Astrophysics and particle physics with high-energy cosmic neutrinos *today and in the future*

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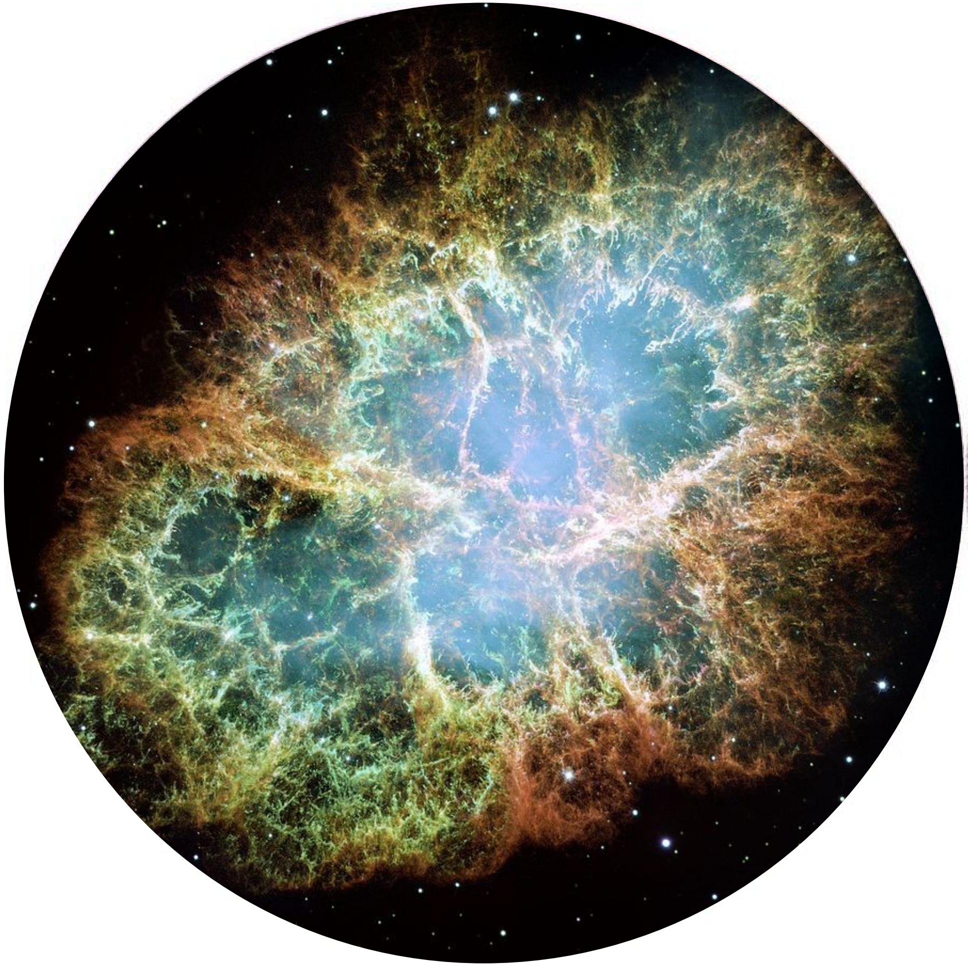
Niels Bohr Institute, University of Copenhagen

MPP Astroparticle Physics Seminar
April 22, 2021

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

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



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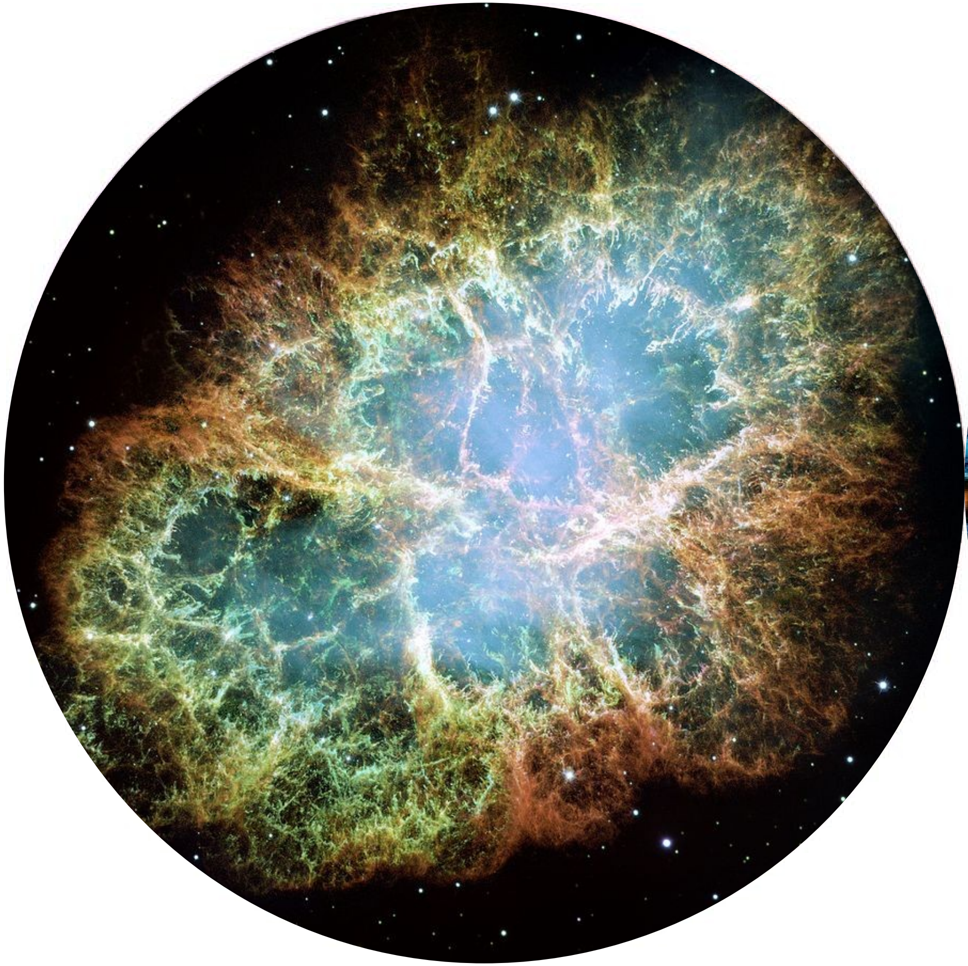

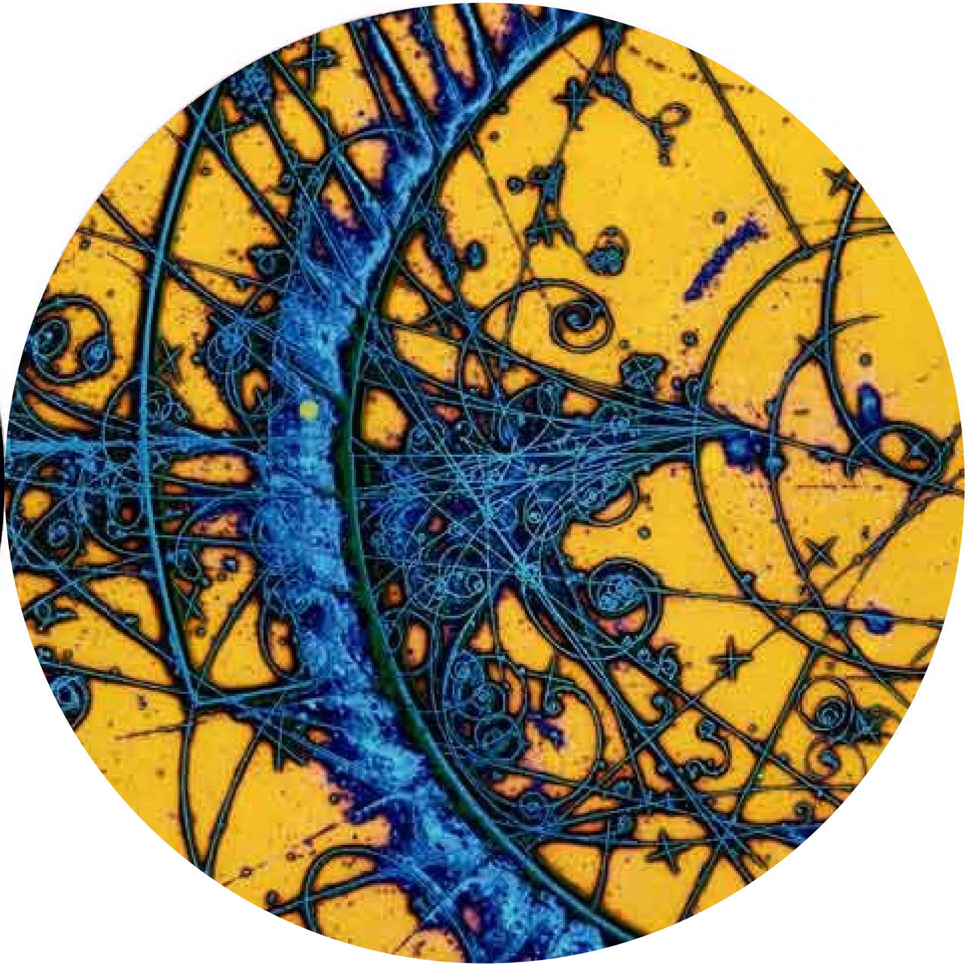

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What makes high-energy cosmic ν exciting?

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   Astro: Probe the highest-energy non-thermal astrophysical sources

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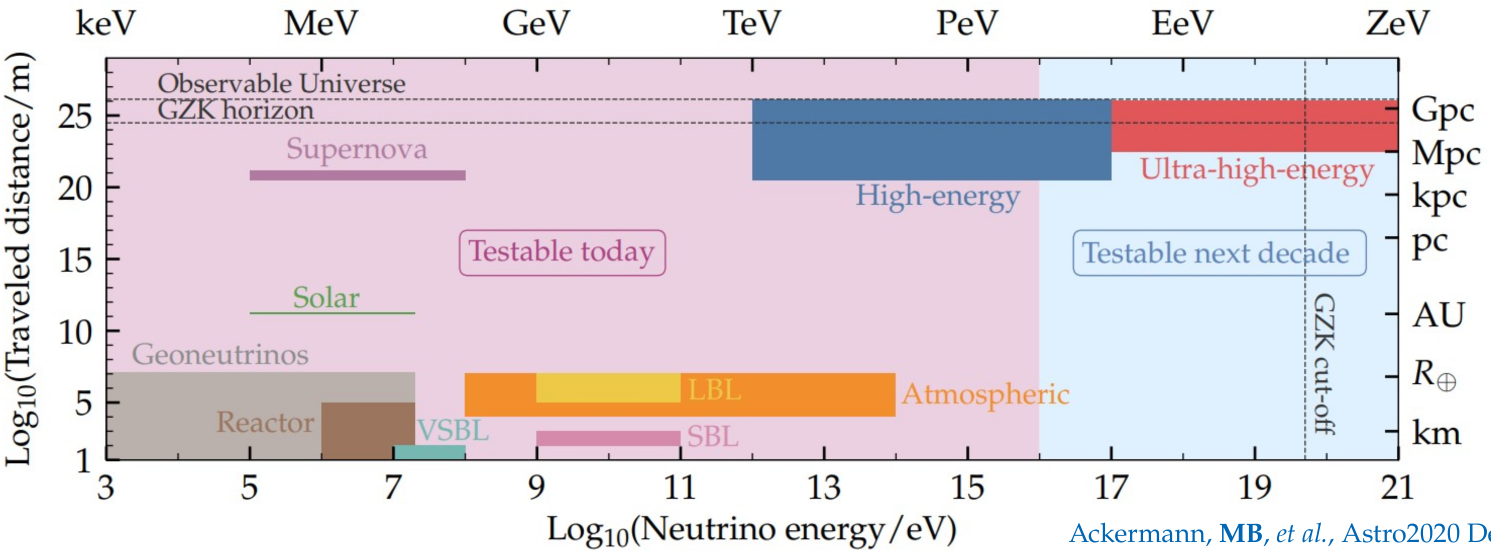

Ackermann, **MB**, *et al.*, Astro2020 Decadal Survey (1903.04333)

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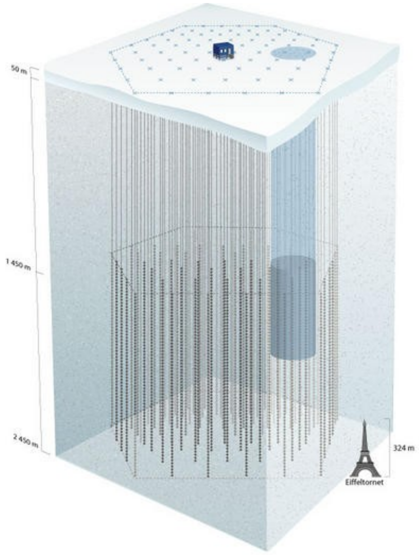
4 Neutrinos have a unique quantum number: flavor

Particle: Versatile probe of flavor-sensitive new physics

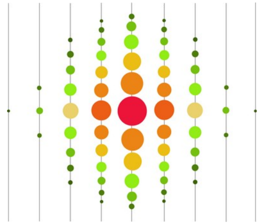
Astro: Can reveal the neutrino production mechanism

IceCube (~8 years)

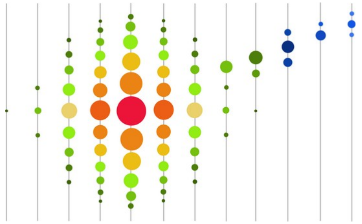
km³ in-ice
Cherenkov detector



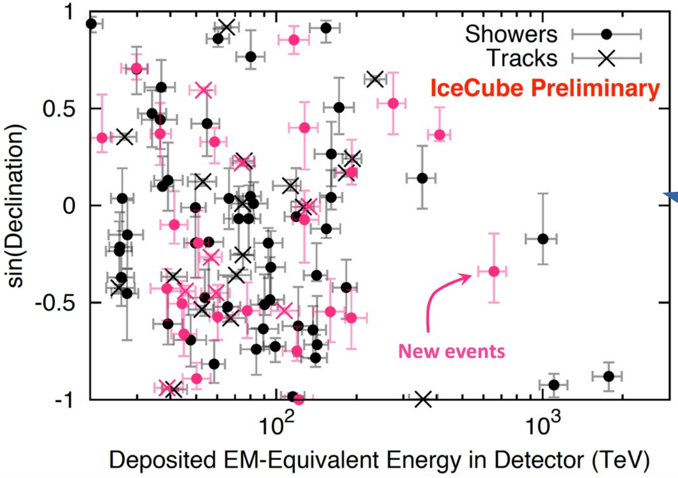
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)



~100 contained events, 15 TeV–2 PeV



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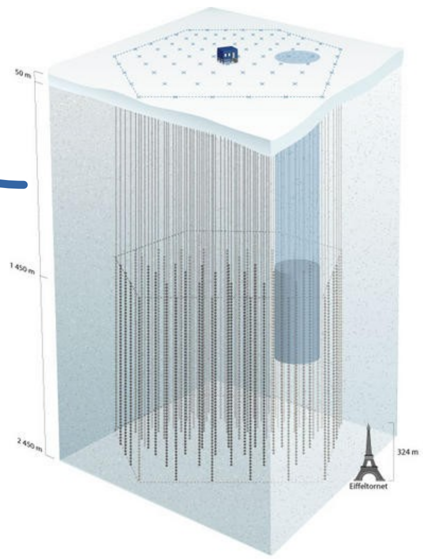

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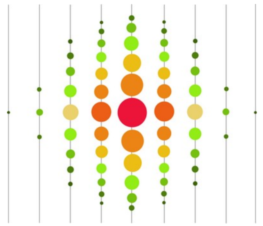

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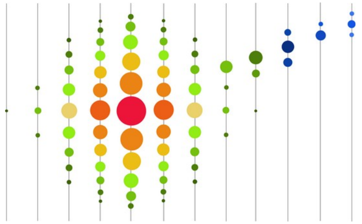

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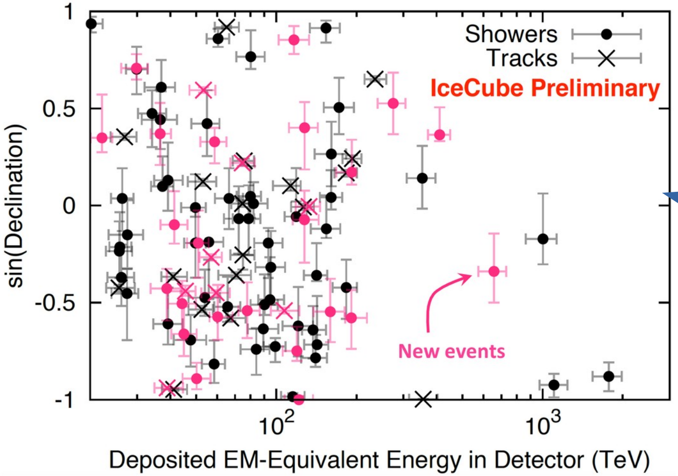

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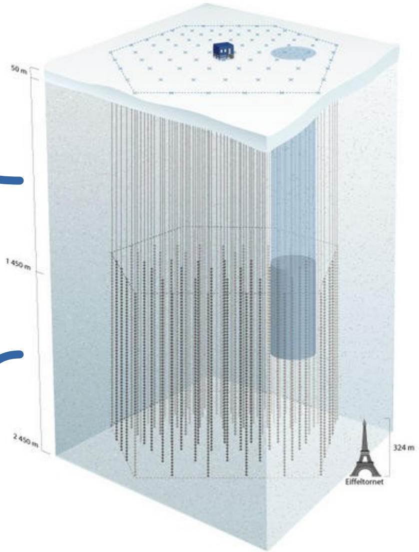
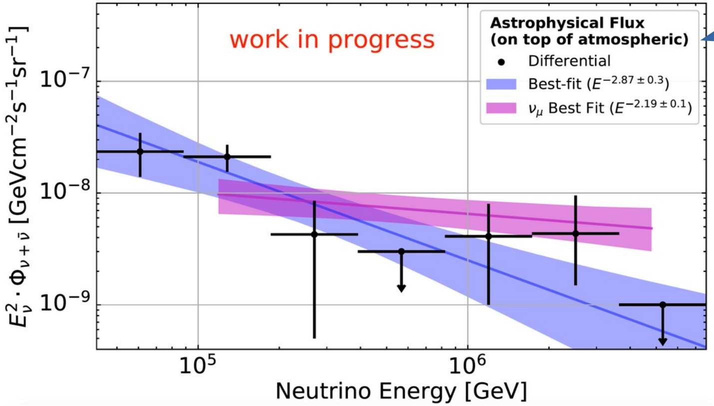


Astrophysical ν flux detected at > 7σ



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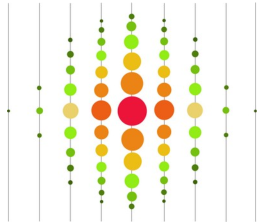

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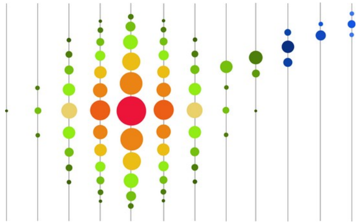

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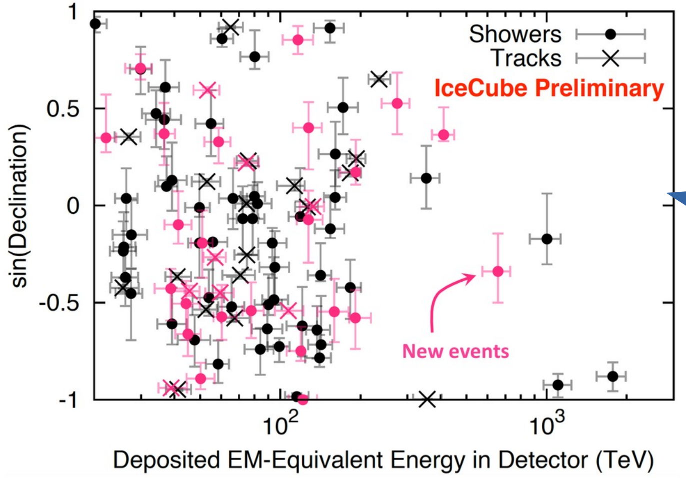

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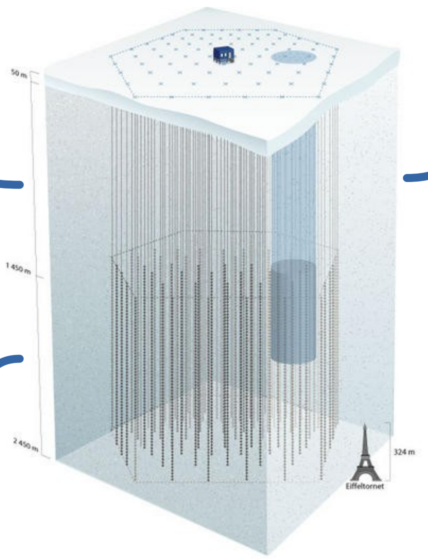
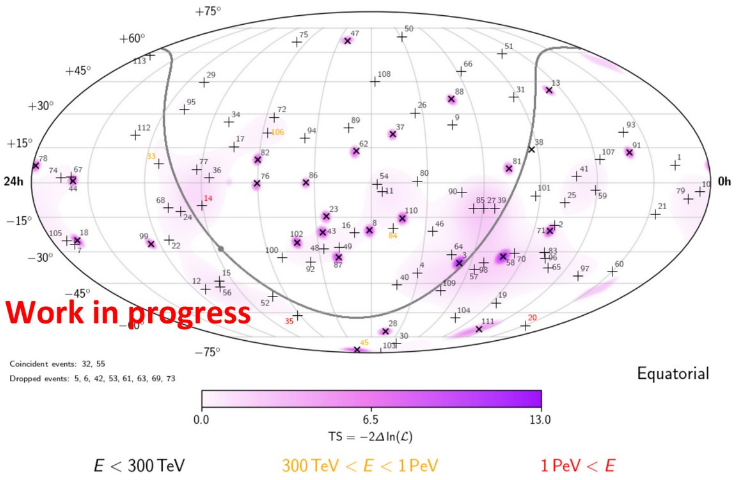


Arrival directions compatible with isotropy



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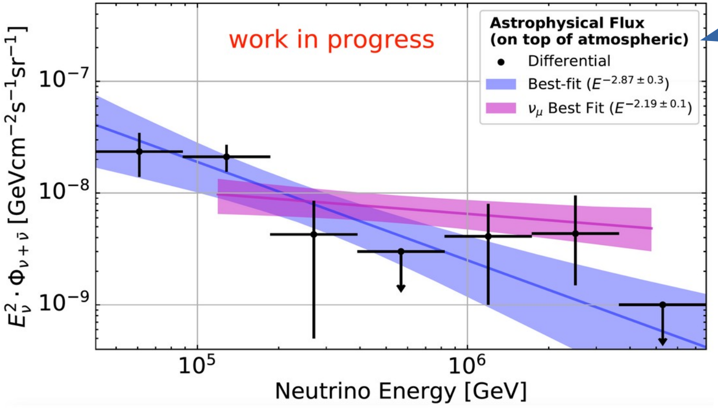

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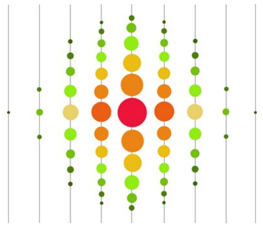

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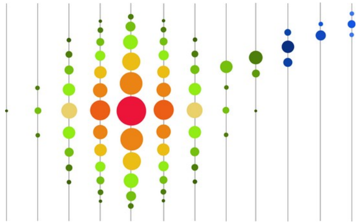

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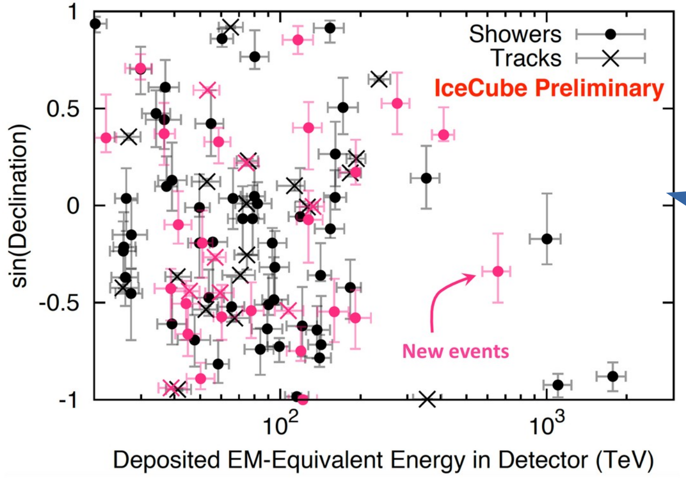

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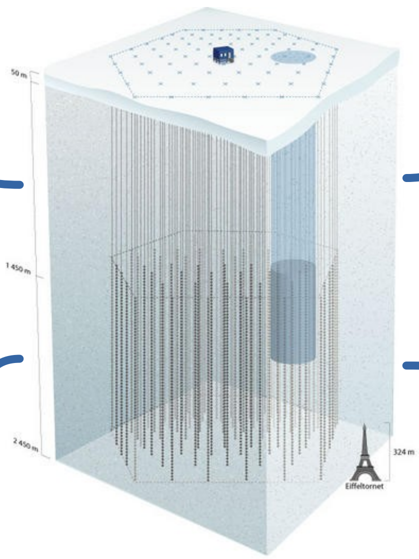

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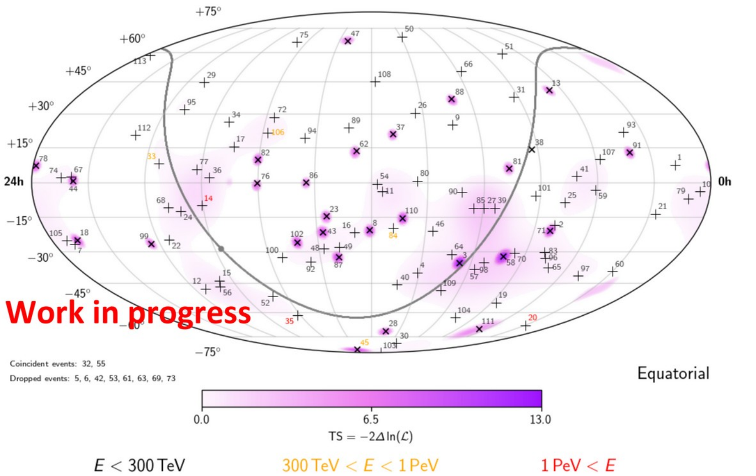

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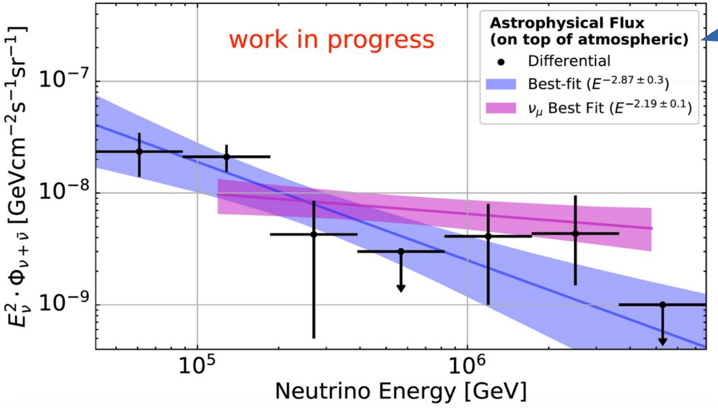

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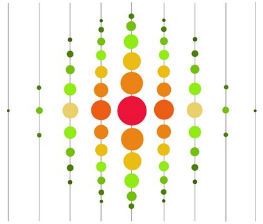

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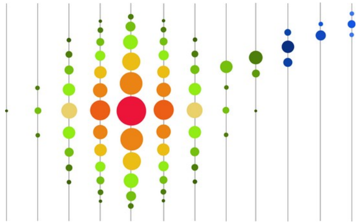
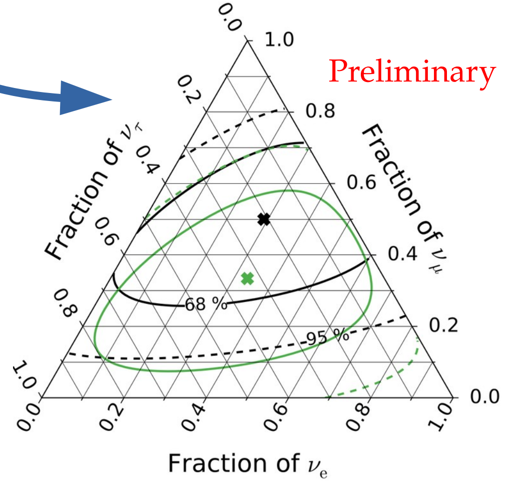


Flavor composition



Status quo of high-energy cosmic neutrinos

What we know

- Isotropic distribution of sources
- Spectrum is a power law $\propto E^{-p}$
- At least some sources are gamma-ray transients
- No correlation between directions of cosmic rays and neutrinos
- Flavor composition: compatible with equal number of ν_e, ν_μ, ν_τ
- No evident new physics

What we don't know

- The sources of the diffuse ν flux
- The ν production mechanism
- The spectral index of the spectrum
- A spectral cut-off at a few PeV?
- Are there Galactic ν sources?
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- Is there new physics?

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But we have solid theory expectations
+ fast experimental progress

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I.
The story so far

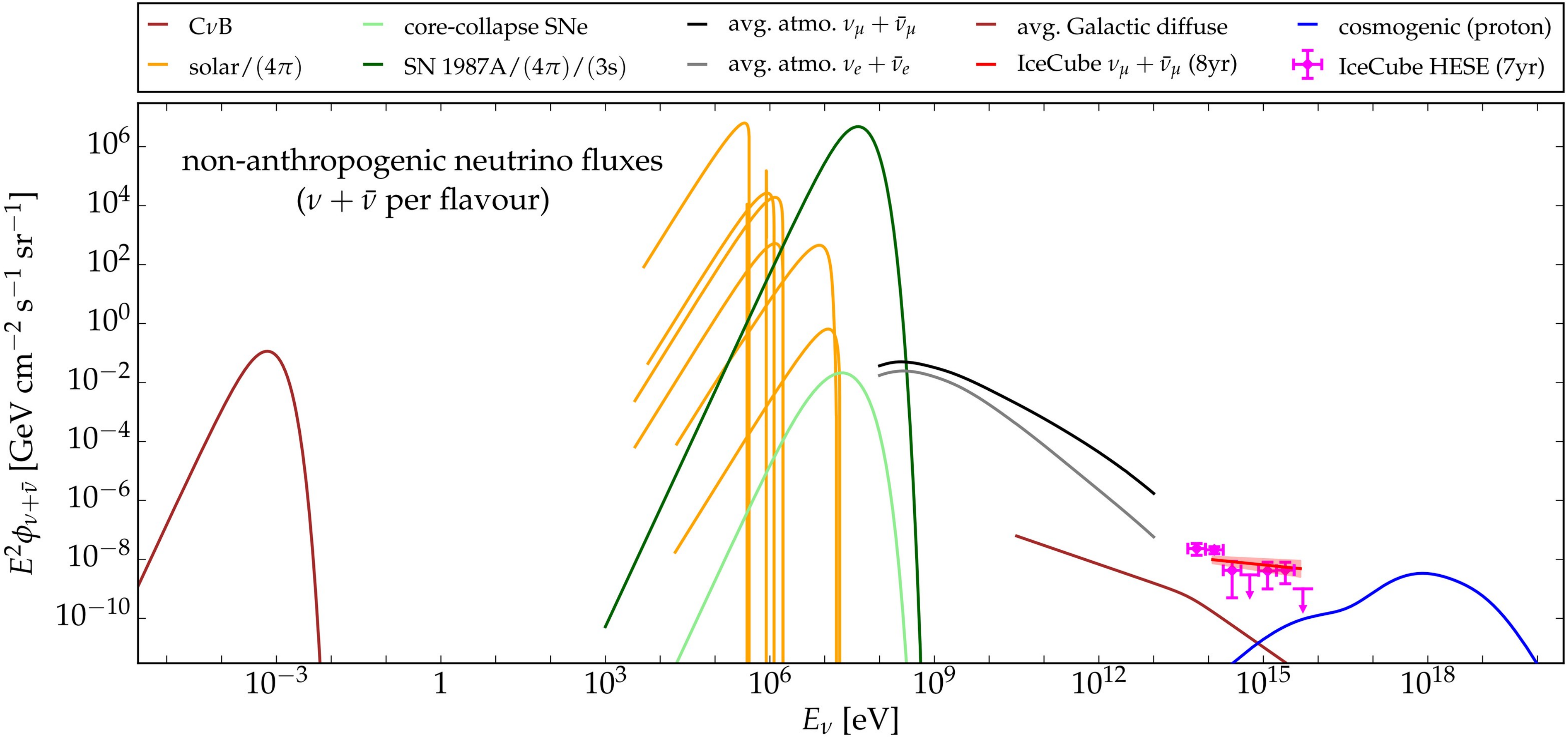
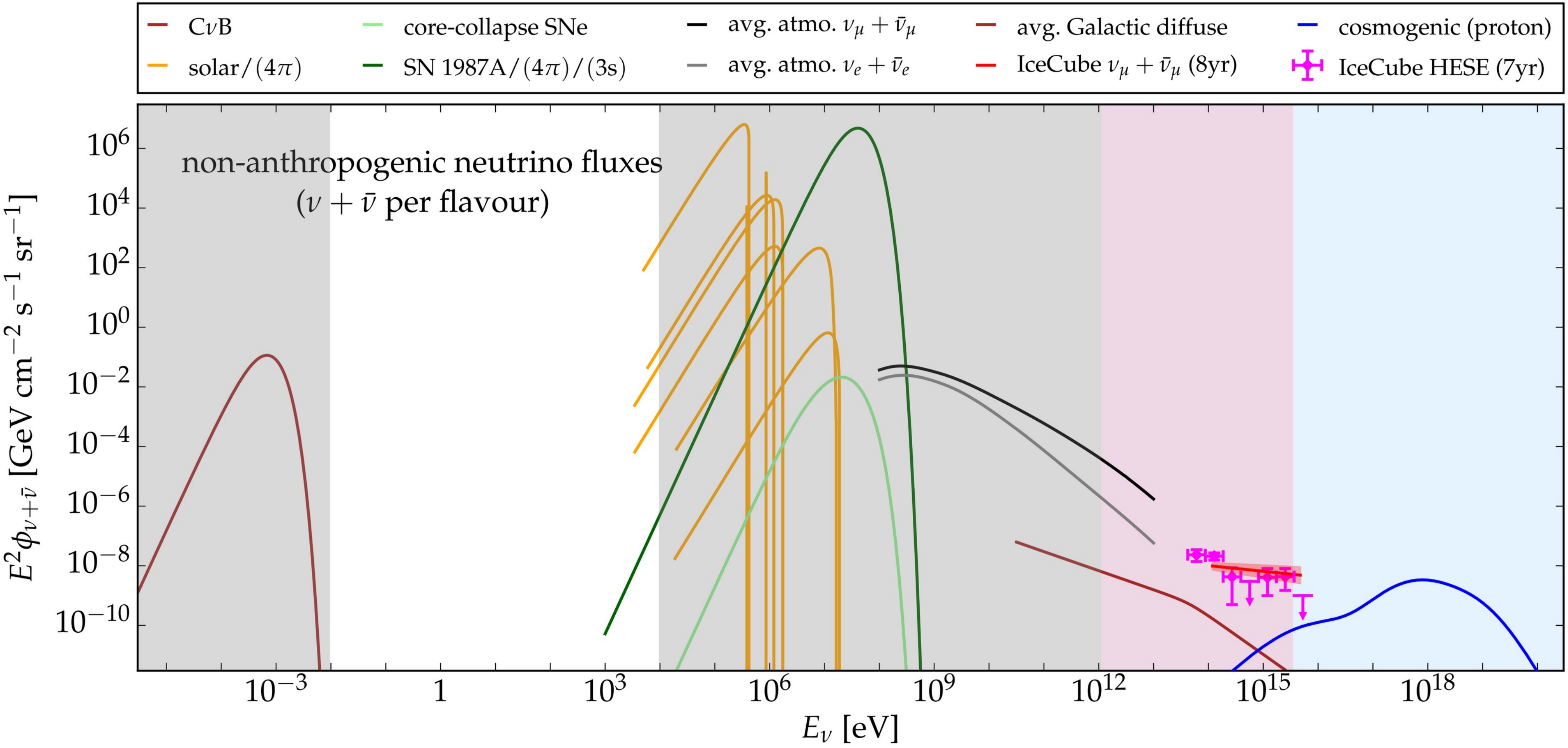


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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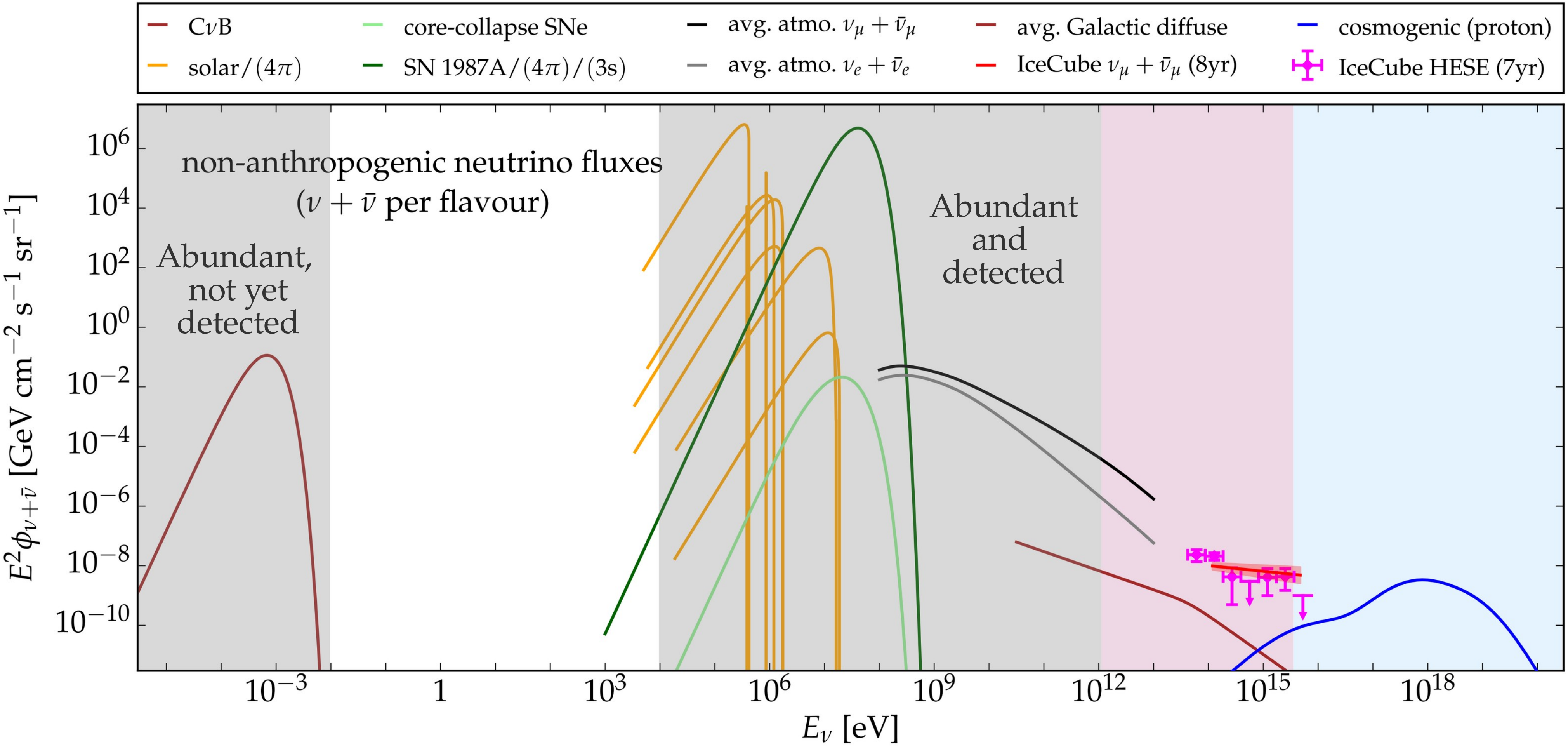

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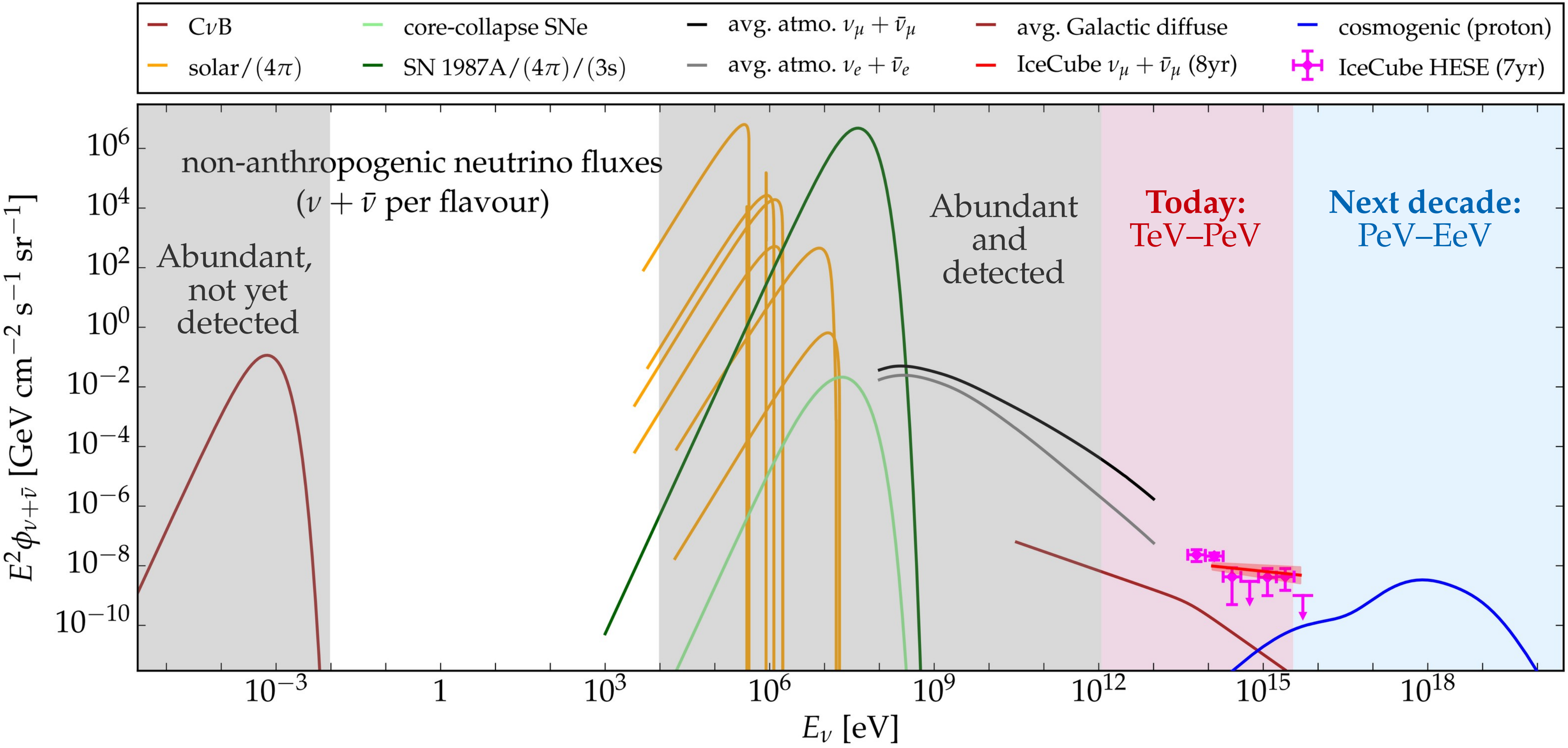

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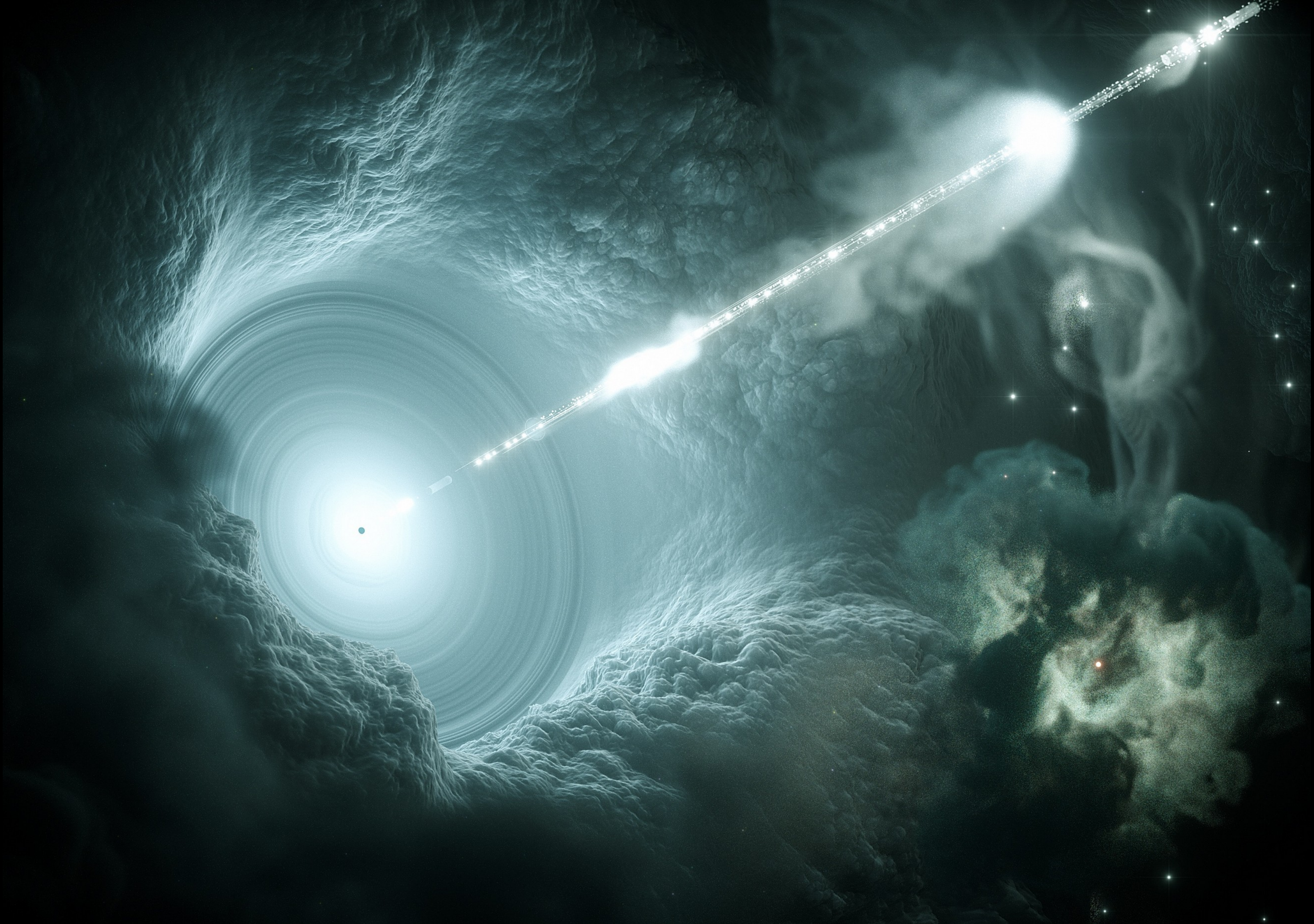

DESY

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The multi-messenger connection: a simple picture

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

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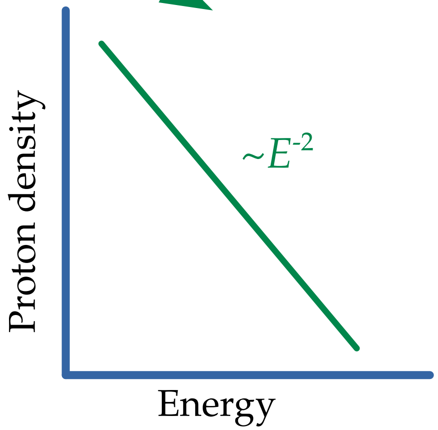

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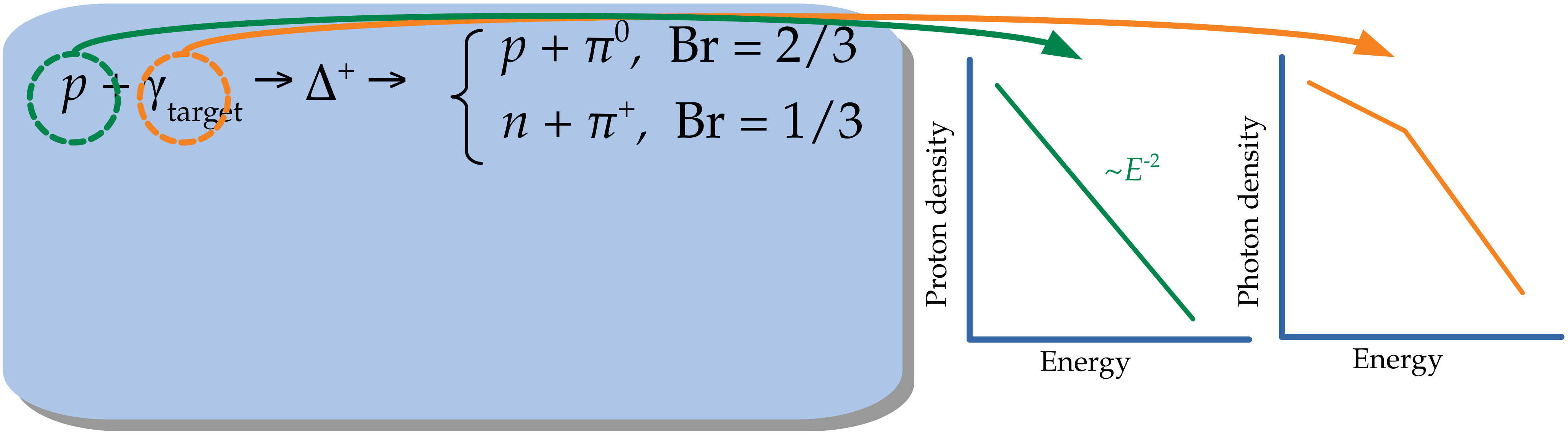

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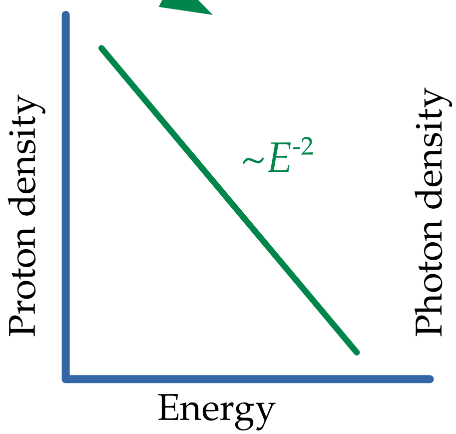
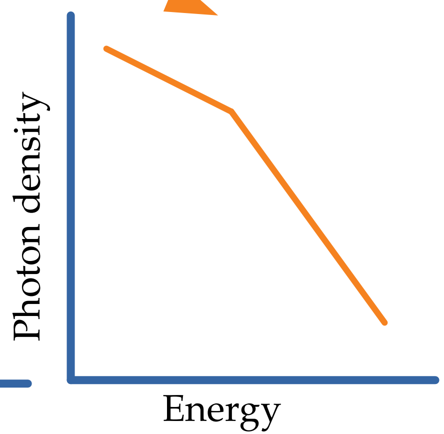
$$\pi^0 \rightarrow \gamma + \gamma$$

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

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





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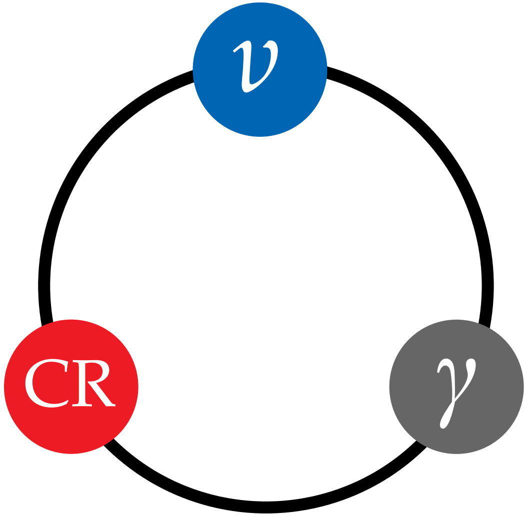

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

The multi-messenger connection: a simple picture

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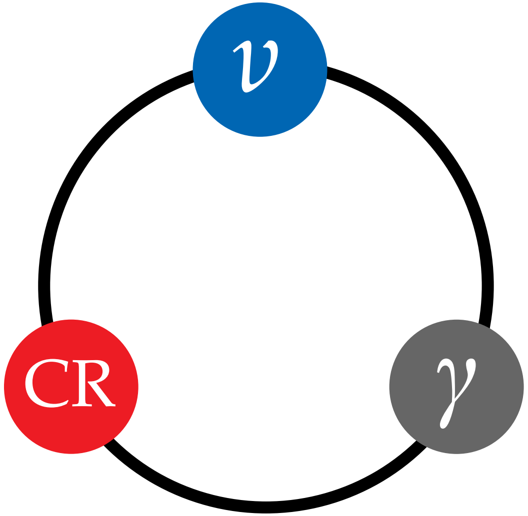

1 PeV 20 PeV

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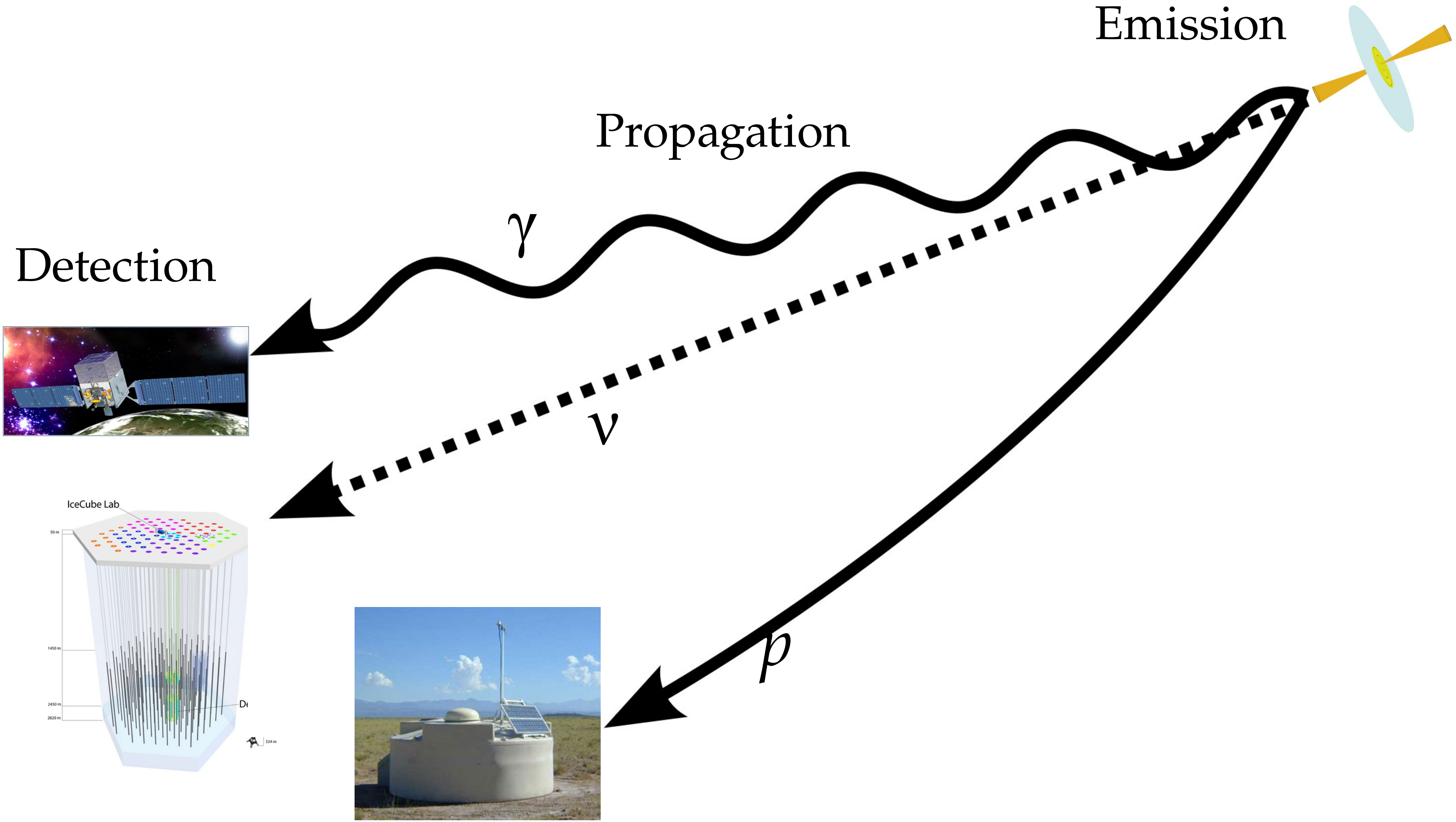
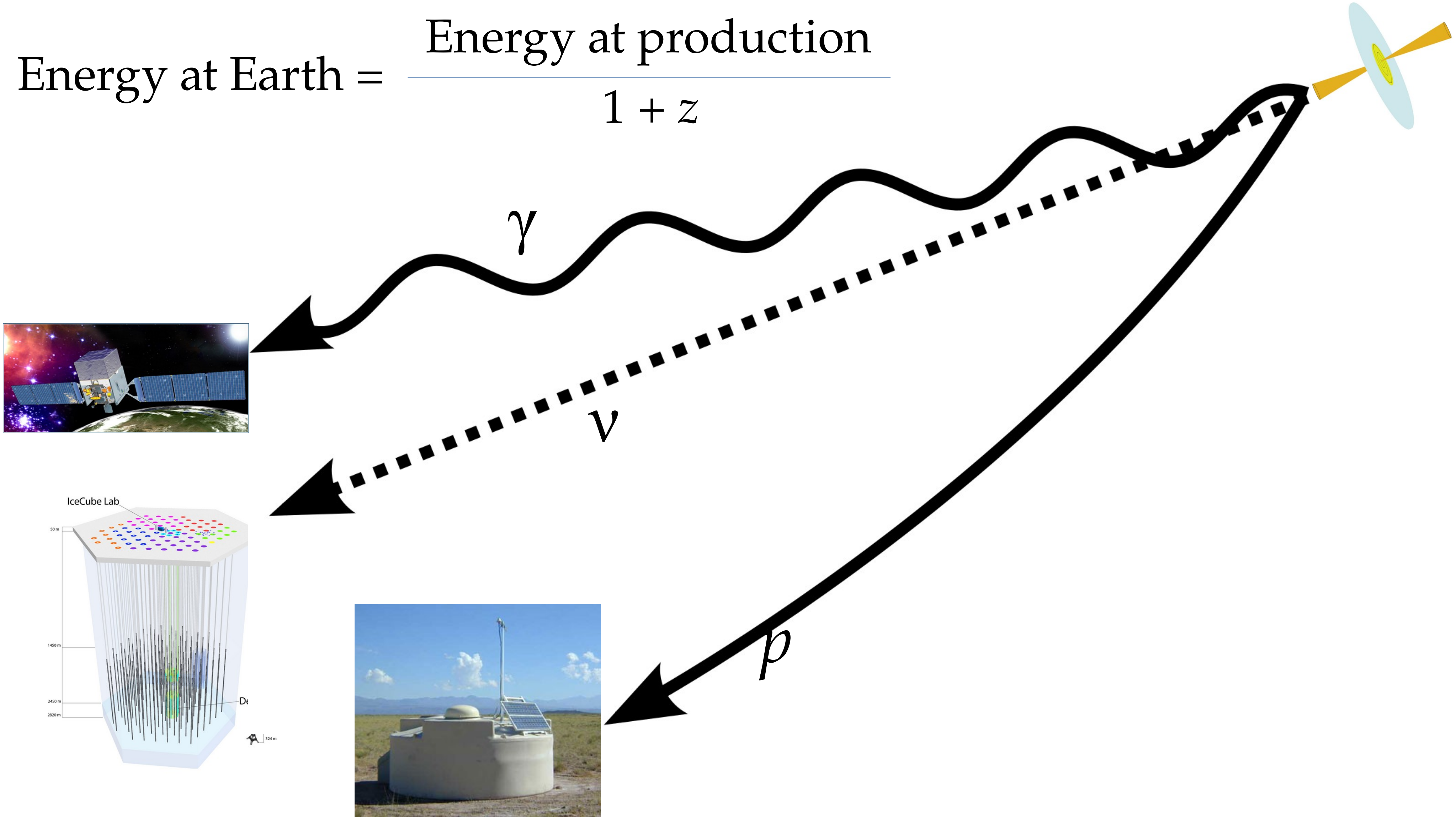


Emission
Propagation
γ
ν
p
Detection
IceCube Lab
50 m
1450 m
2450 m
2820 m
324 m

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



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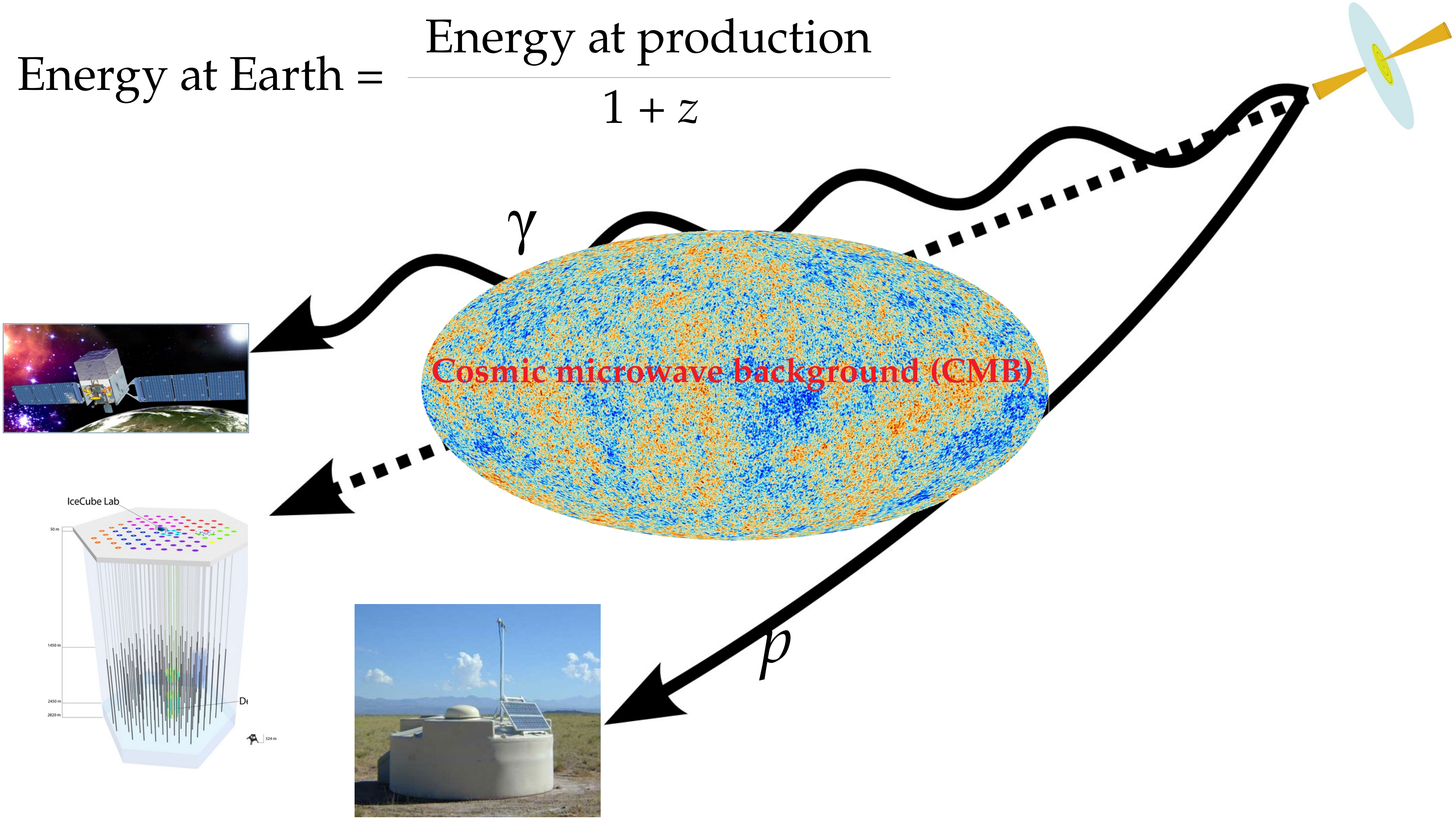
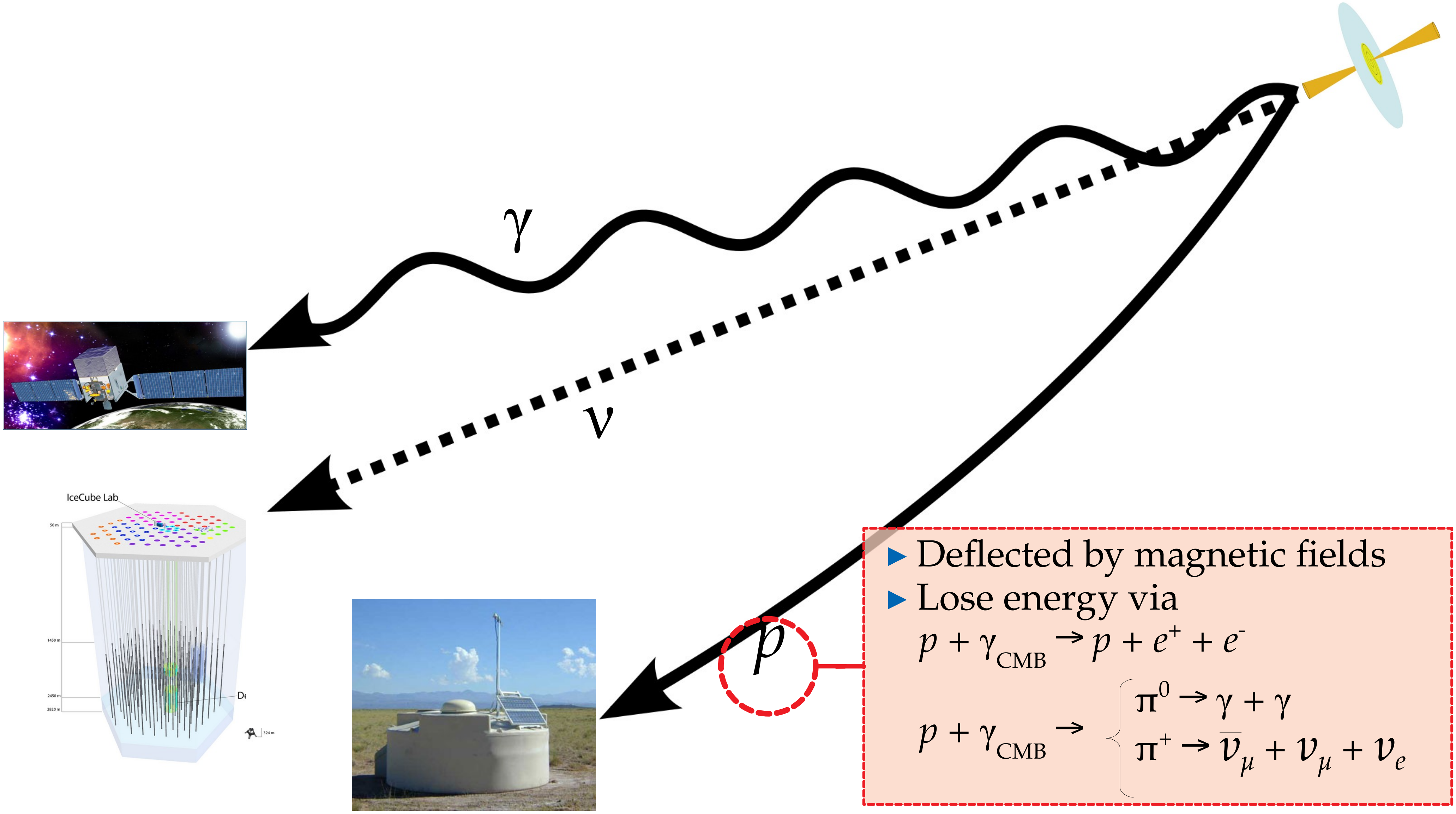
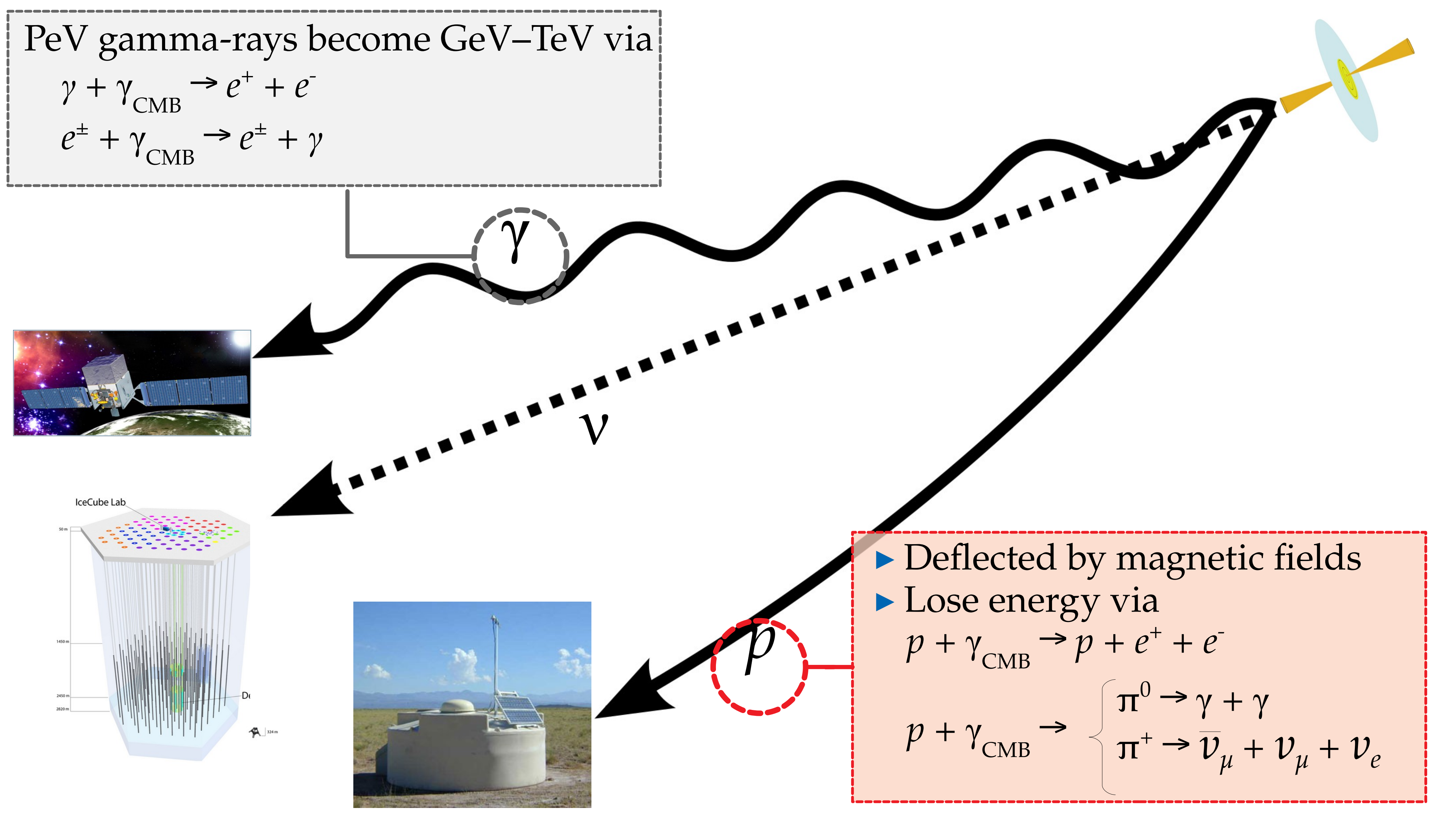




γ
ν
p
IceCube Lab
50 m
1450 m
2450 m
2820 m
324 m
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow p + e^{+} + e^{-}$
$p + \gamma_{CMB} \rightarrow \begin{cases} \pi^0 \rightarrow \gamma + \gamma \\ \pi^+ \rightarrow \bar{\nu}_\mu + \nu_\mu + \nu_e \end{cases}$


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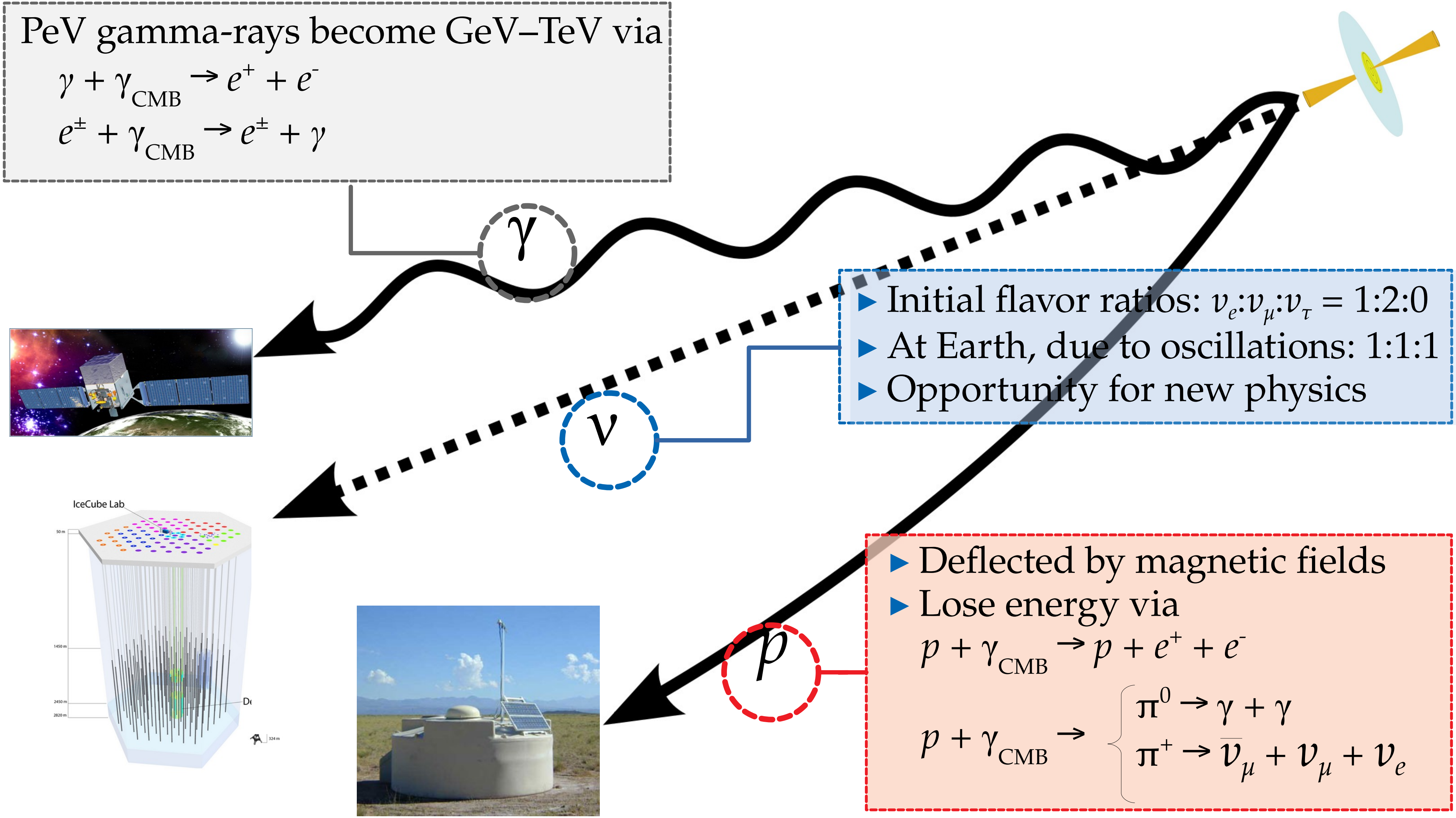
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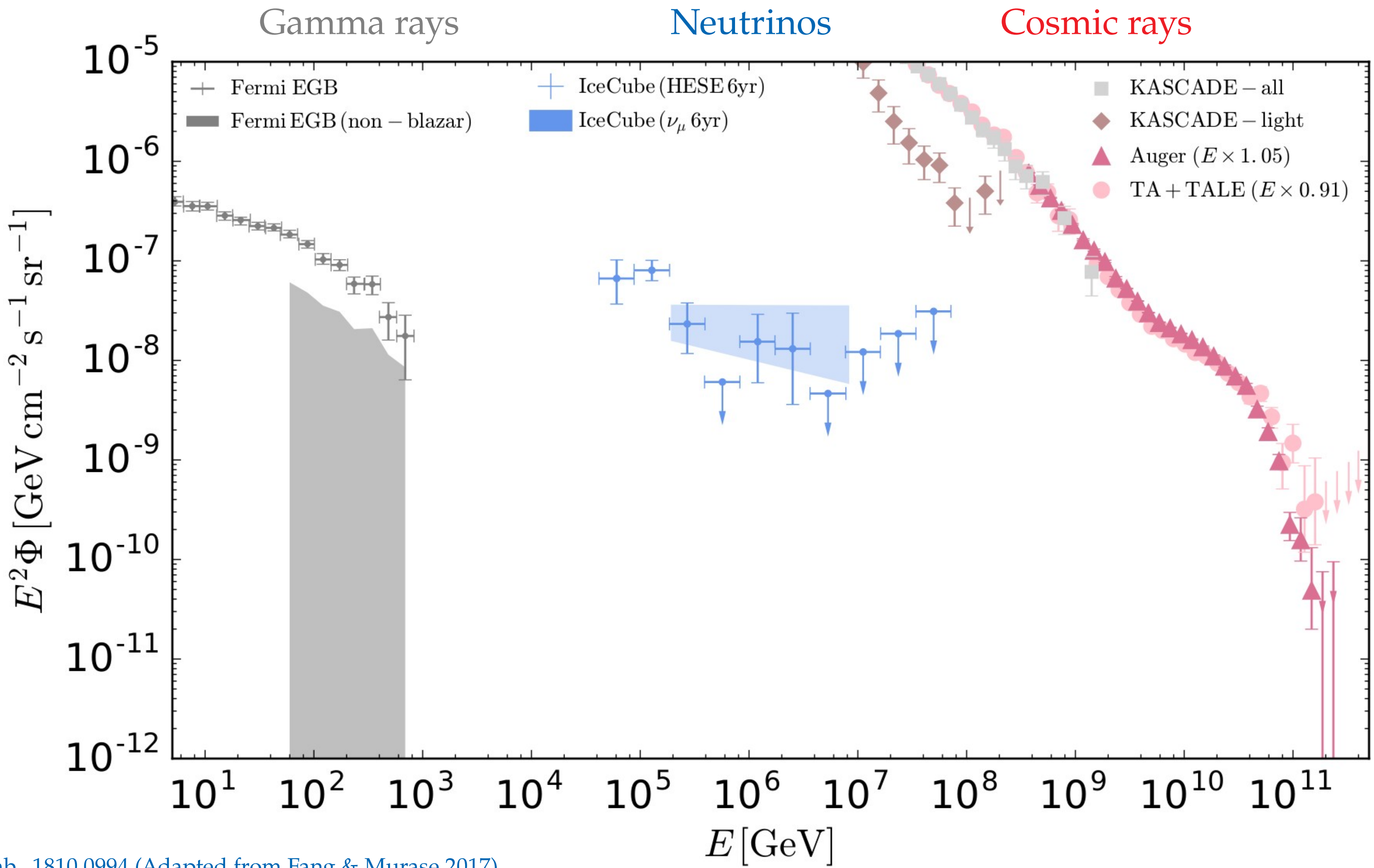
$\gamma + \gamma_{CMB} \rightarrow e^+ + e^-$
$e^\pm + \gamma_{CMB} \rightarrow e^\pm + \gamma$
γ
ν
Initial flavor ratios: $\nu_e:\nu_\mu:\nu_\tau$ = 1:2:0
At Earth, due to oscillations: 1:1:1
Opportunity for new physics
IceCube Lab
p
Deflected by magnetic fields
Lose energy via
$p + \gamma_{CMB} \rightarrow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

Fluxes at Earth



GRAND Collab., 1810.0994 (Adapted from Fang & Murase 2017)

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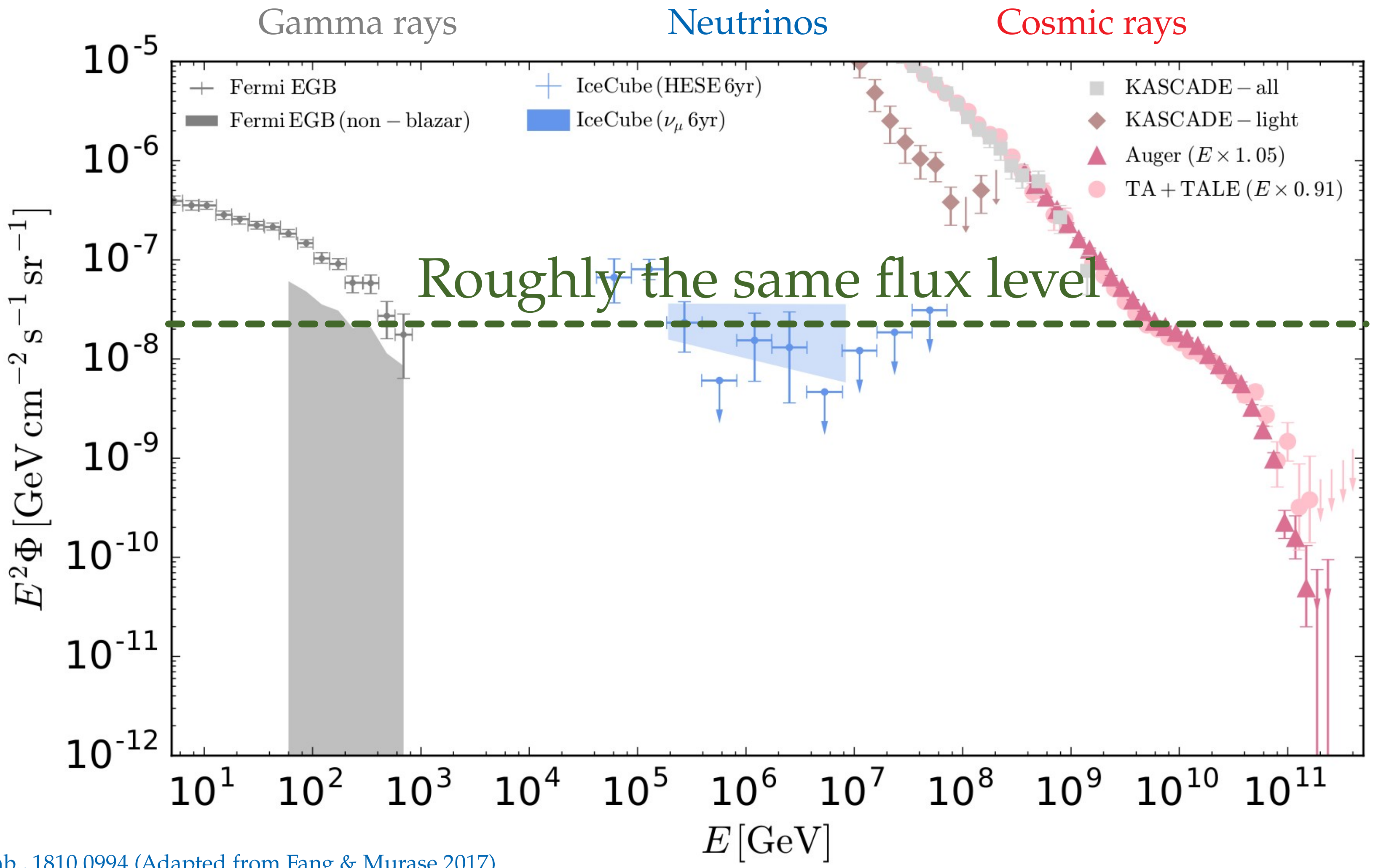

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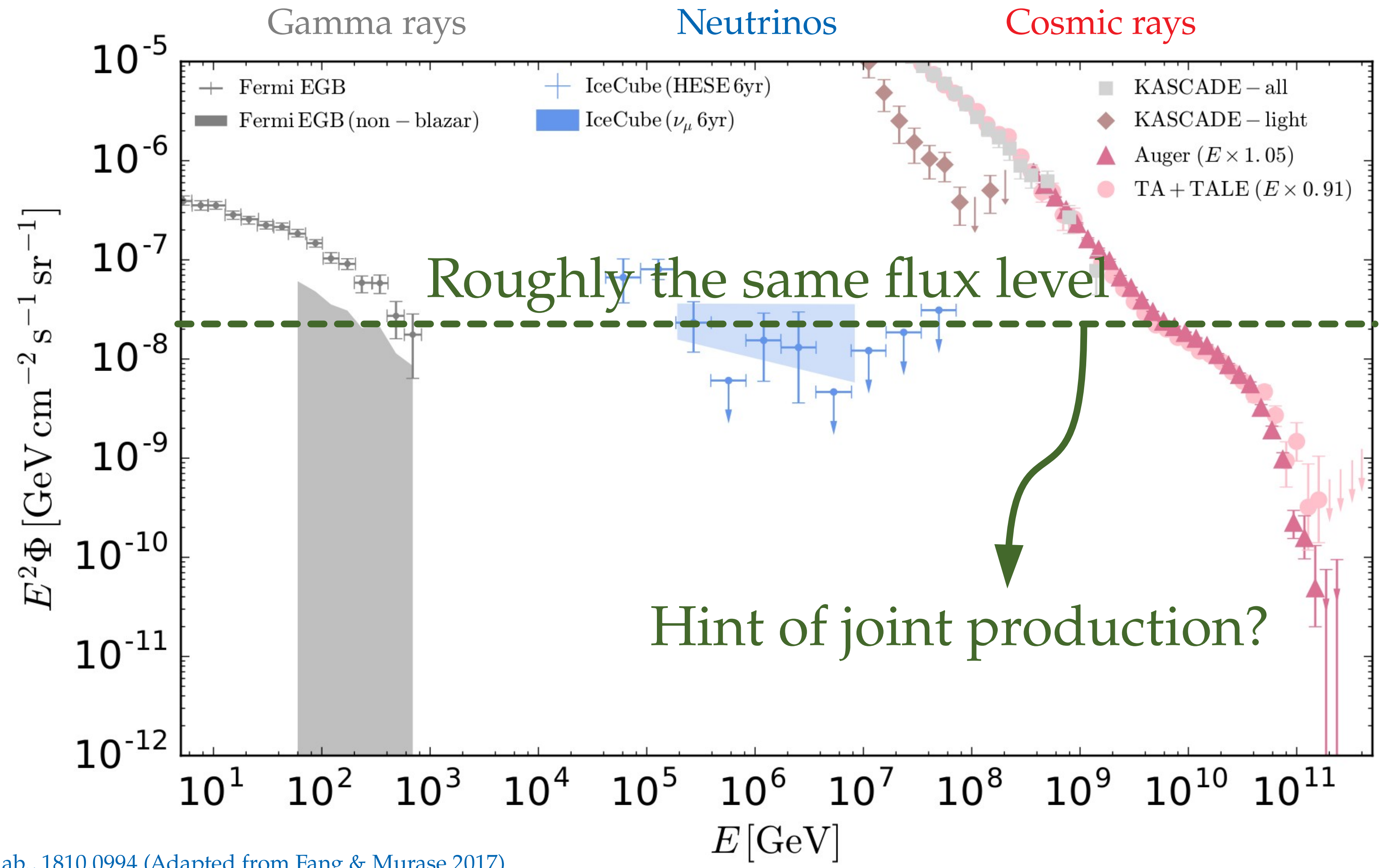

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Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources			
Size of horizon			
Energy degradation			
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

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Point back at sources	Yes	Yes	No
Size of horizon	10 Mpc (at EeV)	Size of the Universe	100 Mpc (> 40 EeV)
Energy degradation	Severe	Tiny	Severe
Relative ease to detect			

Note: This is a simplified view

Neutrinos – The ultimate smoking gun of cosmic accelerators

	Gamma rays	Neutrinos	UHE Cosmic rays
Point back at sources	Yes	Yes	No
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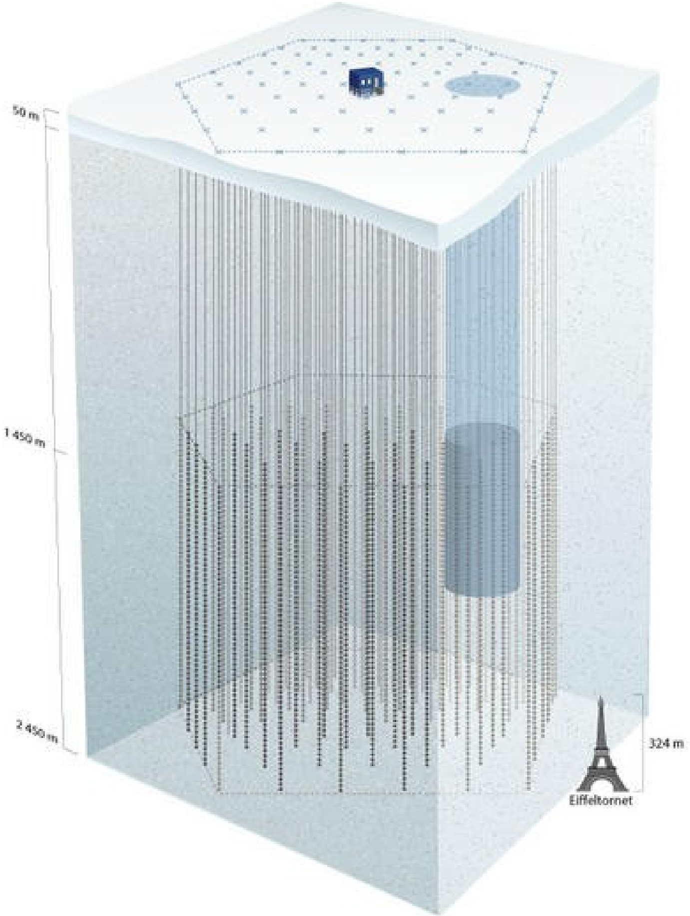
Note: This is a simplified view

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)

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

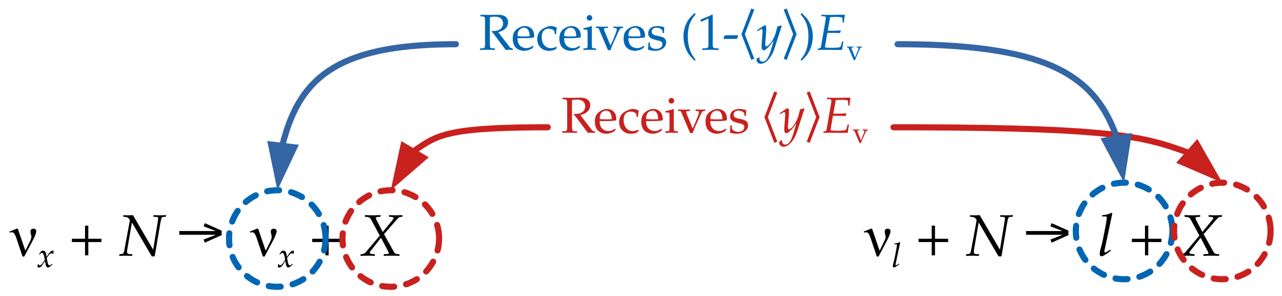
Charged current (CC)

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

How does IceCube see TeV–PeV neutrinos?

Deep inelastic neutrino-nucleon scattering

Neutral current (NC) Charged current (CC)

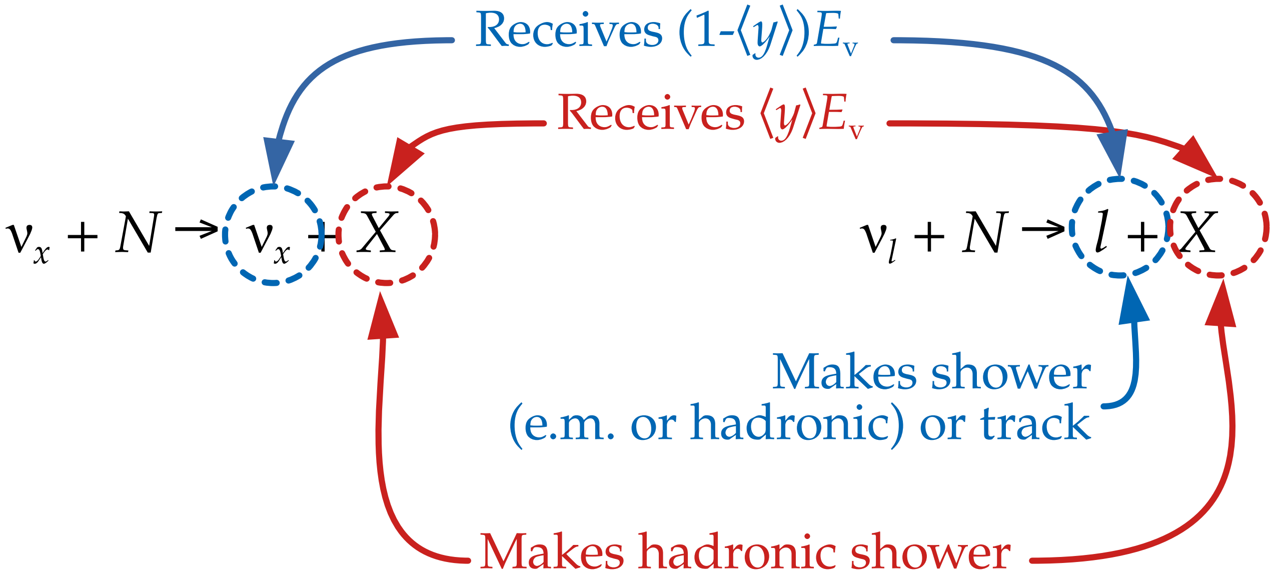


At TeV–PeV, the average inelasticity $\langle y \rangle = 0.25$–0.30

How does IceCube see TeV–PeV neutrinos?

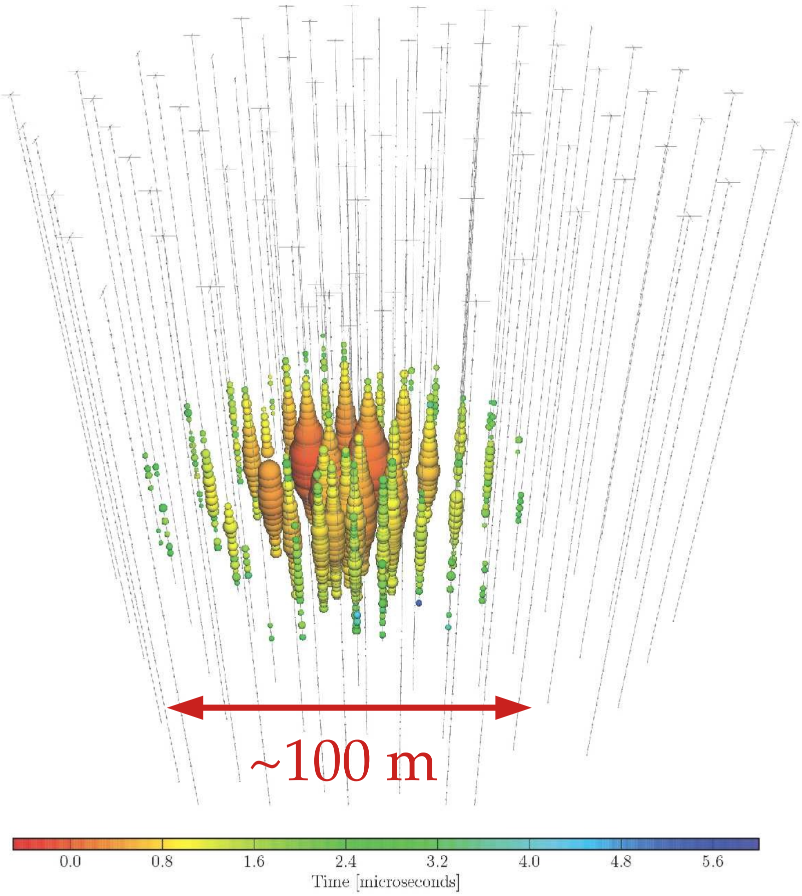
Deep inelastic neutrino-nucleon scattering

Neutral current (NC) — Charged current (CC)



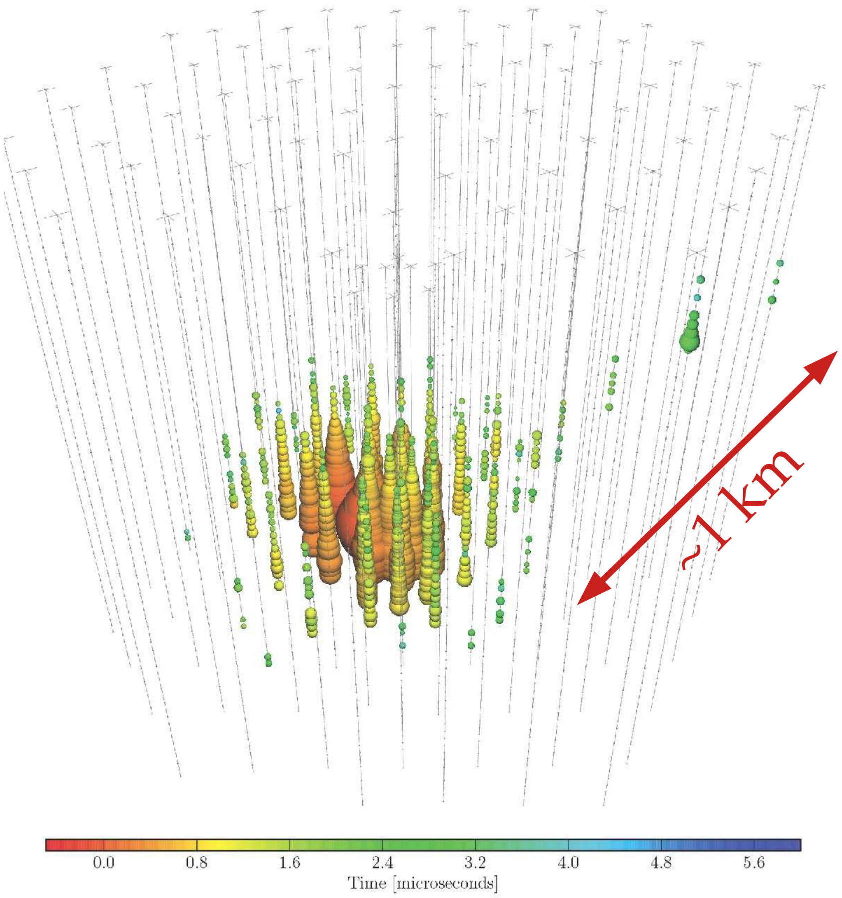
At TeV–PeV, the average inelasticity $\langle y \rangle$ = 0.25–0.30

Shower
(mainly from ν_e and ν_τ)

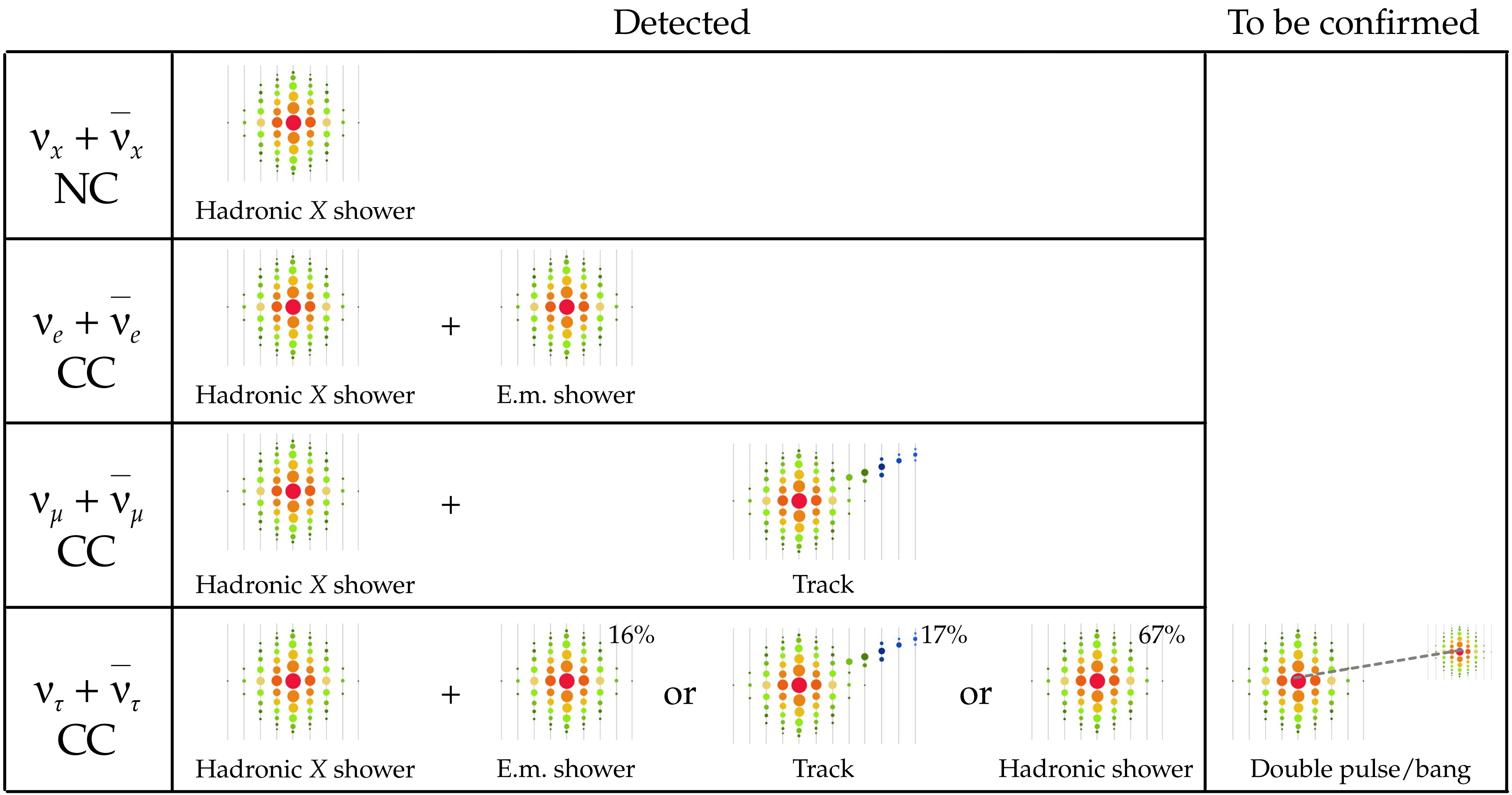


Poor angular resolution: ~10°

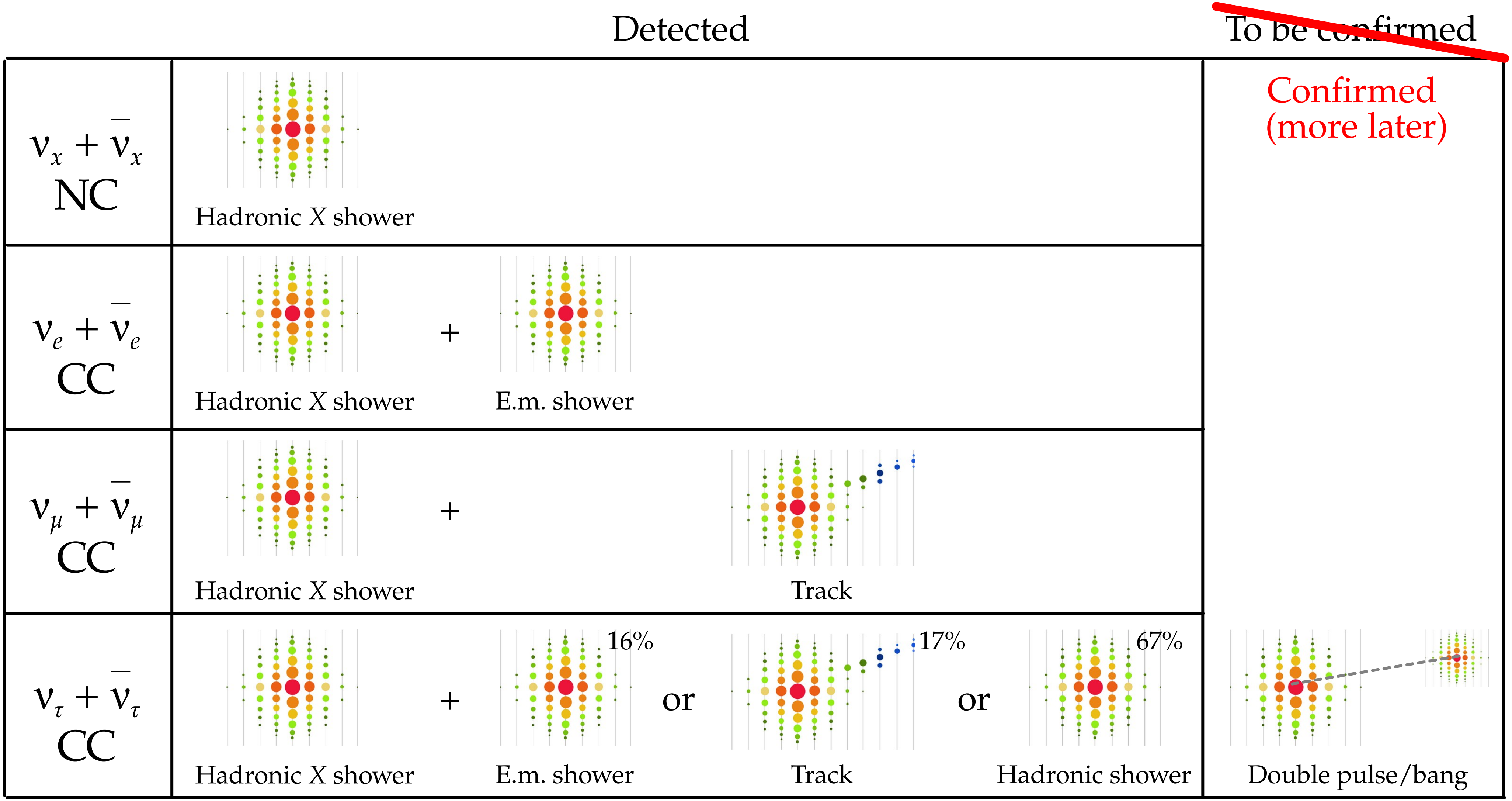
Track
(mainly from ν_μ)



Angular resolution: < 1°



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
+
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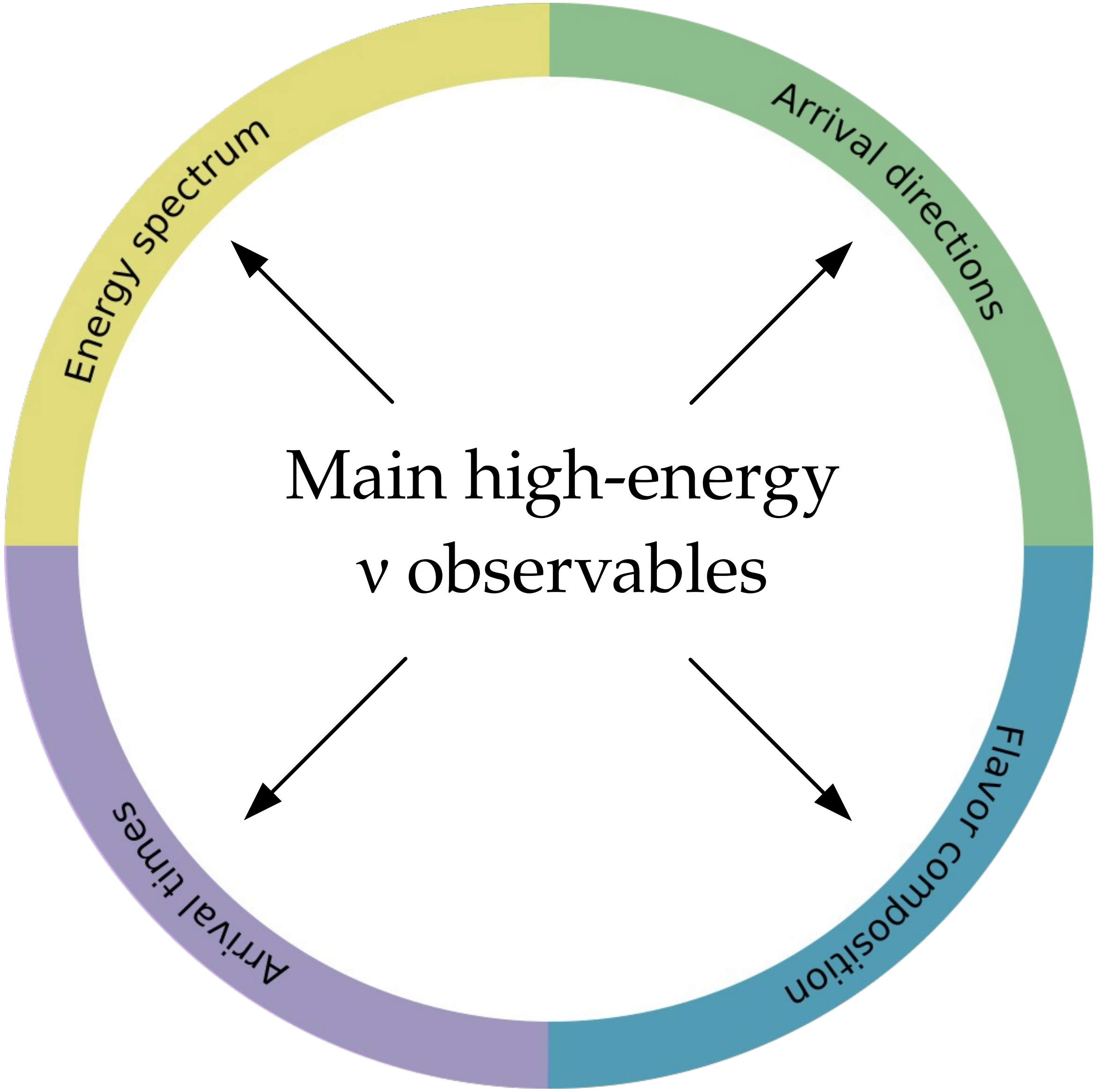
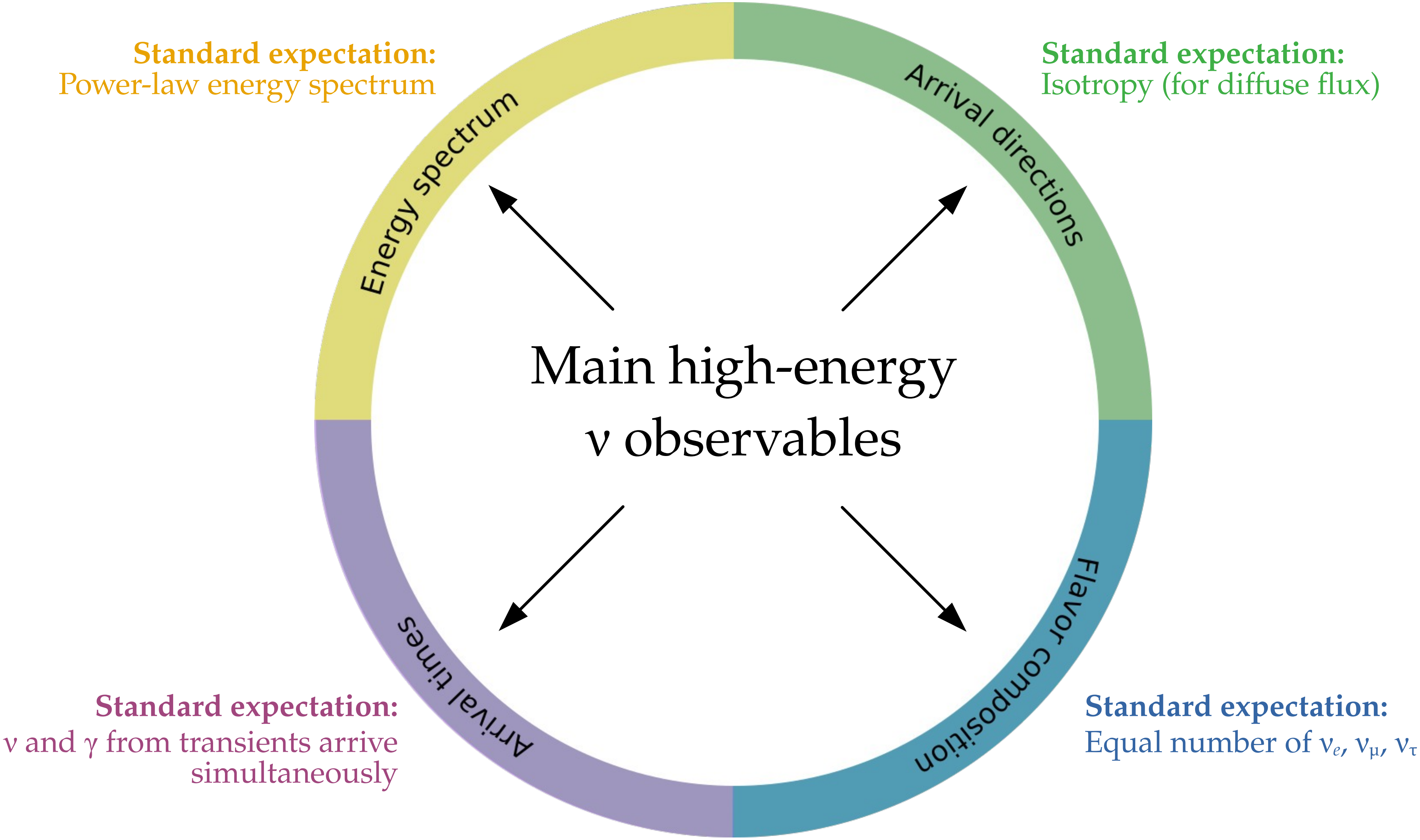
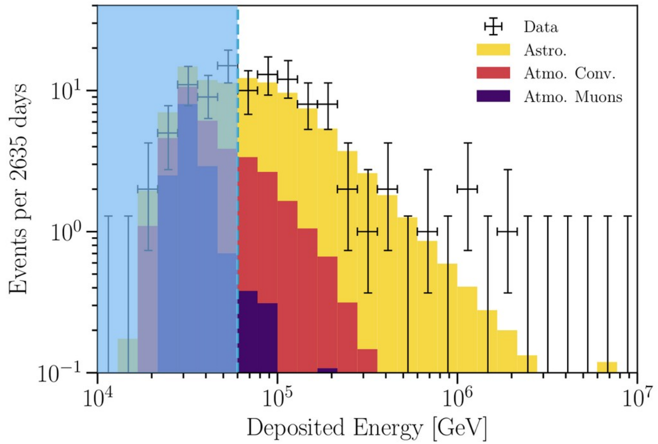
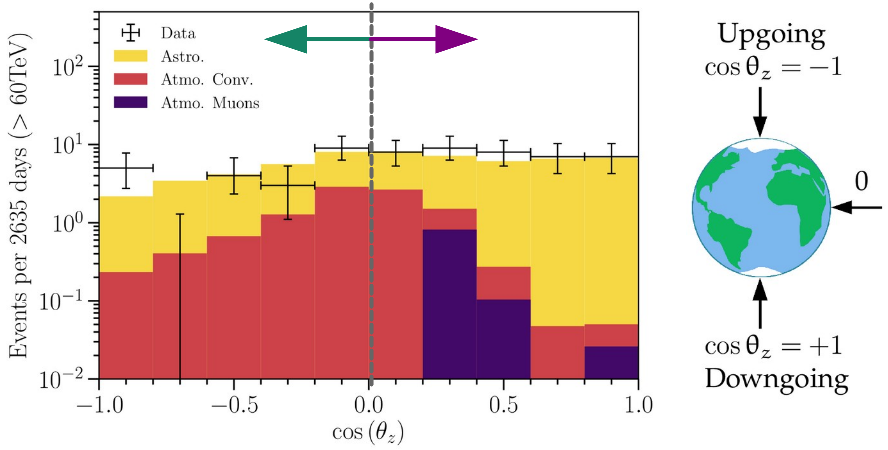

Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition


Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Energy spectrum
Arrival directions
Main high-energy
ν observables
Arrival times
Flavor composition
Standard expectation:
ν and γ from transients arrive simultaneously
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Neutrino energy spectrum

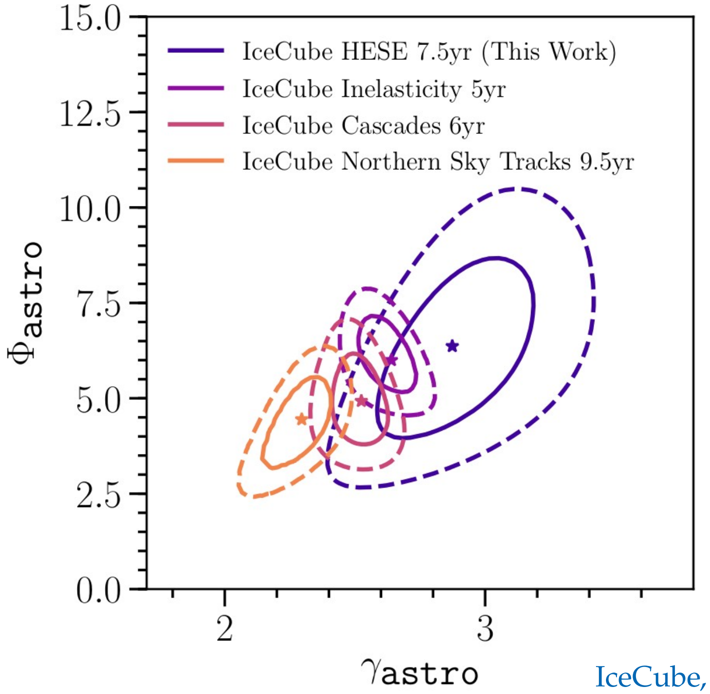
100+ contained events above 60 TeV:





Data is fit well by a single power law:

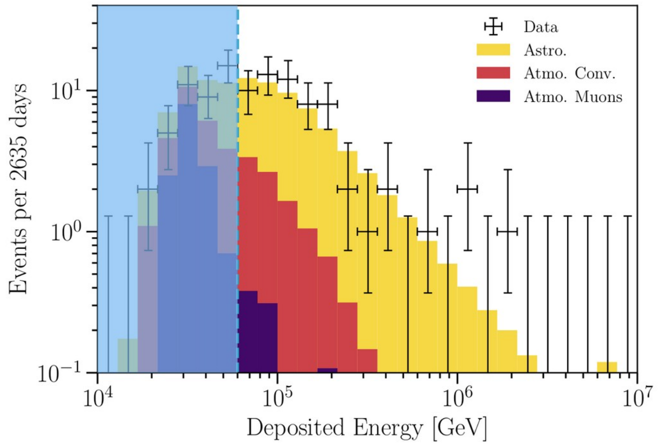
$$\frac{d\Phi_{6\nu}}{dE_\nu} = \Phi_{\text{astro}} \left(\frac{E_\nu}{100\ \text{TeV}} \right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$



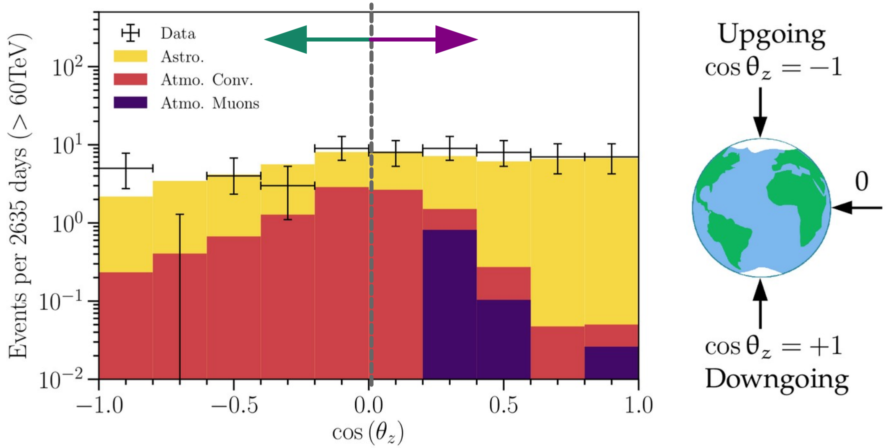
IceCube, 2011.03545

Neutrino energy spectrum

100+ contained events above 60 TeV:



ν attenuated by Earth   Atm. ν and μ vetoed



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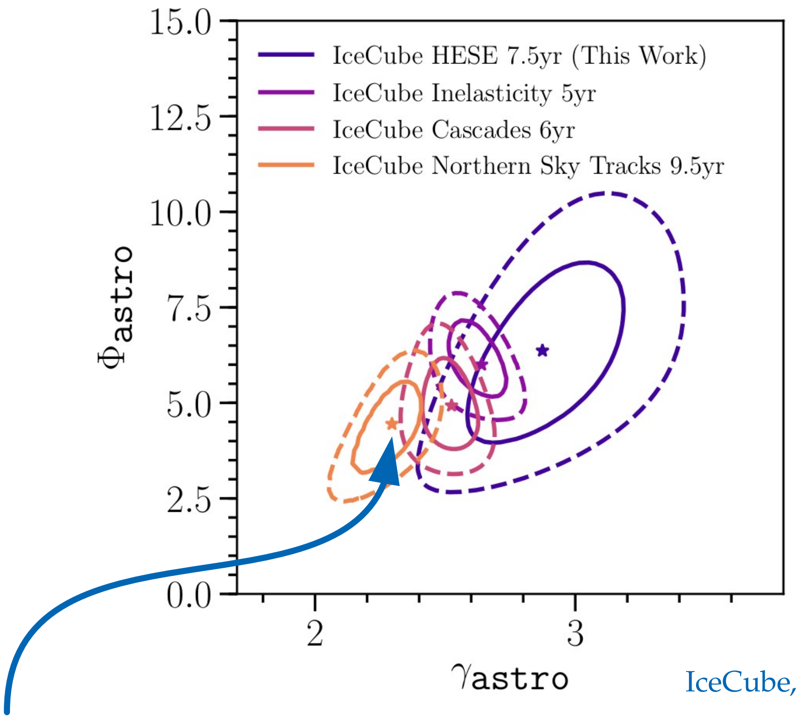
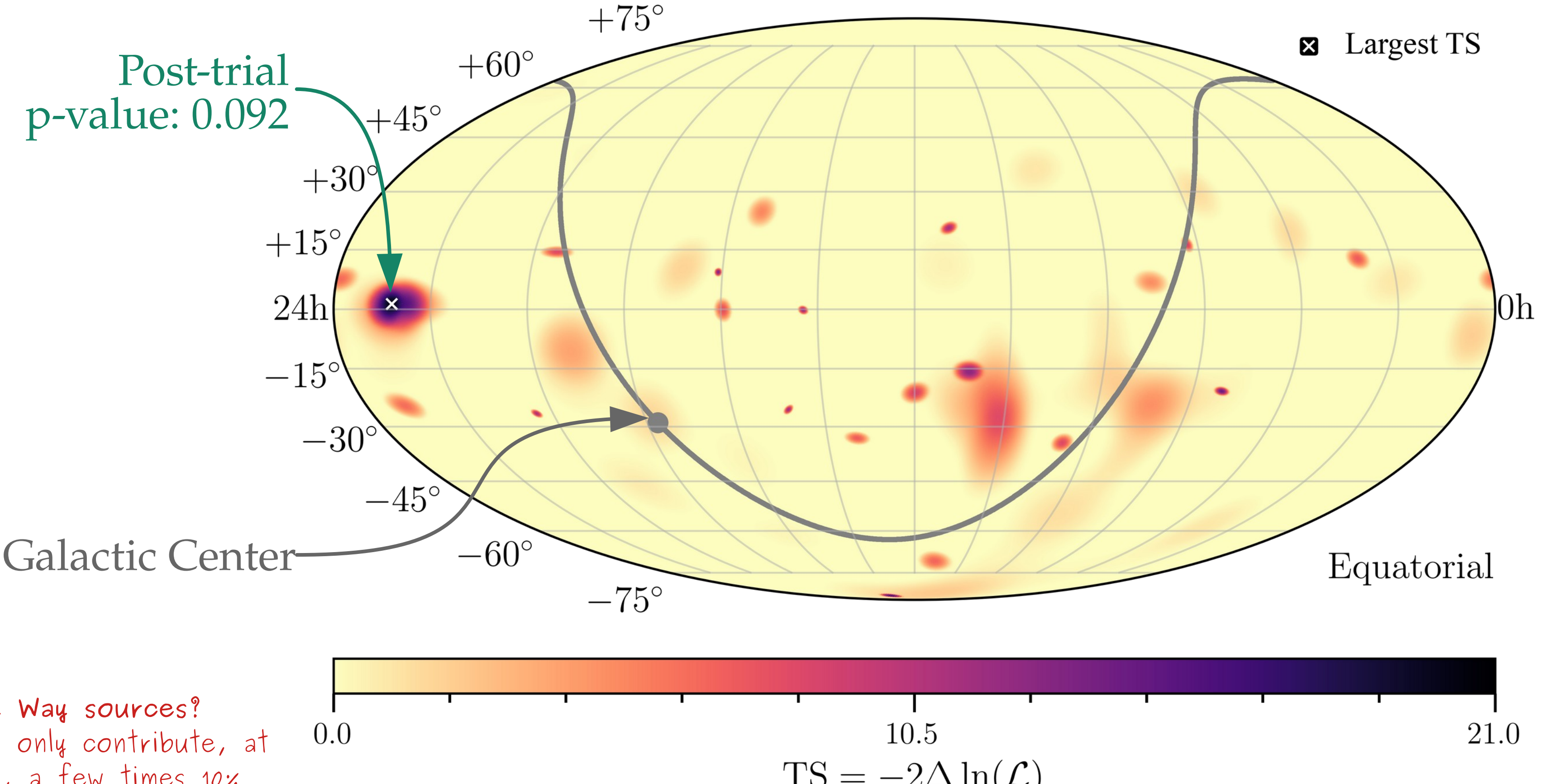


IceCube, 2011.03545

Spectrum looks harder for through-going ν_μ

Distribution of arrival directions

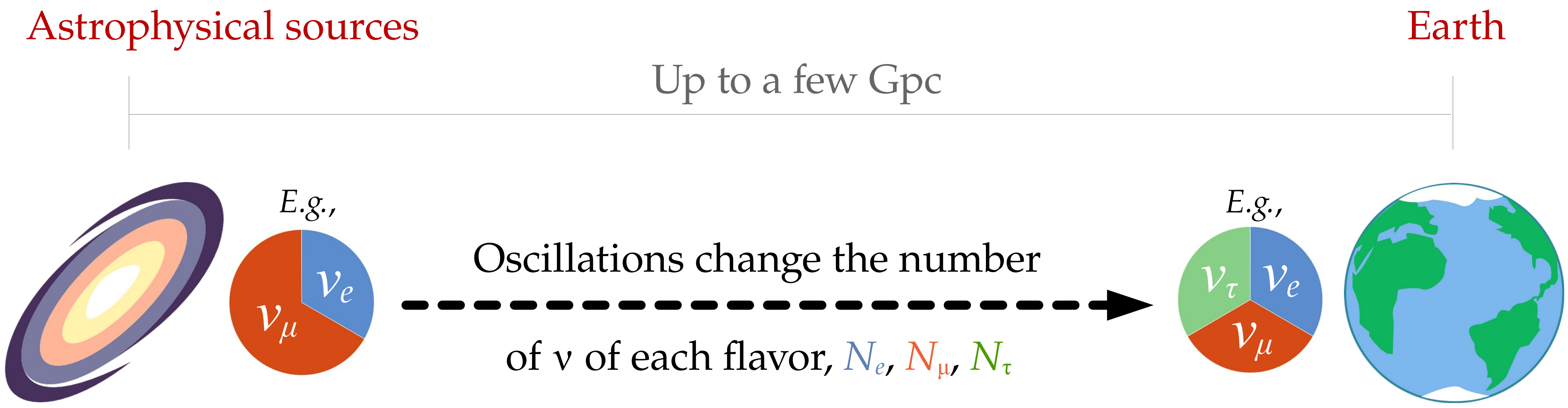
Distribution of arrival directions (7.5 yr) shows no significant excess:



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

IceCube, 2011.03545

See also: Ackermann, **MB** *et al.*, Astro2020 Decadal Survey (1903.04334)

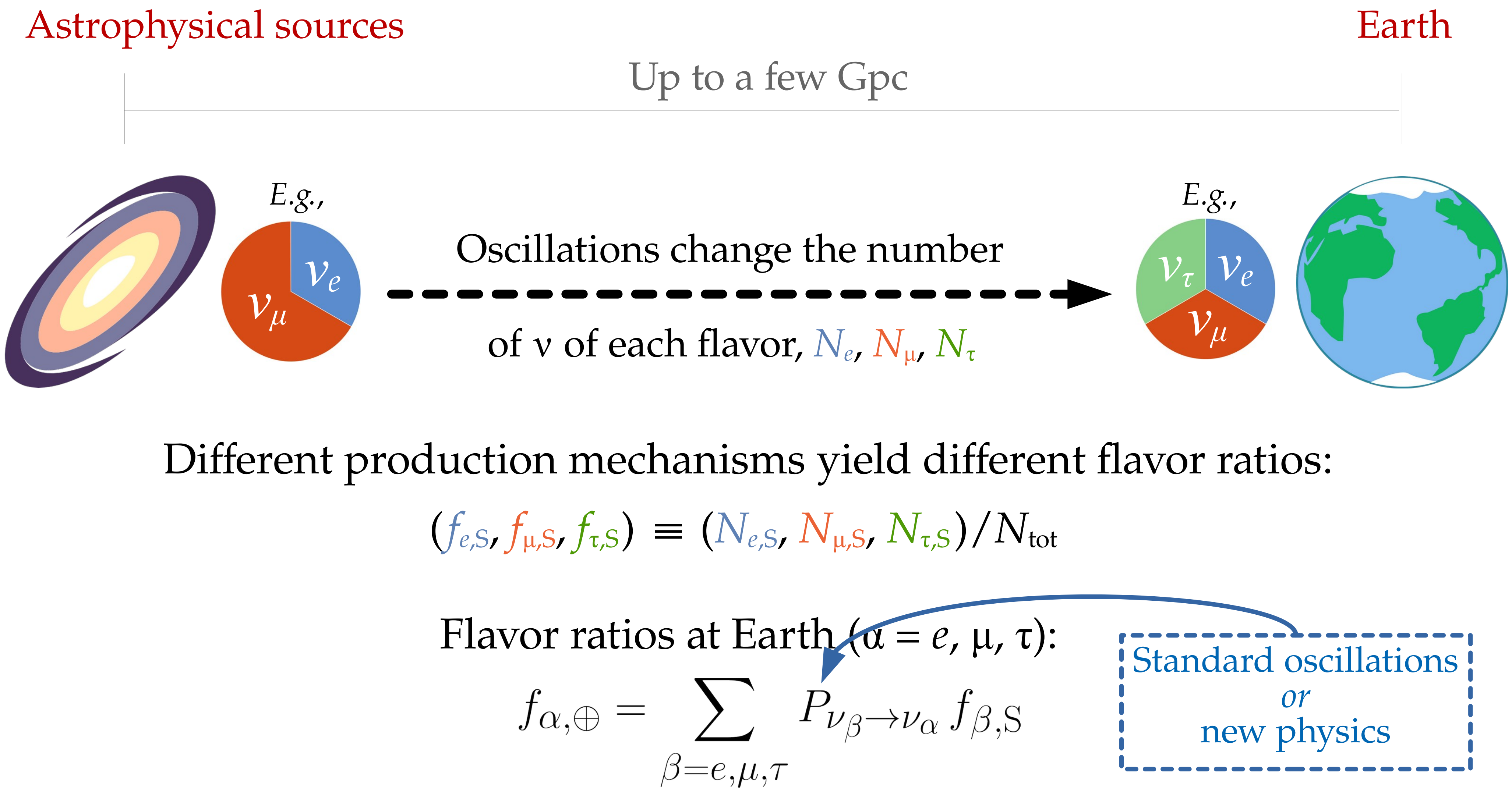


Different production mechanisms yield different flavor ratios:

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

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

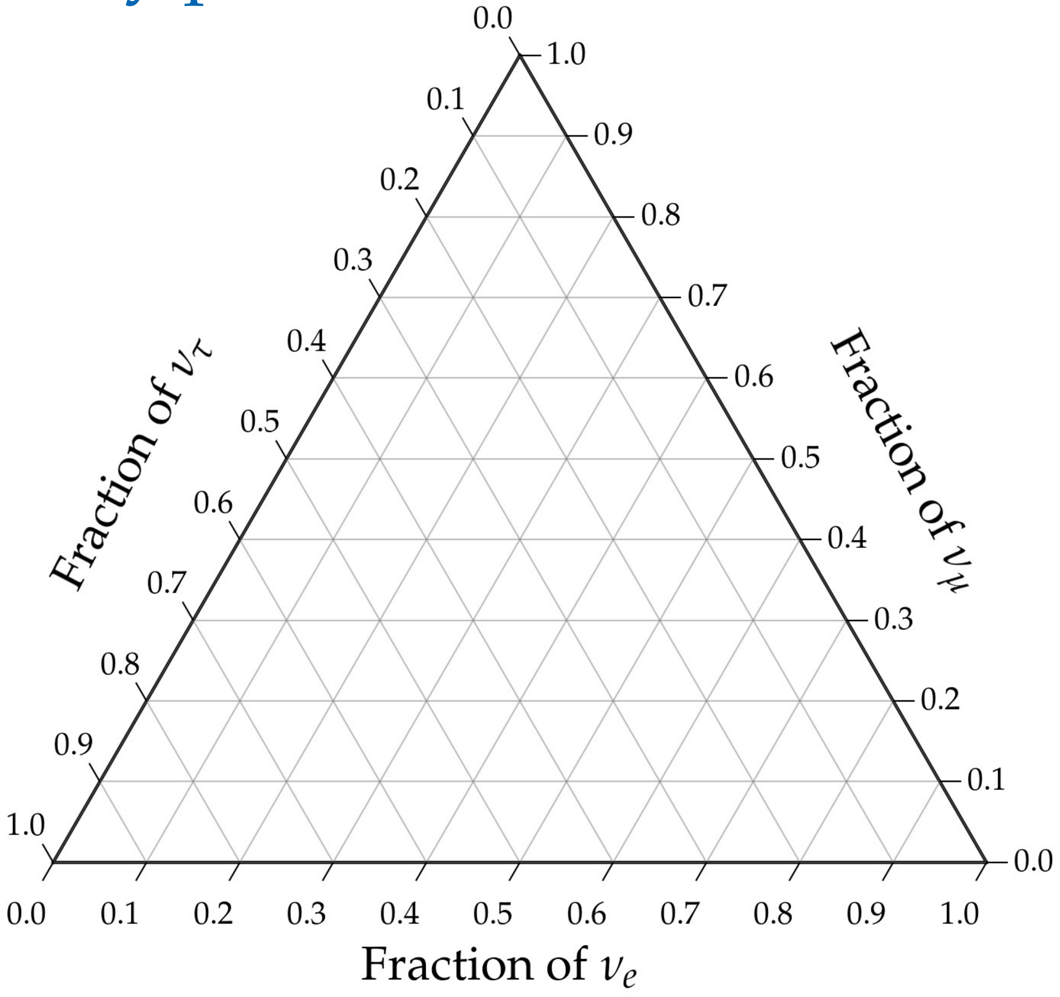
Quick aside: how to read a ternary plot

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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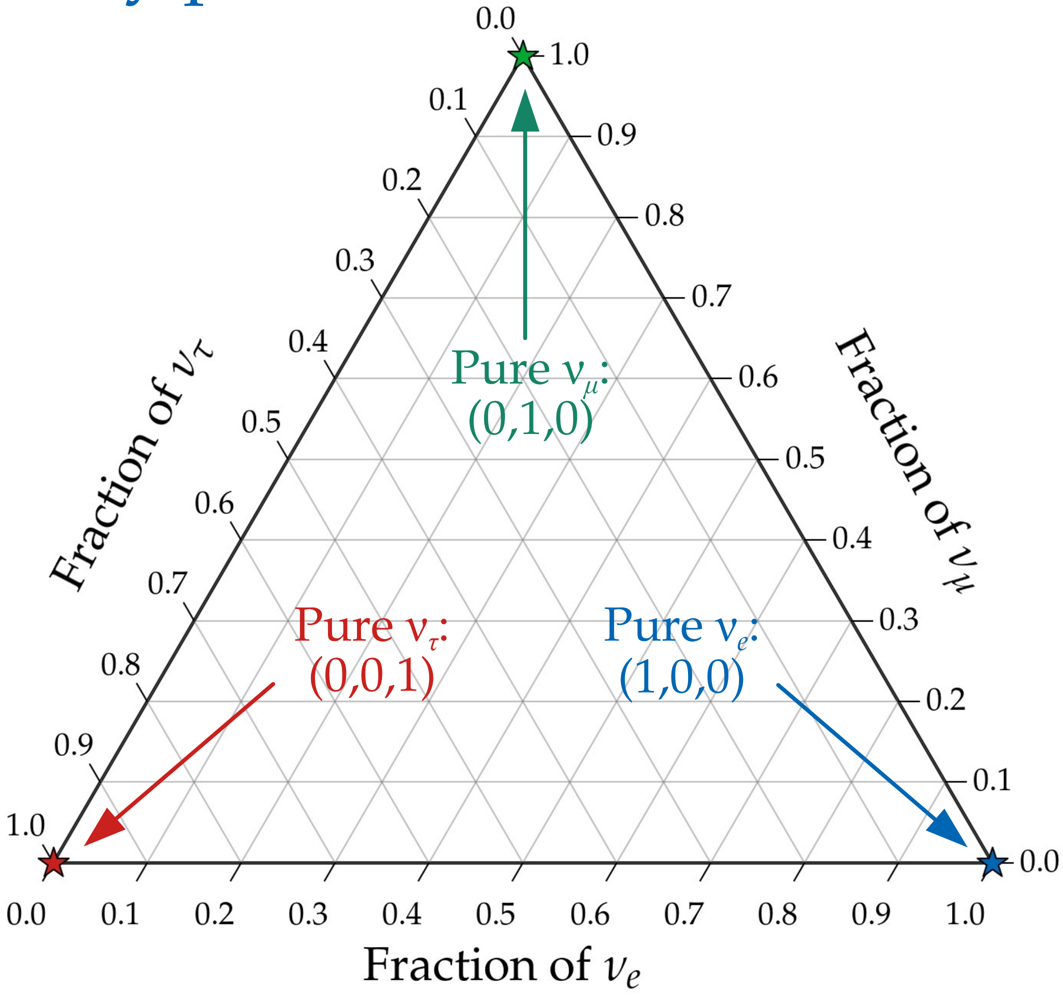

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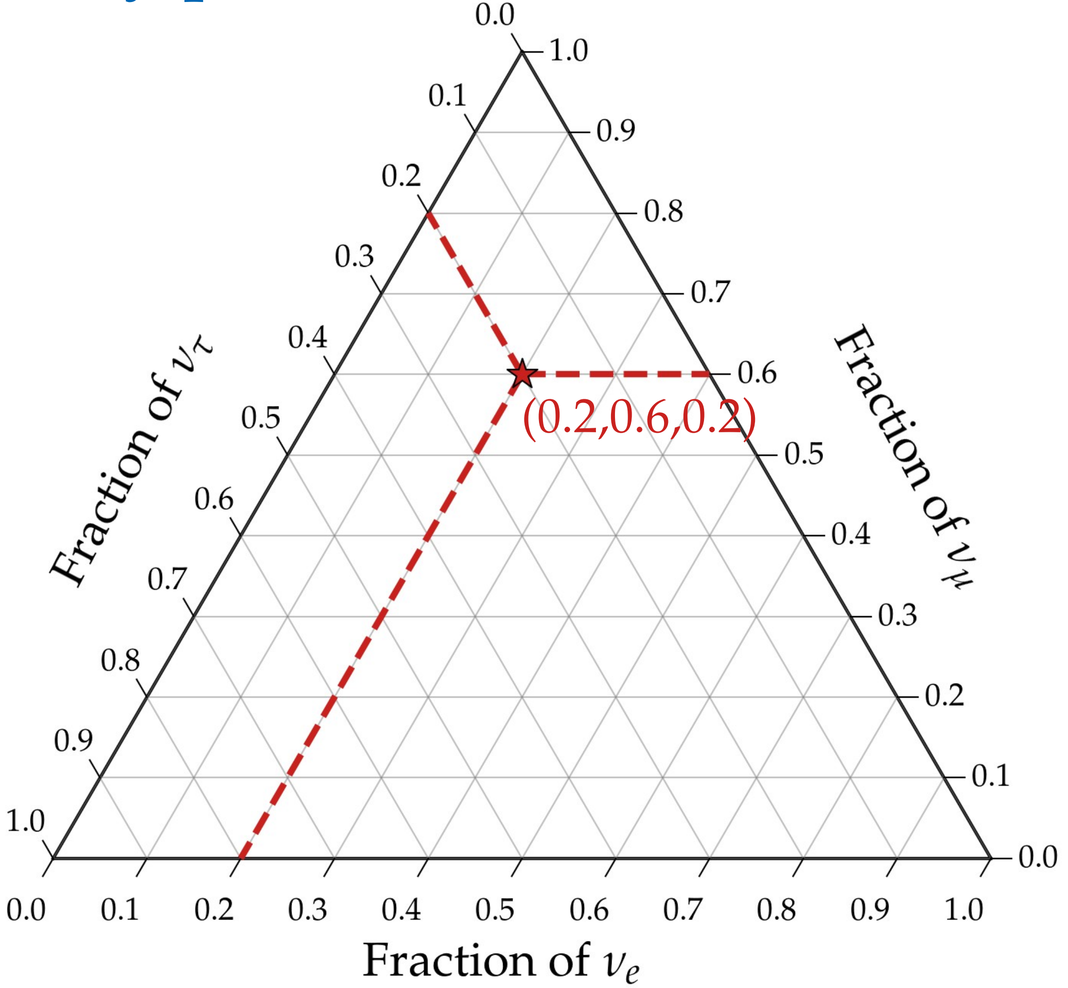

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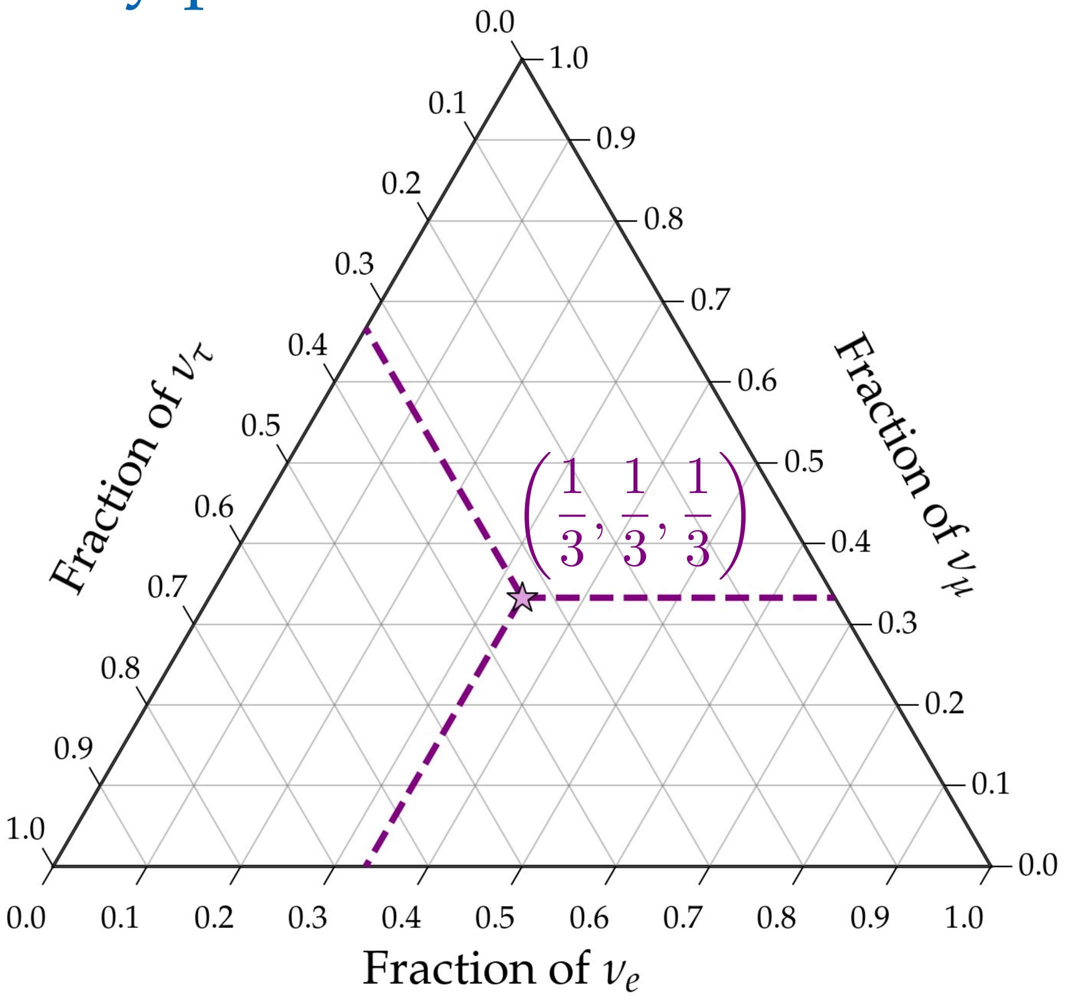

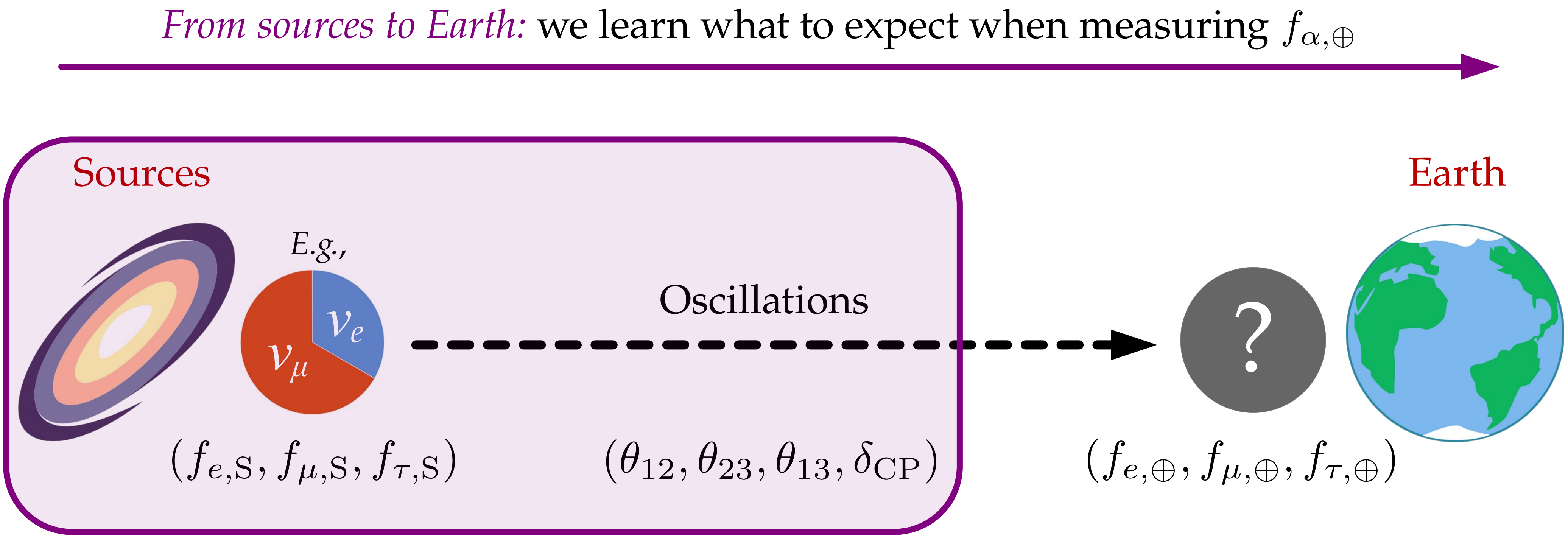

From sources to Earth: we learn what to expect when measuring $f_{\alpha,\oplus}$
Sources
E.g.,
ν_e
ν_μ
Oscillations
Earth
?
$(f_{e,\rm S}, f_{\mu,\rm S}, f_{\tau,\rm S})$
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$

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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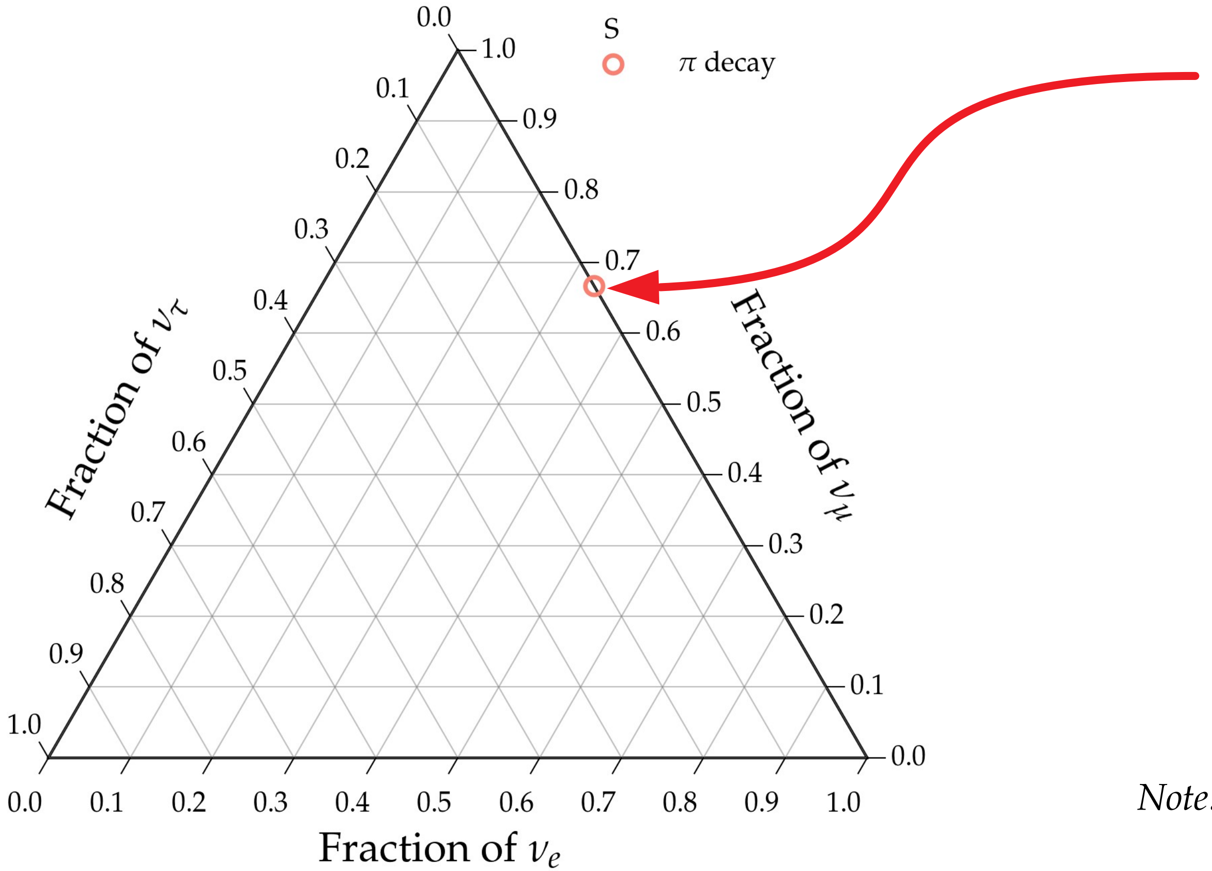

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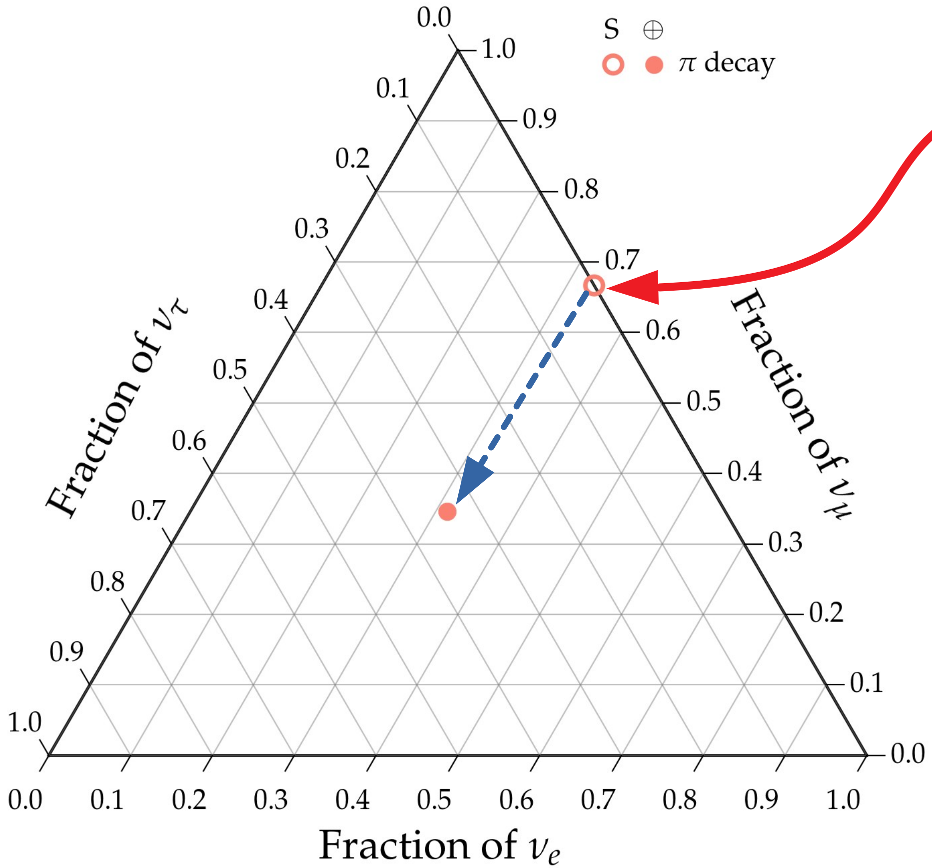

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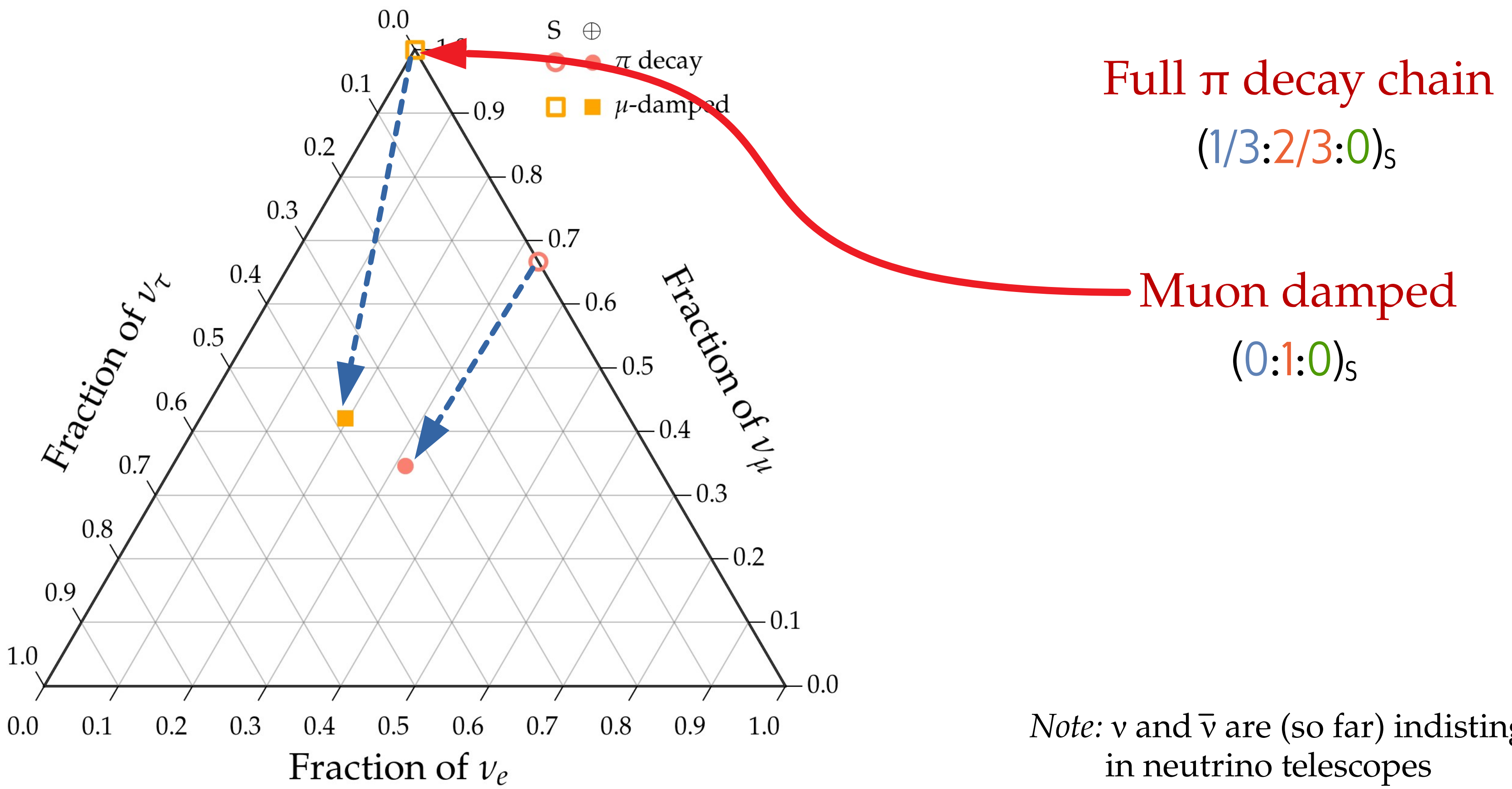

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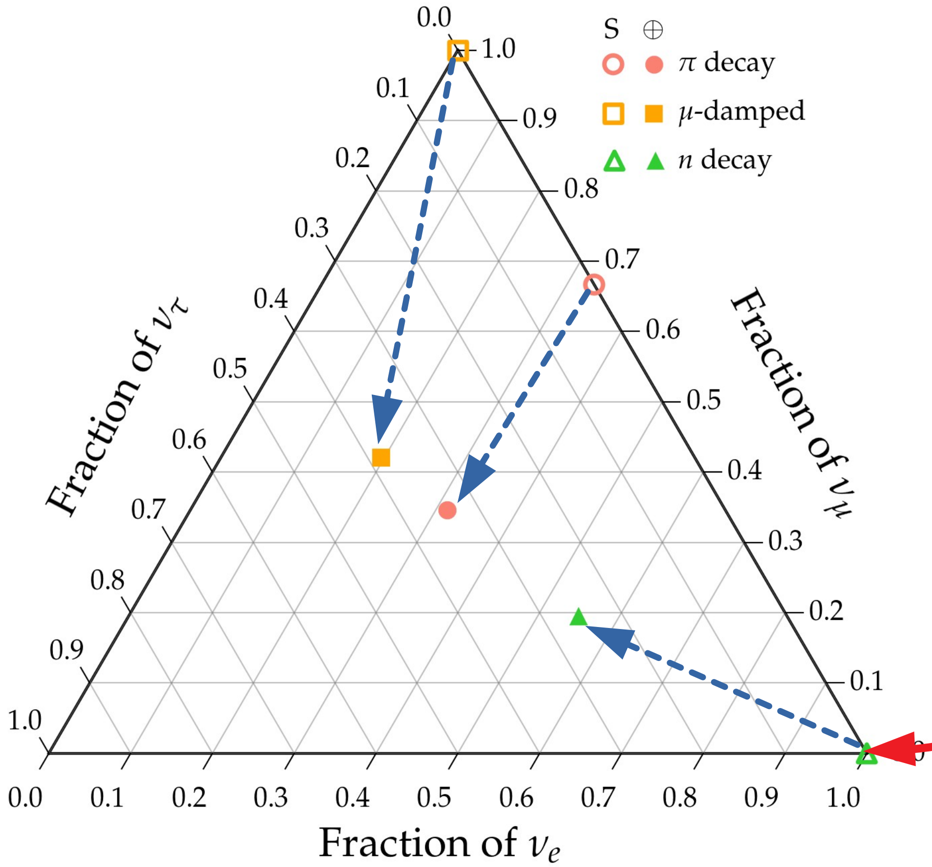


Full π decay chain

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

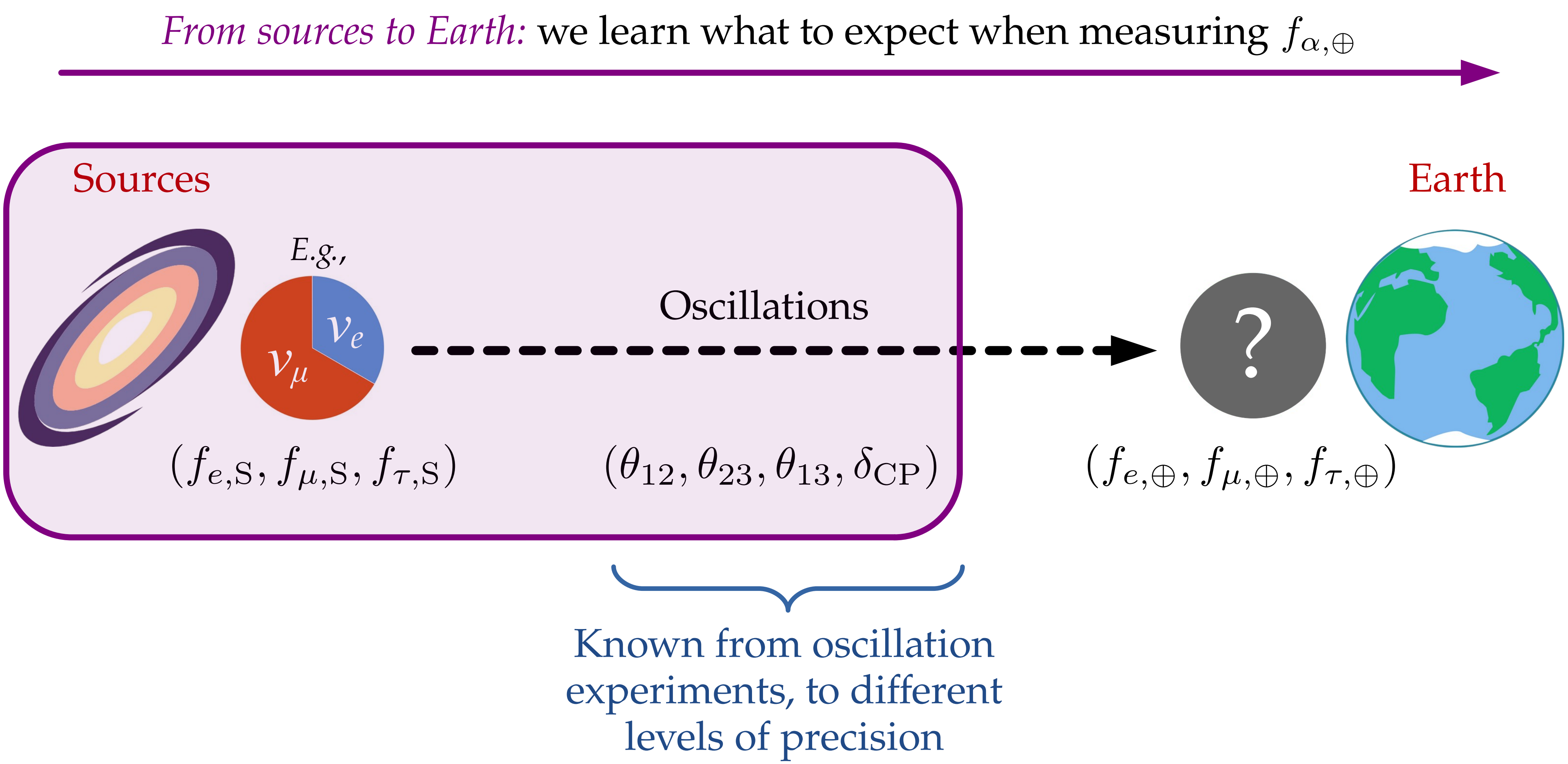
Muon damped

$(0:1:0)_S$

Neutron decay

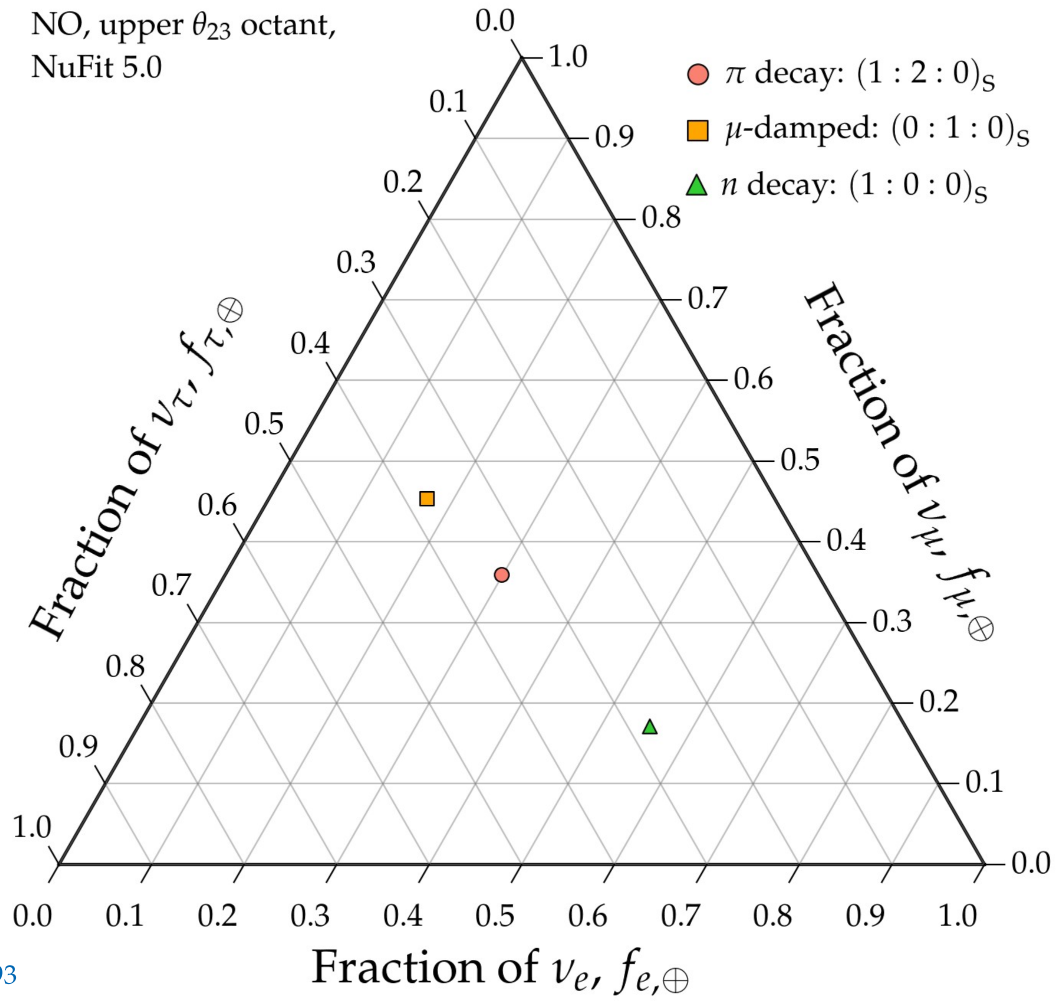
$(1:0:0)_S$

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

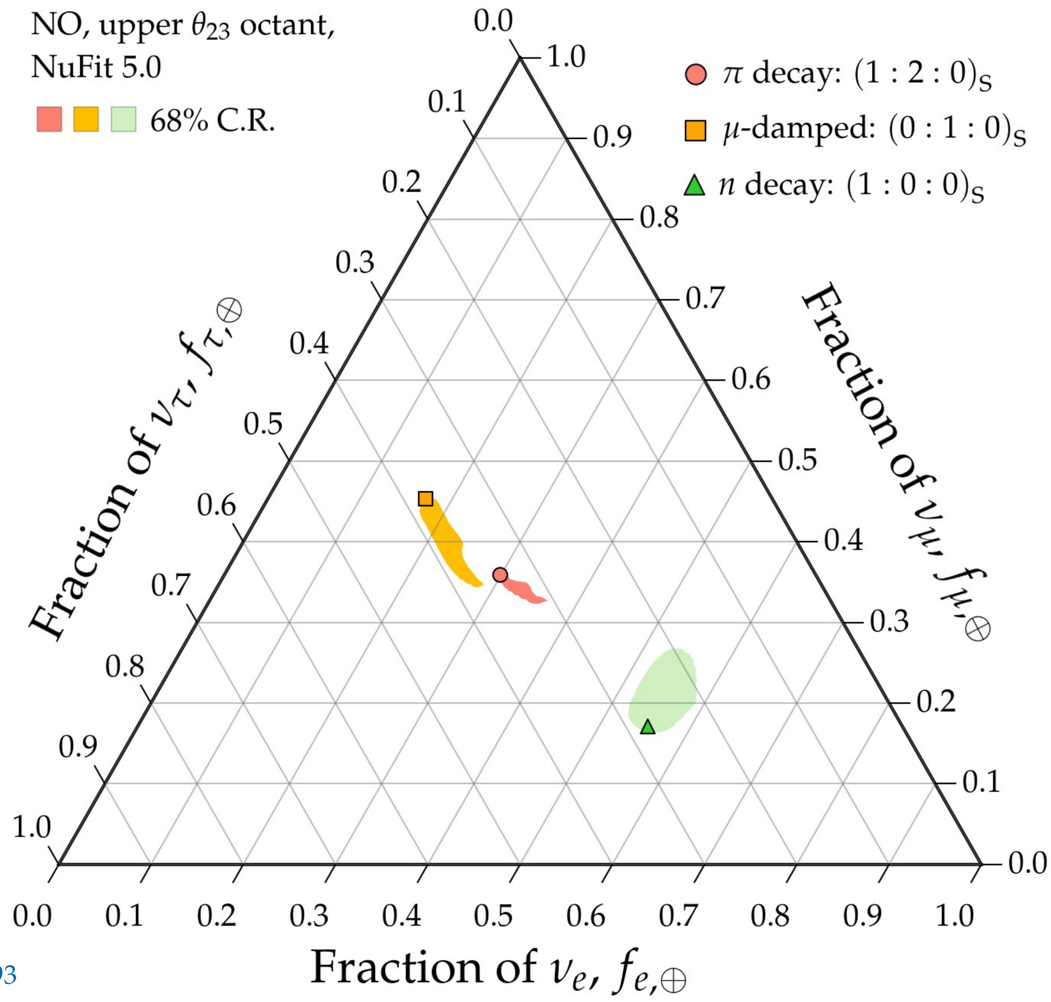
Theoretically palatable regions: today (2020)



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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today (2020)



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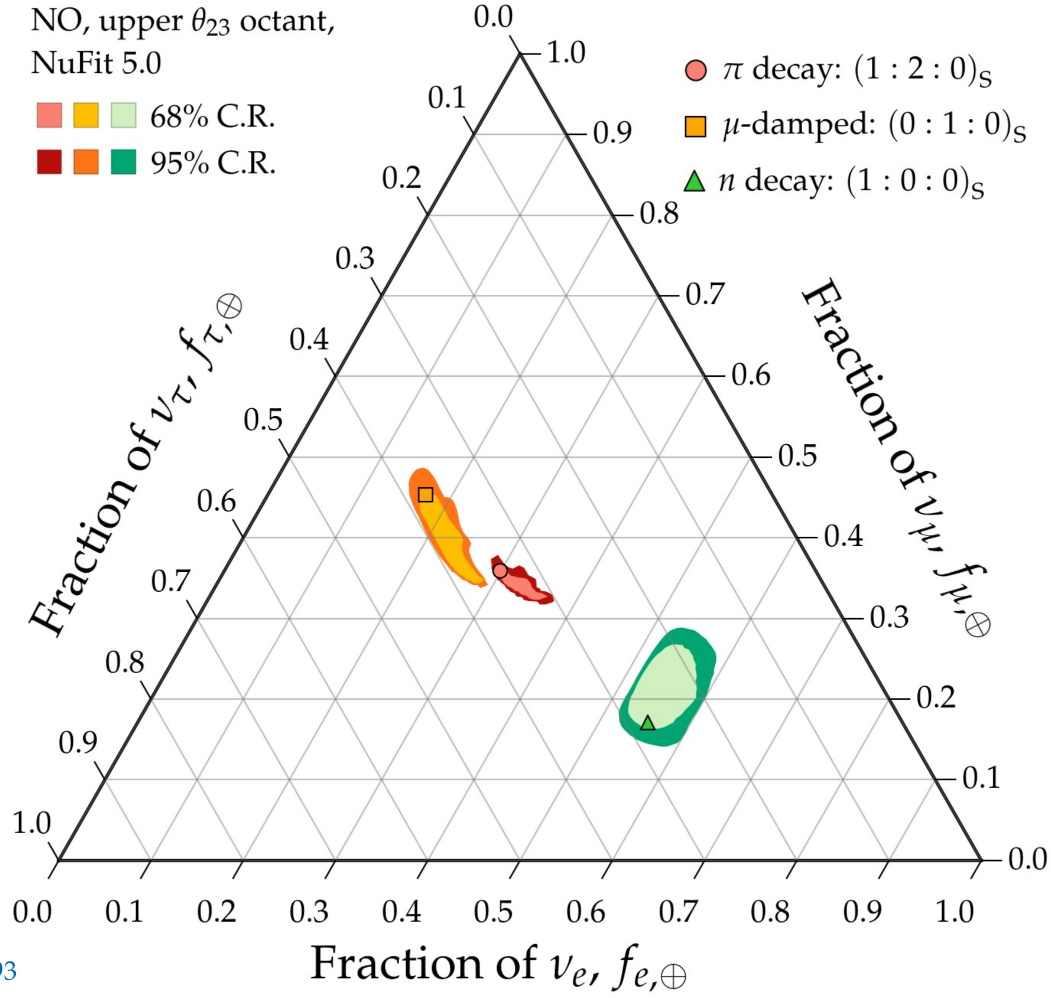

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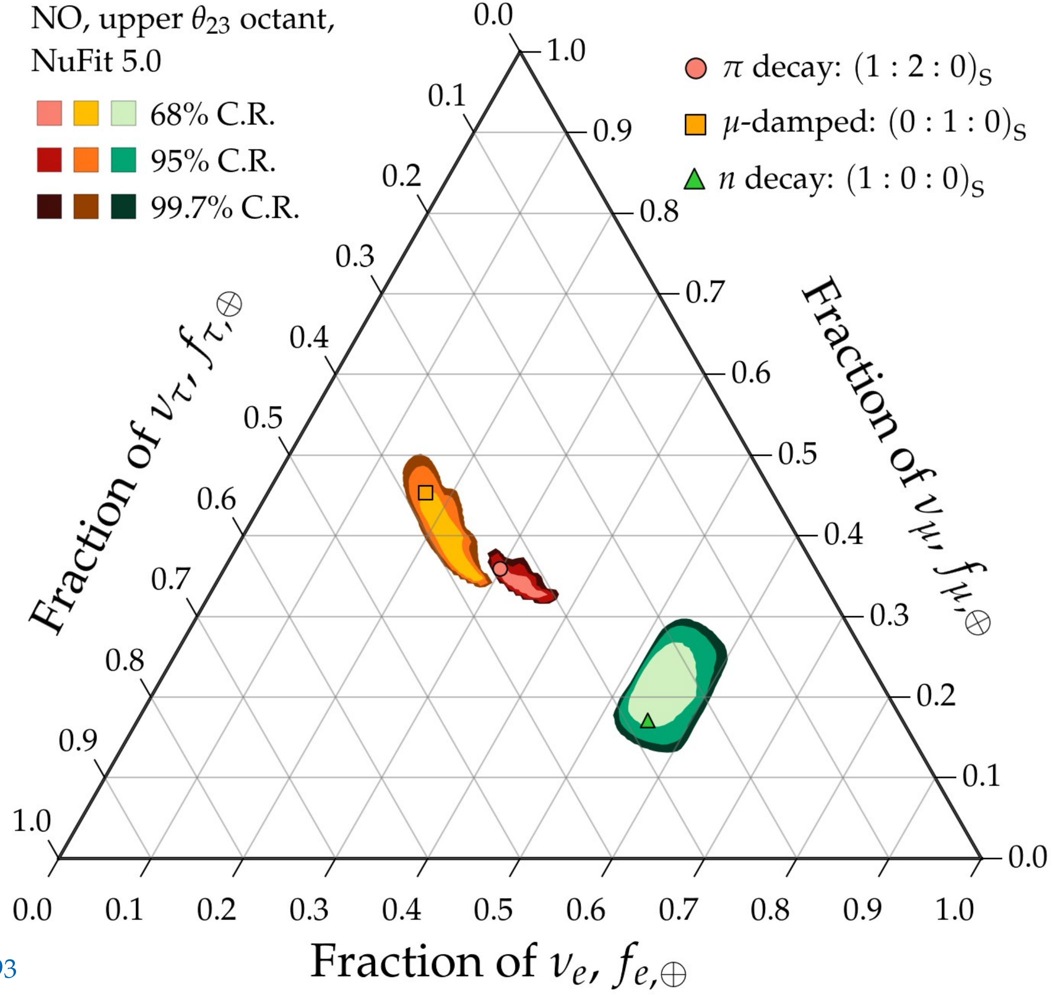

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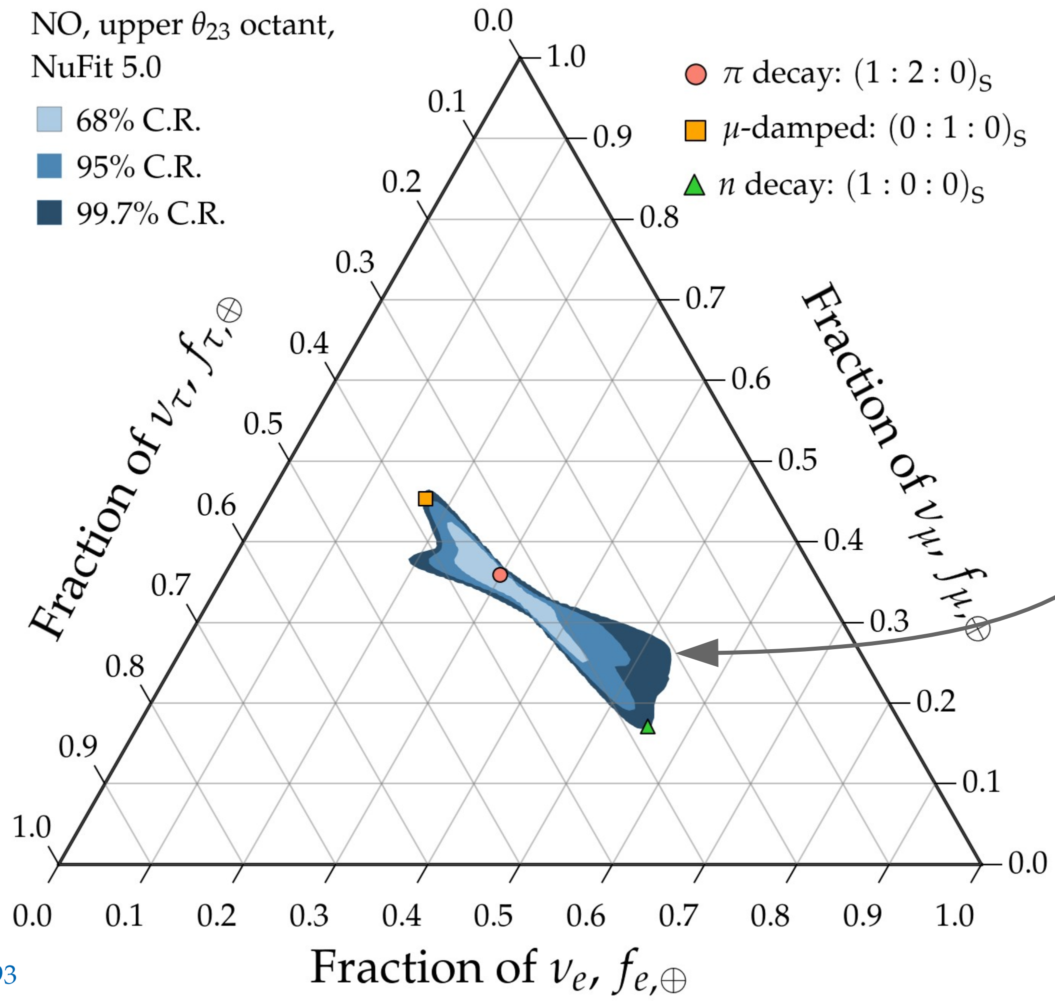

Varying over all possible flavor ratios at the source

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

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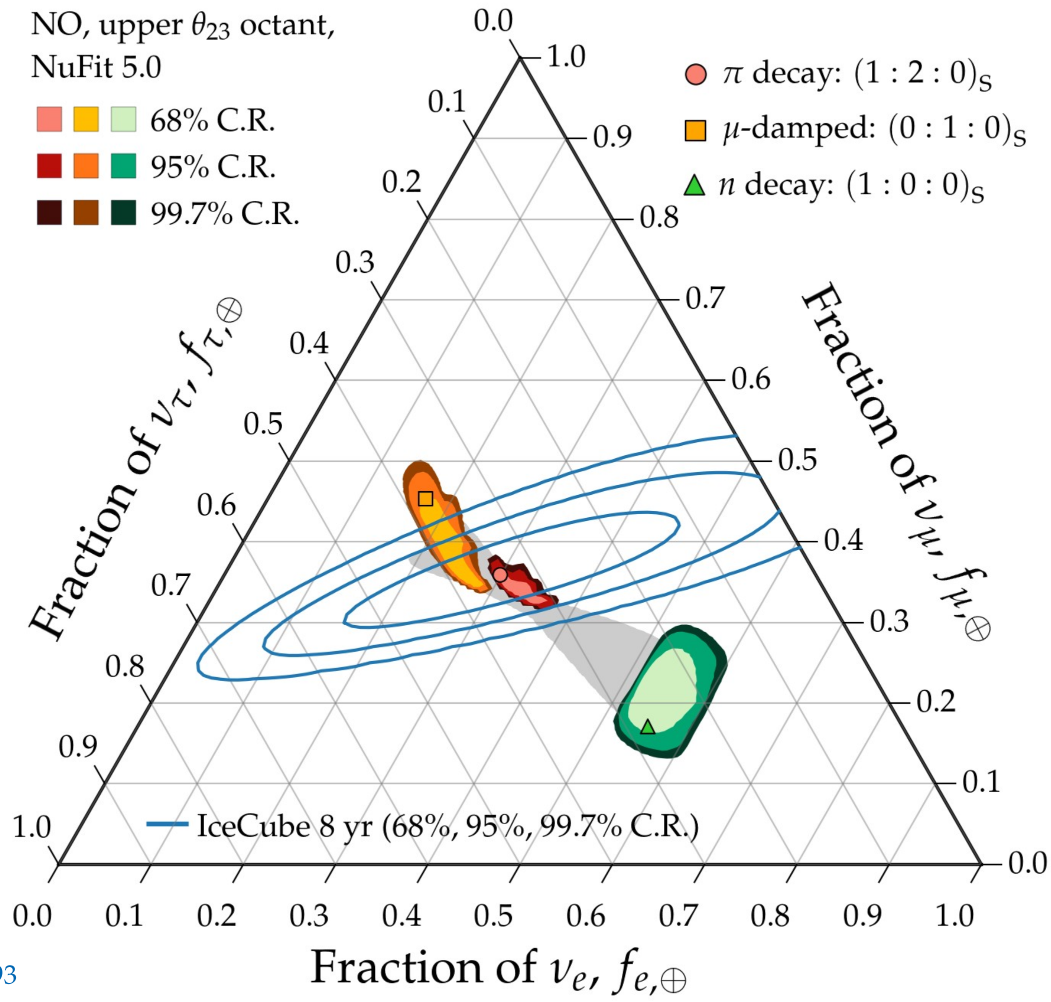
Theoretically palatable regions: today (2020)



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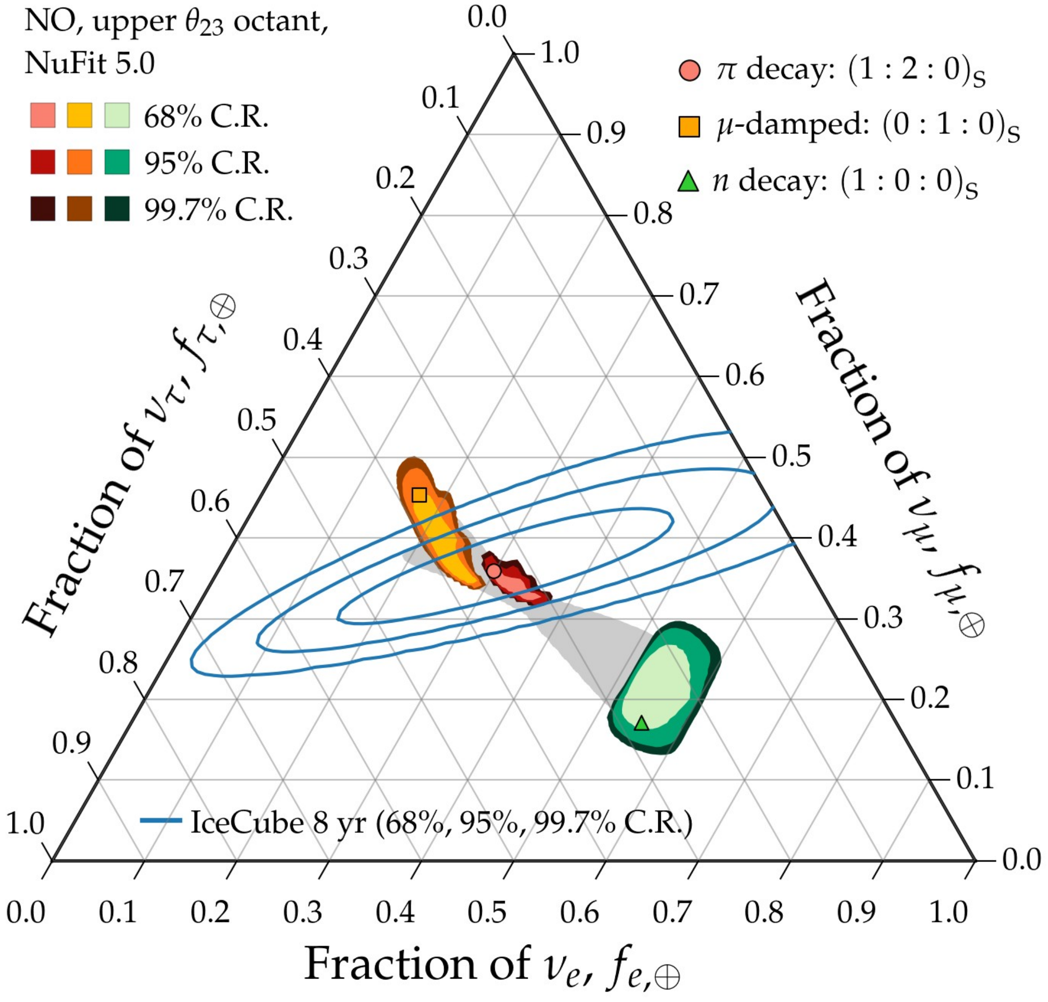
Theoretically palatable regions: today (2020)



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, 2012.12893
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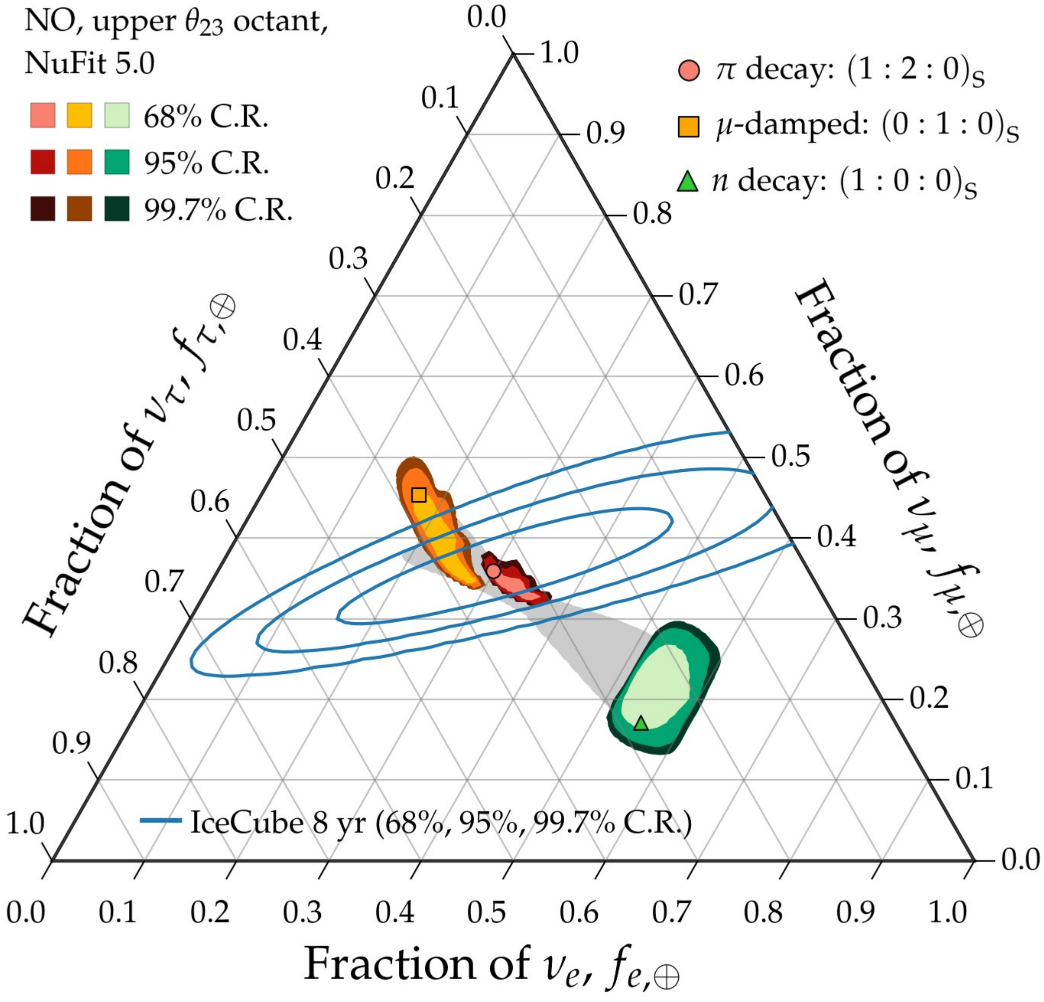
Theoretically palatable regions: today (2020)



Two limitations:

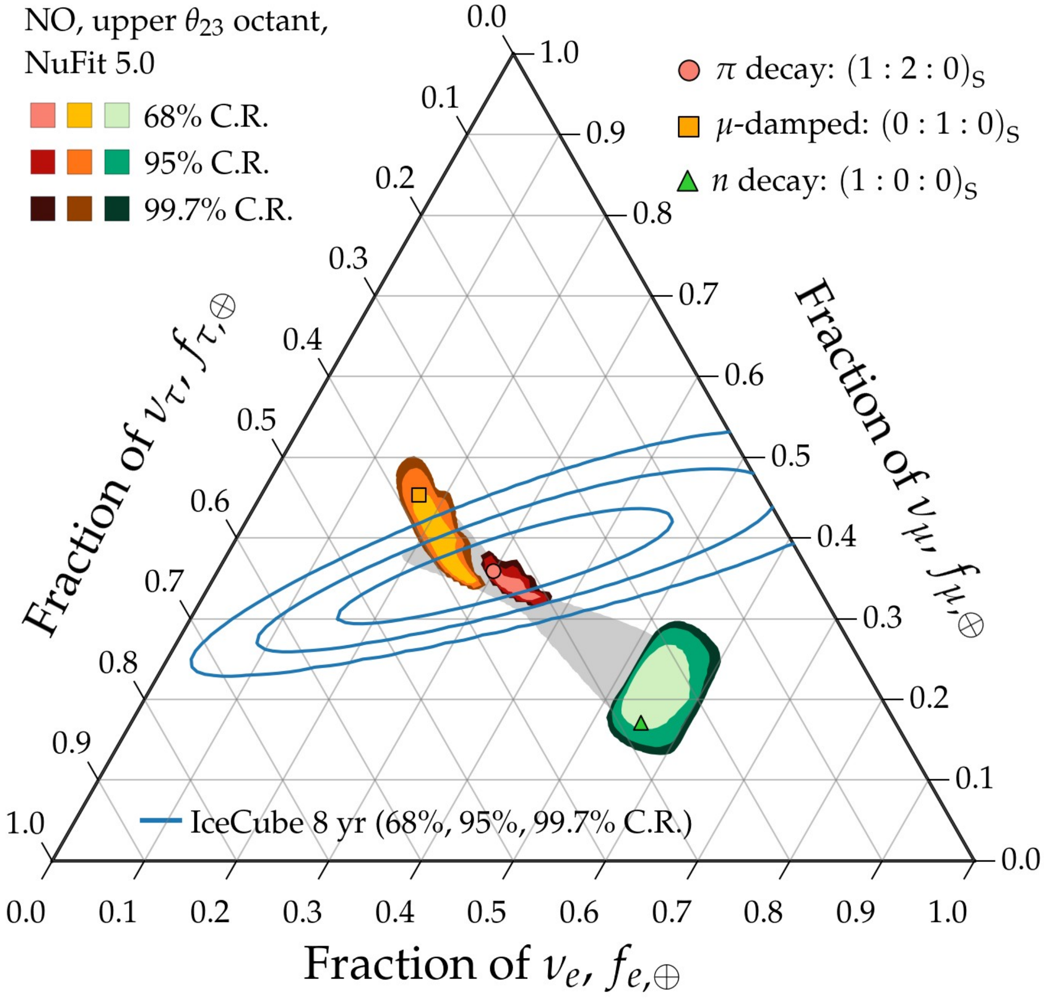
Allowed flavor regions overlap –
Insufficient precision in the mixing parameters

Will be overcome by 2030

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

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015

Theoretically palatable regions: today (2020)



Two limitations:

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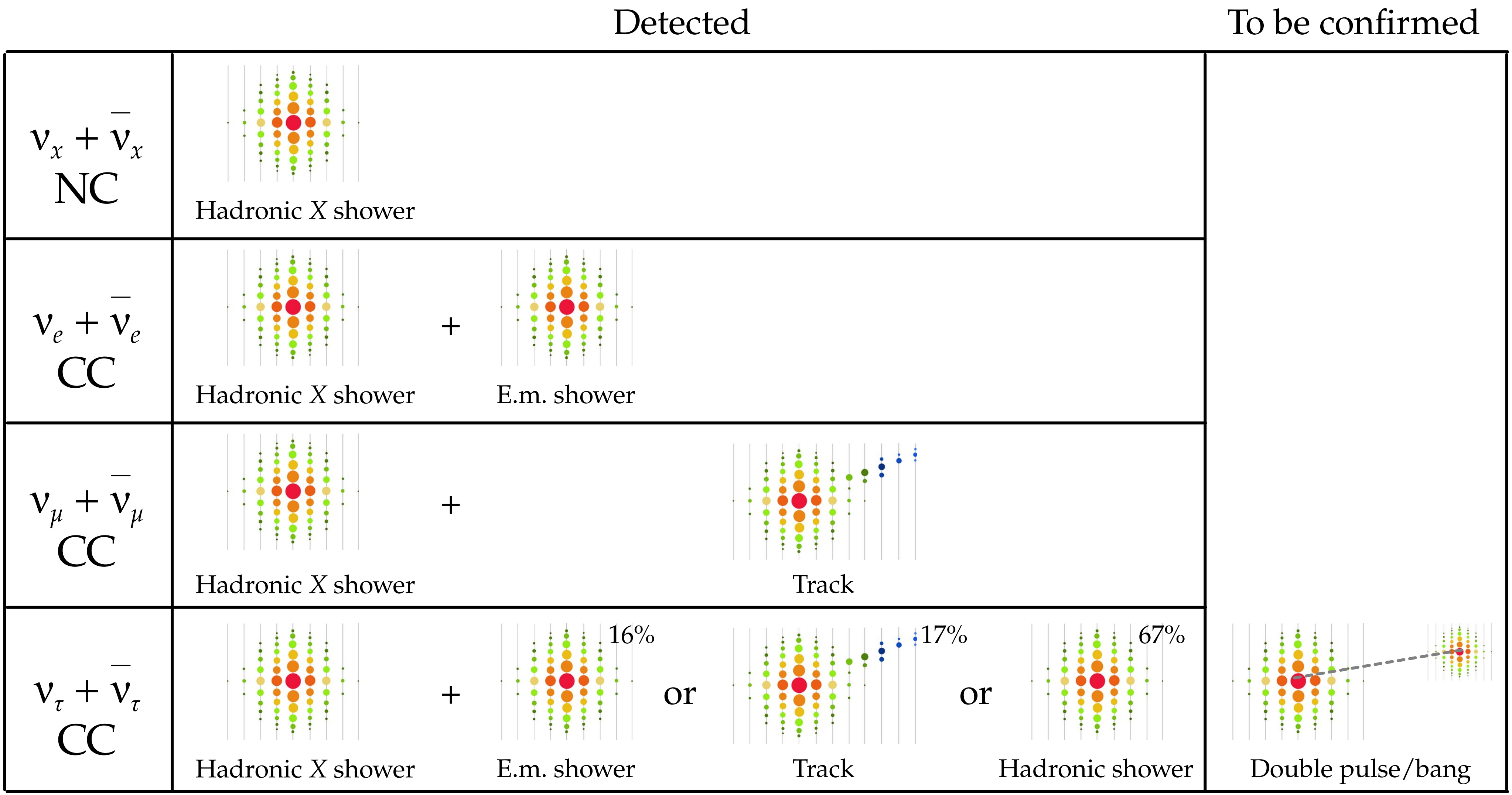
Will be overcome by 2030

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, 2012.12893
See also: **MB**, Beacom, Winter, *PRL* 2015


Detected
To be confirmed
$\nu_x + \bar{\nu}_x$ NC
Hadronic X shower
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Track
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16%
E.m. shower
or
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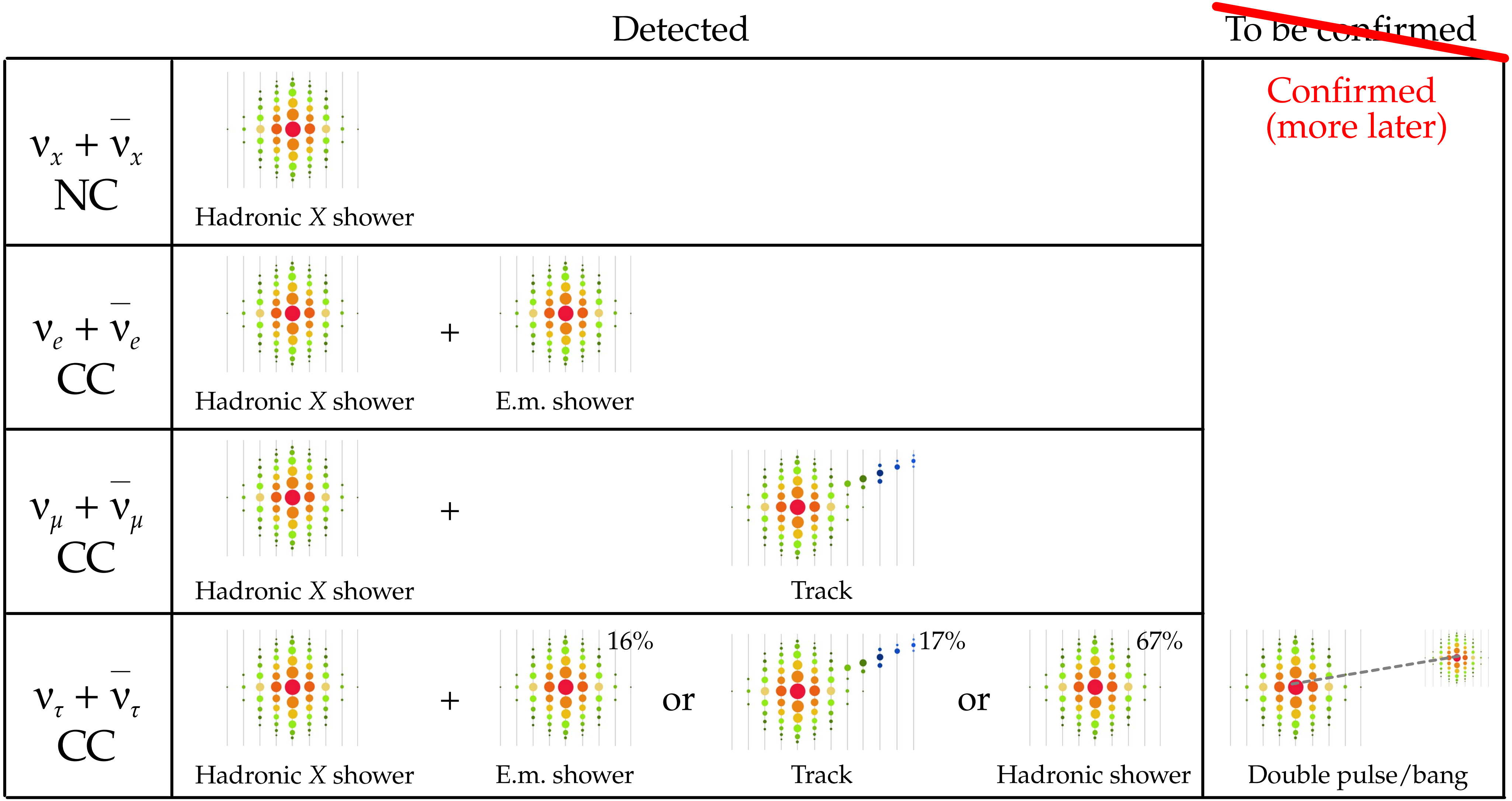
Track
or
67%
Hadronic shower
Double pulse/bang



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
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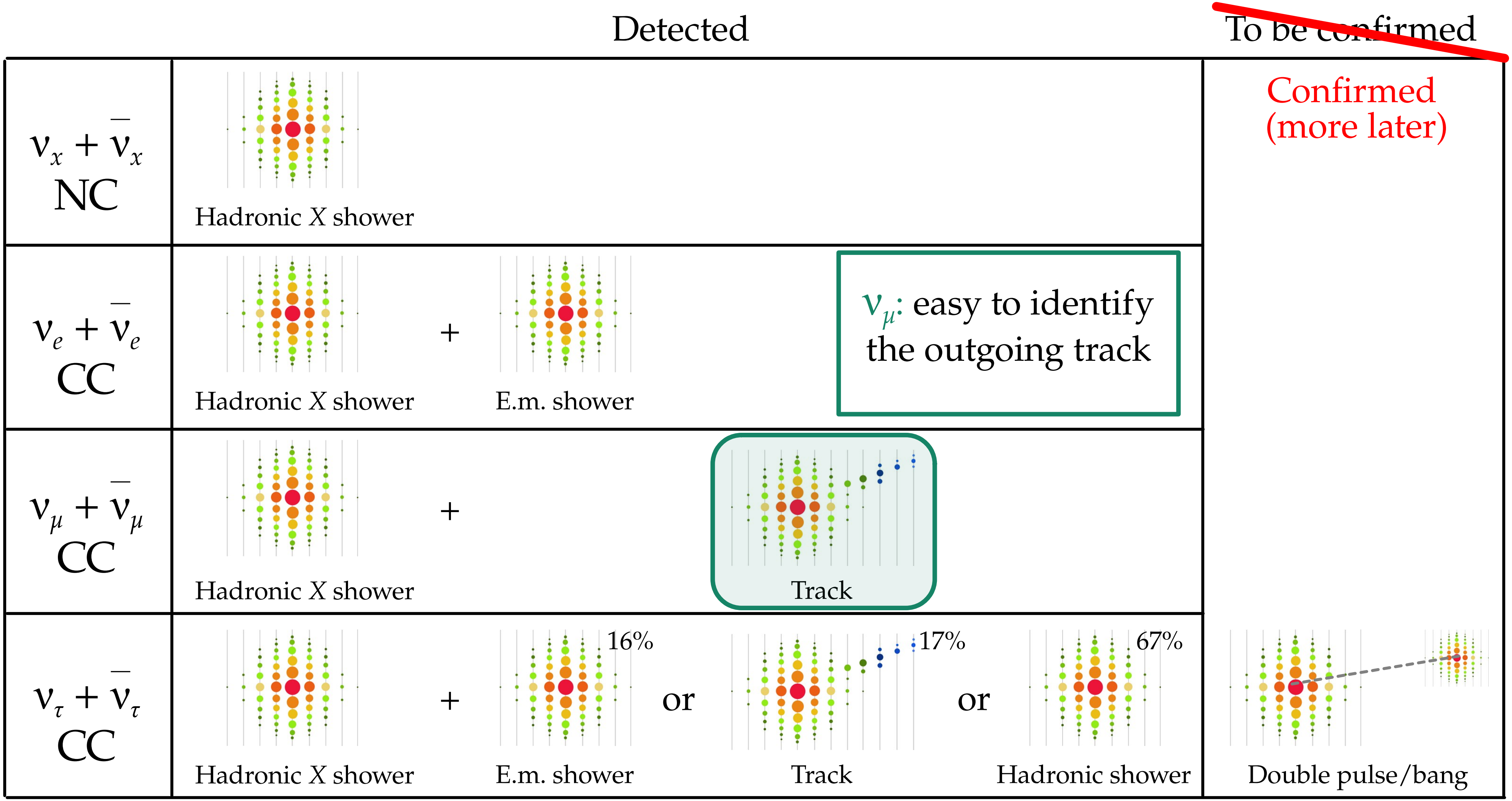

Detected
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Confirmed
(more later)
$\nu_x + \bar{\nu}_x$
NC
Hadronic X shower
$\nu_e + \bar{\nu}_e$
CC
Hadronic X shower
+
E.m. shower
ν_μ: easy to identify the outgoing track
$\nu_\mu + \bar{\nu}_\mu$
CC
Hadronic X shower
+
Track
$\nu_\tau + \bar{\nu}_\tau$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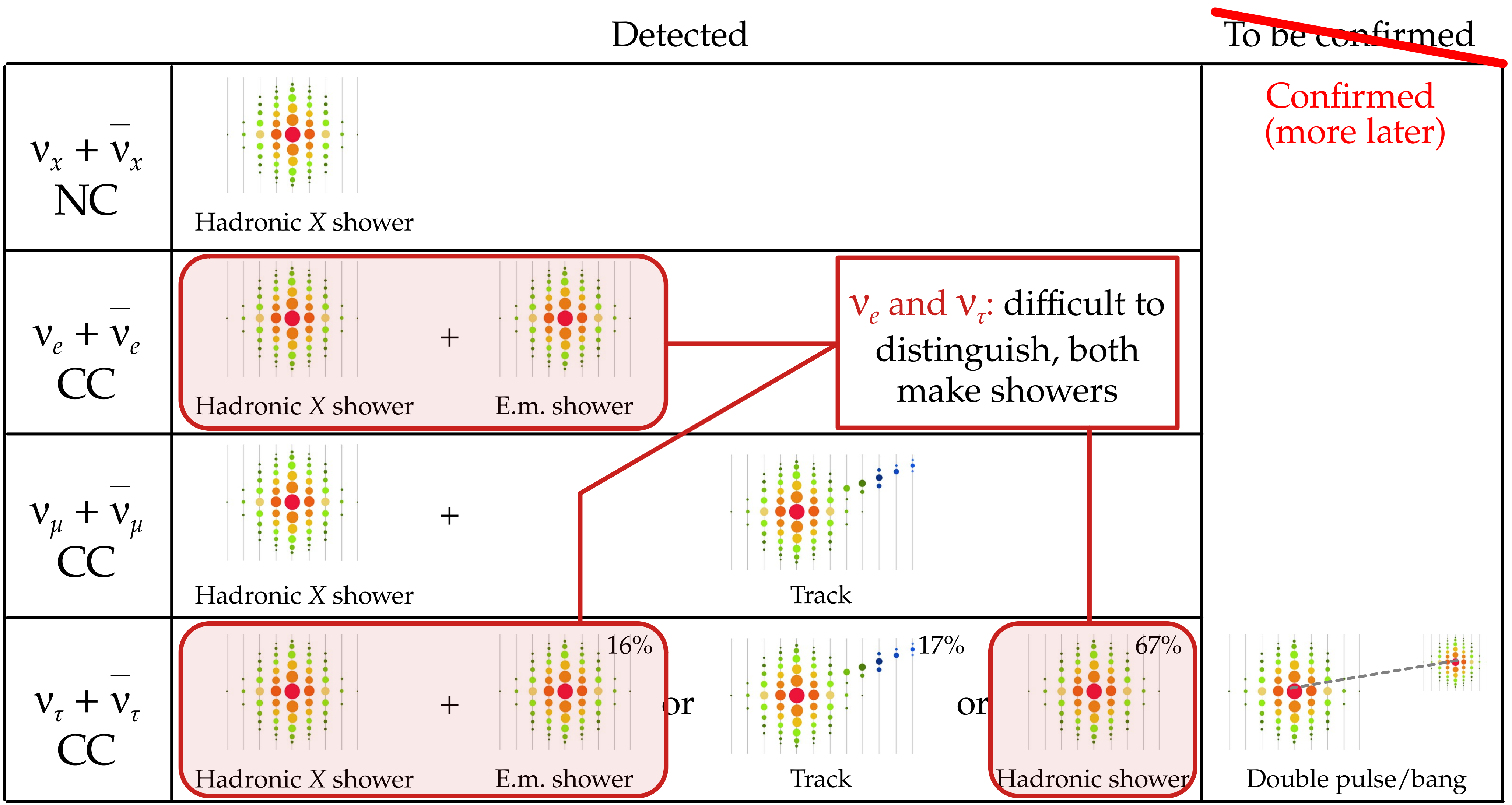
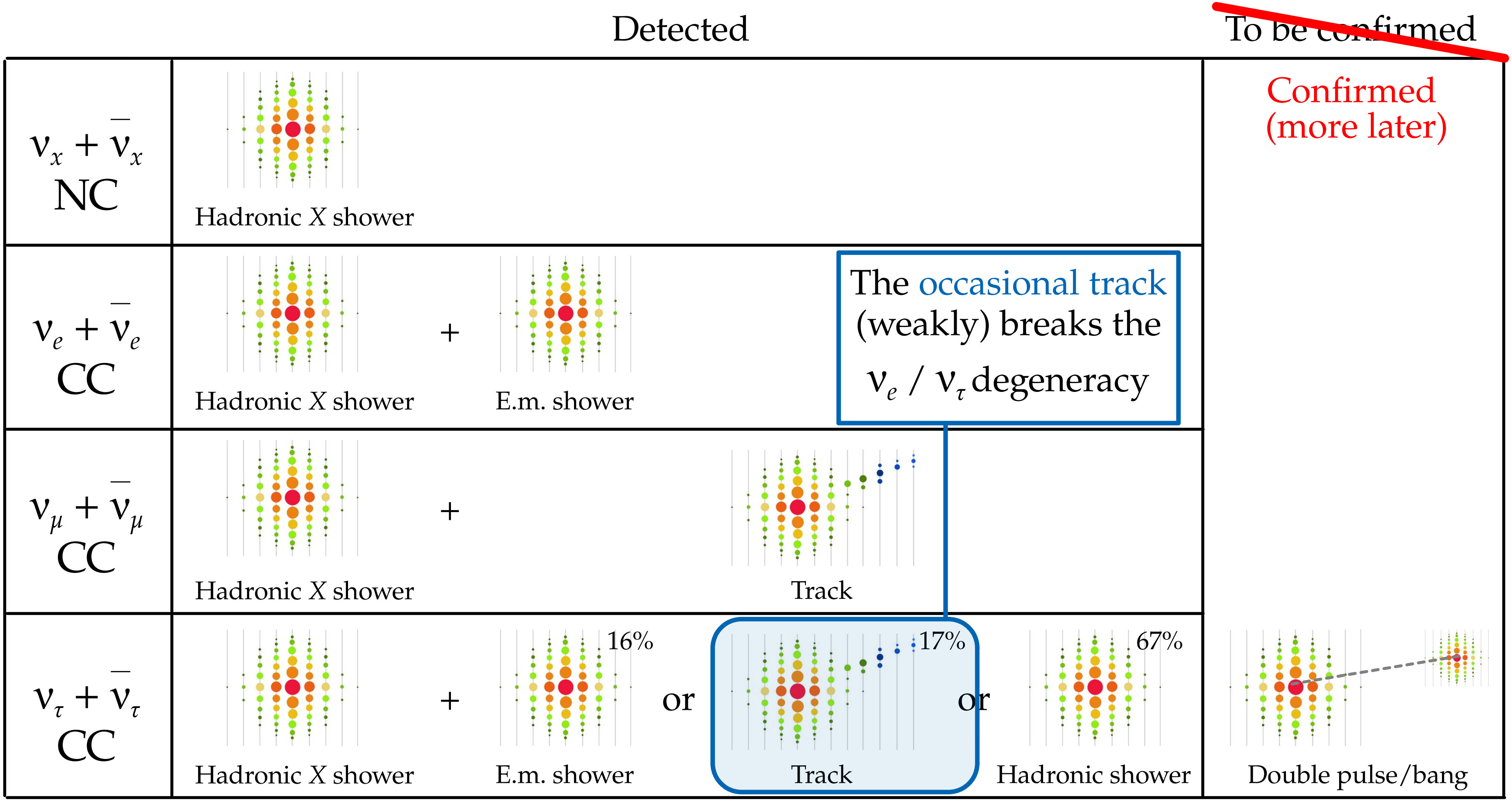
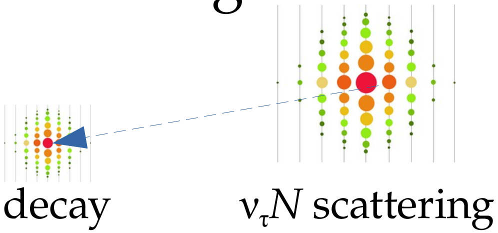
17%
Track
or
67%
Hadronic shower
Double pulse/bang


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

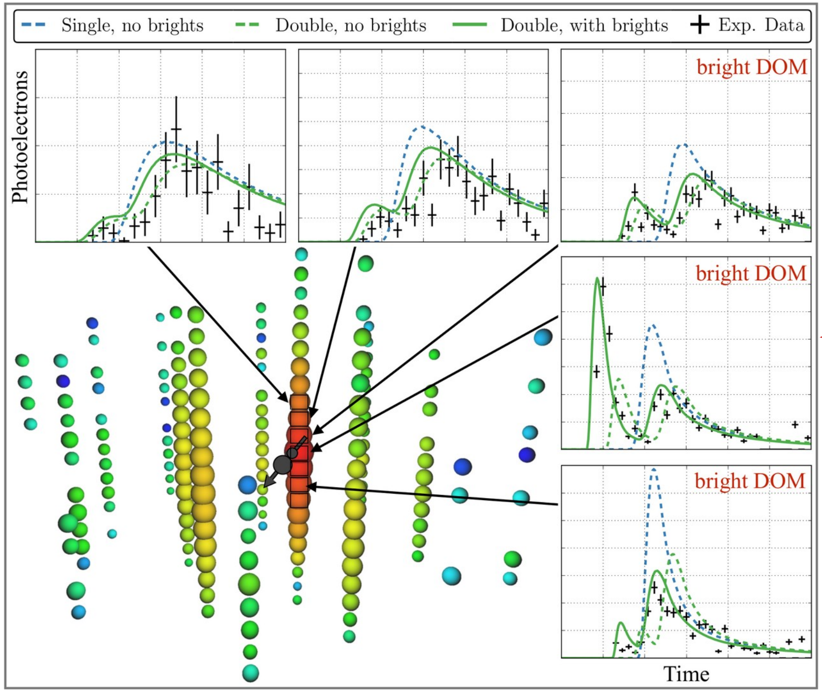
First identified high-energy astrophysical ν_τ

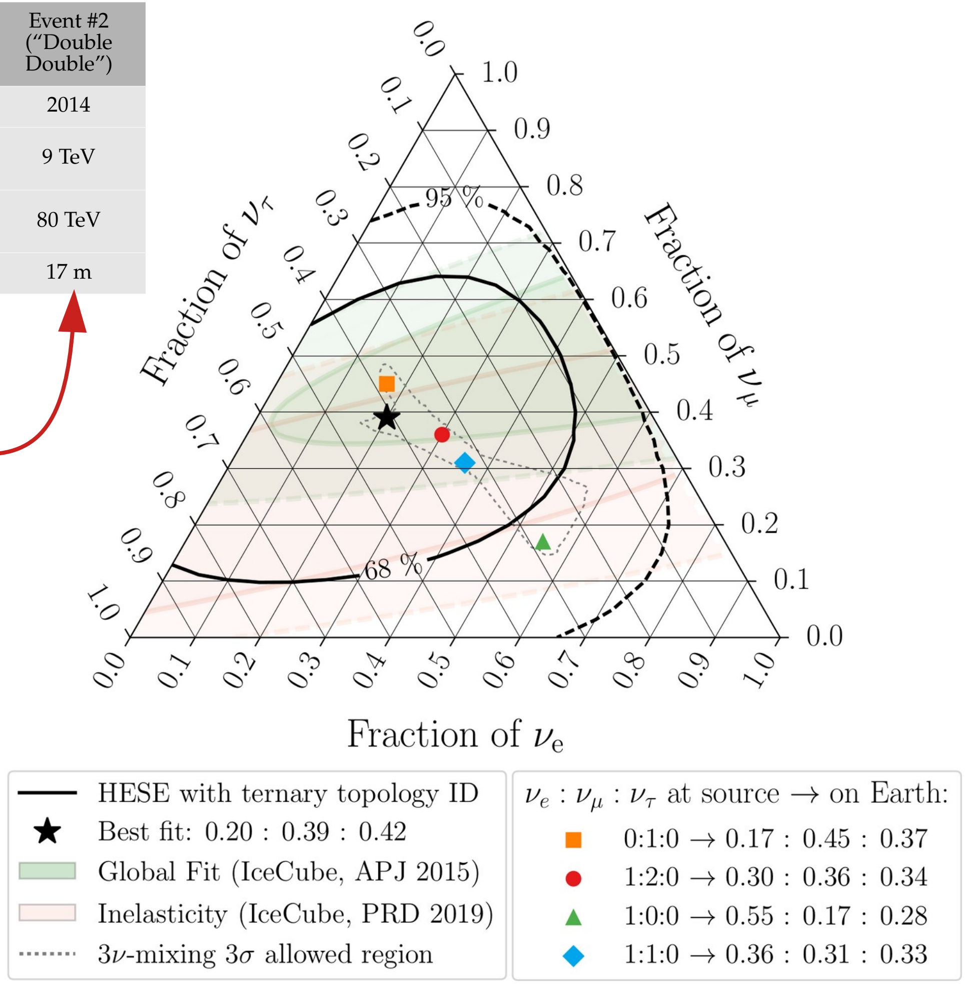
Double bang:



	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

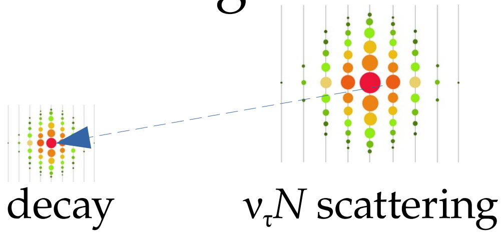




IceCube, 2011.03561

First identified high-energy astrophysical ν_τ

Double bang:



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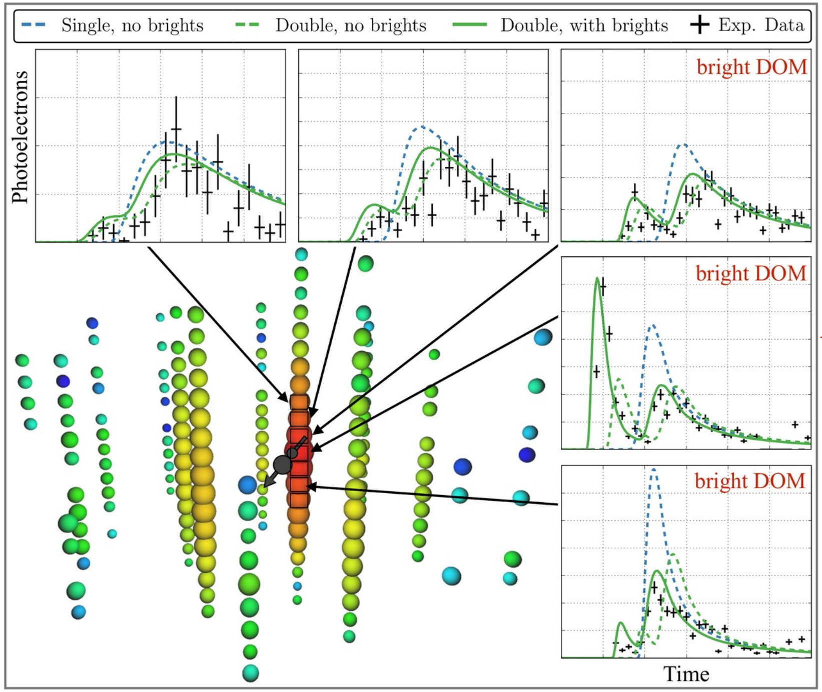

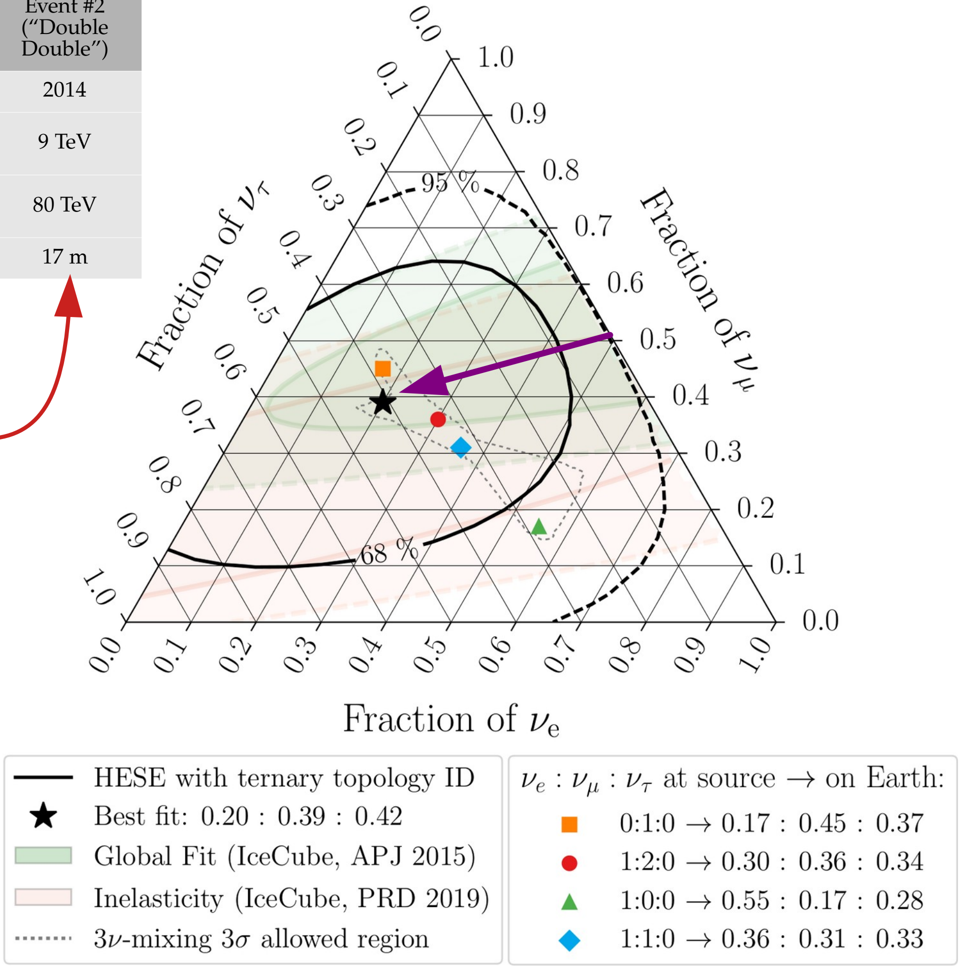

IceCube, 2011.03561

Measuring flavor composition: 2015–2040

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

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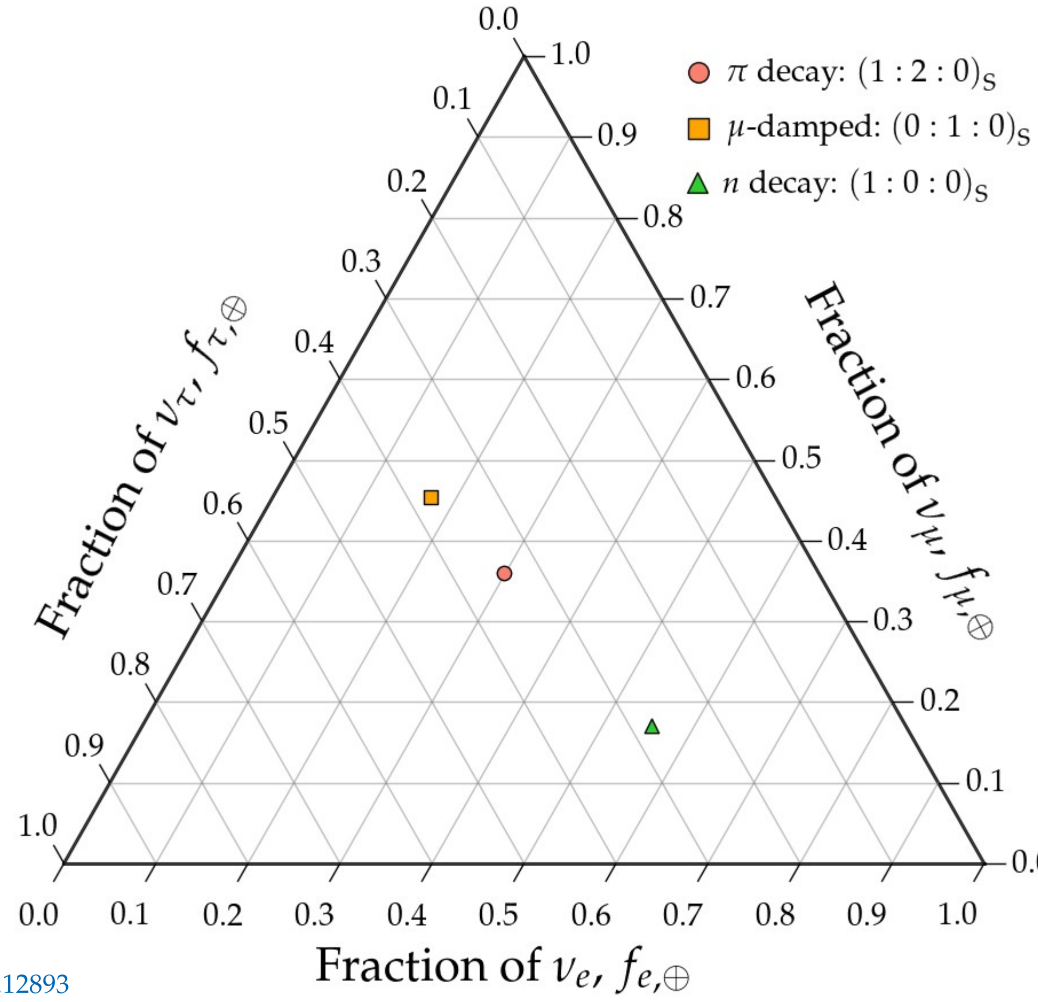
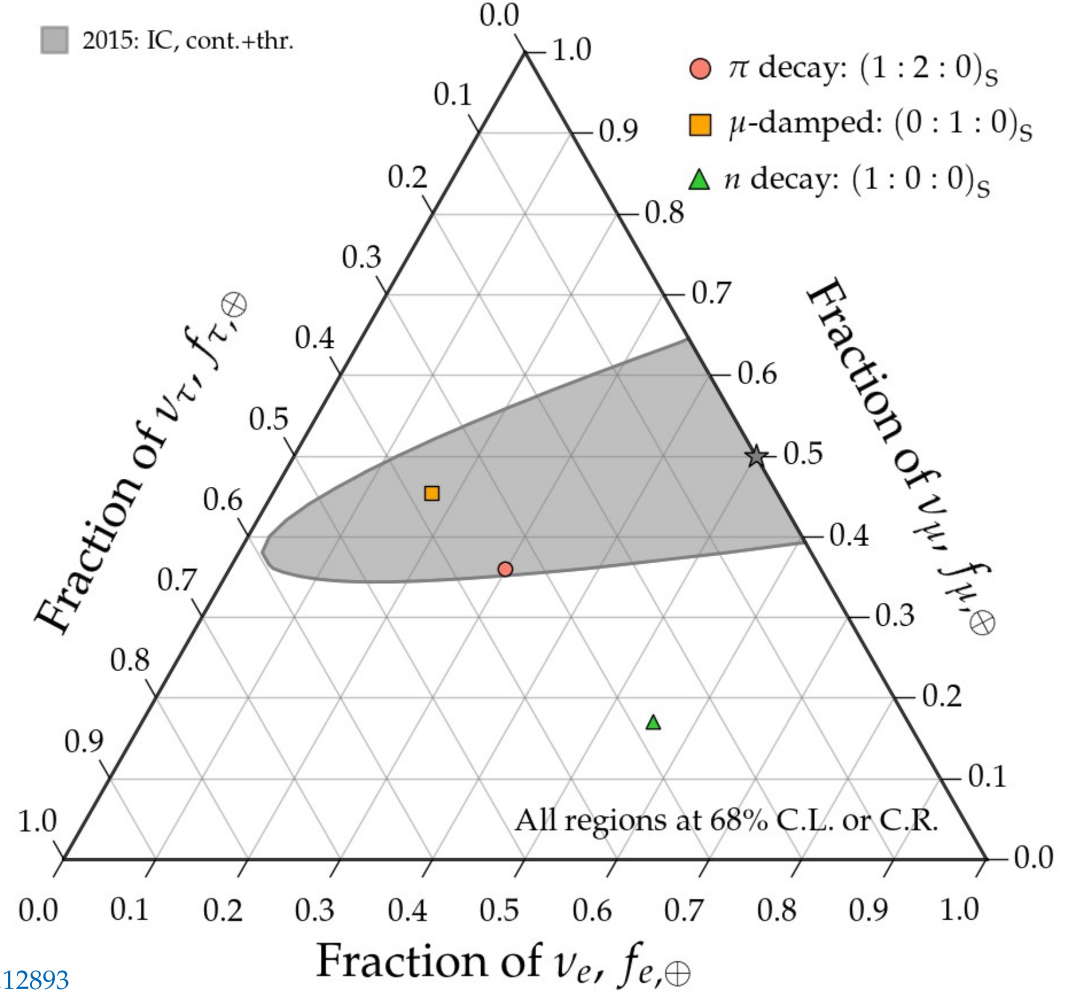


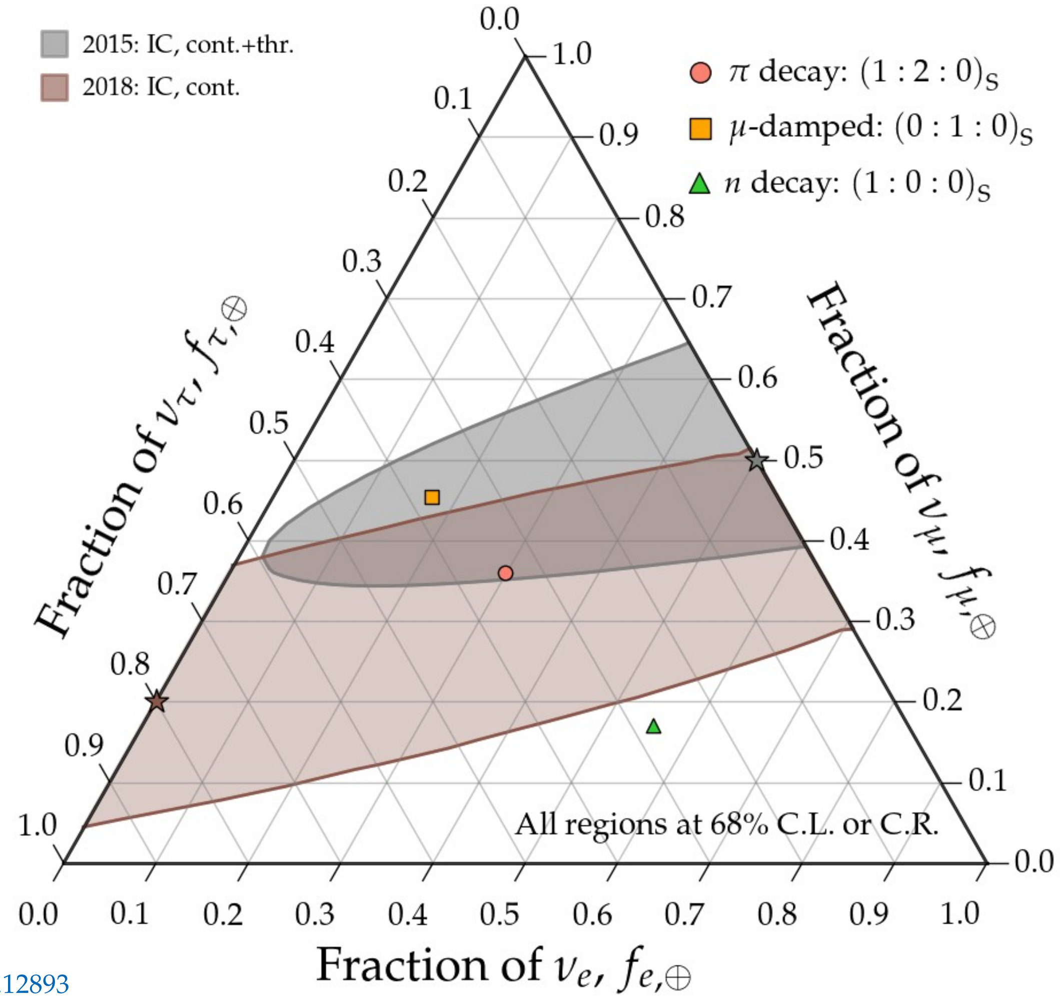
Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

Measuring flavor composition: 2015–2040



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

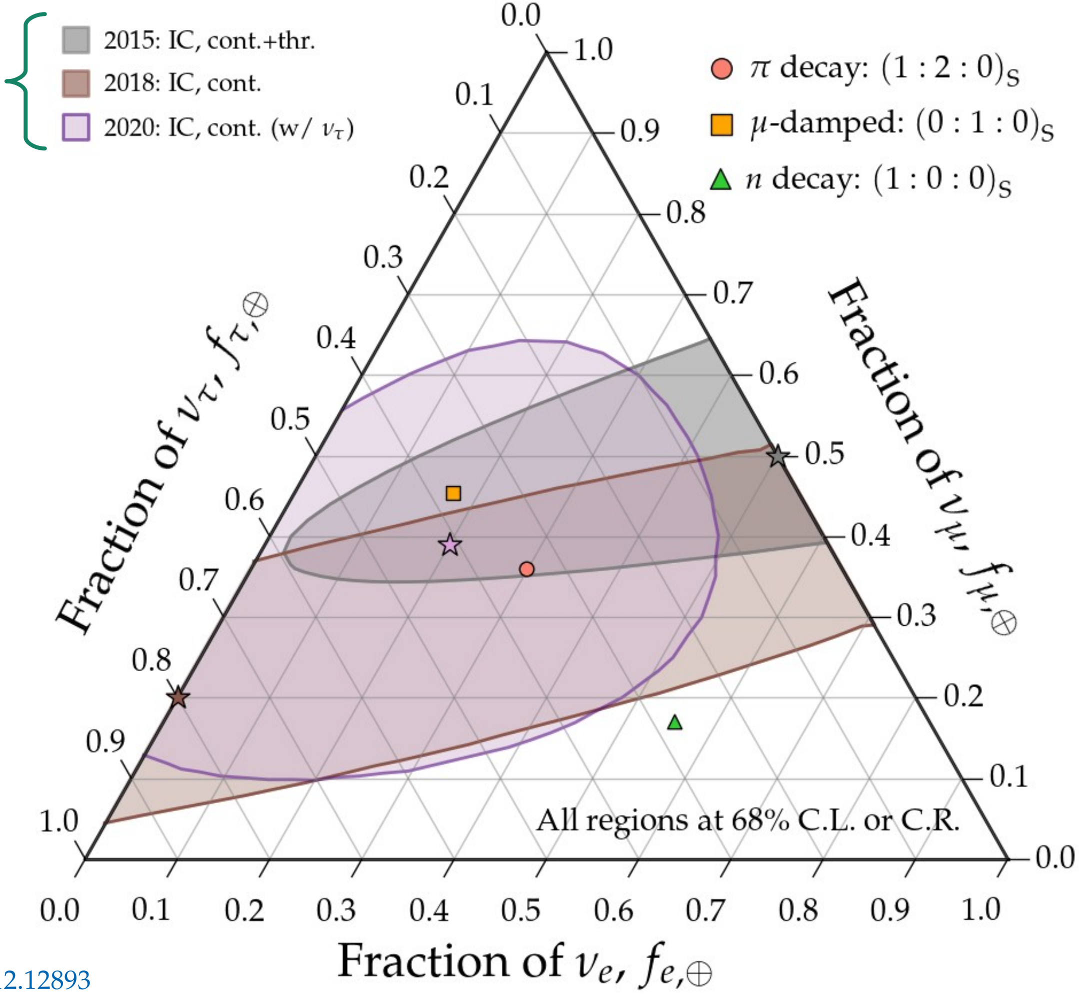
Measuring flavor composition: 2015–2040



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

Measuring flavor composition: 2015–2040

Based on real data



Status today:
Measurements are compatible with standard expectations (but errors are large!)

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

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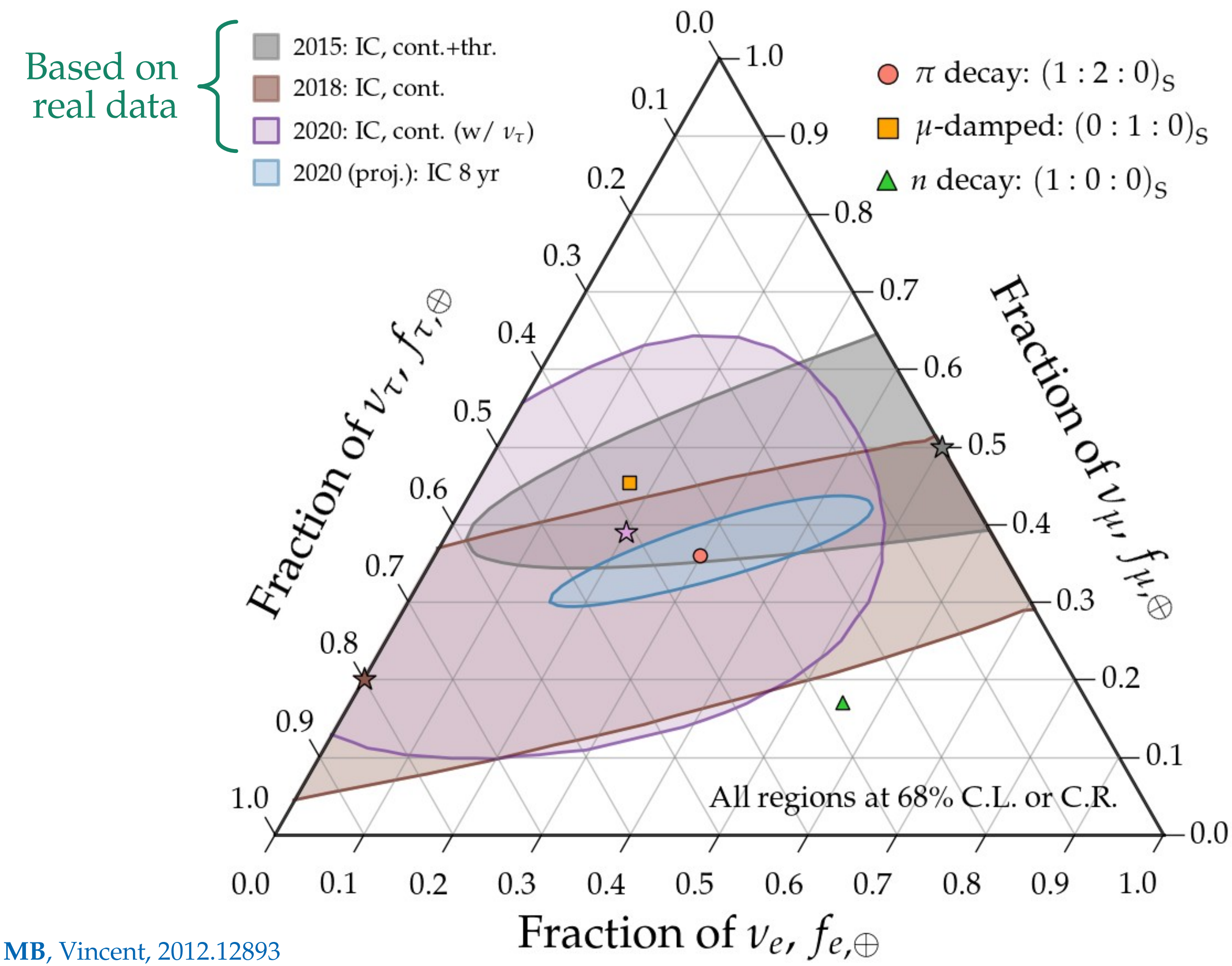

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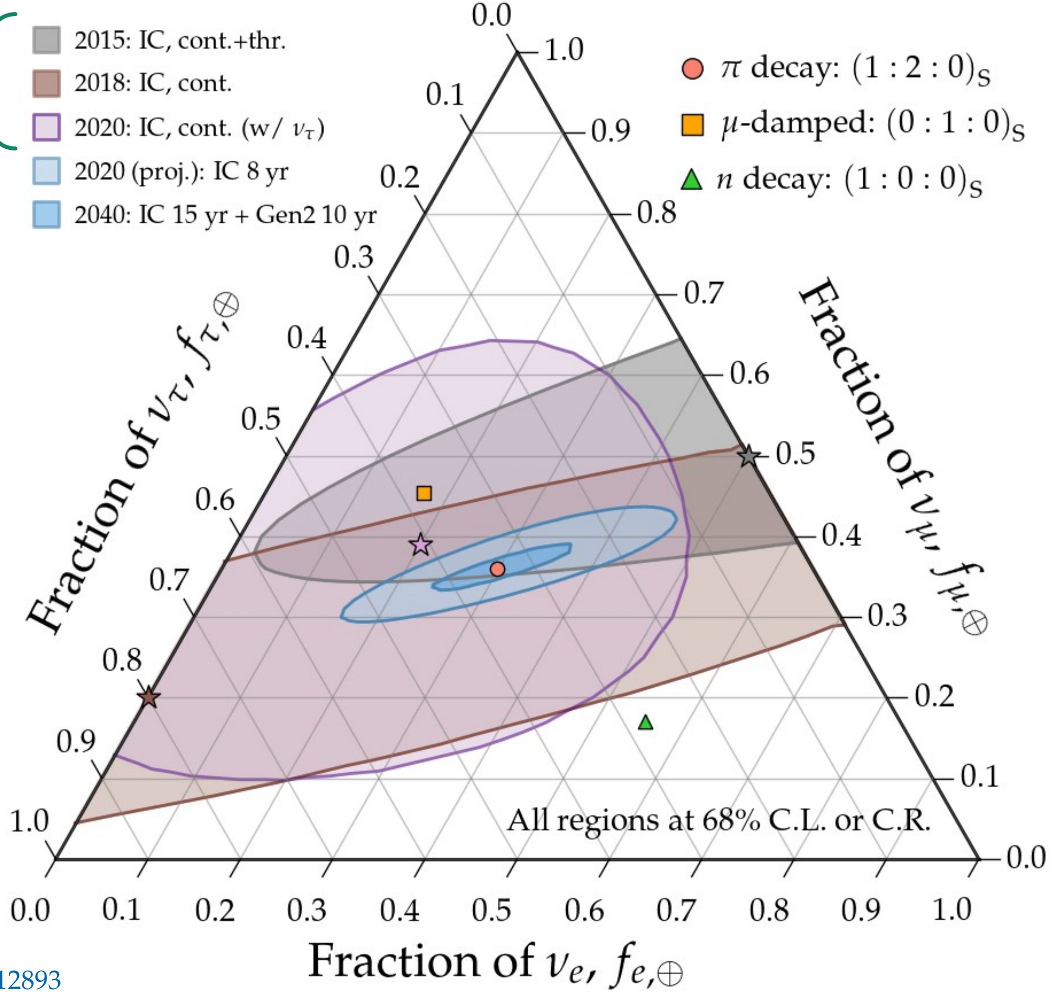
Projections:

Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

Measuring flavor composition: 2015–2040

Based on real data



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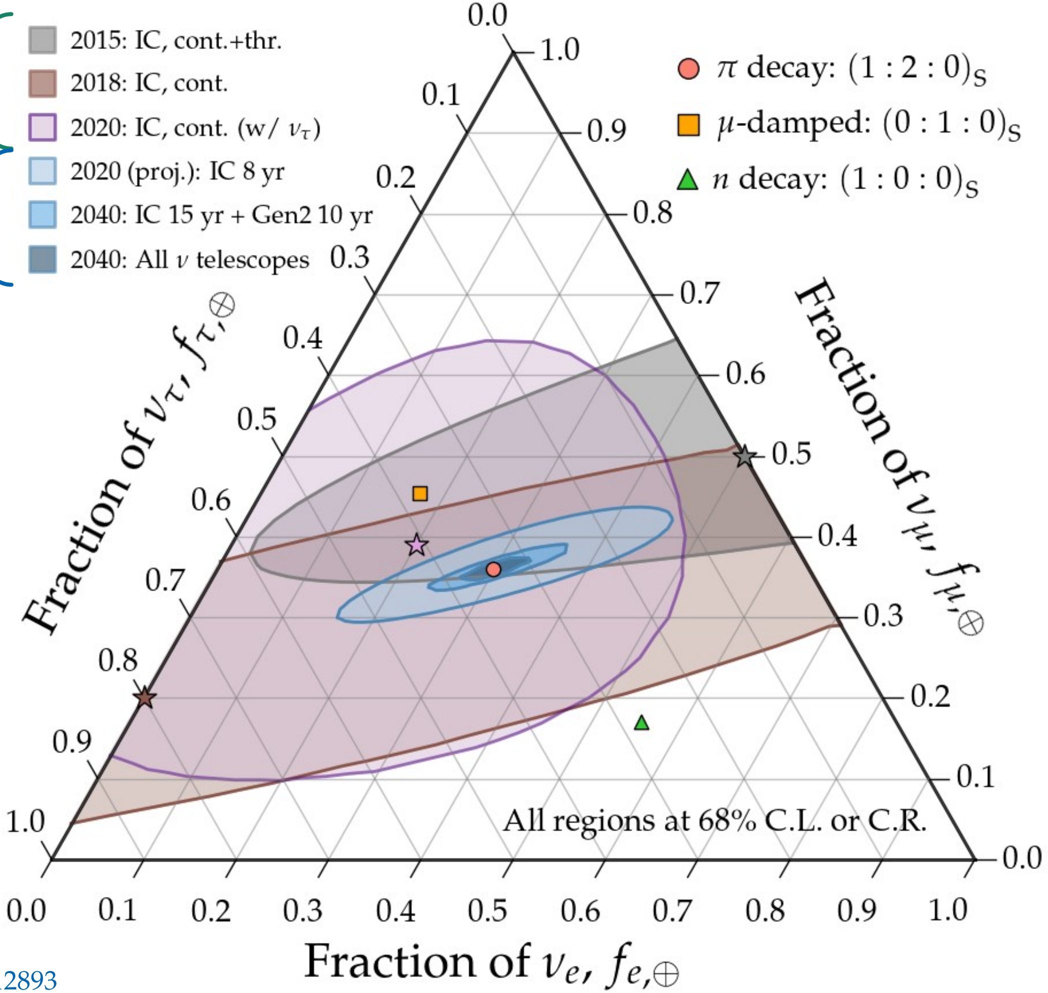
Measuring flavor composition: 2015–2040

Based on real data

Projections



Status today:
Measurements are compatible with standard expectations (but errors are large!)

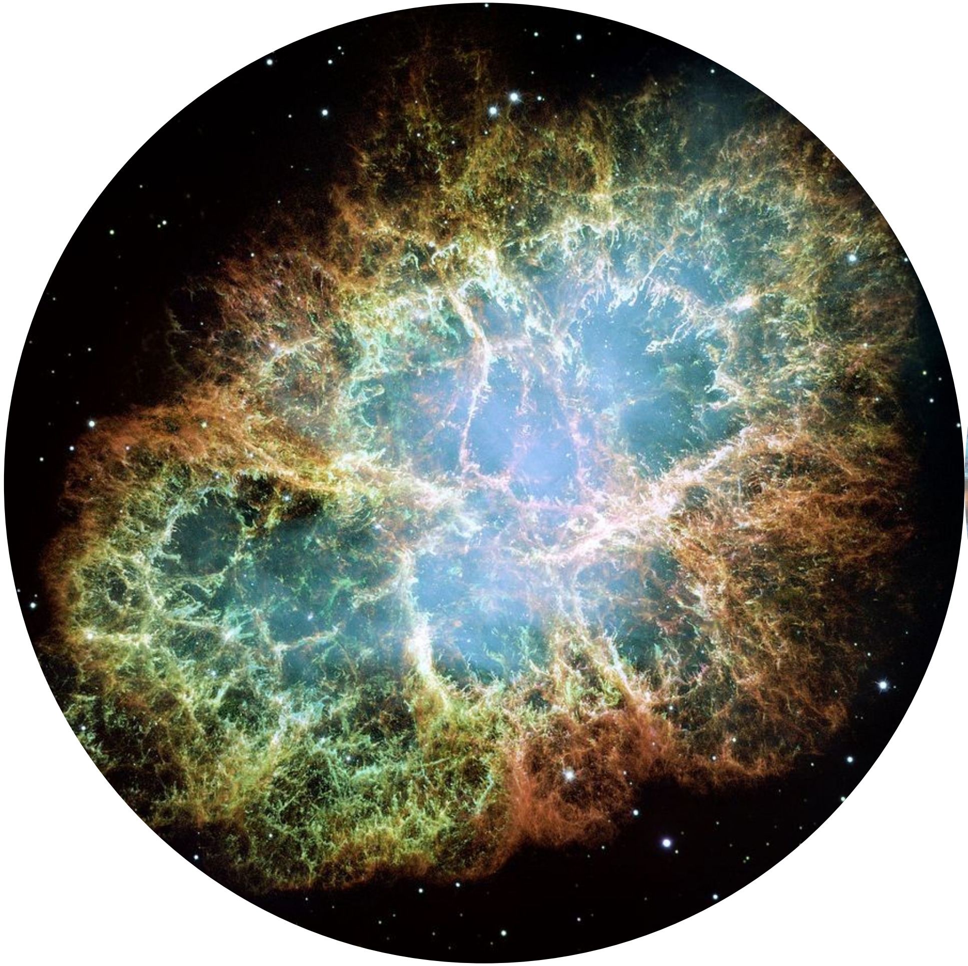
Projections:

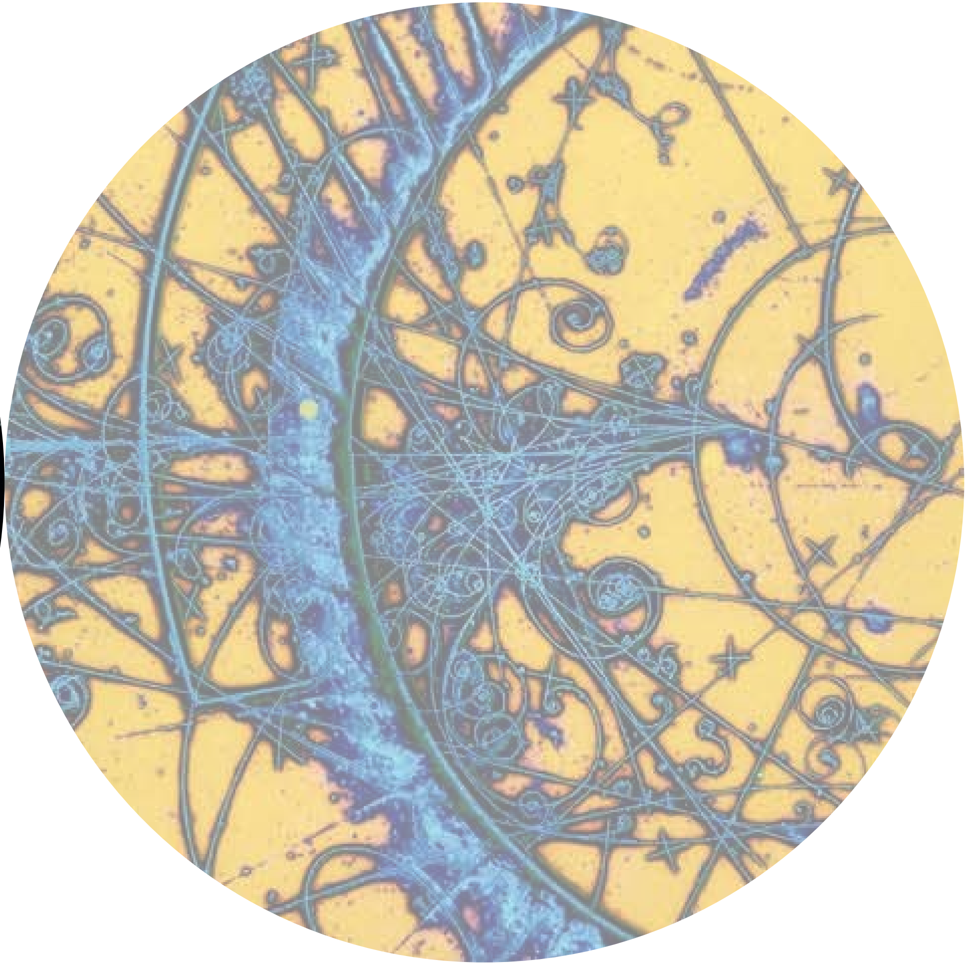
Near future (~2020):
× 5 reduction using 8 yr of IC contained + thru.

Coming up (~2040):
× 10 reduction using Gen2 and all ν telescopes

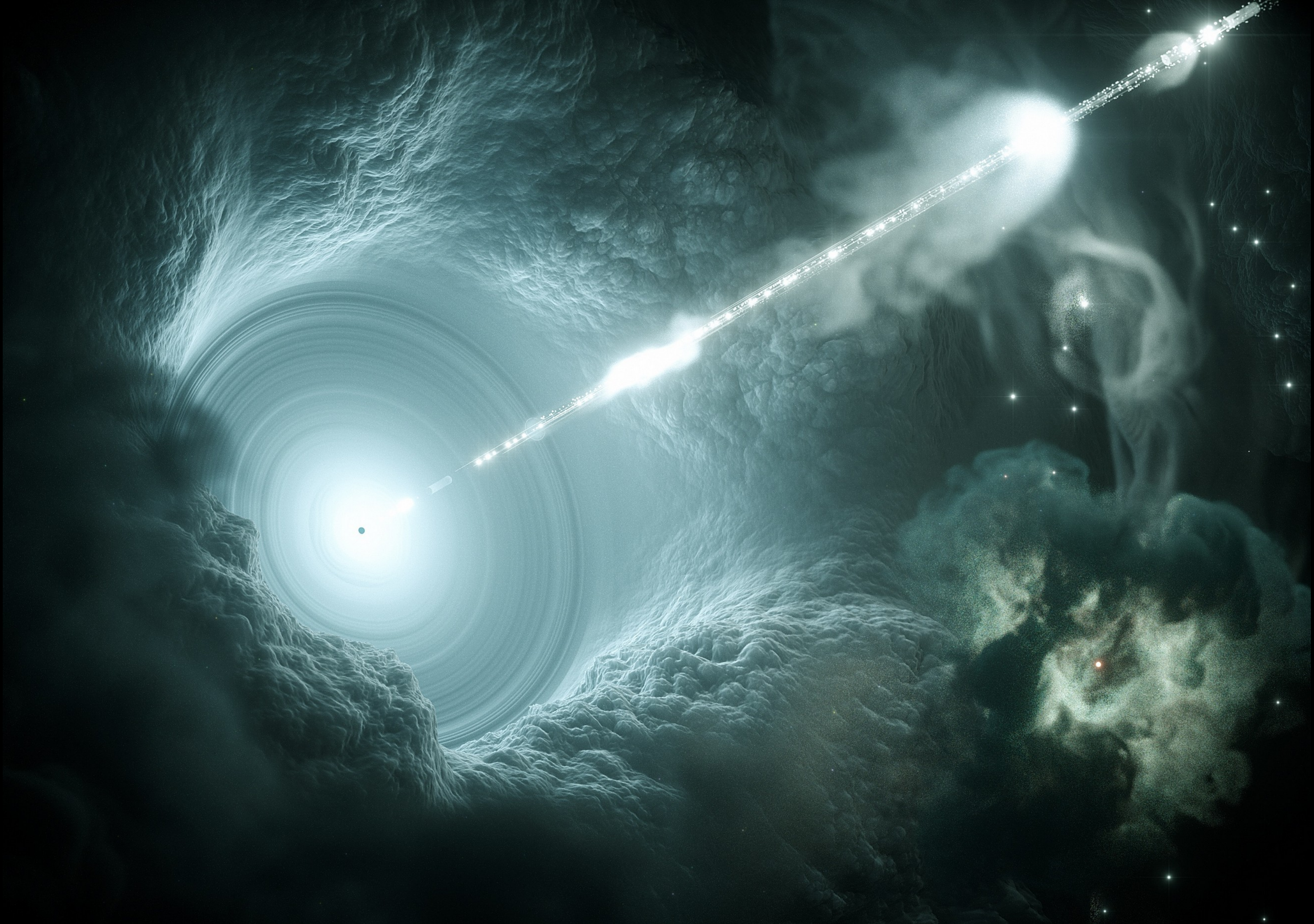
Song, Li, Argüelles, **MB**, Vincent, 2012.12893
IceCube, *PRL* 2015, *ApJ* 2015, *PRD* 2019, 2008.04323, 2011.03561

II.
Astrophysics with high-energy cosmic neutrinos



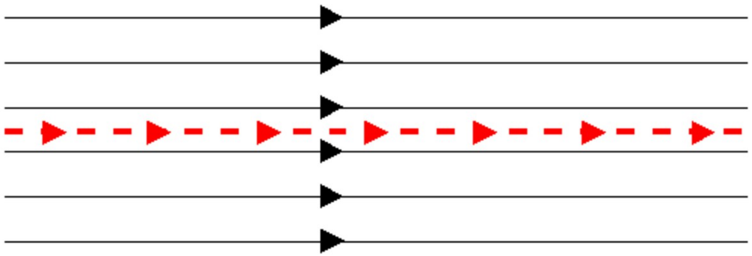
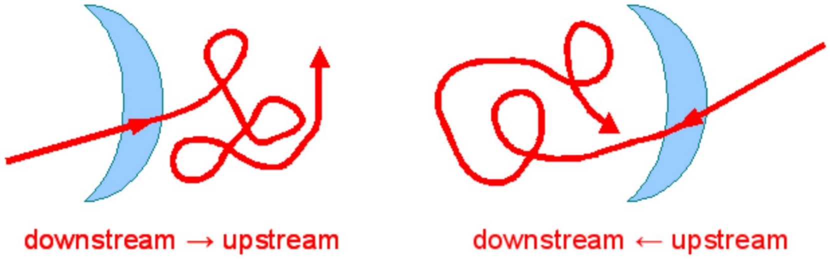


Banco Central de Reserva del Perú / NASA / ESA / CERN / Symmetry Magazine



DESY

Luckily, UHECR Sources Should Be Wasteful…

	Man-made accelerators	Astrophysical accelerators
		
Acceleration	In vacuum	In a medium
E.m. fields	Ordered	Messy
Beam dumps	Precisely regulated	Fully unregulated

Astrophysical accelerators *inevitably* make high-energy secondaries

The Hillas criterion

- Necessary condition for a source to accelerate cosmic rays

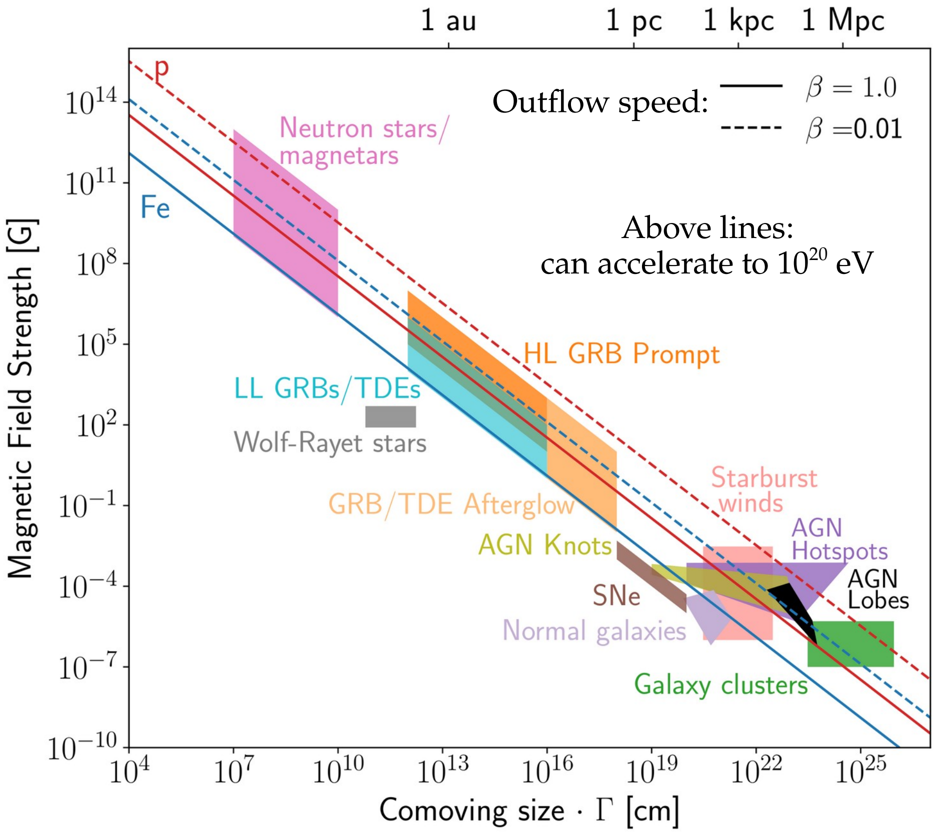
- Particles must stay confined:

Larmor radius < Size of acceleration region

$$R_L = E/(Z\,e\,B) < (R\,\Gamma)$$

- Maximum energy:

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

Alves Batista, **MB** *et al.*, *Frontiers* 2019
See also: Winter, *PRD* 2011

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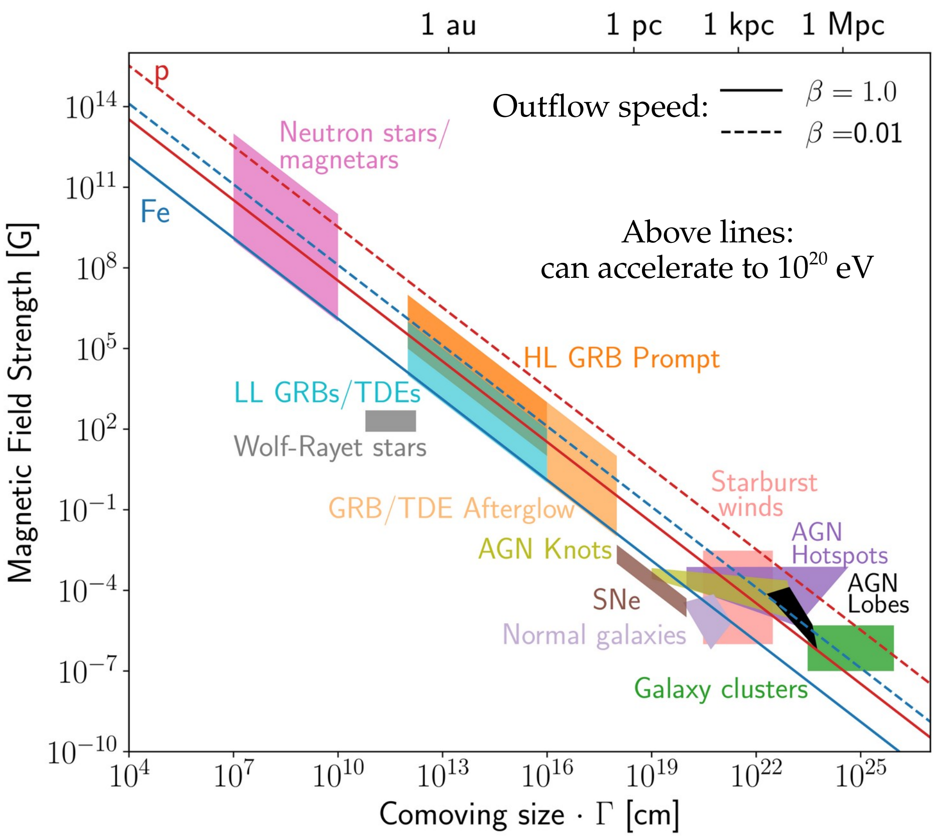

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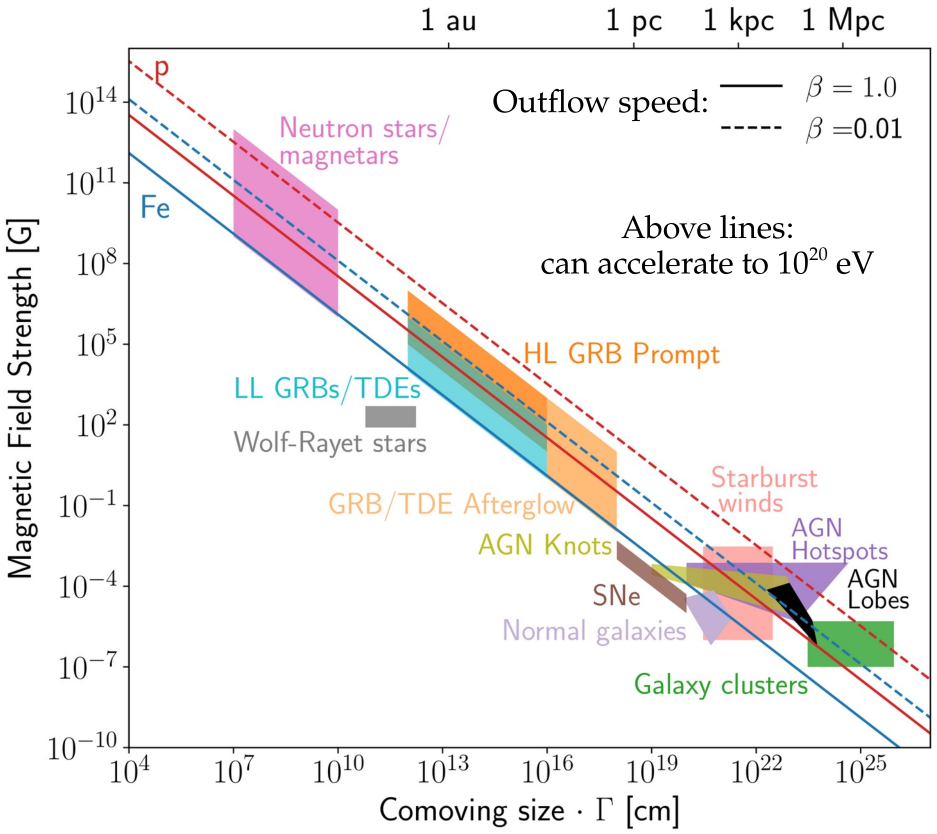
Bulk Lorentz factor of accelerating region

- Maximum energy:

Acceleration efficiency ($\eta = 1$ for perfect efficiency)

$$E_{\max} \approx \left(3 \cdot 10^{20}\ \mathrm{eV}\right) \eta^{-1} \beta_{\rm sh} Z \left(\frac{\Gamma R}{10^{16}\ \mathrm{cm}}\right) \left(\frac{B}{100\ \mathrm{G}}\right)$$

Speed $v_{\rm sh}/c$ of the outflow



Hillas, *Ann. Rev. Astron. Astrophys.* 1984

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See also: Winter, *PRD* 2011

Three strategies to reveal sources of TeV–PeV ν

Look at bright e.m. point sources

- **Examine single sources** → No evident single steady source, two *likely* transient source
- **Stack several similar sources** → Ruled out gamma-ray bursts, most blazars as dominant

Look for neutrino multiplets

- **Clustered in direction** → Placed generic limits on source number density and luminosity
- **Clustered in direction *and* time** → Used to trigger follow-ups by other detectors

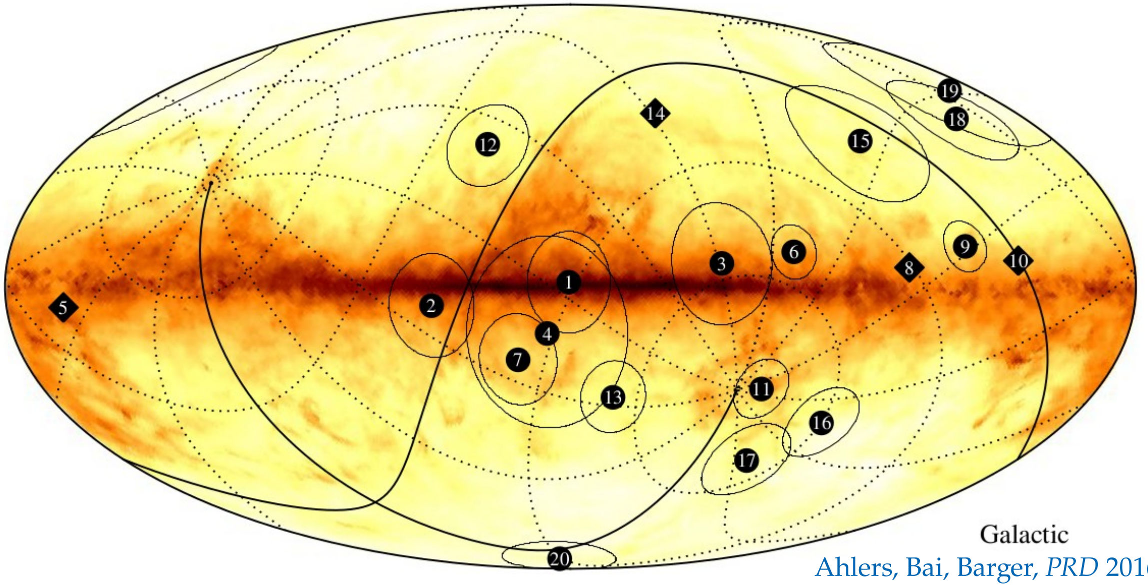
Use the diffuse neutrino flux → Any population of candidate sources must account for all or part of it

PeV neutrino sources in the Milky Way?

Candidates for full or partial contribution:

- Diffuse Galactic gamma-ray emission
- Unidentified gamma-ray sources
- Fermi bubbles
- Supernova remnants
- Pulsars
- Microquasars
- Sagitarius A*
- Galactic halo
- Heavy dark matter decay

HESE 3yr with $E_{dep} > 60$ TeV, $n_{tot} = 20$, $\widehat{f}_{iso} = 0.81$, $\lambda = 0.74$



Ahlers, Bai, Barger, *PRD* 2016

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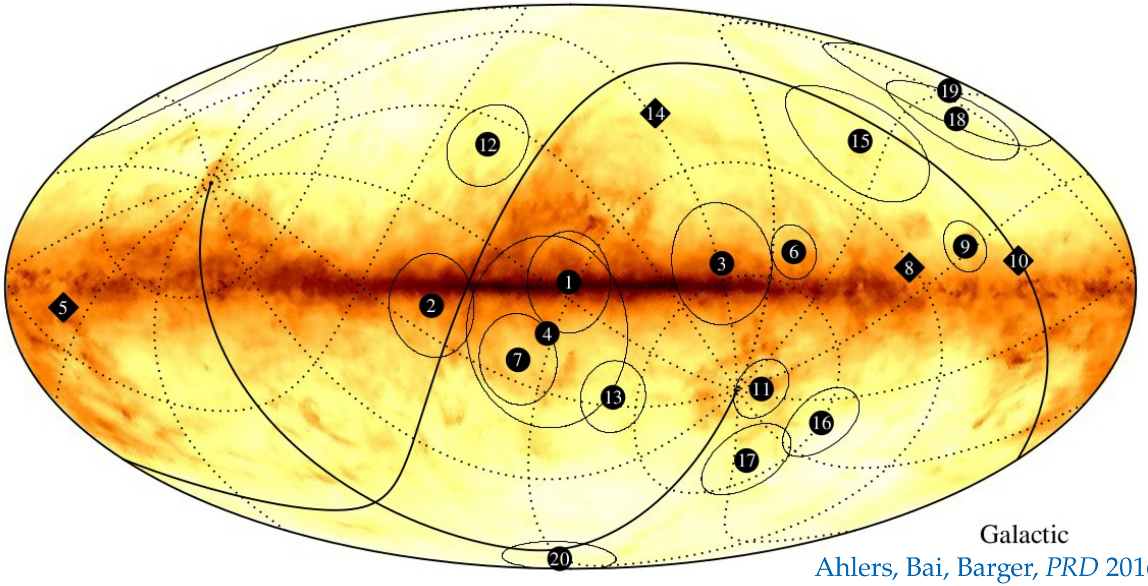

Ahlers, Bai, Barger, *PRD* 2016

Contribution from Galactic sources: < 14%

IceCube, *ApJ* 2017

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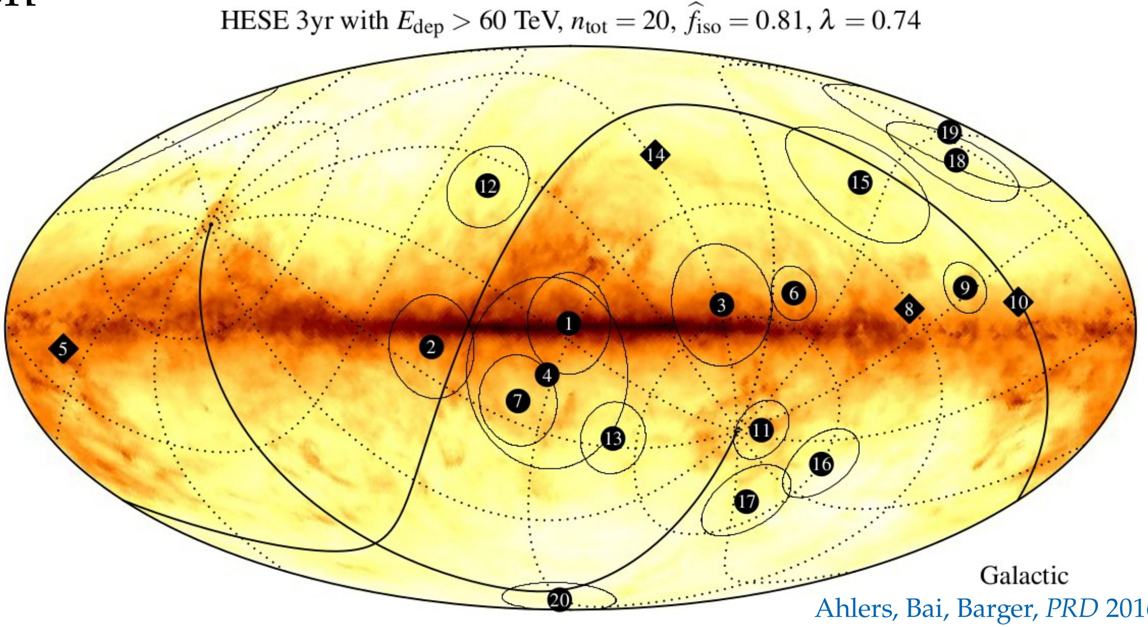
Q: What about the 0.1–1 PeV Galactic gamma rays seen by Tibet ASGamma (PRL 2021)?



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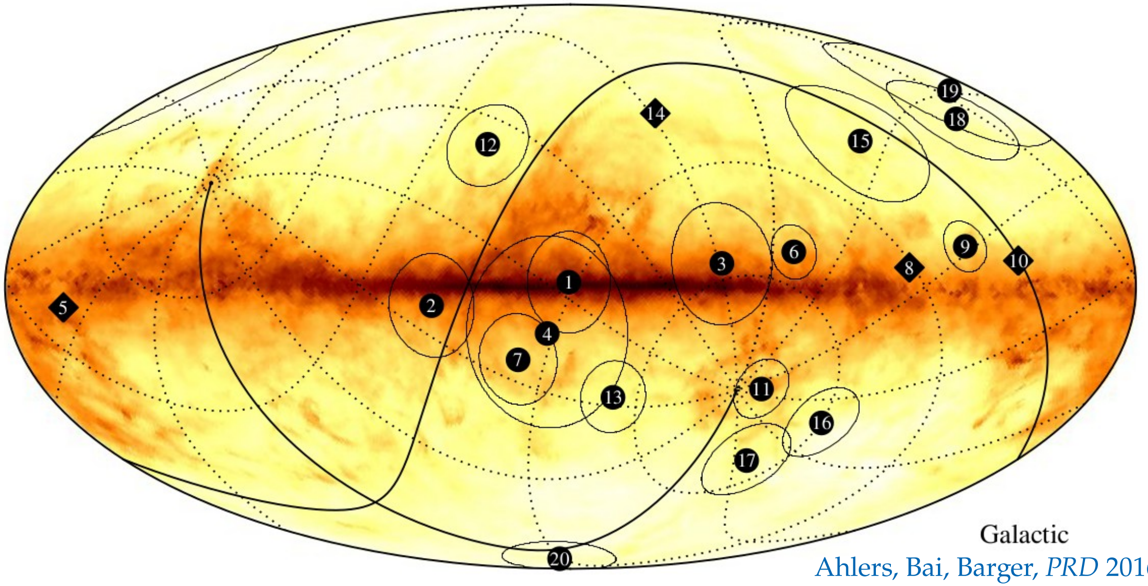

Ahlers, Bai, Barger, *PRD* 2016

Q: What about the 0.1–1 PeV Galactic gamma rays seen by Tibet ASGamma (PRL 2021)?

A: The accompanying ν emission from the Galactic Plane is < 5–10% of the diffuse ν flux seen by IceCube (2104.09491)

Contribution from Galactic sources: < 14%

IceCube, *ApJ* 2017

Bright in gamma rays, bright in high-energy neutrinos

Energy in neutrinos ∝ energy in gamma rays

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

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

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Fraction of total p energy
given to pions

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Fraction of p energy given to π in one interaction (~20%)

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Baryonic loading

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D. Guetta *et al.*, *Astropart. Phys.* 2004

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Fraction of total p energy given to pions

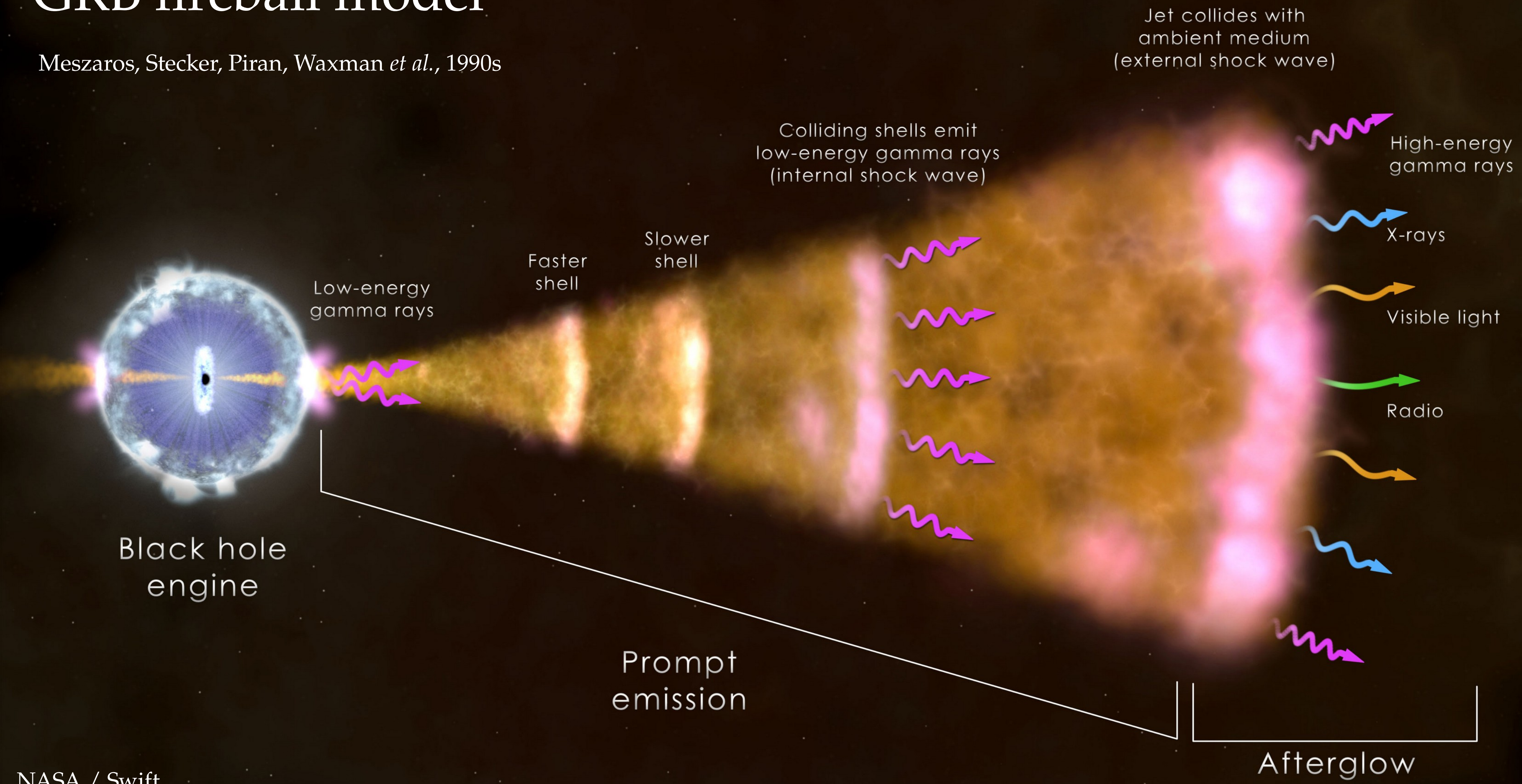
Baryonic loading

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

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

GRB fireball model

Meszaros, Stecker, Piran, Waxman *et al.*, 1990s



NASA / Swift

GRB fireball model

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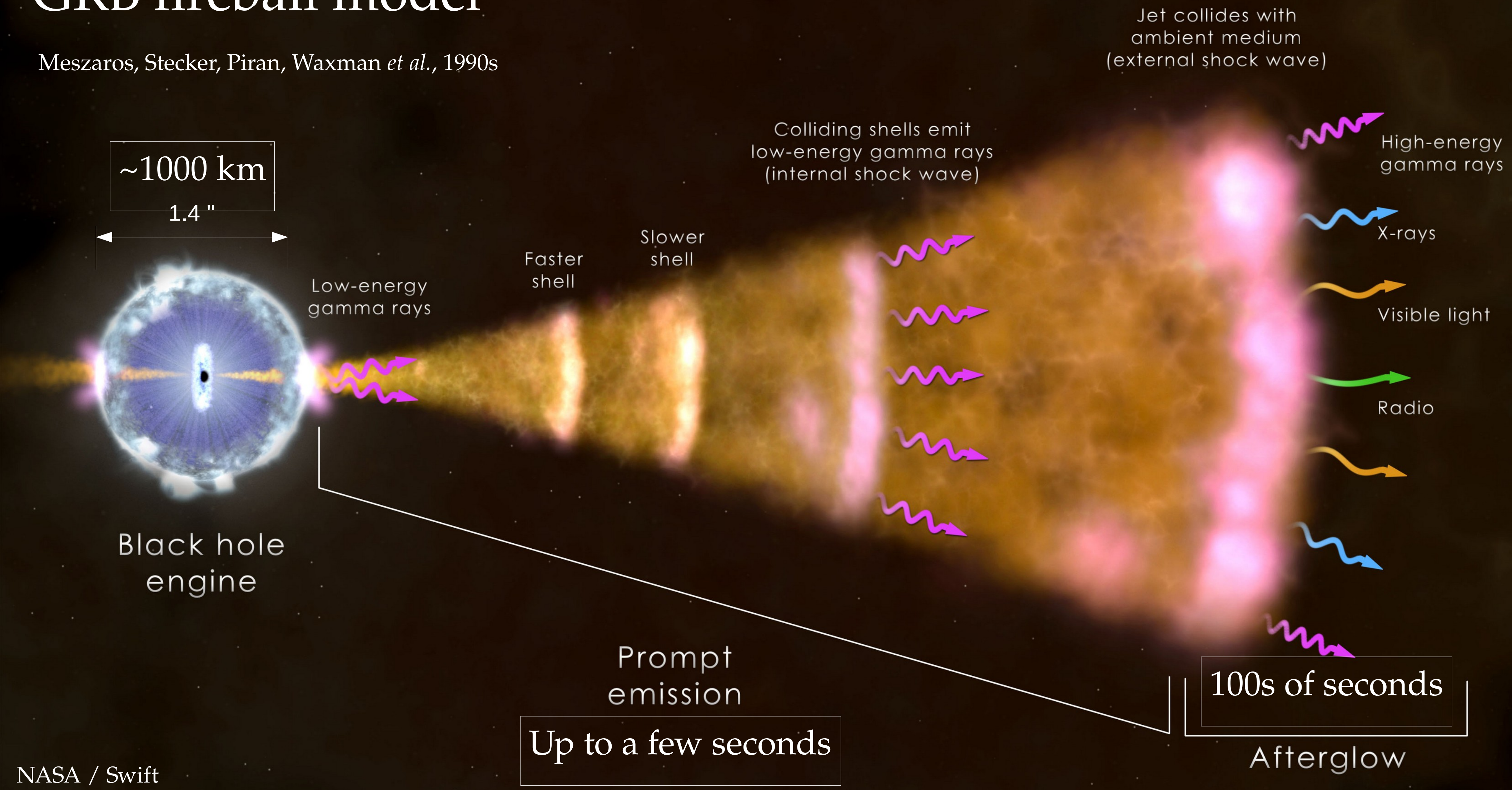

NASA / Swift

GRB fireball model

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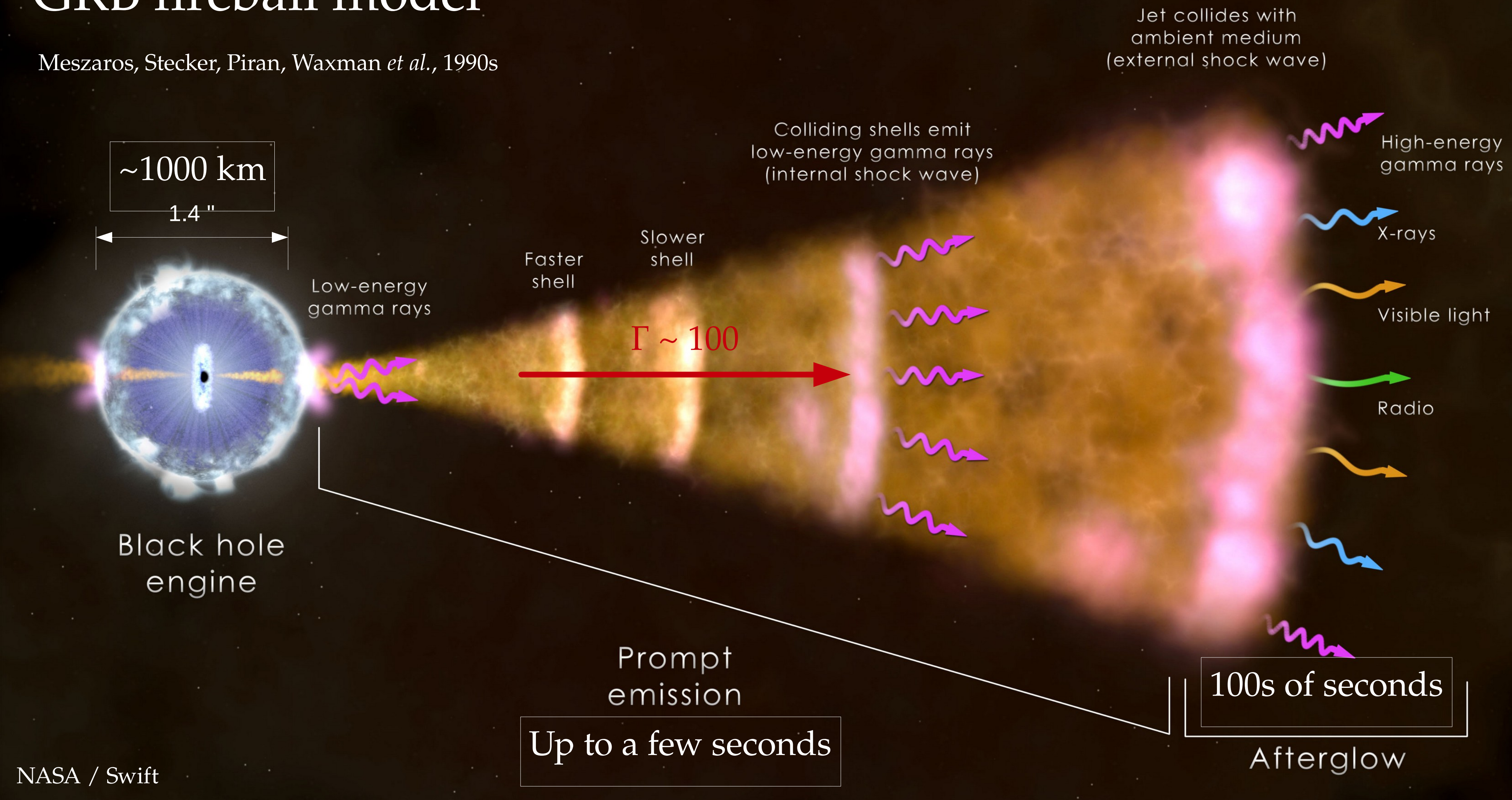
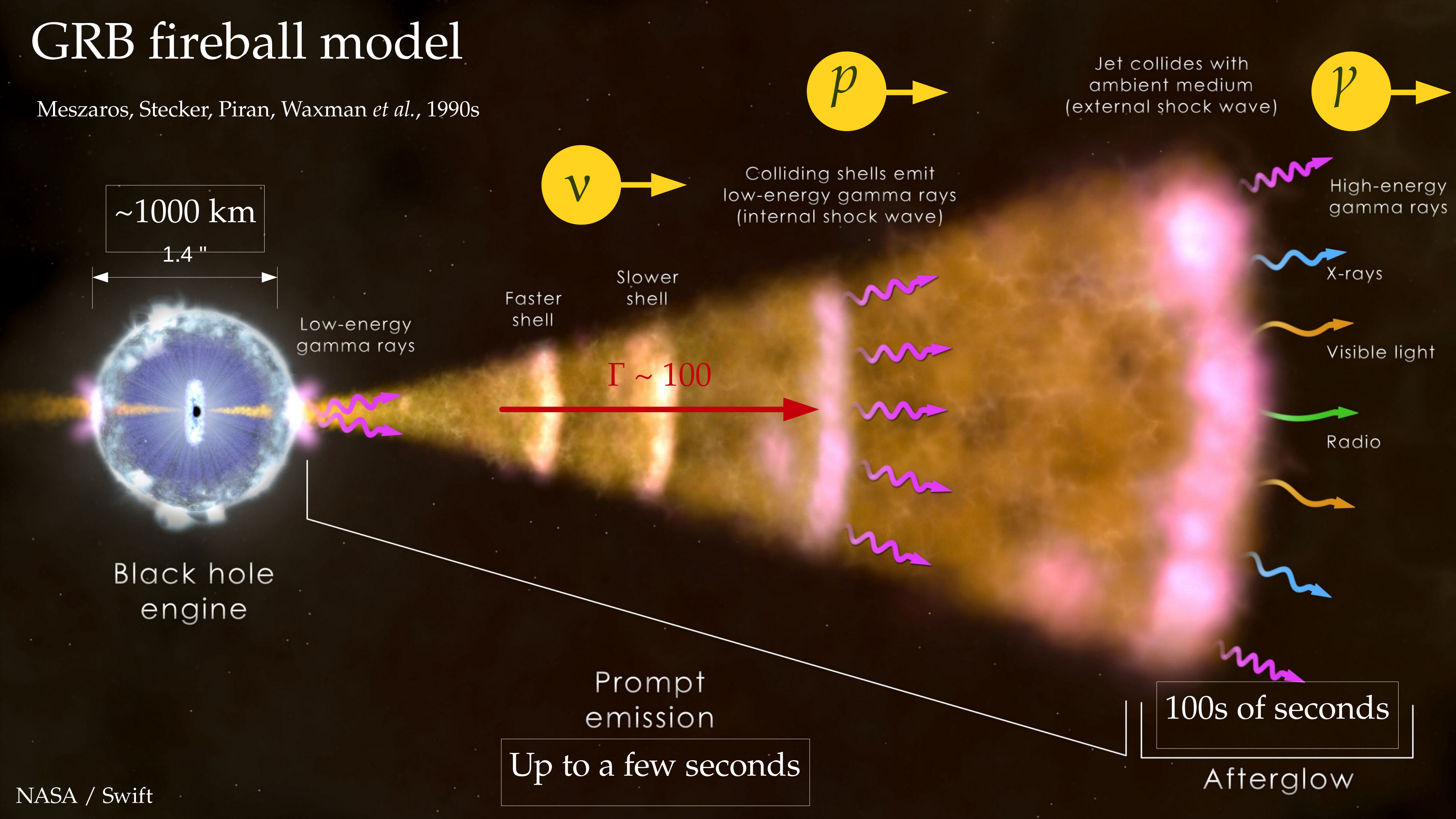
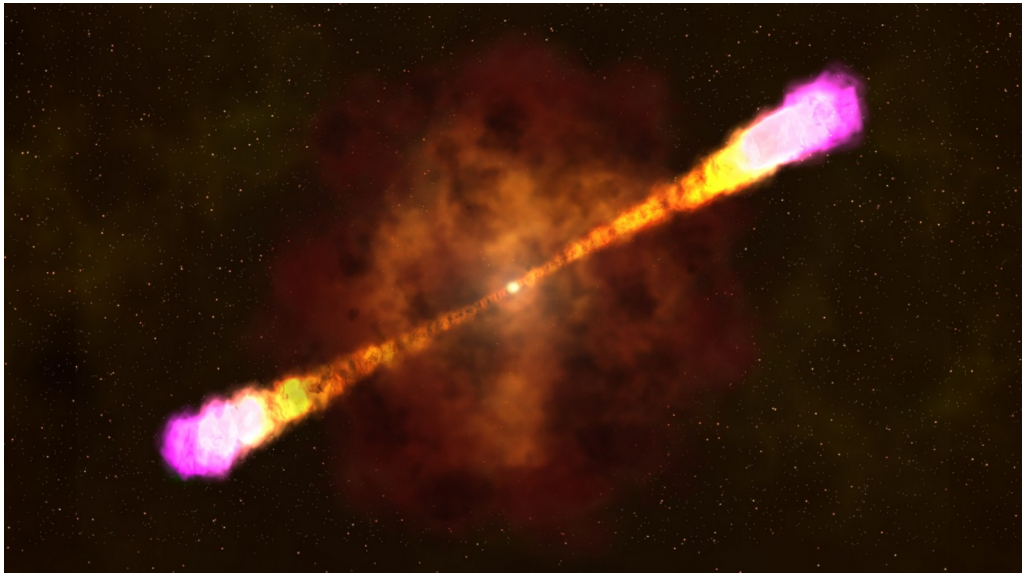



GRB fireball model
Meszaros, Stecker, Piran, Waxman et al., 1990s
~1000 km
1.4 "
Black hole engine
Low-energy gamma rays
ν
Faster shell
Slower shell
Γ ~ 100
p
Colliding shells emit low-energy gamma rays (internal shock wave)
Jet collides with ambient medium (external shock wave)
γ
High-energy gamma rays
X-rays
Visible light
Radio
Prompt emission
Up to a few seconds
100s of seconds
Afterglow
NASA / Swift

Gamma-ray bursts and blazars – *not* dominant

Gamma-ray bursts



Blazars

Gamma-ray bursts and blazars – *not* dominant

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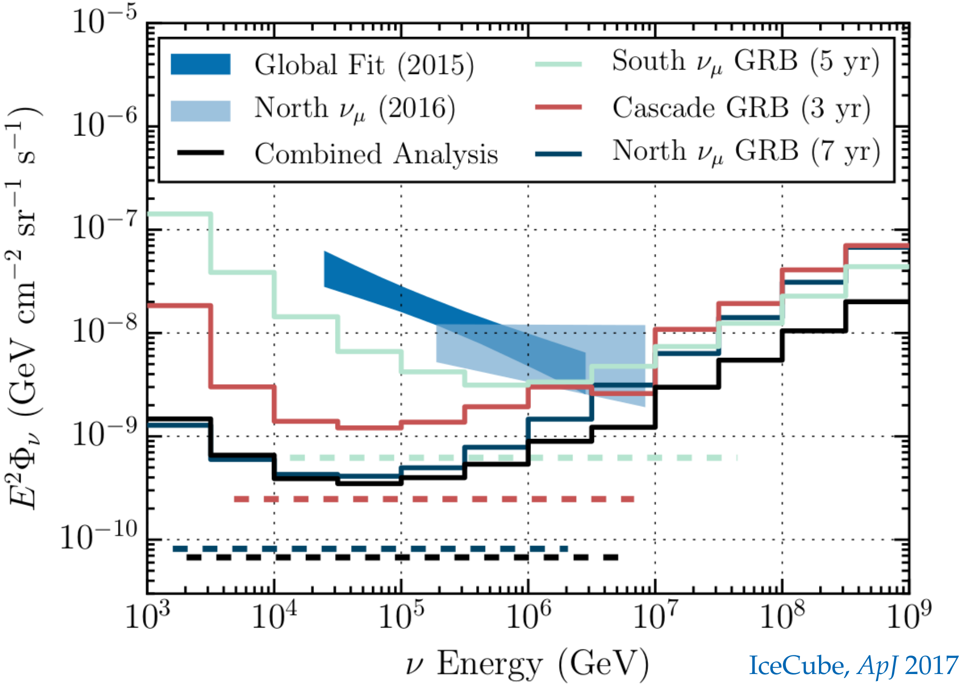
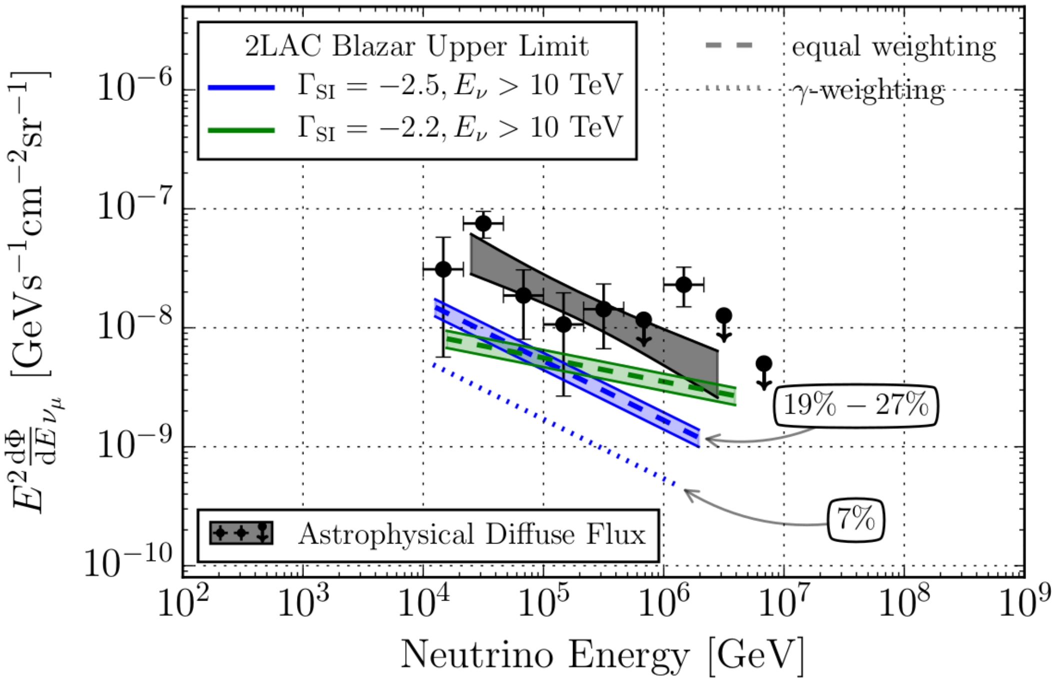


IceCube, *ApJ* 2017

1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux

Blazars



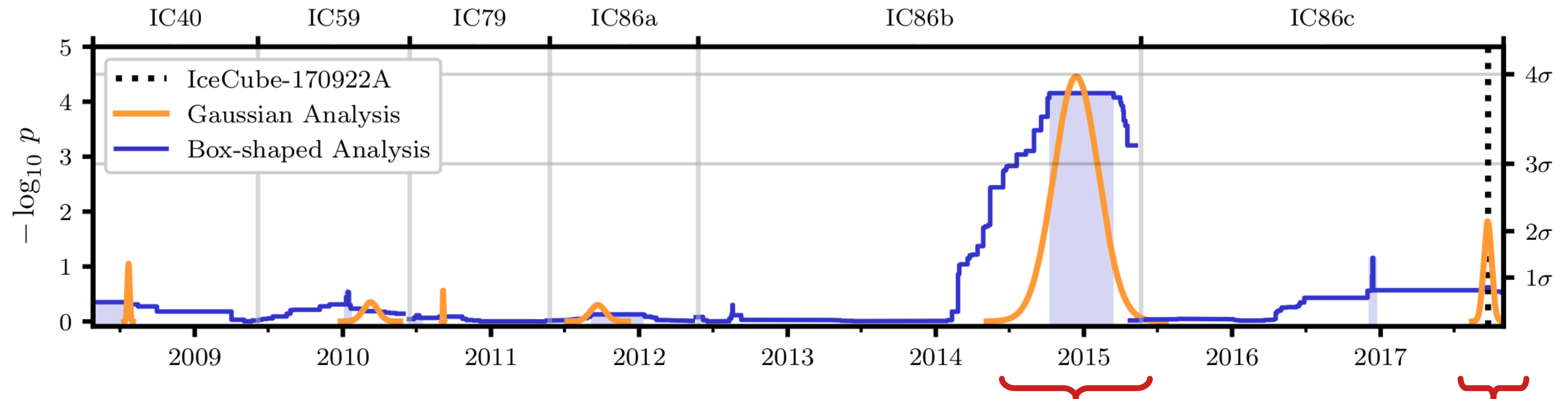
862 blazars inspected, no correlation found

< 27% contribution to diffuse flux

… but we have seen *one* blazar neutrino flare!

Blazar TXS 0506+056:

IceCube, *Science* 2018



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

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

Combined (pre-trial): 4.1σ

Hard fluence: $E^2 J_{100} = 2.1^{+0.9}_{-0.7} \left(\frac{E}{100\ \text{TeV}}\right)^{-2.1\pm0.2}\ \text{TeV cm}^{-2}$

Joint modeling of the two periods is challenging; see ICRC 2019 talk by Walter Winter

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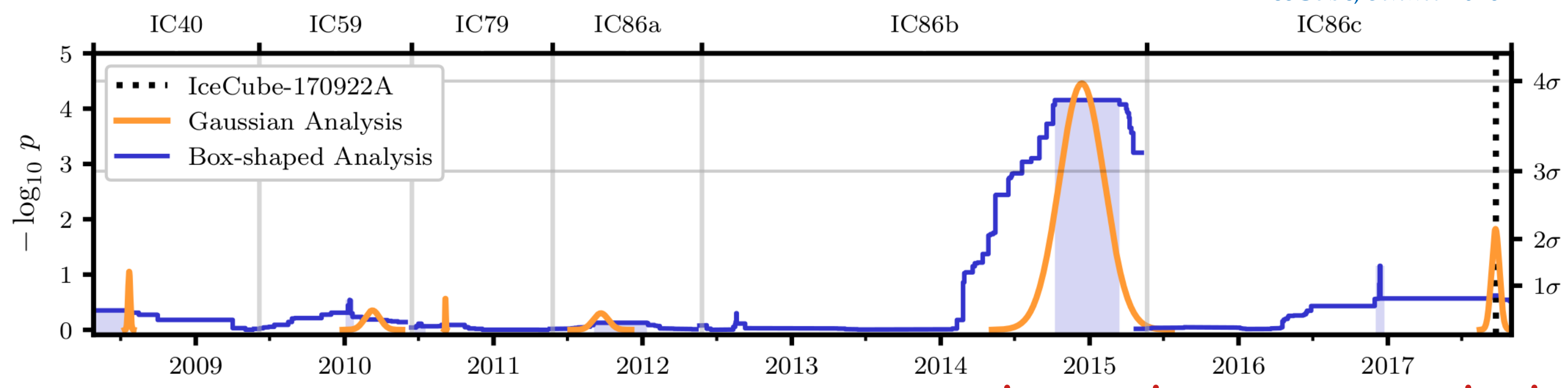

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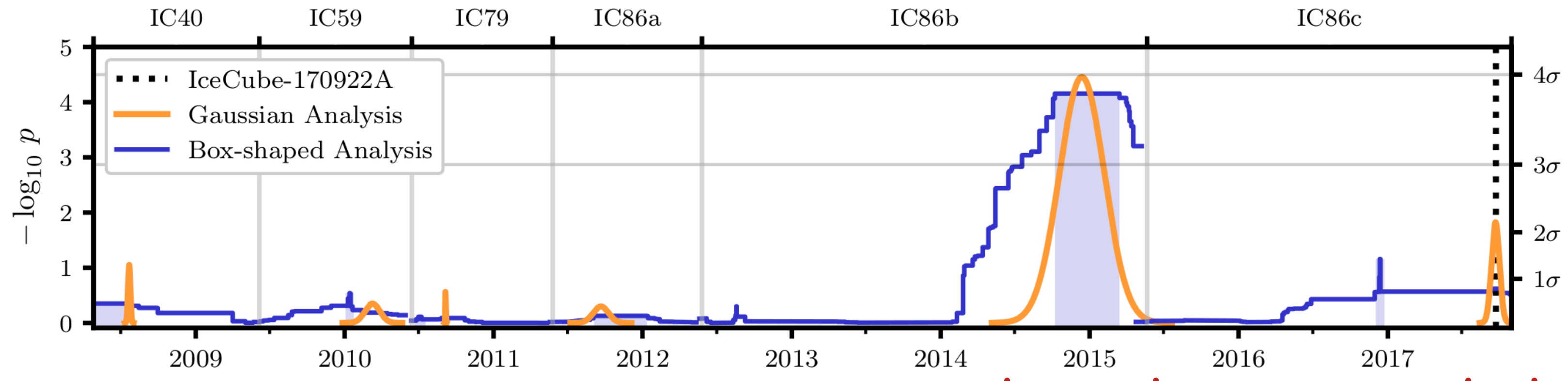

After re-analysis (2101.09836), significance dropped from $p=7\times10^{-5}$ to $p=8\times10^{-3}$

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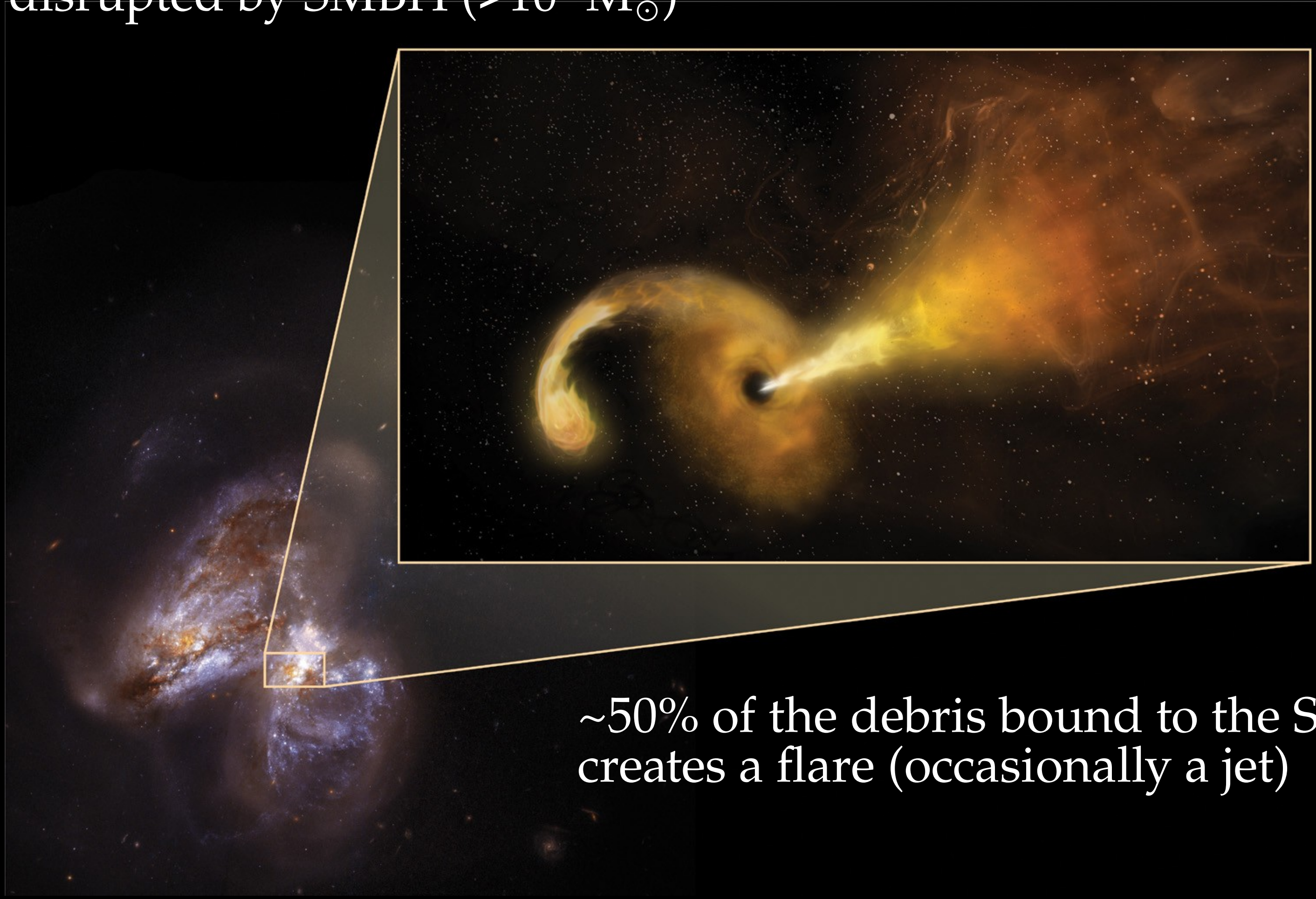
Tidal disruption events

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



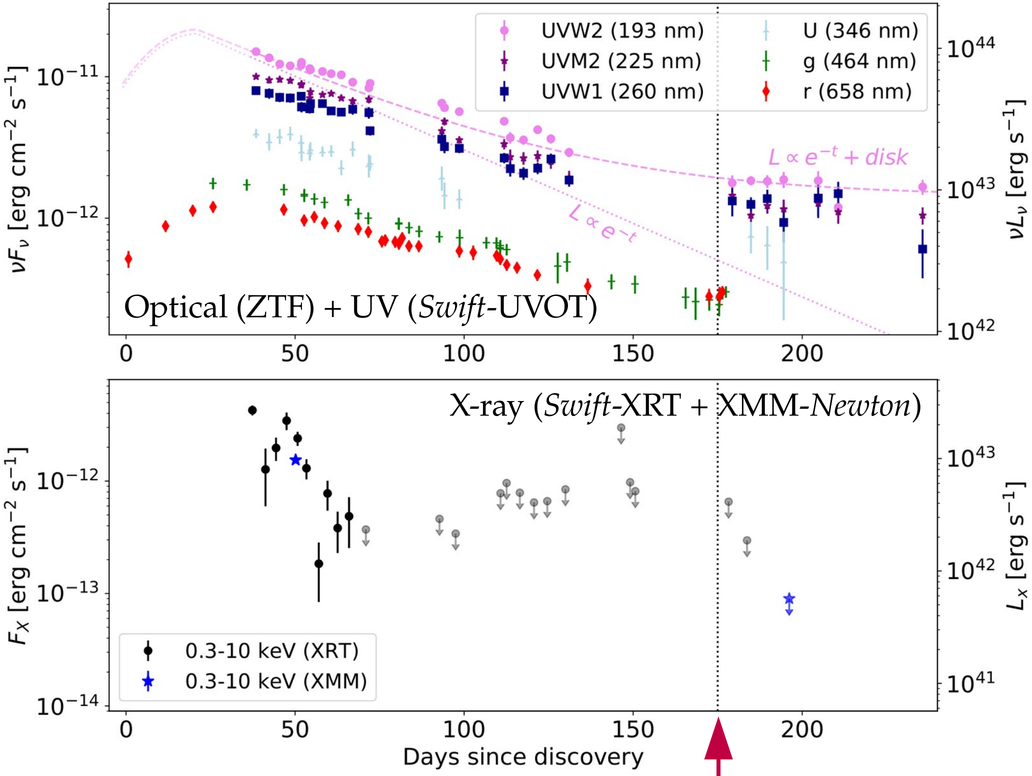
~50% of the debris bound to the SMBH, creates a flare (occasionally a jet)

NASA

An apparent TDE neutrino source

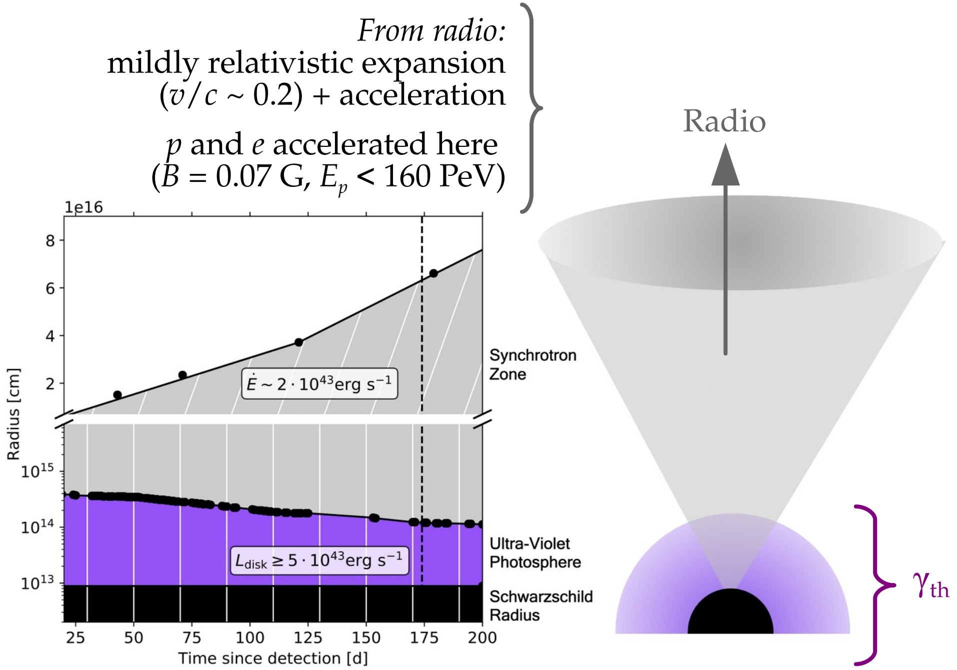
Radio-emitting TDE AT2019dsg coincident with neutrino event IC191001A:

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



IC191001A, ~200 TeV

Multi-zone model:



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

Stein *et al.*, 2005.05340 – See also: Winter & Lunardini, 2005.06097; Murase *et al.*, 2005.08937

Can we learn something about the neutrino sources without knowing them?

Can we learn something about the neutrino sources without knowing them?

Yes.

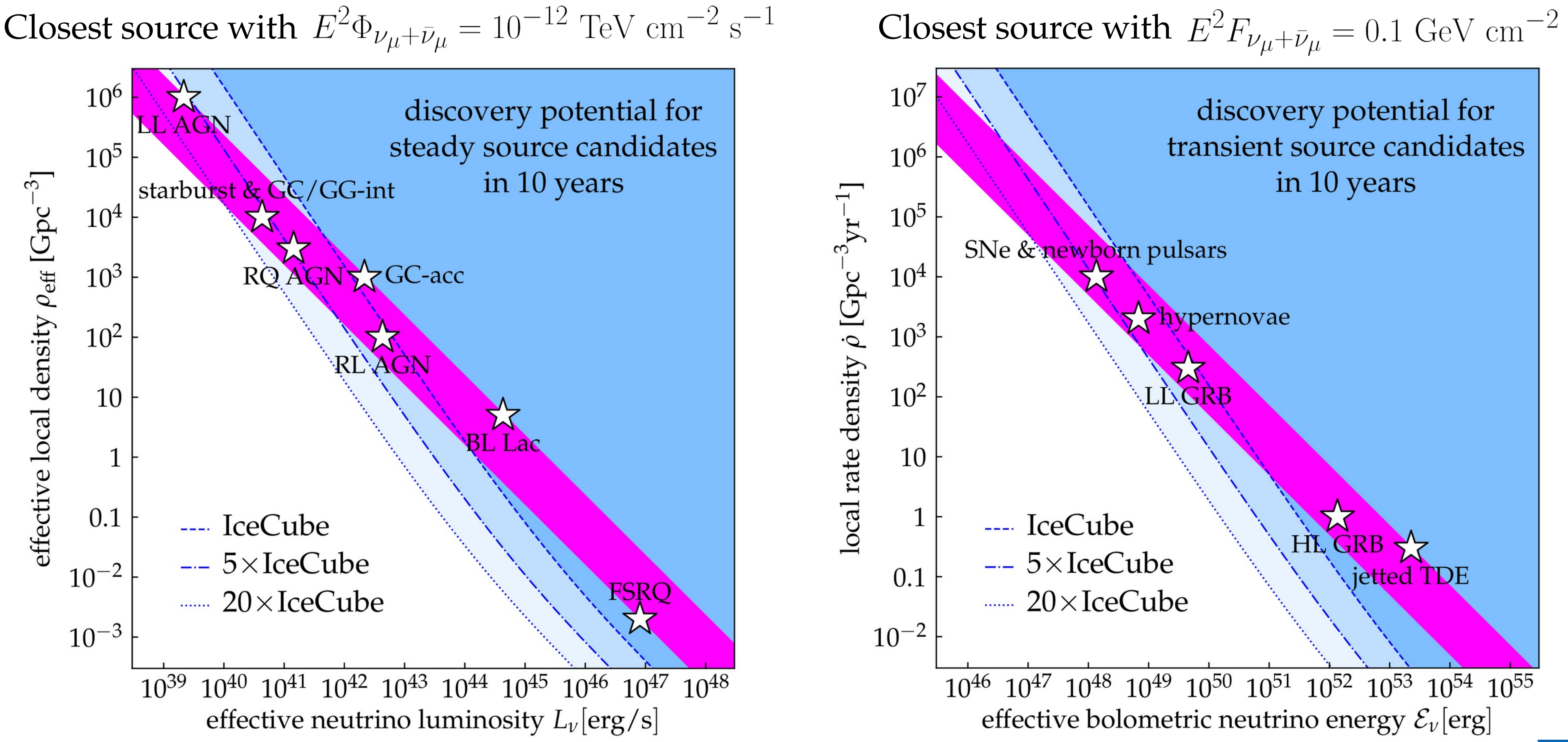
Can we learn something about the neutrino sources without knowing them?

Yes.

Already today.

Source discovery potential: today and in the future

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



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

Using high-energy neutrinos as magnetometers

If sources have strong magnetic fields, charged particles cool via synchrotron:

$$p + \gamma(p) \to \pi^+ \to \mu^+ + \nu_\mu$$
$$\hookrightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

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Proton cooling

Induce a high-energy cut-off in the emitted ν spectrum:

$$E_\nu'^2 \frac{dN_\nu}{dE_\nu'} \propto E_\nu'^{2-\alpha_\nu} e^{-E_\nu'/E_\nu'^{\max}}$$

$$E_\nu^{\max} \approx \frac{10^{10}\Gamma\ \mathrm{GeV}}{\sqrt{B'/\mathrm{G}}}$$

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MB, Tamborra, *PRD* 2020

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Muon cooling

Change flavor composition:

$$(f_{e,\text{S}}, f_{\mu,\text{S}}, f_{\tau,\text{S}}) = \begin{cases} (\frac{1}{3}, \frac{2}{3}, 0), & \text{if } E_\nu < E_{\nu,\mu}^{\text{sync}} \\ (0, 1, 0), & \text{if } E_\nu \geq E_{\nu,\mu}^{\text{sync}} \end{cases}$$

$$E_{\nu,\mu}^{\text{sync}} \approx 10^9 \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

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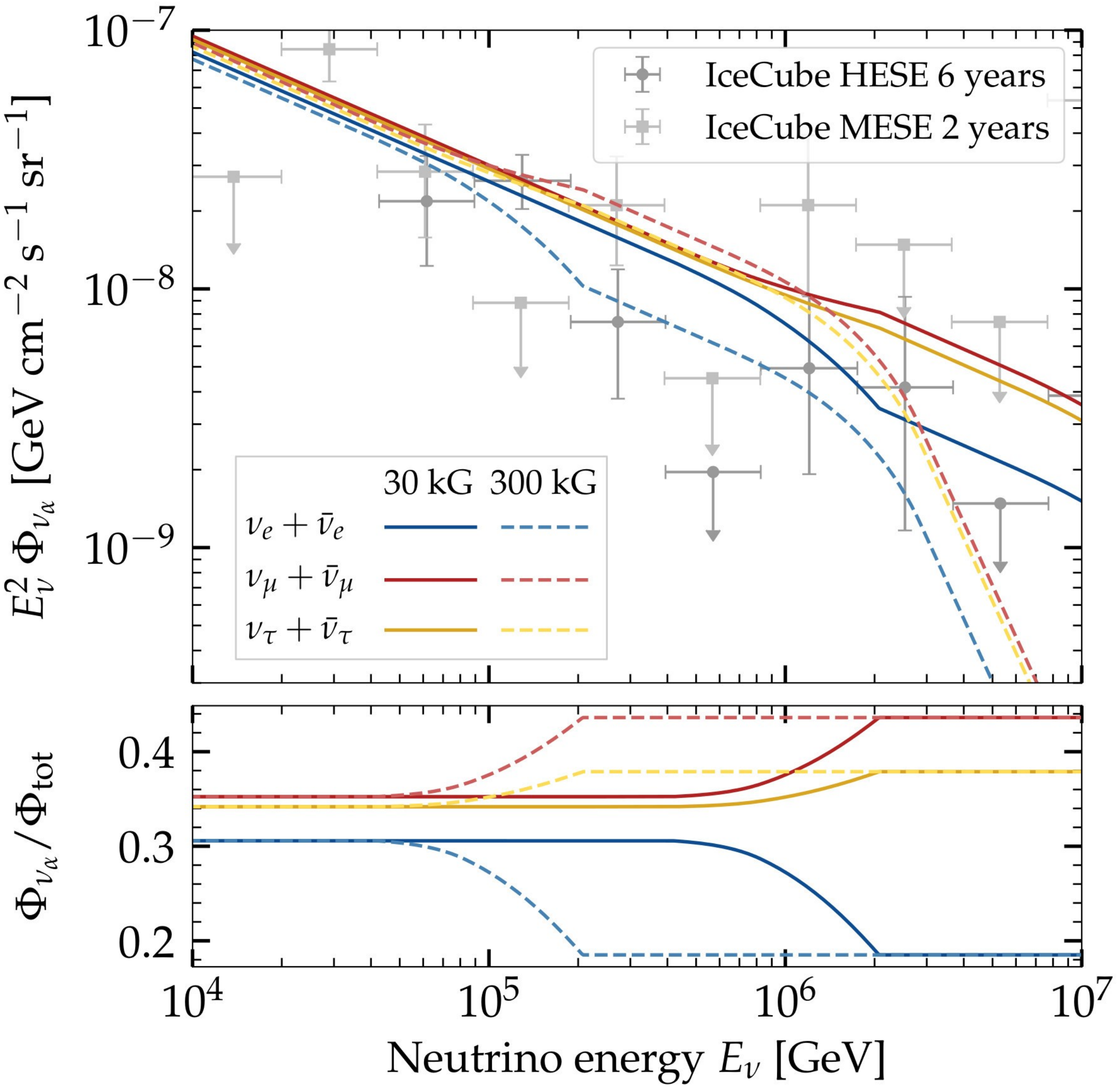
$$\mu^+ \rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Pion cooling

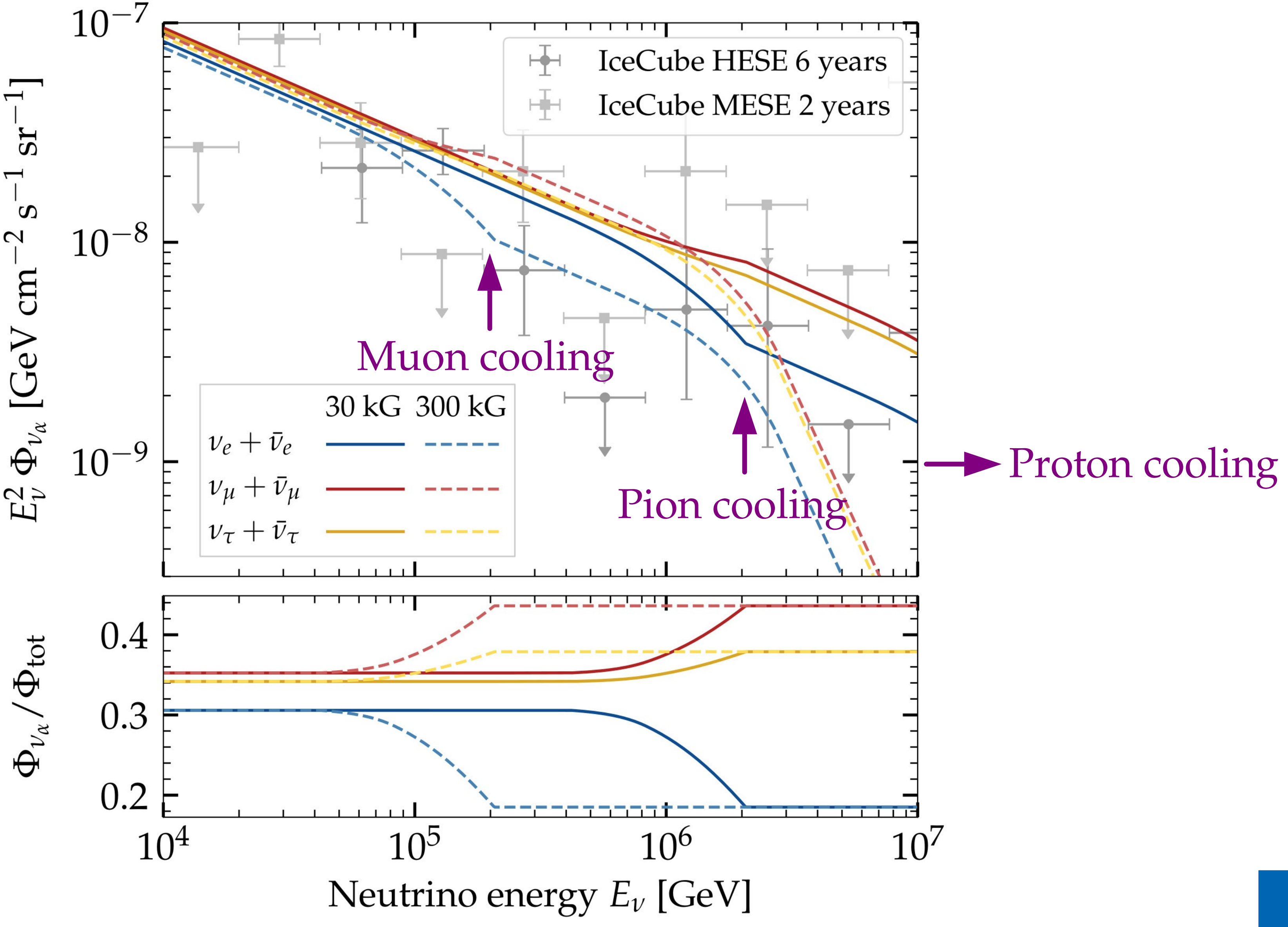
Steepen the ν spectrum: $\alpha_\nu = \begin{cases} \gamma, & \text{if } E_\nu < E^{\text{sync}}_{\nu,\pi} \\ \gamma + 2, & \text{if } E_\nu \geq E^{\text{sync}}_{\nu,\pi} \end{cases}$

$$E^{\text{sync}}_{\nu,\pi} \approx 10^{10} \Gamma \frac{\text{G}}{B'} \text{ GeV}$$

MB, Tamborra, *PRD* 2020



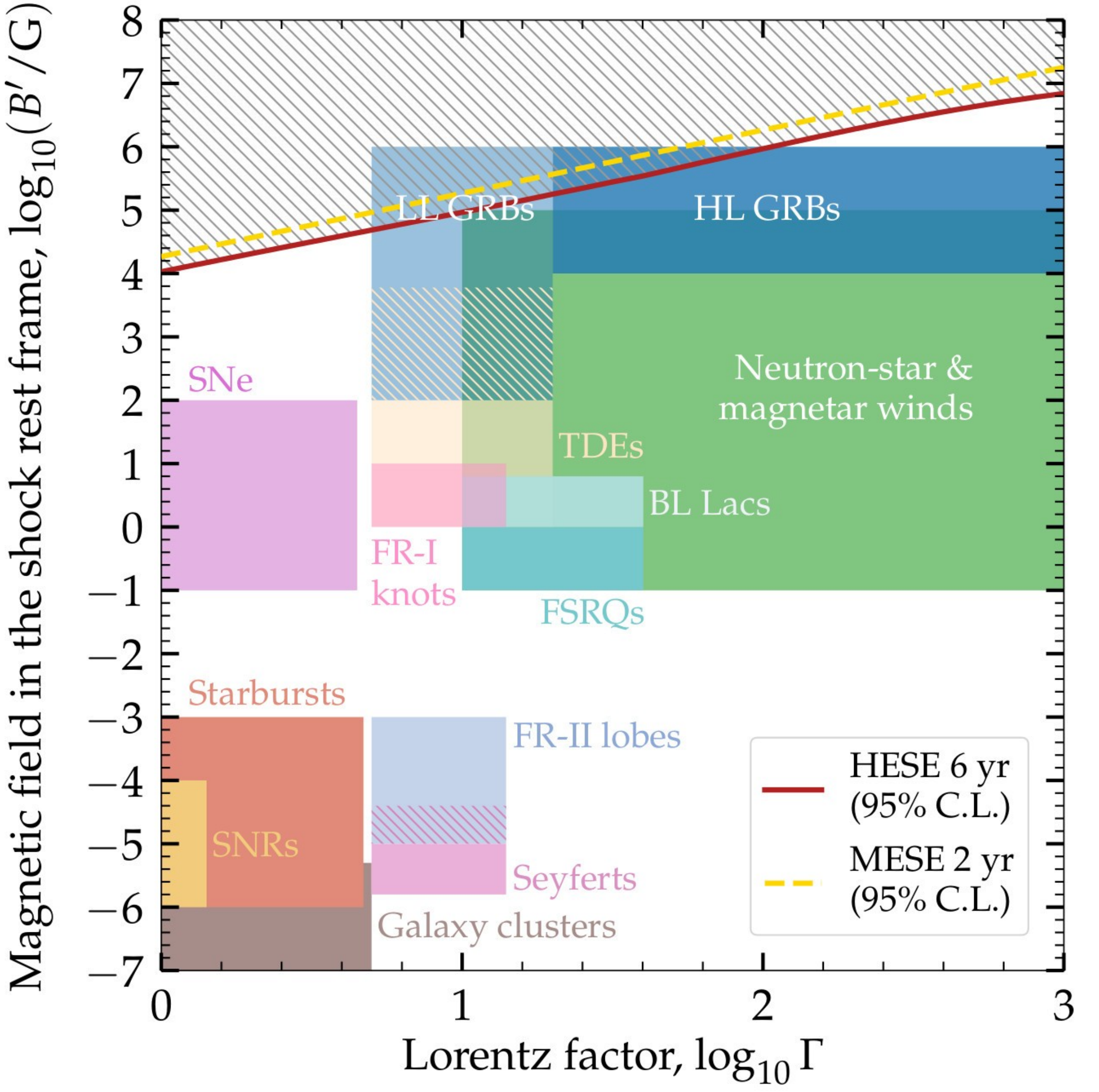
MB, Tamborra, *PRD* 2020



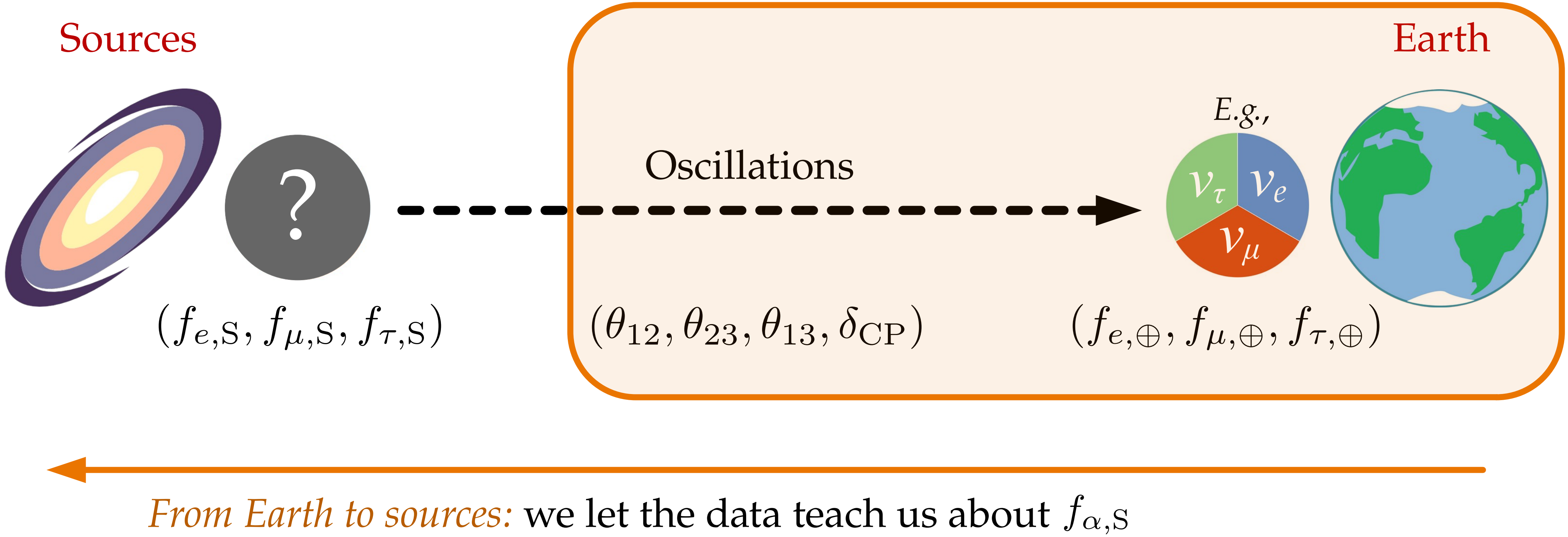
MB, Tamborra, *PRD* 2020

ν sources with strong B' are likely not dominant

Average B' must be < 10kG–10 MG



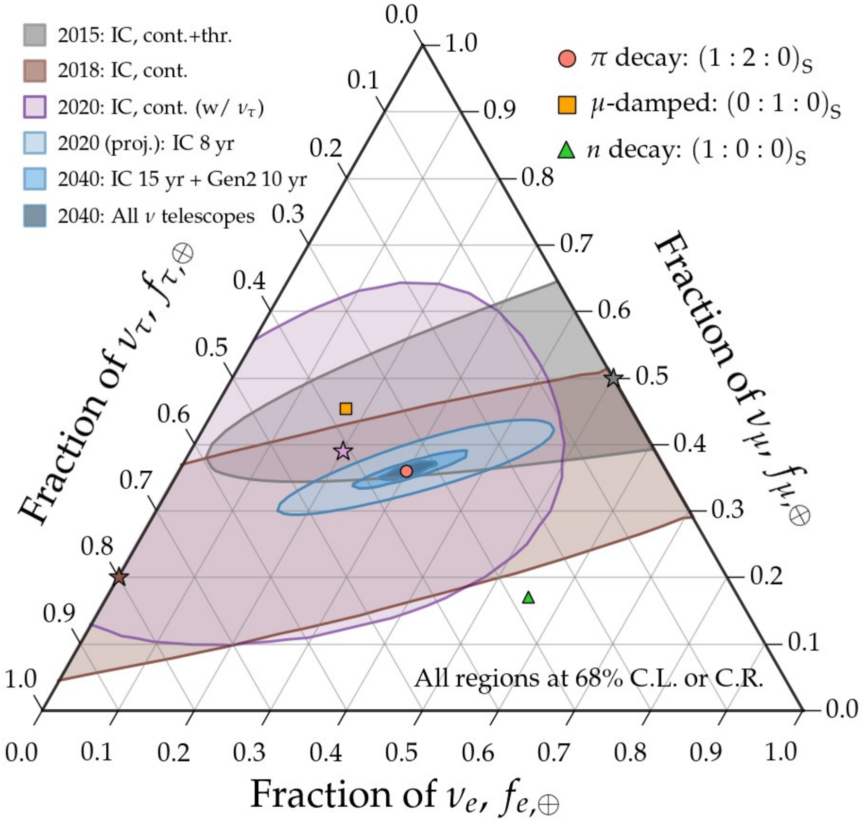
MB, Tamborra, *PRD* 2020



Sources
Earth
E.g.,
Oscillations
?
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 $f_{\alpha,\mathrm{S}}$

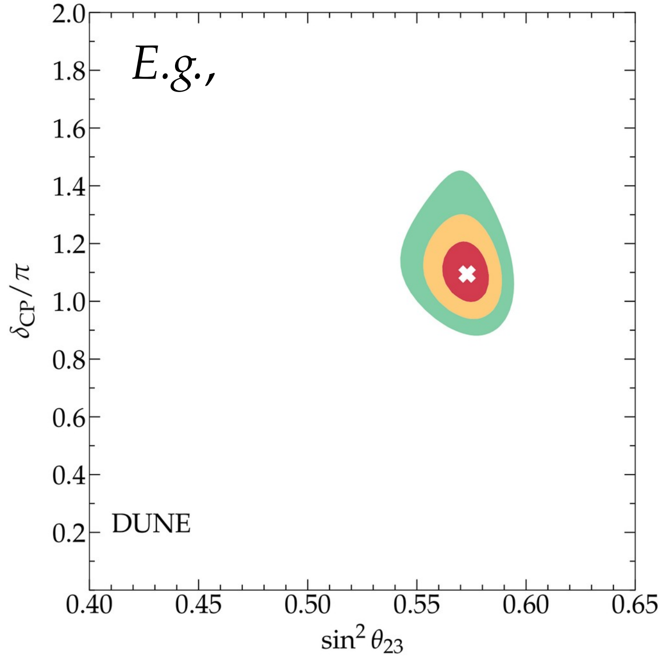
Inferring the flavor composition at the sources

Ingredient #1:
Flavor ratios measured at Earth,
$(f_{e,\oplus}, f_{\mu,\oplus}, f_{\tau,\oplus})$



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

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



Song, Li, Argüelles, **MB**, Vincent, 2012.12893
MB & Ahlers, *PRL* 2019

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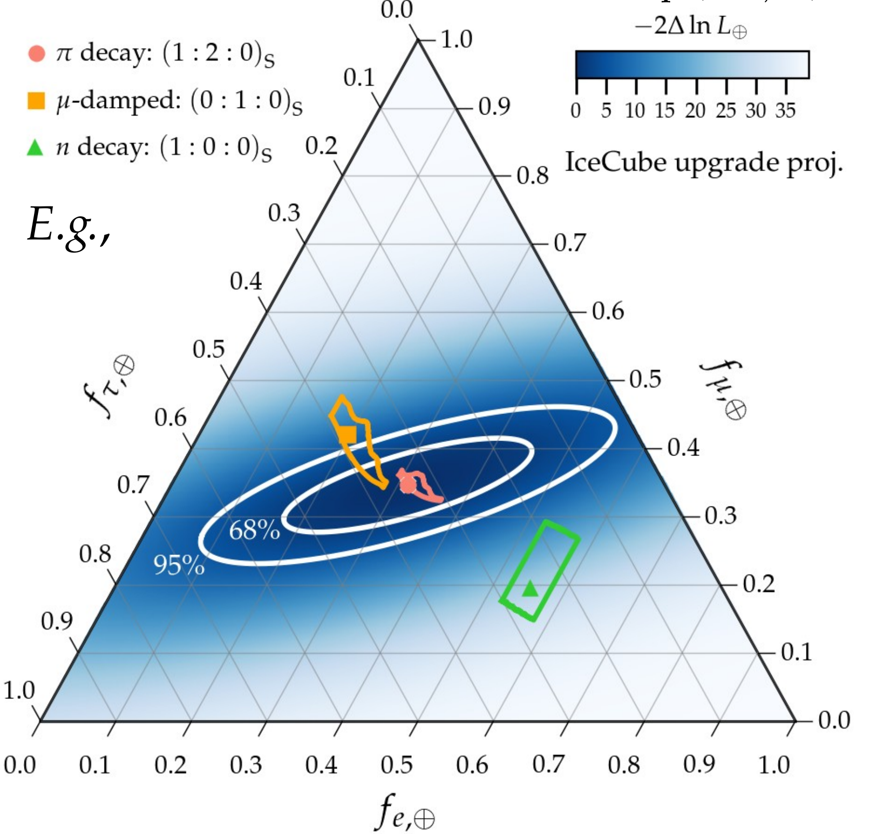
$\mathcal{P}_{\rm exp}(f_{\alpha,\oplus})$



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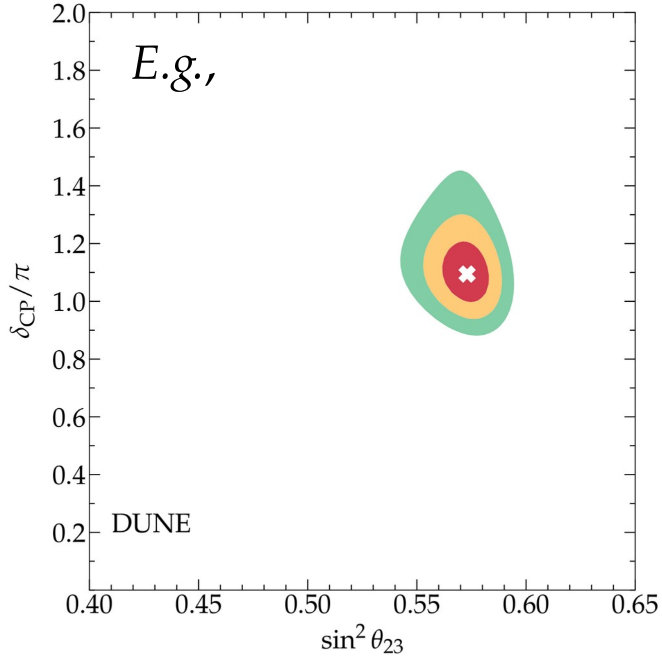

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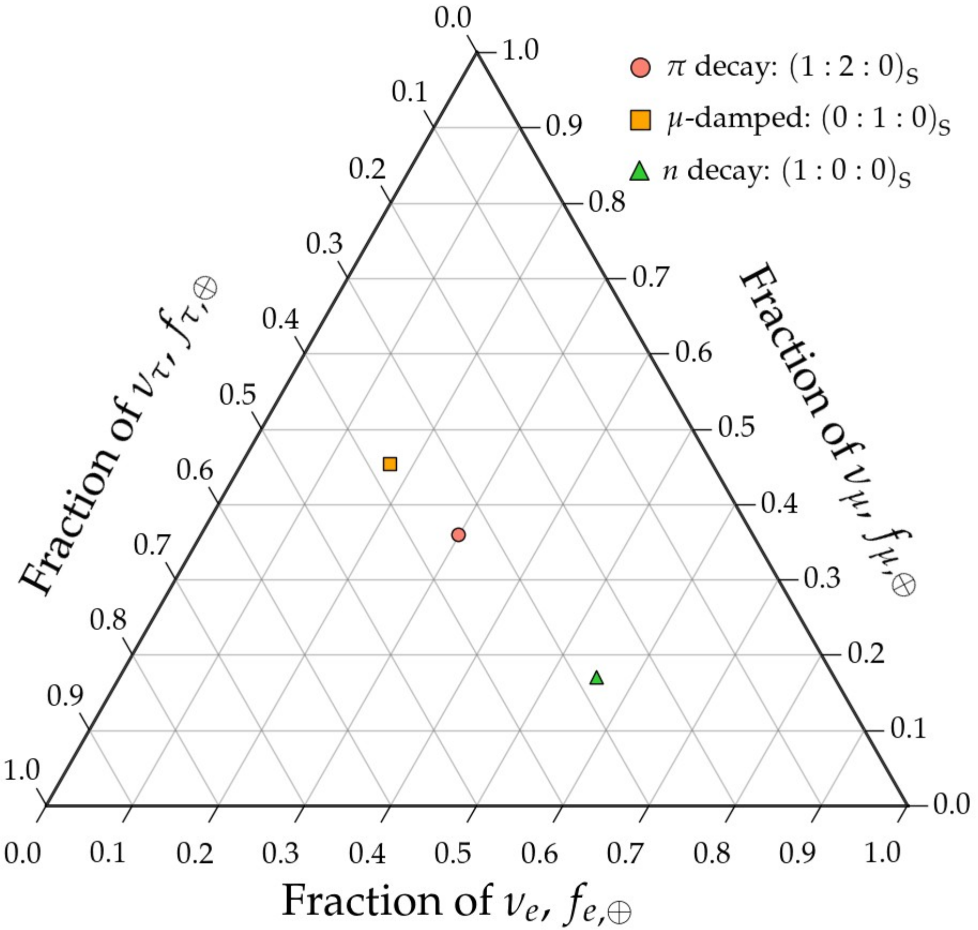
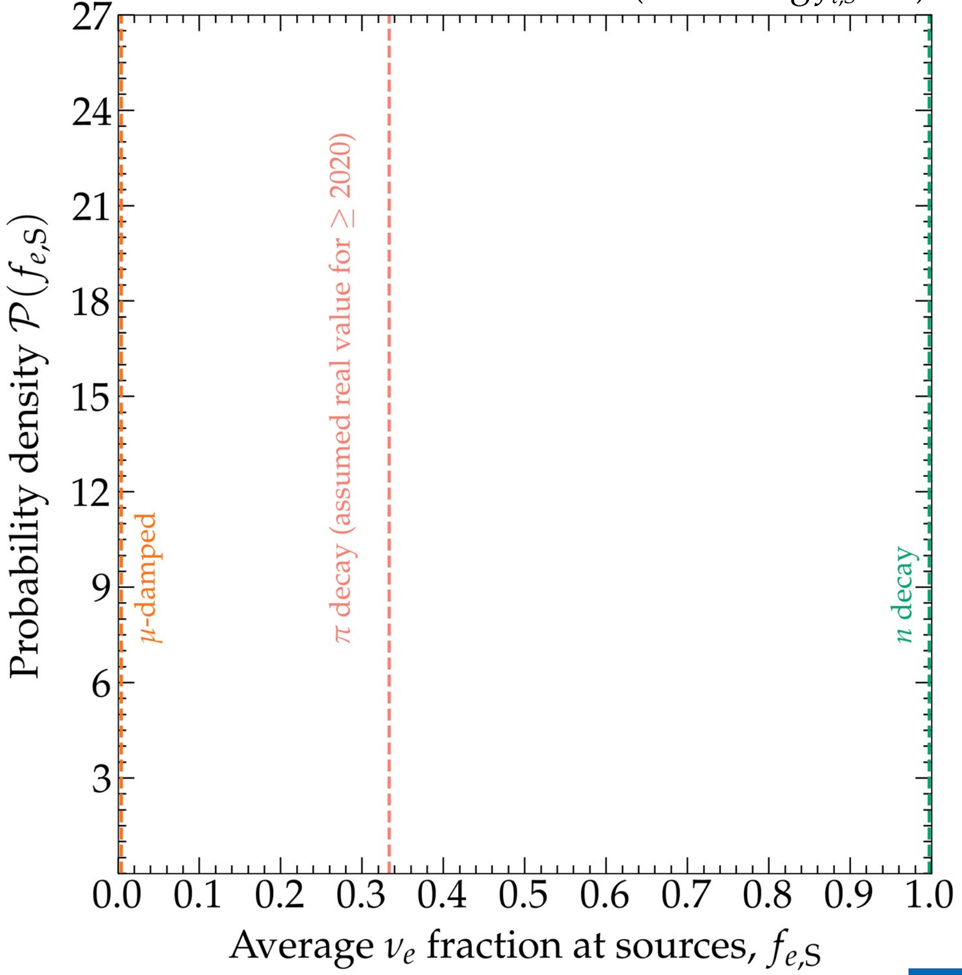


(Assuming $f_{\tau,S} = 0$)



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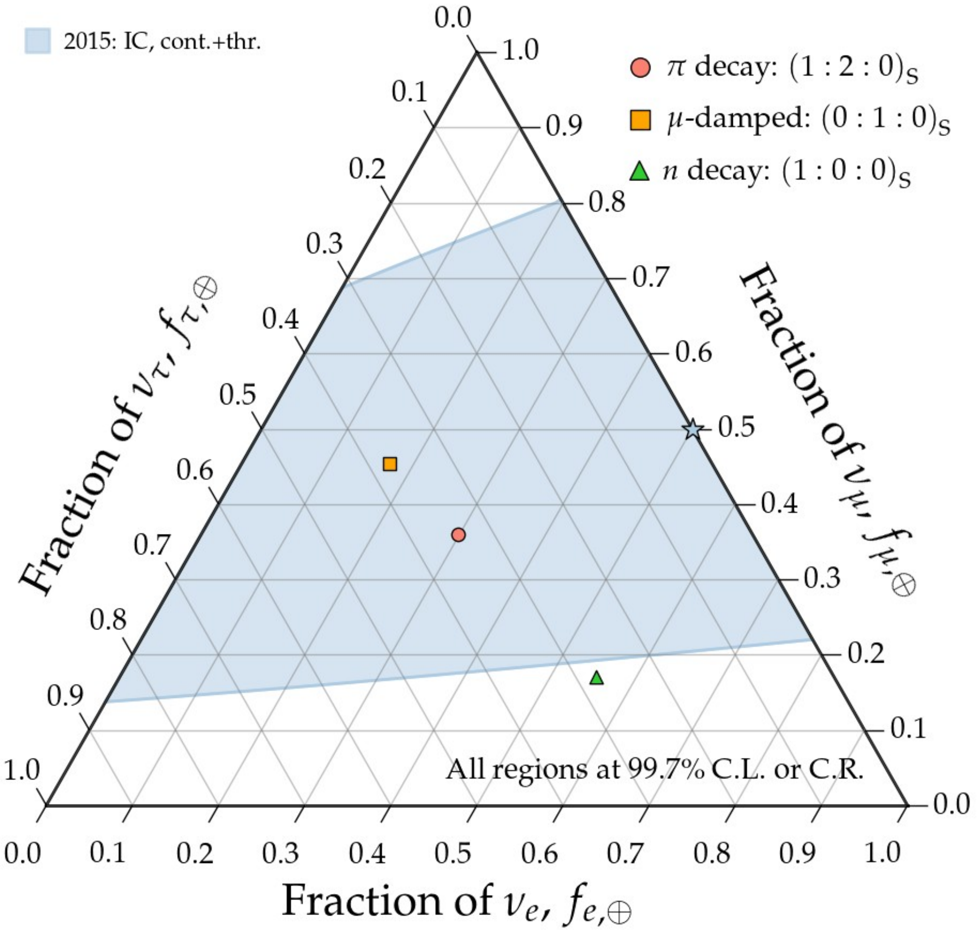

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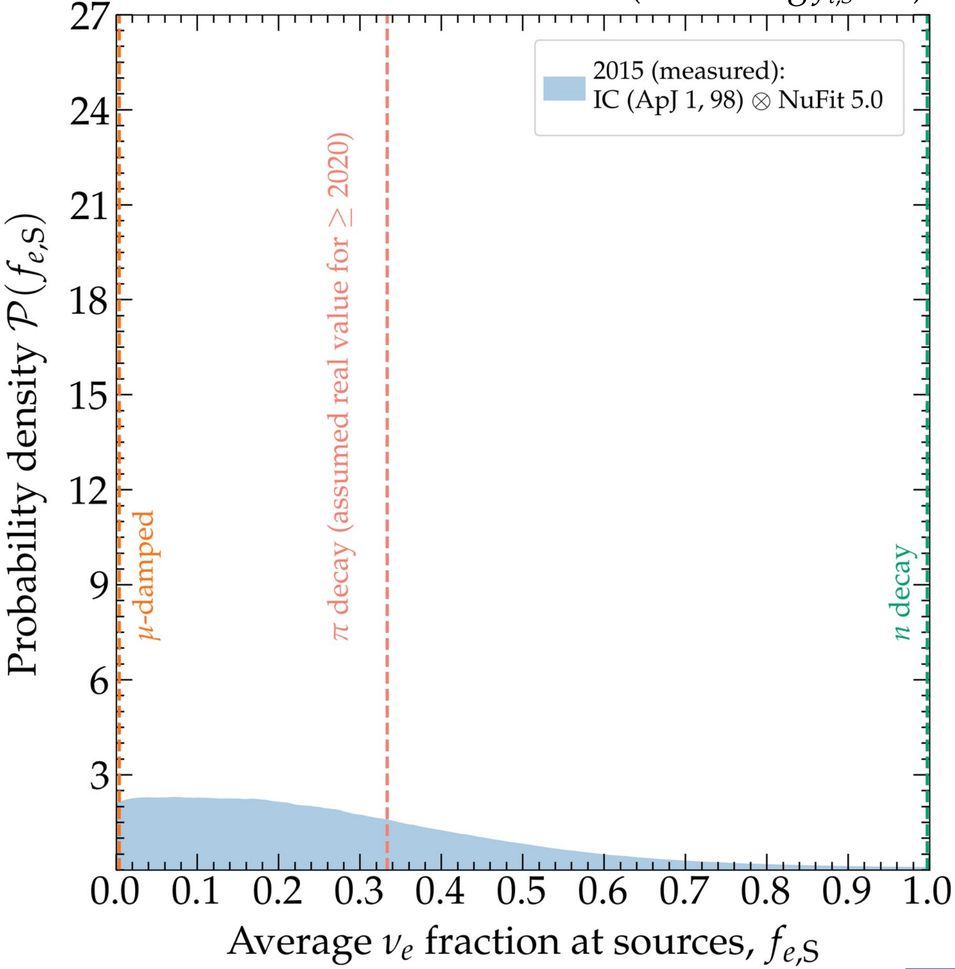

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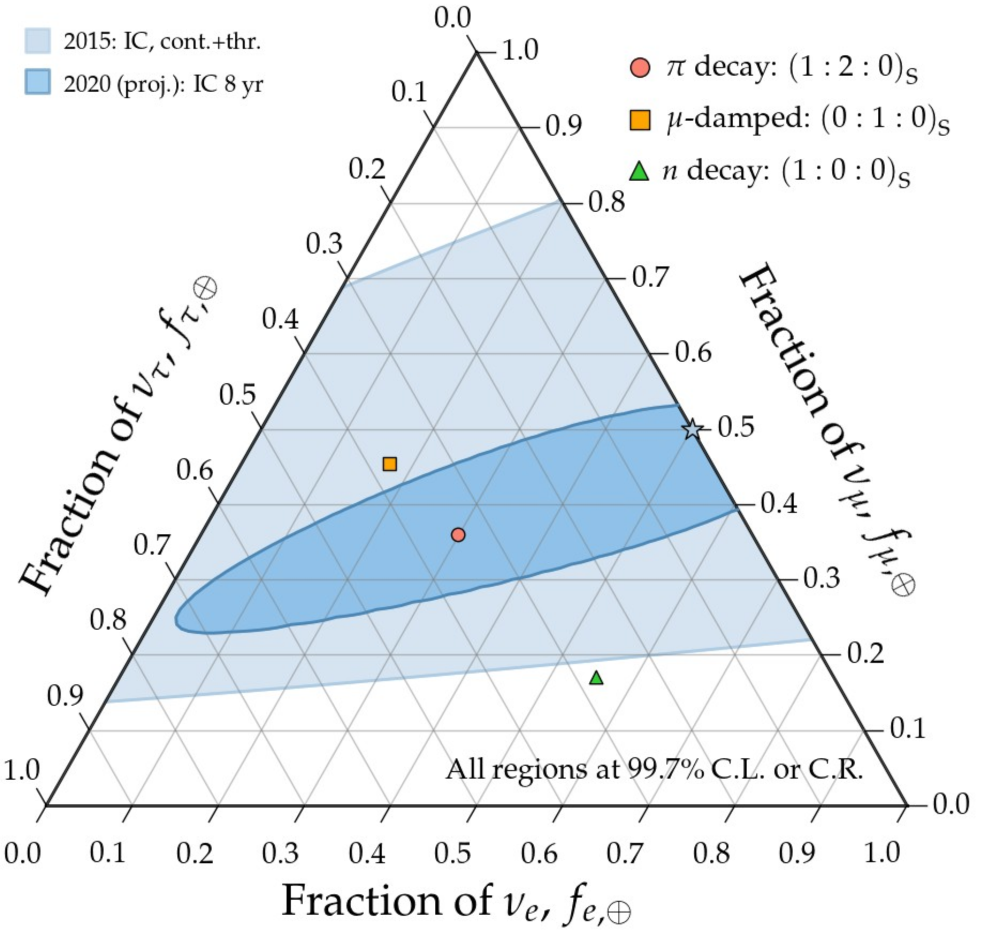

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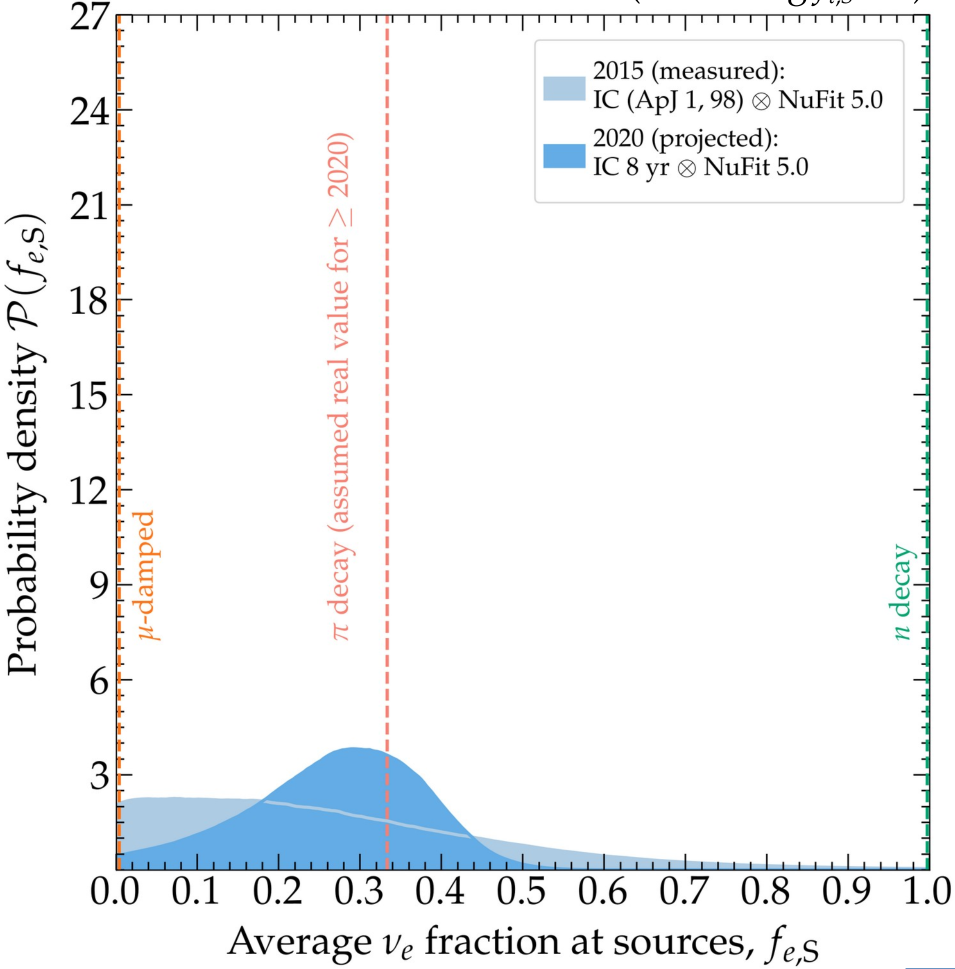

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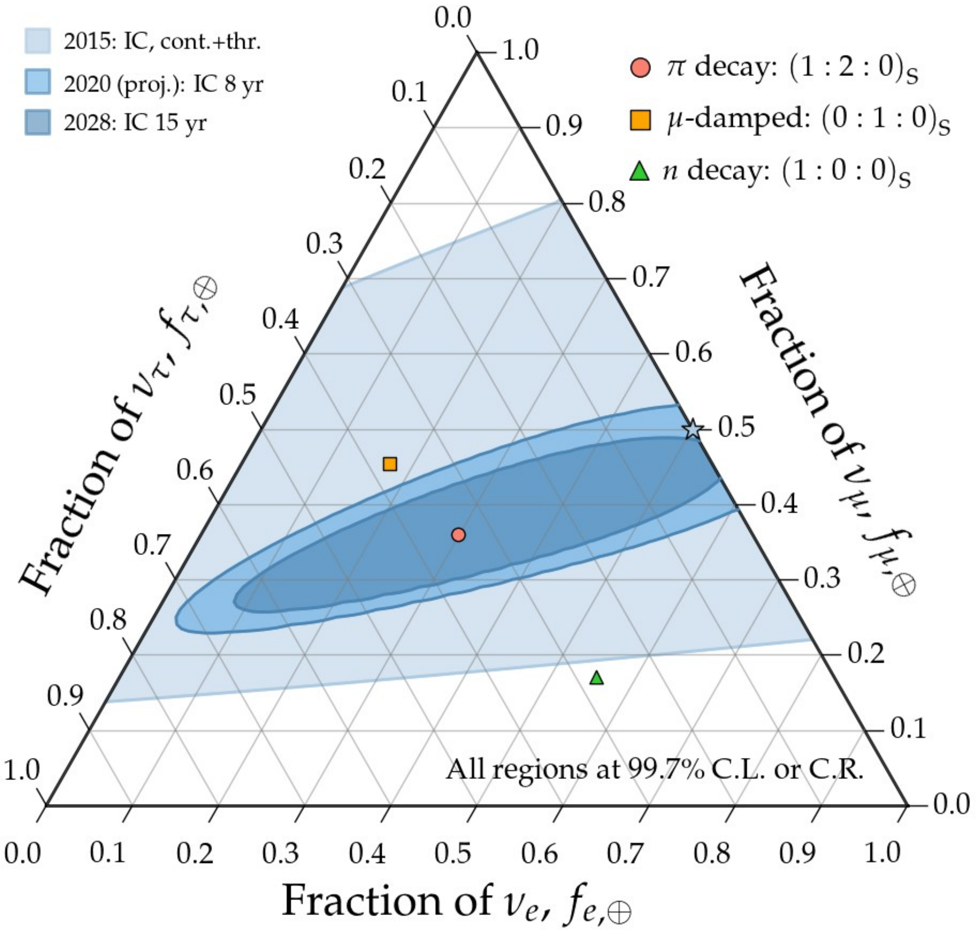

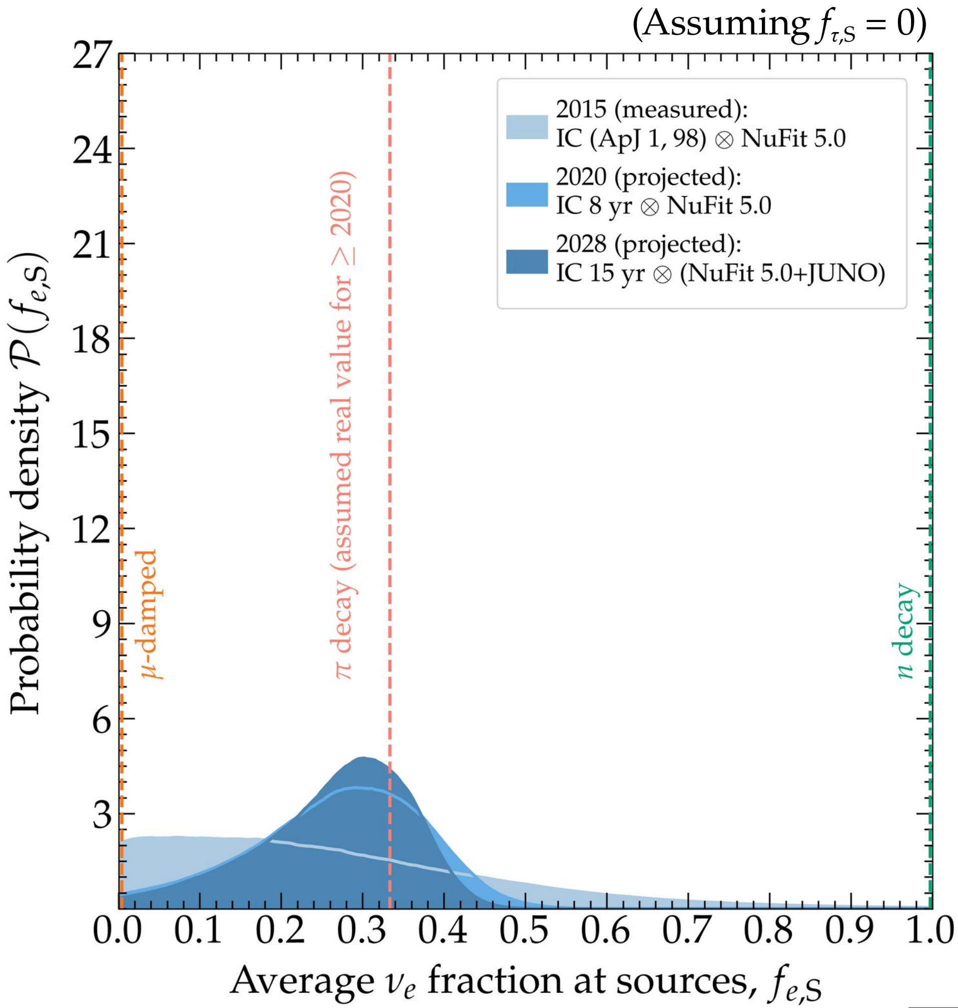

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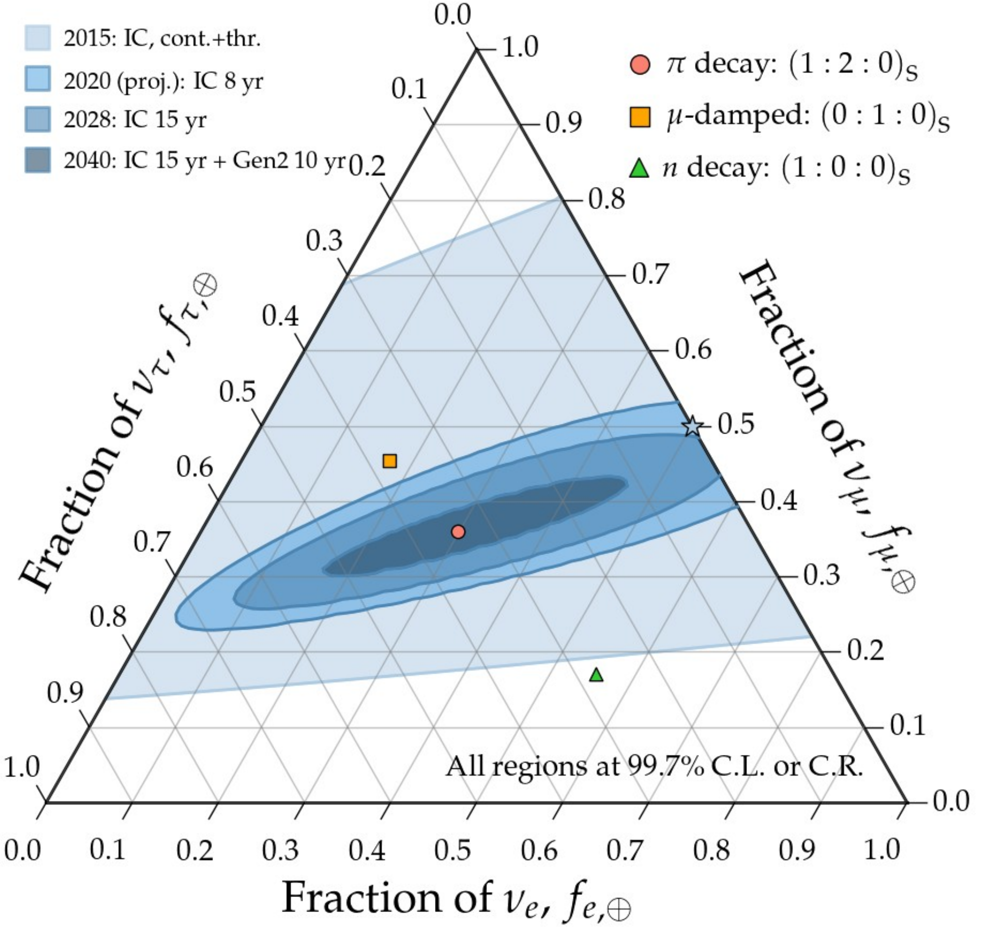

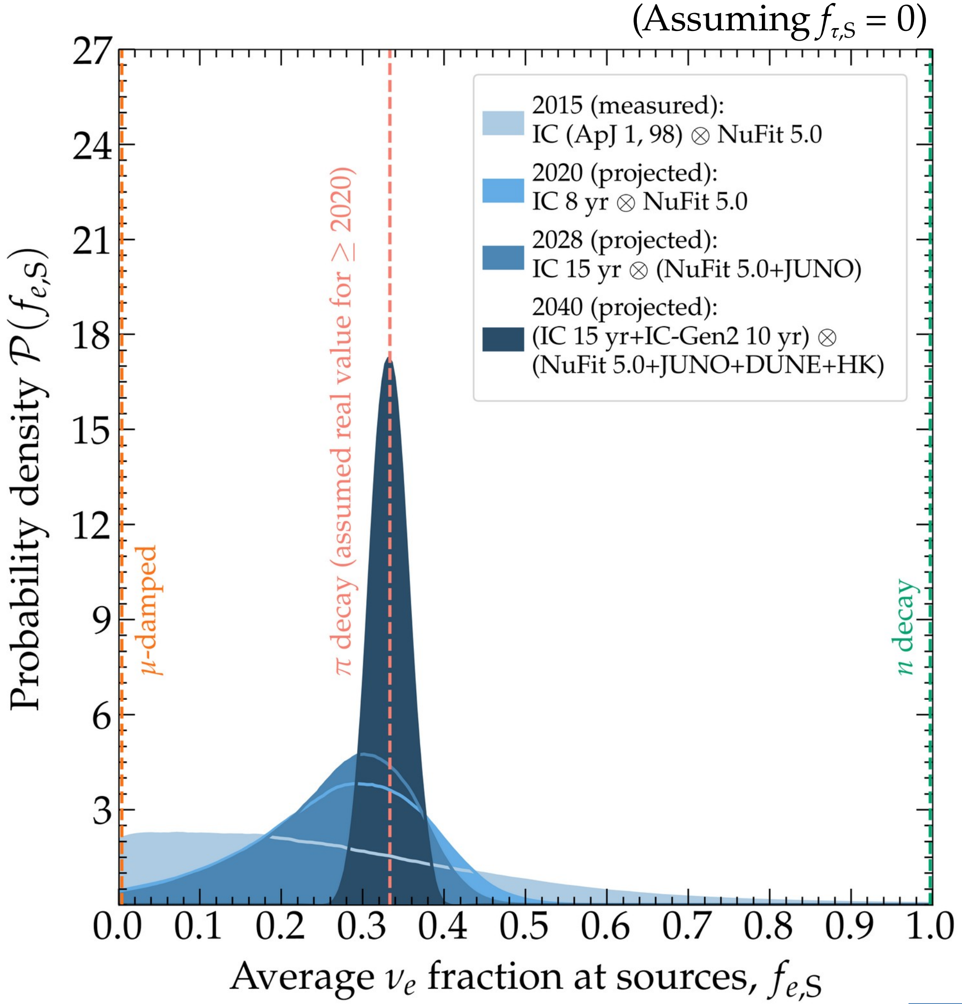

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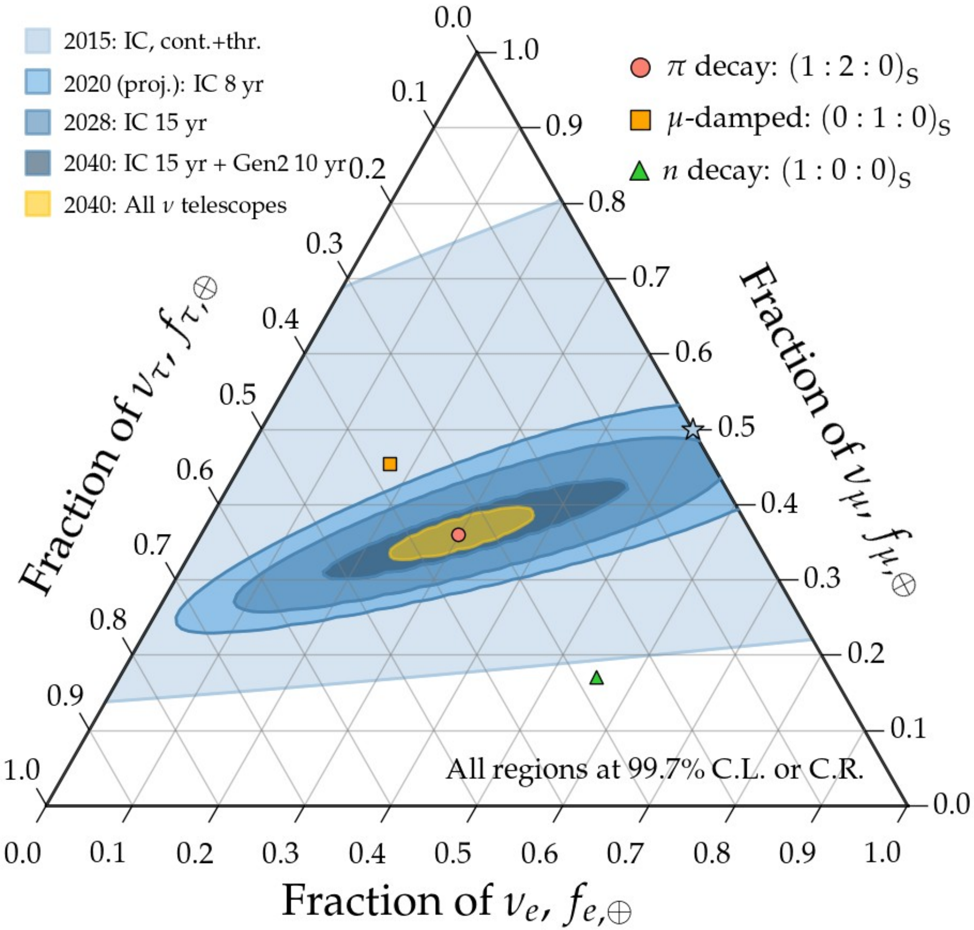

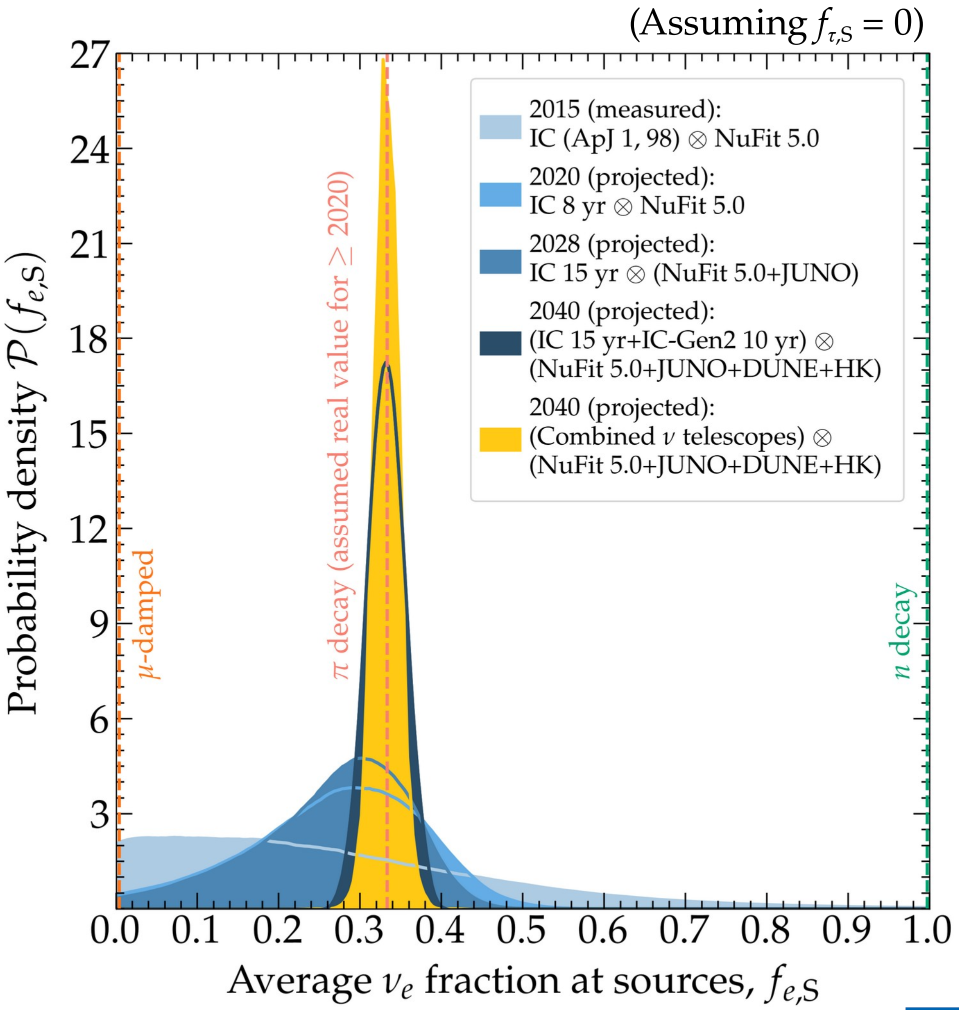

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More than one production mechanism?

Can we detect the contribution of multiple ν production mechanisms?

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

Propagate to Earth ↓

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

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

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

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

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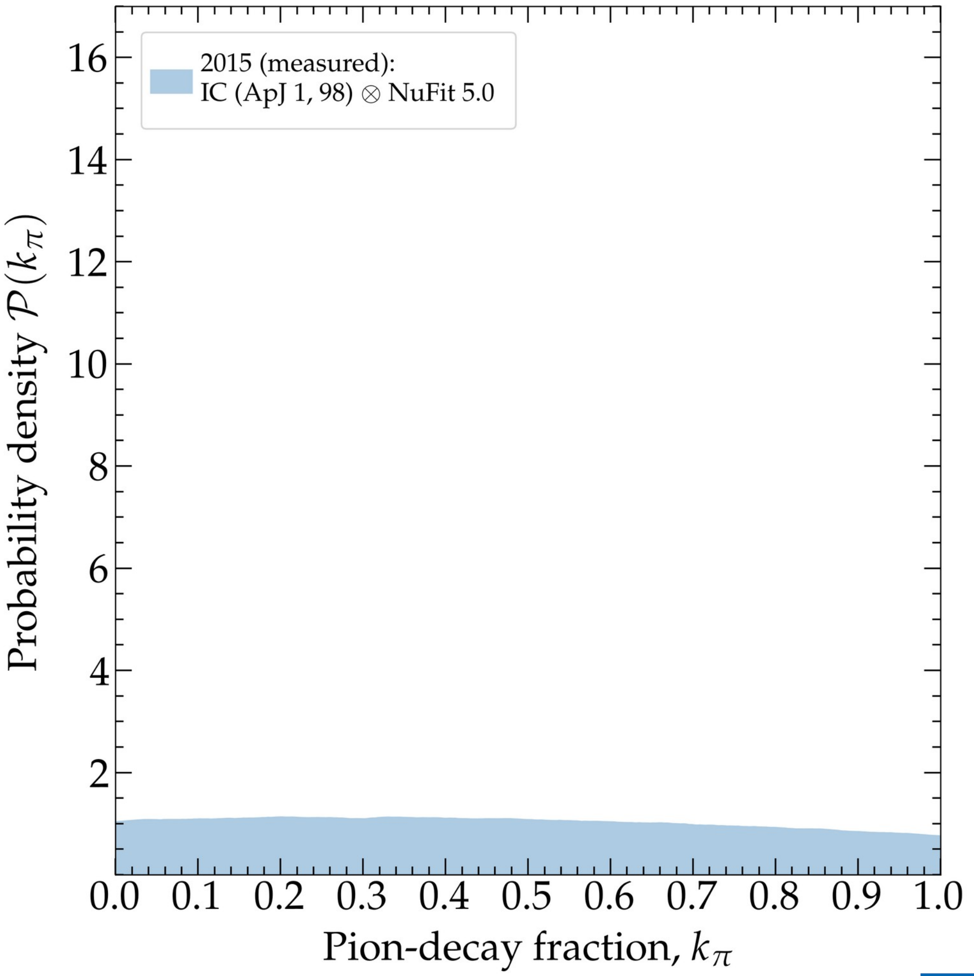

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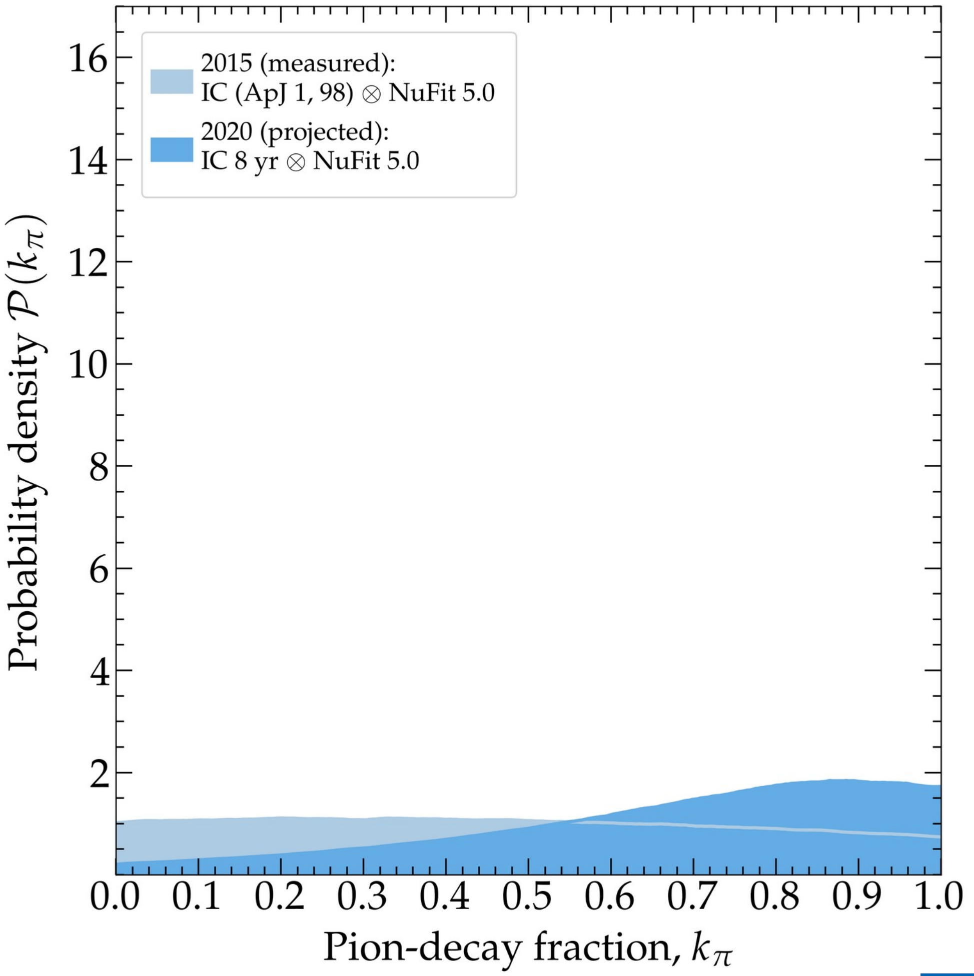

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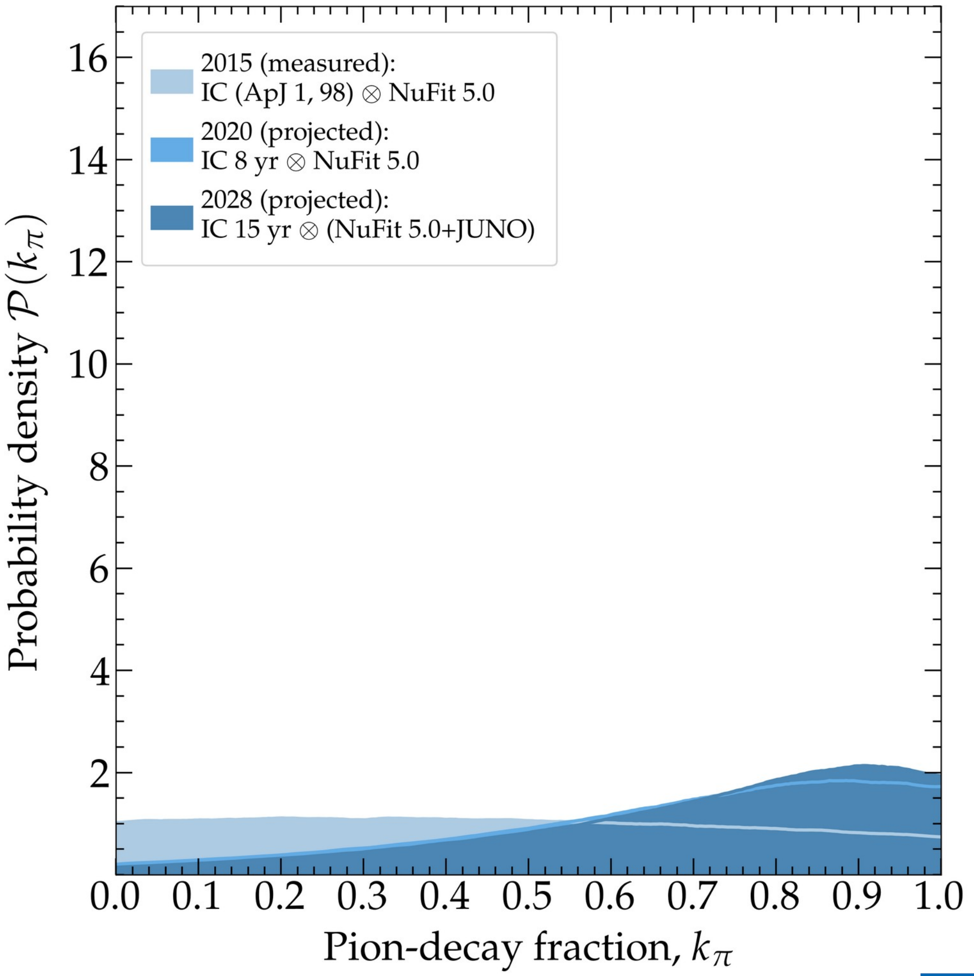

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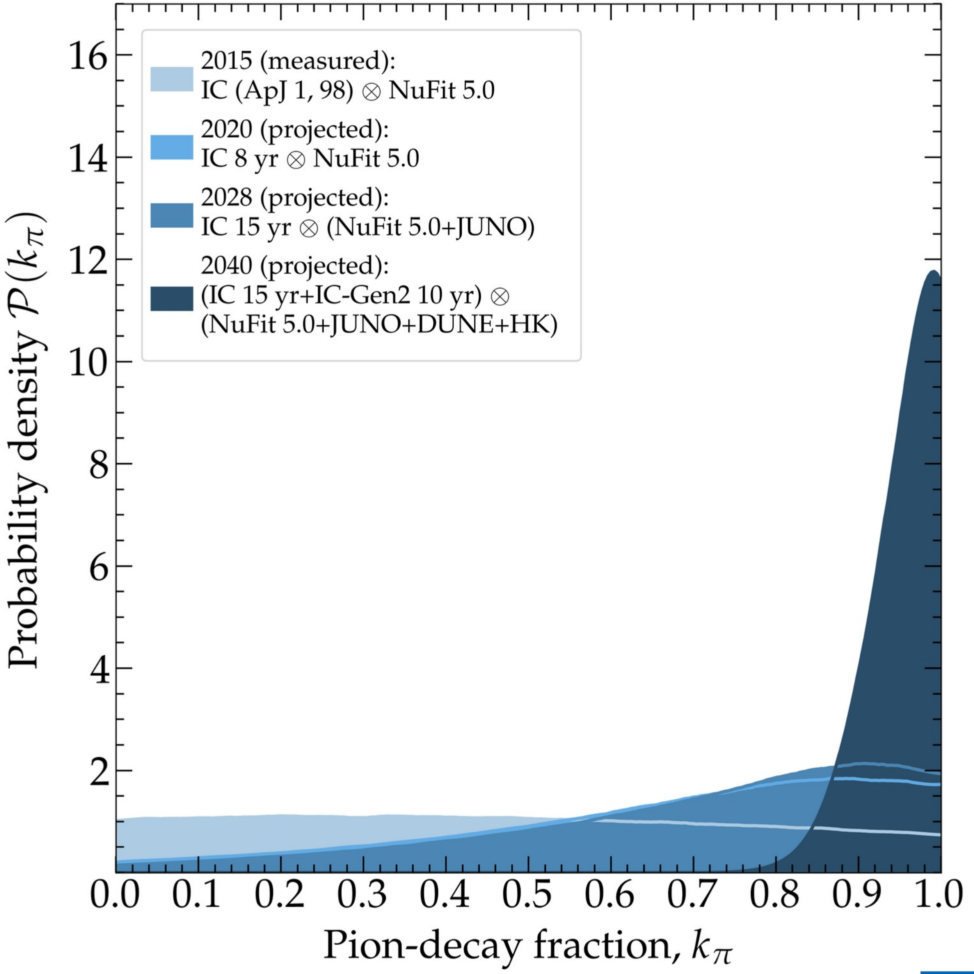

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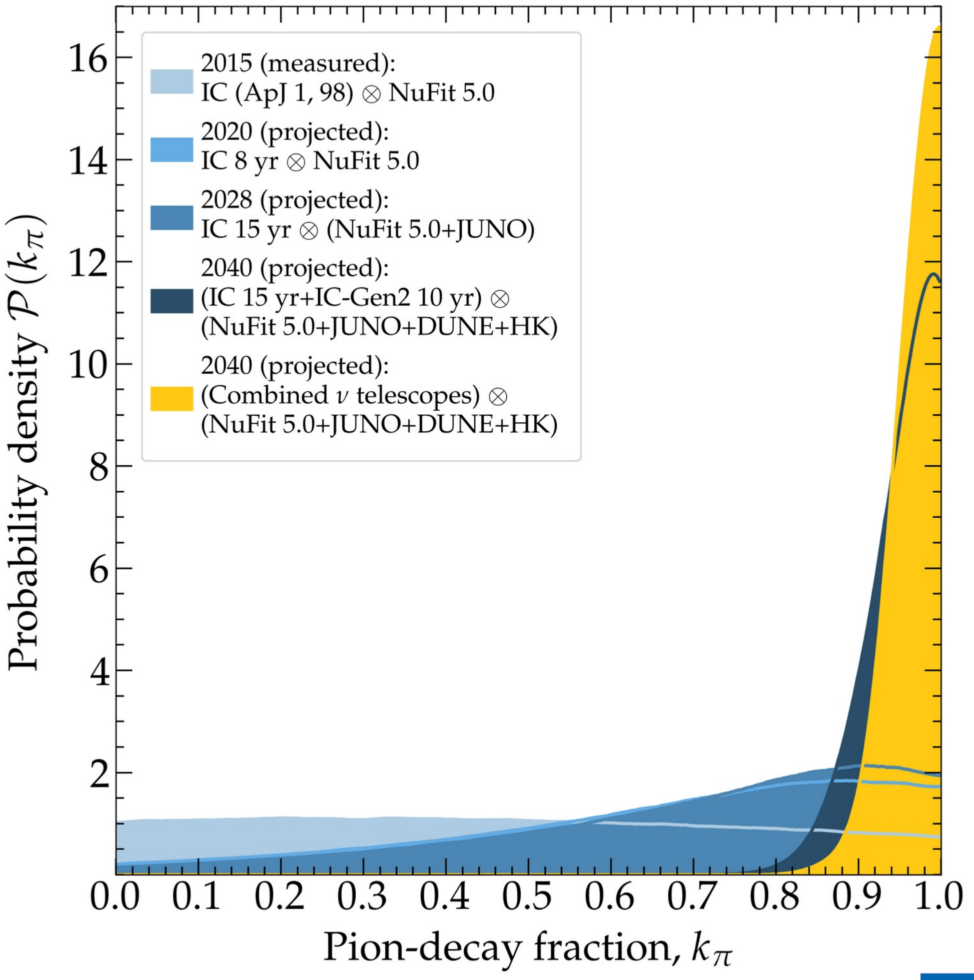

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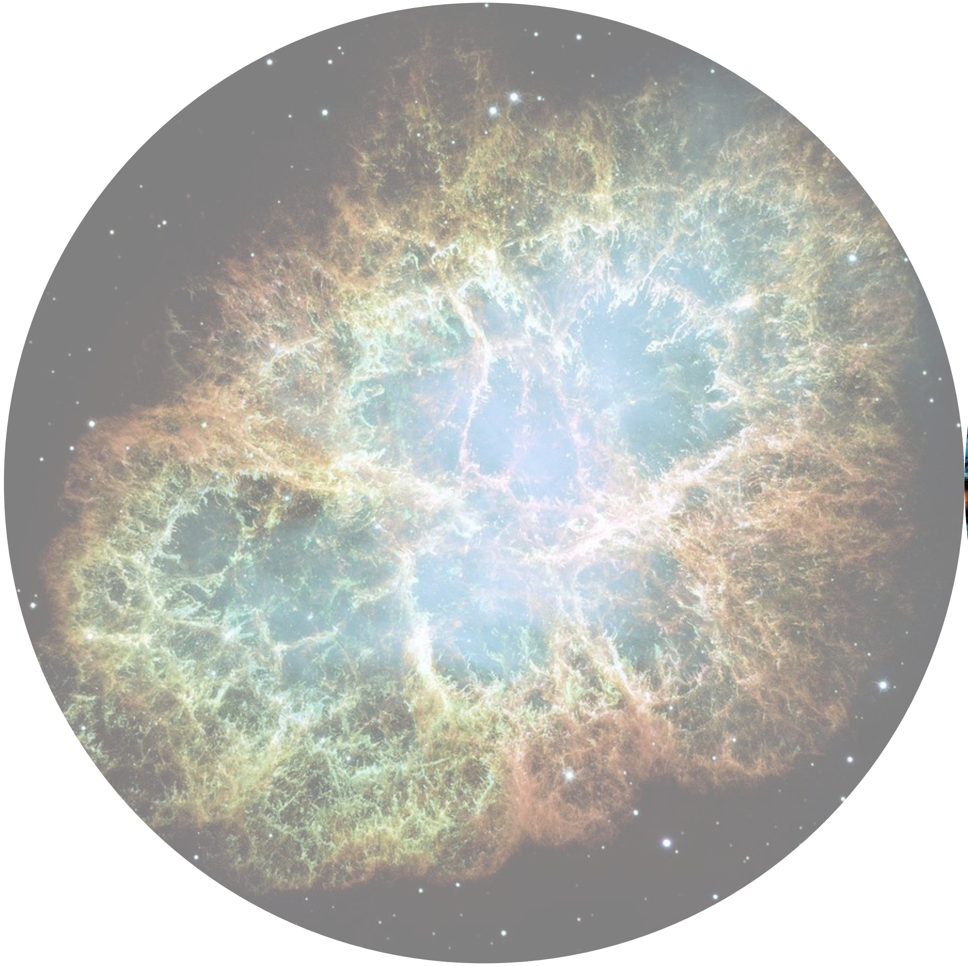
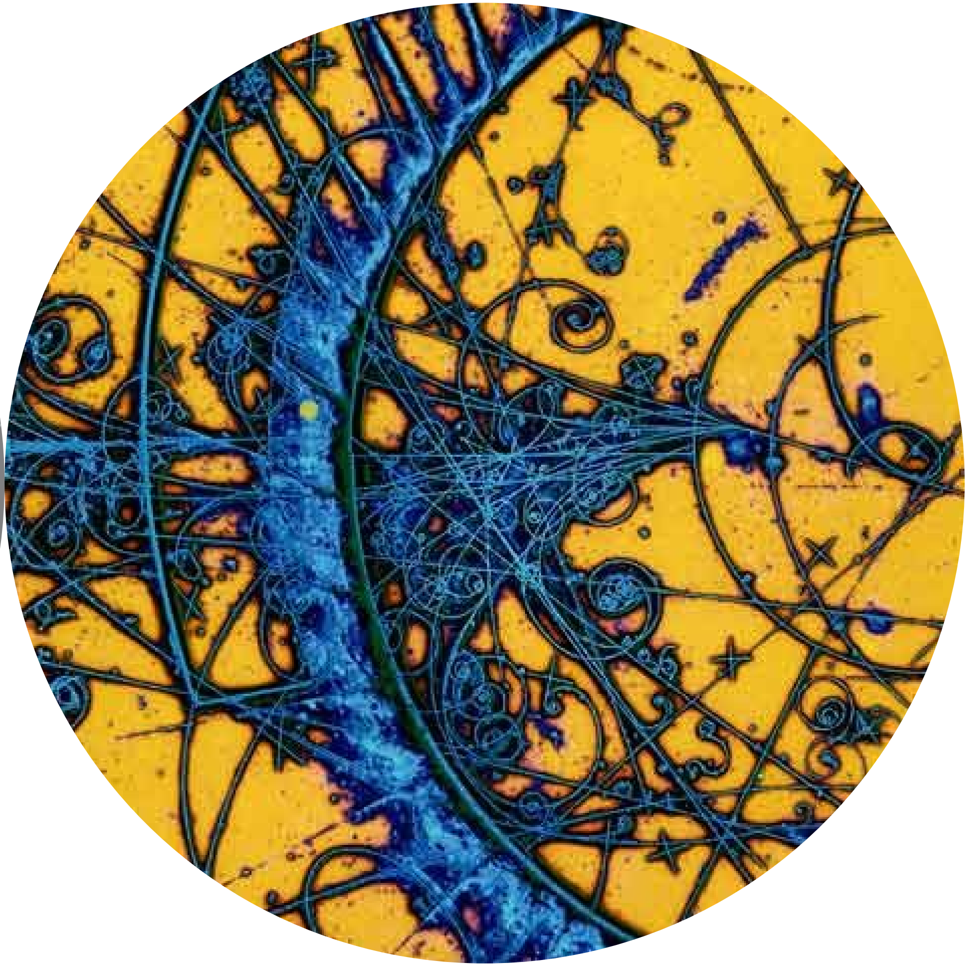
III.
Particle physics with high-energy cosmic neutrinos





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

In the face of astrophysical unknowns,
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Yes.

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Neutrino physicist

Note: Not an exhaustive list

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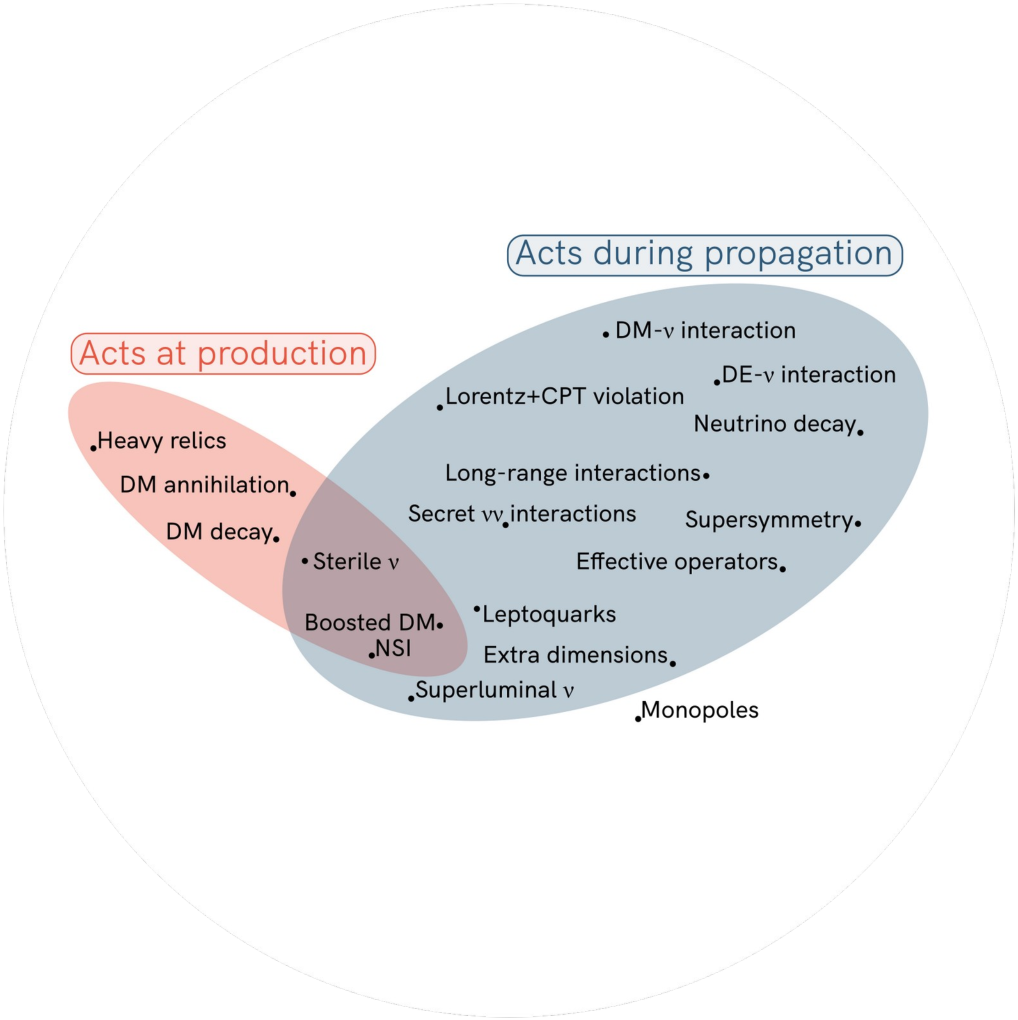
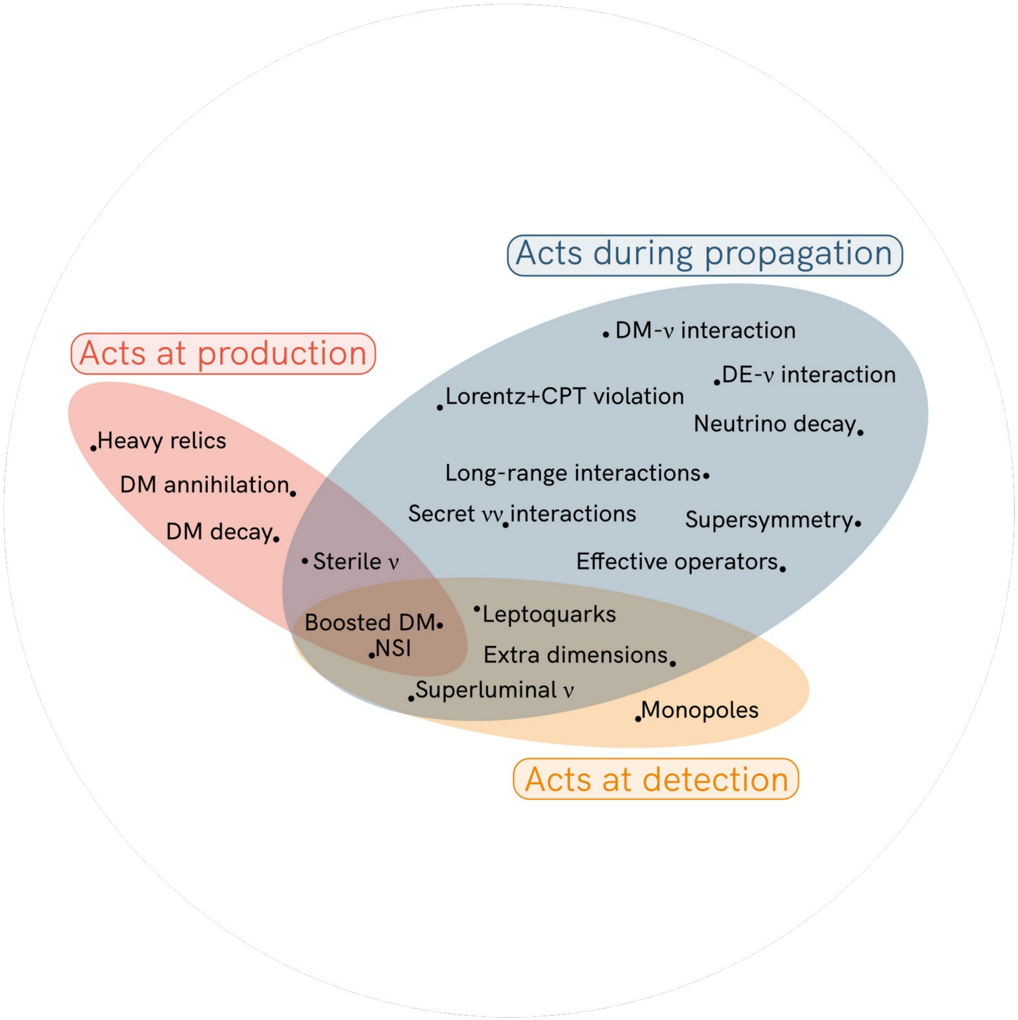


Note: Not an exhaustive list



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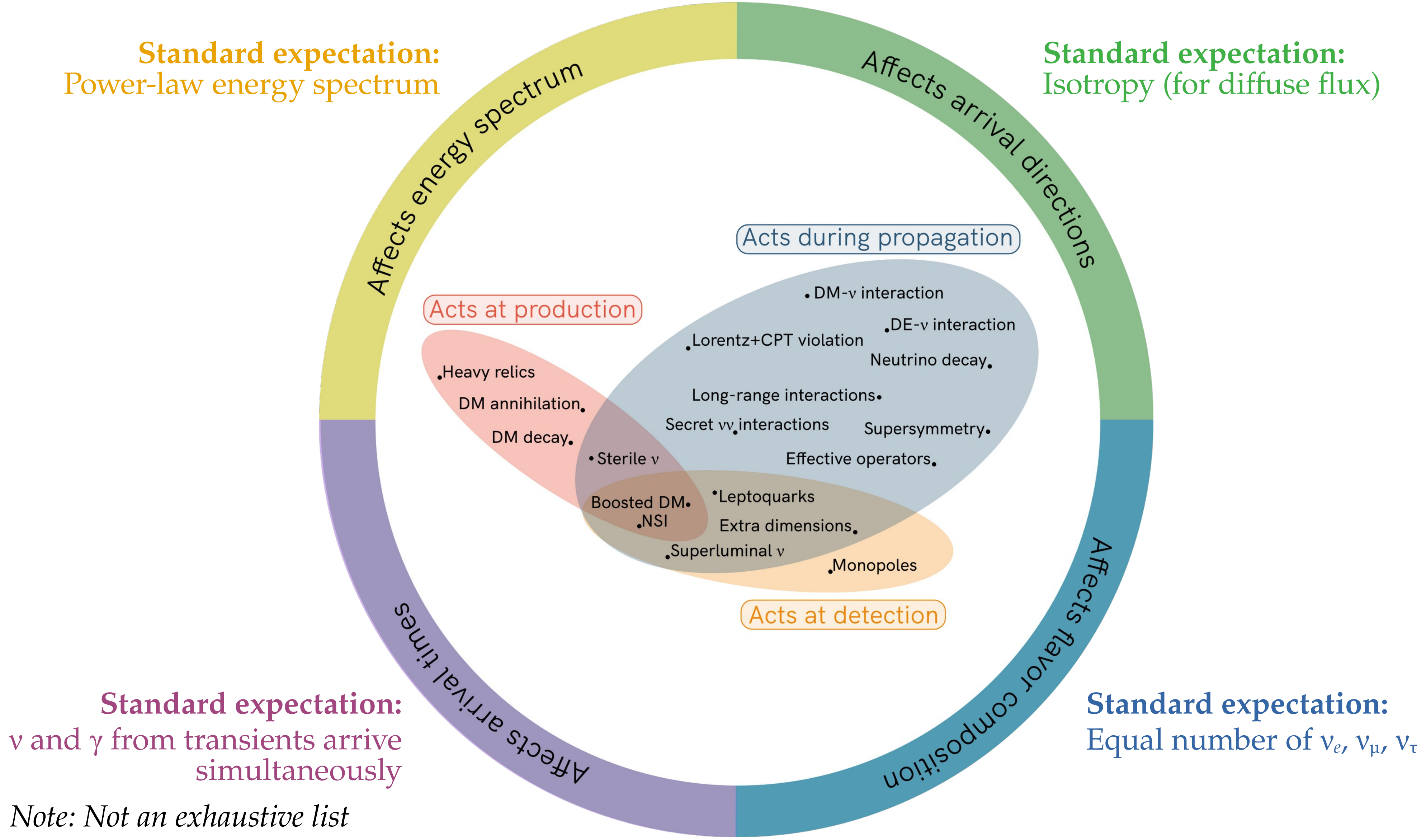
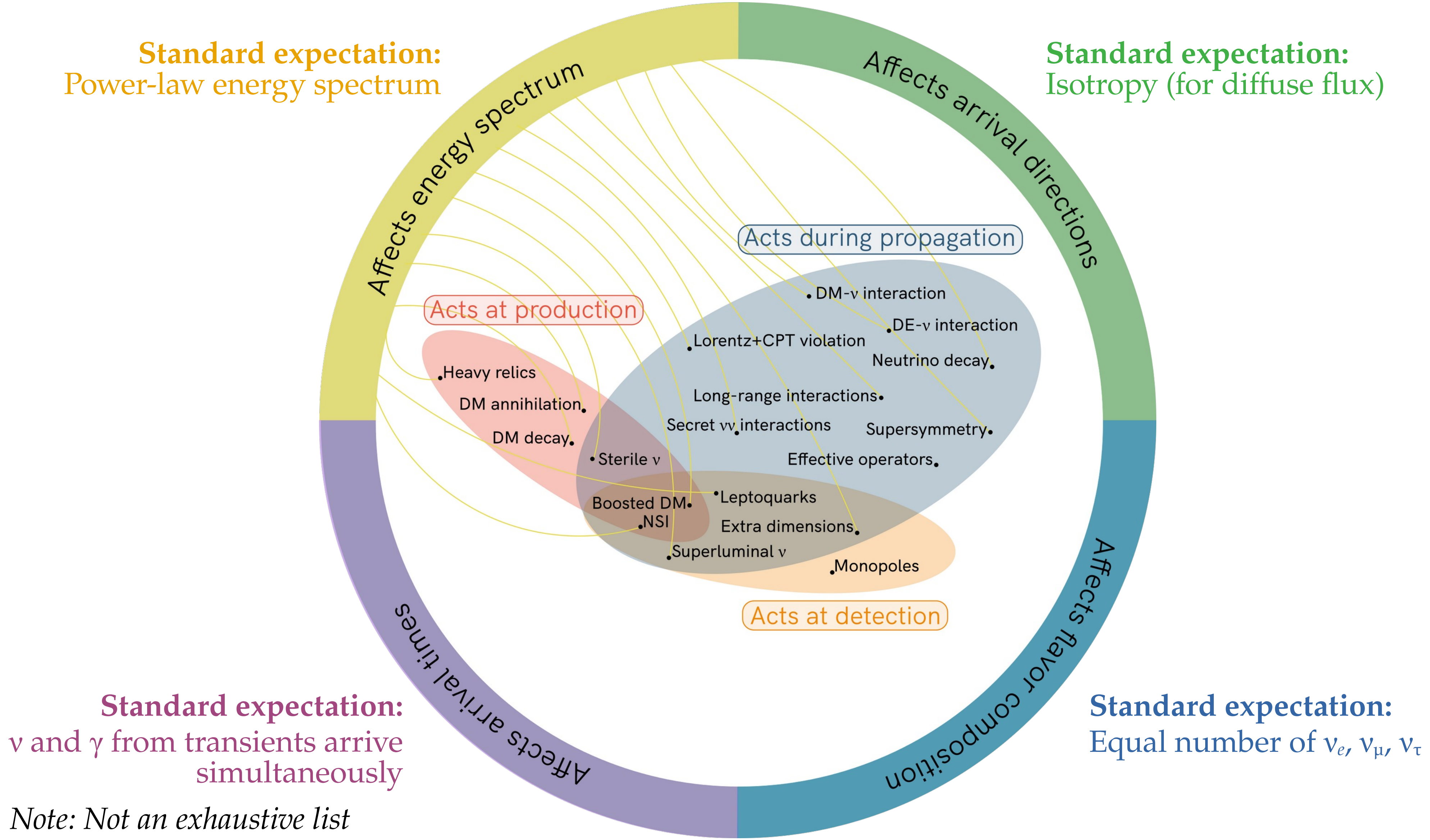

Standard expectation:
Power-law energy spectrum
Standard expectation:
Isotropy (for diffuse flux)
Affects energy spectrum
Affects arrival directions
Affects flavor composition
Affects arrival times
Acts during propagation
Acts at production
Acts at detection
DM-ν interaction
DE-ν interaction
Lorentz+CPT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



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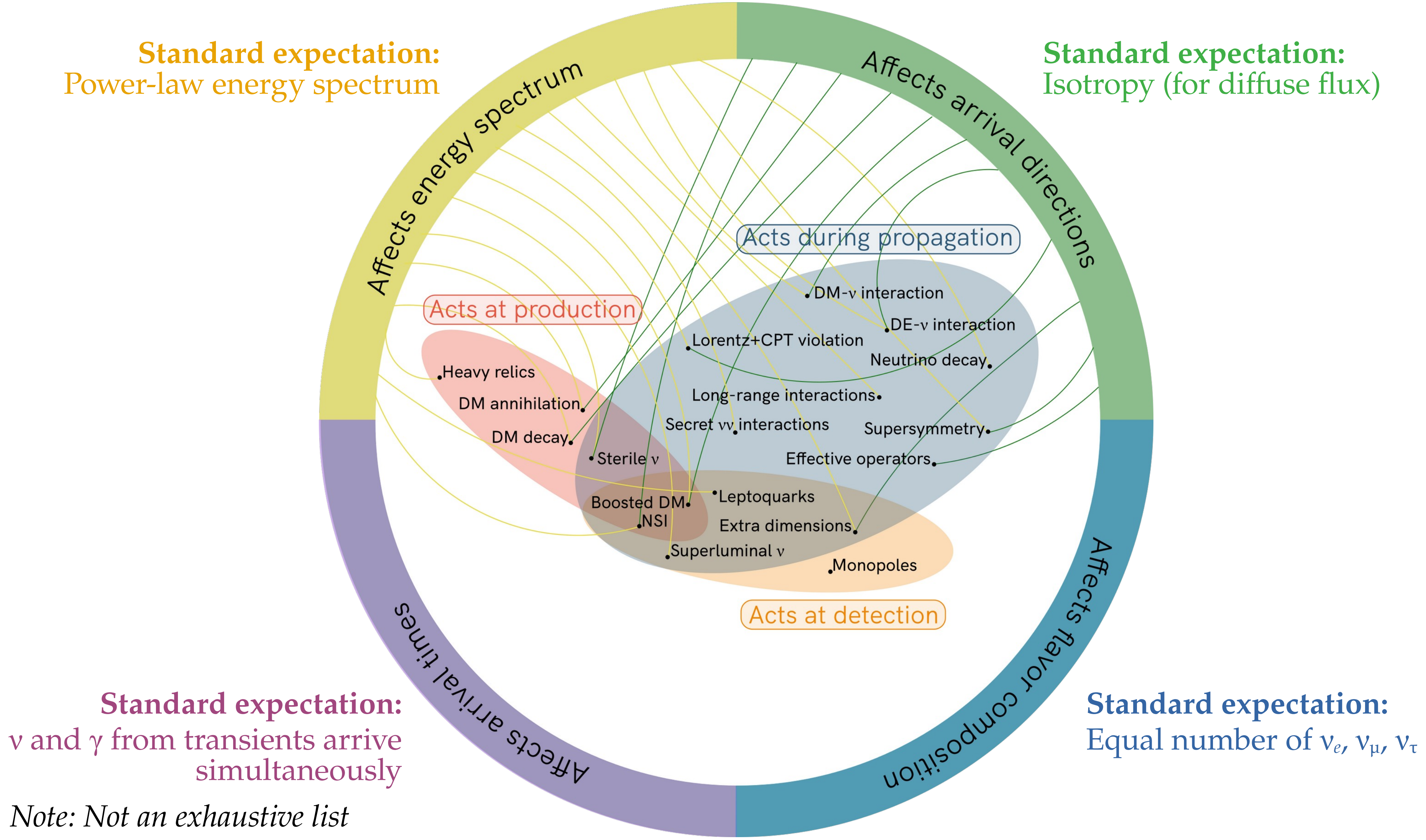

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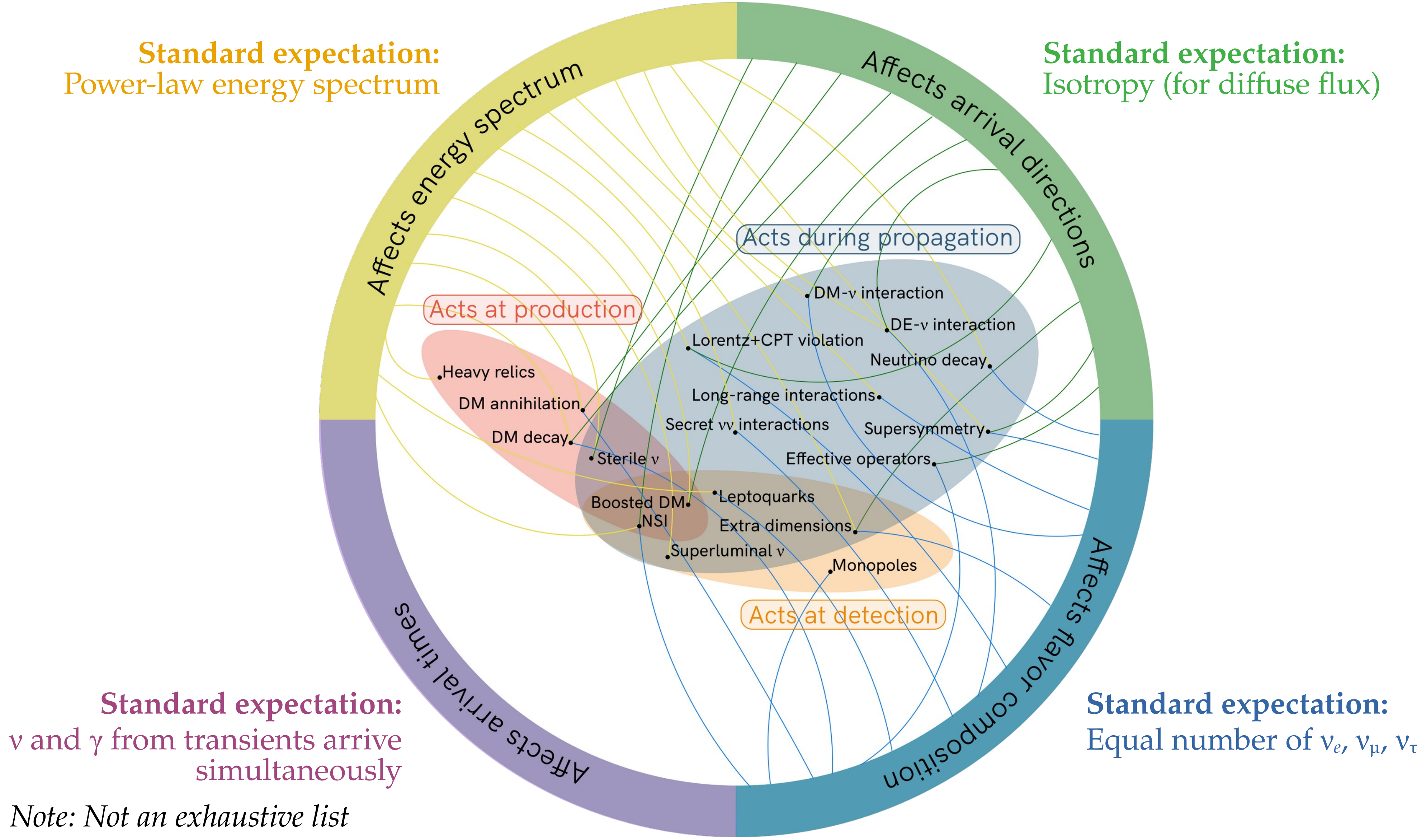
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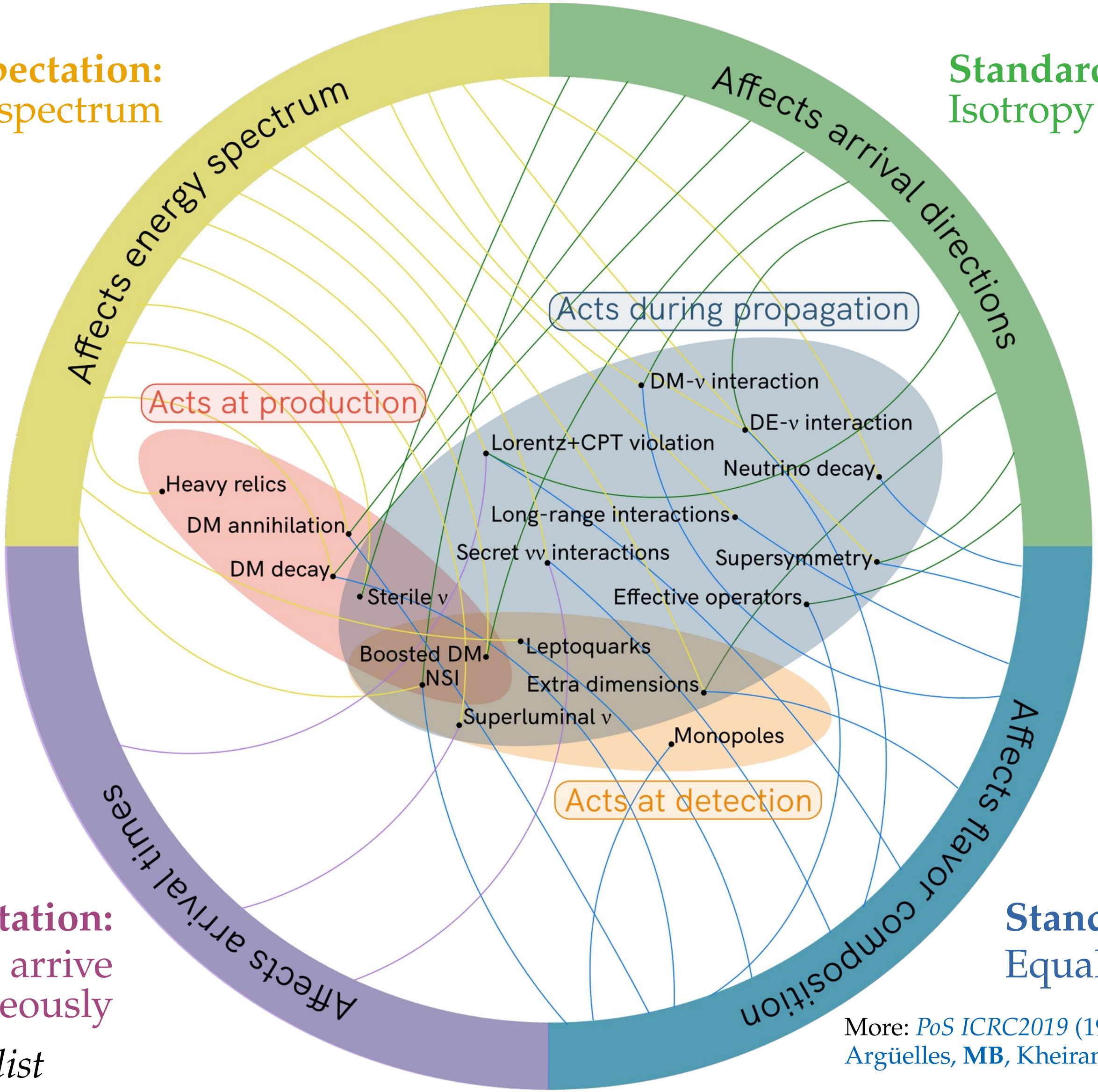

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Note: Not an exhaustive list

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

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Power-law energy spectrum

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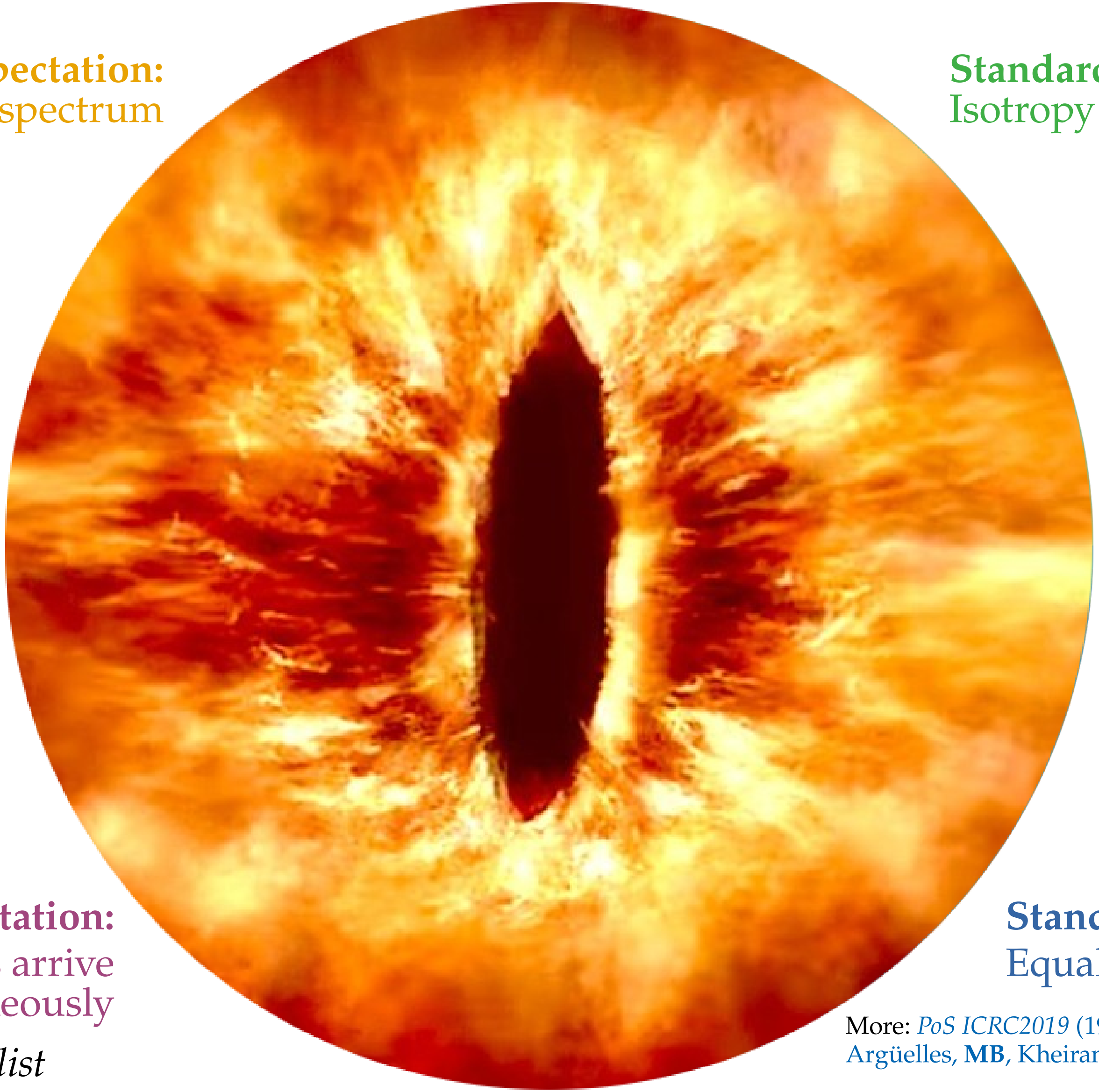

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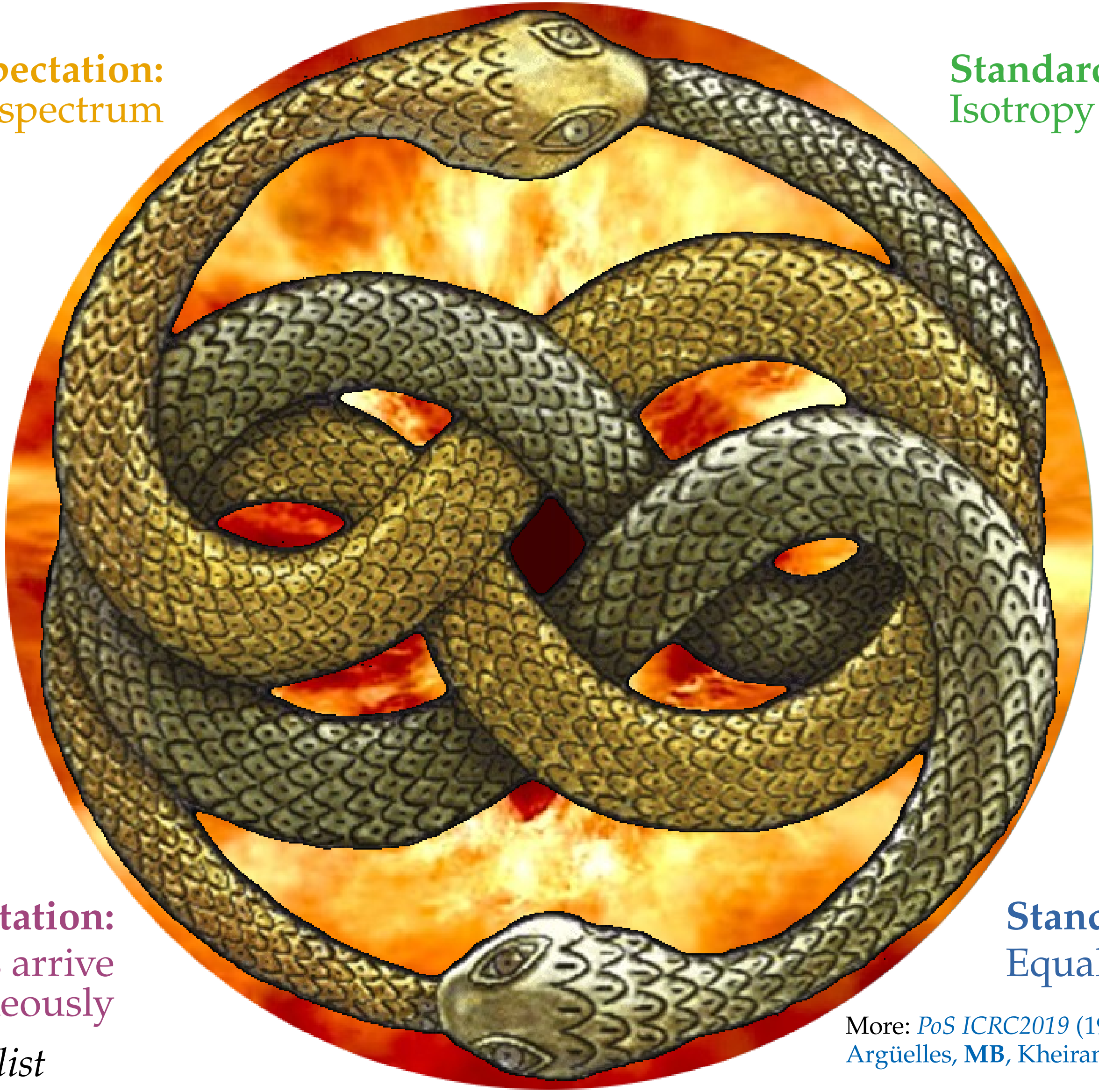

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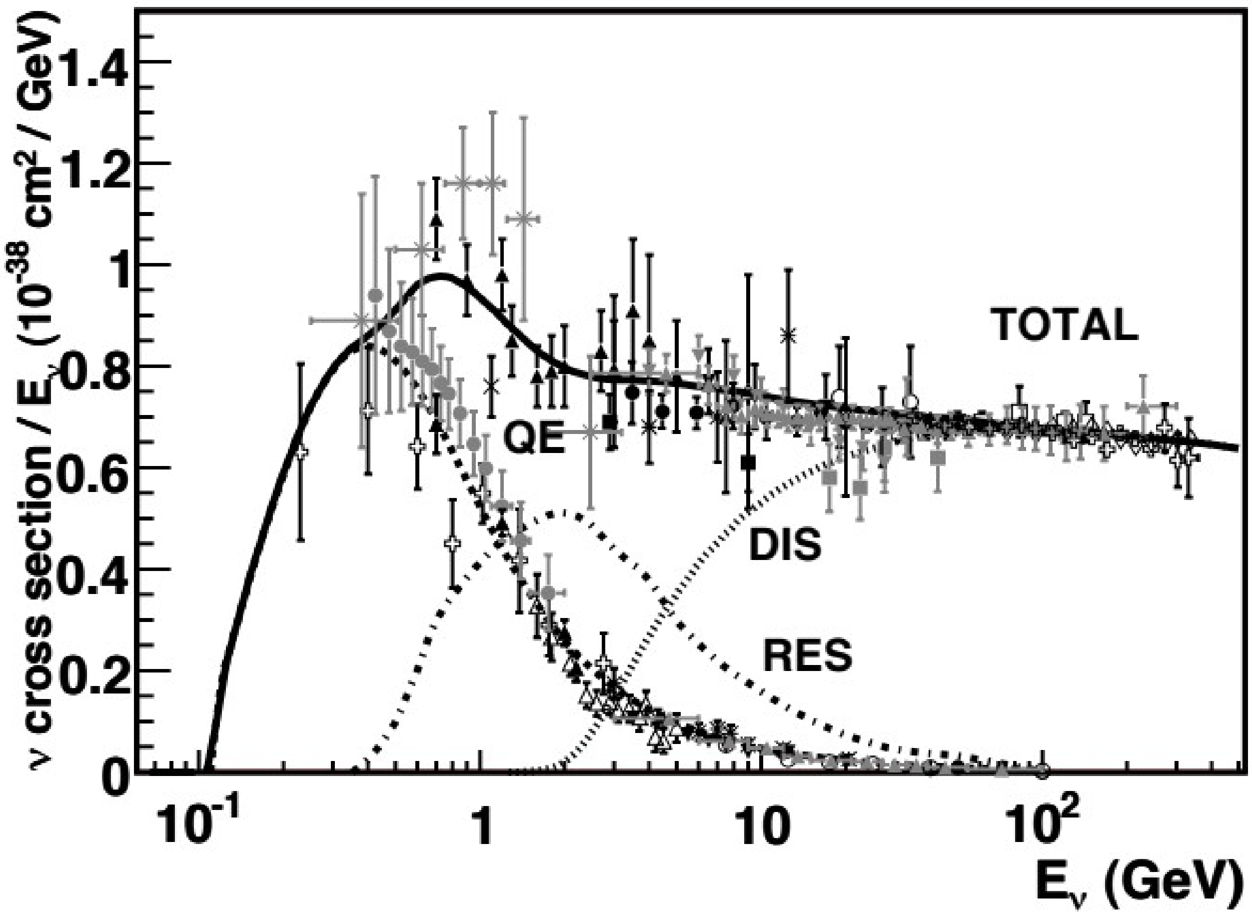
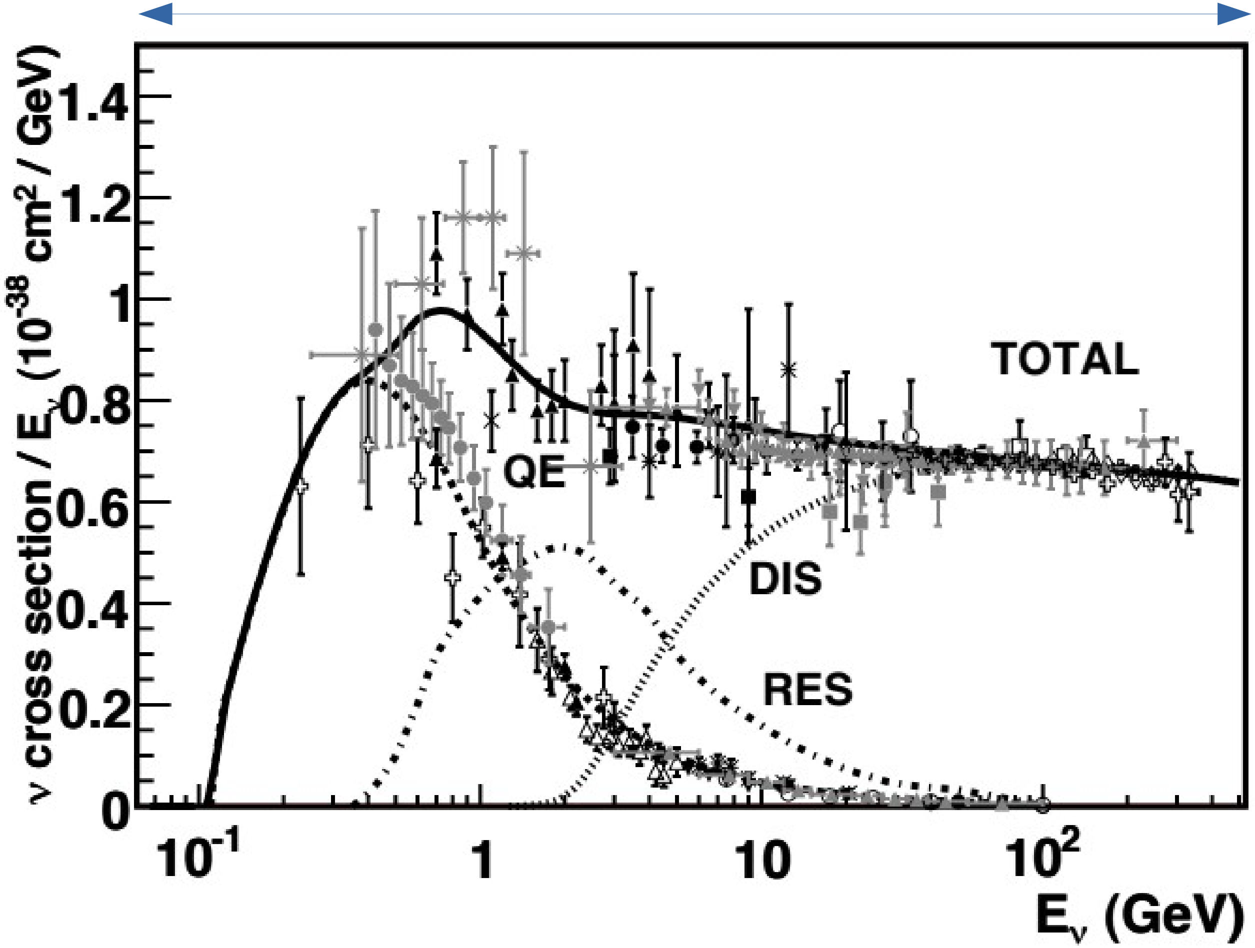
Example 1:
Measuring TeV–PeV ν cross sections



Particle Data Group

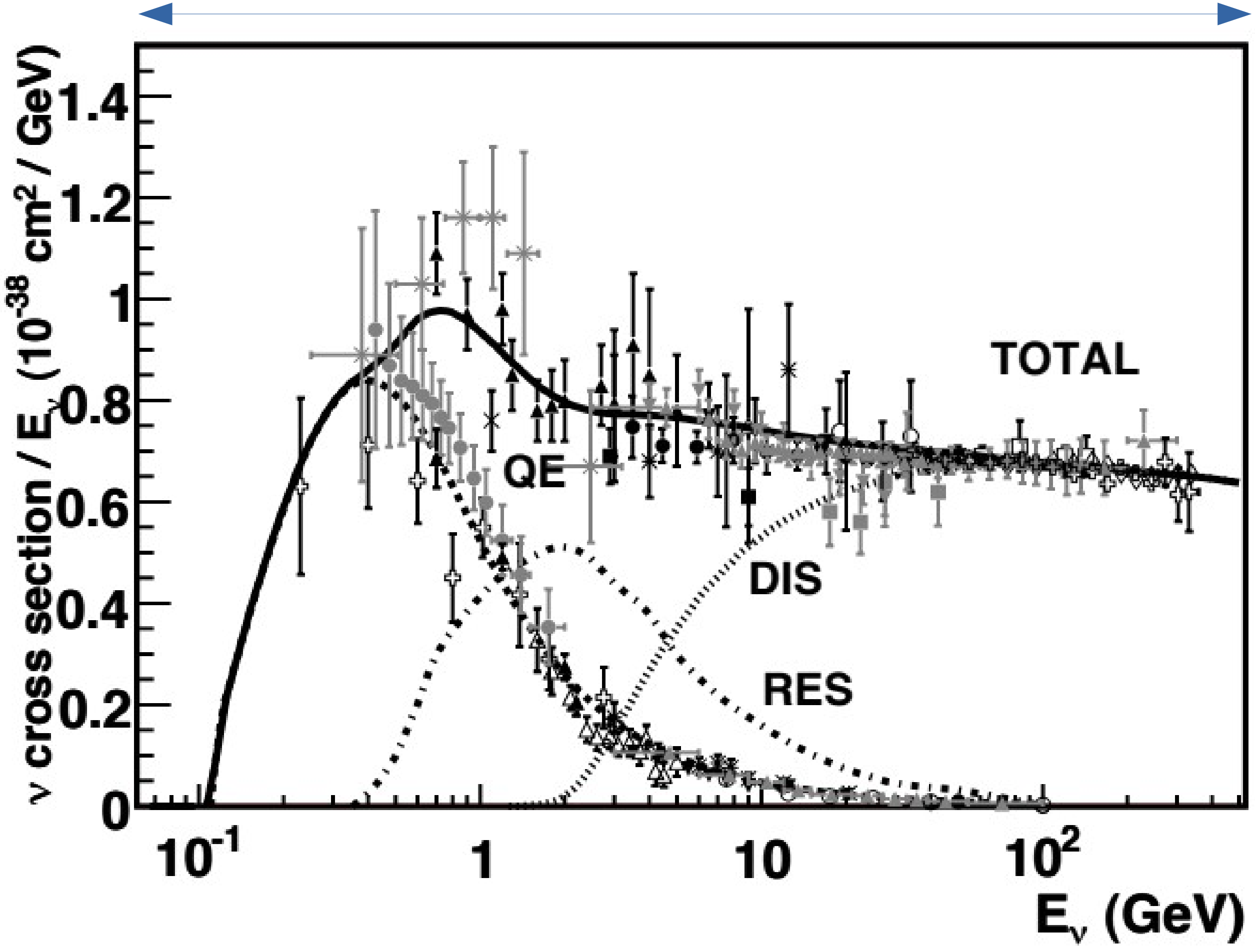
Accelerator experiments



Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group

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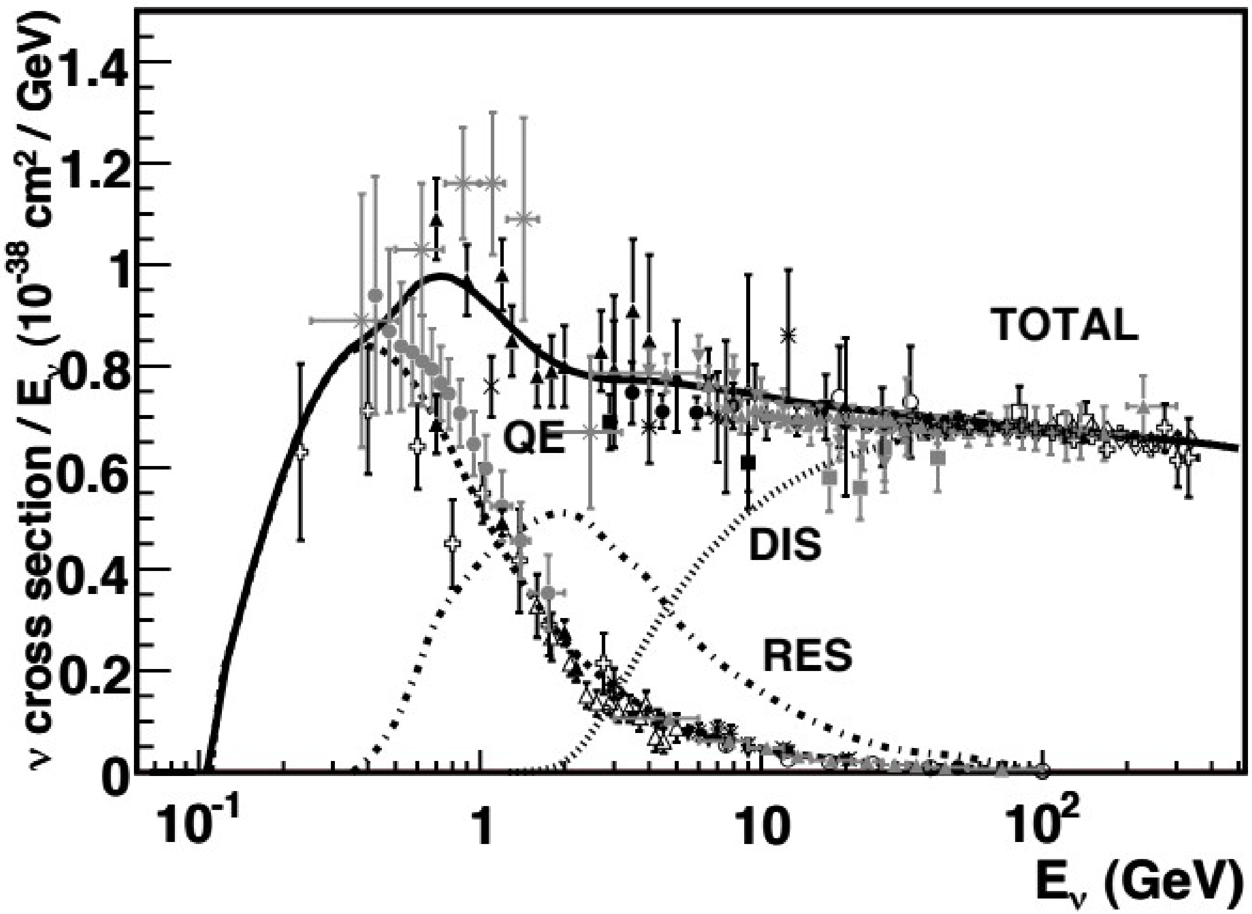
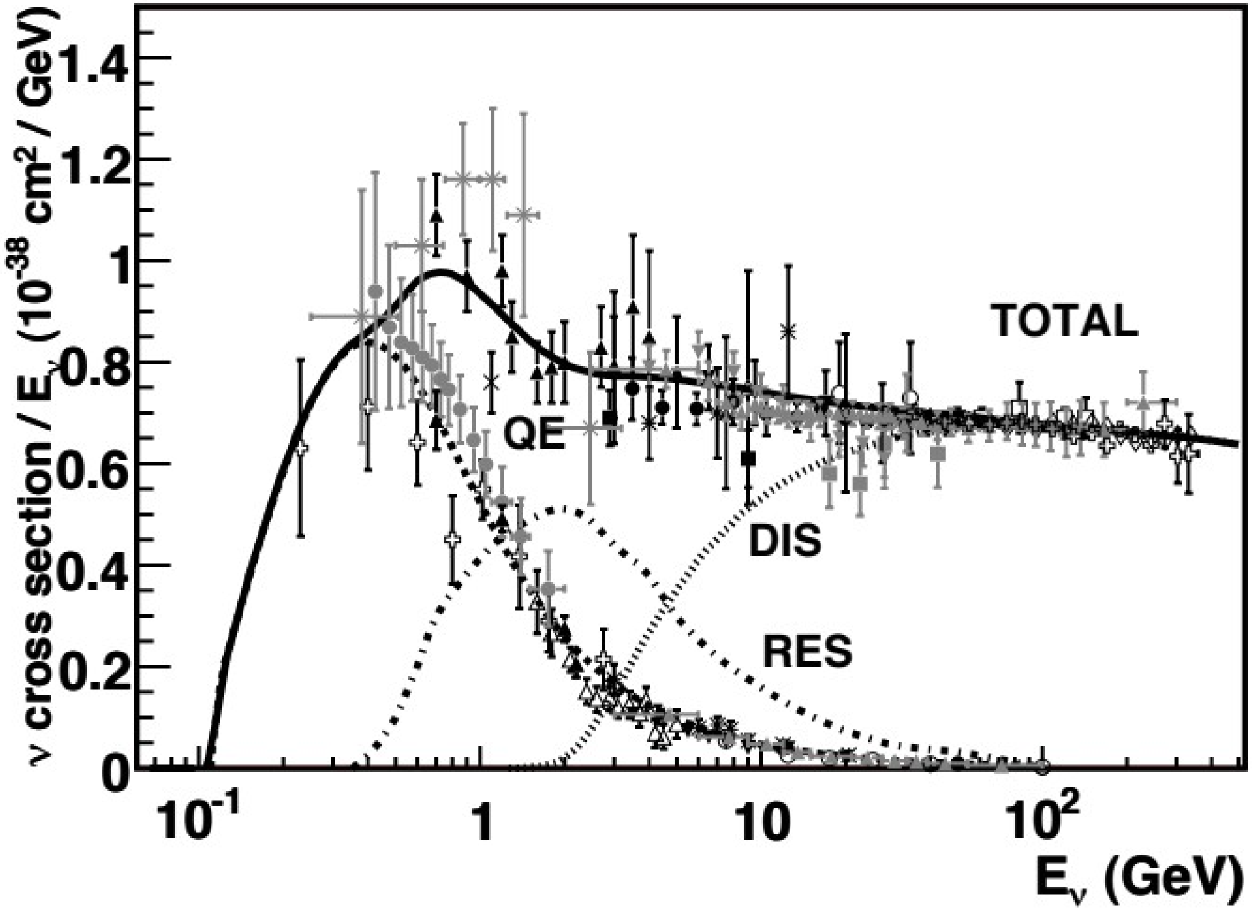


No measurements … until recently!

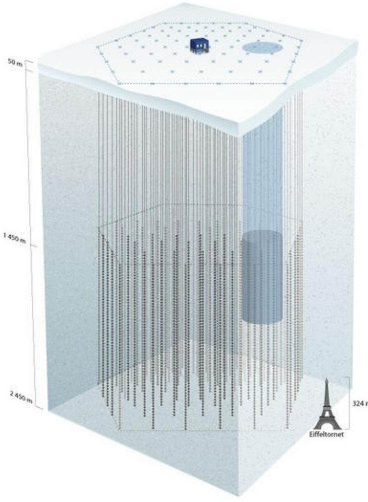
Particle Data Group

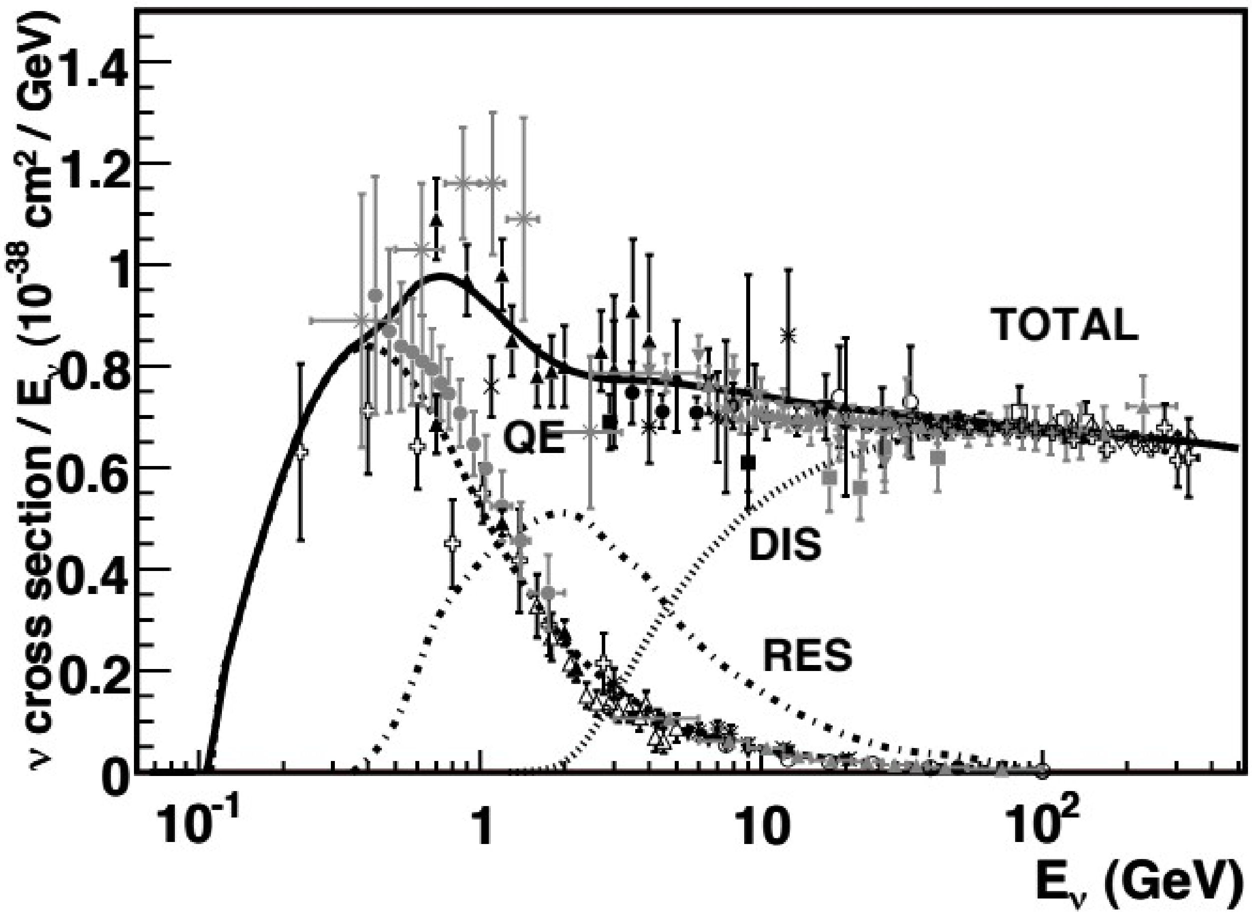
Accelerator experiments

One recent measurement (COHERENT)



Particle Data Group



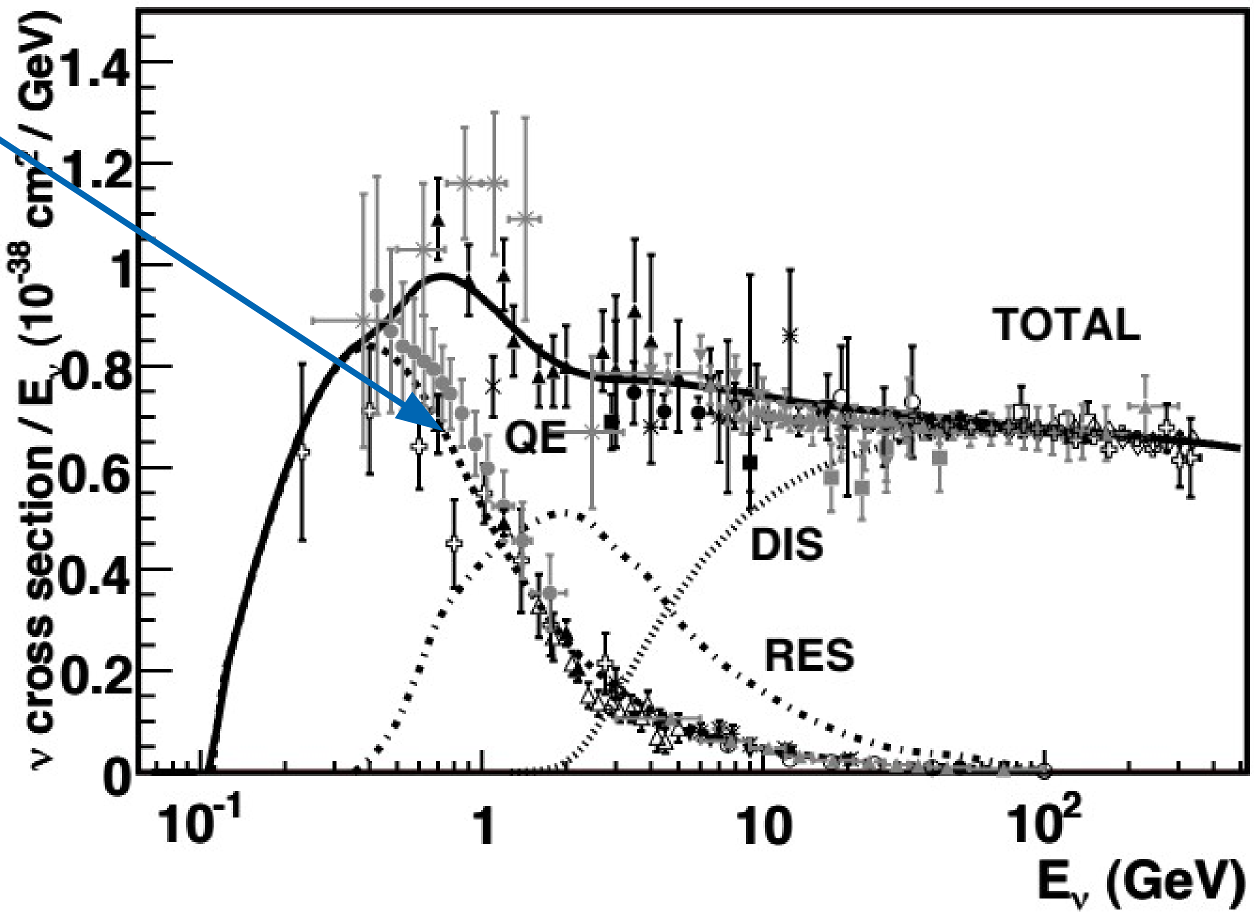


Particle Data Group

Quasi-elastic scattering:

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

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



Particle Data Group

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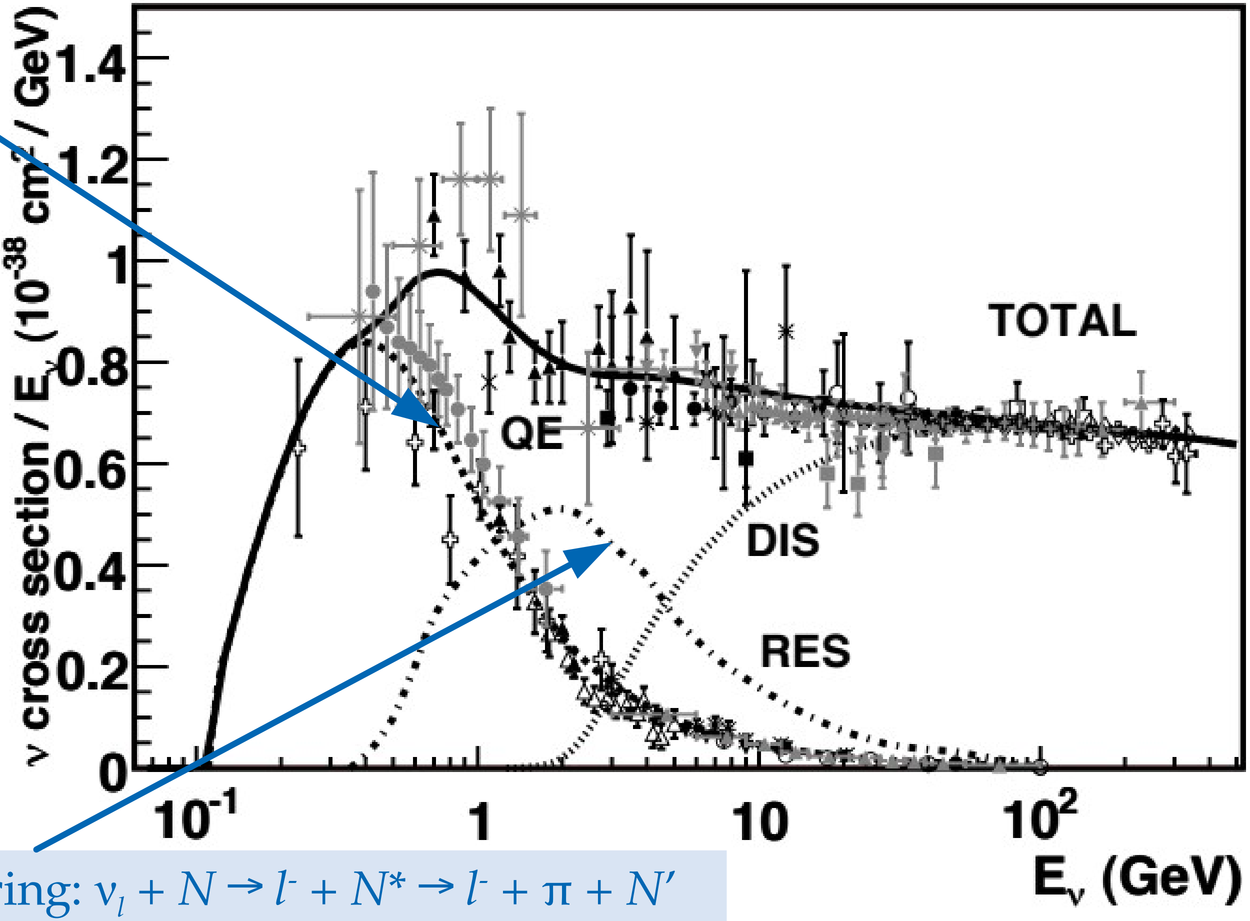

Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Quasi-elastic scattering:

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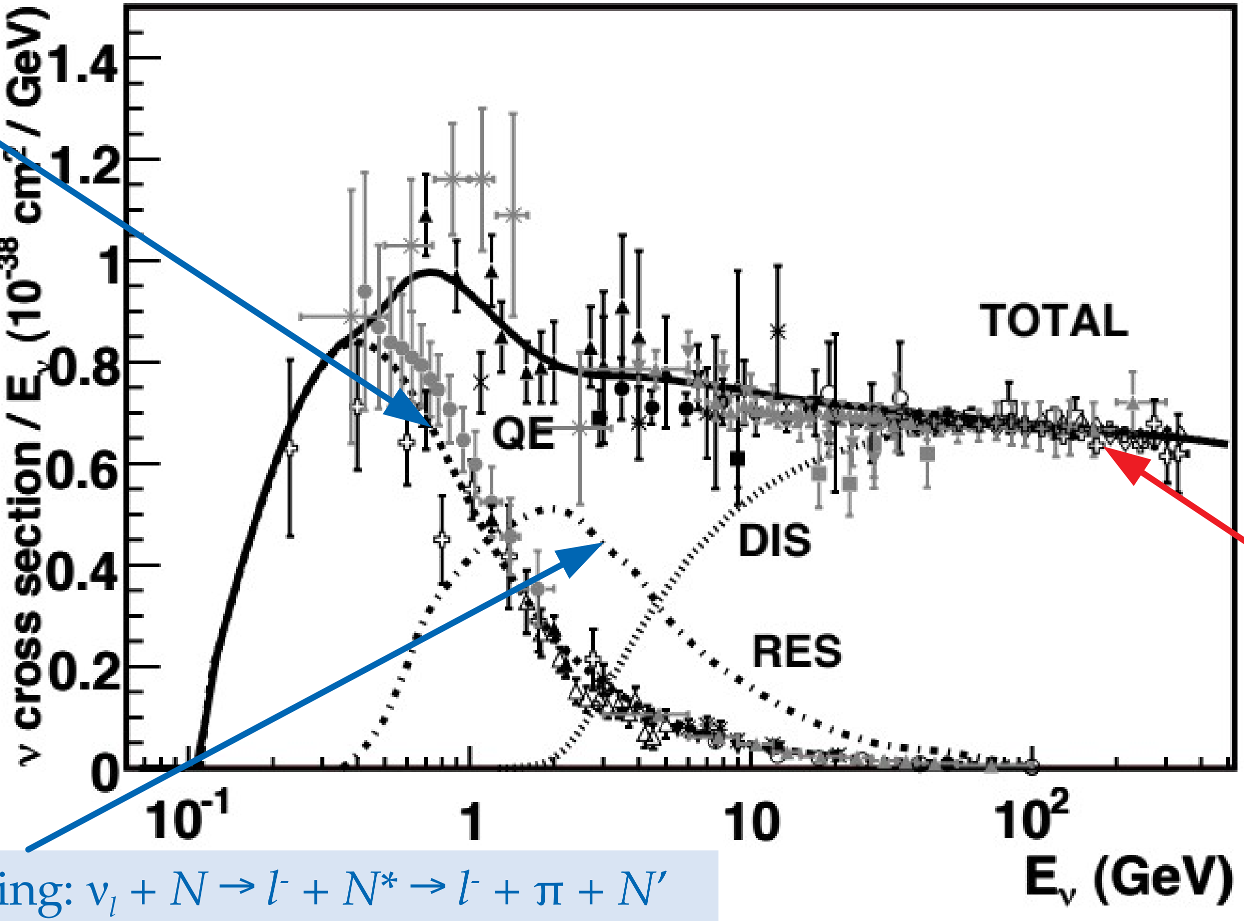
$\bar{\nu}_l + p \rightarrow l^+ + n$



Deep inelastic scattering:

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

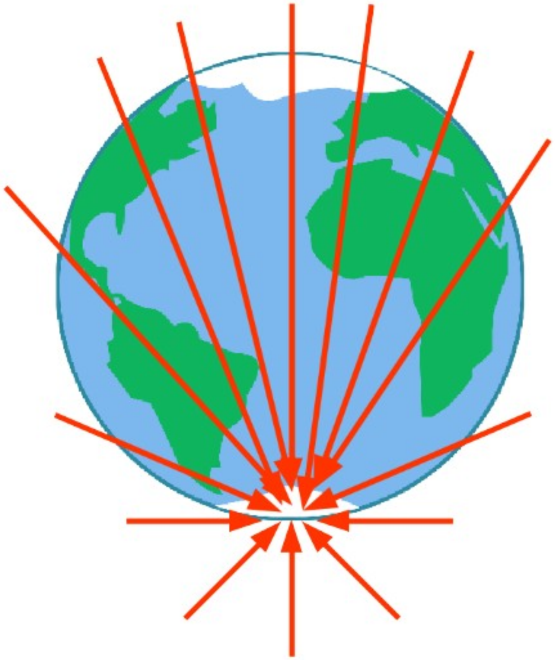
$\bar{\nu}_l + N \rightarrow l^+ + X$

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

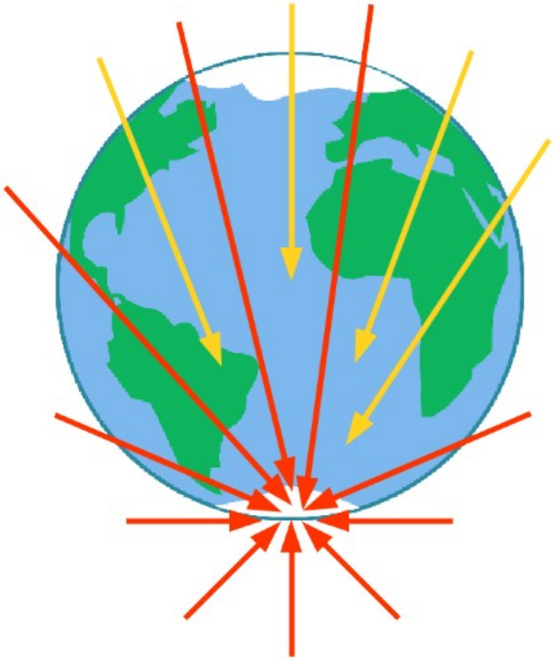
Particle Data Group

Measuring the high-energy cross section

Below ~ 10 TeV: Earth is transparent



Above ~ 10 TeV: Earth is opaque



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

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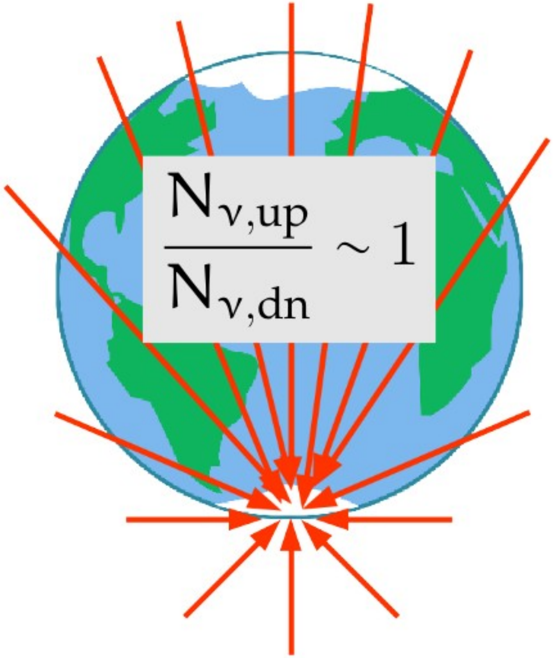

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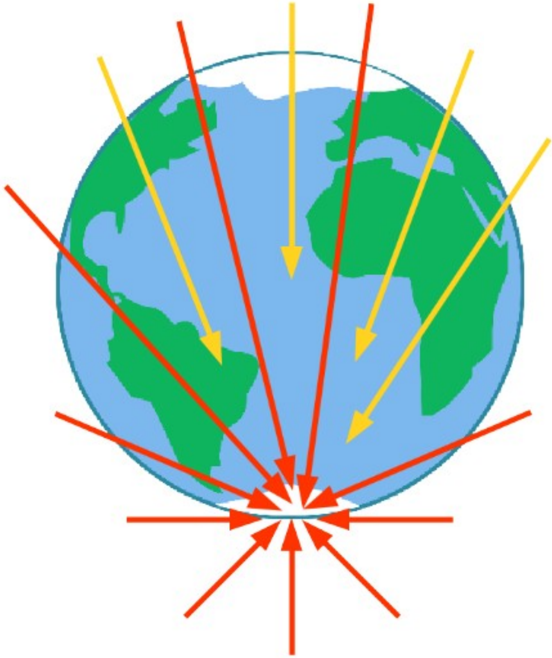

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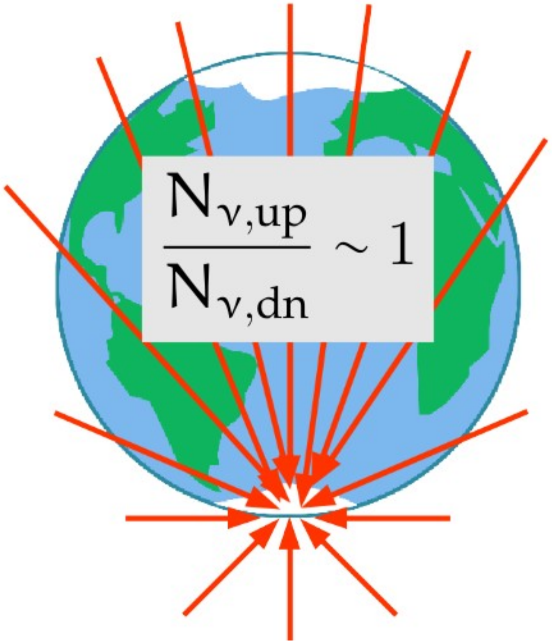

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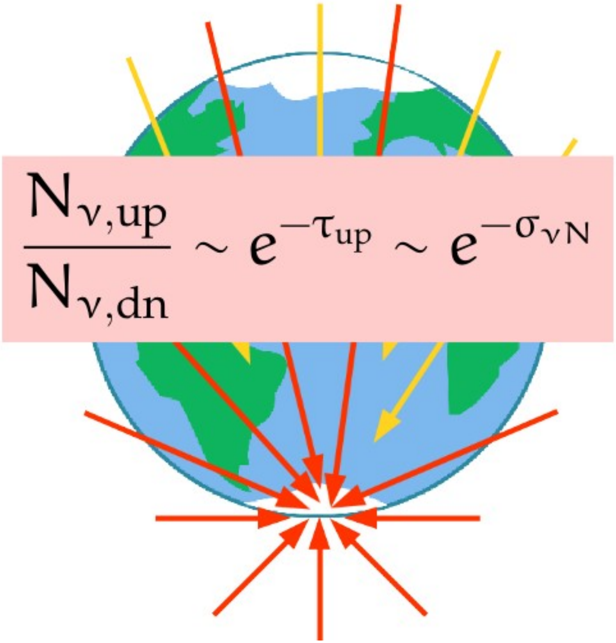

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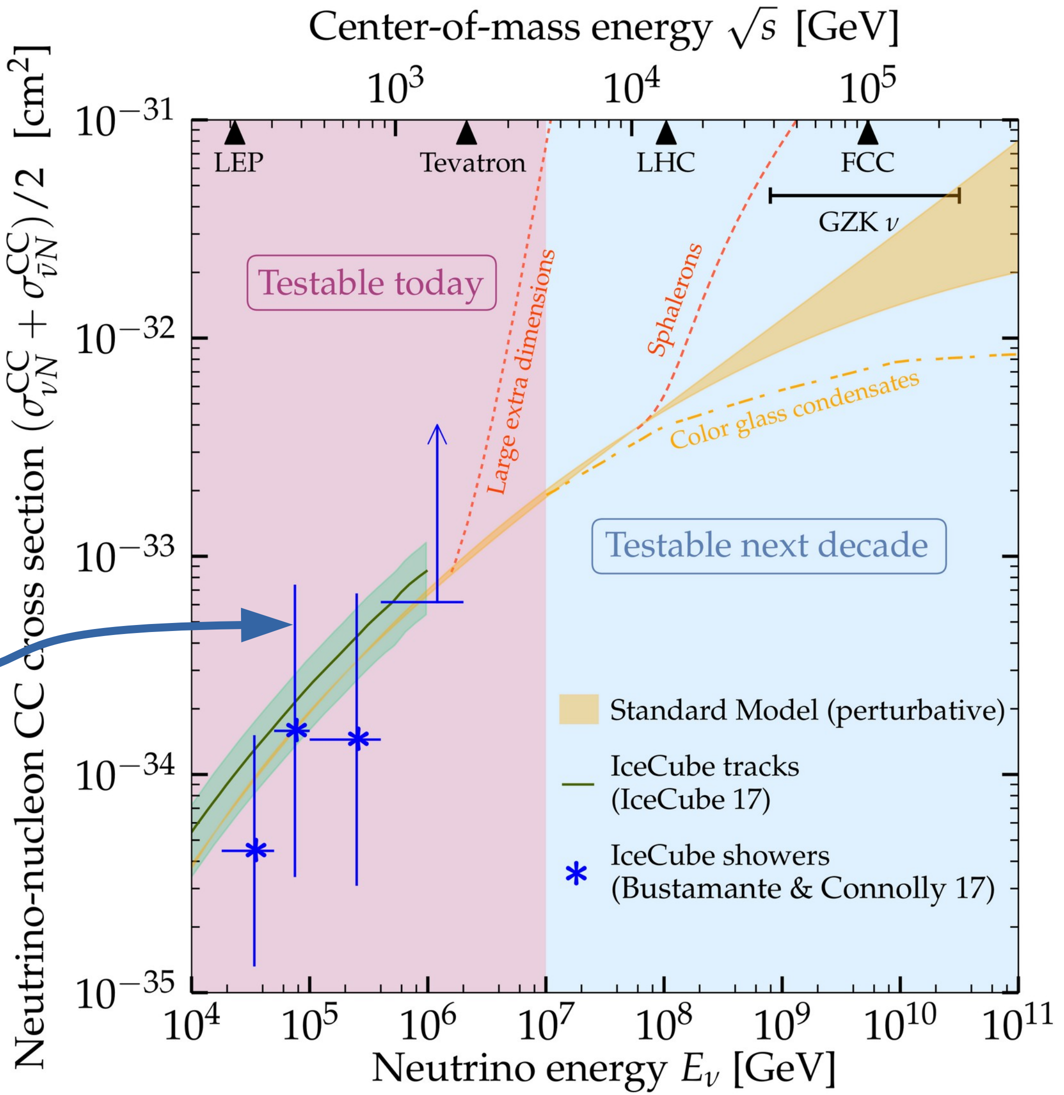
- Fold in astrophysical unknowns (spectral index, normalization)
- Compatible with SM predictions
- Still room for new physics
- Today, using IceCube:
  - Extracted from ~60 showers in 6 yr
  - Limited by statistics
- Future, using IceCube-Gen2:
  - × 5 volume ⇒ 300 showers in 6 yr
  - Reduce statistical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

Example 2:
Secret neutrino interactions

Astrophysical neutrino sources

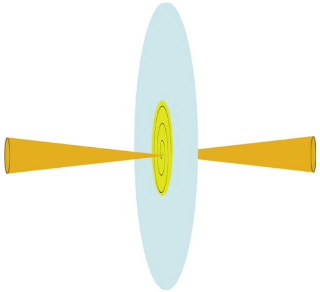
Earth

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

Astrophysical neutrino sources

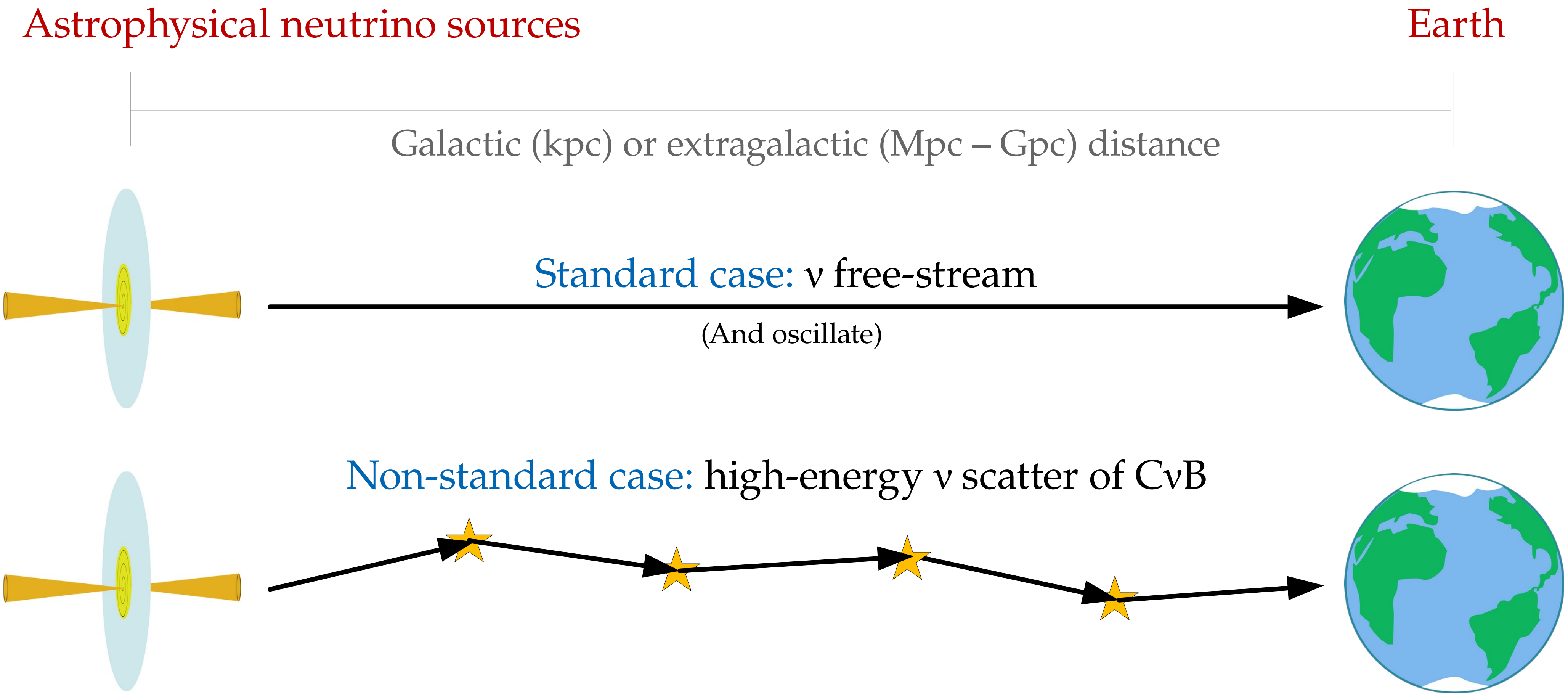
Earth

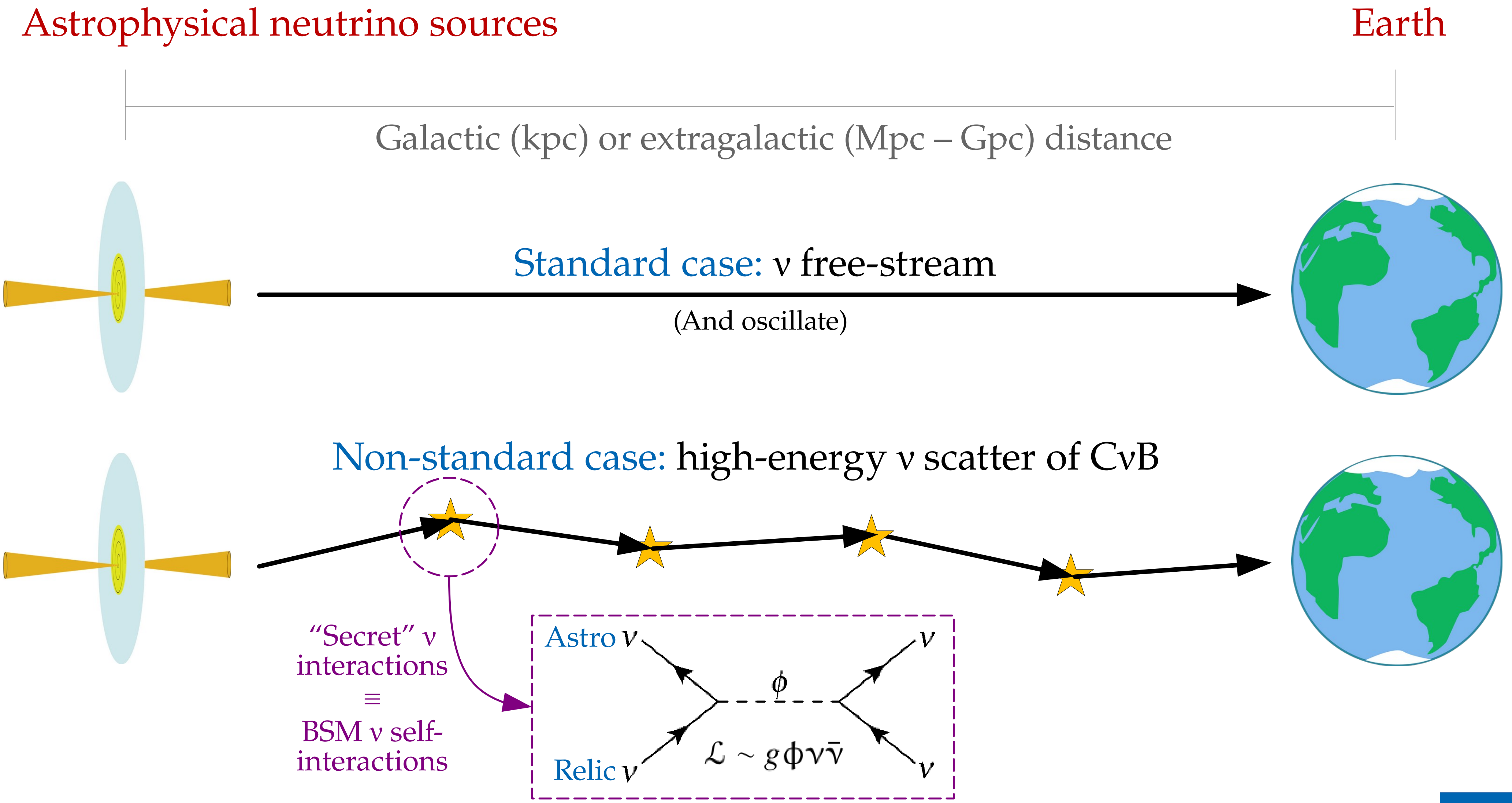
Galactic (kpc) or extragalactic (Mpc – Gpc) distance



Standard case: ν free-stream

(And oscillate)


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



Astrophysical neutrino sources
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(And oscillate)
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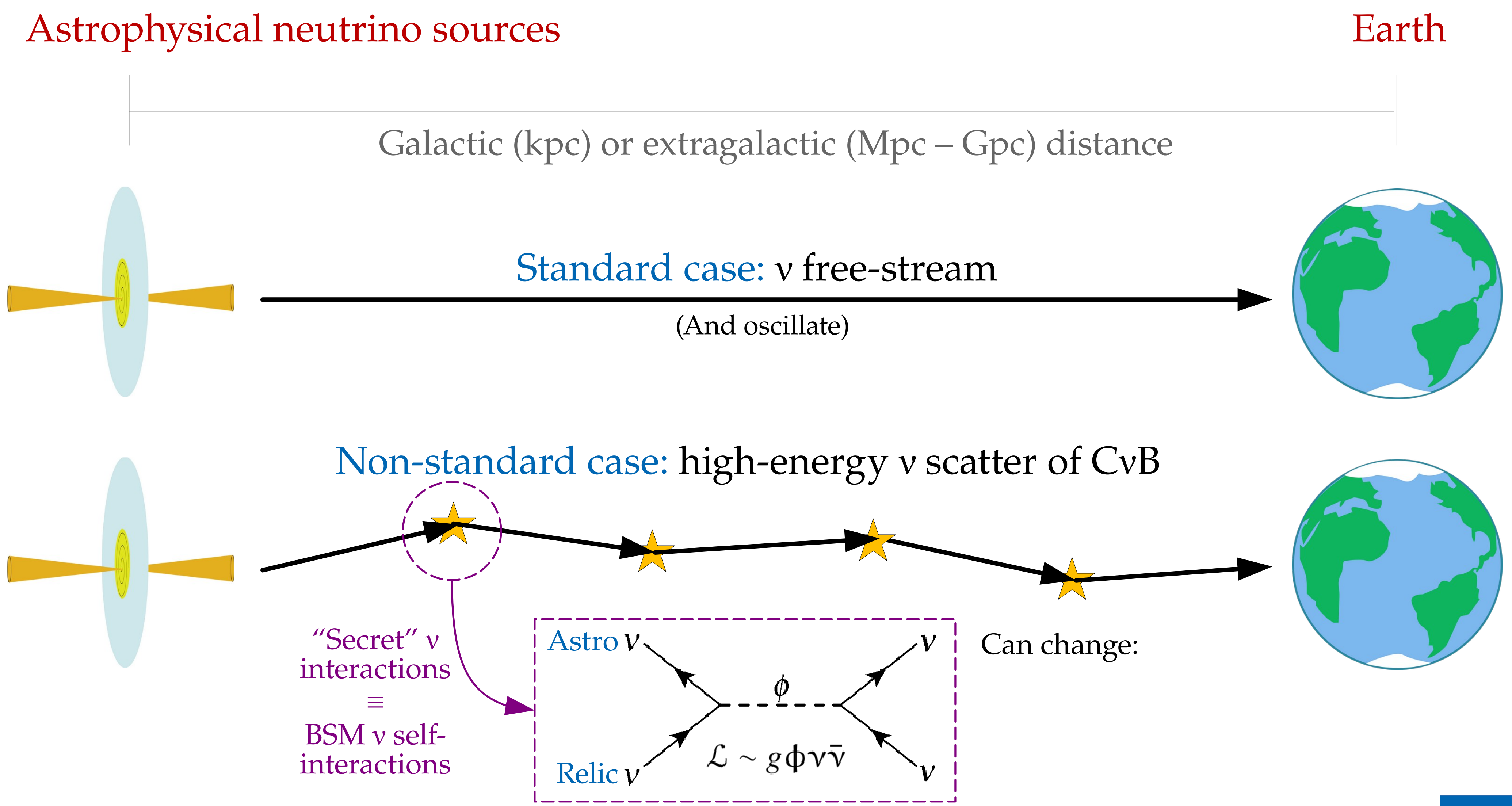
“Secret” ν interactions
≡
BSM ν self-interactions
Astro ν
Relic ν
ν
ν
ϕ
$\mathcal{L} \sim g\phi\nu\bar{\nu}$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Astro ν
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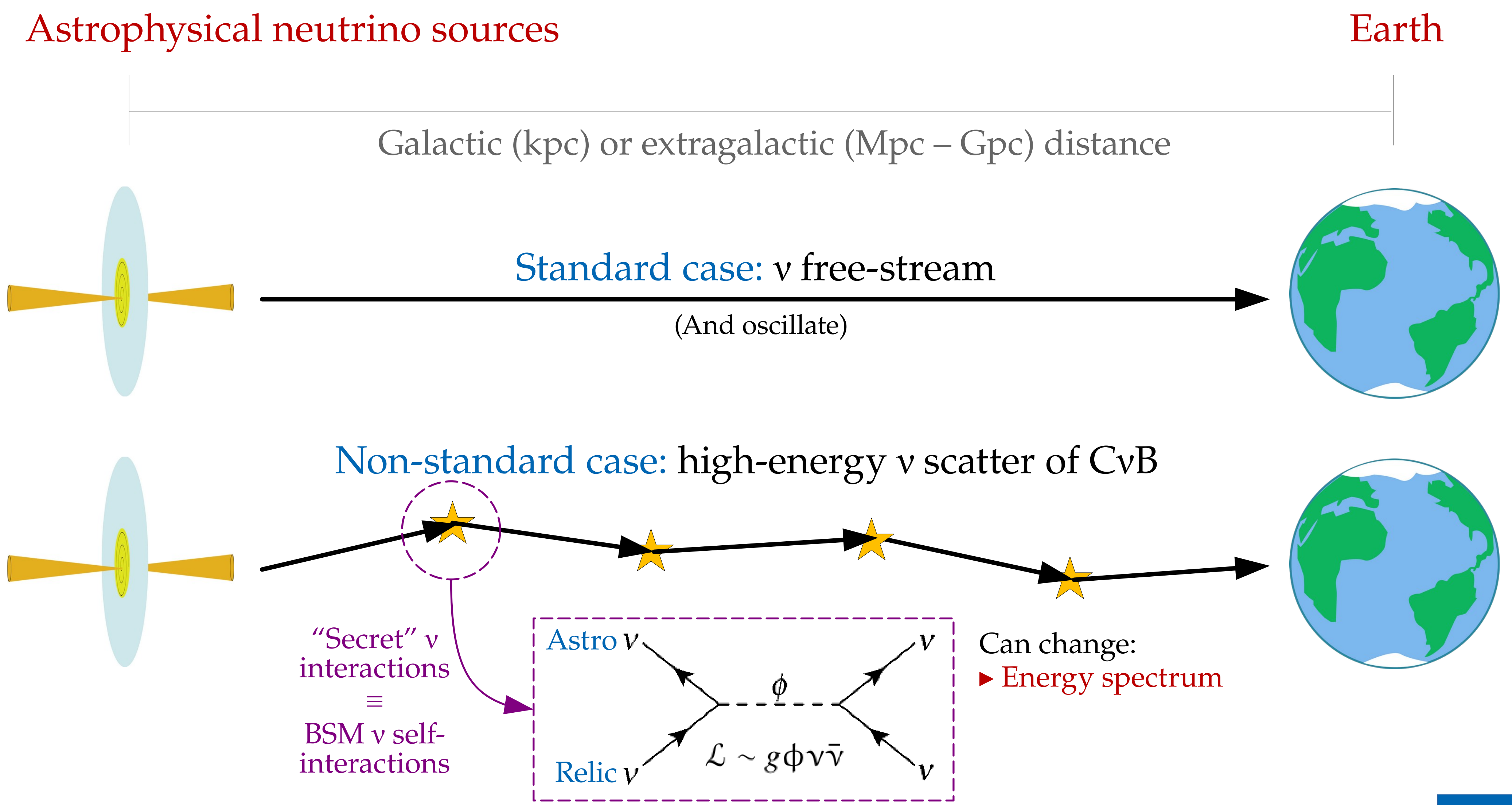
$\mathcal{L} \sim g\phi\nu\bar{\nu}$
Can change:



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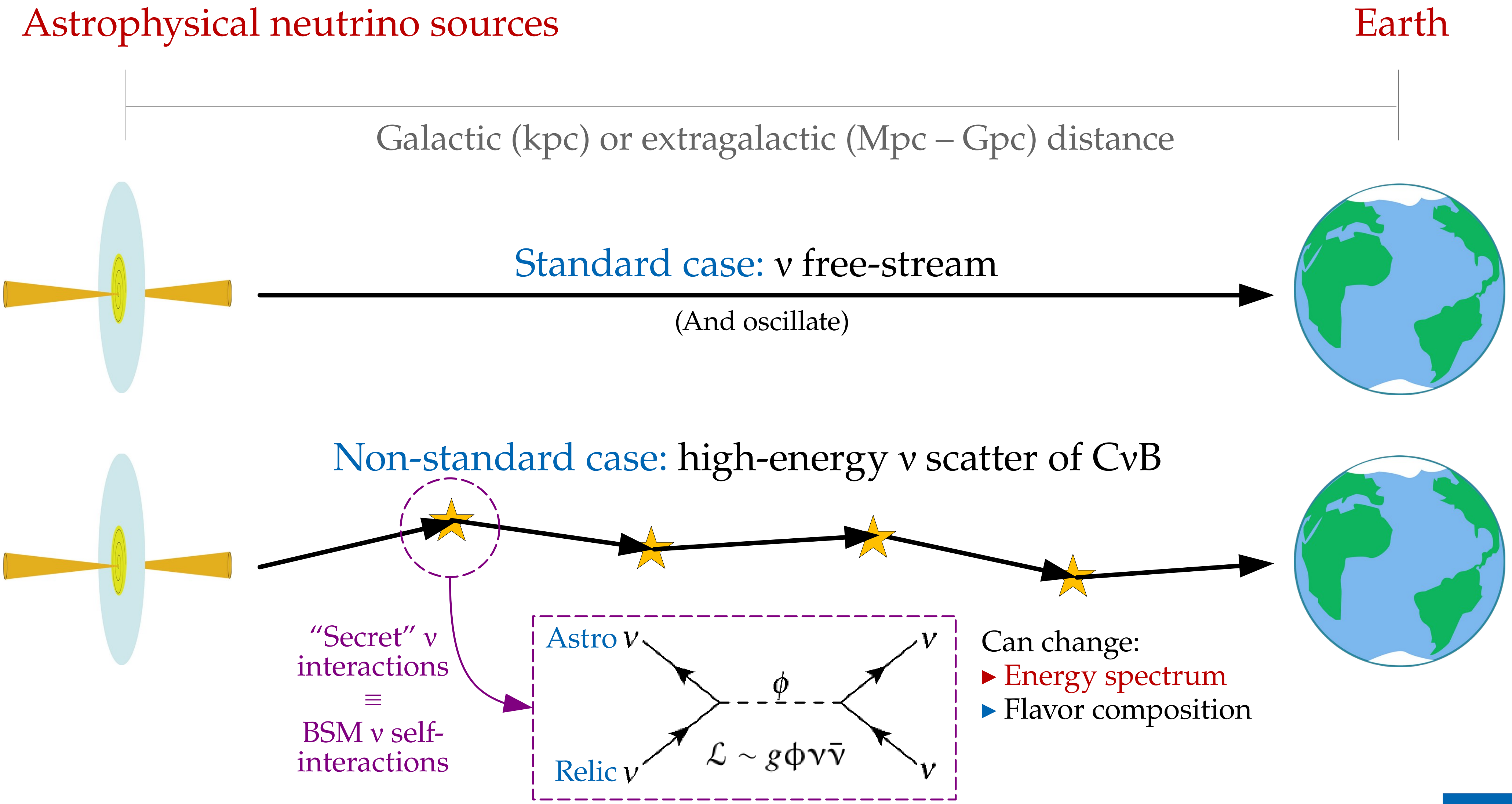
Can change:
▸ Energy spectrum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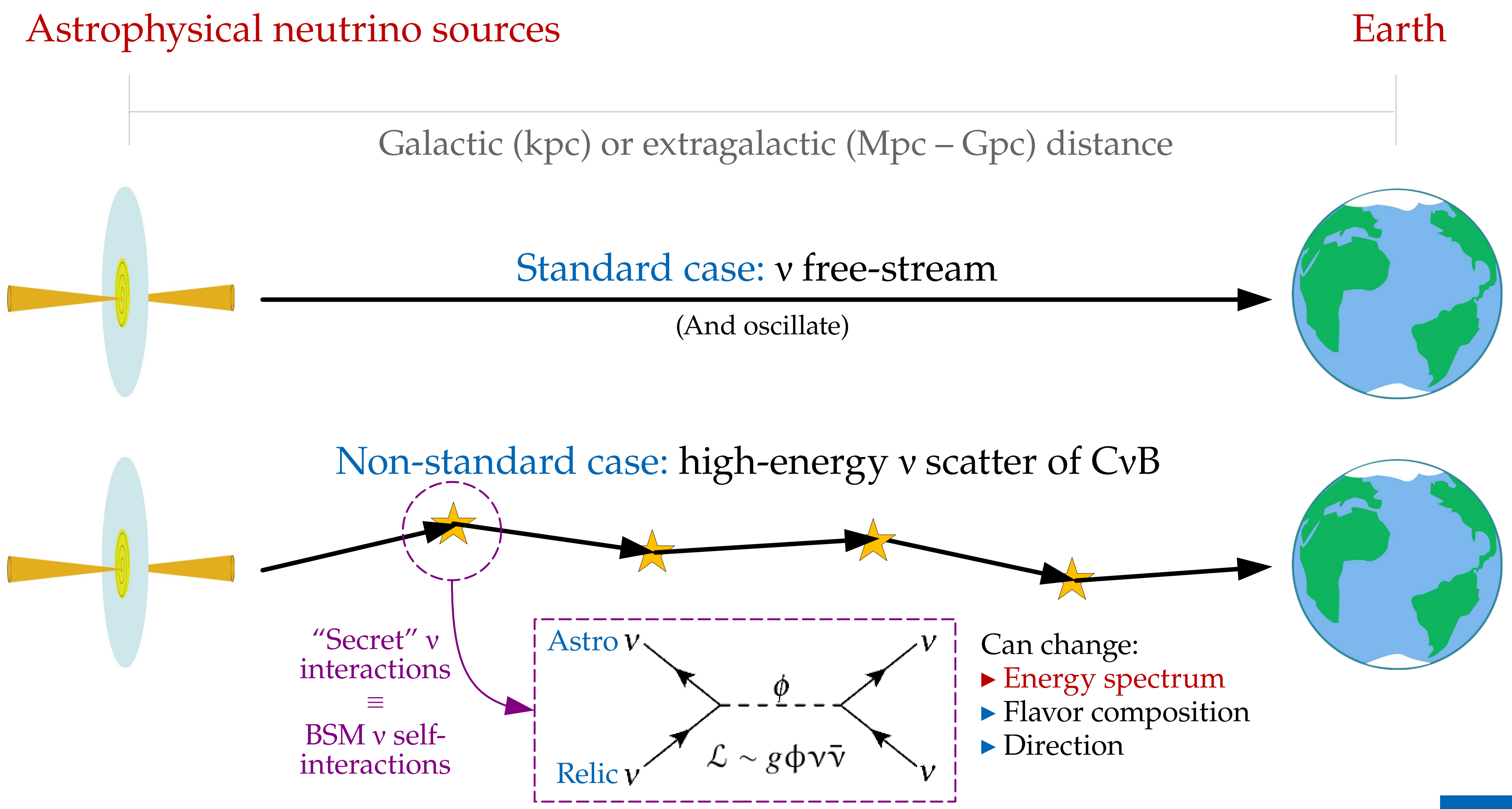
Can change:
Energy spectrum
Flavor composition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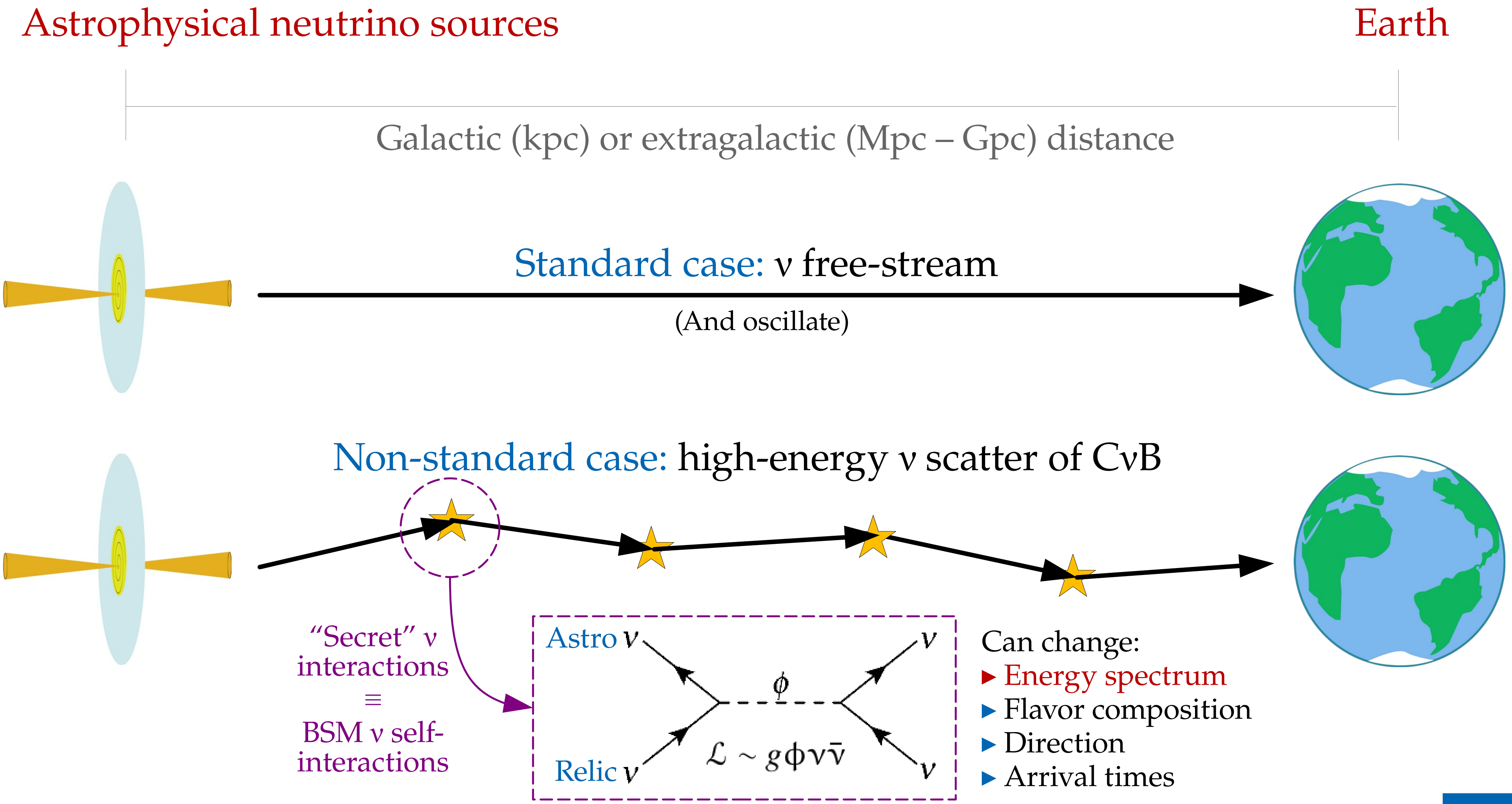
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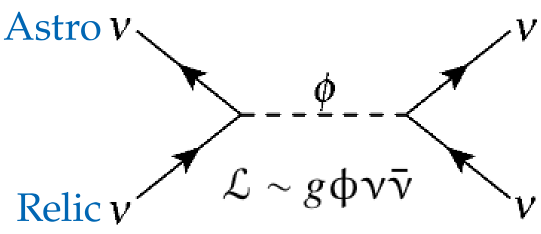
▸ Flavor composition
▸ Direction
▸ Arrival times

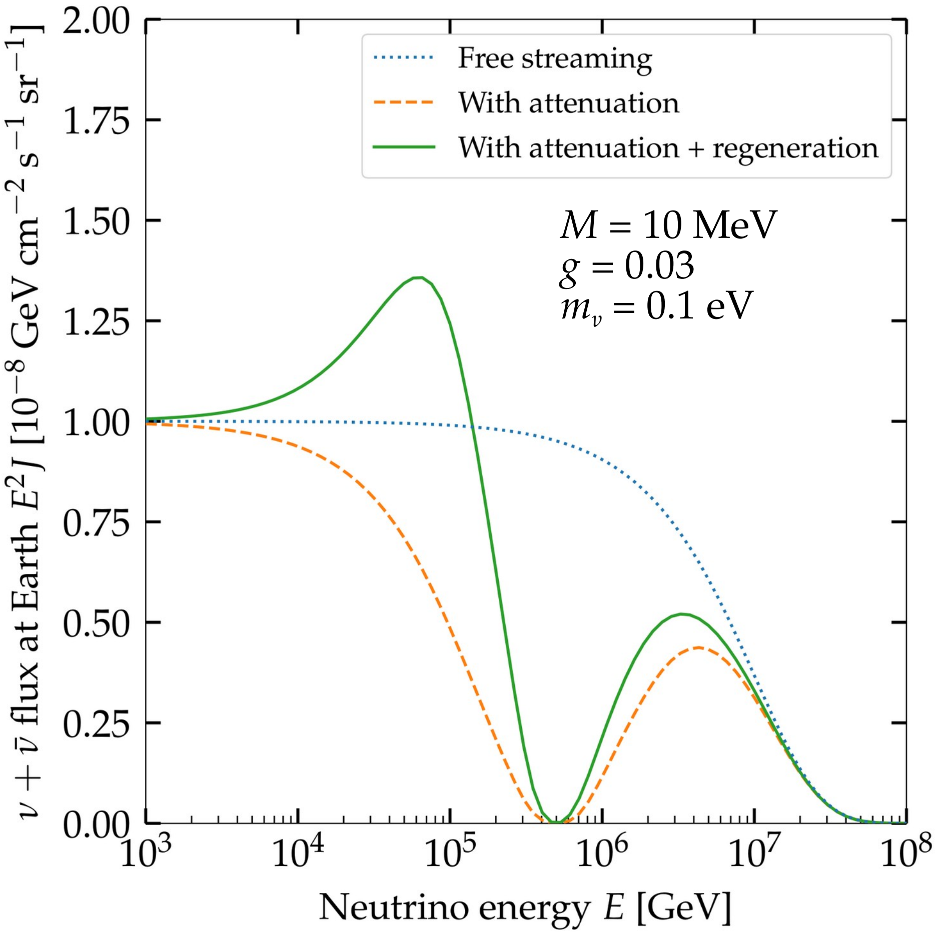
Secret interactions of high-energy astrophysical neutrinos

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



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

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



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

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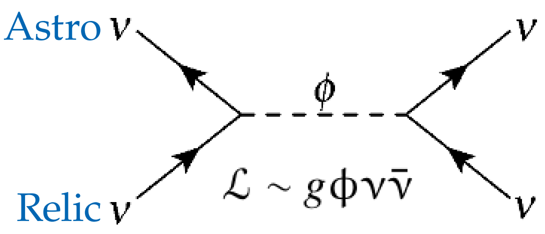
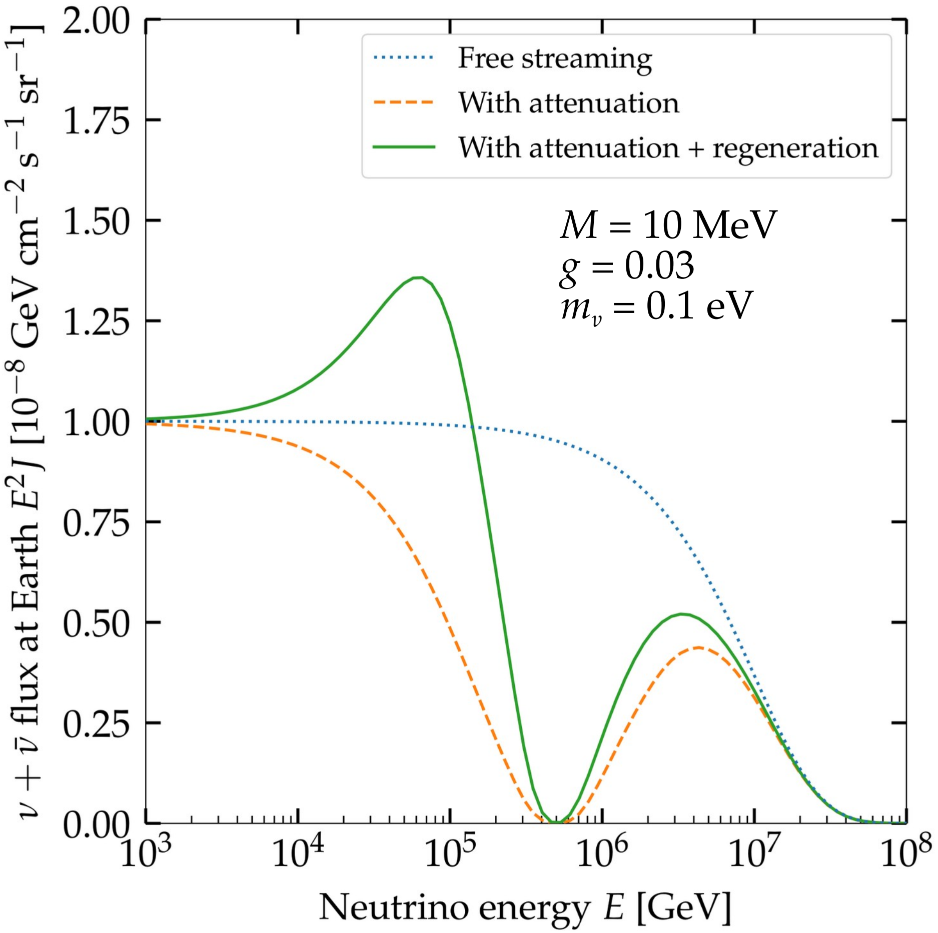


New coupling

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

Mediator mass

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



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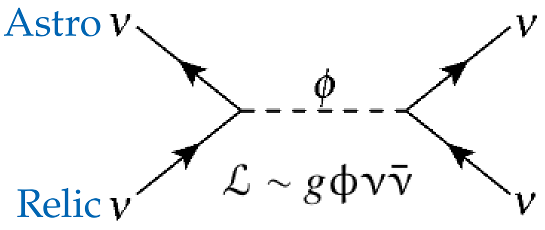

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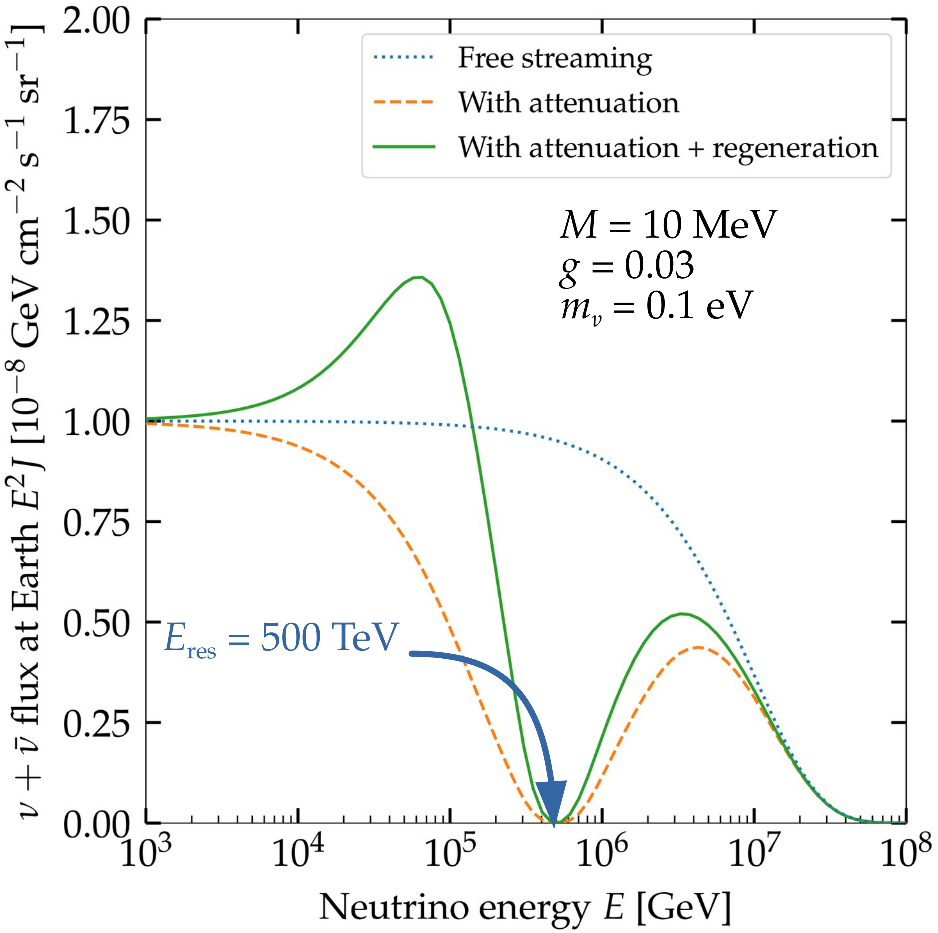

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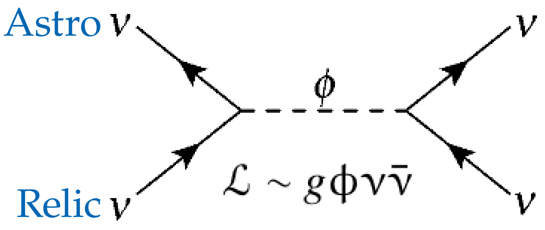

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Mediator mass

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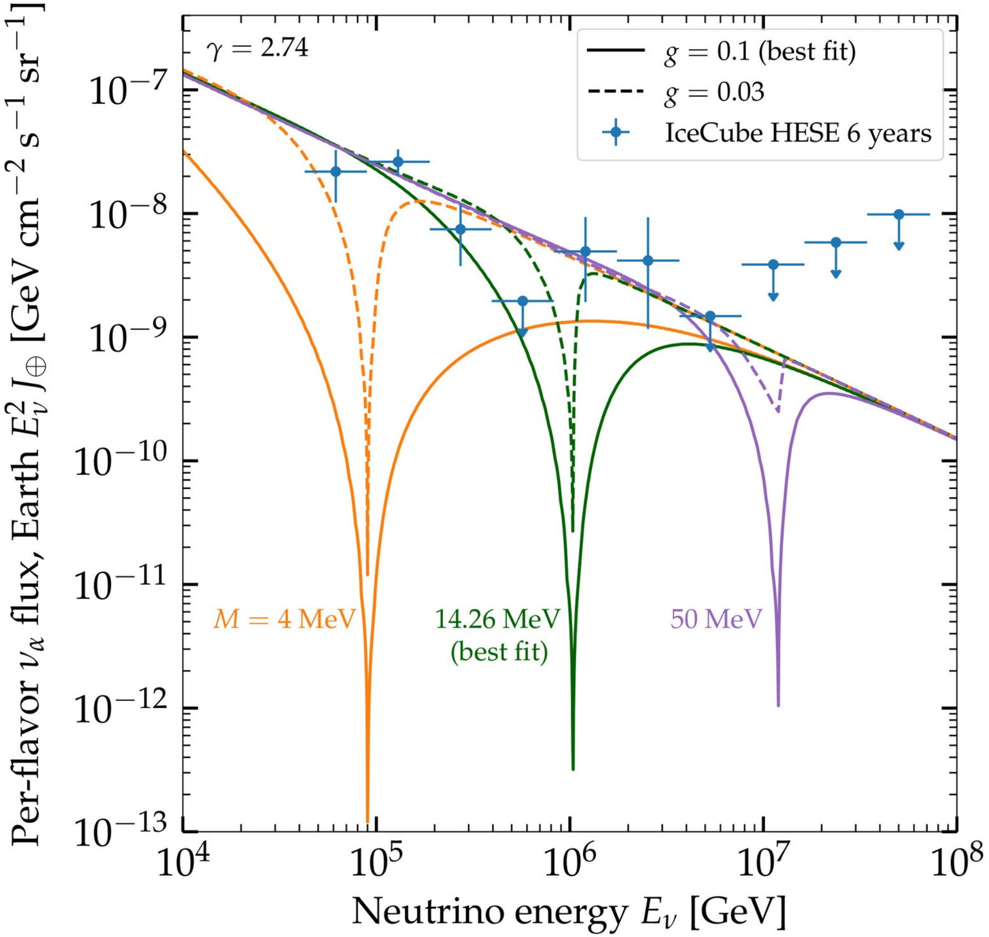

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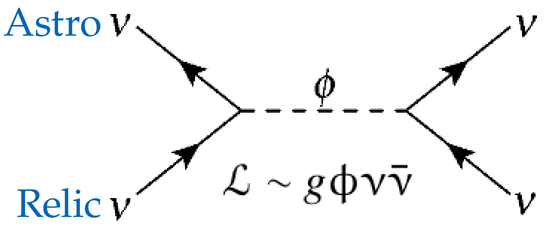

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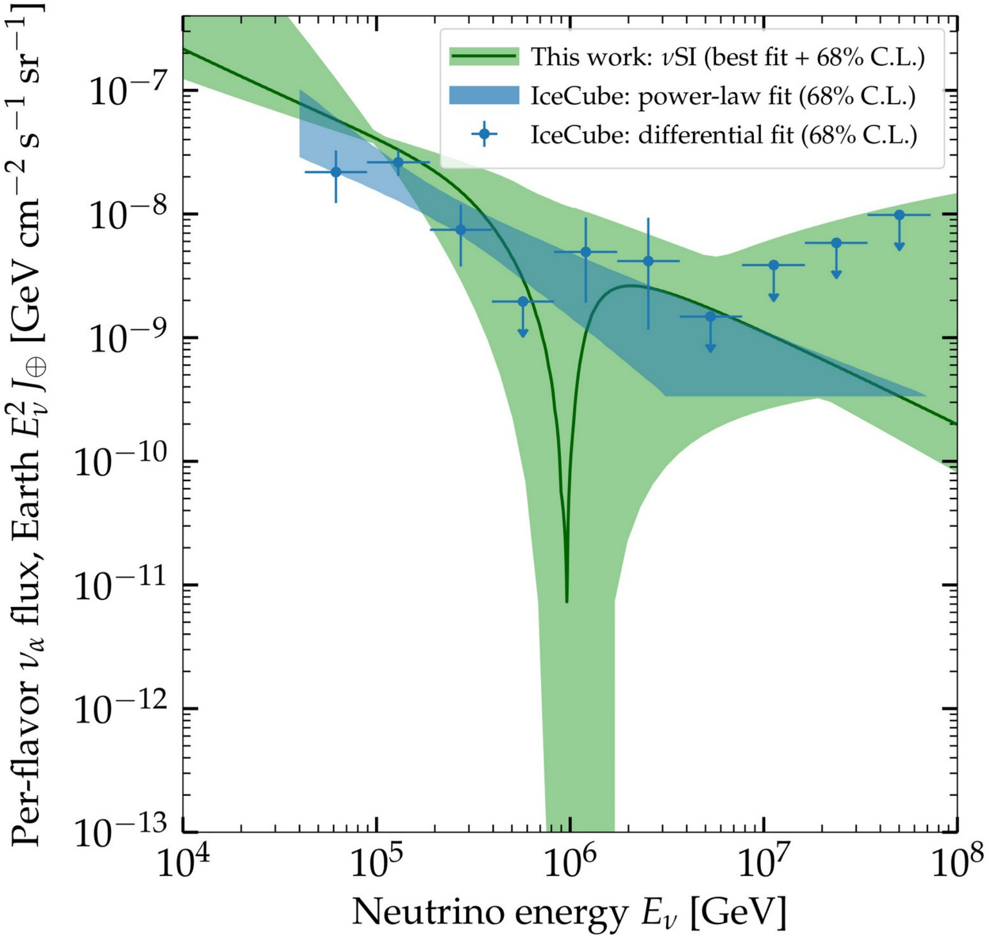
Blum, Hook, Murase, 1408.3799

Looking for evidence of νSI

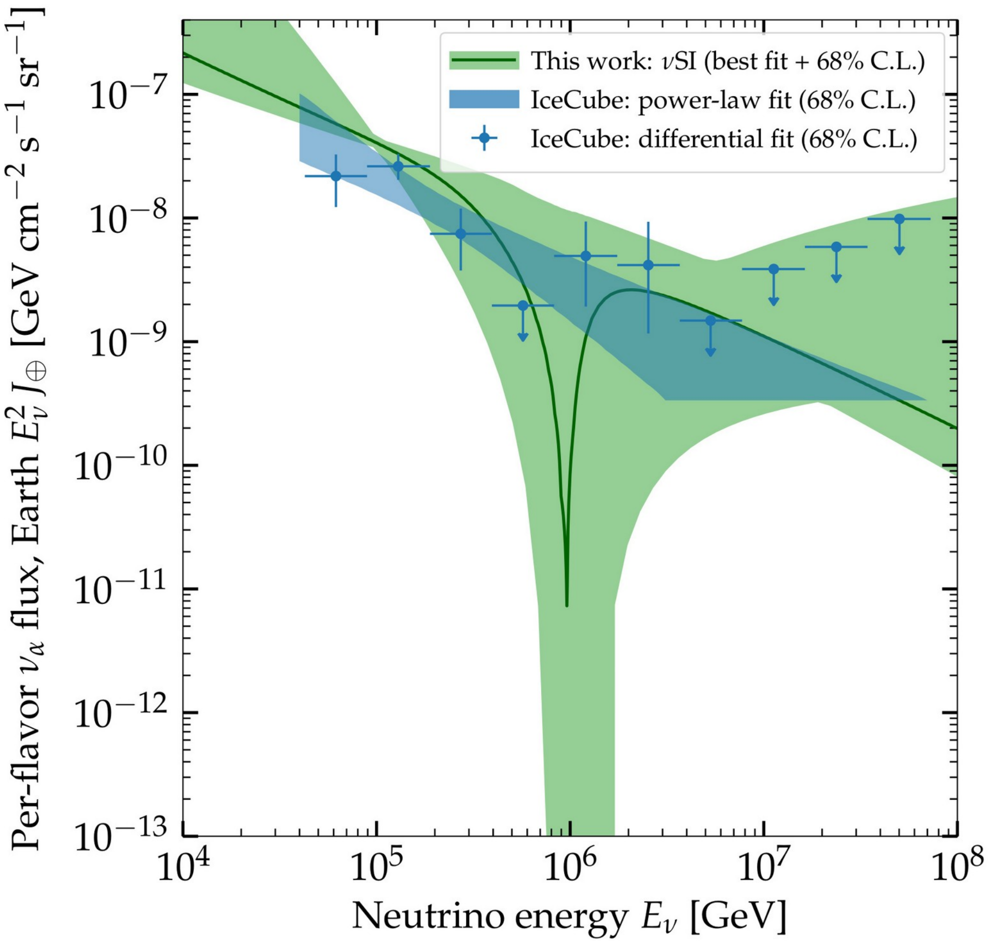
- Look for dips in 6 years of public IceCube data (HESE)
- 80 events, 18 TeV–2 PeV
- Assume flavor-diagonal and universal: $g_{\alpha\alpha} = g\,\delta_{\alpha\alpha}$
- Bayesian analysis varying M, g, shape of emitted flux (γ)
- Account for atmospheric ν, in-Earth propagation, detector uncertainties

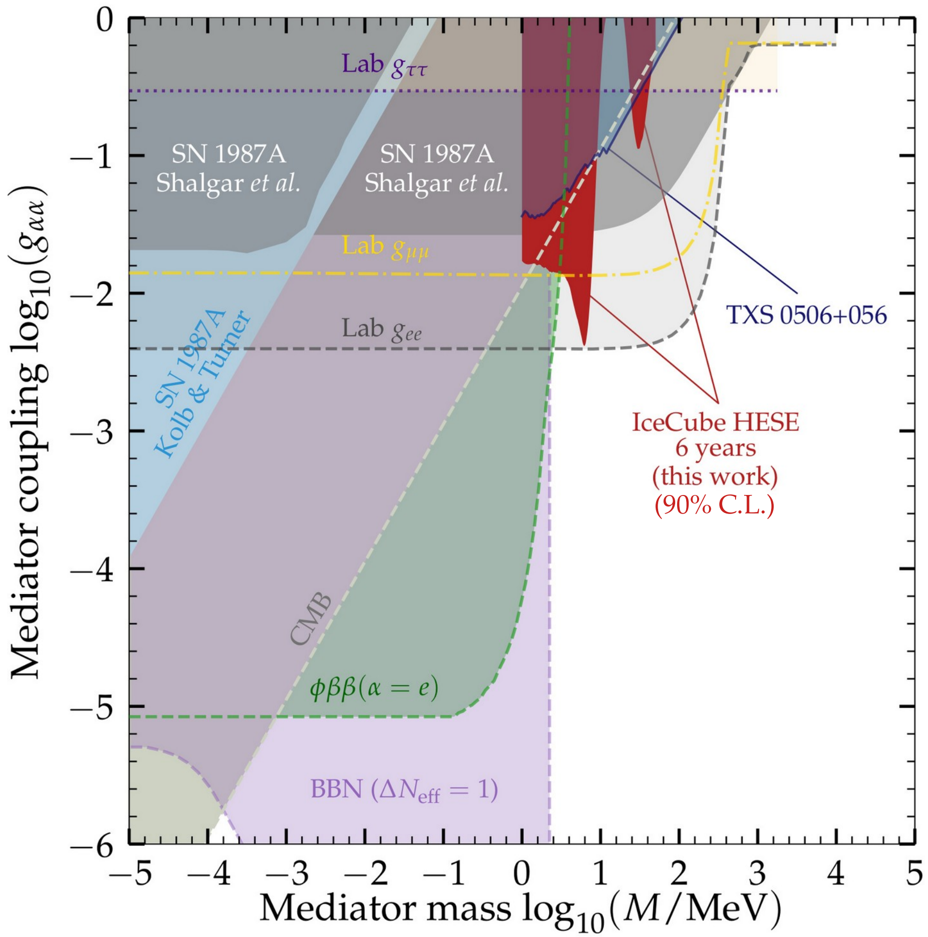
No significant (> 3σ) evidence for a spectral dip …



MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

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





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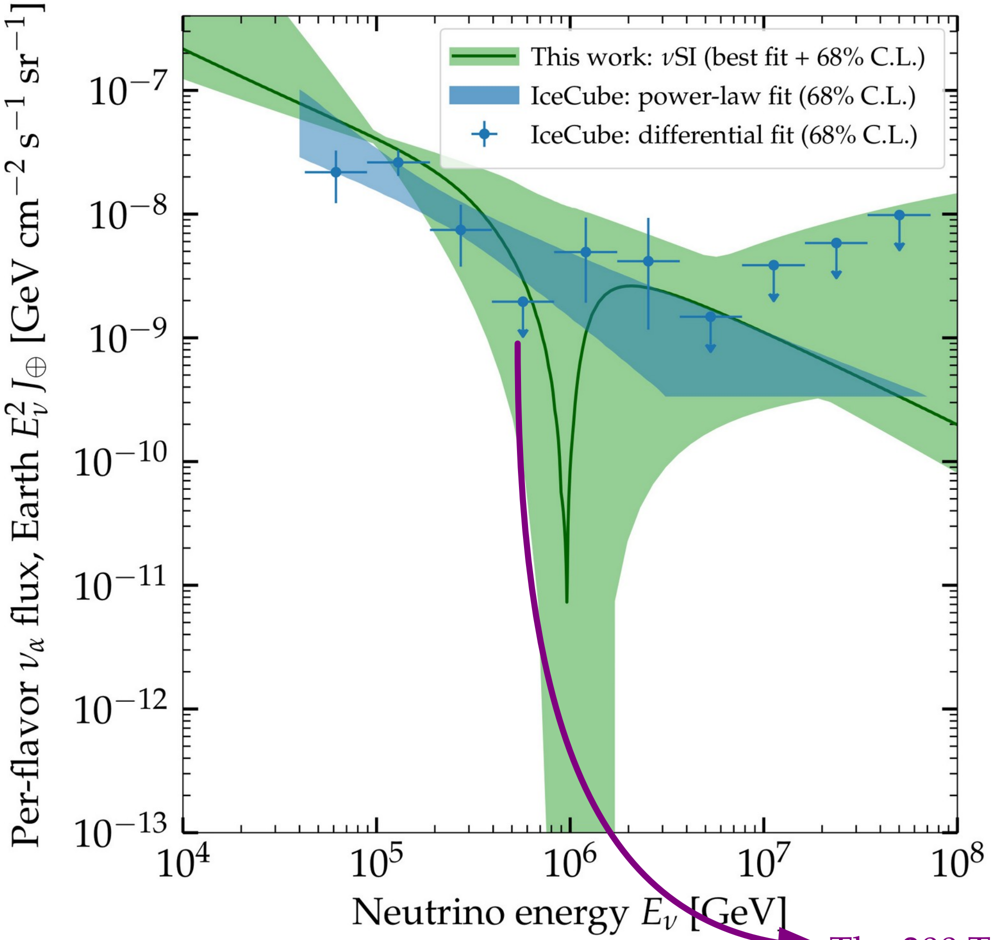
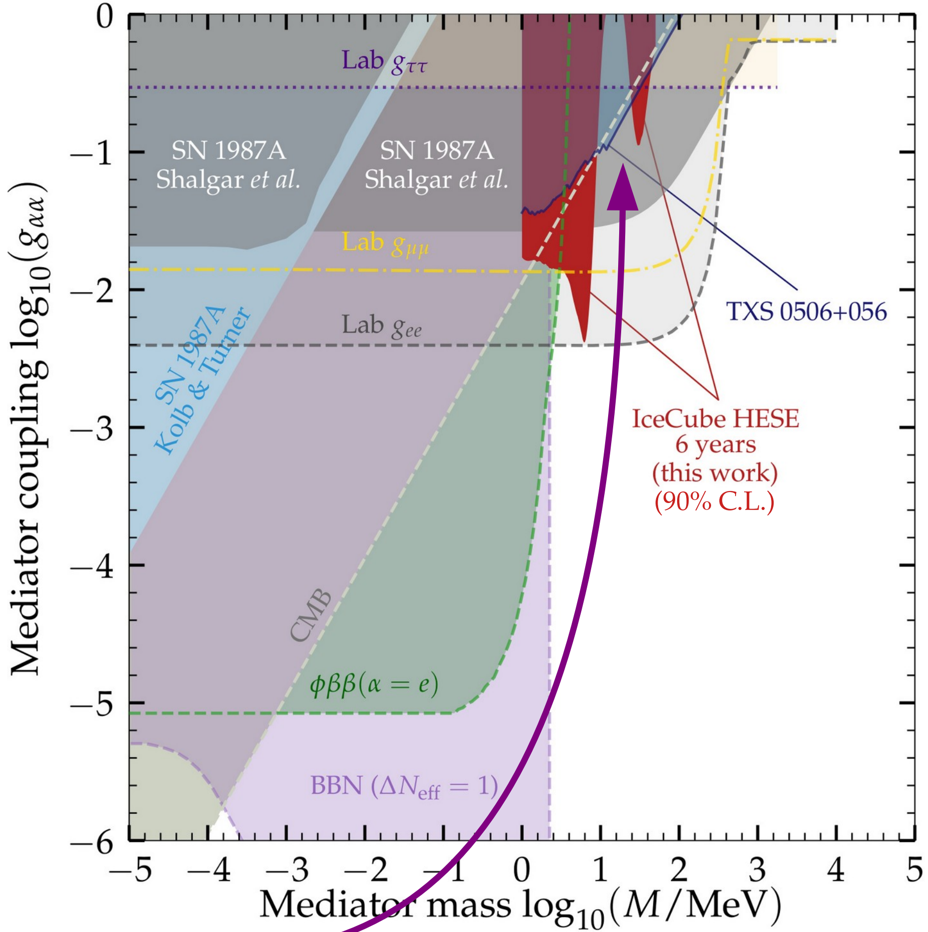




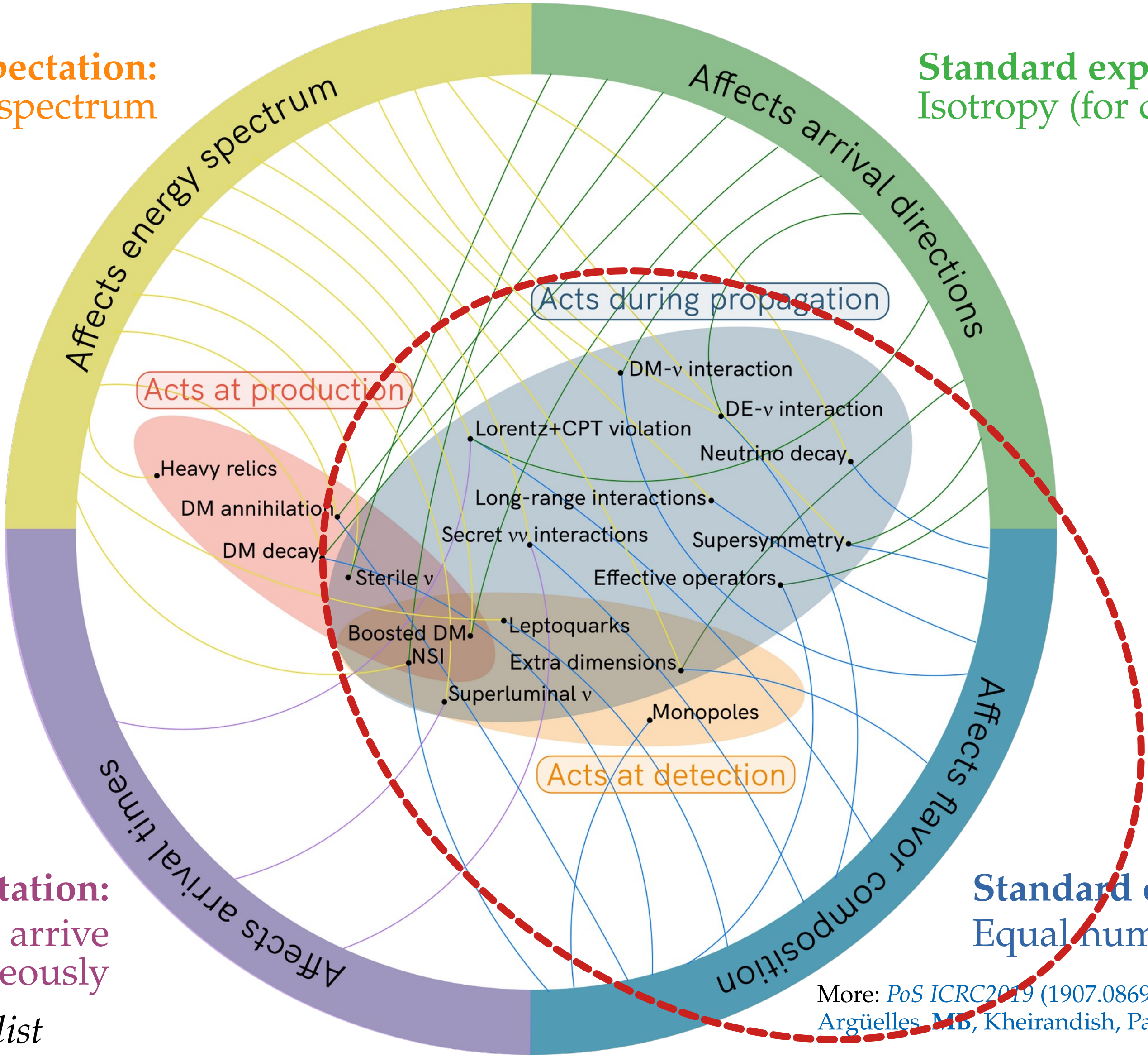
The 300 TeV–1 PeV "gap" degrades the limit at ~10 MeV

MB, Rosenstroem, Shalgar, Tamborra, *PRD* 2020
See also: Shalgar, **MB**, Tamborra, 1912.09115

Example 3:
New physics via flavor

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Note: Not an exhaustive list

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

New physics in flavor composition

Repurpose the flavor sensitivity to test new physics:

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

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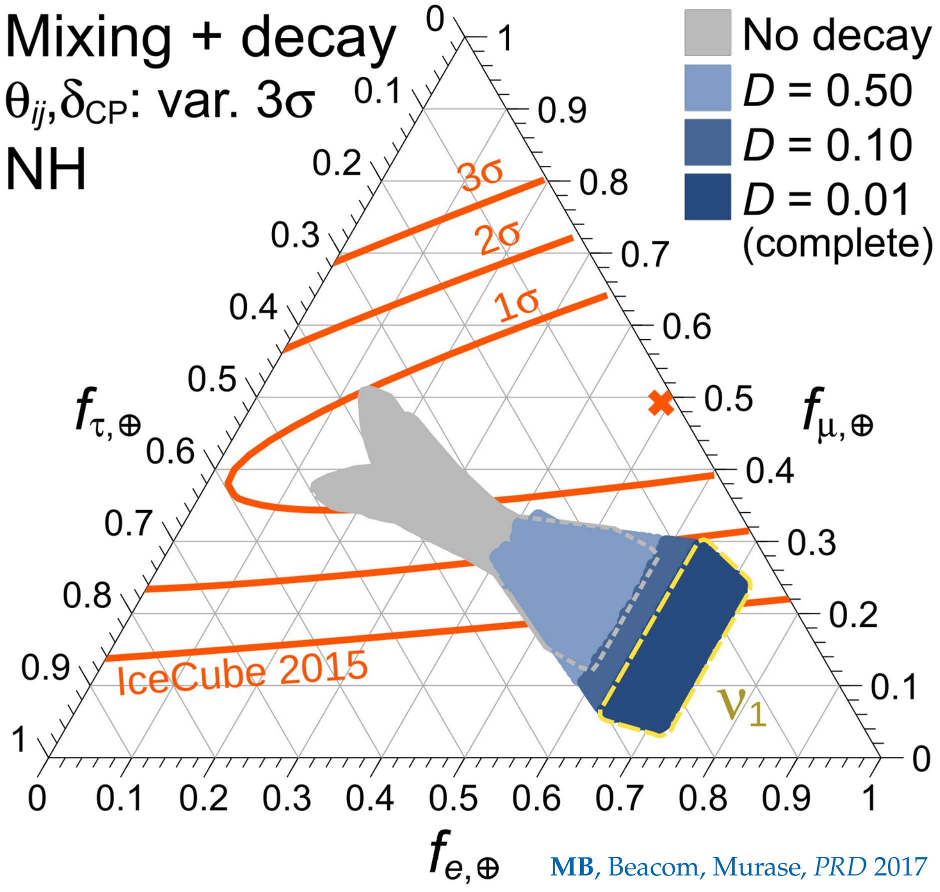

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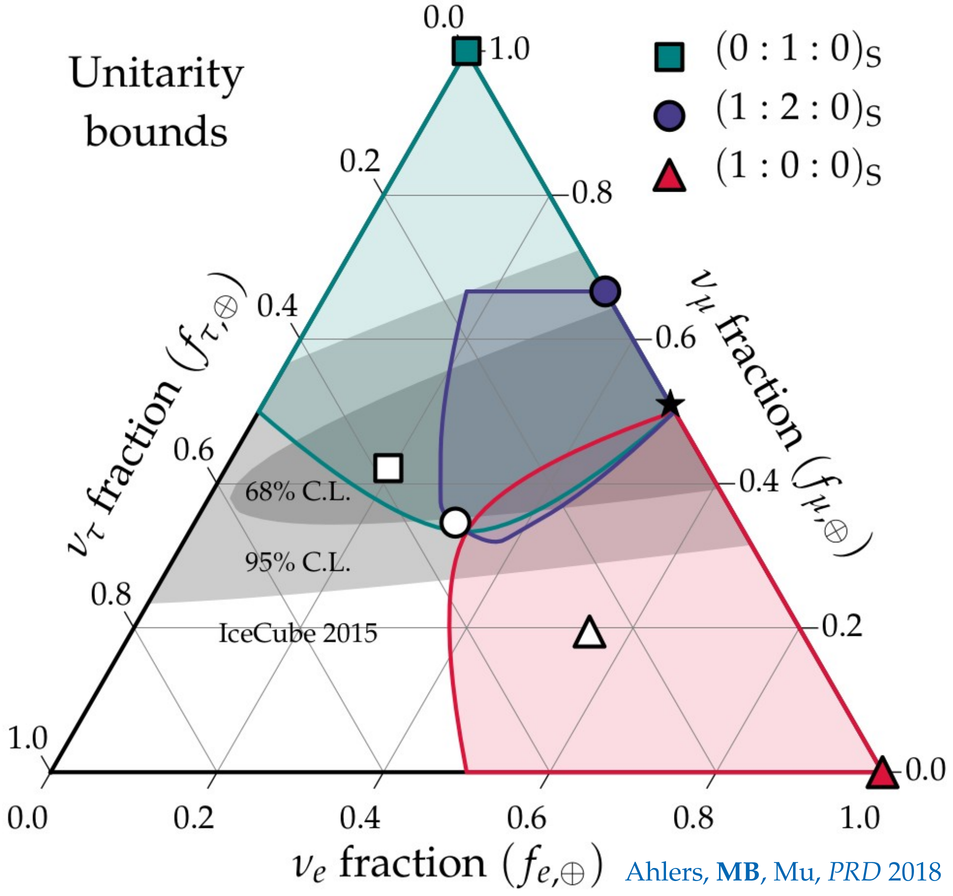
  [Xu, He, Rodejohann, *JCAP* 2014; Ahlers, **MB**, Mu, *PRD* 2018; Ahlers, **MB**, Nortvig, 2009.01253]



Ahlers, **MB**, Mu, *PRD* 2018

Reviews:
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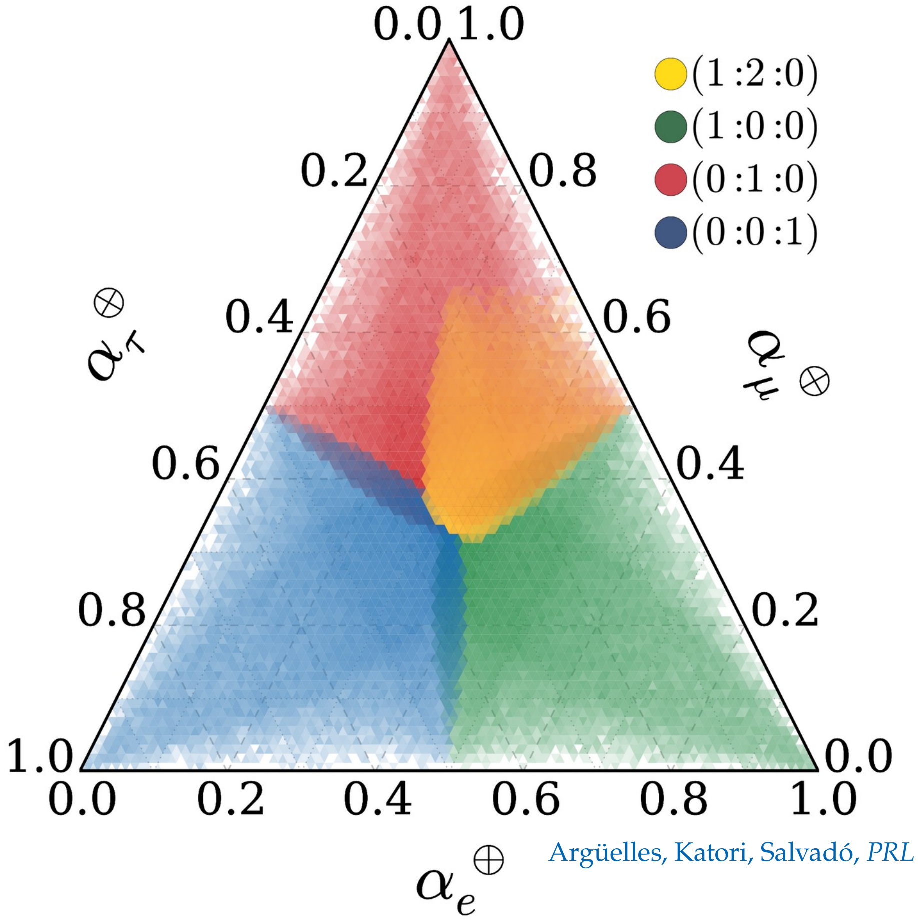

Argüelles, Katori, Salvadó, *PRL* 2015

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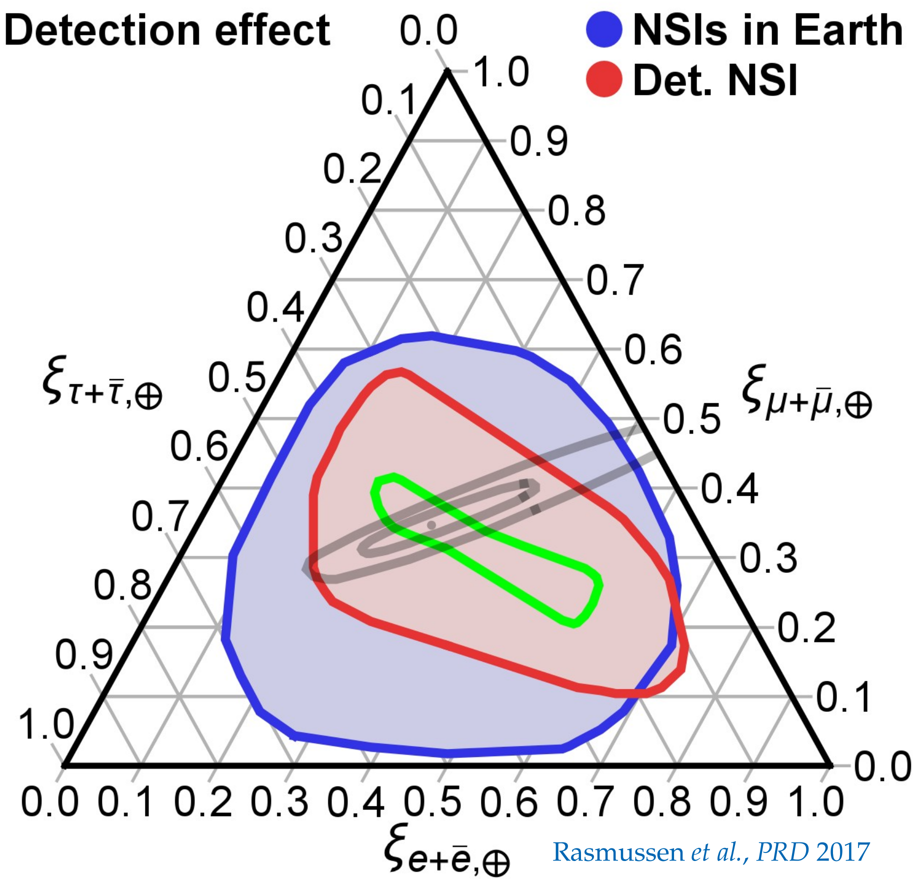

Rasmussen *et al.*, *PRD* 2017

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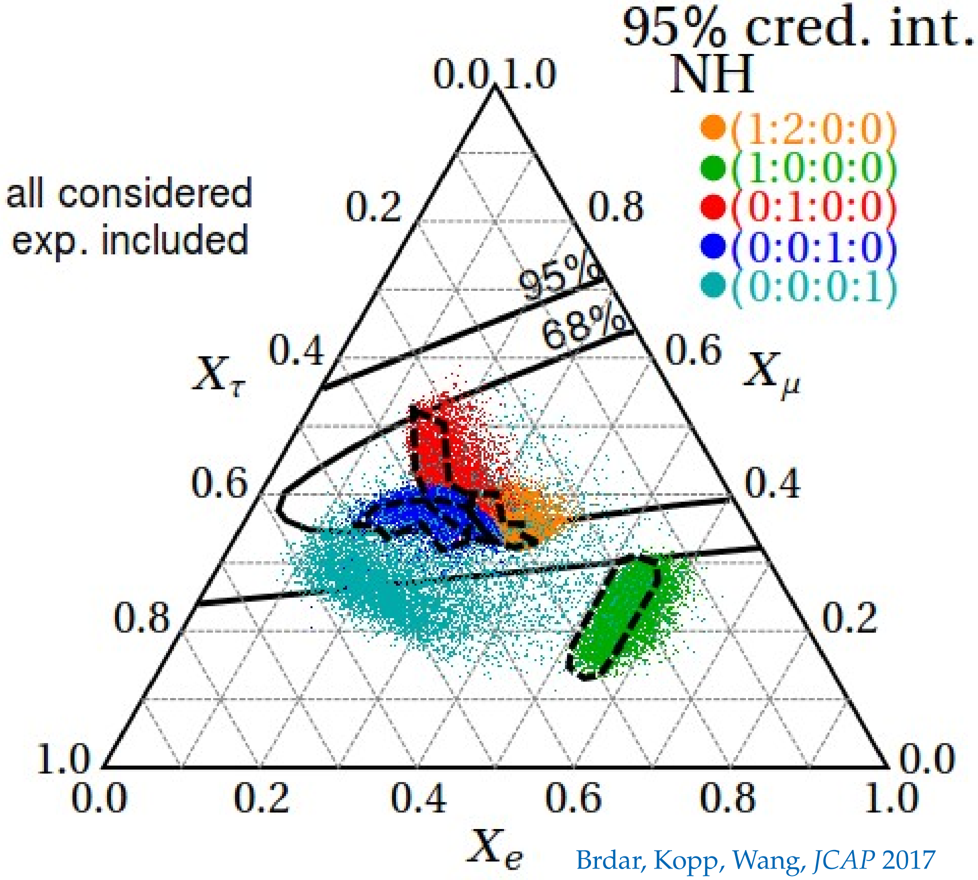

Brdar, Kopp, Wang, *JCAP* 2017

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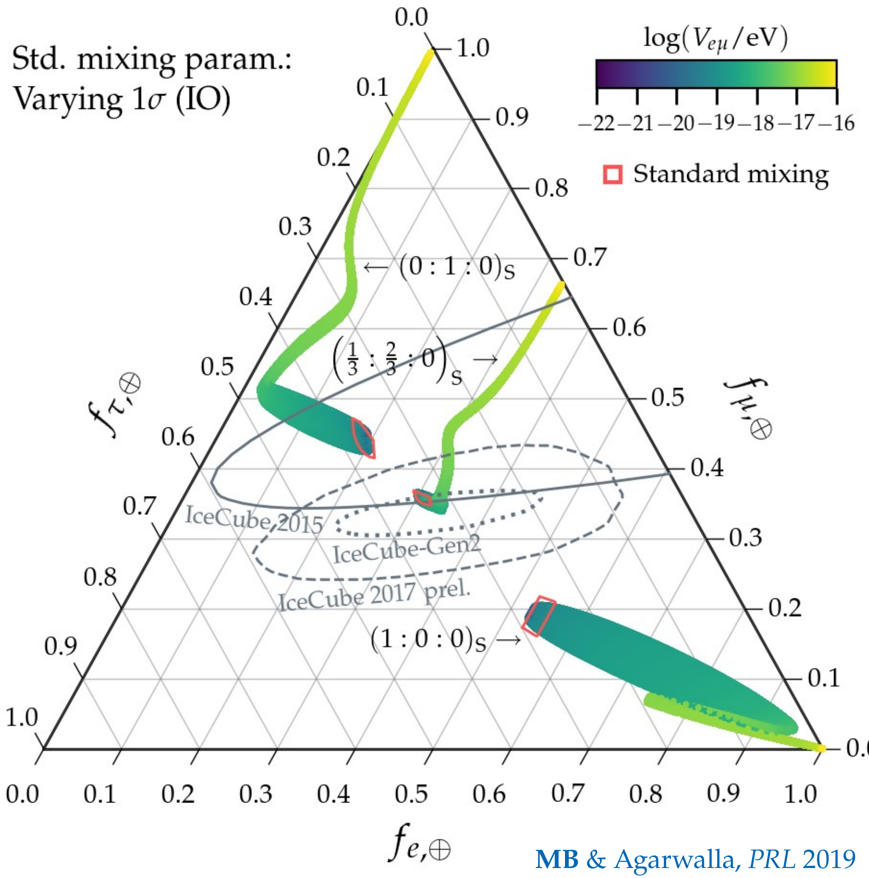
- Long-range *e*ν interactions
  [**MB** & Agarwalla, *PRL* 2019]

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



MB & Agarwalla, *PRL* 2019

IV.
The future

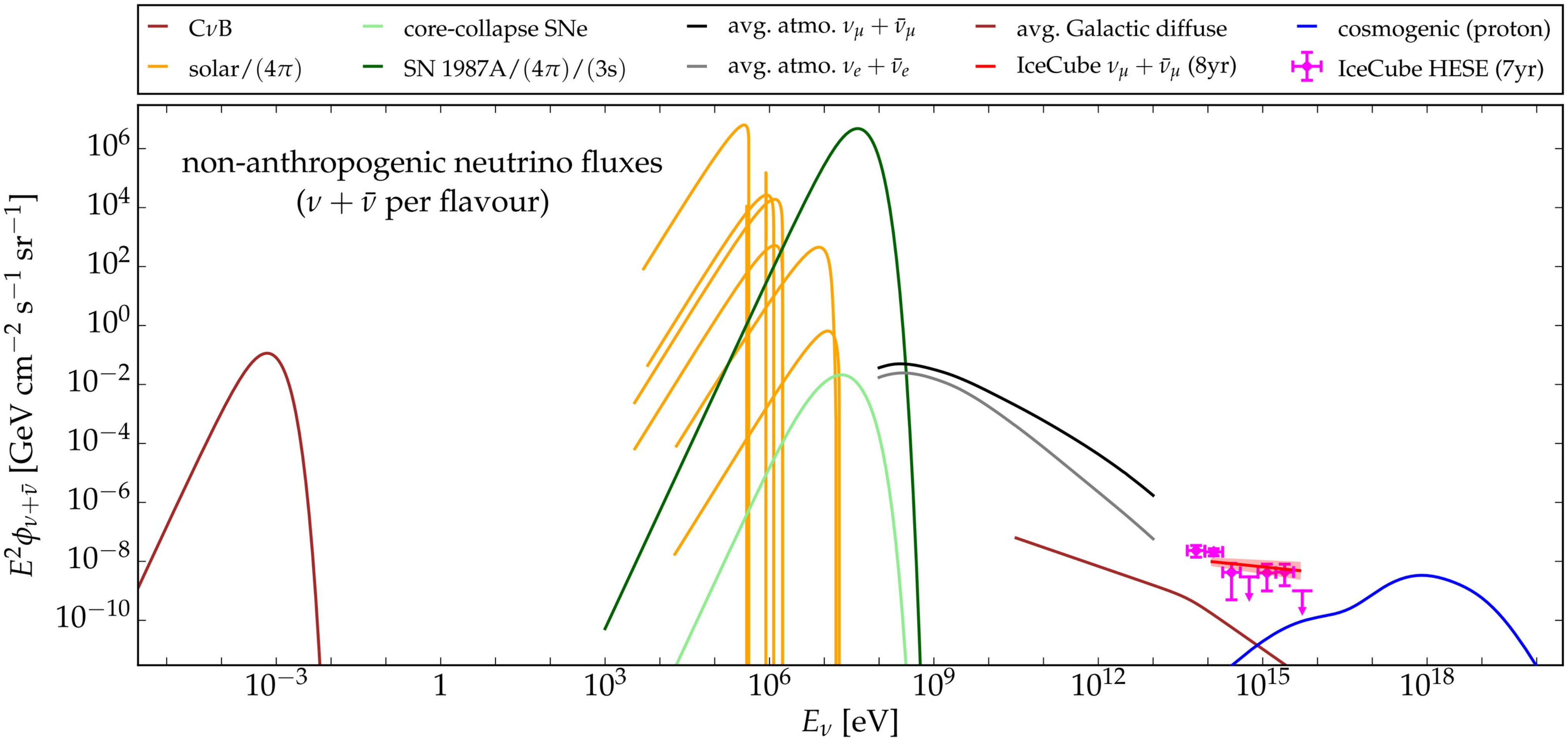
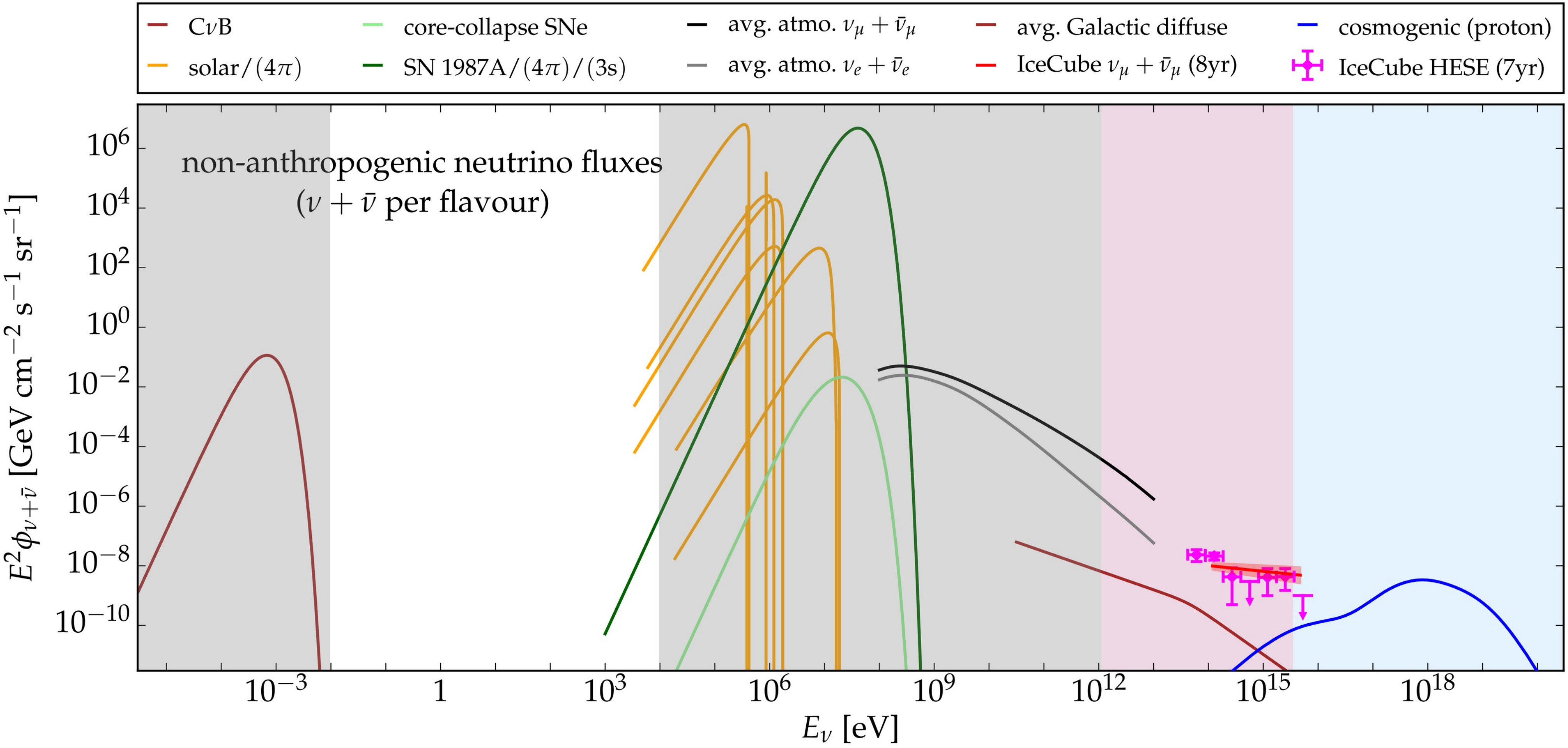


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023



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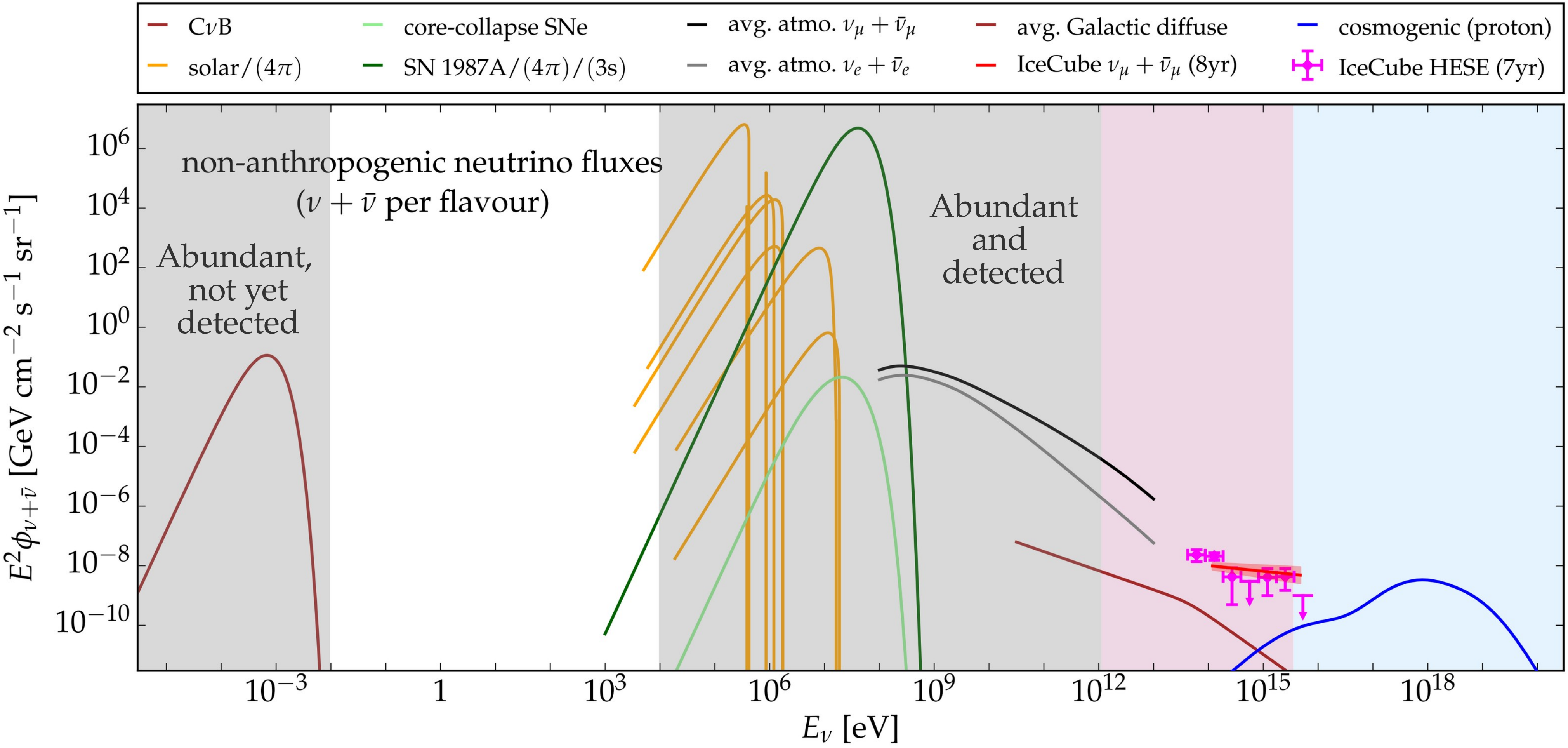

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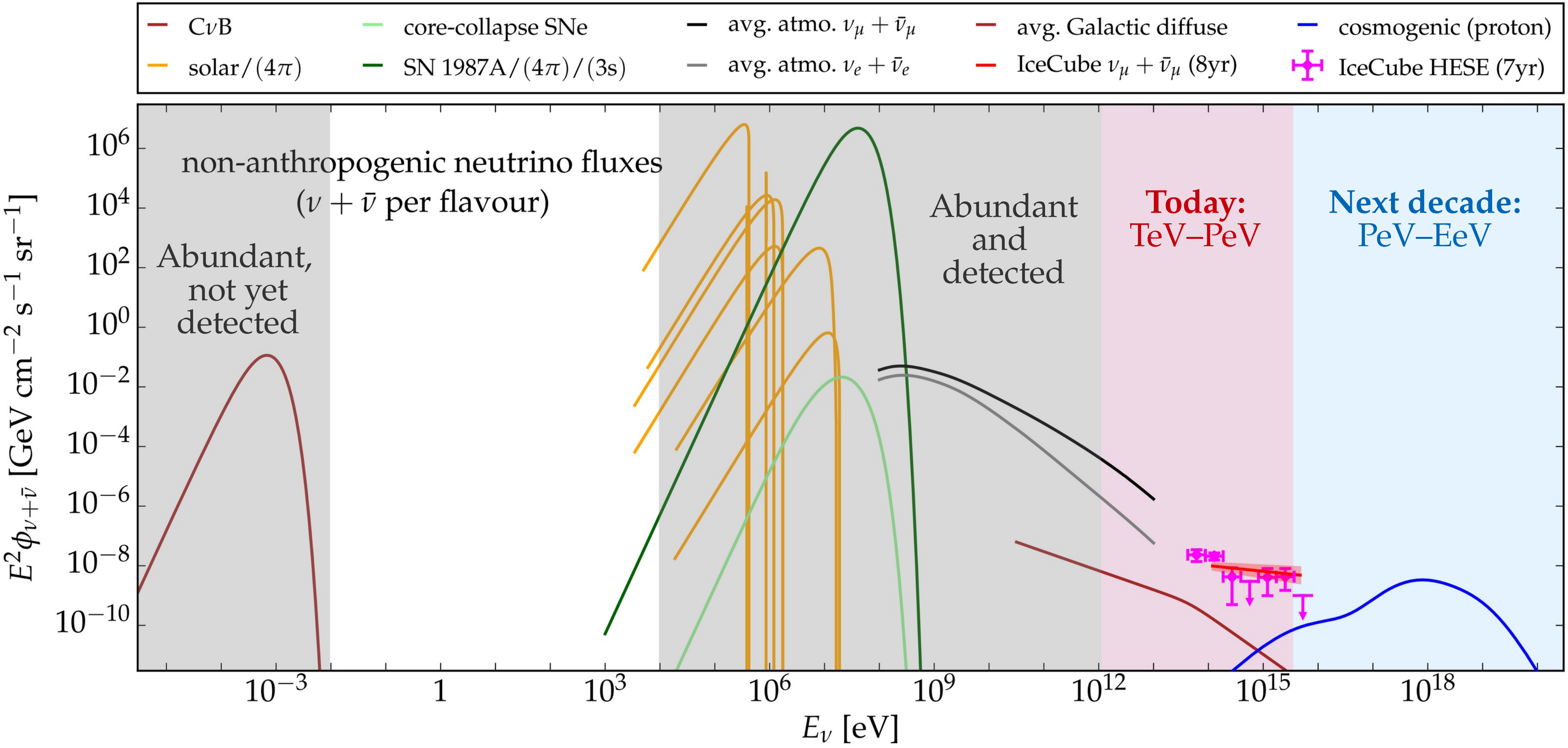
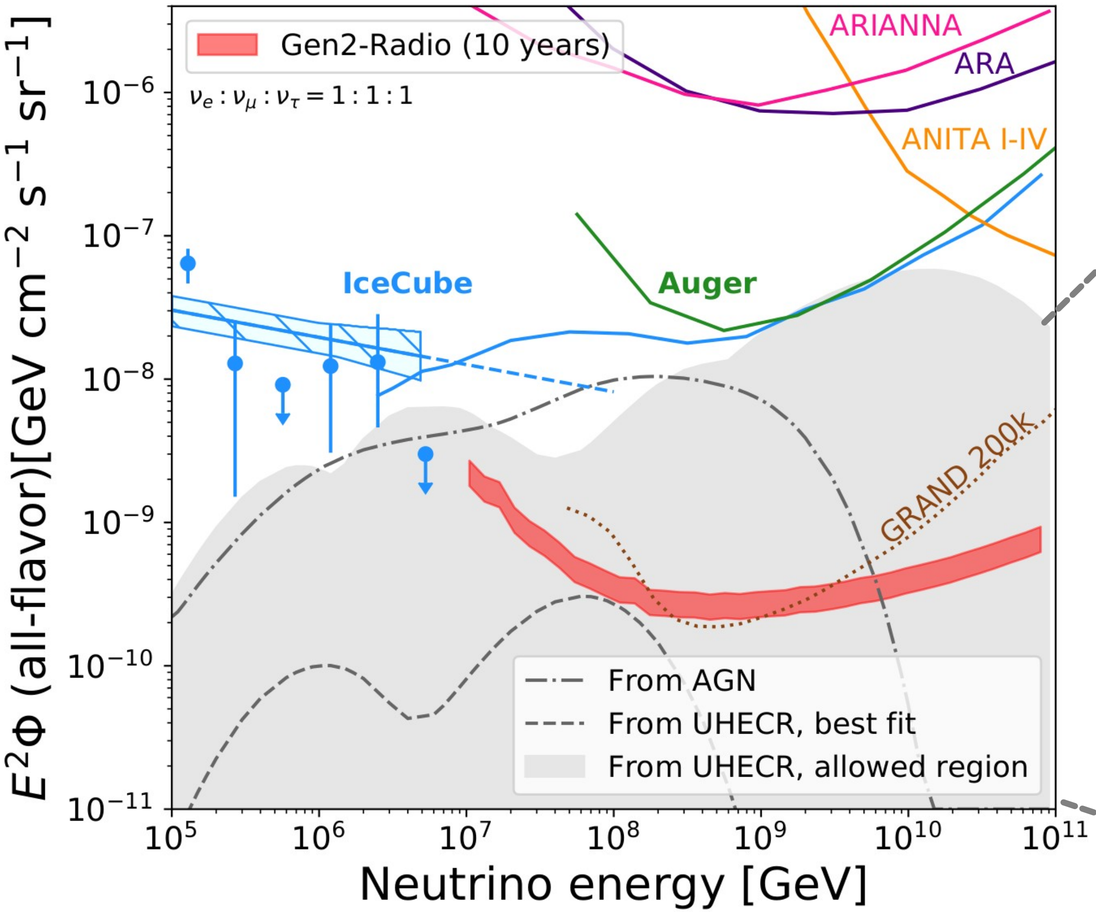
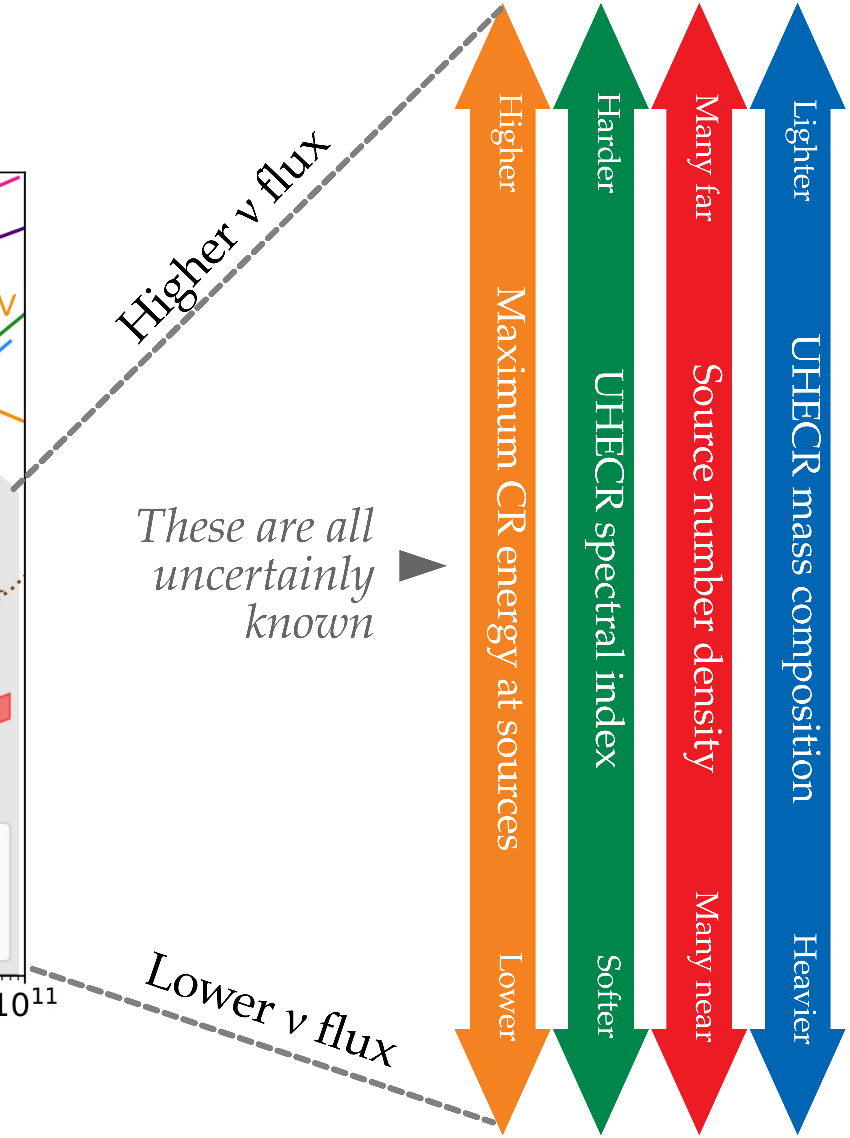


Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023

Cosmogenic ν flux: how low?

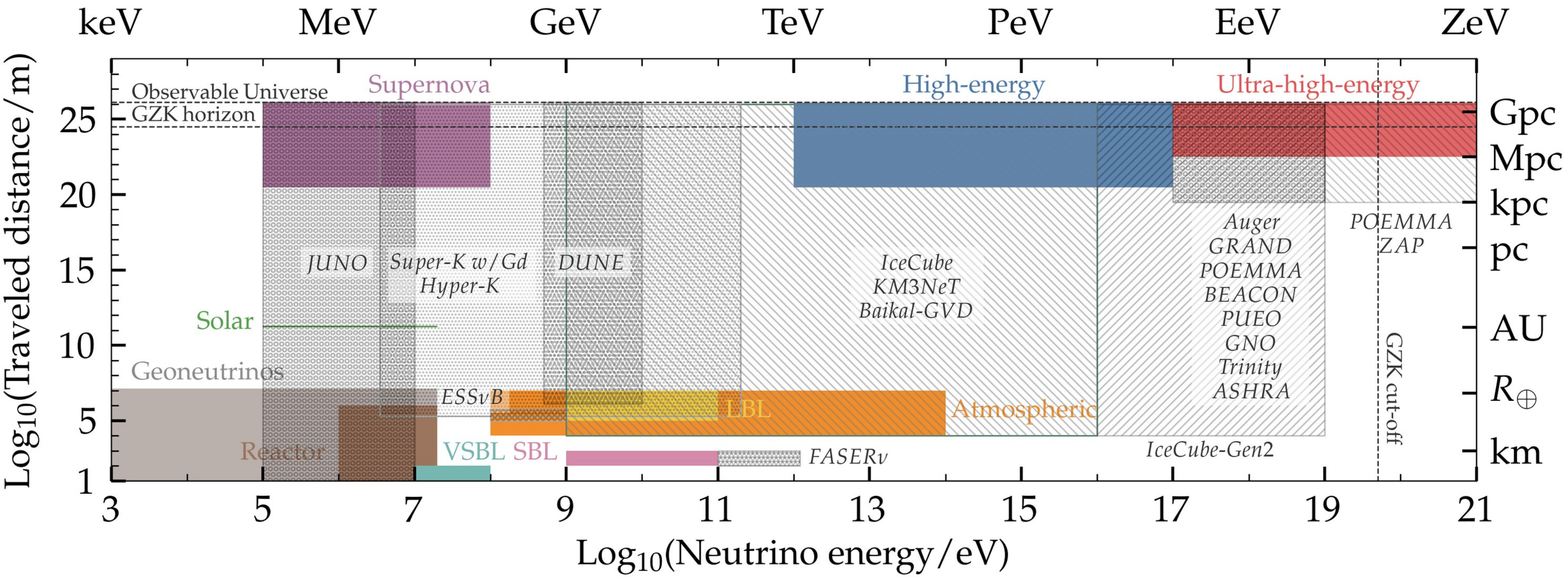




These are all uncertainly known

IceCube-Gen2, 2008.04323

Next decade: a host of planned neutrino detectors



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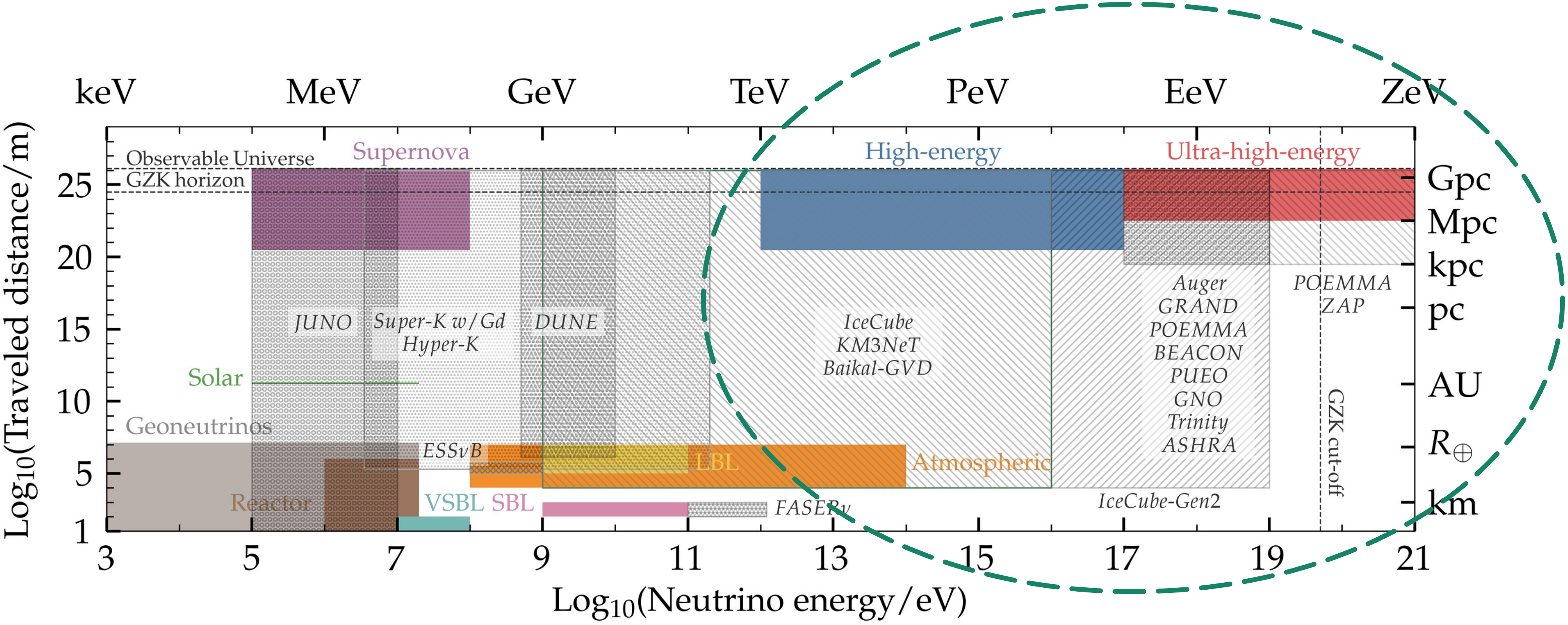

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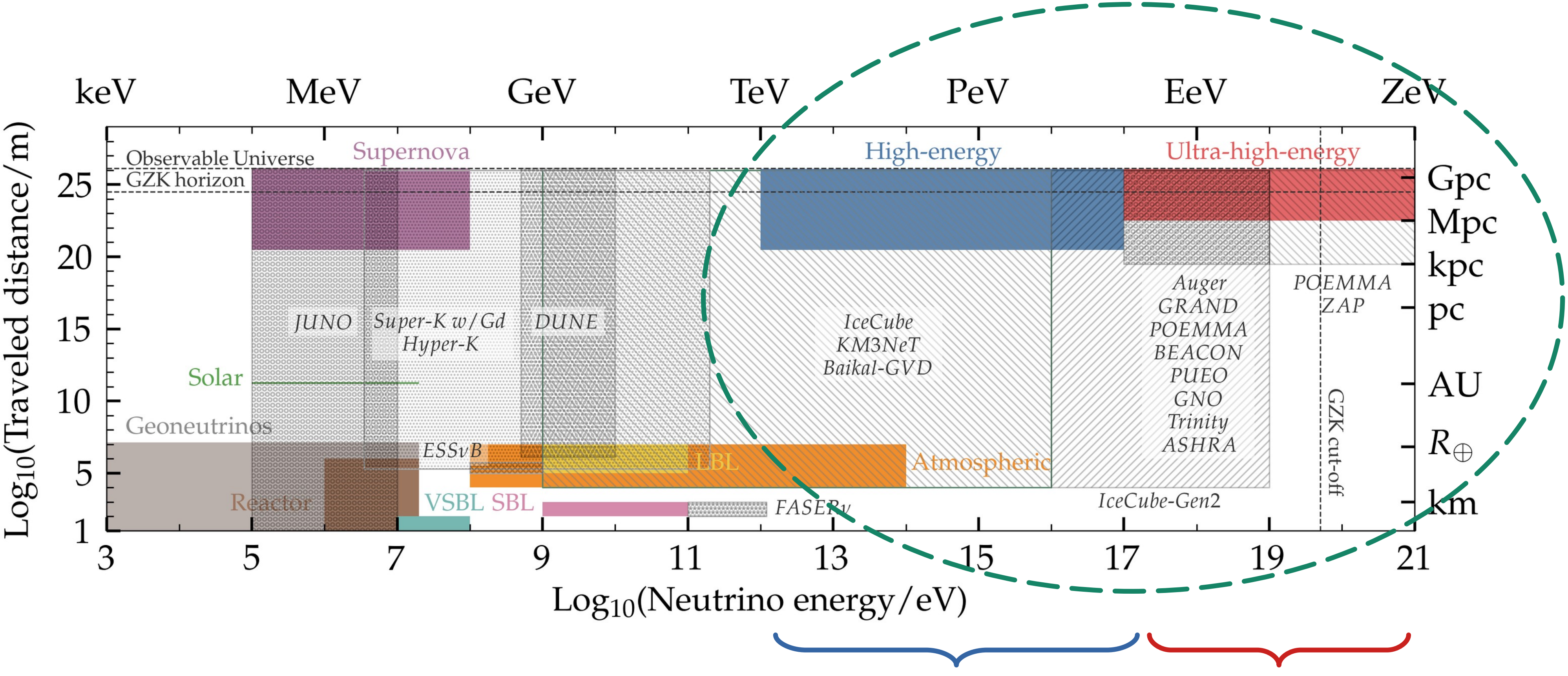

Increase TeV–PeV
ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest

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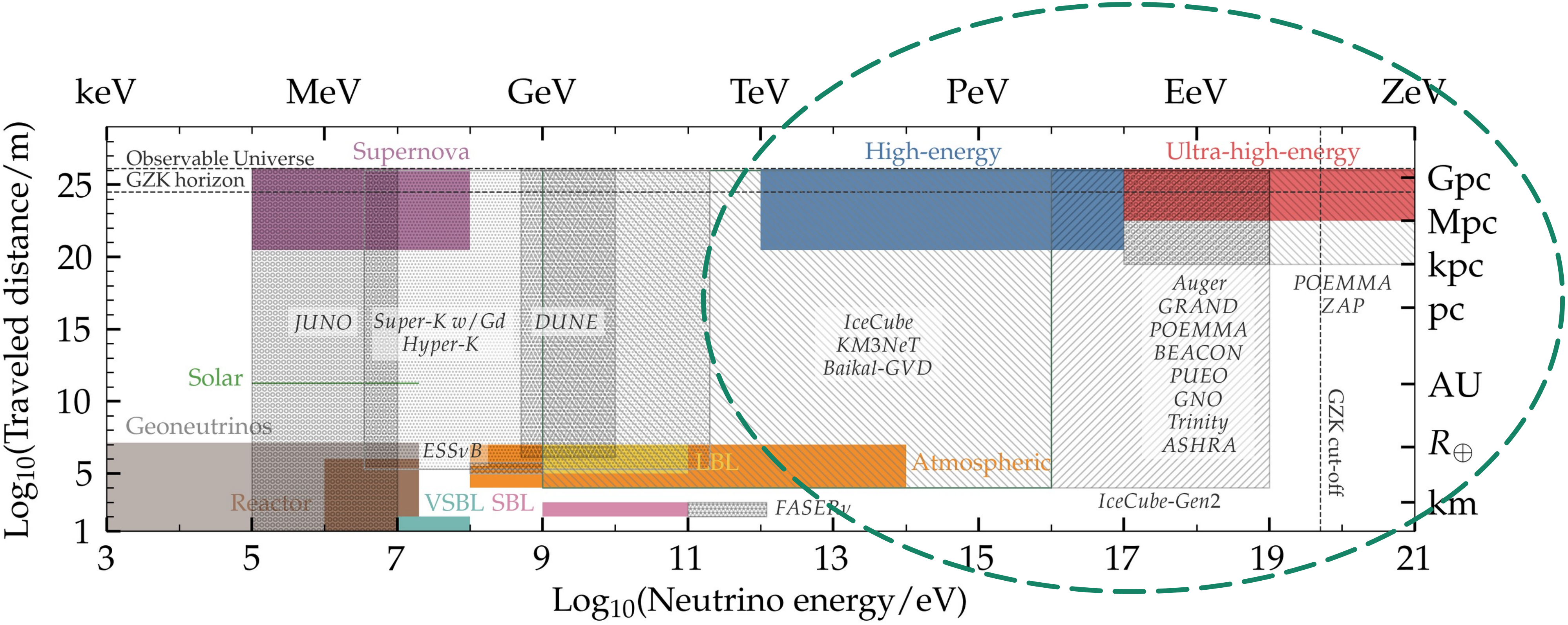


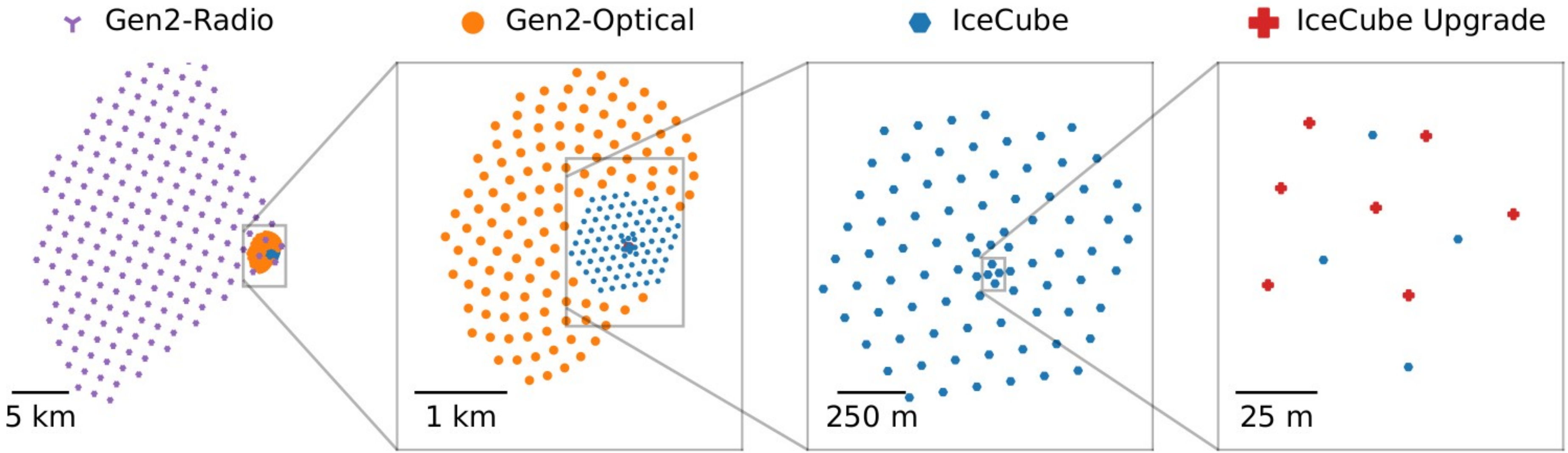
Synergies with lower energies

Increase TeV–PeV
ν statistics

Discover > EeV ν

MB *et al.*, Snowmass 20201 Letter of interest

IceCube-Gen2



~2040

10s km^3

> 100 PeV ν

~8 km^3

TeV–10 PeV ν

Today

1 km^3

TeV–few PeV ν

2023

7 new strings

GeV–TeV ν

IceCube-Gen2, 2008.04323

What are you taking home?

- Cosmic TeV–PeV neutrinos are firmly detected:
  Powerful probes of the non-thermal Universe and high-energy particle physics

- We have detected *tentative* sources — but it is challenging to understand them

- Still unknown, but getting there:
  - Where do most neutrinos come from?
  - What are, precisely, their spectrum, arrival directions, flavor composition?

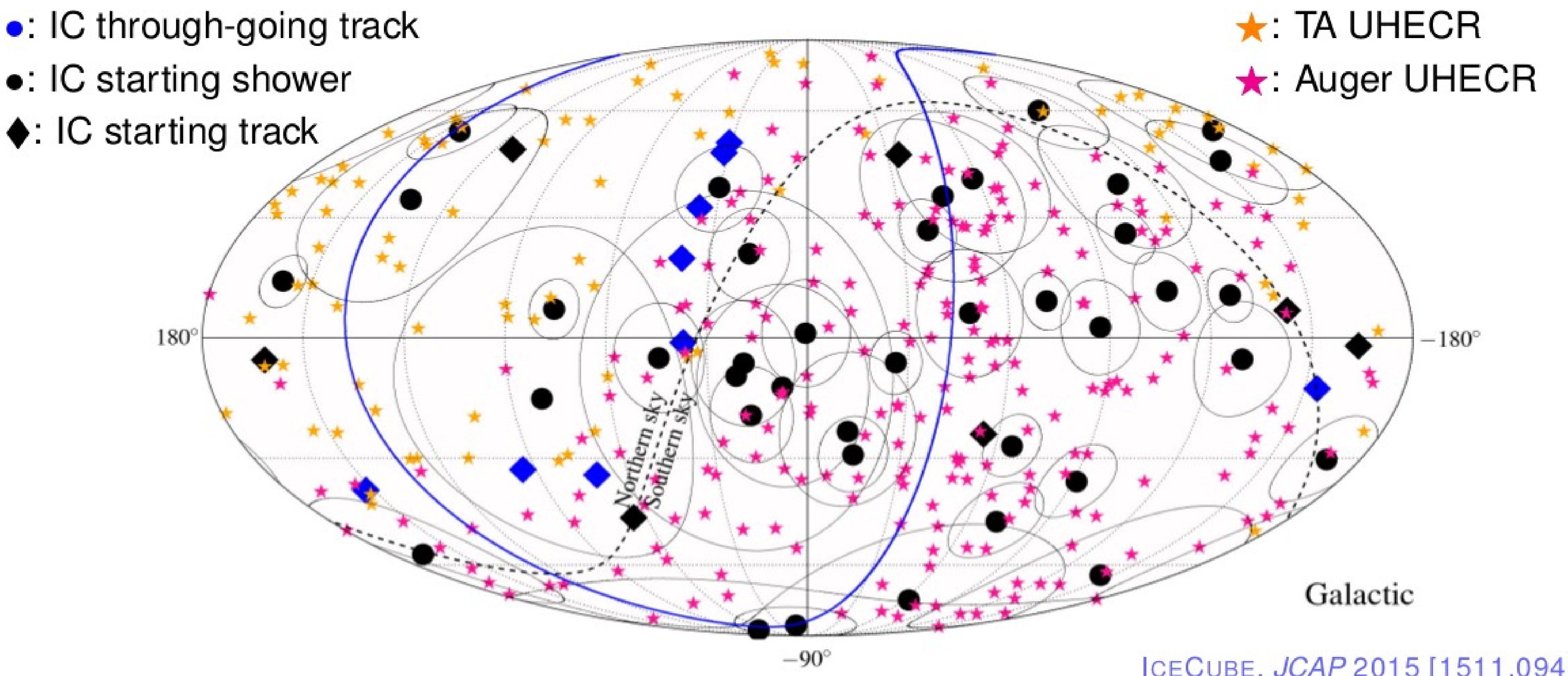
- Exciting prospects: larger statistics, better reconstruction, higher energies

Want more? Here is a start:

- *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, 1903.04333
- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

Backup slides

Neutrino–UHECR angular correlation?



IceCube, *JCAP* 2015 [1511.09408]

No significant correlation with UHECRs (<3.3σ)

Flavor at the Earth: *theoretically palatable regions*

Theoretically palatable flavor regions

$\equiv$

MB, Beacom, Winter, *PRL* 2015

Allowed regions of flavor ratios at Earth derived from oscillations

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

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Ingredient #1:

Flavor ratios at the source,

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

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

or

Explore all possible combinations

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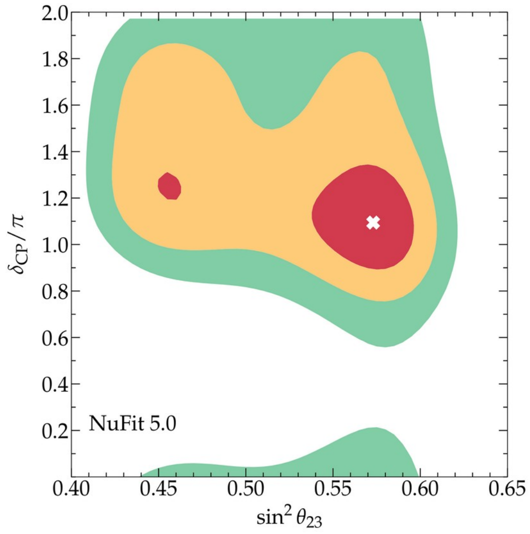
2020: Use χ^2 profiles from the NuFit 5.0 global fit (solar + atmospheric + reactor + accelerator)

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



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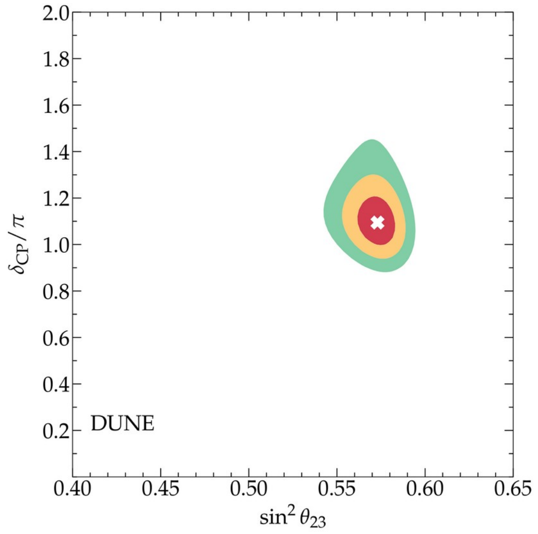
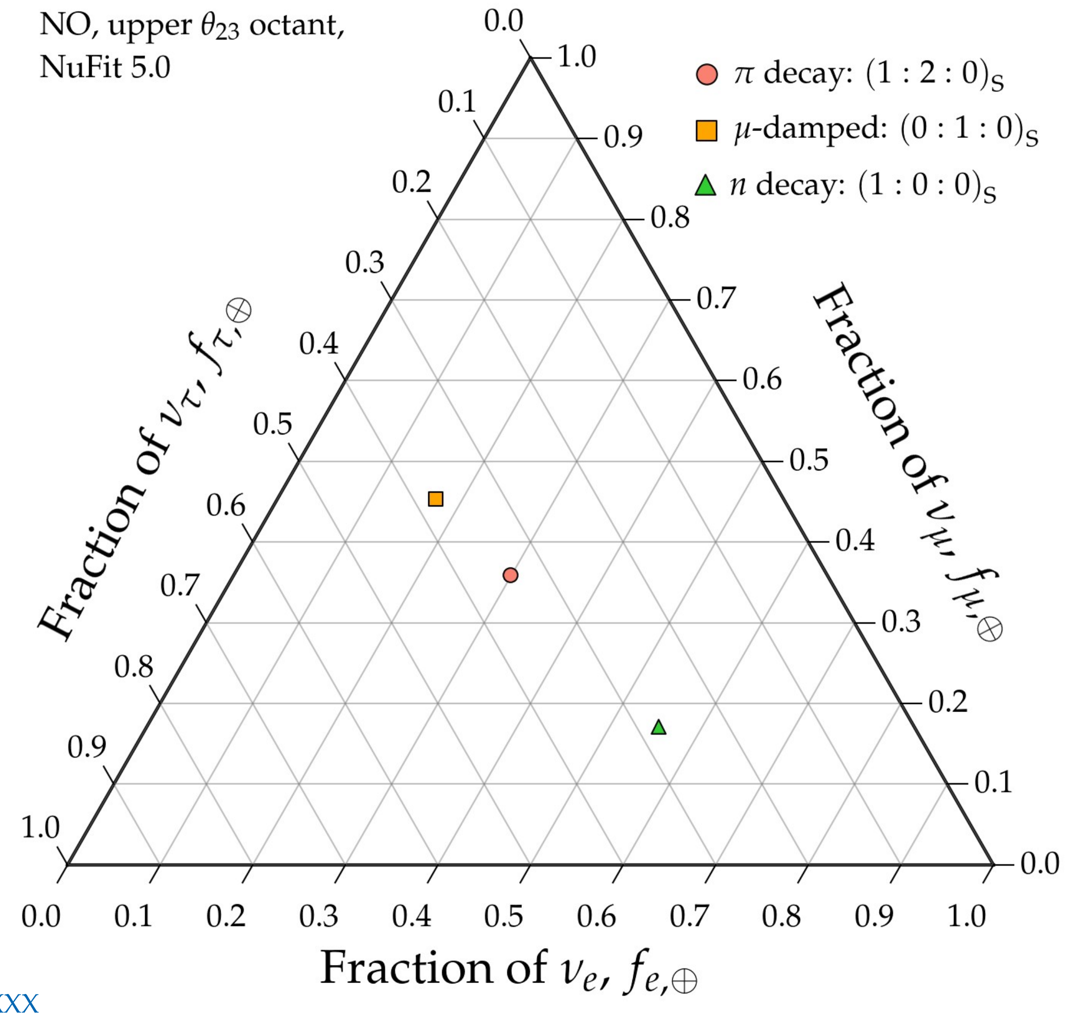
Esteban *et al.*, *JHEP* 2020
www.nu-fit.org

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

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



Theoretically palatable regions: today (2020)



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

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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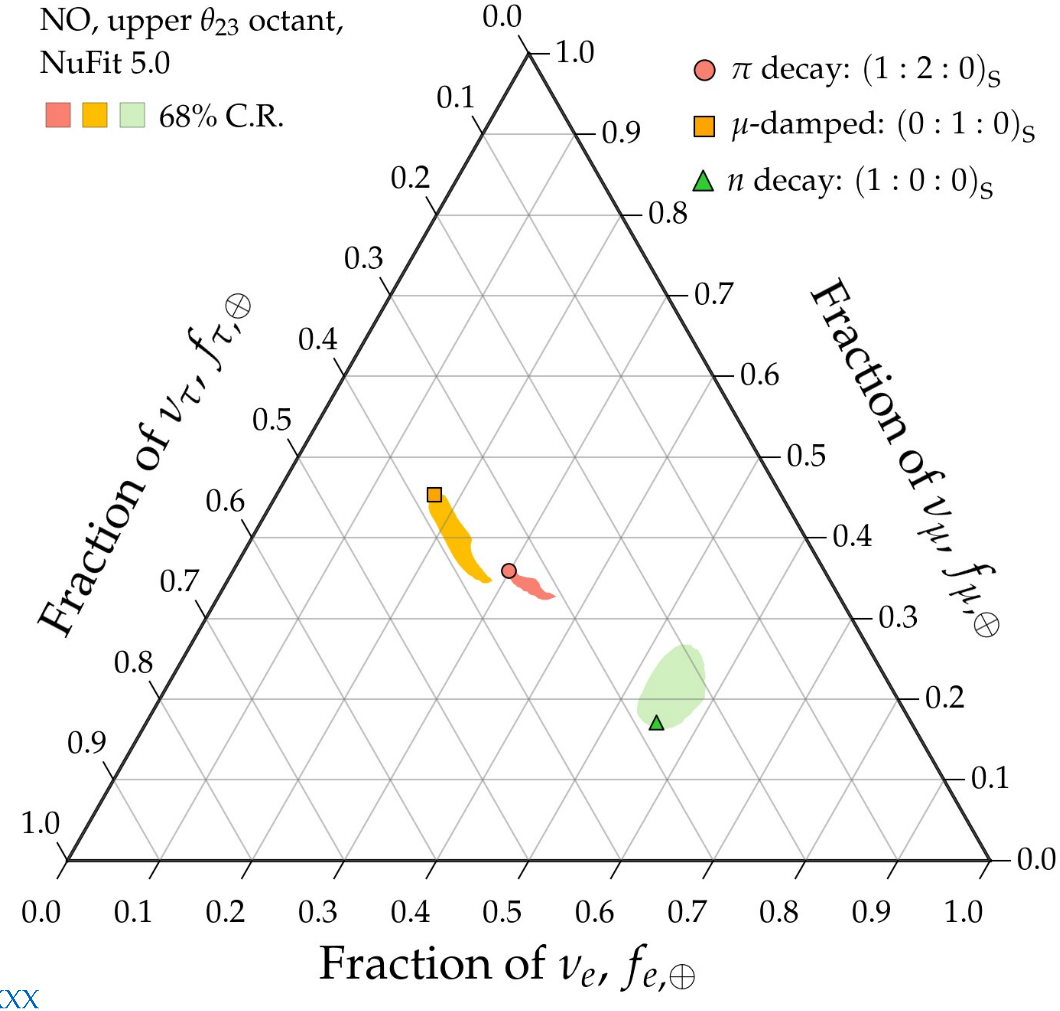

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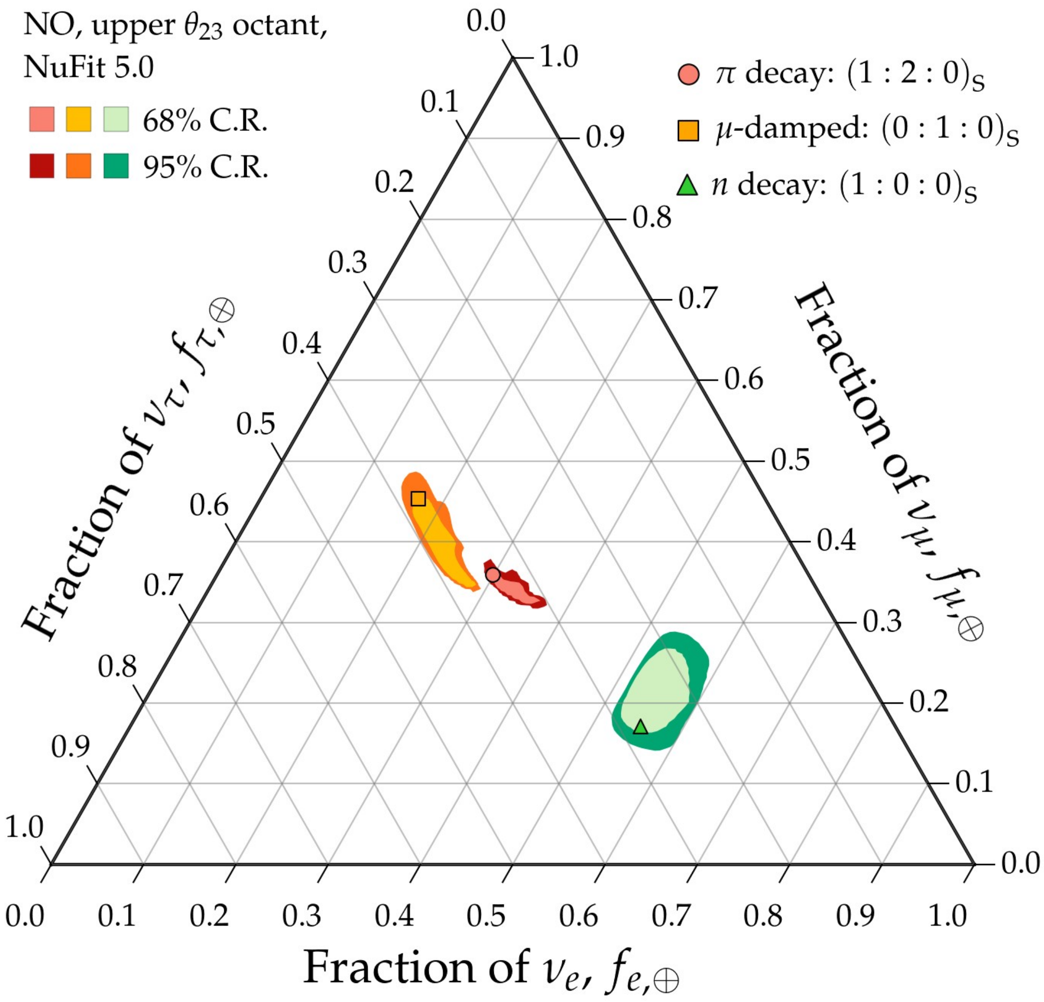

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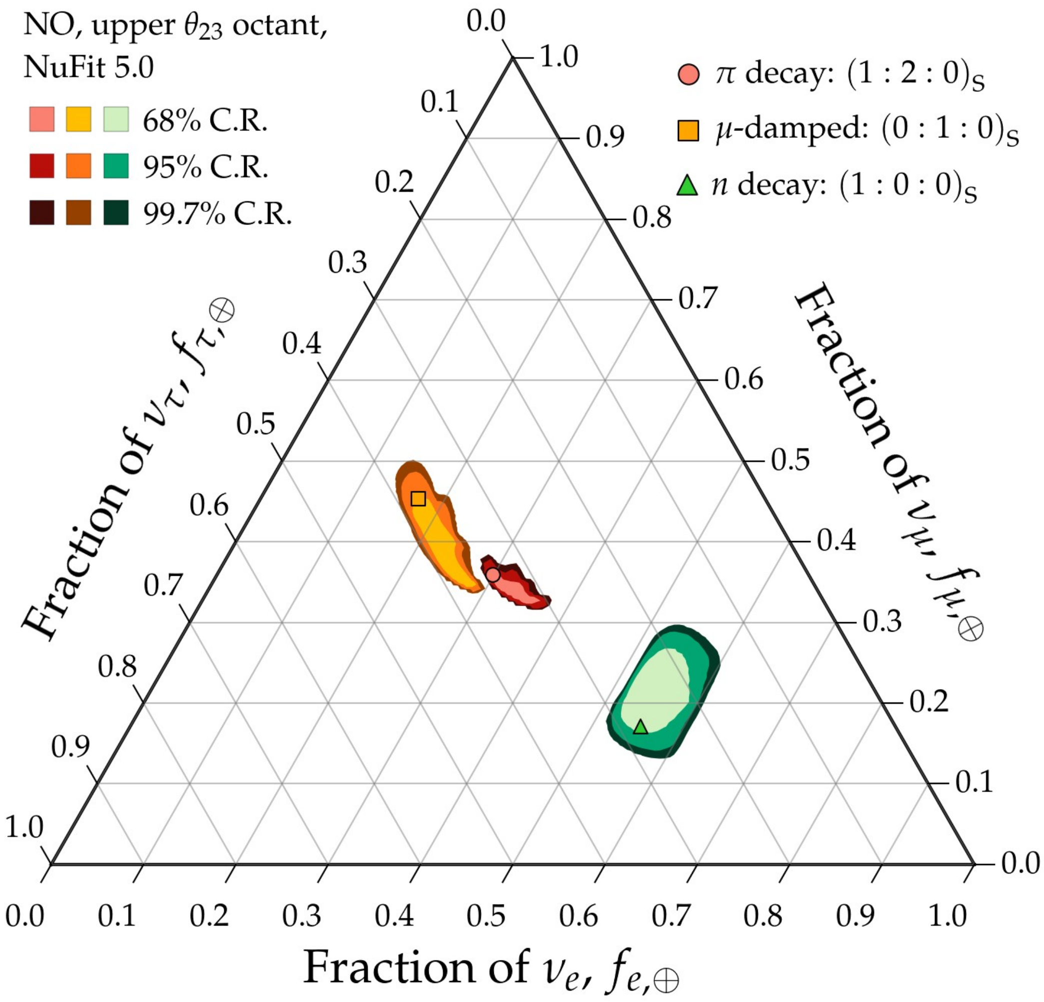

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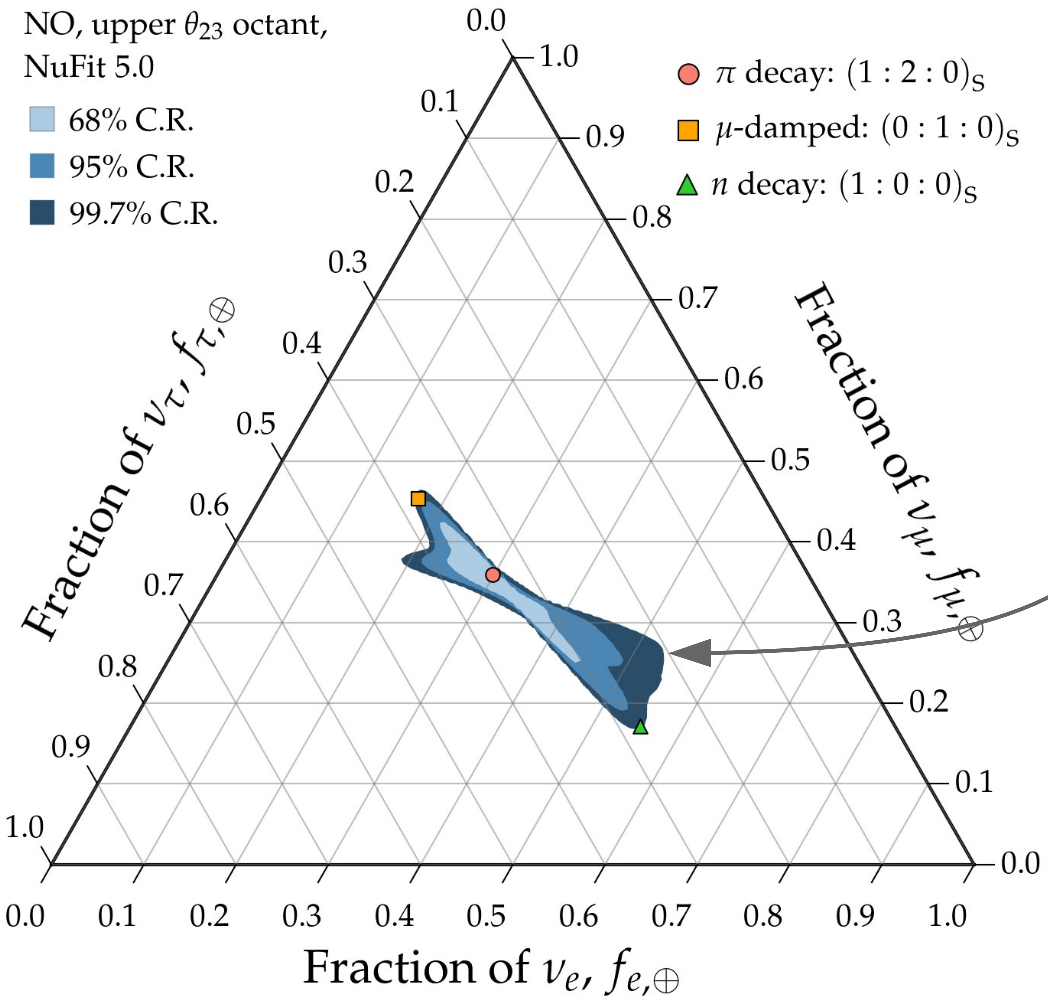

Varying over all possible flavor ratios at the source

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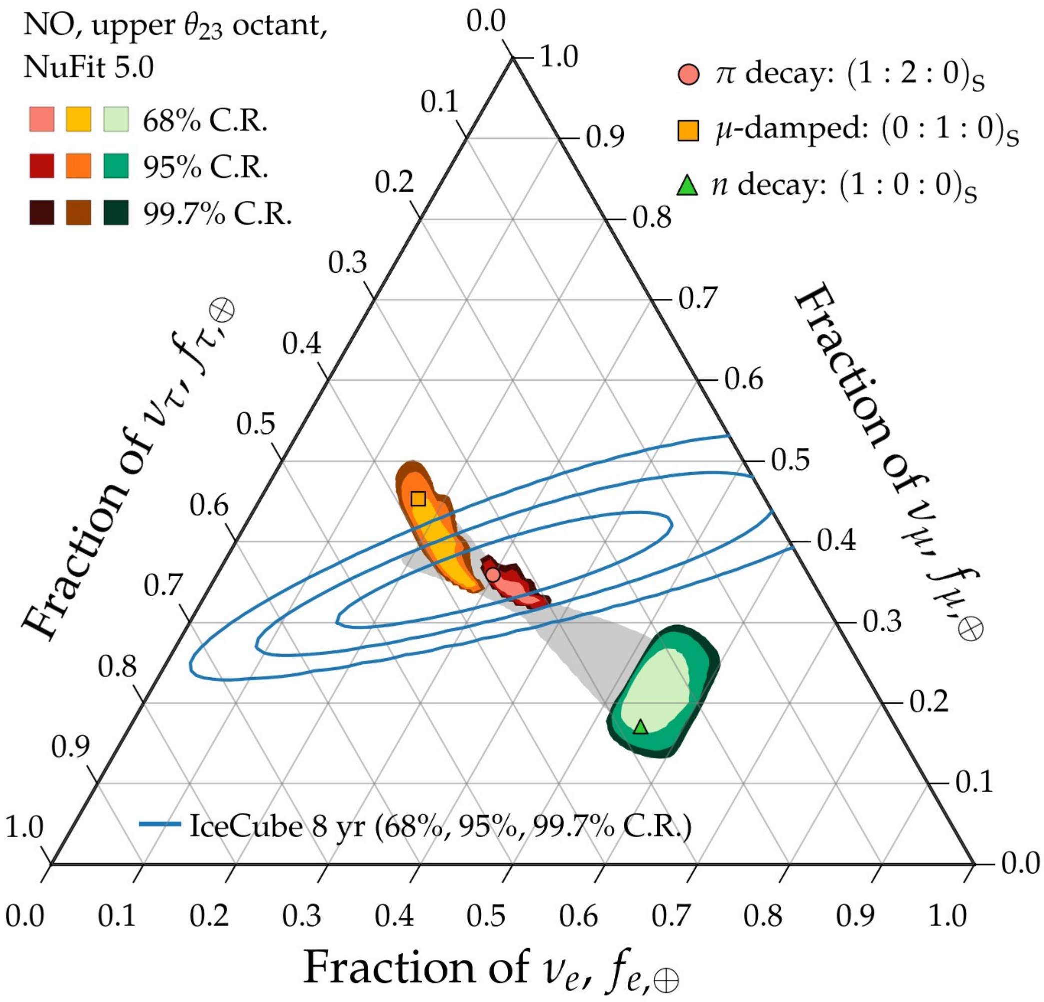
Song, Li, **MB**, Argüelles, Vincent, 2012.X

Theoretically palatable regions: today (2020)



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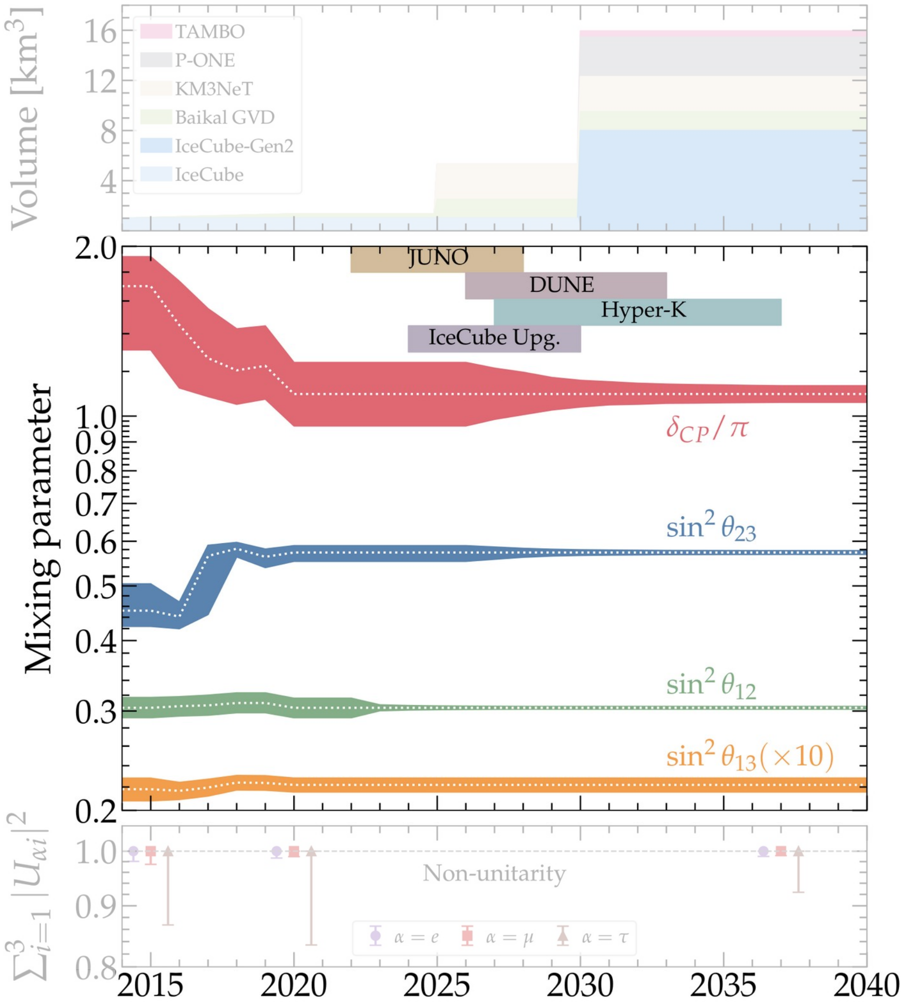
How knowing the mixing parameters better helps

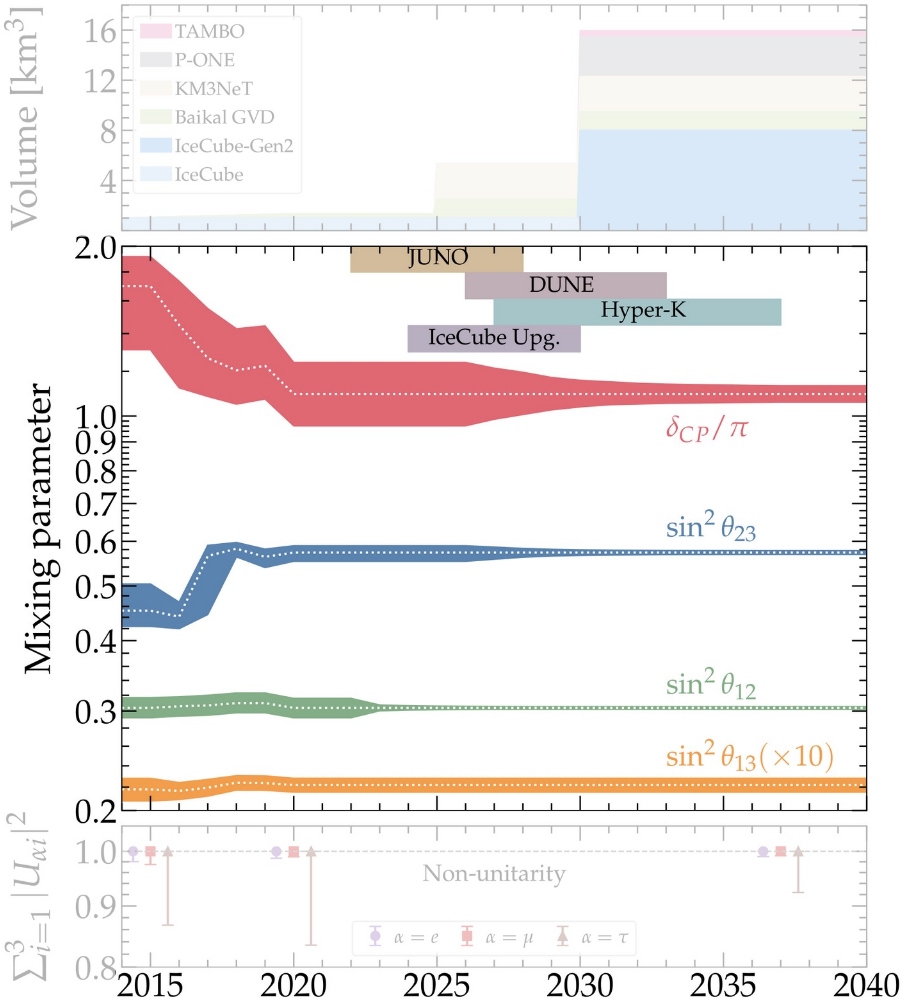


We can compute the oscillation probability more precisely:

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

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

How knowing the mixing parameters better helps



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

Best fit from NuFit 5.0

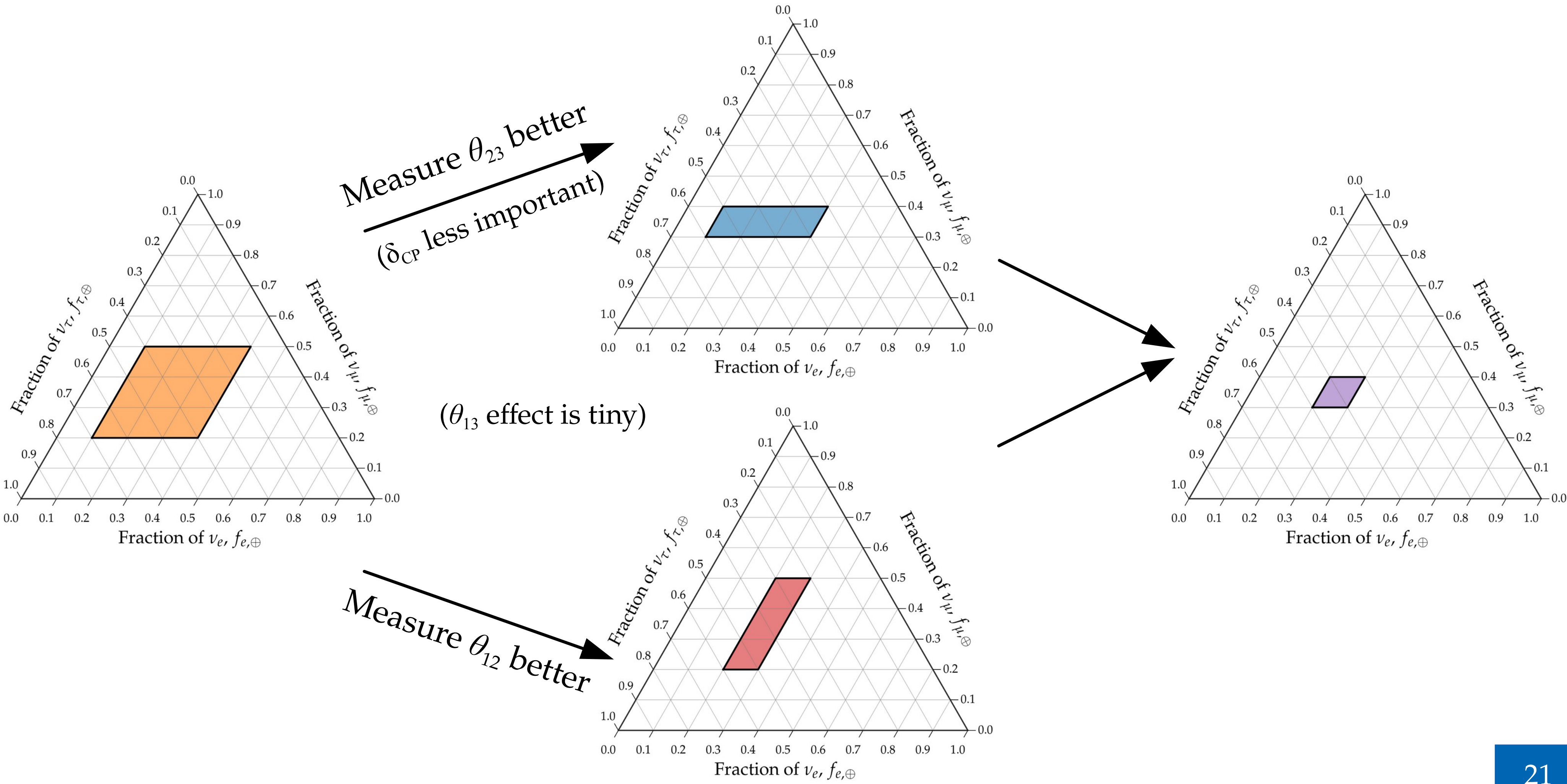
$$\chi^2_\varepsilon(\boldsymbol{\vartheta}) = \sum_i \frac{(\vartheta_i - \bar{\vartheta}_i)^2}{\sigma^2_{i,\varepsilon}}$$

From our simulations

We combine experiments in a likelihood:

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

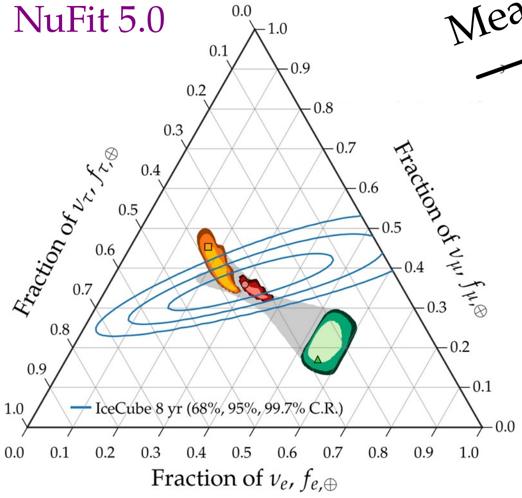
How knowing the mixing parameters better helps



How knowing the mixing parameters better helps

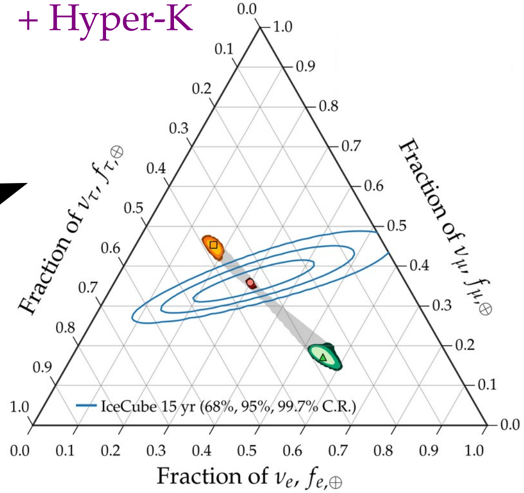
2020

NuFit 5.0



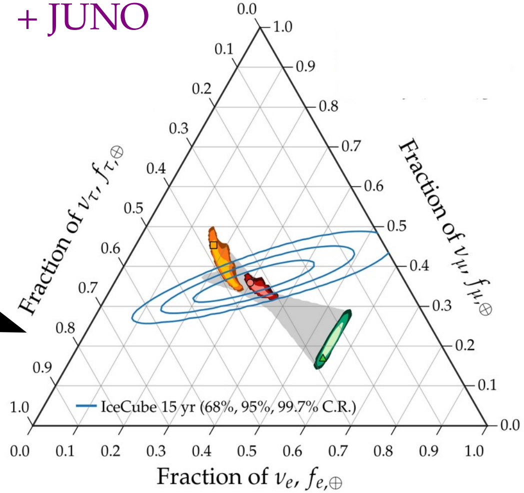
Measure θ_{23} better

+ Hyper-K



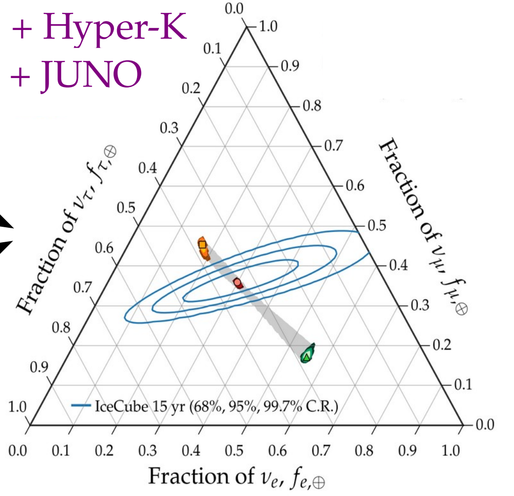
Measure θ_{12} better

+ JUNO



~2030

+ Hyper-K
+ JUNO



In our results:
JUNO + Hyper-K + DUNE

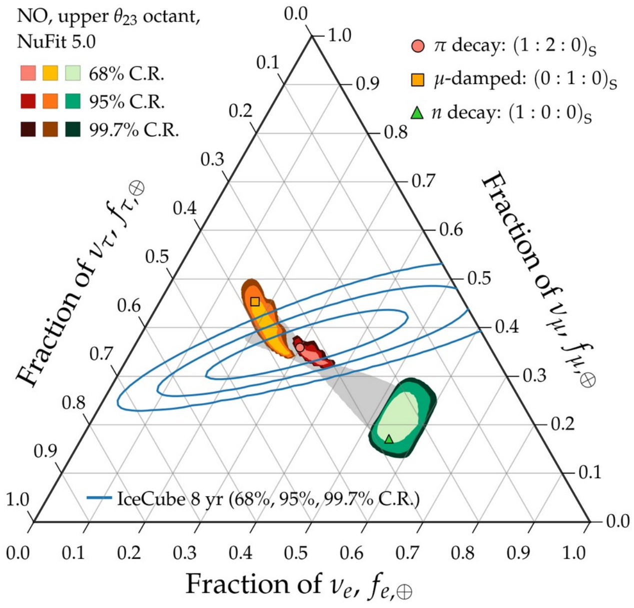
Marginal improvement til 2040

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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

Theoretically palatable regions: 2020 → 2030 → 2040

2020



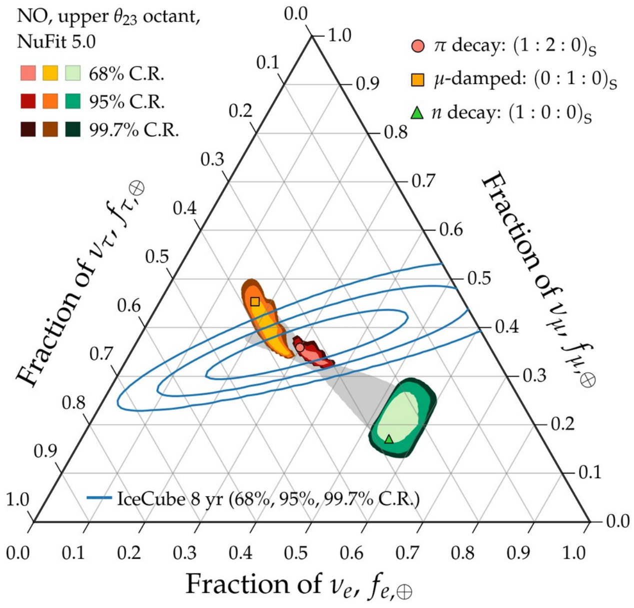
Allowed regions: overlapping

Measurement: imprecise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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Not ideal

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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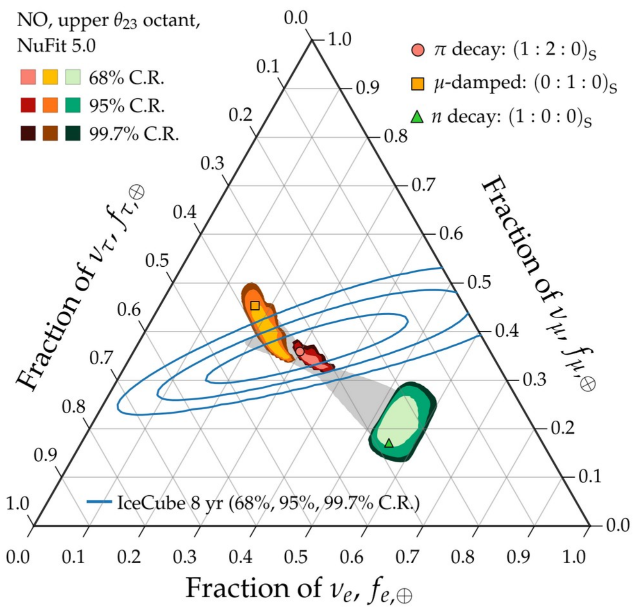

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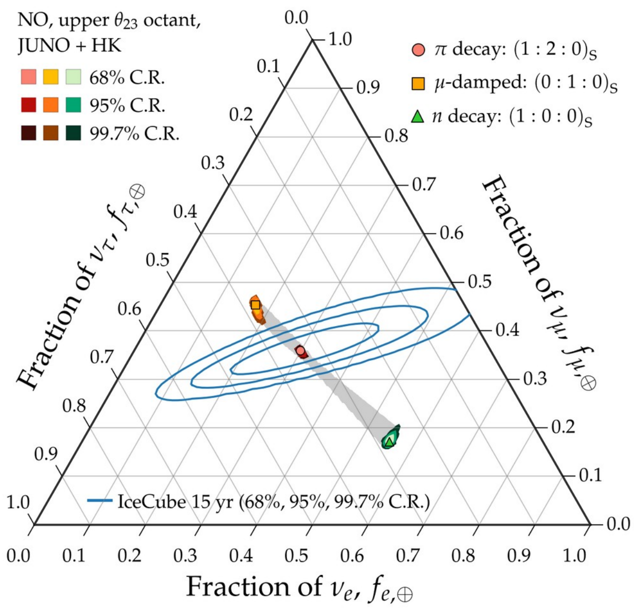
Measurement: imprecise

Not ideal

2030



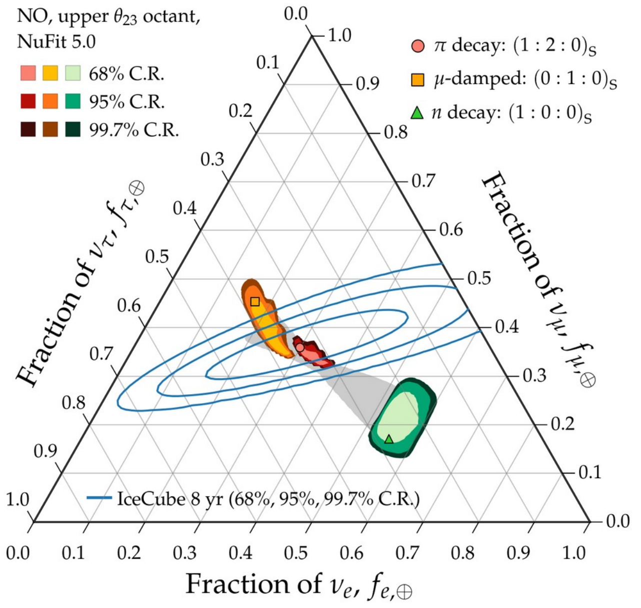
Allowed regions: well separated

Measurement: improving

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

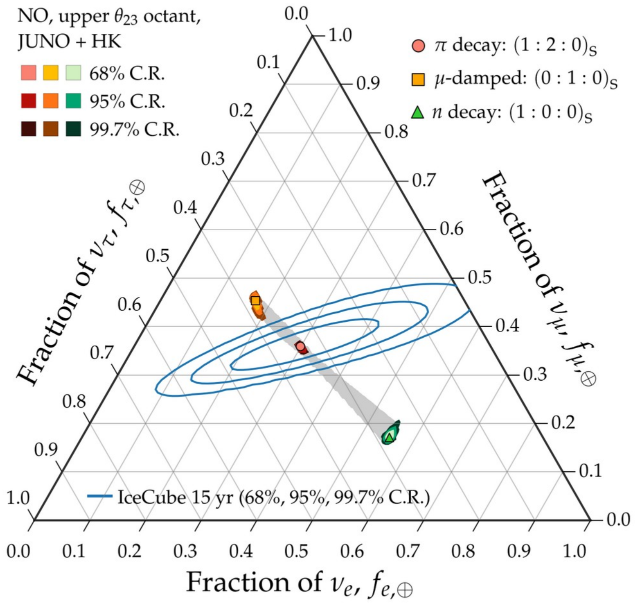


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030



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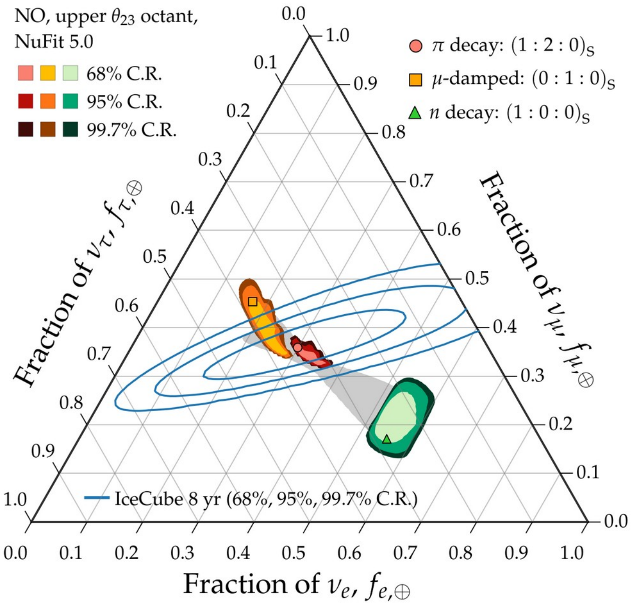
Measurement: improving

Nice

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020



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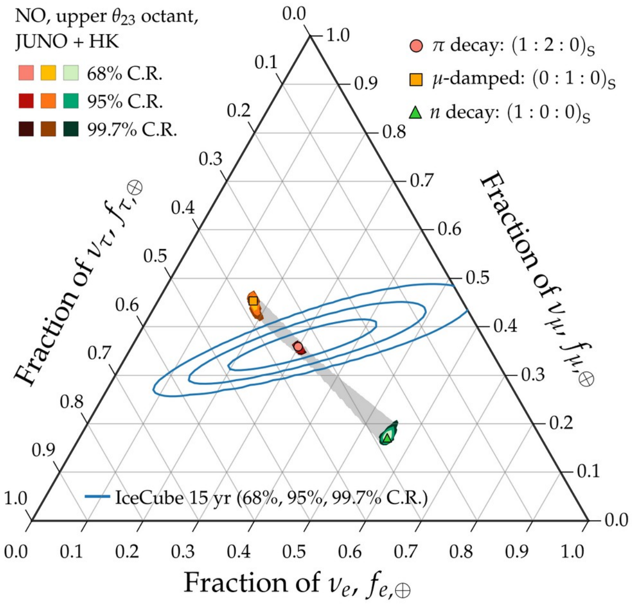
Measurement: imprecise

Not ideal

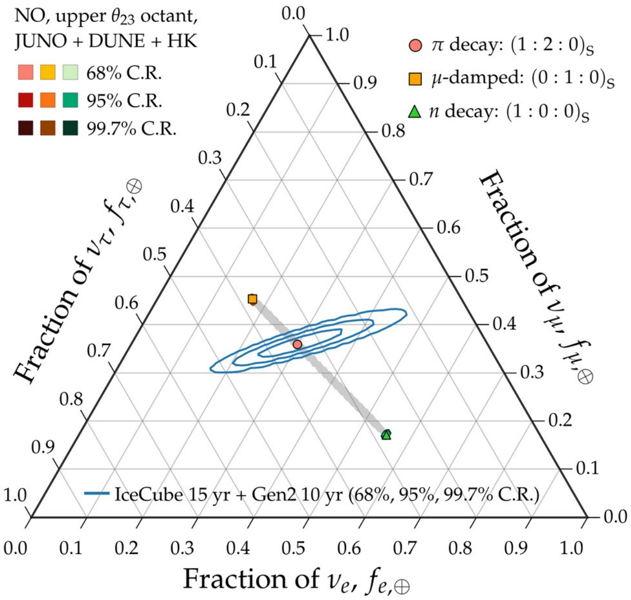
2030



Allowed regions: well separated
Measurement: improving

Nice

2040

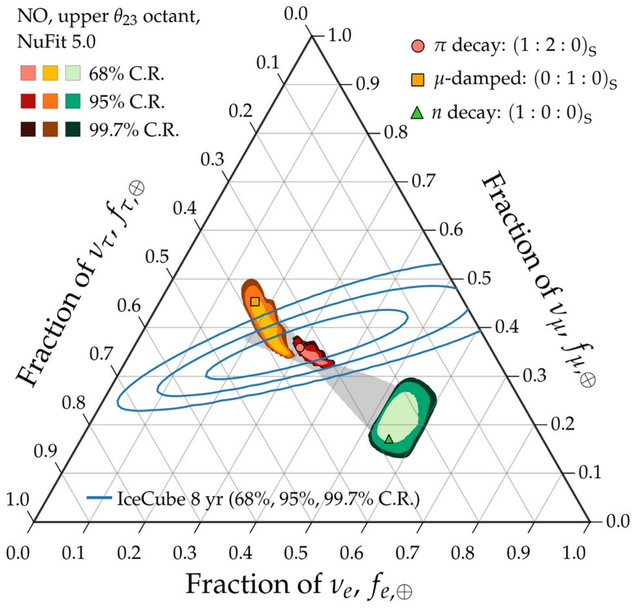


Allowed regions: well separated
Measurement: precise

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 → 2030 → 2040

2020

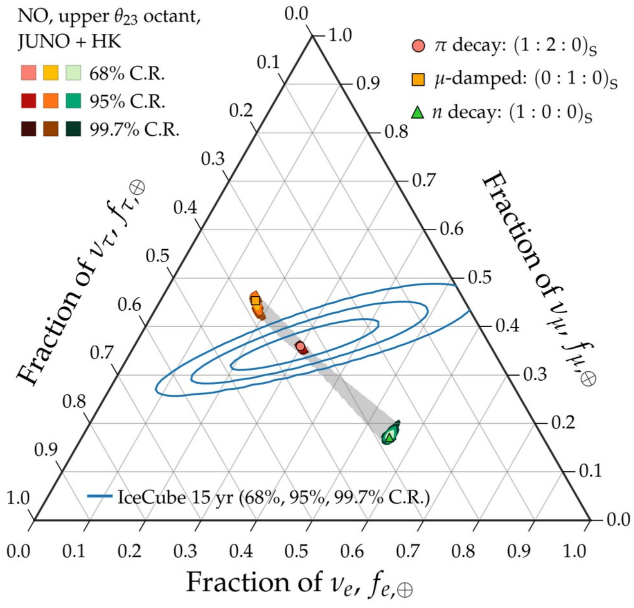


Allowed regions: overlapping

Measurement: imprecise

Not ideal

2030

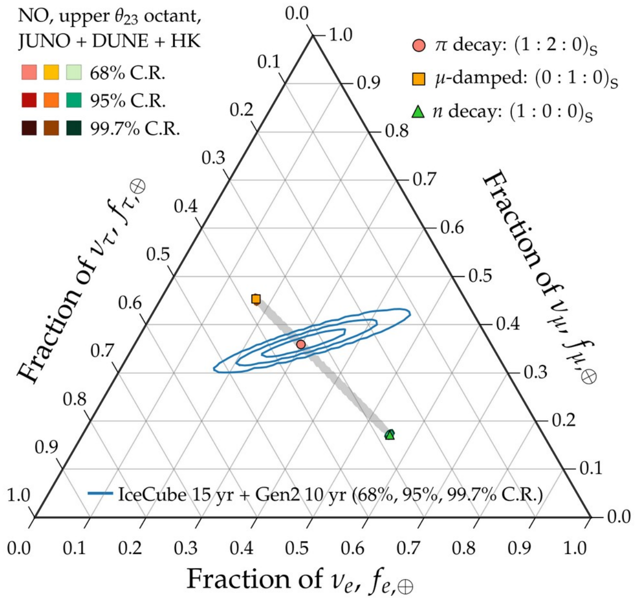


Allowed regions: well separated

Measurement: improving

Nice

2040



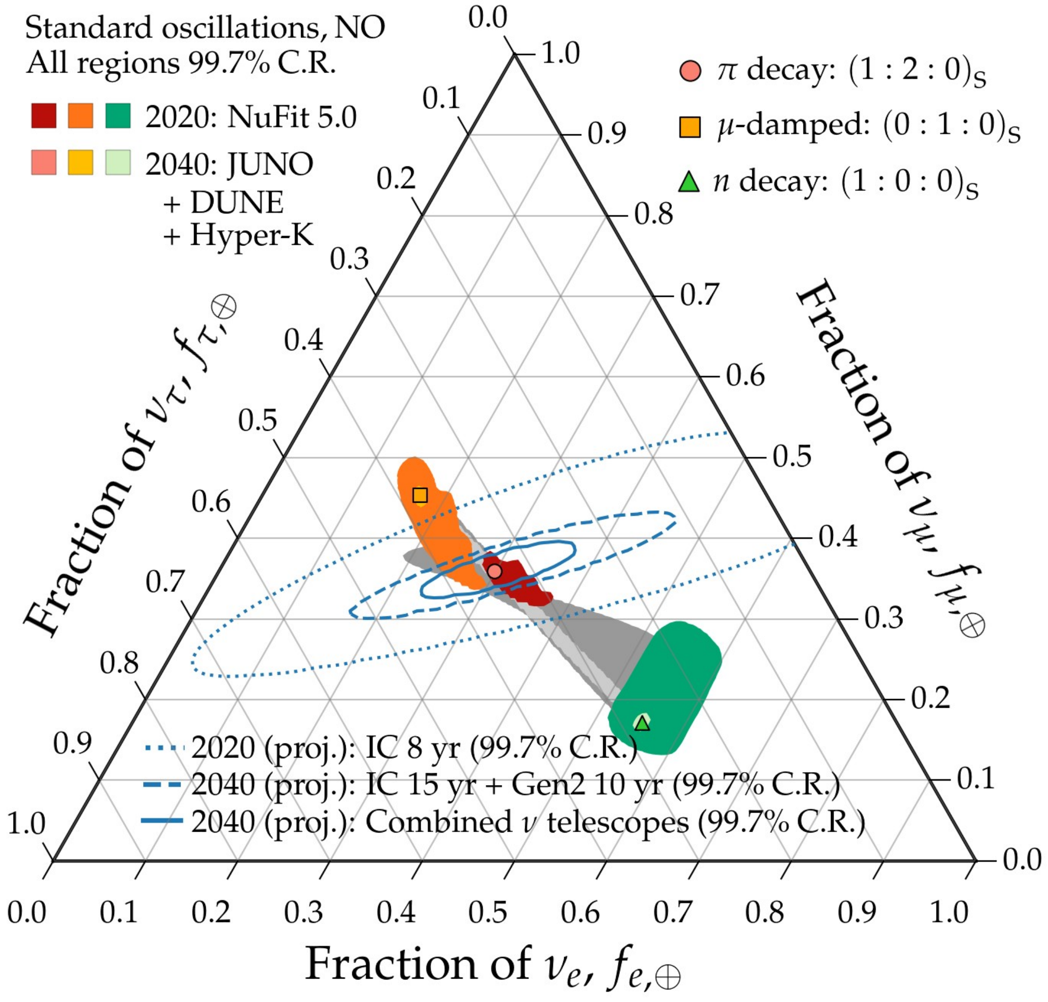
Allowed regions: well separated

Measurement: precise

Success

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Theoretically palatable regions: 2020 *vs.* 2040



By 2040:

Theory –
Mixing parameters known precisely: allowed flavor regions are *almost* points (already by 2030)

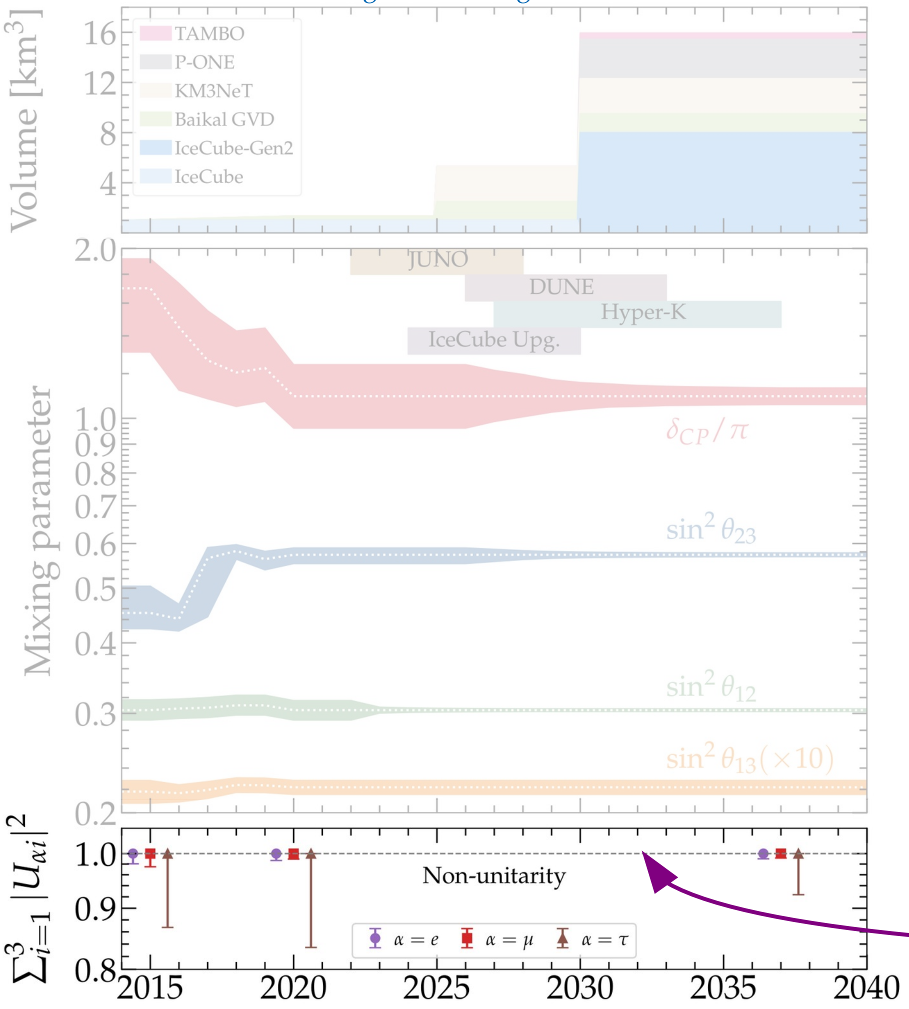
Measurement of flavor ratios –
Can distinguish between similar predictions at 99.7% C.R. (3σ)

Can finally use the full power of flavor composition for astrophysics and neutrino physics

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*

Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX



The 3×3 active mixing matrix is a non-unitary sub-matrix of a bigger one:

Active flavors

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \cdots & \cdots & \cdots & \ddots \end{pmatrix}$$

Additional sterile flavors

The elements $|U_{\alpha i}|^2$ for active flavors can be measured *without* assuming unitarity

Because the sub-matrix is not-unitary ($U_{3\nu}^\dagger U_{3\nu} \neq 1$), the "row sum" may be < 1

Ellis, Kelly, Li, 2008.01088
Parke & Ross-Lonergan, *PRD* 2016

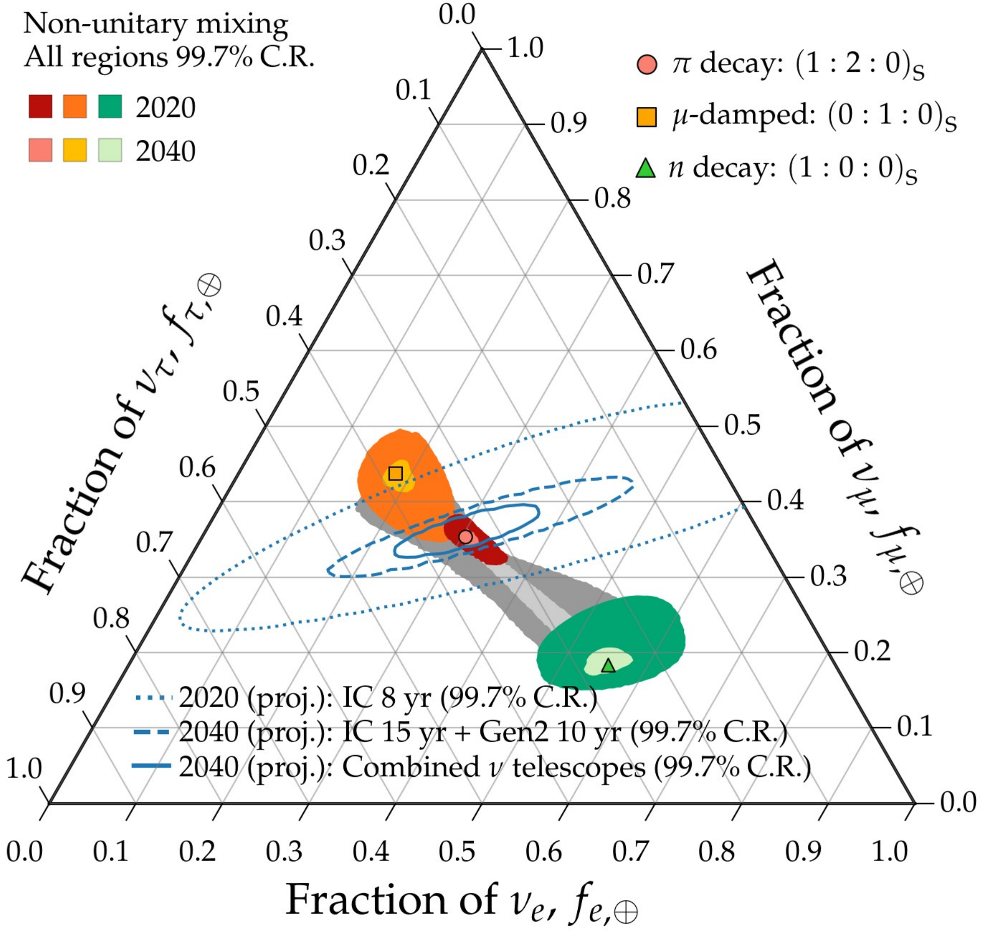
No unitarity? *No problem*

Flavor ratios at Earth:

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

Same as for standard oscillations…

… but the probability is computed directly using the values of the $|U_{\alpha i}|^2$ (instead of the mixing angles)



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

No unitarity? *No problem*

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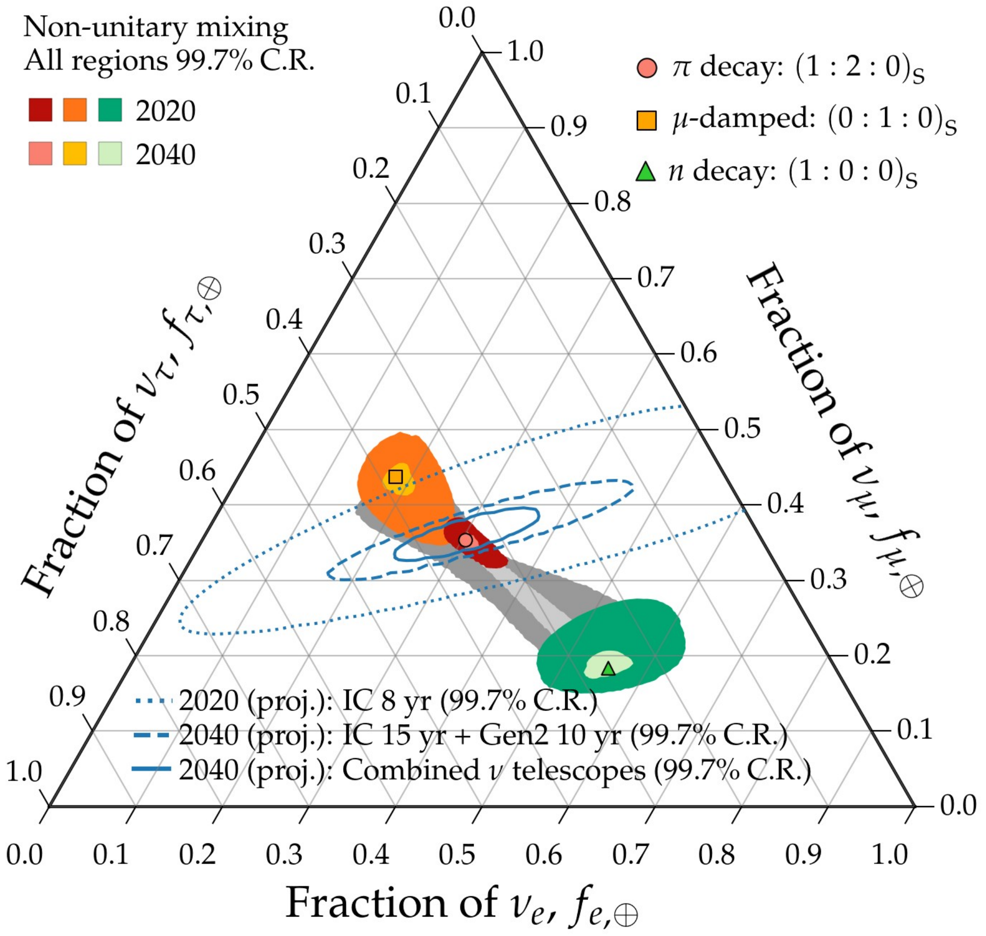

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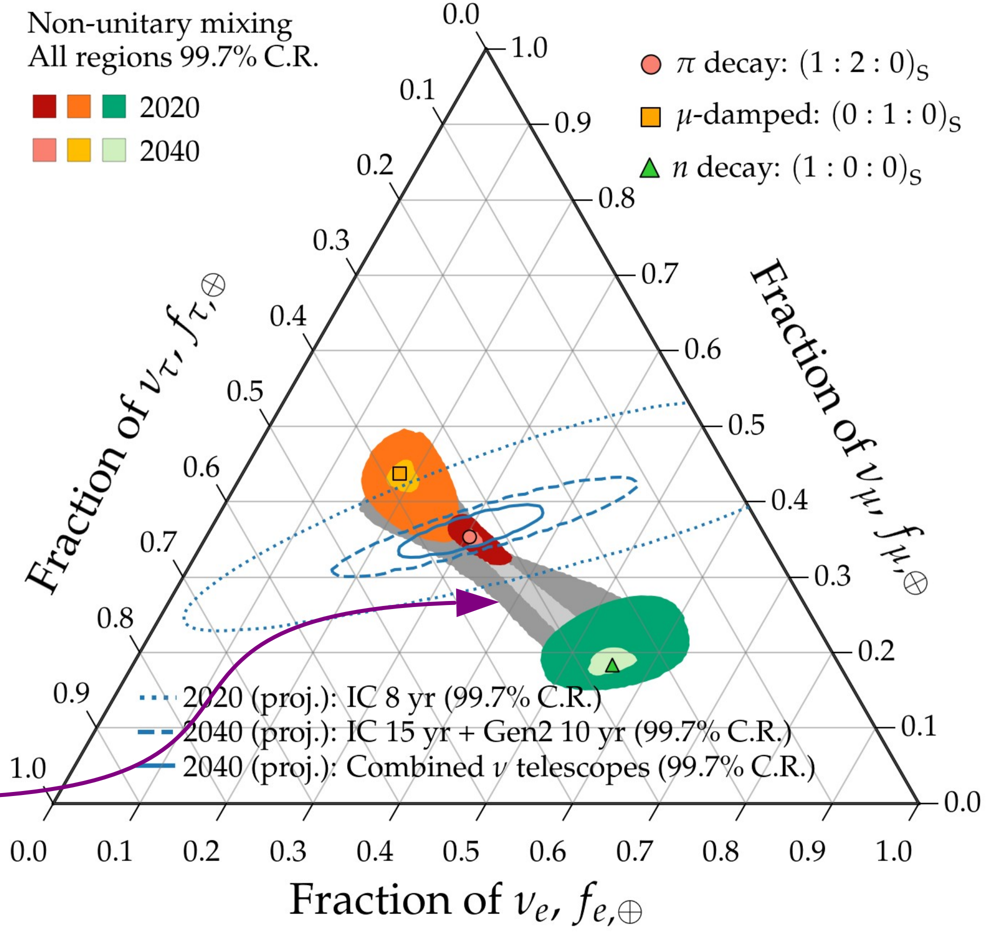
The allowed flavor regions are bigger, but *not much bigger*!



Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

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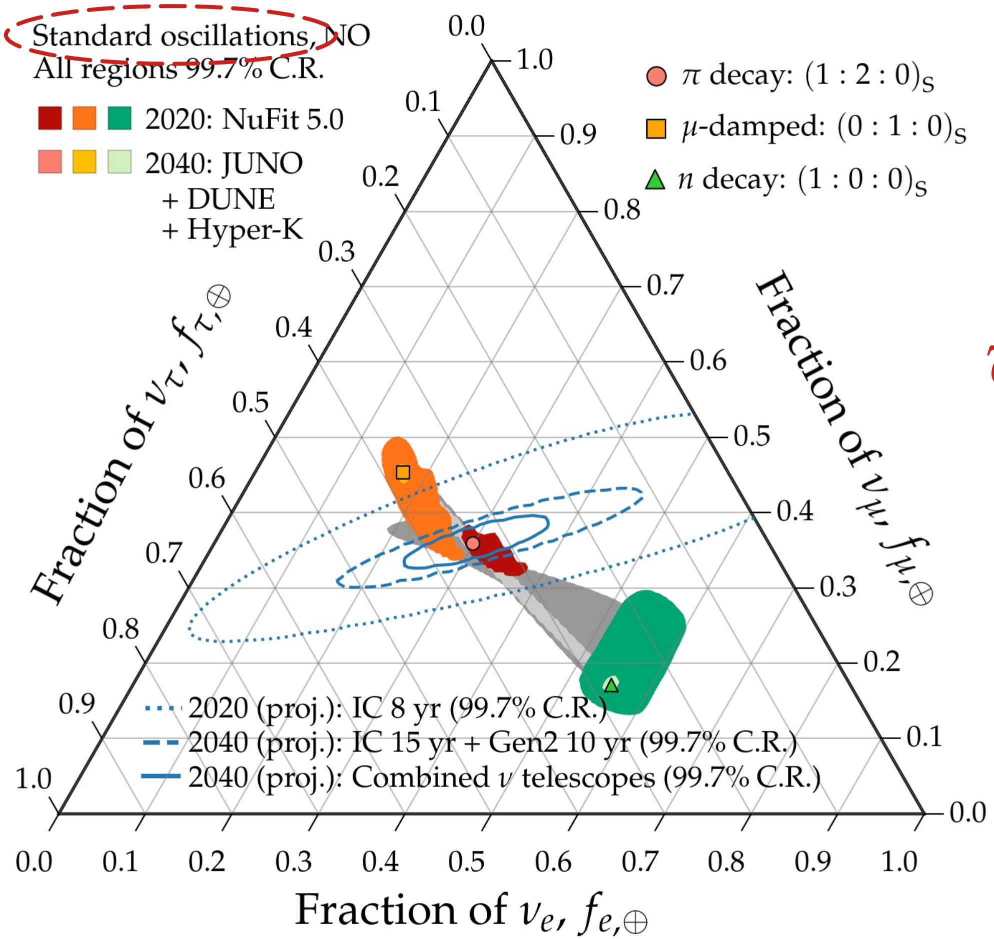
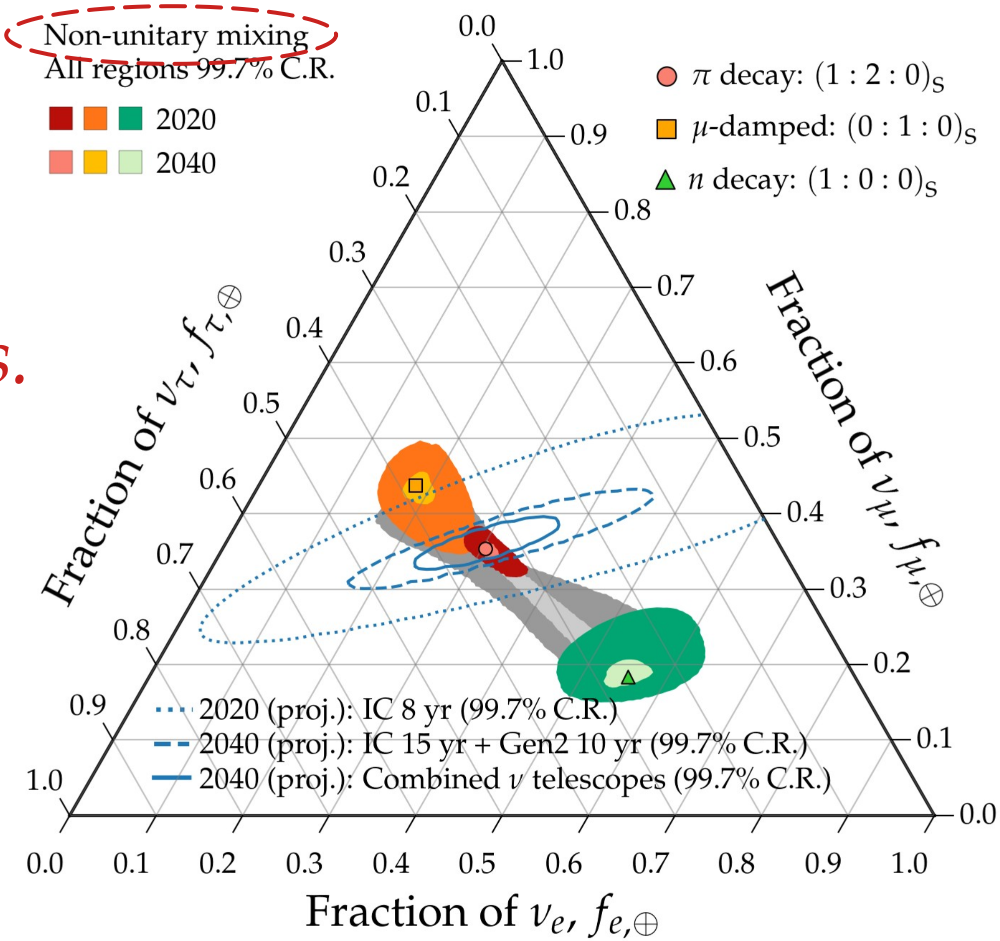


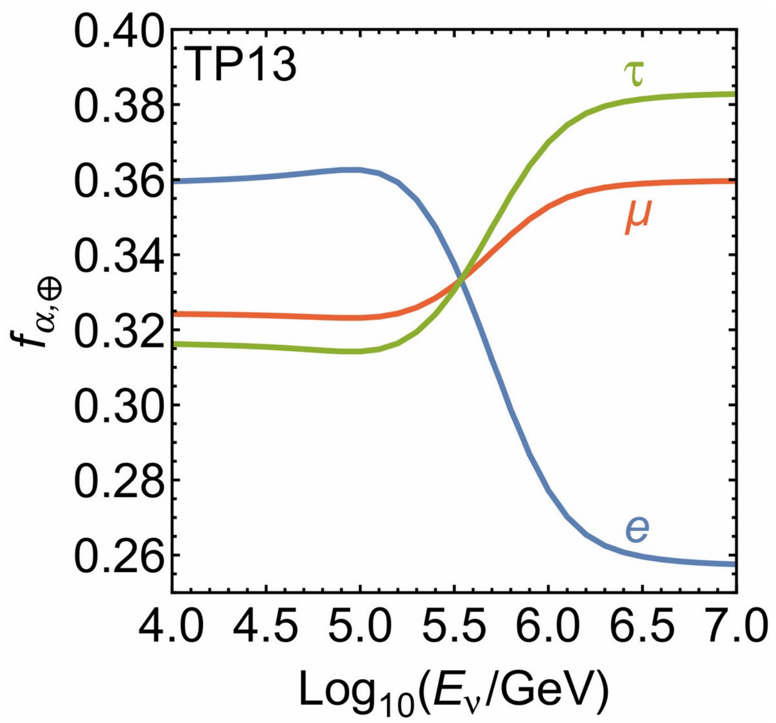
vs.

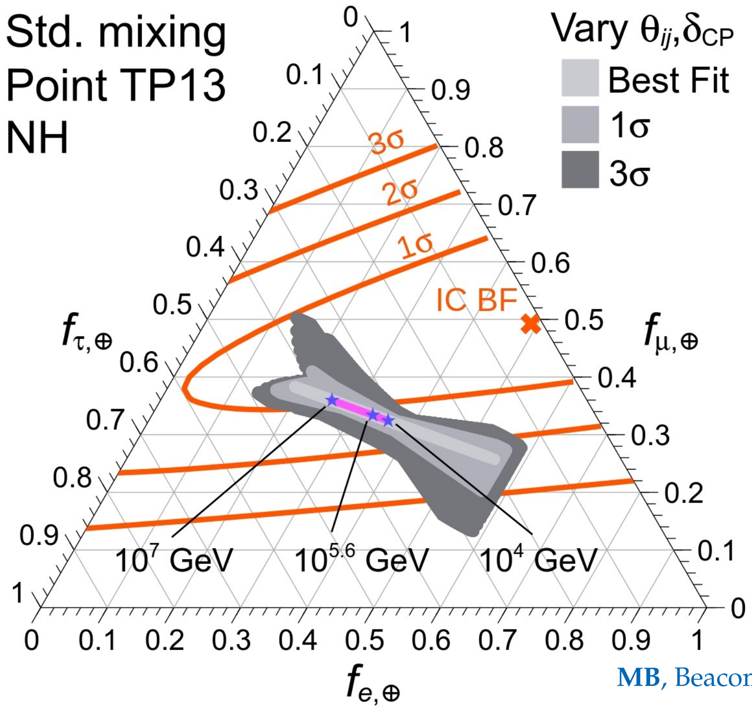


Song, Li, **MB**, Argüelles, Vincent, 2012.XXXXX

Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



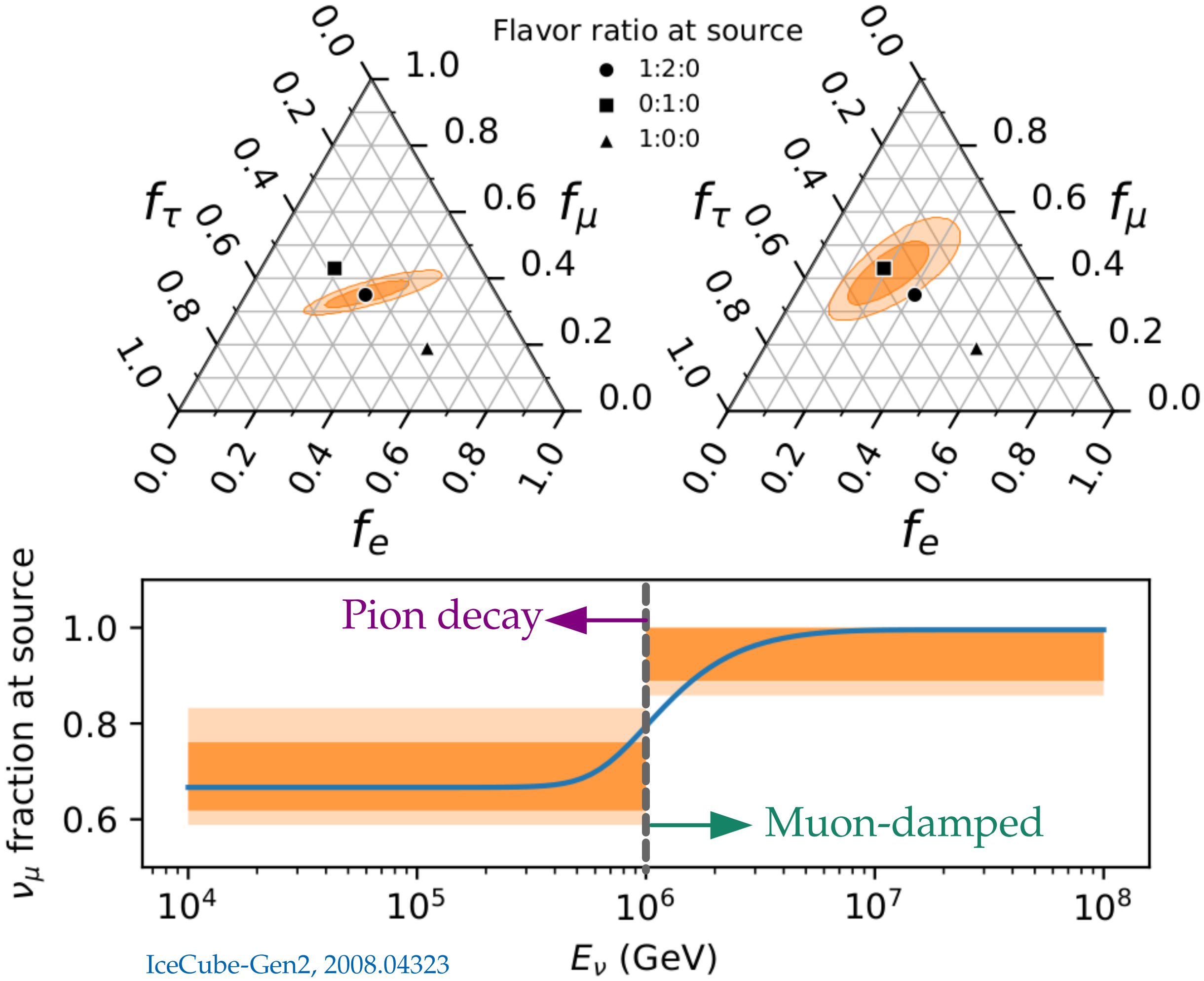


MB, Beacom, Winter, *PRL* 2015

- ▸ 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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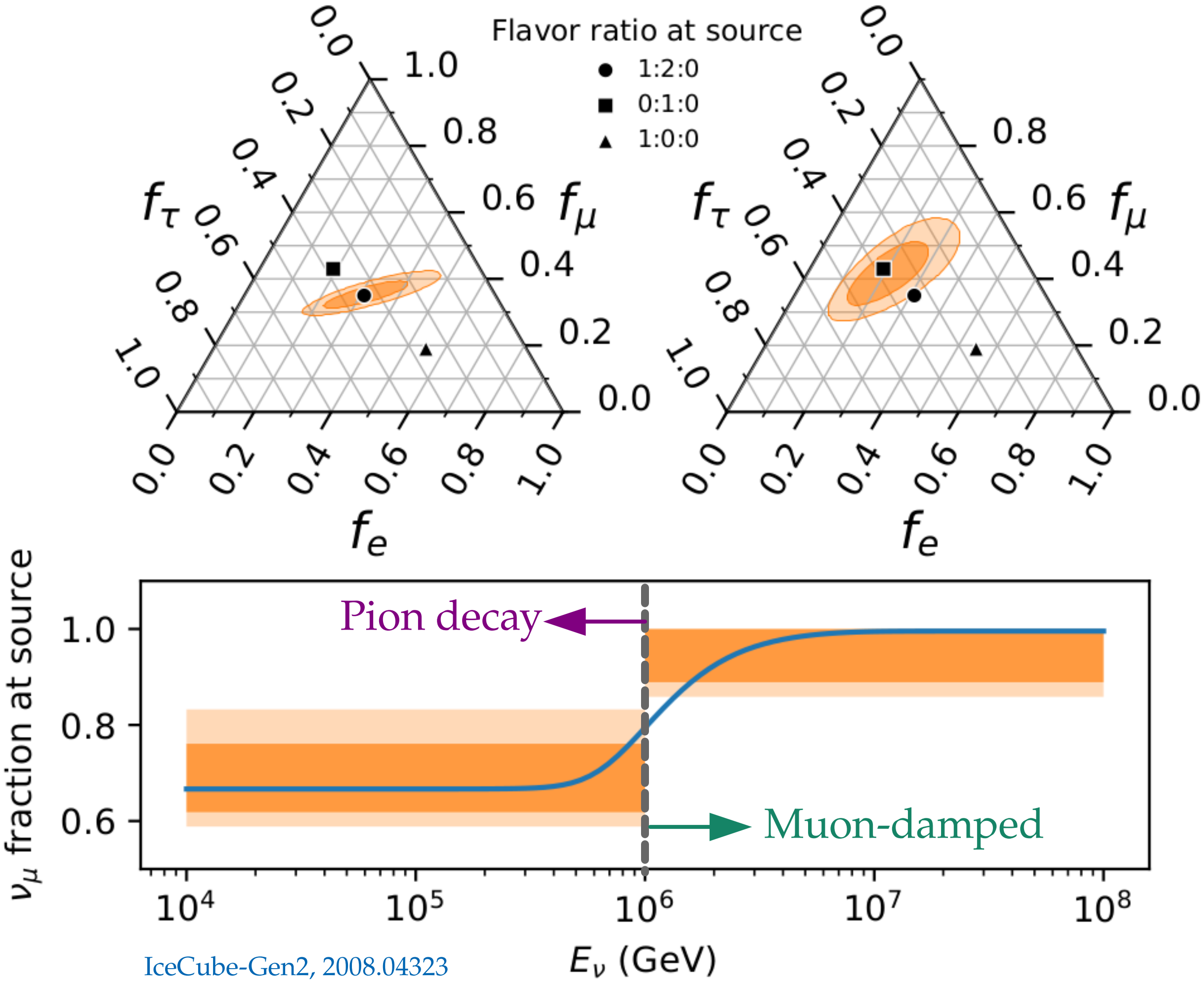
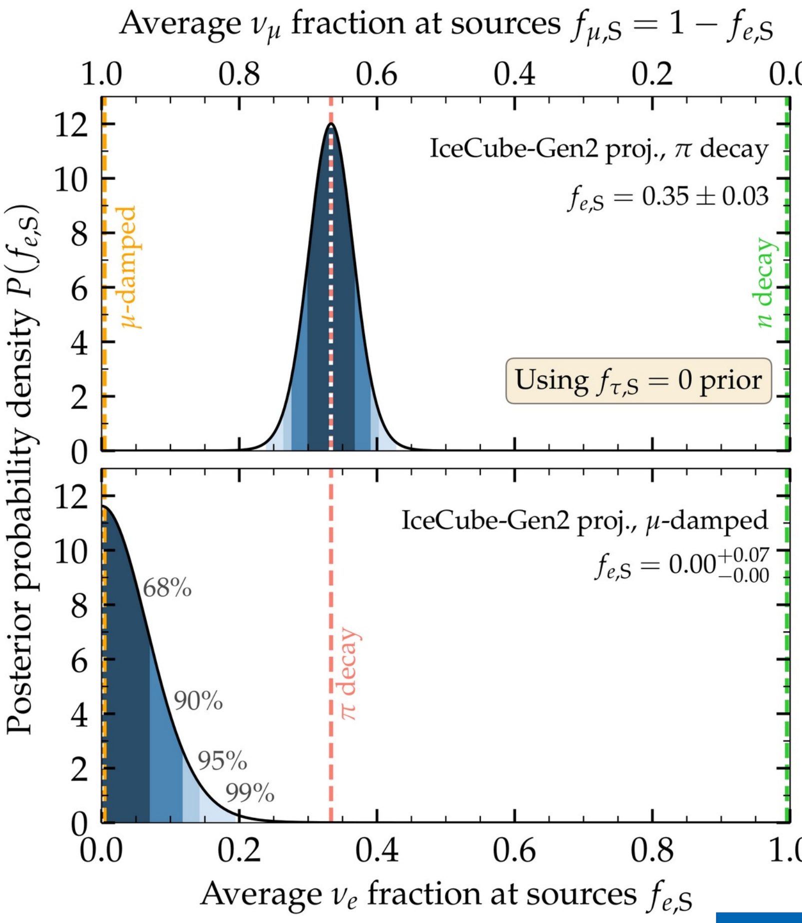


IceCube-Gen2, 2008.04323

Inferred (at sources):



MB & Ahlers, *PRL* 2019

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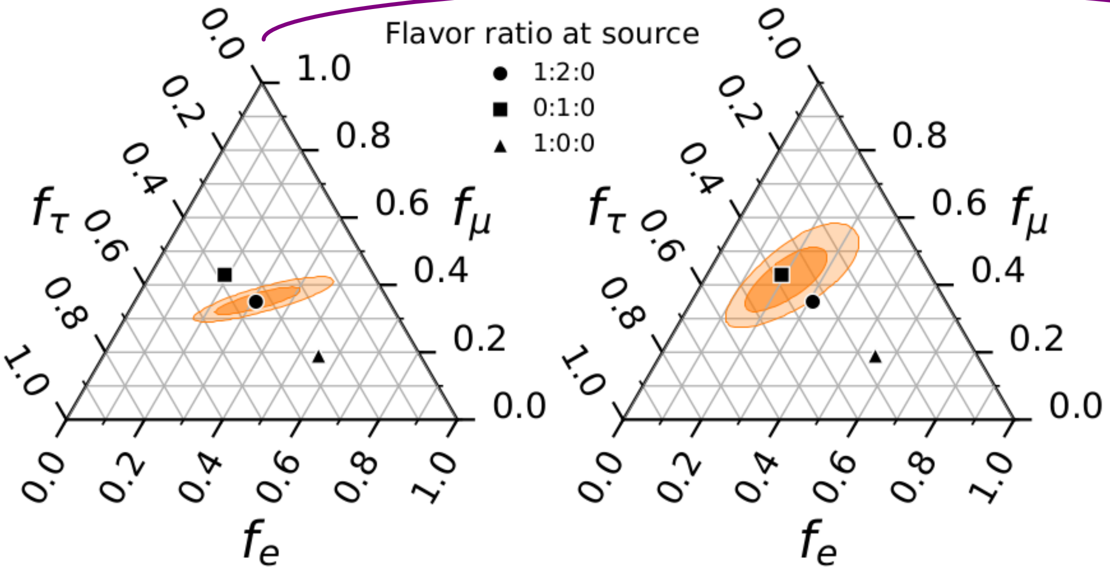

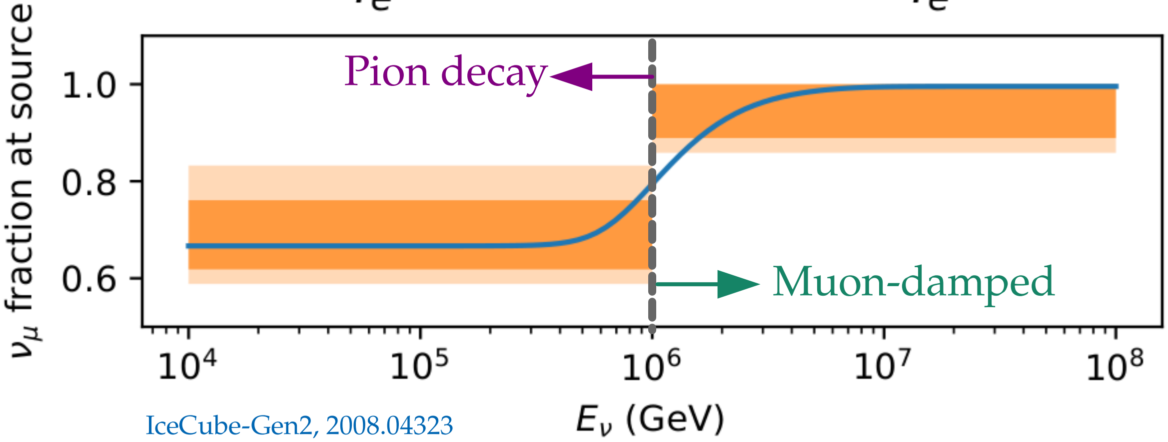

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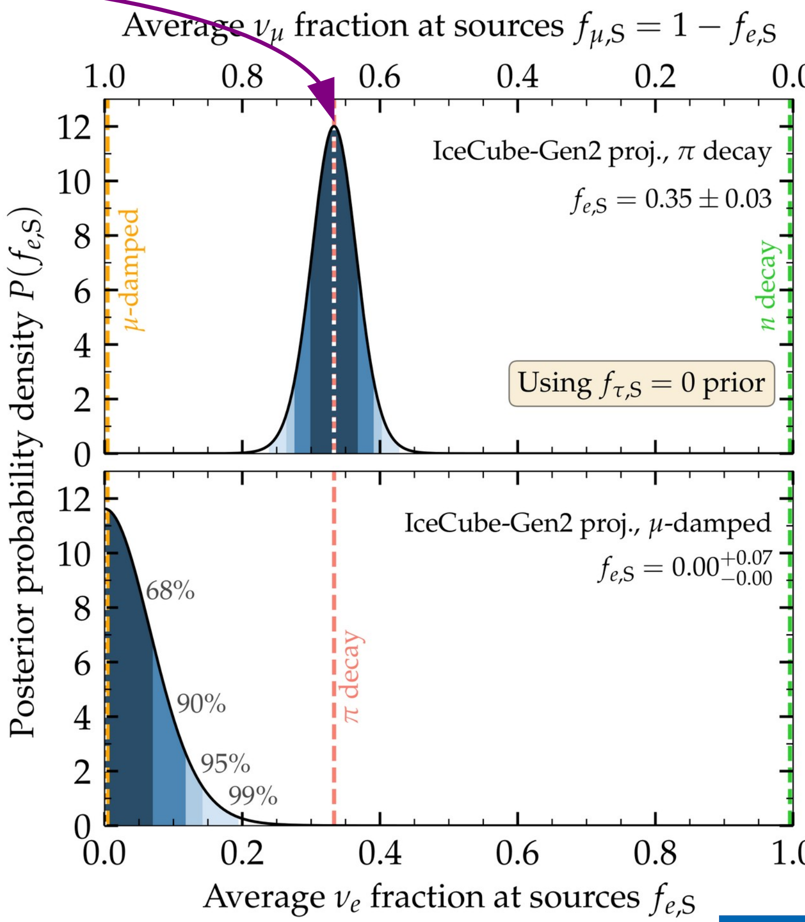

MB & Ahlers, *PRL* 2019

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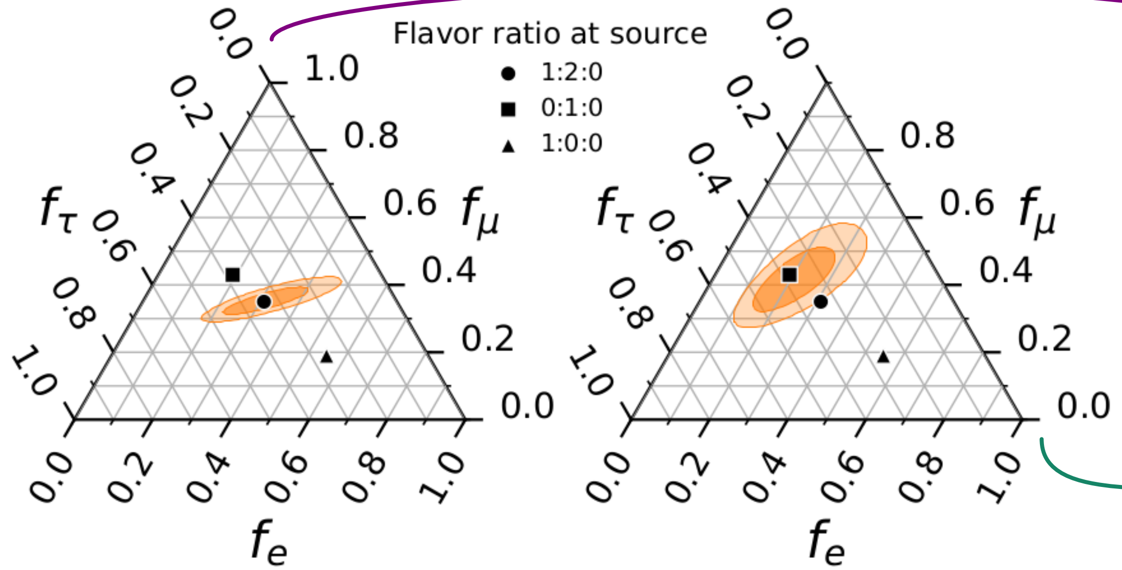

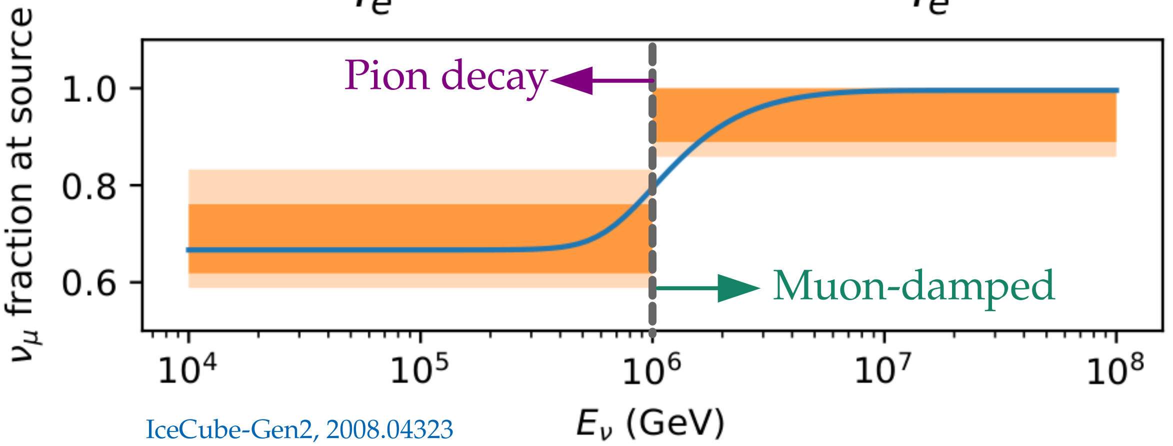

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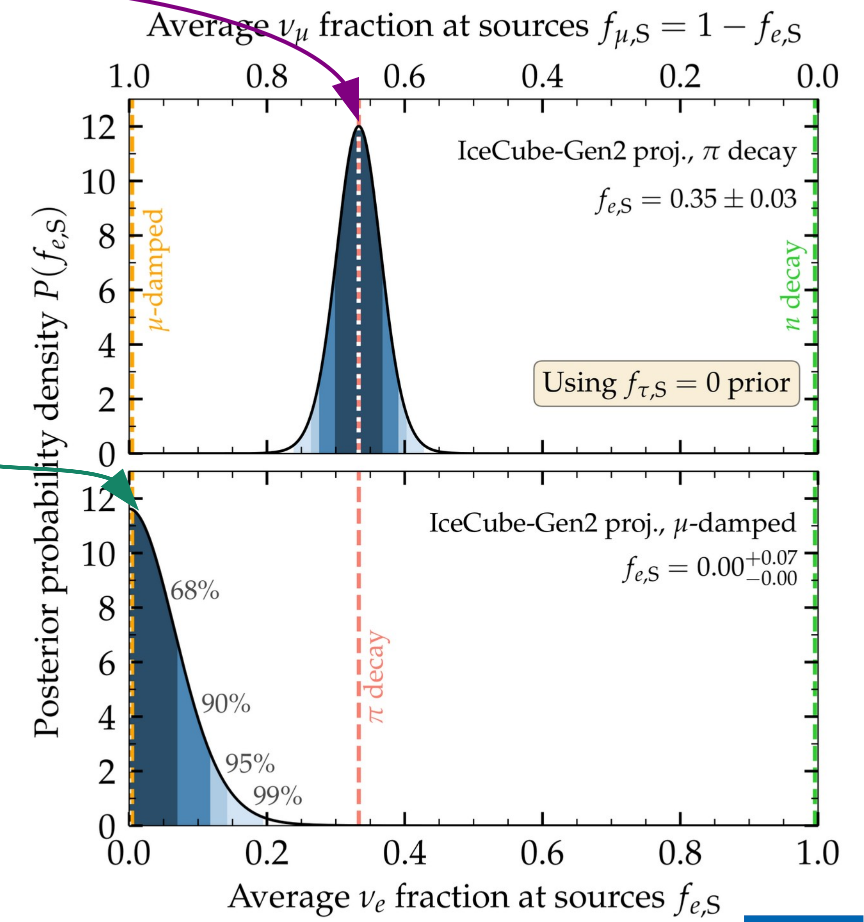

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MB & Ahlers, *PRL* 2019

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 $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\rm CP})$

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, 2012.12893
MB & Ahlers, *PRL* 2019

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Oscillation experiments Neutrino telescopes

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

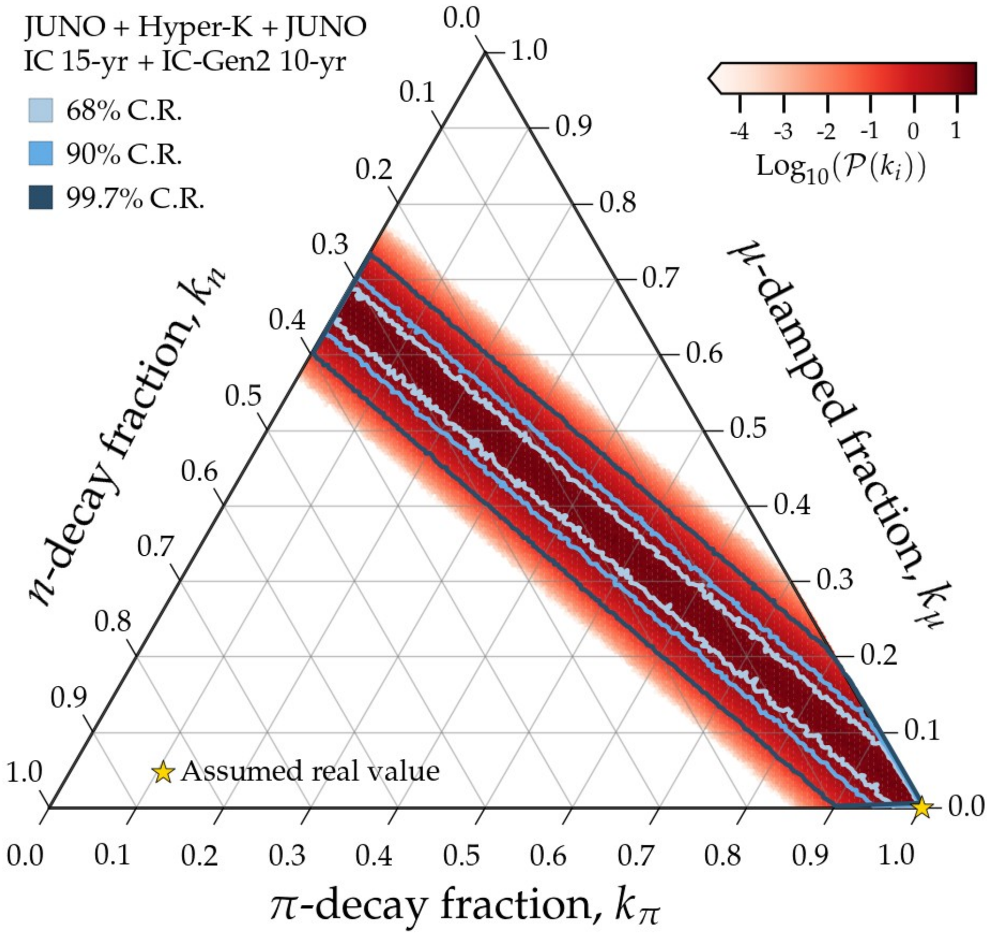
Propagate to Earth

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

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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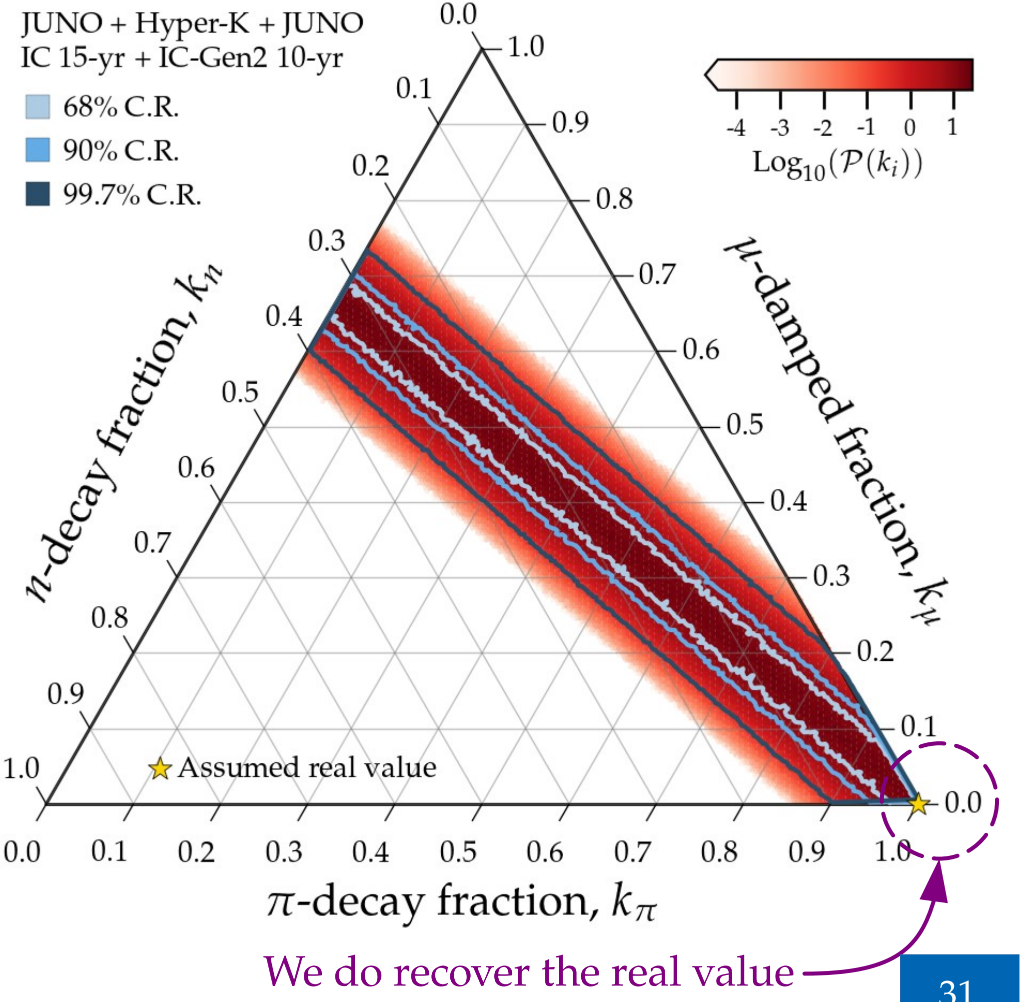

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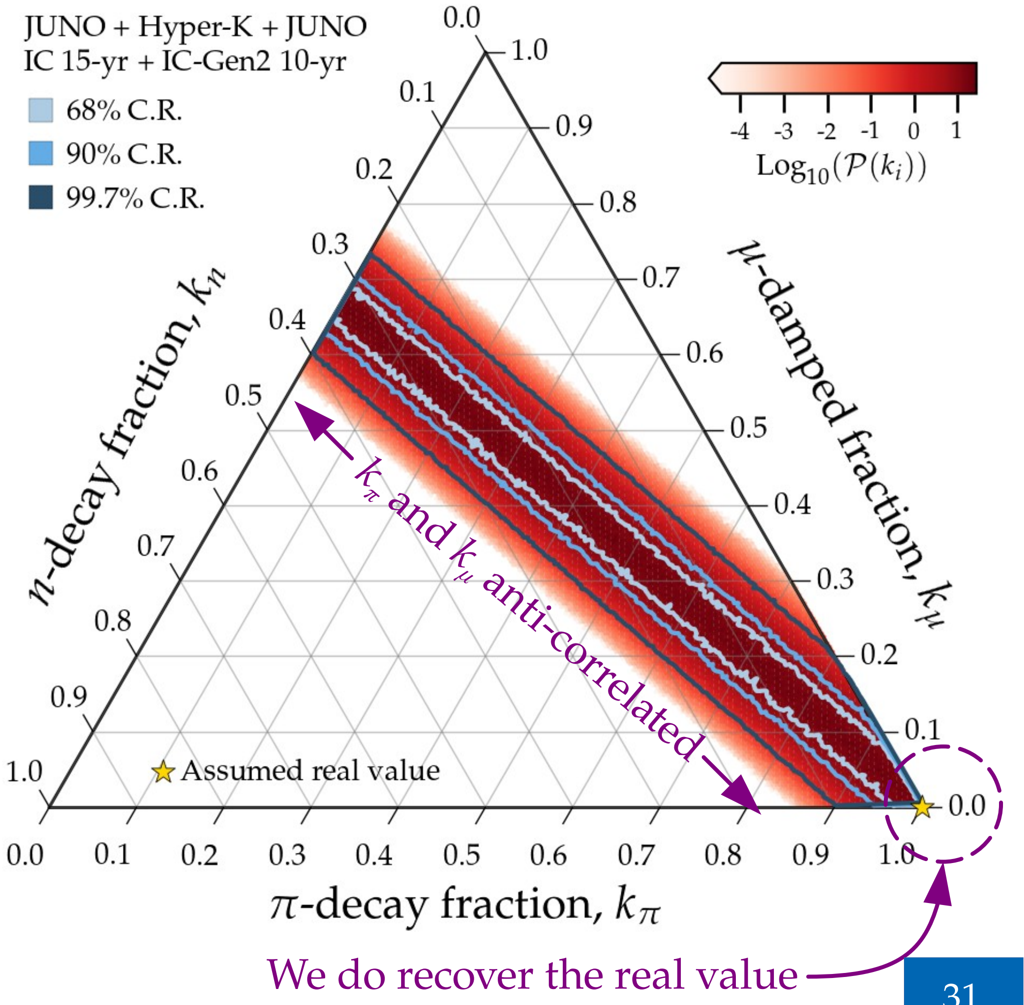

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π decay: (1/3, 2/3, 0) — μ damped: (0, 1, 0) — n decay: (1, 0, 0)

Propagate to Earth

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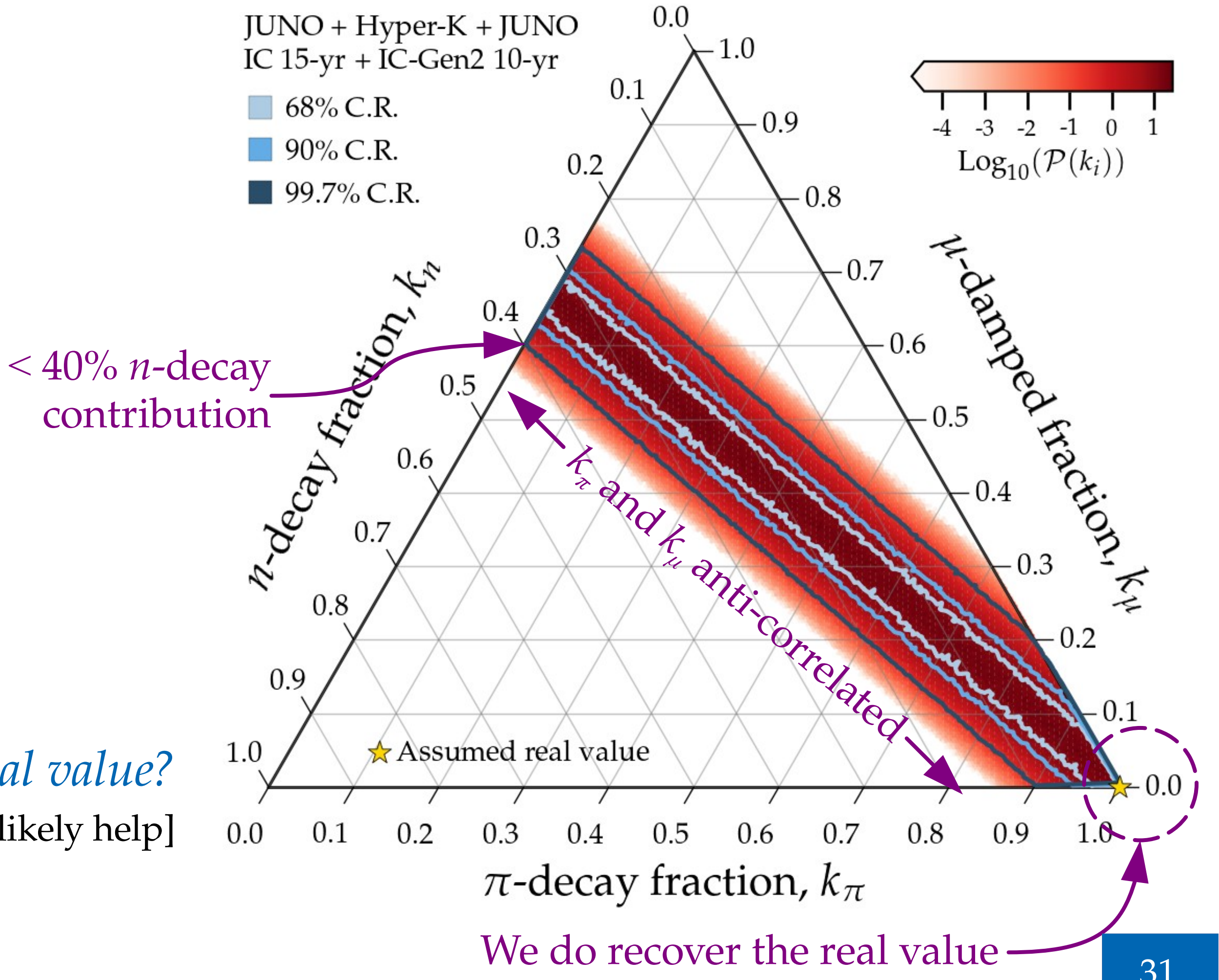

Song, Li, Argüelles, **MB**, Vincent, 2012.12893

Fundamental physics with HE cosmic neutrinos

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

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

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

- Fundamental physics can be extracted from four neutrino observables:
  - Spectral shape
  - Angular distribution
  - Flavor composition
  - Timing

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  - Flavor composition
  - Timing

  In spite of
  poor energy, angular, flavor reconstruction
  & astrophysical unknowns

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}U_{e1}^* & U_{e2}^* & U_{e3}^*\\ U_{\mu1}^* & U_{\mu2}^* & U_{\mu3}^*\\ U_{\tau1}^* & U_{\tau2}^* & U_{\tau3}^*\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

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

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

Flavor-transition probability: the quick and dirty of it

- In matrix form: $$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

- Pontecorvo-Maki-Nakagawa-Sakata matrix ($c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$):

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Atmospheric | Cross mixing | Solar | Majorana CP phases

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… But high-energy neutrinos oscillate *fast*

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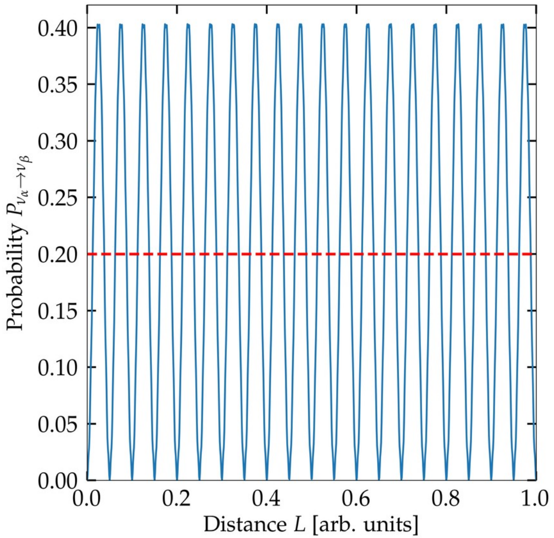

Oscillation length for 1-TeV ν: $2\pi \times 2E/\Delta m^2 \sim 0.1$ pc

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

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

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

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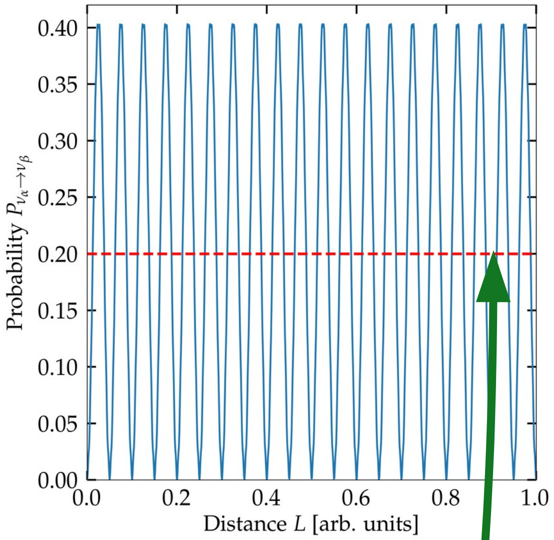

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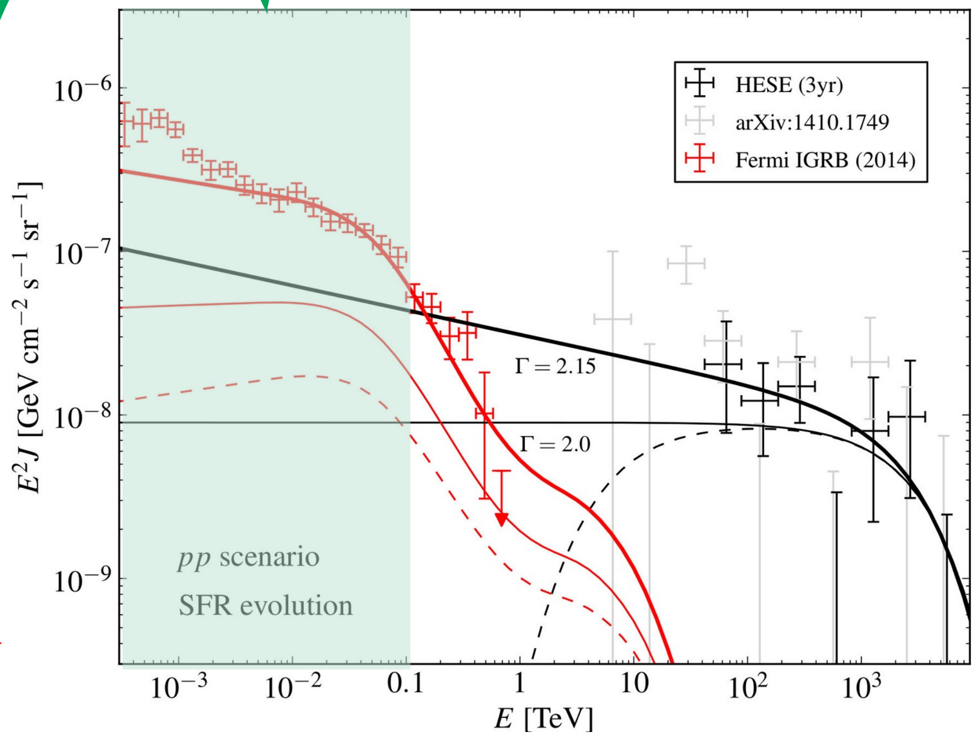
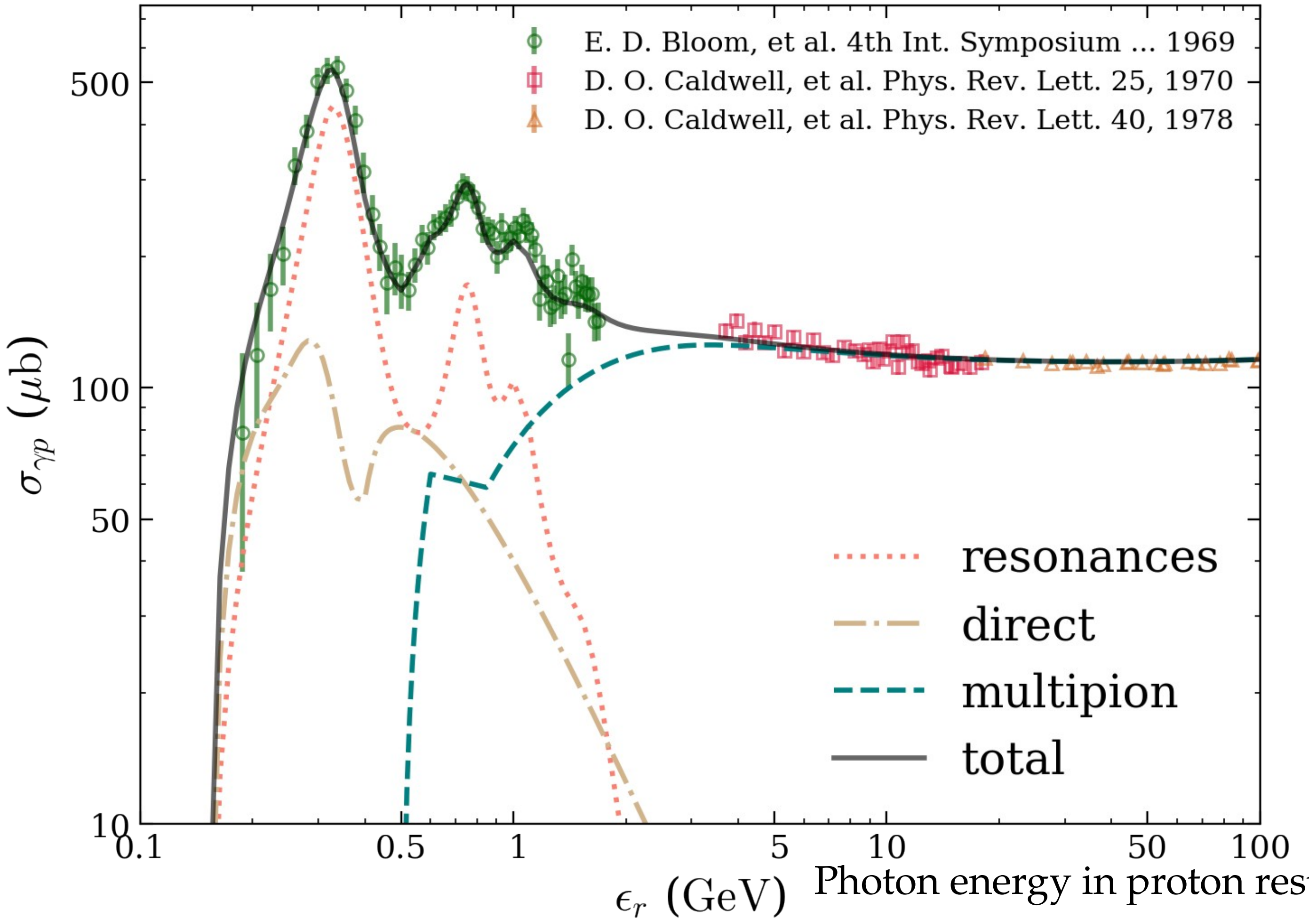
Constraints from the gamma-ray background

- Production via *pp*: ν and gamma-ray spectra follow the CR spectrum $E^{-\Gamma}$
- Gamma-ray interactions on the CMB make them pile up at GeV
- *Fermi* gamma-ray background is not exceeded only if $\Gamma < 2.2$
- But IceCube found Γ = 2.5–2.7
- Therefore, production via *pp* is disfavored between 10–100 TeV

Murase, Ahlers, Lacki, *PRD* 2013



Beyond the Δ resonance (1/2)

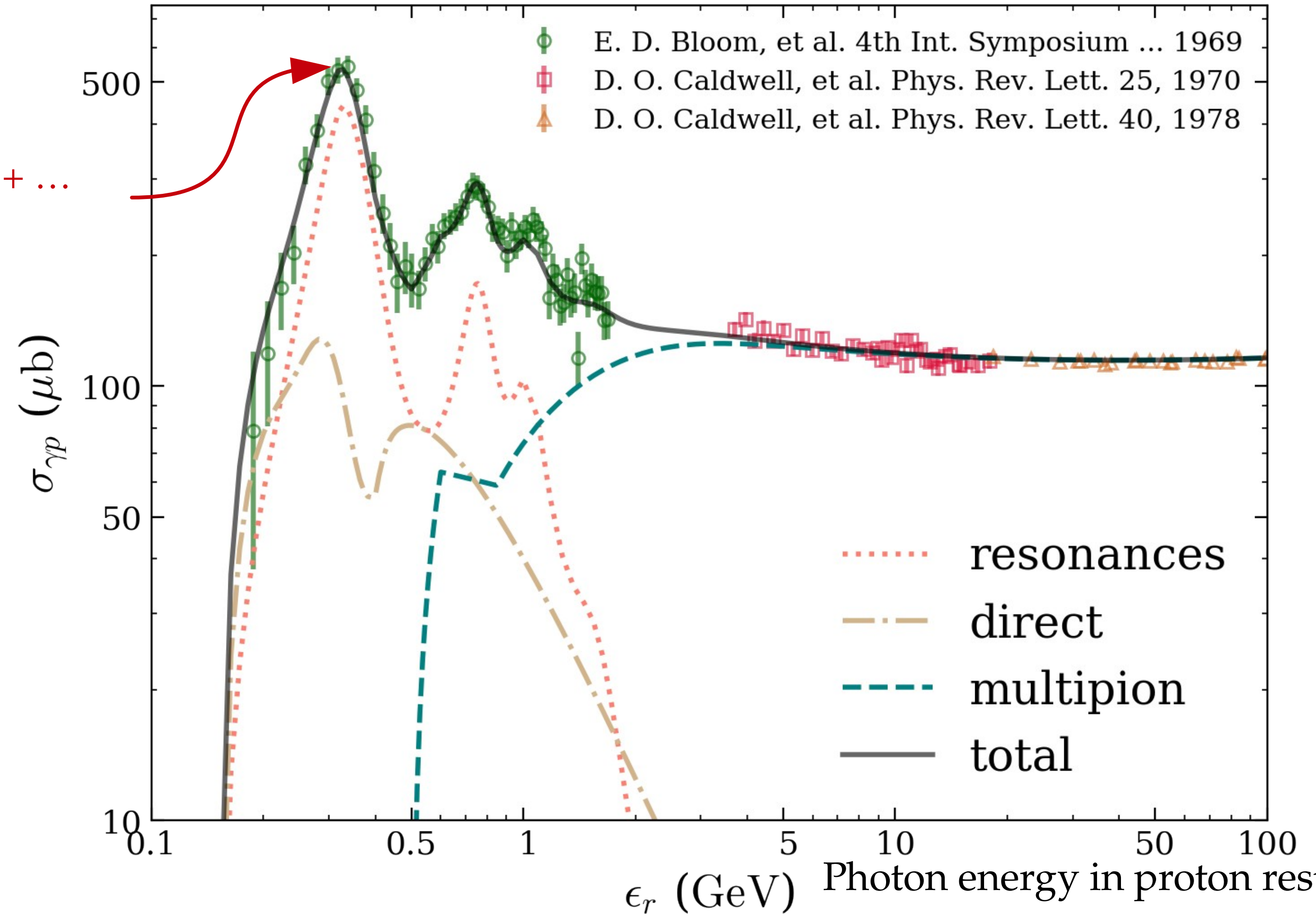


Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (1/2)

Delta resonance:
$p + \gamma \to \Delta \to \pi^{+} \to 3\nu + \ldots$



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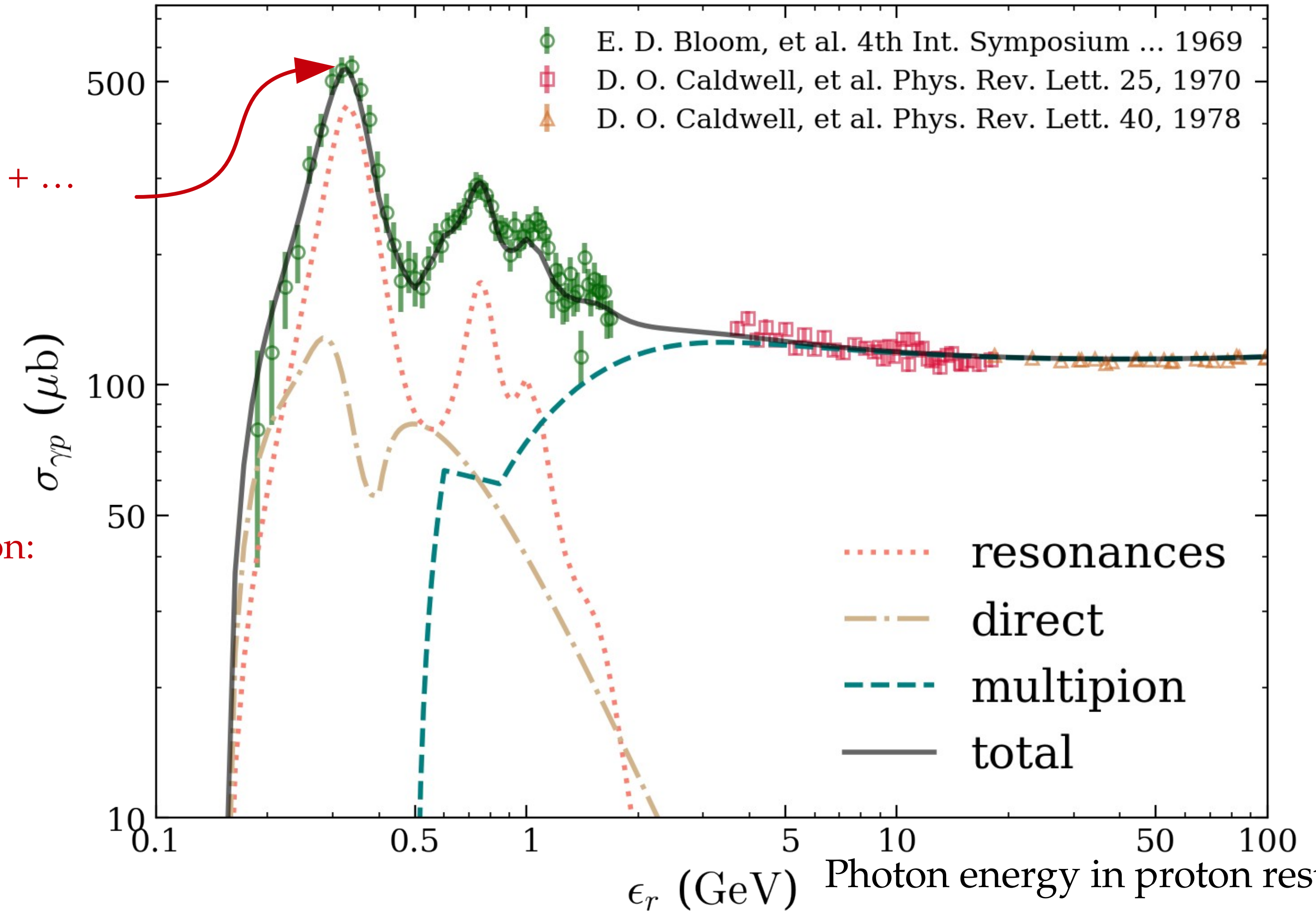
$p + \gamma \rightarrow \Delta \rightarrow \pi^+ \rightarrow 3\nu + \ldots$

Resonance condition:
$E_p \times E_\nu \sim 0.2\ \mathrm{GeV}^2$



Photon energy in proton rest frame

Morejón *et al.*, 1904.07999

Beyond the Δ resonance (2/2)

(1) Δ-resonance region

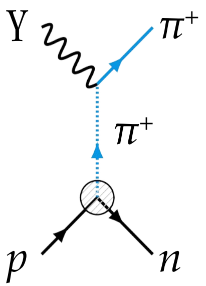
$$p + \gamma \xrightarrow{\Delta(1232)} p' + \pi$$

(2) Higher resonances

$$p + \gamma \xrightarrow{\Delta,N} \Delta' + \pi \ , \quad \Delta' \rightarrow p' + \pi$$

(3) Direct production (t channel)

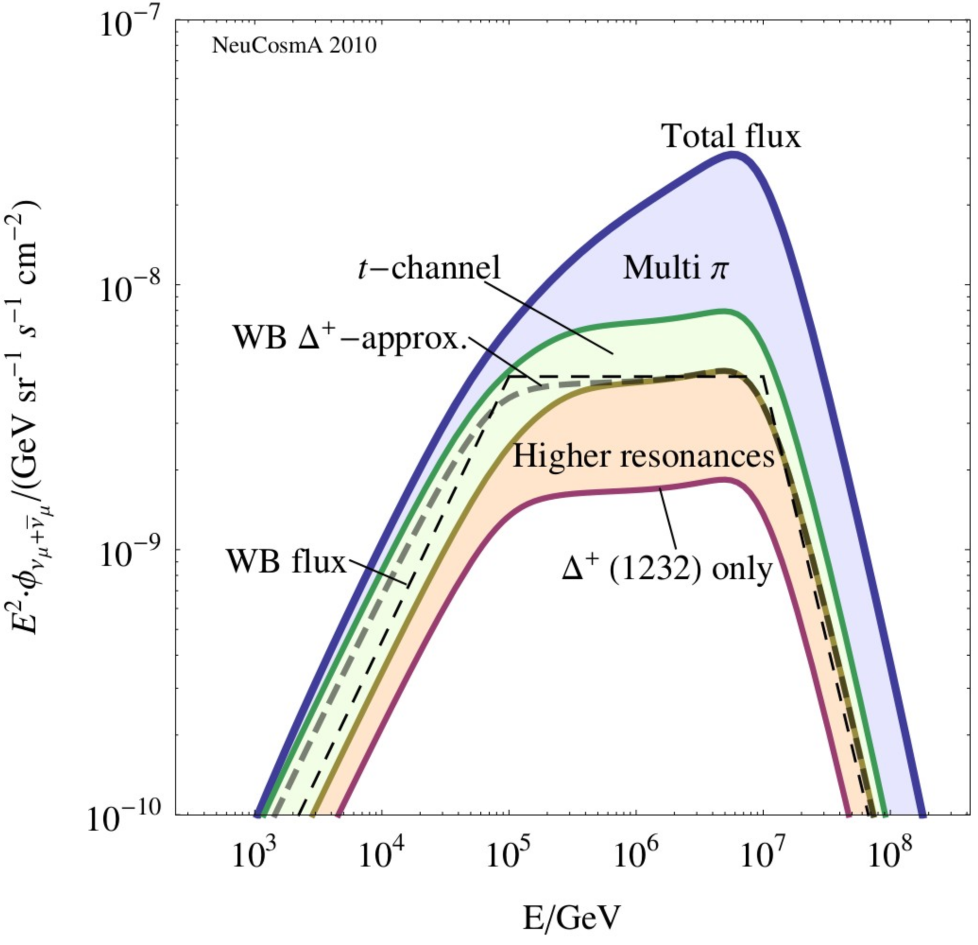
Same as (1) and (2), but in the t channel, *i.e.*, with a virtual pion



(4) Multi-pion production

Statistical production of two or more pions

E.g., neutrinos from a gamma-ray burst:



Mücke *et al.*, *Comput. Phys. Comm.* 2000
Hümmer *et al.*, *ApJ* 2010; Baerwald, Hümmer, Winter, *PRD* 2011

The Universe is opaque to UHECRs

Photohadronic processes:

$$p + \gamma \rightarrow \Delta \rightarrow \begin{cases} p + \pi^0 \quad (\pi^0 \rightarrow \gamma + \gamma) \\ n + \pi^+ \quad (\pi^+ \rightarrow \nu_\mu + \bar{\nu}_\mu + \nu_e + e^+) \end{cases}$$

Pair production:

$$p + \gamma \rightarrow p + e^- + e^+$$

Greisen-Zatsepin-Kuzmin (GZK) cut-off:

$$E_p \approx \frac{0.16 \text{ GeV}}{0.66 \text{ meV}} \approx 2 \cdot 10^{11} \text{ GeV}$$

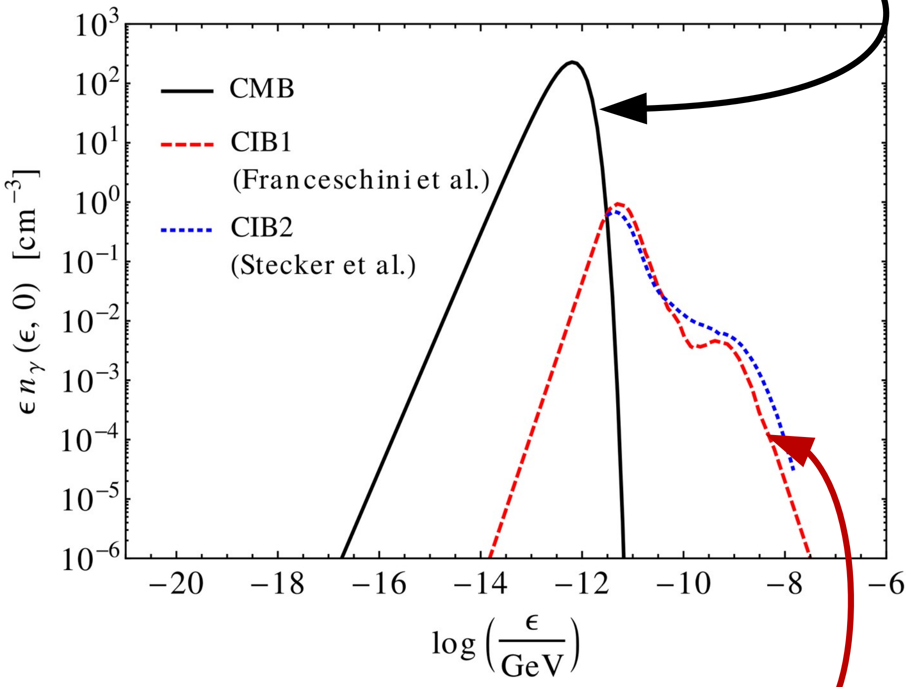
(Assuming only photohadronic interaction)

Accounting also for pair production and CMB width:

$$E_p \approx 5 \cdot 10^{10} \text{ GeV}$$

Target photon spectra (at $z = 0$):

CMB: Microwave (black body, $\langle\epsilon\rangle \sim 0.66$ meV)



CIB: optical (stars) + infrared (dust remission)

$n_\gamma(z) = (1+z)^3\, n_\gamma(z=0)$ (exact only for CMB)

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

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Mean free path:

$$(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} = (413 \text{ cm}^{-3} \times 200 \text{ µbarn})^{-1} \approx 10^{25} \text{ cm} \approx 4 \text{ Mpc}$$

Energy-loss scale:

$$L = (E/\Delta E)(n_\gamma \langle\sigma\rangle_{p\gamma})^{-1} \approx (1/0.2) \times 4 \text{ Mpc} \approx 20 \text{ Mpc}$$

A more detailed calculation yields

$$L_{\text{GZK}} = 50 \text{ Mpc}$$

Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is opaque to UHECRs

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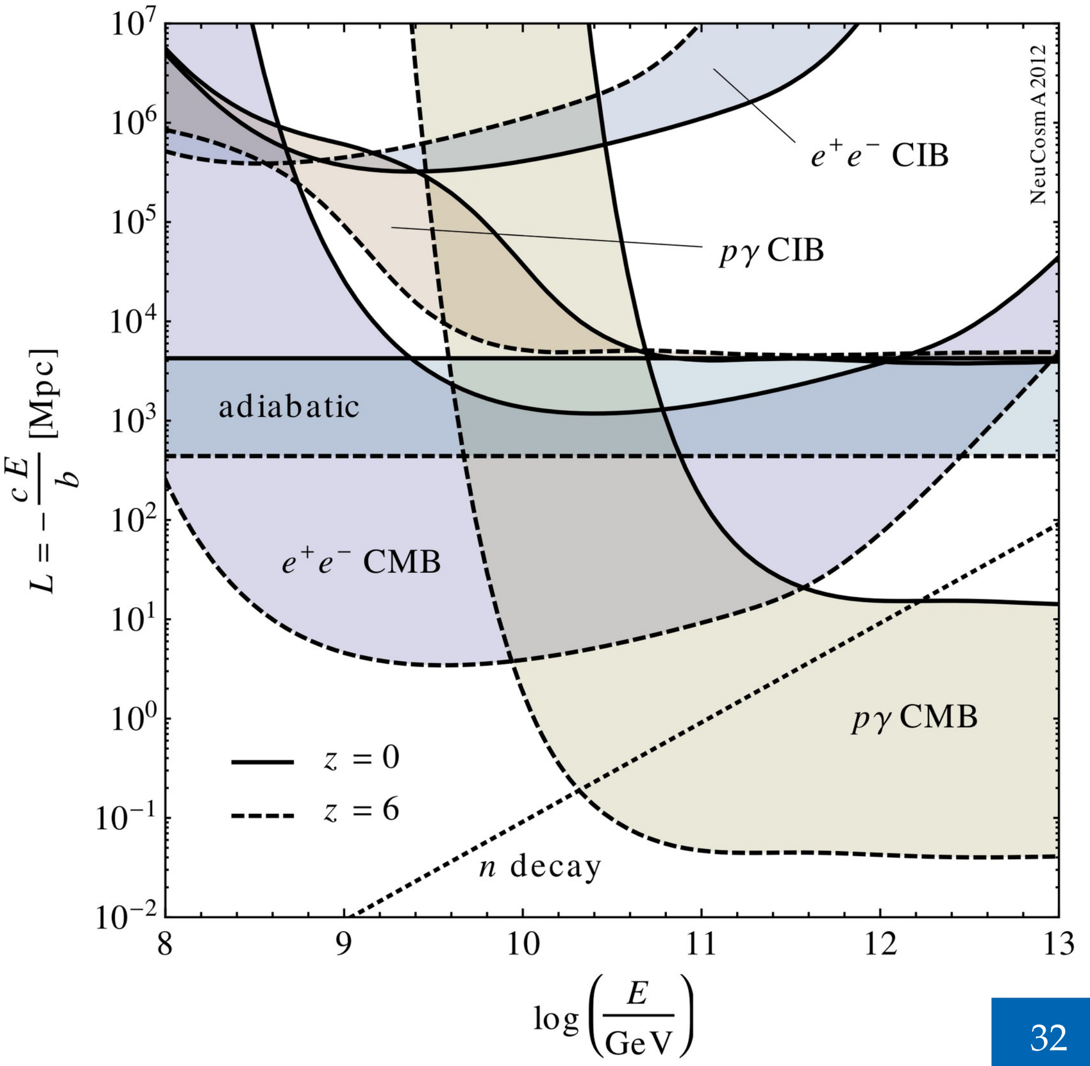


Greisen *PRL* 1966; Zatsepin & Kuzmin, *JETP* 1966

The Universe is *also* opaque to PeV gamma rays

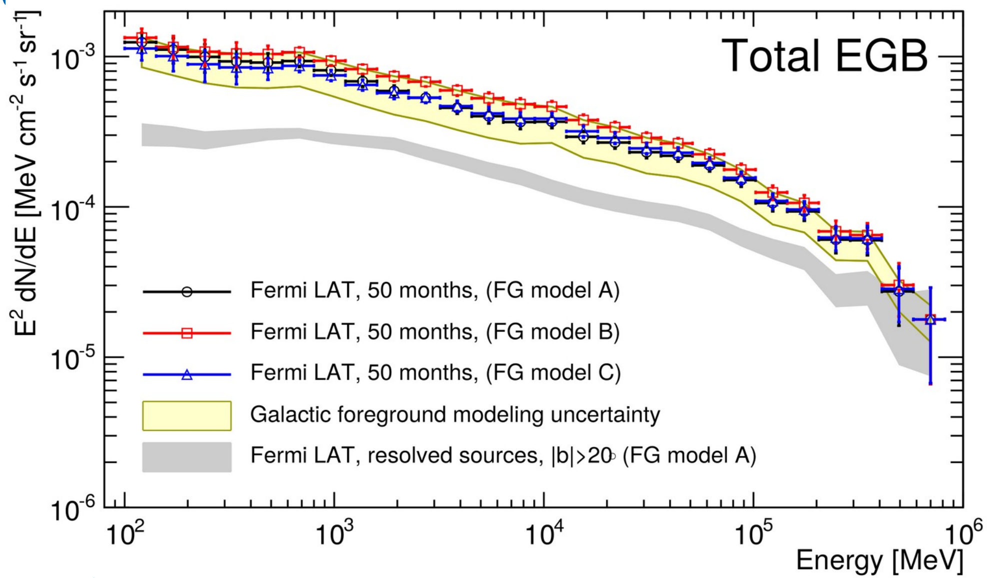
Pair production:

$$\gamma_{astro} + \gamma_{cosmo} \rightarrow e^- + e^+$$

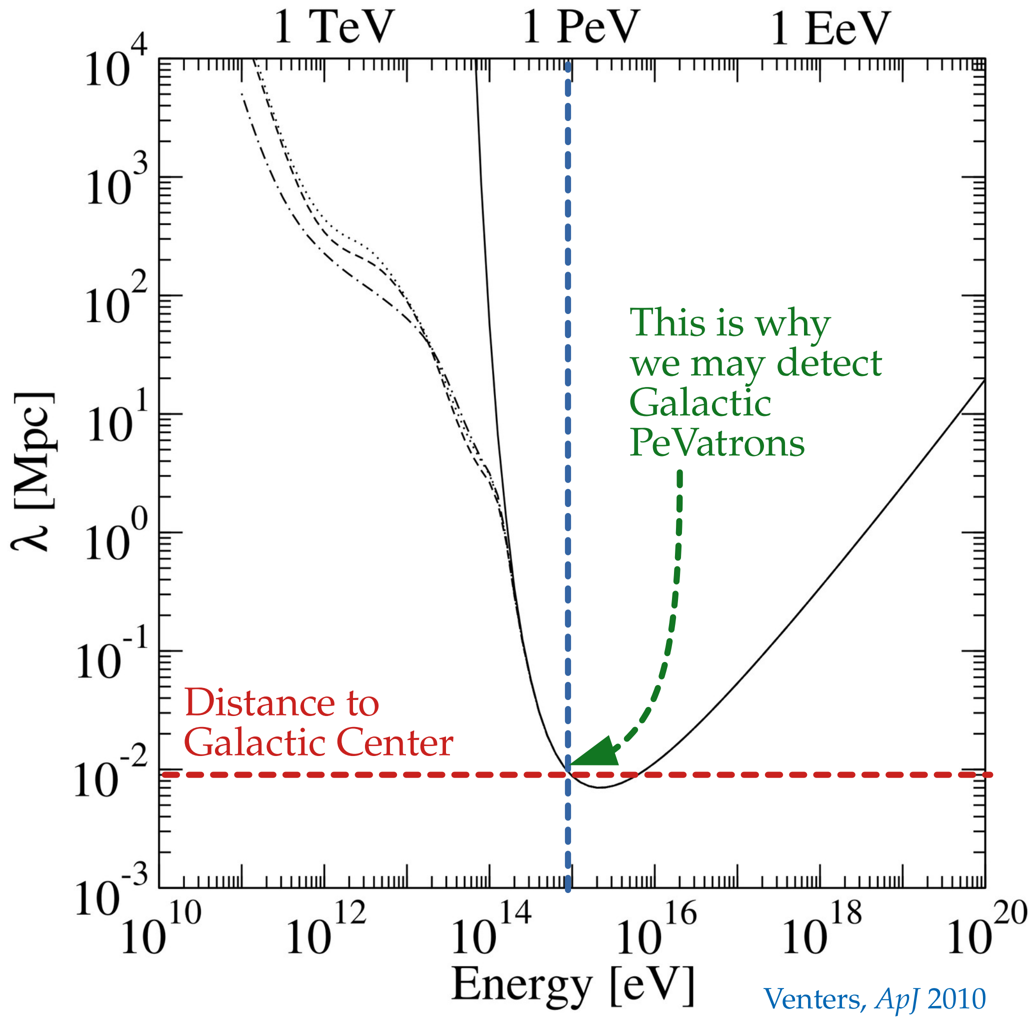
Inverse Compton scattering:

$$e^\pm + \gamma_{cosmo} \rightarrow e^\pm + \gamma$$

PeV gamma rays cascade down to MeV–GeV:



Fermi-LAT, *ApJ* 2015



Venters, *ApJ* 2010

Statistical analysis

We look for synchrotron effects in two public IceCube data sets:

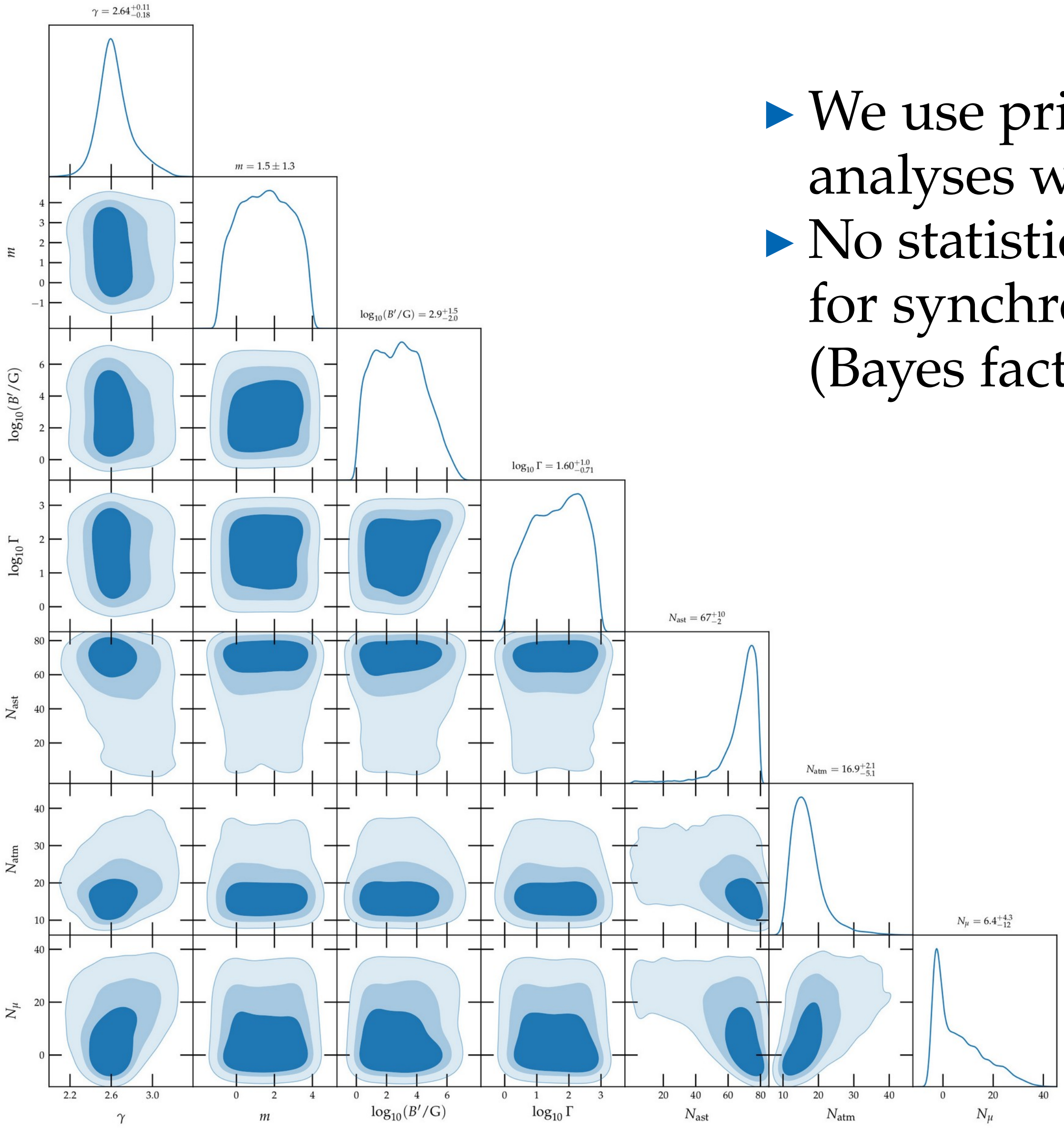
- 6 years of High Energy Starting Events (HESE): 80 events
- 2 years of Medium Energy Starting Events (HESE): 54 events

Bayesian analysis with likelihood function

$$\mathcal{L}(\gamma, m, \Gamma, B', N_{\rm ast}, N_{\rm atm}, N_\mu) = e^{-N_{\rm ast}-N_{\rm atm}-N_\mu} \prod_{i=1}^{N_{\rm obs}} \mathcal{L}_i(\gamma, m, \Gamma, B', N_{\rm ast}, N_{\rm atm}, N_\mu)$$

Partial likelihood: $\mathcal{L}_i = N_{\rm ast}\mathcal{P}_{i,{\rm ast}}(\gamma, m, \Gamma, B') + N_{\rm atm}\mathcal{P}_{i,{\rm atm}} + N_\mu \mathcal{P}_{i,\mu}$

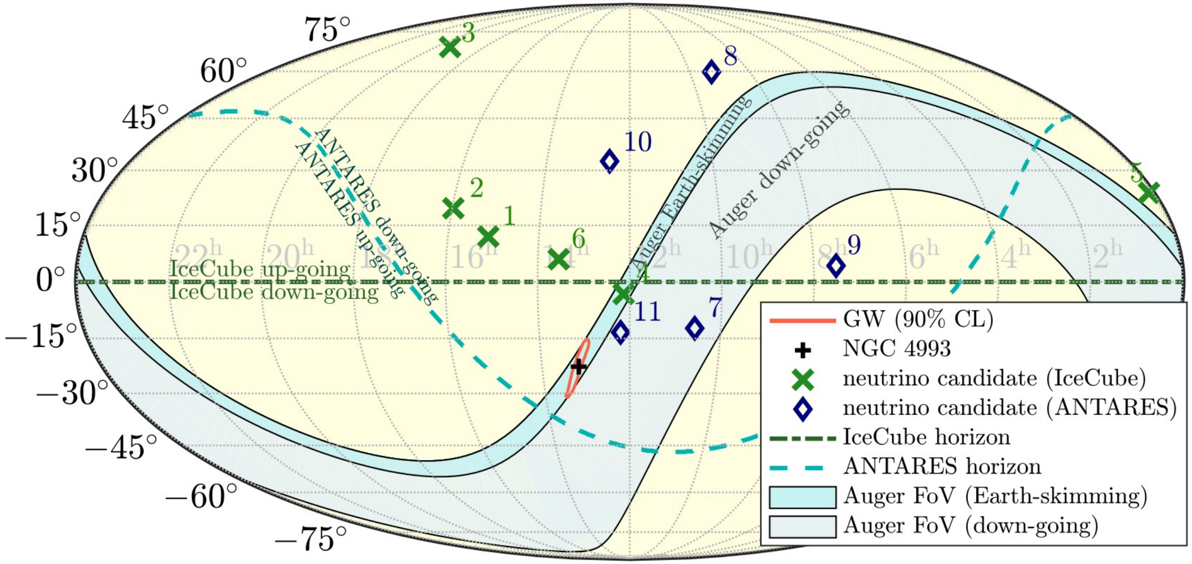
Probability distribution function, *e.g.*, $\mathcal{P}_{i,{\rm ast}} = \dfrac{dN_i/dE_{\rm dep}}{\int dE_{\rm dep} dN_i/dE_{\rm dep}}$

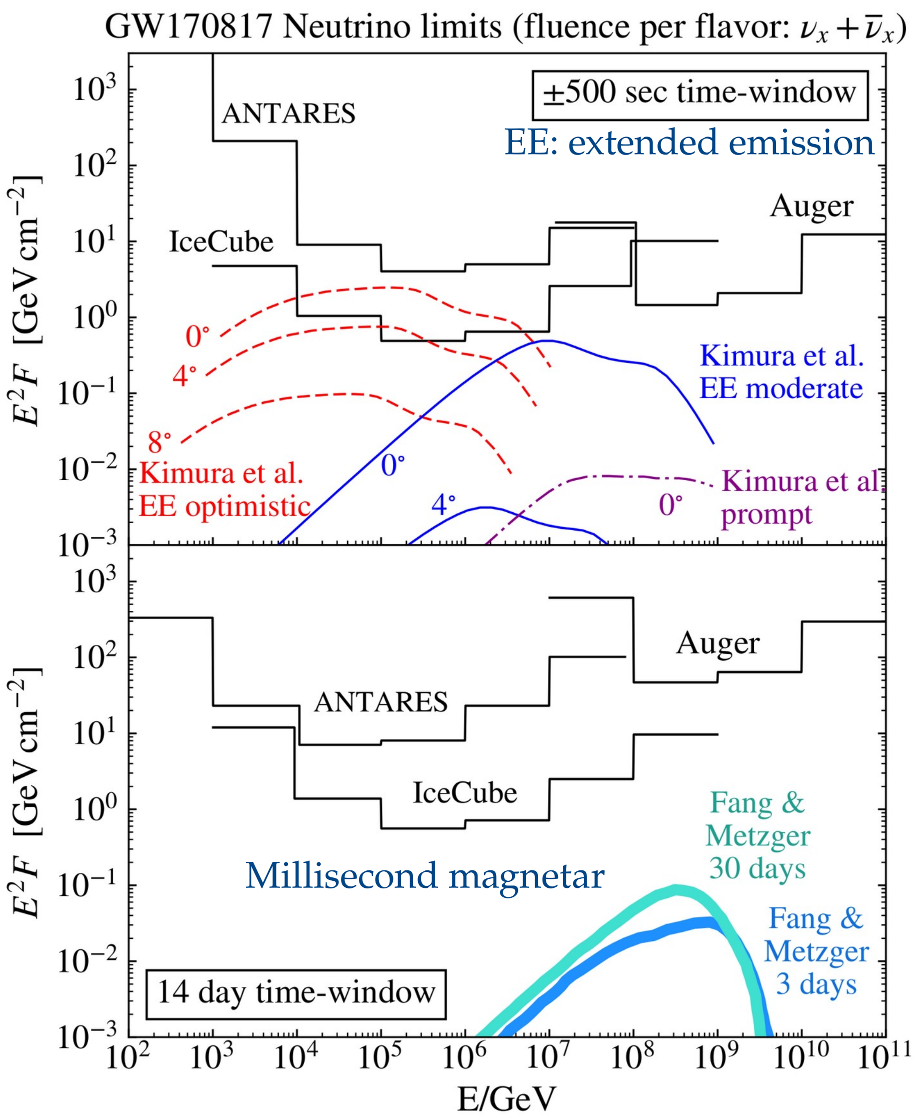


- We use priors informed by IceCube analyses when possible
- No statistically significant evidence for synchrotron-loss features (Bayes factor ~ 2)

GW170817 (NS-NS merger)

- Short GRB seen in *Fermi*-GBM, INTEGRAL
- Neutrino search by IceCube, ANTARES, and Auger
- MeV–EeV neutrinos, 14-day window
- Non-detection consistent with off-axis





ANTARES, IceCube, Pierre Auger Collab., *ApJL* 2017

Are GRBs still good UHECR source candidates?

- High-luminosity bursts: Not so much
- Low-luminosity bursts: Yes!

	HL GRBs	LL GRBs
Luminosity (erg s^{-1})	> 10^{49}	< 10^{49}
Rate (Gpc^{-3} yr^{-1})	1	300 (predicted)
Survival of heavy nuclei in jet?	Unlikely	Likely
Can explain IceCube ν?	No	Yes

D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

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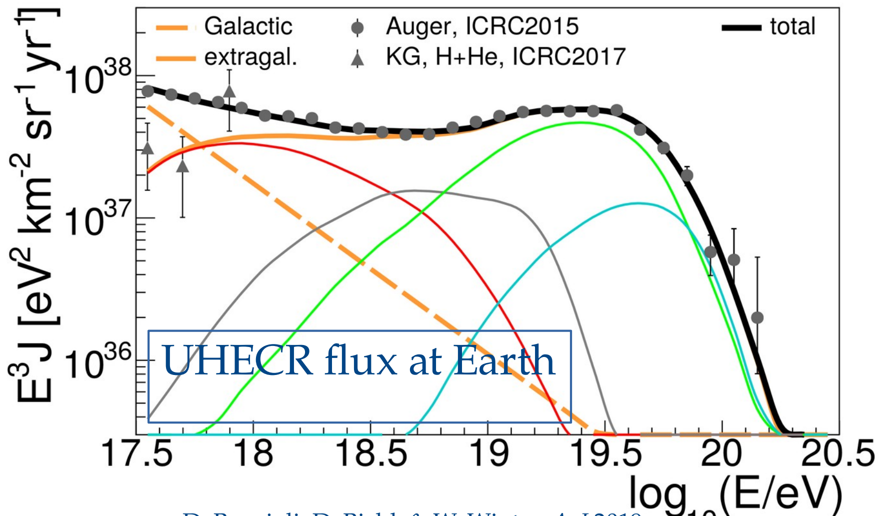

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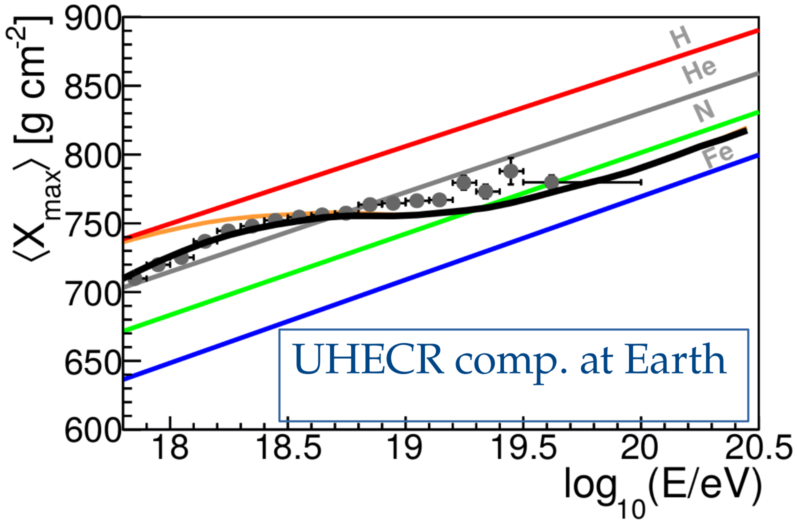

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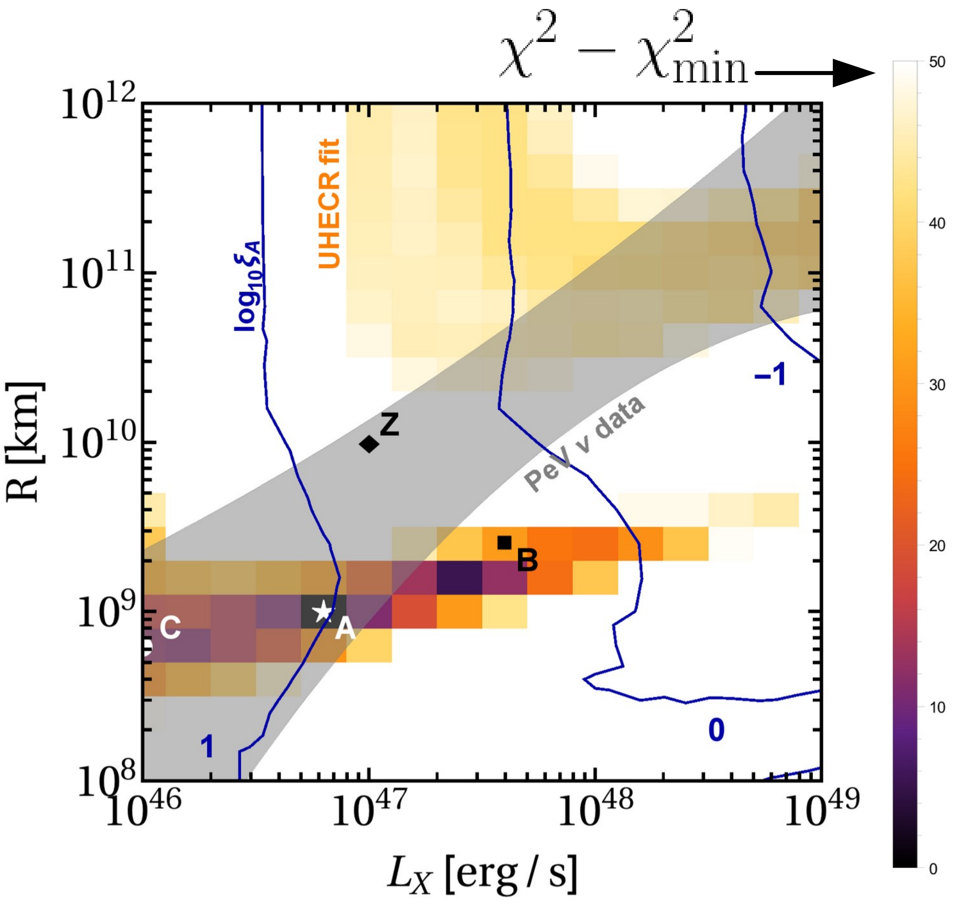
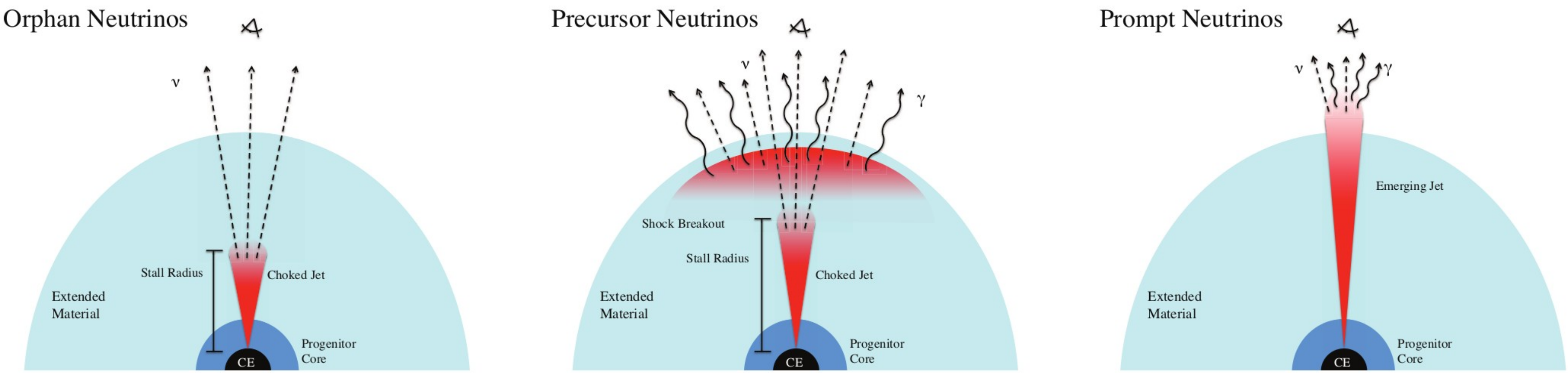


D. Boncioli, D. Biehl, & W. Winter, *ApJ* 2019; B.T. Zhang *et al.*, *PRD* 2018

Low-luminosity and dark GRBs

In jetted supernovae, the jet might be choked —



N. Senno, K. Murase, & P. Meszaros, *PRD* 2016

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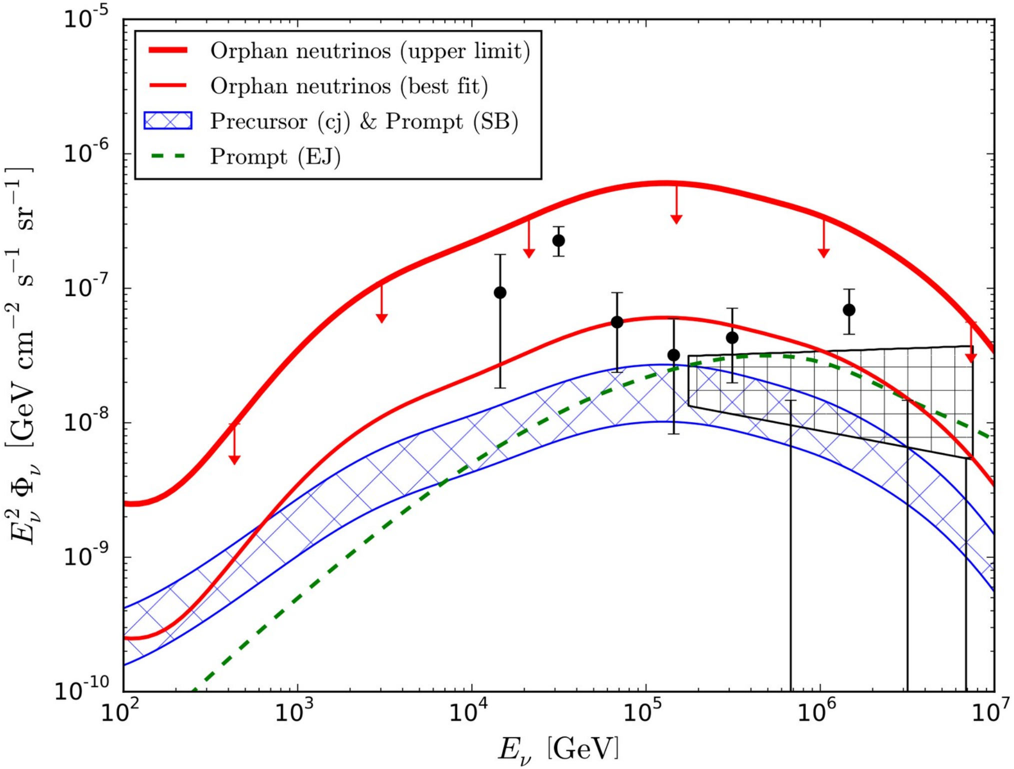

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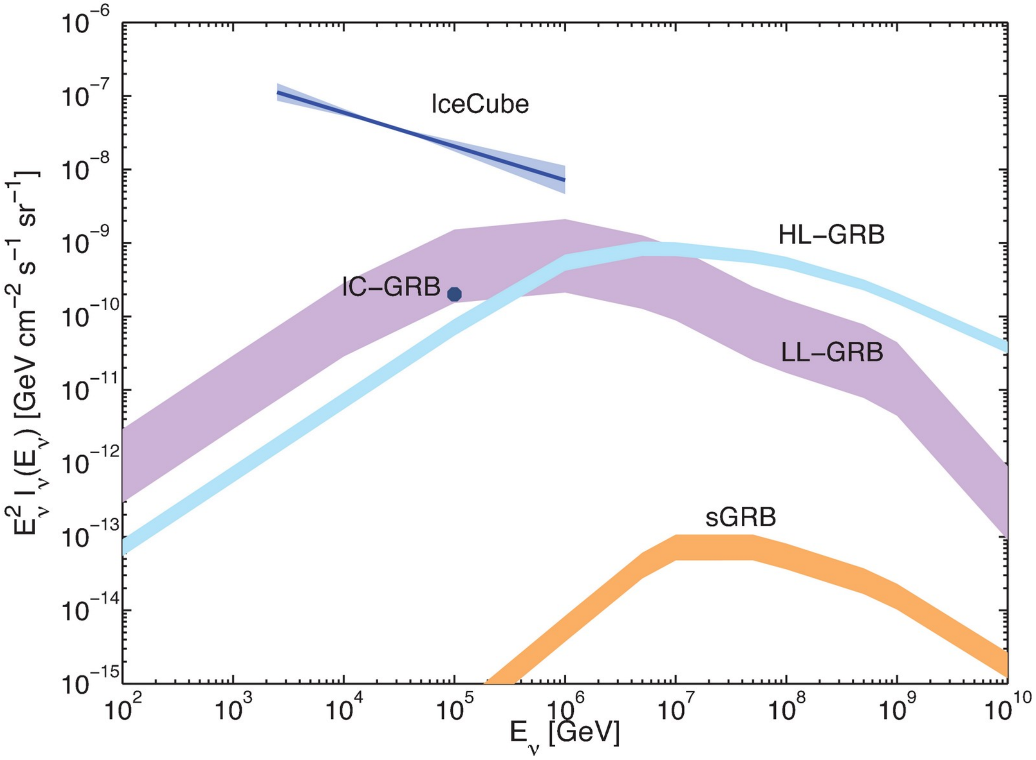
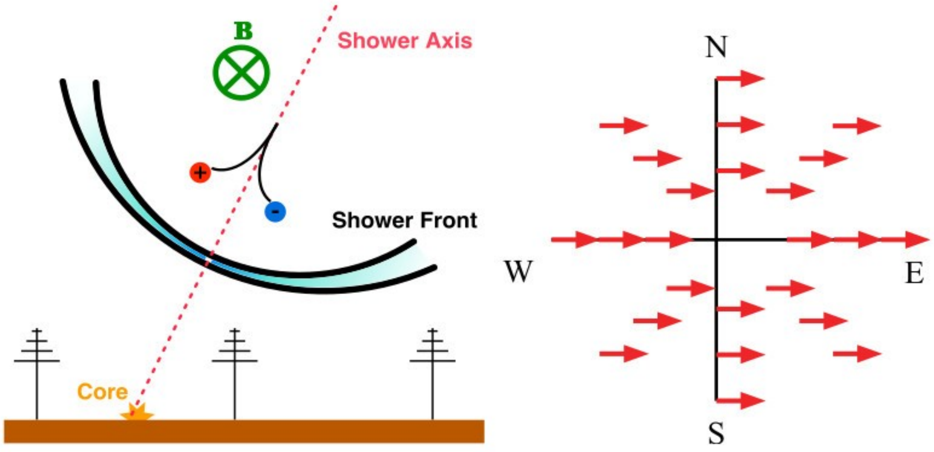


I. Tamborra & S. Ando, *JCAP* 2015

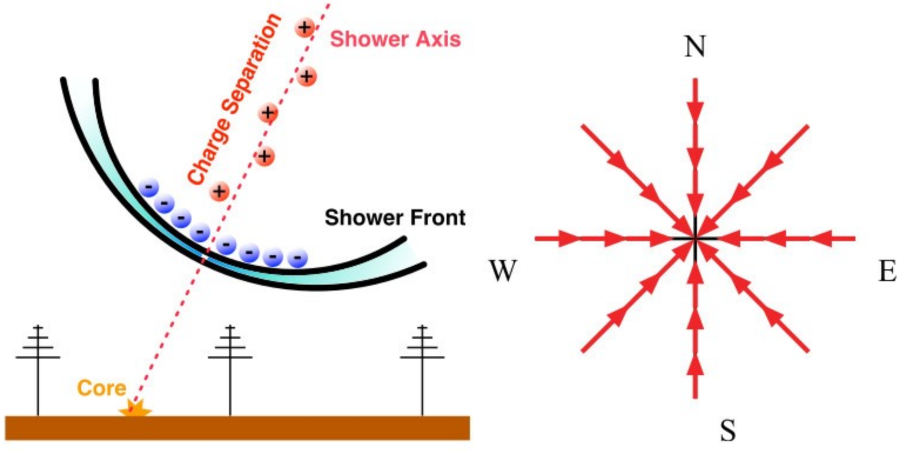
Radio emission: geomagnetic and Askaryan

Geomagnetic



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

Askaryan



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

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

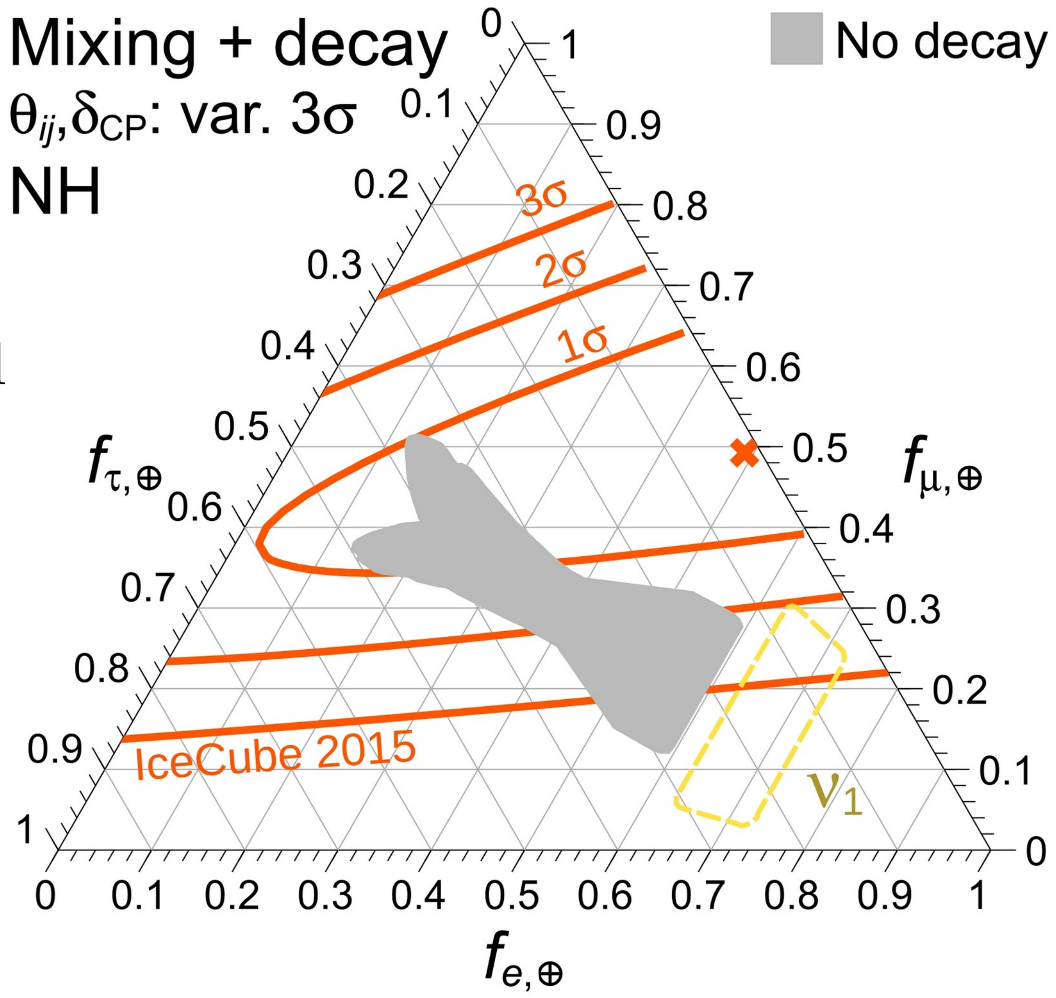
Radio emission: geomagnetic and Askaryan

Measuring the neutrino lifetime

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- Any value of mixing parameters; and
- Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)



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

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Fraction of ν_2, ν_3 remaining at Earth

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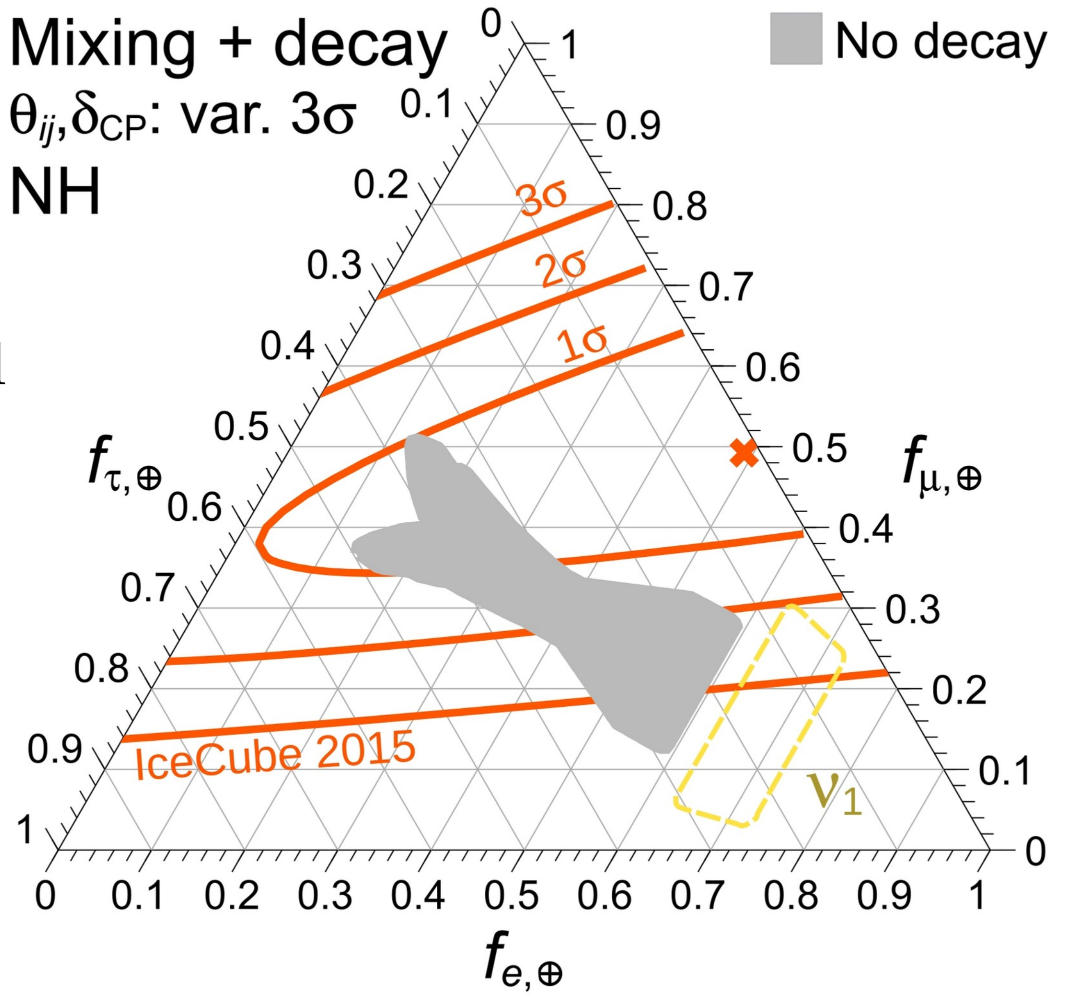

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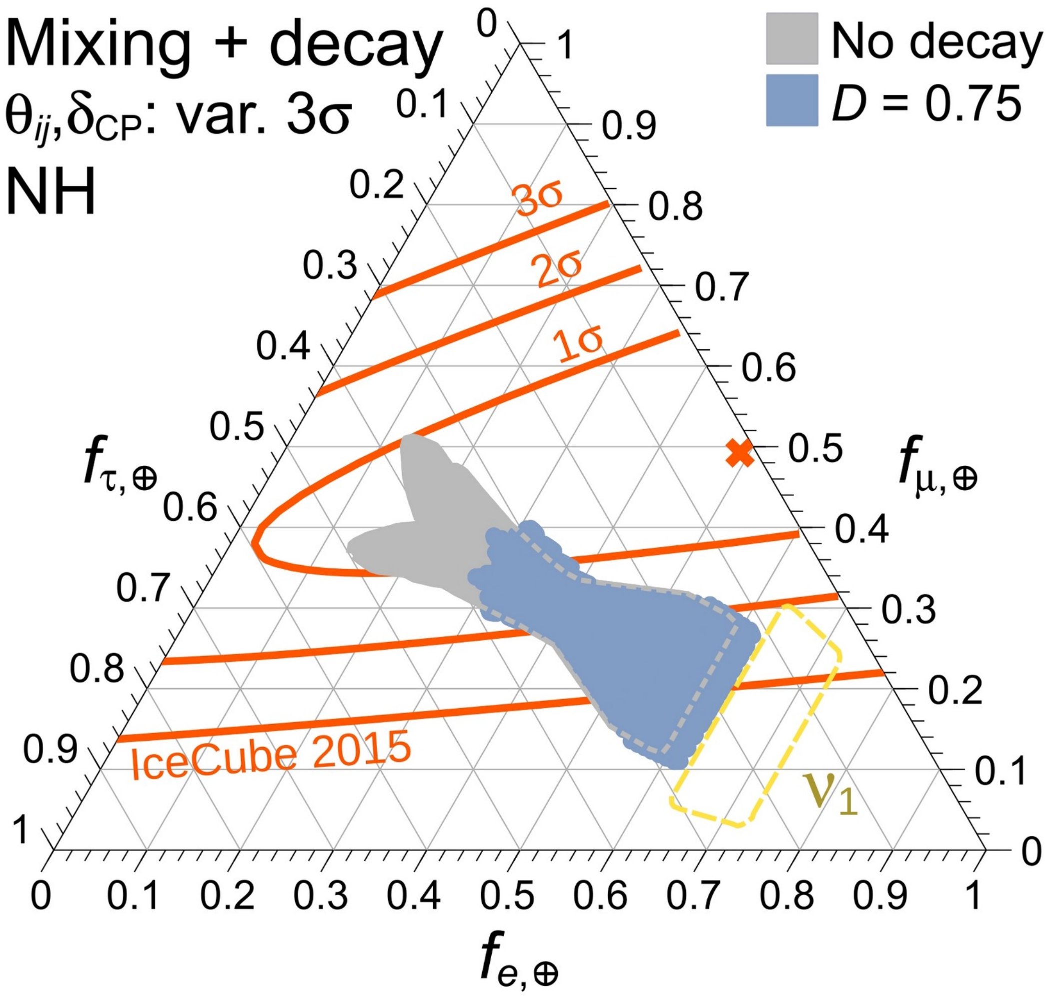

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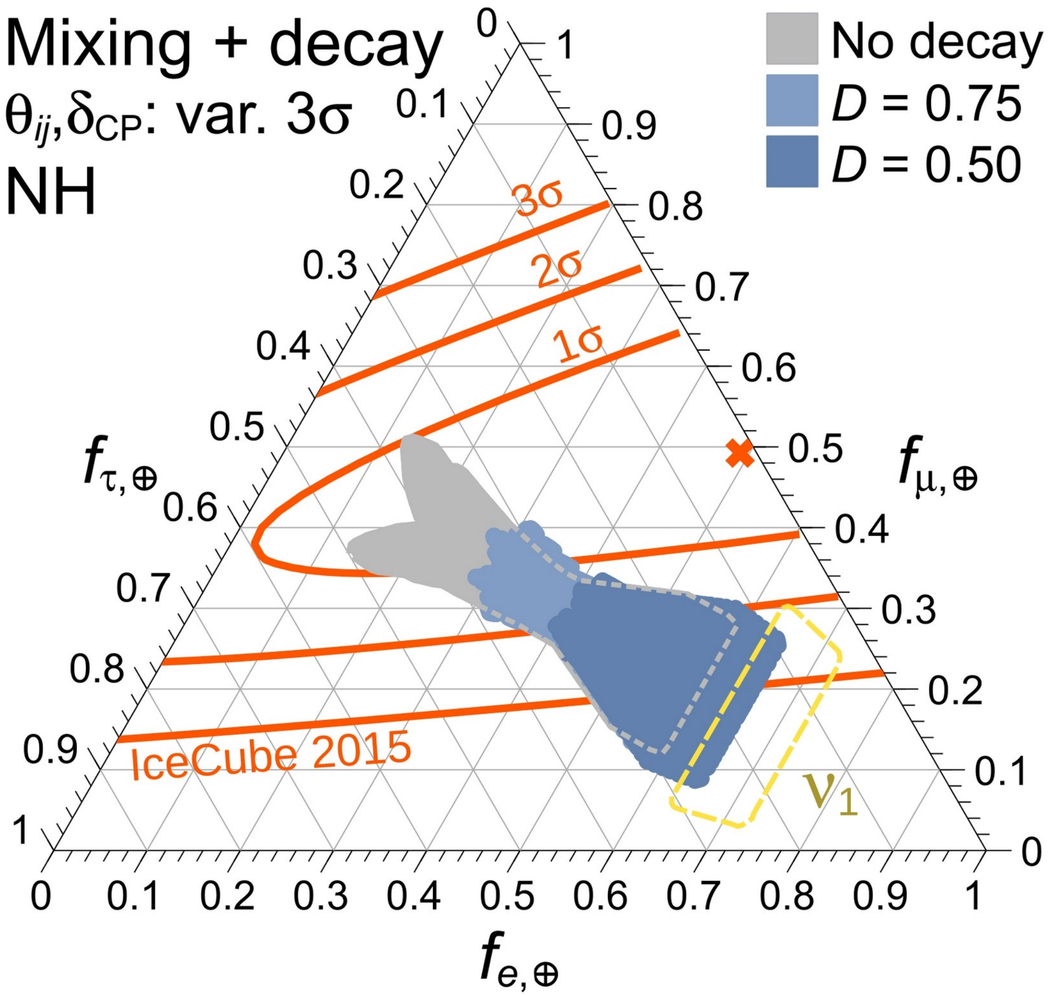

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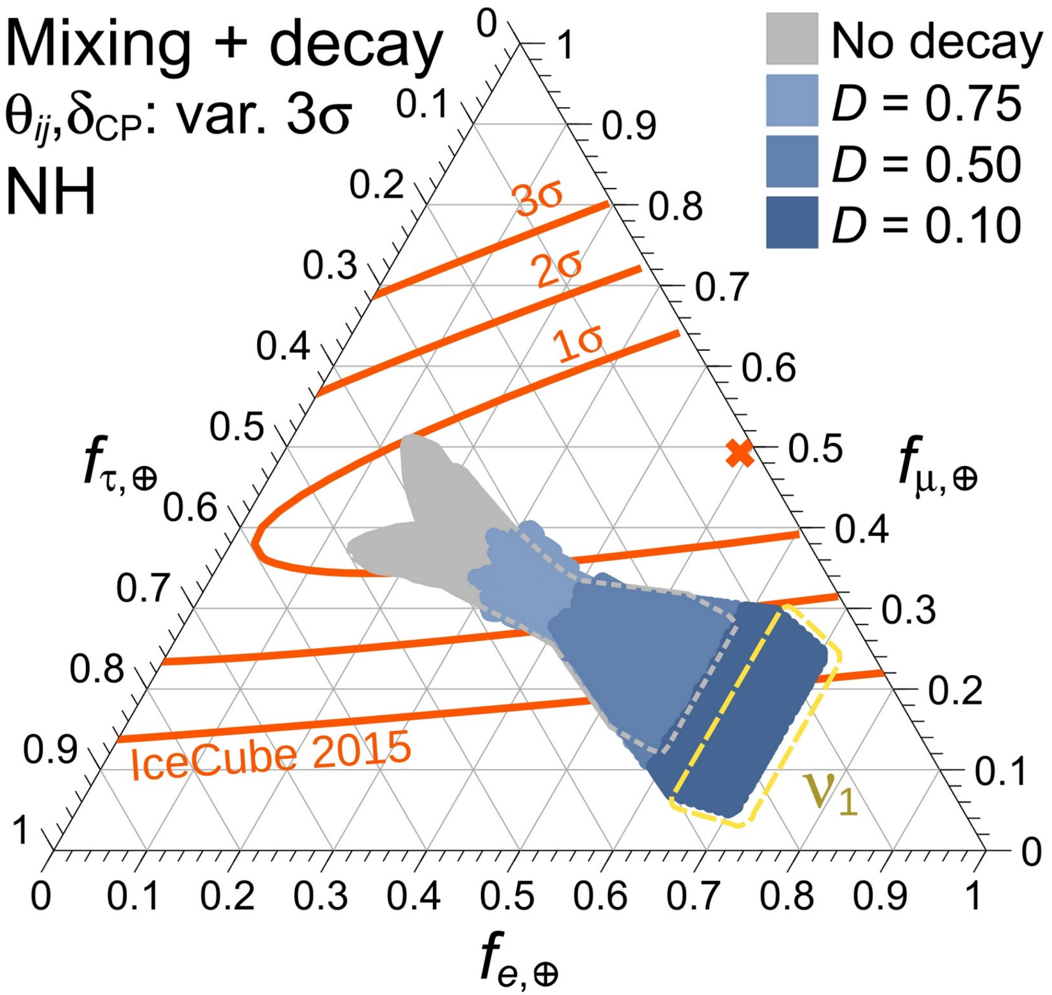

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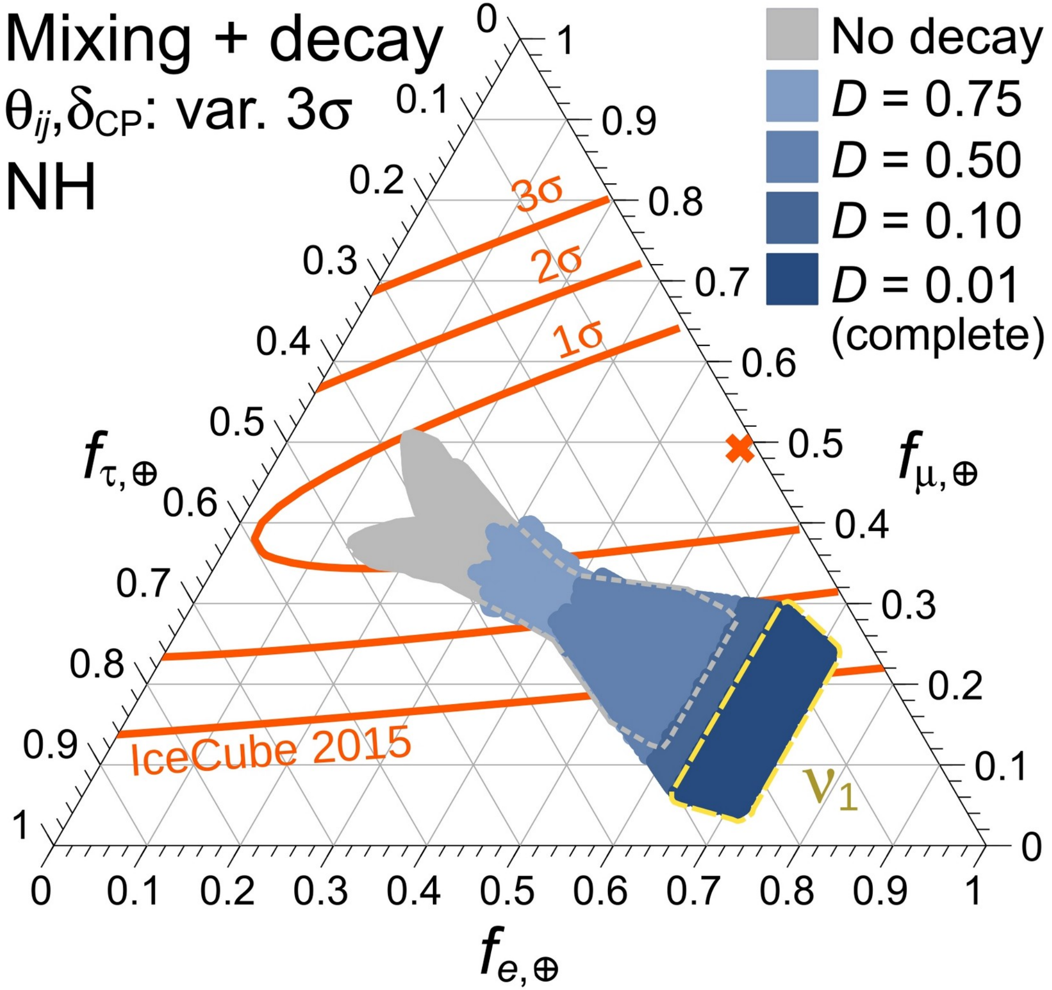

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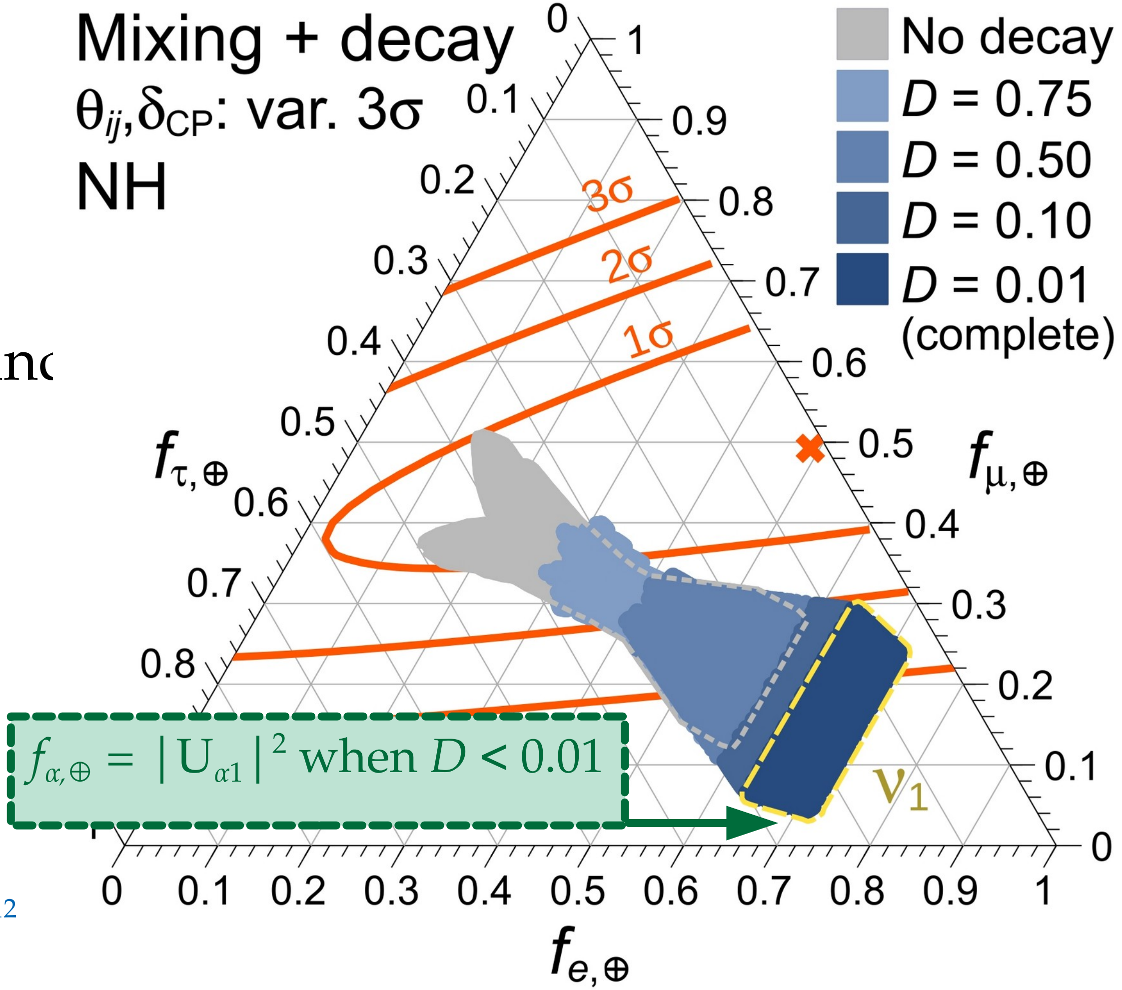
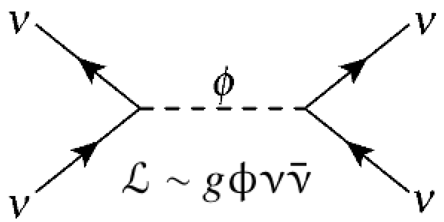


MB, Beacom, Murase, *PRD* 2017
Baerwald, **MB**, Winter, *JCAP* 2012

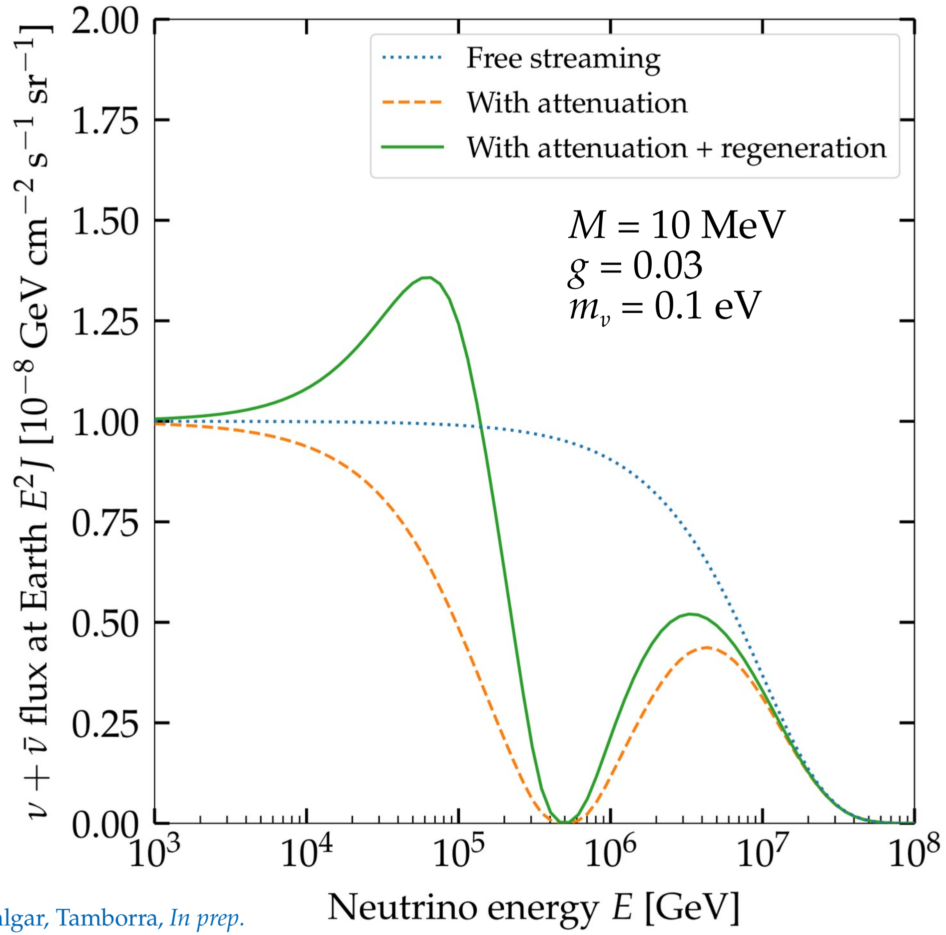
New physics in the spectral shape: νν interactions

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



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

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



MB, Rosenstroem, Shalgar, Tamborra, *In prep.*
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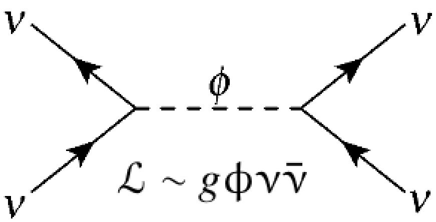

New coupling

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Mediator mass

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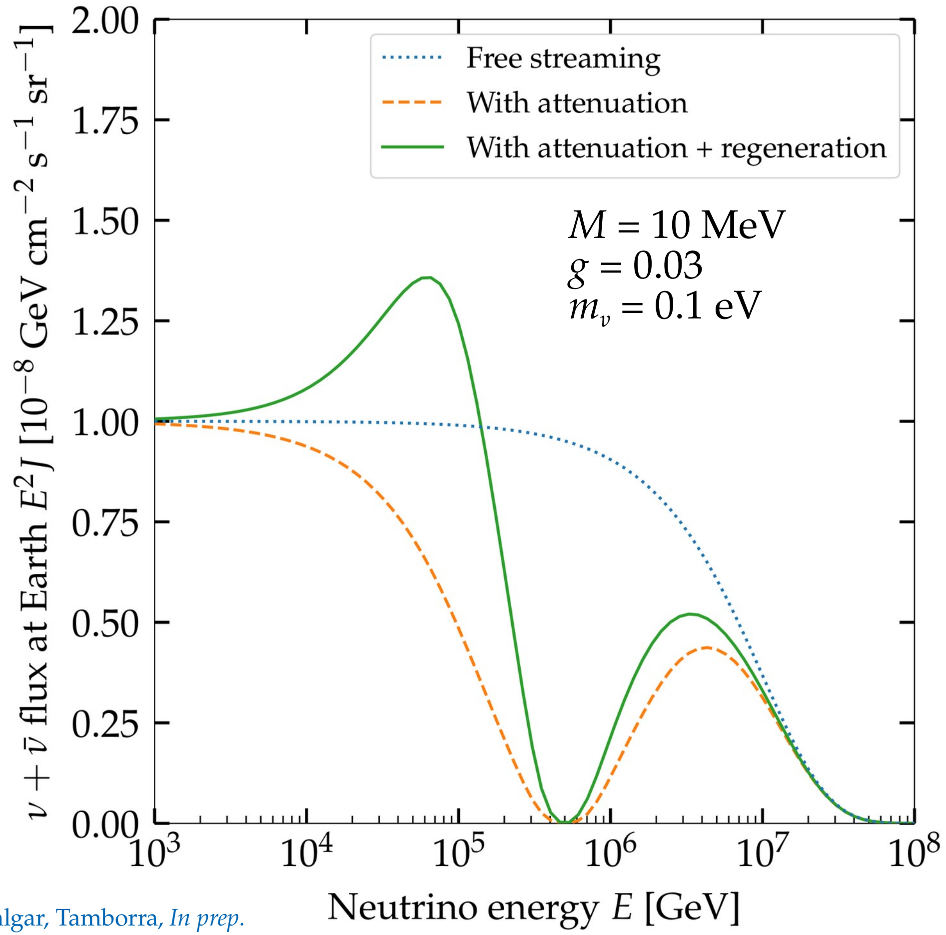

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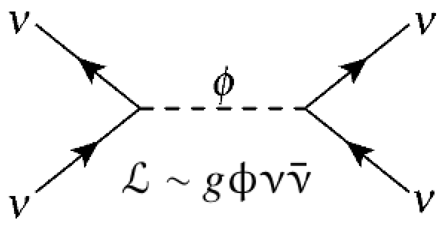

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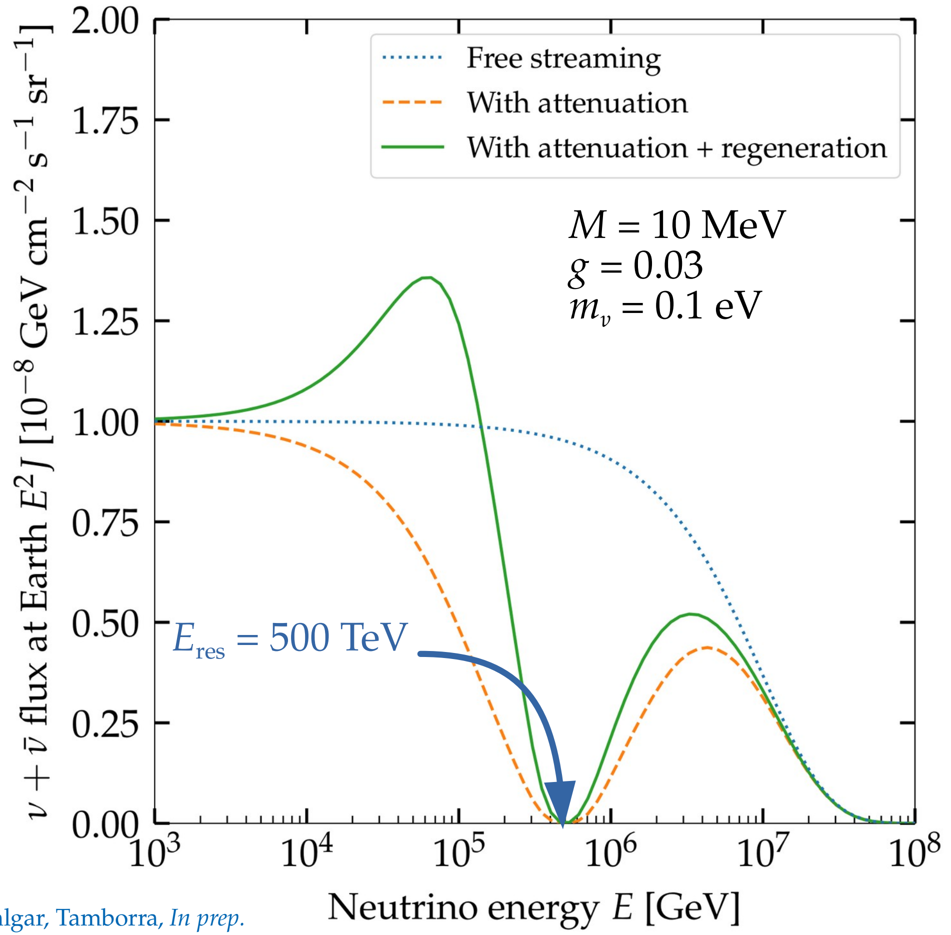

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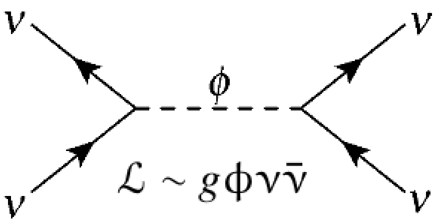

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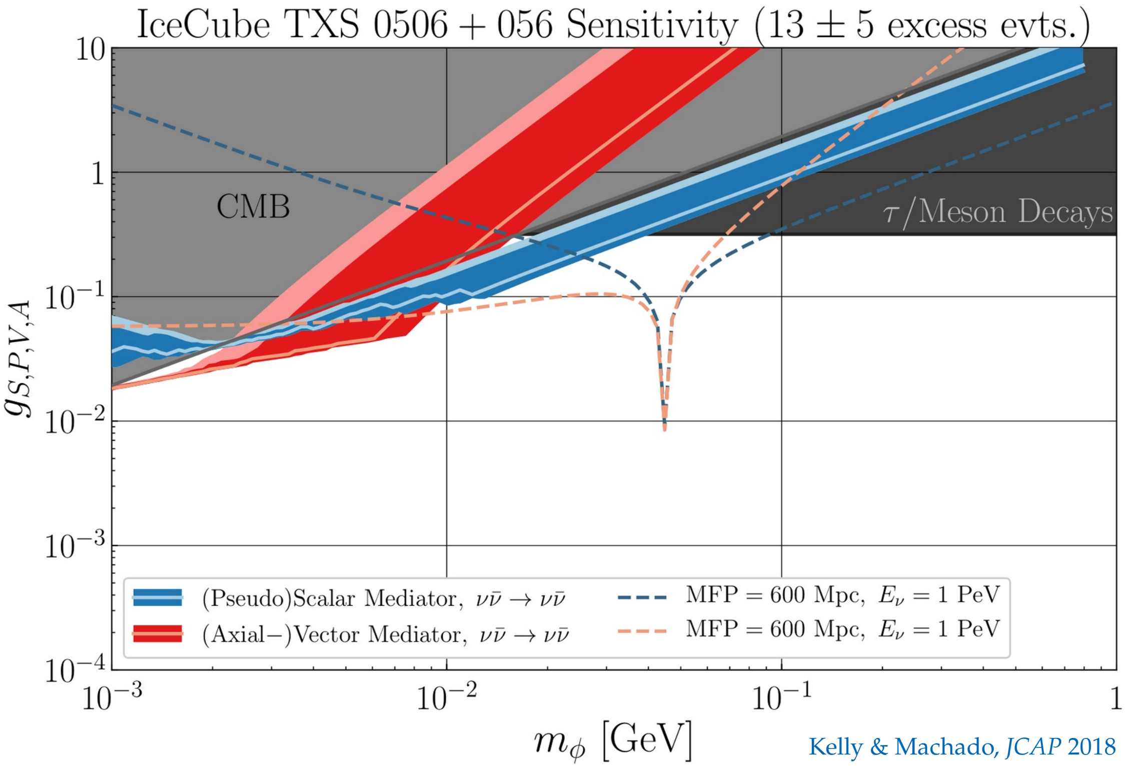
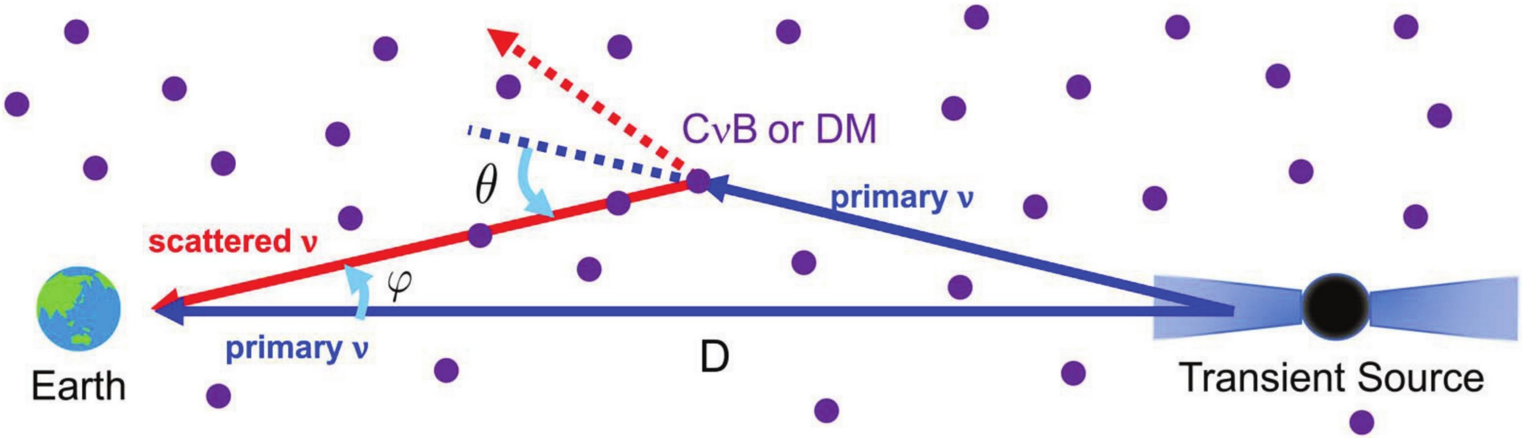


Kelly & Machado, *JCAP* 2018

Delays from secret interactions

Multiple secret νν scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, *PRL* 2019

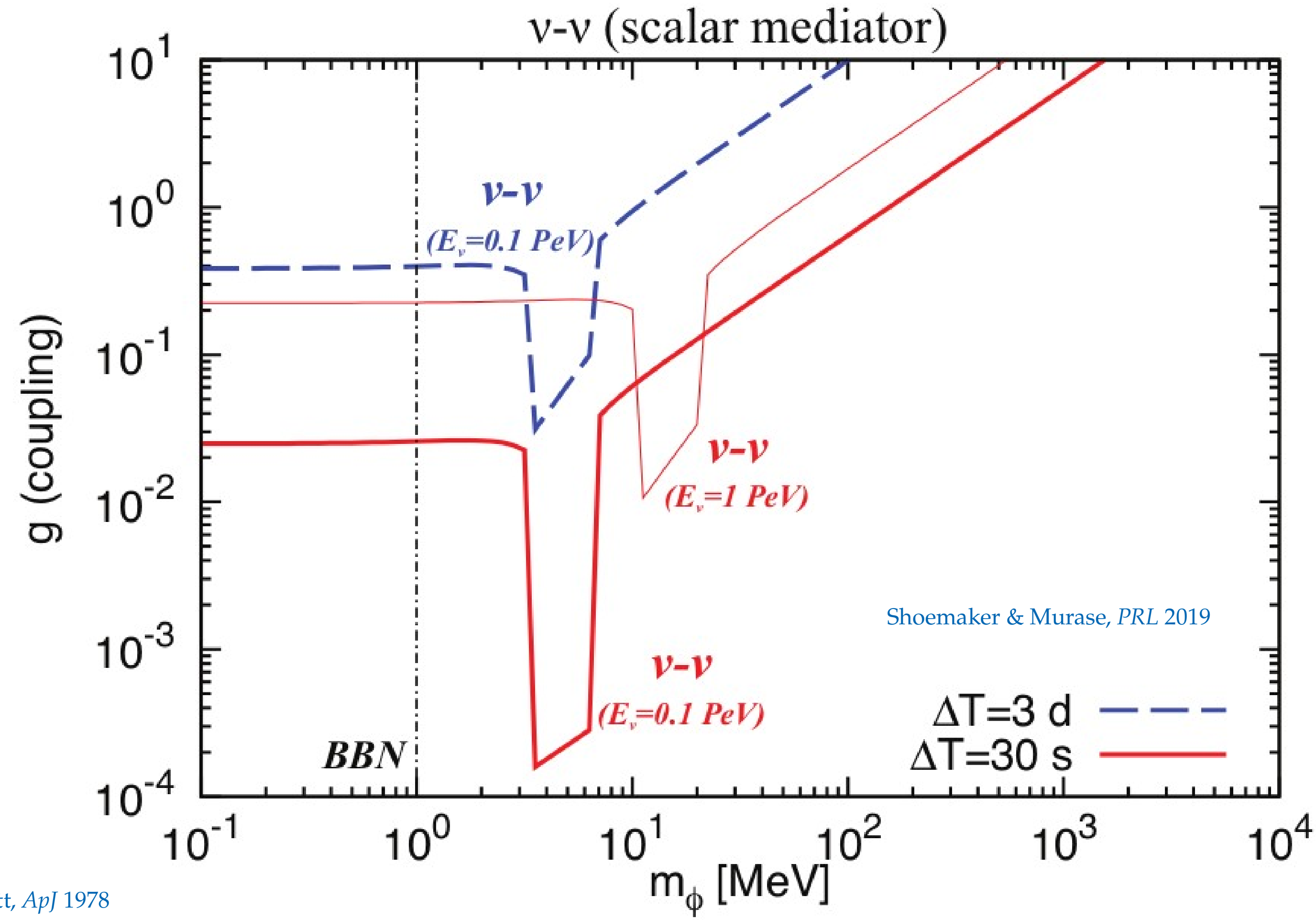
Characteristic time delay —

Optical depth to νν: $\tau_{\nu\nu} = n_\nu \sigma_{\nu\nu} D$

$$\Delta t \approx 1500\,\mathrm{s} \left(\frac{\tau_{\nu\nu}}{30}\right) \left(\frac{D}{3\ \mathrm{Gpc}}\right) \left(\frac{m_\nu}{0.1\ \mathrm{eV}}\right) \left(\frac{0.1\ \mathrm{PeV}}{E_\nu}\right)$$

See also: Alcock & Hatchett, *ApJ* 1978

Delays from secret interactions



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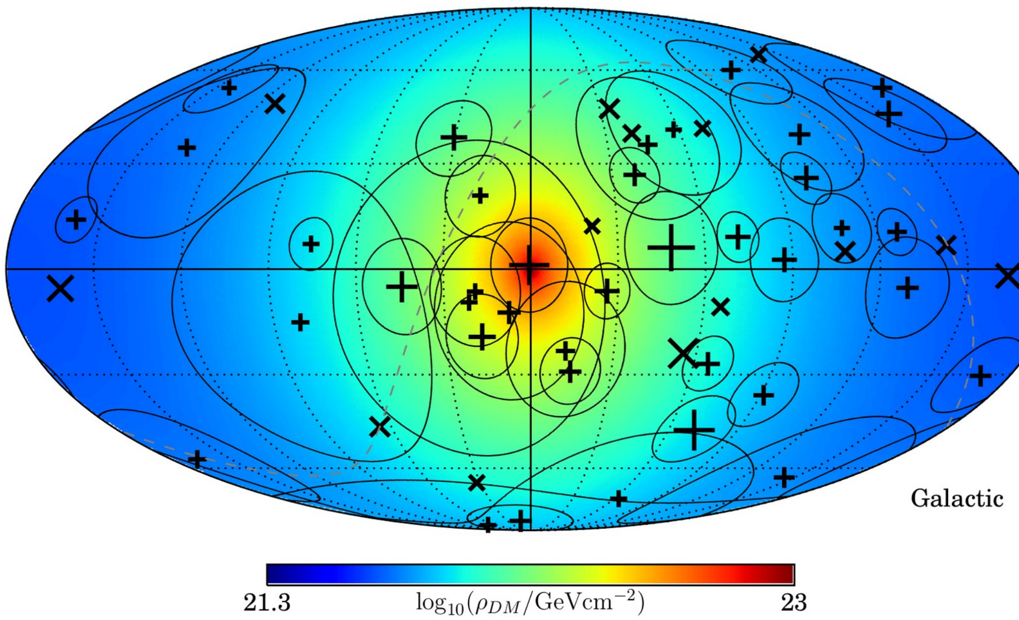
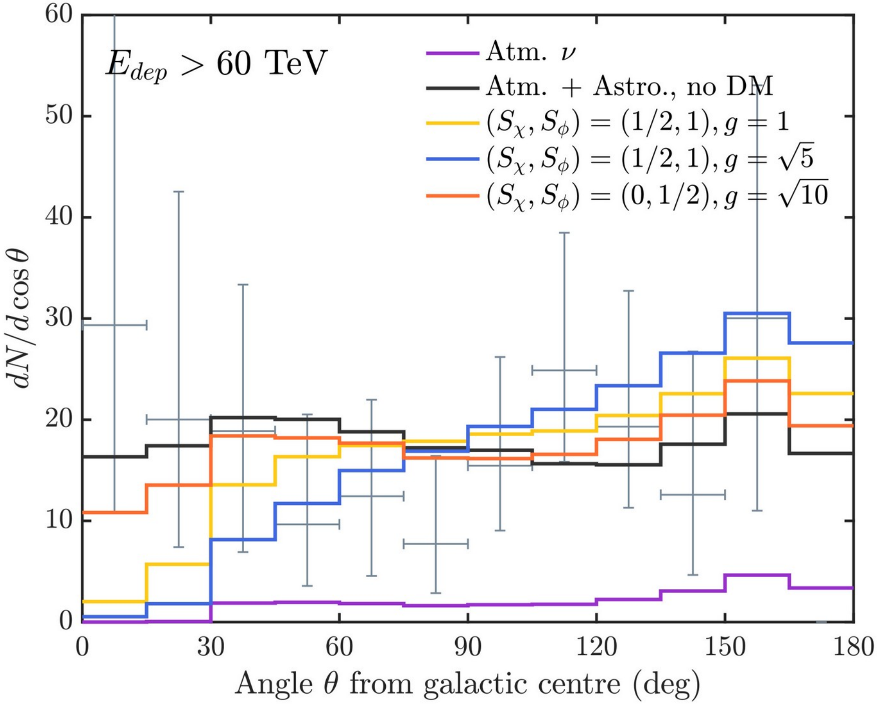
New physics in the angular distribution: ν-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile –





Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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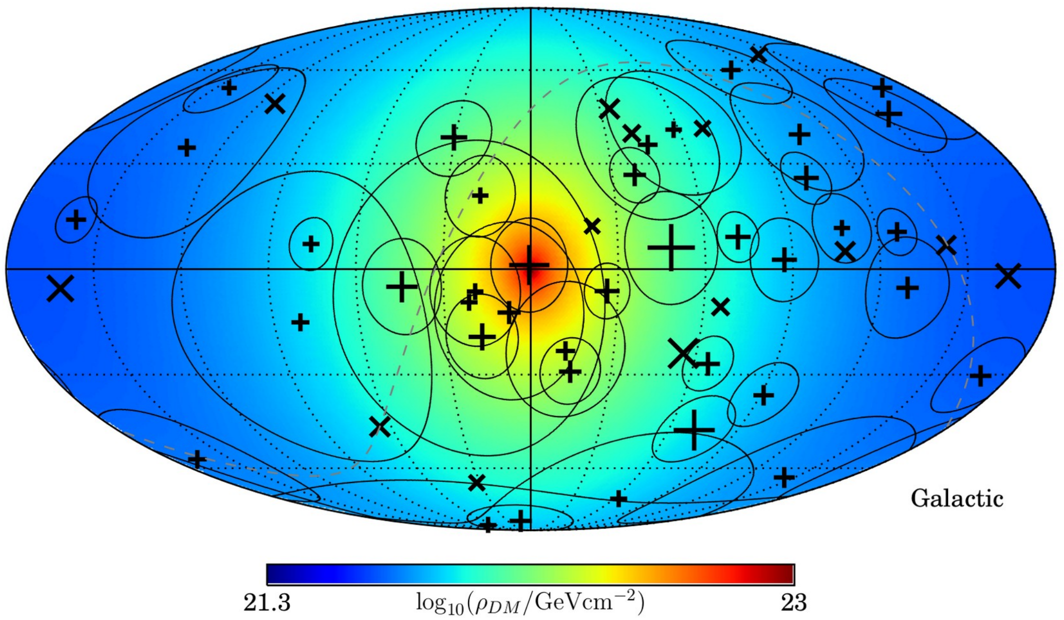

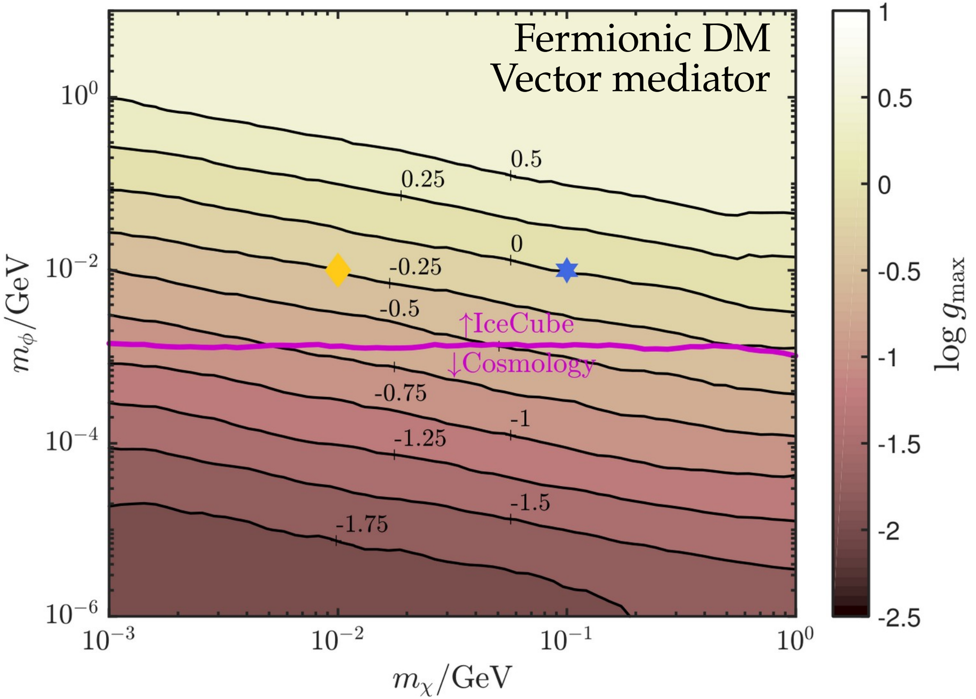

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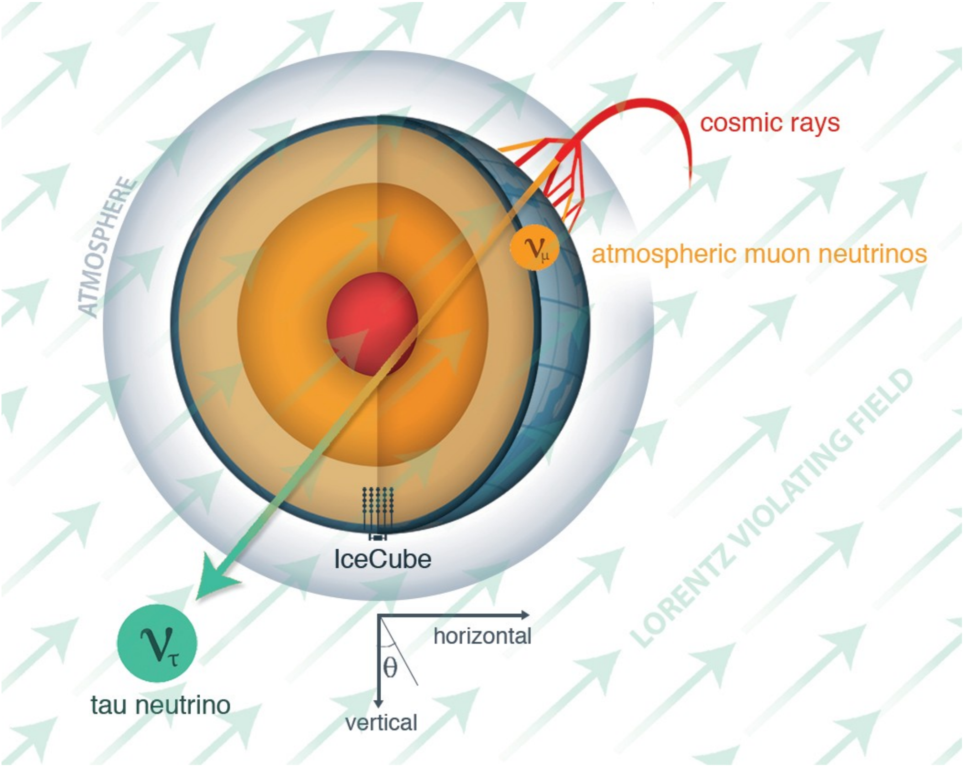
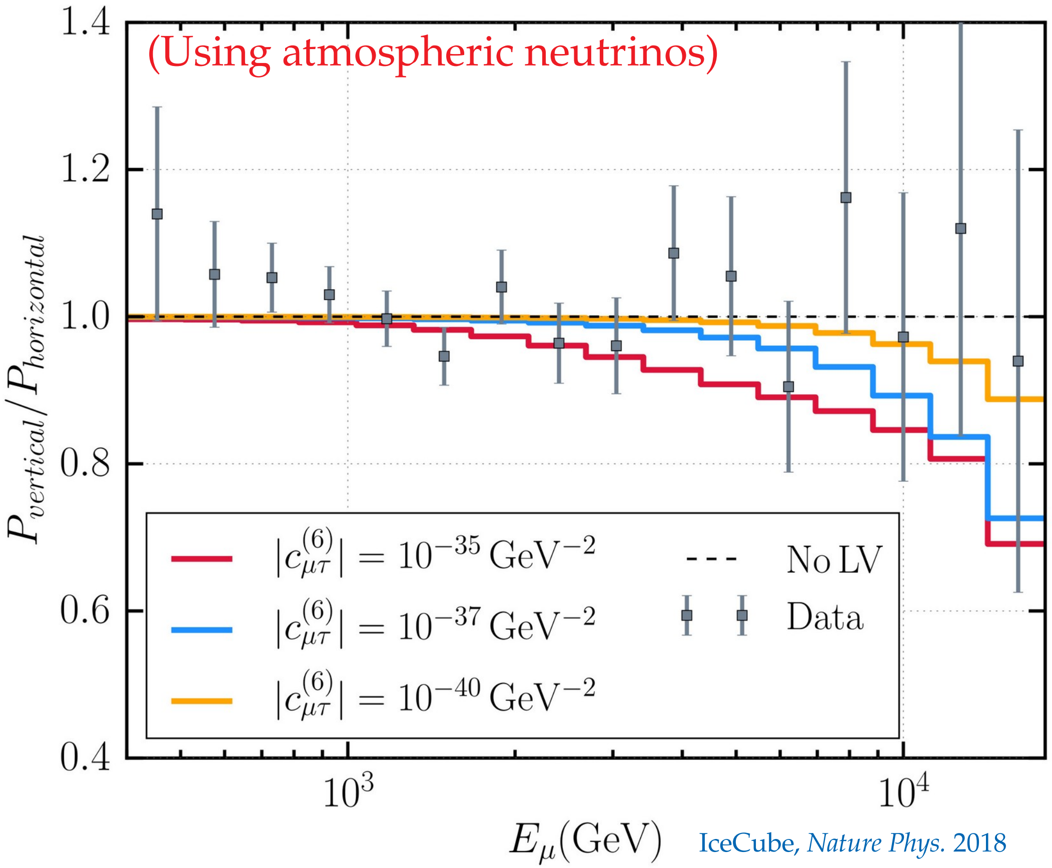
New physics in the energy & angular distribution

Lorentz invariance violation – Hamiltonian: $H \sim m^2/(2E) + a^{(3)} - E \cdot c^{(4)} + E^2 \cdot a^{(5)} - E^3 \cdot c^{(6)}$





IceCube, *Nature Phys.* 2018

New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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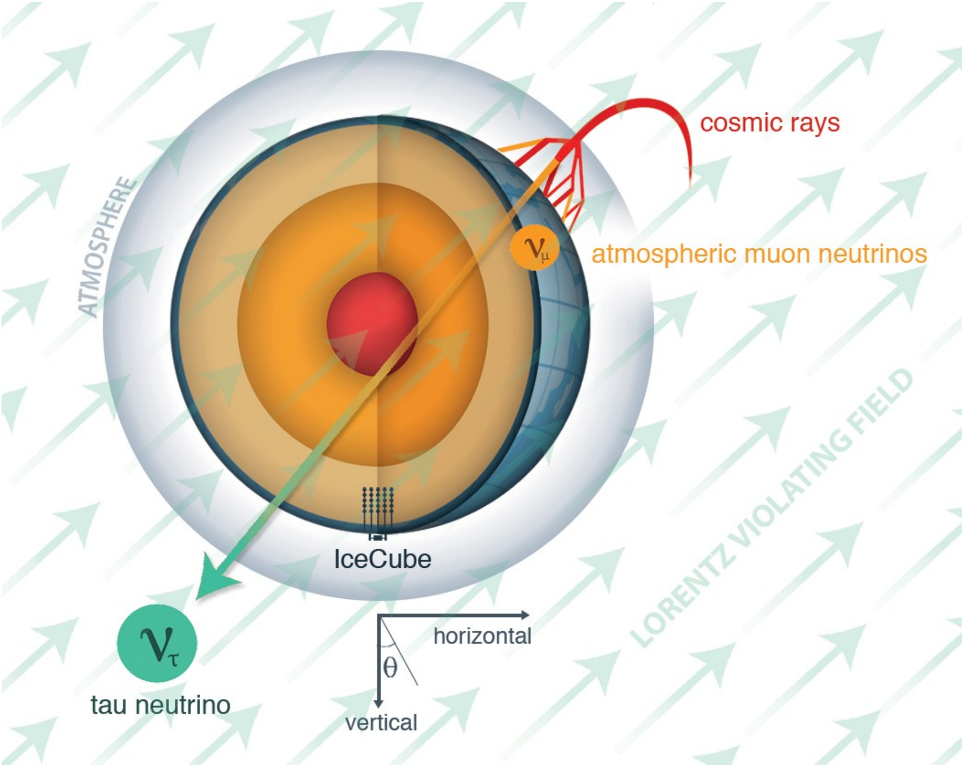

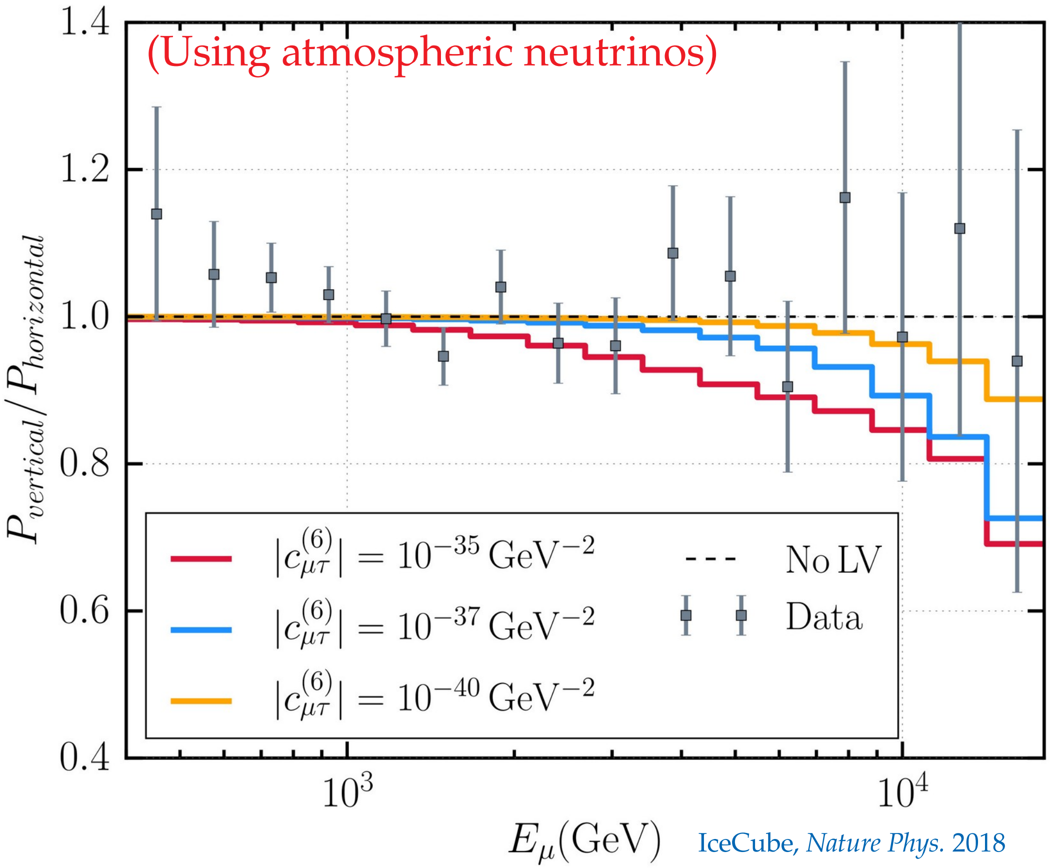

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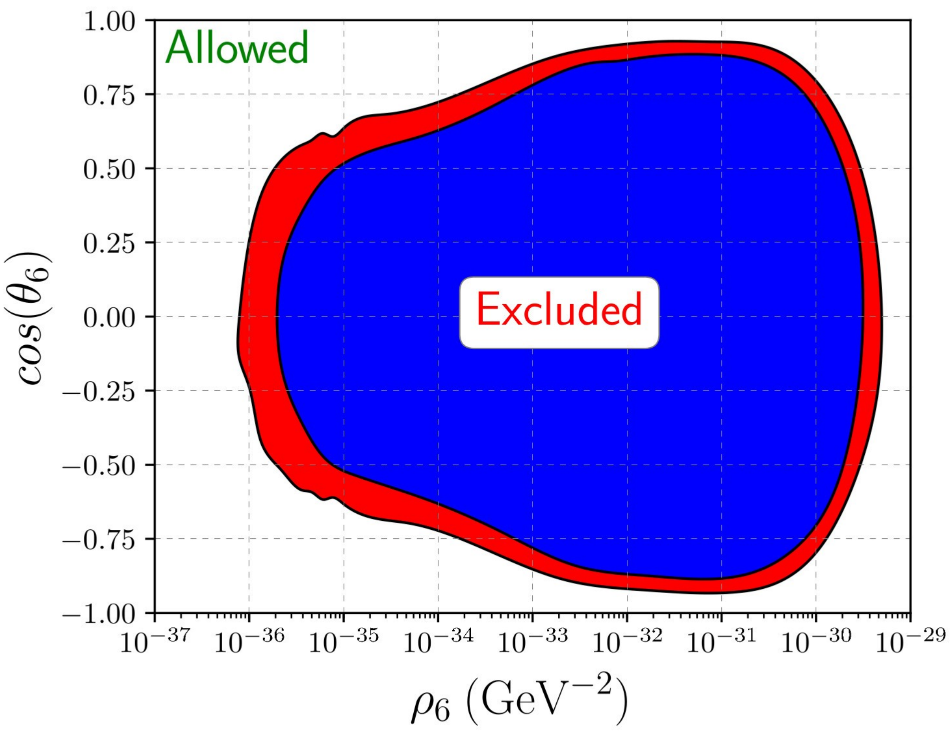
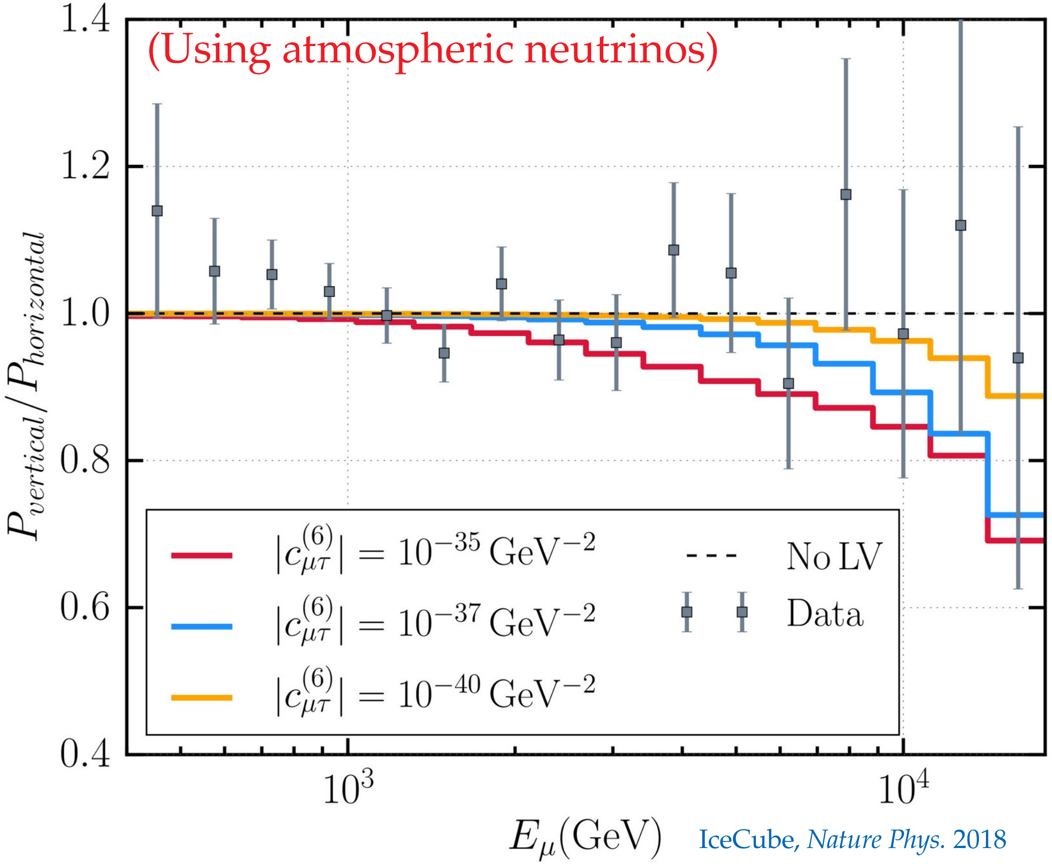
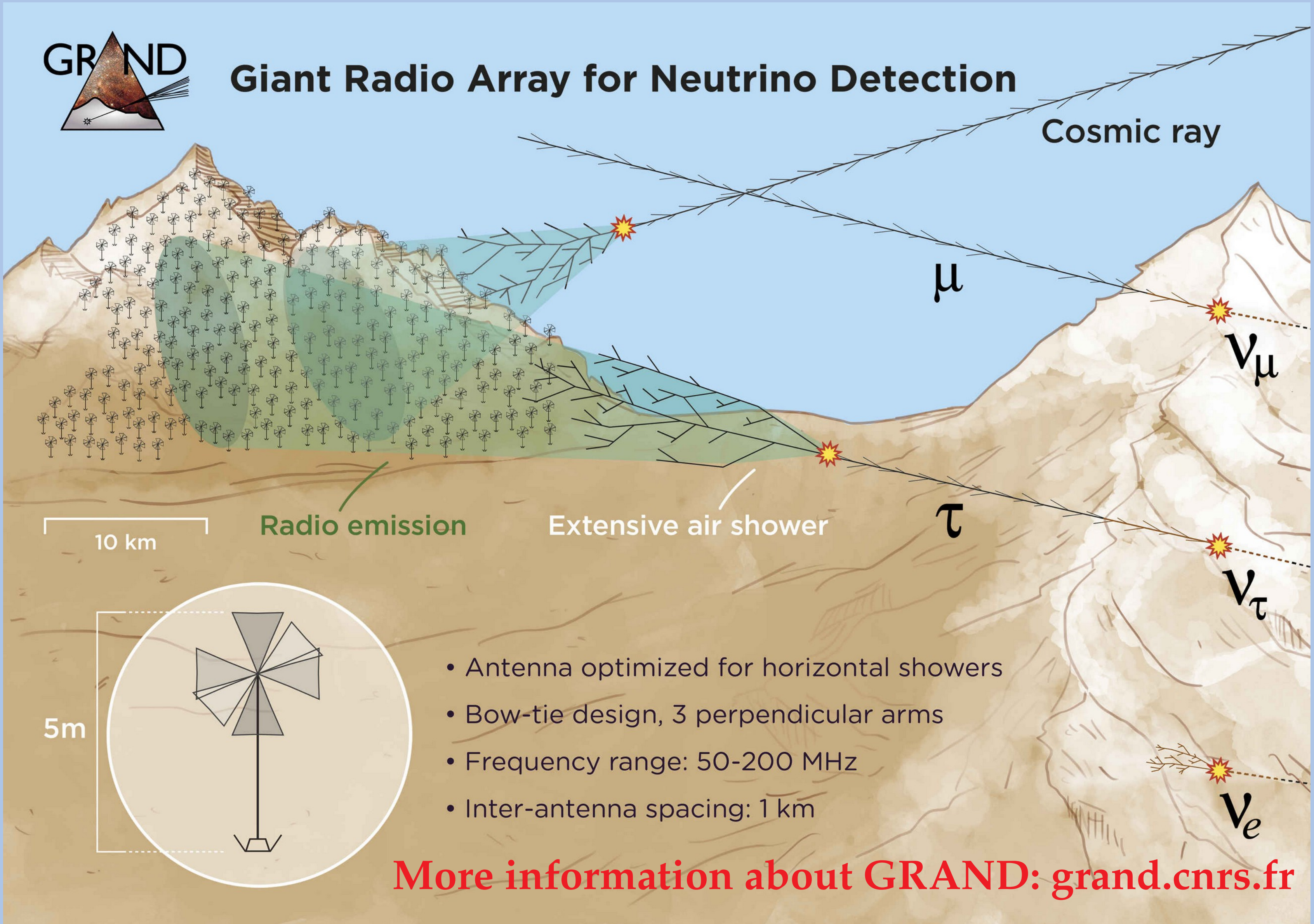
Best bounds come from IceCube





IceCube, *Nature Phys.* 2018

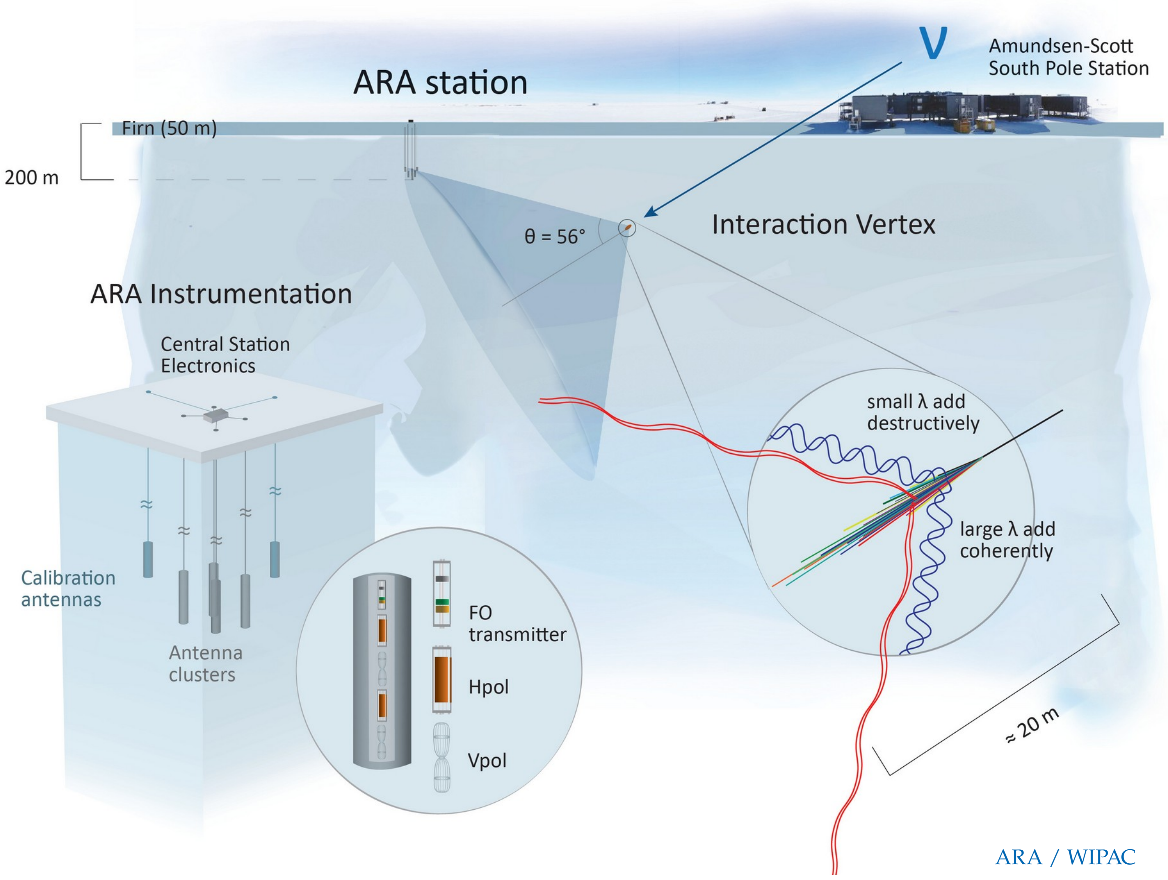

GRAND
Giant Radio Array for Neutrino Detection
Cosmic ray
μ
ν_μ
τ
ν_τ
ν_e
10 km
Radio emission
Extensive air shower
5m
• Antenna optimized for horizontal showers
• Bow-tie design, 3 perpendicular arms
• Frequency range: 50-200 MHz
• Inter-antenna spacing: 1 km
More information about GRAND: grand.cnrs.fr

Radio-detection of UHE neutrinos in ice

- Radio attenuation length in ice: few km (*vs.* 100 m for light)
- Larger monitored volume than IceCube
- ARA, ARIANNA: antennas buried in ice
- ANITA: antennas mounted on a balloon

No ν detected yet

(But UHECRs detected regularly!)



ARA / WIPAC

The TeV–PeV ν flavor composition

How to fill out the flavor triangle?

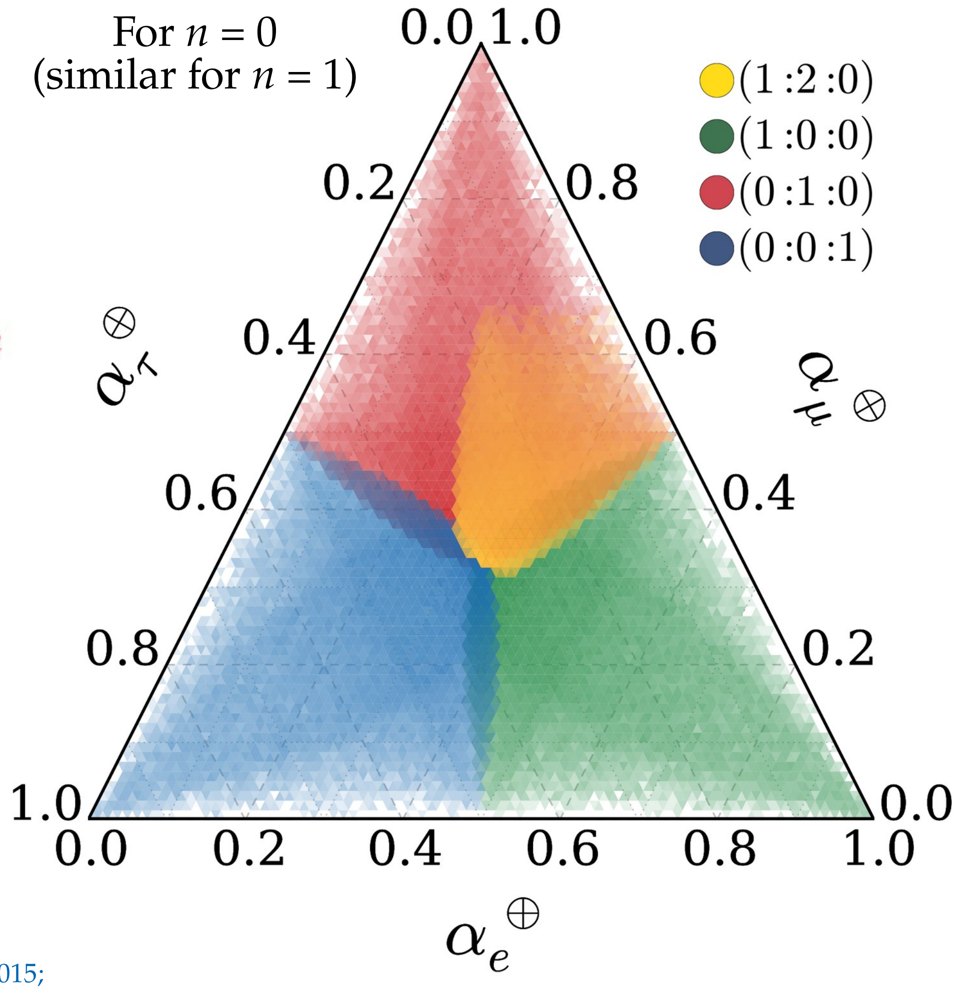
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

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

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

This can populate *all* of the triangle –

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



Argüelles, Katori, Salvadó, *PRL* 2015

See also: Ahlers, **MB**, Mu, *PRD* 2018; Rasmusen *et al.*, *PRD* 2017; **MB**, Beacom, Winter *PRL* 2015; **MB**, Gago, Peña-Garay *JCAP* 2010; Bazo, **MB**, Gago, Miranda *IJMPA* 2009; + many others

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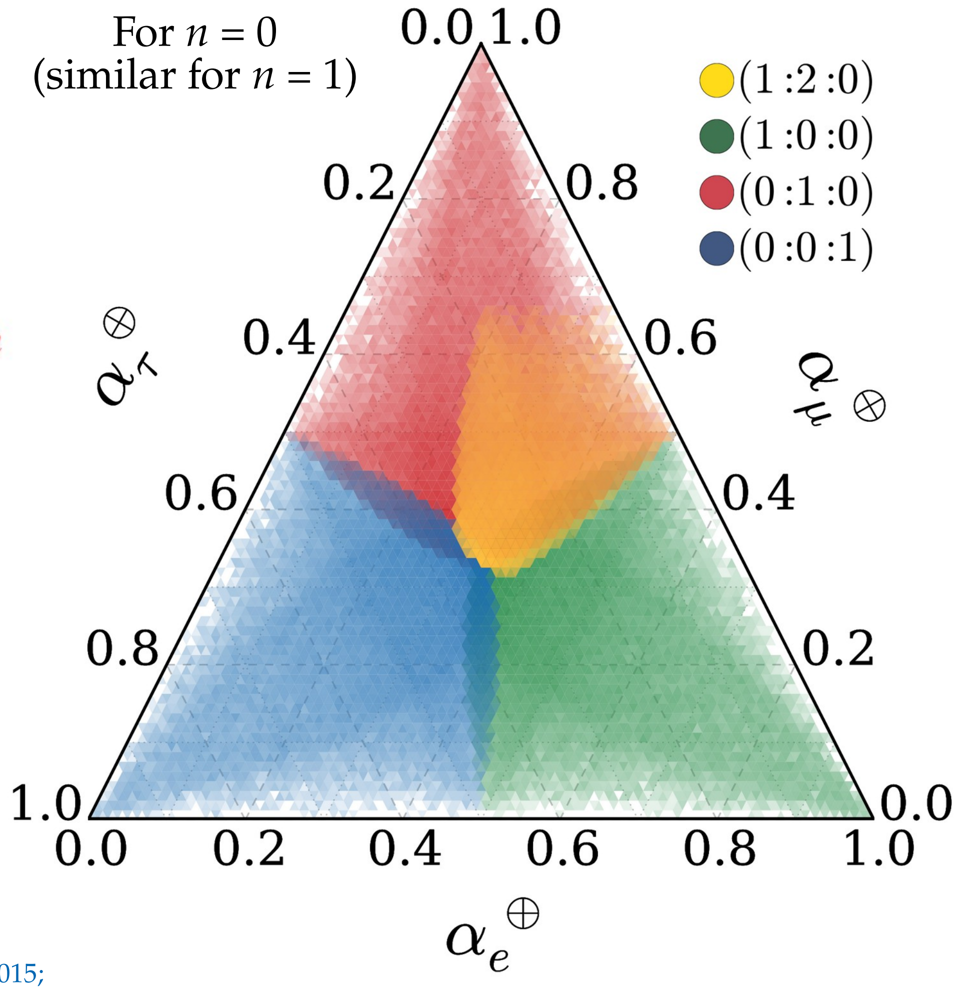

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Neutrino decay

Are neutrinos forever?

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

  } » Age of Universe (~ 14.5 Gyr)

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

- 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

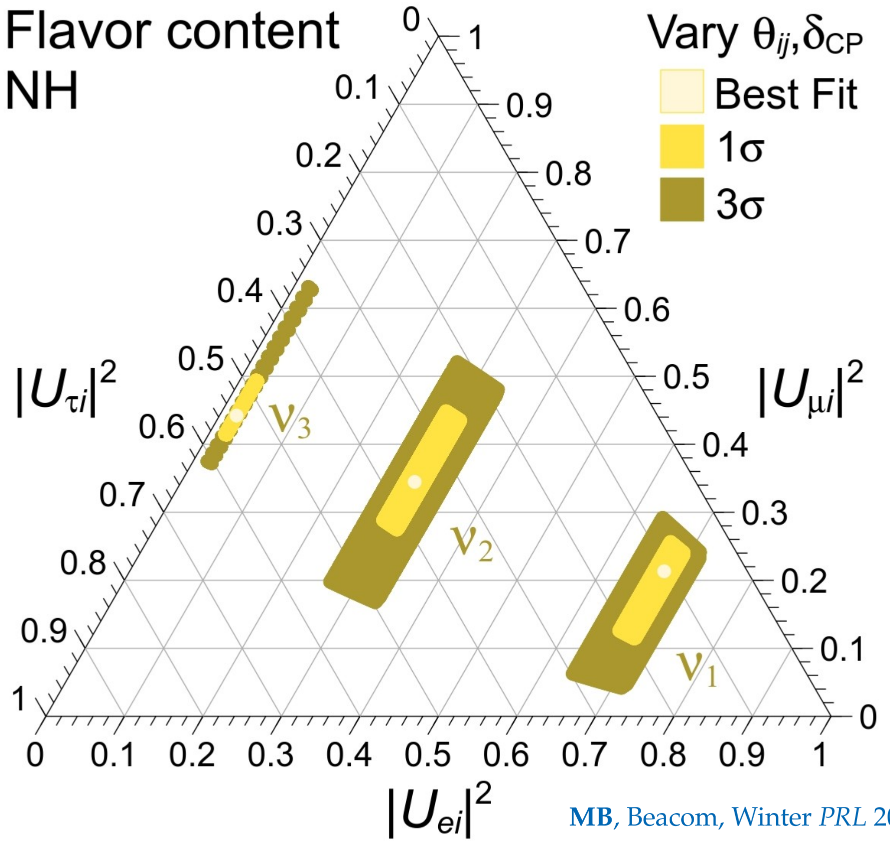
Flavor content of neutrino mass eigenstates

Known to within 2%

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

Known to within 8%

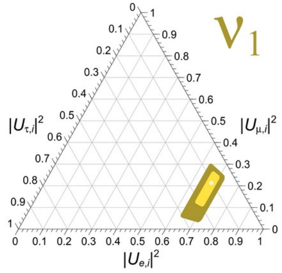
Known to within 20% (or worse)



MB, Beacom, Winter *PRL* 2015

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

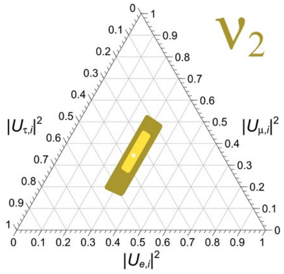
w_1 [



]

+

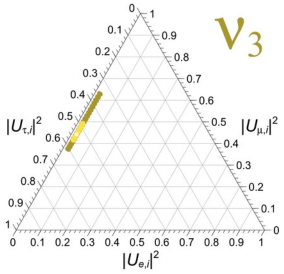
w_2 [



]

+

w_3 [



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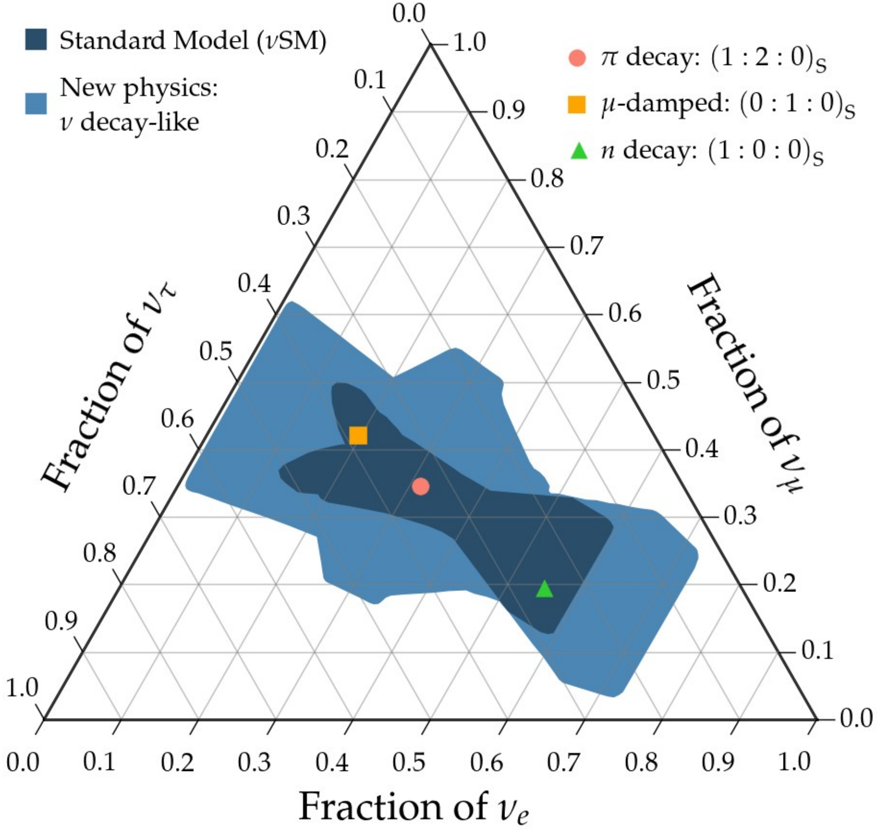
→

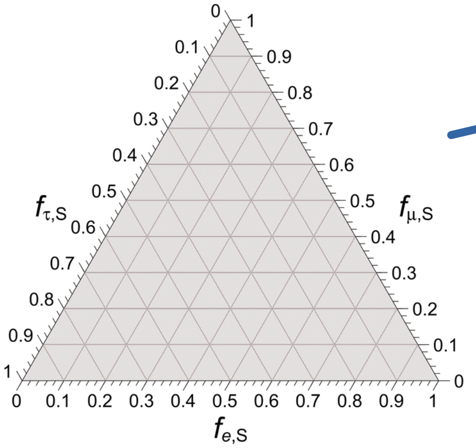
Varying all possible combinations of weights w_i and mixing parameters



Complete decay selects particular weights ▸ with striking consequences for flavor

Measuring the neutrino lifetime

Sources



$\nu_2, \nu_3 \rightarrow \nu_1$

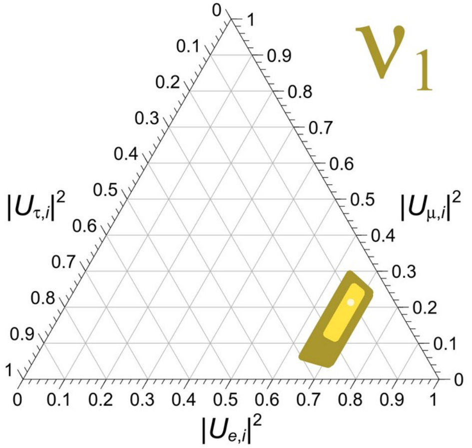
ν_1 lightest and stable
(normal mass ordering)

If all unstable neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$

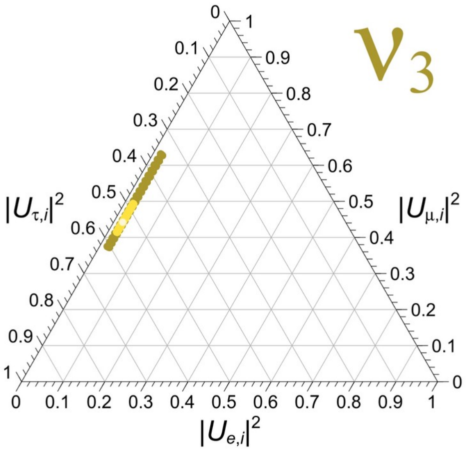
ν_3 lightest and stable
(inverted mass ordering)

Earth



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

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

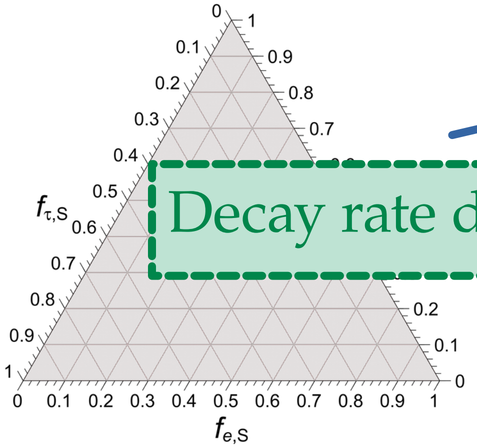


$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

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

Measuring the neutrino lifetime

Sources



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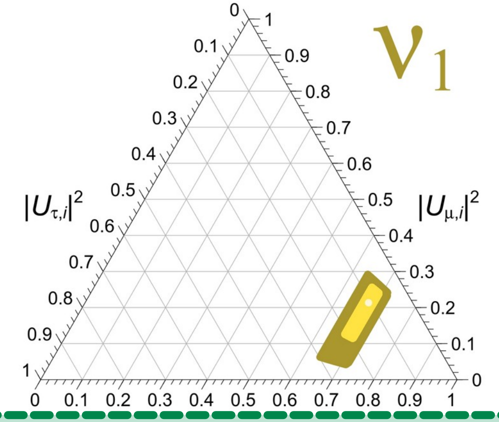

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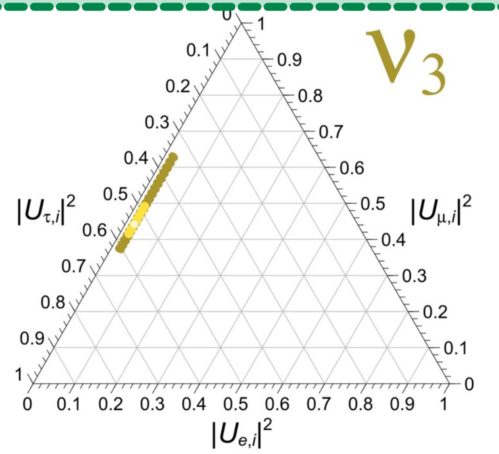

ν_3

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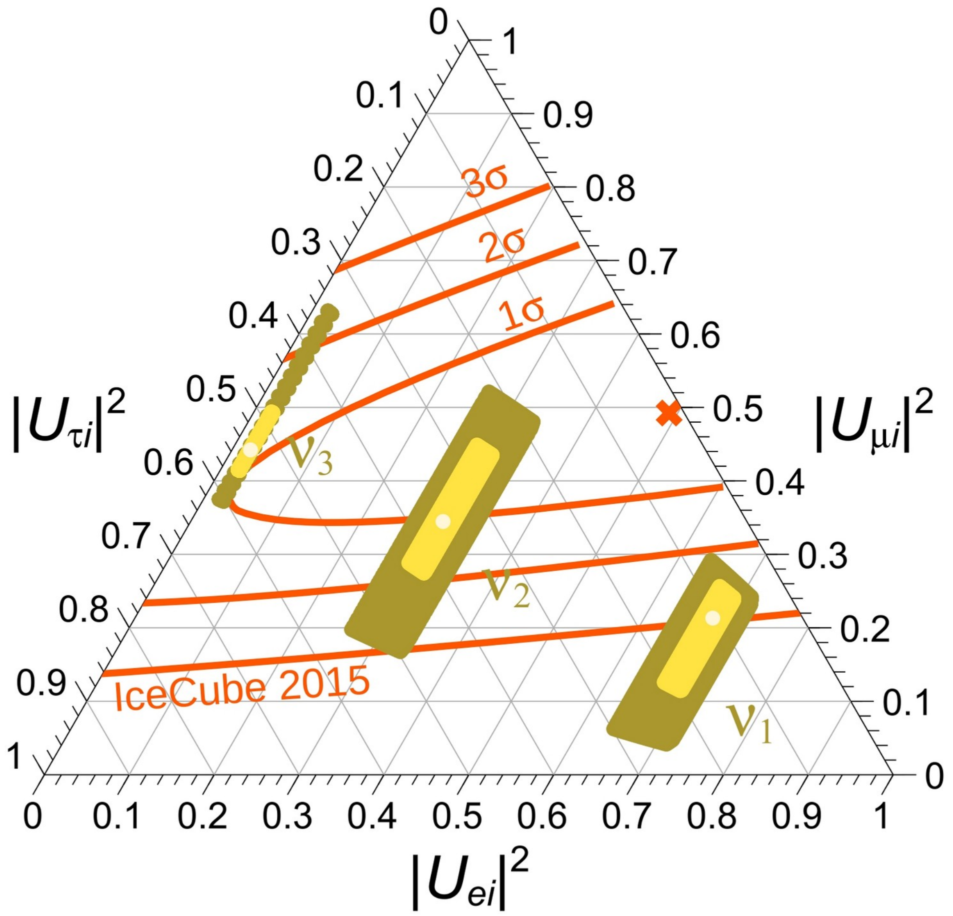
Decay rate depends on $\exp[- t \,/\, (\gamma\, \tau_i)] = \exp[- (L/E) \cdot (m_i/\tau_i)]$



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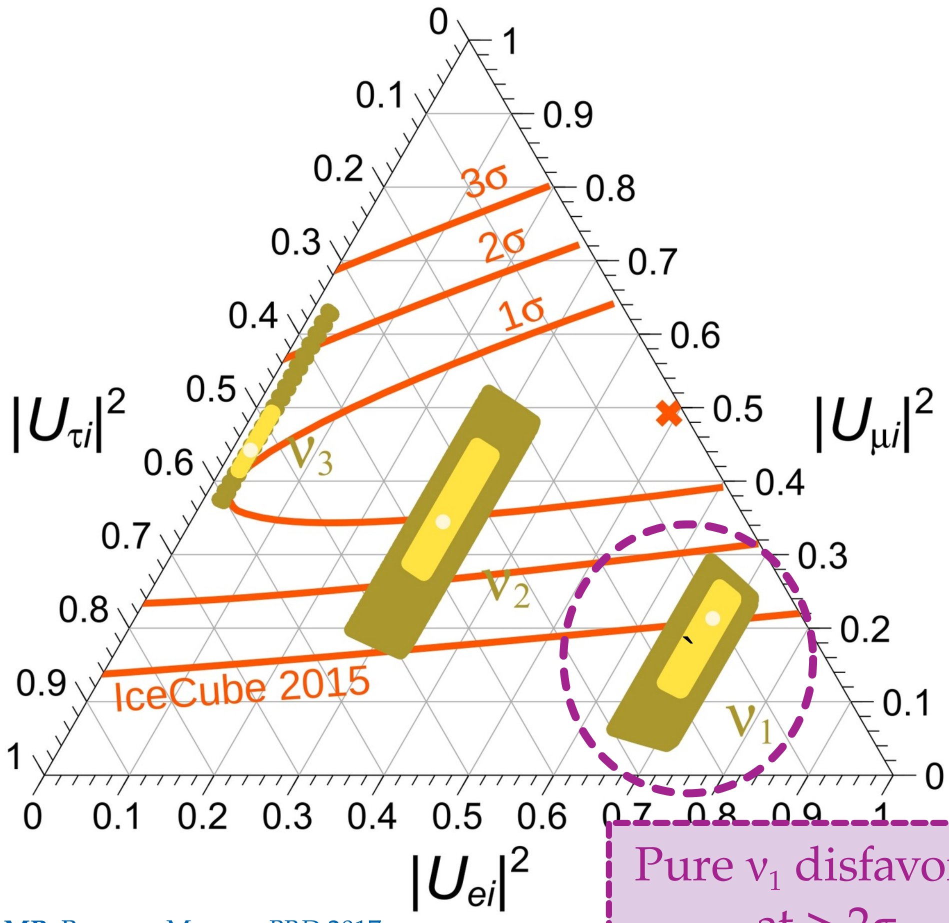

Pure ν_1 disfavored at > 2σ

MB, Beacom, Murase, *PRD* 2017
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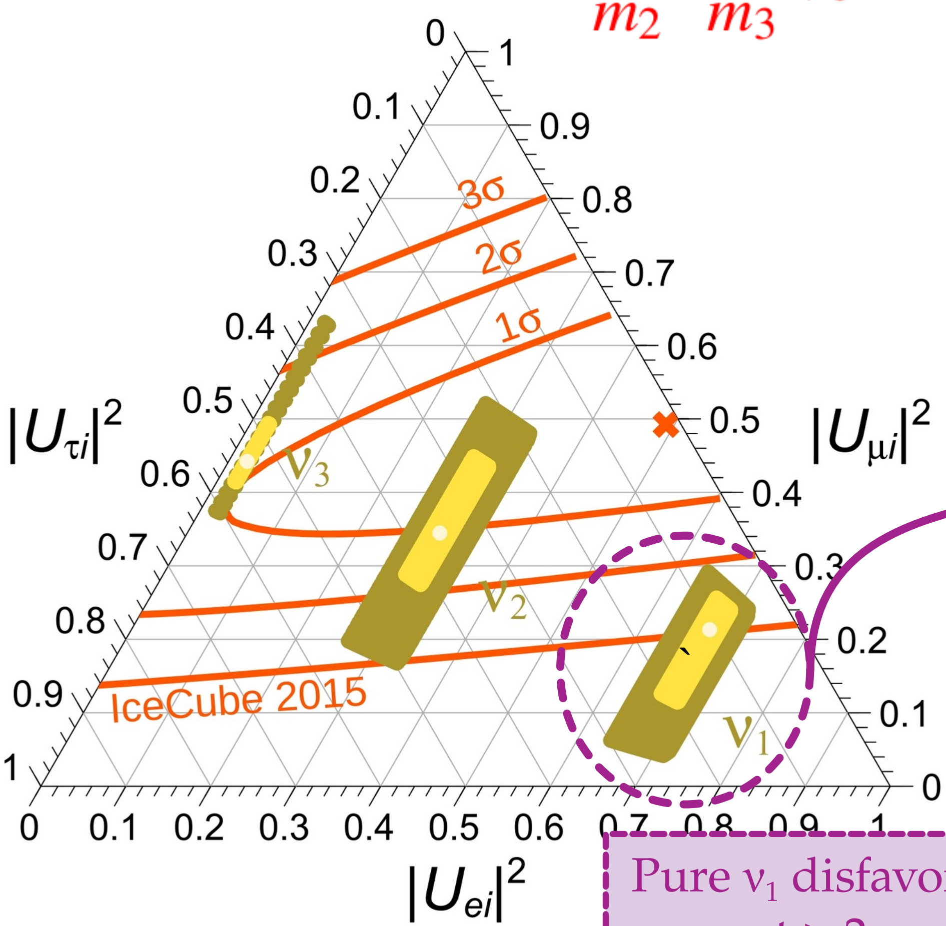
$$\frac{\tau_2}{m_2}, \frac{\tau_3}{m_3} \gtrsim 10 \, \frac{\text{s}}{\text{eV}}$$



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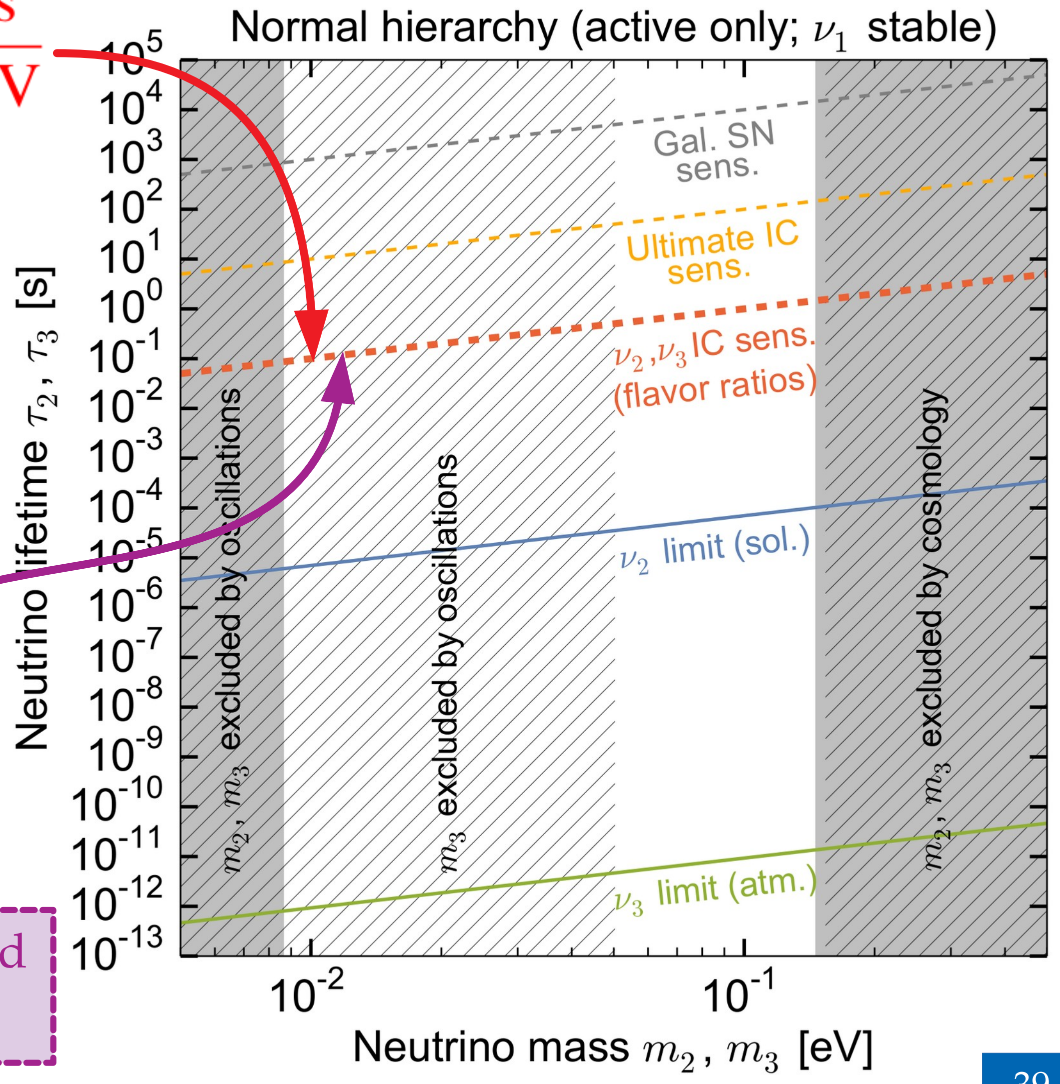

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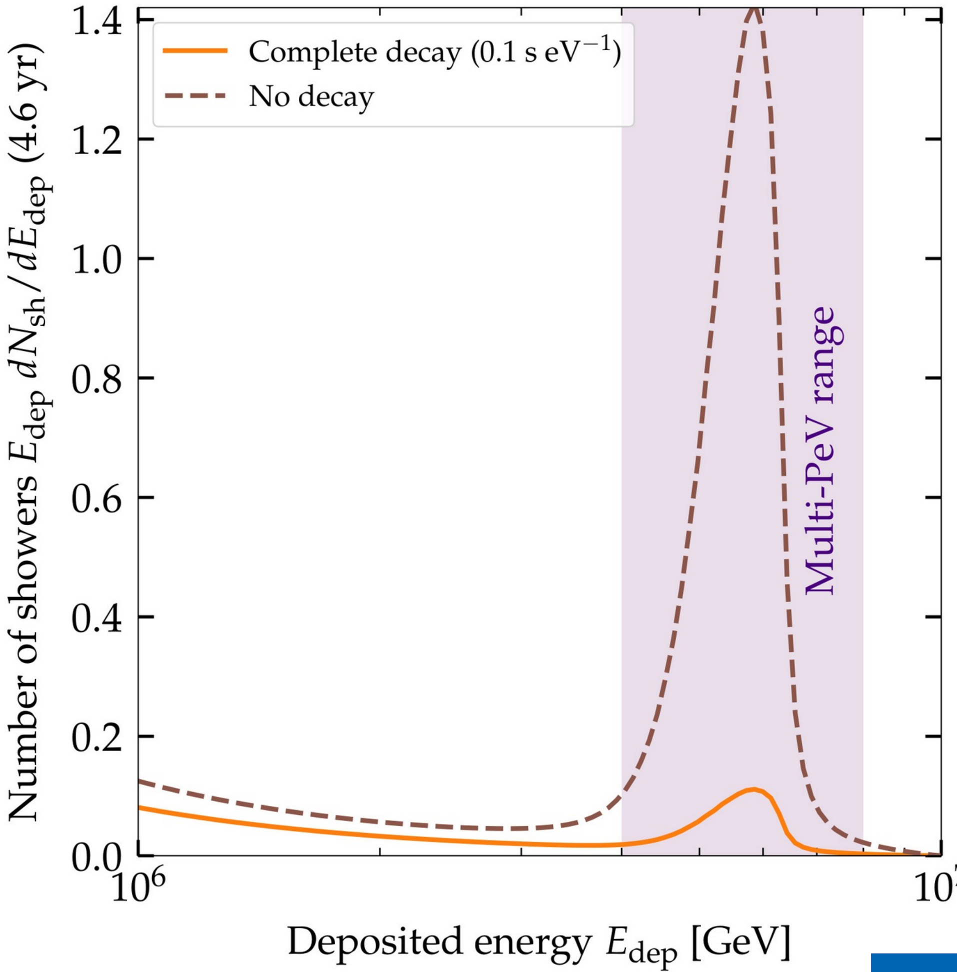
Using the Glashow resonance to test decay

- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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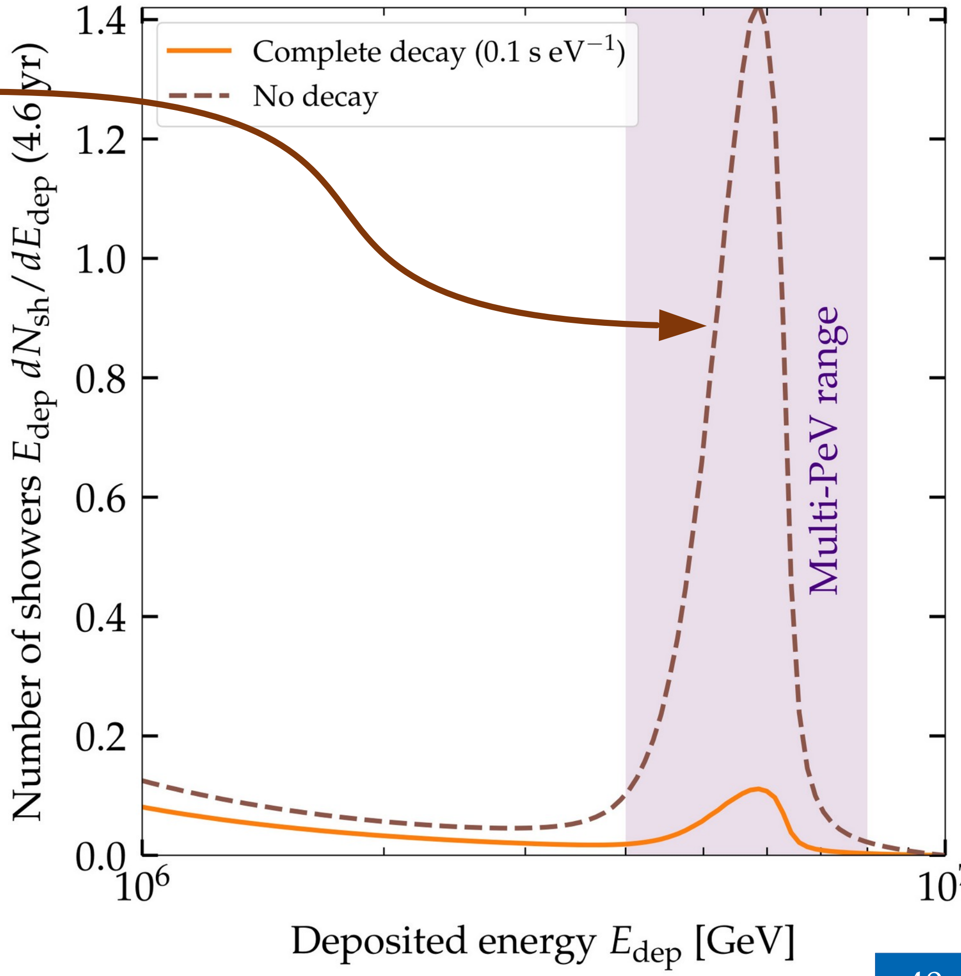

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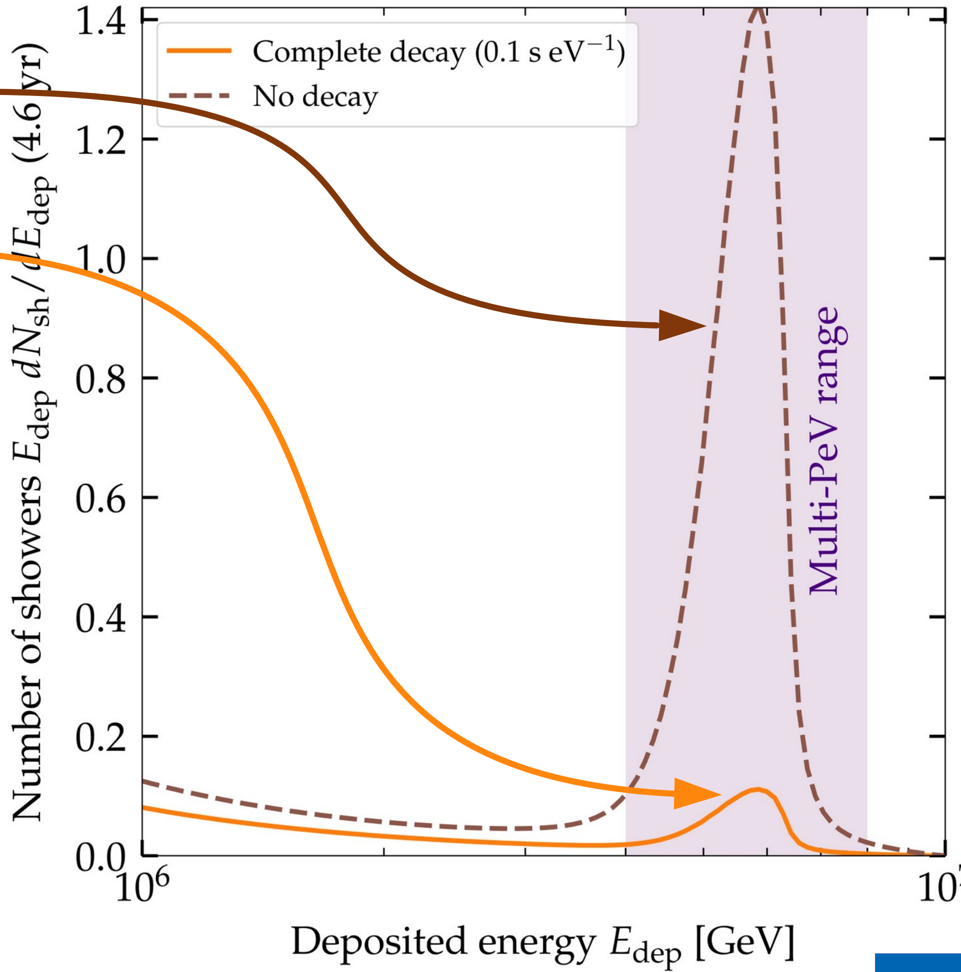

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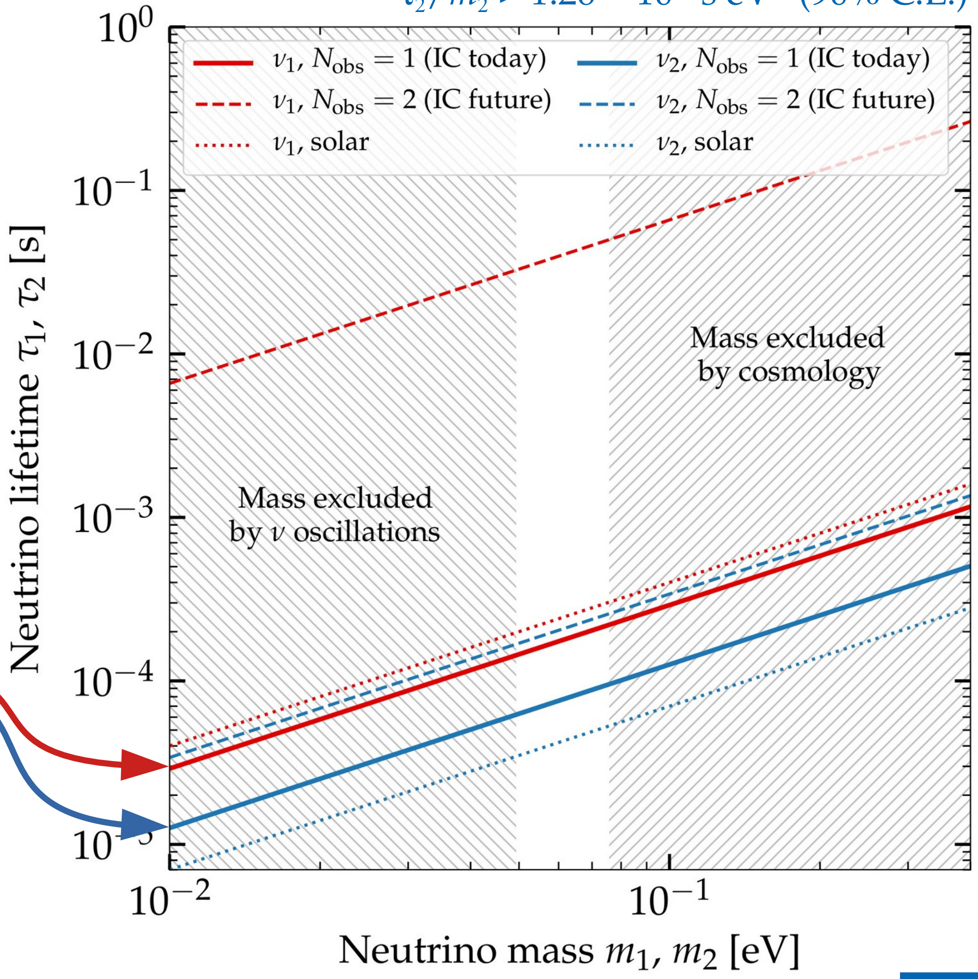
- At 6.3 PeV, the Glashow resonance ($\bar{\nu}_e + e \to W$) should trigger showers in IceCube
- … unless ν_1, ν_2 decay to ν_3 en route to Earth (the surviving ν_3 have little electron content)
- IceCube has seen 1 shower in the 4–8 PeV range, so ν_1, ν_2 *must* make it to Earth
- So we set *lower* limits on their lifetimes (in the inverted mass ordering)
- Translated into *upper* limits on coupling

$\tau_1/m_1 > 2.91 \times 10^{-3}$ s eV^{-1} (90% C.L.)
$\tau_2/m_2 > 1.26 \times 10^{-3}$ s eV^{-1} (90% C.L.)



MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

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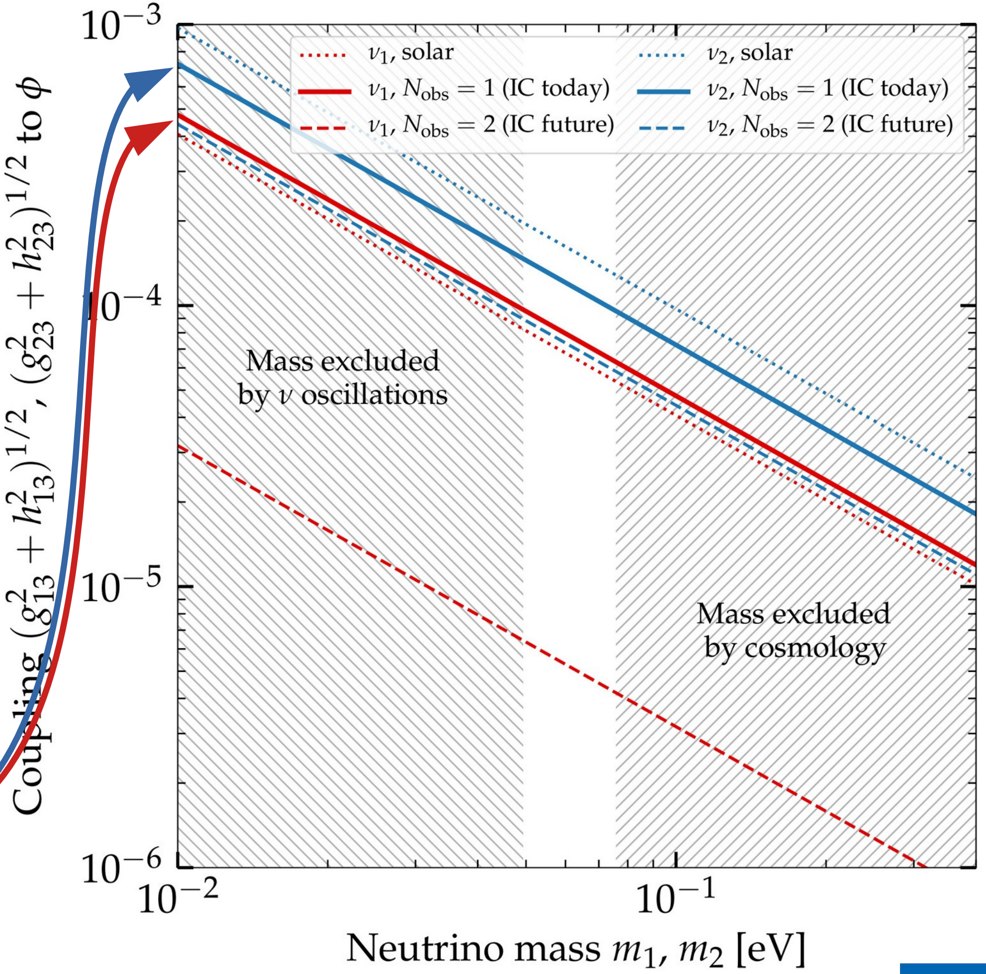
$$\mathcal{L} = g_{ij}\bar{\nu}_i\nu_j\phi + h_{ij}\bar{\nu}_i\gamma_5\nu_j\phi + \text{h.c.}$$

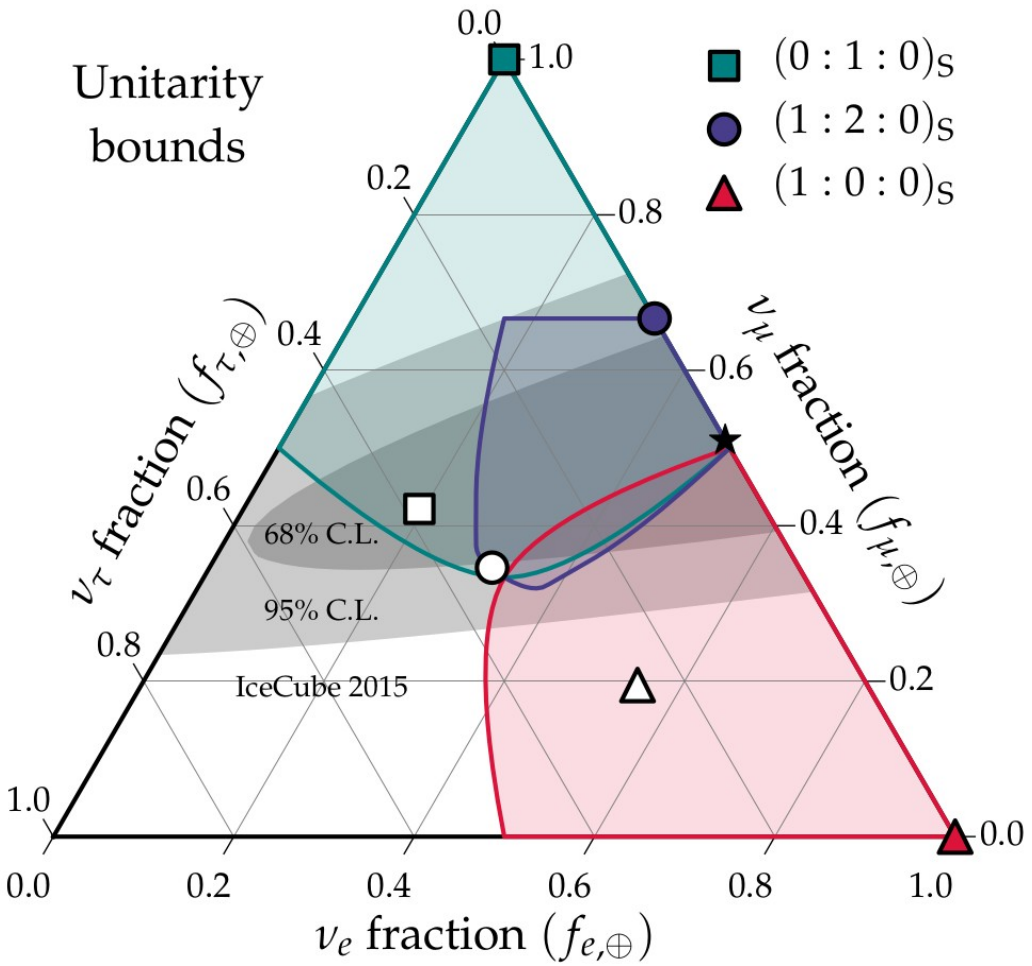


MB, 2004.06844
See also: **MB**, Beacom, Murase, *PRD* 2017

Using unitarity to constrain new physics

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

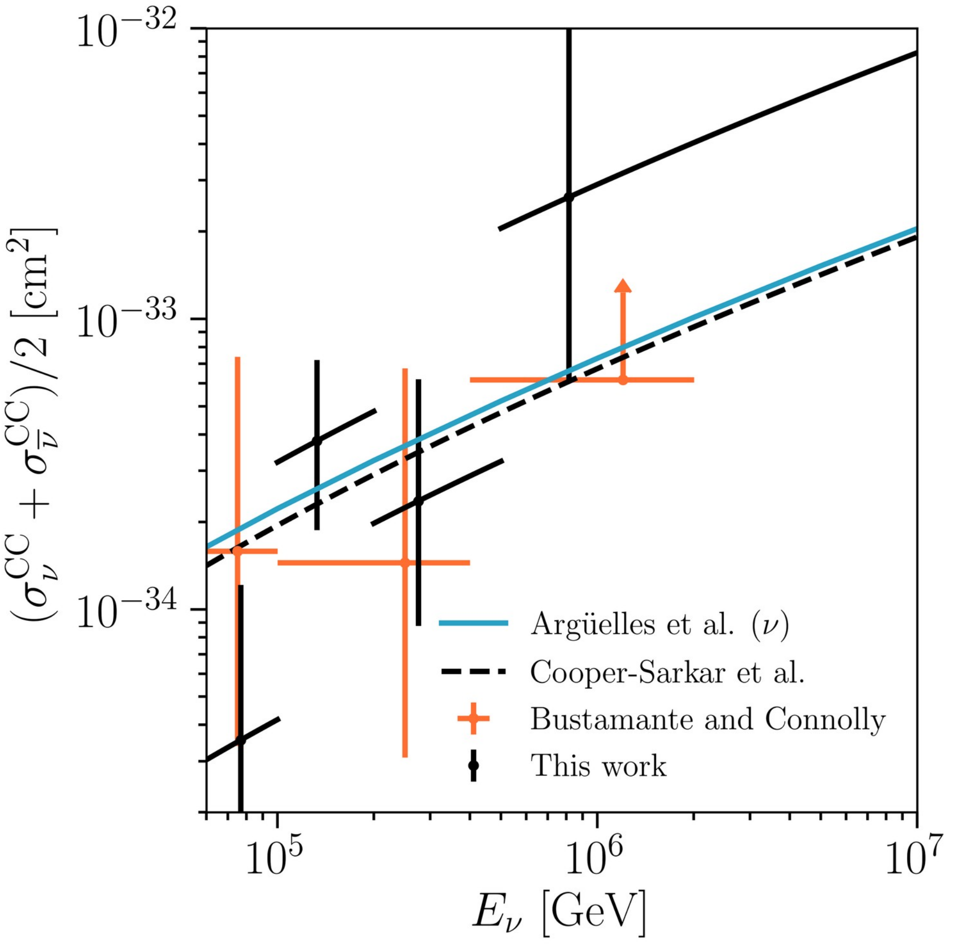
- New mixing angles unconstrained
- Use unitarity ($U_{NP}U_{NP}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

Updated cross section measurement

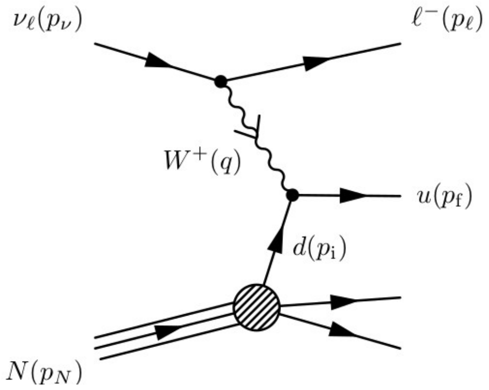
- Uses 7.5 years of IceCube data
- Uses starting showers + tracks
  - *Vs.* starting showers only in Bustamante & Connolly 2017
  - *Vs.* throughgoing muons in IceCube 2017
- Extends measurement to 10 PeV
- Still compatible with Standard Model predictions
- Higher energies? Work in progress by Valera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



Extrapolating the cross section to high energies

Extrapolating the cross section to high energies

SM



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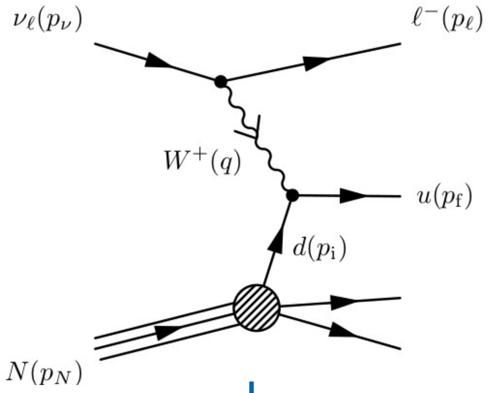

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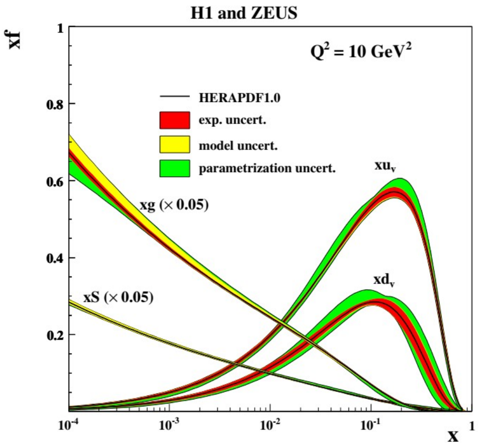
PDFs



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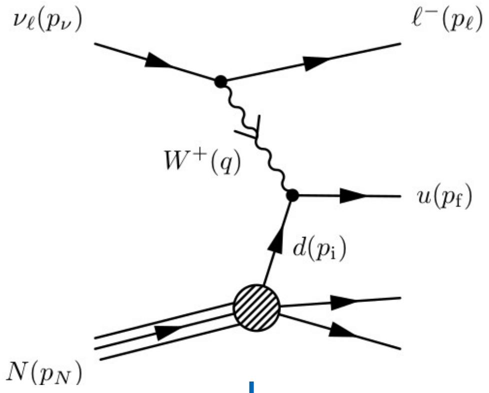

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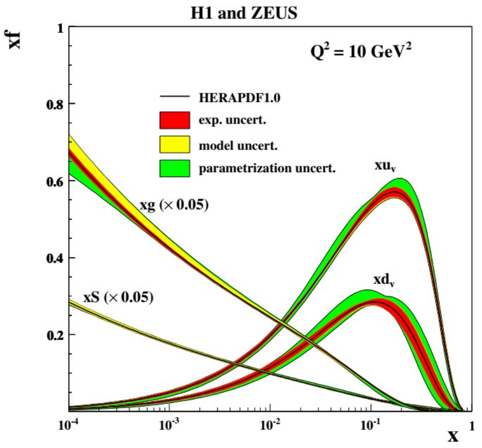

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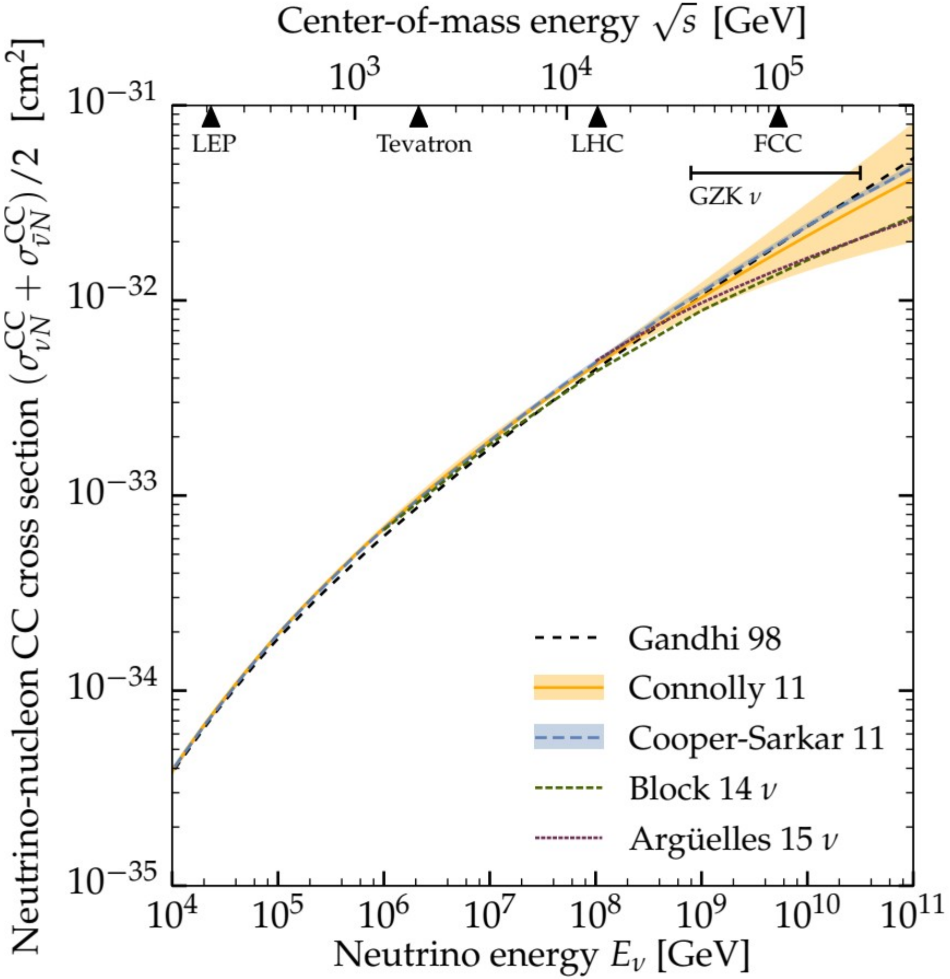

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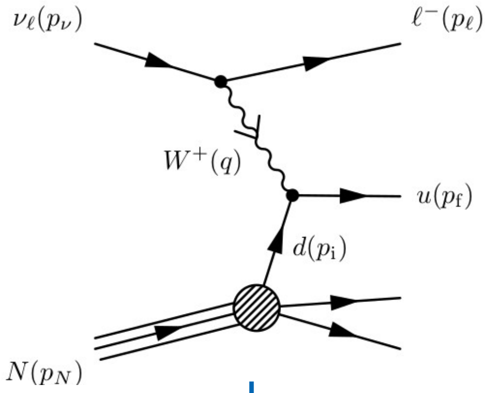

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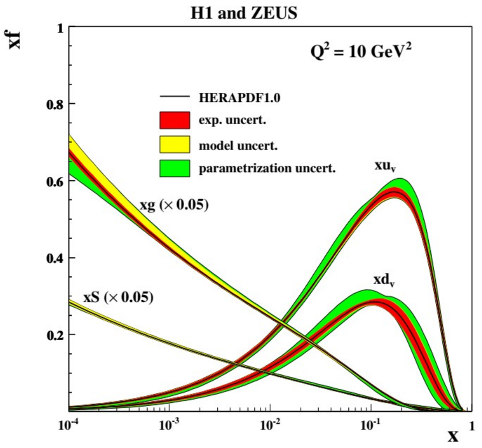

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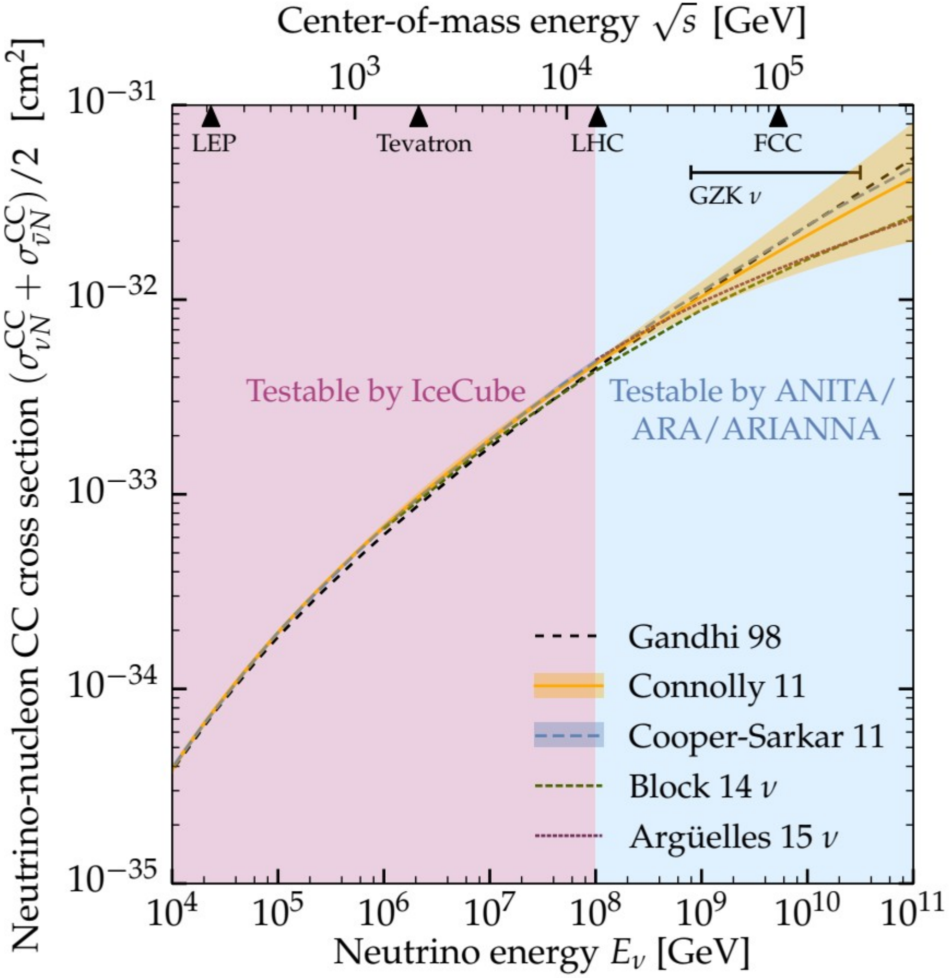


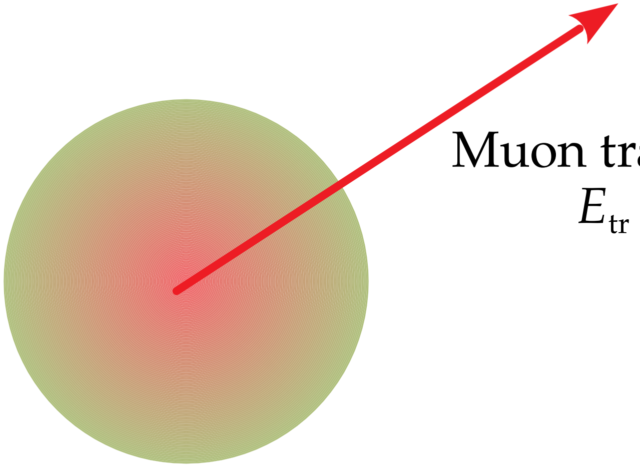
Bonus: Measuring the inelasticity $\langle y \rangle$

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

- 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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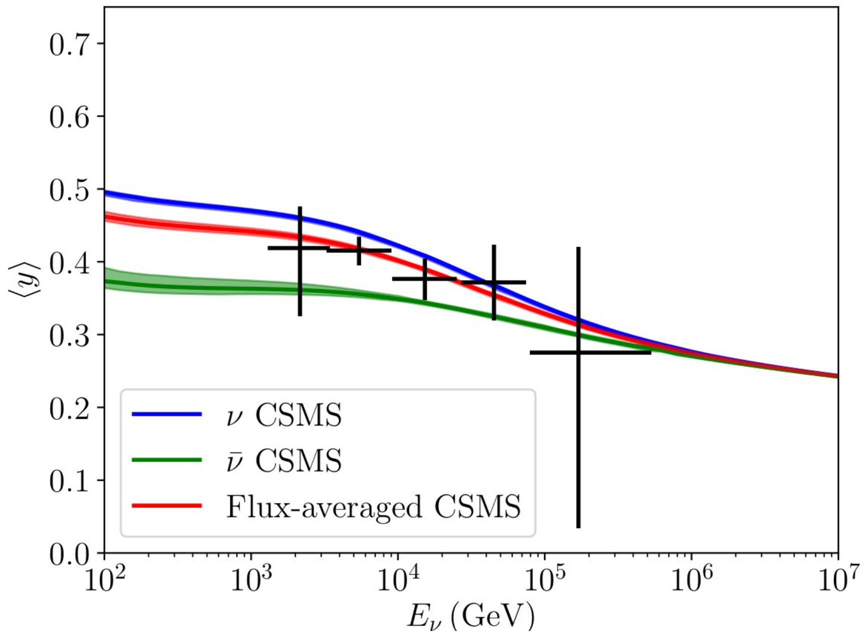


IceCube, *PRD* 2019

Neutrino zenith angle distribution

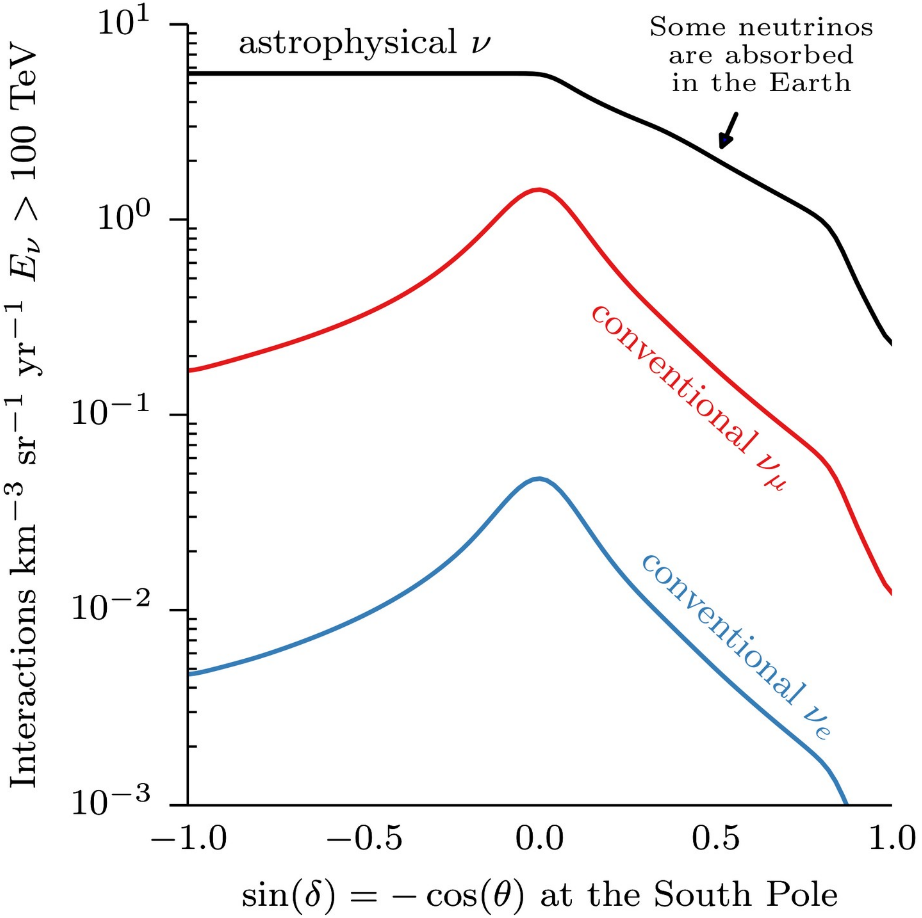
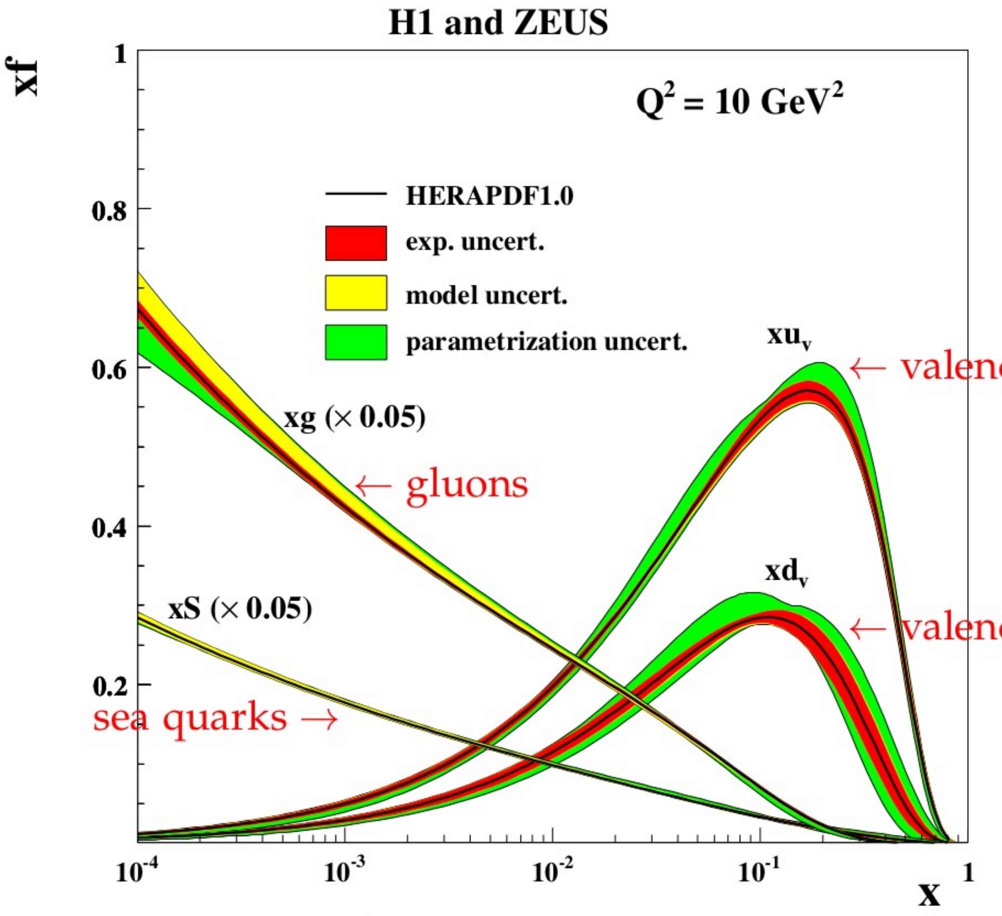


Figure by
Jakob Van Santen
ICRC 2017

Peeking inside a proton



(Parton distribution function)

← gluons

← valence up quark

← valence down quark

sea quarks →

← Extrapolation

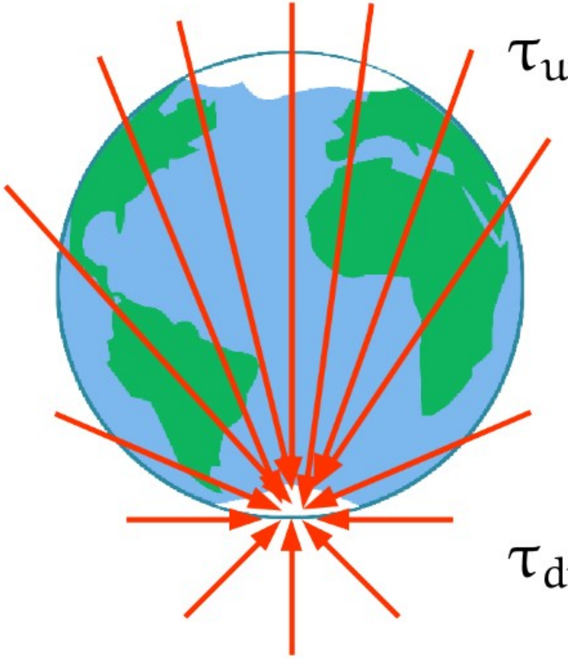
(Fraction of momentum carried by parton)

A. Cooper-Sarkar 2012

Measuring the high-energy cross section

$$\text{Optical depth to } \nu\text{N int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

Below ~ 10 TeV: Earth is transparent



$\tau_{up} \ll 1$

$\tau_{dn} \ll 1$

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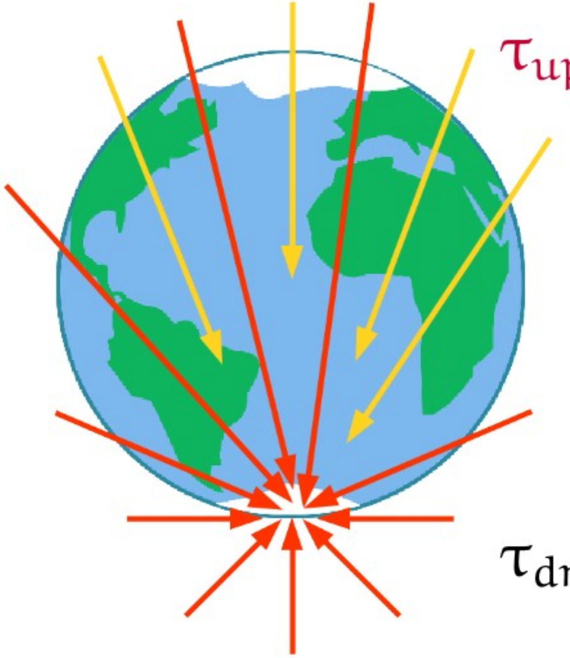

$\tau_{up} \sim 1$

$\tau_{dn} \ll 1$

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

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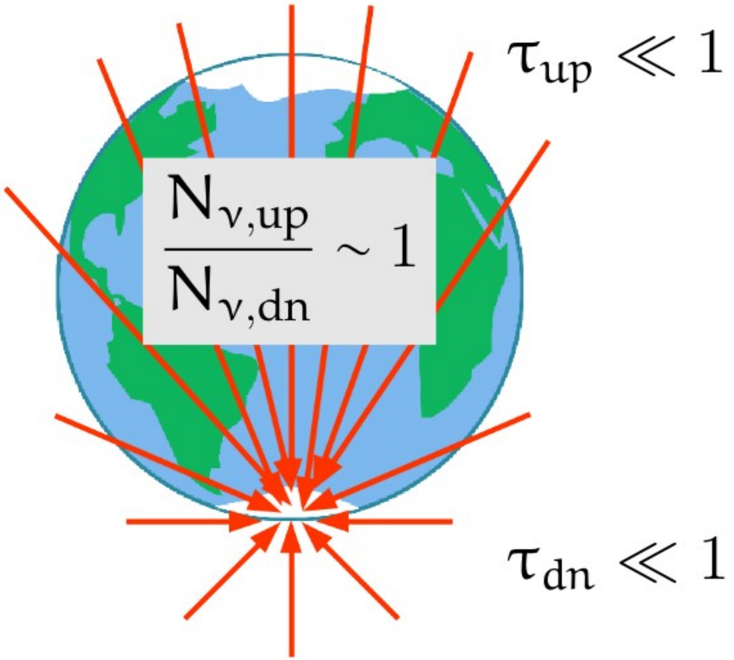

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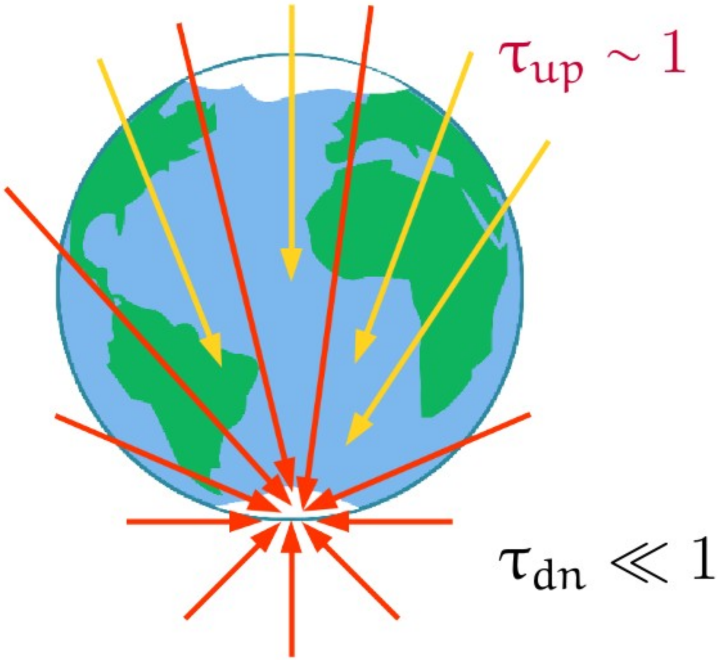

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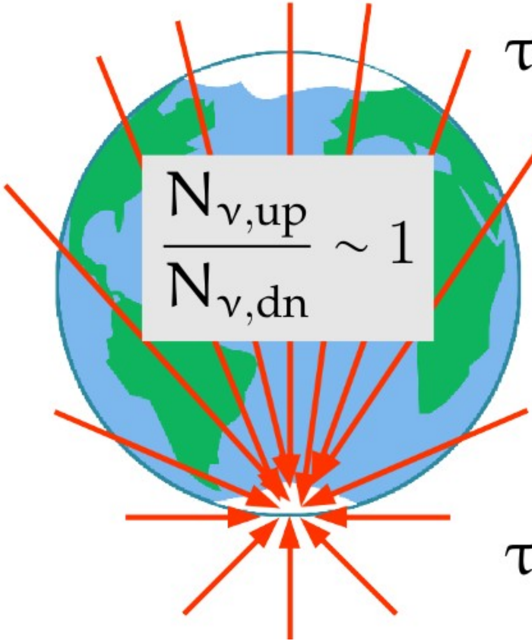
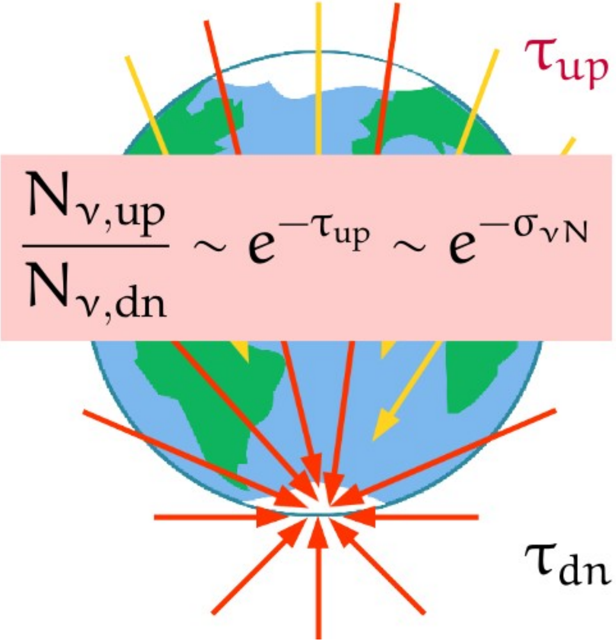


$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim 1$$

$\tau_{\mathrm{up}} \ll 1$

$\tau_{\mathrm{dn}} \ll 1$

Above ~ 10 TeV: Earth is opaque

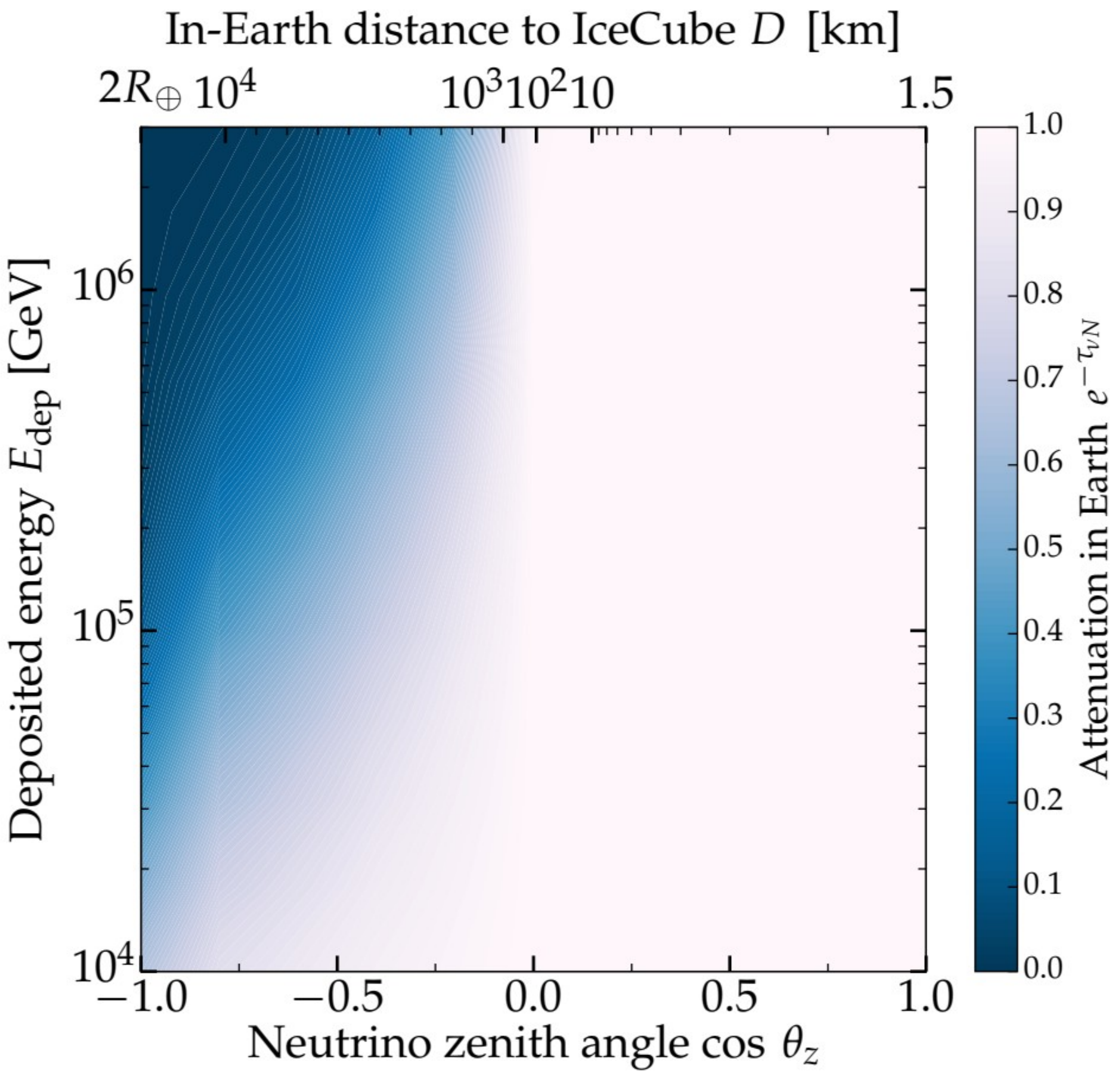


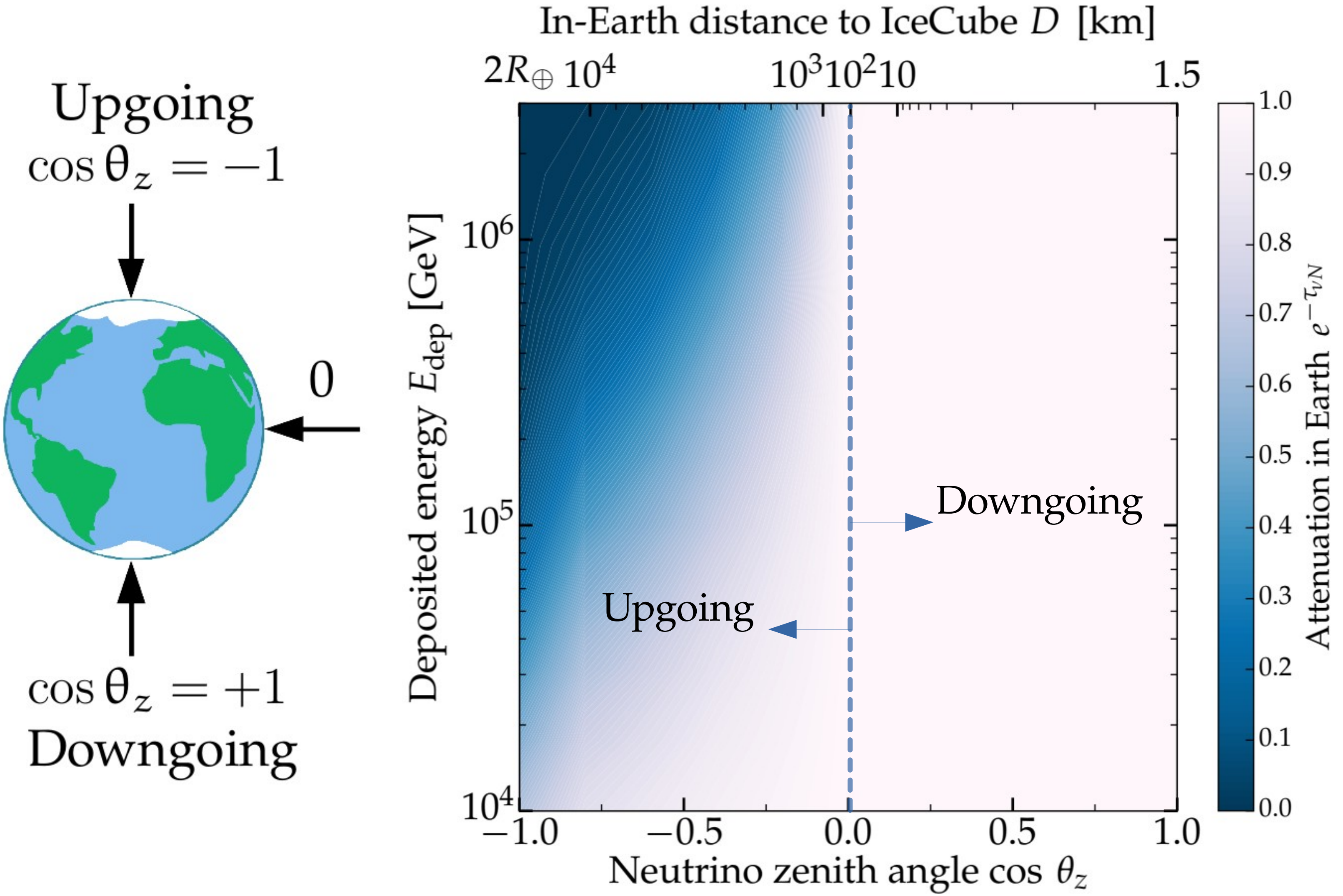
$$\frac{N_{\nu,\mathrm{up}}}{N_{\nu,\mathrm{dn}}} \sim e^{-\tau_{\mathrm{up}}} \sim e^{-\sigma_{\nu N}}$$

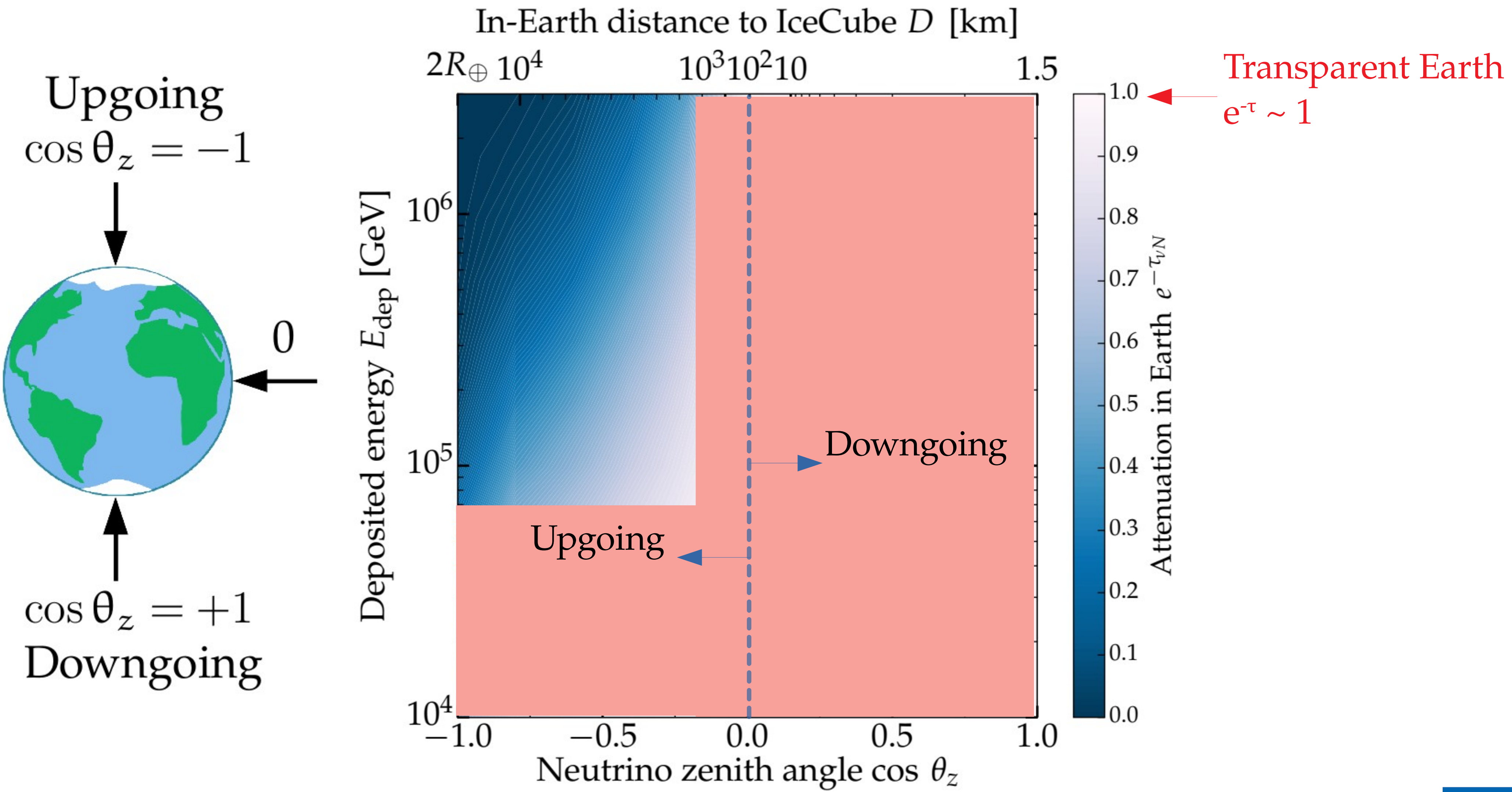
$\tau_{\mathrm{up}} \sim 1$

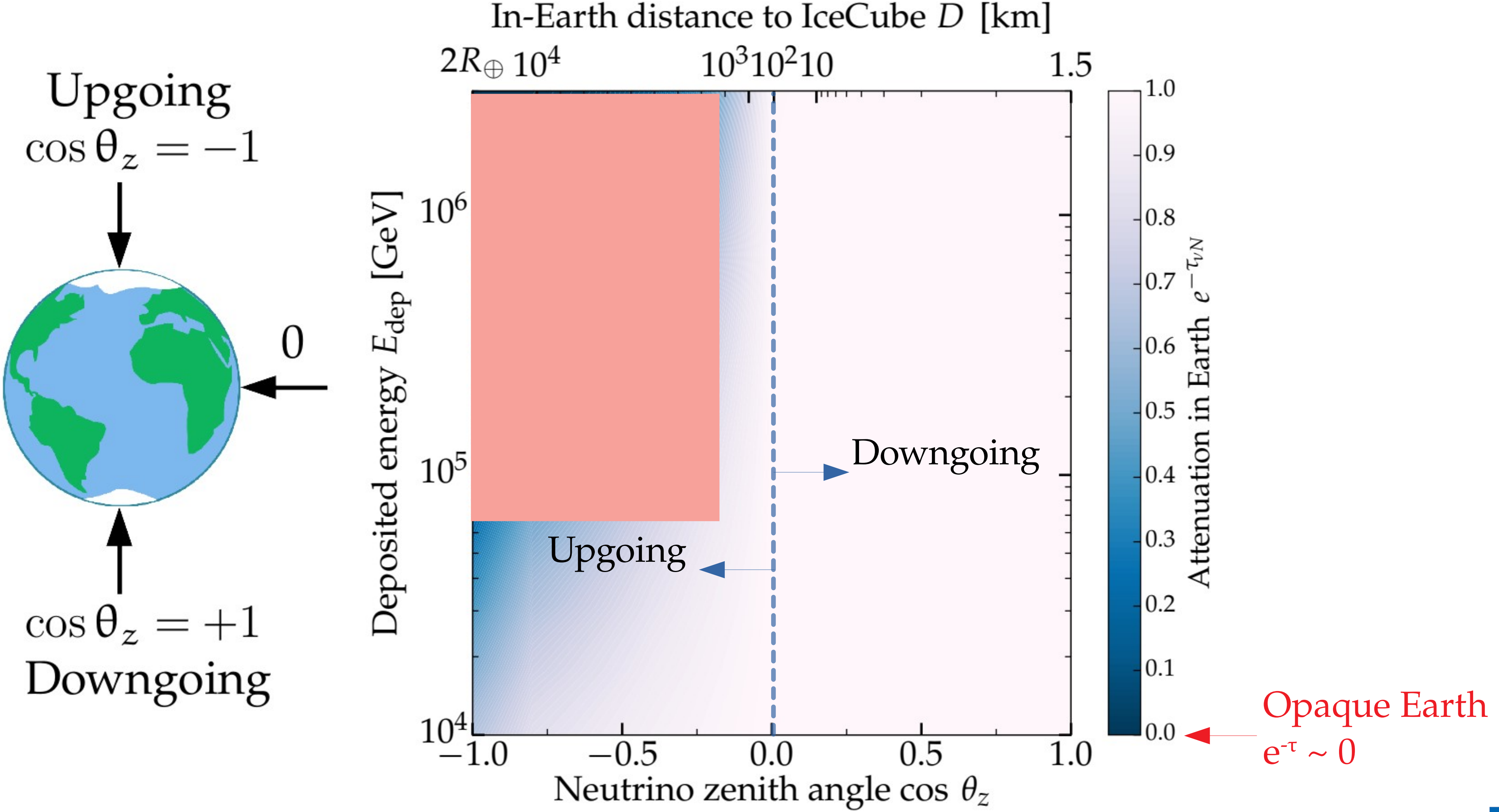
$\tau_{\mathrm{dn}} \ll 1$

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


In-Earth distance to IceCube D [km]
2R⊕ 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 θ_z
Attenuation in Earth e^{−τ_νN}
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]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos θ_z
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0


Upgoing
cos θ_z = −1
0
cos θ_z = +1
Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
Deposited energy E_dep [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle cos θ_z
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^{−τ_{νN}}
Transparent Earth
e^{-τ} ~ 1


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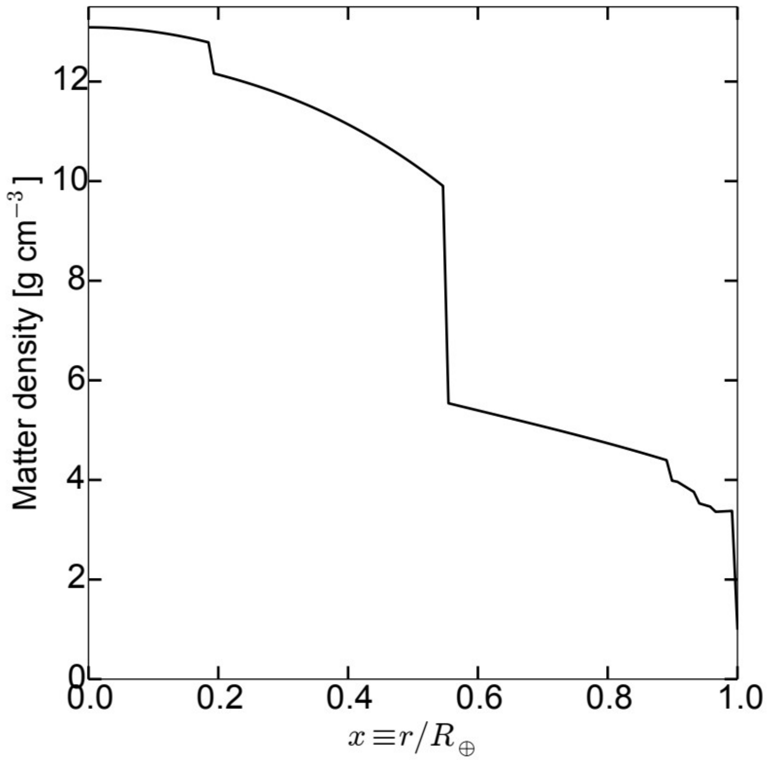
Downgoing
In-Earth distance to IceCube D [km]
$2R_\oplus$ 10^4 10^3 10^2 10 1.5
Deposited energy E_{dep} [GeV]
10^6
10^5
10^4
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth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

A feel for the in-Earth attenuation

Earth matter density

(Preliminary Reference Earth Model)



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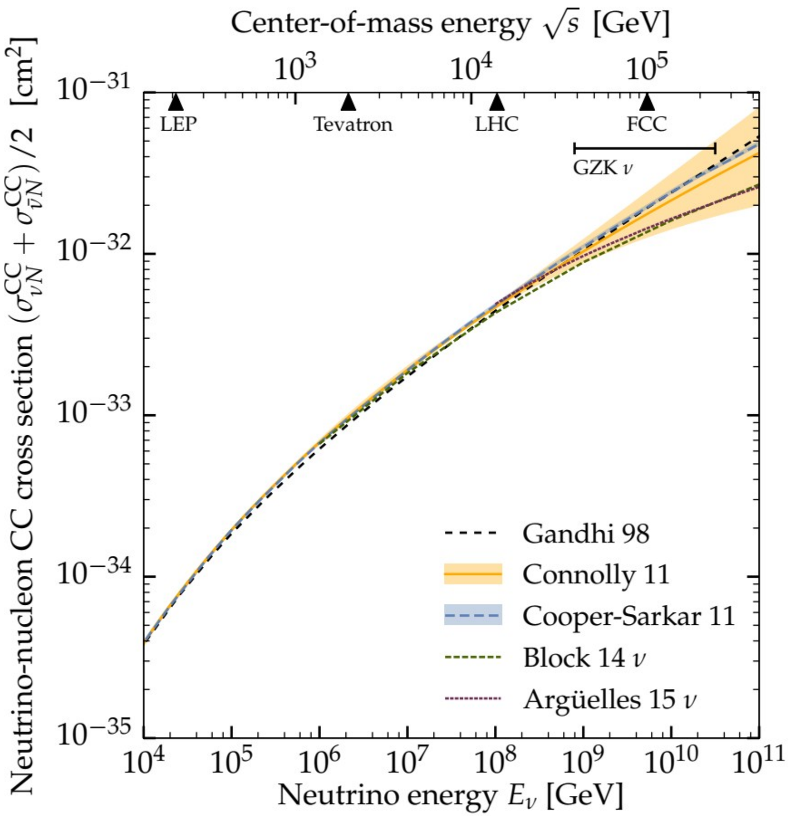
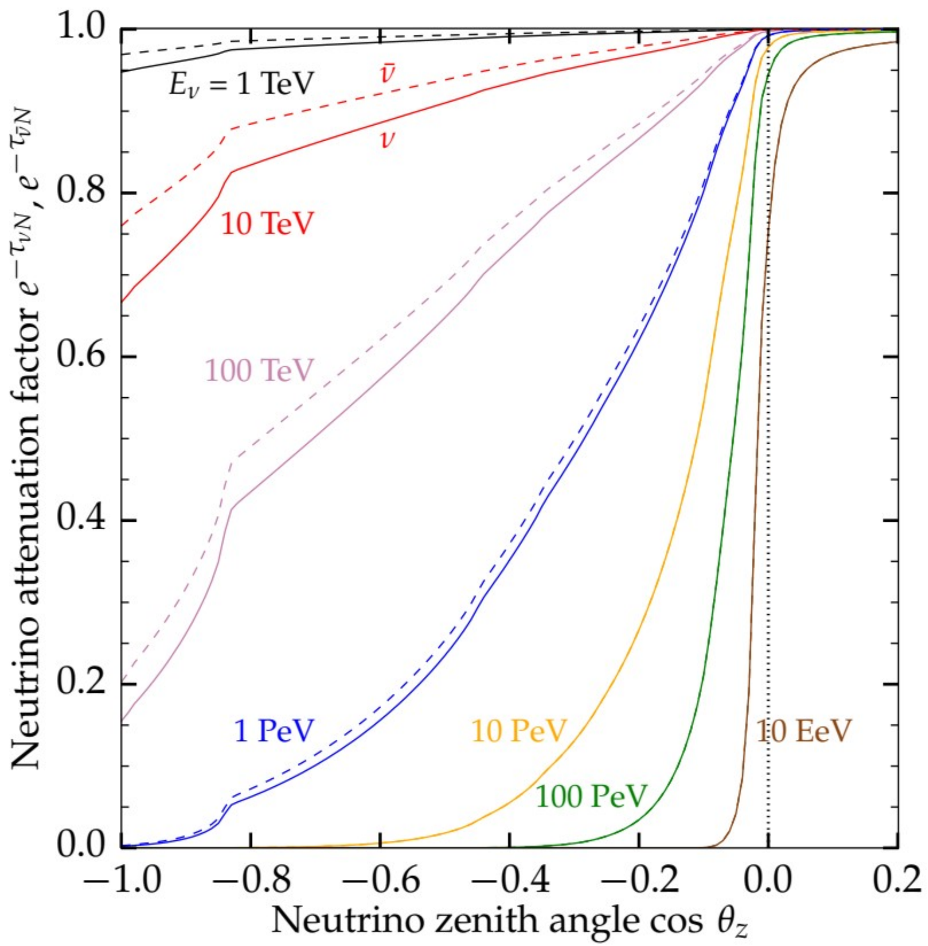
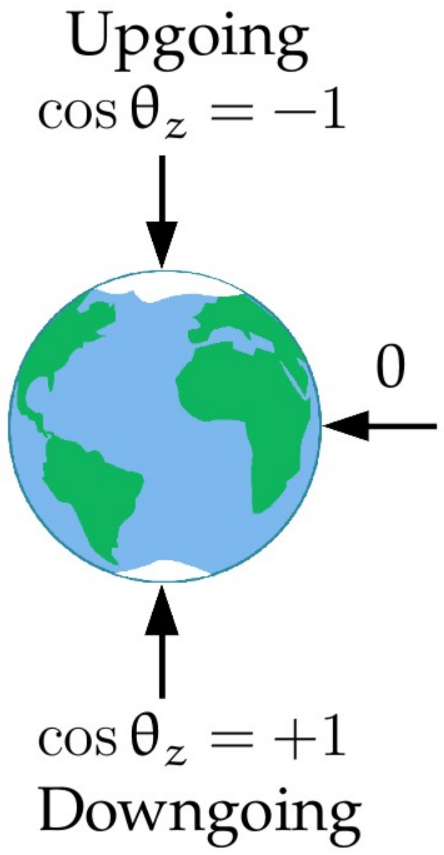
Neutrino-nucleon cross section

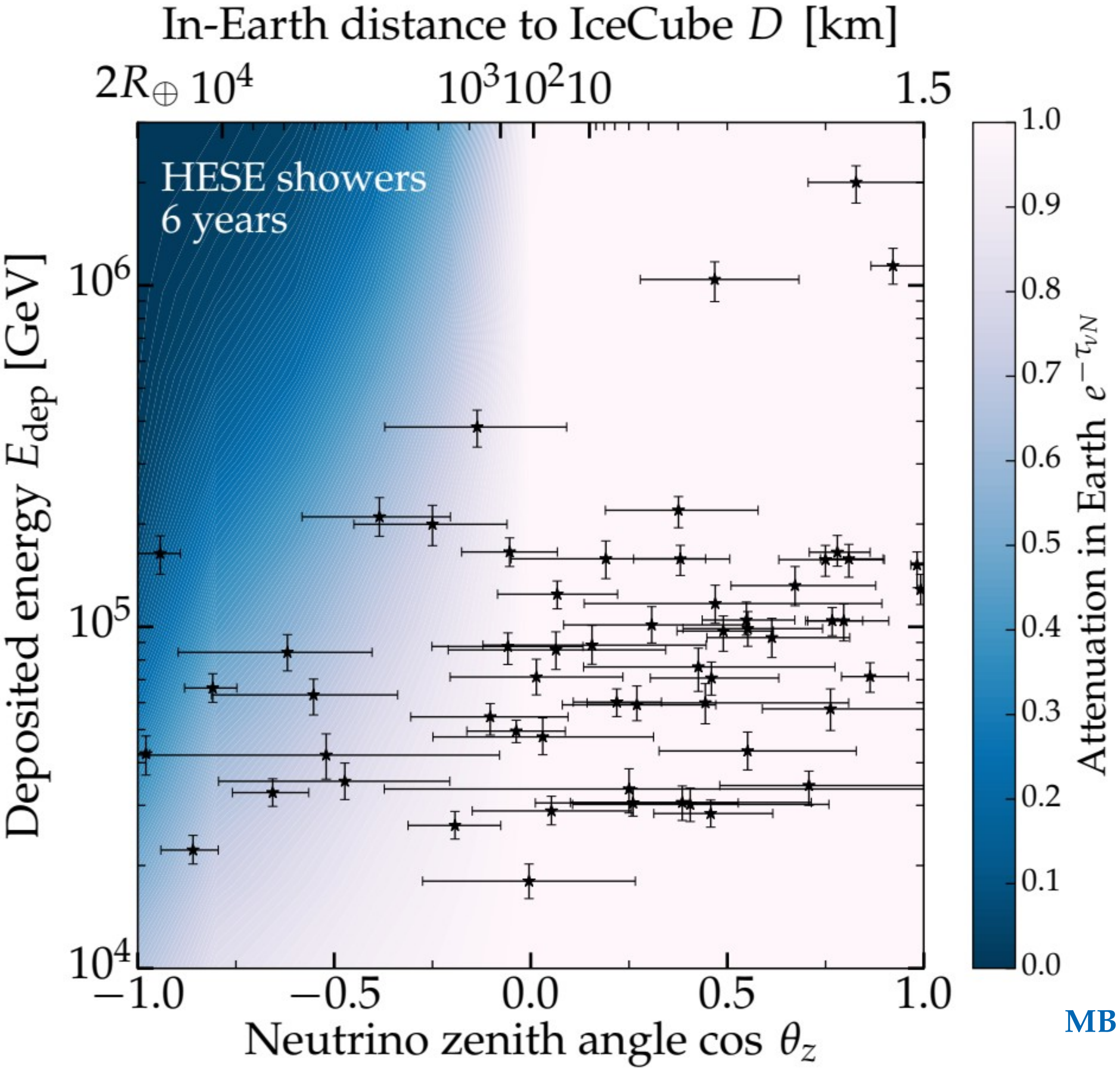


A feel for the in-Earth attenuation

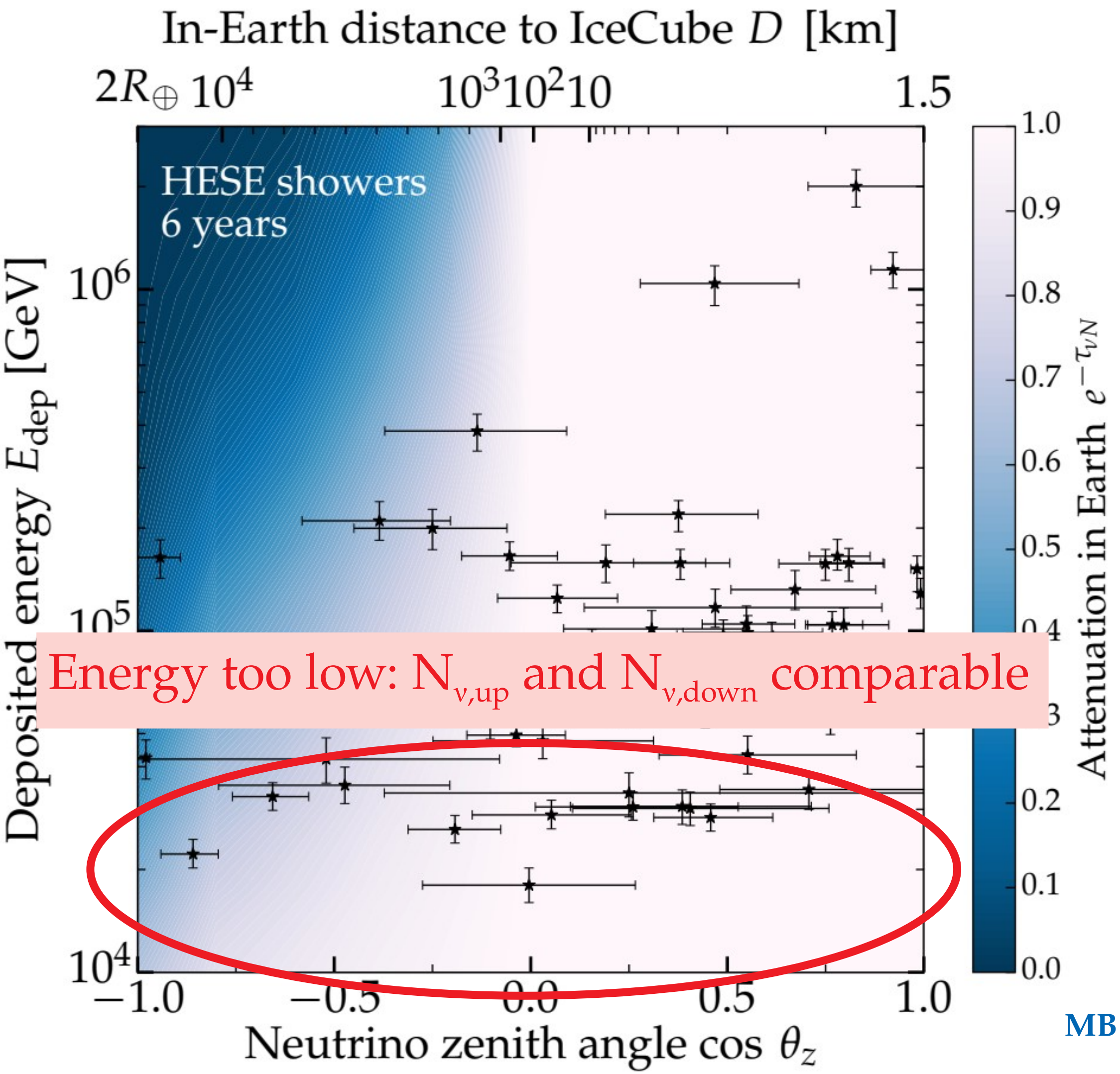
=







MB & Connolly, *PRL* 2019



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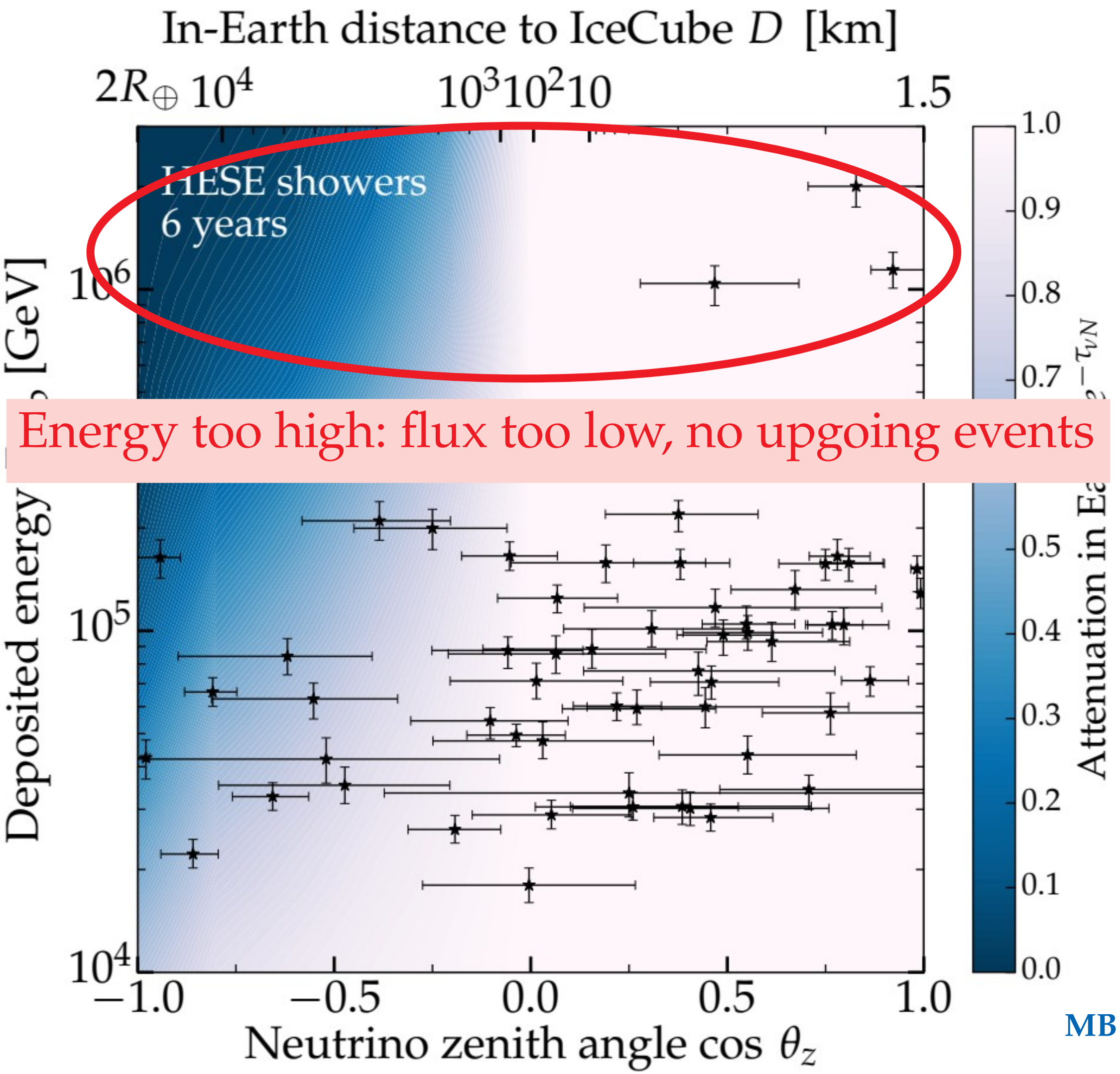

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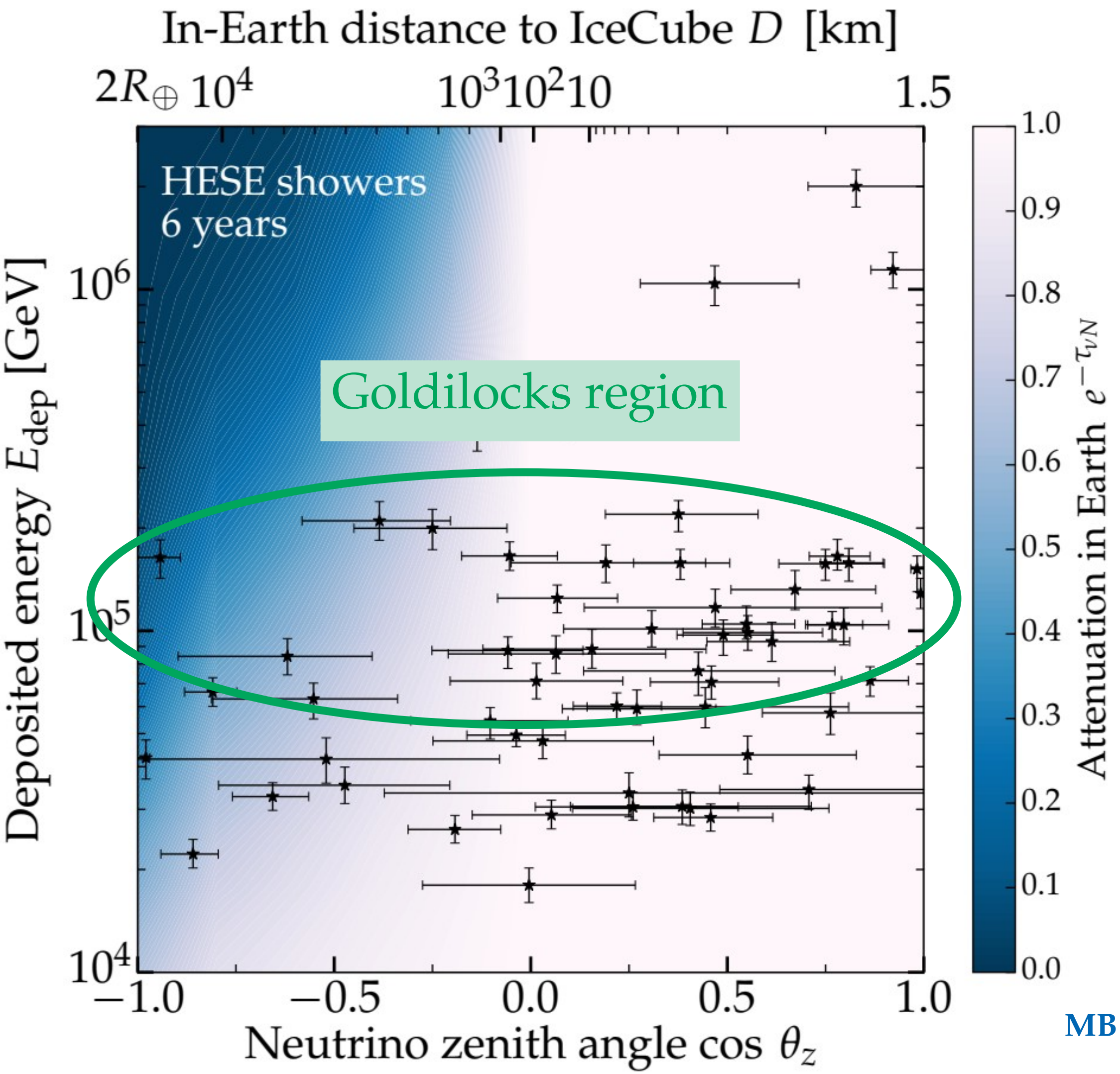

MB & Connolly, *PRL* 2019

What goes into the (likelihood) mix?

- Inside each energy bin, we freely vary
  - N_{ast} (showers from astrophysical neutrinos)
  - N_{atm} (showers from atmospheric neutrinos)
  - γ (astrophysical spectral index)
  - σ_{CC} (neutrino-nucleon charged-current cross section)
- For each combination, we generate the angular and energy shower spectrum…
- … and compare it to the observed HESE spectrum via a likelihood
- Maximum likelihood yields σ_{CC} (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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Including detector resolution (10% in energy, 15° in direction)

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Marginalized cross section in each bin

TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle \cdot \sigma_{\nu N}^{\rm CC}$ — where $\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$ is the average ratio of $\bar{\nu}$ to ν cross sections calculated using the standard prediction from Ref. [60] — and $\sigma_{\nu N}^{\rm NC} = \sigma_{\nu N}^{\rm CC}/3$, $\sigma_{\bar{\nu} N}^{\rm NC} = \sigma_{\bar{\nu} N}^{\rm CC}/3$. Uncertainties are statistical plus systematic, added in quadrature.

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\rm CC} / \sigma_{\nu N}^{\rm CC} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\rm CC} + \sigma_{\bar{\nu} N}^{\rm CC})/{\rm cm}^2]$
18–50	32	0.752	-34.35 ± 0.53
50–100	75	0.825	-33.80 ± 0.67
100–400	250	0.888	-33.84 ± 0.67
400–2004	1202	0.957	> -33.21 (1σ)

MB & A. Connolly, 1711.11043

Energy and angular shower spectra

Rate from all flavors, CC + NC:

$$\frac{d^2 N_{\rm sh}}{dE_{\rm sh} d\cos\theta_z} = \frac{d^2 N^{\rm CC}_{{\rm sh},e}}{dE_{\rm sh} d\cos\theta_z} + \underbrace{{\rm Br}_{\tau\to{\rm sh}}}_{=\,0.83} \frac{d^2 N^{\rm CC}_{{\rm sh},\tau}}{dE_{\rm sh} d\cos\theta_z} + \sum_{l=e,\mu,\tau} \frac{d^2 N^{\rm NC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}$$

Contribution from one flavor CC:

$$\frac{d^2 N^{\rm CC}_{{\rm sh},l}}{dE_{\rm sh} d\cos\theta_z}(E_{\rm sh}, \cos\theta_z) \simeq -2\pi \rho_{\rm ice} N_A V T \left\{ \Phi_l(E_\nu) \sigma^{\rm CC}_{\nu N}(E_\nu) e^{-\tau_{\nu N}(E_\nu,\theta_z)} + \Phi_{\bar{l}}(E_\nu) \sigma^{\rm CC}_{\bar{\nu} N}(E_\nu) e^{-\tau_{\bar{\nu} N}(E_\nu,\theta_z)} \right\} \Big|_{E_\nu = E_{\rm sh}/f_{l,{\rm CC}}}$$

Conversion between shower energy and neutrino energy:

$$f_{l,t} \equiv \frac{E_{\rm sh}}{E_\nu} \simeq \begin{cases} 1 & \text{for } l = e \text{ and } t = {\rm CC} \\ [\langle y \rangle + 0.7\,(1 - \langle y \rangle)] \simeq 0.8 & \text{for } l = \tau \text{ and } t = {\rm CC} \\ \langle y \rangle \simeq 0.25 & \text{for } l = e, \mu, \tau \text{ and } t = {\rm NC} \end{cases}$$

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

$$\frac{d^2N_{\rm sh}}{dE_{\rm dep}d\cos\theta_z} = \int dE_{\rm sh} \int d\cos\theta'_z \frac{d^2N_{\rm sh}}{dE_{\rm sh}d\cos\theta'_z} R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z})$$

Energy resolution: [Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016; MB, Beacom. Murase, *PRD* 2016]

$$R_E(E_{\rm sh}, E_{\rm dep}, \sigma_E(E_{\rm sh})) = \frac{1}{\sqrt{2\pi\sigma_E^2(E_{\rm sh})}} \exp\left[-\frac{(E_{\rm sh} - E_{\rm dep})^2}{2\sigma_E^2(E_{\rm sh})}\right]$$ with $\sigma_E(E_{\rm sh}) = 0.1 E_{\rm sh}$

IceCube, *JINST* 2014

Angular resolution:

$$R_\theta(\cos\theta'_z, \cos\theta_z, \sigma_{\cos\theta_z}) = \frac{1}{\sqrt{2\pi\sigma^2_{\cos\theta_z}}} \exp\left[-\frac{(\cos\theta'_z - \cos\theta_z)^2}{2\sigma^2_{\cos\theta_z}}\right]$$

with $\sigma_{\cos\theta_z} \equiv \frac{1}{2}\left[|\cos(\theta_z + \sigma_{\theta_z}) - \cos\theta_z| + |\cos(\theta_z - \sigma_{\theta_z}) - \cos\theta_z|\right]$ and $\sigma_{\theta_z} = 15^\circ$

MB & A. Connolly, 1711.11043

Likelihood

In an energy bin containing $N_{\rm sh}^{\rm obs}$ observed showers, the likelihood is

Each energy bin is independent

$$\mathcal{L} = \frac{e^{-(N_{\rm sh}^{\rm atm}+N_{\rm sh}^{\rm ast})}}{N_{\rm sh}^{\rm obs}!} \prod_{i=1}^{N_{\rm sh}^{\rm obs}} \mathcal{L}_i$$

Partial likelihood, *i.e.*, relative probability of the *i*-th shower being from an atmospheric neutrino or an astrophysical neutrino:

Depends on $\sigma_{\nu N}$

$$\mathcal{L}_i = N_{\rm sh}^{\rm atm}\,\mathcal{P}_i^{\rm atm} + N_{\rm sh}^{\rm ast}\,\mathcal{P}_i^{\rm ast}$$

$$\mathcal{P}_i^{\rm atm} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm atm}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an atmospheric ν

$$\mathcal{P}_i^{\rm ast} = \left(\int_{E_{\rm dep}^{\rm min}}^{E_{\rm dep}^{\rm max}} dE_{\rm dep} \int_{-1}^{1} d\cos\theta_z \frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right)^{-1} \left(\left.\frac{d^2N_{\rm sh}^{\rm ast}}{dE_{\rm dep}d\cos\theta_z}\right|_{E_{{\rm dep},i},\cos\theta_{z,i}}\right)$$

PDF for this shower to be made by an astrophysical ν

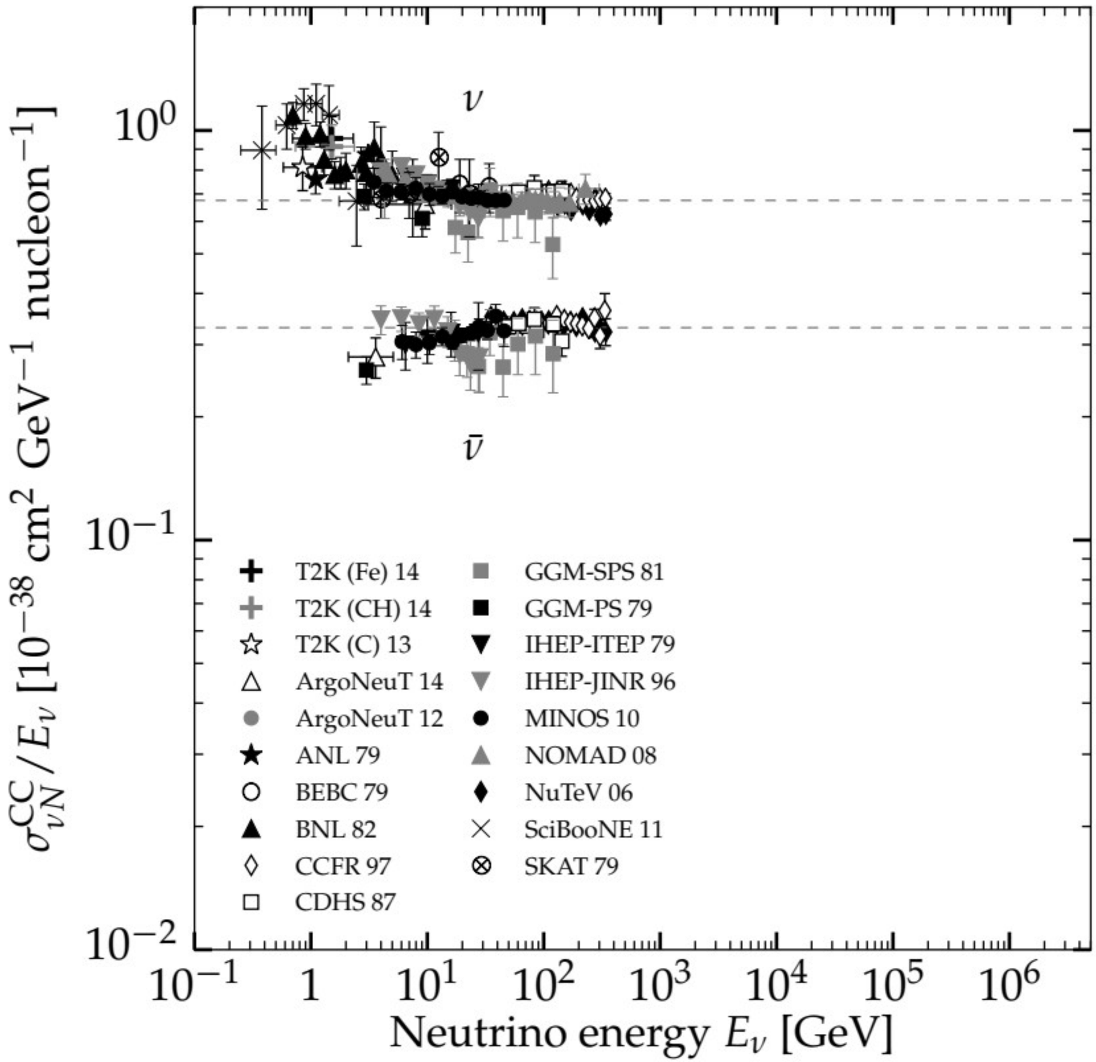
Depends on γ and $\sigma_{\nu N}$

MB & A. Connolly, 1711.11043

See also: Palomares-Ruiz, Vincent, Mena *PRD* 2015; Vincent, Palomares-Ruiz, Mena *PRD* 2016

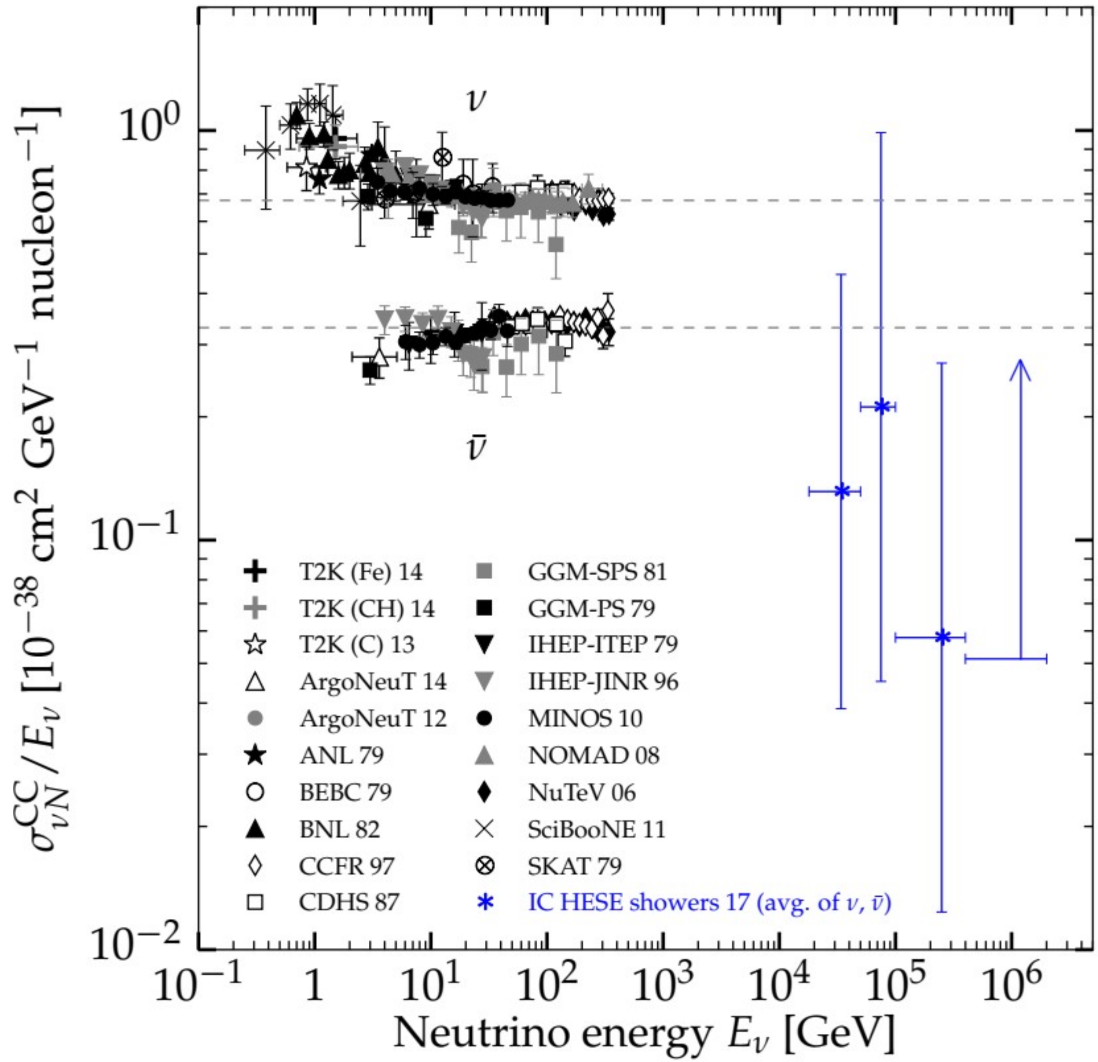
The fine print

- High-energy ν's: astrophysical (isotropic) + atmospheric (**anisotropic**)
  ↦ We take into account the shape of the atmospheric contribution
- The shape of the astrophysical ν **energy spectrum** is still uncertain
  ↦ We take a $E^{-\gamma}$ spectrum in *narrow* energy bins
- **NC showers** are sub-dominant to **CC showers**, but they are indistinguishable
  ↦ Following Standard-Model predictions, we take $\sigma_{NC} = \sigma_{CC}/3$
- IceCube does not **distinguish ν from $\bar{\nu}$**, and their cross-sections are different
  ↦ We assume equal fluxes, expected from production via pp collisions
  ↦ We assume the avg. ratio $\langle\sigma_{\bar{\nu}N}/\sigma_{\nu N}\rangle$ in each bin known, from SM predictions
- The **flavor composition** of astrophysical neutrinos is still uncertain
  ↦ We assume equal flux of each flavor, compatible with theory and observations

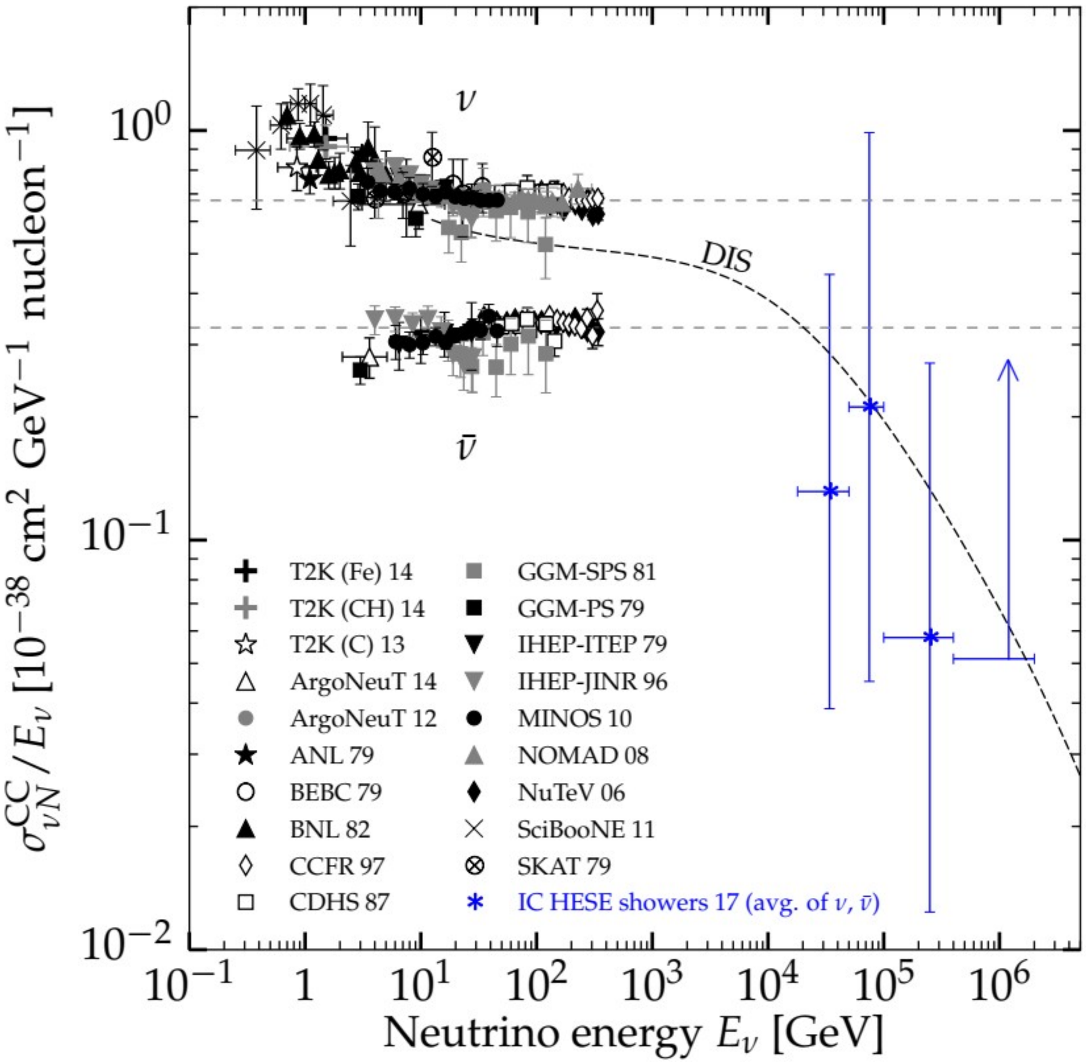


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017

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

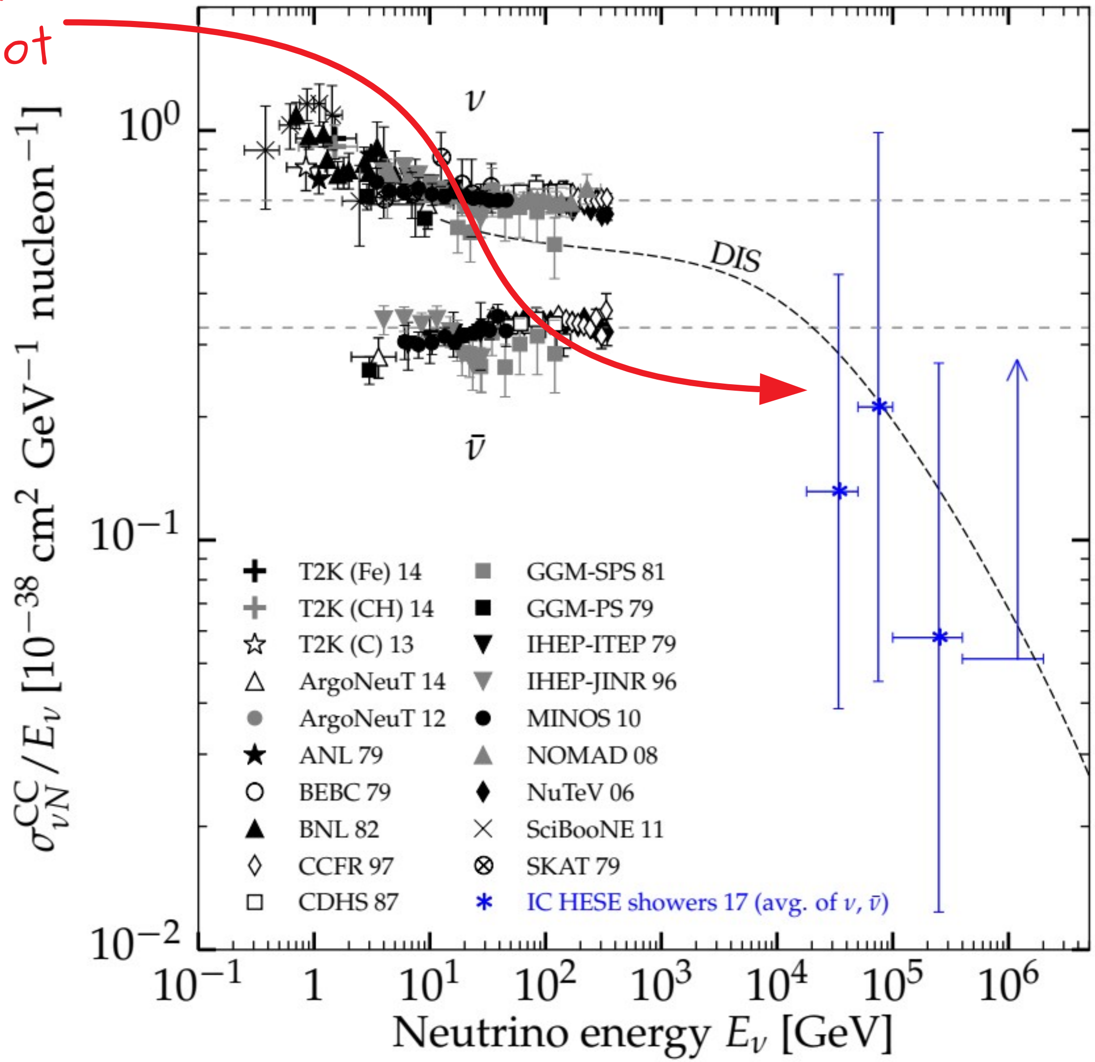


MB & Connolly *PRL* 2019
See also: IceCube, *Nature* 2017



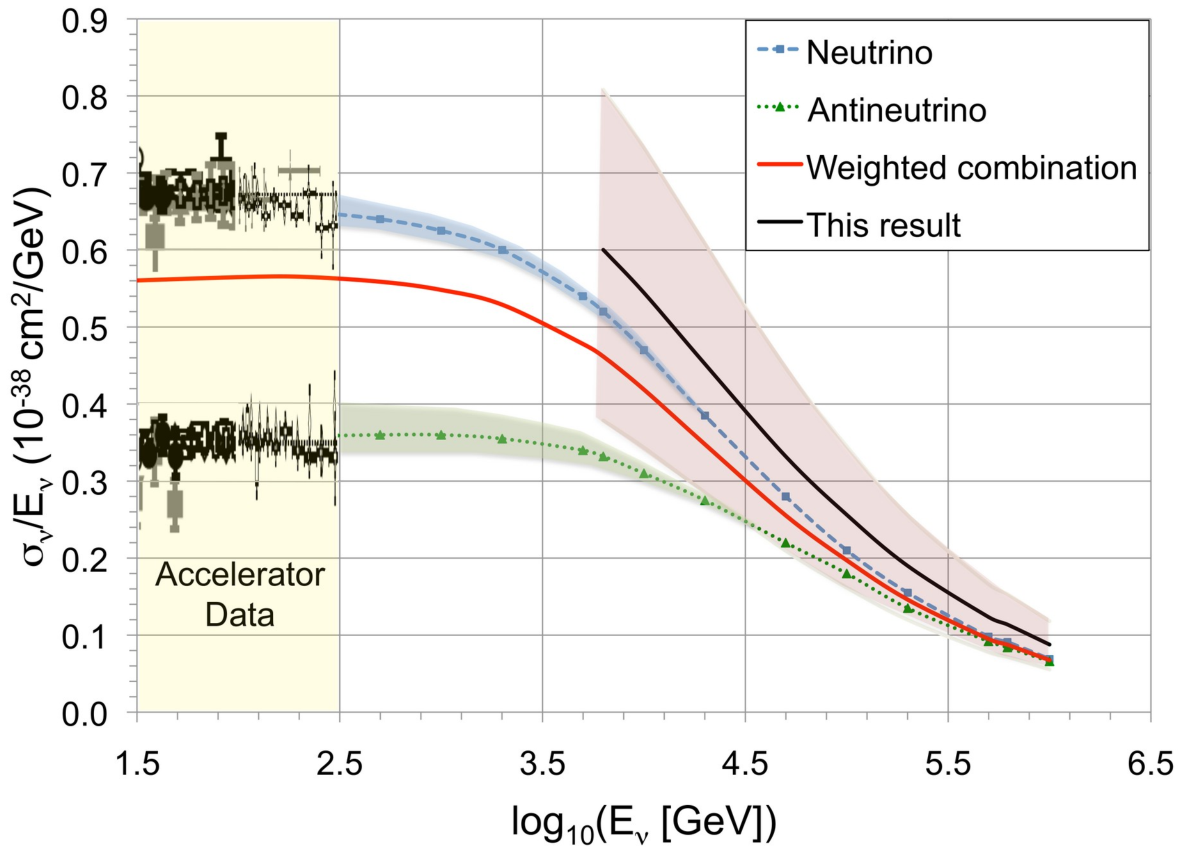
Extending the PDG cross-section plot

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



Using through-going muons instead

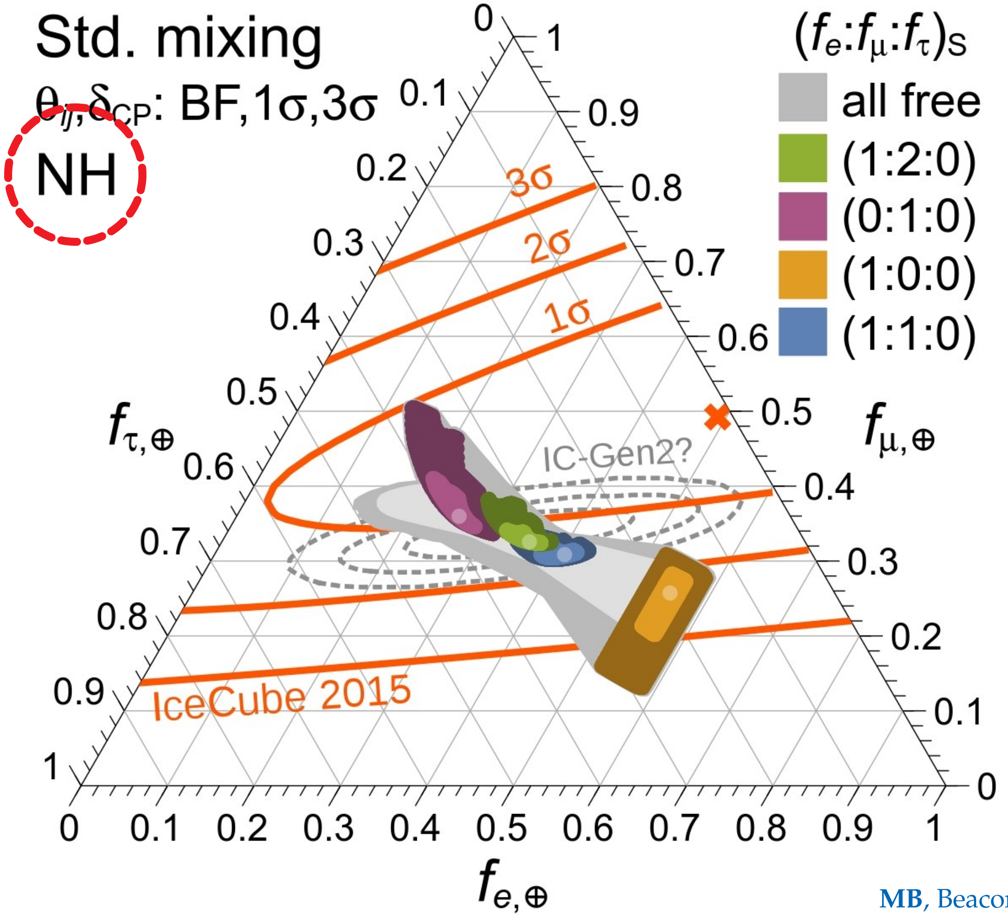
- Use ~10^4 through-going muons
- Measured: $\mathrm{d}E_\mu/\mathrm{d}x$
- Inferred: $E_\mu \approx \mathrm{d}E_\mu/\mathrm{d}x$
- From simulations (uncertain): most likely E_ν given E_μ
- Fit the ratio σ_{obs}/σ_{SM}
  $1.30\,^{+0.21}_{-0.19}(\mathrm{stat.})\,^{+0.39}_{-0.43}(\mathrm{syst.})$
- All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

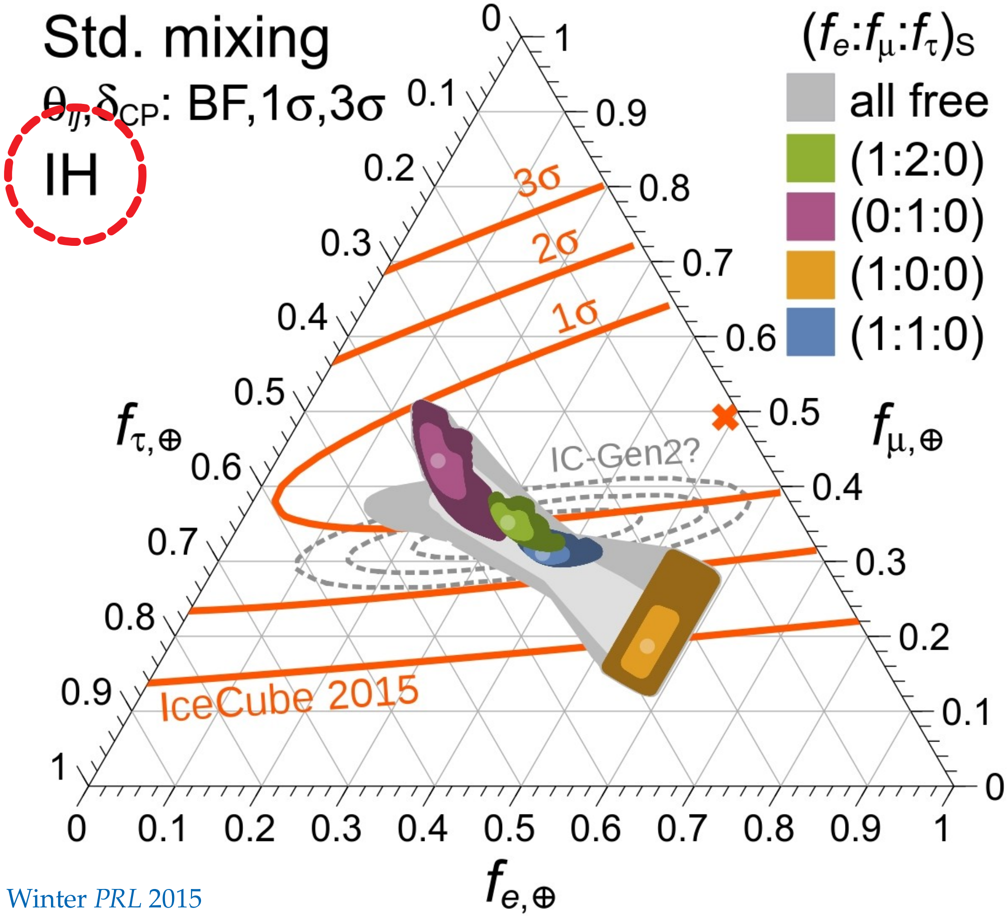


IceCube, *Nature* 2017

Flavor composition – a few source choices

Flavor composition – a few source choices

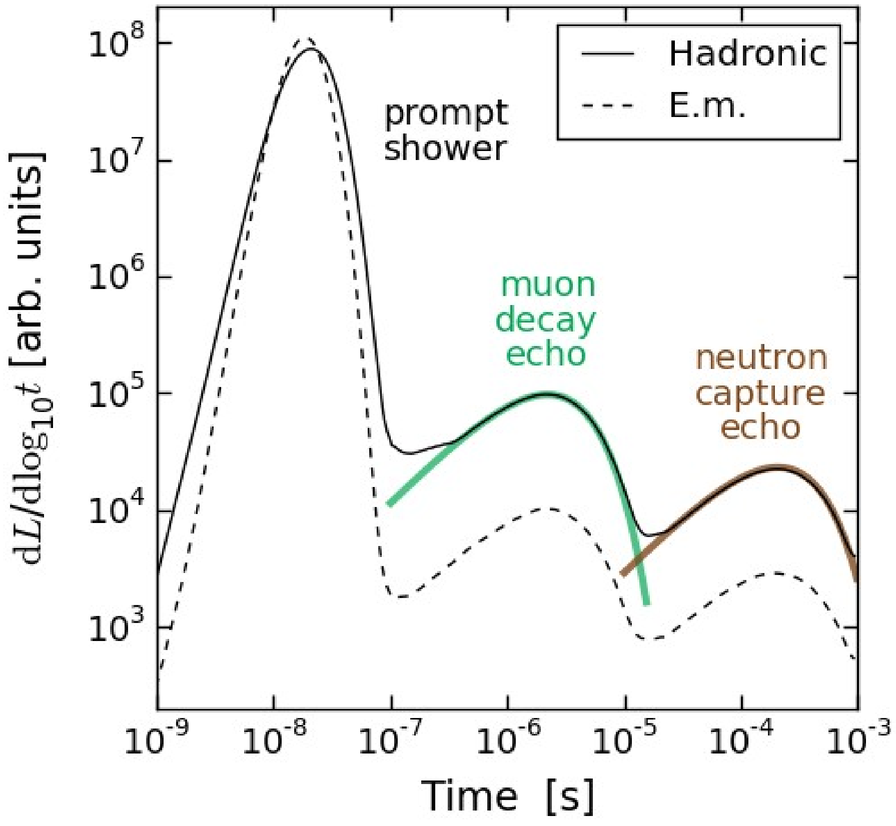


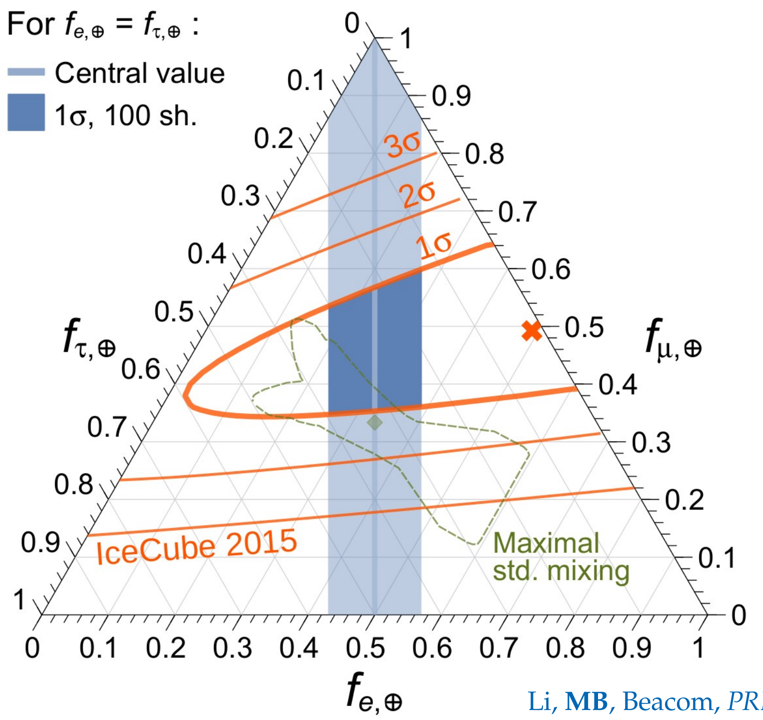


MB, Beacom, Winter *PRL* 2015

Side note: Improving flavor-tagging using *echoes*

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



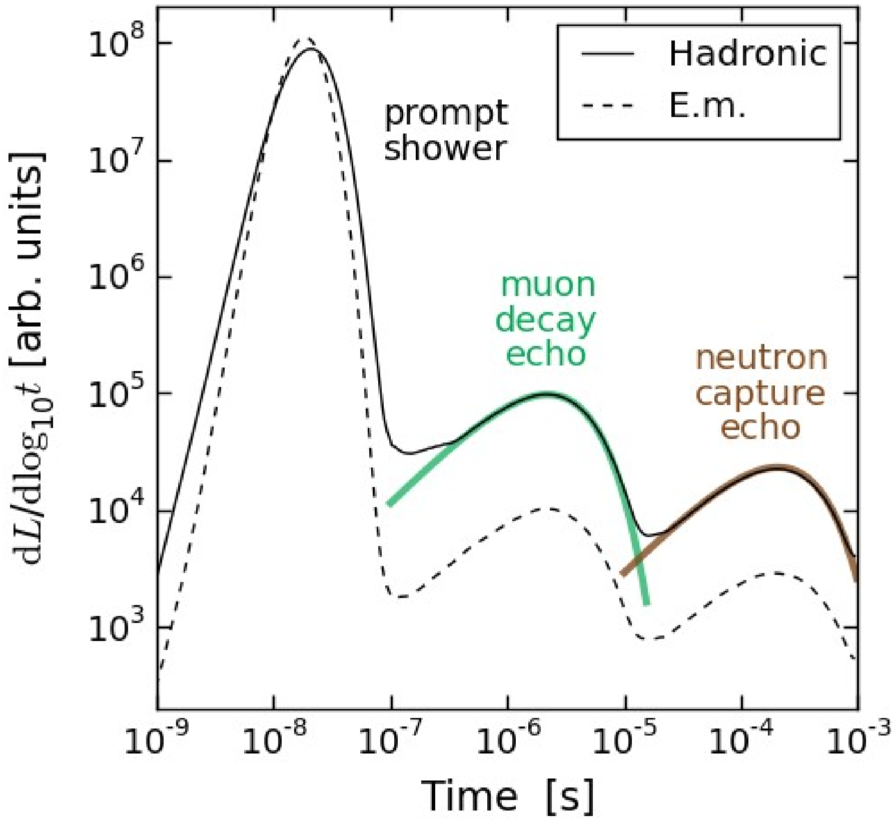


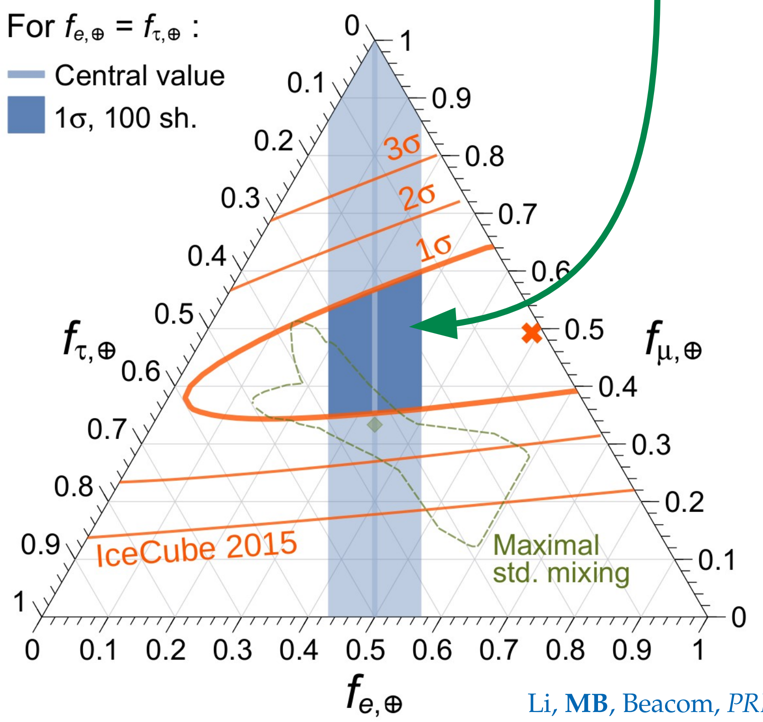
Li, **MB**, Beacom, *PRL* 2019

Side note: Improving flavor-tagging using *echoes*

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

~10 × improvement over current measurement





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

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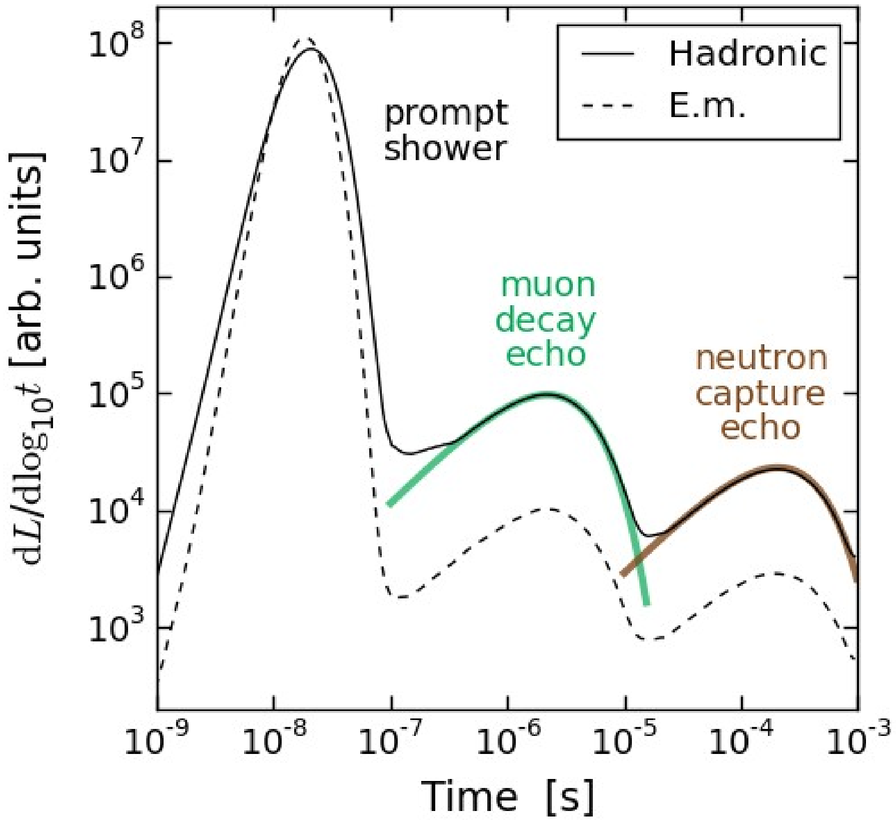

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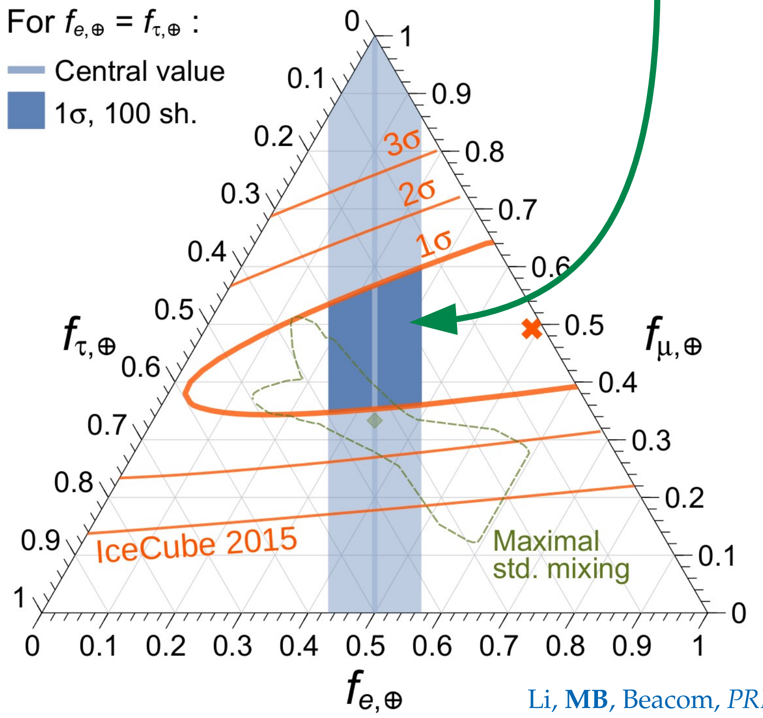
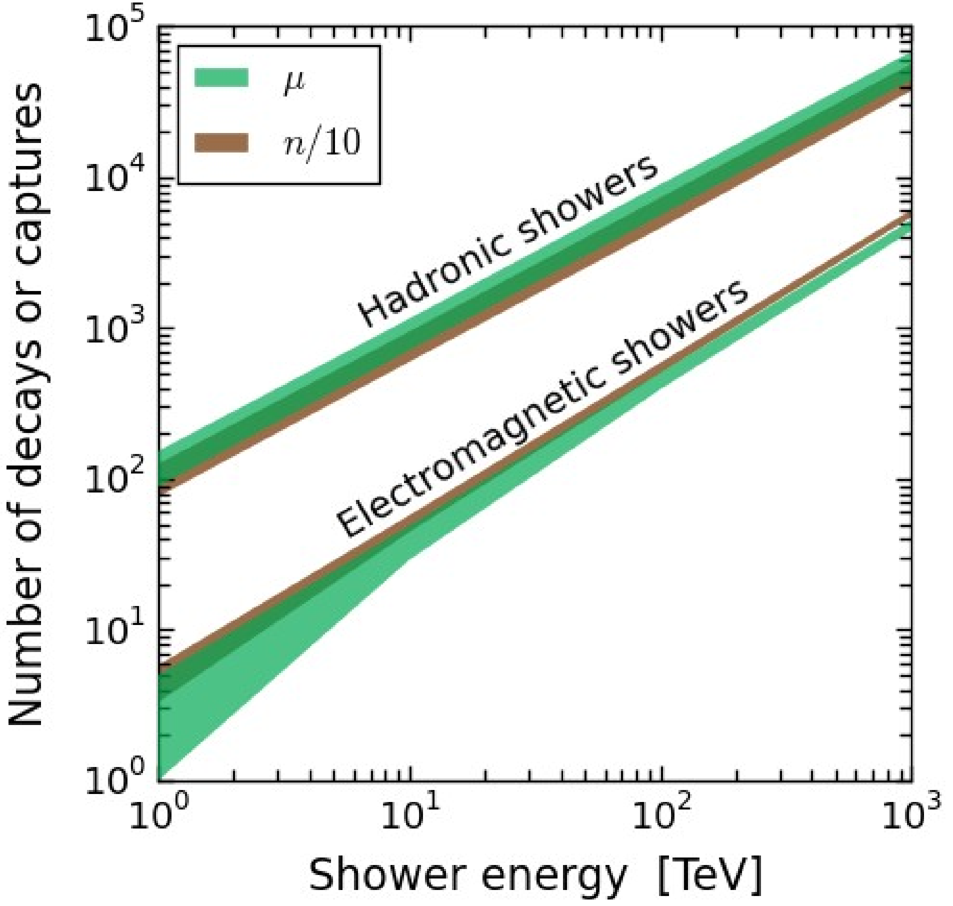
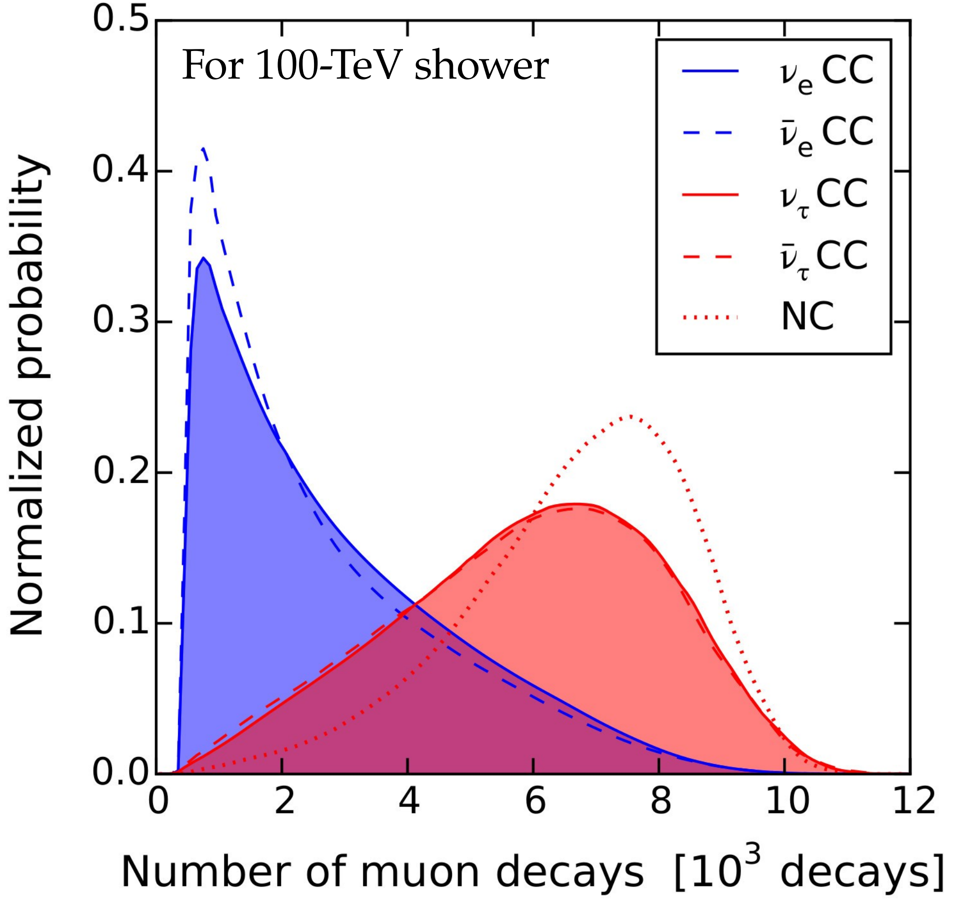


Li, **MB**, Beacom, *PRL* 2019

Hadronic *vs.* electromagnetic showers





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

Connecting flavor-ratio predictions to experiment

1. Integrate potential in redshift, weighed by source number density
   $\mapsto$ Assume star formation rate

$$\langle V_{e\beta}^{\cos} \rangle \propto \int dz \; \rho_{\rm SFR}(z) \cdot \frac{dV_{\rm c}}{dz} \cdot V_{e\beta}^{\cos}(z)$$

Density of cosmological *e* grows with *z*

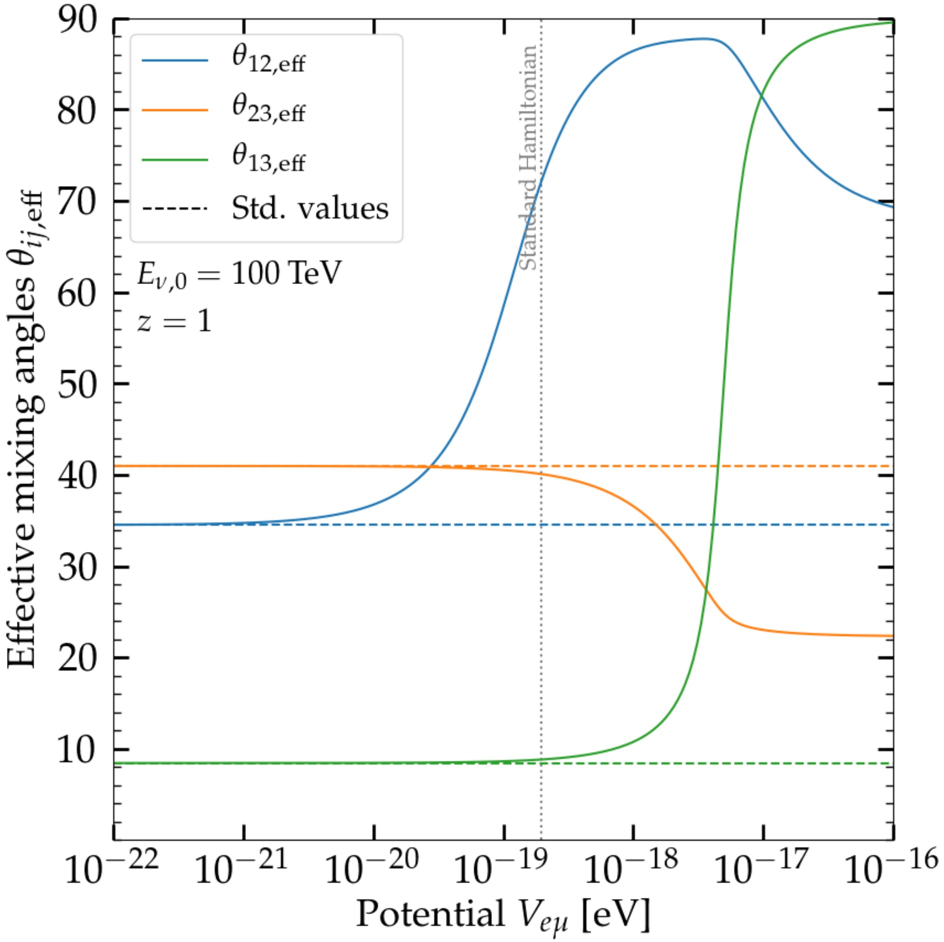
2. Convolve flavor ratios with observed neutrino energy spectrum
   $\mapsto$ Either $E^{-2.50}$ (combined analysis) or $E^{-2.13}$ (through-going muons)

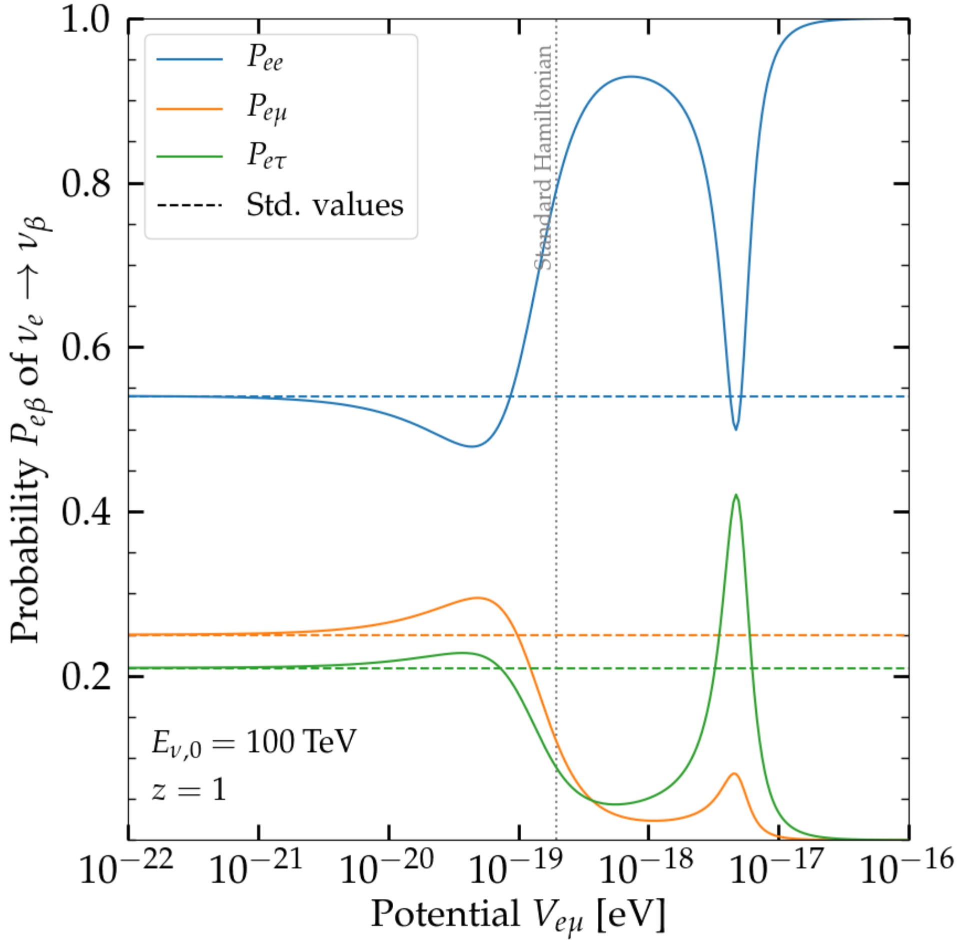
$$\langle \Phi_\alpha \rangle \propto \int dE_\nu \; f_{\alpha,\oplus}(E_\nu) \; E_\nu^{-\gamma} \quad \Rightarrow \quad \langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}$$

Energy-averaged flux

Energy-averaged flavor ratios

Resonance due to the L_e-L_μ symmetry





Resonance due to the L_e-L_μ symmetry (*cont.*)