# Fundamental Physics with High-Energy Astrophysical Neutrinos *Today* and in the Future

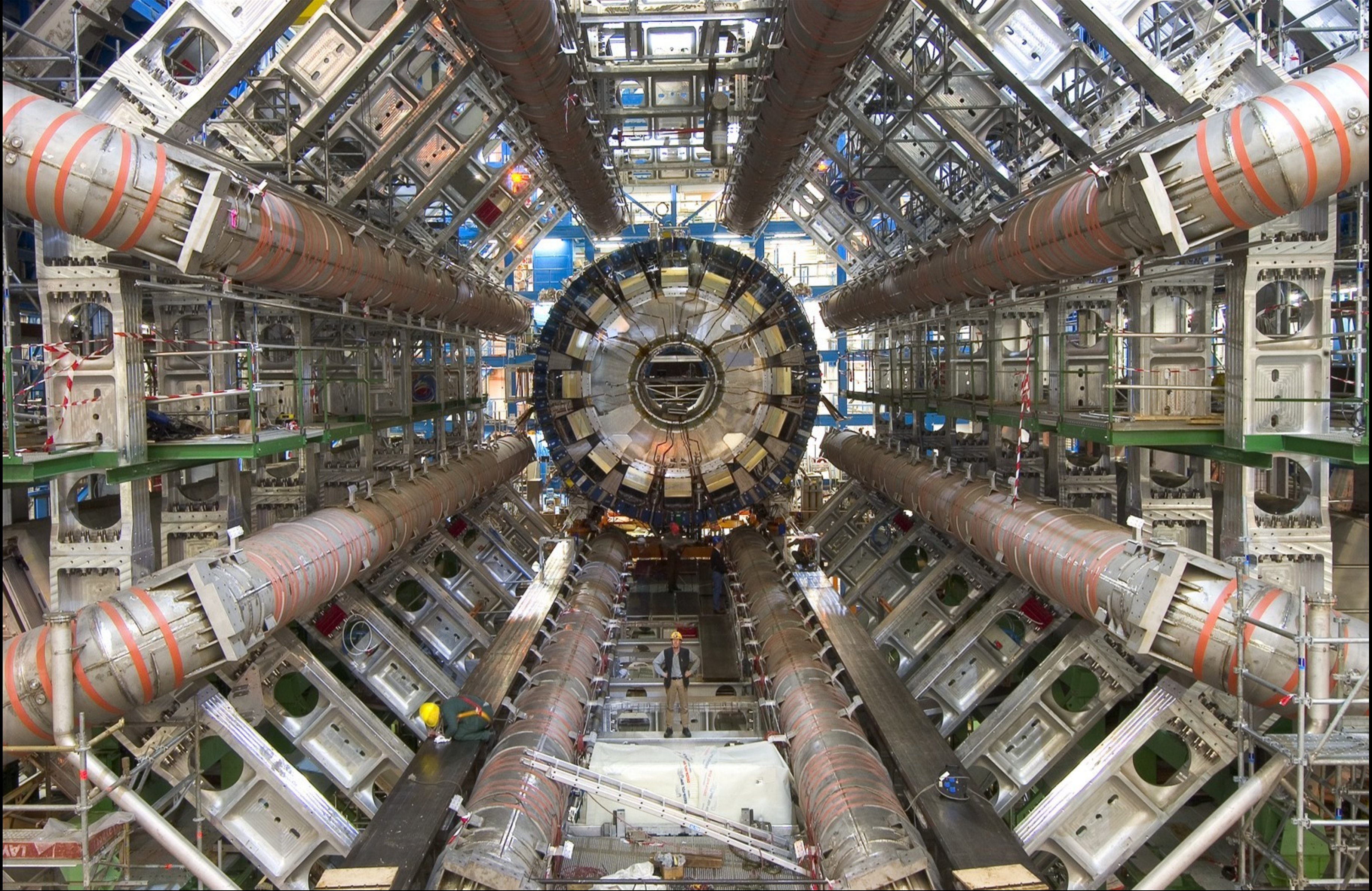
Mauricio Bustamante
Niels Bohr Institute, University of Copenhagen

*In collaboration with:*
Carlos A. Argüelles, Ali Kheirandish,
Sergio Palomares-Ruiz, Jordi Salvadó, Aaron C. Vincent

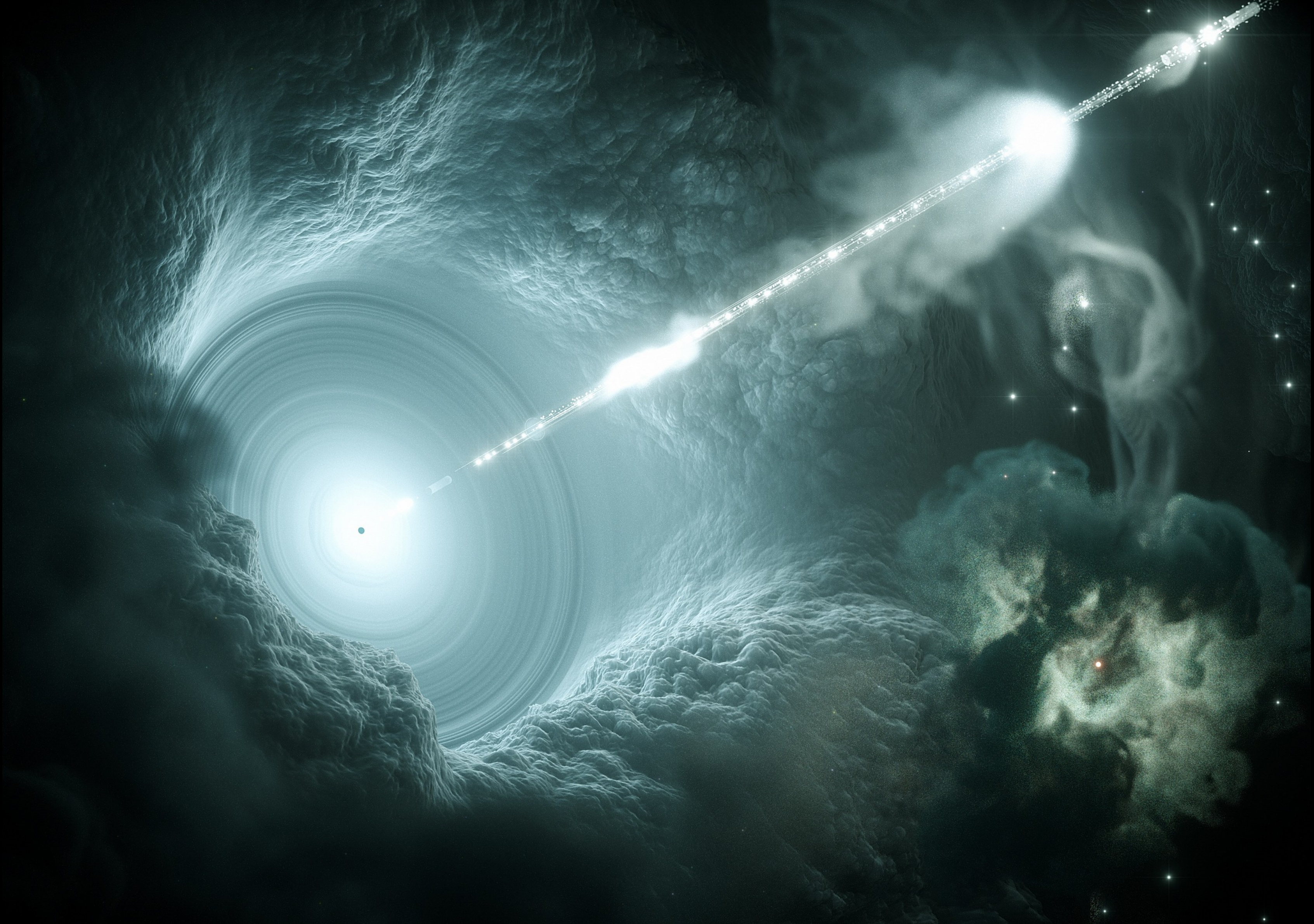
36th ICRC
Madison, WI, July 25, 2019

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN



ATLAS


DESY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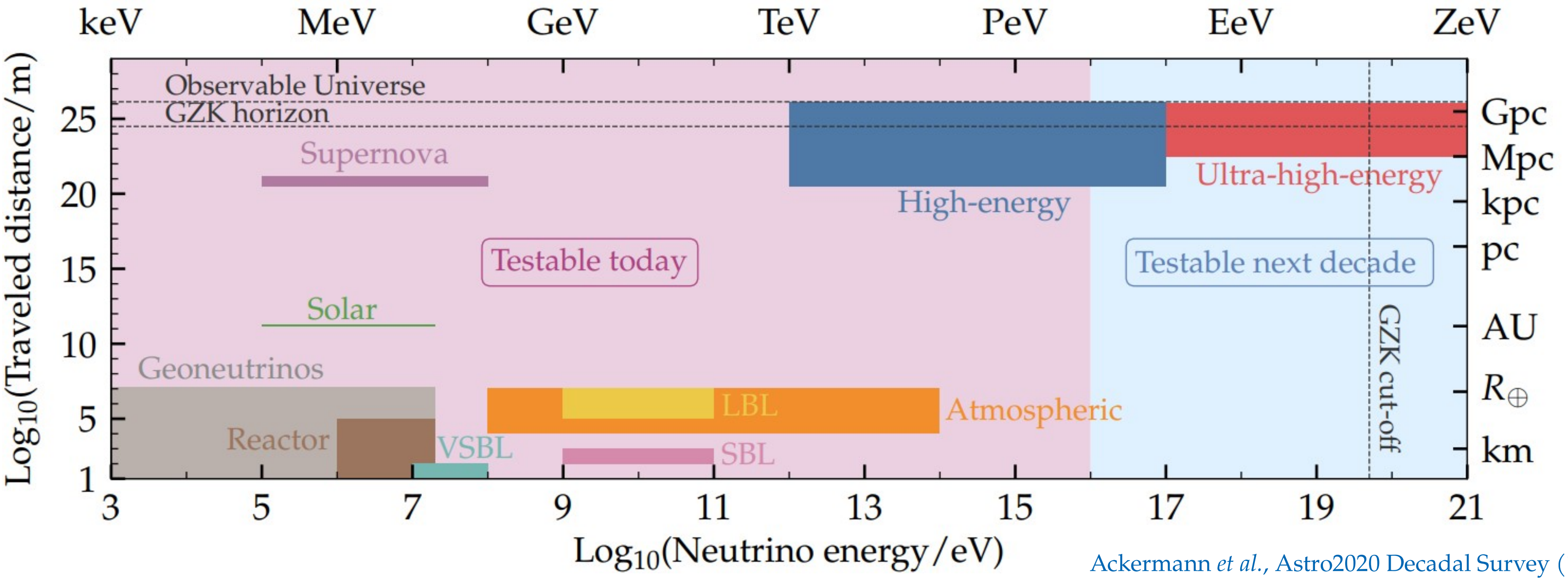


Ackermann *et al.*, Astro2020 Decadal Survey (1903.04333)

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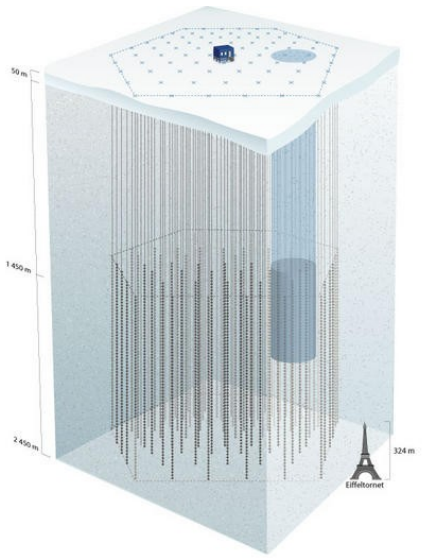
5. It comes *for free*

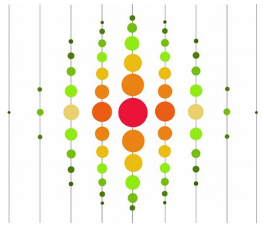
# IceCube (8 years)

km³ in-ice
Cherenkov detector




## Showers

(mostly from $\nu_e$, $\nu_\tau$)



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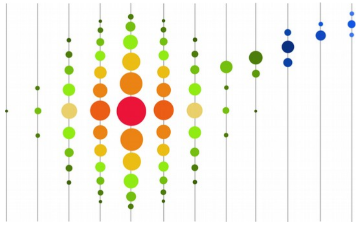
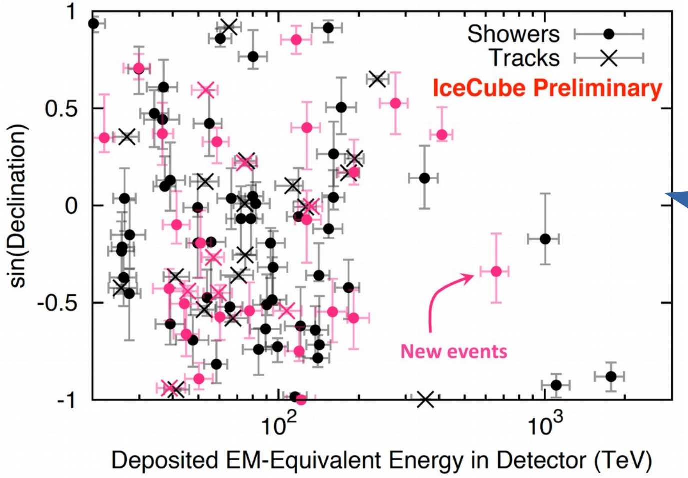


## 103 contained events, 15 TeV–2 PeV

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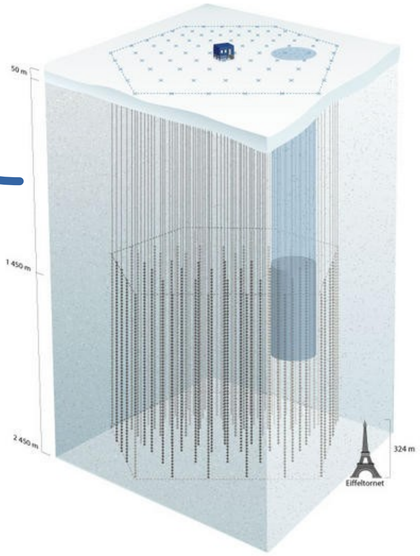


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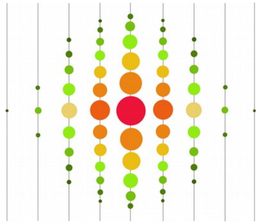

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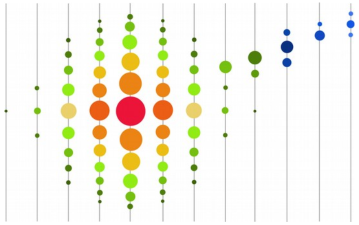

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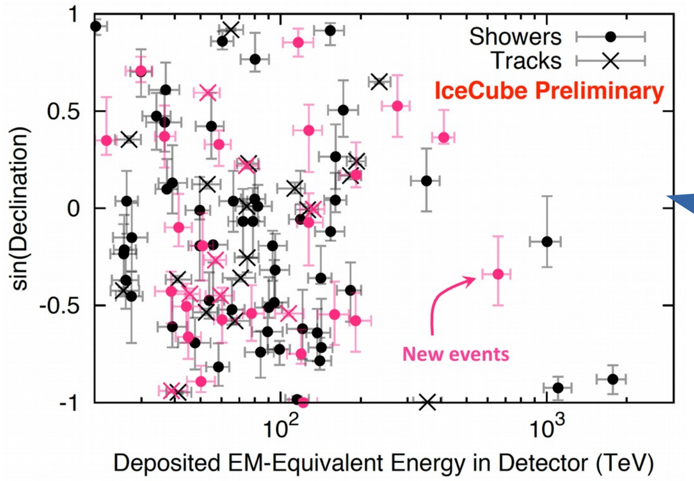


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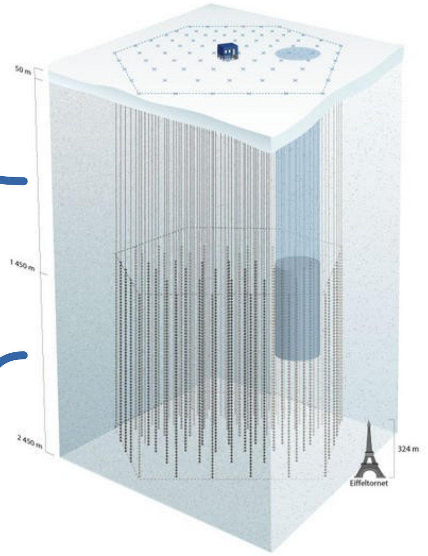

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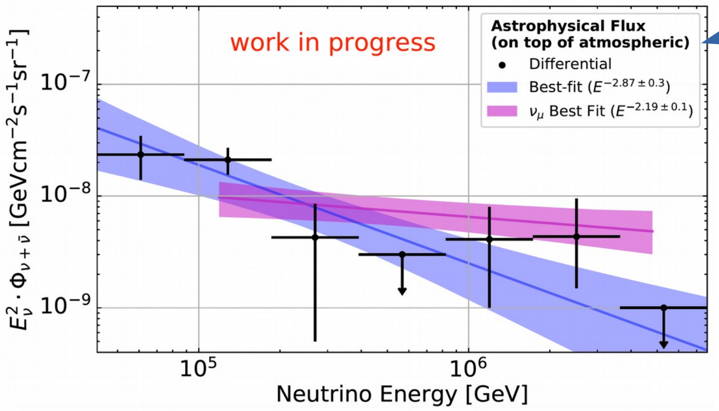


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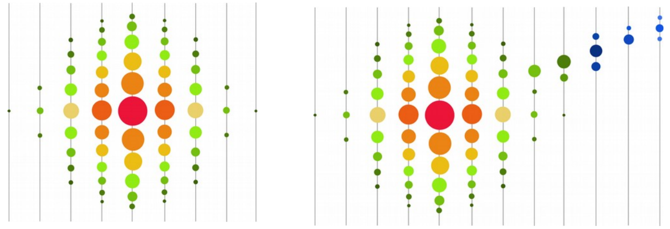

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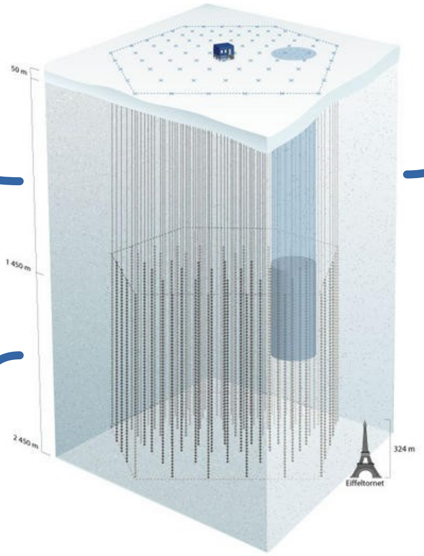


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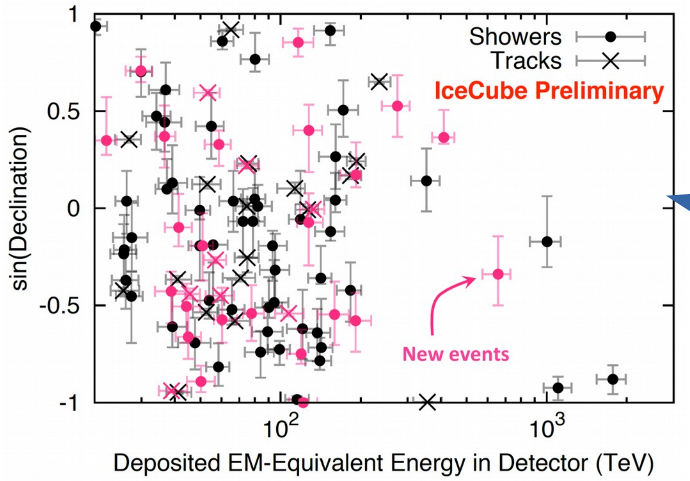


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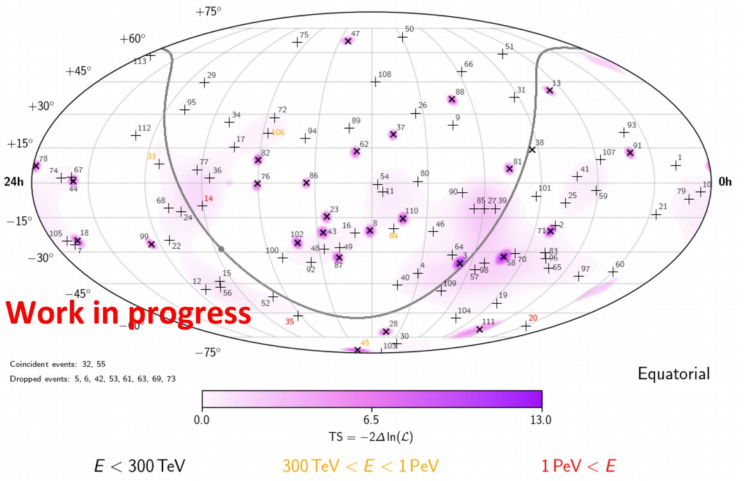


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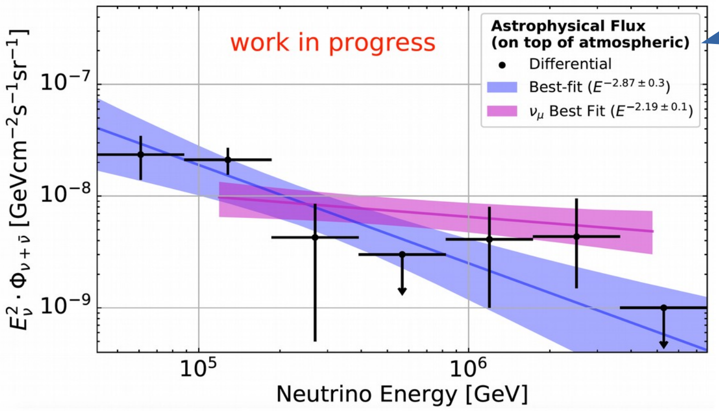


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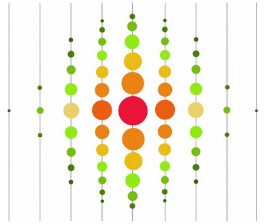

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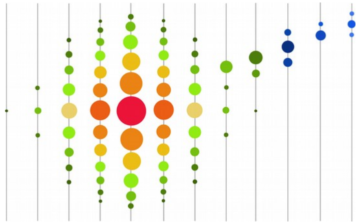

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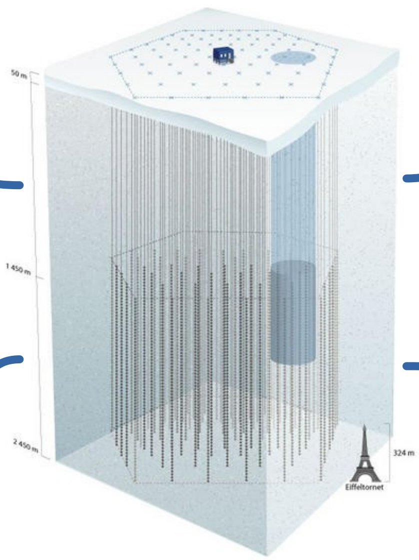


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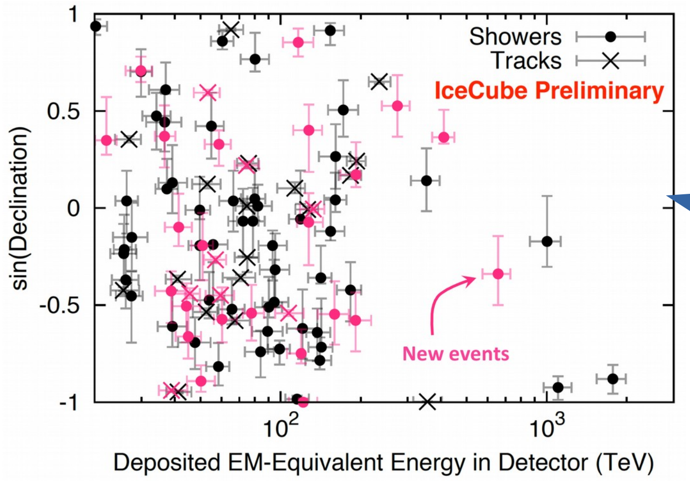


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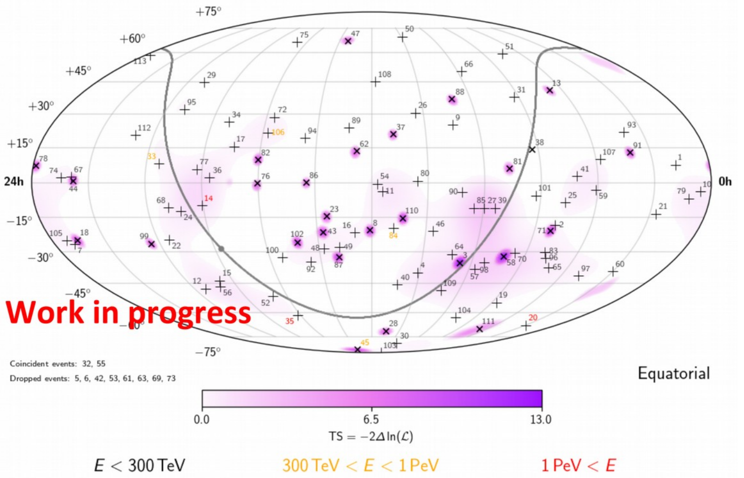


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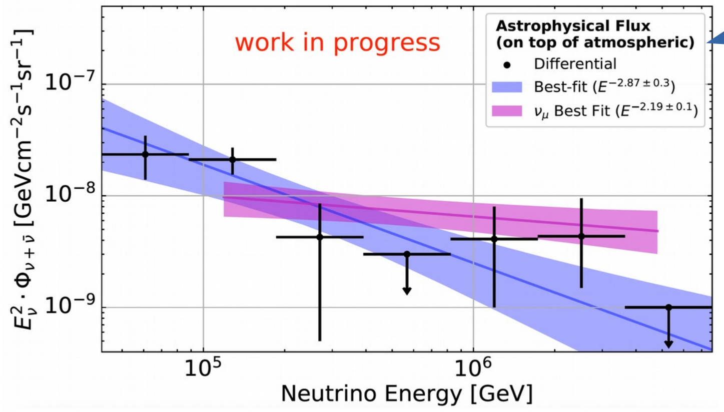


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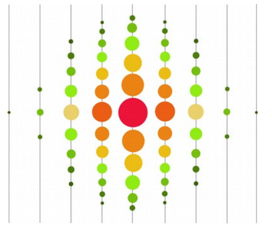

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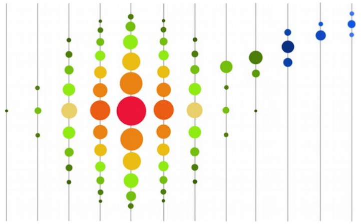

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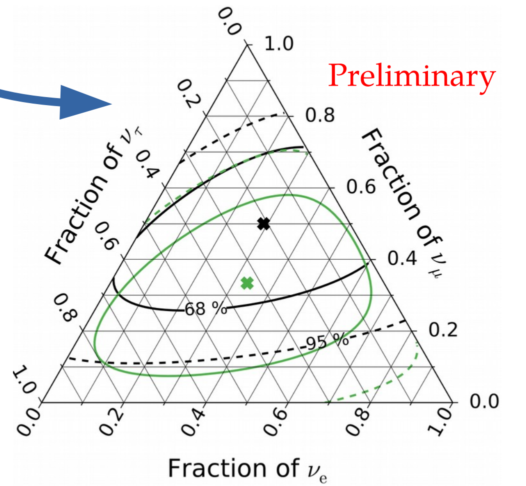

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*Already today.*

Astrophysical unknowns


Netflix


Netflix

# Fundamental physics with HE cosmic neutrinos

- Numerous new-physics effects grow as $\sim \kappa_n \cdot E^n \cdot L$
- So we can probe $\kappa_n \sim 4 \cdot 10^{-47}\ (E/\mathrm{PeV})^{-n}\ (L/\mathrm{Gpc})^{-1}\ \mathrm{PeV}^{1-n}$
- Improvement over current limits: $\kappa_0 < 10^{-29}$ PeV, $\kappa_1 < 10^{-33}$
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*In spite of*
poor energy, angular, flavor reconstruction
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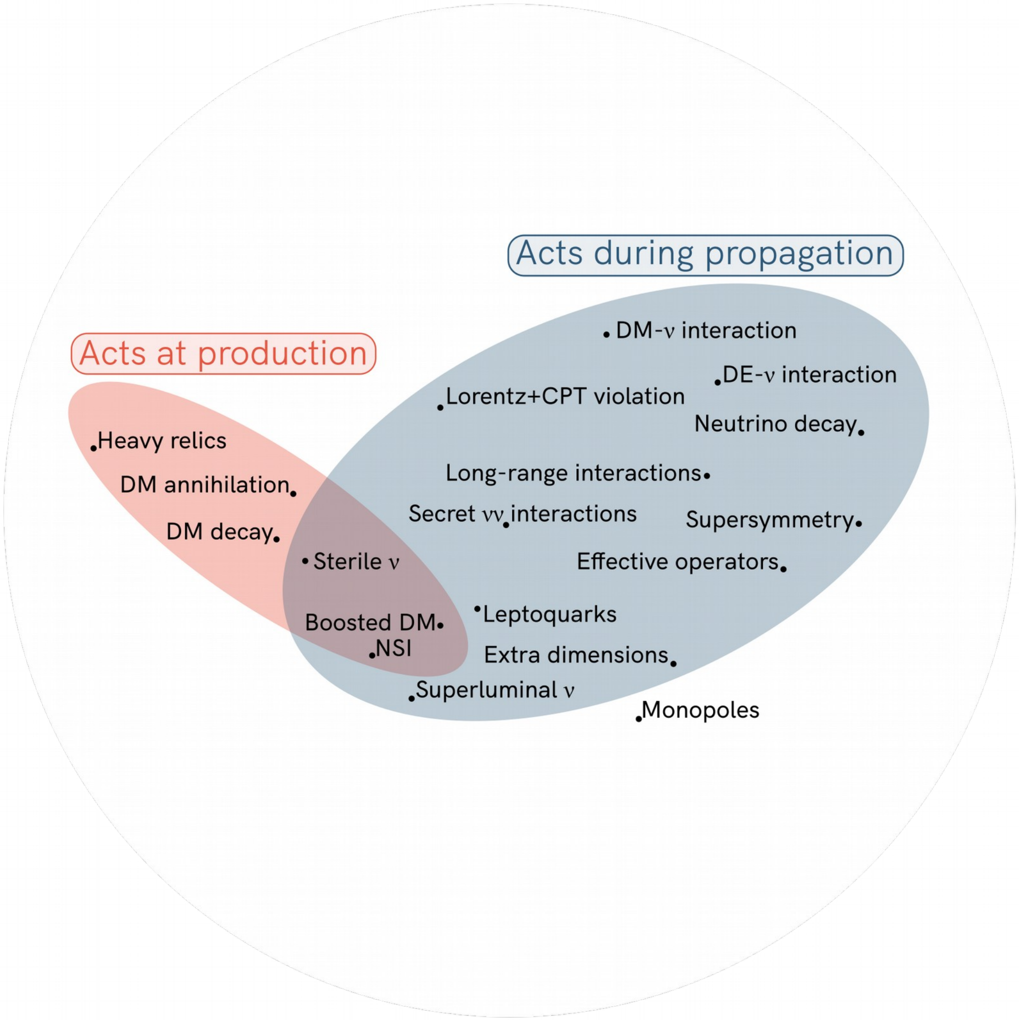


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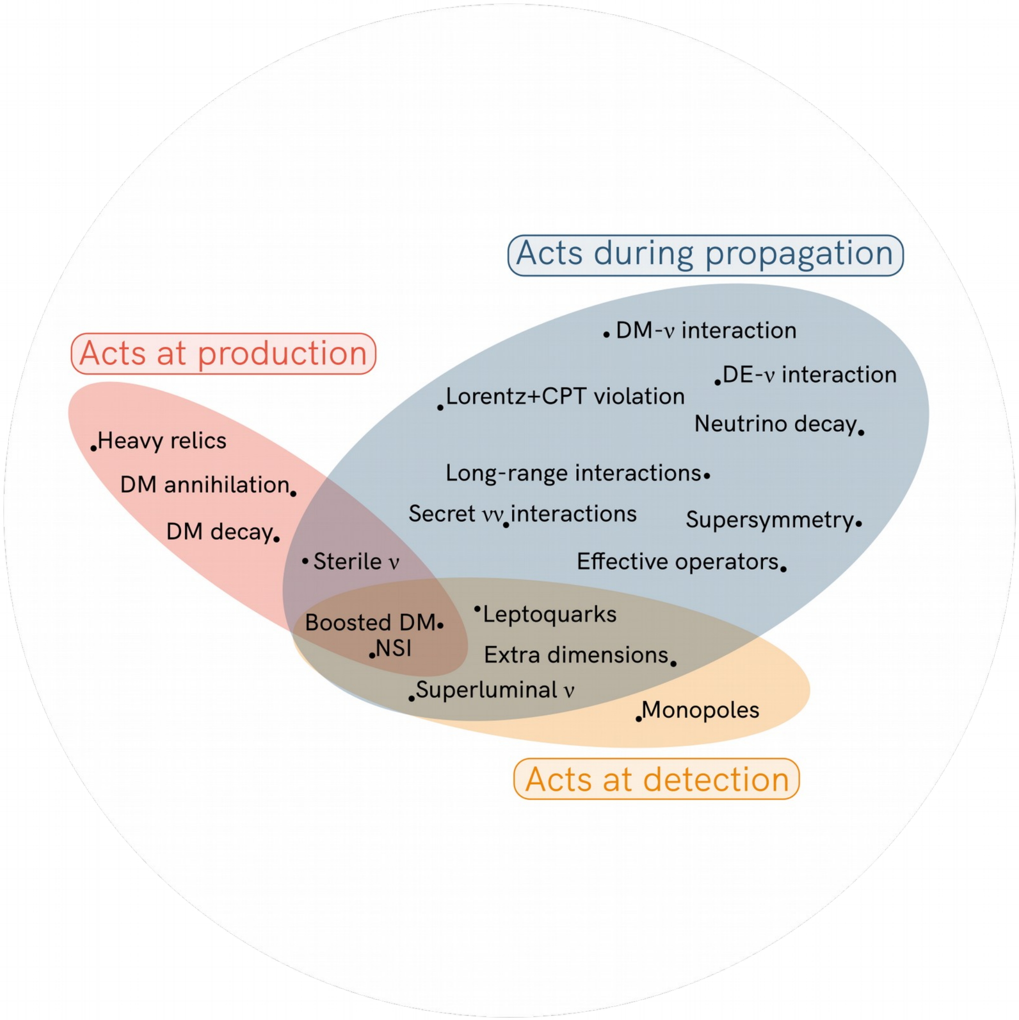


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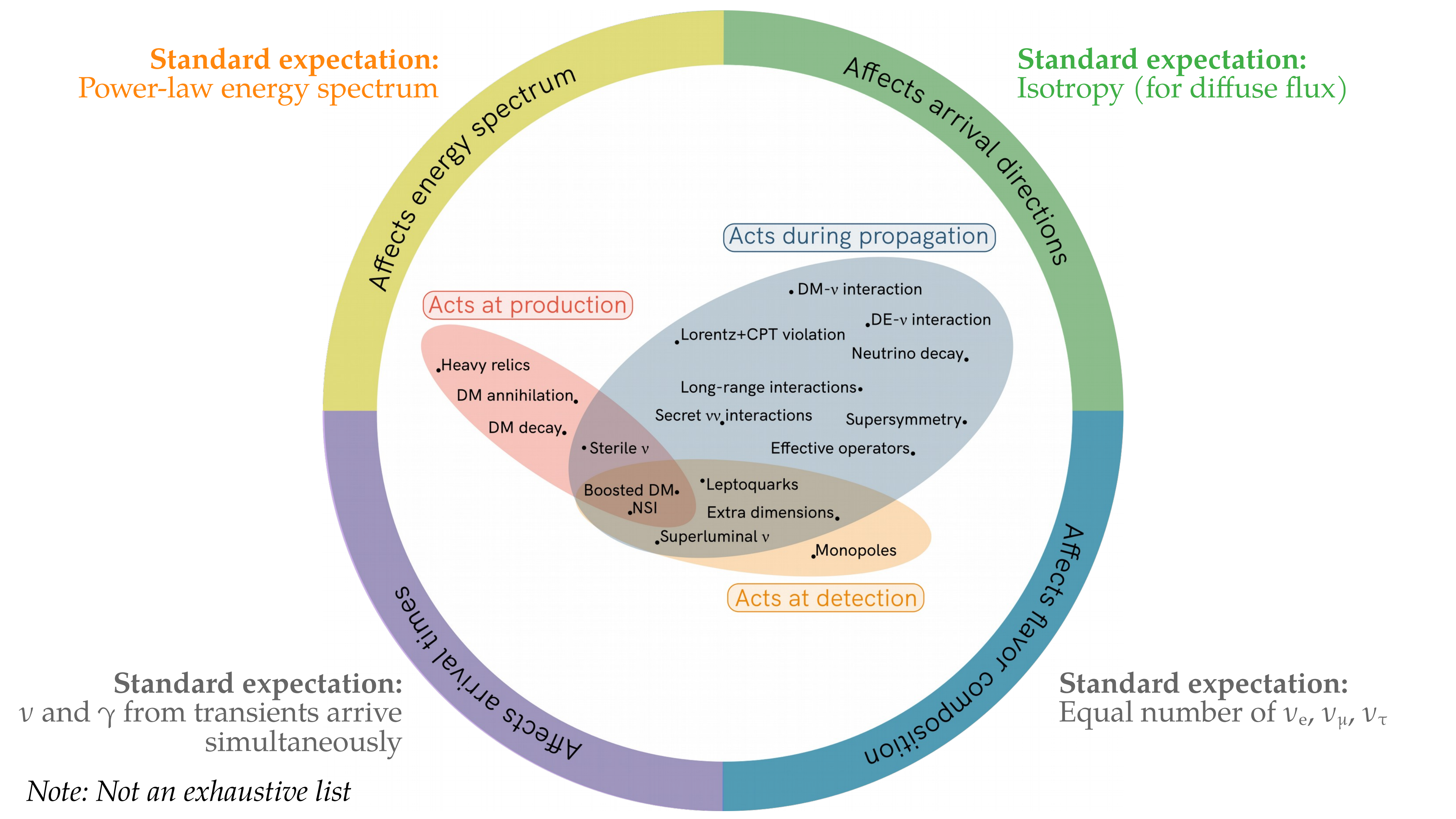
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Affects arrival directions
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DE-ν interaction
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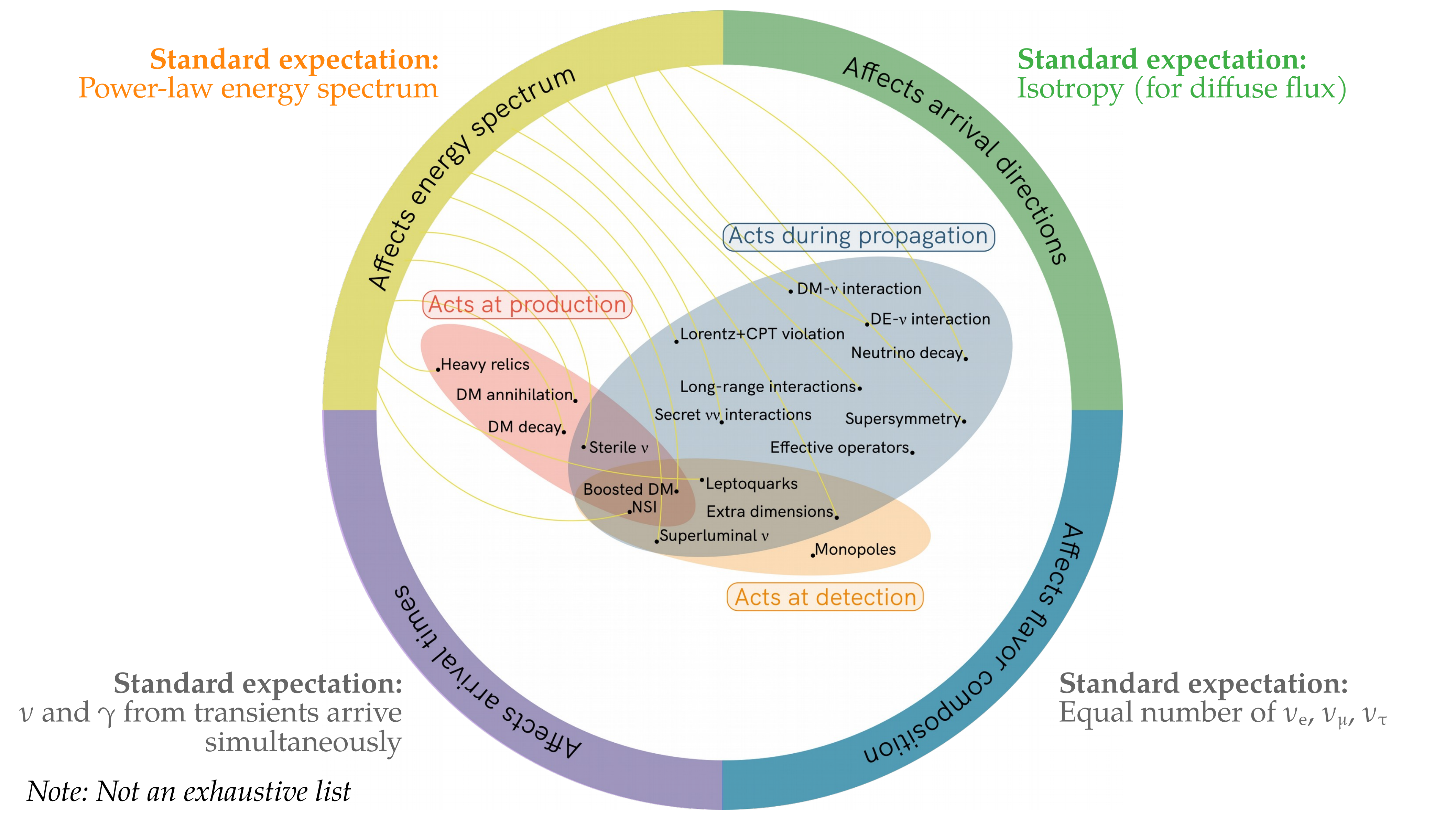

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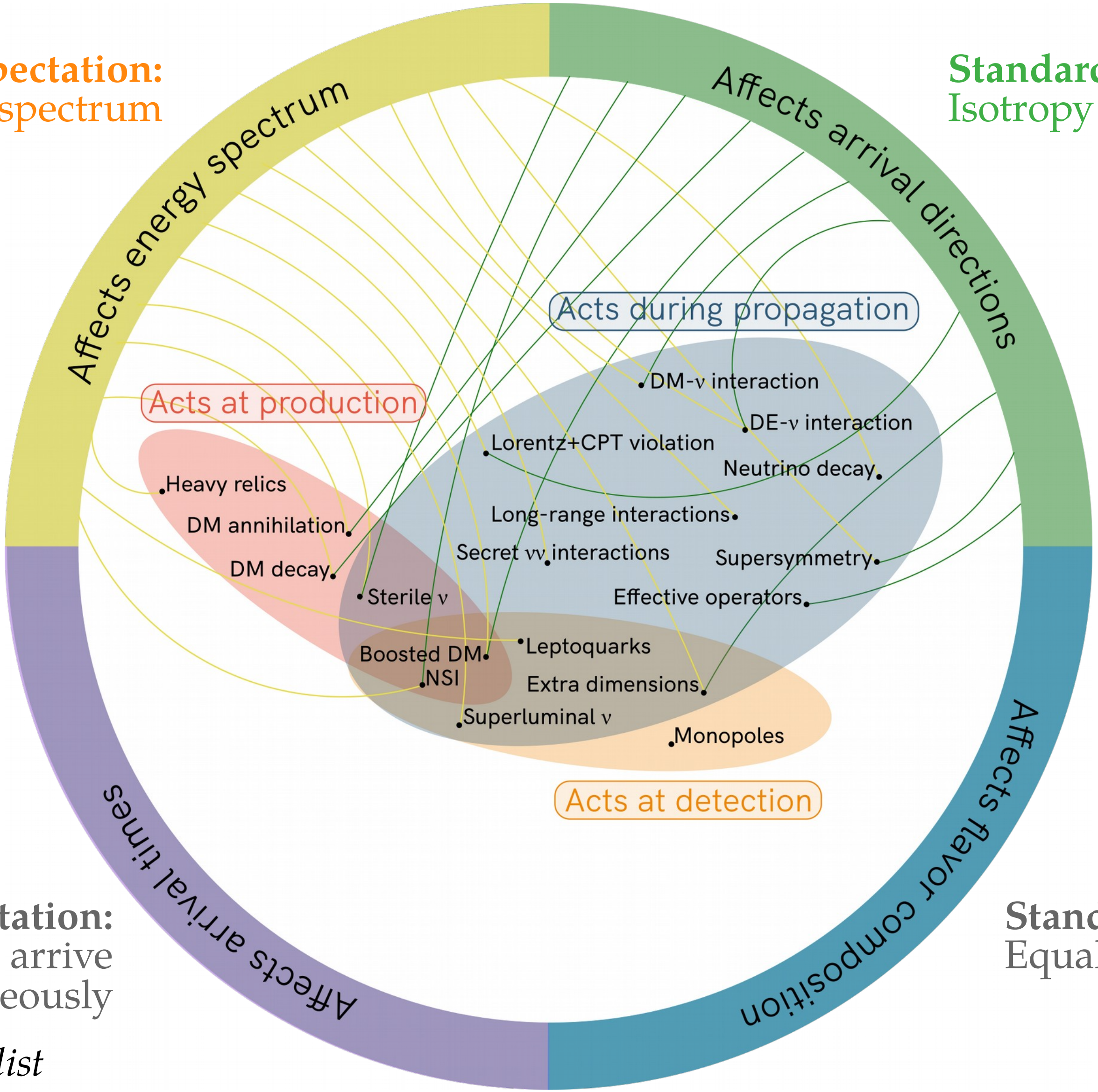


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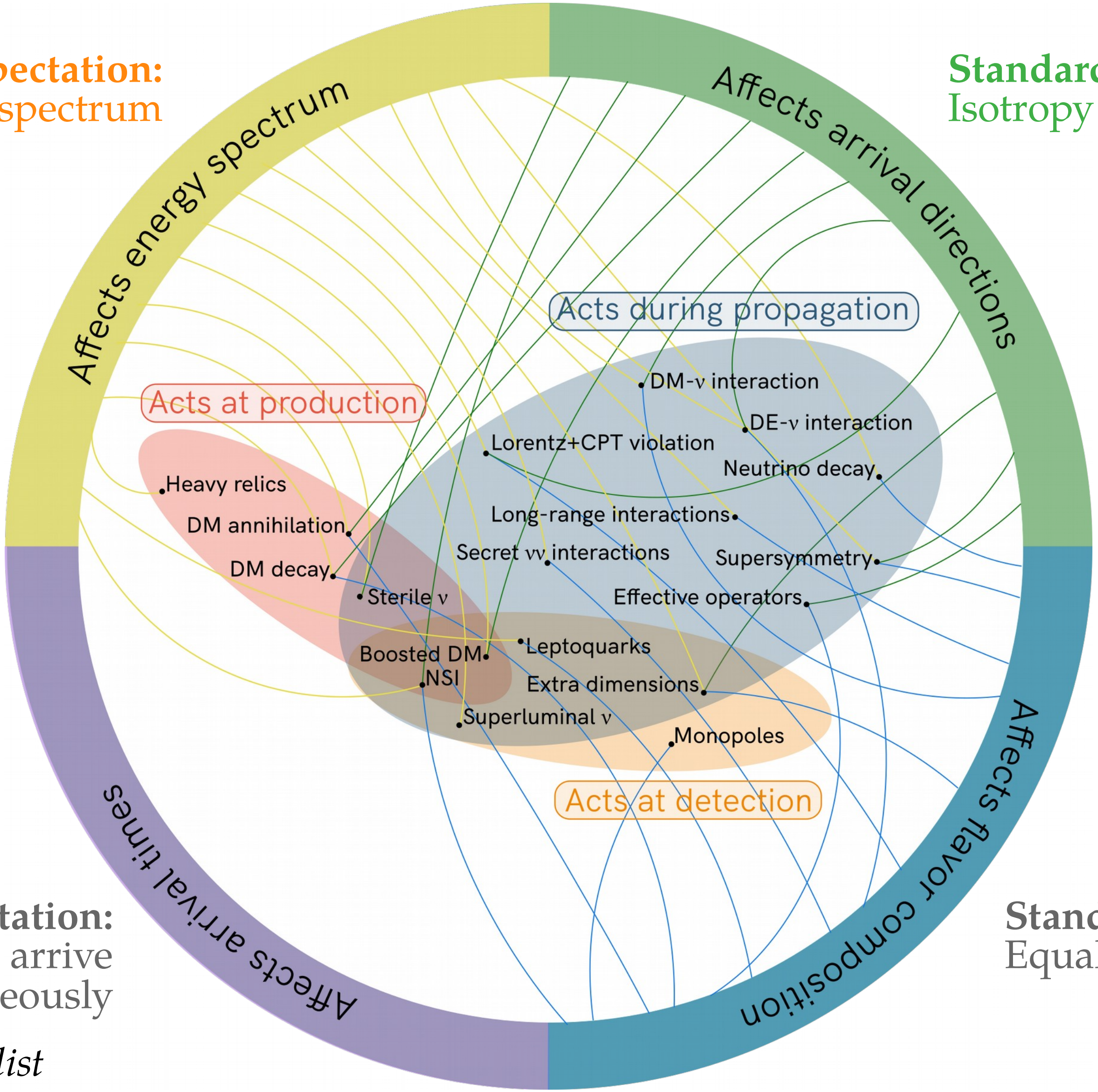


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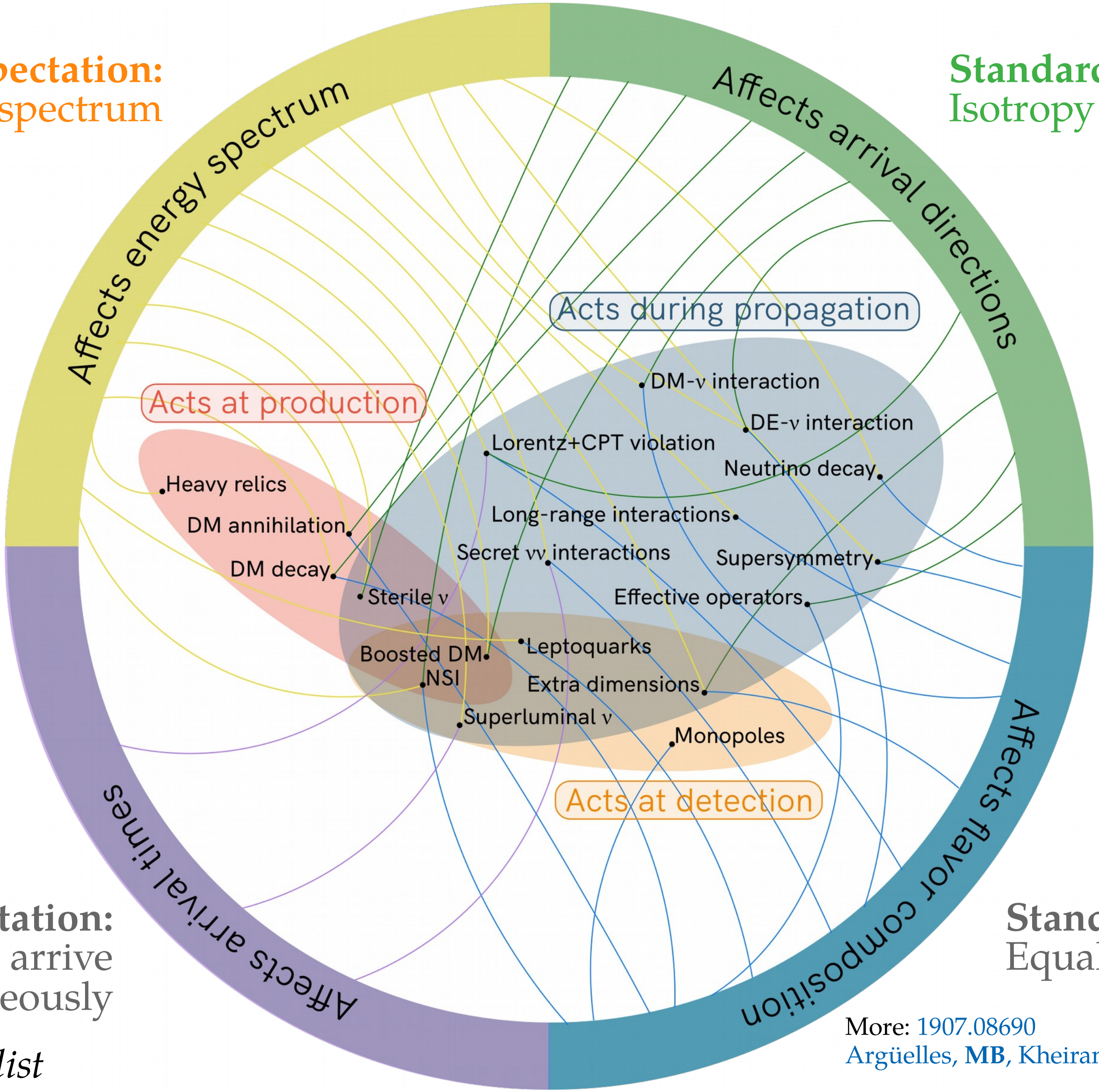


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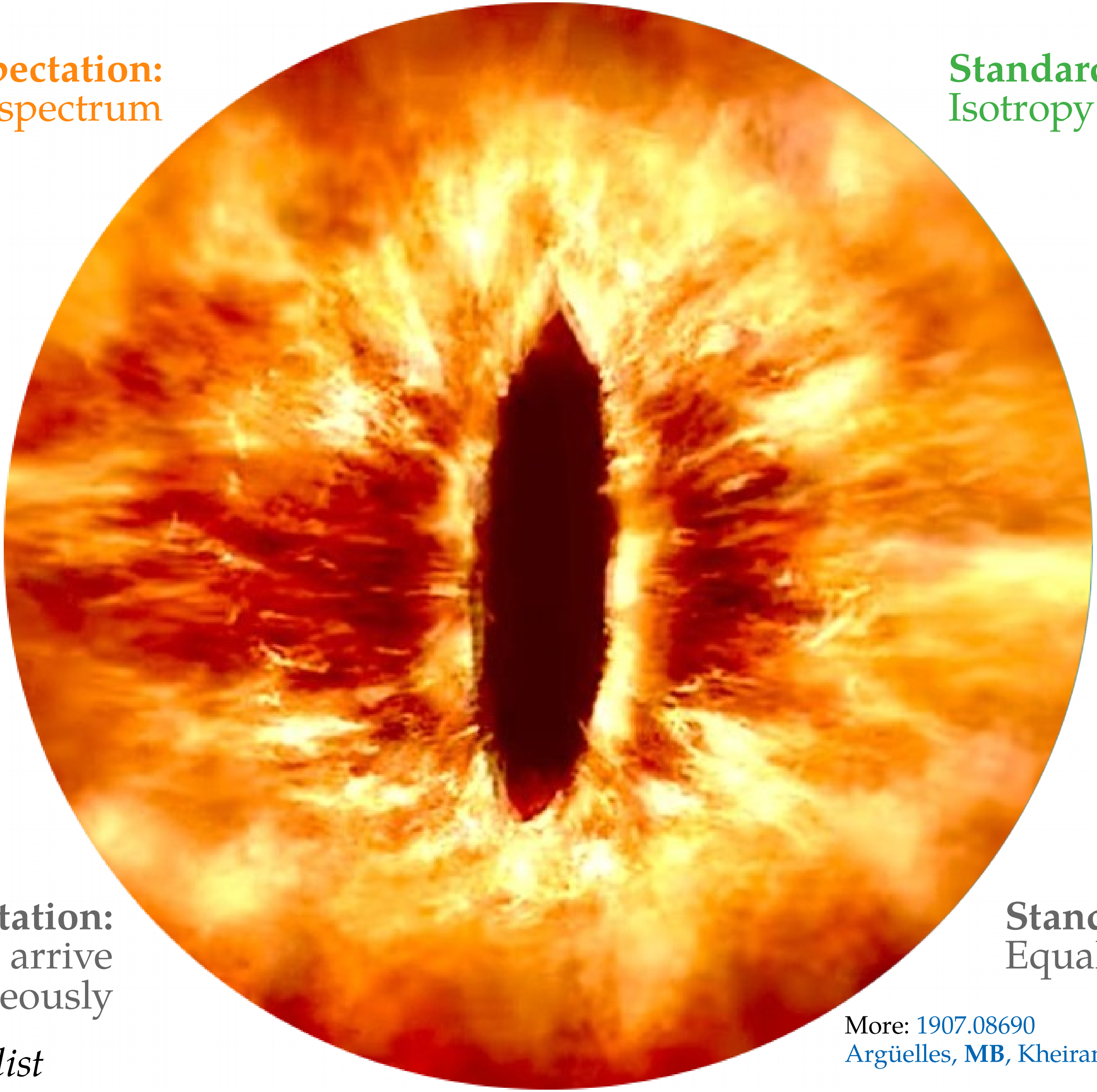

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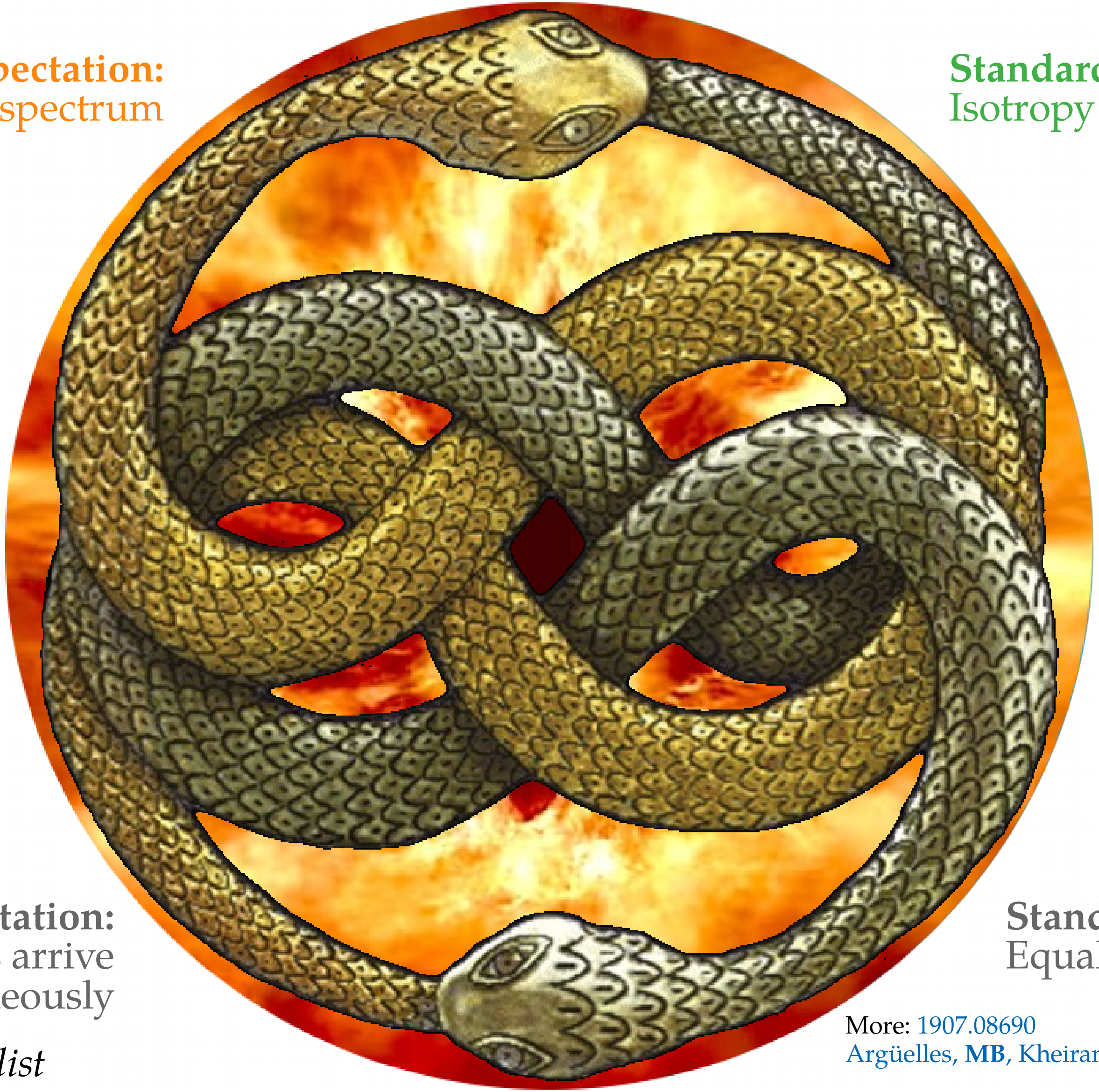

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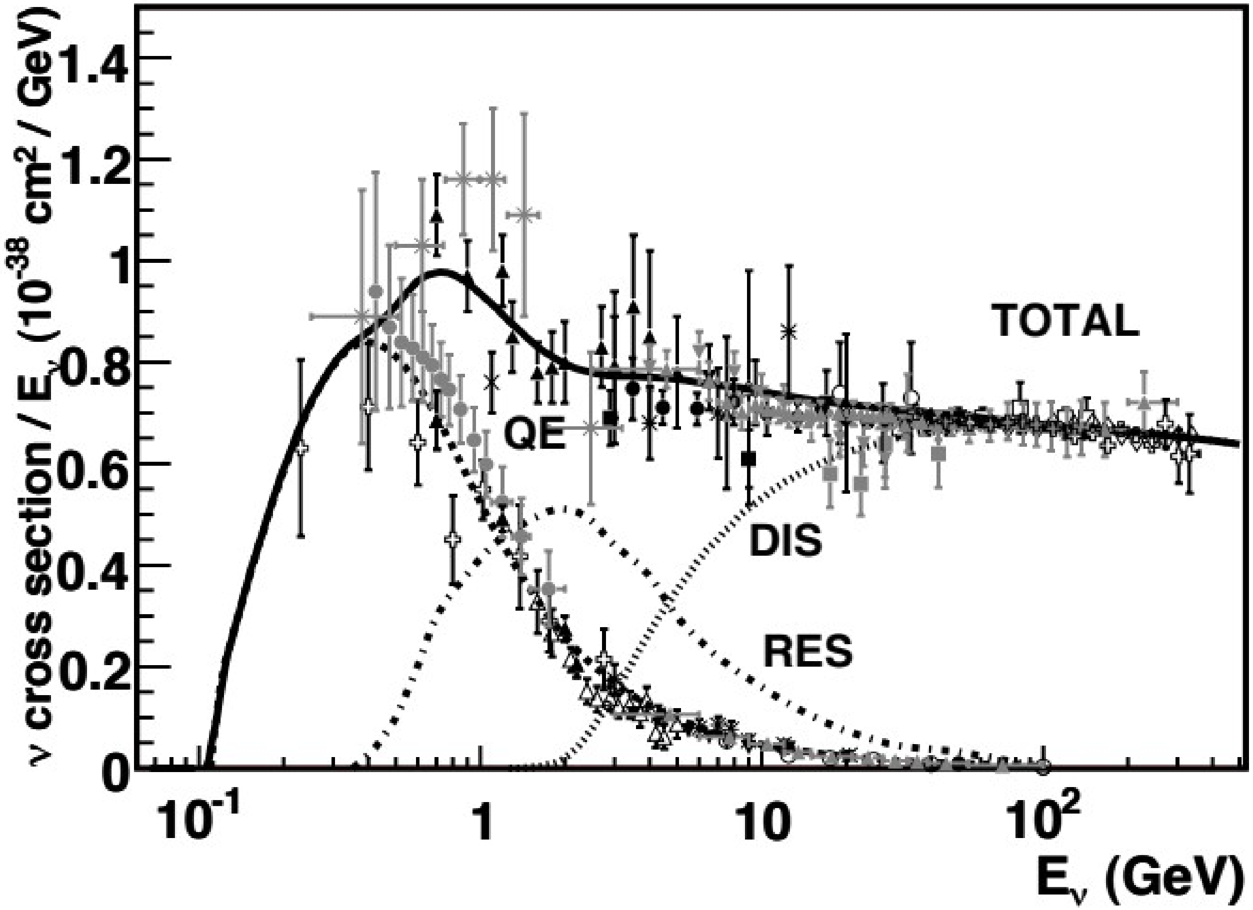
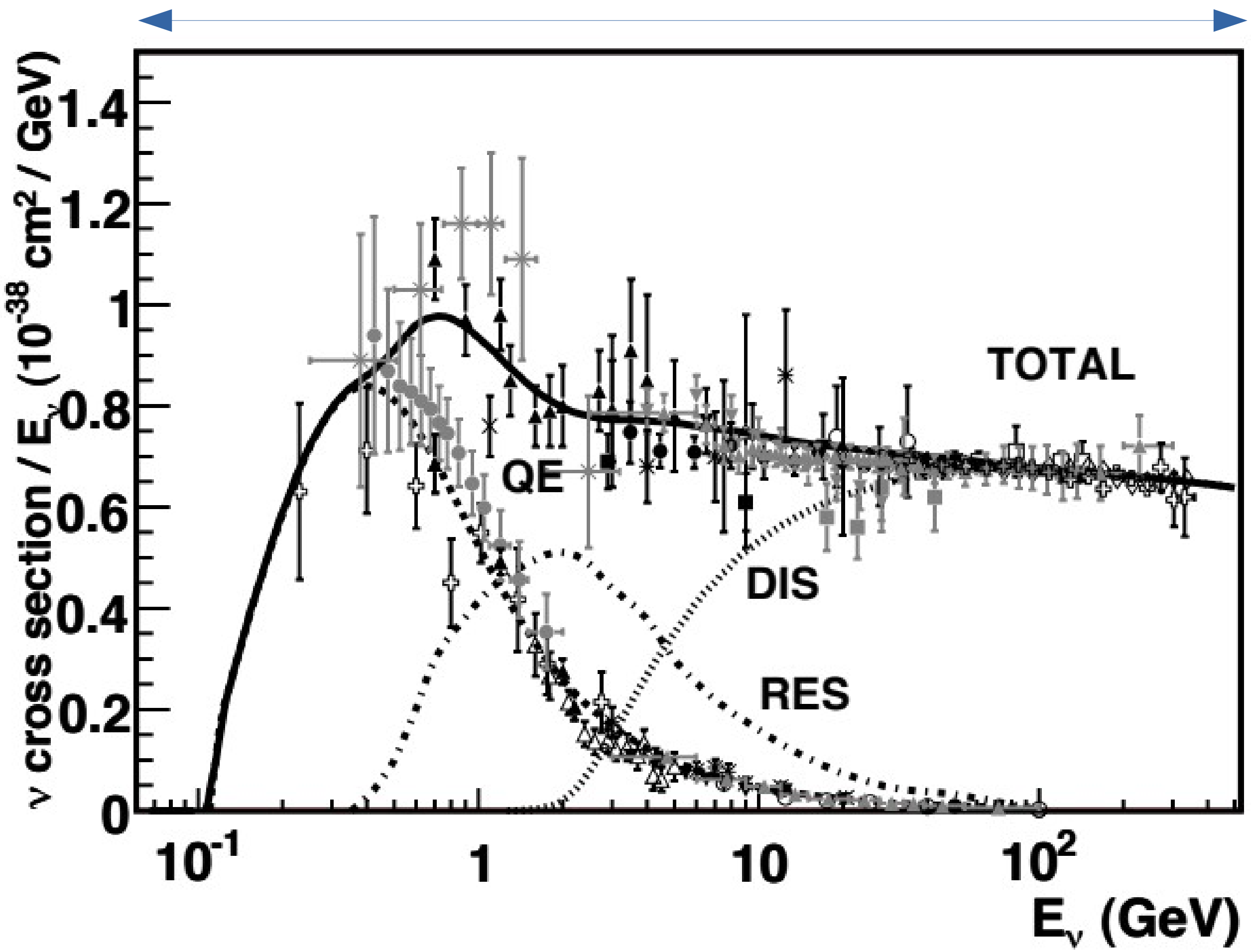



Particle Data Group

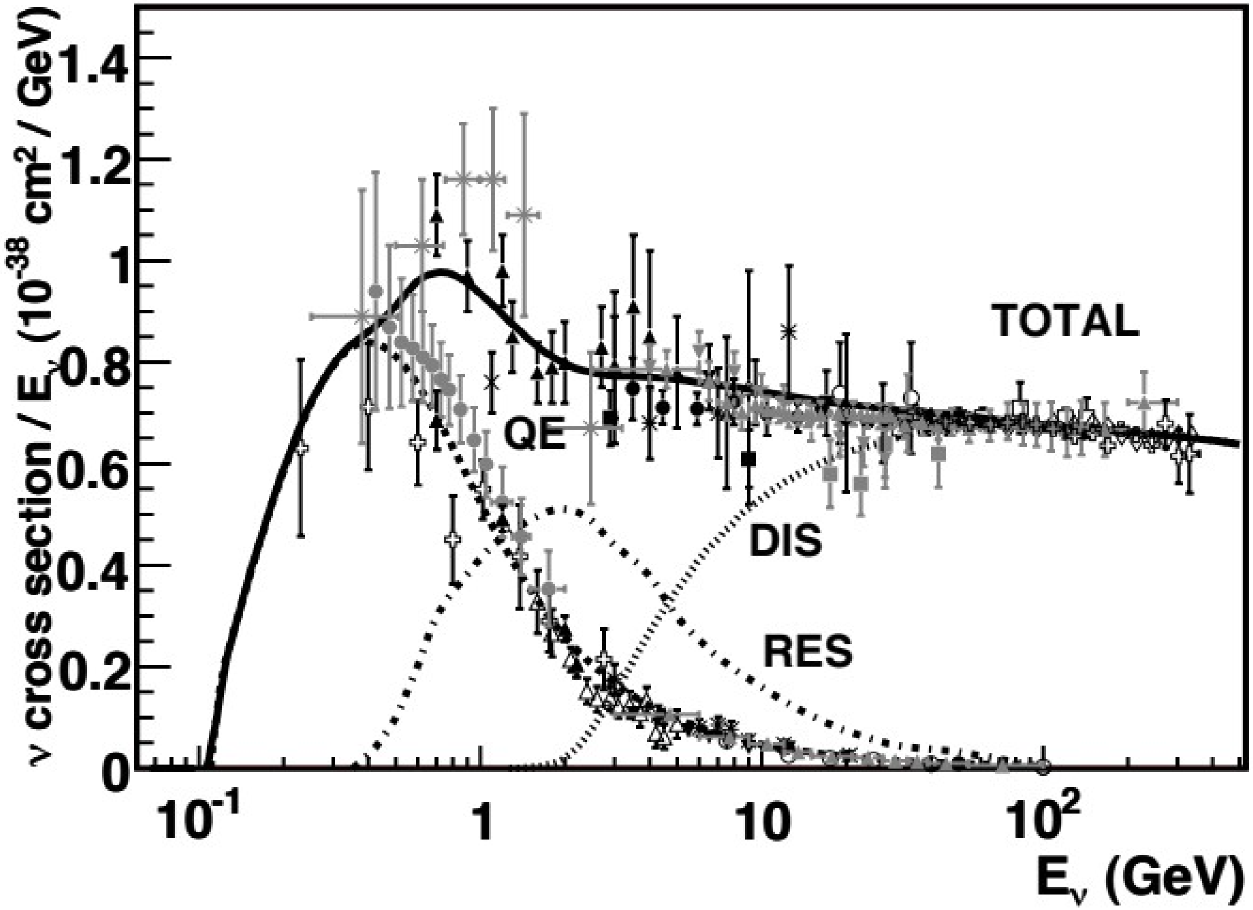
# Accelerator experiments




Particle Data Group

Accelerator experiments

One recent measurement (COHERENT)

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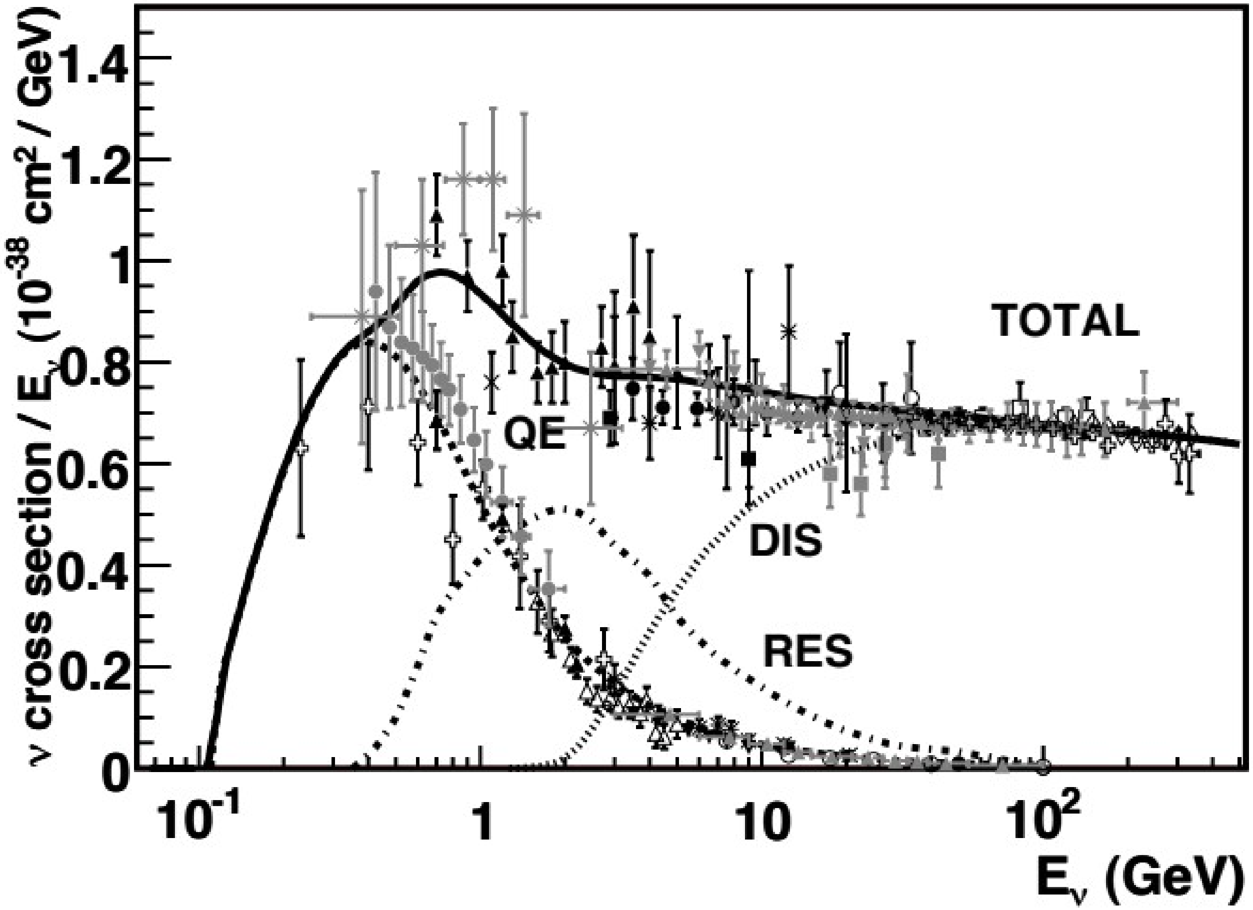


No measurements

… until recently!

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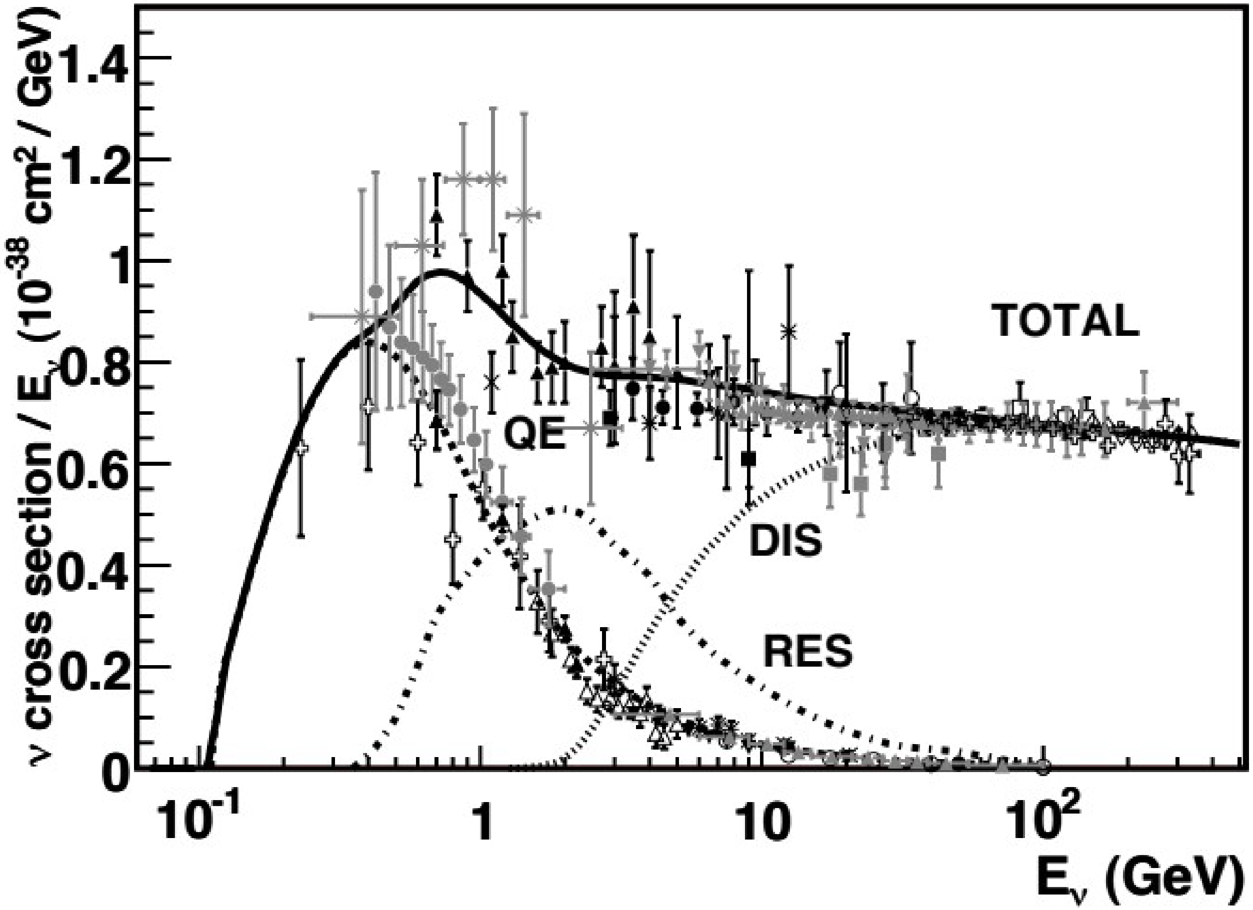


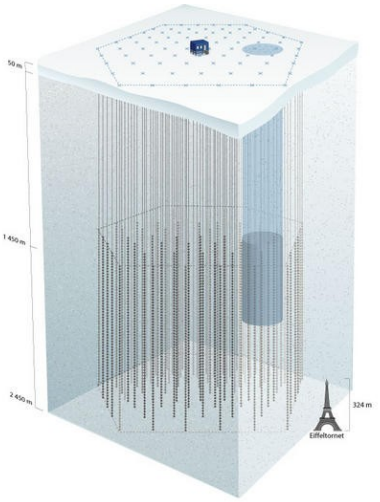

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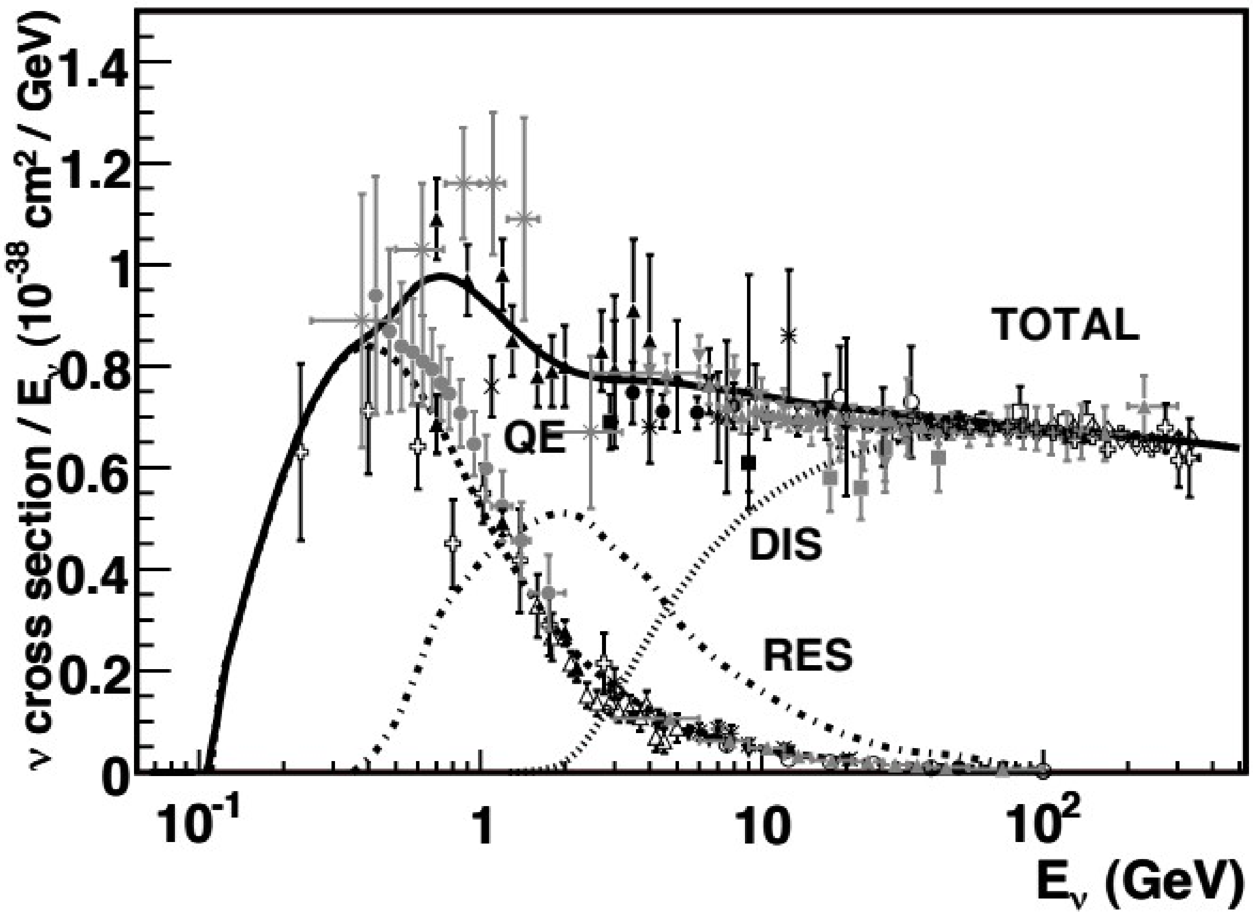


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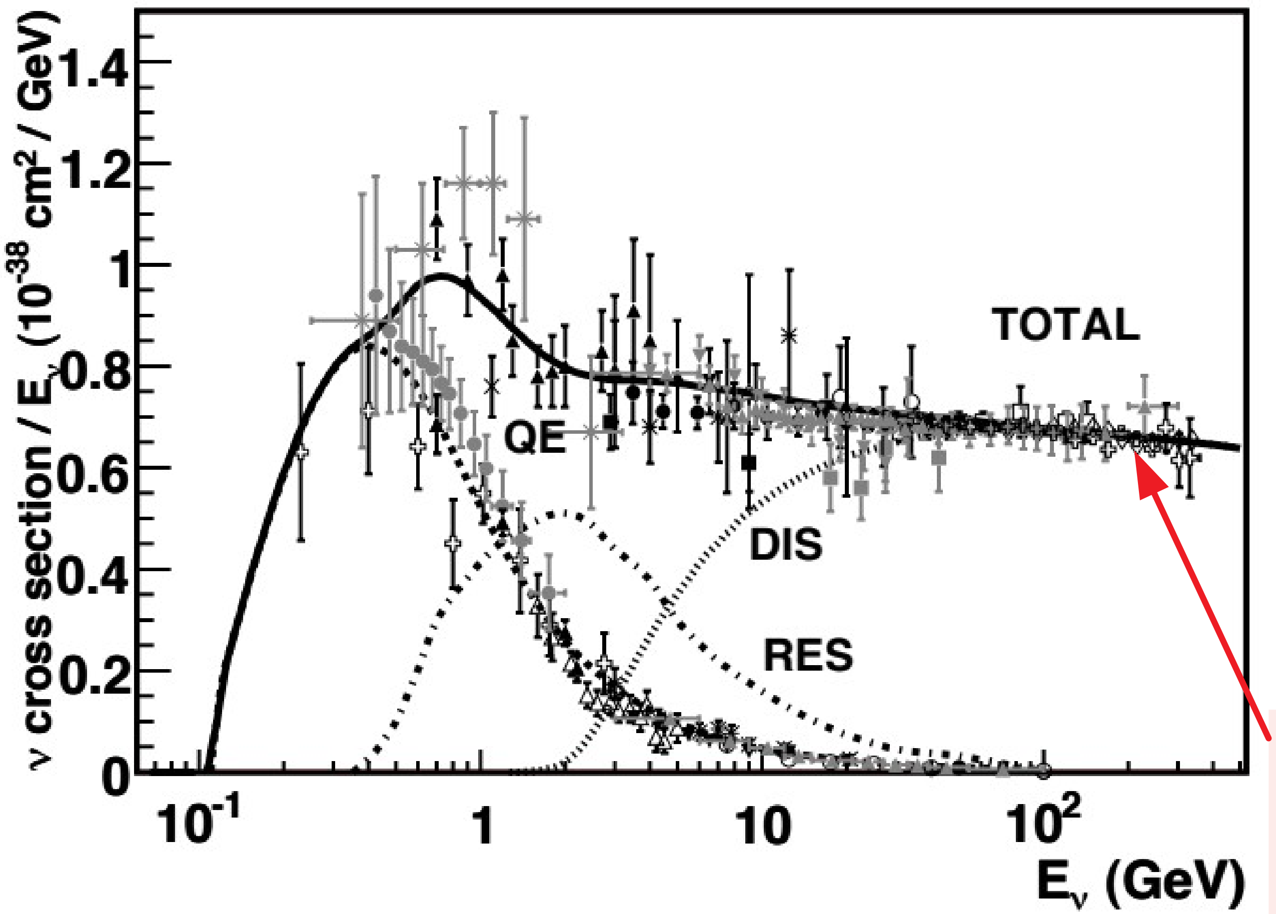



Particle Data Group

Deep inelastic scattering:

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

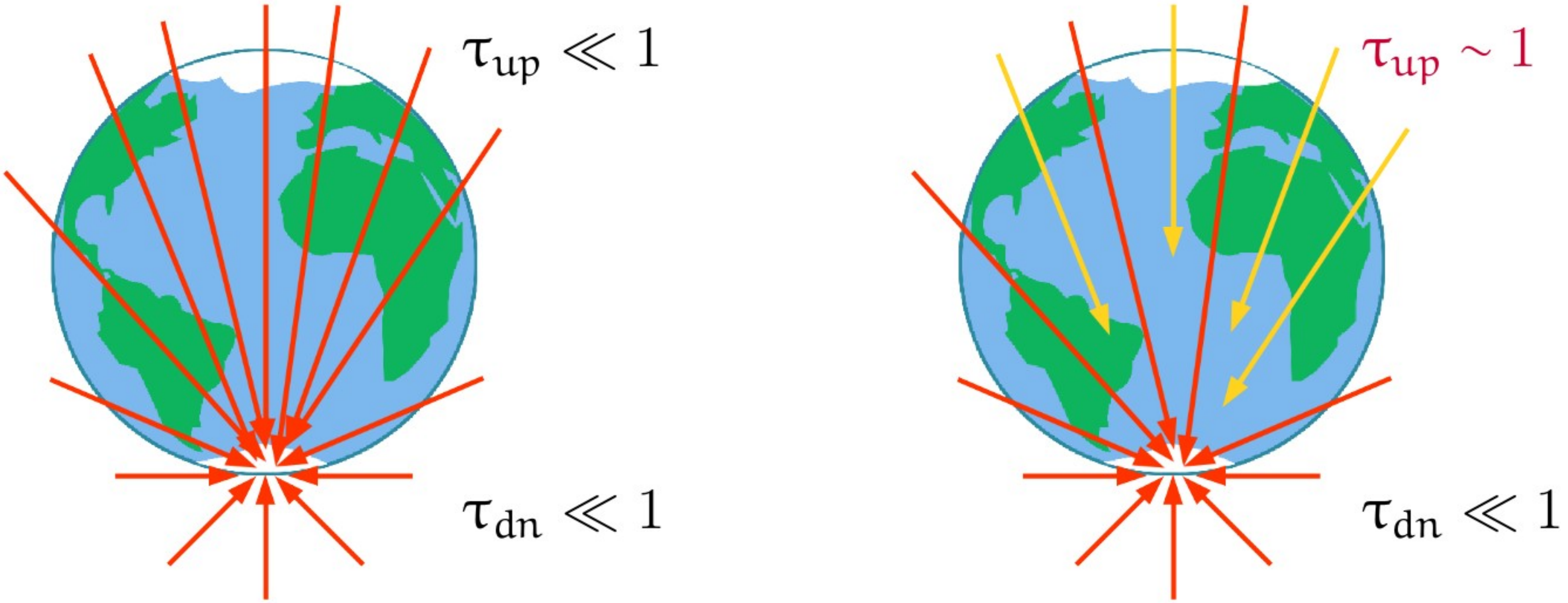
$\bar{\nu}_l + N \to l^+ + X$

# 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




Hooper, *PRD* 2002; Hussain *et al.*, *PRL* 2006; Borriello *et al.*, *PRD* 2008
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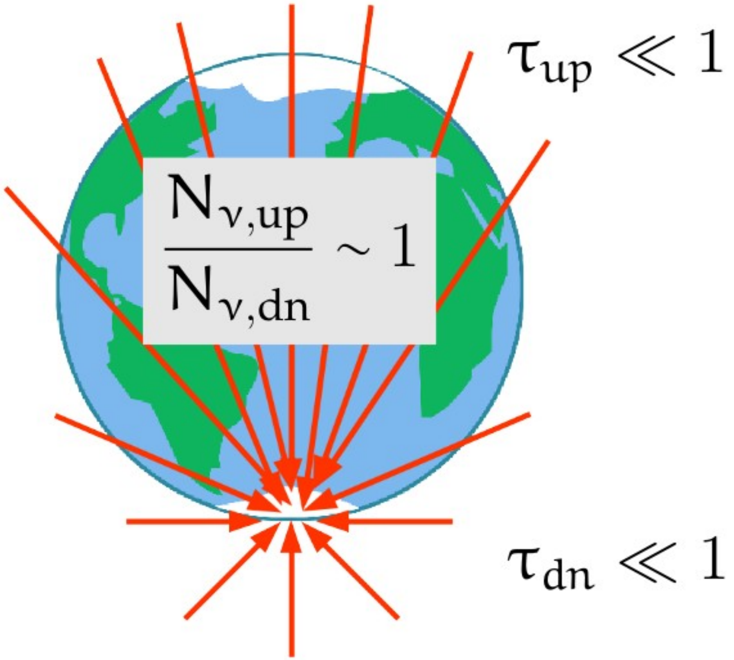


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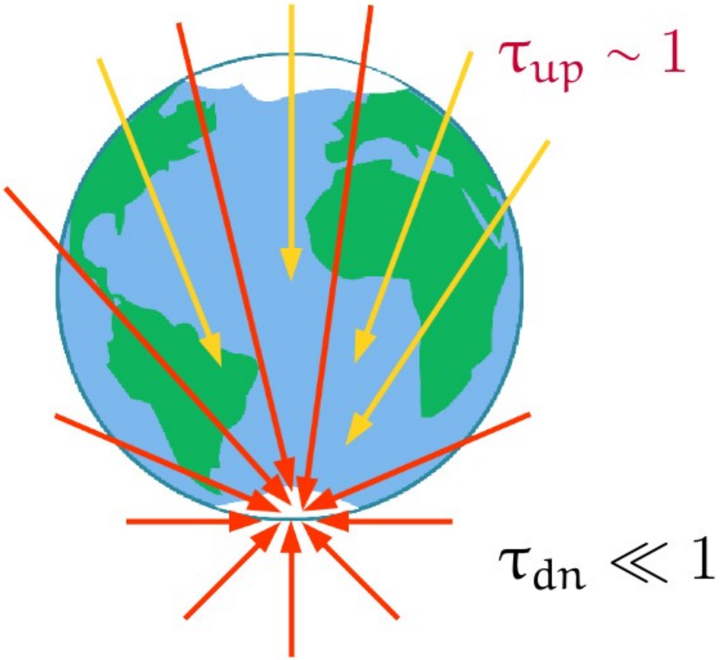


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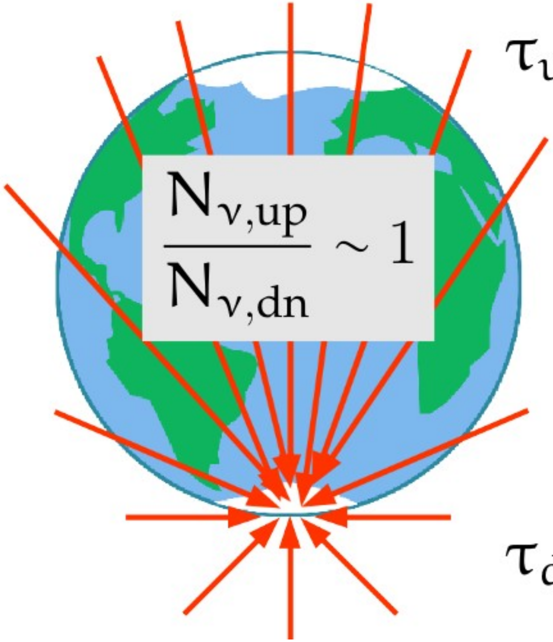
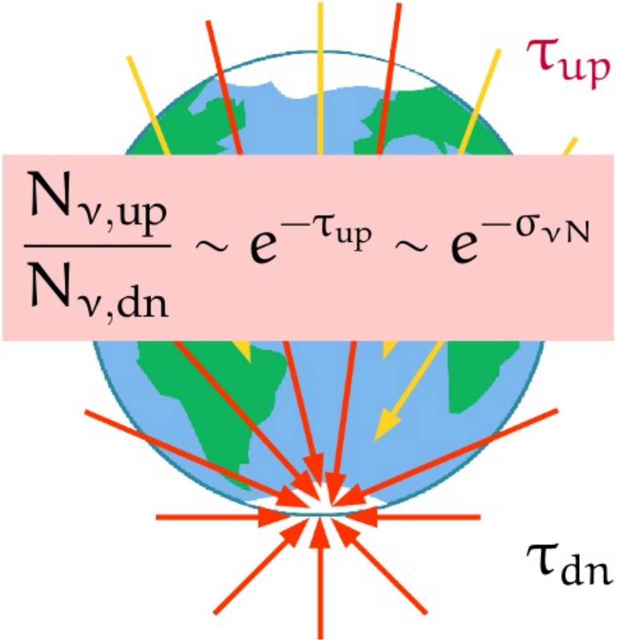



$\tau_{up} \ll 1$

$\tau_{dn} \ll 1$

Above ~ 10 TeV: Earth is opaque

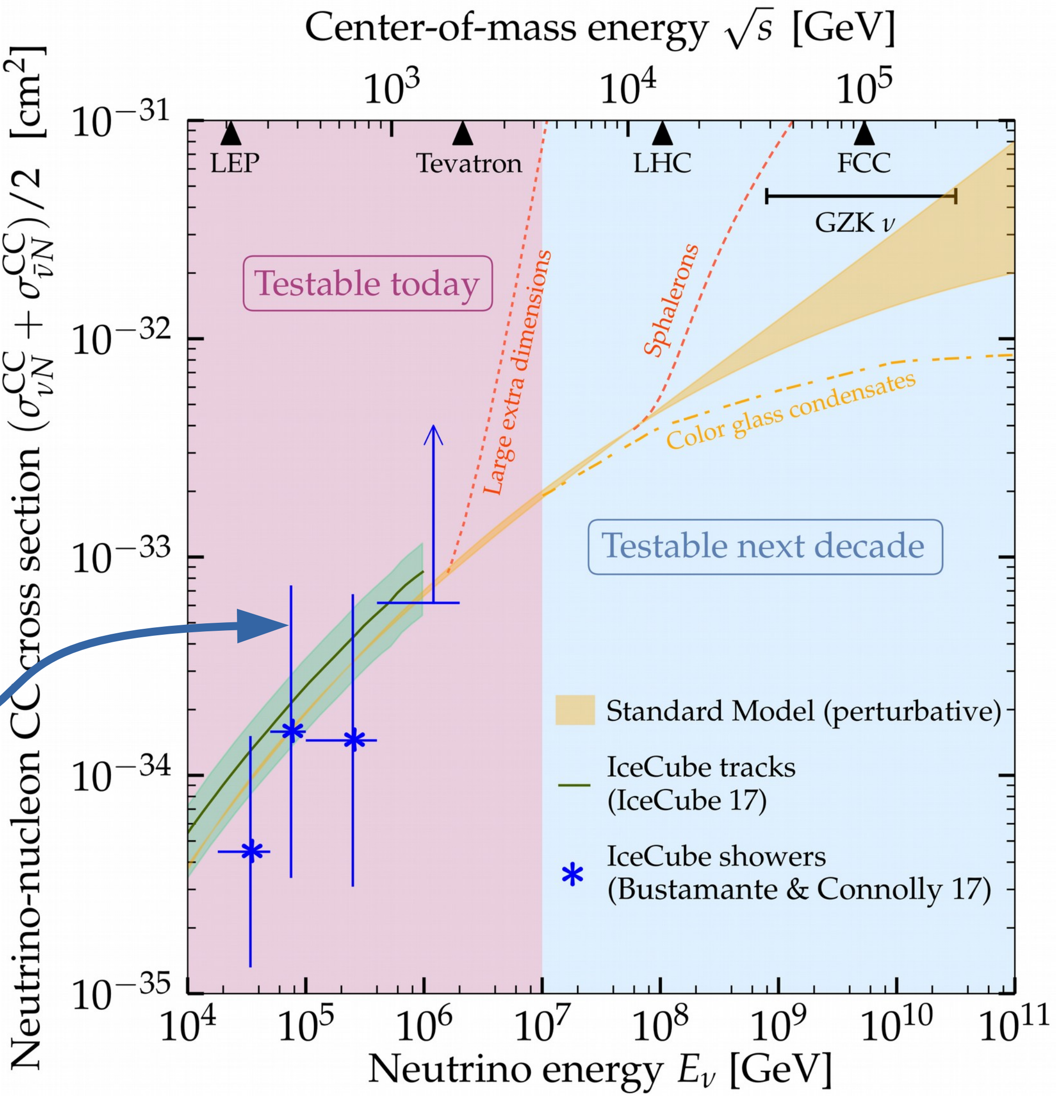



$\tau_{up} \sim 1$

$\tau_{dn} \ll 1$

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

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




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

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

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

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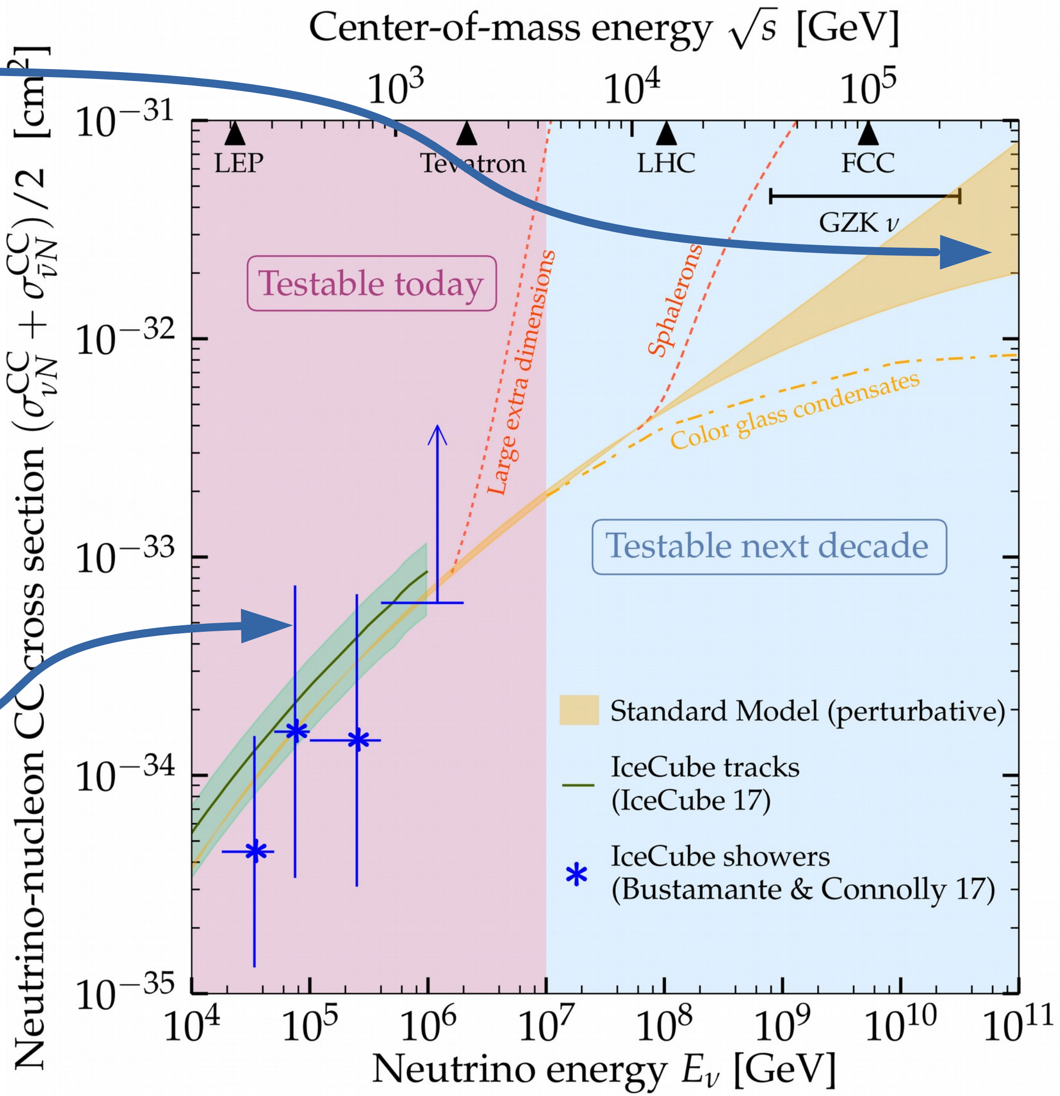


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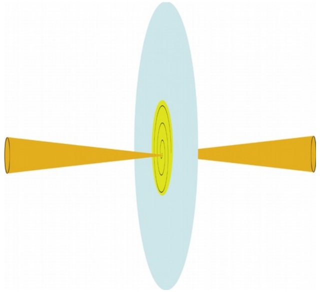
# Flavor composition

Astrophysical neutrino sources — Earth

Up to a few Gpc



$\nu_e$

$\nu_\mu$

$\nu_\tau$

Flavor mixing changes the number

of $\nu$ of each flavor, $N_e$, $N_\mu$, $N_\tau$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

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

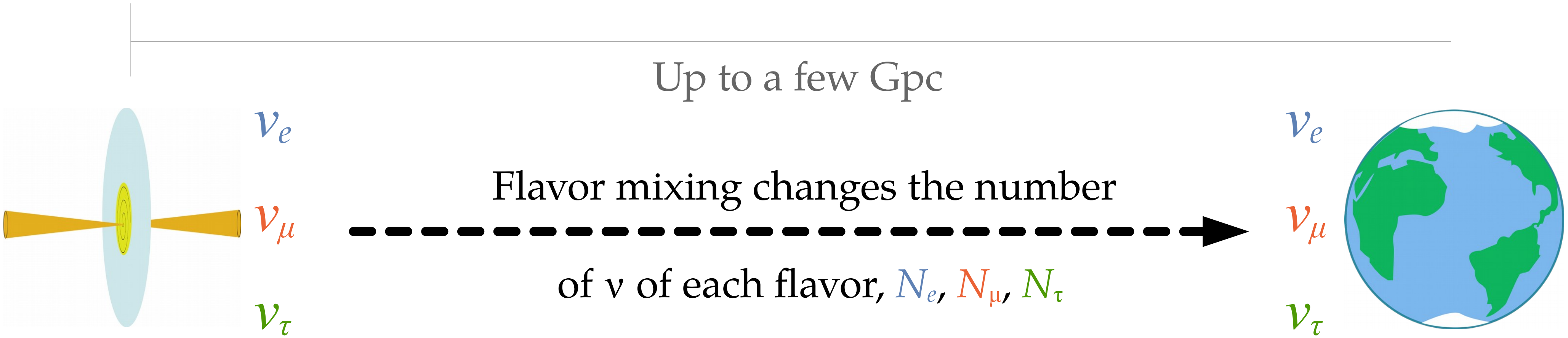
$$(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$$

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

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

# Flavor composition

Astrophysical neutrino sources Earth

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

Standard oscillations
*or*
new physics

# One likely TeV–PeV $\nu$ production scenario:

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

**Full $\pi$ decay chain**

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

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

Flavor can also probe the sources themselves: **MB** & Ahlers, *PRL* 2019 → Poster session 2 (Sat 27 & Mon 29)

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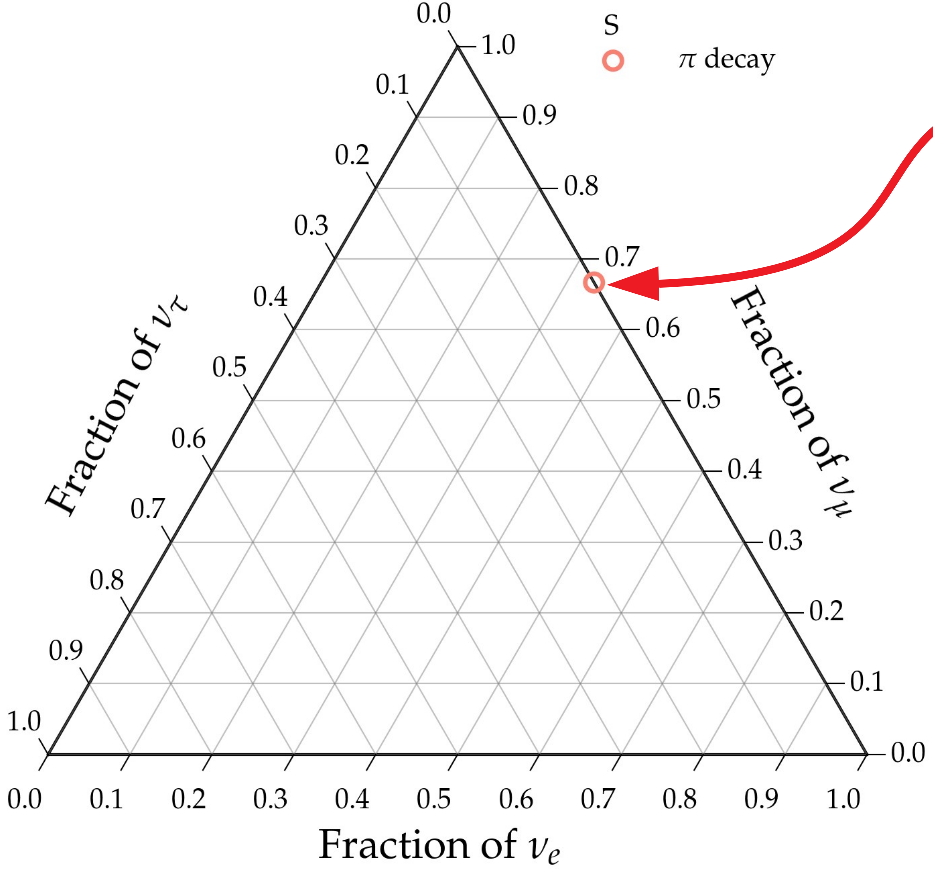


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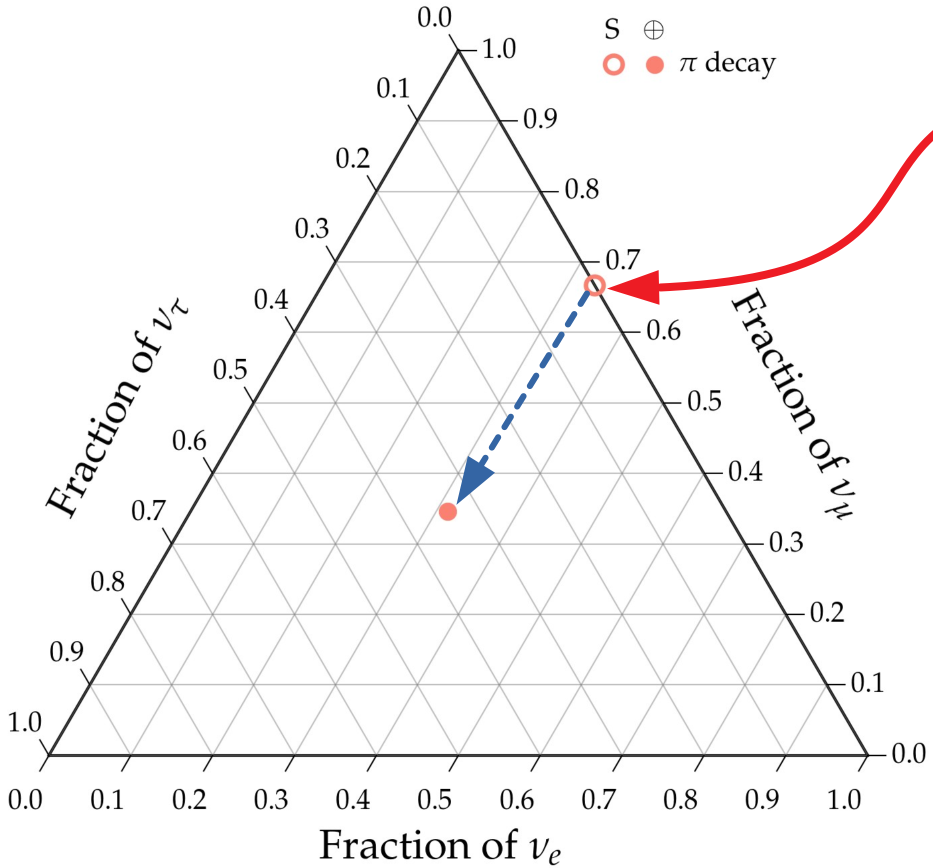


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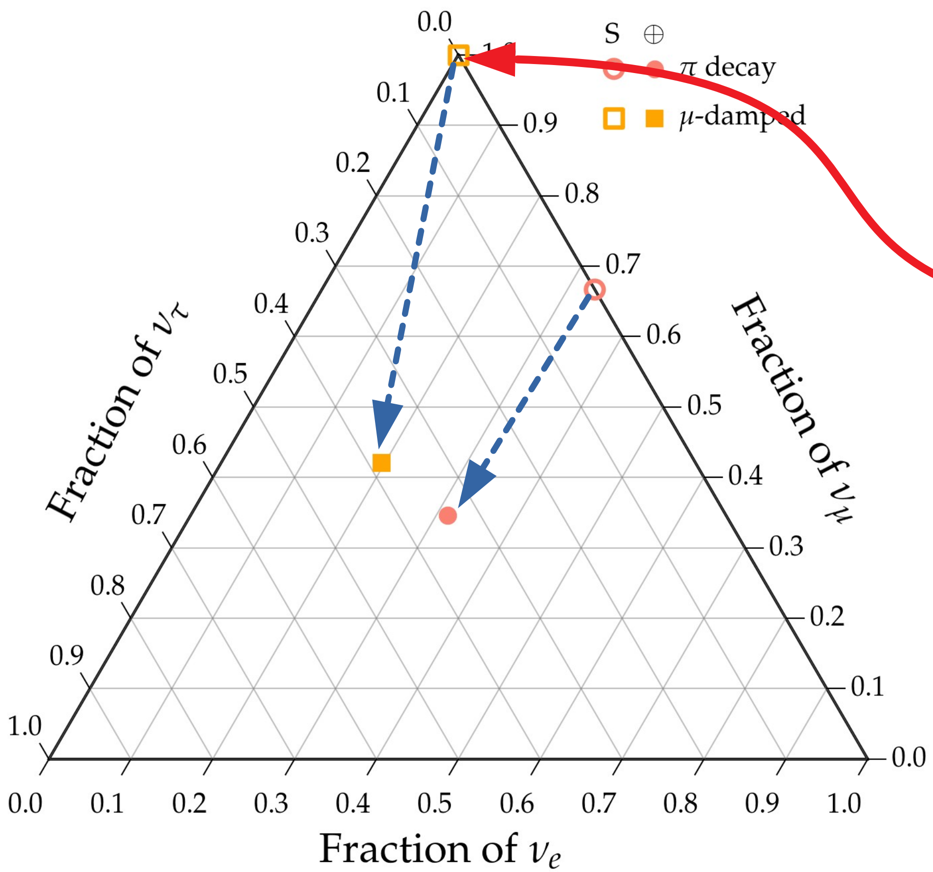


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Muon damped

$(0:1:0)_S$

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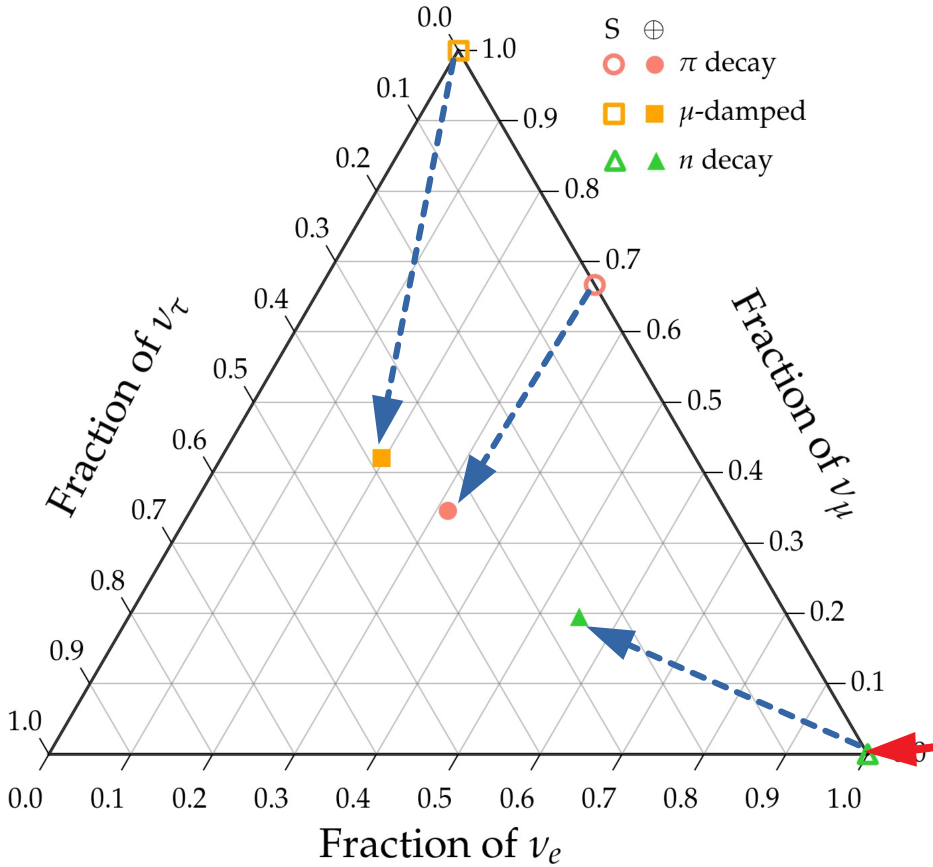


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**Neutron decay**

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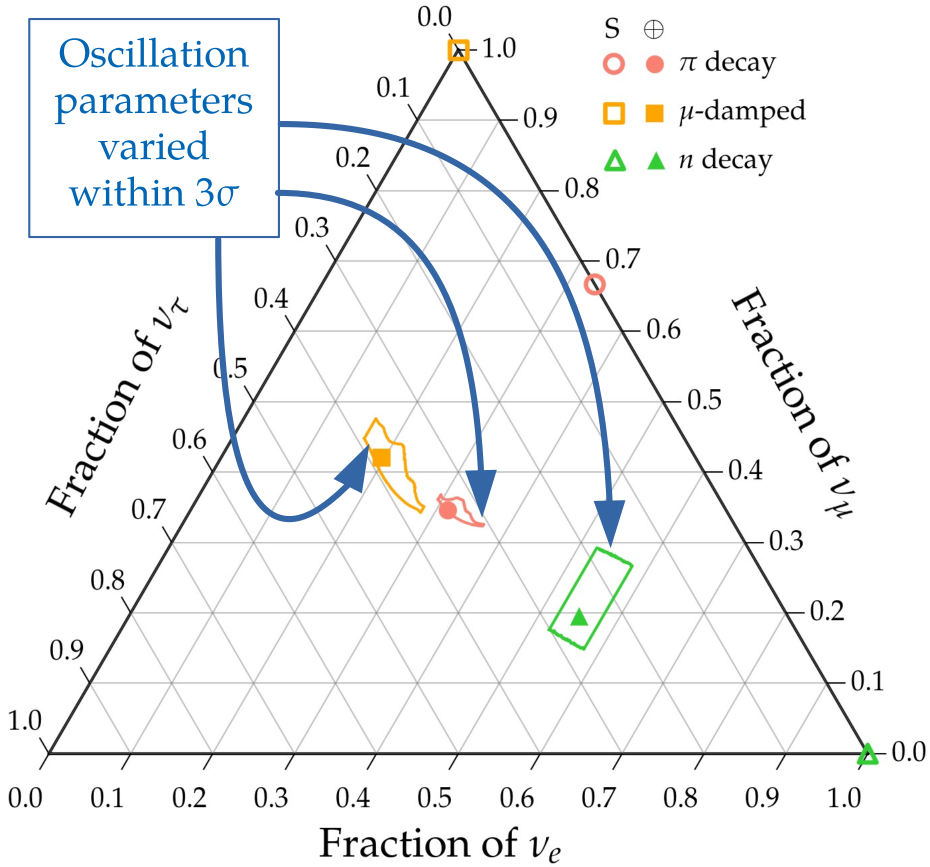


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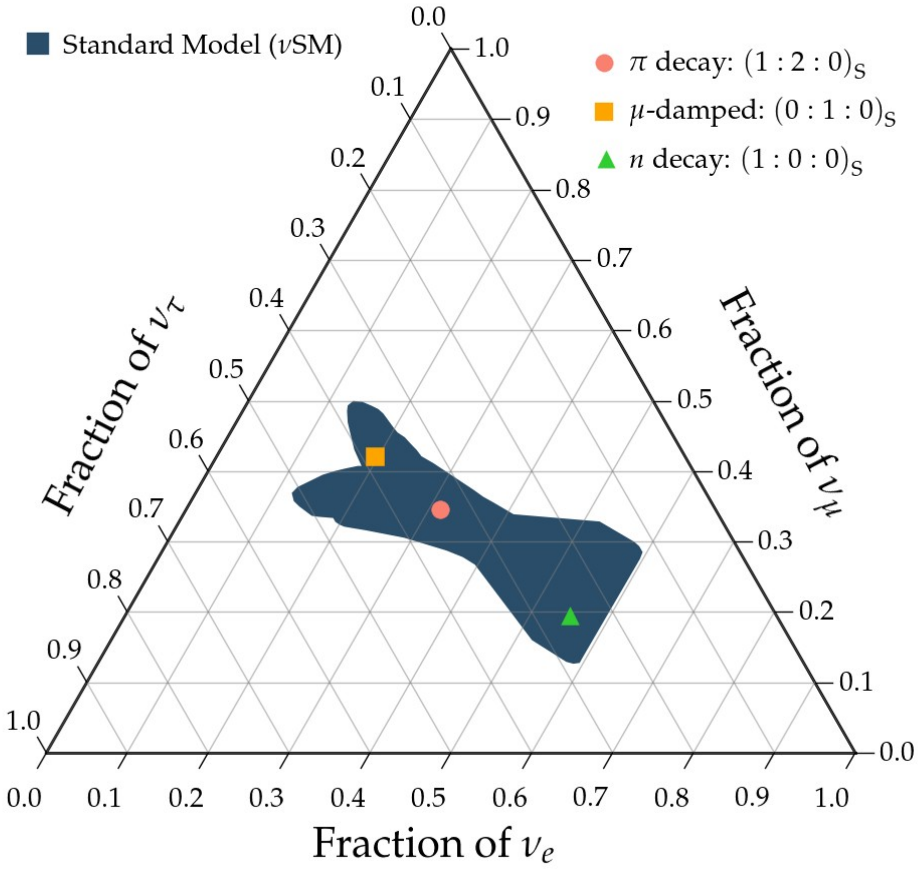


All possible flavor ratios at the sources

+

Vary oscillation parameters within $3\sigma$

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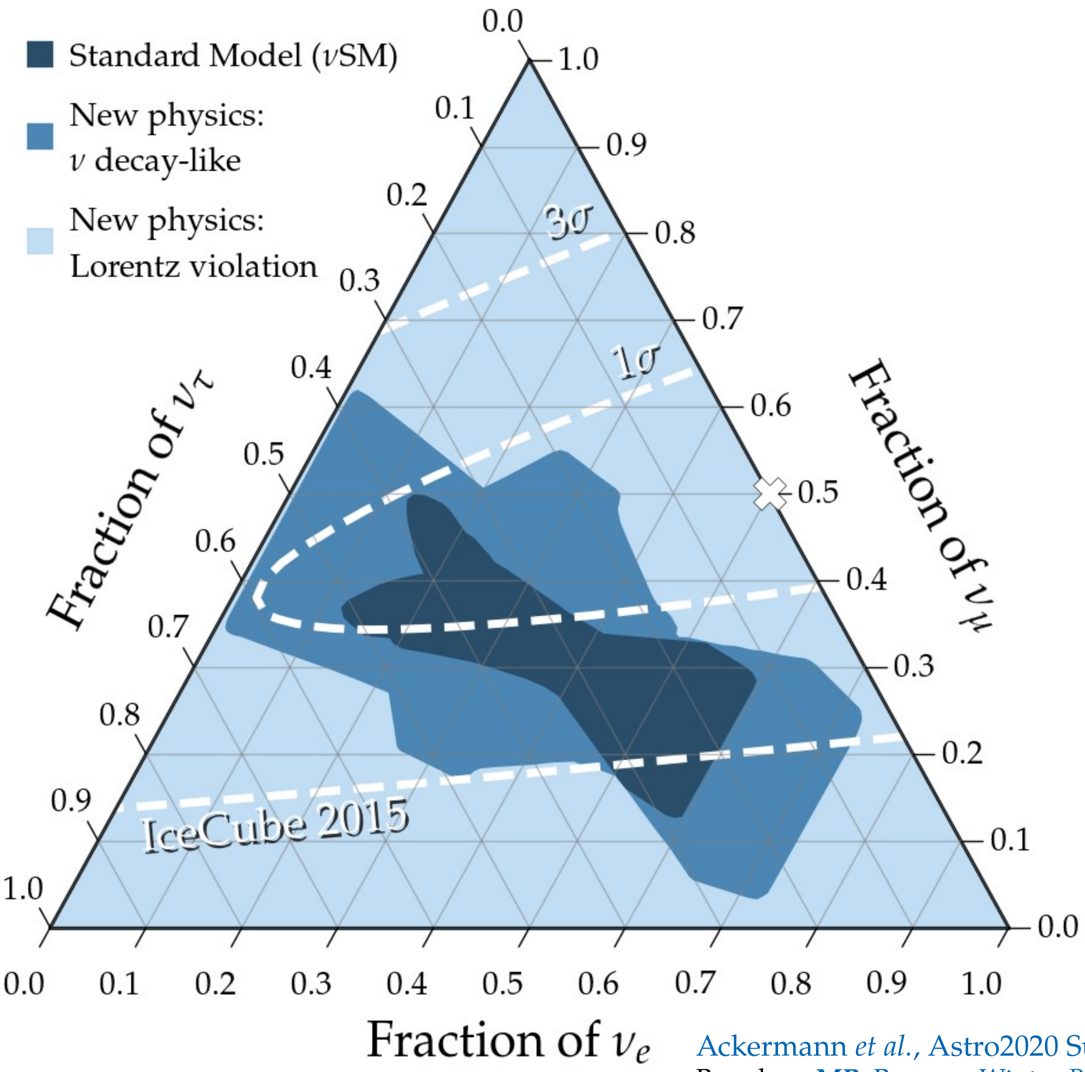
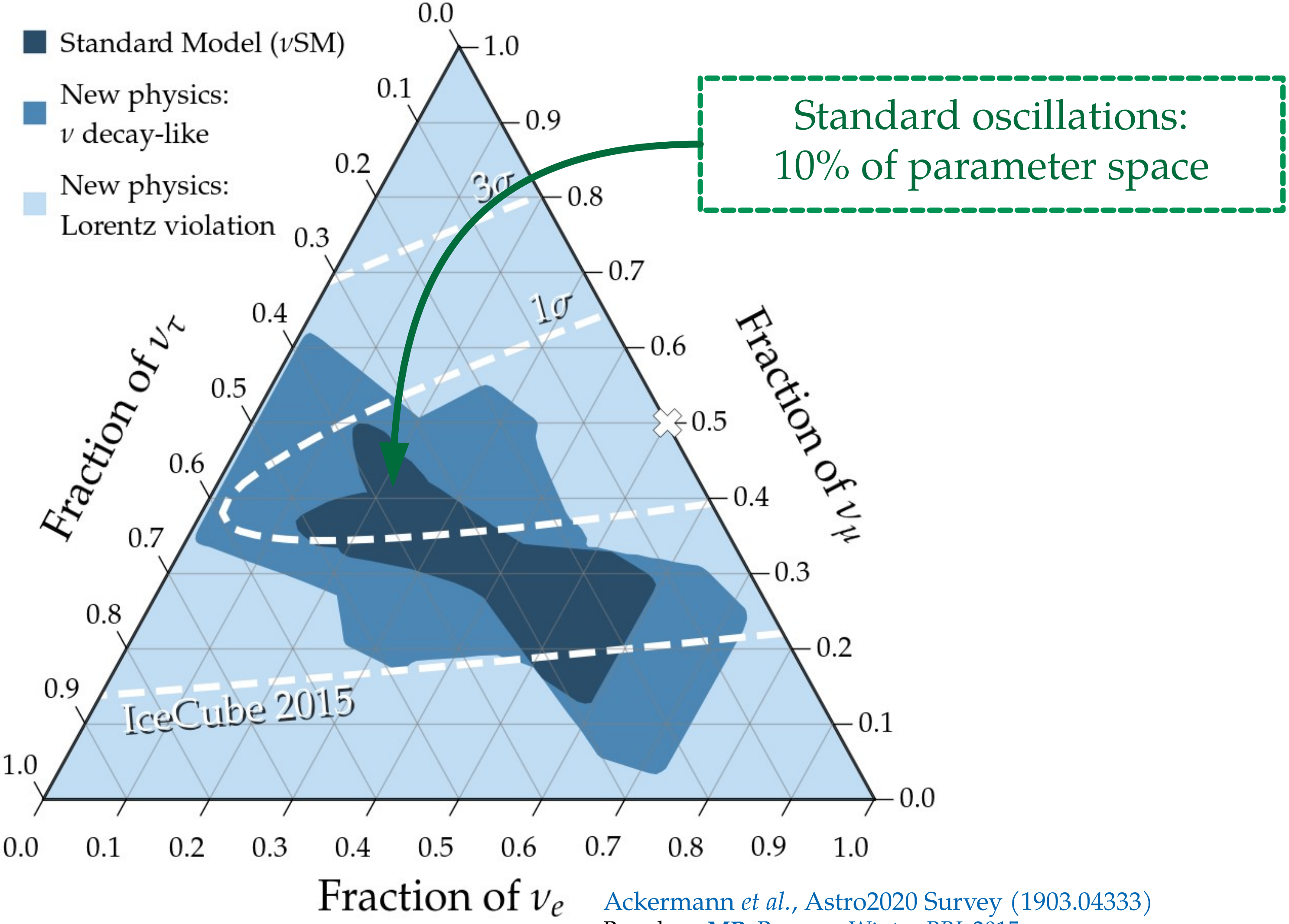



Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

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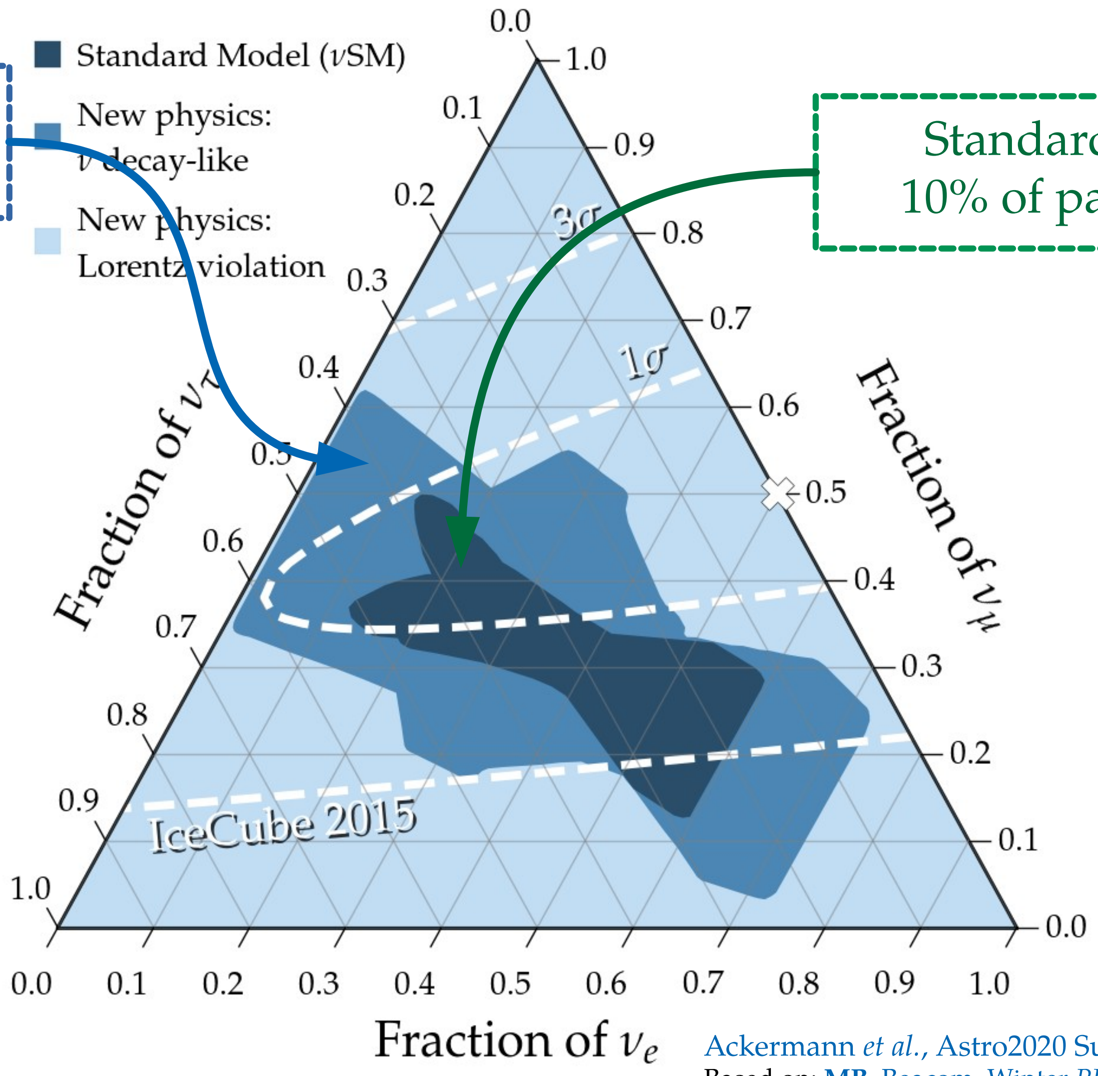
Neutrino decay
30% of parameter space

Standard oscillations:
10% of parameter space

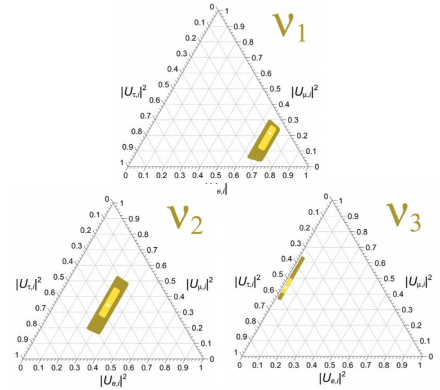



Ackermann *et al.*, Astro2020 Survey (1903.04333)
Based on: **MB**, Beacom, Winter *PRL* 2015

Neutrino decay
30% of parameter space

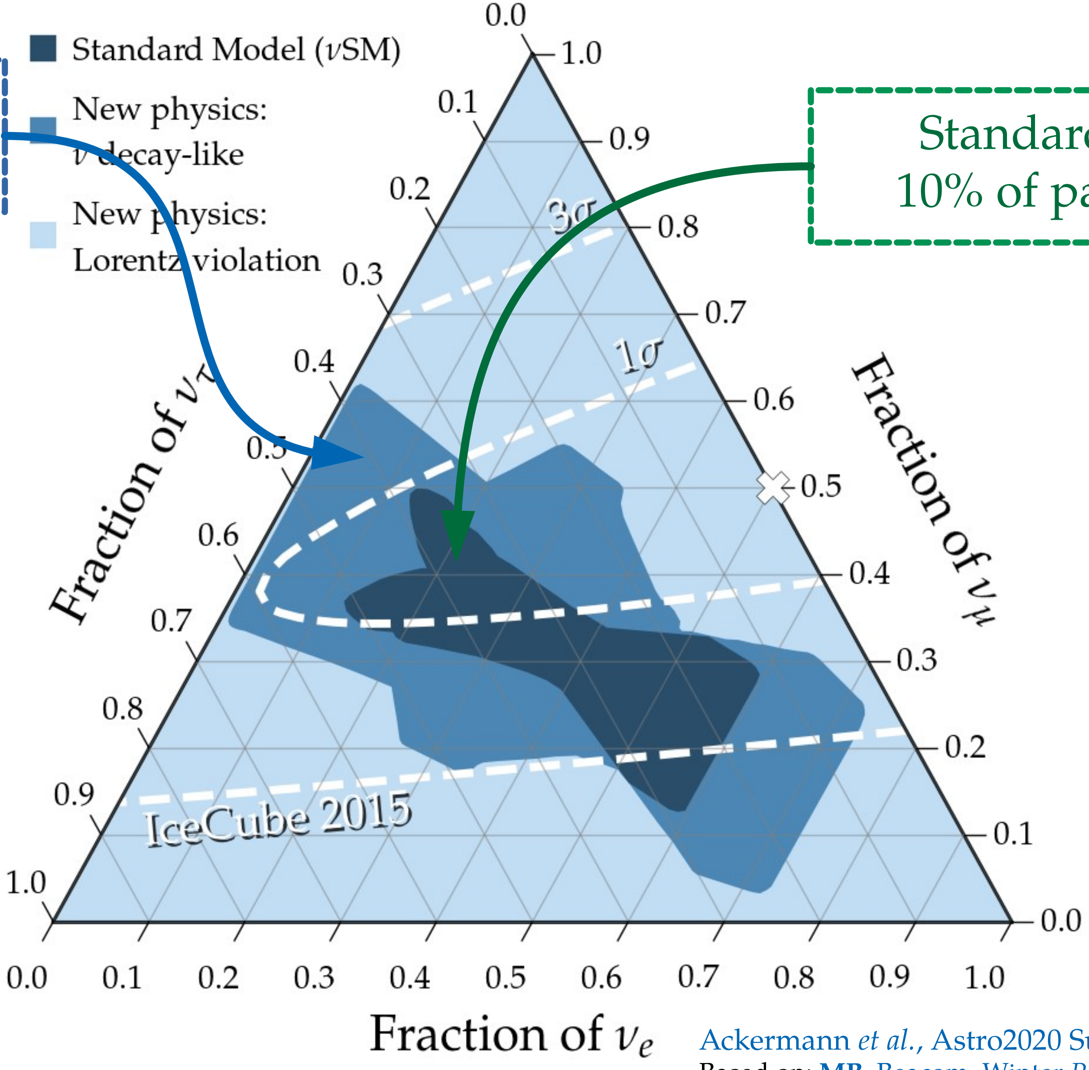
$\nu_2, \nu_3 \rightarrow \nu_1$ or $\nu_1, \nu_2 \rightarrow \nu_3$

Flavor ratios determined by how many $\nu_1, \nu_2, \nu_3$ survive:




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

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

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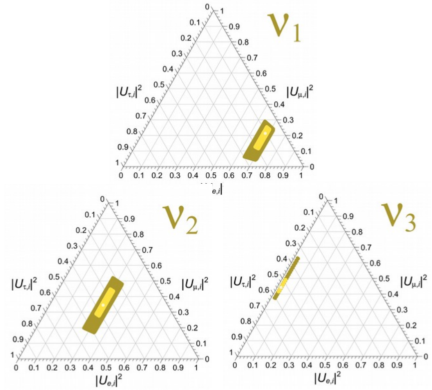


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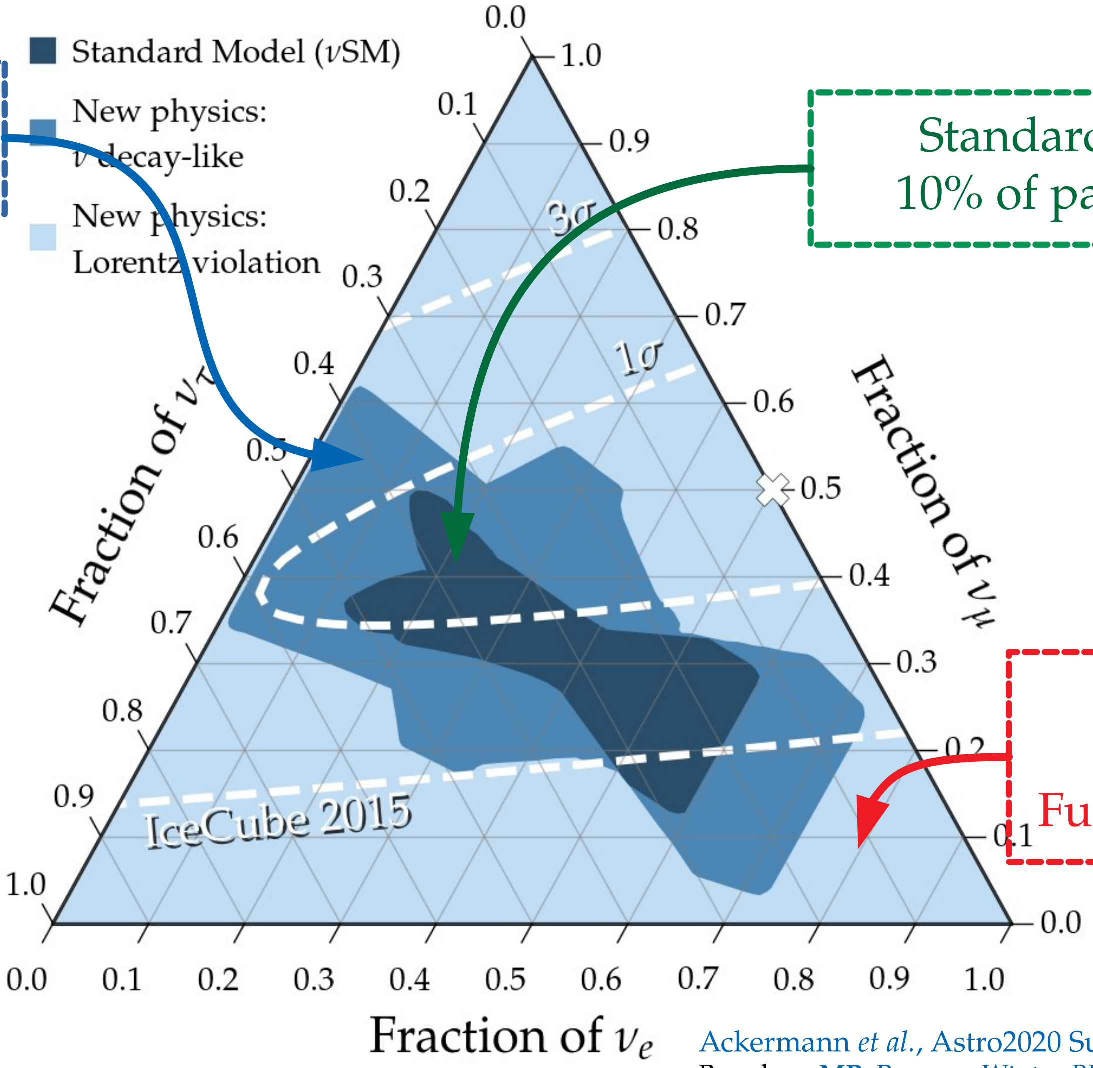


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Lorentz, CPT violation, etc:
Full parameter space

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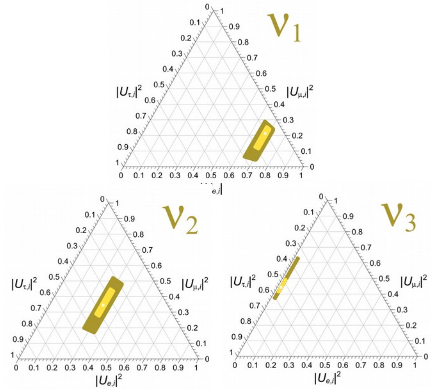


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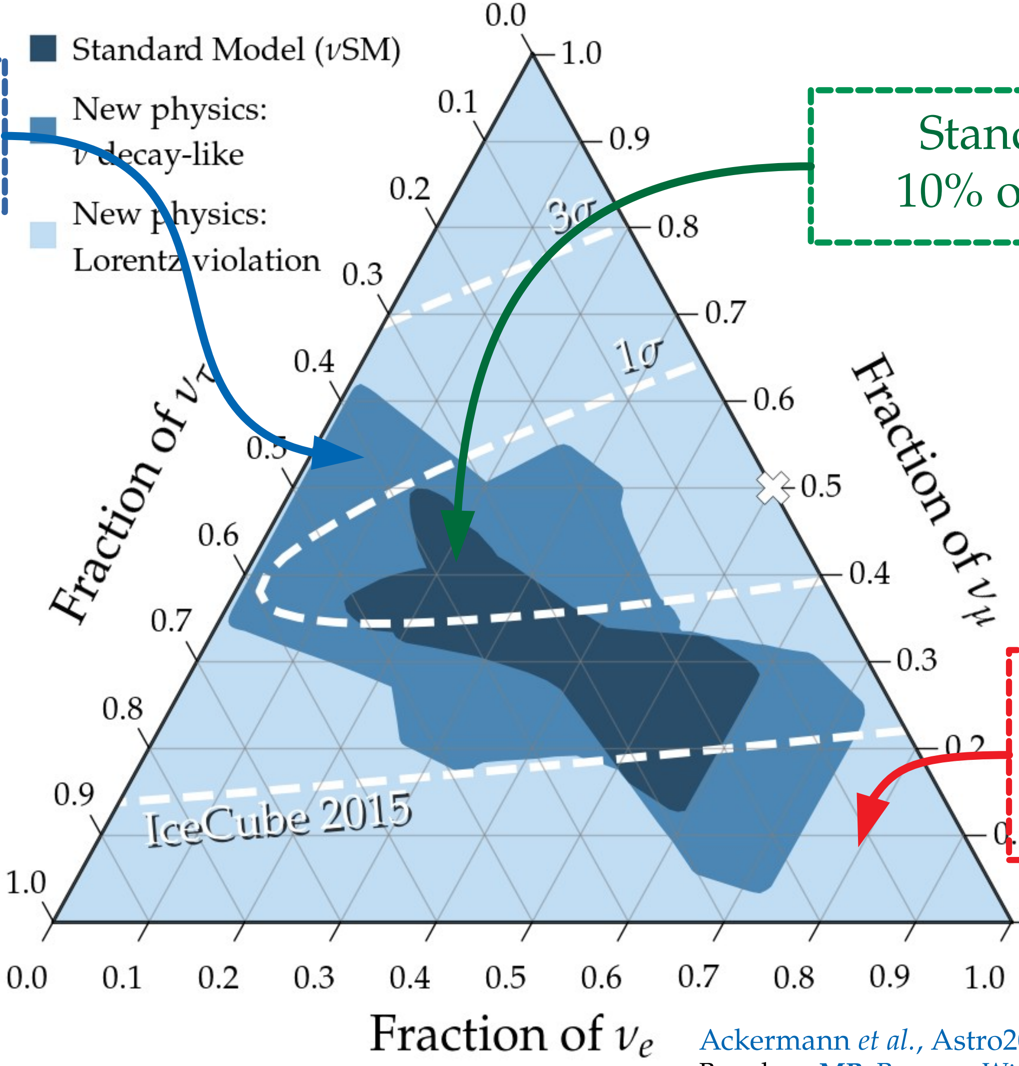


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# New physics – High-energy effects

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

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

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

This can populate *all* of the triangle –

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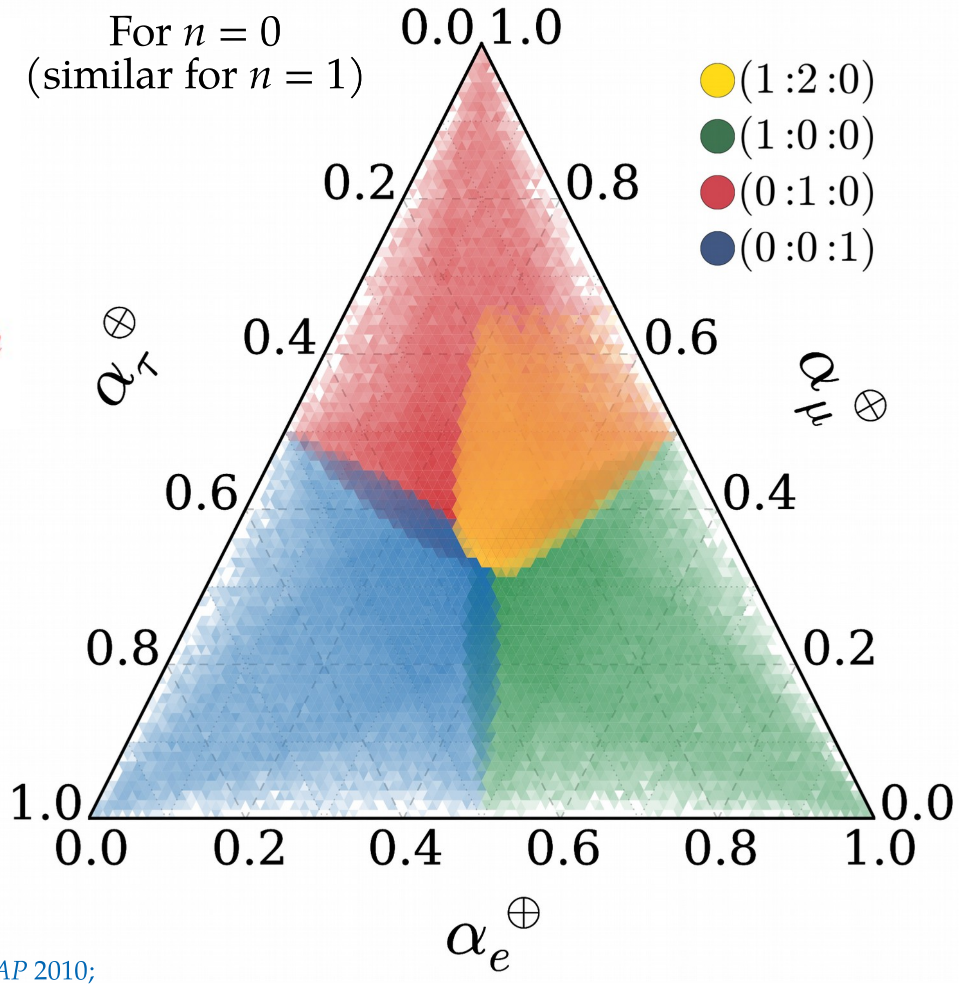
- Sample the unknown new mixing angles




Argüelles, Katori, Salvadó, *PRL* 2015

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

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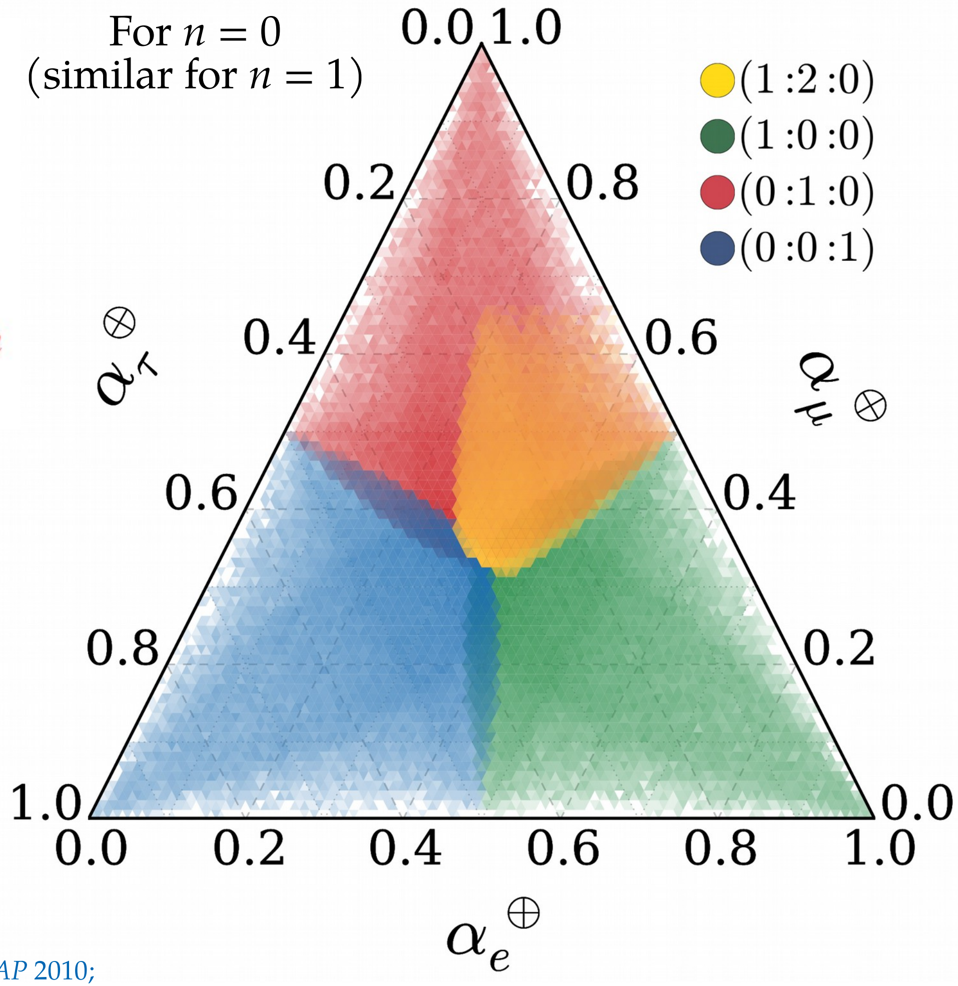


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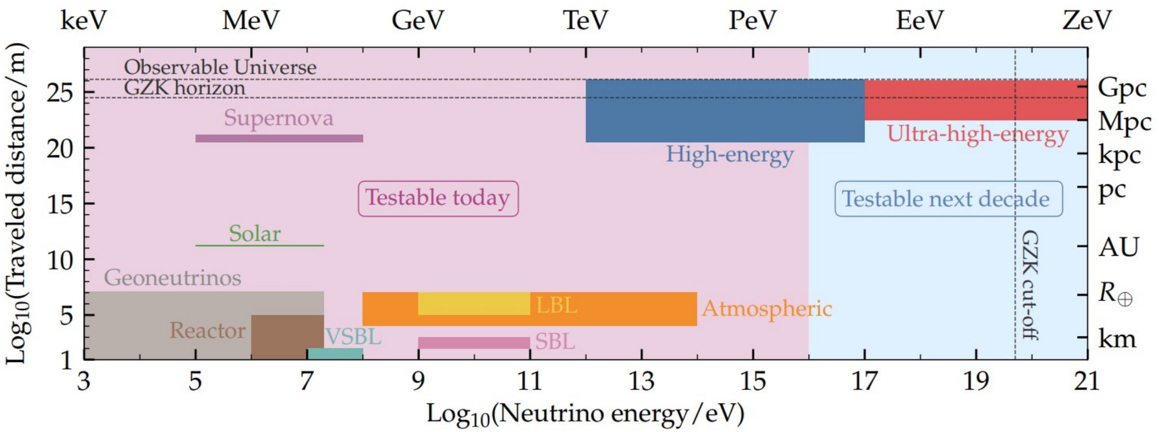
# An exciting decade ahead




**Today:** TeV–PeV astrophysical $\nu$

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

IceCube + ANTARES + Baikal

+ Growing statistics

+ Improved systematics

**Next decade:** EeV cosmogenic $\nu$

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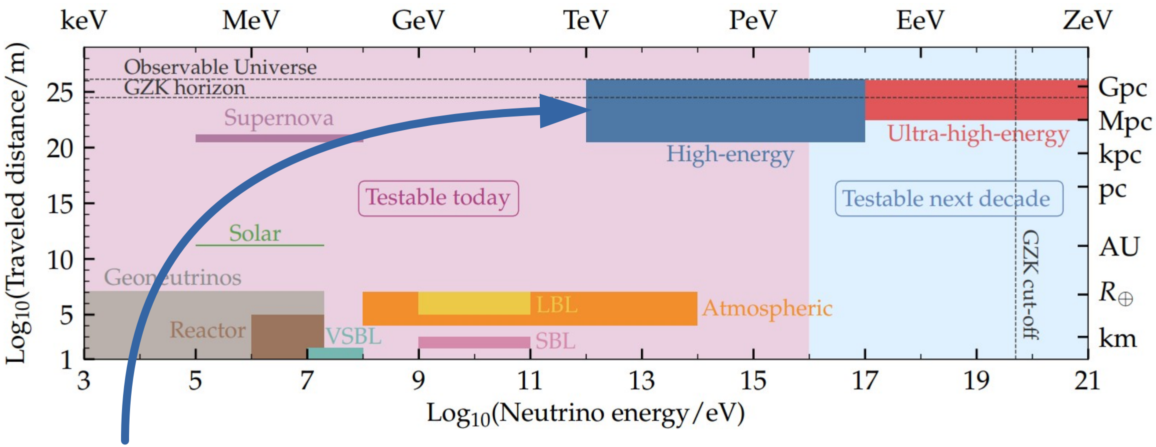


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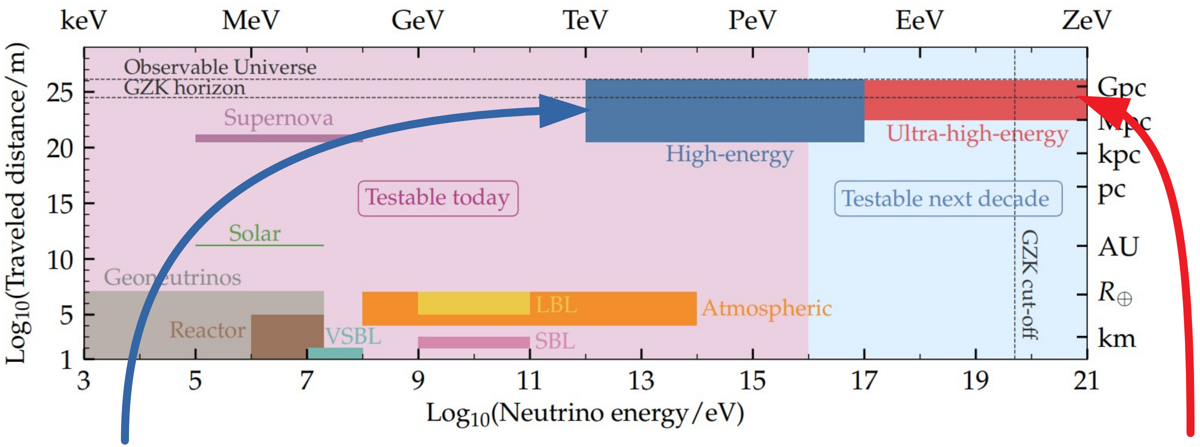


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# What are you taking home?

- 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

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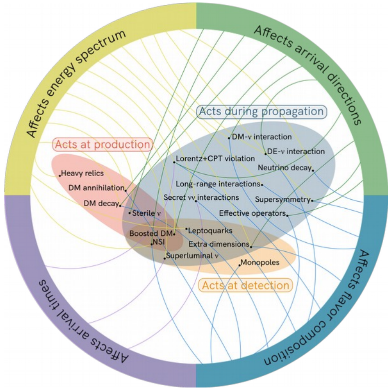


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- *Astro2020: Astrophysics uniquely enabled by observations of high-energy cosmic neutrinos*, 1903.04334

# Backup slides

# 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]

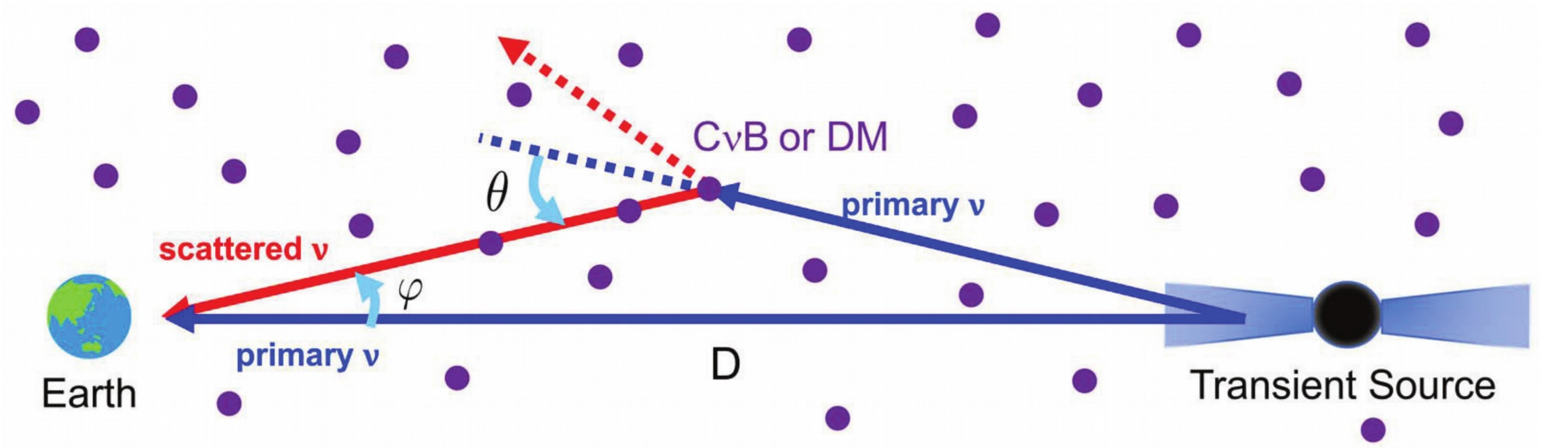
- Flavor-violating physics
  - New neutrino-electron interactions
    [**MB** & Agarwalla, *PRL* 2019]
  - New $\nu\nu$ interactions
    [Ng & Beacom, *PRD* 2014; Cherry, Friedland, Shoemaker, 1411.1071; Blum, Hook, Murase, 1408.3799]

- …

Toho Company Ltd.

# New physics 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 $\nu\nu$: $\tau_{\nu\nu} = n_\nu \, \sigma_{\nu\nu} \, D$

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

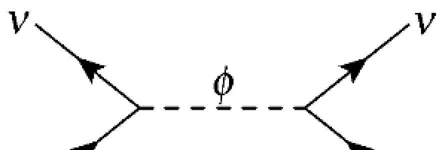
See also: Alcock & Hatchett, *ApJ* 1978

# New physics in timing — TeV–PeV

See also: Alcock & Hatchett, *ApJ* 1978

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

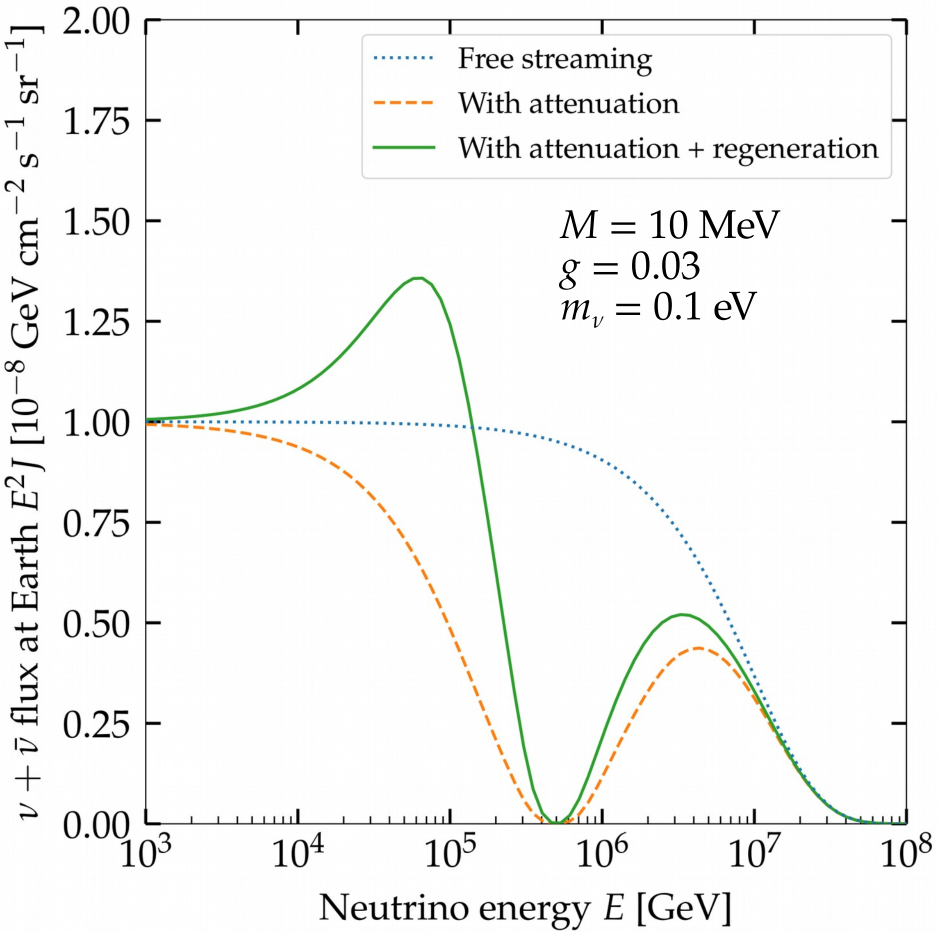
"Secret" neutrino interactions between astrophysical $\nu$ (PeV) and relic $\nu$ (0.1 meV):




$$\mathcal{L} \sim g\phi\nu\bar{\nu}$$

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

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





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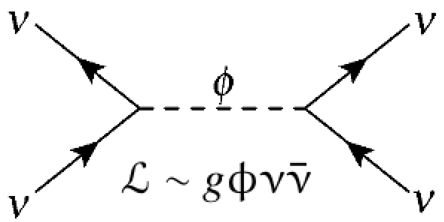
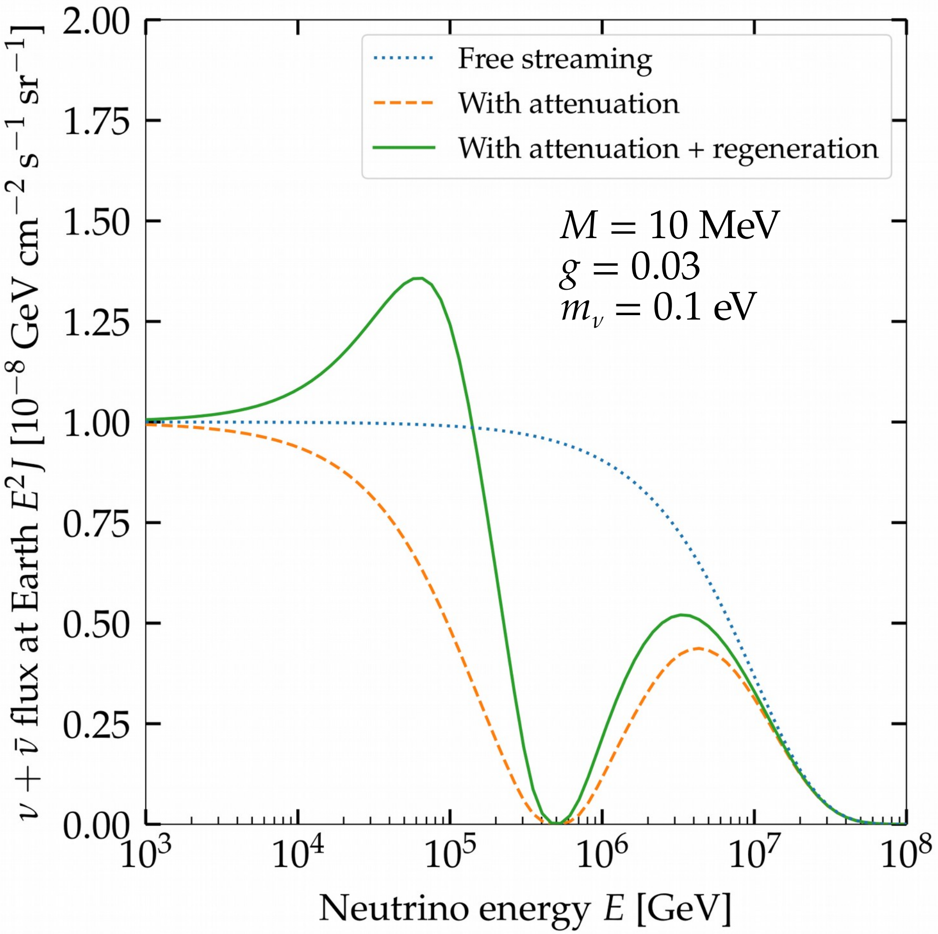



New coupling

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

Mediator mass

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

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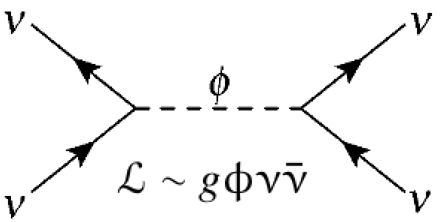


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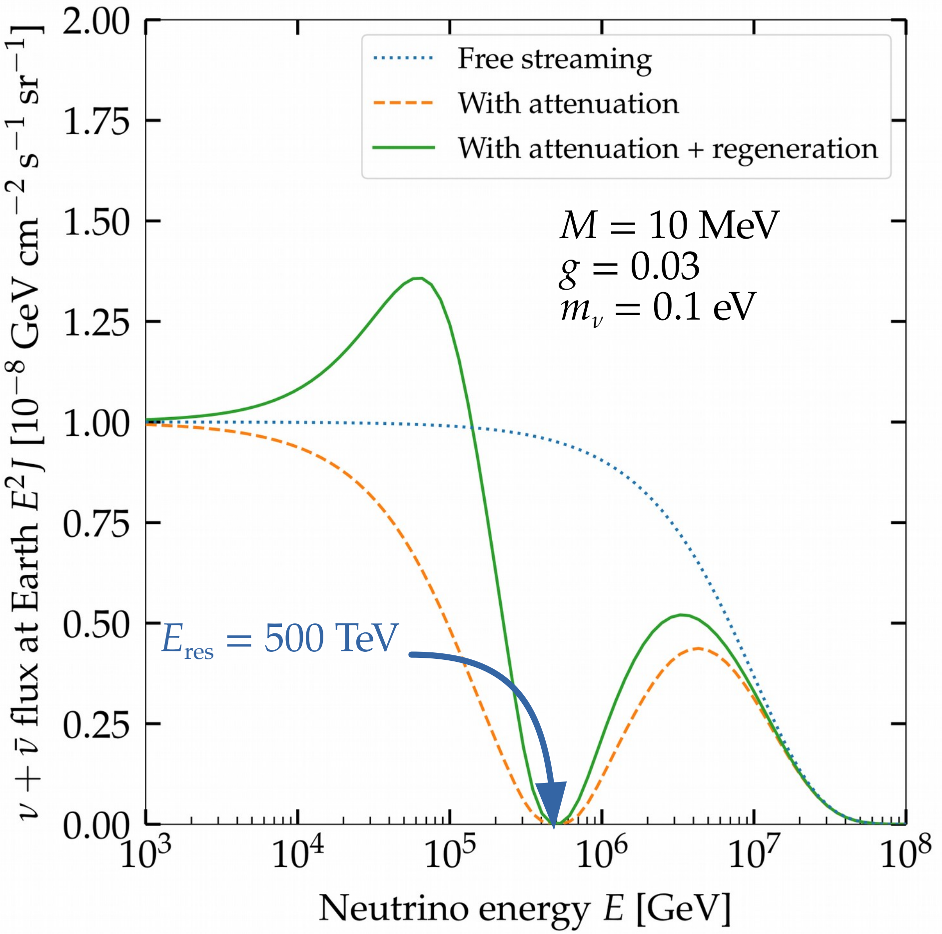


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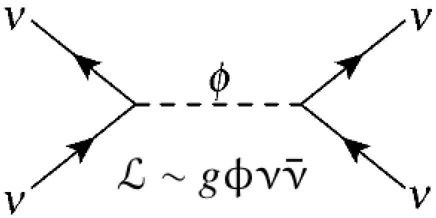


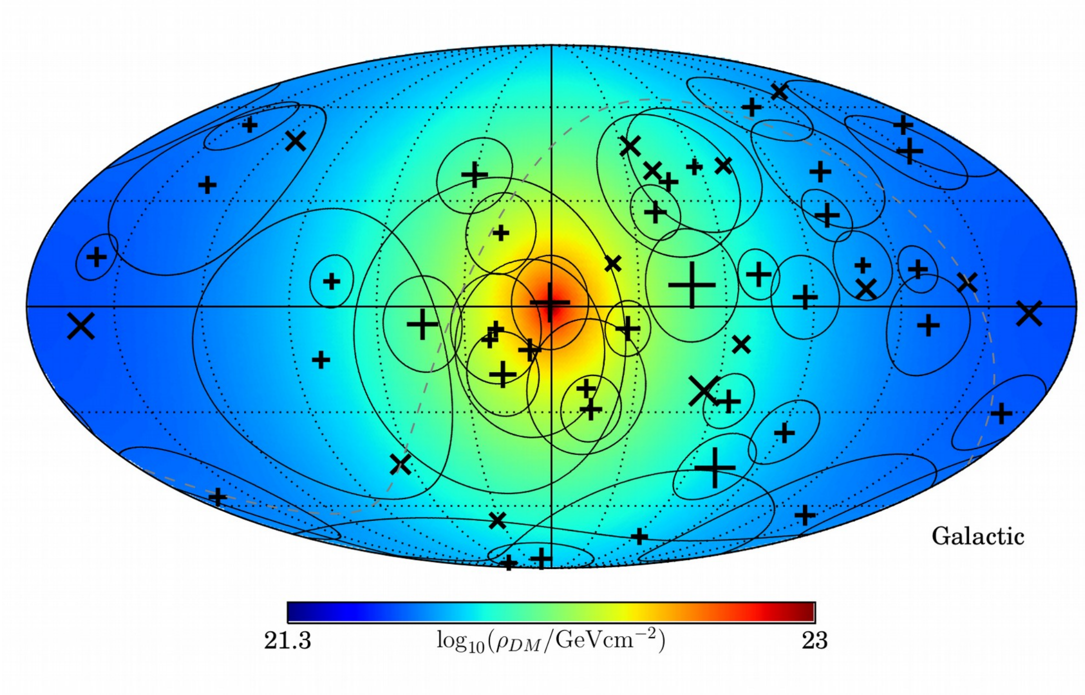

$M = 10$ MeV
$g = 0.03$
$m_\nu = 0.1$ eV

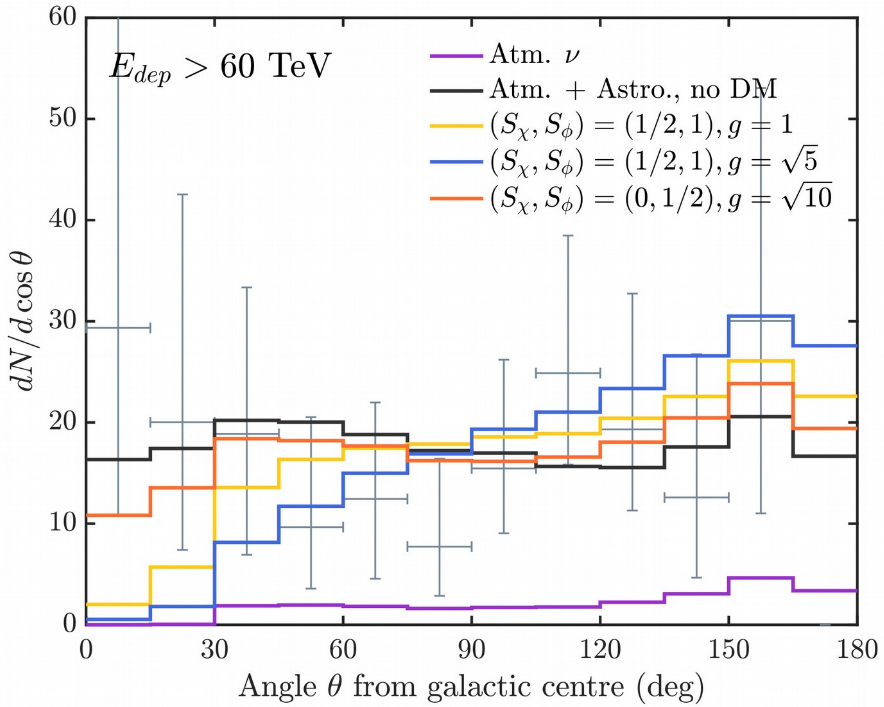
Cross section: $$\sigma = \frac{g^4}{4\pi} \frac{s}{(s - M^2)^2 + M^2\Gamma^2}$$

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

# New physics in the angular distribution: $\nu$-DM interactions

Interaction between astrophysical neutrinos and the Galactic dark matter profile —




Expected: Fewer neutrinos coming from the Galactic Center

Observed: Isotropy

Argüelles, Kheirandish, Vincent, *PRL* 2017

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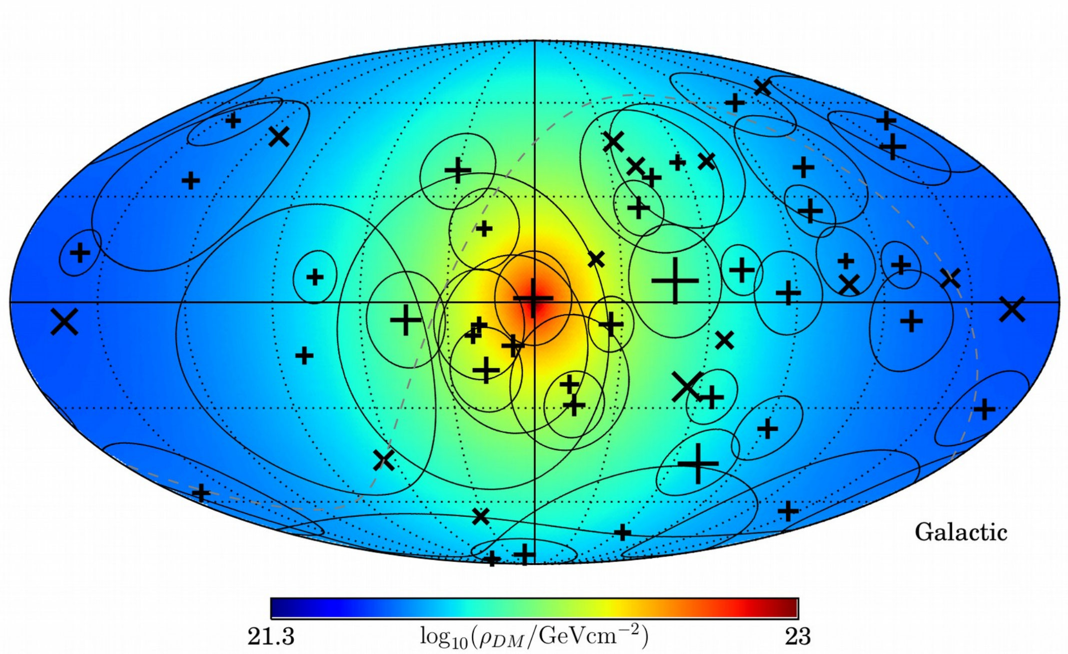


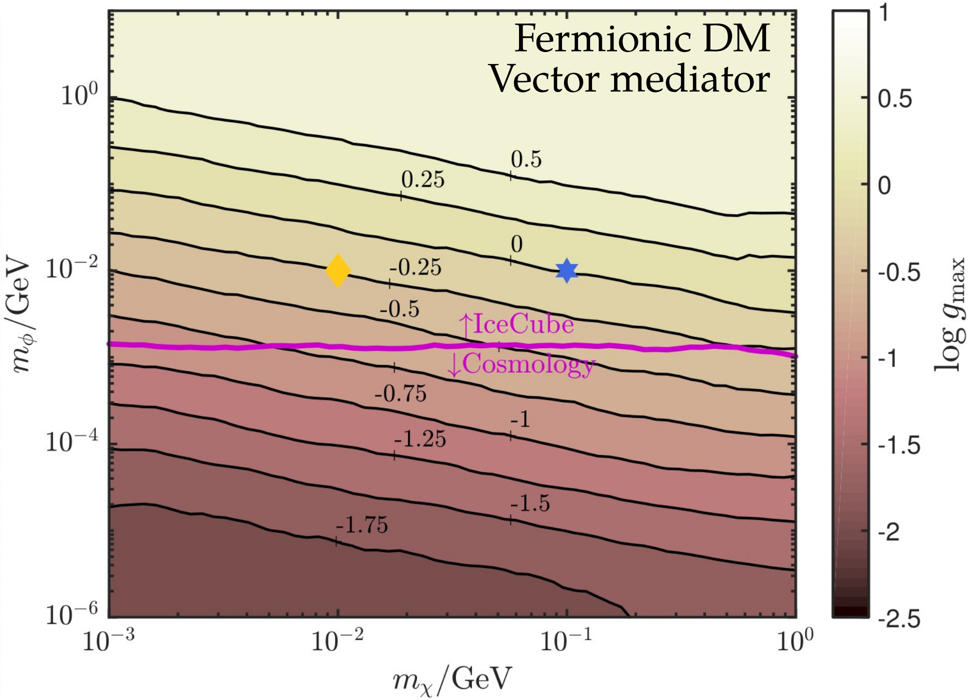


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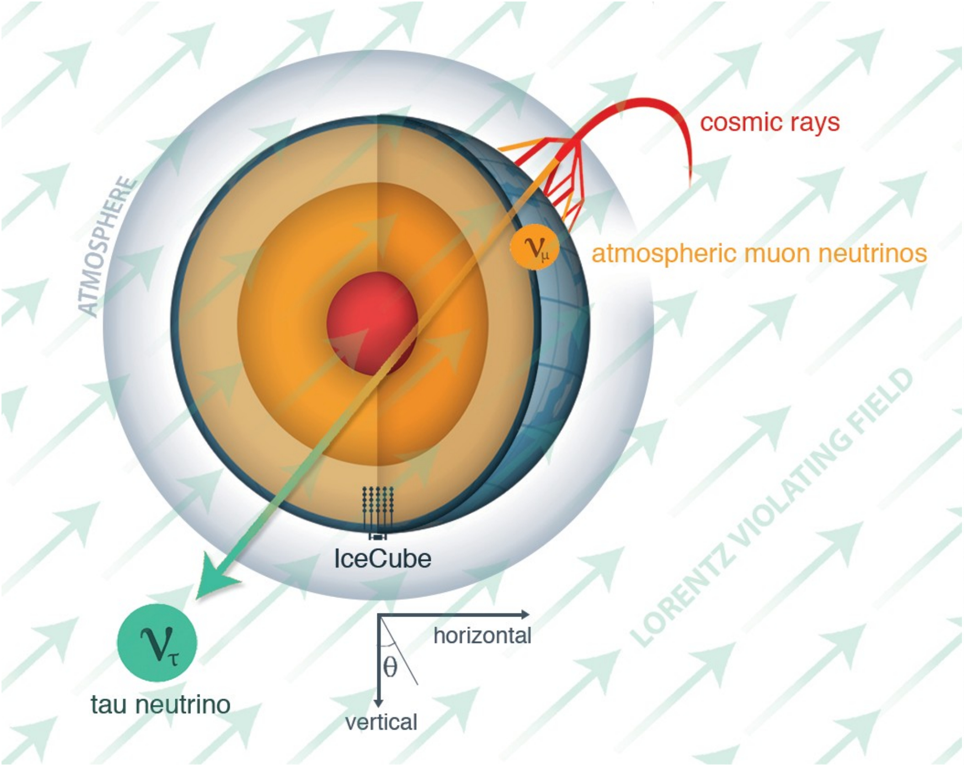
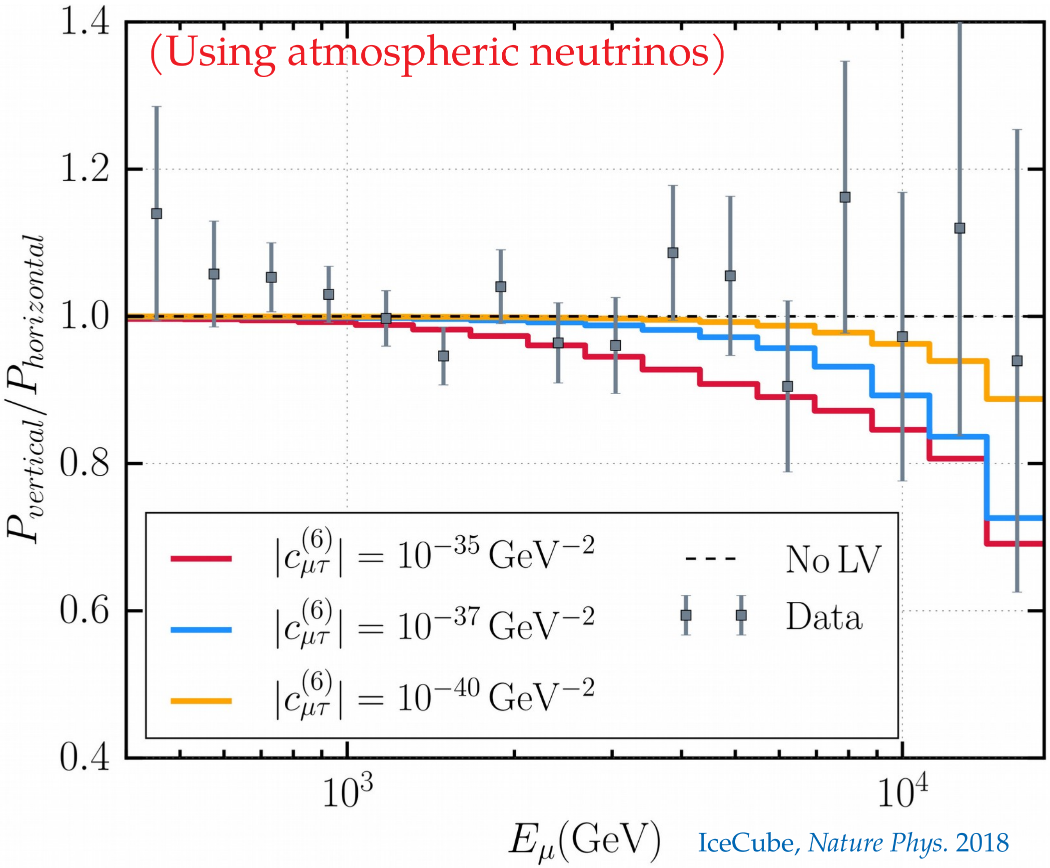
# New physics in the energy & angular distribution

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




IceCube, *Nature Phys.* 2018

# New physics in the energy & angular distribution

Lorentz violation

Standard oscillations

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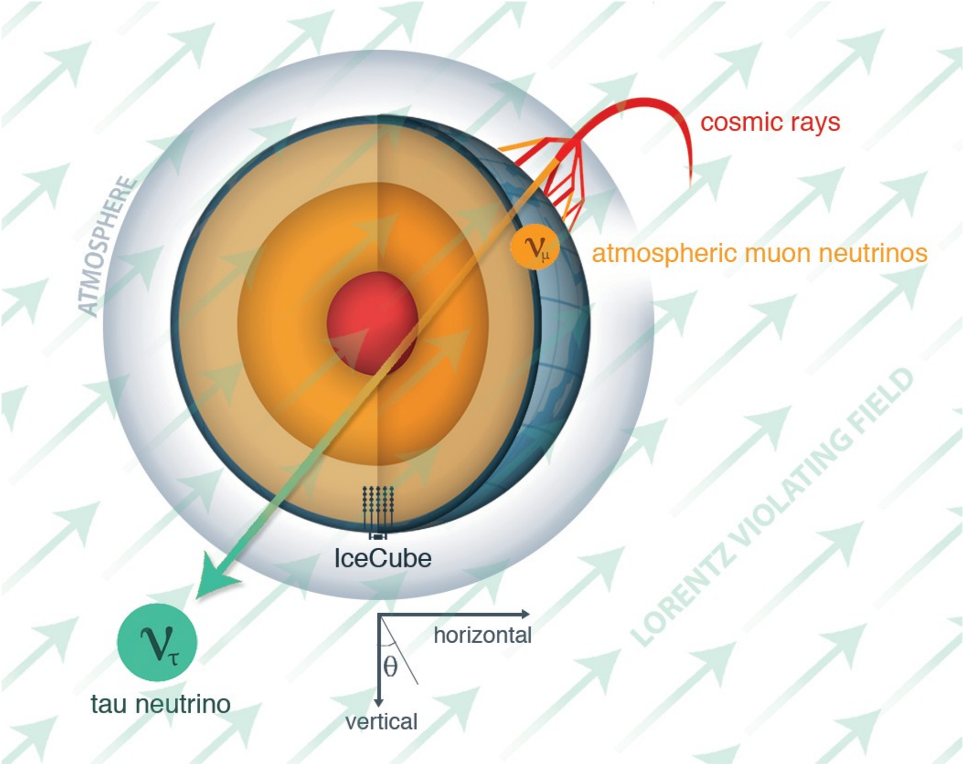


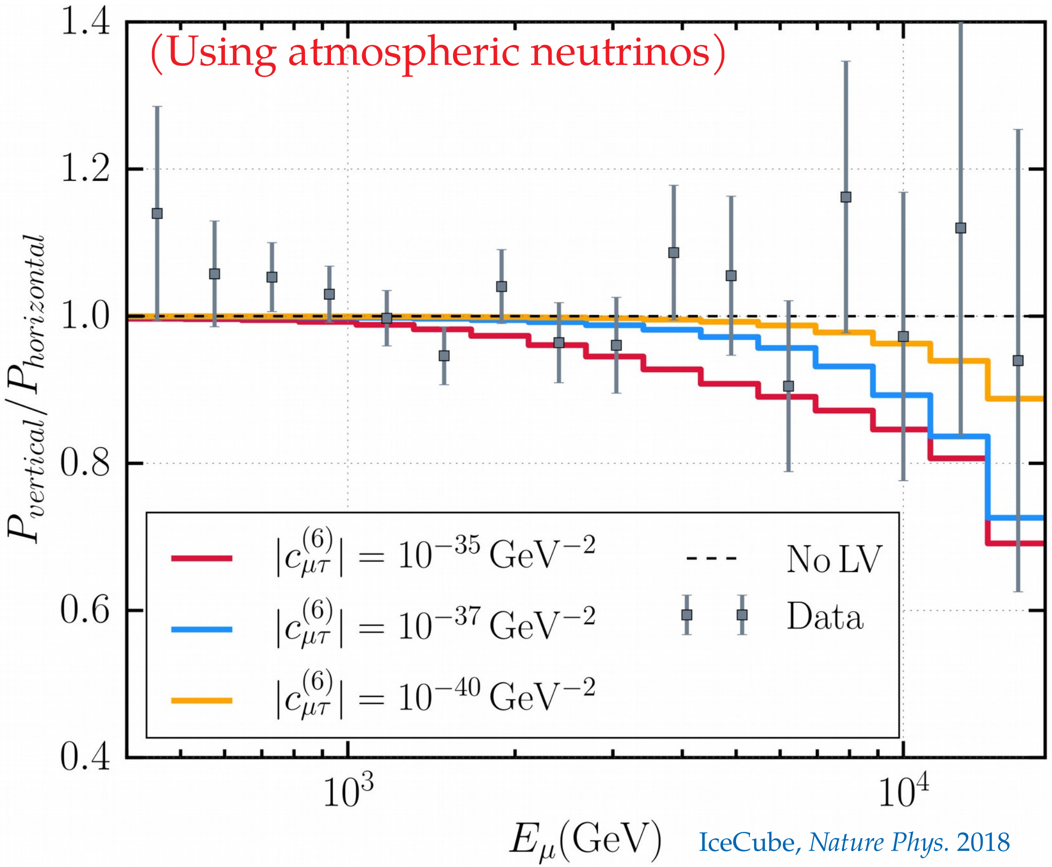


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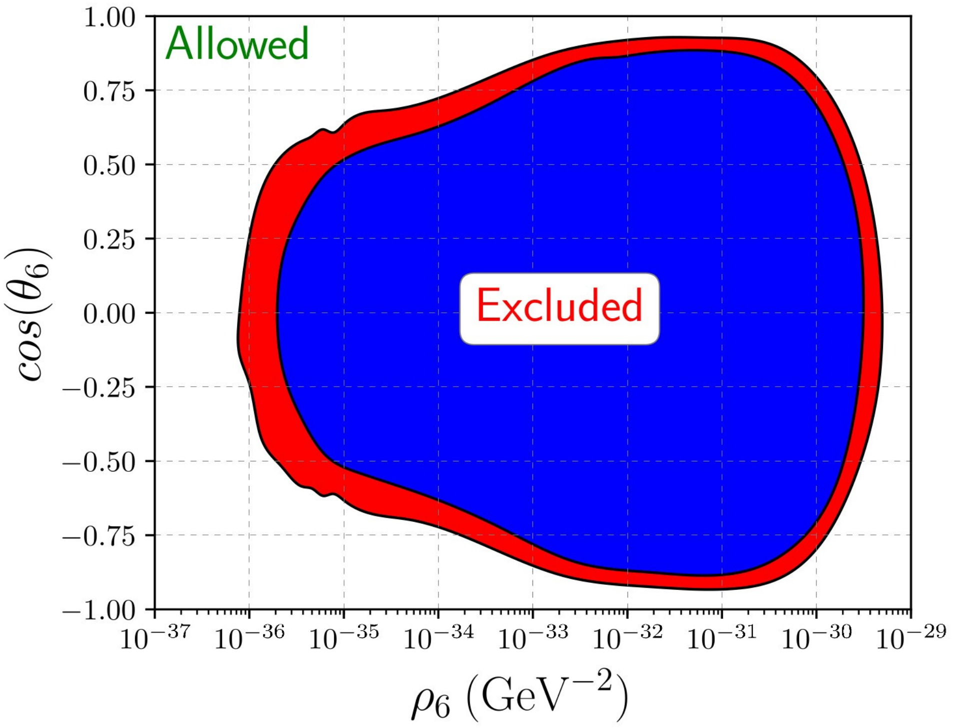
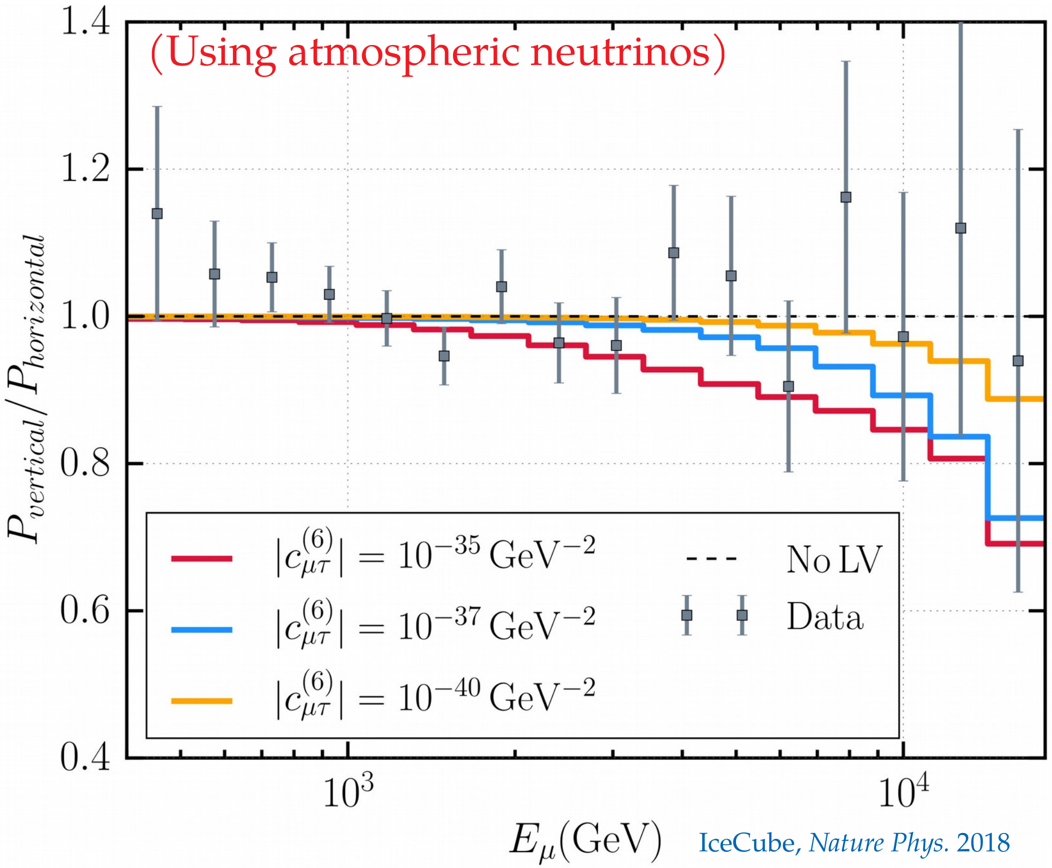
Best bounds come from IceCube




IceCube, *Nature Phys.* 2018

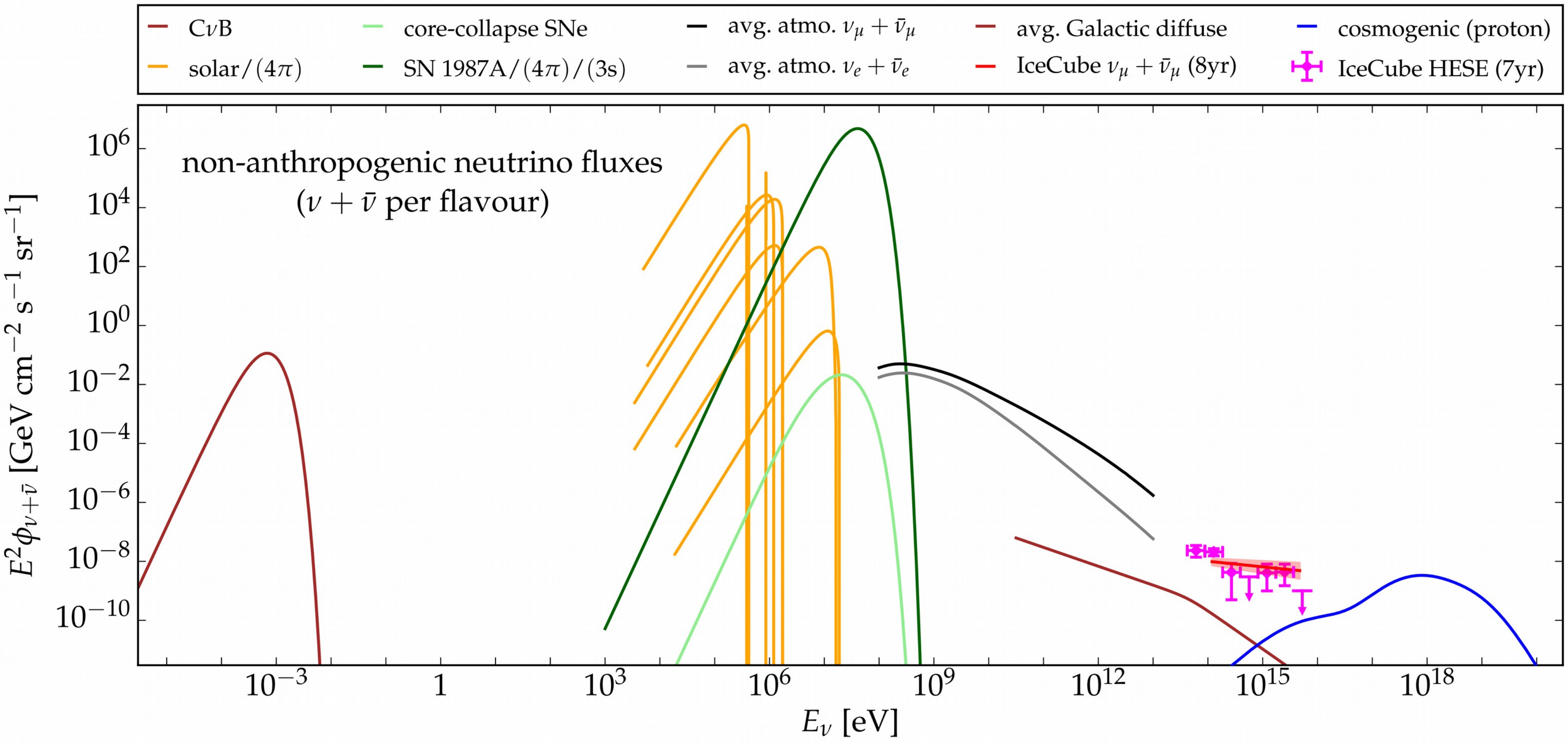
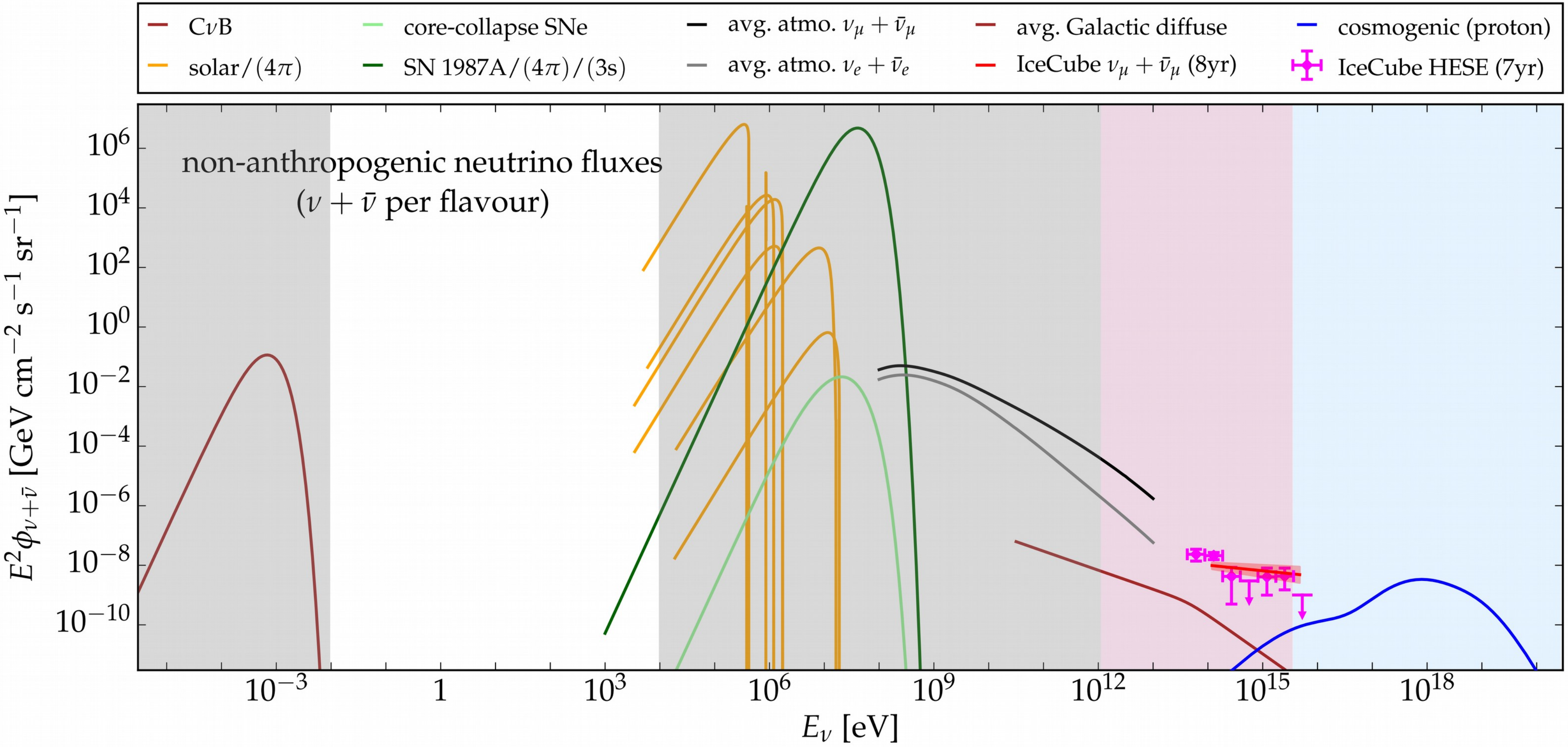



Figure courtesy of Markus Ahlers
Also in: Van Elewyck *et al.*, PoS(ICRC2019), 1023

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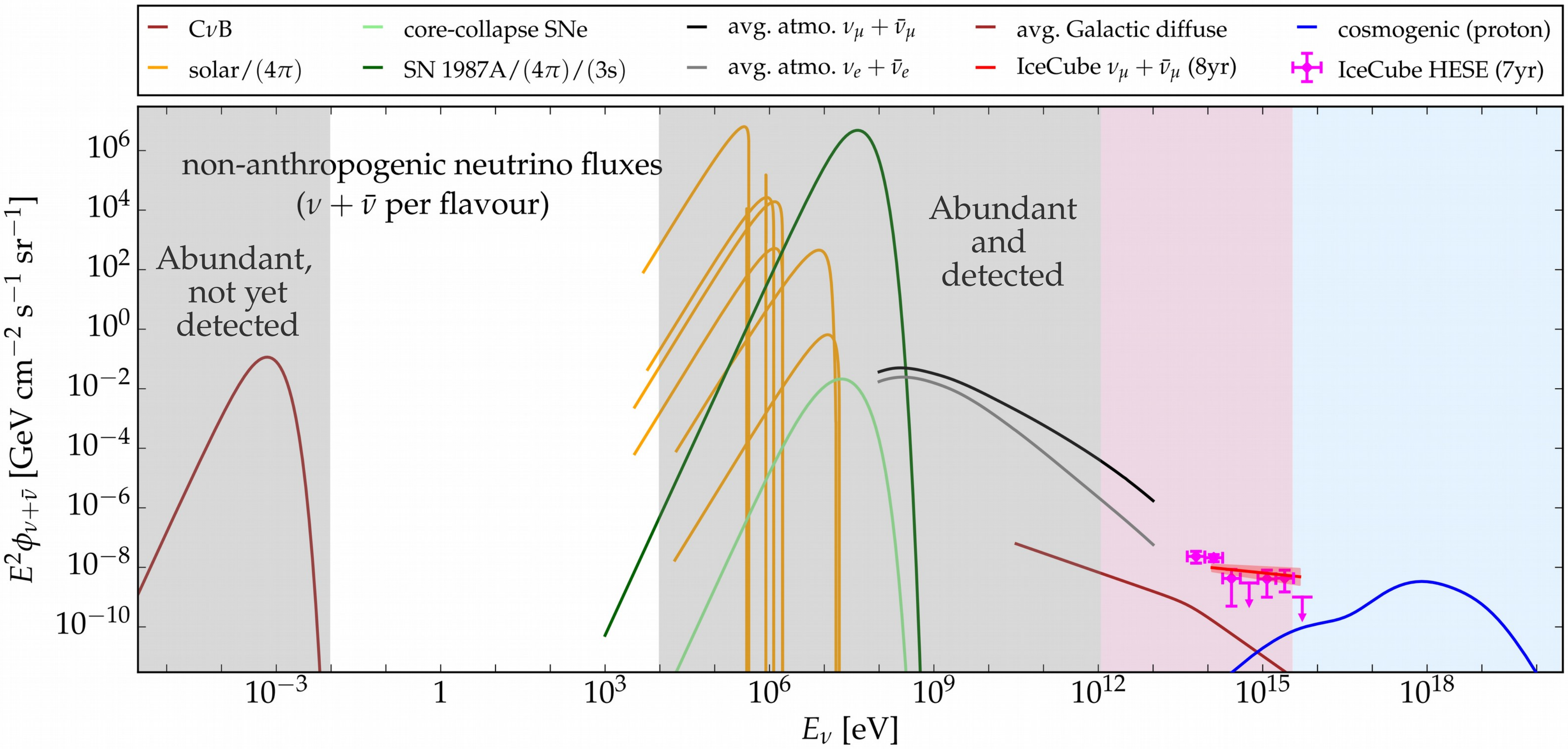


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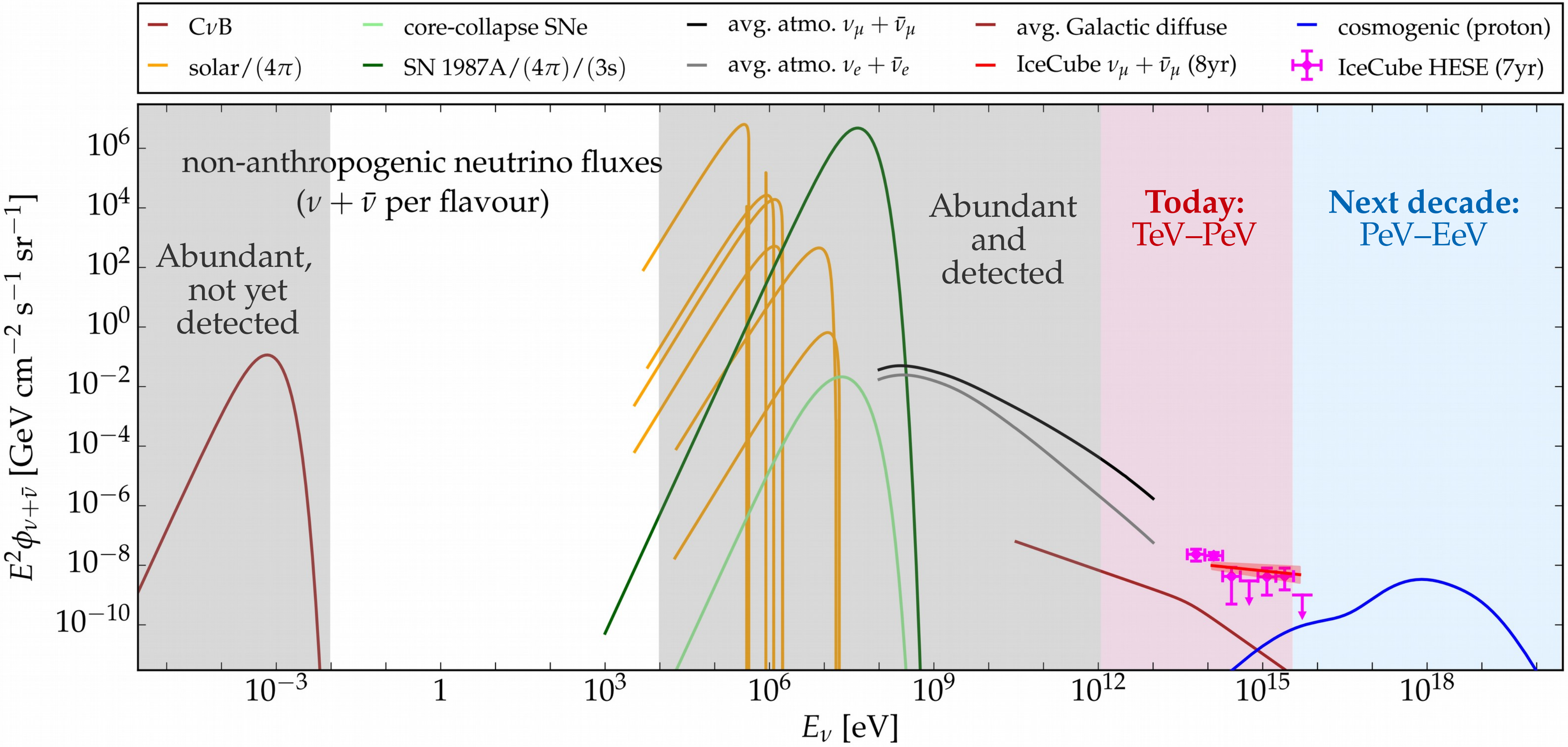


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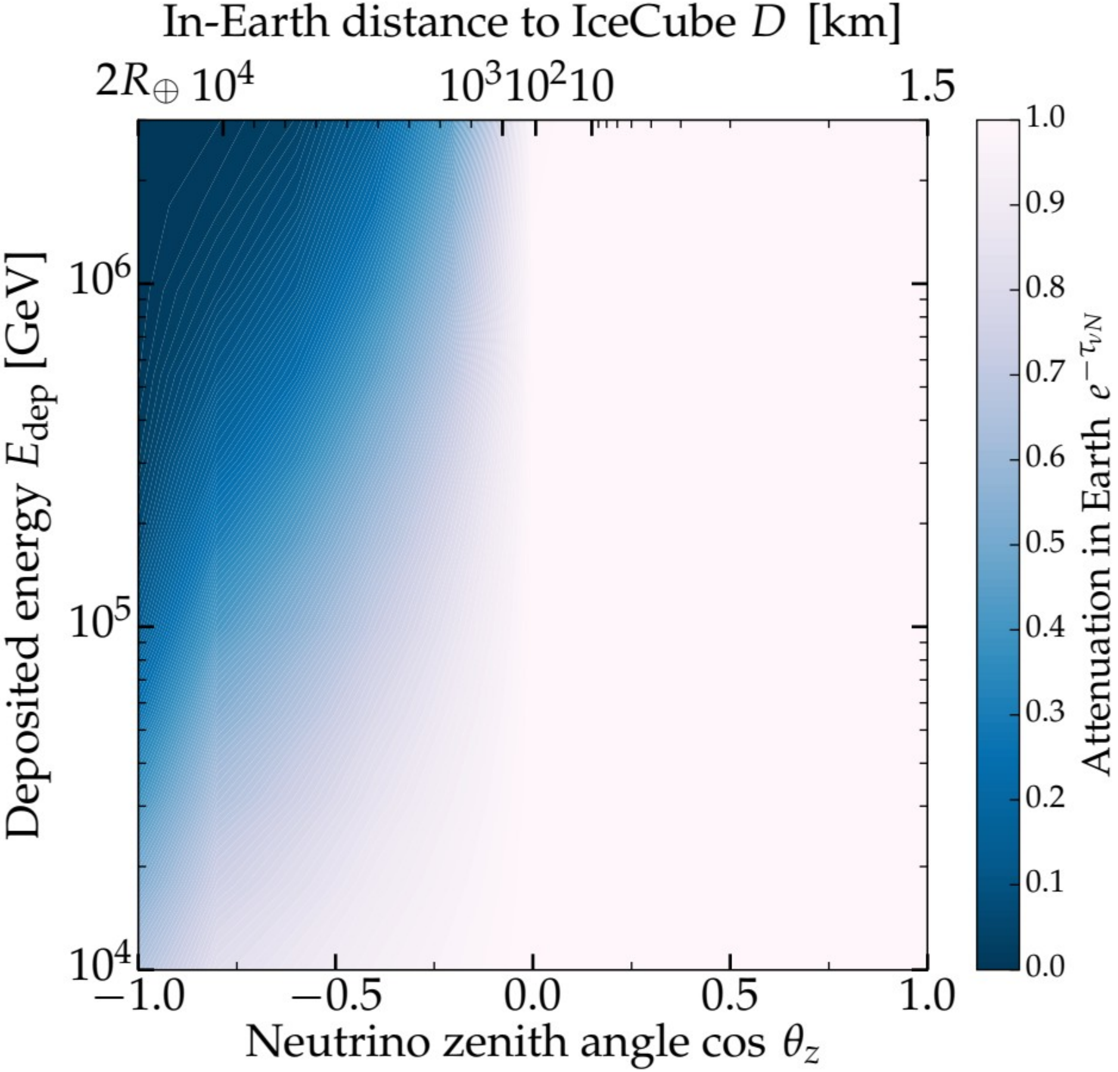
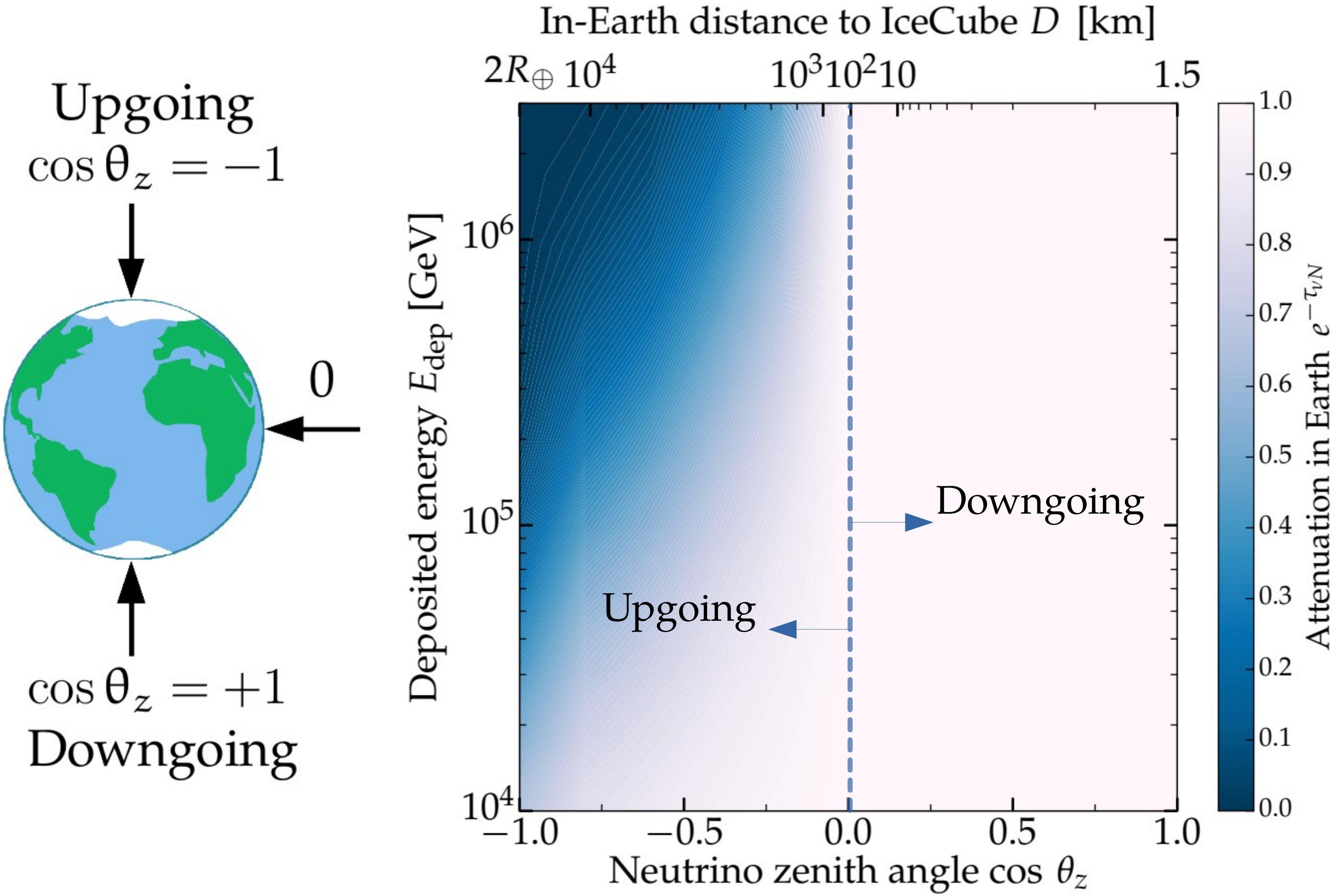
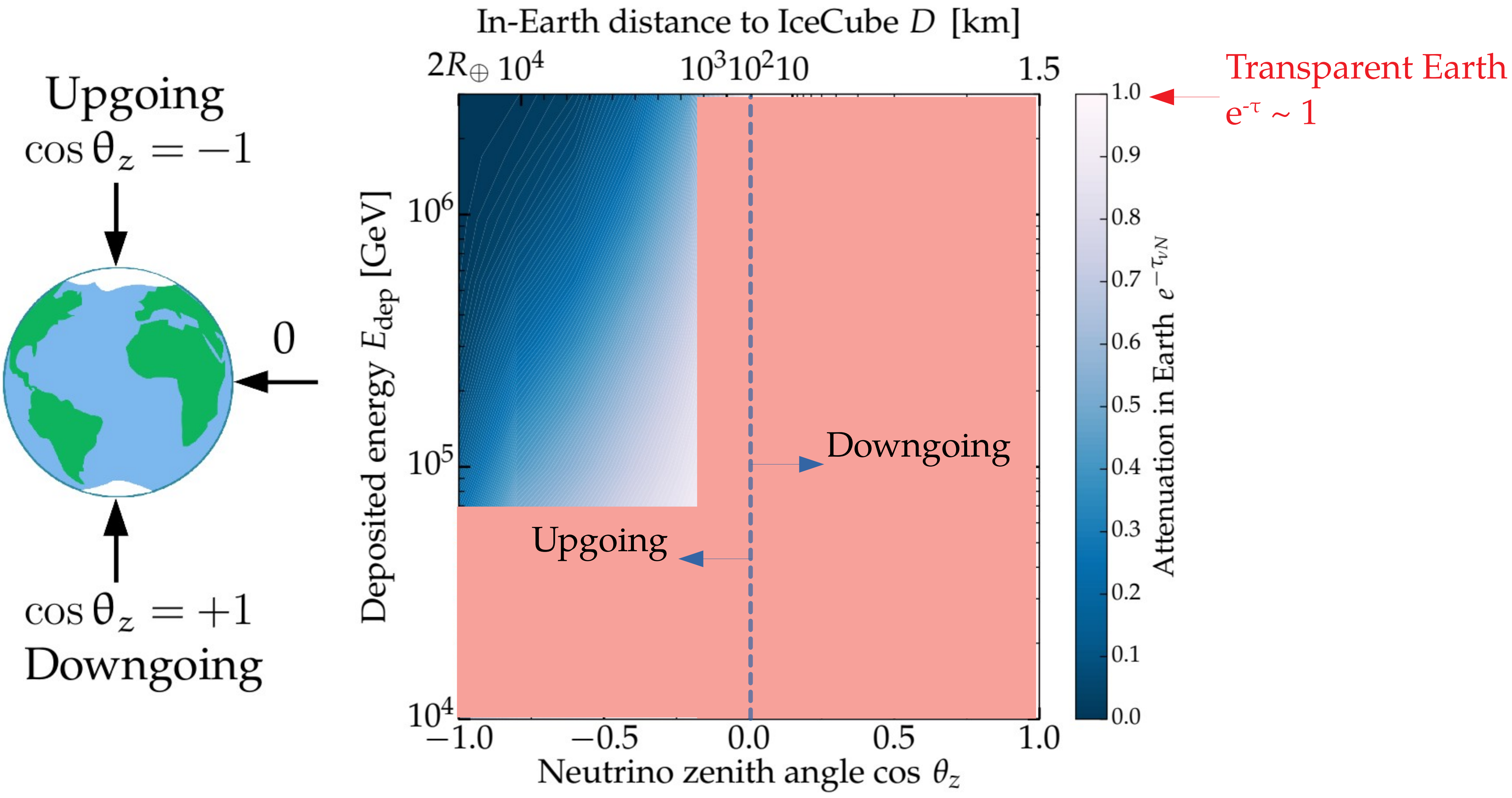


In-Earth distance to IceCube $D$ [km]
$2R_\oplus$ $10^4$
$10^3$ $10^2$ $10$
1.5
Deposited energy $E_{dep}$ [GeV]
$10^6$
$10^5$
$10^4$
−1.0
−0.5
0.0
0.5
1.0
Neutrino zenith angle $\cos\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0


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



Upgoing
cos θ_z = −1
0
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Downgoing
In-Earth distance to IceCube D [km]
2R⊕ 10^4
10^3 10^2 10
1.5
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10^6
10^5
10^4
Downgoing
Upgoing
−1.0
−0.5
0.0
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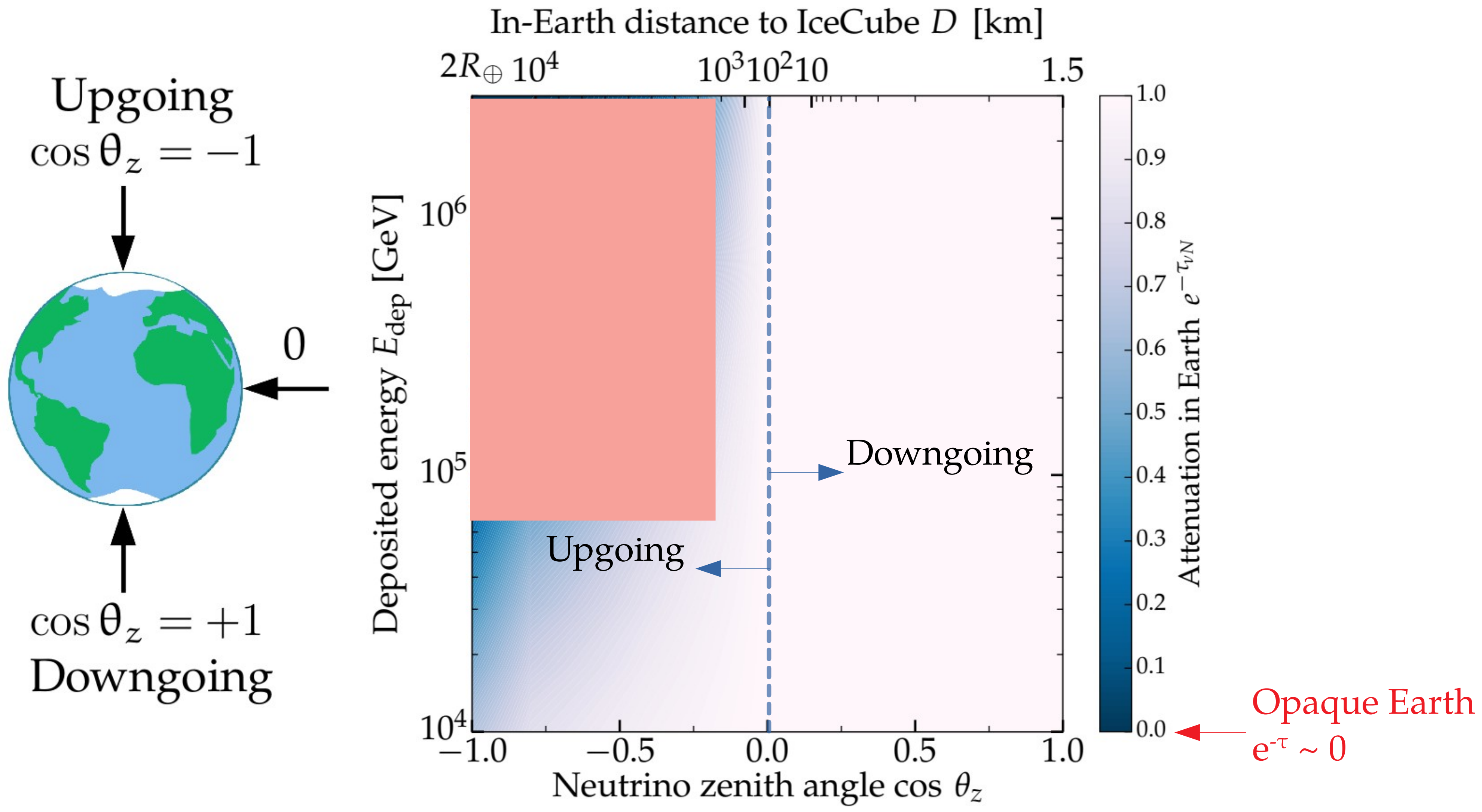
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Attenuation in Earth e^−τ_νN
Transparent Earth
e^-τ ~ 1



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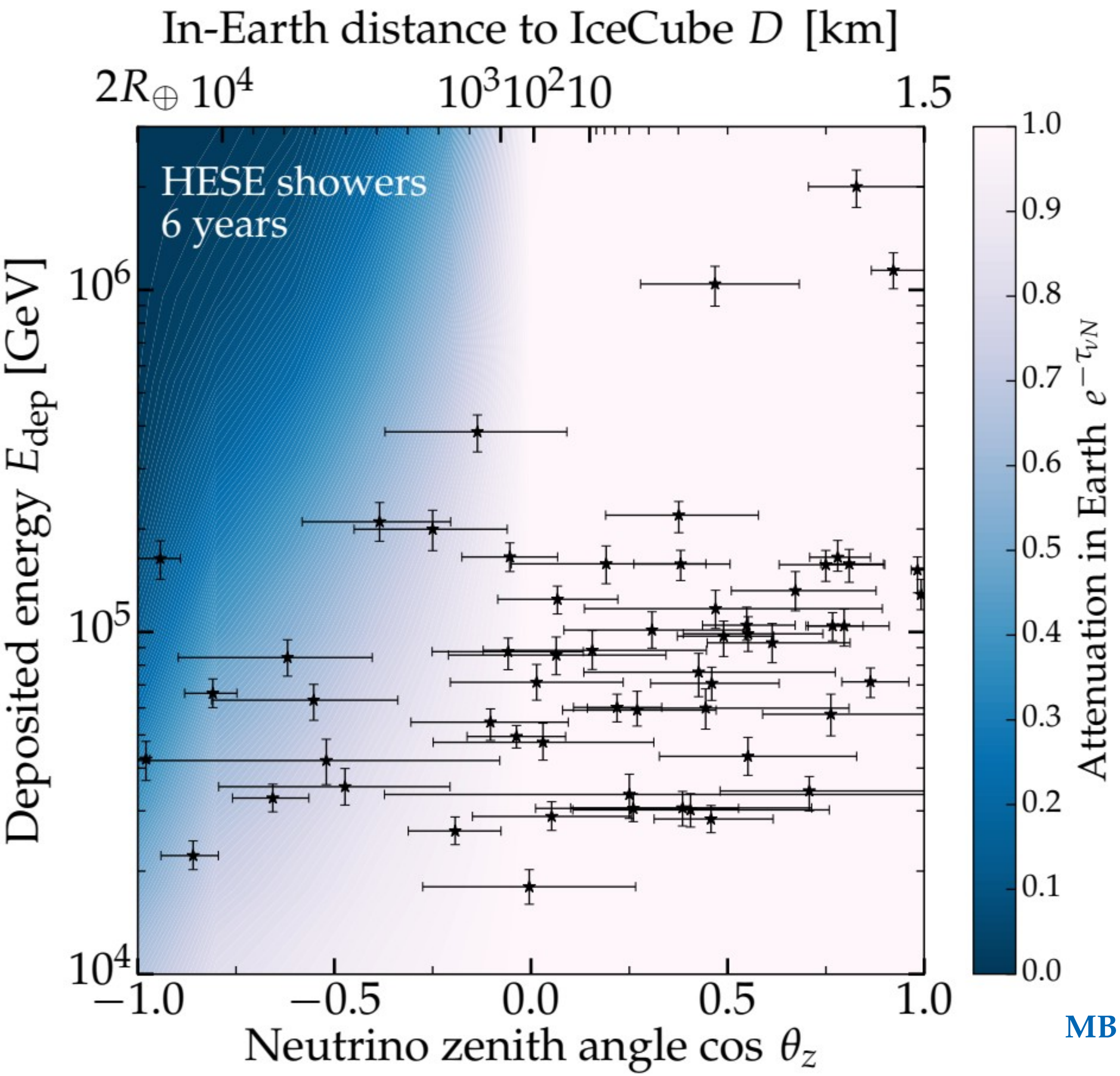
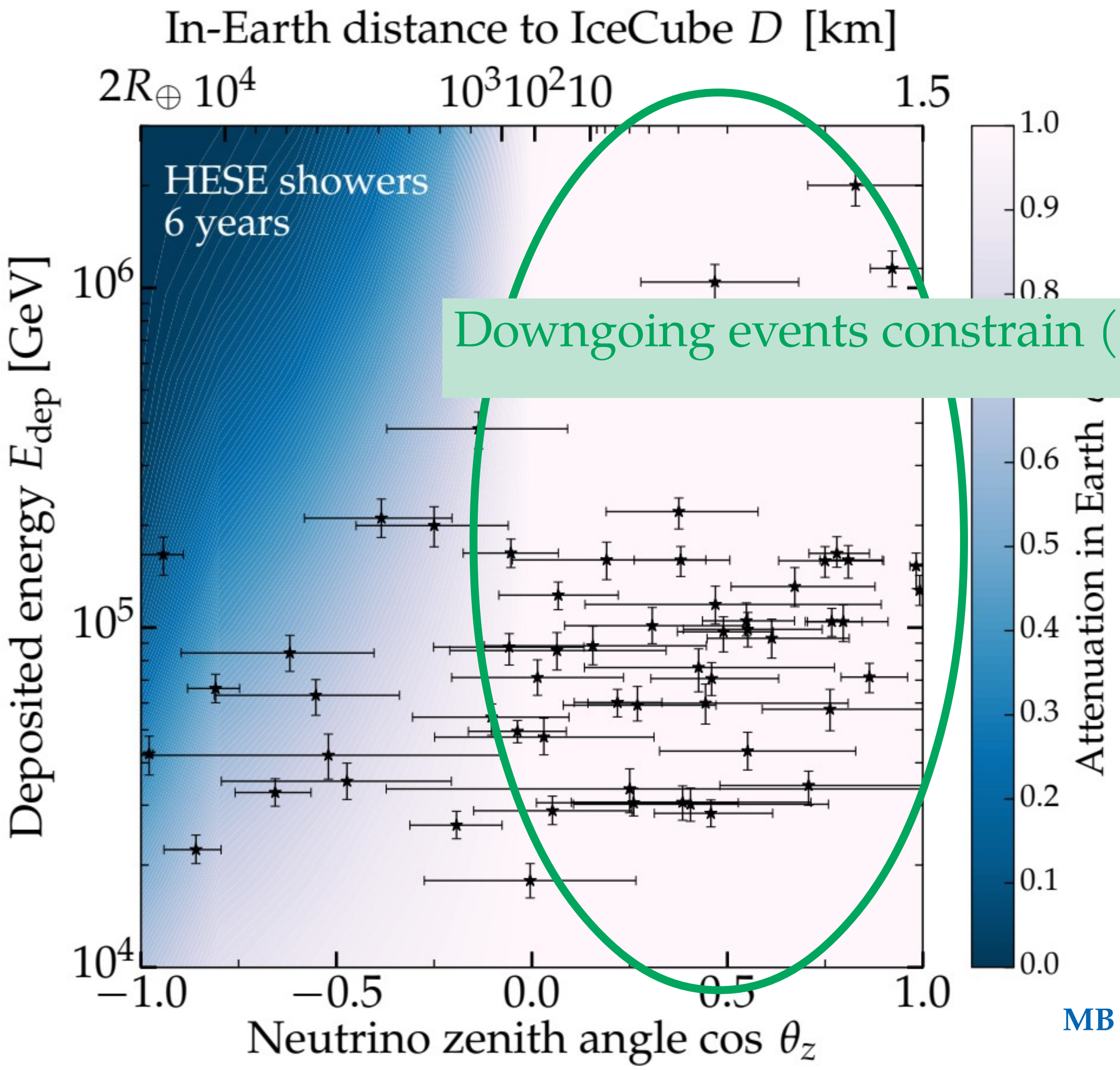
$10^6$
$10^5$
$10^4$
Downgoing
Upgoing
−1.0 −0.5 0.0 0.5 1.0
Neutrino zenith angle cos $\theta_z$
Attenuation in Earth $e^{-\tau_{\nu N}}$
1.0 0.9 0.8 0.7 0.6 0.5 0.4 0.3 0.2 0.1 0.0
Opaque Earth
$e^{-\tau} \sim 0$




**MB** & Connolly, *PRL* 2019

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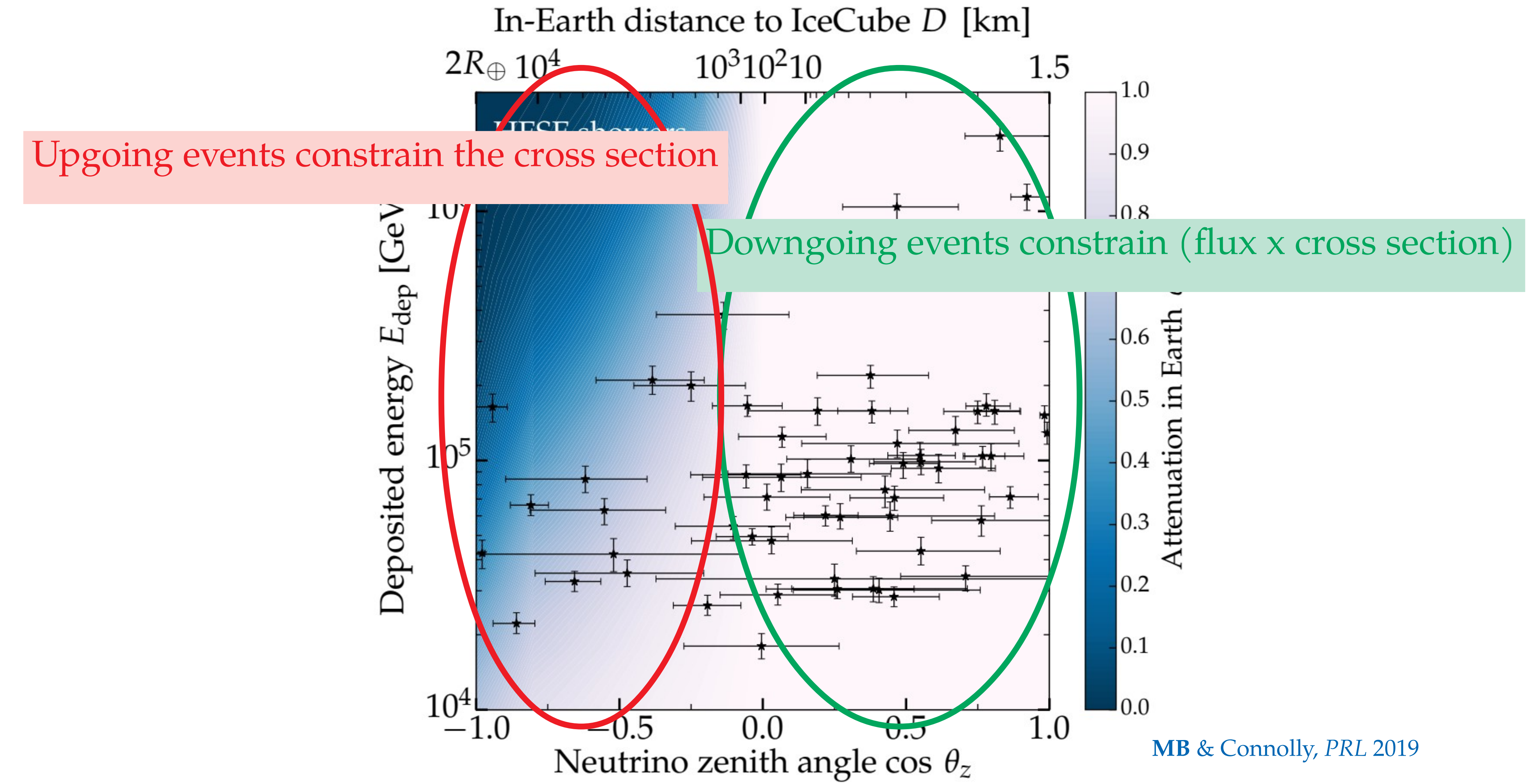


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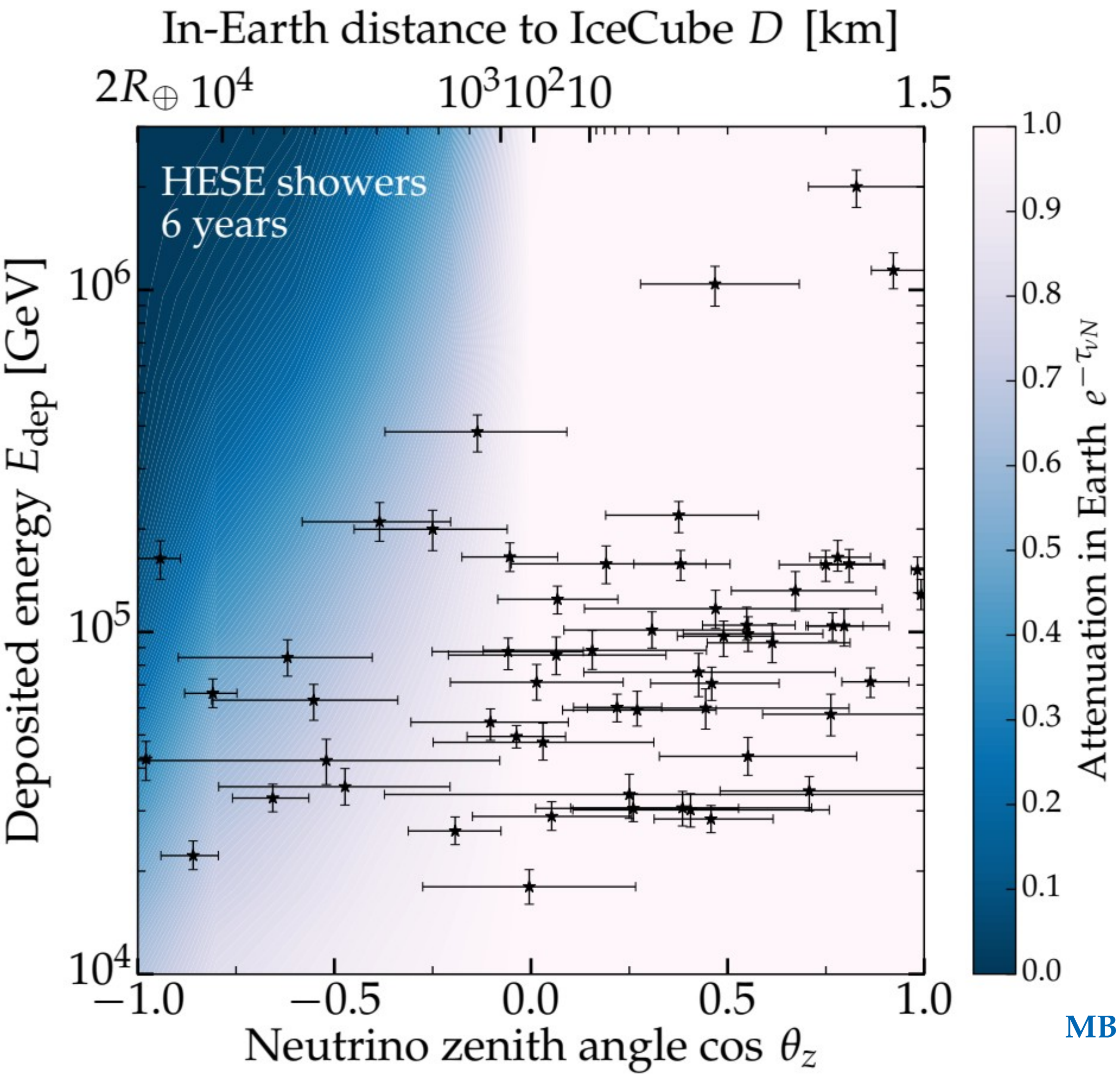


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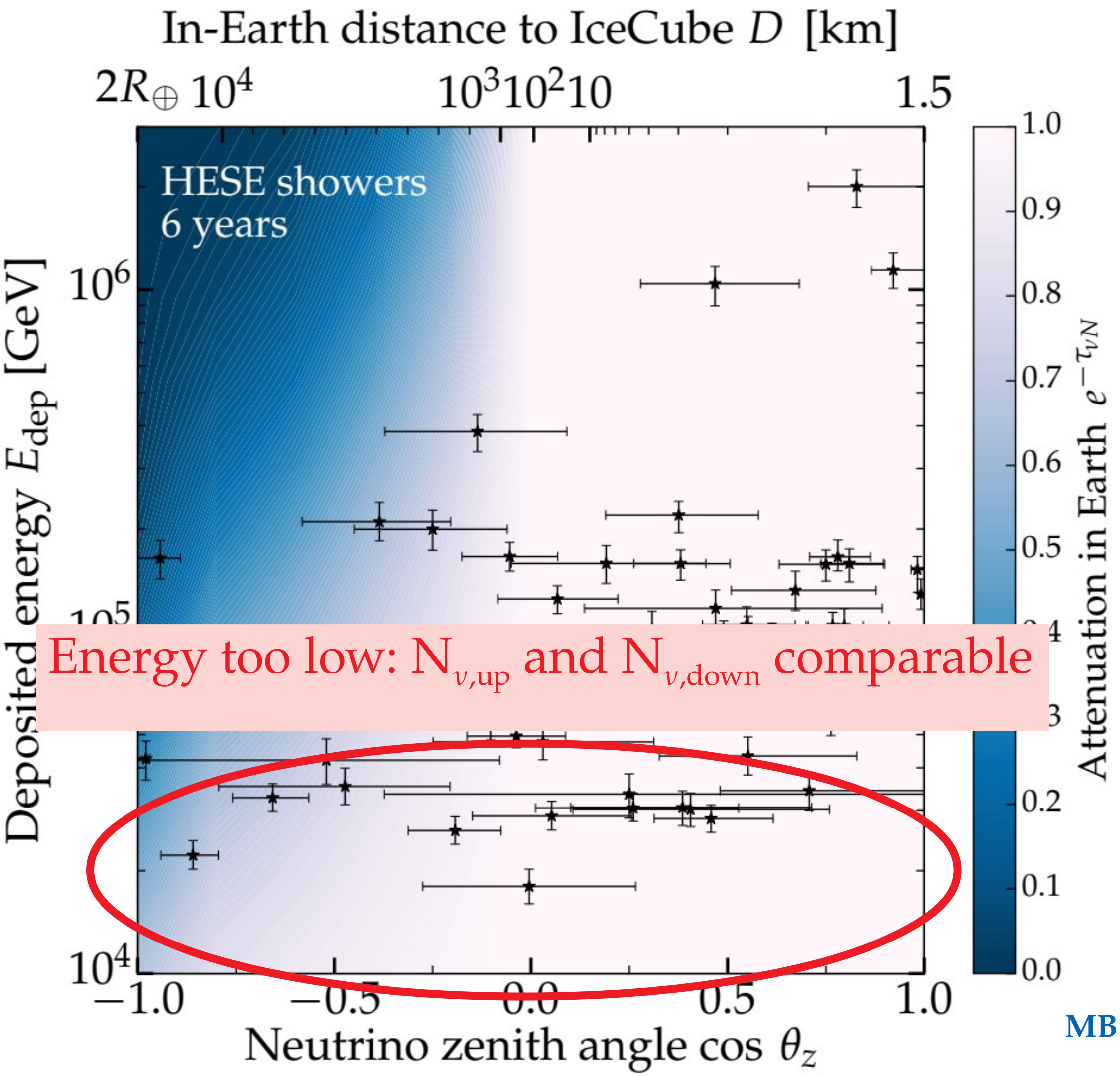


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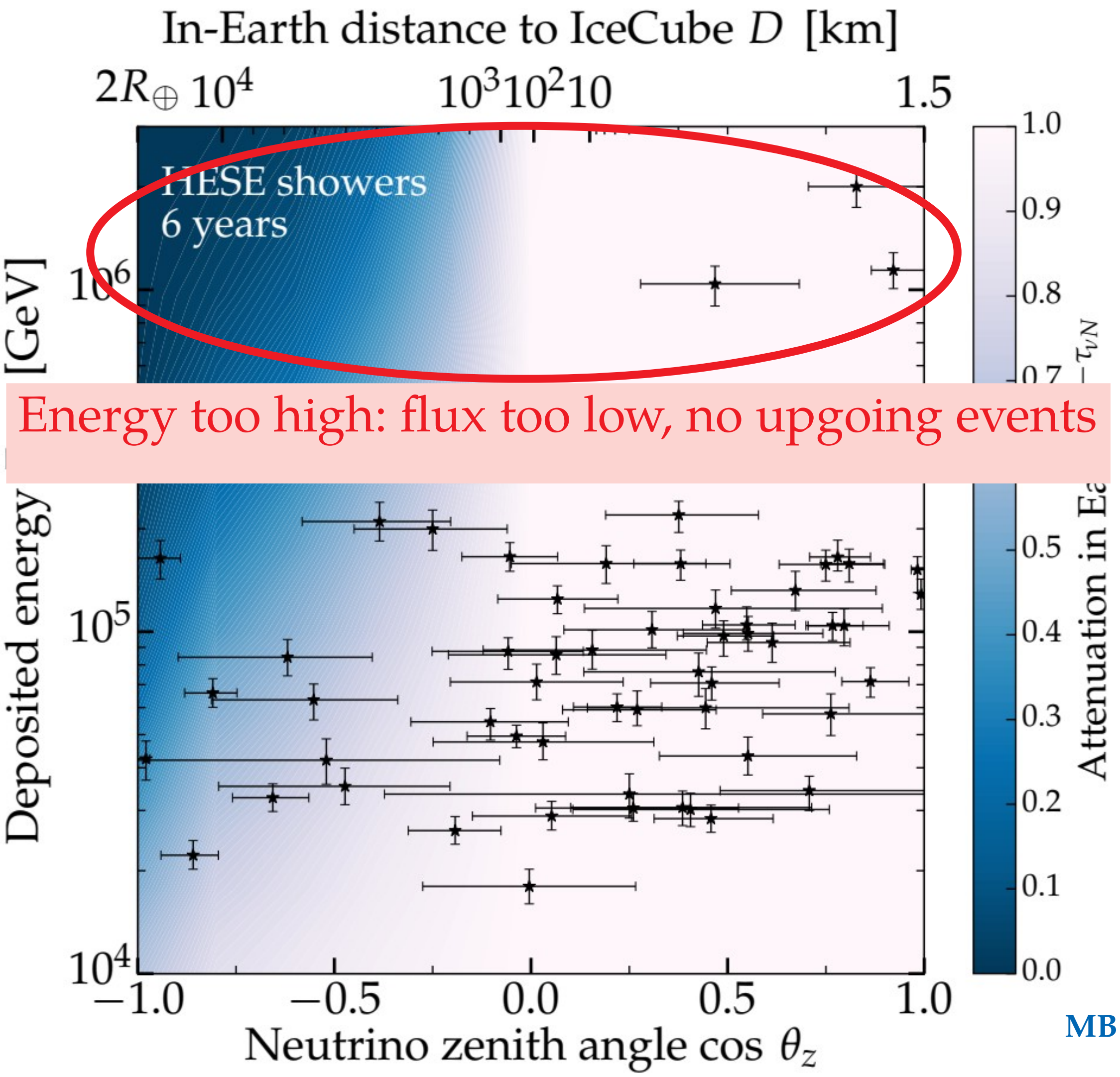
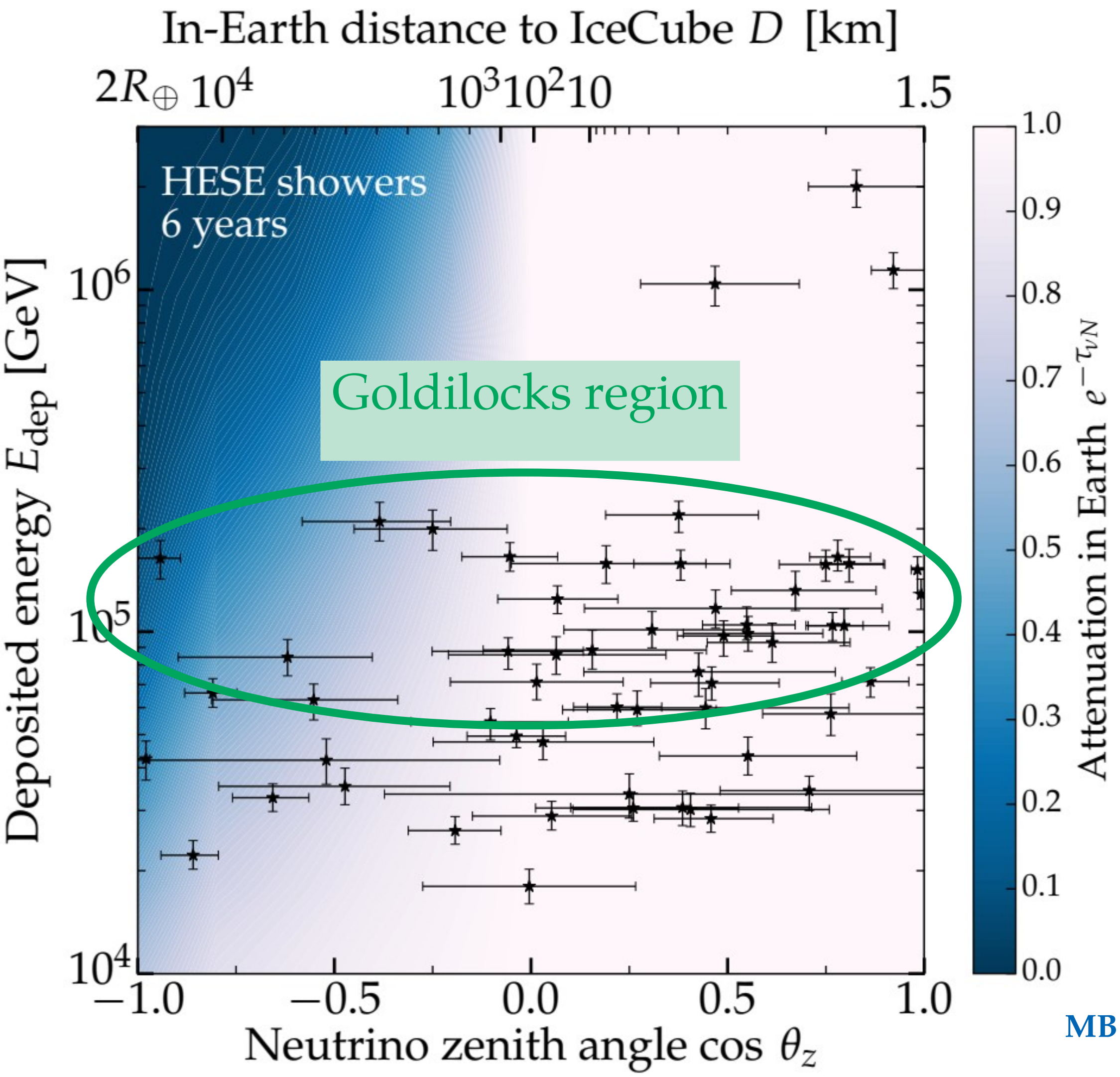



**MB** & Connolly, *PRL* 2019




**MB** & Connolly, *PRL* 2019

# The fine print

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

# 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)
  - $\gamma$ (astrophysical spectral index)
  - $\sigma_{CC}$ (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 $\sigma_{CC}$ (marginalized over nuisance parameters)
- Bins are independent of each other – there are no (significant) cross-bin correlations

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

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# Marginalized cross section in each bin

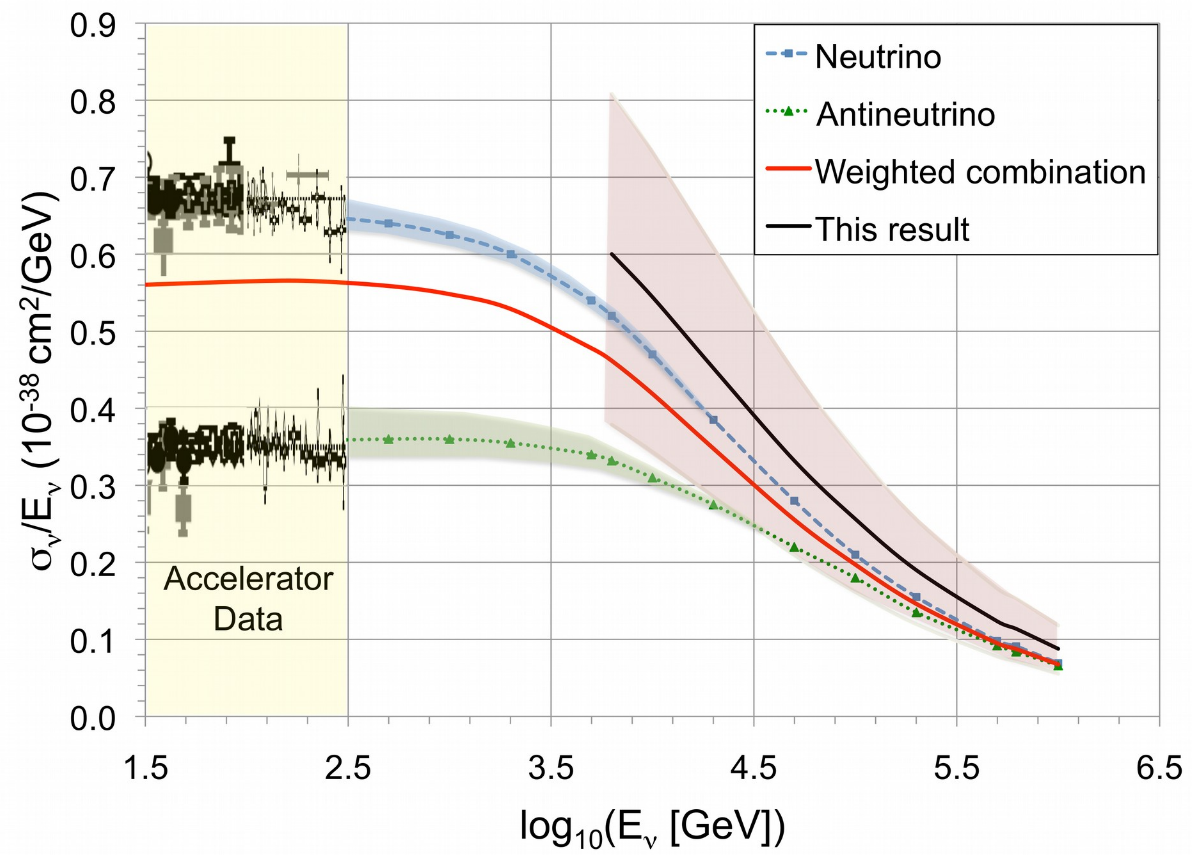
TABLE I. Neutrino-nucleon charged-current inclusive cross sections, averaged between neutrinos ($\sigma_{\nu N}^{\rm CC}$) and anti-neutrinos ($\sigma_{\bar{\nu} N}^{\rm CC}$), extracted from 6 years of IceCube HESE showers. To obtain these results, we fixed $\sigma_{\bar{\nu} N}^{\rm CC} = \langle \sigma_{\bar{\nu}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

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

MB & A. Connolly, 1711.11043

# Using through-going muons instead

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




IceCube, *Nature* 2017

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

- Inelasticity in CC $\nu_\mu$ interaction $\nu_\mu + N \to \mu + X$:

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

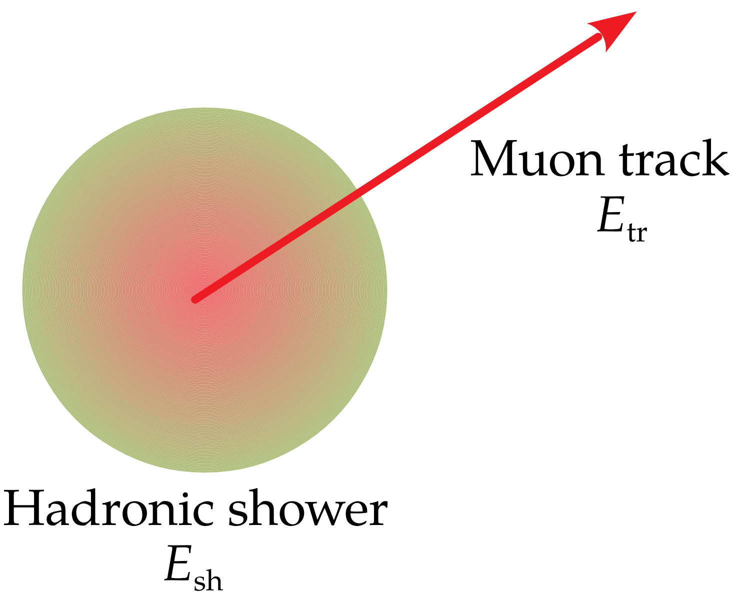
- The value of $y$ follows a distribution $\mathrm{d}\sigma/\mathrm{d}y$

- In a HESE starting track:

  $E_X = E_{sh}$ (energy of shower)
  $E_\mu = E_{tr}$ (energy of track)

  $y = (1 + E_{tr}/E_{sh})^{-1}$

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




IceCube, *PRD* 2019

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- In a HESE starting track:

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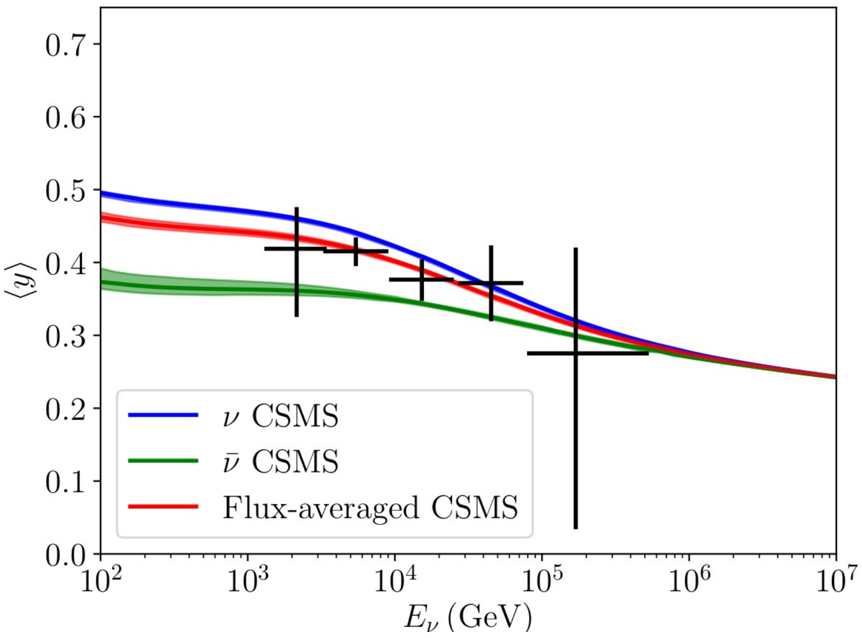
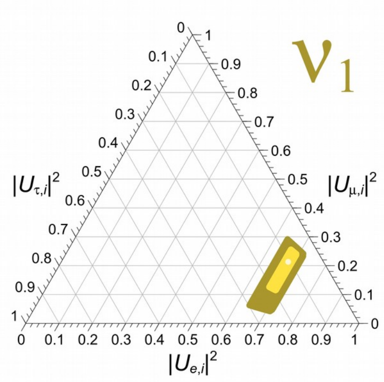
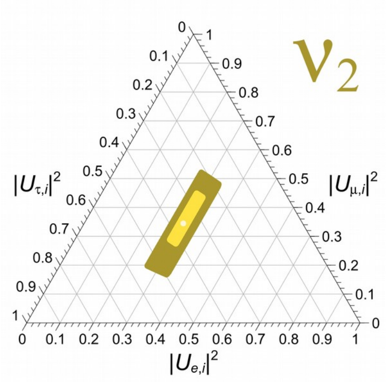


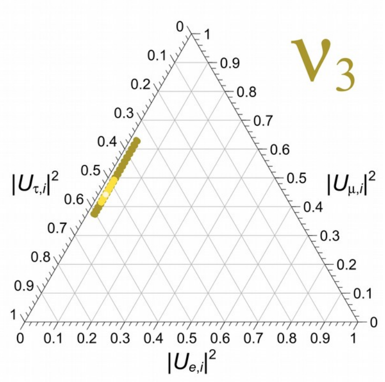

IceCube, *PRD* 2019

# Two classes of new physics

- Neutrinos propagate as an incoherent mix of $\nu_1$, $\nu_2$, $\nu_3$
- Each one has a different flavor content:



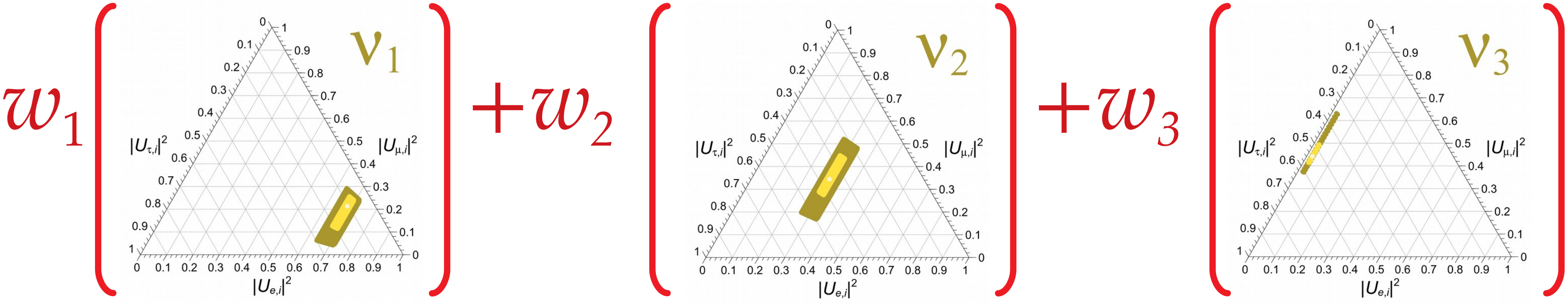




- Flavor ratios at Earth are the result of their combination
- New physics may:
  - Only reweigh the proportion of each $\nu_i$ reaching Earth (*e.g.*, $\nu$ decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

# Two classes of new physics

- Neutrinos propagate as an incoherent mix of $\nu_1, \nu_2, \nu_3$
- 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 $\nu_i$ reaching Earth (*e.g.*, $\nu$ decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

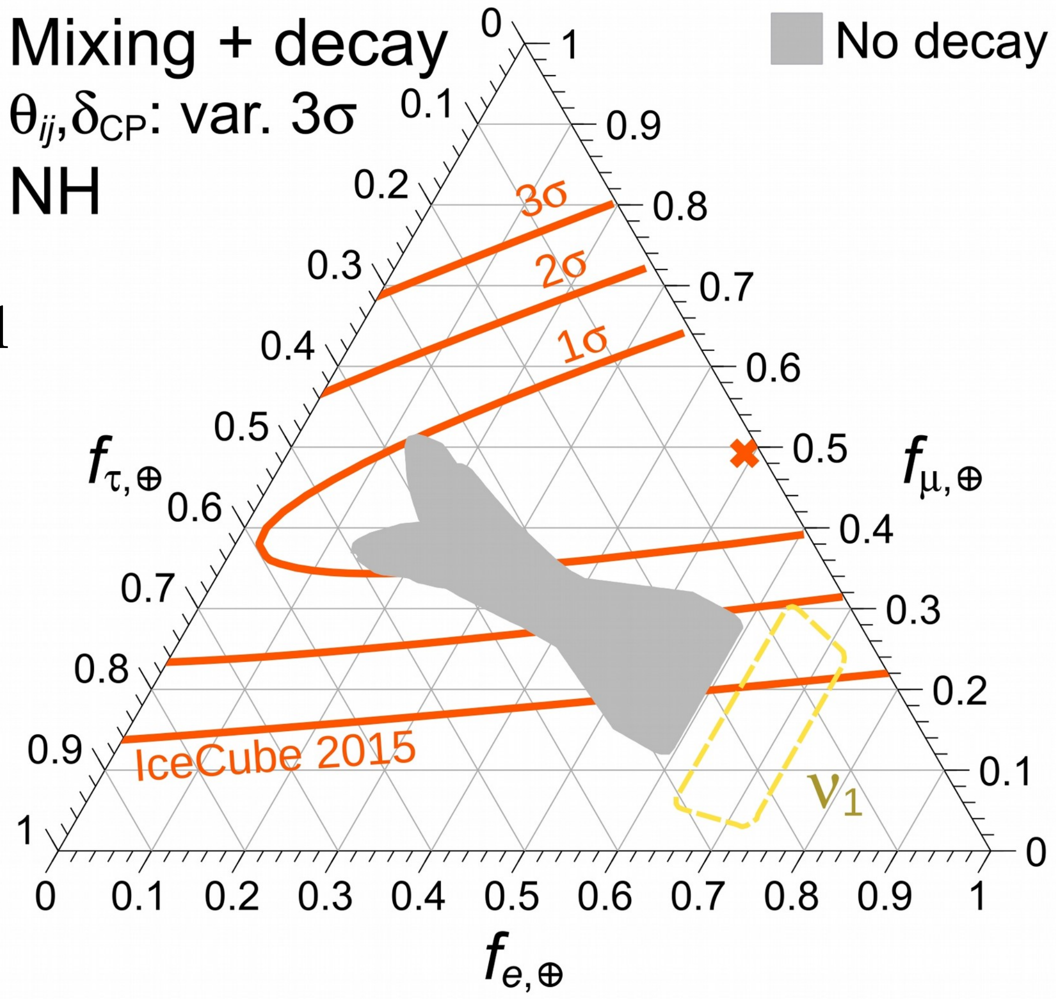
# Measuring the neutrino lifetime

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 $\nu_2$, $\nu_3$)

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



# Measuring the neutrino lifetime

Fraction of $\nu_2$, $\nu_3$ remaining at Earth

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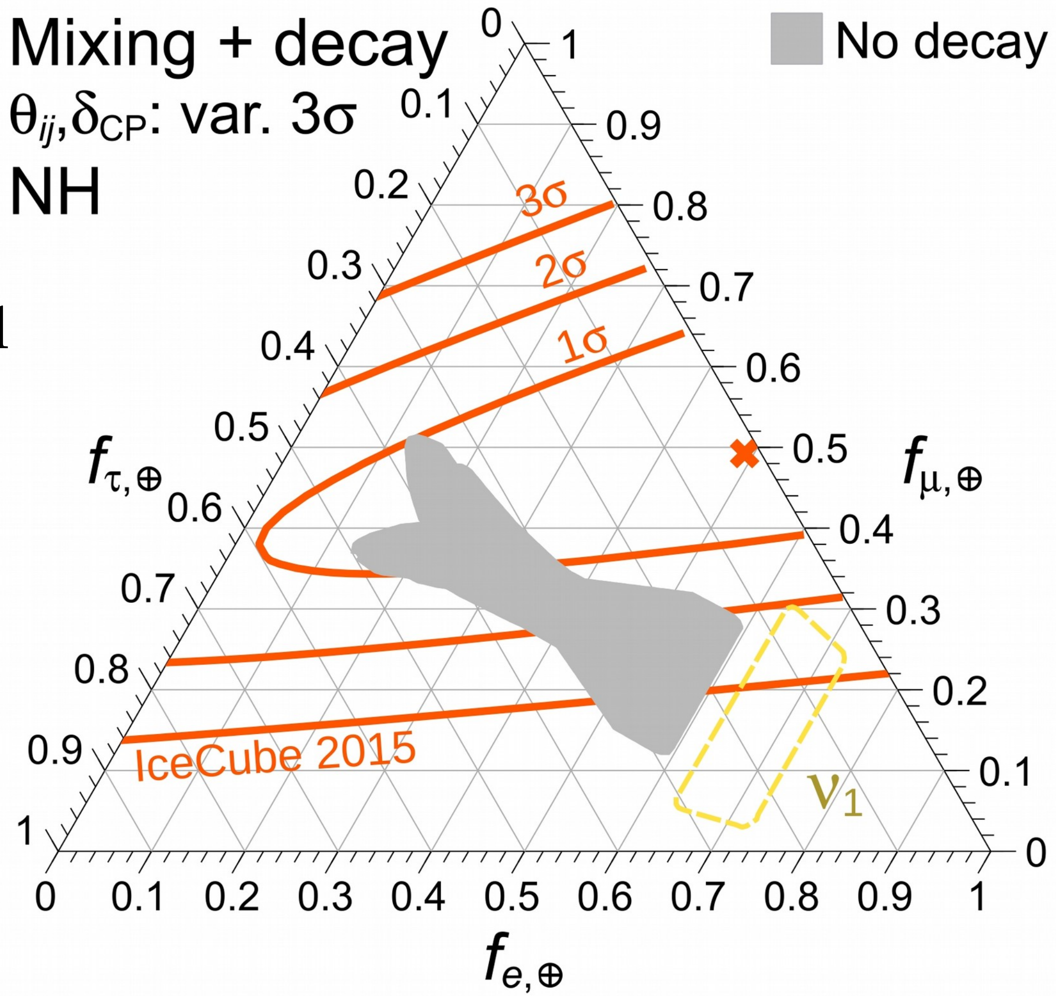


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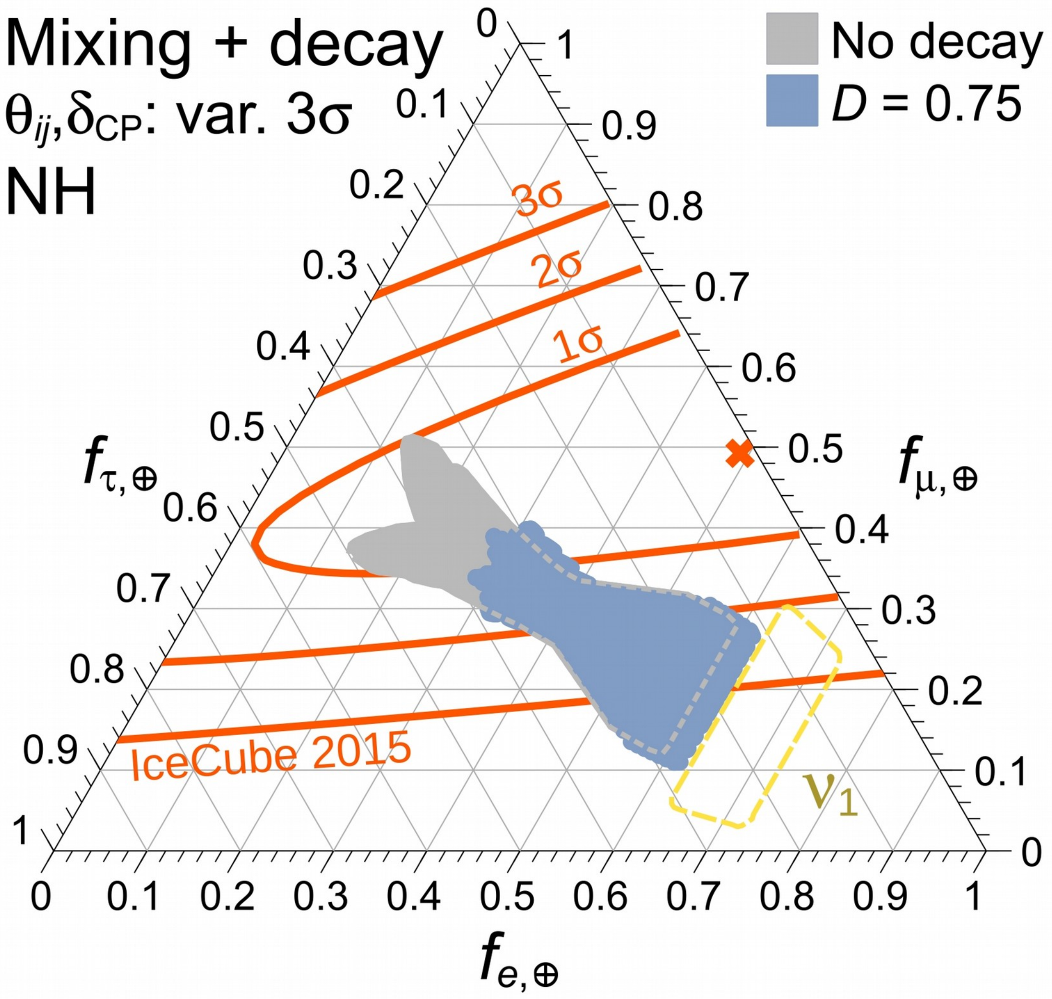

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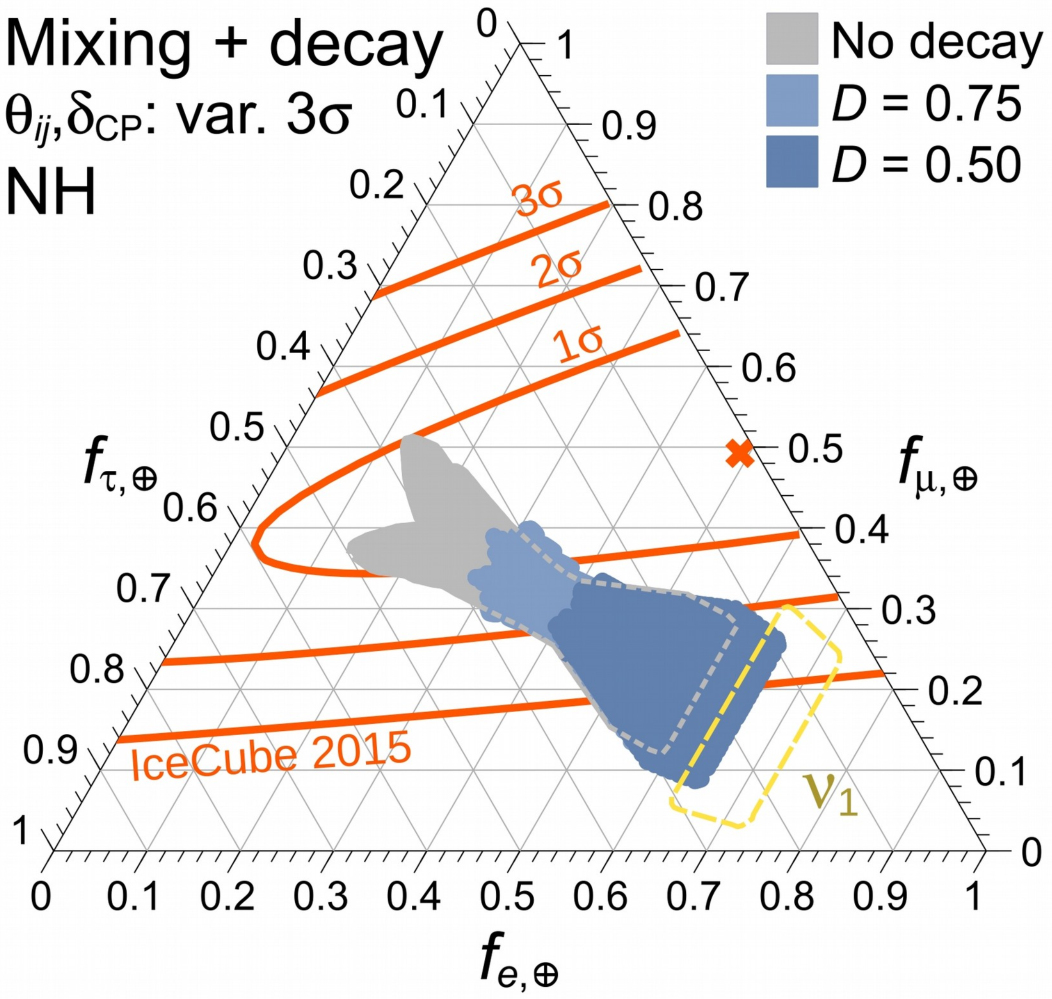


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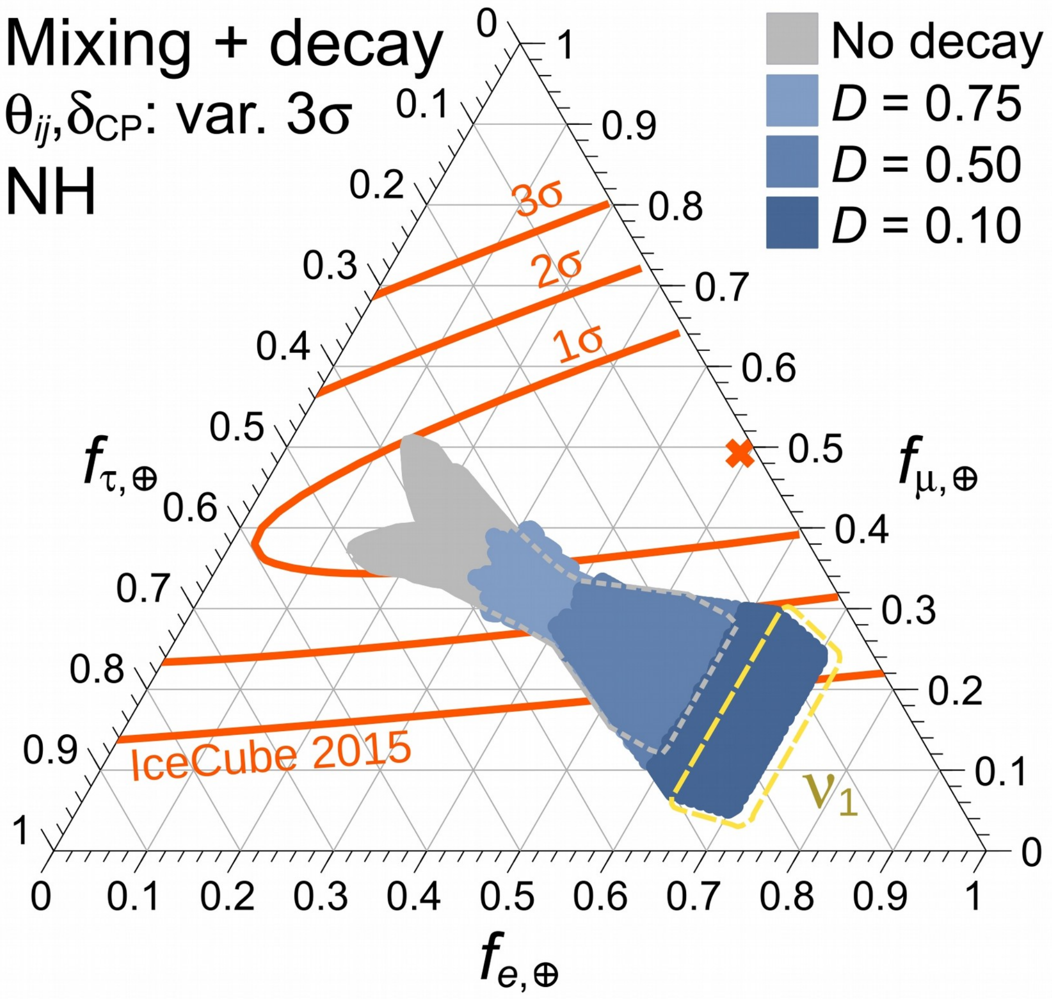

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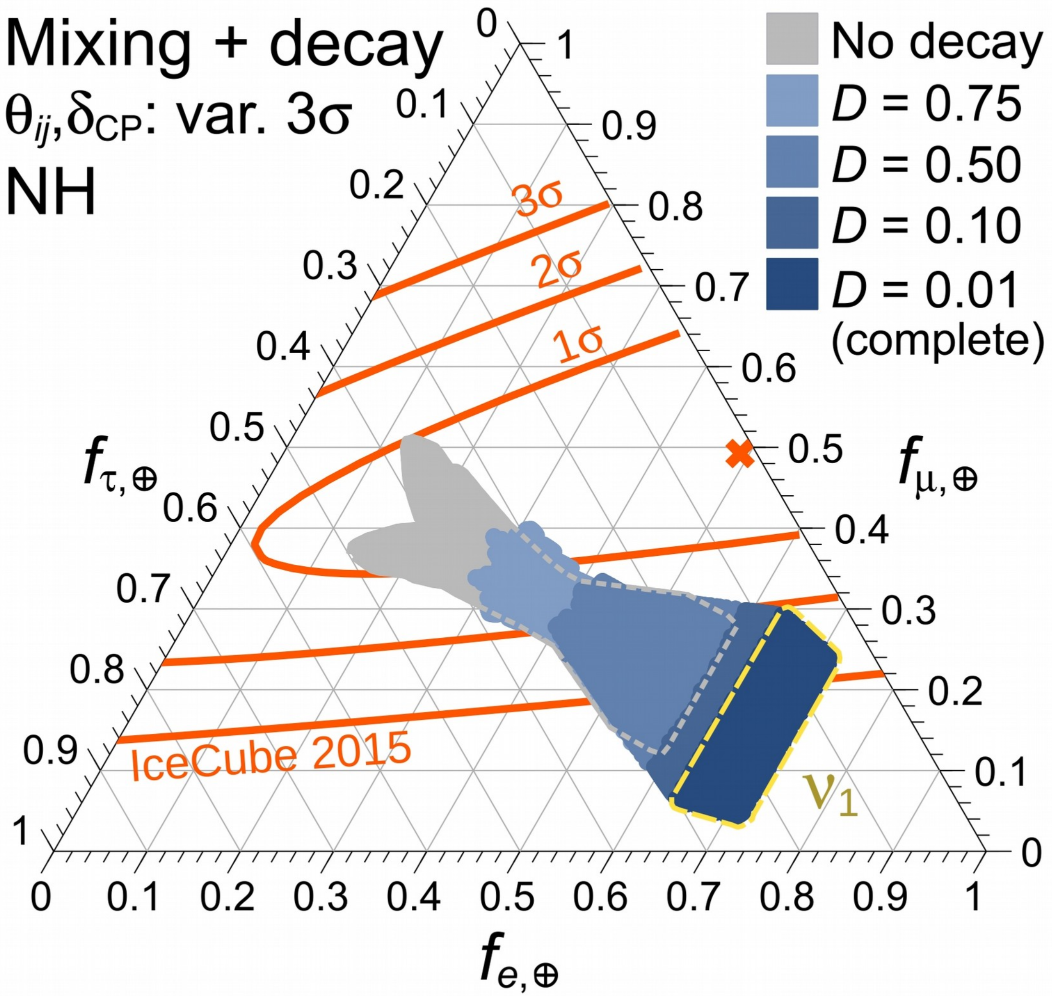

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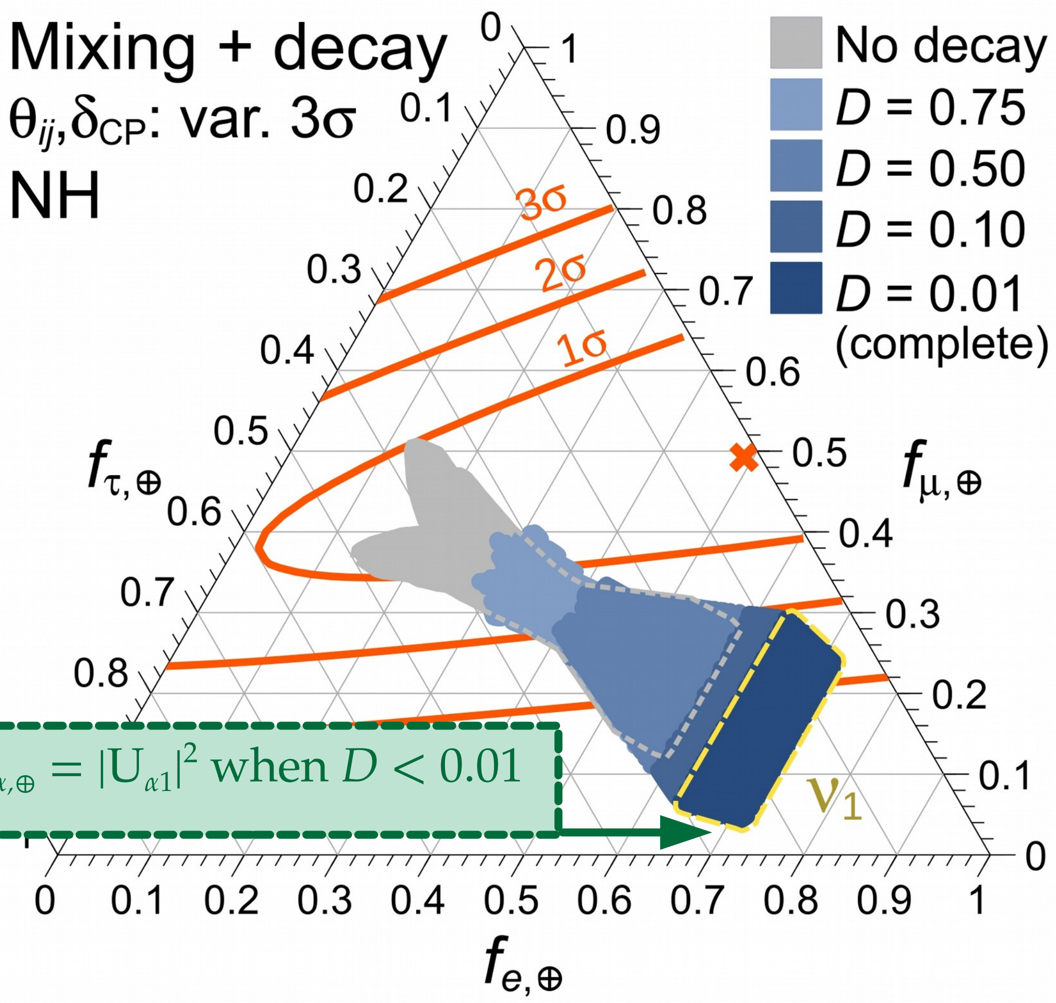
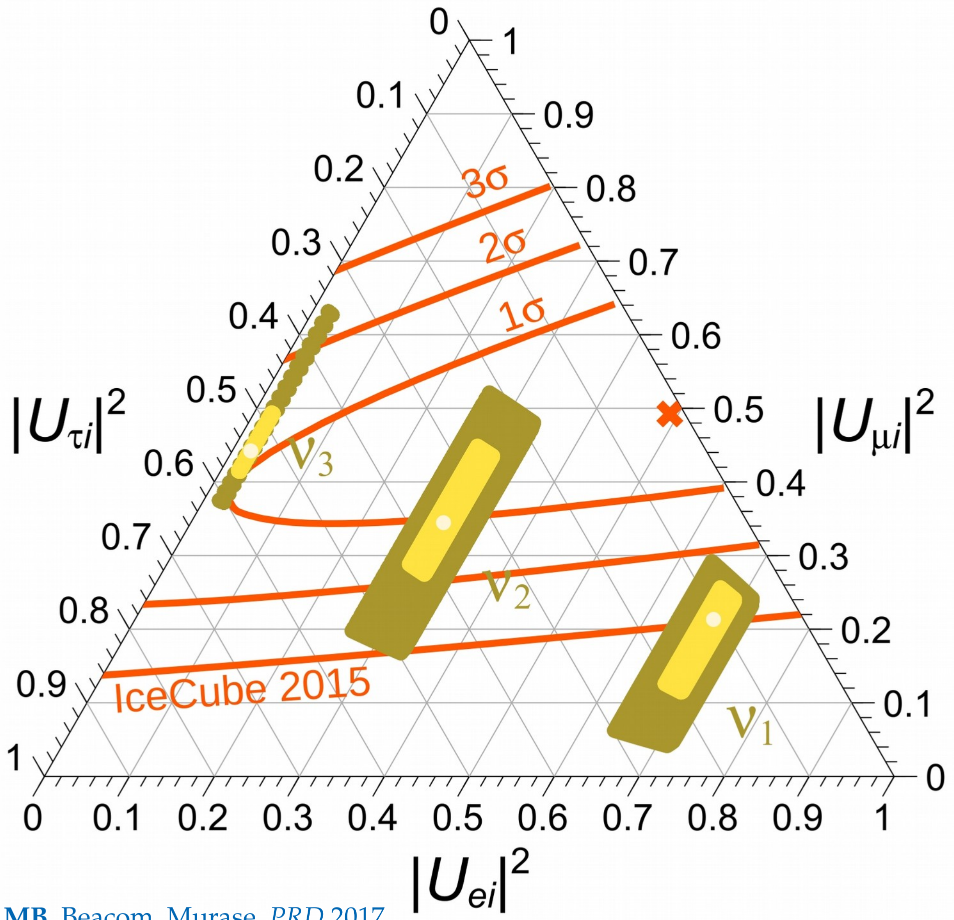
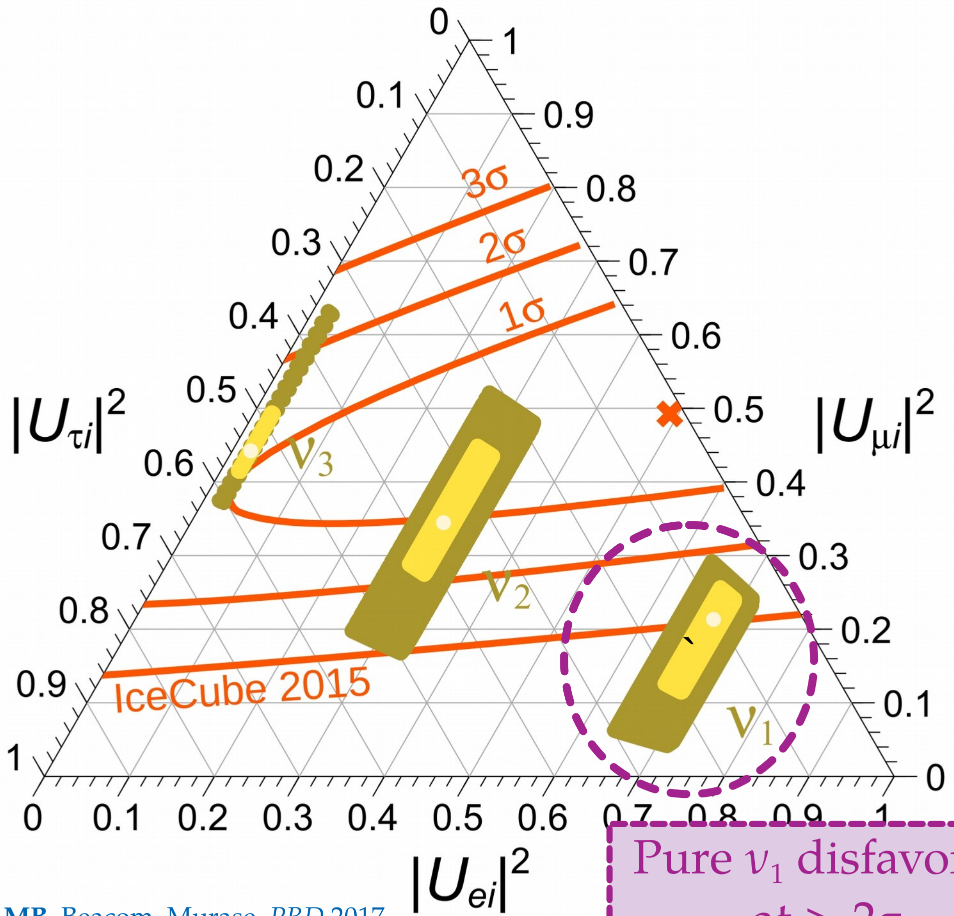



$f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D < 0.01$

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

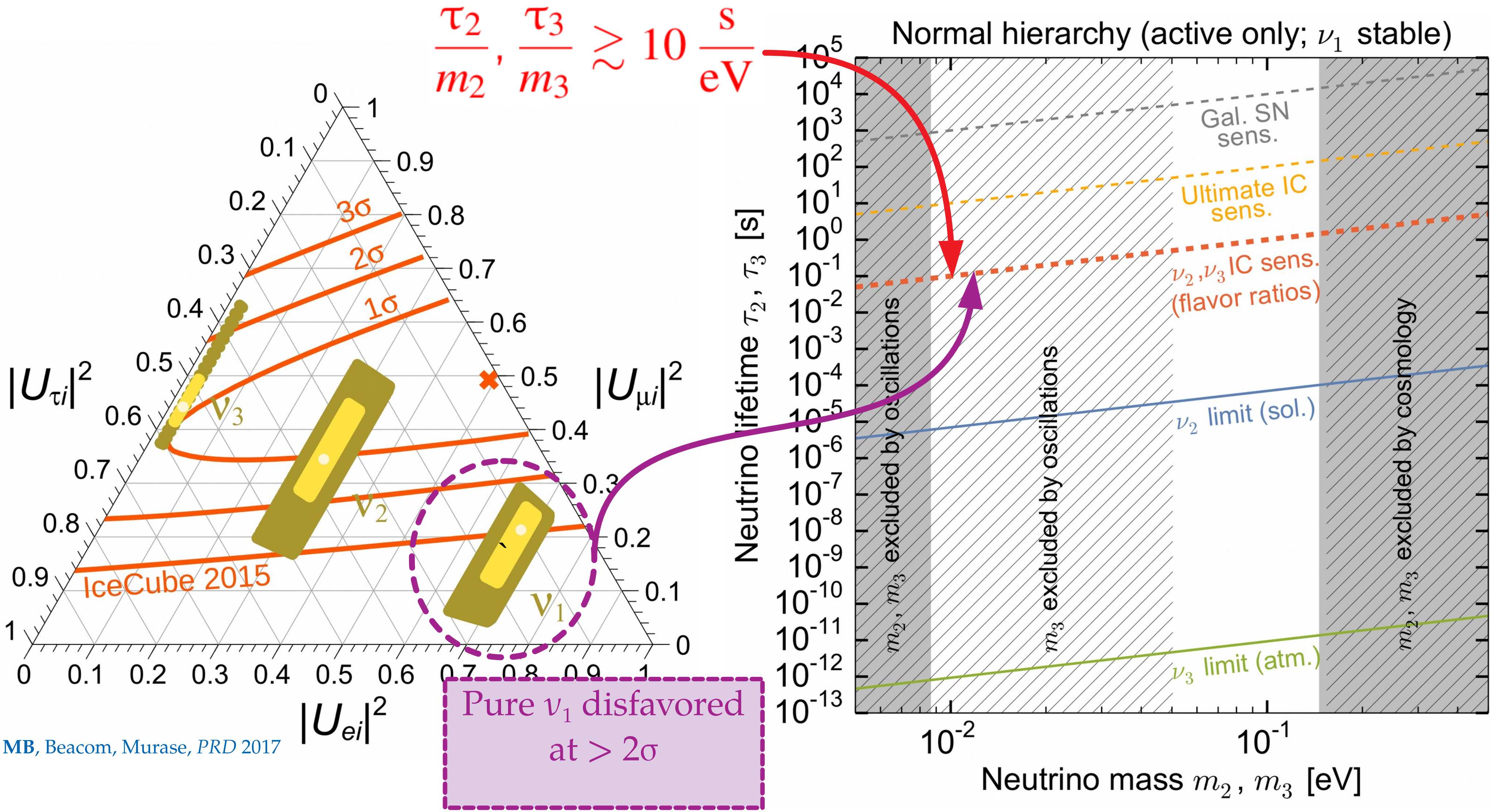



**MB**, Beacom, Murase, *PRD* 2017




Pure $\nu_1$ disfavored at > 2σ

**MB**, Beacom, Murase, *PRD* 2017



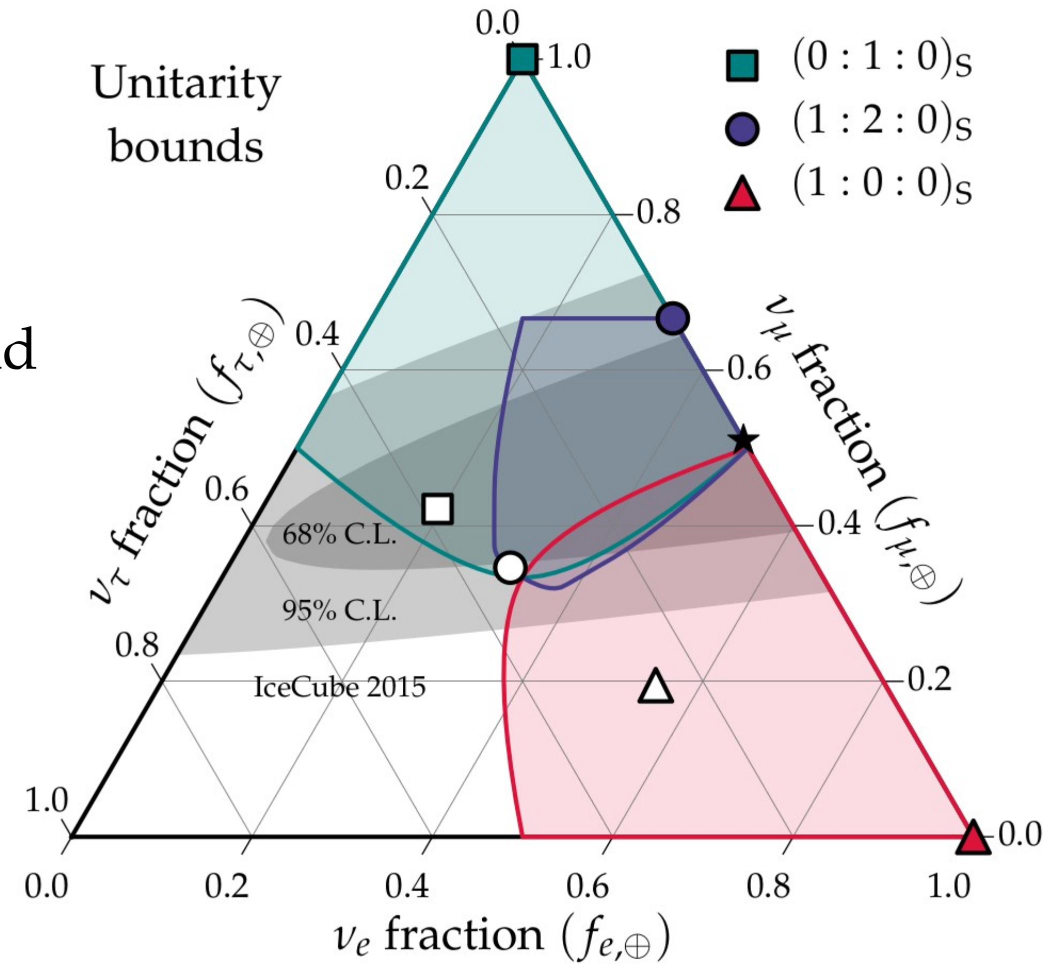

**MB**, Beacom, Murase, *PRD* 2017

Pure $\nu_1$ disfavored at > 2σ

# Using unitarity to constrain new physics

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

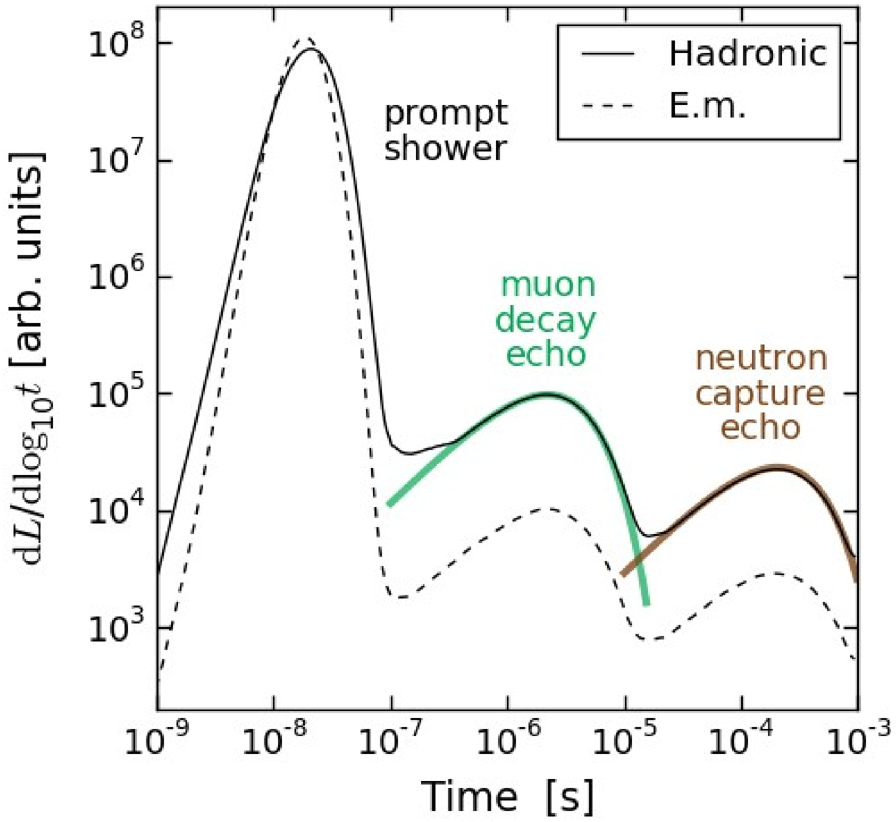
- New mixing angles unconstrained
- Use unitarity ($U_{NP}U_{NP}^{\dagger} = 1$) to bound all possible flavor ratios at Earth
- Can be used as prior in new-physics searches in IceCube

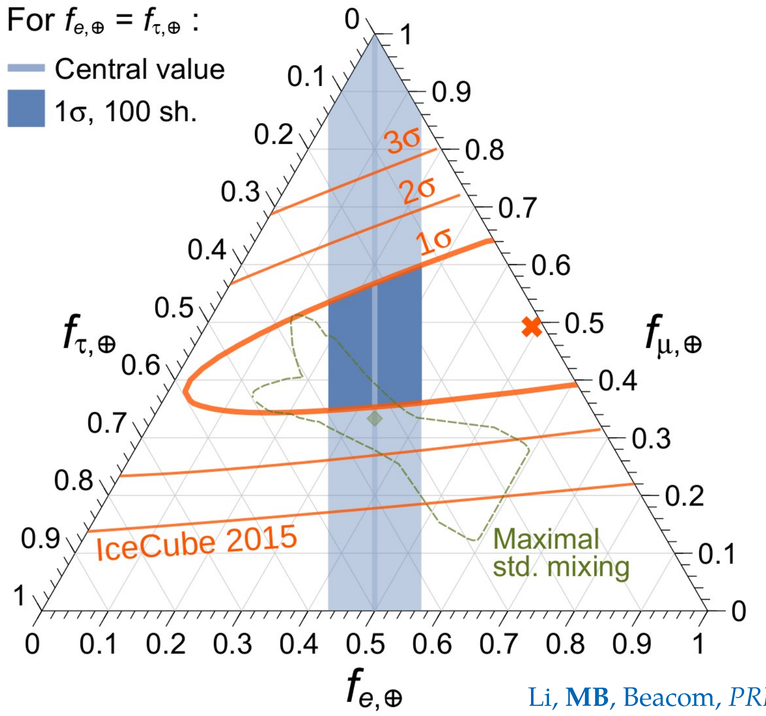



Ahlers, **MB**, Mu, *PRD* 2018
See also: Xu, He, Rodejohann, *JCAP* 2014

# Side note: Improving flavor-tagging using *echoes*

Late-time light (*echoes*) from muon decays and neutron captures can separate showers made by $\nu_e$ and $\nu_\tau$ –




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

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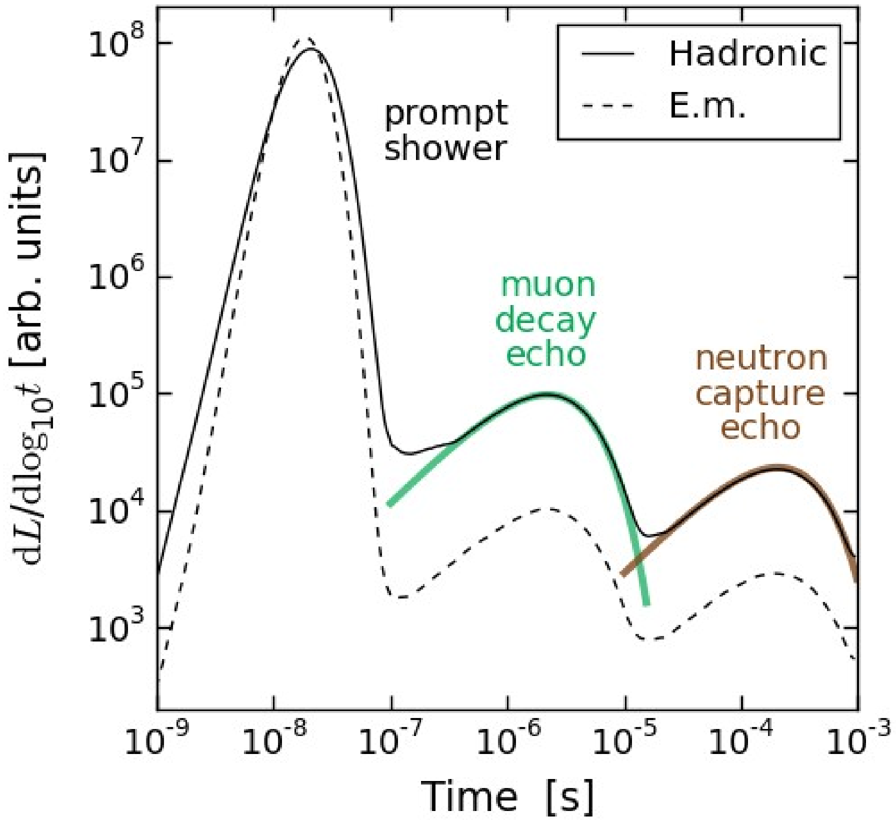
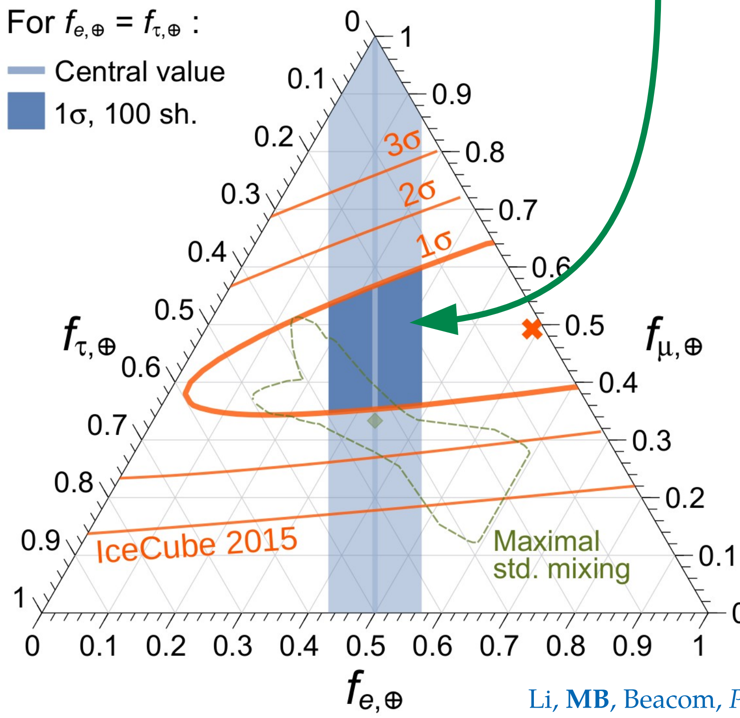



~10 × improvement over current measurement




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

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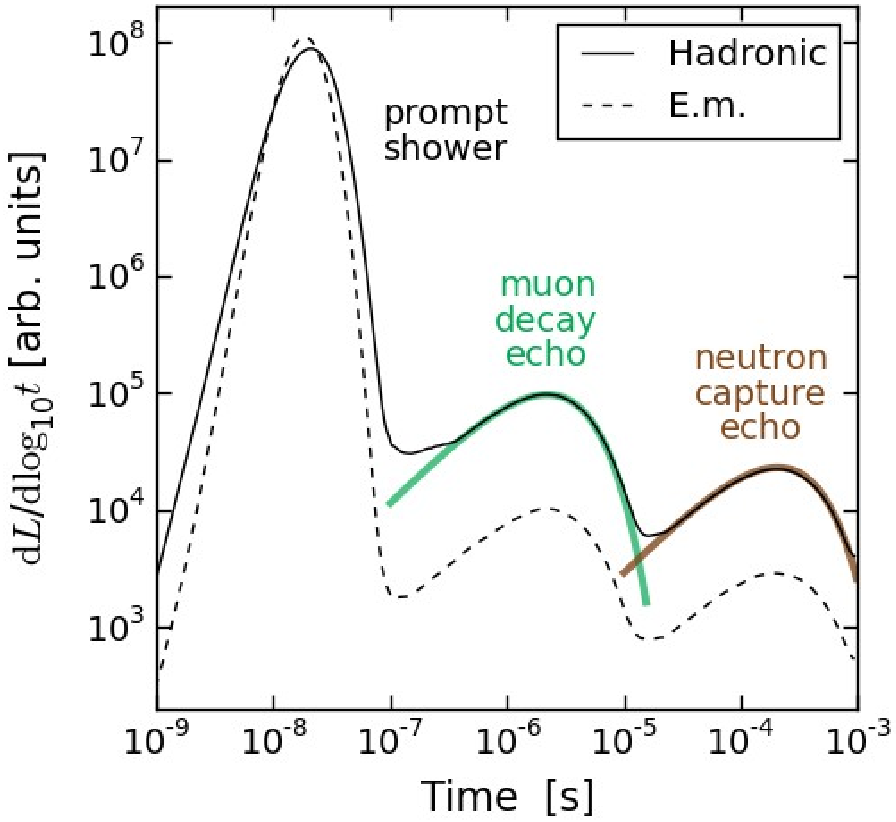


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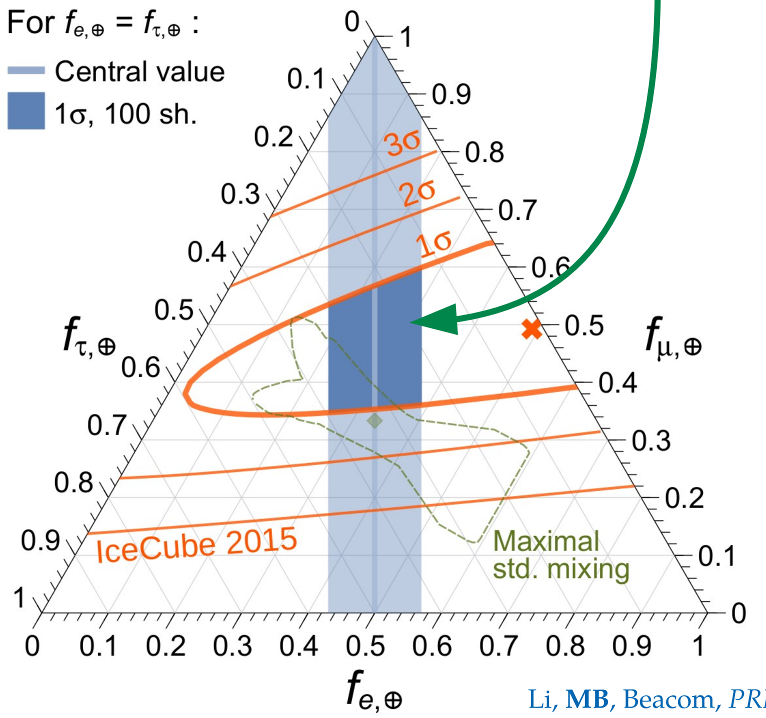
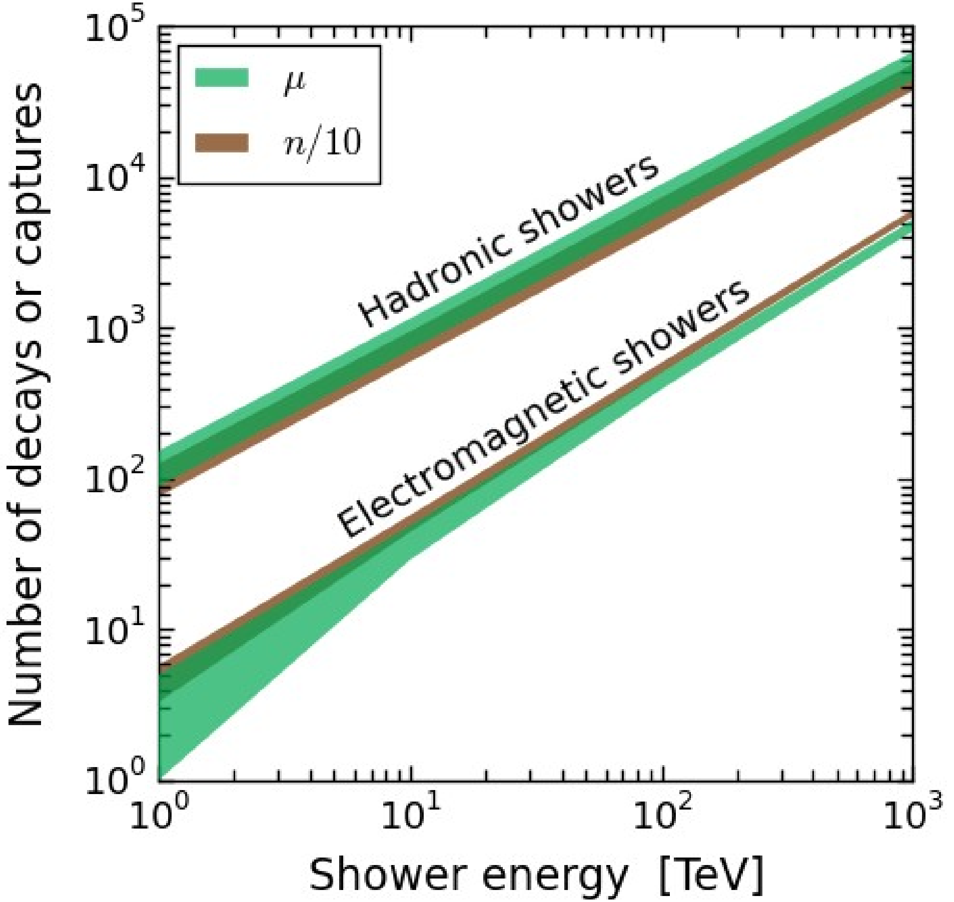
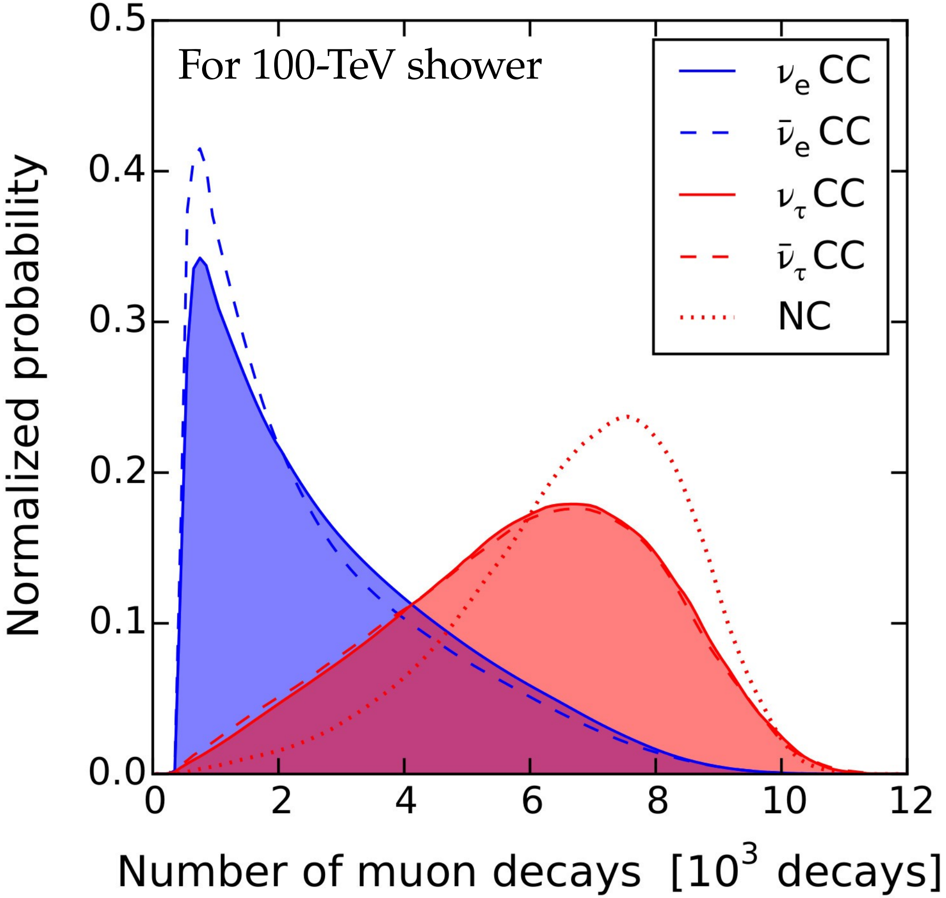



Li, **MB**, Beacom, *PRL* 2019

# Hadronic *vs.* electromagnetic showers

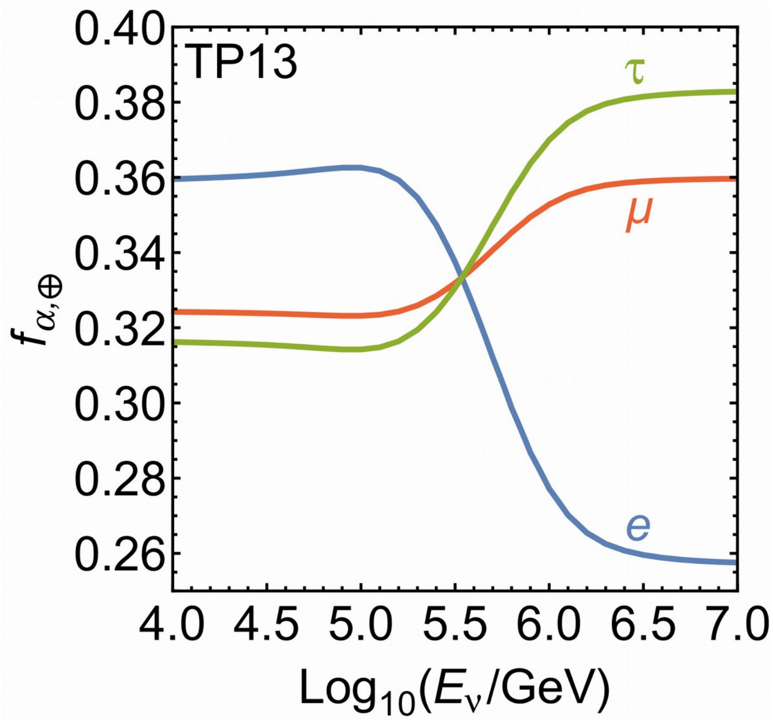


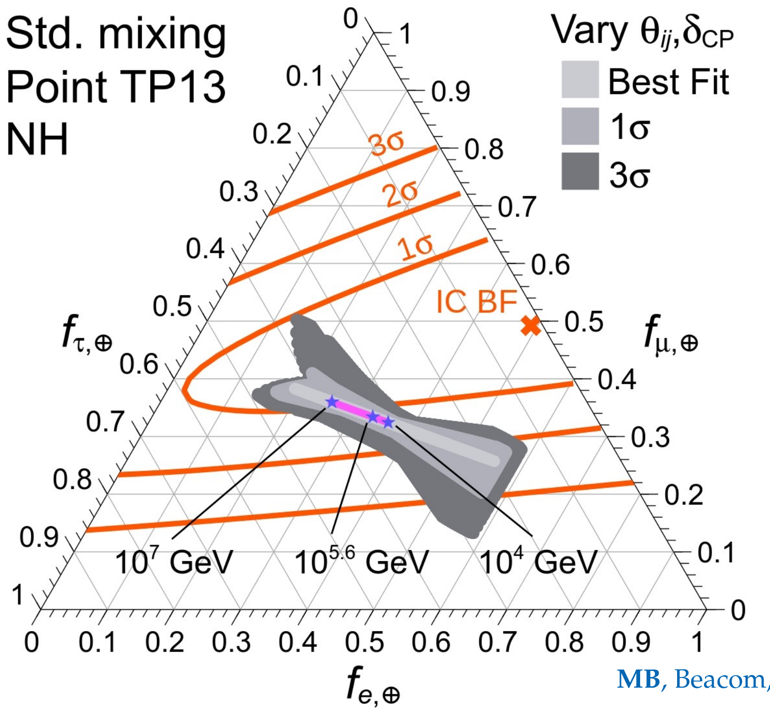




Li, **MB**, Beacom, *PRL* 2019

# Energy dependence of the flavor composition?

Different neutrino production channels accessible at different energies –




**MB**, Beacom, Winter *PRL* 2015

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