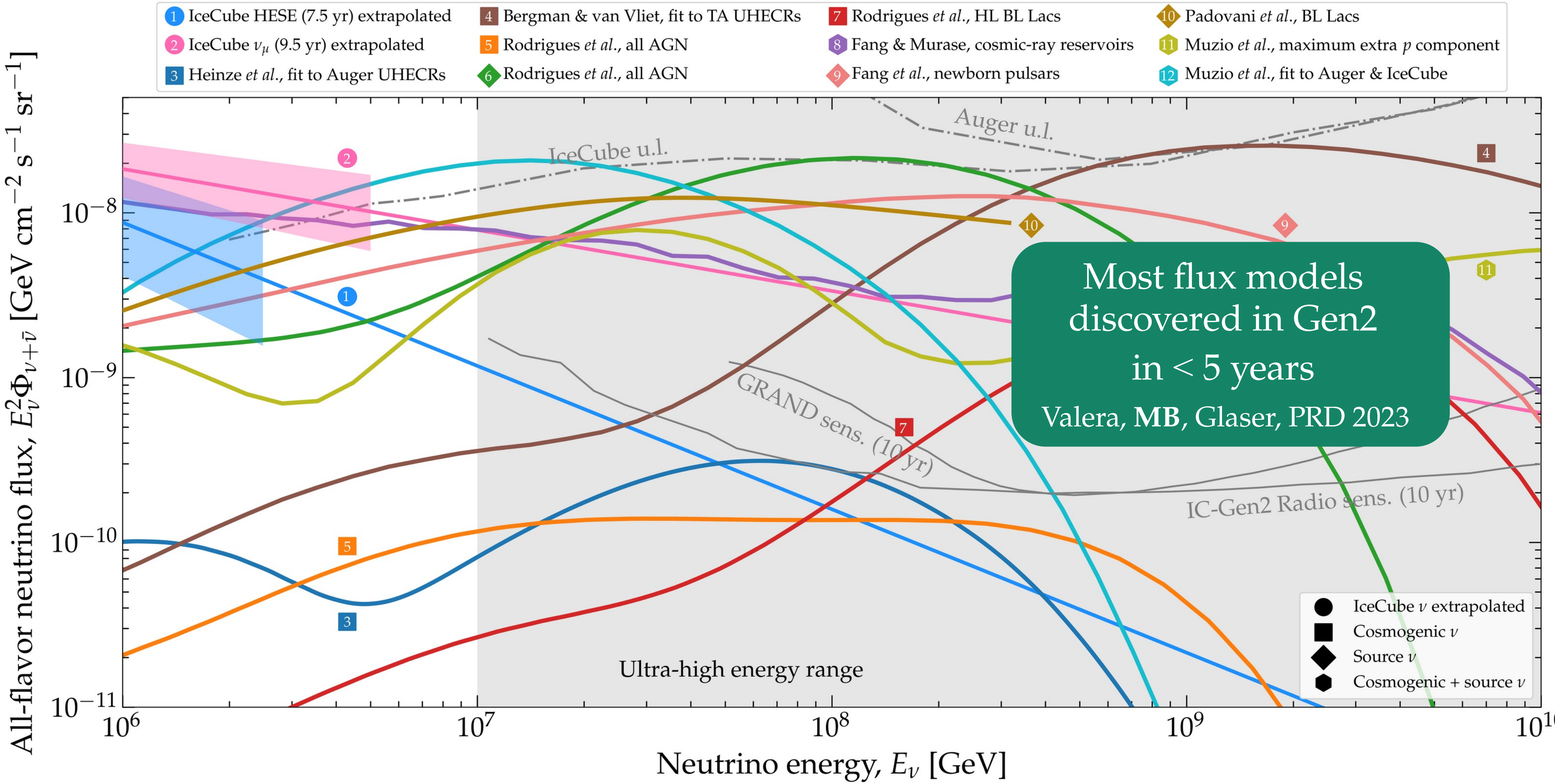
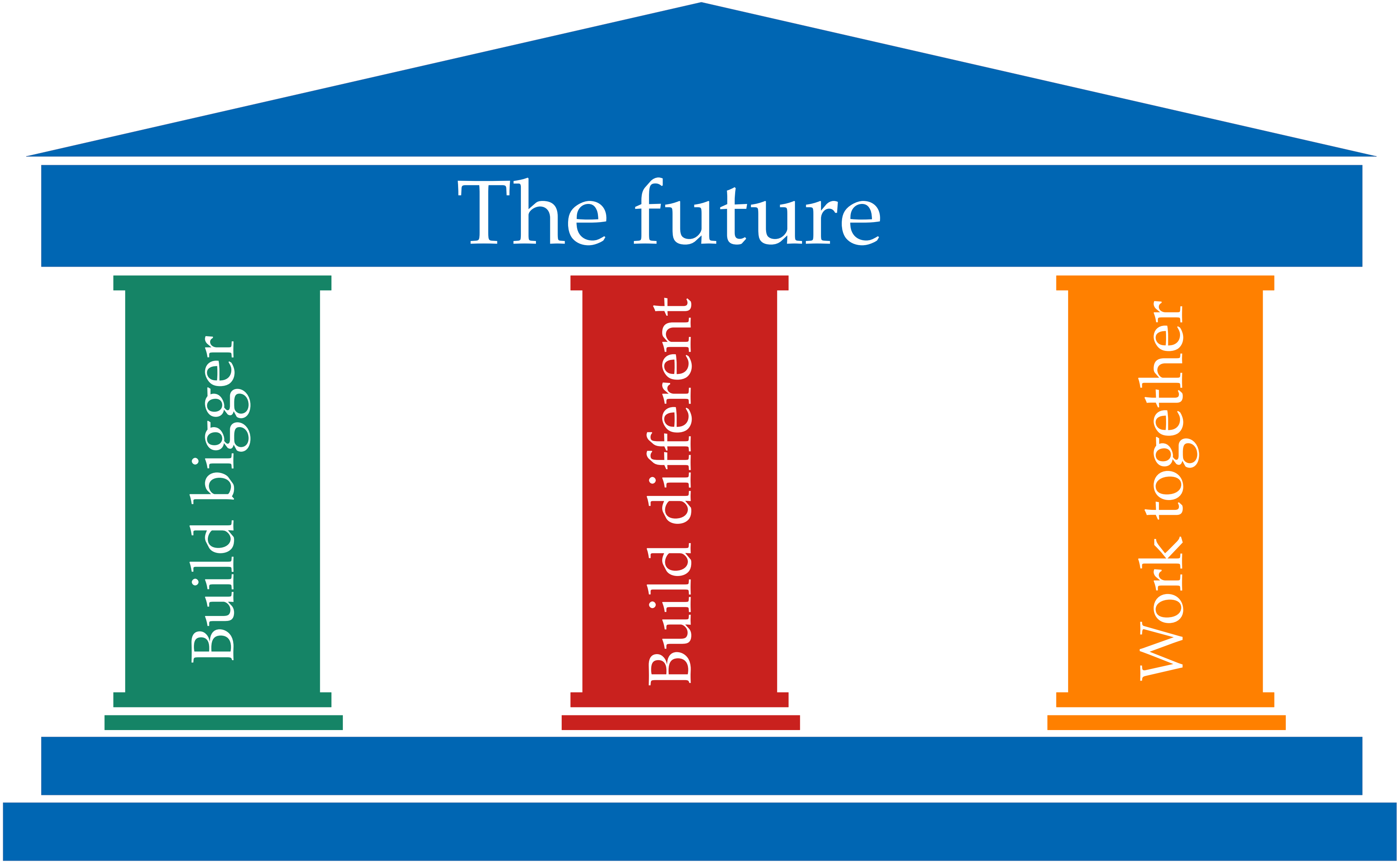
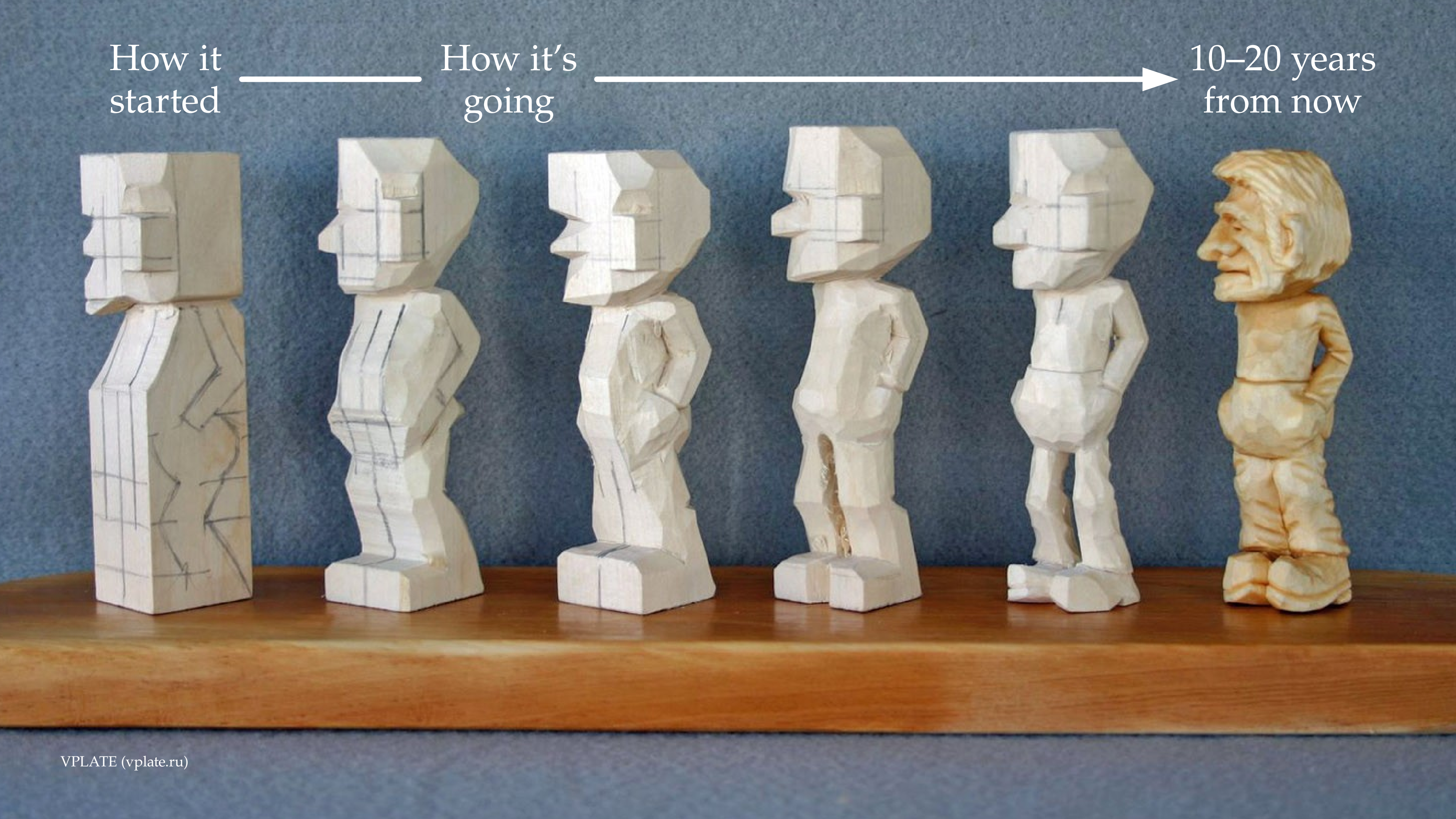
IceCube u.l.
Auger u.l.
GRAND sens. (10 yr)
IC-Gen2 Radio sens. (10 yr)
Ultra-high energy range
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9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

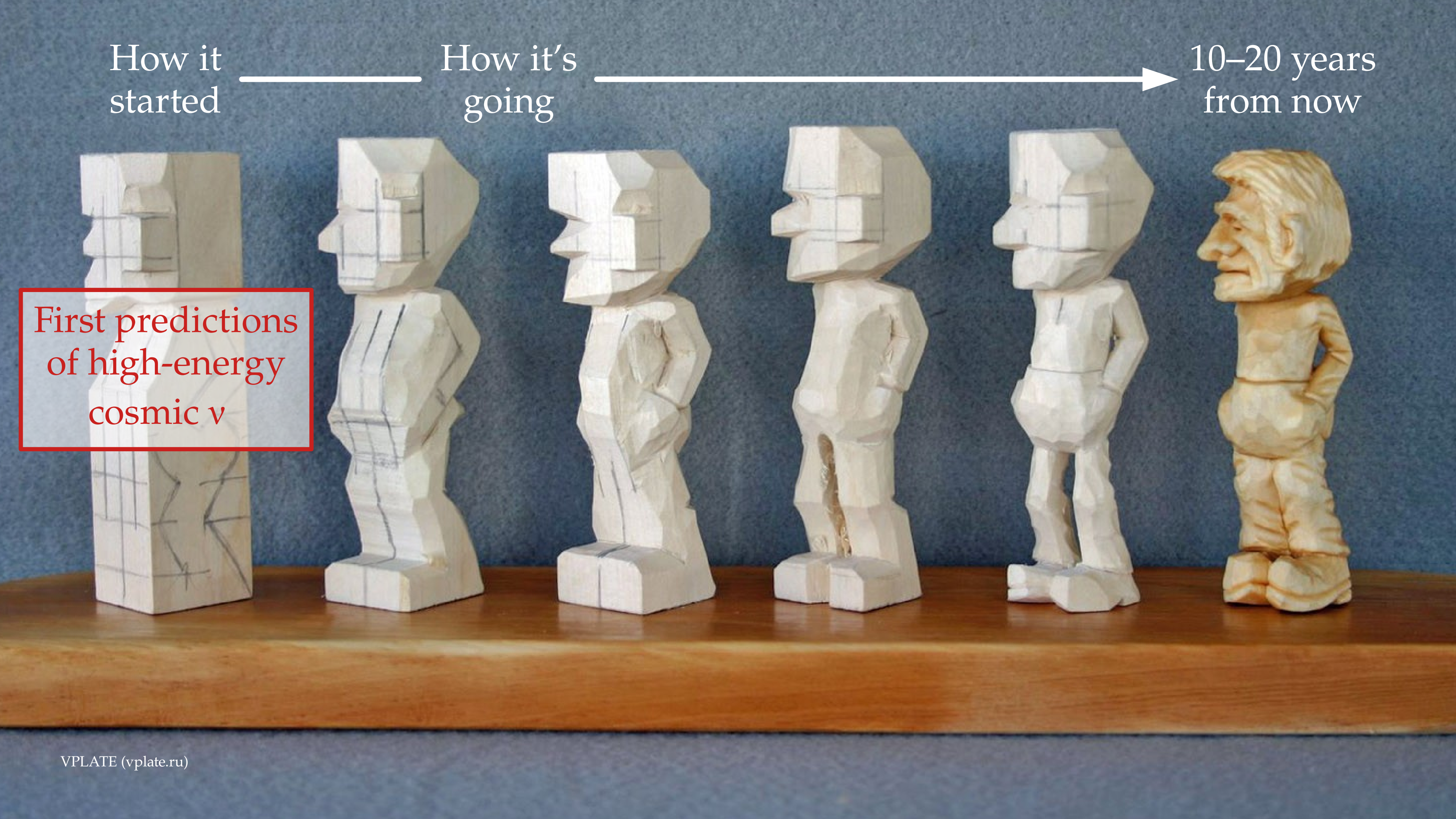


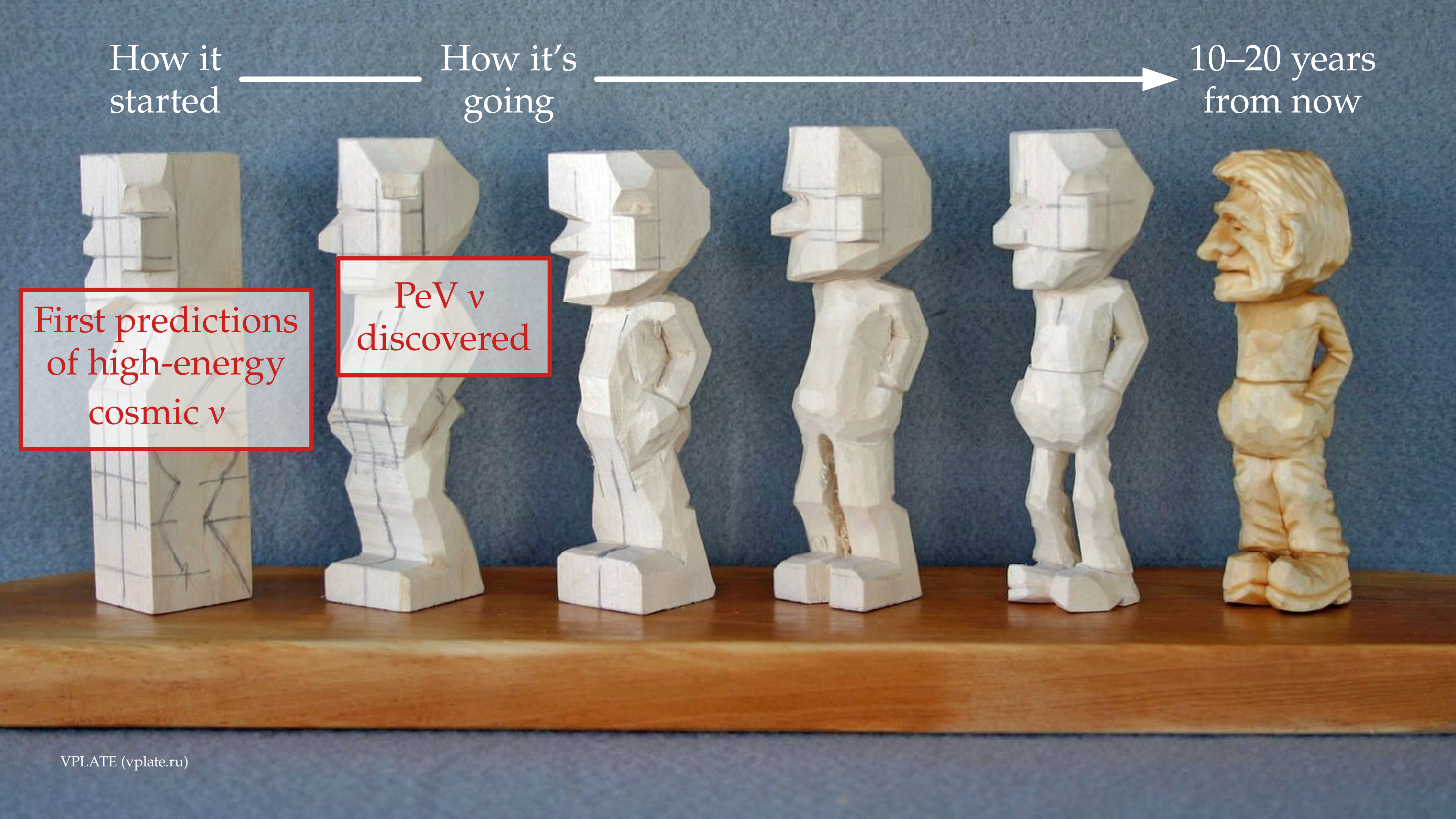
Most flux models discovered in Gen2 in < 5 years

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


The future
Build bigger
Build different
Work together


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


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


How it started
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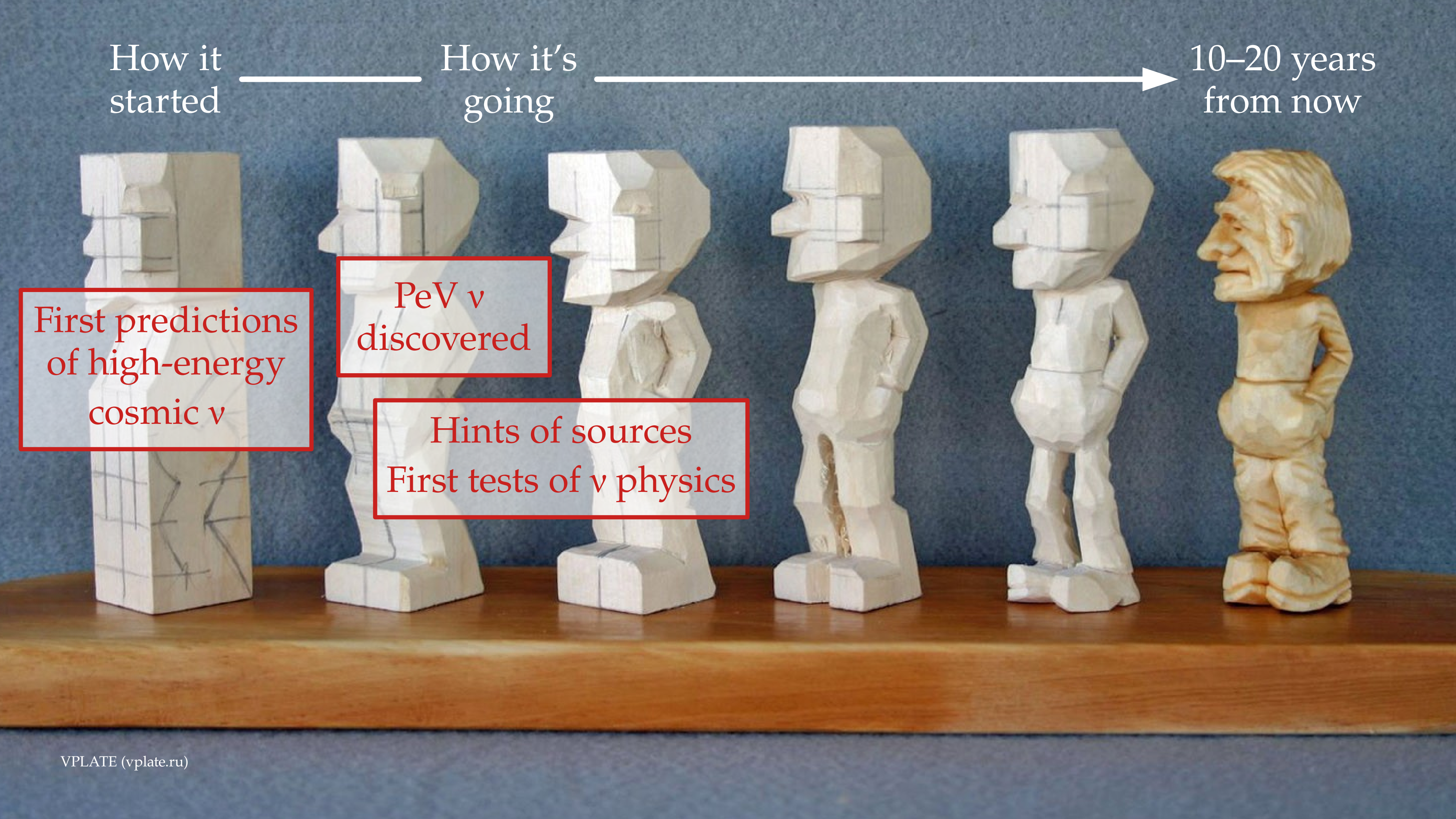
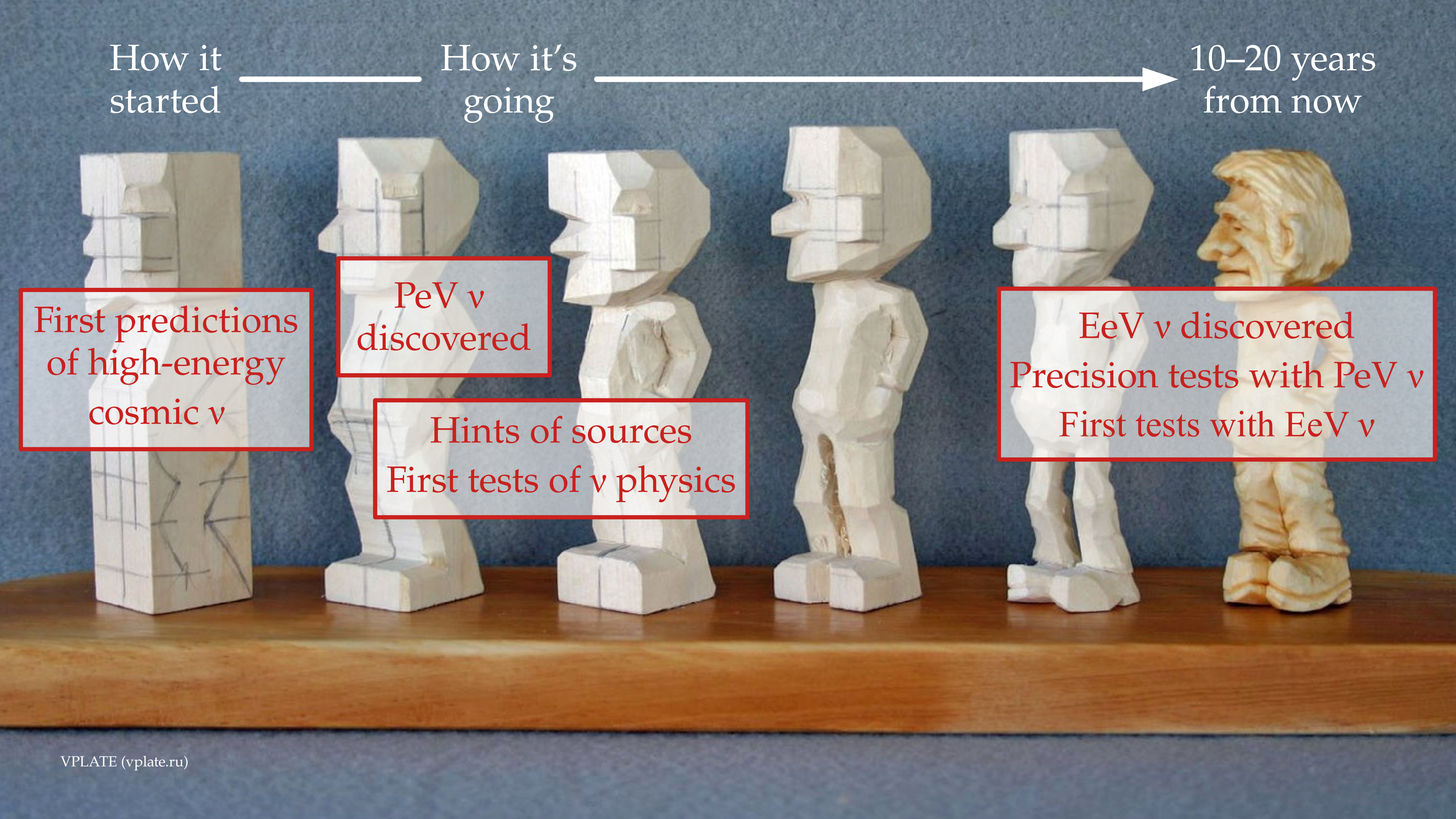
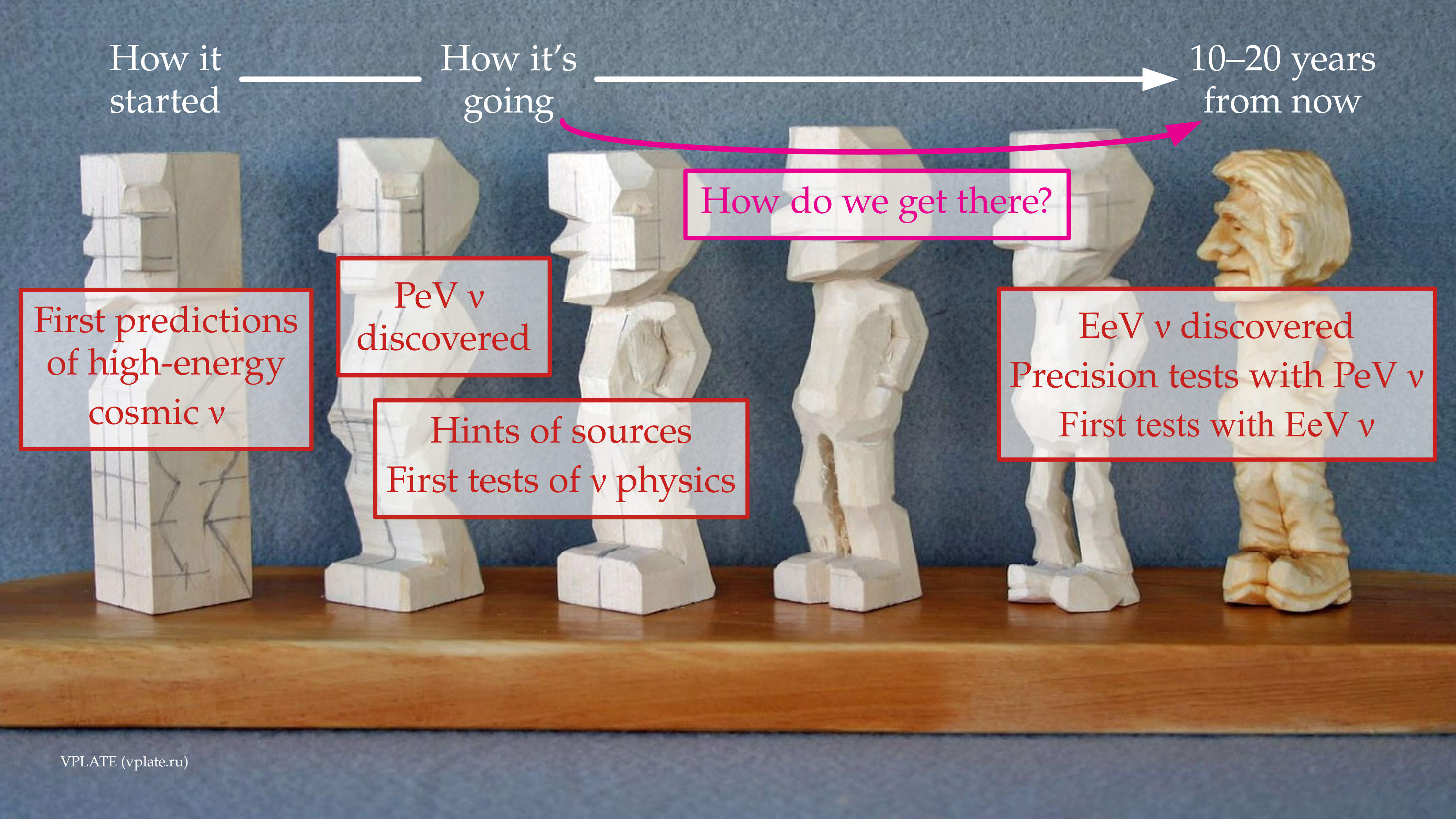
First predictions of high-energy cosmic ν
PeV ν discovered
VPLATE (vplate.ru)


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)

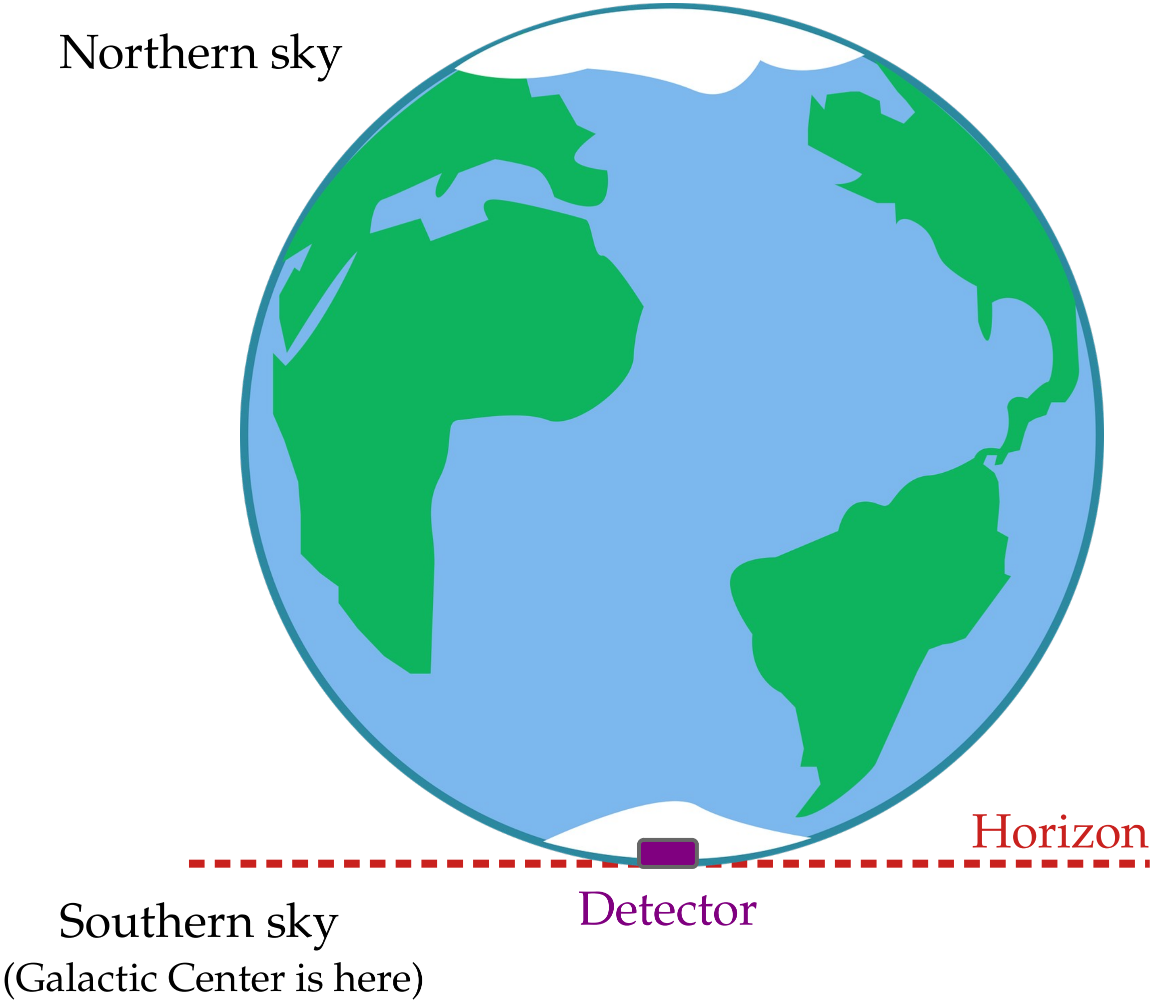

How it started
How it's going
10–20 years from now
First predictions of high-energy cosmic ν
PeV ν discovered
Hints of sources
First tests of ν physics
EeV ν discovered
Precision tests with PeV ν
First tests with EeV ν
VPLATE (vplate.ru)


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)

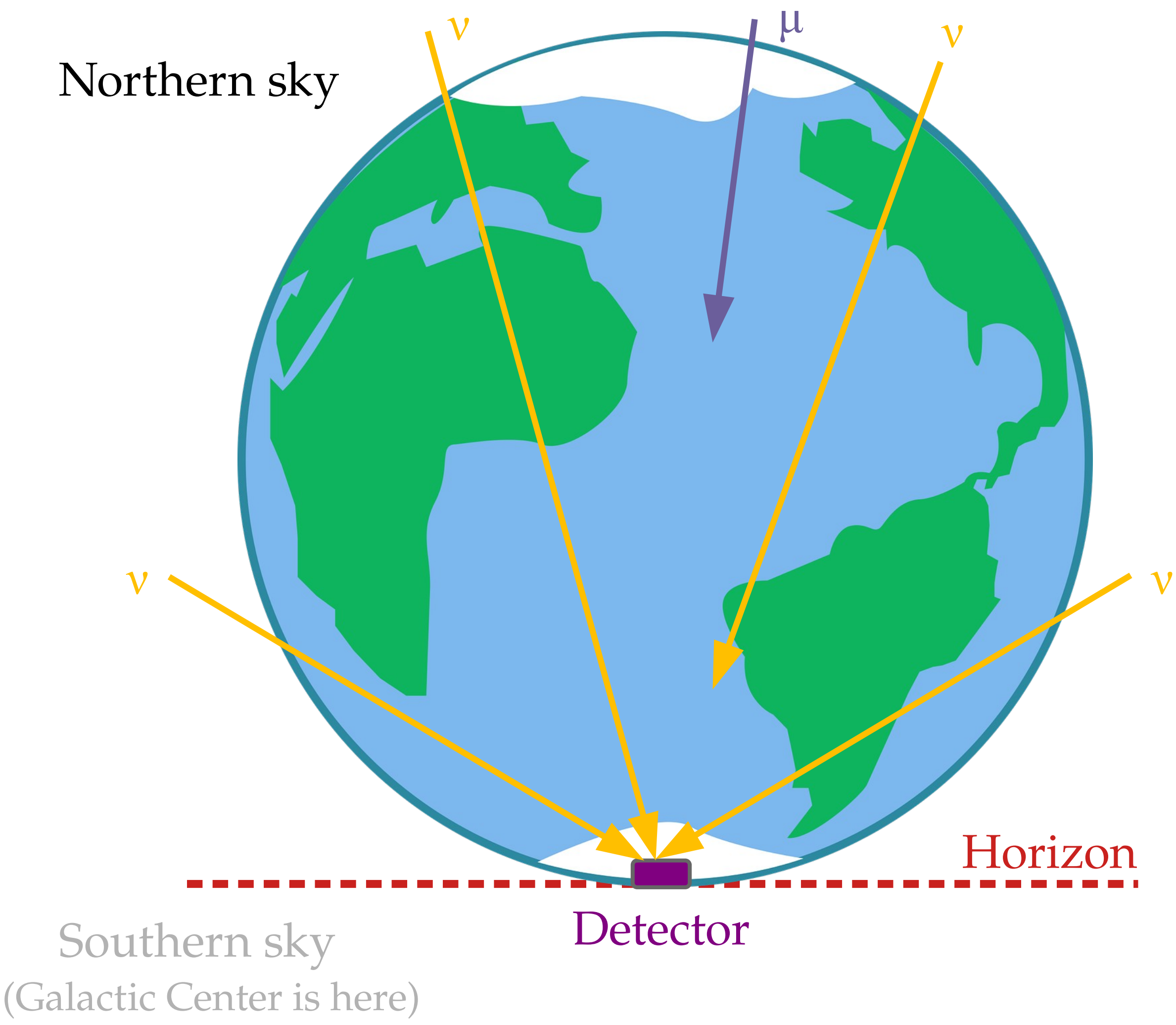
Thanks!

Backup slides

Upgoing *vs.* downgoing neutrinos



Upgoing *vs.* downgoing neutrinos



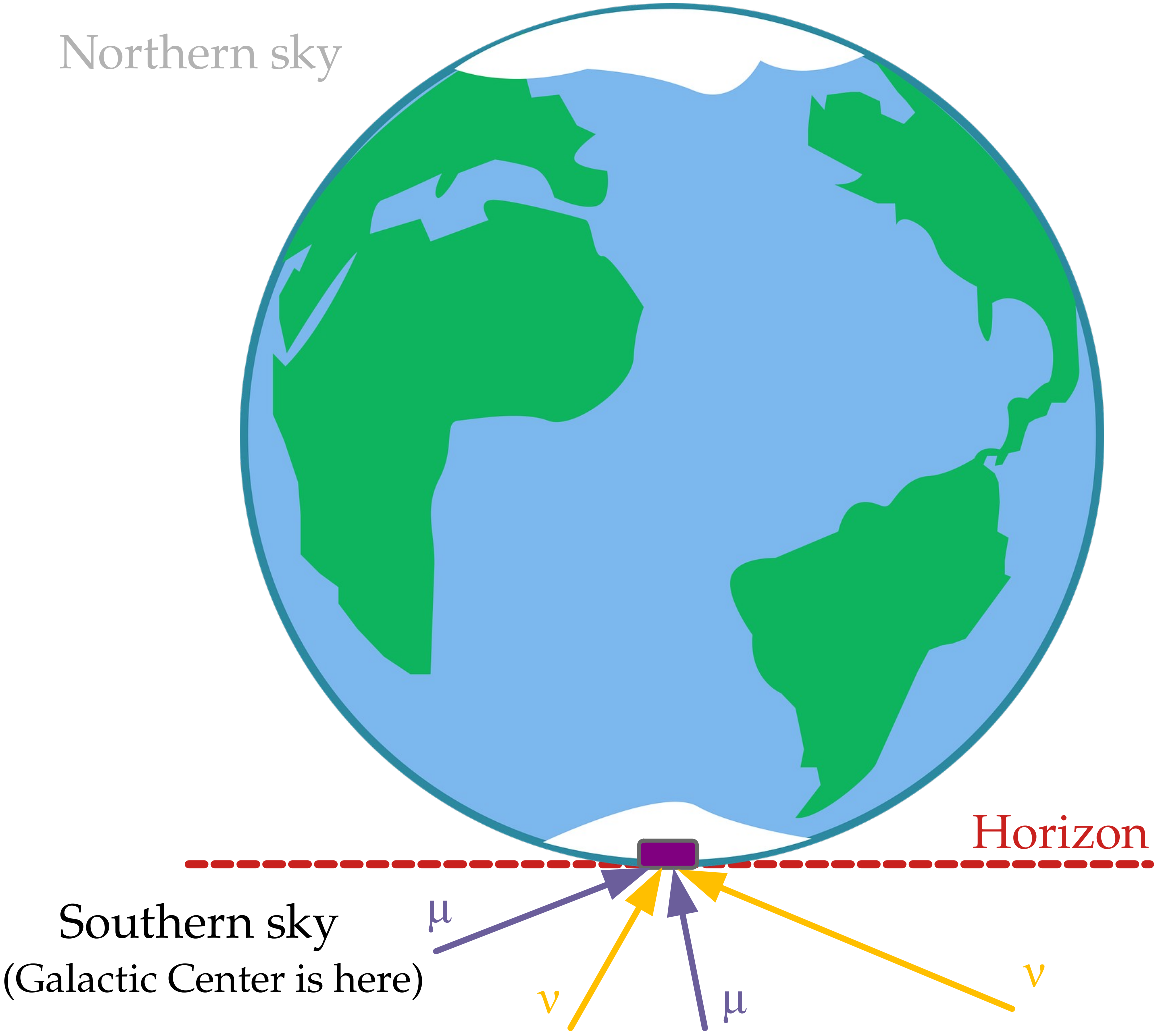
Neutrinos from the Northern sky

≡

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

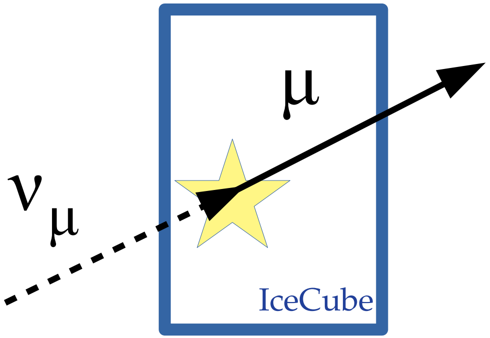


Neutrinos from the Southern sky
≡
Downgoing neutrinos

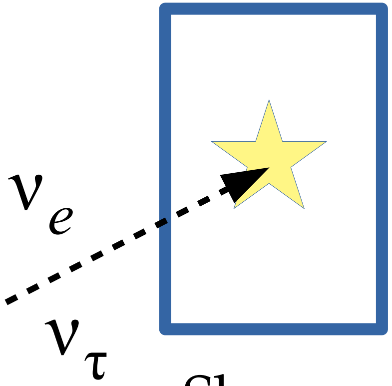
- Need to mitigate atmospheric muons and ν:
  - Use higher-energy events
  - Use starting a self-veto
- Dominated by astrophysical ν (*after* event selection)
- Low statistics
- Good for measuring the diffuse flux of astrophysical ν

Contained *vs.* uncontained events

Contained events



Starting track

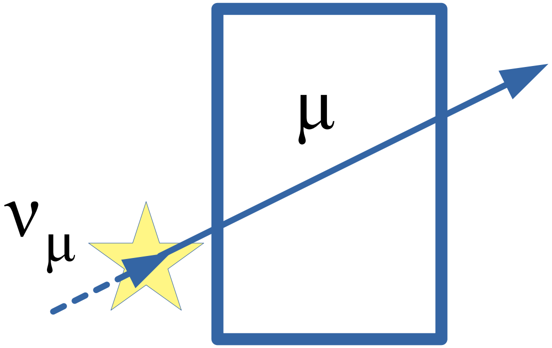


Shower

Pro: Clean determination of E_ν

Con: Few events (~100 in 10 yr)

Through-going muons



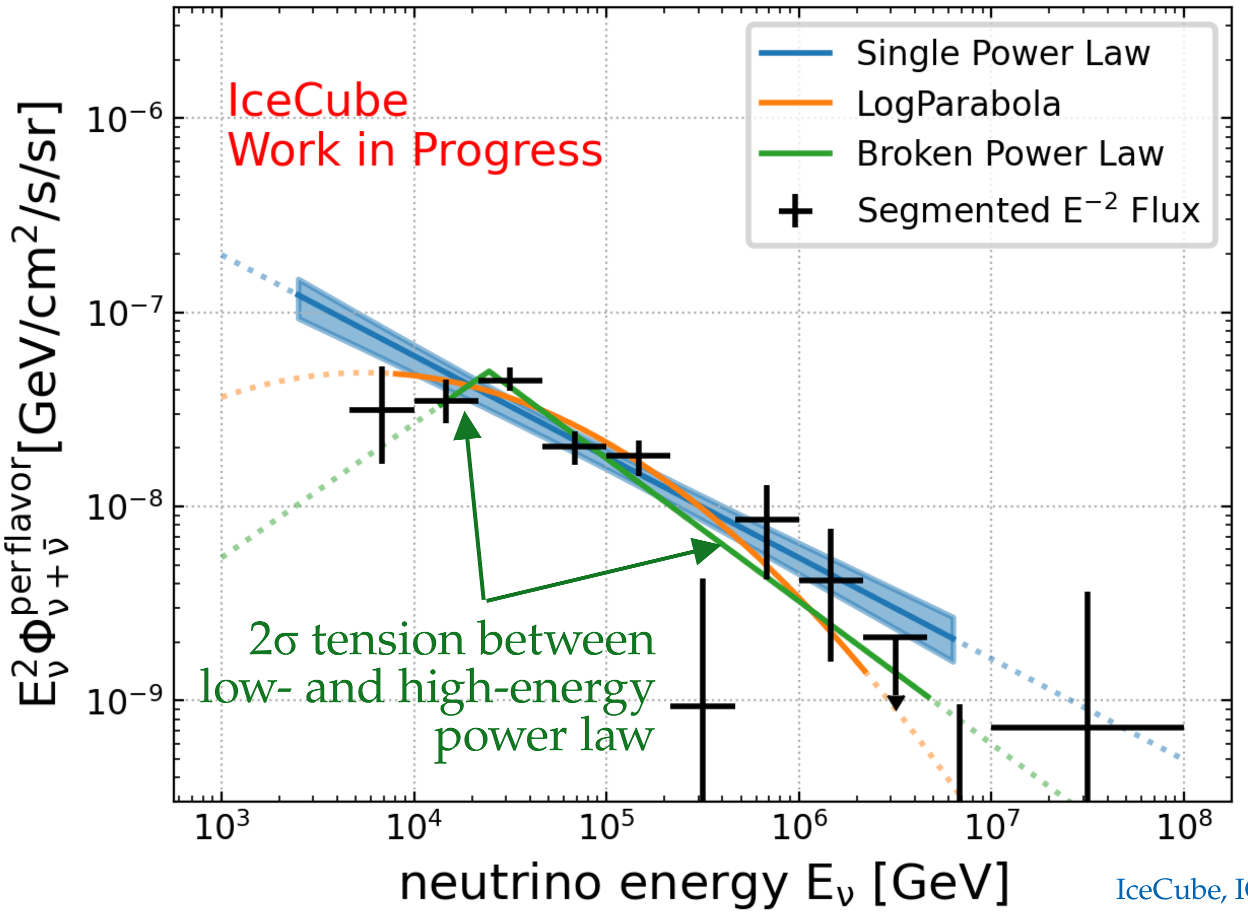
Through-going muon

Pro: Lots of events (few 100k)

Con: Uncertain estimates of E_ν

Neutrino energy spectrum

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

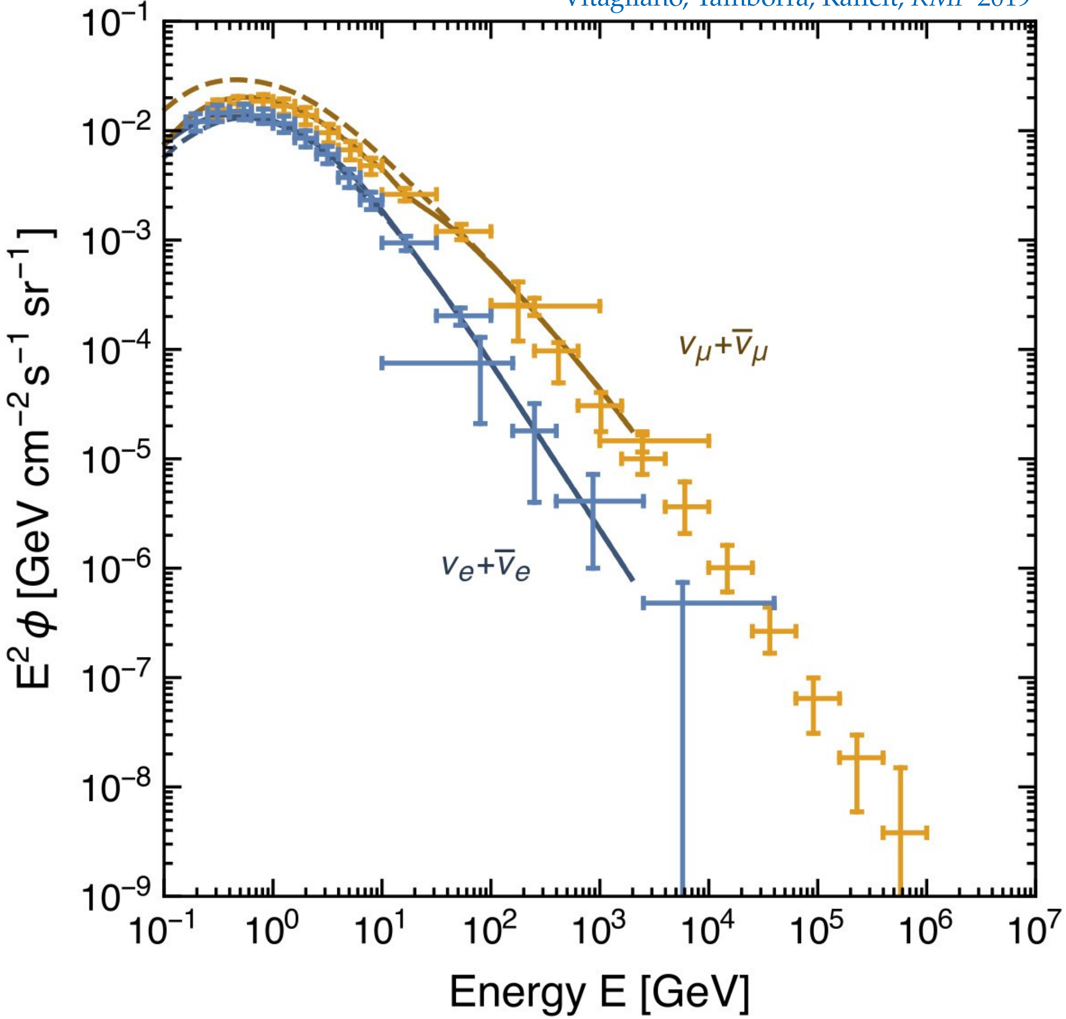


Different spectra might reflect different source populations

IceCube, ICRC 2023

High-energy neutrinos from the Galactic Plane

Vitagliano, Tamborra, Raffelt, *RMP* 2019



See also: Beacom & Candia, *JCAP* 2004

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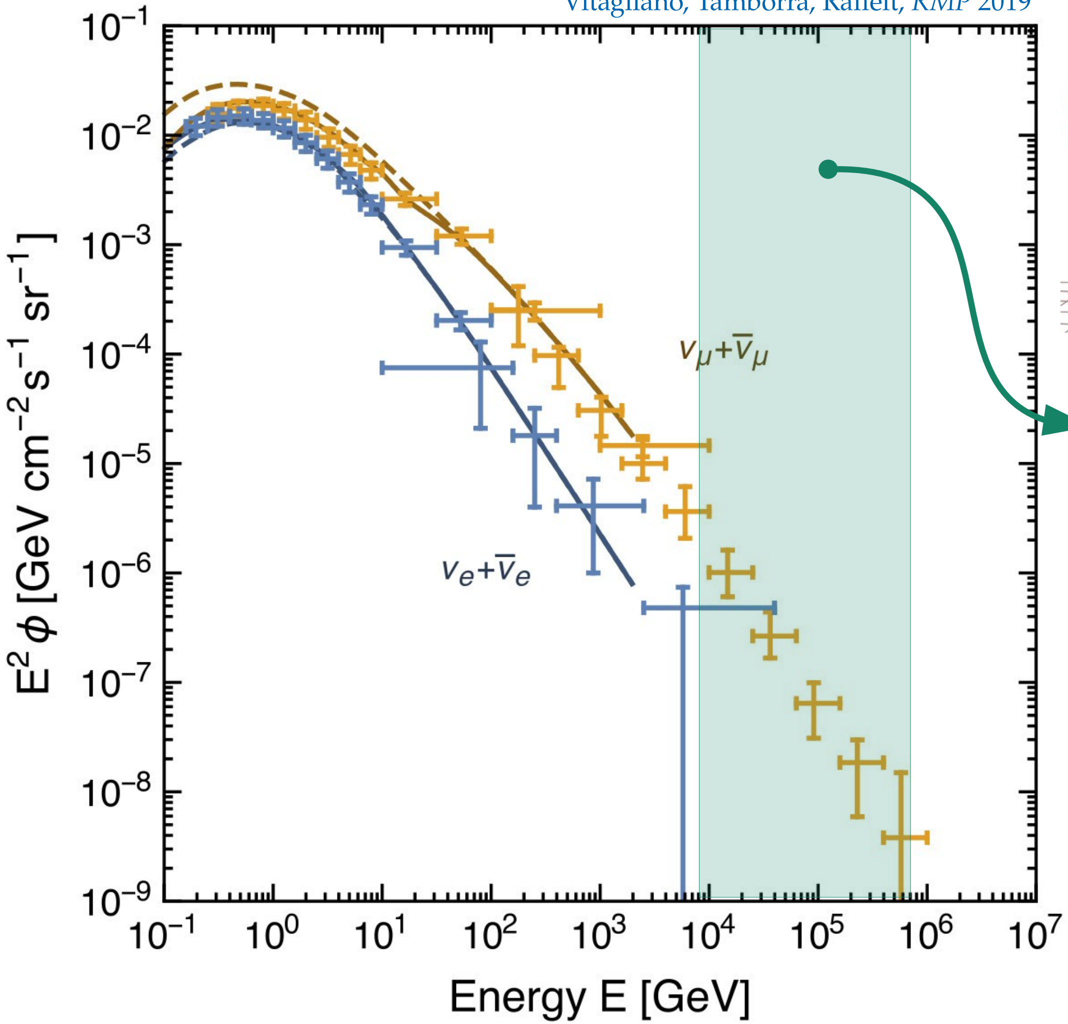

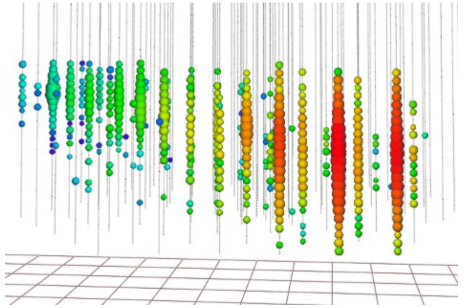

Search for **>10-TeV** astrophysical ν

- Use **muon tracks**
- Pointing accuracy: ~1°
- Atm. bg. is mostly ν_μ
- Self-veto screens for atm. muons to cut ν bg.

See also: Beacom & Candia, *JCAP* 2004

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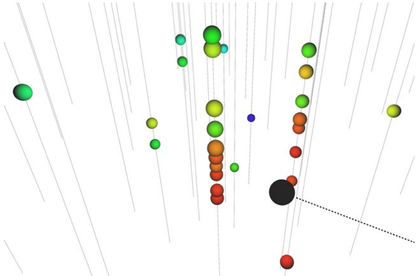

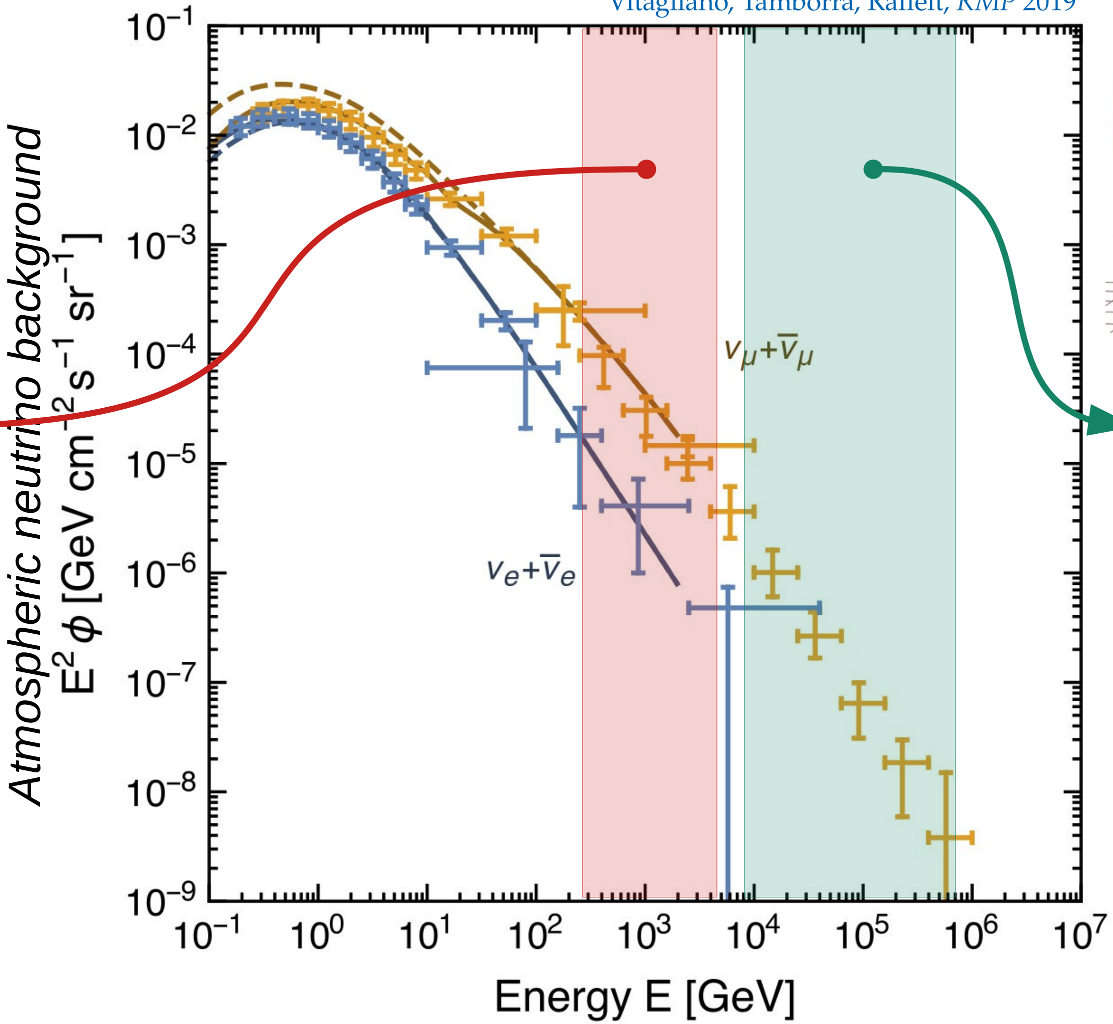

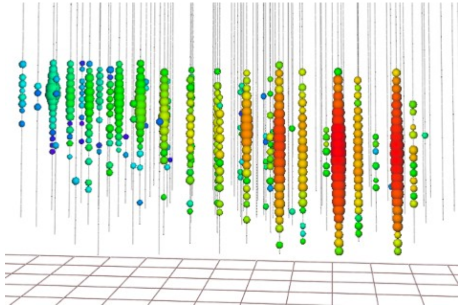

Search for **TeV** astrophysical ν

- But GP ν are TeV
- Use **cascades**
- Atm. ν_e bg. ×10 lower
- Bg.-to-signal: 10^8:1
- *Deep learning retains 20 times more events, ×2 better angular res.*

Search for **>10-TeV** astrophysical ν

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Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos $\propto$ energy in gamma rays

$$\int_0^\infty \mathrm{d}E_\nu E_\nu F_\nu(E_\nu) = \frac{1}{8}\left[1 - \left(1 - \langle x_{p\to\pi}\rangle\right)^{\tau_{p\gamma}}\right] \frac{f_p}{f_e} \int_{1\ \mathrm{keV}}^{10\ \mathrm{MeV}} \mathrm{d}E_\gamma E_\gamma F_\gamma(E_\gamma)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

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Fraction of total p energy
given to pions

E. Waxman & J. Bahcall, *PRL* 1997
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Fraction of *p* energy given to π in one interaction (~20%)

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Fraction of total p energy given to pions

Baryonic loading

Optical depth to $p\gamma$: $$\tau_{p\gamma} = \left(\frac{L_\gamma^{\mathrm{iso}}}{10^{52}\mathrm{erg s}^{-1}}\right)\left(\frac{0.01}{t_\mathrm{v}}\right)\left(\frac{300}{\Gamma}\right)^4\left(\frac{\mathrm{MeV}}{\epsilon_{\gamma,\mathrm{break}}}\right)$$

E. Waxman & J. Bahcall, *PRL* 1997
D. Guetta *et al.*, *Astropart. Phys.* 2004

Flavor-transition probability

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U^*_{e1} & U^*_{e2} & U^*_{e3}\\ U^*_{\mu1} & U^*_{\mu2} & U^*_{\mu3}\\ U^*_{\tau1} & U^*_{\tau2} & U^*_{\tau3}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$
- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

$$U = \underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}}_{\text{Atmospheric}} \underbrace{\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}}_{\text{Cross mixing}} \underbrace{\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}} \underbrace{\begin{pmatrix}e^{i\alpha_1/2} & 0 & 0\\ 0 & e^{i\alpha_2/2} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Majorana CP phases}}$$

- Probability for $\nu_\alpha \rightarrow \nu_\beta$: $$P_{\nu_\alpha\rightarrow\nu_\beta} = \delta_{\alpha\beta} - 4\sum_{i>j}\mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\left(\Delta m^2_{ij}\frac{L}{4E}\right) + 2\sum_{i>j}\mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\left(\Delta m^2_{ij}\frac{L}{2E}\right)$$

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$\theta_{23} \approx 48°$
$\theta_{13} \approx 9°$
$\theta_{12} \approx 34°$
$\delta \approx 222°$

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… But high-energy neutrinos oscillate *fast*

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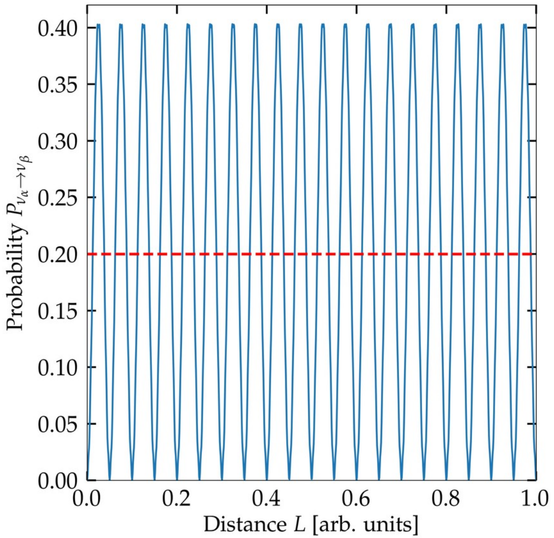

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

~ 8% of the way to Proxima Centauri
≪ Distance to Galactic Center (8 kpc)
≪ Distance to Andromeda (1 Mpc)
≪ Cosmological distances (few Gpc)

We cannot resolve oscillations, so we use instead the average probability:

$$\langle P_{\nu_\alpha \to \nu_\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 \, |U_{\beta i}|^2$$

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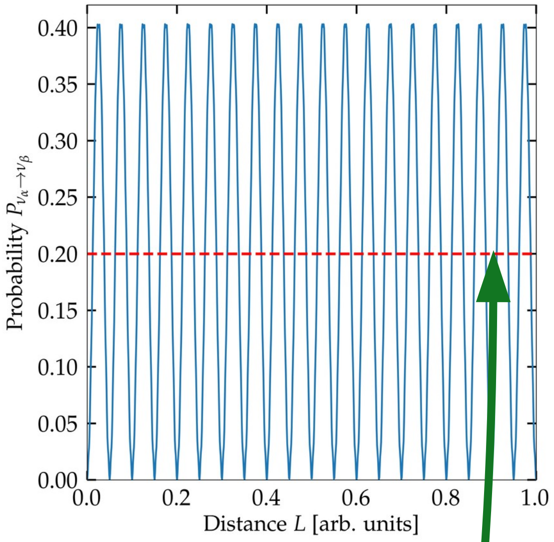

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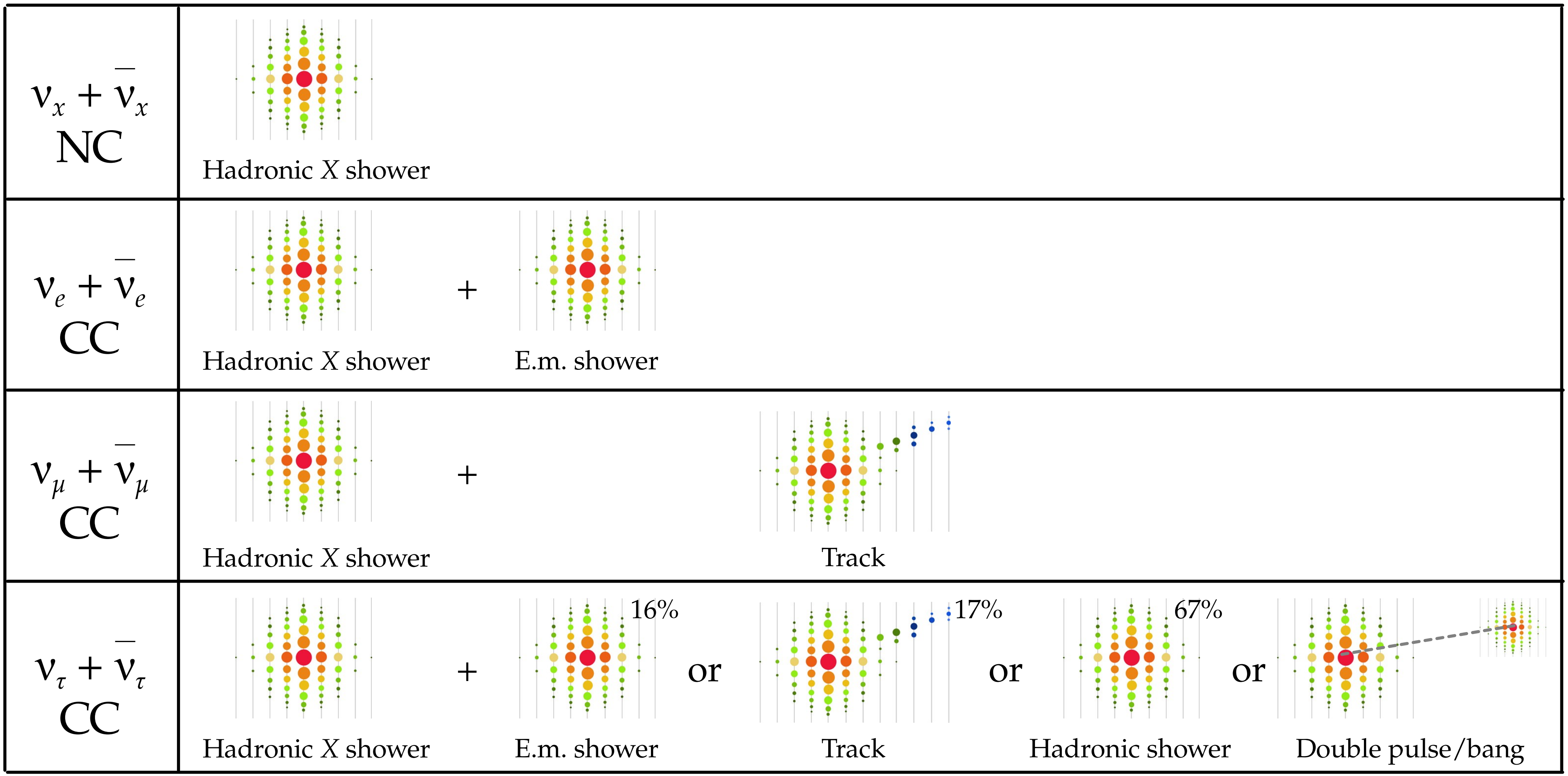
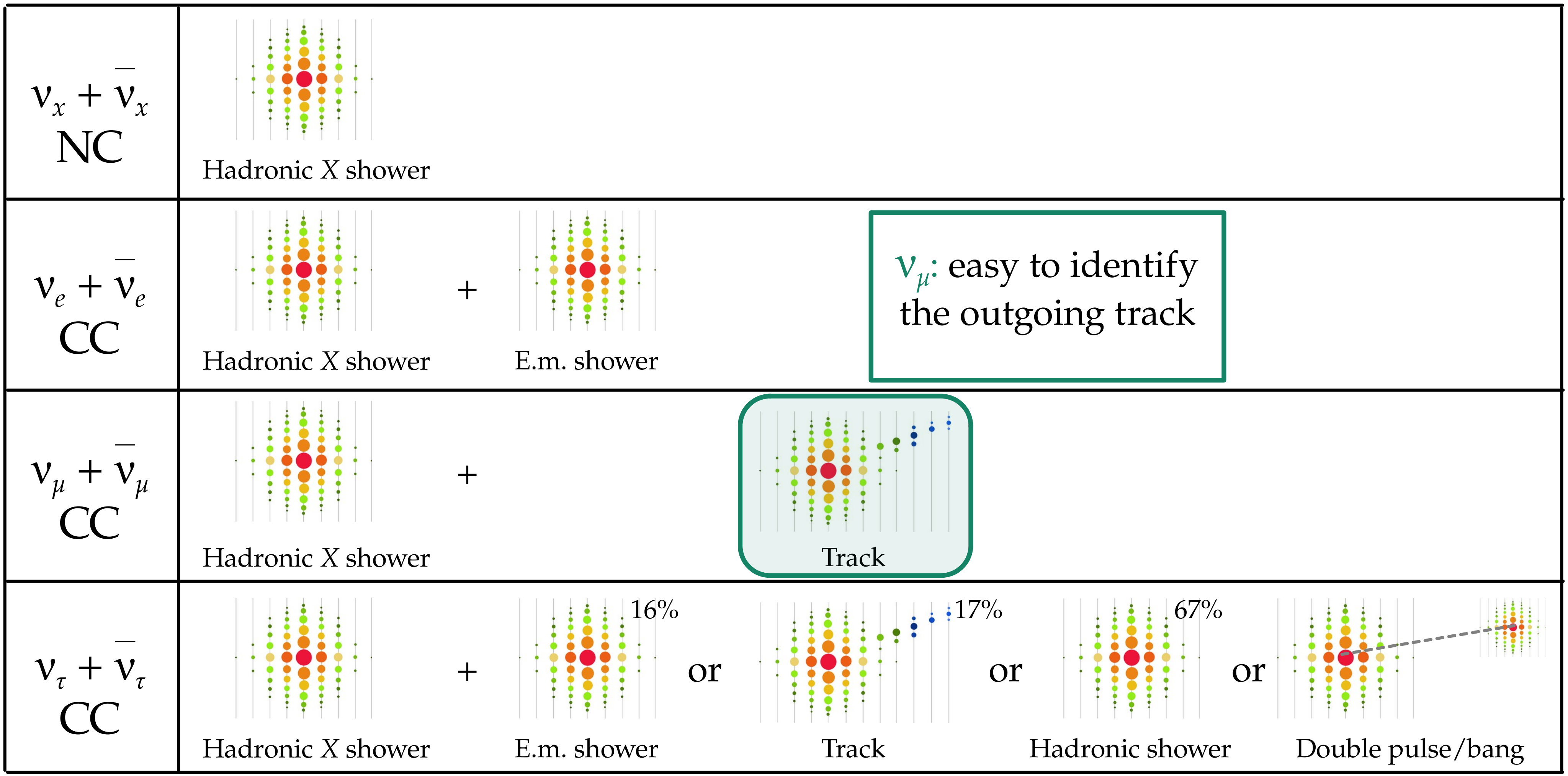
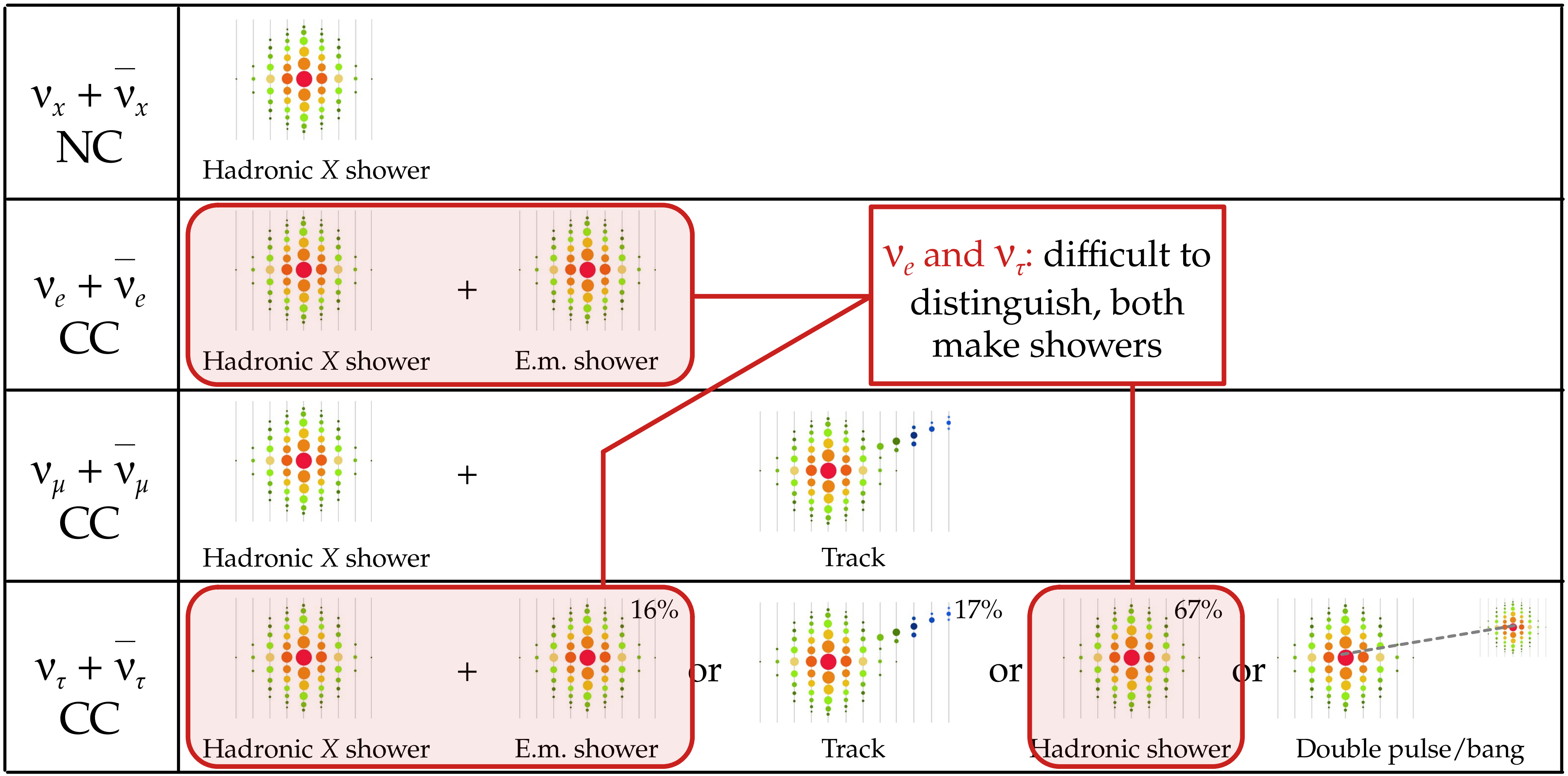
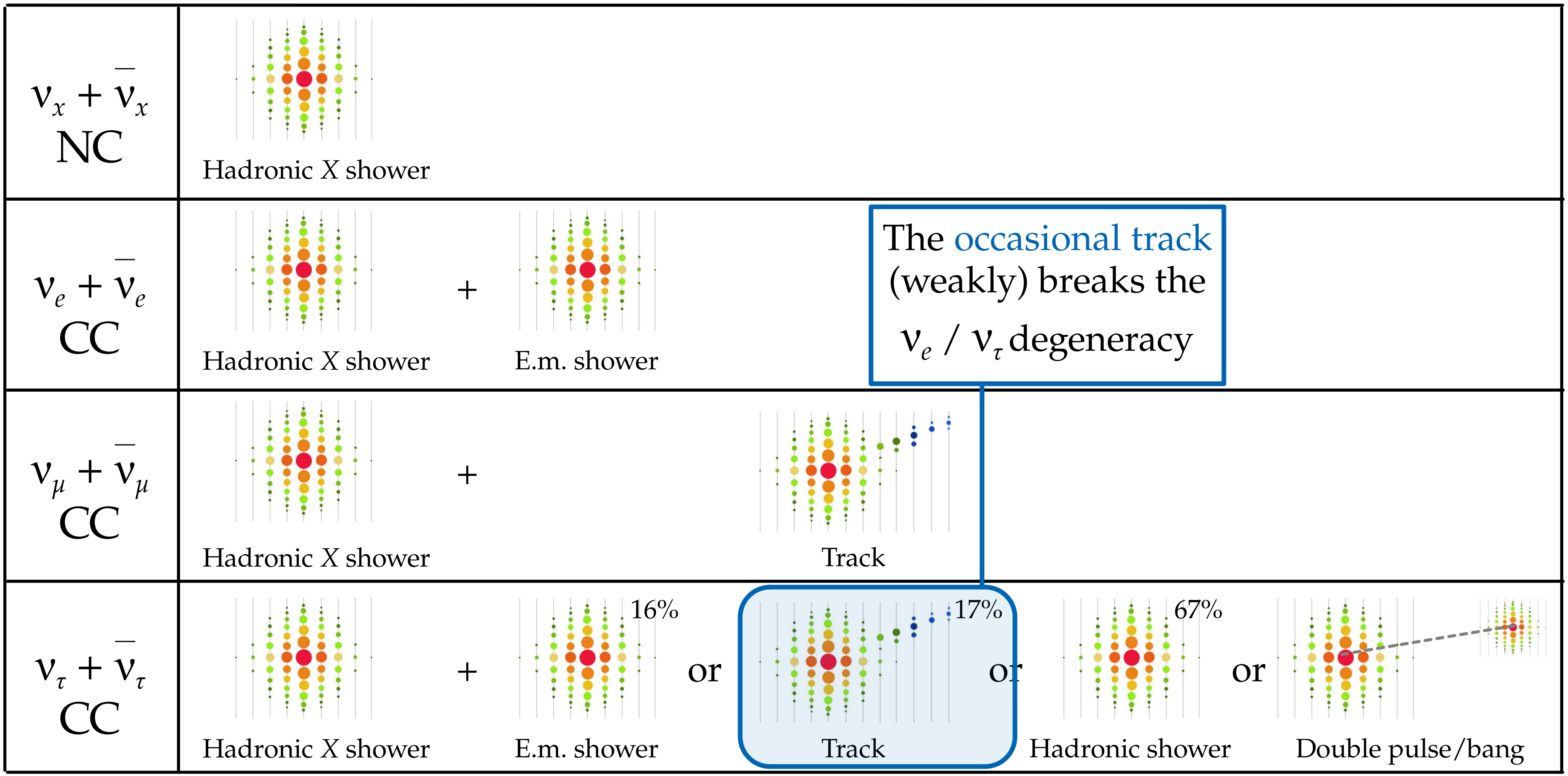

$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
or
Double pulse/bang



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


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



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

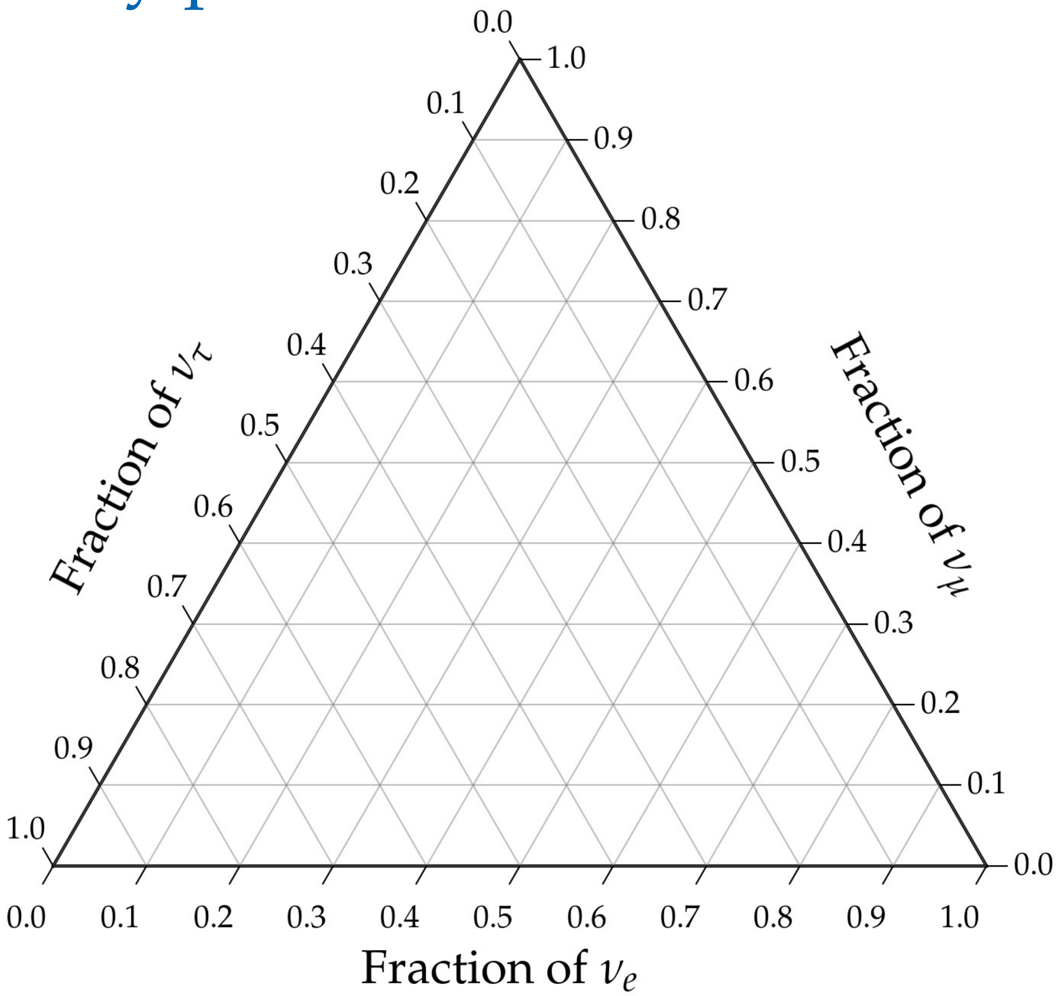
Quick aside: how to read a ternary plot

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

How to read it:

Follow the tilt of the tick marks

Always in this order: (f_e, f_μ, f_τ)



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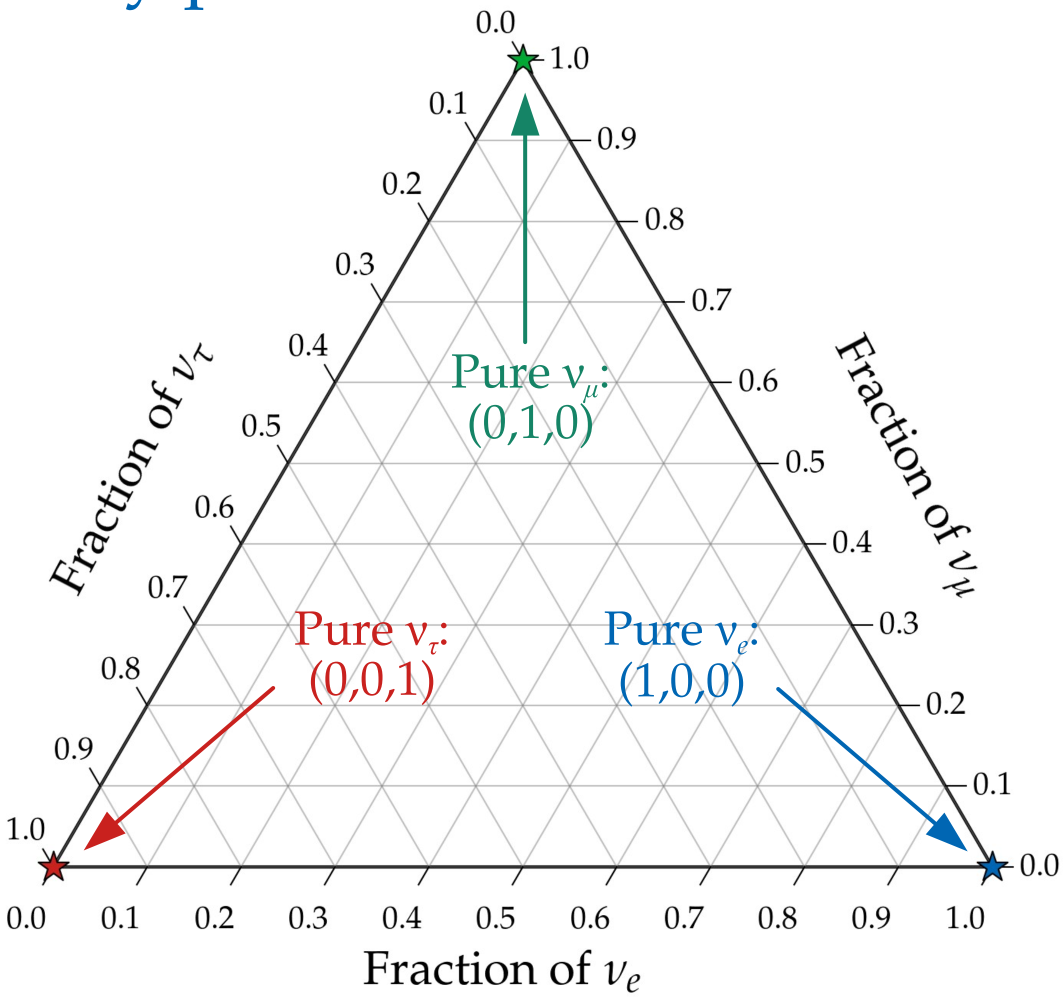

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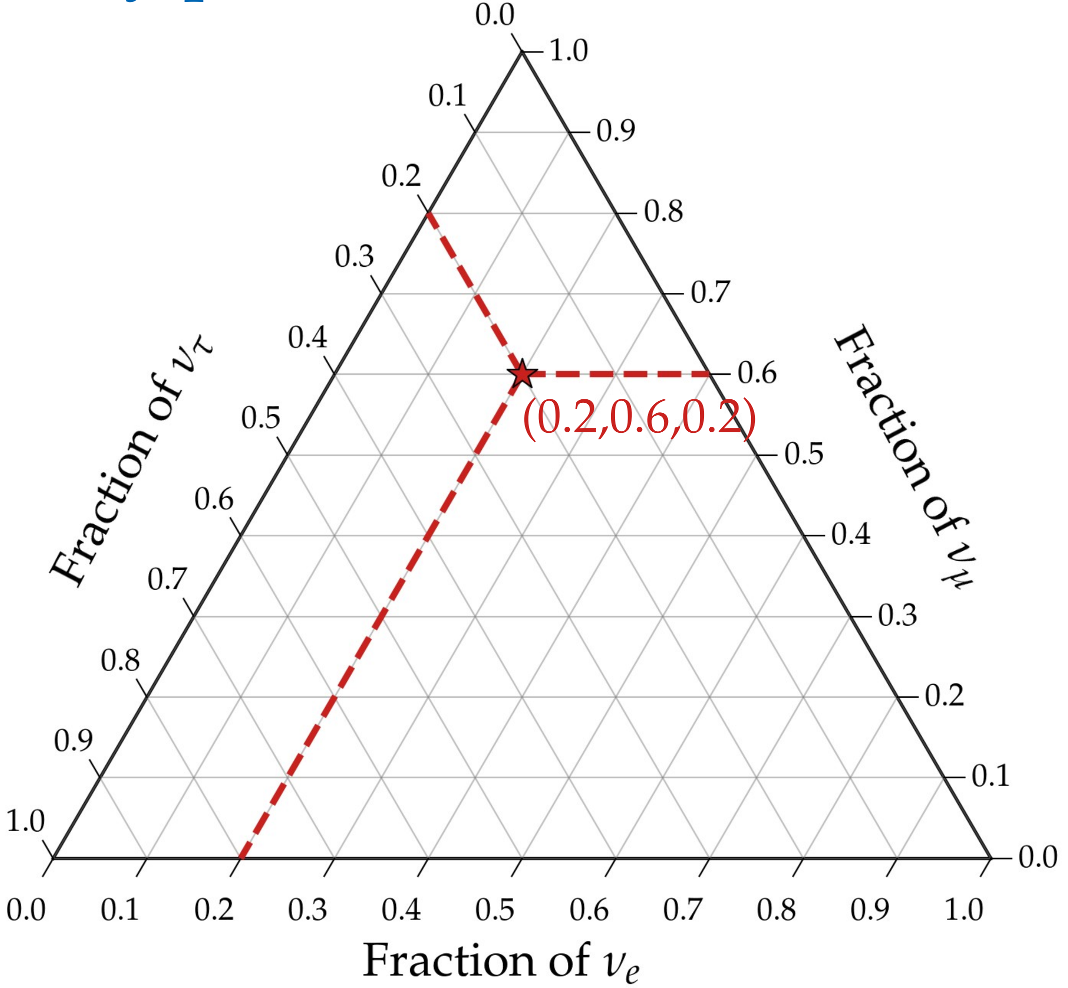

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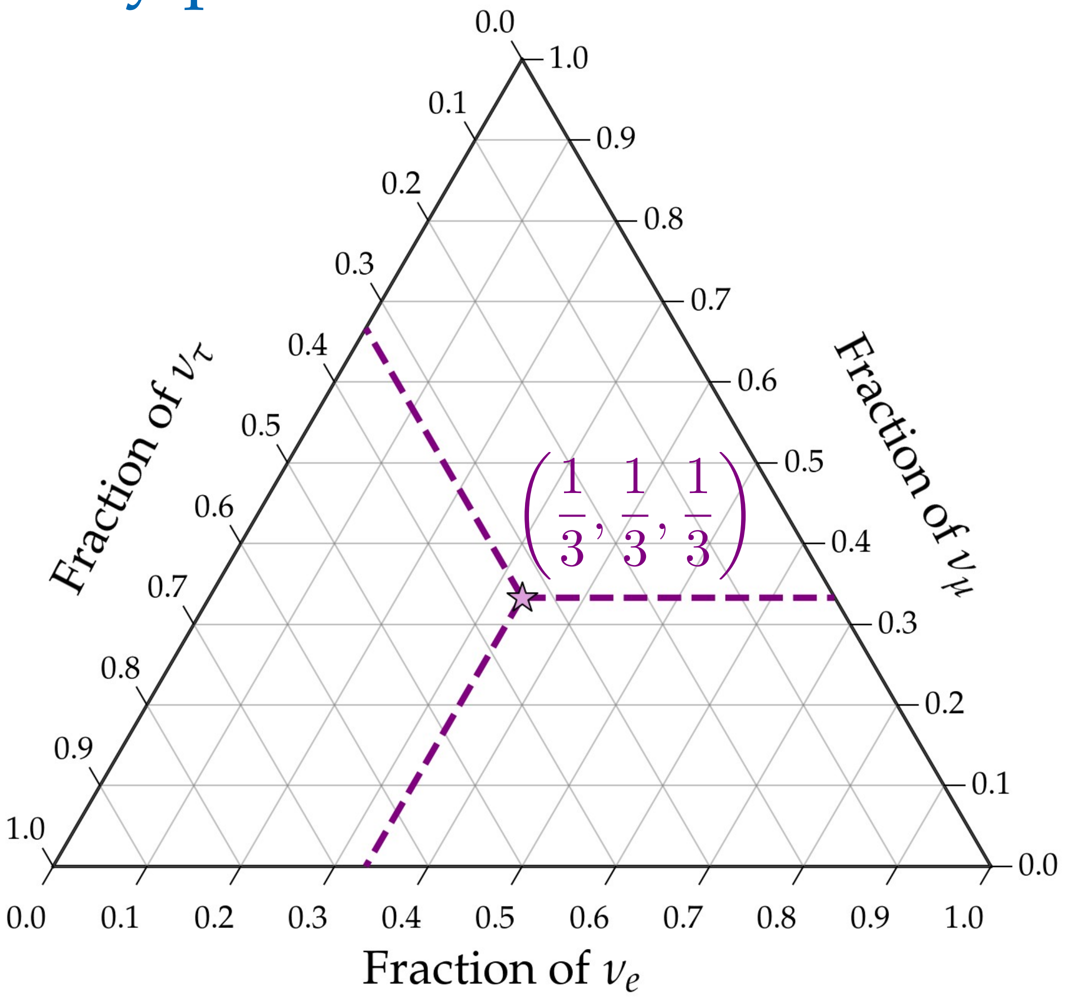

Measuring flavor composition: 2015–2040

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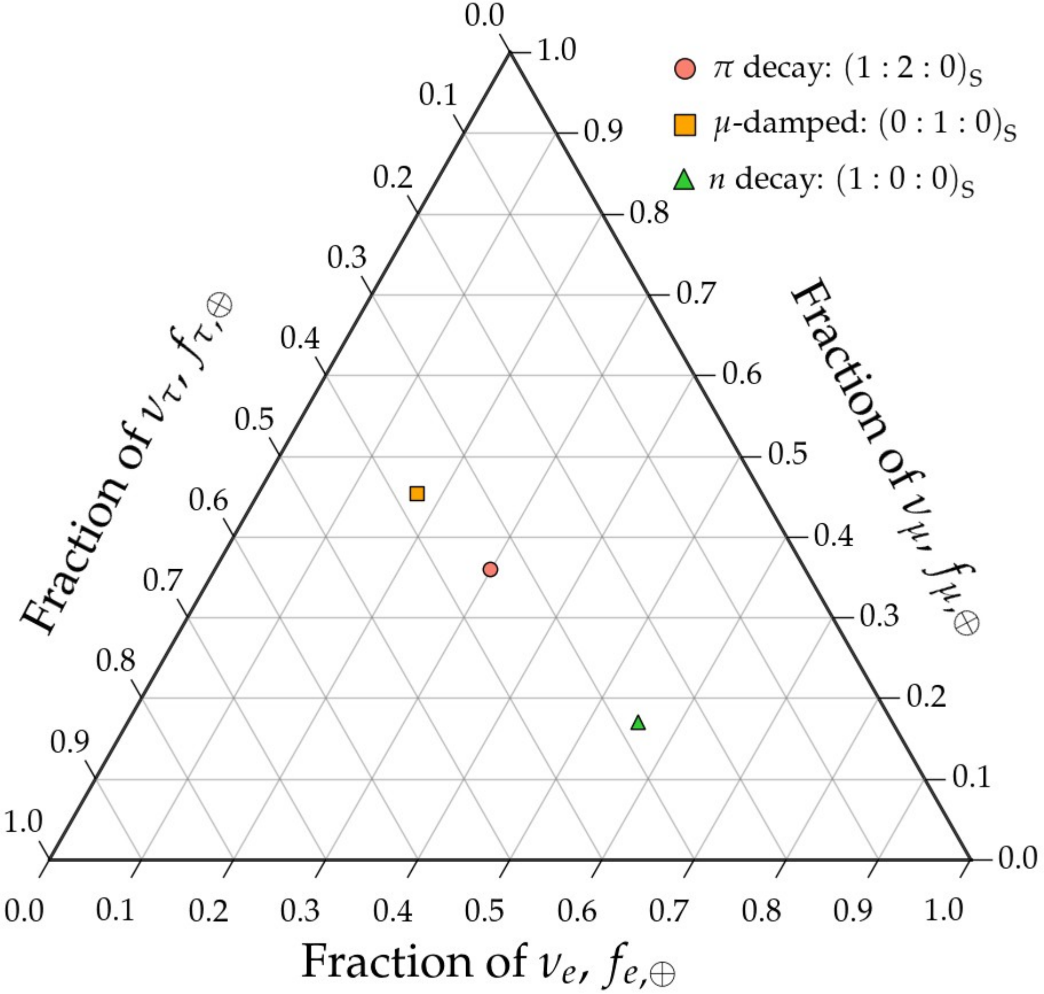

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

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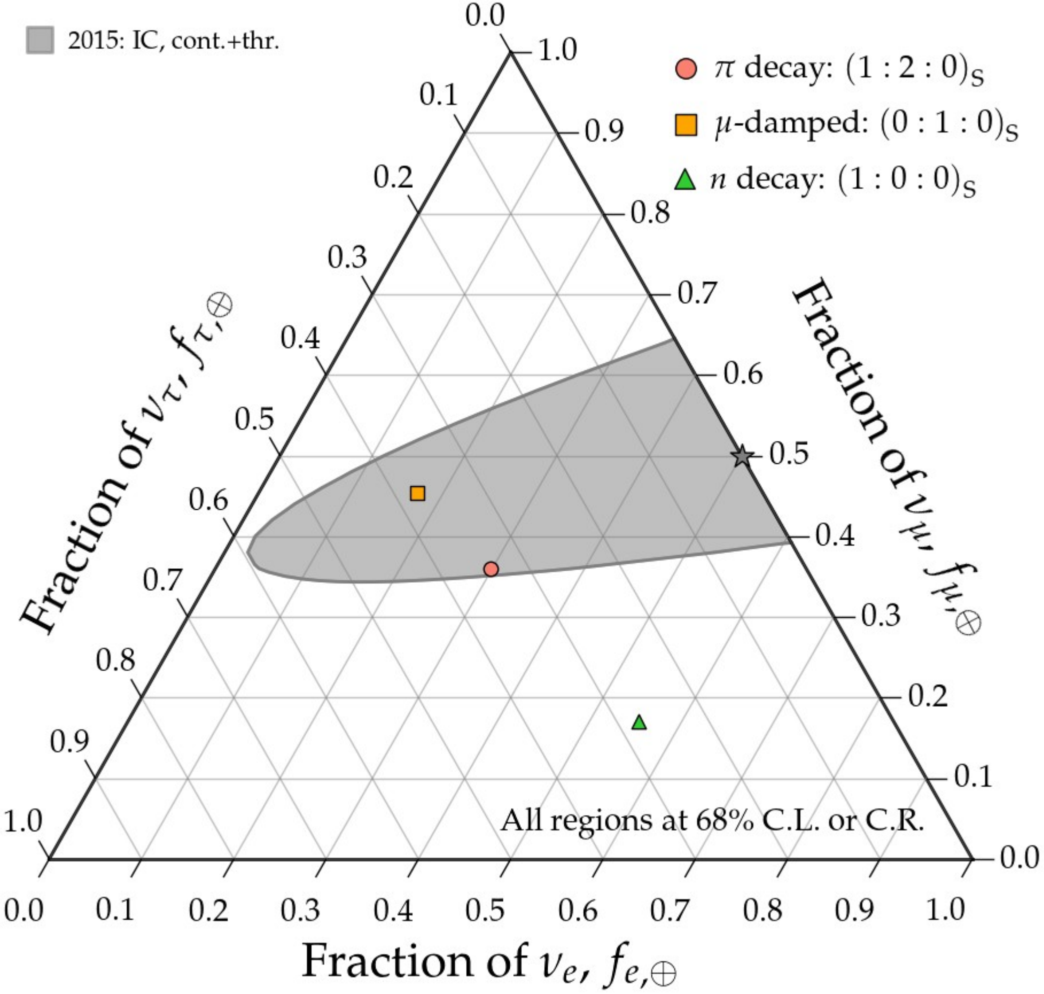

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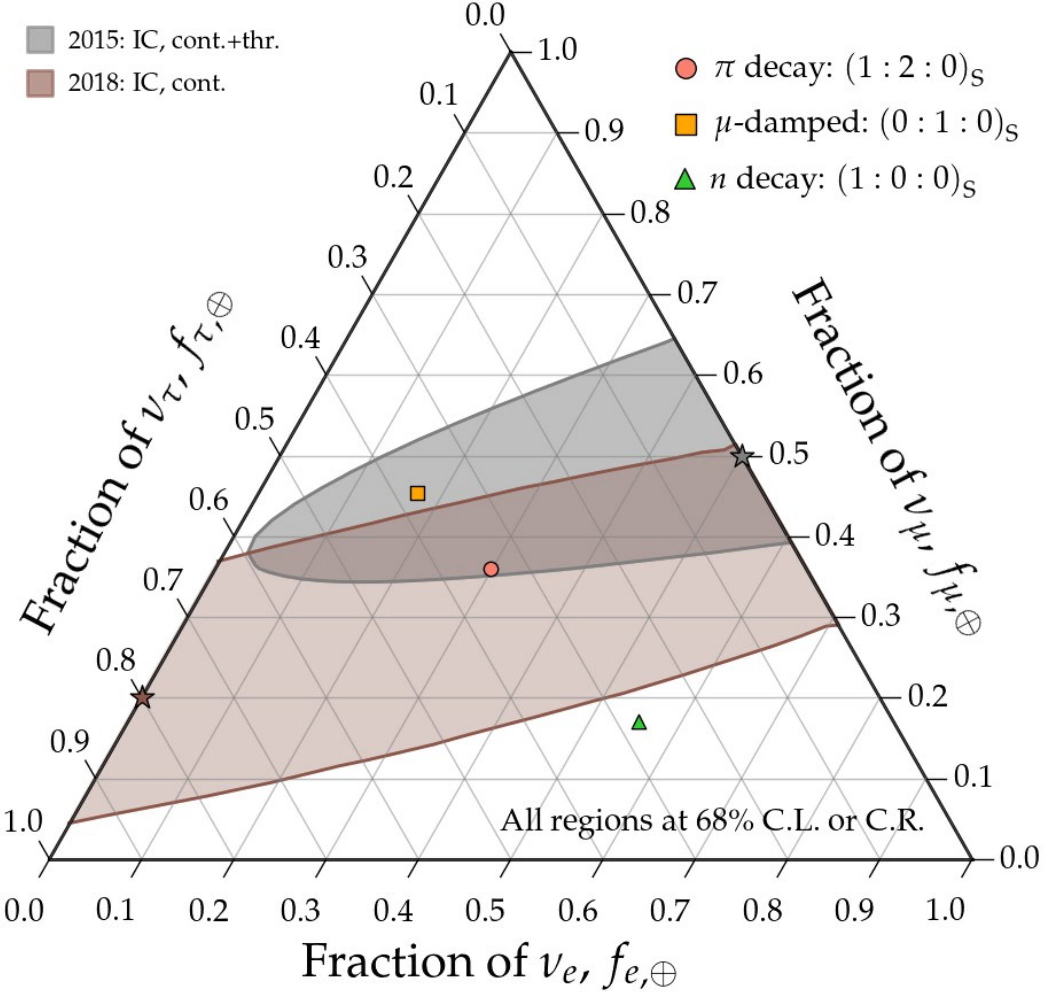

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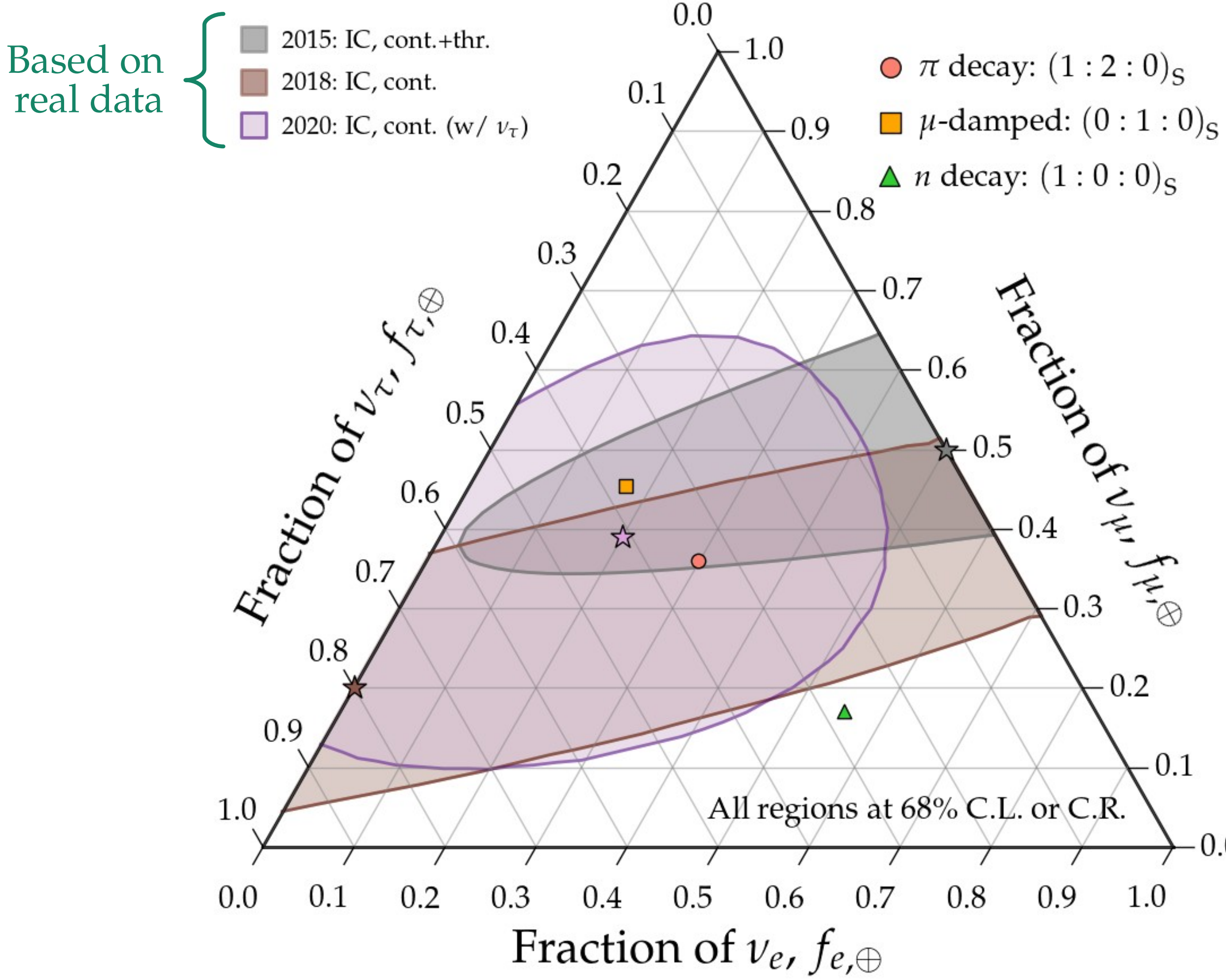

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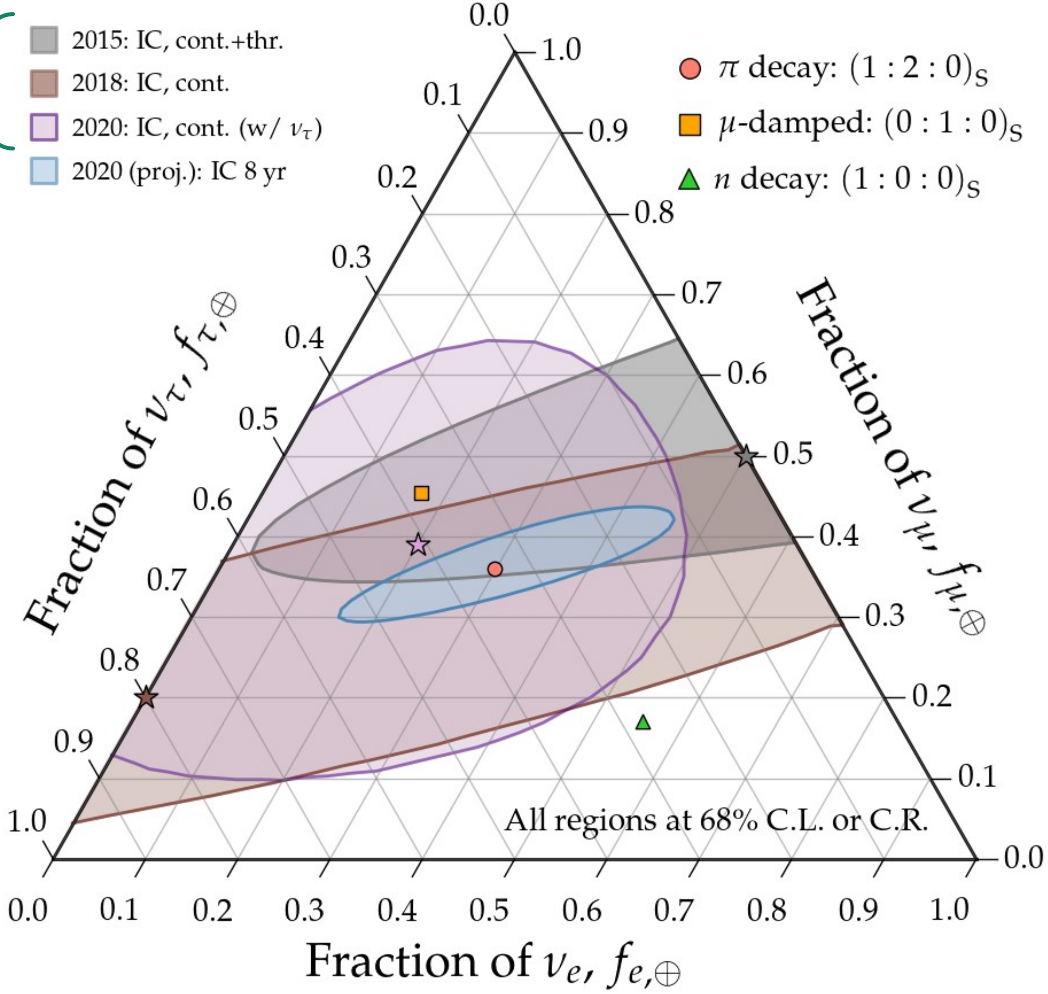
Measuring flavor composition: 2015–2040

Based on real data



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

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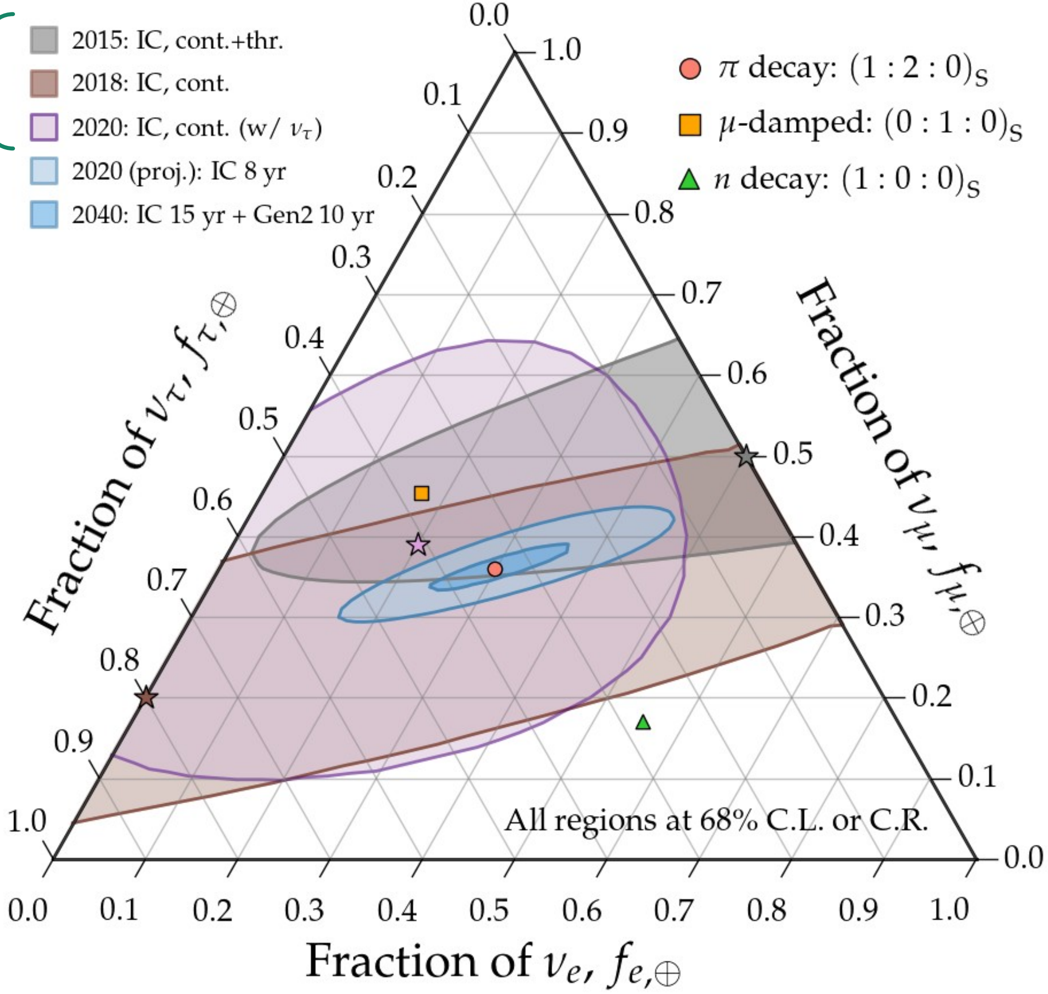
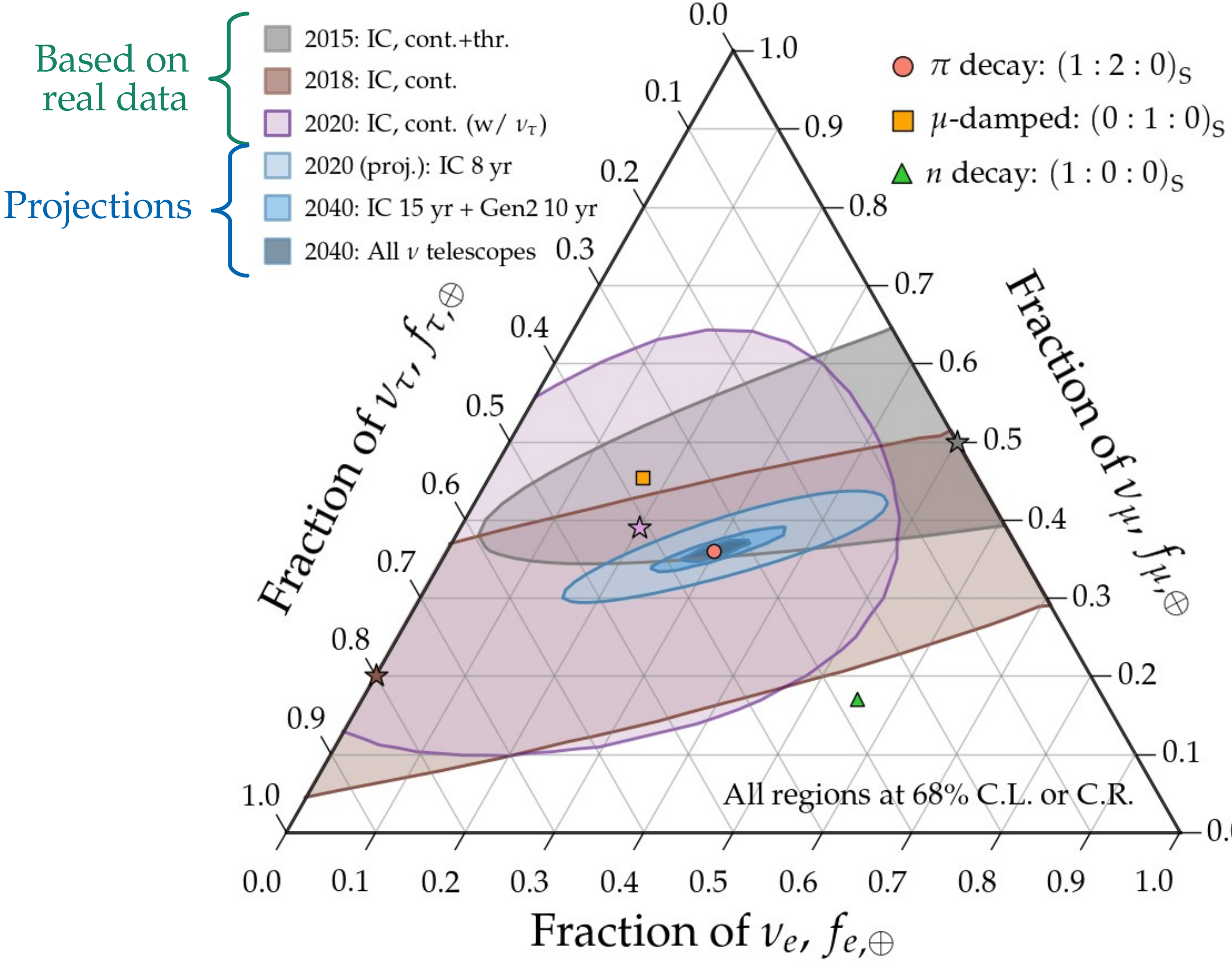


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

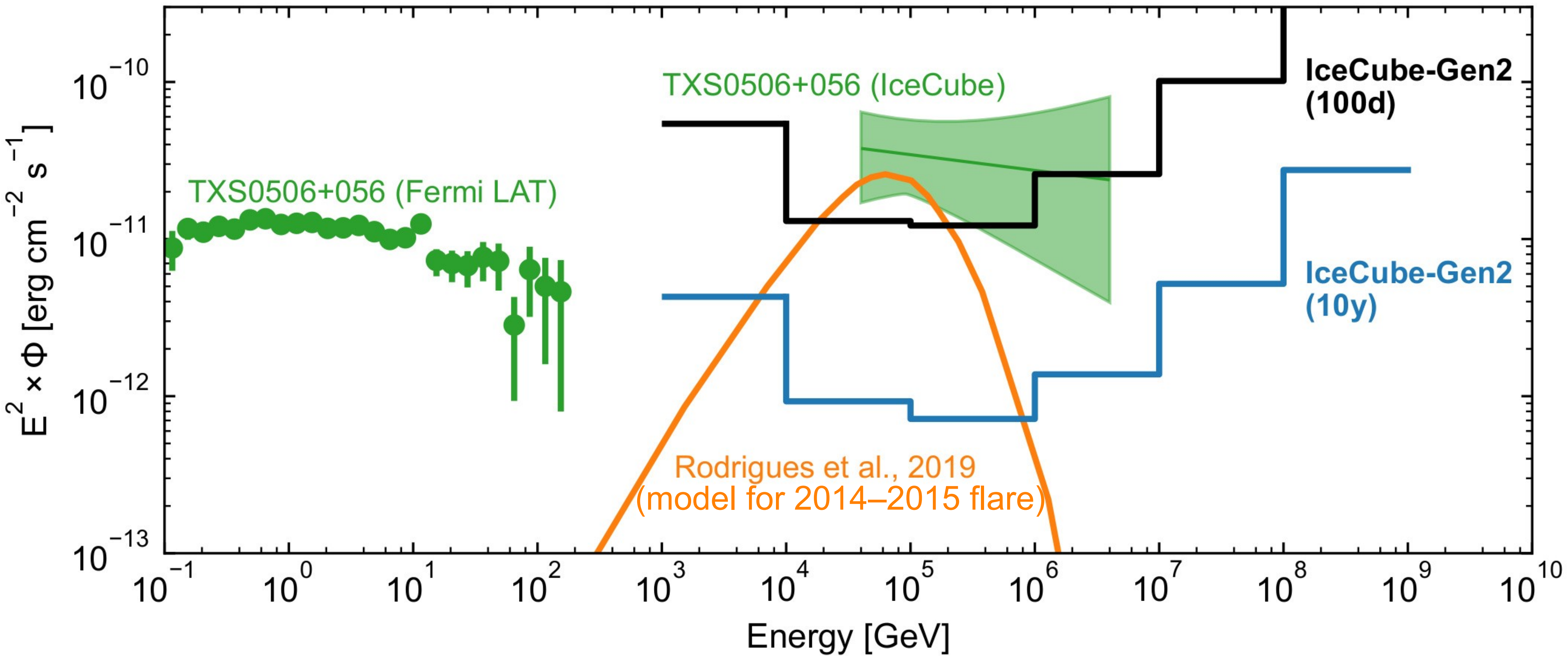
Measuring flavor composition: 2015–2040



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

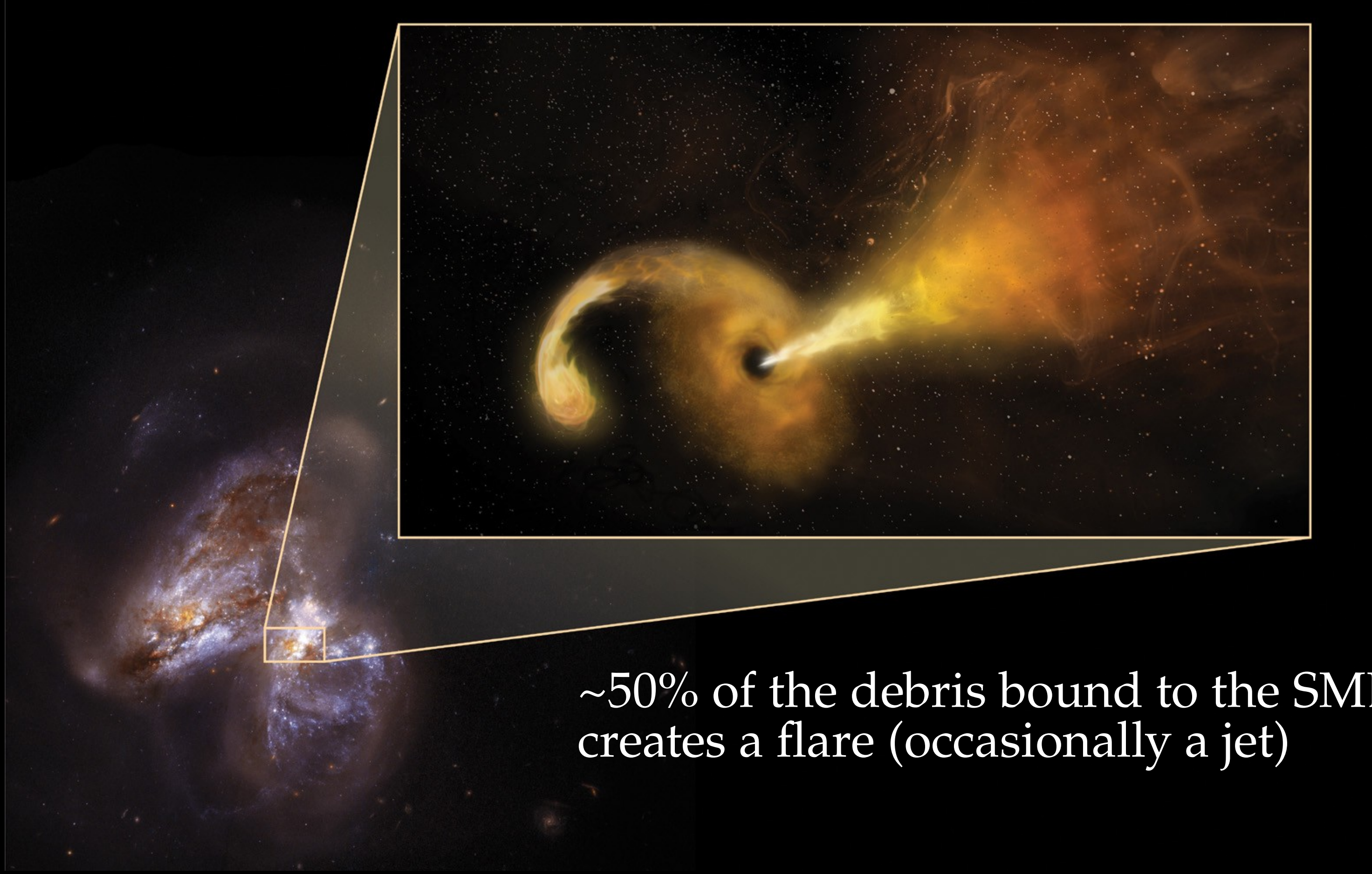
High-statistics neutrino blazar flares

Observing the 2014–2015 TXS 0506+056 at 5σ:



Tidal disruption events

Solar-mass star disrupted by SMBH (>10^5 $M_\odot$)



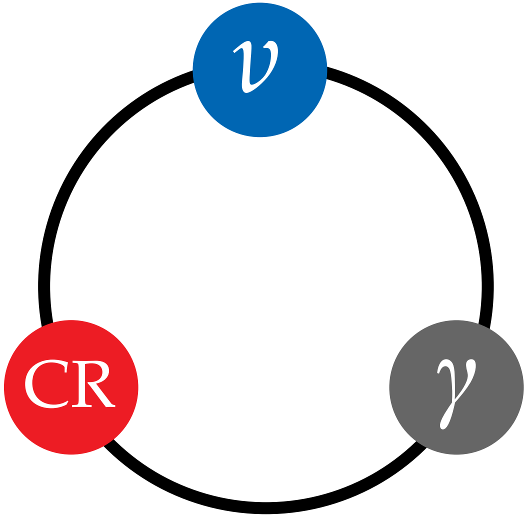
~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

Bright in gamma rays, bright in high-energy neutrinos (?)

Energy in neutrinos $\propto$ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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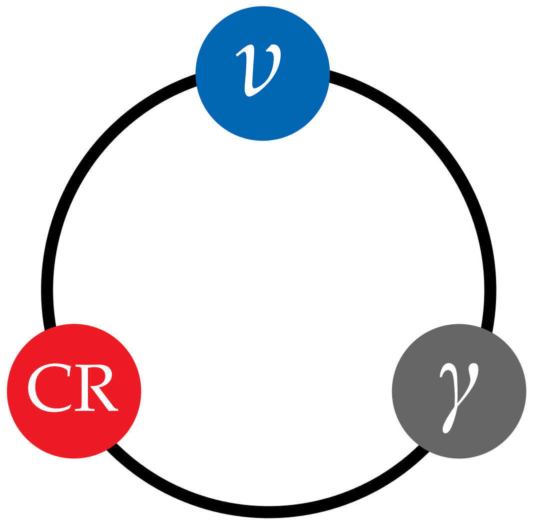
Fudge factors:
Source properties (*e.g.*, baryonic loading)
Particle effects (*e.g.*, ν-producing channels)



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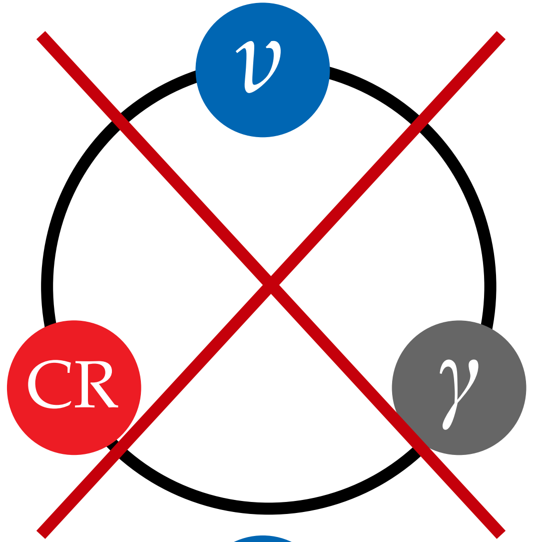
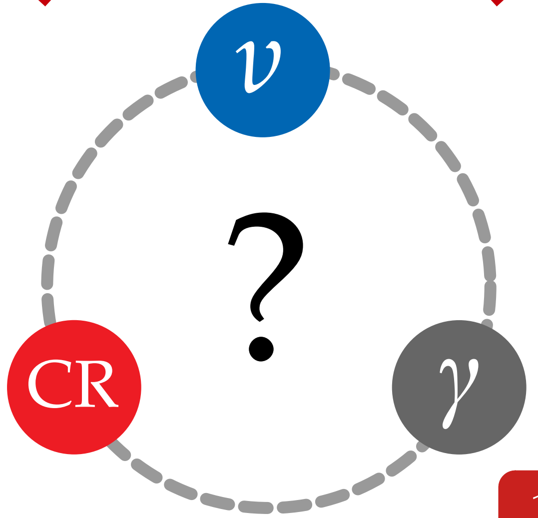


But the correlation between ν and γ may be more nuanced:

Gao, Pohl, Winter, *ApJ* 2017



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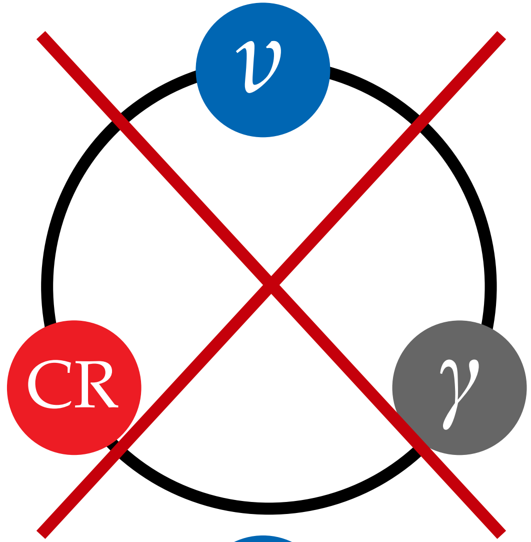


But the correlation between ν and γ may be more nuanced:

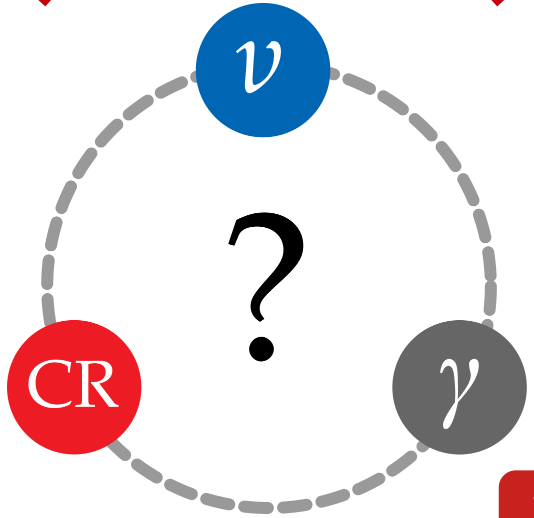
Gao, Pohl, Winter, *ApJ* 2017

Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

Murase, Guetta, Ahlers, *PRL* 2016

Modeling of *p*γ interactions & nuclear cascading
in the sources is complex and uncertain

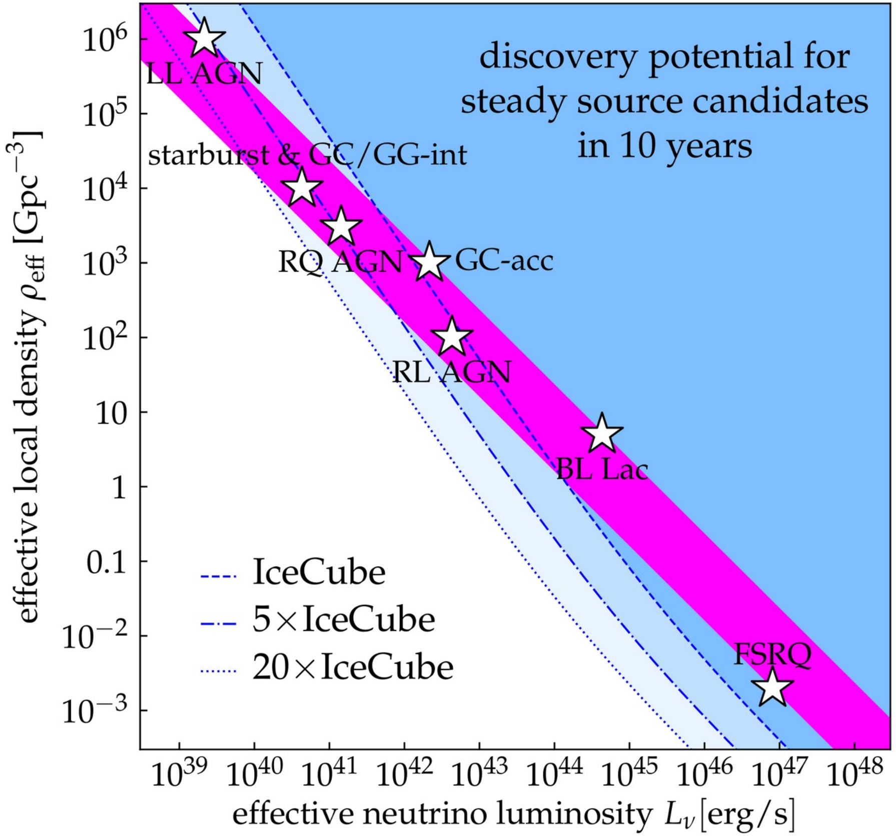
Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017



Source discovery potential: today and in the future

Accounts for the observed diffuse ν flux (lower/upper edge: rapid/no redshift evolution)

Closest source with $E^2\phi_{\nu_\mu+\bar{\nu}_\mu} = 10^{-9}\ \mathrm{GeV cm^{-2} s^{-1}}$



Ackermann, **MB** *et al.*, Astro2020 Survey (1903.04333) – See also: Silvestri & Barwick, *PRD* 2010; Murase & Waxman, *PRD* 2016

Measuring the high-energy *νN* cross section

Number of detected neutrinos (simplified for presentation):

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

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

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Downgoing neutrinos
(L short → no matter)

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

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

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

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Downgoing neutrinos
(L short → no matter)

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

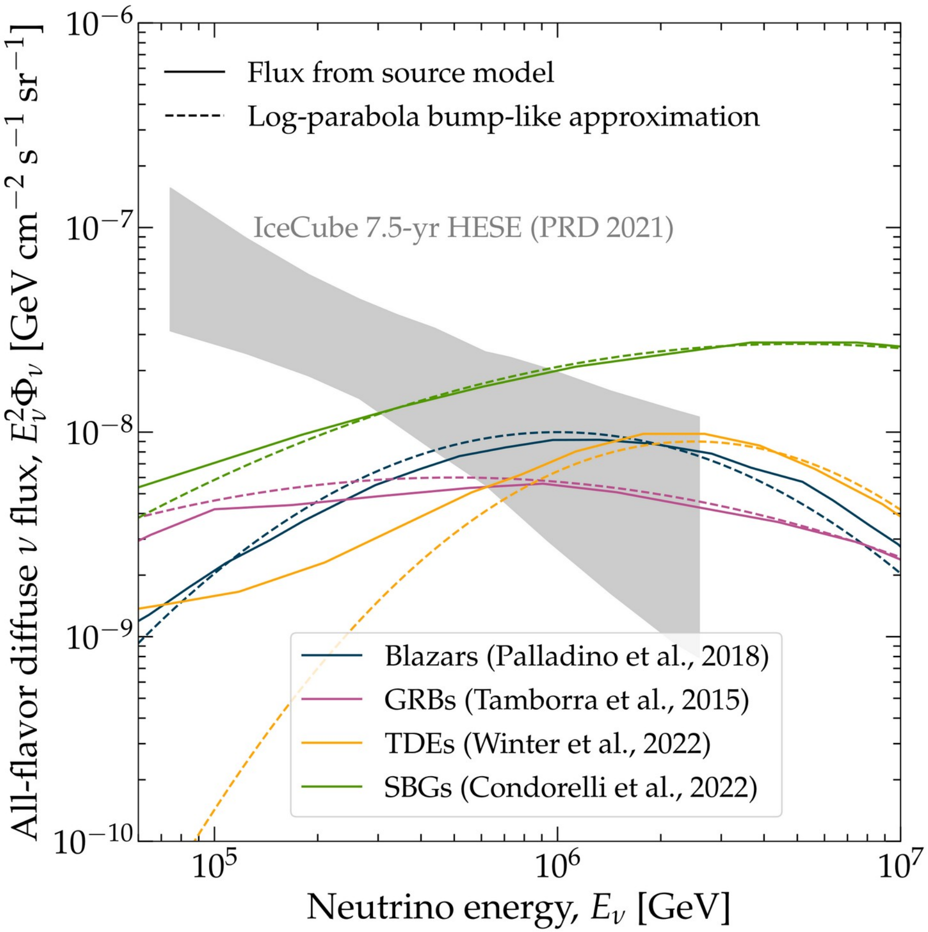
Upgoing neutrinos
(L long → lots of matter)

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

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

Bump-hunting in the diffuse flux of high-energy neutrinos

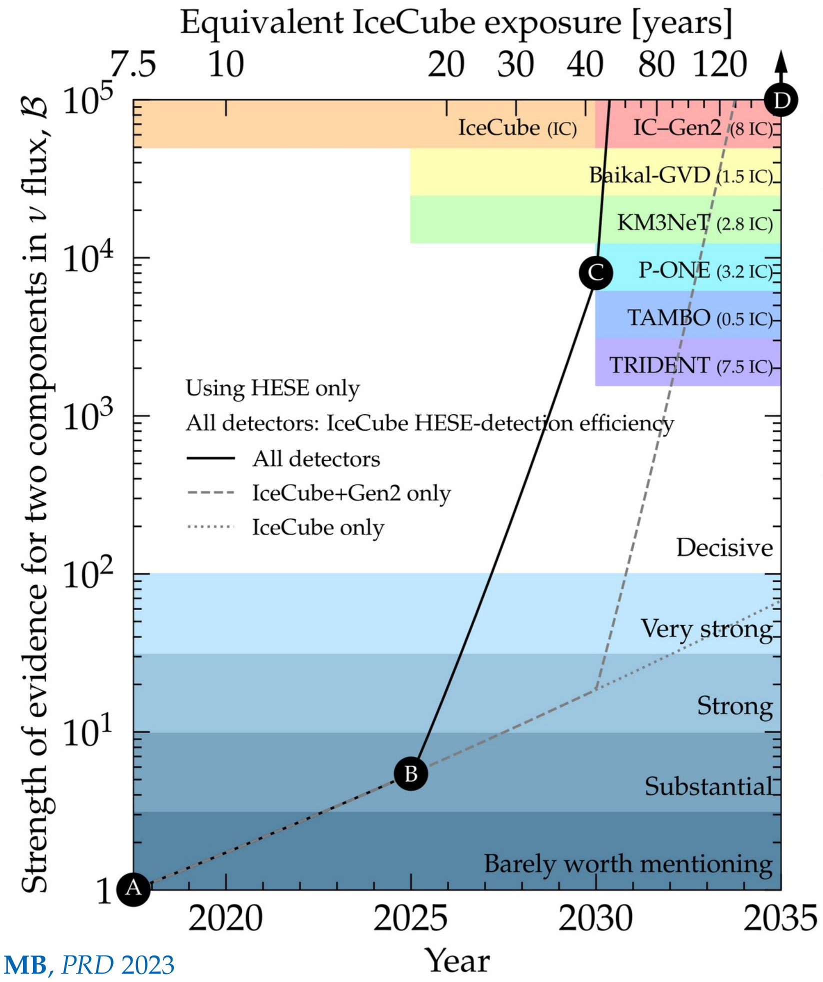
Bump-like spectra can reveal the presence of ν production via $p\gamma$:

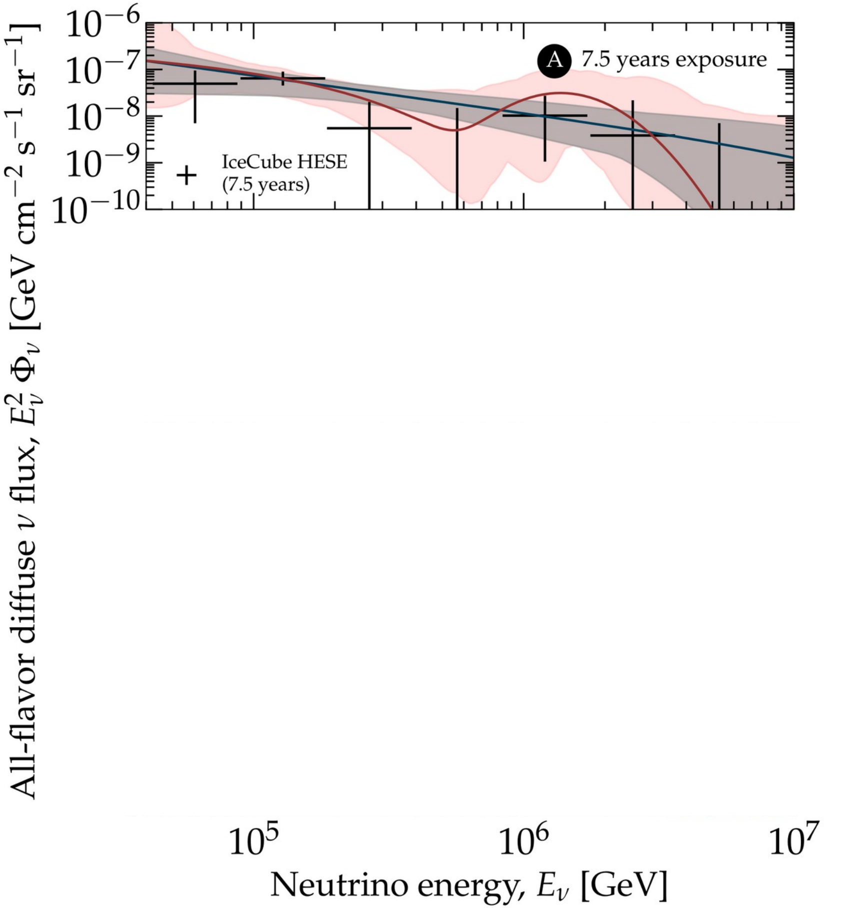


D. F. G. Fiorillo, **MB**, *PRD* 2023

Bump-hunting in the diffuse flux of high-energy neutrinos

Bump-like spectra can reveal the presence of ν production via $p\gamma$:





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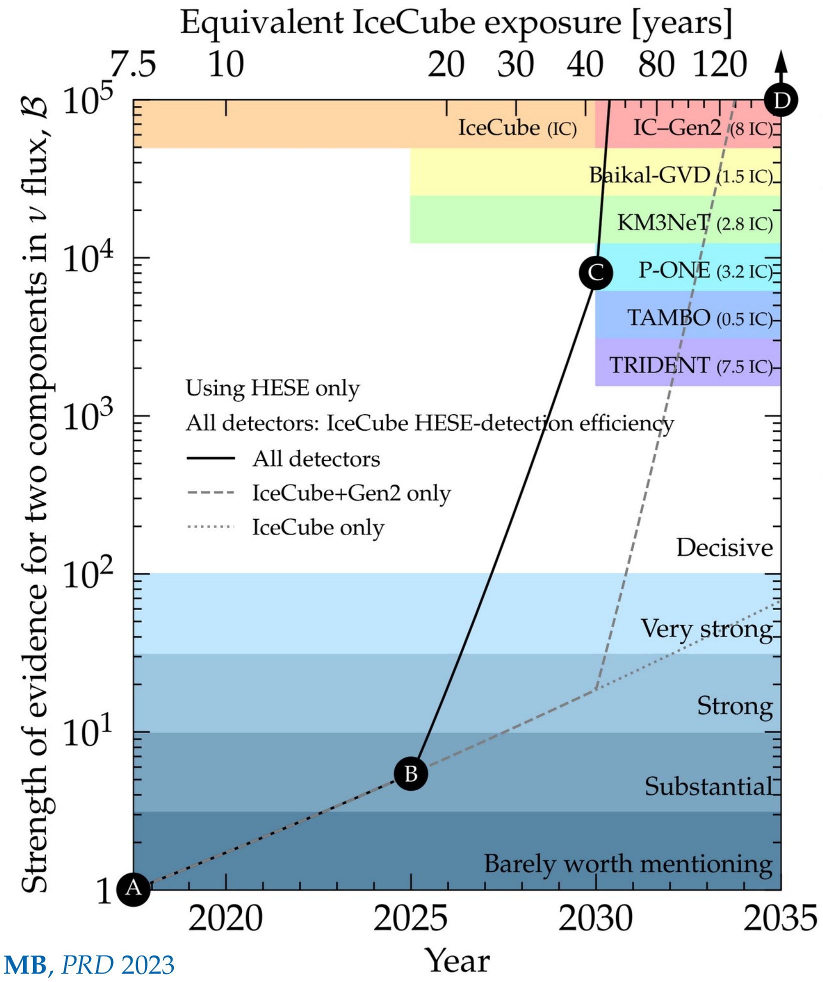

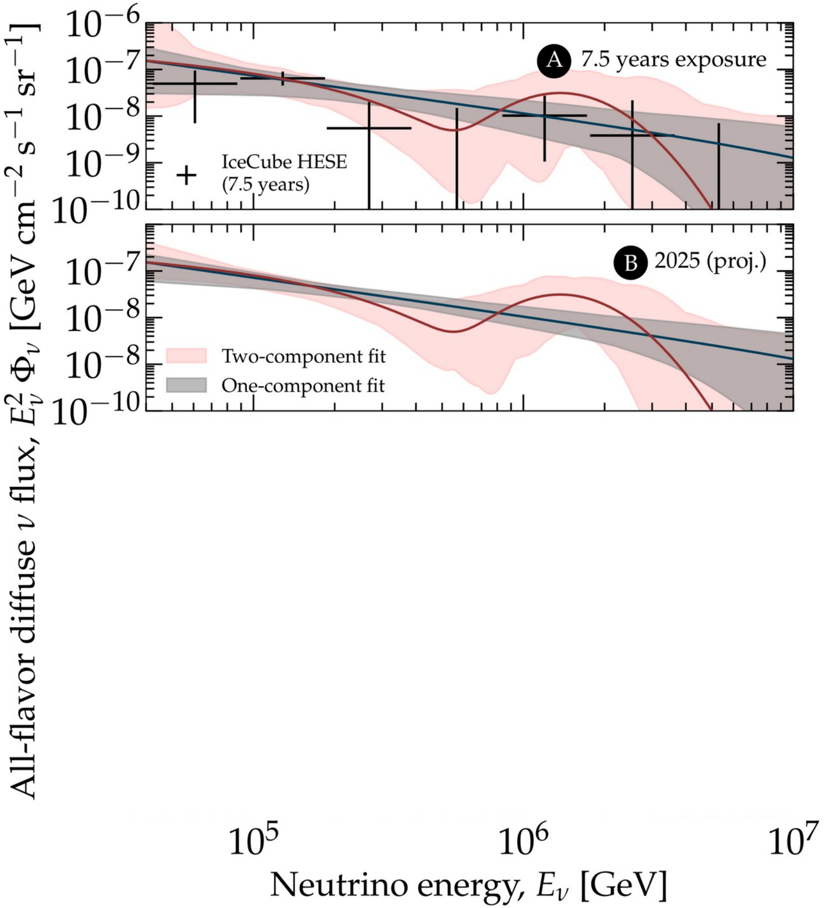

D. F. G. Fiorillo, **MB**, *PRD* 2023

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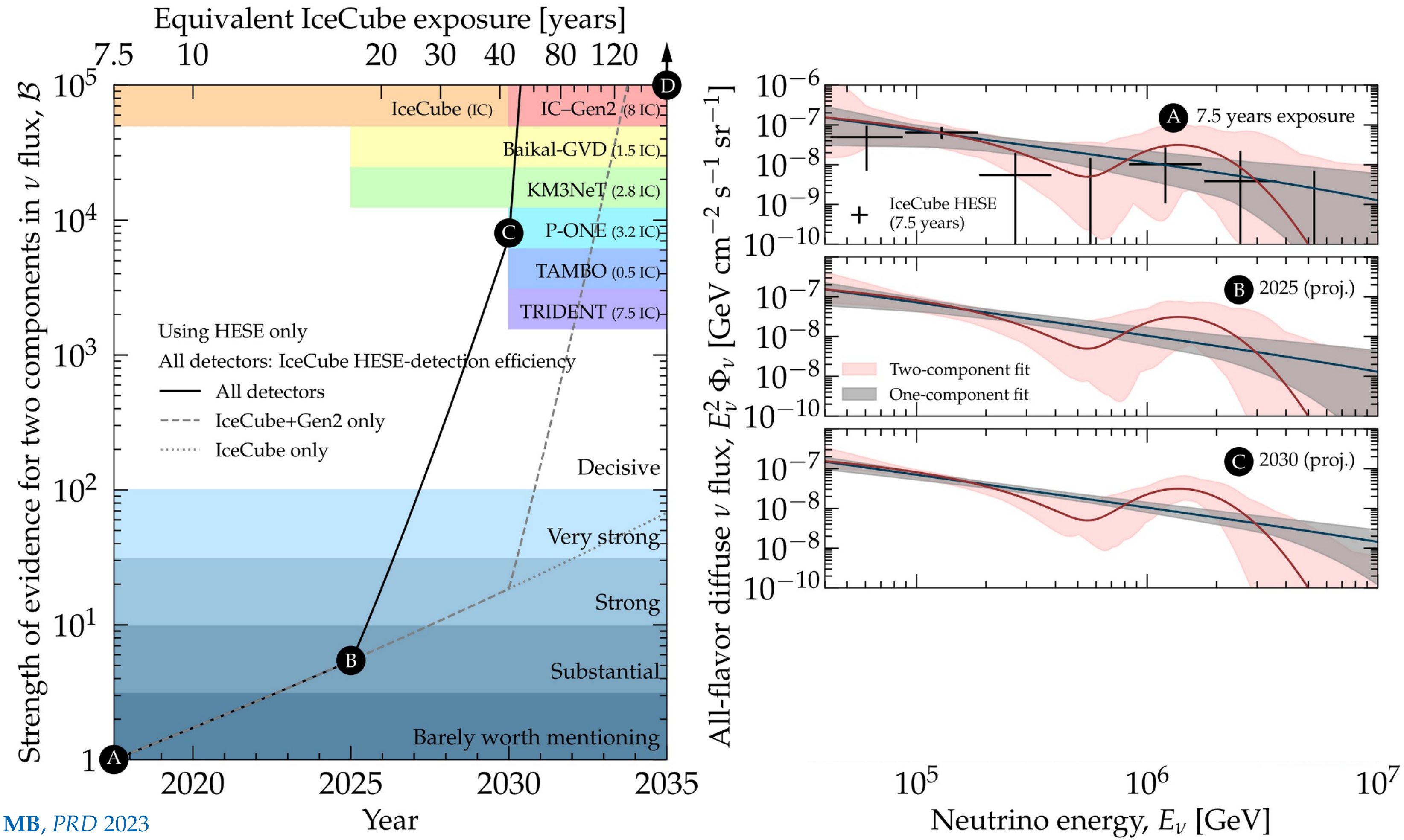

D. F. G. Fiorillo, **MB**, *PRD* 2023

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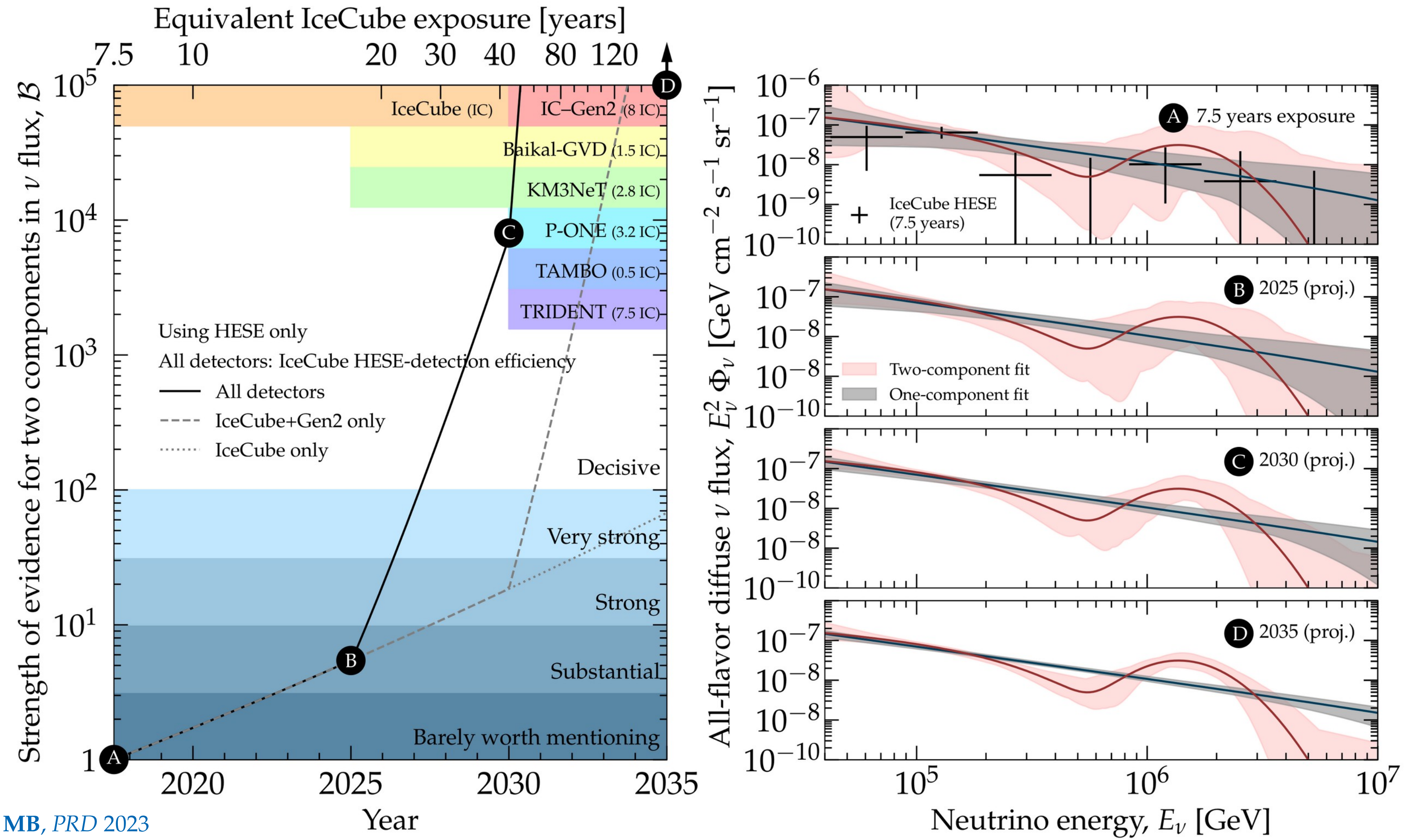
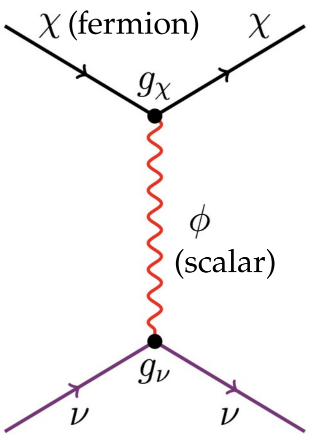


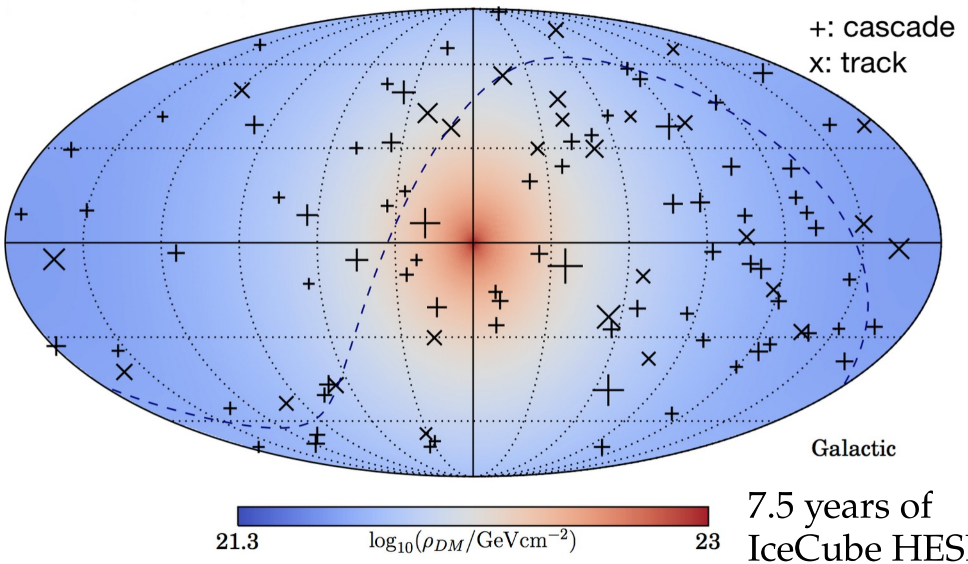
D. F. G. Fiorillo, **MB**, *PRD* 2023

Neutrino-dark matter scattering



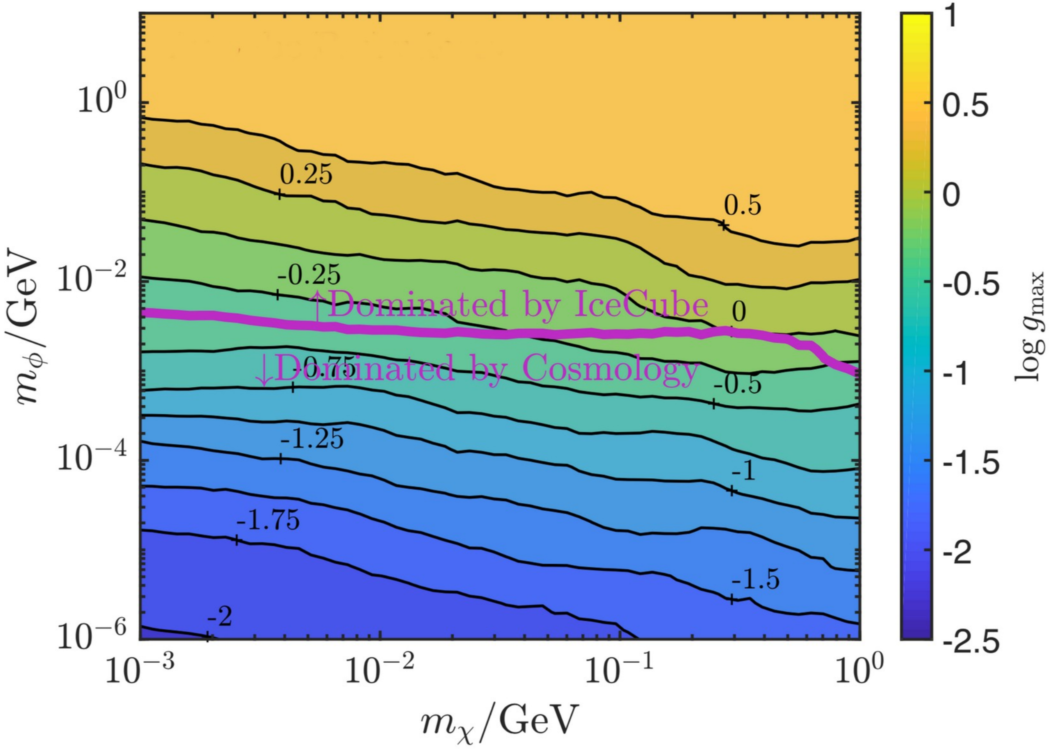
Signature:

Deficit of high-energy ν from the Galactic Center



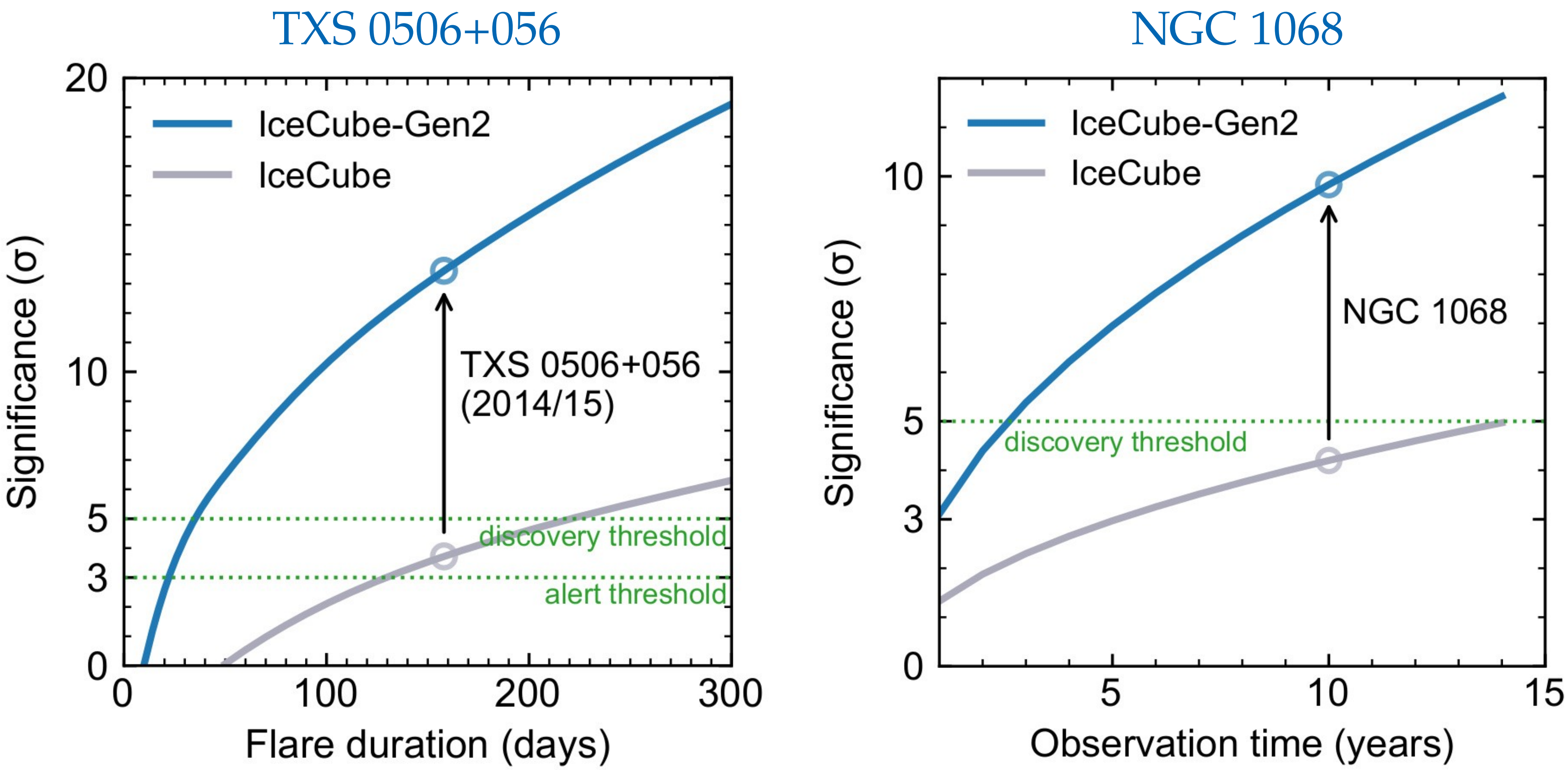
7.5 years of IceCube HESE data

Upper limits (90% C.L.) on $g_{\max} = \sqrt{g_\chi g_\nu}$



IceCube, *JCAP* 2023
Argüelles, Kheirandish, Vincent, *PRL* 2017

Discovering sources fast, with high significance

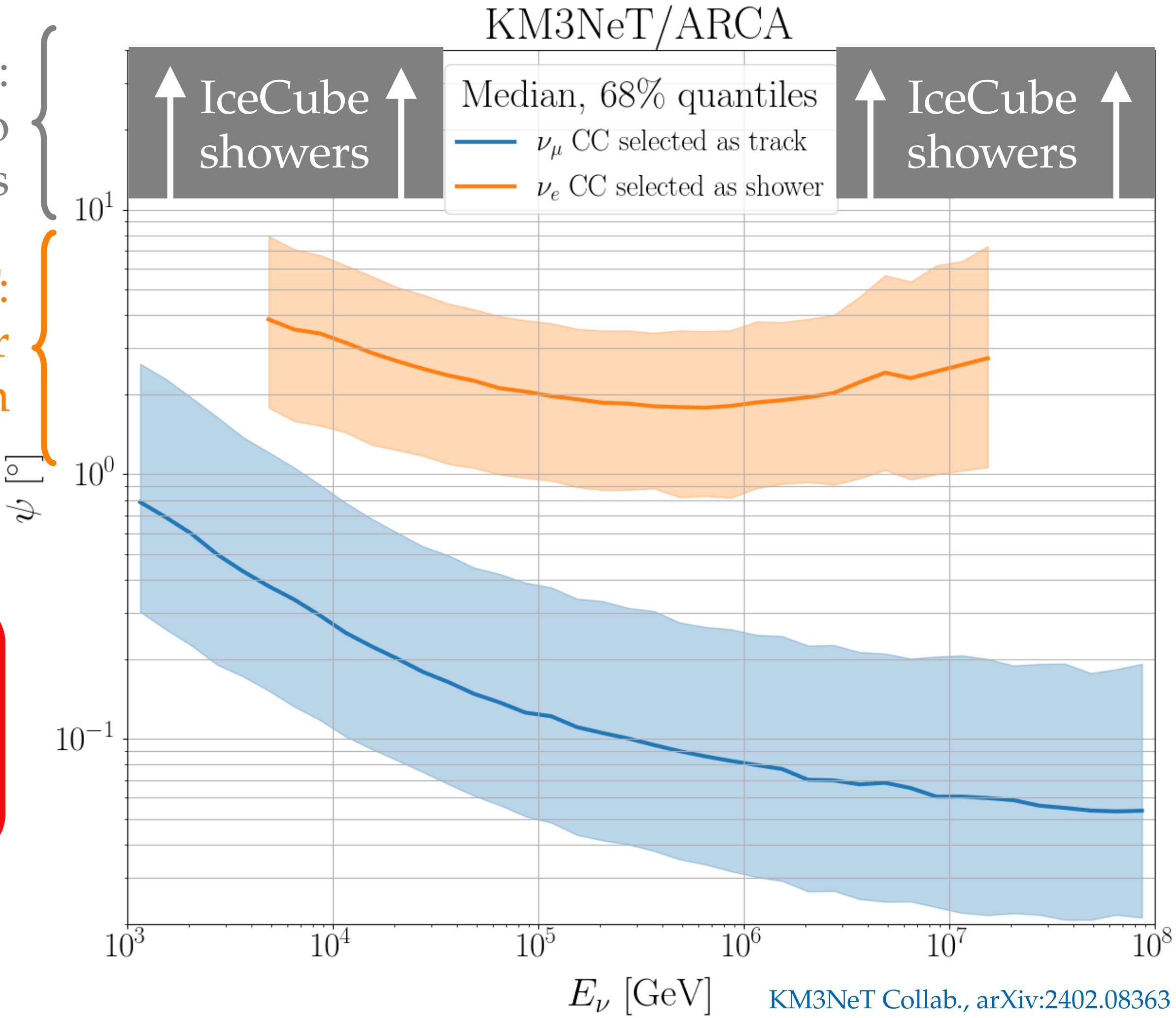


IceCube-Gen2 Collab. Technical Design Report Part I

Boosting source searches with showers

IceCube:
Hard to use showers to find point sources

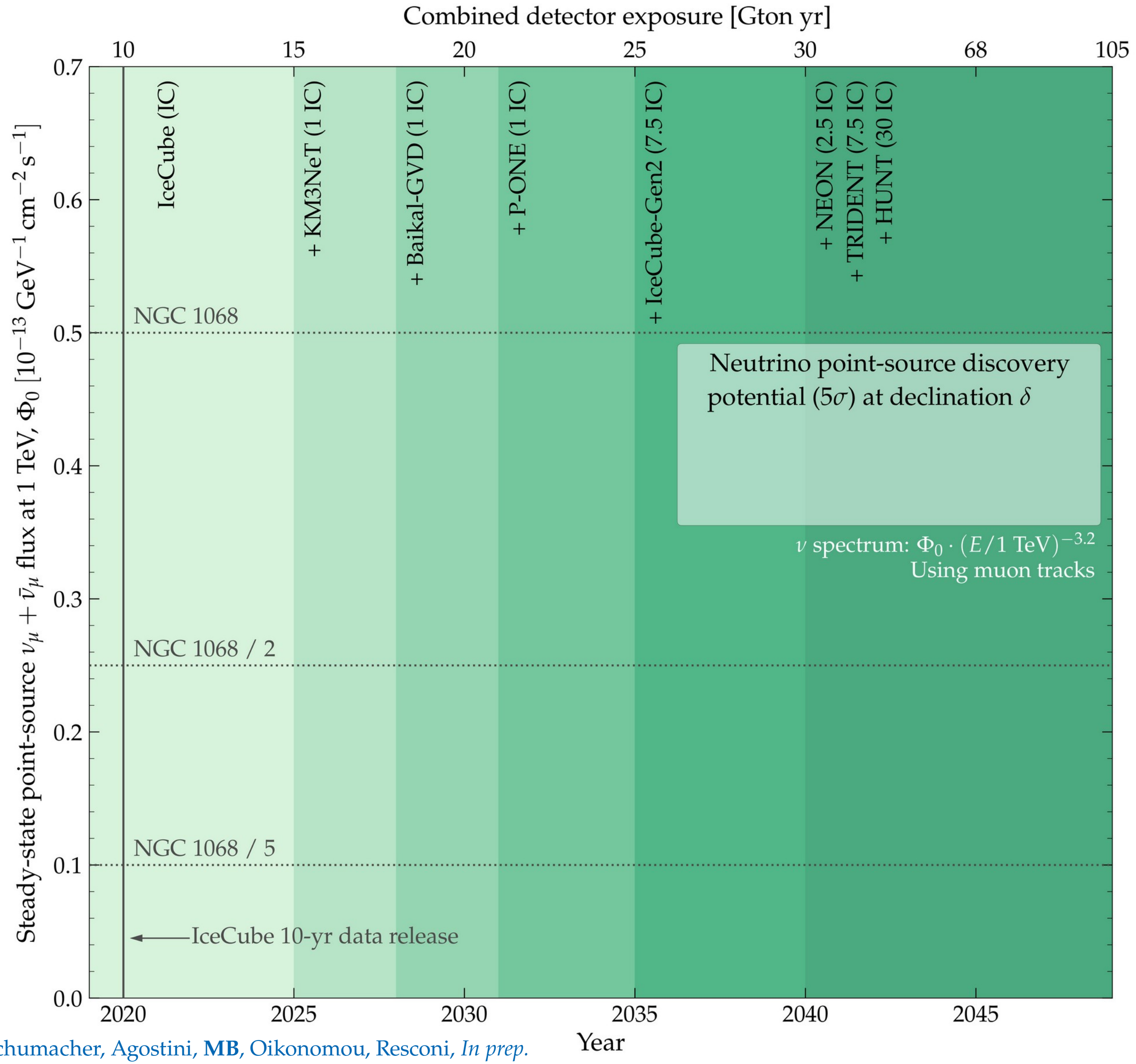
KM3NeT:
Degree-scale shower Angular resolution



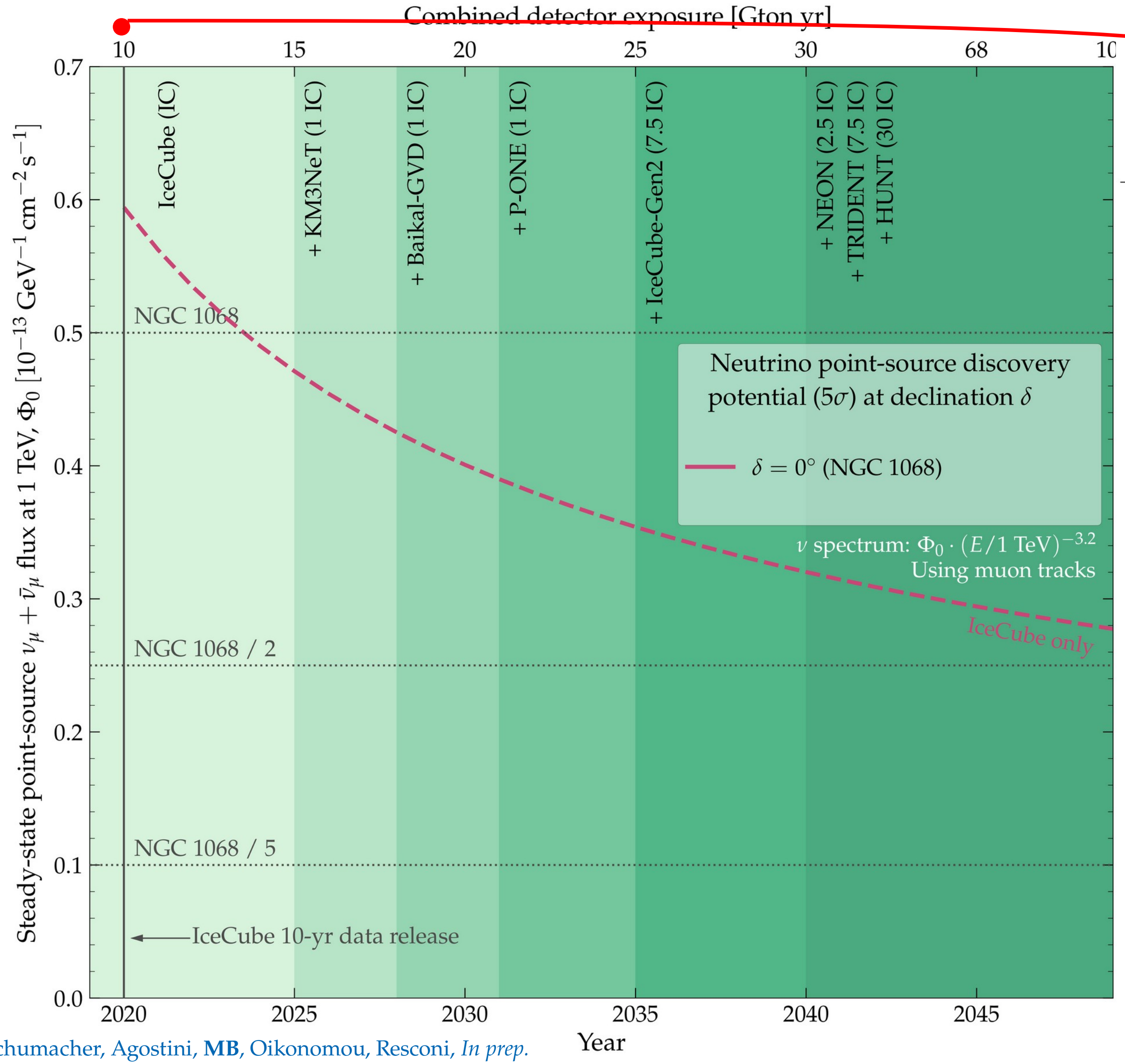
Light scattering length in water > in ice (100–300 m *vs.* 4–40 m)

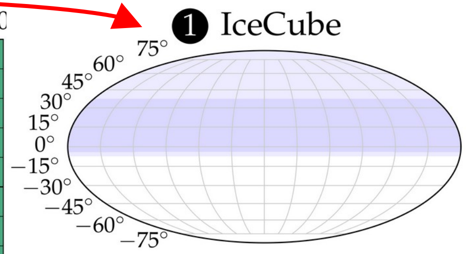
IceCube Collab., *NIM* 2013
ANTARES Collab., *Astropart. Phys.* 2005

KM3NeT Collab., arXiv:2402.08363



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





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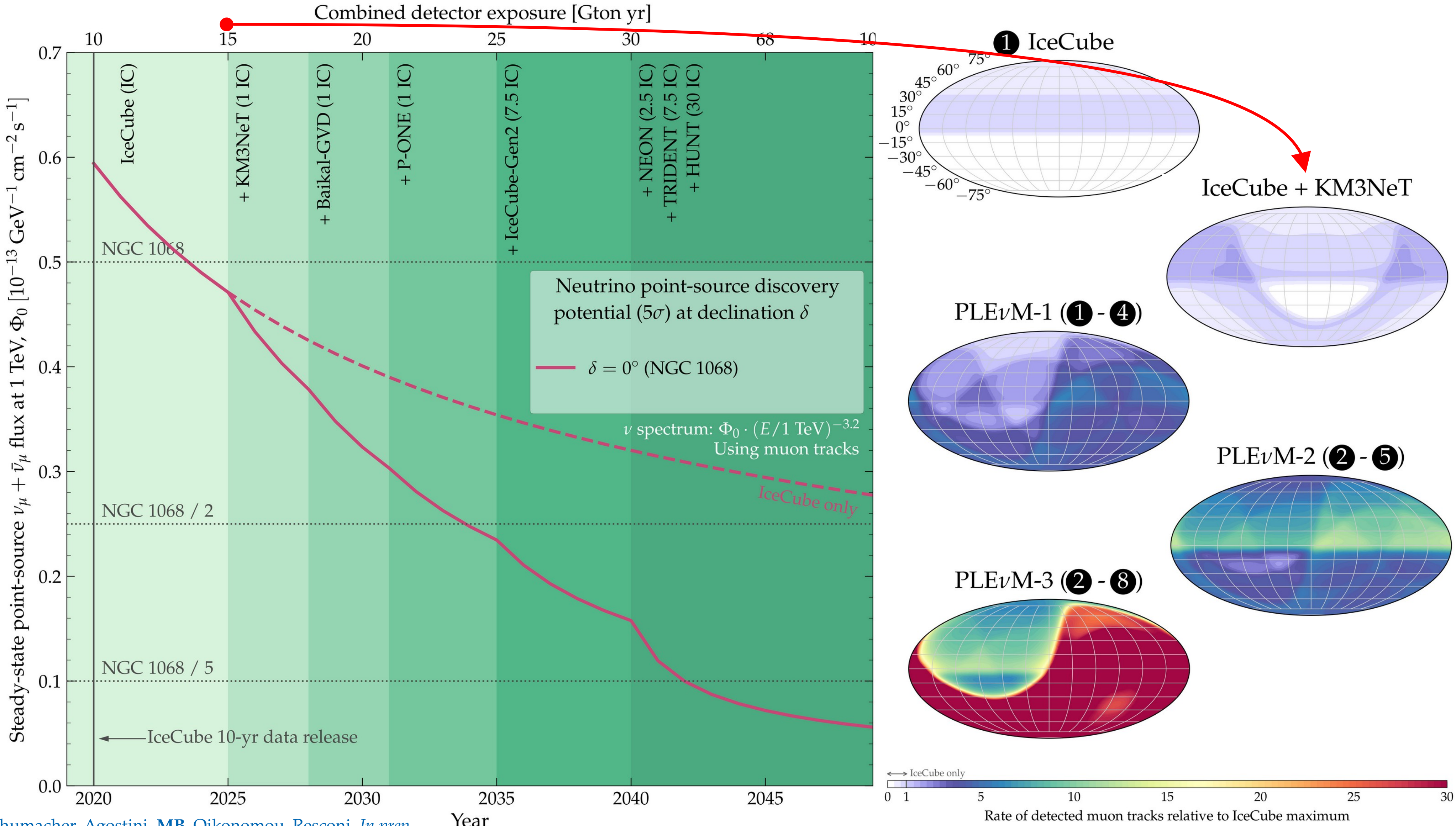

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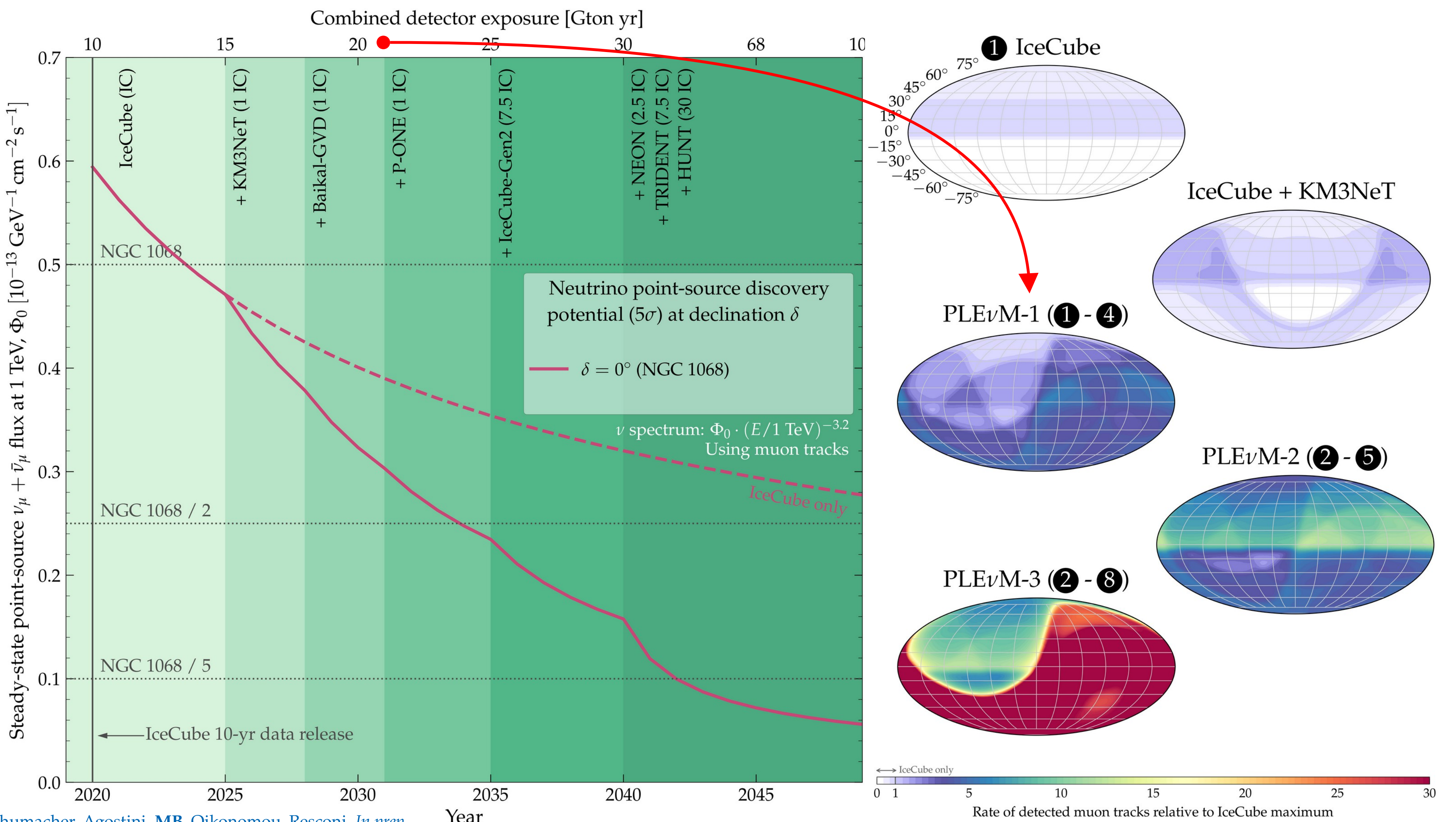

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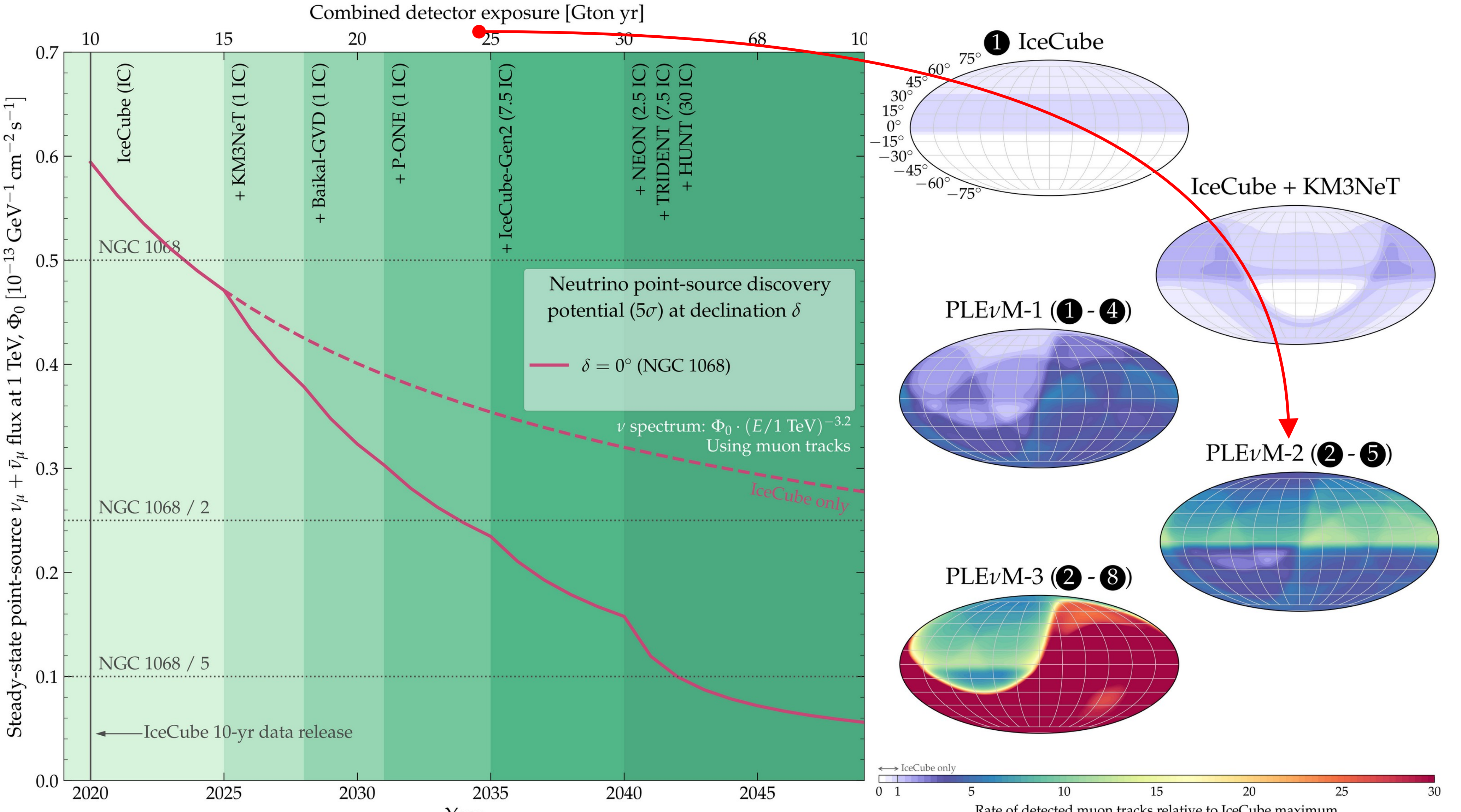

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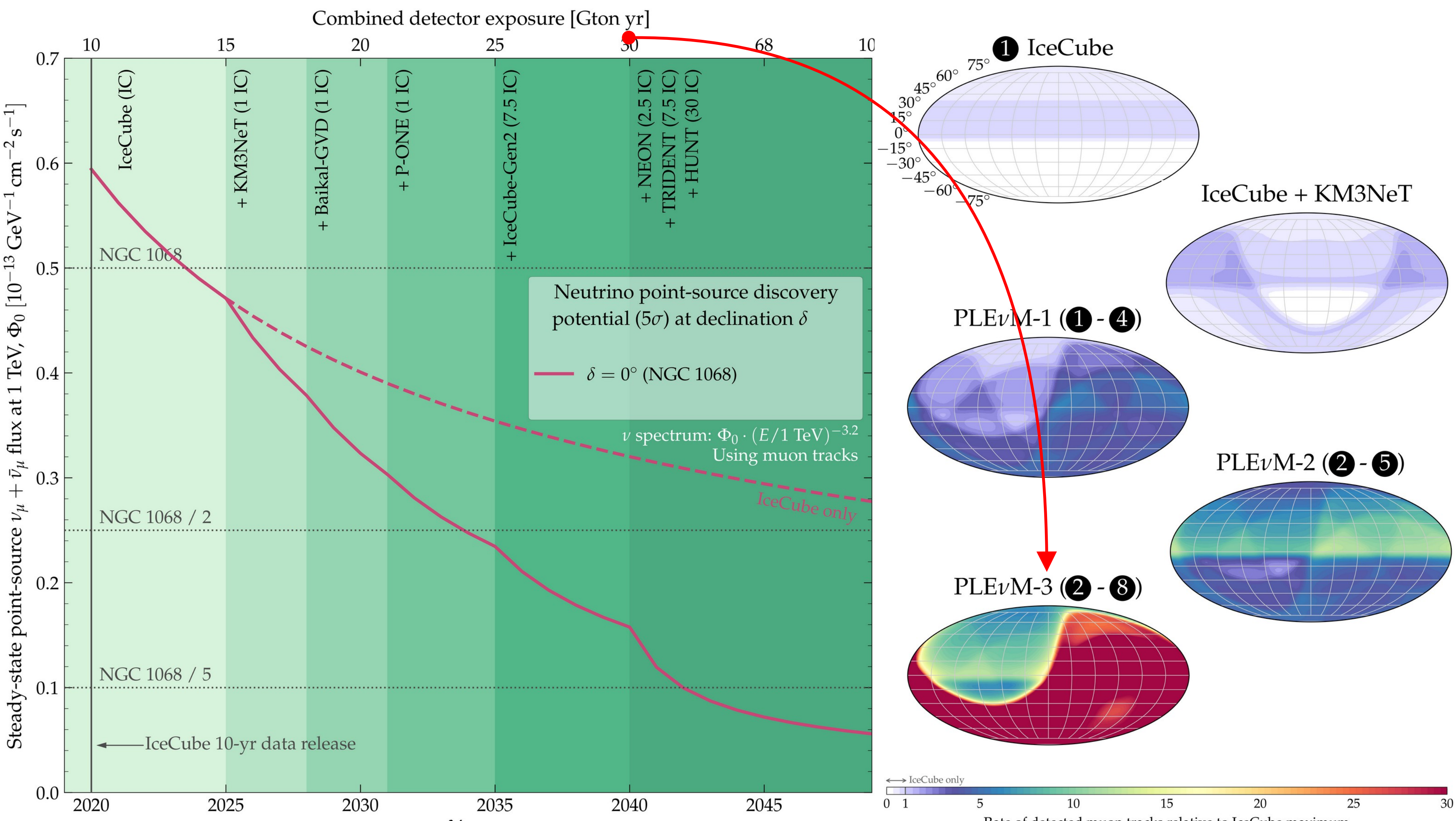

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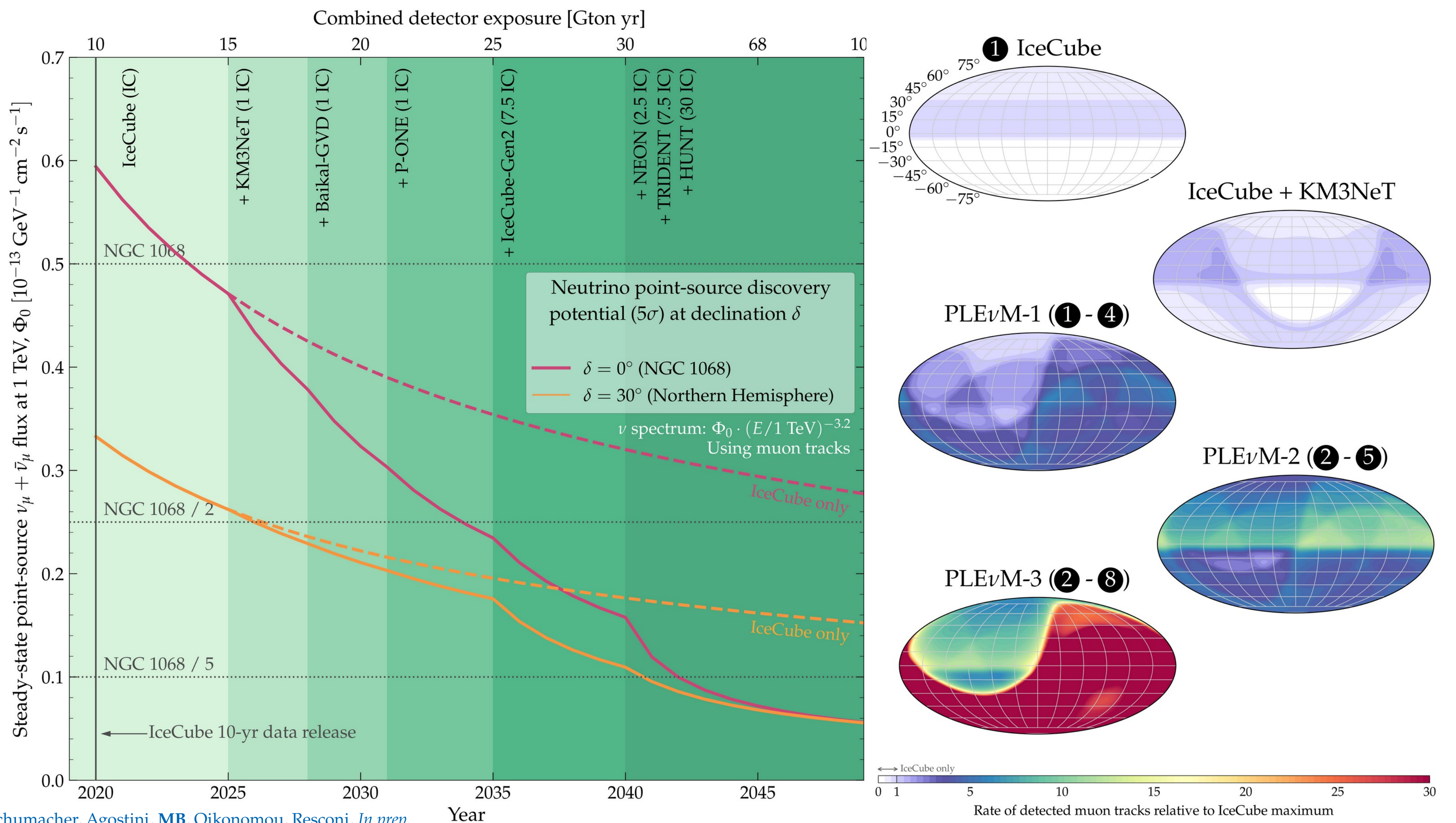

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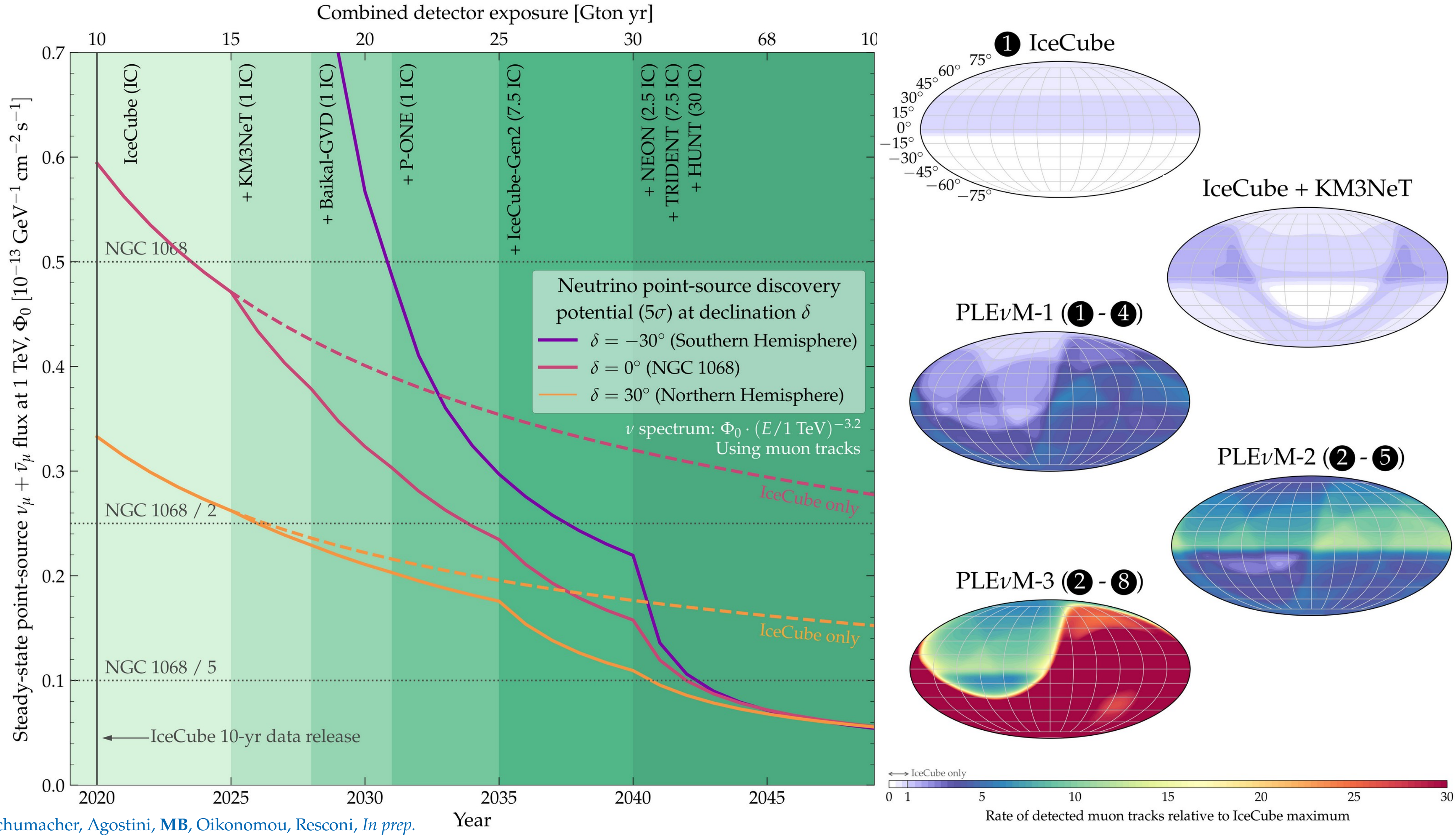

Schumacher, Agostini, **MB**, Oikonomou, Resconi, *In prep.*

3. Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

First observation of a Glashow resonance

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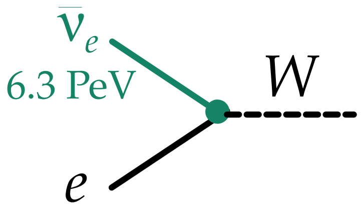

IceCube, *Nature* 2021
Glashow, *PR* 1960

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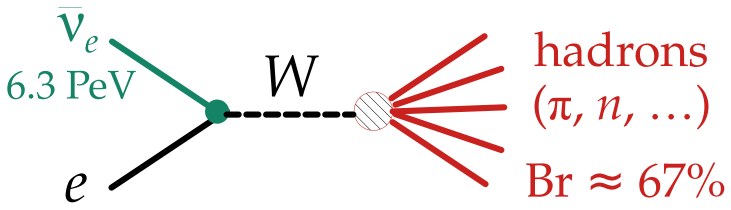
Predicted in 1960:



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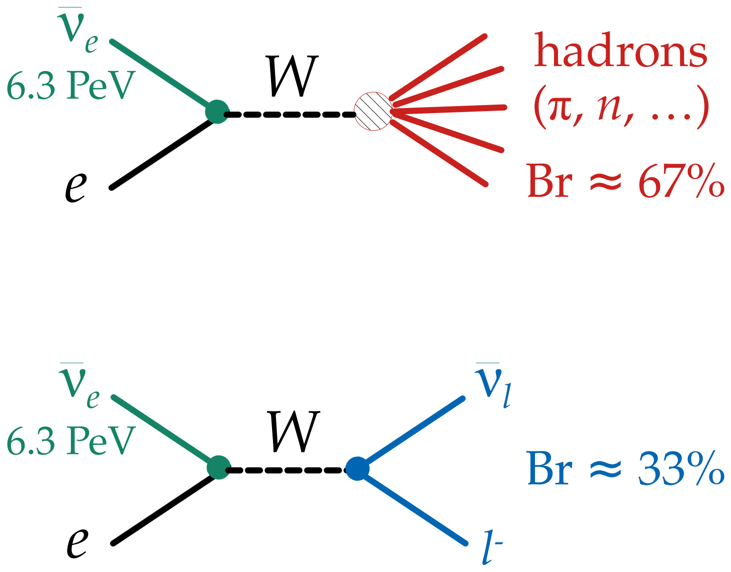

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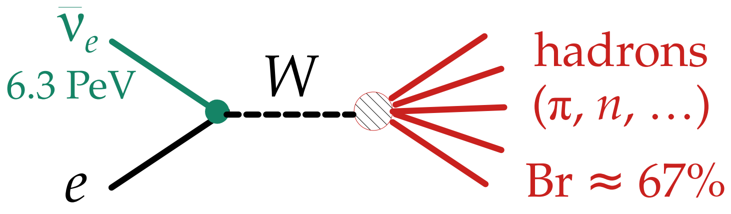
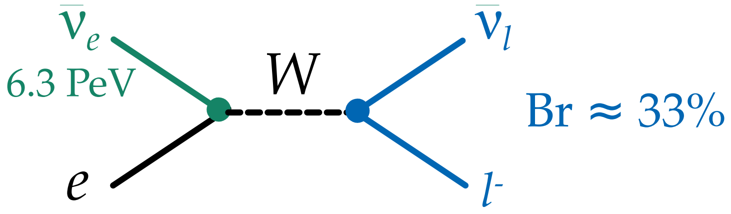
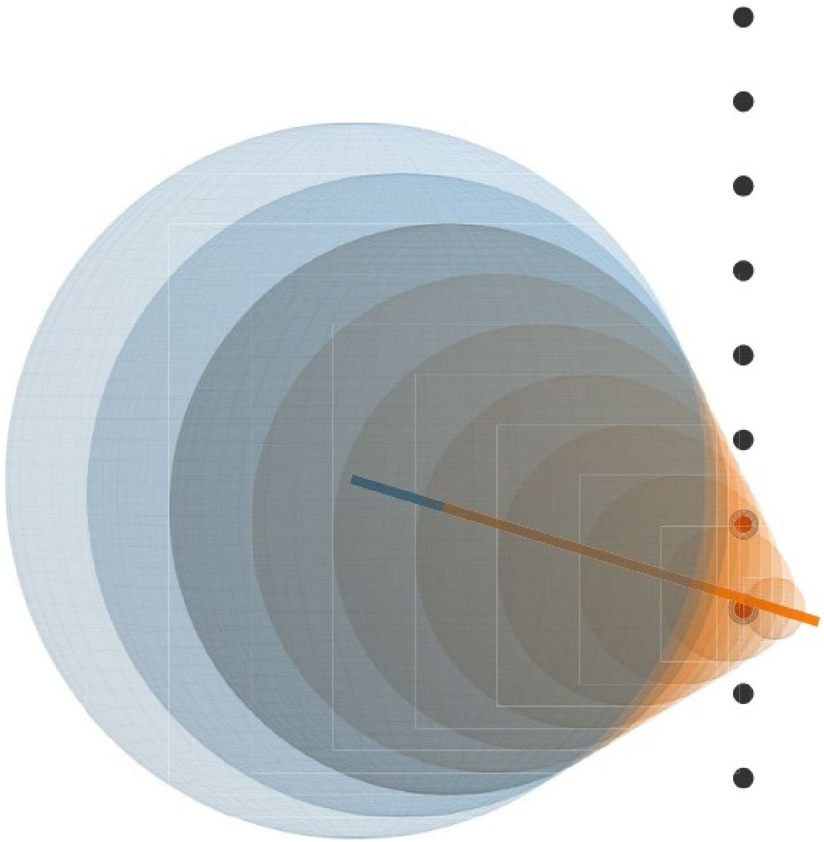




First reported by IceCube in 2021:



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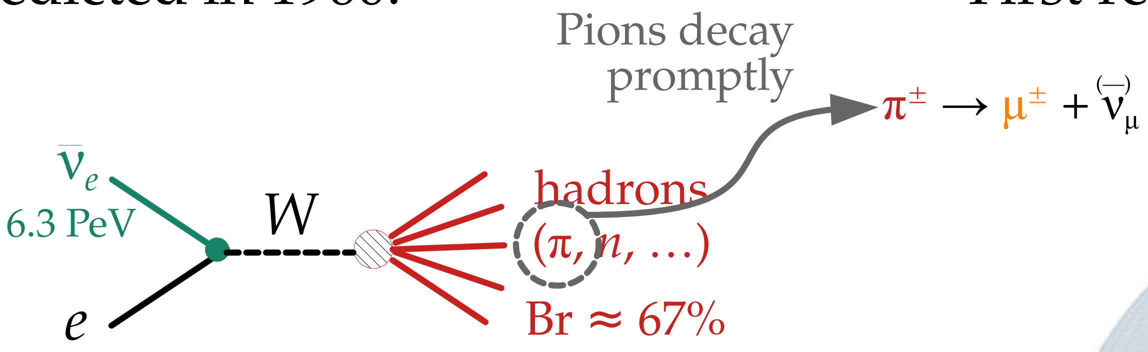

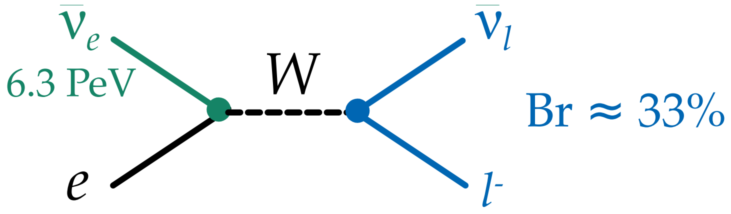

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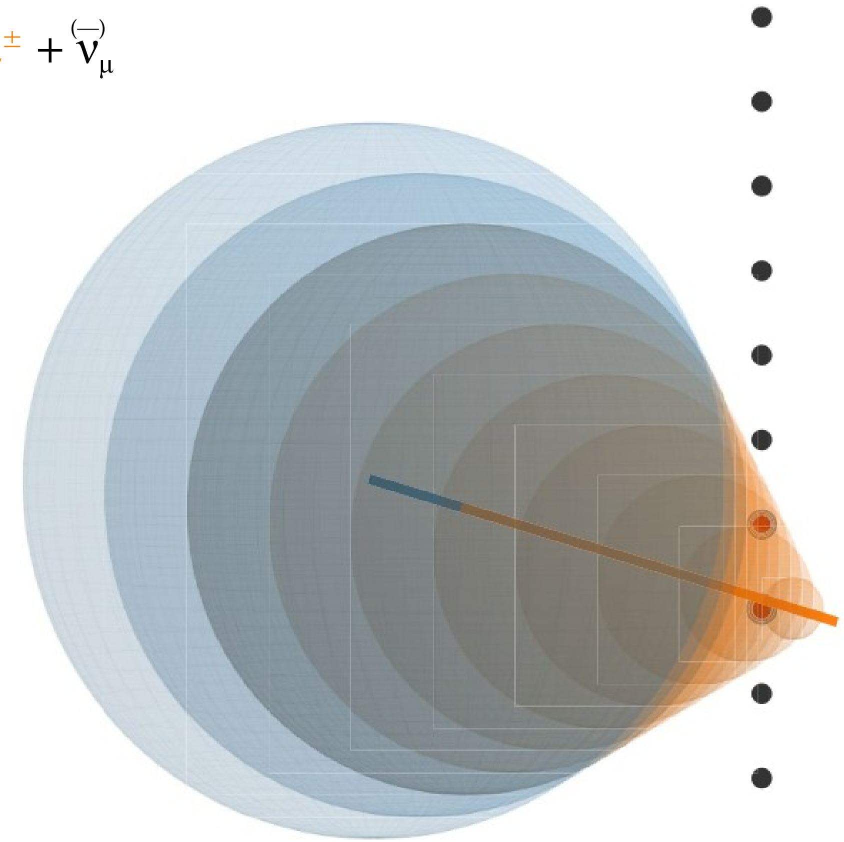


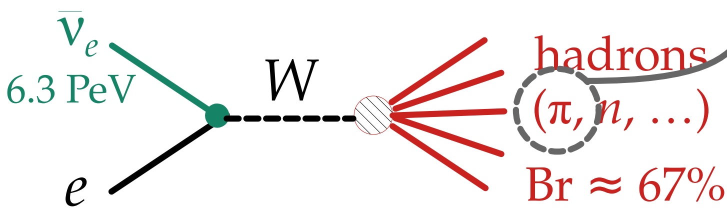
IceCube, *Nature* 2021
Glashow, *PR* 1960

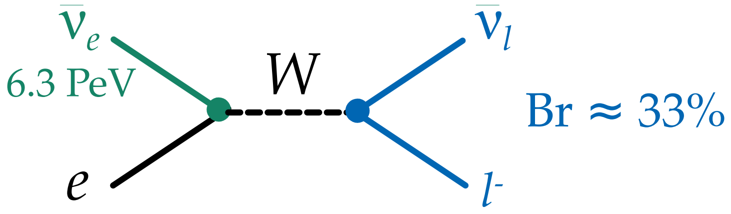
First observation of a Glashow resonance

Predicted in 1960:

Pions decay promptly

$\pi^{\pm} \longrightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$





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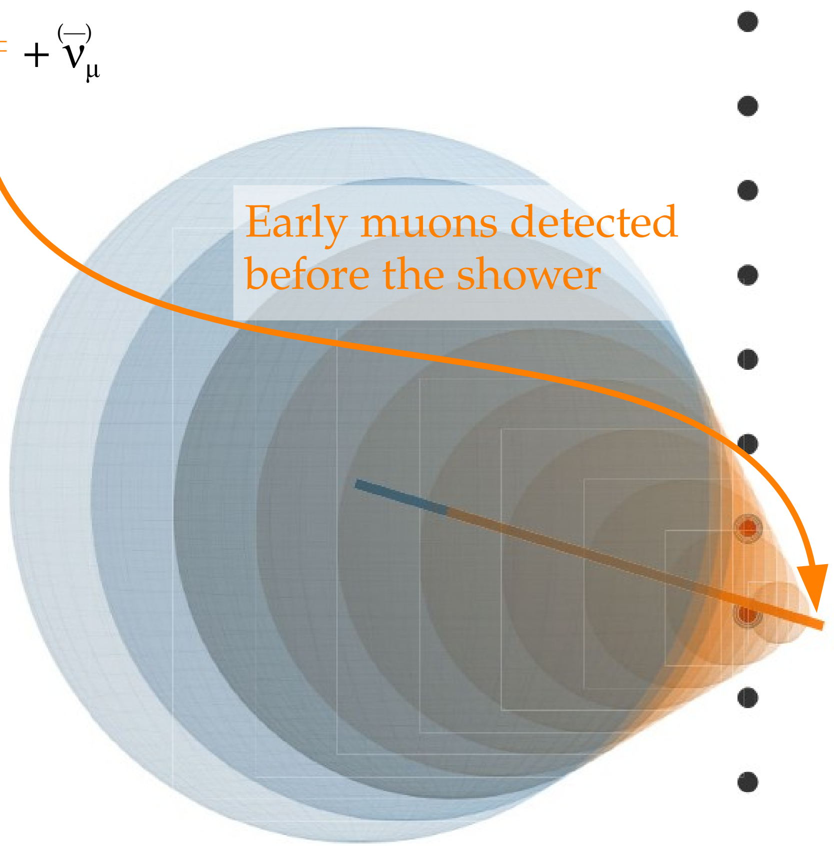

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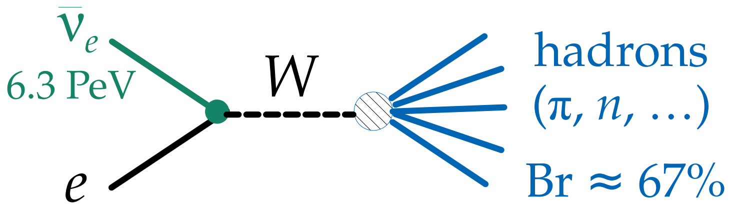

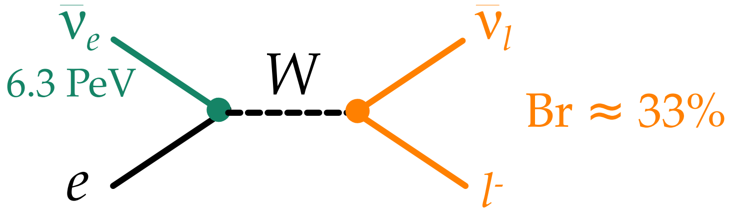

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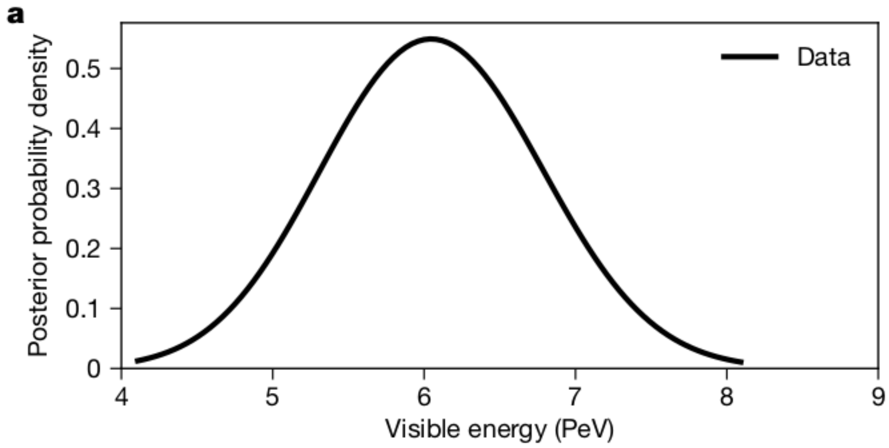

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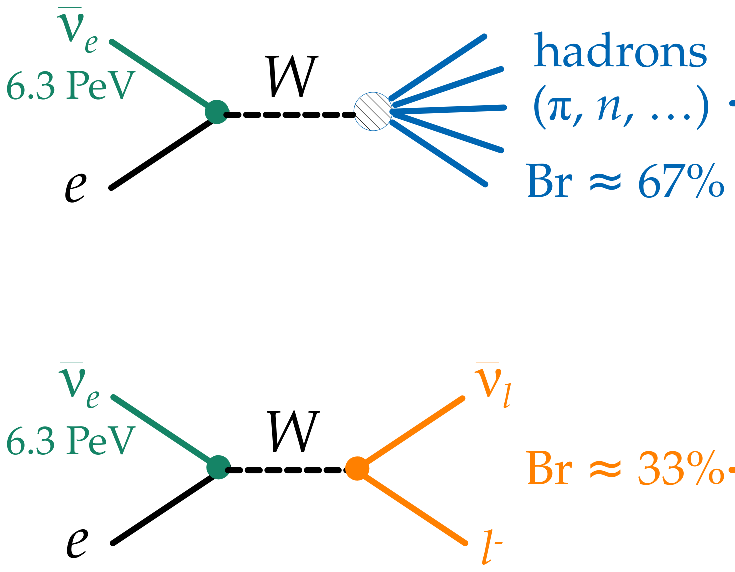

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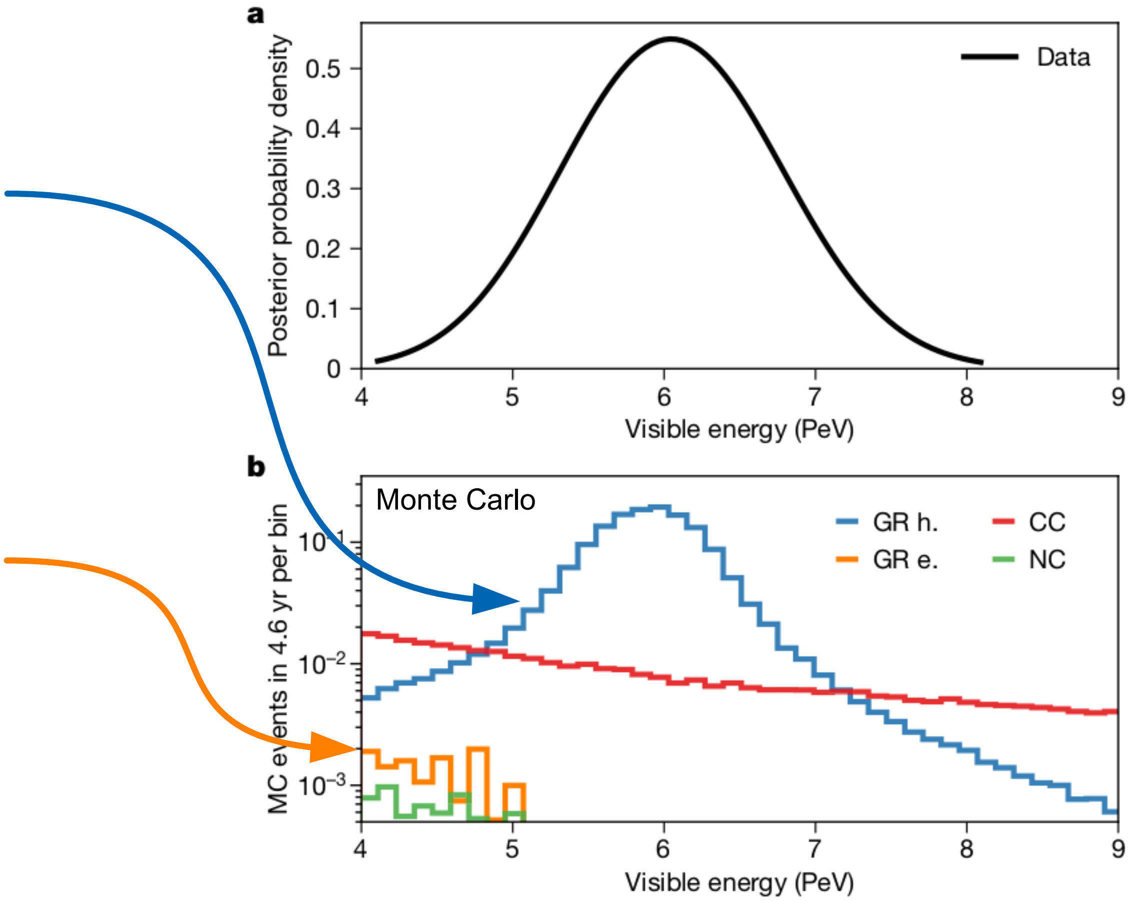


IceCube, *Nature* 2021
Glashow, *PR* 1960

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

Astrophysical neutrino sources

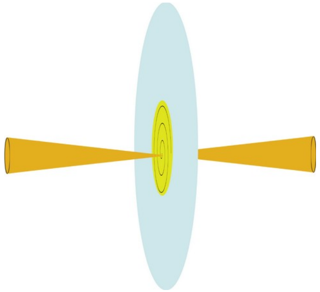
Earth

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

Astrophysical neutrino sources

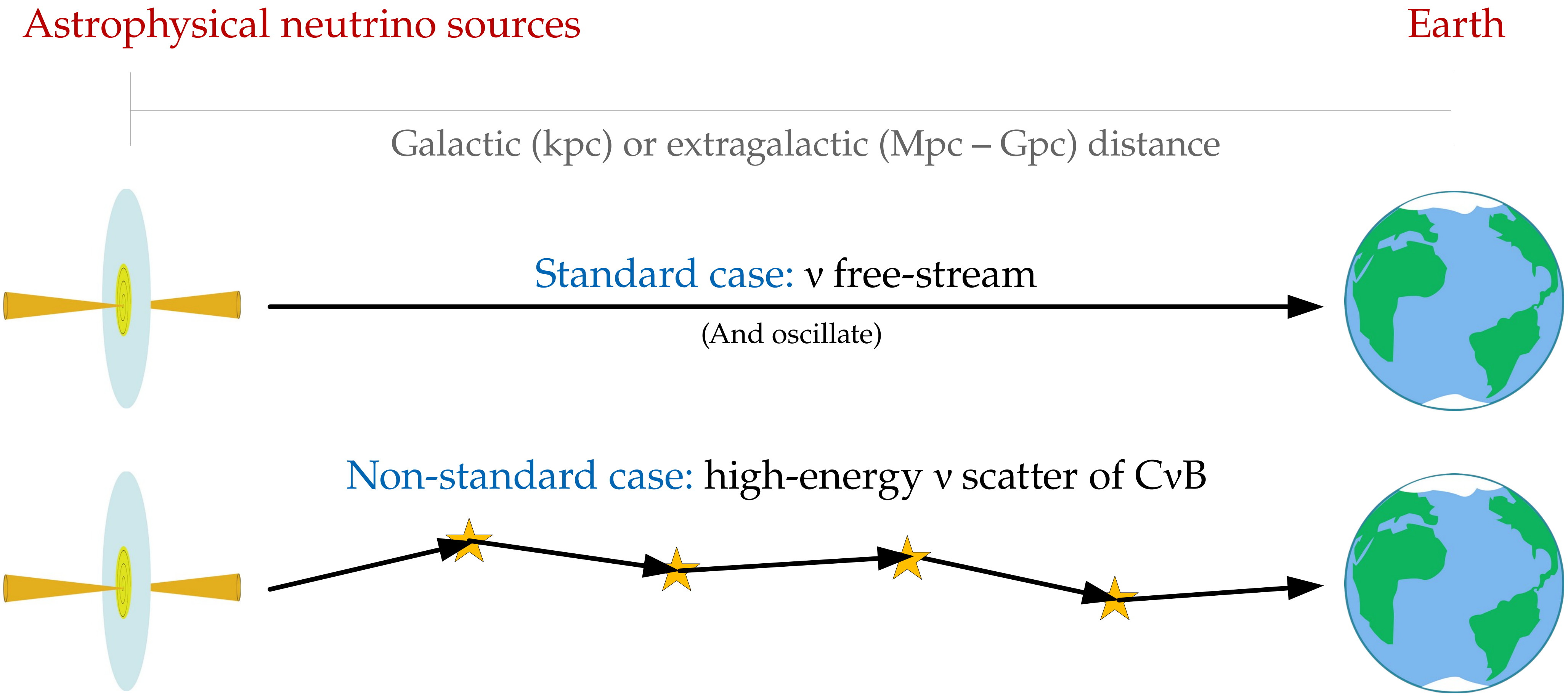
Earth

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



Standard case: ν free-stream

(And oscillate)


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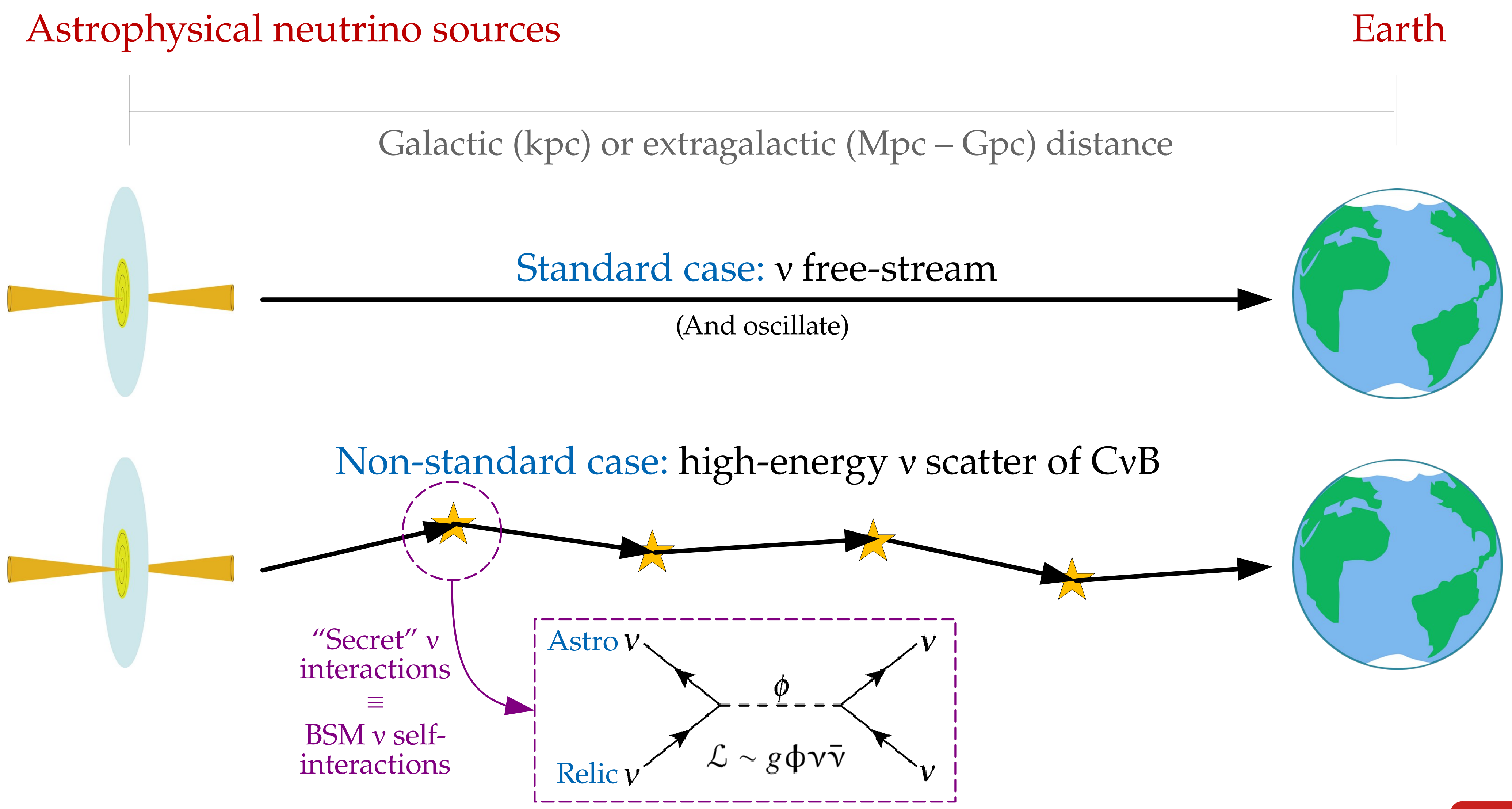
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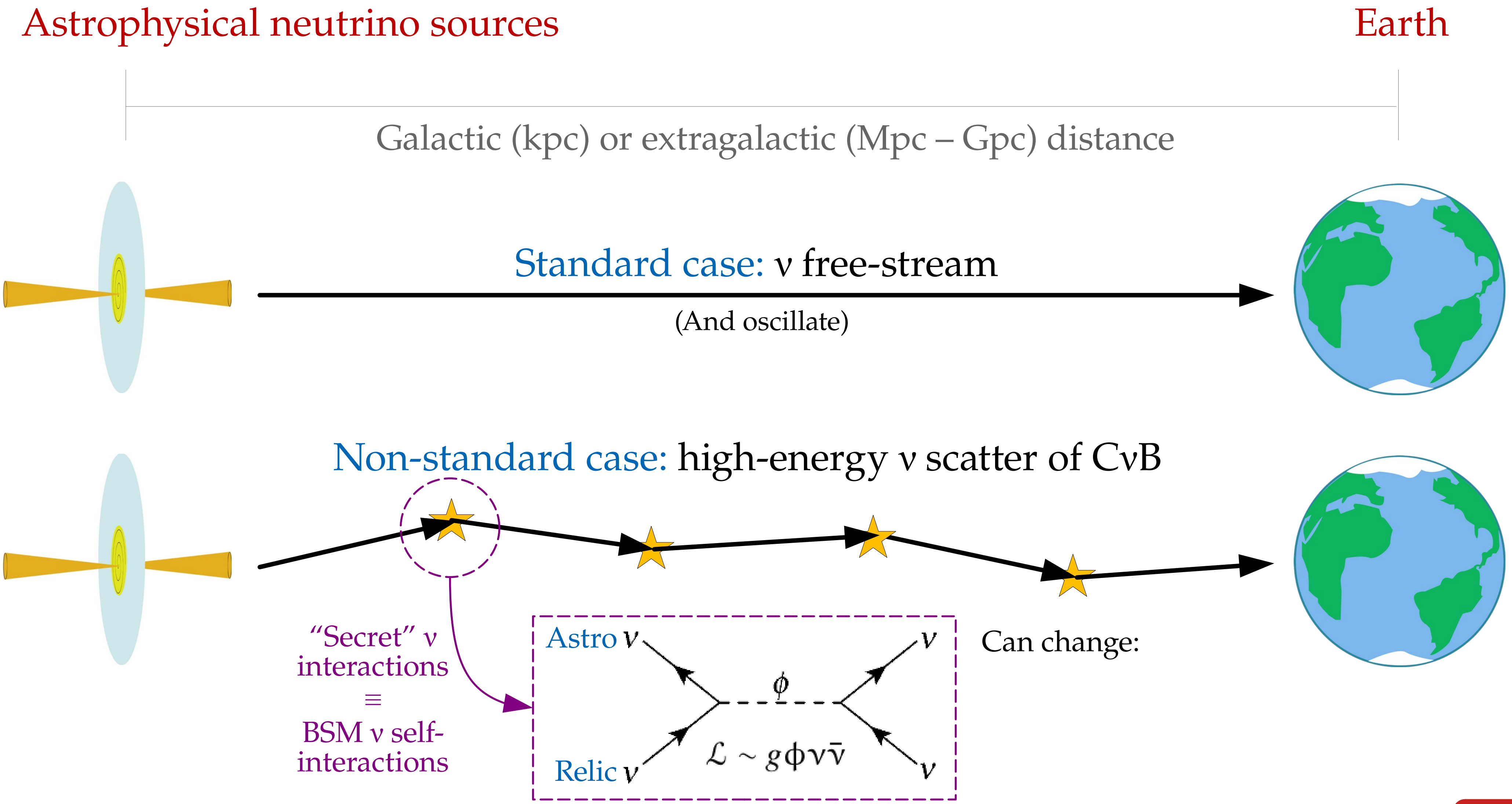
"Secret" ν interactions ≡ BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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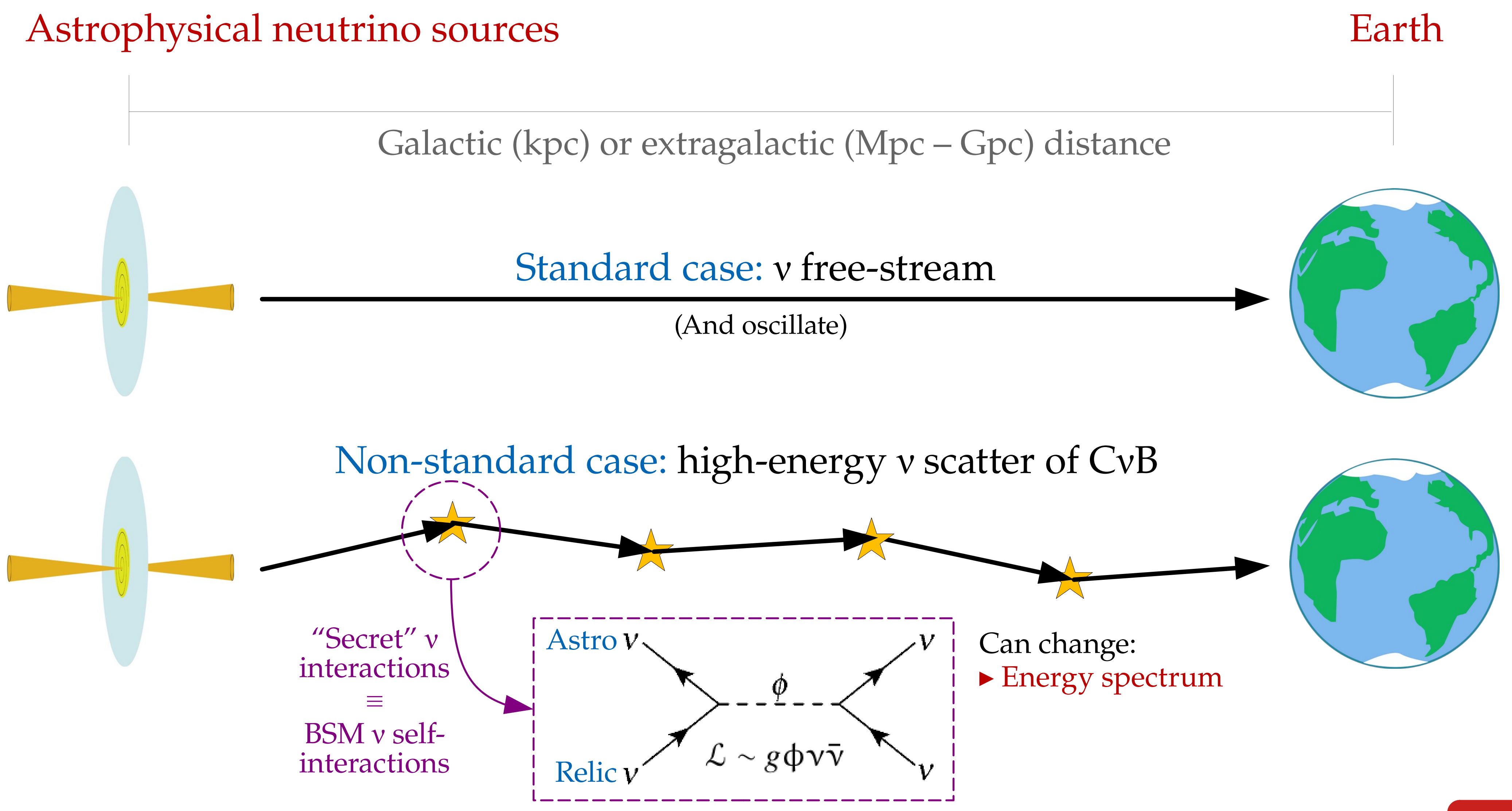

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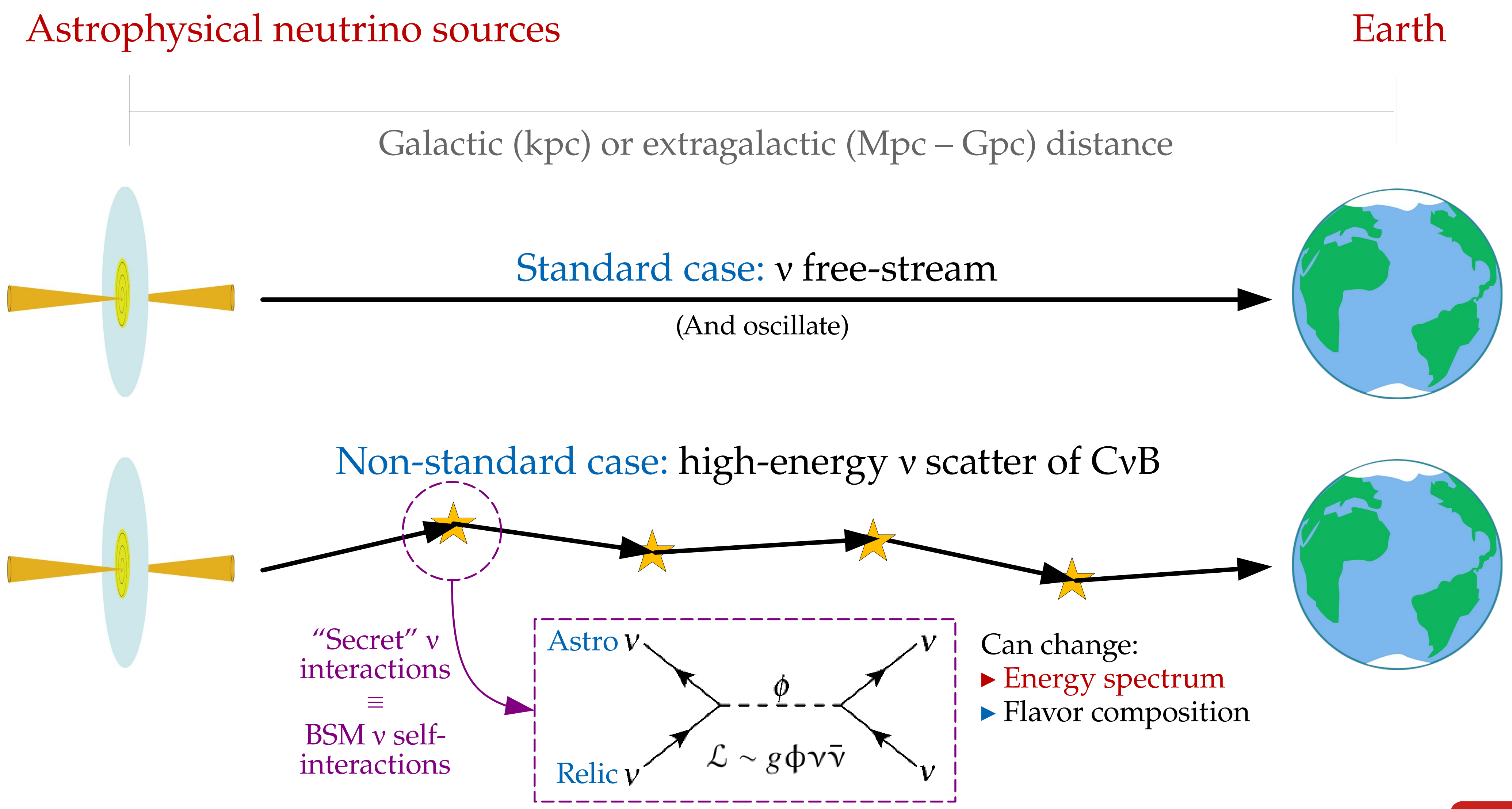
▸ Energy spectrum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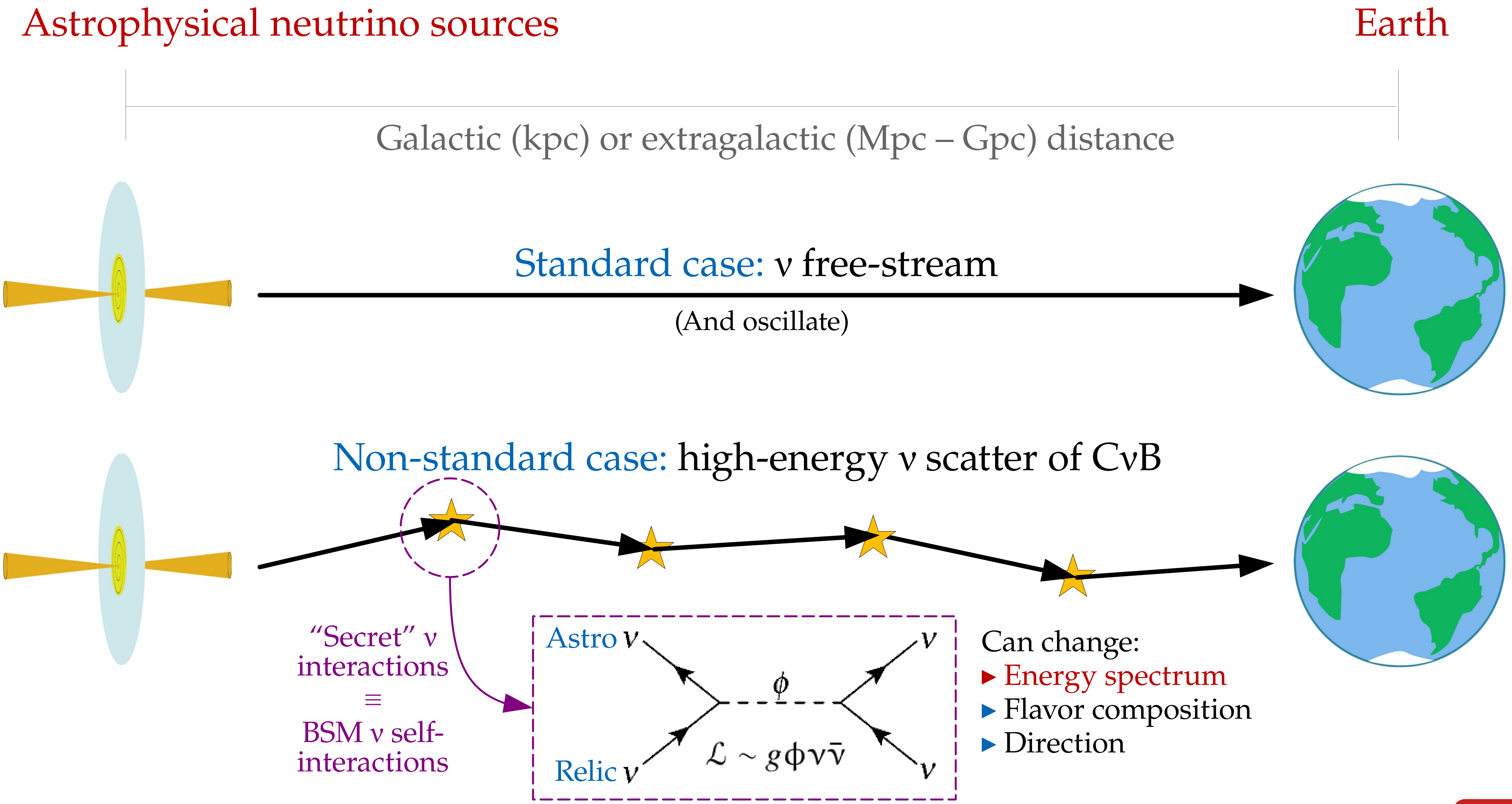
Can change:
Energy spectrum
Flavor composition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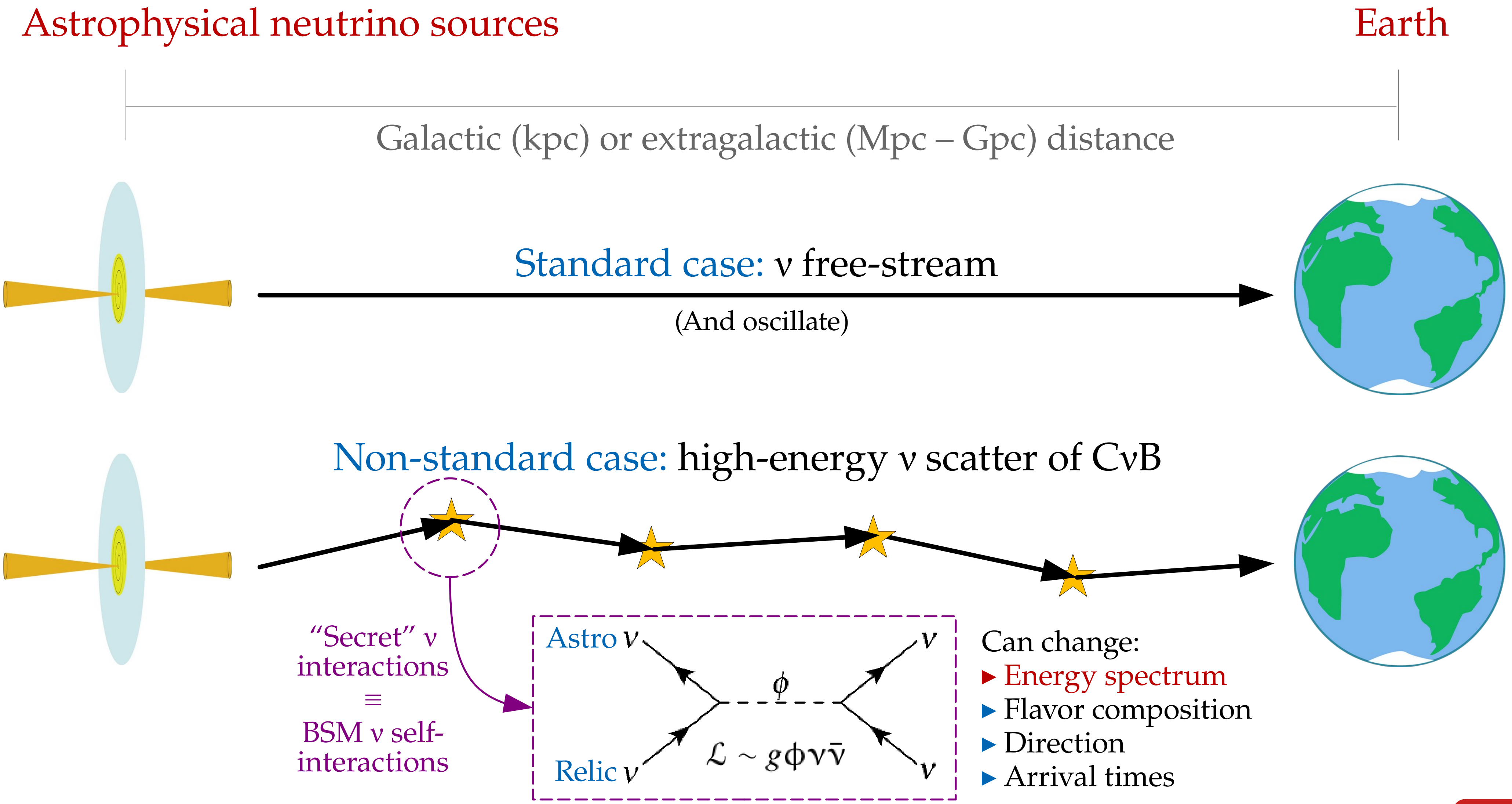
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ϕ
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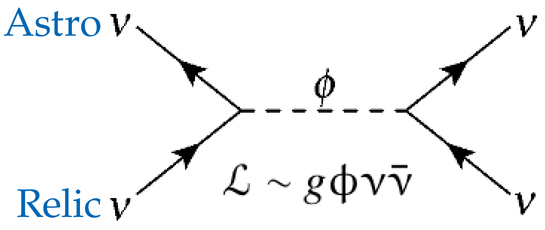
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:
▸ Energy spectrum
▸ Flavor composition
▸ Direction
▸ Arrival times

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
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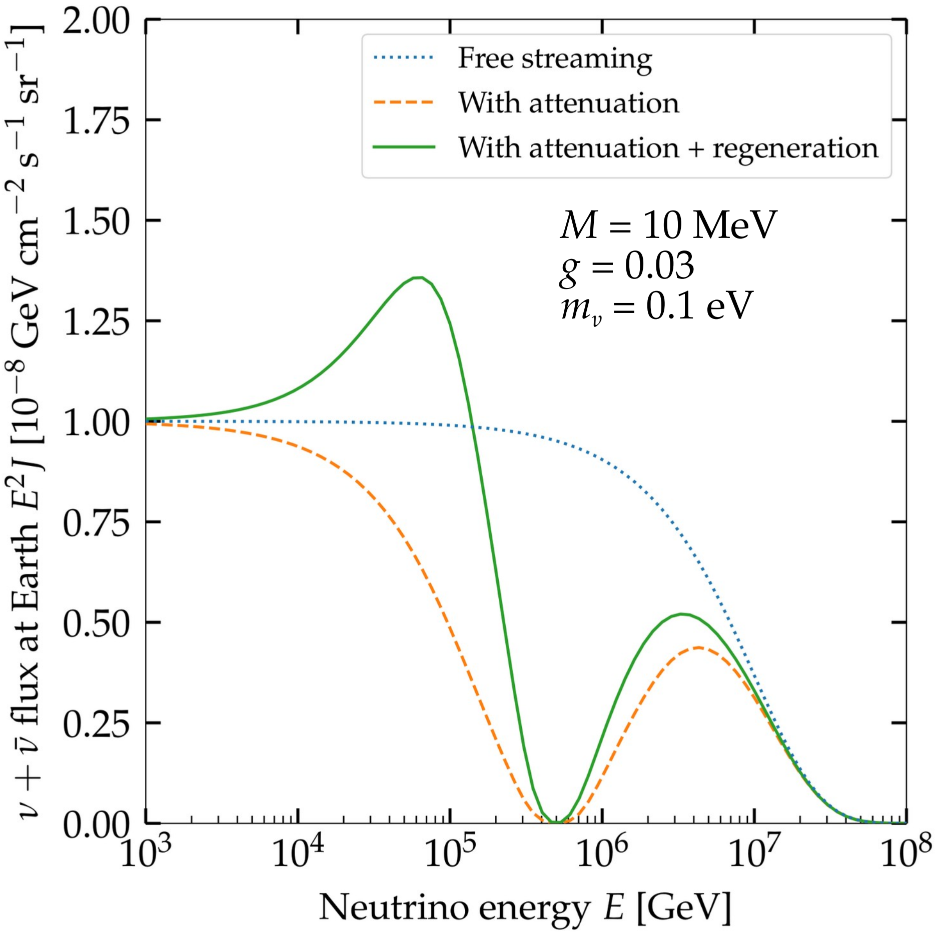

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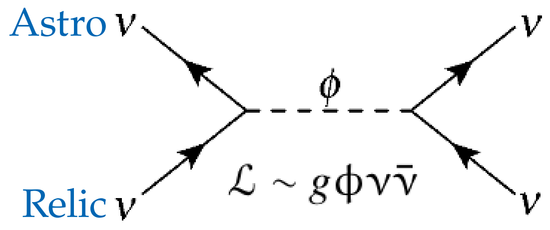
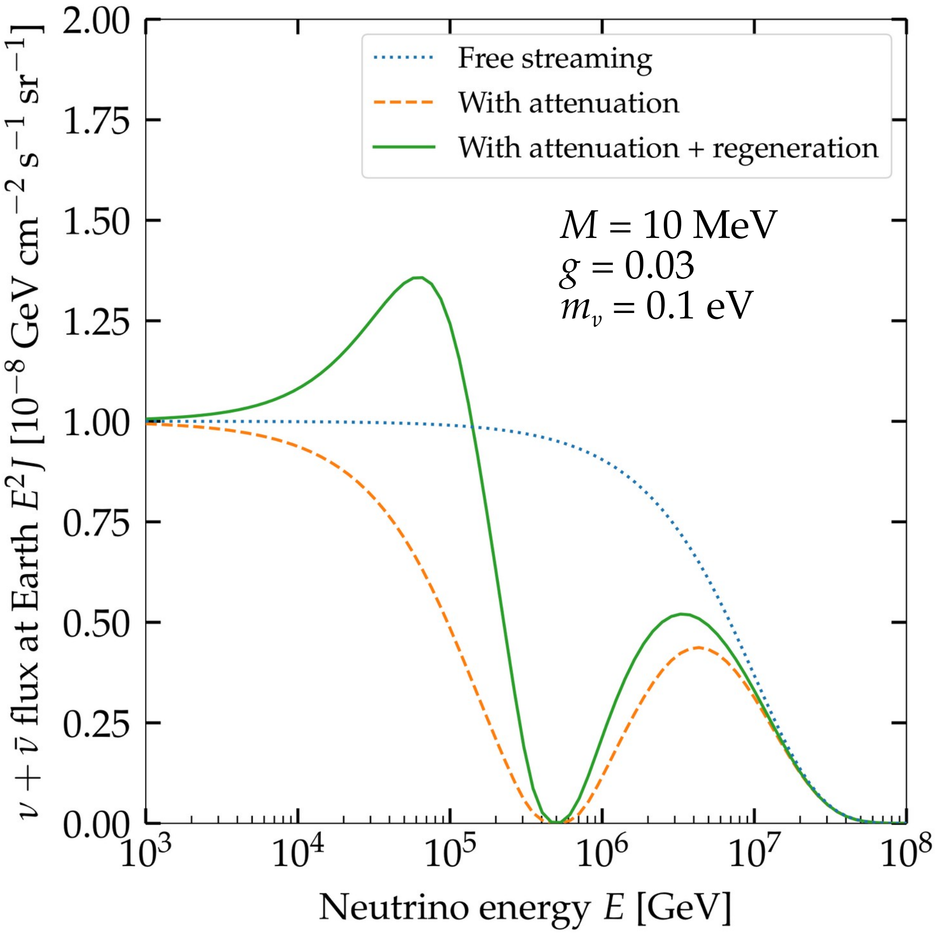


New coupling

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

Mediator mass

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



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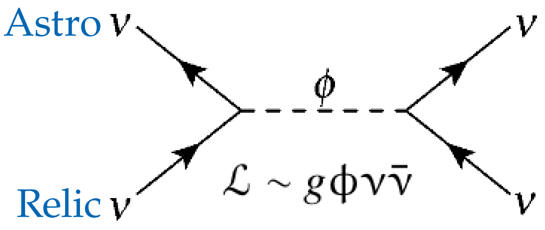

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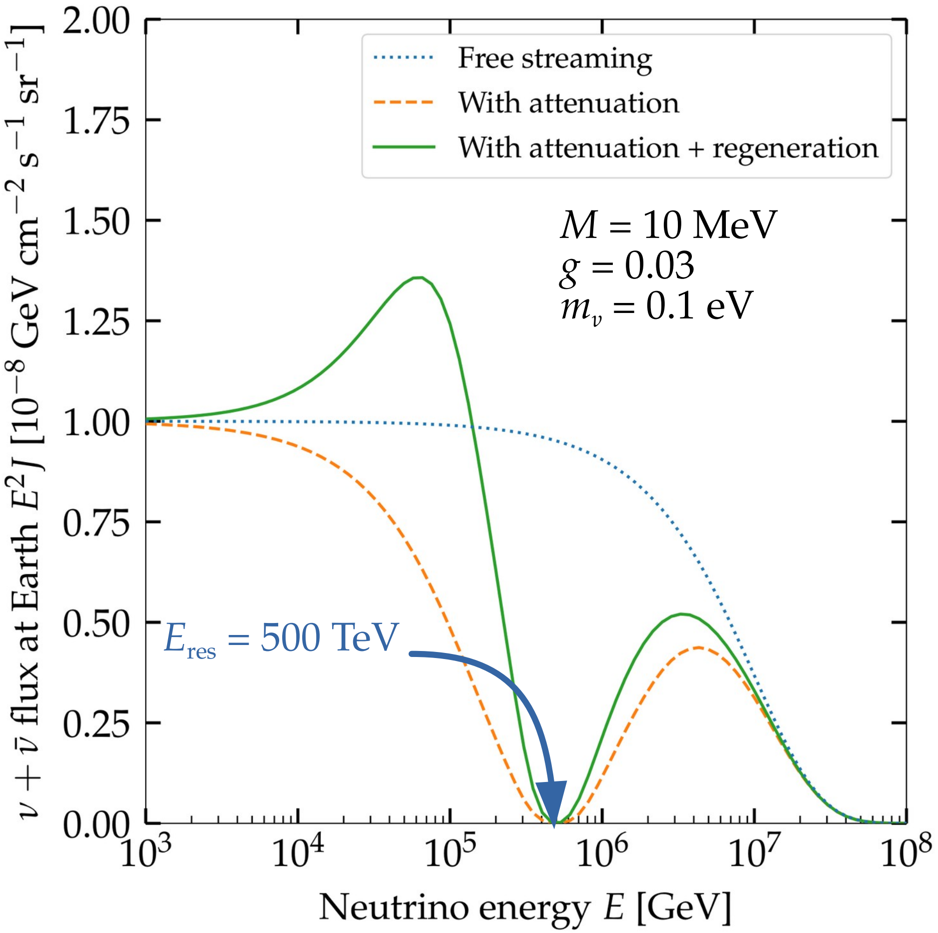

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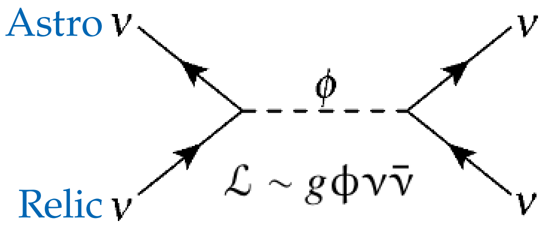

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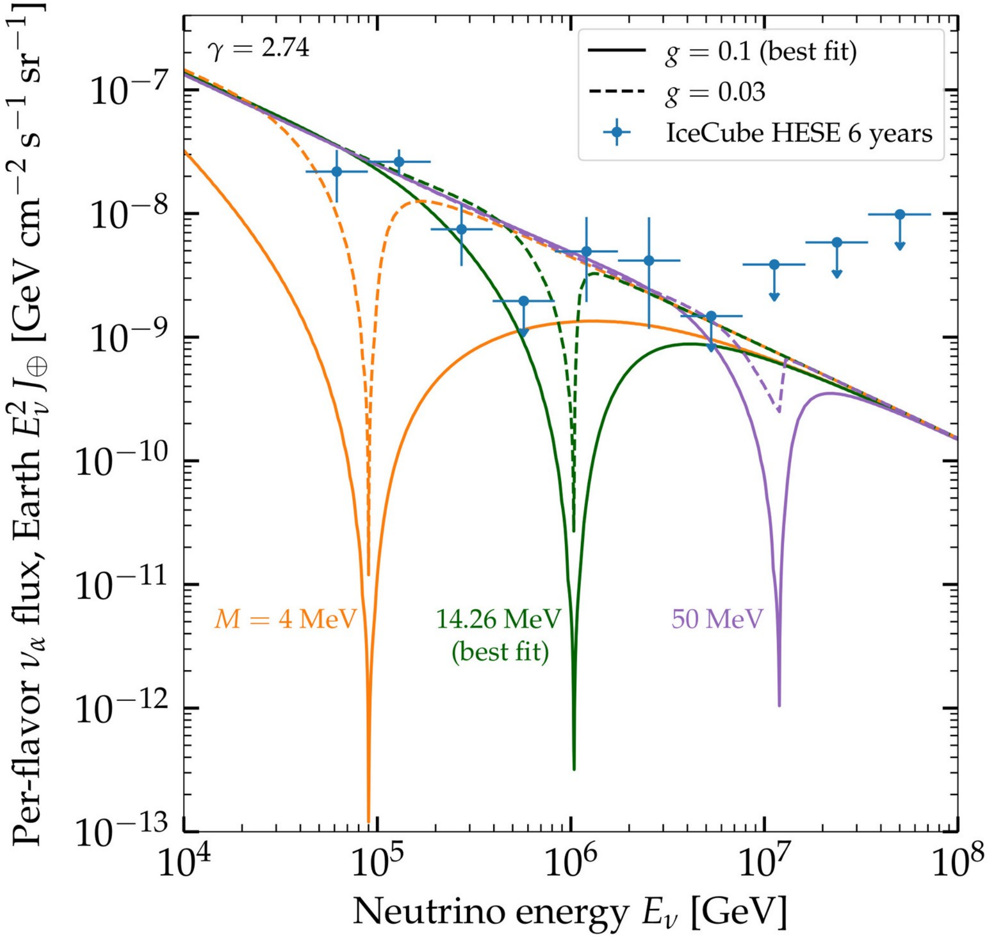

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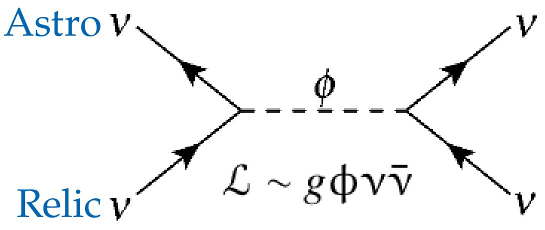

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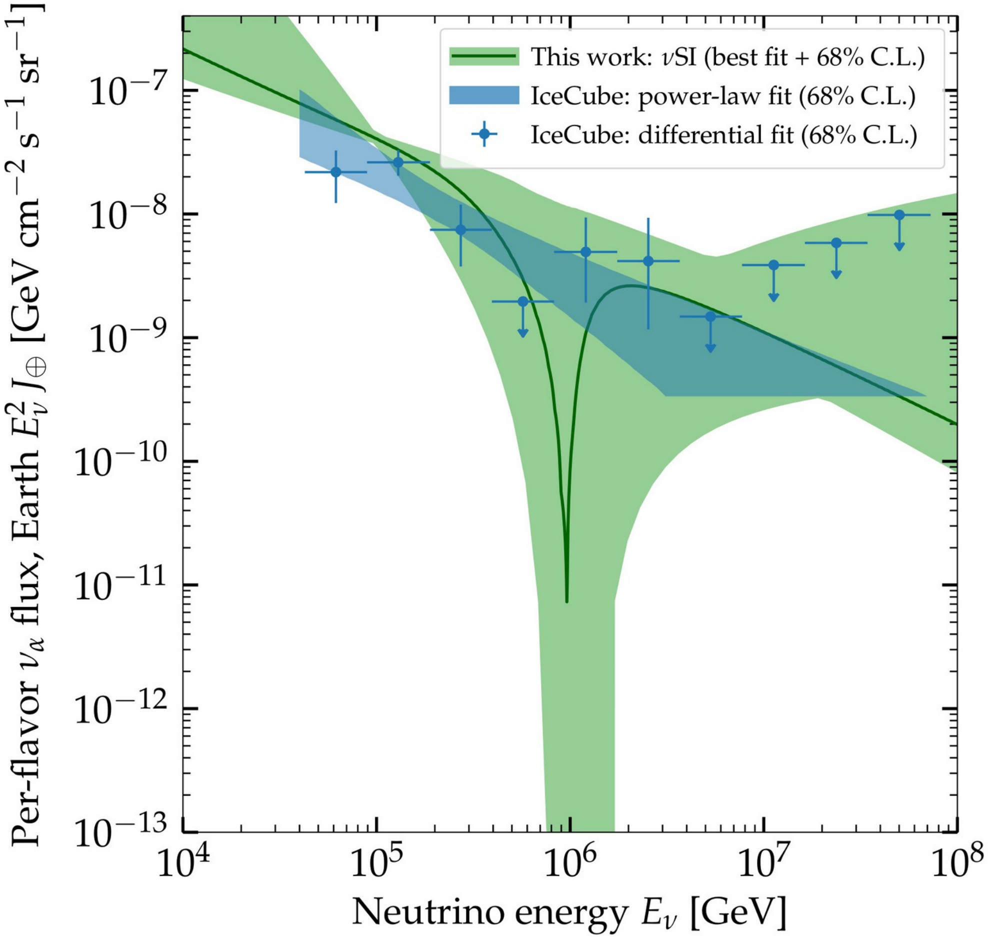
Looking for evidence of νSI

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

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



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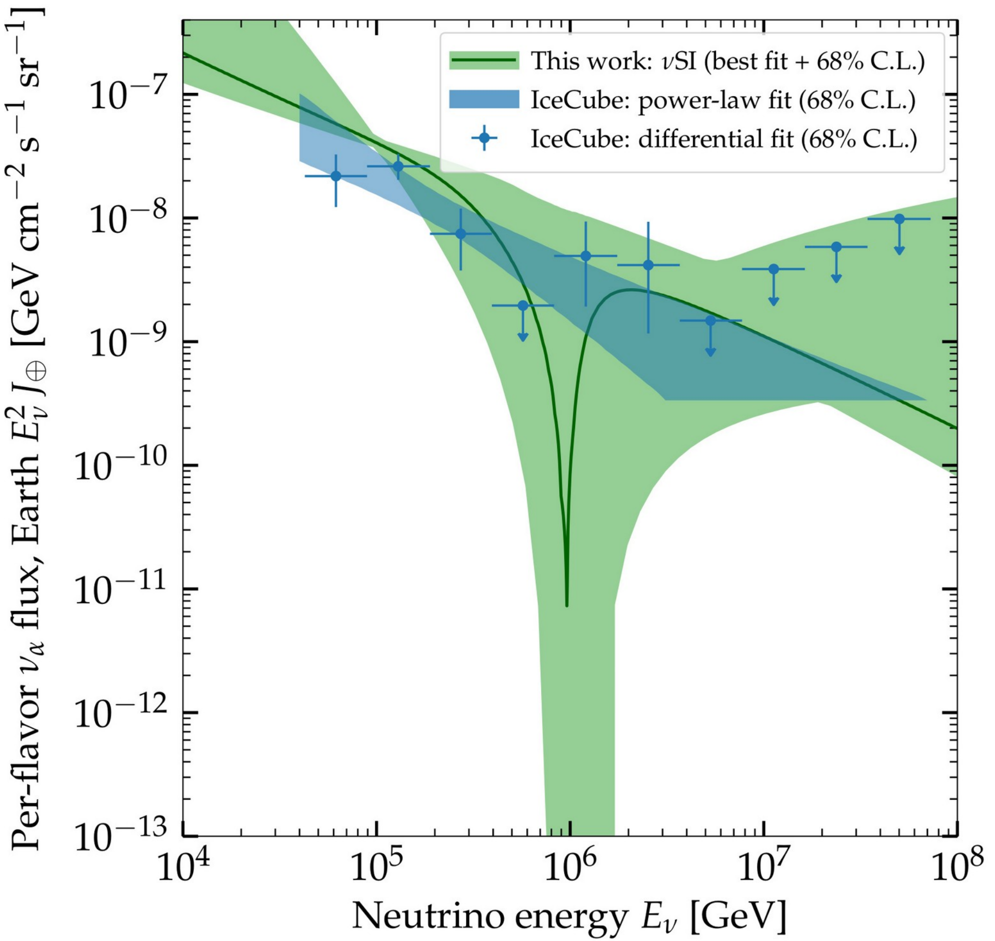

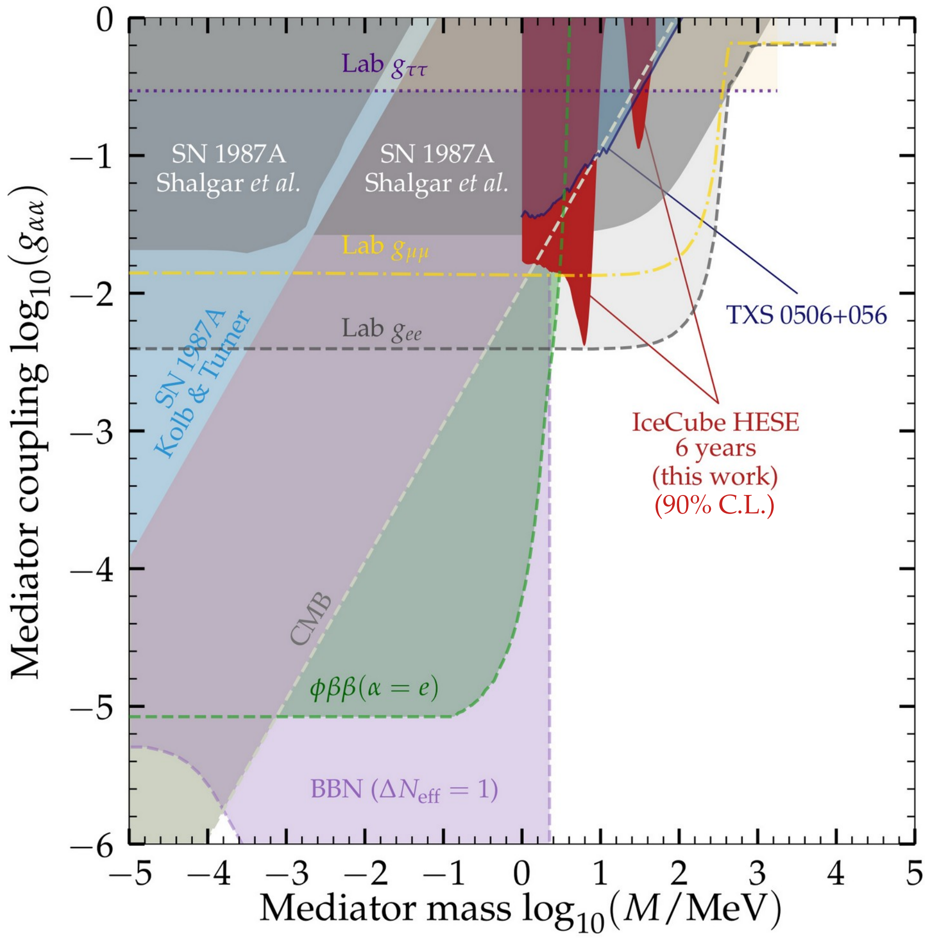

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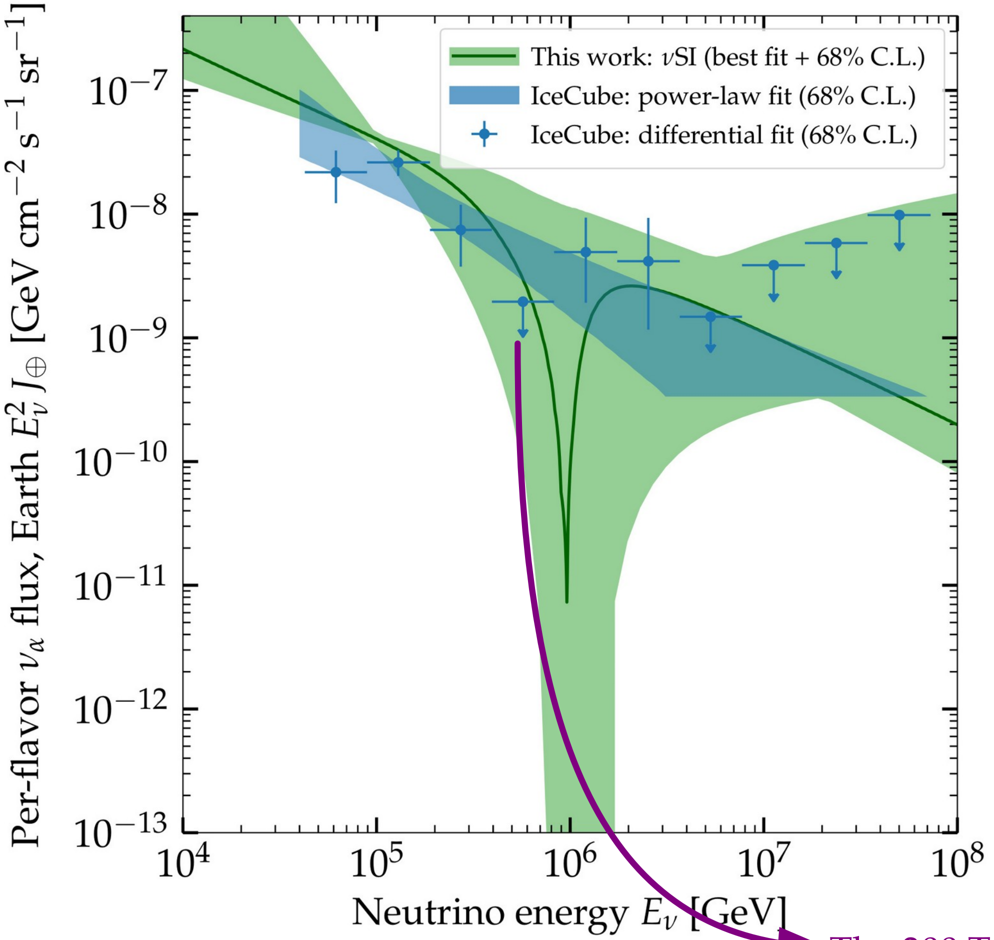

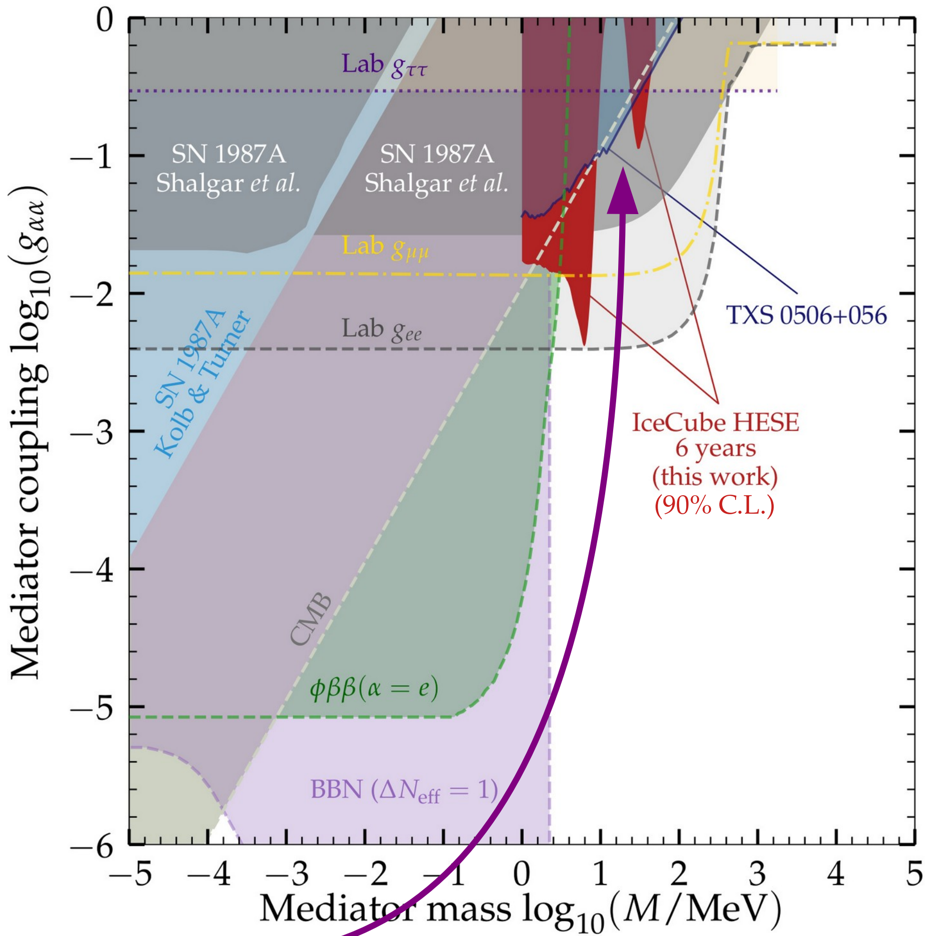

The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

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

5. Flavor

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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

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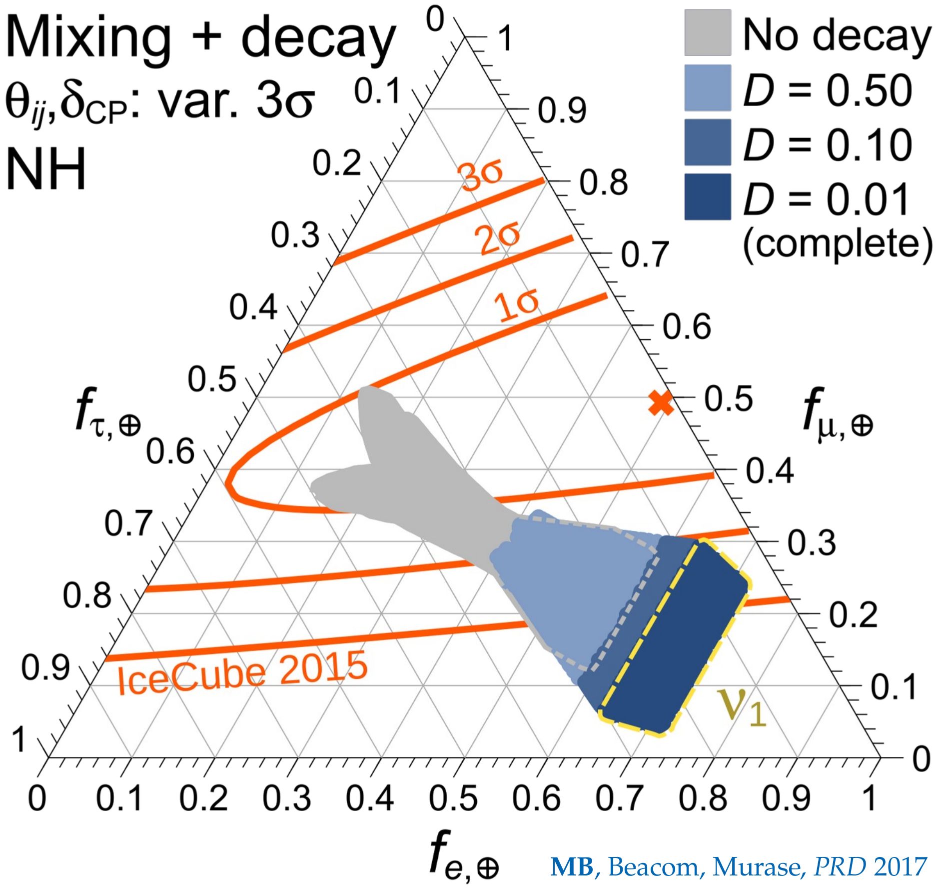

MB, Beacom, Murase, *PRD* 2017

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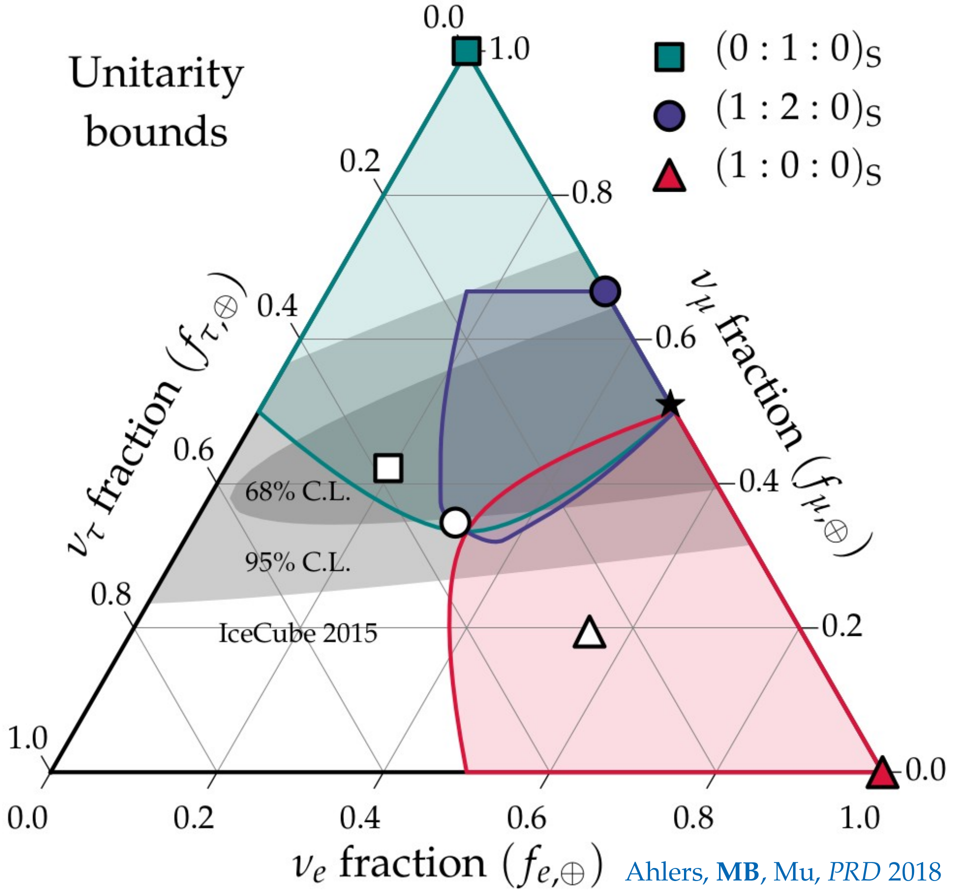

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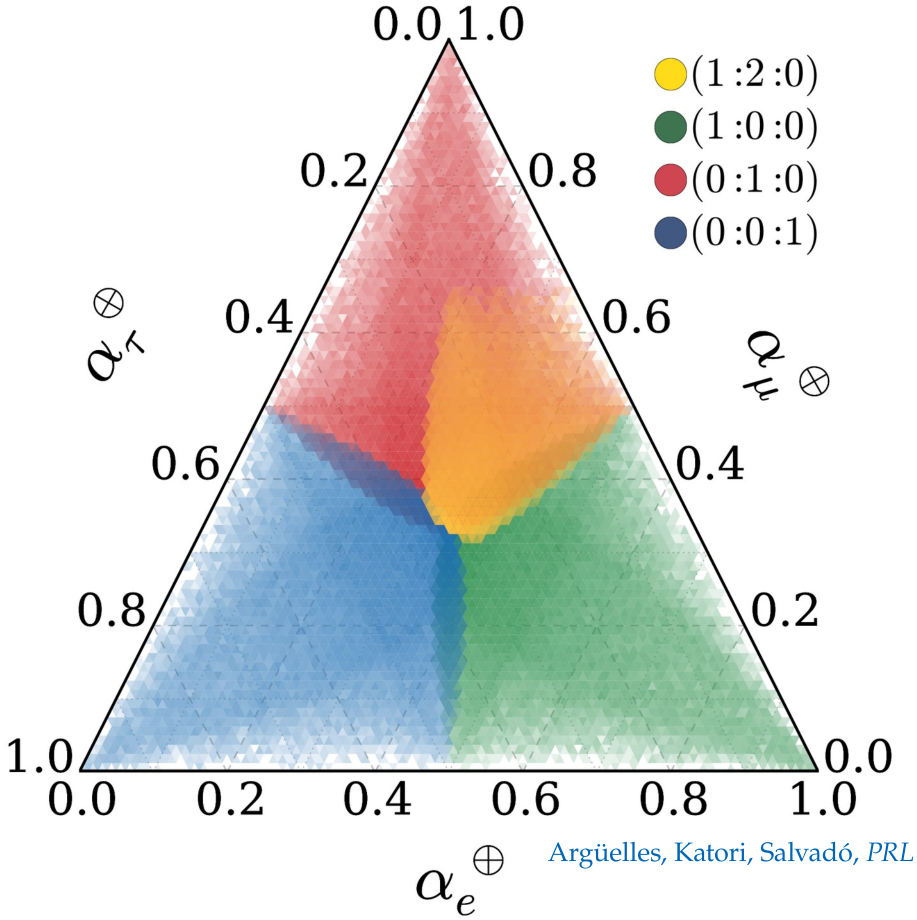

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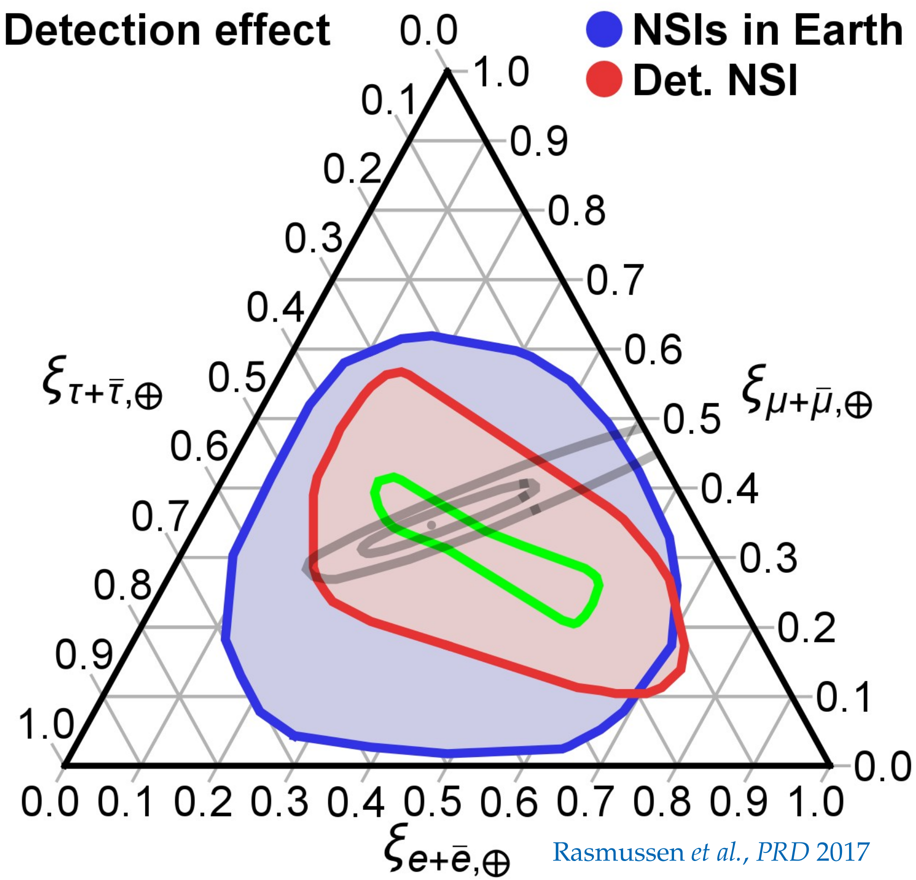

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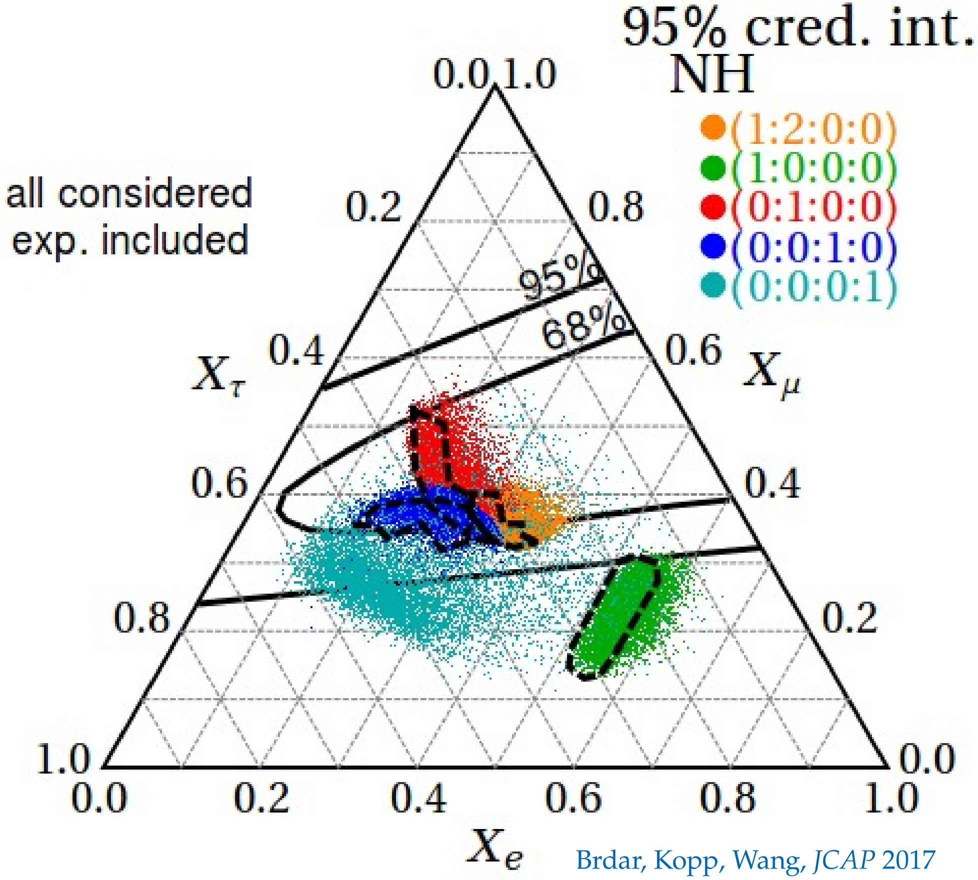

Brdar, Kopp, Wang, *JCAP* 2017

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- ▸ Long-range *e*ν interactions
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Reviews:
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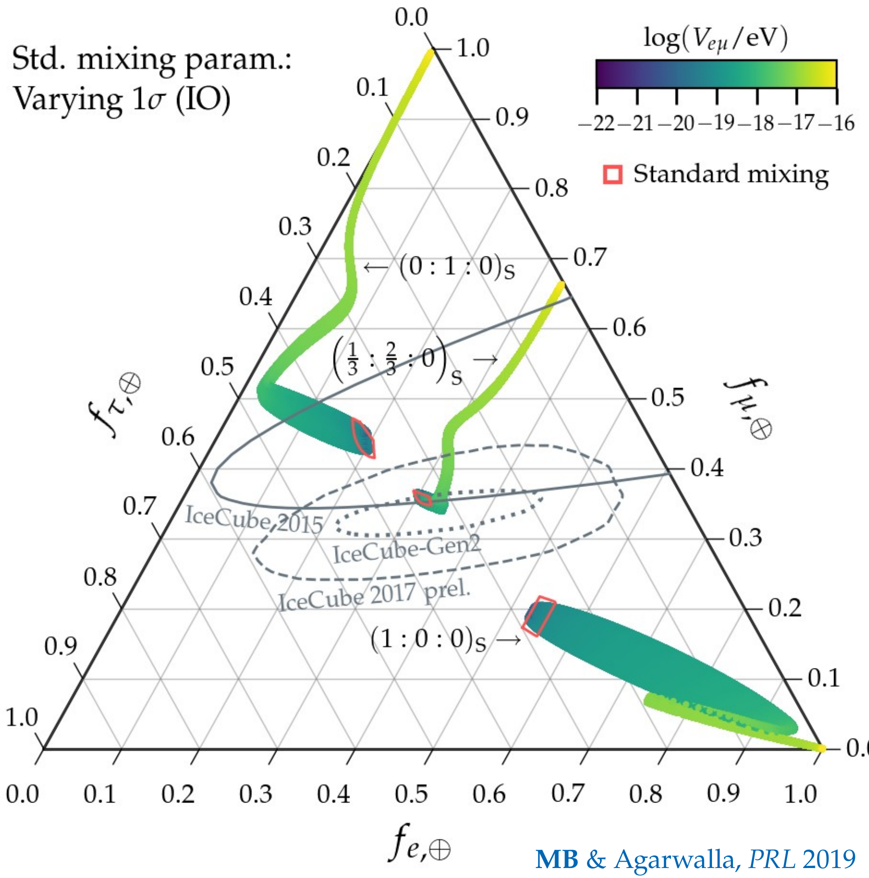

MB & Agarwalla, *PRL* 2019

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 ($\nu_i \to \nu_j + \gamma$): $\tau > 10^{36}\ (m_i/\mathrm{eV})^{-5}$ yr
  - Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$): $\tau > 10^{57}\ (m_i/\mathrm{eV})^{-9}$ yr
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  » Age of Universe (~ 14.5 Gyr)

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

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

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  Nambu-Goldstone boson of a broken symmetry

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

Astrophysical sources

Earth

L ~ up to a few Gpc

E.g.,

Decay changes the number

of each ν mass eigenstate, N_1, N_2, N_3

?

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

Mass of ν_i Lifetime of ν_i

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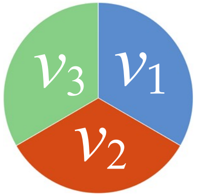

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Only sensitive to their ratio

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

Mass of ν_i Lifetime of ν_i

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Lower-E ν are longer-lived…

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

… but ν that travel longer L are more attenuated!

Astrophysical sources

Earth

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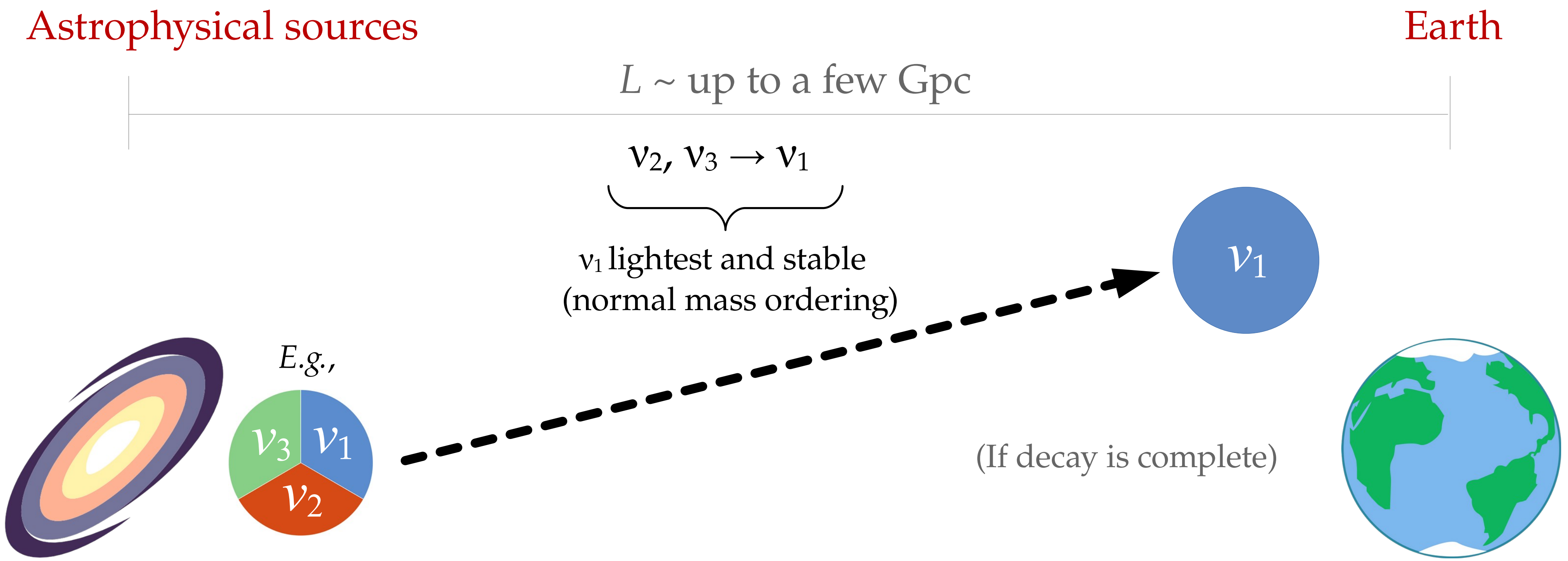
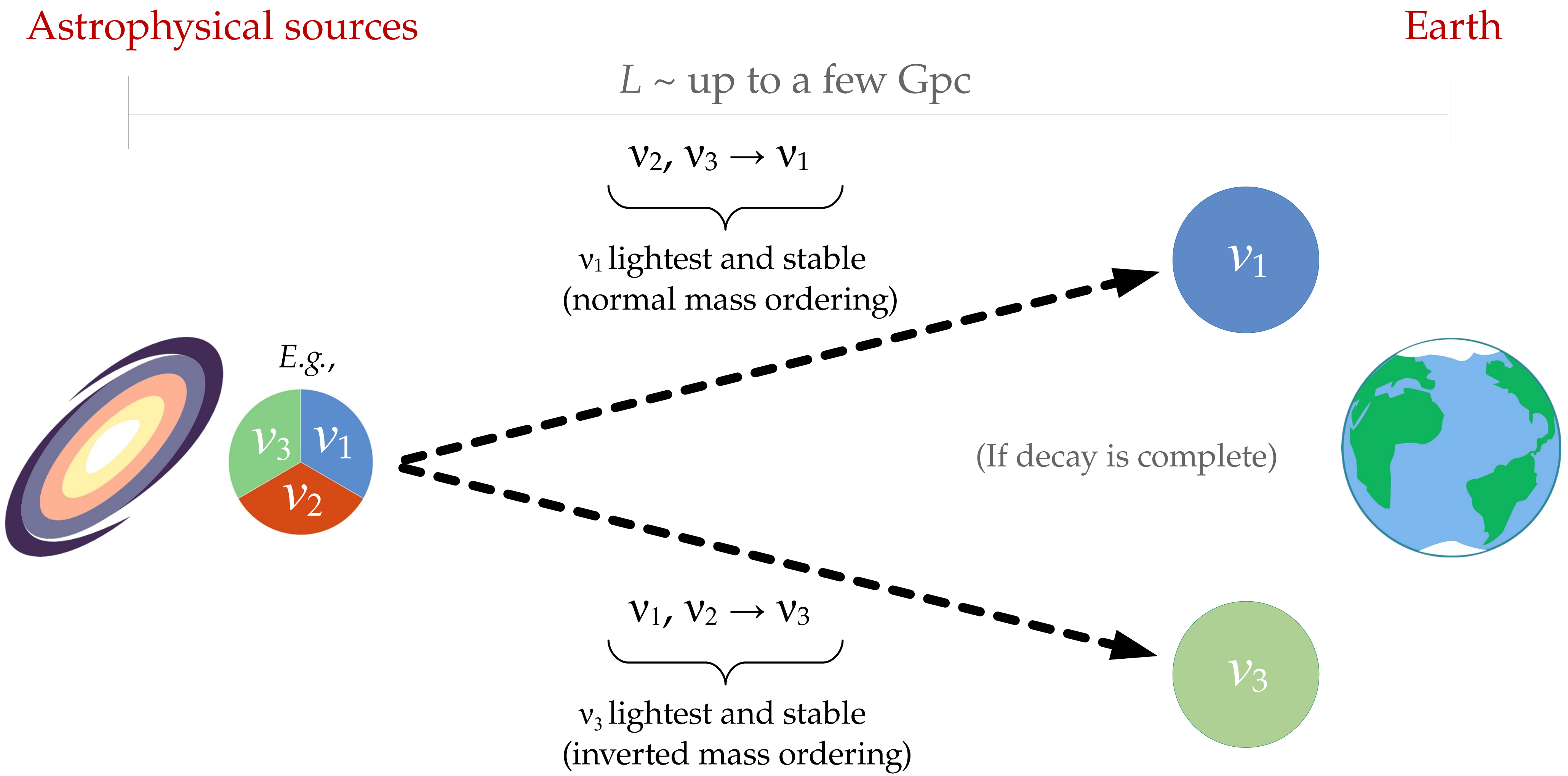
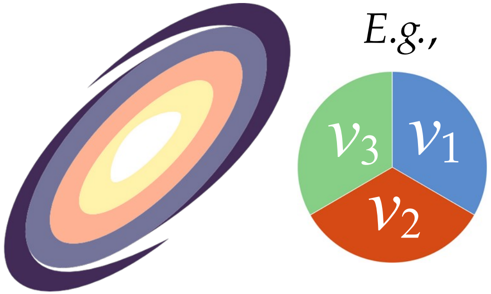

Astrophysical sources
Earth
L ~ up to a few Gpc
$\nu_2, \nu_3 \rightarrow \nu_1$
ν_1 lightest and stable
(normal mass ordering)
ν_1
E.g.,
ν_3
ν_1
ν_2
(If decay is complete)


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

Astrophysical sources   Earth

L ~ up to a few Gpc



E.g.,

$\nu_2, \nu_3 \to \nu_1$

ν_1 lightest and stable
(normal mass ordering)

(If decay is complete)

$\nu_1, \nu_2 \to \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

Fine print:

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

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_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

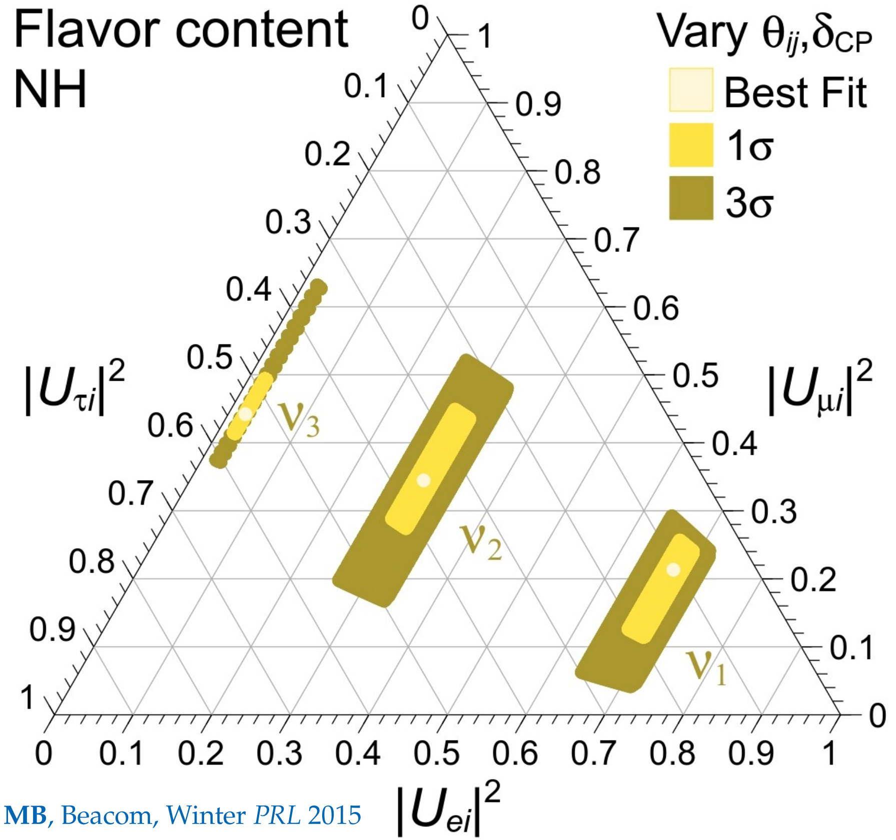
Flavor content of mass eigenstates:

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)

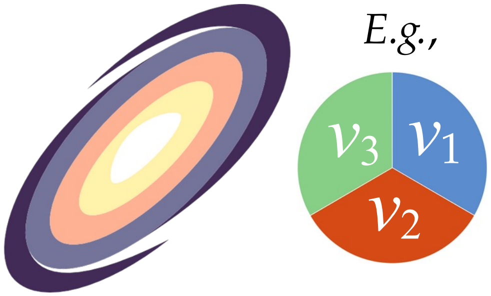


MB, Beacom, Winter *PRL* 2015

What does neutrino decay change?

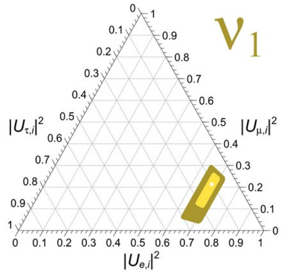
Flavor composition ⟺ Spectrum shape ⟺ Event rate

E.g.,



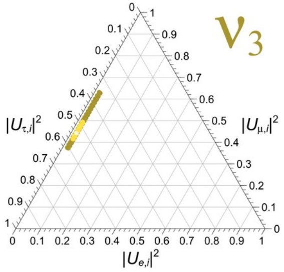
$\nu_2, \nu_3 \rightarrow \nu_1$

ν_1 lightest and stable
(normal mass ordering)



$\nu_1, \nu_2 \rightarrow \nu_3$

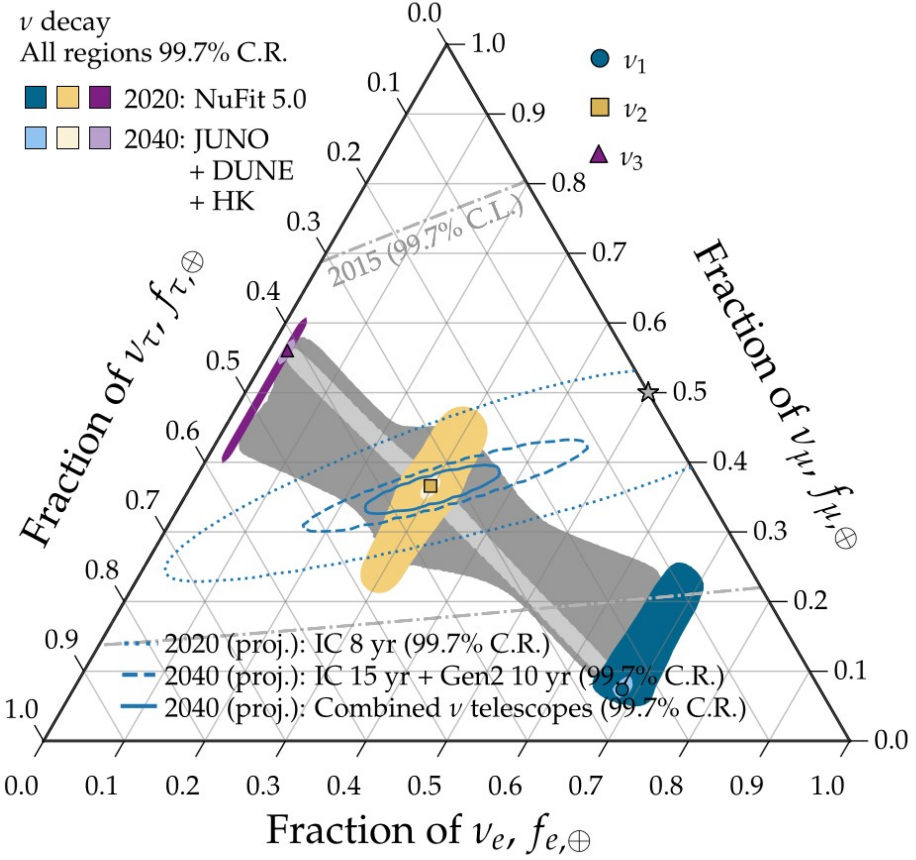
ν_3 lightest and stable
(inverted mass ordering)



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

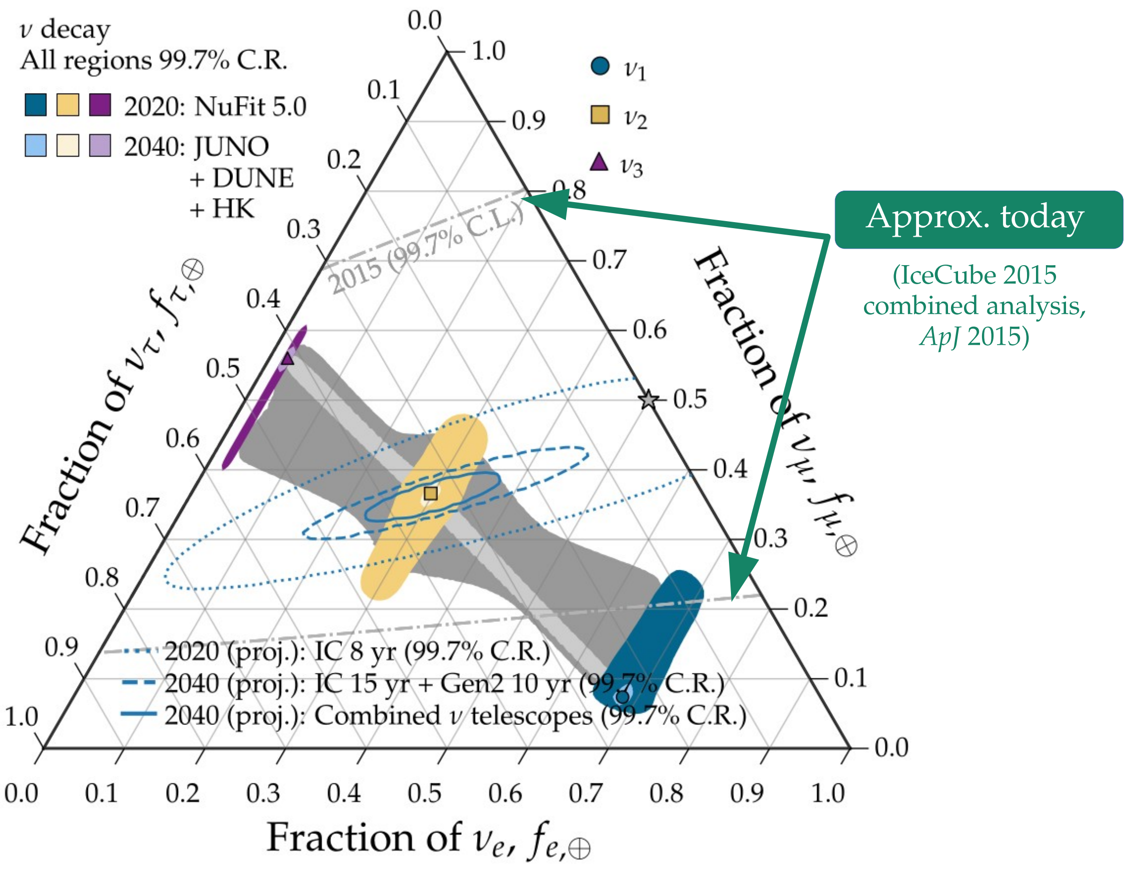
Flavor composition ⇔ Spectrum shape ⇔ Event rate



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?

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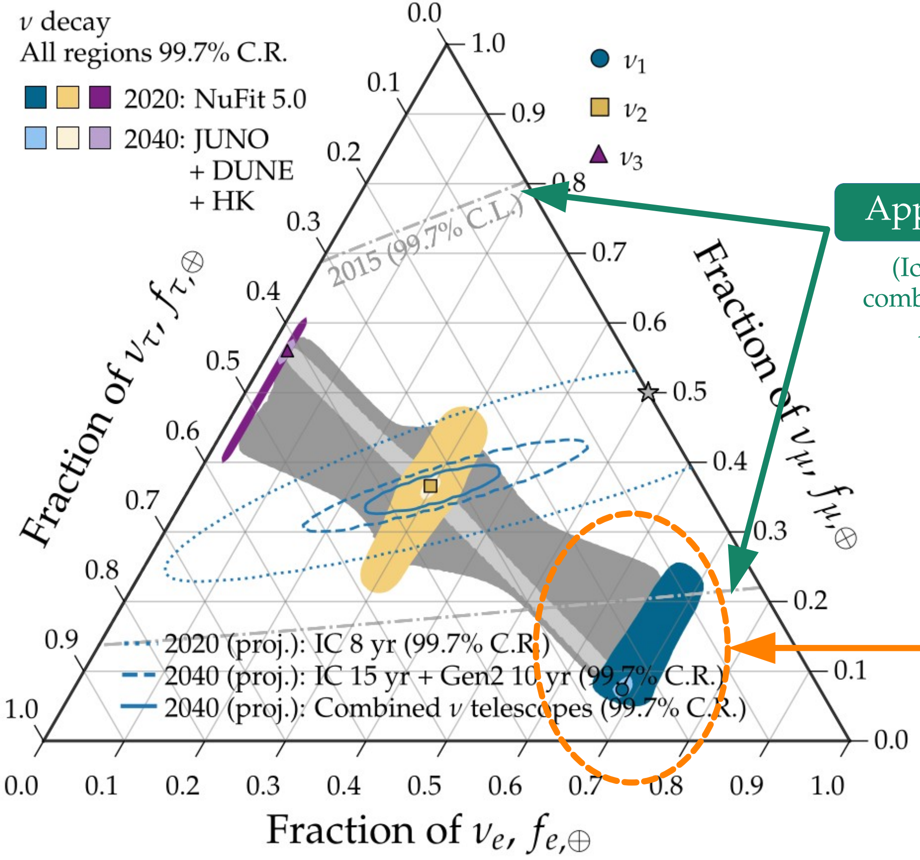
Flavor composition ⟺ Spectrum shape ⟺ Event rate



Approx. today

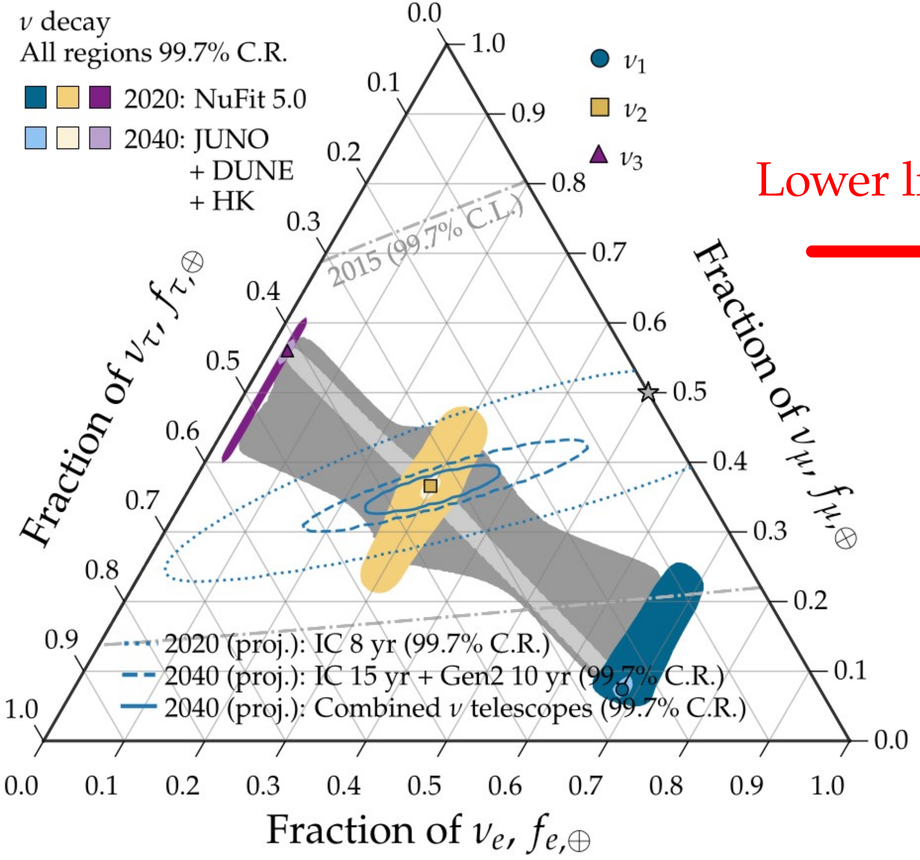
(IceCube 2015 combined analysis, *ApJ* 2015)

Complete decay into ν_1 disfavored by 2015 IceCube flavor measurement

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

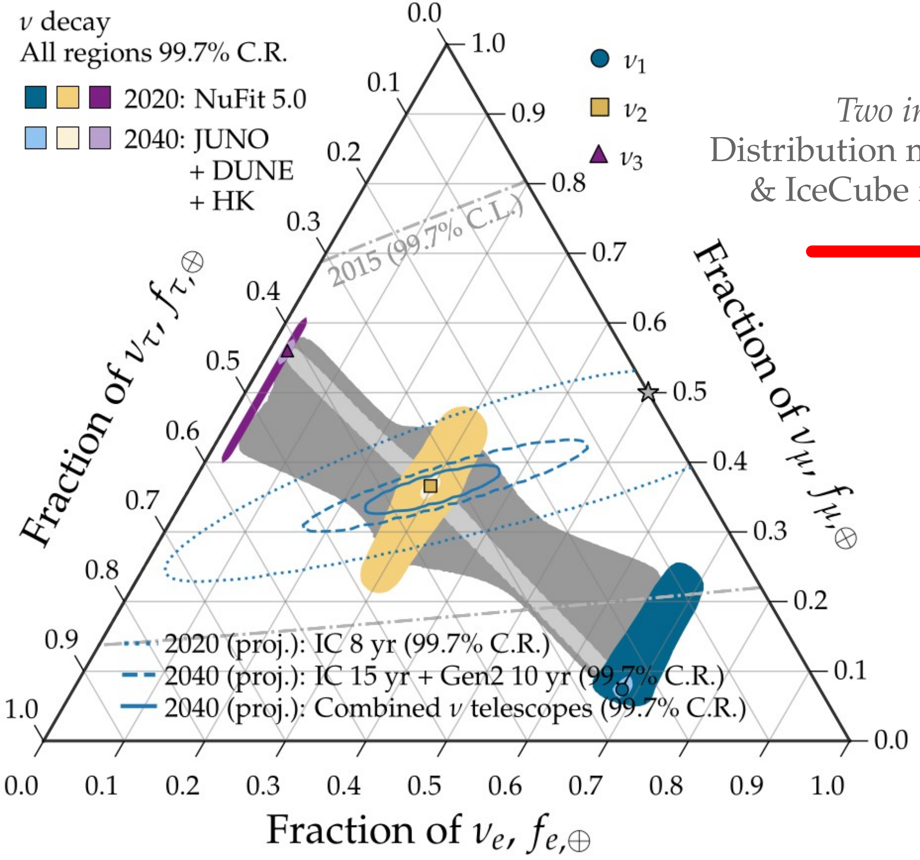


Lower limit on τ/m →

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

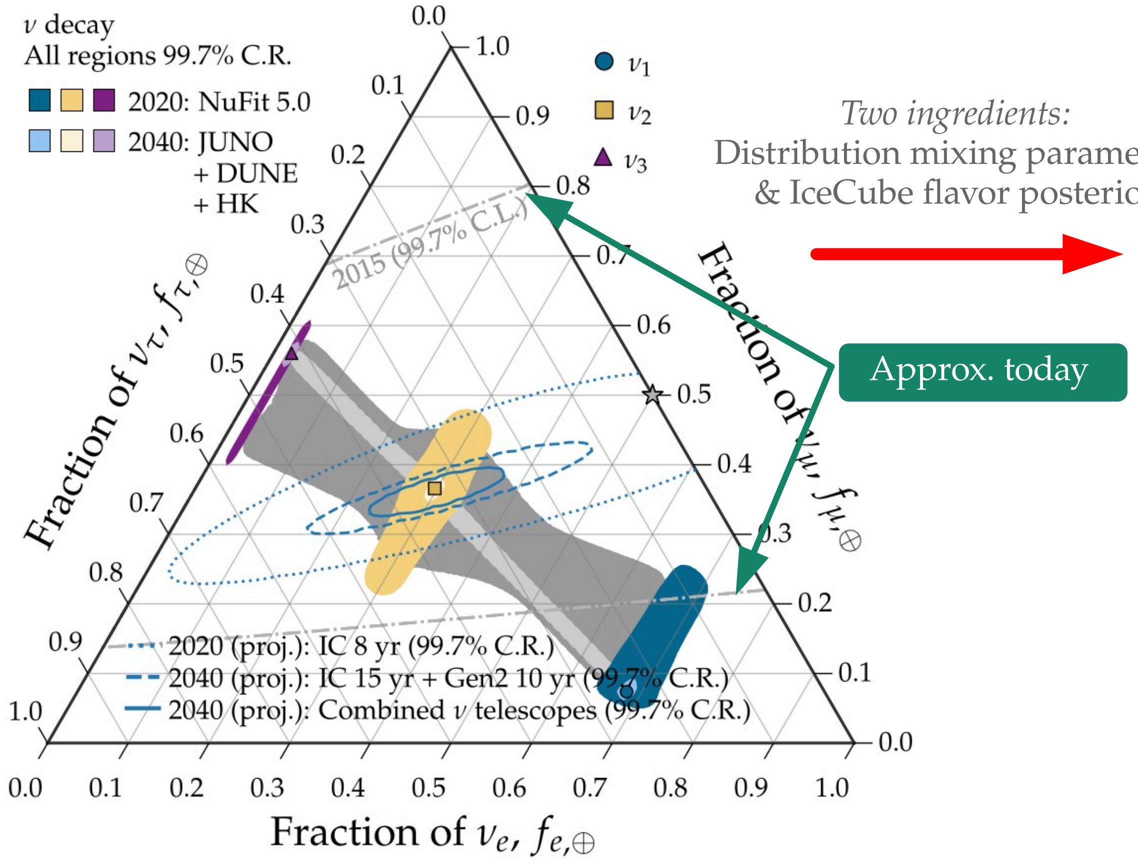


Two ingredients:
Distribution mixing parameters
& IceCube flavor posterior

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



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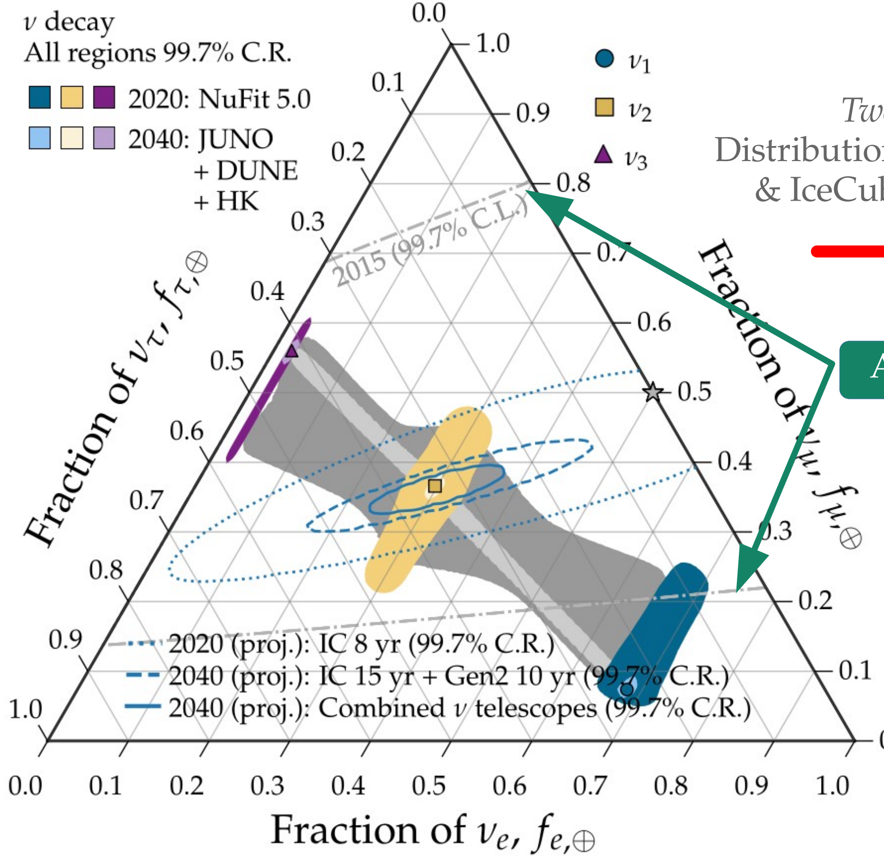
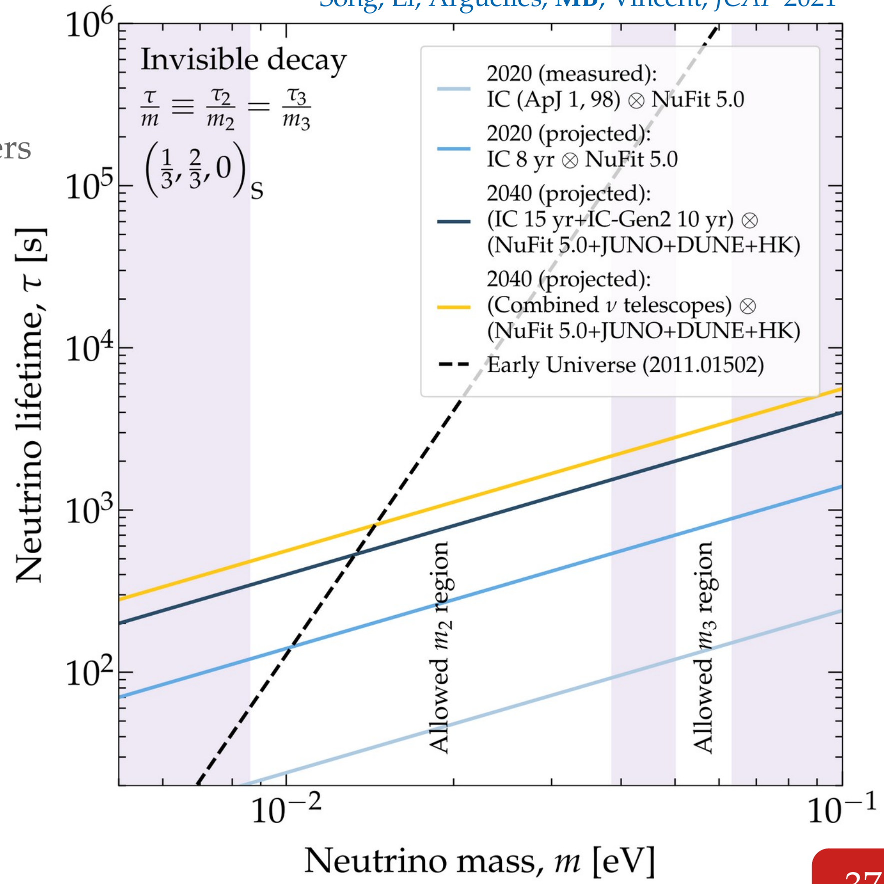
Flavor composition ⇔ Spectrum shape ⇔ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

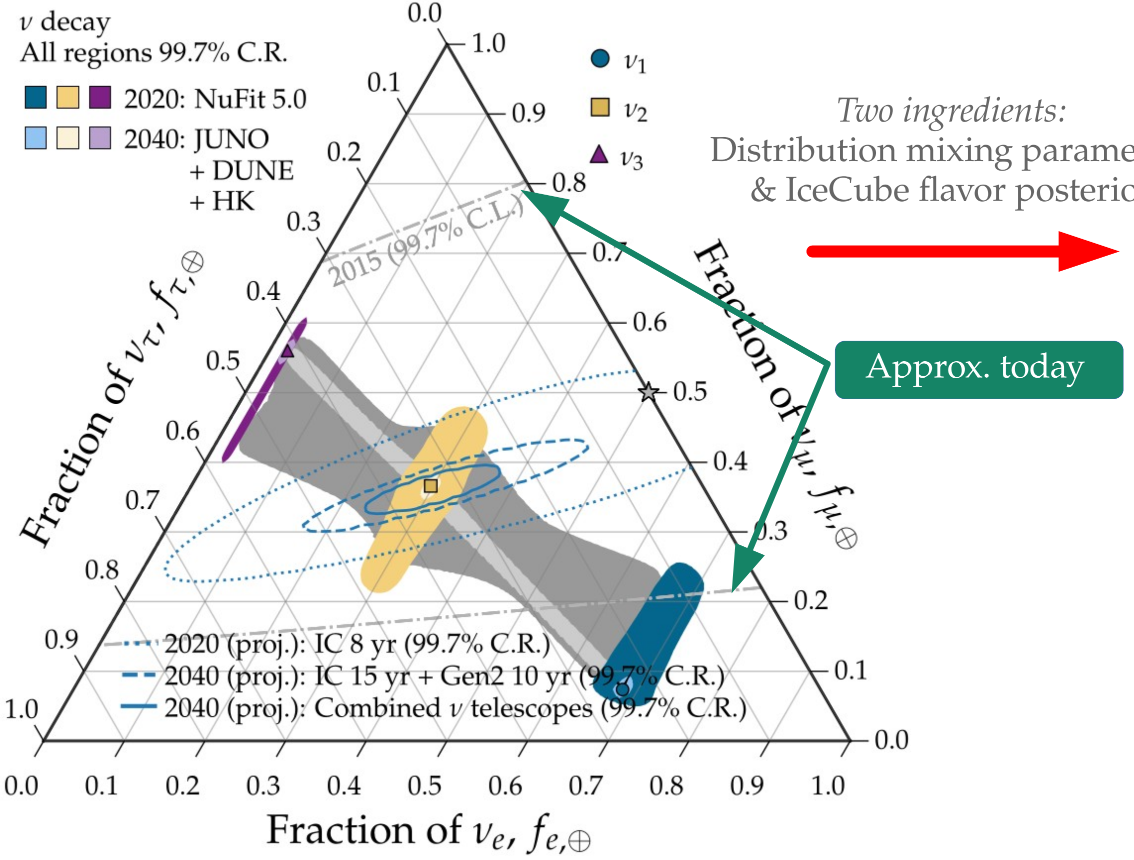
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

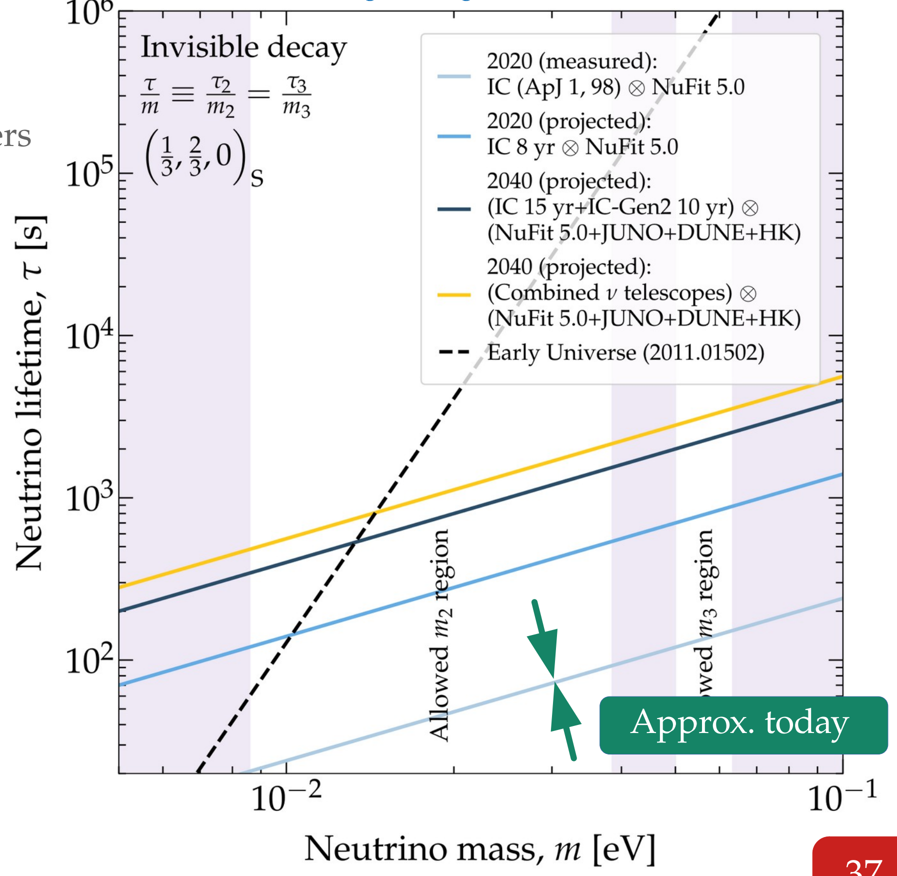
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

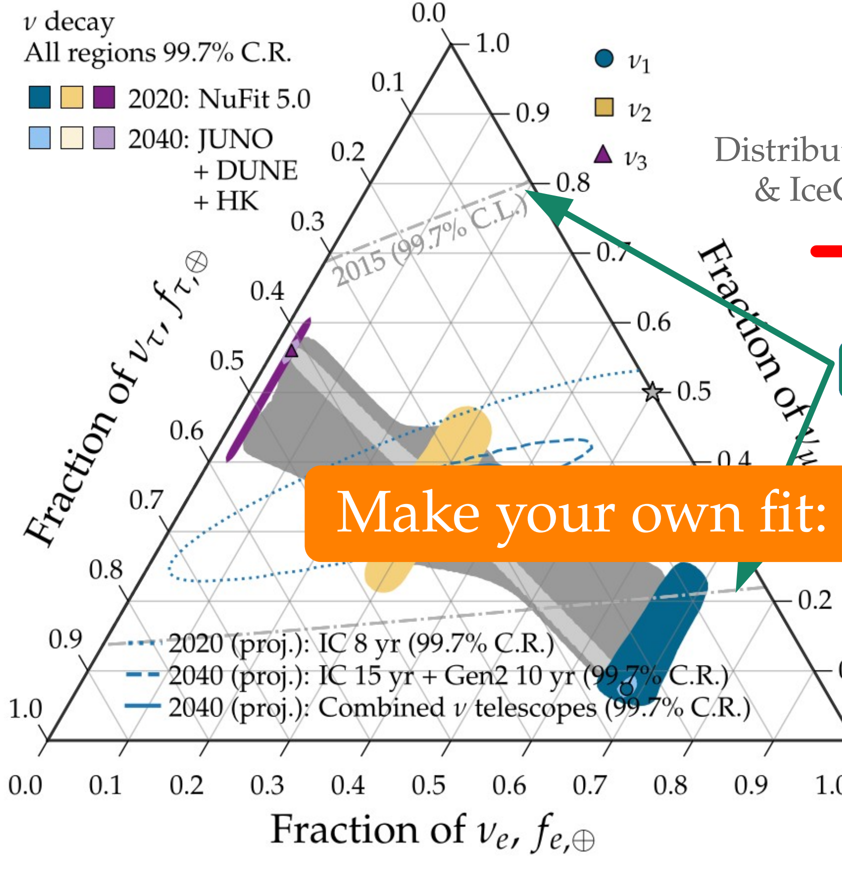
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021



What does neutrino decay change?

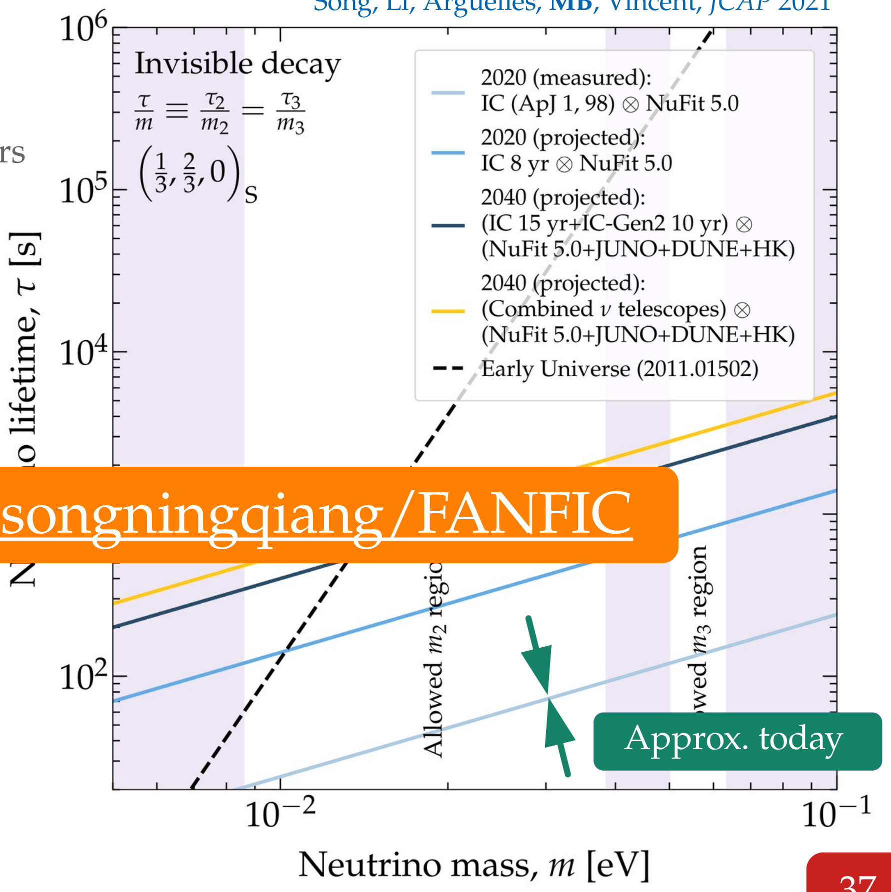
See also: Beacom *et al.*, *PRL* 2002 / Baerwald, **MB**, Winter, *JCAP* 2012 / **MB**, Beacom, Murase, *PRD* 2017 / Rasmussen *et al.*, *PRD* 2017 / Denton & Tamborra, *PRL* 2018 / Abdullahi & Denton, *PRD* 2020 / **MB**, 2004.06844

Flavor composition ⟺ Spectrum shape ⟺ Event rate



Two ingredients:
Distribution mixing parameters & IceCube flavor posterior

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

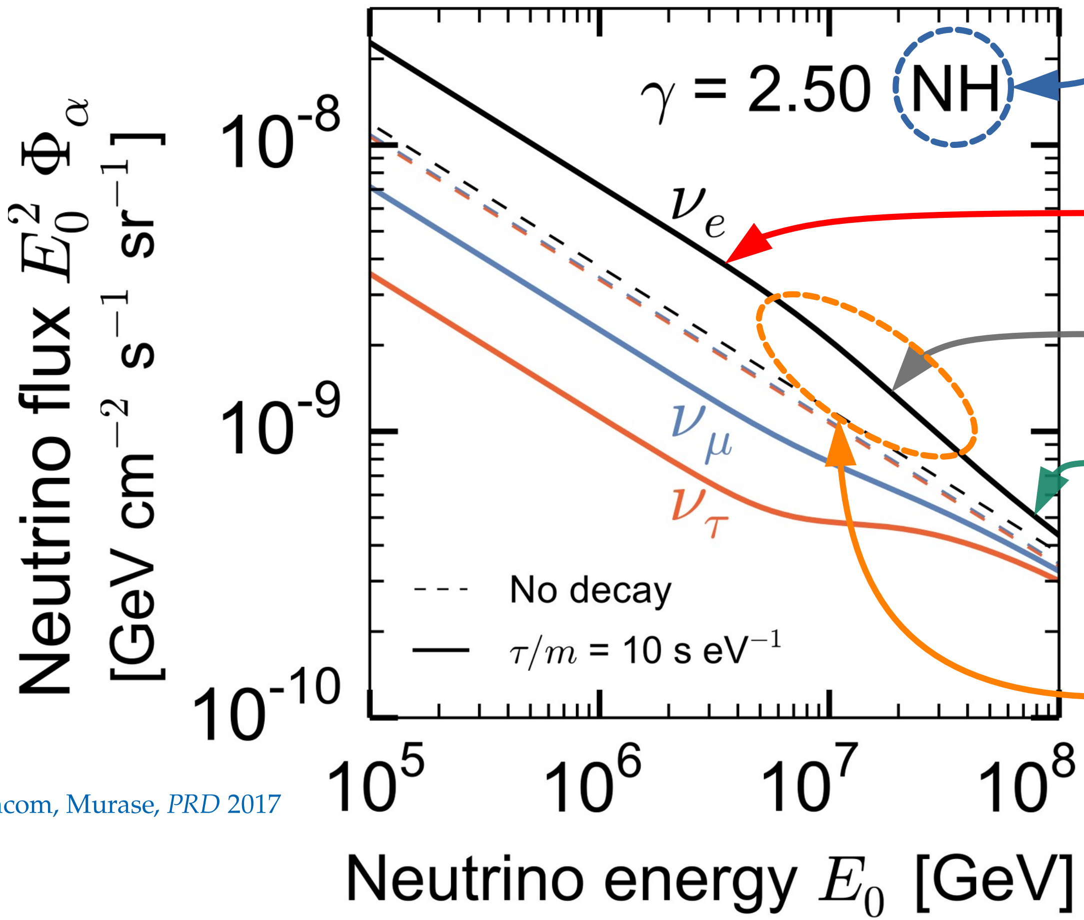


Make your own fit: github.com/songningqiang/FANFIC

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



MB, Beacom, Murase, *PRD* 2017

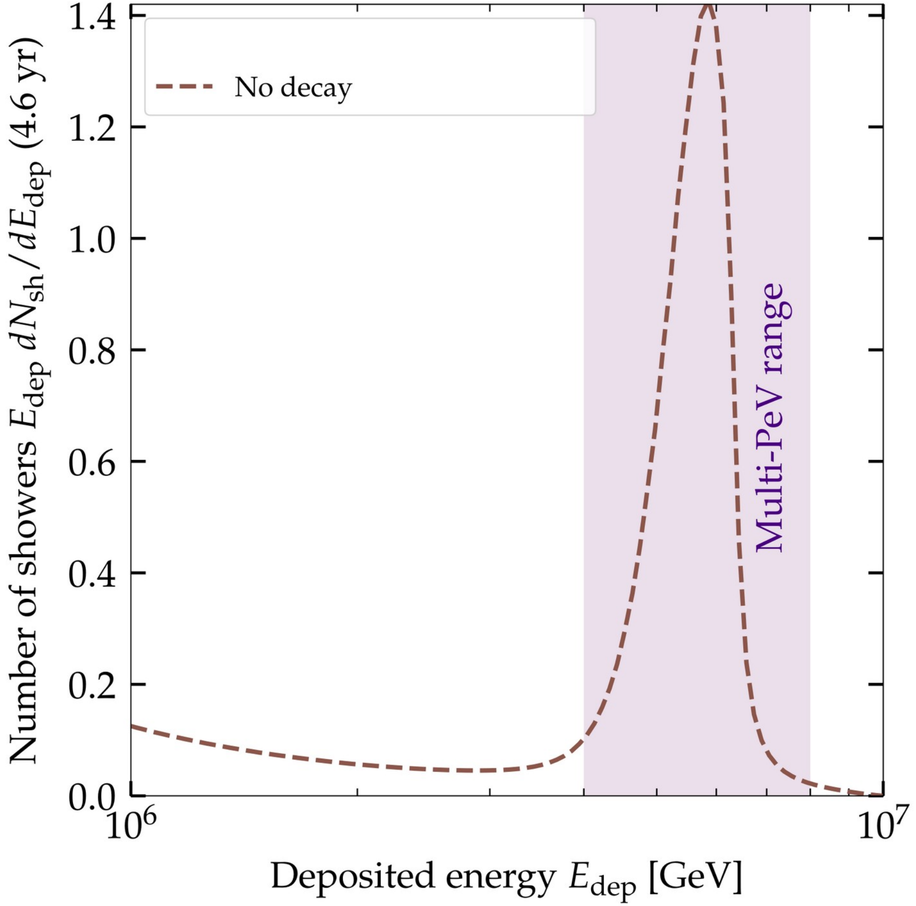
Look for sigmoid-like transition in spectrum: *challenging, but possible with more statistics*!

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

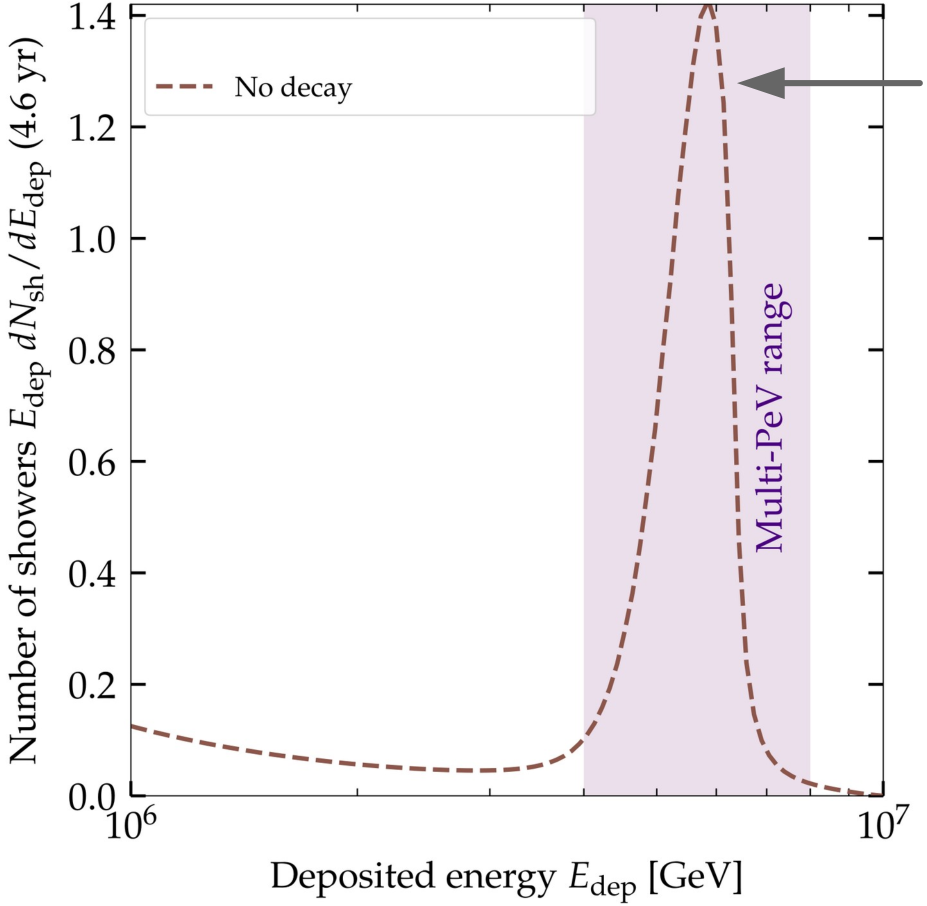


What does neutrino decay change?

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):

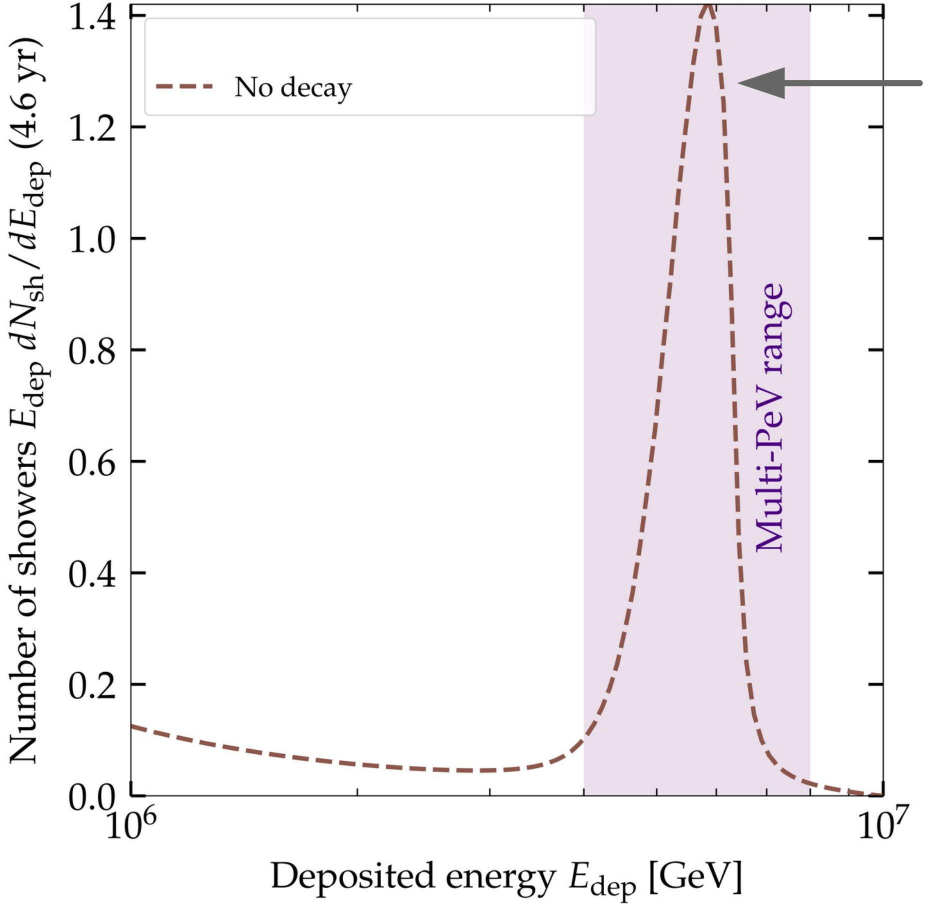
$\bar{\nu}_e + e \to W \to$ hadrons $\to$ shower

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

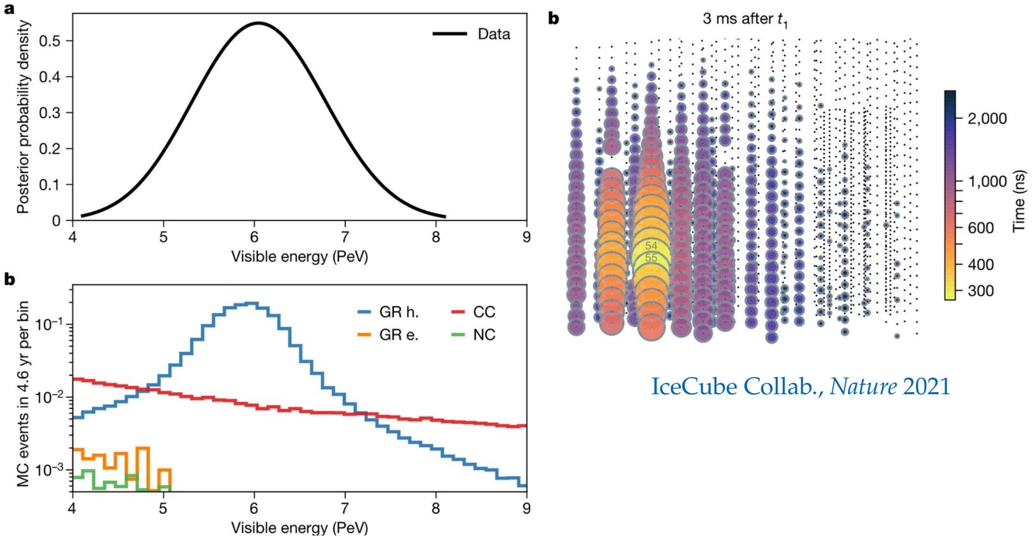
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

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:



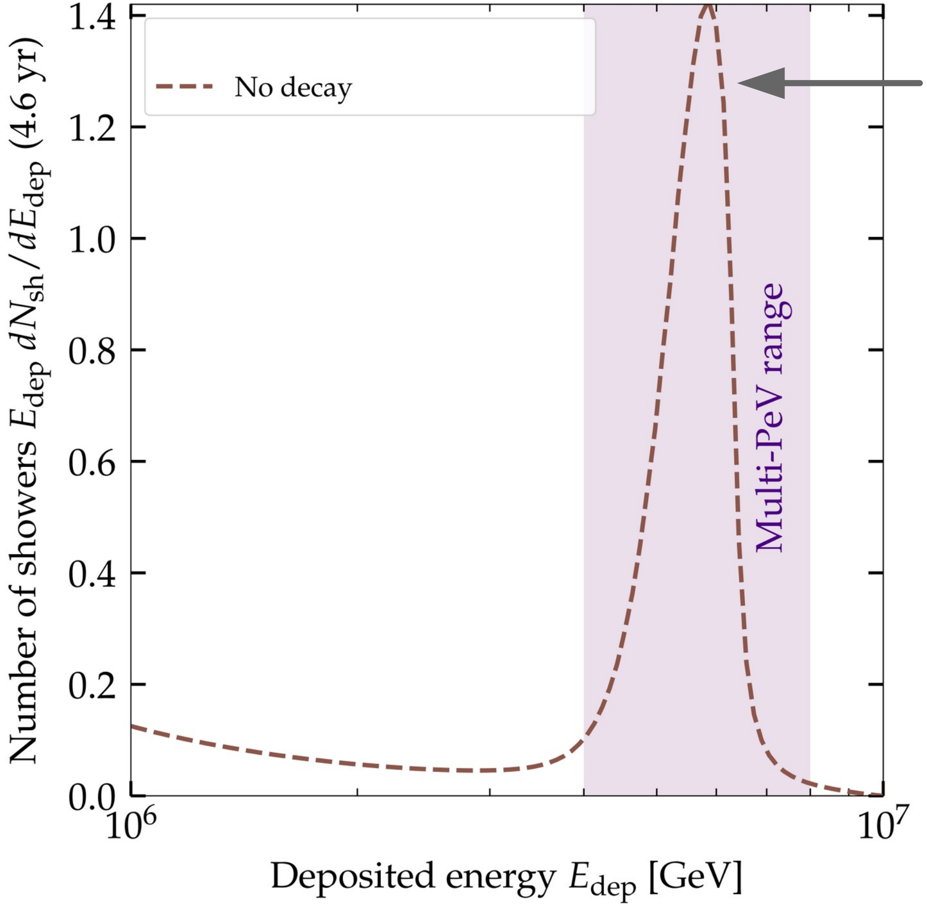
IceCube Collab., *Nature* 2021

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

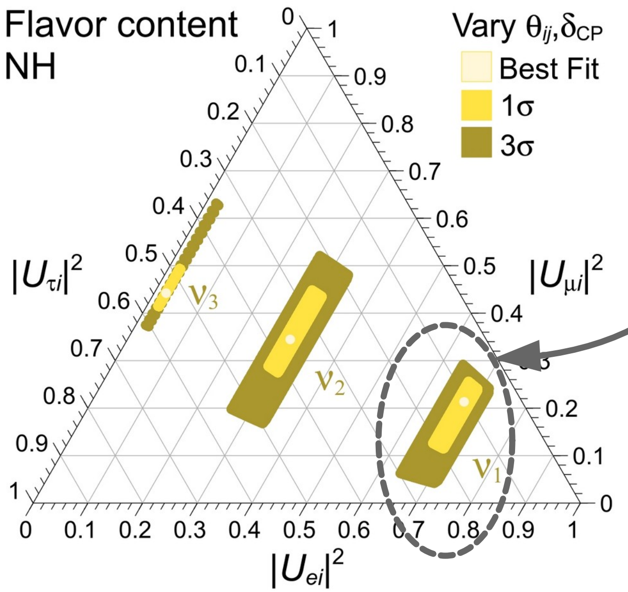
Flavor composition ⟺ Spectrum shape ⟺ Event rate

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

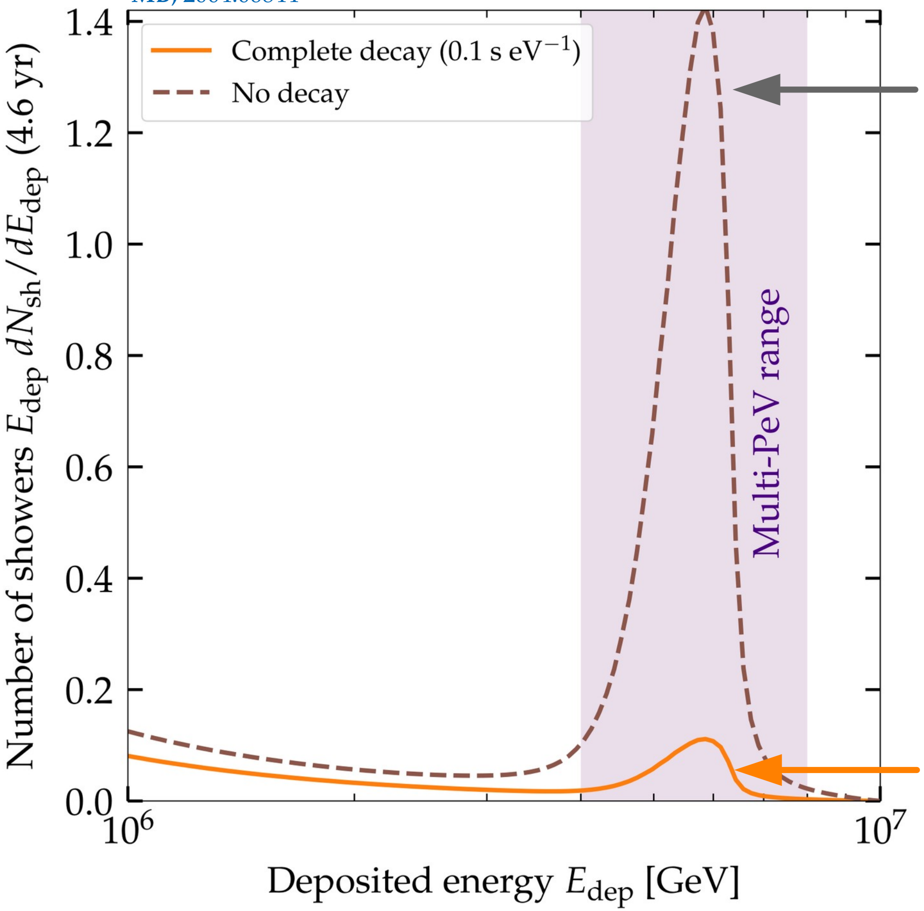


What does neutrino decay change?

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

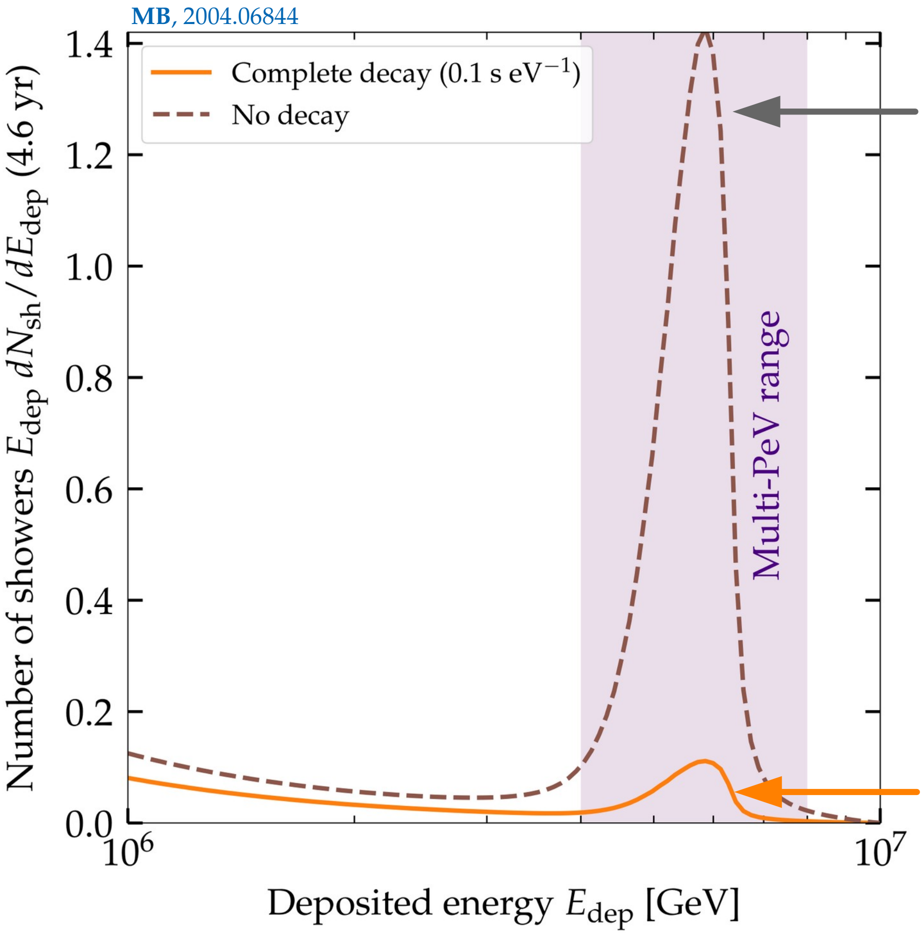
If $\bar{\nu}_1$ had decayed en route to Earth,
there would not have been $\bar{\nu}_e$ left to trigger a GR

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):
$\bar{\nu}_e + e \rightarrow W \rightarrow$ hadrons $\rightarrow$ shower

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

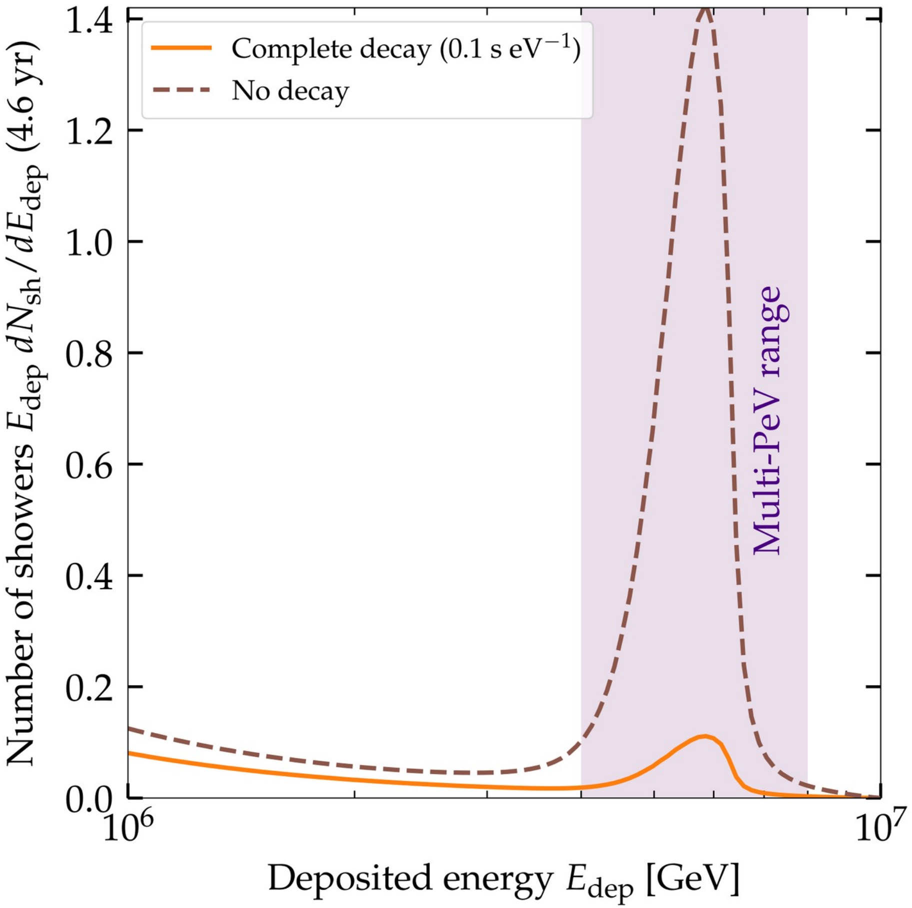
If $\bar{\nu}_1$ had decayed en route to Earth, there would not have been $\bar{\nu}_e$ left to trigger a GR

What does neutrino decay change?

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

Flavor composition ⟺ Spectrum shape ⟺ Event rate

MB, 2004.06844



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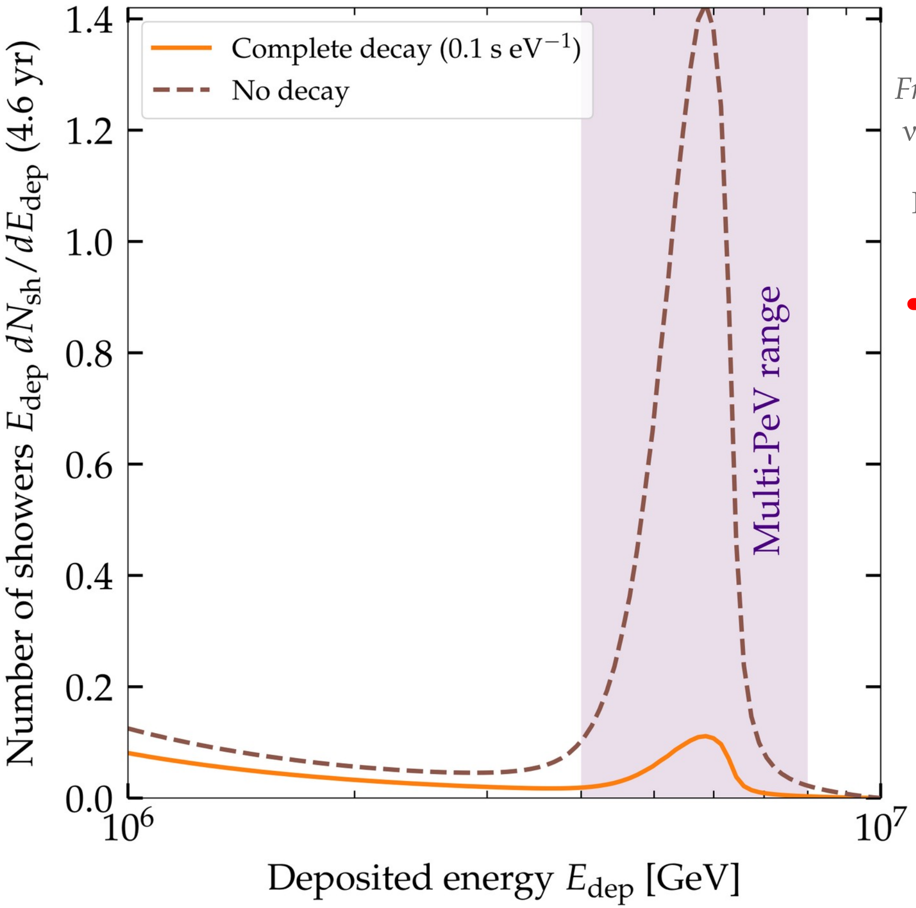
Flavor composition ⟺ Spectrum shape ⟺ **Event rate**

MB, 2004.06844

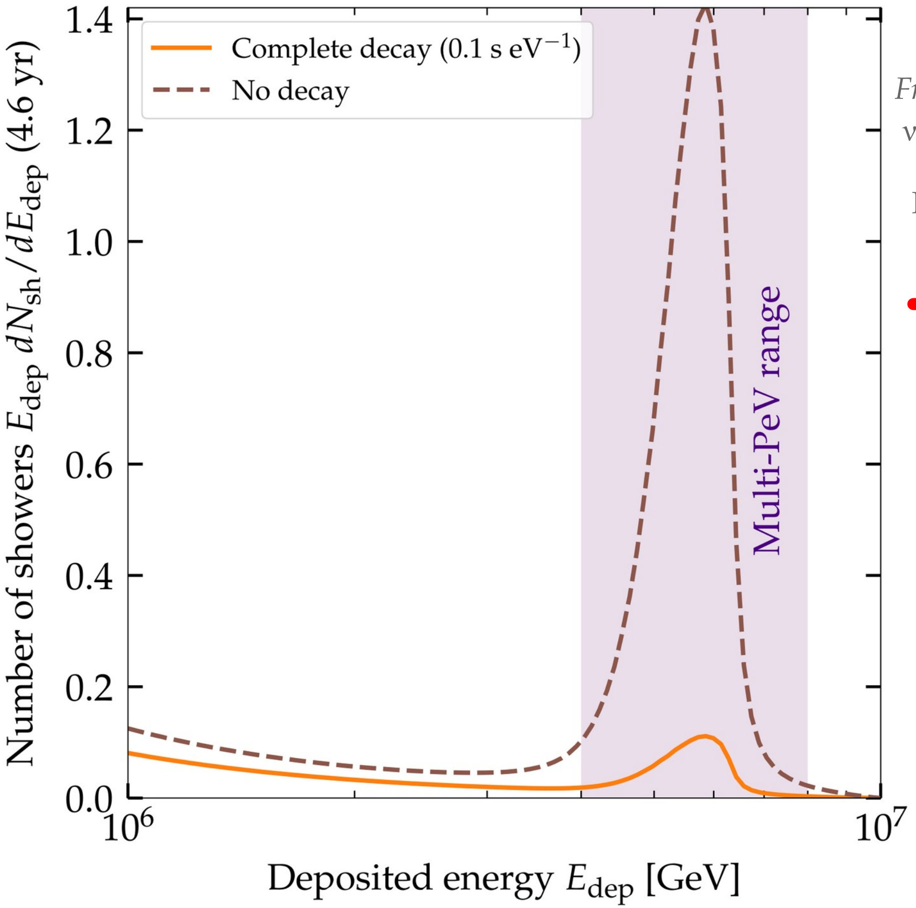


Free parameters:
ν_1, ν_2 lifetimes
Mix. par.
Flavor ratios
$\bar{\nu}/\nu$ ratio

What does neutrino decay change?

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

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



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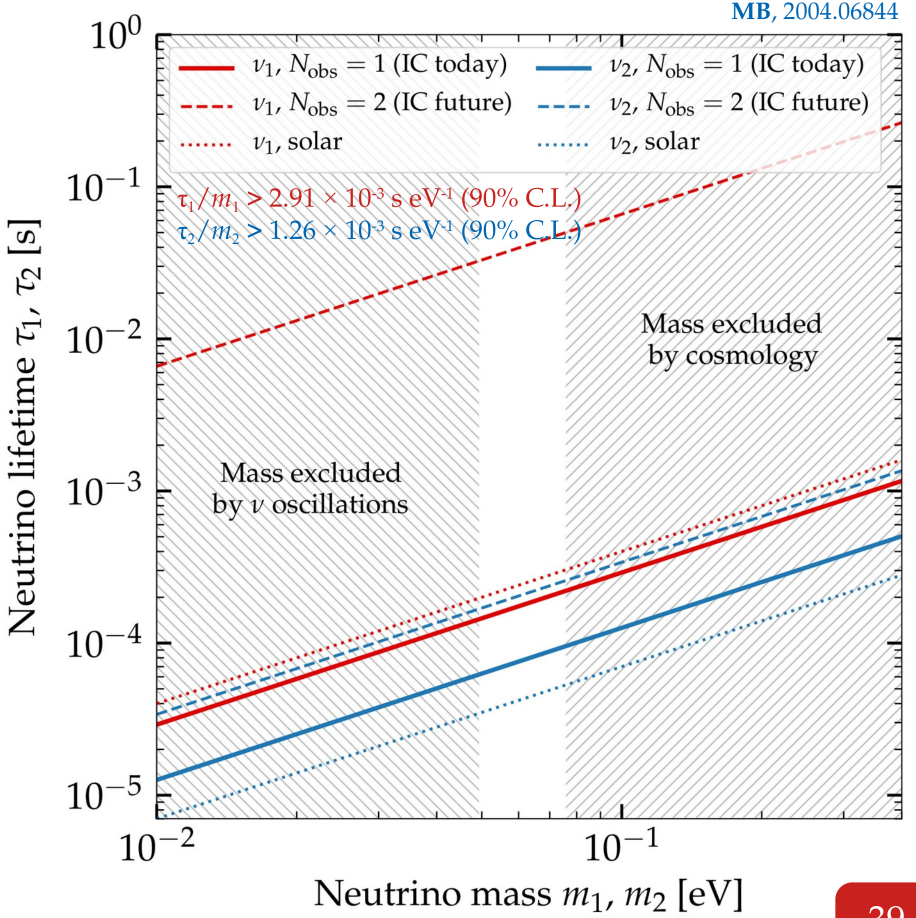
MB, 2004.06844



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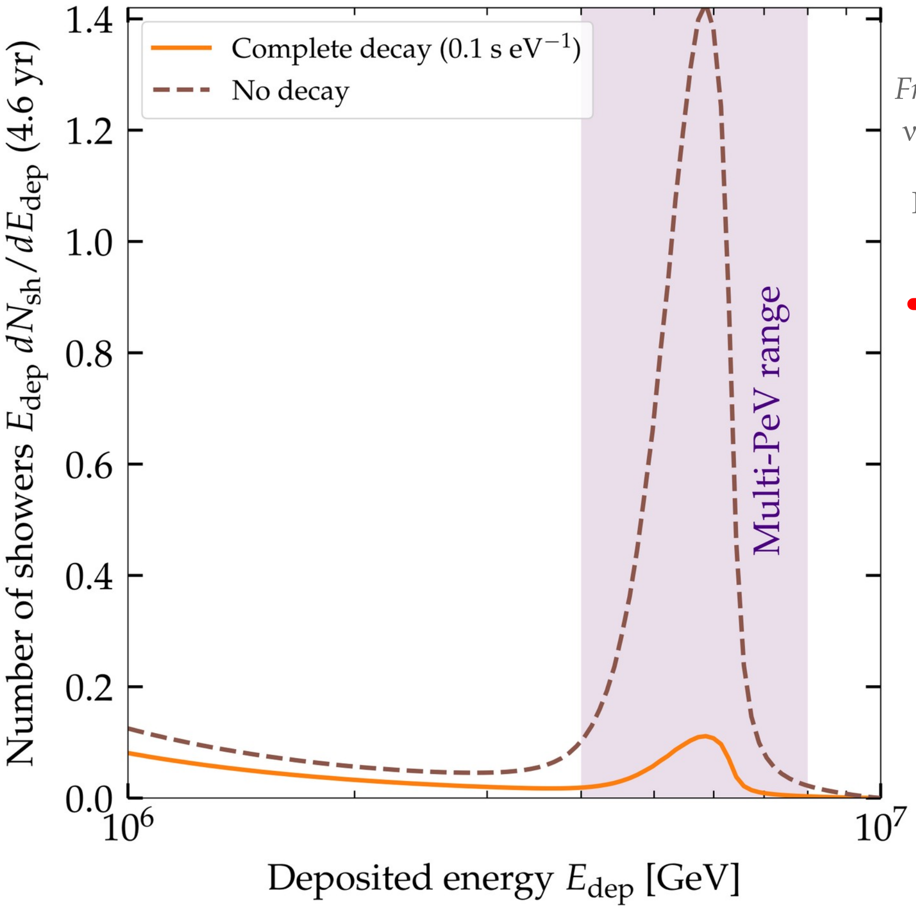
Flavor composition ⟺ Spectrum shape ⟺ Event rate



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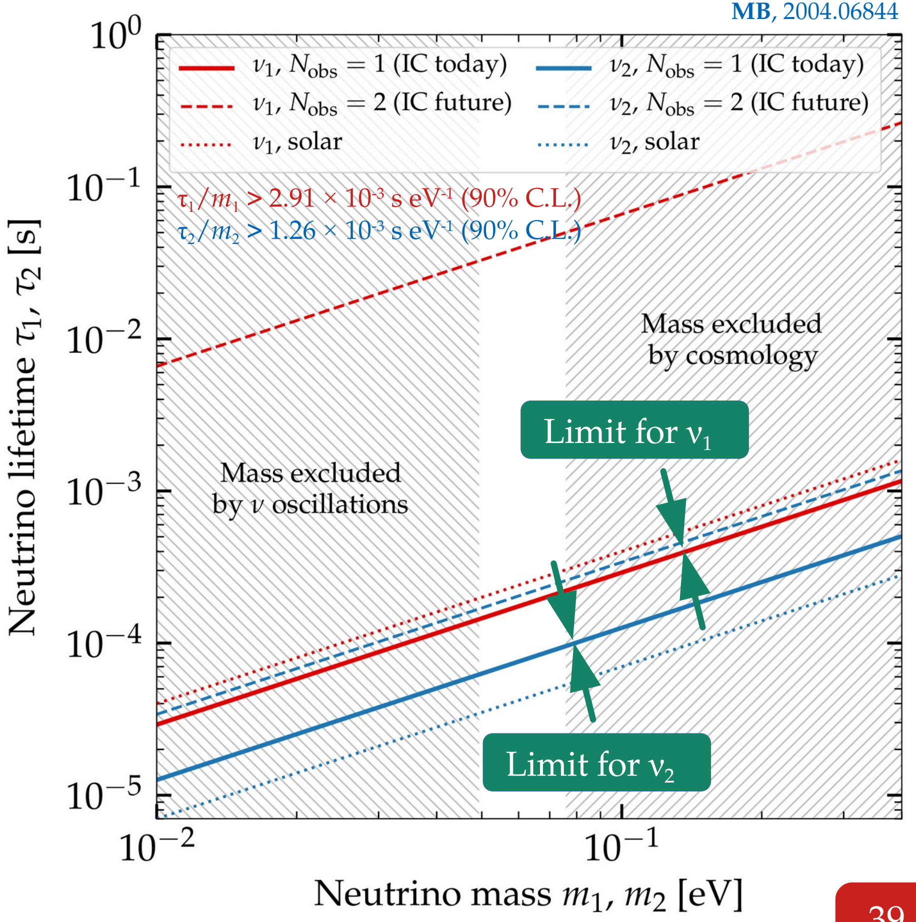
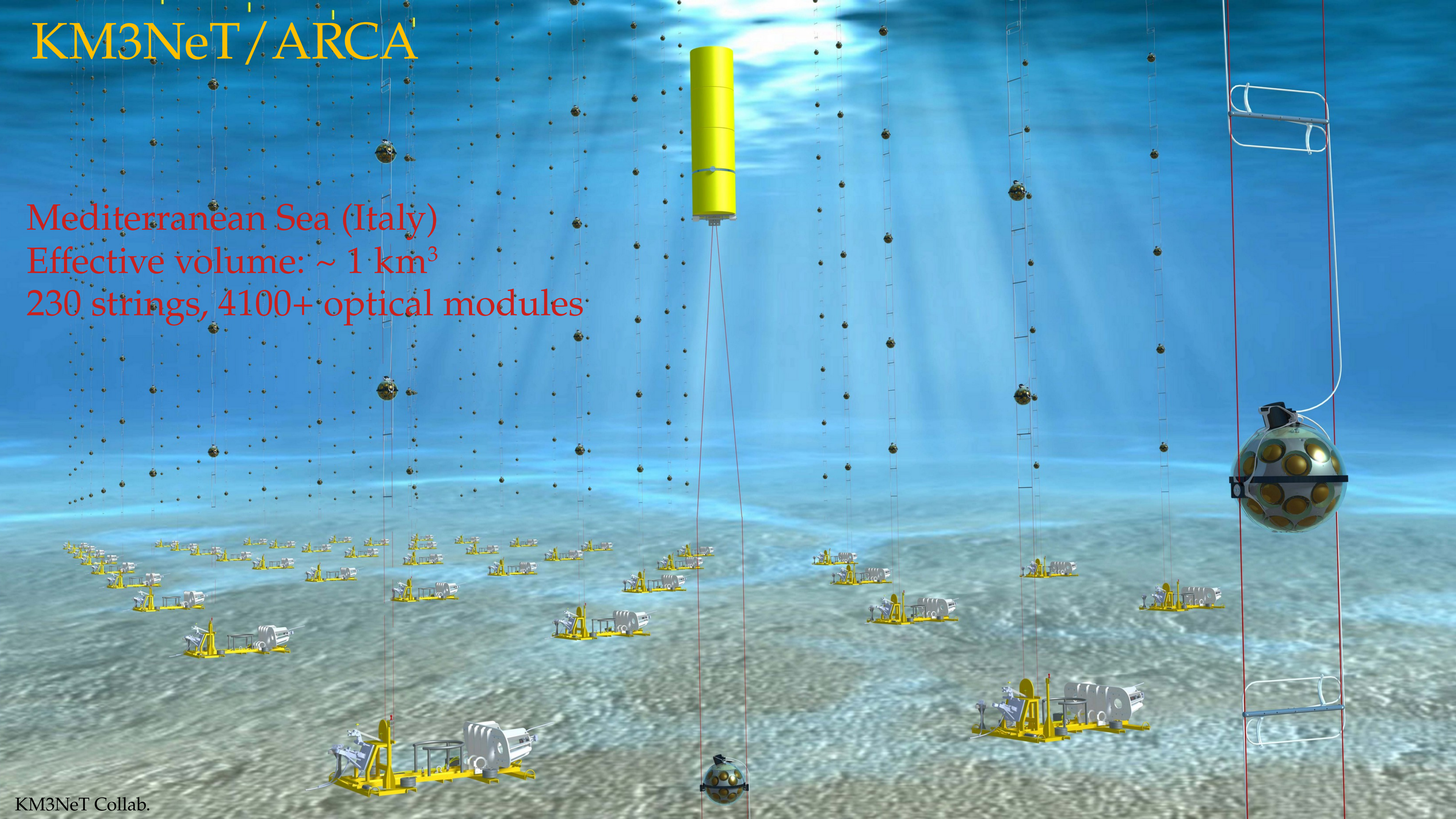
MB, 2004.06844




Baikal-GVD
Lake Baikal, Russia
Effective volume: ~ 1.5 km3
90 strings, 1000+ optical modules
1415
525
1292
JINR


KM3NeT / ARCA
Mediterranean Sea (Italy)
Effective volume: ~ 1 km³
230 strings, 4100+ optical modules
KM3NeT Collab.

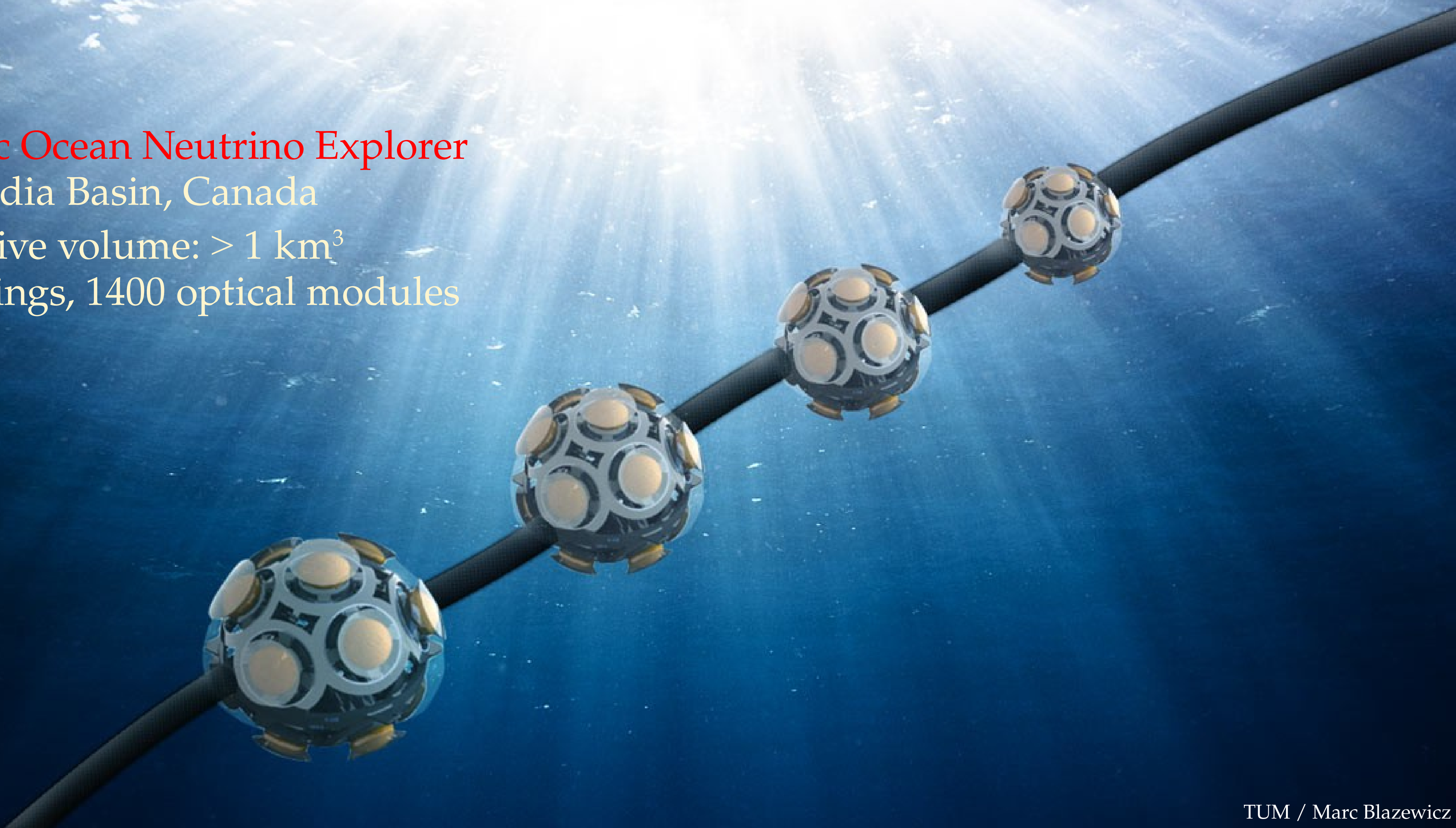
P-ONE

Pacific Ocean Neutrino Explorer

Cascadia Basin, Canada

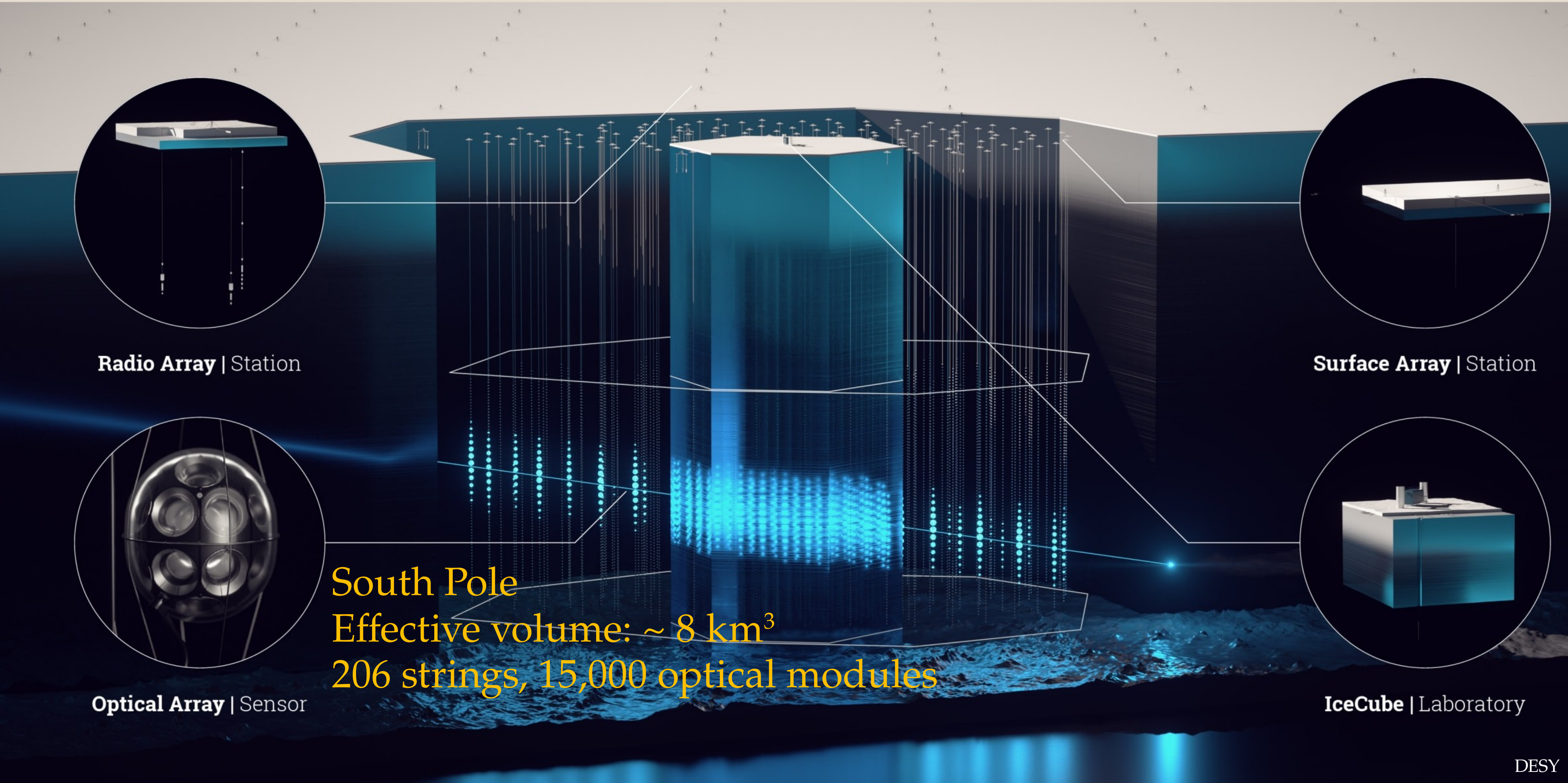
Effective volume: > 1 km^3

70 strings, 1400 optical modules



TUM / Marc Blazewicz

IceCube-Gen2



South Pole
Effective volume: ~ 8 km^3
206 strings, 15,000 optical modules

TRIDENT

The tRopIcal Deep-sea Neutrino Telescope

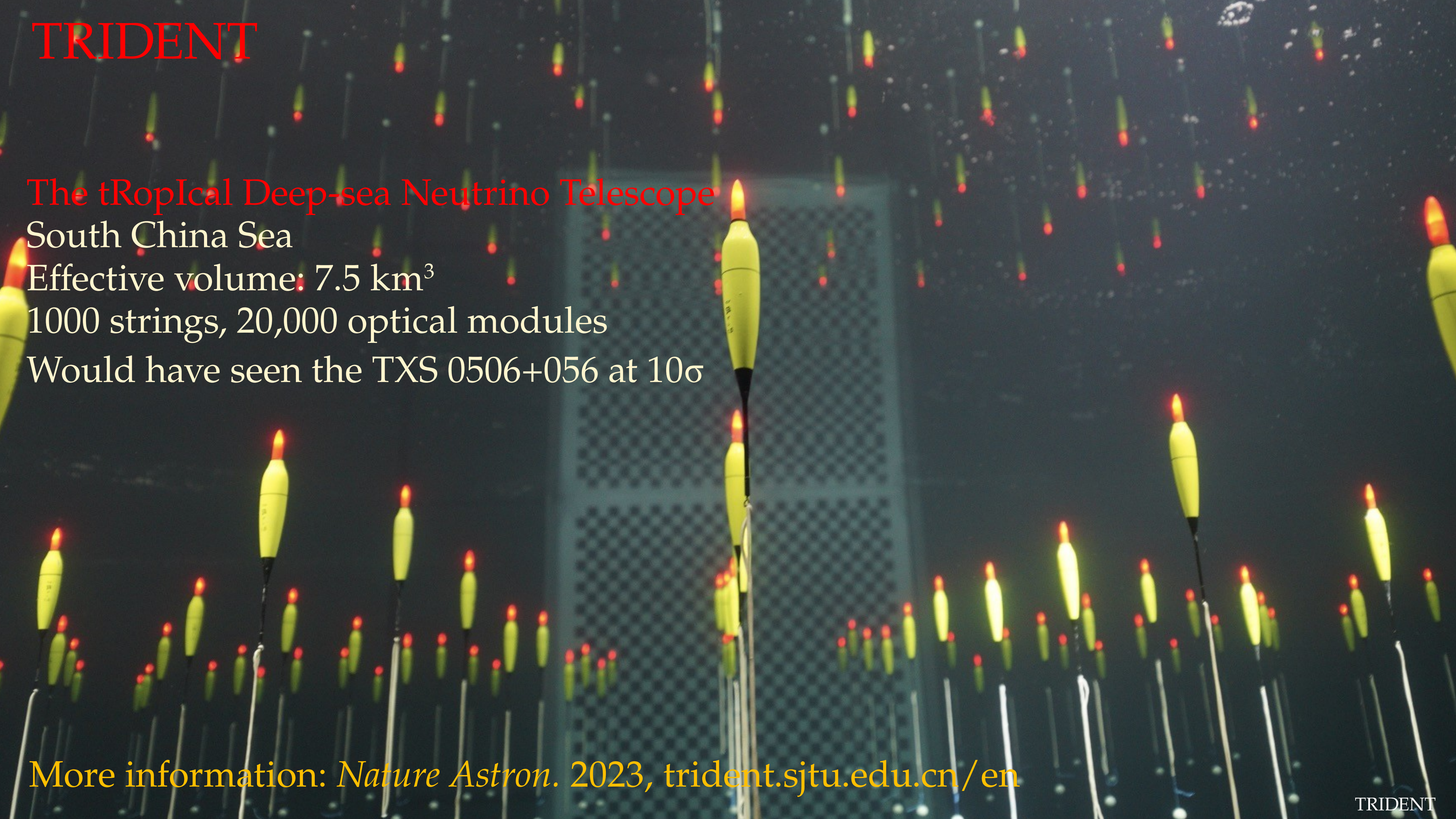
South China Sea

Effective volume: 7.5 km^3

1000 strings, 20,000 optical modules

Would have seen the TXS 0506+056 at 10σ

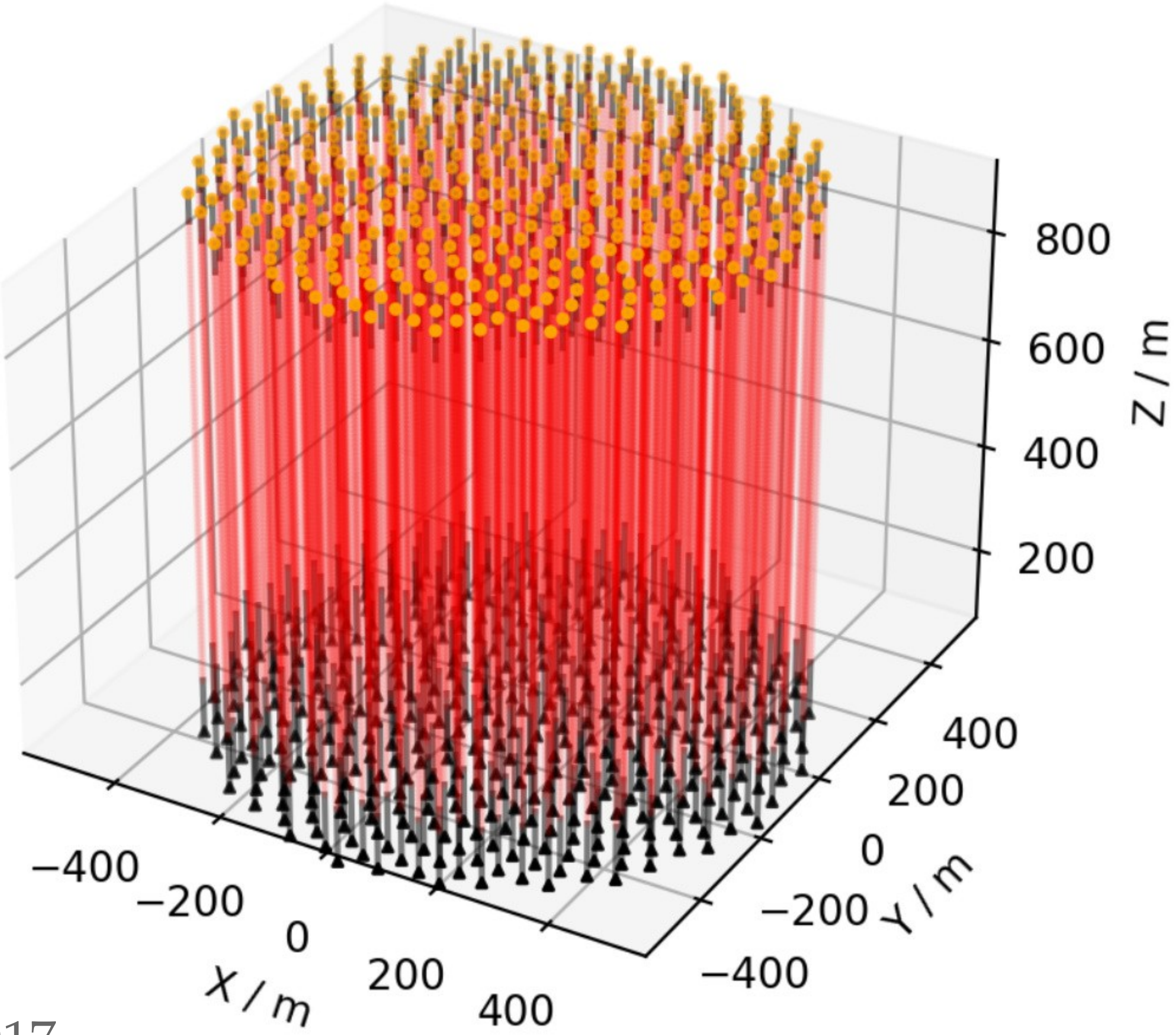
More information: *Nature Astron.* 2023, trident.sjtu.edu.cn/en



TRIDENT

NEON

Neutrino Observatory in the Nanhai
South China Sea
Effective volume: 10 km^3
400 strings, 40,000 optical modules



More information: PoS (ICRC2023) 1017

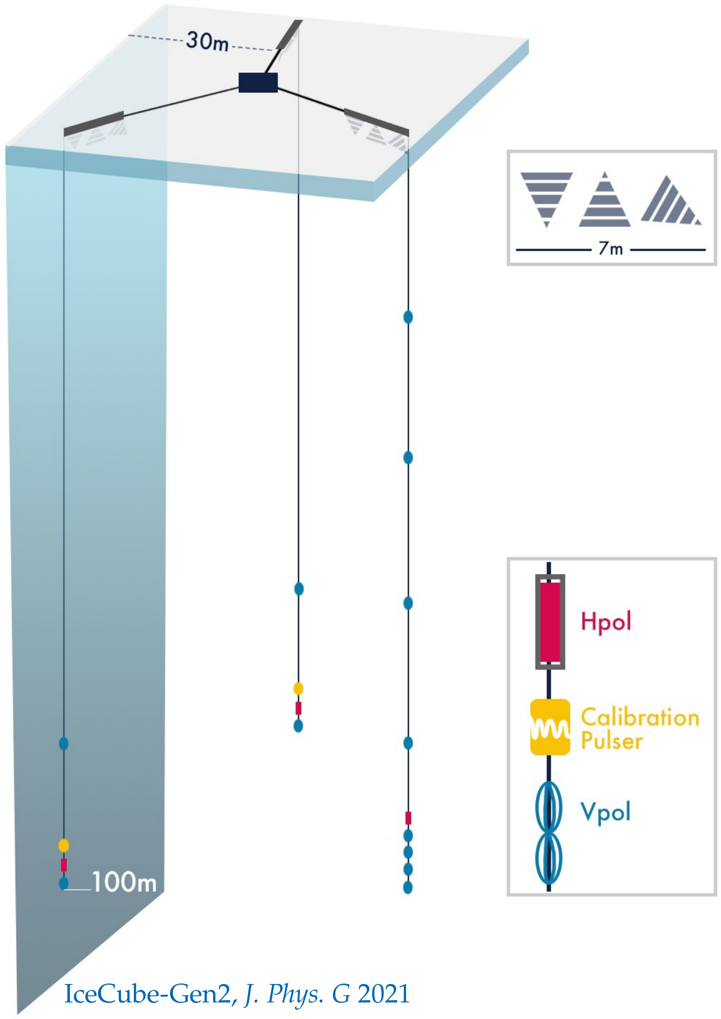
HUNT

High-energy Underwater Neutrino Telescope
South China Sea or Lake Baikal
Effective volume: 30 km^3
2304 strings, 55,296 optical modules

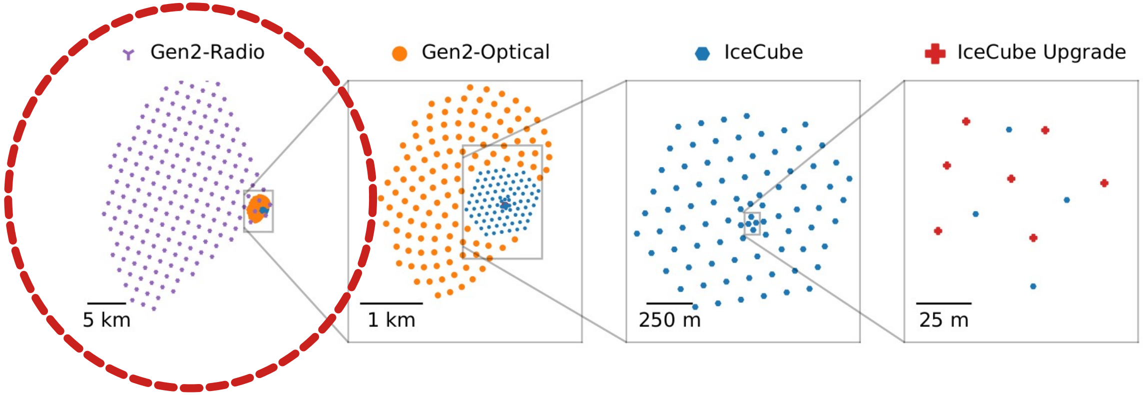
Muon track angular resolution
as good as 0.05°
(for tracks of 6 km in length)

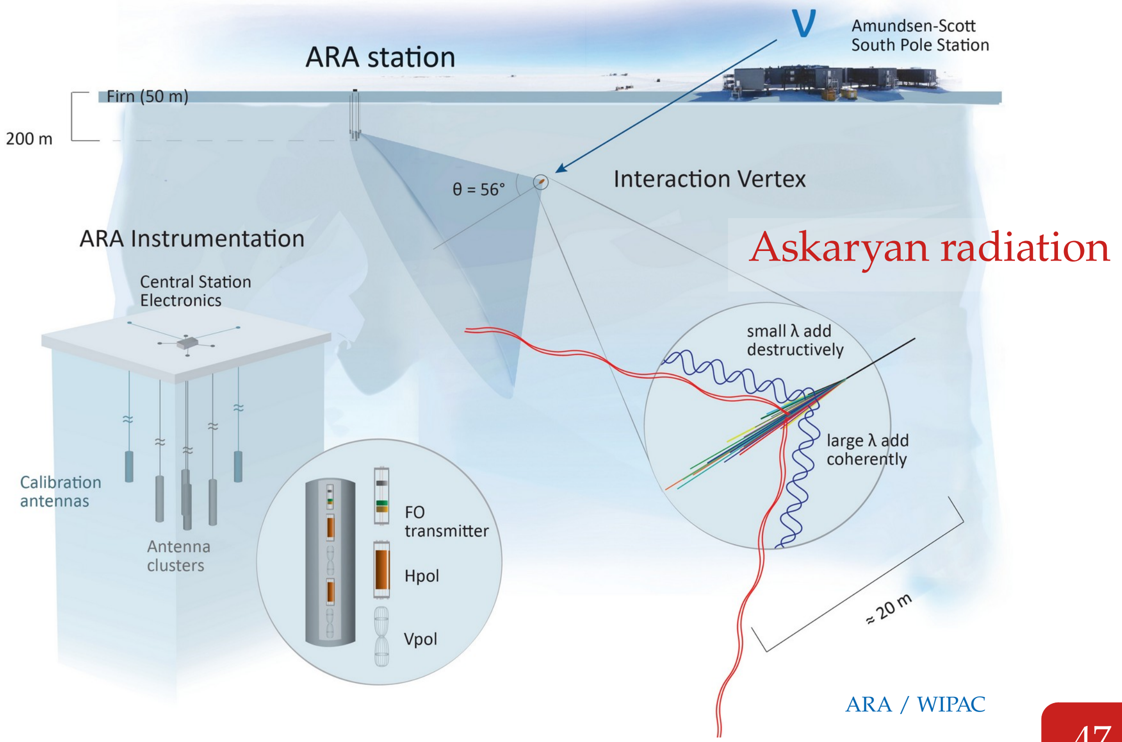
More information: hunt.ihep.ac.cn

IceCube-Gen2 Radio



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

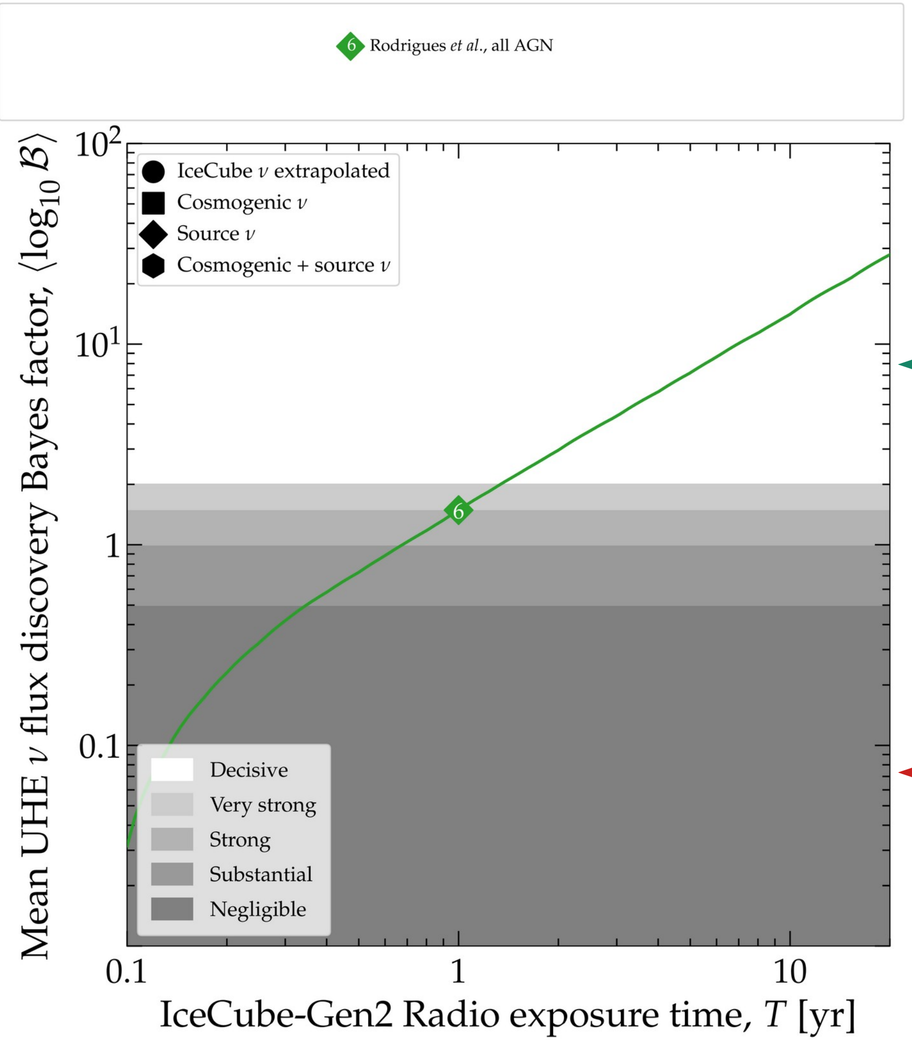




ARA / WIPAC

Discovering the diffuse flux of UHE neutrinos

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



High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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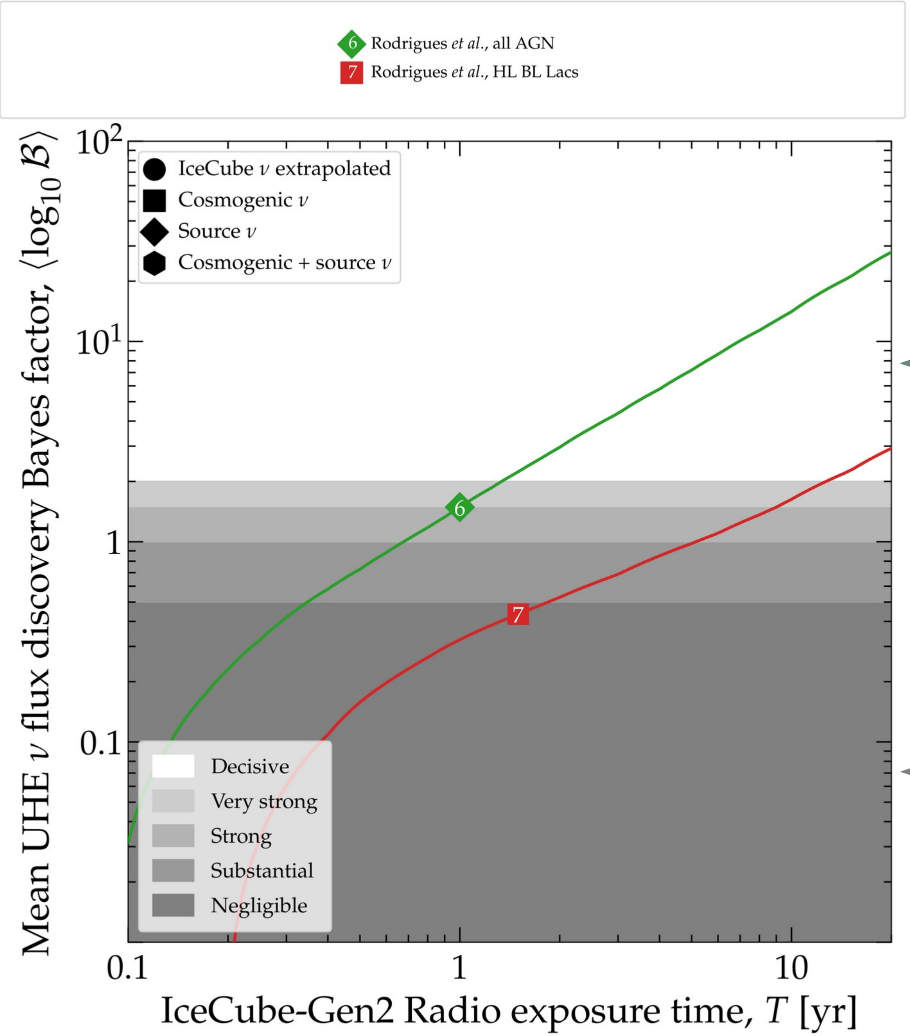

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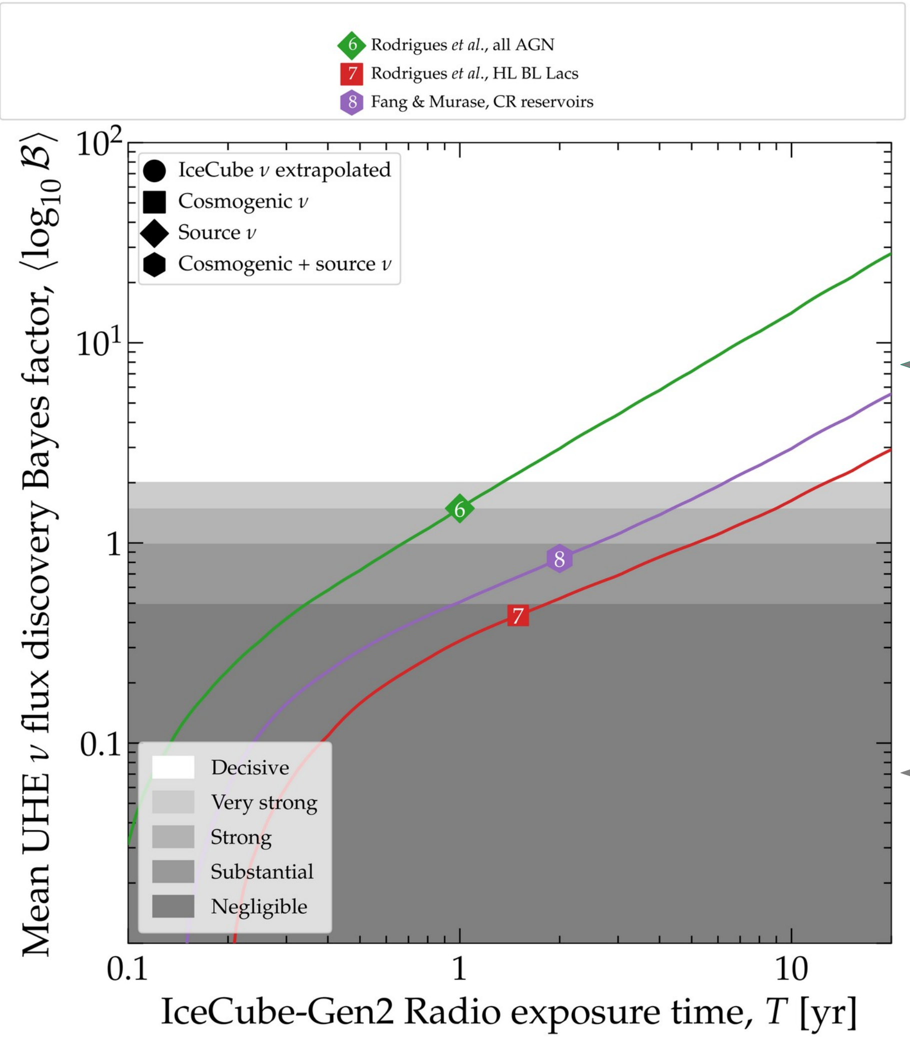

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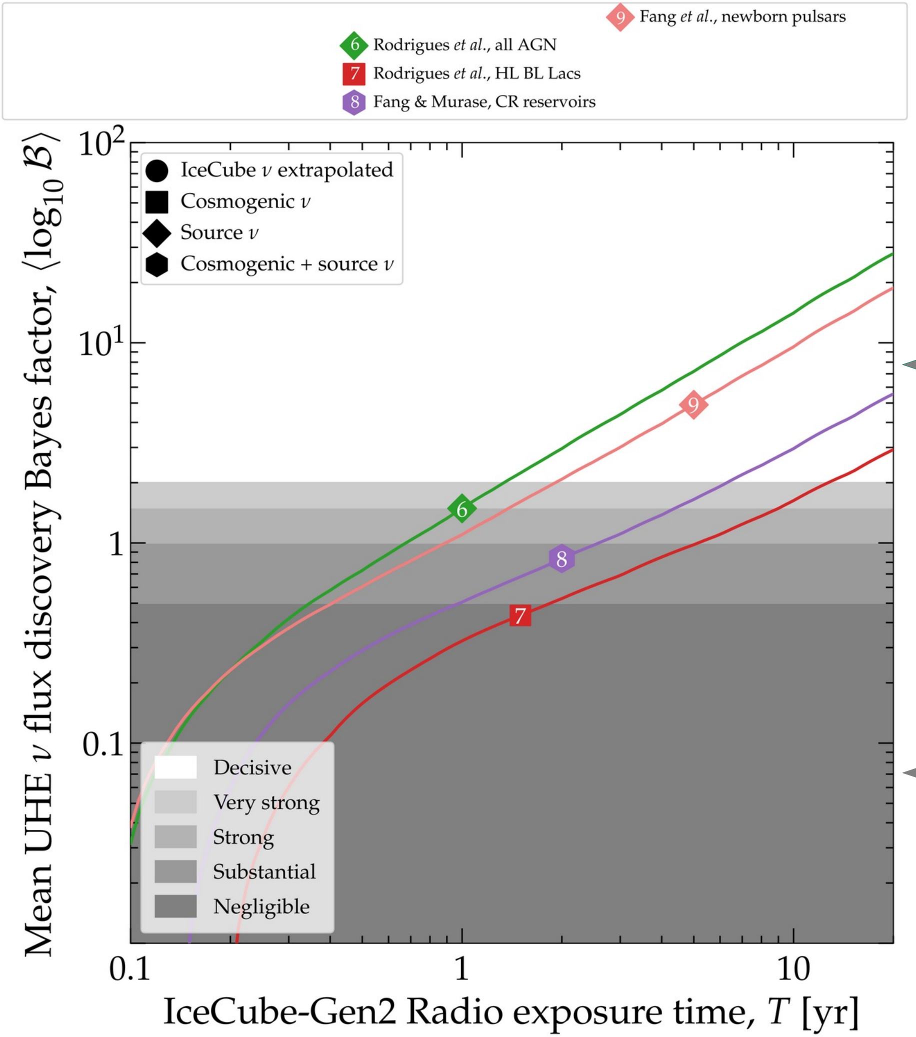

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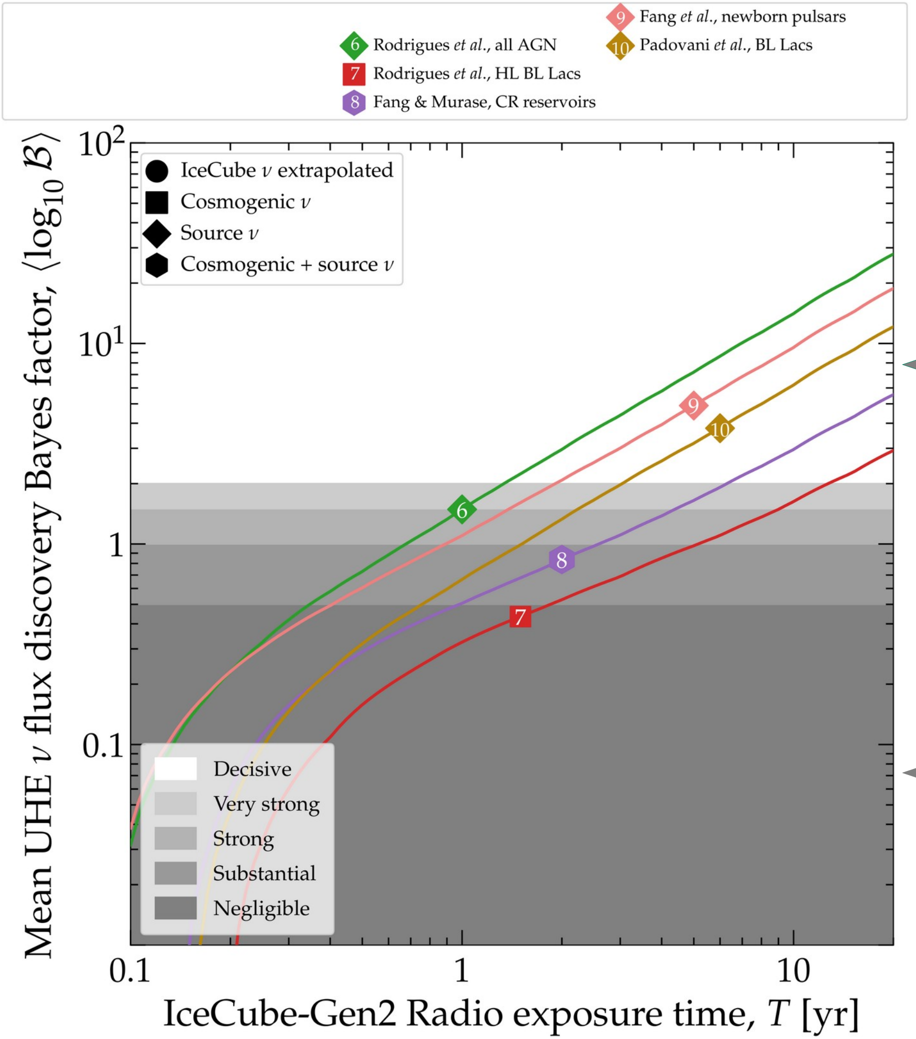

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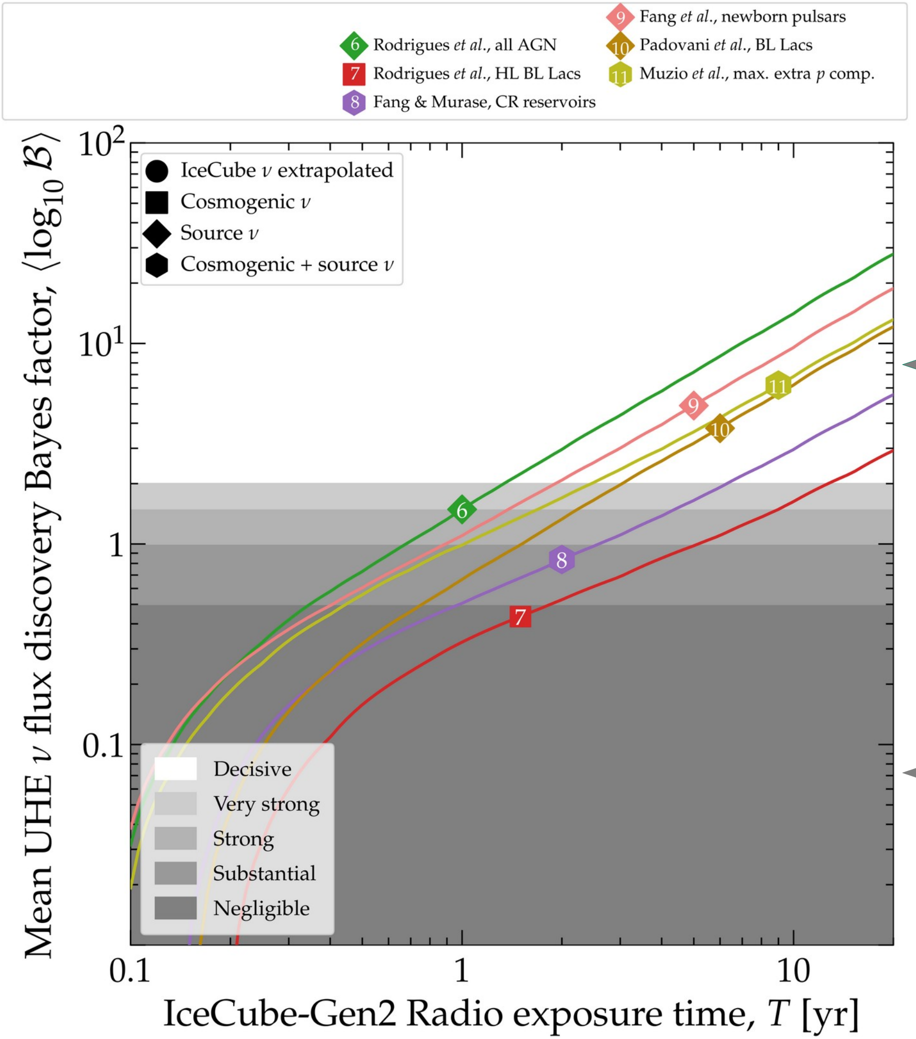

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Valera, **MB**, Glaser, *PRD* 2023

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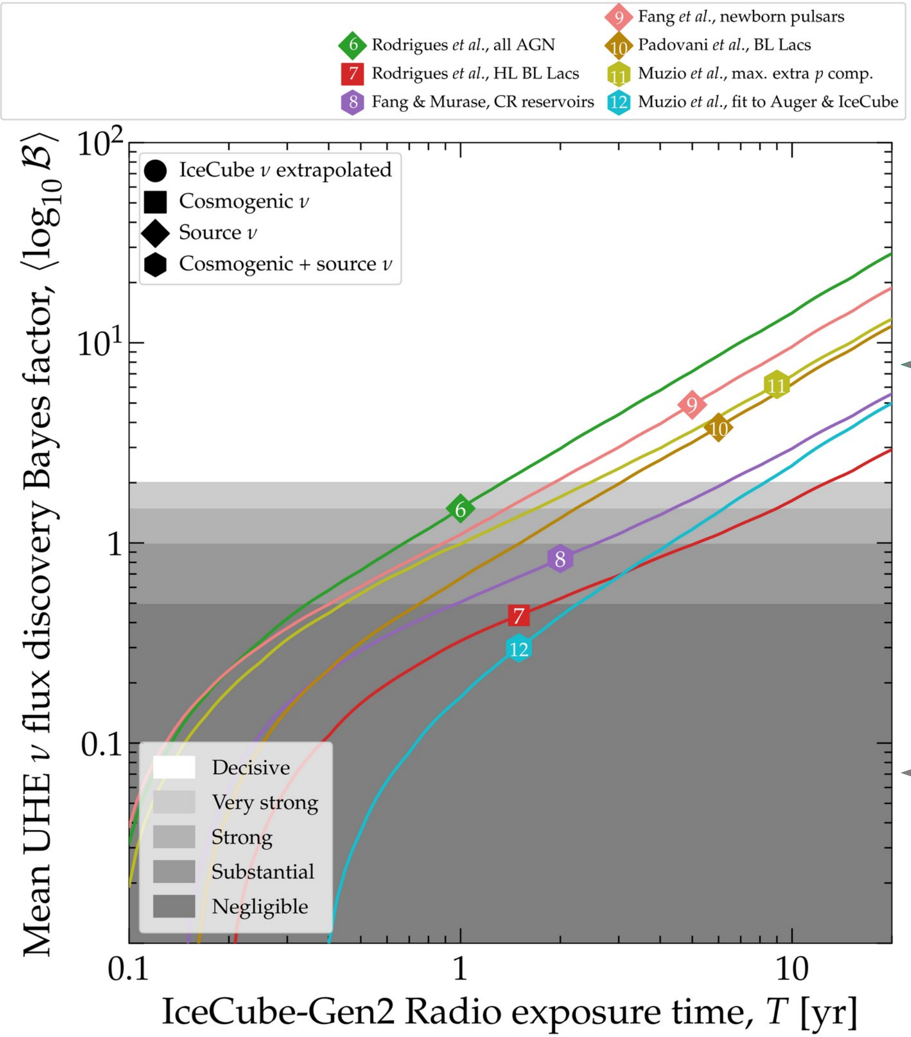

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Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

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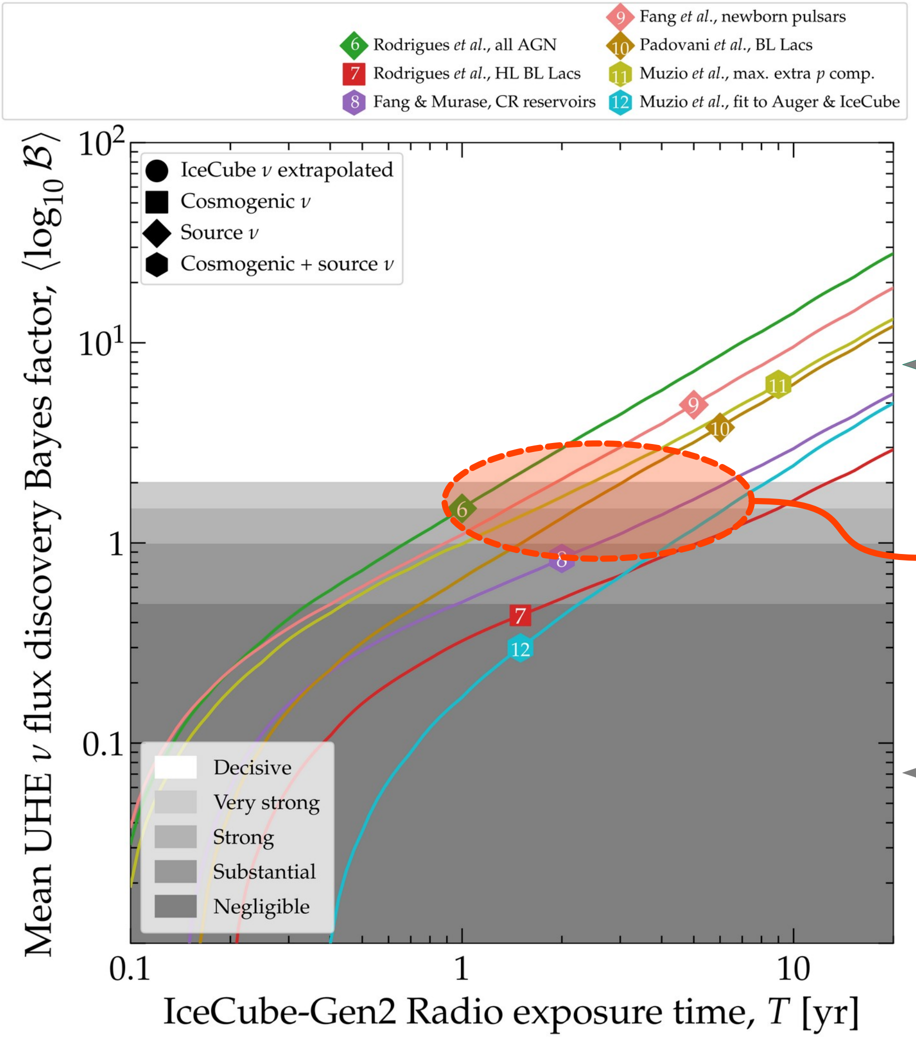


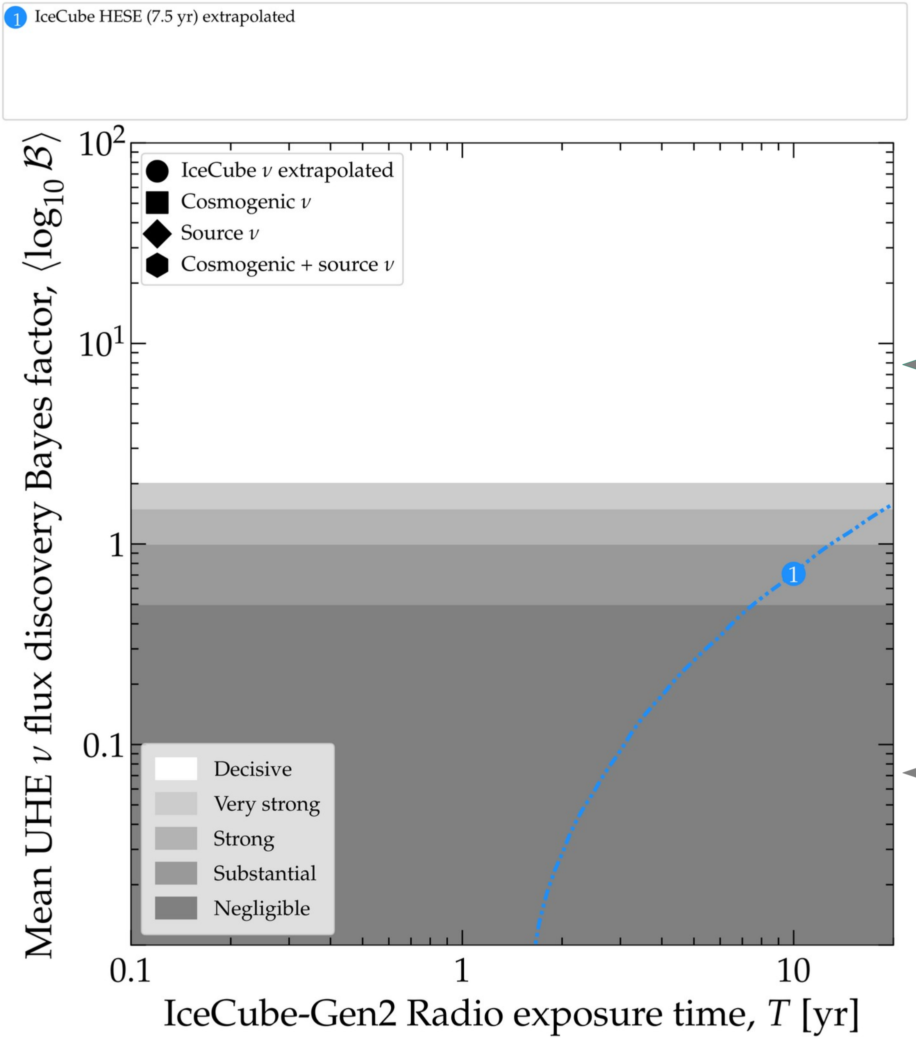
High Bayes factor
→ Decisive flux discovery

Most flux models are discoverable within a few years

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos



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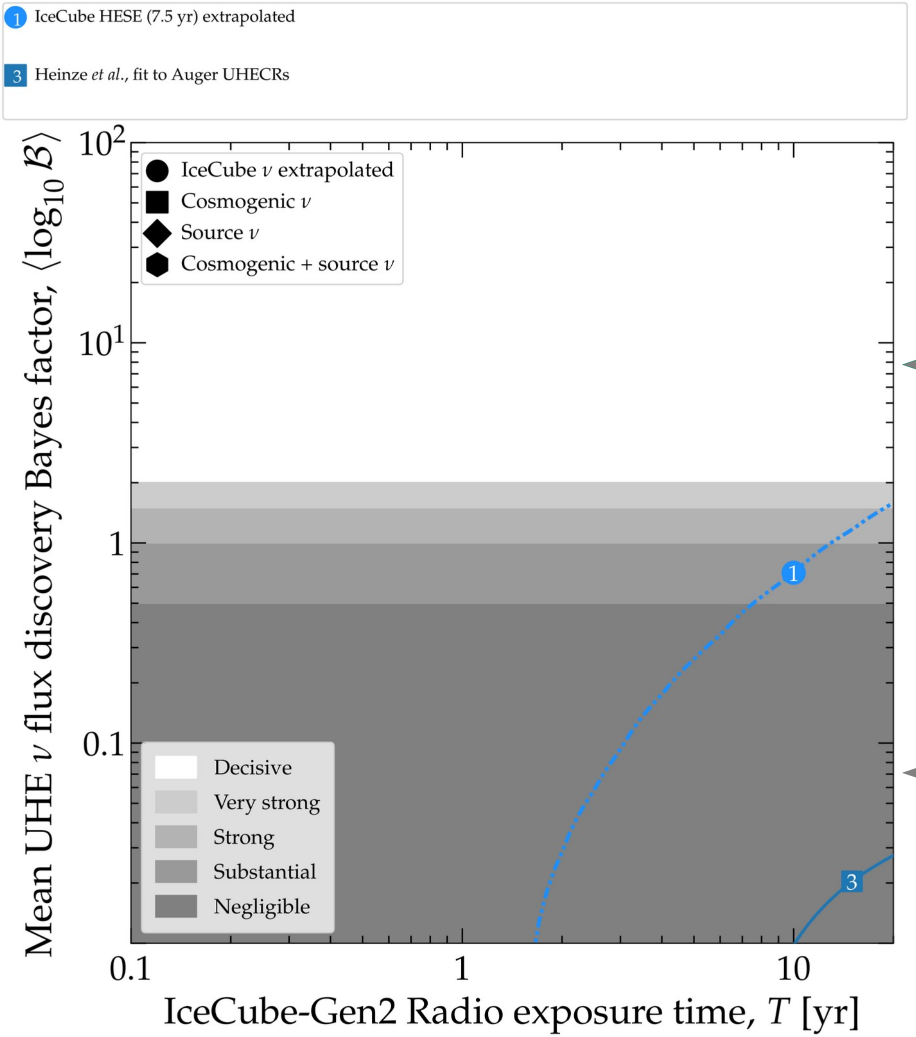
High Bayes factor → Decisive flux discovery

Low Bayes factor → No flux discovered

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

Discovering the diffuse flux of UHE neutrinos



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High Bayes factor → Decisive flux discovery

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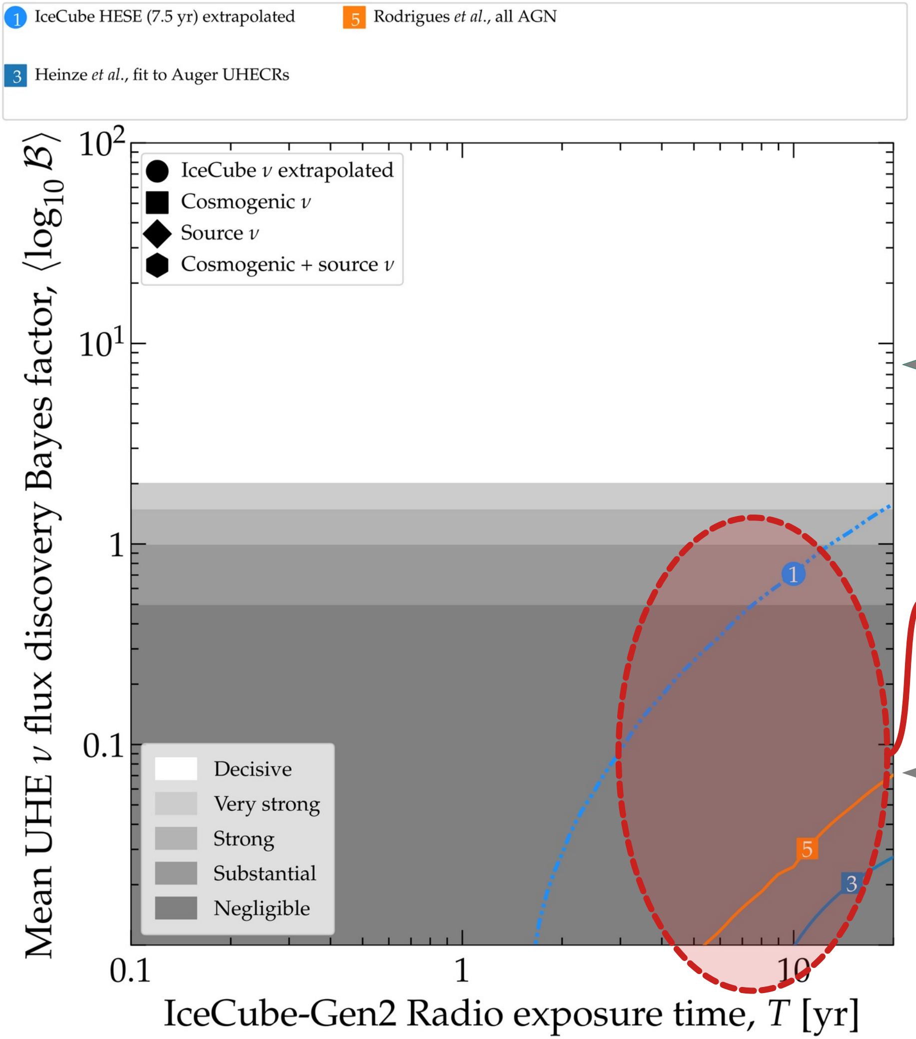
Valera, **MB**, Glaser, *PRD* 2023

Discovering the diffuse flux of UHE neutrinos

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



High Bayes factor
→ Decisive flux discovery

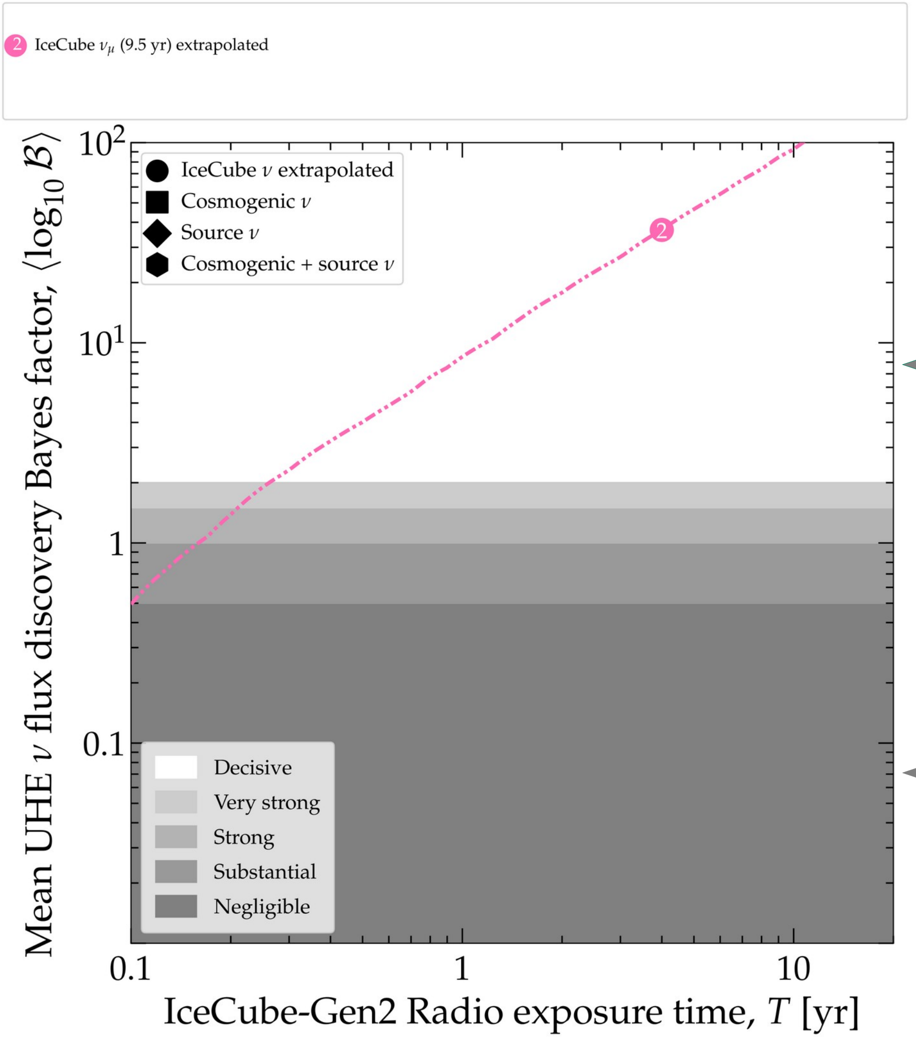
Some models will *not* be discovered

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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



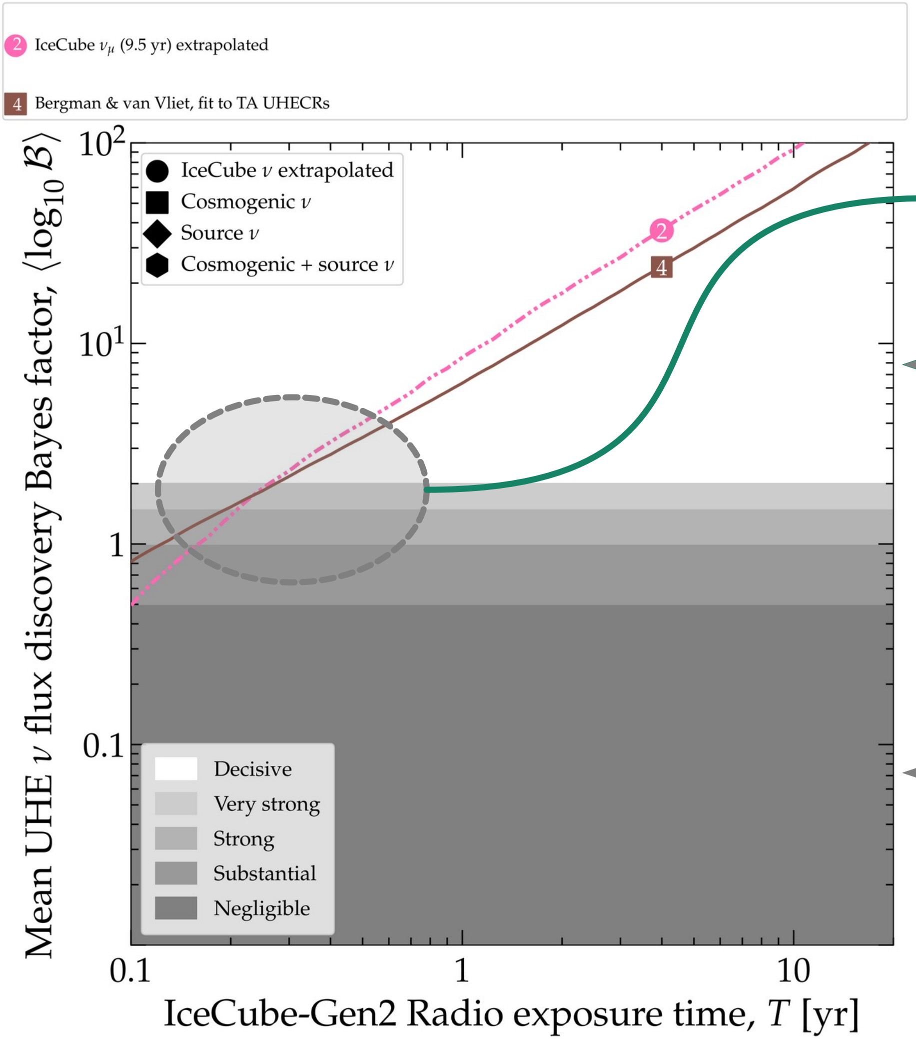
High Bayes factor
→ Decisive flux discovery

Low Bayes factor
→ No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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



Some models will be discovered right away

High Bayes factor → Decisive flux discovery

Low Bayes factor → No flux discovered

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

Discovering the diffuse flux of UHE neutrinos

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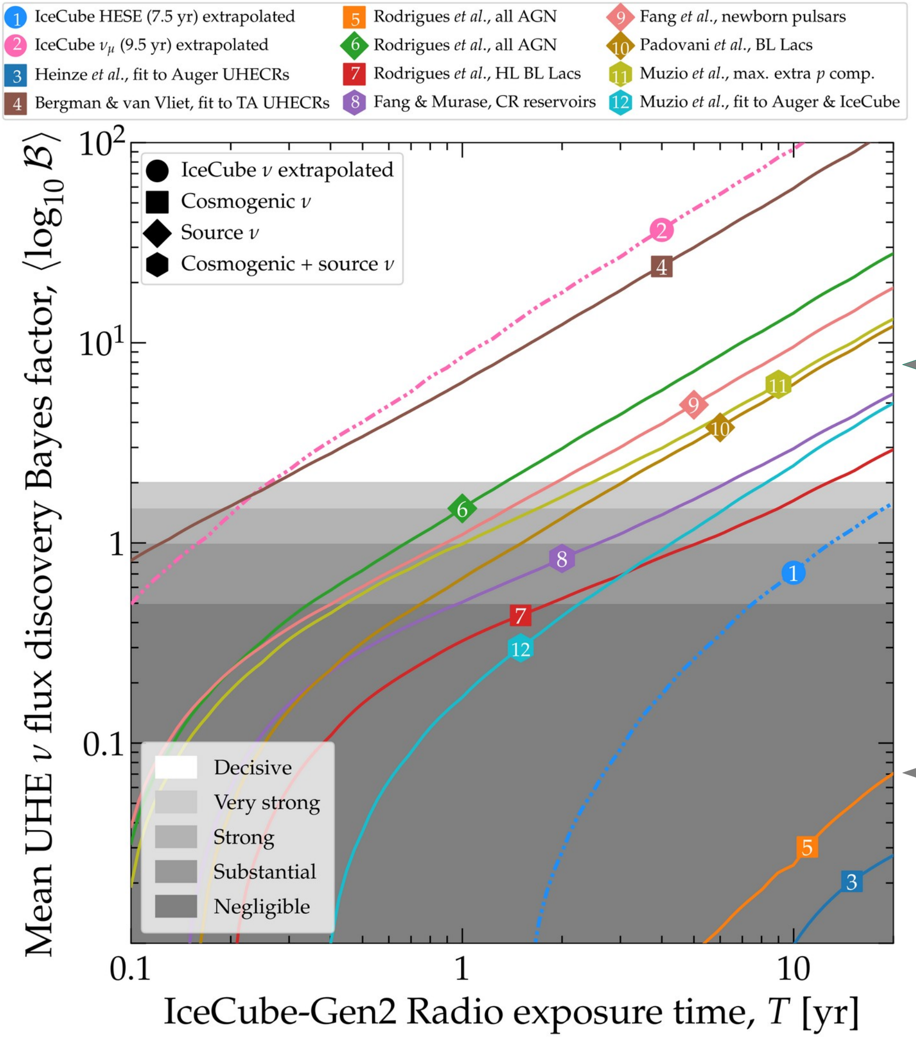


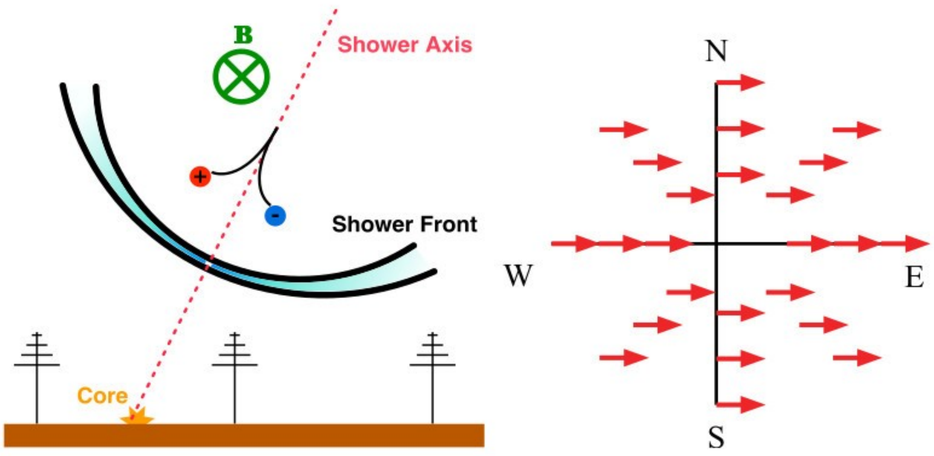
High Bayes factor → Decisive flux discovery

Low Bayes factor → No flux discovered

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

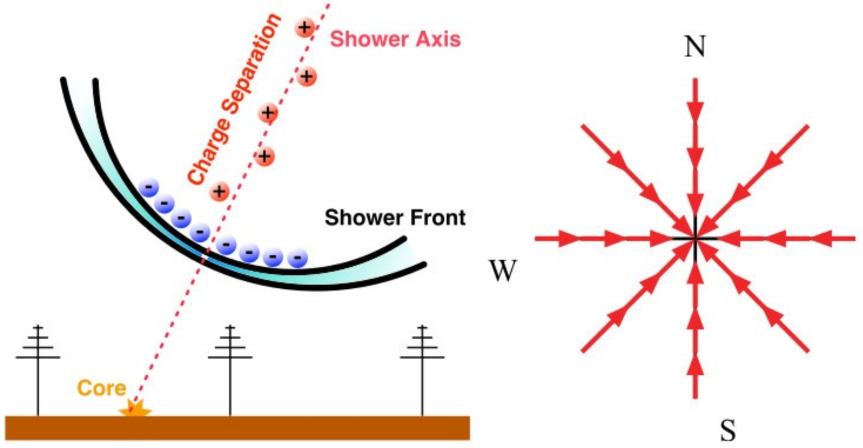
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

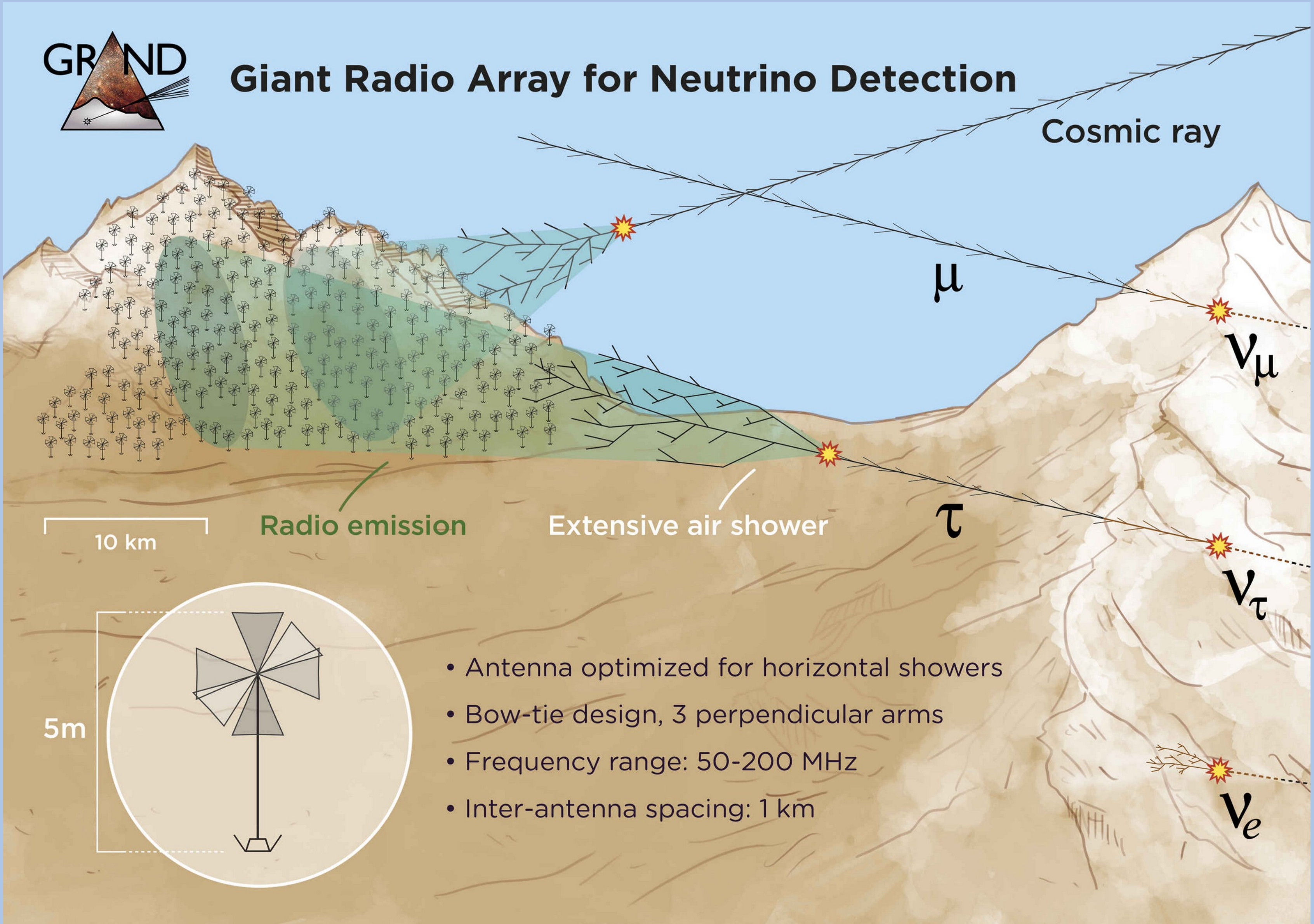
Askaryan

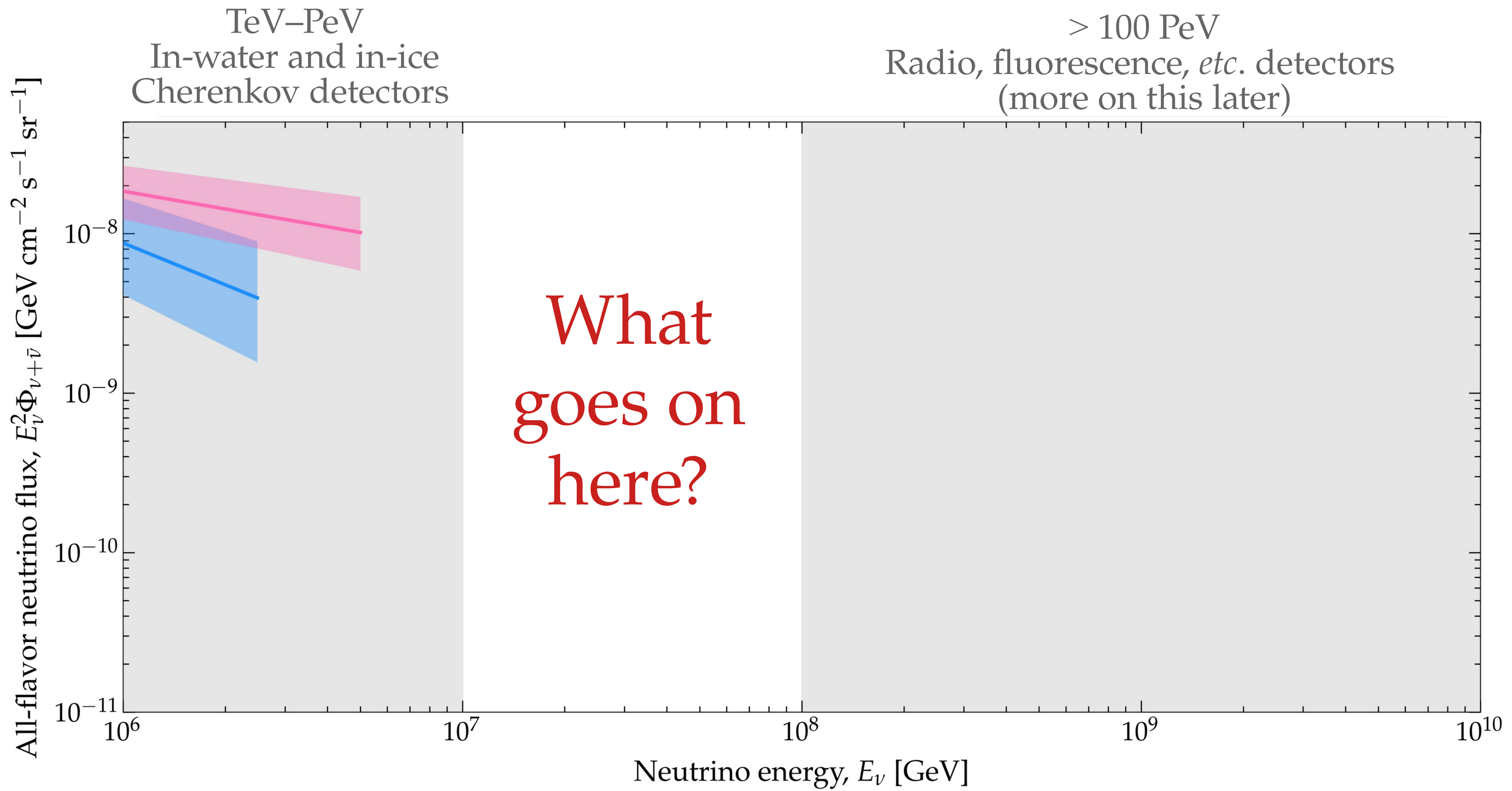


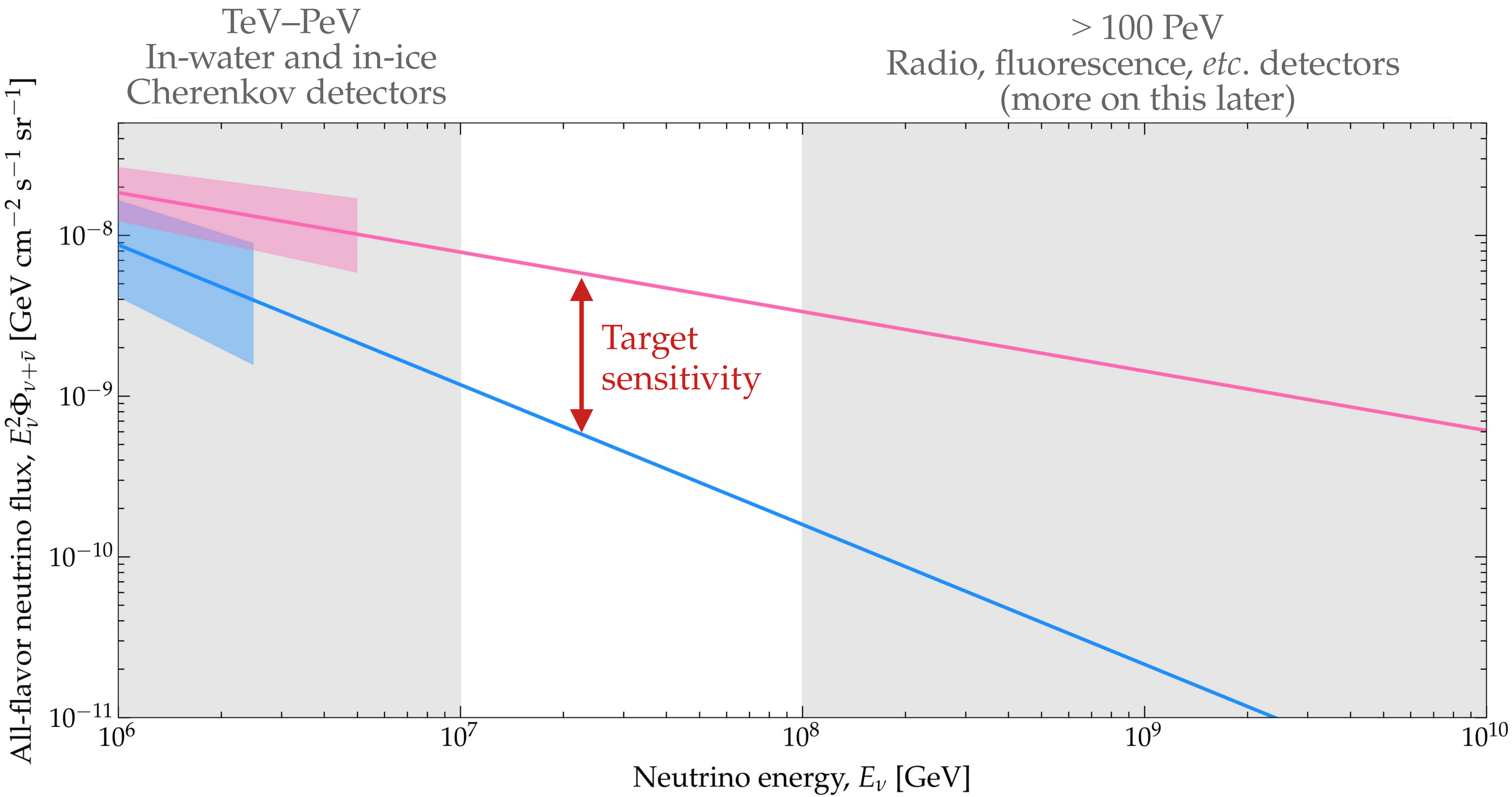
- Time-varying negative-charge ~20% excess
- Linearly polarized towards axis
- Sub-dominant in air showers

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

Radio emission: geomagnetic and Askaryan

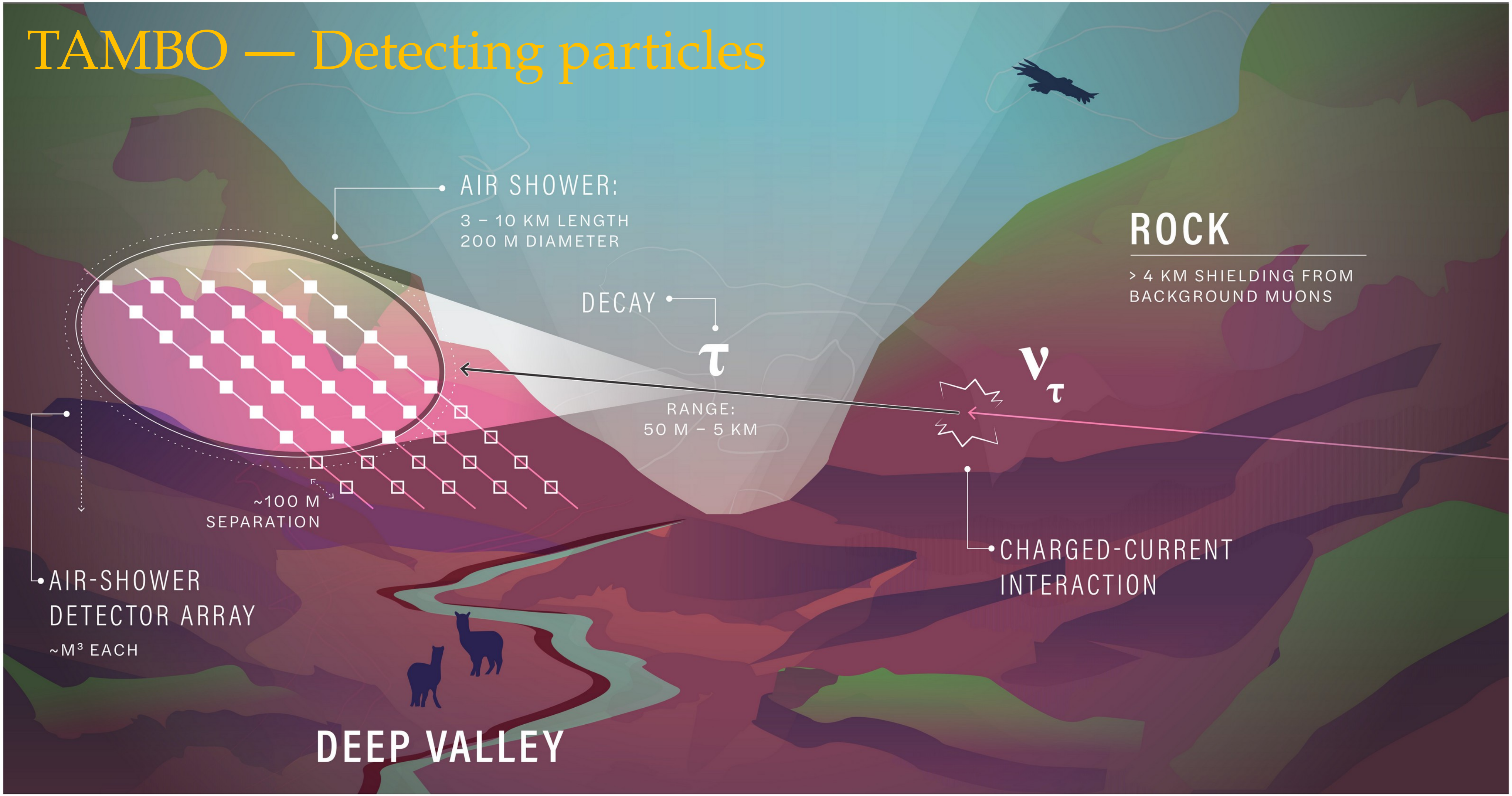

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km


TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, etc. detectors
(more on this later)
What
goes on
here?
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
Neutrino energy, E_ν [GeV]



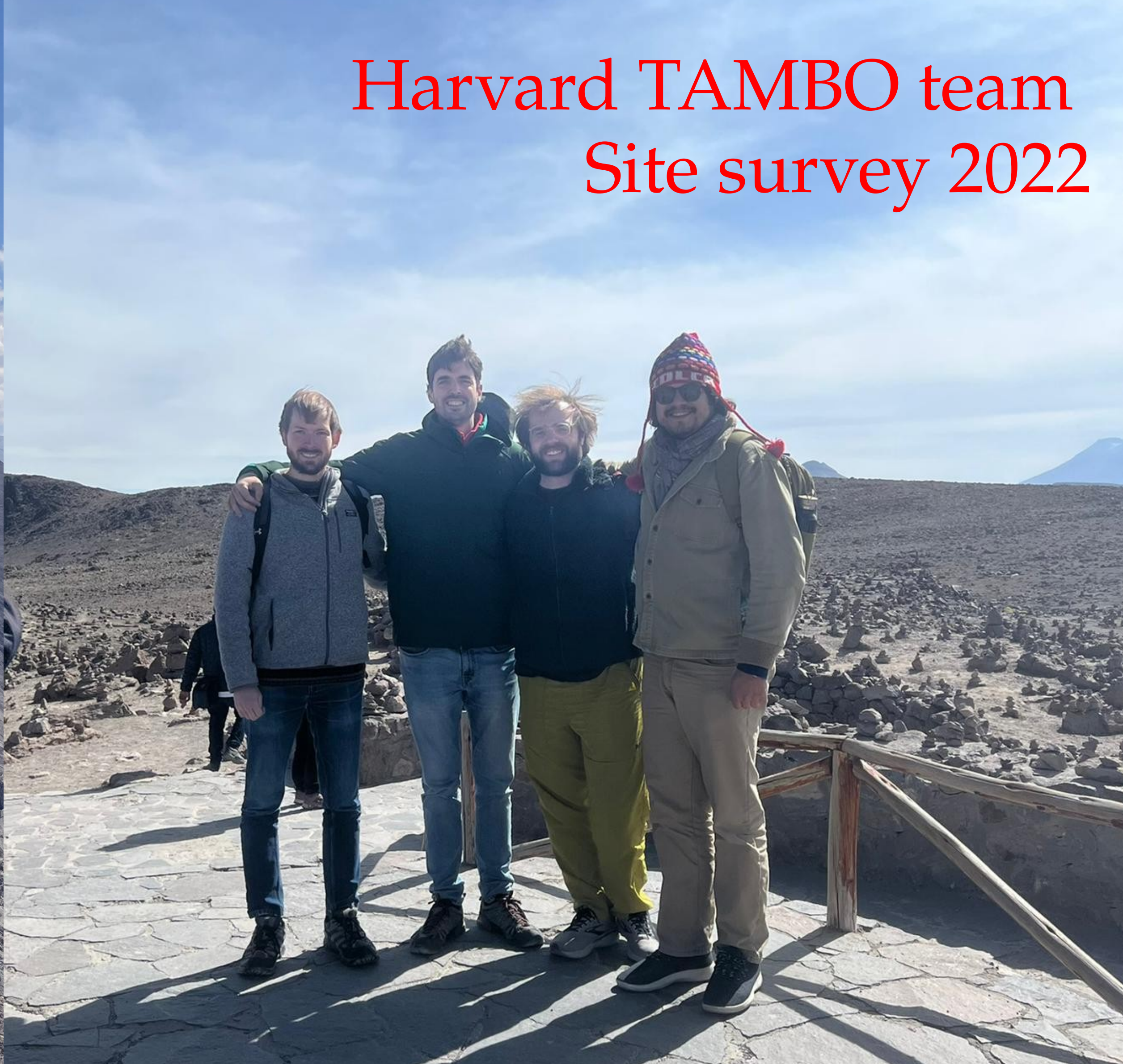
TeV–PeV
In-water and in-ice
Cherenkov detectors
> 100 PeV
Radio, fluorescence, etc. detectors
(more on this later)
Target
sensitivity
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

TAMBO — Detecting particles



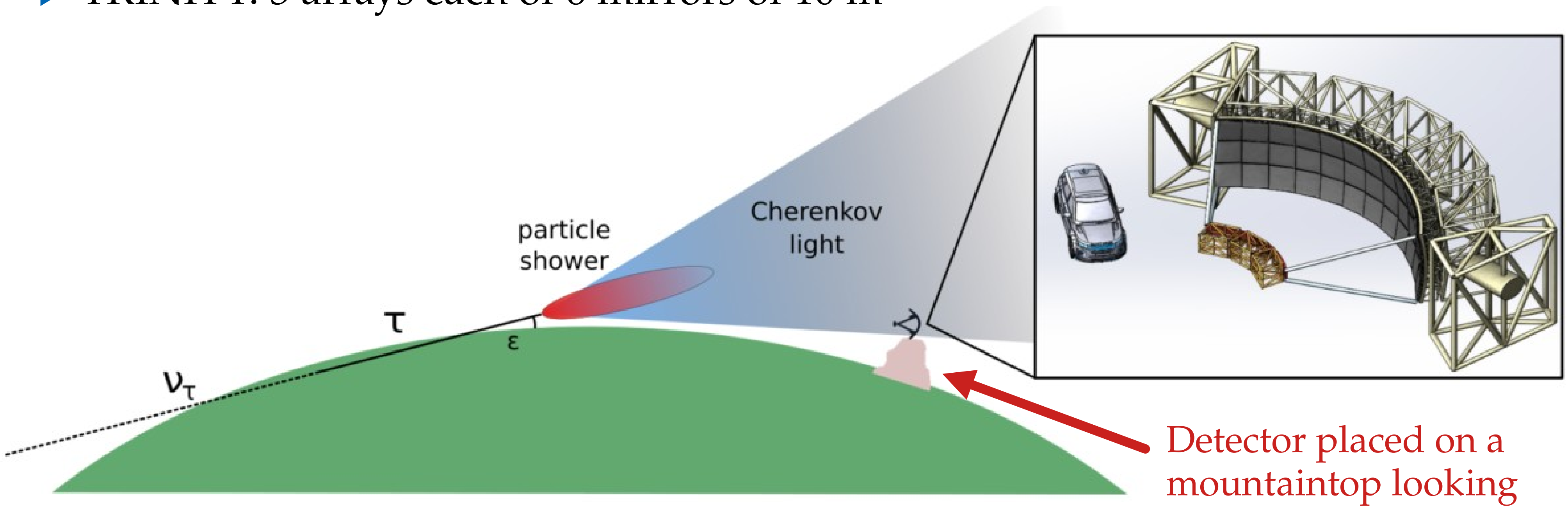
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU


Colca Valley, Peru
2000 (bottom) to 4000 (top) m.a.s.l.

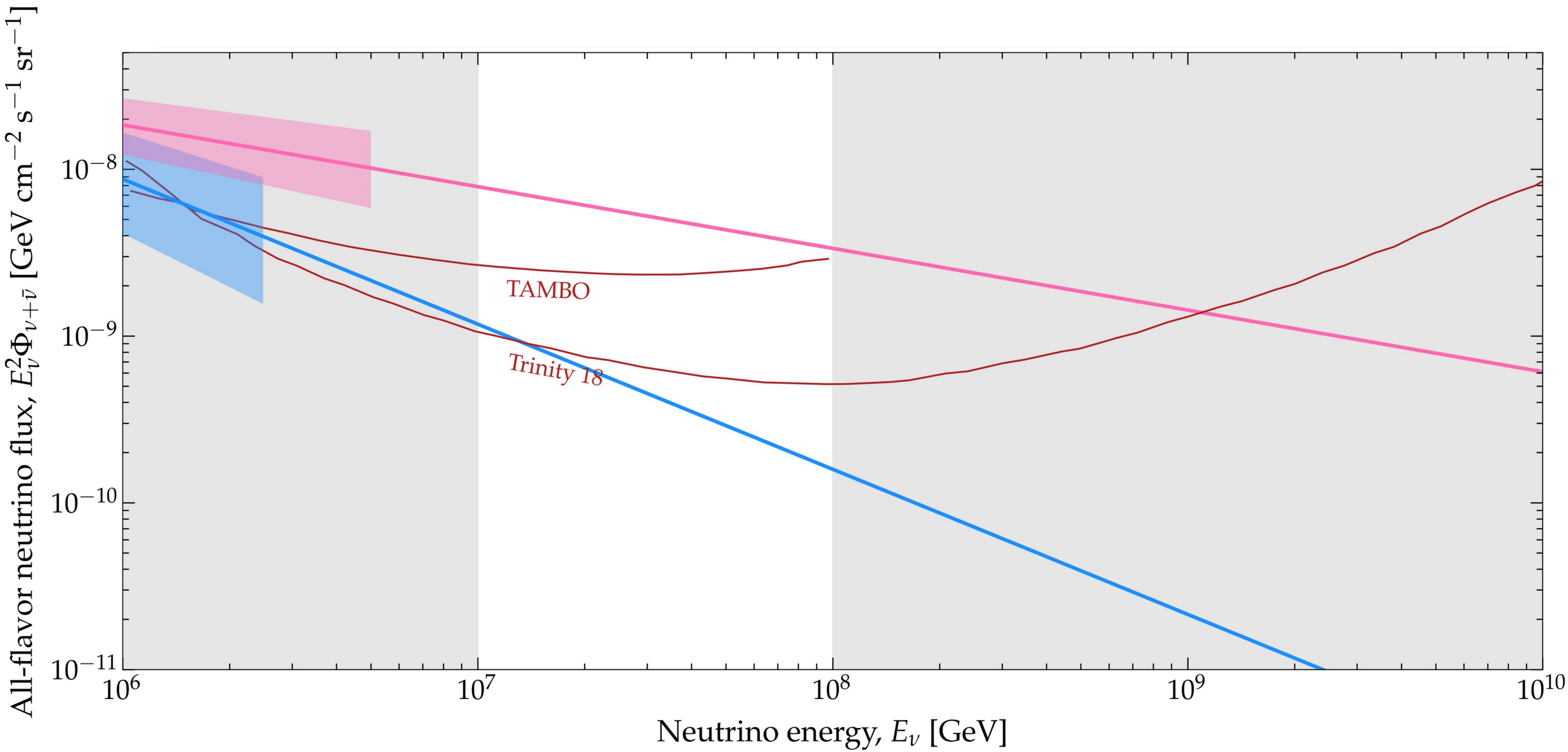

Harvard TAMBO team
Site survey 2022

TRINITY — Detecting Cherenkov light

- Atmospheric Cherenkov imaging applied to PeV neutrinos
- Pioneered by MAGIC (pointing at Atlantic), ASHRA, and NTA (Mauna Kea)
- TRINITY: 3 arrays each of 6 mirrors of 10 m^2

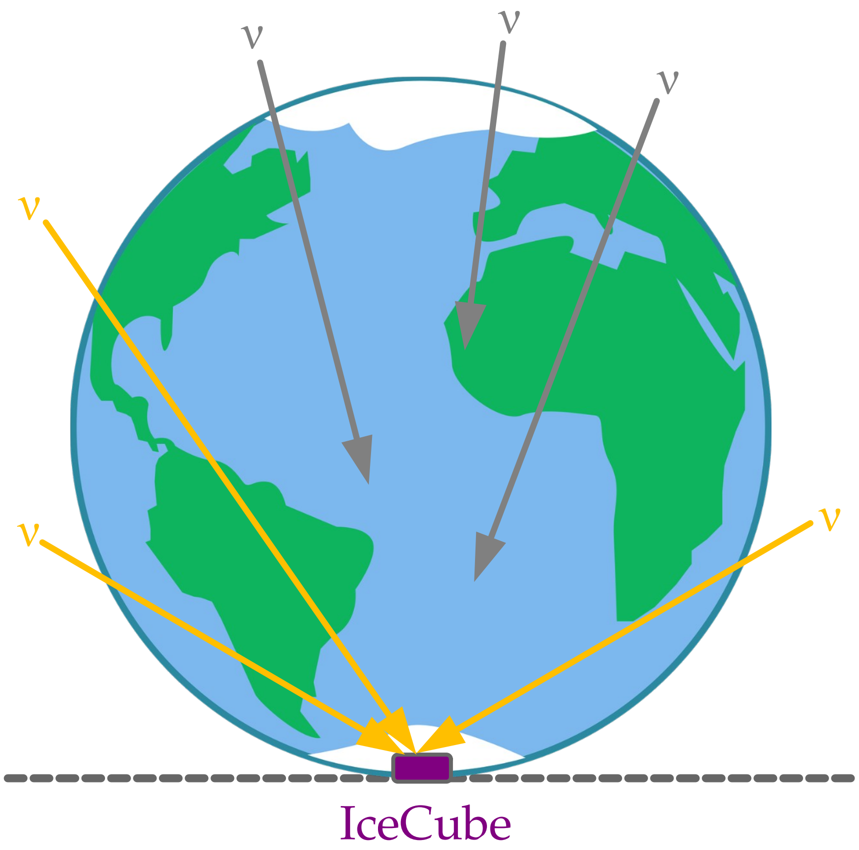


Detector placed on a mountaintop looking towards the horizon



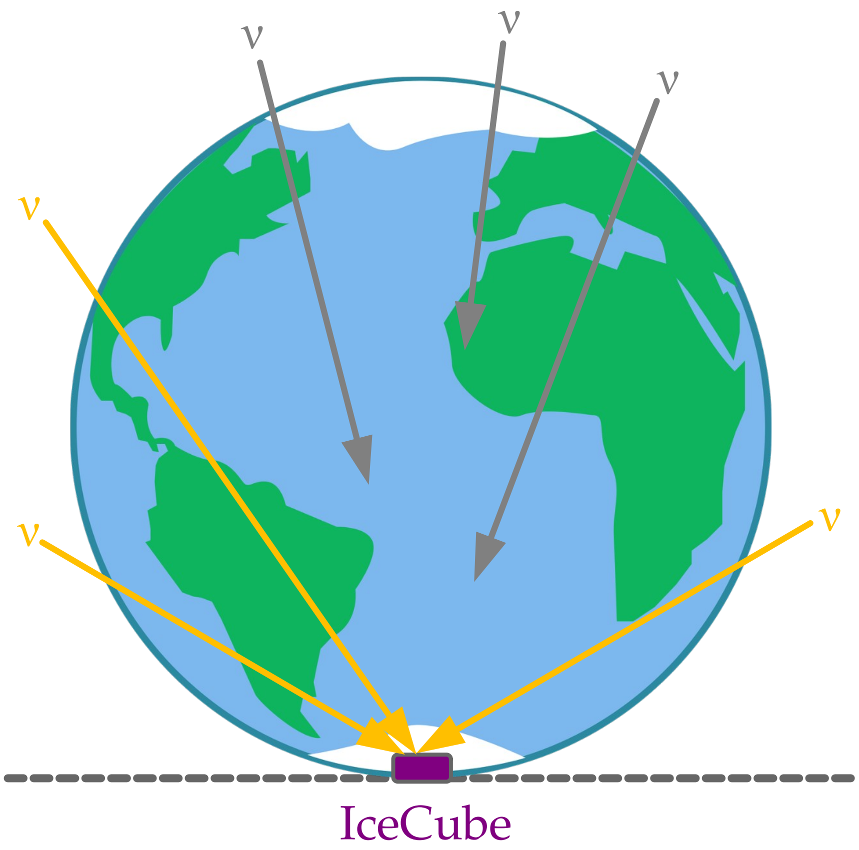
All-flavor neutrino flux, $E_\nu^2 \Phi_{\nu+\bar{\nu}}$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
TAMBO
Trinity 18
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy, E_ν [GeV]

TeV–PeV:



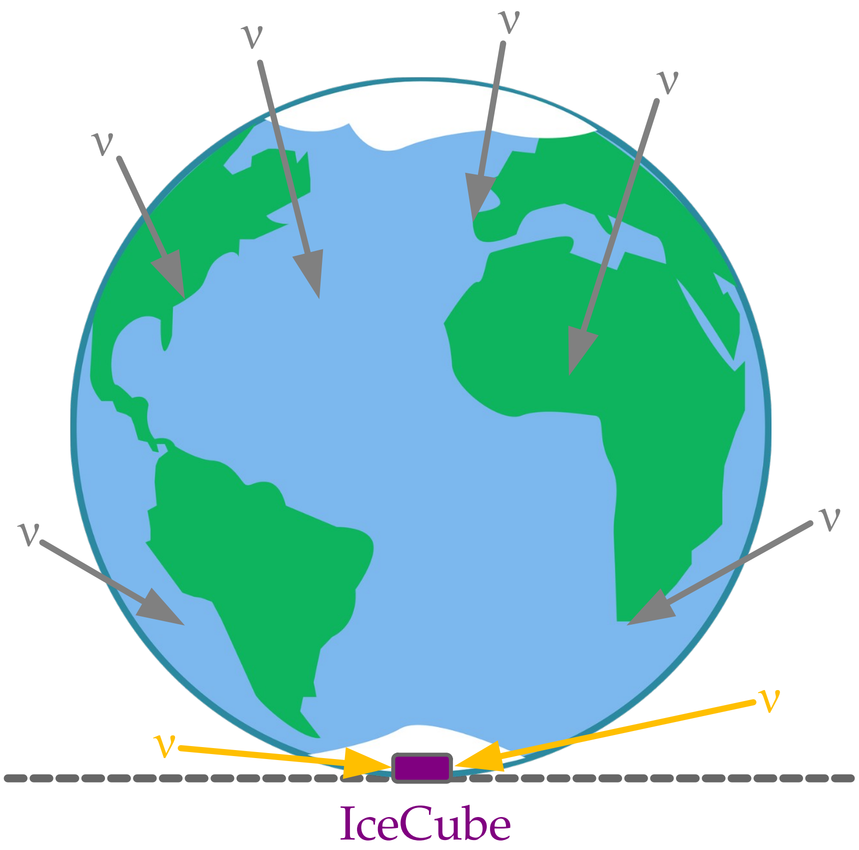
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:

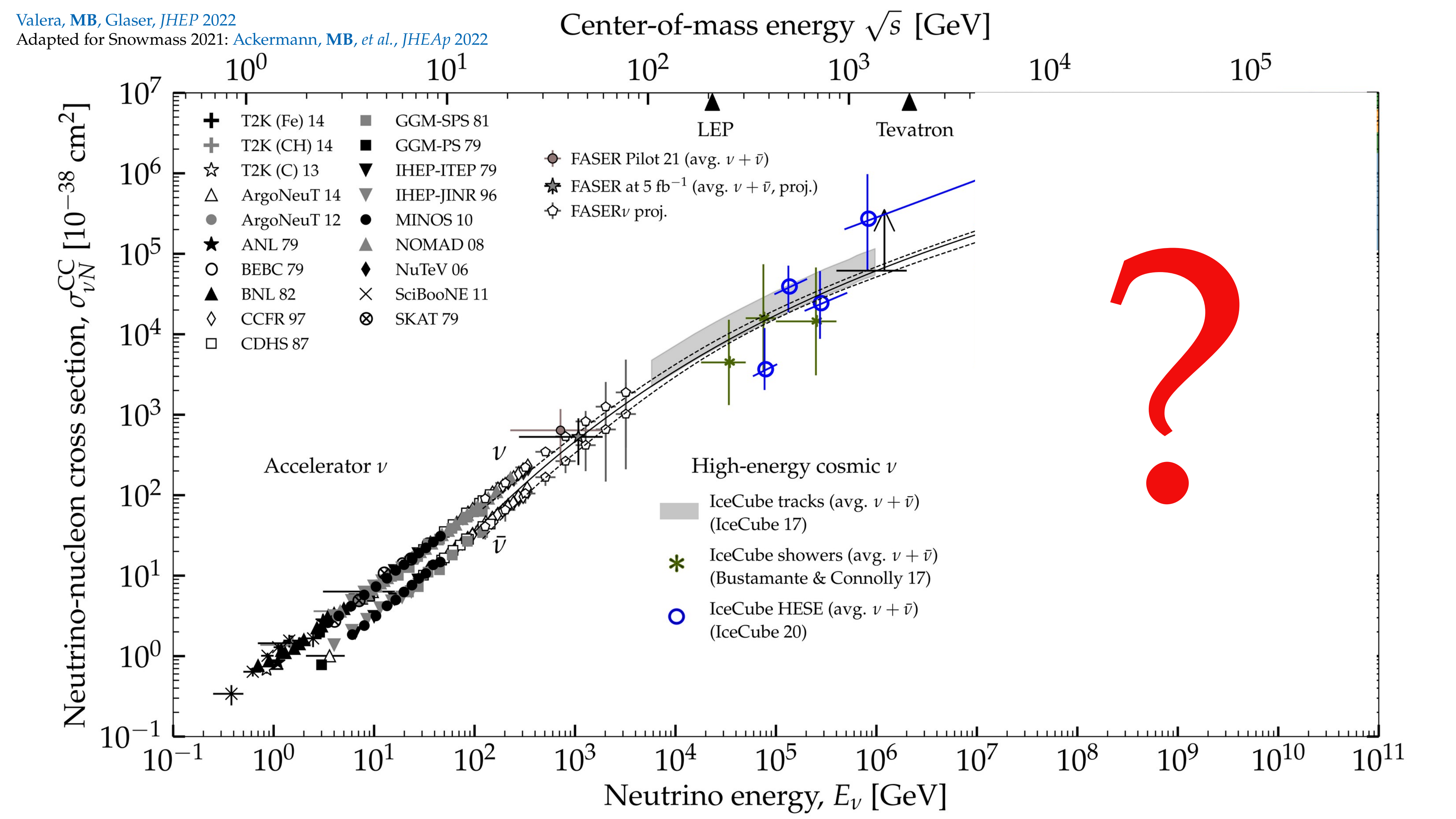


Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:

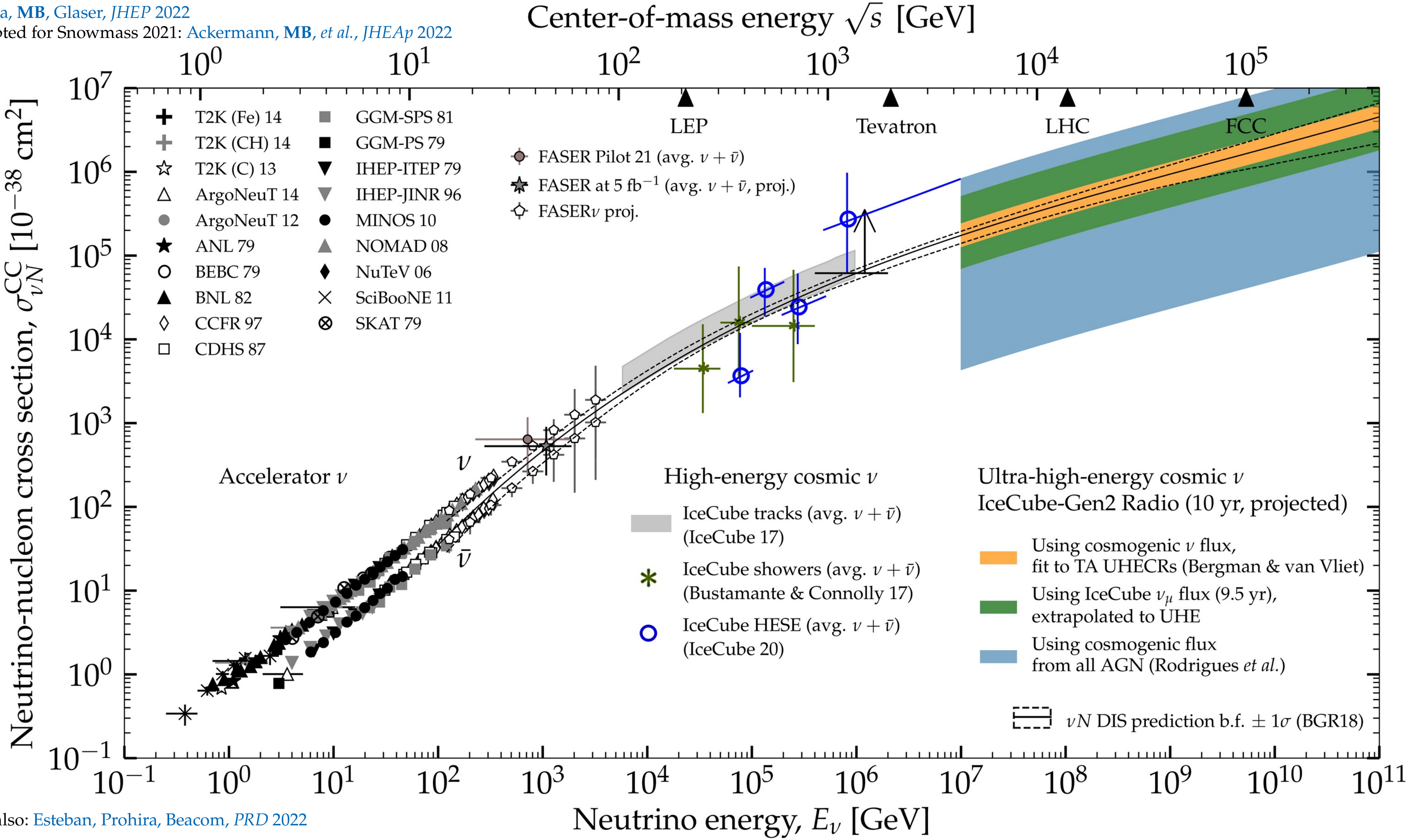


Earth is *completely* opaque,
but horizontal ν still make it through



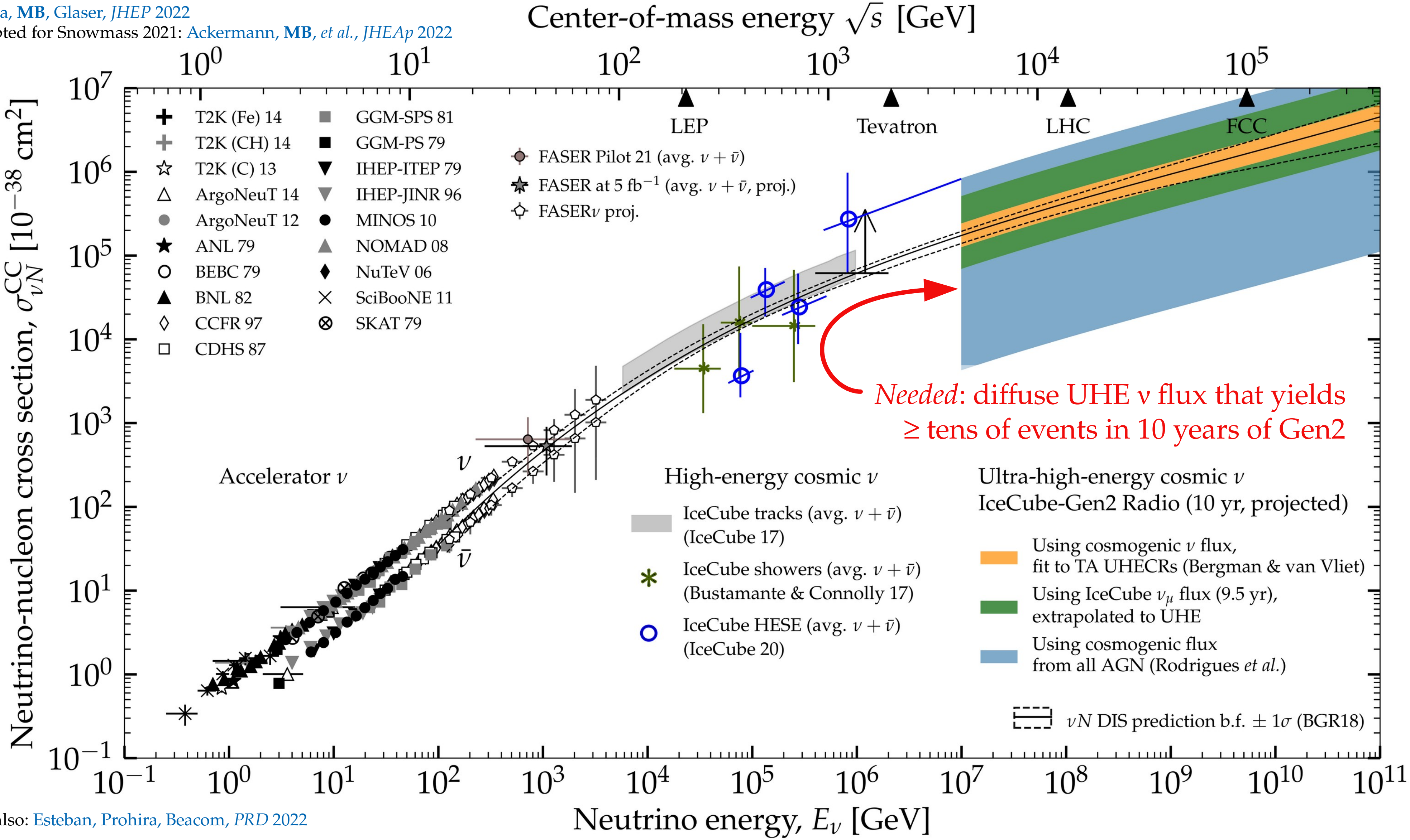
Valera, MB, Glaser, JHEP 2022
Adapted for Snowmass 2021: Ackermann, MB, et al., JHEAp 2022
Center-of-mass energy √s [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
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)
?

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

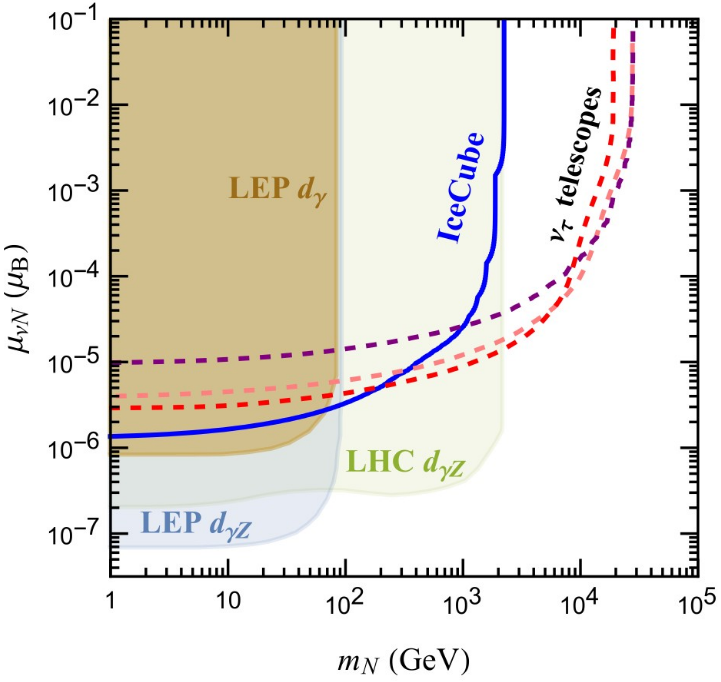


See also: Esteban, Prohira, Beacom, *PRD* 2022

New physics in the UHE νN cross section

New physics in the UHE νN cross section

Heavy sterile neutrinos
via the dipole portal



Huang, Jana, Lindner, Rodejohann, 2204.10347

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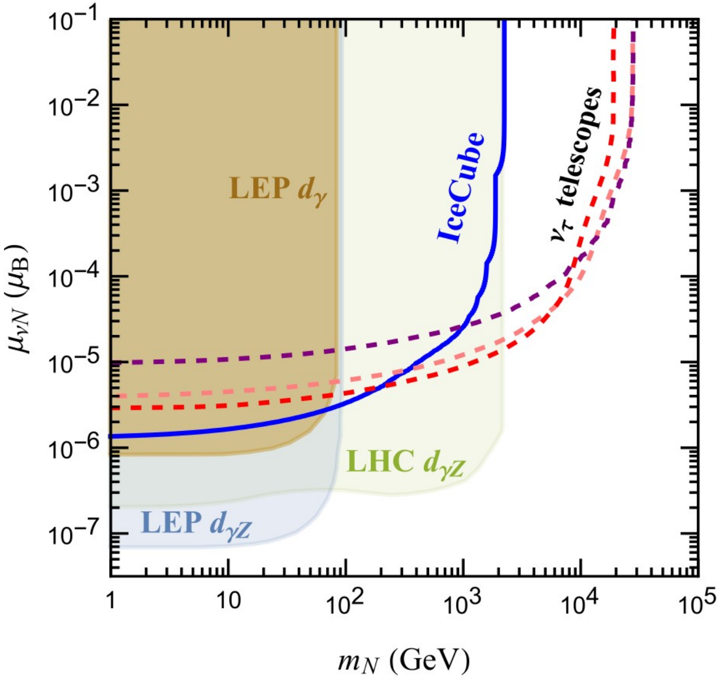
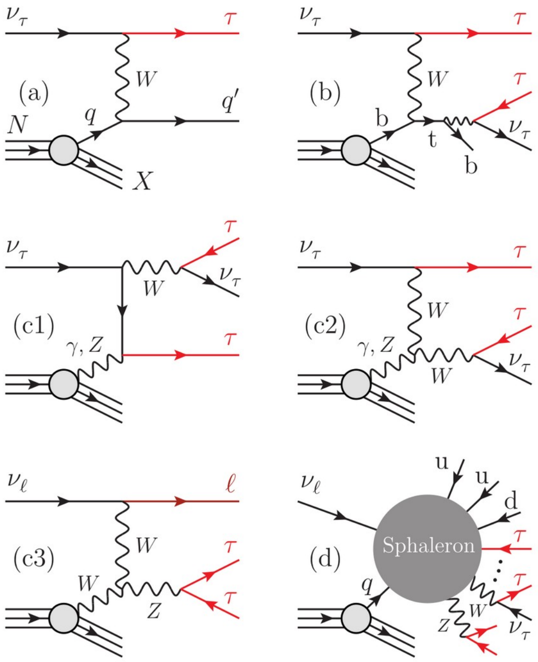


Huang, Jana, Lindner, Rodejohann, 2204.10347

Multiple ν_τ-induced bangs



Huang, *EPJC* 2022 [2207.02222]

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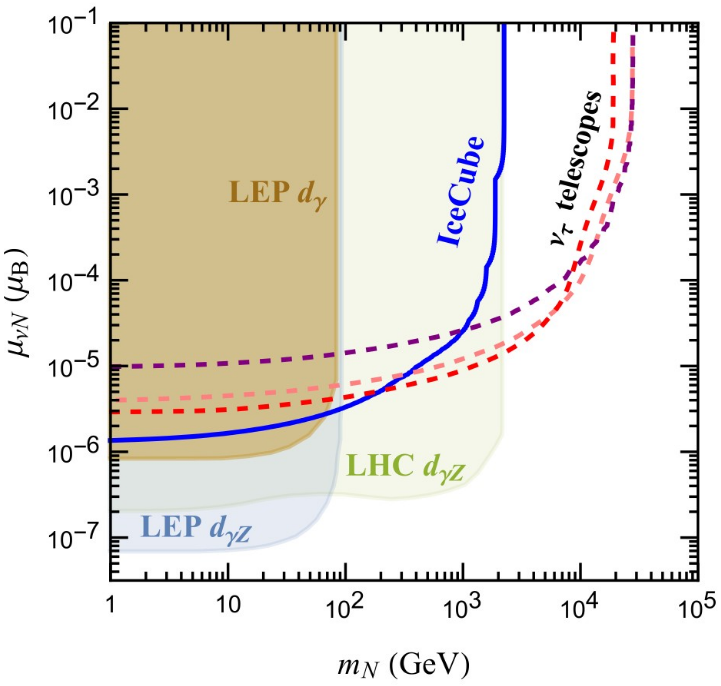

Huang, Jana, Lindner, Rodejohann, 2204.10347

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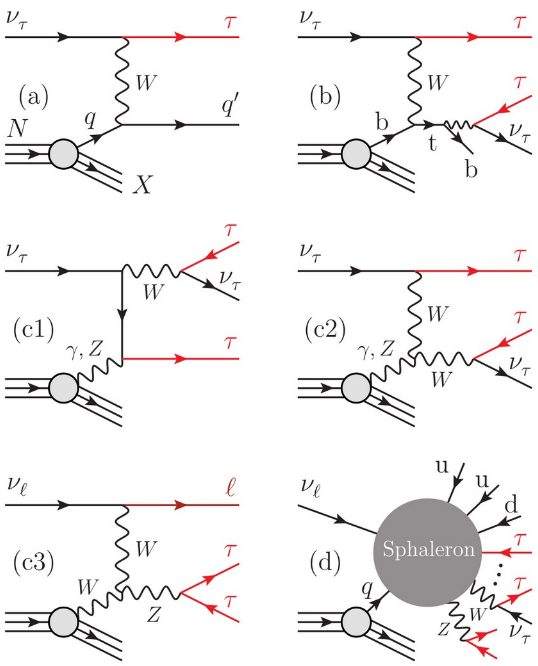
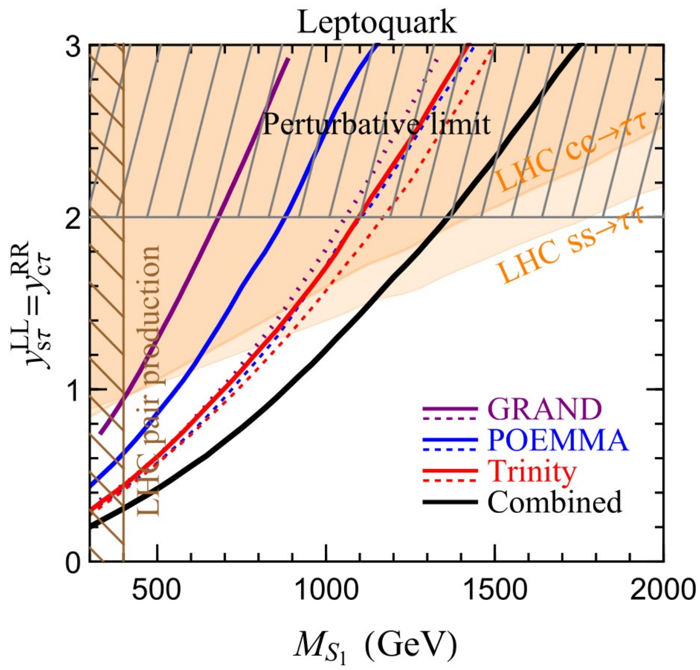


Huang, *EPJC* 2022 [2207.02222]

Leptoquarks, charged Higgs, *etc*.



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