Astrophysics and fundamental physics from high-energy cosmic messengers

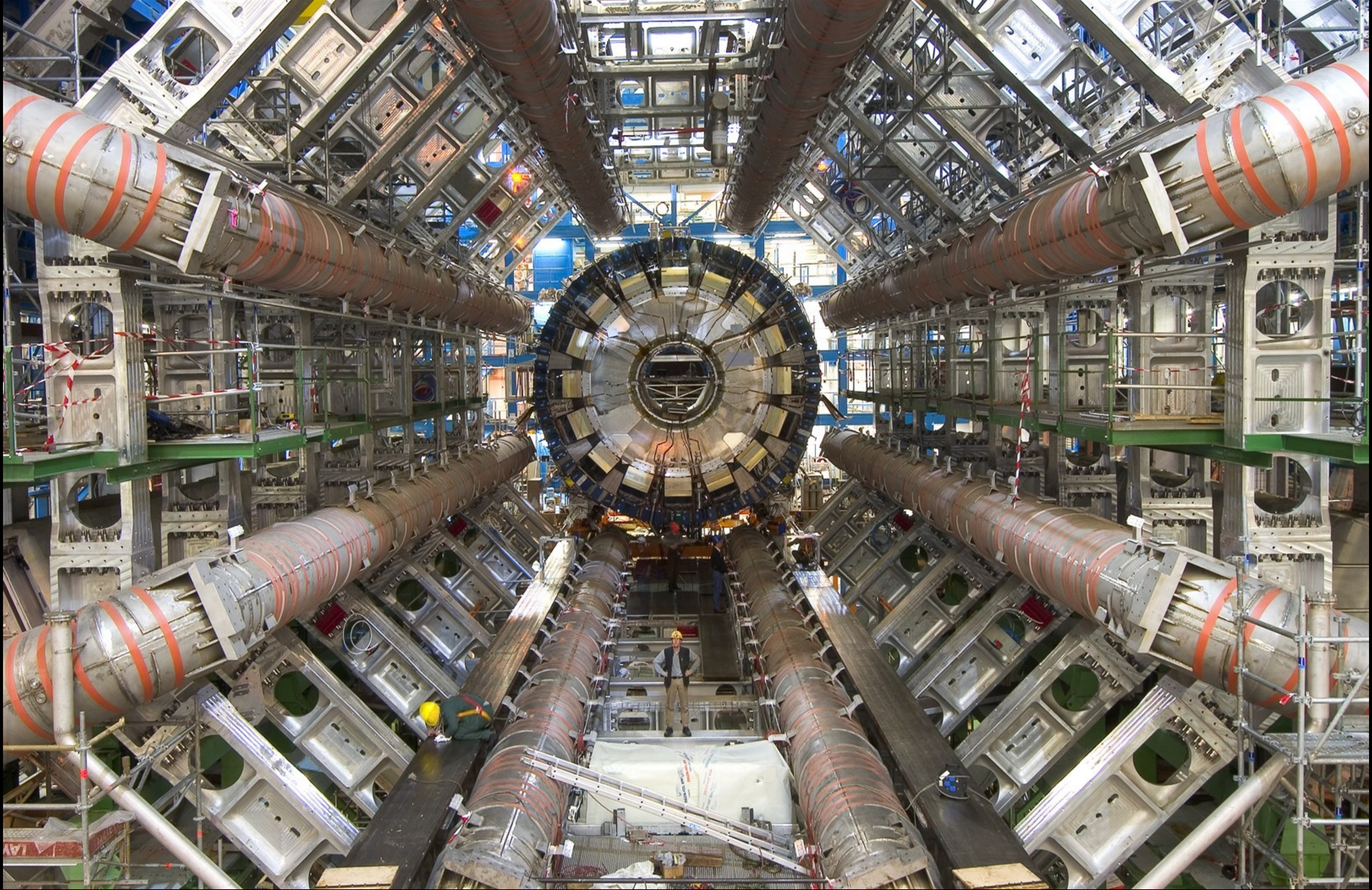
Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

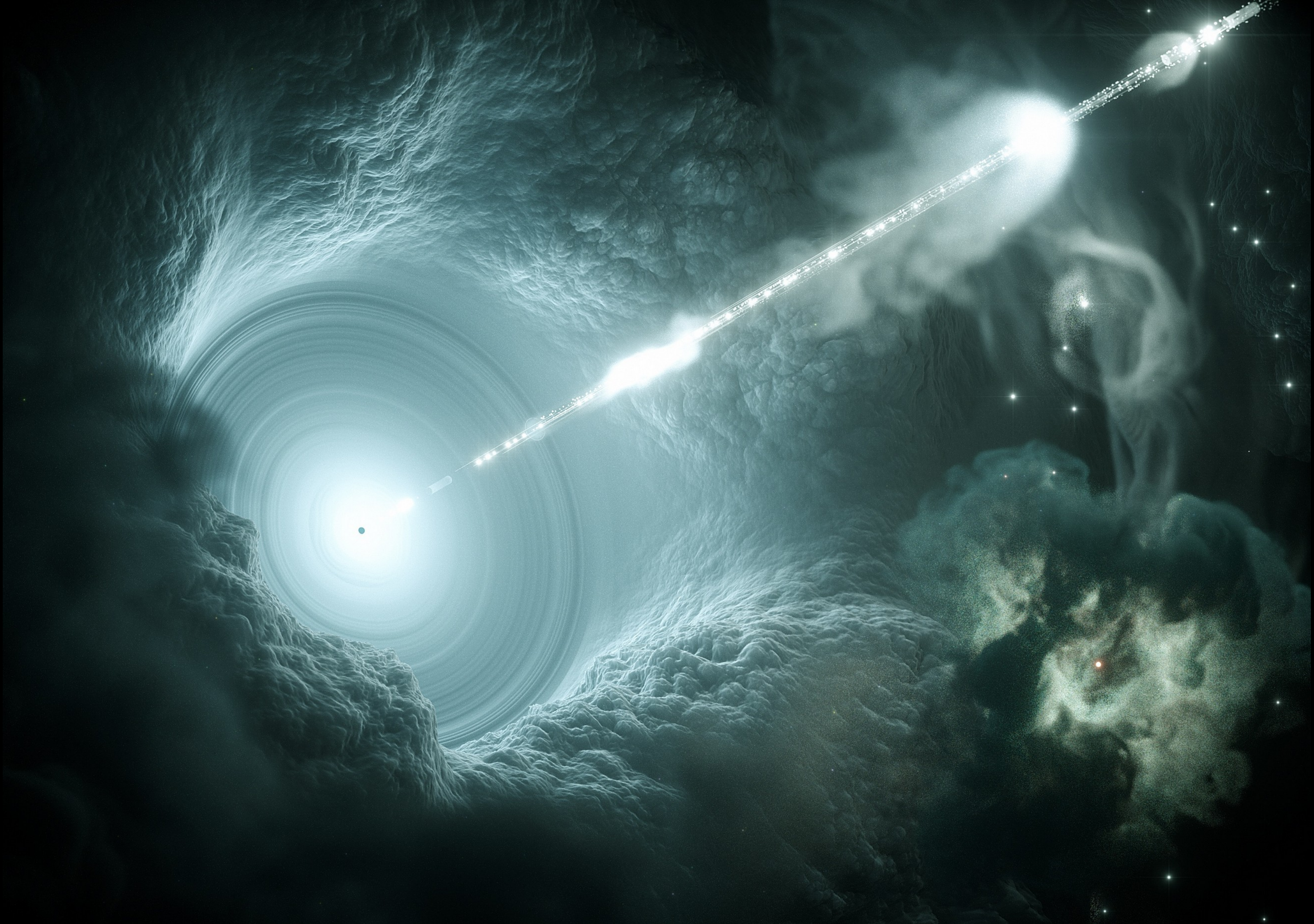
XIV SILAFAE
Quito, November 14, 2022

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

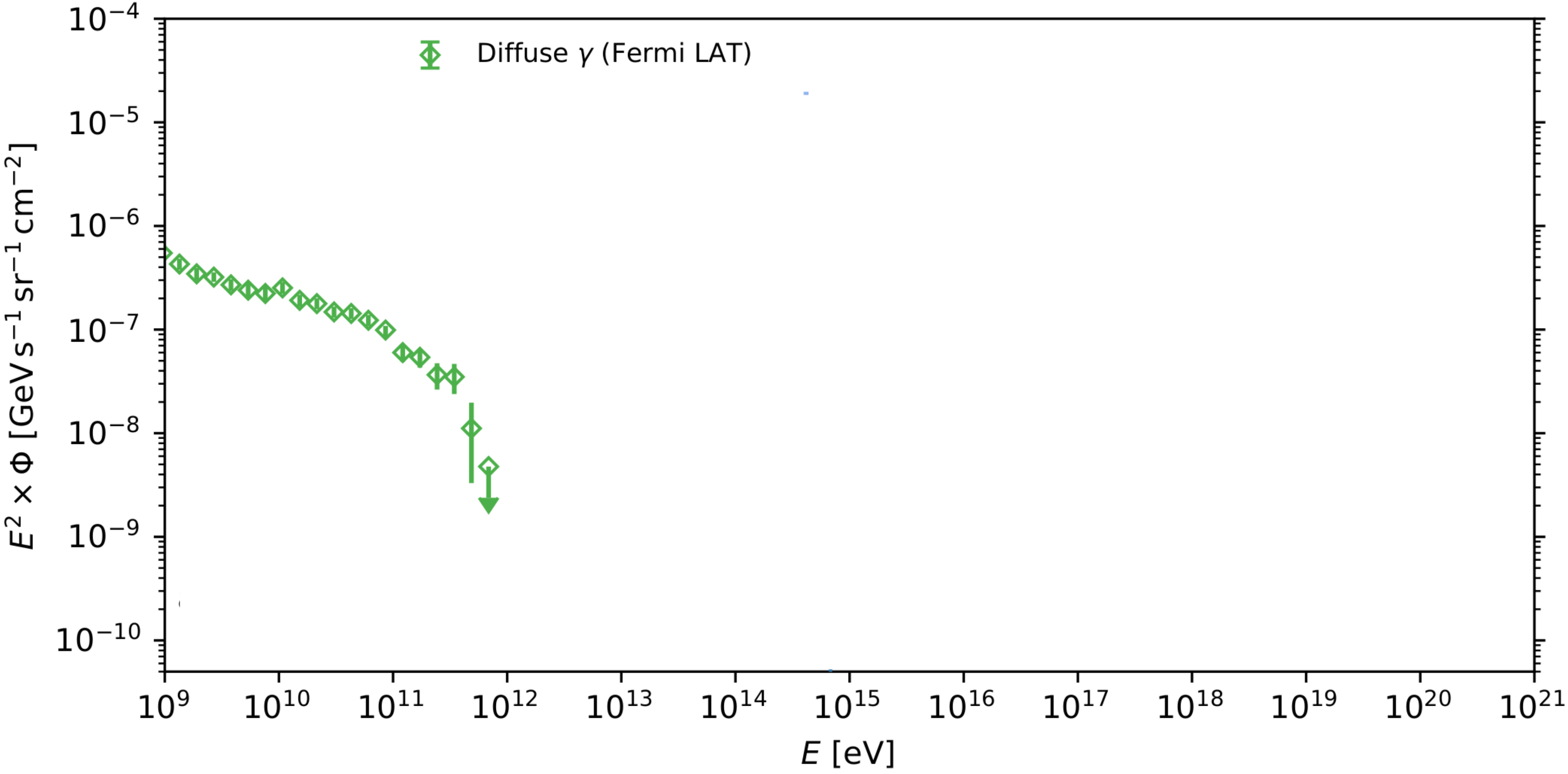


ATLAS

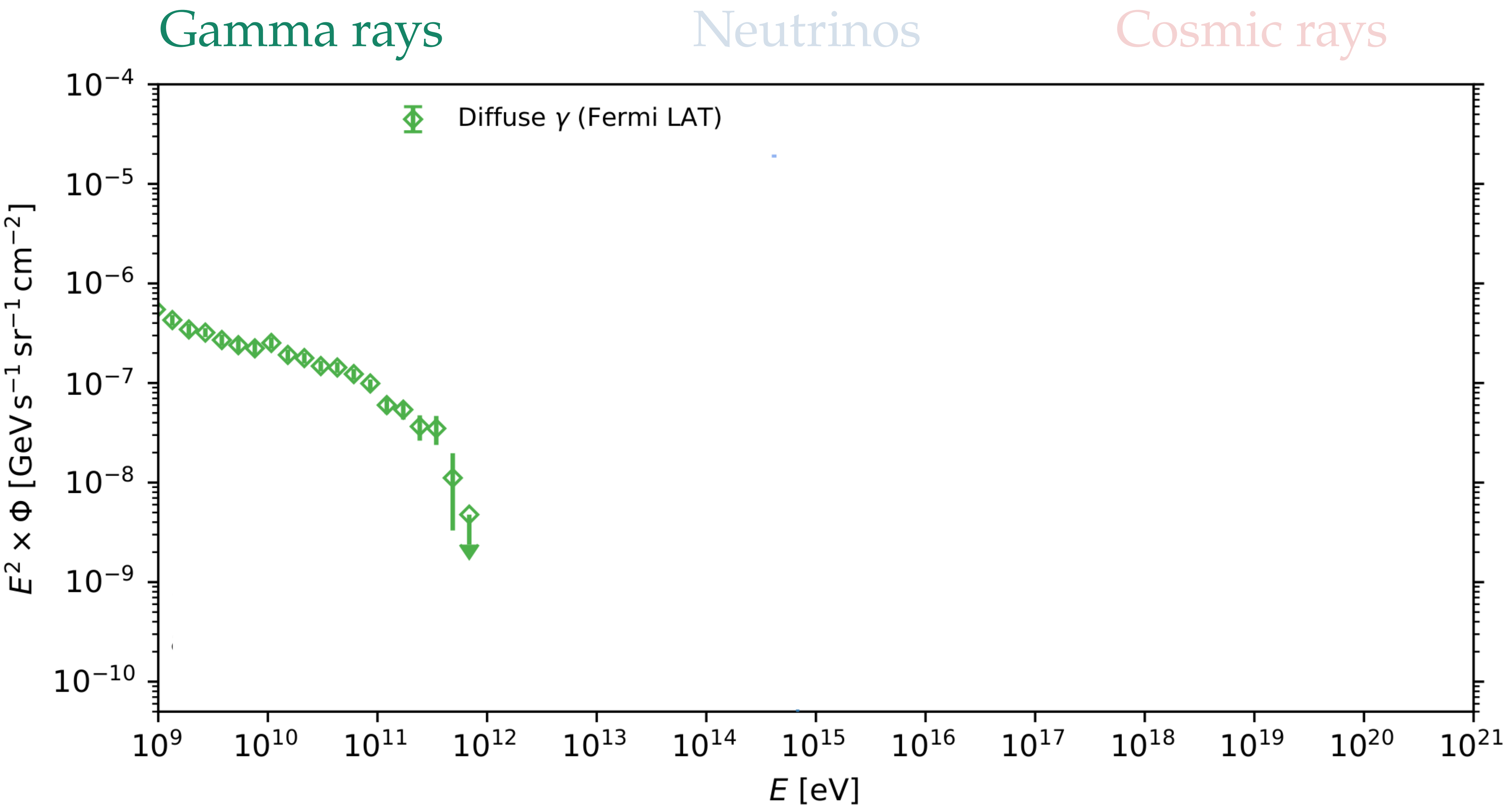


DESY

Gamma rays Neutrinos Cosmic rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]



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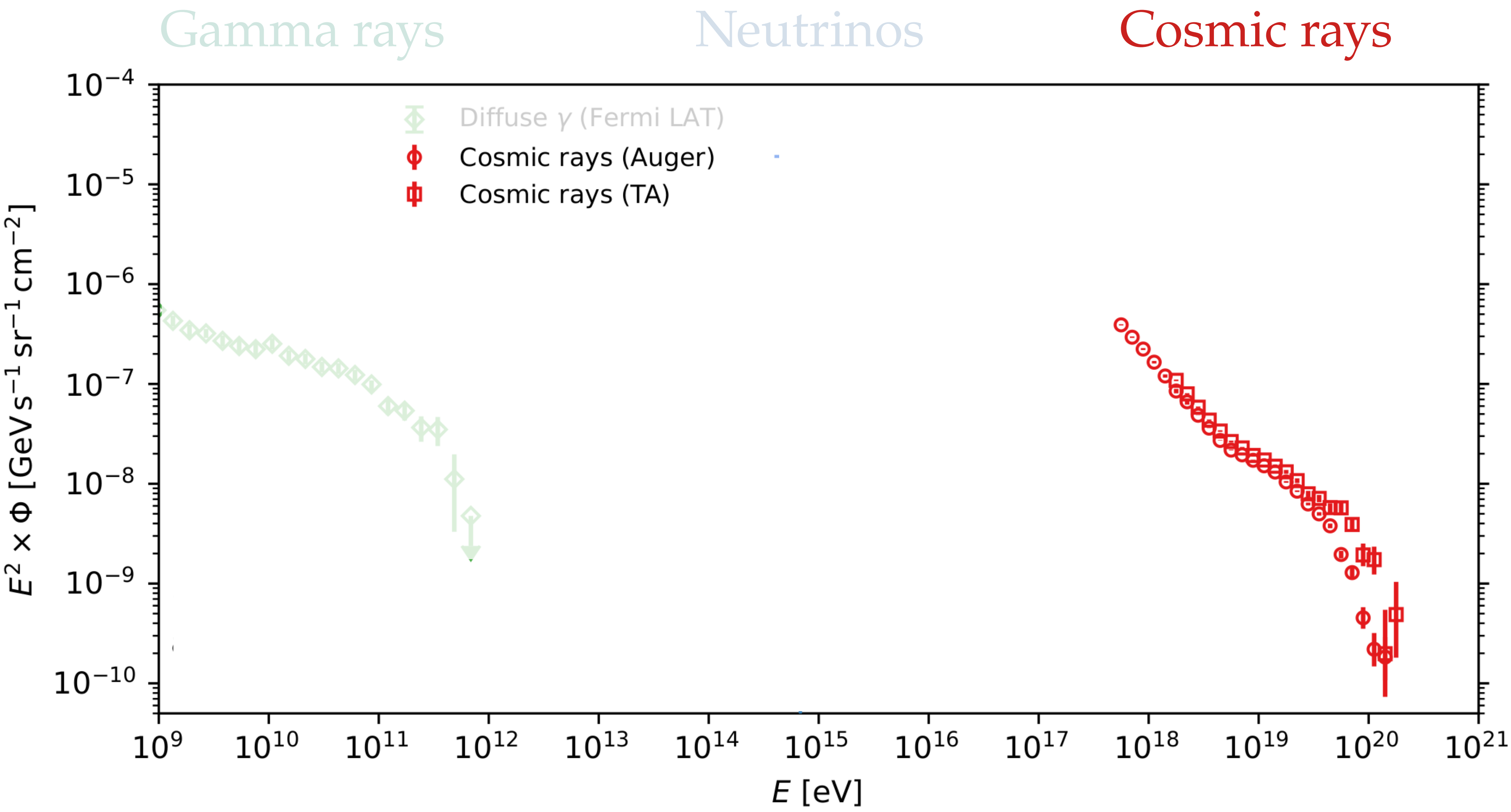

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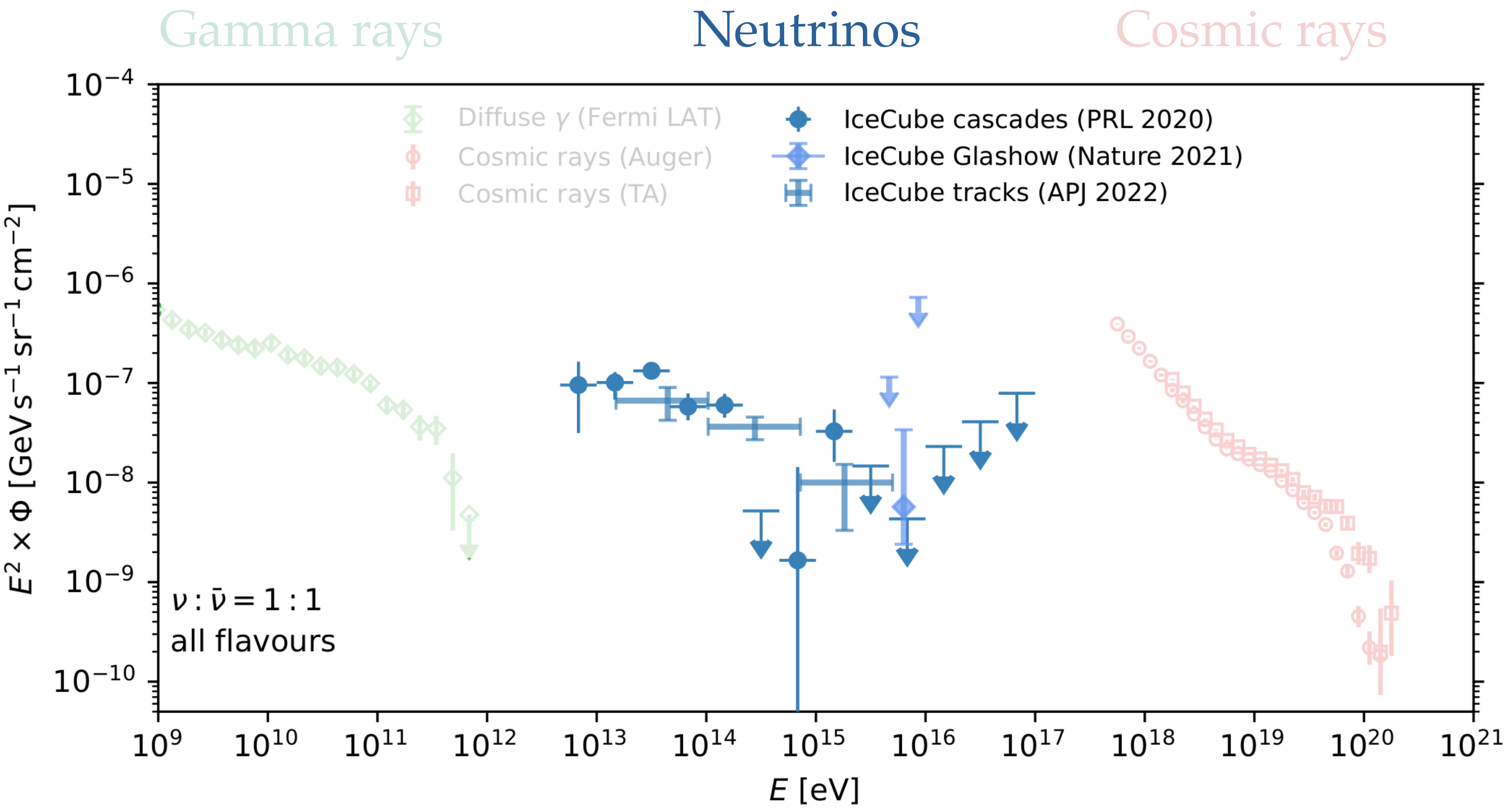

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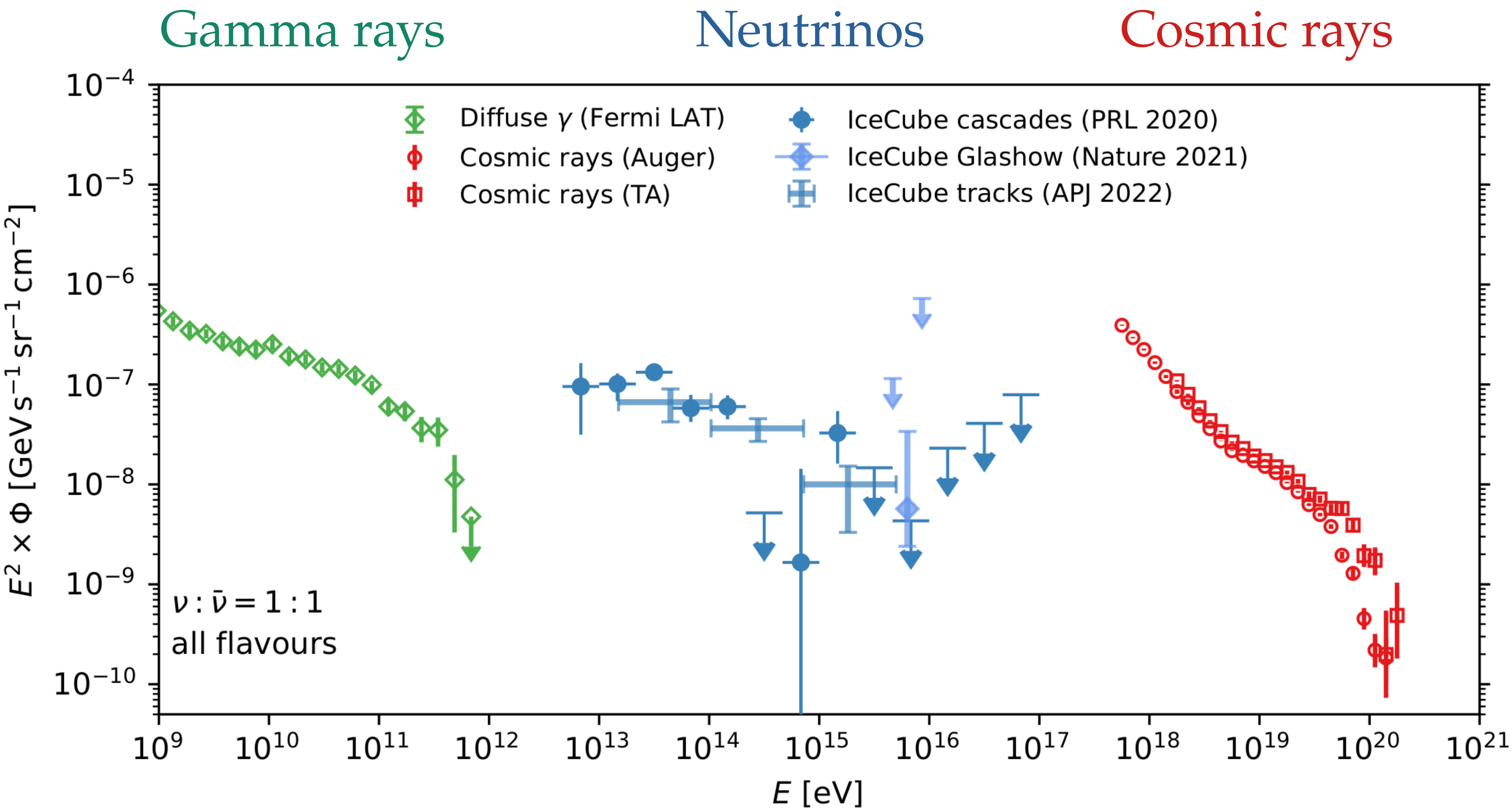

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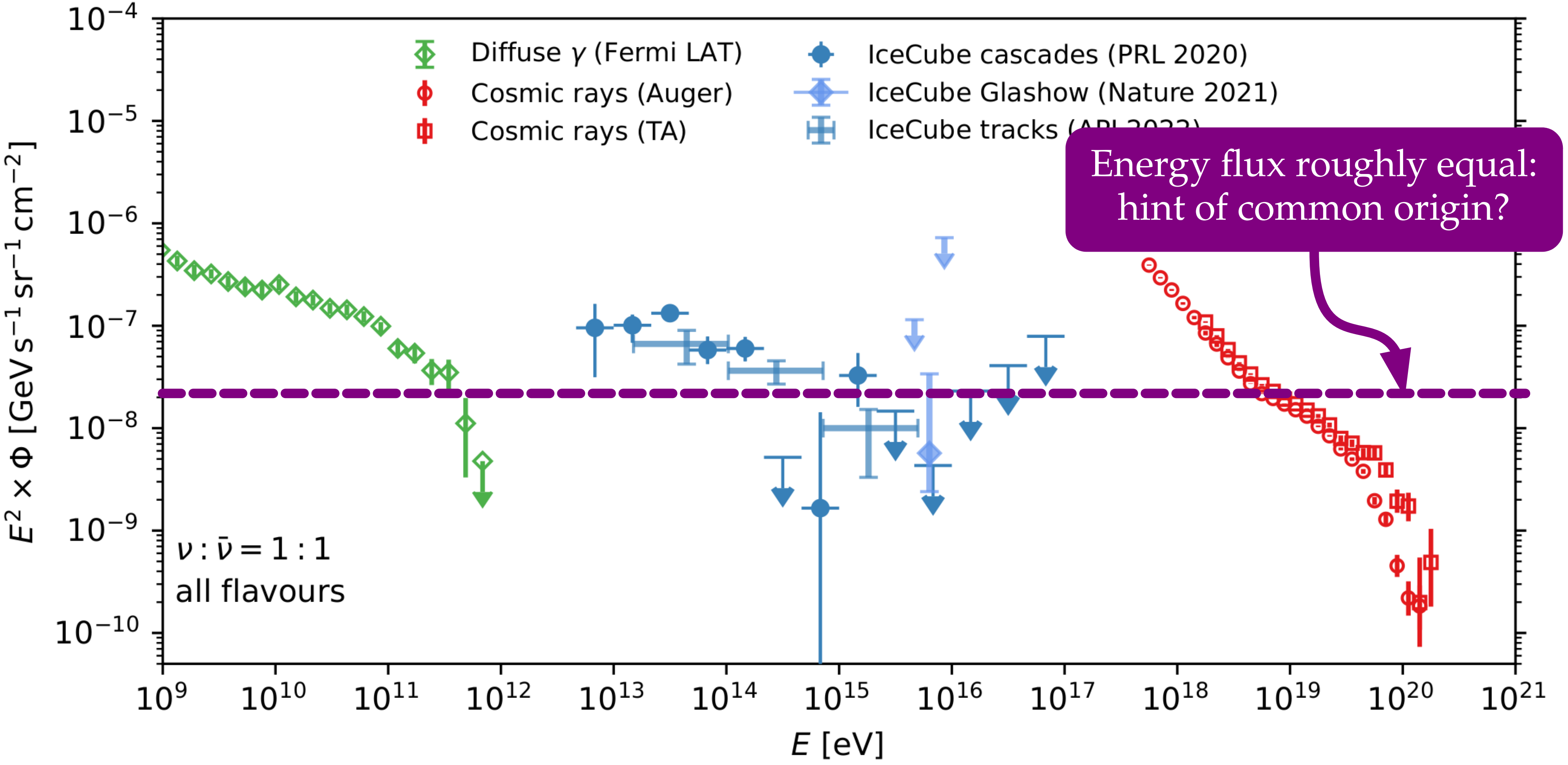


M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

What about gravitational waves?

They're equally important!

See talk by James Dent on Thu 17/11

Particle physics & astrophysics with high-energy particles

Pros

Highest energies known/expected:

Particle: Test BSM theories

Astro: Most energetic sources

Baselines ~size of visible Universe:

Particle: Tiny effects can accumulate

Astro: Most distant/ancient sources

Cons

We don't know the sources

(especially for ν and CRs)

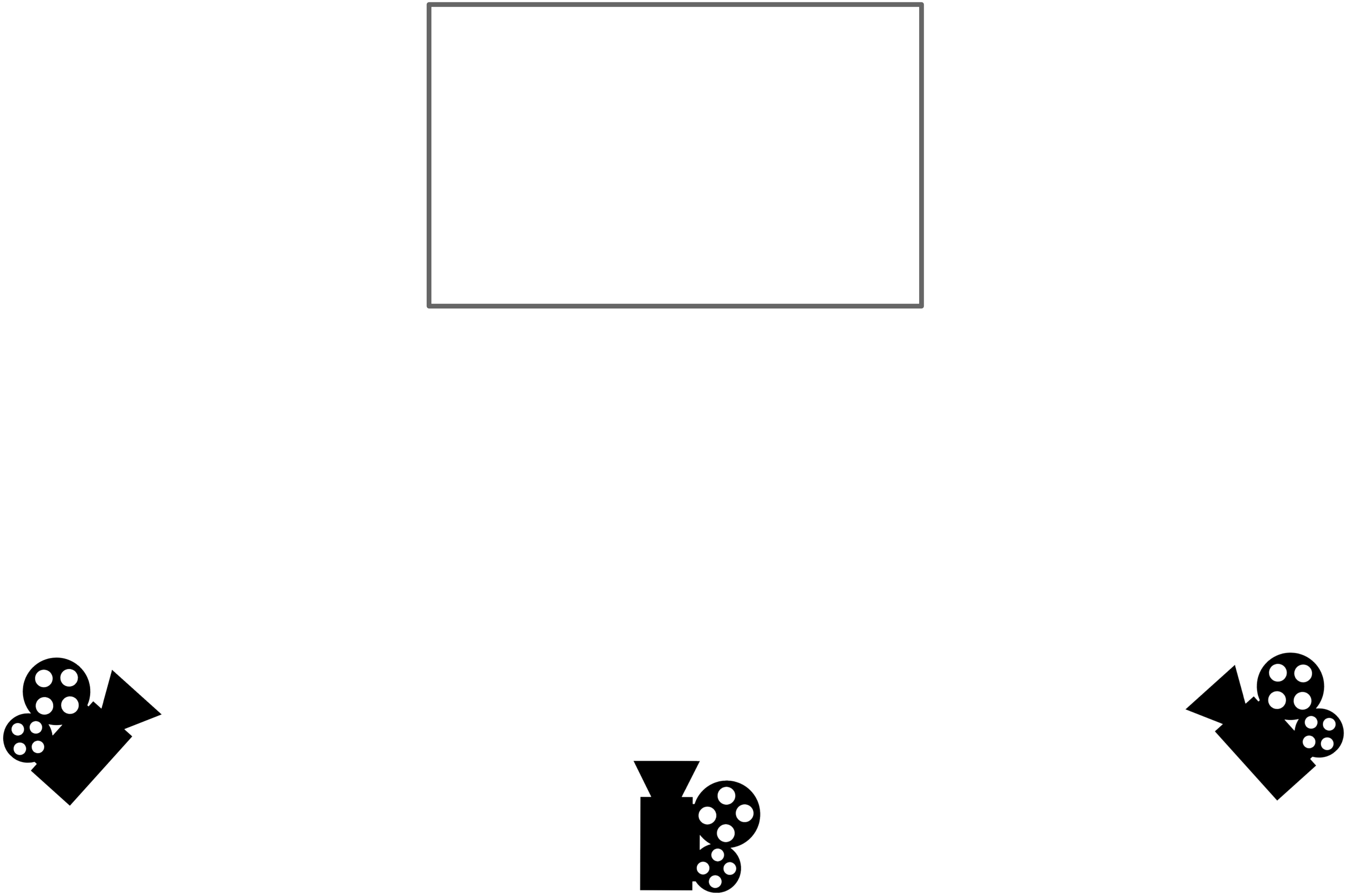
We don't know production mechanisms

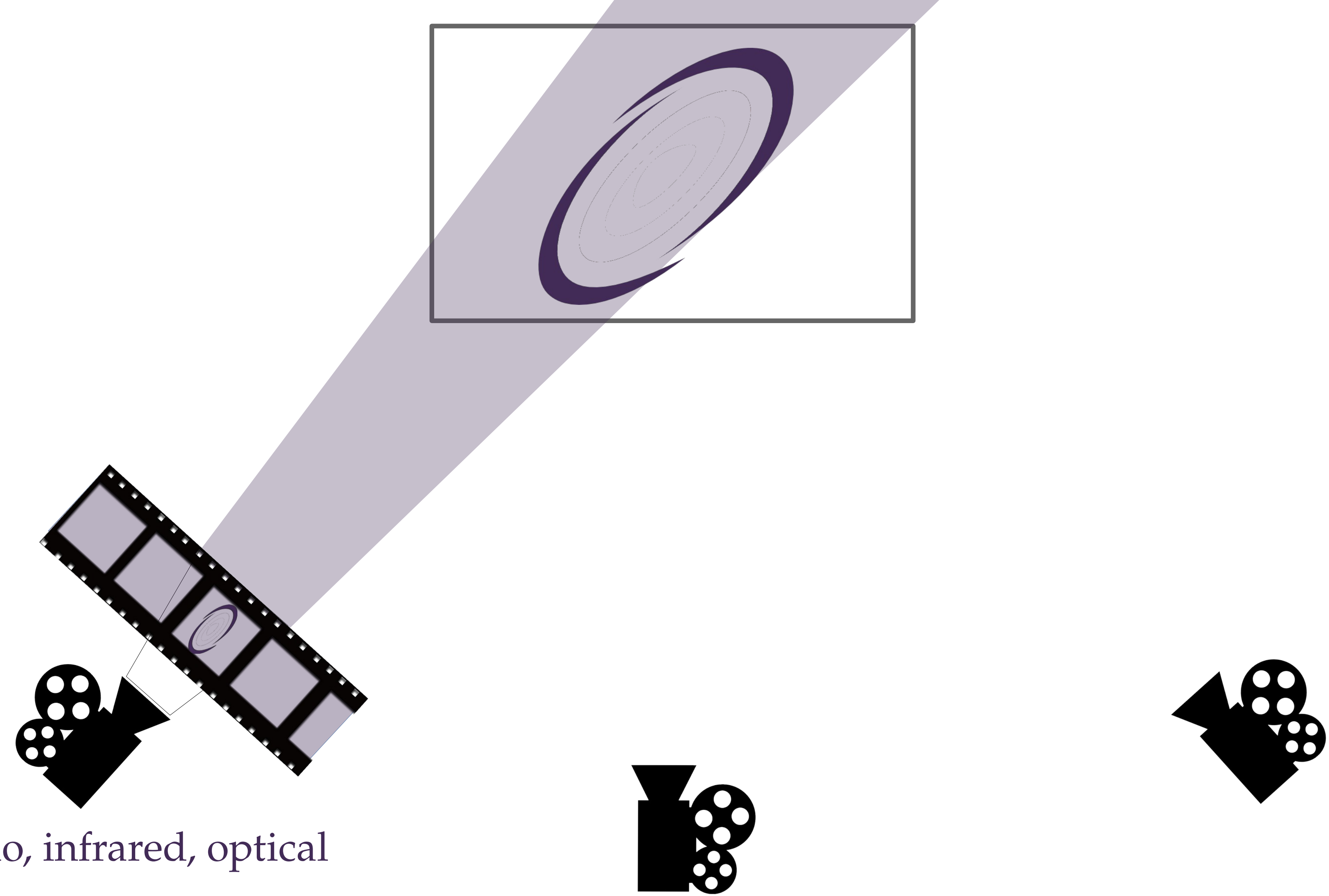
We don't know how particles act at PeV+

Detectors are coarser than in colliders

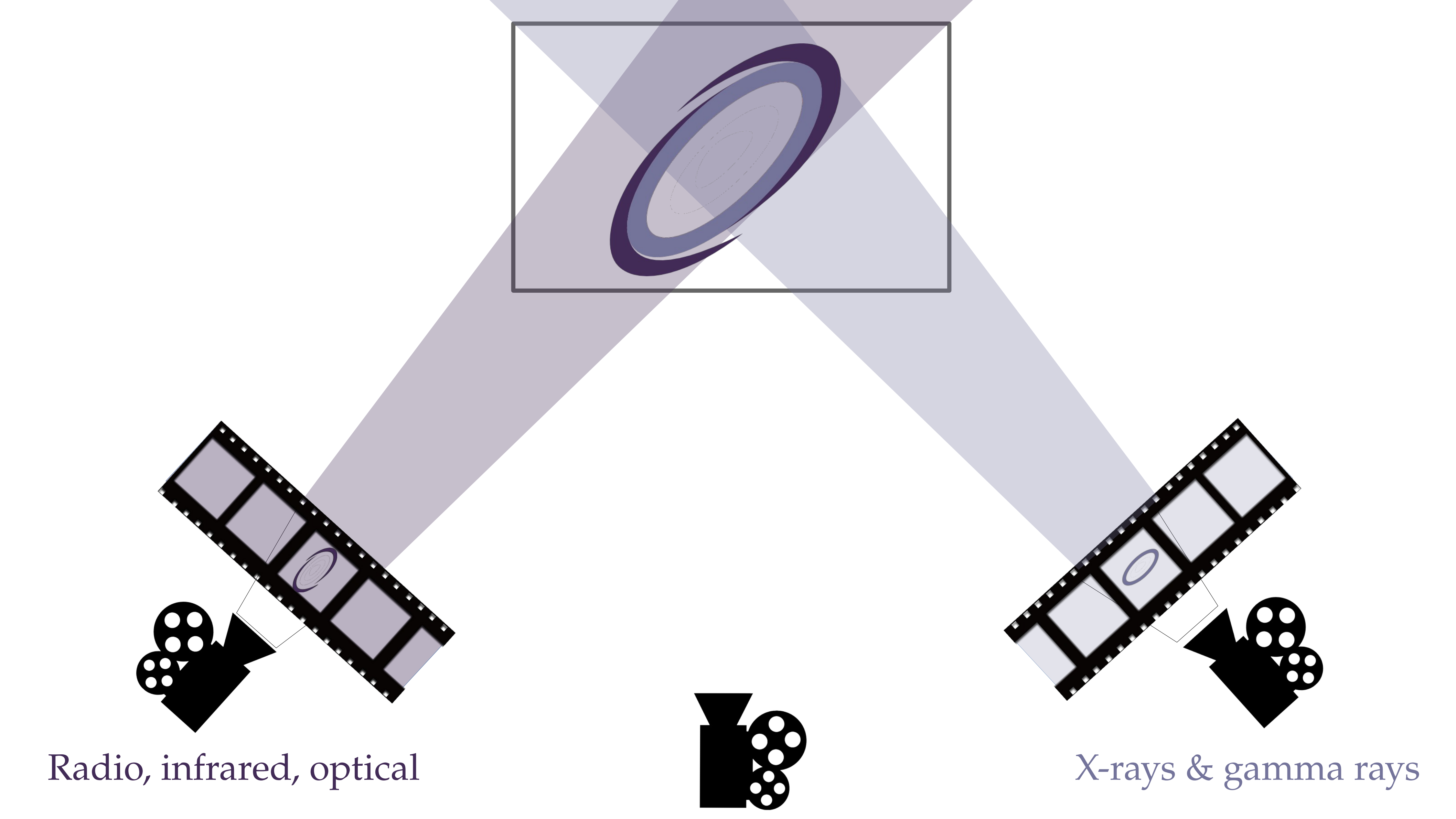
Today: Large particle and astro unknowns

$\Rightarrow$ *Measurements are as much of particle physics as of astrophysics!*

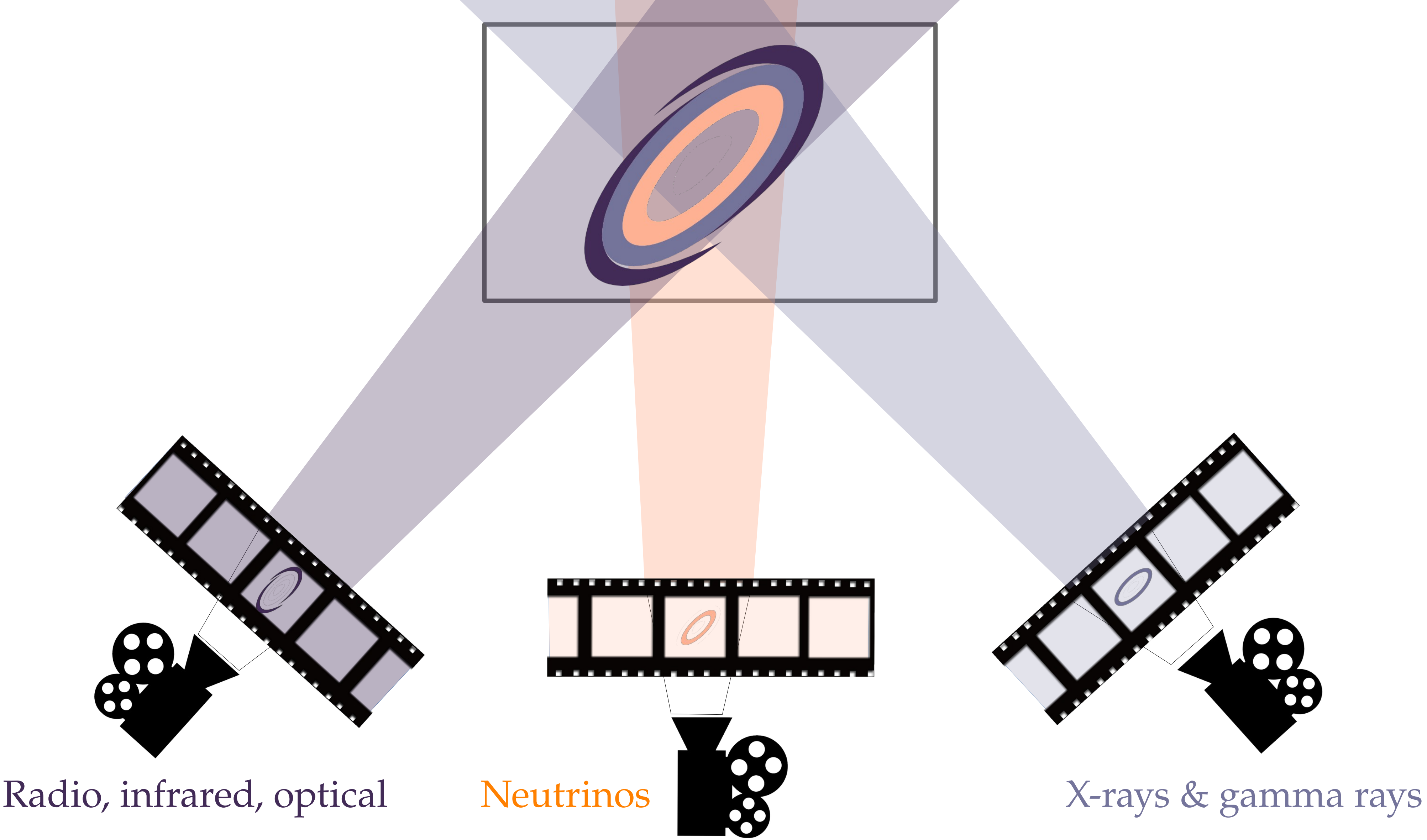




Radio, infrared, optical



Radio, infrared, optical
X-rays & gamma rays


Radio, infrared, optical
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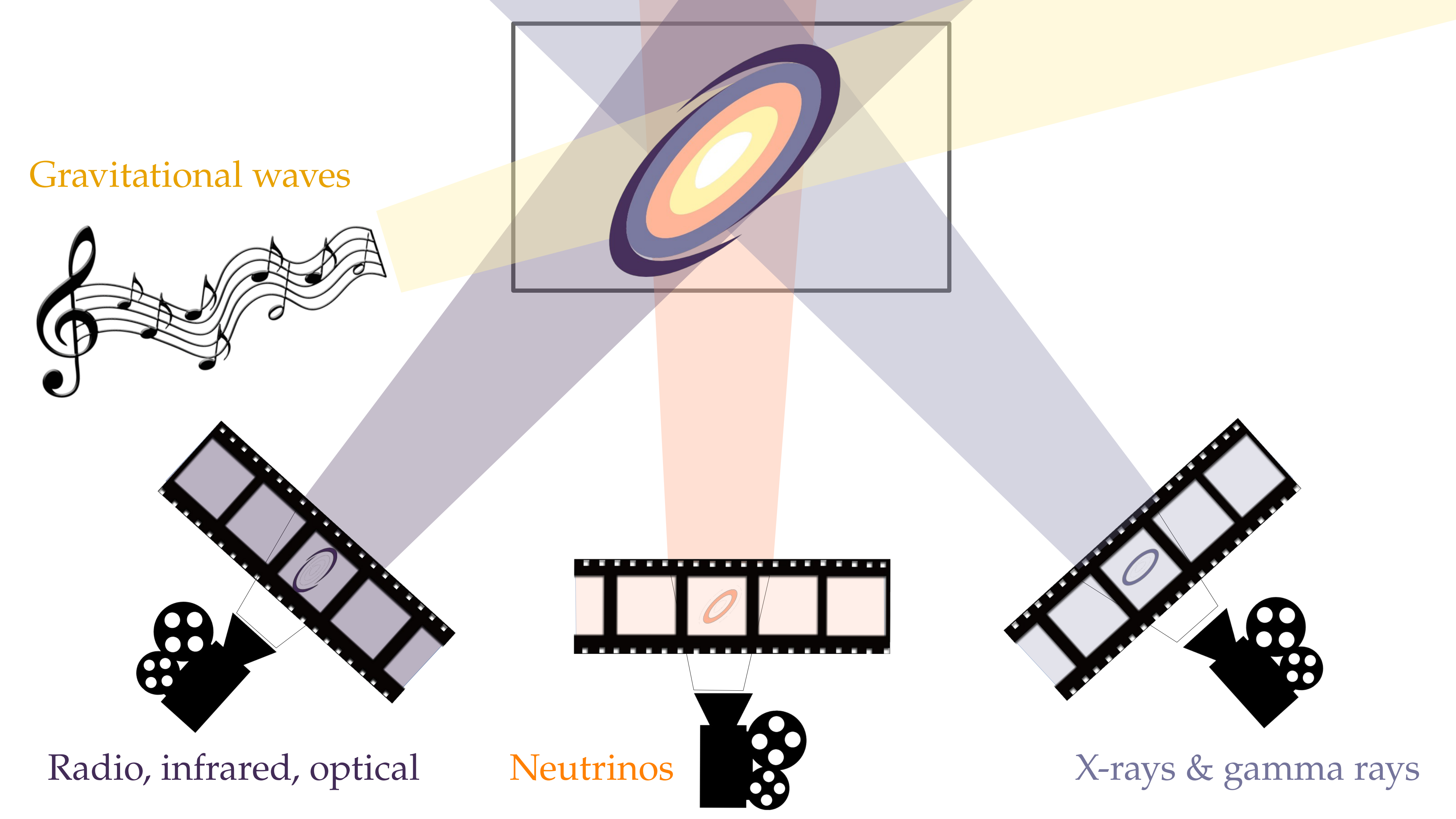
Gravitational waves
Radio, infrared, optical
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X-rays & gamma rays

Making high-energy astrophysical neutrinos: a toy model

(or $p + p$)

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

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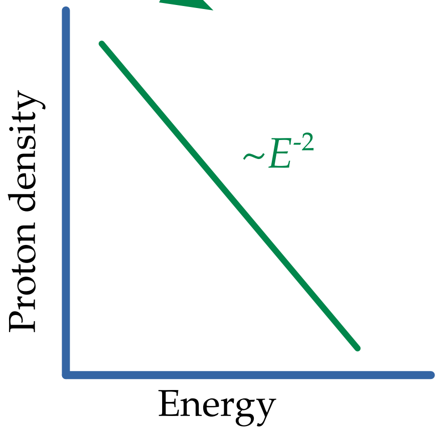

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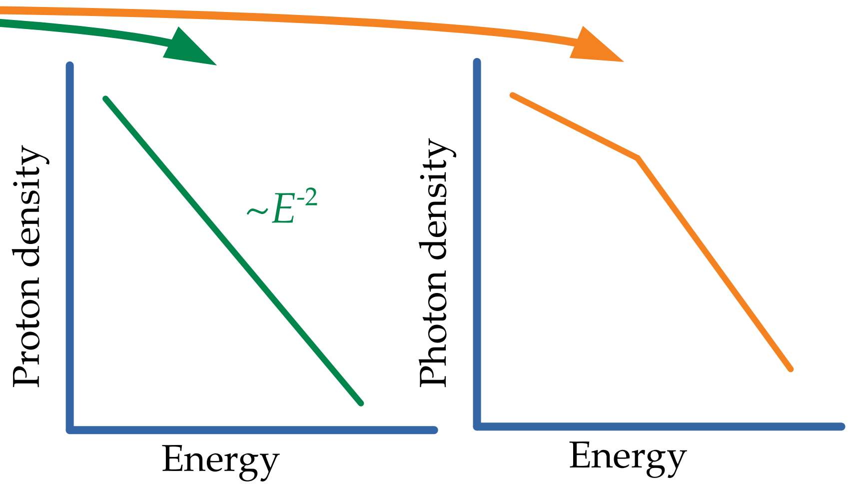

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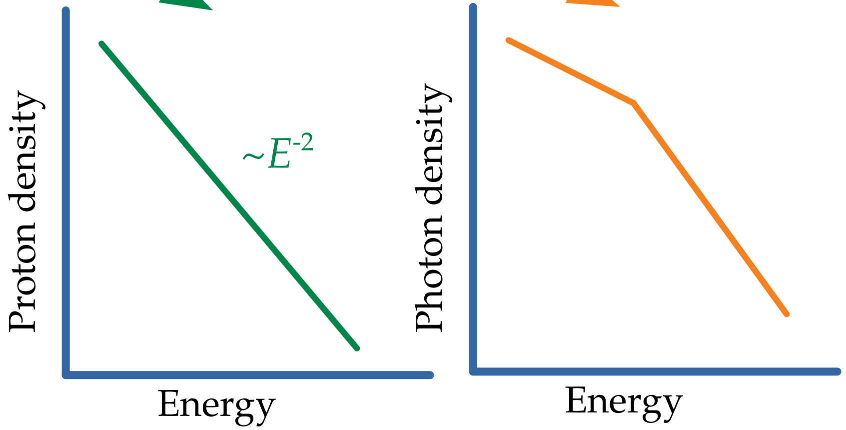
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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



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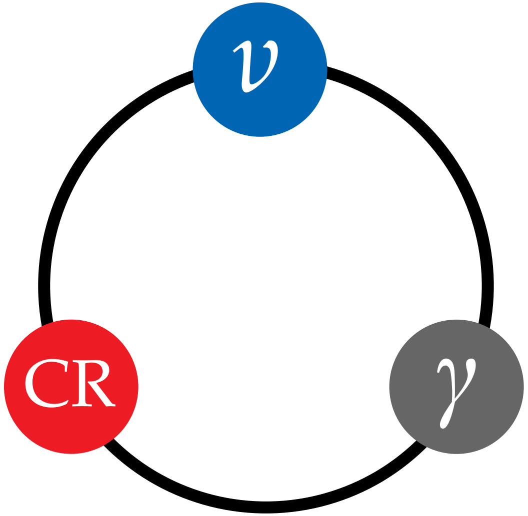


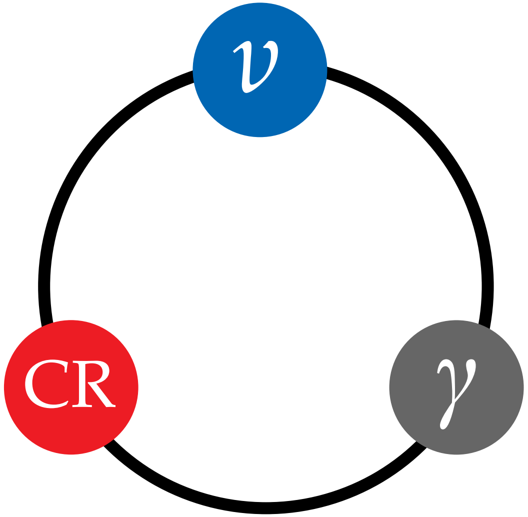
Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

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

Energy in neutrinos ∝ energy in gamma rays

Waxman & Bahcall, *PRL* 1997



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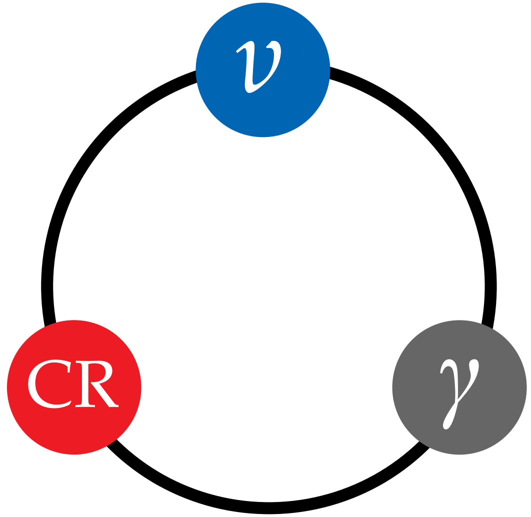
Fudge factors:
Source properties (*e.g.*, baryonic loading)
Particle effects (*e.g.*, ν-producing channels)



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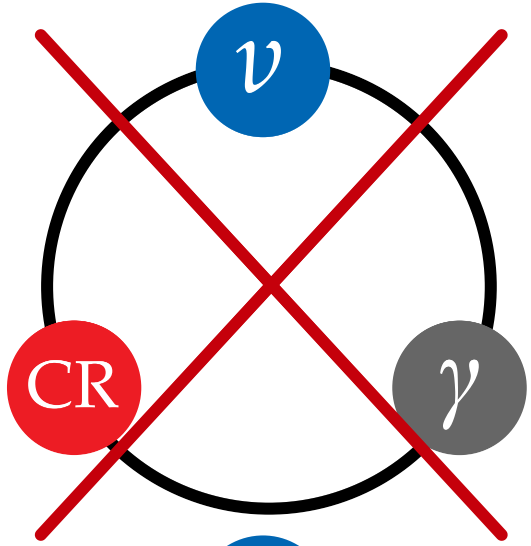
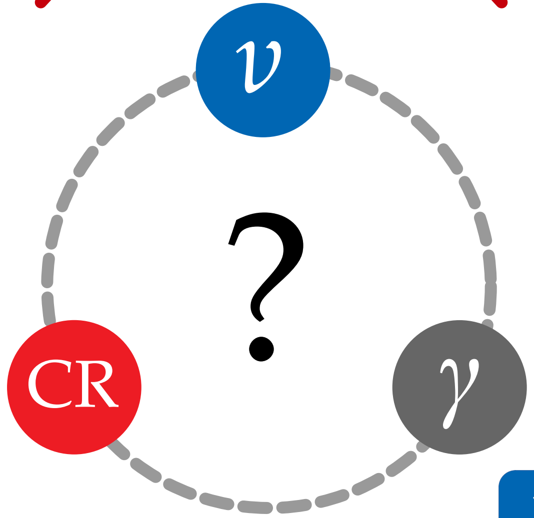


But the correlation between ν and γ may be more nuanced:

Gao, Pohl, Winter, *ApJ* 2017



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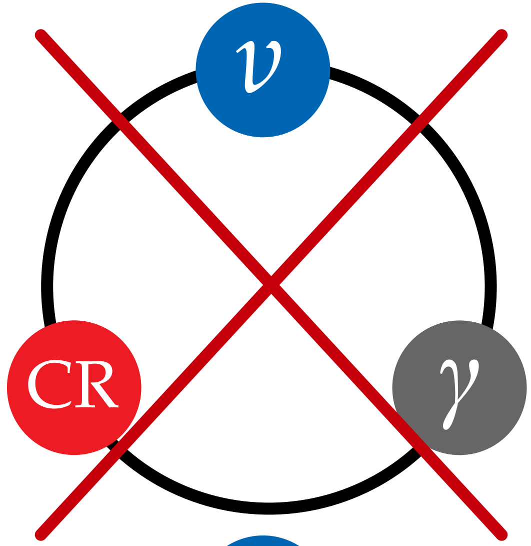

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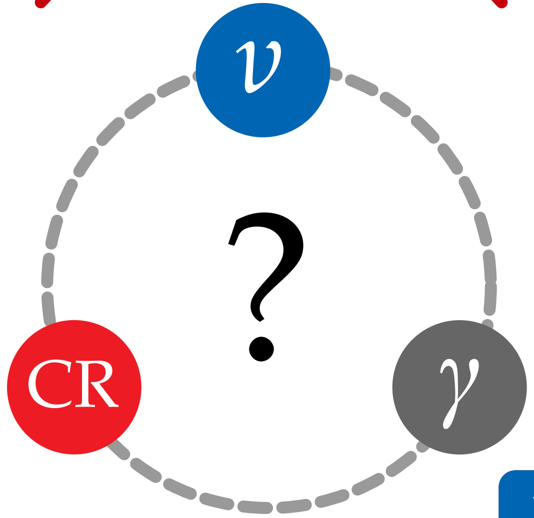
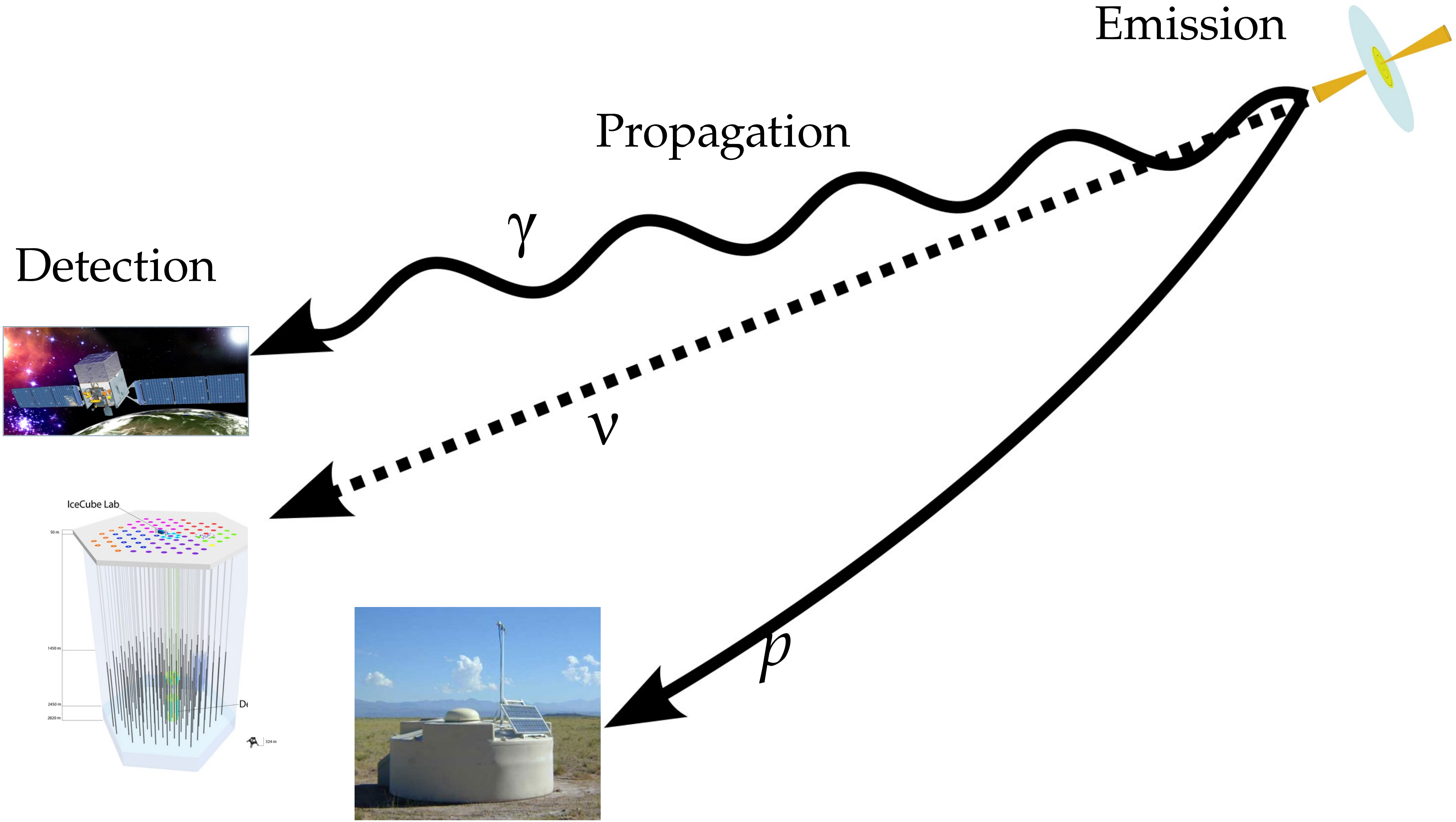
Sources that make neutrinos via *p*γ
may be opaque to 1–100 MeV gamma rays

Murase, Guetta, Ahlers, *PRL* 2016

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

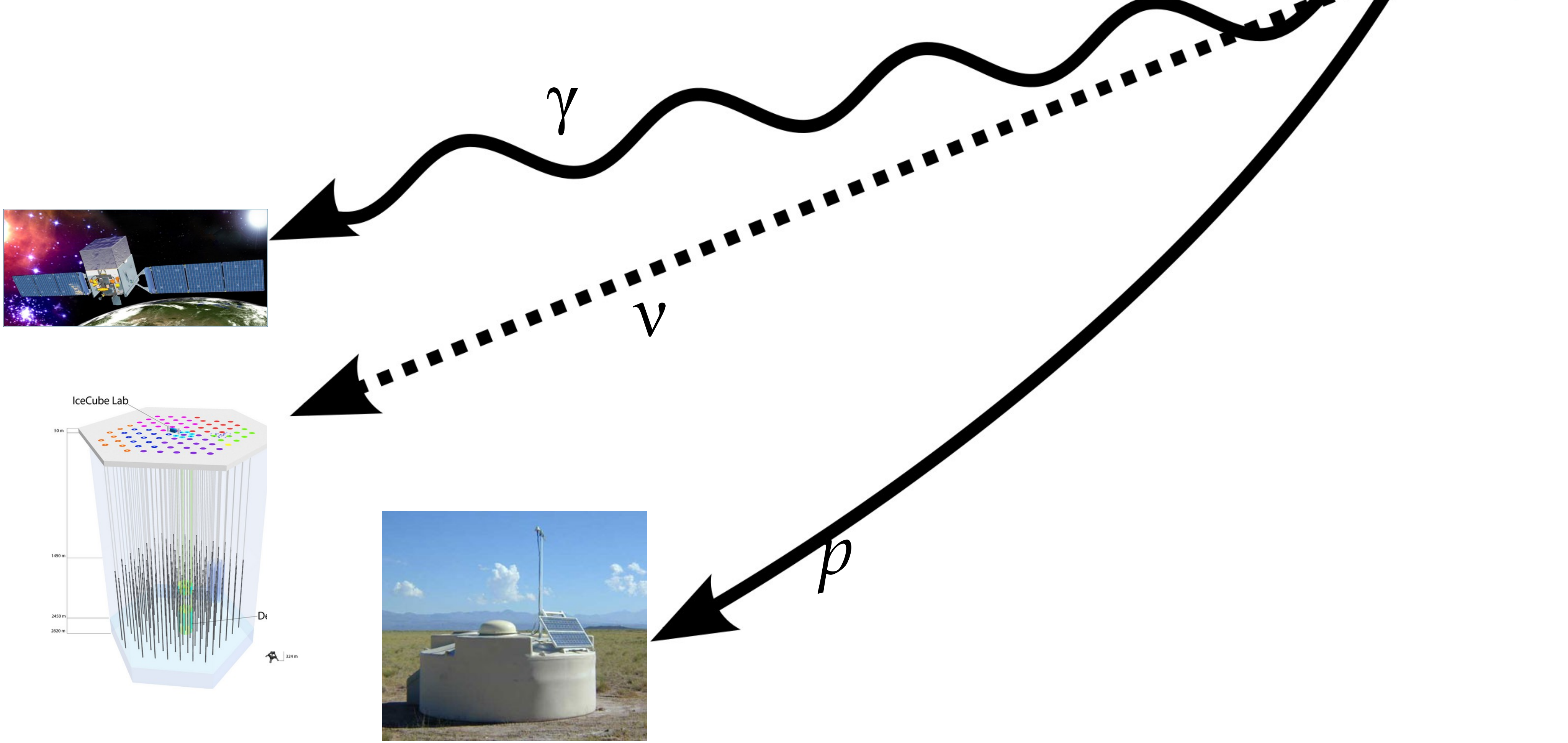
Morejon, Fedynitch, Boncioli, Winter, *JCAP* 2019
Boncioli, Fedynitch, Winter, *Sci. Rep.* 2017





Emission
Propagation
Detection
γ
ν
p
IceCube Lab

$$\text{Energy at Earth} = \frac{\text{Energy at production}}{1 + z}$$



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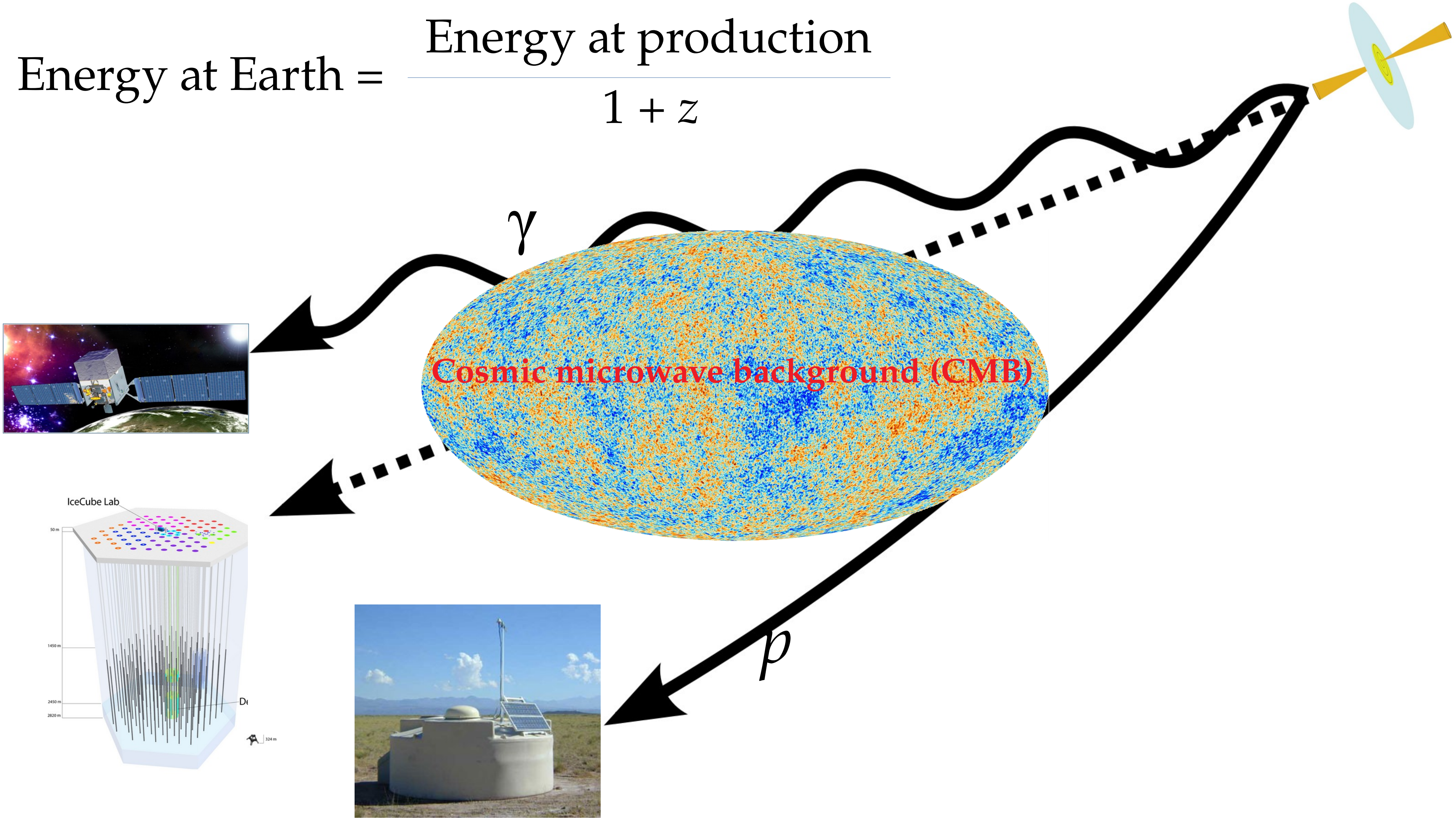
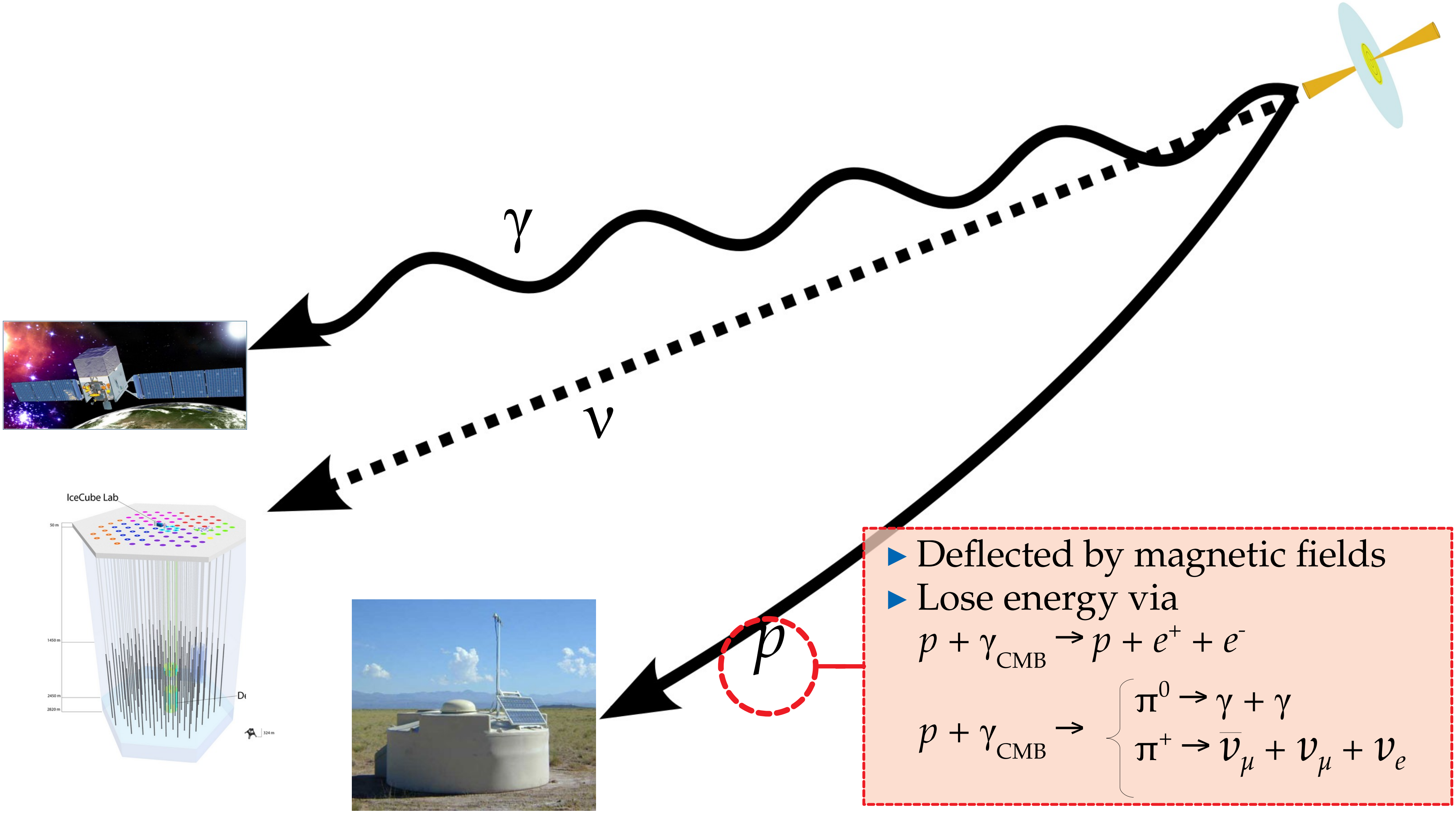
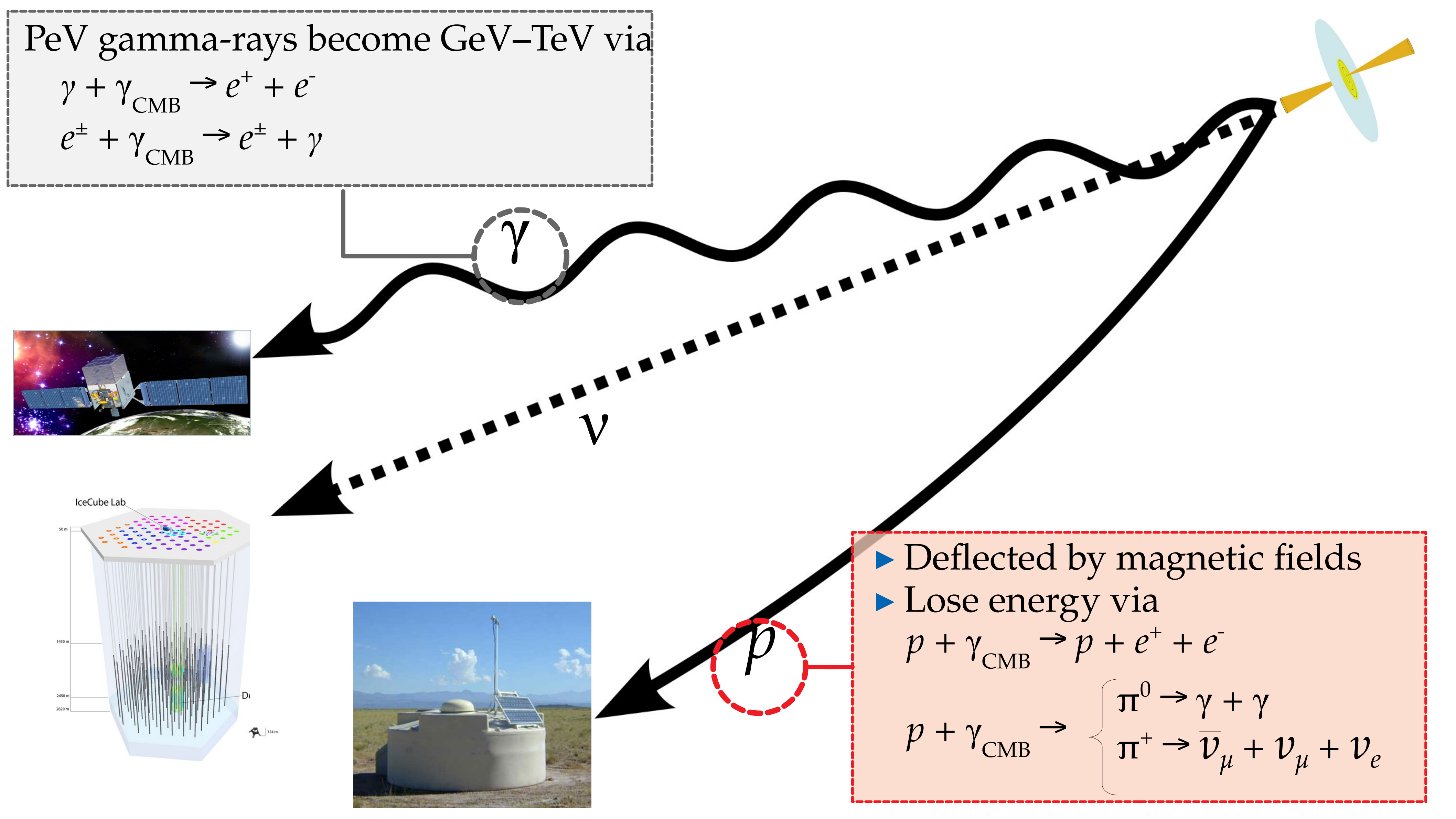



γ
ν
p
IceCube Lab
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^+ + e^-$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$


PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{\rm CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{\rm CMB} \rightarrow e^\pm + \gamma$
γ
ν
p
IceCube Lab
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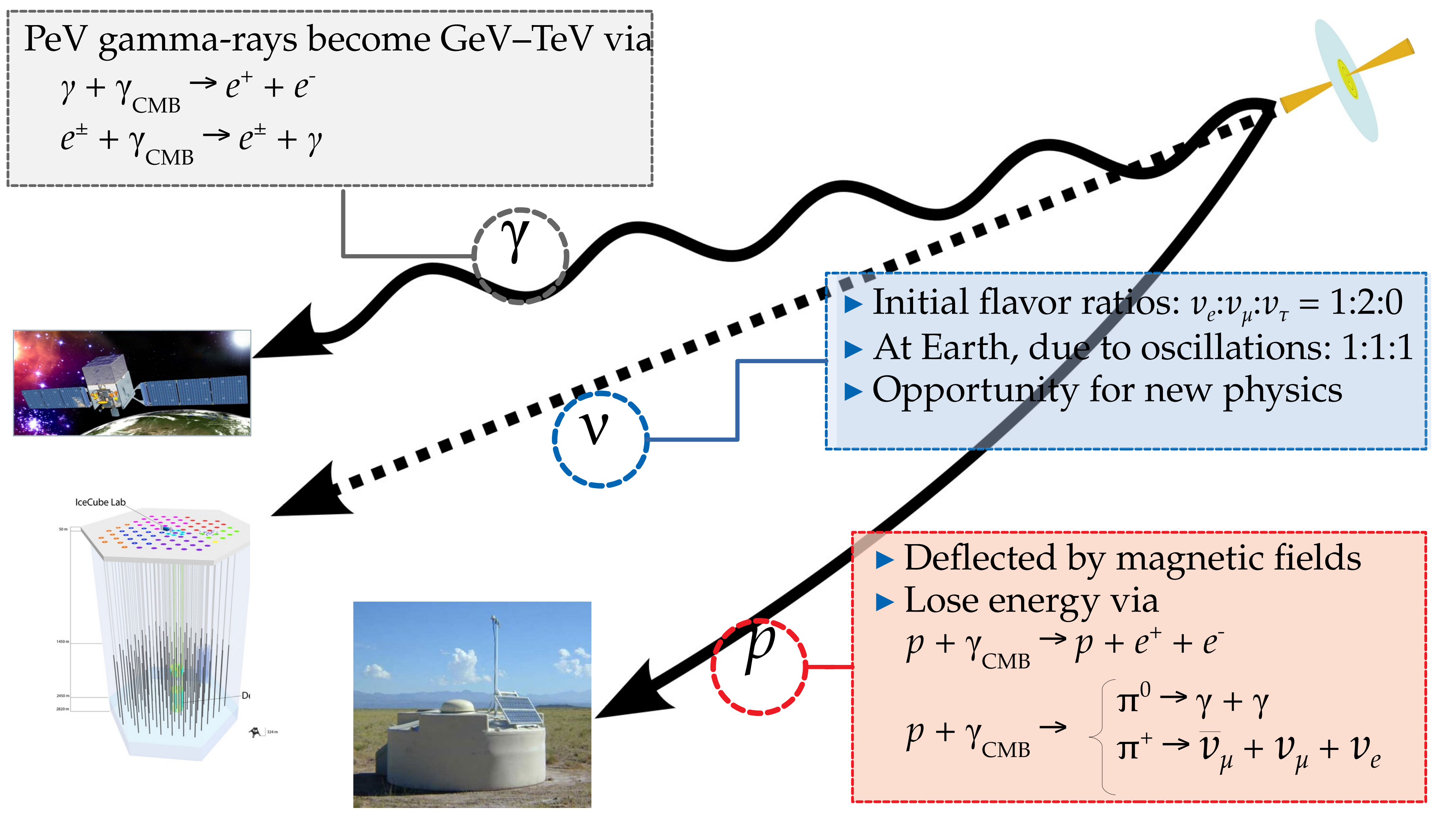

PeV gamma-rays become GeV–TeV via
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
▶ Initial flavor ratios: $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
▶ At Earth, due to oscillations: 1:1:1
▶ Opportunity for new physics
IceCube Lab
p
▶ Deflected by magnetic fields
▶ Lose energy via
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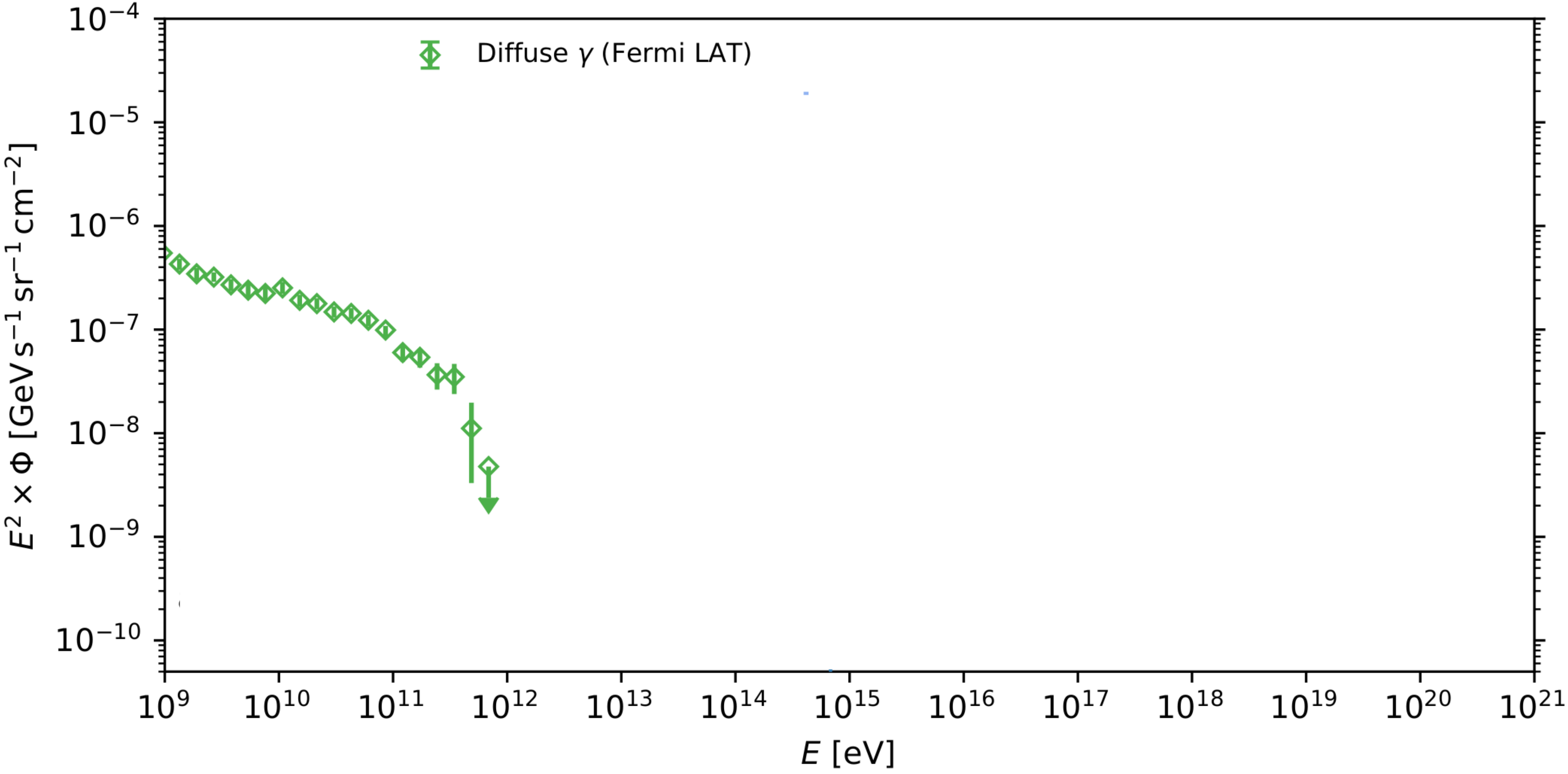
Gamma rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

See talk by Claudio Dib!

(Immediately after mine)

GRB 221009A: The brightest GRB seen so far

October 9th, 2022

By *Swift*-BAT, *Fermi*-GBM, *Fermi*-LAT

~0.6 Gpc ($z = 0.151$)

LHAASO: 18 TeV photon

Carpet-2: 251 TeV photon

International Gemini Observatory/NOIRLab/NSF/AURA/B. O'Connor (UMD/GWU) & J. Rastinejad & W Fong (Northwestern U.). Image processing: T.A. Rector (U. Alaska Anchorage/NSF NOIRLab), J. Miller, M. Zamani & D. de Martin (NSF NOIRLab)

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

Did we just discover new physics with GRB 221009A?

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Claim:
An 18-TeV photon should *not* survive the trip,
so new physics is invoked to make it happen

Examples: Lorentz-invariance violation (2210.06338, 2210.1126, 2210.11376)
Axion-photon conversion (2210.09250, 2210.10022)
Heavy neutrino decay (2210.14178, 2211.00634)

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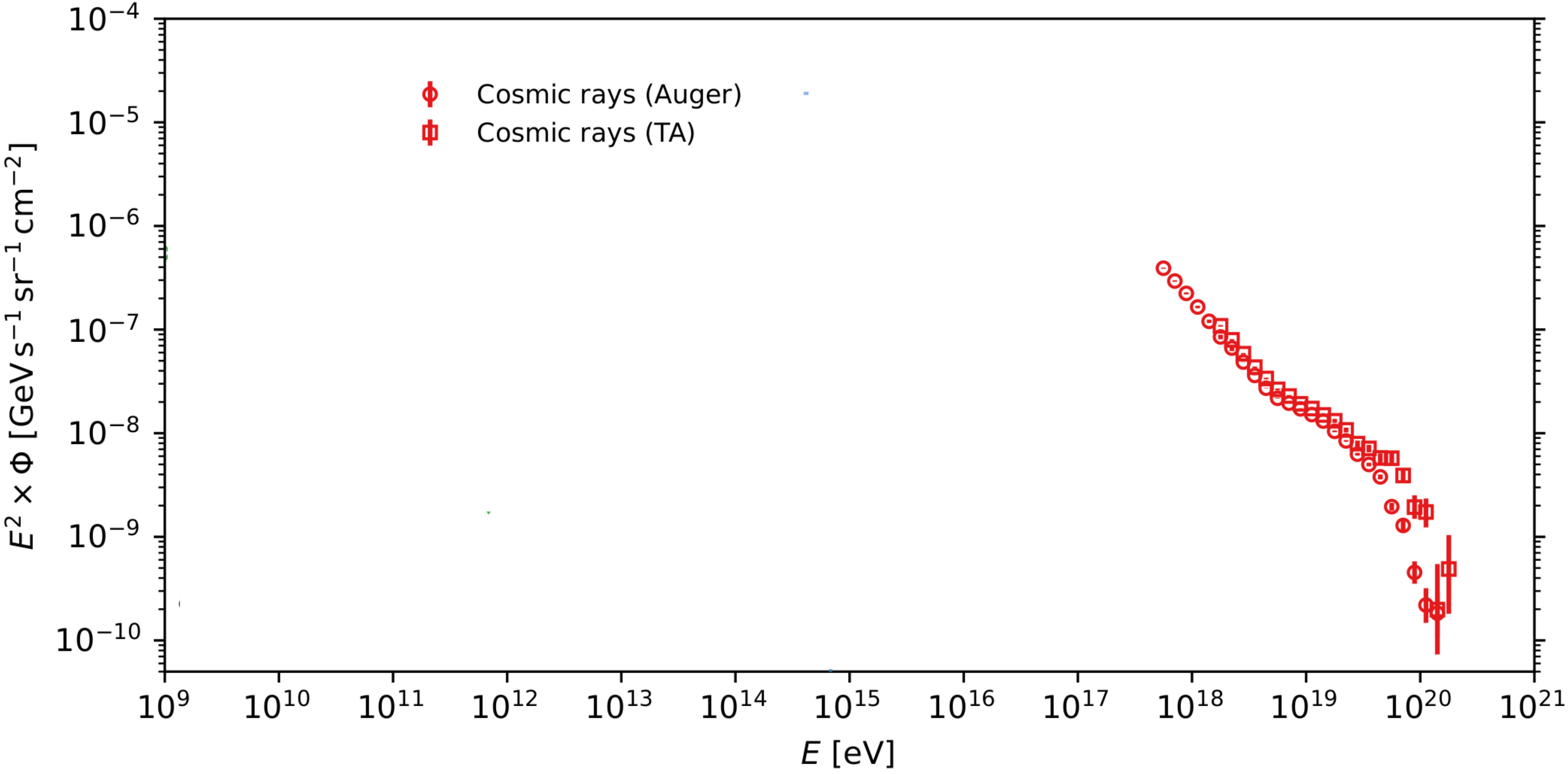
Axion-photon conversion (2210.09250, 2210.10022)
Heavy neutrino decay (2210.14178, 2211.00634)

Correct answer:

New physics is not needed to explain the high-energy photons

These photons can be cosmogenic, *i.e.*, made during UHECR propagation (2210.12855)
(See also 2210.10778)

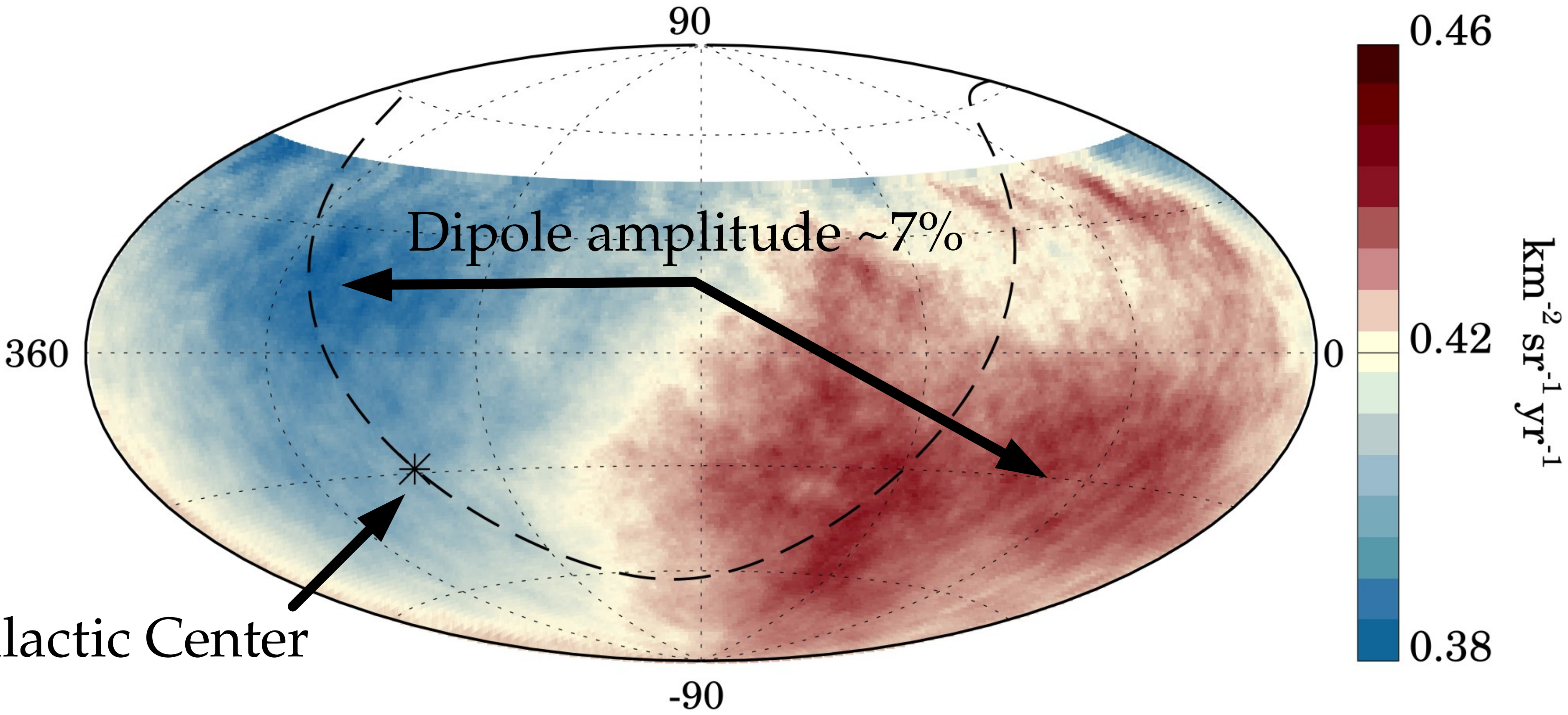
Cosmic rays



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]

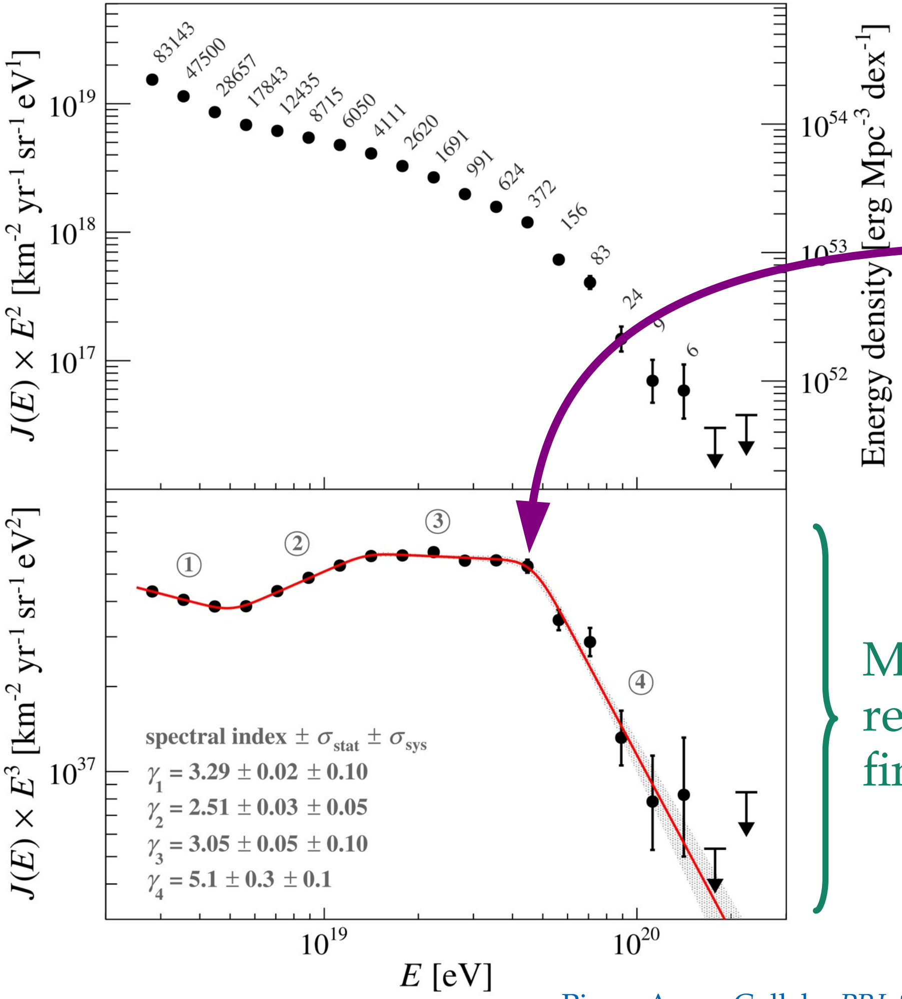
UHECRs are extragalactic

5.2σ dipole in the arrival directions of UHECRs above 8×10^{18} eV



Pierre Auger Collab., *Science* 357, 1266 (2017)

The UHECR spectrum has lots of features



Pierre Auger Collab., *PRL* 2020 [2008.06448]

- At what energy do CRs change from Galactic to extragalactic
- Is the flux dampening around 5×10^{19} eV the GZK cut-off or a limitation of the sources?

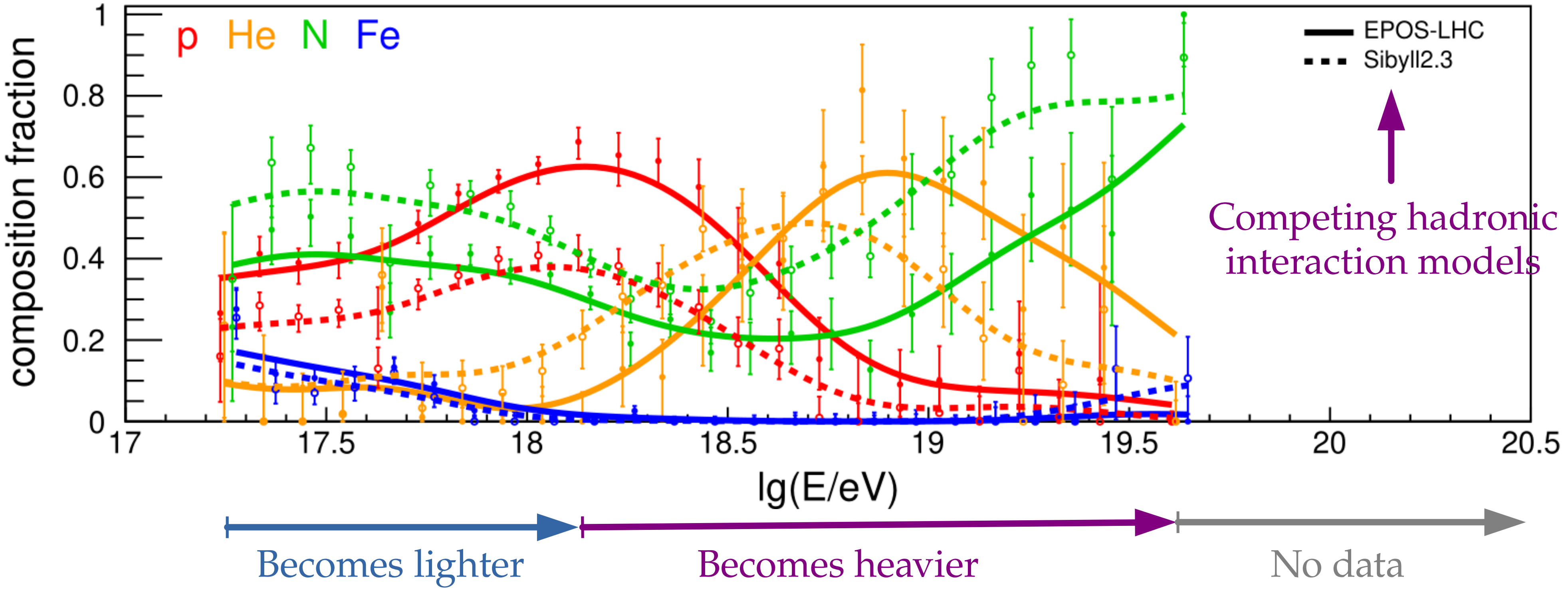
More data reveals finer features

But at least two key questions remain

Answers need to account for mass composition, too ▸

Measuring UHECR mass composition is hard

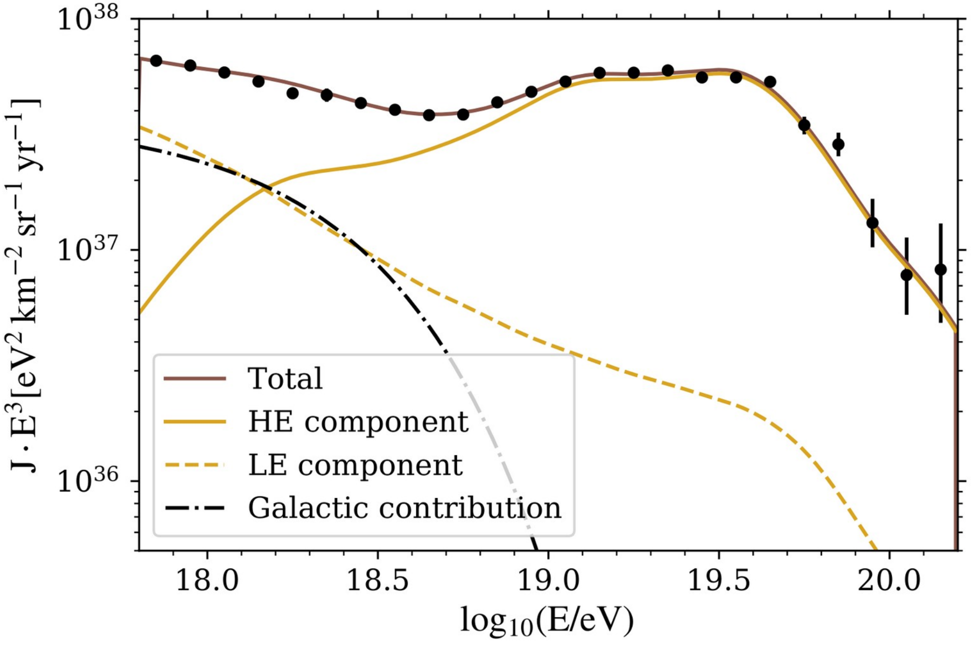
Infer mass composition from the depth of shower maximum, X_{max}:



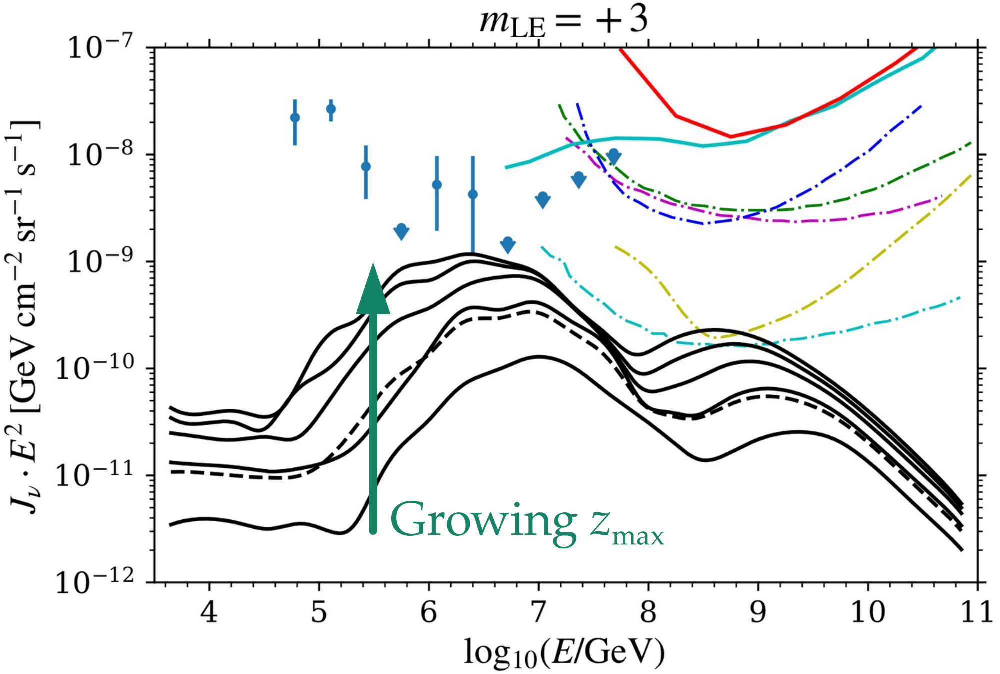
R. Alves-Batista, J. Biteau, **MB**, et al., *Front. Astron. Space Sci.* 6, 23 (2019) [1903.06714]
Based on Auger data from J. Bellido (for Auger), PoS (ICRC 2017), 301, 506 (2018)

UHECRs: details reveal insight

Low-energy + high-energy flux components can explain features:



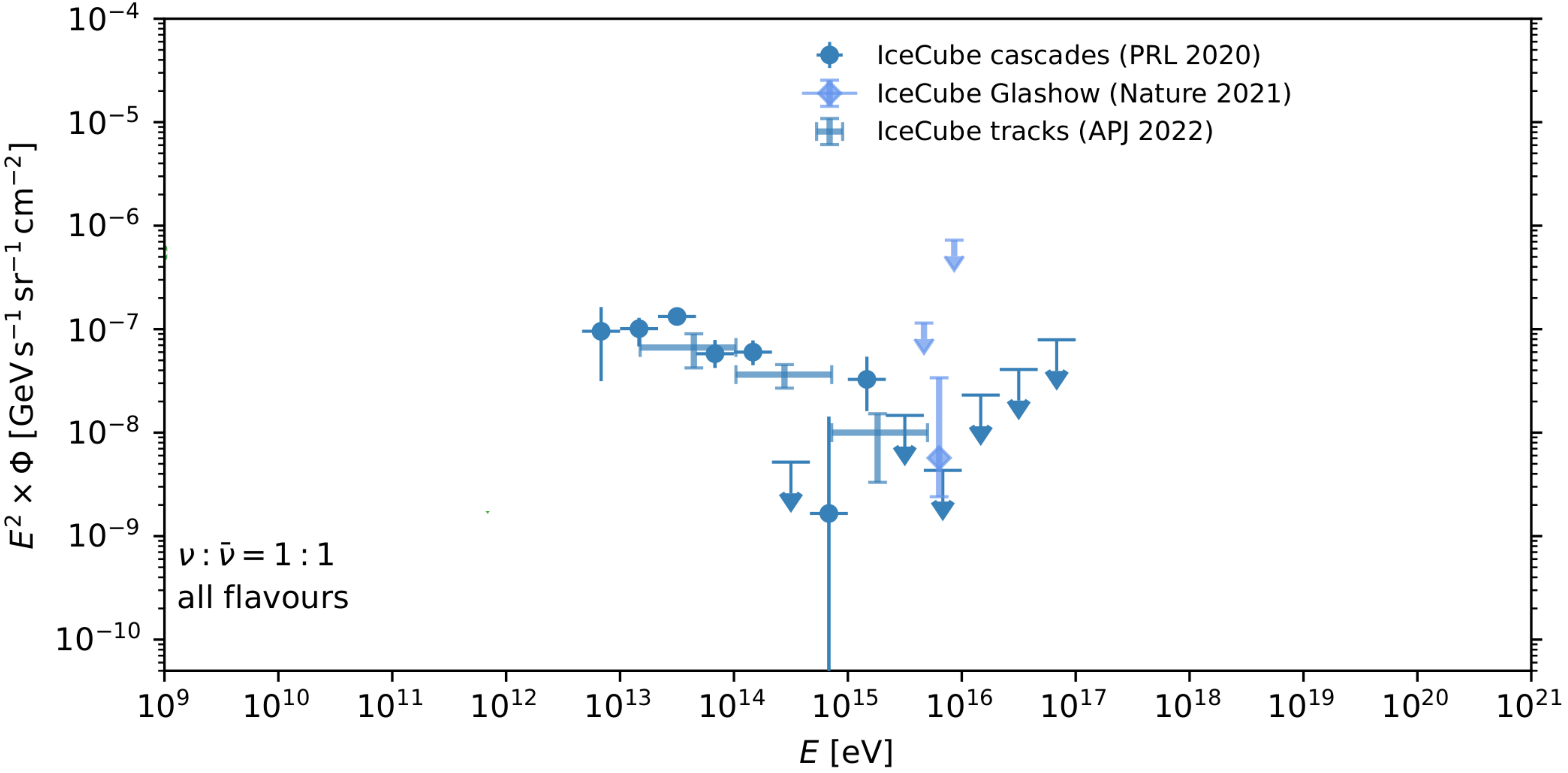
Evolution of LE flux, $(1+z)^m$, testable with cosmogenic ν:



More on UHE neutrinos later ▸

Pierre Auger Collab., 2211.02857

Neutrinos



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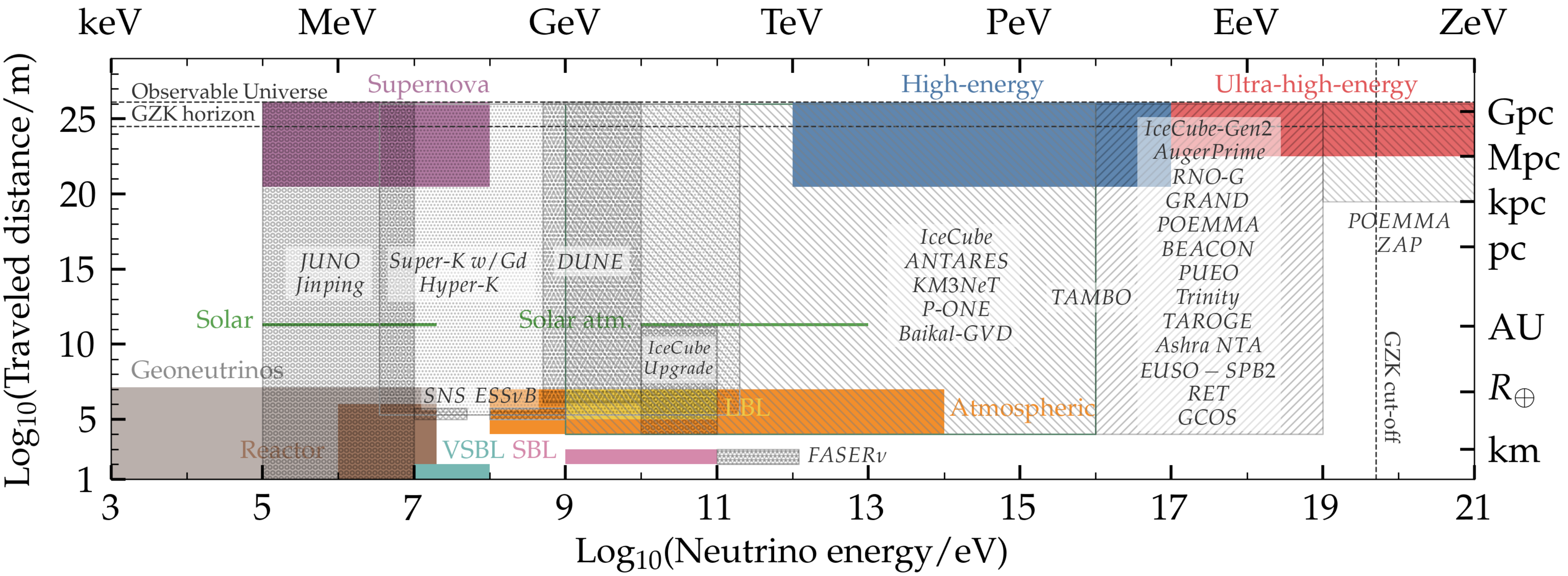
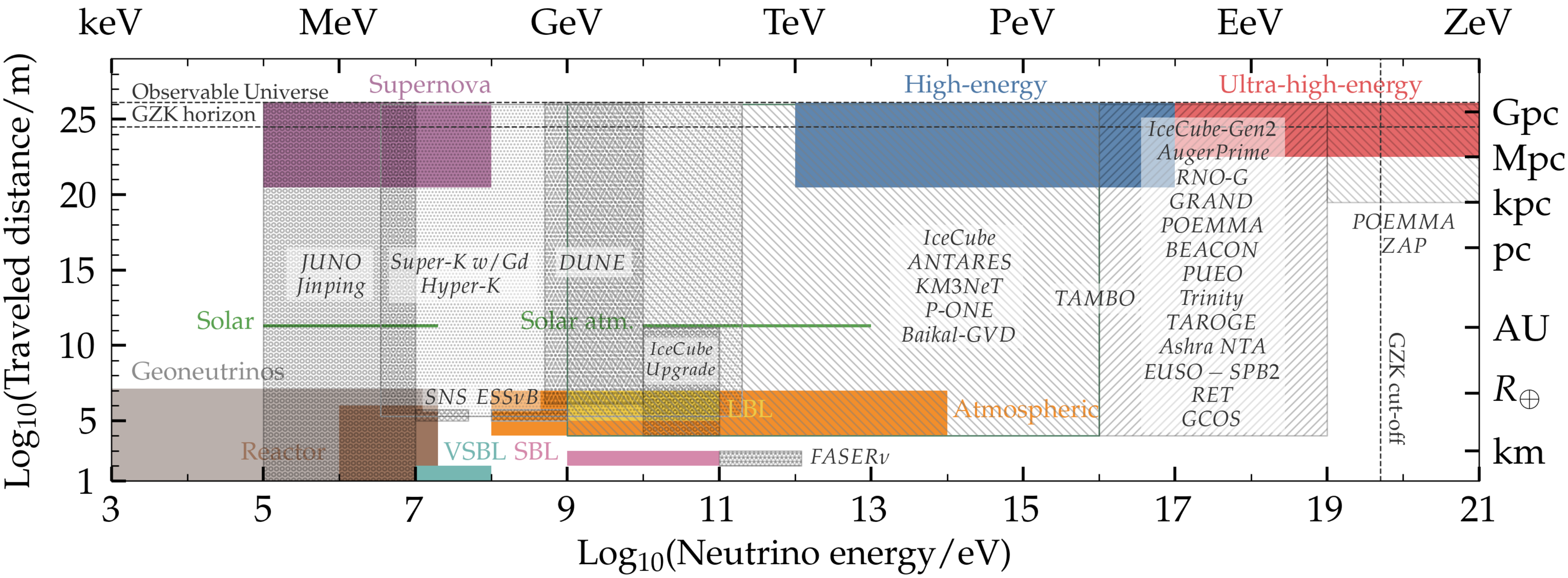


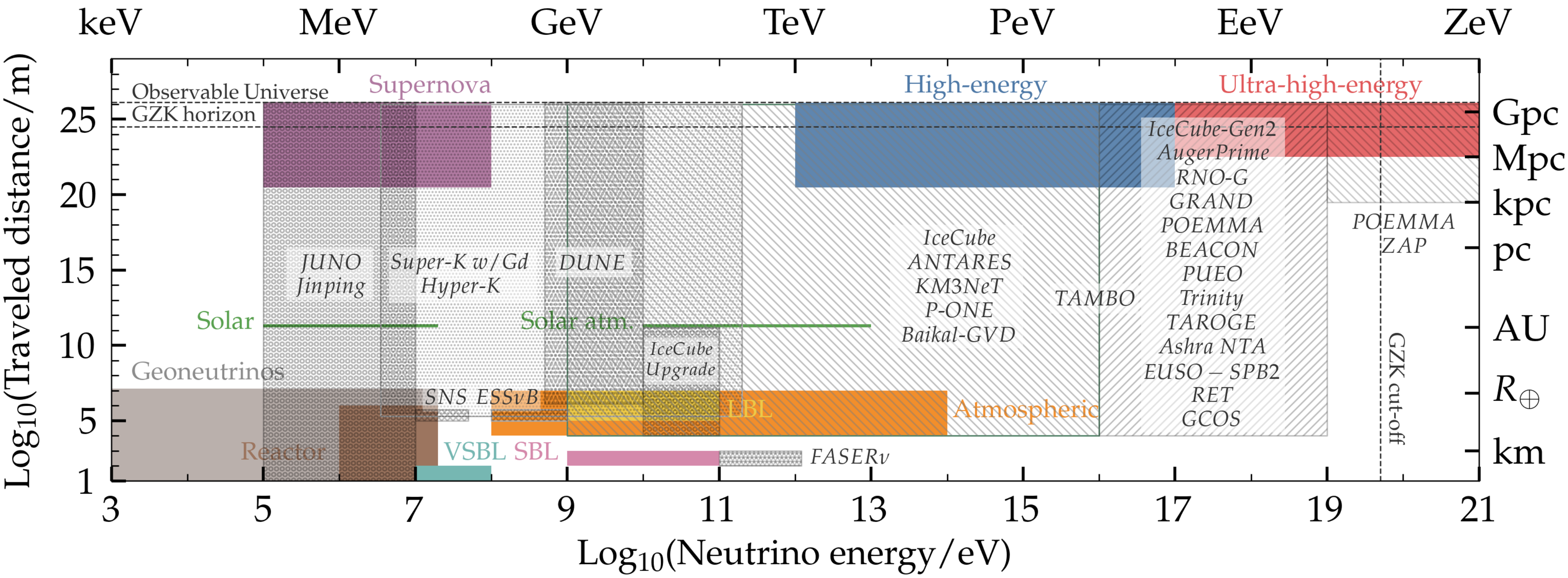
keV
MeV
GeV
TeV
PeV
EeV
ZeV
Log10(Traveled distance / m)
Observable Universe
GZK horizon
Supernova
High-energy
Ultra-high-energy
Gpc
Mpc
kpc
pc
AU
$R_\oplus$
km
IceCube-Gen2
AugerPrime
RNO-G
GRAND
POEMMA
BEACON
PUEO
Trinity
TAROGE
Ashra NTA
EUSO – SPB2
RET
GCOS
POEMMA
ZAP
JUNO
Jinping
Super-K w/Gd
Hyper-K
DUNE
IceCube
ANTARES
KM3NeT
P-ONE
Baikal-GVD
TAMBO
Solar
Solar atm.
IceCube Upgrade
Geoneutrinos
SNS ESSνB
LBL
Atmospheric
GZK cut-off
Reactor
VSBL SBL
FASERν
Log10(Neutrino energy / eV)



Synergies with lower energies

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

Discovered in 2013
by IceCube



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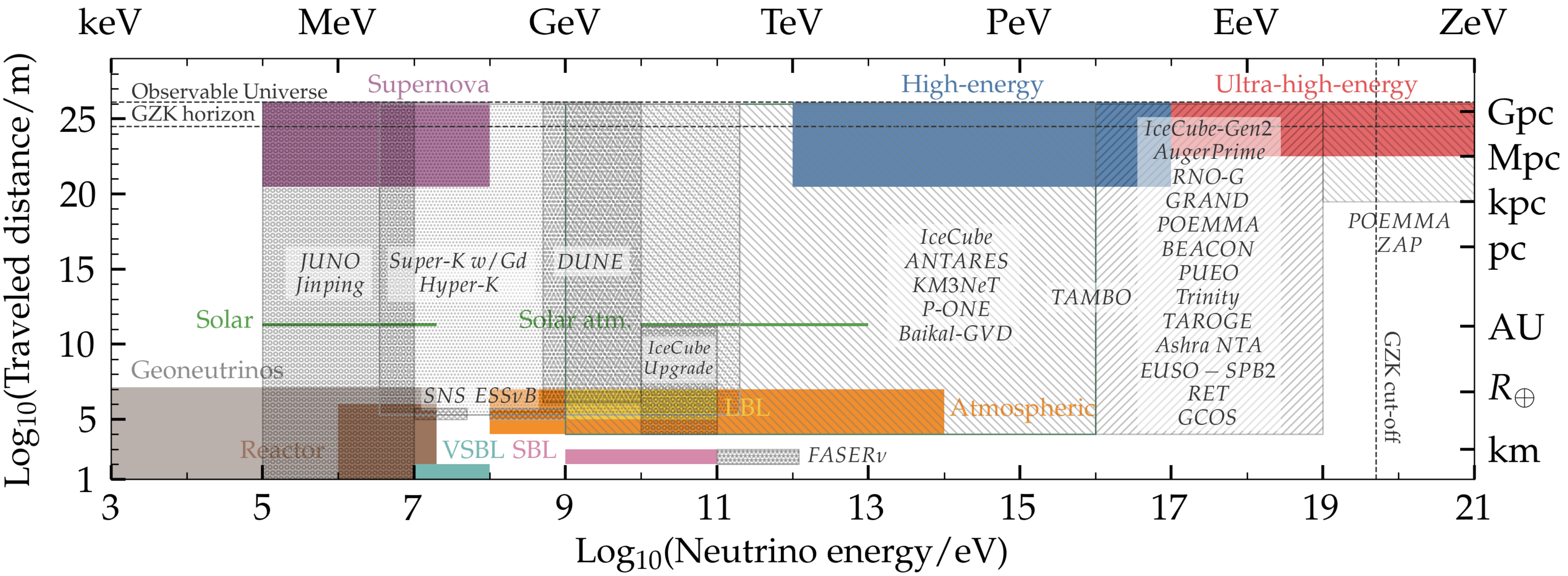

Synergies with lower energies

Increase TeV–PeV
ν statistics

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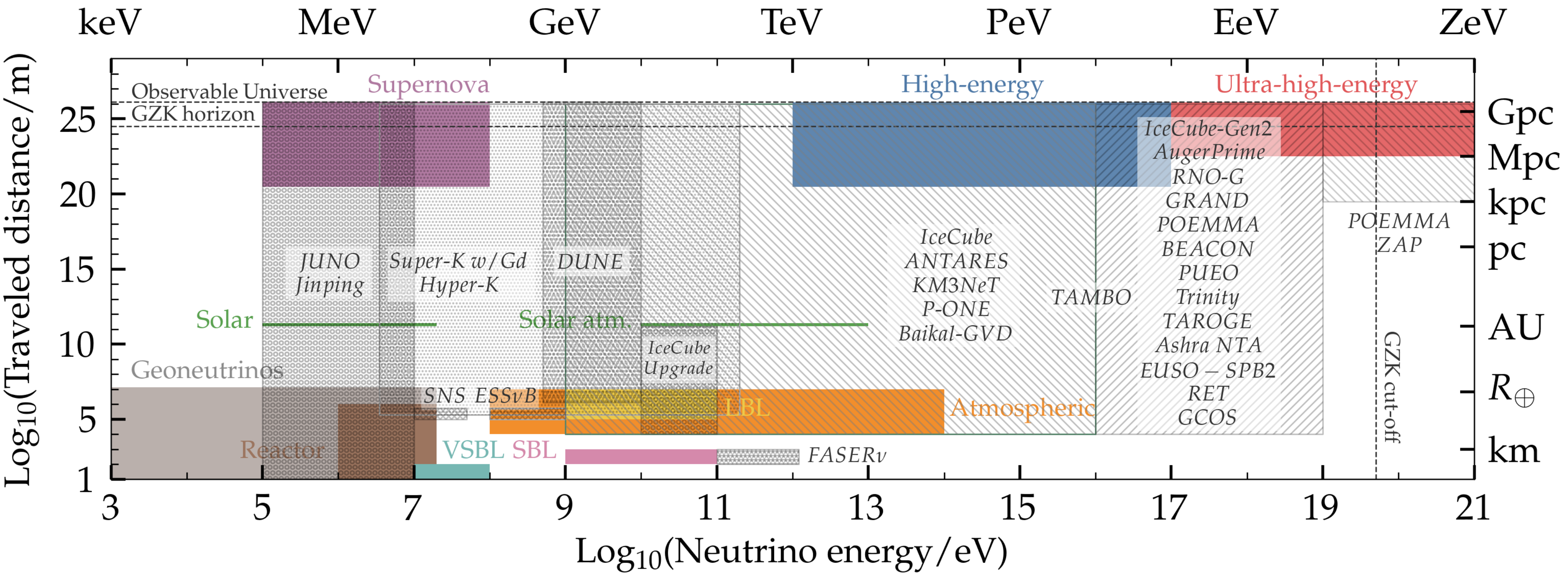

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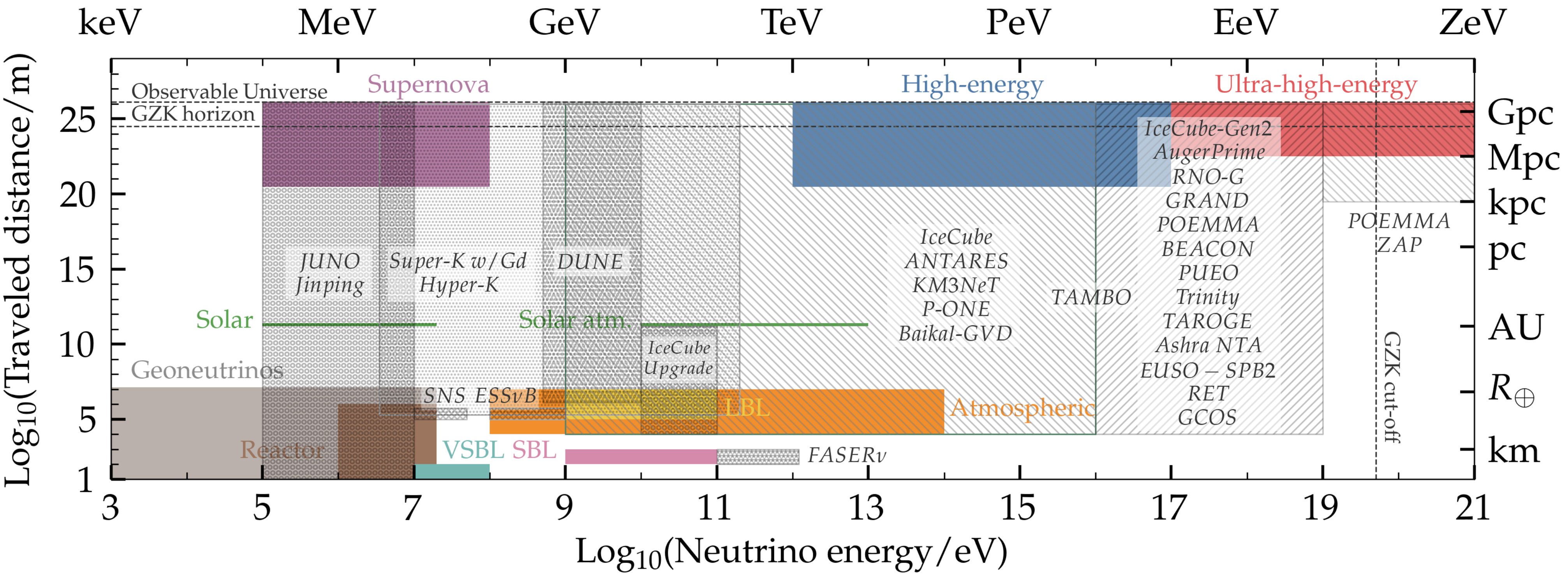


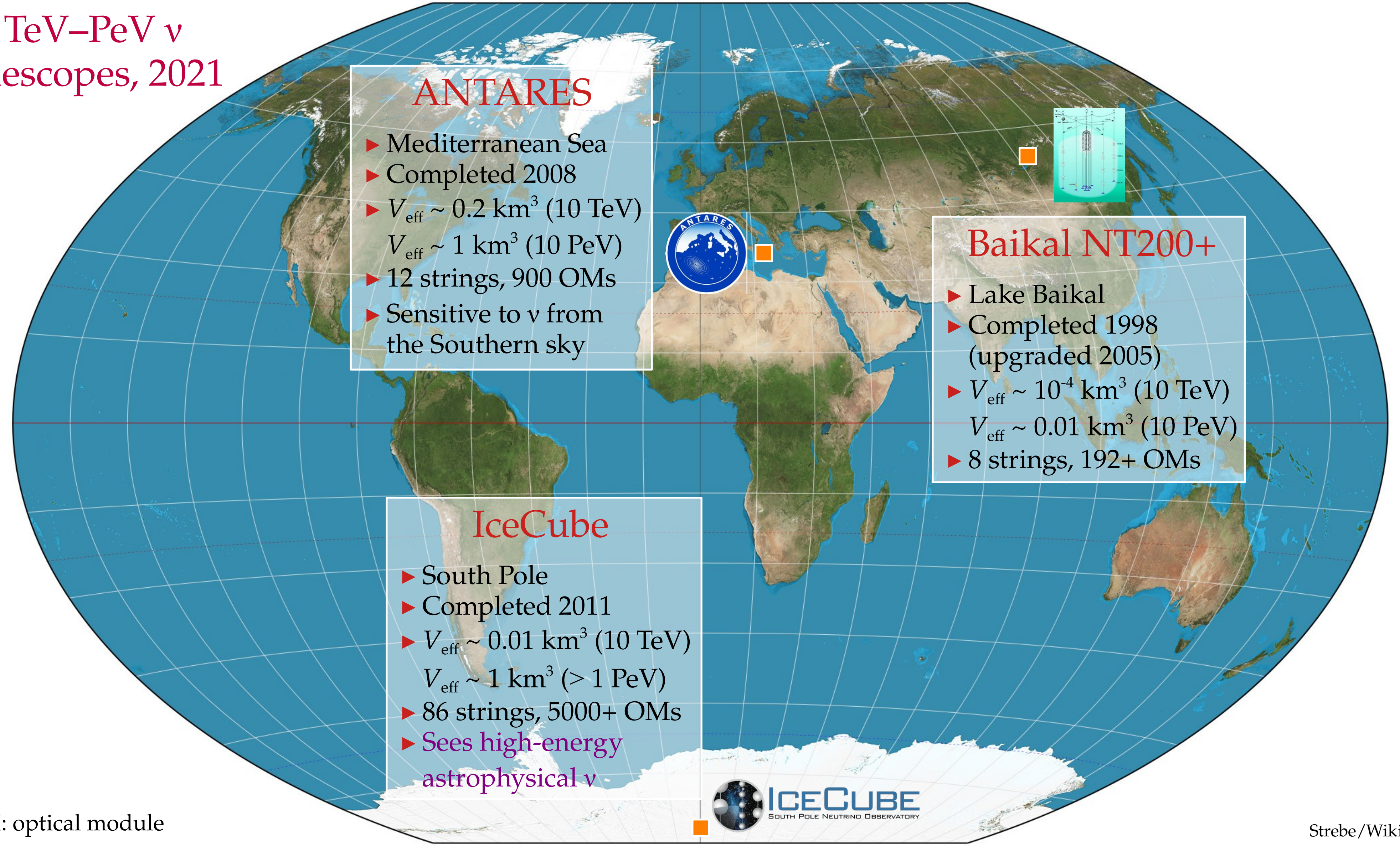
Synergies with lower energies

Increase TeV–PeV ν statistics

Discover > EeV ν

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

TeV–PeV ν telescopes, 2021



ANTARES

- Mediterranean Sea
- Completed 2008
- $V_{eff} \sim 0.2$ km³ (10 TeV)
  $V_{eff} \sim 1$ km³ (10 PeV)
- 12 strings, 900 OMs
- Sensitive to ν from the Southern sky

Baikal NT200+

- Lake Baikal
- Completed 1998 (upgraded 2005)
- $V_{eff} \sim 10^{-4}$ km³ (10 TeV)
  $V_{eff} \sim 0.01$ km³ (10 PeV)
- 8 strings, 192+ OMs

IceCube

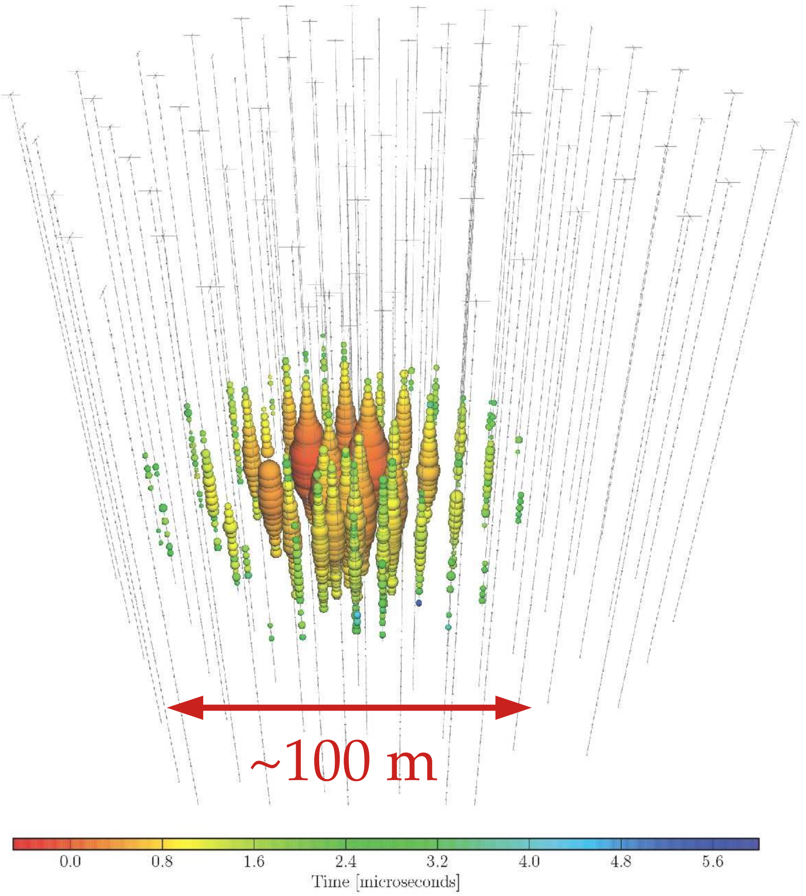
- South Pole
- Completed 2011
- $V_{eff} \sim 0.01$ km³ (10 TeV)
  $V_{eff} \sim 1$ km³ (> 1 PeV)
- 86 strings, 5000+ OMs
- Sees high-energy astrophysical ν

OM: optical module

Strebe/Wikipedia

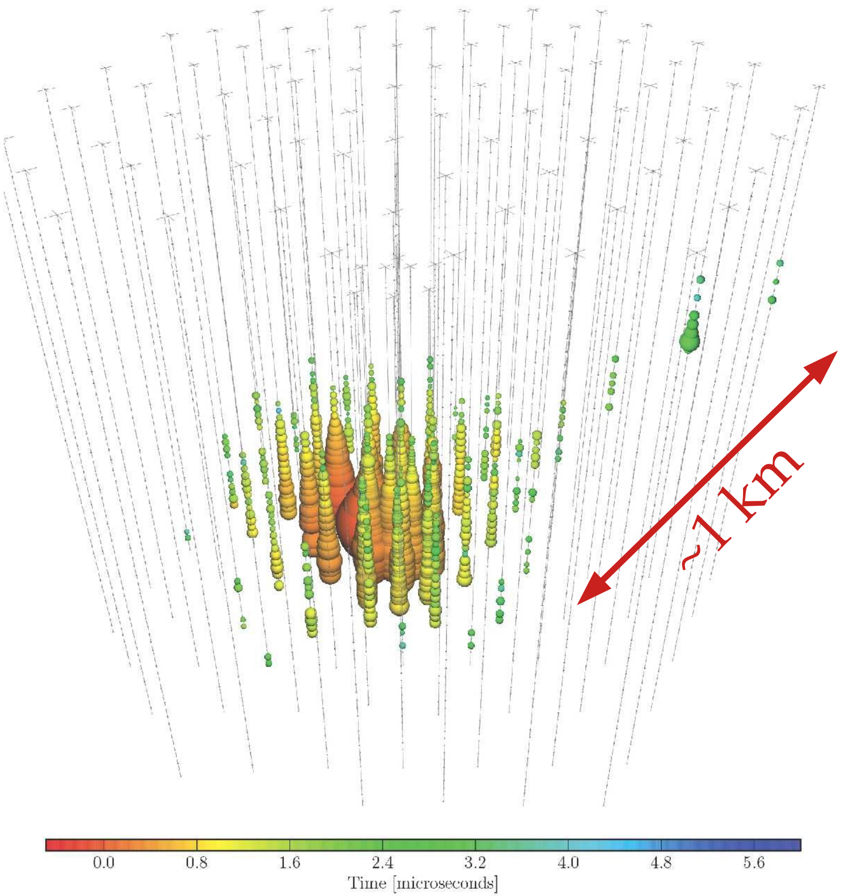
Yuya Makino, IceCube/NSF

Shower
(mainly from ν_e and ν_τ)

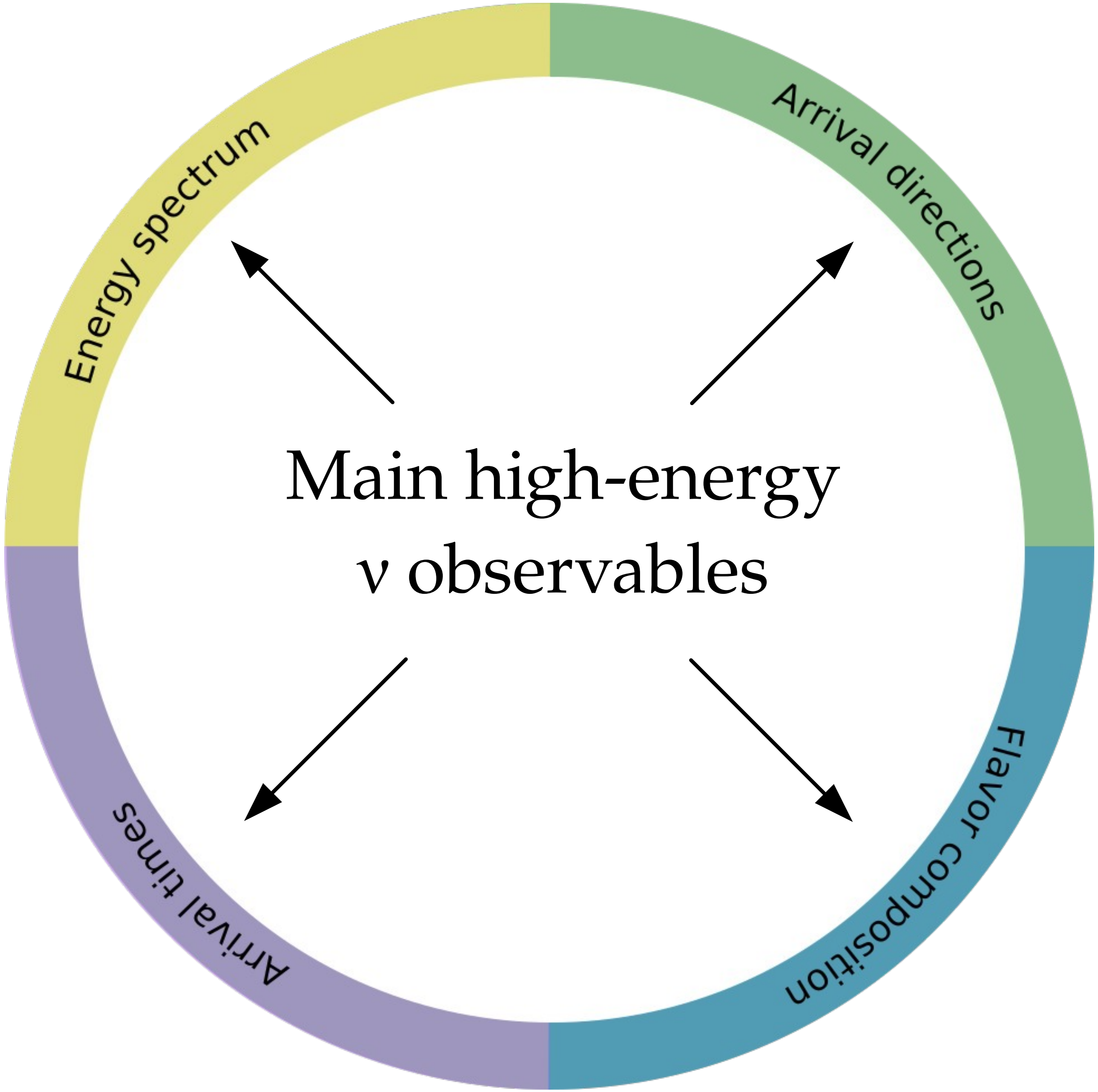


Poor angular resolution: ~10°

Track
(mainly from ν_μ)

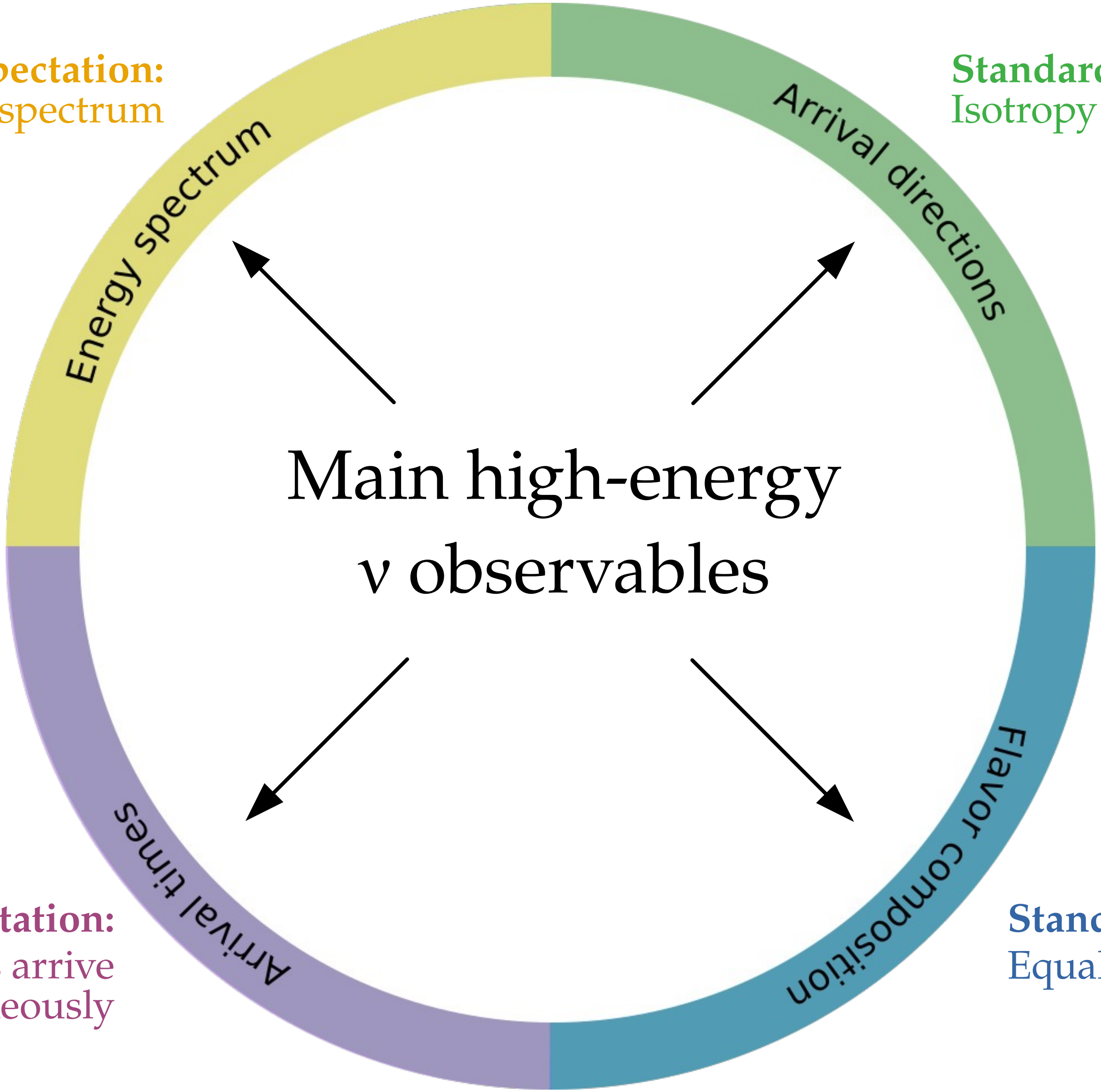


Angular resolution: < 1°


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

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

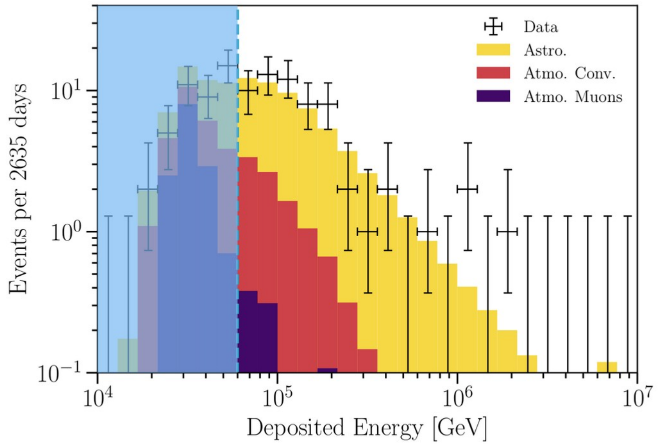


Standard expectation:
ν and γ from transients arrive simultaneously

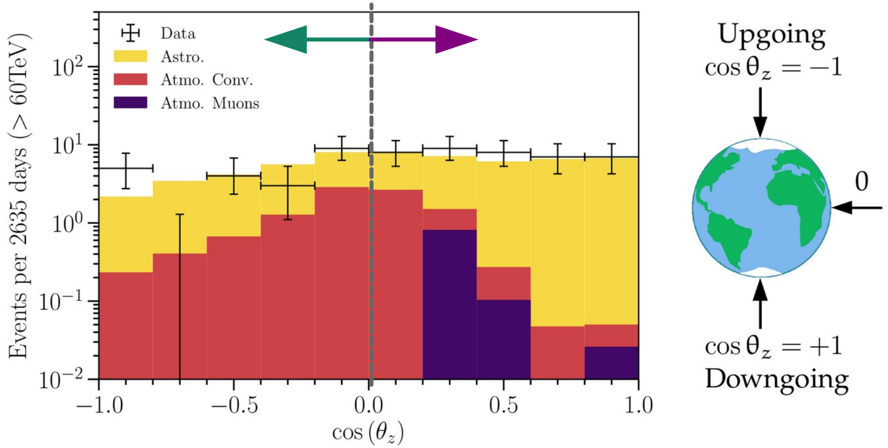
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Energy spectrum (7.5 yr)

100+ contained events above 60 TeV:

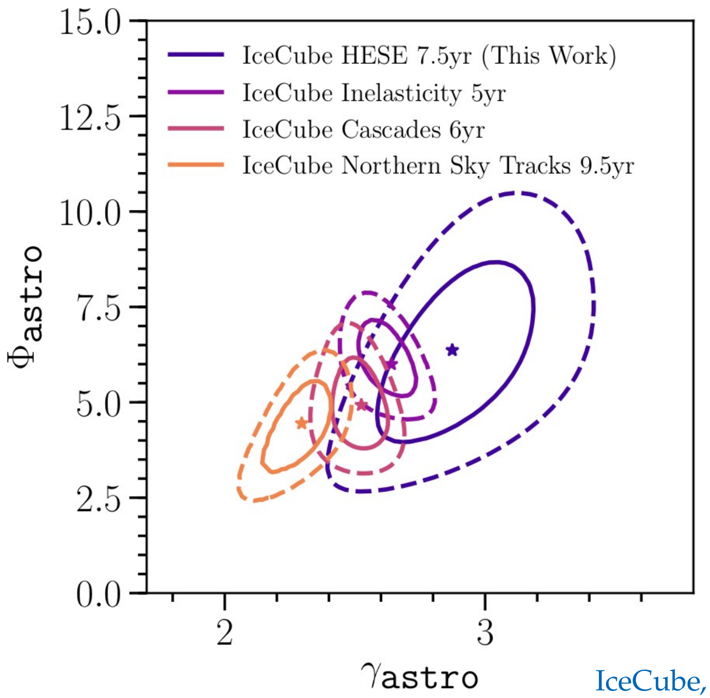


ν attenuated by Earth   Atm. ν and μ vetoed



Data is fit well by a single power law:

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



IceCube, 2011.03545

Energy spectrum (7.5 yr)

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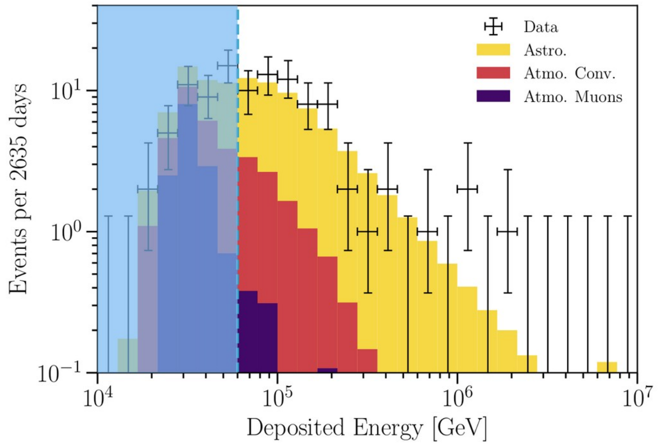

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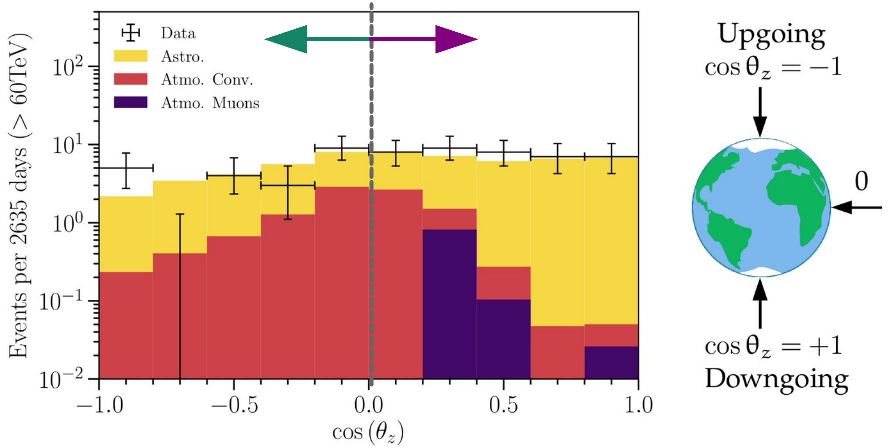

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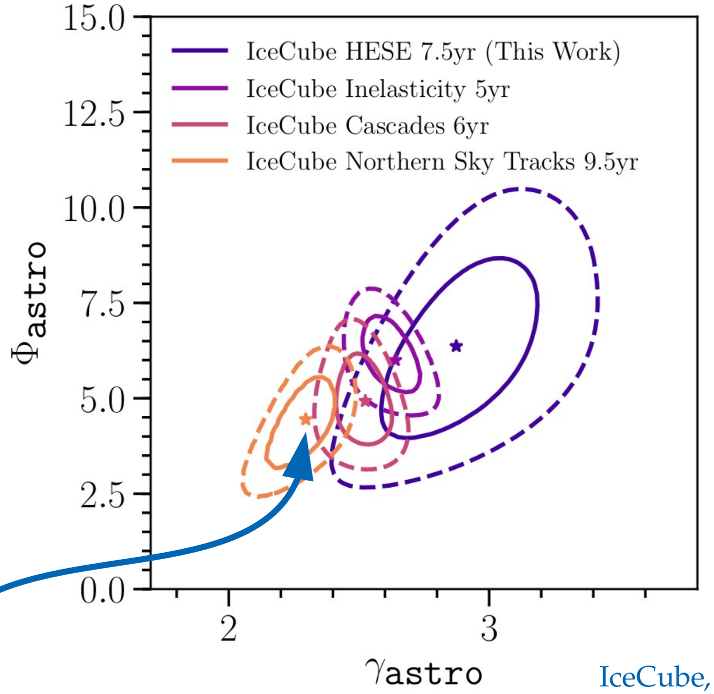
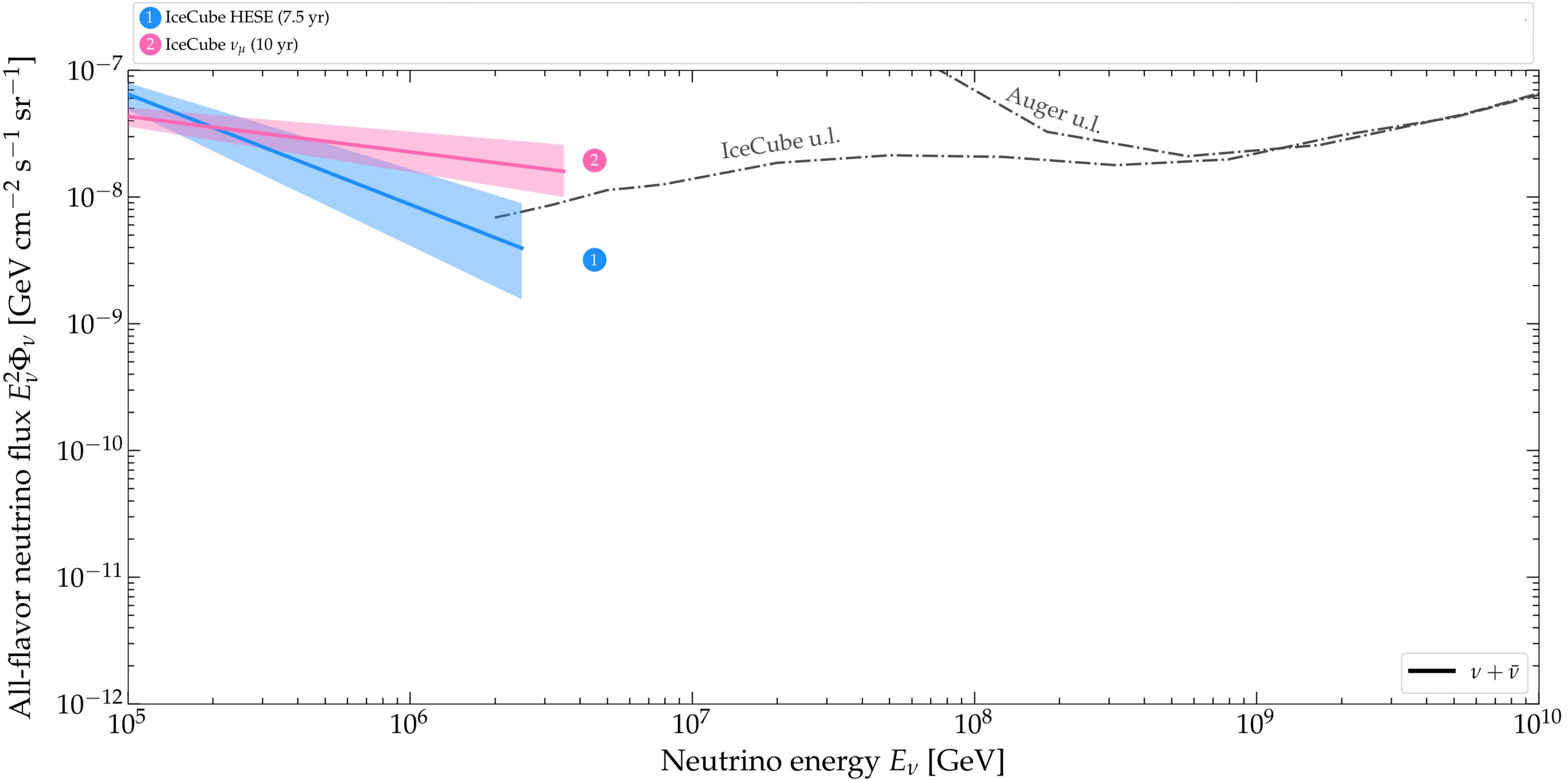


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ



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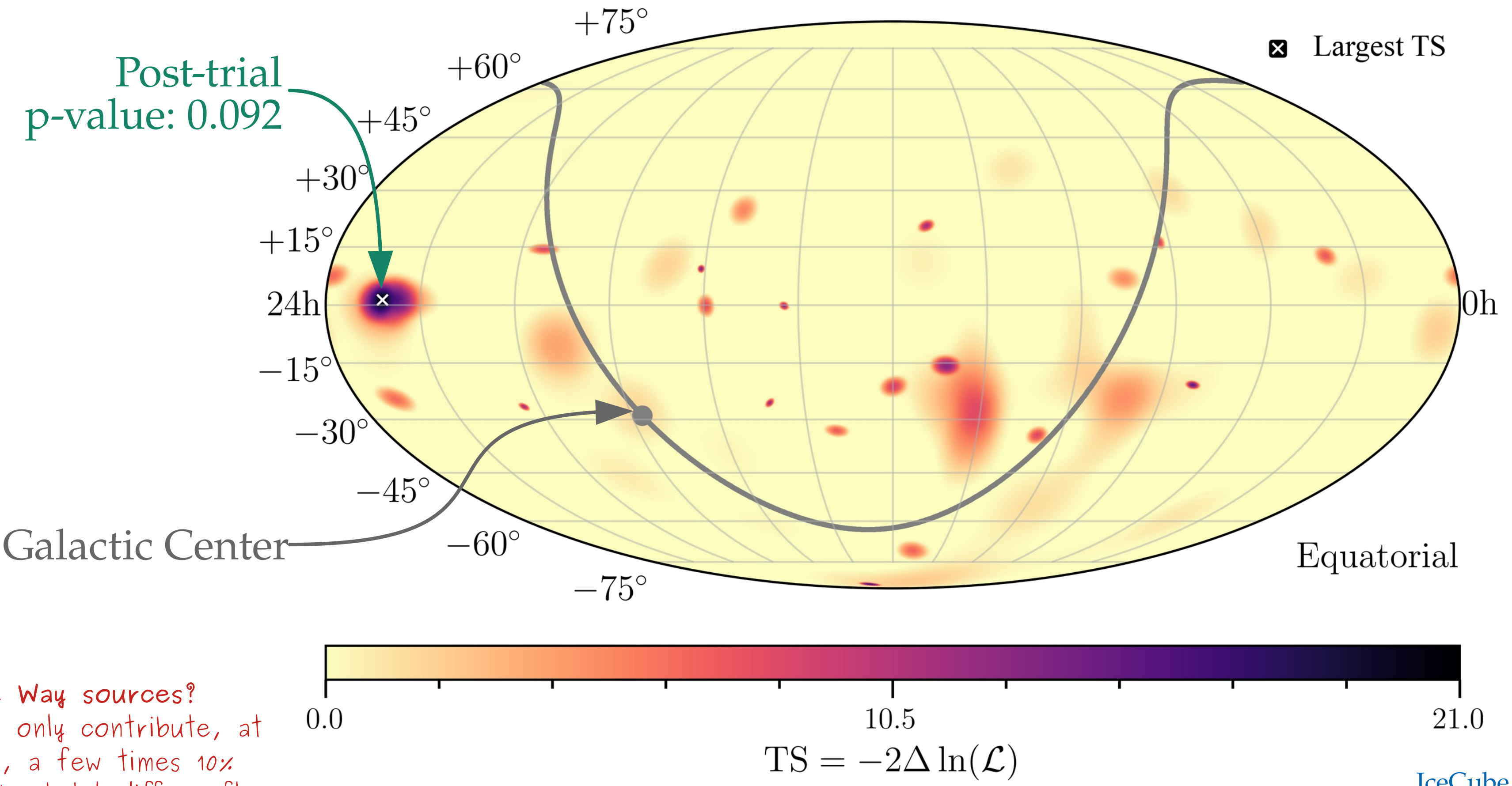
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}

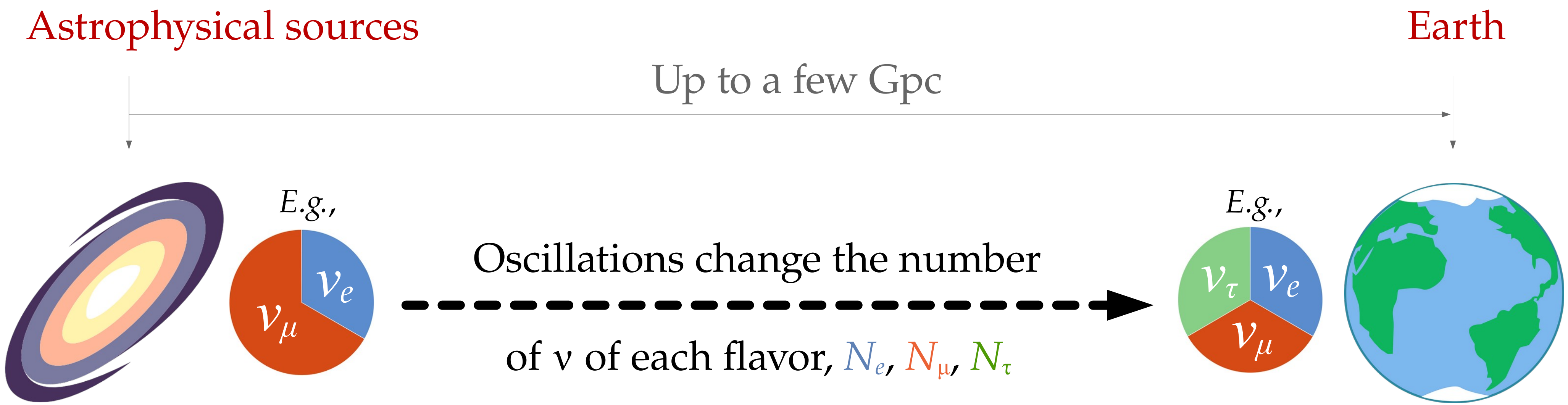
Arrival directions (7.5 yr)

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, 2011.03545

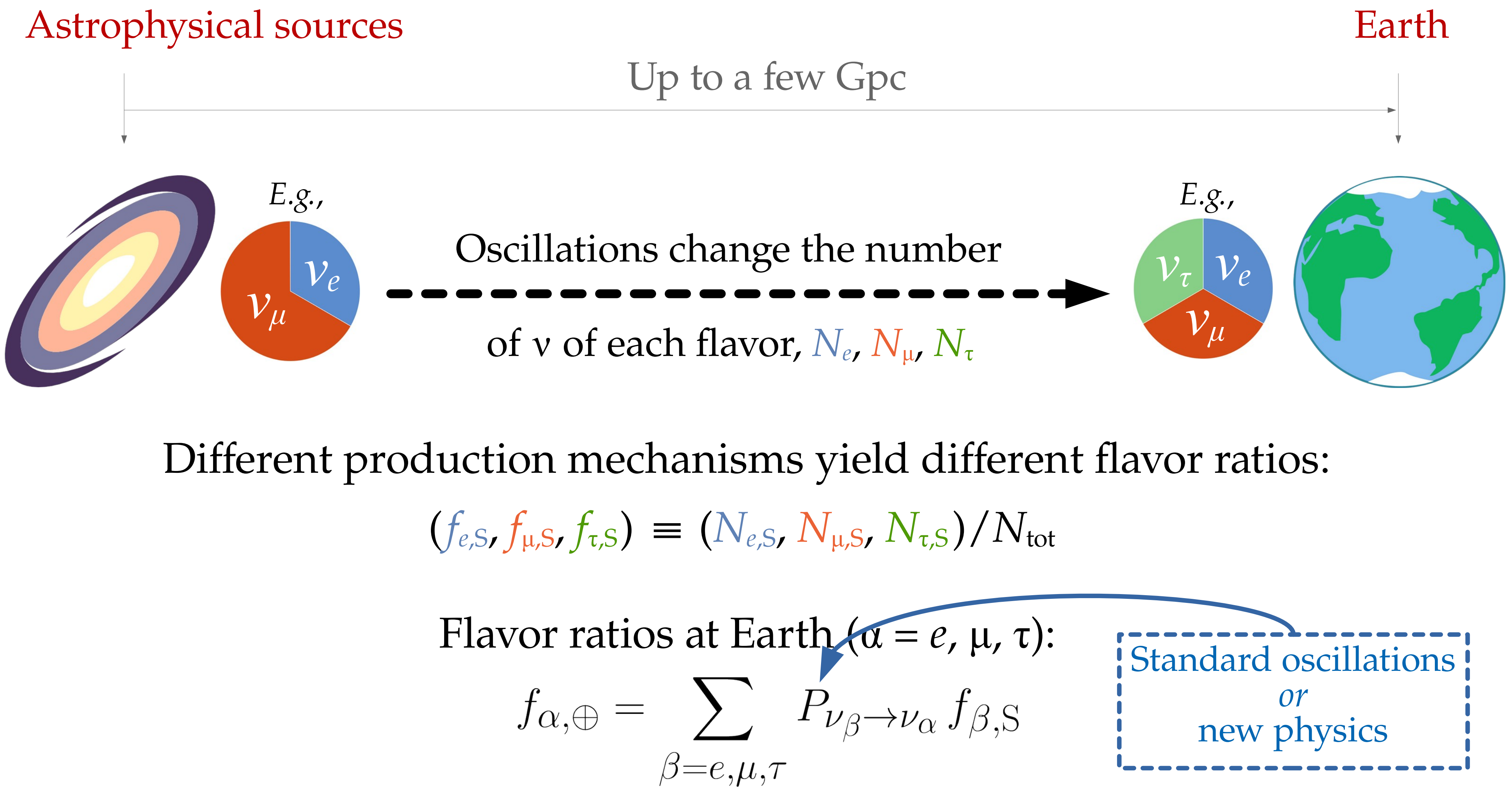


Different production mechanisms yield different flavor ratios:

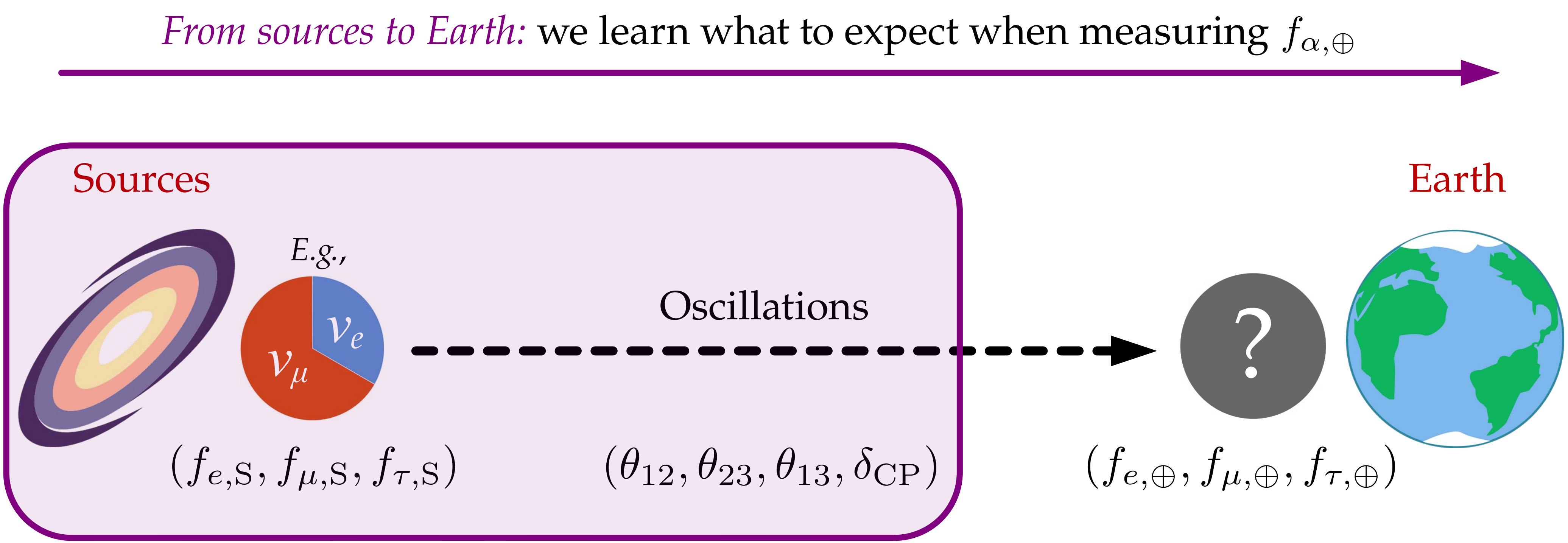
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

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
E.g.,
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
Oscillations
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
Earth
?
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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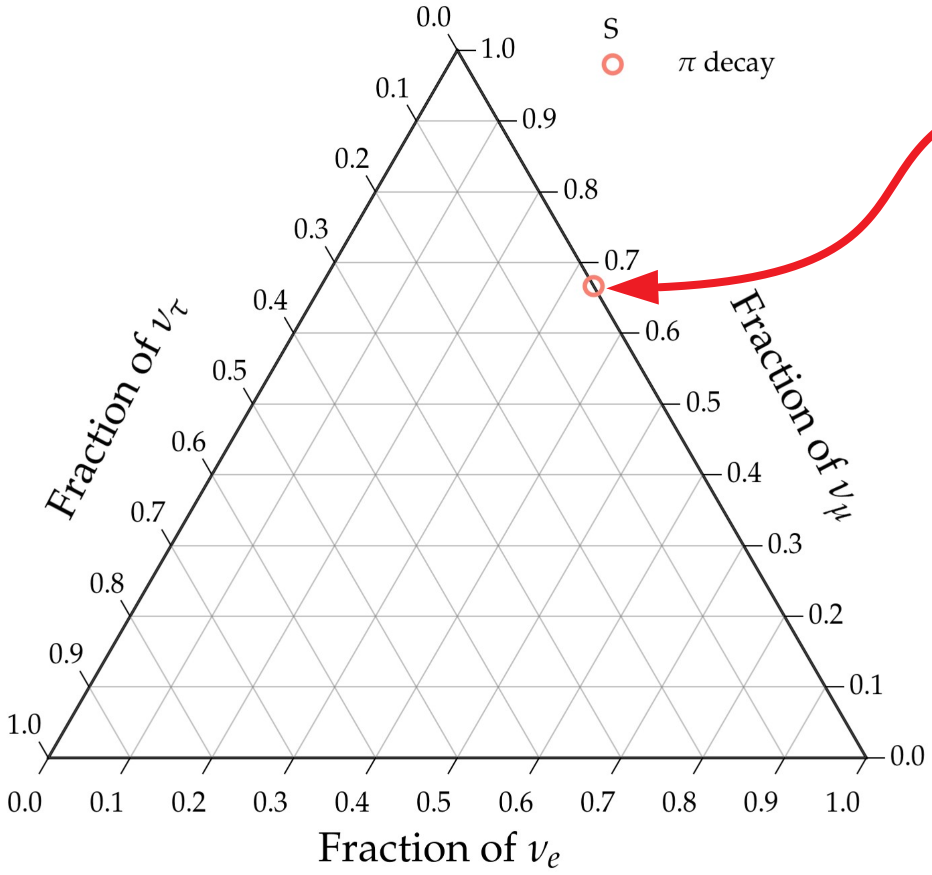

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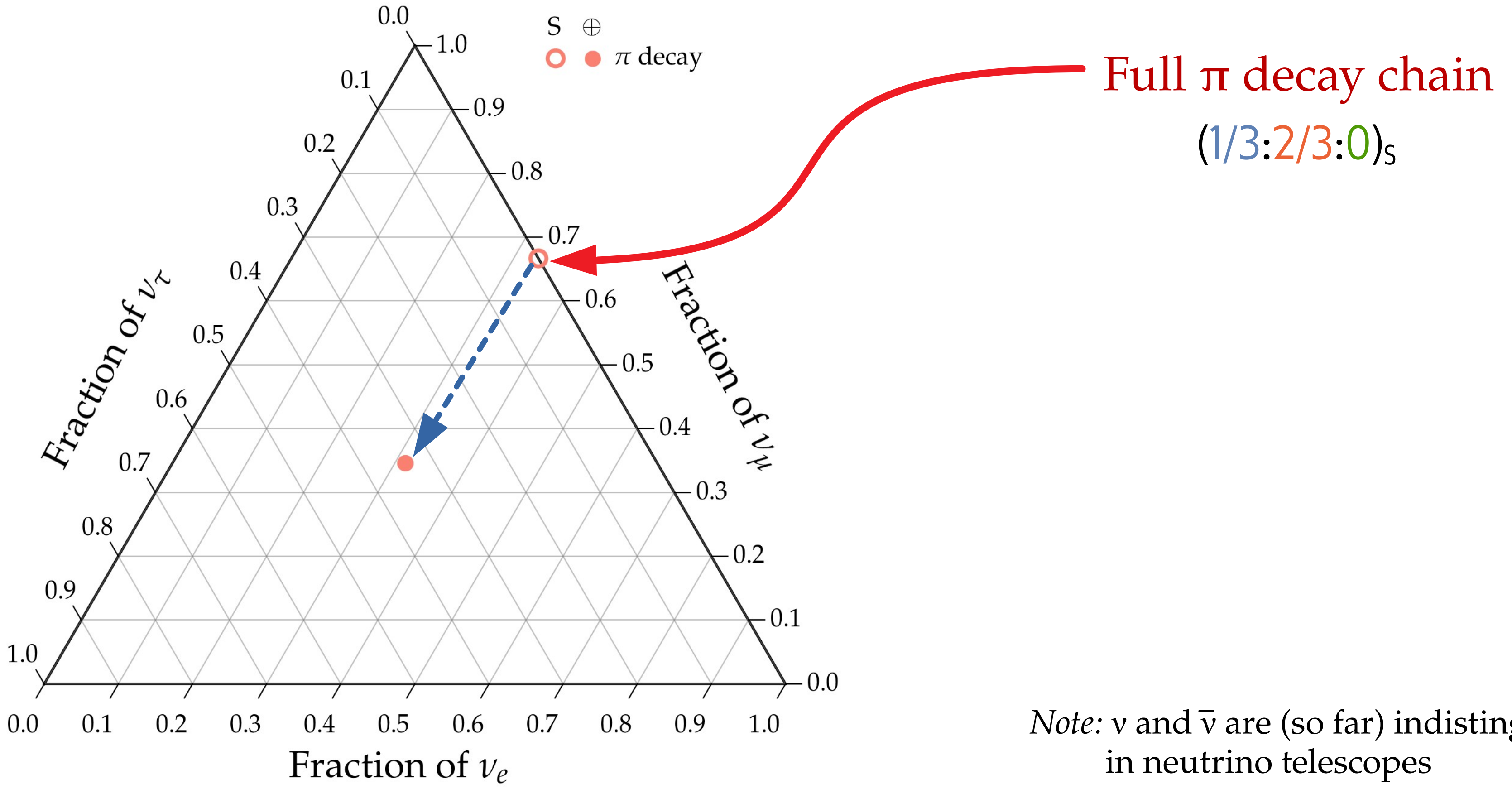

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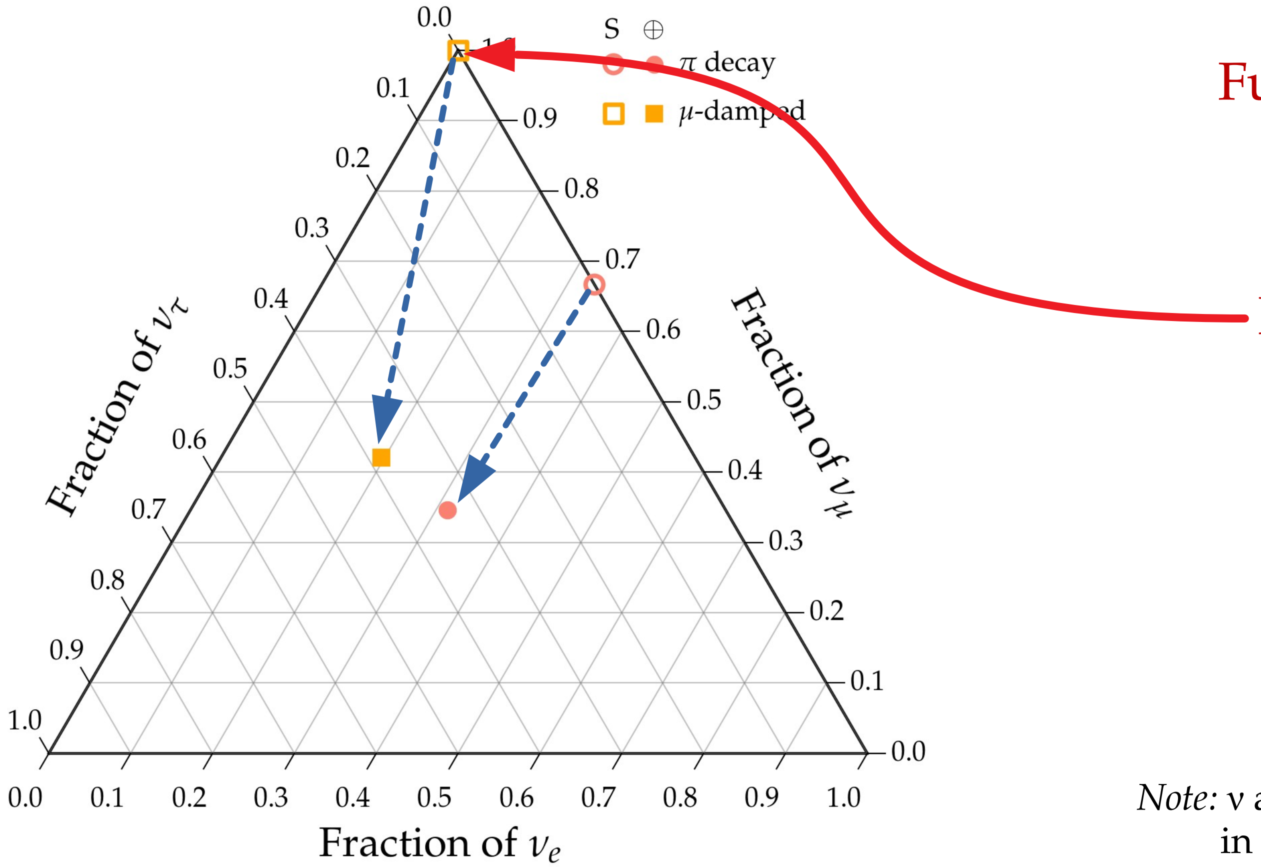

Full π decay chain

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

Muon damped

$(0:1:0)_S$

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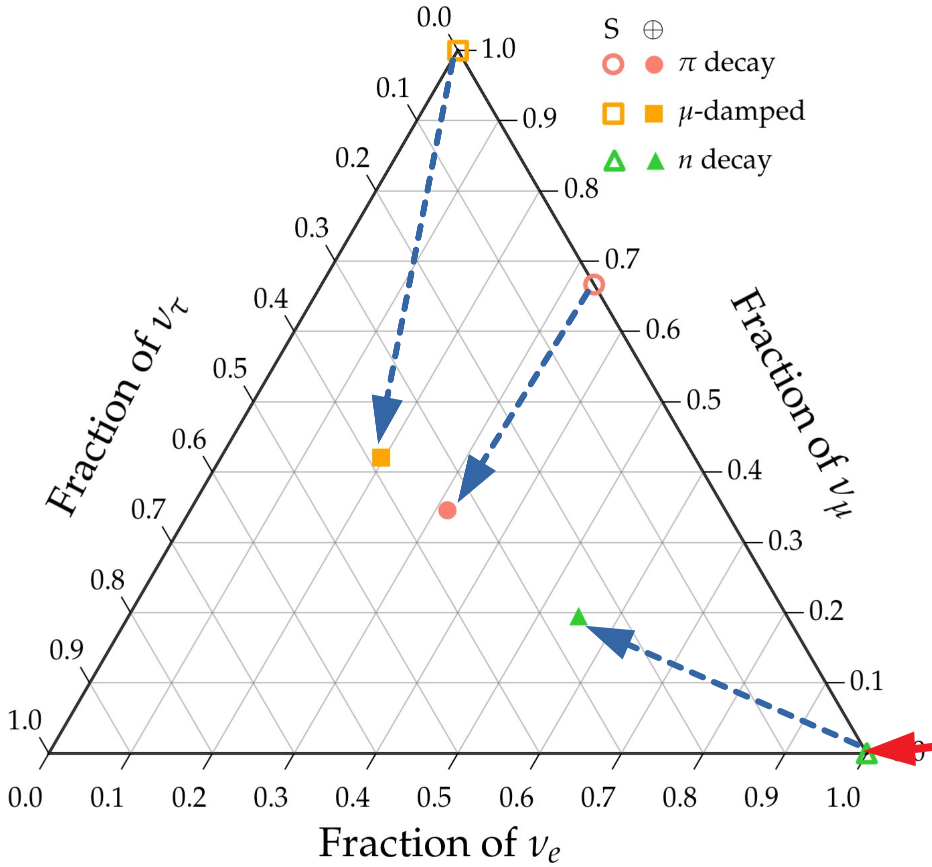


Full π decay chain

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

Muon damped

$(0:1:0)_S$

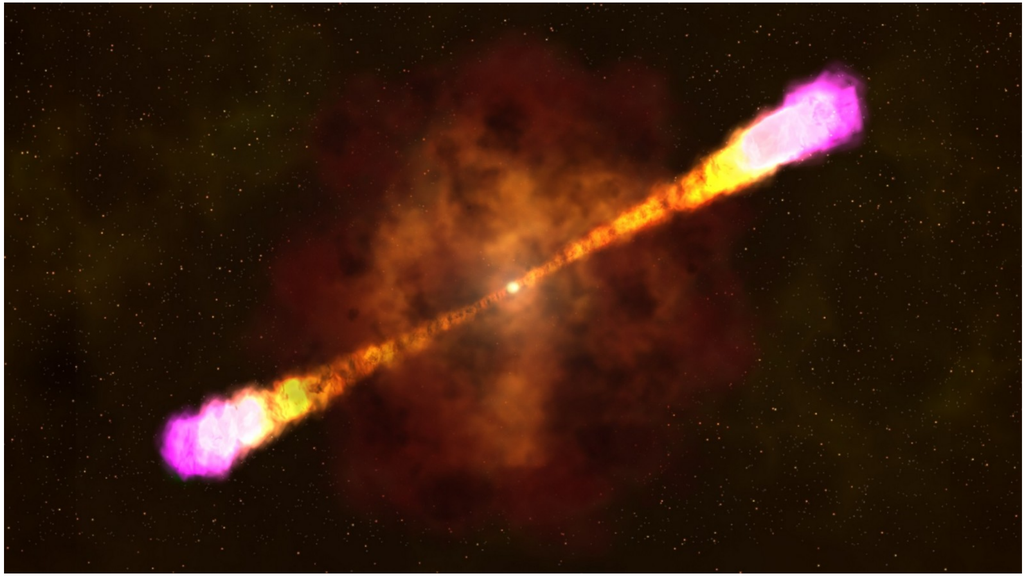
Neutron decay

$(1:0:0)_S$

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

Gamma-ray bursts and blazars – *not* dominant

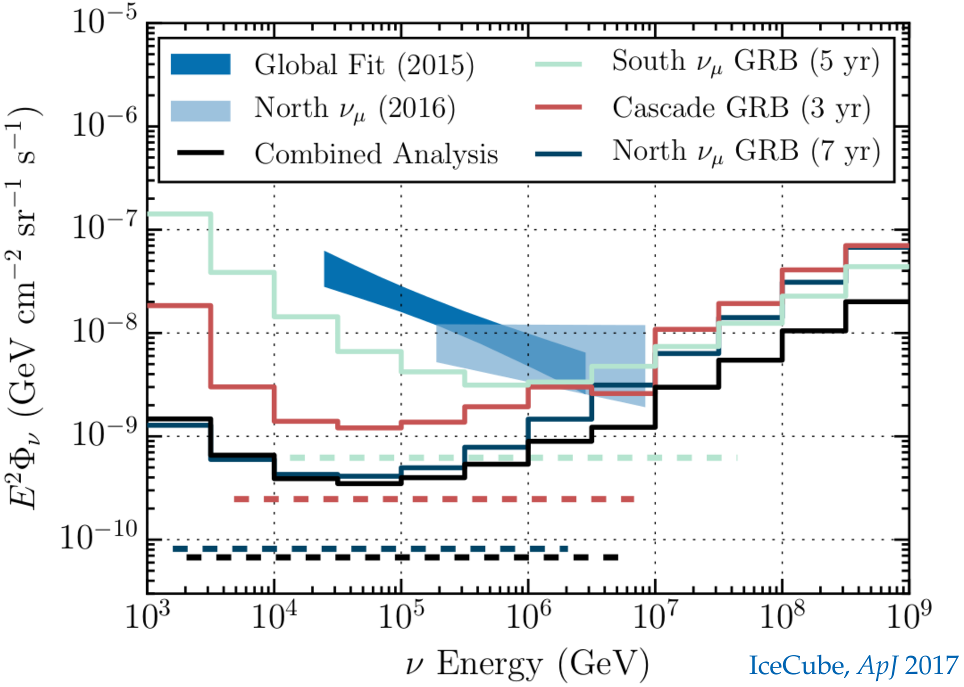
Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts

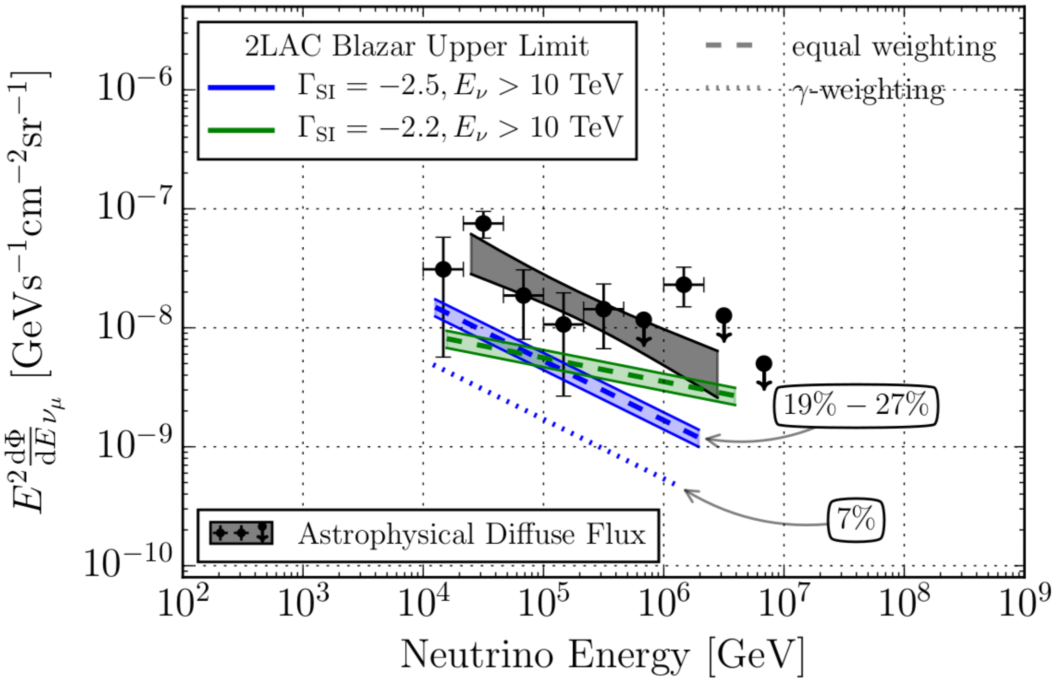


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars

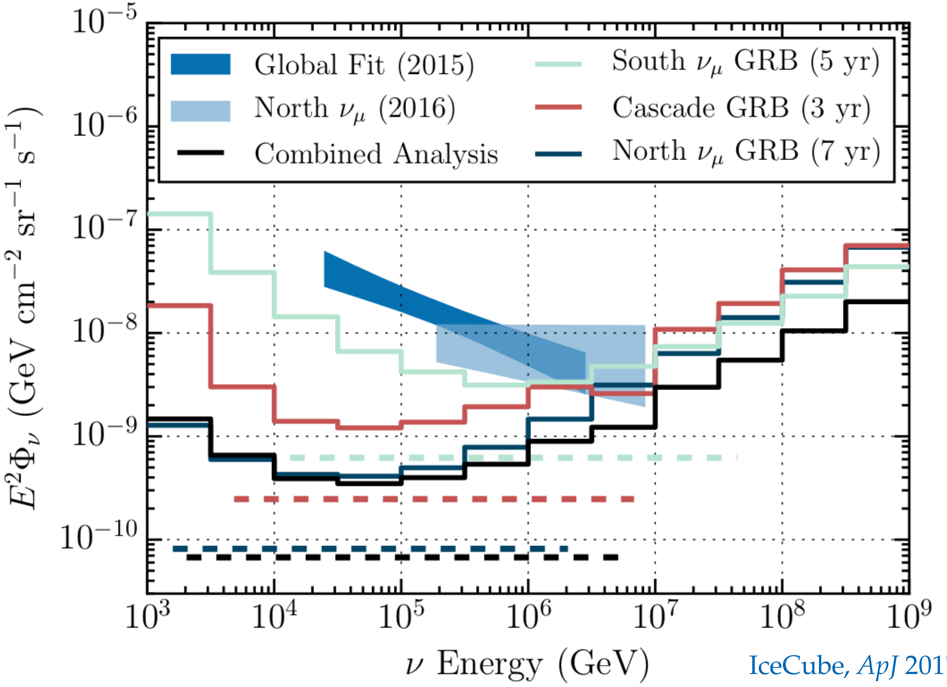


862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



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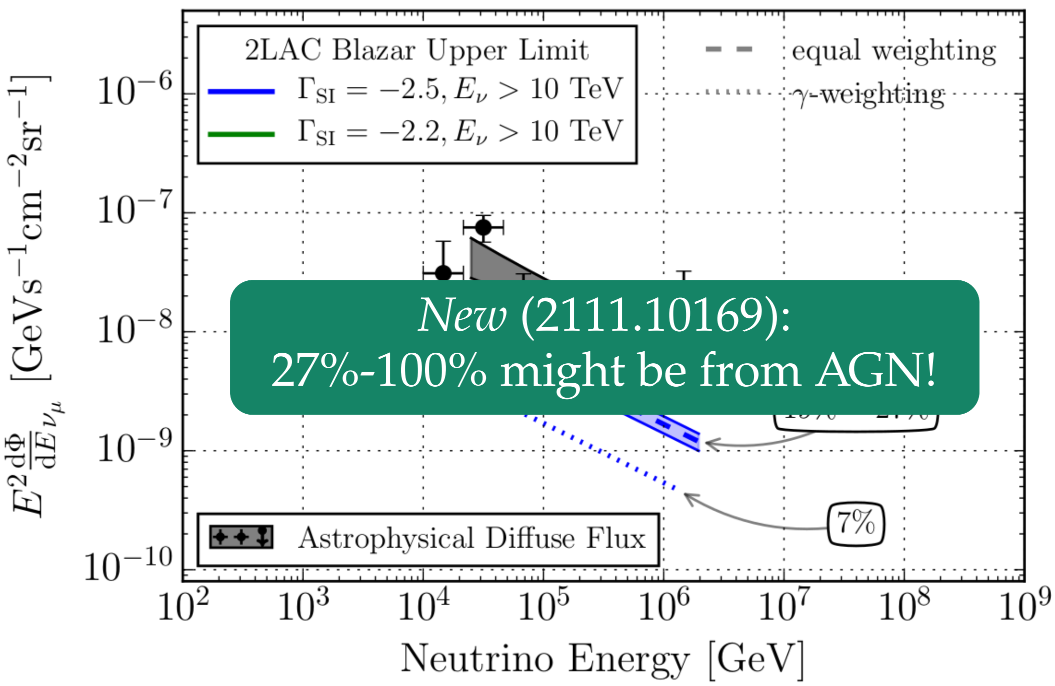
Blazars



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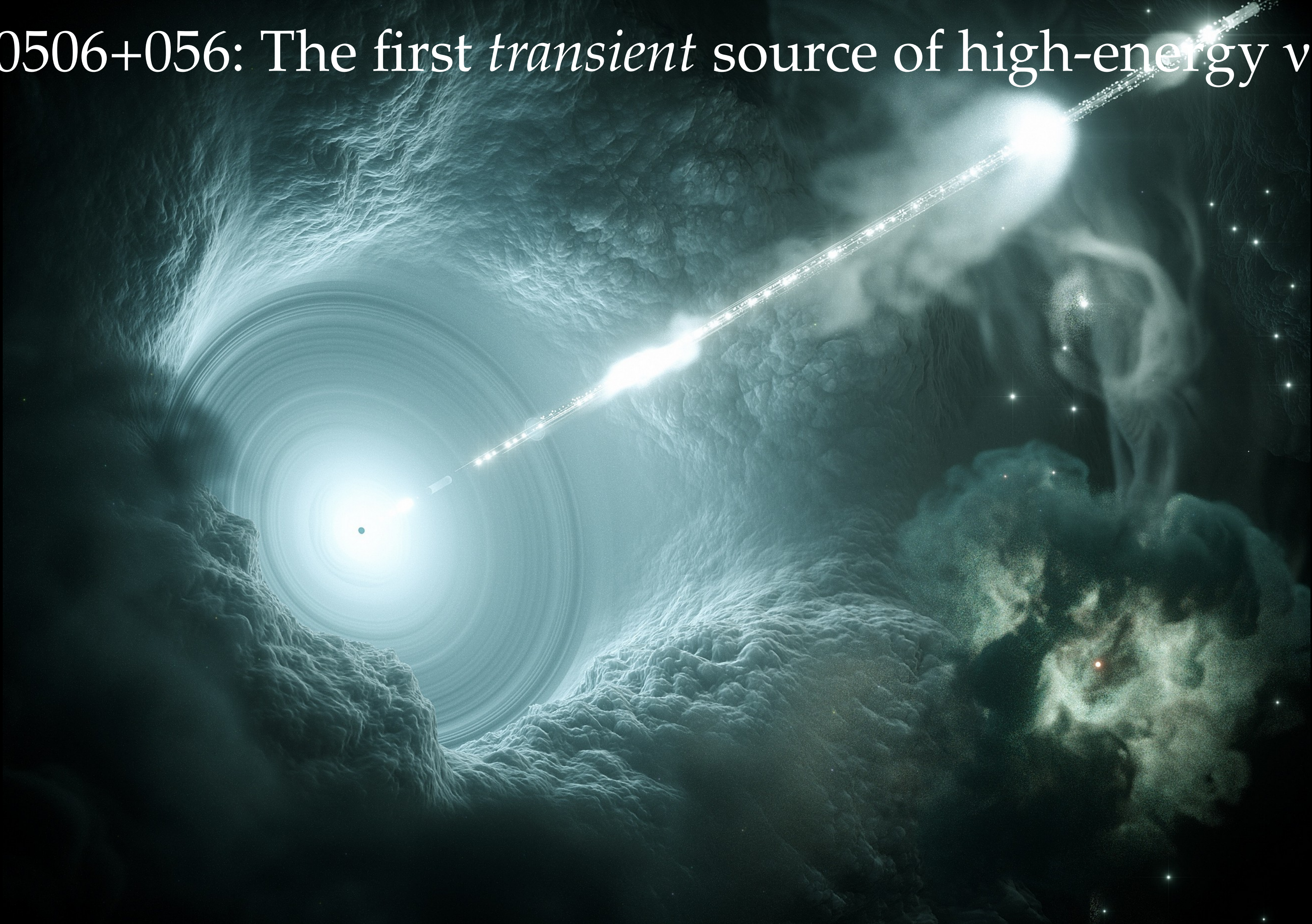
TXS 0506+056: The first *transient* source of high-energy ν

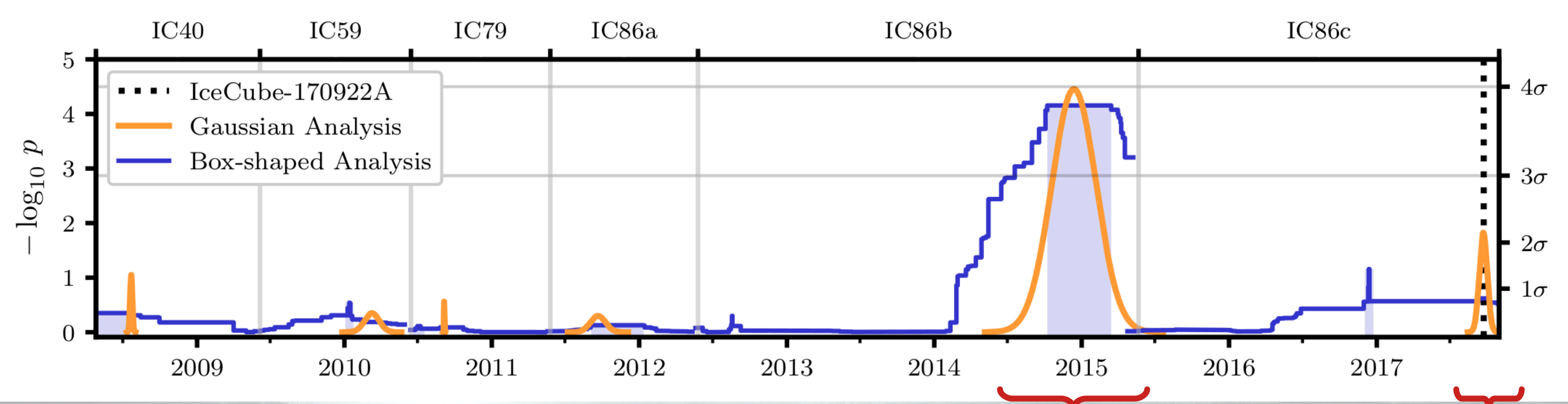


DESY

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

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

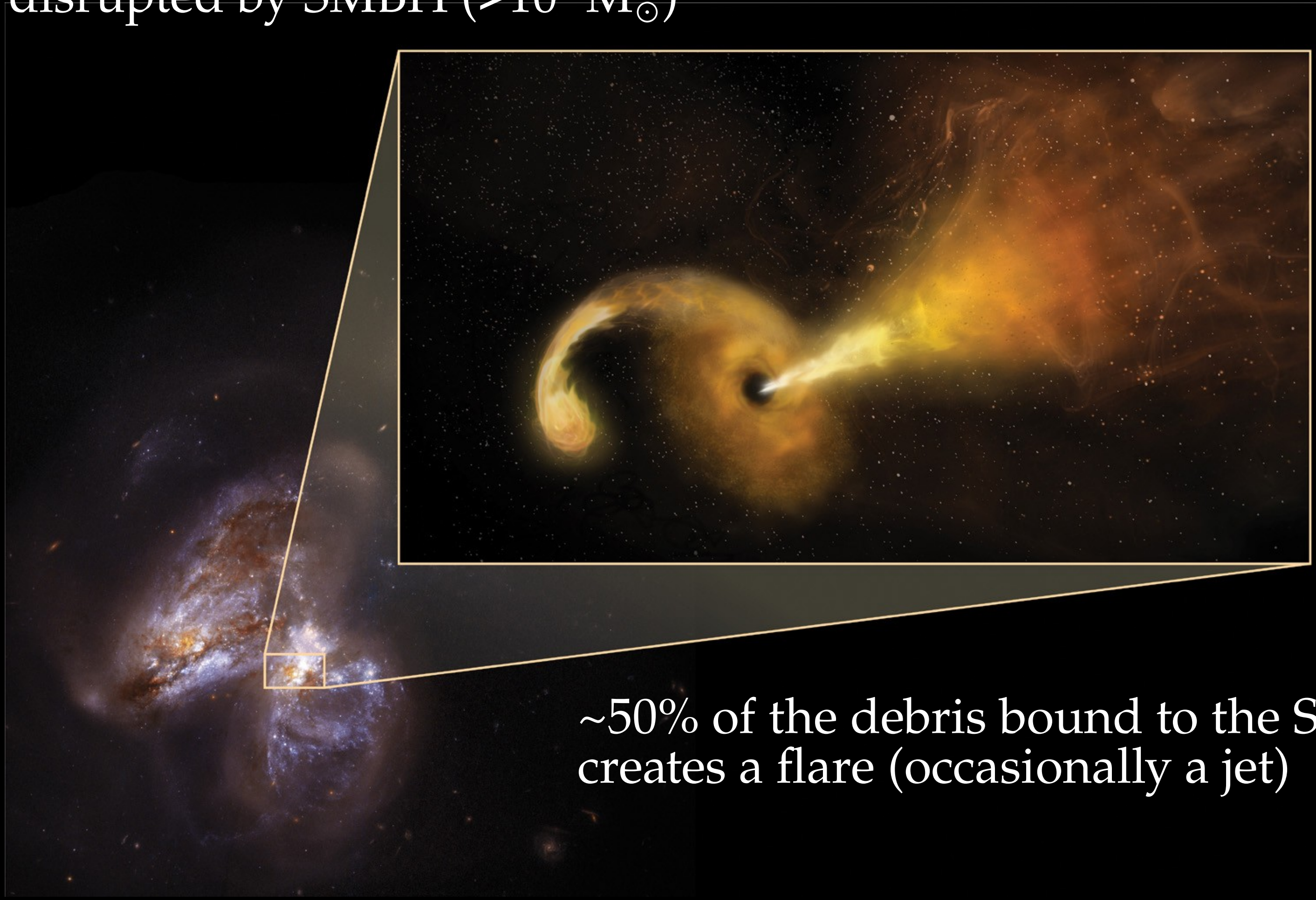
2014–2015: 13±5 ν flare, no X-ray flare
3.5σ significance of correlation (post-trial)

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

Combined (pre-trial): 4.1σ

Tidal disruption events

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



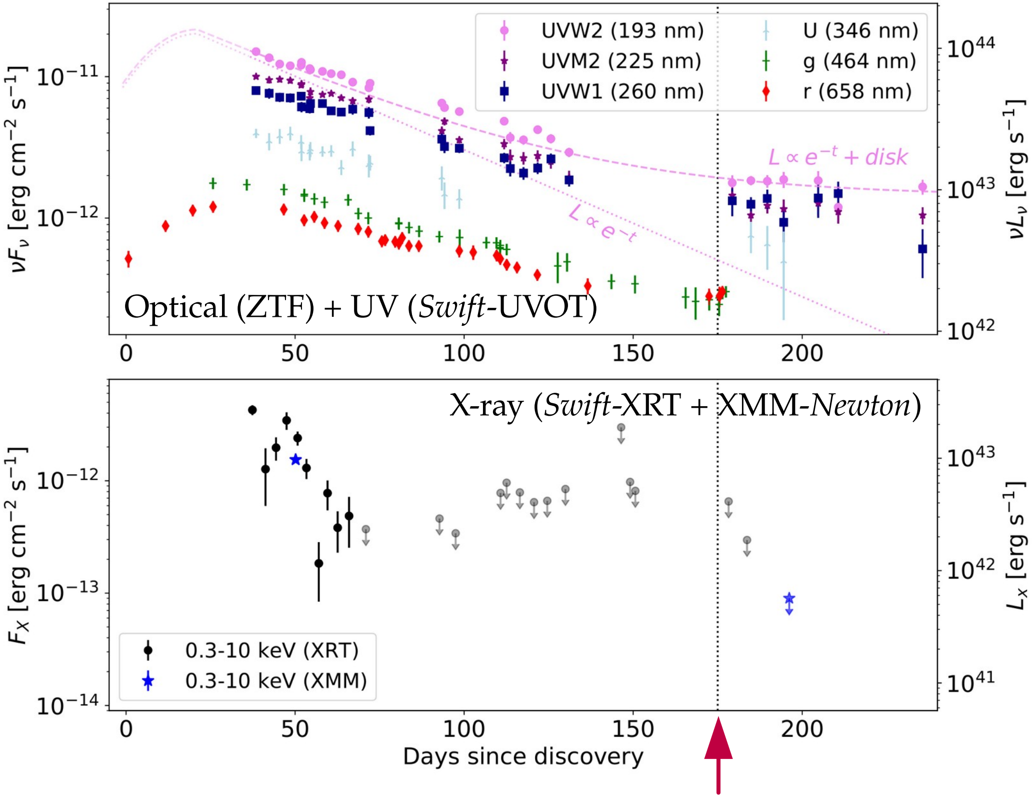
~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

AT2019dsg: Apr 9, 2019 / $z = 0.051$ (230 Mpc) / $M_{BH} = 3 \times 10^7 M_\odot$

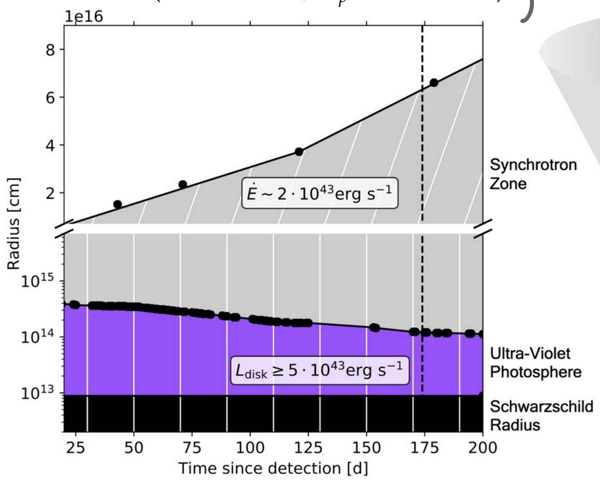


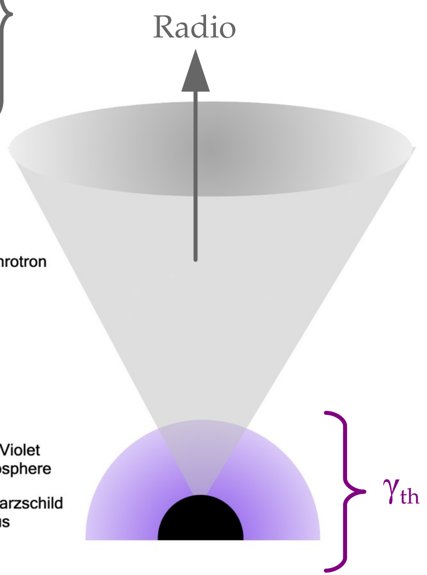
IC191001A, ~200 TeV

Multi-zone model:

From radio:
mildly relativistic expansion
($v/c \sim 0.2$) + acceleration

p and e accelerated here
($B = 0.07$ G, $E_p < 160$ PeV)





$$p + \gamma_{th} \text{ (or } p) \rightarrow \nu$$

Stein *et al.*, *Nature Astron.* 2021 – See also: Winter & Lunardini, *Nature Astron.* 2021; Murase, Kimura, Zhang, Oikonomou, Petropoulou, *ApJ* 2020

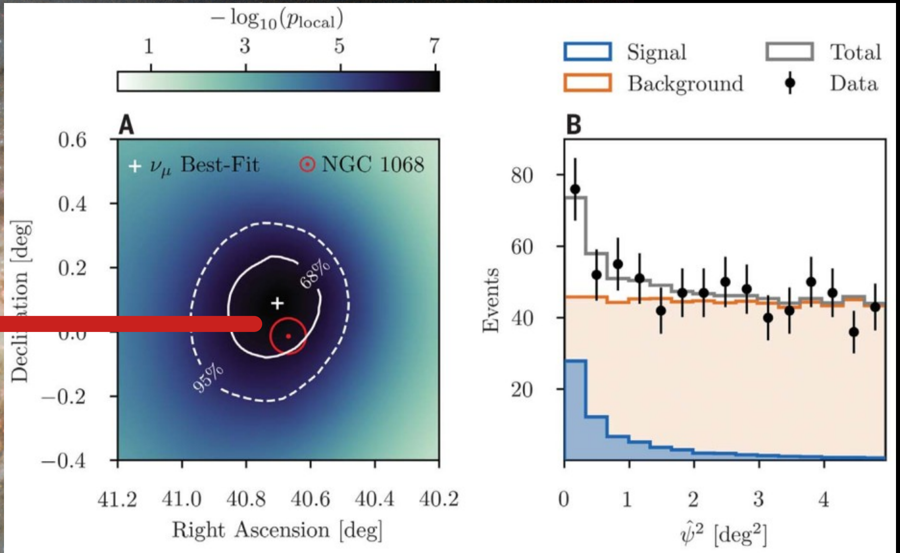
NGC1068: The first *steady-state* source of high-energy ν

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

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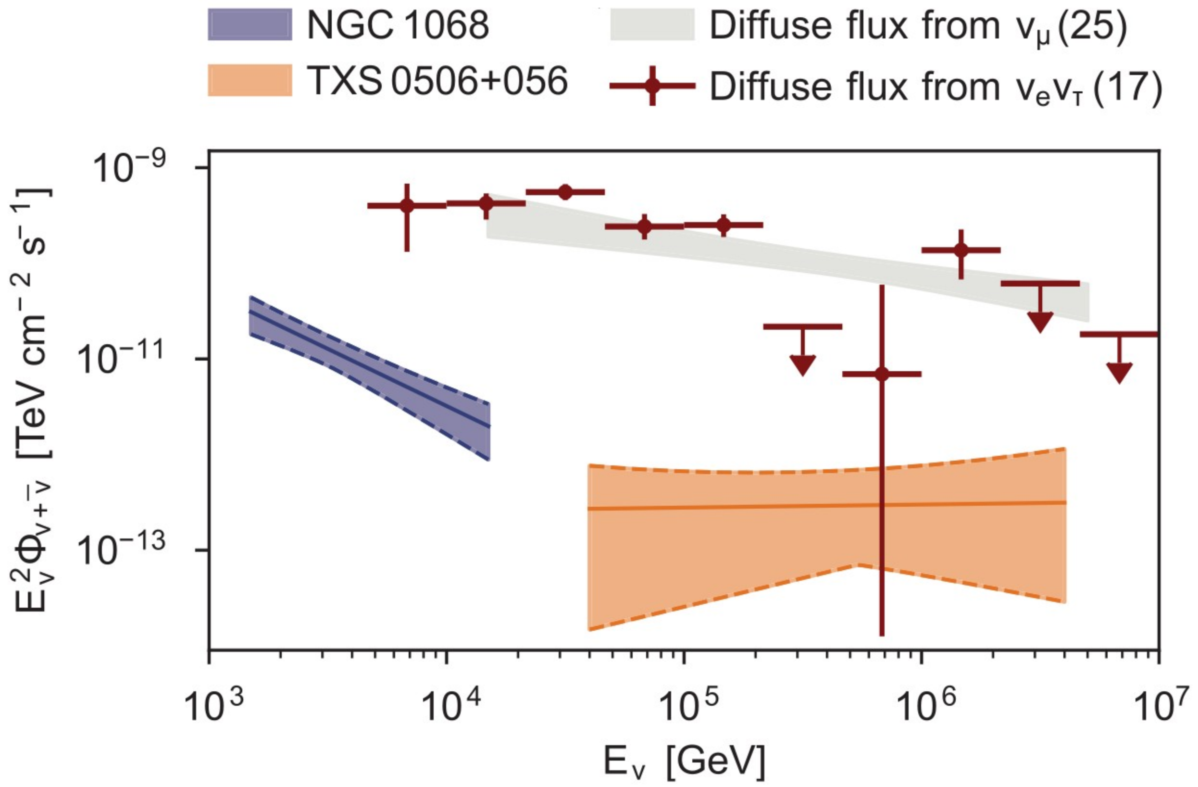


IceCube Collab., *Science* 378, 538 (2022)

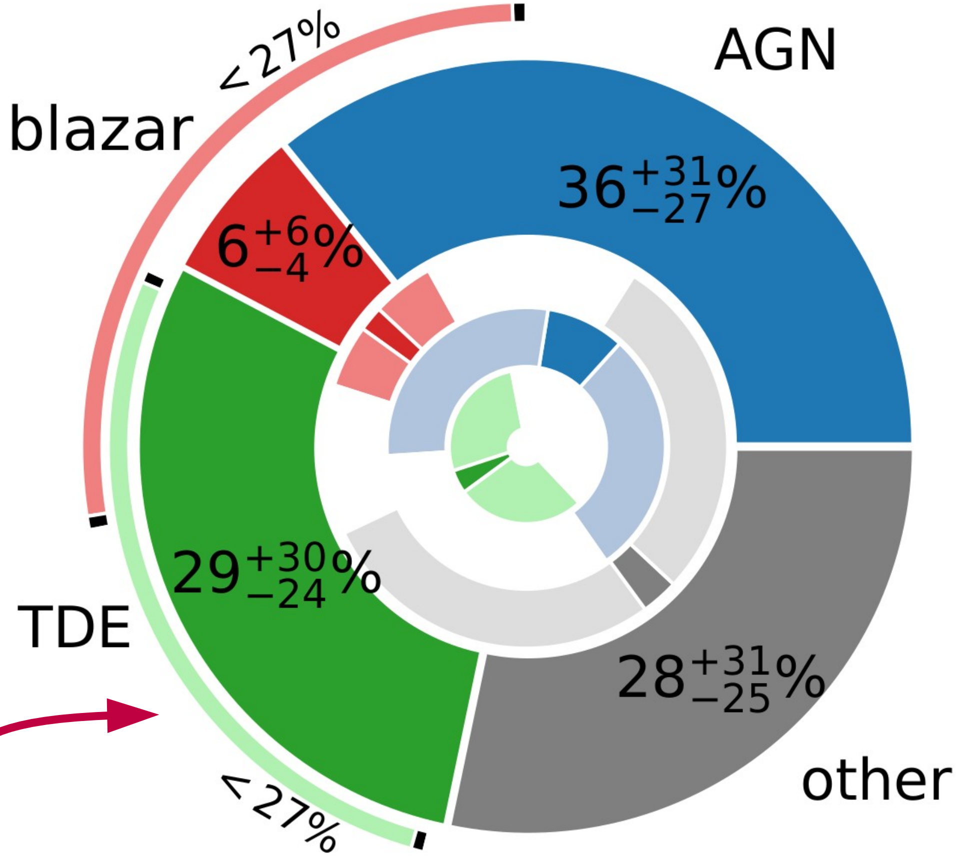
Hubble Space Telescope,
NASA, ESA & A. van der Hoeven

The IceCube pie chart

Sources with associated ν emission:

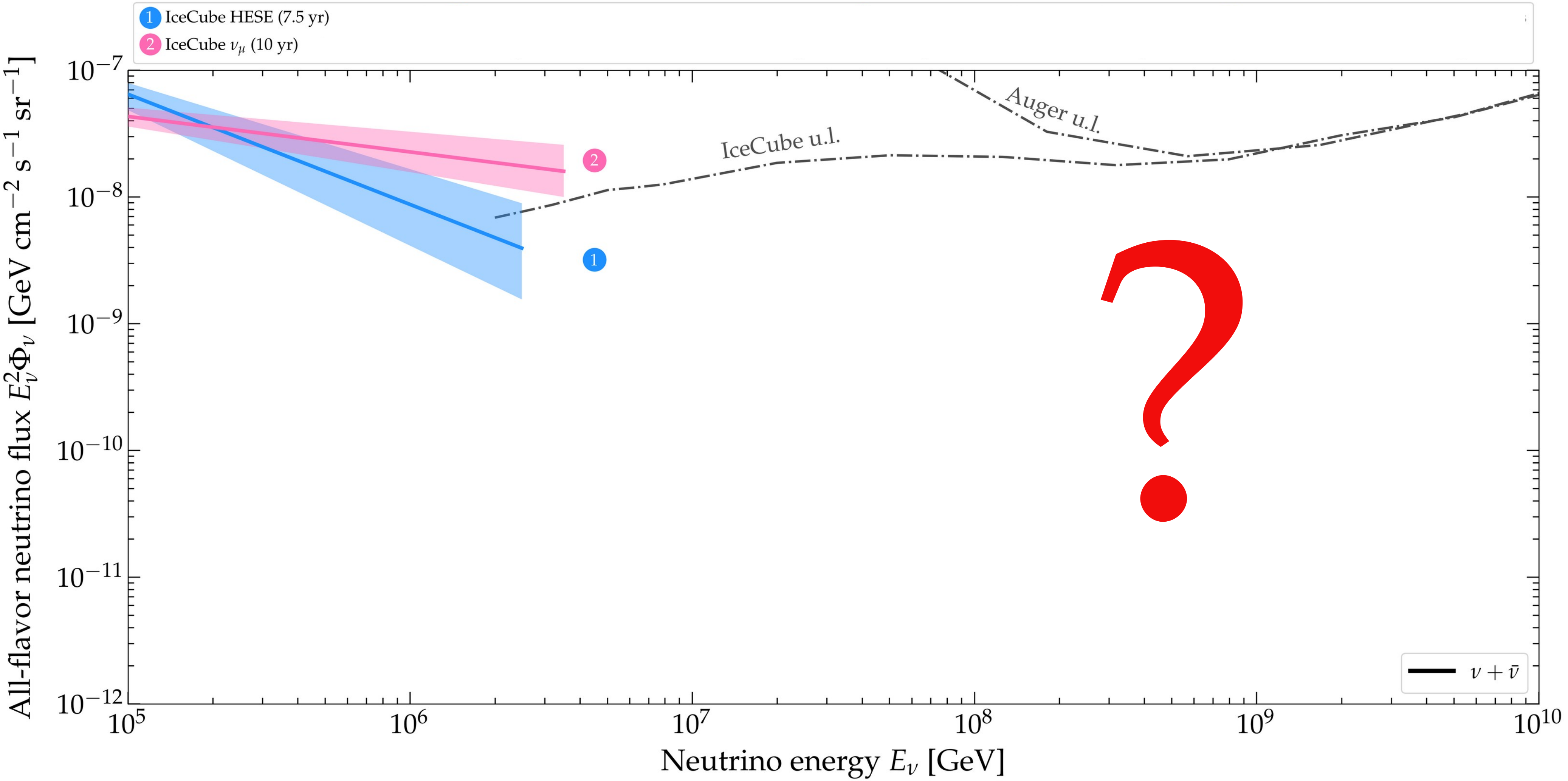
Name	Type	p
NGC 1068	AGN	0.008
TXS 0506+056	blazar	0.001
PKS 1502+106	blazar	0.01
PKS 1424-41	blazar	0.05
AT2019dsg	TDE	0.002

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

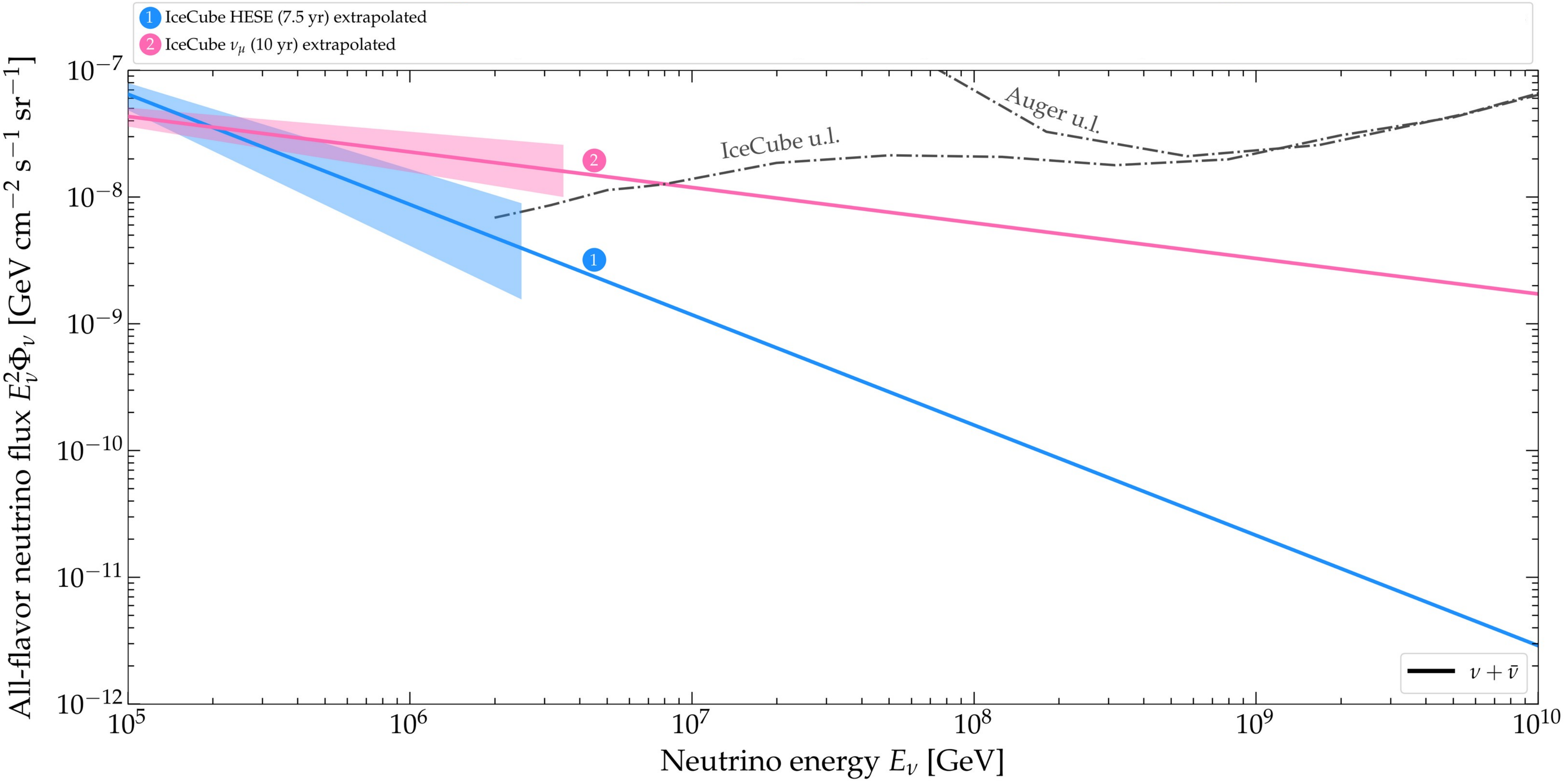


I. Bartos *et al.*, *ApJ* 2021 [2105.03792]

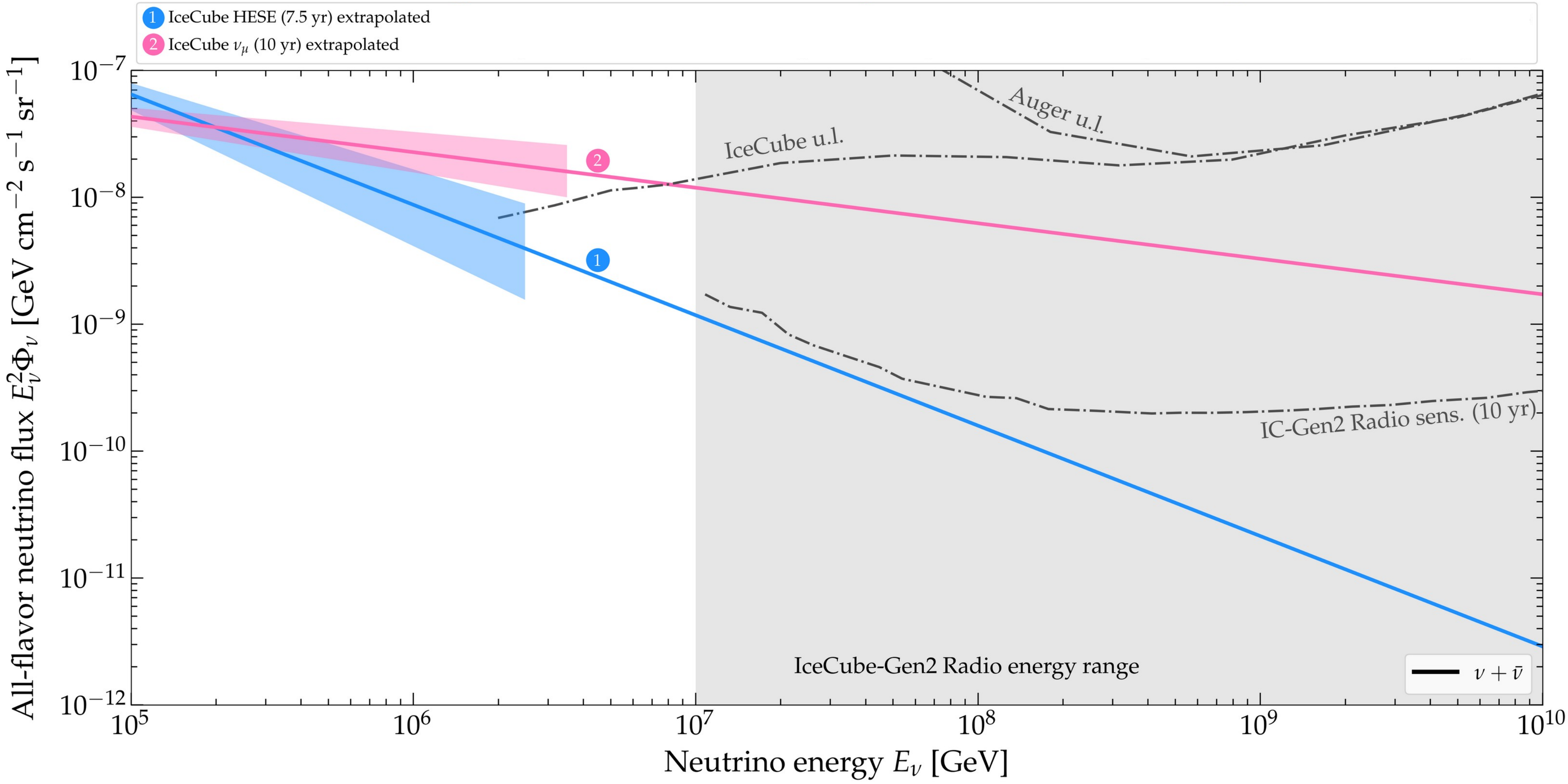
Note: Outer rings are from separate stacking analyses



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



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



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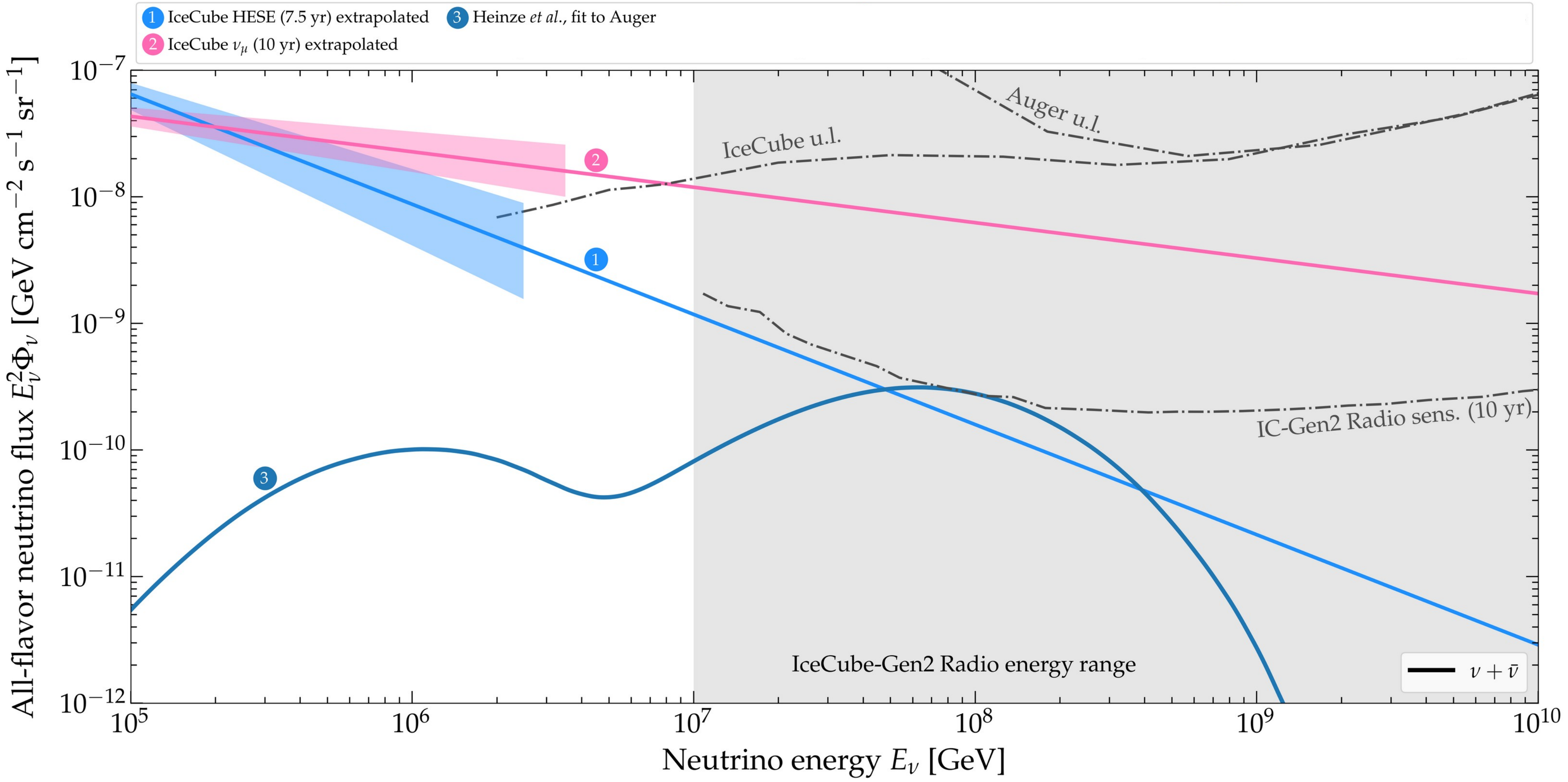
10^6
10^7
10^8
10^9
10^{10}



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Auger u.l.
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All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
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10^{-11}
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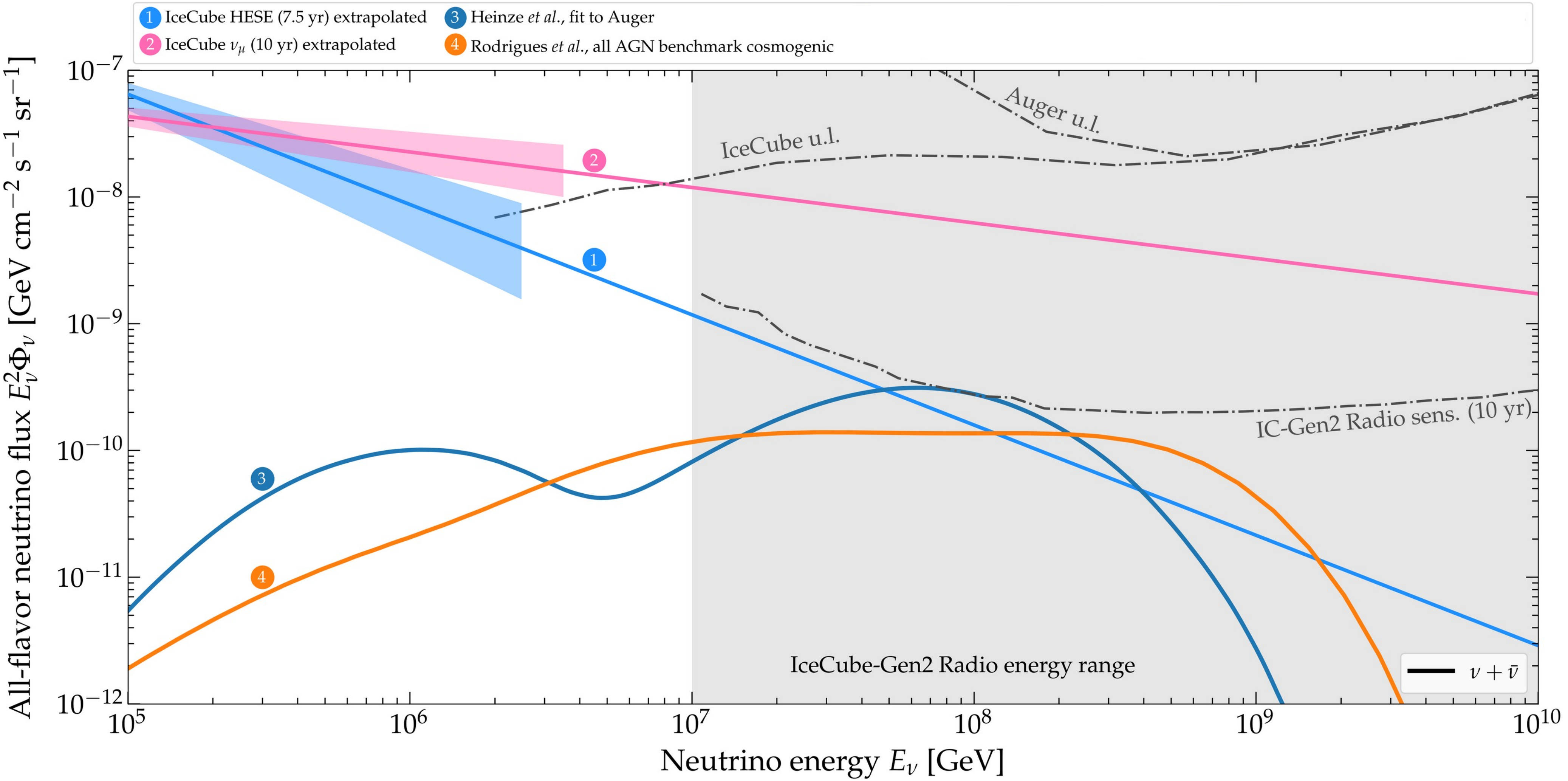
10^{9}
10^{10}



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4 Rodrigues *et al.*, all AGN benchmark cosmogenic
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
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10^5
10^6
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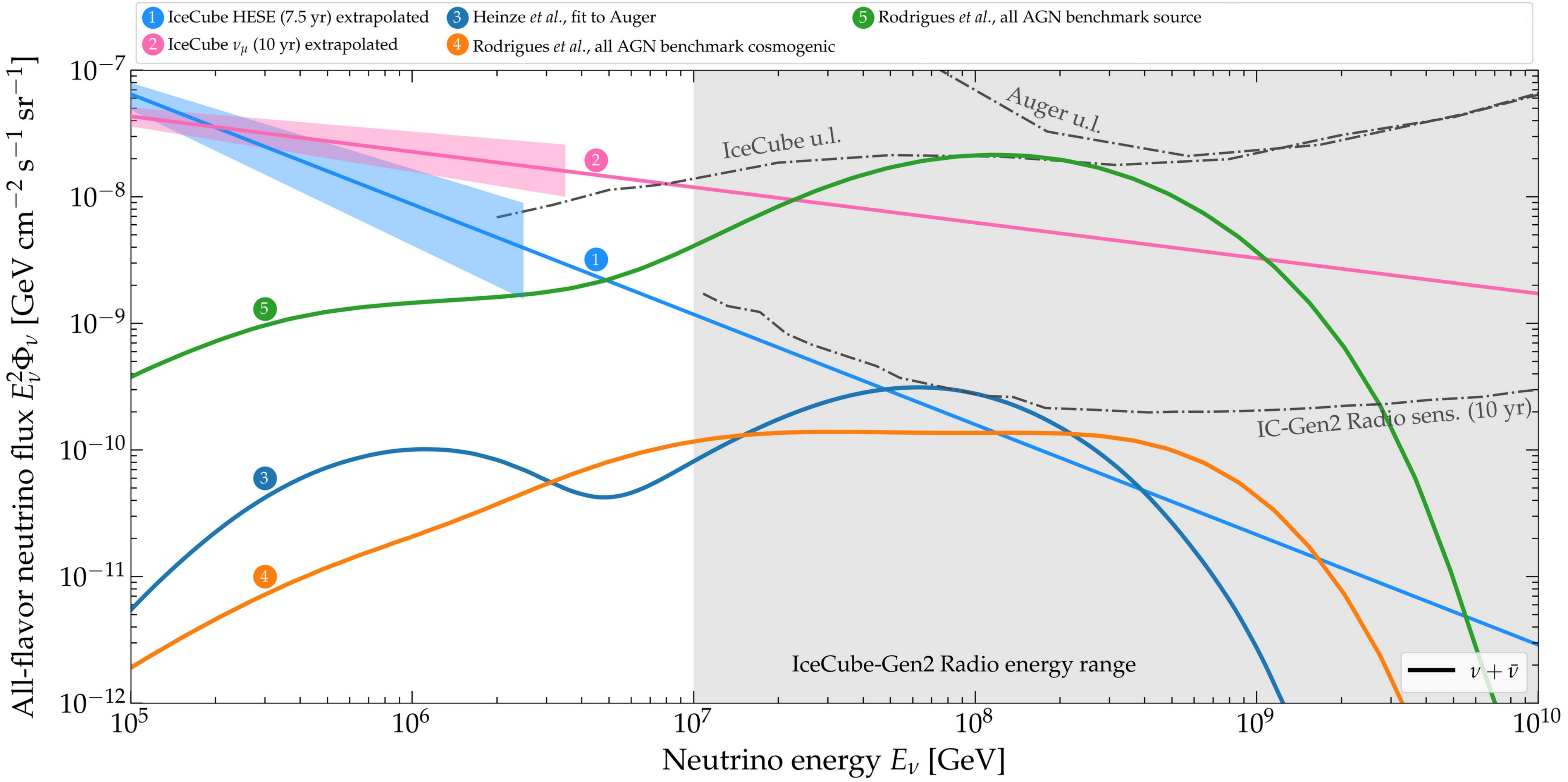

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IceCube-Gen2 Radio energy range
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Neutrino energy E_ν [GeV]
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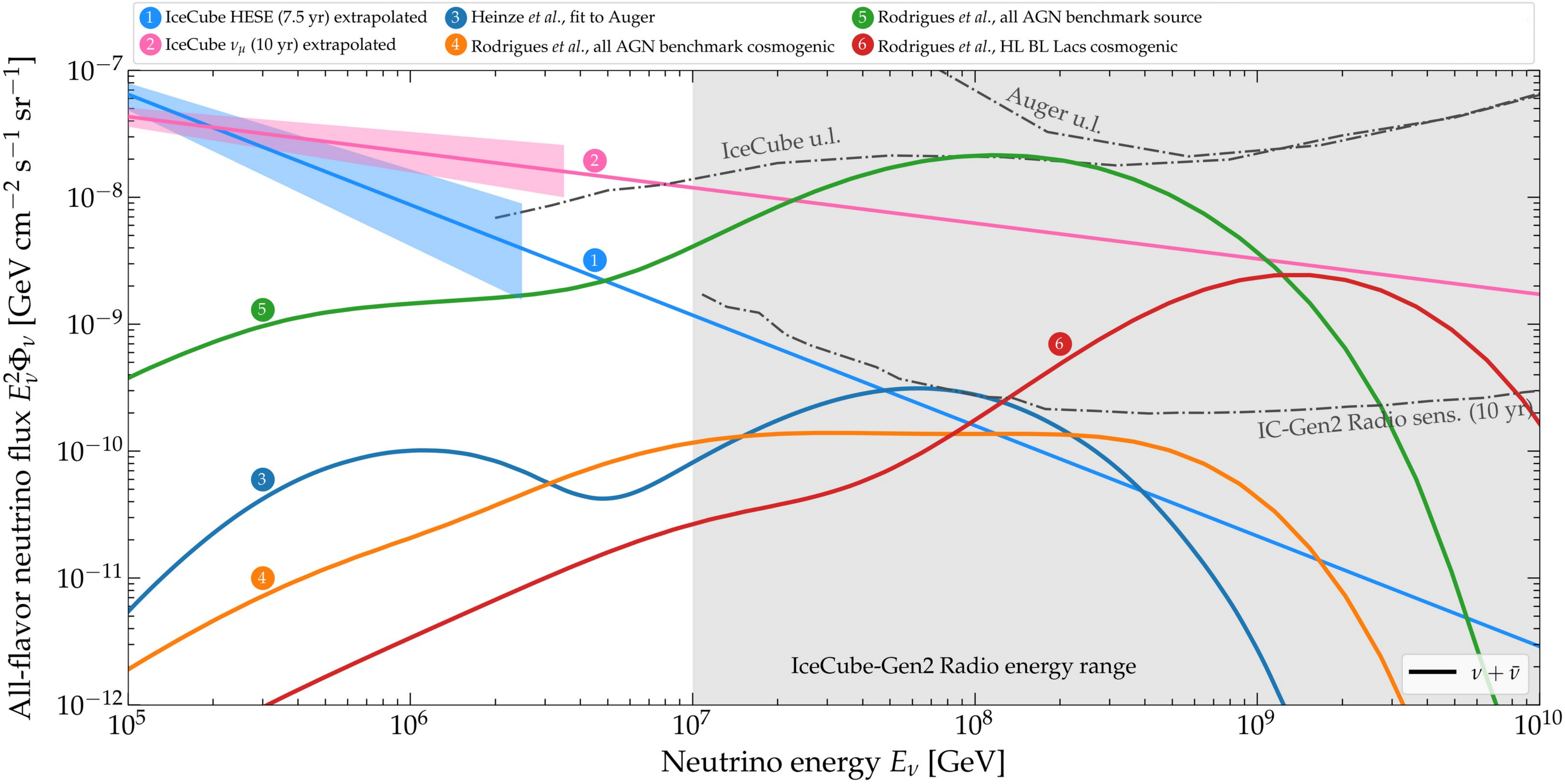
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



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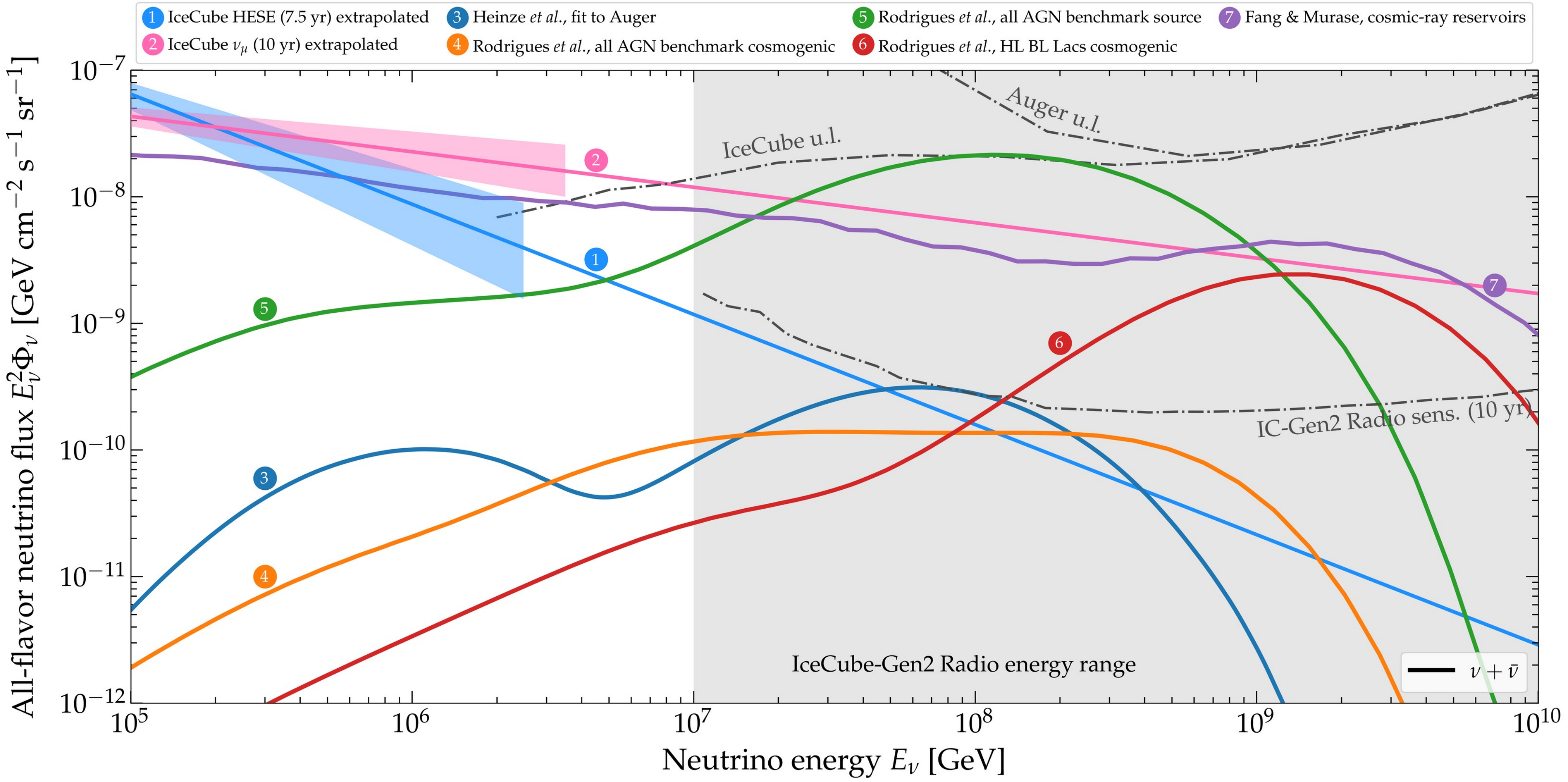
IceCube u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}



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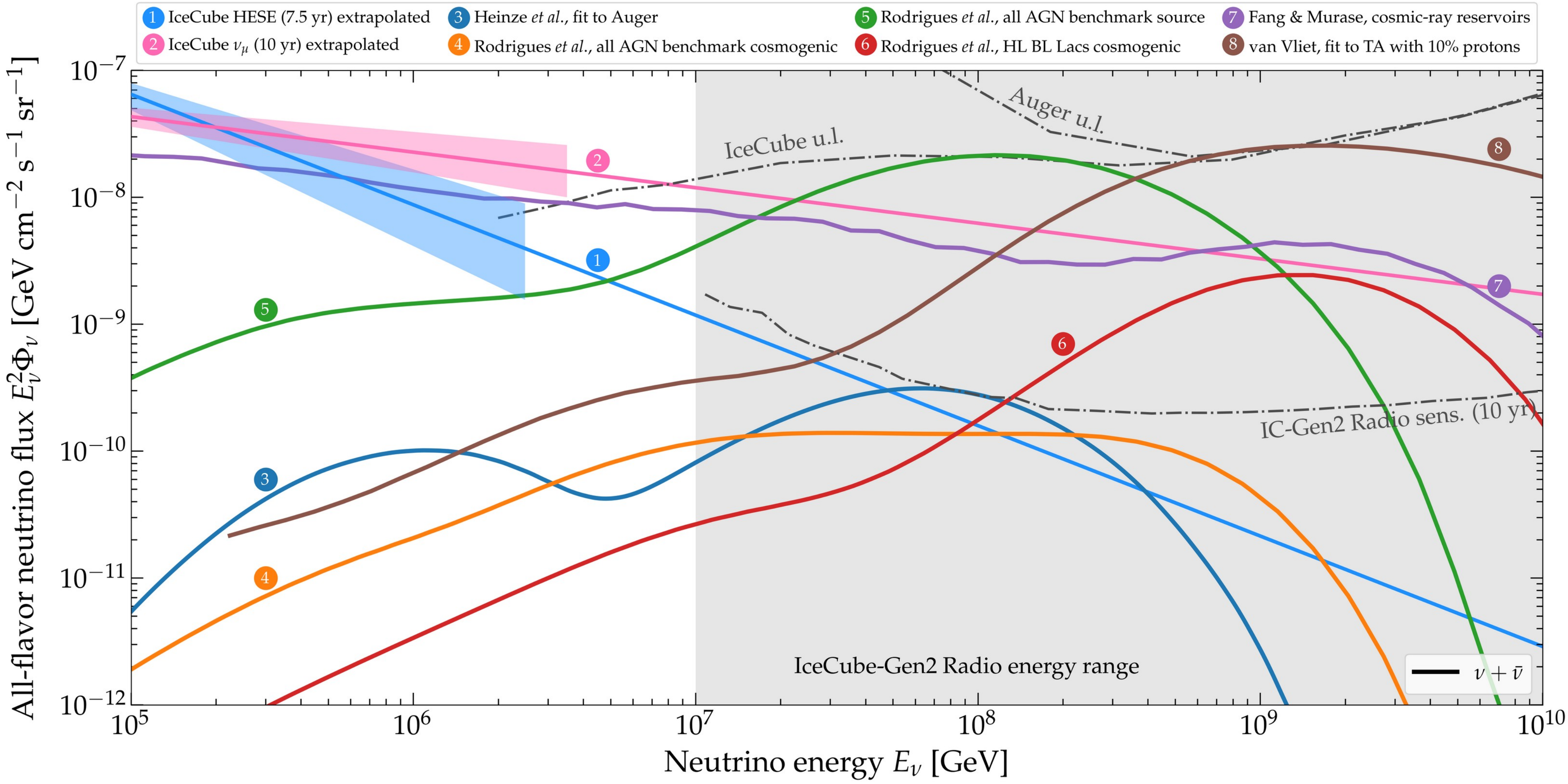
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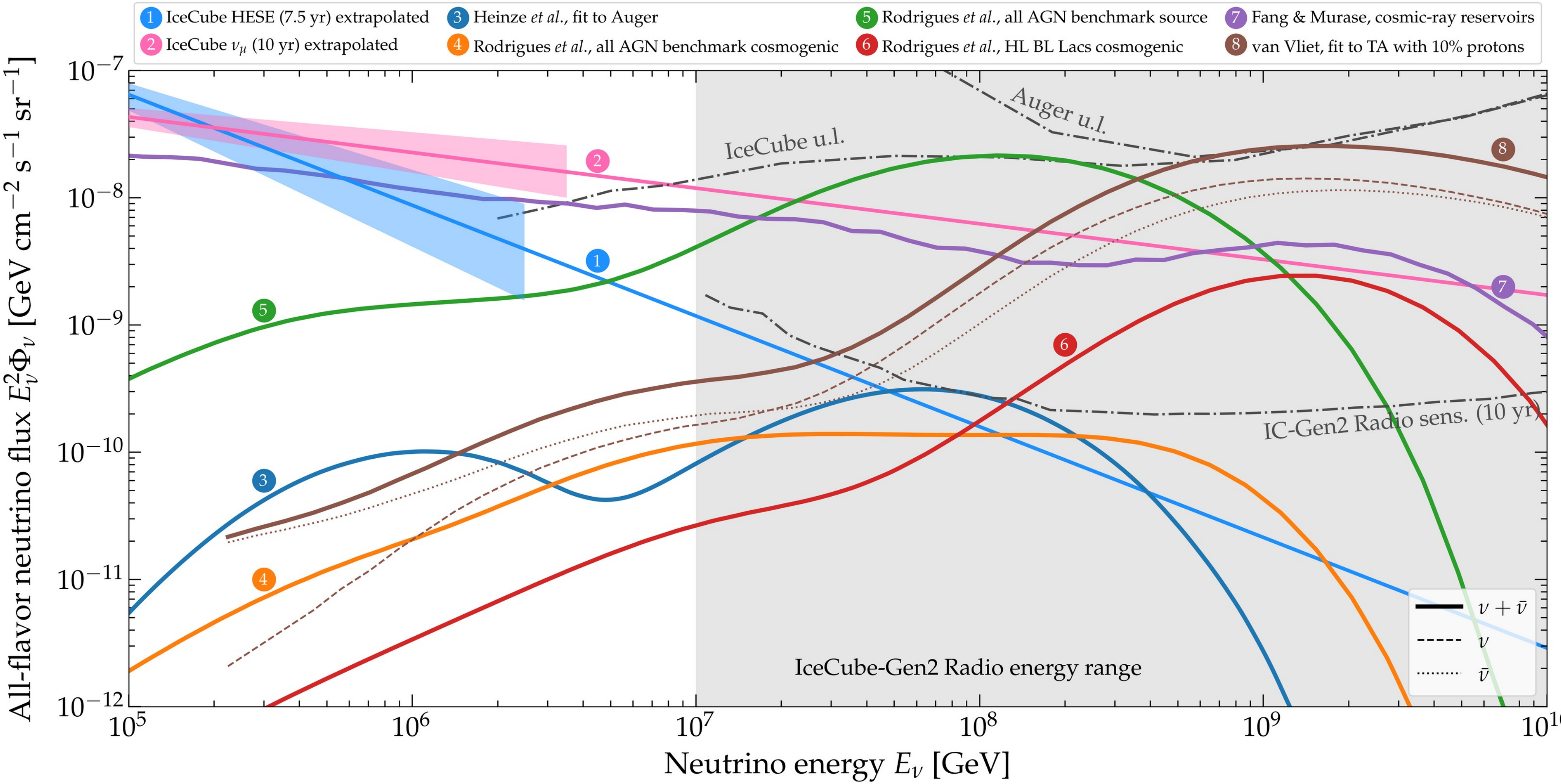

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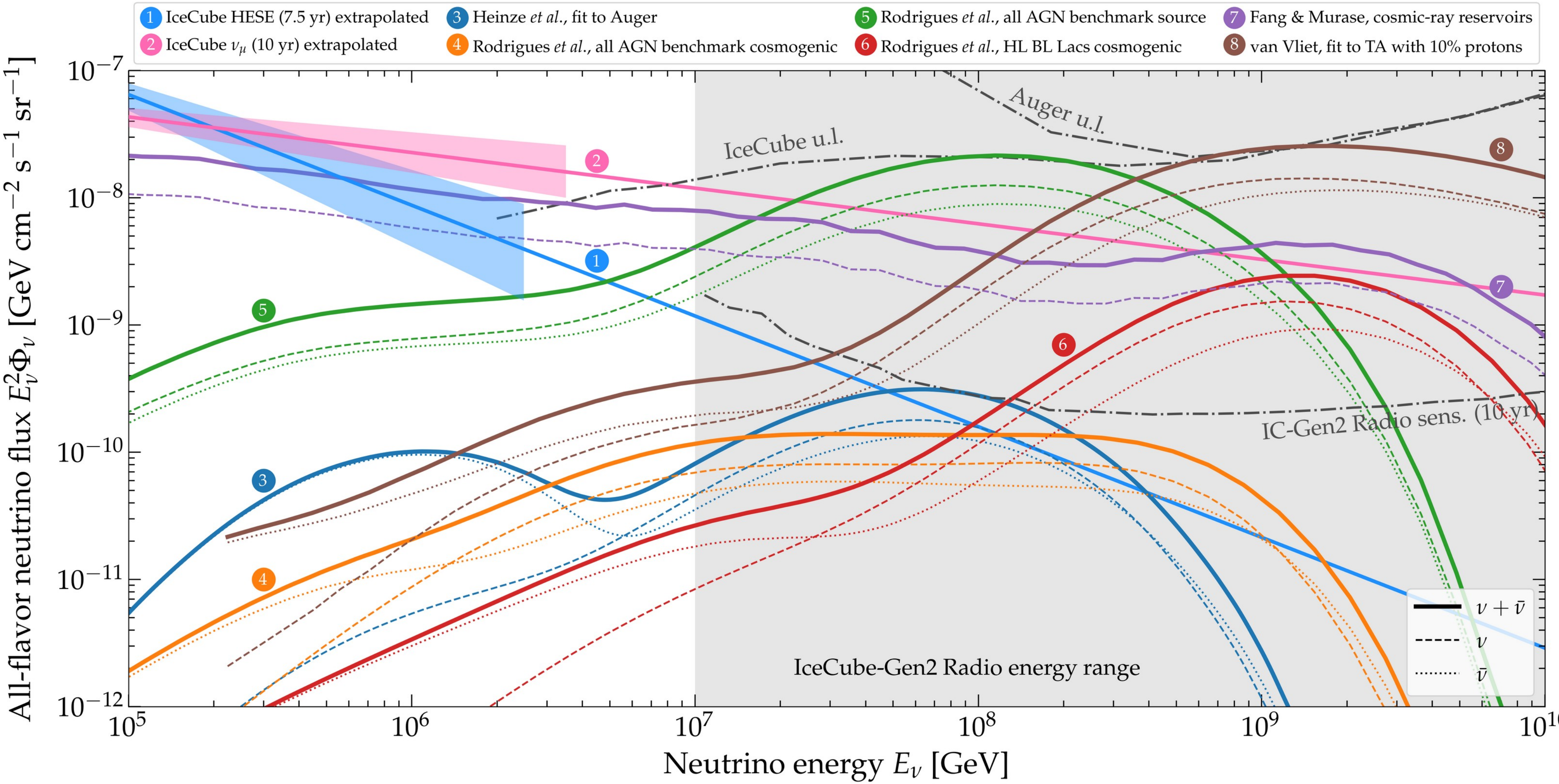

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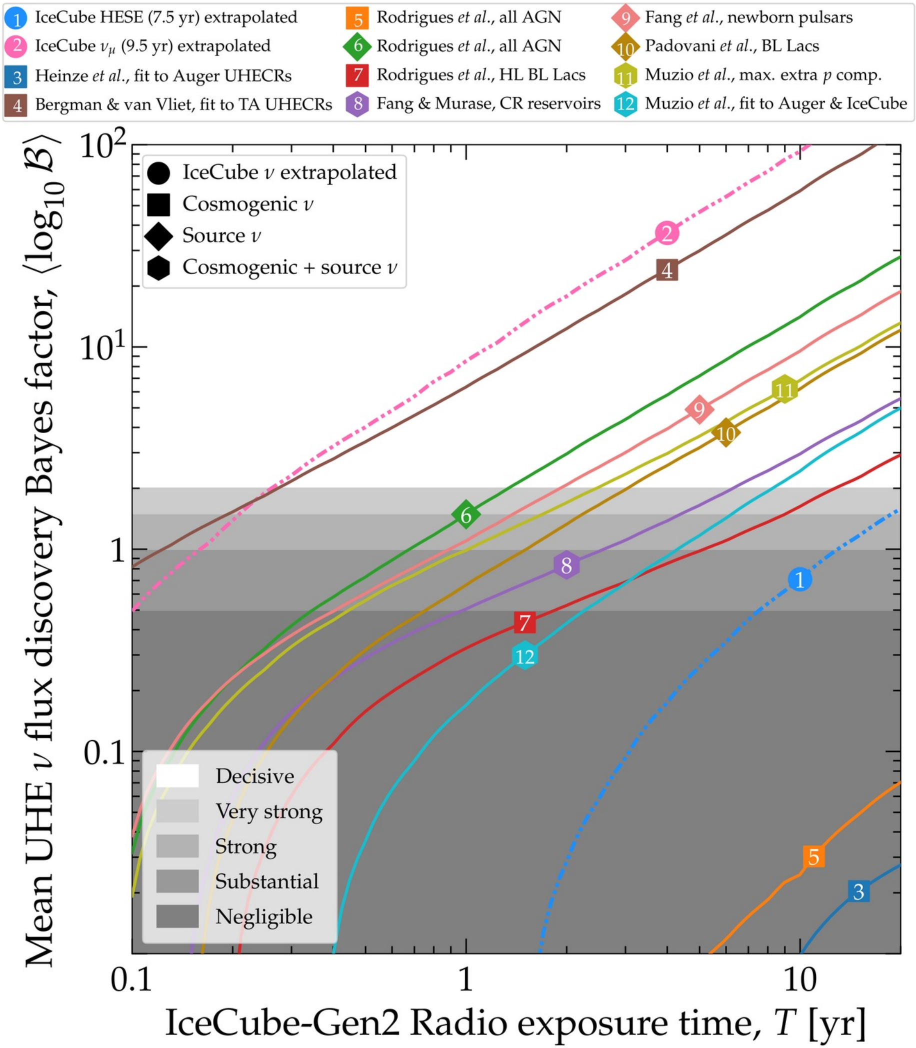
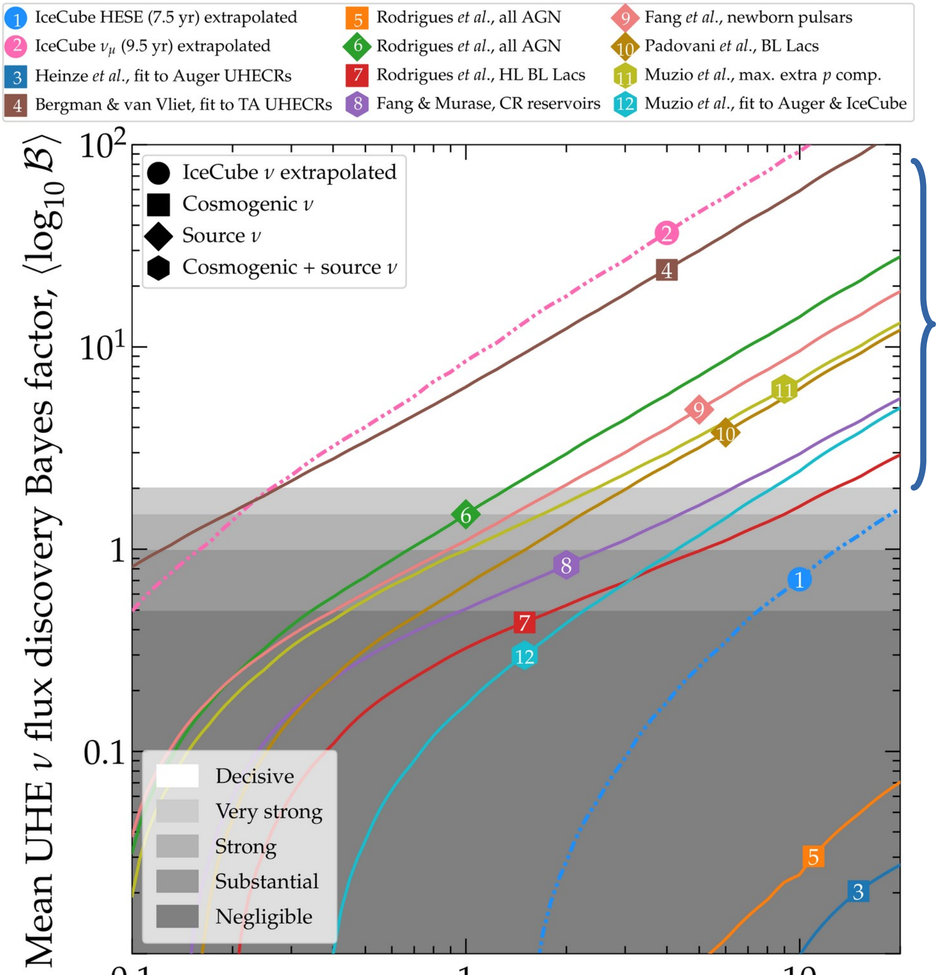
Discovering the diffuse flux of UHE neutrinos



V. B. Valera, **MB**, C. Glaser, 2210.03756

Discovering the diffuse flux of UHE neutrinos

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



Large Bayes factor = decisive flux discover

V. B. Valera, **MB**, C. Glaser, 2210.03756

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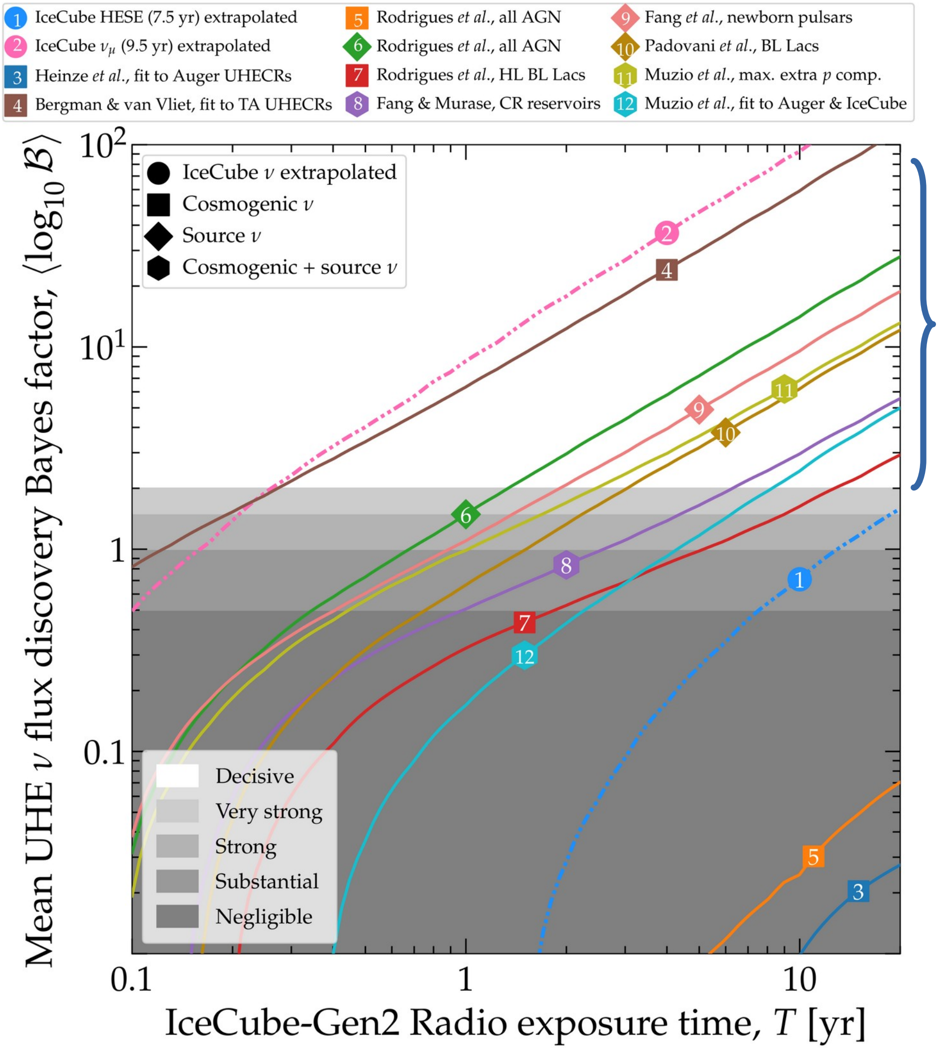

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Forecasts are state-of-the-art:
- Neutrino propagation inside Earth
- Detailed simulation of radio in ice
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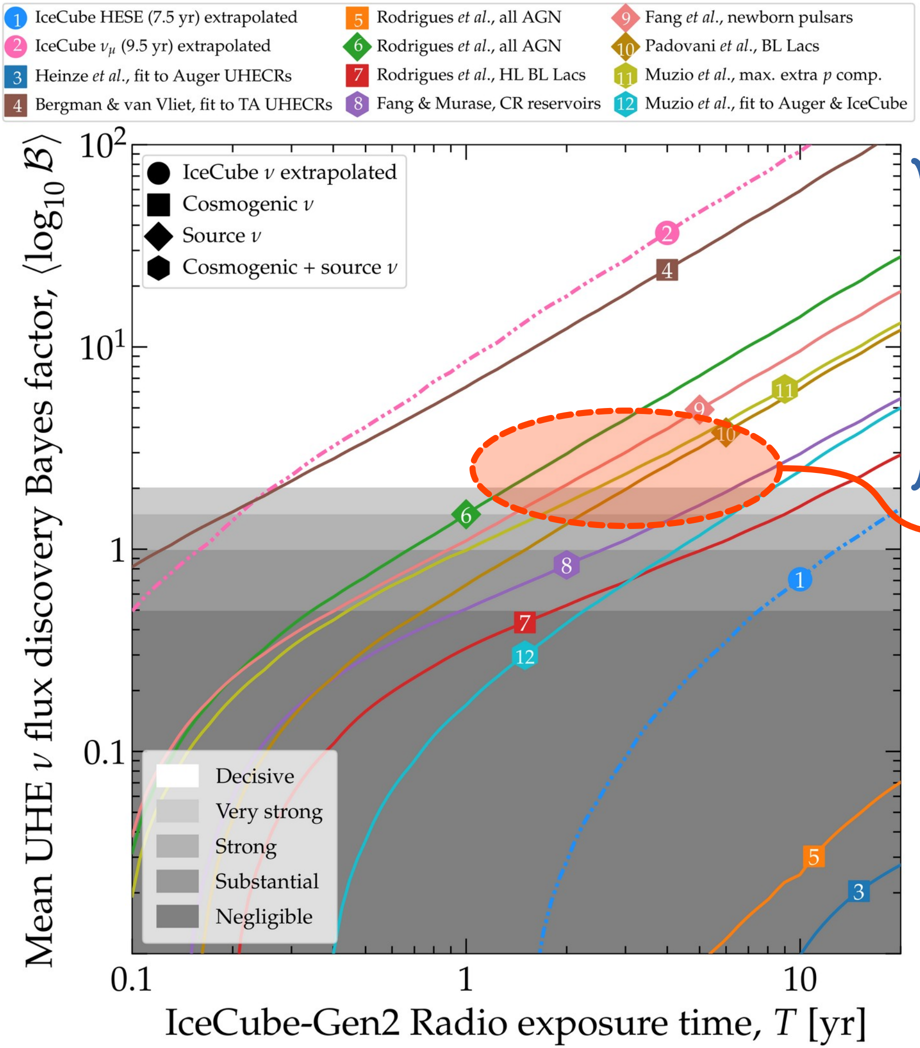

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V. B. Valera, **MB**, C. Glaser, 2210.03756

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Work led by
Víctor Valera

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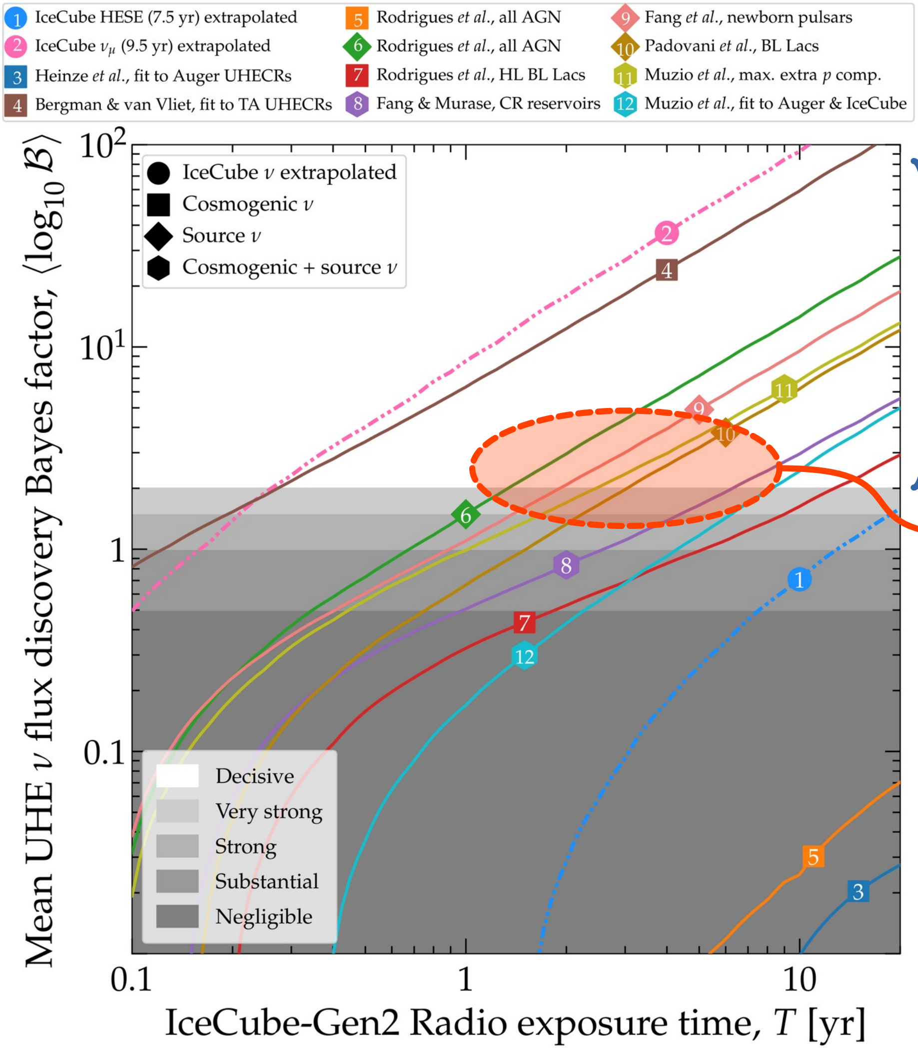

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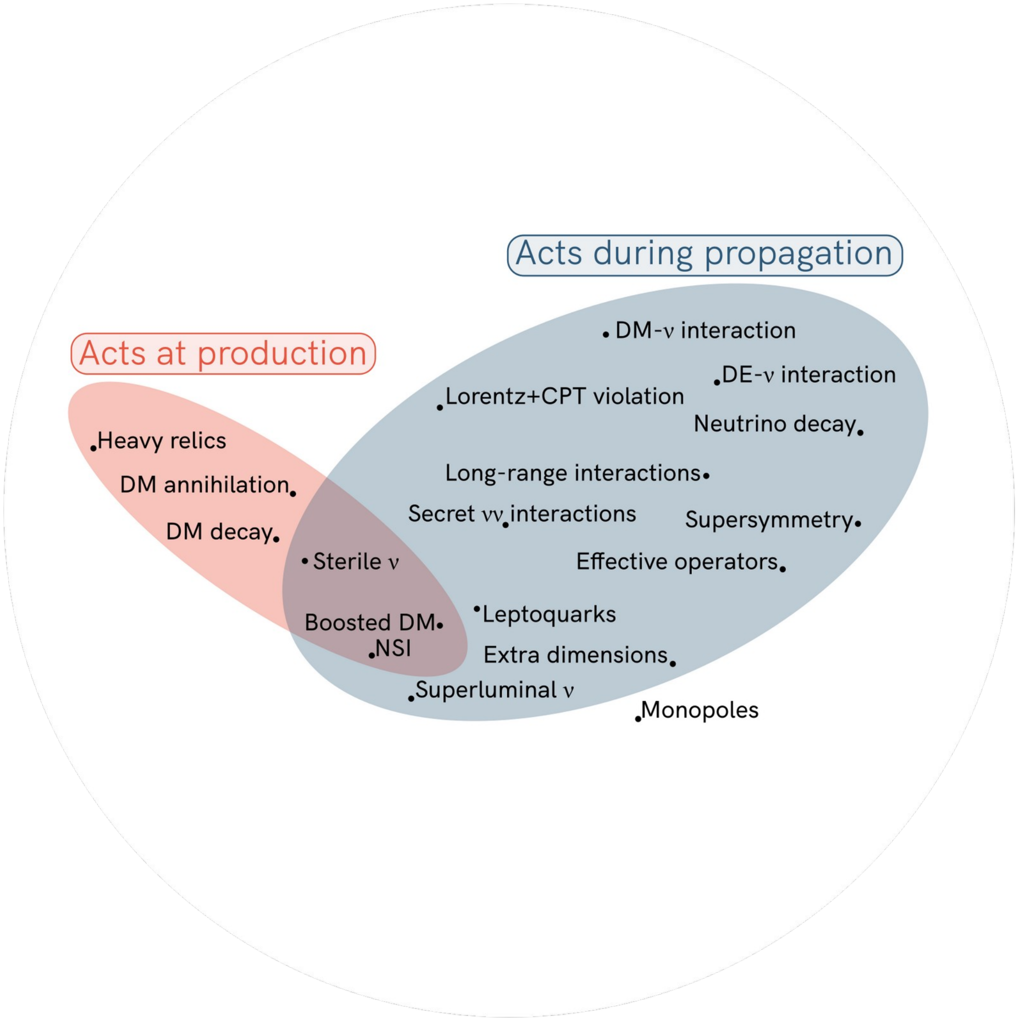

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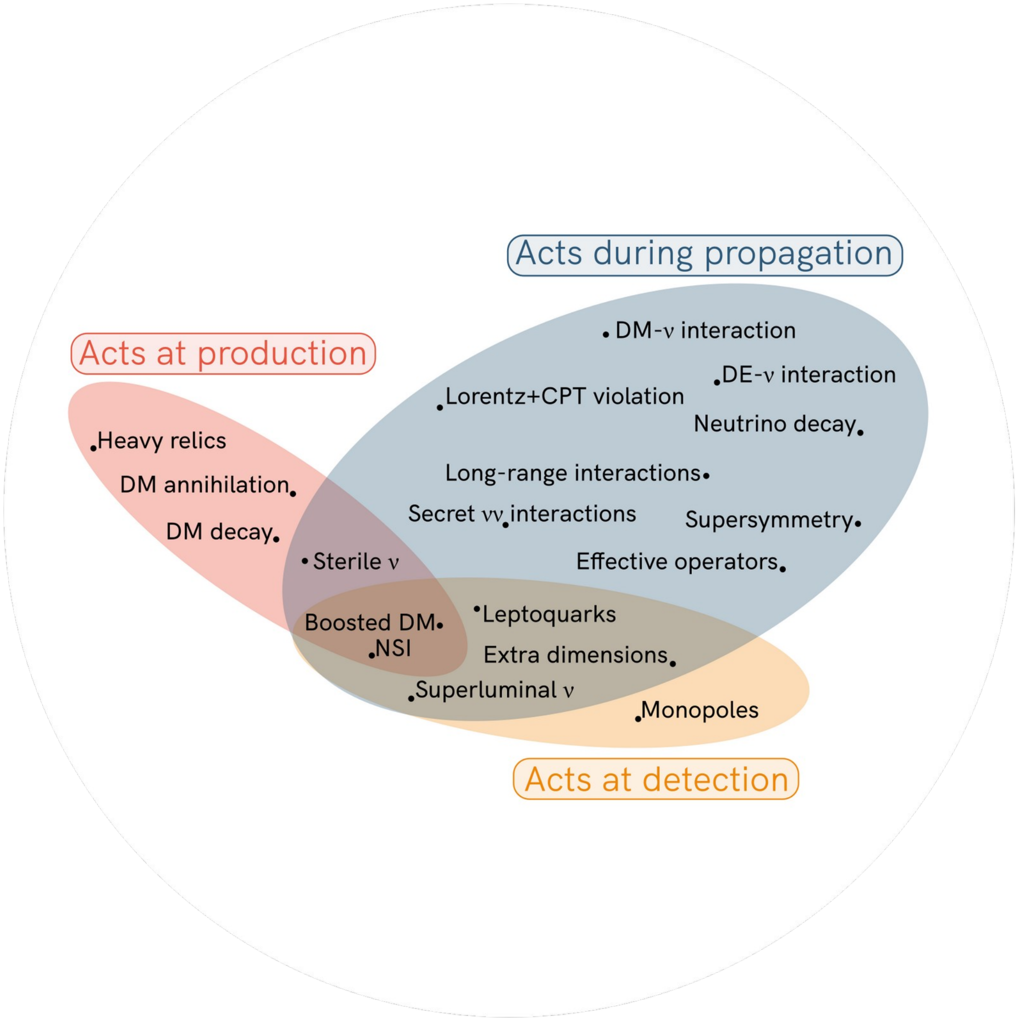

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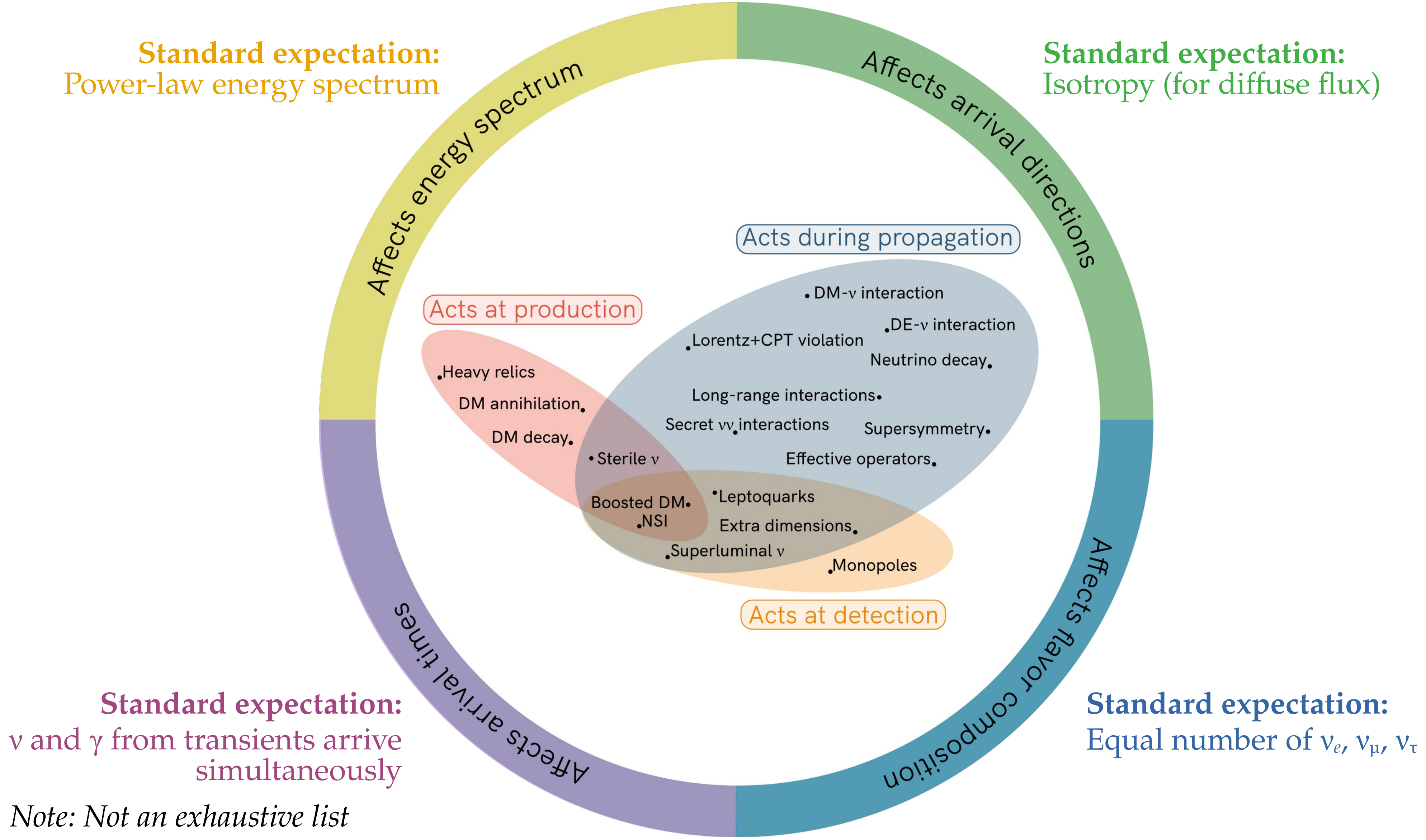

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Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects arrival times
Affects flavor composition
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT violation
Neutrino decay
Heavy relics
DM annihilation
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Secret νν interactions
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Standard expectation:
ν and γ from transients arrive simultaneously
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Equal number of ν_e, ν_μ, ν_τ
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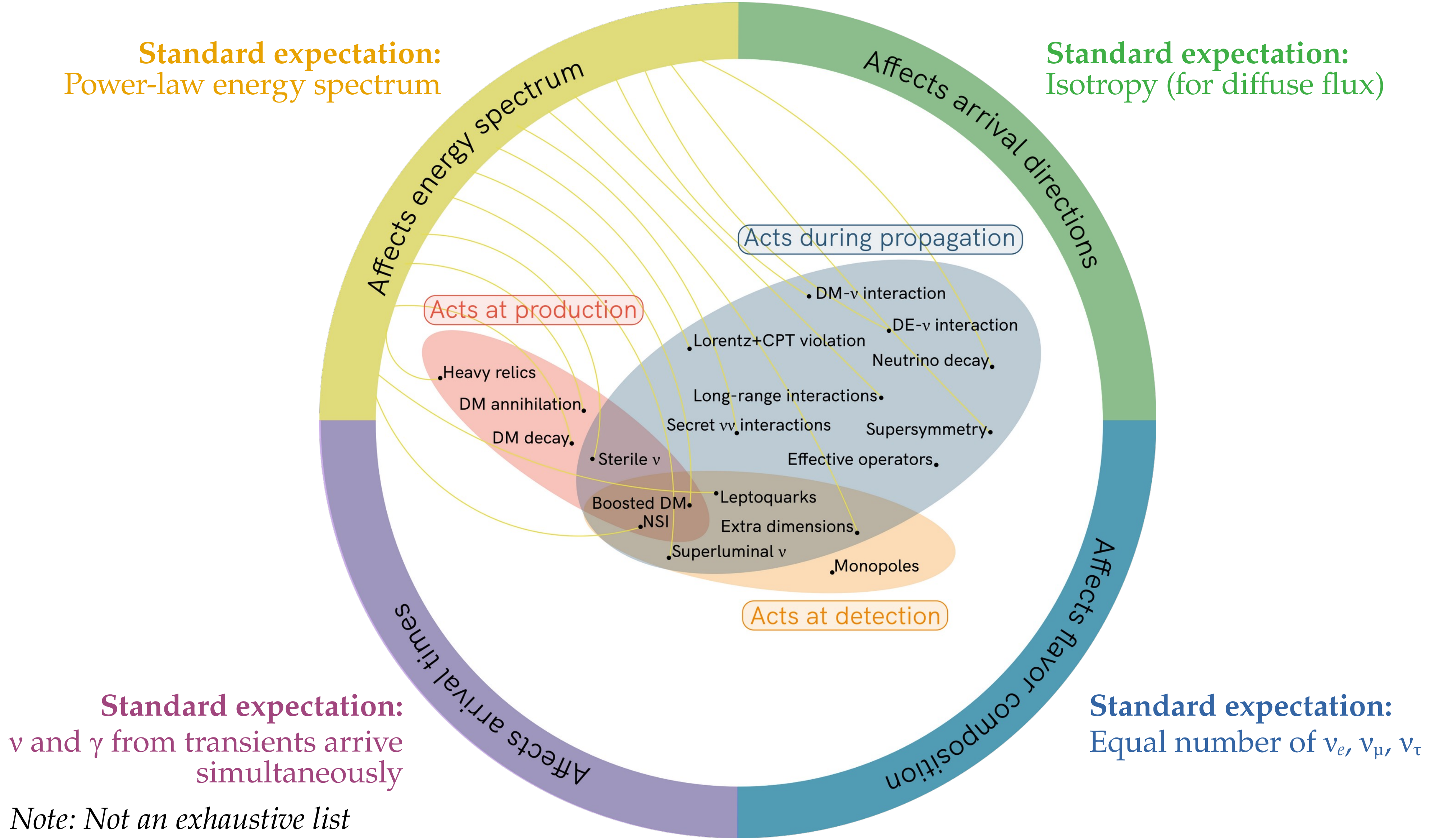
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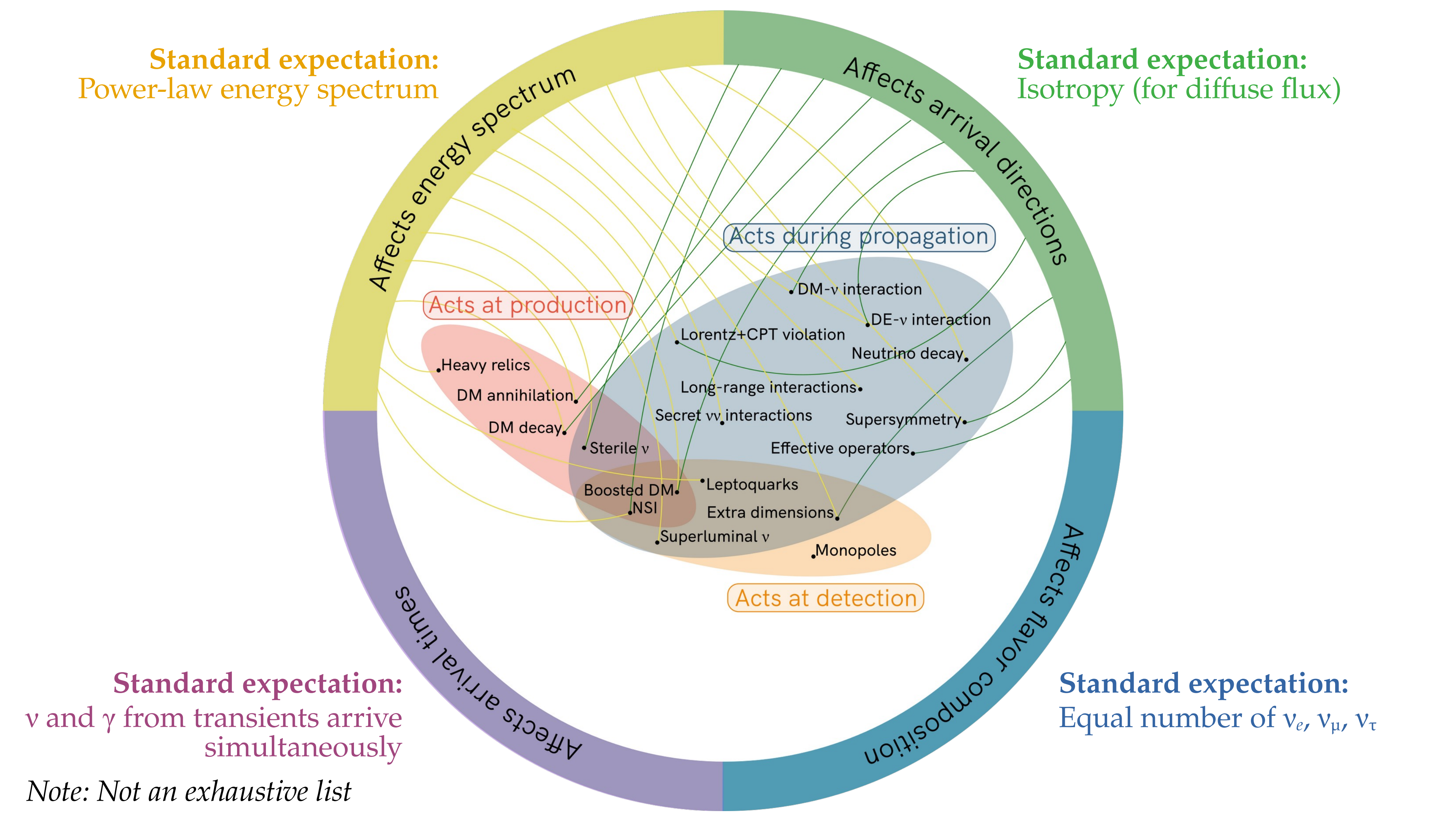

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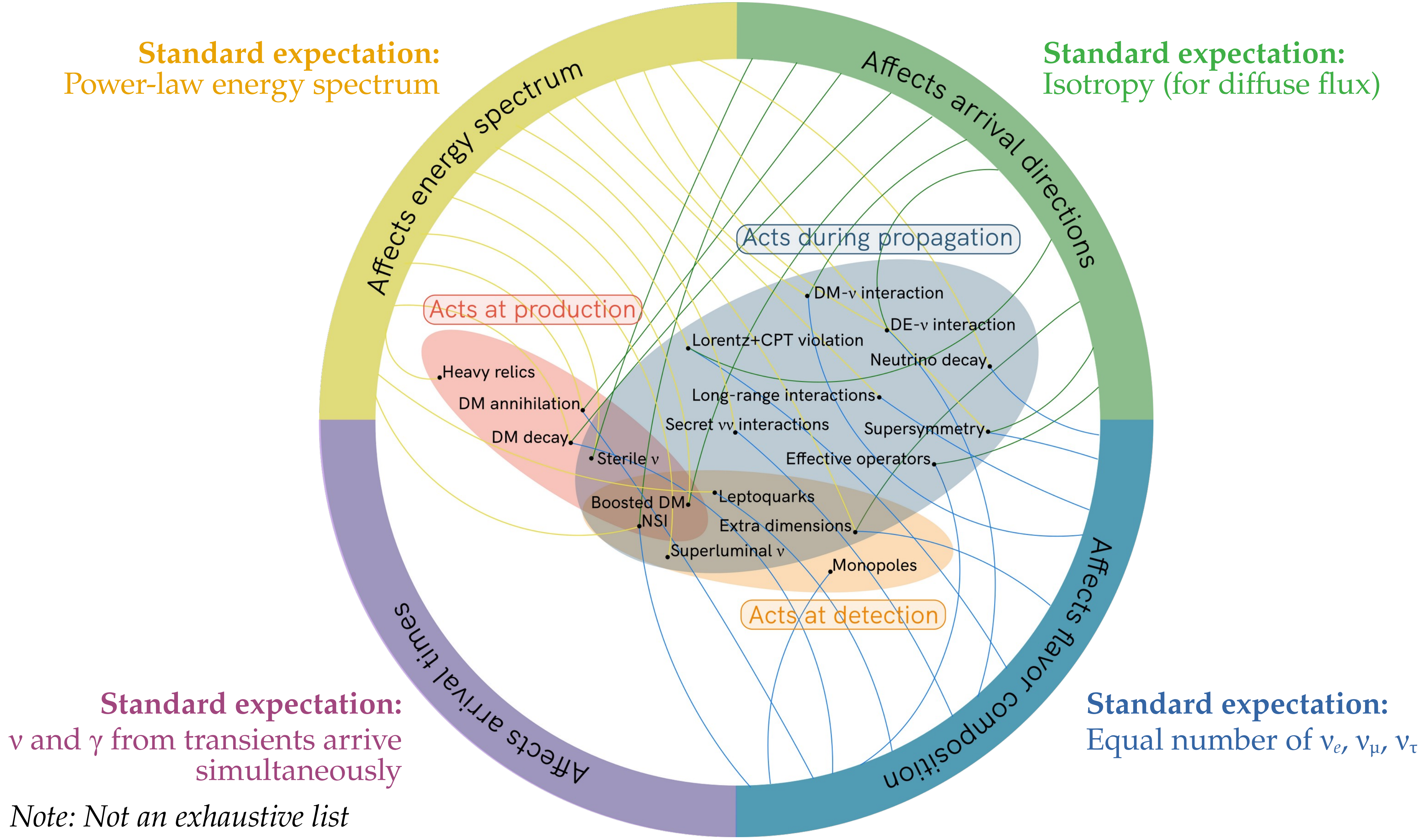
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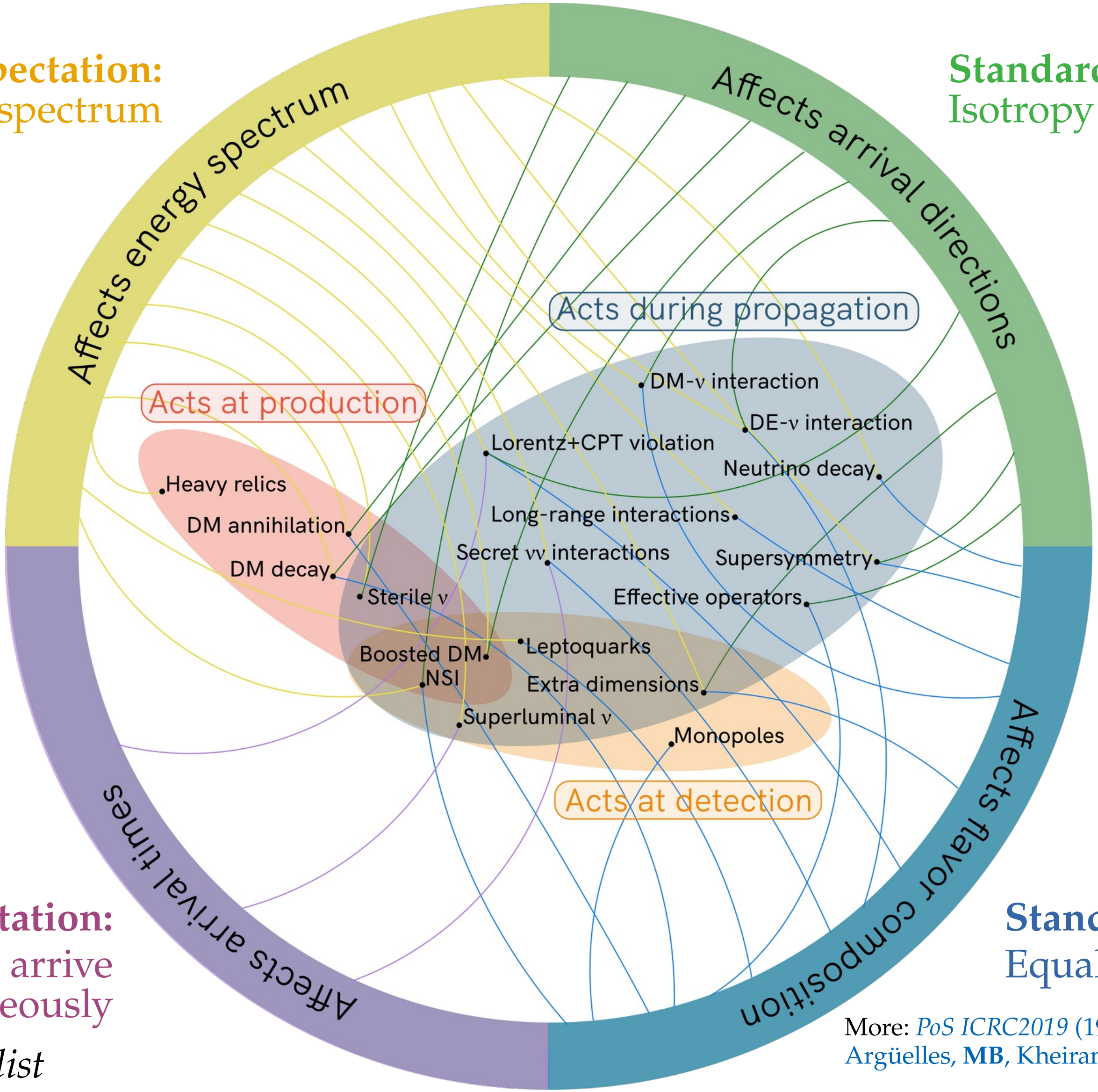

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More: *PoS ICRC2019* (1907.08690)
Argüelles, **MB**, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

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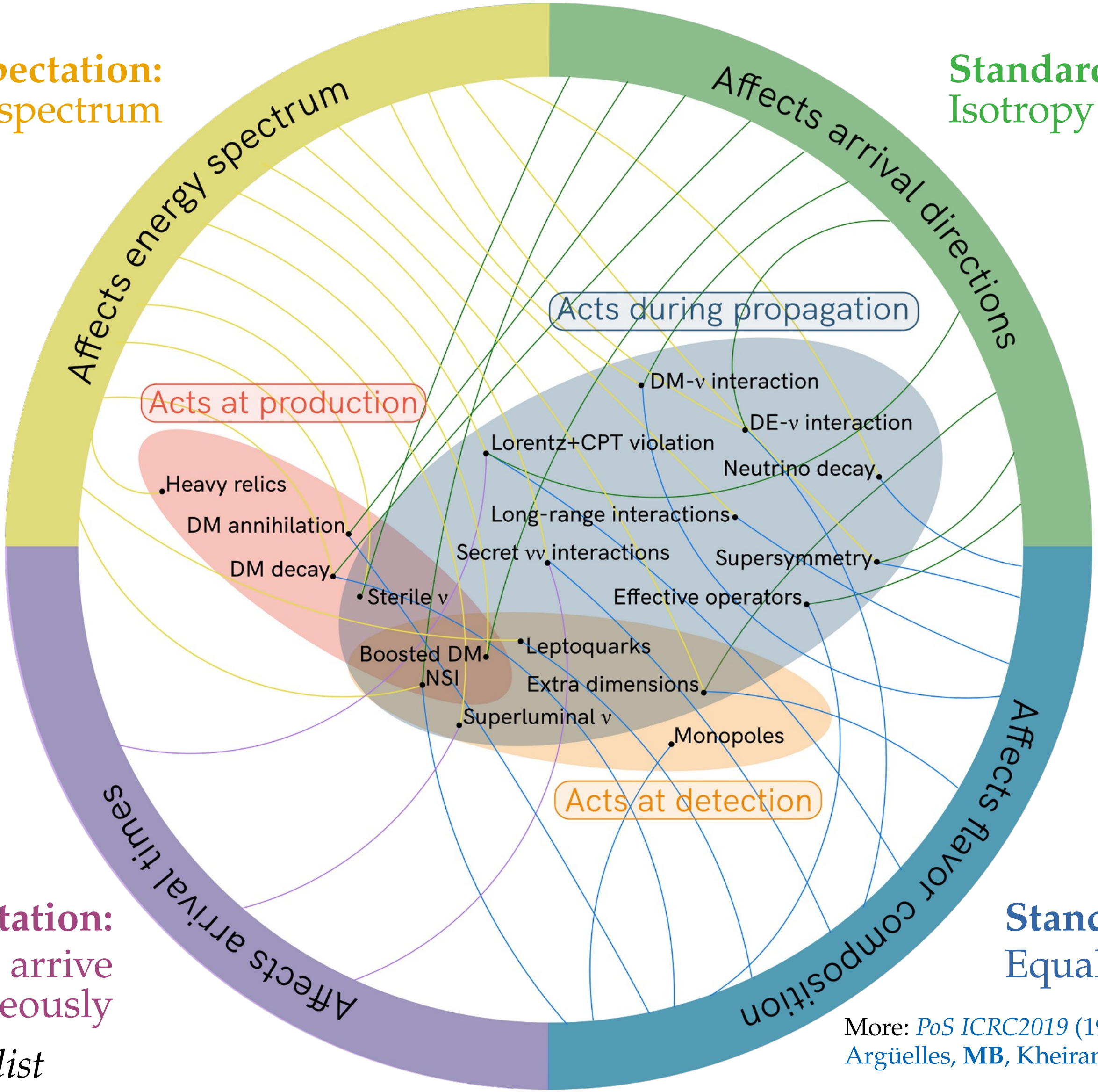

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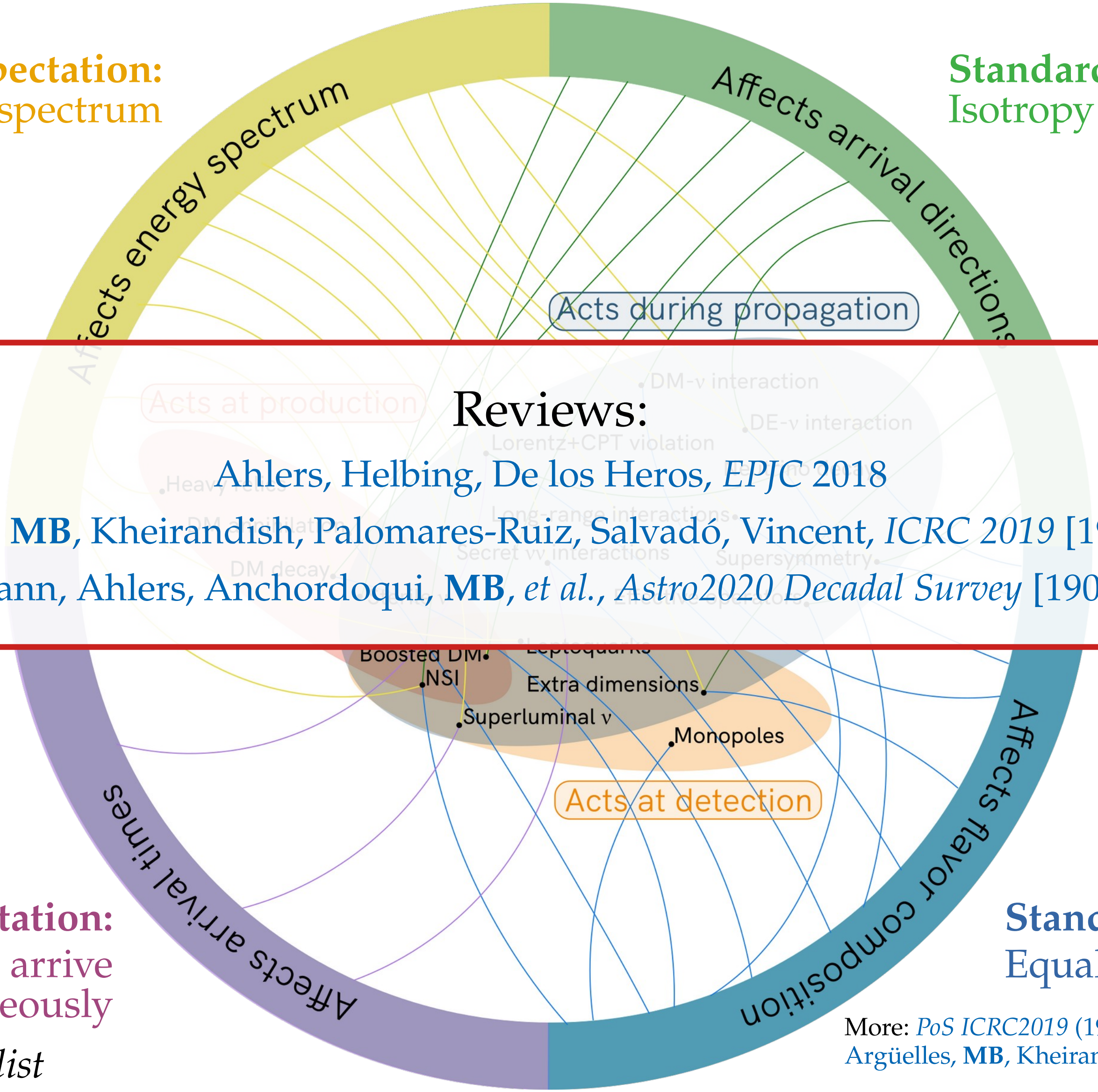

Reviews:

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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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, $\kappa_1 < 10^{-33}$
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  In spite of
  poor energy, angular, flavor reconstruction
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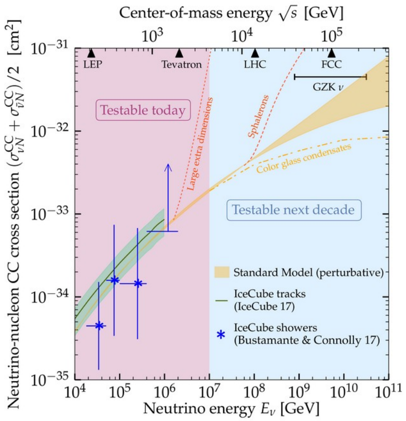
TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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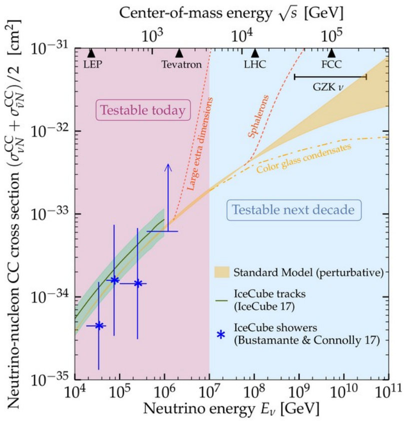
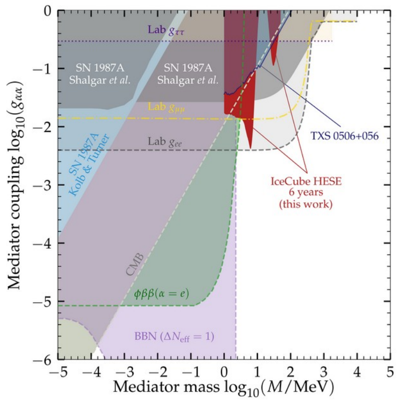


MB & Connolly, *PRL* 2019

ν self-interactions



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

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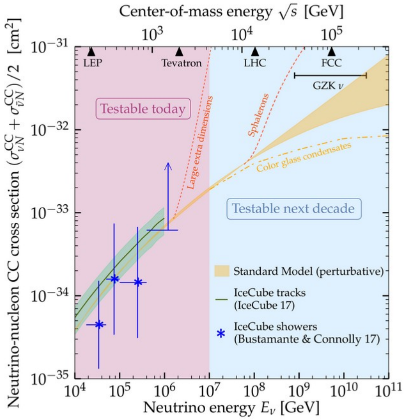

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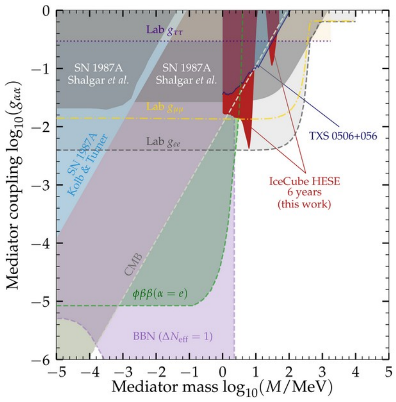
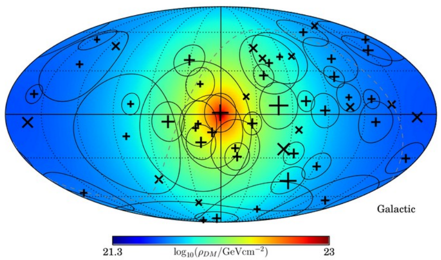


MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



Argüelles, Kheirandish, Vincent, *PRL* 2017

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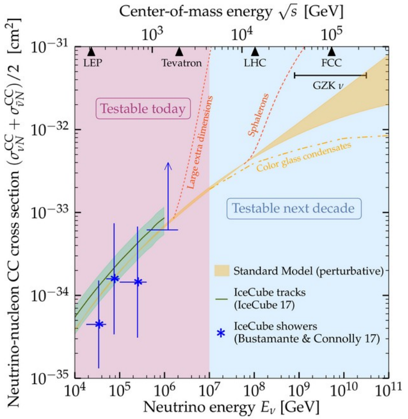

MB & Connolly, *PRL* 2019

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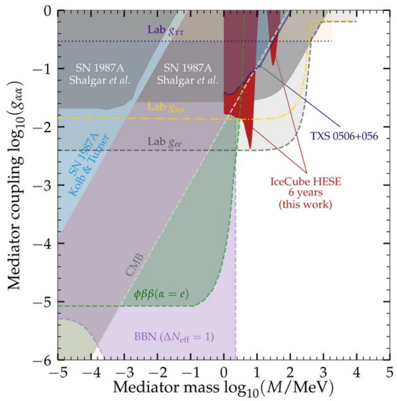

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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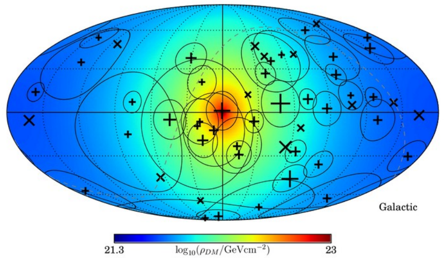
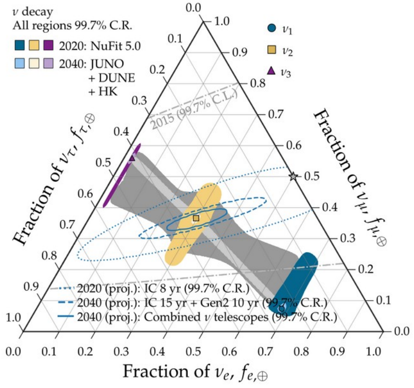


Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

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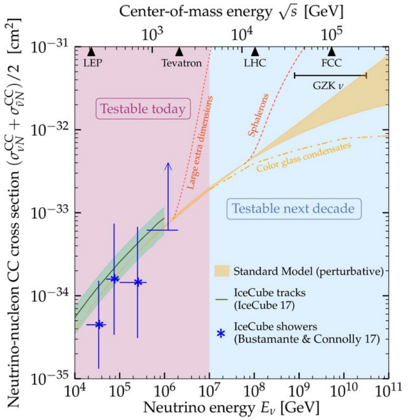

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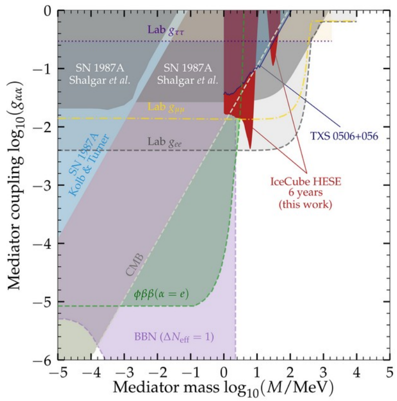

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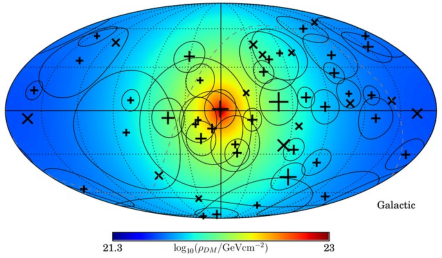

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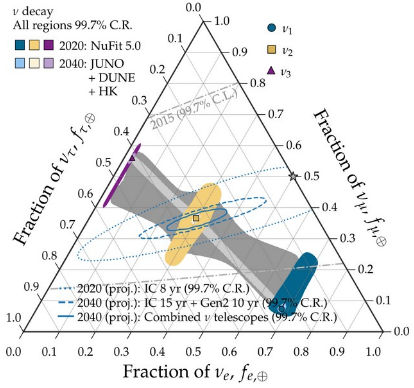
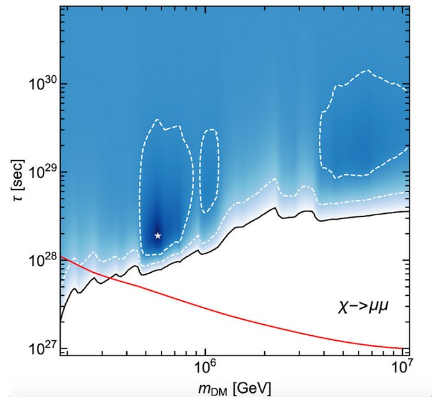


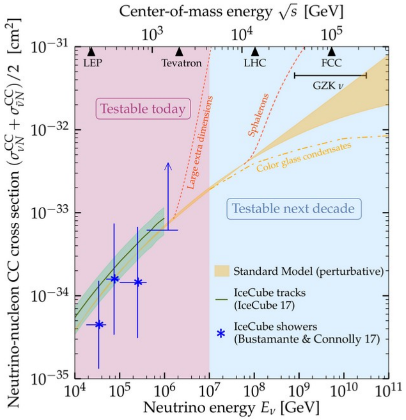
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

TeV–EeV ν cross sections



MB & Connolly, *PRL* 2019

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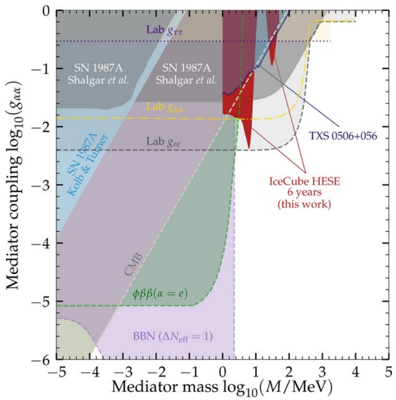

MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

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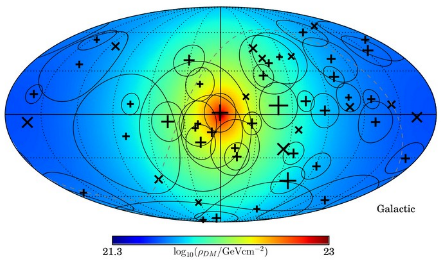

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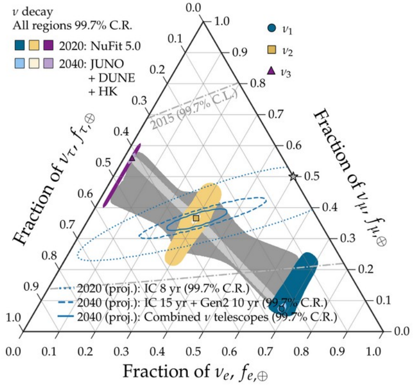
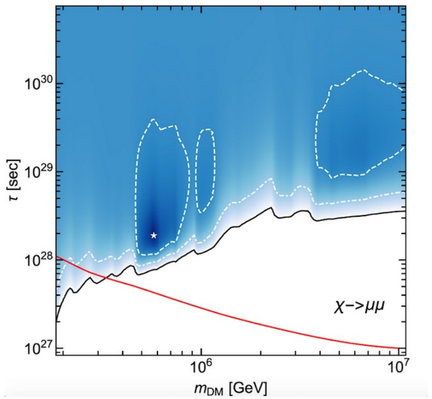


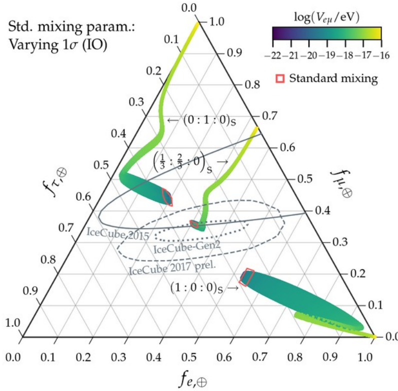
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



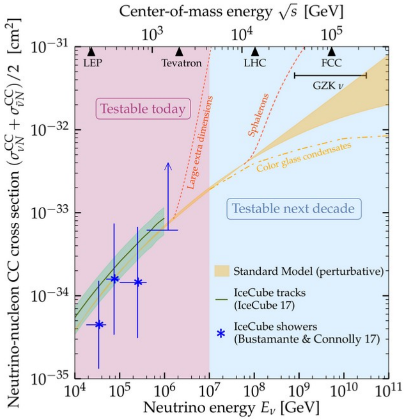
Chianese, Fiorillo, Miele, Morisi, Pisanti, *JCAP* 2019

ν-electron interaction



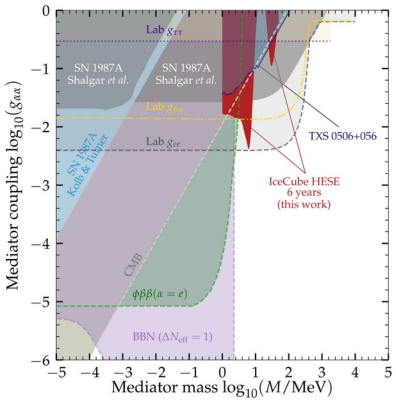
MB & Agarwalla, *PRL* 2019

TeV–EeV ν cross sections



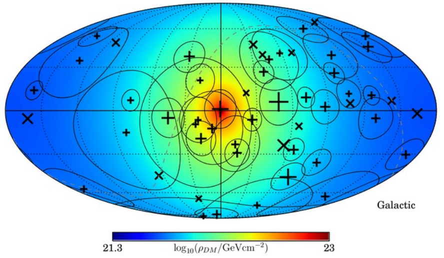
MB & Connolly, *PRL* 2019

ν self-interactions



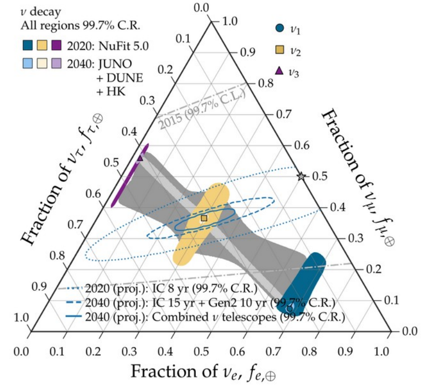
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



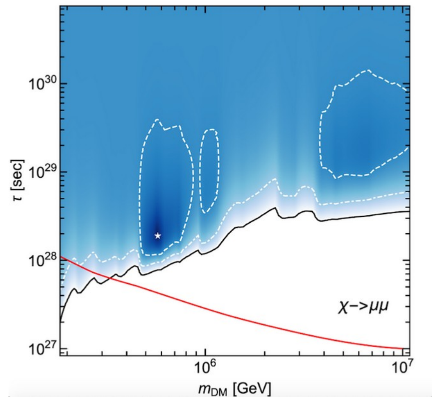
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



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

Dark matter decay



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

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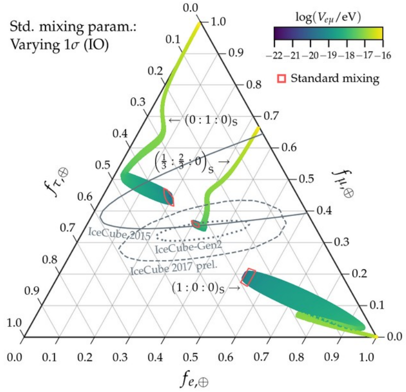
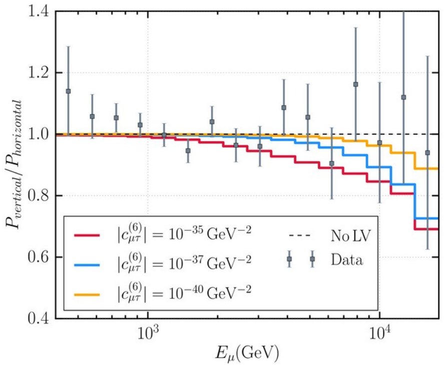


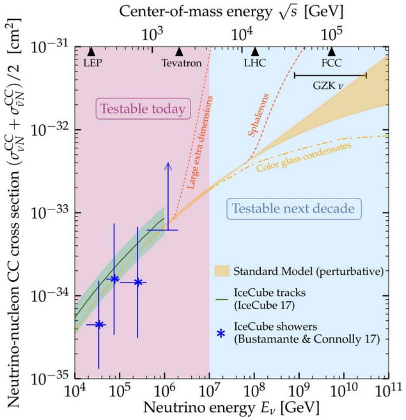
MB & Agarwalla, *PRL* 2019

Lorentz-invariance violation



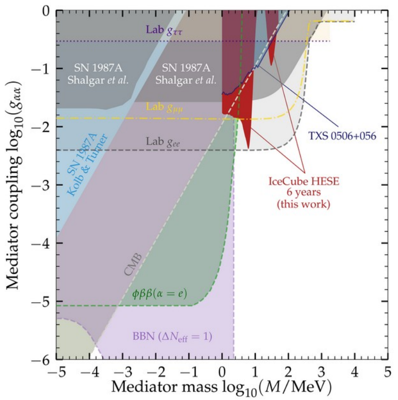
IceCube, *Nature Phys.* 2018

TeV–EeV ν cross sections



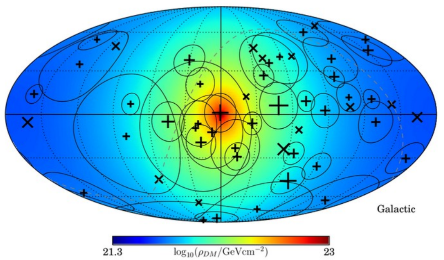
MB & Connolly, *PRL* 2019

ν self-interactions



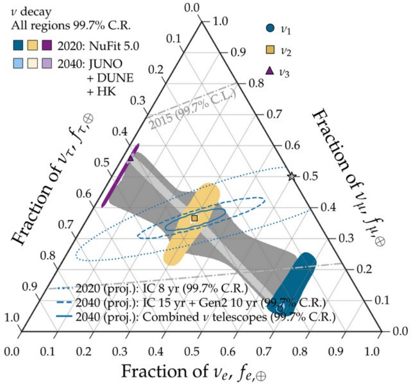
MB, Rosenstrøm, Shalgar, Tamborra, *PRD* 2020

ν scattering on Galactic DM



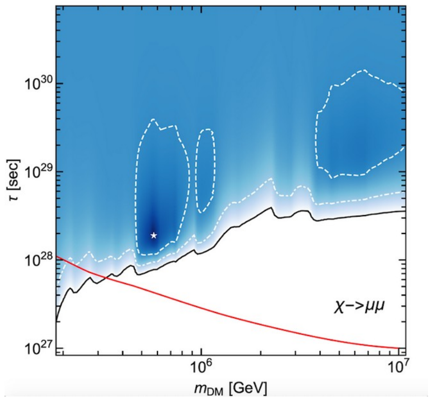
Argüelles, Kheirandish, Vincent, *PRL* 2017

ν decay



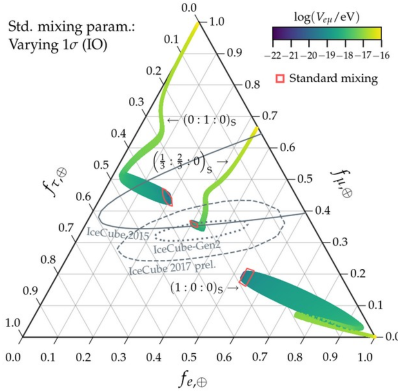
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Dark matter decay



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

ν-electron interaction



MB & Agarwalla, *PRL* 2019

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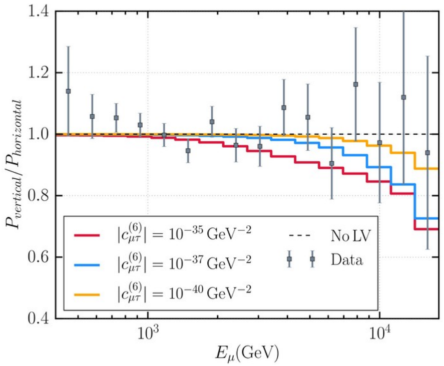
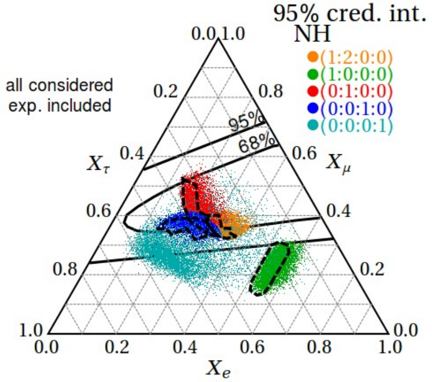
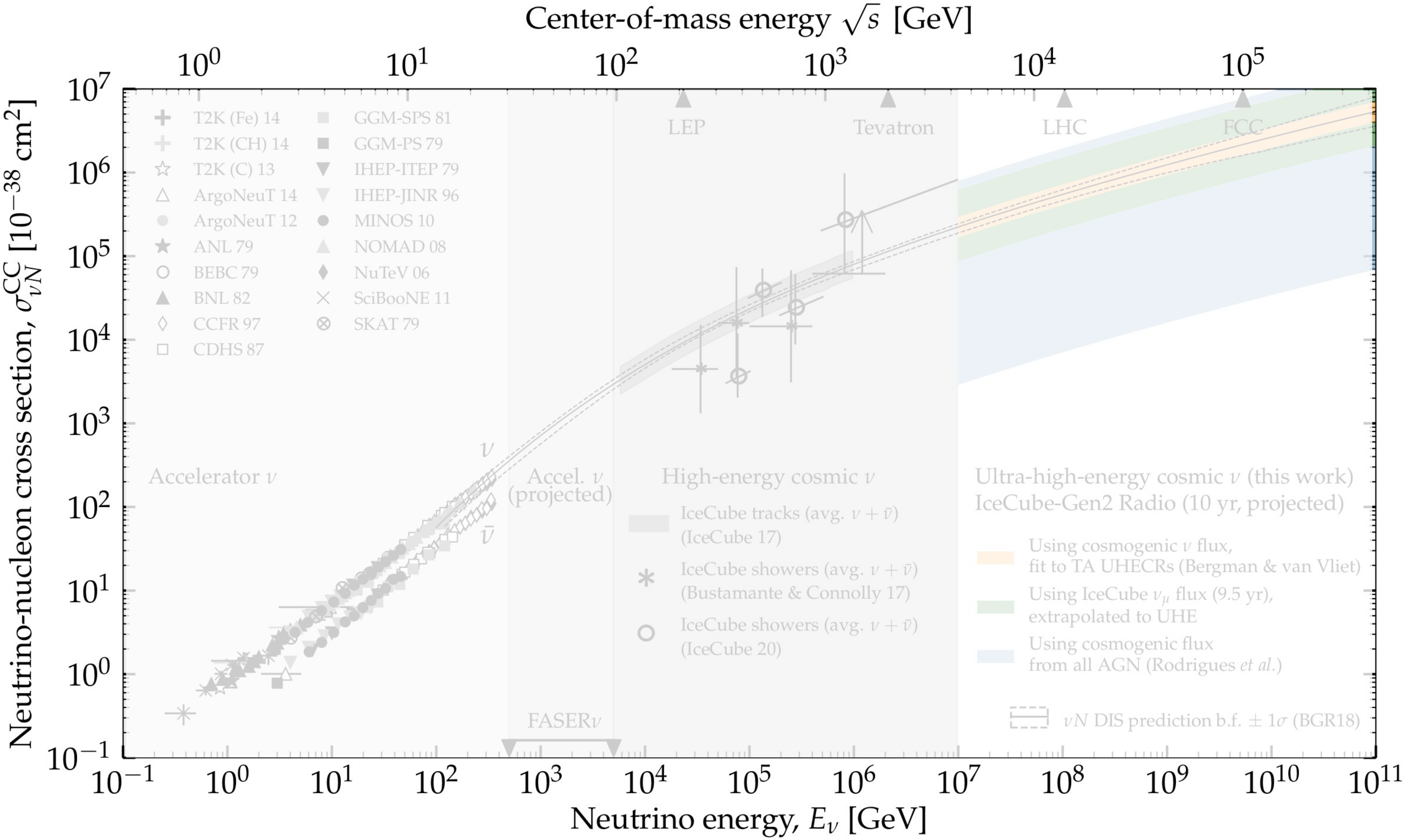


IceCube, *Nature Phys.* 2018

Sterile neutrinos



Brdar, Kopp, Wang, *JCAP* 2017



Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
LHC
FCC
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
Ultra-high-energy cosmic ν (this work)
IceCube-Gen2 Radio (10 yr, projected)
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
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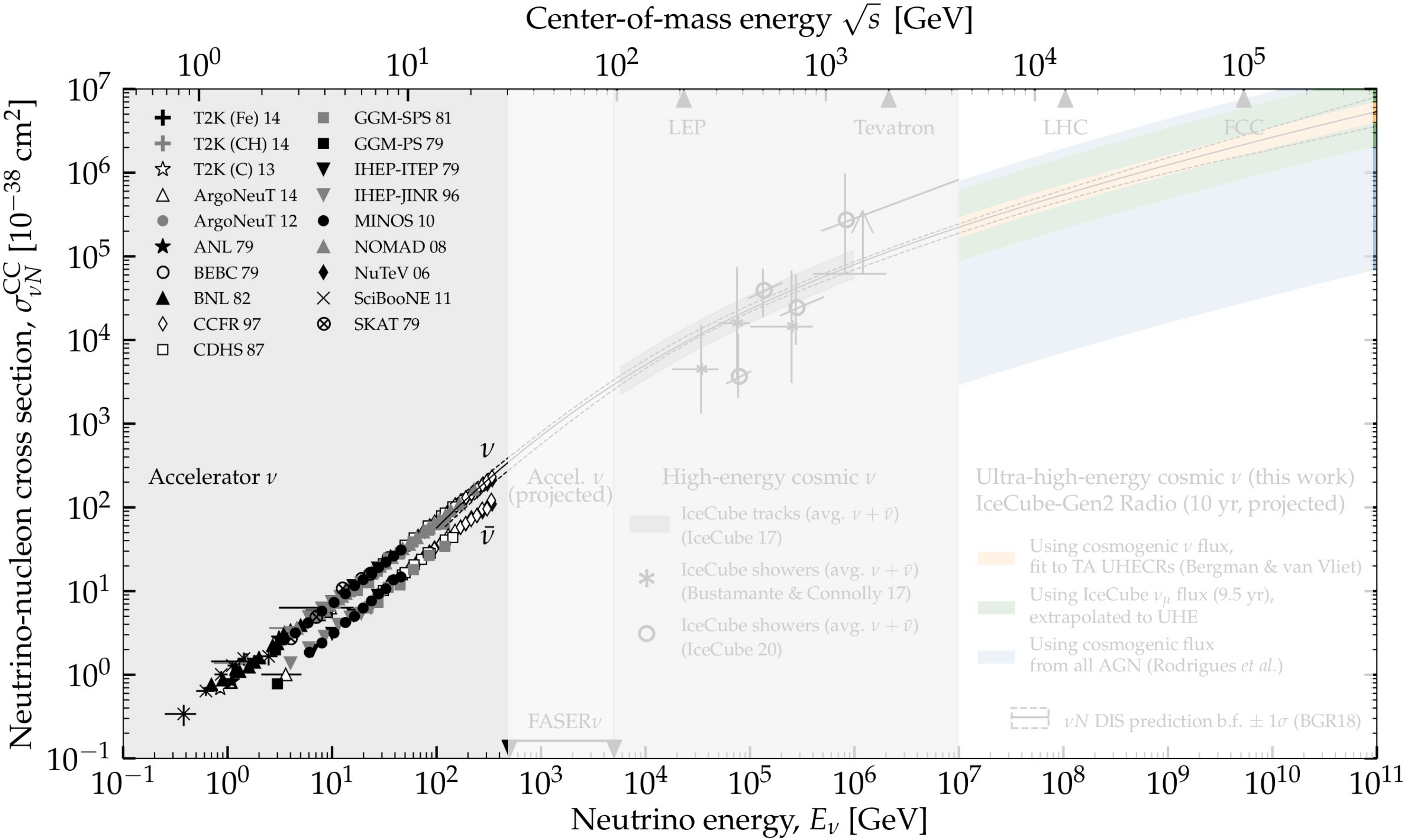
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν



Center-of-mass energy $\sqrt{s}$ [GeV]
10^0
10^1
10^2
10^3
10^4
10^5
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
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BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
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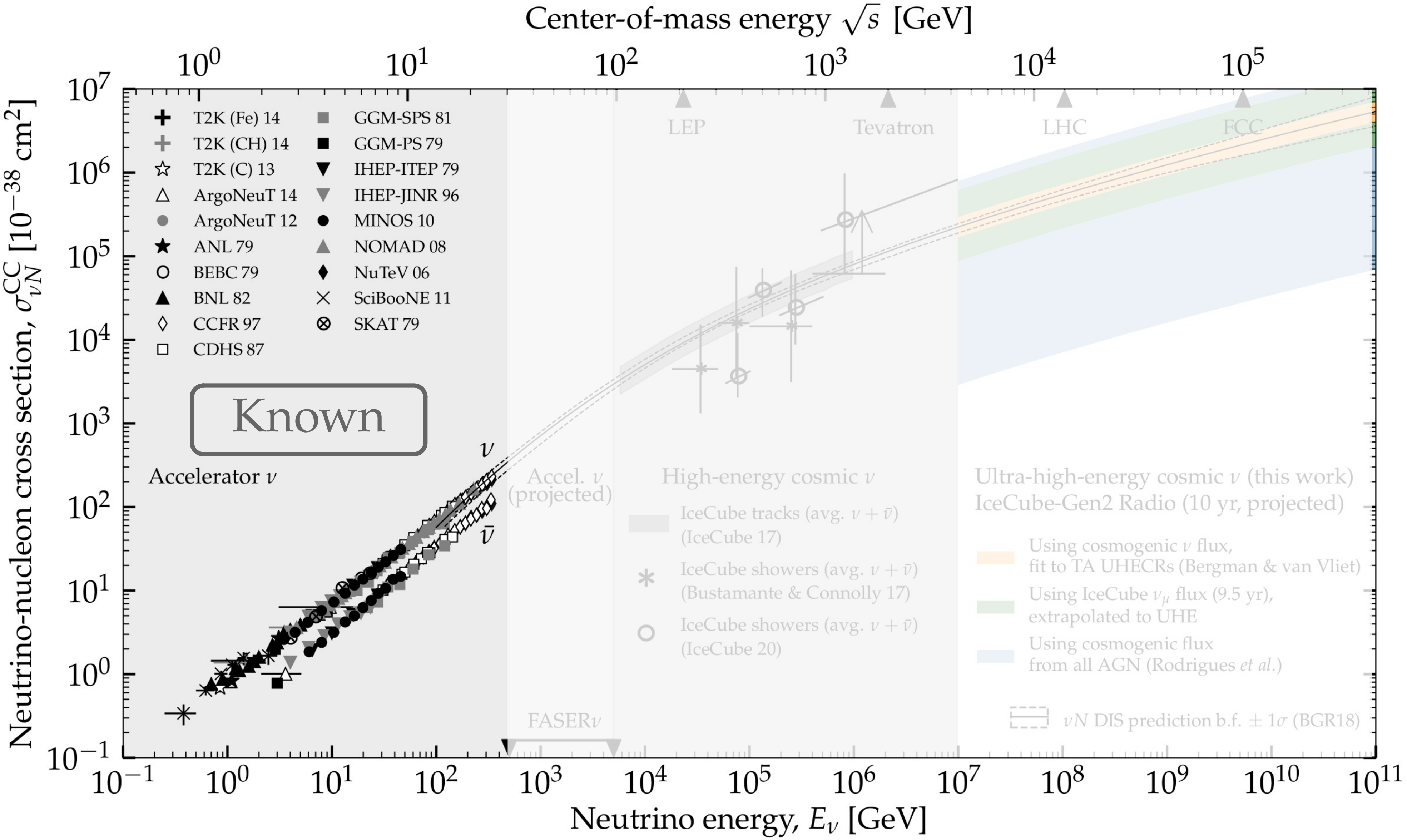
FASERν
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



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Known
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ν
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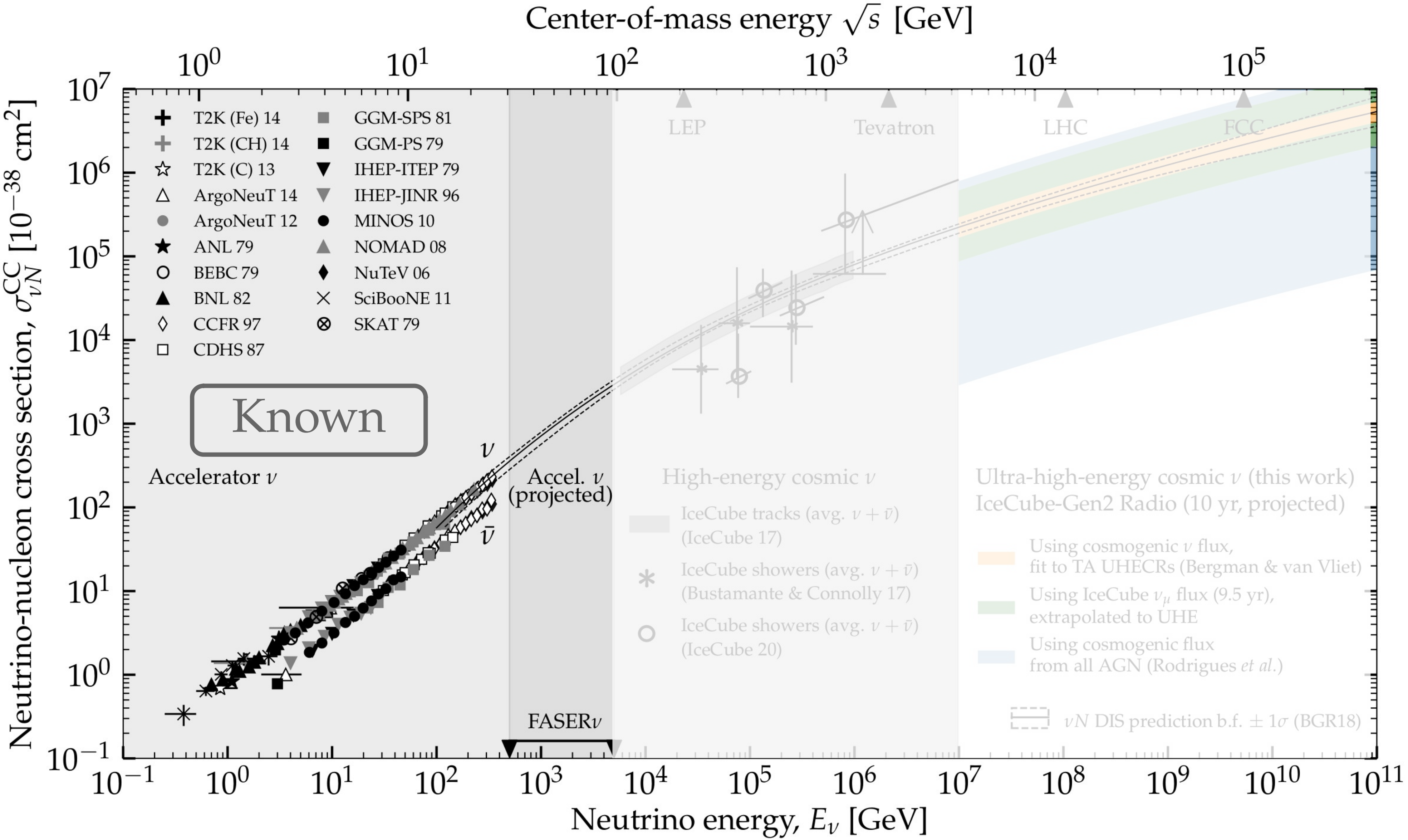

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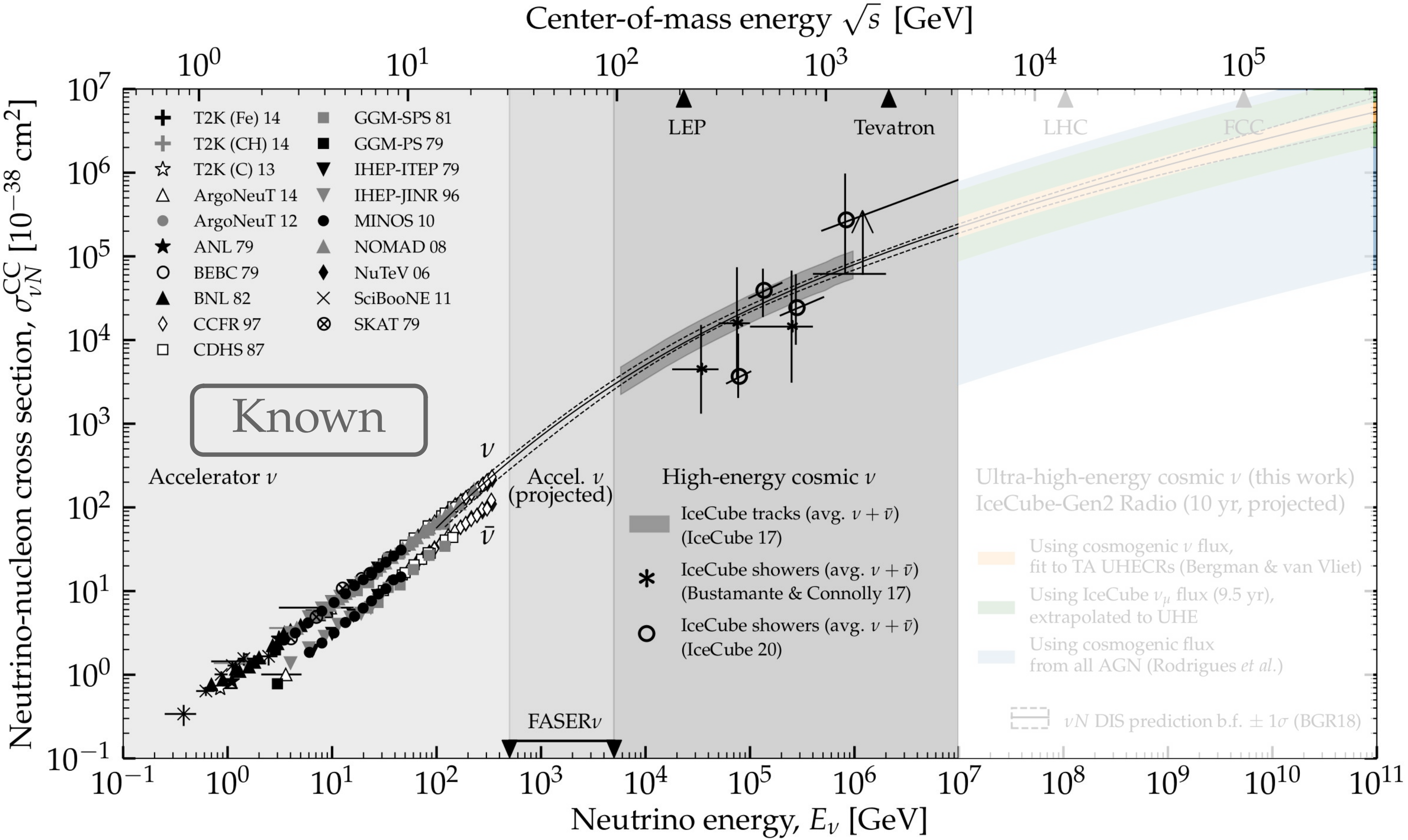

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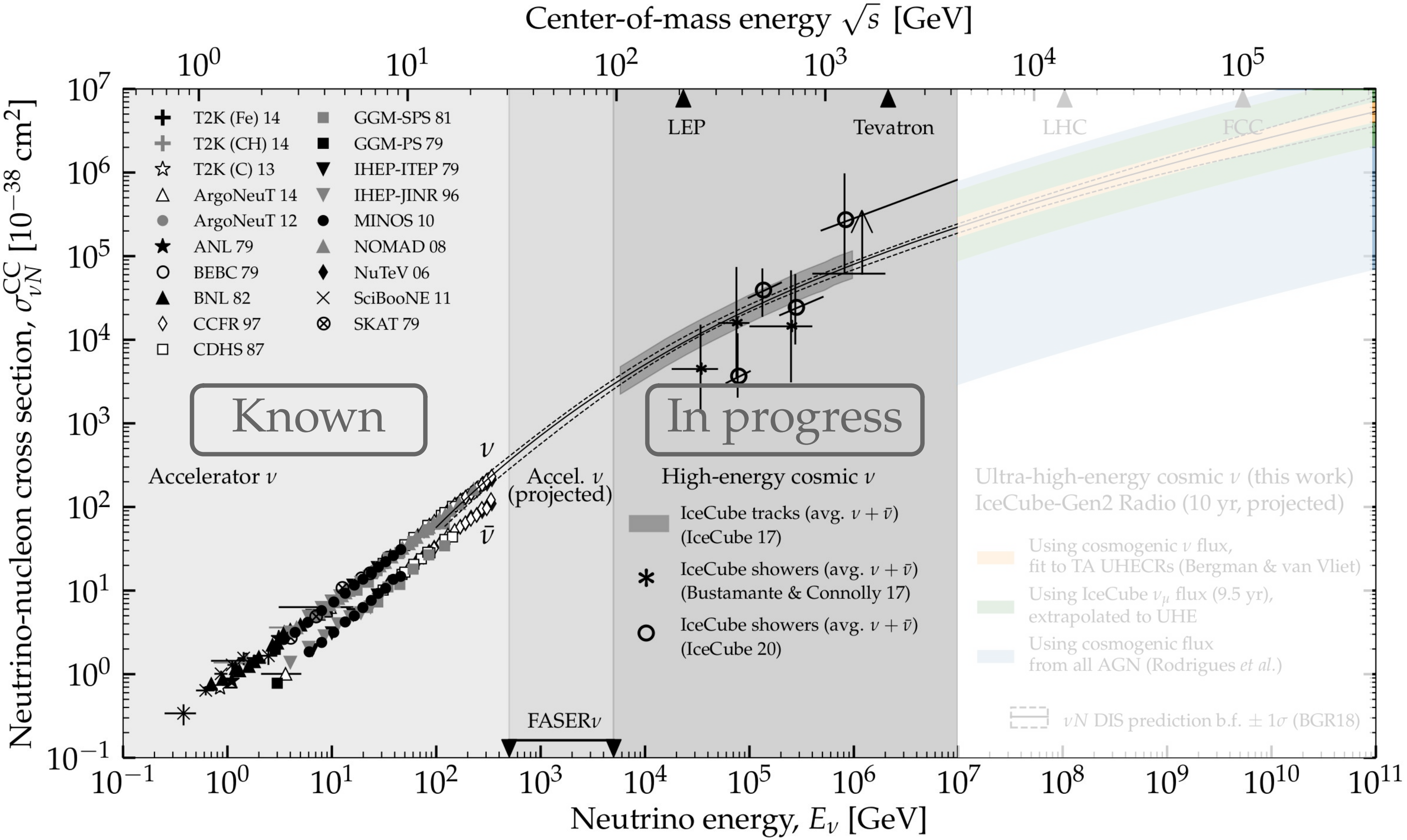

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10^0
10^1
10^2
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10^4
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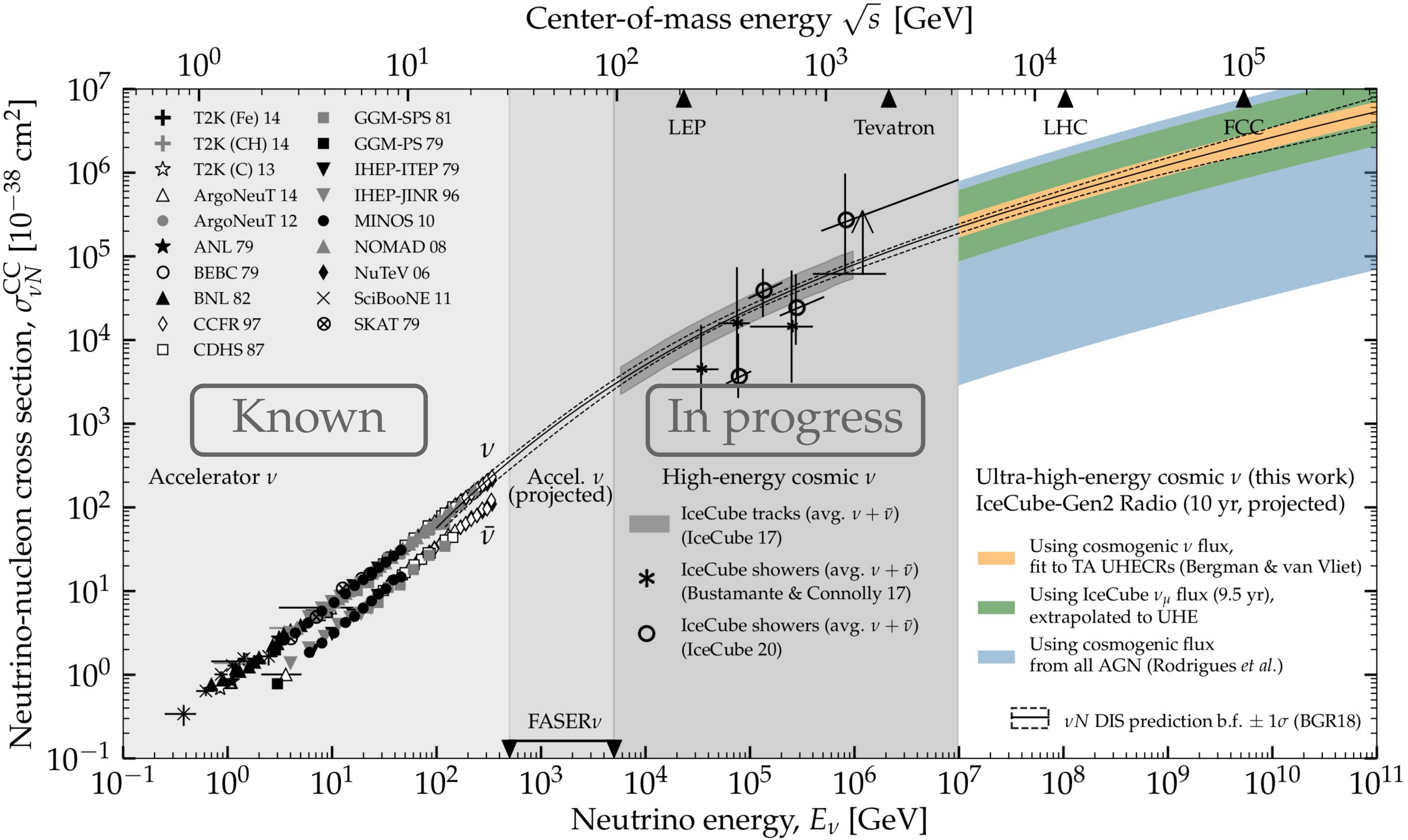
10^{-1}
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
Neutrino energy, E_ν [GeV]



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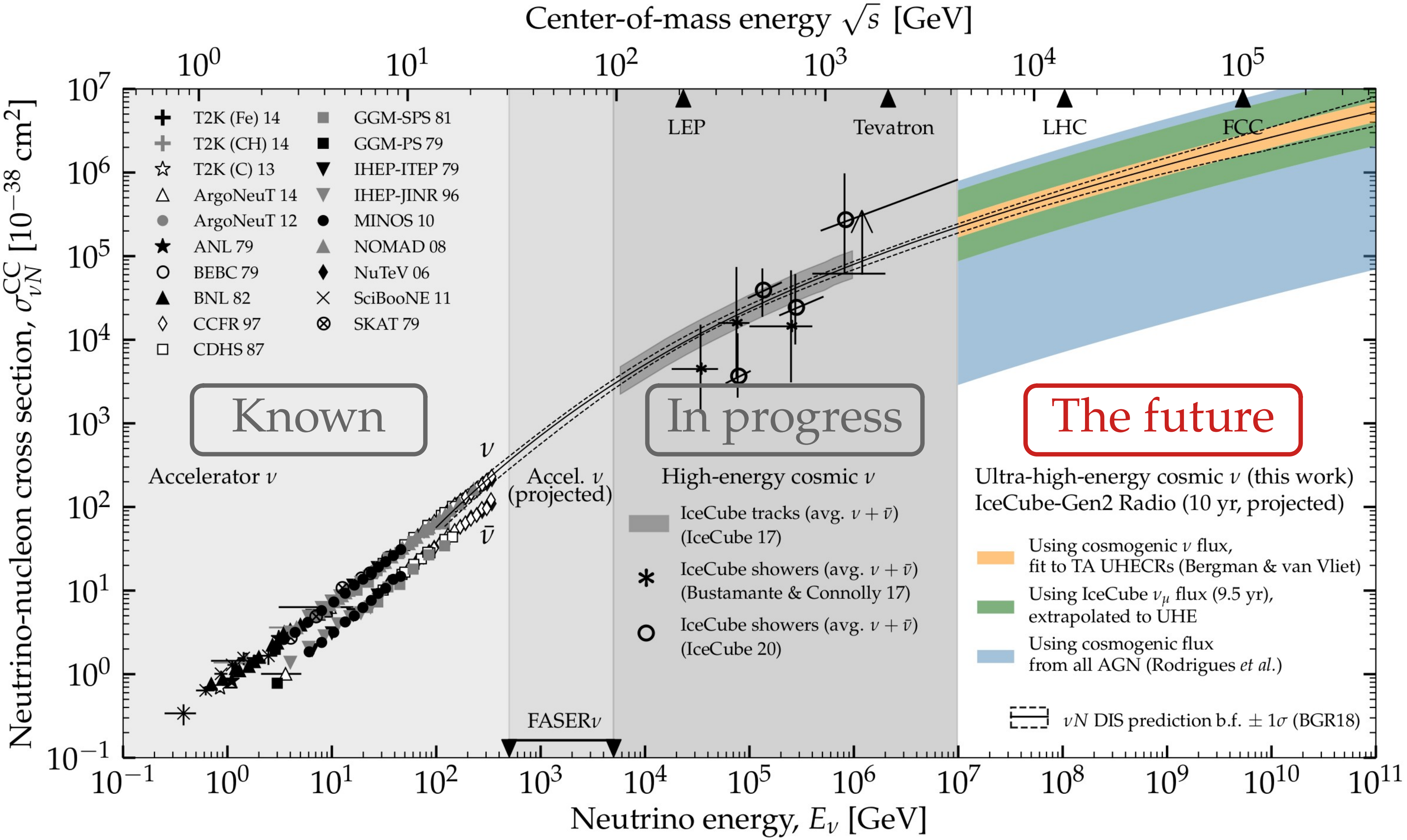

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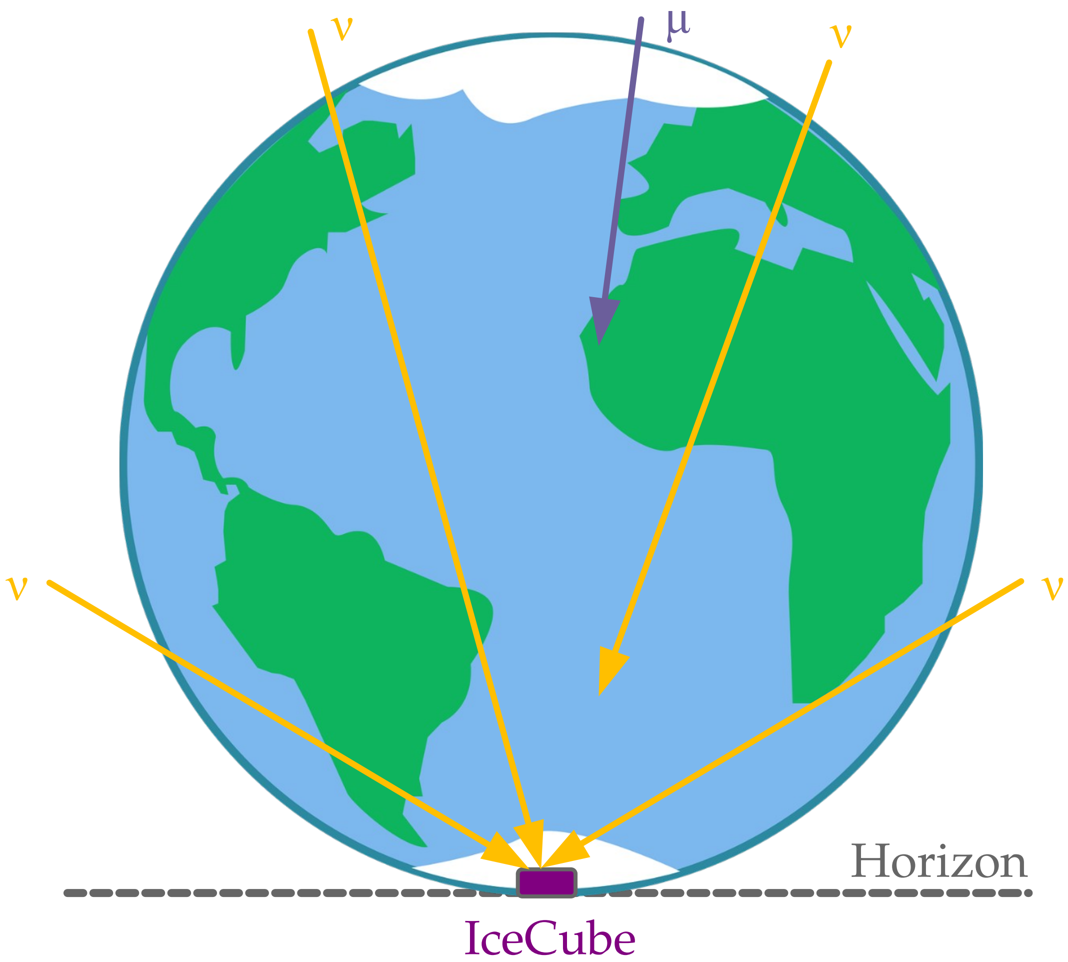
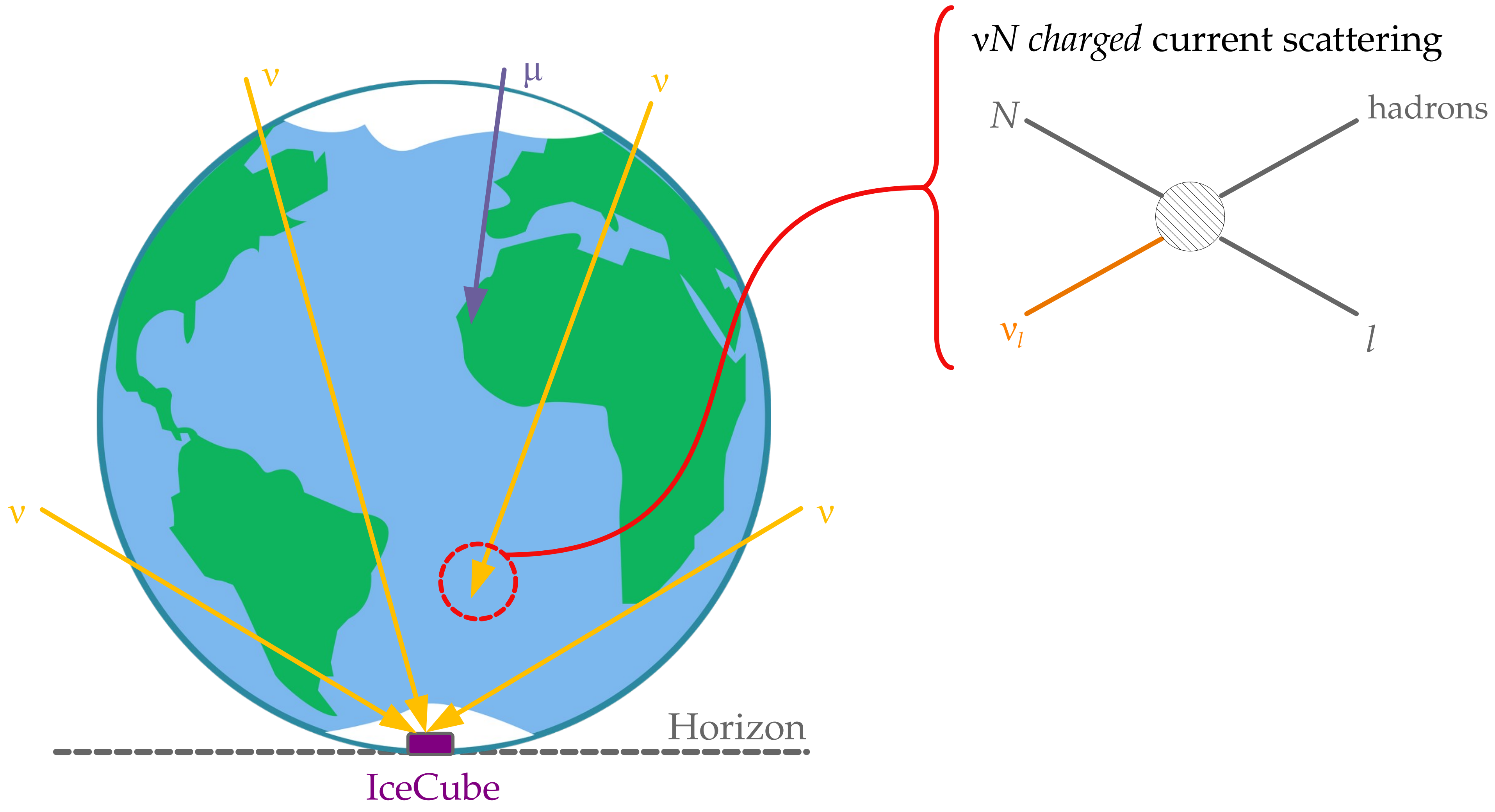
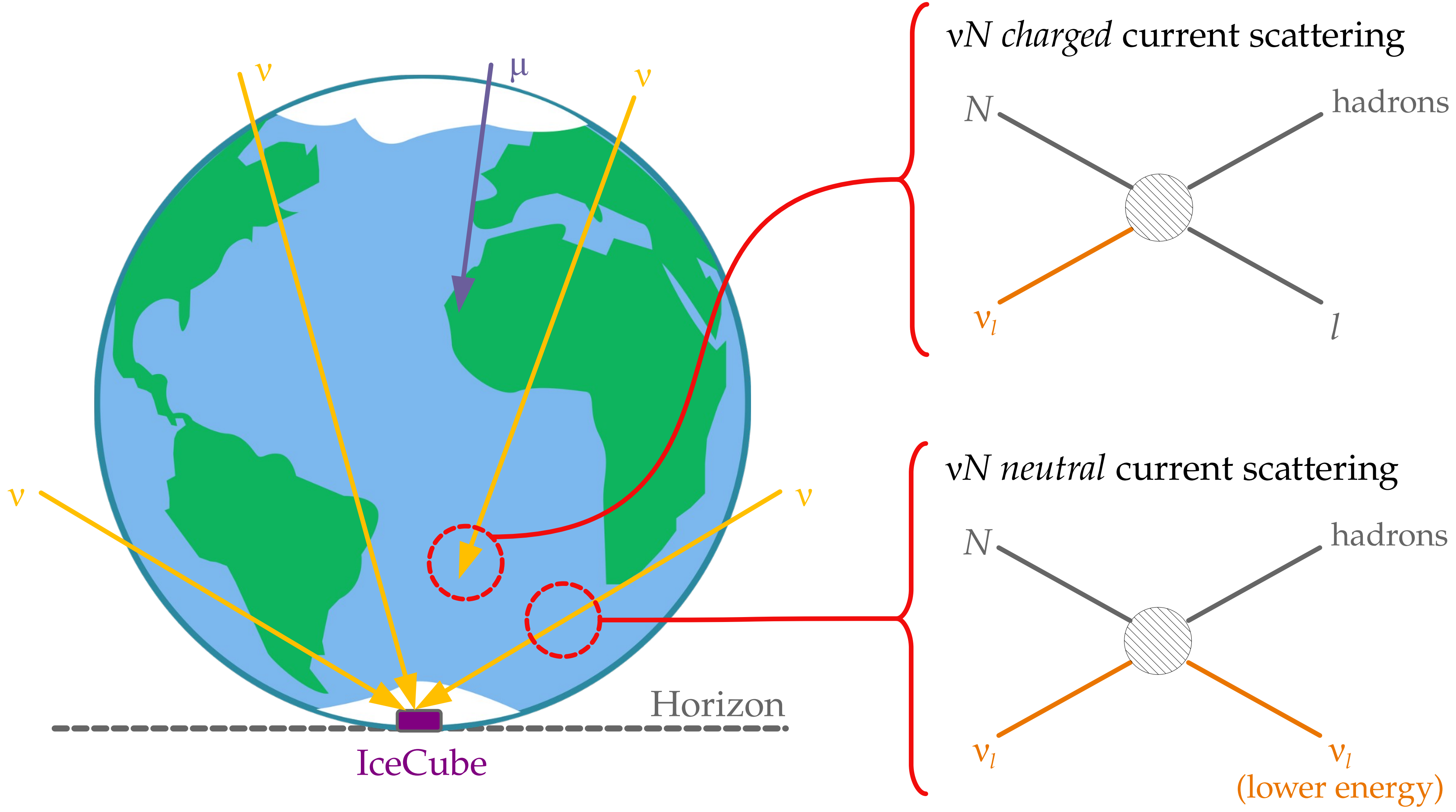
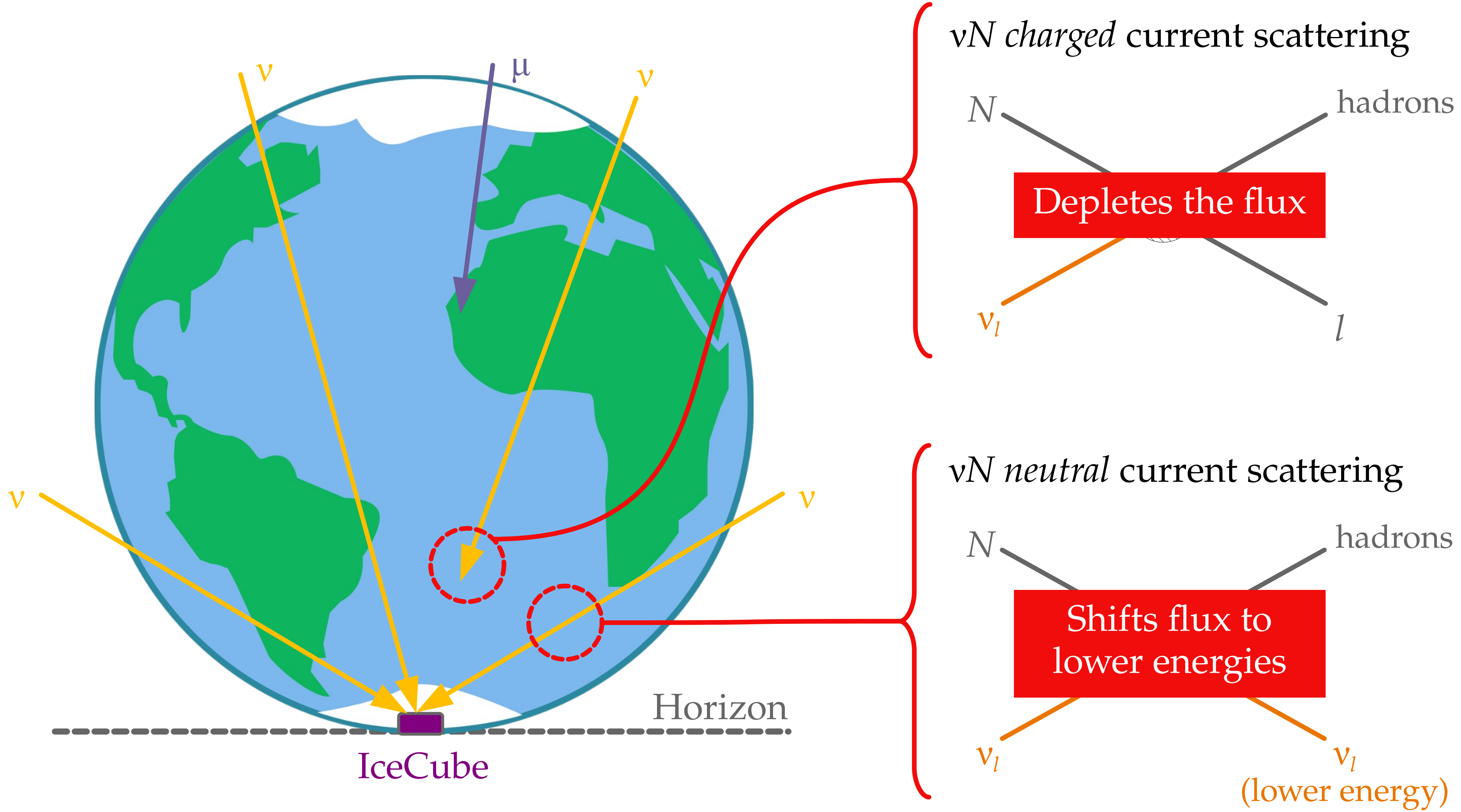


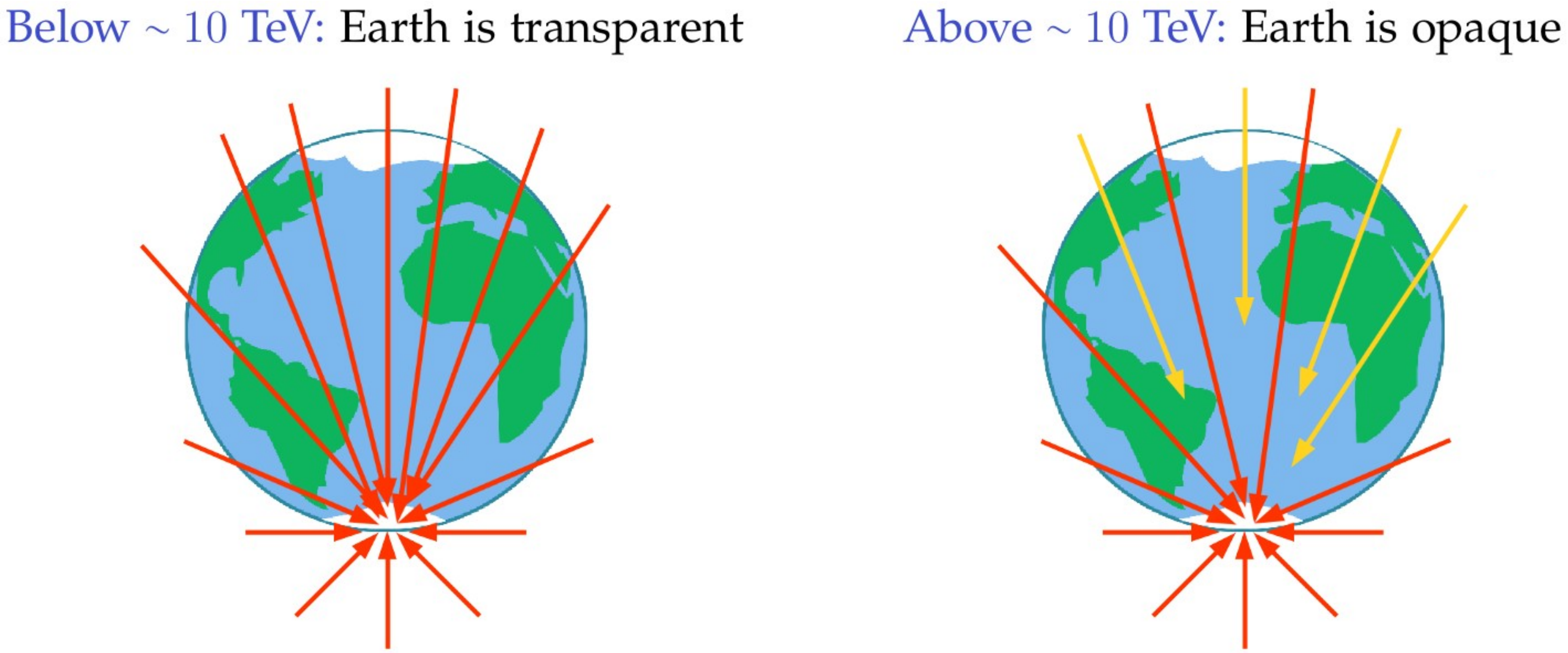
ν
μ
ν
ν
ν
Horizon
IceCube


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


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


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

Measuring the high-energy νN cross section



Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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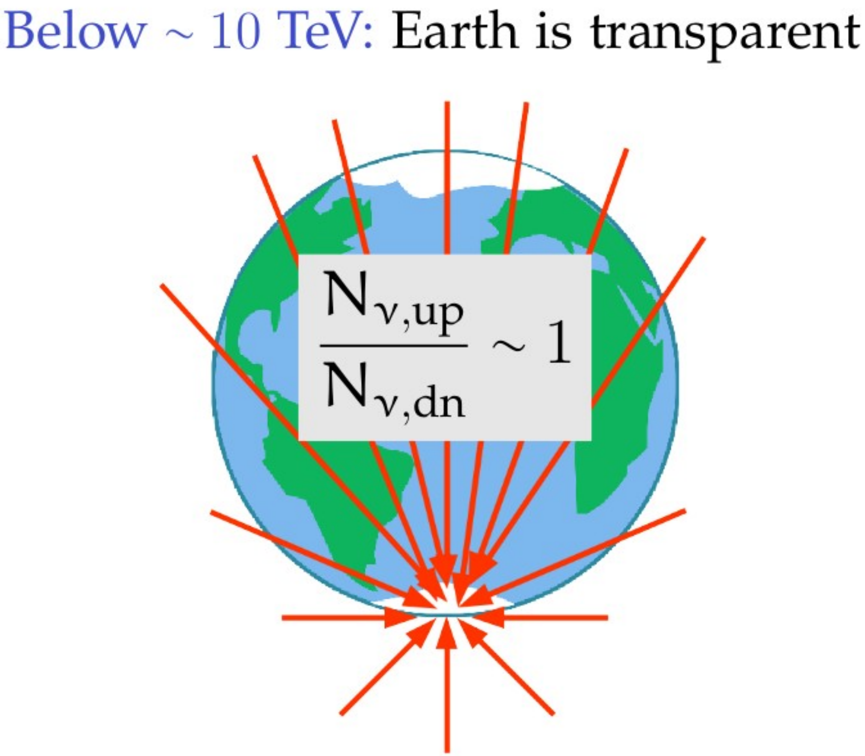
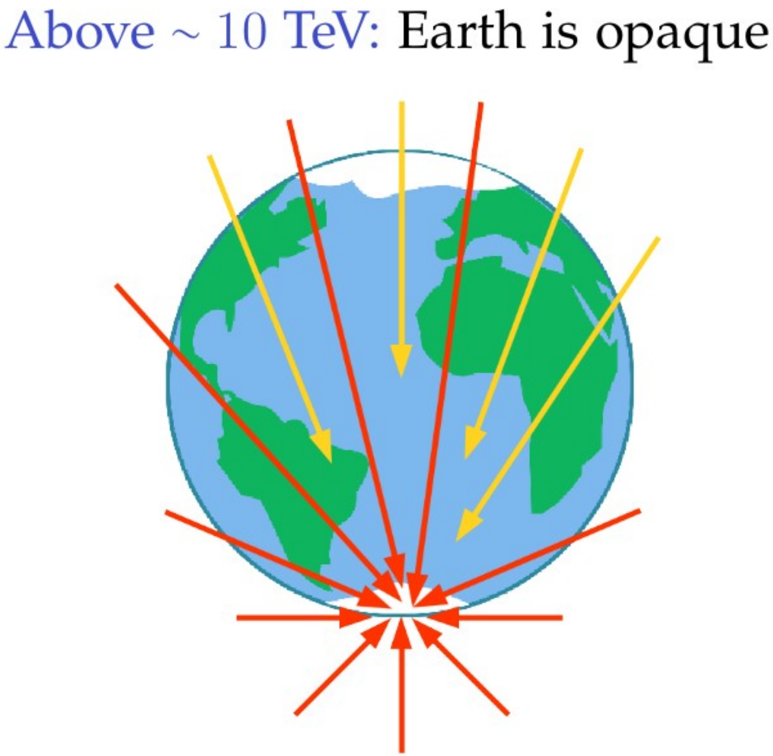
Measuring the high-energy *νN* cross section





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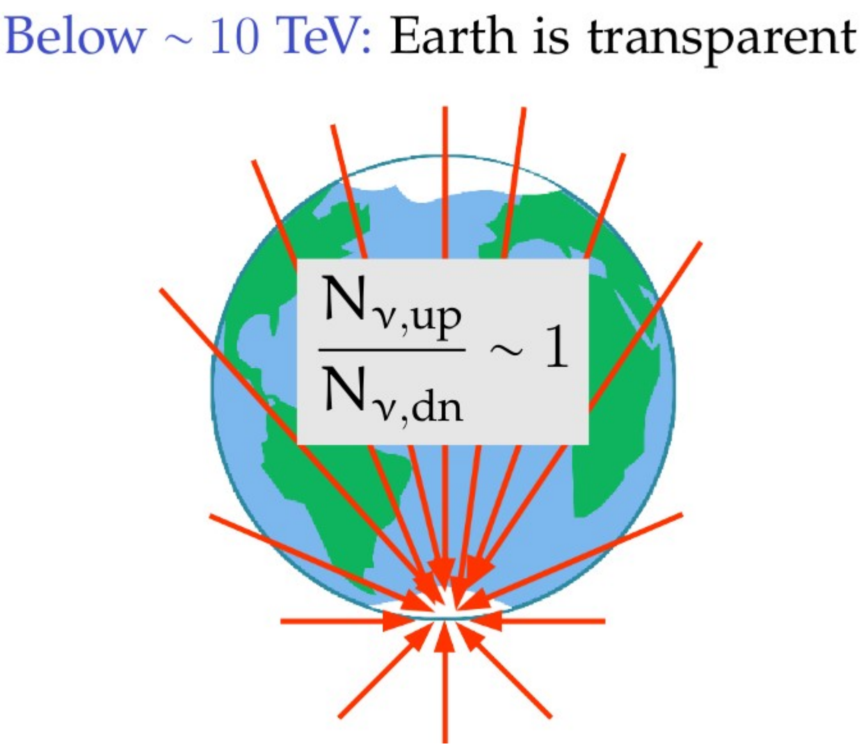
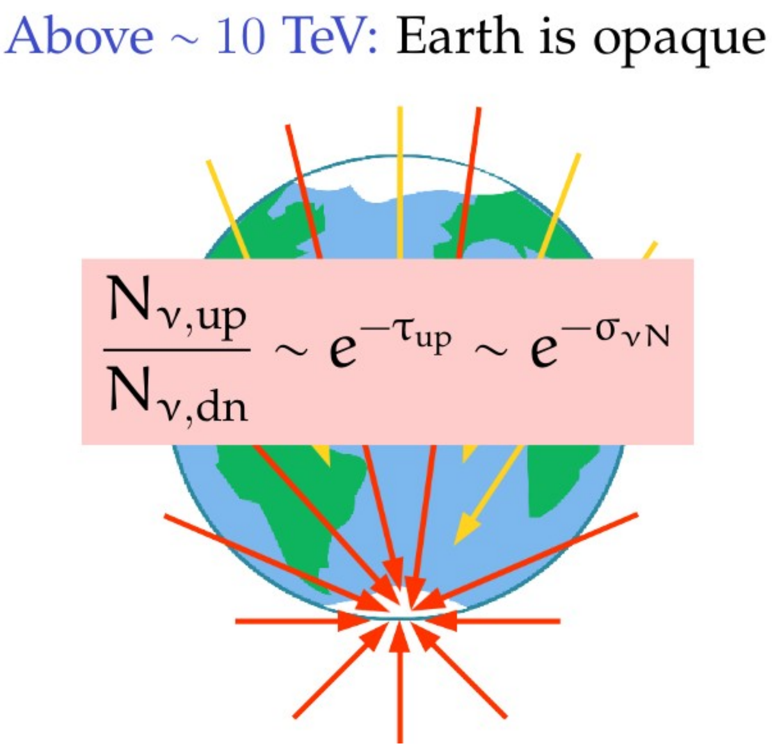
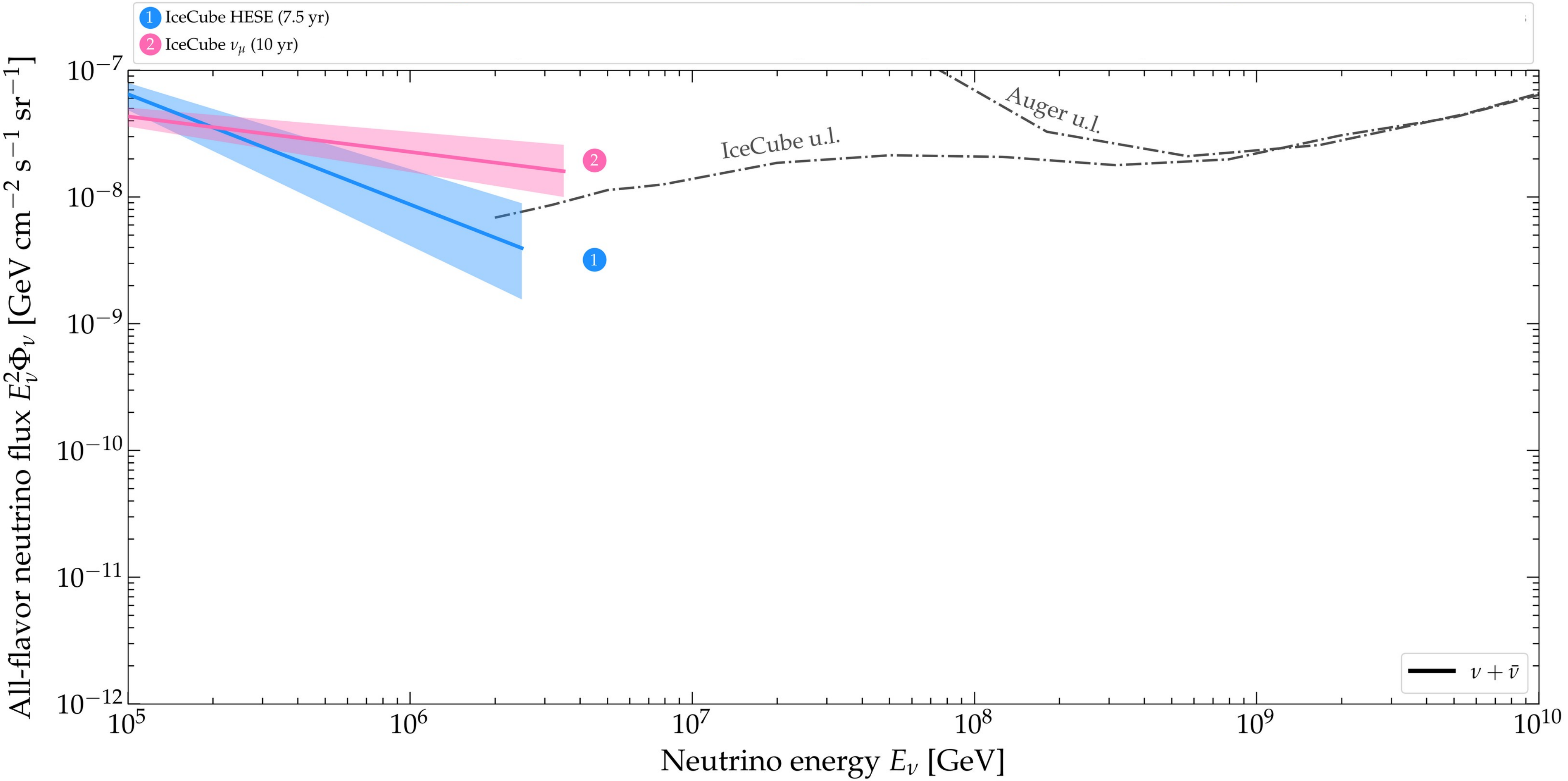
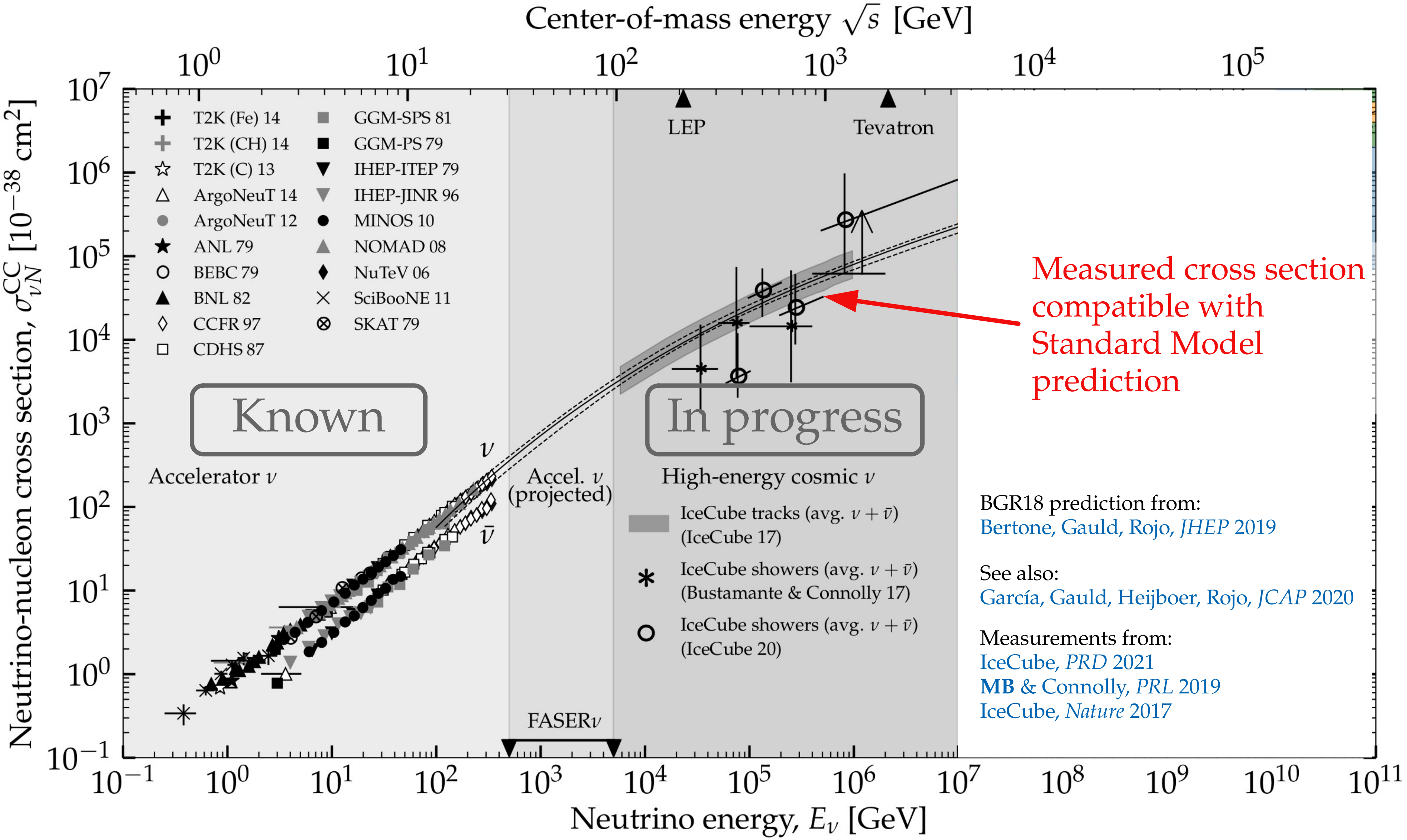




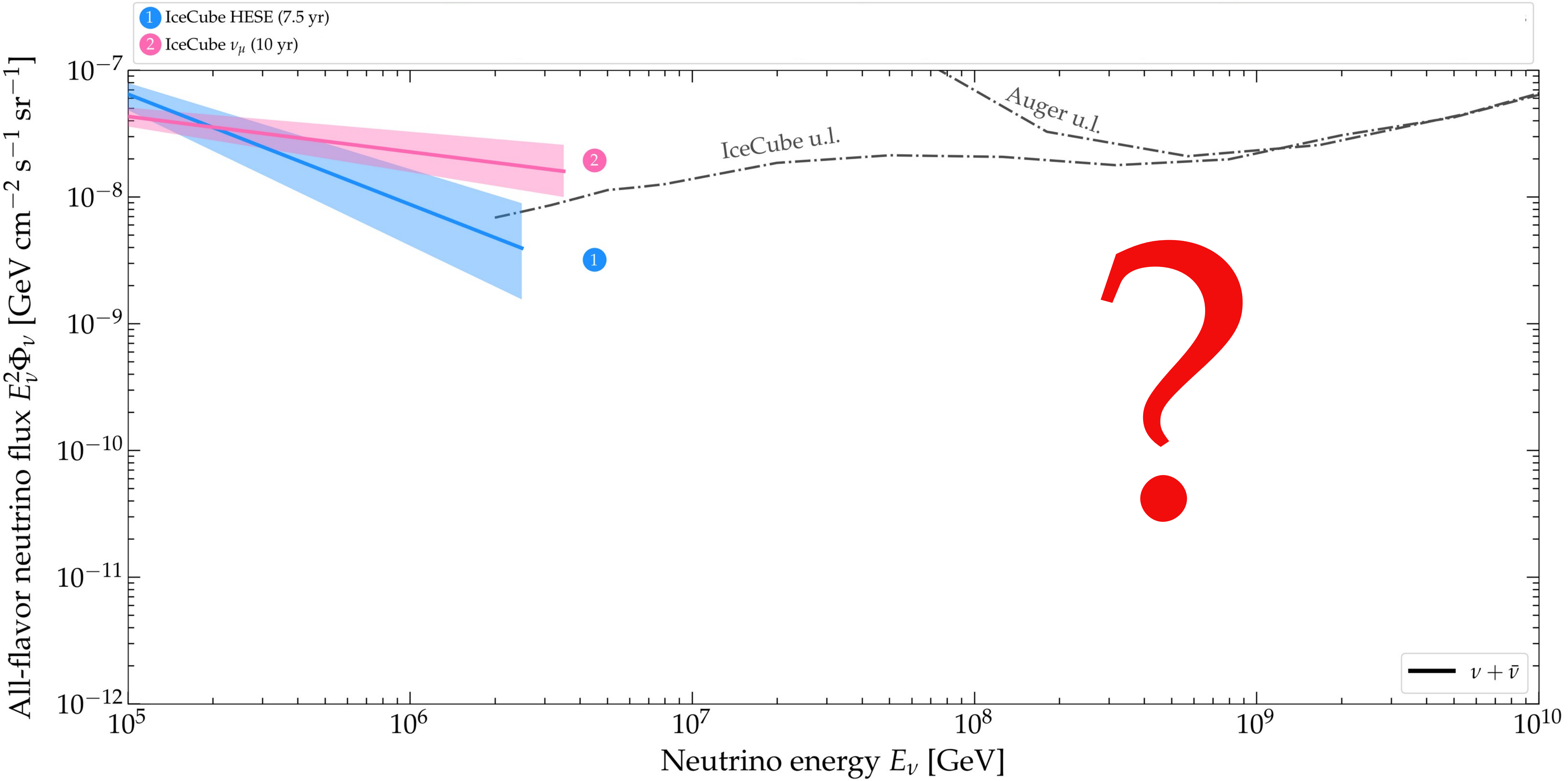
Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
Hussain, Mafatia, McKay, *PRD* 2008 Connolly, Thorne, Waters, *PRD* 2011; Marfatia, McKay, Weiler, *PLB* 2015



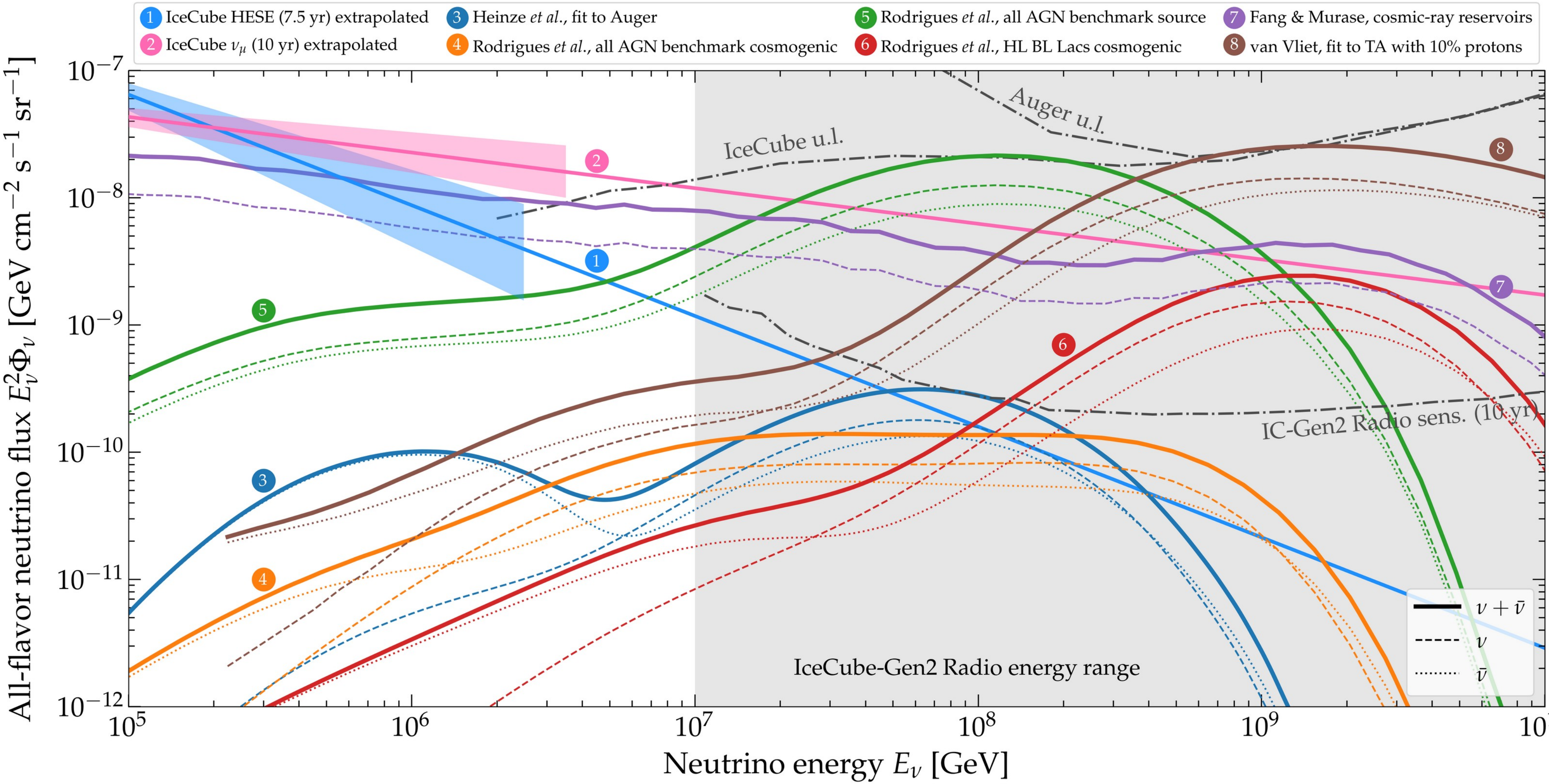
1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
Auger u.l.
IceCube u.l.
$\nu + \bar{\nu}$
All-flavor neutrino flux $E_\nu^2 \Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
Neutrino energy E_ν [GeV]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^5
10^6
10^7
10^8
10^9
10^{10}



Center-of-mass energy $\sqrt{s}$ [GeV]
Neutrino-nucleon cross section, $\sigma_{\nu N}^{CC}$ [10^{-38} cm^2]
Neutrino energy, E_ν [GeV]
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
Known
In progress
Accelerator ν
Accel. ν (projected)
High-energy cosmic ν
FASERν
ν
$\bar{\nu}$
IceCube tracks (avg. $\nu + \bar{\nu}$) (IceCube 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (Bustamante & Connolly 17)
IceCube showers (avg. $\nu + \bar{\nu}$) (IceCube 20)
Measured cross section compatible with Standard Model prediction
BGR18 prediction from:
Bertone, Gauld, Rojo, *JHEP* 2019
See also:
García, Gauld, Heijboer, Rojo, *JCAP* 2020
Measurements from:
IceCube, *PRD* 2021
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

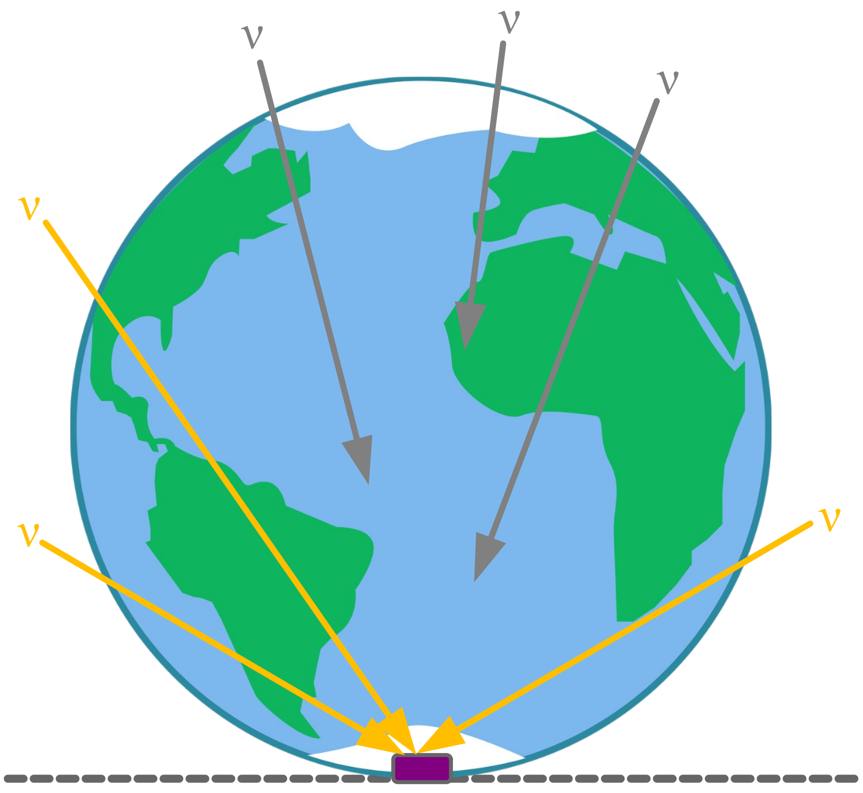


1 IceCube HESE (7.5 yr)
2 IceCube ν_μ (10 yr)
All-flavor neutrino flux $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
Auger u.l.
IceCube u.l.
2
1
?
$\nu + \bar{\nu}$
10^5
10^6
10^7
10^8
10^9
10^{10}
Neutrino energy E_ν [GeV]



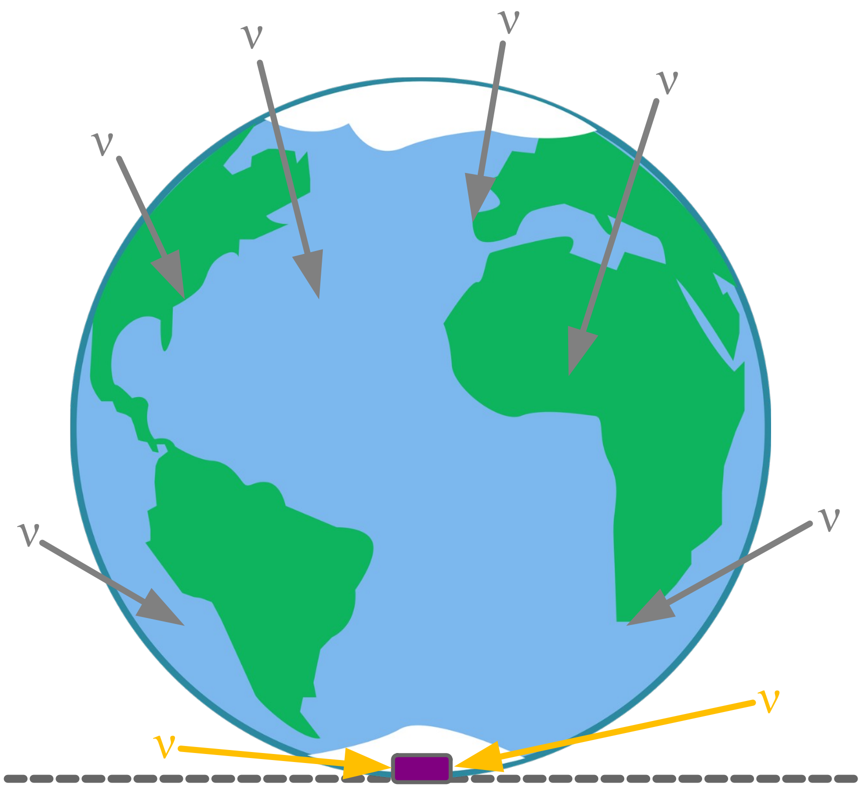
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze *et al.*, fit to Auger
4 Rodrigues *et al.*, all AGN benchmark cosmogenic
5 Rodrigues *et al.*, all AGN benchmark source
6 Rodrigues *et al.*, HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit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

TeV–PeV:



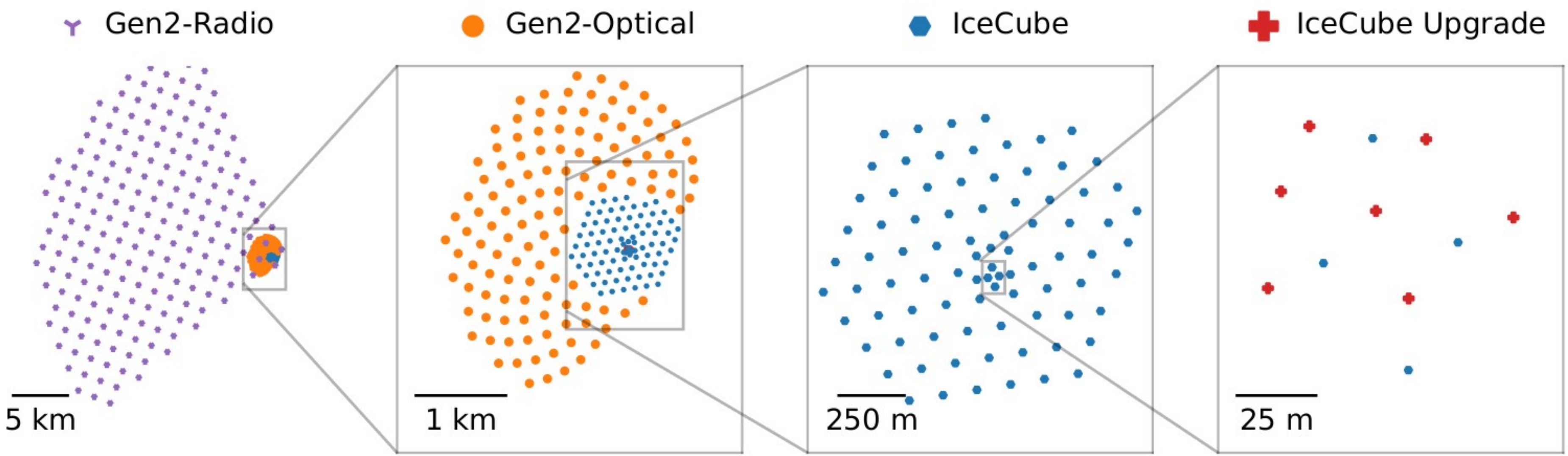
Earth is *almost fully* opaque,
some upgoing ν still make it through

> 100 PeV:



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

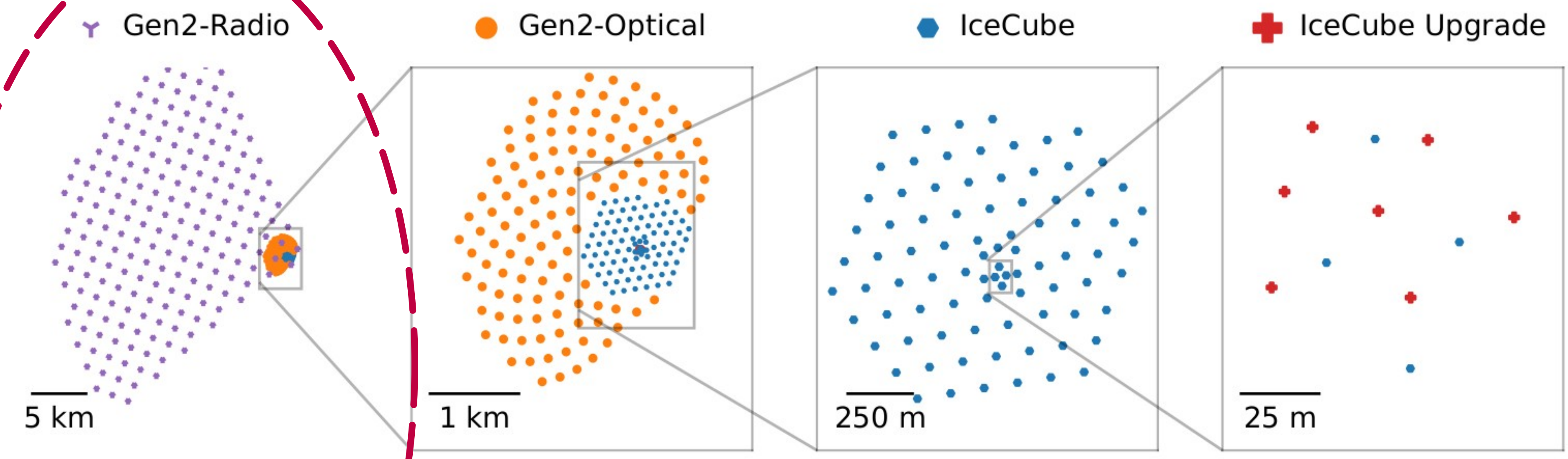
> 100 EeV ν: IceCube-Gen2



~2040		Today	Soon
10s km^3	~8 km^3	1 km^3	7 new strings
> 100 PeV ν	TeV–10 PeV ν	TeV–few PeV ν	GeV–TeV ν

IceCube-Gen2, 2008.04323

> 100 EeV ν: IceCube-Gen2



~2040

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

Today

1 km^3

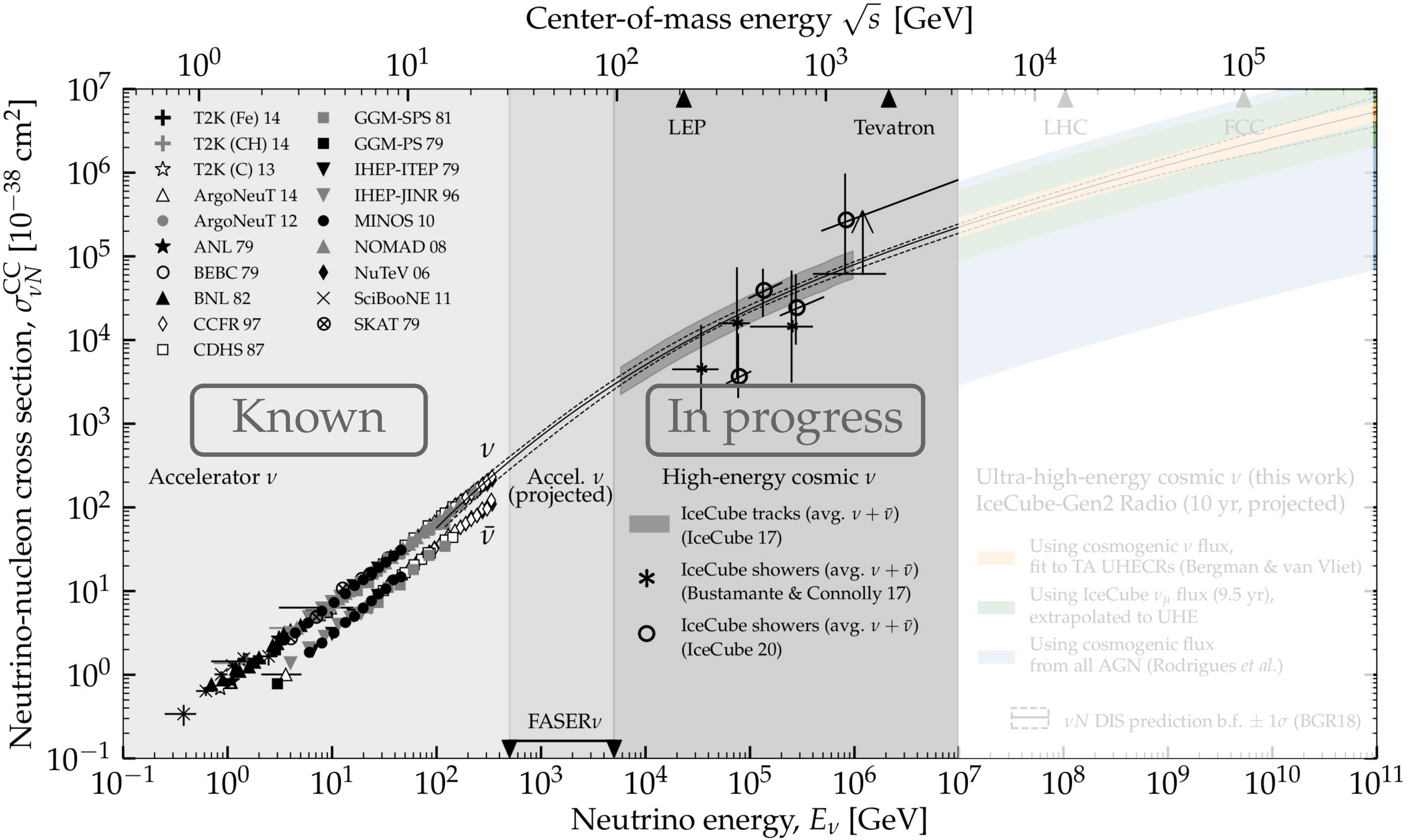
TeV–few PeV ν

Soon

7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323



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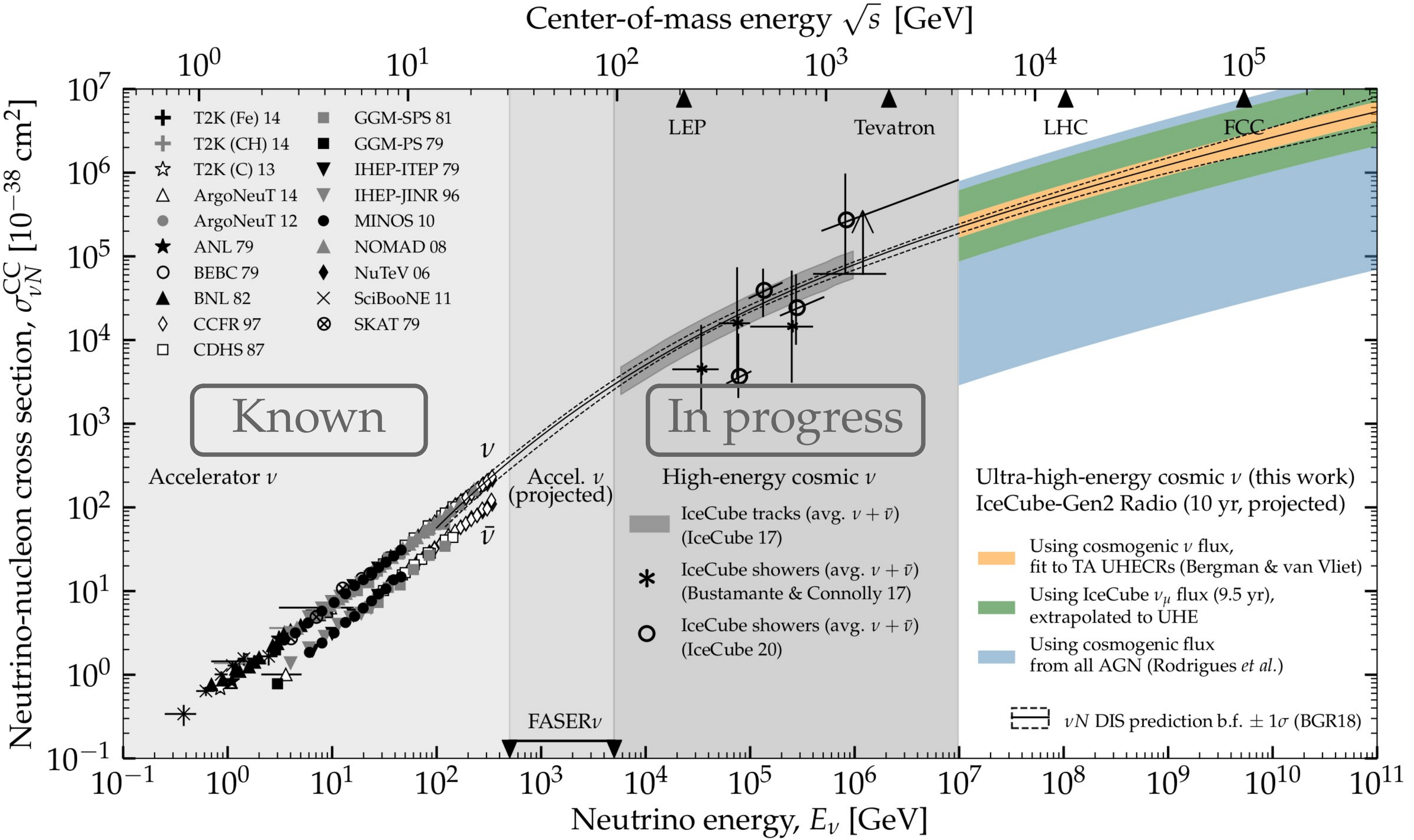
νN DIS prediction b.f. $\pm 1\sigma$ (BGR18)
FASERν
ν
$\bar{\nu}$



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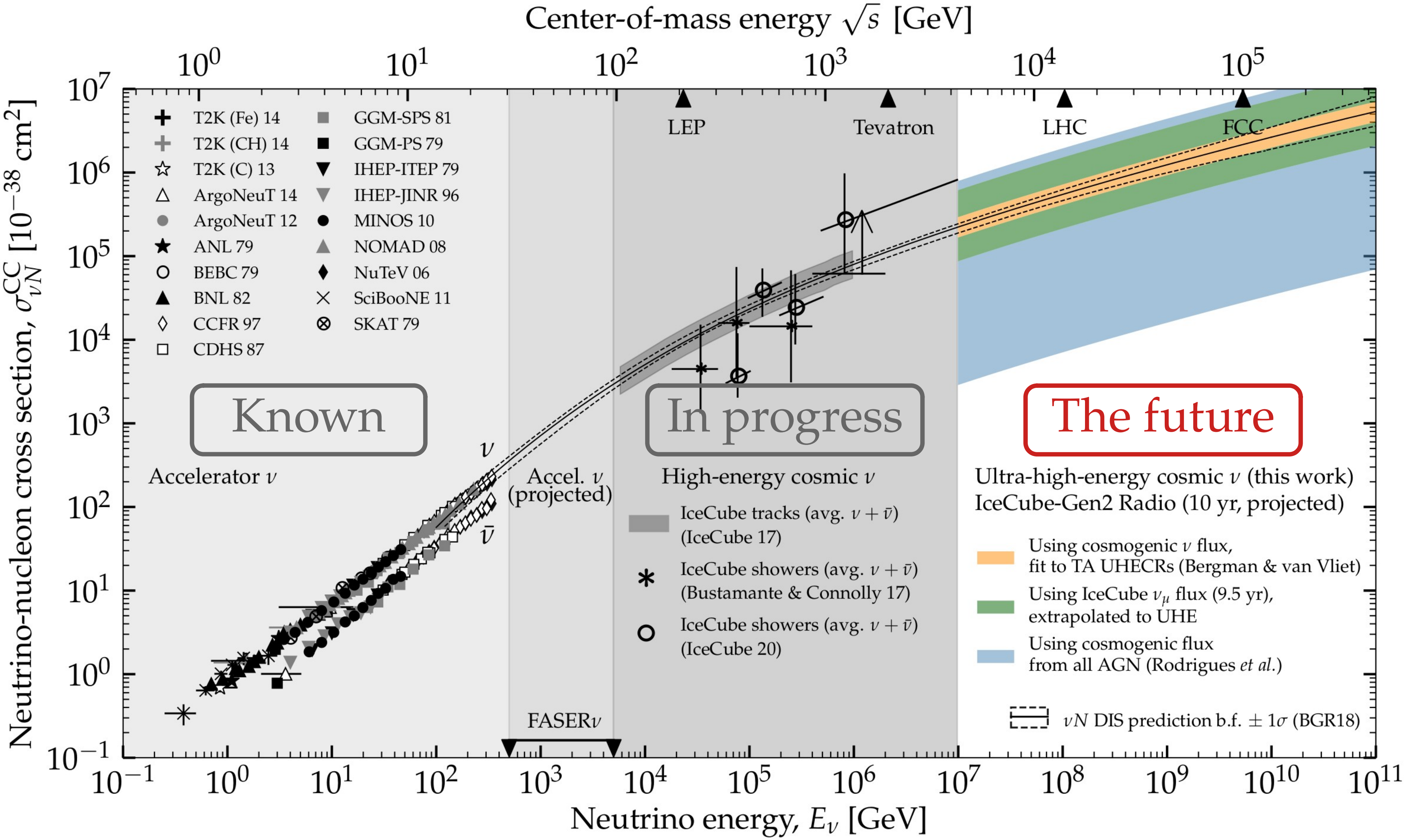

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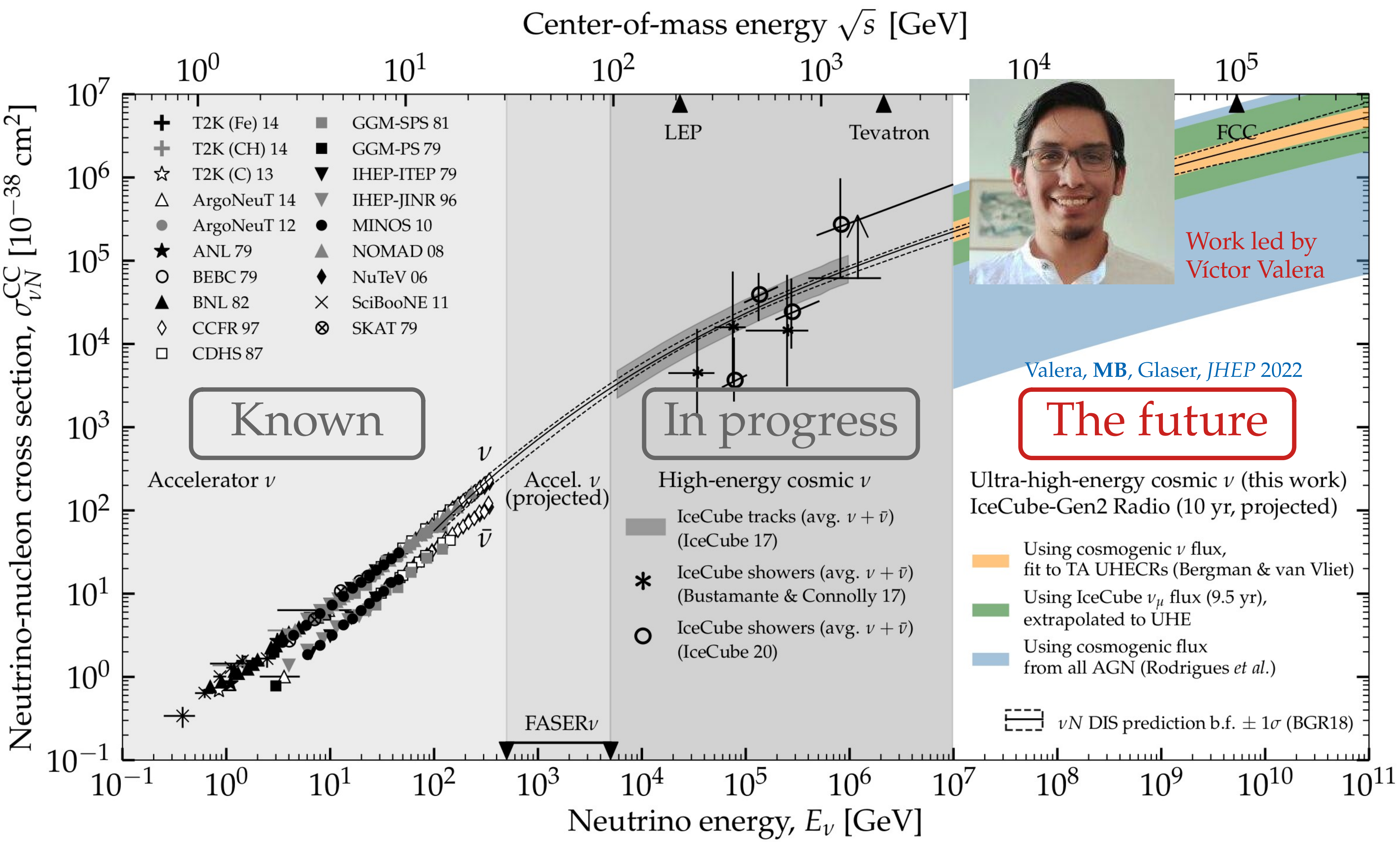
FASERν



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Work led by Víctor Valera
Valera, **MB**, Glaser, *JHEP* 2022
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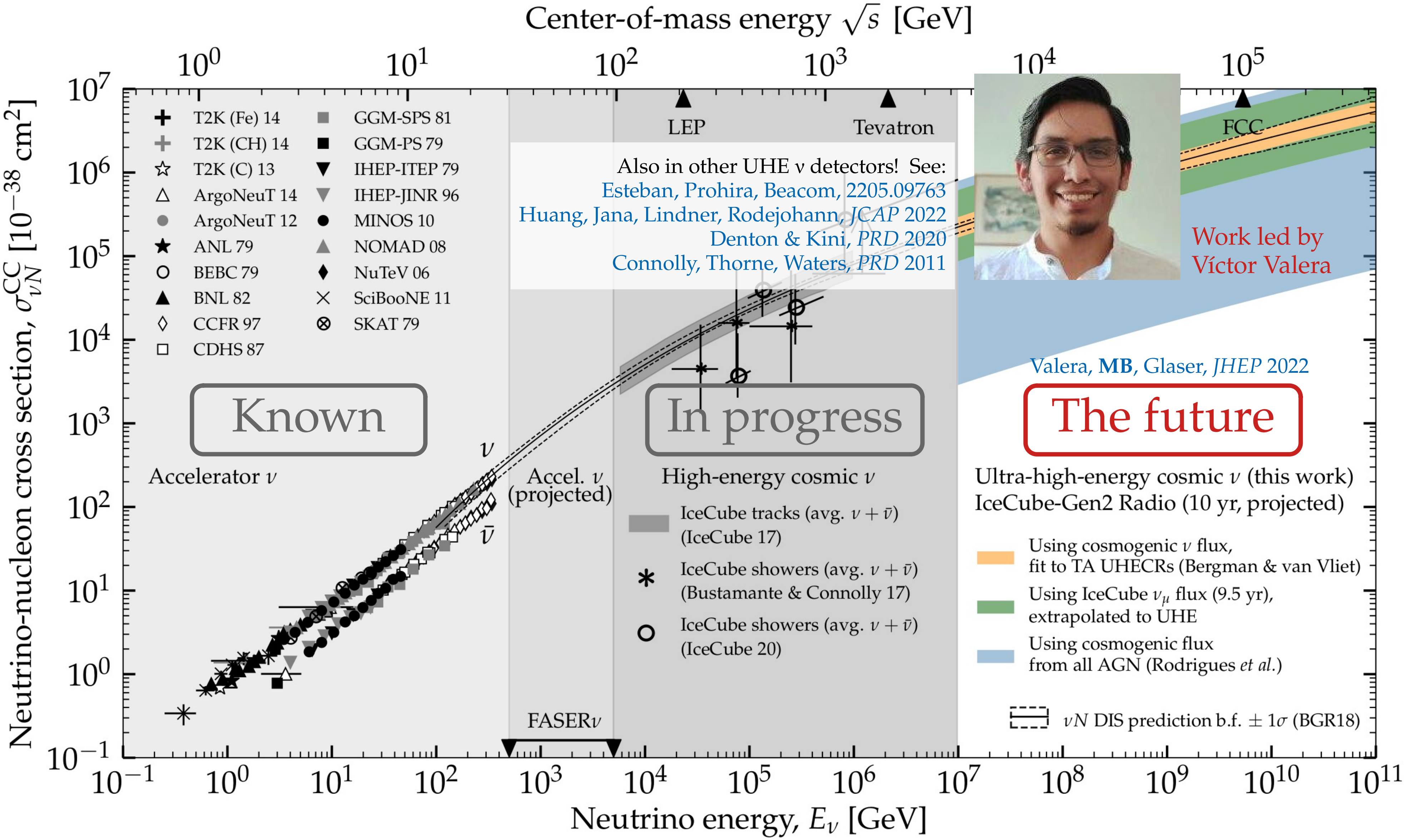
FASERν
ν
$\bar{\nu}$



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MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
LEP
Tevatron
FCC
Also in other UHE ν detectors! See:
Esteban, Prohira, Beacom, 2205.09763
Huang, Jana, Lindner, Rodejohann, *JCAP* 2022
Denton & Kini, *PRD* 2020
Connolly, Thorne, Waters, *PRD* 2011
Work led by Víctor Valera
Valera, **MB**, Glaser, *JHEP* 2022
Known
In progress
The future
Accelerator ν
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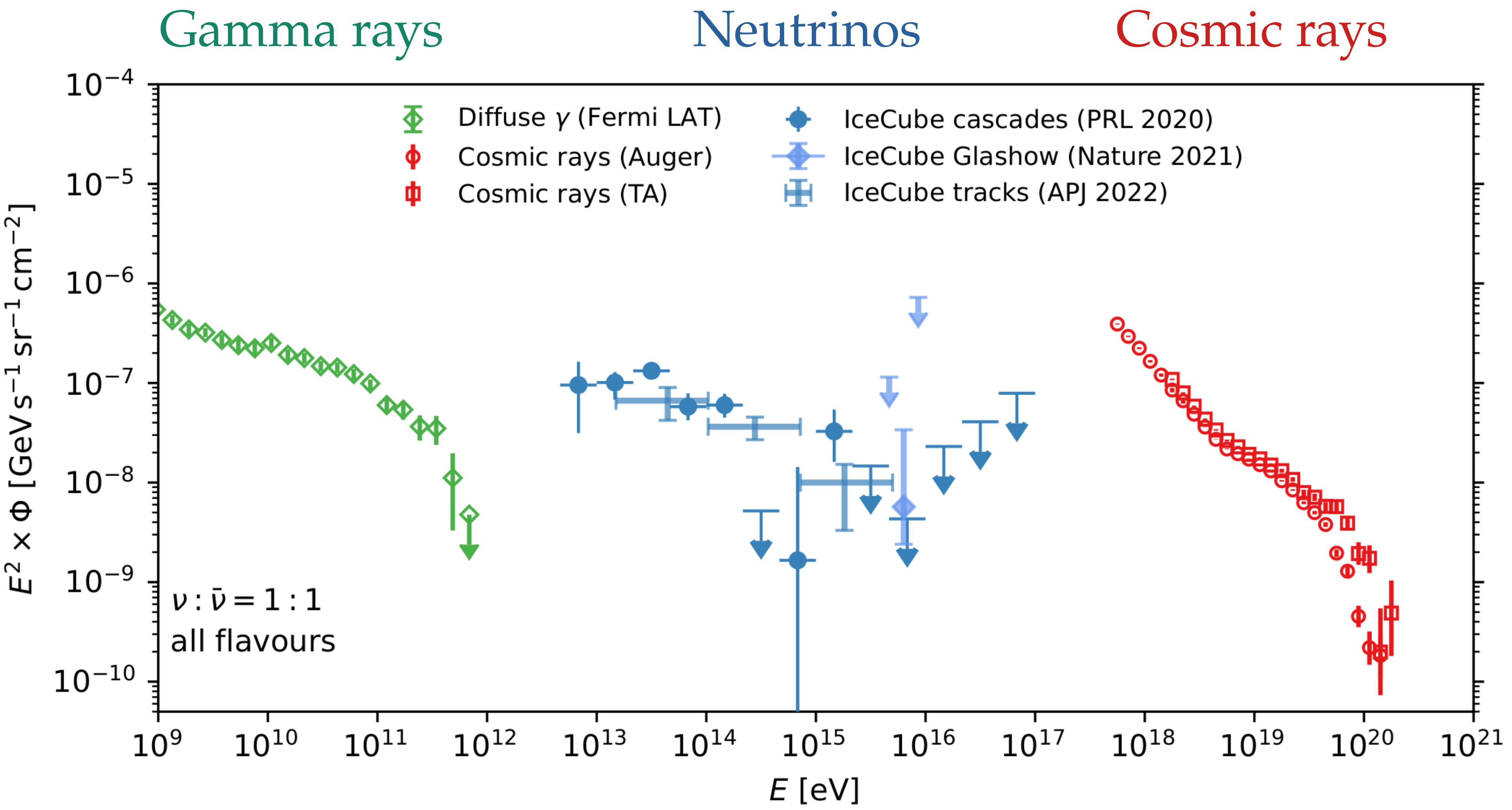
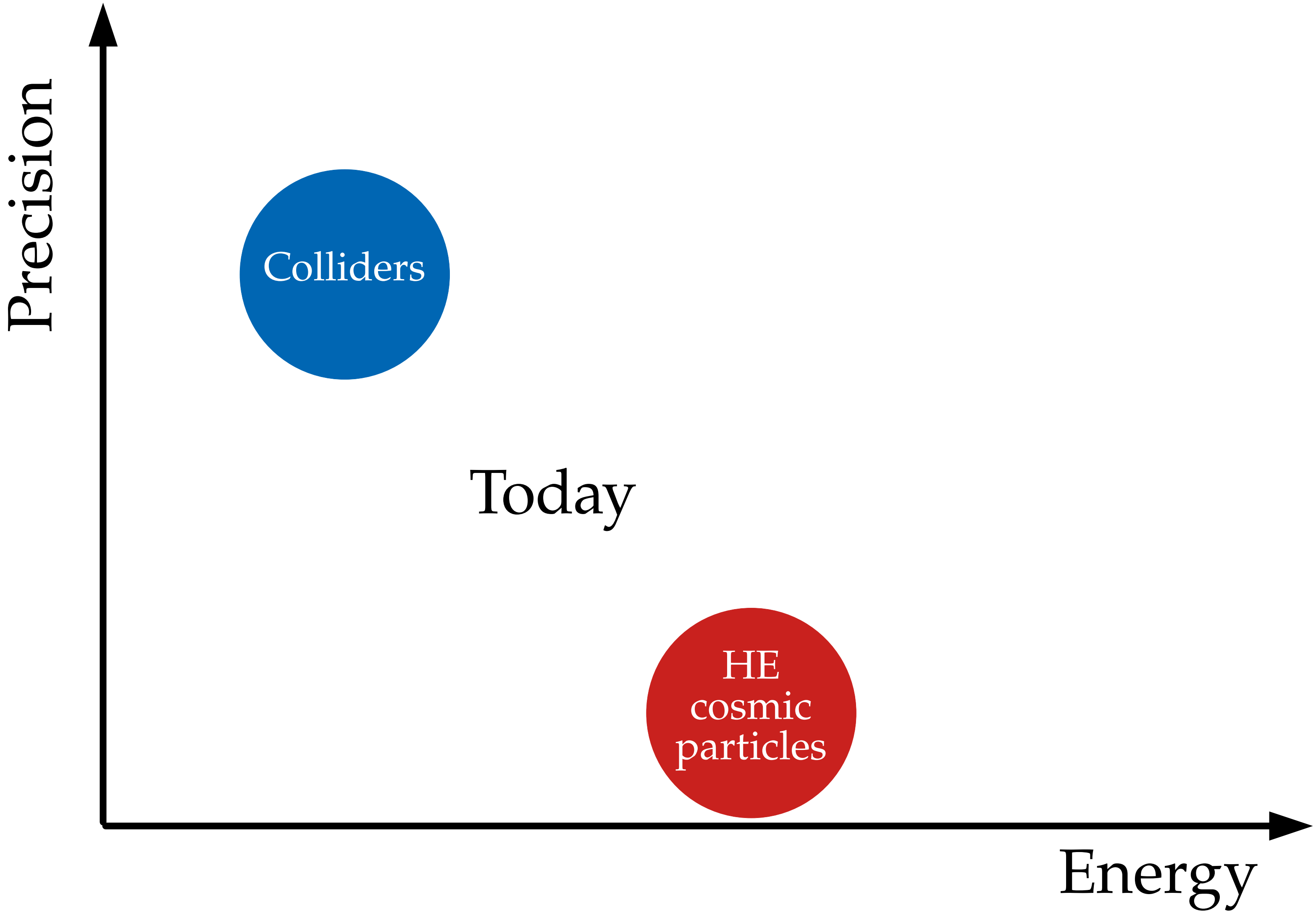
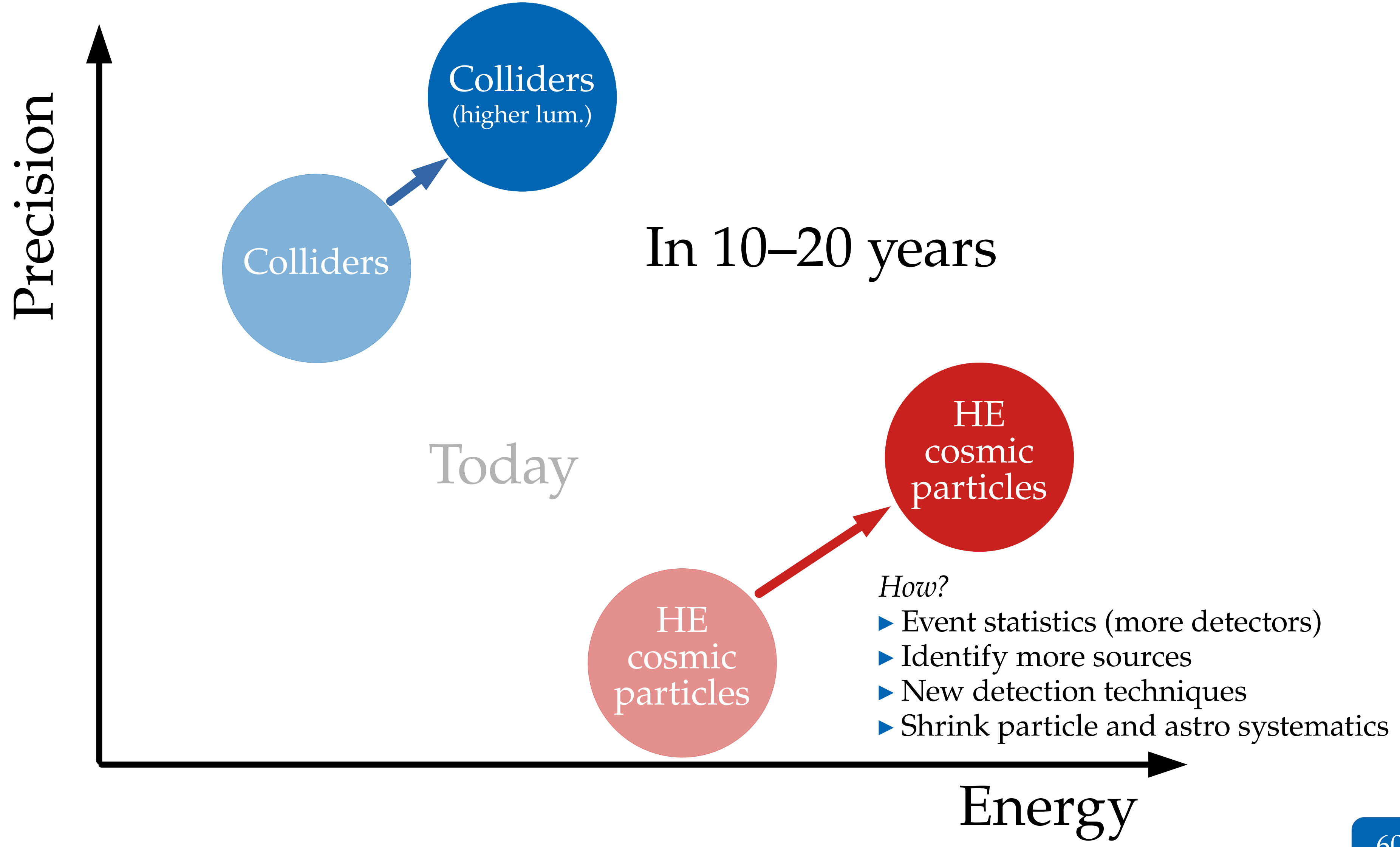
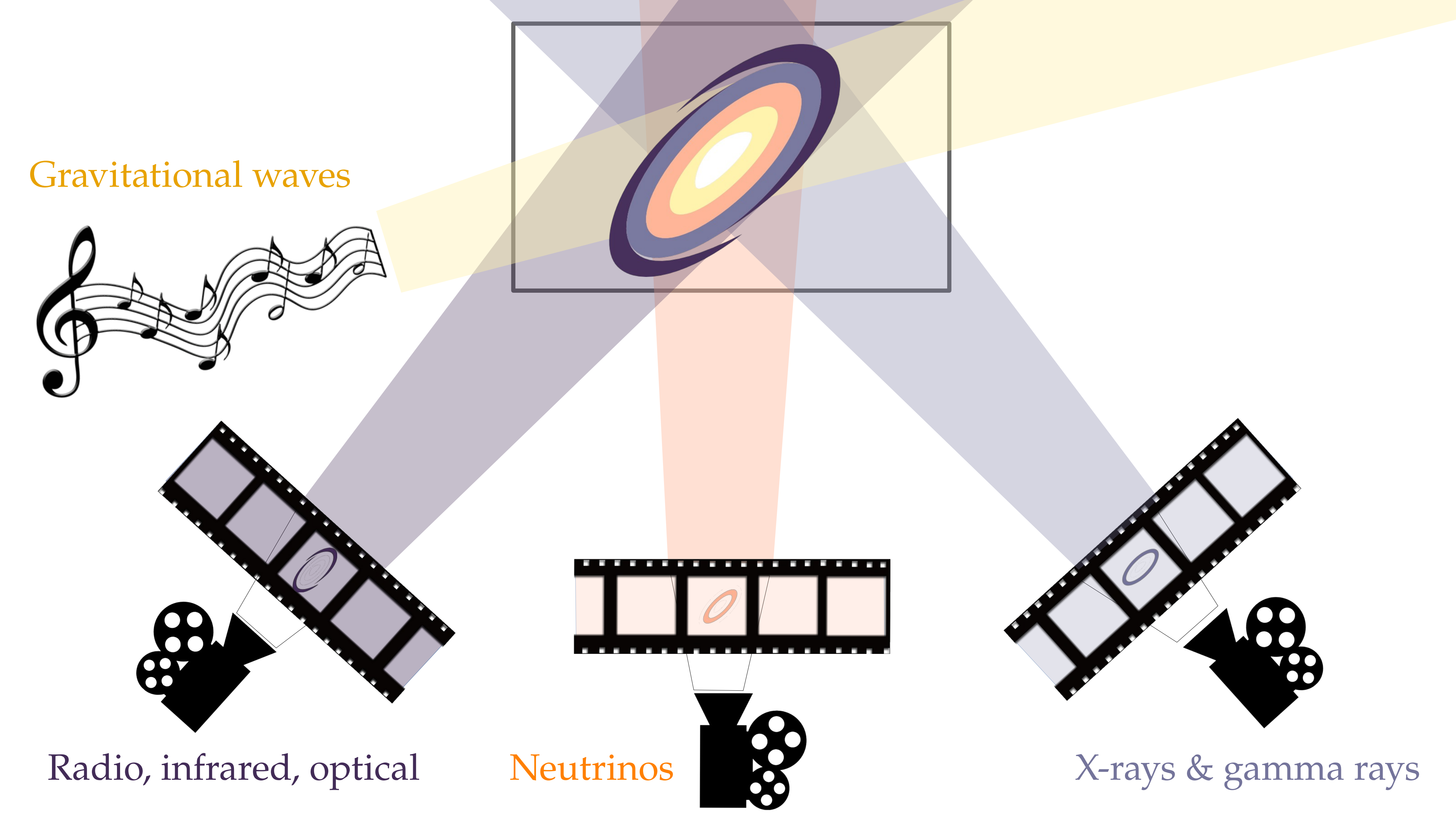
FASERν
ν
$\bar{\nu}$



M. Ackermann, **MB**, *et al.*, *JHEAp* 35, 55 (2022) [2203.08096]


Precision
Colliders
Today
HE
cosmic
particles
Energy


Precision
Colliders
(higher lum.)
Colliders
In 10–20 years
Today
HE
cosmic
particles
HE
cosmic
particles
How?
▸ Event statistics (more detectors)
▸ Identify more sources
▸ New detection techniques
▸ Shrink particle and astro systematics
Energy

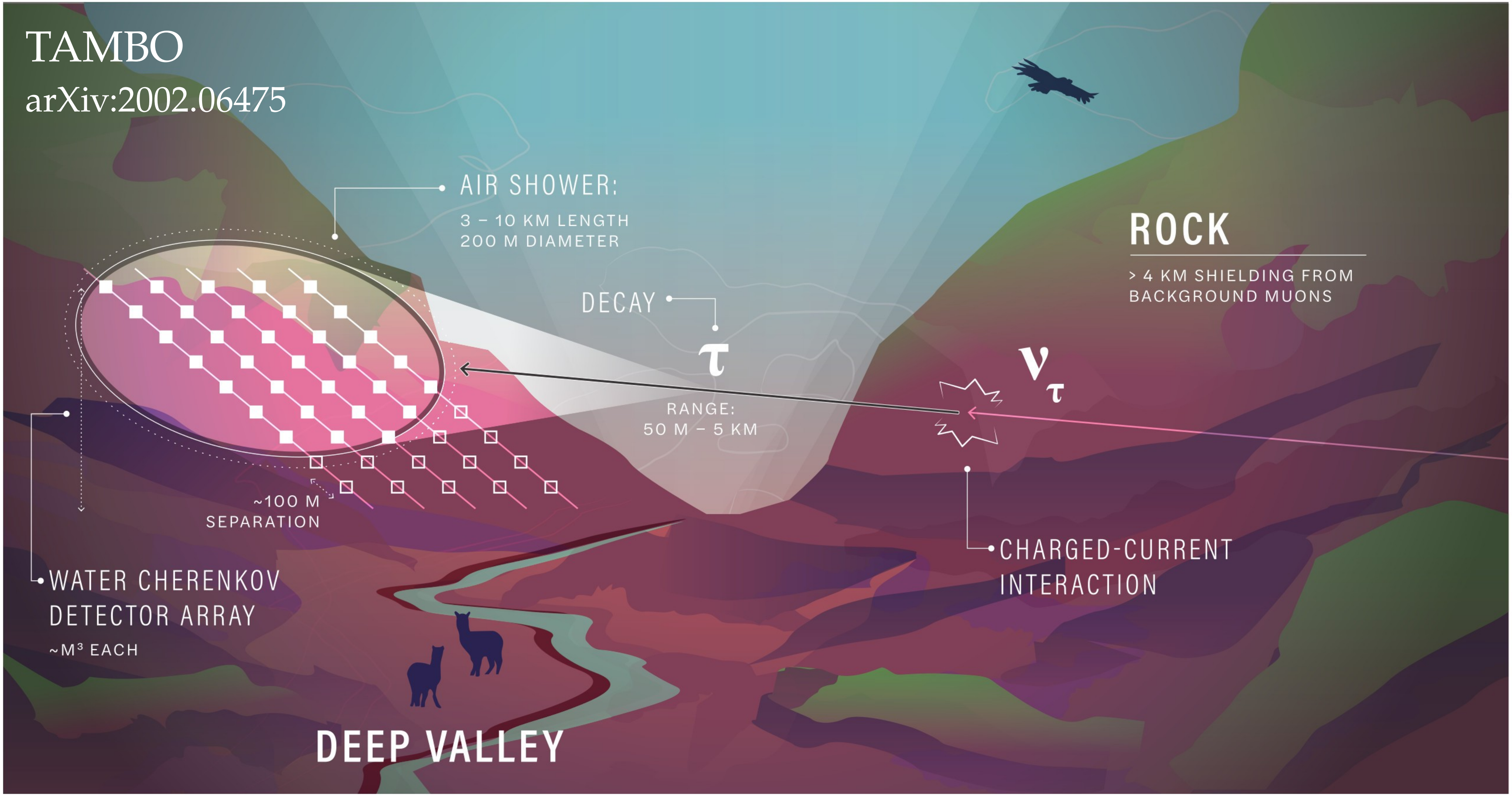


Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

Thanks!

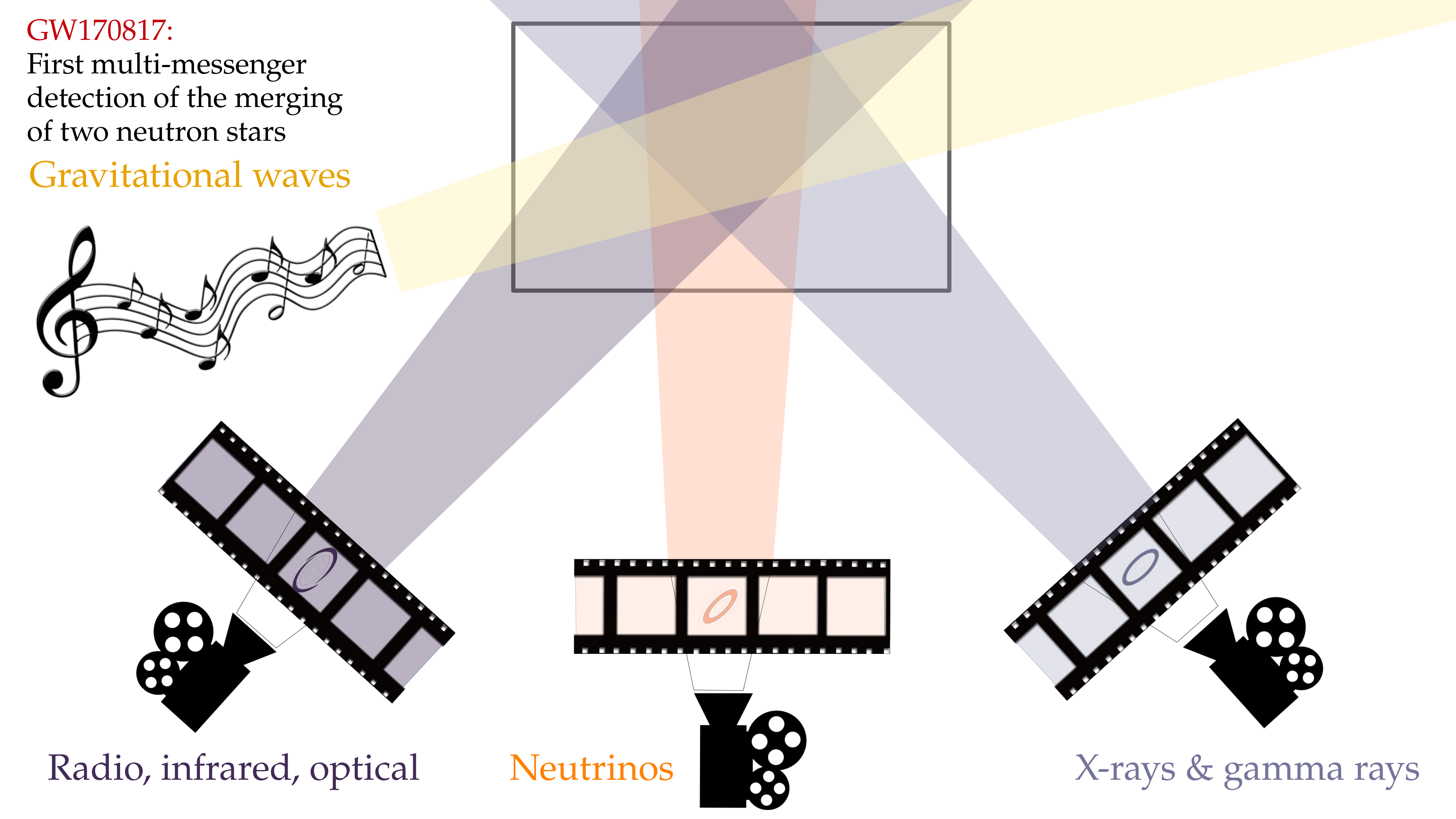
TAMBO

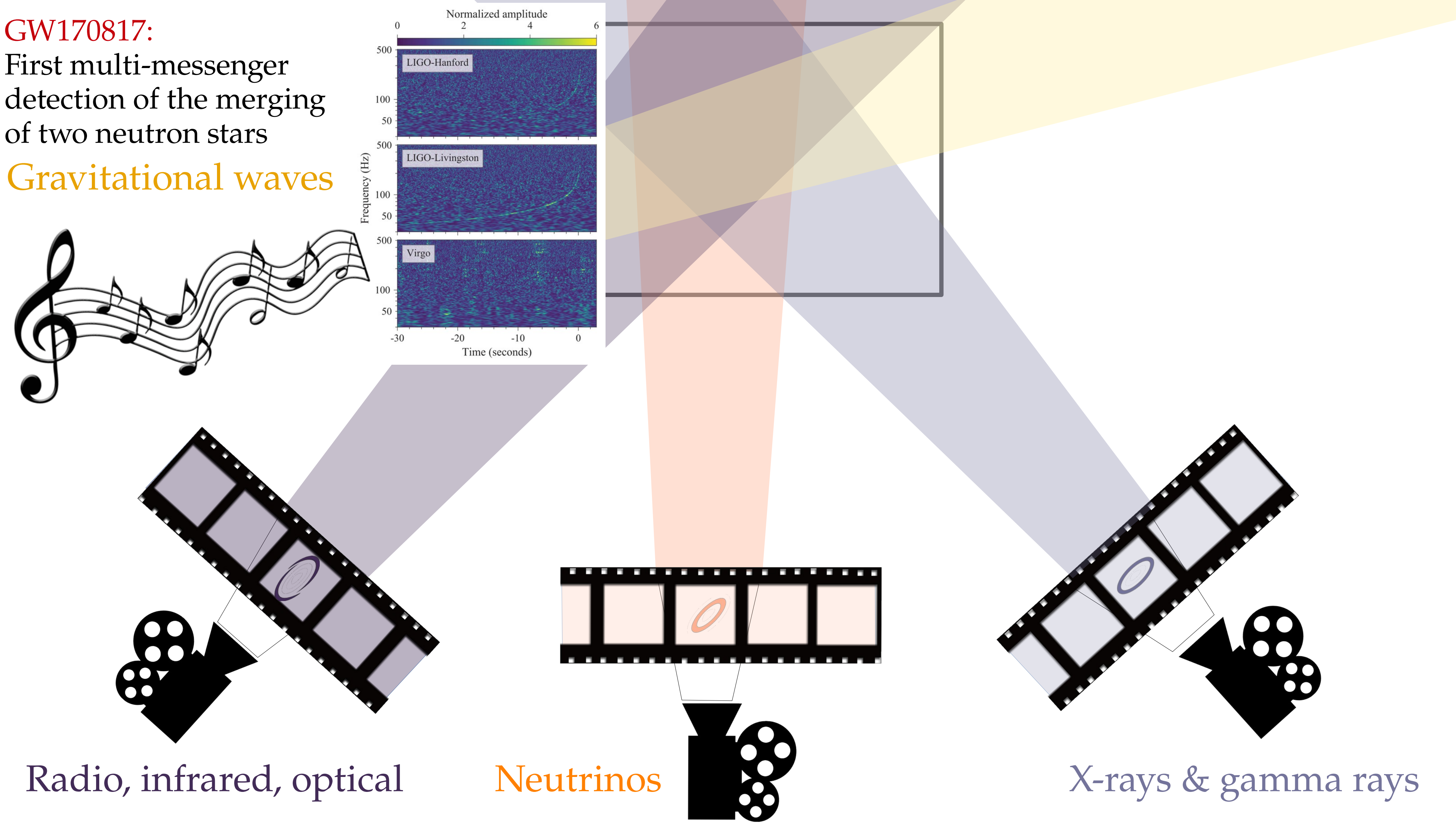
arXiv:2002.06475



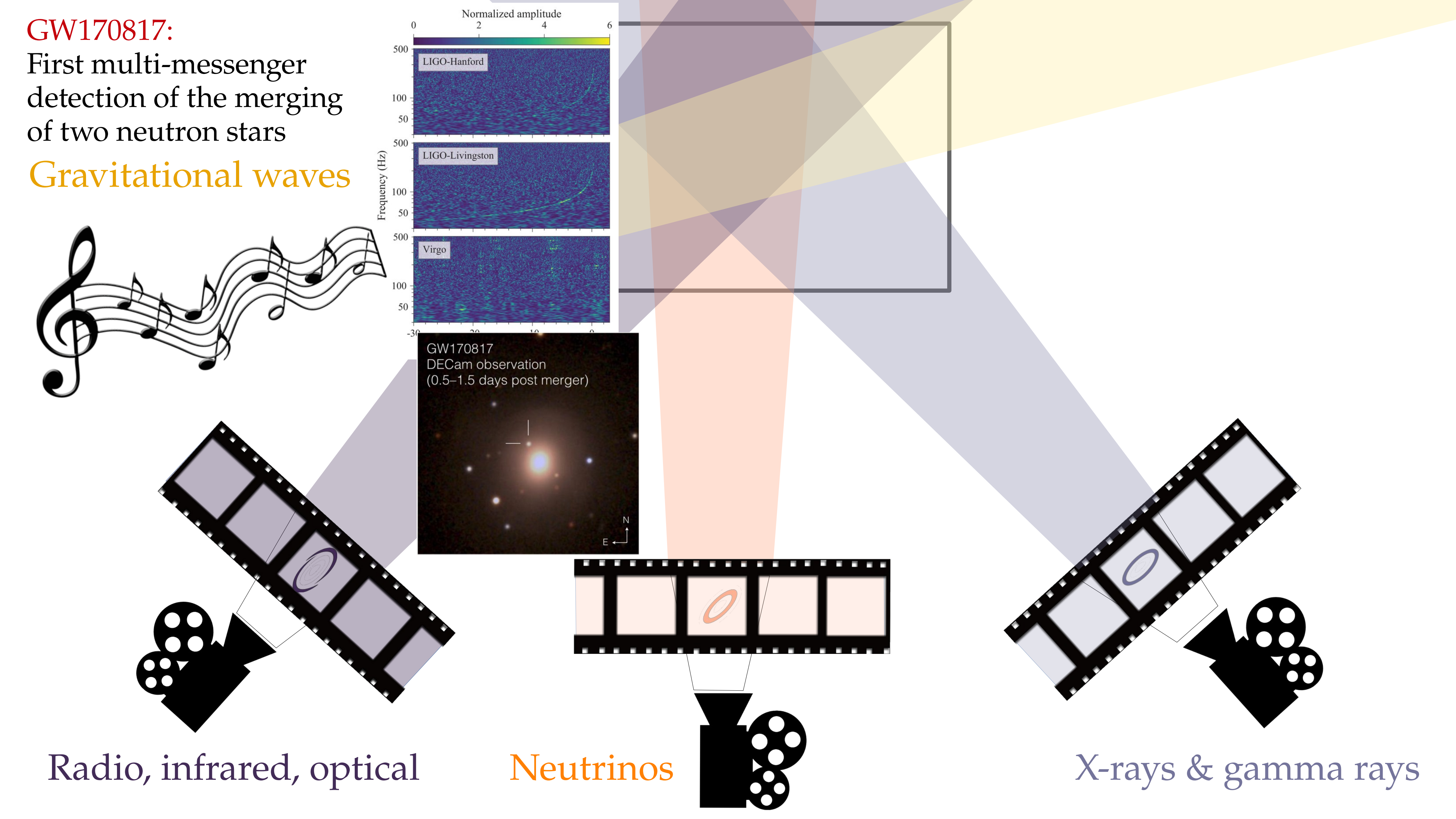
TAU AIR-SHOWER MOUNTAIN-BASED OBSERVATORY (TAMBO) · COLCA VALLEY, PERU

Backup slides


GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Radio, infrared, optical
Neutrinos
X-rays & gamma rays



GW170817:
First multi-messenger detection of the merging of two neutron stars
Gravitational waves
Normalized amplitude
0
2
4
6
500
100
50
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
-30
-20
-10
0
Time (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays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500
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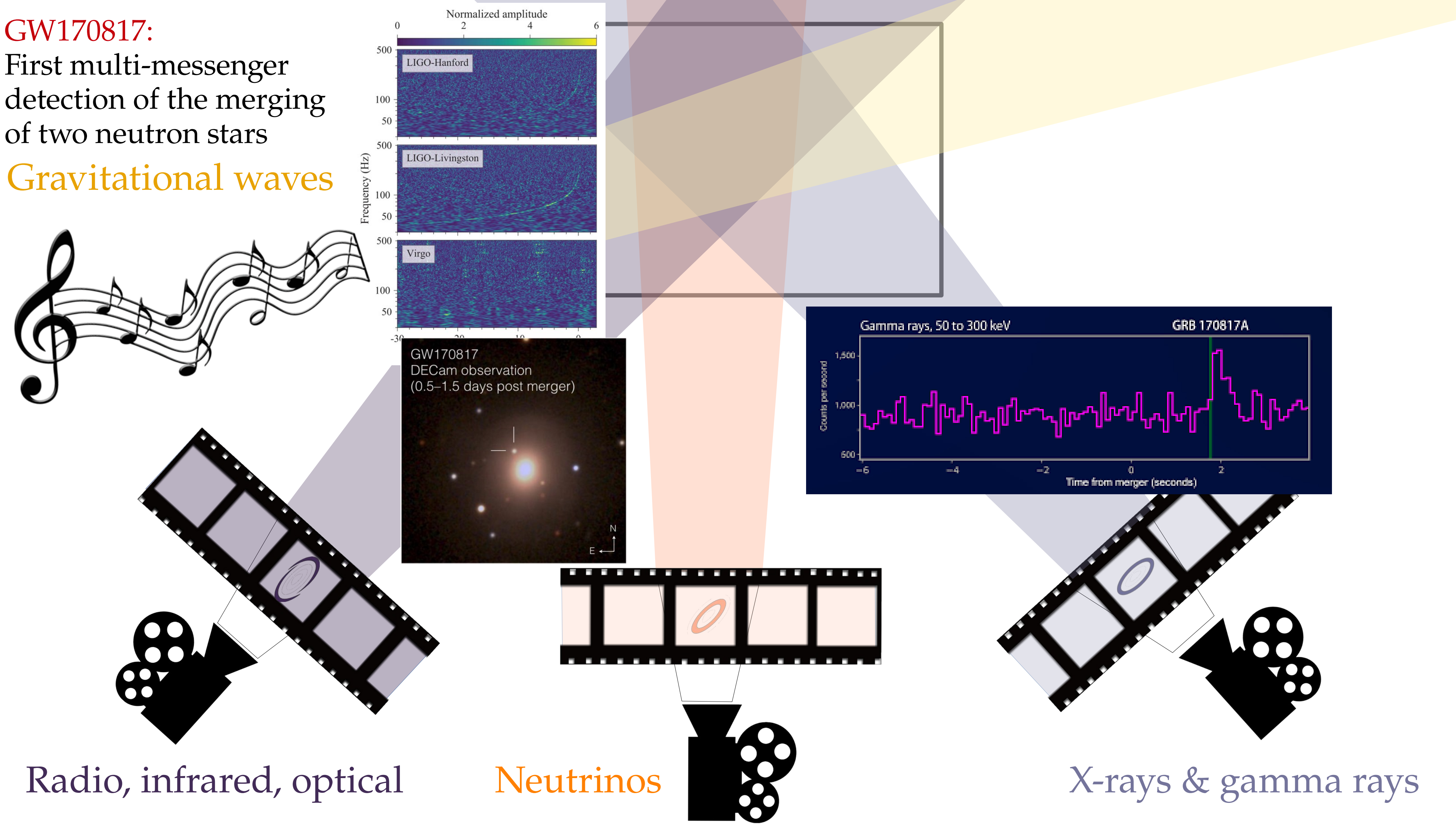
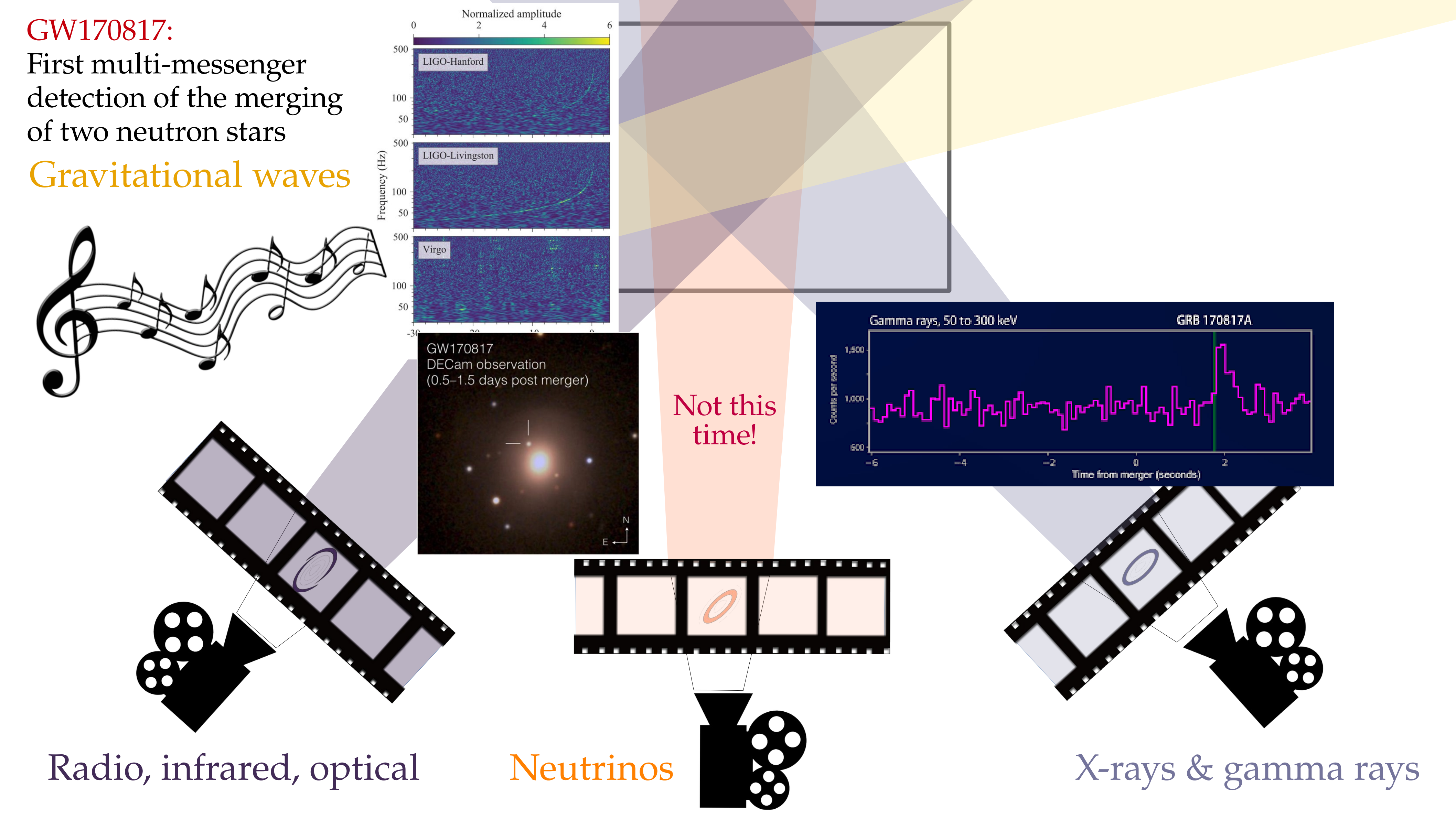
LIGO-Hanford
LIGO-Livingston
Virgo
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

GW170817:
First multi-messenger detection of the merging of two neutron stars

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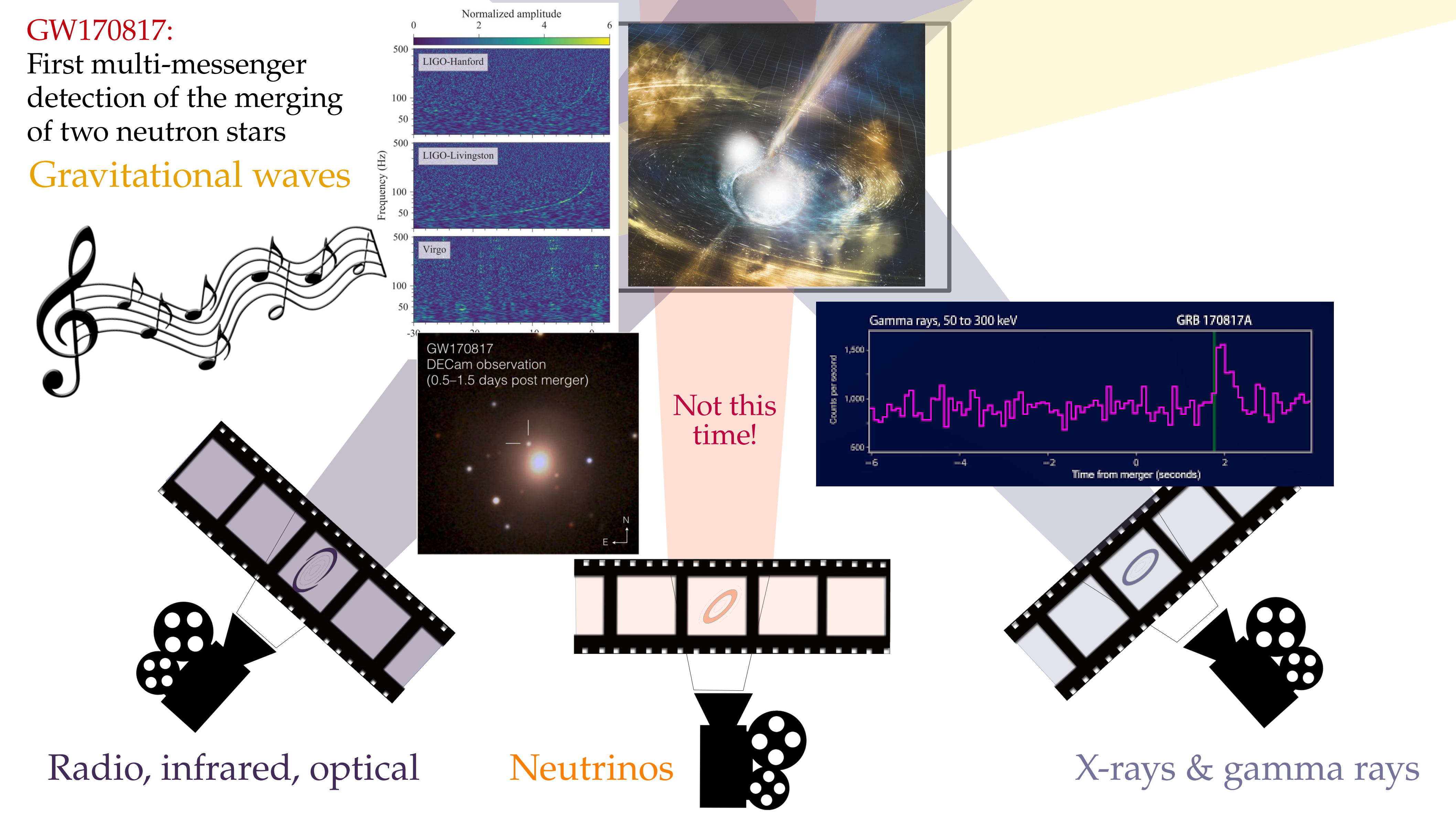
50
GW170817
DECam observation
(0.5–1.5 days post merger)
N
E
Not this time!
Gamma rays, 50 to 300 keV
GRB 170817A
Counts per second
1,500
1,000
600
−6 −4 −2 0 2
Time from merger (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays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Normalized amplitude
0 2 4 6
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LIGO-Livingston
Virgo
Frequency (Hz)
500 100 50
GW170817
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Gamma rays, 50 to 300 keV
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1,500
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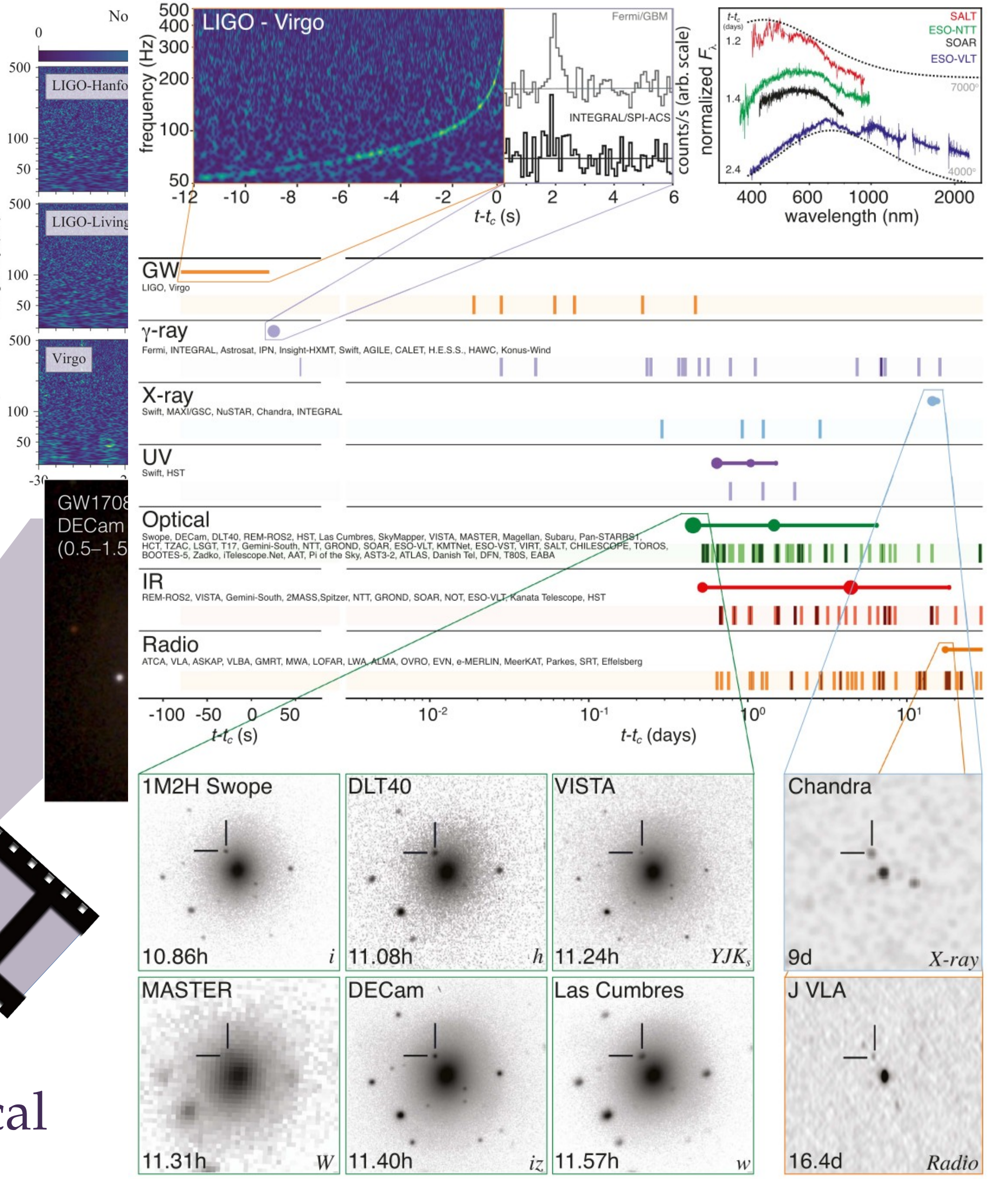
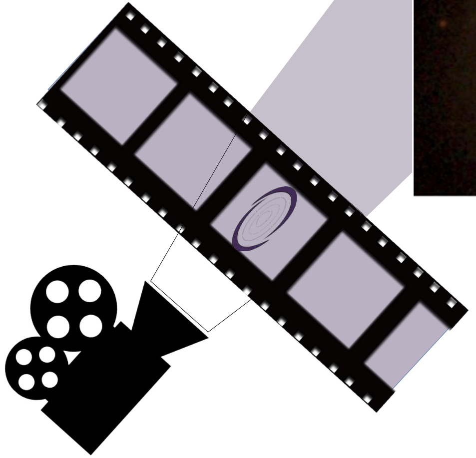
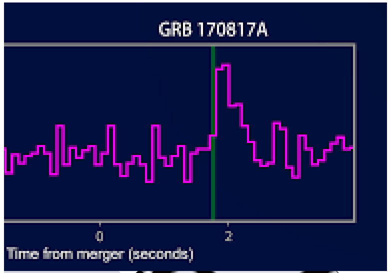
Time from merger (seconds)
Radio, infrared, optical
Neutrinos
X-rays & gamma rays

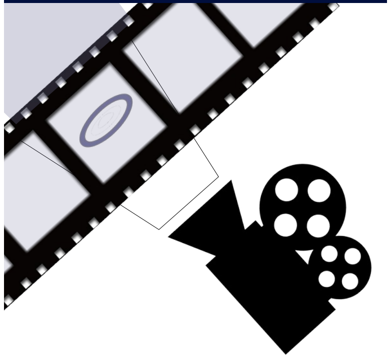
GW170817:
First multi-messenger detection of the merging of two neutron stars

Gravitational waves









Radio, infrared, optical

X-rays & gamma rays

Glashow resonance:
Long-sought, finally seen

First observation of a Glashow resonance

Predicted in 1960:

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

First observation of a Glashow resonance

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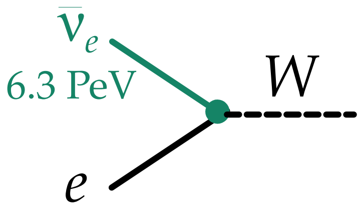

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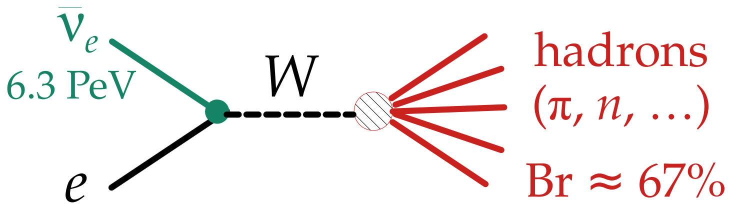

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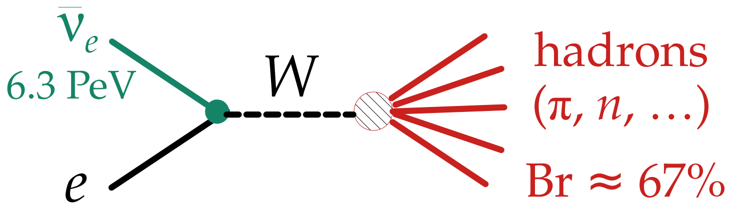
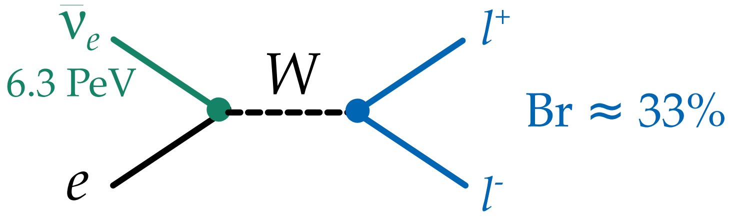
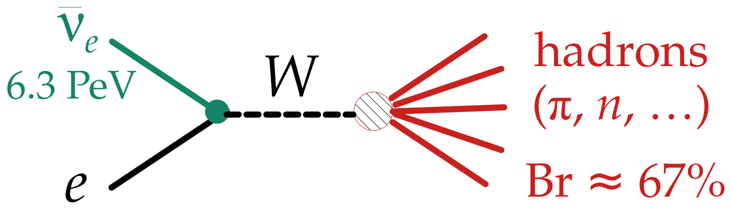


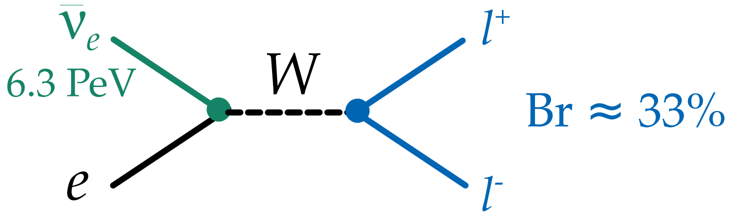


IceCube, *Nature* 2021
Glashow, *PR* 1960

First observation of a Glashow resonance

Predicted in 1960:





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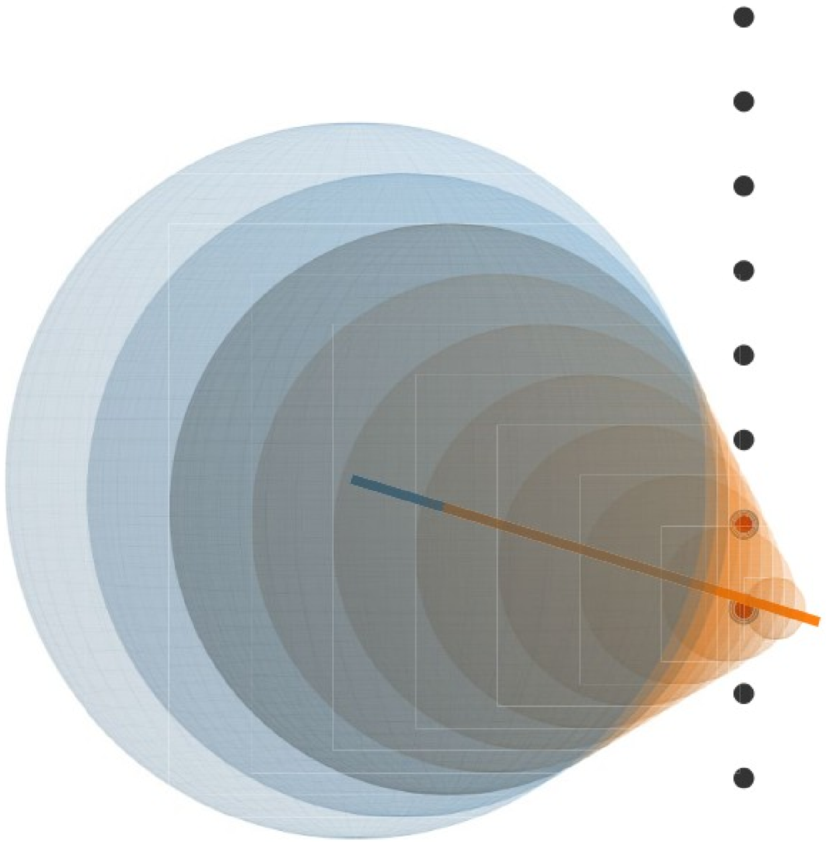

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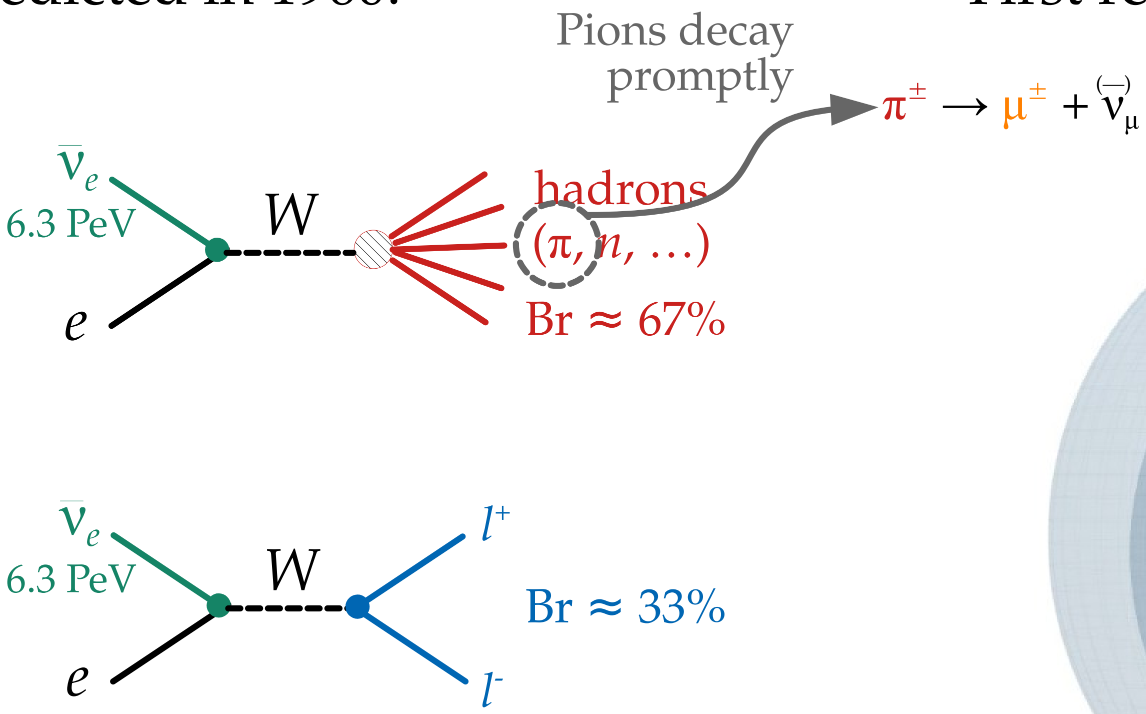

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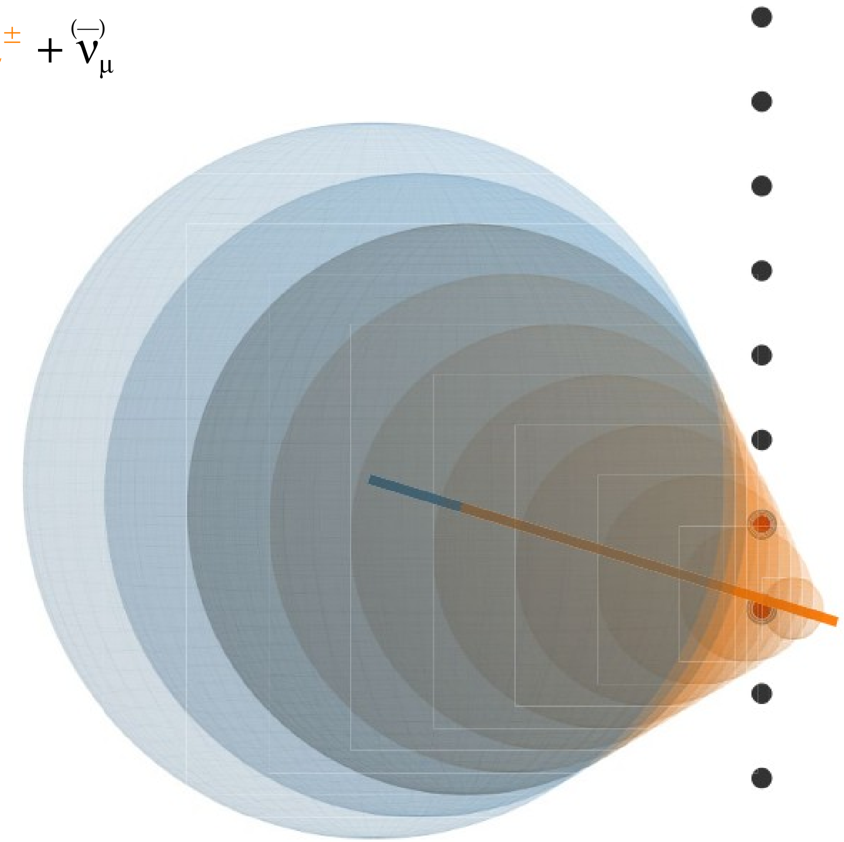

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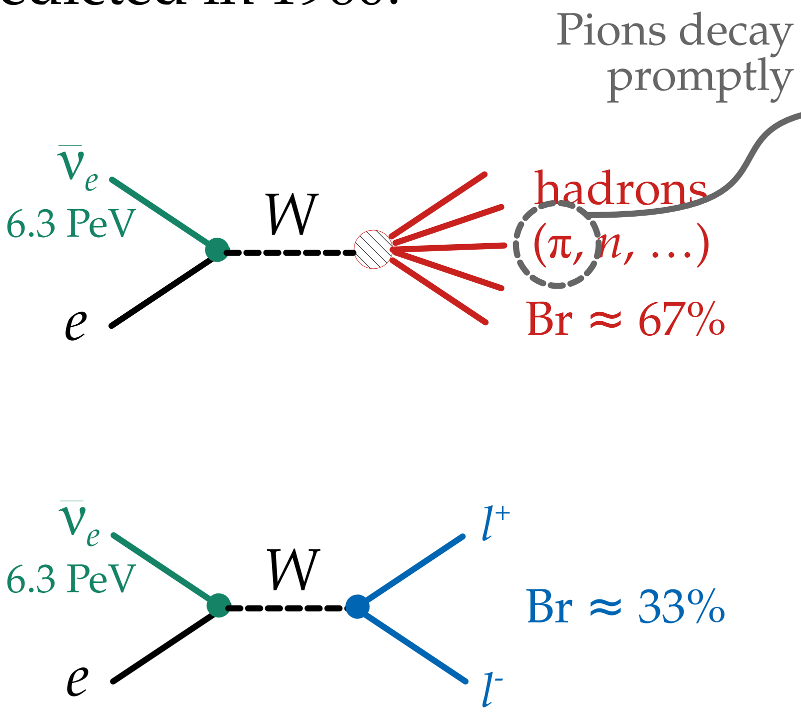
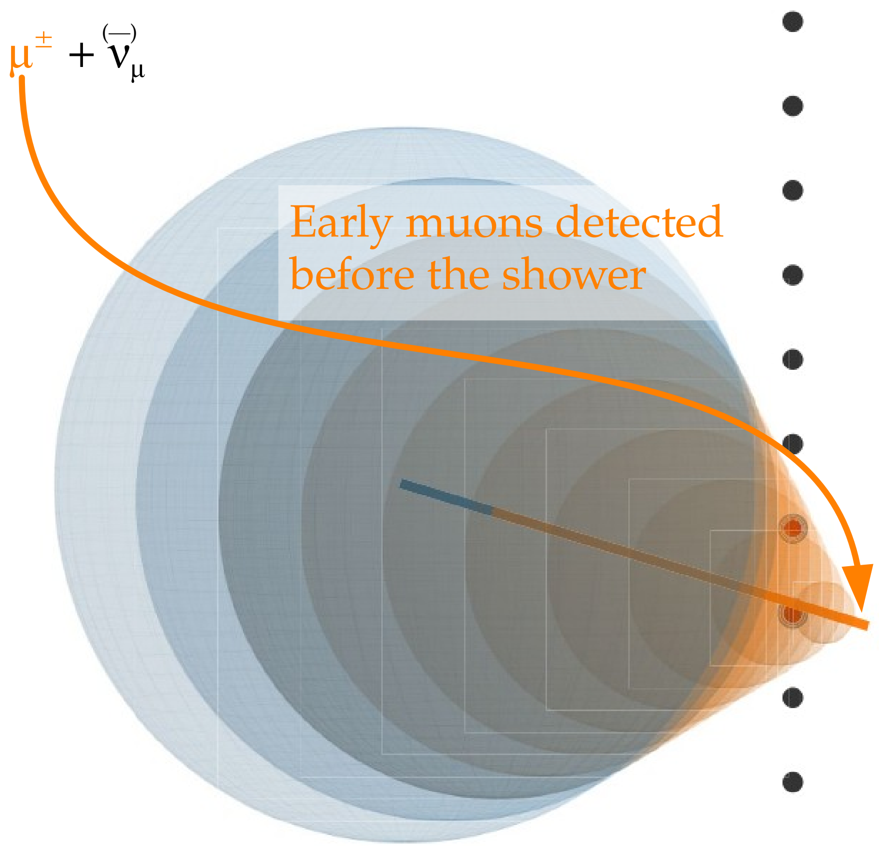


First reported by IceCube in 2021:

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



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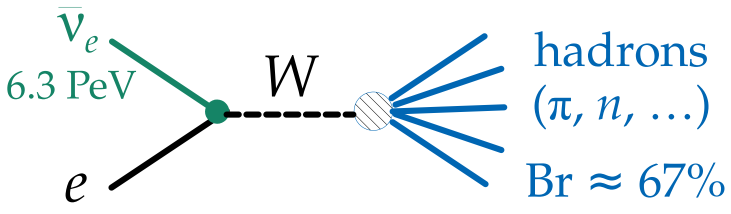

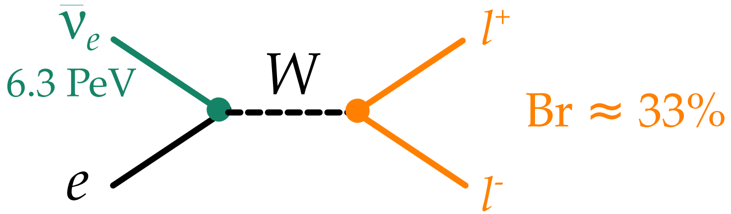

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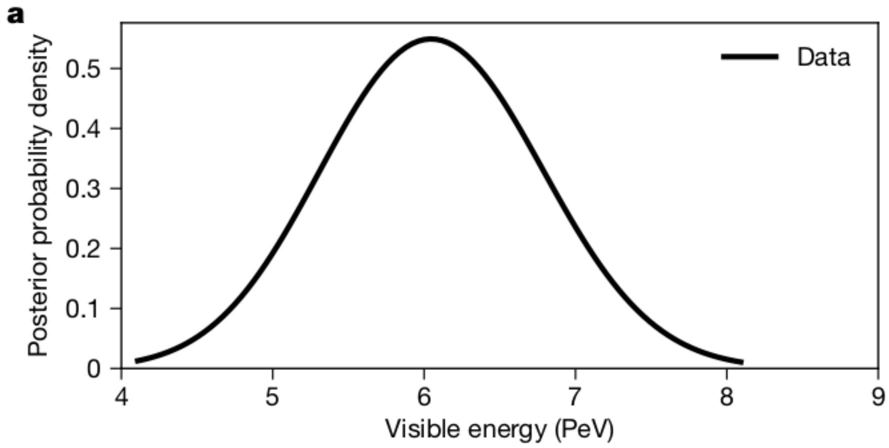

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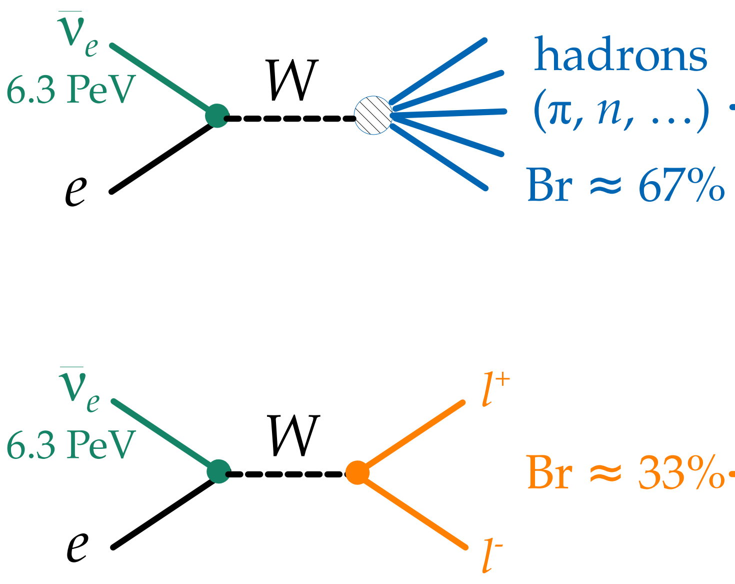

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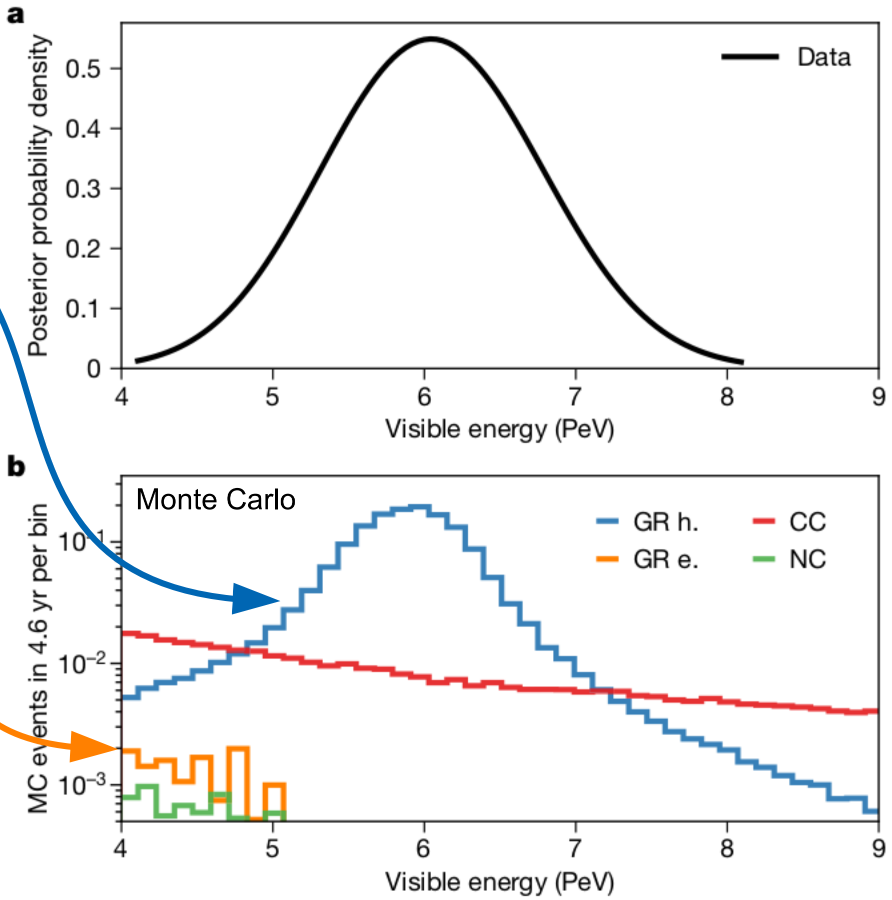


IceCube, *Nature* 2021
Glashow, *PR* 1960

Flavor:
Towards precision, finally

(with the help of lower-energy experiments)

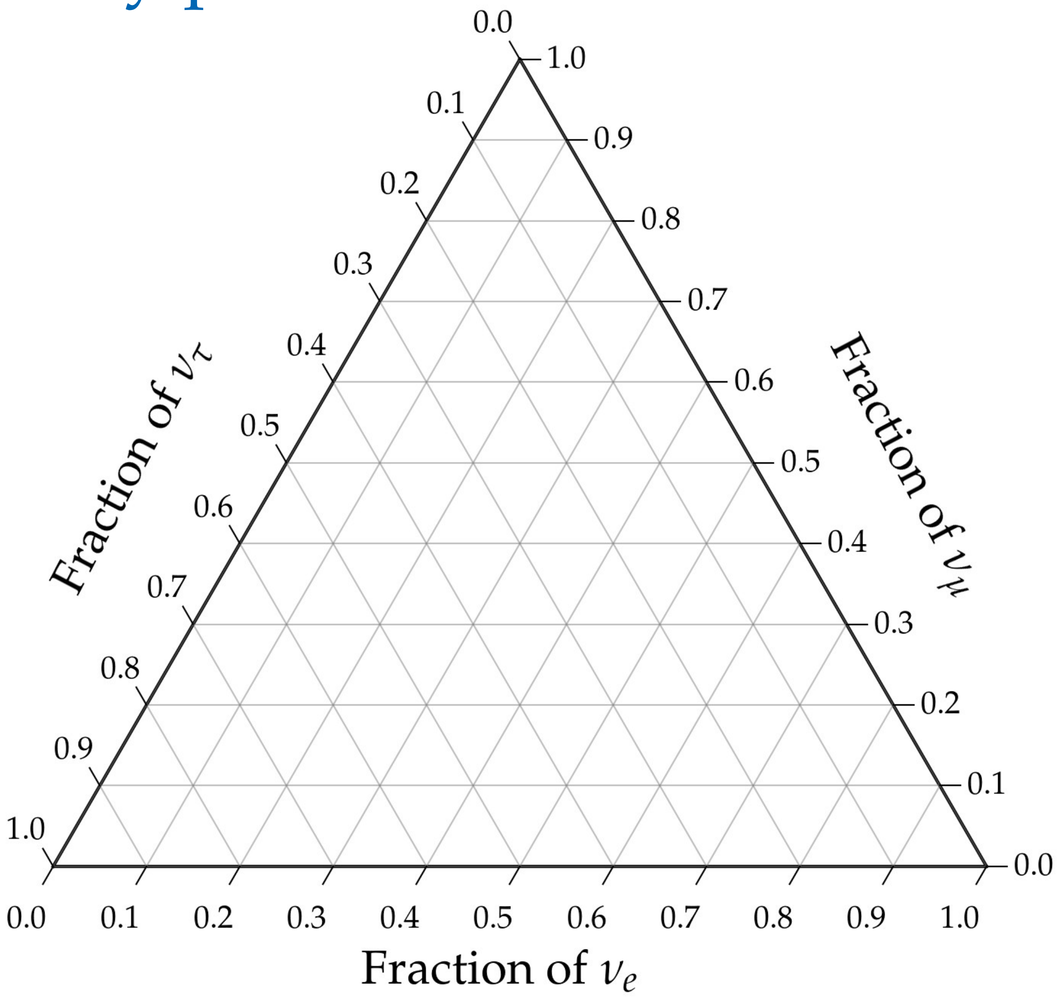
Quick aside: how to read a ternary plot

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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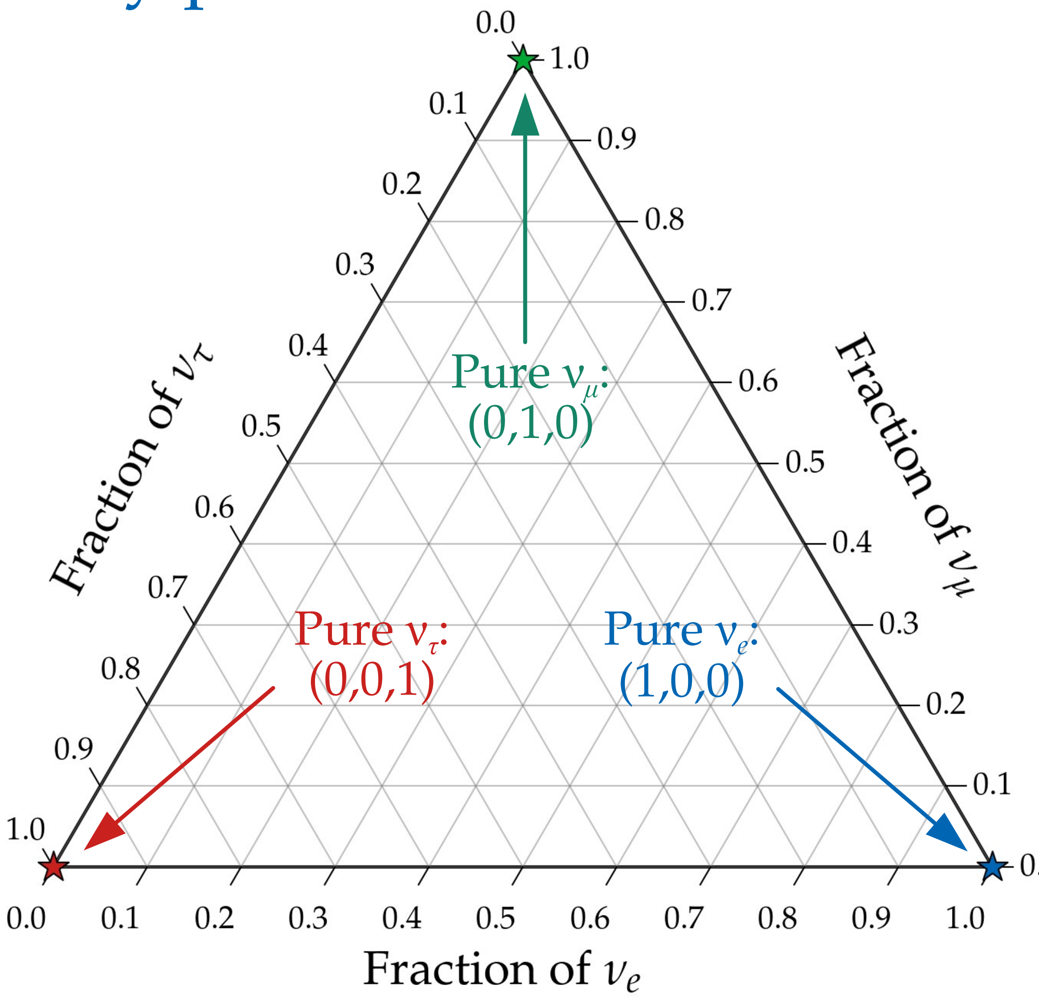

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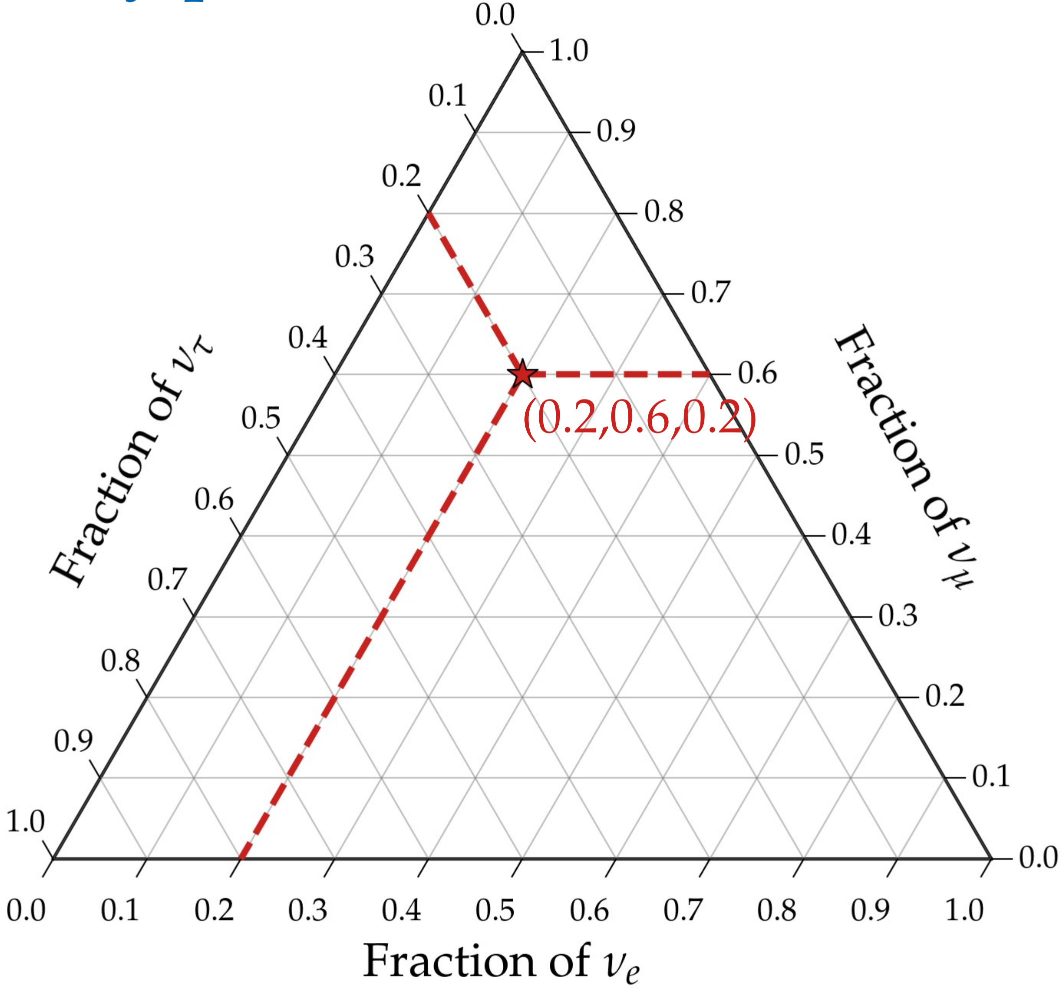

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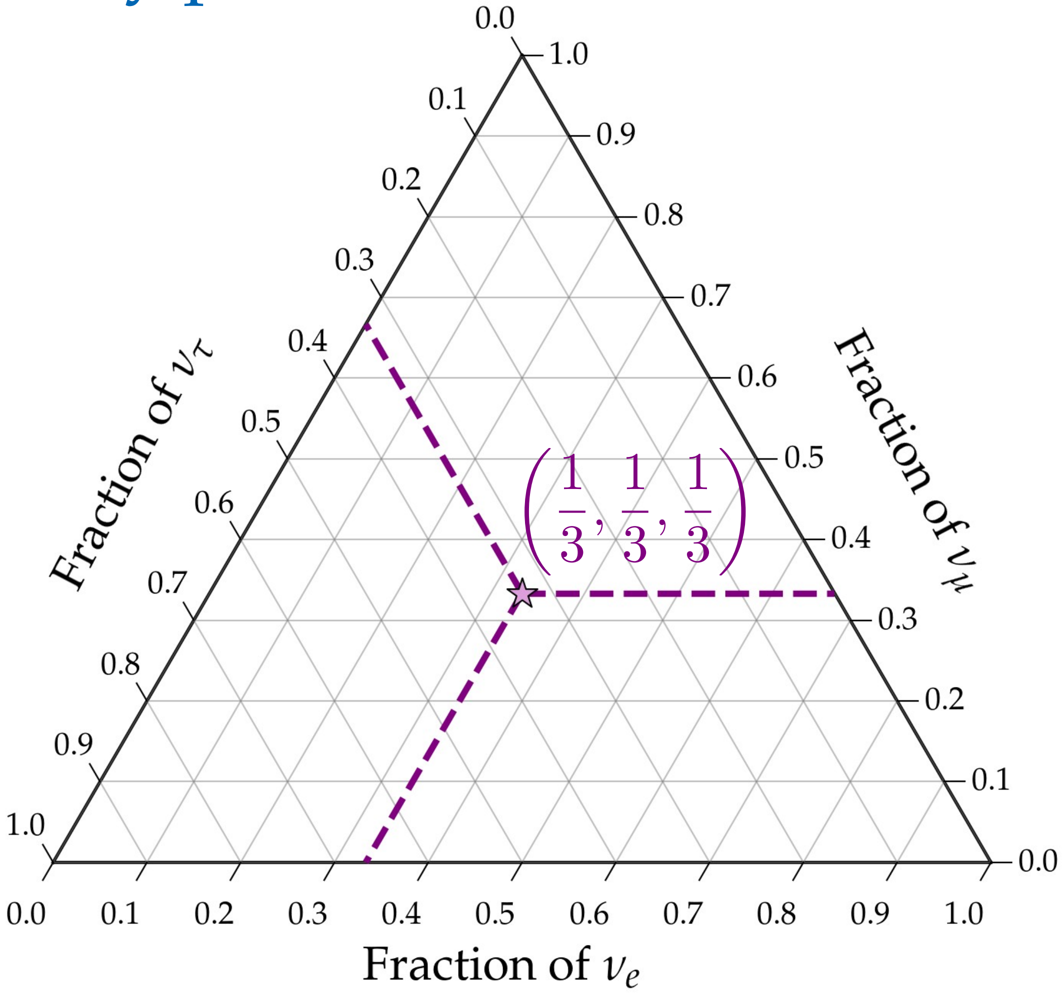

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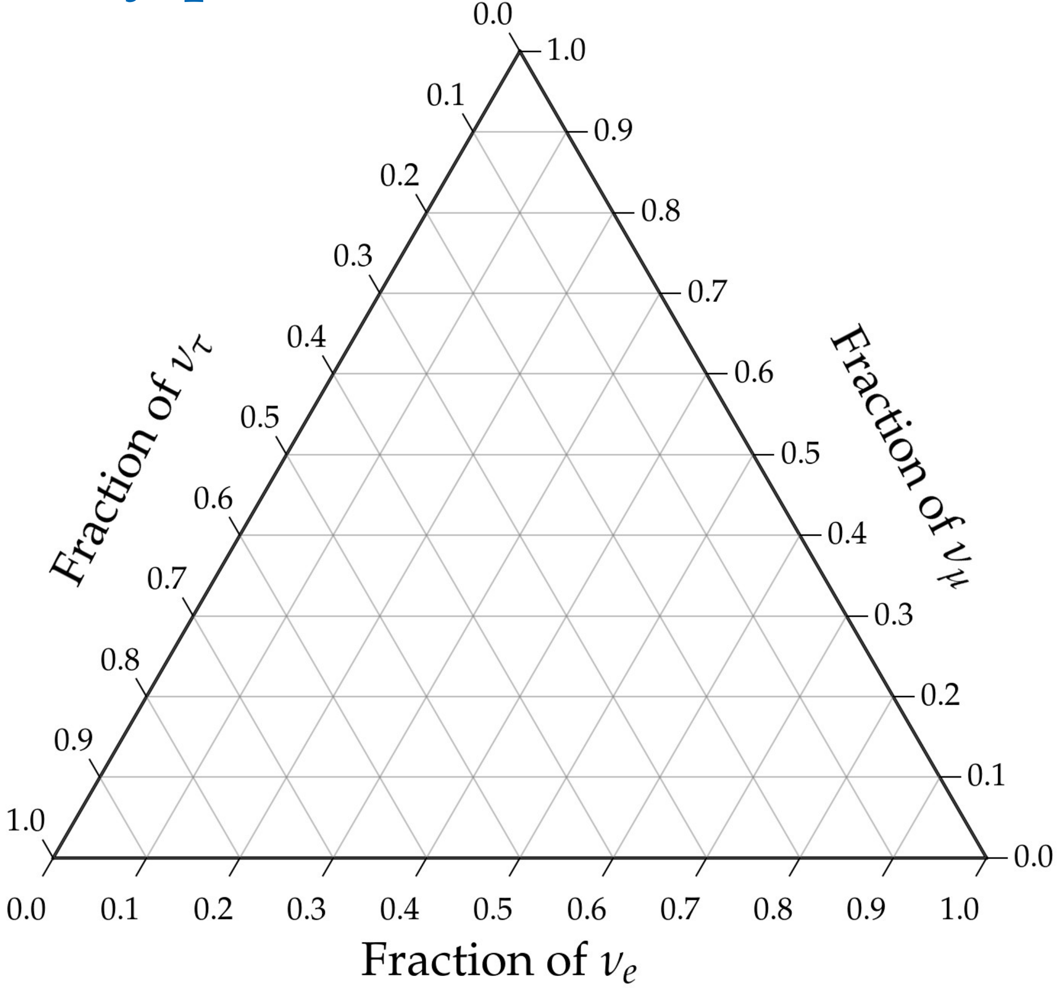

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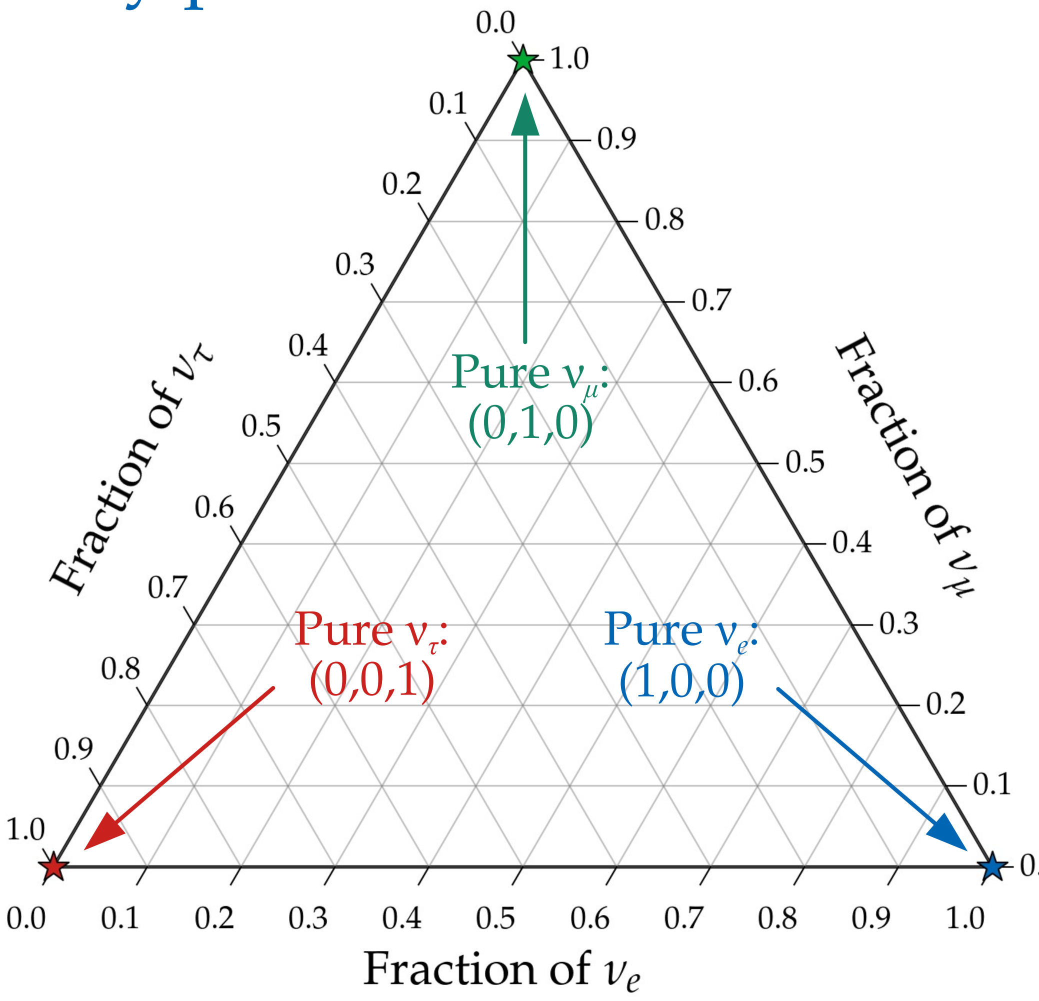

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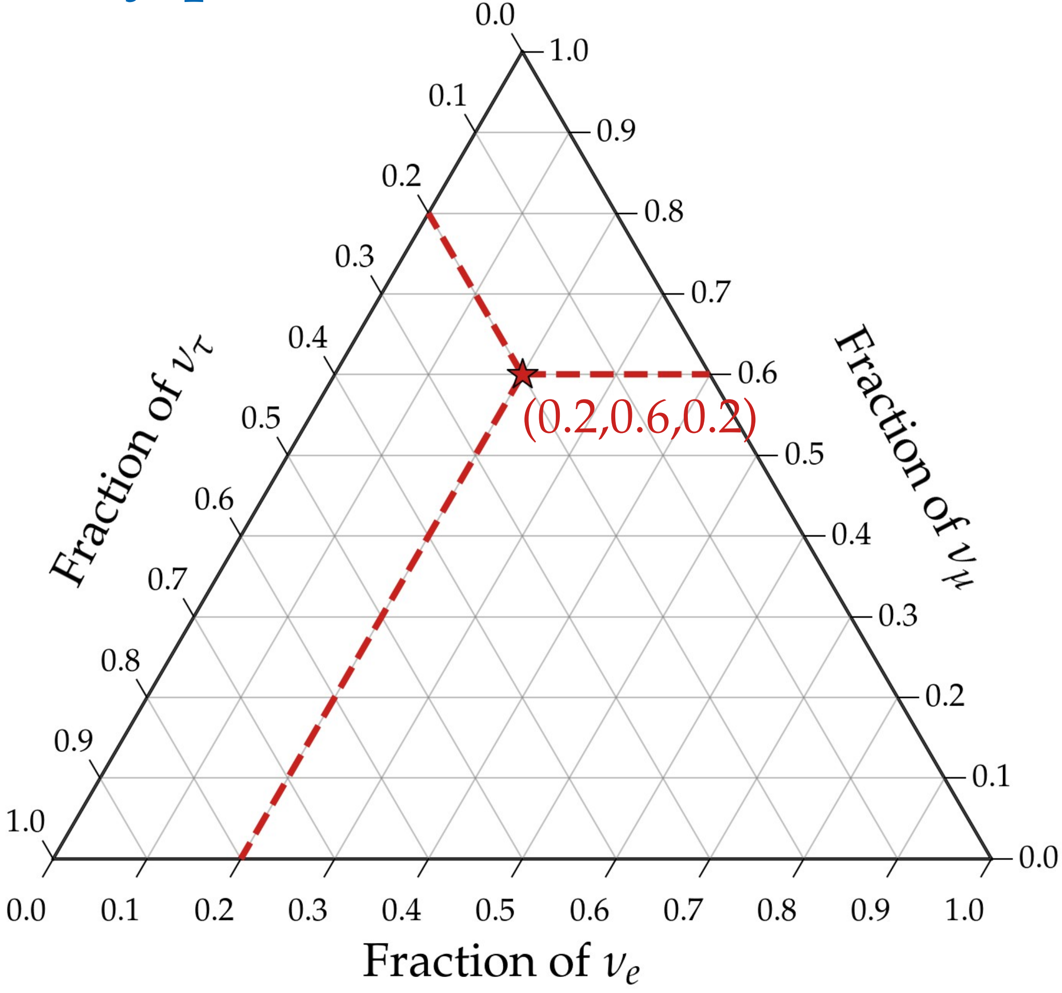

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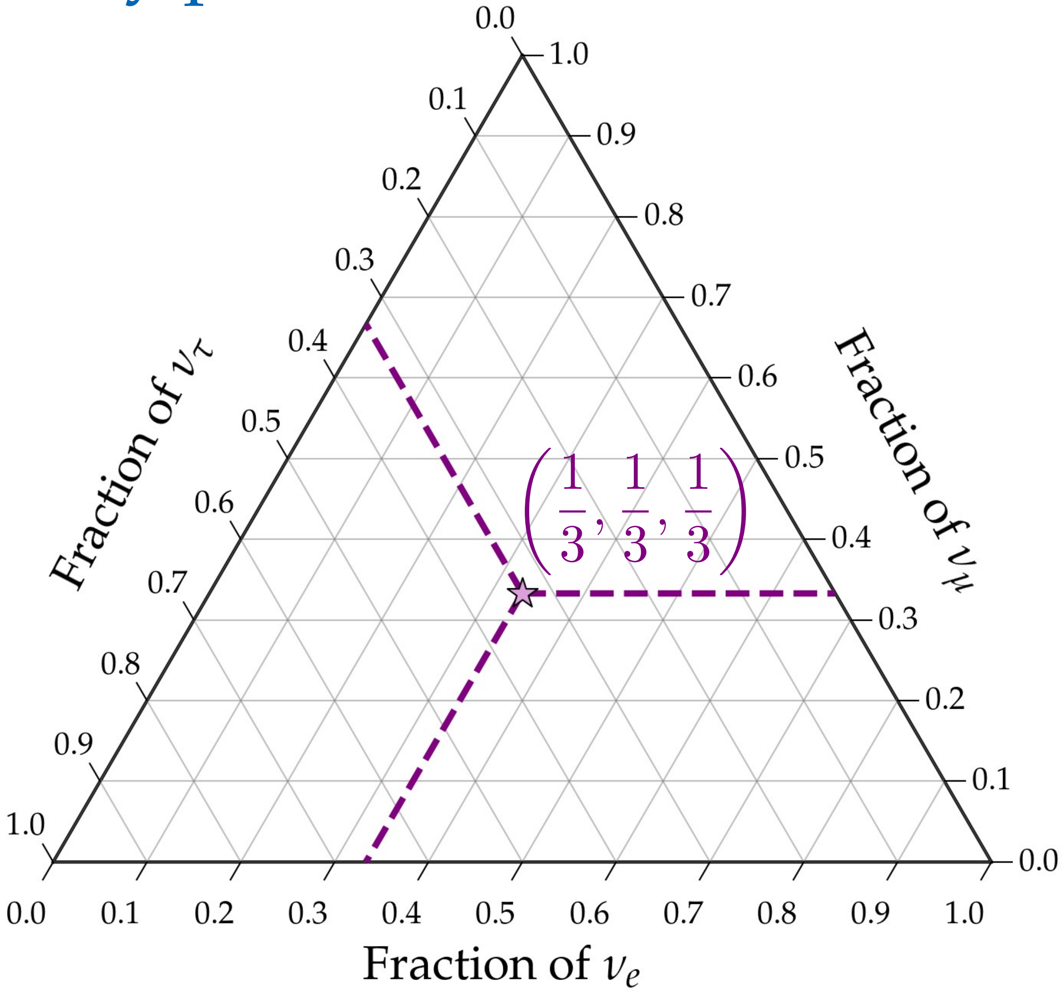
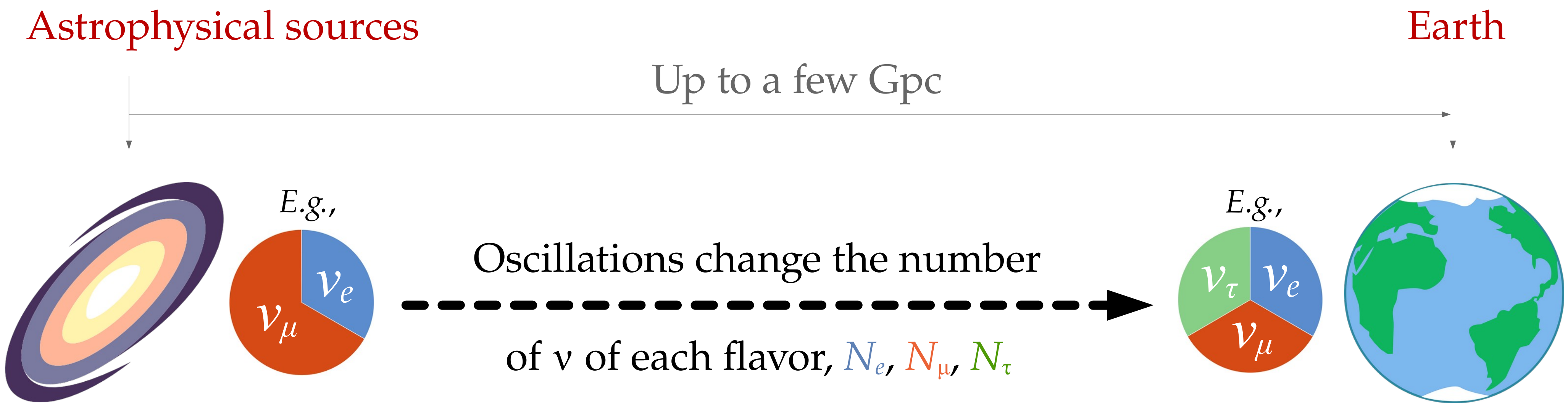


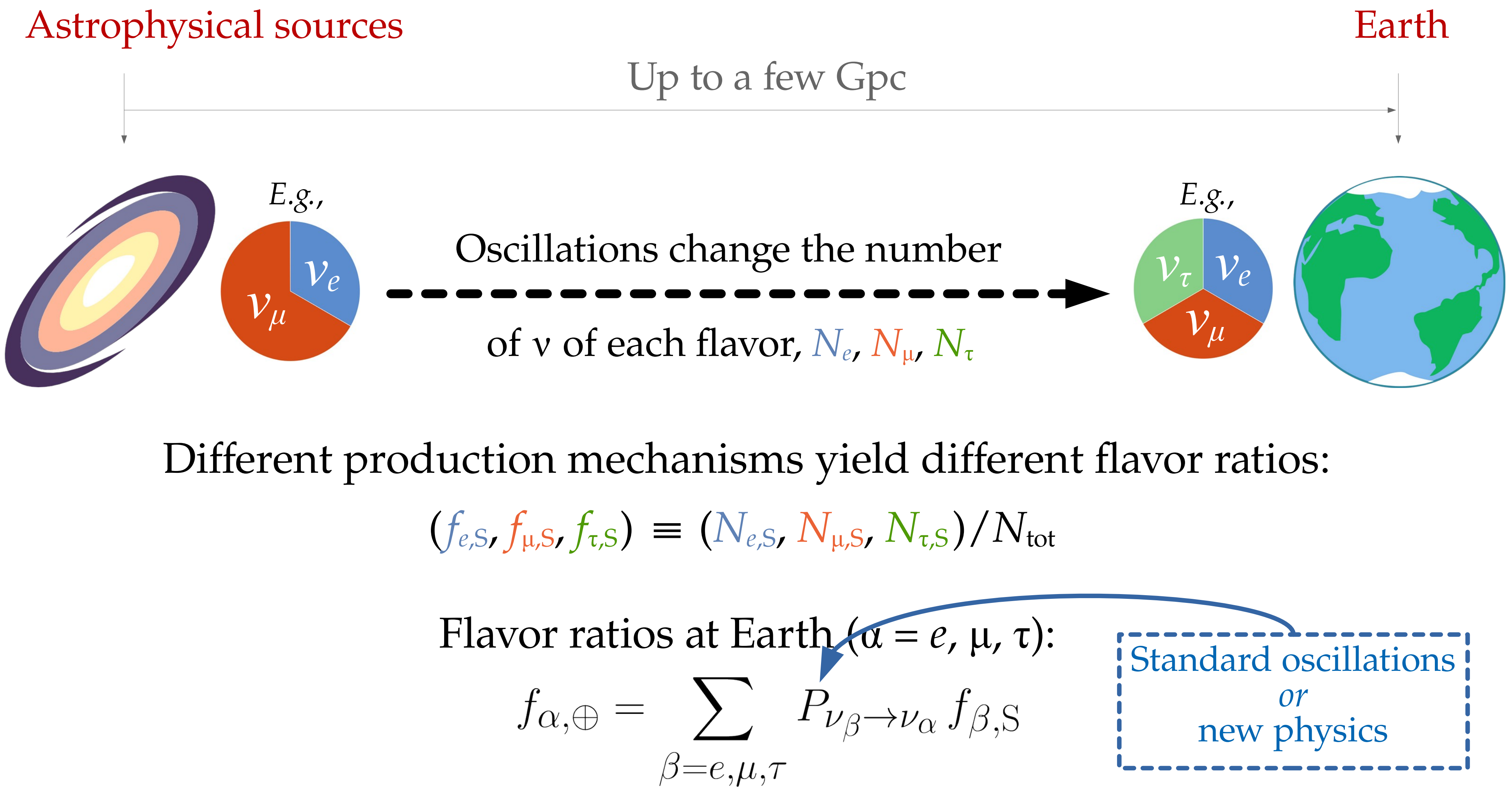


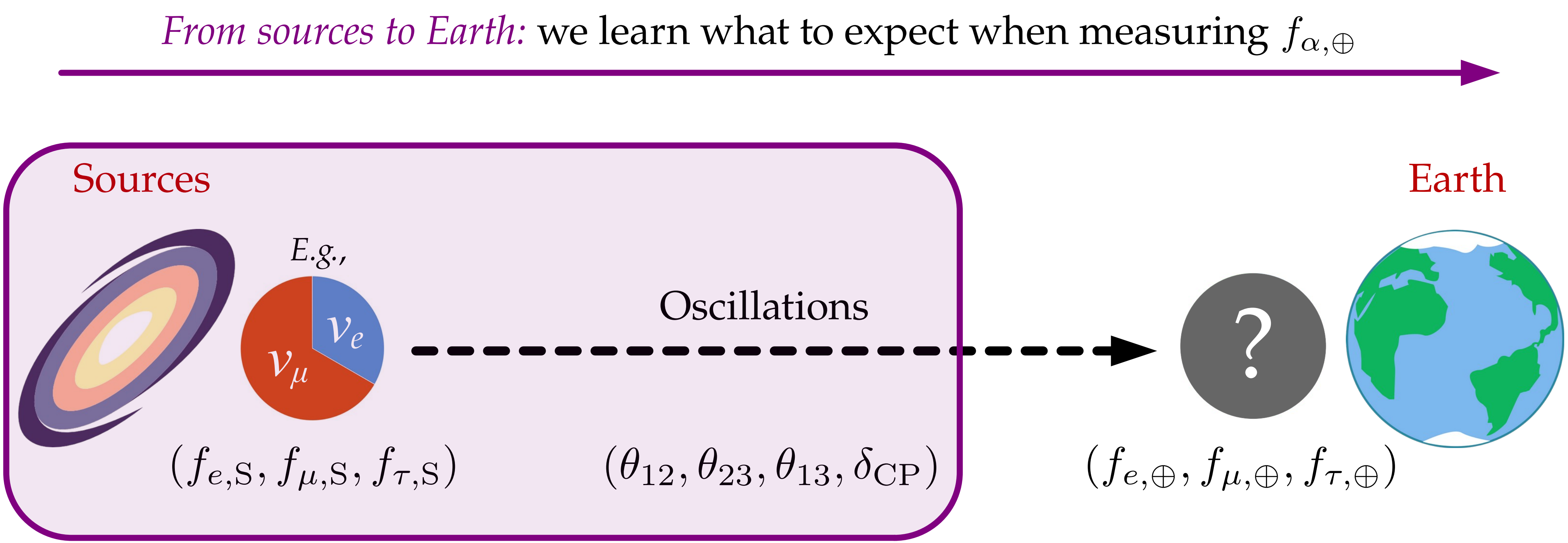
Different production mechanisms yield different flavor ratios:

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

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

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


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



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

One likely TeV–PeV ν production scenario:

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

Full π decay chain

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

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

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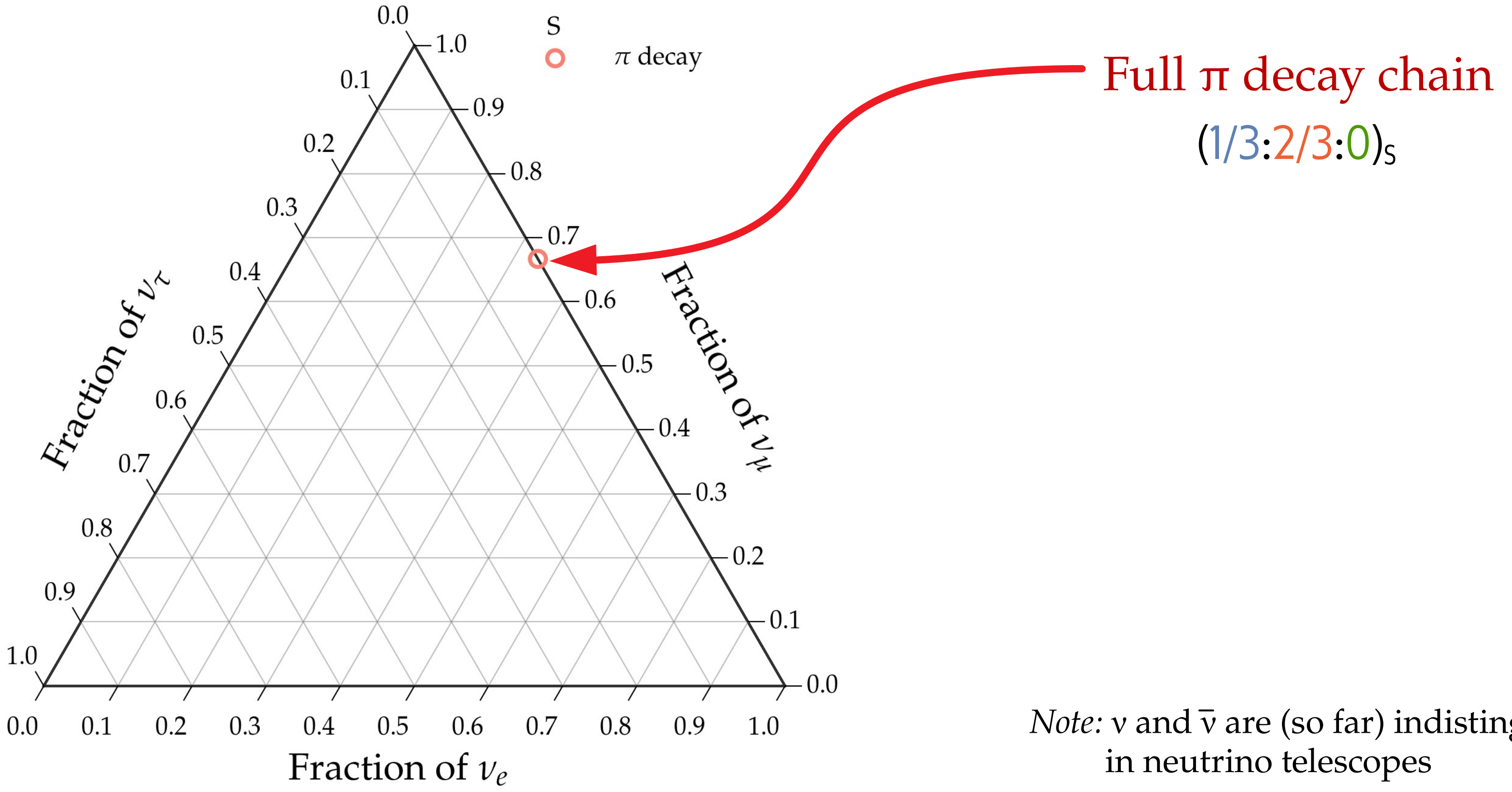

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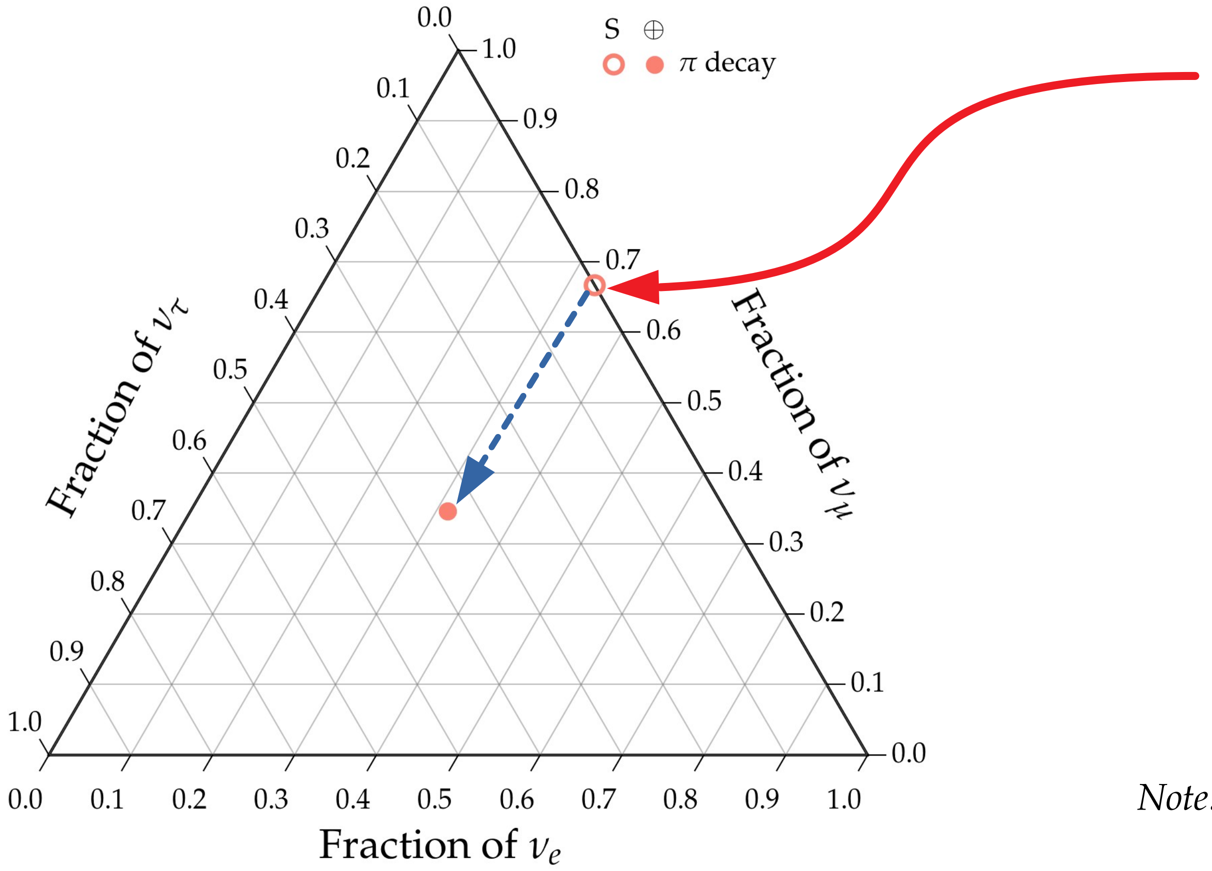

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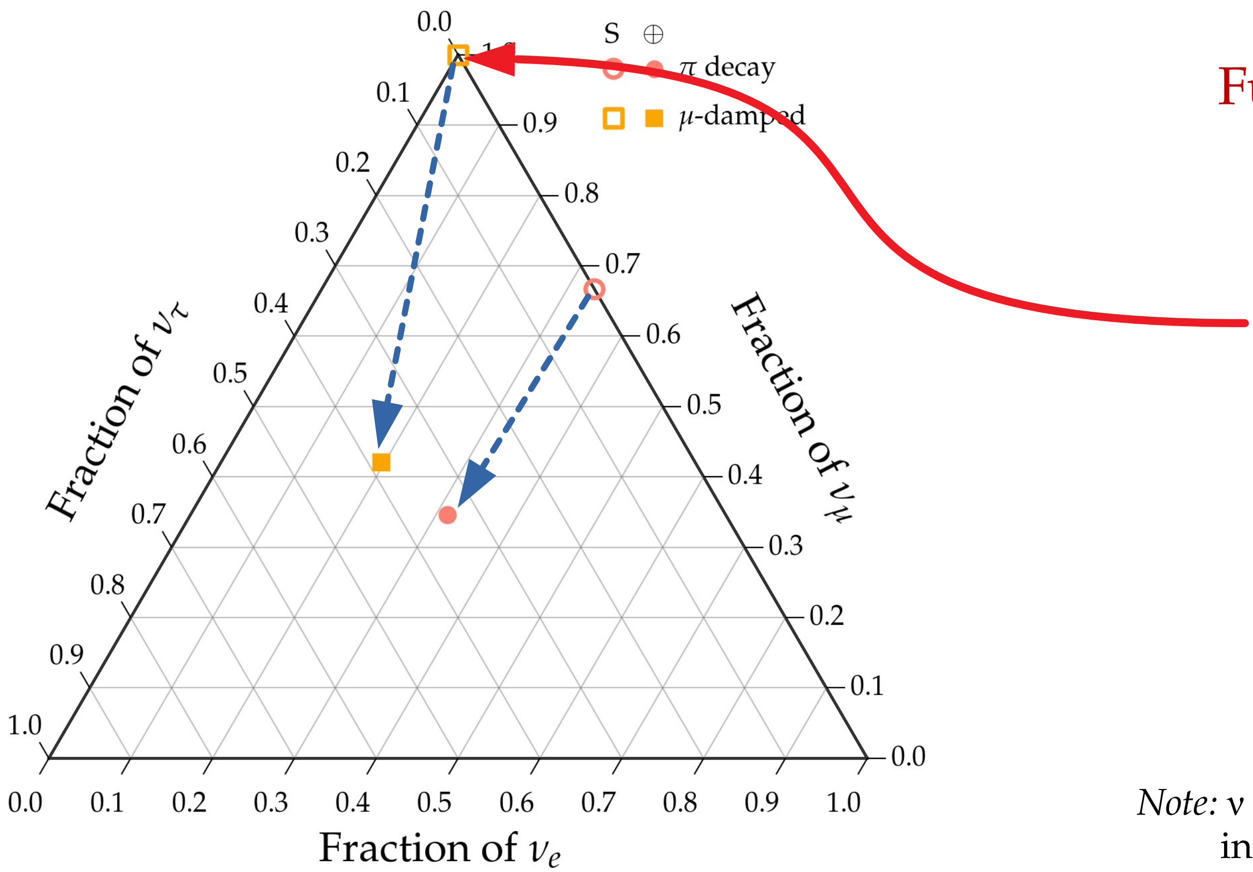

Full π decay chain

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

Muon damped

(0:1:0)$_S$

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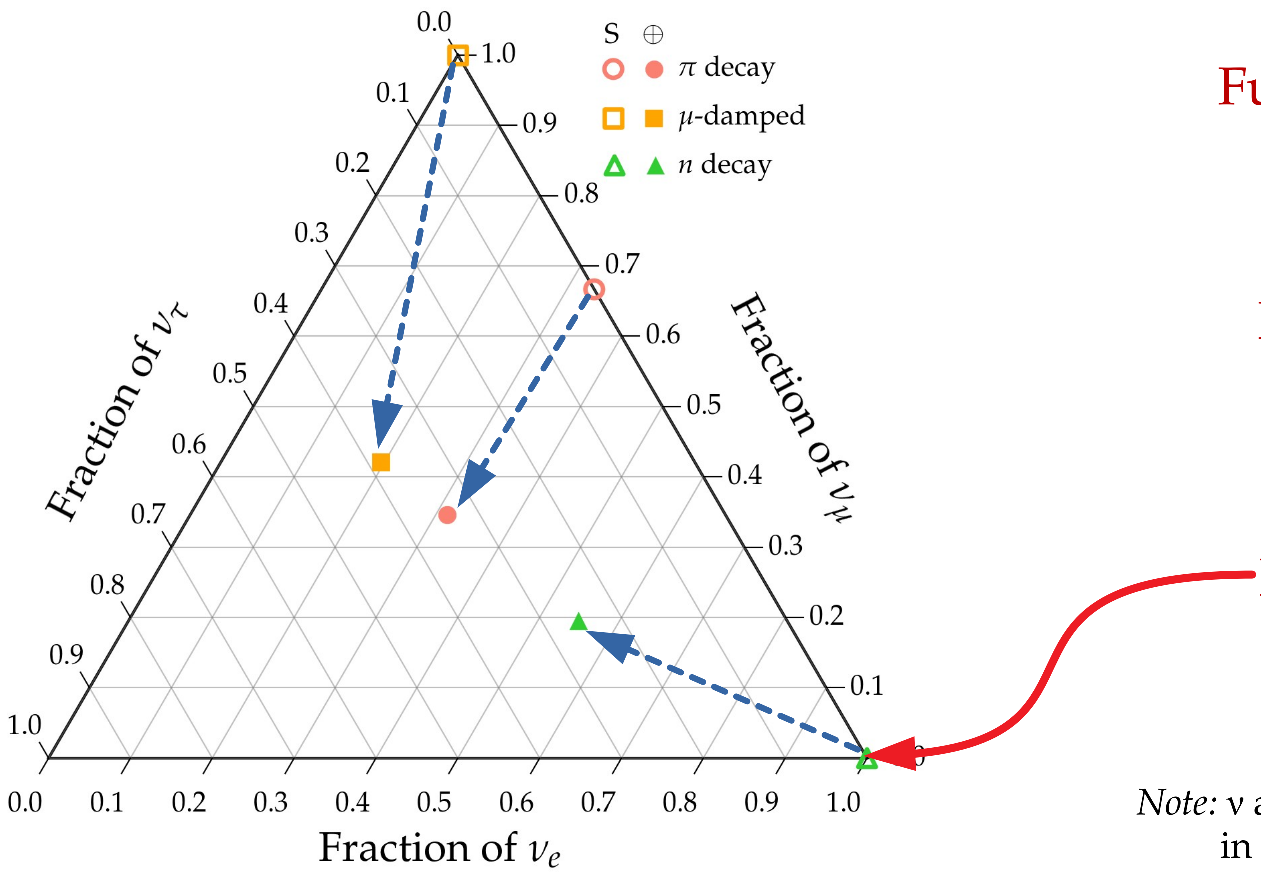


Full π decay chain

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

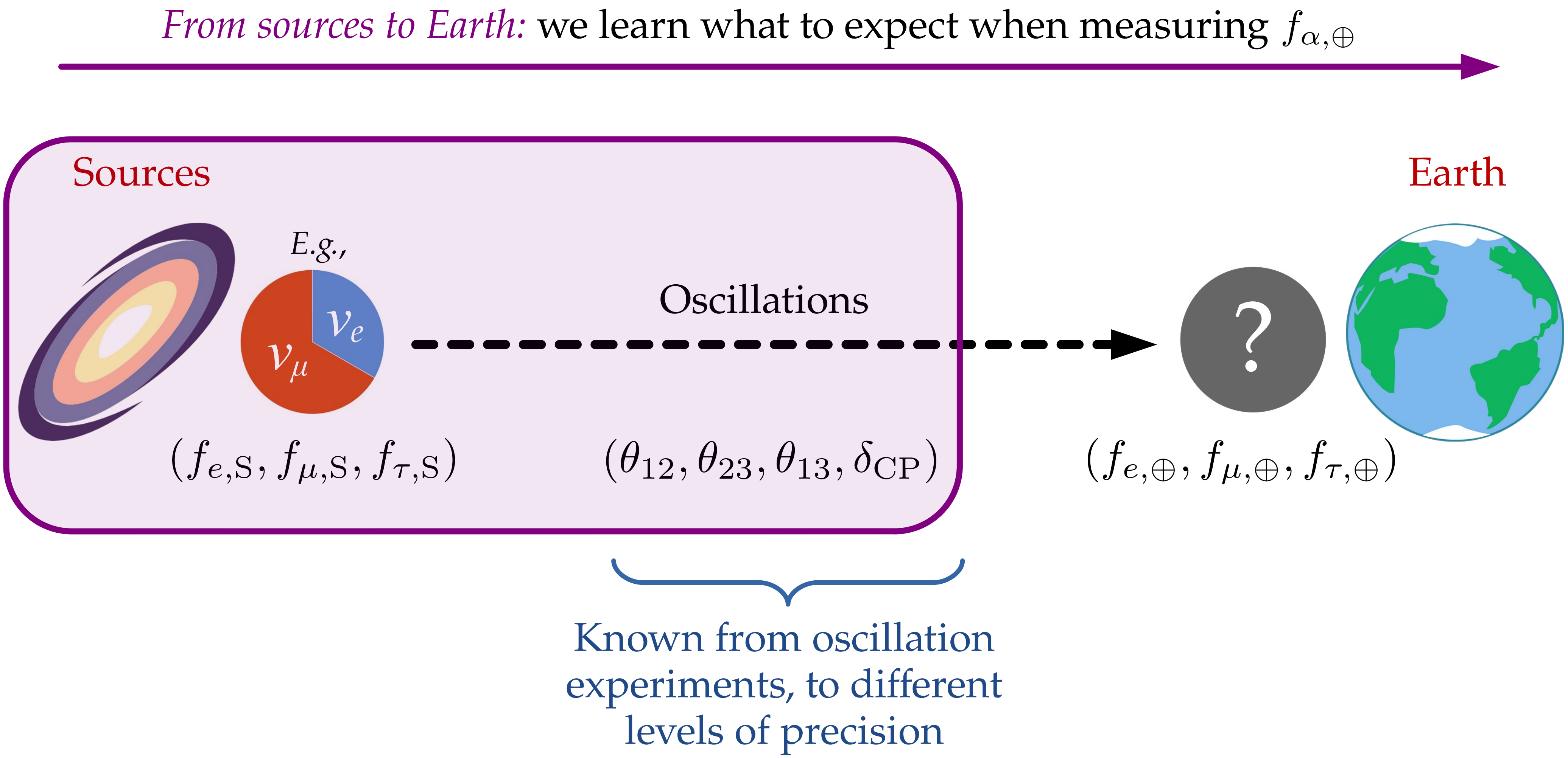
Muon damped

$(0 : 1 : 0)_S$

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

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

Allowed regions of flavor ratios at Earth derived from oscillations

MB, Beacom, Winter, *PRL* 2015

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

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Flavor ratios at the source,

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

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

or

Explore all possible combinations

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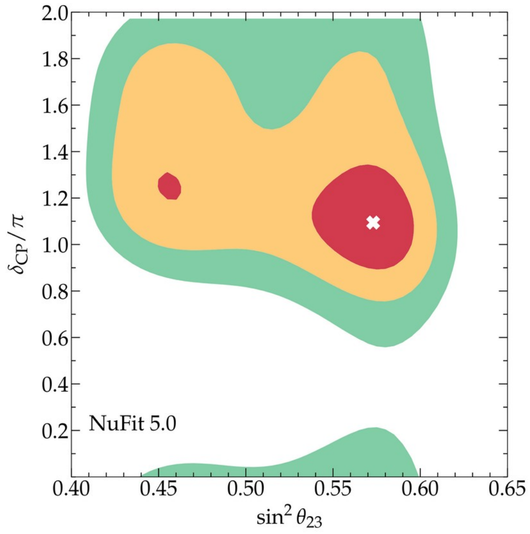
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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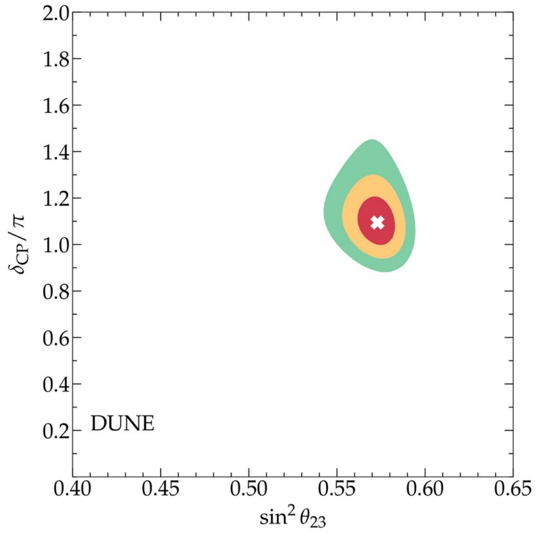
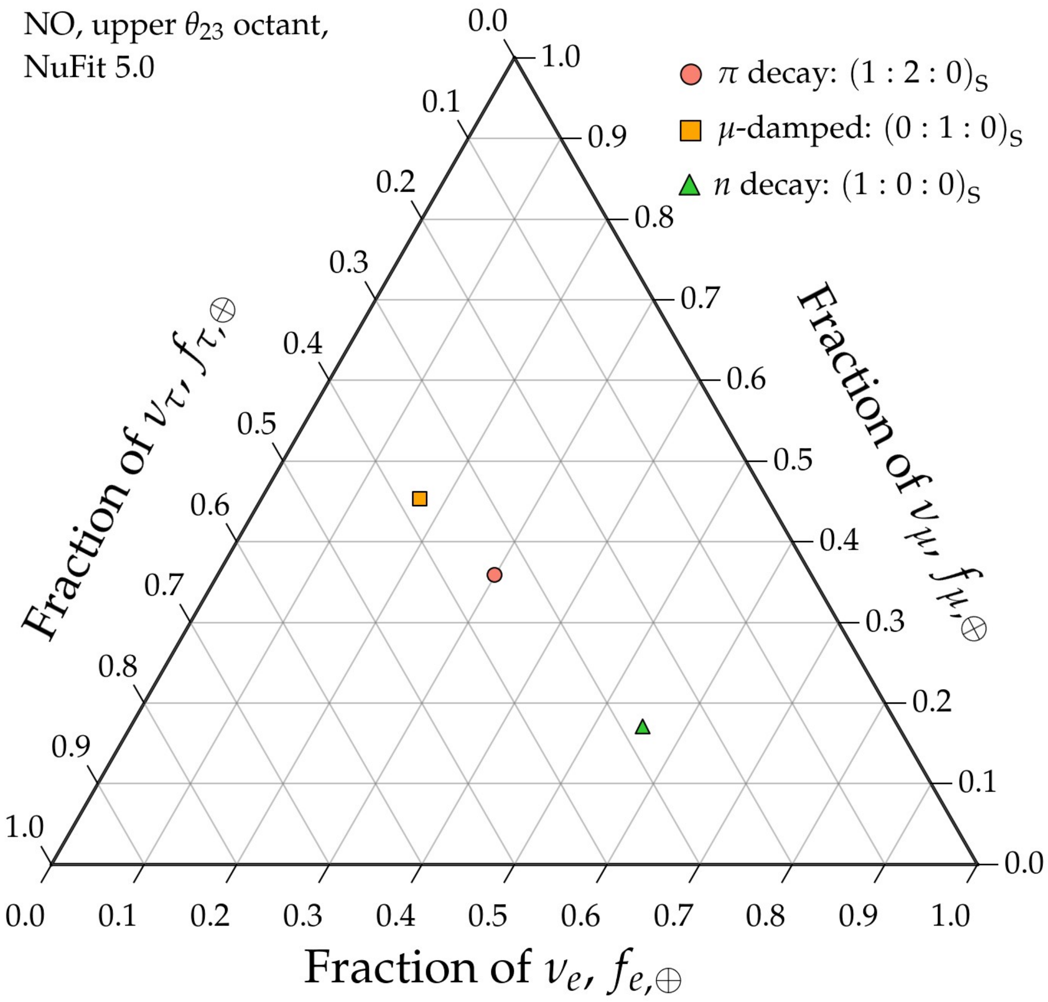
Post-2020: Build our own profiles using simulations of JUNO, DUNE, Hyper-K

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



Theoretically palatable regions: today (2021)



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

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

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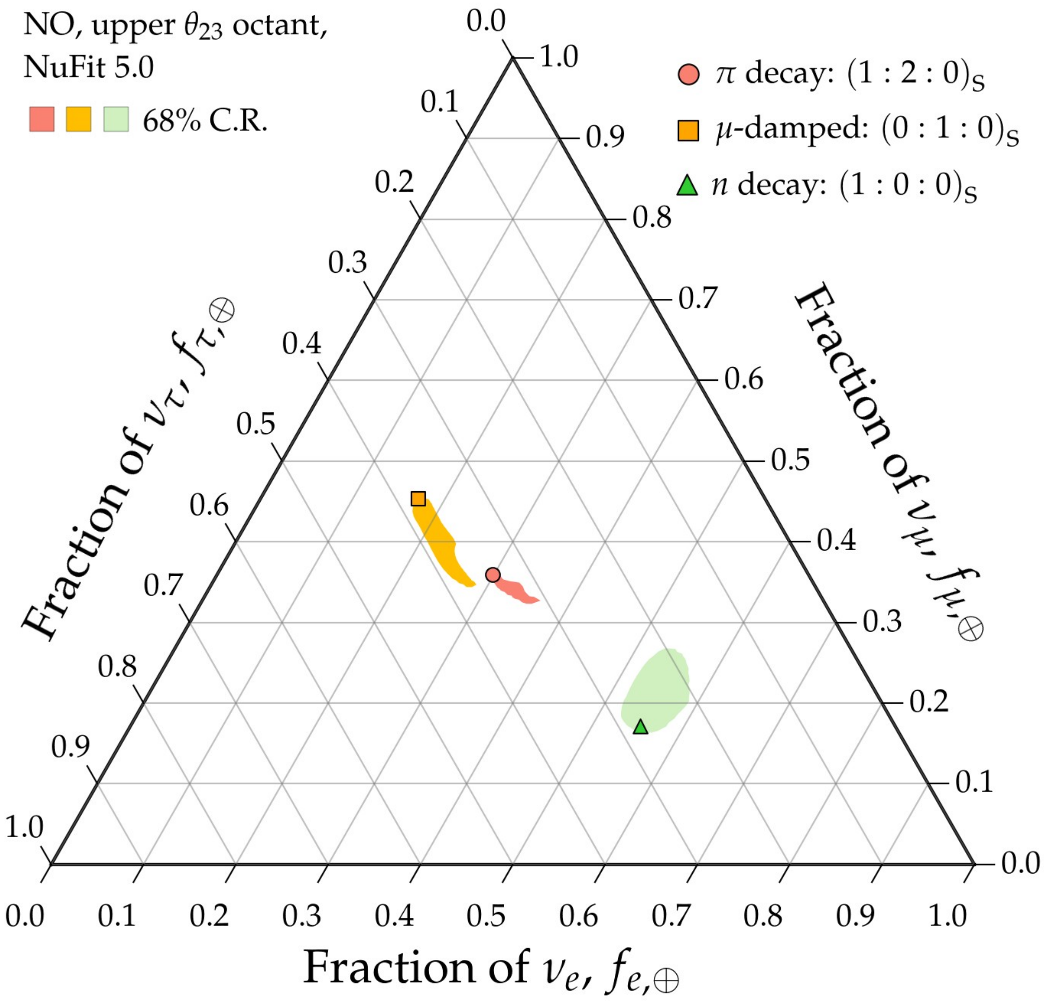

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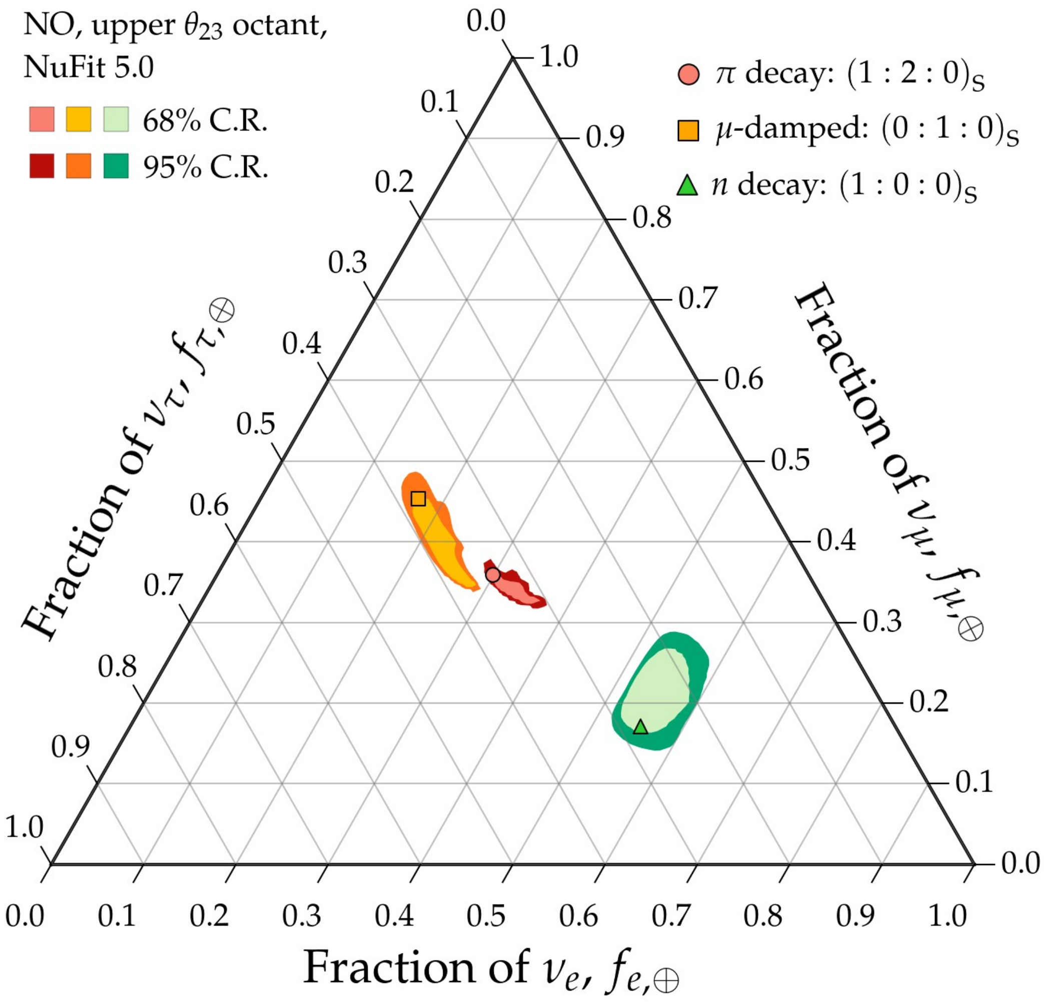

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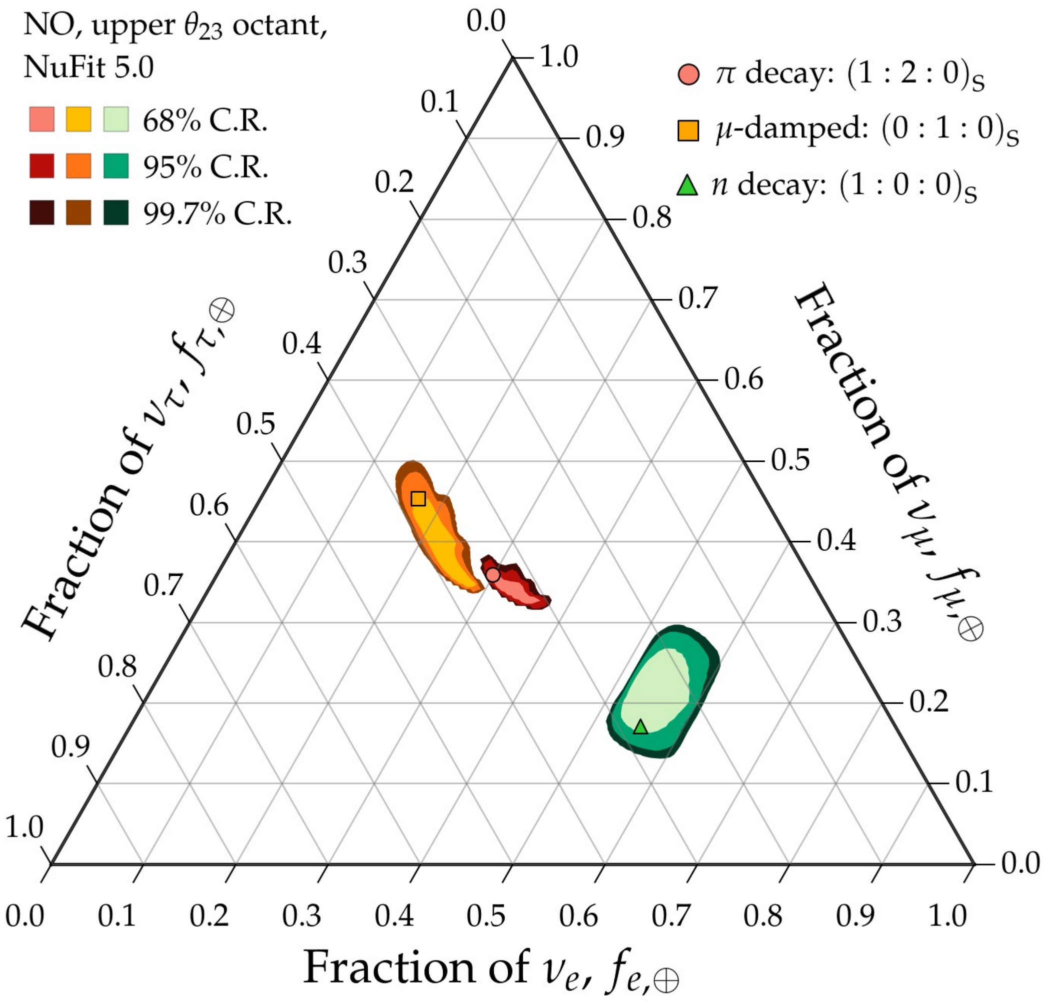

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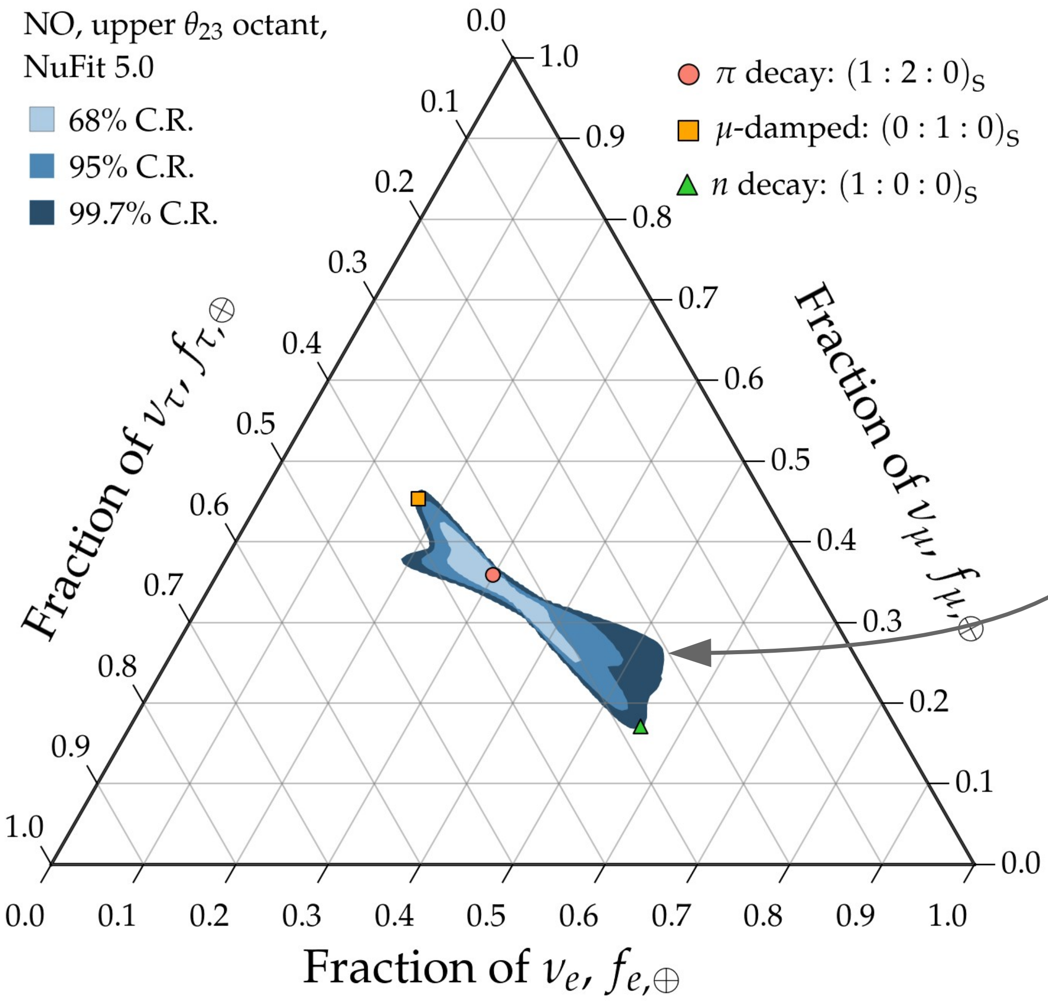

Varying over all possible flavor ratios at the source

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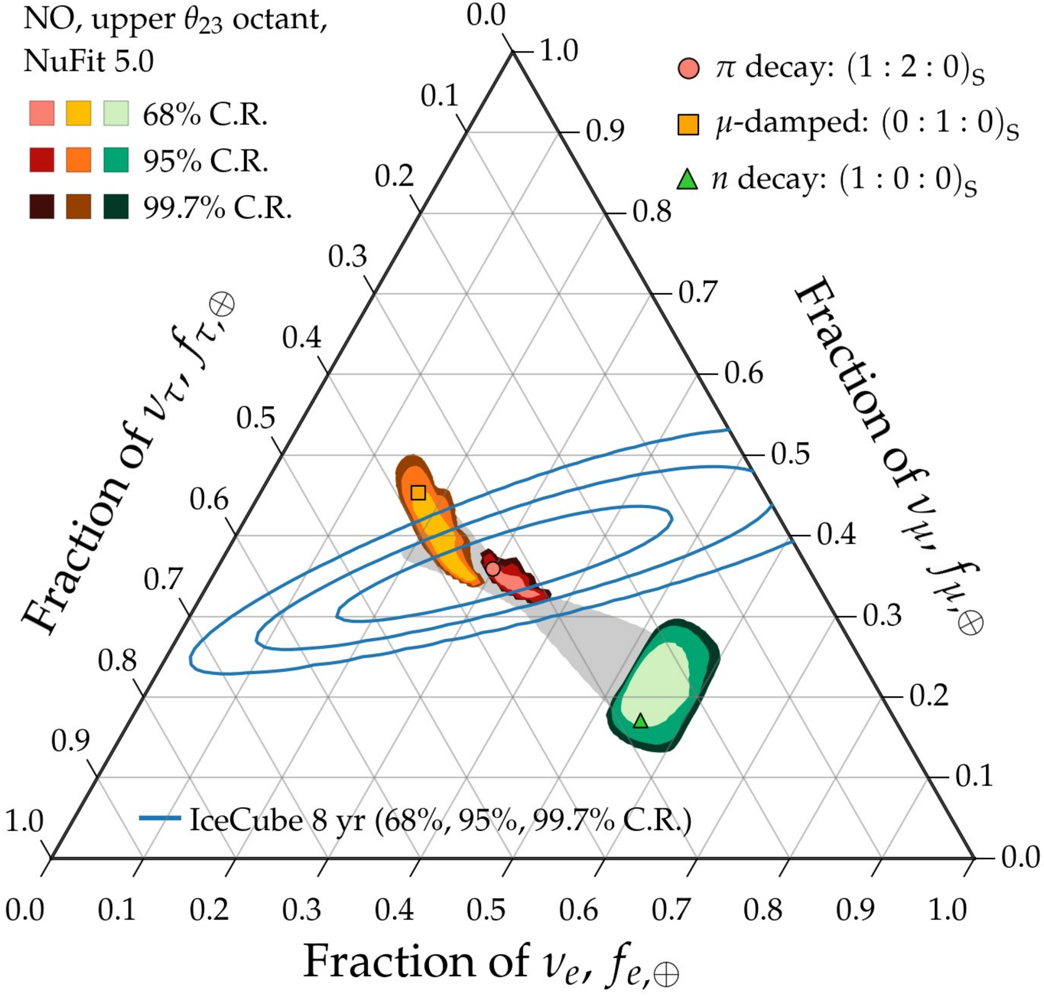
Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Theoretically palatable regions: today (2021)



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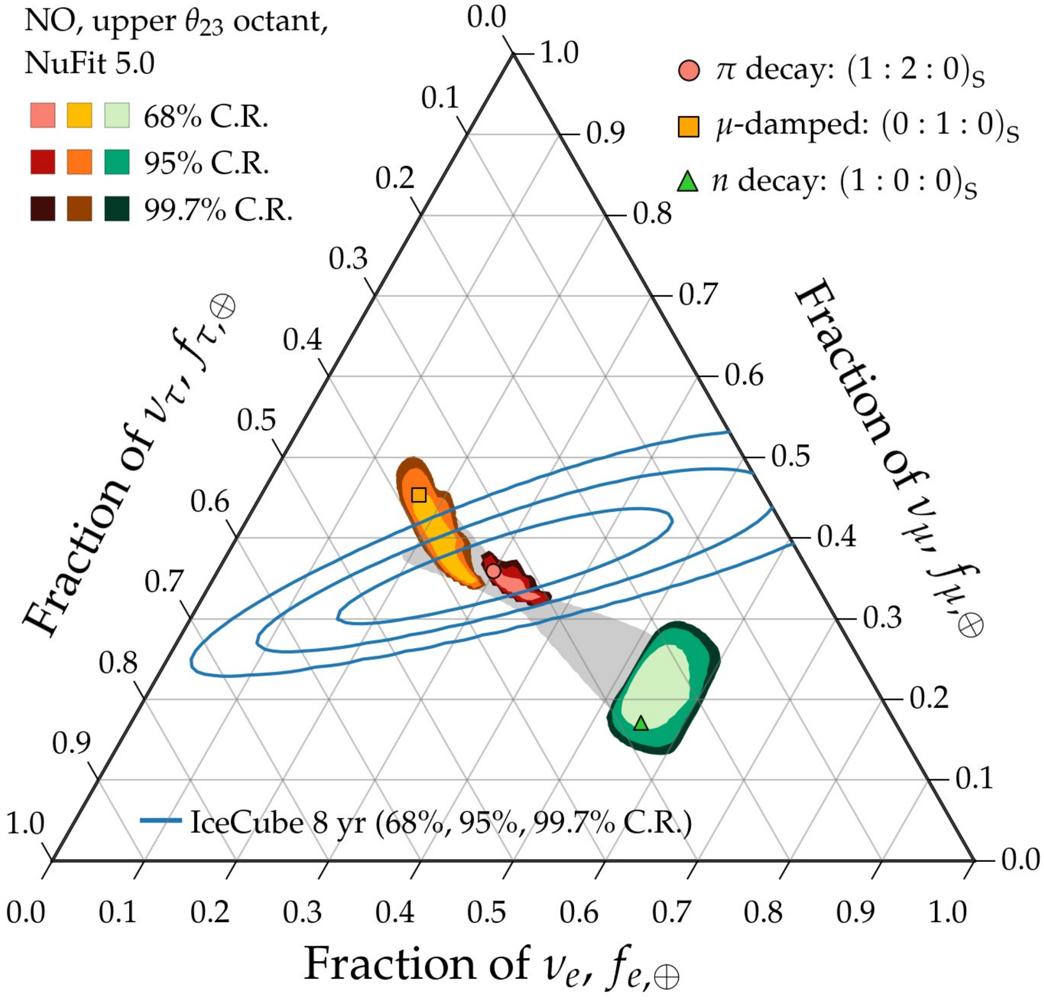

Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

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

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

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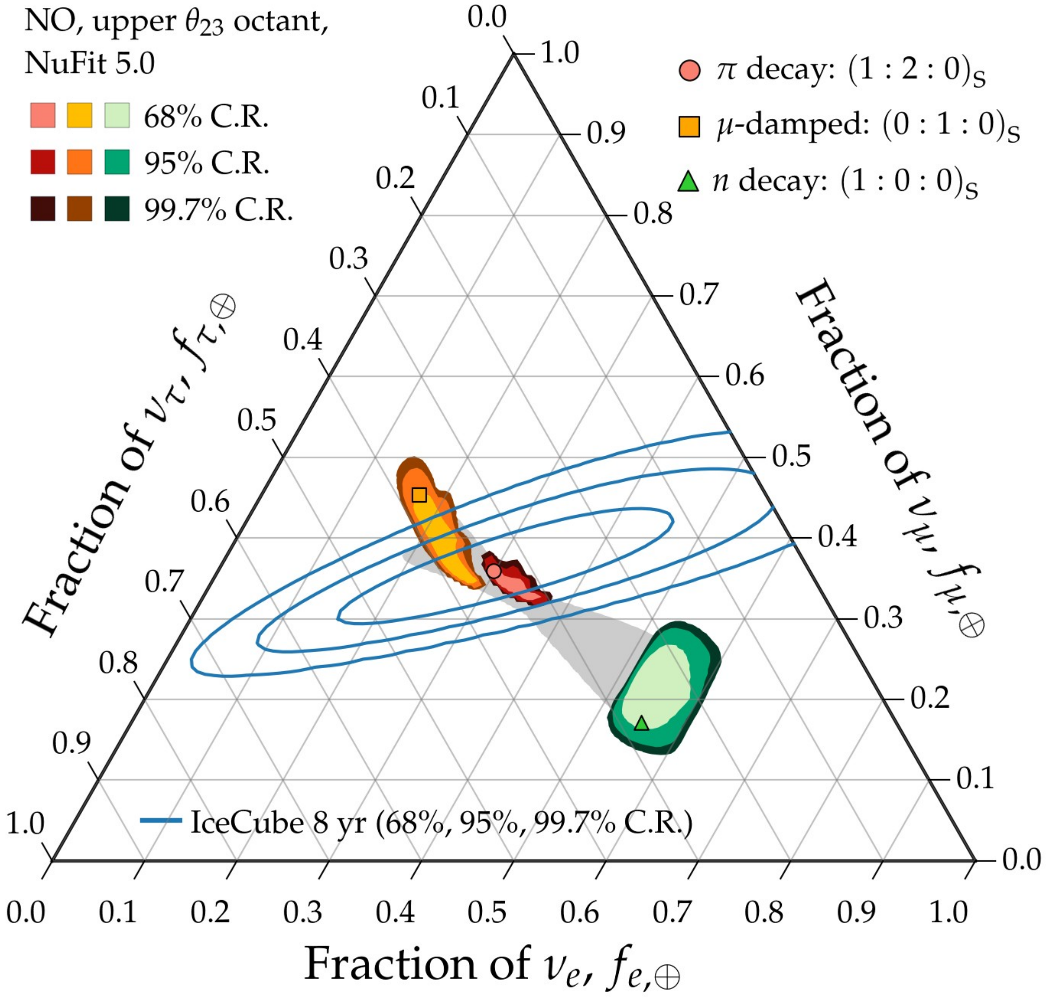

Two limitations:

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Will be overcome by 2030

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

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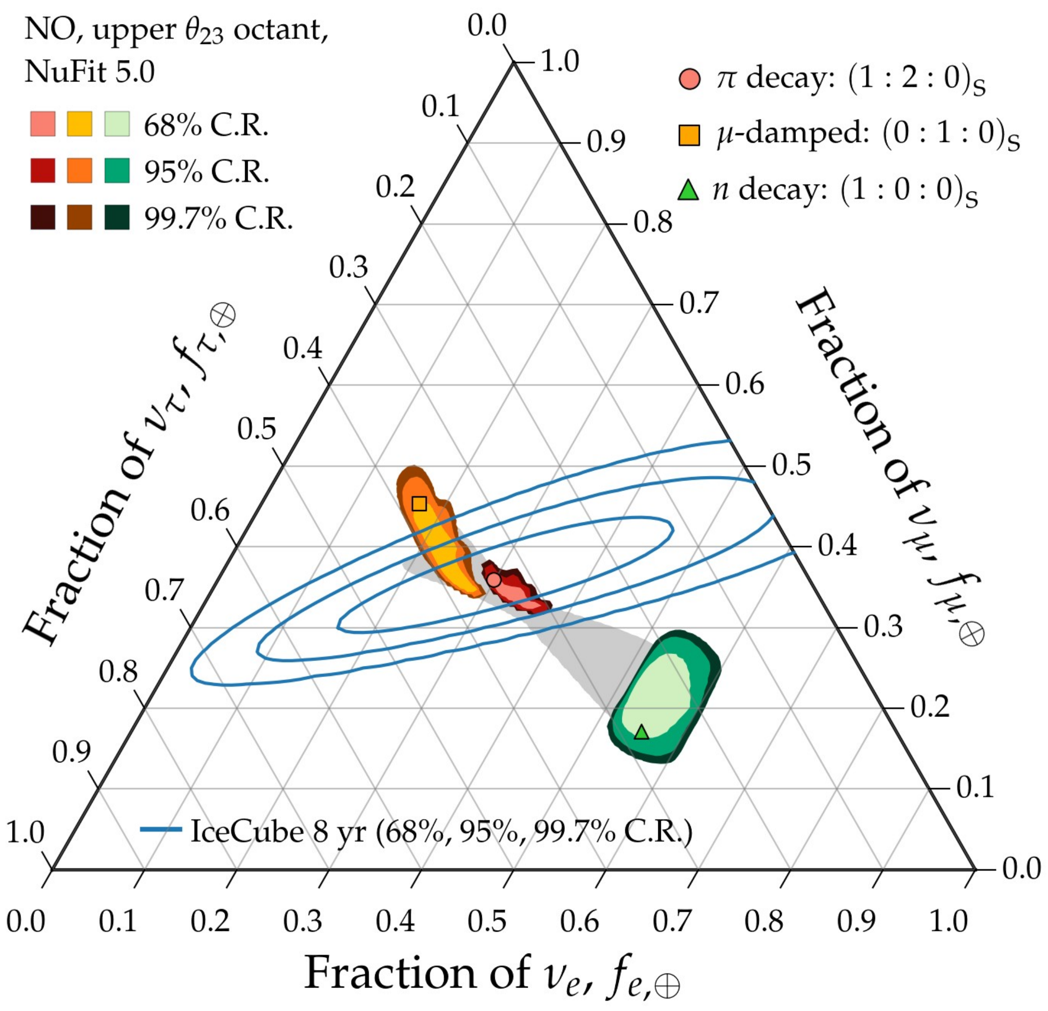

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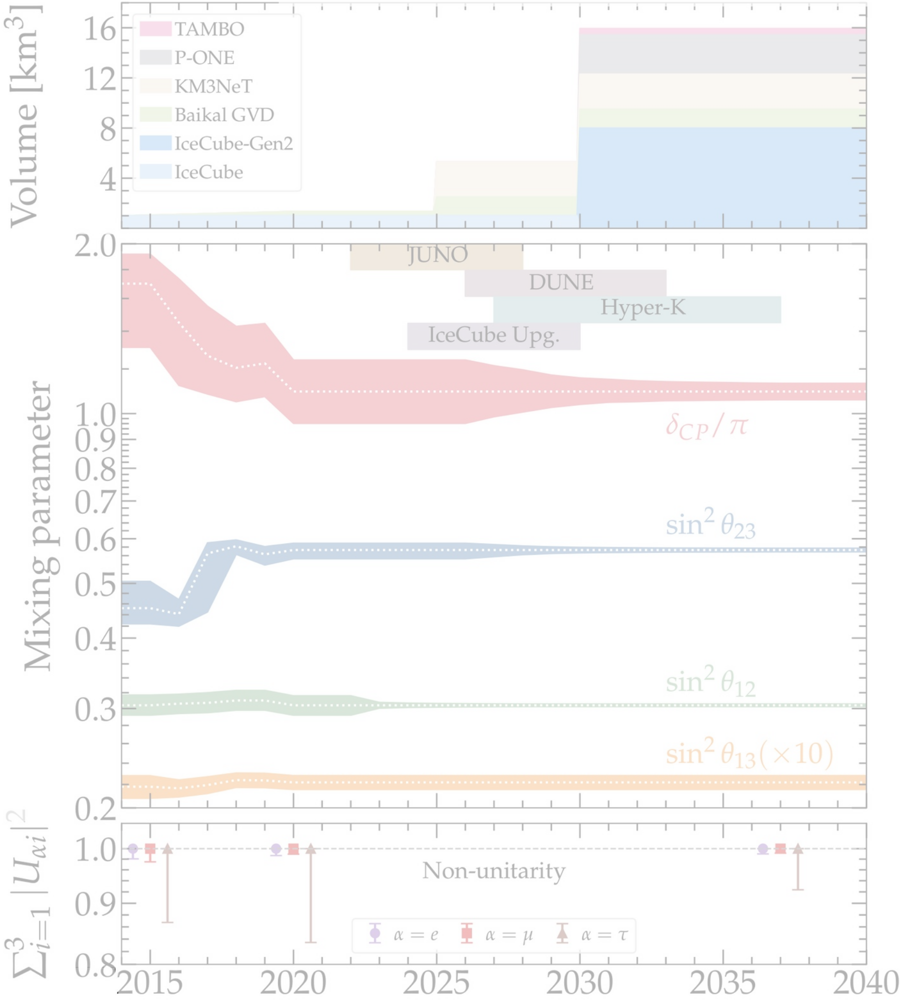
Will be overcome by 2040

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

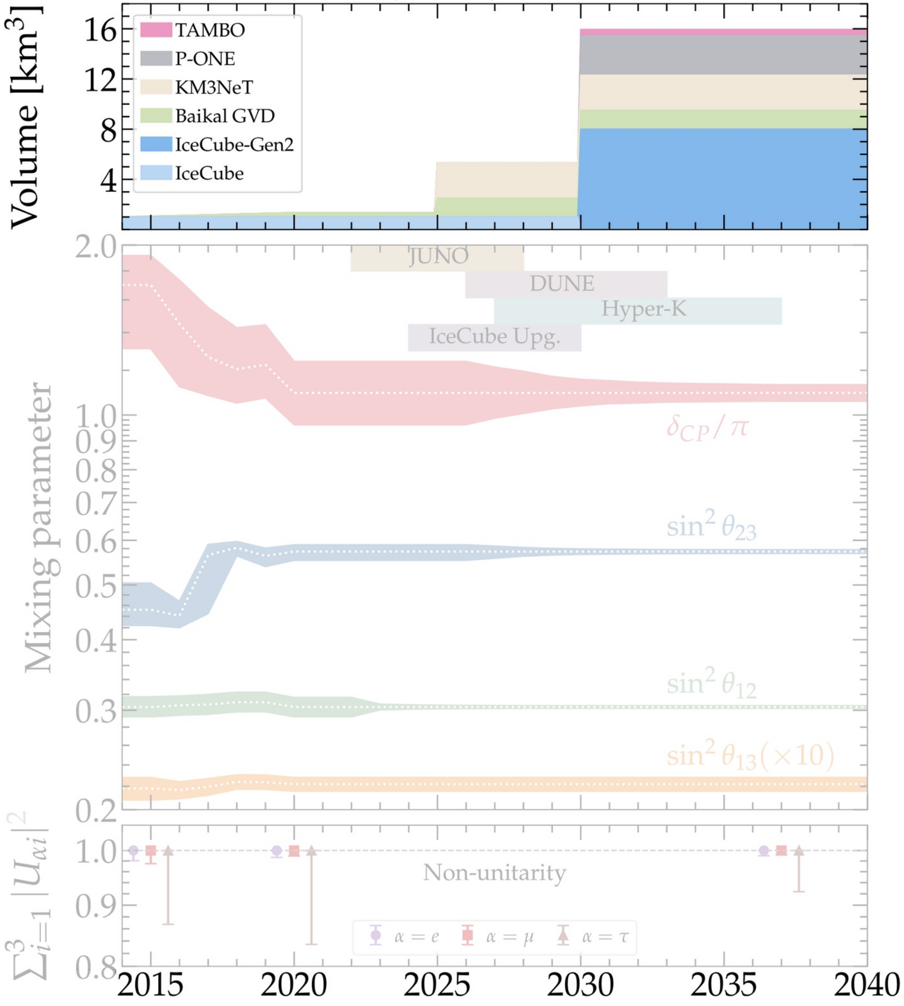
Three reasons to be excited

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



Three reasons to be excited

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



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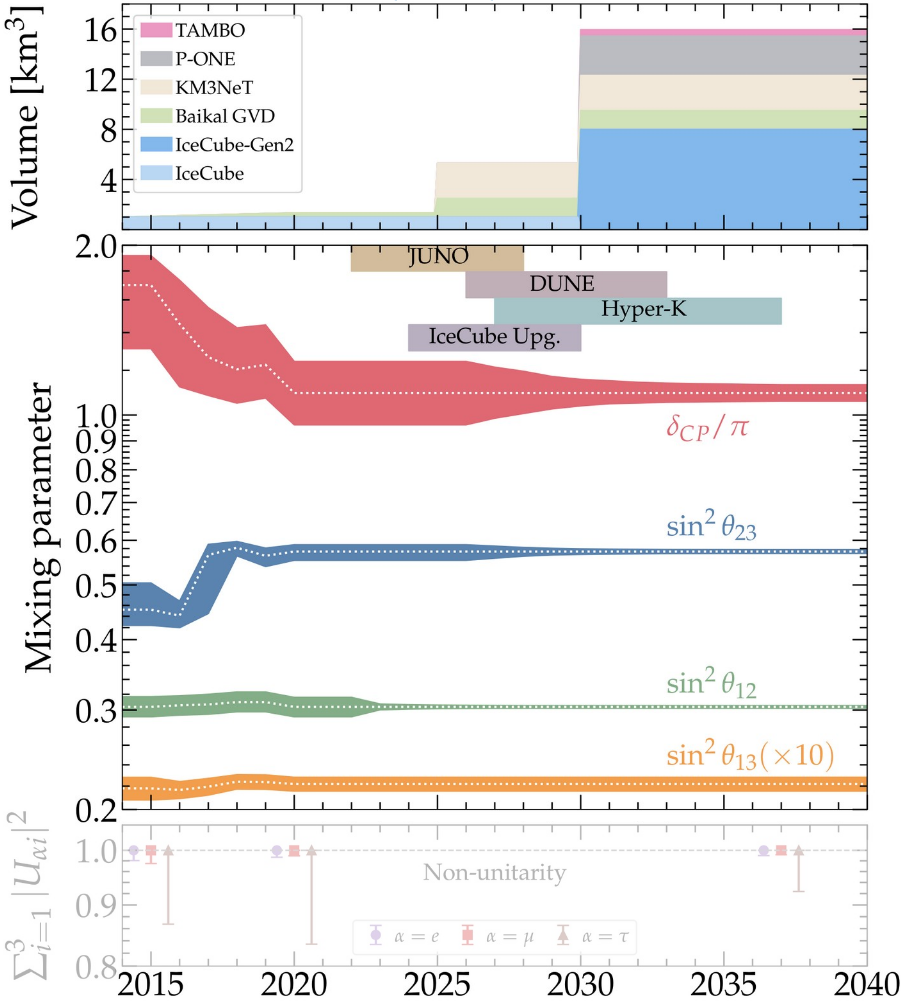

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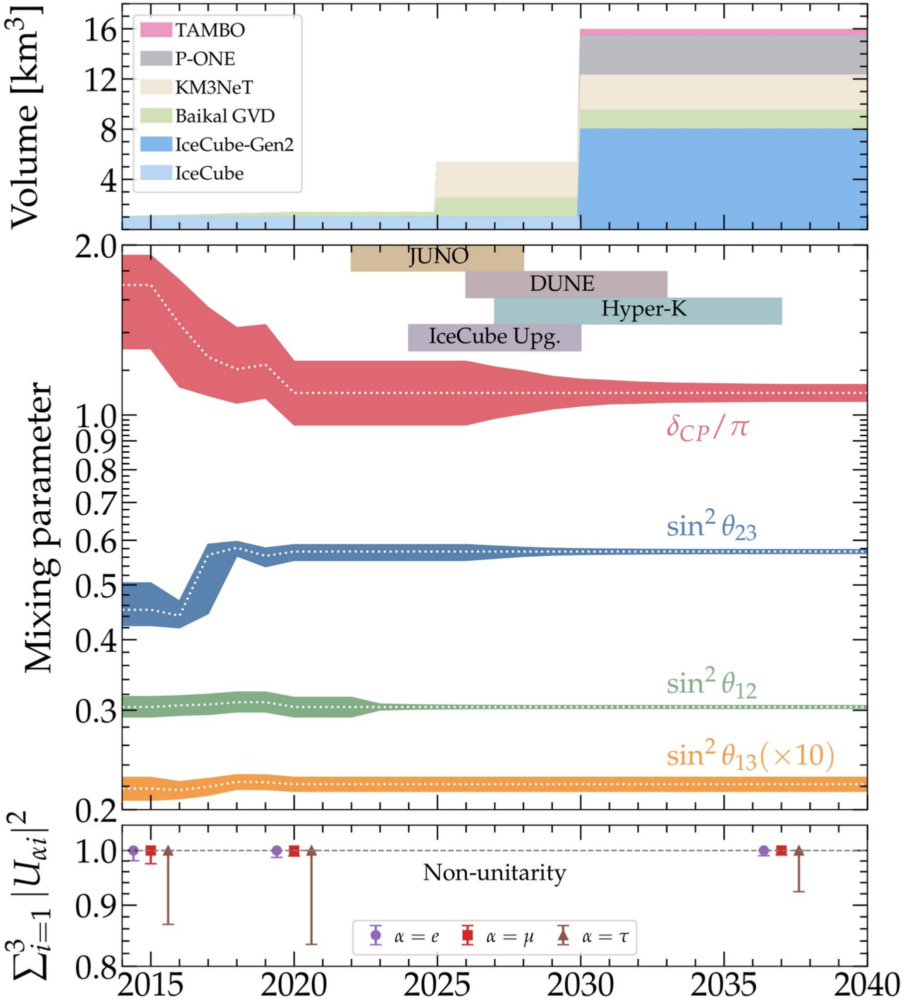

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Measuring flavor composition: 2015–2040

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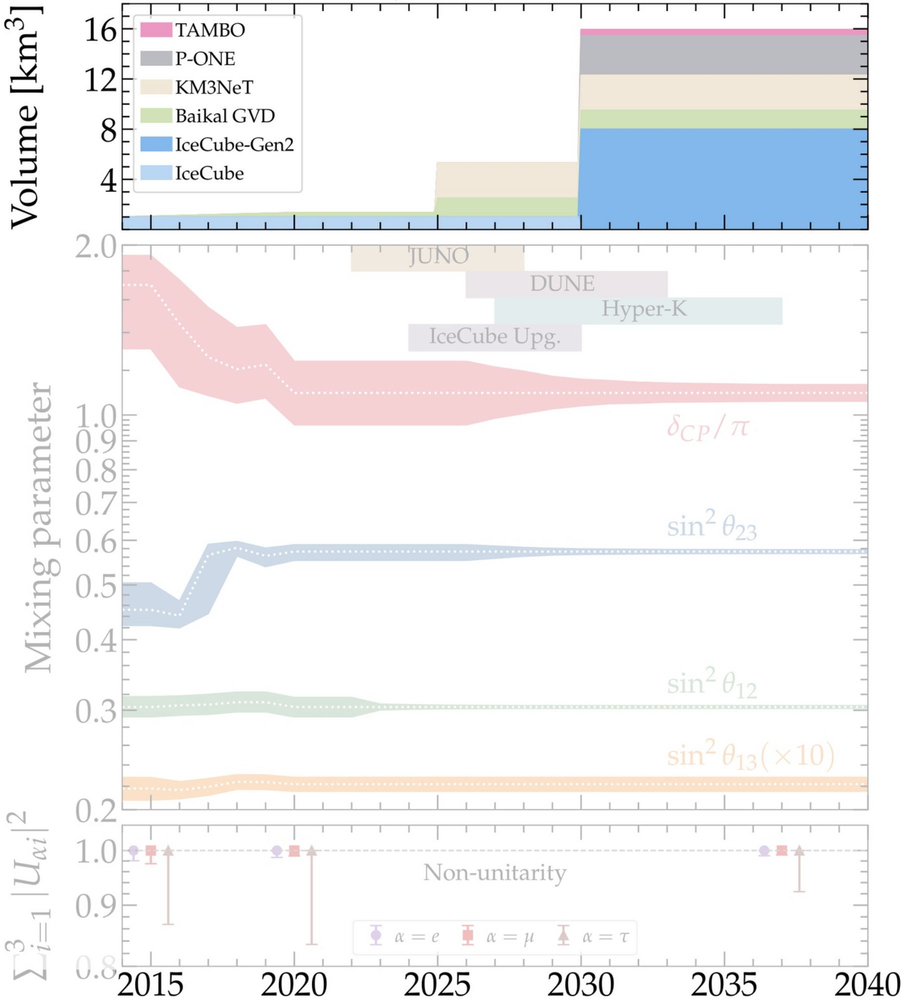

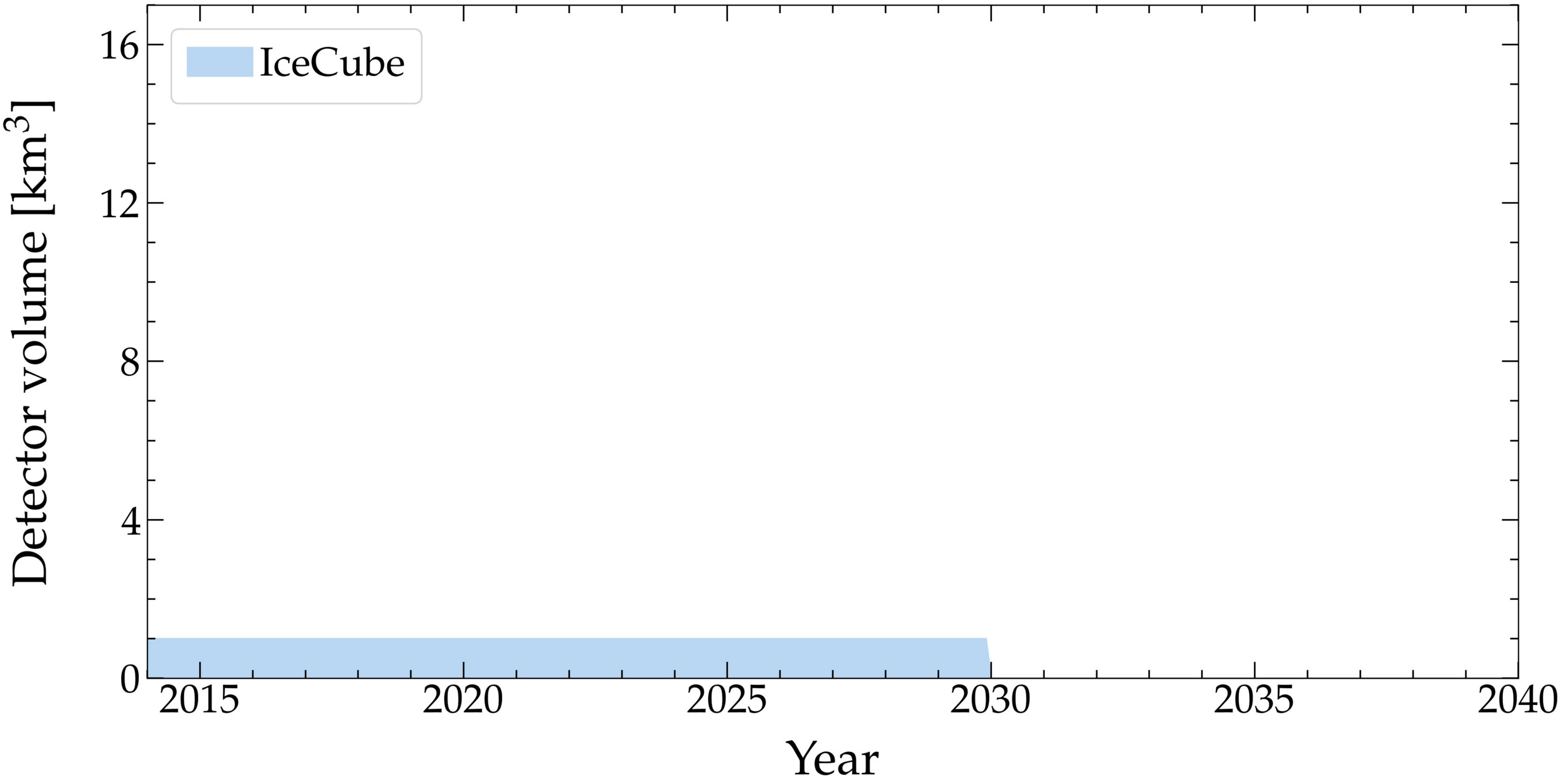

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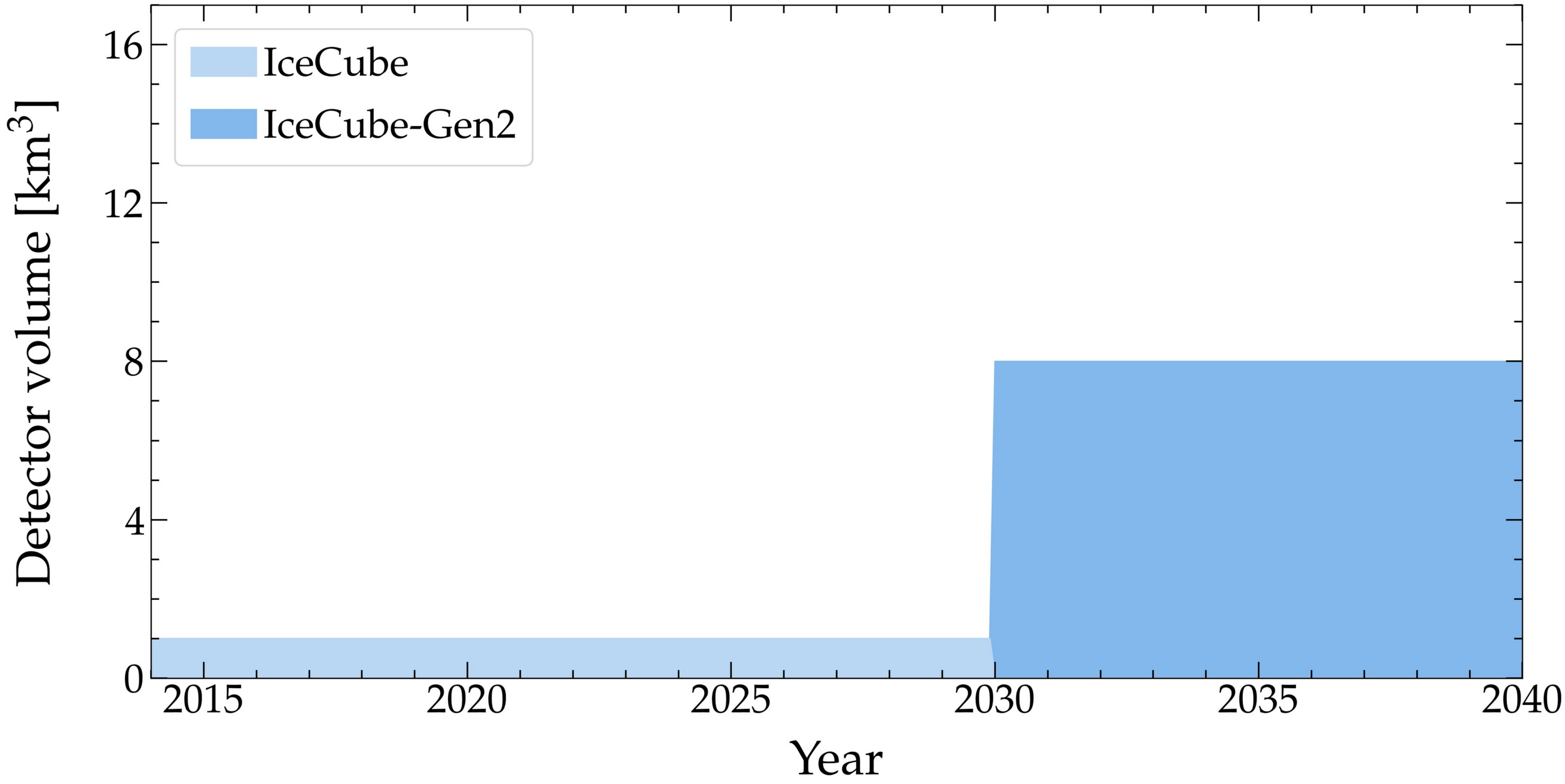

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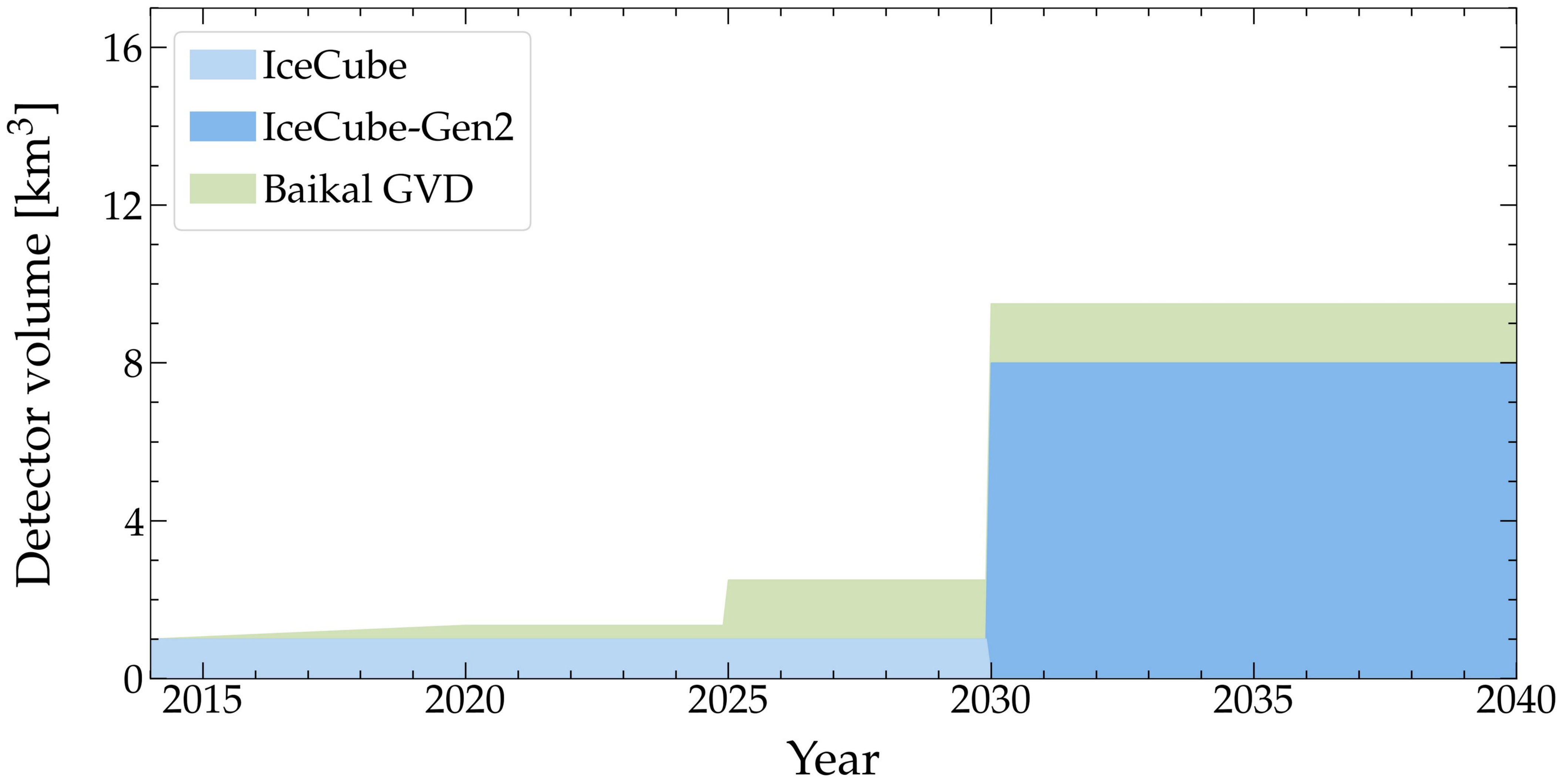

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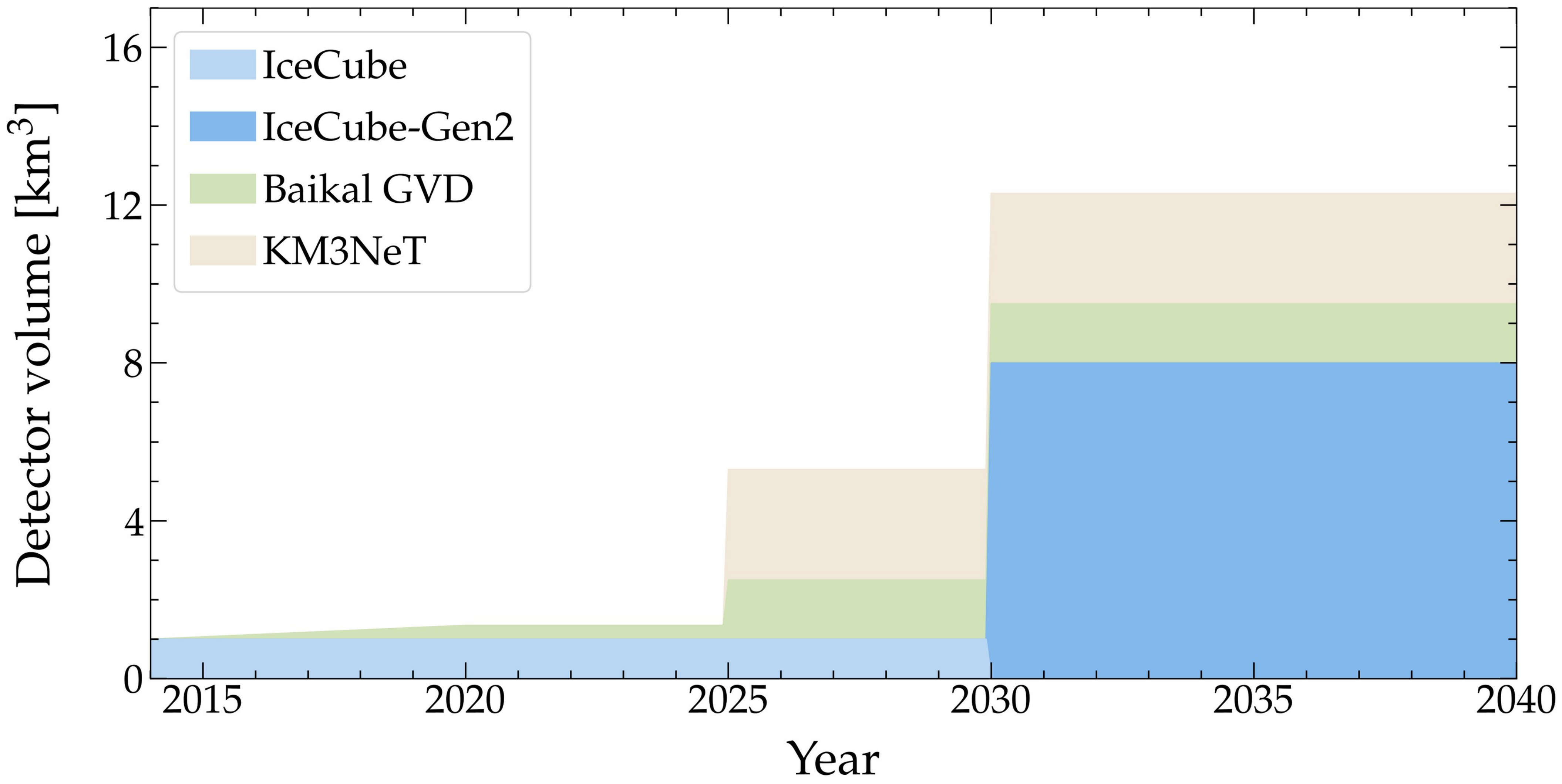

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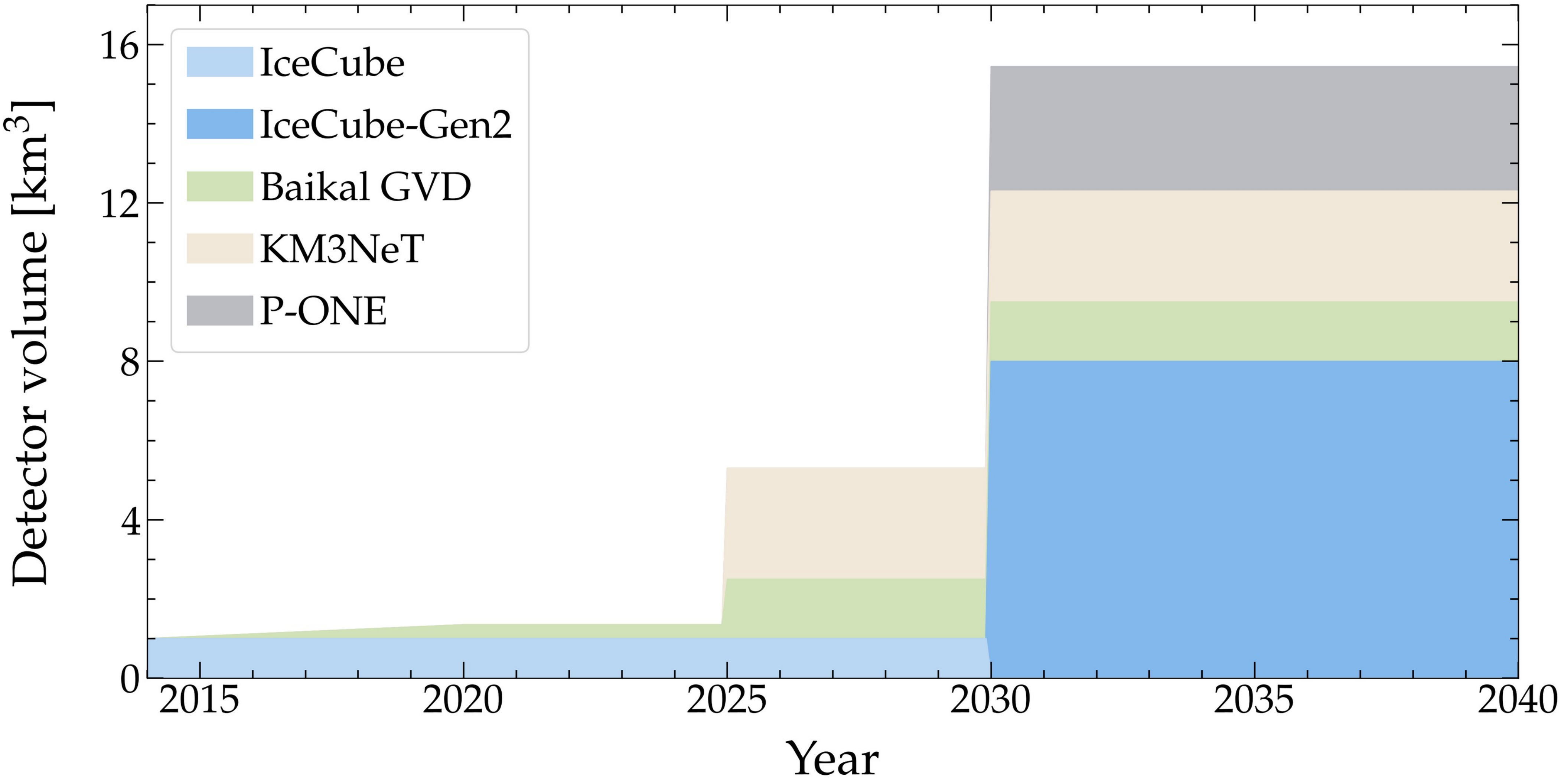

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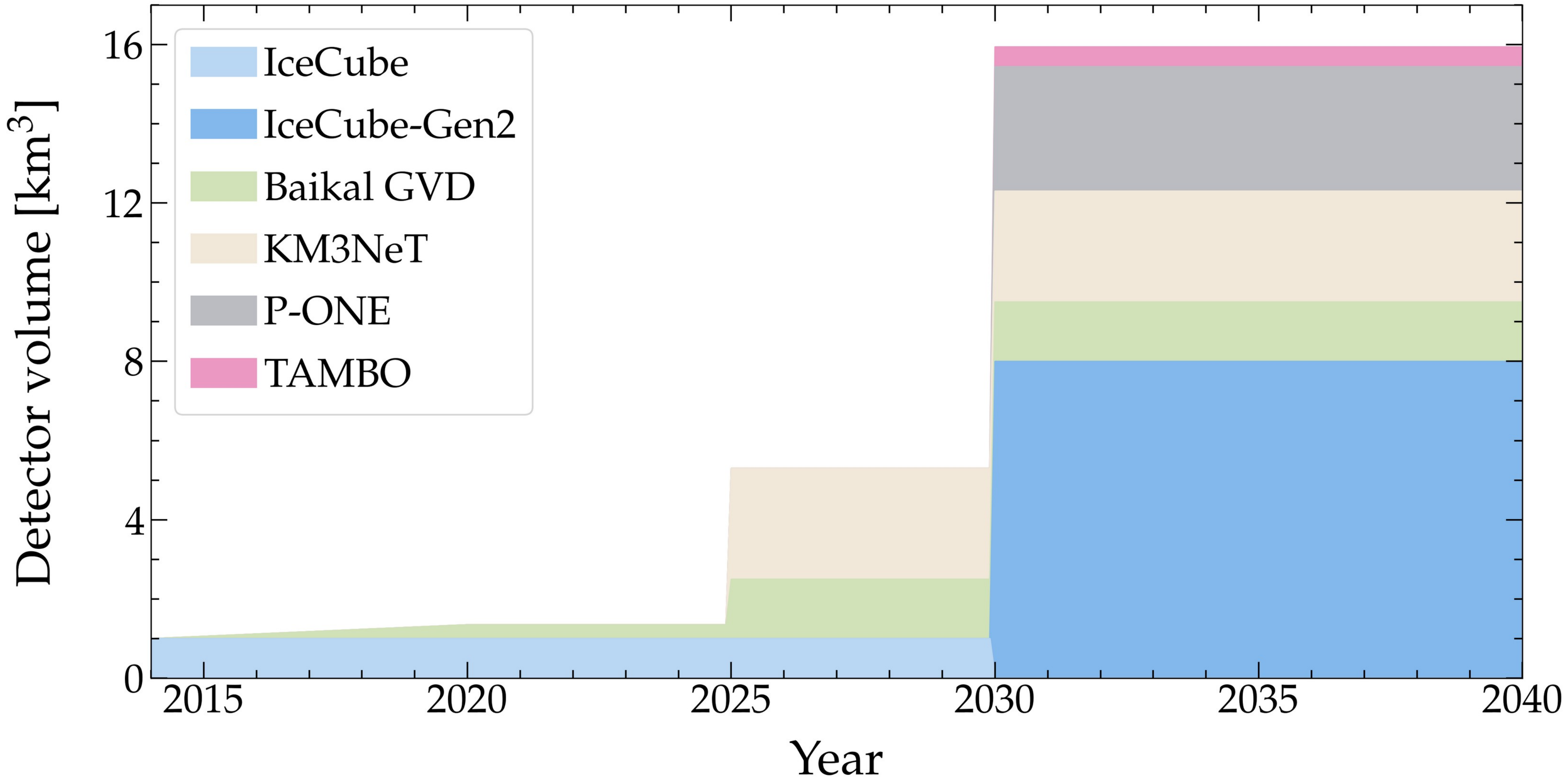

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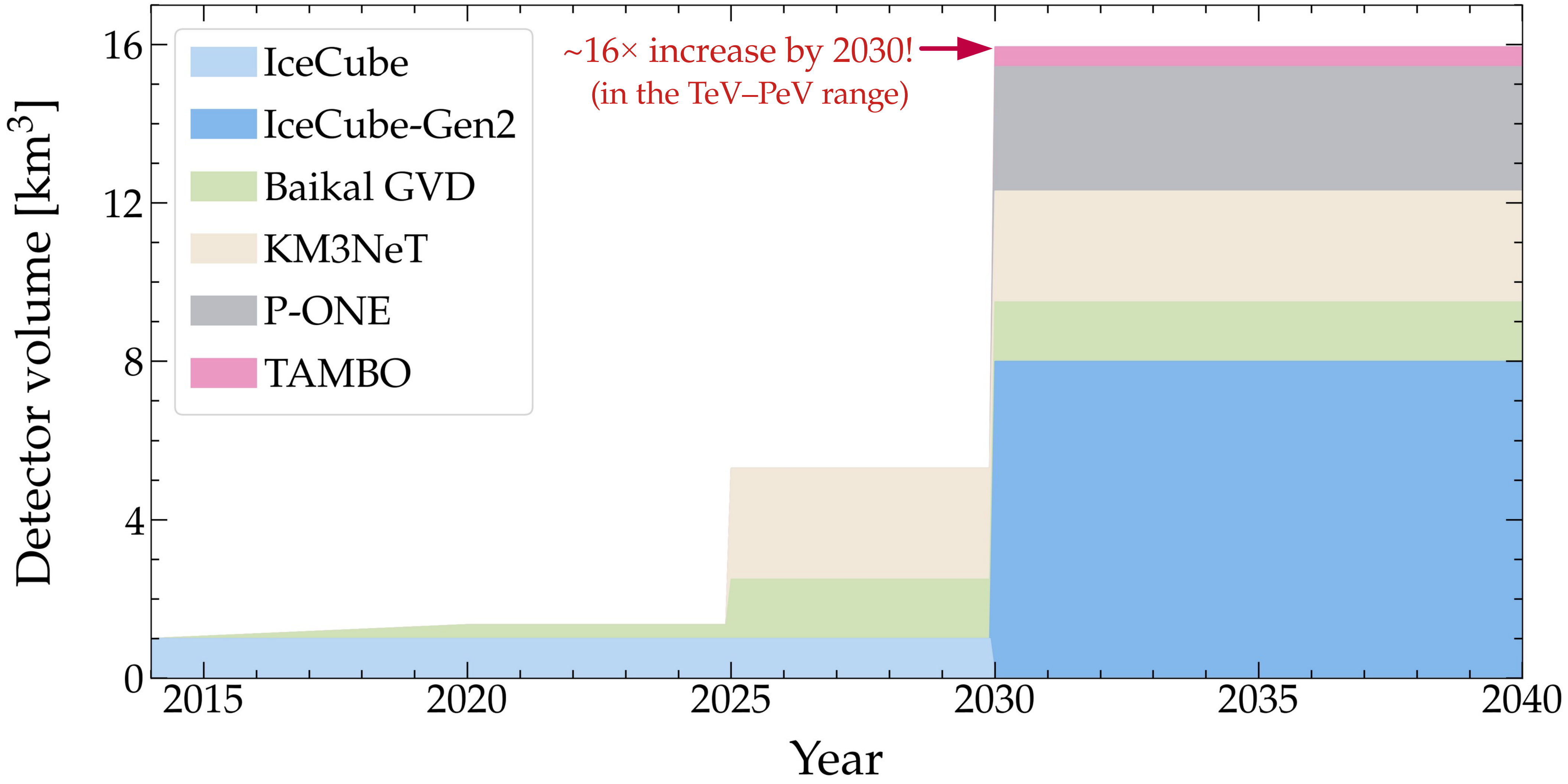

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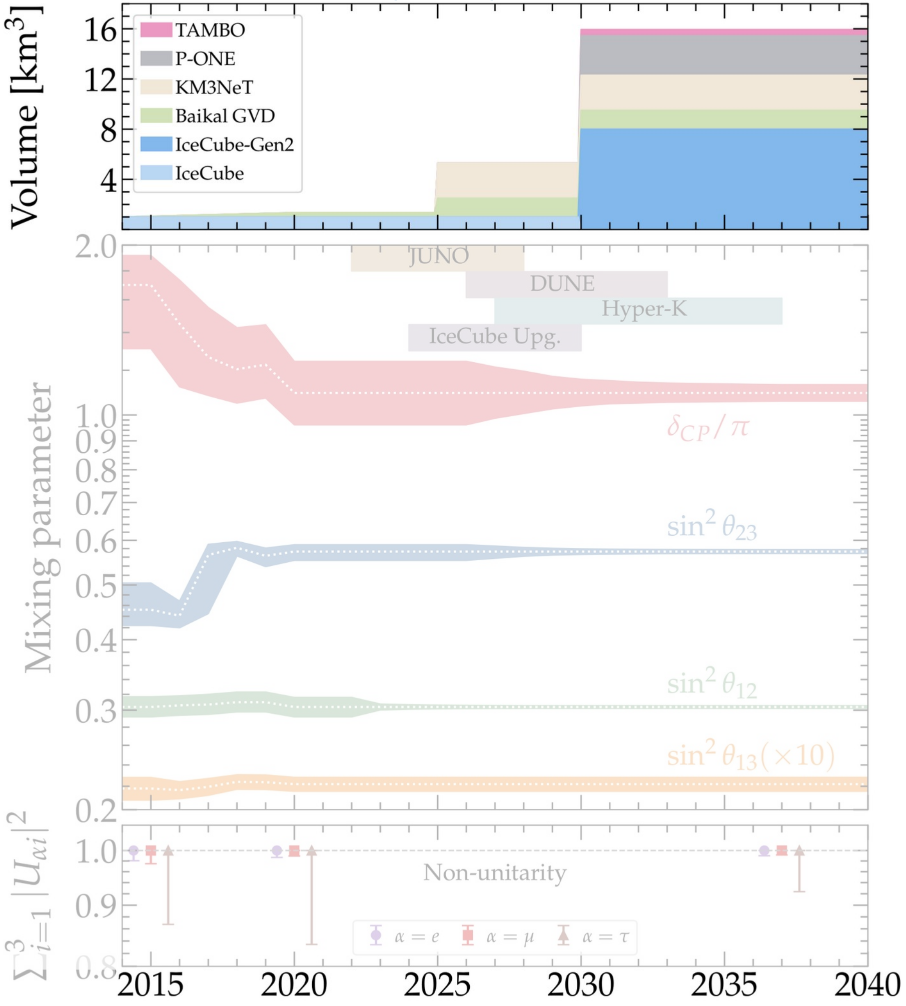
Measuring flavor composition: 2015–2040

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



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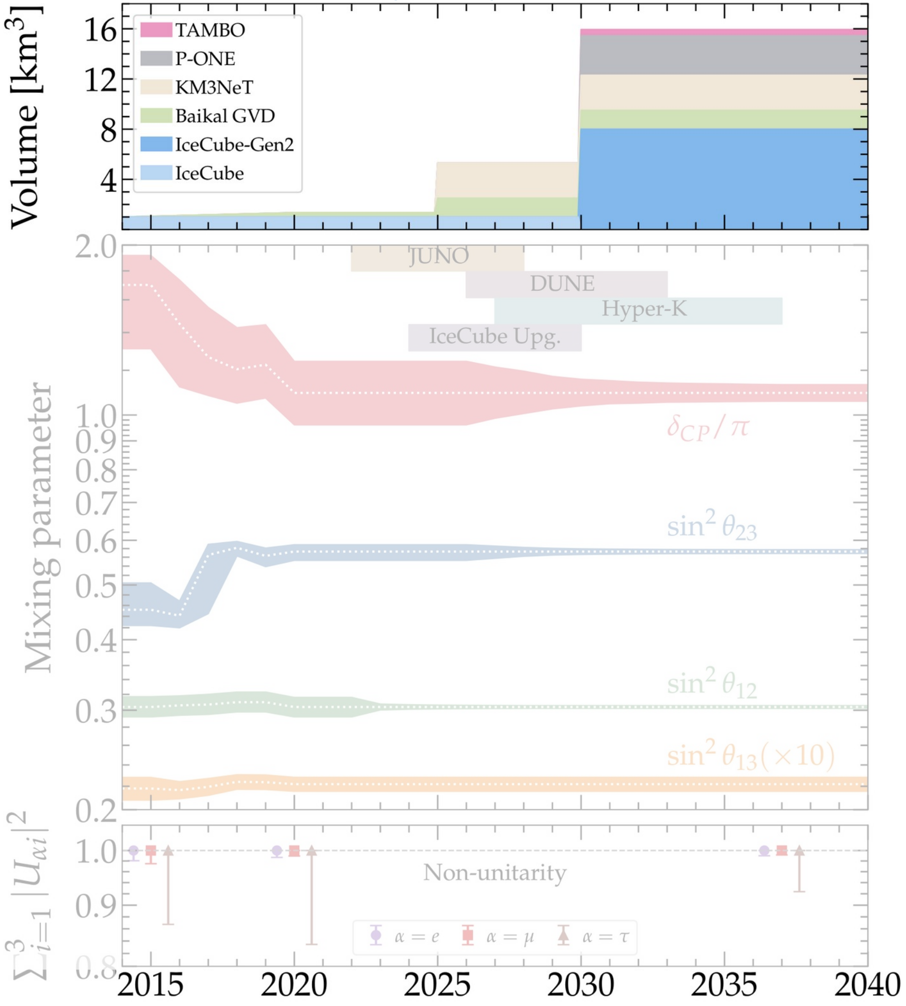

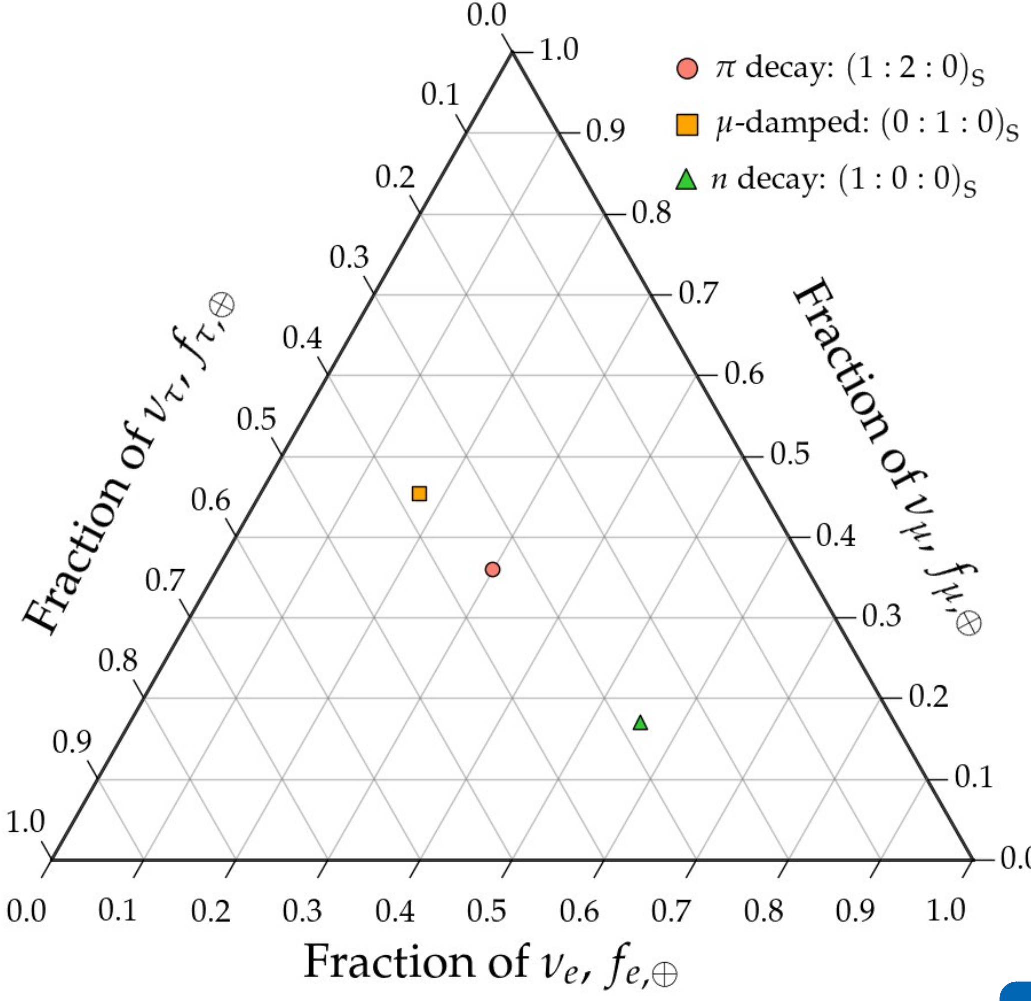

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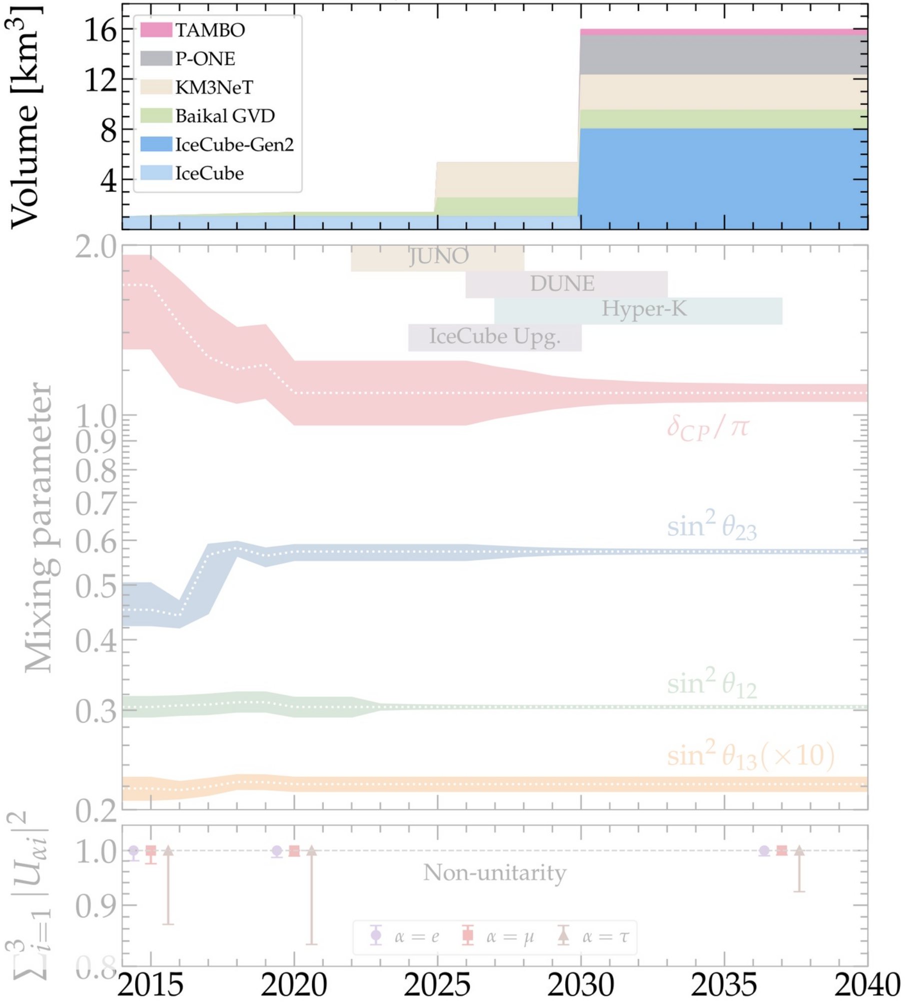

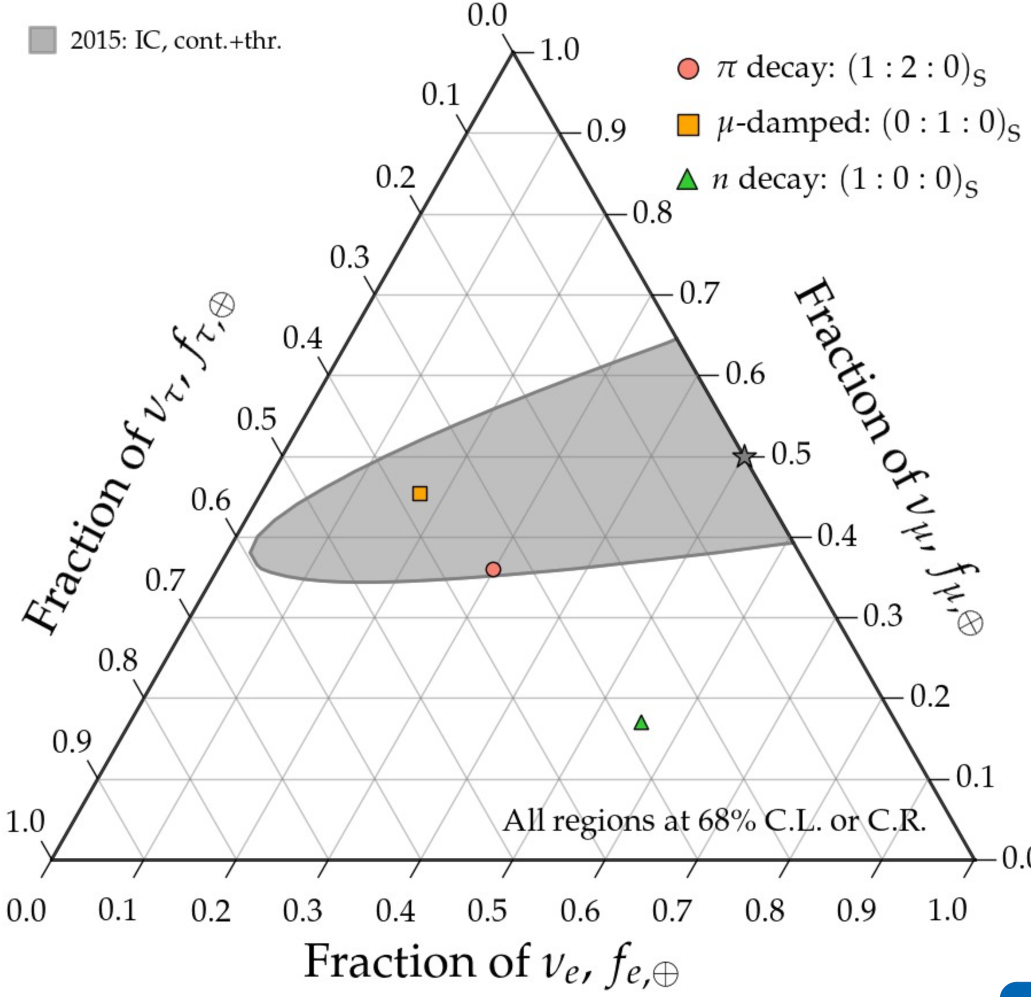

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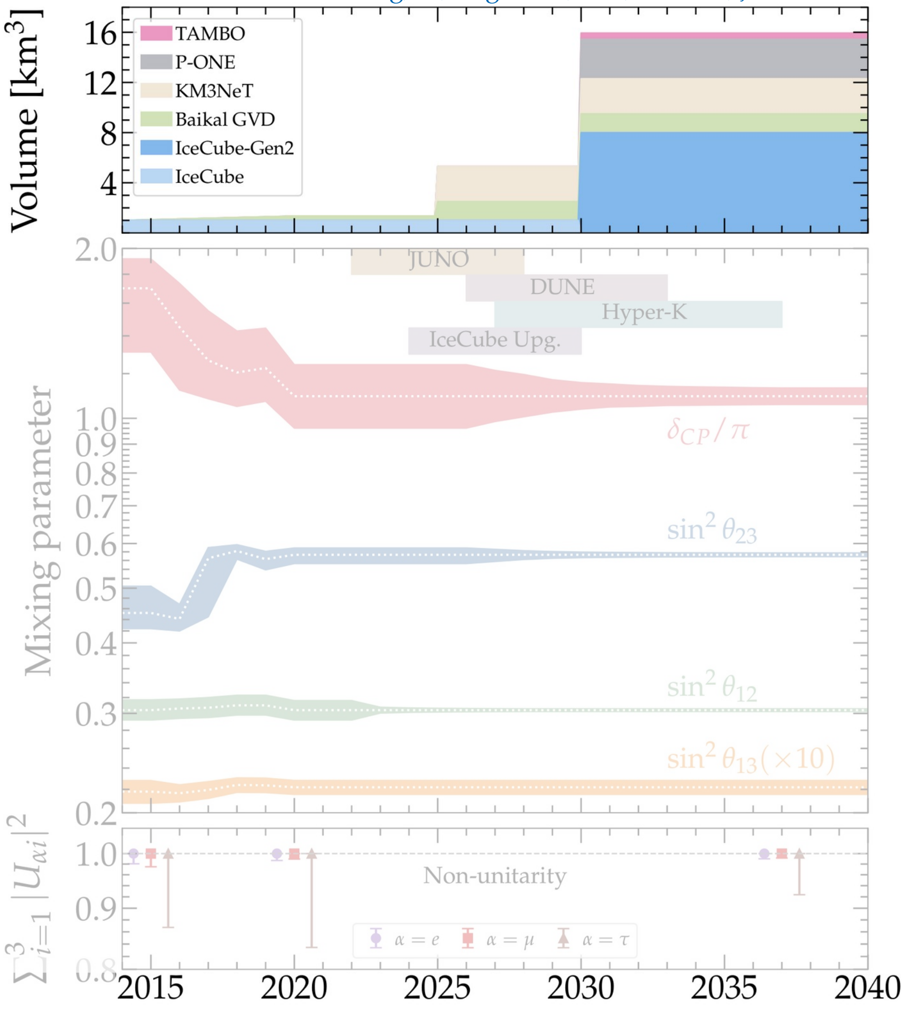

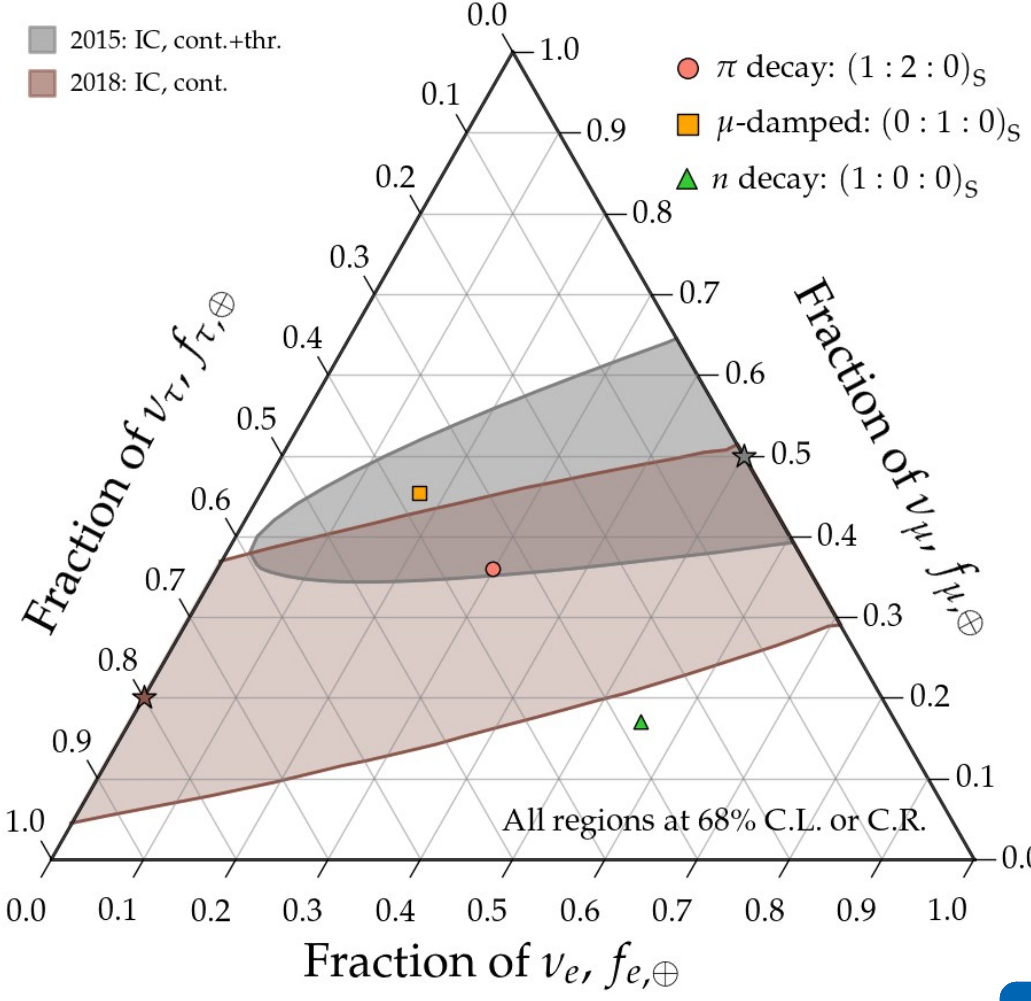

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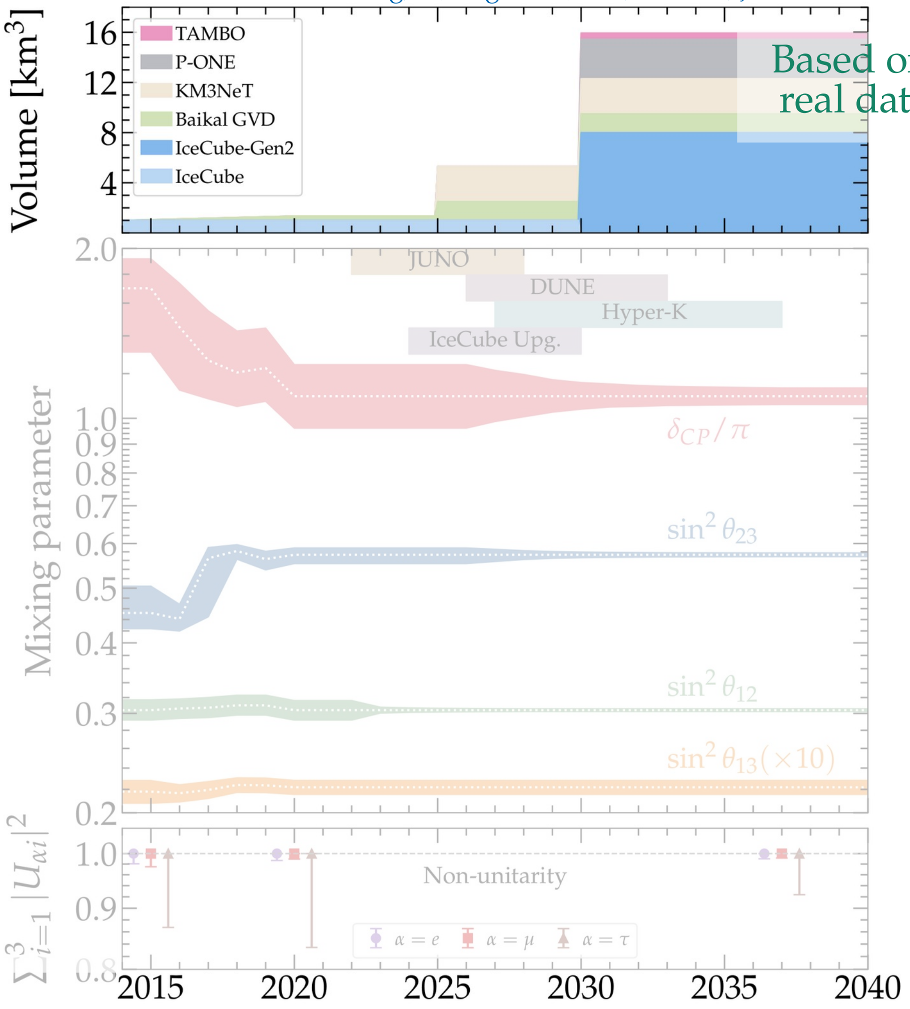
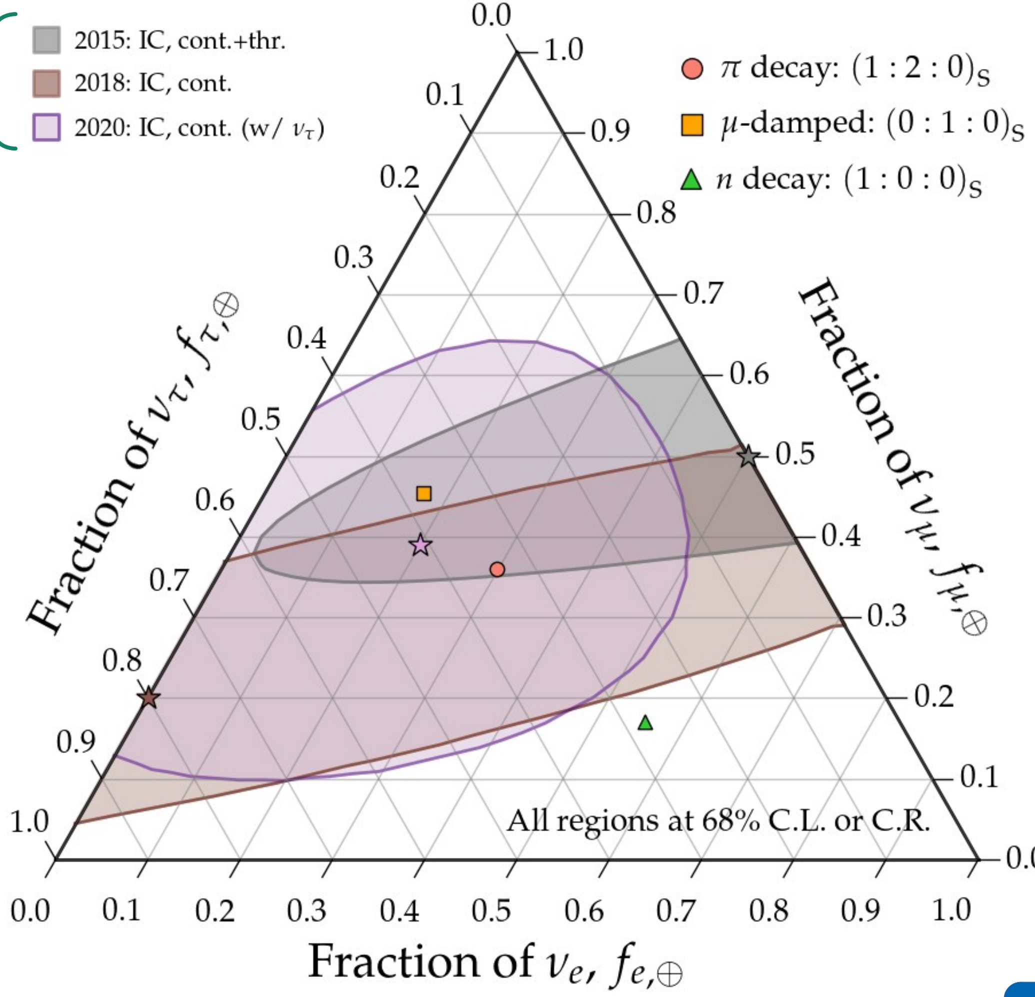


Based on real data



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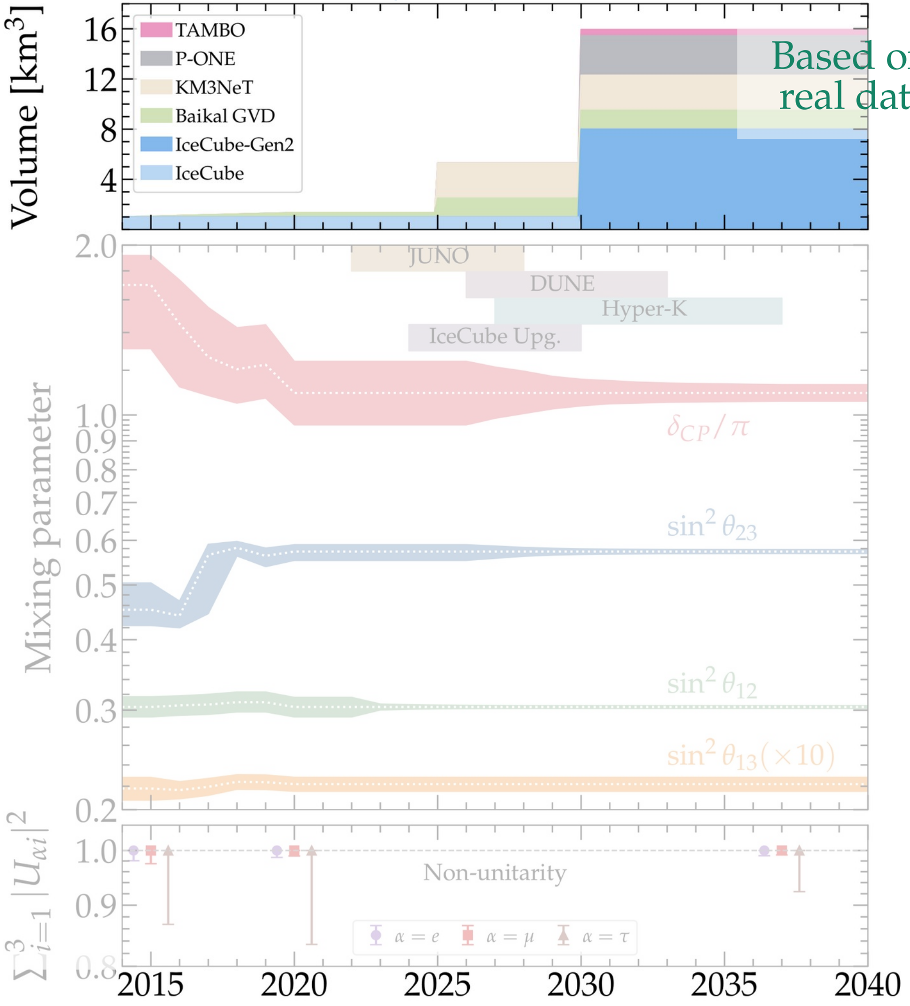

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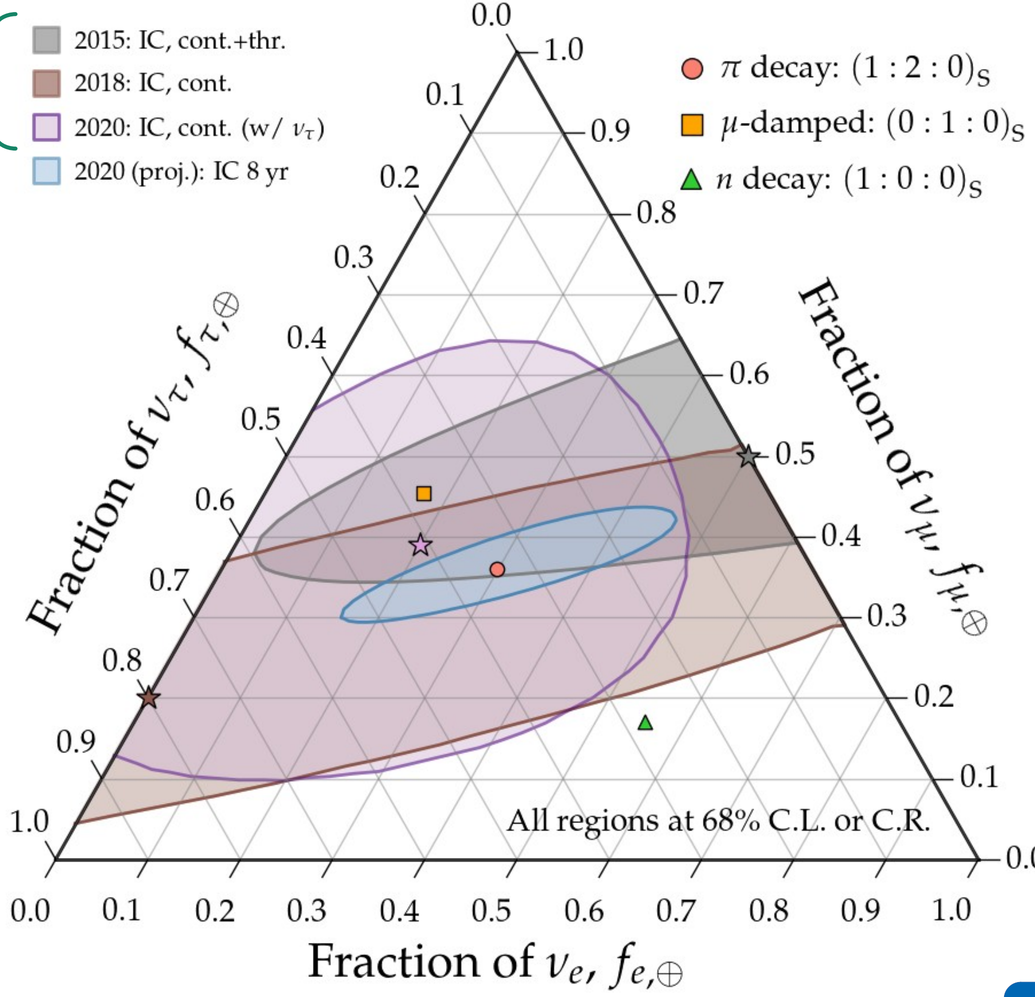

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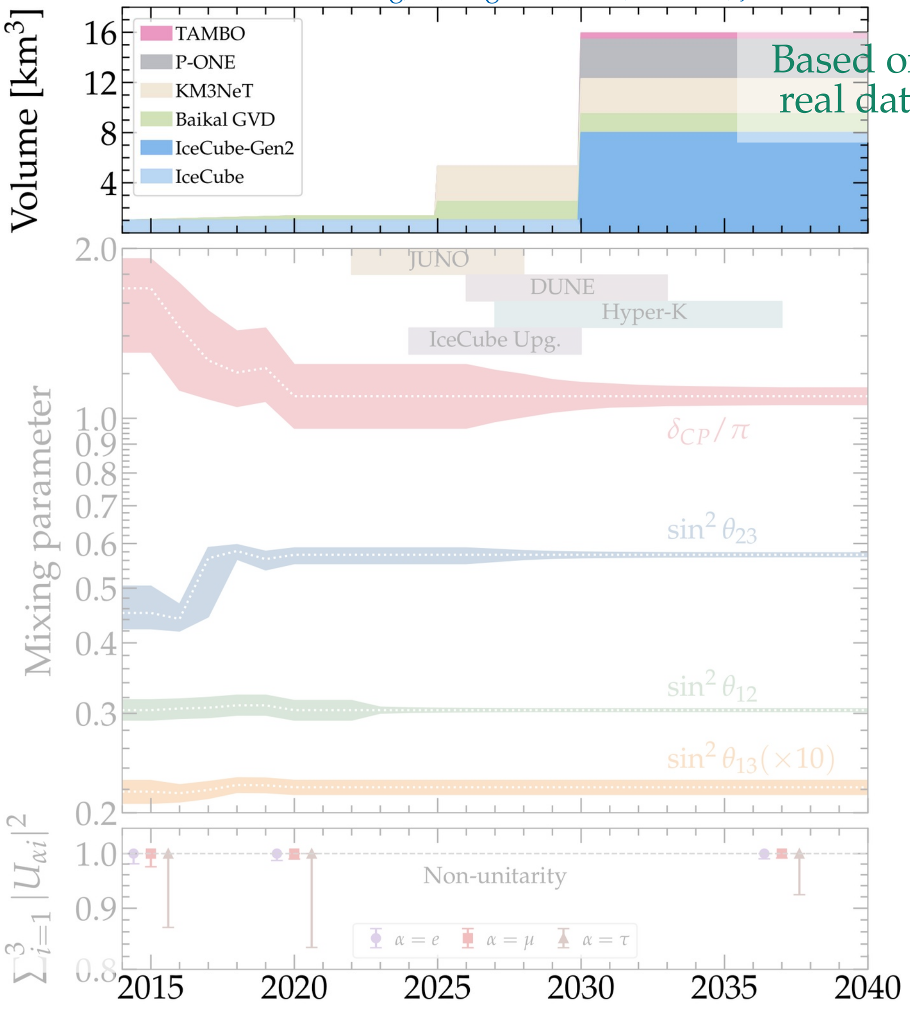

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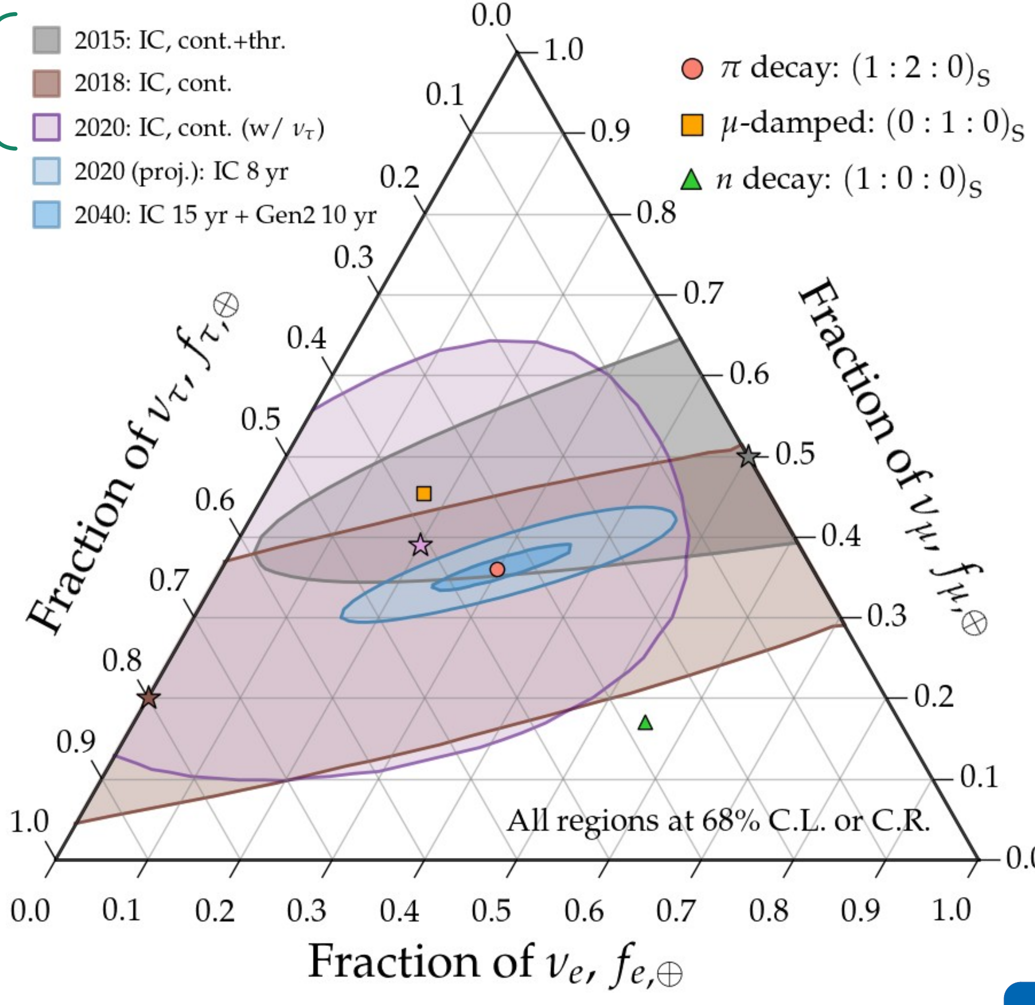

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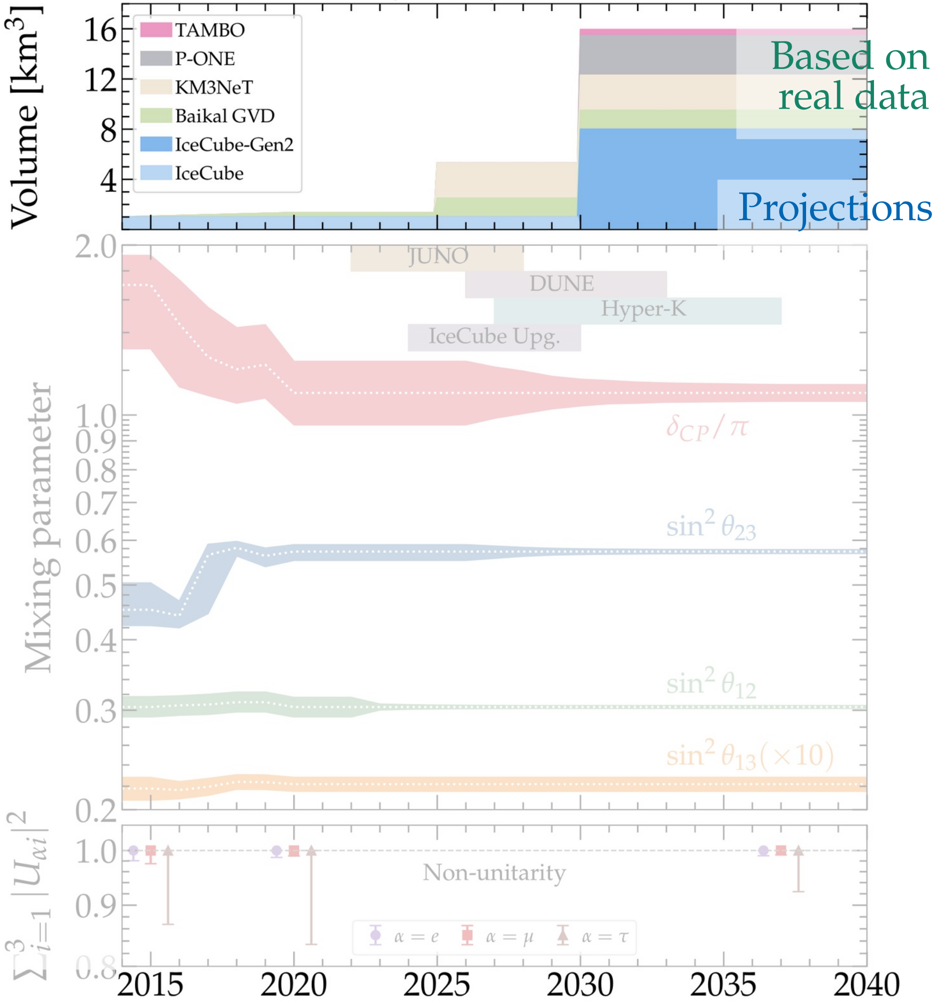
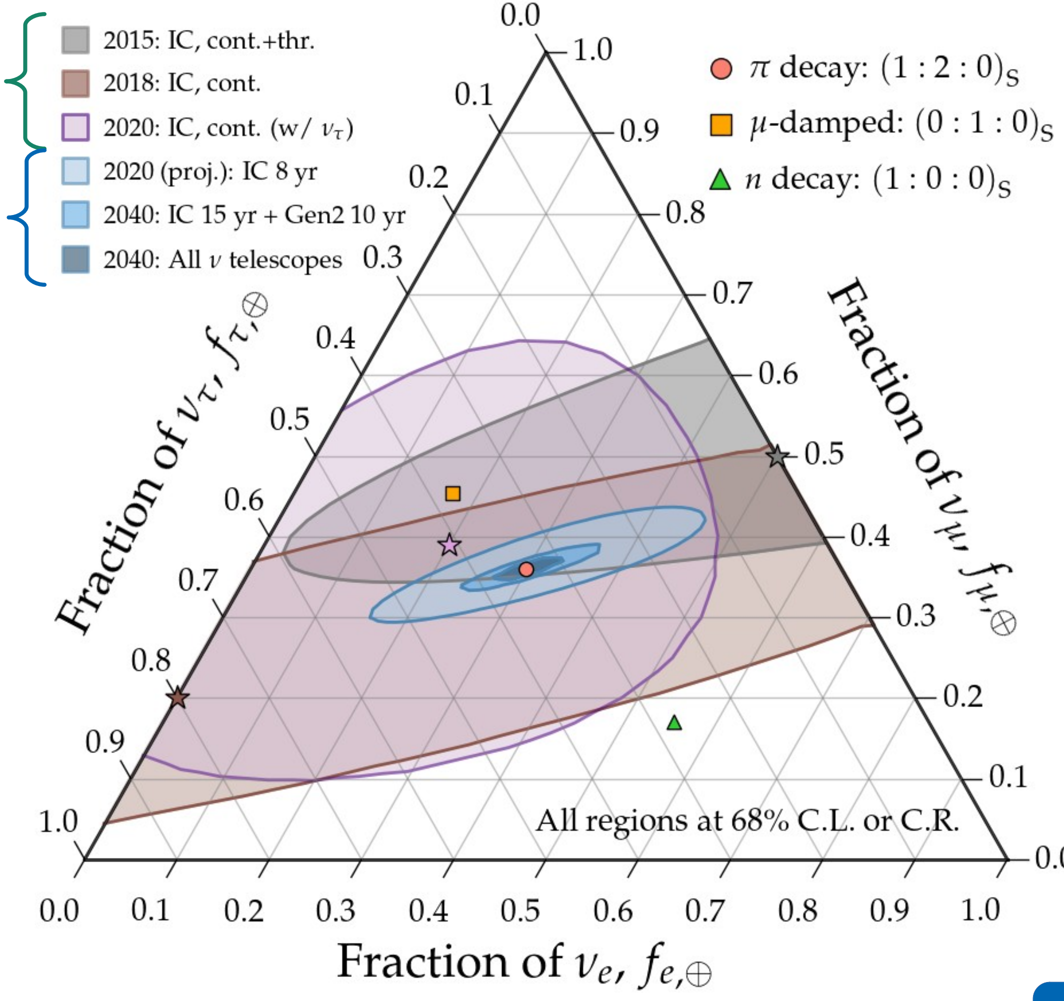
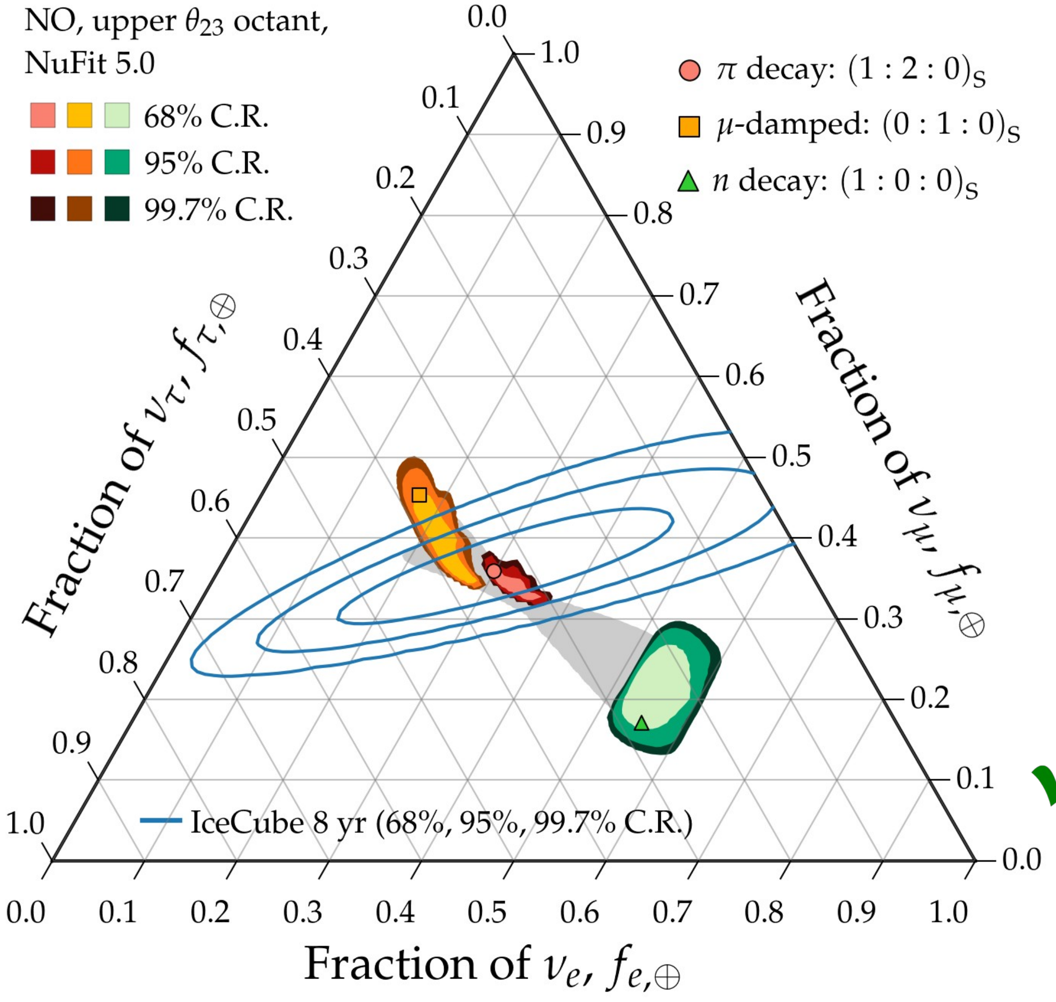




Theoretically palatable regions: today (2021)



Two limitations:

Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

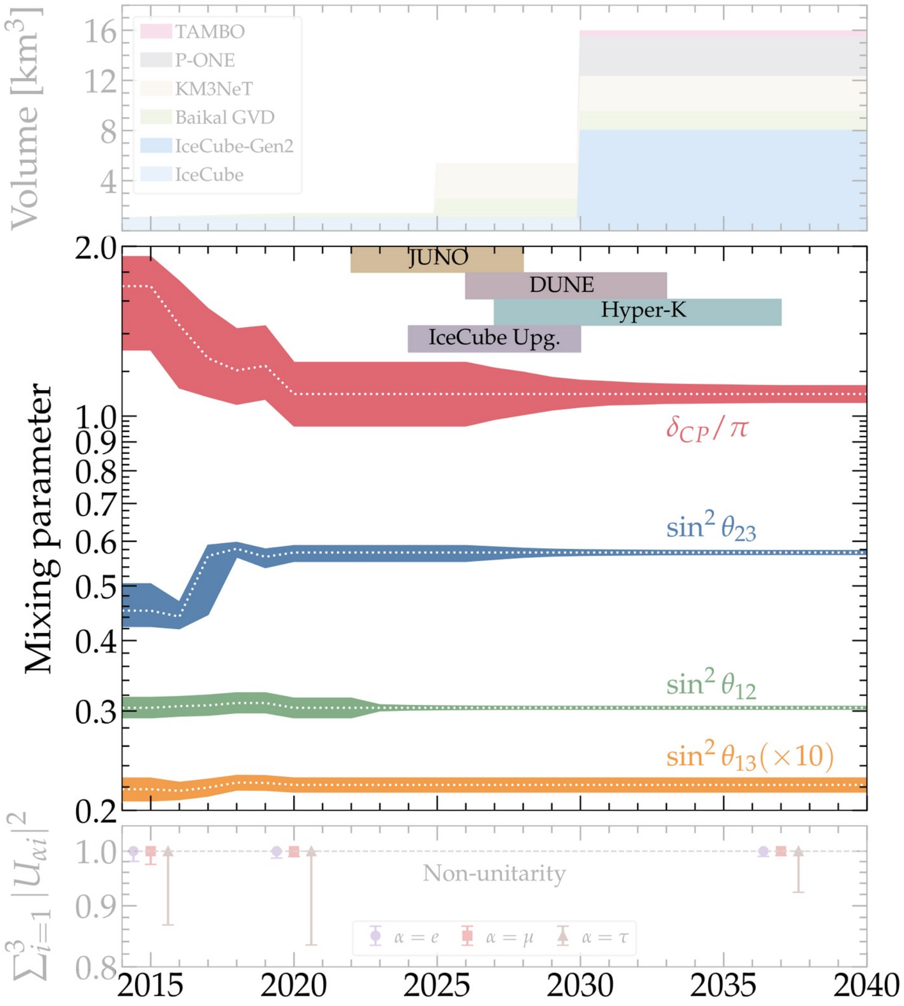
Will be overcome by 2030

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

✓ *Will be overcome by 2040*

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

How knowing the mixing parameters better helps

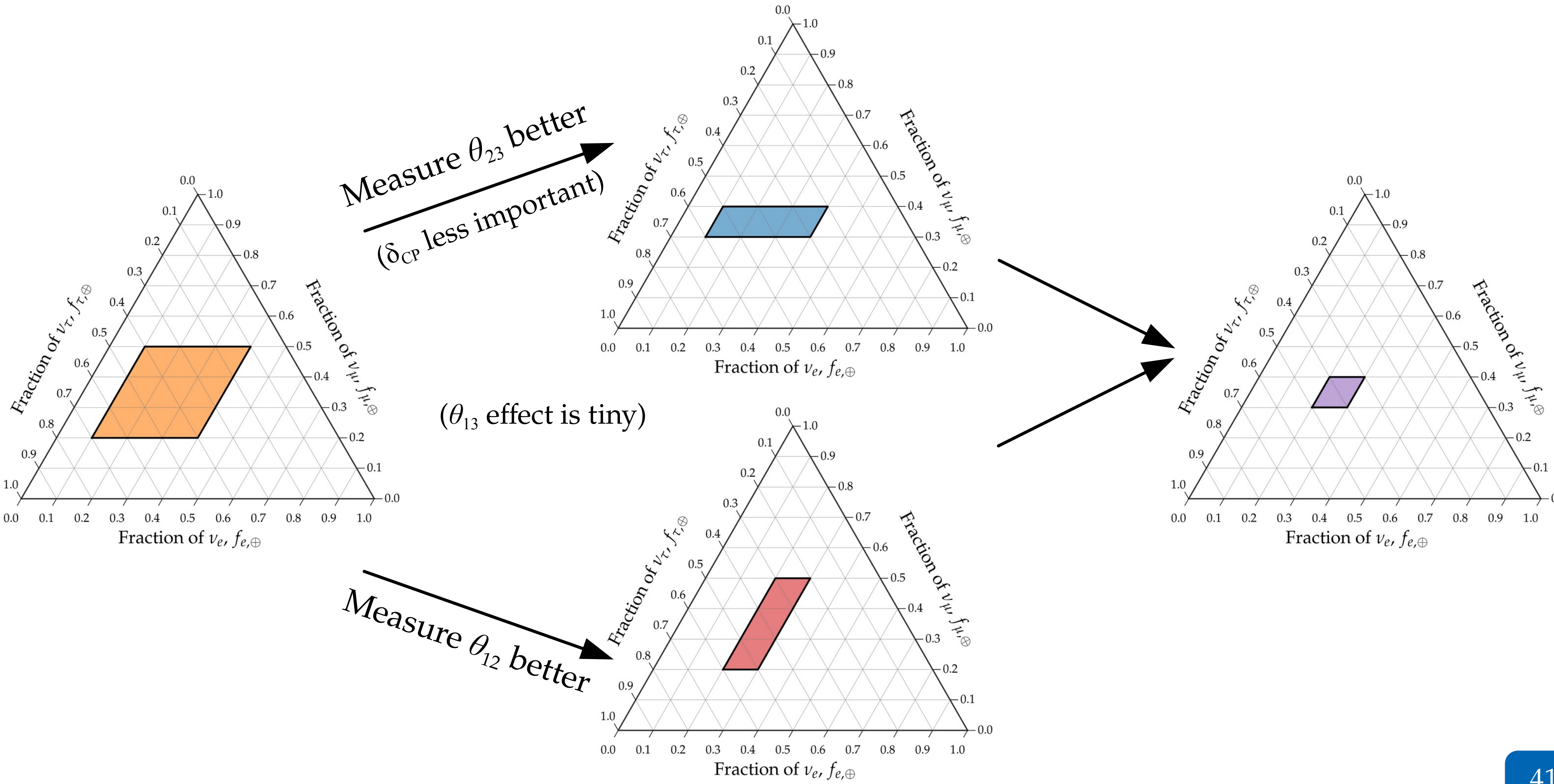


We can compute the oscillation probability more precisely:

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

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

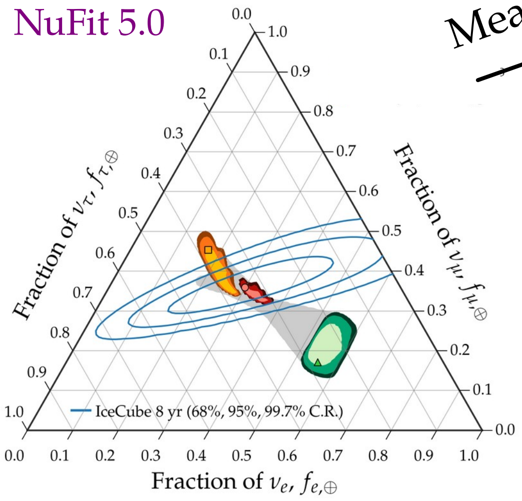
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

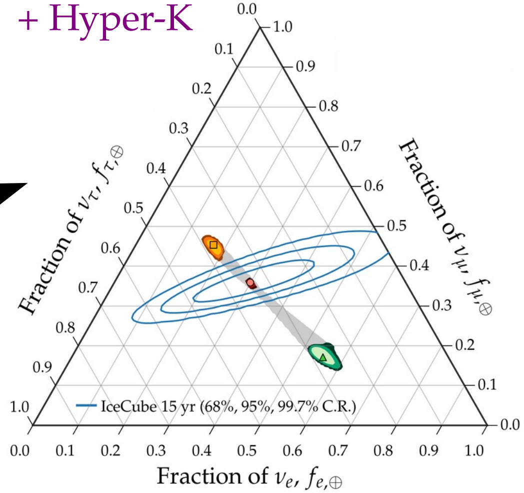
2020

NuFit 5.0

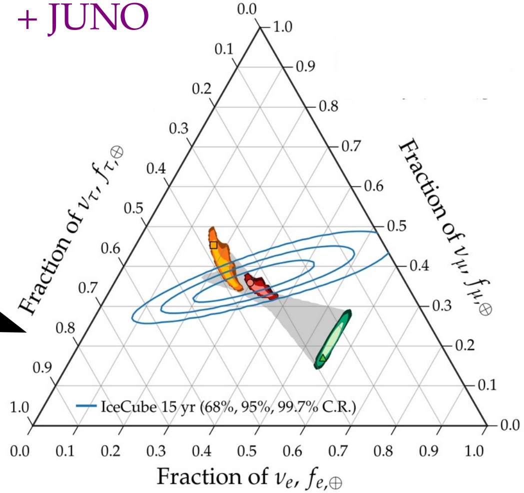


Measure θ_{23} better

+ Hyper-K



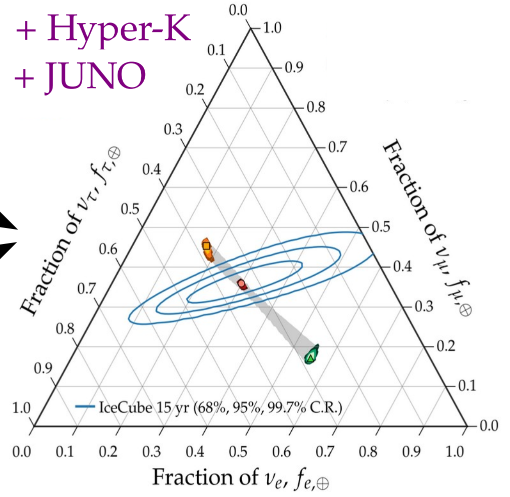
+ JUNO



Measure θ_{12} better

~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

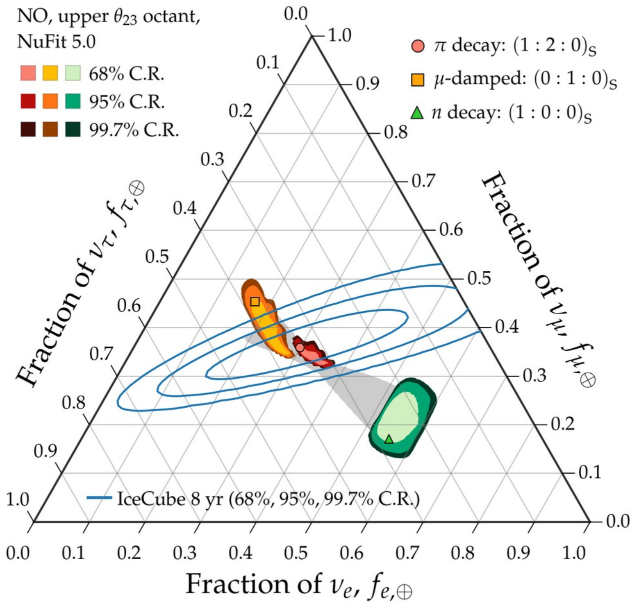
Marginal improvement til 2040

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

Theoretically palatable regions: 2020 $\rightarrow$ 2030 $\rightarrow$ 2040

Theoretically palatable regions: 2020 → 2030 → 2040

2020



Allowed regions: overlapping

Measurement: imprecise

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

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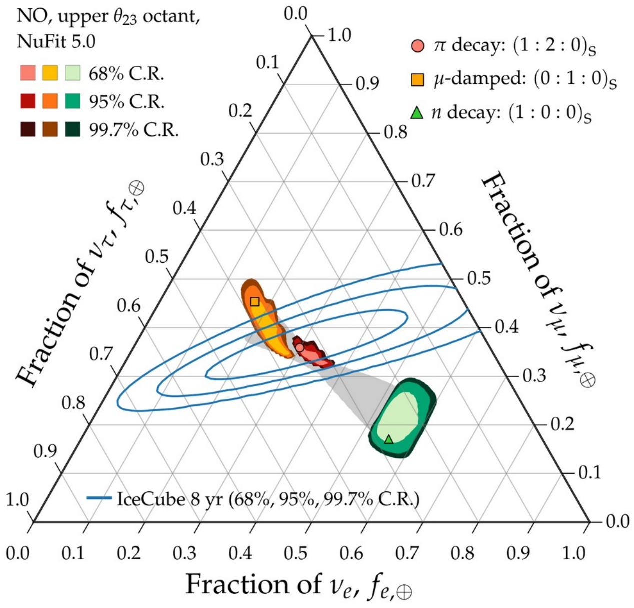

Allowed regions: overlapping

Measurement: imprecise

Not ideal

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

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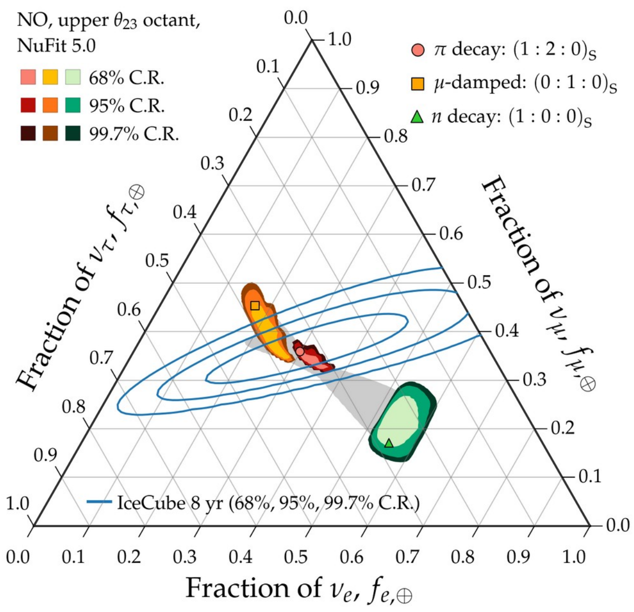

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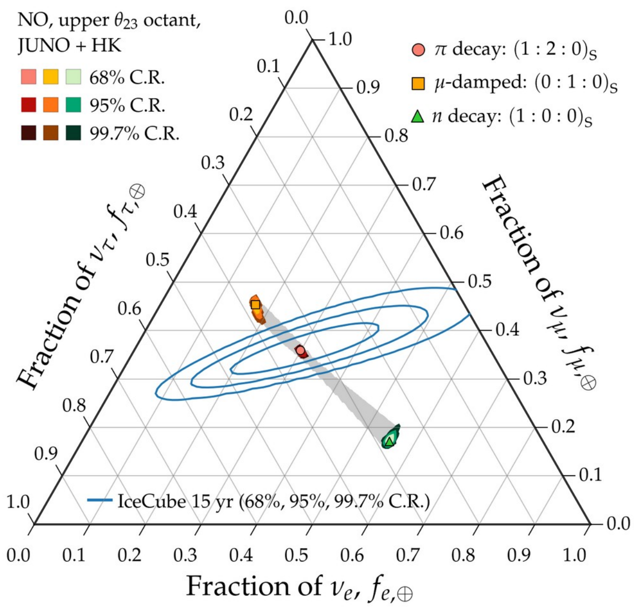
2030



Allowed regions: well separated

Measurement: improving

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

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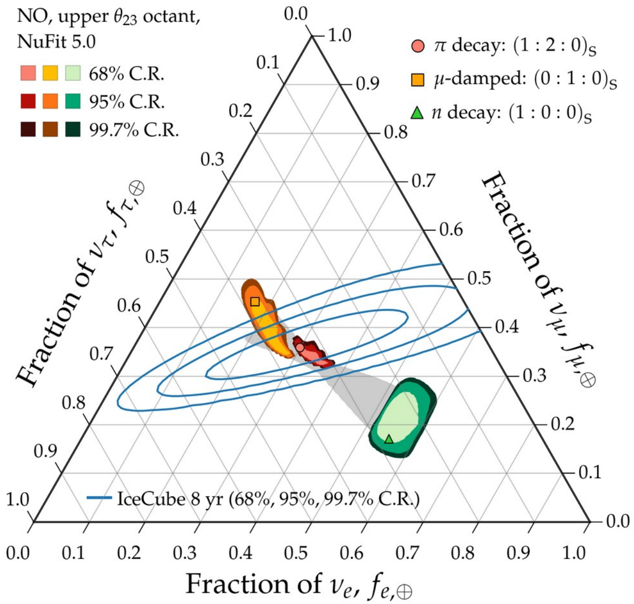

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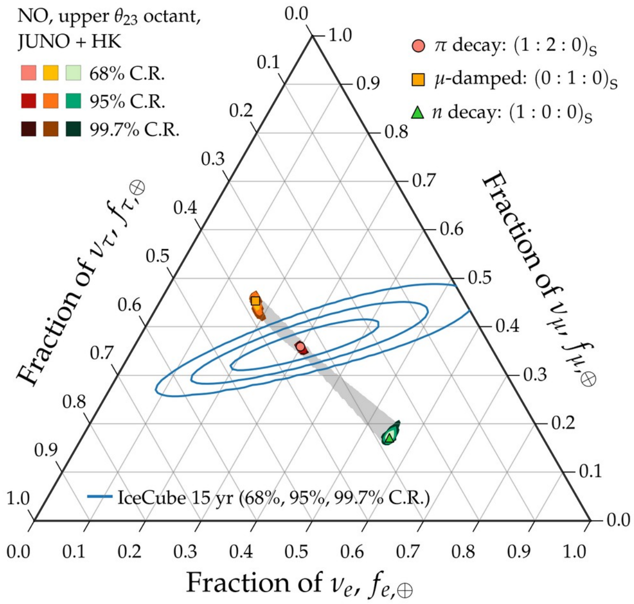

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Nice

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

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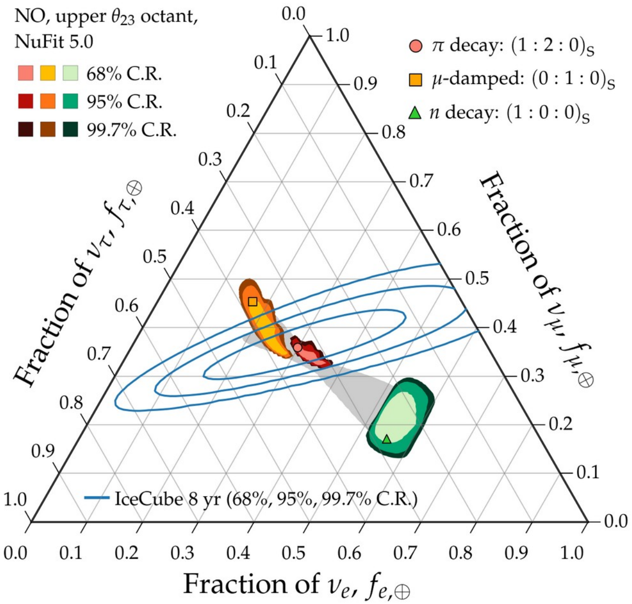

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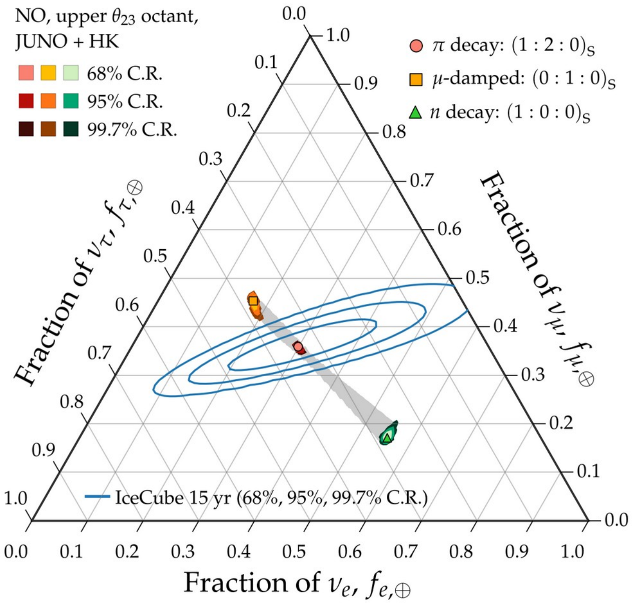

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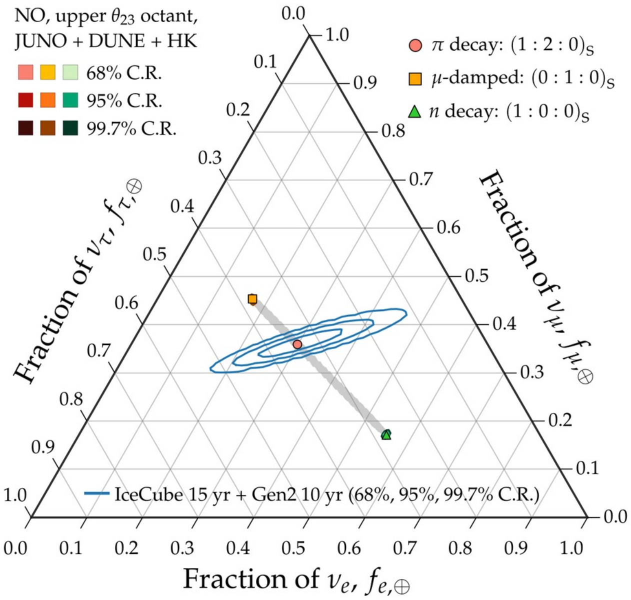
Nice

2040



Allowed regions: well separated

Measurement: precise

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

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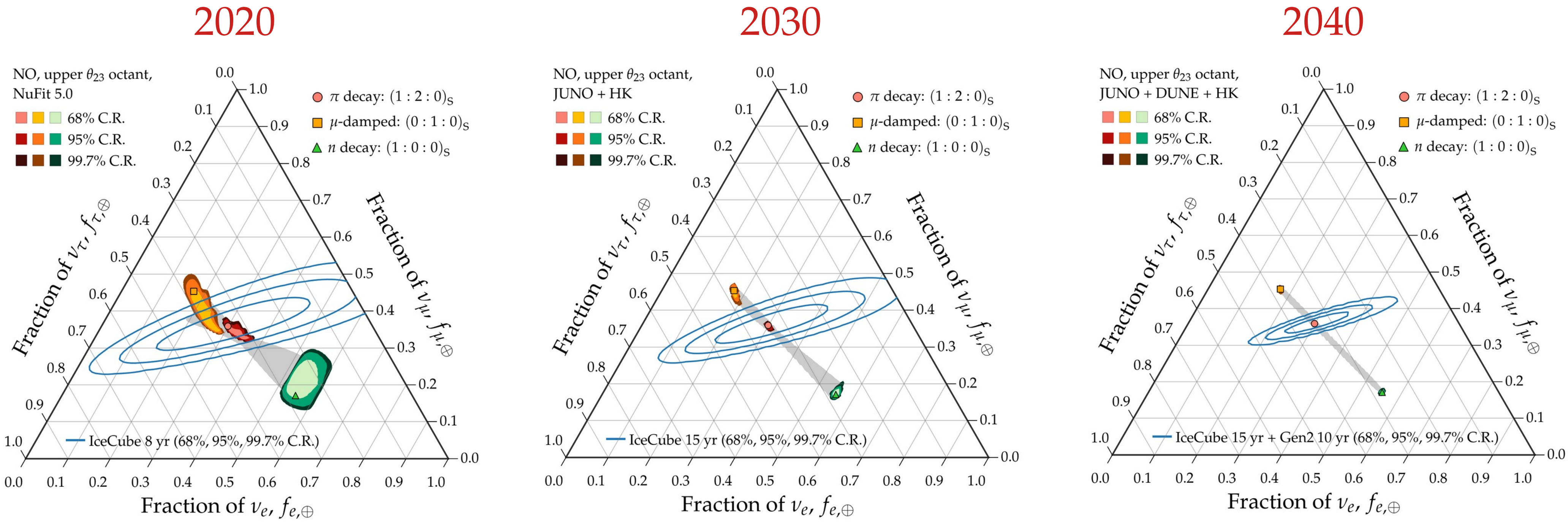

Allowed regions: overlapping	Allowed regions: well separated	Allowed regions: well separated
Measurement: imprecise	Measurement: improving	Measurement: precise
Not ideal	*Nice*	*Success*

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

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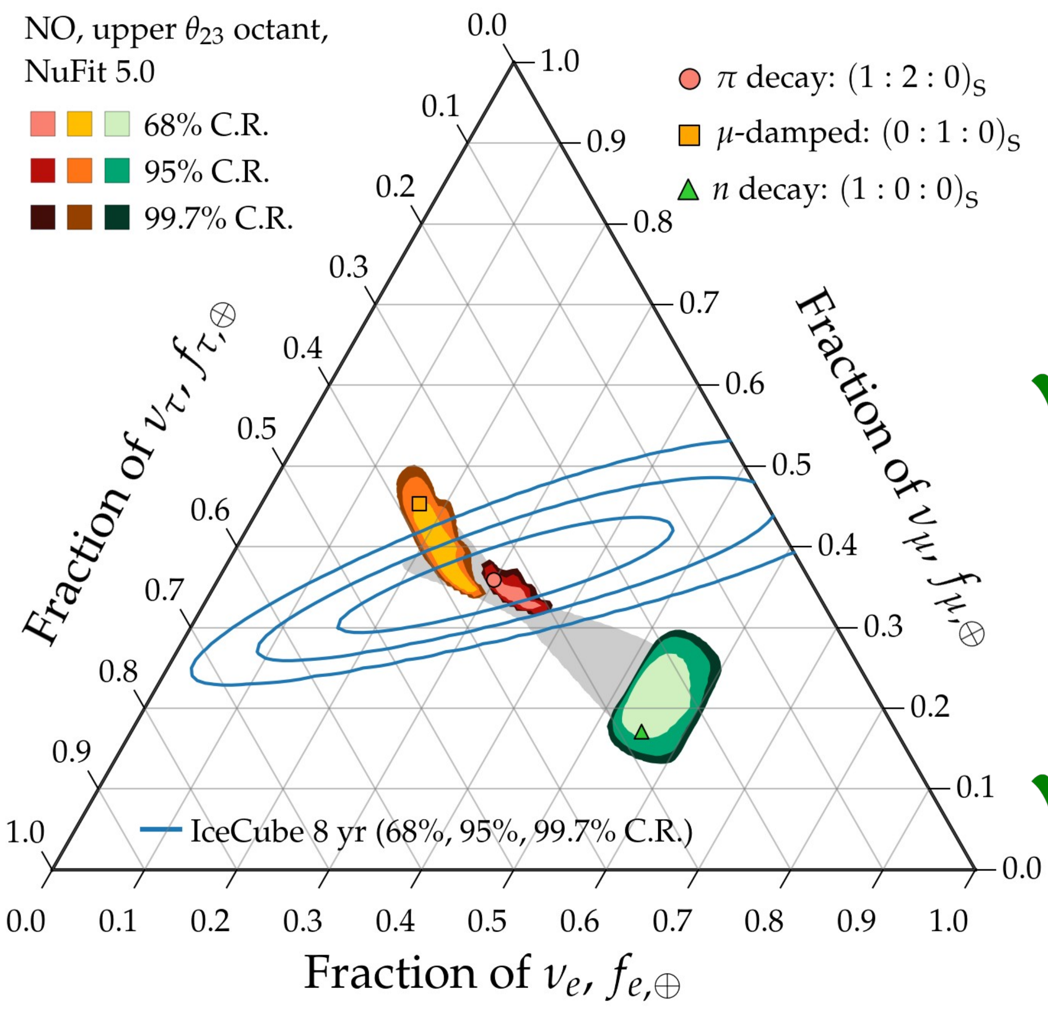

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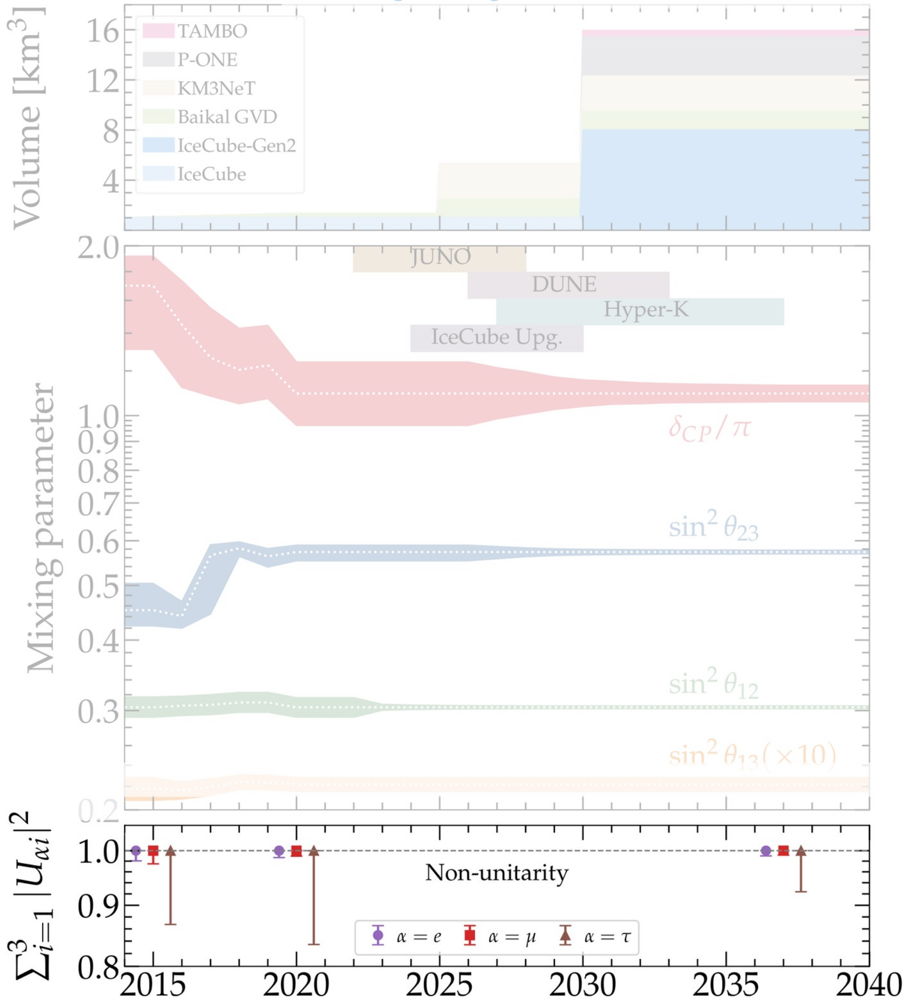

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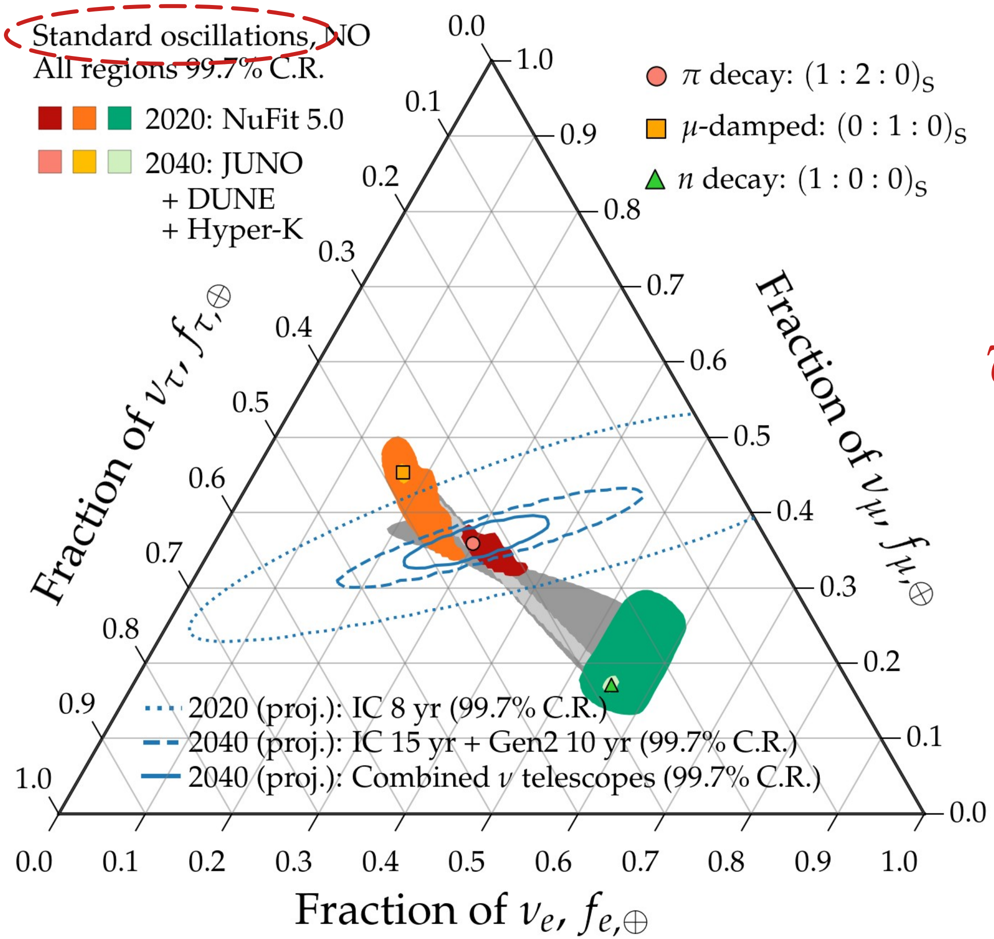
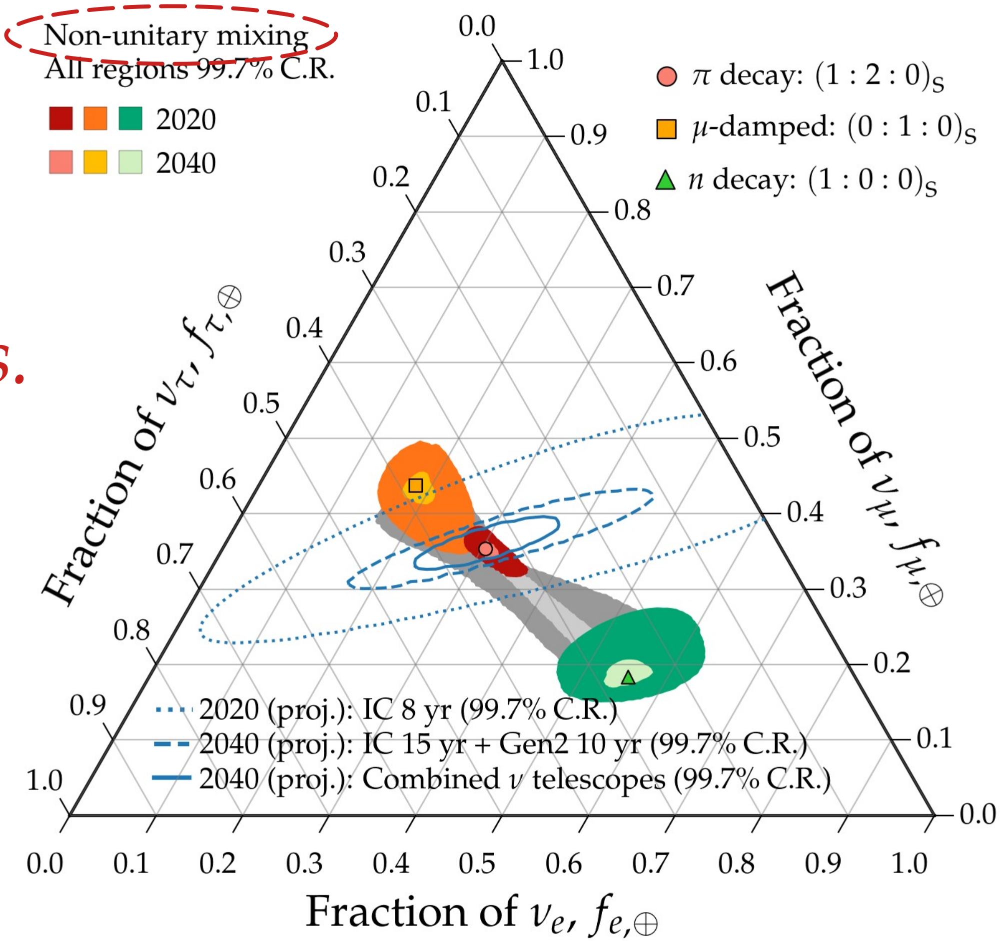
No unitarity? *No problem*



vs.



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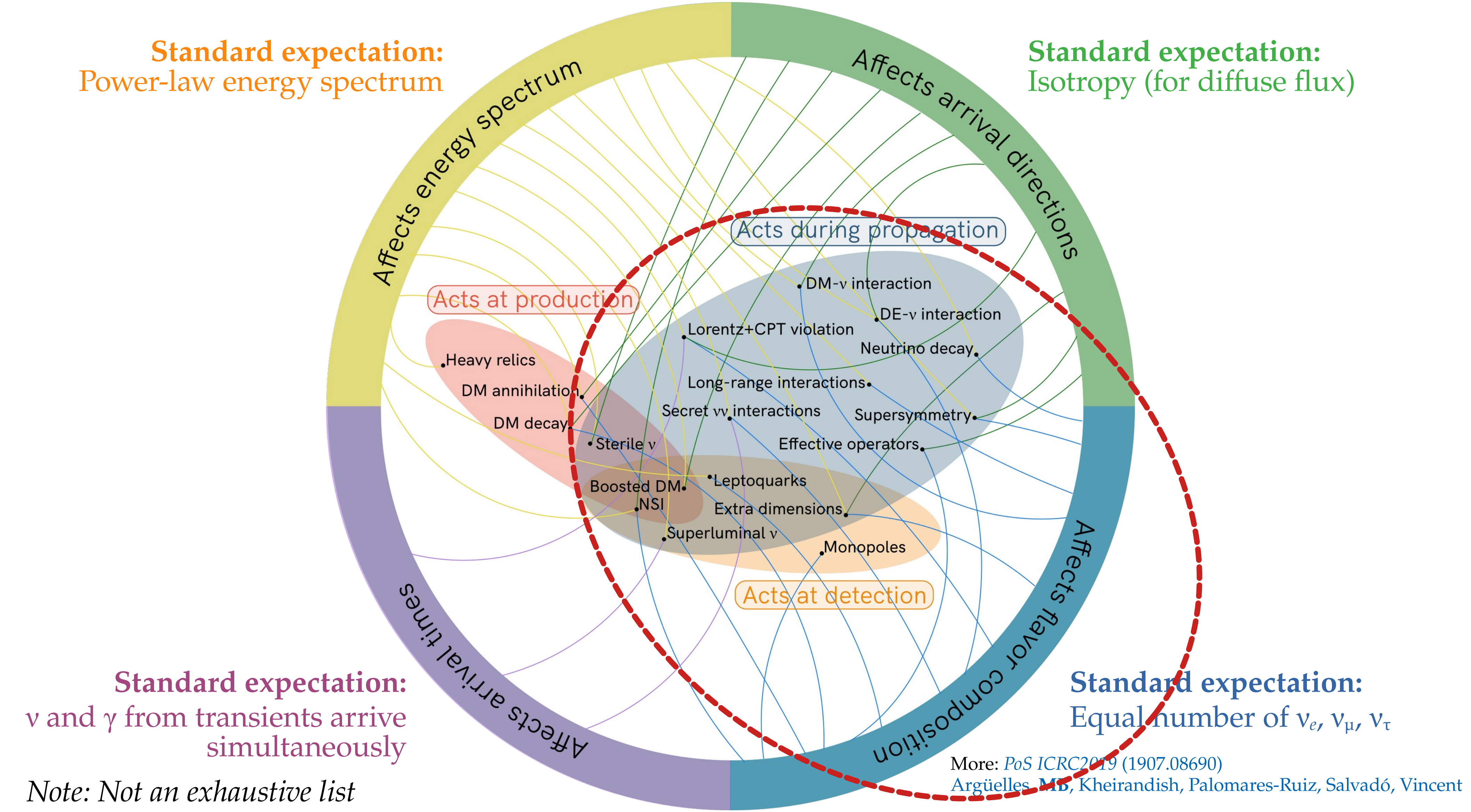

More: *PoS ICRC2019* (1907.08690)
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Note: Not an exhaustive list

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

New physics in flavor composition

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Reviews:
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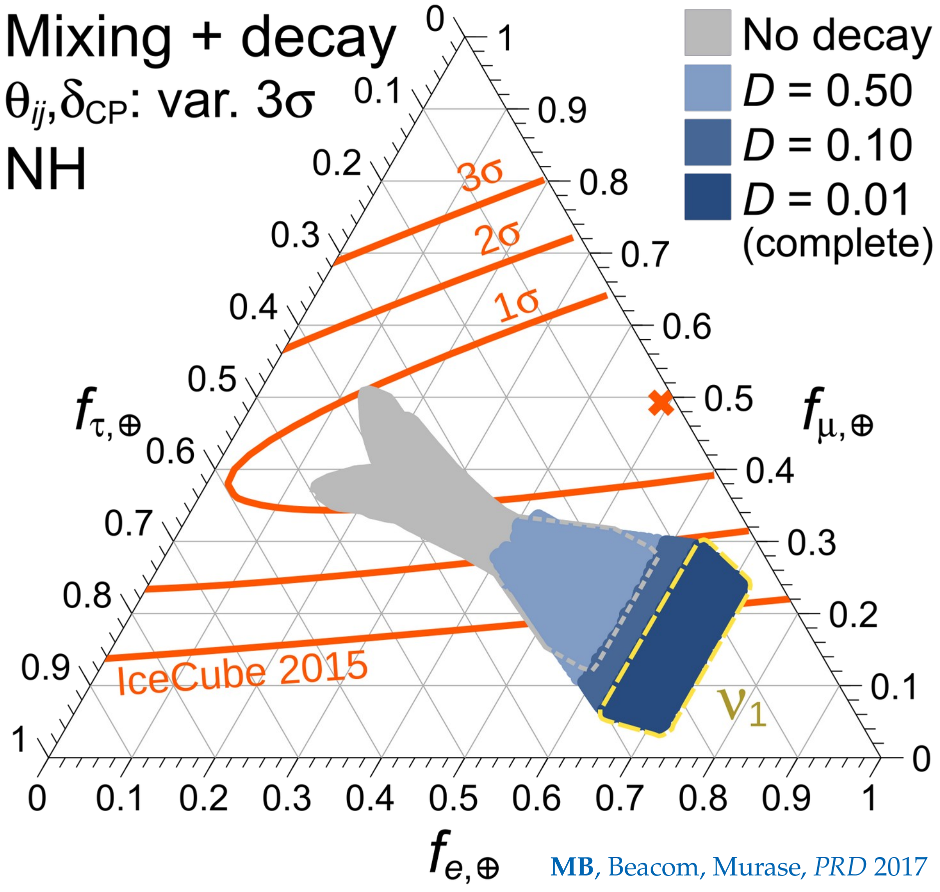
New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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



MB, Beacom, Murase, *PRD* 2017

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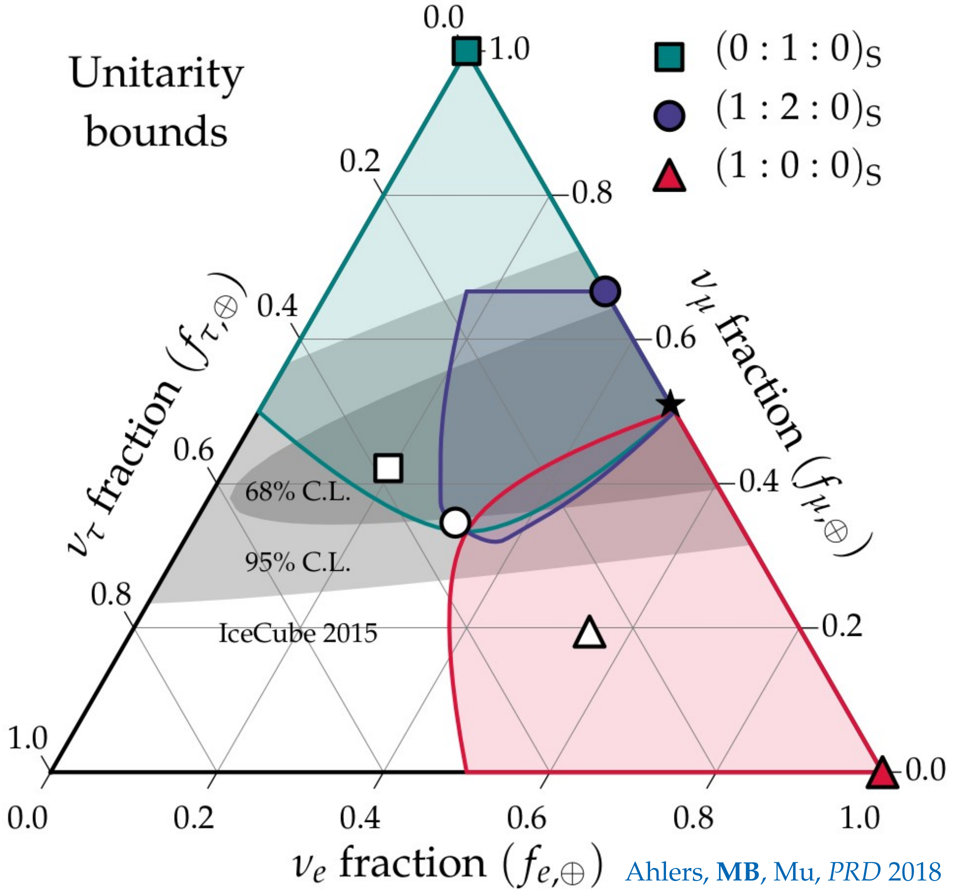

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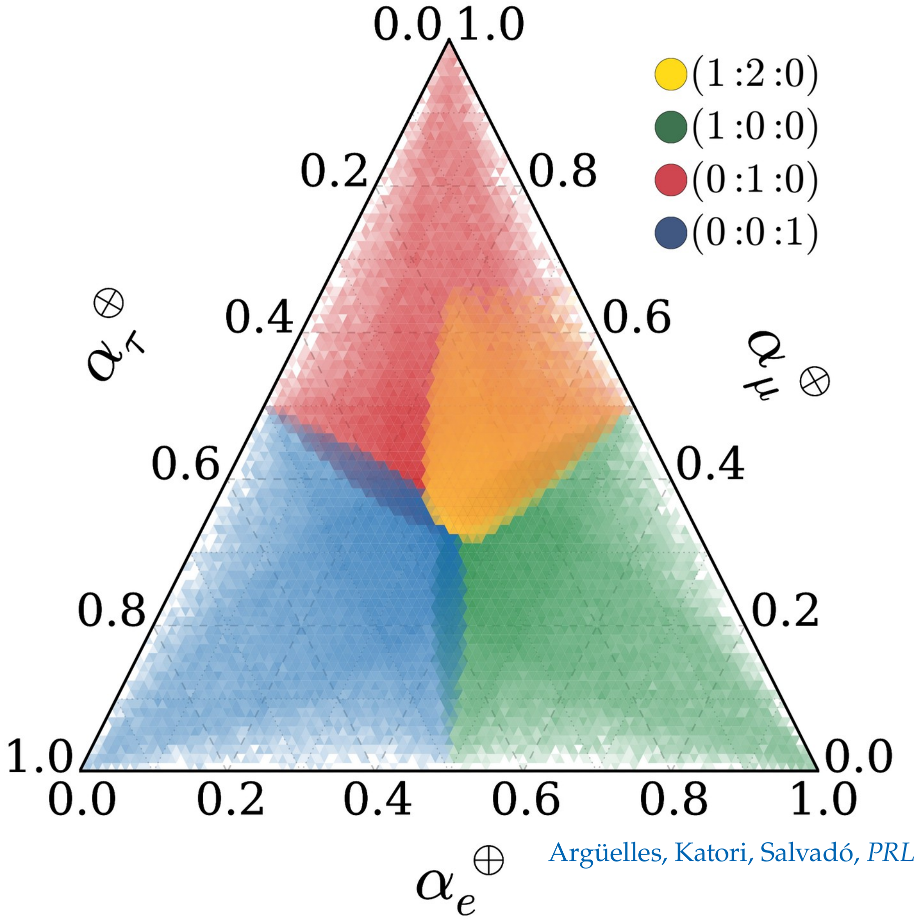

Argüelles, Katori, Salvadó, *PRL* 2015

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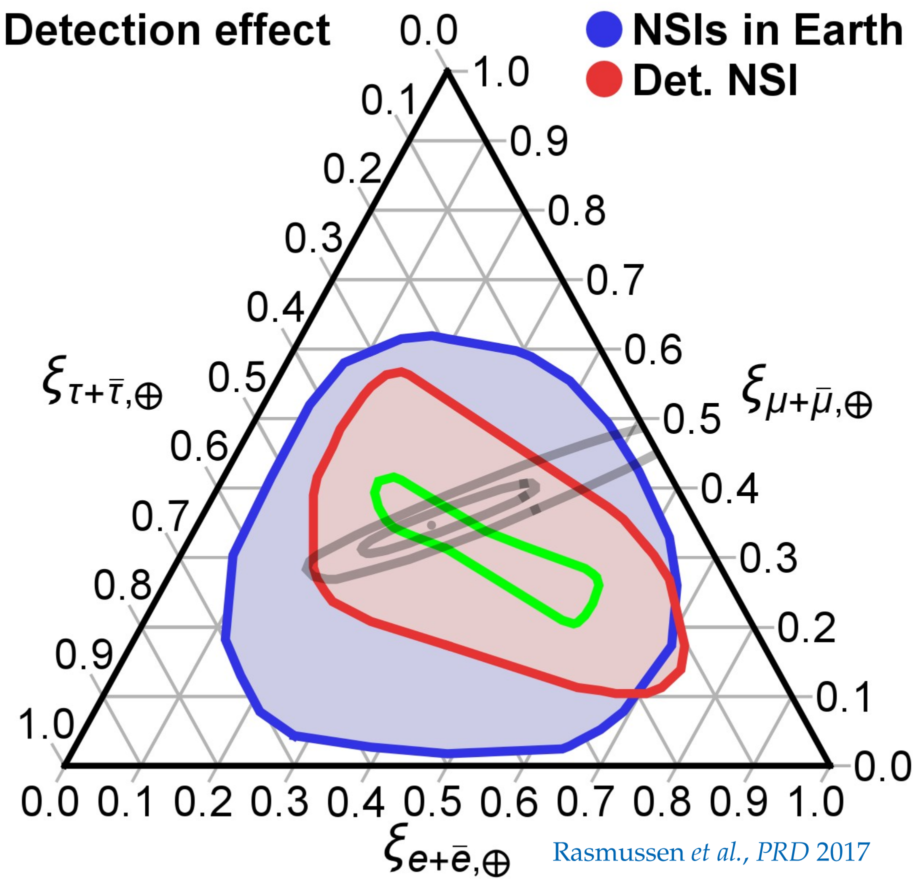
- Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]



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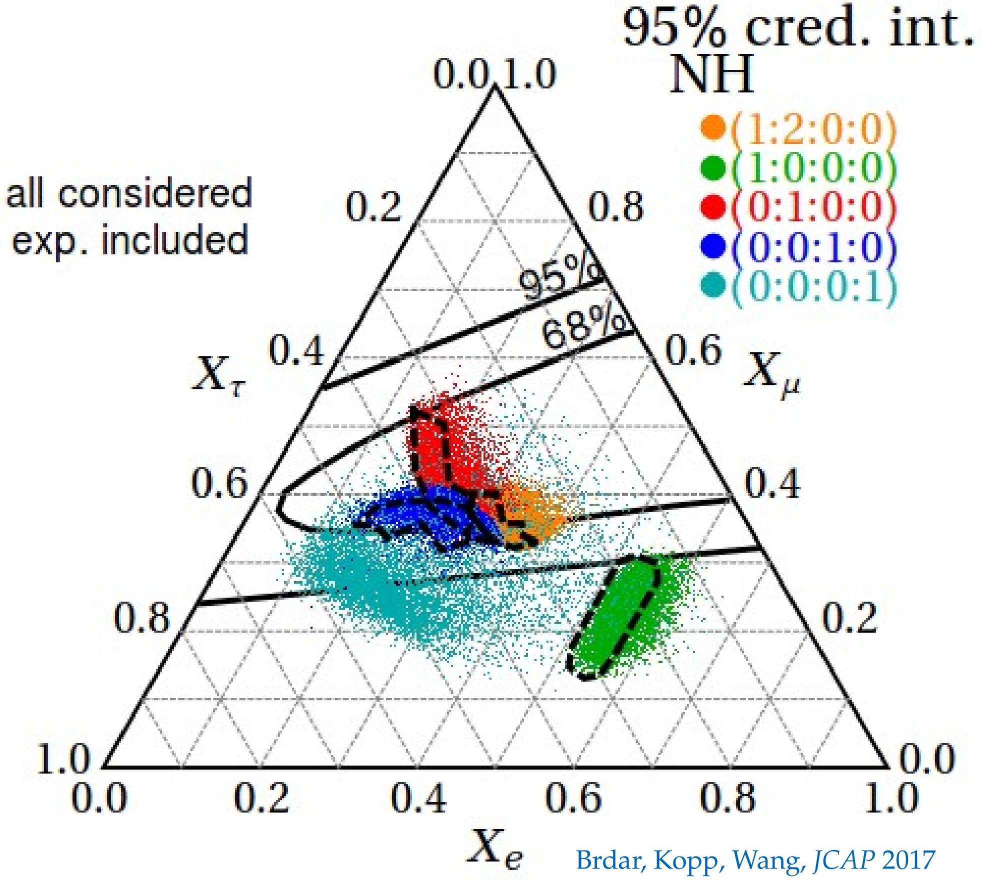
- ▸ Neutrino decay
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010;
  MB, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
- ▸ Tests of unitarity at high energy
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018;
  Ahlers, **MB**, Nortvig, *JCAP* 2021]
- ▸ Lorentz- and CPT-invariance violation
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010;
  Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- ▸ Non-standard interactions
  [González-García *et al.*, *Astropart. Phys.* 2016;
  Rasmussen *et al.*, *PRD* 2017]
- ▸ Active-sterile ν mixing
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017;
  Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]



Brdar, Kopp, Wang, *JCAP* 2017

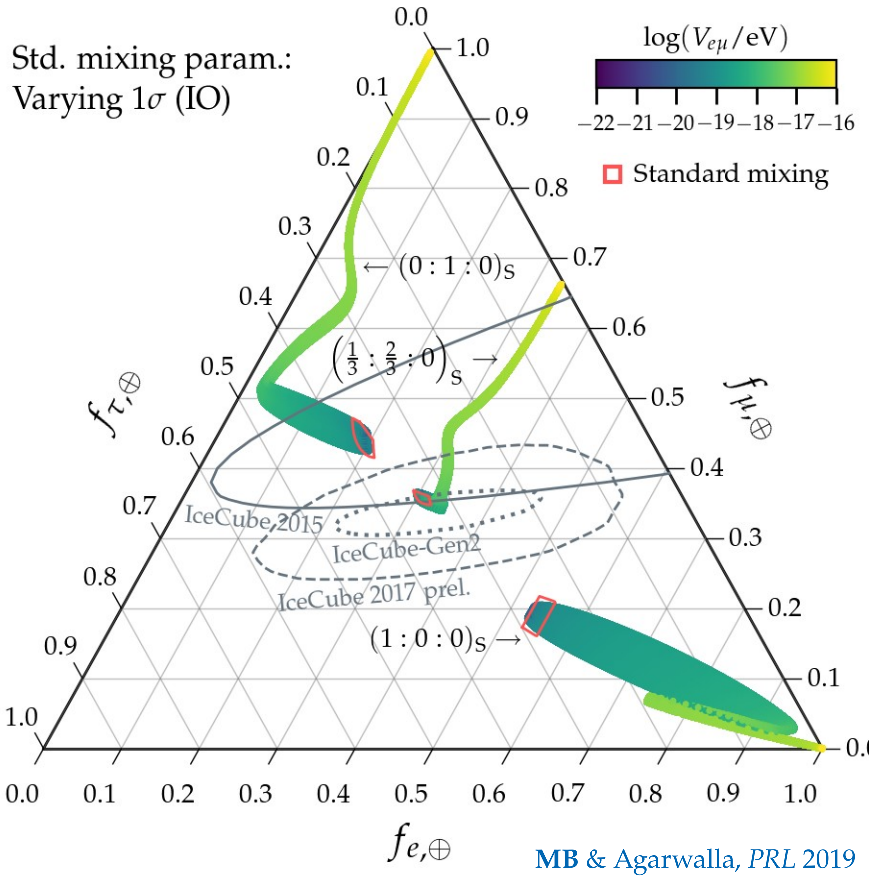
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

- **Neutrino decay**
  [Beacom *et al.*, *PRL* 2003; Baerwald, **MB**, Winter, JCAP 2010; **MB**, Beacom, Winter, *PRL* 2015; **MB**, Beacom, Murase, *PRD* 2017]
- **Tests of unitarity at high energy**
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, *JCAP* 2021]
- **Lorentz- and CPT-invariance violation**
  [Barenboim & Quigg, *PRD* 2003; **MB**, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004; Argüelles, Katori, Salvadó, *PRL* 2015]
- **Non-standard interactions**
  [González-García *et al.*, *Astropart. Phys.* 2016; Rasmussen *et al.*, *PRD* 2017]
- **Active-sterile ν mixing**
  [Aeikens *et al.*, *JCAP* 2015; Brdar, Kopp, Wang, *JCAP* 2017; Argüelles *et al.*, *JCAP* 2020; Ahlers, **MB**, *JCAP* 2021]
- **Long-range *e*ν interactions**
  [**MB** & Agarwalla, *PRL* 2019]

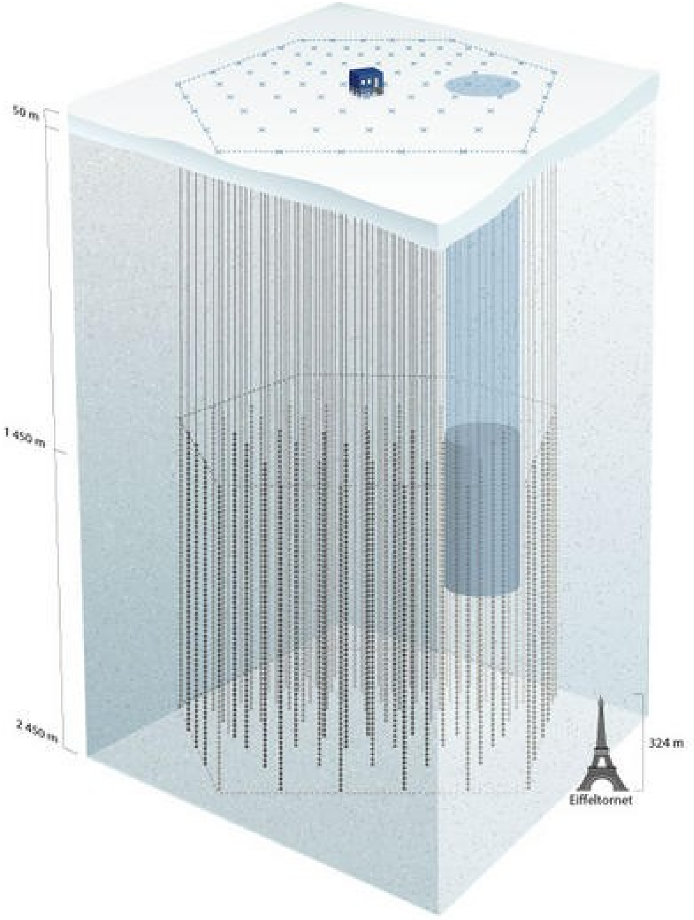
Reviews:
Mehta & Winter, *JCAP* 2011; Rasmussen *et al.*, *PRD* 2017



MB & Agarwalla, *PRL* 2019

IceCube

IceCube – What is it?



- Km^3 in-ice Cherenkov detector in Antarctica
- > 5000 PMTs at 1.5–2.5 km of depth
- Sensitive to neutrino energies > 10 GeV

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC)

$\nu_x + N \rightarrow \nu_x + X$

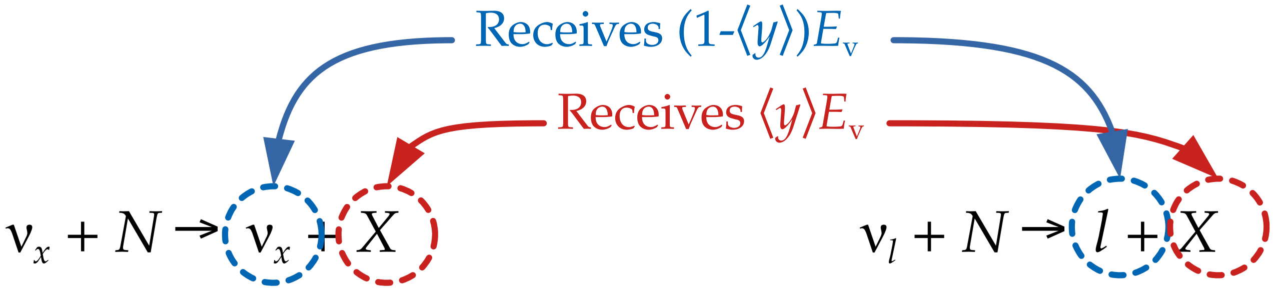
Charged current (CC)

$\nu_l + N \rightarrow l + X$

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC) | Charged current (CC)

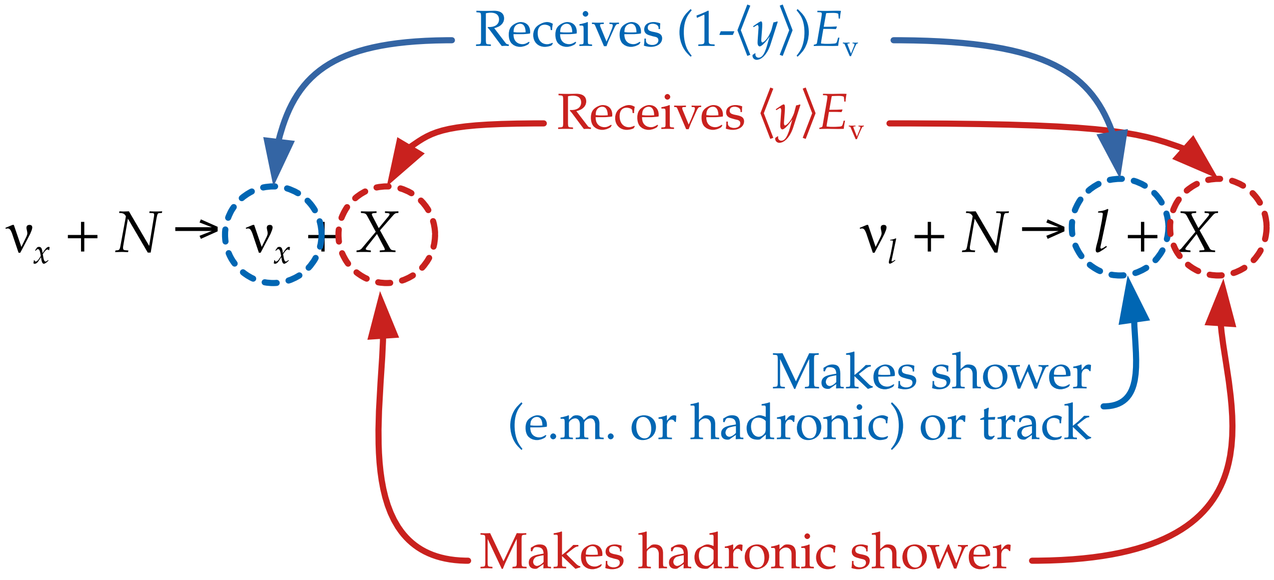


At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25$–0.30

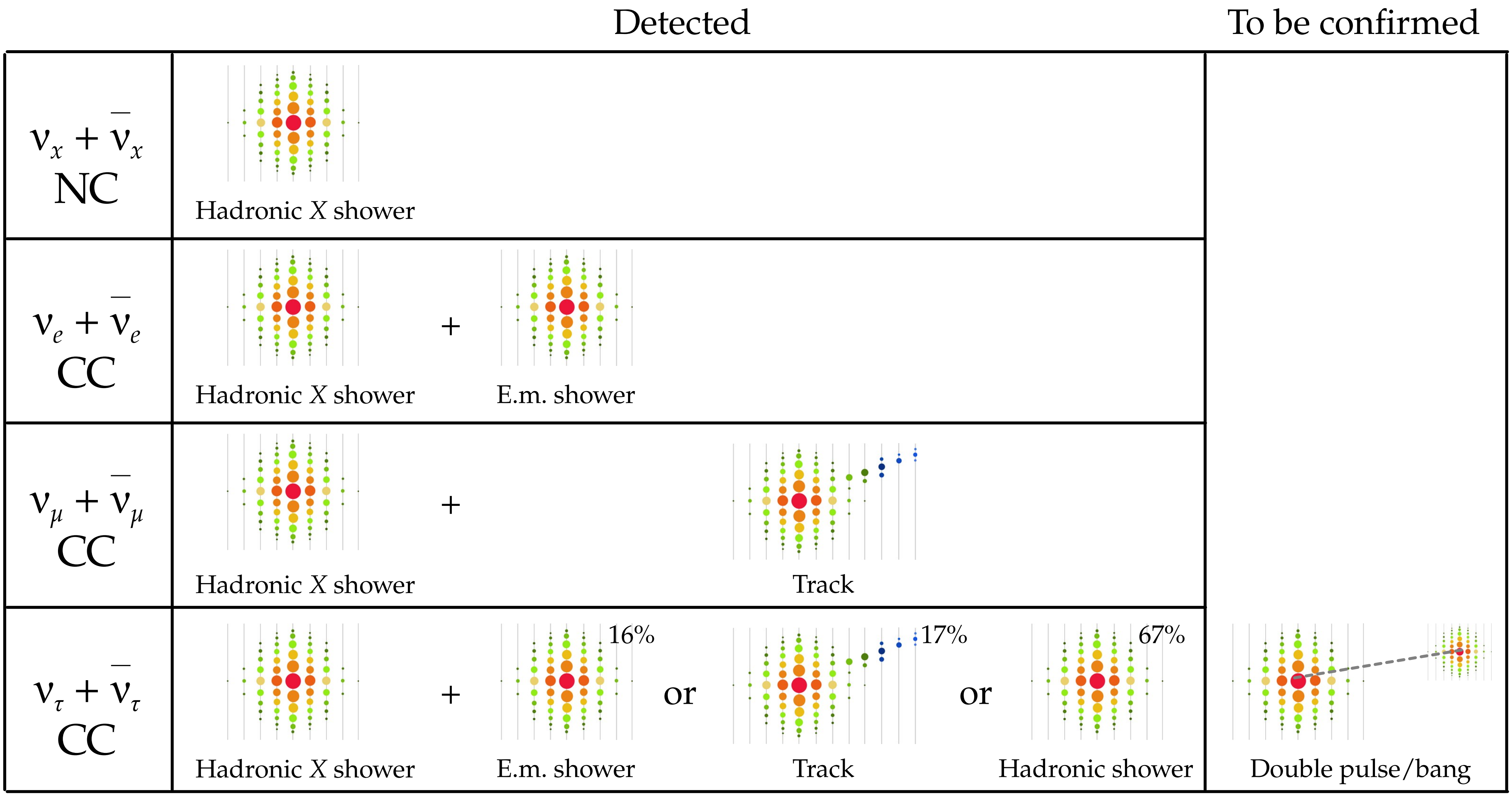
How does IceCube see TeV–PeV neutrinos?

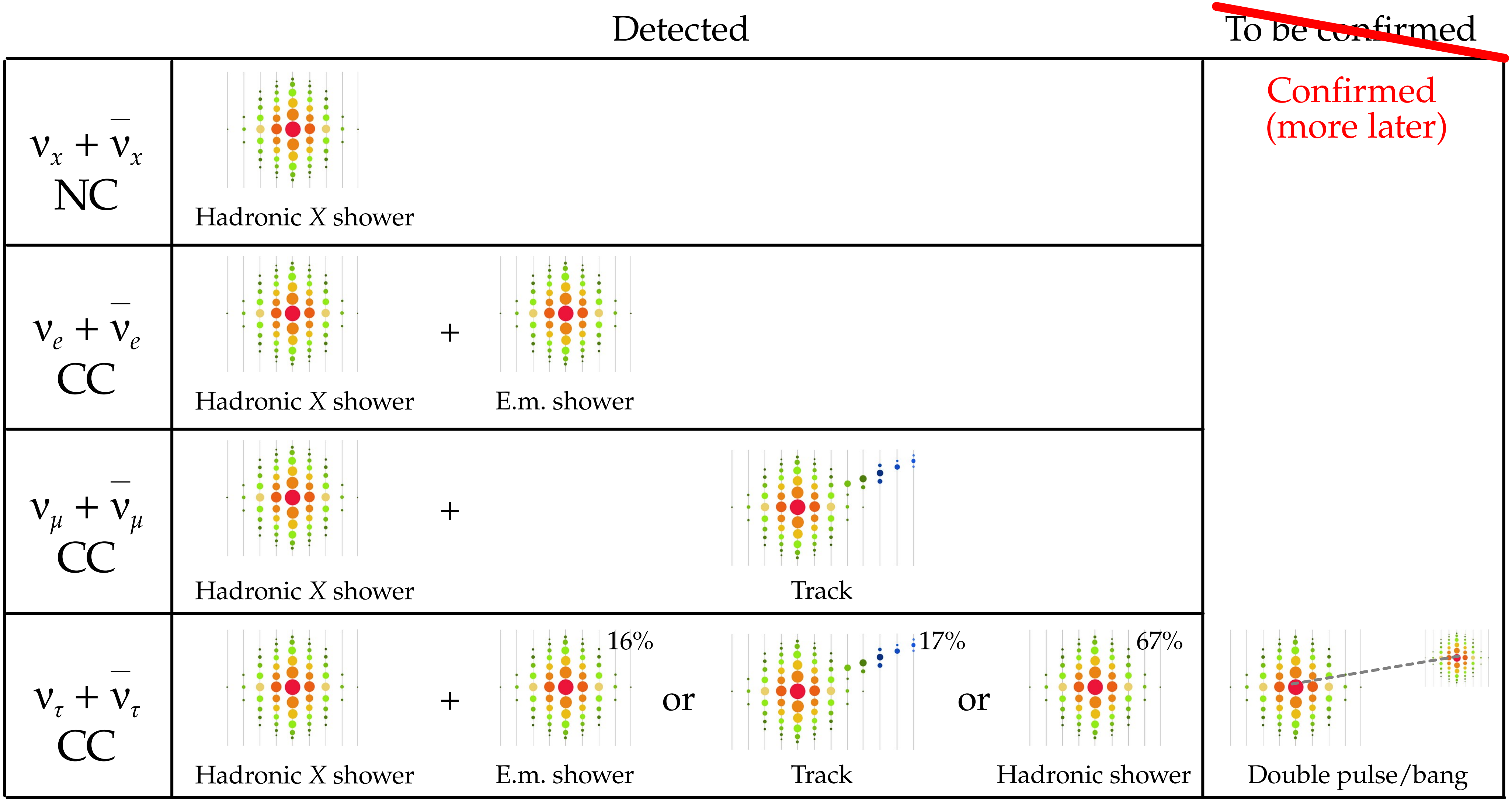
Deep inelastic neutrino-nucleon scattering

Neutral current (NC) | Charged current (CC)

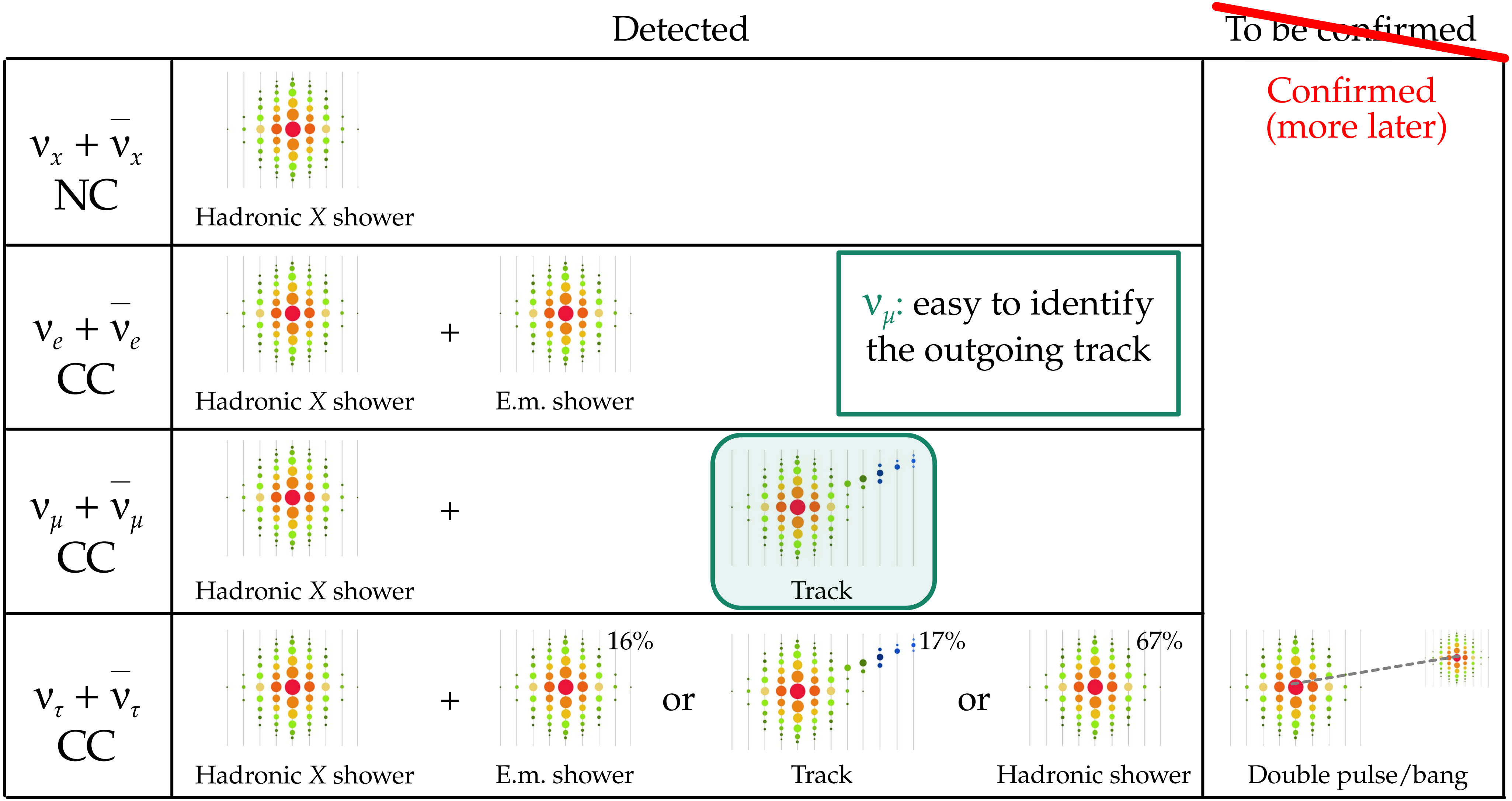


At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30

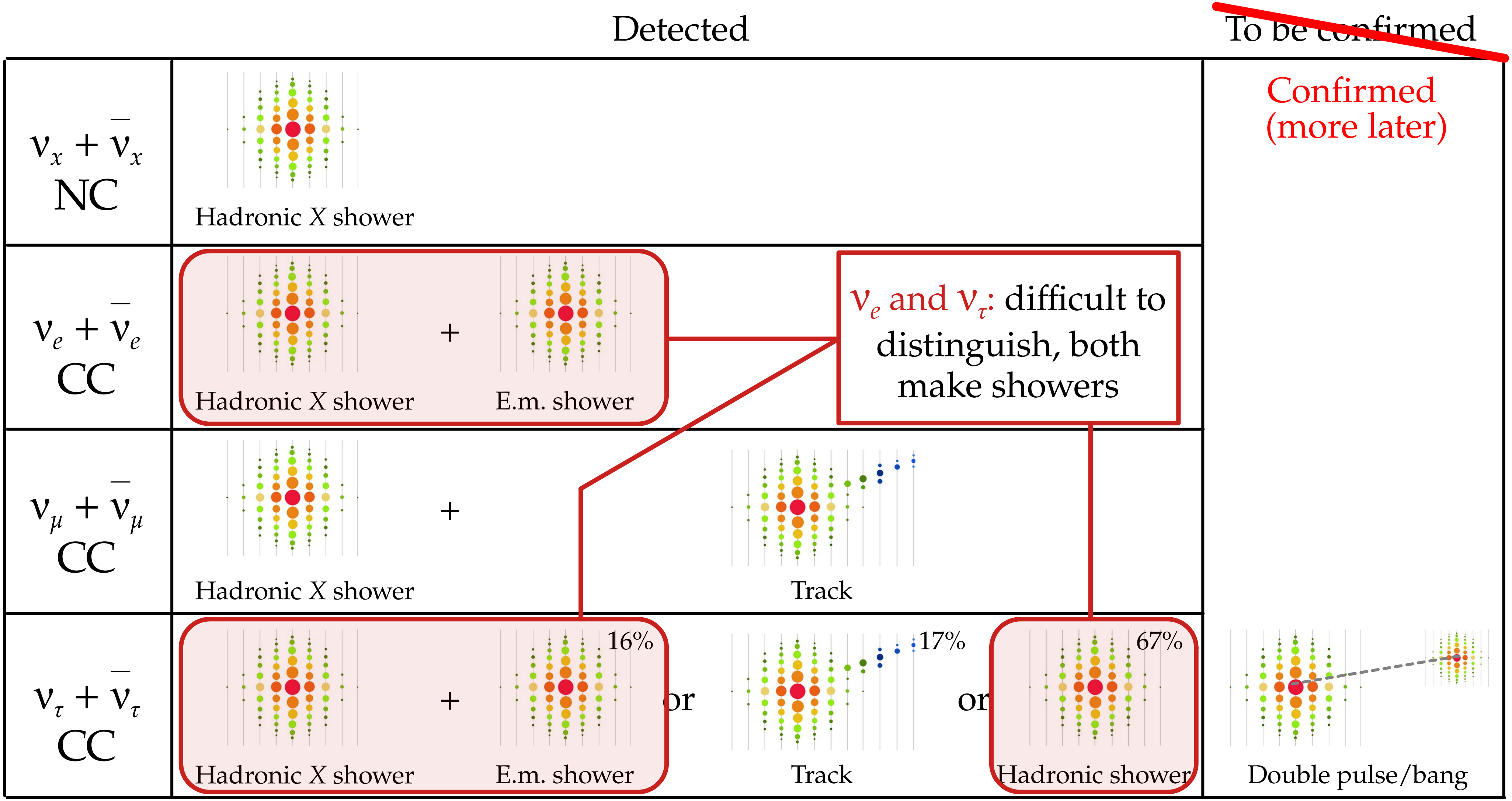

Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower
+
16%
E.m. shower
or
17%
Track
or
67%
Hadronic shower
Double pulse/bang



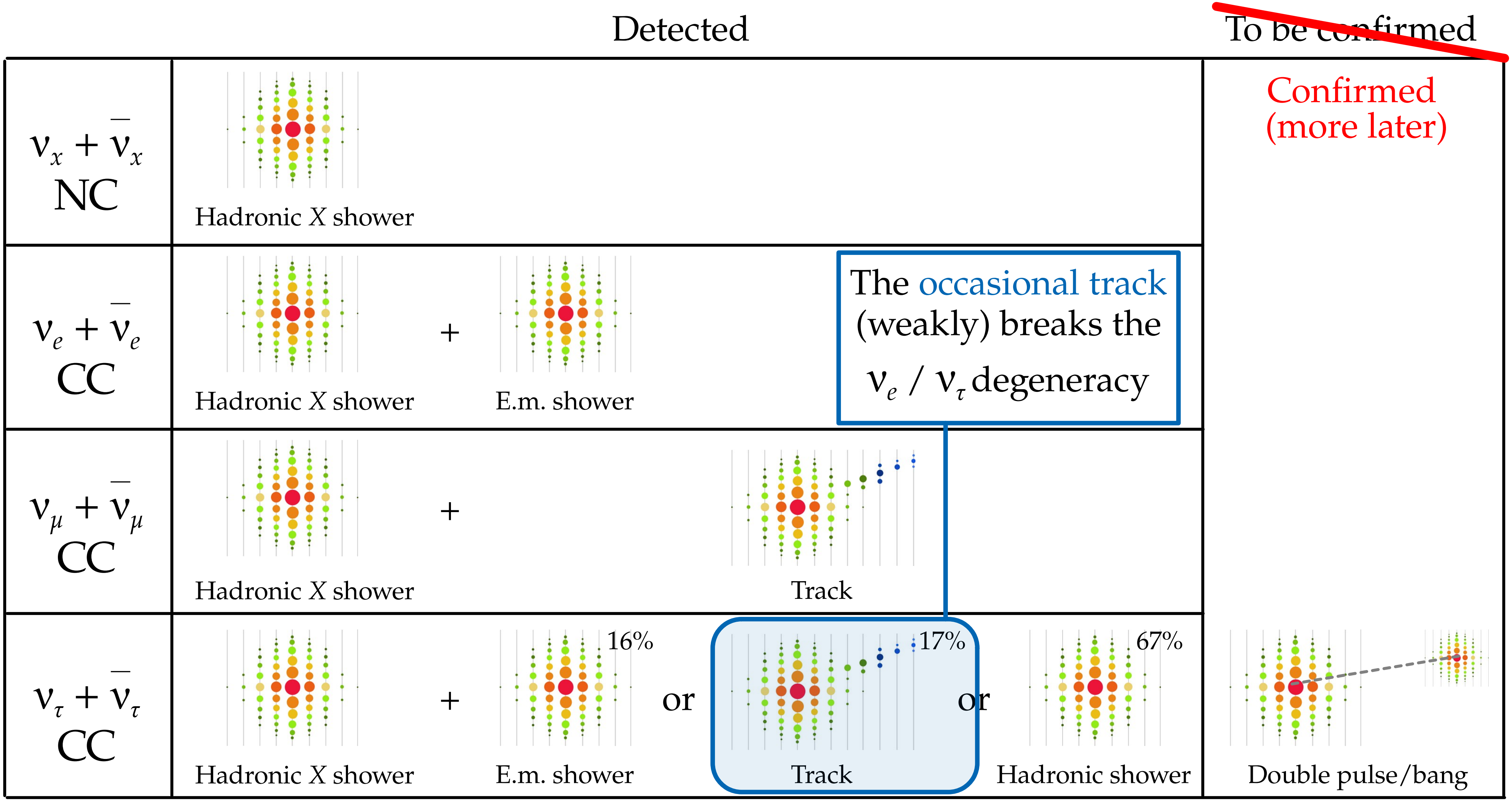
Detected
~~To be confirmed~~
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower + E.m. shower
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower + Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X shower + E.m. shower 16% or Track 17% or Hadronic shower 67%
Double pulse/bang



Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ 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
Double pulse/bang



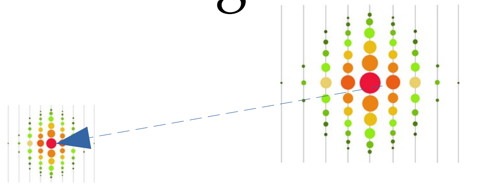
Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
ν_e and ν_τ: difficult to distinguish, both make showers
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic X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



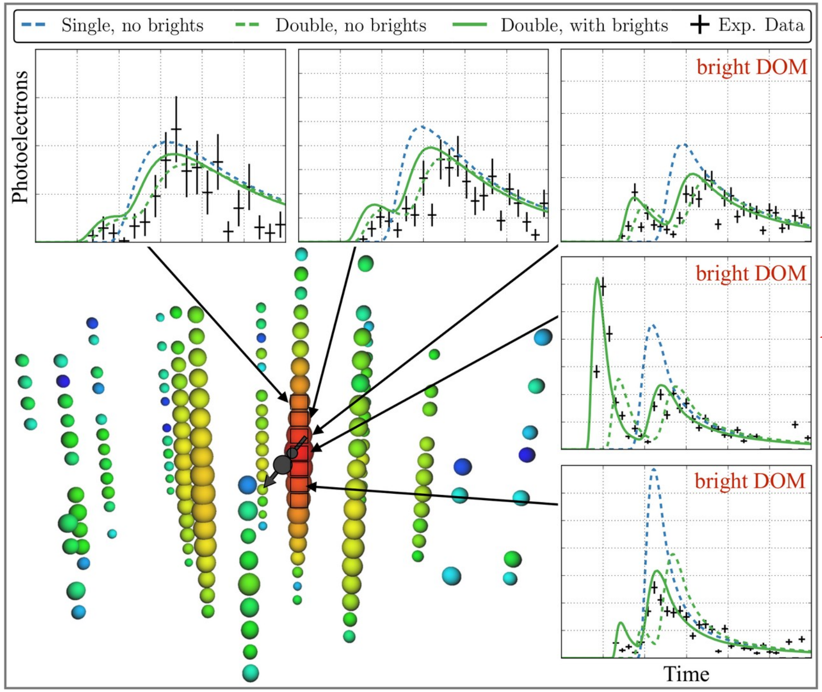
Detected
To be confirmed
Confirmed
(more later)
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$ CC
Hadronic X shower
+
E.m. shower
The occasional track (weakly) breaks the ν_e / ν_τ degeneracy
$\nu_\mu + \bar{\nu}_\mu$ CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$ CC
Hadronic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

First identified high-energy astrophysical ν_τ

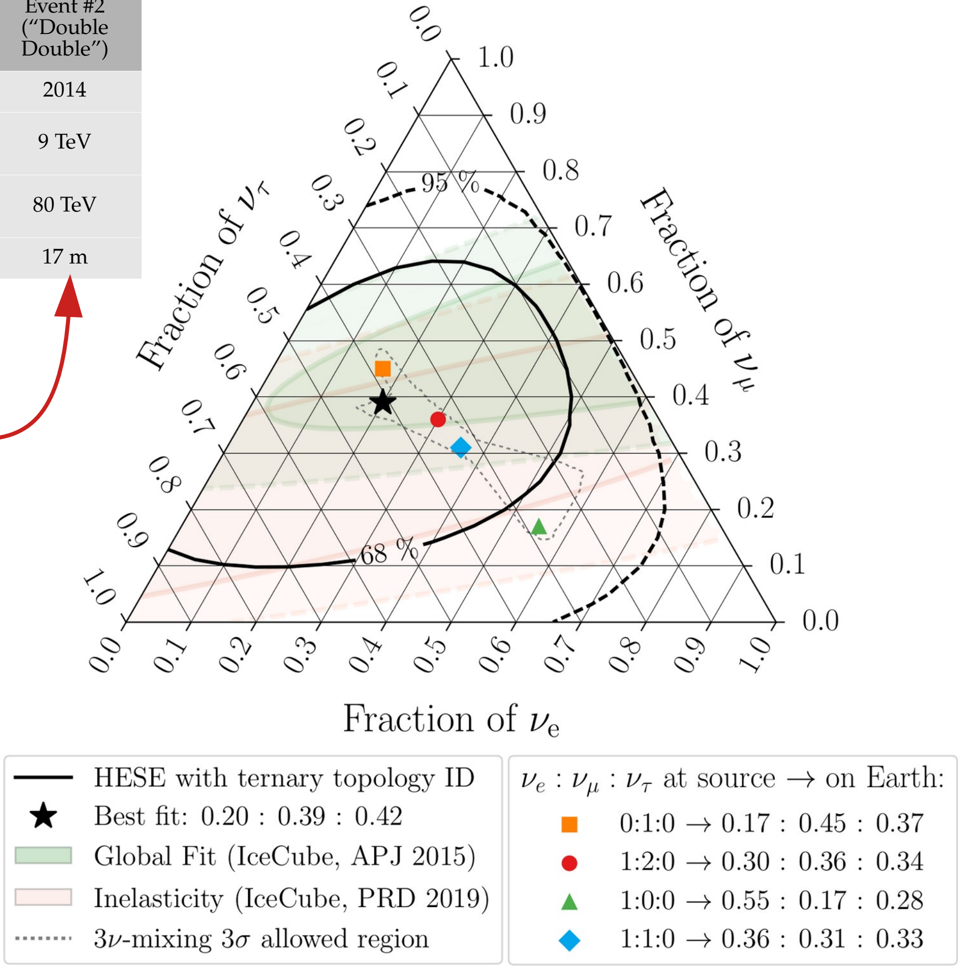
Double bang:



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



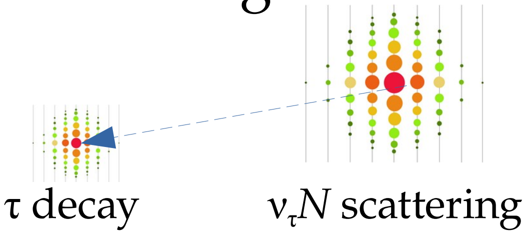
Most likely to be a ν_τ



IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:



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Year	2012	2014
Energy 1st cascade	1.2 PeV	9 TeV
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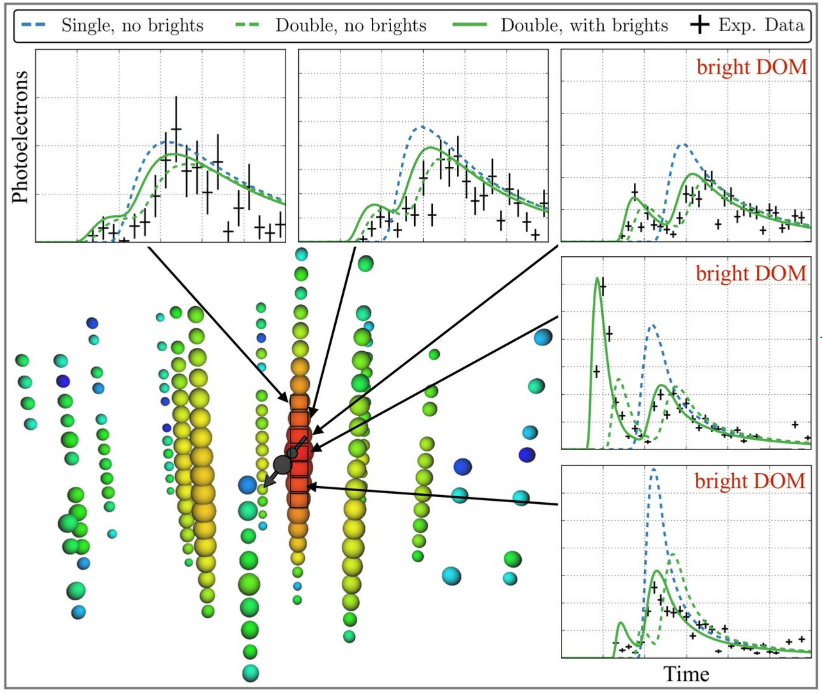
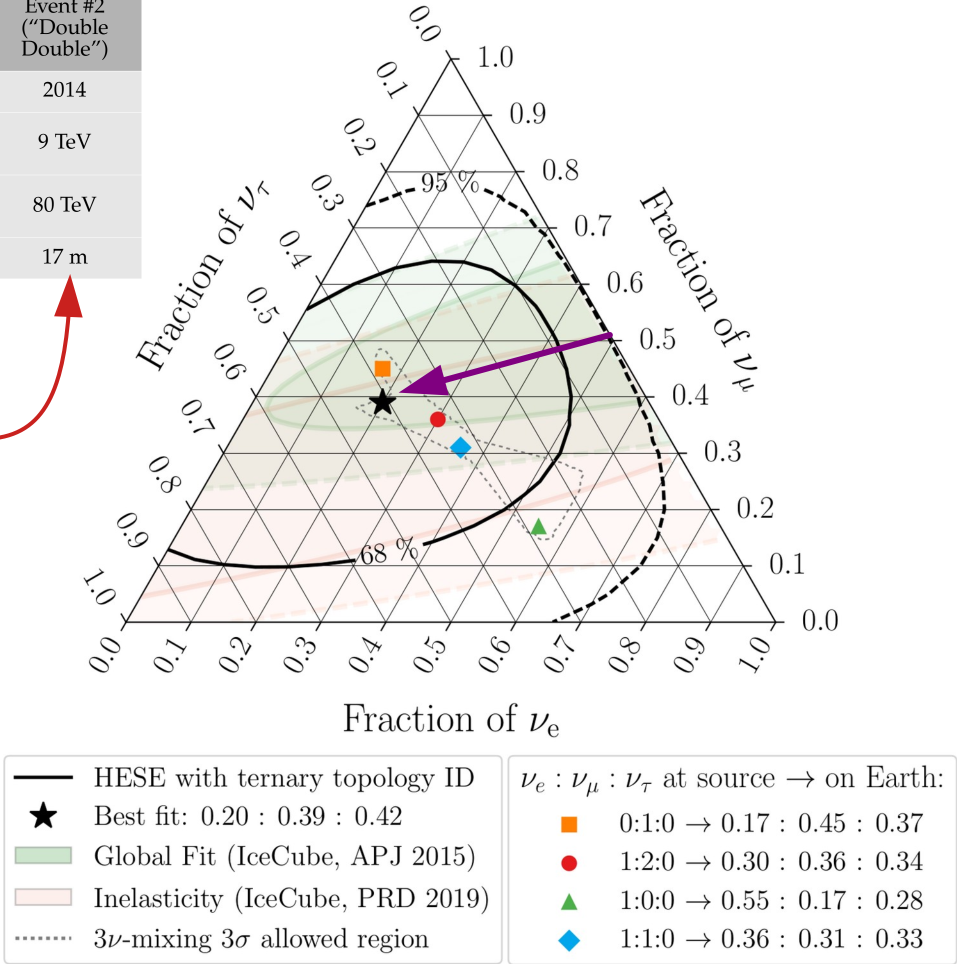
Length	16 m	17 m

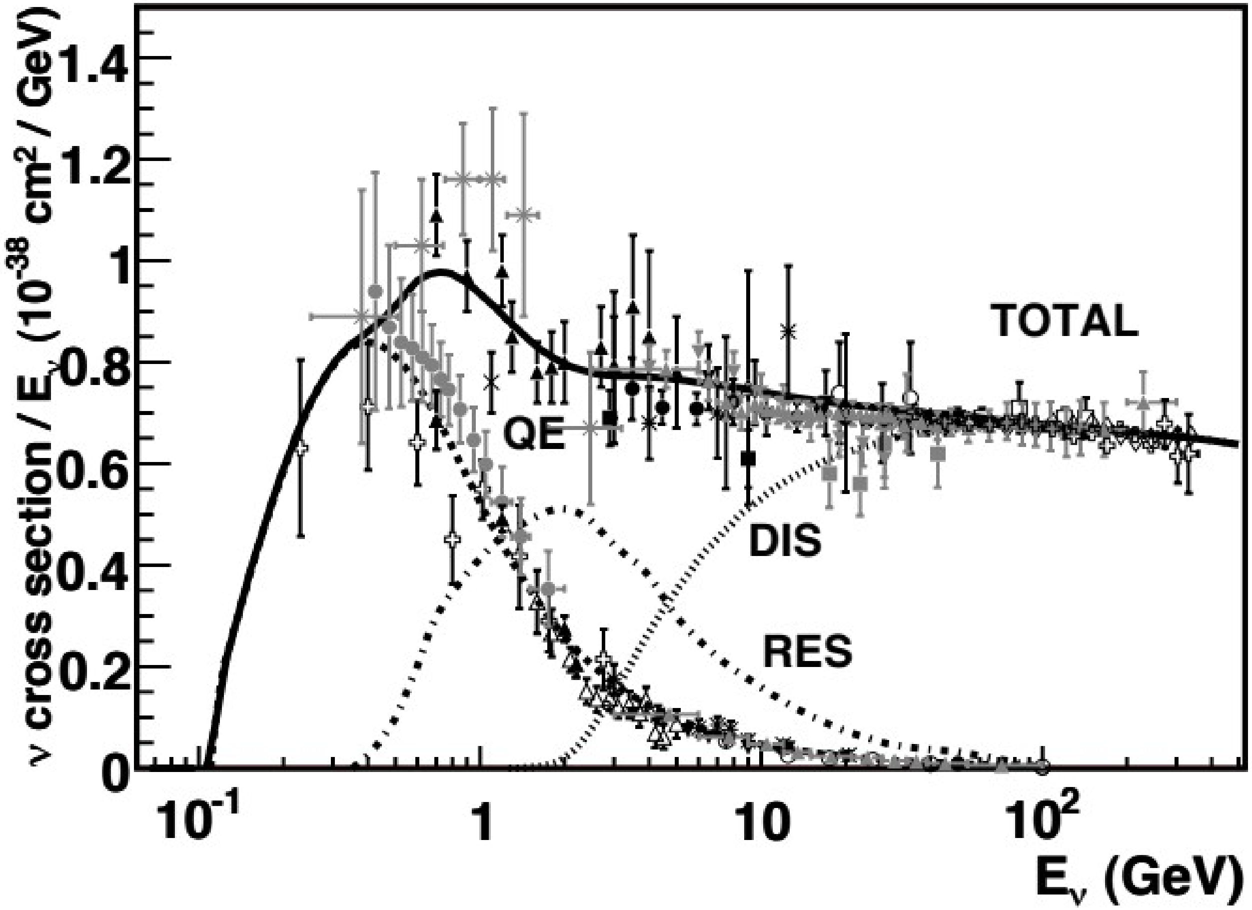
Most likely to be a ν_τ





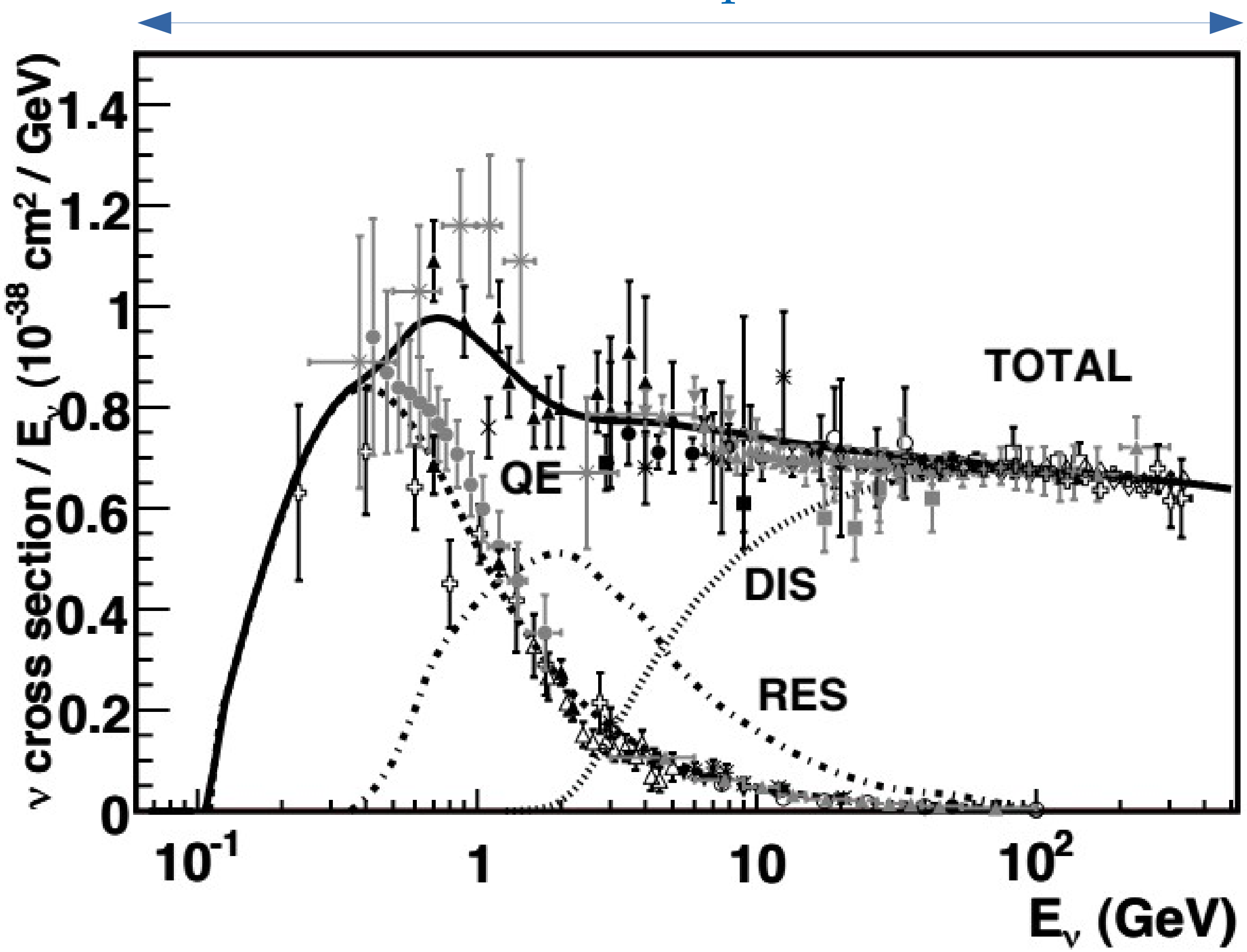
IceCube, 2011.03561

Example:
Measuring νN cross sections



Particle Data Group

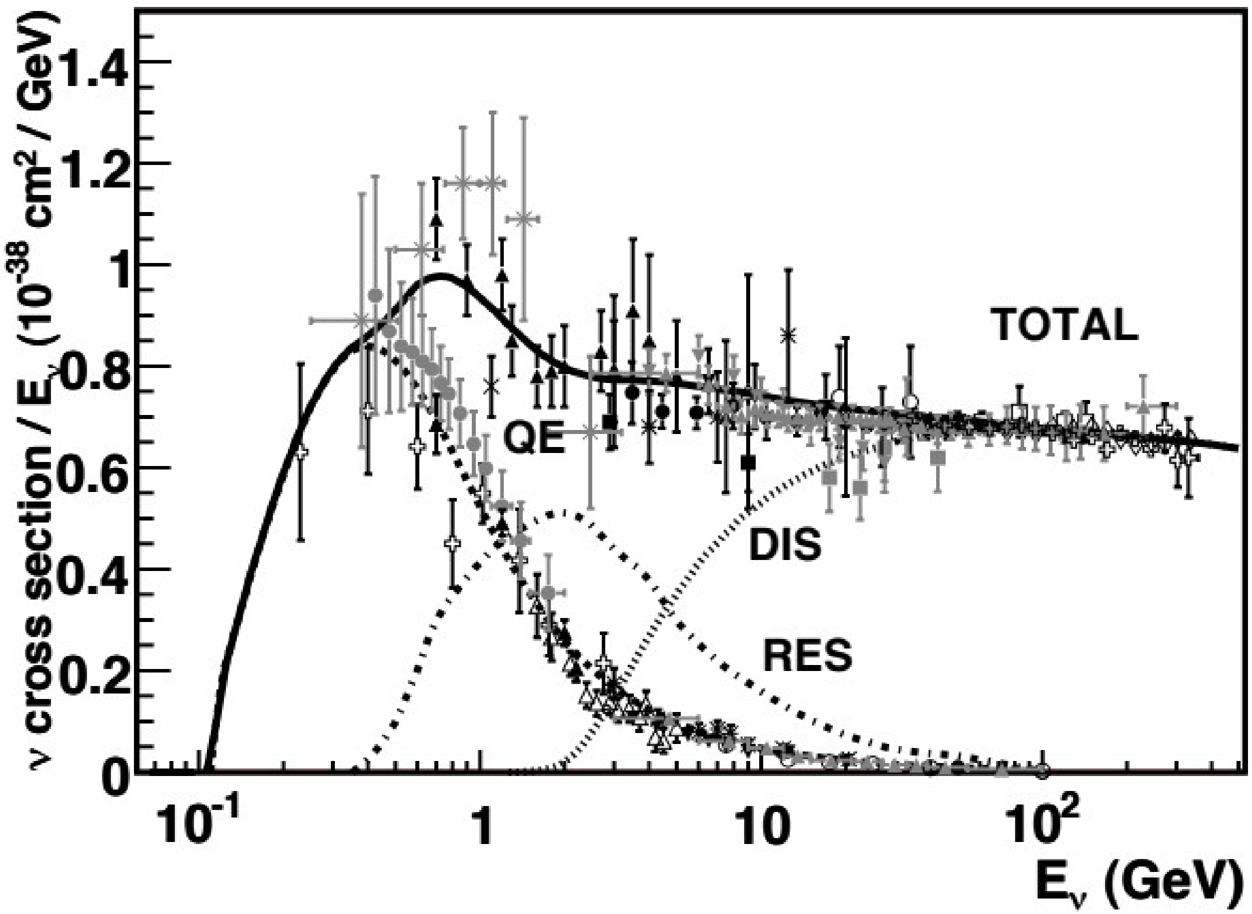
Accelerator experiments



Particle Data Group

Accelerator experiments

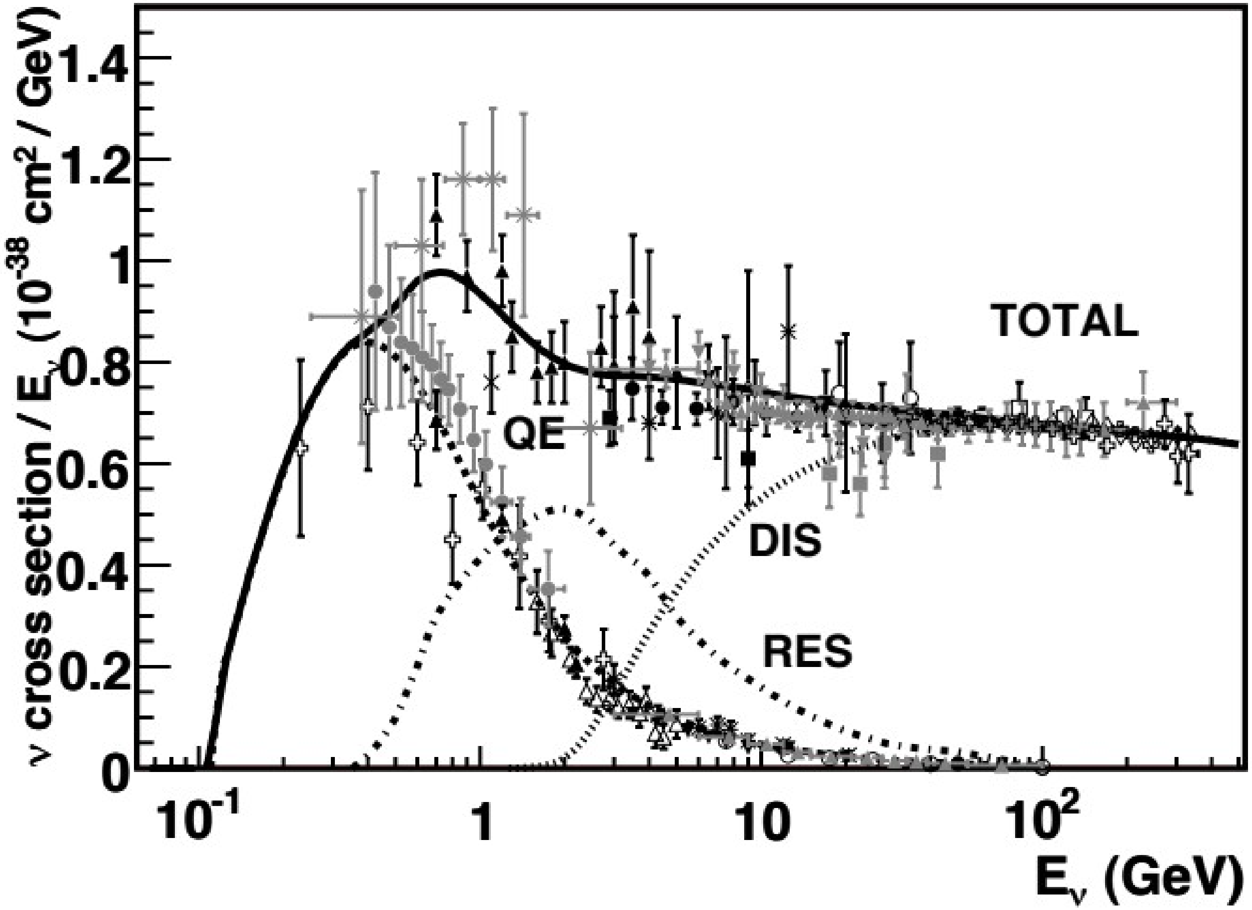
One recent measurement (COHERENT)



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)

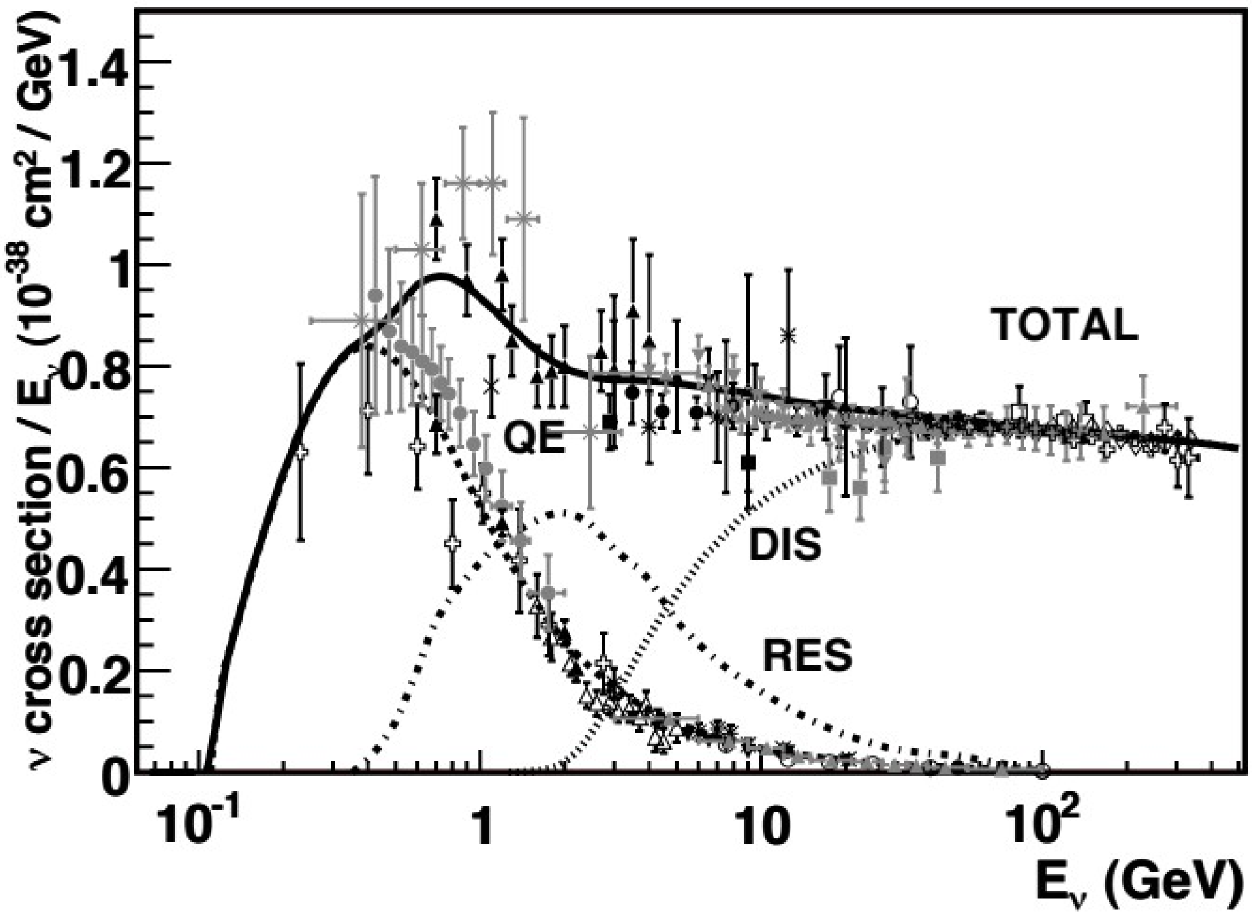


Particle Data Group

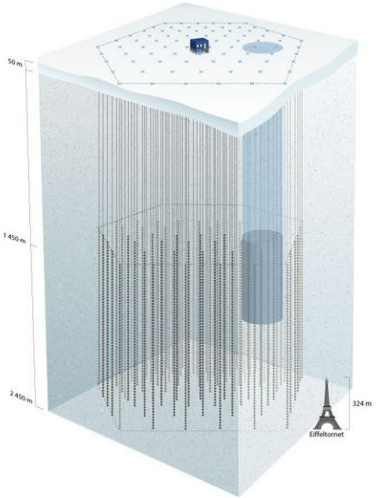
No measurements … until recently!

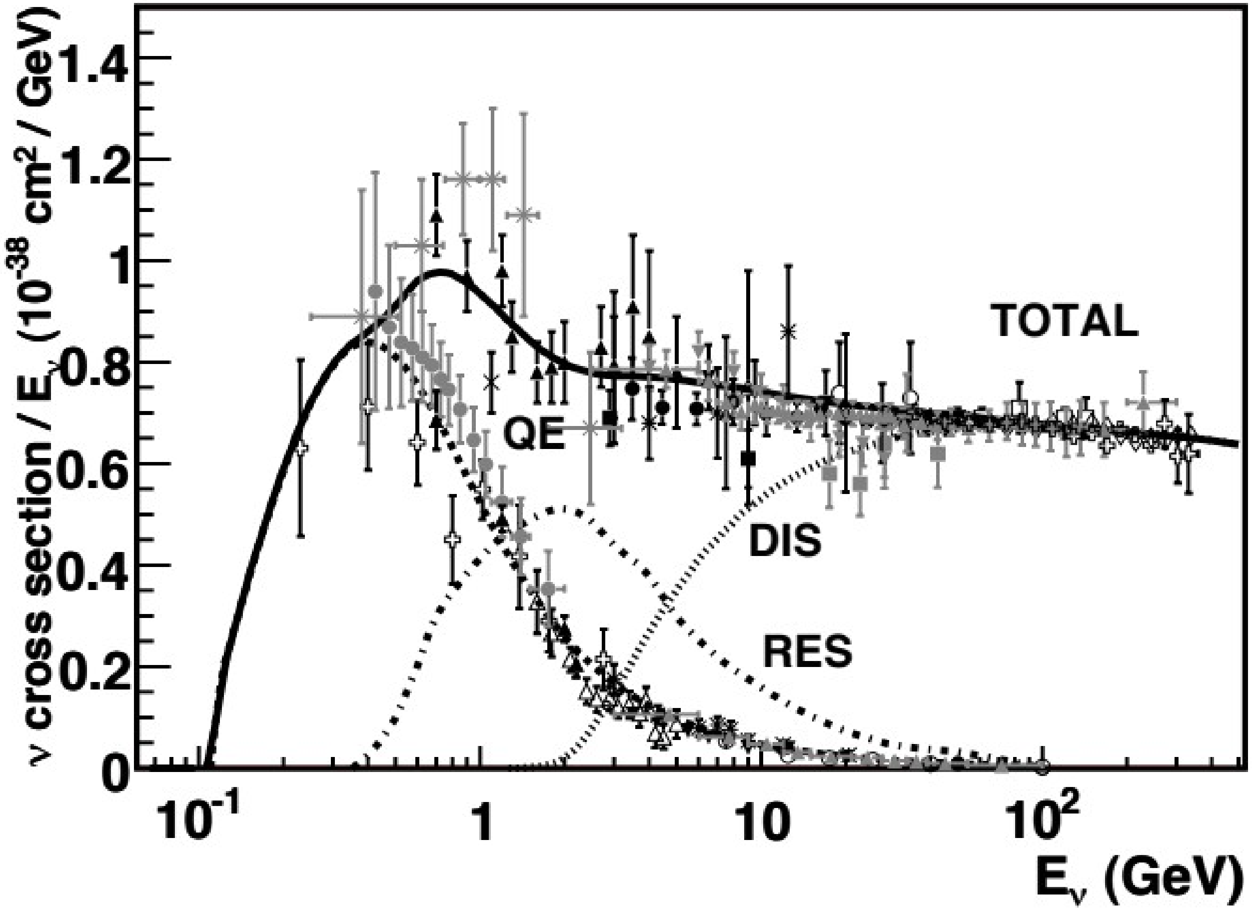
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



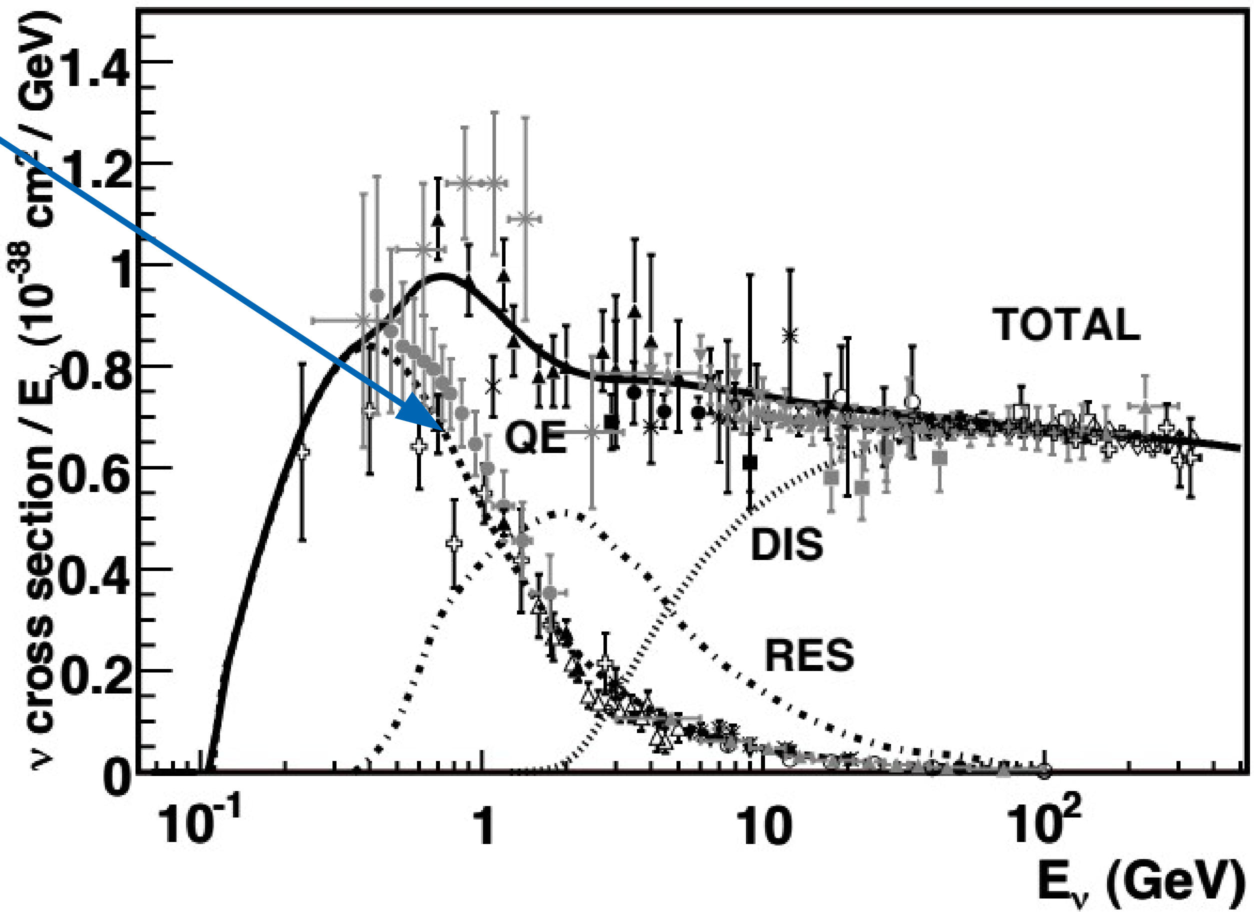


Particle Data Group

Quasi-elastic scattering:

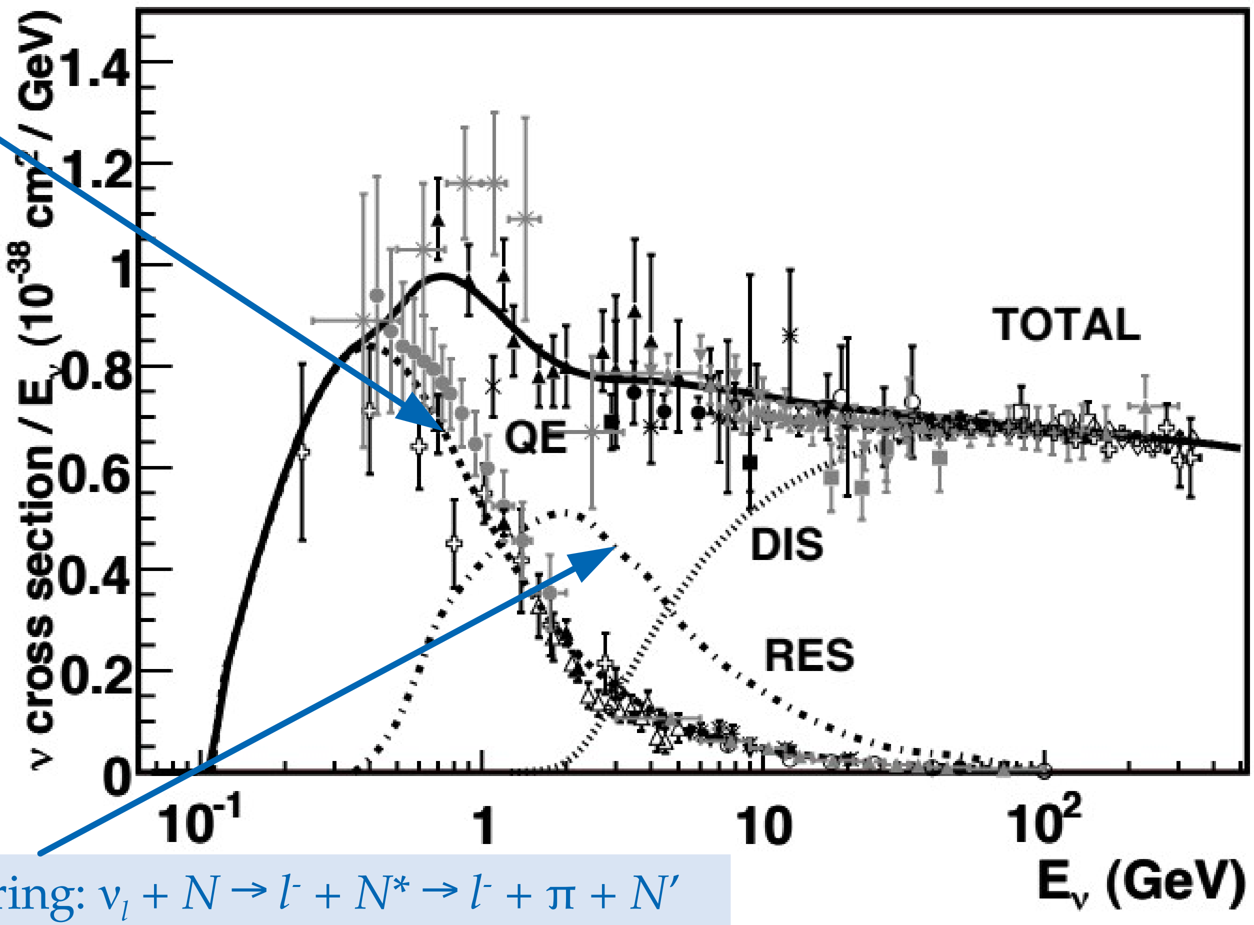
$\nu_l + n \rightarrow l^- + p$

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



Particle Data Group

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



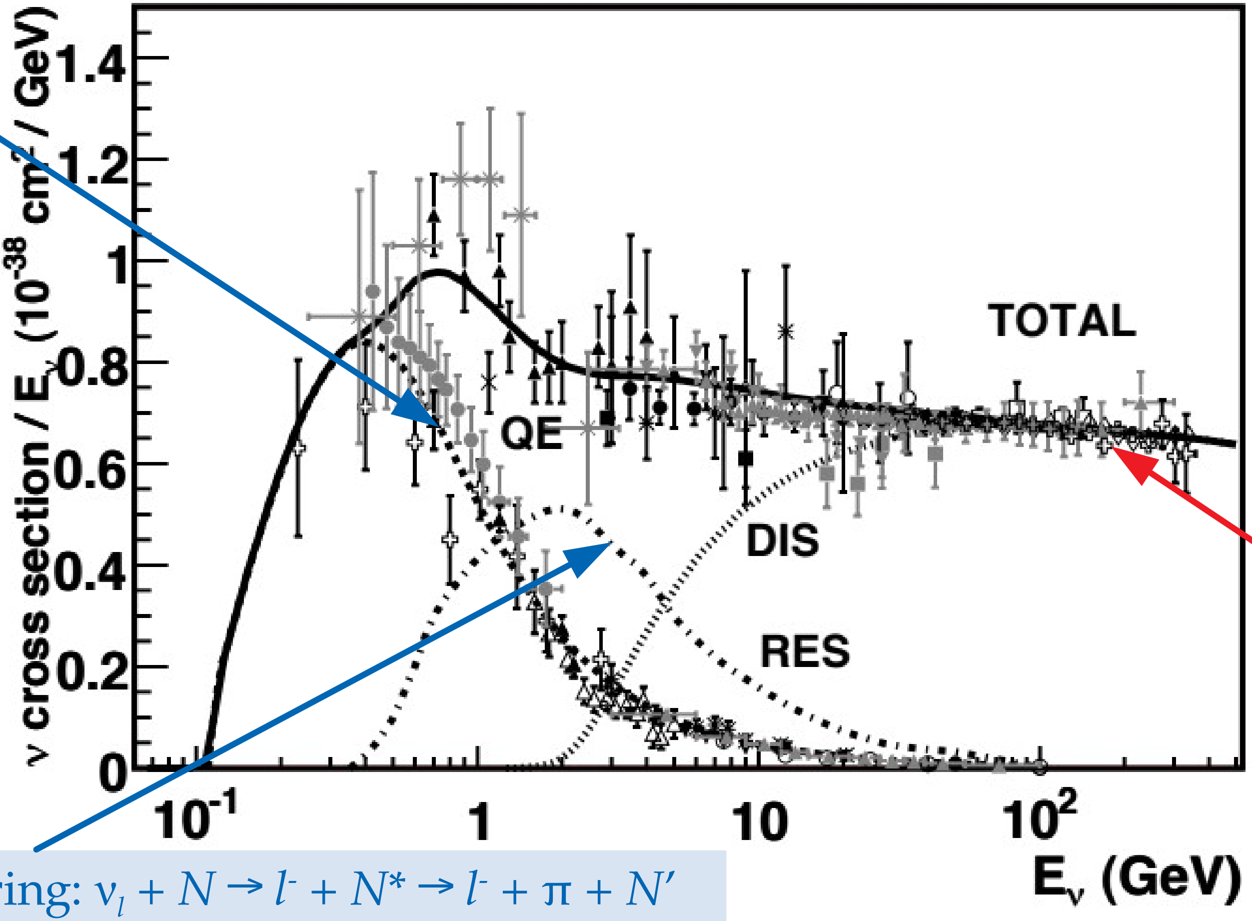
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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

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



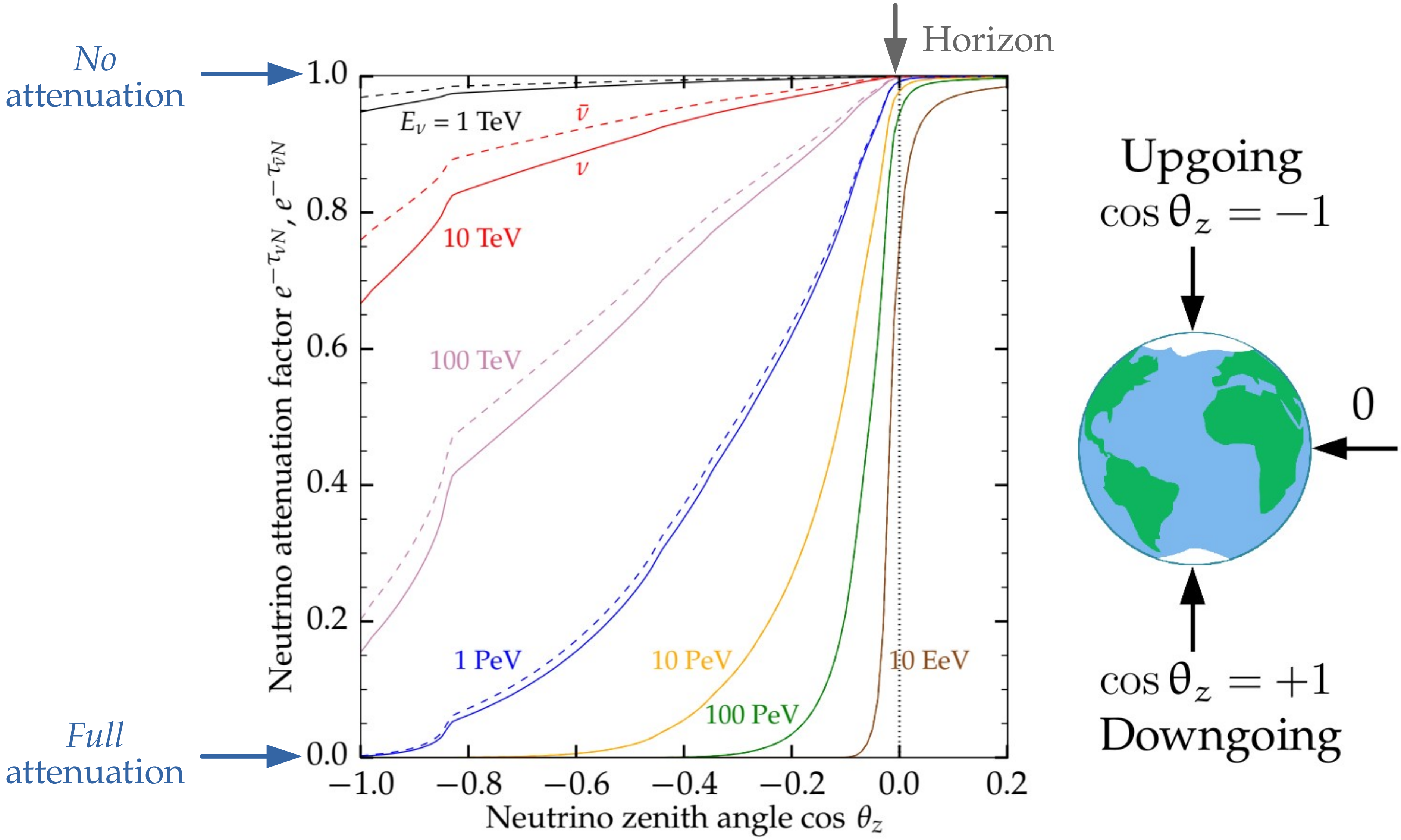
Deep inelastic scattering:

$\nu_l + N \rightarrow l^- + X$

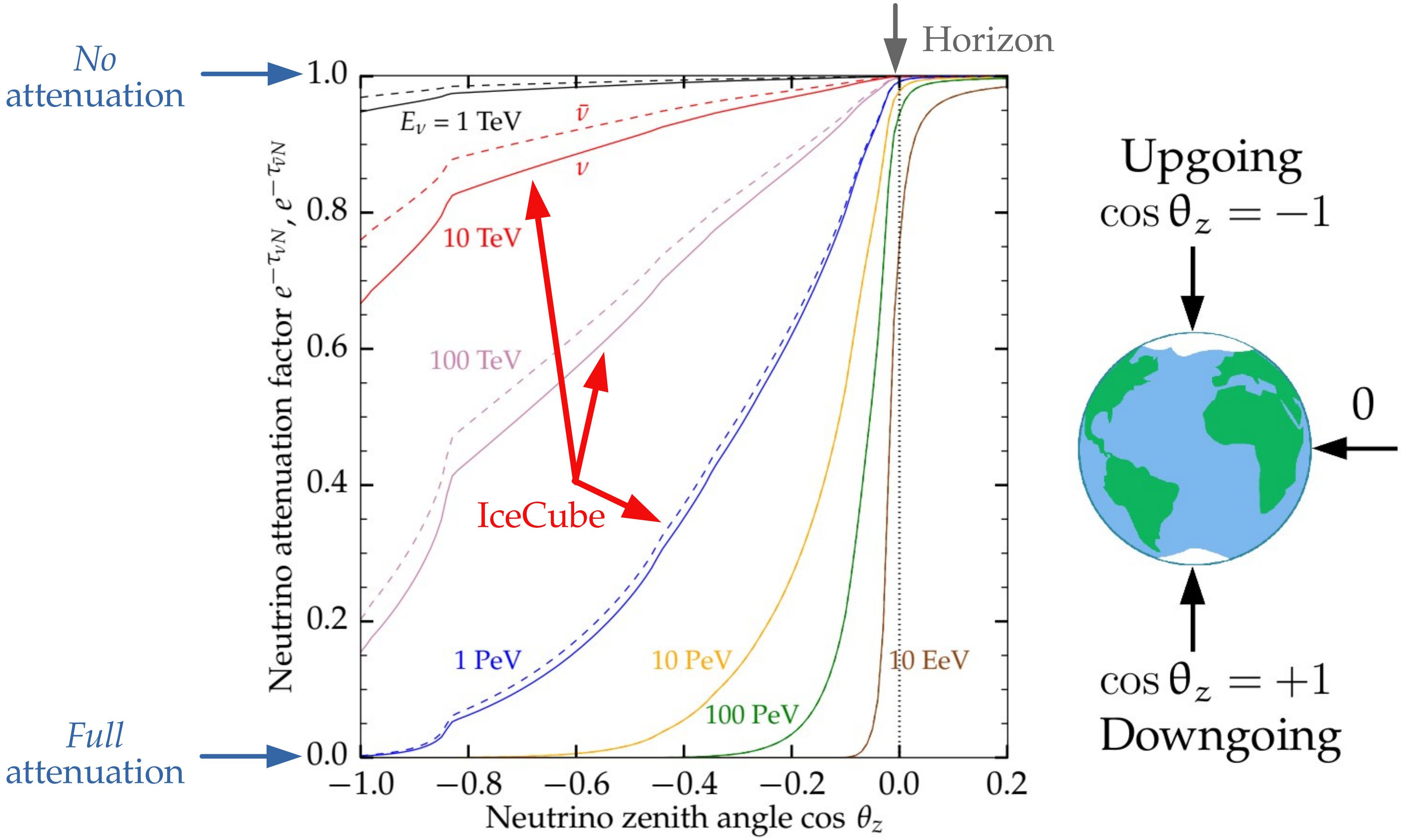
$\bar{\nu}_l + N \rightarrow l^+ + X$

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

Particle Data Group

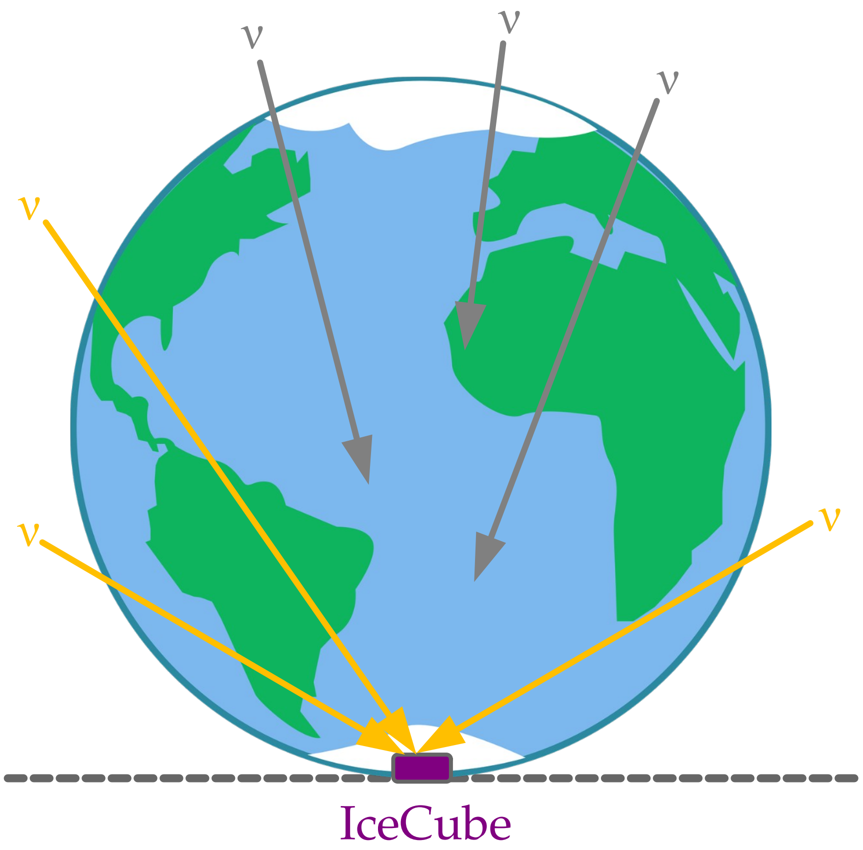


No
attenuation
Full
attenuation
Horizon
Neutrino attenuation factor $e^{-\tau_{\nu N}}, e^{-\tau_{\bar{\nu} N}}$
Neutrino zenith angle $\cos\theta_z$
E_ν = 1 TeV
$\bar{\nu}$
ν
10 TeV
100 TeV
1 PeV
10 PeV
100 PeV
10 EeV
1.0
0.8
0.6
0.4
0.2
0.0
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing



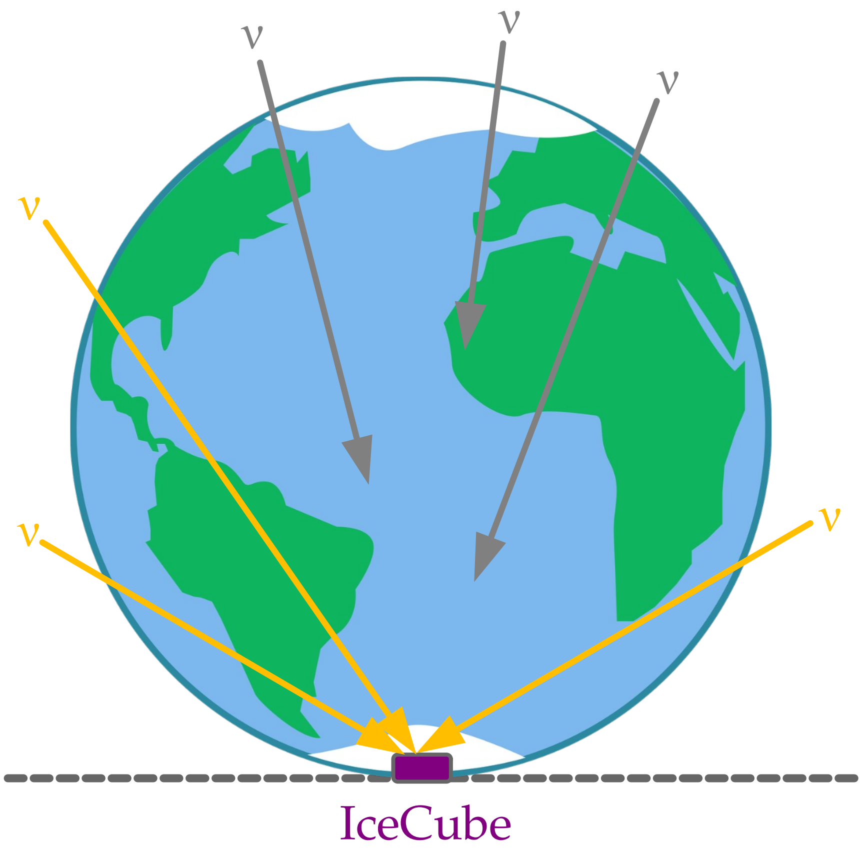
MB & Connolly, *PRL* 2019

TeV–PeV:



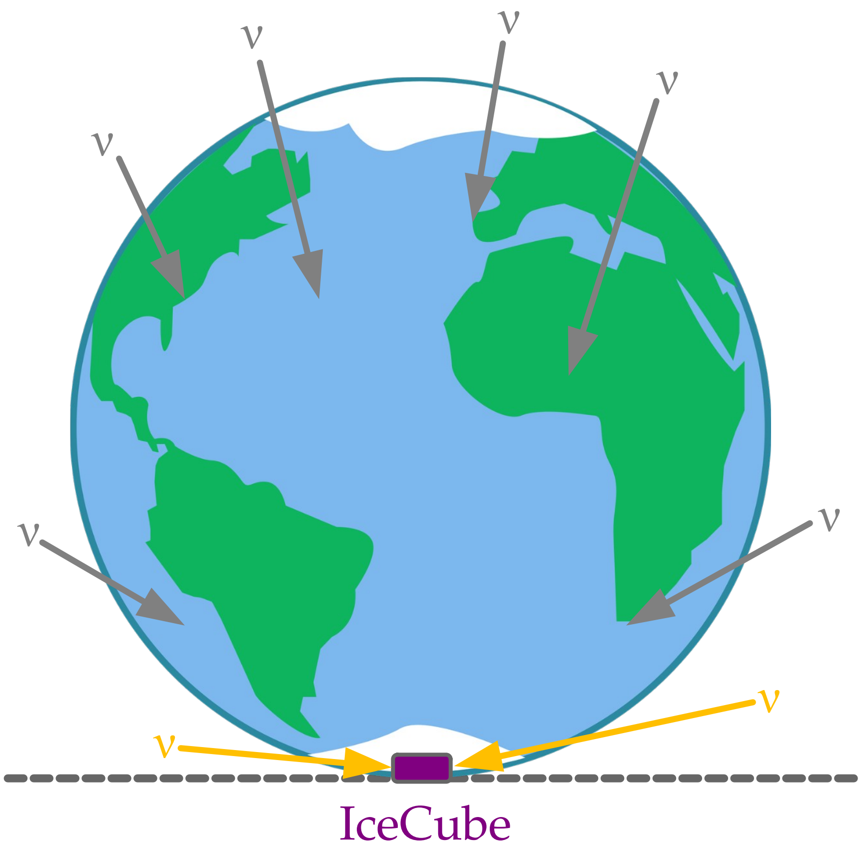
Earth is *almost fully* opaque,
some upgoing ν still make it through

TeV–PeV:



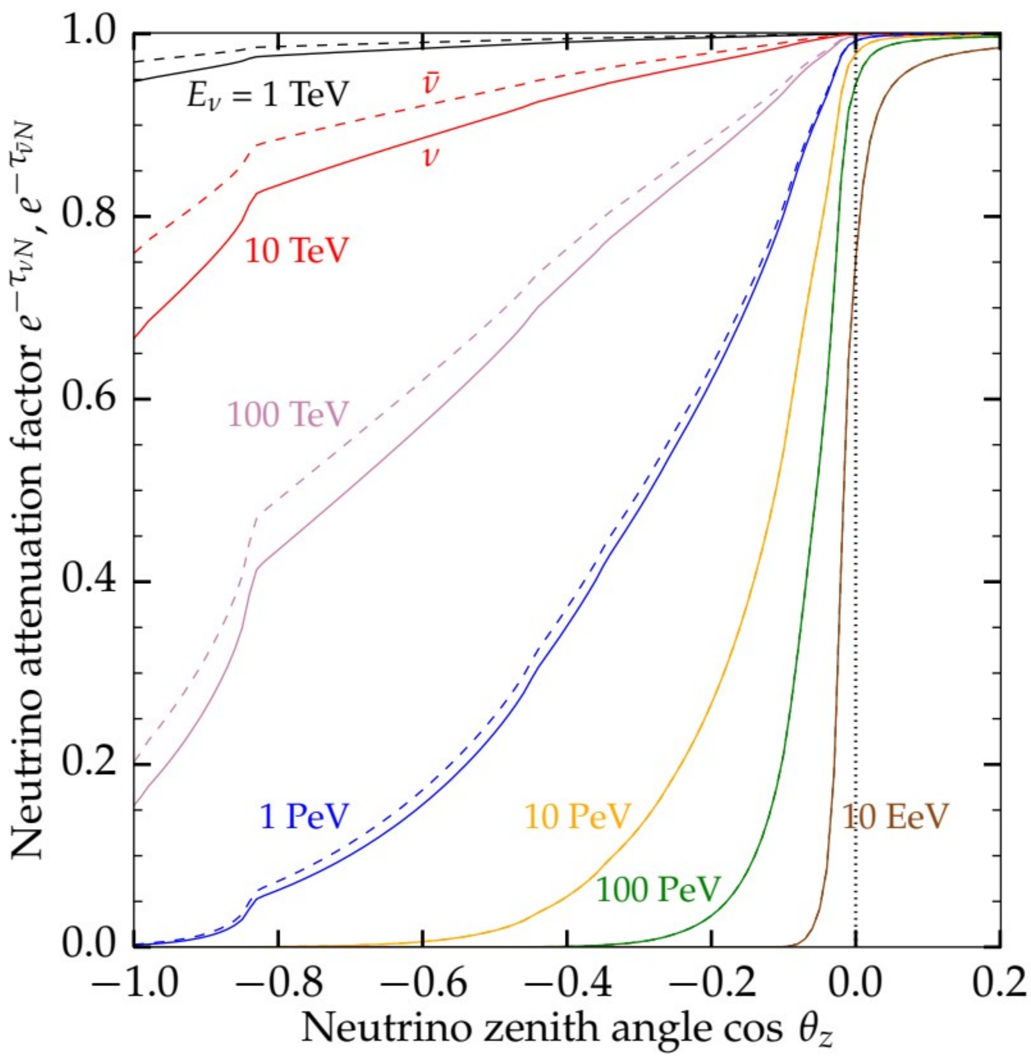
Earth is *almost fully* opaque,
some upgoing ν still make it through

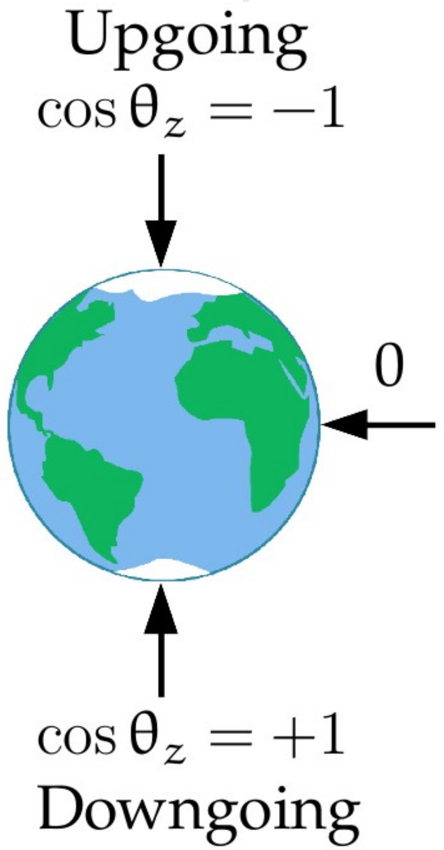
>100 PeV:



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

TeV–PeV ... 100 PeV:

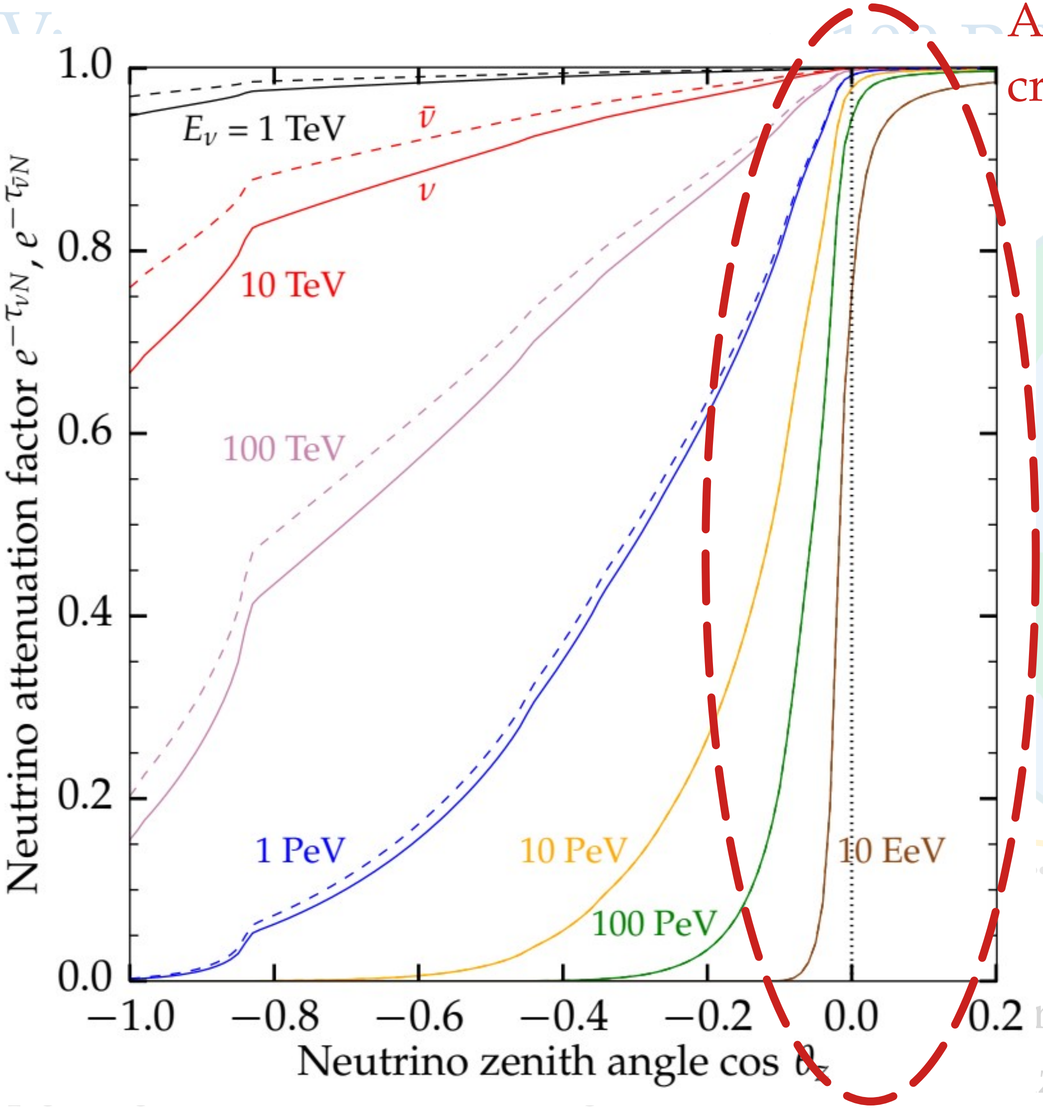


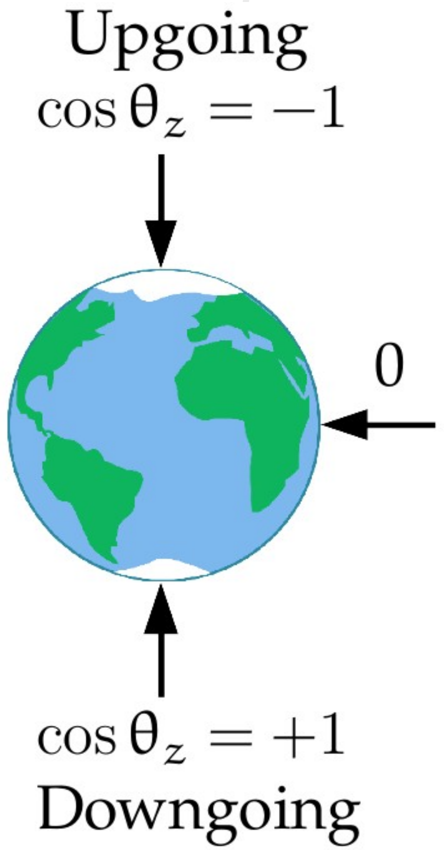


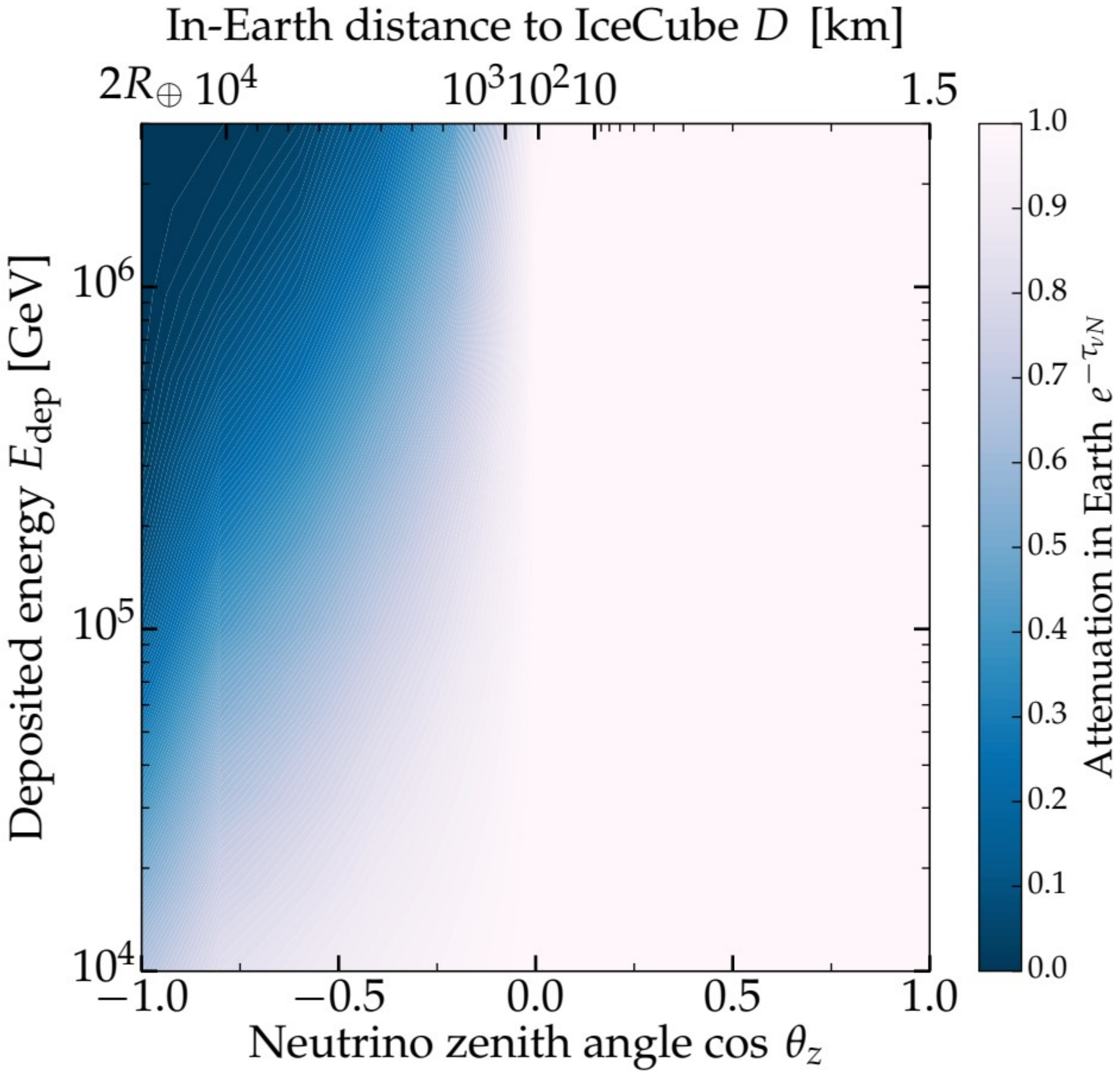
Ea... rth is *completely* opaque,

some ... zontal ν still make it through

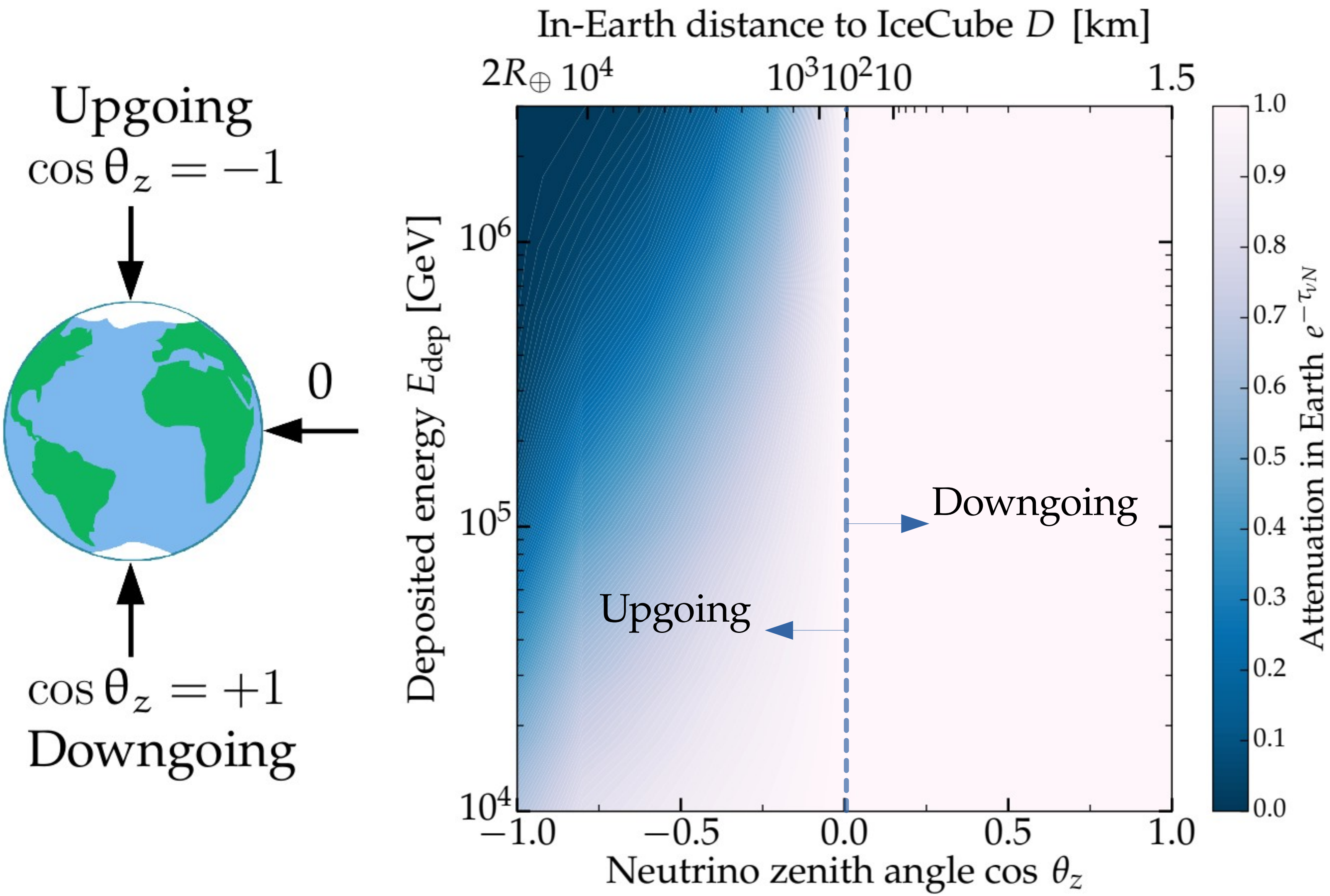
At UHE, we can only extract the cross section using horizontal ν

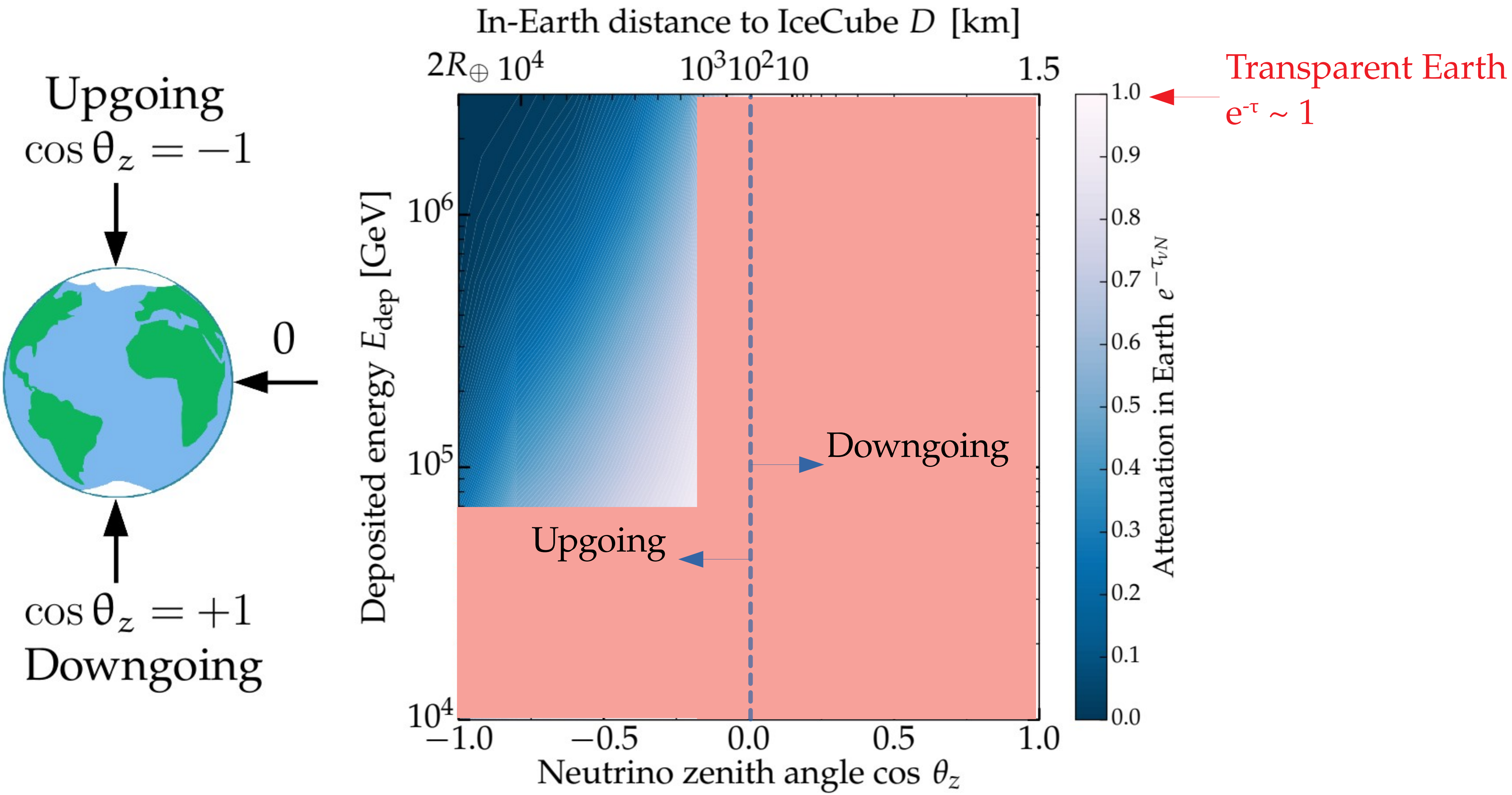




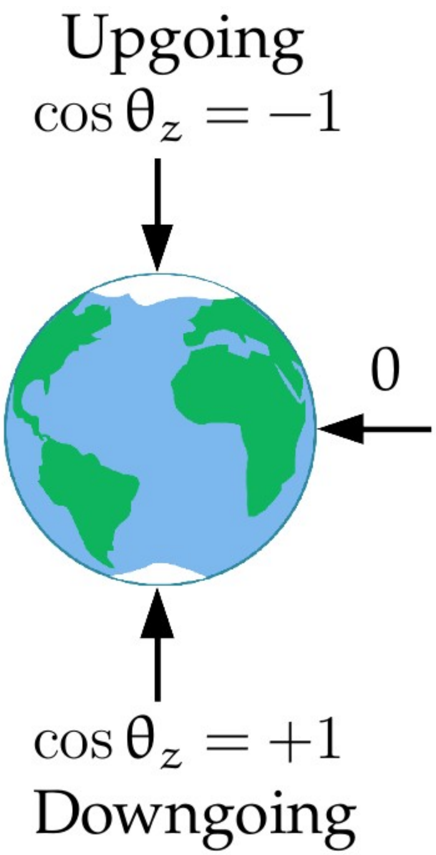


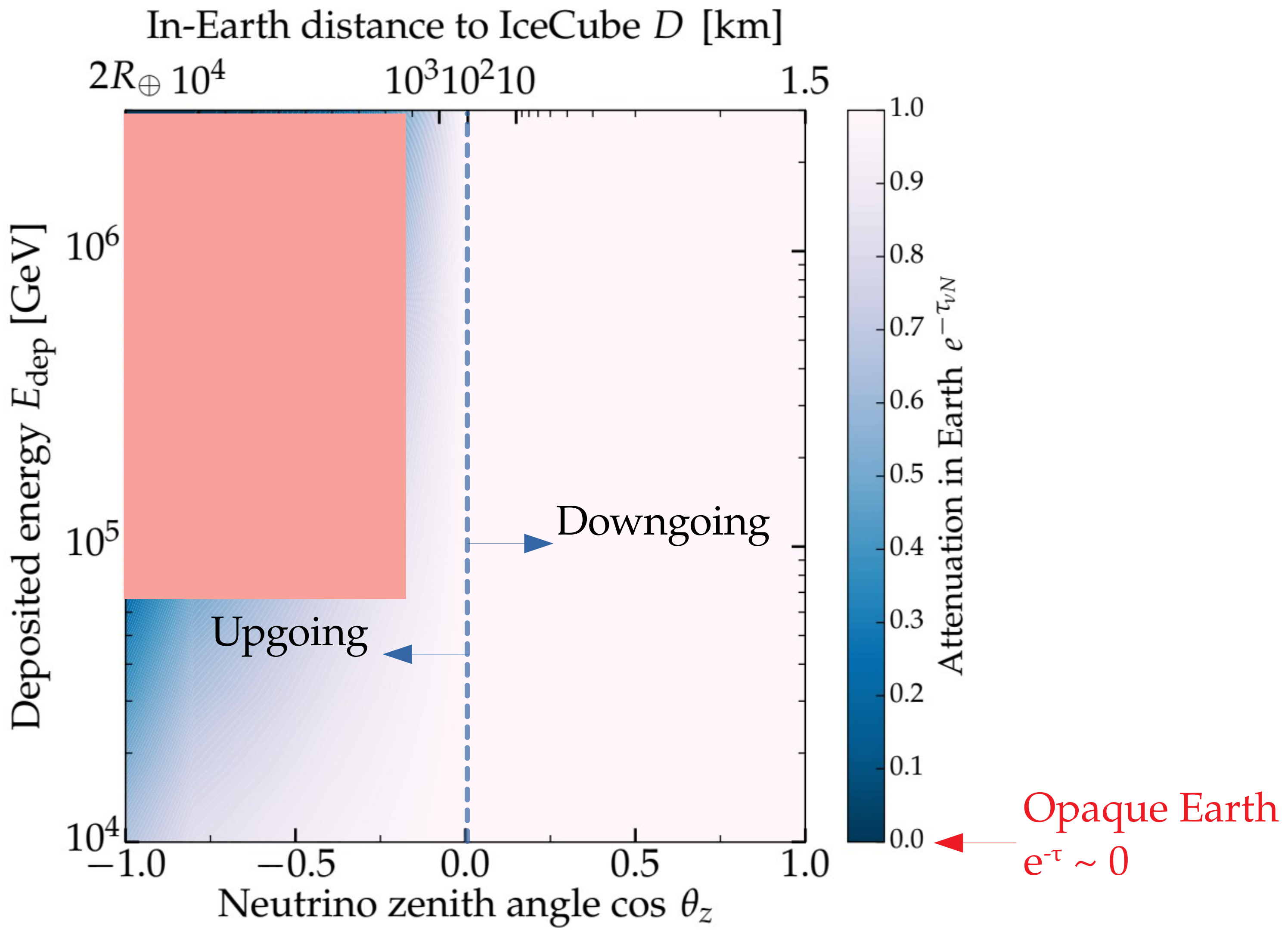
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
-1.0 -0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\,\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0


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



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

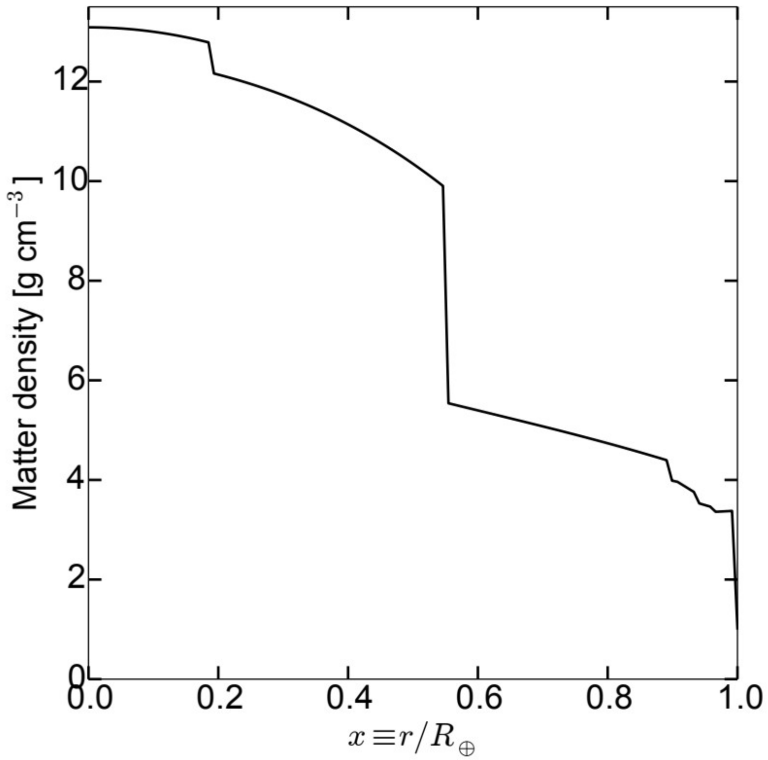

Upgoing
$\cos\theta_z = -1$
0
$\cos\theta_z = +1$
Downgoing


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

A feel for the in-Earth attenuation

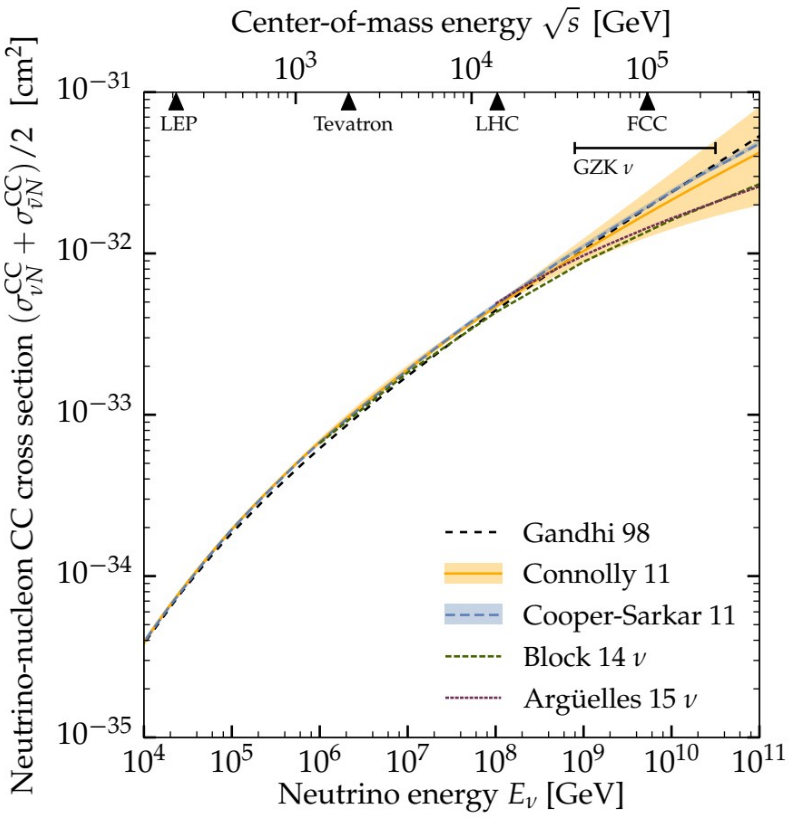
Earth matter density

(Preliminary Reference Earth Model)



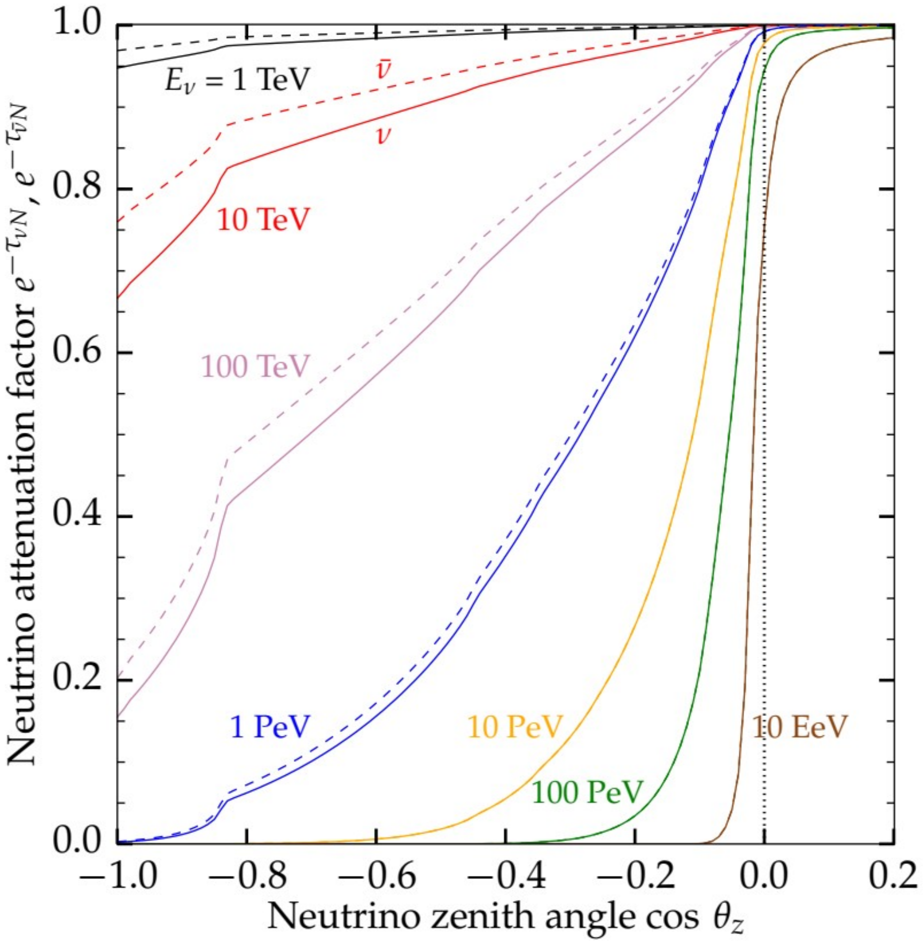
+

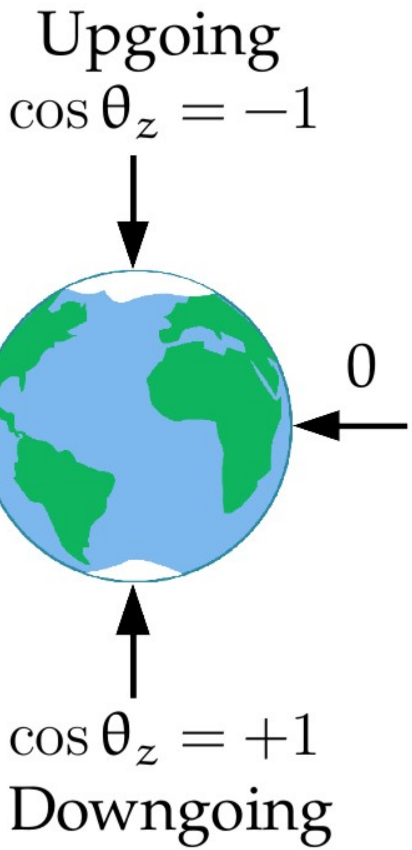
Neutrino-nucleon cross section



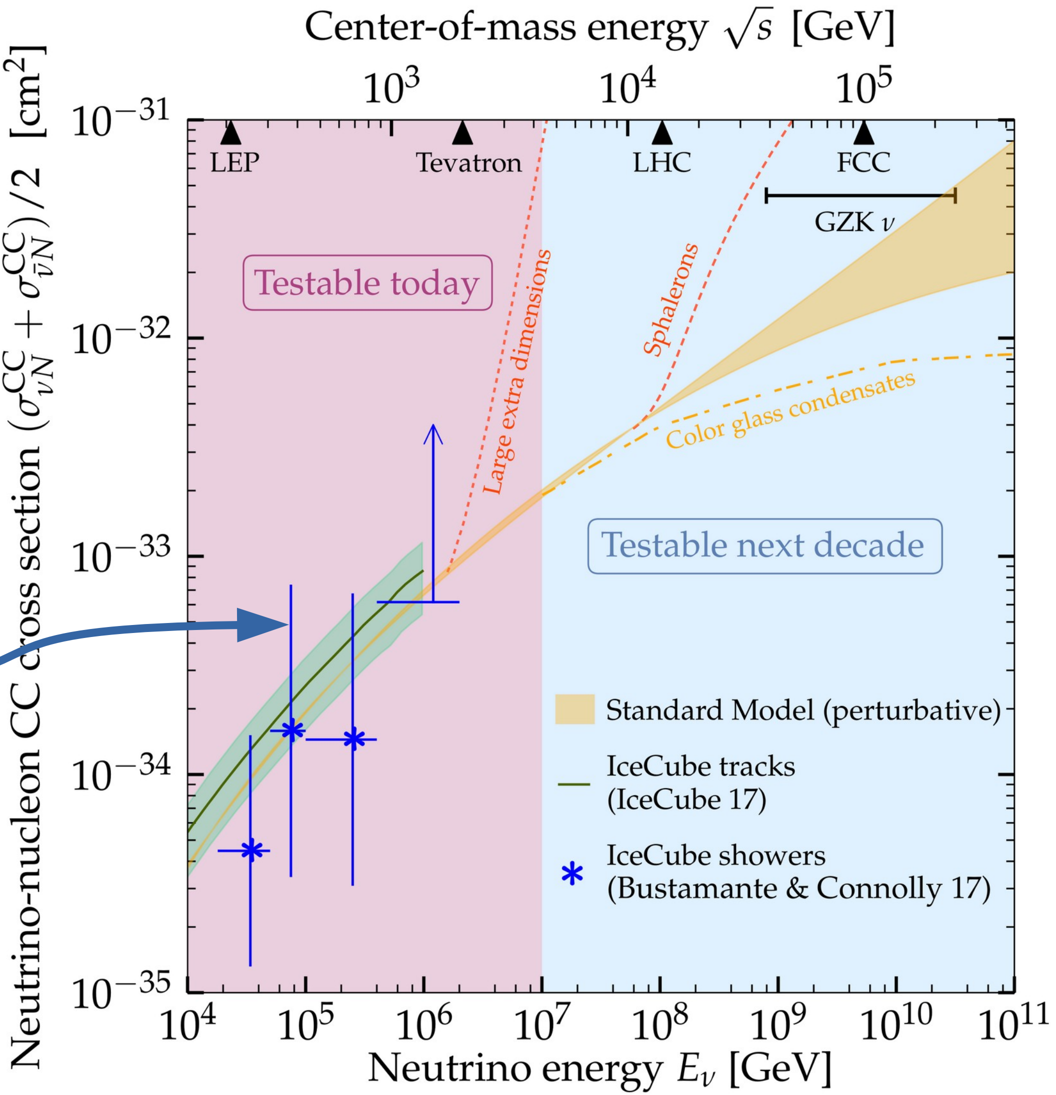
A feel for the in-Earth attenuation

=





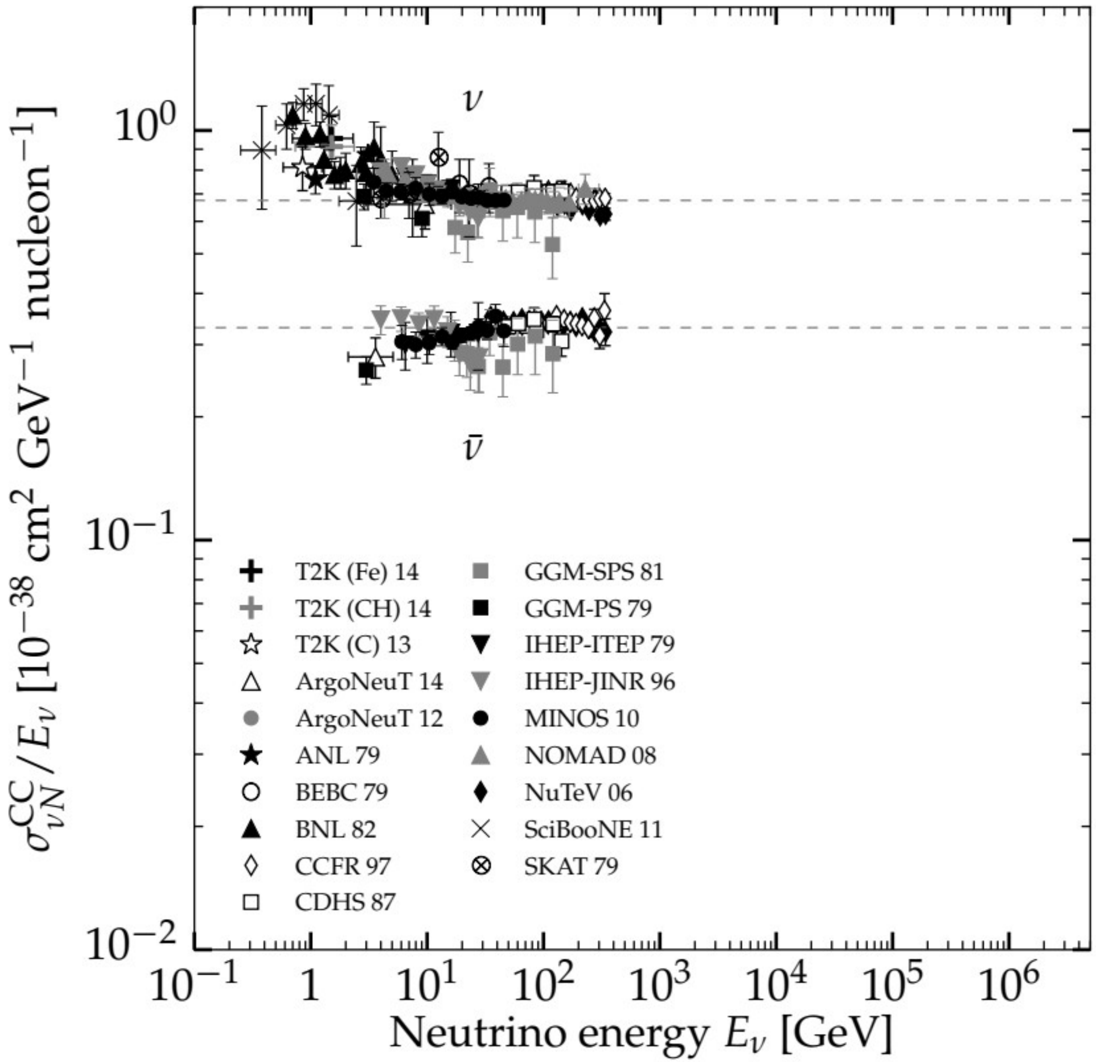
- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical error by 40%



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

Cross sections from:
MB & Connolly, *PRL* 2019
IceCube, *Nature* 2017

Recent update:
IceCube, 2011.03560



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

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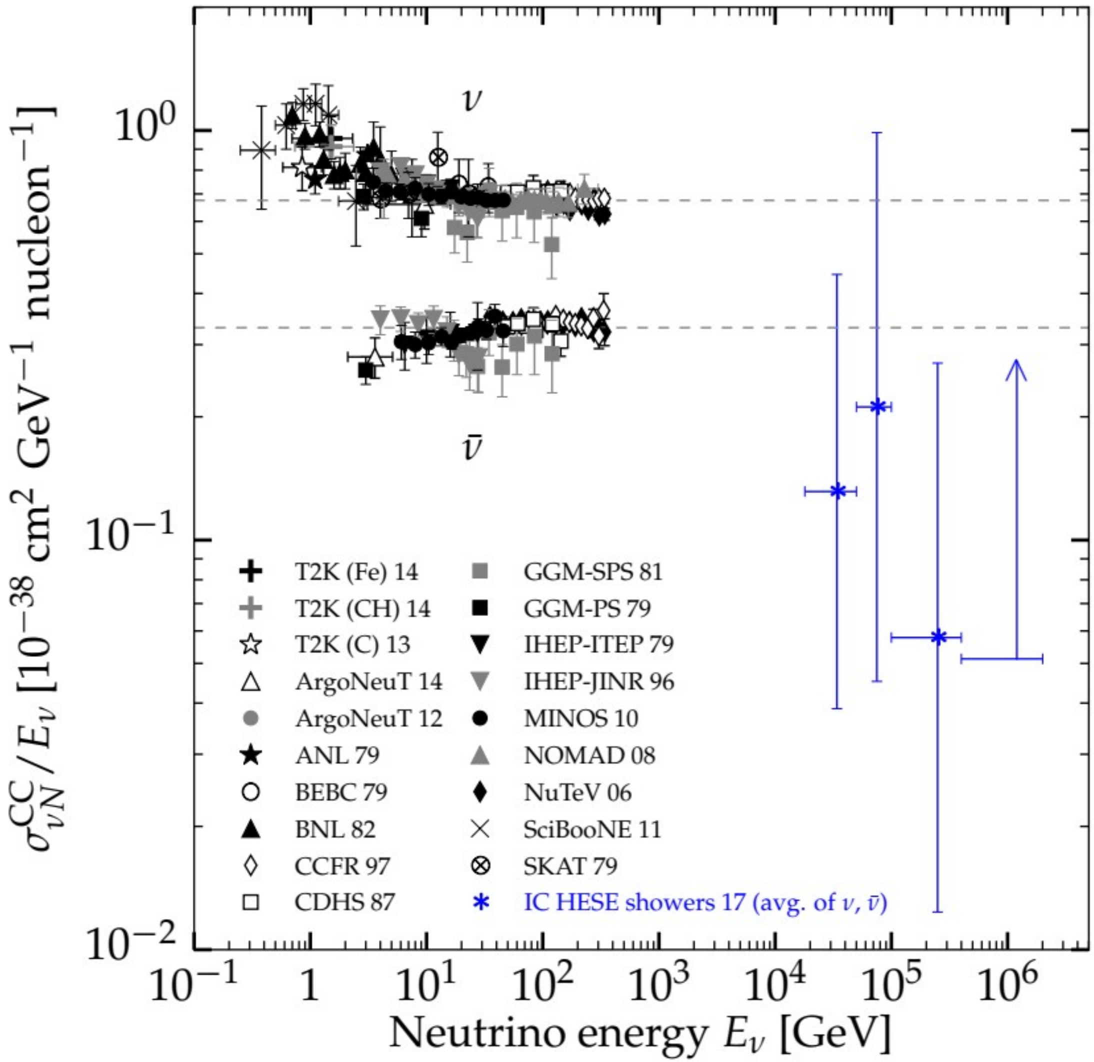
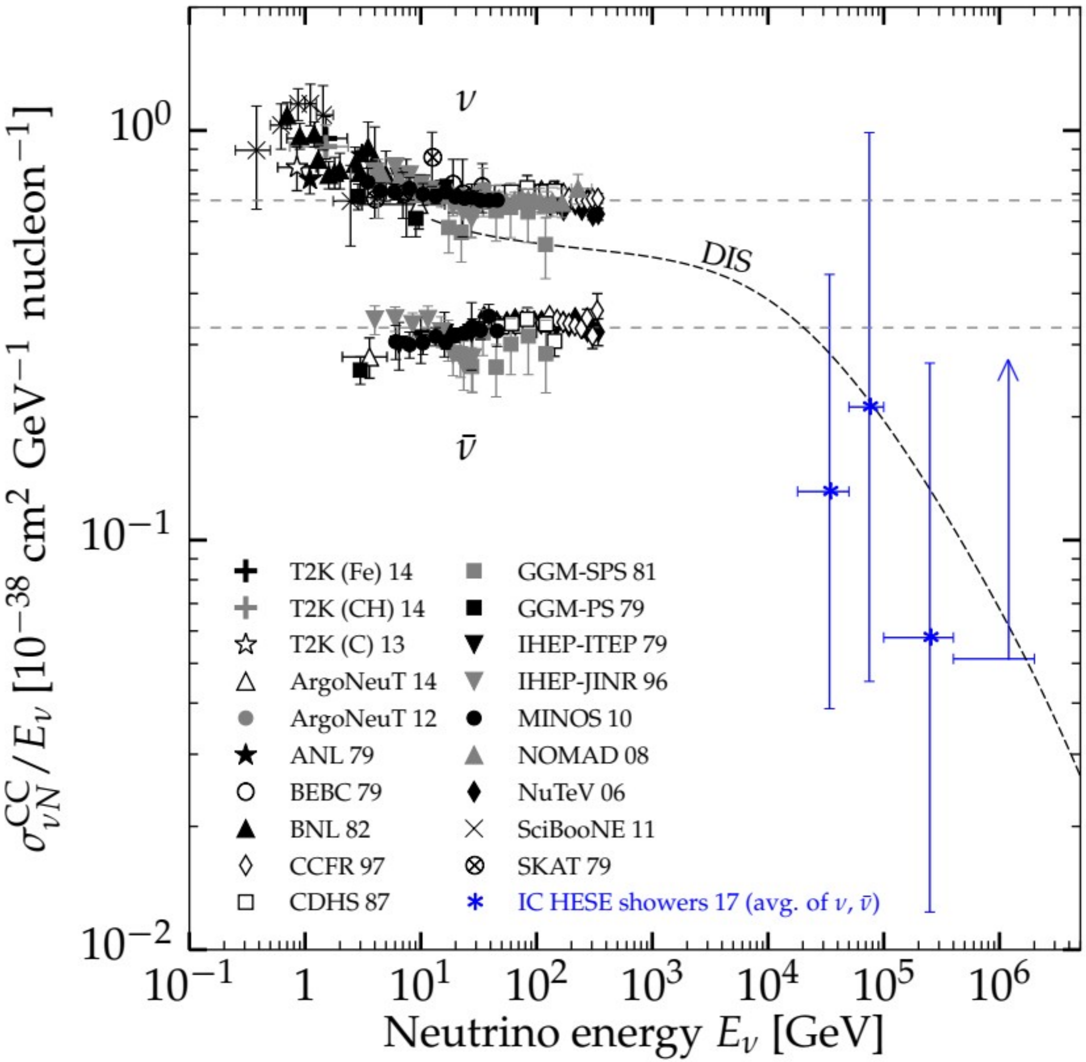
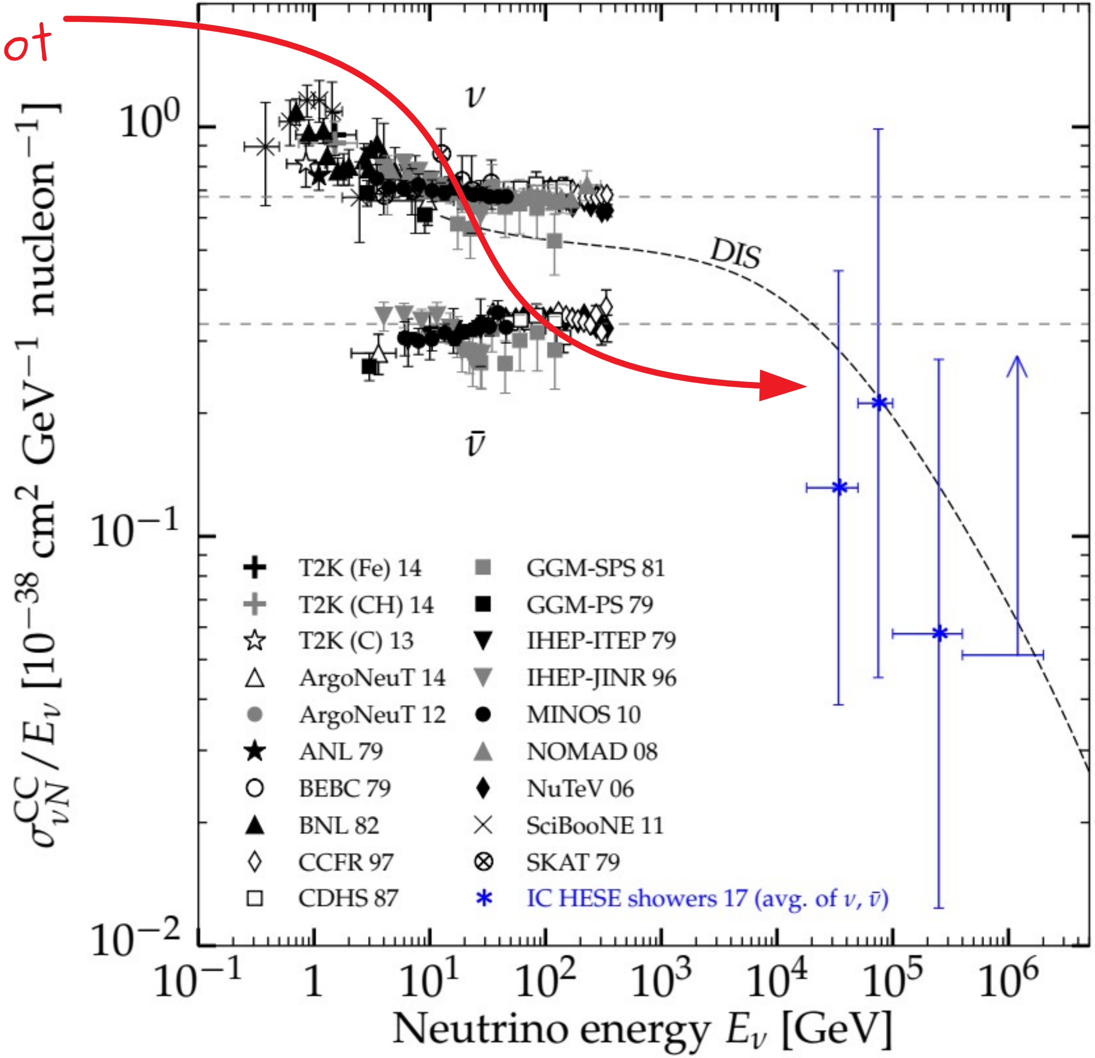




MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

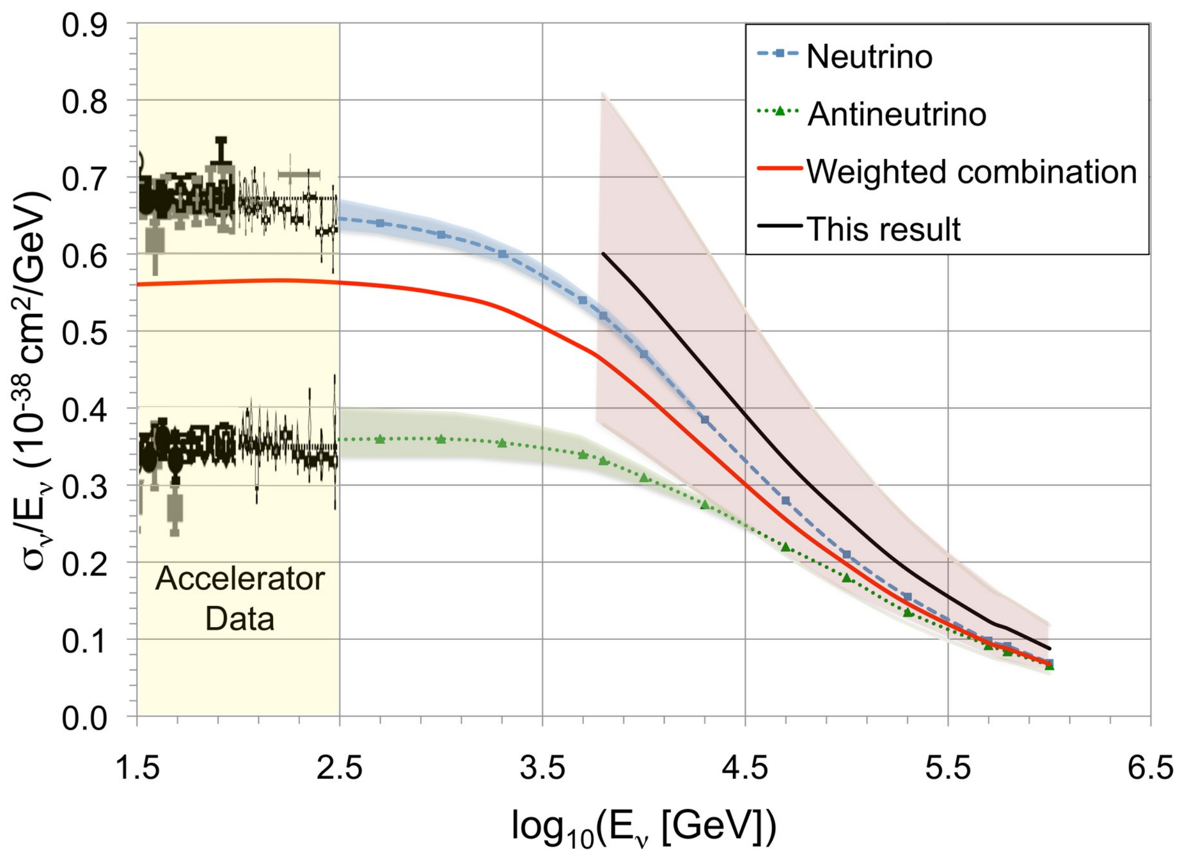
Extending the PDG cross-section plot



MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

Using through-going muons instead

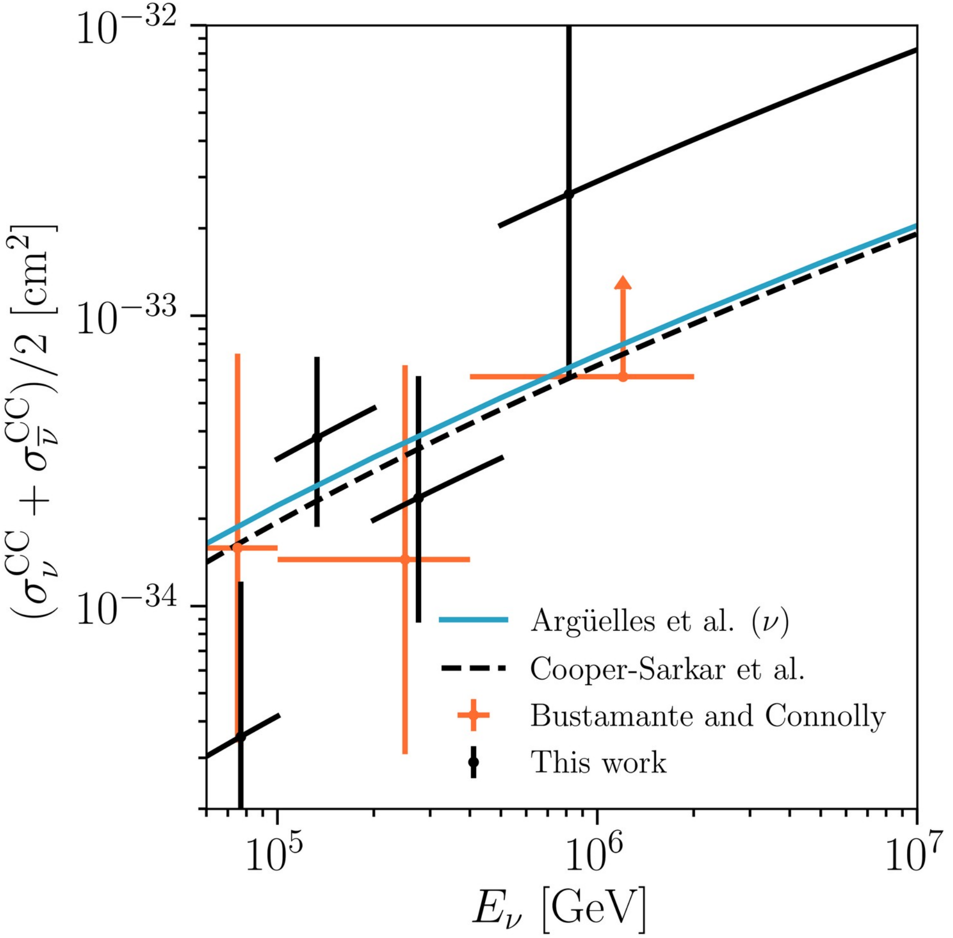
- Use ~10^4 through-going muons
- Measured: dE_μ/dx
- Inferred: $E_\mu \approx dE_\mu/dx$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30^{+0.21}_{-0.19}$(stat.) $^{+0.39}_{-0.43}$(syst.)
- All events grouped in a single energy bin 6–980 TeV



IceCube, *Nature* 2017

Updated cross section measurement

- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera & MB



IceCube, 2011.03560

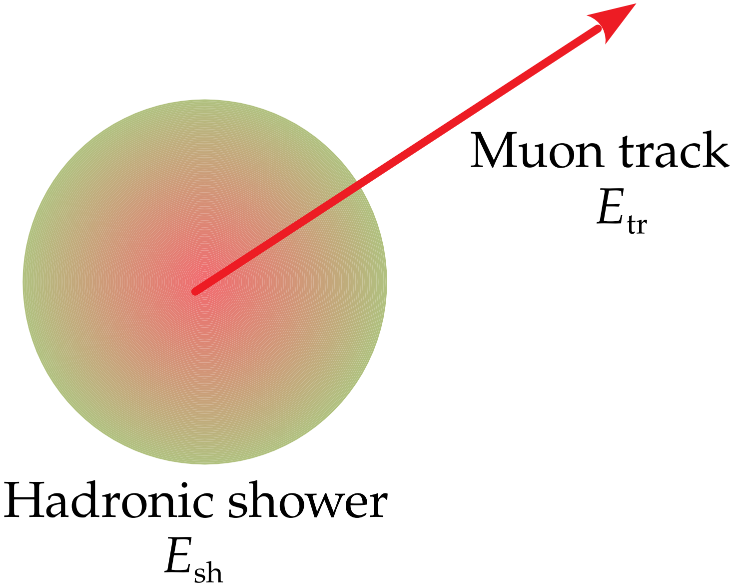
Bonus: Measuring the inelasticity $\langle y \rangle$

- Inelasticity in CC ν_μ interaction $\nu_\mu + N \to \mu + X$:
  $E_X = y\, E_\nu$ and $E_\mu = (1\text{-}y)\, E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$

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

- In a HESE starting track:
  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)
  $\Big\}\; y = (1 + E_{tr}/E_{sh})^{-1}$

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



IceCube, *PRD* 2019

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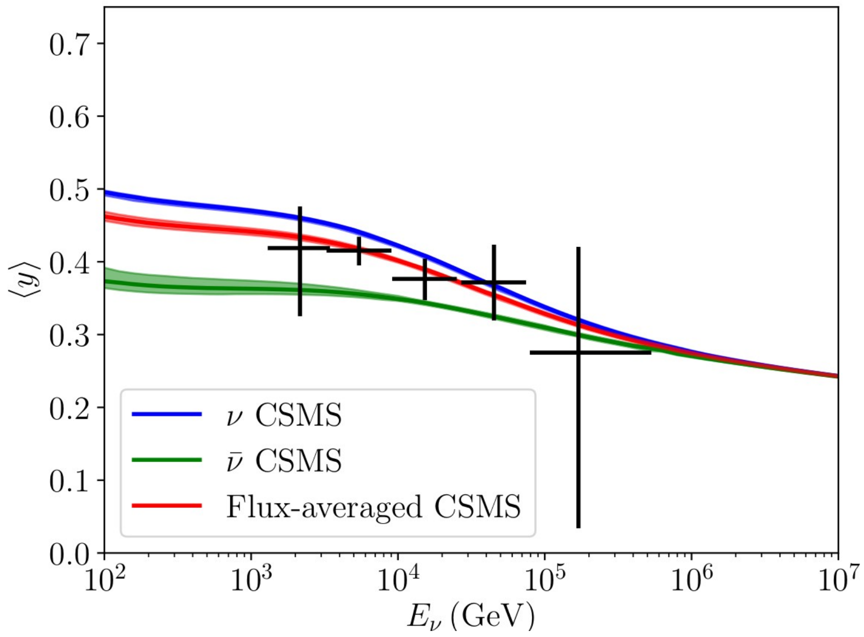
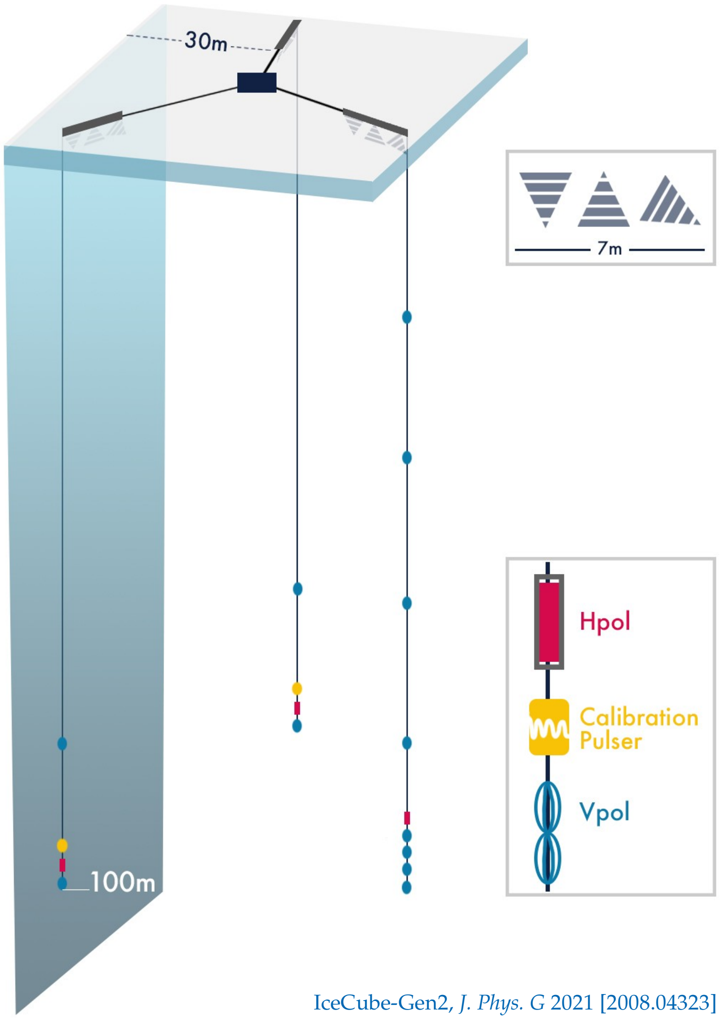
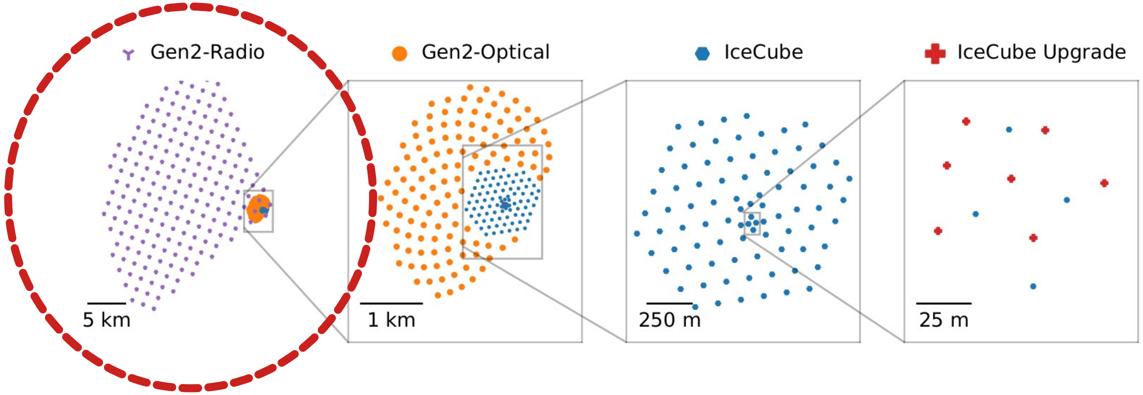
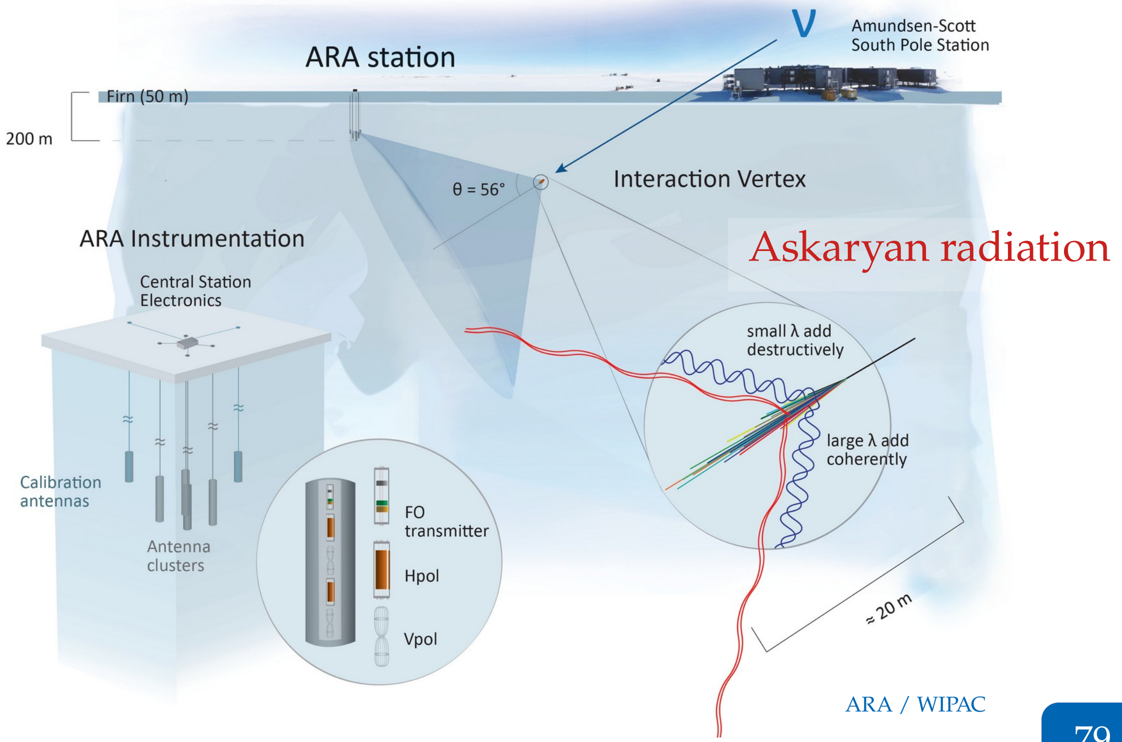


IceCube, *PRD* 2019

IceCube-Gen2 Radio







IceCube-Gen2, *J. Phys. G* 2021 [2008.04323]

ARA / WIPAC

Example:
Secret neutrino interactions

νSI with the UHE diffuse flux

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

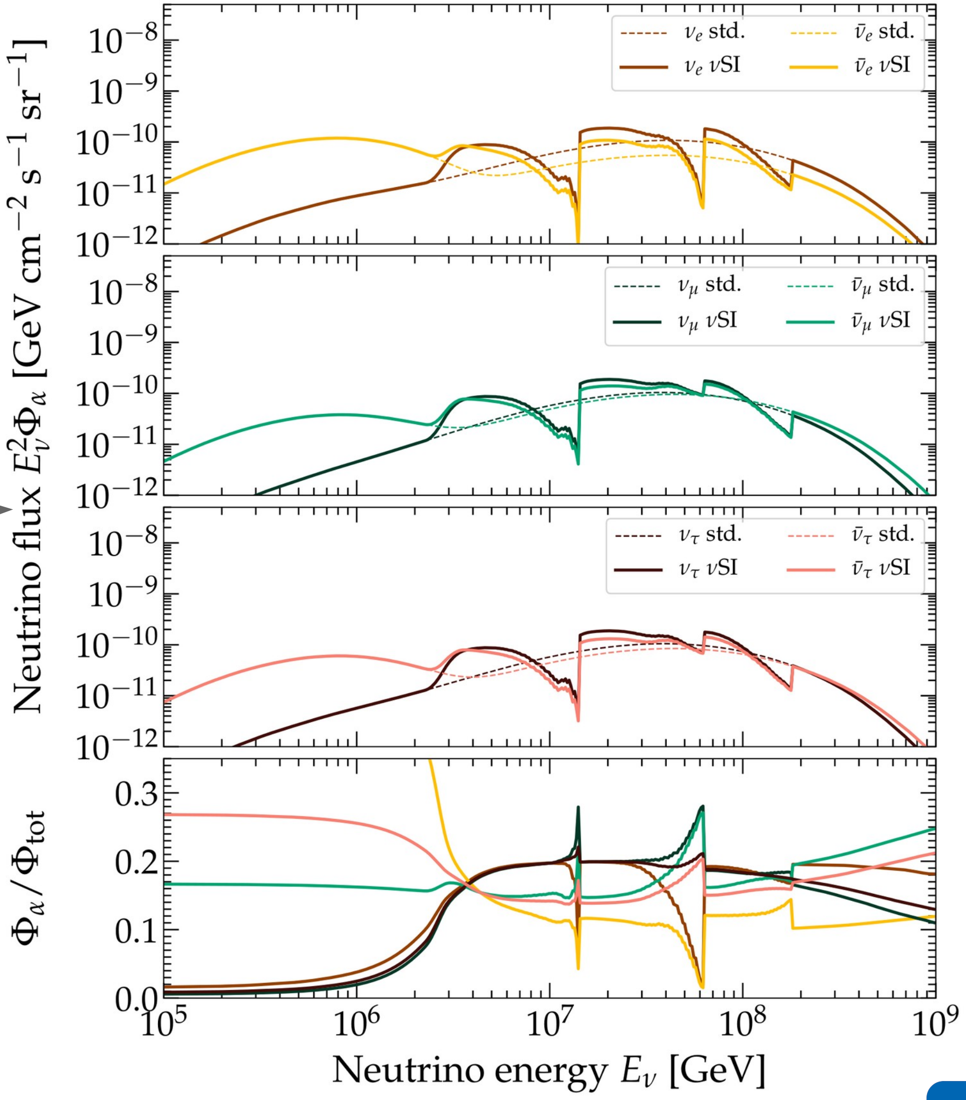
Coupling matrix:

Different flavors can have different couplings

$$\mathbf{G} \equiv \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{e\mu} & g_{\mu\mu} & g_{\mu\tau} \\ g_{e\tau} & g_{\mu\tau} & g_{\tau\tau} \end{pmatrix}$$

νSI dips and bumps in the diffuse UHE ν flux:

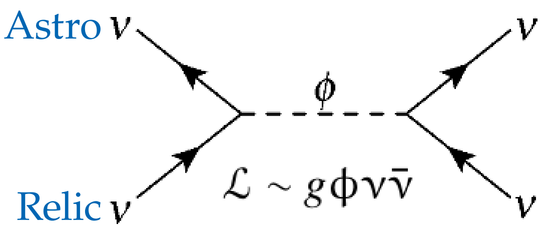
- In the cosmogenic flux
- In the flux from sources



MB, Másson, Valera, In prep.

But we need enough events to detect the spectral features – we need POEMMA-360!

νSI with the UHE transient flux



If this happens repeatedly, high-energy neutrinos disappear

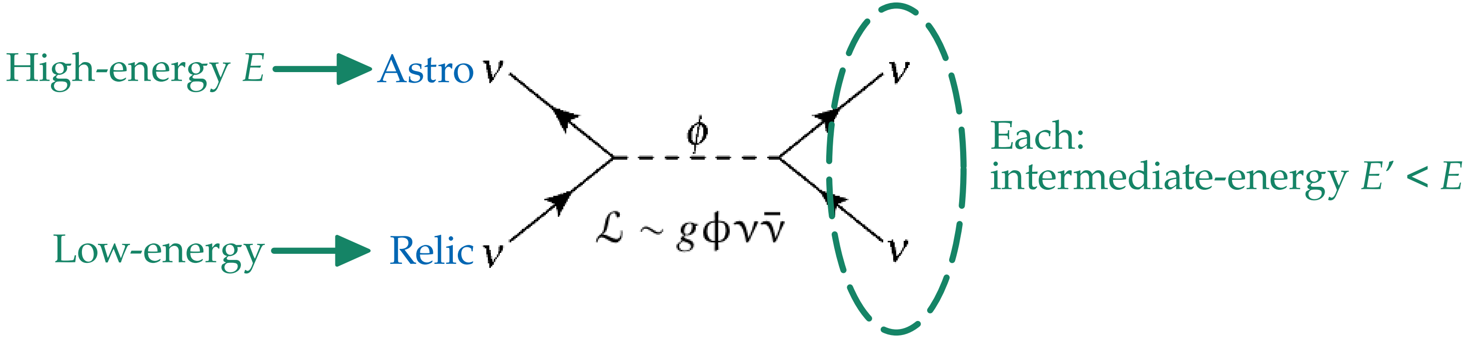
So, if we see high-energy neutrinos, we can set an upper limit on the νSI strength

Original idea by Kolb & Turner, using SN1987A (*PRD* 1987)

Mean free path of a ν of energy E: $l_{\rm int}(E) = [n_{\rm C\nu B}\sigma_{\nu\nu}(E)]^{-1}$

Estimated optical depth if emitted by a source at a distance L: $\tau(E) = \frac{l_{\rm int}(E)}{L}$

νSI with the UHE transient flux



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Example: Neutrino decay

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

- BSM decays may have significantly higher rates: $\nu_i \to \nu_j + \varphi$
- φ: Nambu-Goldstone boson of a broken symmetry (*e.g.*, Majoron)
- We work in a model-independent way:
  the nature of φ is unimportant if it is invisible to neutrino detectors

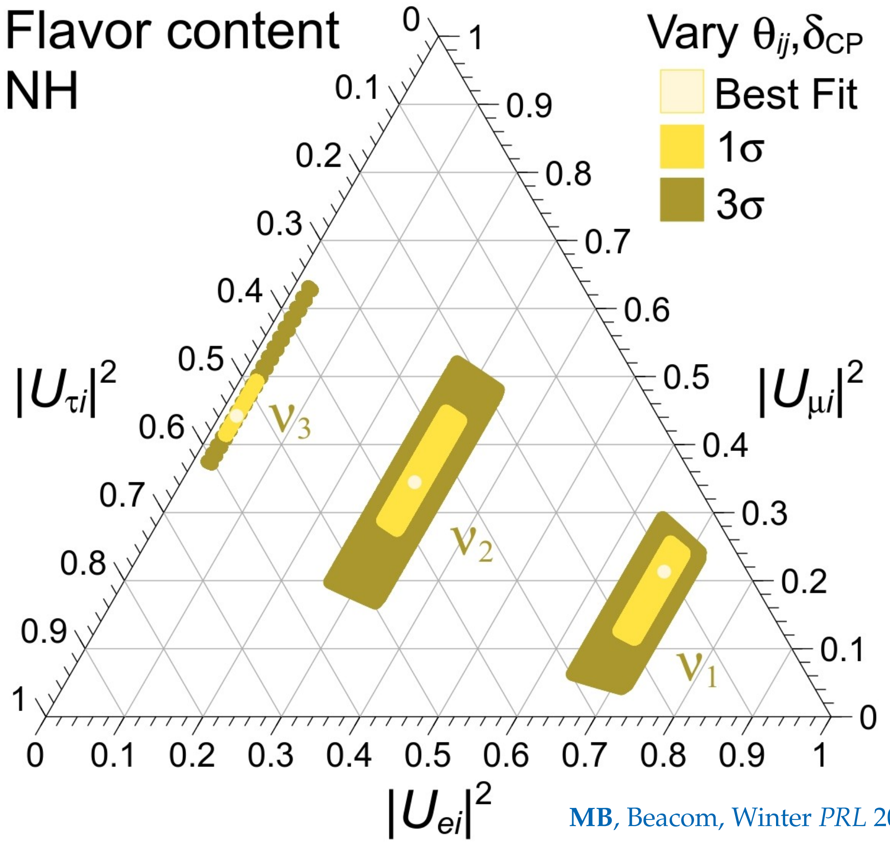
Flavor content of neutrino mass eigenstates

Known to within 2%

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

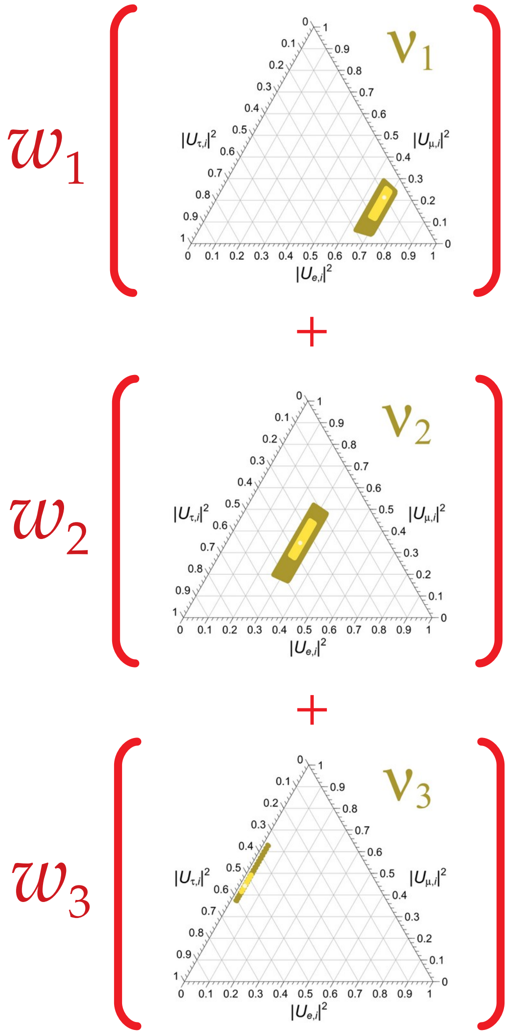
Known to within 8%

Known to within 20%
(or worse)

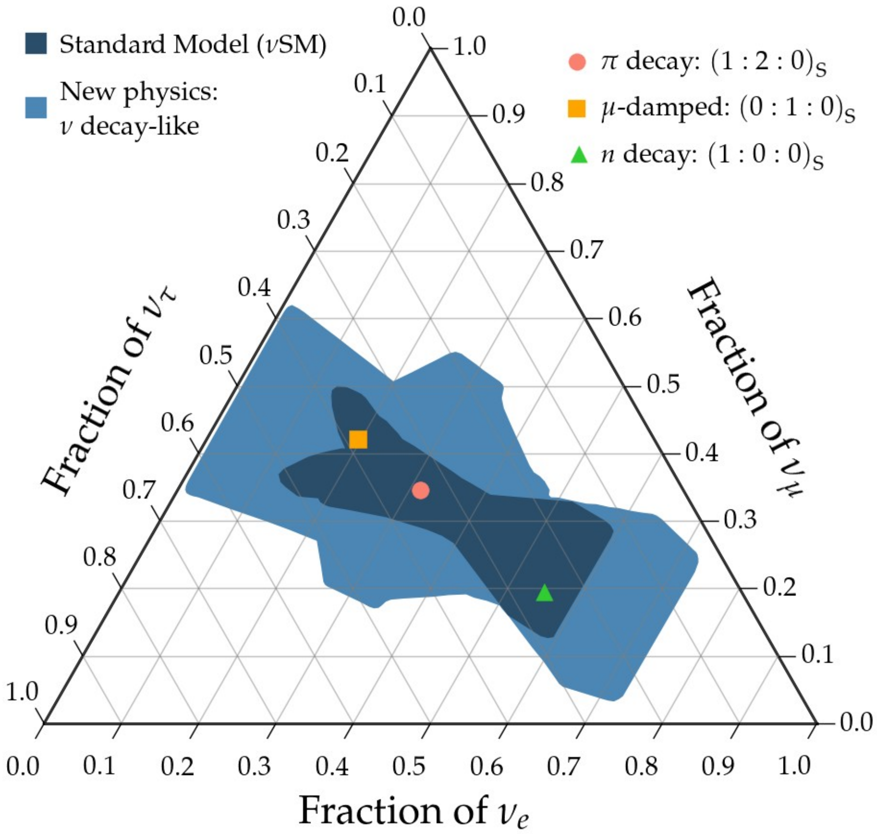


MB, Beacom, Winter *PRL* 2015

Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3 —



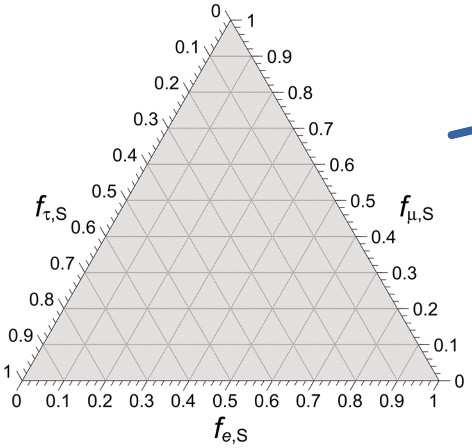
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights with striking consequences for flavor ▸

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

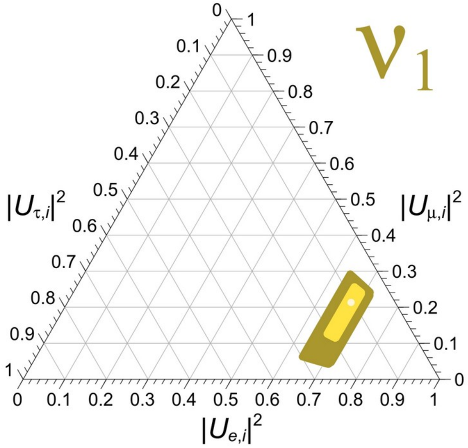
ν_1 lightest and stable
(normal mass ordering)

If all unstable
neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$

ν_3 lightest and stable
(inverted mass ordering)

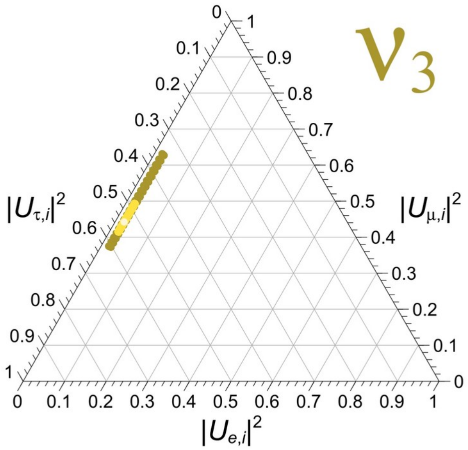
Earth



ν_1

$$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$$

$(w_1 \sim 1; w_2, w_3 \sim 0)$



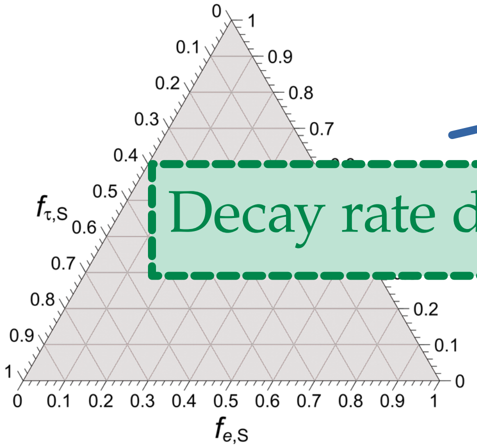
ν_3

$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

$(w_3 \sim 1; w_1, w_2 \sim 0)$

Measuring the neutrino lifetime

Sources



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

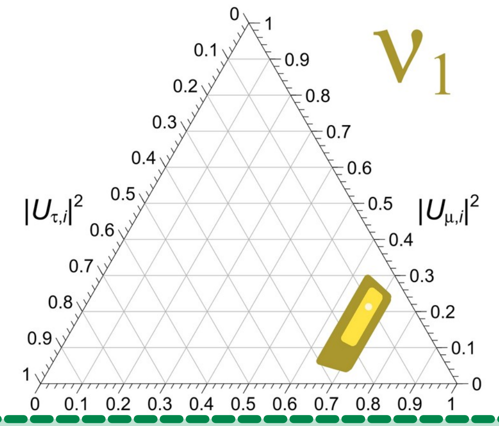
ν_1 lightest and stable
(normal mass ordering)

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

ν_3 lightest and stable
(inverted mass ordering)

Decay rate depends on $\exp[-t / (\gamma \tau_i)] = \exp[-(L/E) \cdot (m_i/\tau_i)]$

Earth



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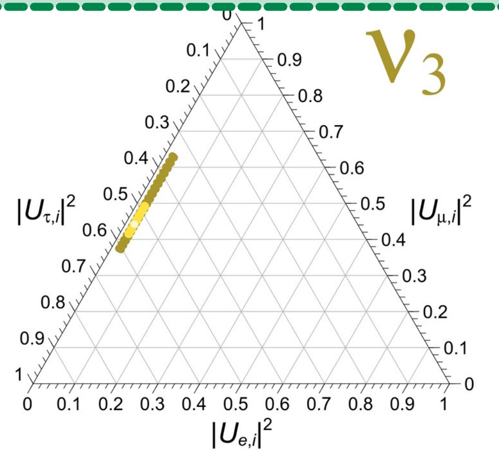

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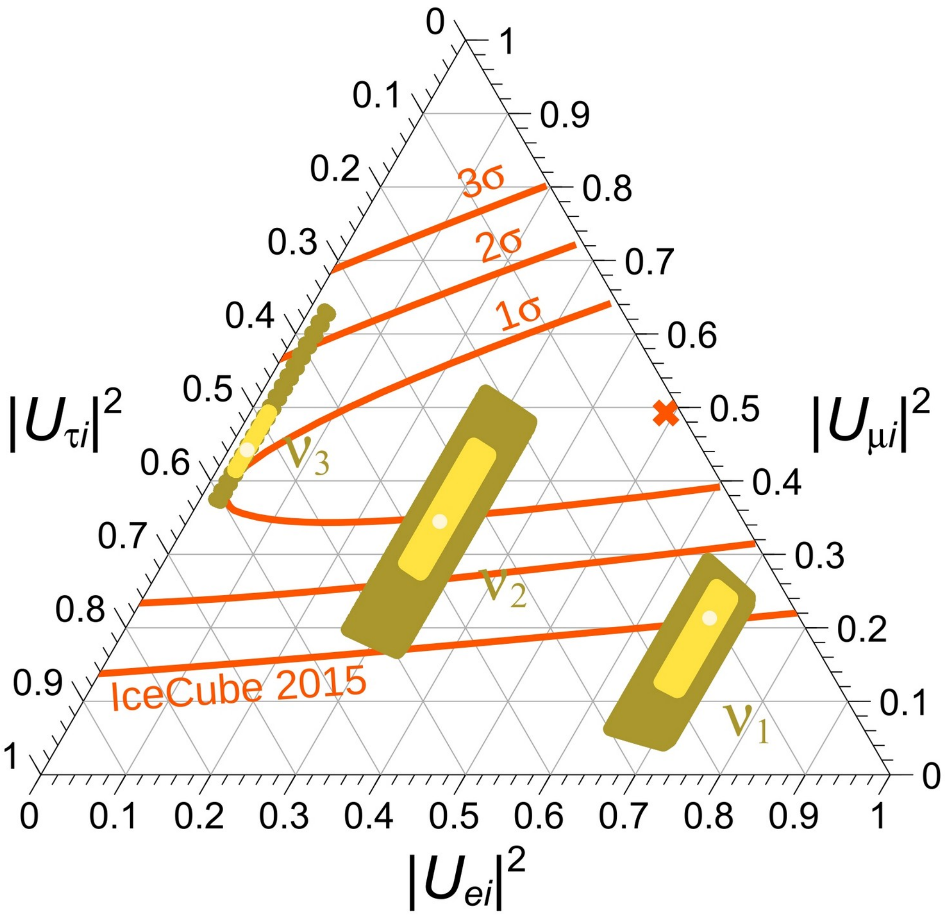
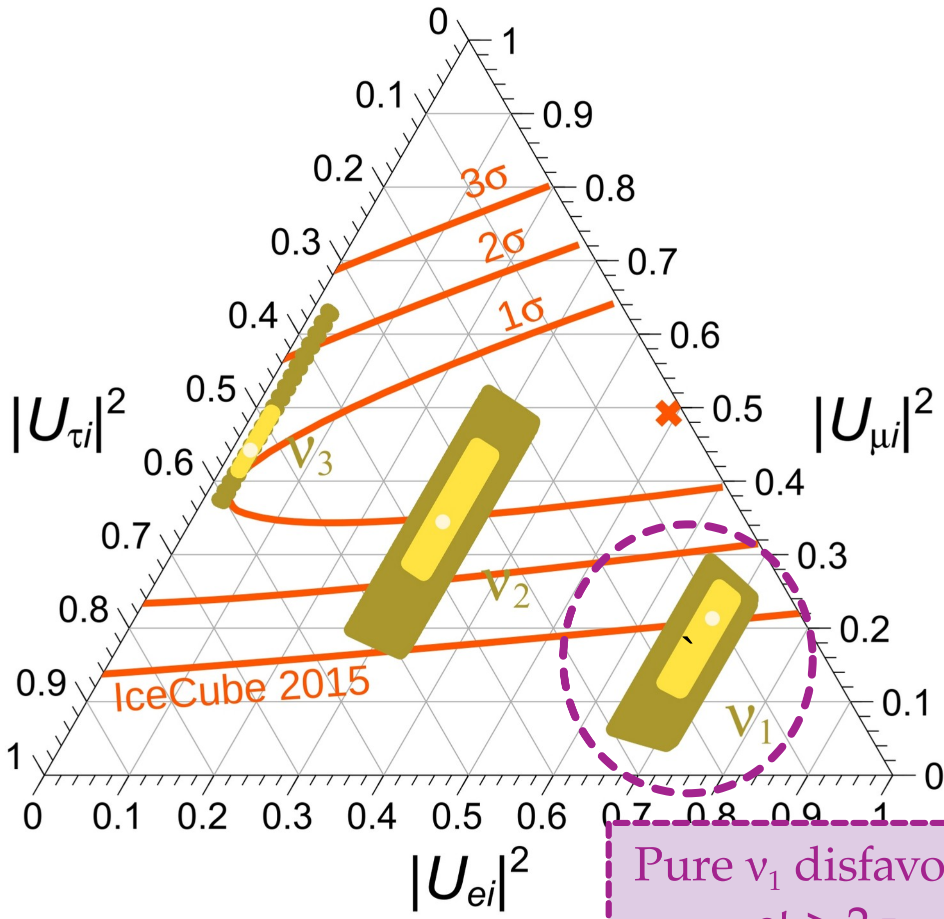


MB, Beacom, Murase, *PRD* 2017

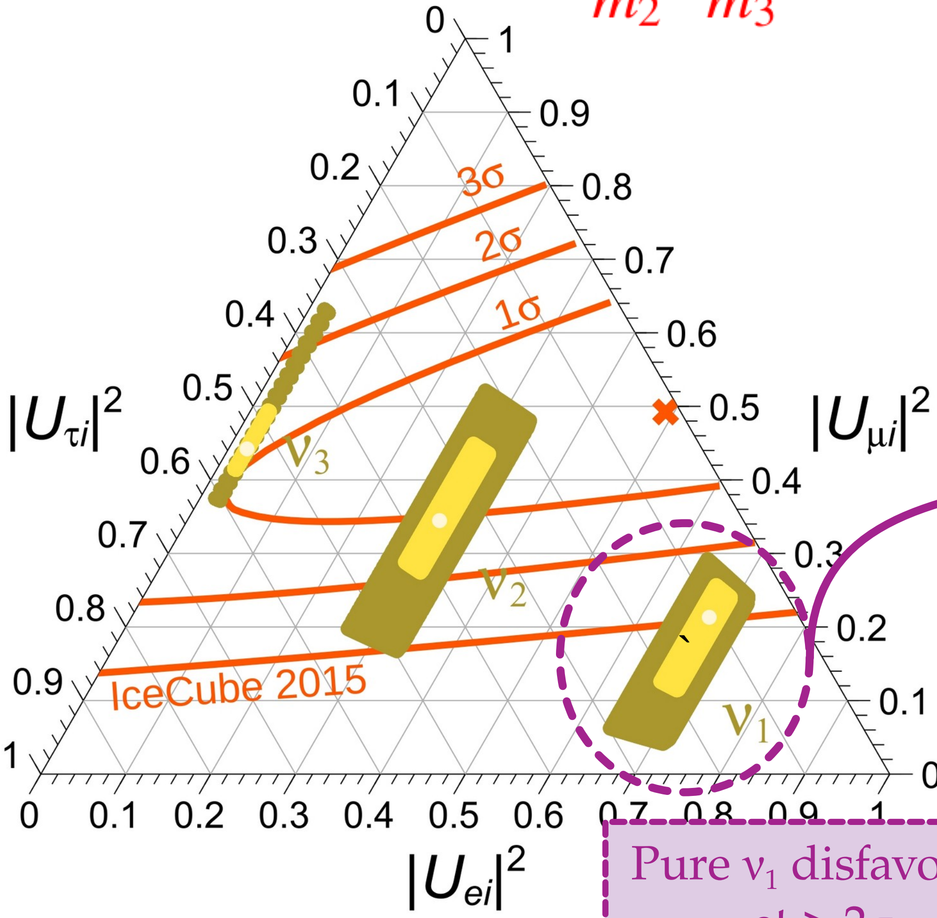
Baerwald, **MB**, Winter, *JCAP* 2012

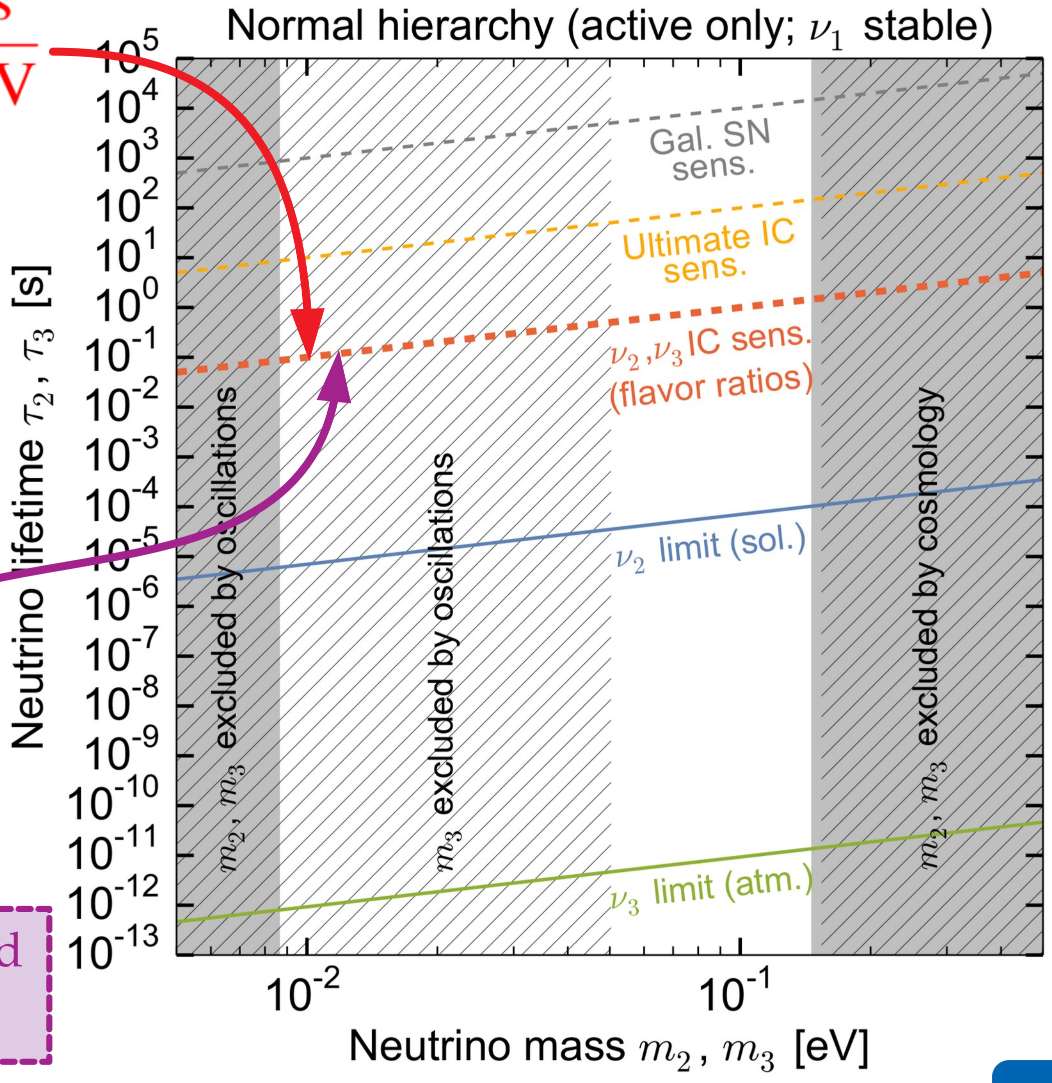


Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \frac{\text{s}}{\text{eV}}$$





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Flavor composition

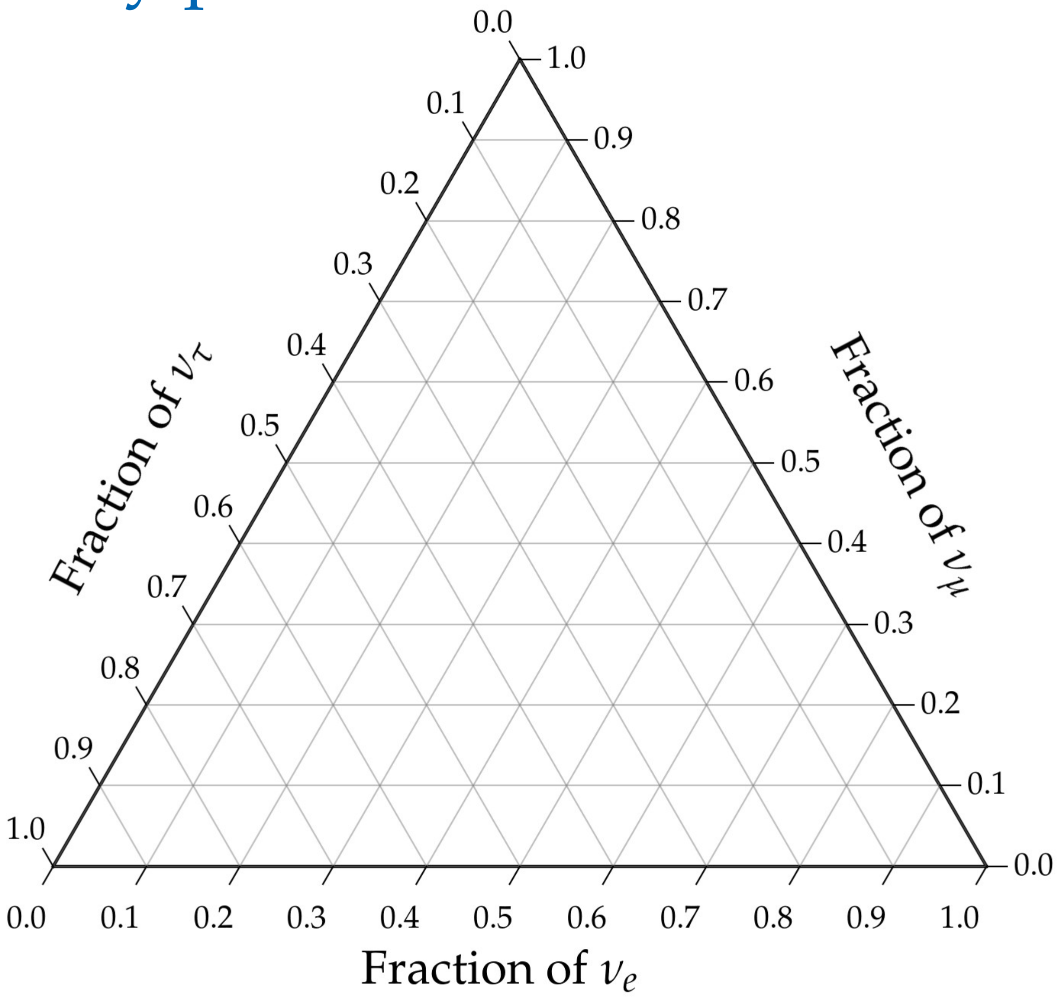
Quick aside: how to read a ternary plot

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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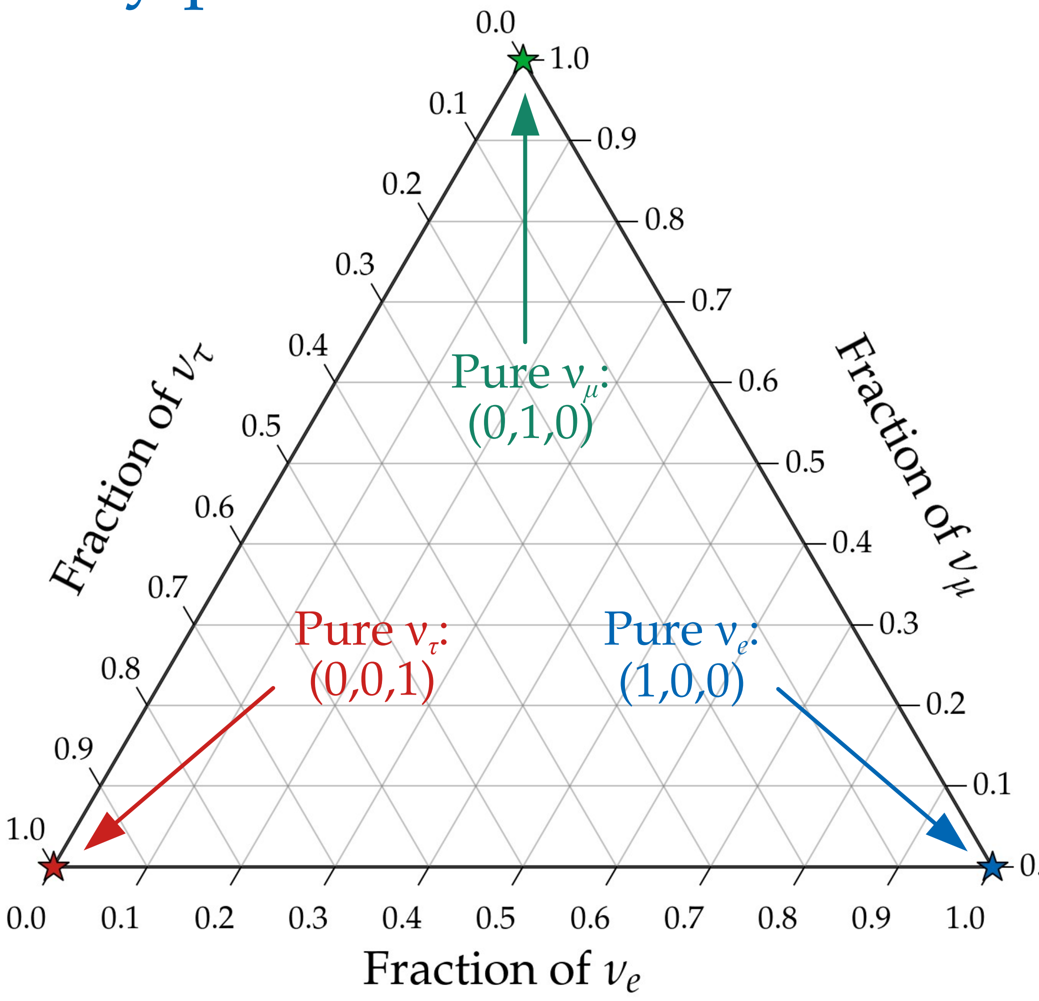

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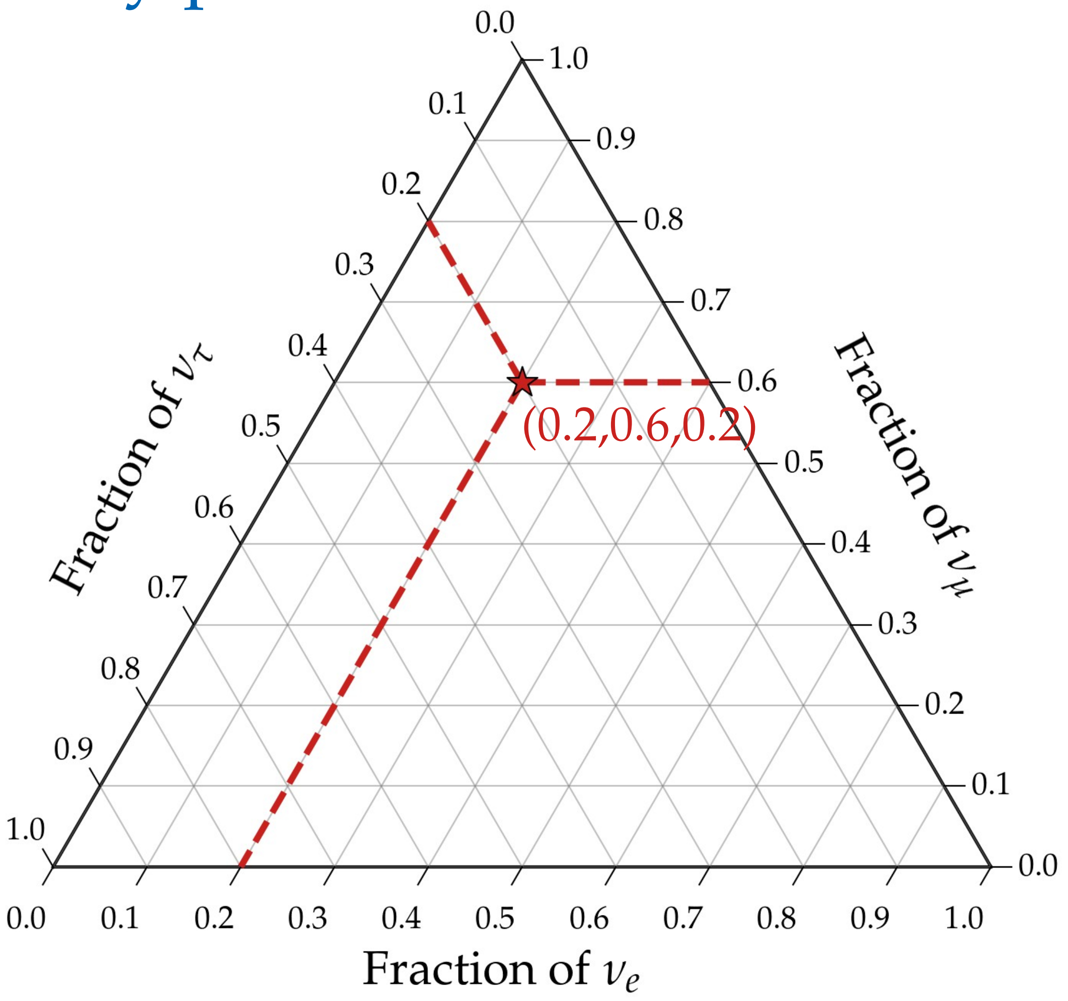

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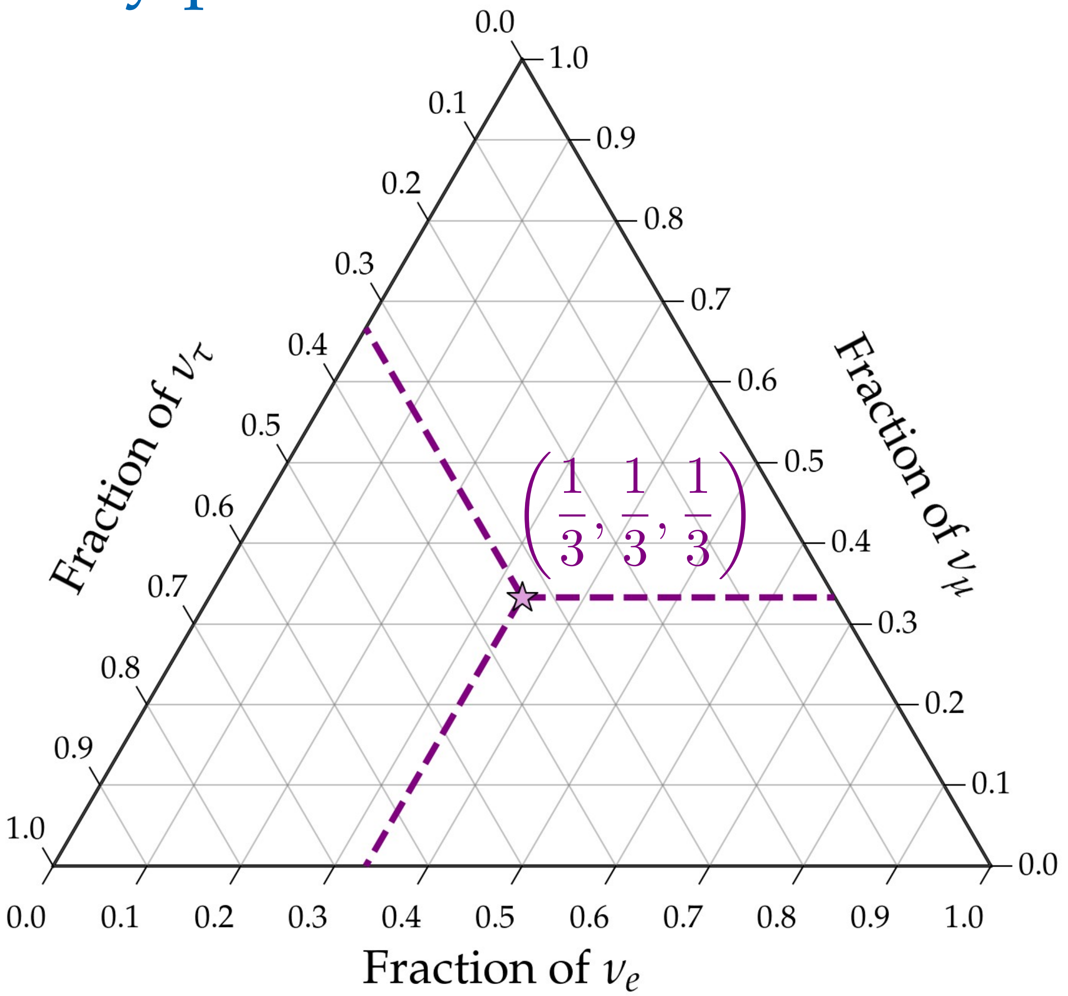
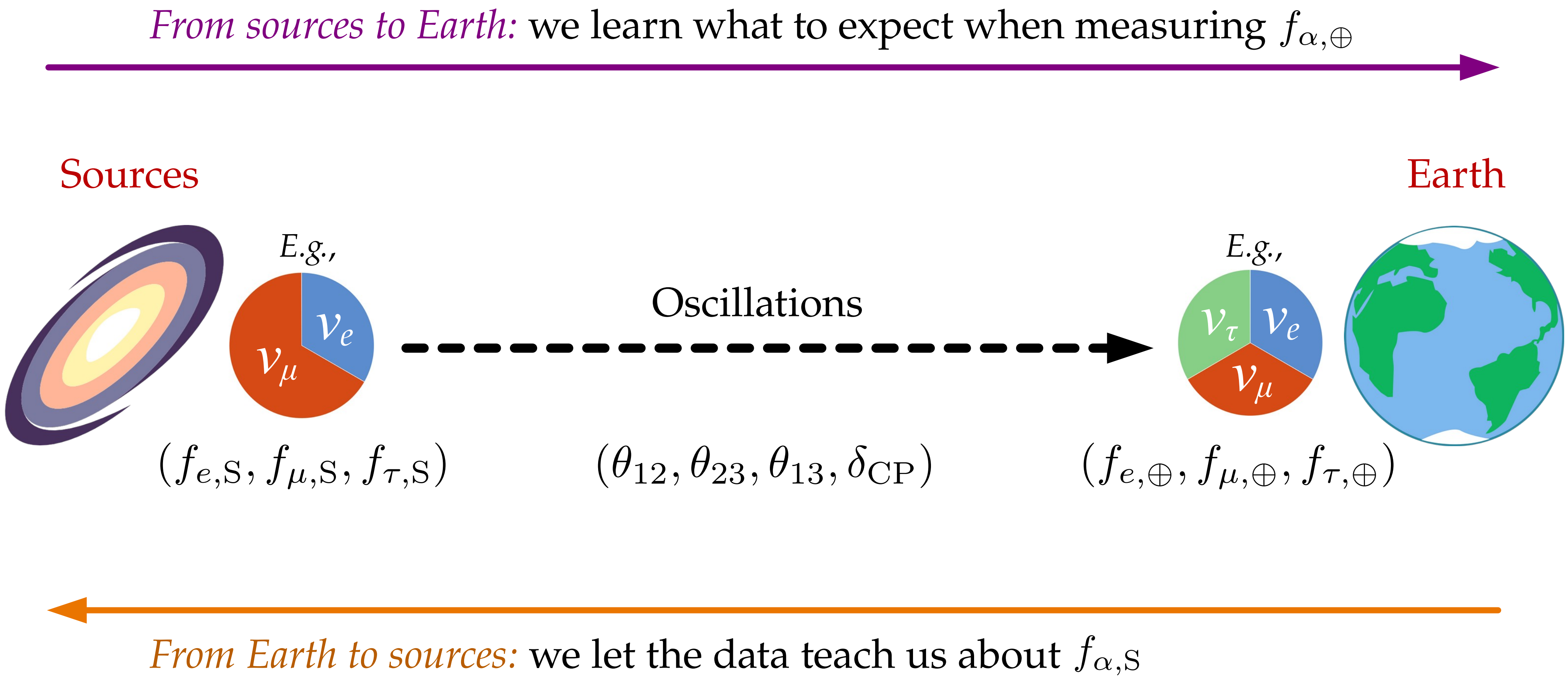
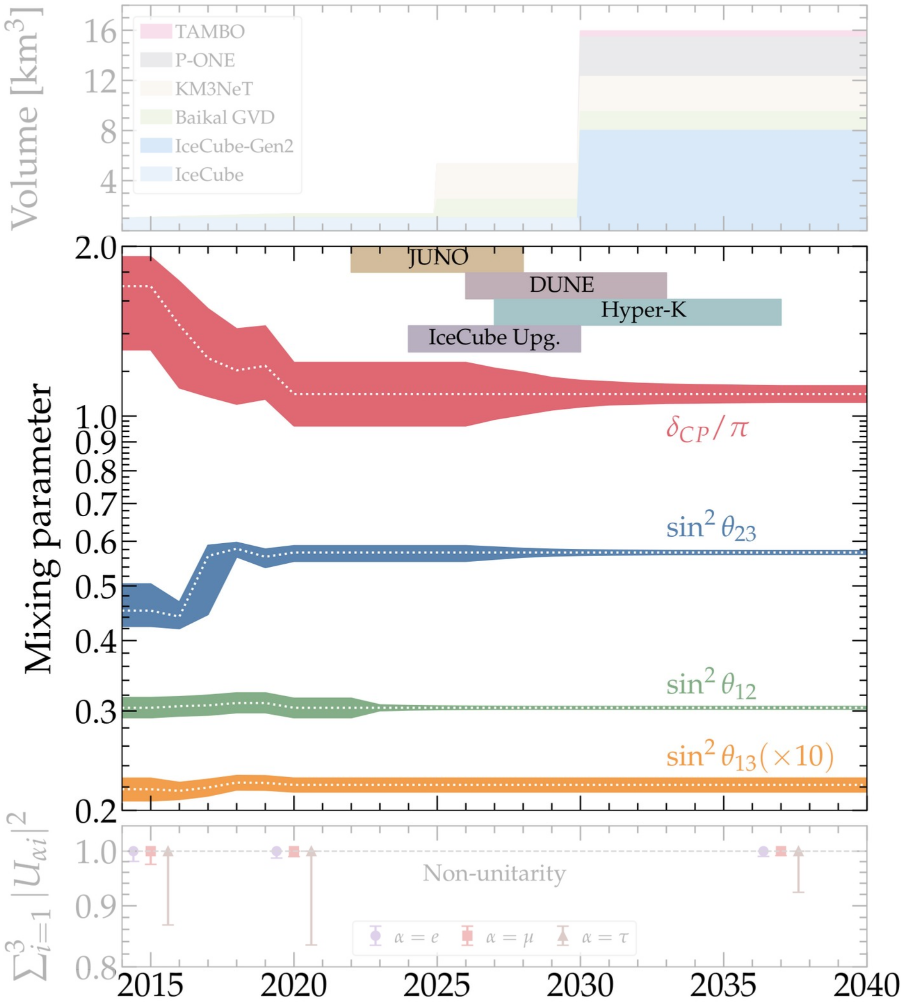



From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
Earth
E.g.,
ν_e
ν_μ
Oscillations
E.g.,
ν_τ
ν_e
ν_μ
$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$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

How knowing the mixing parameters better helps



For a future experiment
ε = JUNO, DUNE, Hyper-K:

Best fit from NuFit 5.0

$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

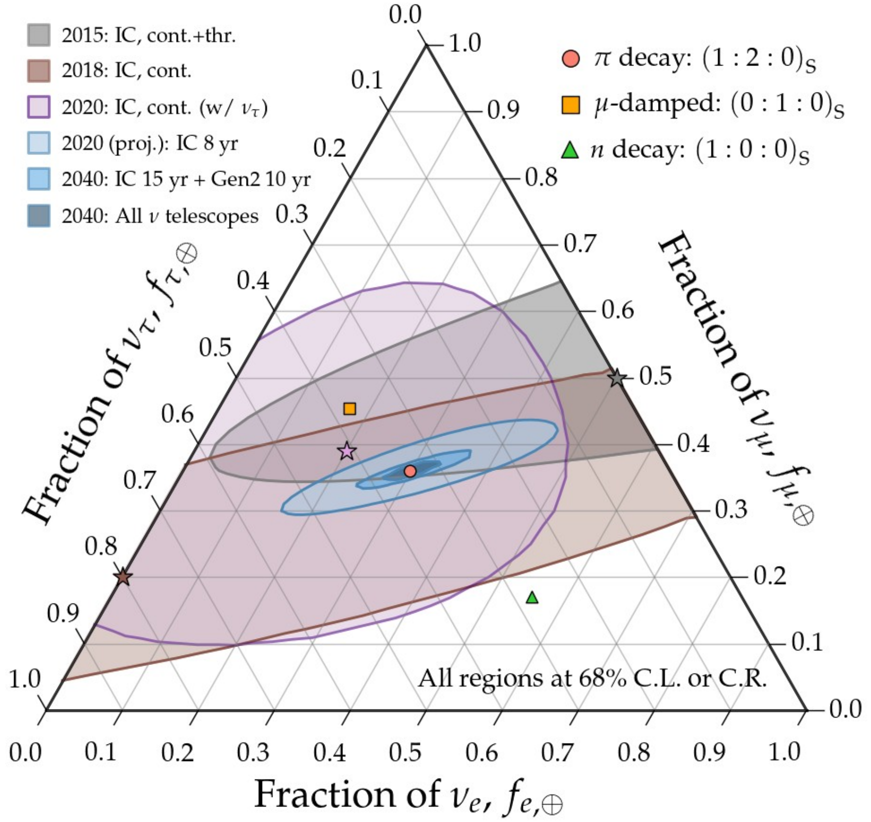
$$-2\log\mathcal{L}(\boldsymbol{\theta}) = \sum_\varepsilon \chi^2_\varepsilon(\boldsymbol{\vartheta})$$

Inferring the flavor composition at the sources

Ingredient #1:

Flavor ratios measured at Earth,

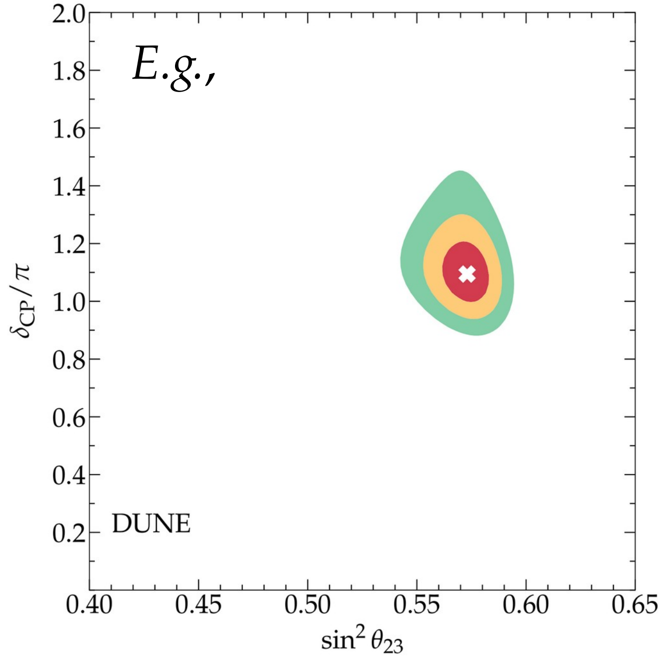
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



Ingredient #2:

Probability density of mixing parameters (θ_{12}, θ_{23}, θ_{13}, δ_{CP})

$\mathcal{L}(\boldsymbol{\vartheta})$



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

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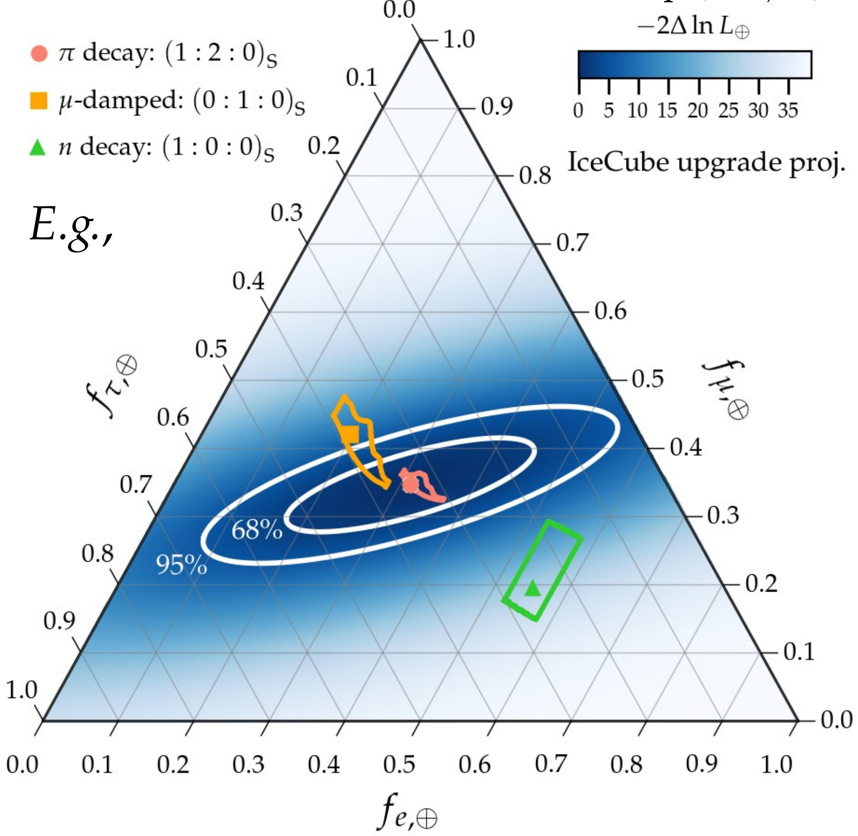
$\mathcal{P}_{\exp}(f_{\alpha,\oplus})$



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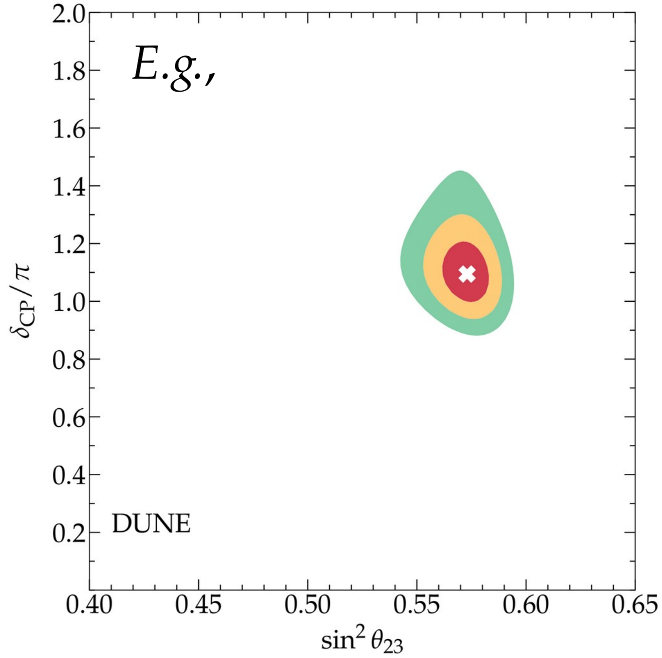

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \mathcal{L}(\boldsymbol{\vartheta}) \mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))$$

Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
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Posterior probability of $f_{\alpha,\rm S}$ [**MB** & Ahlers, *PRL* 2019]:

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

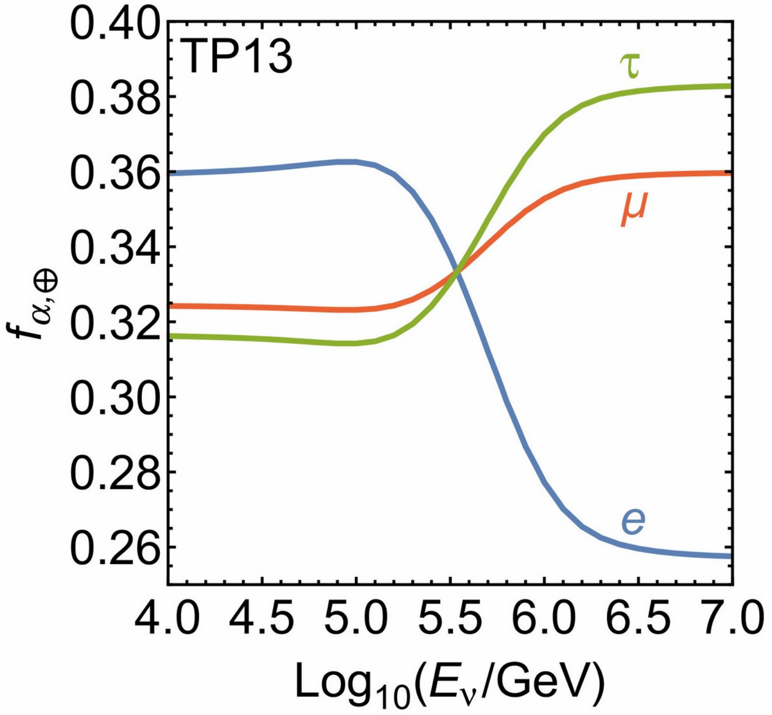
$$\mathcal{P}(\boldsymbol{f}_s) = \int d\boldsymbol{\vartheta} \underbrace{\mathcal{L}(\boldsymbol{\vartheta})}_{\text{Oscillation experiments}} \underbrace{\mathcal{P}_{\rm exp}(\boldsymbol{f}_\oplus(\boldsymbol{f}_{\rm S}, \boldsymbol{\vartheta}))}_{\text{Neutrino telescopes}}$$

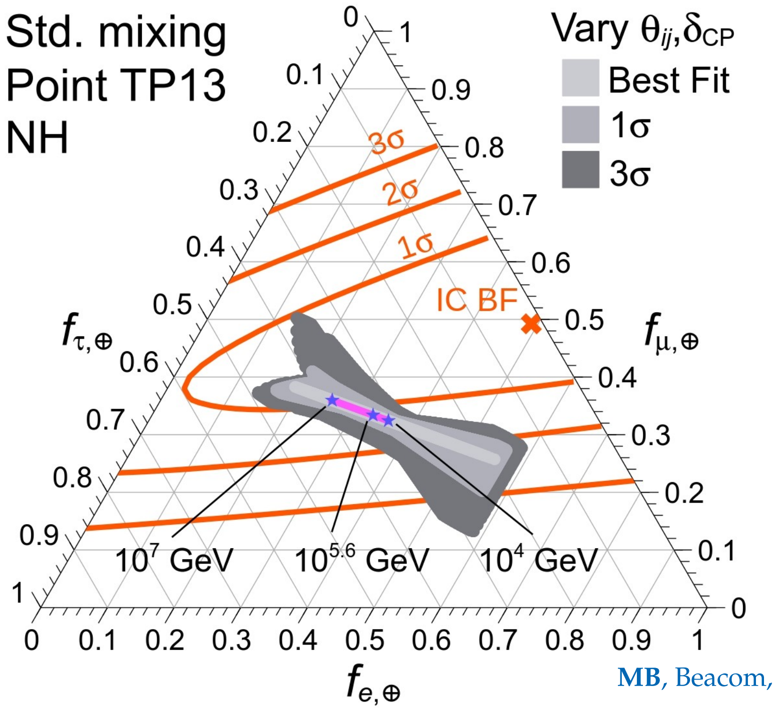
Oscillation experiments Neutrino telescopes

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

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



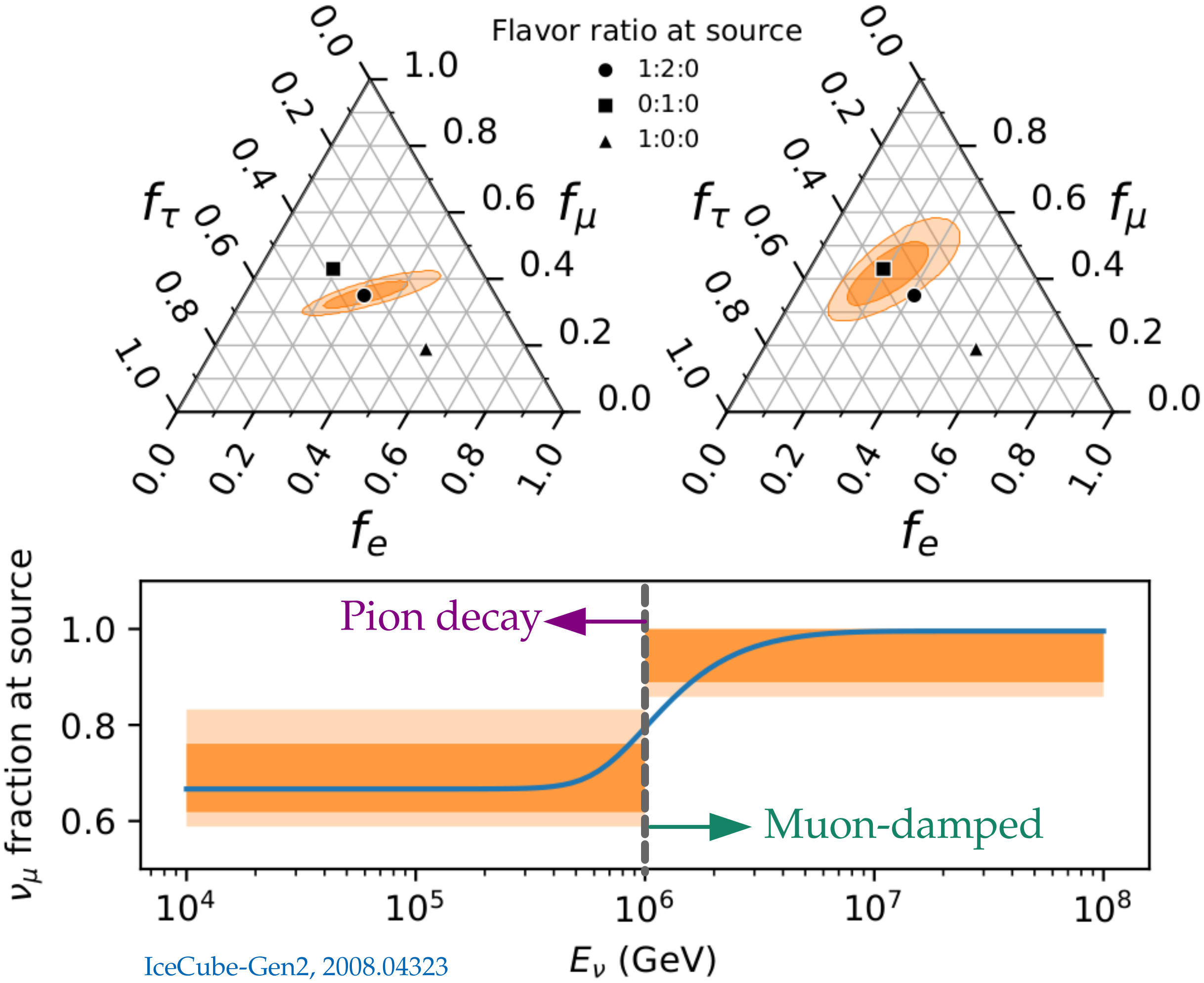


MB, Beacom, Winter, *PRL* 2015

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

Energy dependence of flavor ratios – in IceCube-Gen2

Measured:



IceCube-Gen2, 2008.04323

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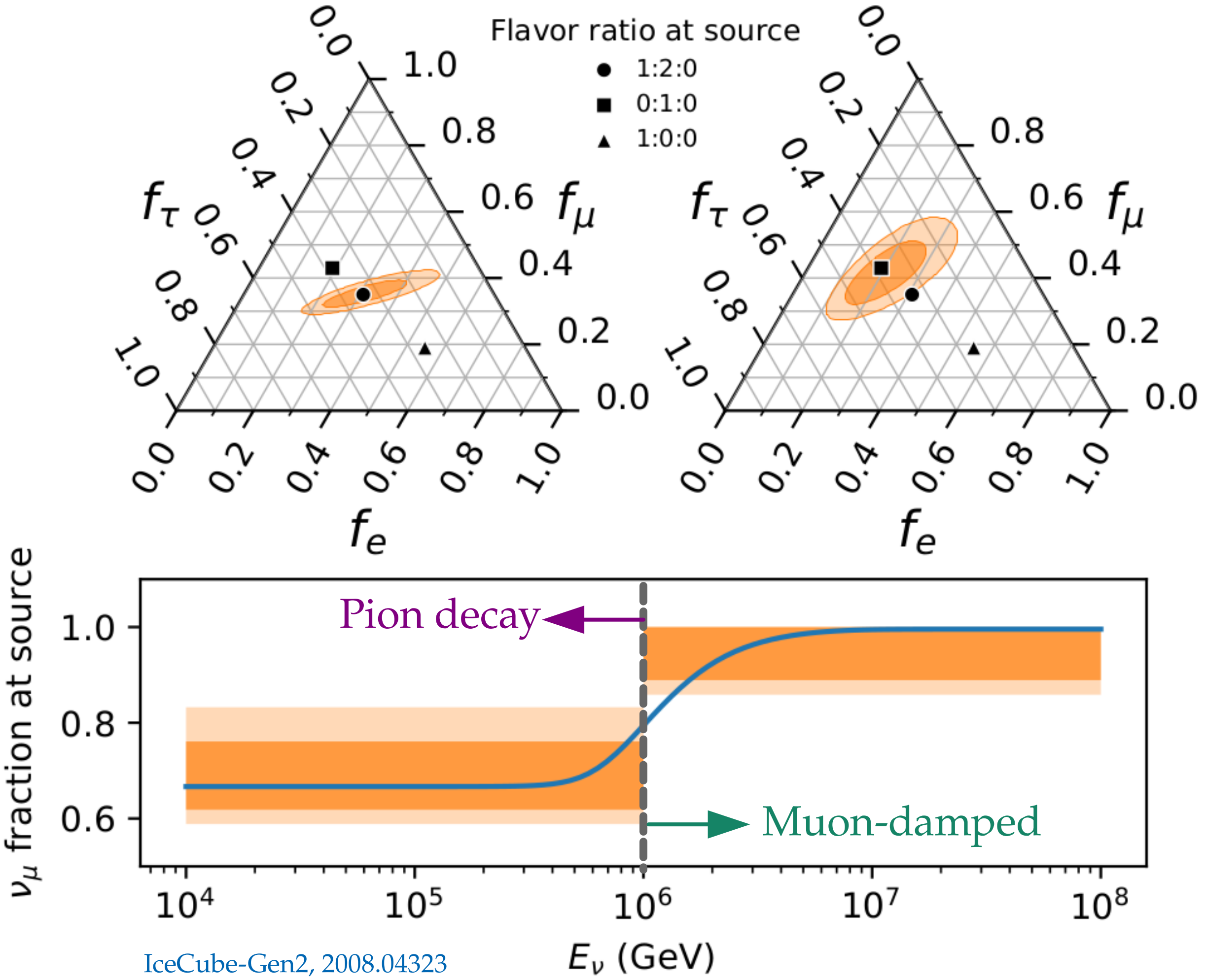

IceCube-Gen2, 2008.04323

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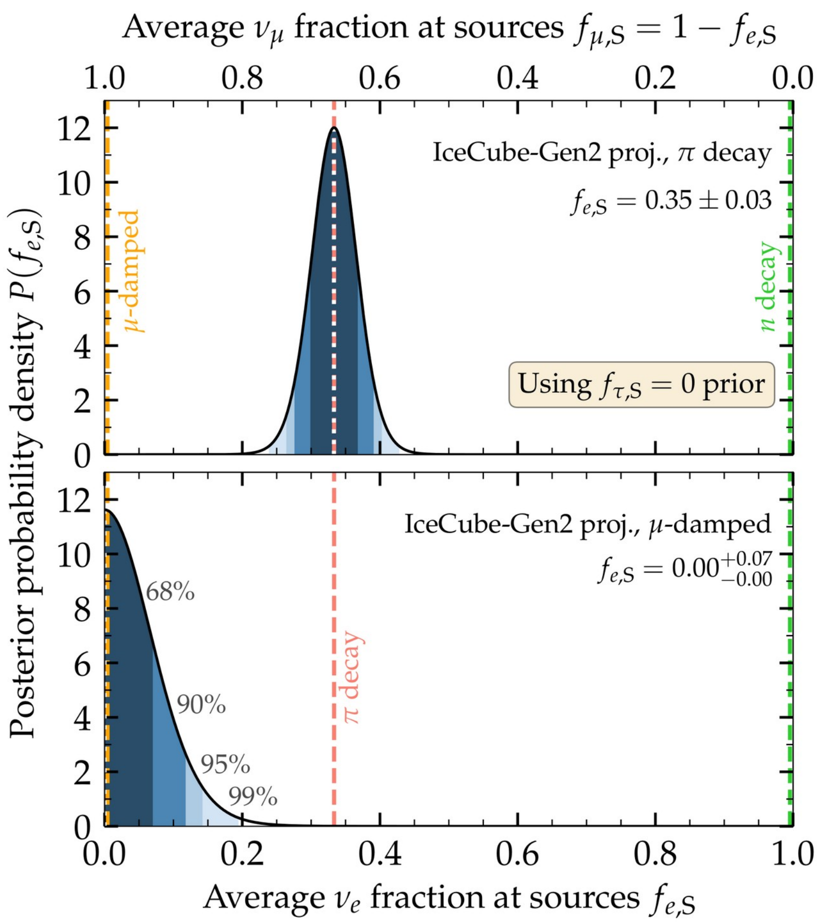

MB & Ahlers, *PRL* 2019

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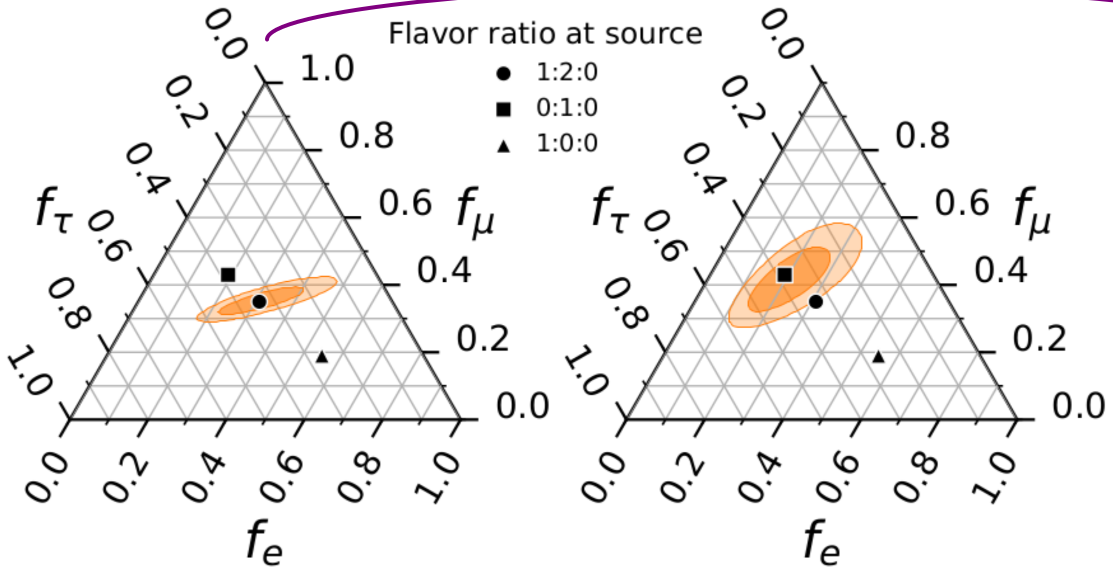

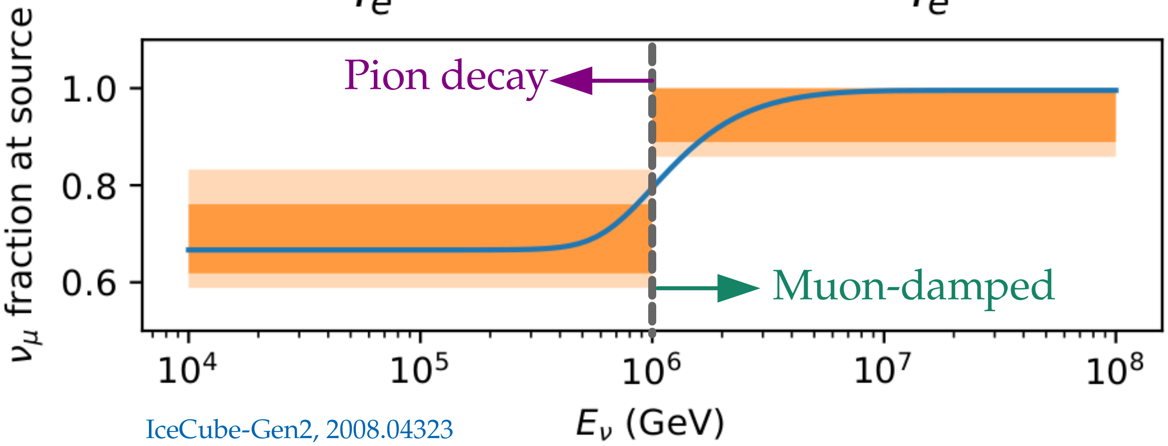

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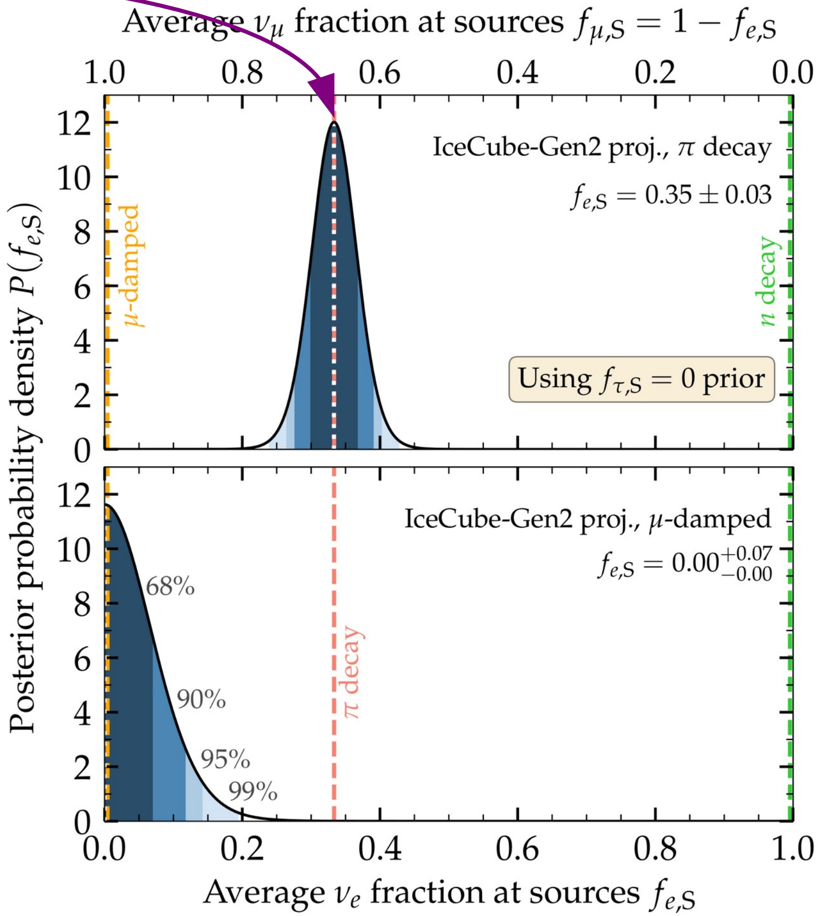

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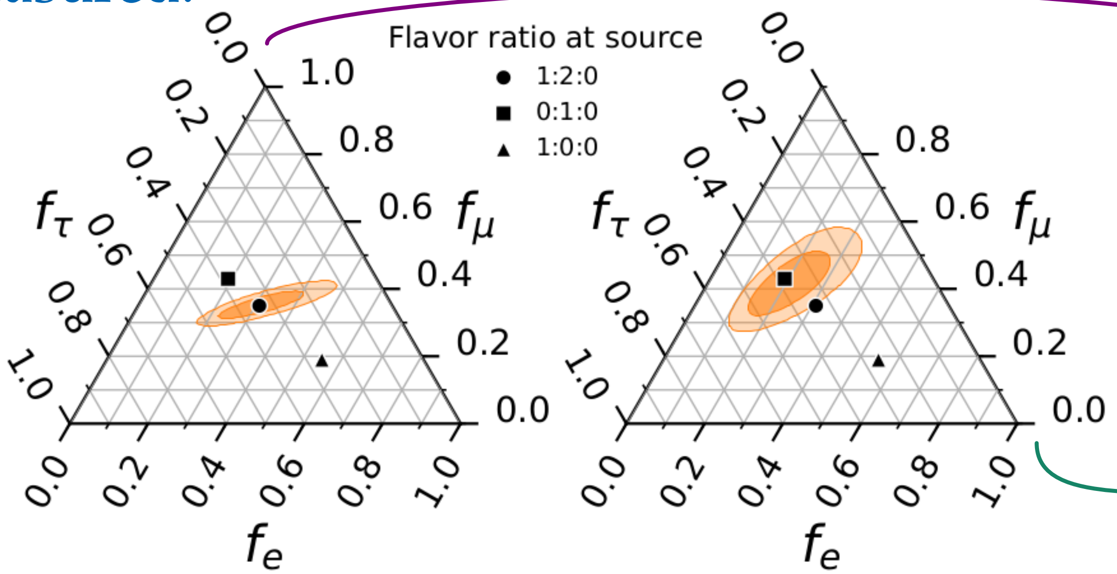

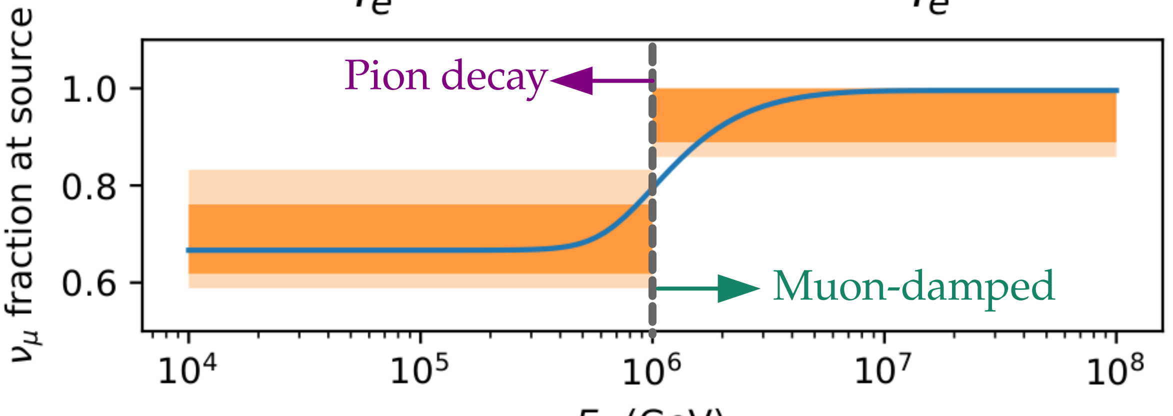

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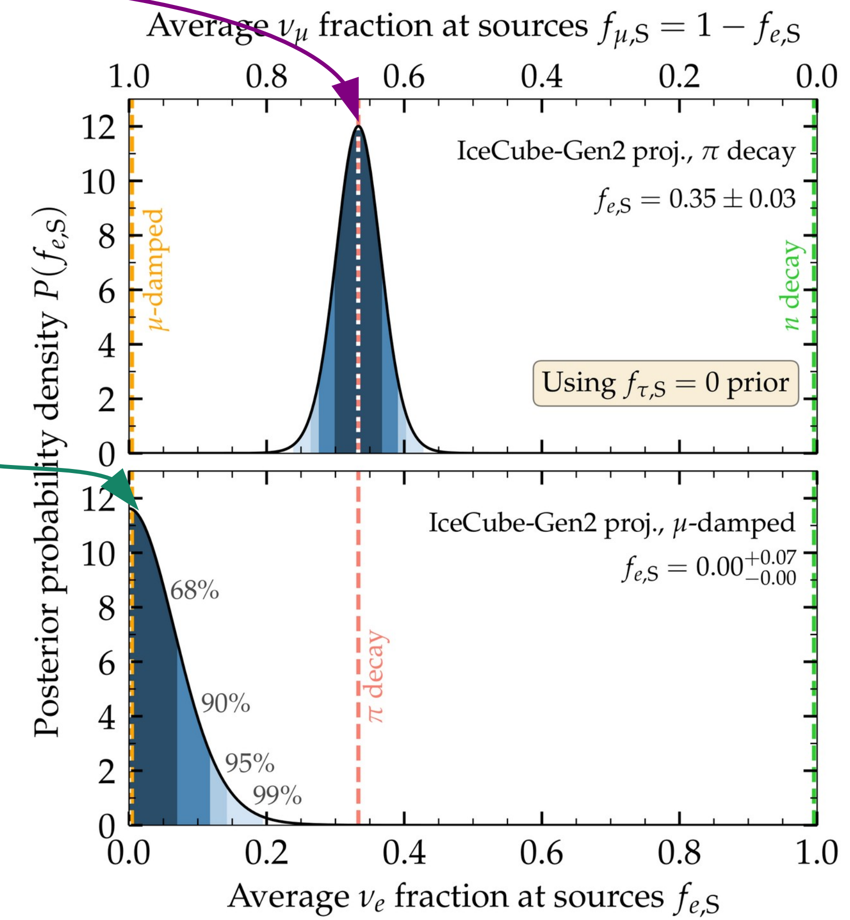

MB & Ahlers, *PRL* 2019

Inferring the flavor composition at the sources

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

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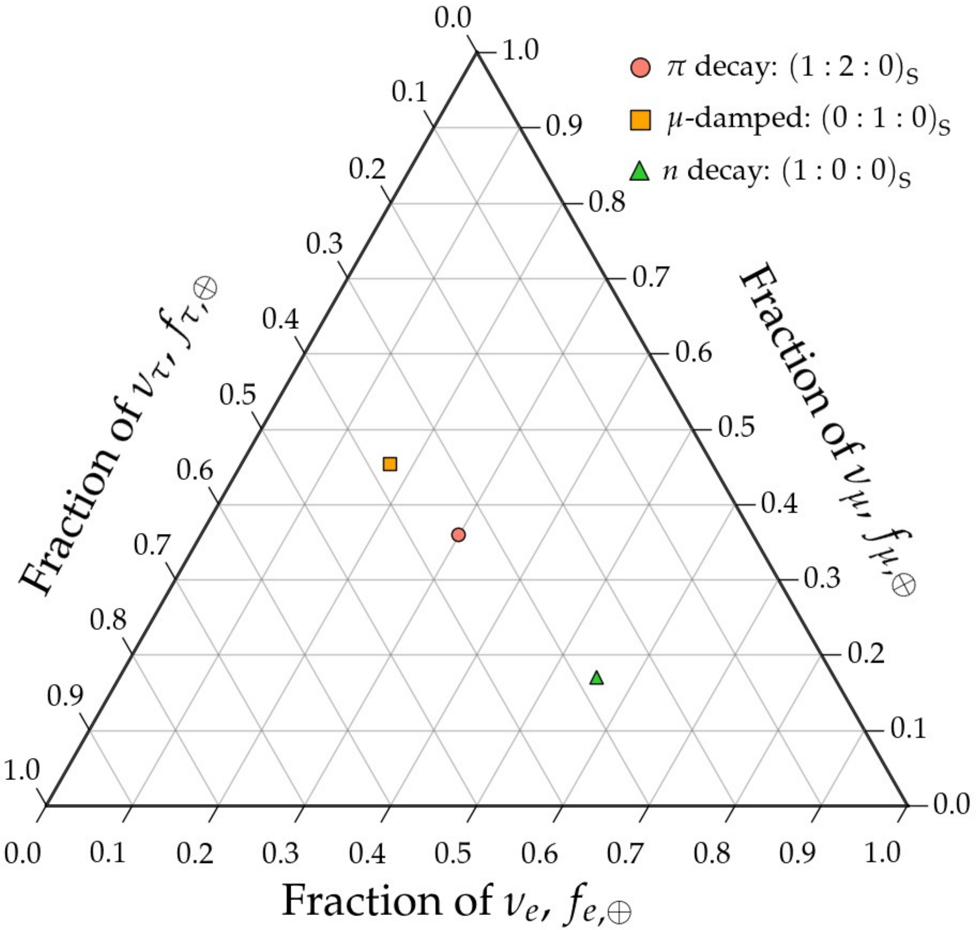

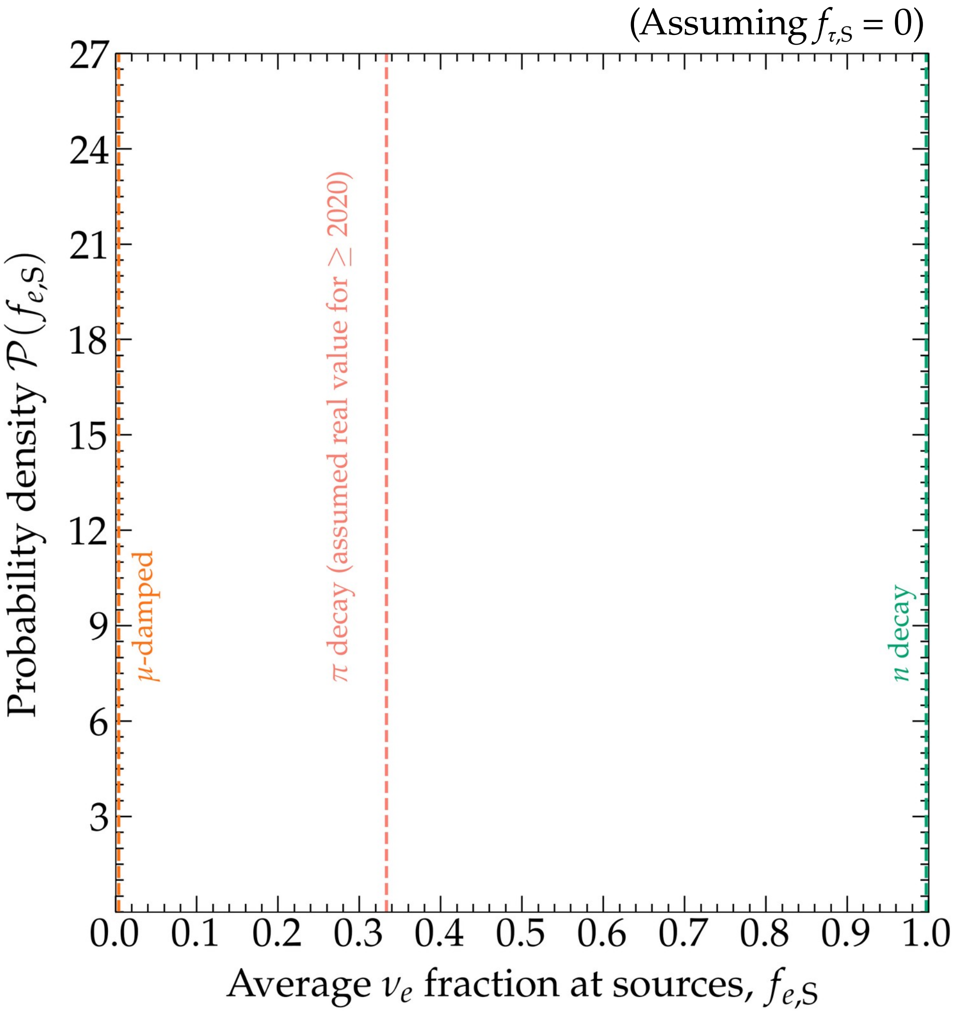

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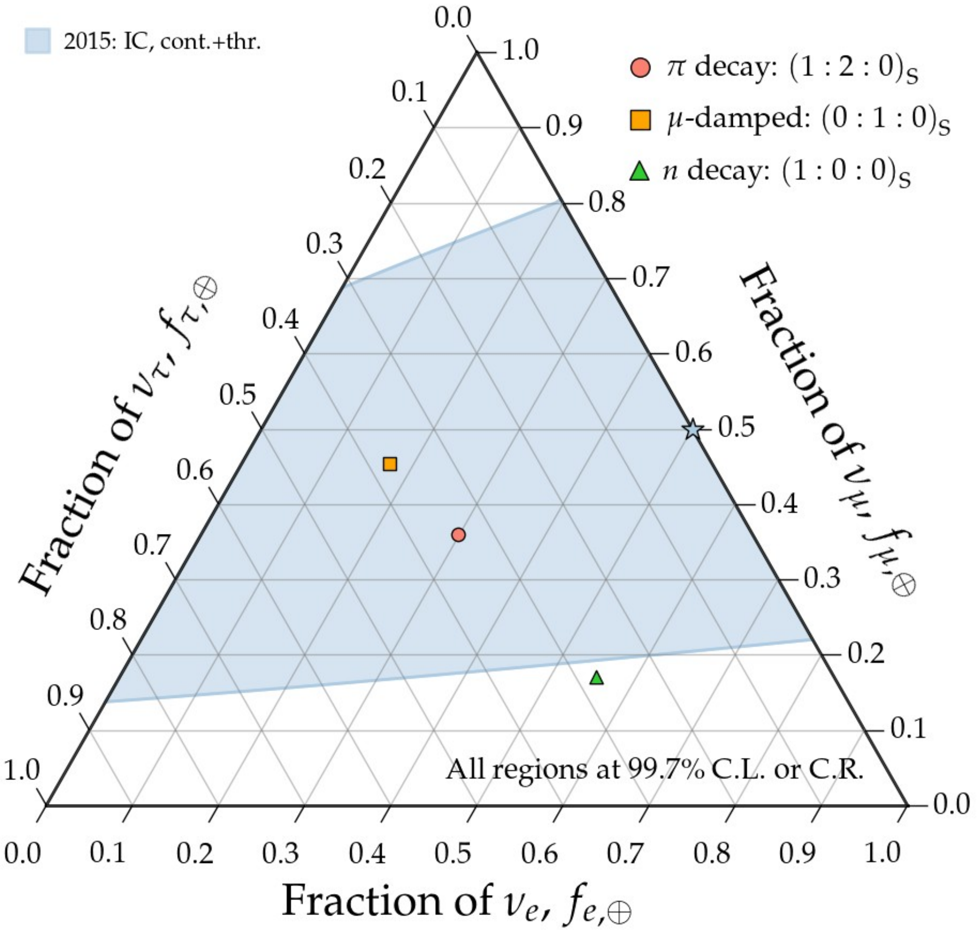
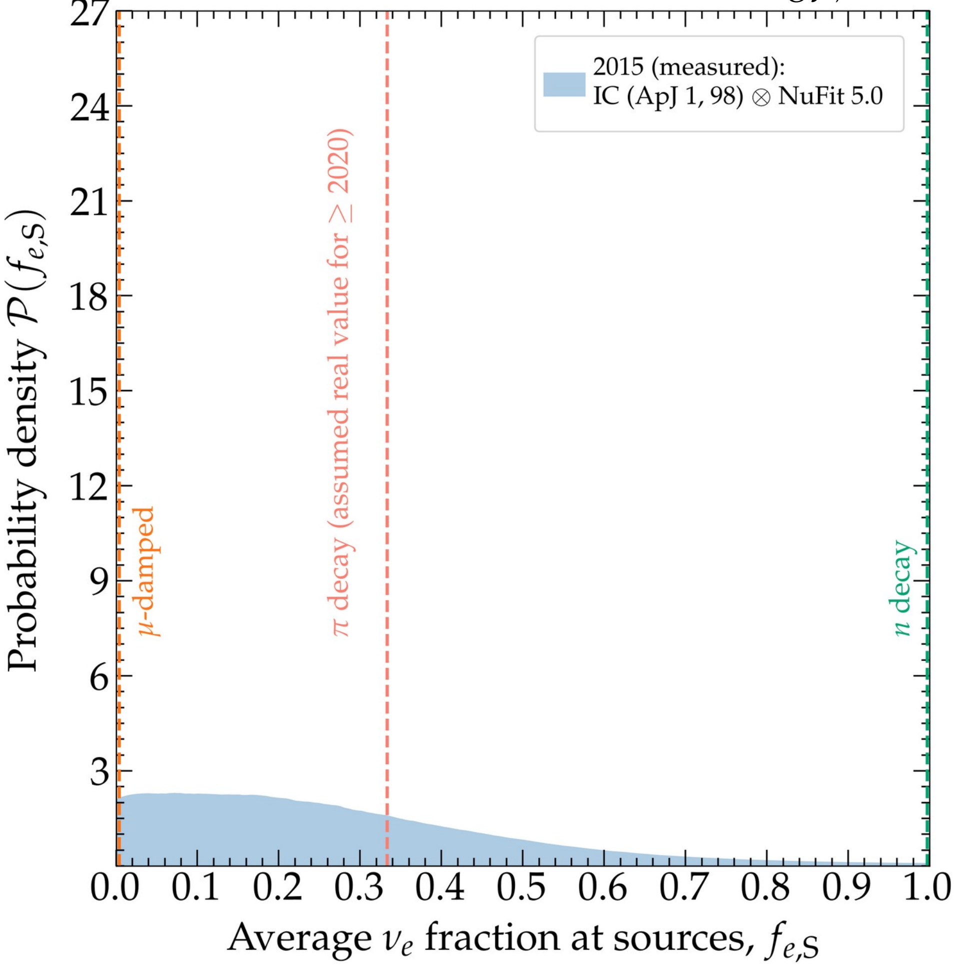


(Assuming $f_{\tau,S} = 0$)



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MB & Ahlers, *PRL* 2019

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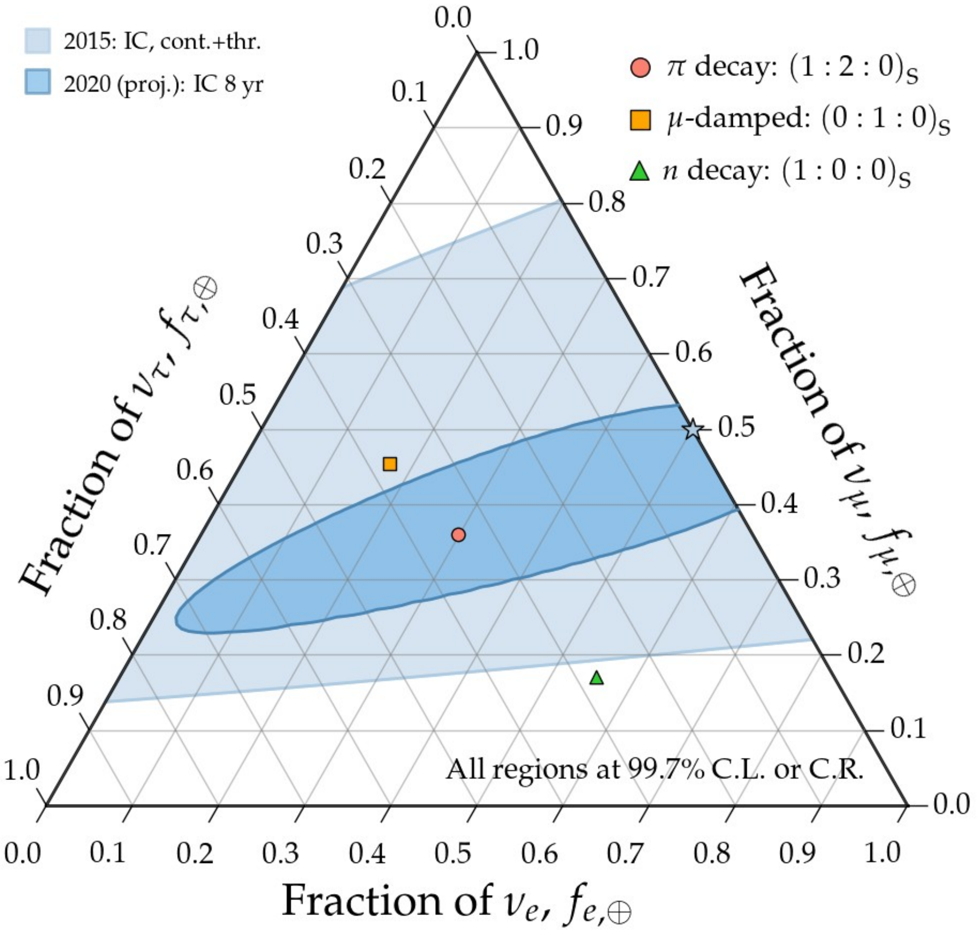

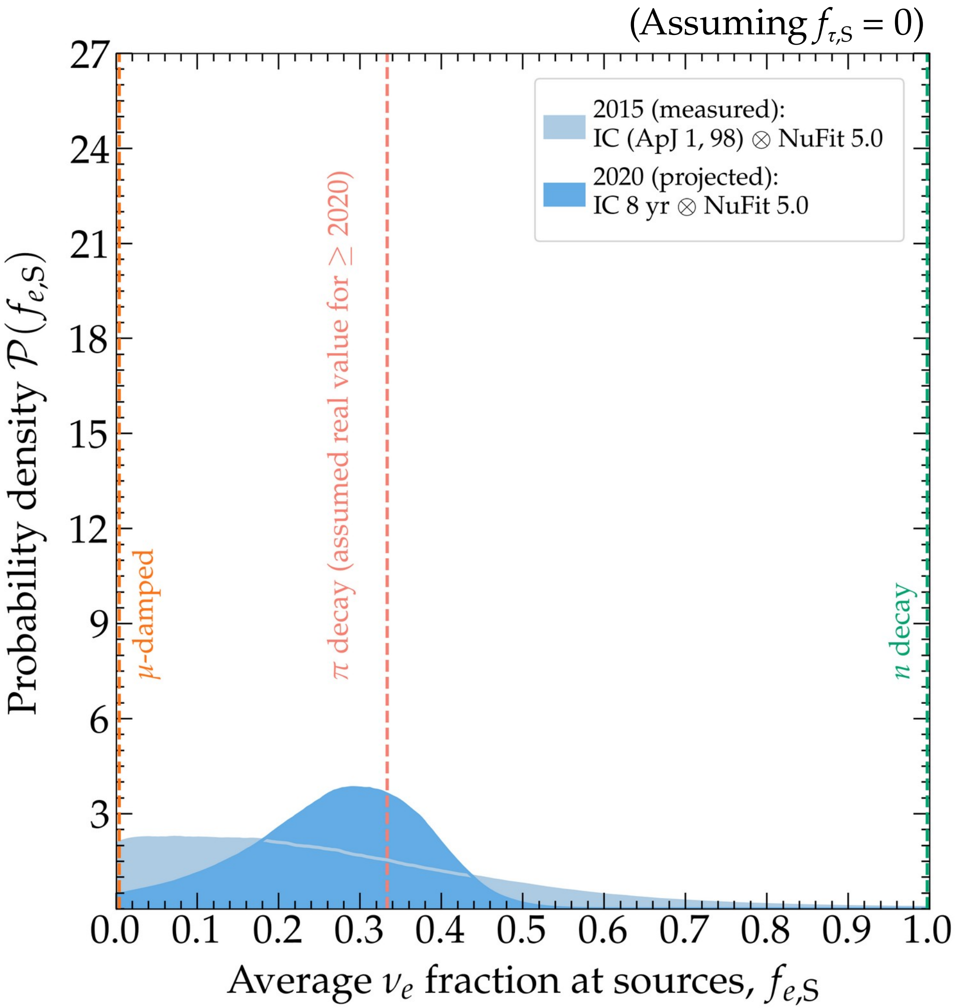

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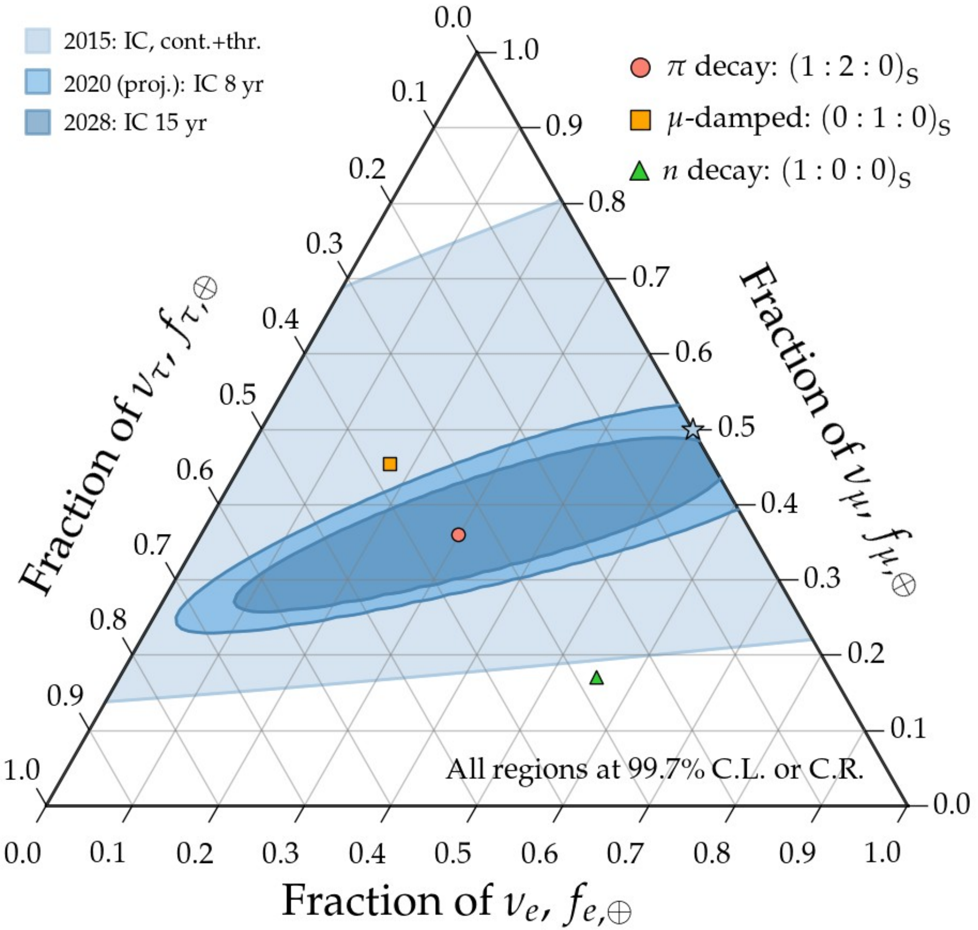

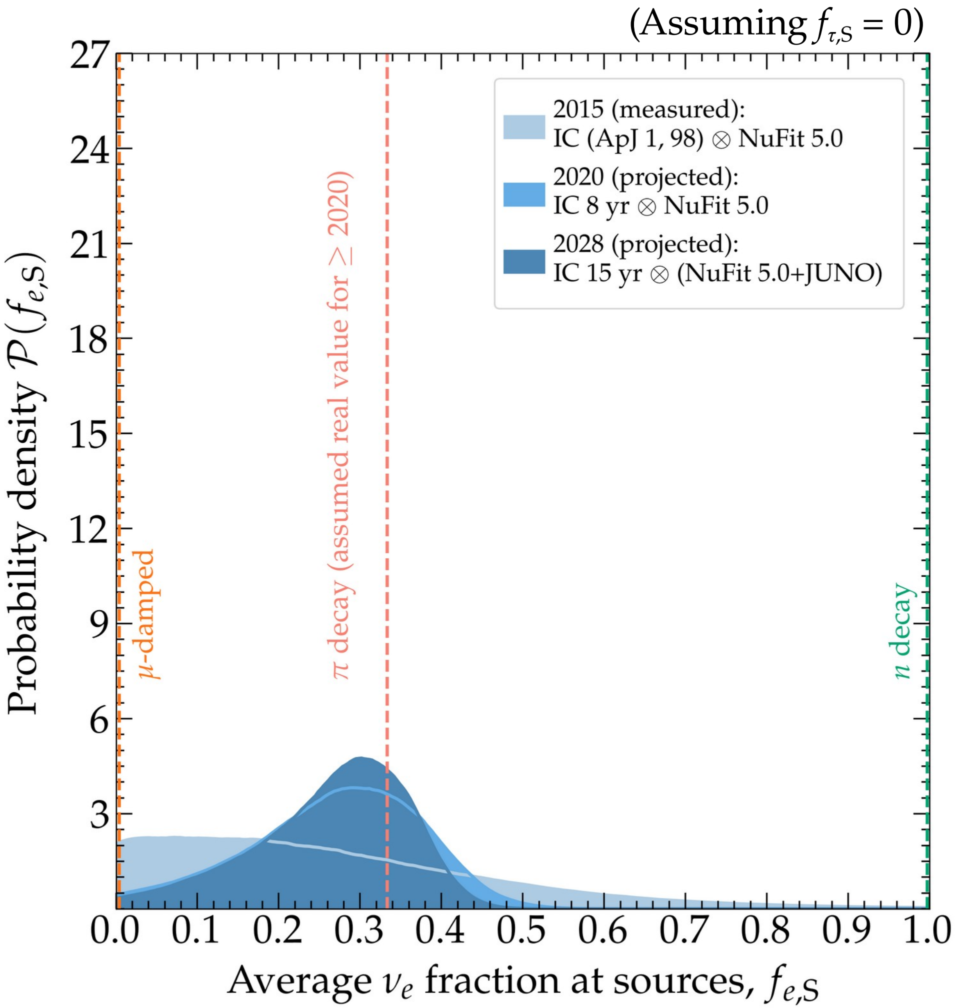

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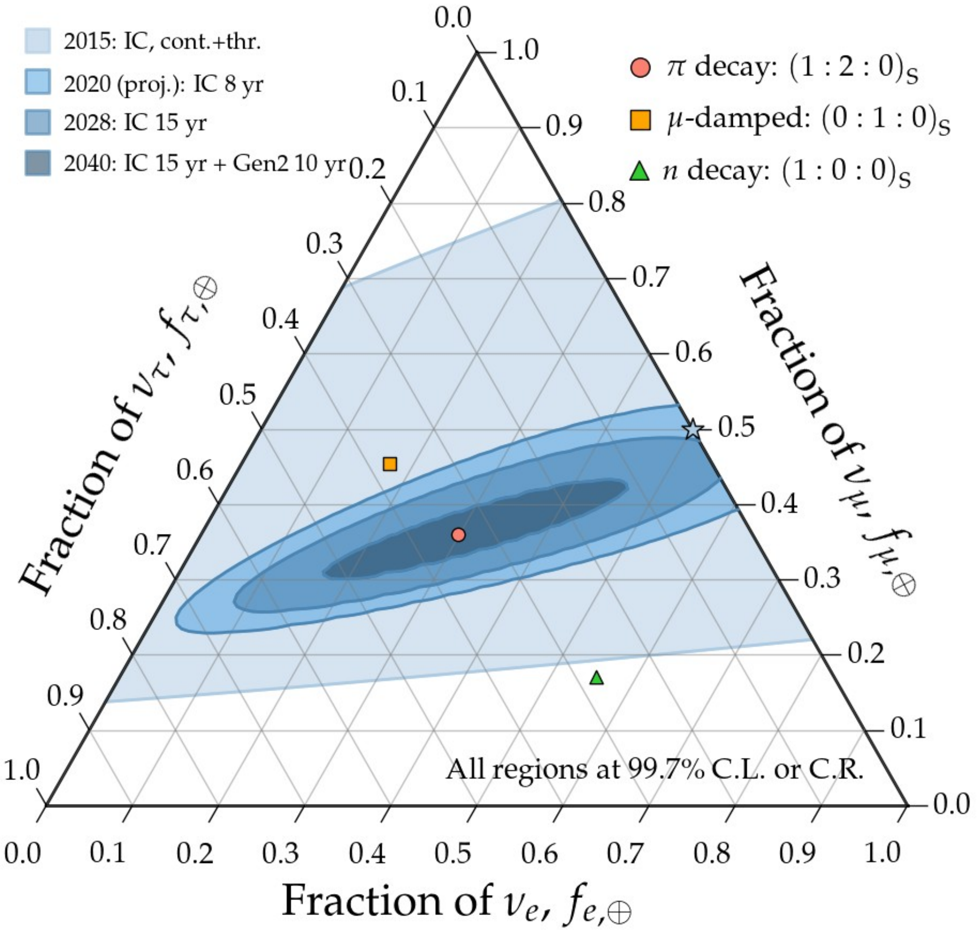

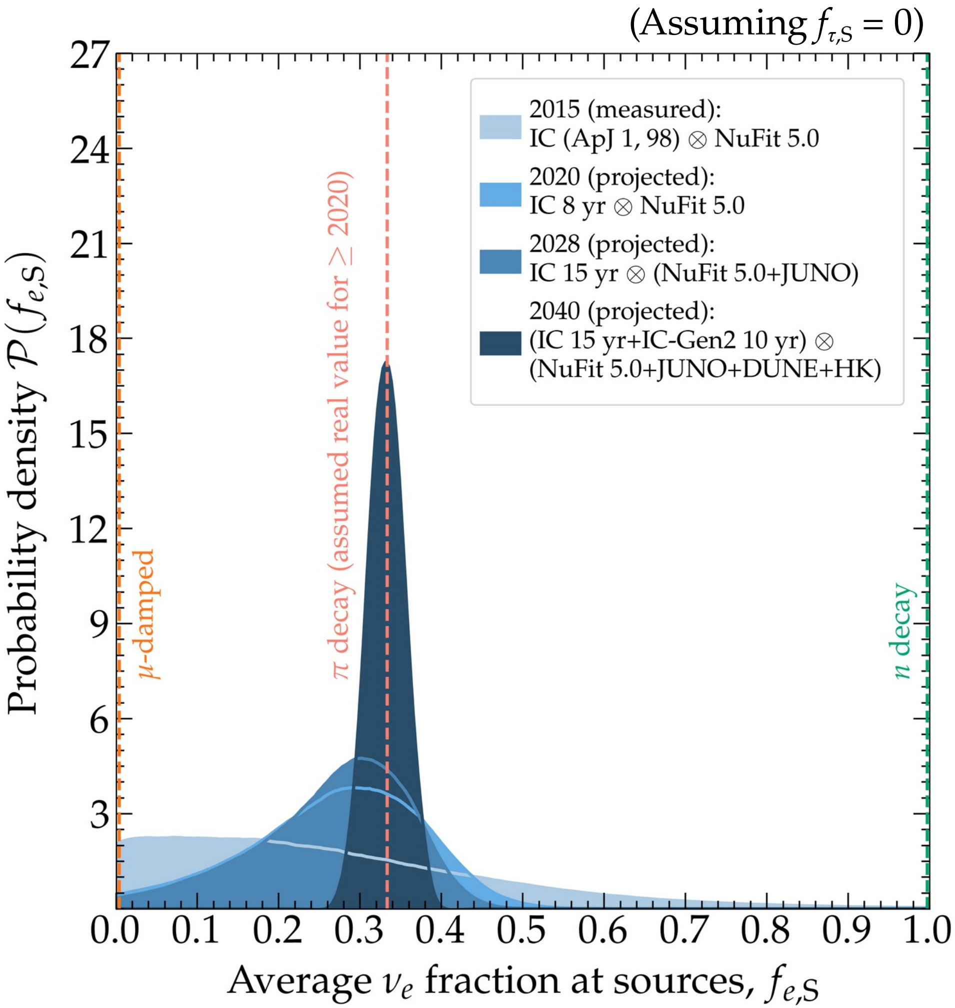

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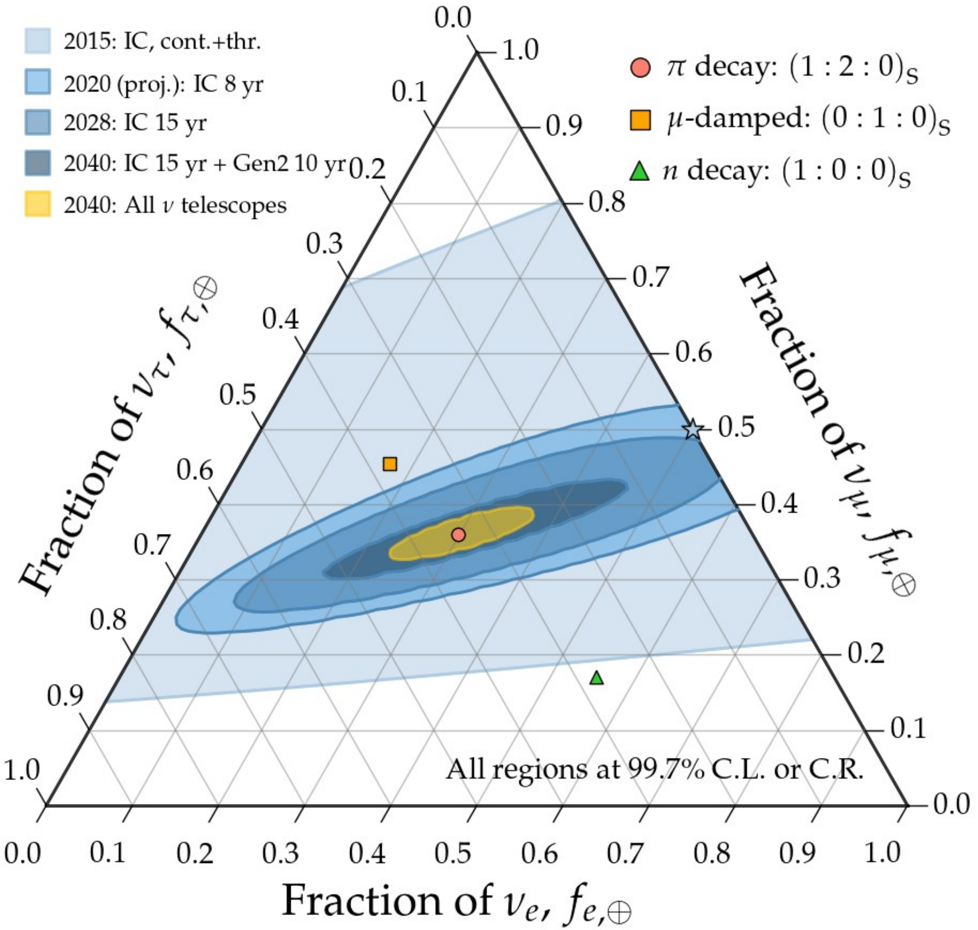
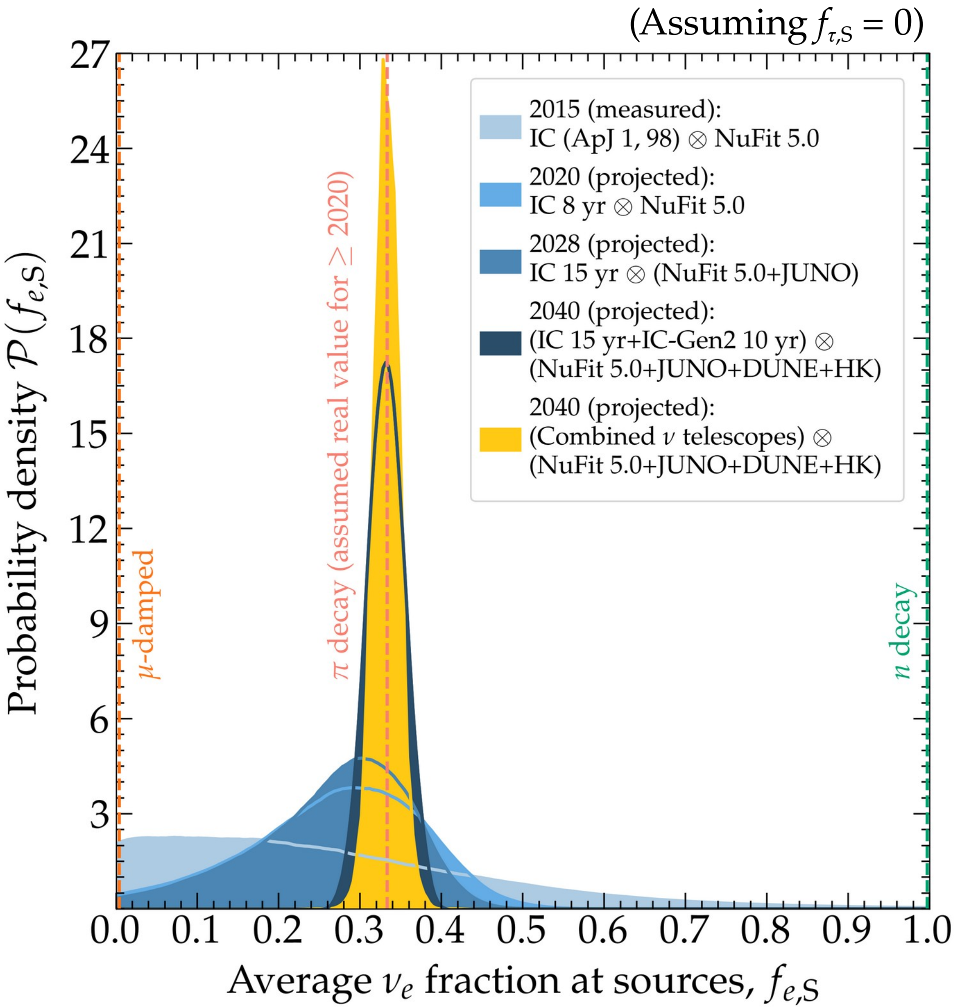




Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021
MB & Ahlers, *PRL* 2019

More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

π decay: (1/3, 2/3, 0) μ damped: (0, 1, 0) *n* decay: (1, 0, 0)

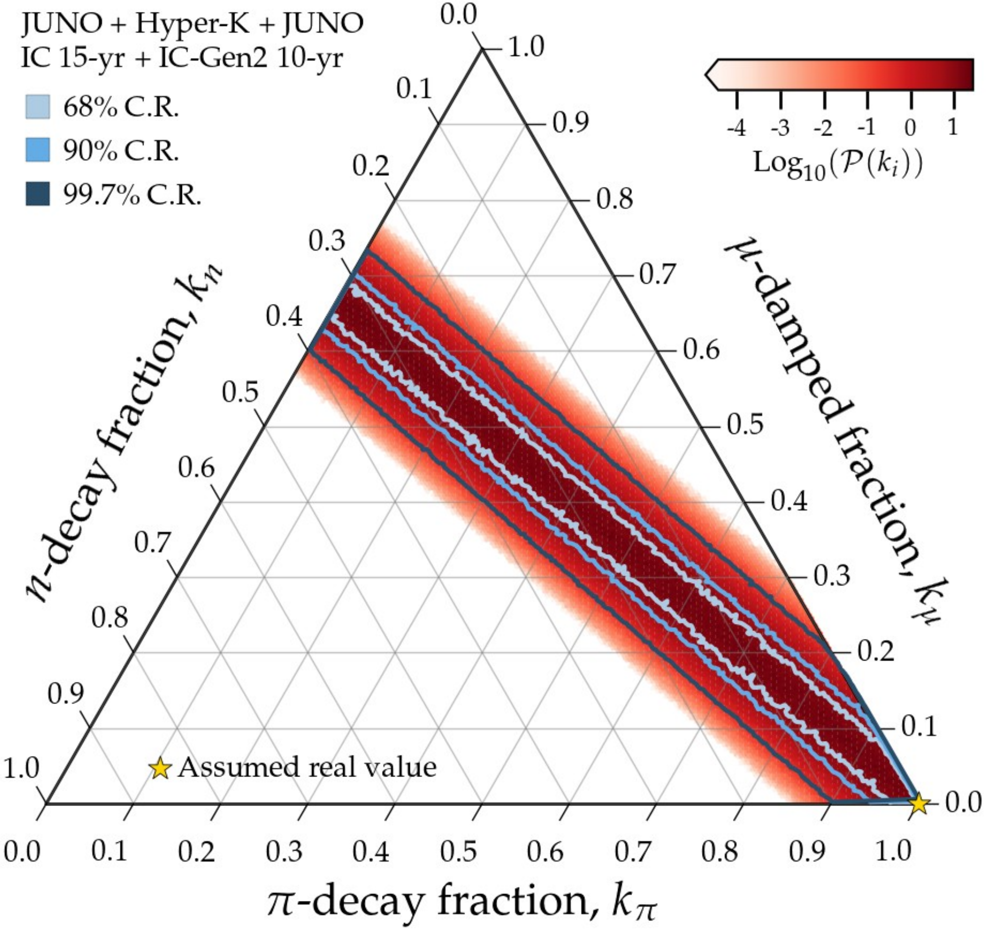
Propagate to Earth

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

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

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

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



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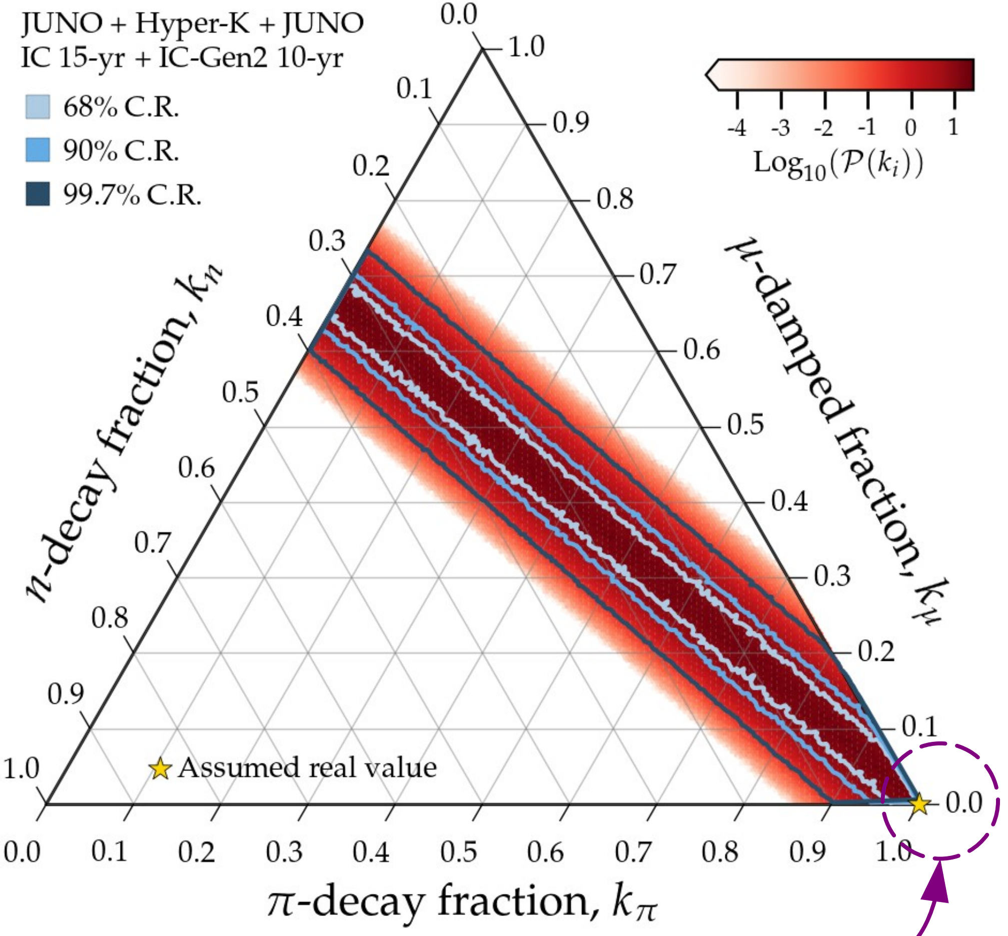

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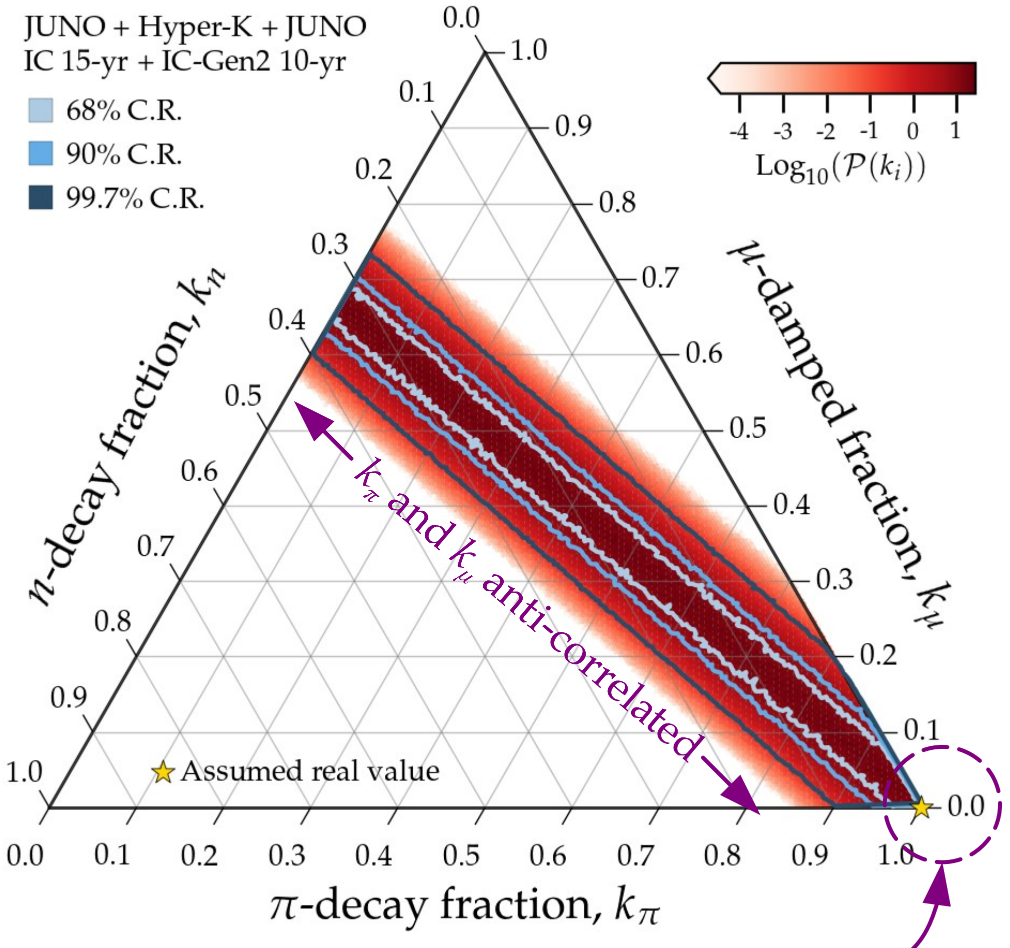

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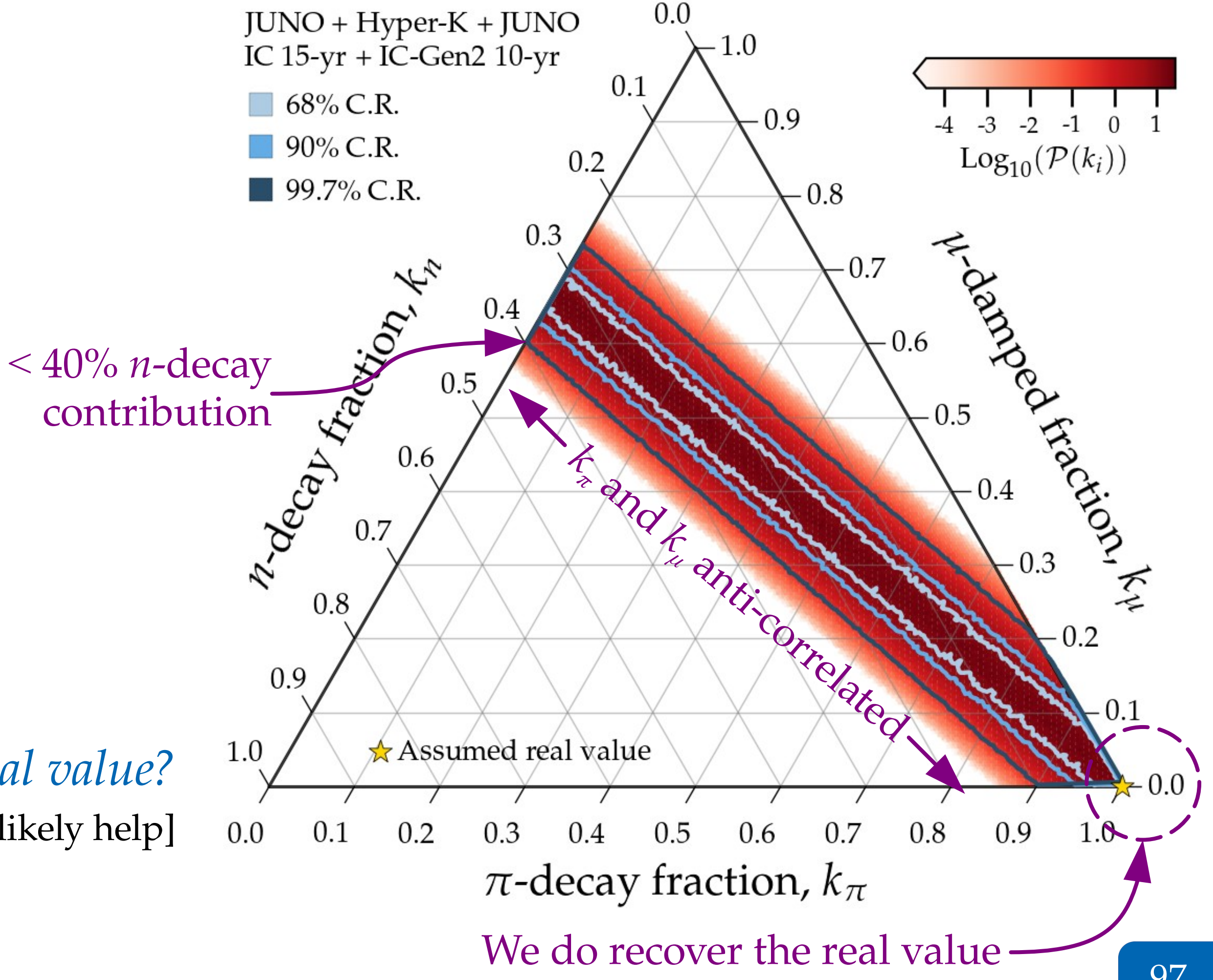

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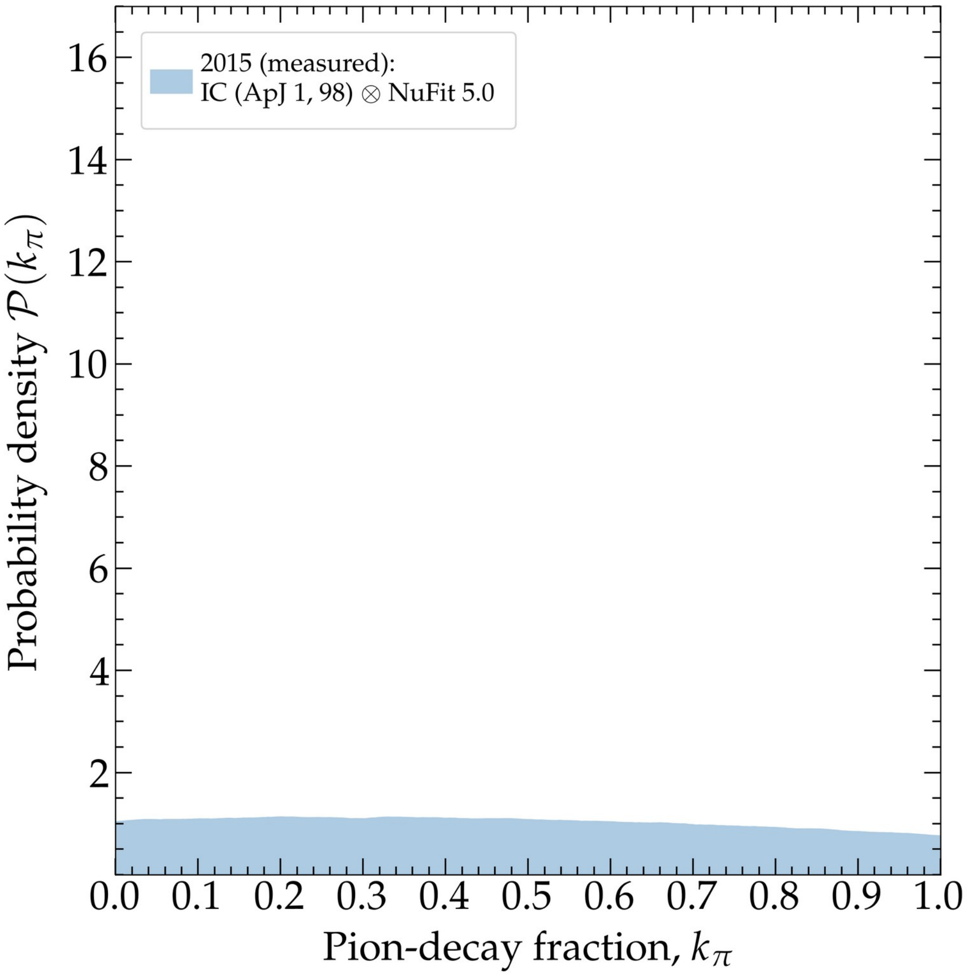

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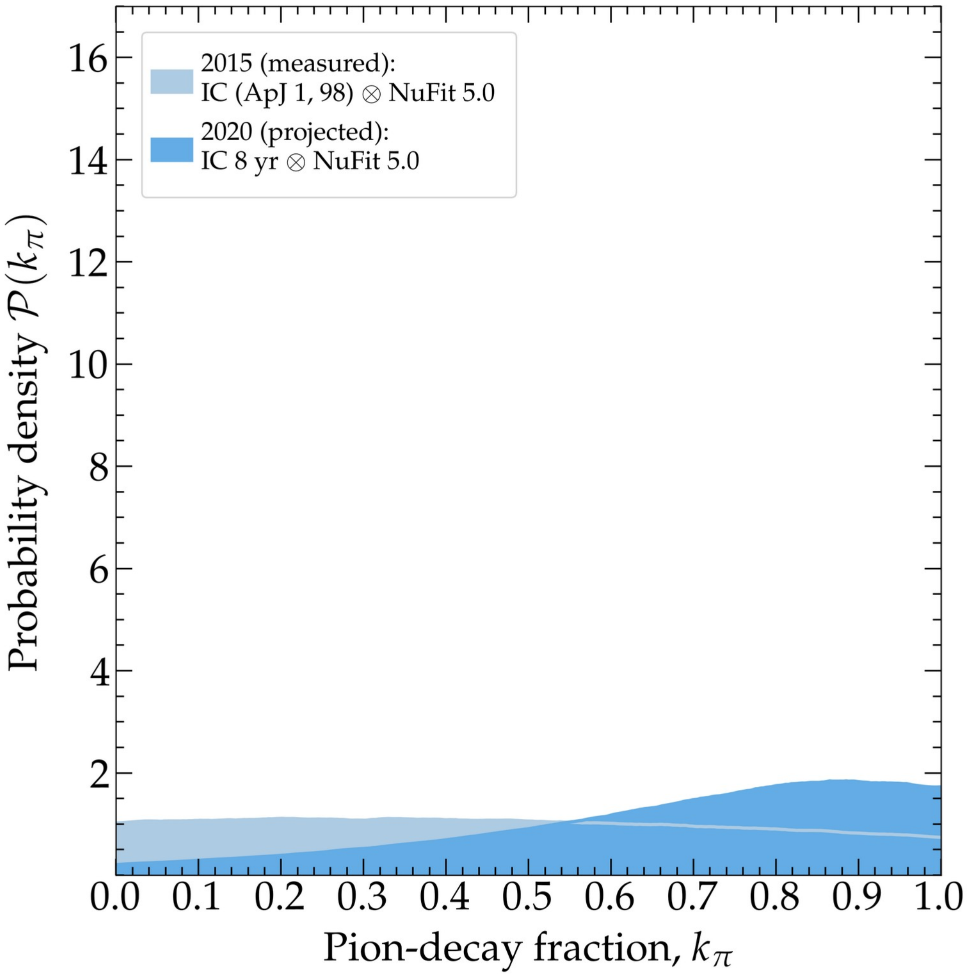

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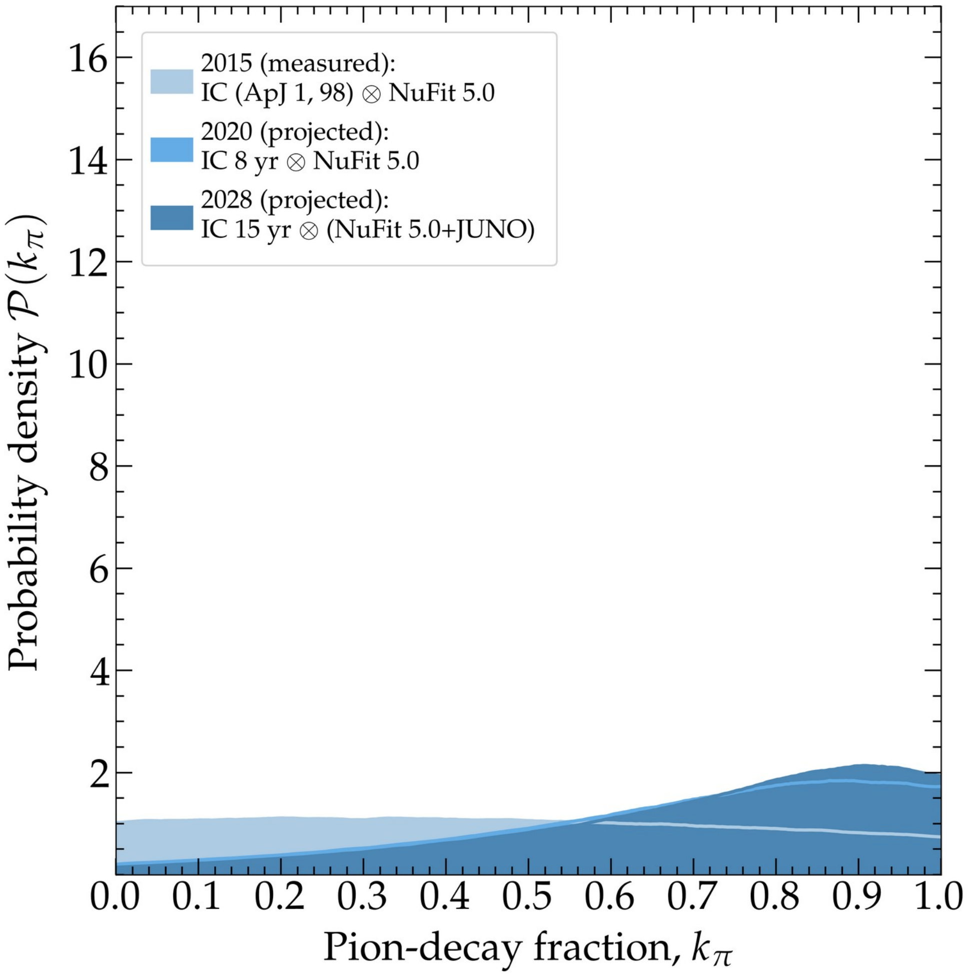

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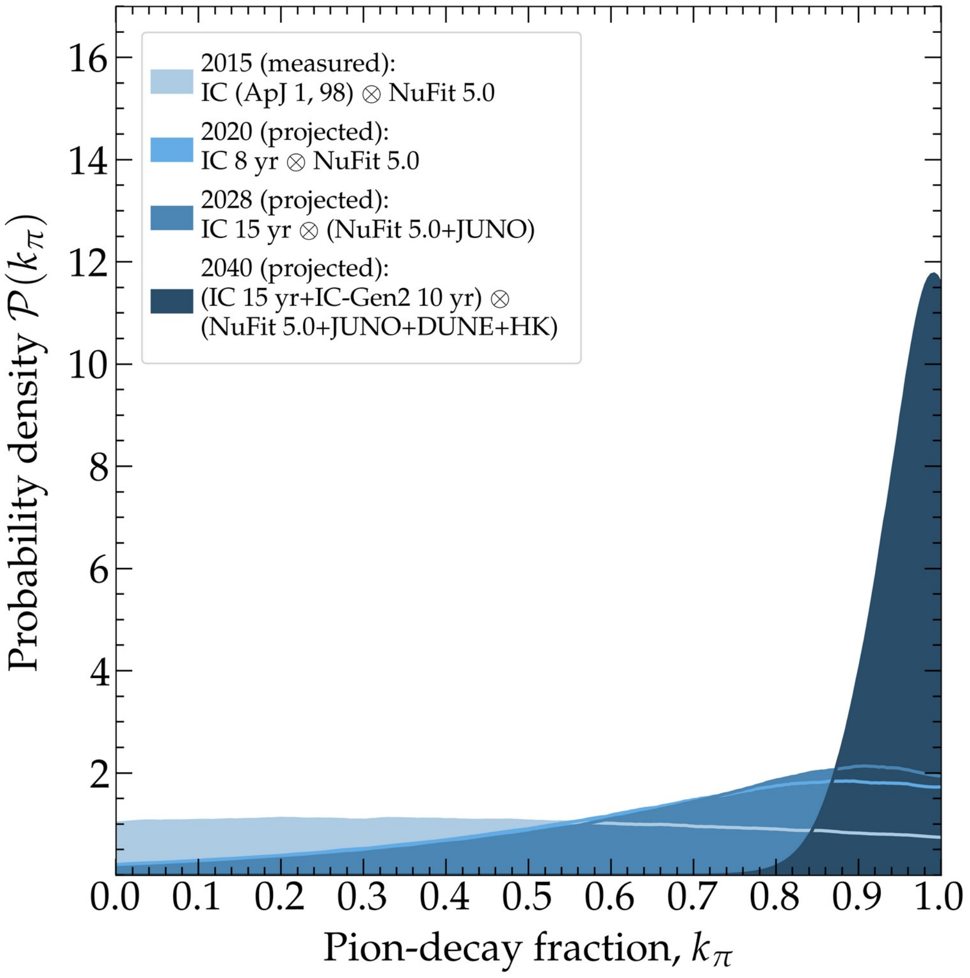

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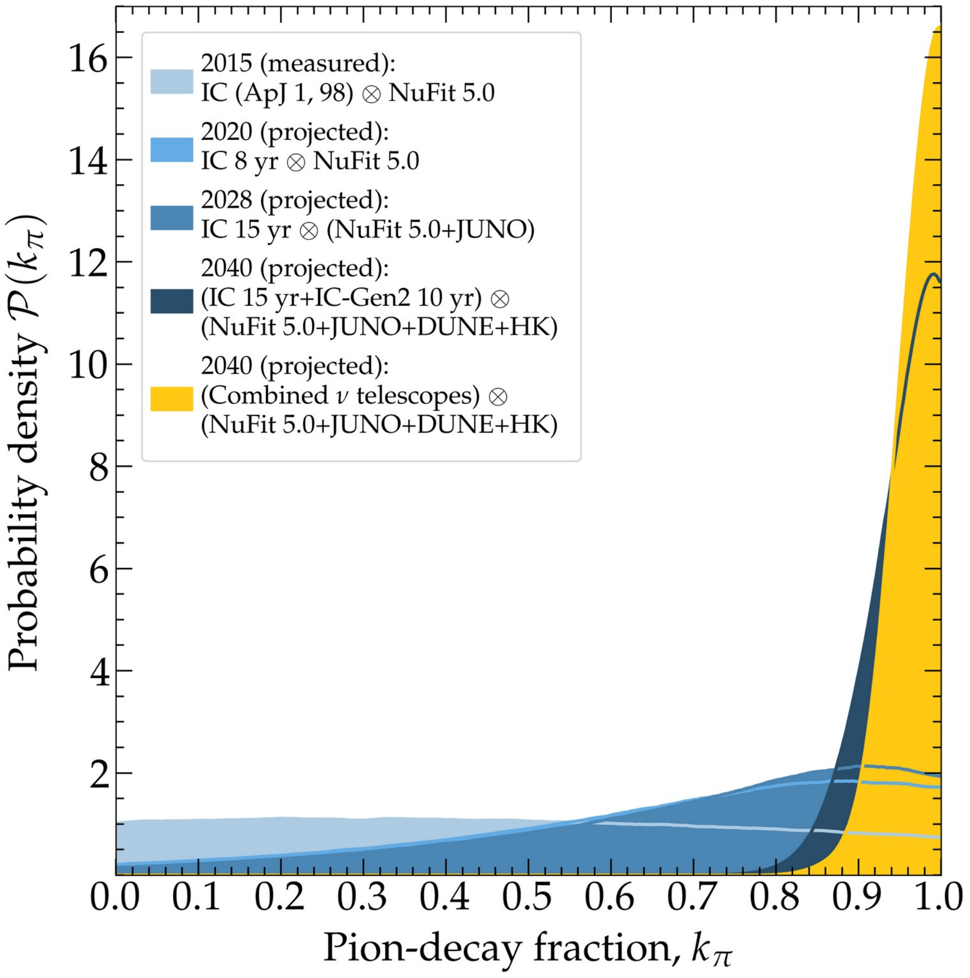
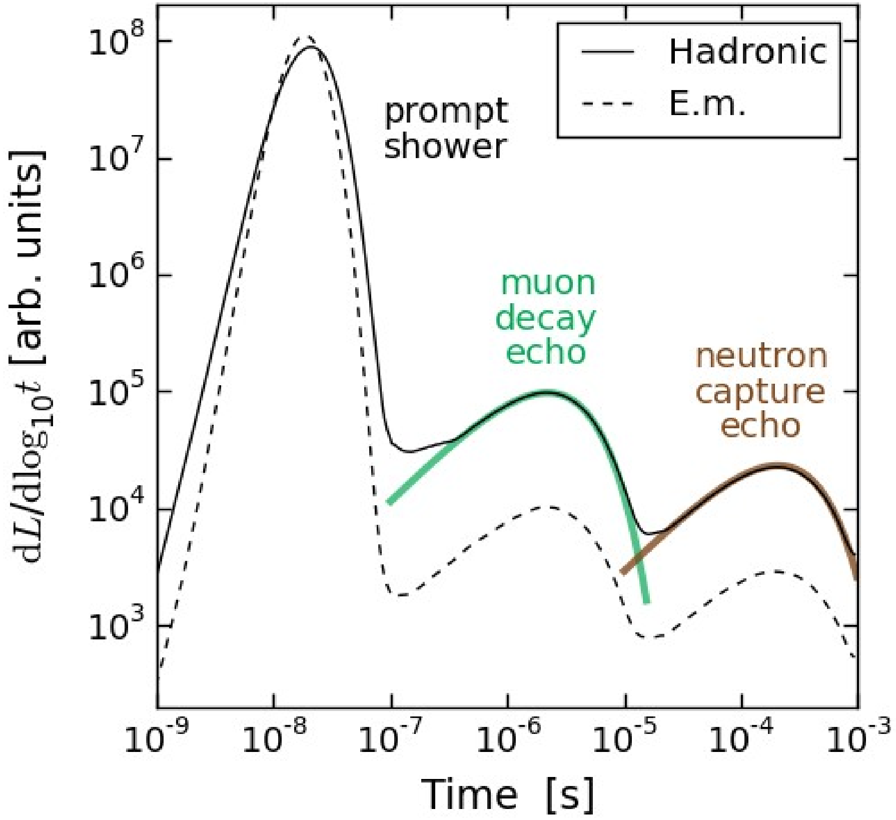
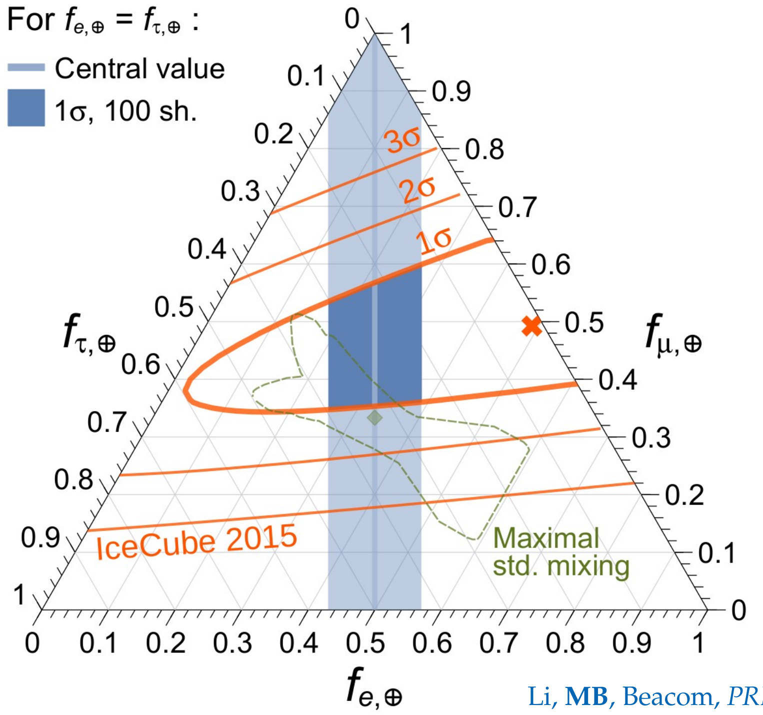


Song, Li, Argüelles, **MB**, Vincent, *JCAP* 2021

Side note: Improving flavor-tagging using *echoes*

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





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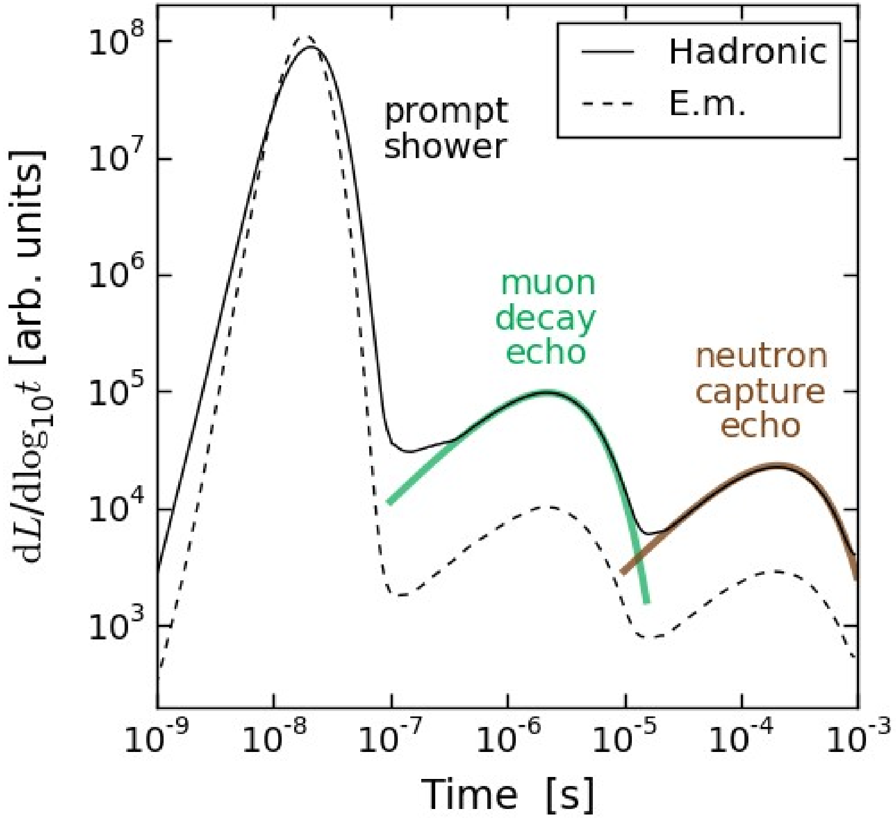
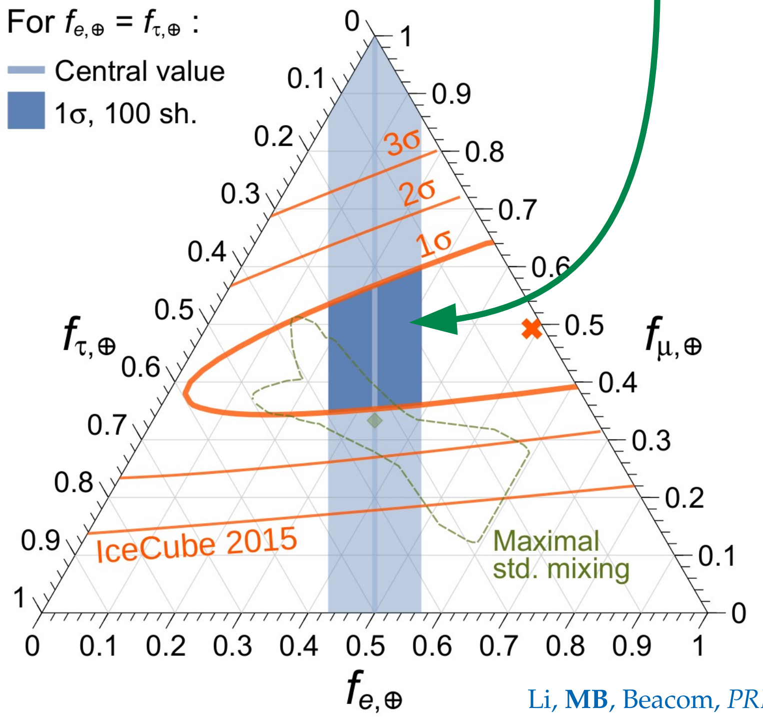


~10 × improvement over current measurement



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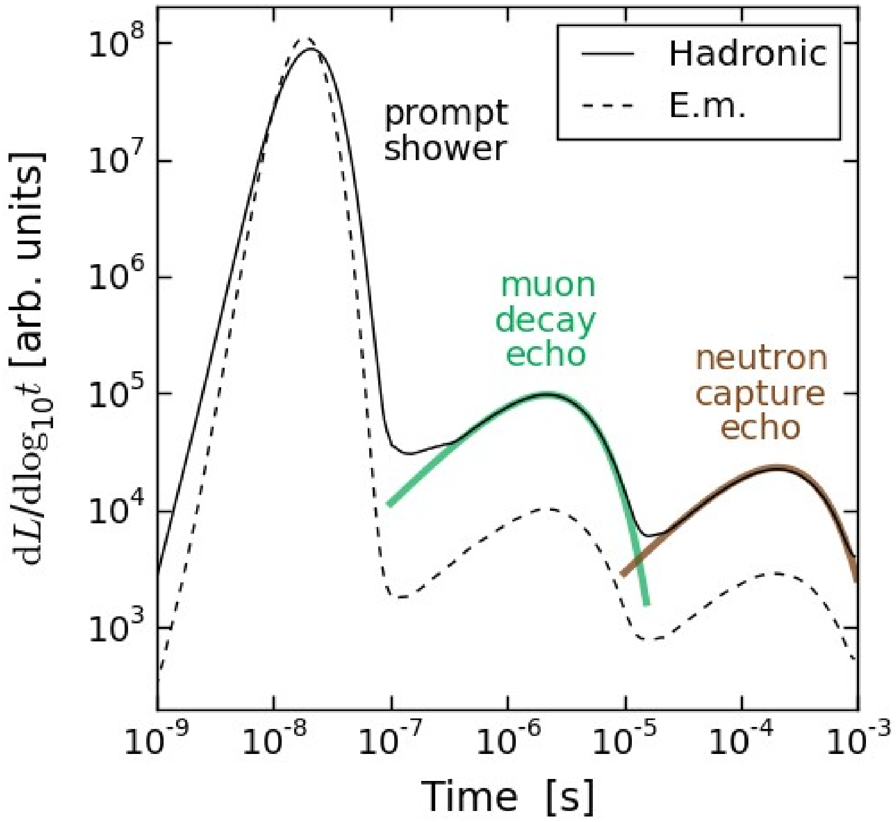

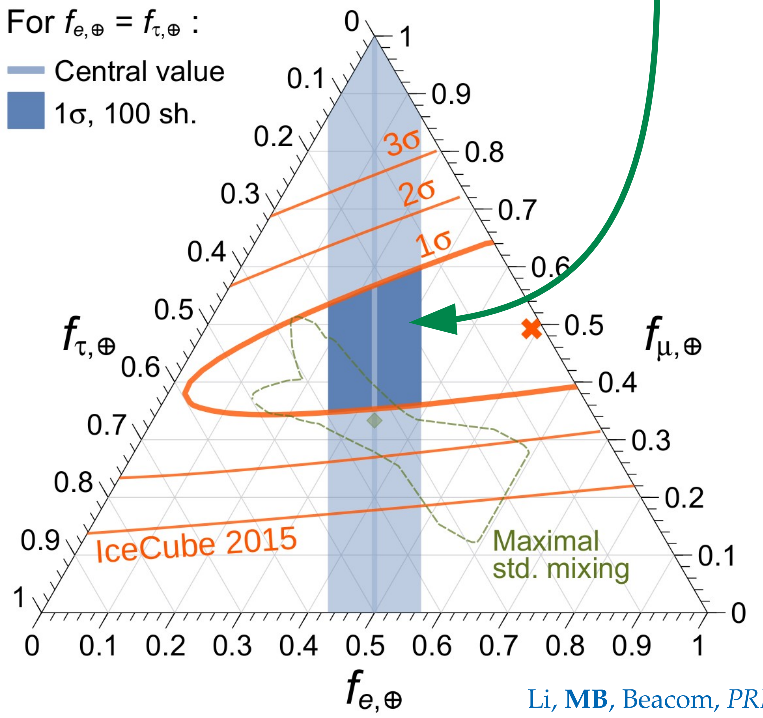

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