

Pushing Neutrino Physics to the Cosmic Frontier

Mauricio Bustamante

Niels Bohr Institute, University of Copenhagen

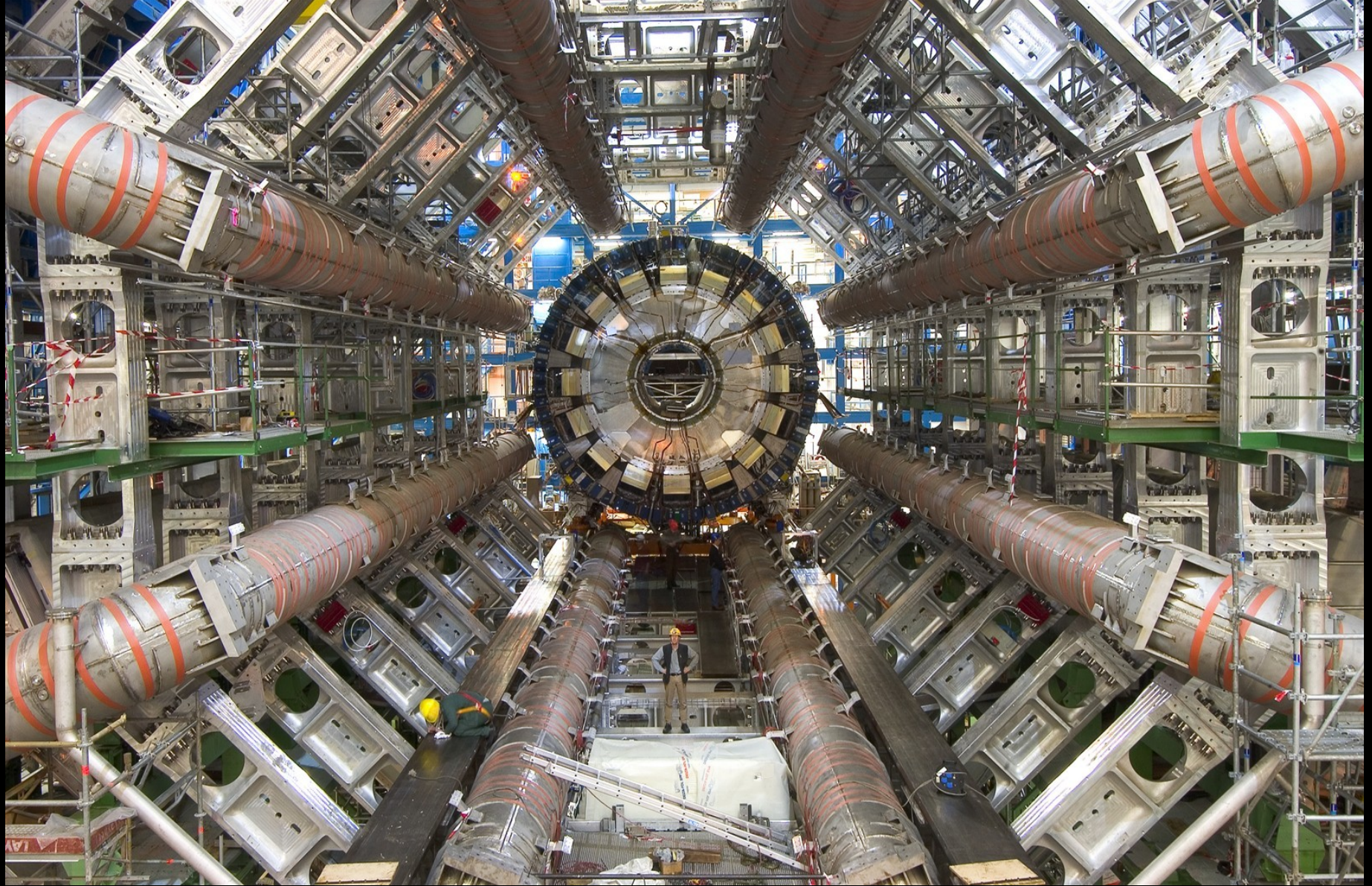
Particle Astrophysics Seminar
August 02, 2019

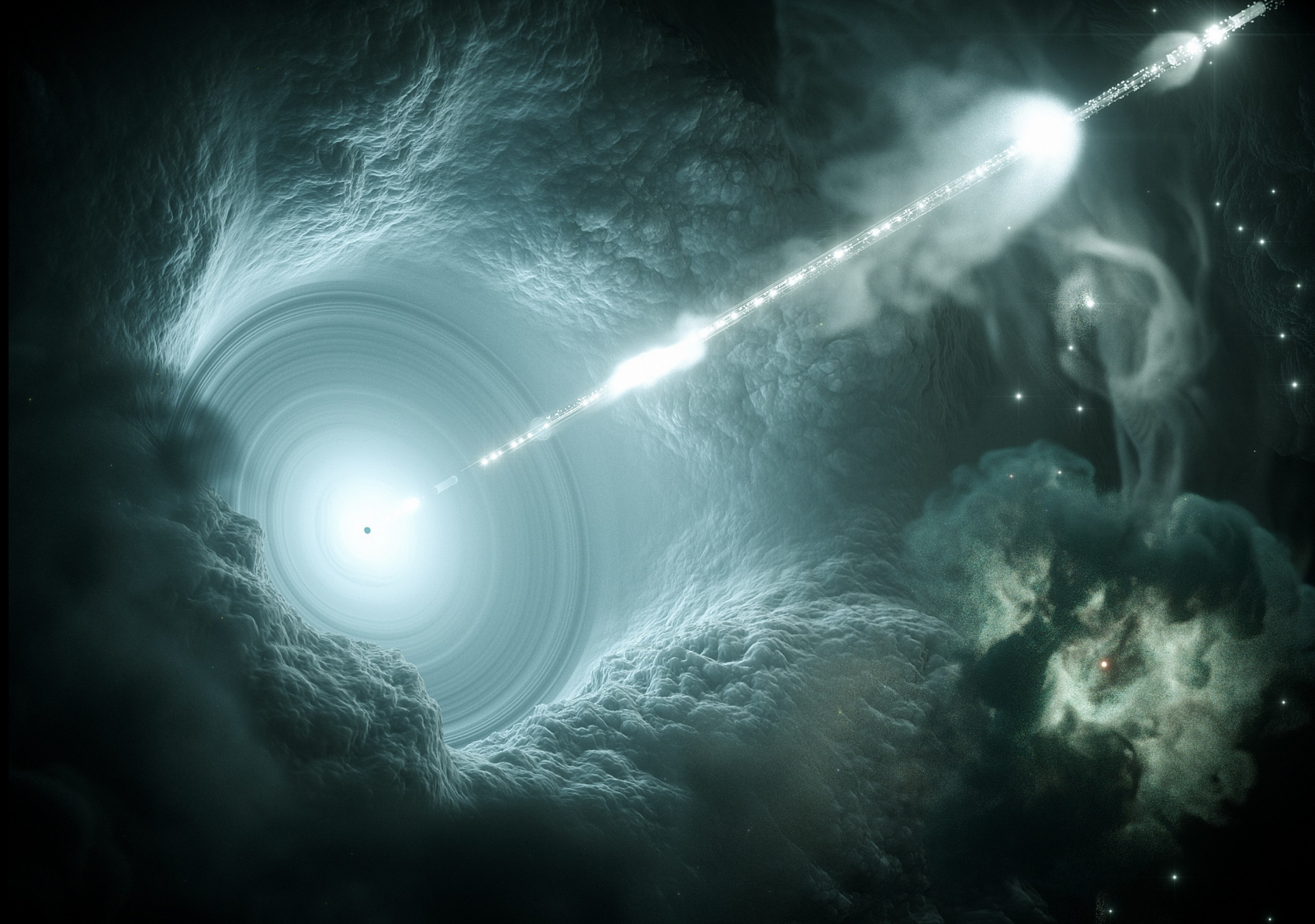
UNIVERSITY OF
COPENHAGEN

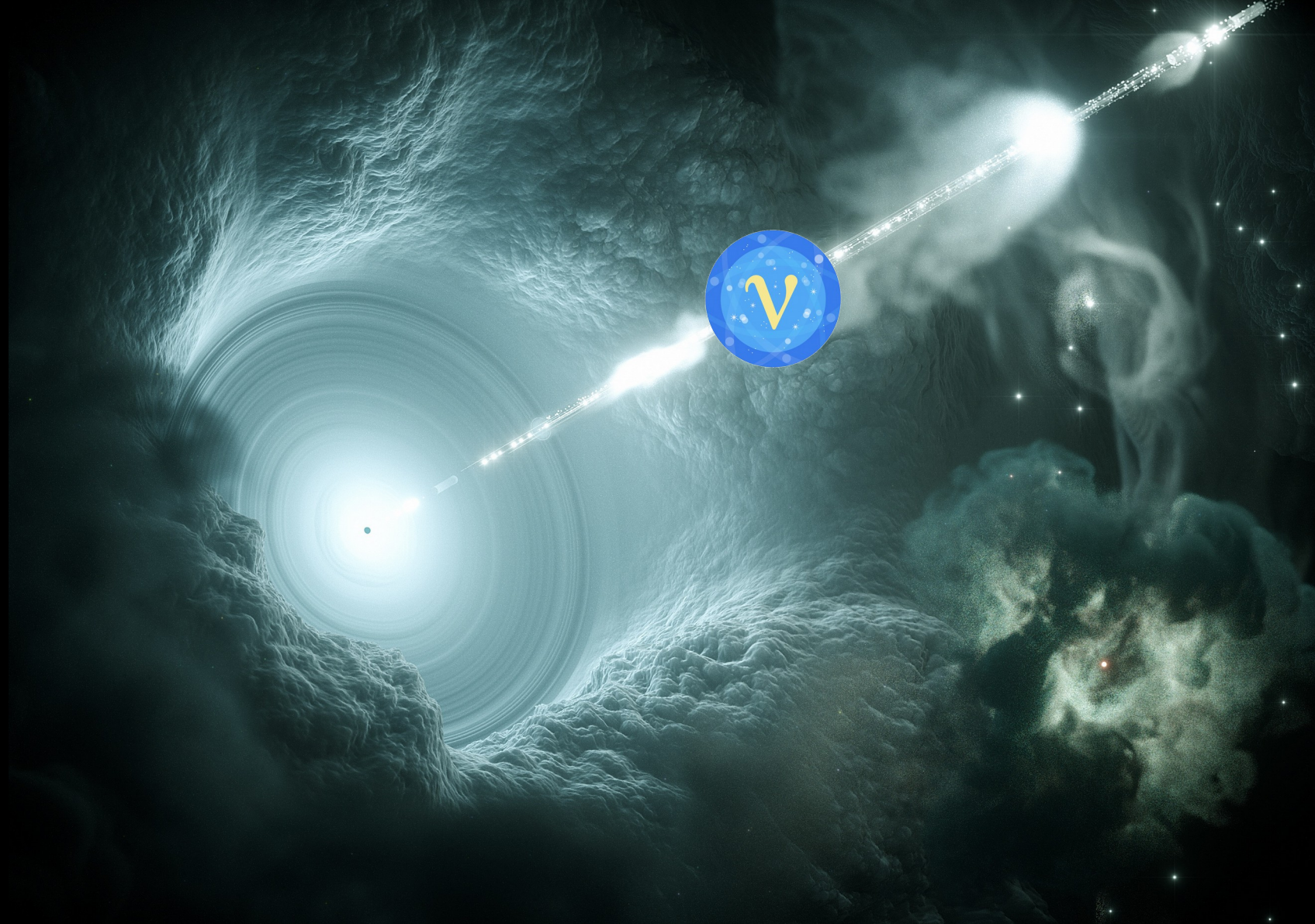


VILLUM FONDEN









Why study fundamental physics with HE cosmic ν ?

Why study fundamental physics with HE cosmic ν ?

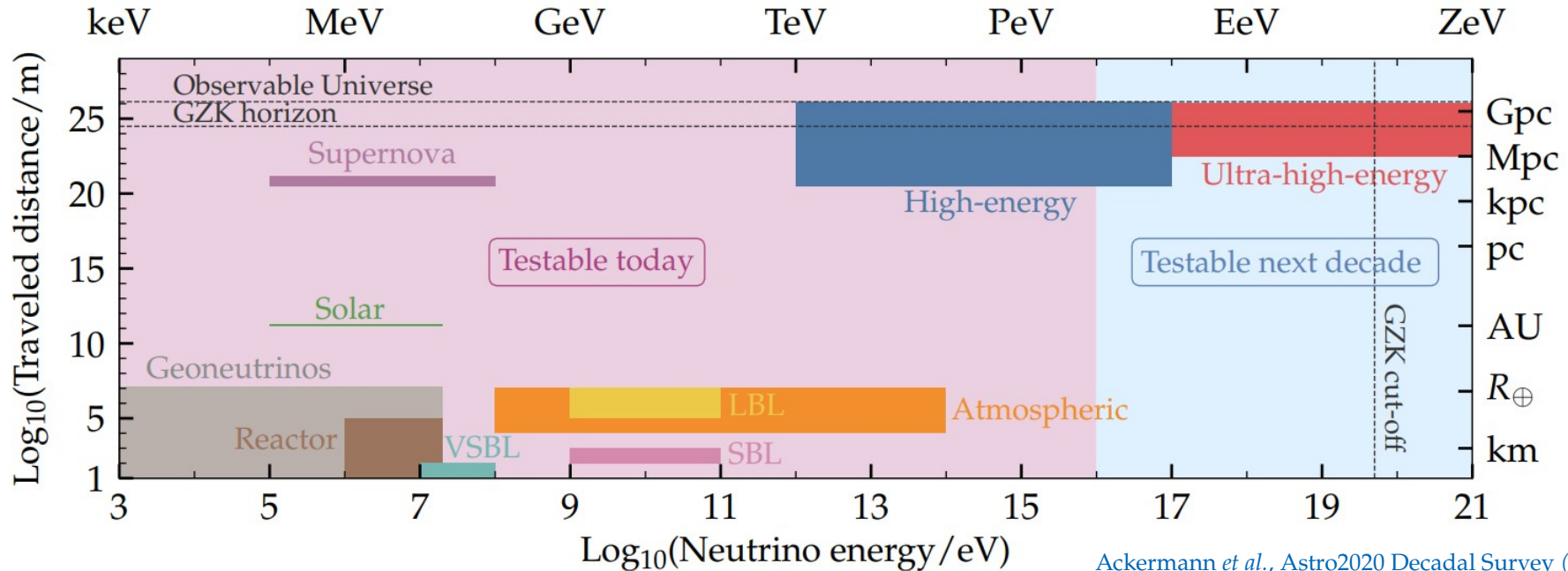
- 1 They have the **highest energies** ($\sim \text{PeV}$)
→ Probe physics at new energy scales

Why study fundamental physics with HE cosmic ν ?

- 1 They have the **highest energies** ($\sim$ PeV)
→ Probe physics at new energy scales
- 2 They have the **longest baselines** ($\sim$ Gpc)
→ Tiny effects can accumulate and become observable

Why study fundamental physics with HE cosmic ν ?

- 1 They have the **highest energies** ($\sim$ PeV)
→ Probe physics at new energy scales
- 2 They have the **longest baselines** ($\sim$ Gpc)
→ Tiny effects can accumulate and become observable



Why study fundamental physics with HE cosmic ν ?

Why study fundamental physics with HE cosmic ν ?

- 3 Neutrinos are weakly interacting
 - New effects may stand out more clearly

Why study fundamental physics with HE cosmic ν ?

- 3 Neutrinos are **weakly interacting**
 - New effects may stand out more clearly

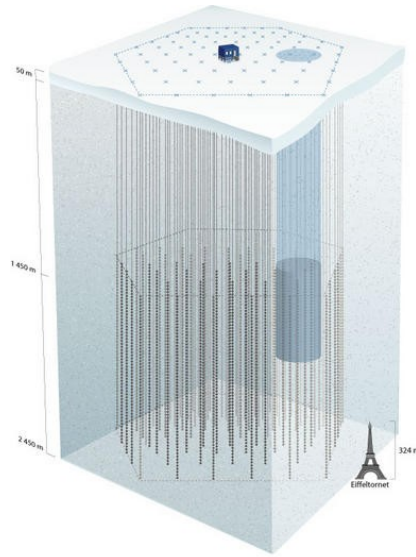
- 4 Neutrinos have a unique quantum number: **flavor**
 - Powerful probe of neutrino physics (and astrophysics)

Why study fundamental physics with HE cosmic ν ?

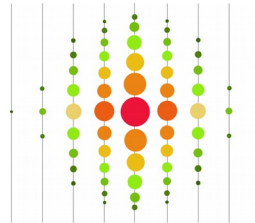
- 3 Neutrinos are **weakly interacting**
→ New effects may stand out more clearly
- 4 Neutrinos have a unique quantum number: **flavor**
→ Powerful probe of neutrino physics (and astrophysics)
- 5 It comes *for free*

IceCube (8 years)

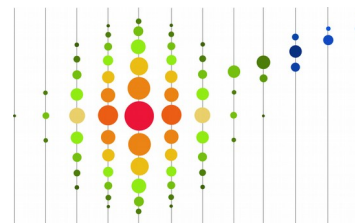
km³ in-ice
Cherenkov detector



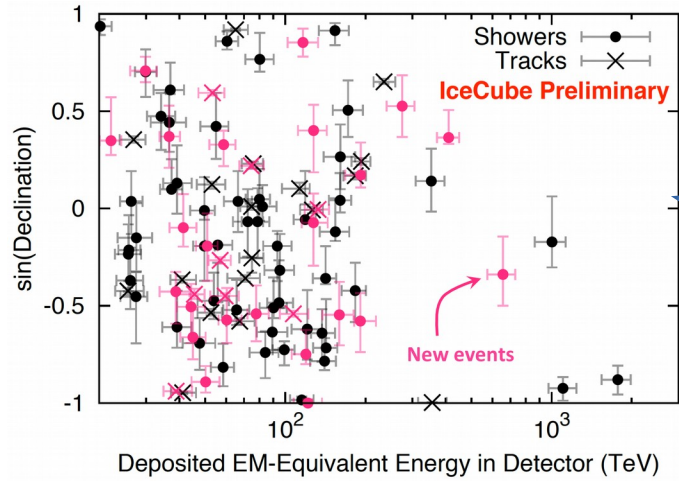
Showers
(mostly from ν_e , ν_τ)



Tracks
(from ν_μ)

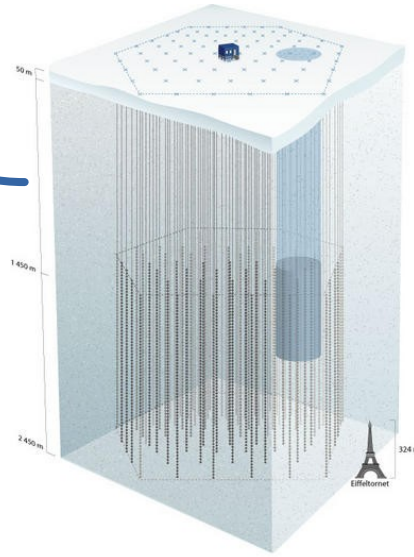


103 contained events, 15 TeV–2 PeV

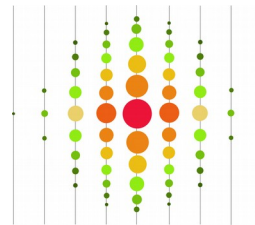


IceCube (8 years)

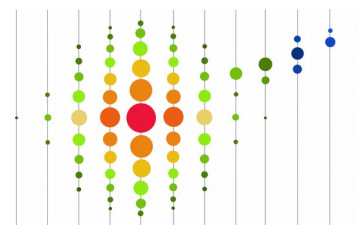
km³ in-ice
Cherenkov detector



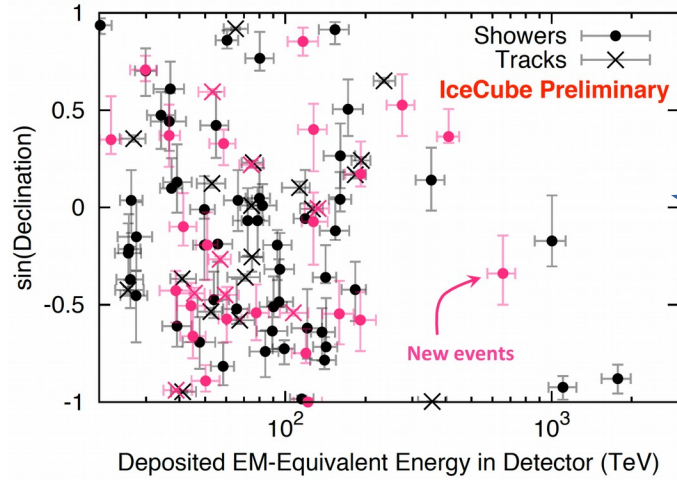
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)

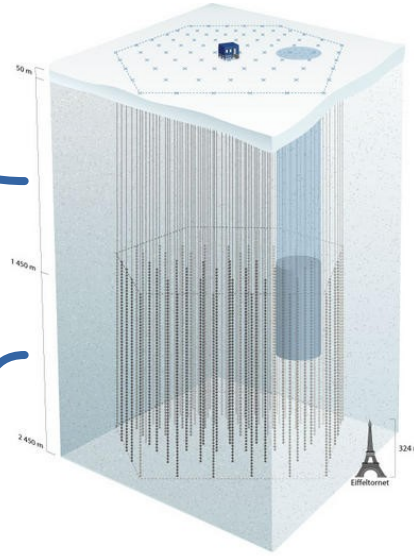


103 contained events, 15 TeV–2 PeV

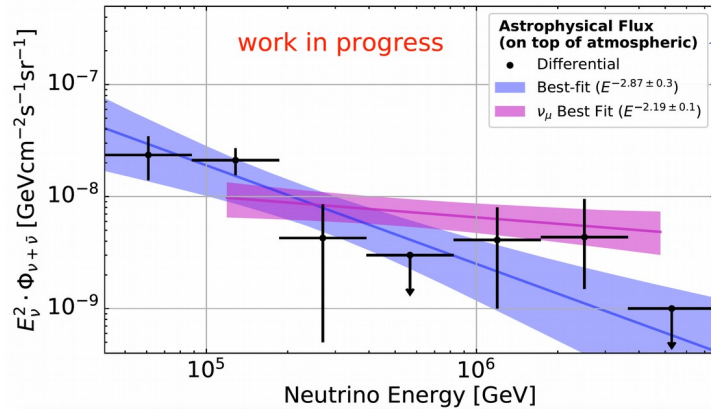


IceCube (8 years)

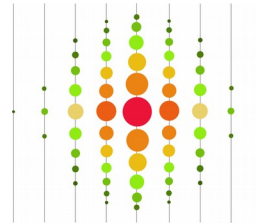
km³ in-ice
Cherenkov detector



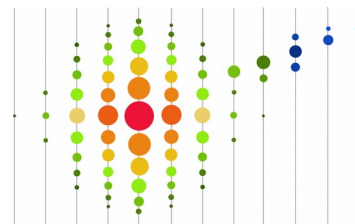
Astrophysical ν flux detected at $> 7\sigma$



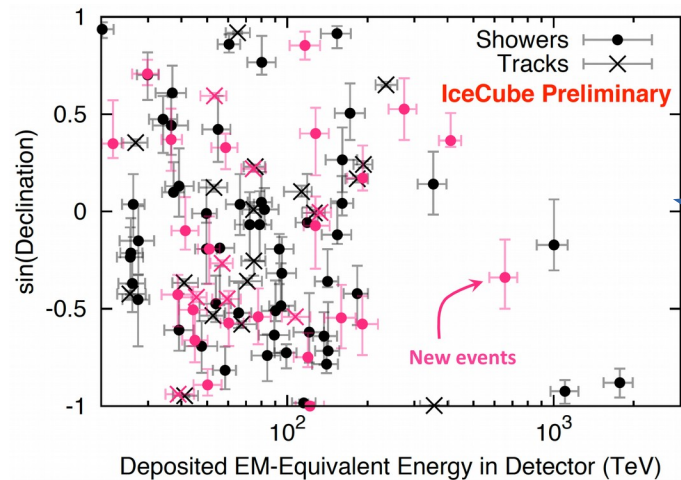
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)

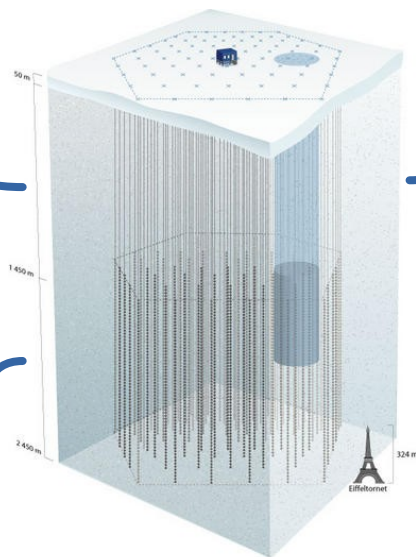


103 contained events, 15 TeV–2 PeV

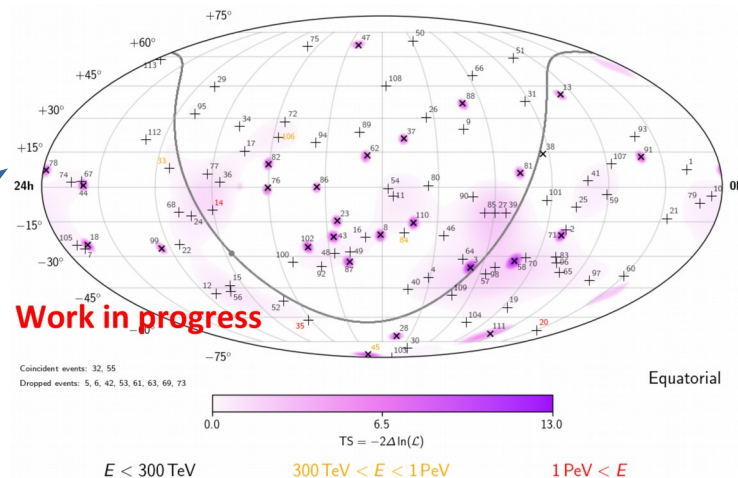


IceCube (8 years)

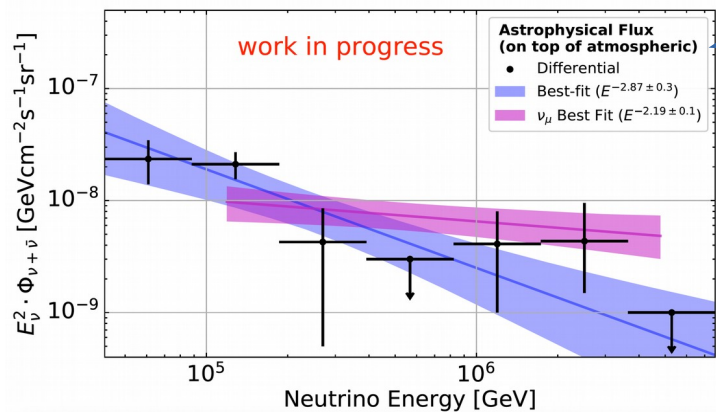
km³ in-ice
Cherenkov detector



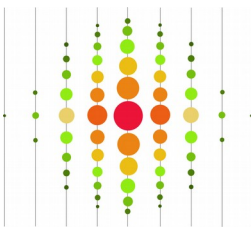
Arrival directions compatible with isotropy



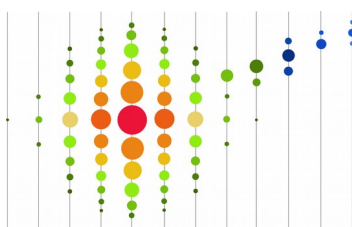
Astrophysical ν flux detected at $> 7\sigma$



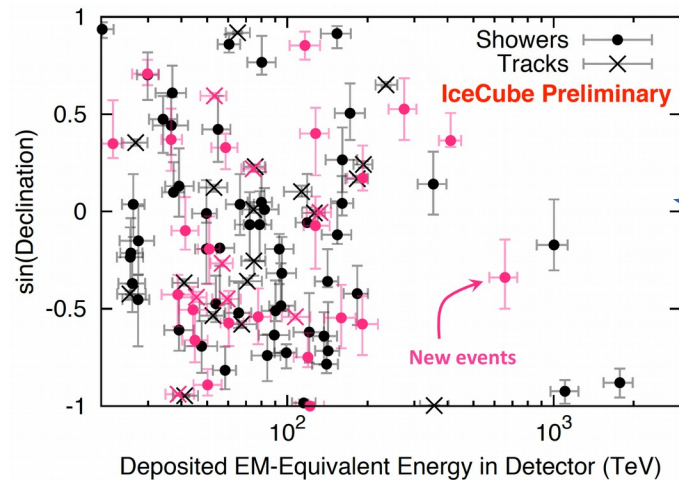
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)

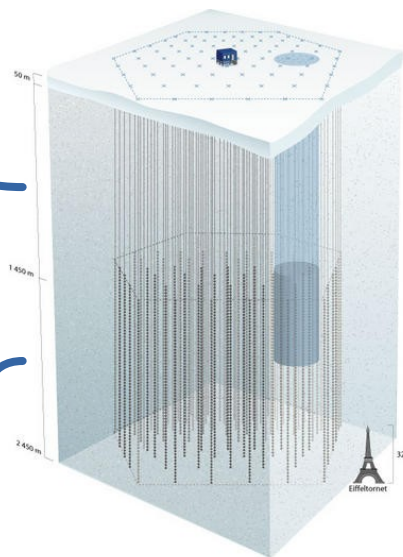


103 contained events, 15 TeV–2 PeV

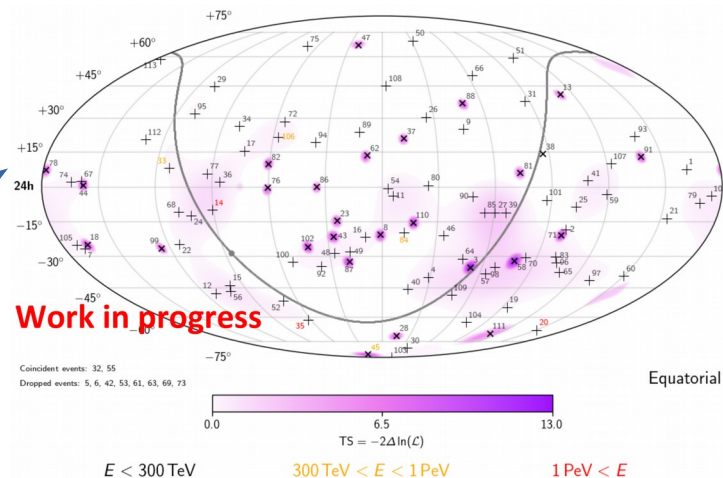


IceCube (8 years)

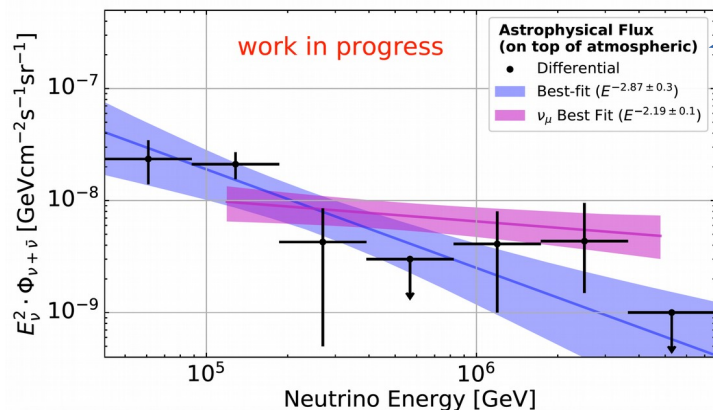
km³ in-ice
Cherenkov detector



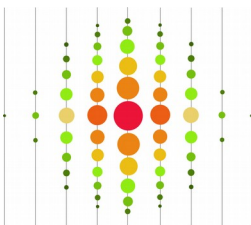
Arrival directions compatible with isotropy



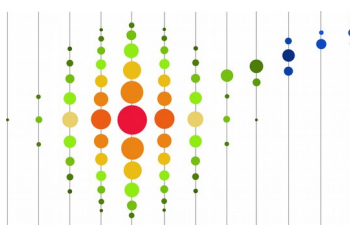
Astrophysical ν flux detected at $> 7\sigma$



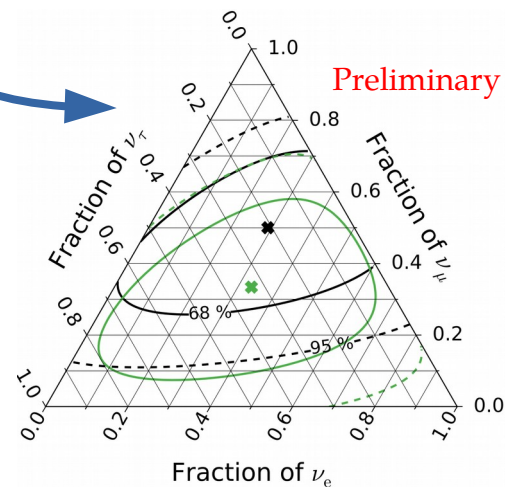
Showers
(mostly from ν_e, ν_τ)



Tracks
(from ν_μ)



Flavor composition



In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

Yes.

In the face of astrophysical unknowns,
can we extract fundamental TeV–PeV ν physics?

Yes.

Already today.

Astrophysical unknowns





Neutrino physicist

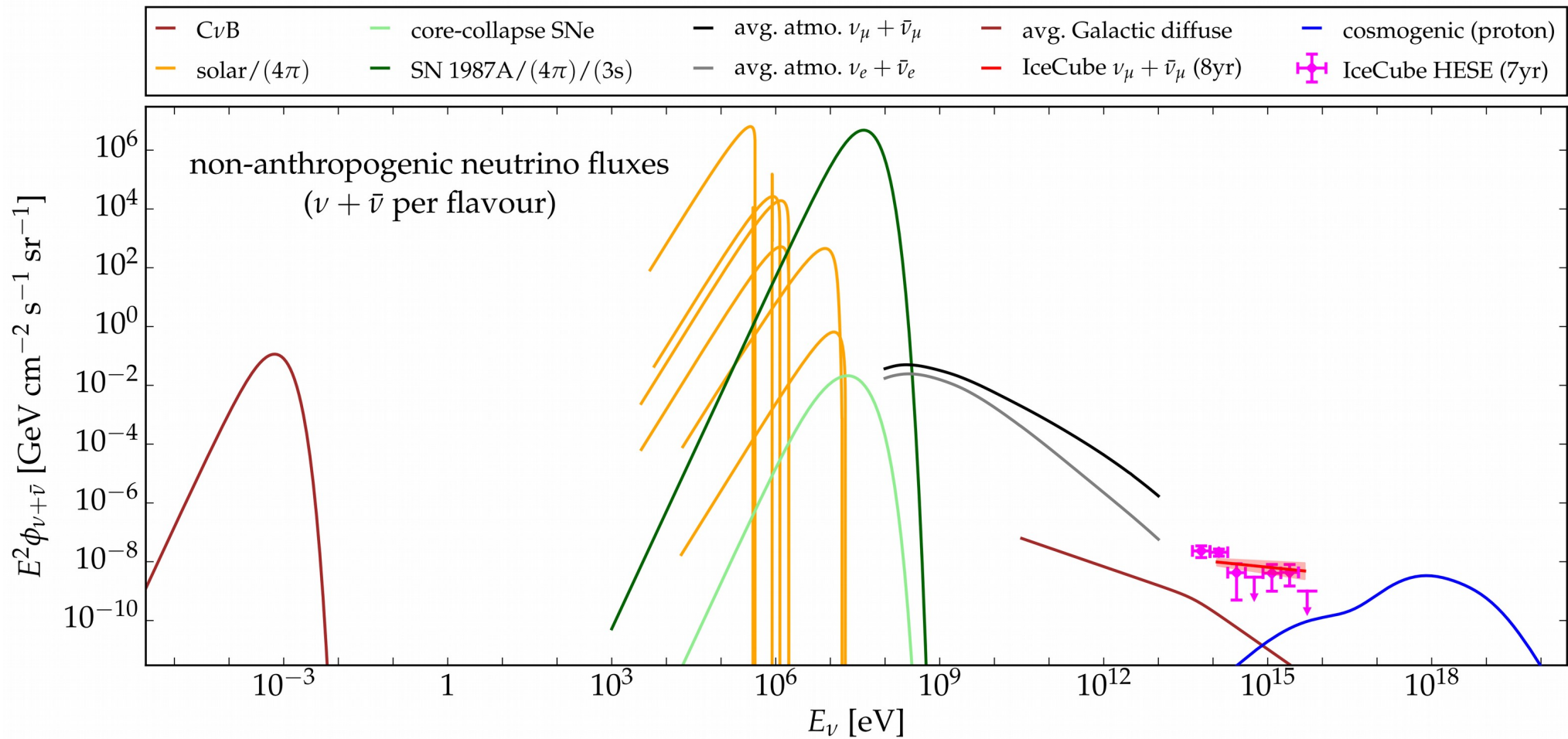


Figure courtesy of Markus Ahlers
Also in: [Van Elewyck et al., PoS\(ICRC2019\), 1023](#)

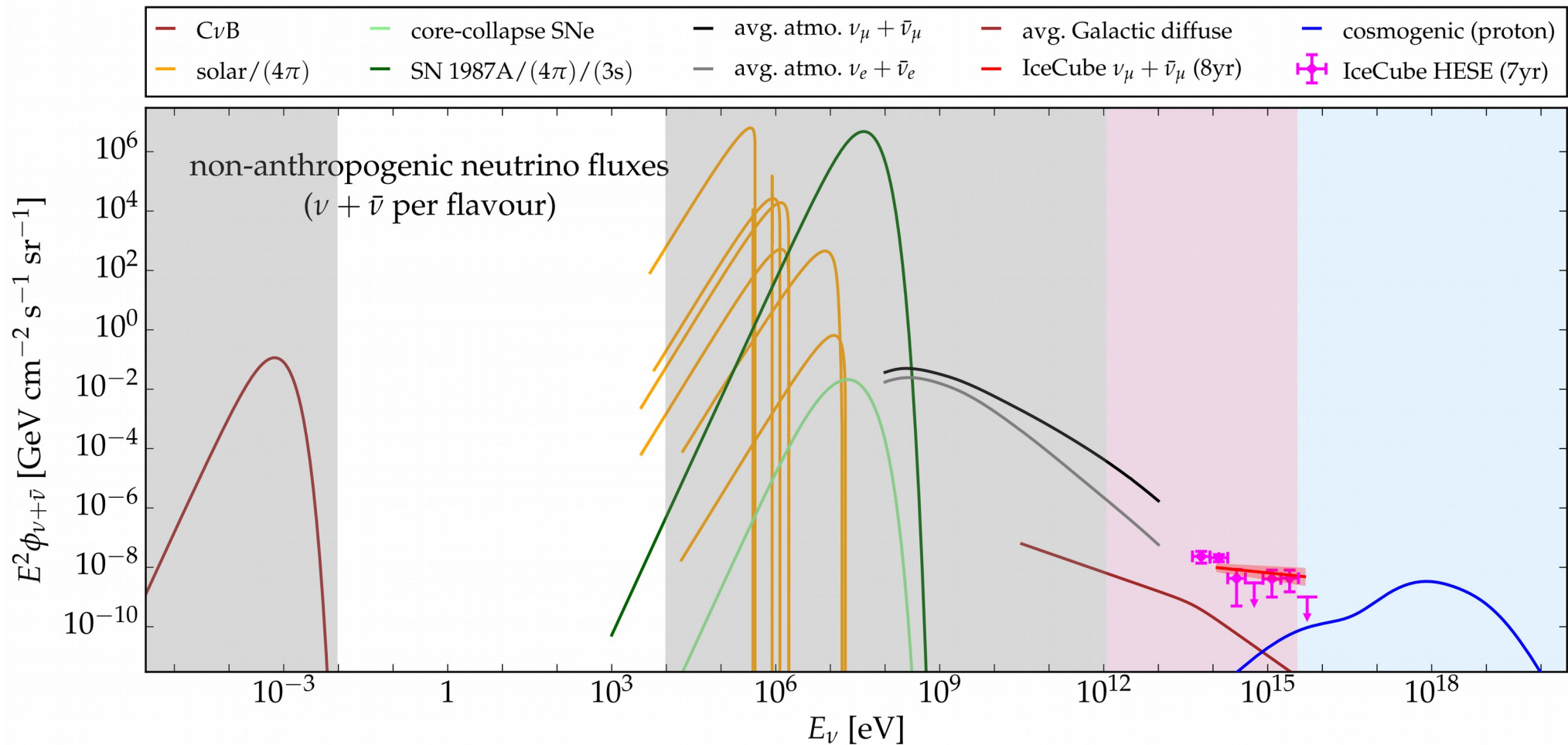


Figure courtesy of Markus Ahlers
Also in: [Van Elewyck et al., PoS\(ICRC2019\), 1023](#)

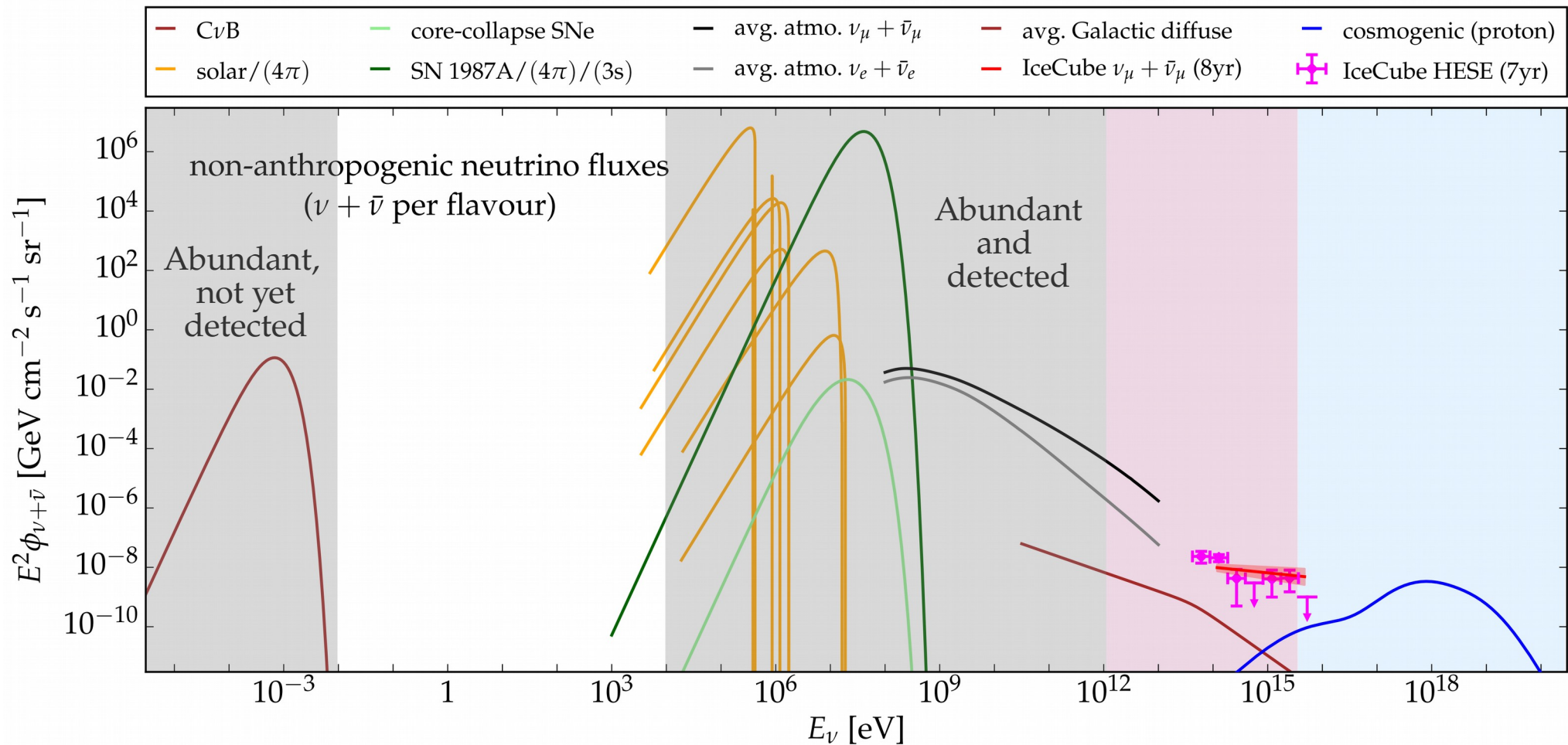


Figure courtesy of Markus Ahlers
 Also in: [Van Elewyck *et al.*, PoS\(ICRC2019\), 1023](#)

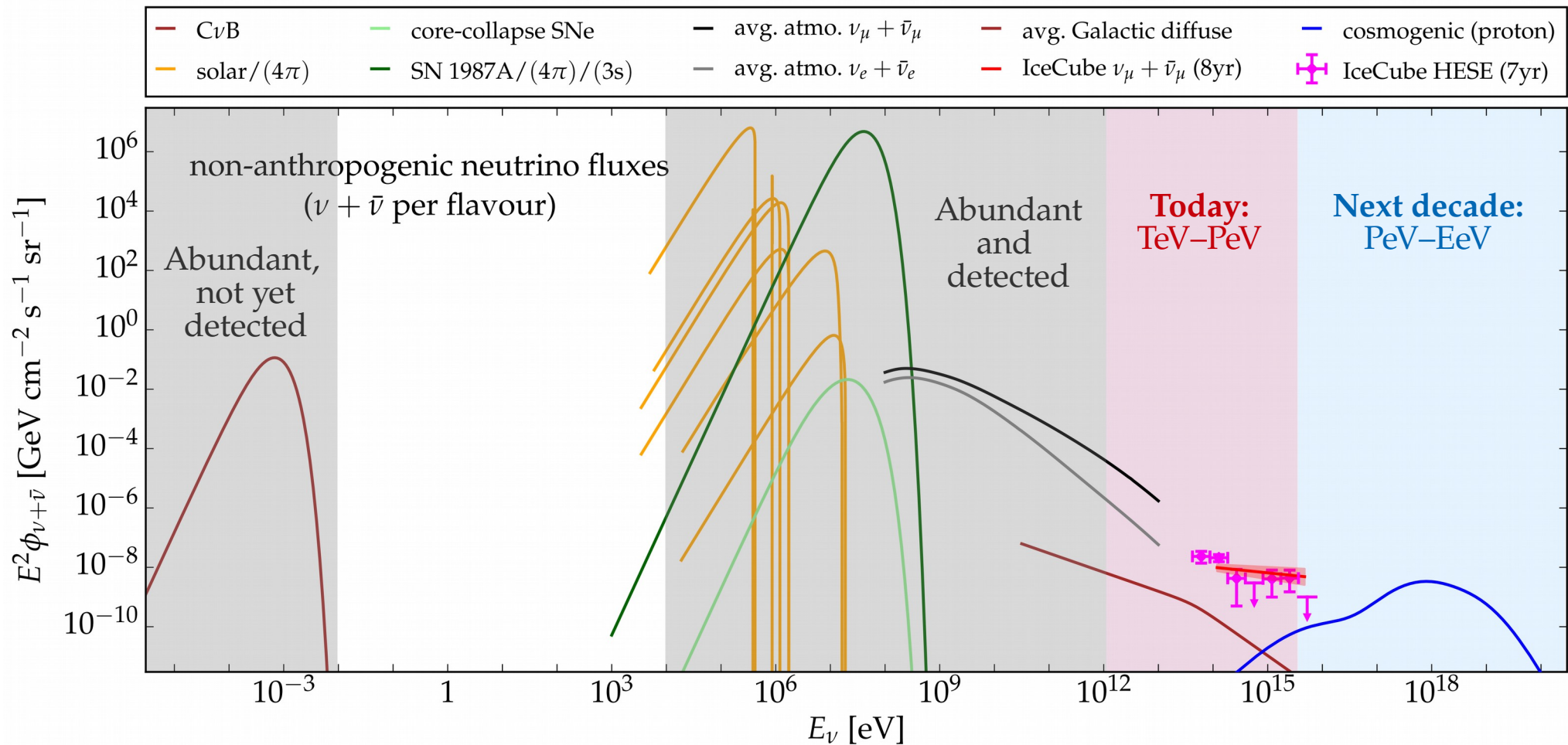
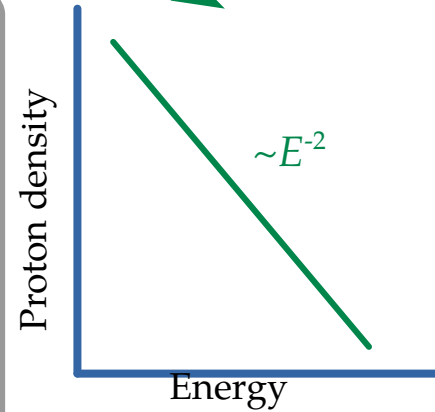
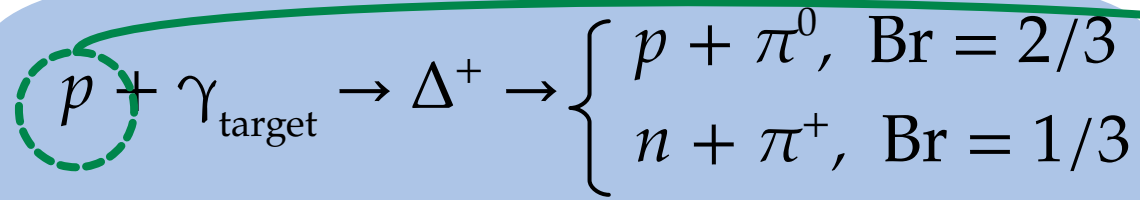


Figure courtesy of Markus Ahlers
 Also in: [Van Elewyck et al., PoS\(ICRC2019\), 1023](#)

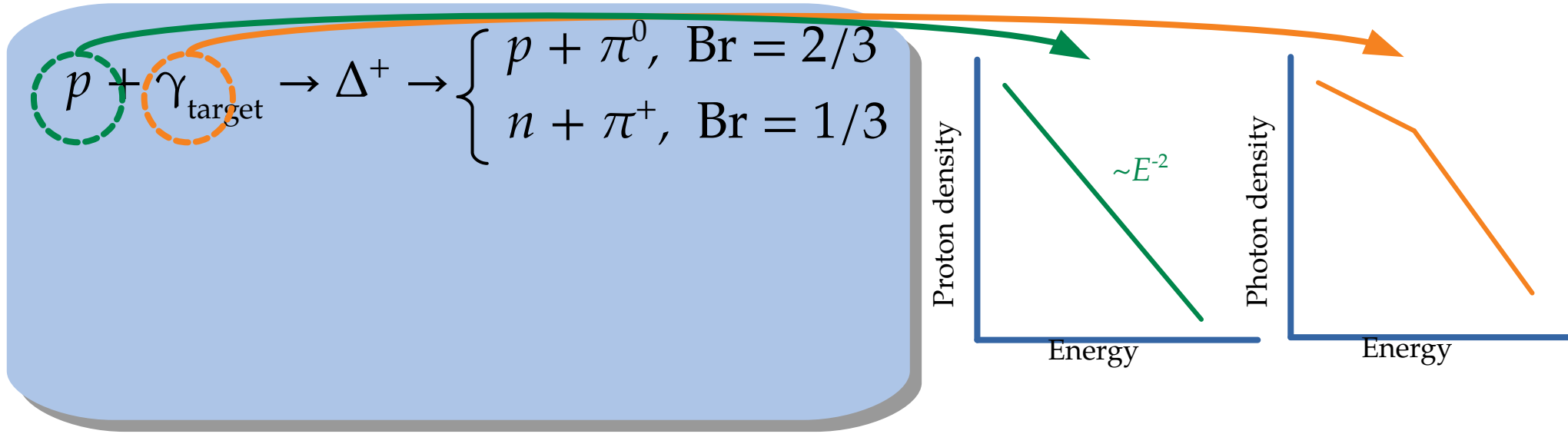
The multi-messenger connection

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

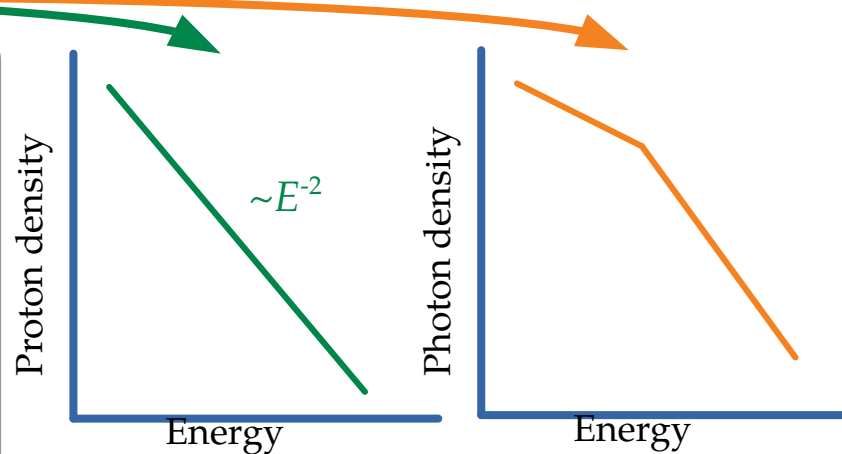
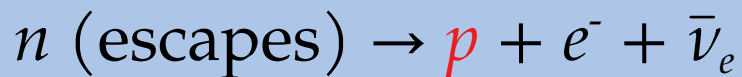
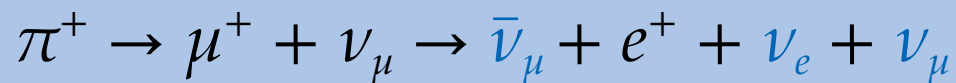
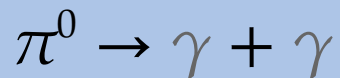
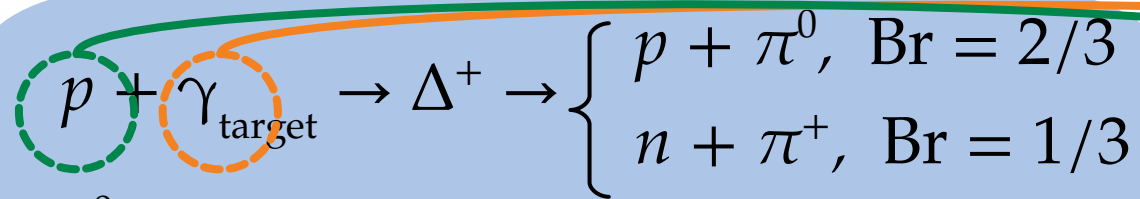
The multi-messenger connection



The multi-messenger connection



The multi-messenger connection



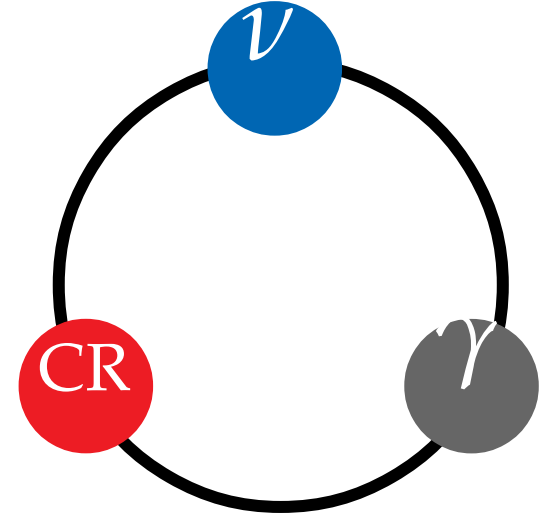
The multi-messenger connection

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

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

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

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



Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

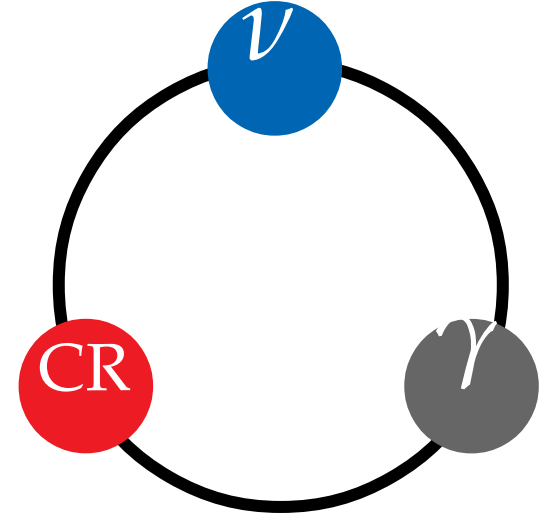
The multi-messenger connection

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

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

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

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



1 PeV

20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

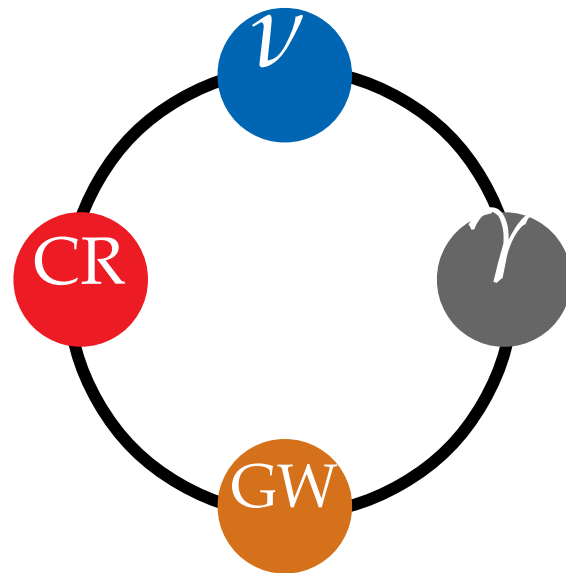
The multi-messenger connection

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

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

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

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



1 PeV

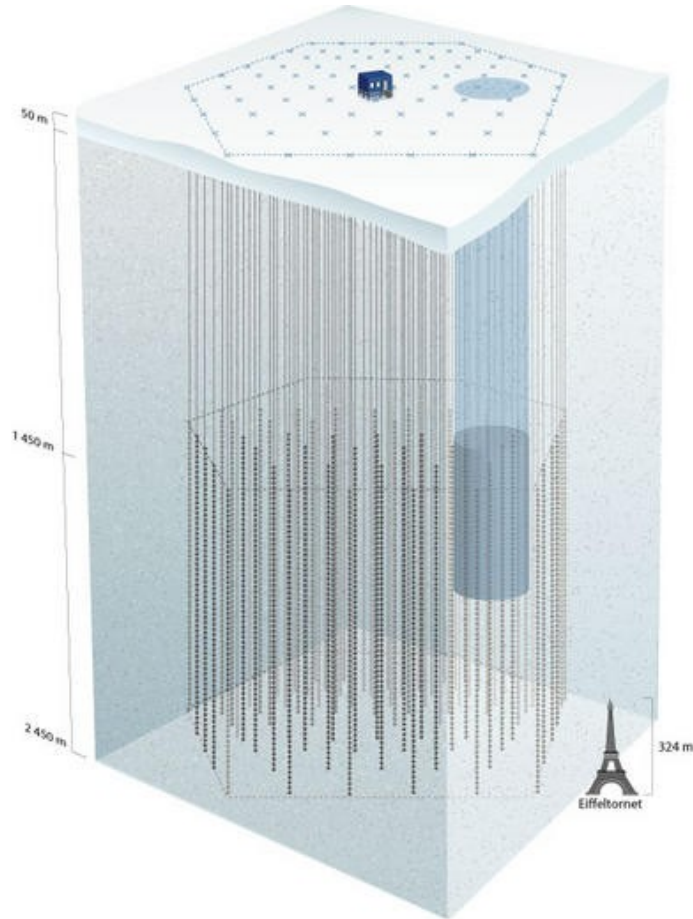
20 PeV

Neutrino energy = Proton energy / 20

Gamma-ray energy = Proton energy / 10

IceCube – What is it?

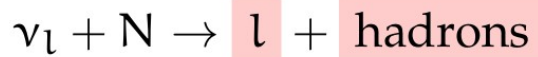
- ▶ Km^3 in-ice Cherenkov detector in Antarctica
- ▶ >5000 PMTs at 1.5–2.5 km of depth
- ▶ Sensitive to neutrino energies $> 10 \text{ GeV}$



How does IceCube see neutrinos?

Two types of fundamental interactions ...

Charged-current (CC)



Neutral-current (NC)



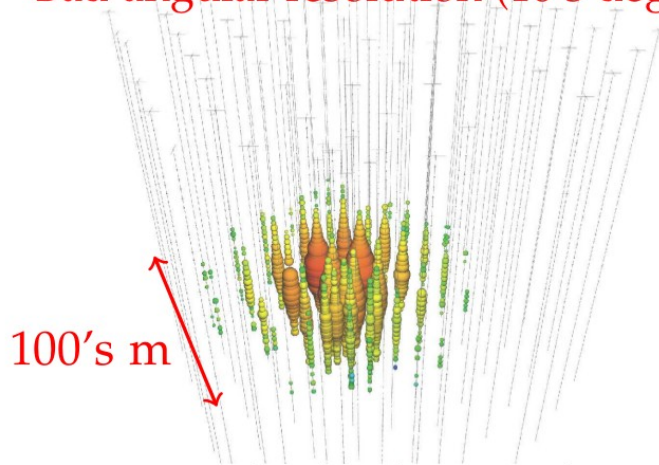
...create two event topologies ...

These shower and make light

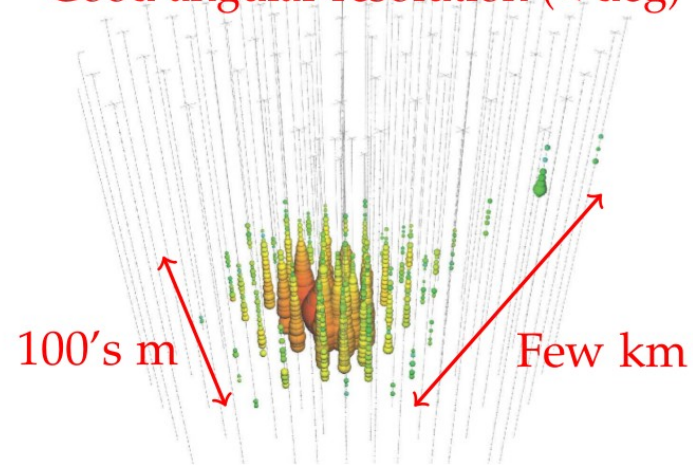
Showers — From CC ν_e or ν_τ , or NC ν_χ

Tracks — From CC ν_μ mainly

Bad angular resolution (10's deg)



Good angular resolution (< deg)

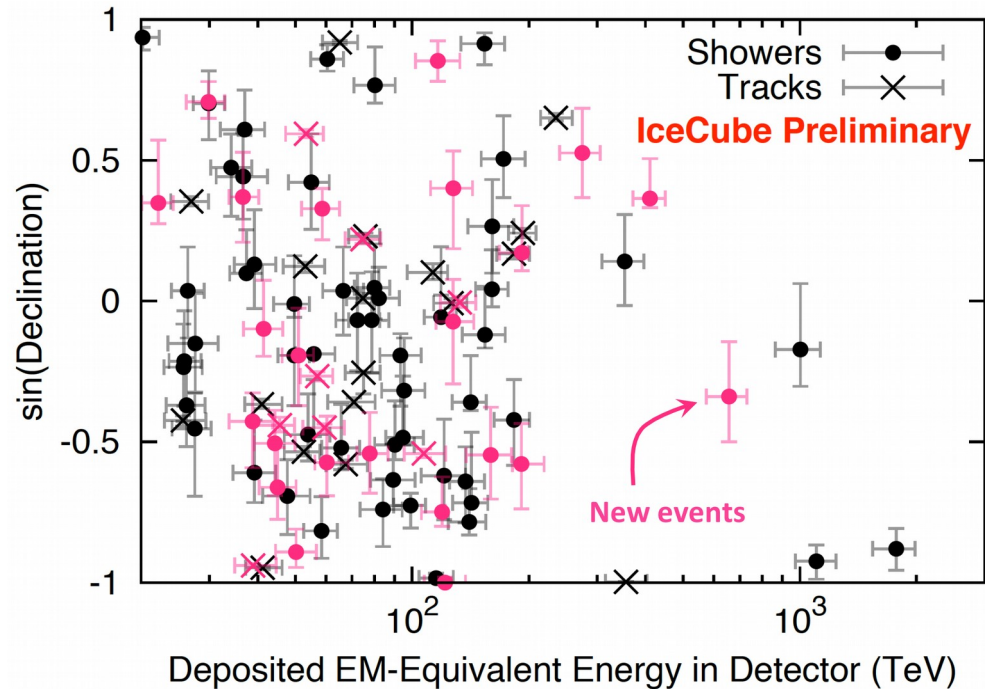


What has IceCube found so far (7.5 years)?

What has IceCube found so far (7.5 years)?

What has IceCube found so far (7.5 years)?

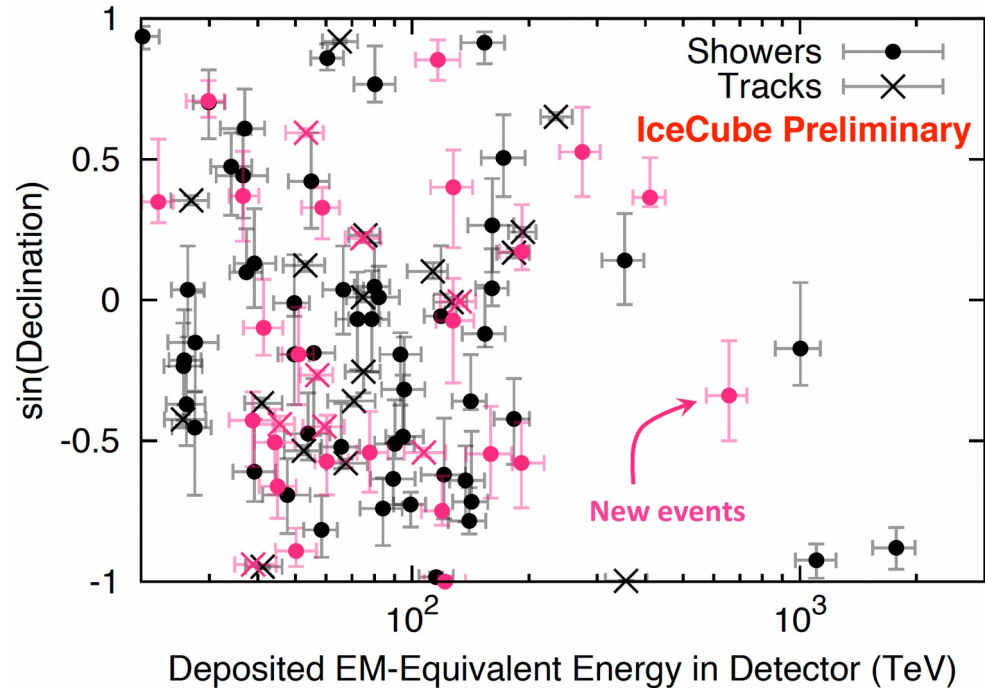
103 contained events between 15 TeV – 2 PeV



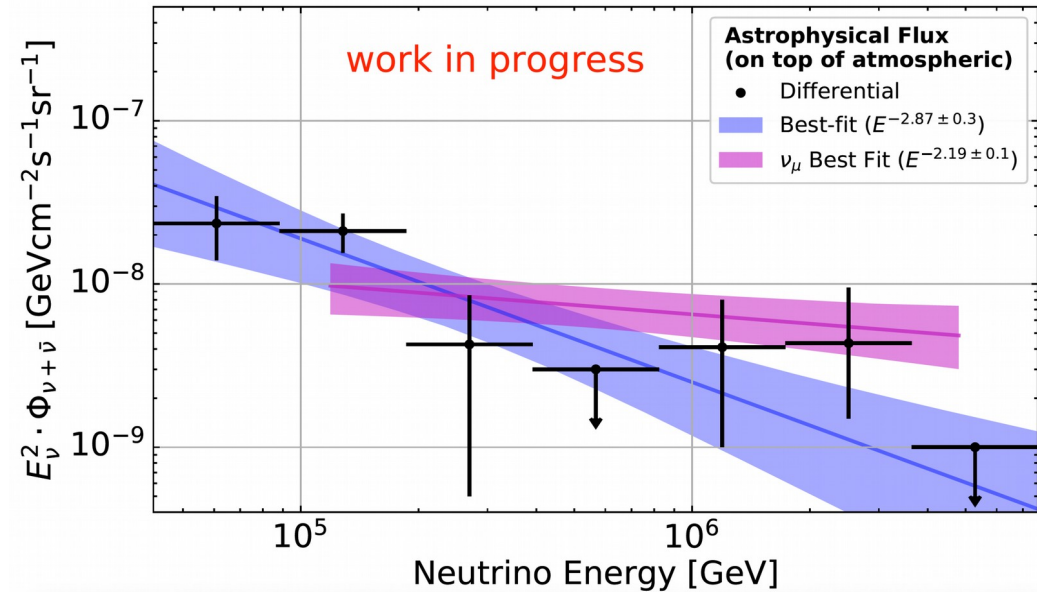
I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

103 contained events between 15 TeV – 2 PeV



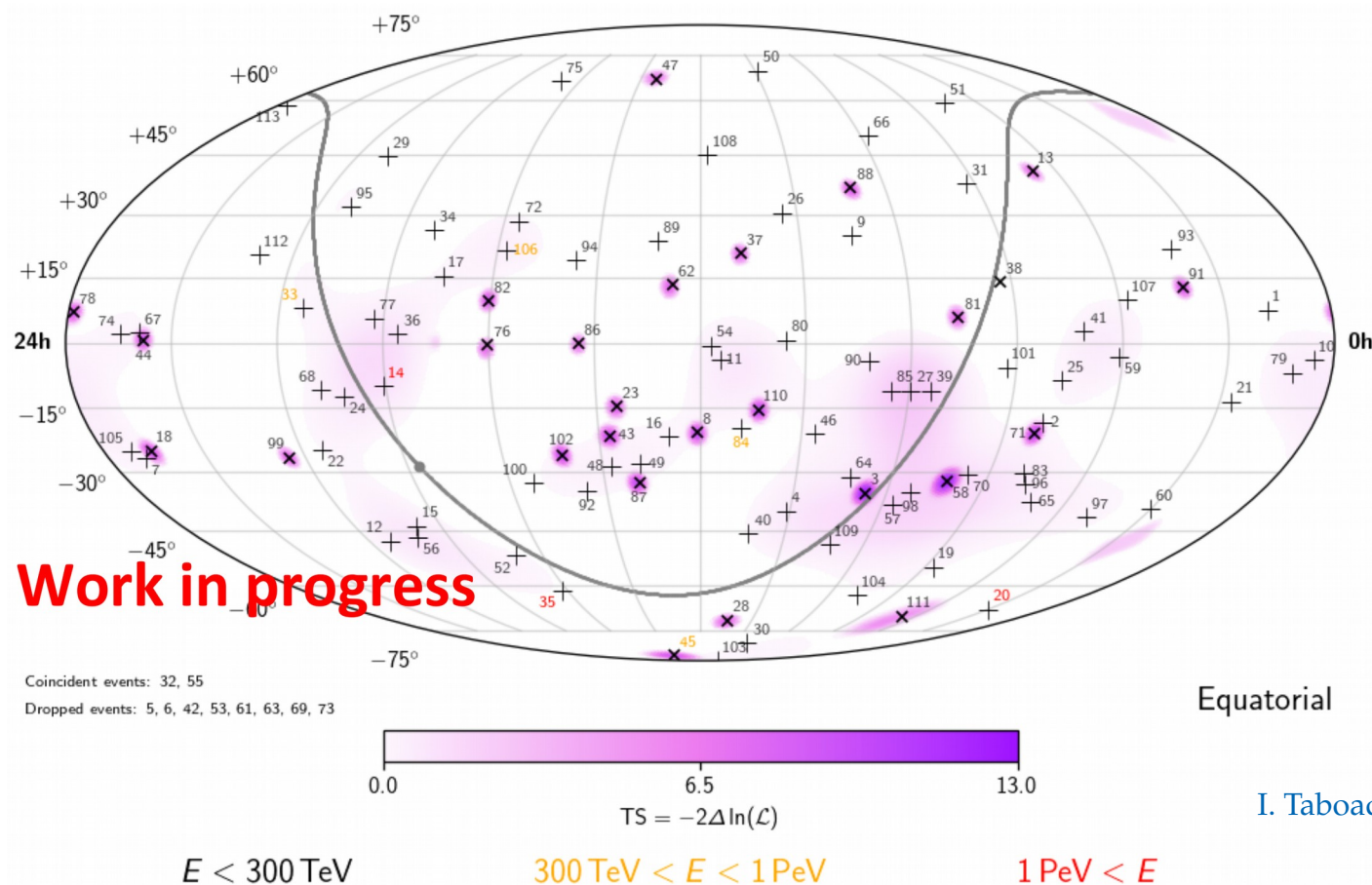
Astrophysical ν flux detected at $> 7\sigma$
(Normalization ok, but steep spectrum)



I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

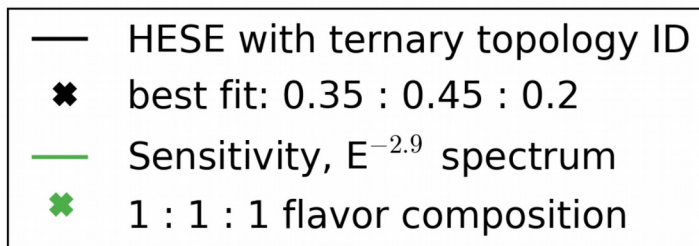
Arrival directions compatible with isotropy



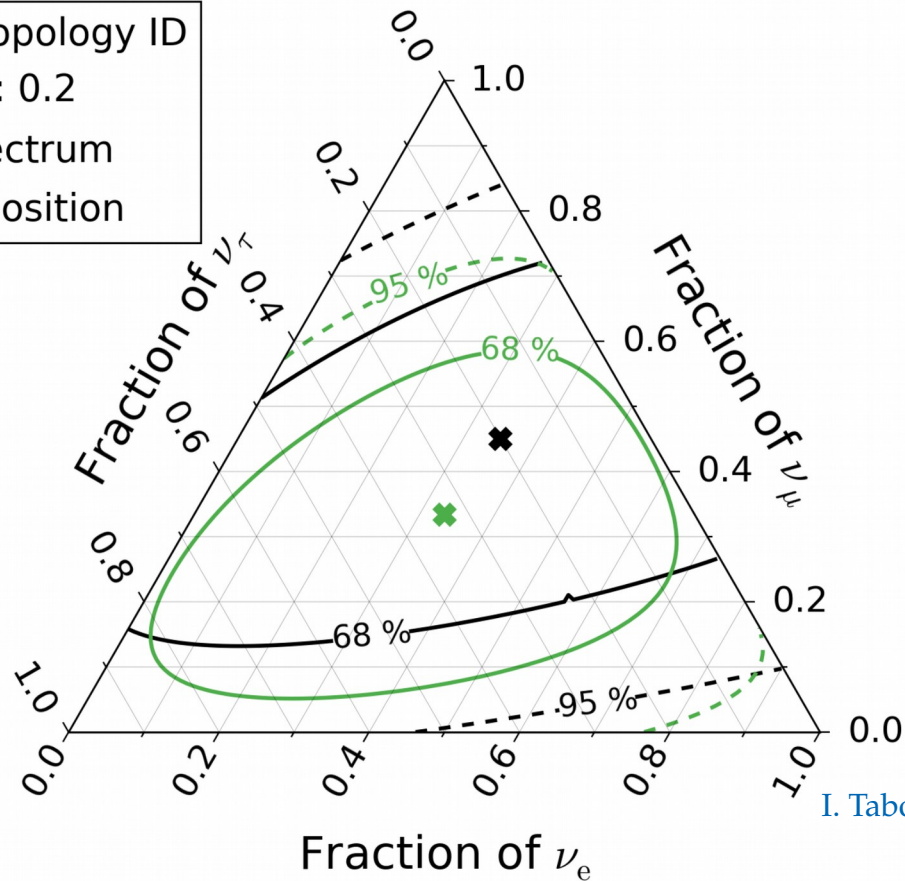
I. Taboada, Neutrino 2018

What has IceCube found so far (7.5 years)?

Flavor composition compatible with equal proportion of each flavor



WORK IN PROGRESS



I. Taboada, Neutrino 2018

Fundamental physics with HE cosmic neutrinos

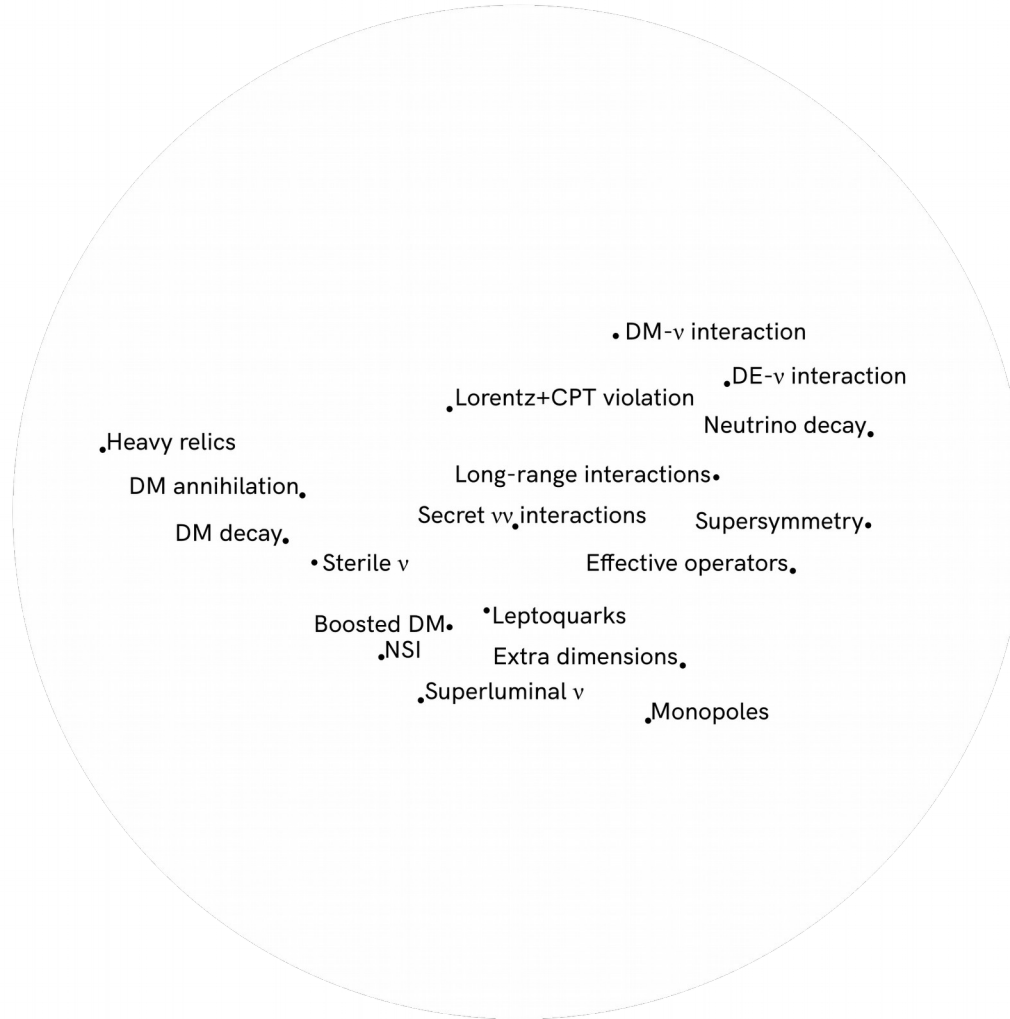
- ▶ Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over current limits: $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$
- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing

Fundamental physics with HE cosmic neutrinos

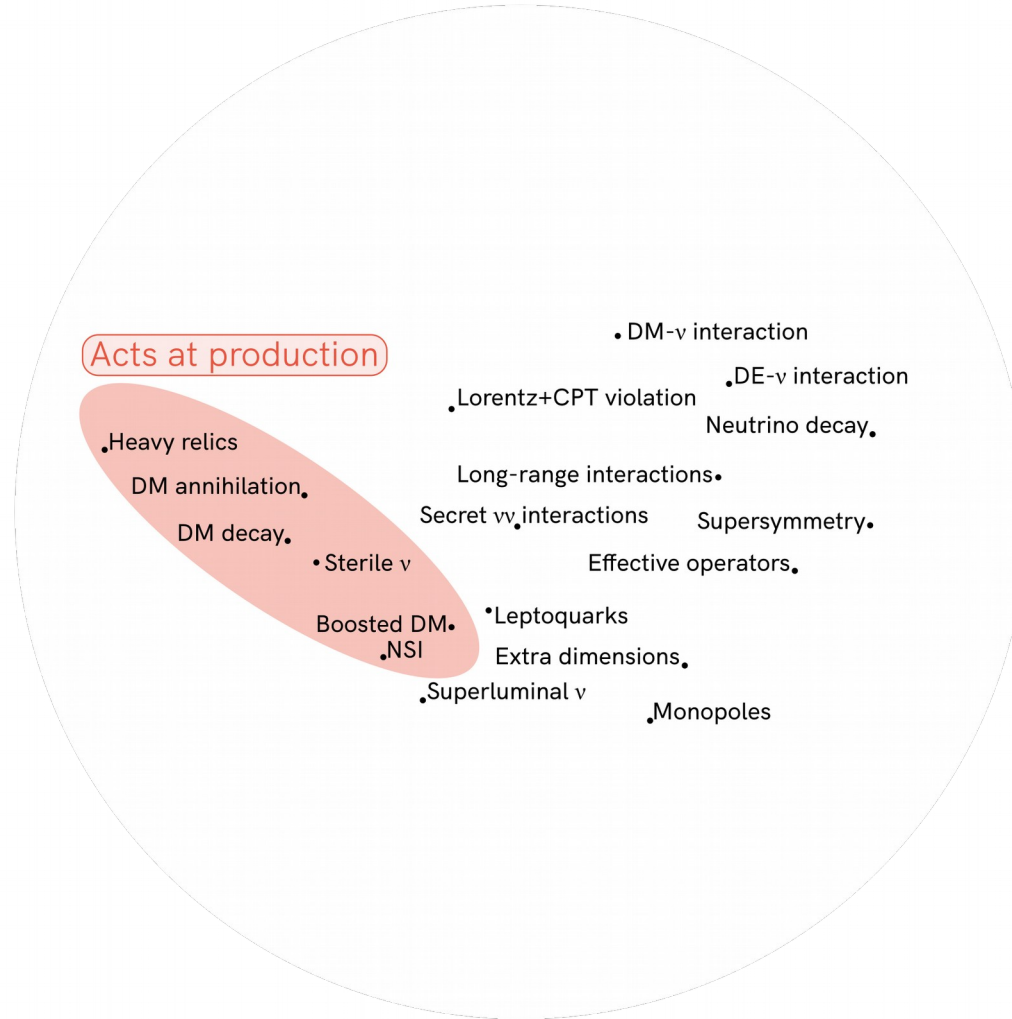
- ▶ Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left\{ \begin{array}{l} n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right.$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over current limits: $\kappa_0 < 10^{-29} \text{PeV}$, $\kappa_1 < 10^{-33}$
- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing

Fundamental physics with HE cosmic neutrinos

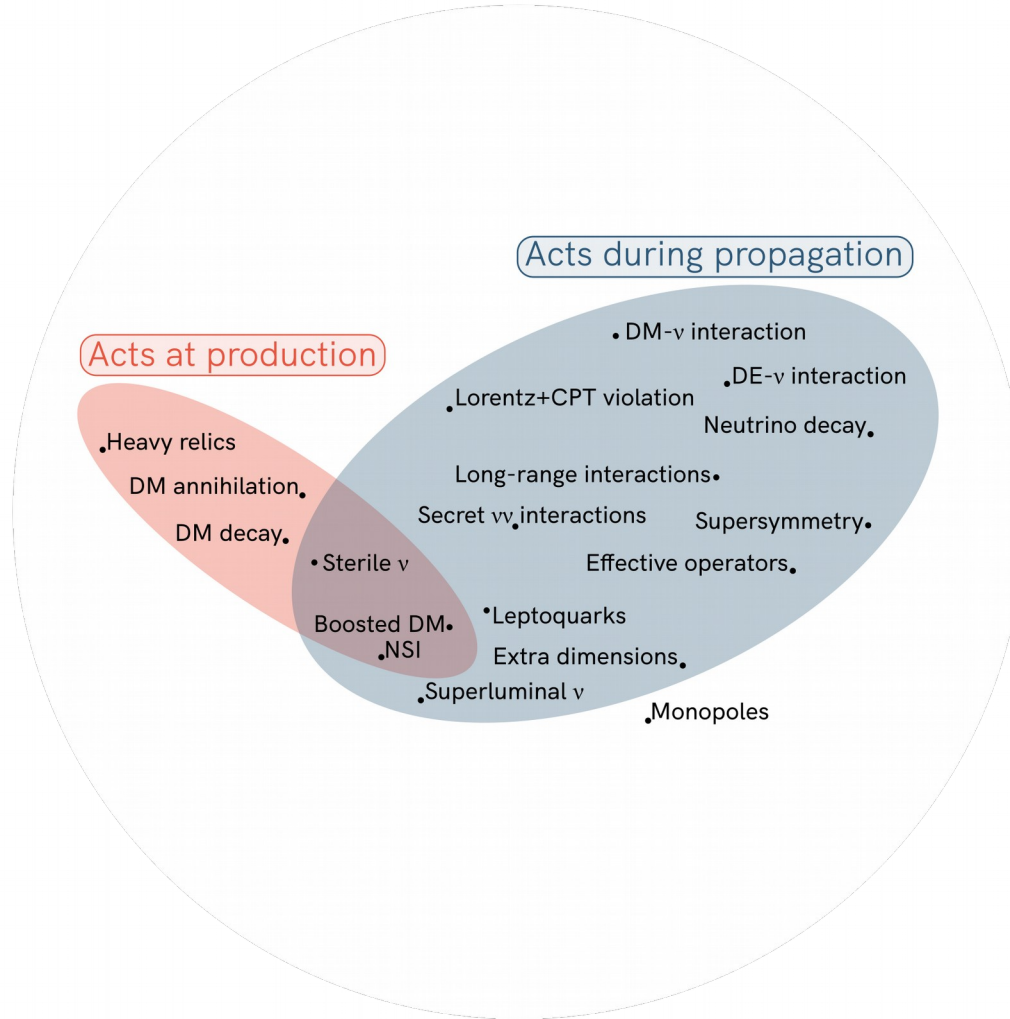
- ▶ Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$ $\left. \begin{array}{l} n = -1: \text{neutrino decay} \\ n = 0: \text{CPT-odd Lorentz violation} \\ n = +1: \text{CPT-even Lorentz violation} \end{array} \right\}$
- ▶ So we can probe $\kappa_n \sim 4 \cdot 10^{-47} (E/\text{PeV})^{-n} (L/\text{Gpc})^{-1} \text{PeV}^{1-n}$
- ▶ Improvement over current limits: $\kappa_0 < 10^{-29} \text{PeV}, \kappa_1 < 10^{-33}$
- ▶ Fundamental physics can be extracted from four neutrino observables:
 - ▶ Spectral shape
 - ▶ Angular distribution
 - ▶ Flavor composition
 - ▶ Timing $\left. \begin{array}{l} \text{Spectral shape} \\ \text{Angular distribution} \\ \text{Flavor composition} \\ \text{Timing} \end{array} \right\} \text{In spite of} \\ \text{poor energy, angular, flavor reconstruction} \\ \text{\& astrophysical unknowns}$



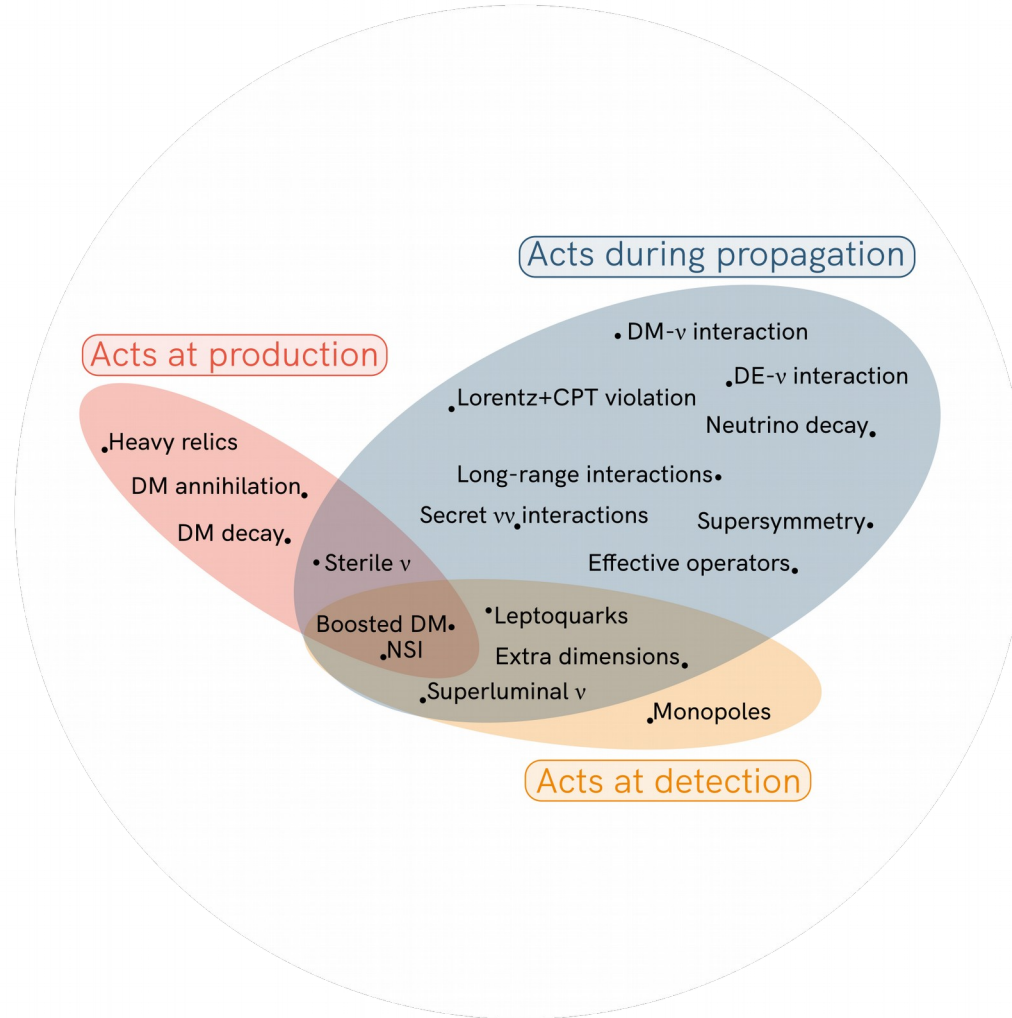
Note: Not an exhaustive list



Note: Not an exhaustive list



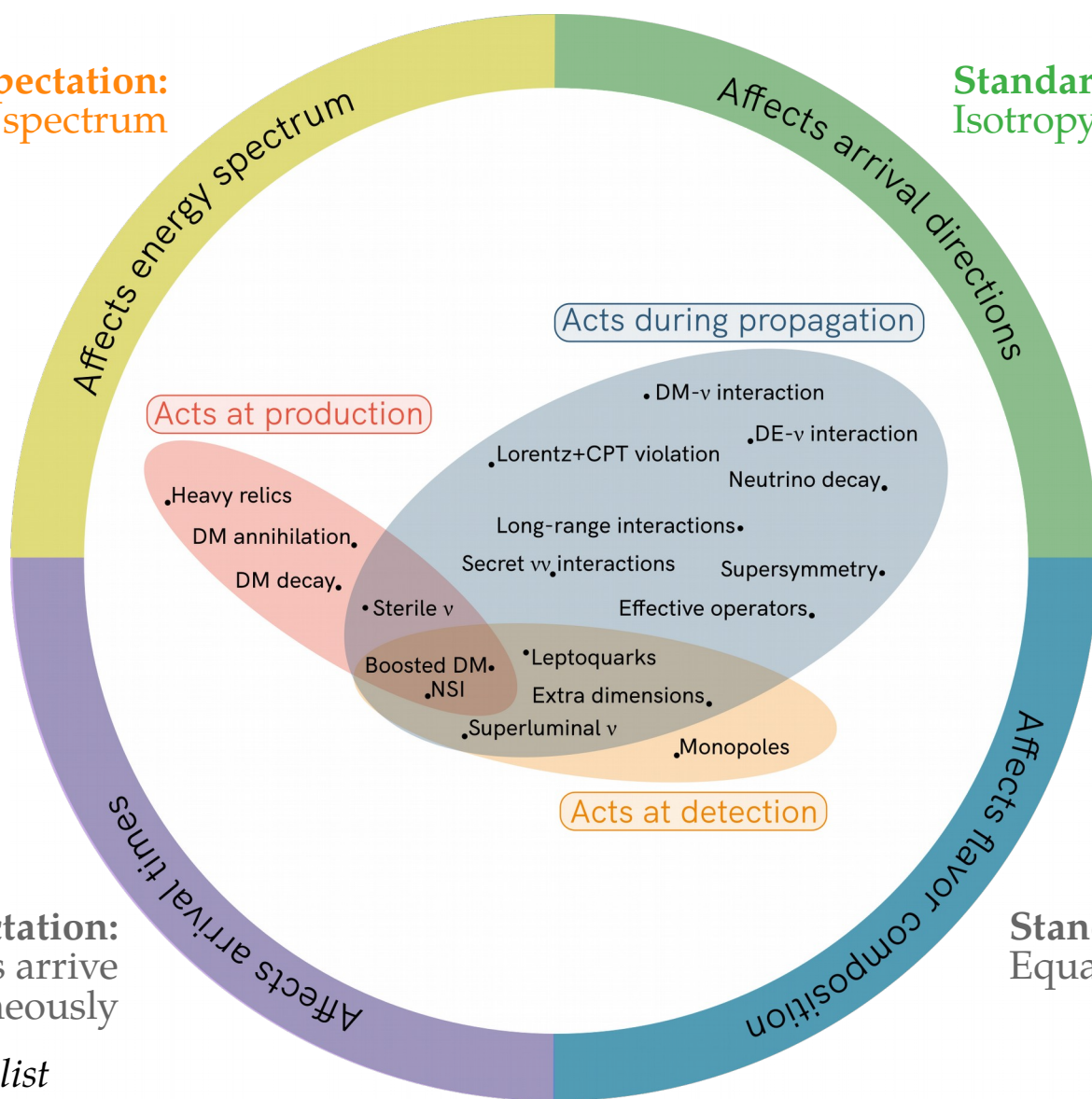
Note: Not an exhaustive list



Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



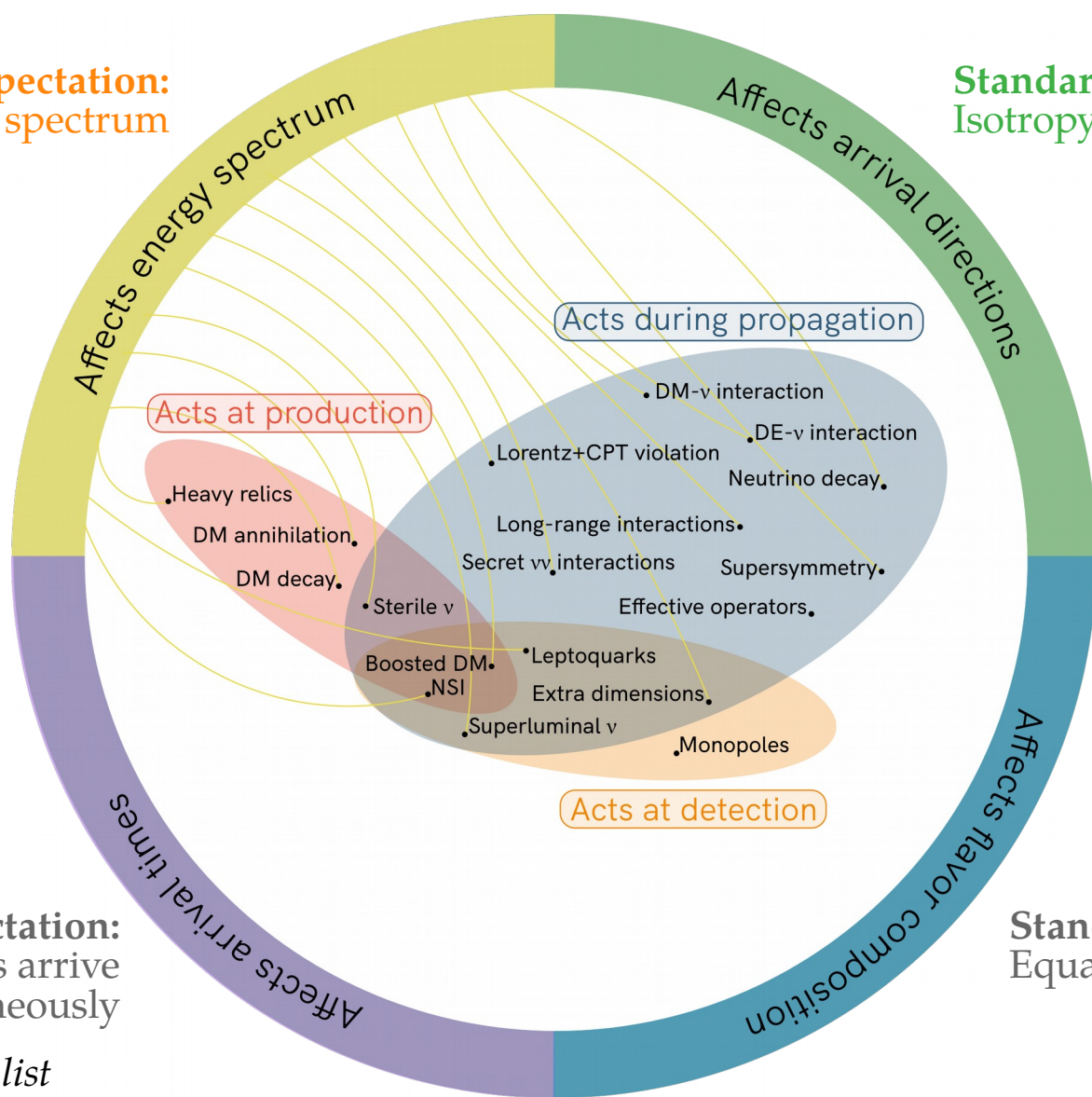
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive
simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



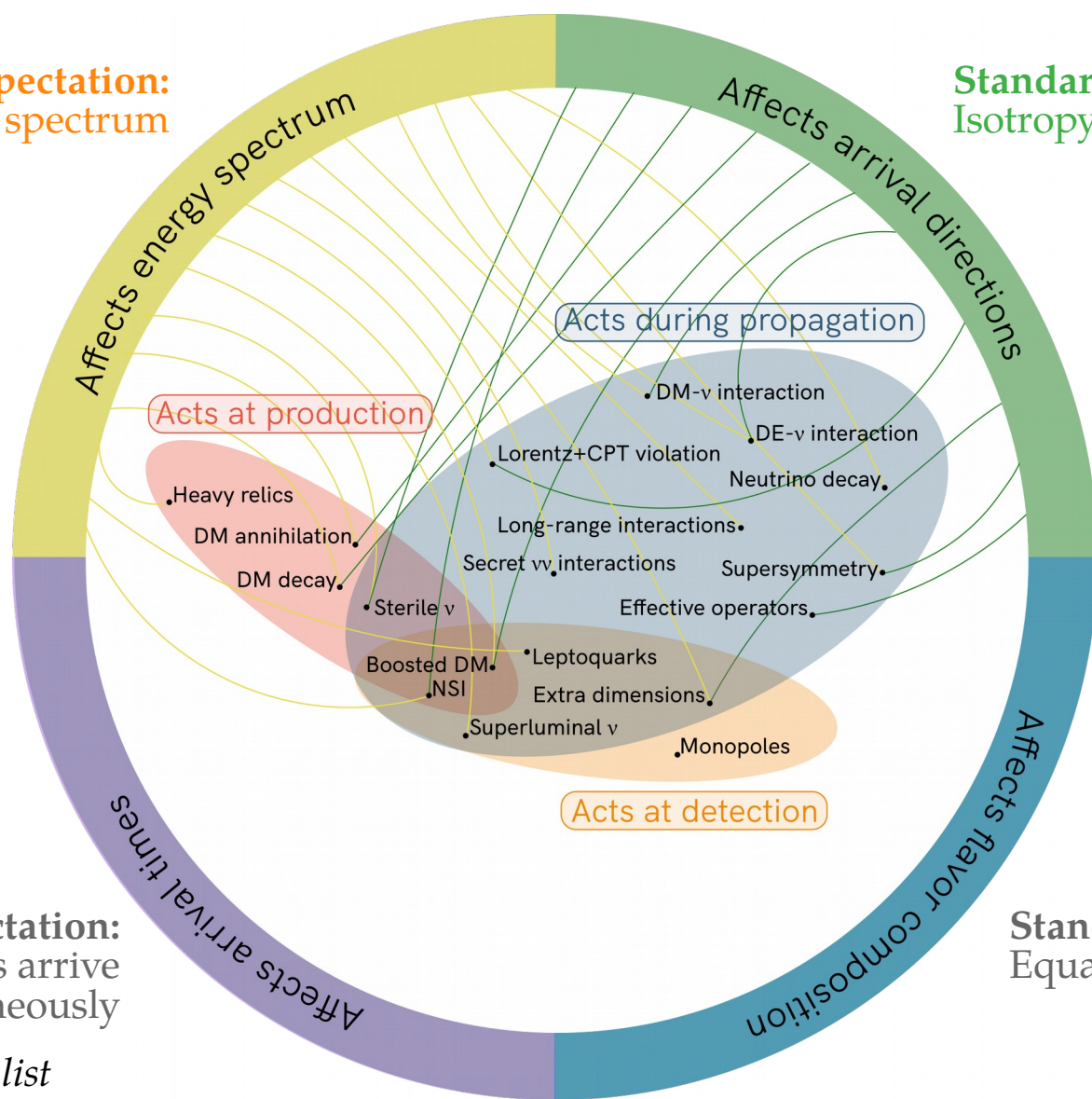
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



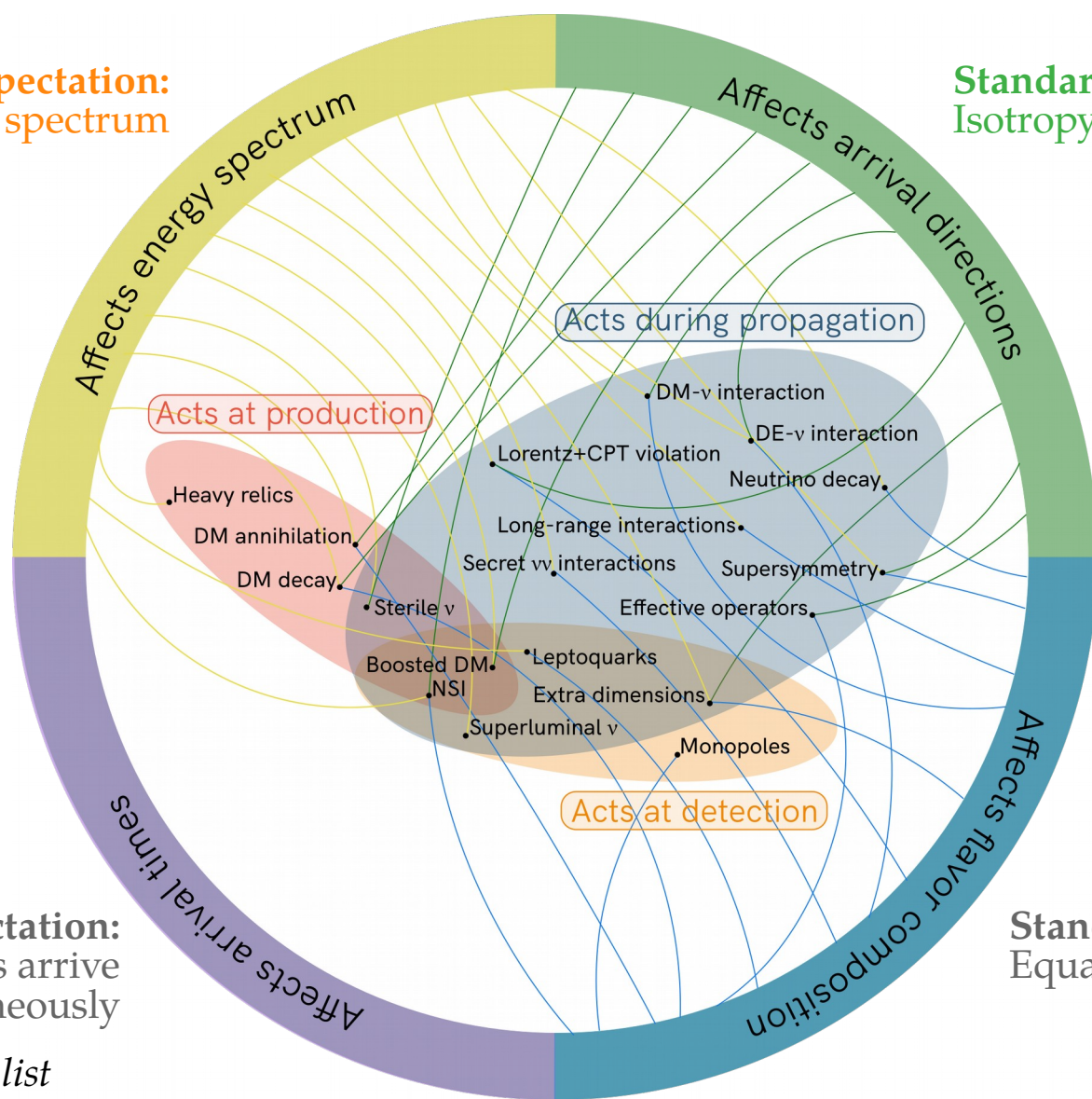
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



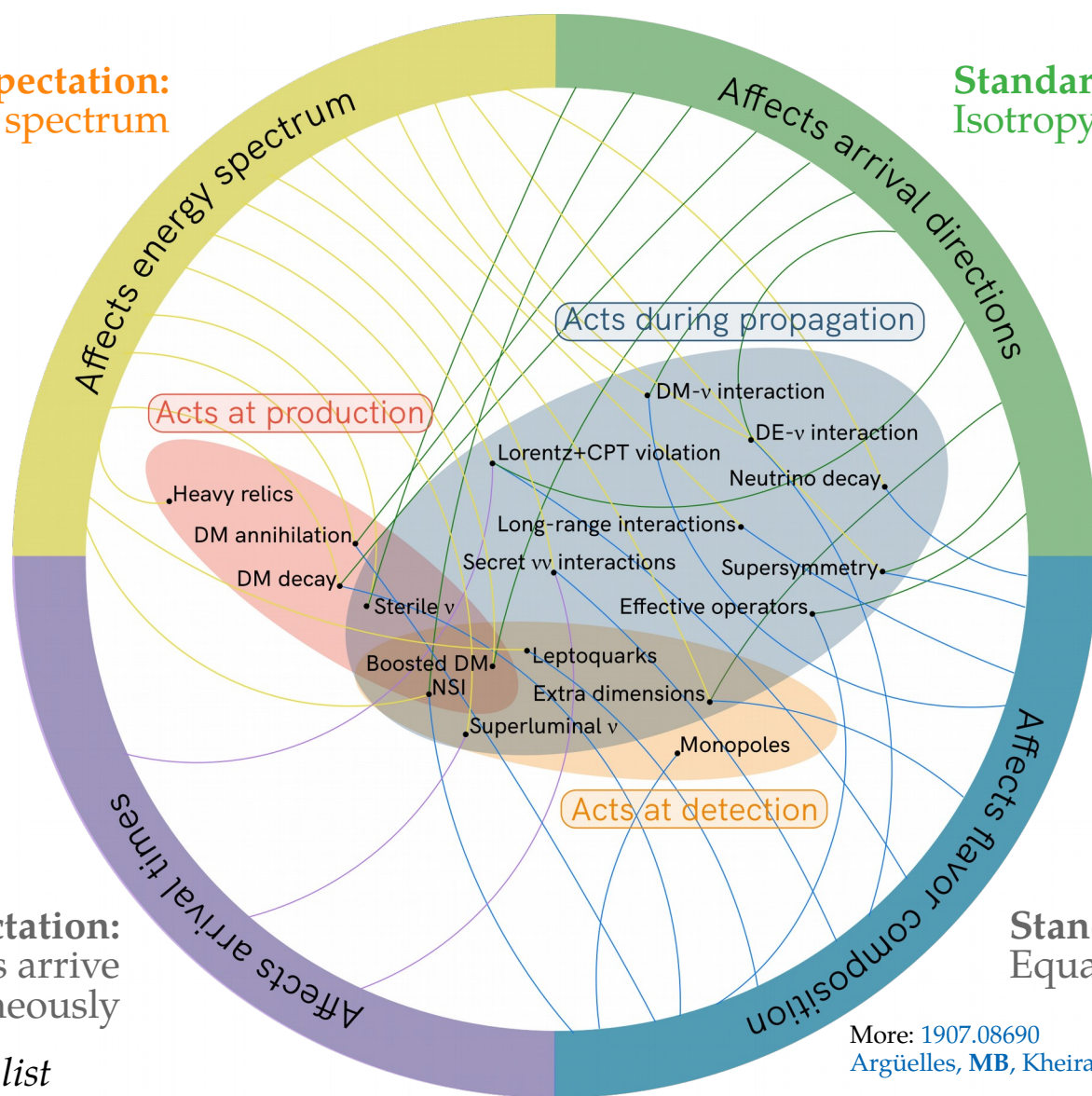
Standard expectation:
Equal number of ν_e, ν_μ, ν_τ

Standard expectation:
 ν and γ from transients arrive simultaneously

Note: Not an exhaustive list

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
 ν and γ from transients arrive simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

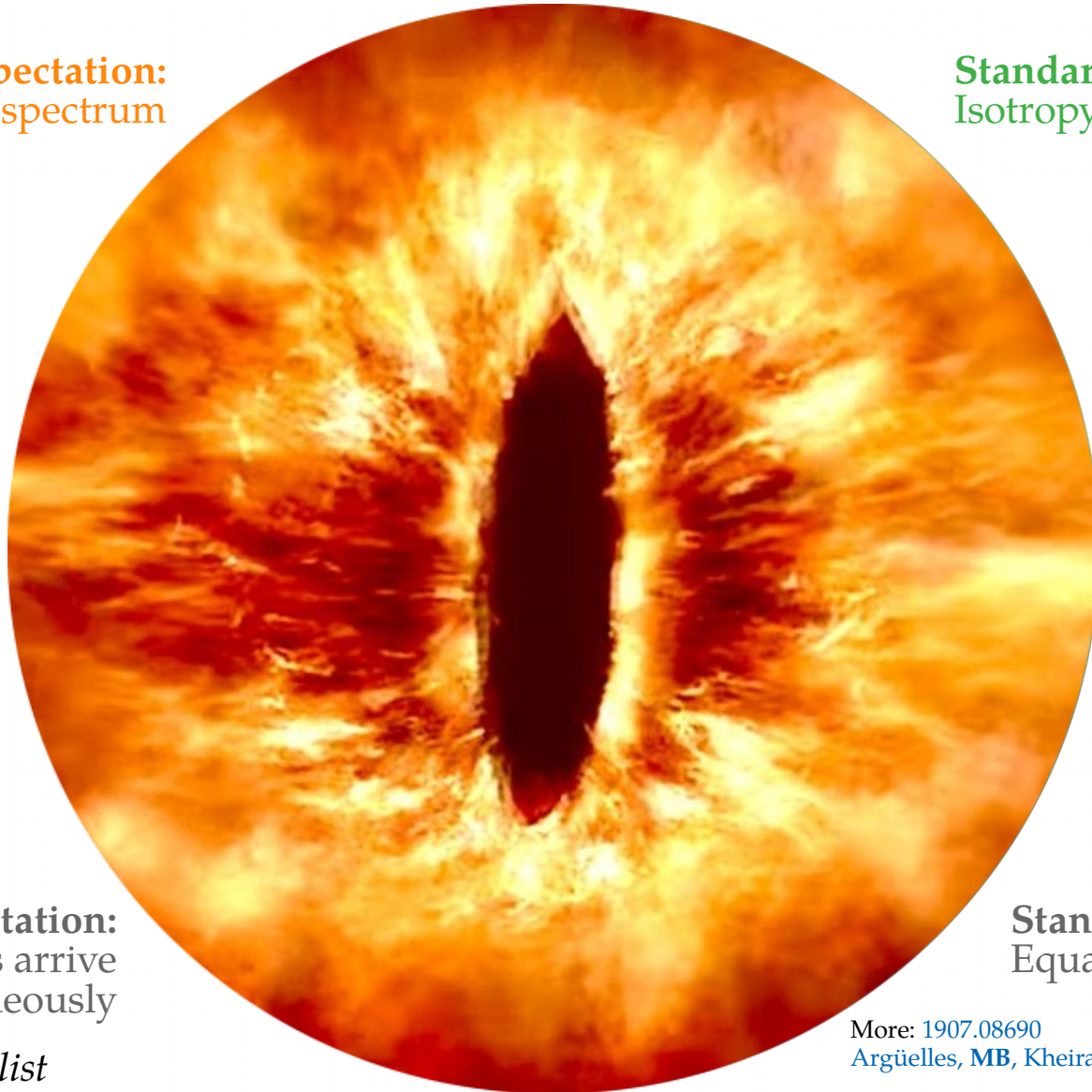
Note: Not an exhaustive list

More: 1907.08690

Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)



Standard expectation:
 ν and γ from transients arrive
simultaneously

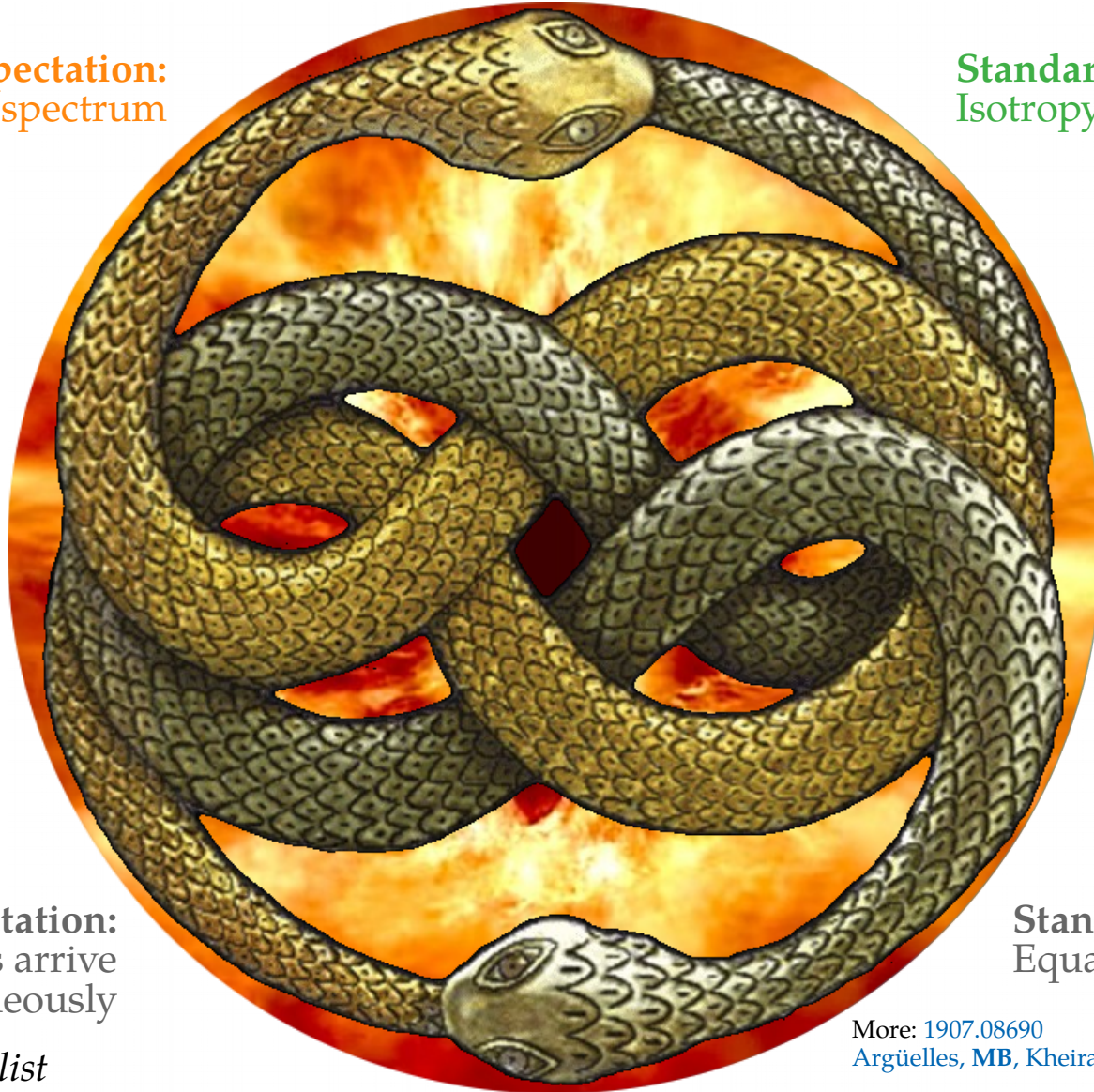
Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

Note: Not an exhaustive list

More: 1907.08690
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent

Standard expectation:
Power-law energy spectrum

Standard expectation:
Isotropy (for diffuse flux)

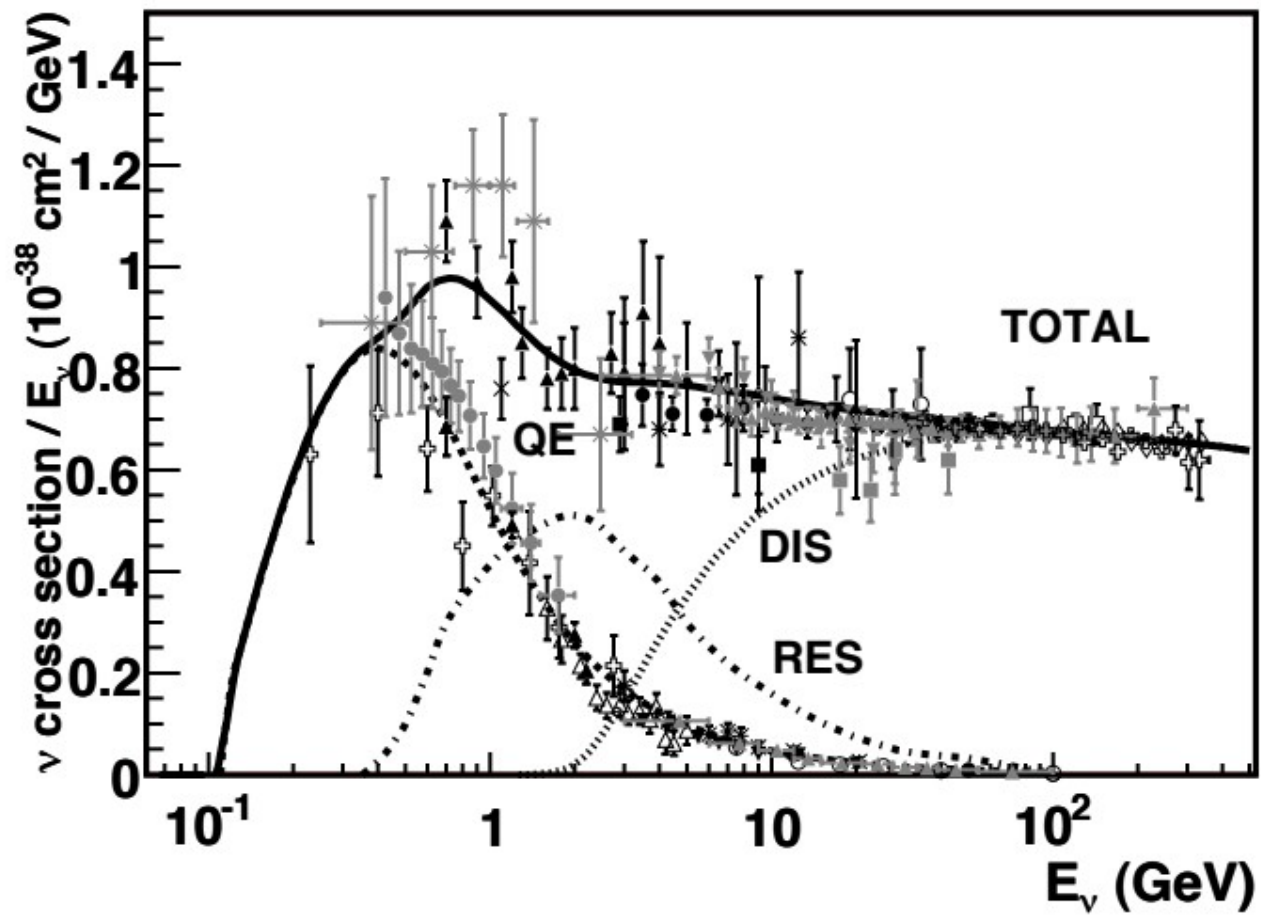


Standard expectation:
 ν and γ from transients arrive
simultaneously

Standard expectation:
Equal number of ν_e , ν_μ , ν_τ

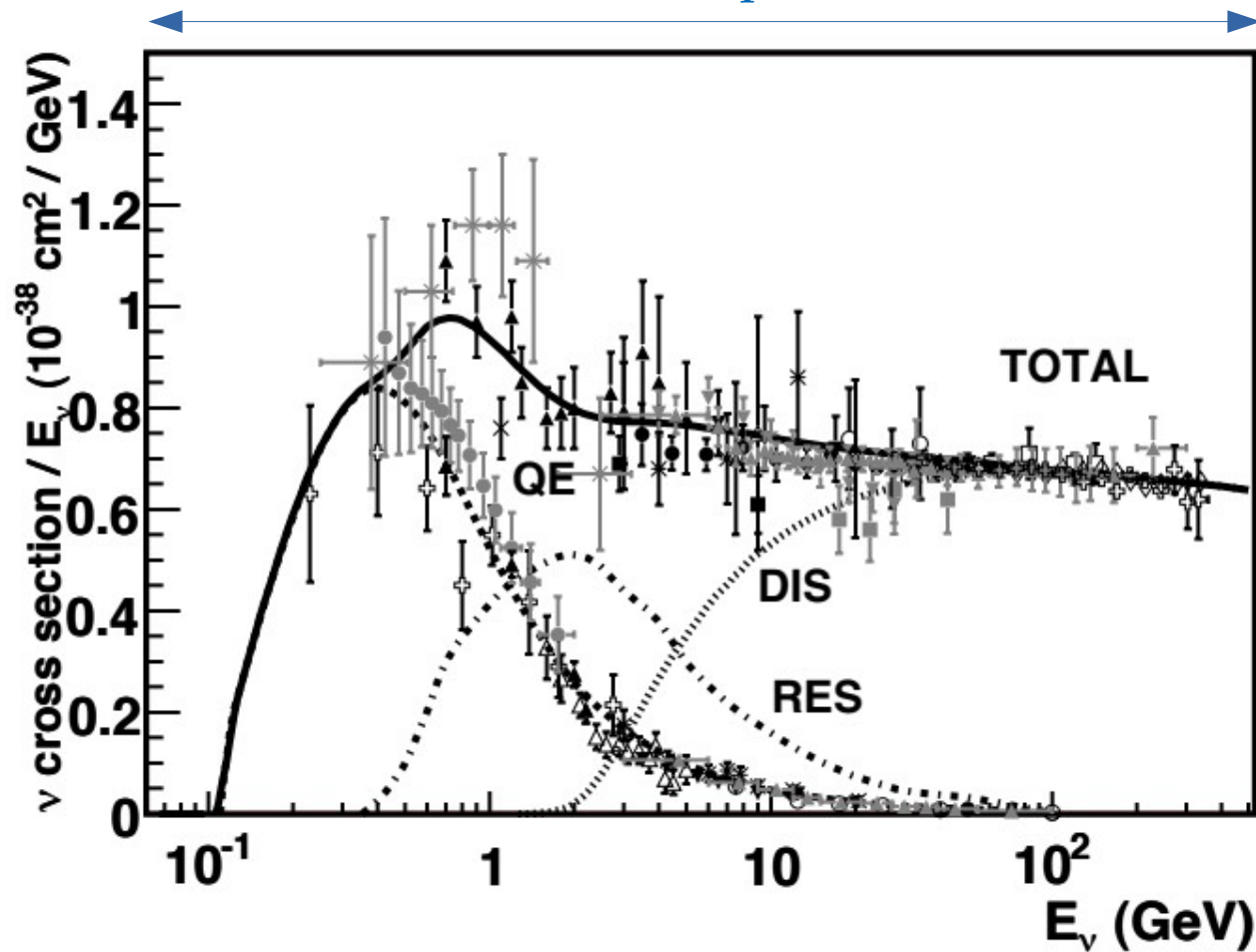
Note: Not an exhaustive list

More: 1907.08690
Argüelles, MB, Kheirandish, Palomares-Ruiz, Salvadó, Vincent



Particle Data Group

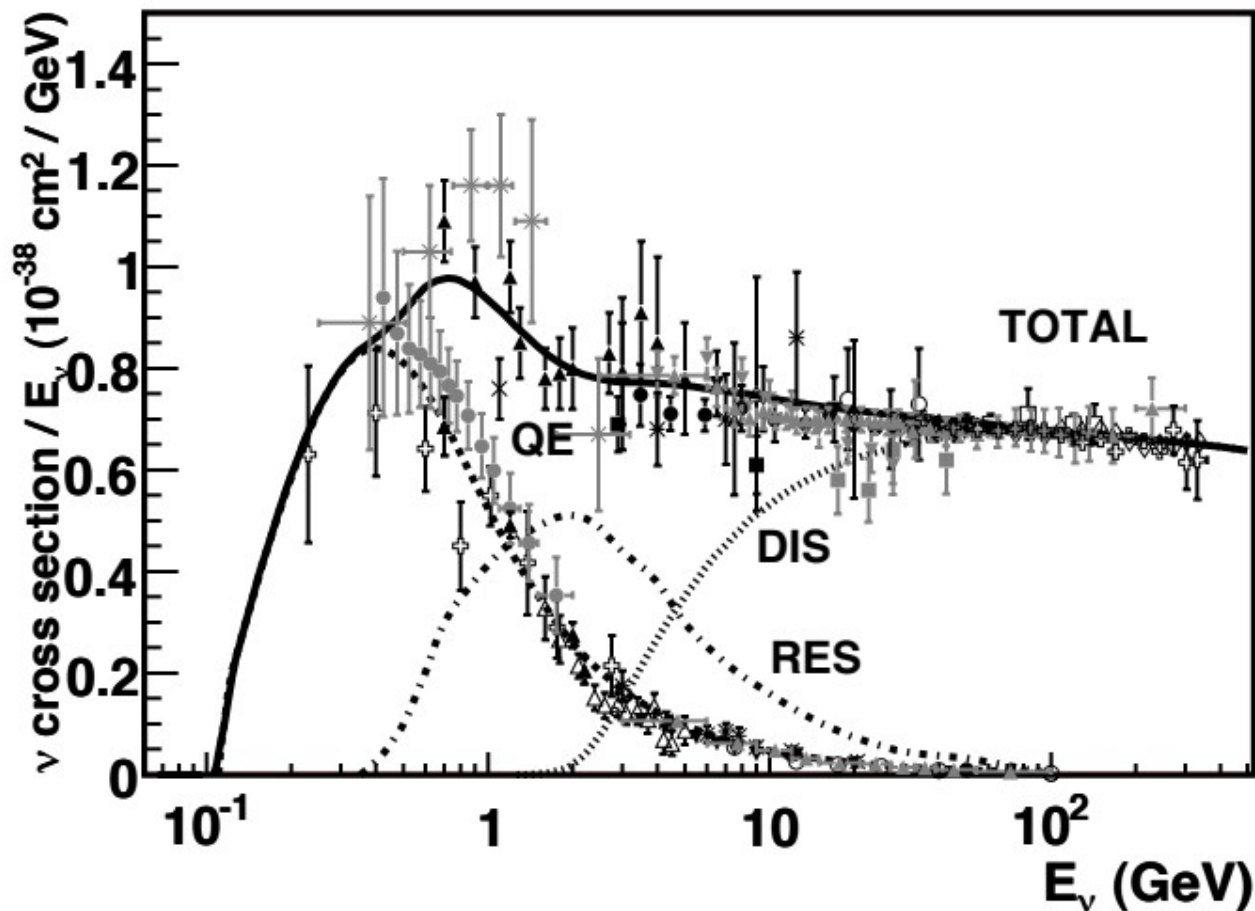
Accelerator experiments



Particle Data Group

Accelerator experiments

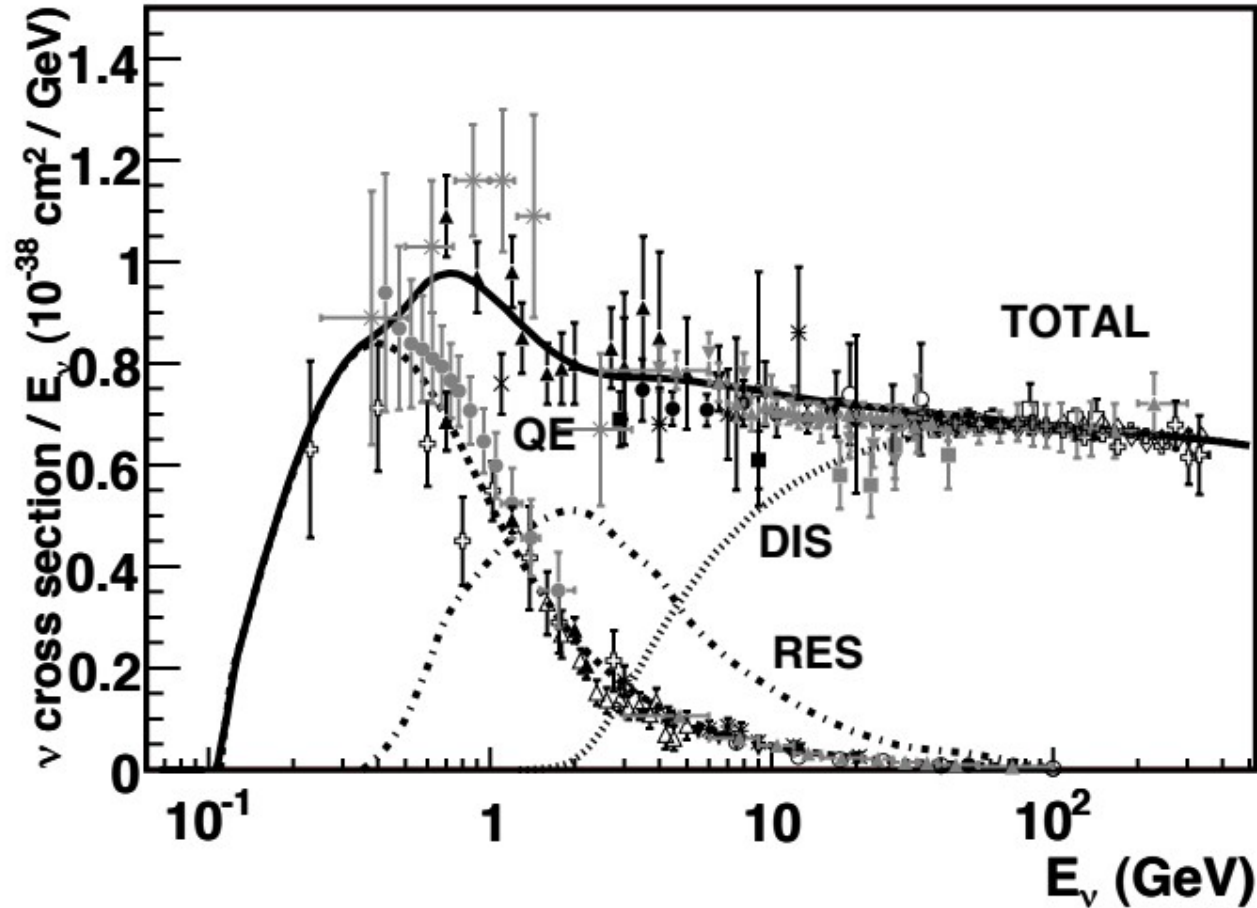
One recent
measurement
(COHERENT)



Particle Data Group

Accelerator experiments

One recent
measurement
(COHERENT)

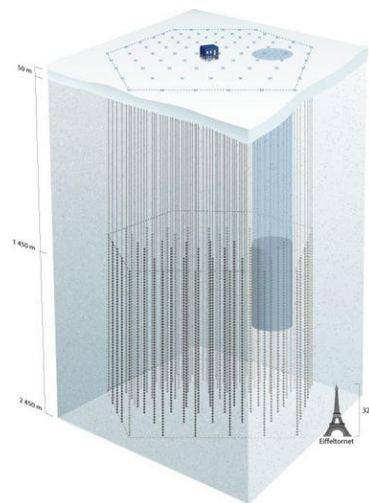
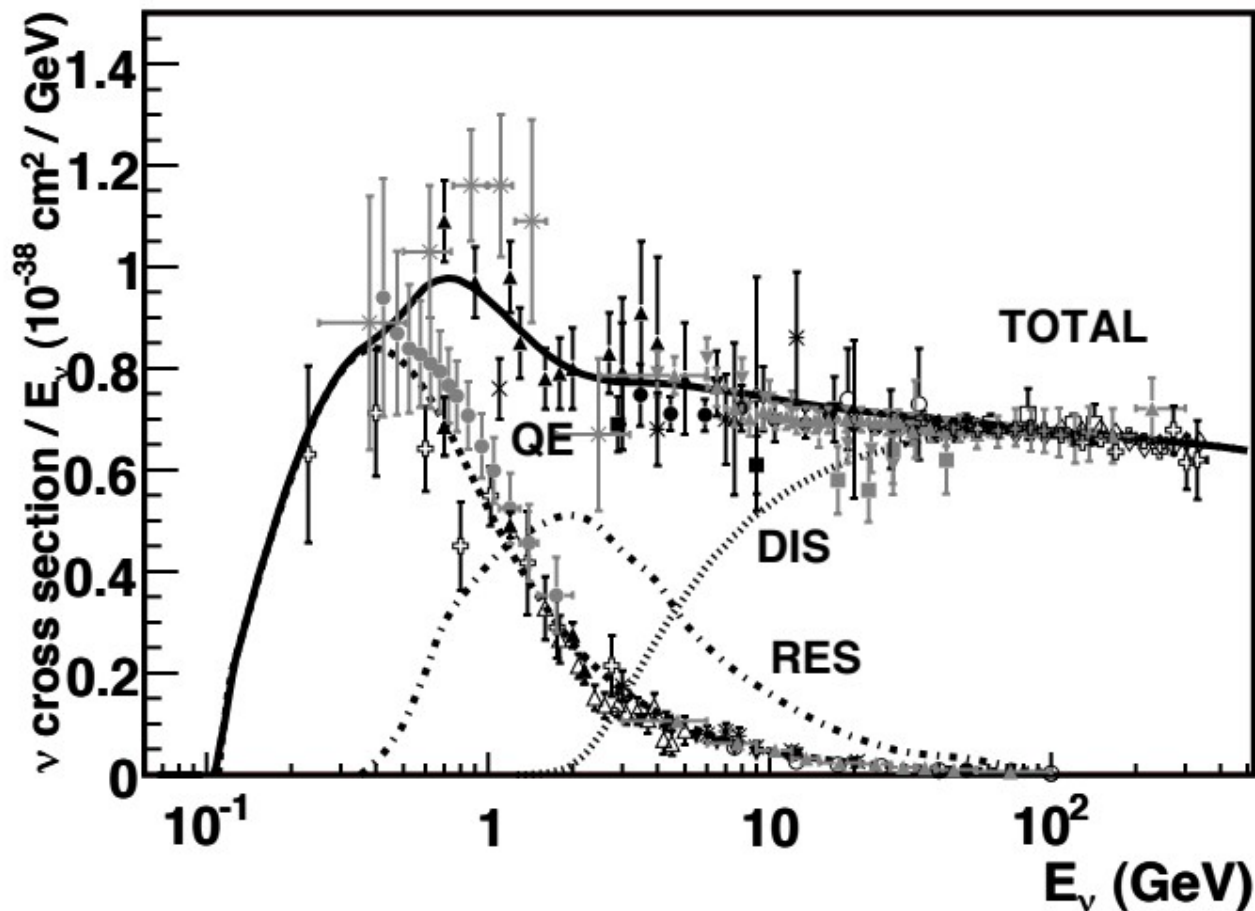


No
measurements
... until recently!

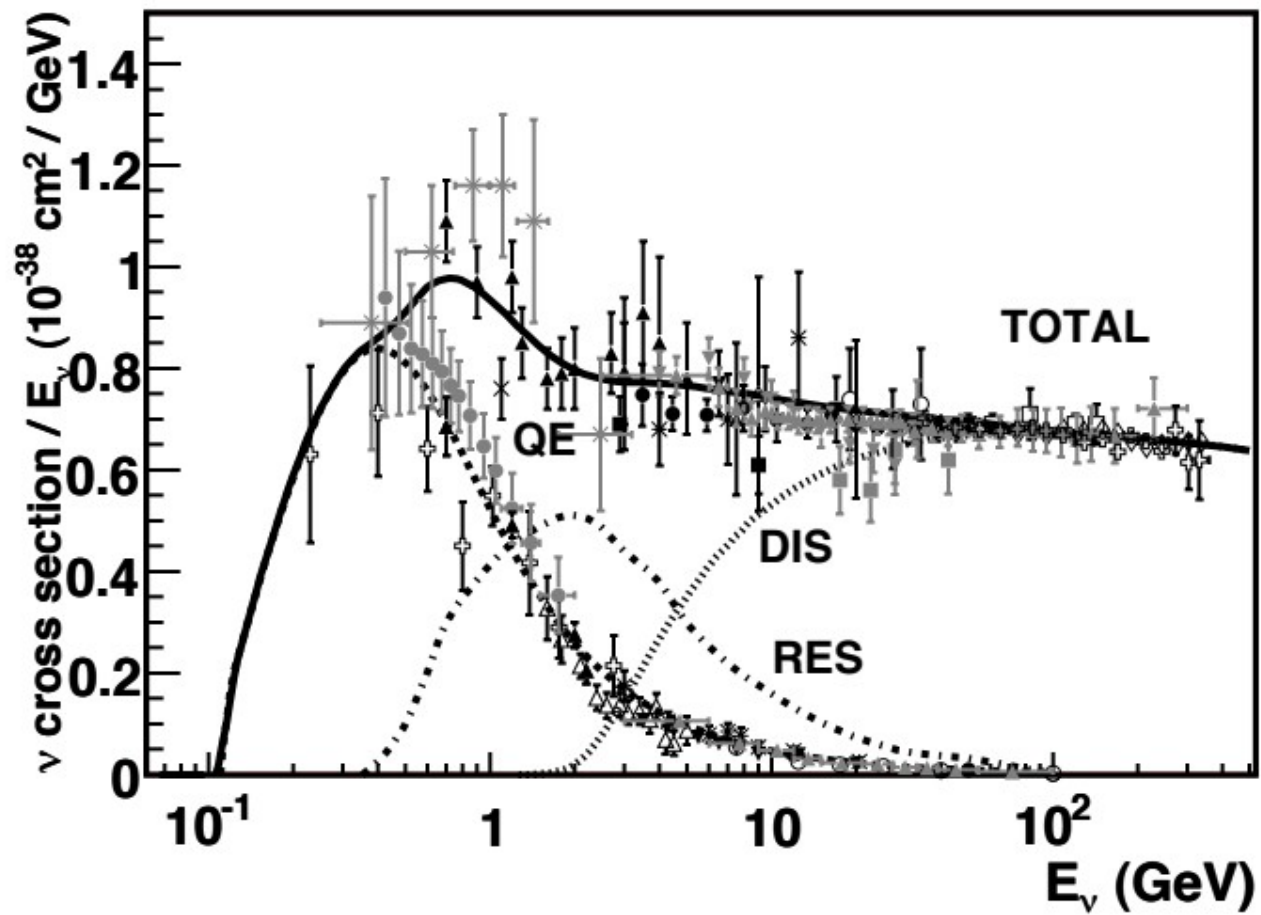
Particle Data Group

Accelerator experiments

One recent
measurement
(COHERENT)



Particle Data Group

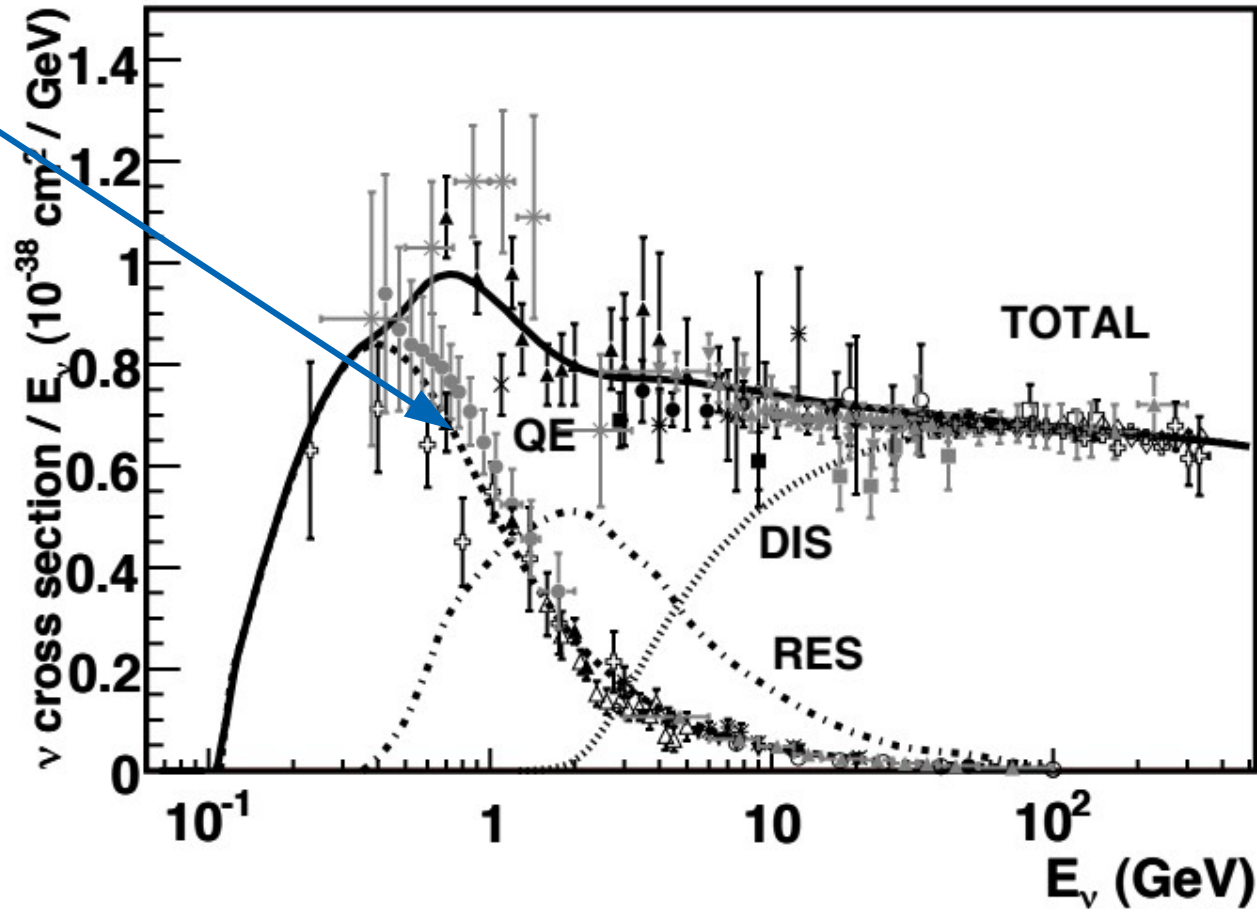


Particle Data Group

Quasi-elastic
scattering:

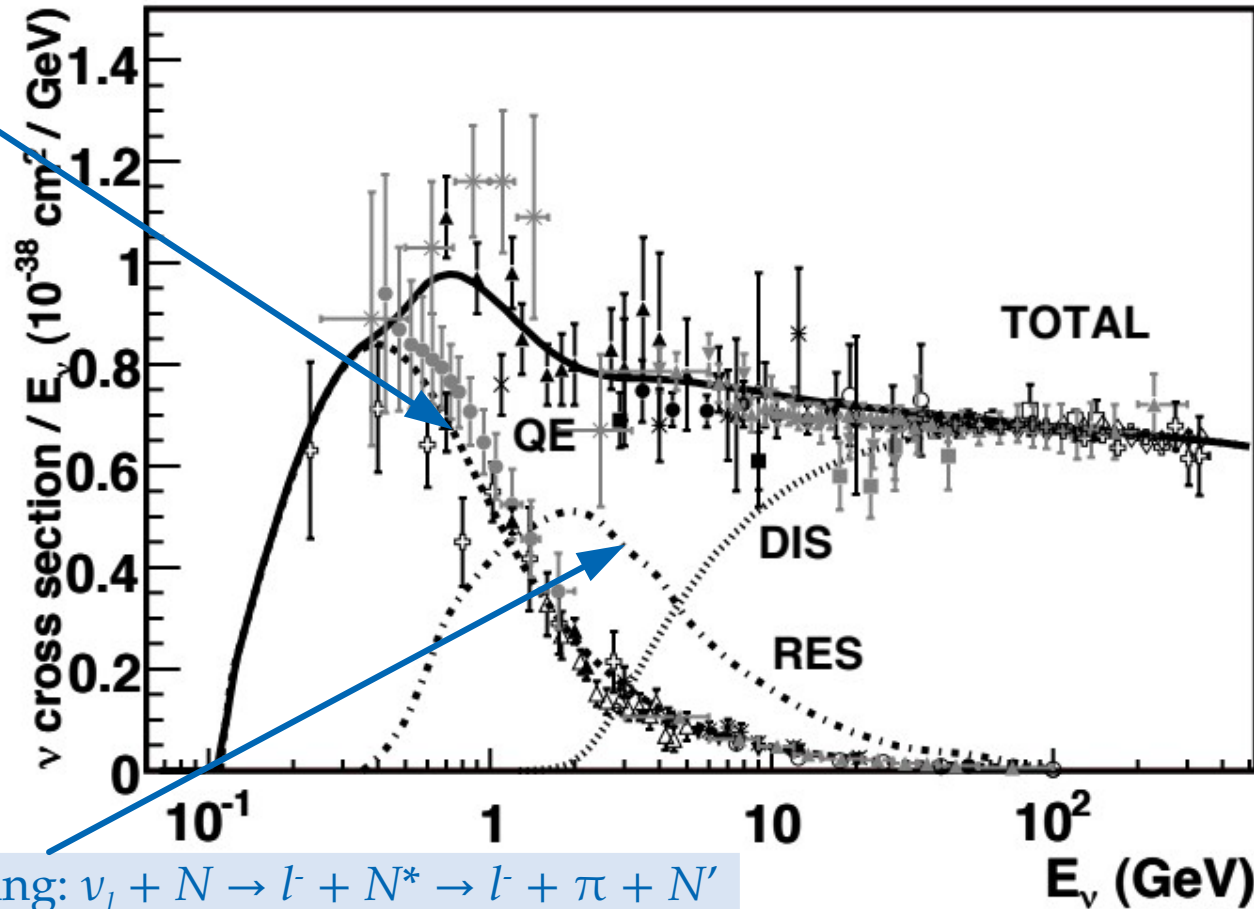
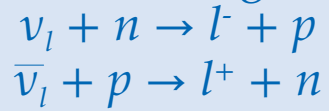
$$\nu_l + n \rightarrow l^- + p$$

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



Particle Data Group

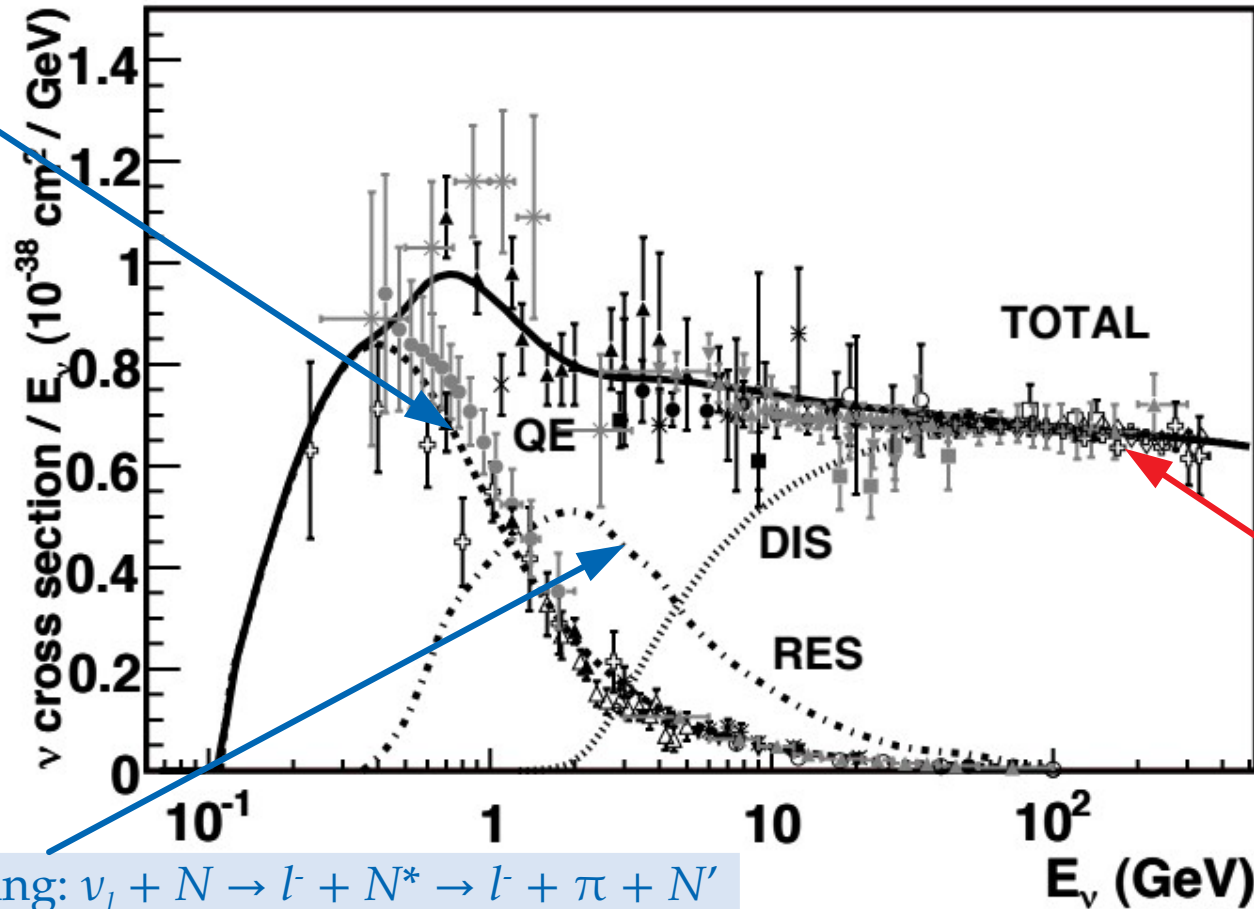
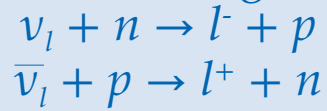
Quasi-elastic
scattering:



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

Particle Data Group

Quasi-elastic
scattering:



Deep inelastic
scattering:

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

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

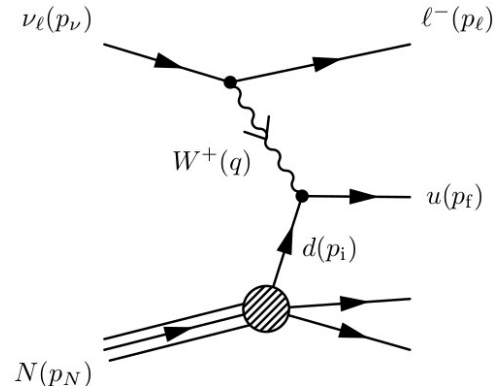
Resonant scattering: $\nu_l + N \rightarrow l^- + N^* \rightarrow l^- + \pi + N'$

Particle Data Group

Extrapolating the cross section to high energies

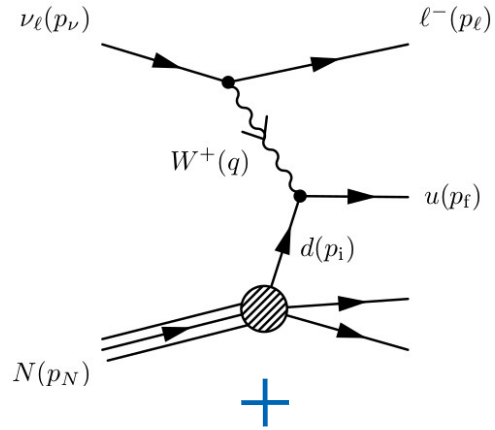
Extrapolating the cross section to high energies

SM

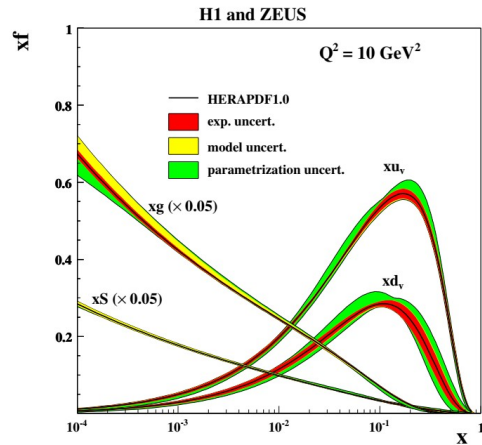


Extrapolating the cross section to high energies

SM

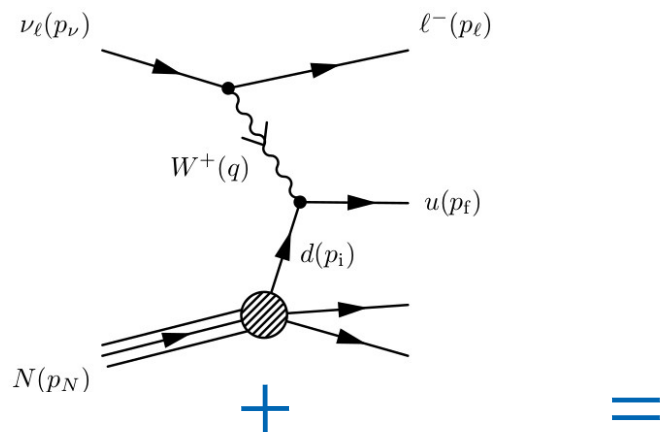


PDFs

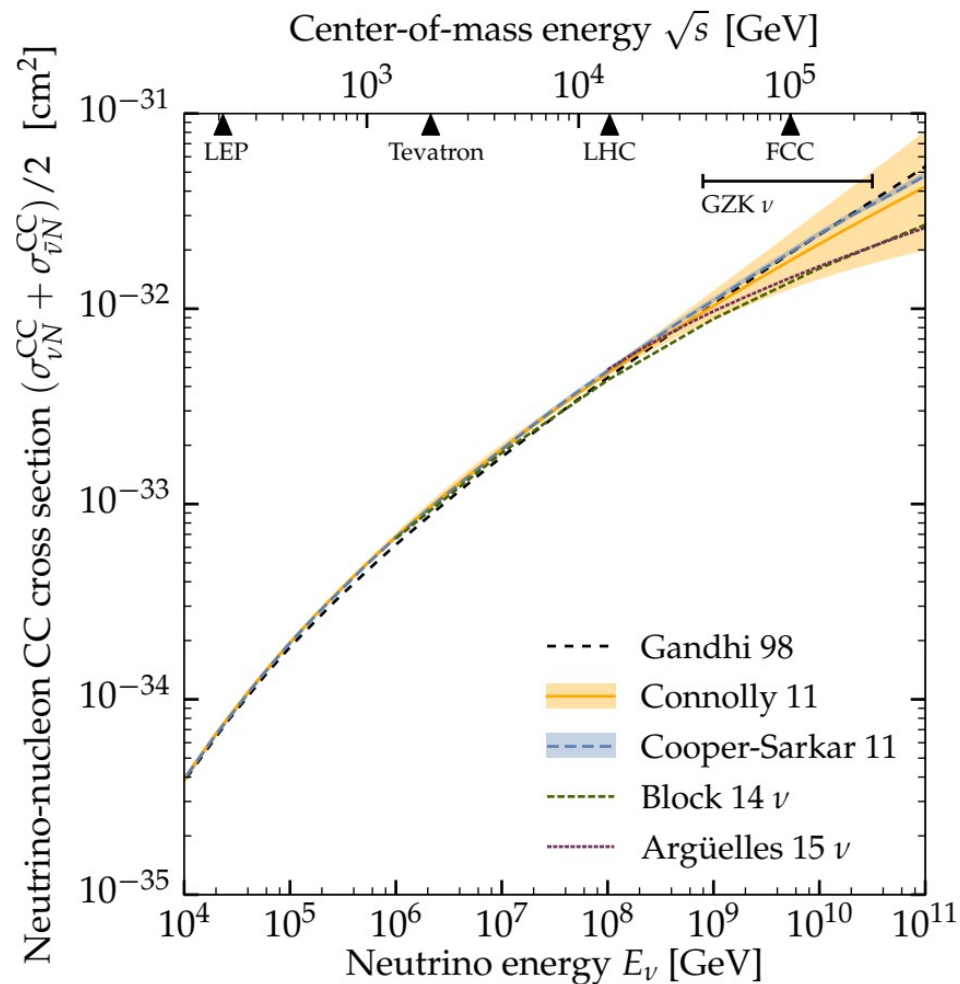
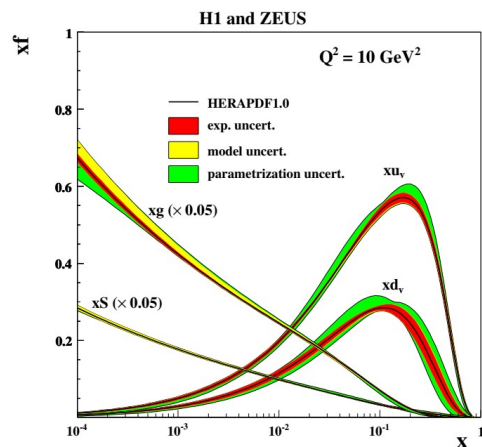


Extrapolating the cross section to high energies

SM

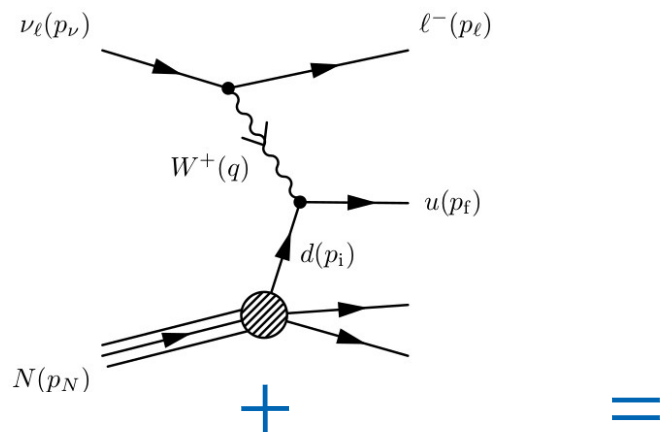


PDFs

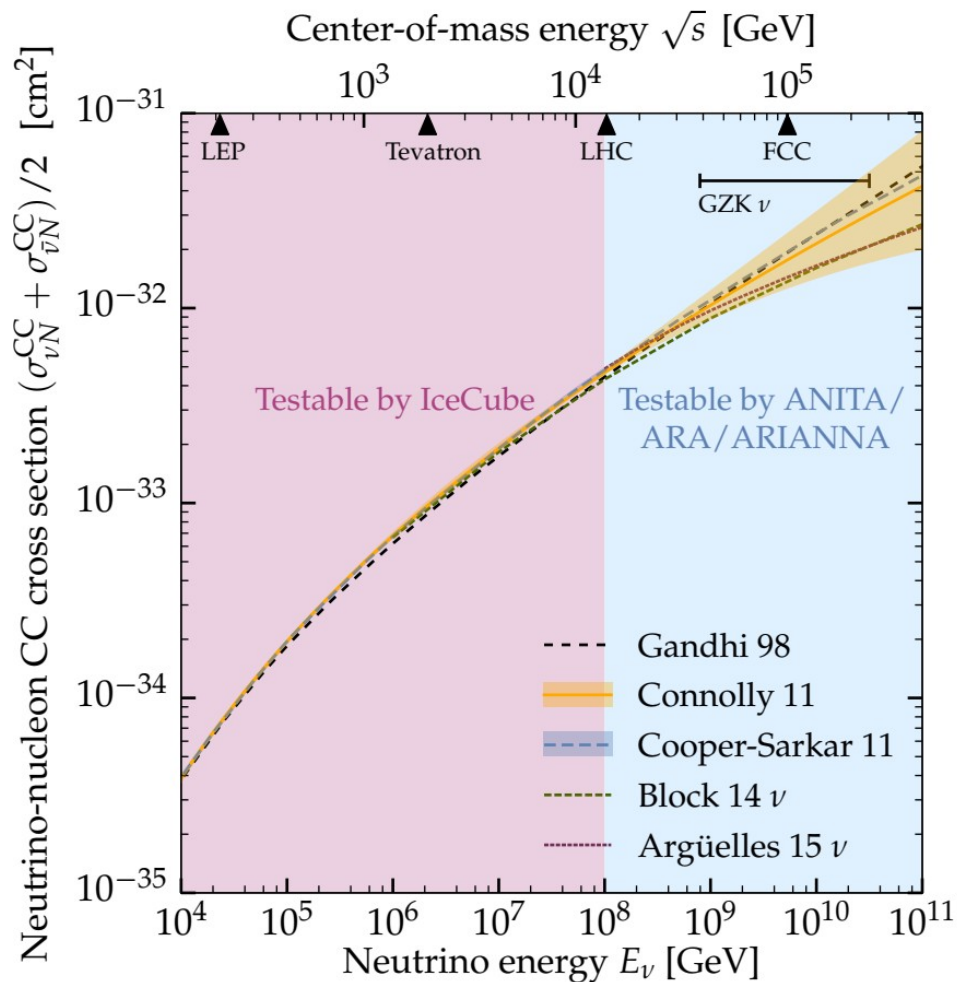
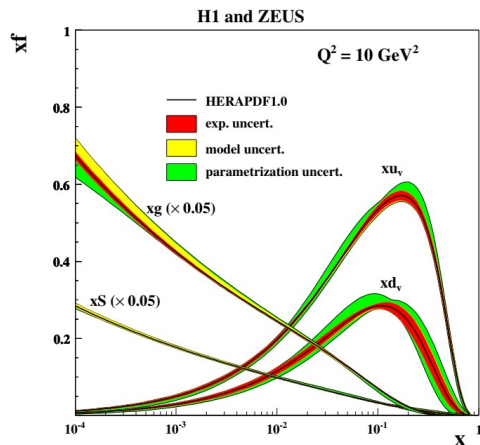


Extrapolating the cross section to high energies

SM



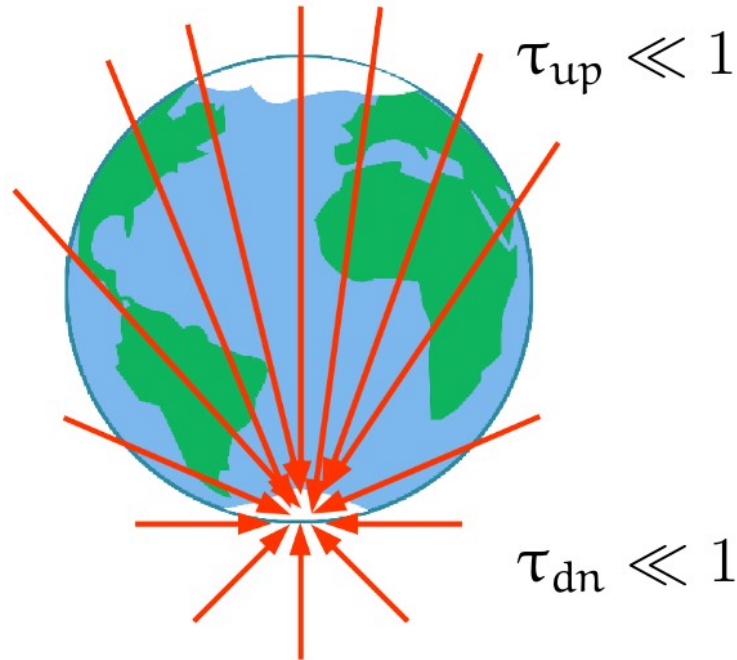
PDFs



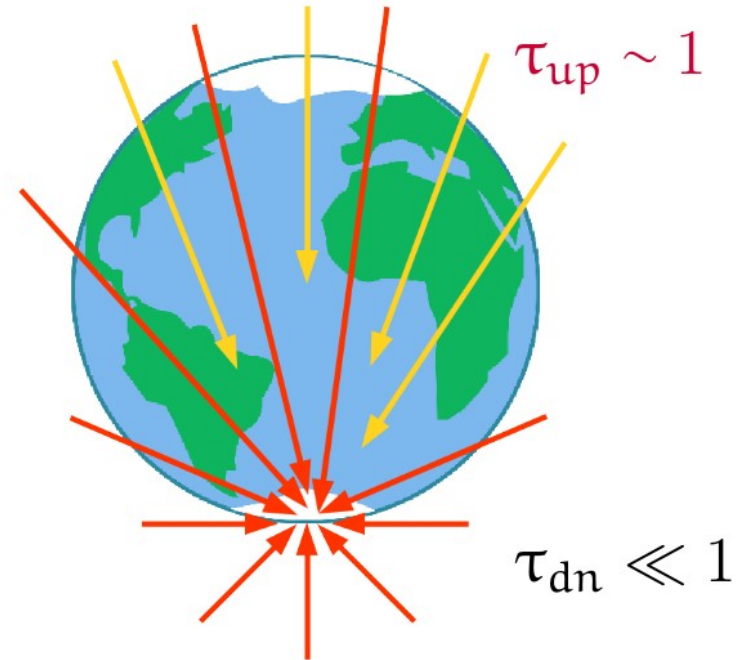
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



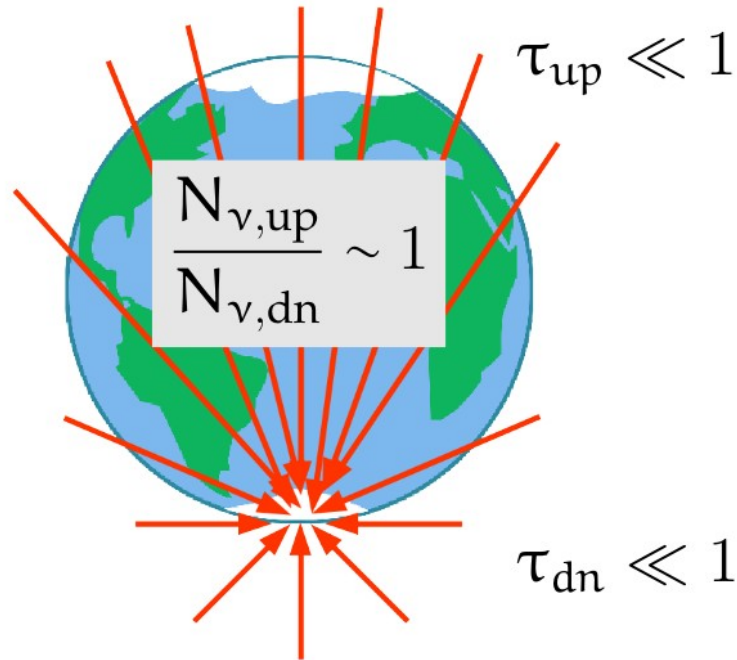
Above ~ 10 TeV: Earth is opaque



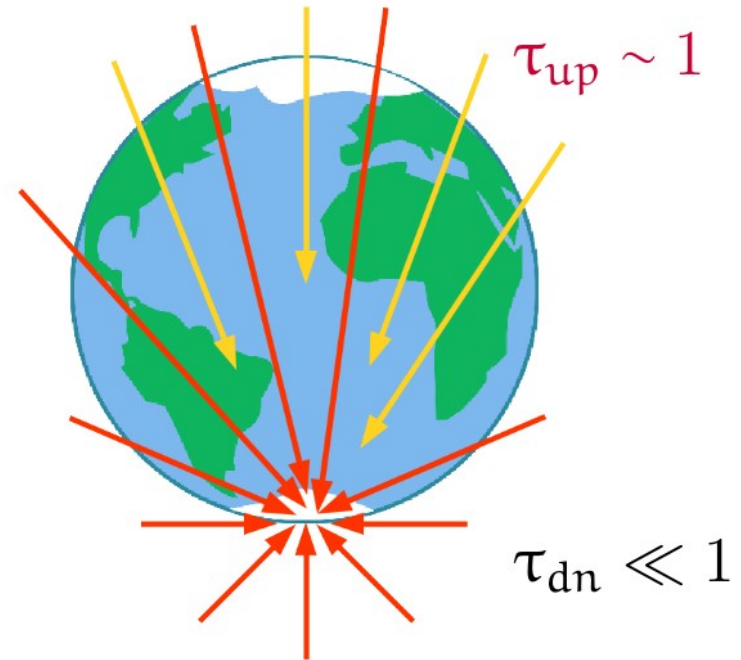
Measuring the high-energy cross section

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

Below ~ 10 TeV: Earth is transparent



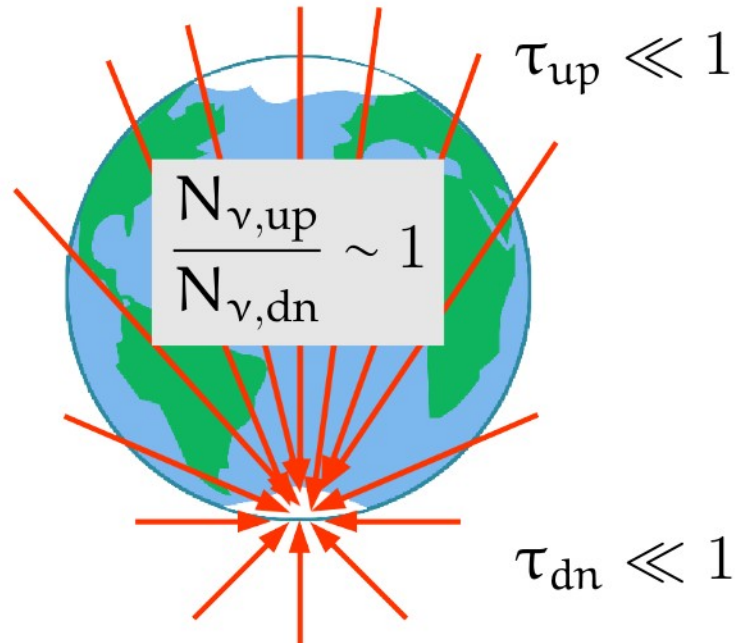
Above ~ 10 TeV: Earth is opaque



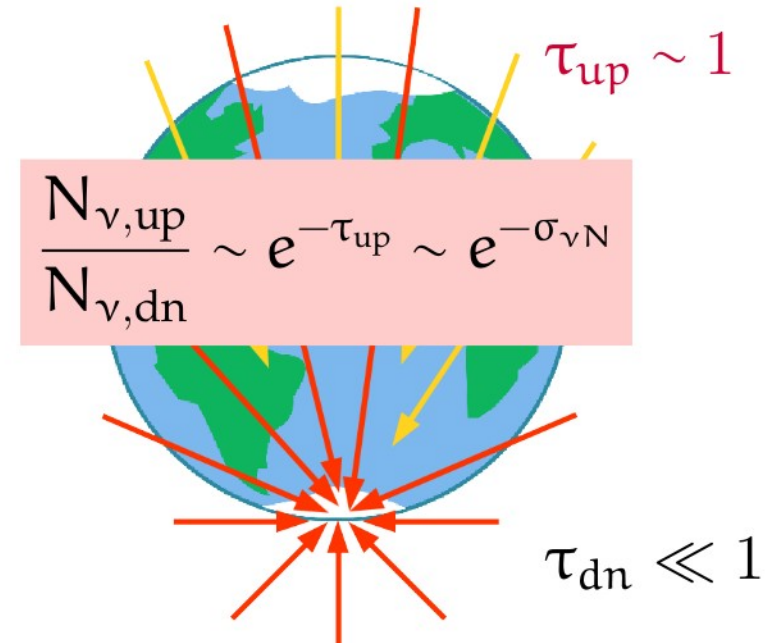
Measuring the high-energy cross section

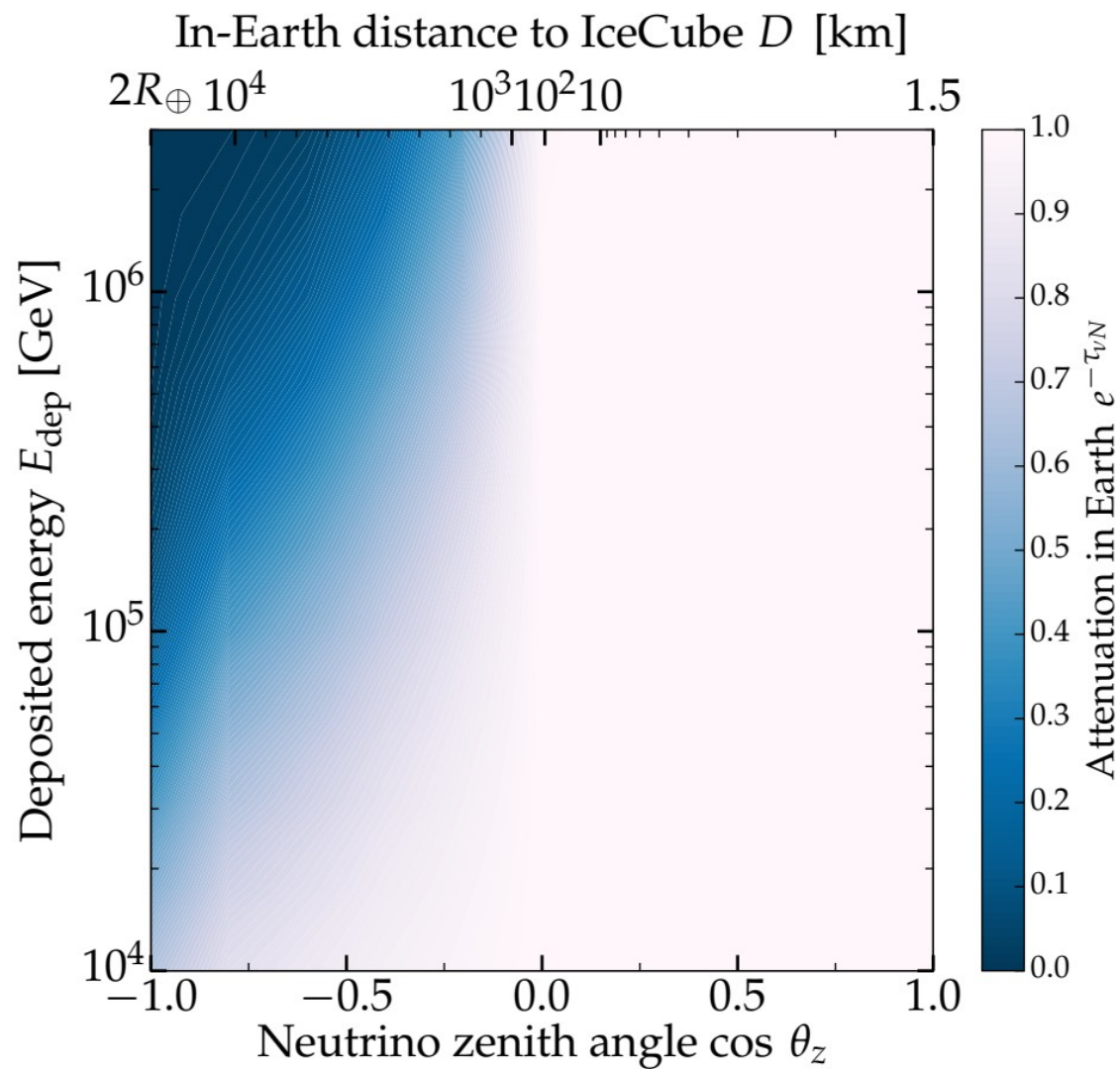
$$\text{Optical depth to } \nu N \text{ int's} = \frac{\text{Distance from Earth's surface to IceCube}}{\text{Mean free path inside Earth}} \equiv \tau(E_\nu, \theta_z) \propto \sigma_{\nu N}$$

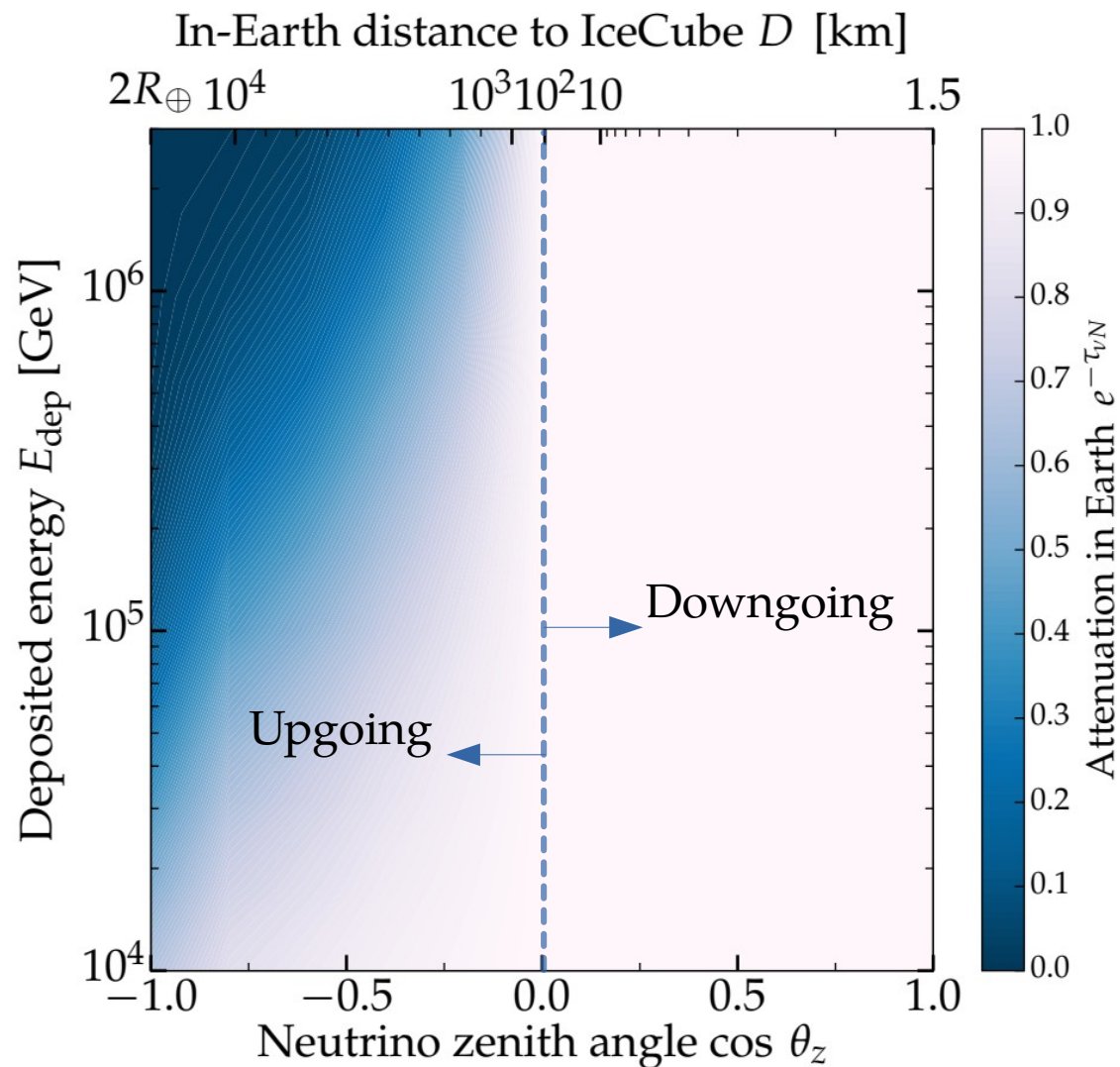
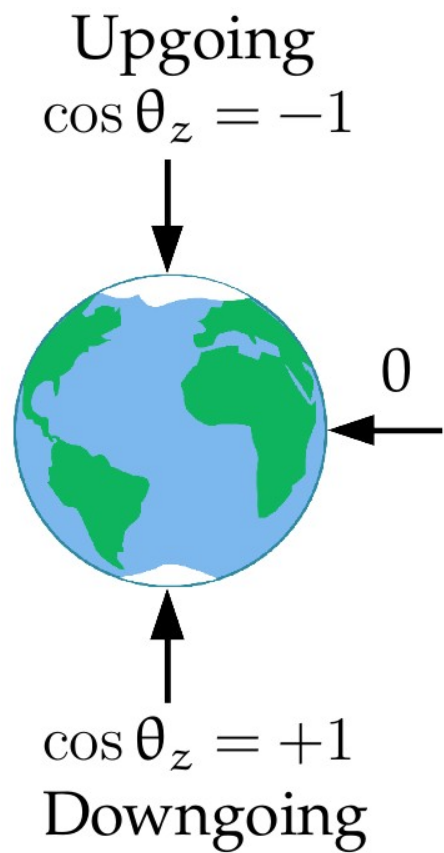
Below ~ 10 TeV: Earth is transparent

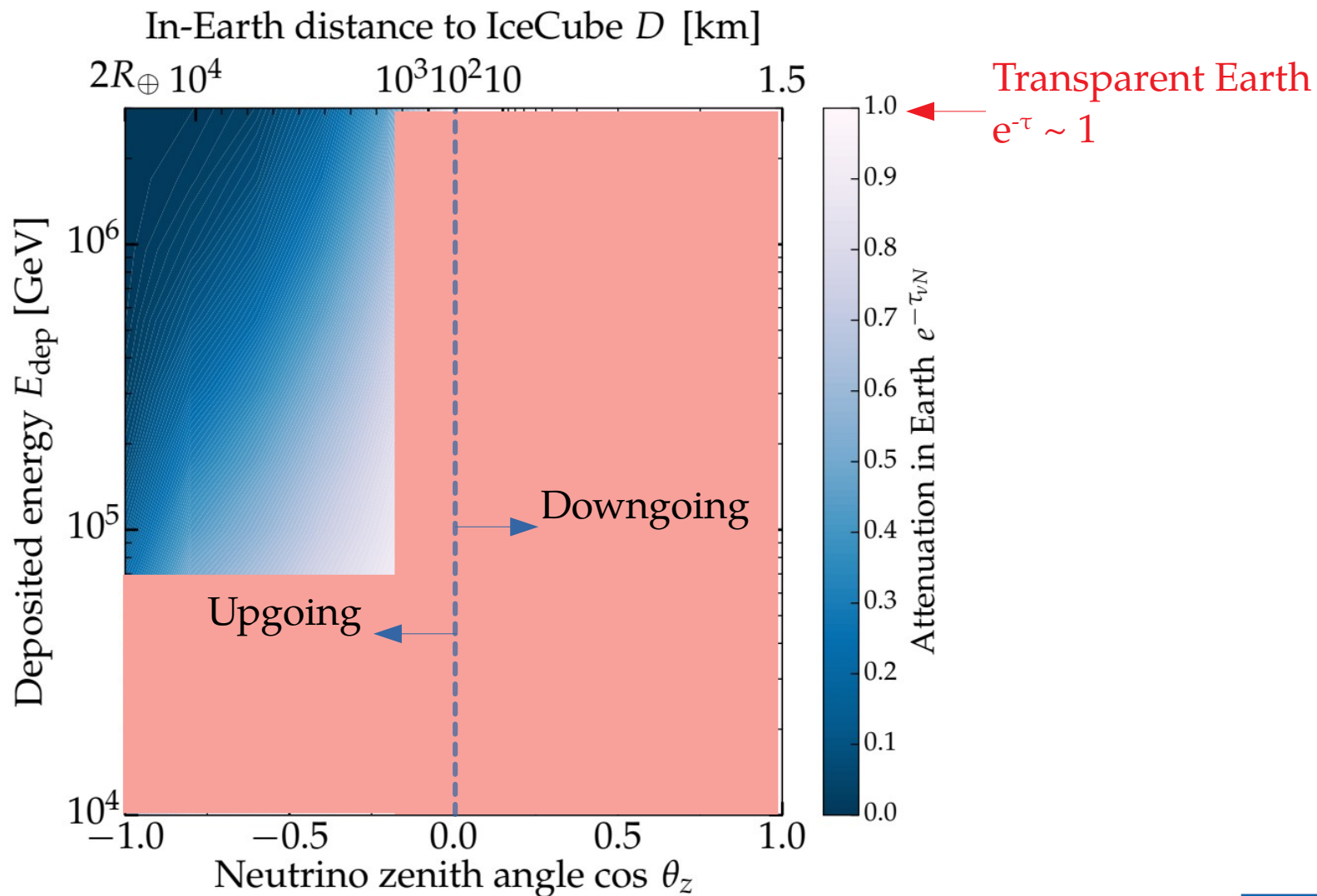
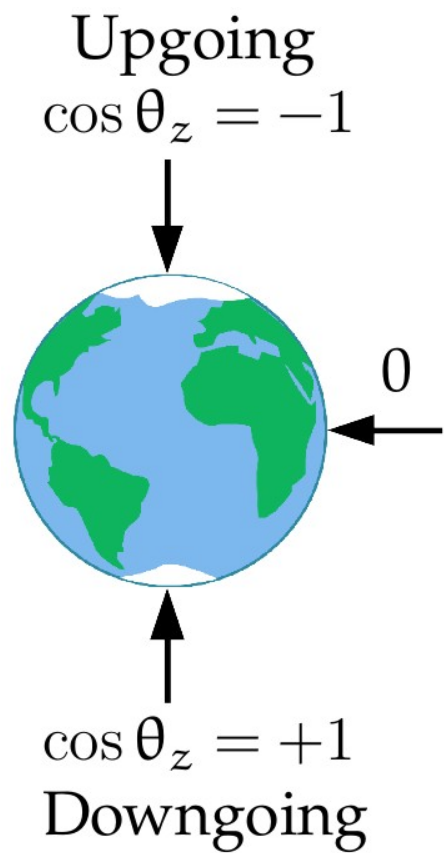


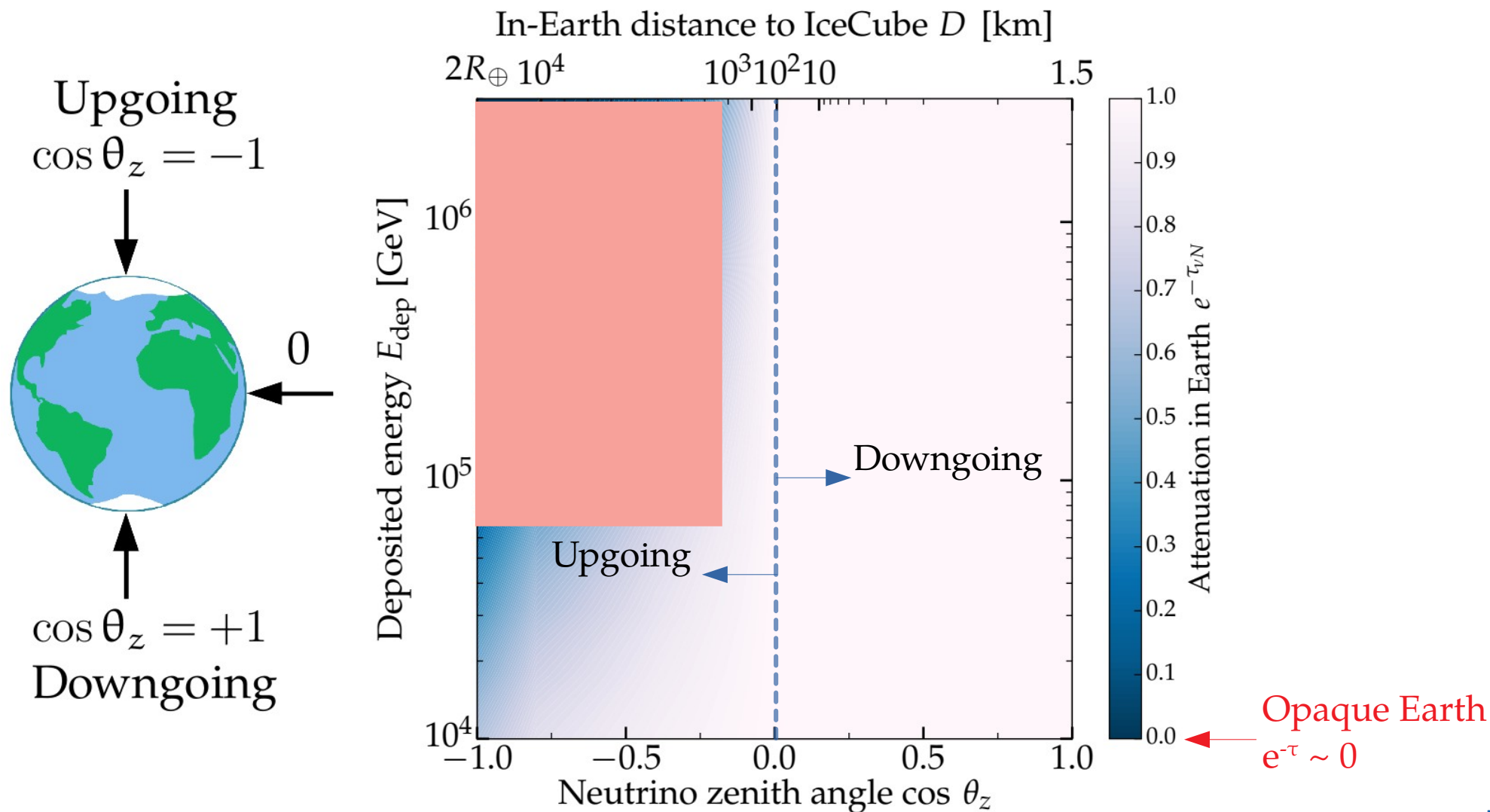
Above ~ 10 TeV: Earth is opaque

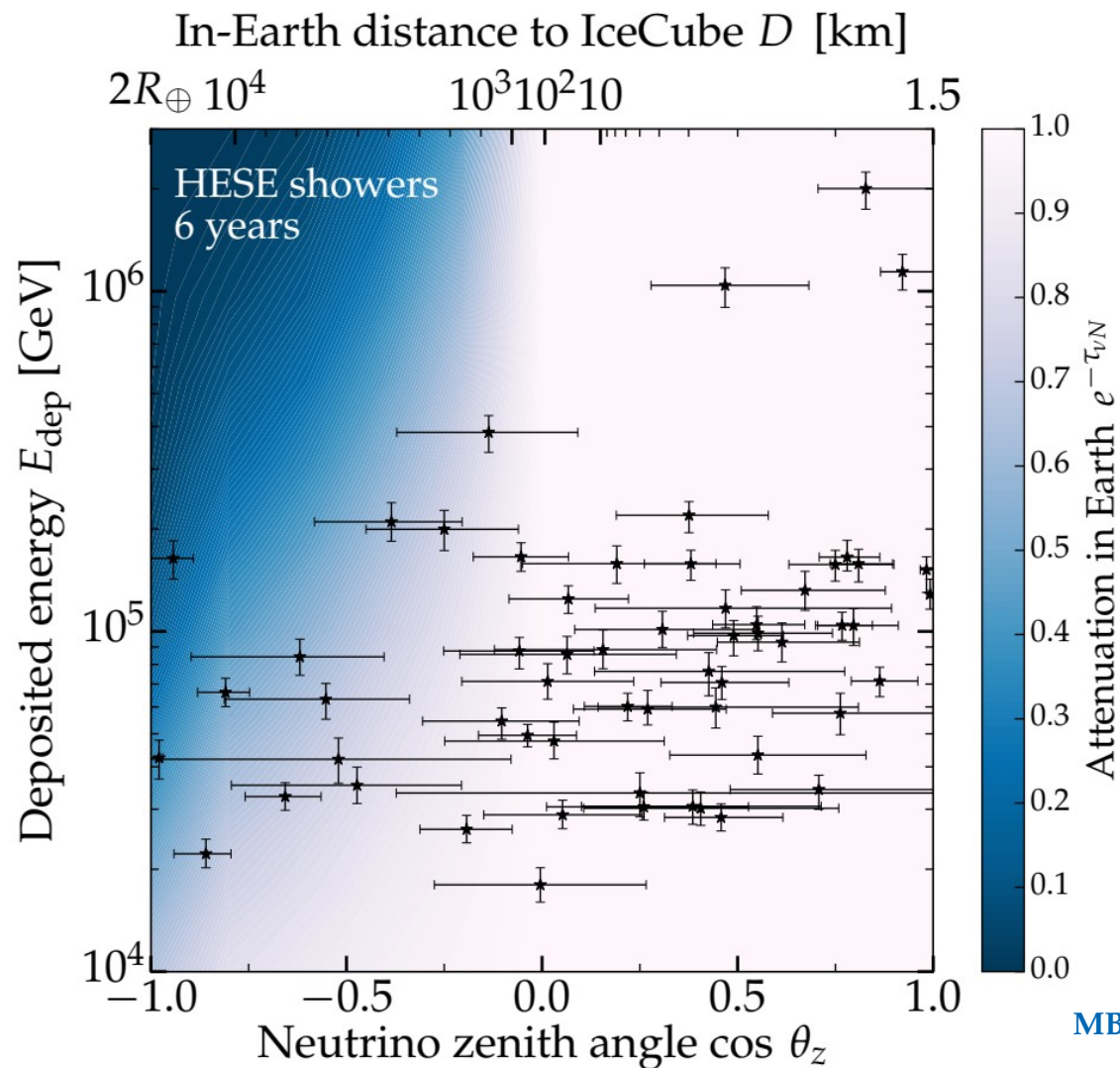




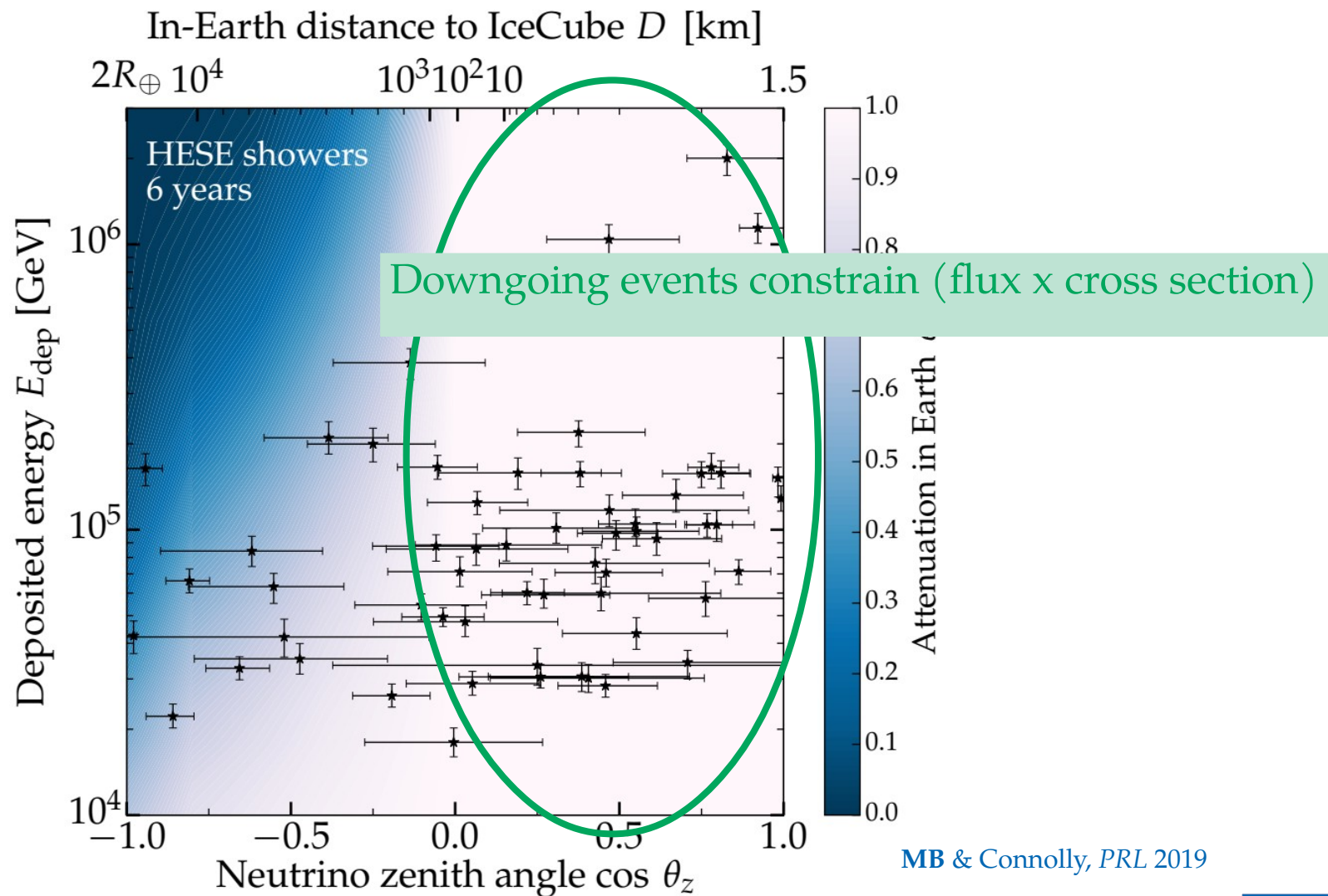




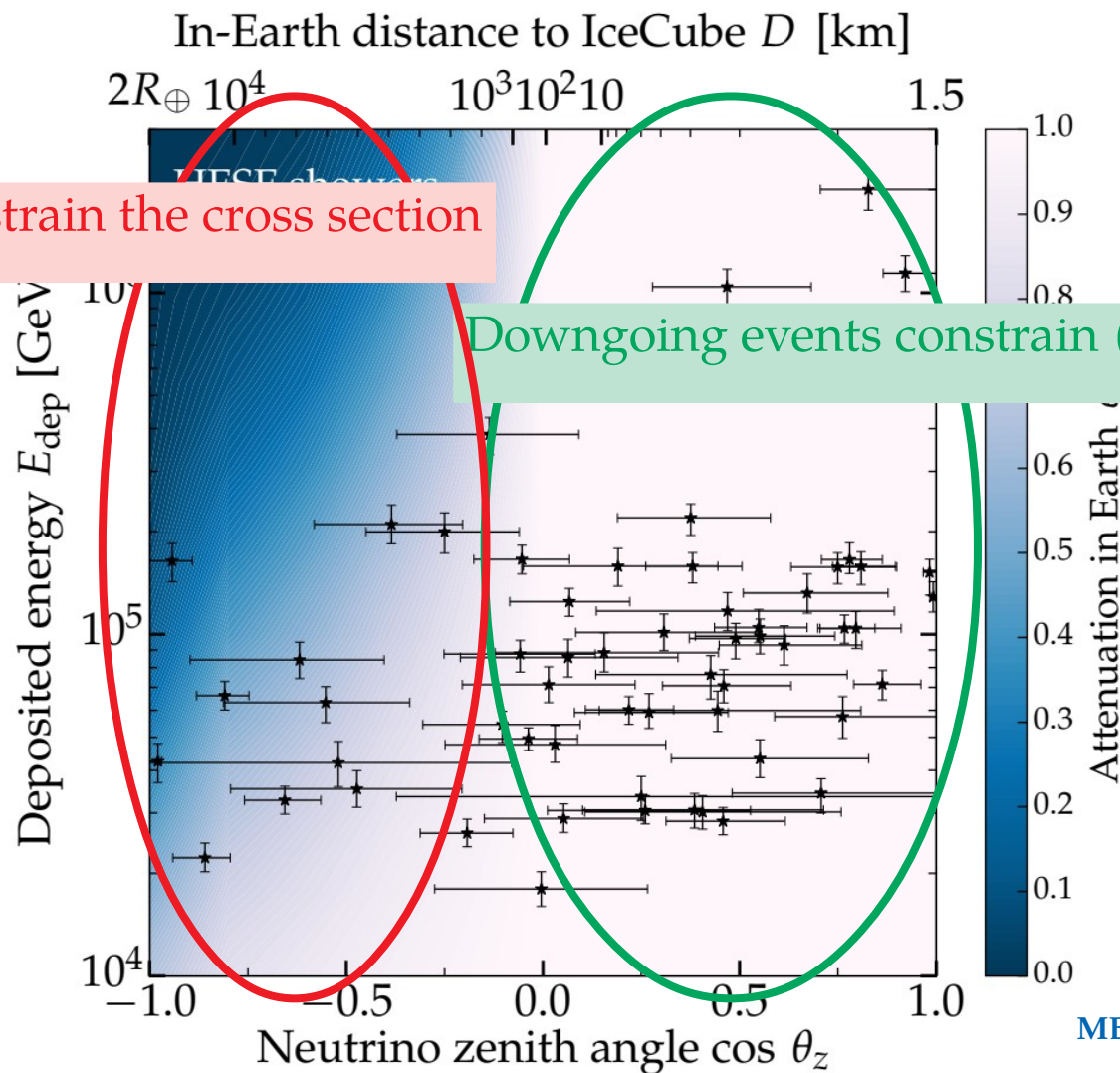




MB & Connolly, *PRL* 2019

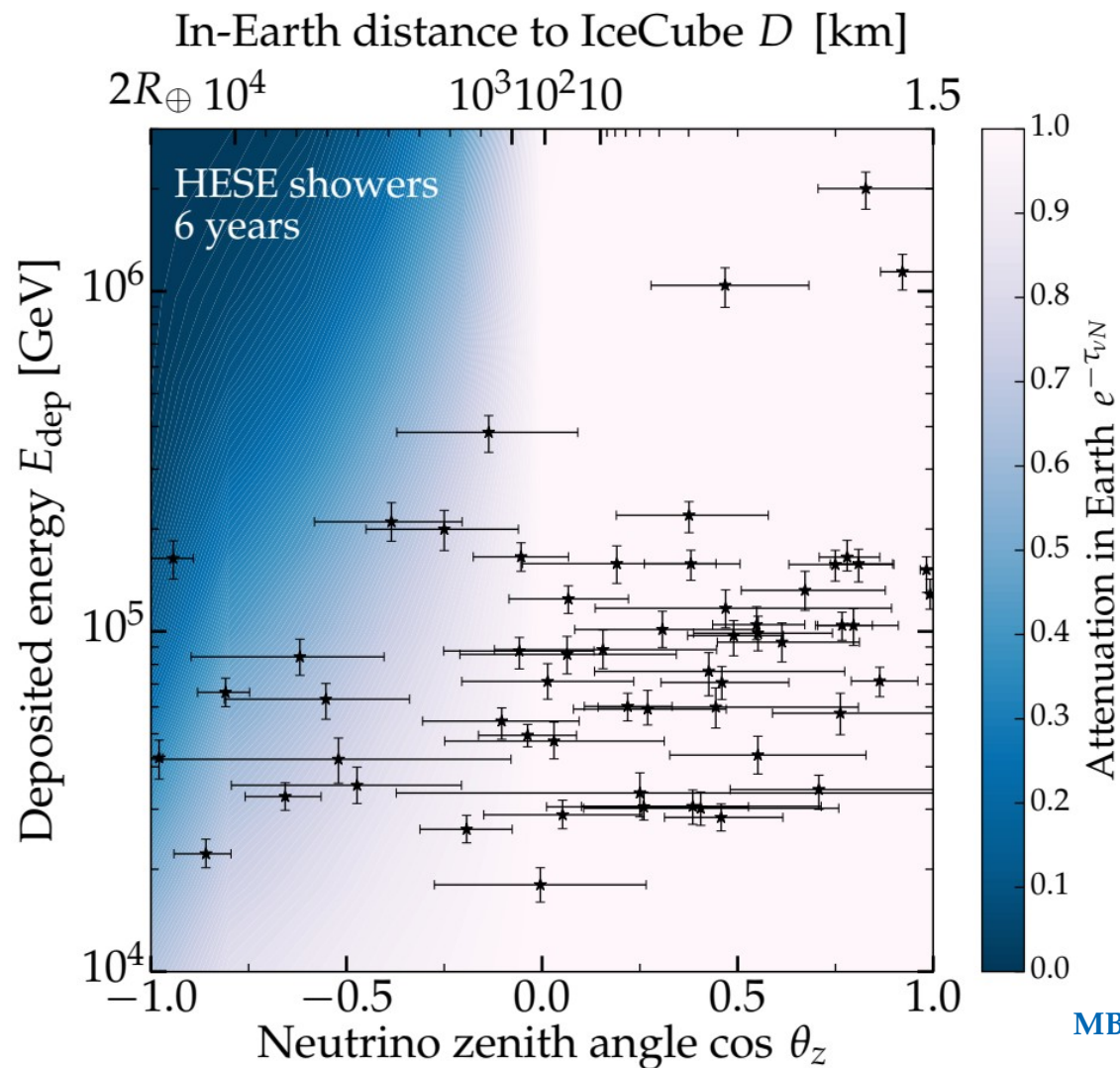


Upgoing events constrain the cross section

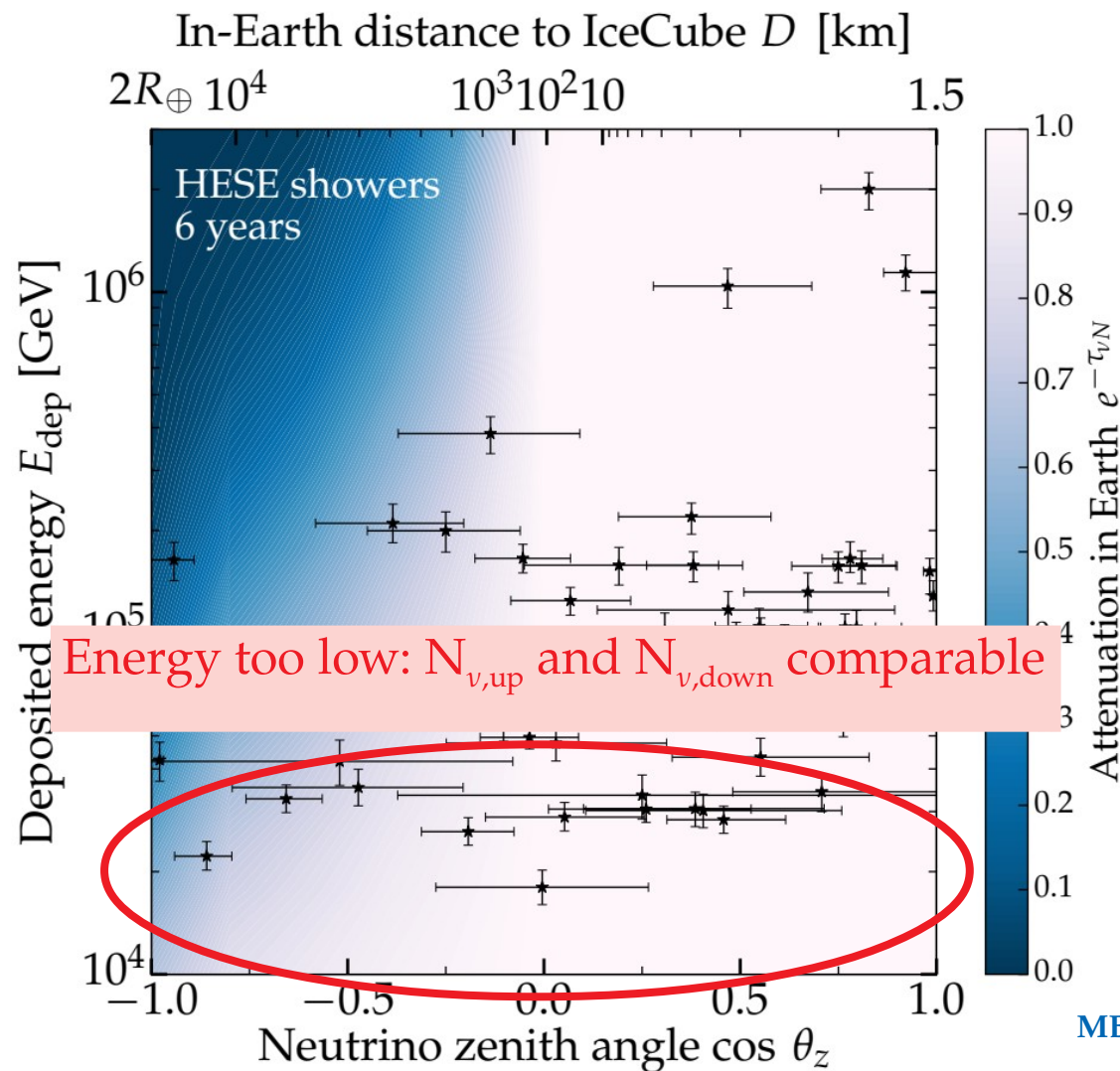


Downgoing events constrain (flux x cross section)

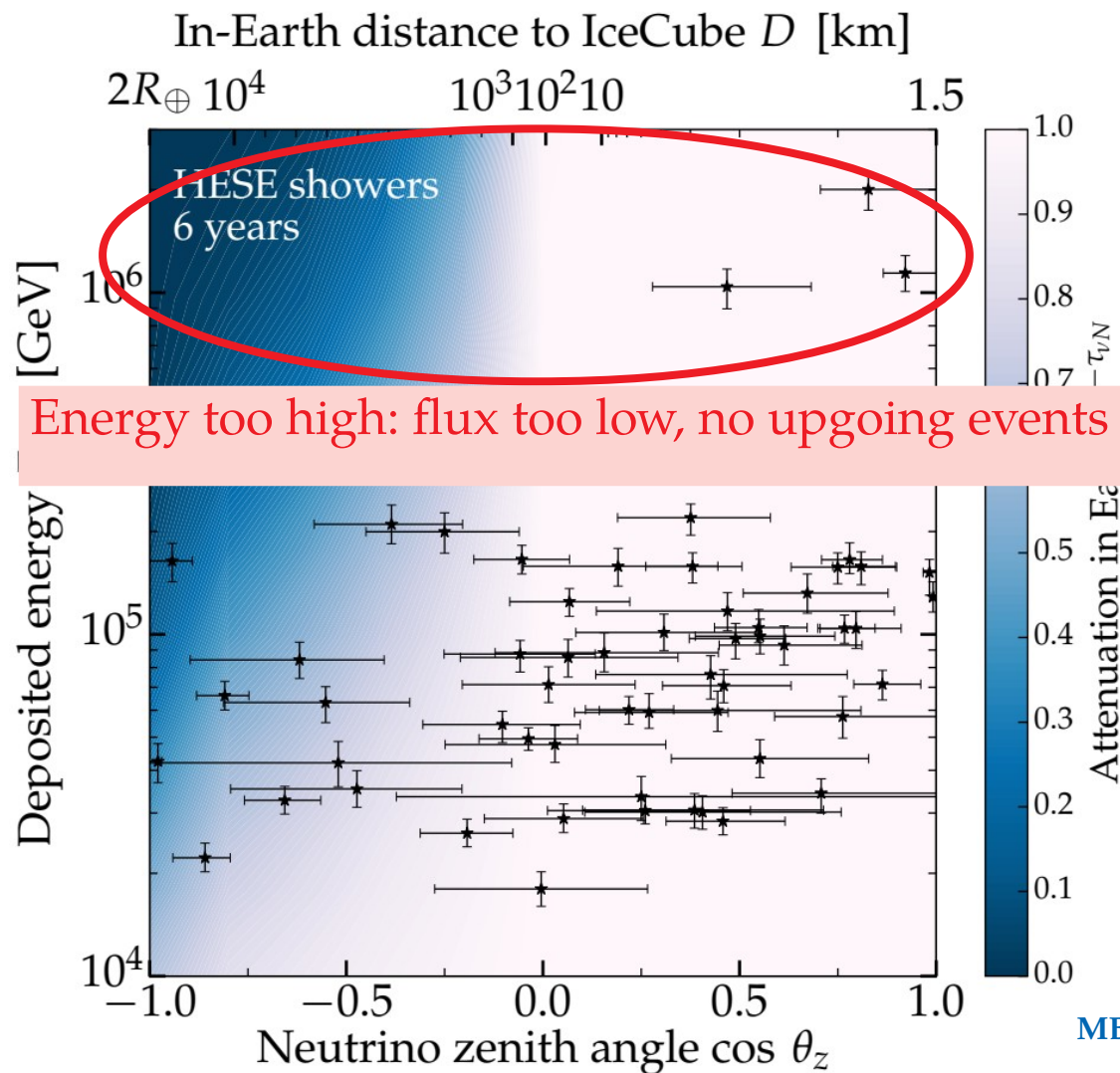
MB & Connolly, *PRL* 2019



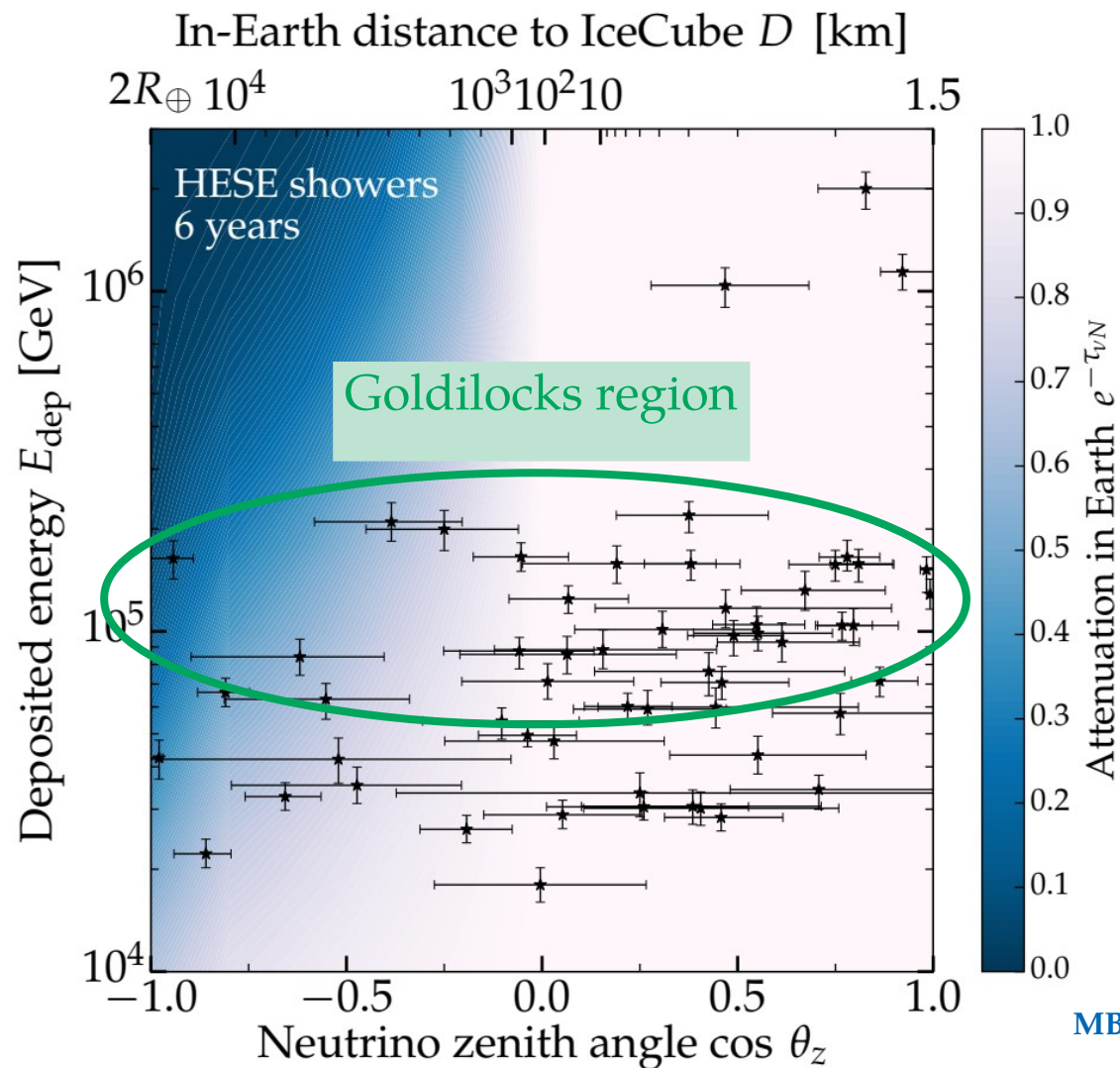
MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

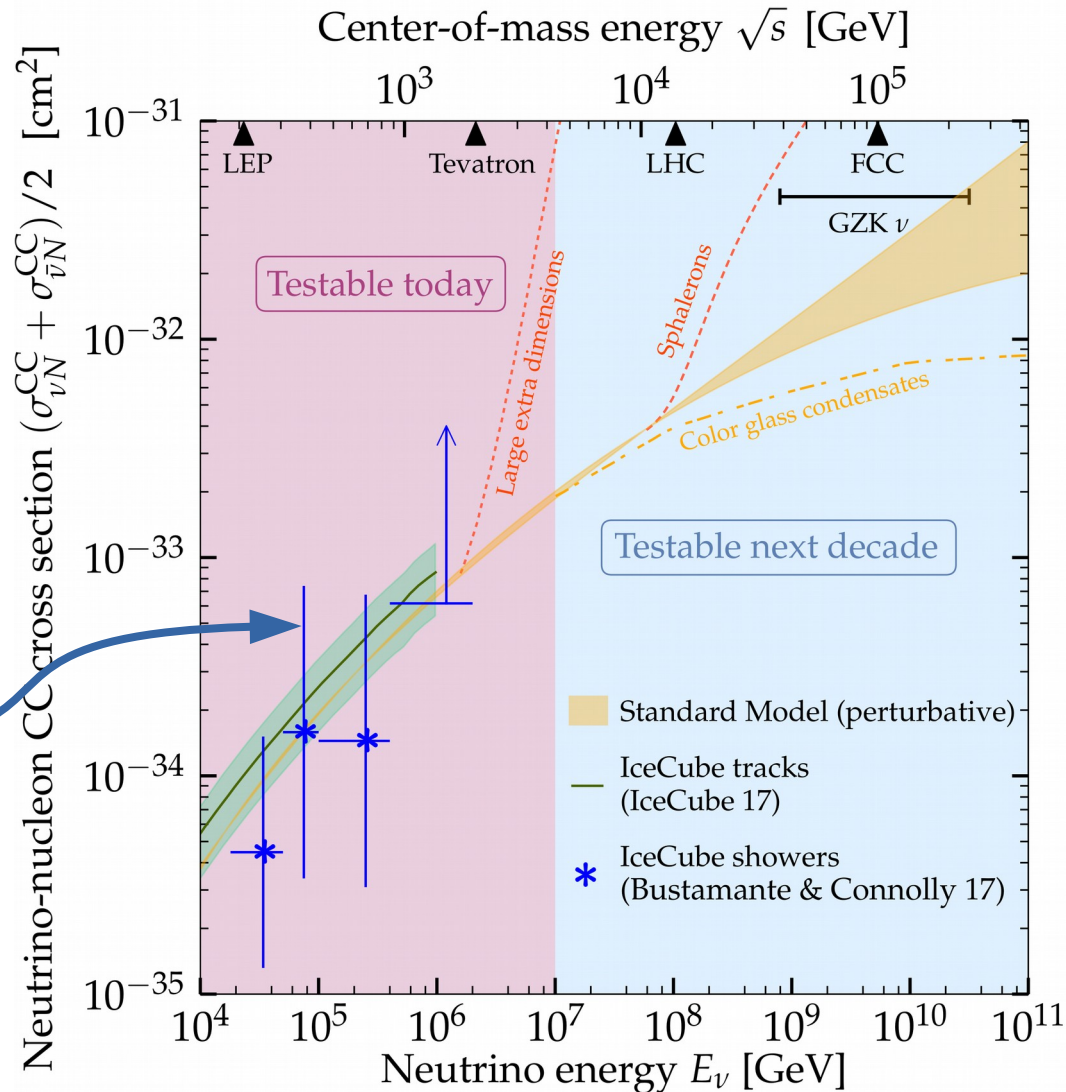


MB & Connolly, *PRL* 2019



MB & Connolly, *PRL* 2019

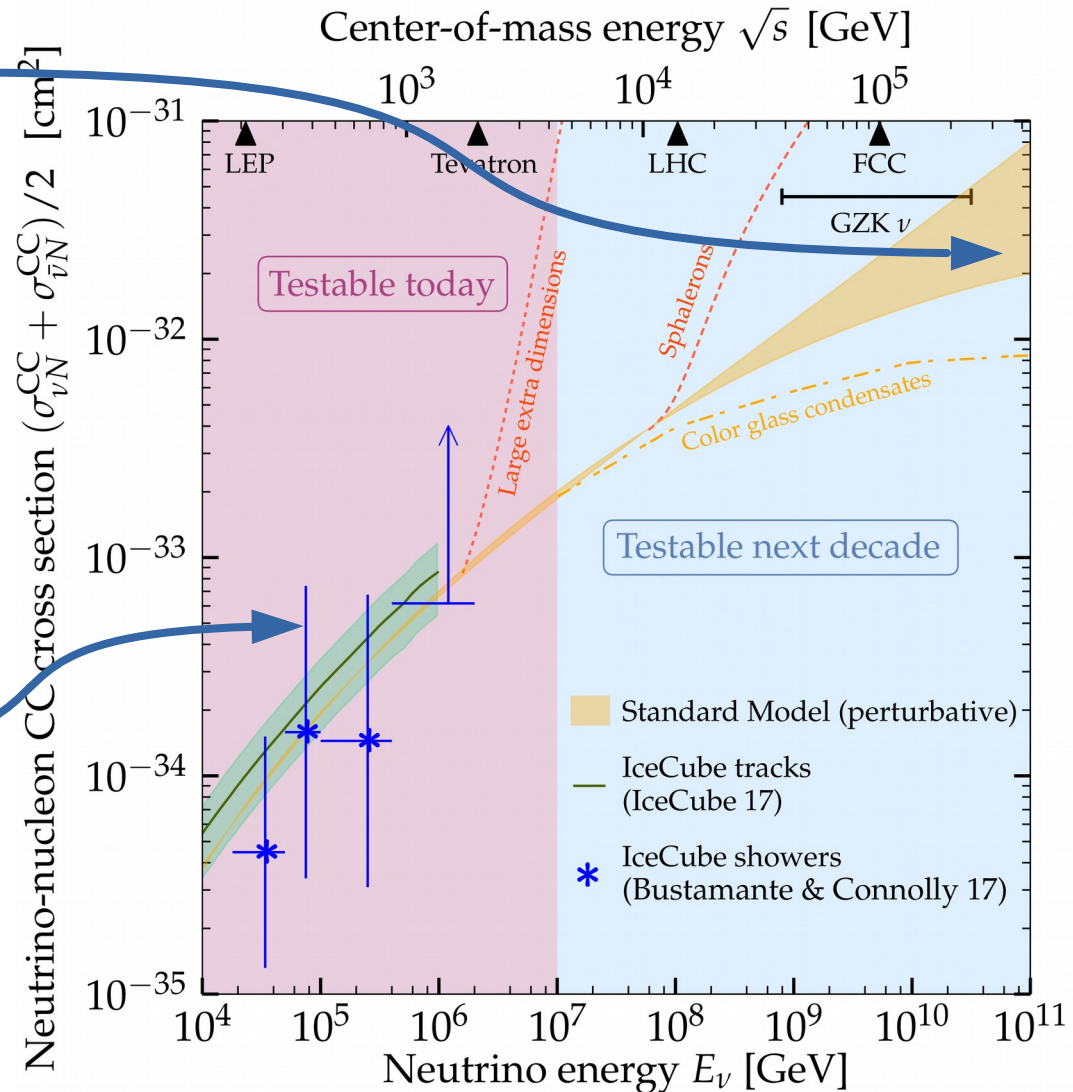
- ▶ Fold in astrophysical unknowns (spectral index, normalization)
- ▶ Compatible with SM predictions
- ▶ Still room for new physics
- ▶ Today, using IceCube:
 - ▶ Extracted from ~60 showers in 6 yr
 - ▶ Limited by statistics
- ▶ Future, using IceCube-Gen2:
 - ▶ $\times 5$ volume $\Rightarrow$ 300 showers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



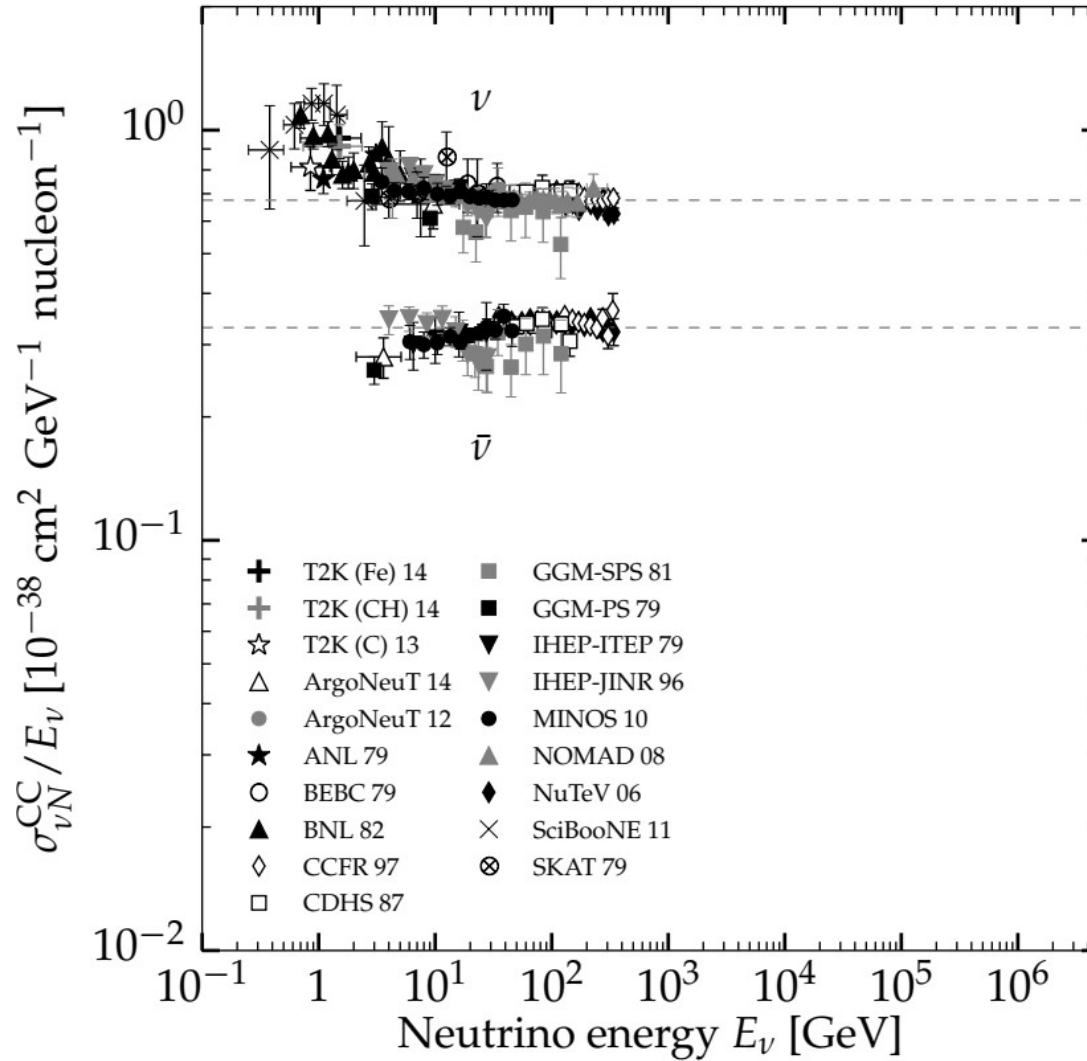
UHE uncertainties can be smaller:
 Cooper-Sarkar, Mertsch, Sarkar *et al.*, *JHEP* 2011

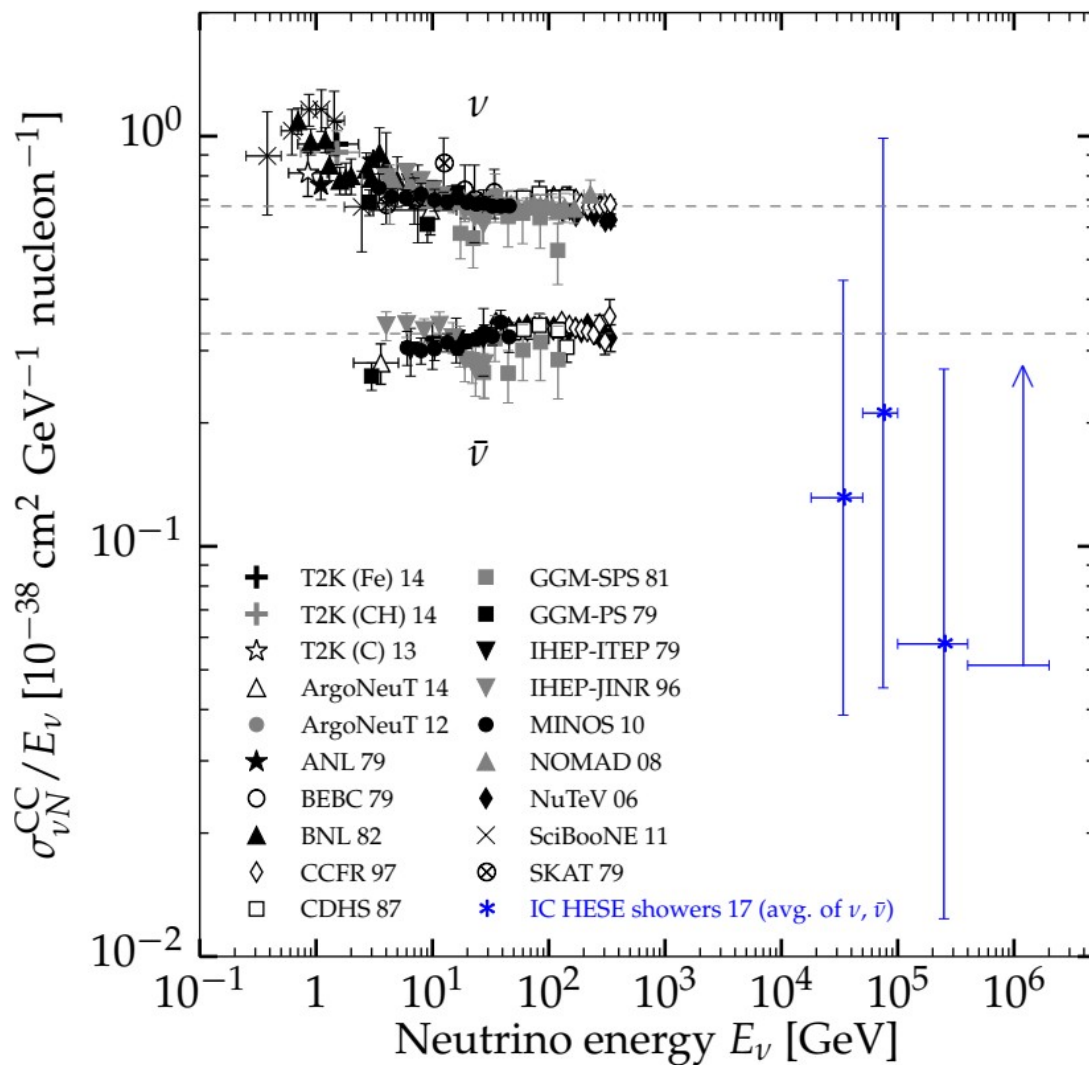
- ▶ Fold in astrophysical unknowns (spectral index, normalization)
- ▶ Compatible with SM predictions
- ▶ Still room for new physics
- ▶ Today, using IceCube:
 - ▶ Extracted from ~60 showers in 6 yr
 - ▶ Limited by statistics
- ▶ Future, using IceCube-Gen2:
 - ▶ $\times 5$ volume $\Rightarrow$ 300 showers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

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

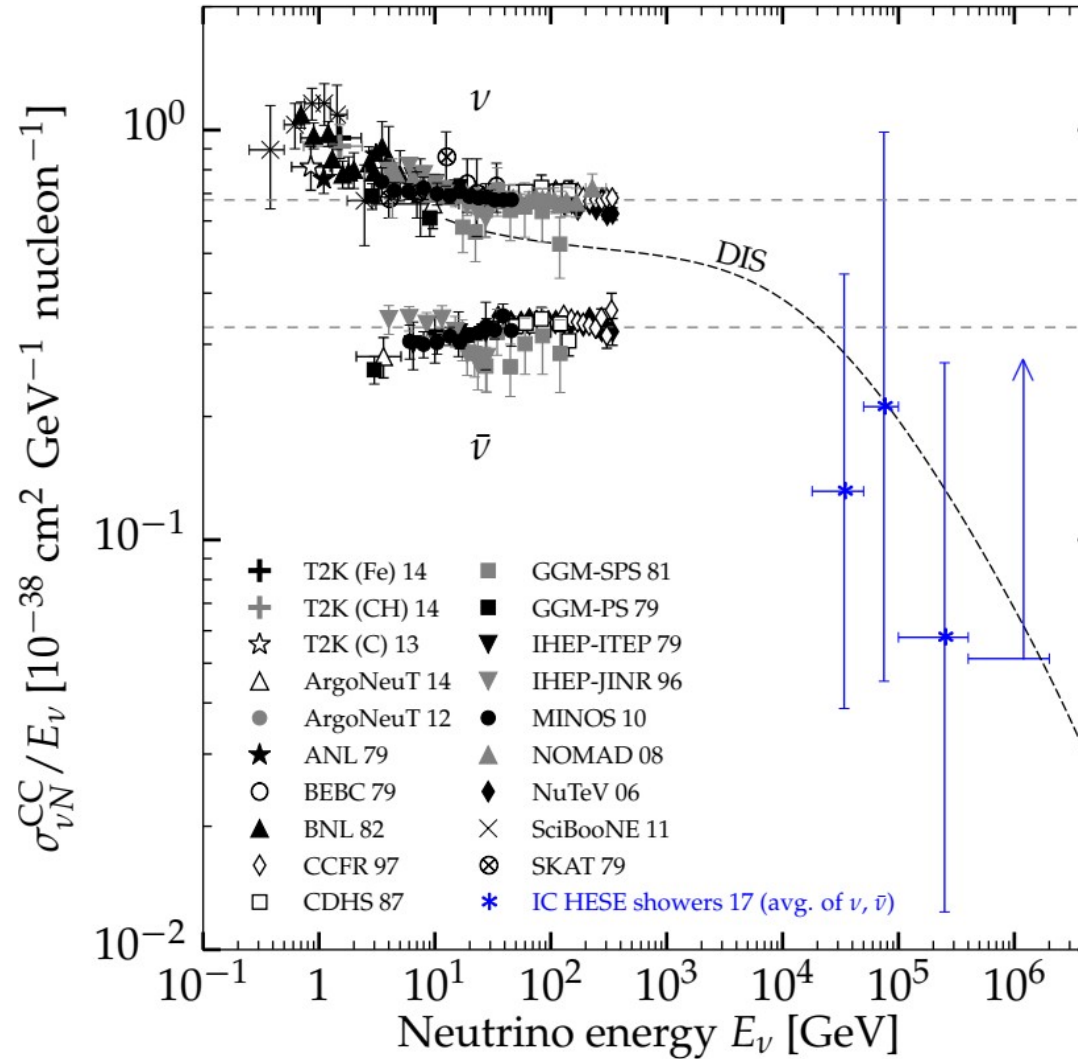


Ackermann *et al.*, *Astro2020 Decadal Survey* (1903.04333)

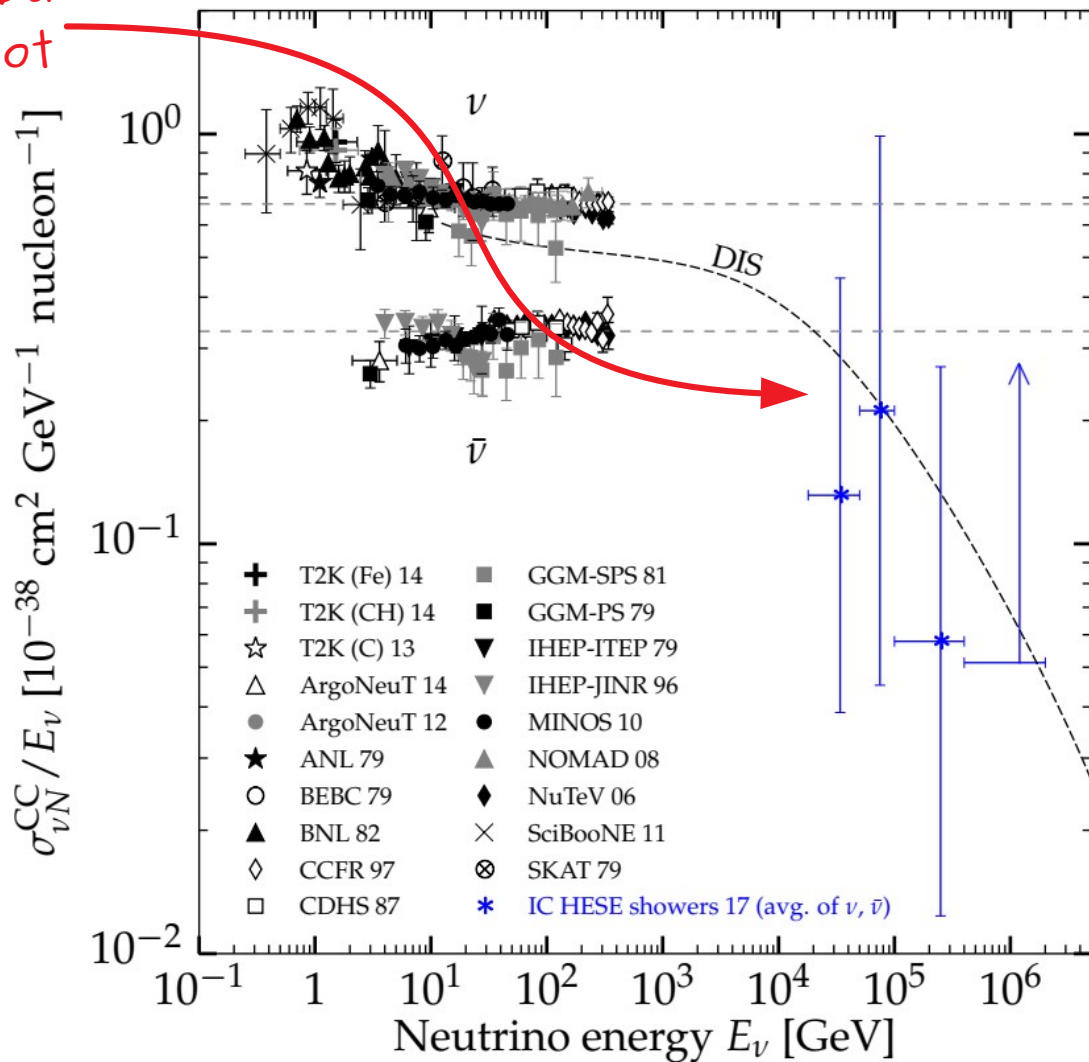




MB & A. Connolly PRL 2019
See also: IceCube, Nature 2017



Extending the PDG
cross-section plot



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

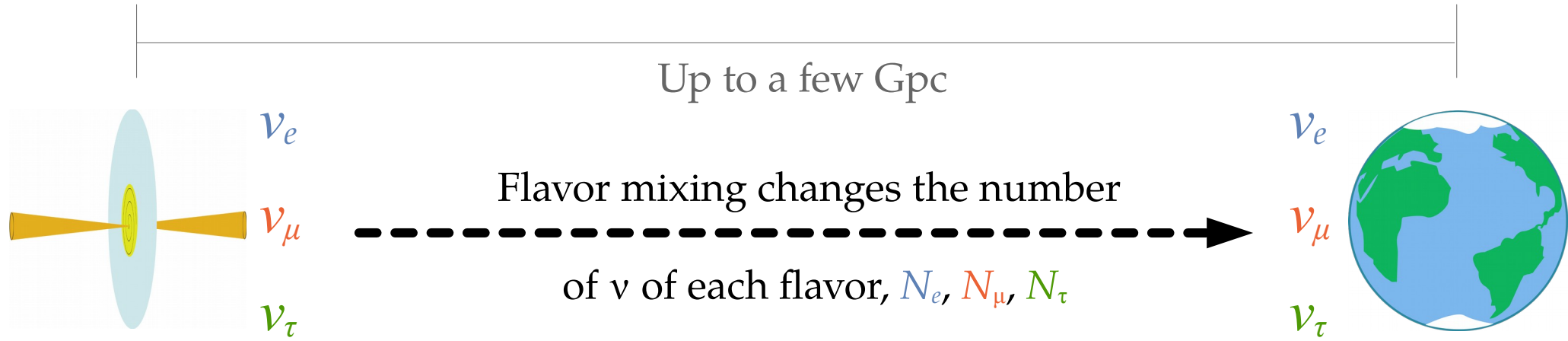
The fine print

- ▶ 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 $\sigma_{\text{NC}} = \sigma_{\text{CC}}/3$
- ▶ 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 $\langle \sigma_{\nu\text{N}} / \bar{\sigma}_{\nu\text{N}} \rangle$ 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

Flavor composition

Astrophysical neutrino sources

Earth



- Different processes yield different ratios of neutrinos of each flavor:

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

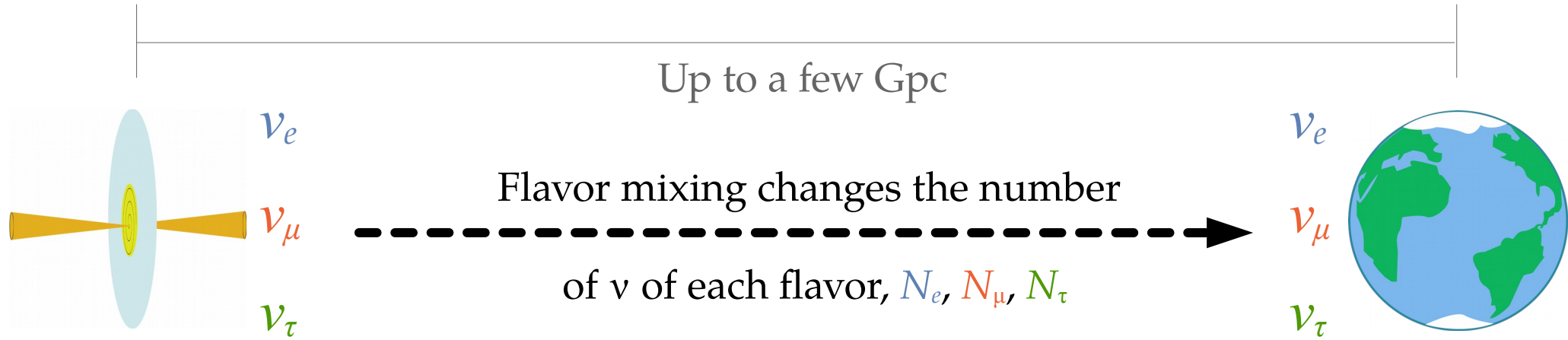
- Flavor ratios at Earth ($\alpha = e, \mu, \tau$):

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

Flavor composition

Astrophysical neutrino sources

Earth



- Different processes yield different ratios of neutrinos of each flavor:

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

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

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

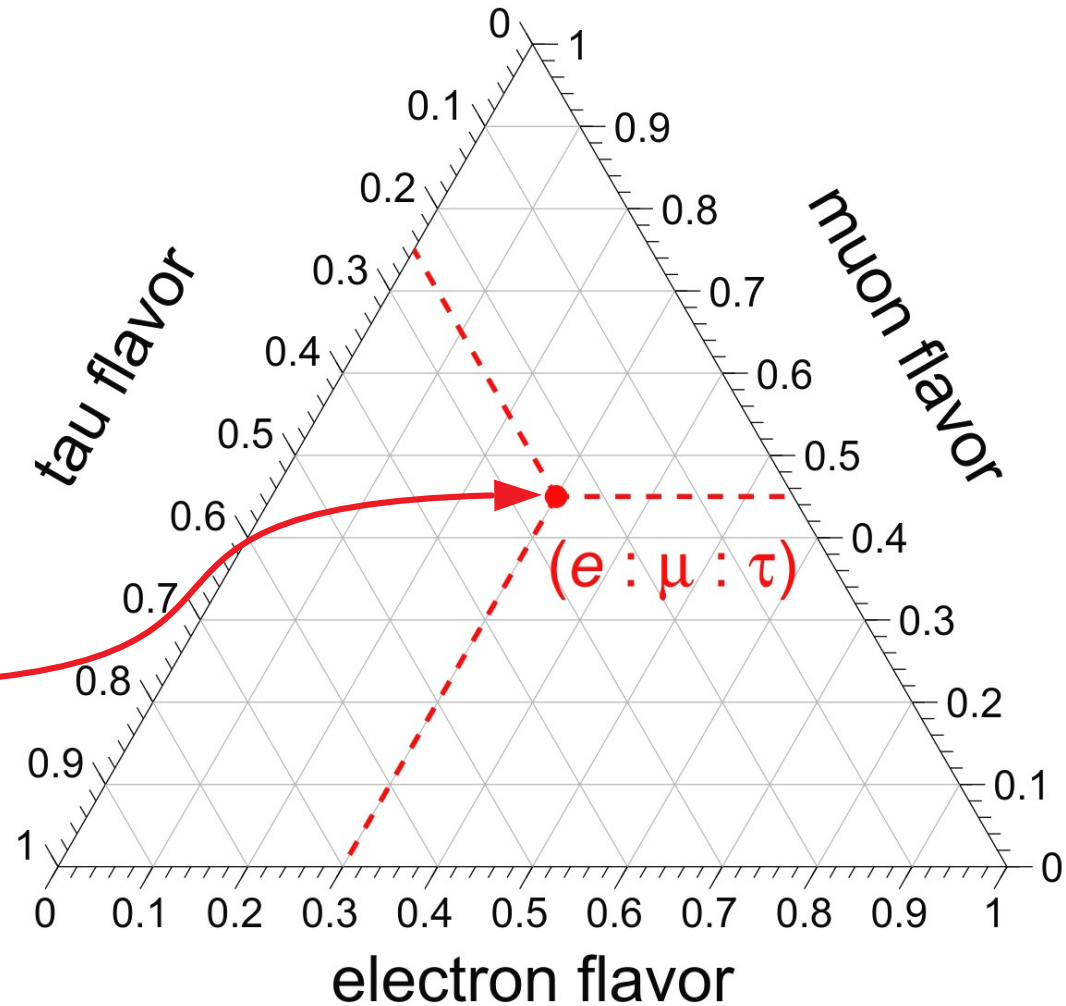
Standard oscillations
or
new physics

Reading 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, *e.g.*,

$$(e:\mu:\tau) = (0.30:0.45:0.25)$$



One likely TeV–PeV ν production scenario:

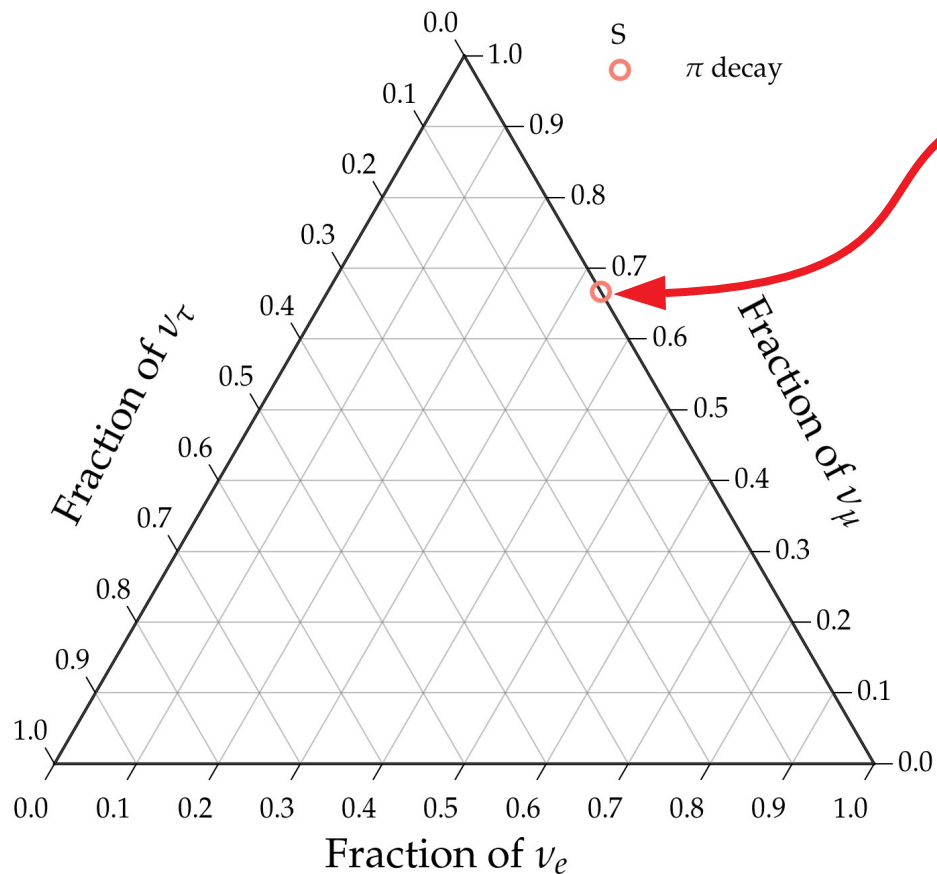
$$p + \gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \text{ followed by } \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

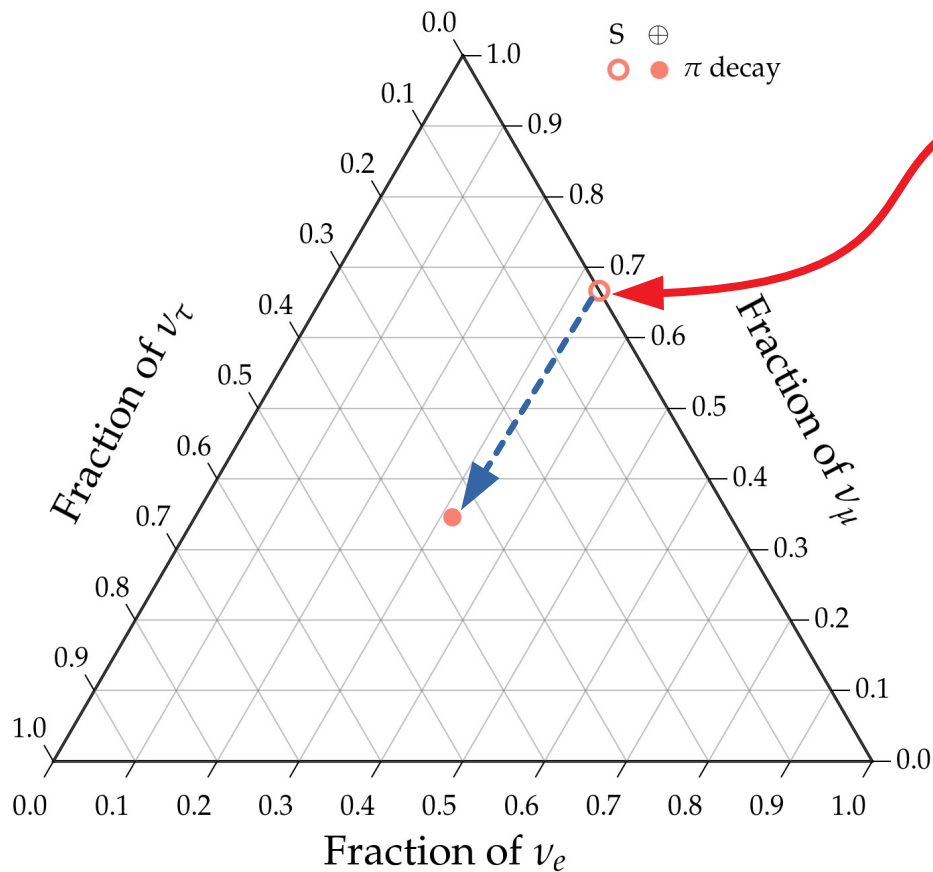


Full π decay chain

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

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

One likely TeV–PeV ν production scenario:

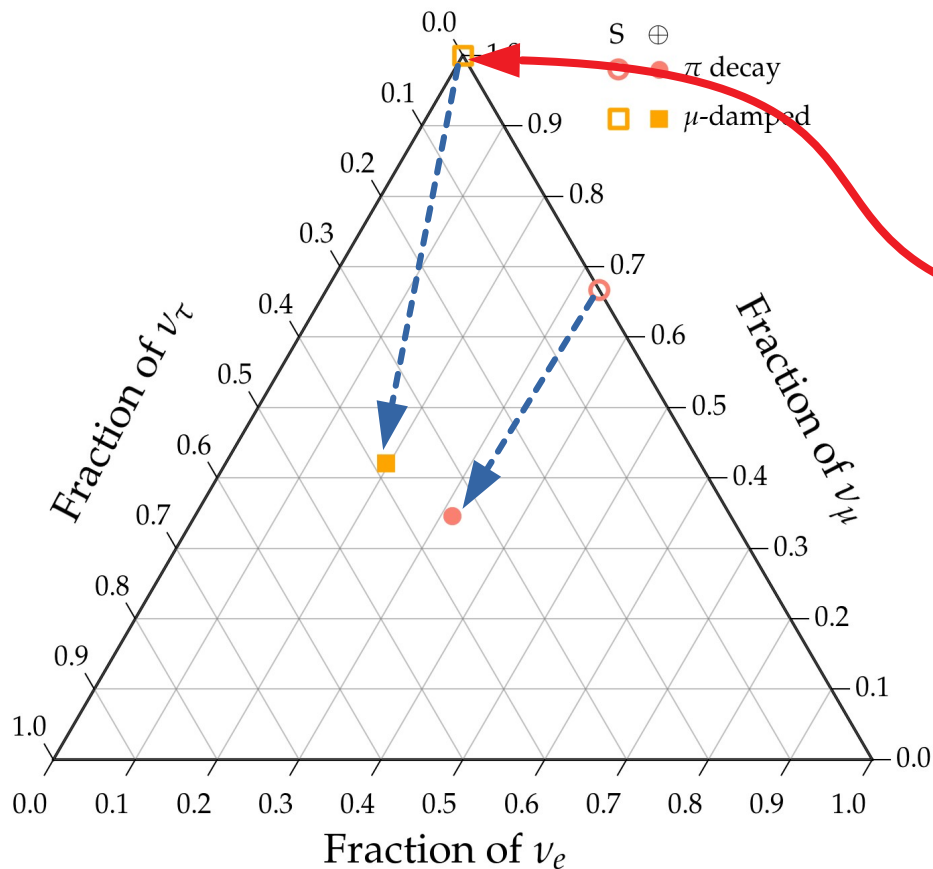


Full π decay chain

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

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

One likely TeV–PeV ν production scenario:



Full π decay chain

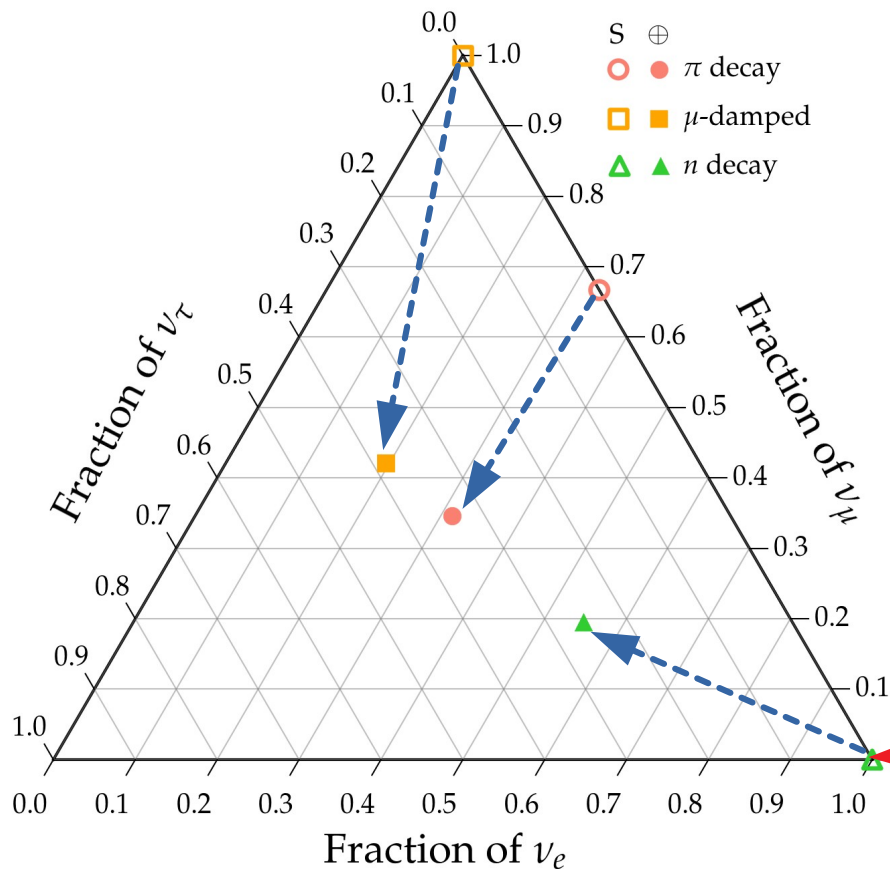
$(1/3:2/3:0)_S$

Muon damped

$(0:1:0)_S$

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

One likely TeV–PeV ν production scenario:



Full π decay chain

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

Muon damped

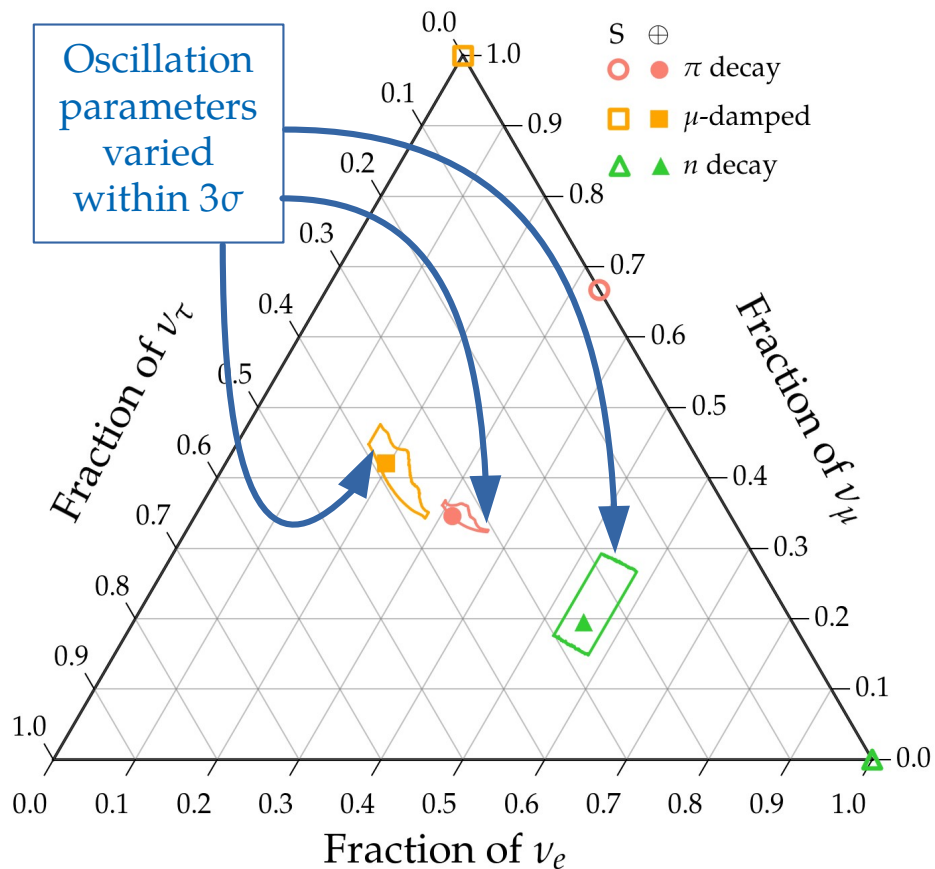
$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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

One likely TeV–PeV ν production scenario:



Full π decay chain

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

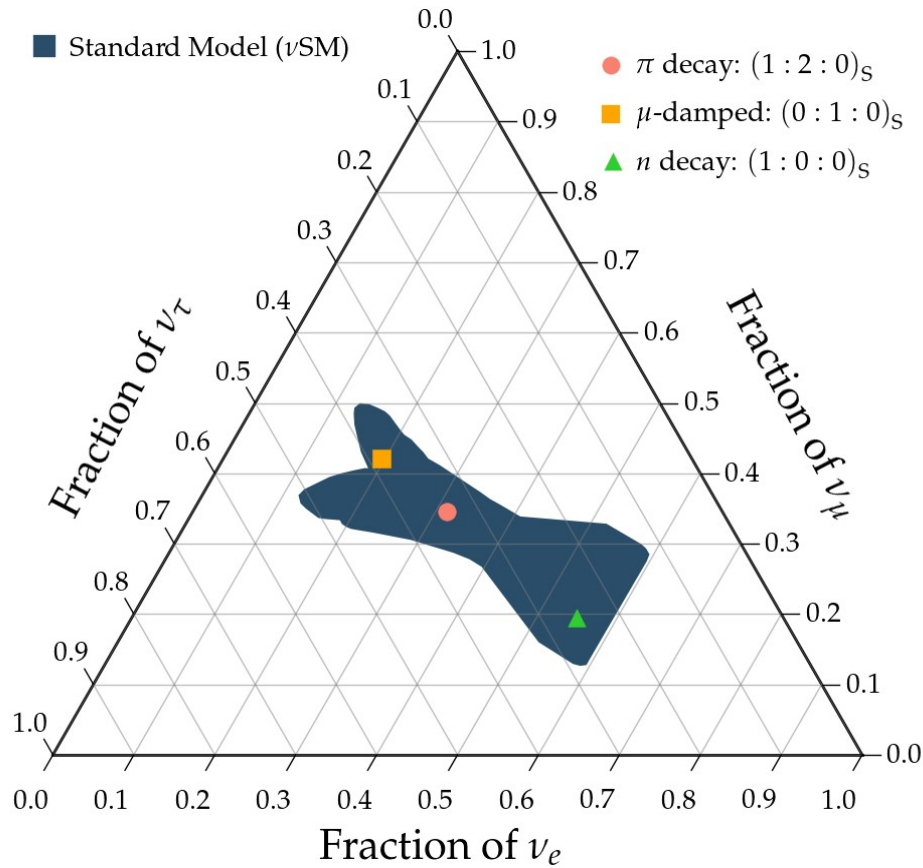
Muon damped

$(0:1:0)_S$

Neutron decay

$(1:0:0)_S$

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



All possible flavor
ratios at the sources

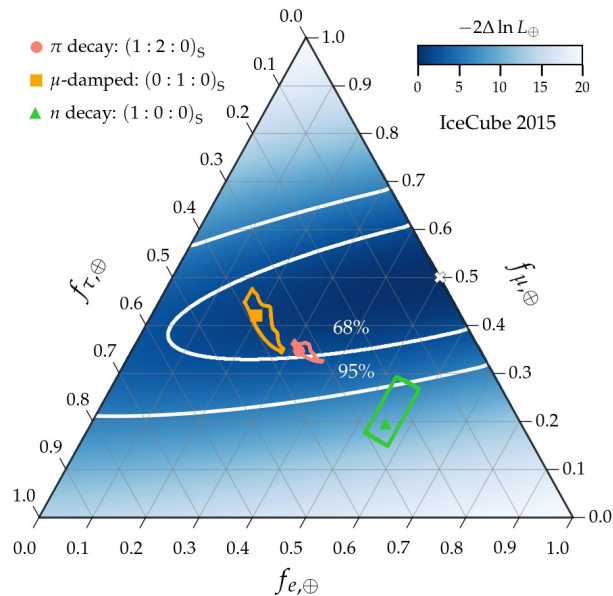
+

Vary oscillation
parameters within 3σ

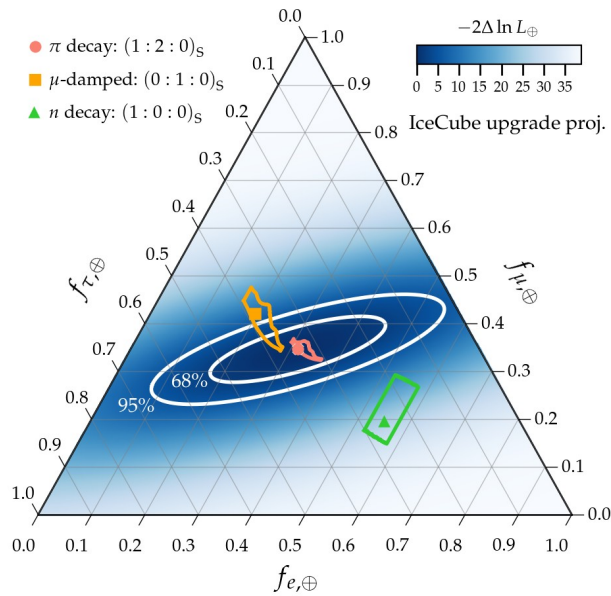
Note: ν and $\bar{\nu}$ are (so far) indistinguishable
in neutrino telescopes

IceCube flavor composition

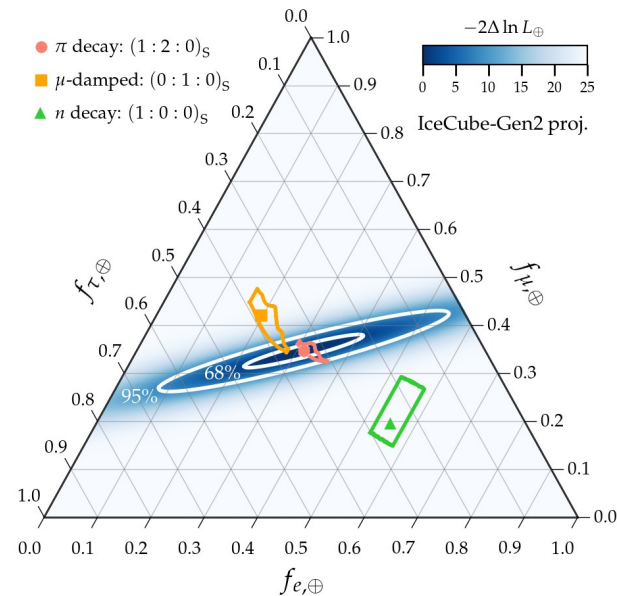
Today
IceCube



Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2



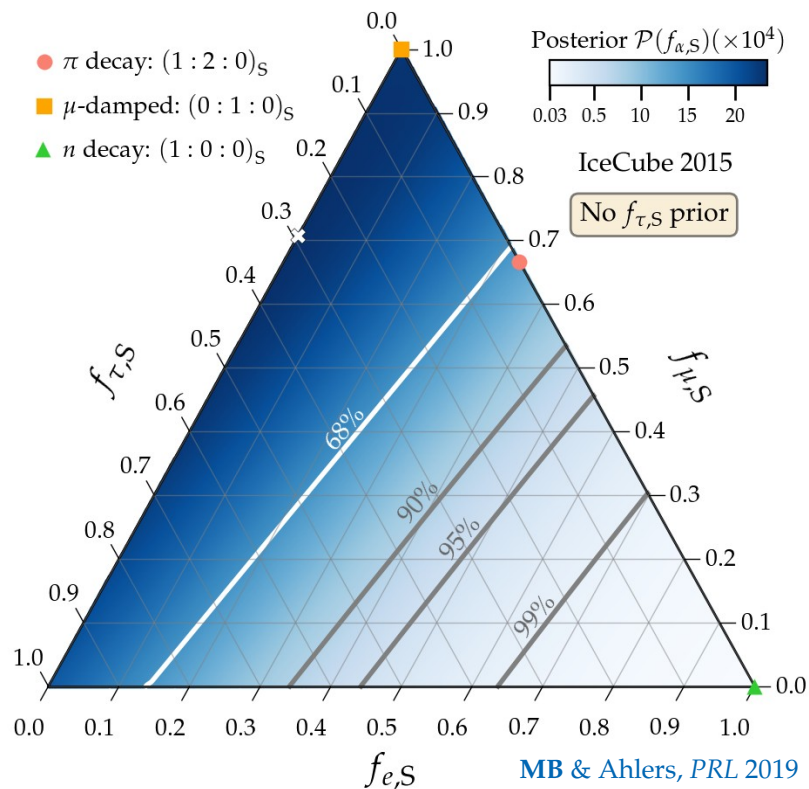
- ▶ Best fit:
 $(f_e:f_\mu:f_\tau)_\oplus = (0.49:0.51:0)_\oplus$
- ▶ Compatible with standard source compositions
- ▶ Hints of one ν_τ (not shown)

Assuming production by the full pion decay chain

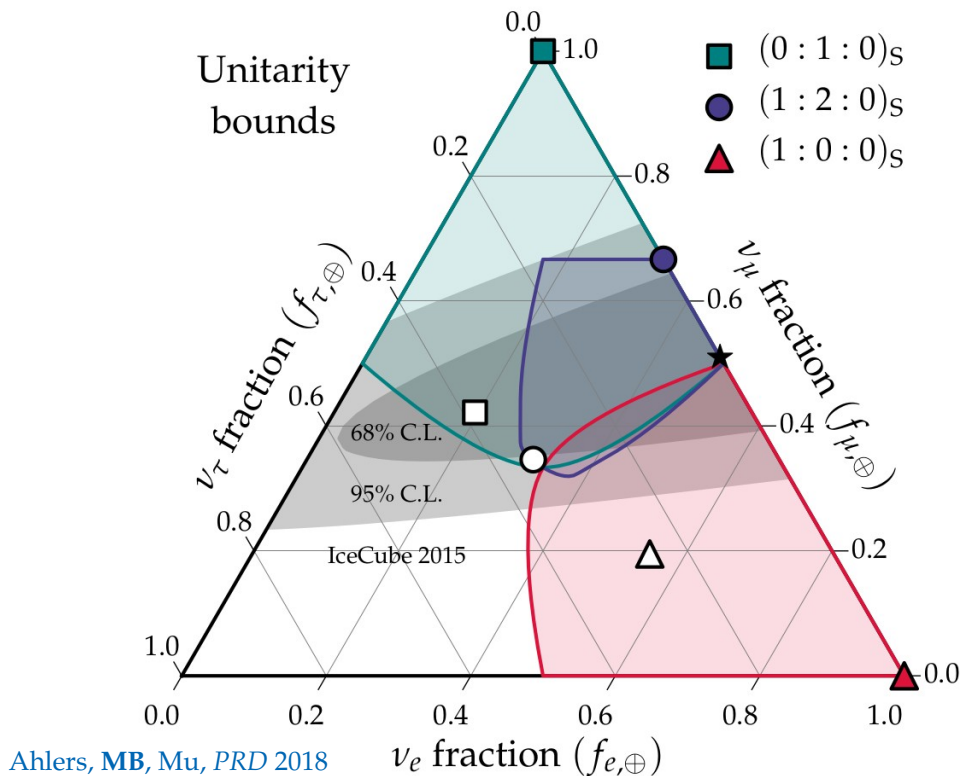
Plus possibly better flavor-tagging, *e.g.*, muon and neutron echoes
[Li, MB, Beacom PRL 2019]

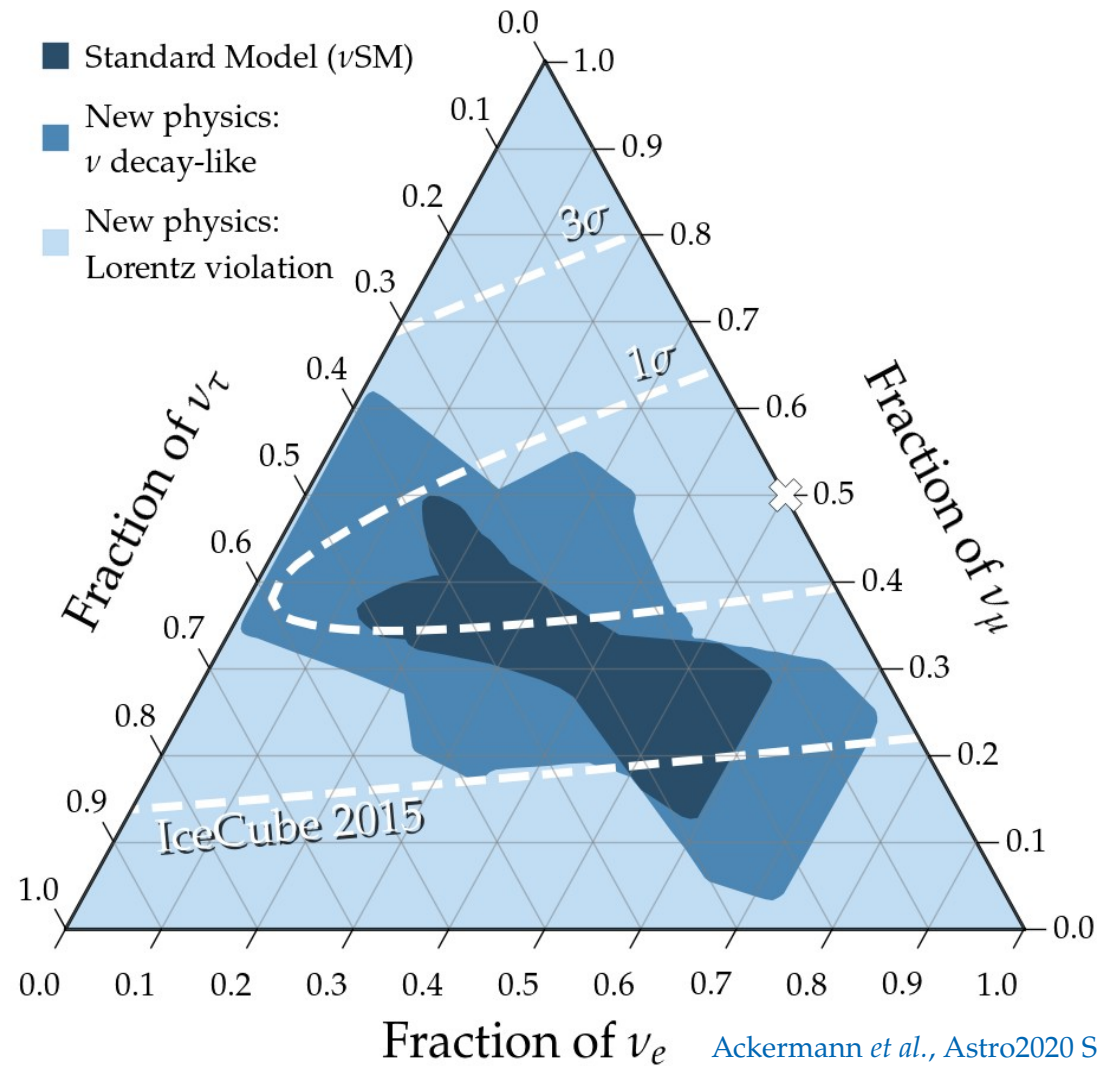
Flavor – What is it good for?

Trusting **particle physics**
and learning about **astrophysics**

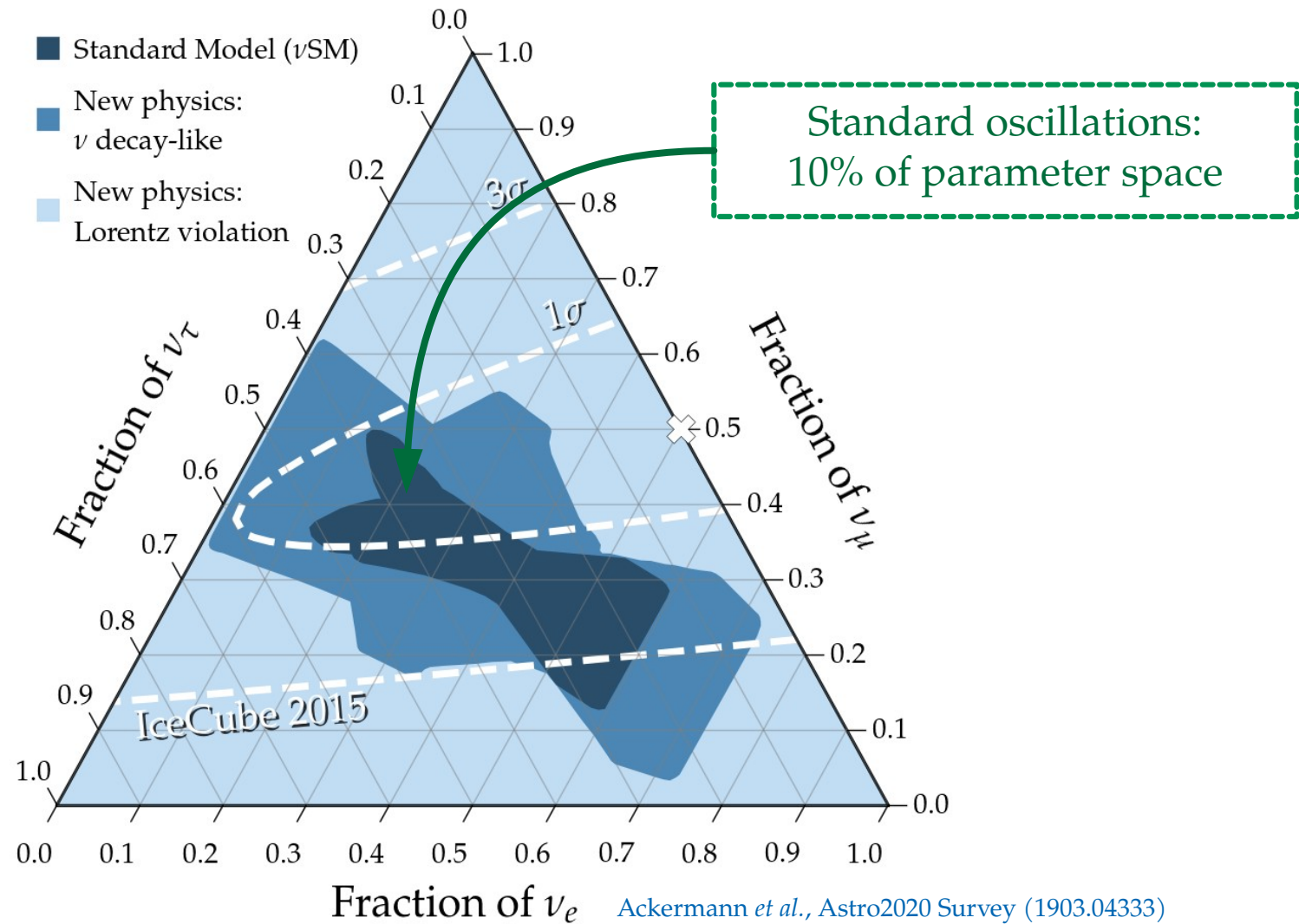


Trusting **astrophysics**
and learning about **particle physics**





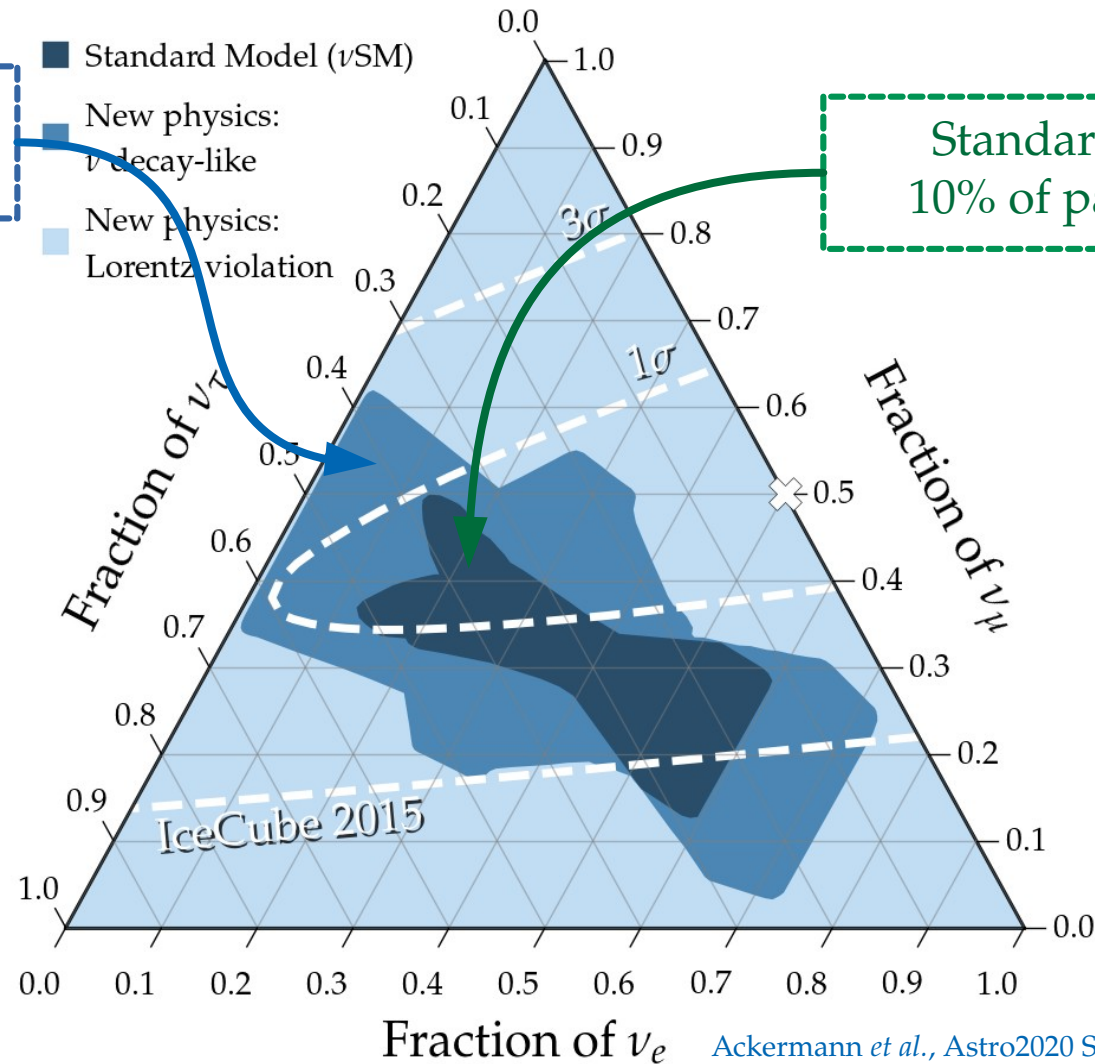
Ackermann *et al.*, *Astro2020 Survey* (1903.04333)
 Based on: MB, Beacom, Winter *PRL* 2015



Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: MB, Beacom, Winter PRL 2015

Neutrino decay
30% of parameter space

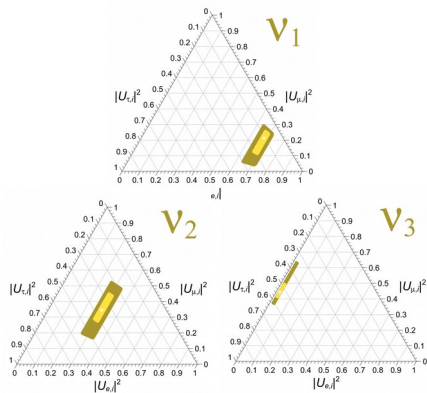
Standard oscillations:
10% of parameter space



Neutrino decay
30% of parameter space

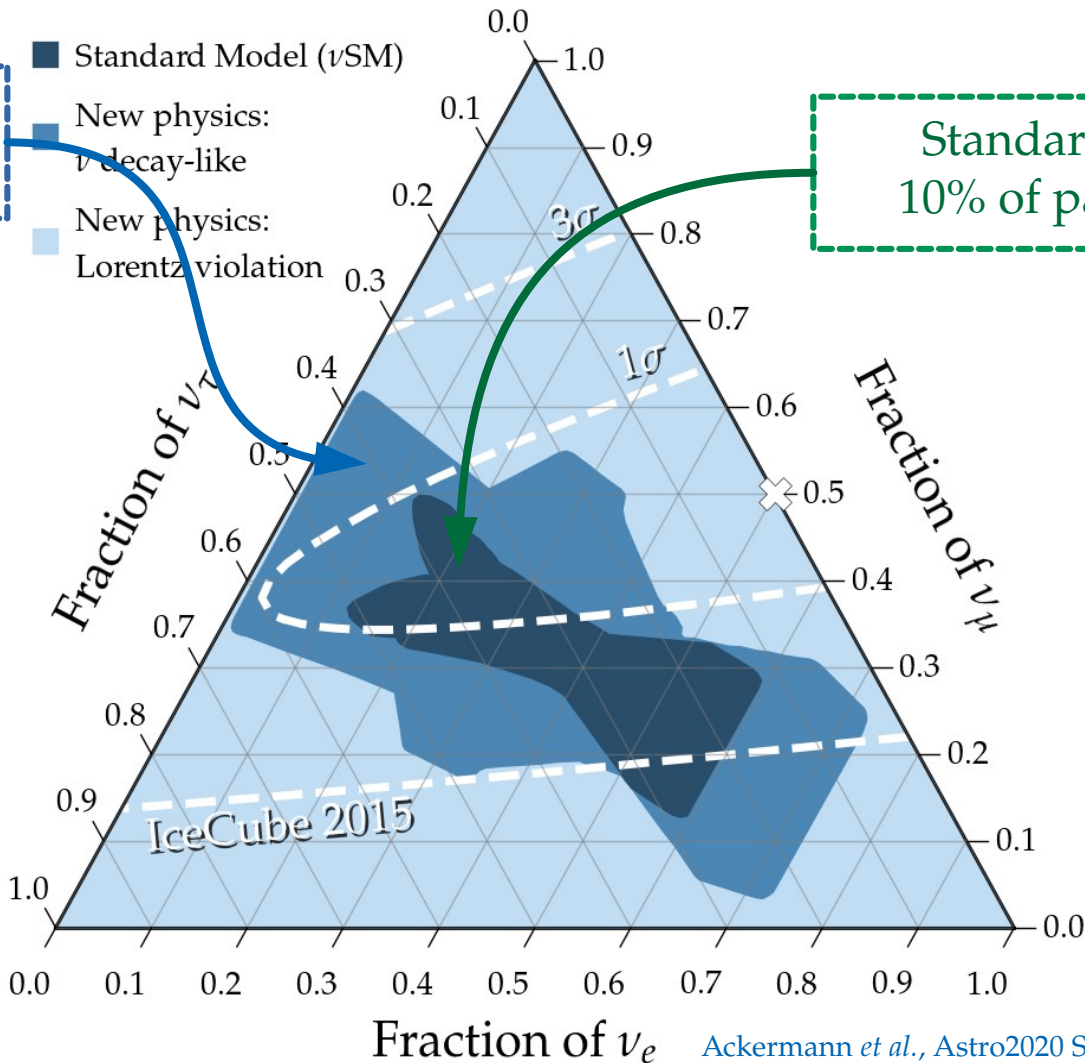
$\nu_2, \nu_3 \rightarrow \nu_1$ OR $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by
how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10 \text{ s eV}^{-1}$

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



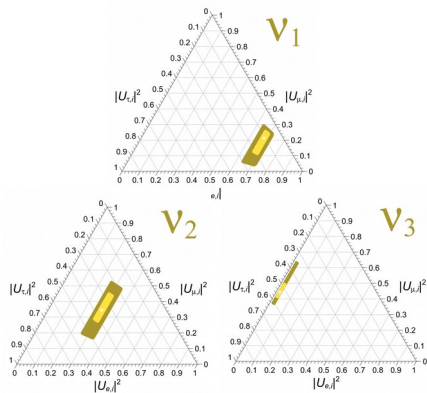
Standard oscillations:
10% of parameter space

Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: MB, Beacom, Winter PRL 2015

Neutrino decay
30% of parameter space

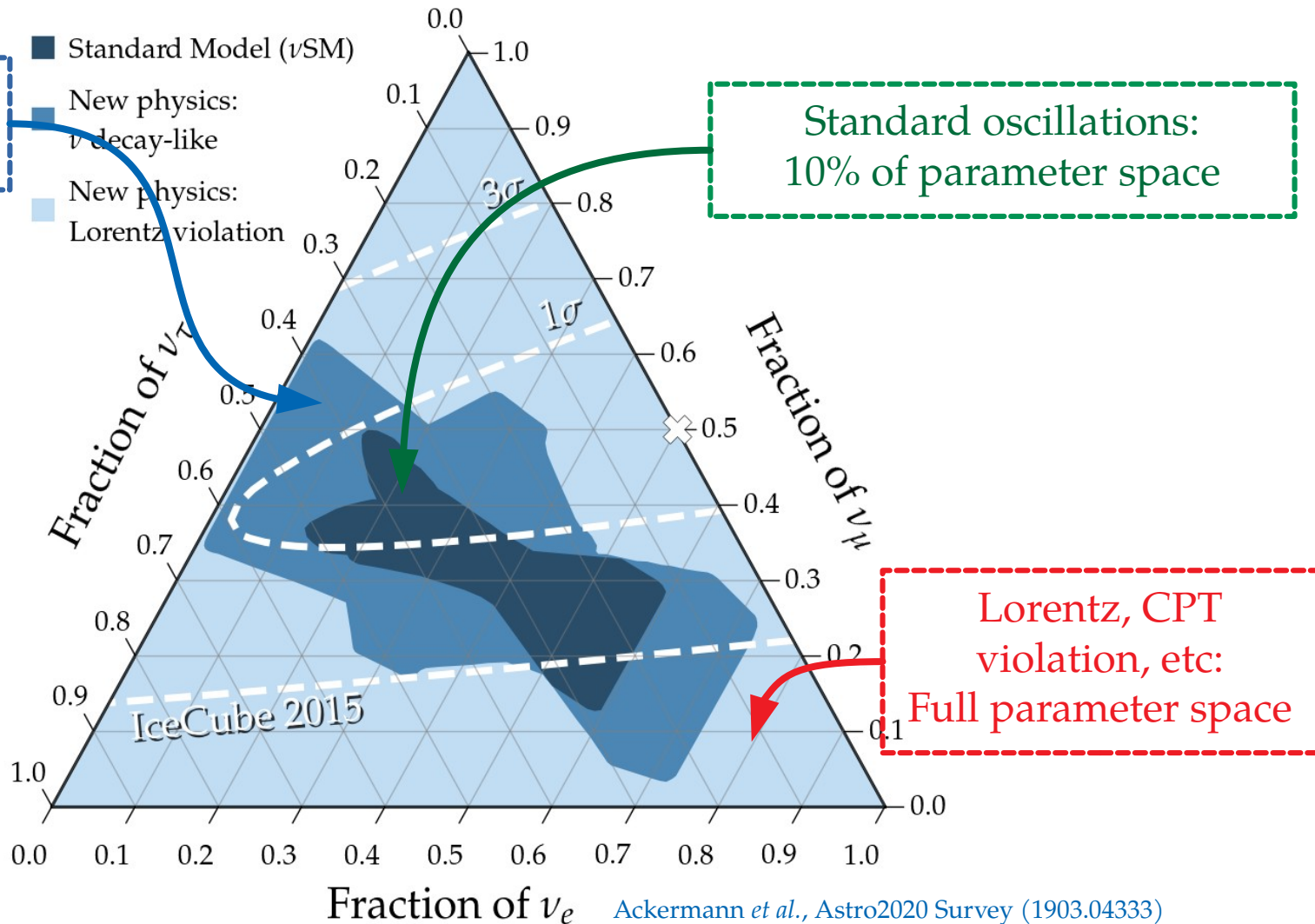
$\nu_2, \nu_3 \rightarrow \nu_1$ OR $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by
how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10 \text{ s eV}^{-1}$

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



Standard oscillations:
10% of parameter space

Lorentz, CPT
violation, etc:
Full parameter space

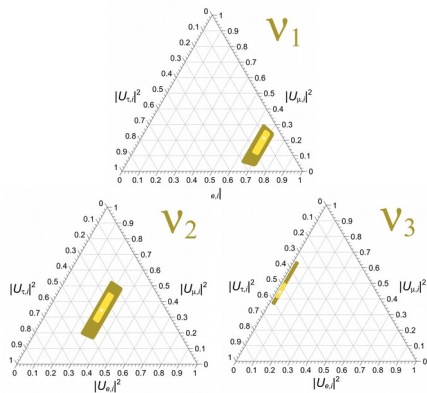
Fraction of ν_e

Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: MB, Beacom, Winter PRL 2015

Neutrino decay
30% of parameter space

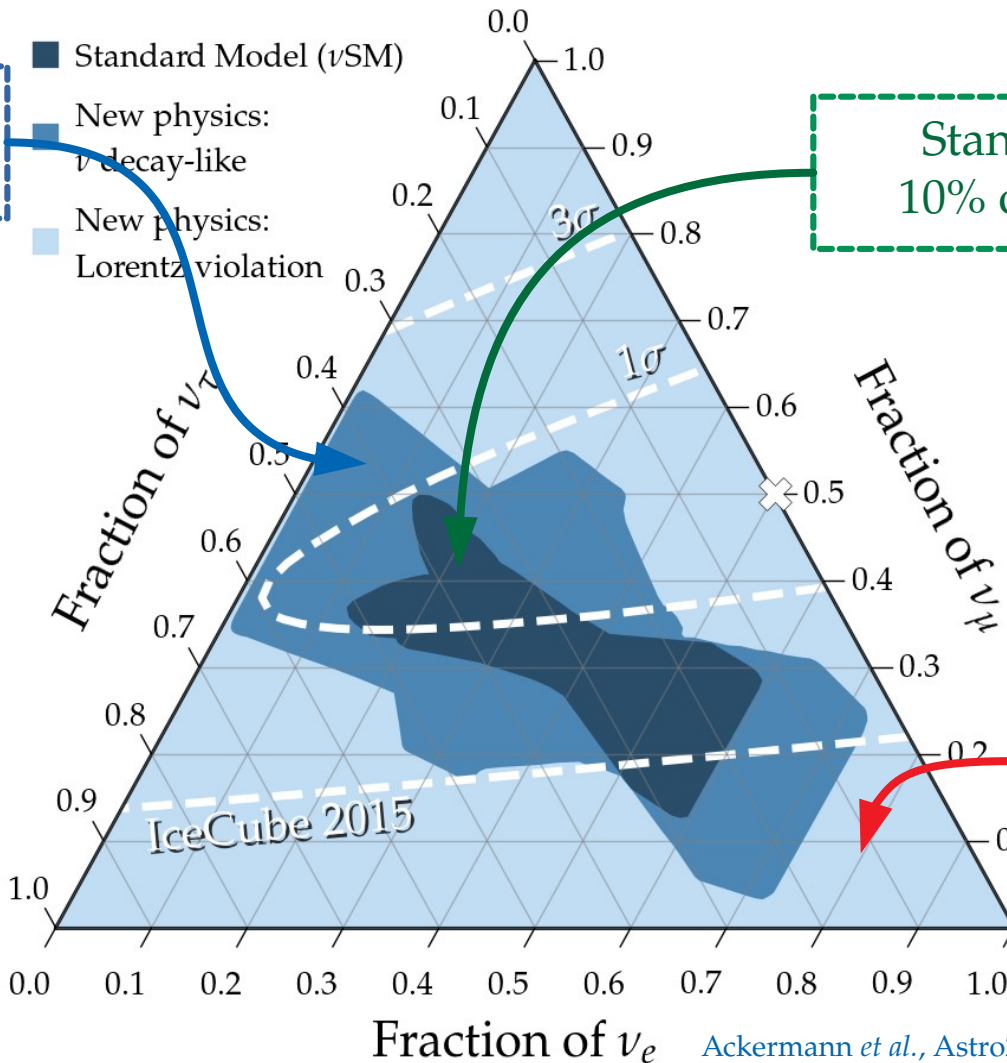
$\nu_2, \nu_3 \rightarrow \nu_1$ OR $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by
how many ν_1, ν_2, ν_3 survive:



$\tau_2/m_2, \tau_3/m_3 > 10 \text{ s eV}^{-1}$

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



Standard oscillations:
10% of parameter space

Lorentz, CPT
violation, etc:
Full parameter space



Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: MB, Beacom, Winter PRL 2015

What lies beyond? *Take your pick*

- ▶ High-energy effective field theories
 - ▶ Violation of Lorentz and CPT invariance
[Barenboim & Quigg, *PRD* 2003; MB, Gago, Peña-Garay, *JHEP* 2010; Kostelecky & Mewes 2004]
 - ▶ Violation of equivalence principle
[Gasperini, *PRD* 1989; Glashow *et al.*, *PRD* 1997]
 - ▶ Coupling to a gravitational torsion field
[De Sabbata & Gasperini, *Nuovo Cim.* 1981]
 - ▶ Renormalization-group-running of mixing parameters
[MB, Gago, Jones, *JHEP* 2011]
 - ▶ General non-unitary propagation
[Ahlers, MB, Mu, *PRD* 2018]
- ▶ Active-sterile mixing
[Aeikens *et al.*, *JCAP* 2015; Brdar, *JCAP* 2017]
- ▶ Flavor-violating physics
 - ▶ New neutrino-electron interactions
[MB & Agarwalla, *PRL* 2019]
 - ▶ New $\nu\nu$ interactions
[Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]
- ▶ ...



Toho Company Ltd.

New physics – High-energy effects

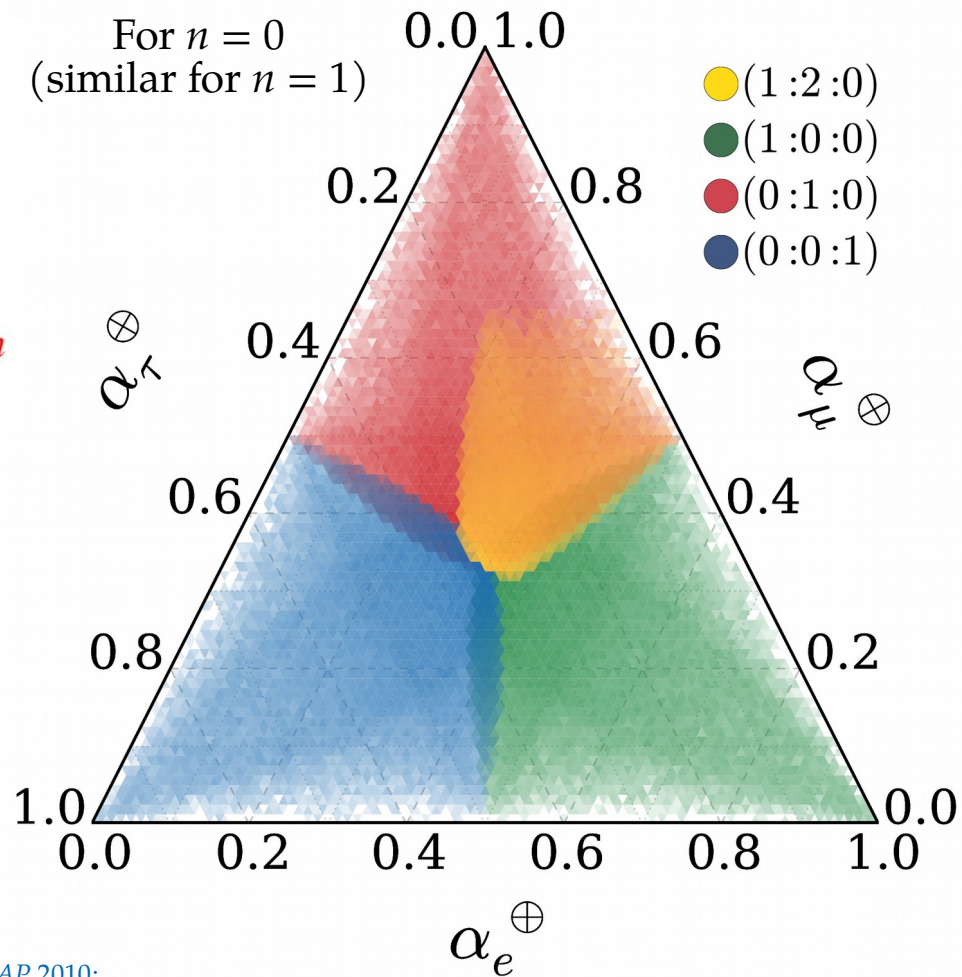
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

$$H_{\text{std}} = \frac{1}{2E} U_{\text{PMNS}}^\dagger \text{diag} (0, \Delta m_{21}^2, \Delta m_{31}^2) U_{\text{PMNS}}$$

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

This can populate *all* of the triangle –

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



See also: [Rasmusen et al., PRD 2017](#); [MB, Beacom, Winter PRL 2015](#); [MB, Gago, Peña-Garay JCAP 2010](#); [Bazo, MB, Gago, Miranda IJMPA 2009](#); + many others

Argüelles, Katori, Salvadó, PRL 2015

New physics – High-energy effects

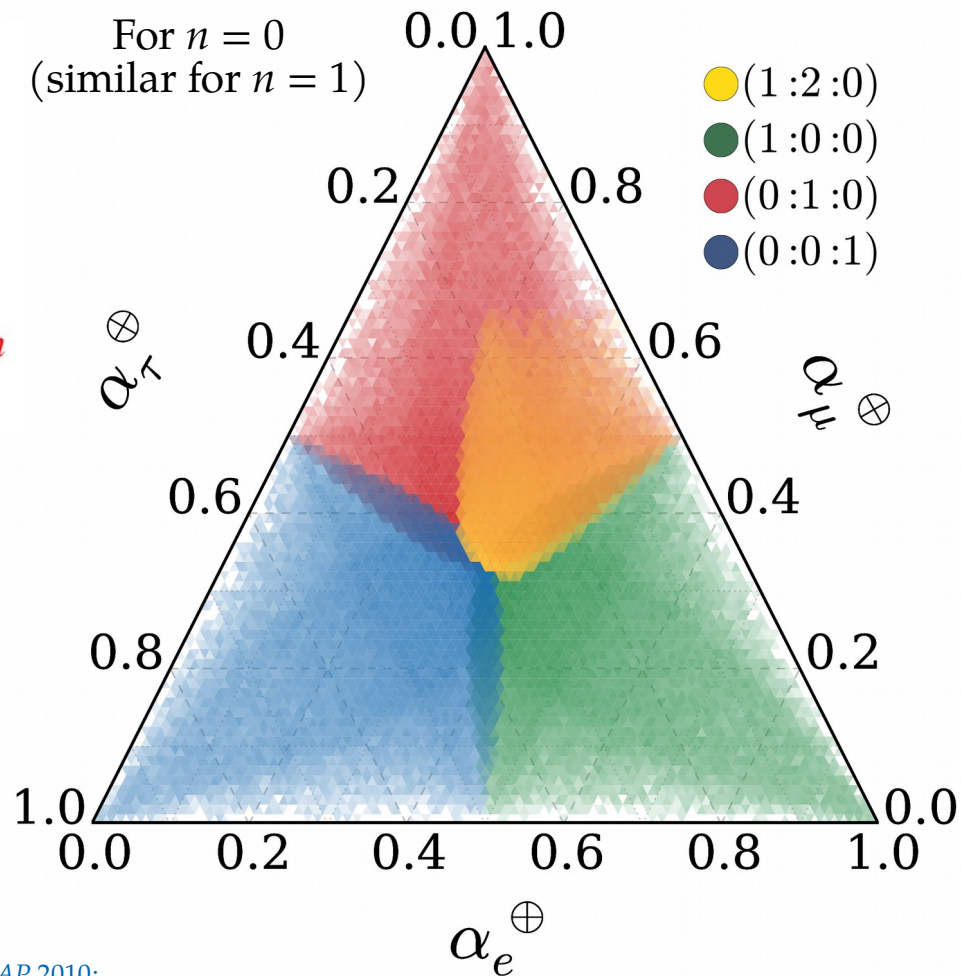
$$H_{\text{tot}} = H_{\text{std}} + H_{\text{NP}}$$

$$H_{\text{std}} = \frac{1}{2E} U_{\text{PMNS}}^\dagger \text{diag} (0, \Delta m_{21}^2, \Delta m_{31}^2) U_{\text{PMNS}}$$

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

This can populate *all* of the triangle –

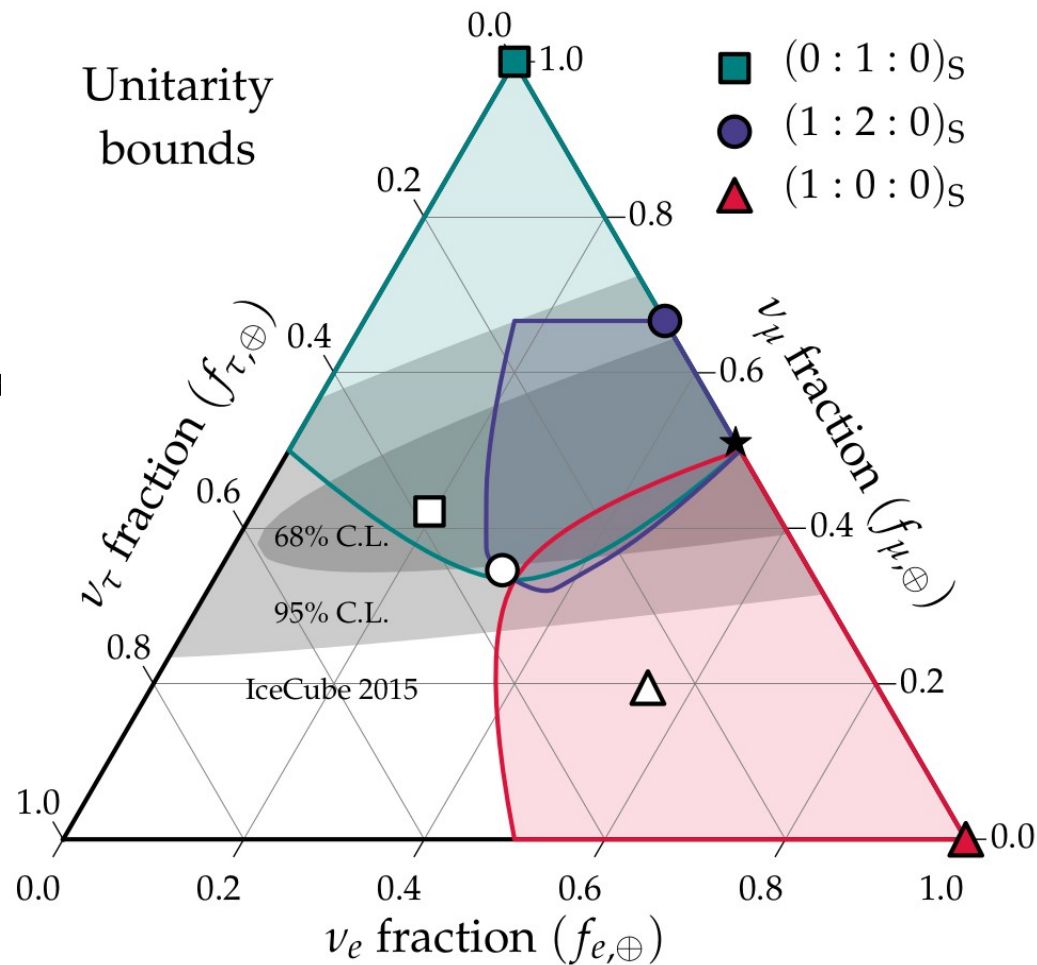
- Use current atmospheric bounds on $O_{n,i}$:
 $O_0 < 10^{-23} \text{ GeV}$, $O_1/\Lambda_1 < 10^{-27} \text{ GeV}$
- Sample the unknown new mixing angles



Using unitarity to constrain new physics

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

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



Ultra-long-range flavorful interactions

- ▶ **Simple extension of the SM:** Promote the global lepton-number symmetries L_e-L_μ , L_e-L_τ to local symmetries
- ▶ They introduce new interaction between electrons and ν_e and ν_μ or ν_τ mediated by a new neutral vector boson (Z'):
 - ▶ Affects oscillations
 - ▶ If the Z' is *very* light, *many* electrons can contribute

X.-G. He, G.C. Joshi, H. Lew, R. R. Volkas, *PRD* 1991 / R. Foot, X.-G. He, H. Lew, R. R. Volkas, *PRD* 1994
A. Joshipura, S. Mohanty, *PLB* 2004 / J. Grifols & E. Massó, *PLB* 2004 / A. Bandyopadhyay, A. Dighe, A. Joshipura, *PRD* 2007
M.C. González-García, P.C. de Holanda, E. Massó, R. Zukanovich Funchal, *JCAP* 2007 / A. Samanta, *JCAP* 2011
S.-S. Chatterjee, A. Dasgupta, S. Agarwalla, *JHEP* 2015

The new potential sourced by an electron

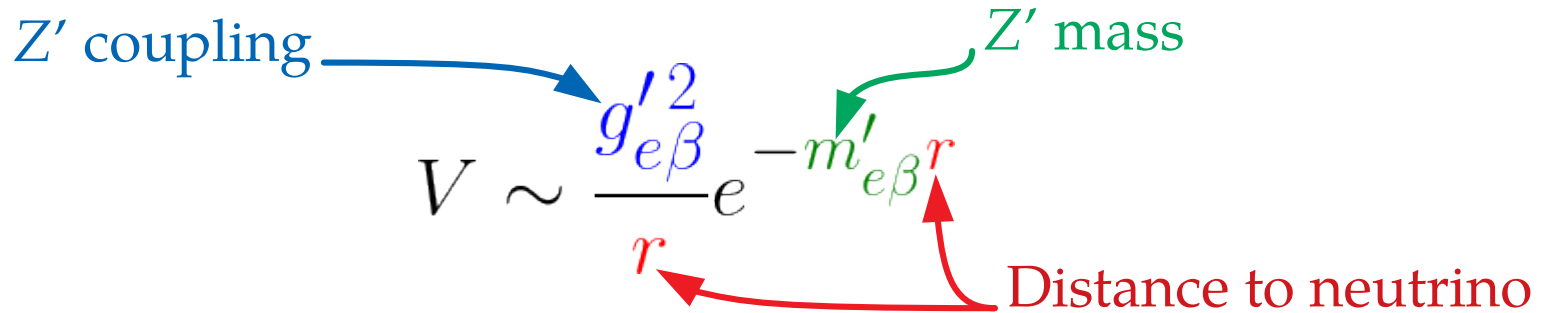
Under the L_e - L_μ or L_e - L_τ symmetry, an electron sources a Yukawa potential —

$$V \sim \frac{g_{e\beta}'^2}{r} e^{-m'_{e\beta} r}$$

A neutrino “feels” all the electrons within the interaction range $\sim (1/m')$

The new potential sourced by an electron

Under the L_e-L_μ or L_e-L_τ symmetry, an electron sources a Yukawa potential —



The diagram shows the Yukawa potential equation $V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$ with three color-coded annotations: a blue arrow points from the text "Z' coupling" to the $g'^2_{e\beta}$ term; a green arrow points from the text "Z' mass" to the $m'_{e\beta}$ term; and a red arrow points from the text "Distance to neutrino" to the r term in the denominator.

$$V \sim \frac{g'^2_{e\beta}}{r} e^{-m'_{e\beta} r}$$

A neutrino “feels” all the electrons within the interaction range $\sim (1/m')$

Electron-neutrino interactions can kill oscillations

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}}$$


Standard oscillations:
Neutrinos change flavor
because this is non-diagonal

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}}$$


Standard oscillations:
Neutrinos change flavor
because this is non-diagonal



$$P_{\nu_\alpha \rightarrow \nu_\beta}(\theta_{ij}, \delta_{\text{CP}})$$

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + \underbrace{V_{e\beta}}_{= \text{diag}(V_{e\mu}, -V_{e\mu}, 0)}$$

New neutrino-electron interaction:
This is diagonal

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + \underbrace{V_{e\beta}}_{= \text{diag}(V_{e\mu}, -V_{e\mu}, 0)}$$

New neutrino-electron interaction:
This is diagonal

↓

$$P_{\nu_\alpha \rightarrow \nu_\beta} \left(\theta_{ij}, \delta_{\text{CP}}, \Delta m_{ij}^2, E_\nu, \overbrace{g'_{e\mu}, m'_{e\mu}}^{\text{Z' parameters}} \right)$$

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + \underbrace{V_{e\beta}}_{= \text{diag}(V_{e\mu}, -V_{e\mu}, 0)}$$

New neutrino-electron interaction:
This is diagonal

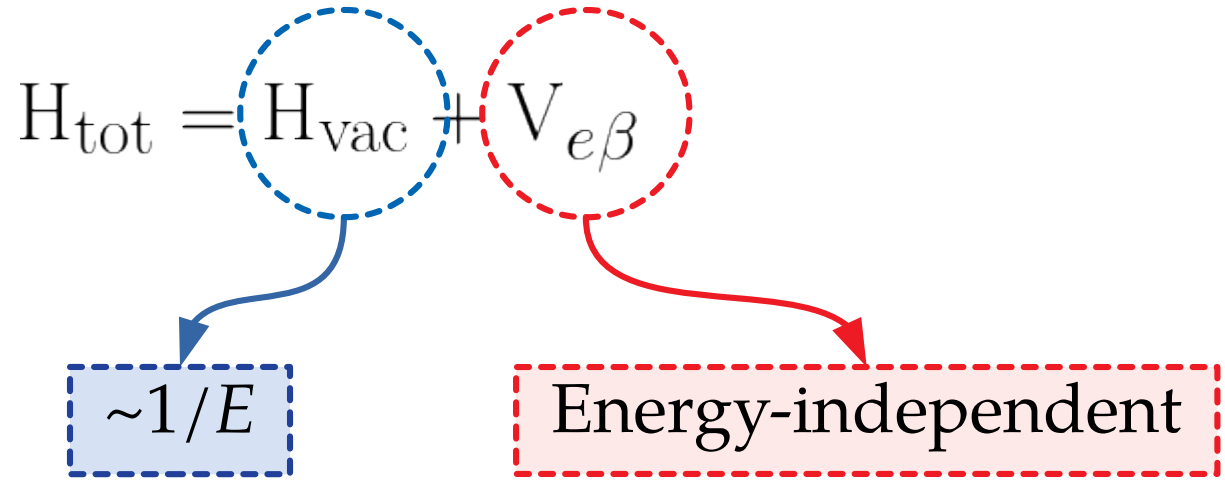
$$P_{\nu_\alpha \rightarrow \nu_\beta} \left(\theta_{ij}, \delta_{\text{CP}}, \Delta m_{ij}^2, E_\nu, \overbrace{g'_{e\mu}, m'_{e\mu}}^{\text{Z' parameters}} \right)$$

If $V_{e\beta}$ dominates ($g' \gg 1, m' \ll 1$), oscillations turn off

Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + V_{e\beta}$$

Electron-neutrino interactions can kill oscillations



Electron-neutrino interactions can kill oscillations

$$H_{\text{tot}} = H_{\text{vac}} + V_{e\beta}$$

$\sim 1/E$

Energy-independent

$\therefore$ We can use high-energy astrophysical neutrinos

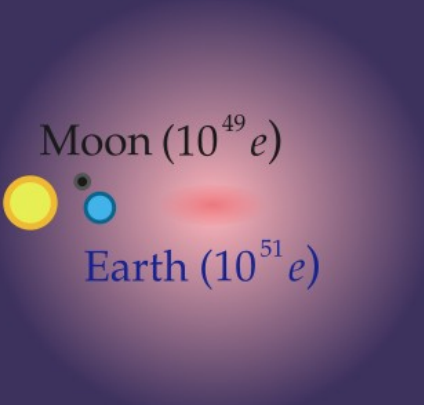
The total potential

Cosmological electrons ($10^{79} e$)

Sun ($10^{57} e$)

Moon ($10^{49} e$)

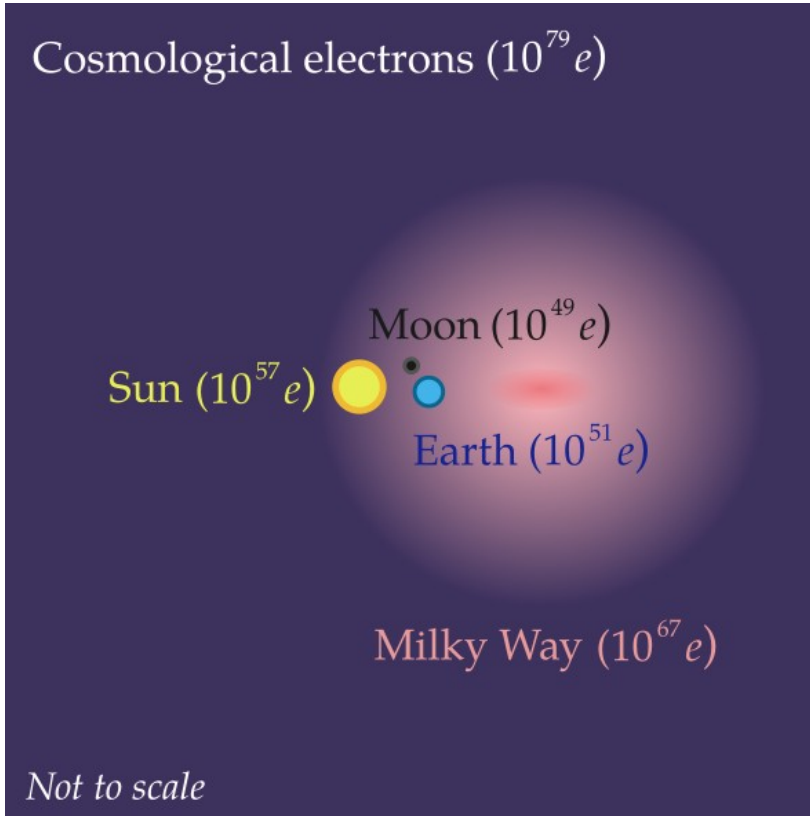
Earth ($10^{51} e$)



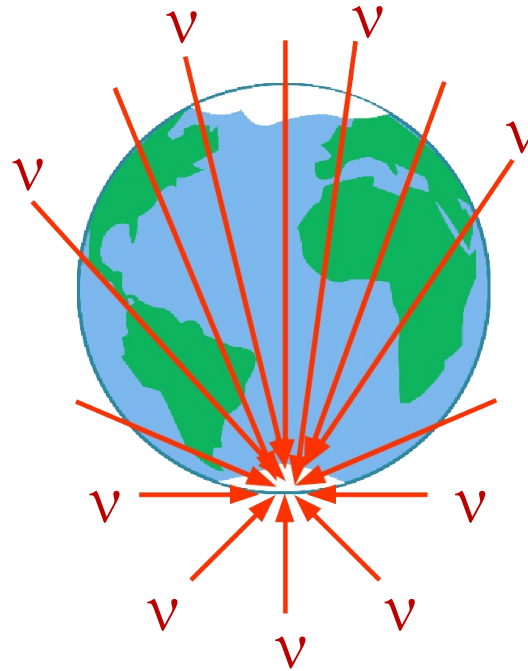
Milky Way ($10^{67} e$)

Not to scale

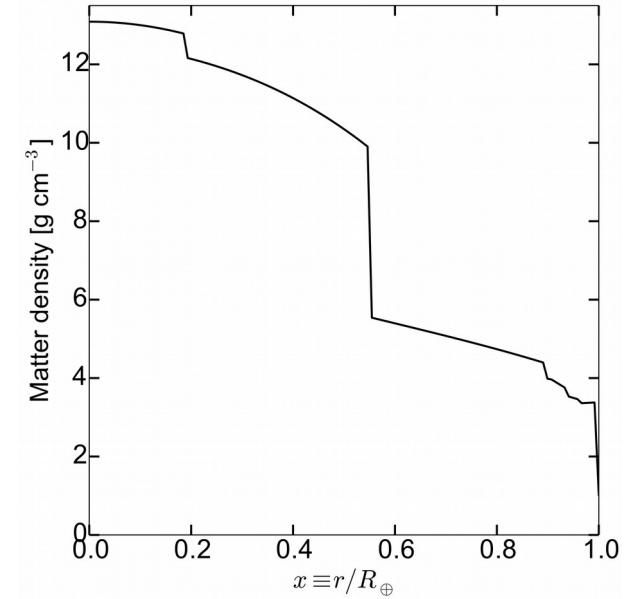
The total potential



Earth:



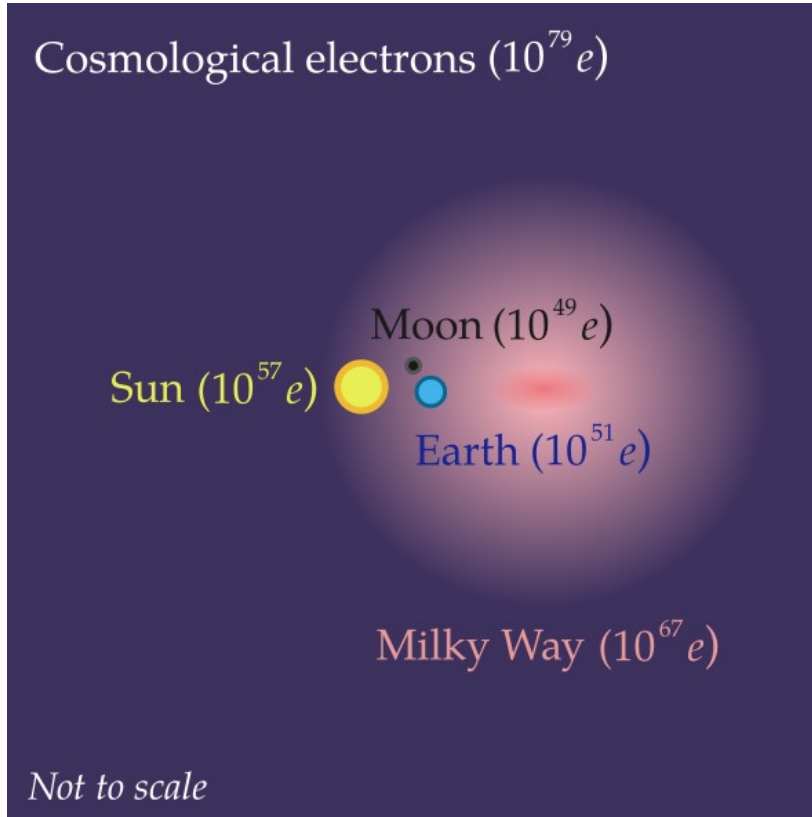
Preliminary Reference Earth Model
Dziewonski & Anderson 1981



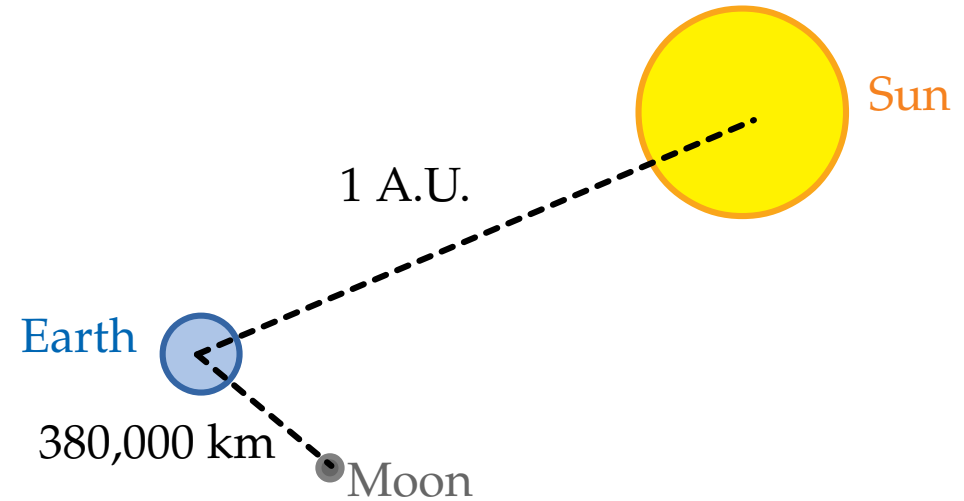
Neutrinos traverse different electron column depths

$$V_{e\beta} = V_{e\beta}^{\oplus}$$

The total potential



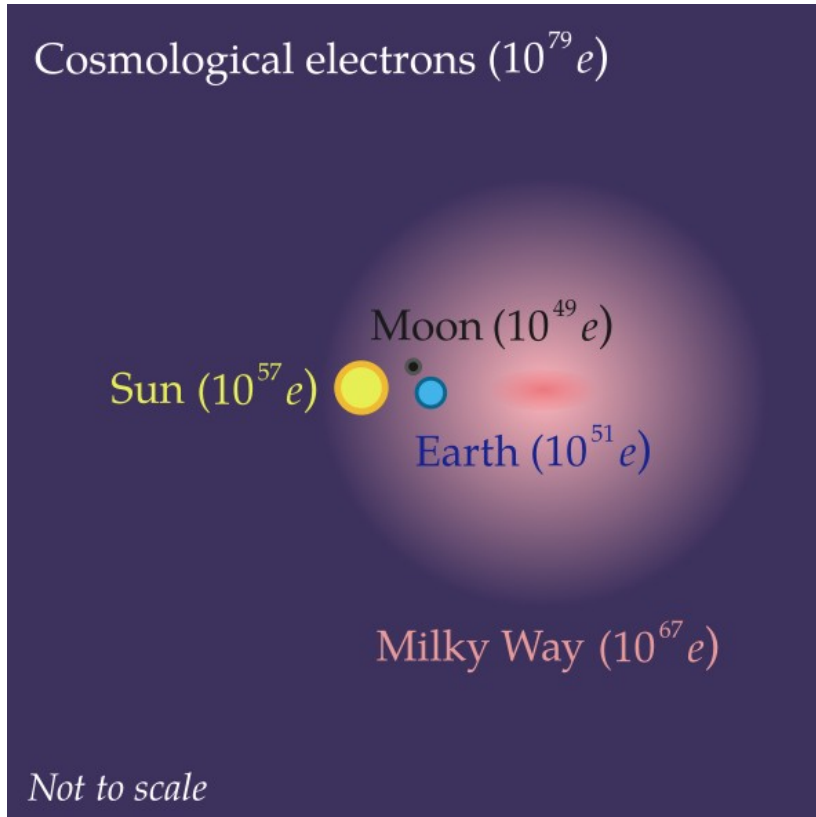
Moon and Sun:



Treated as point sources of electrons

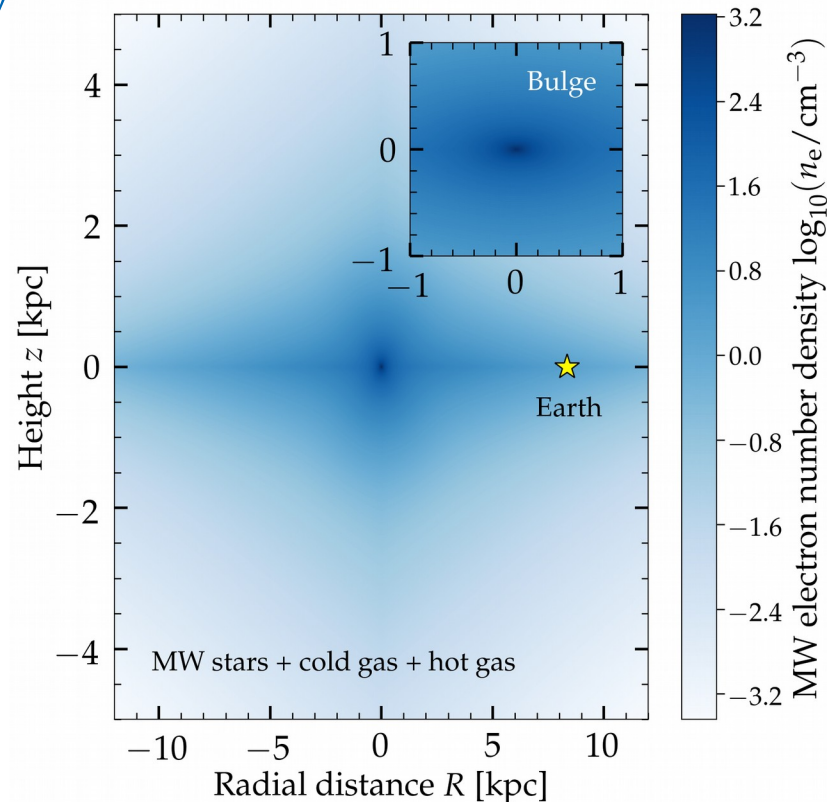
$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot}$$

The total potential



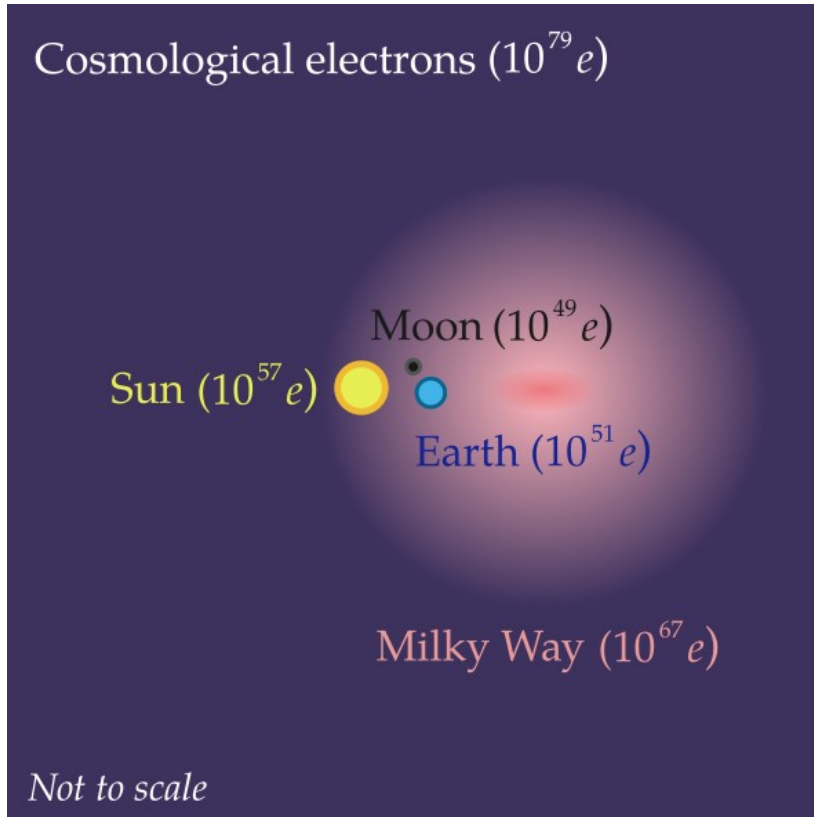
Milky Way:

P. McMillan 2011
M.J. Miller & J.N. Bregman 2013

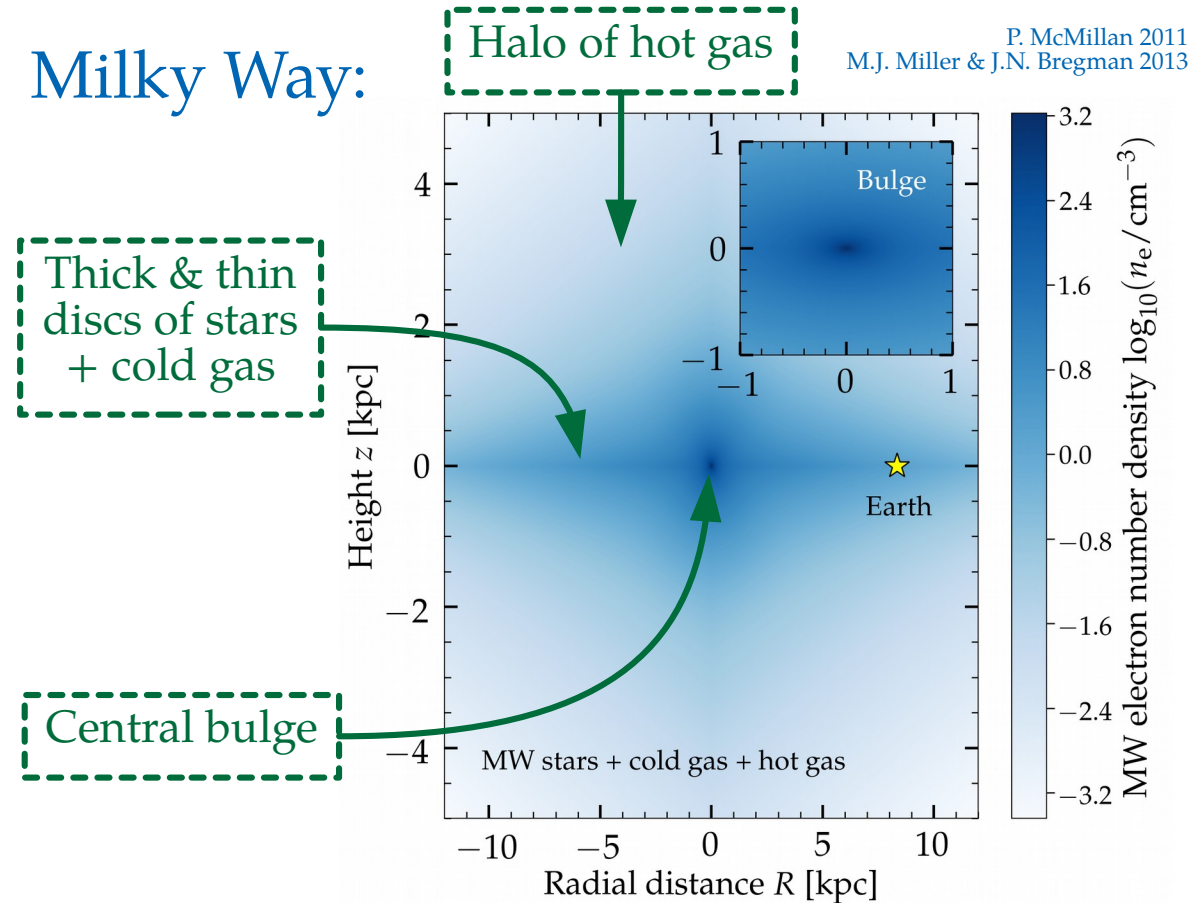


$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

The total potential



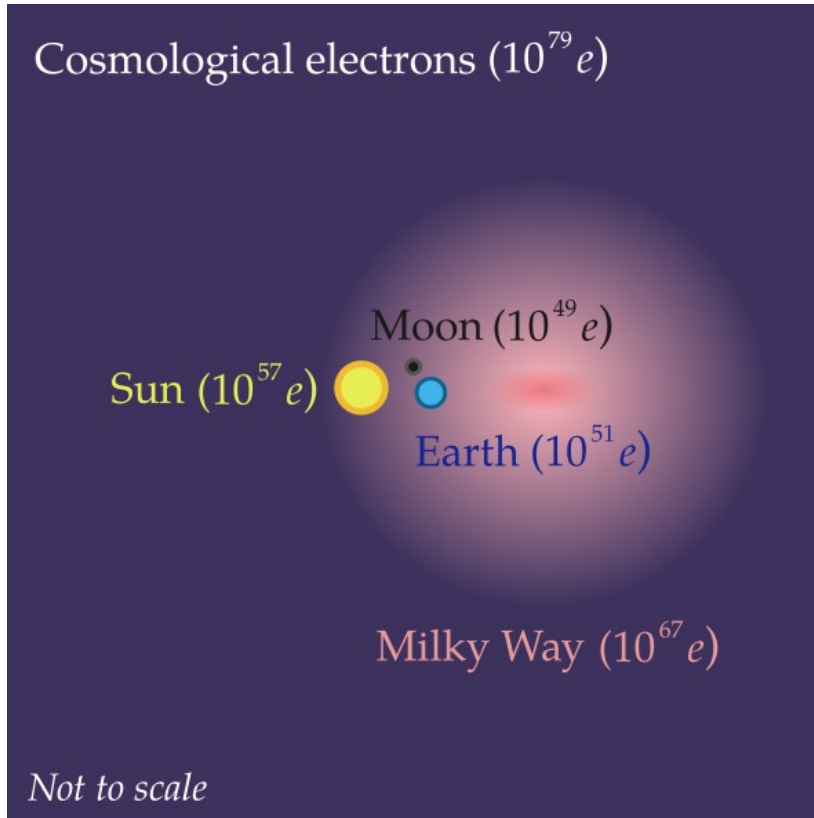
Milky Way:



P. McMillan 2011
M.J. Miller & J.N. Bregman 2013

$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}}$$

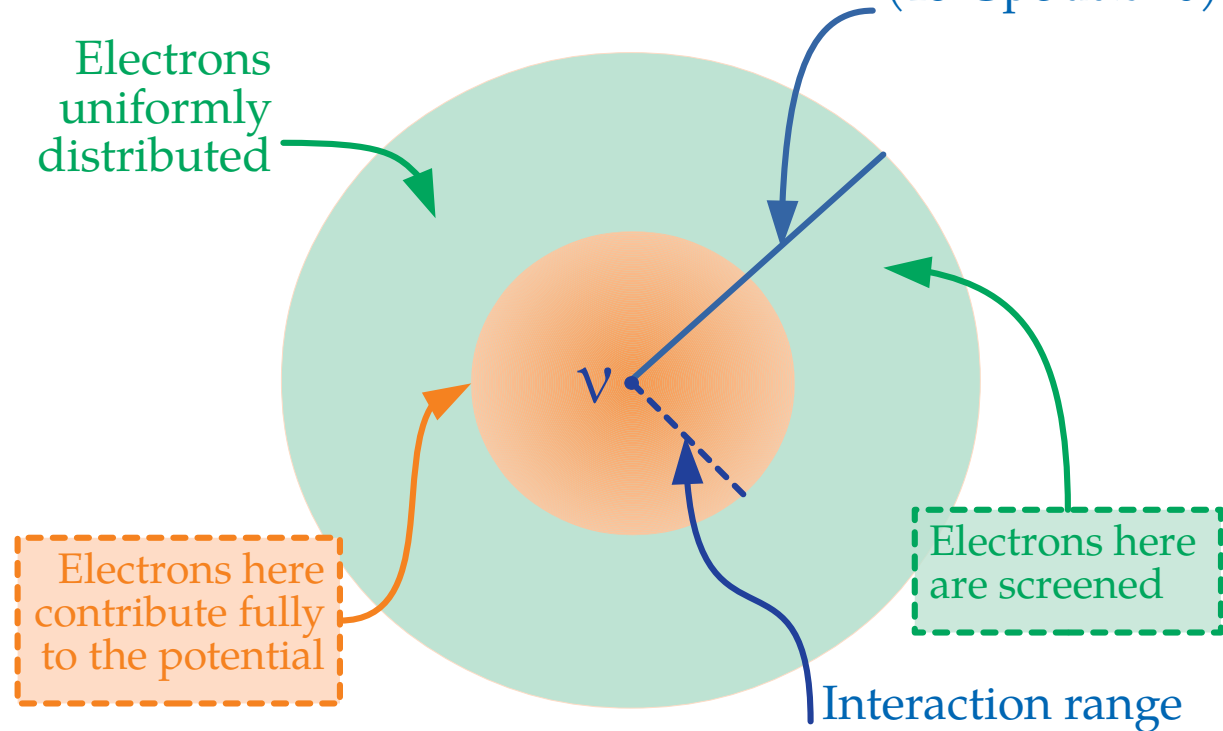
The total potential



Cosmological electrons:

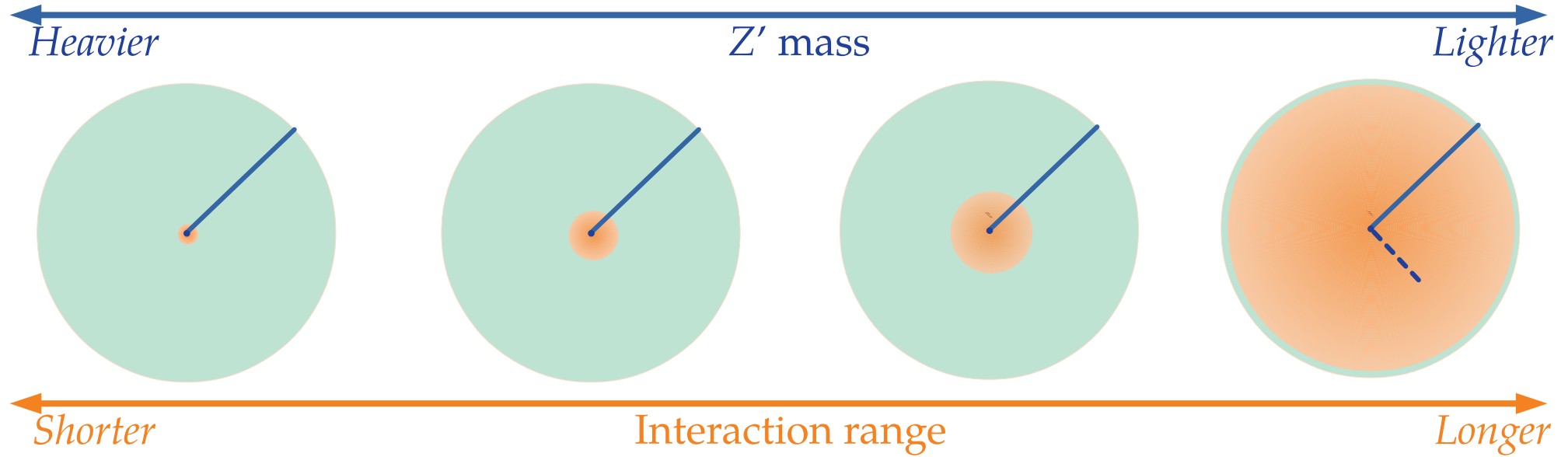
Electrons
uniformly
distributed

Causal horizon
(15 Gpc at $z=0$)



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}} + V_{e\beta}^{\text{cos}}$$

The total potential



$$V_{e\beta} = V_{e\beta}^{\oplus} + V_{e\beta}^{\text{Moon}} + V_{e\beta}^{\odot} + V_{e\beta}^{\text{MW}} + V_{e\beta}^{\cos}$$

Electrons in the local and distant Universe

Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

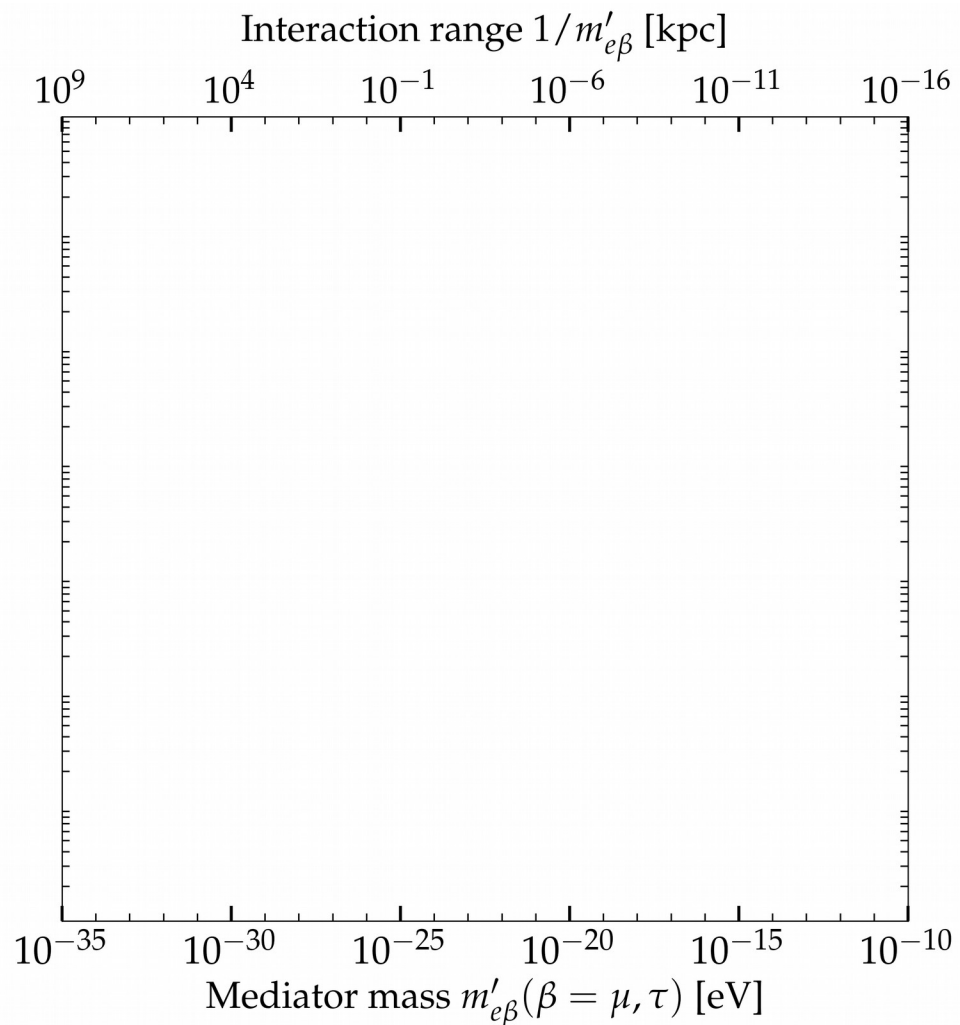
Electrons in the local and distant Universe

Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe

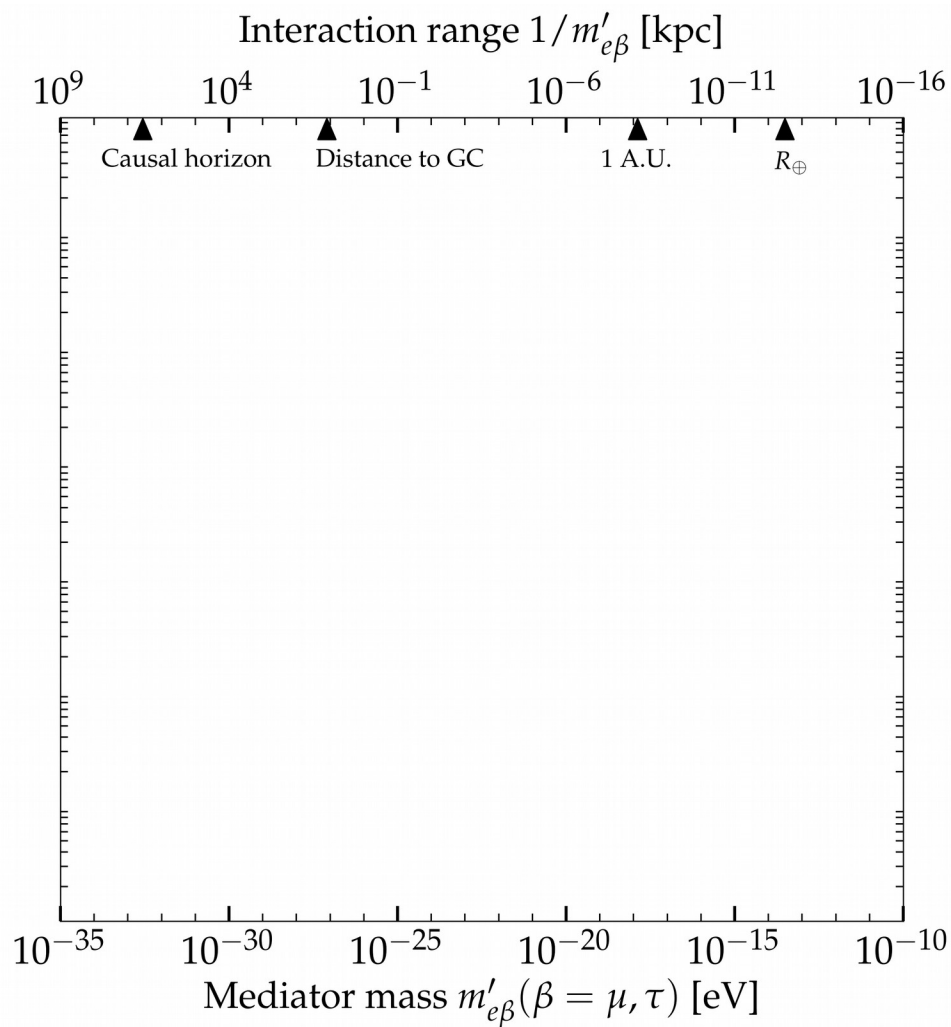


Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe

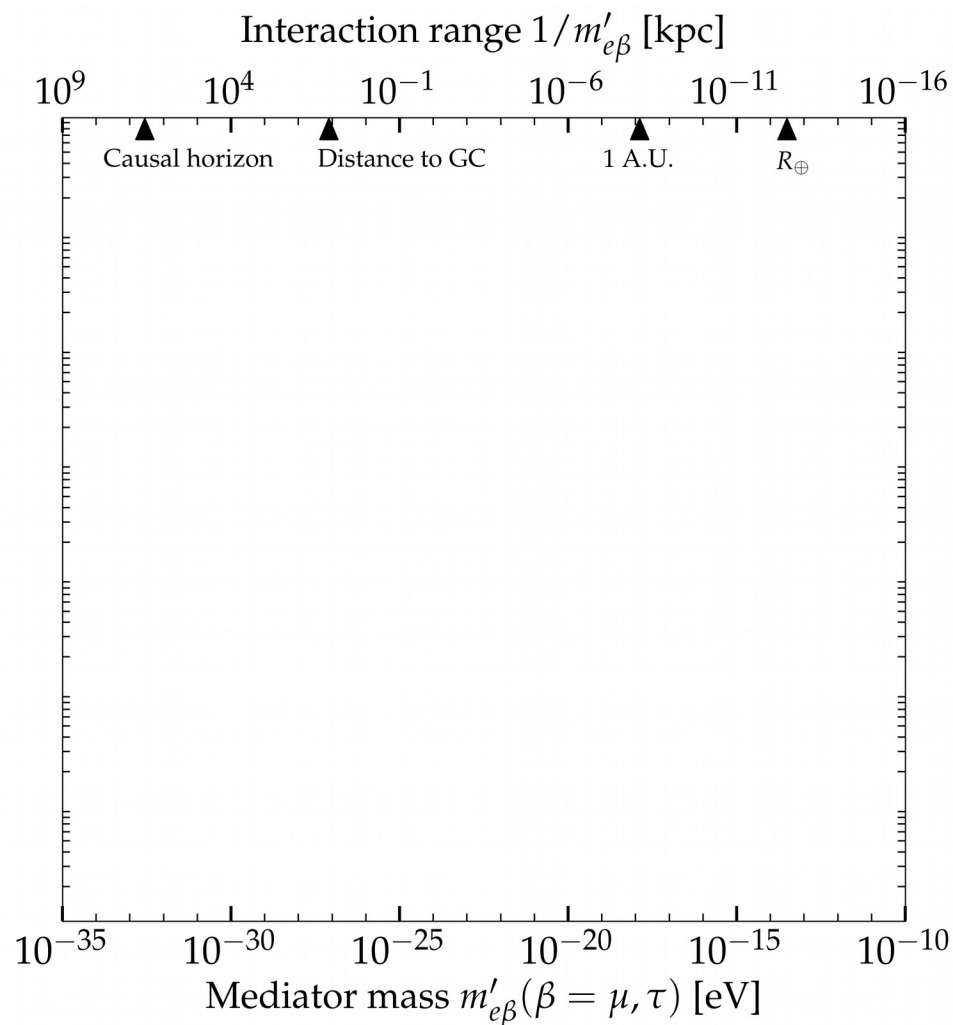


Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

Interaction range: $\frac{1}{m'_{e\beta}}$

Electrons in the local and distant Universe



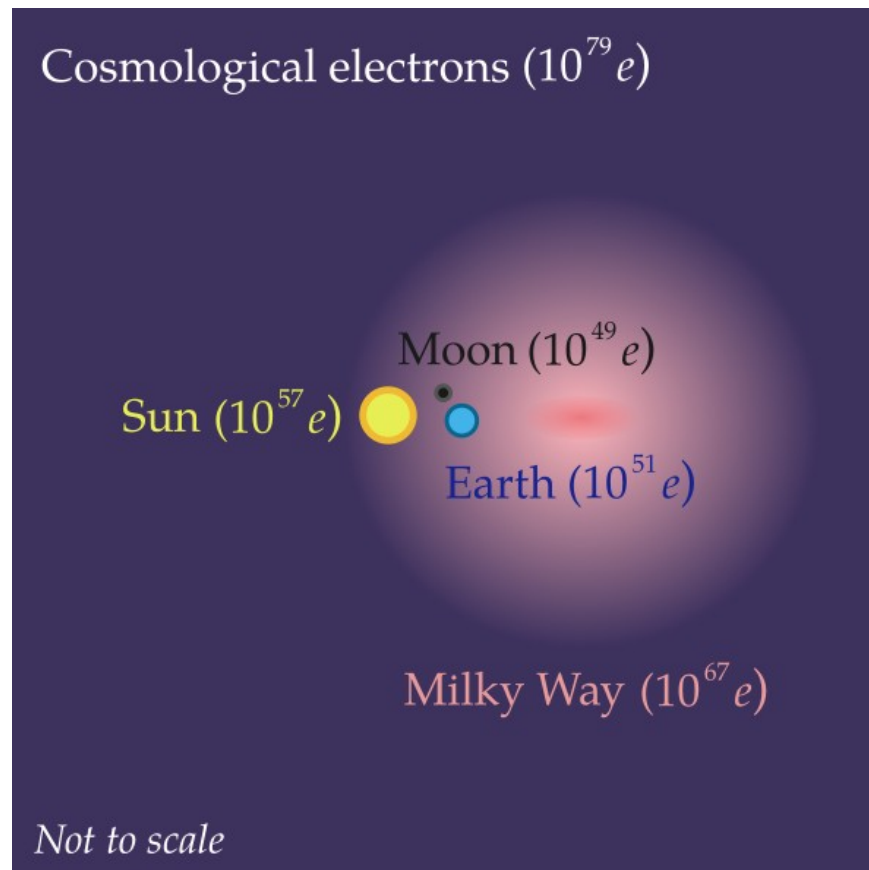
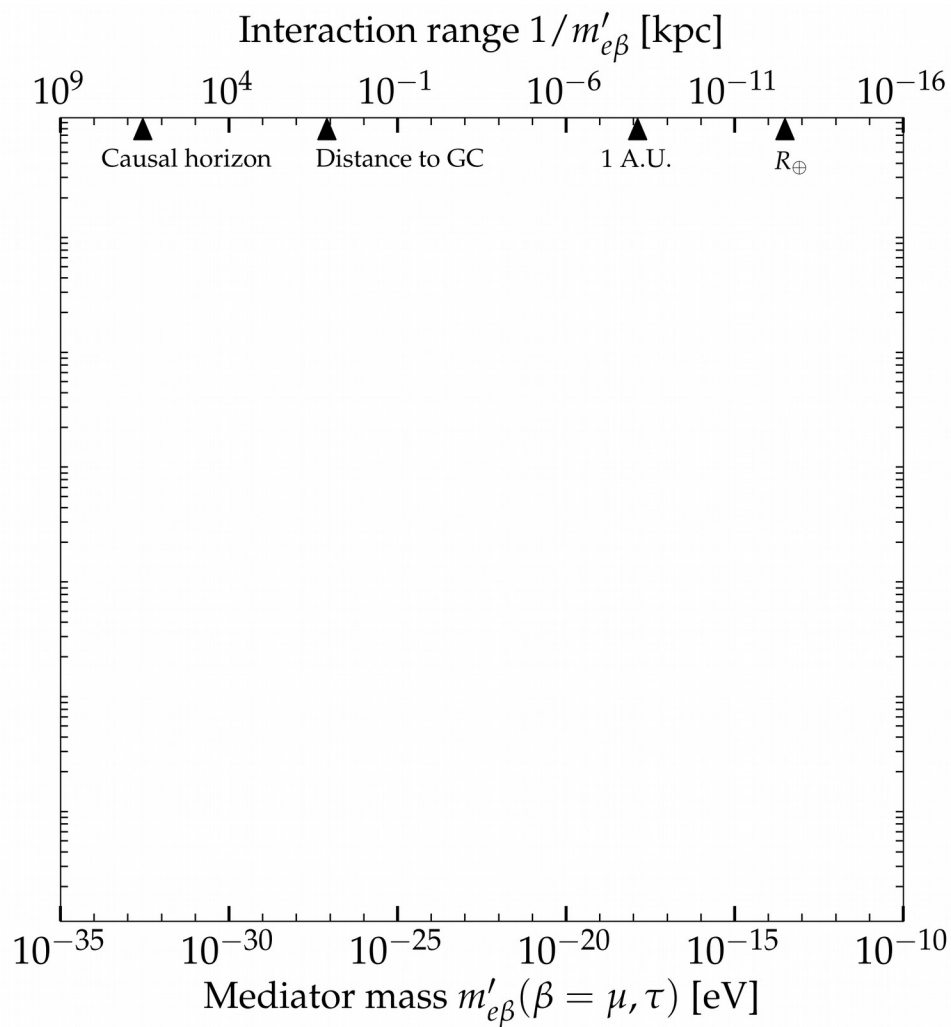
Potential:

$$V_{e\beta} \propto \frac{1}{r} e^{-m'_{e\beta} r}$$

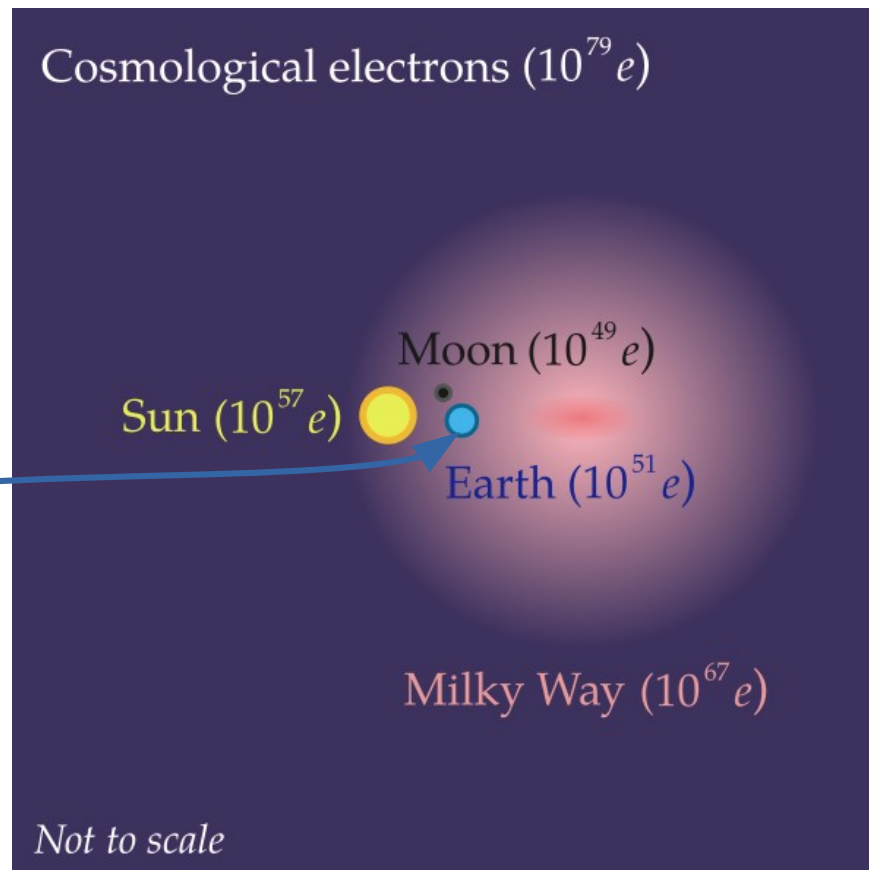
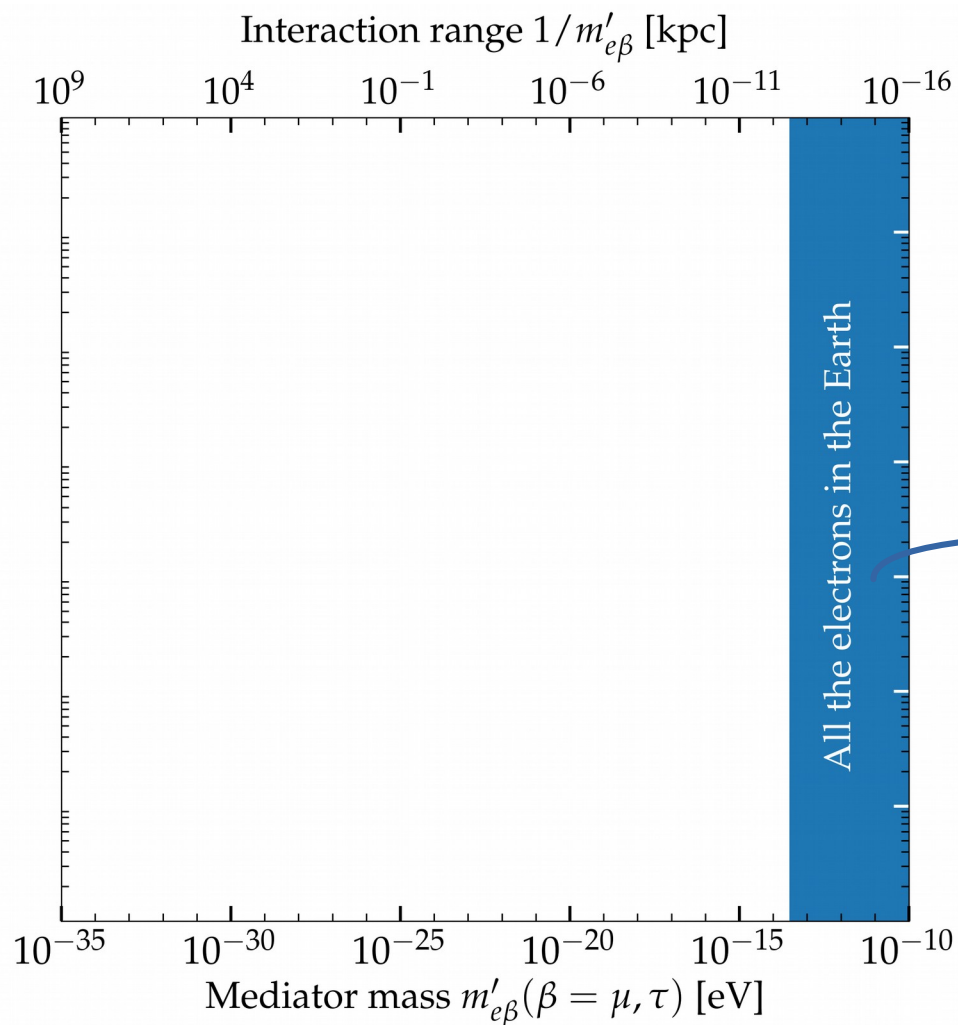
Interaction range: $\frac{1}{m'_{e\beta}}$

Light mediators
 $\Rightarrow$ Long interaction ranges

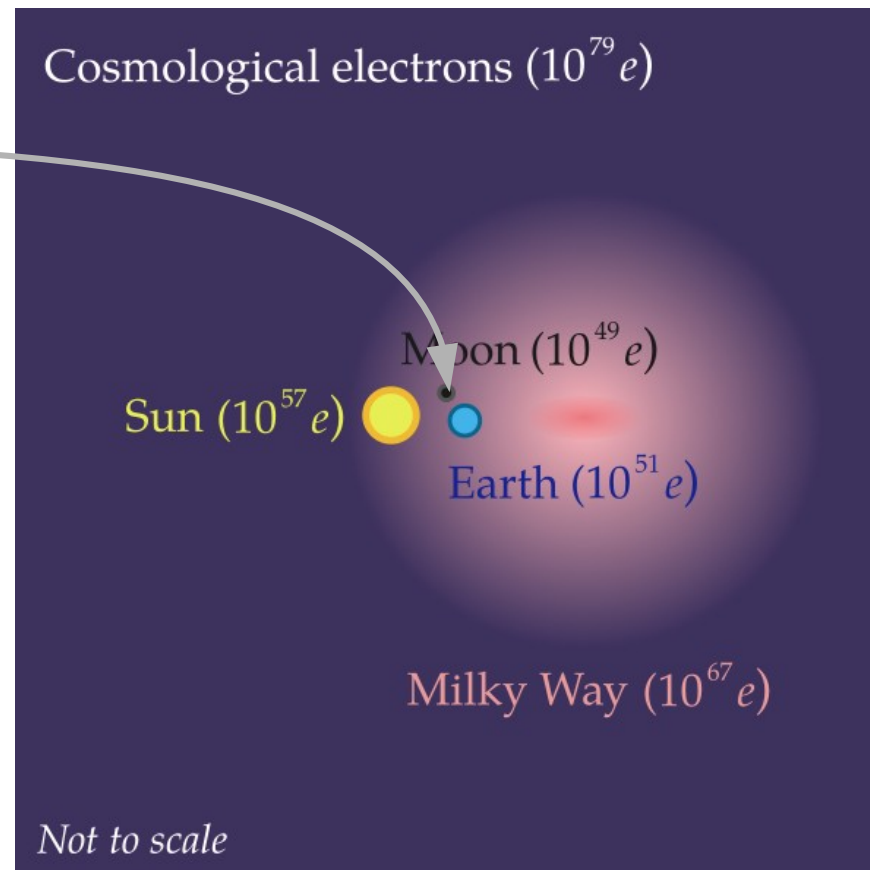
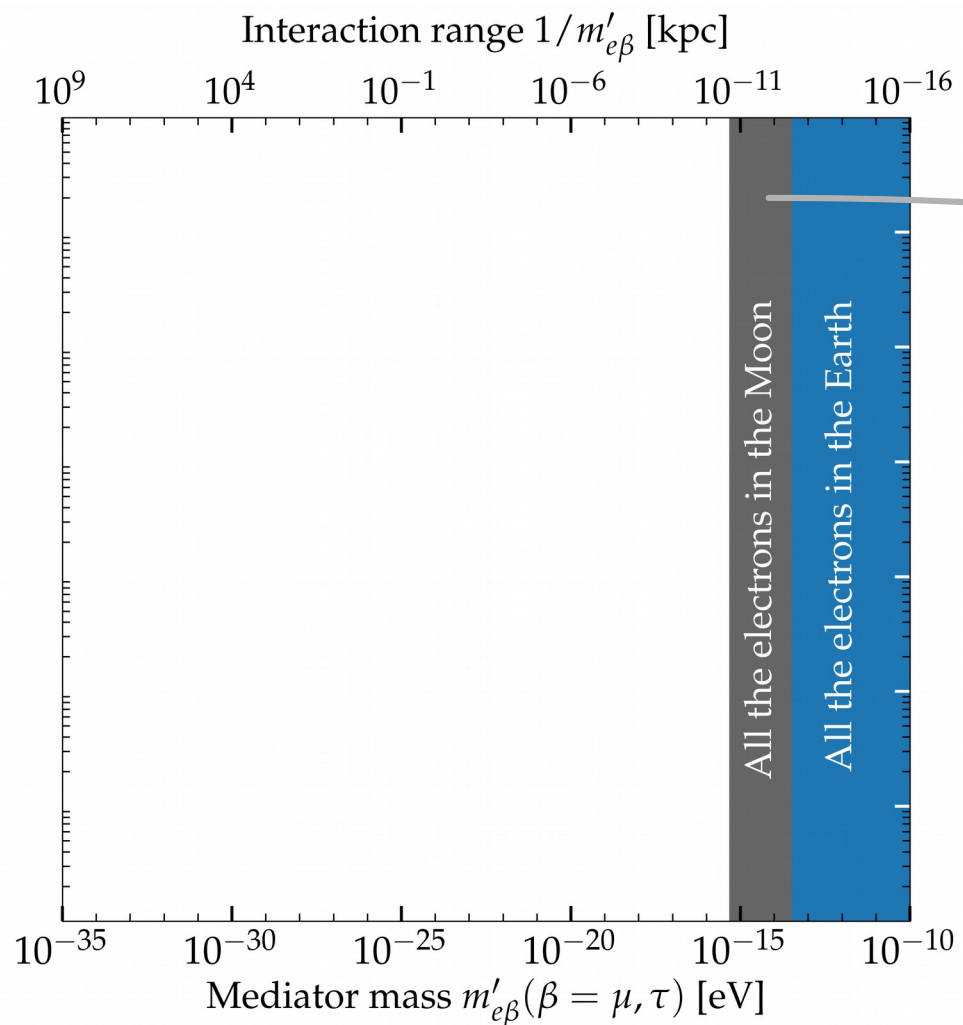
Electrons in the local and distant Universe



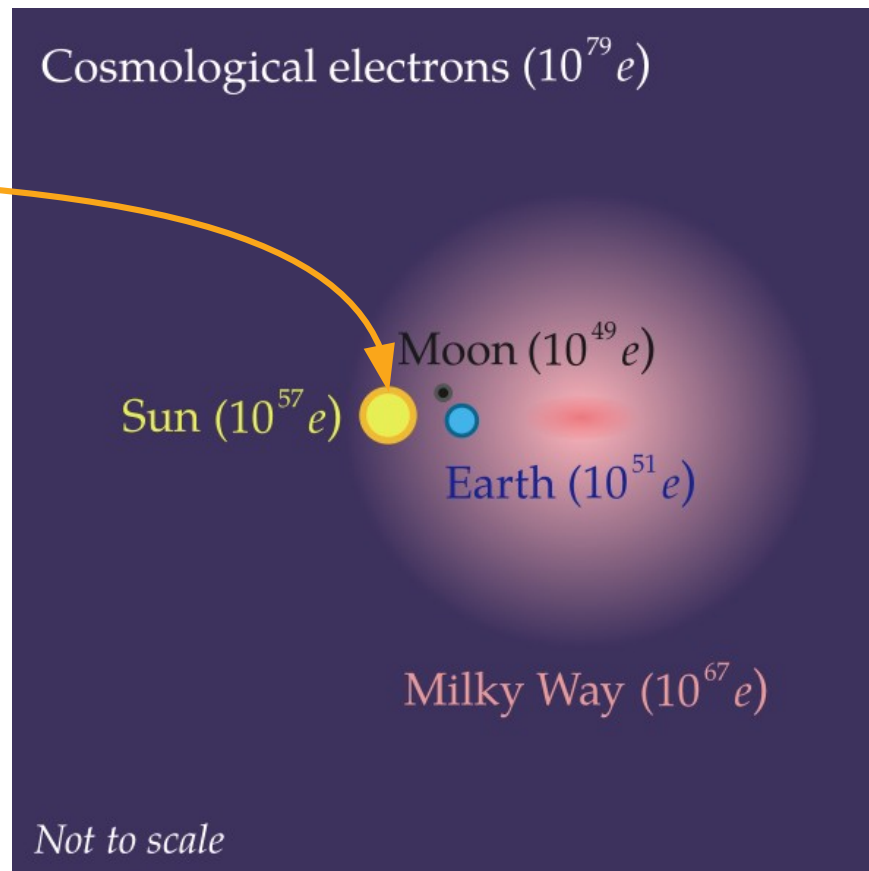
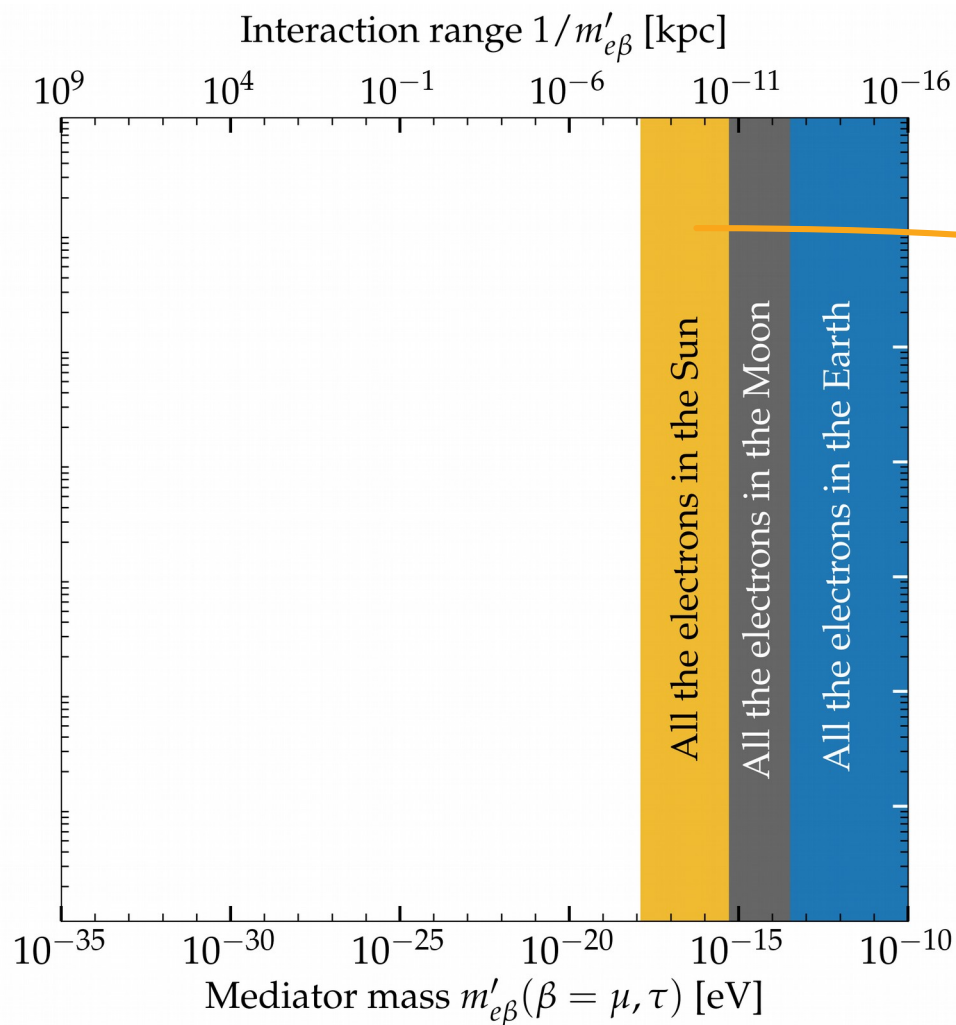
Electrons in the local and distant Universe



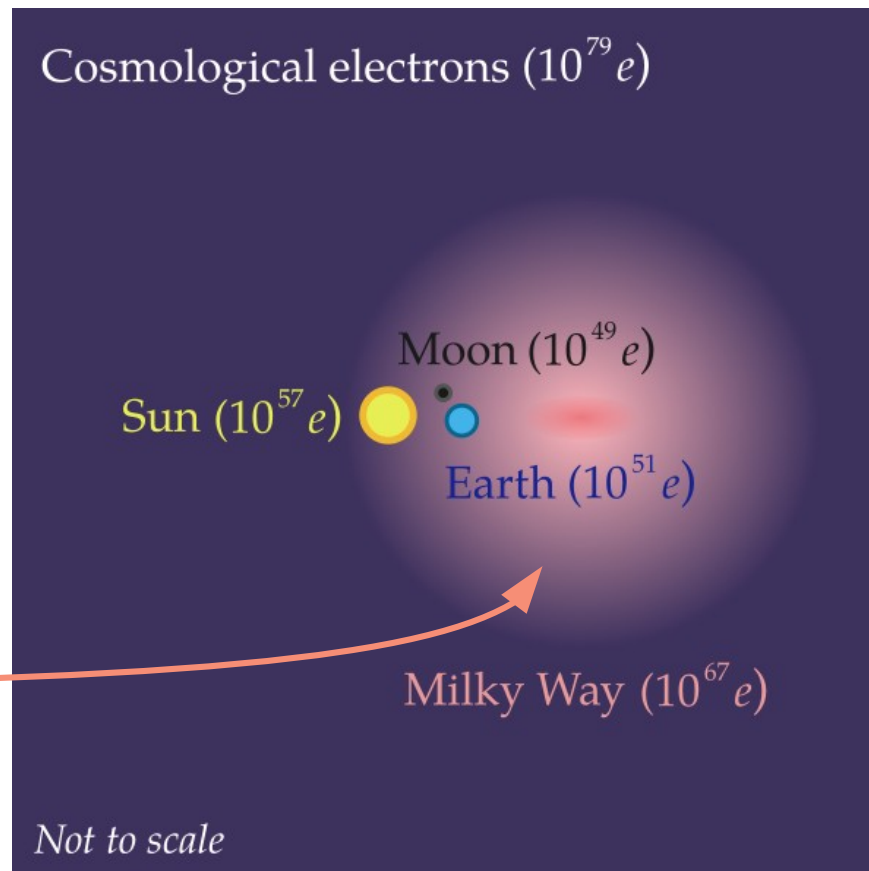
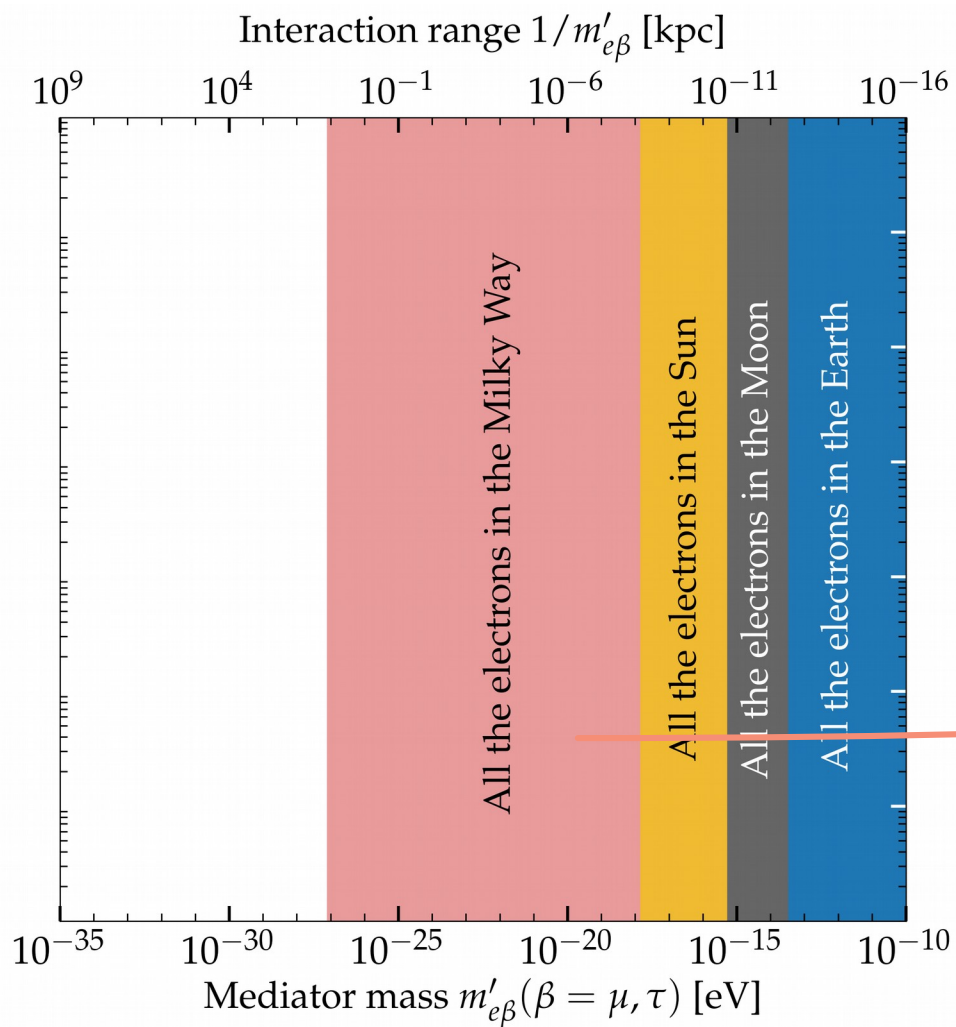
Electrons in the local and distant Universe



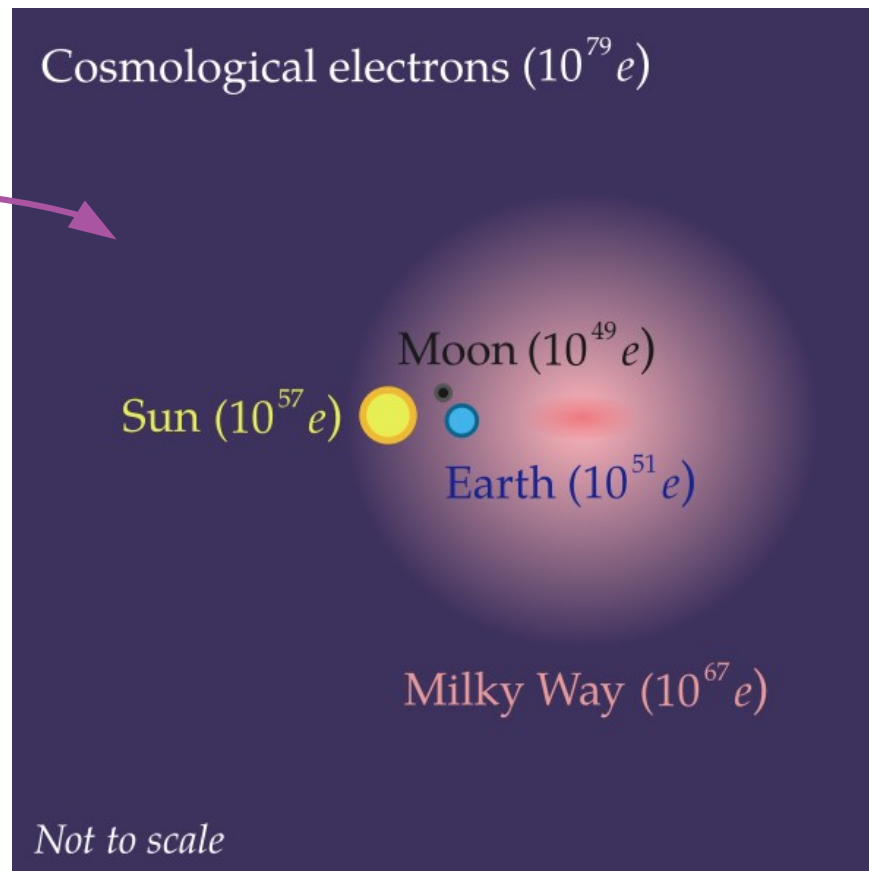
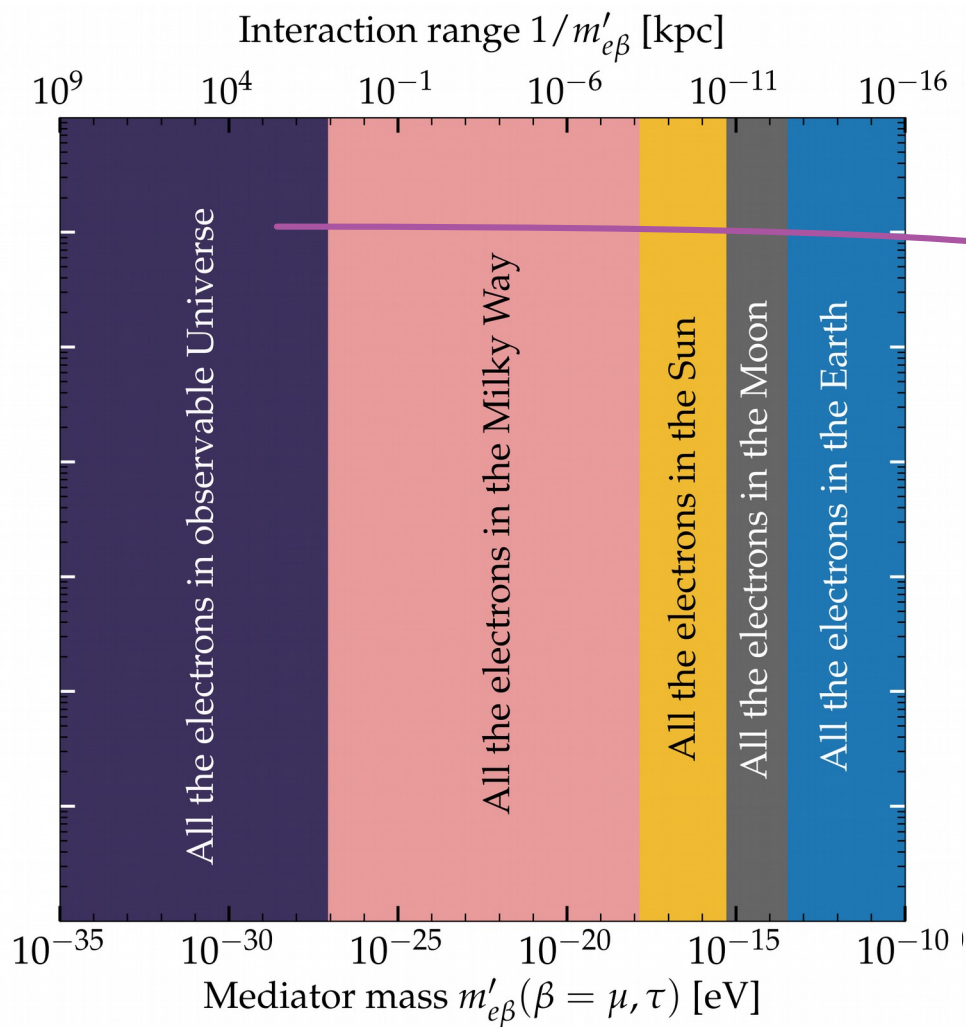
Electrons in the local and distant Universe



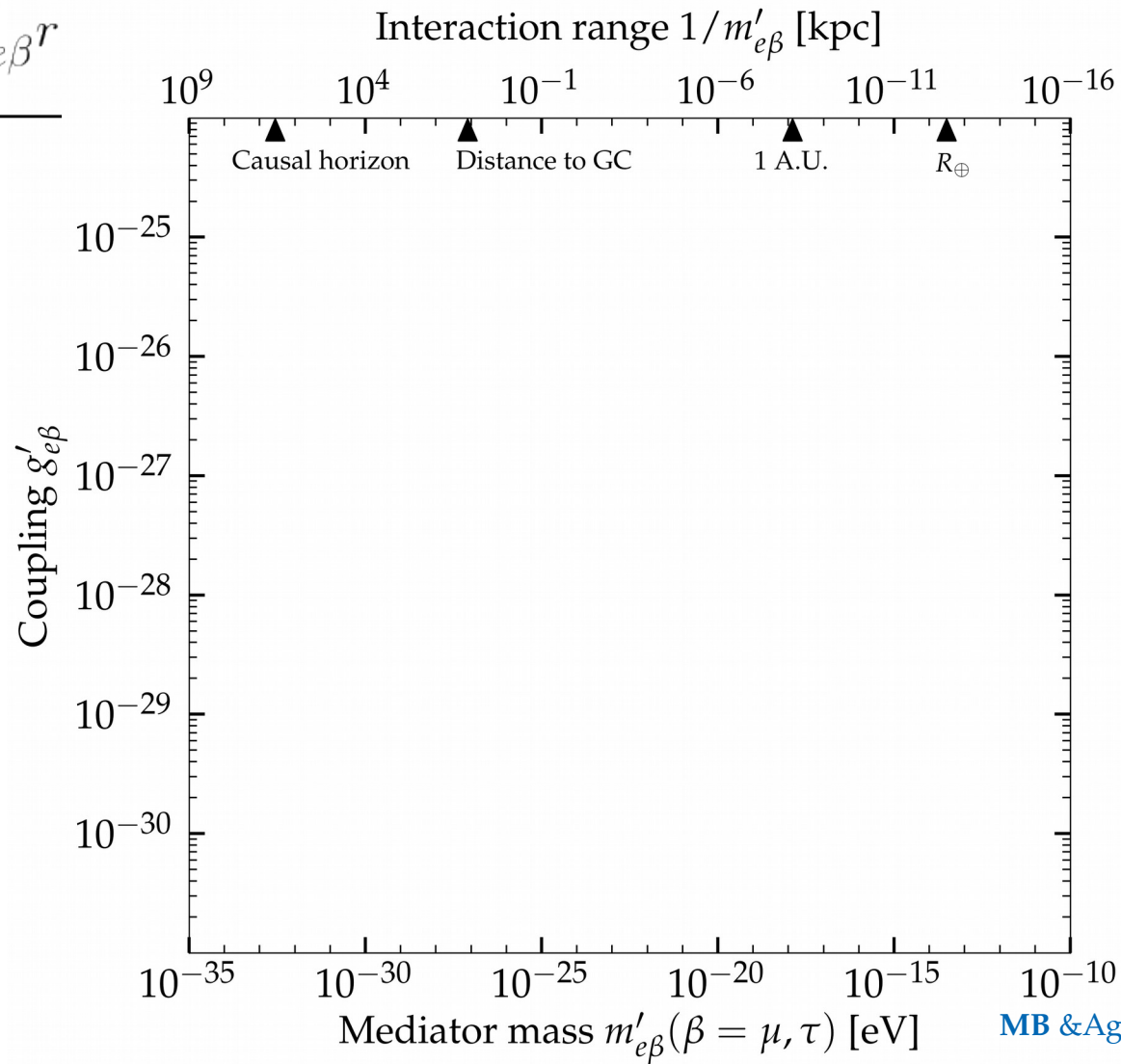
Electrons in the local and distant Universe



Electrons in the local and distant Universe

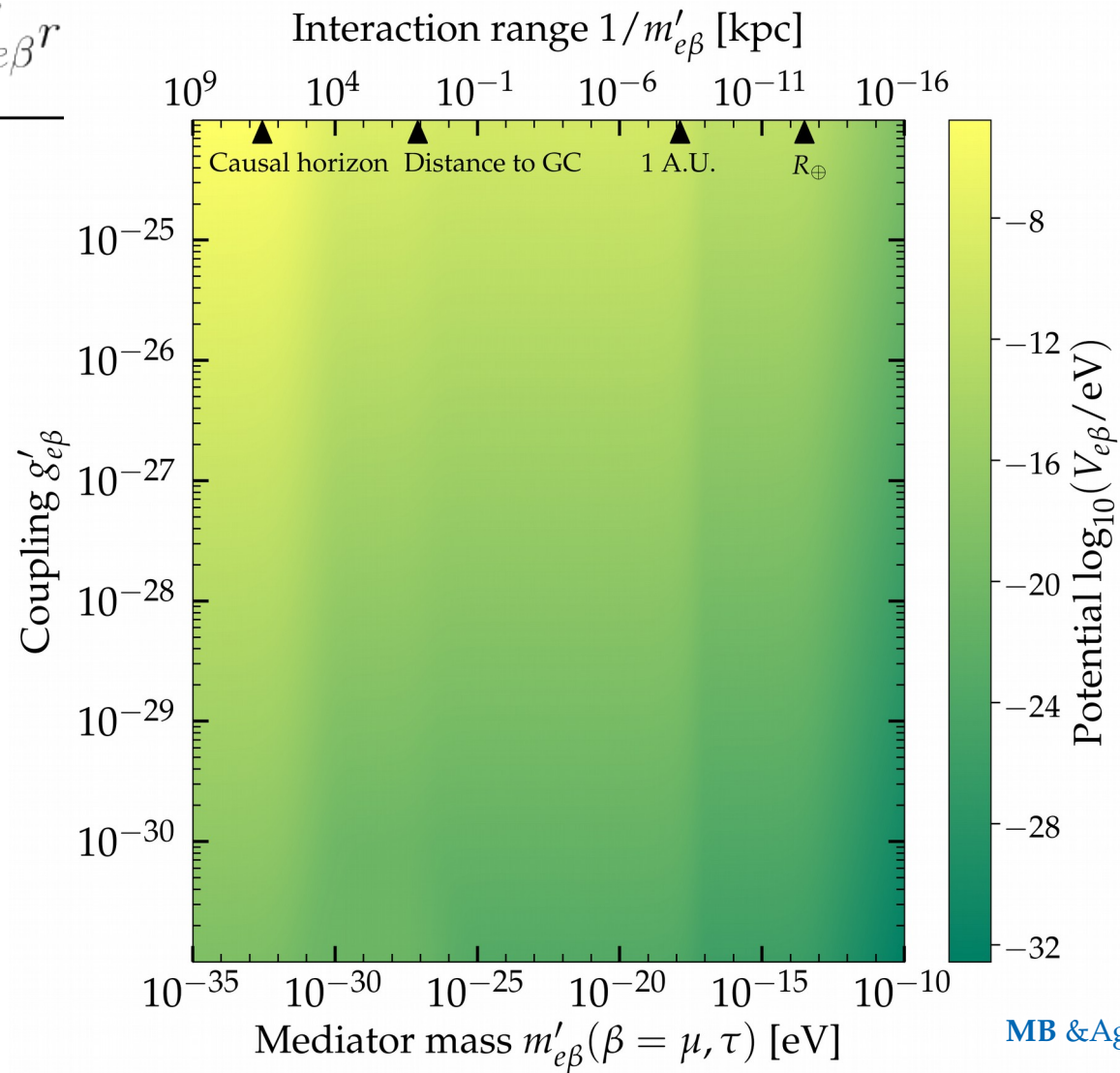


$$V_{e\beta} = \frac{g_{e\beta}'^2}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



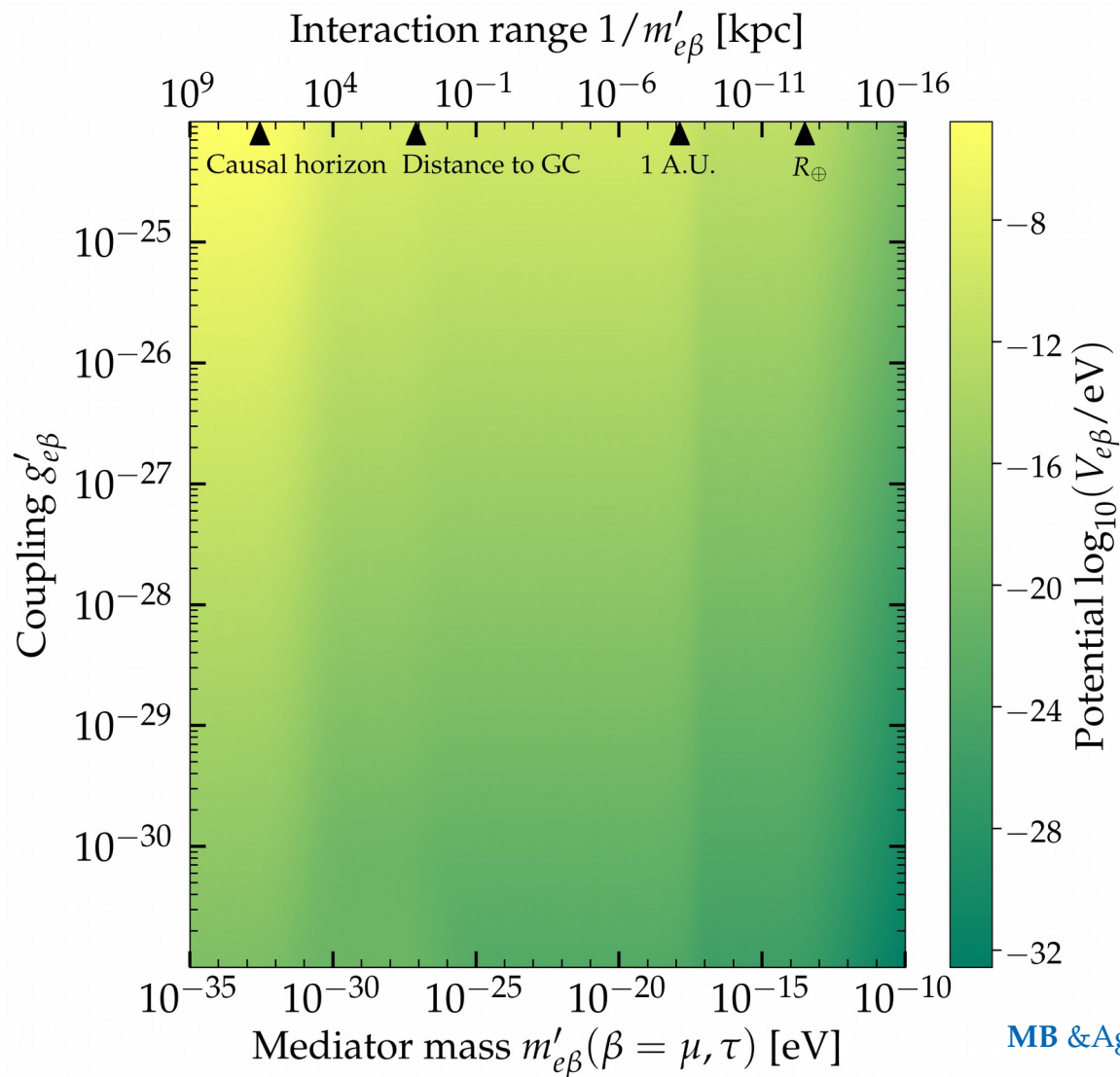
MB & Agarwalla, *PRL* 2019

$$V_{e\beta} = \frac{g_{e\beta}'^2}{4\pi} \frac{e^{-m'_{e\beta} r}}{r}$$



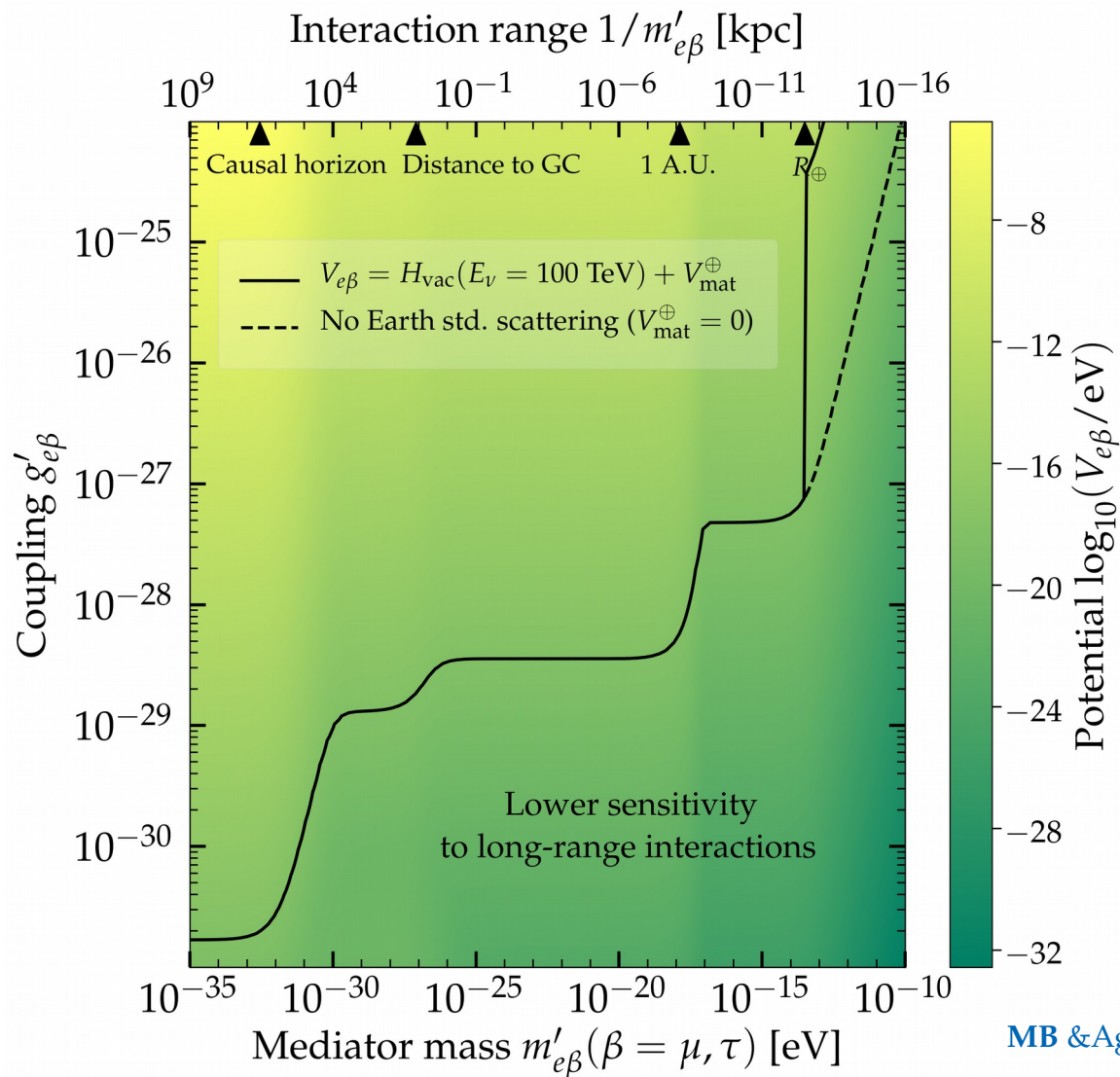
MB & Agarwalla, *PRL* 2019

$$\begin{aligned}
 g_{\text{strong}} &\sim 13.5 \\
 g_{\text{e.m.}} &\sim 0.3 \\
 g_{\text{weak}} &\sim 0.01 \\
 g_{\text{gravity}} &\sim 10^{-19}
 \end{aligned}$$



MB & Agarwalla, *PRL* 2019

$$\begin{aligned}
 g_{\text{strong}} &\sim 13.5 \\
 g_{\text{e.m.}} &\sim 0.3 \\
 g_{\text{weak}} &\sim 0.01 \\
 g_{\text{gravity}} &\sim 10^{-19}
 \end{aligned}$$



$g_{\text{strong}} \sim 13.5$
 $g_{\text{e.m.}} \sim 0.3$
 $g_{\text{weak}} \sim 0.01$
 $g_{\text{gravity}} \sim 10^{-19}$



Interaction range $1/m'_{e\beta}$ [kpc]

10^9 10^4 10^{-1} 10^{-6} 10^{-11} 10^{-16}

Causal horizon Distance to GC 1 A.U. $R_{\oplus}$

Coupling $g'_{e\beta}$

10^{-25}
 10^{-26}
 10^{-27}
 10^{-28}
 10^{-29}
 10^{-30}
 10^{-35}

Dominated by Milky-Way e

Dominated by cosmological e

Mediator mass $m'_{e\beta} (\beta = \mu, \tau)$ [eV]

10^{-35} 10^{-30} 10^{-25} 10^{-20} 10^{-15} 10^{-10}

Lower sensitivity to long-range interactions

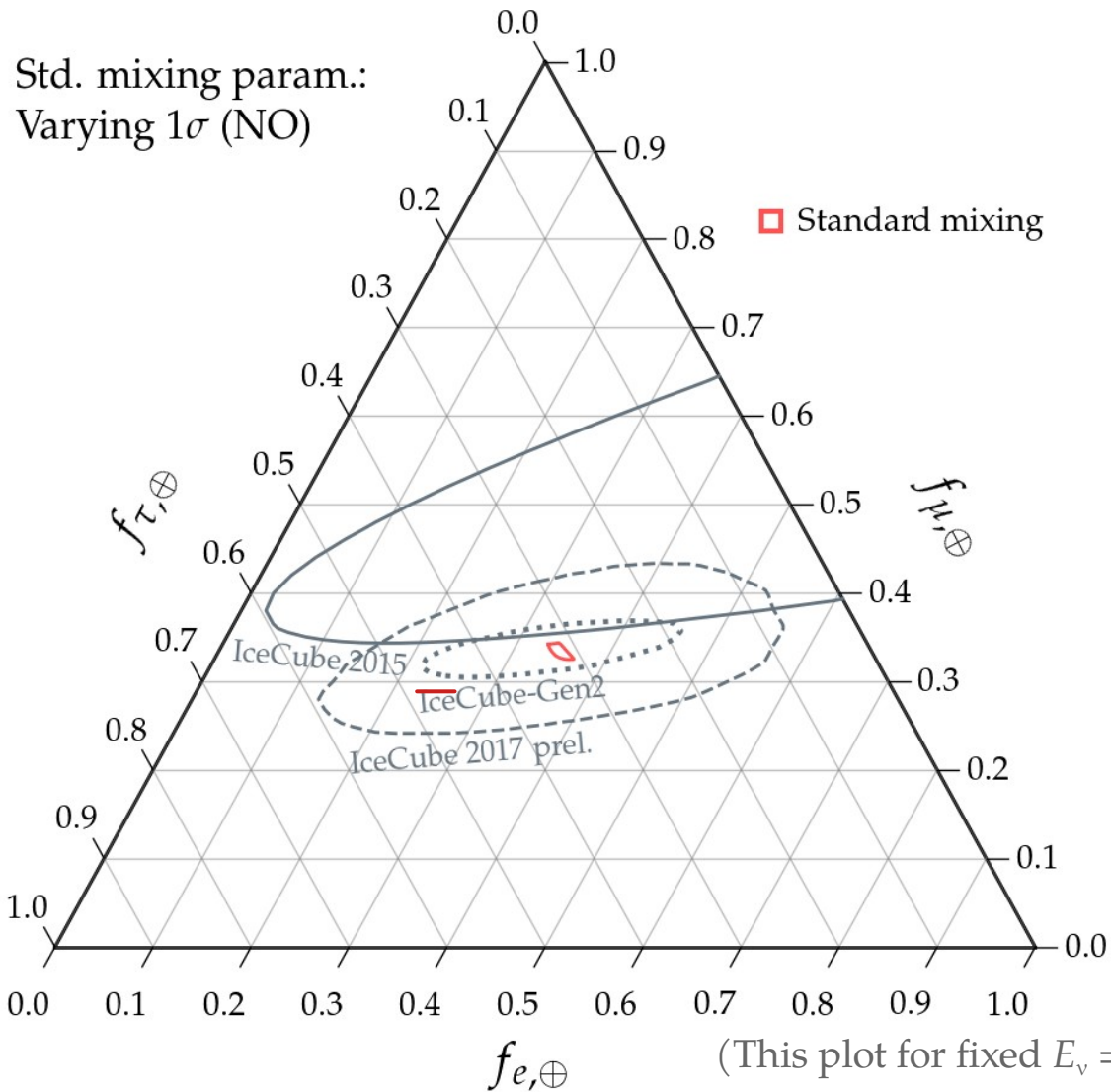
— $V_{e\beta} = H_{\text{vac}}(E_\nu = 100 \text{ TeV}) + V_{\text{mat}}^\oplus$
 - - - No Earth std. scattering ($V_{\text{mat}}^\oplus = 0$)

Dominated by electrons in the Earth + Moon

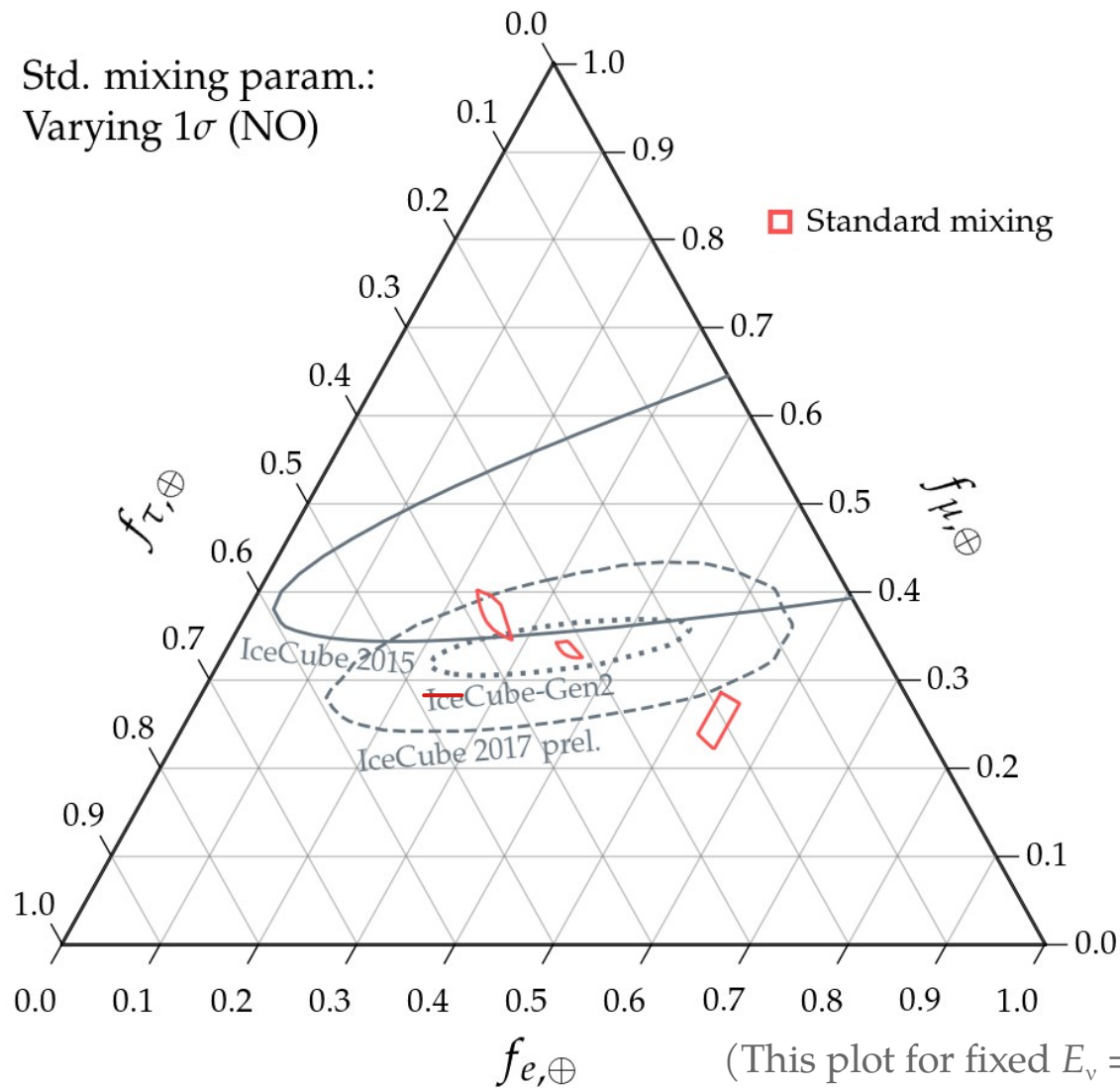
Dominated by solar electrons (+ Milky-Way e)

Potential $\log_{10}(V_{e\beta}/\text{eV})$

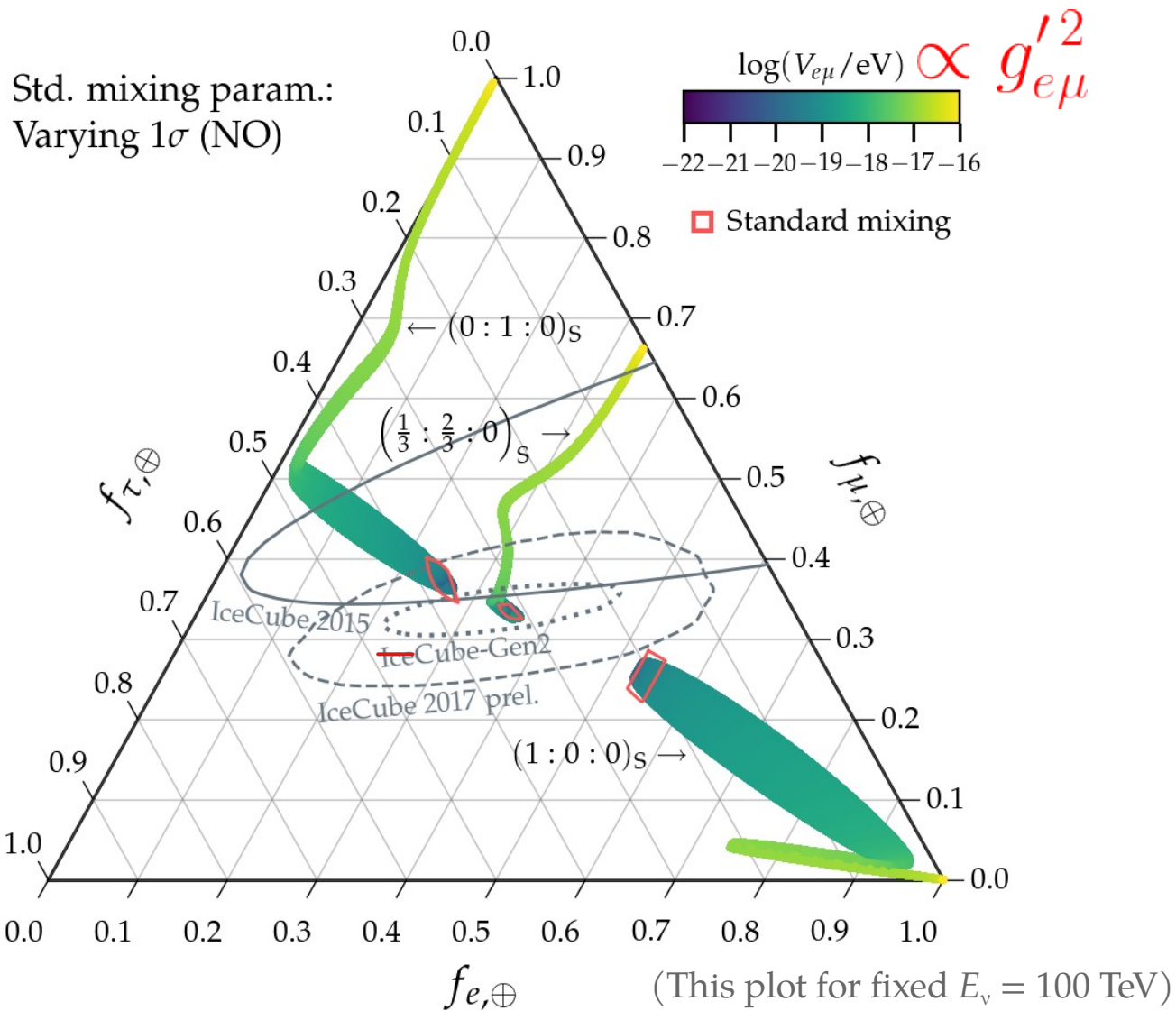
MB & Agarwalla, PRL 2019

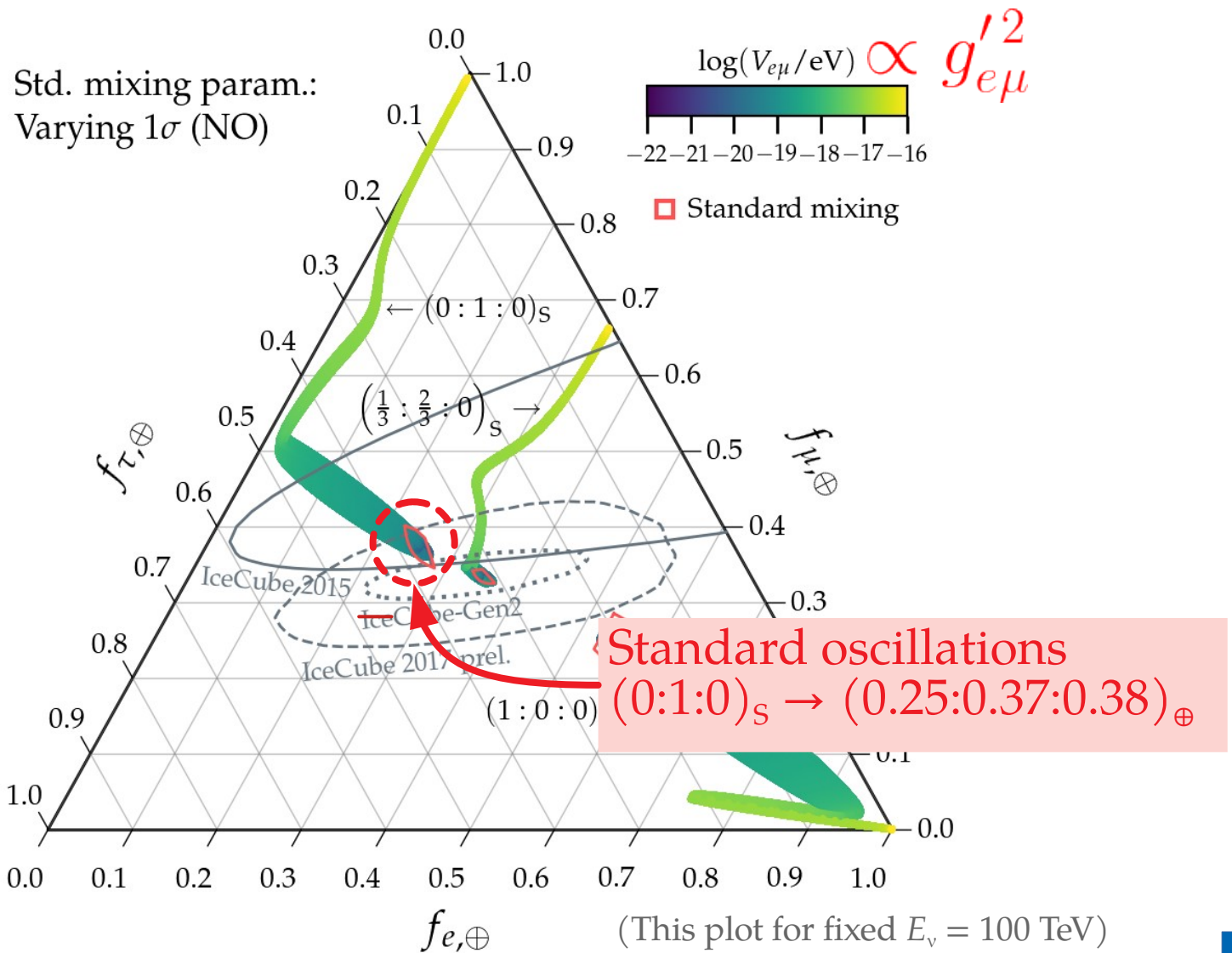


Std. mixing param.:
Varying 1σ (NO)



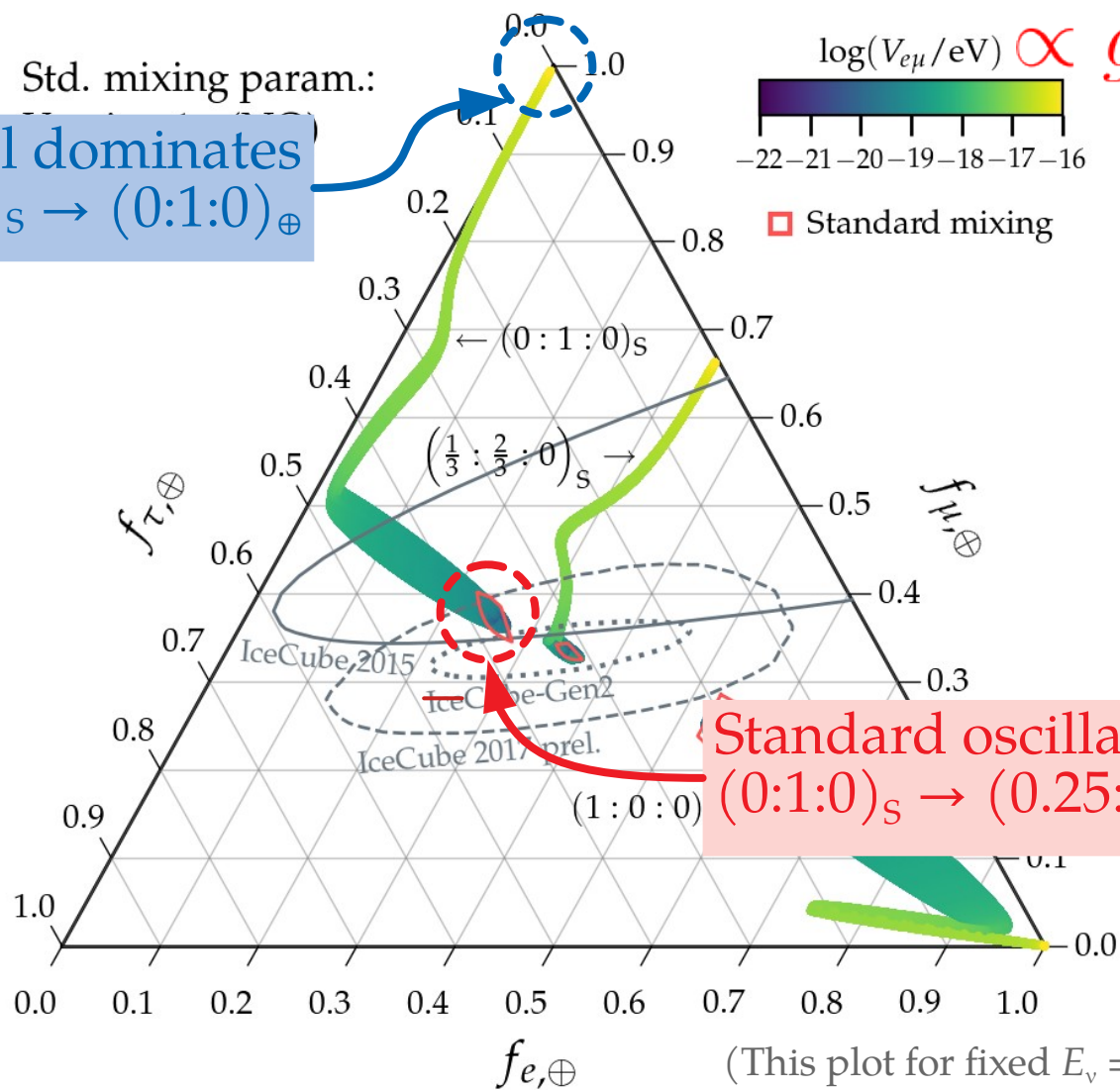
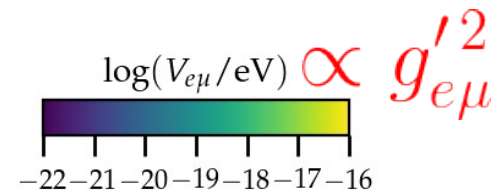
MB & Agarwalla, PRL 2019





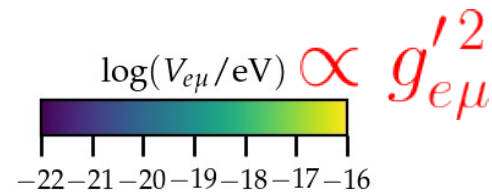
New potential dominates
 $(0:1:0)_S \rightarrow (0:1:0)_\oplus$

Std. mixing param.:



New potential dominates
 $(0:1:0)_s \rightarrow (0:1:0)_\oplus$

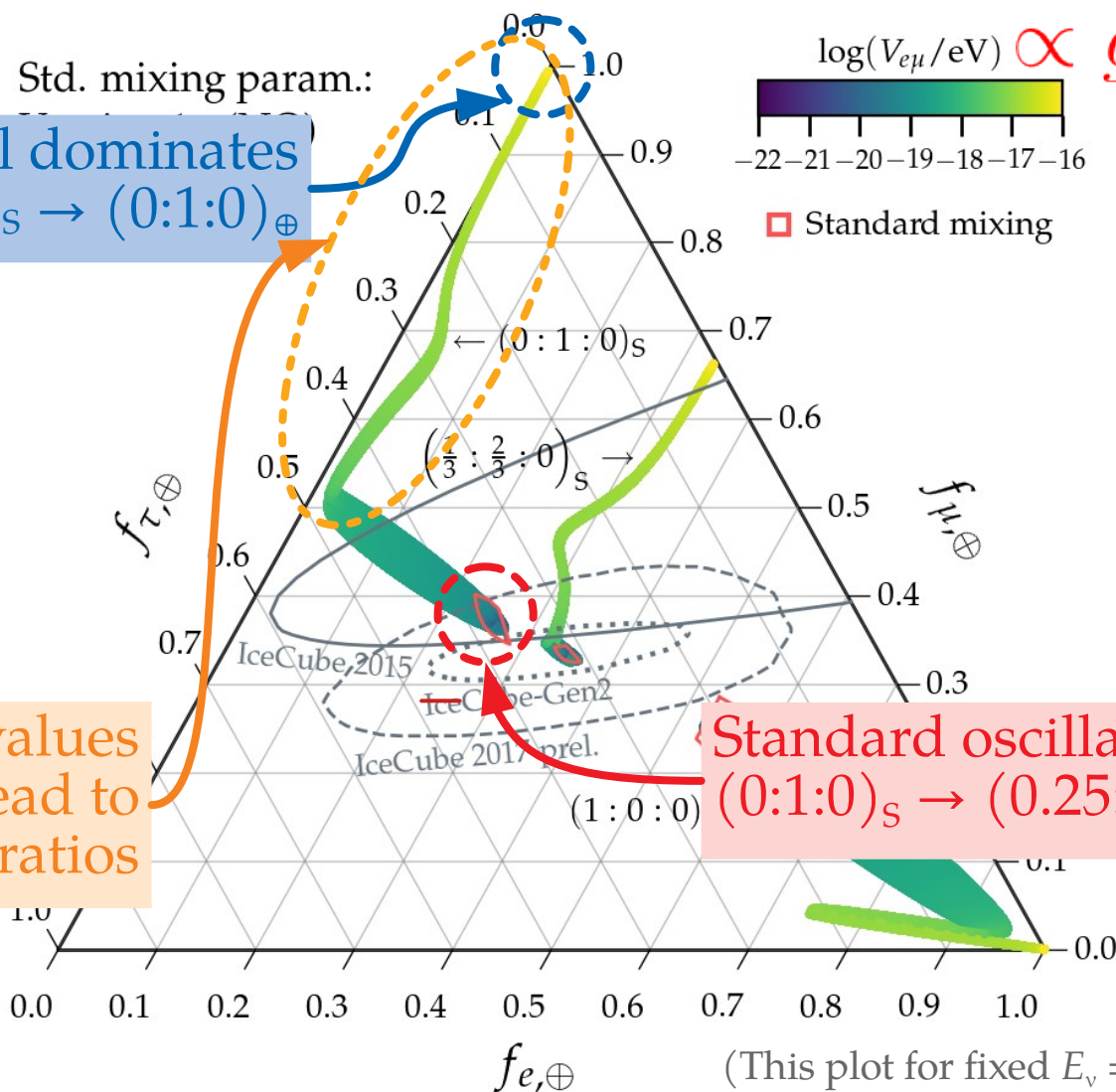
Std. mixing param.:

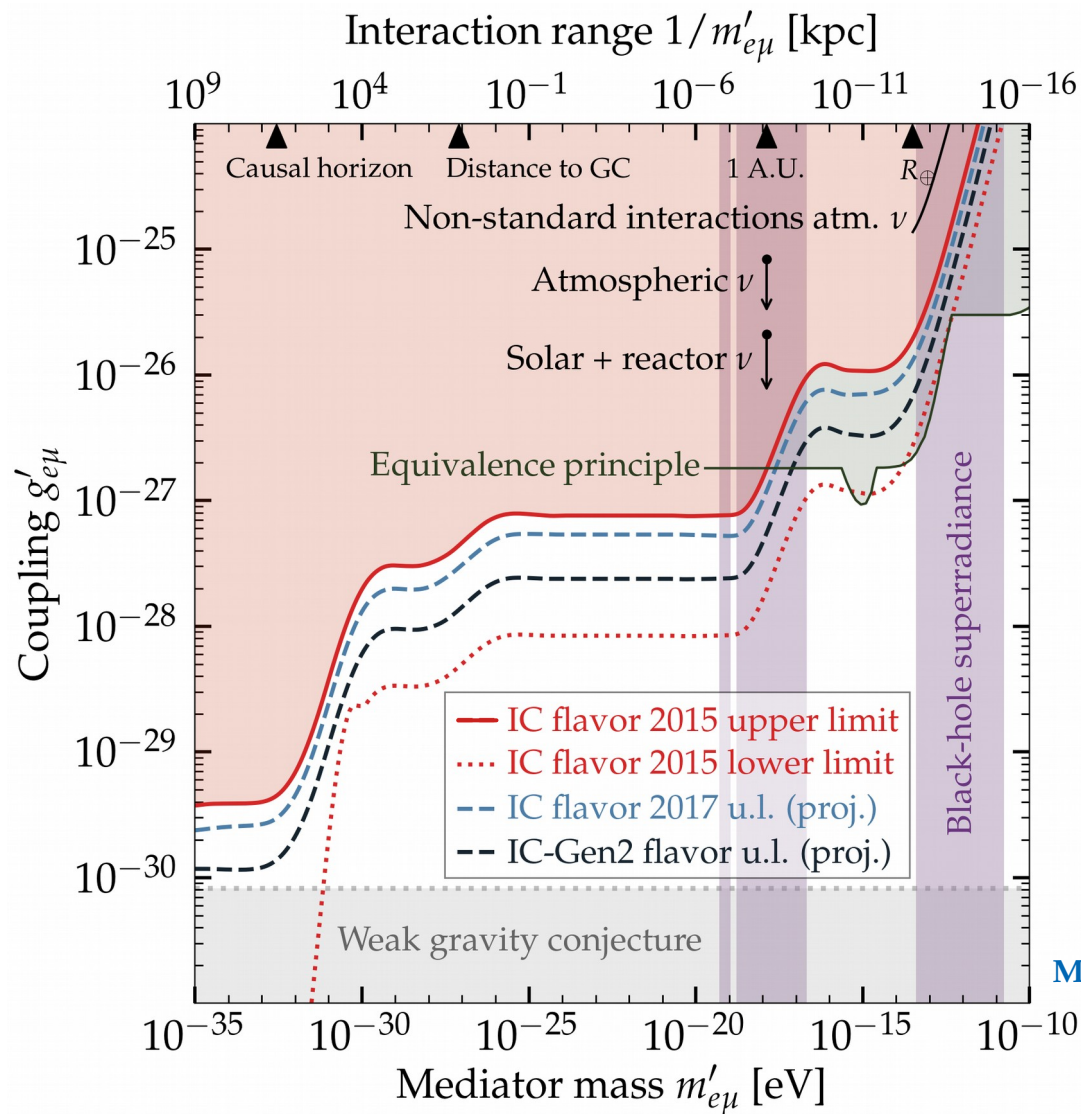


Standard mixing

We can disfavor all values of m' and g' that lead to these flavor ratios

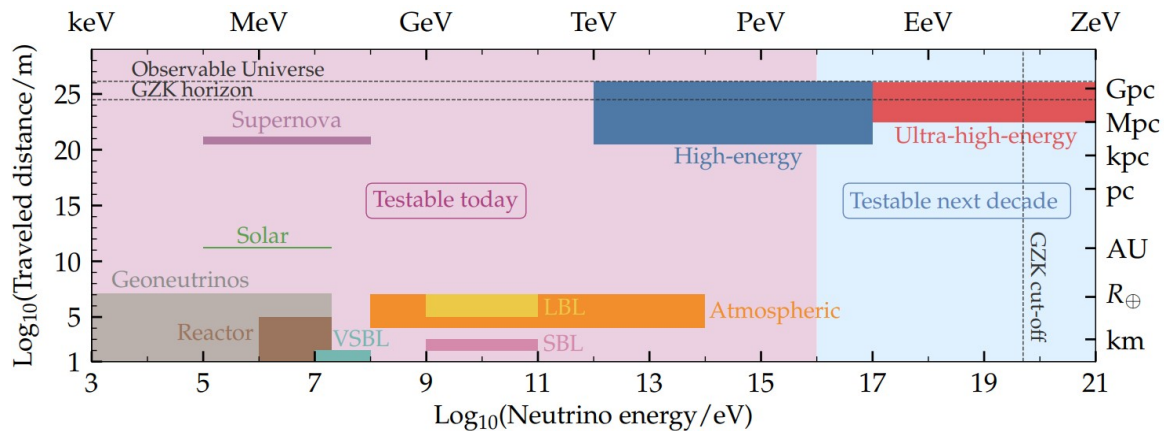
Standard oscillations
 $(0:1:0)_s \rightarrow (0.25:0.37:0.38)_\oplus$





MB & Agarwalla, PRL 2019

An exciting decade ahead



Today: TeV–PeV astrophysical ν

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

IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

Next decade: EeV cosmogenic ν

$$\kappa_n \sim 4 \cdot 10^{-50} (E/\text{EeV})^{-n} (L/\text{Gpc})^{-1} \text{EeV}^{1-n}$$

IceCube upgrade

IceCube-Gen2

KM3NeT

ANITA

ARA

ARIANNA

Baikal-GVD

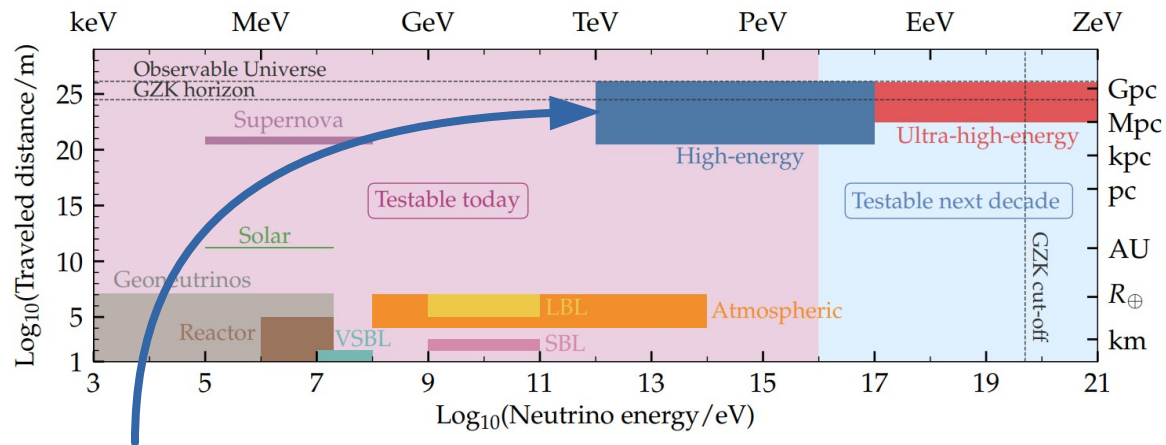
BEACON

GRAND

POEMMA

TRINITY

An exciting decade ahead



Today: TeV–PeV astrophysical ν

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

IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

Next decade: EeV cosmogenic ν

$$\kappa_n \sim 4 \cdot 10^{-50} (E/\text{EeV})^{-n} (L/\text{Gpc})^{-1} \text{EeV}^{1-n}$$

IceCube upgrade

IceCube-Gen2

KM3NeT

ANITA

ARA

ARIANNA

Baikal-GVD

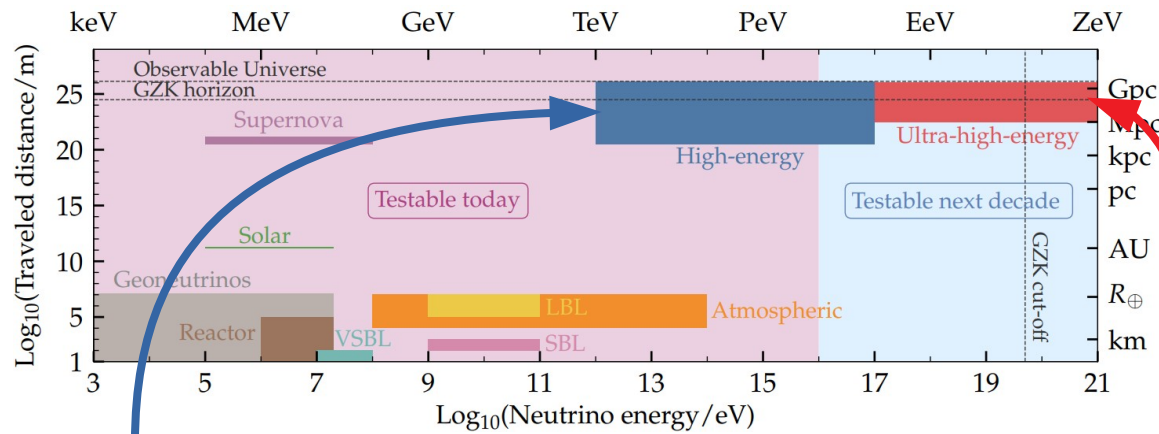
BEACON

GRAND

POEMMA

TRINITY

An exciting decade ahead



Today: TeV–PeV astrophysical ν

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

IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

Next decade: EeV cosmogenic ν

$$\kappa_n \sim 4 \cdot 10^{-50} (E/\text{EeV})^{-n} (L/\text{Gpc})^{-1} \text{EeV}^{1-n}$$

IceCube upgrade

IceCube-Gen2

KM3NeT

ANITA

ARA

ARIANNA

Baikal-GVD

BEACON

GRAND

POEMMA

TRINITY

What are you taking home?

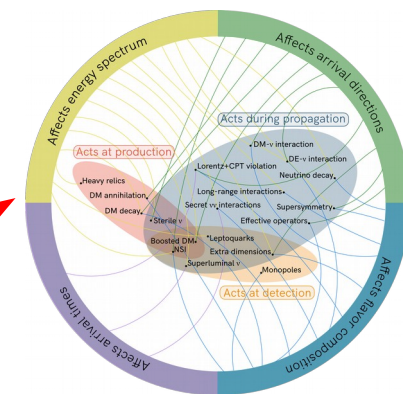
- ▶ Cosmic neutrinos are incisive probes of TeV–PeV physics
- ▶ We can do this *now*, in spite of astrophysical unknowns
- ▶ New physics comes in many shapes — so we need to be thorough
- ▶ Exciting prospects: larger statistics, better reconstruction, higher energies

More?

- ▶ *Fundamental physics with high-energy cosmic neutrinos today and in the future*, [1907.08690](#)
- ▶ *Astro2020: Fundamental physics with high-energy cosmic neutrinos*, [1903.04333](#)
- ▶ *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, [1903.04334](#)

What are you taking home?

- ▶ Cosmic neutrinos are incisive probes of TeV–PeV physics
- ▶ We can do this *now*, in spite of astrophysical unknowns
- ▶ New physics comes in many shapes — so we need to be thorough
- ▶ Exciting prospects: larger statistics, better reconstruction, higher energies



More?

- ▶ *Fundamental physics with high-energy cosmic neutrinos today and in the future*, [1907.08690](#)
- ▶ *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

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

- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

$$E_X = y E_\nu \quad \text{and} \quad E_\mu = (1-y) E_\nu \Rightarrow y = (1 + E_\mu/E_X)^{-1}$$

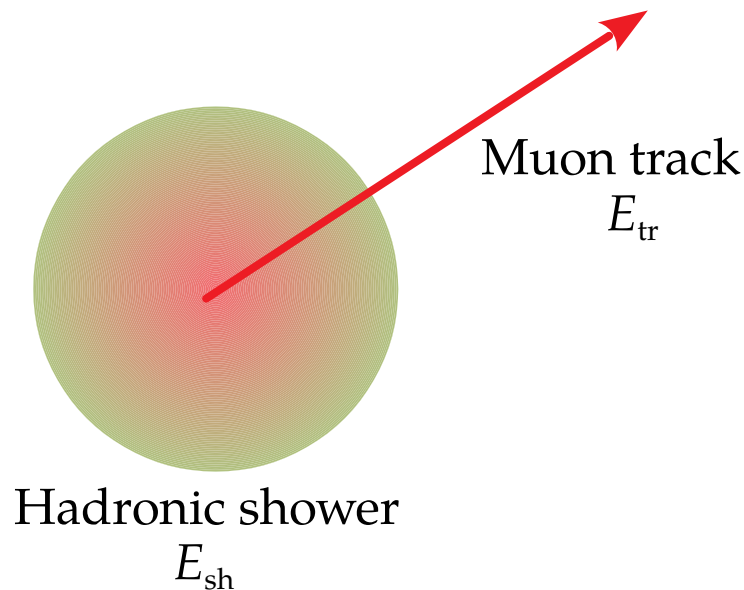
- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

$$\left. \begin{array}{l} E_X = E_{\text{sh}} \text{ (energy of shower)} \\ E_\mu = E_{\text{tr}} \text{ (energy of track)} \end{array} \right\} y = (1 + E_{\text{tr}}/E_{\text{sh}})^{-1}$$

- ▶ New IceCube analysis:

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



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

- ▶ Inelasticity in CC ν_μ interaction $\nu_\mu + N \rightarrow \mu + X$:

$$E_X = y E_\nu \quad \text{and} \quad E_\mu = (1-y) E_\nu \Rightarrow y = (1 + E_\mu/E_X)$$

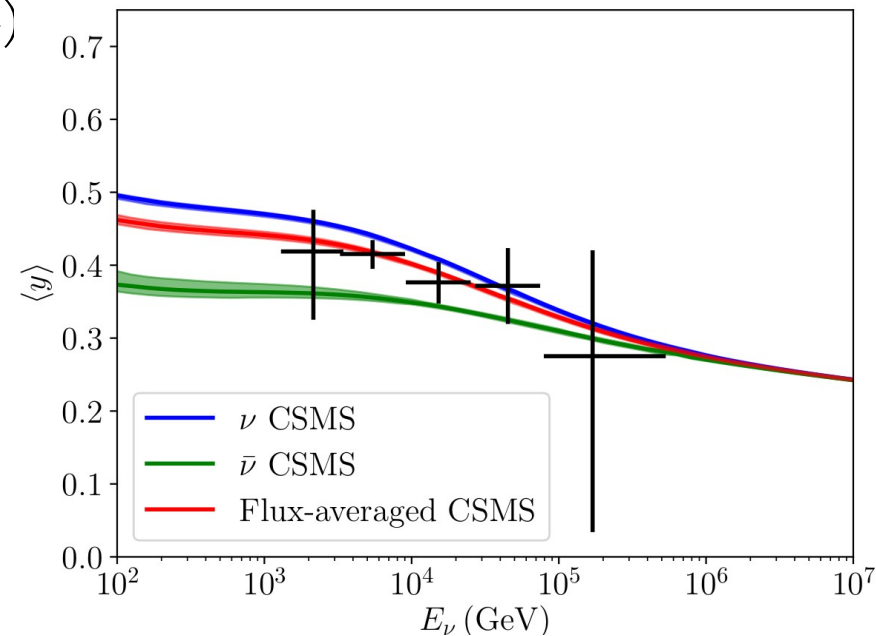
- ▶ The value of y follows a distribution $d\sigma/dy$

- ▶ In a HESE starting track:

$$\left. \begin{array}{l} E_X = E_{\text{sh}} \text{ (energy of shower)} \\ E_\mu = E_{\text{tr}} \text{ (energy of track)} \end{array} \right\} y = (1 + E_{\text{tr}}/E_{\text{sh}})^{-1}$$

- ▶ New IceCube analysis:

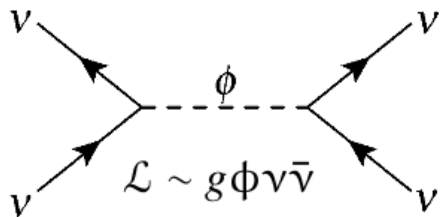
- ▶ 5 years of starting-track data (2650 tracks)
- ▶ Machine learning separates shower from track
- ▶ Different y distributions for ν and $\bar{\nu}$



IceCube, PRD 2019

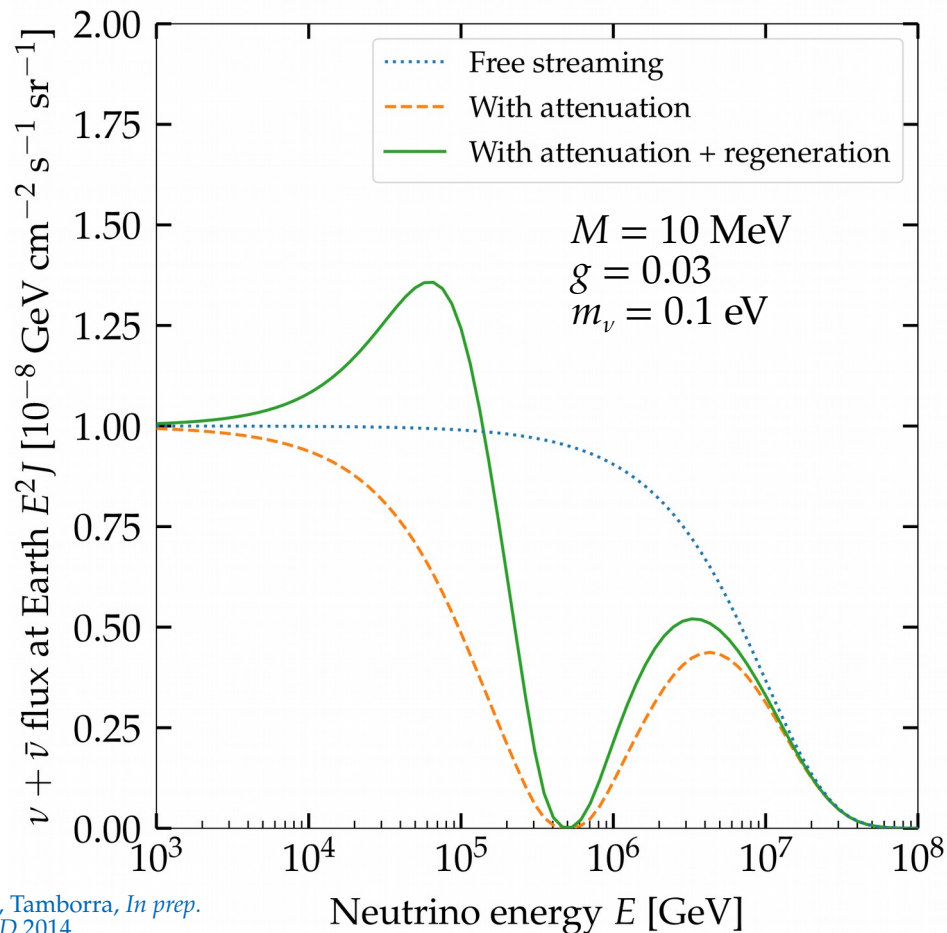
New physics in the spectral shape: $\nu\nu$ interactions

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



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

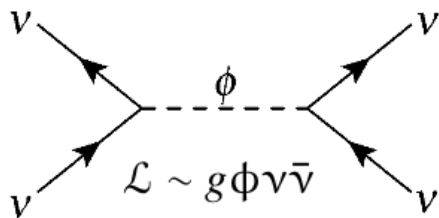
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



MB, Rosenstroem, Tamborra, *In prep.*
Ng & Beacom, *PRD* 2014
Cherry, Friedland, Shoemaker, 1411.1071
Blum, Hook, Murase, 1408.3799

New physics in the spectral shape: $\nu\nu$ interactions

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



New coupling

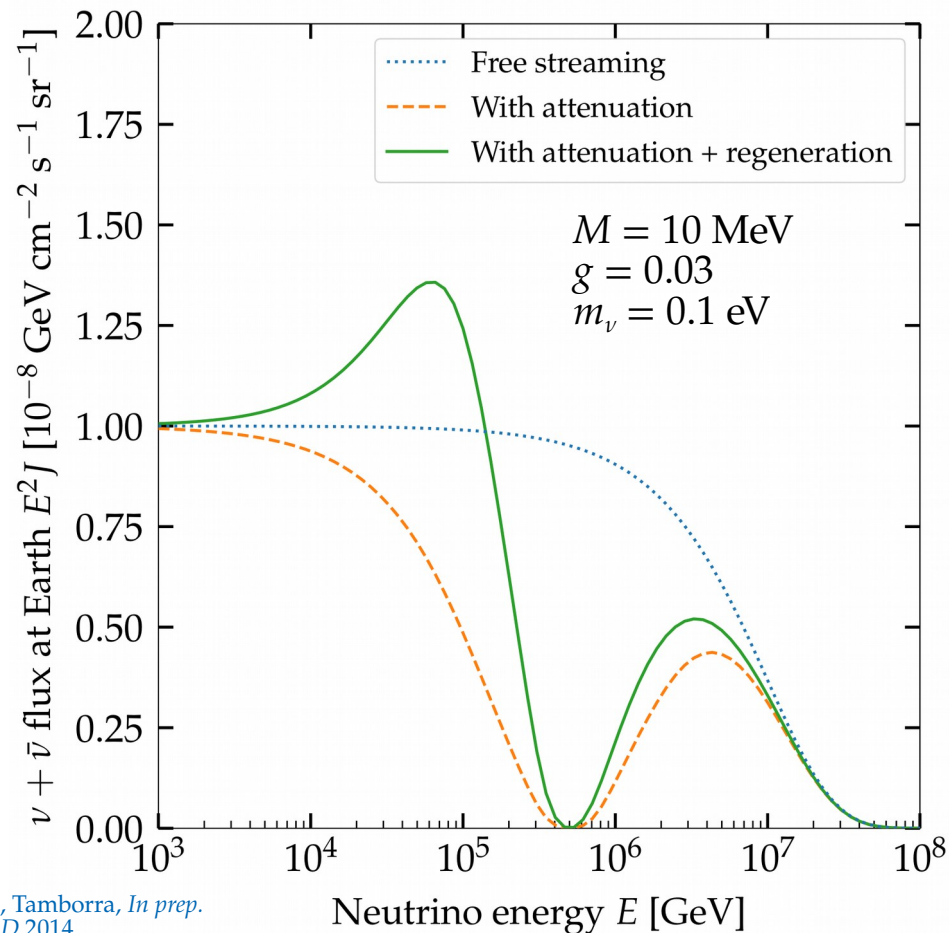
Cross section:

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

Mediator mass

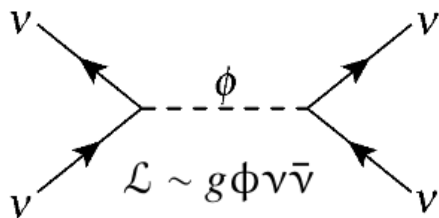
Resonance energy:

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



New physics in the spectral shape: $\nu\nu$ interactions

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



Cross section:

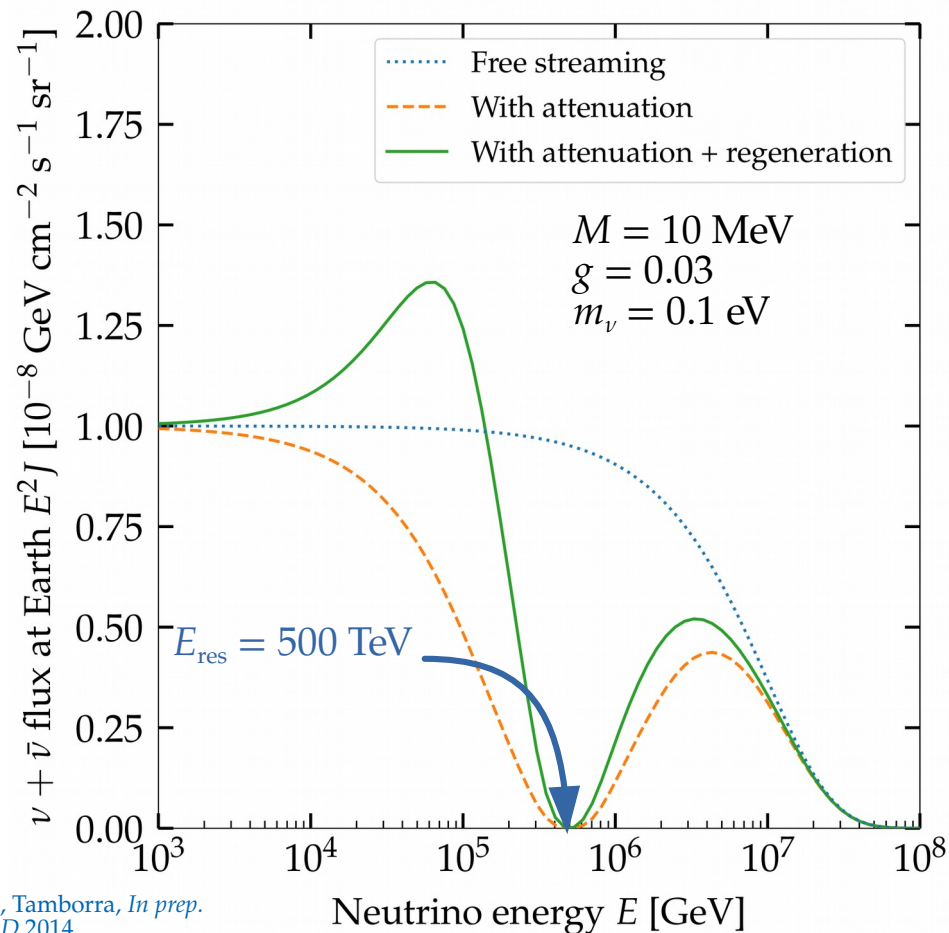
$$\sigma = \frac{g^4 s}{4\pi (s - M^2)^2 + M^2\Gamma^2}$$

New coupling

Mediator mass

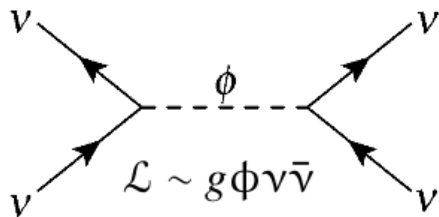
Resonance energy:

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



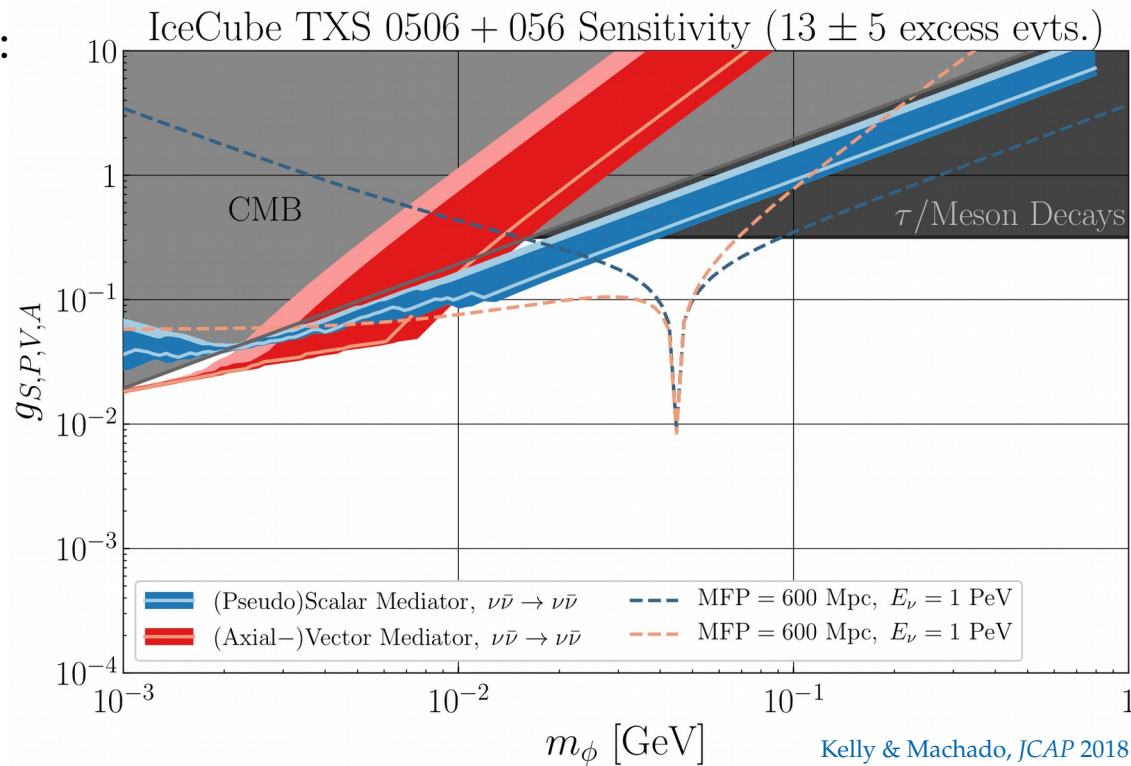
New physics in the spectral shape: $\nu\nu$ interactions

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



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

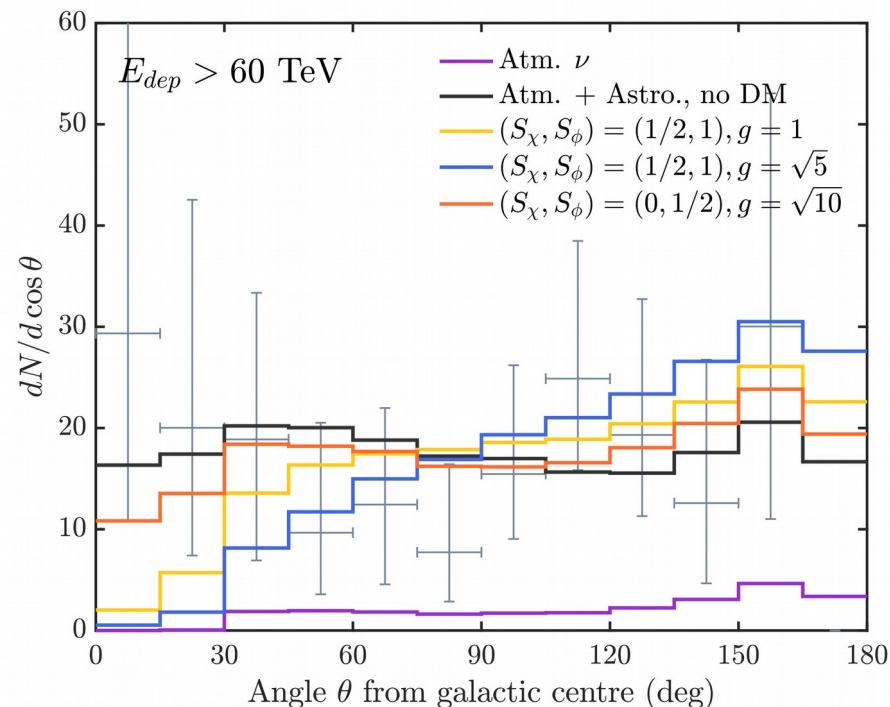
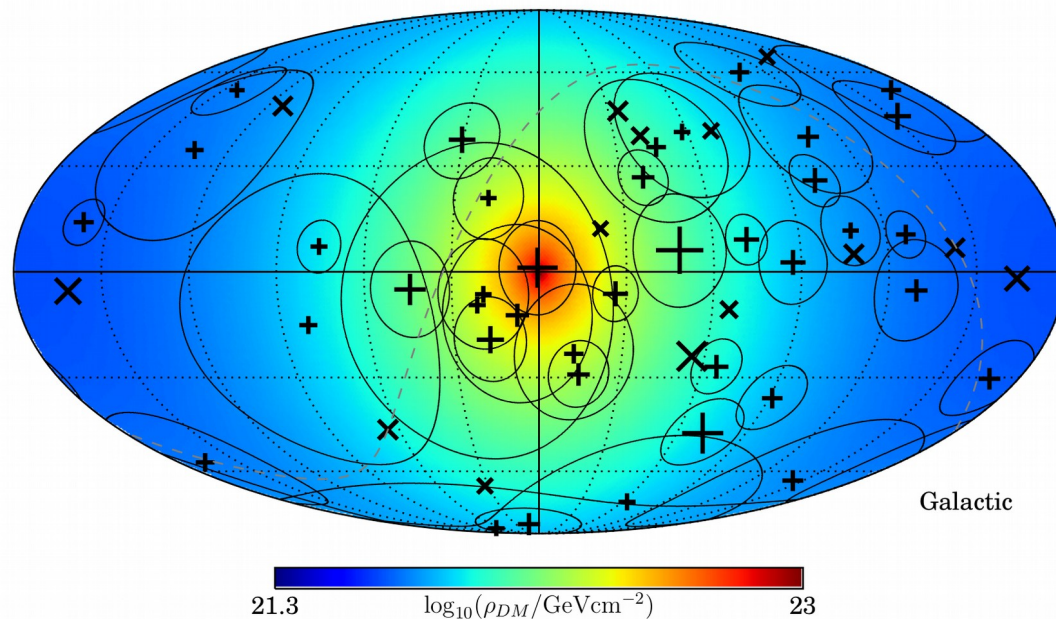
Resonance energy:
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



Kelly & Machado, JCAP 2018

New physics in the angular distribution: ν -DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile —

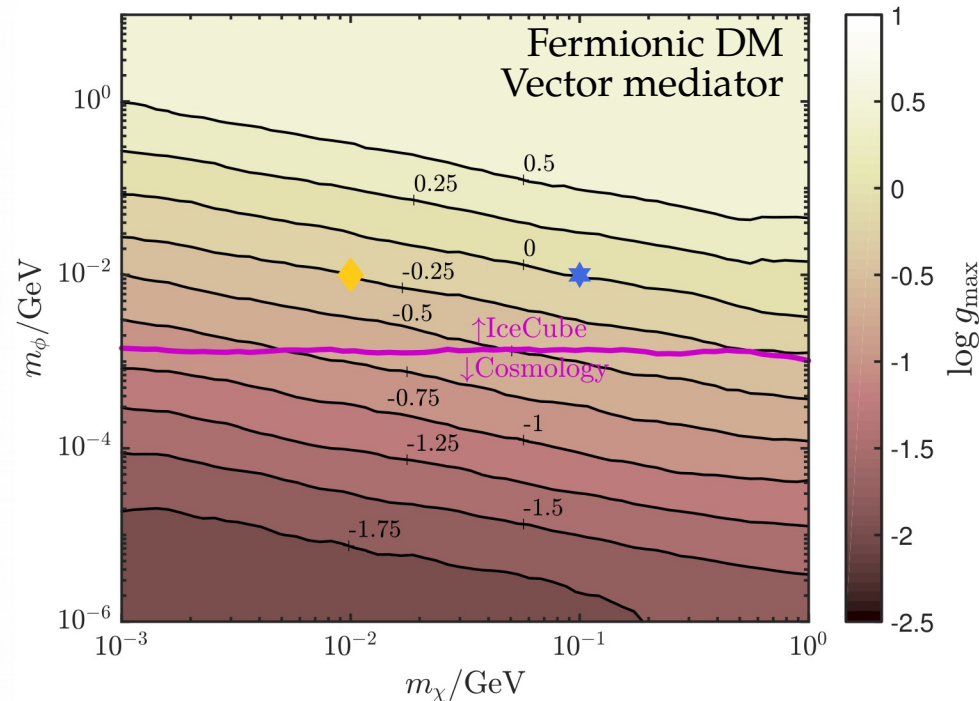
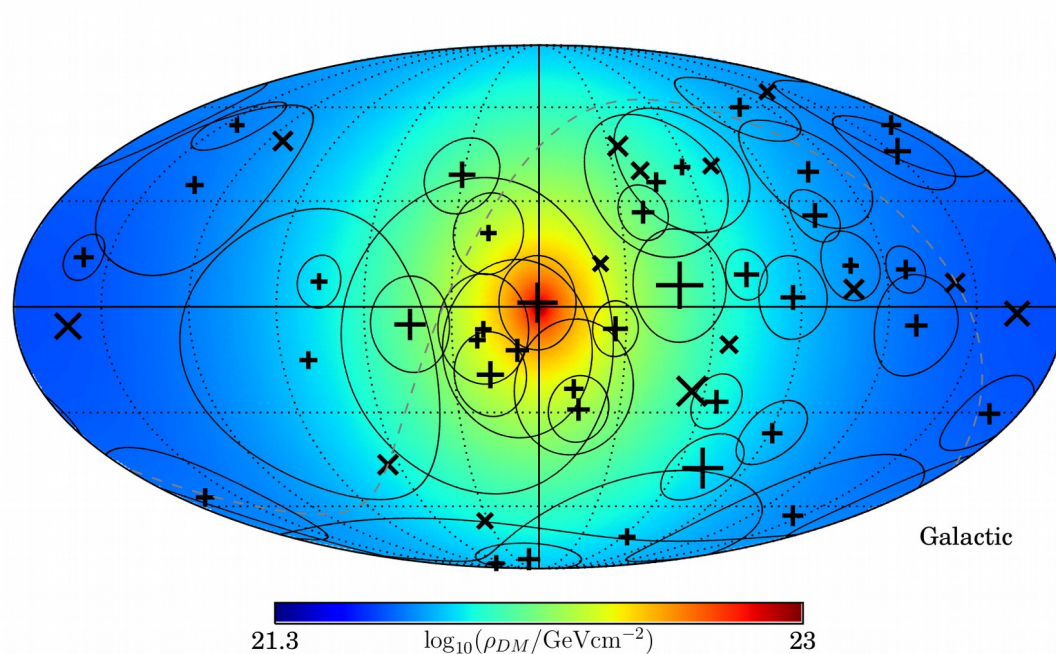


Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

New physics in the angular distribution: ν -DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile —

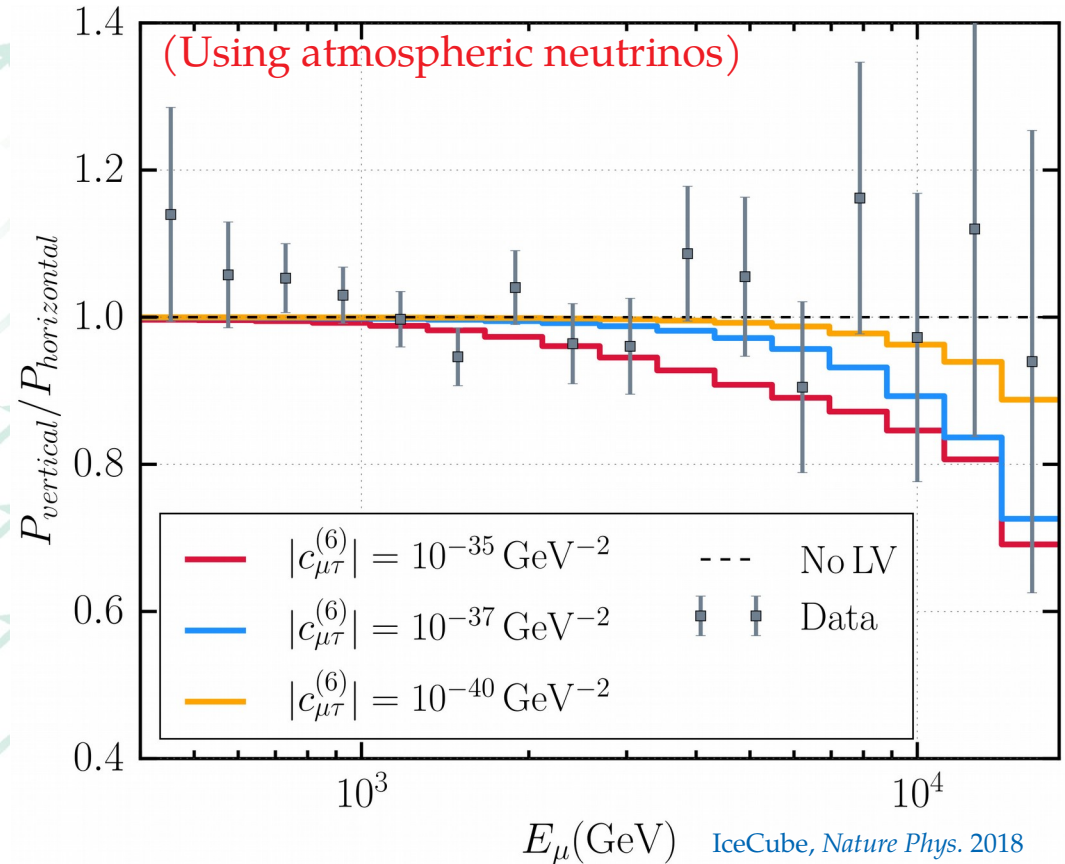
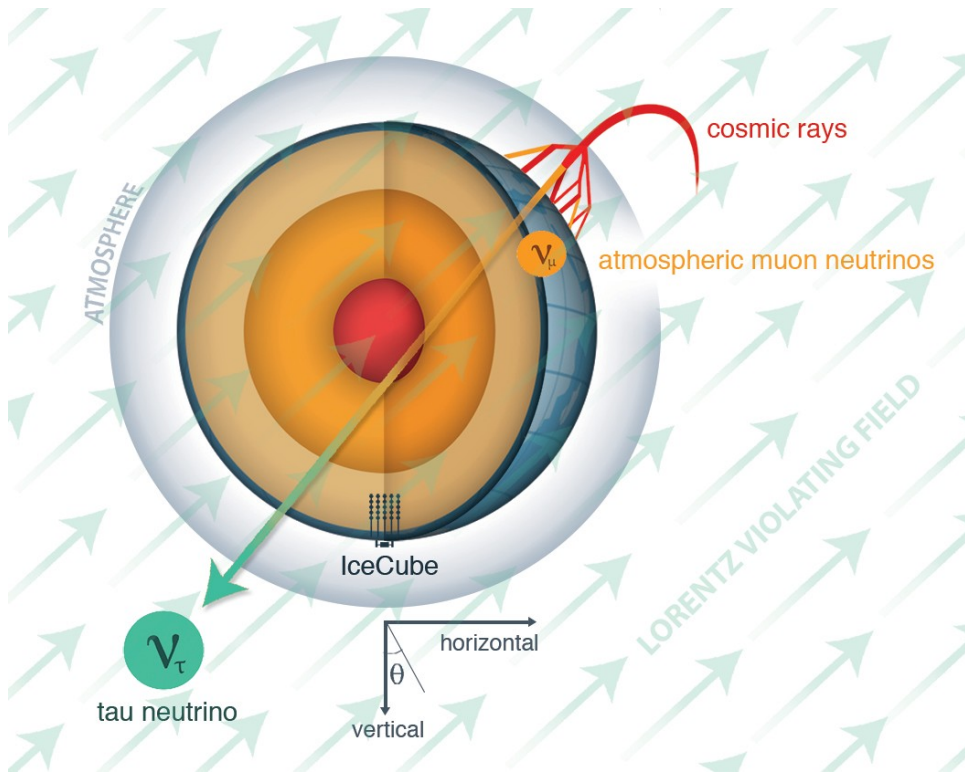


Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

New physics in the energy & angular distribution

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

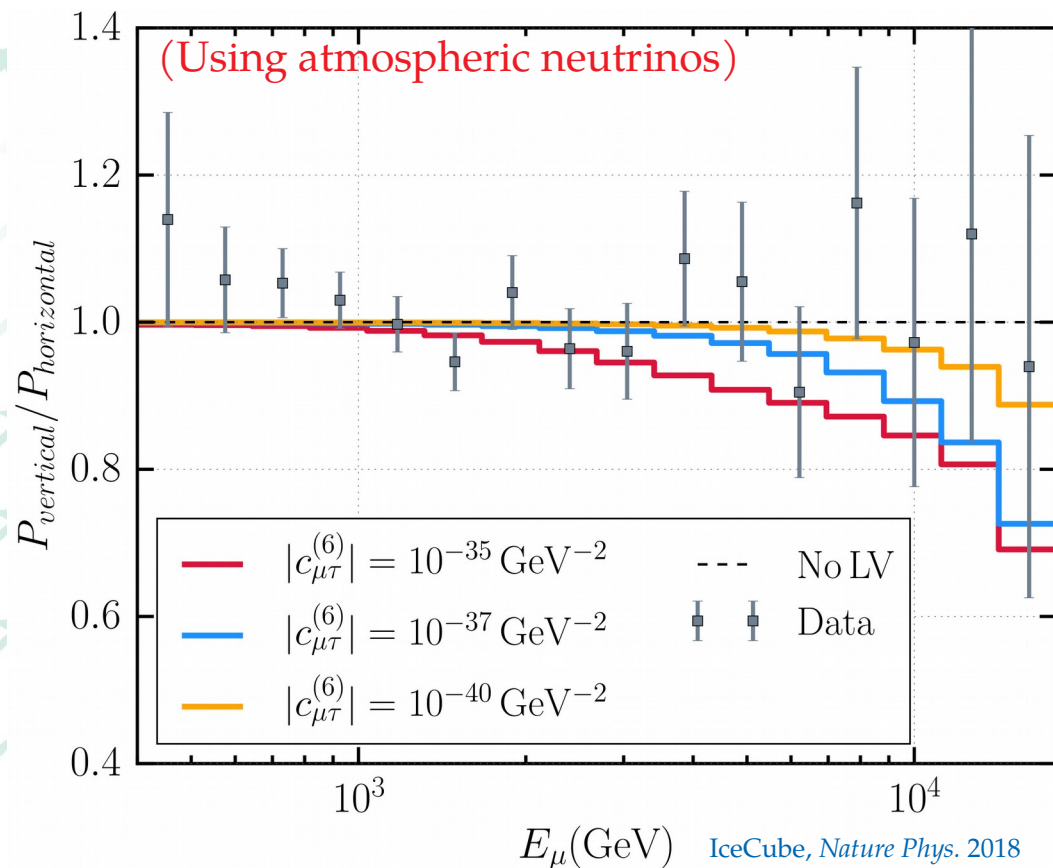
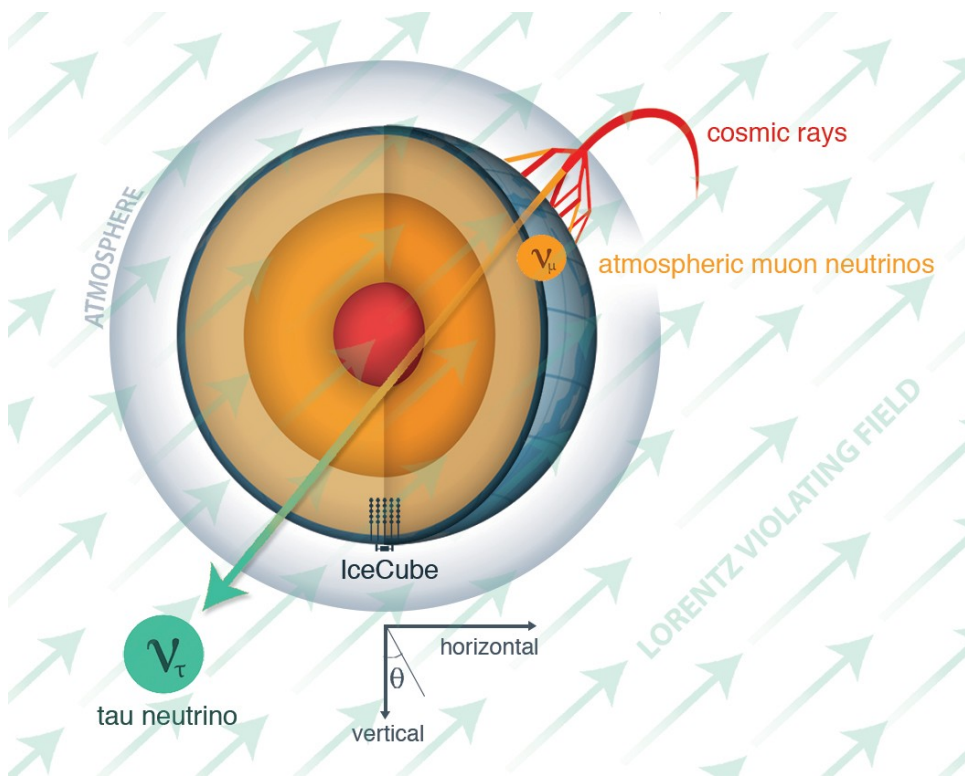


New physics in the energy & angular distribution

Standard oscillations

Lorentz violation

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



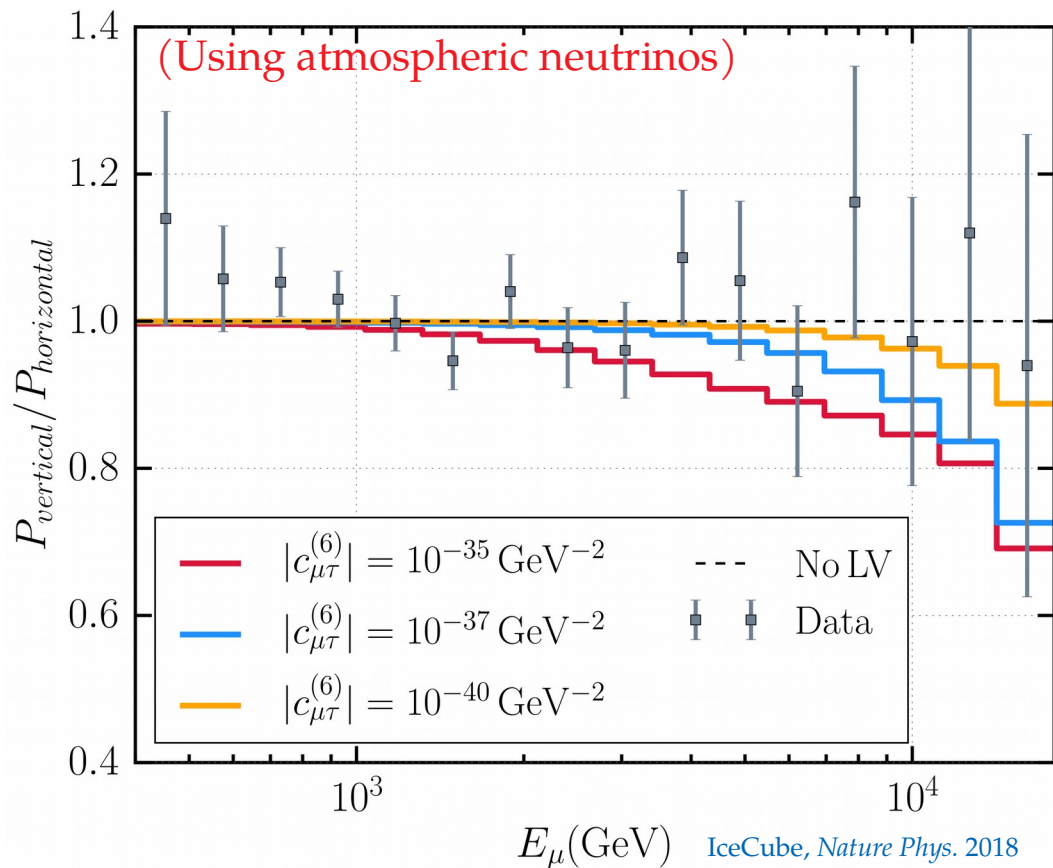
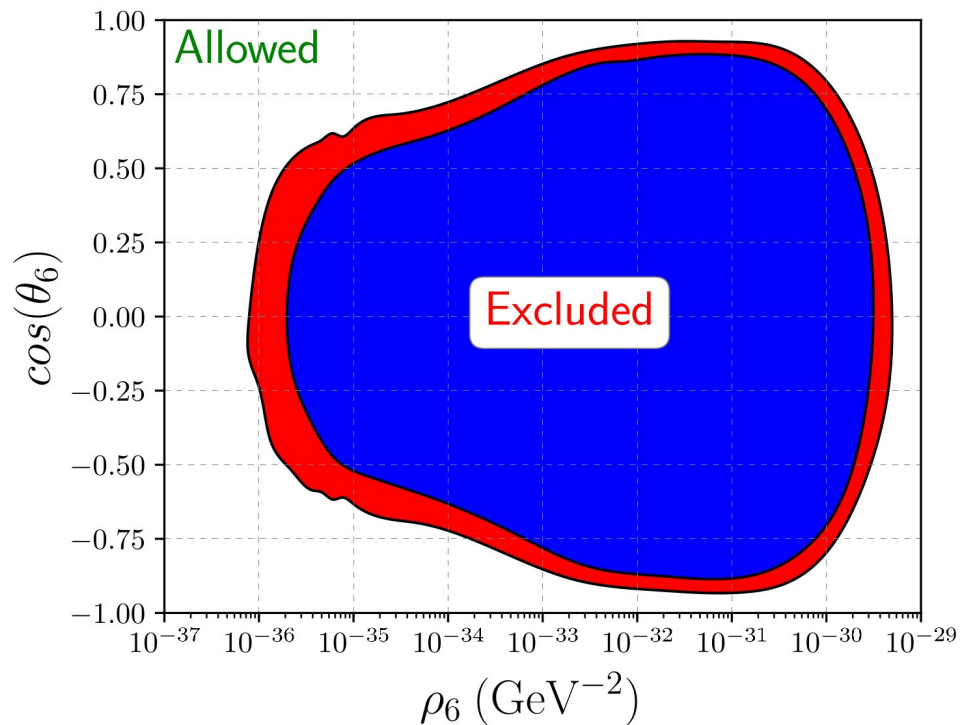
New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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

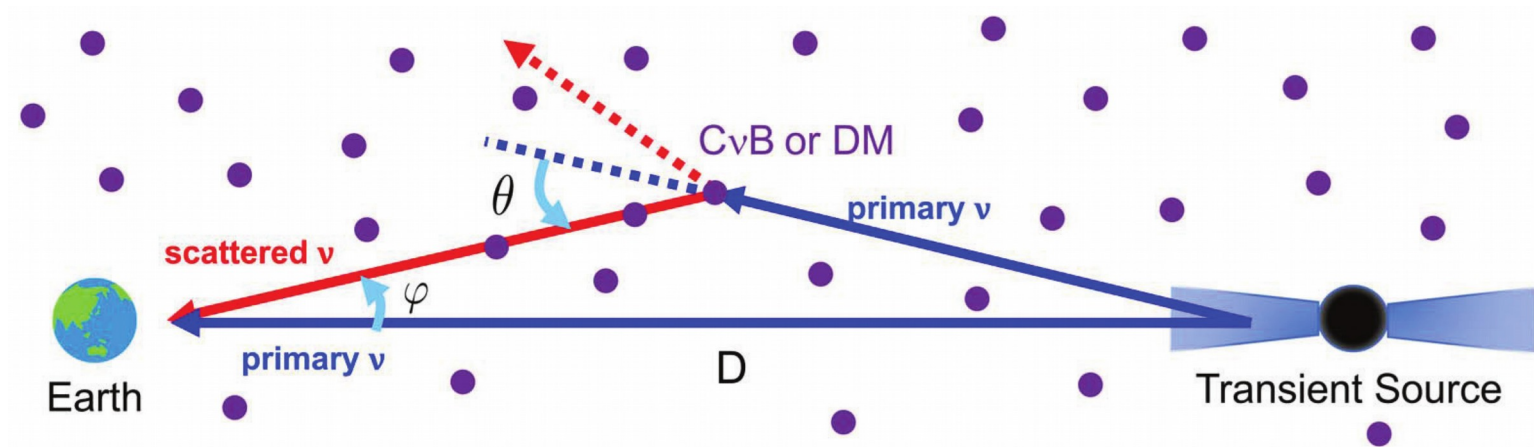
Best bounds come from IceCube



IceCube, Nature Phys. 2018

New physics in timing — TeV–PeV

Multiple secret $\nu\nu$ scatterings may delay the arrival of neutrinos from a transient



Shoemaker & Murase, 1903.08607

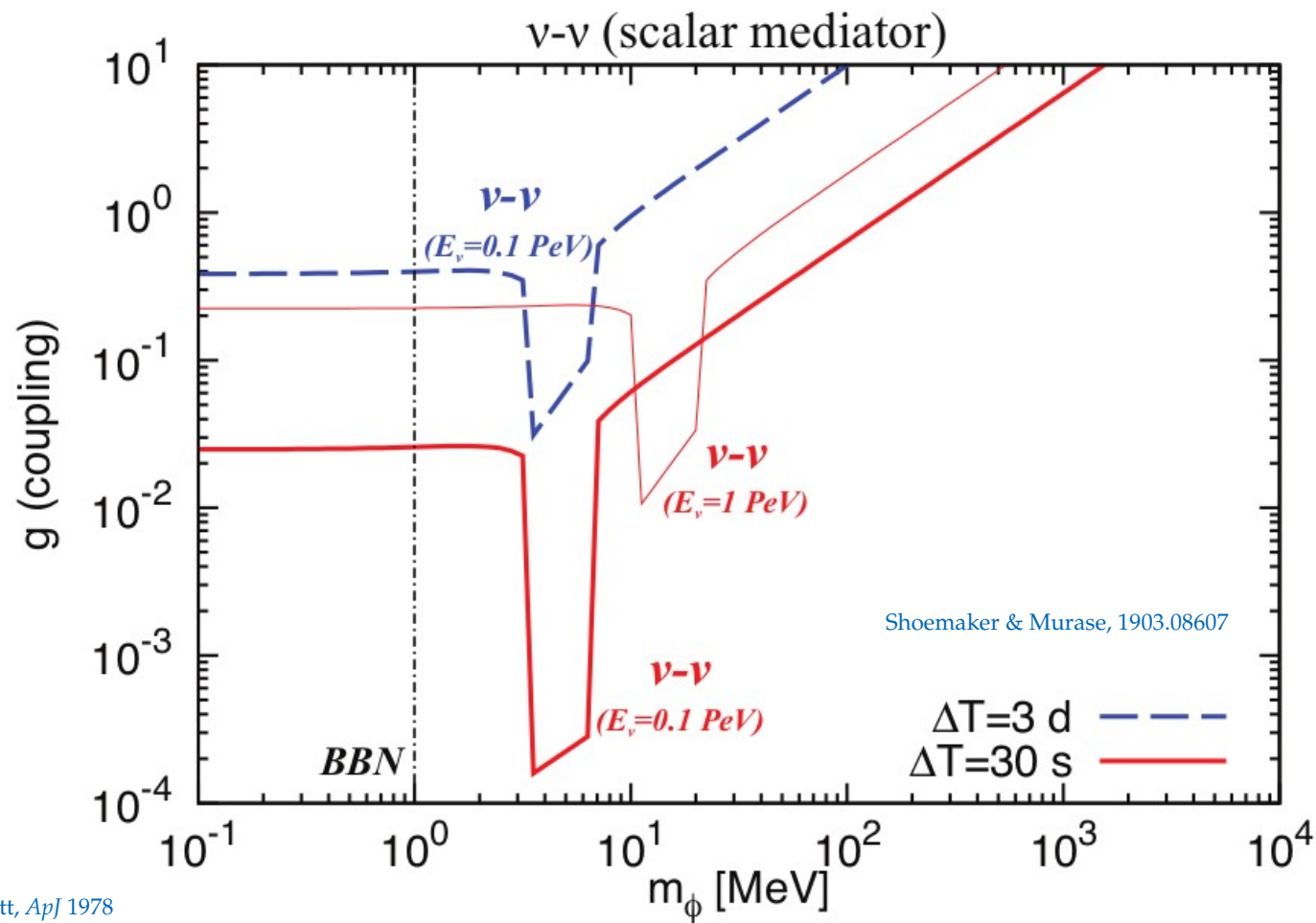
Characteristic time delay —

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

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

See also: Alcock & Hatchett, *ApJ* 1978

New physics in timing — TeV–PeV



See also: Alcock & Hatchett, *ApJ* 1978

Neutrino zenith angle distribution

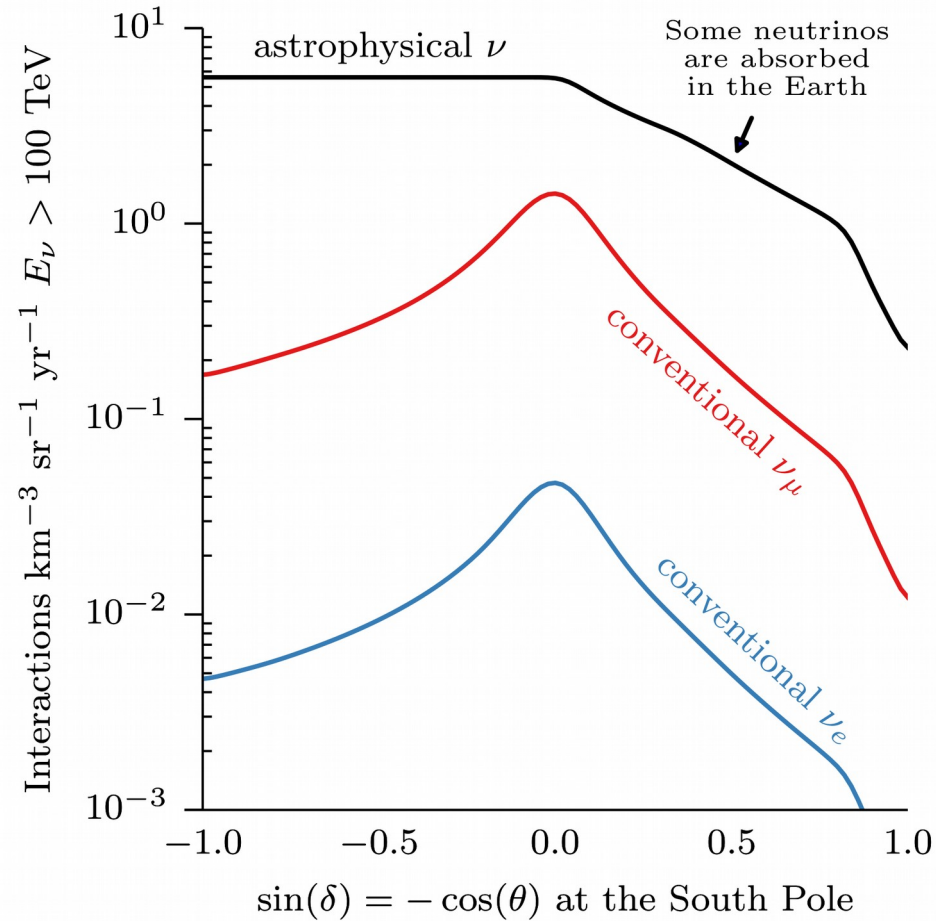
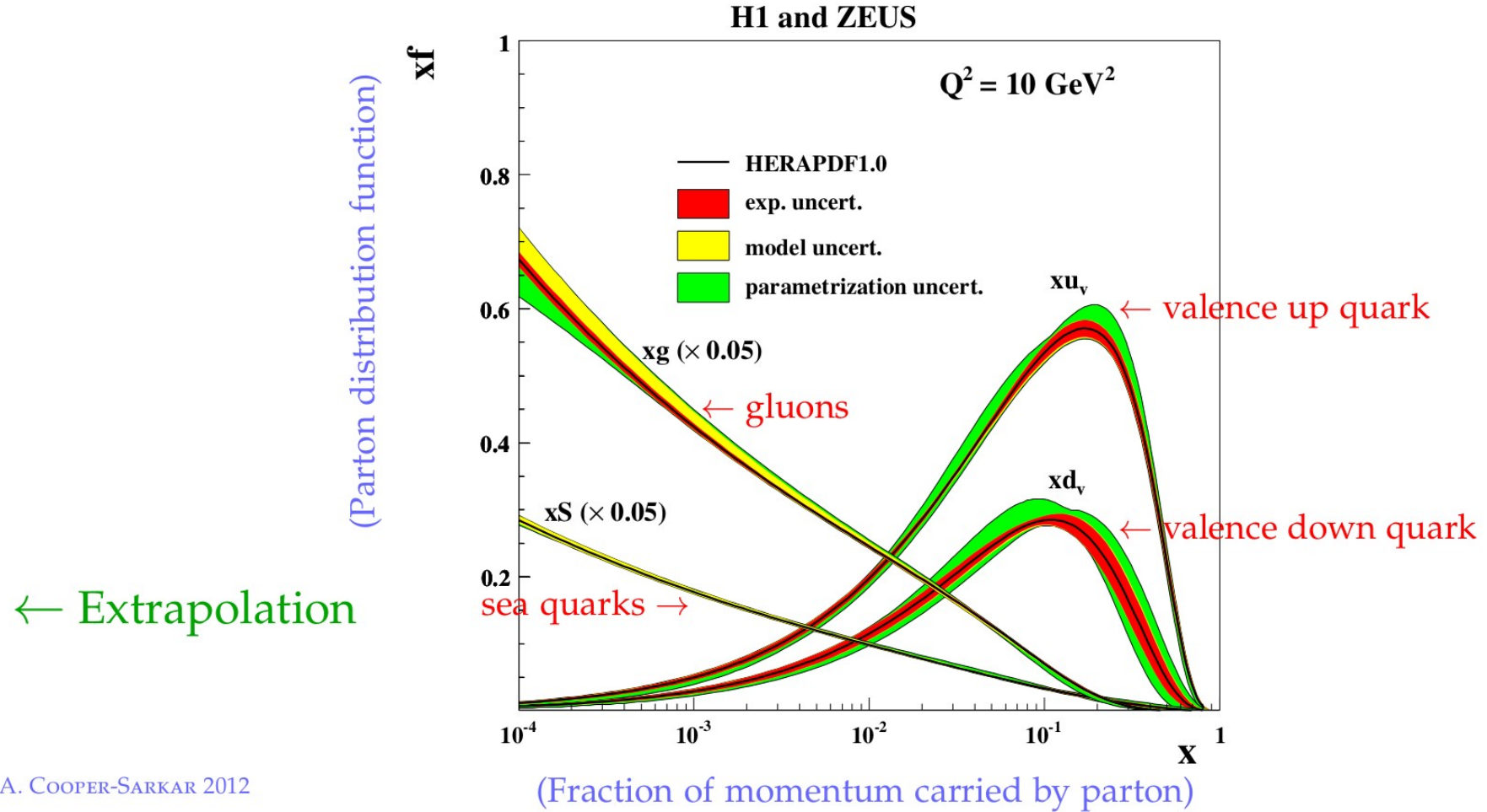


Figure by
Jakob Van Santen
ICRC 2017

Peeking inside a proton

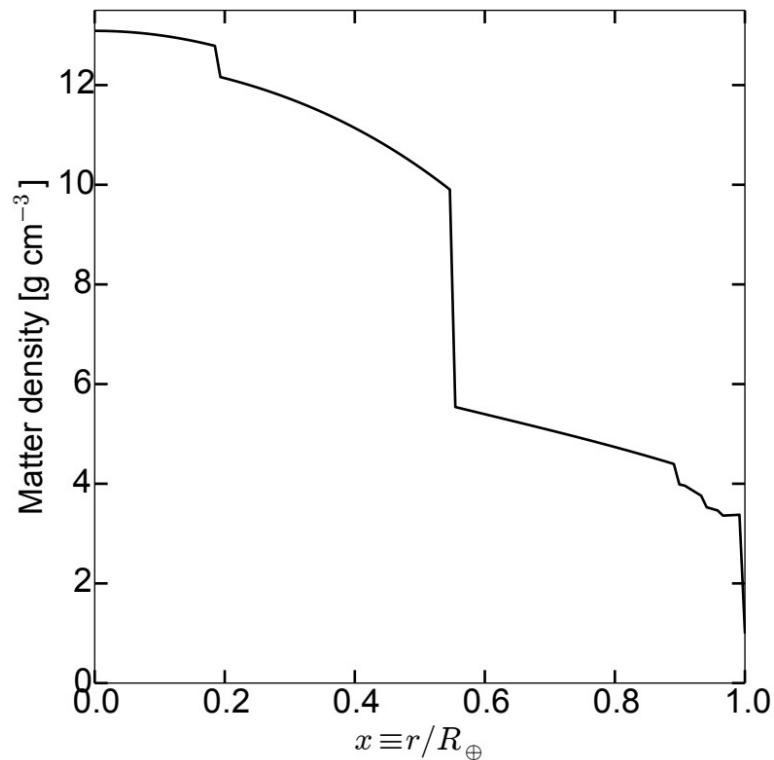


A. COOPER-SARKAR 2012

A feel for the in-Earth attenuation

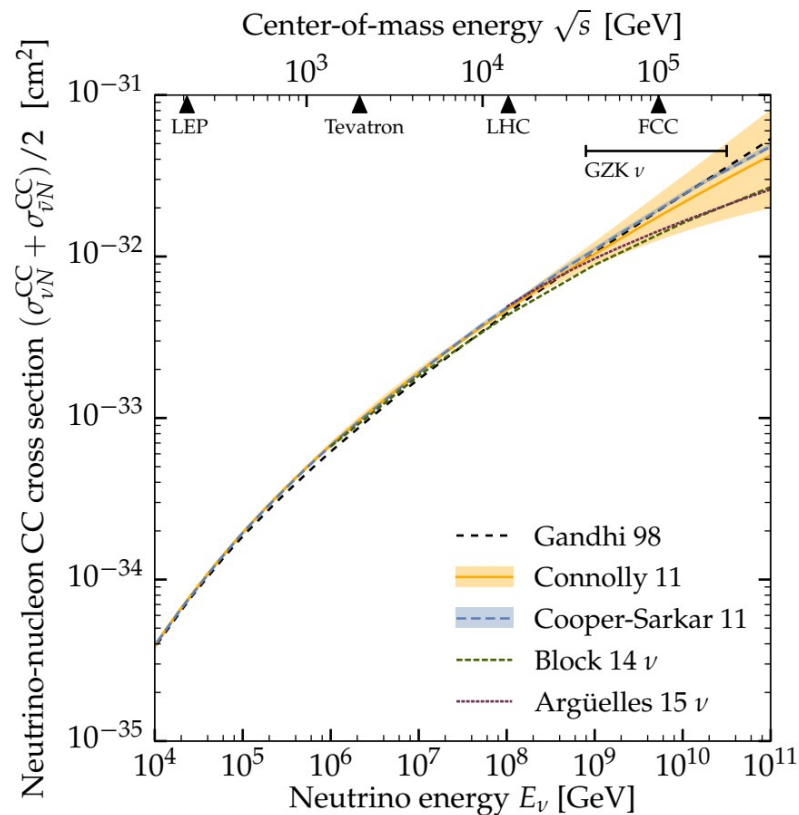
Earth matter density

(Preliminary Reference Earth Model)

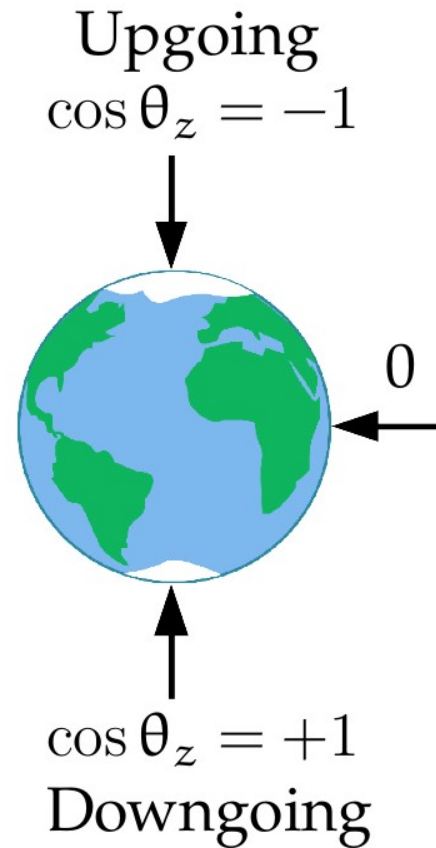
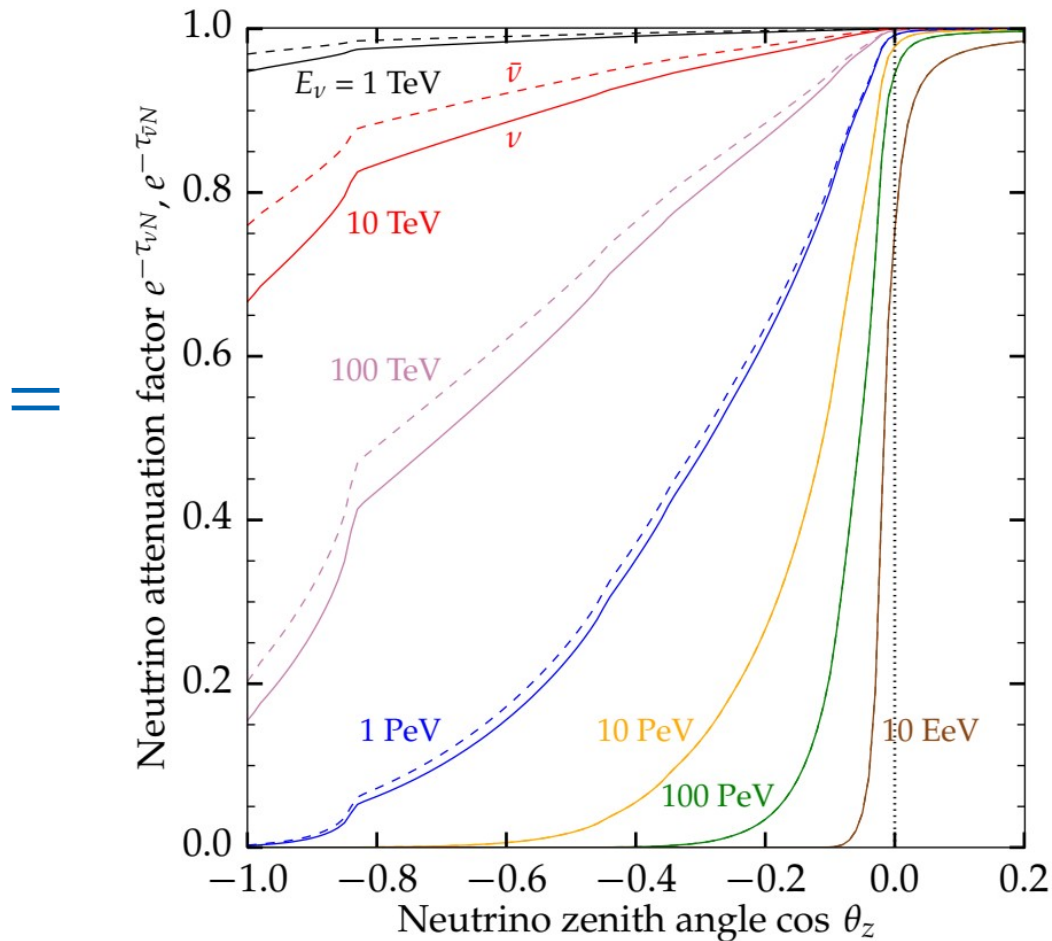


+

Neutrino-nucleon cross section



A feel for the in-Earth attenuation



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

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

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

Marginalized cross section in each bin

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

E_ν [TeV]	$\langle E_\nu \rangle$ [TeV]	$\langle \sigma_{\bar{\nu} N}^{\text{CC}} / \sigma_{\nu N}^{\text{CC}} \rangle$	$\log_{10}[\frac{1}{2}(\sigma_{\nu N}^{\text{CC}} + \sigma_{\bar{\nu} N}^{\text{CC}})/\text{cm}^2]$
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	$> -33.21 (1\sigma)$

MB & A. Connolly, 1711.11043

Energy and angular shower spectra

Rate from all flavors, CC + NC:

$$\frac{d^2 N_{\text{sh}}}{dE_{\text{sh}} d \cos \theta_z} = \frac{d^2 N_{\text{sh},e}^{\text{CC}}}{dE_{\text{sh}} d \cos \theta_z} + \text{Br}_{\tau \rightarrow \text{sh}} \frac{d^2 N_{\text{sh},\tau}^{\text{CC}}}{dE_{\text{sh}} d \cos \theta_z} + \sum_{l=e,\mu,\tau} \frac{d^2 N_{\text{sh},l}^{\text{NC}}}{dE_{\text{sh}} d \cos \theta_z}$$

$\text{Br}_{\tau \rightarrow \text{sh}} = 0.83$

Contribution from one flavor CC:

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

Conversion between shower energy and neutrino energy:

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

MB & A. Connolly, 1711.11043

Detector resolution

Number of contained showers:

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

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

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

IceCube, *JINST* 2014

Angular resolution:

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

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

MB & A. Connolly, 1711.11043

Likelihood

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

Each energy bin is independent

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

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

Depends on $\sigma_{\nu N}$

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

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

PDF for this shower to be made by an atmospheric ν

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

PDF for this shower to be made by an astrophysical ν

Depends on γ and $\sigma_{\nu N}$

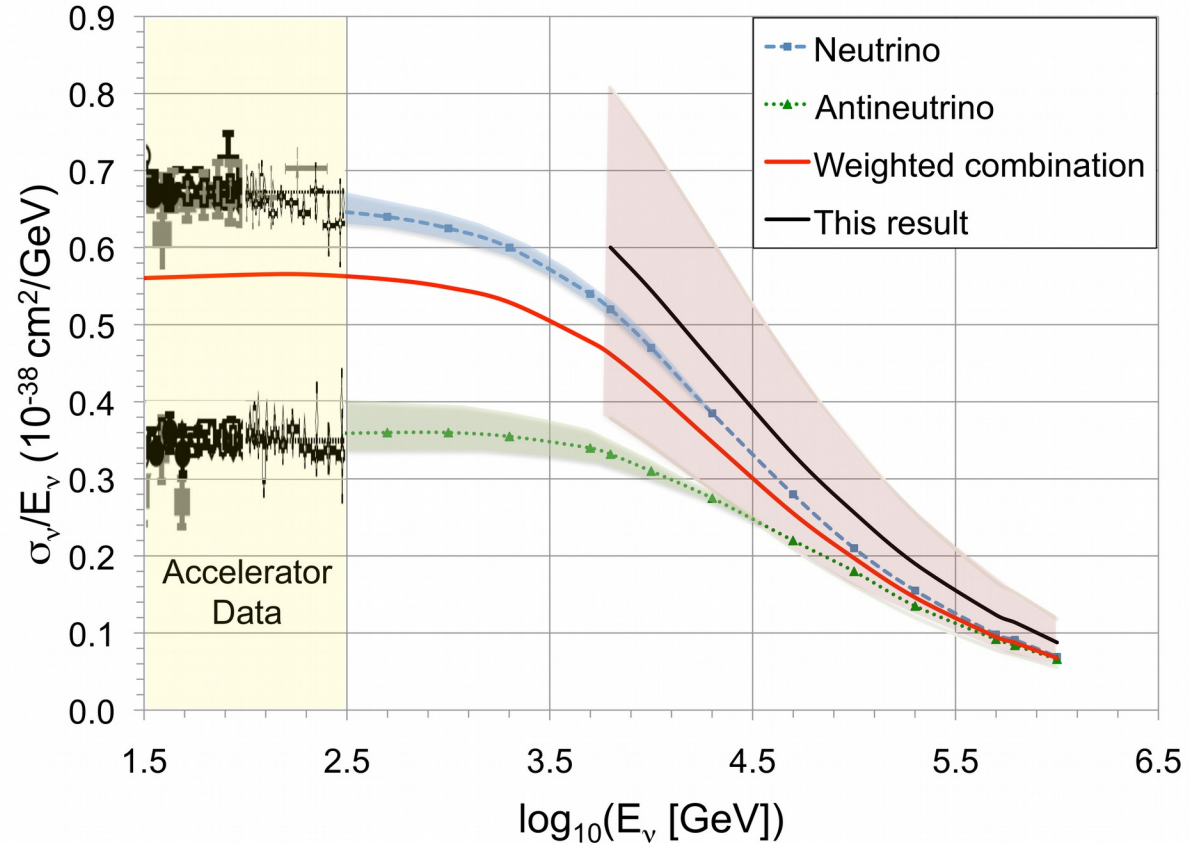
MB & A. Connolly, 1711.11043

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

Mauricio Bustamante (Niels Bohr Institute)

Using through-going muons instead

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



IceCube, Nature 2017

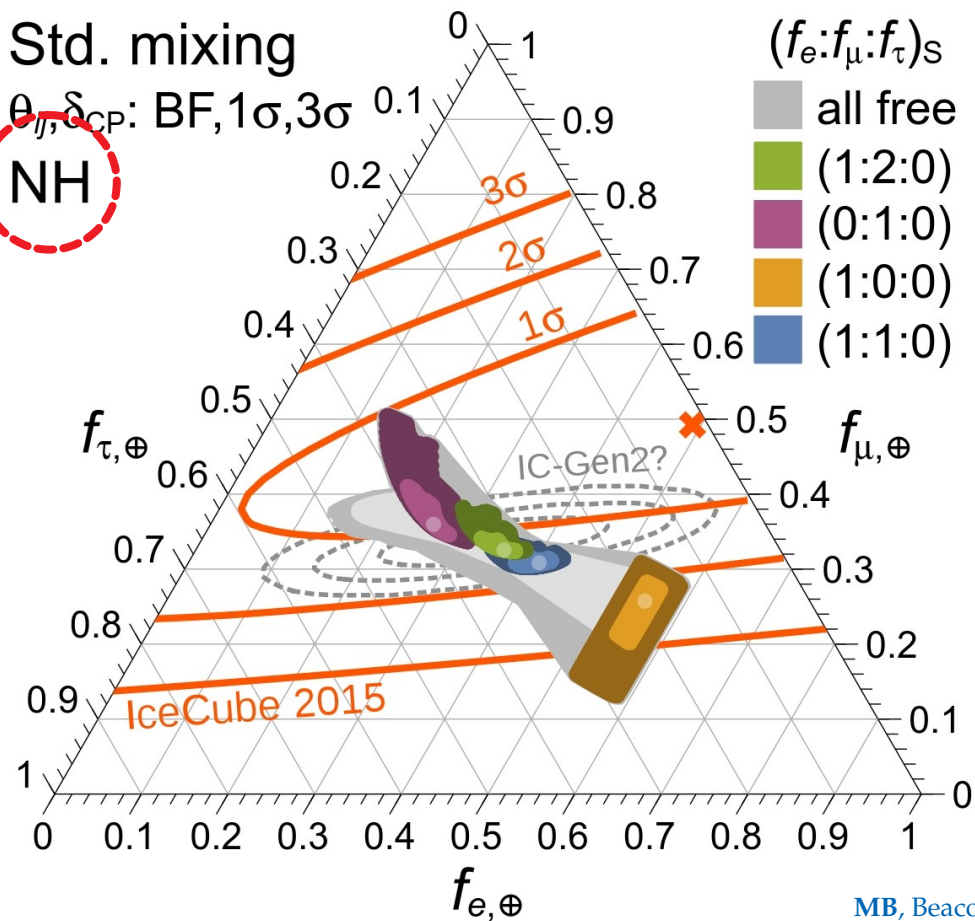
Flavor composition – a few source choices

Flavor composition – a few source choices

Std. mixing

θ_{12}, δ_{CP} : BF, $1\sigma, 3\sigma$

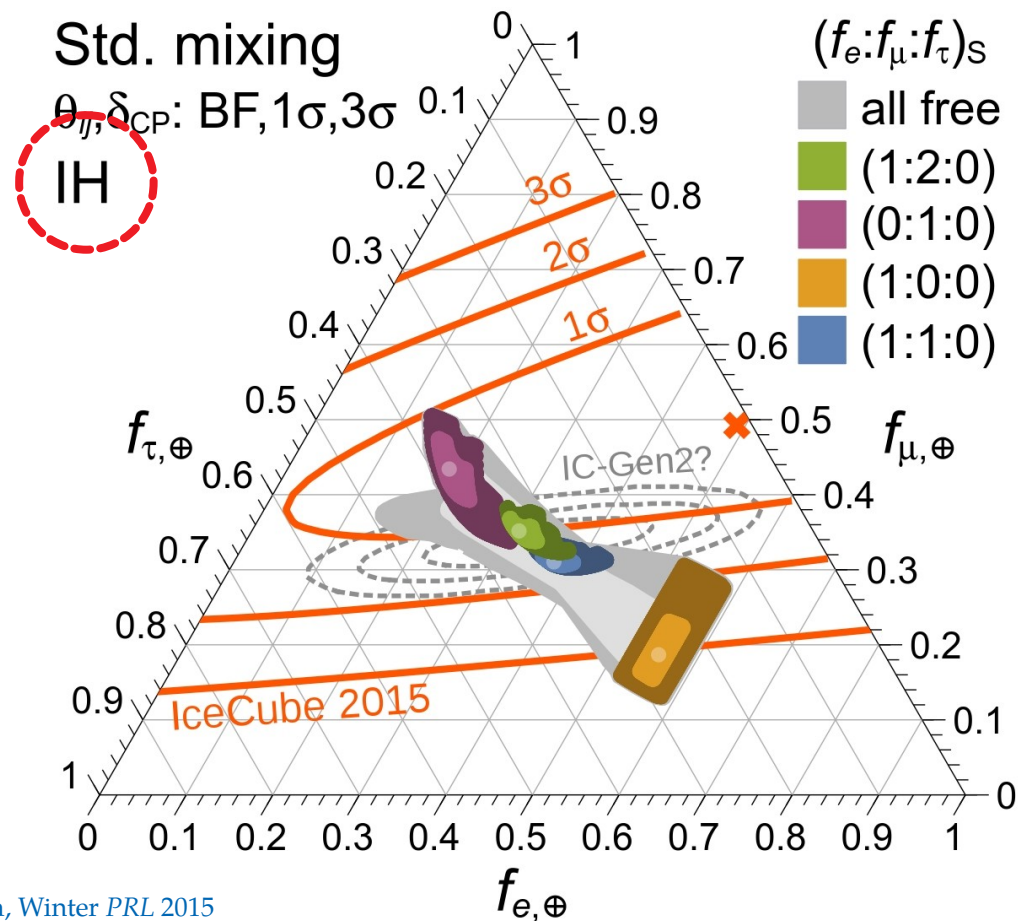
NH



Std. mixing

θ_{12}, δ_{CP} : BF, $1\sigma, 3\sigma$

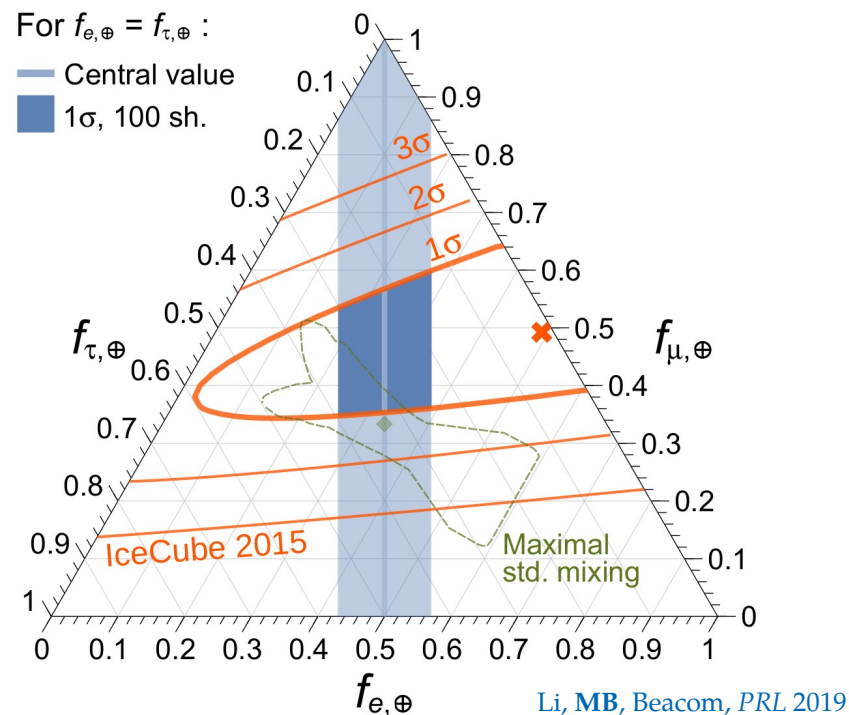
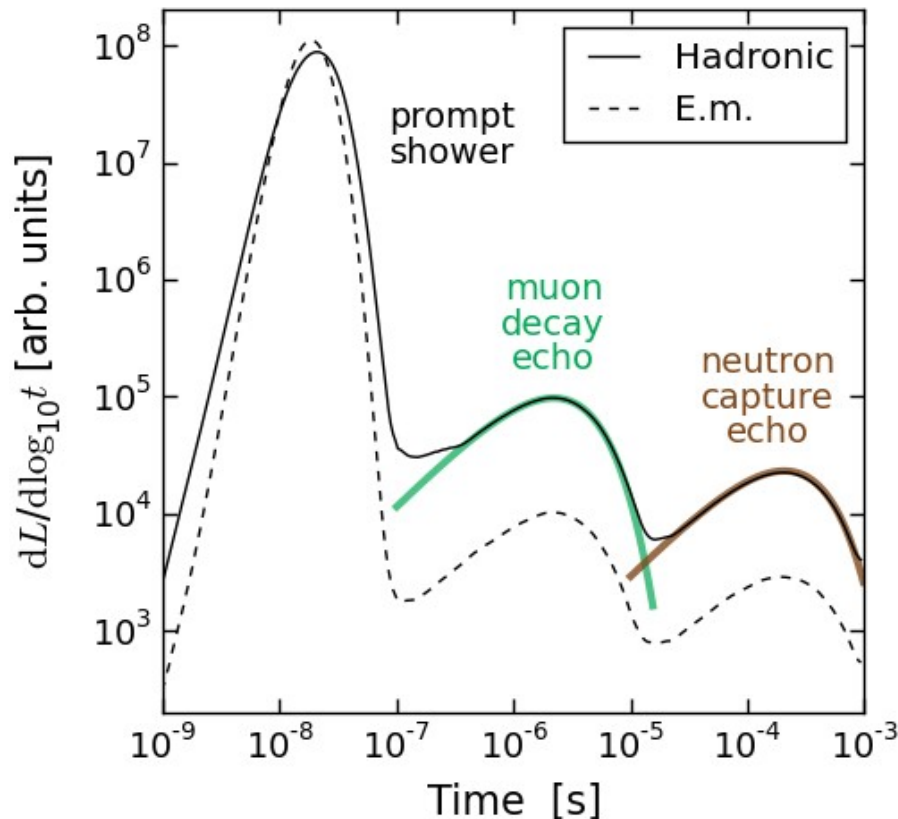
IH



MB, Beacom, Winter PRL 2015

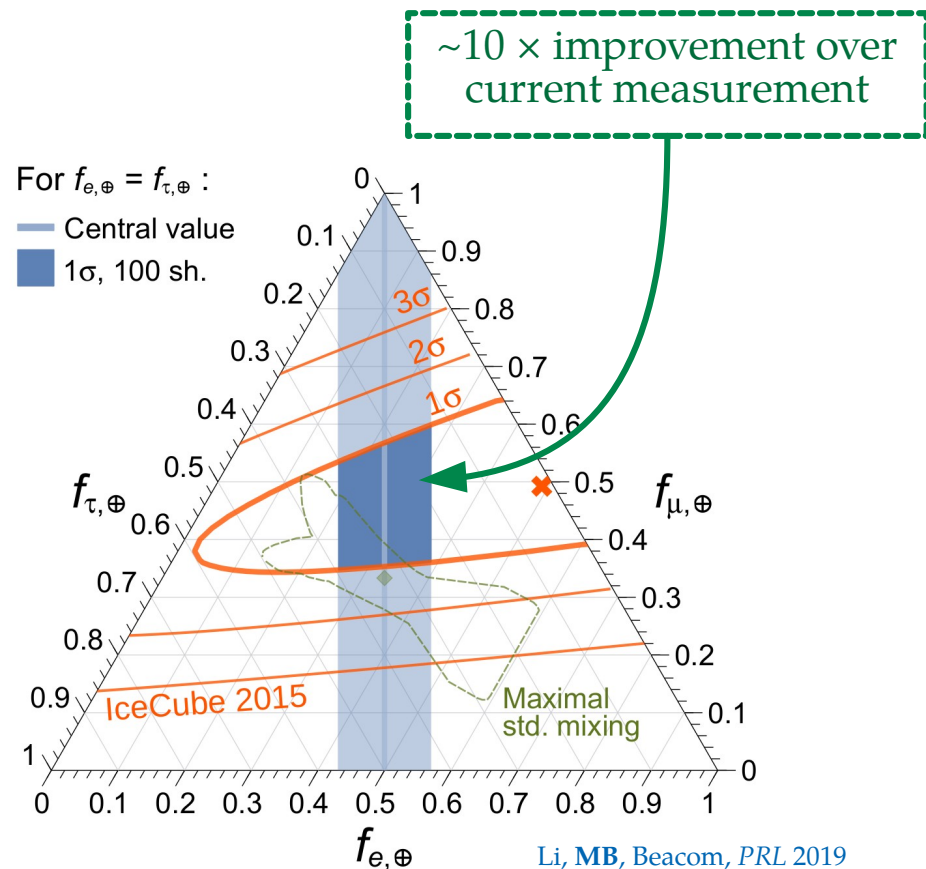
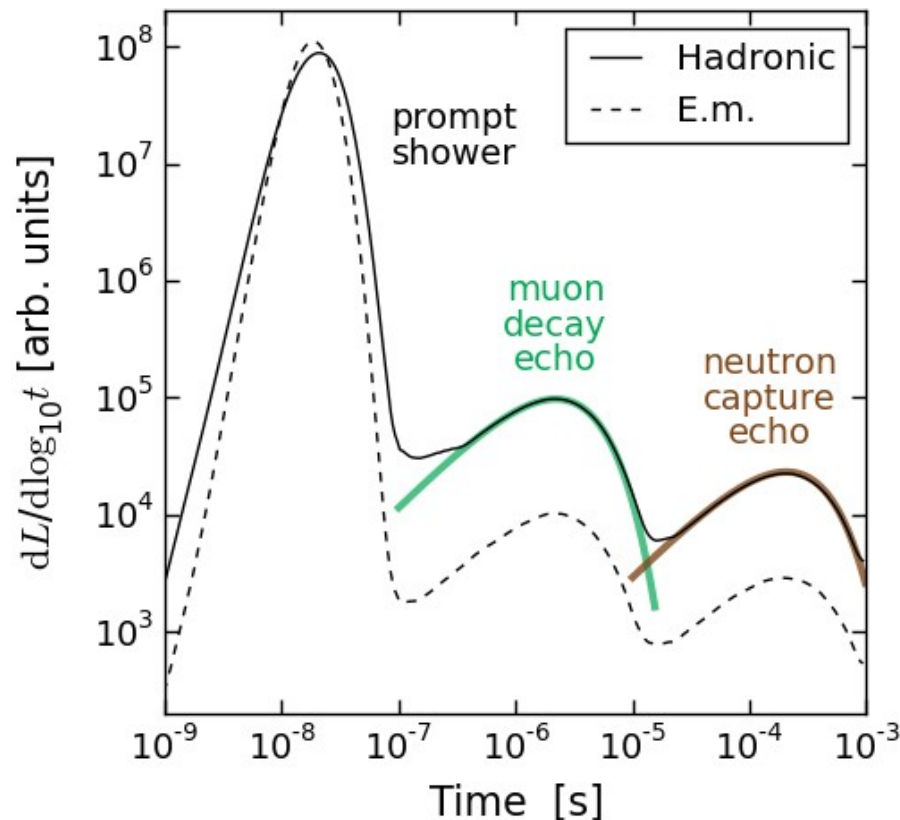
Side note: Improving flavor-tagging using *echoes*

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



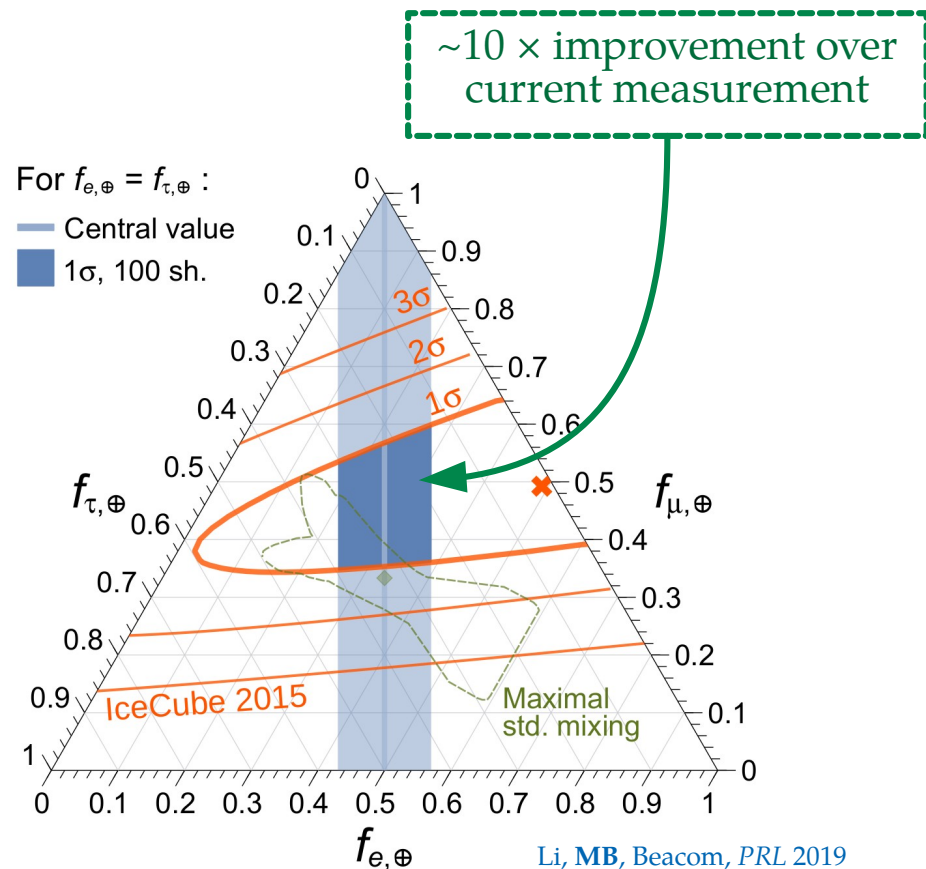
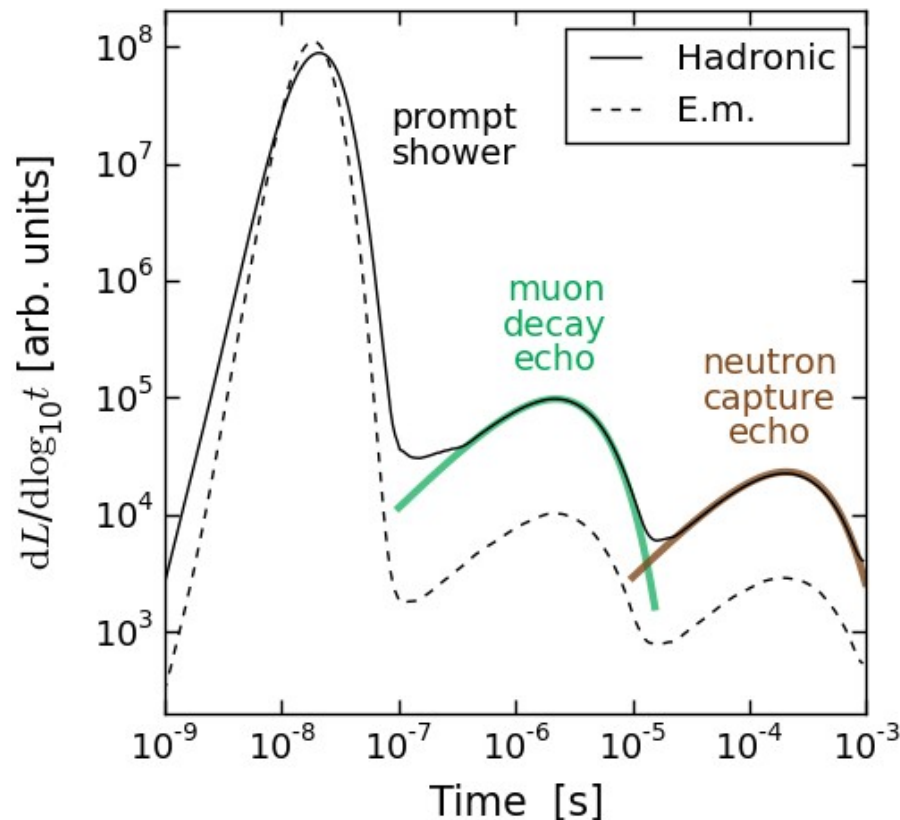
Side note: Improving flavor-tagging using *echoes*

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

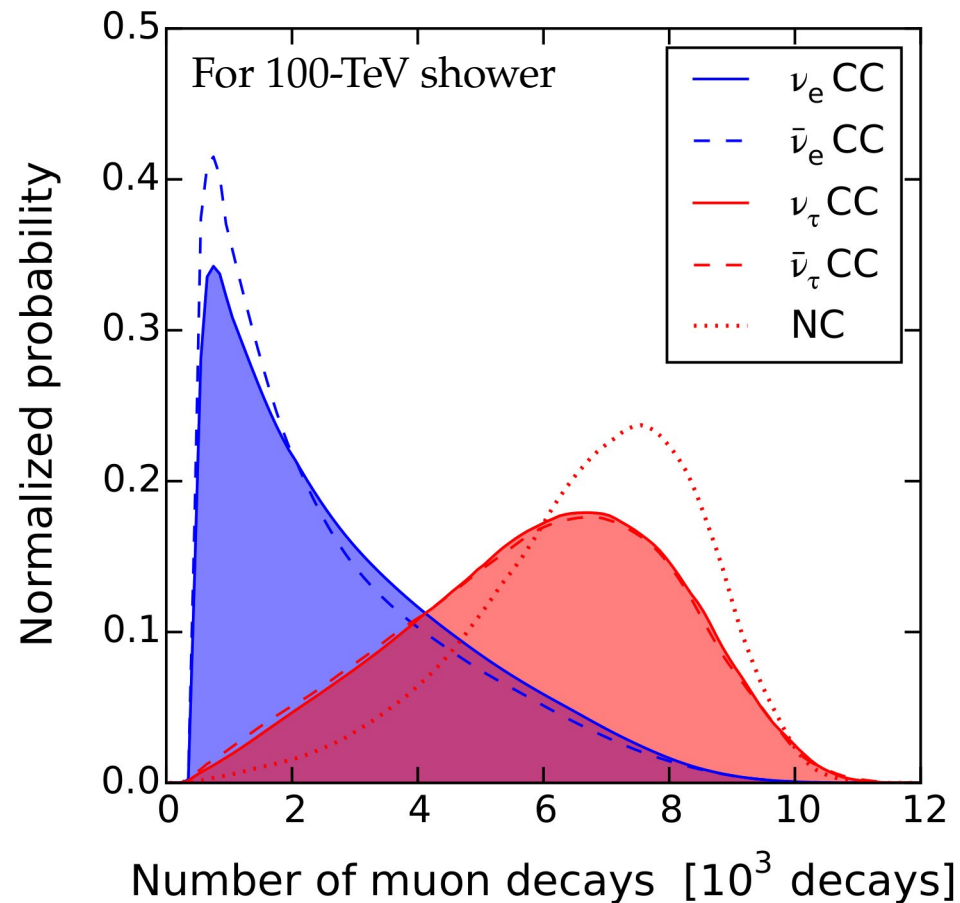
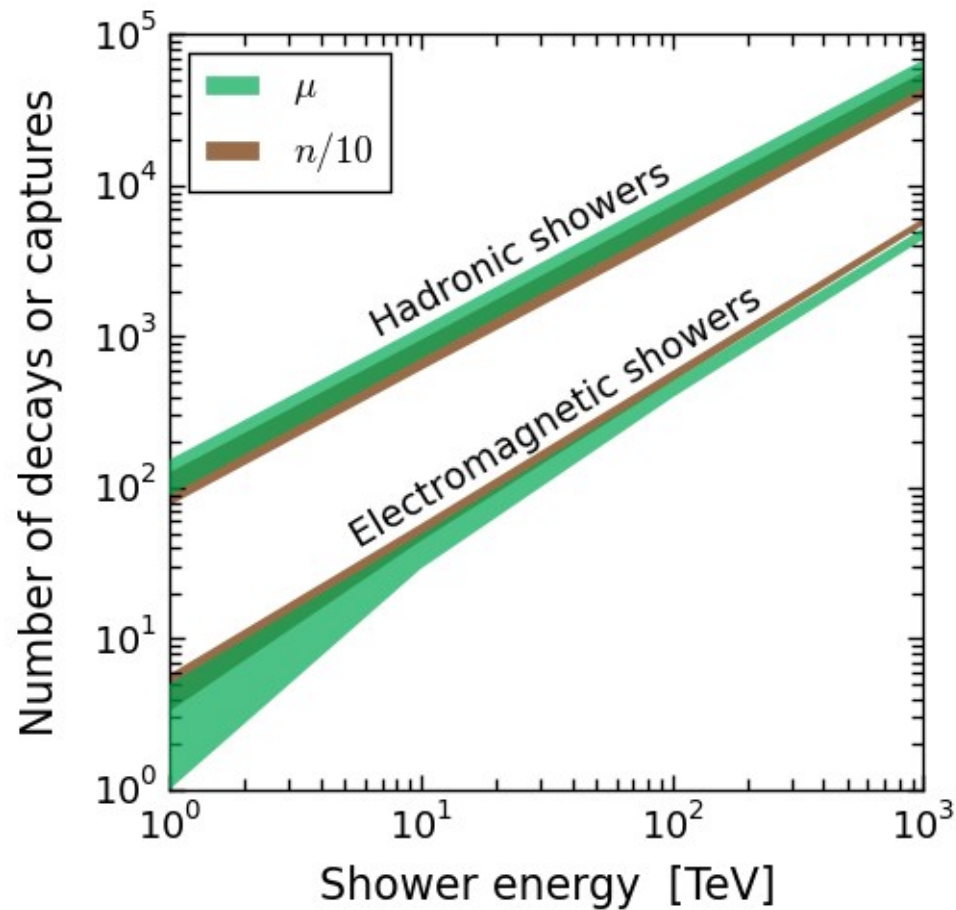


Side note: Improving flavor-tagging using *echoes*

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

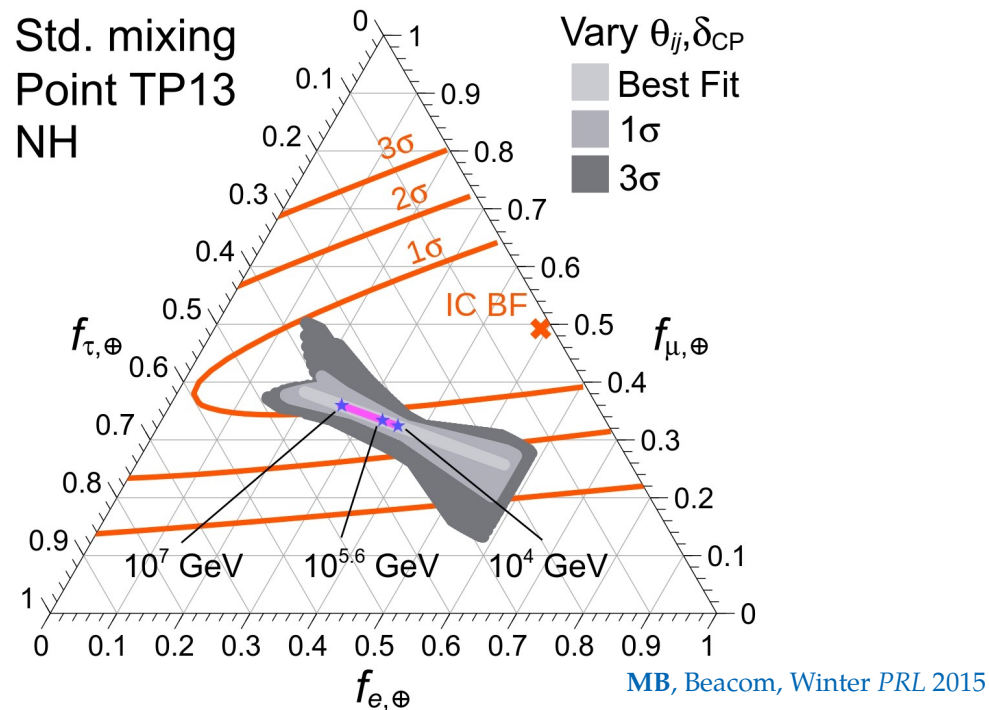
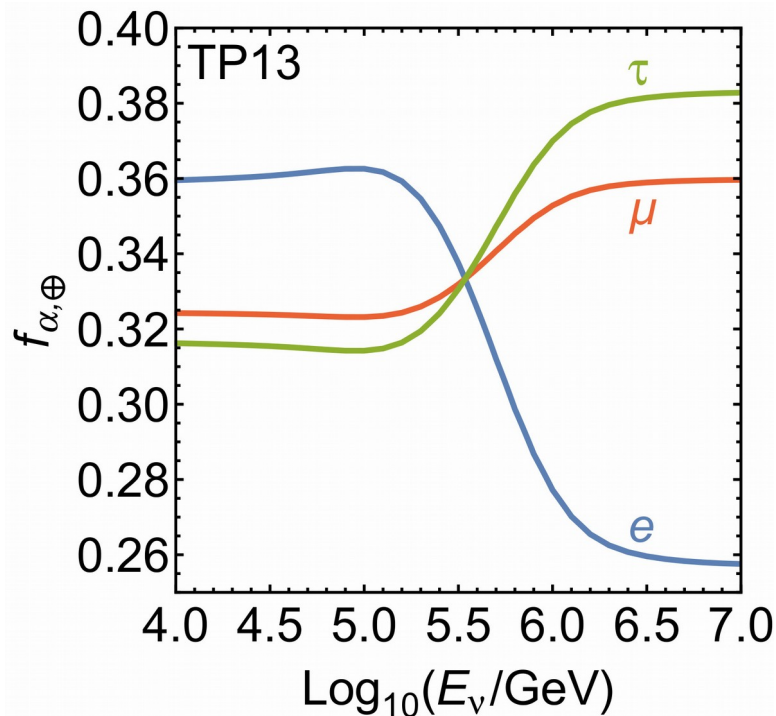


Hadronic *vs.* electromagnetic showers



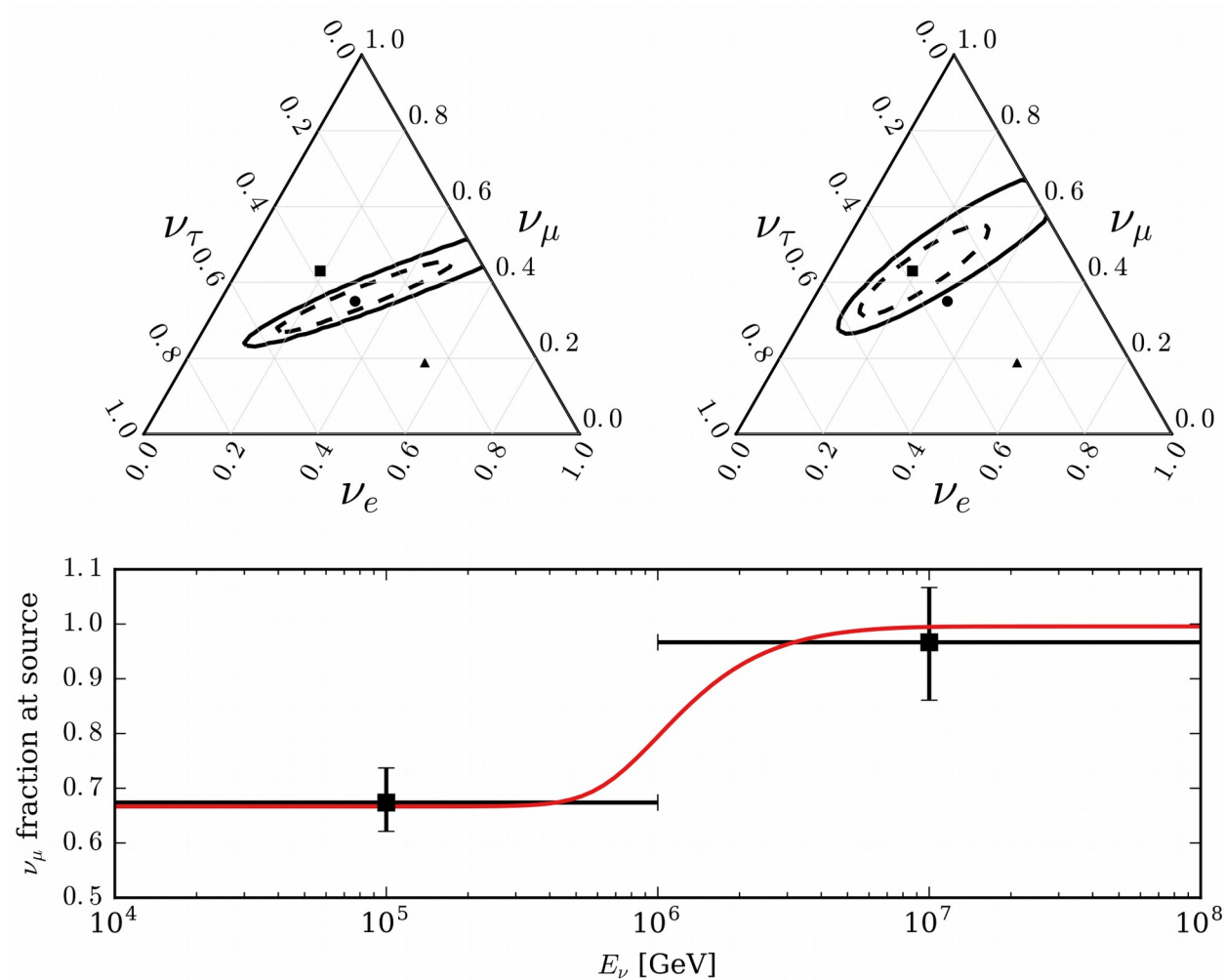
Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –



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

... Observable in IceCube-Gen2?



Borrowed from M. Kowalski

Flavor content of neutrino mass eigenstates

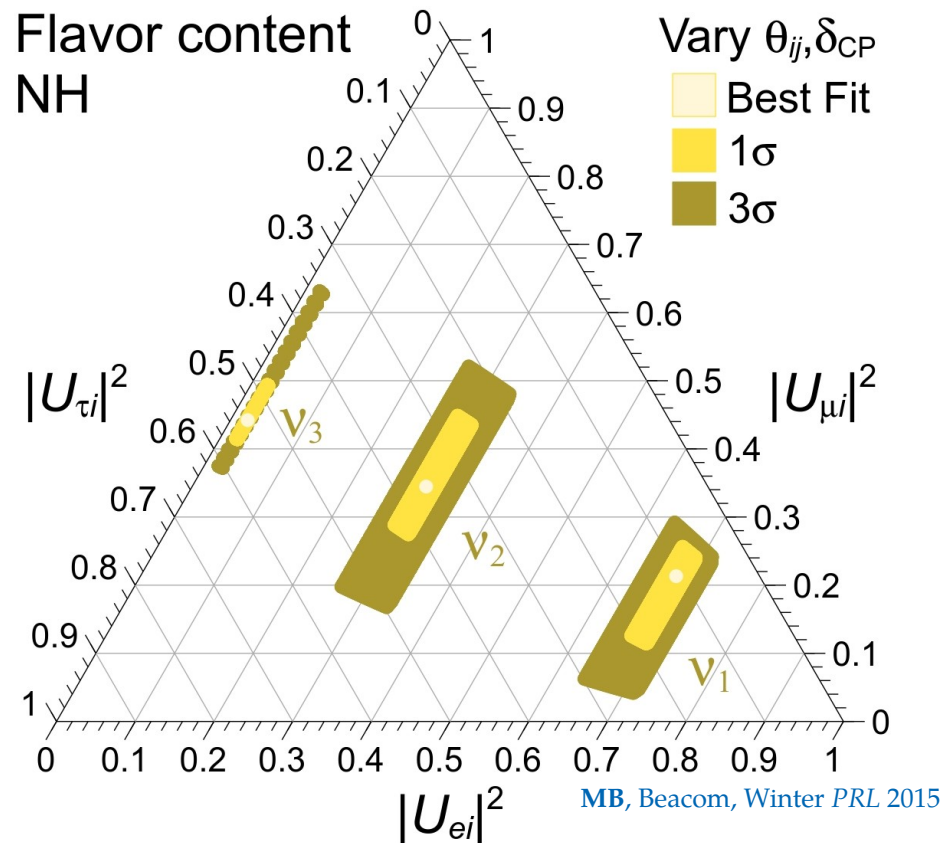
Flavor content for every allowed combination of mixing parameters –

Known to within 2%

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

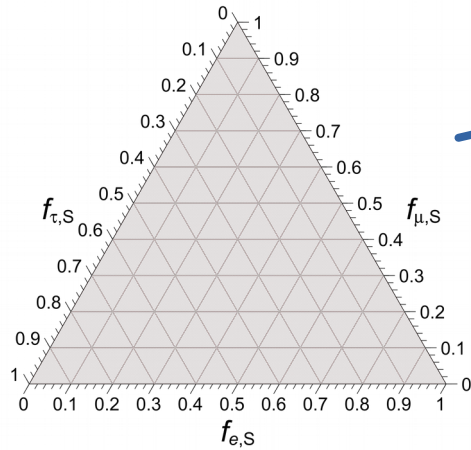
Known to within 8%

Known to within 20%
(or worse)



Measuring the neutrino lifetime

Sources

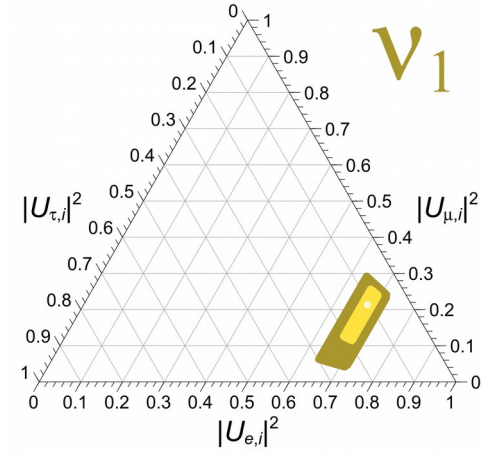


$\nu_2, \nu_3 \rightarrow \nu_1$
 ν_1 lightest and stable

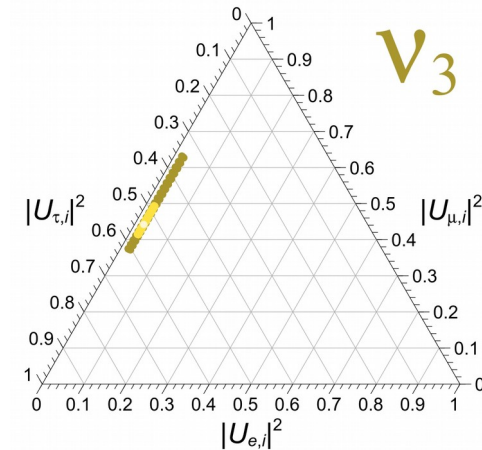
If all unstable
neutrinos decay

$\nu_1, \nu_2 \rightarrow \nu_3$
 ν_3 lightest and stable

Earth



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



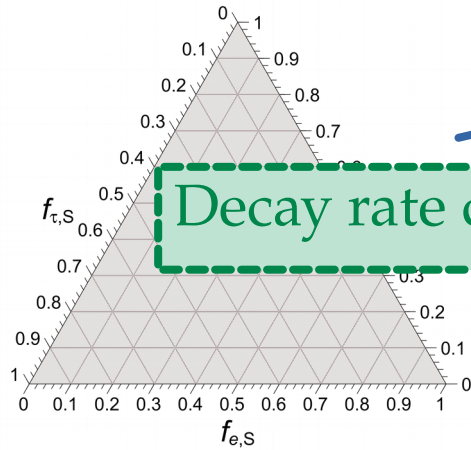
$$f_{\alpha,\oplus} = |U_{\alpha 3}|^2$$

Measuring the neutrino lifetime

Earth

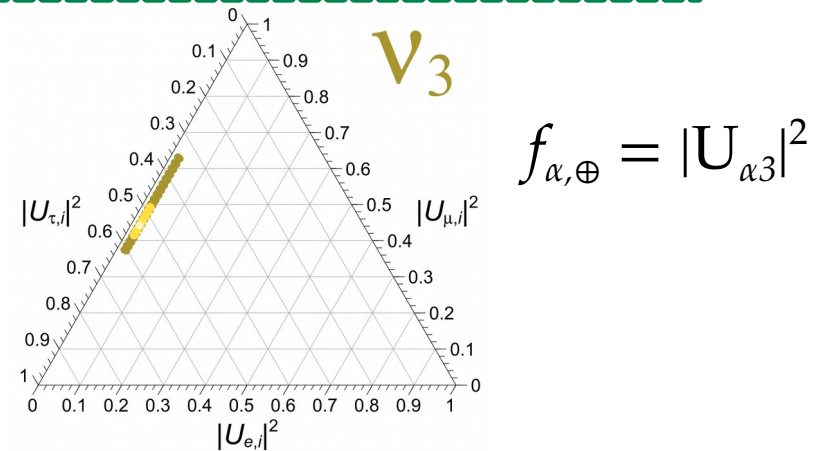
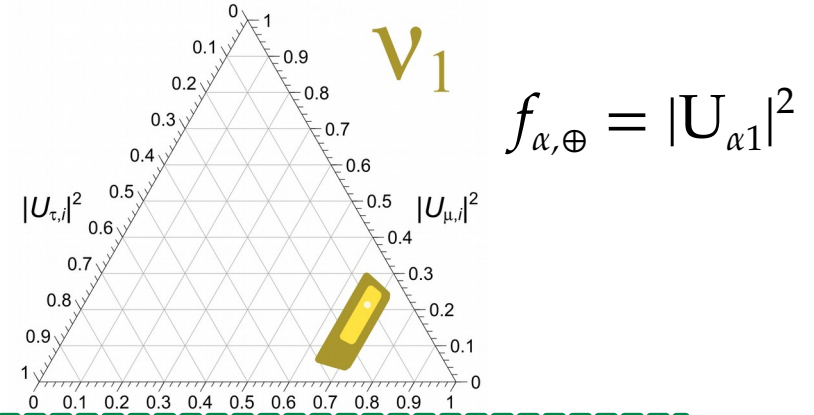
Sources

$\nu_2, \nu_3 \rightarrow \nu_1$
 ν_1 lightest and stable



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

$\nu_1, \nu_2 \rightarrow \nu_3$
 ν_3 lightest and stable



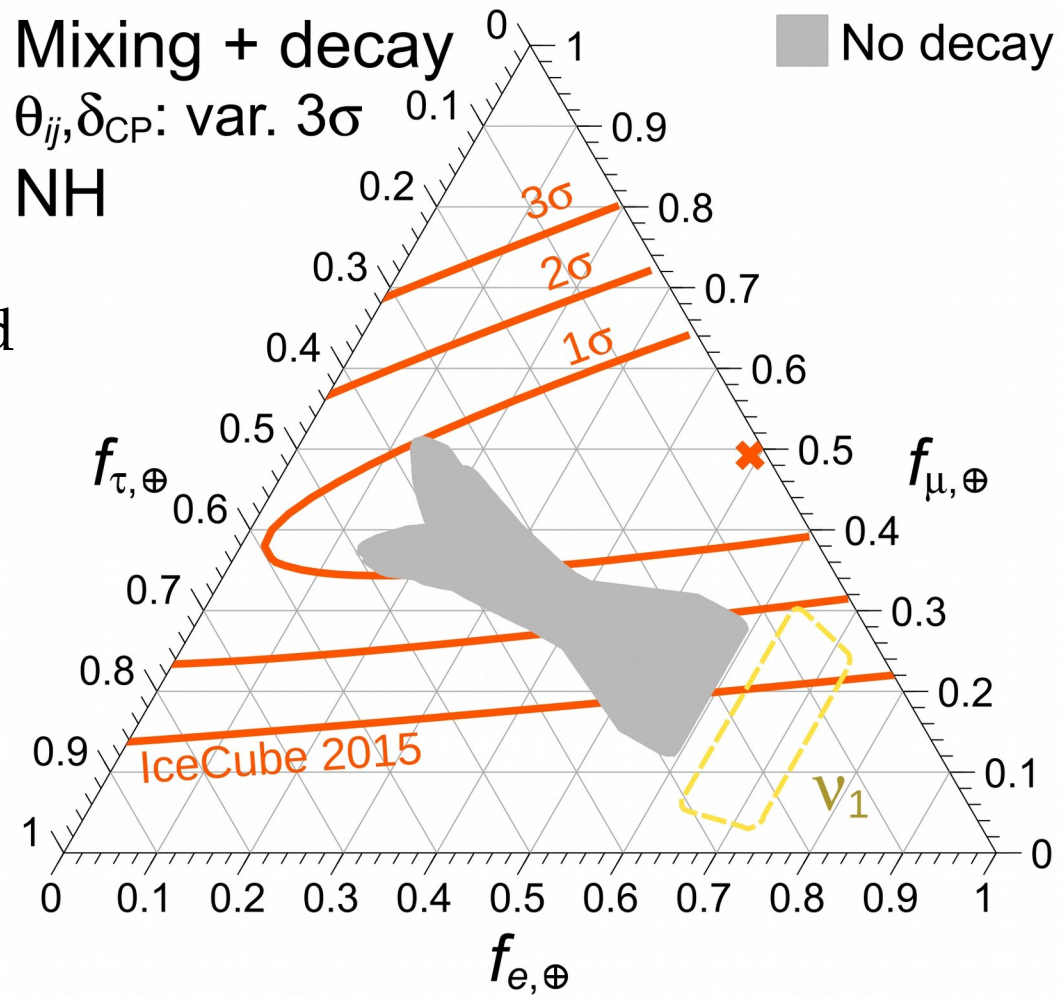
Measuring the neutrino lifetime

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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

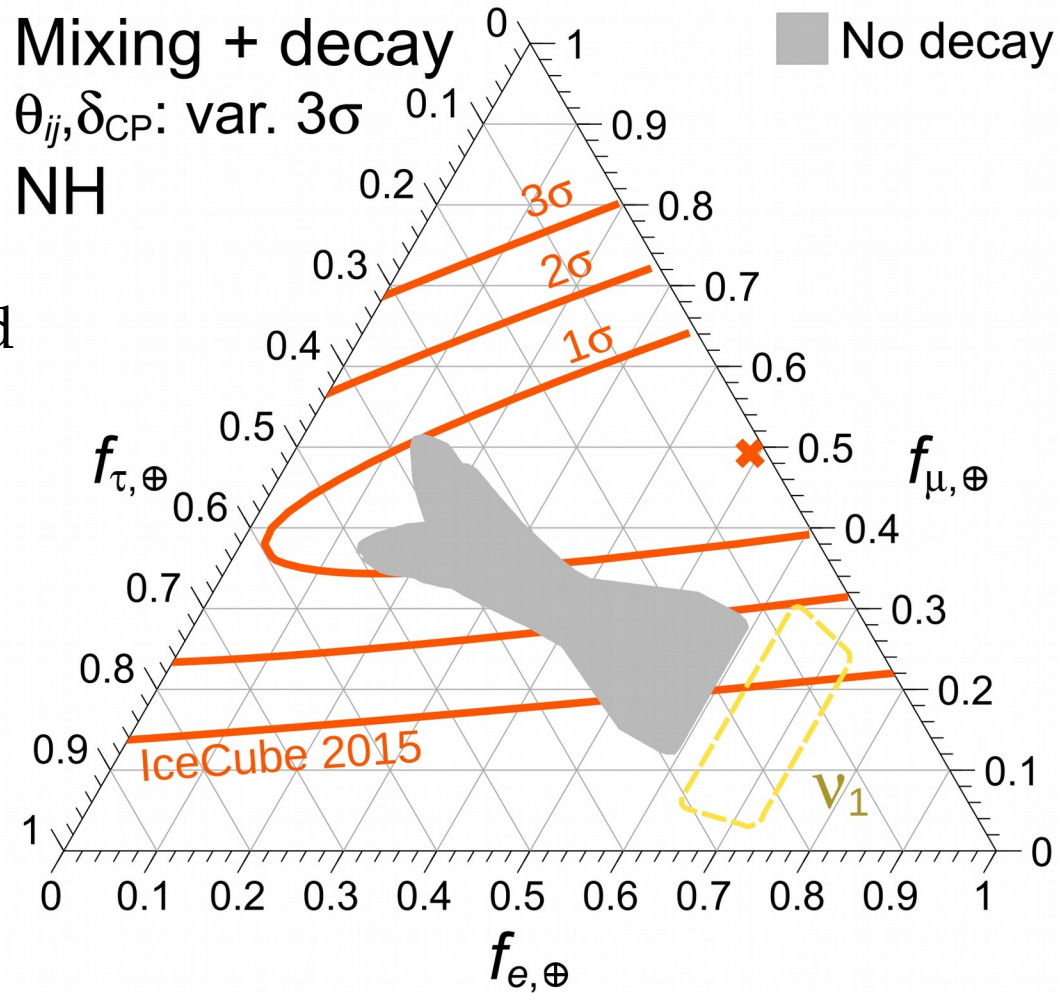


Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- ▶ 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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

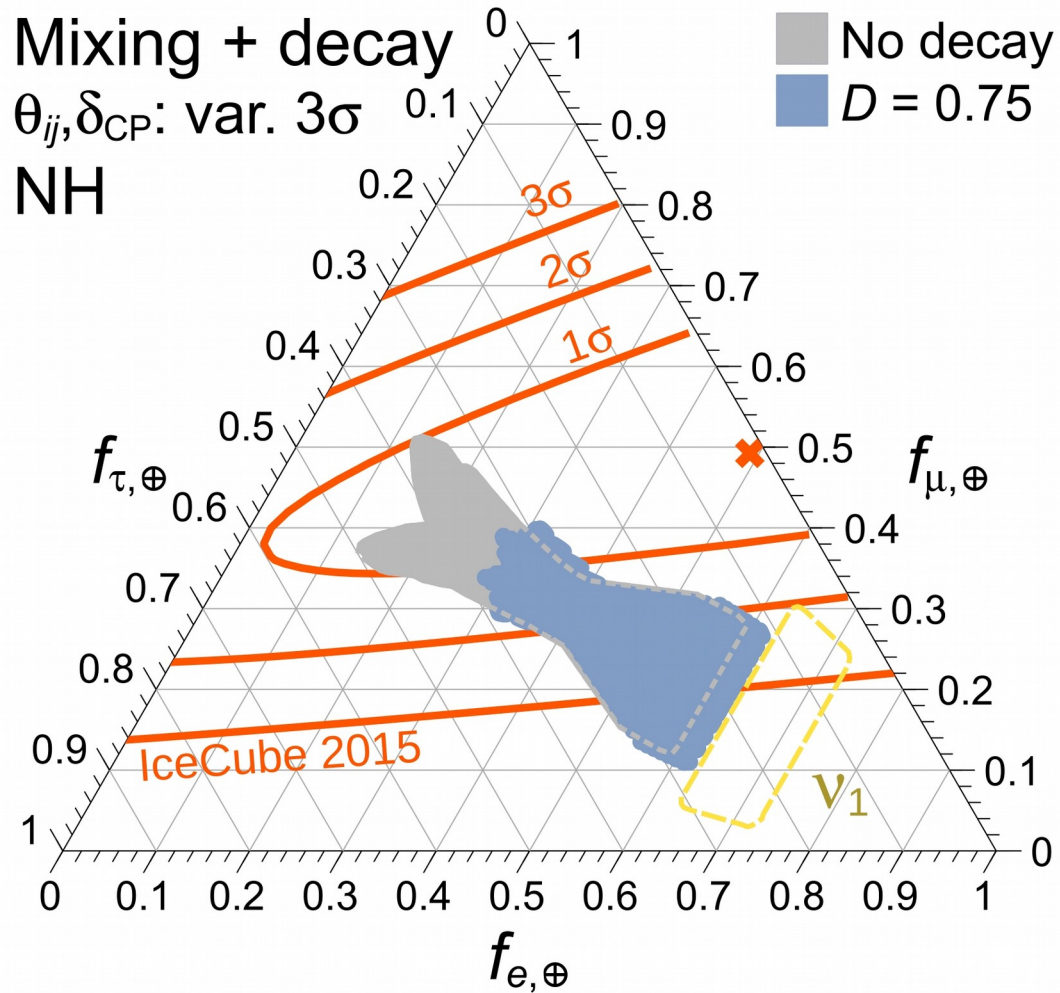


Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- ▶ 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



Measuring the neutrino lifetime

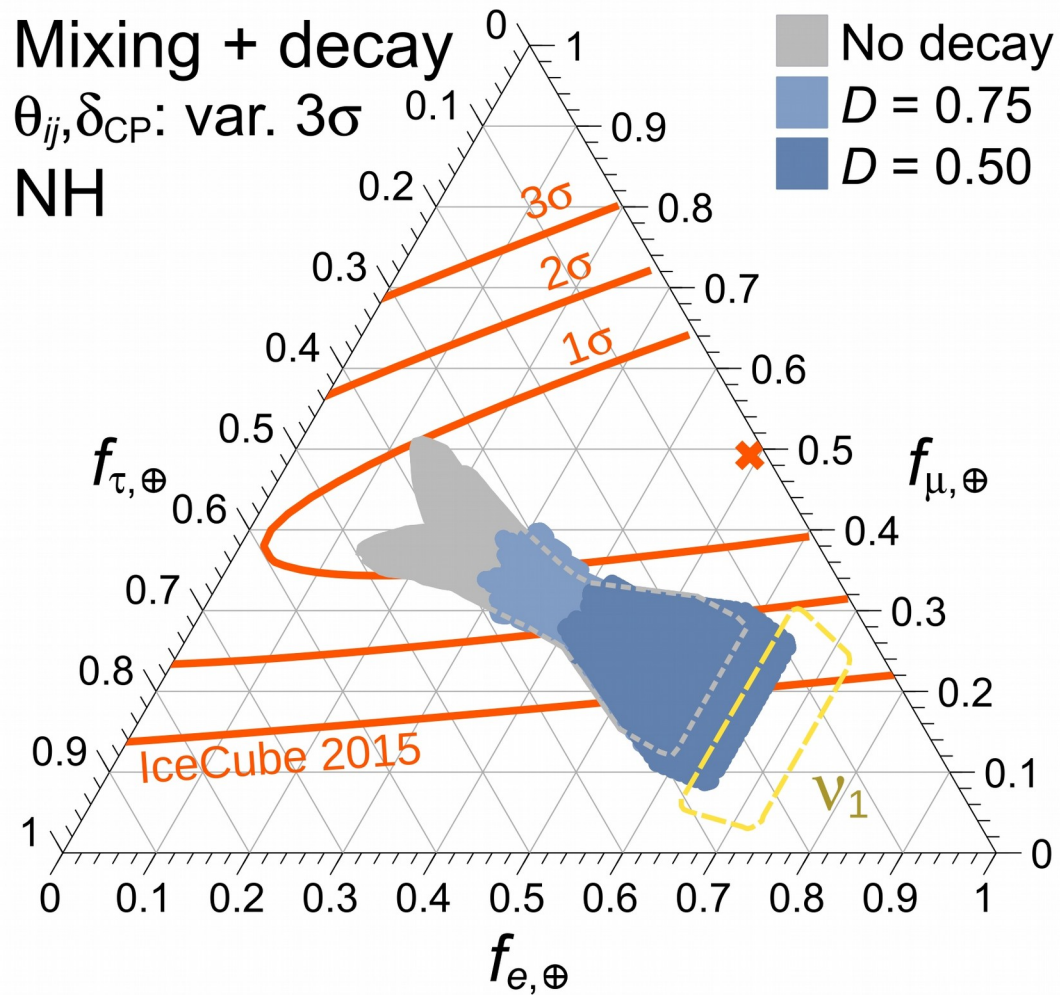
Fraction of ν_2, ν_3 remaining at Earth

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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

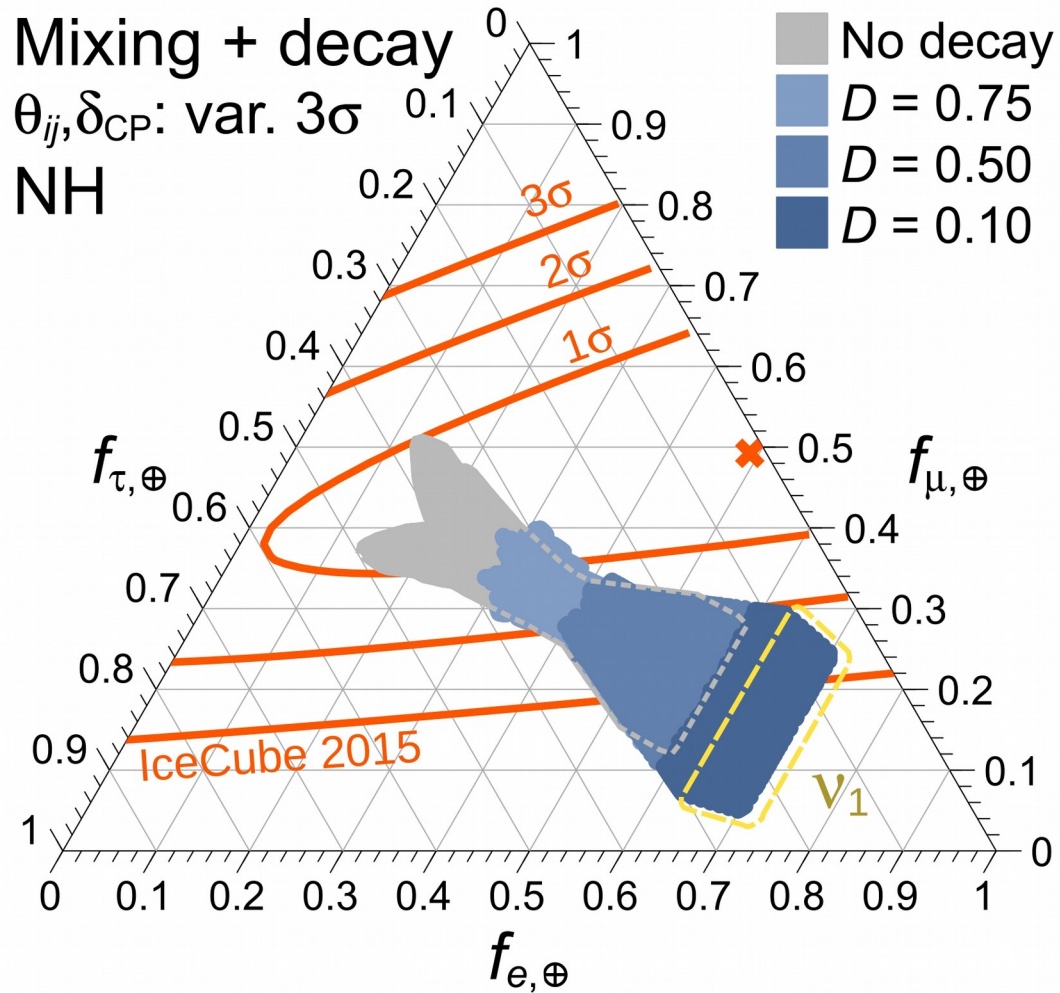


Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- ▶ 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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

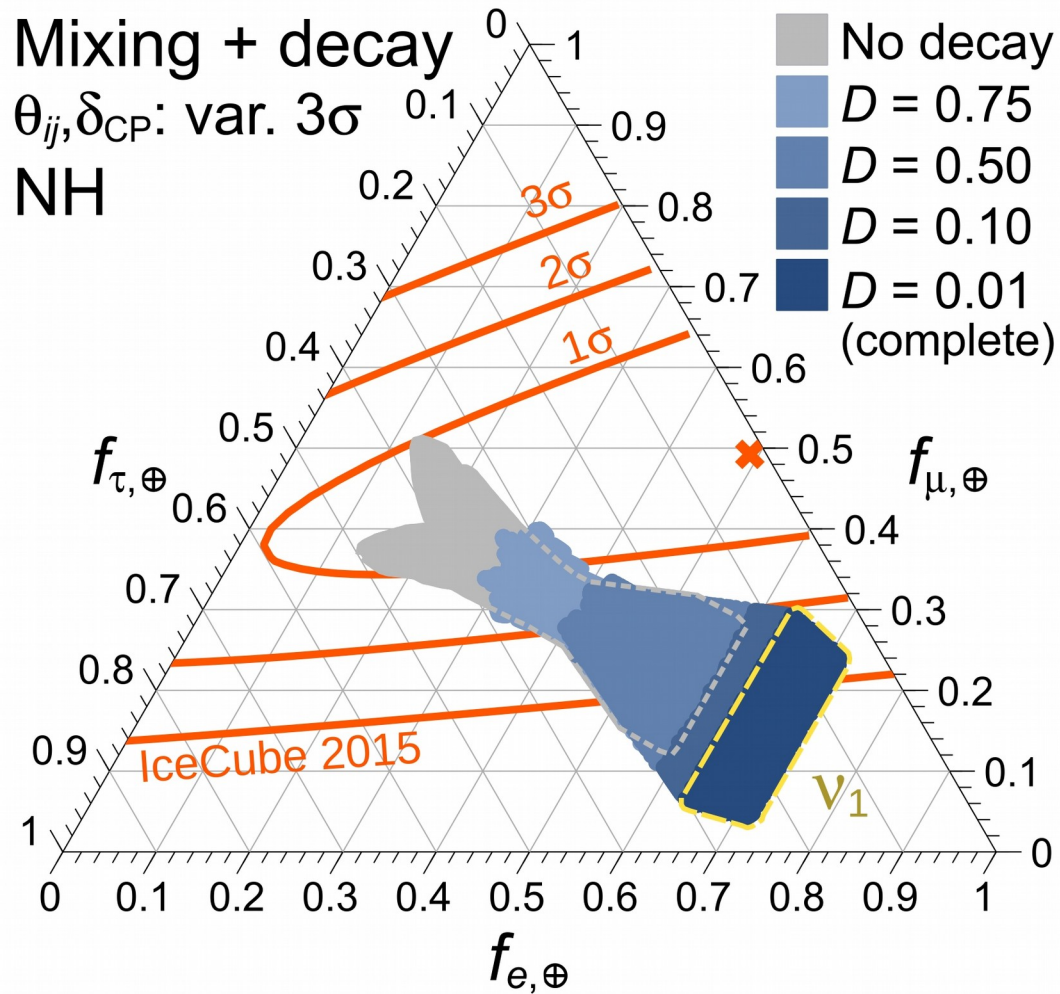


Find the value of D so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- ▶ 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



Measuring the neutrino lifetime

Fraction of ν_2, ν_3 remaining at Earth

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

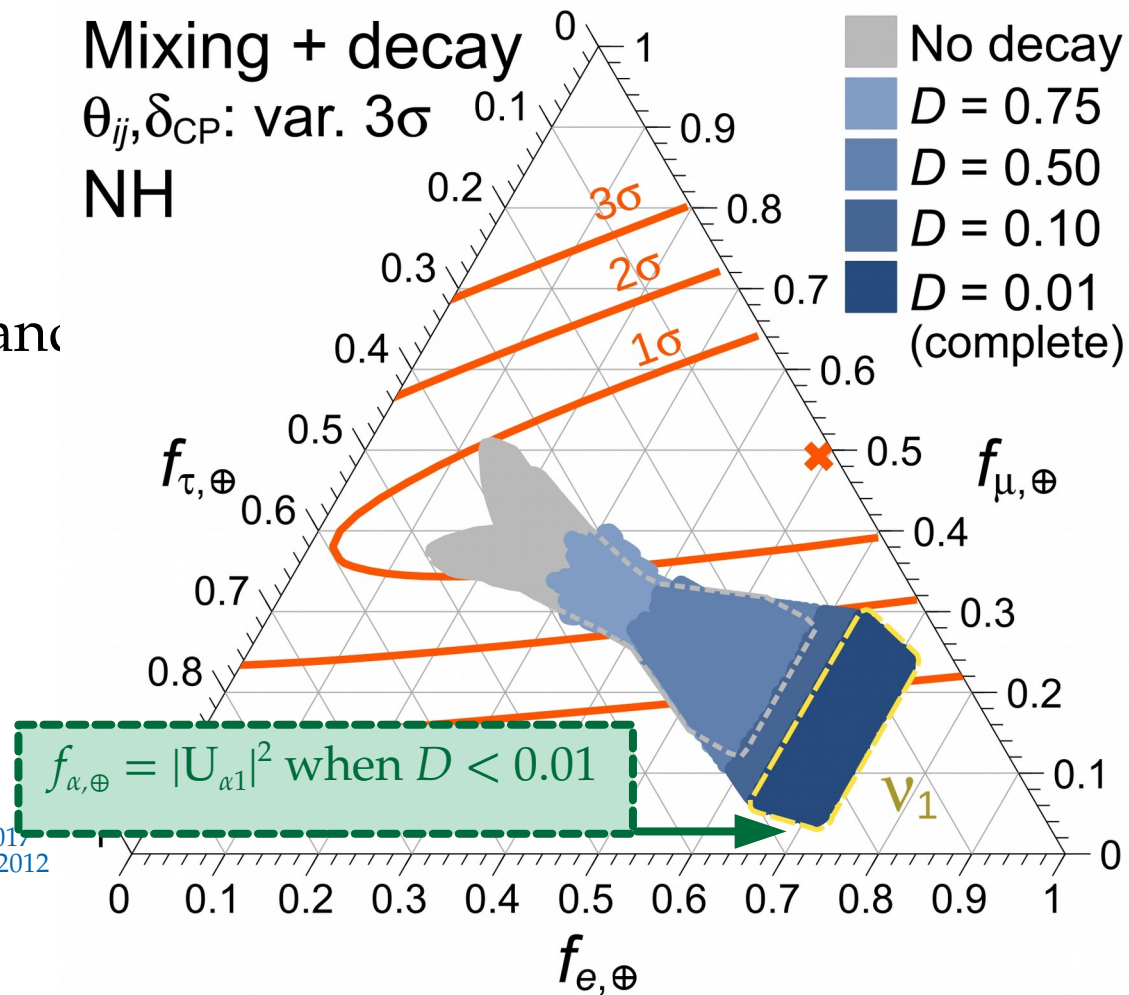
- ▶ Any value of mixing parameters; and
- ▶ Any flavor ratios at the sources

(Assume equal lifetimes of ν_2, ν_3)

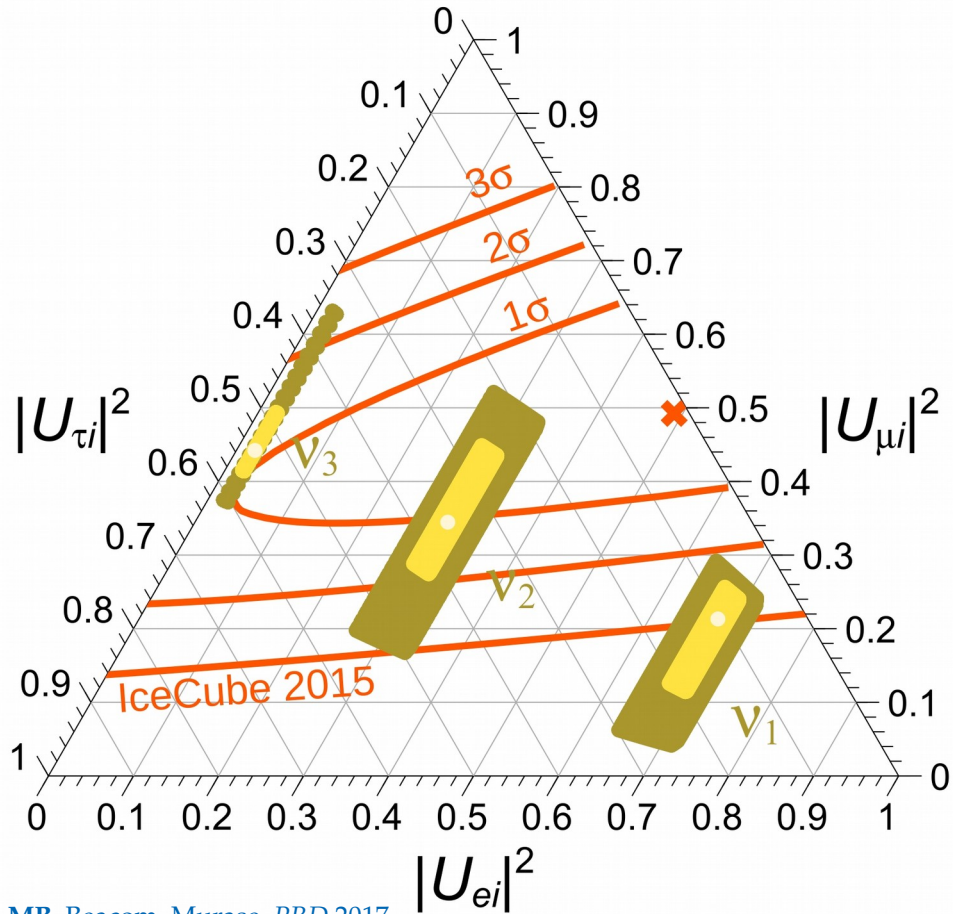
Mixing + decay

θ_{ij}, δ_{CP} : var. 3σ

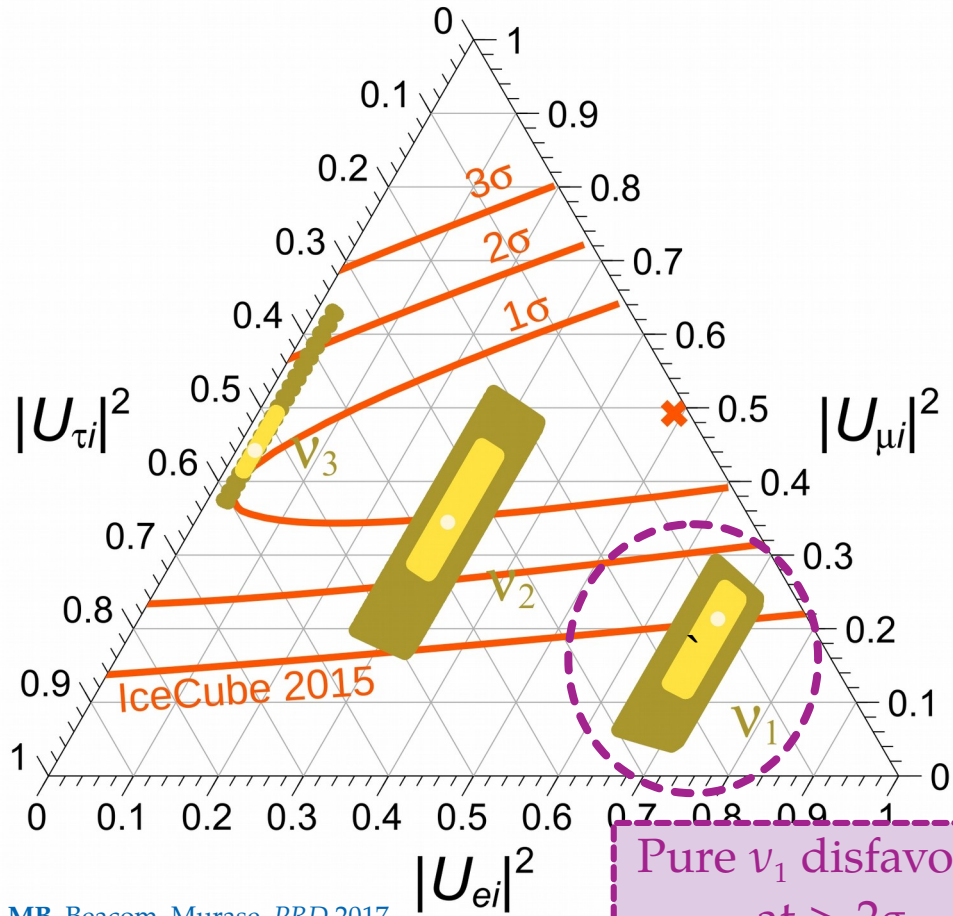
NH



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

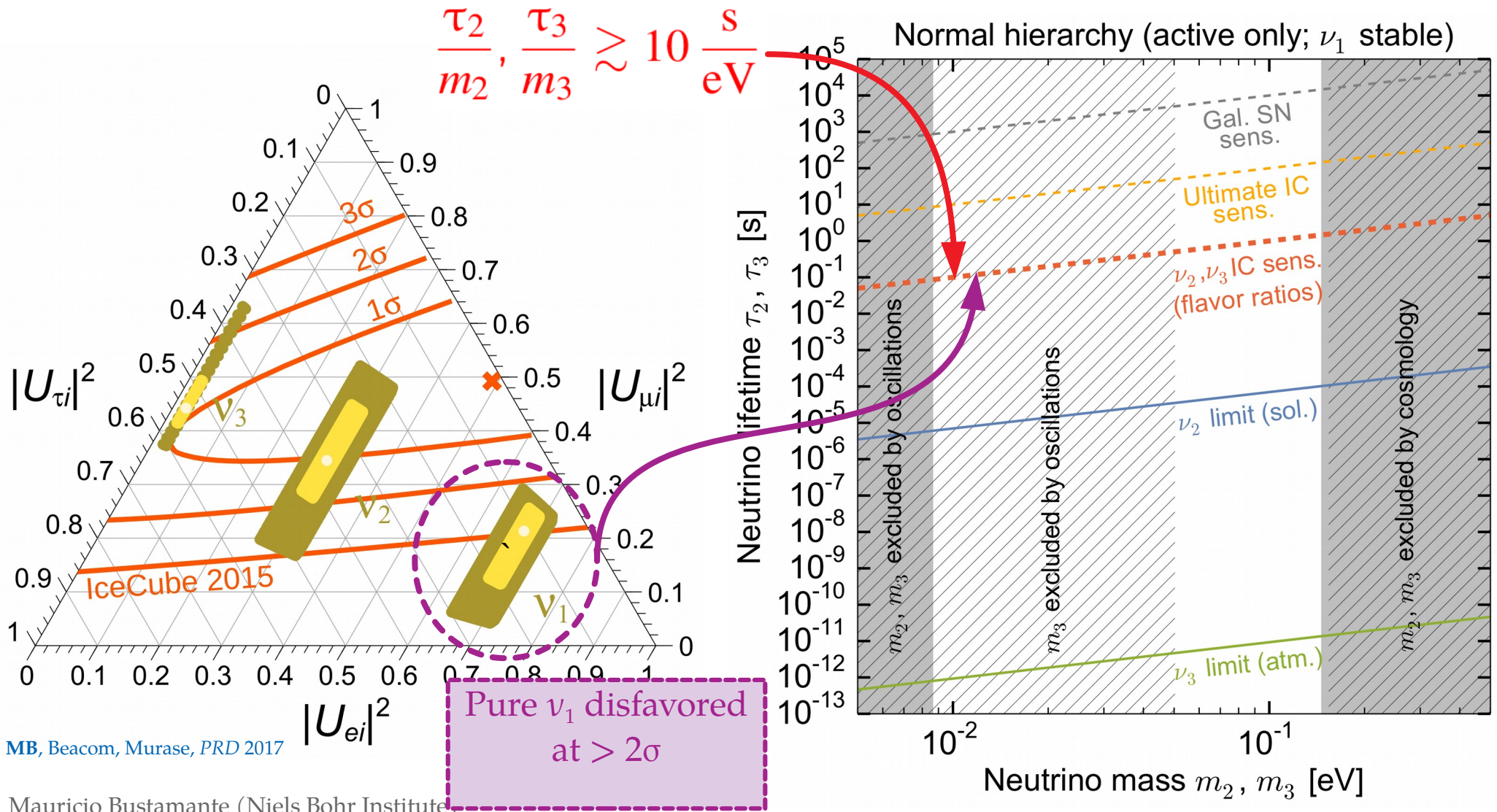


MB, Beacom, Murase, PRD 2017



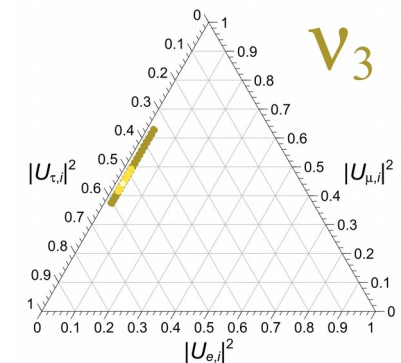
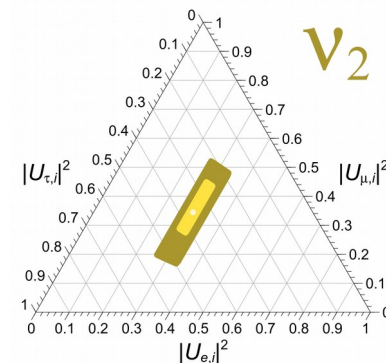
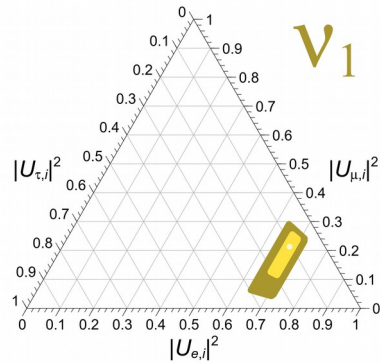
Pure ν_1 disfavored
at $> 2\sigma$

MB, Beacom, Murase, PRD 2017



Two classes of new physics

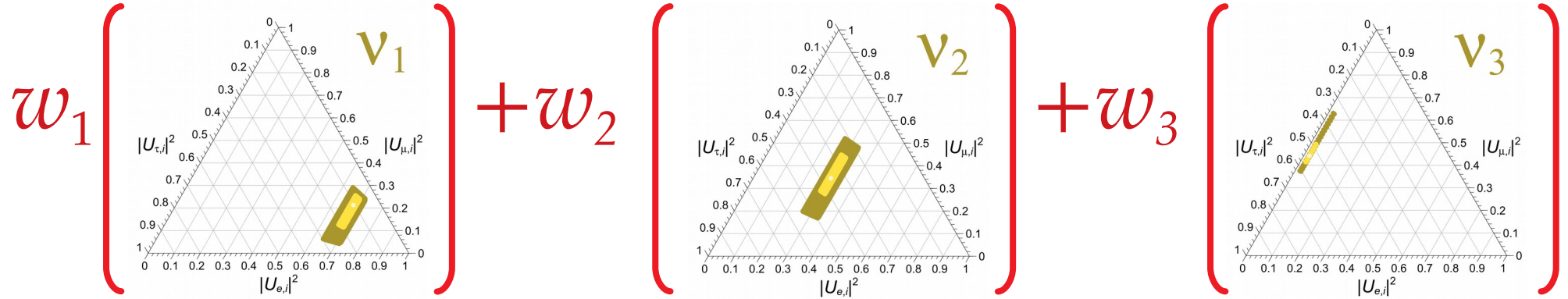
- ▶ Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- ▶ Each one has a different flavor content:



- ▶ Flavor ratios at Earth are the result of their **combination**
- ▶ New physics may:
 - ▶ Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
 - ▶ Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Two classes of new physics

- ▶ Neutrinos propagate as an incoherent mix of ν_1, ν_2, ν_3
- ▶ Each one has a different flavor content:



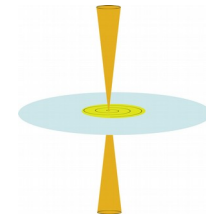
- ▶ Flavor ratios at Earth are the result of their **combination**
- ▶ New physics may:
 - ▶ Only reweigh the proportion of each ν_i reaching Earth (*e.g.*, ν decay)
 - ▶ Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Inferring flavor composition at the sources

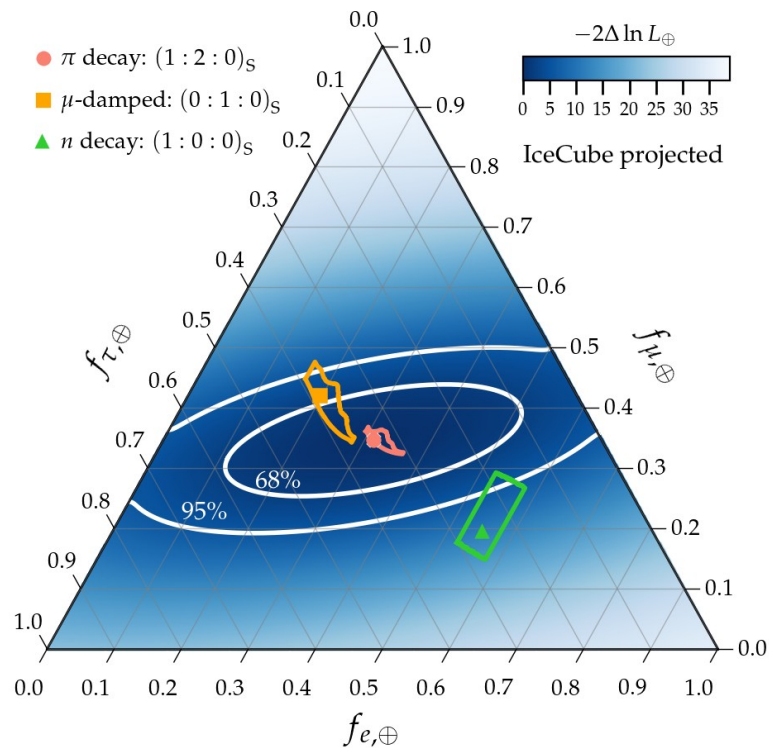
Measured:
Flavor ratios at Earth



Invert flavor oscillations



Inferred:
Flavor ratios at
astrophysical sources

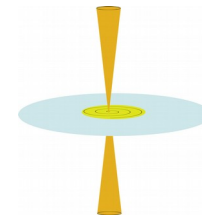


Inferring flavor composition at the sources

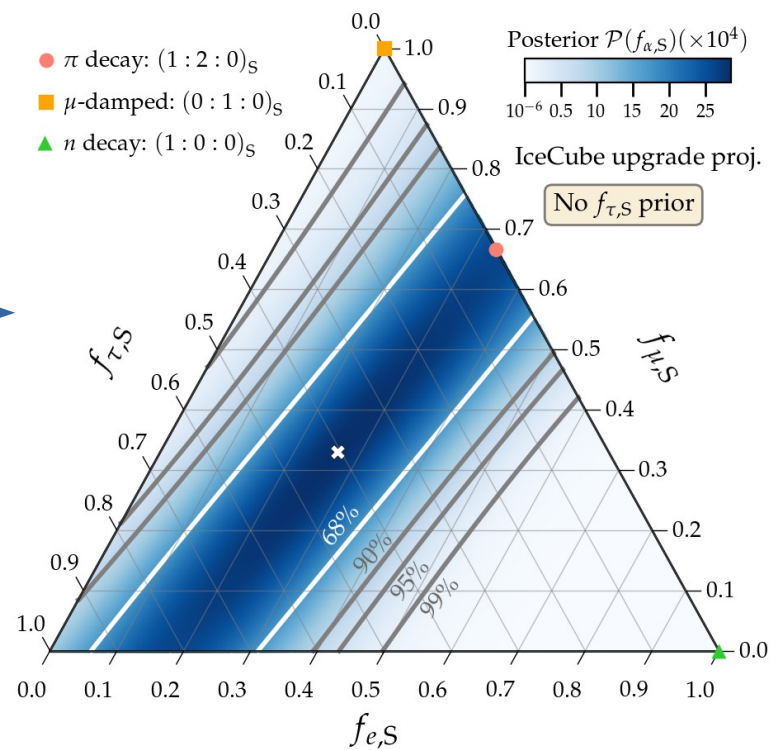
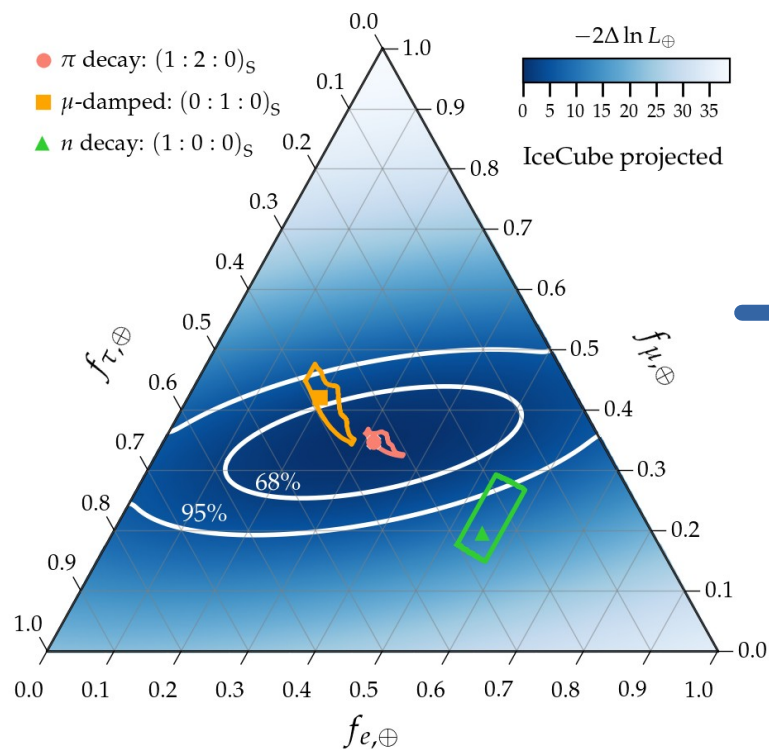
Measured:
Flavor ratios at Earth



Invert flavor oscillations



Inferred:
Flavor ratios at
astrophysical sources

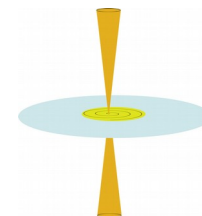


Inferring flavor composition at the sources

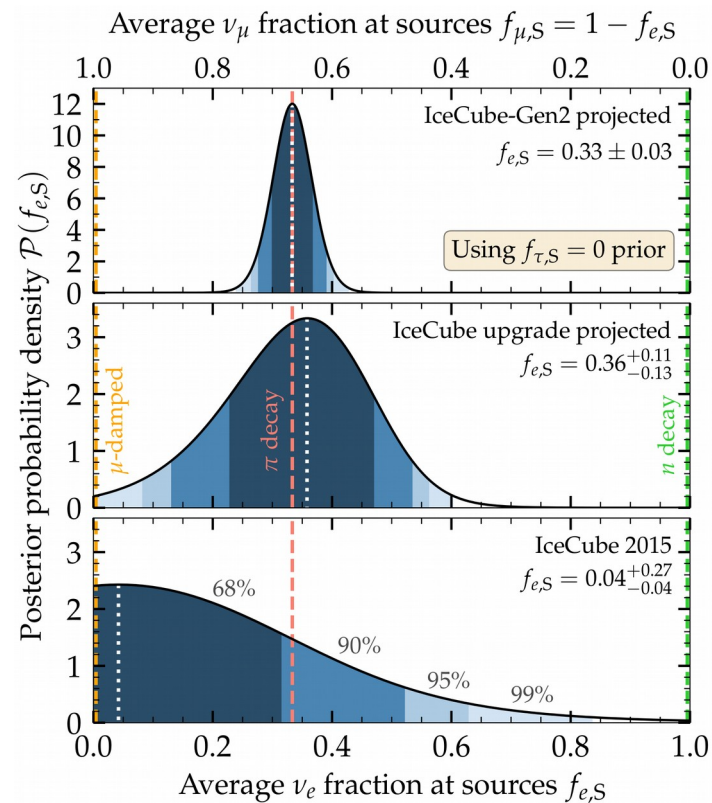
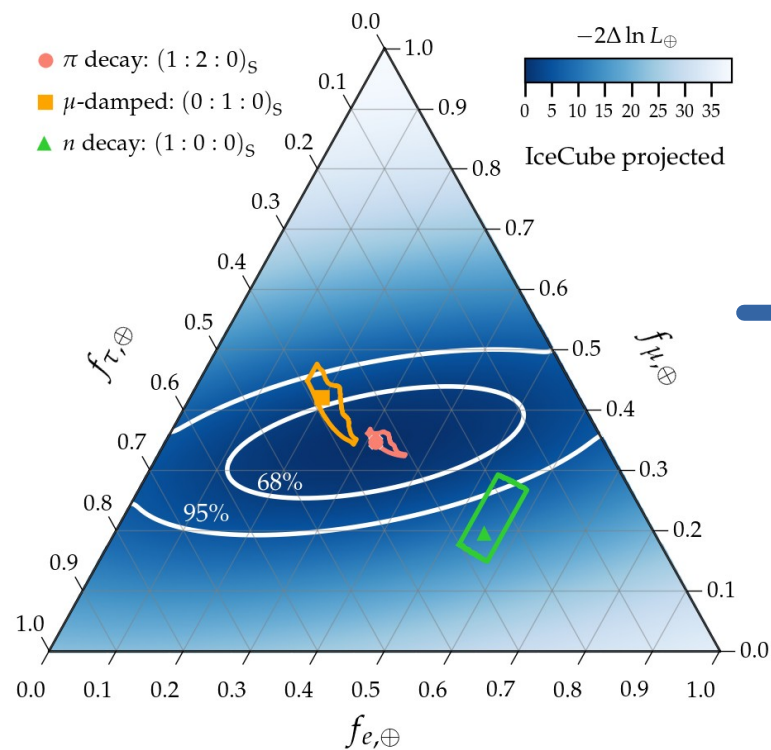
Measured:
Flavor ratios at Earth



Invert flavor oscillations

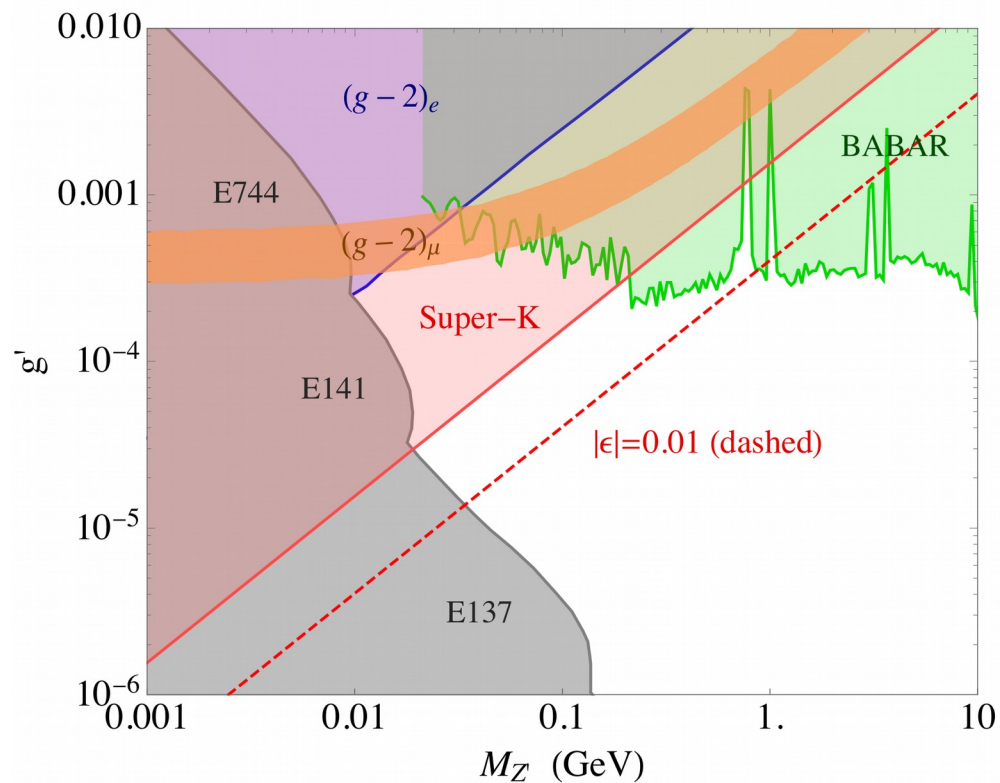


Inferred:
Flavor ratios at
astrophysical sources



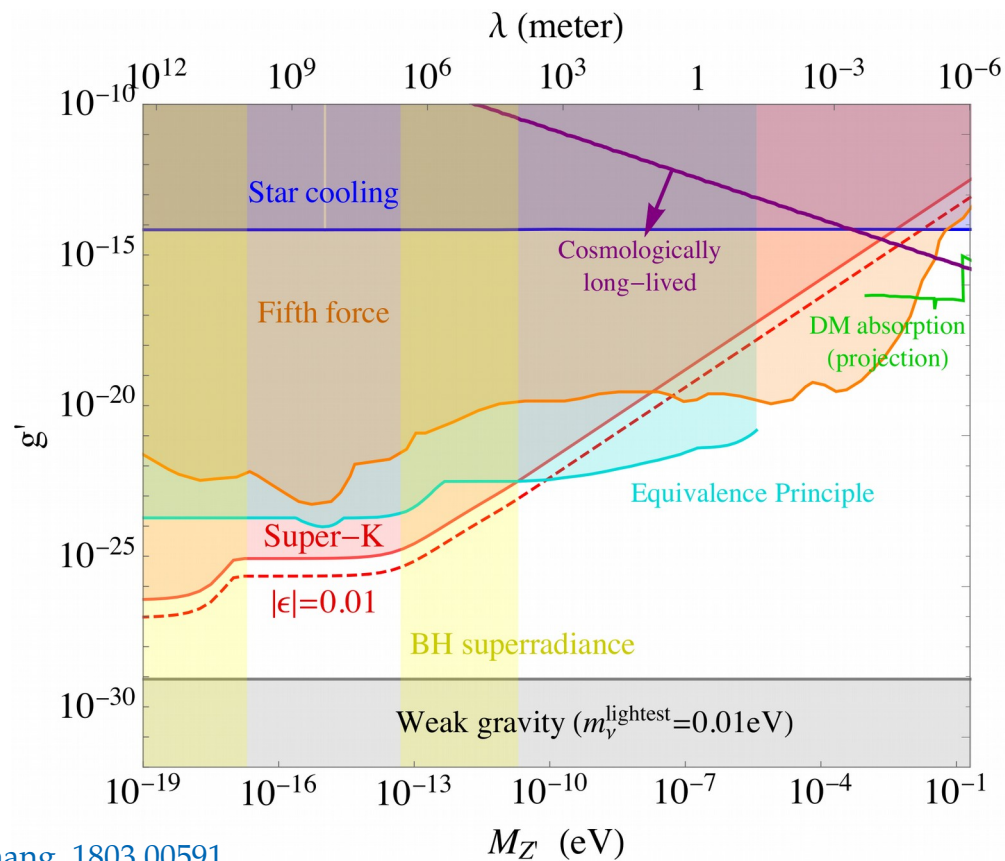
Current limits on the Z'

MeV–GeV masses



M. Wise & Y. Zhang, 1803.00591

Sub-eV masses



Connecting flavor-ratio predictions to experiment

- 1 Integrate potential in redshift, weighed by source number density
→ Assume star formation rate

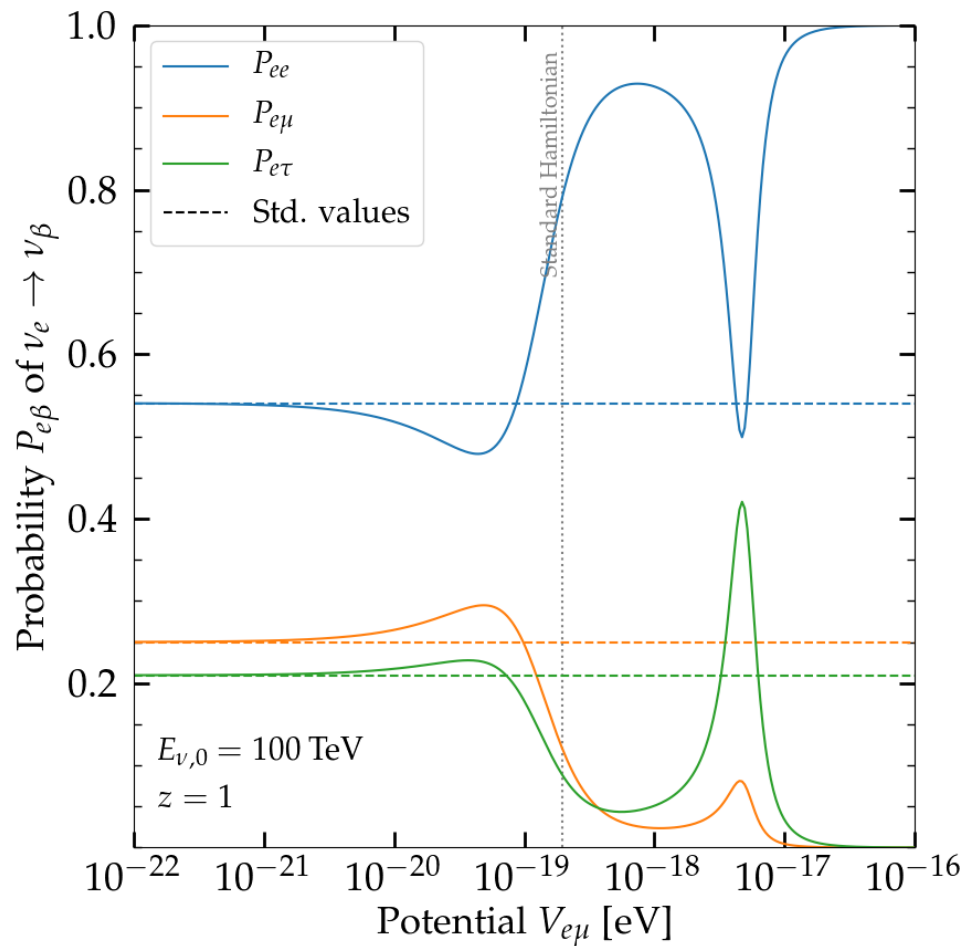
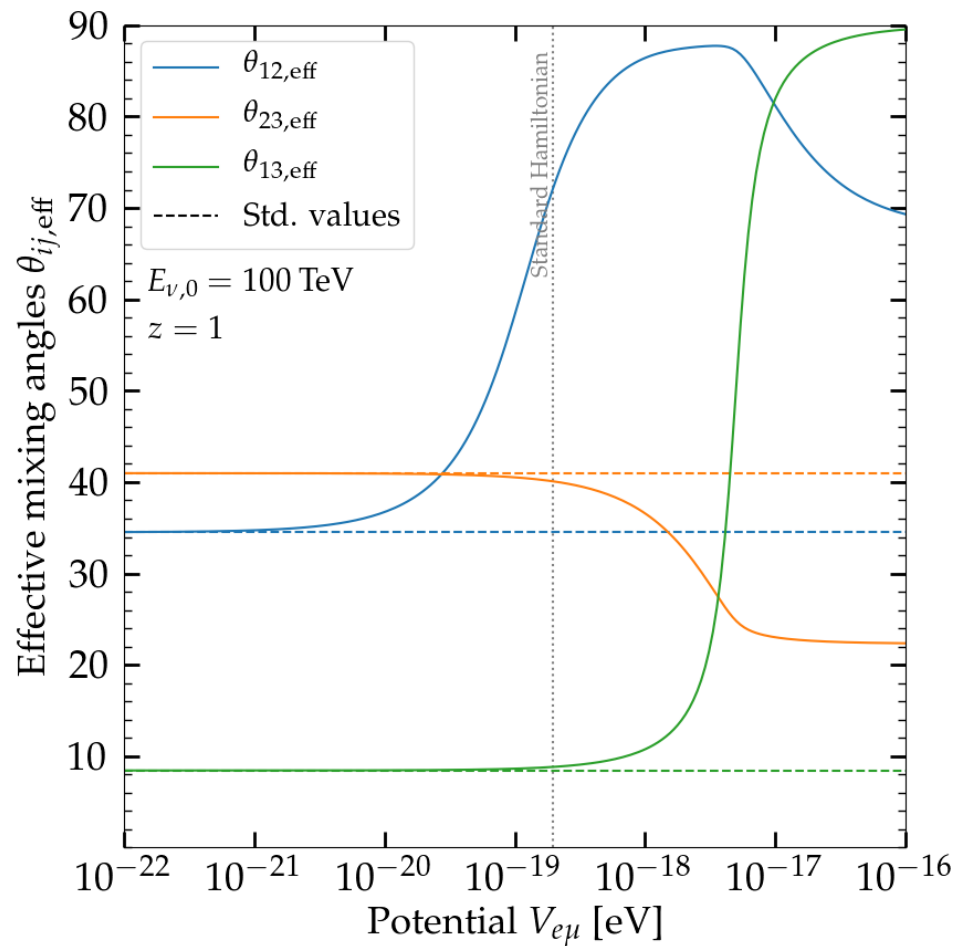
$$\langle V_{e\beta}^{\text{cos}} \rangle \propto \int dz \, \rho_{\text{SFR}}(z) \cdot \frac{dV_c}{dz} \cdot V_{e\beta}^{\text{cos}}(z)$$

Density of cosmological e grows with z

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

$$\underbrace{\langle \Phi_\alpha \rangle \propto \int dE_\nu \, f_{\alpha,\oplus}(E_\nu) \, E_\nu^{-\gamma}}_{\text{Energy-averaged flux}} \Rightarrow \underbrace{\langle f_{\alpha,\oplus} \rangle \equiv \frac{\langle \Phi_\alpha \rangle}{\sum_{\beta=e,\mu,\tau} \langle \Phi_\beta \rangle}}_{\text{Energy-averaged flavor ratios}}$$

Resonance due to the L_e - L_μ symmetry



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

