Fundamental ν physics in GRAND

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The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

Key questions

- Why is looking for new physics important?

  Reveals underlying structure of particles and interactions

- What is currently the biggest challenge in the field?
  - Small effects
  - Tests limited by energy of known ν sources (MeV–PeV)
  - Limited by statistics, mainly (but not exclusively)

- What do we need to solve it?

  Higher energies; large statistics; good energy, angular, flavor resolution

- Why would GRAND help solve it?
  - EeV energies, large statistics, great angular resolution
  - Not great for flavor; unknown energy resolution

Why look for new physics in HE astro. ν's?

- The highest energies ($\sim$ PeV)
  — Probe physics at new energy scales
- The longest baselines ($\sim$ Gpc)
  — Tiny effects can accumulate and become observable
- It comes *for free*

The new-physics reach of HE astrophysical ν's

If new-physics effects are $\sim \kappa E^n L$ (with κ its strength), we can probe

$$\kappa \sim 4 \cdot 10^{-47} \left(\frac{E}{\text{PeV}}\right)^{-n} \left(\frac{L}{\text{Gpc}}\right)^{-1} \text{PeV}^{n+1}$$

(Current limits: $\lesssim 10^{-30}$ PeV)

[Barenboim, Quigg, *PRD* **67**, 073024 (2003)]
[Beacom, Bell, Hooper, Pakvasa, Weiler, *PRL* **90**, 181301 (2003)]
[Maltoni, Winter, *JHEP* **07**, 064 (2008)]
[Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012)]
[Pagliaroli, Palladino, Villanti, Vissani, *PRD* **92**, 113008 (2015)]

The new ν physics tensor

Where it happens?

What it changes?

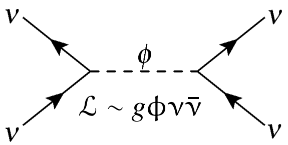
	At source	During propagation	At detection
Spectrum	Matter effects	New interactions, sterile neutrinos	New resonances
Direction	DM decay / annihilation	New ν-N, ν-DM interactions	Anomalous ν magnetic moment
Flavor ratios	Matter effects	ν decay, sterile ν, new operators	Non-standard interactions

How is the new physics introduced? ↗

[ARGÜELLES, BUSTAMANTE, CONRAD, KHEIRANDISH, VINCENT, *In prep.*]

New physics in the spectral shape: ν–ν interaction

Secret neutrino interactions between astrophysical neutrinos and the cosmic neutrino background:

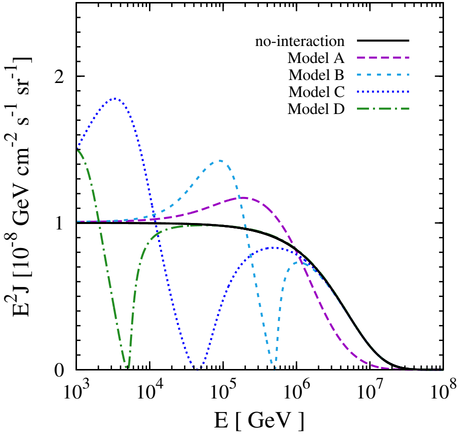


Cross section:

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

Resonance at

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

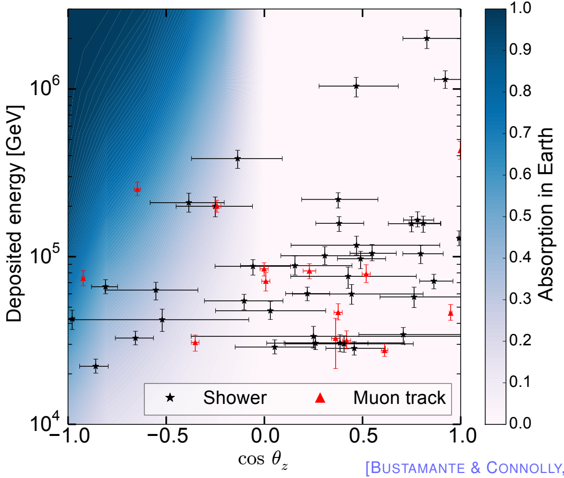


[Ng & Beacom, *PRD* **6**, 065035 (2014)]
[Cherry, Friedland, Shoemaker, 1411.1071]
[Blum, Hook, Murase, 1408.3799]

GRAND: Will need resolution of 0.1–0.2 in $\log_{10} E$

New physics in the angular dist.: ν–N interaction

Angular distribution of IceCube (contained) events (10 TeV–2 PeV) compatible with SM ν–N cross sections —



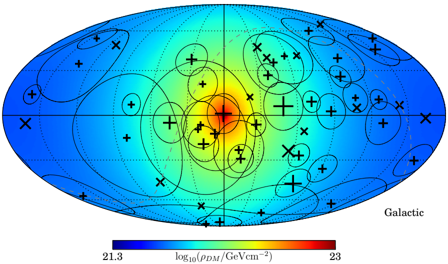
[BUSTAMANTE & CONNOLLY, *In prep.*]

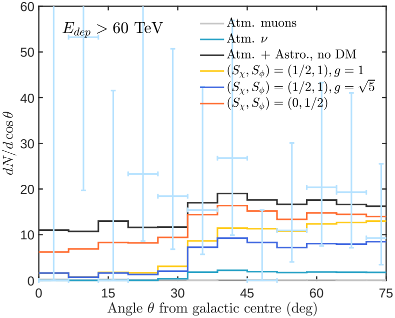
GRAND: Test σ at $E_{\rm cm} \gtrsim 1$ PeV (vs. ~ 25 GeV man-made, $\sim$ TeV IceCube)

[CONNOLLY, THORNE, WATER, *PRD* 2011 [1102.0691]]

New physics in the angular dist.: ν–DM interaction

Interaction between IceCube neutrinos and the Galactic DM profile —





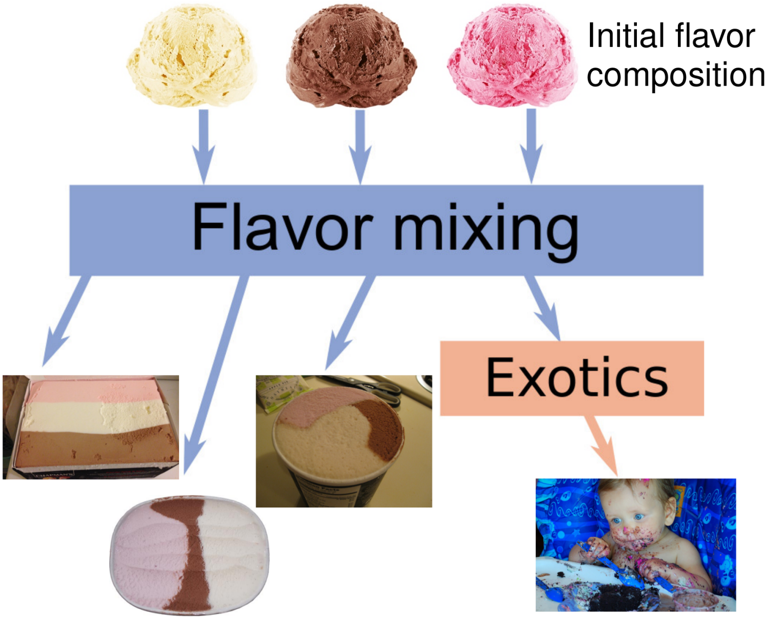
[ARGÜELLES *et al.* 1703.00451]

Expected: fewer events towards the Galactic Center

Observed: Isotropy

GRAND: Angular resolution of $\lesssim 0.05^\circ$ can test the inner GC

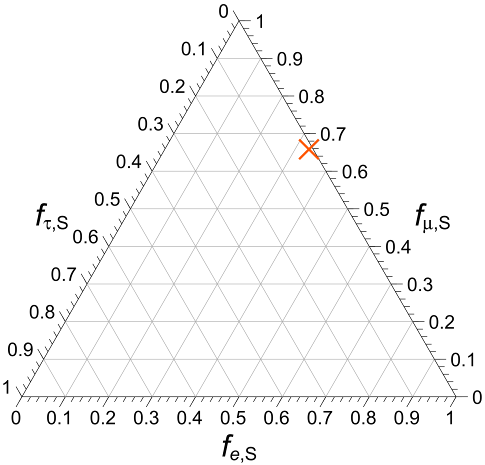
New physics in the flavor composition



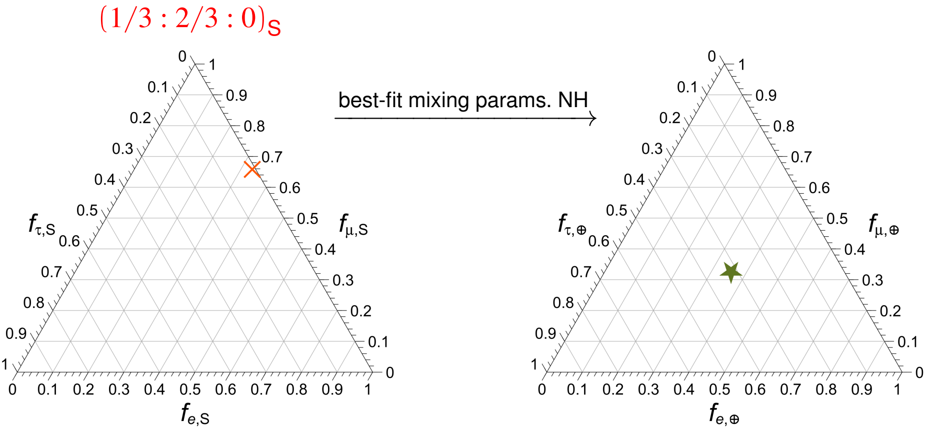
Flavor ratios — at production

$$p\gamma \to \Delta^+(1232) \to \pi^+ n \qquad \pi^+ \to \mu^+ \nu_\mu \to e^+ \nu_e \bar{\nu}_\mu \nu_\mu$$

Flavor ratios at production: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$

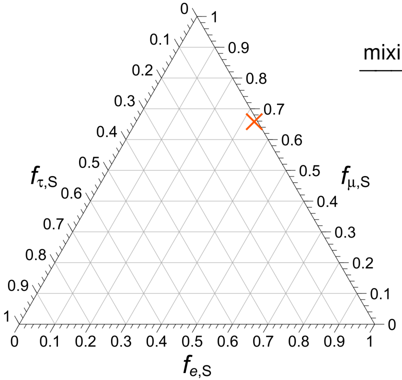


Flavor ratios — at Earth

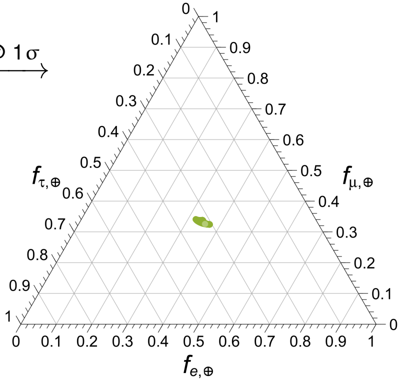


Flavor ratios — at Earth

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



mixing params. @ 1σ $\longrightarrow$



Flavor ratios — at Earth

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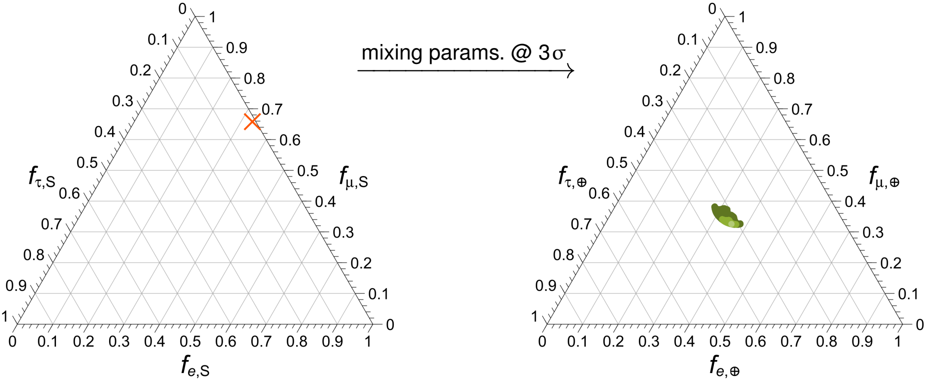

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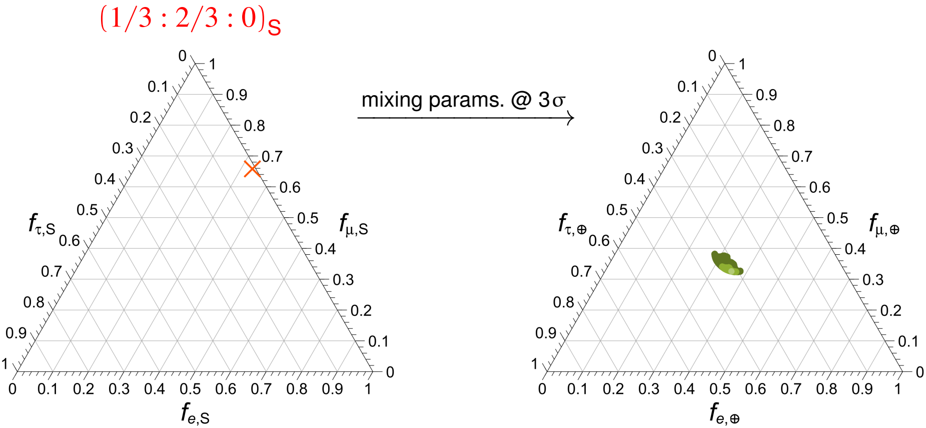


$f_{\tau,\oplus}$ outside [0.30,0.35] could imply new physics

The flavor problem in GRAND

GRAND sees ν_τ (to first order)

- To compute $f_{\tau,\oplus} \equiv \Phi_{\nu_\tau}/\Phi_{\rm tot}$, we need the $\Phi_{\rm tot}$ from elsewhere
- $\Phi_{\rm tot}$ only available if ARA, ARIANNA, ANITA see a flux
- So, flavor studies only possible if the cosmogenic ν flux is $\gtrsim 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}

New physics — of the *truly exotic* kind

What kind of NP lives outside the blue region?

- NP that changes the values of the mixing parameters, *e.g.*,
  - violation of Lorentz and CPT invariance

    [Barenboim, Quigg, *PRD* **67**, 073024 (2003)] [MB, Gago, Peña-Garay, *JHEP* **1004**, 005 (2010)]
  - violation of equivalence principle

    [Gasperini, *PRD* **39**, 3606 (1989)] [Glashow *et al.*, *PRD* **56**, 2433 (1997)]
  - coupling to a torsion field

    [De Sabbata, Gasperini, *Nuovo. Cim.* **A65**, 479 (1981)]
  - renormalization-group running of mixing parameters

    [MB, Gago, Jones, *JHEP* **1105**, 133 (2011)]
- active-sterile mixing [Aeikens *et al.*, *JCAP* **10**, 1510 (2015)] [Brdar *et al.*, 1611.04598]
- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

New physics — high-energy effects (I)

Add a new-physics term to the standard oscillation Hamiltonian:

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

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

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

$n = 0$

- coupling to a torsion field
- CPT-odd Lorentz violation

$n = 1$

- equivalence principle violation
- CPT-even Lorentz violation

Experimental upper bounds from atmospheric ν's:

$O_0 \lesssim 10^{-23}$ GeV $\qquad$ $O_1/\Lambda_1 \lesssim 10^{-27}$ GeV

[Argüelles, Katori, Salvadó, *PRL* **115**, 161303 (2015)]
[MB, Gago, Peña-Garay, *JHEP* **1004**, 005 (2010)]
[IceCube Coll., *PRD* **82**, 112003 (2010)]
[Super-K Coll., *PRD* **91**, 052003 (2015)]

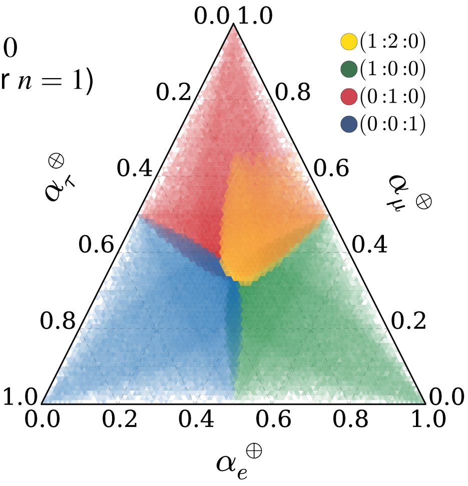
New physics — high-energy effects (II)

Truly exotic new physics is indeed able to populate the white region:

- use current bounds on $O_{n,i}$
- sample the unknown NP mixing angles

[ARGÜELLES, KATORI, SALVADÓ *PRL* **115**, 161303 (2015)]

$n = 0$
(similar for $n = 1$)



Joint production of UHECRs, ν's, and γ's

power law $\sim E^{-2}$

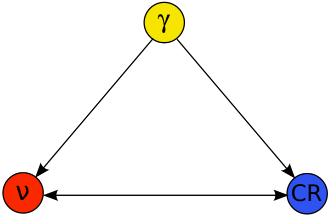
e.g., broken power law

$$p\,\gamma \rightarrow \Delta^{+}(1232) \rightarrow \begin{cases} n\pi^{+}, & \text{BR} = 1/3 \\ p\pi^{0}, & \text{BR} = 2/3 \end{cases}$$

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

$$\pi^{0} \rightarrow \gamma\gamma$$

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



neutrino energy $\simeq$ proton energy / 20

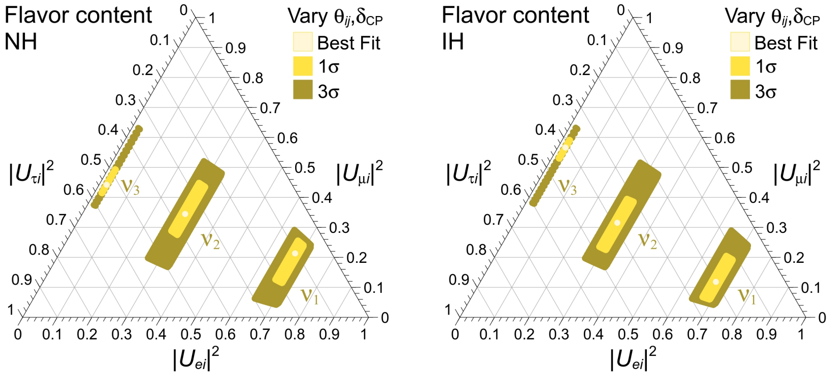
neutrino energy $\simeq$ gamma-ray energy / 2

E.g., 20-PeV protons could make PeV neutrinos and gamma rays

Flavor content of the mass eigenstates

Flavor content for every allowed combination of mixing parameters:

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



MB, Beacom, Winter, *PRL* **115**, 161302 (2015)

Flavor mixing in high-energy astrophysical neutrinos

Probability of $\nu_\alpha \to \nu_\beta$ transition:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{k>j} \text{Re}\left(U_{\alpha j}U^*_{\alpha k}U_{\beta j}U^*_{\beta k}\right)\sin^2\left(\frac{\Delta m^2_{kj}L}{4E}\right) + 2\sum_{k>j}\text{Im}\left(U_{\alpha j}U^*_{\alpha k}U_{\beta j}U^*_{\beta k}\right)\sin\left(\frac{\Delta m^2_{kj}L}{2E}\right)$$

For $\begin{cases} E_\nu \sim 1 \text{ PeV} \\ \Delta m^2_{kj} \sim 10^{-4} \text{ eV}^2 \end{cases} \Rightarrow \underbrace{L_{\text{osc}} \sim 10^{-10} \text{ Mpc}}_{\text{high-energy osc. length}} \ll \underbrace{L = 10 \text{ Mpc} - \text{few Gpc}}_{\text{typical astrophysical baseline}}$

- Therefore, oscillations are very rapid
- They average out after only a few oscillations lengths:

$$\sin^2(\ldots) \to 1/2\,, \quad \sin(\ldots) \to 0$$

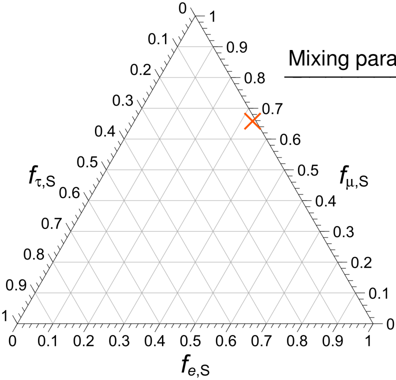
Hence, for high-energy astrophysical neutrinos:

$\langle P_{\alpha\beta}\rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$ ◀ incoherent mixture of mass eigenstates

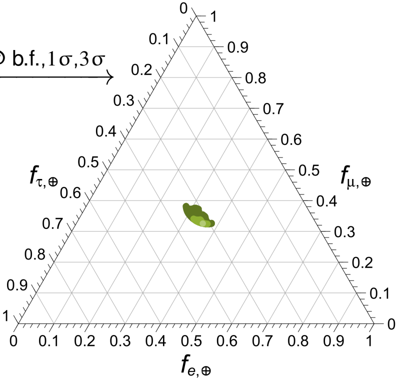
Flavor ratios — at Earth

Due to flavor mixing: $f_{\alpha,\oplus} = \sum_{\beta} \langle P_{\beta\alpha} \rangle f_{\beta,\mathrm{S}} = \sum_{\beta} \left(\sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \right) f_{\beta,\mathrm{S}}$

$$(1/3 : 2/3 : 0)_{\mathrm{S}} \xrightarrow{\text{Best-fit mixing params. NH}} (0.36 : 0.32 : 0.32)_{\oplus}$$



Mixing params. @ b.f.,1σ,3σ $\longrightarrow$



Embracing our ignorance

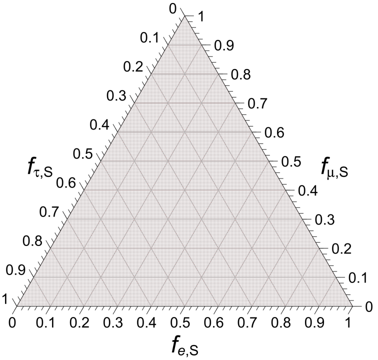
We ignore or do not know perfectly the two key ingredients —

Flavor ratios at the source

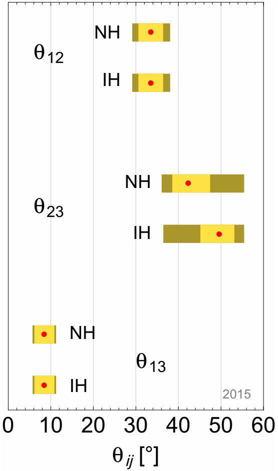
$$0 \leqslant f_{e,\mathrm{S}} \leqslant 1$$

$$0 \leqslant f_{\mu,\mathrm{S}} \leqslant 1 - f_{e,\mathrm{S}}$$

$$0 \leqslant f_{\tau,\mathrm{S}} \leqslant 1 - f_{e,\mathrm{S}} - f_{\mu,\mathrm{S}}$$

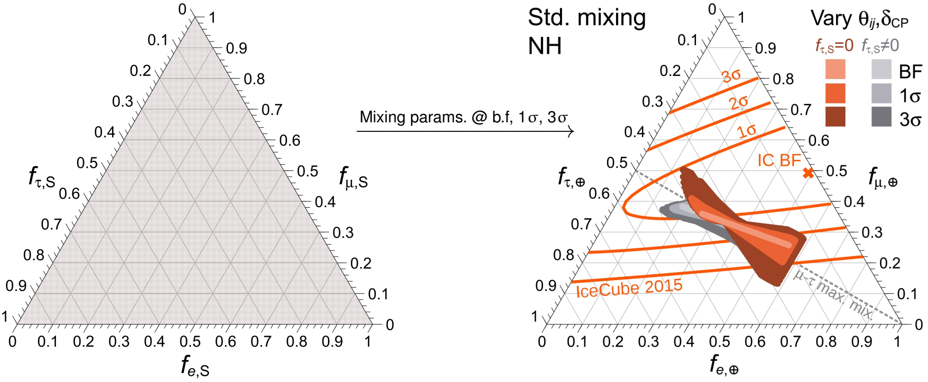


Mixing parameters



Flavor composition — standard allowed region

All possible source flavor ratios



MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Std. mixing can access *only* $\sim 10\%$ of the possible combinations

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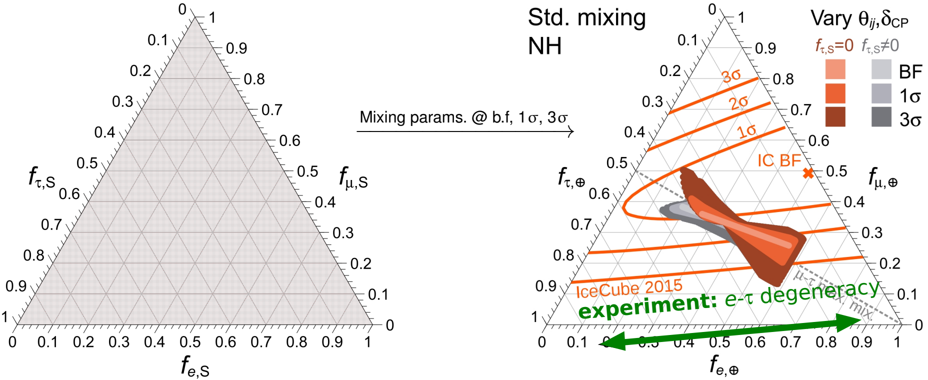

MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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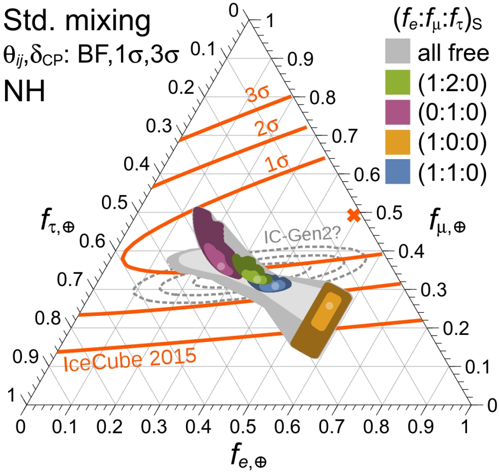
Selected source compositions

We can look at results for particular choices of ratios at the source:



MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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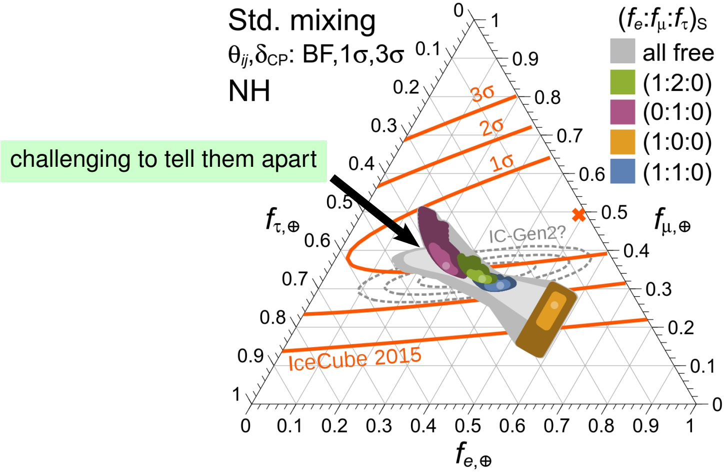

MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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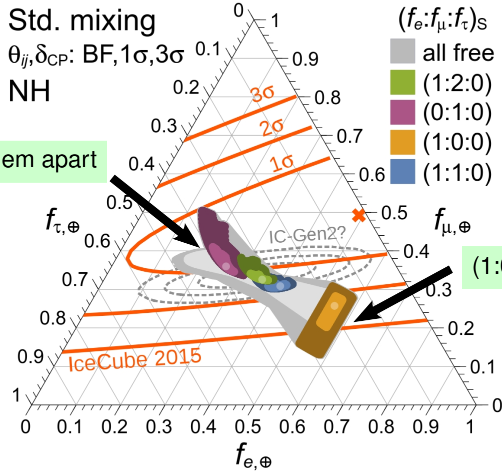


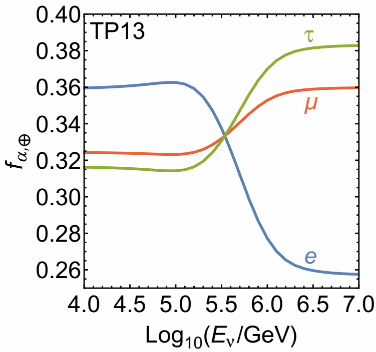
challenging to tell them apart

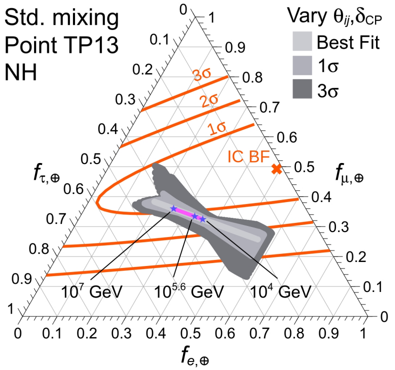
(1:0:0) disfavored at 2σ

MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies



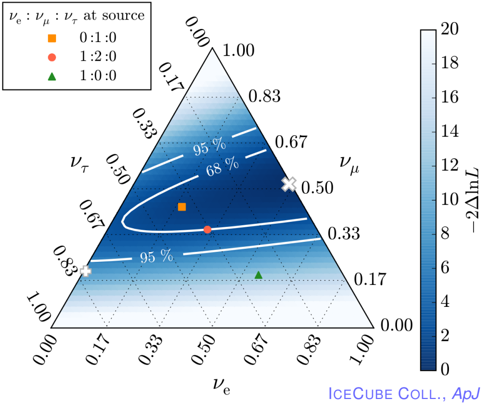


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

- TP13: $p\gamma$ model, target photons from co-accelerated electrons
  [Hümmer *et al.*, *Astropart. Phys.* **34**, 205 (2010)]
- Will be difficult to resolve
  [Kashti, Waxman, *PRL* **95**, 181101 (2005)] [Lipari, Lusignoli, Meloni, *PRD* **75**, 123005 (2007)]

IceCube analysis of flavor composition

Using contained events + throughgoing muons:



ICECUBE COLL., *ApJ* **809**, 98 (2015)

- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Bounds are weak – need more data and better flavor-tagging

How does IceCube see neutrinos?

Two types of fundamental interactions:

Charged-current

$$\nu_l + N \rightarrow l + \text{hadrons}$$

Neutral-current

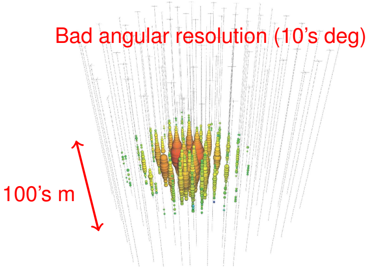
$$\nu_l + N \rightarrow \nu_l + \text{hadrons}$$

these shower and make light

Two event topologies (below $E_\nu \sim 5$ PeV):

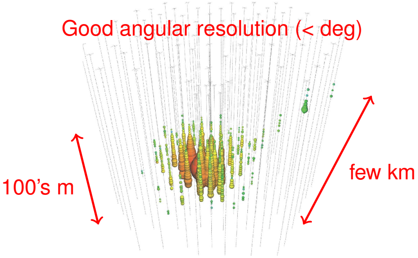
Showers

Made by CC ν_e or ν_τ; or by NC ν_x



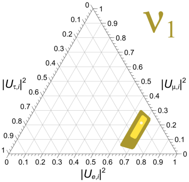
Tracks

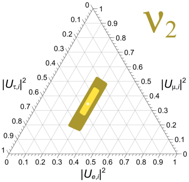
Made mainly by CC ν_μ

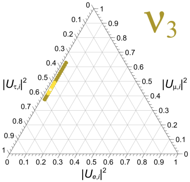


Two classes of new physics

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







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

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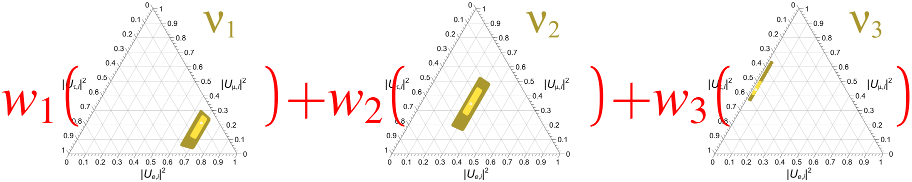

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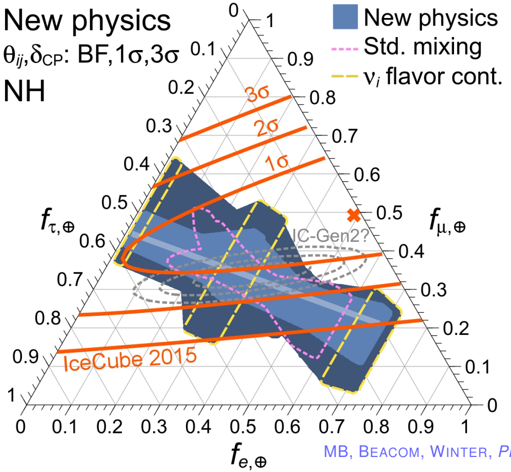
Region of flavor ratios accessible with decay

Region of all linear combinations of ν_1, ν_2, ν_3:



MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Decay can access *only* ~ 25% of the possible combinations

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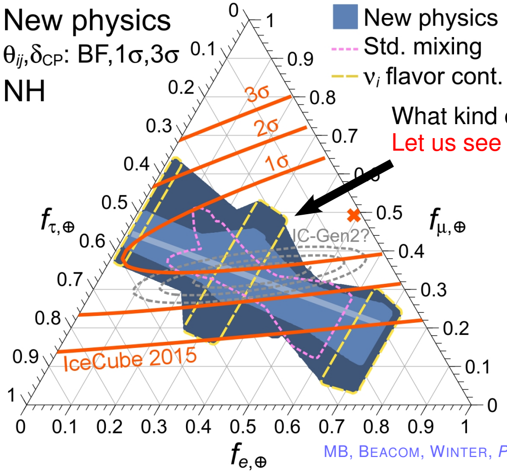

What kind of NP lives outside?

Let us see a few examples

MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Decay can access *only* $\sim 25\%$ of the possible combinations