New Physics Tests with High-Energy Astrophysical Neutrinos

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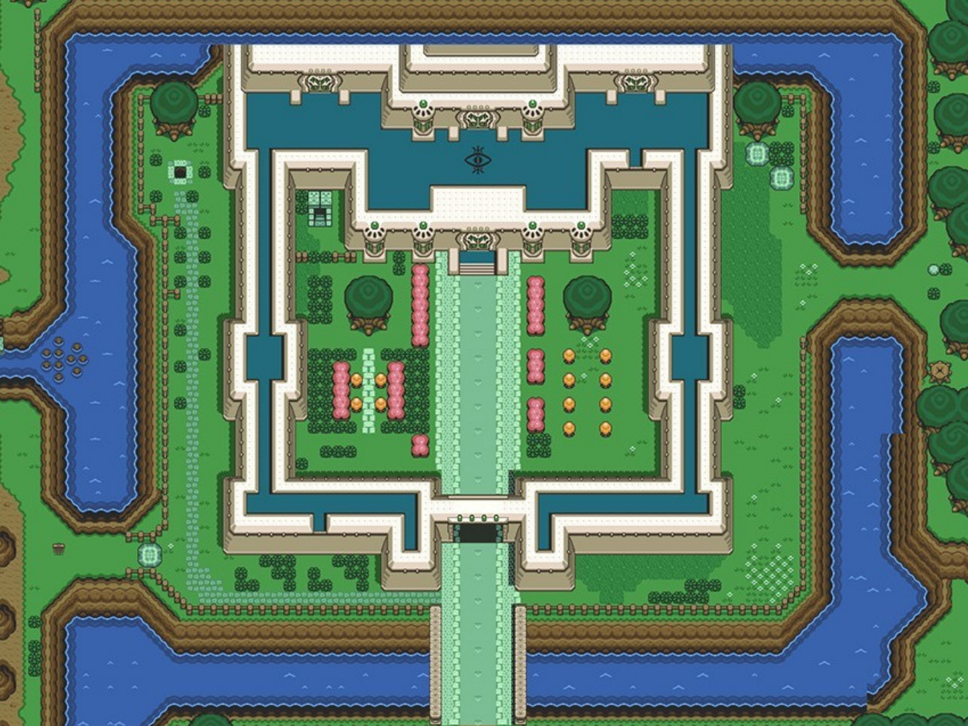
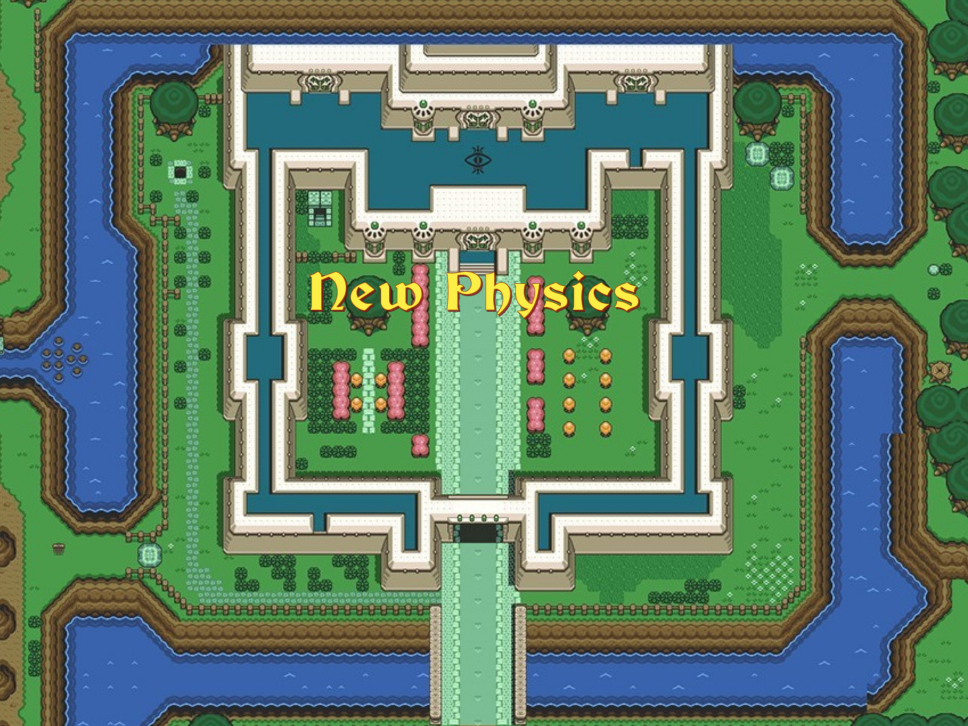
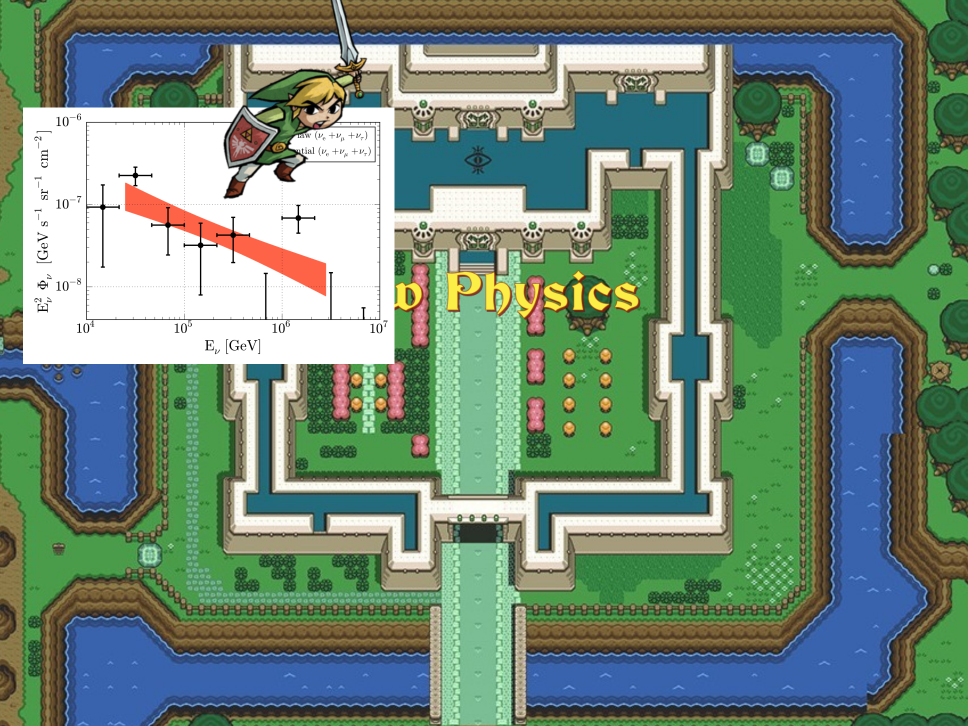
The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

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

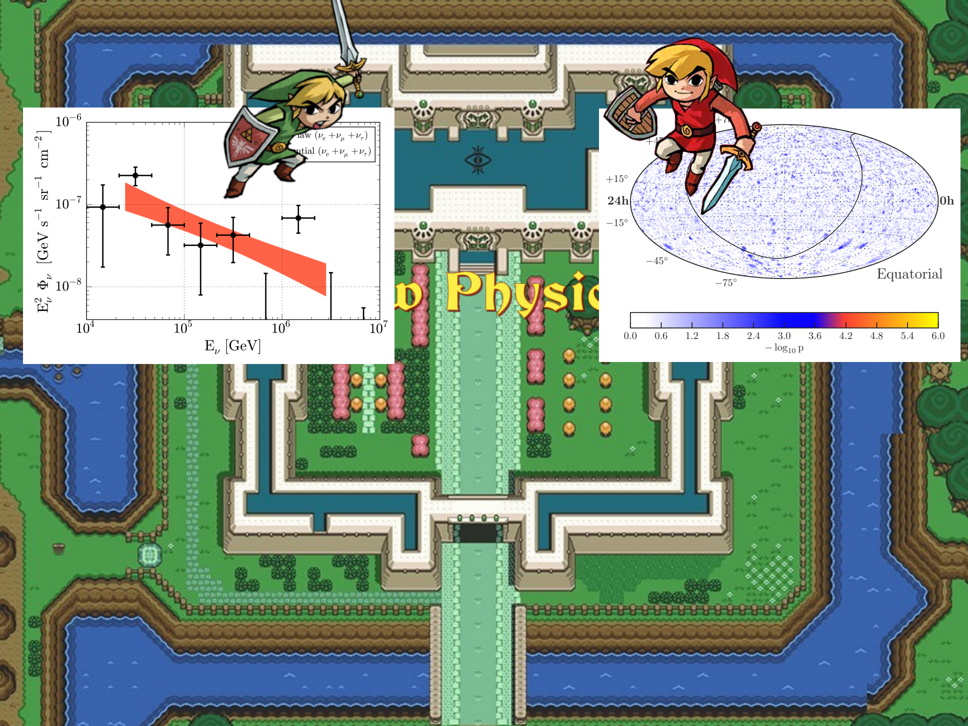
- The highest energies ($\sim$ PeV)
  — Probe physics at new energy scales
- The longest baselines ($\sim$ Gpc)
  — Tiny effects can accumulate and become observable
- It comes *for free*

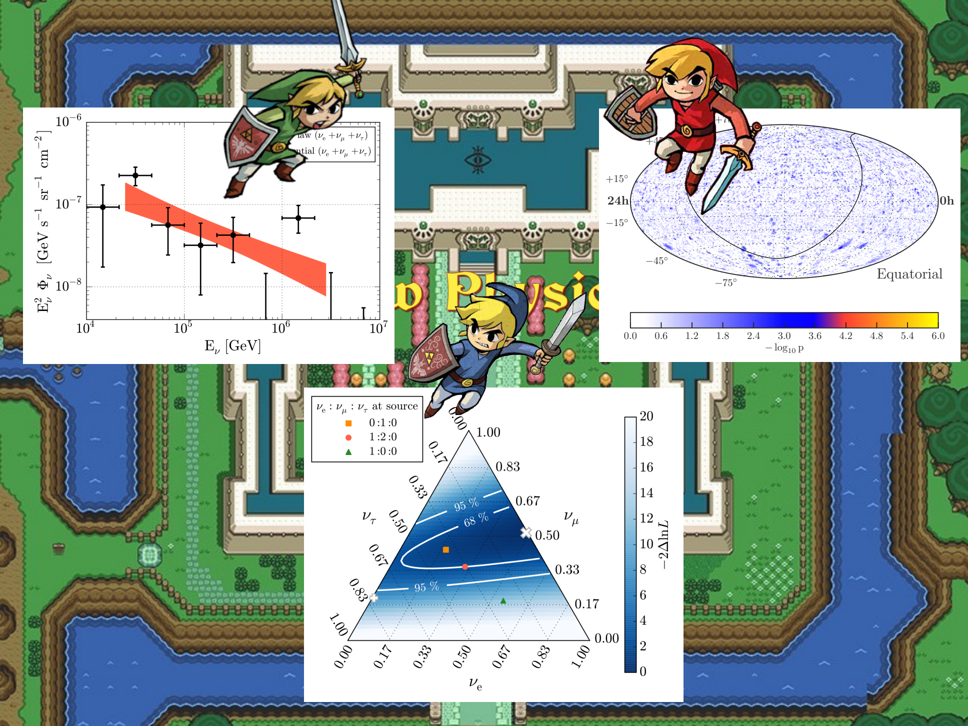



New Physics



Physics
law ($\nu_e + \nu_\mu + \nu_\tau$)
ntial ($\nu_e + \nu_\mu + \nu_\tau$)
$E_\nu^2\,\Phi_\nu$ [GeV s^{-1} sr^{-1} cm^{-2}]
10^{-6}
10^{-7}
10^{-8}
10^4
10^5
10^6
10^7
E_ν [GeV]


10−6
10−7
10−8
E2ν Φν [GeV s−1 sr−1 cm−2]
law (νe +νμ +ντ)
ntial (νe +νμ +ντ)
104
105
106
107
Eν [GeV]
Physic
+15°
24h
−15°
−45°
−75°
0h
Equatorial
0.0
0.6
1.2
1.8
2.4
3.0
3.6
4.2
4.8
5.4
6.0
− log10 p



$E_\nu^2\ \Phi_\nu$ [GeV s^{-1} sr^{-1} cm^{-2}]
10^{-6}
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0.0
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1.8
2.4
3.0
3.6
4.2
4.8
5.4
6.0
$-\log_{10}$ p
$\nu_e : \nu_\mu : \nu_\tau$ at source
0 : 1 : 0
1 : 2 : 0
1 : 0 : 0
95 %
68 %
95 %
ν_τ
ν_μ
ν_e
0.00
0.17
0.33
0.50
0.67
0.83
1.00
$-2\Delta\ln L$
0
2
4
6
8
10
12
14
16
18
20

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?

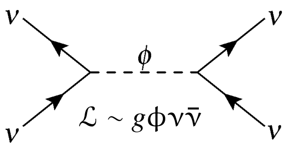
	At source	**During propagation**	**At detection**
Spectrum	Matter effects	New interactions, sterile neutrinos	New resonances
Direction	DM decay / annihilation	New ν-N, ν-DM interactions	Anomalous ν magnetic moment
Flavor ratios	Matter effects	ν decay, sterile ν, new operators	Non-standard interactions

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:

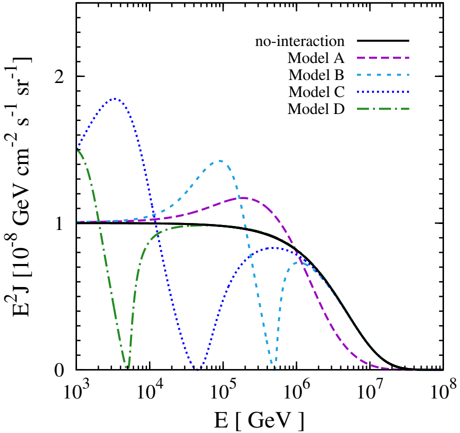


Cross section:

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

Resonance at

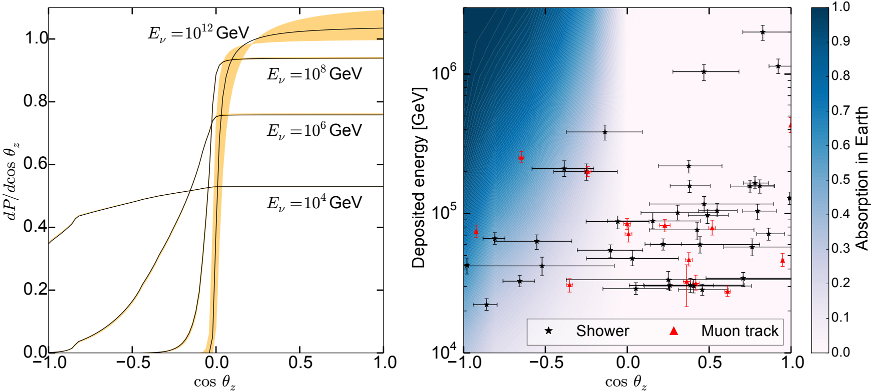
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$



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

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

HESE angular distribution is compatible with SM ν–N cross sections —



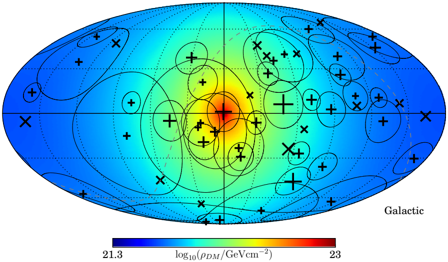
[Bustamante & Connolly, *In prep.*]

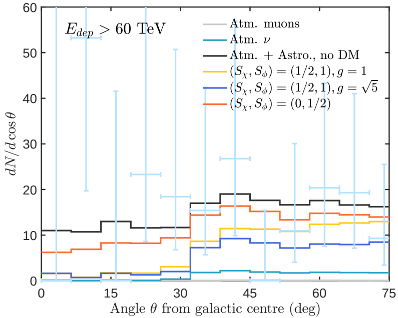
Limits deviations at $E_{\rm cm} \simeq 0.4 - 2$ TeV (vs. ~ 25 GeV man-made)

[Connolly, Thorne, Waters, *PRD* 2011 [1102.0691]]

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

Interaction between astrophysical neutrinos and the Galactic DM profile:



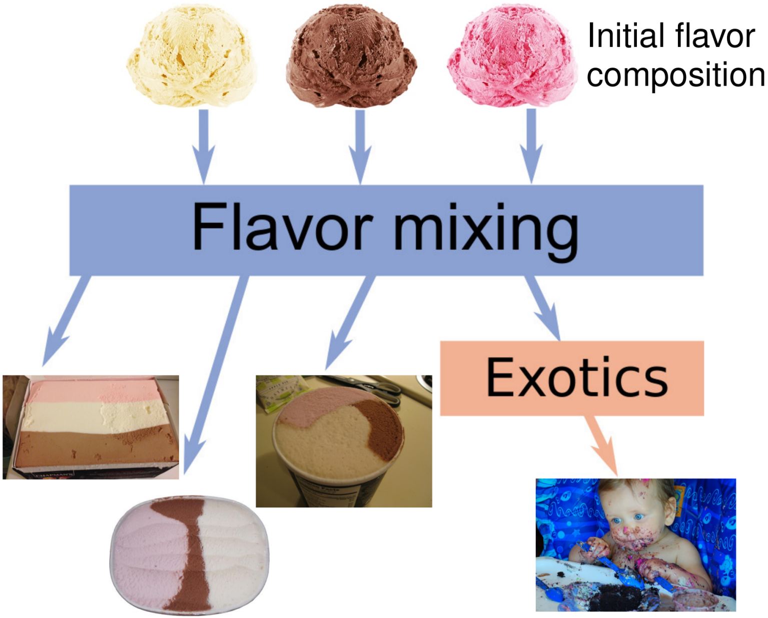


[ARGÜELLES *et al.* 1703.00451]

Expected: fewer events towards the Galactic Center

Observed: Isotropy

New physics in the flavor composition



How does IceCube see neutrinos?

Two types of fundamental interactions:

Charged-current

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

Neutral-current

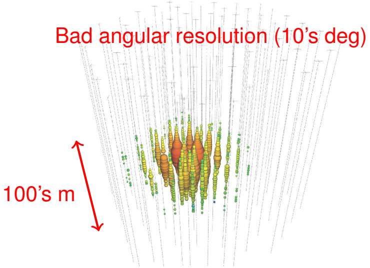
$$\nu_l + N \to \nu_l + \text{hadrons}$$

these shower and make light

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

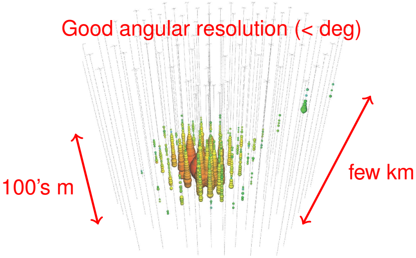
Showers

Made by CC ν_e or ν_τ; or by NC ν_x



Tracks

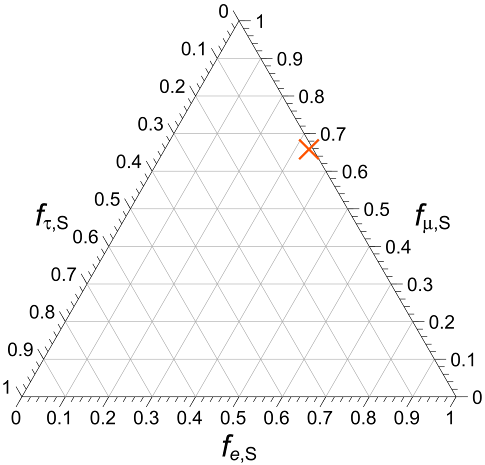
Made mainly by CC ν_μ



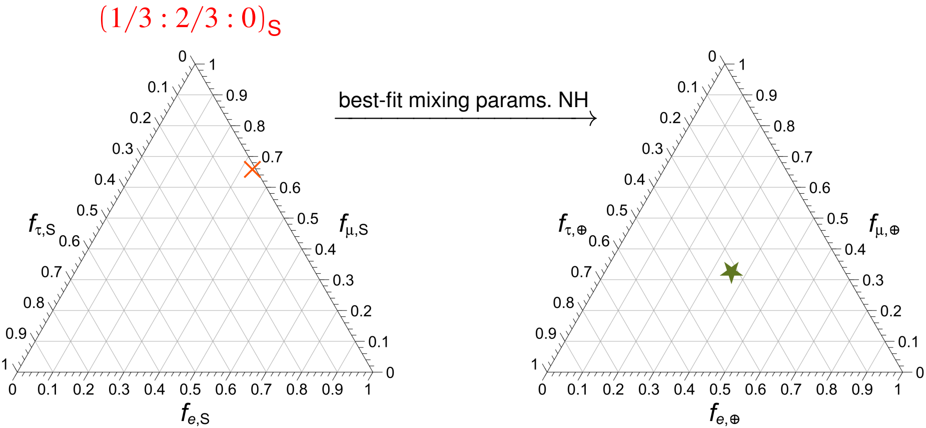
Flavor ratios — at the sources

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

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

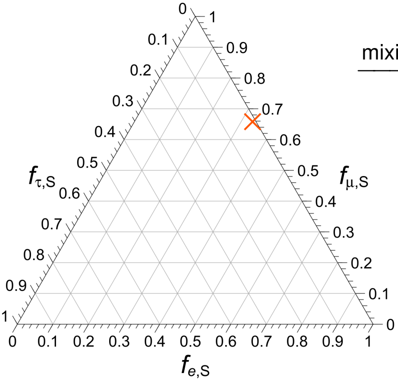


Flavor ratios — at Earth

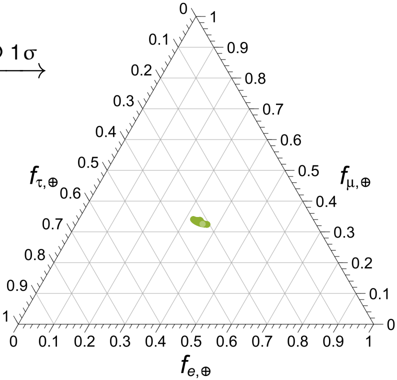


Flavor ratios — at Earth

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



mixing params. @ 1σ →



Flavor ratios — at Earth

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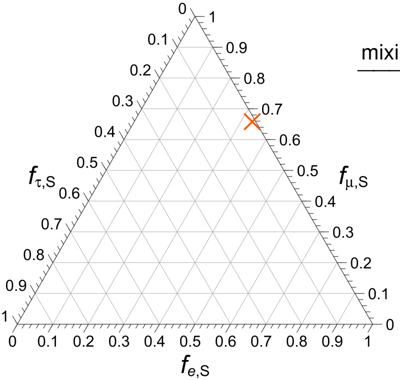
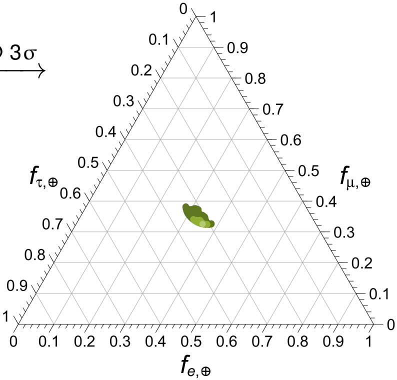
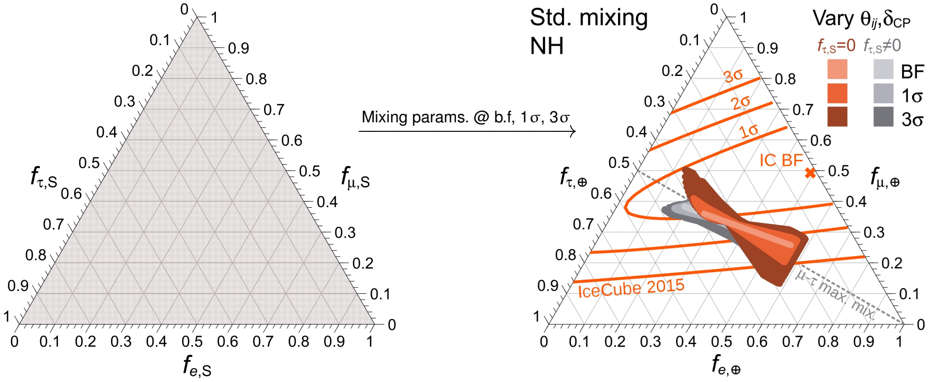


mixing params. @ 3σ



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

Flavor composition — standard allowed region

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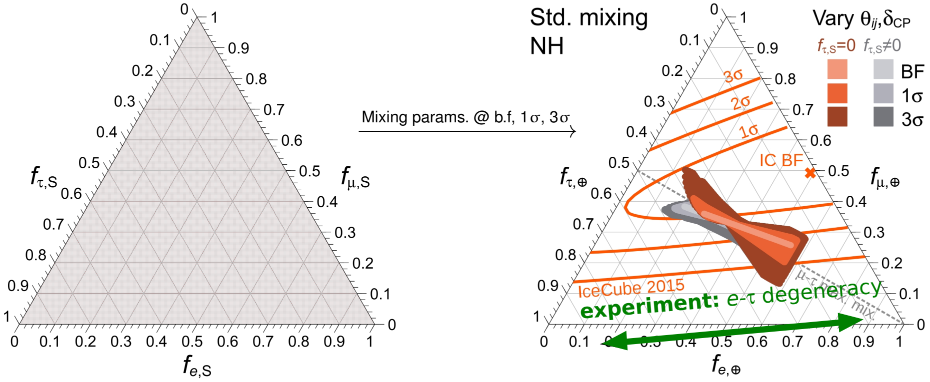

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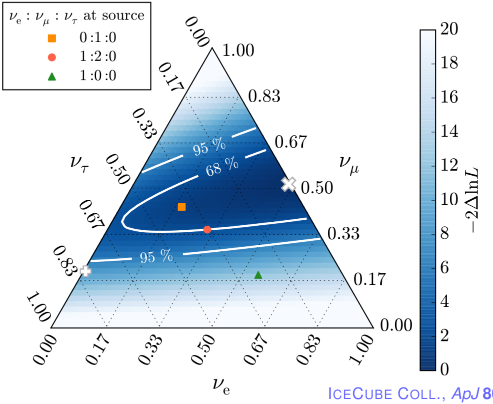
IceCube analysis of flavor composition

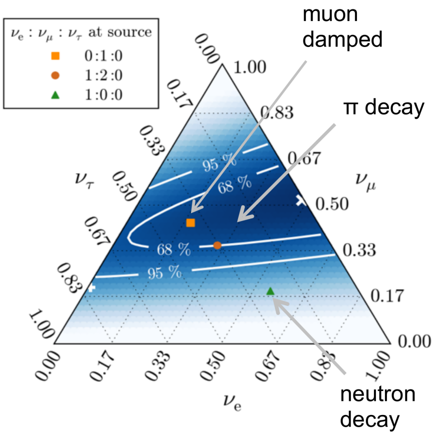
Using contained events + throughgoing muons:

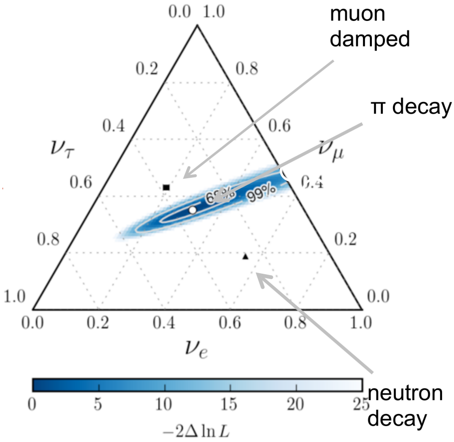


IceCube Coll., *ApJ* **809**, 98 (2015)

- 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

IceCube vs. IceCube-Gen2



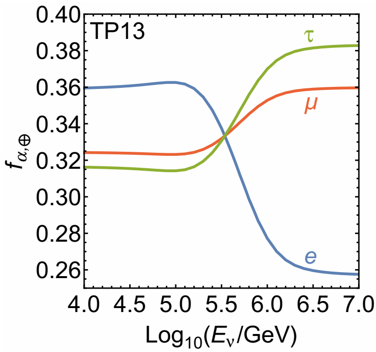


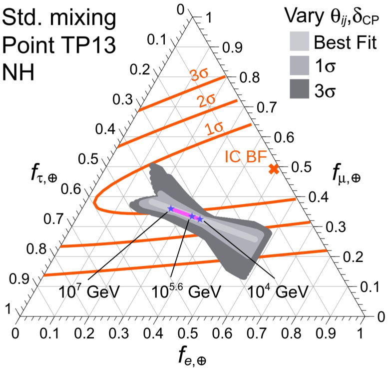
Gen2 (15 yrs)

(Borrowed from M. Kowalski, Weizmann 2017)

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies

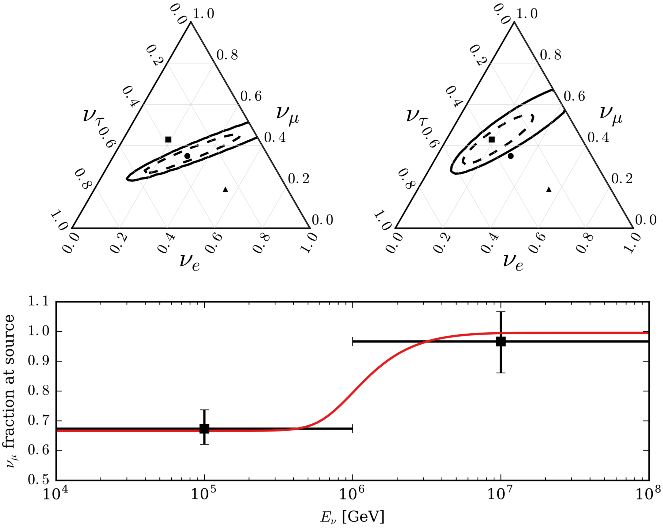




MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

- 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)]

Energy dependence in IceCube-Gen2



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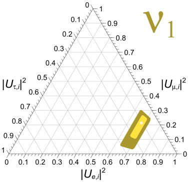
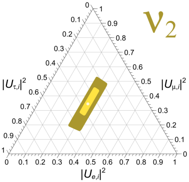
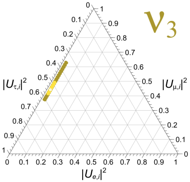
Two classes of new physics

- 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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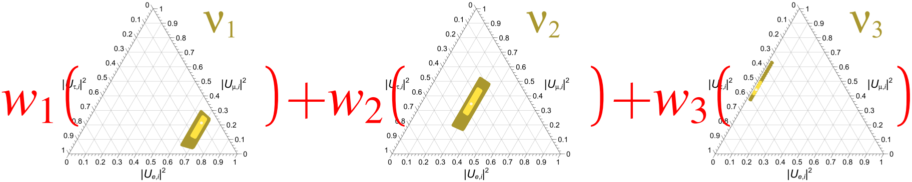

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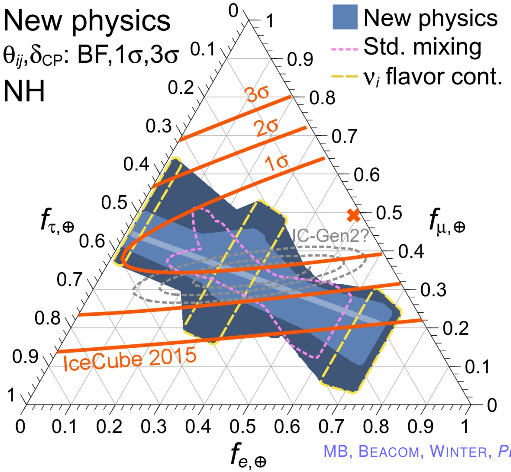
Region of flavor ratios accessible with decay

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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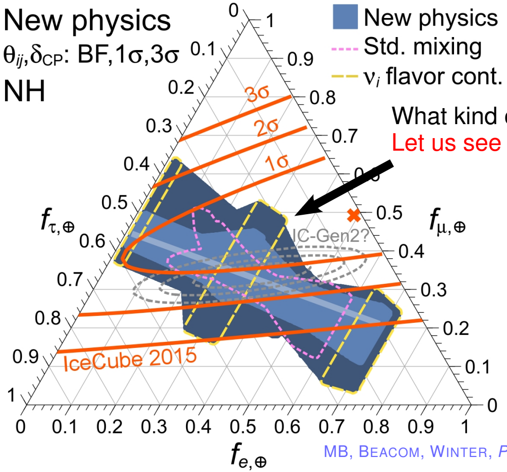

What kind of NP lives outside?

Let us see a few examples

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

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

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)

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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)]

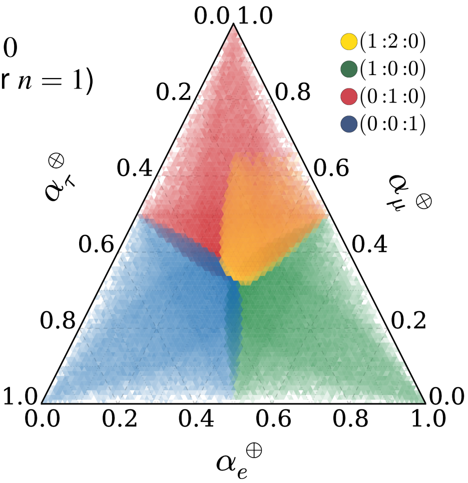
New physics — high-energy effects (II)

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 $n = 1$)

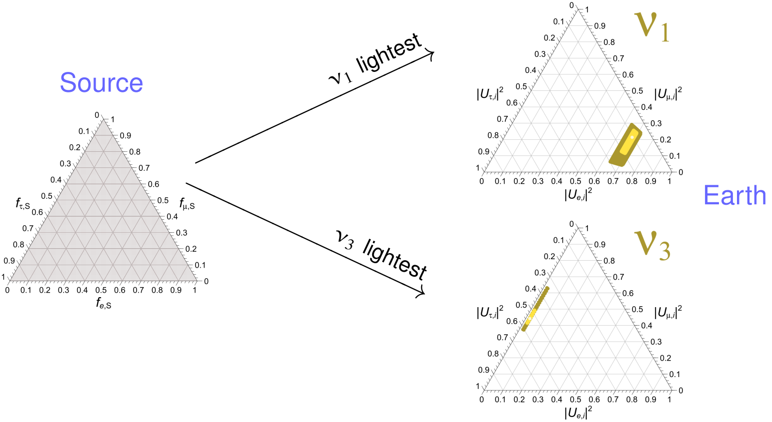


Tasting complete decay

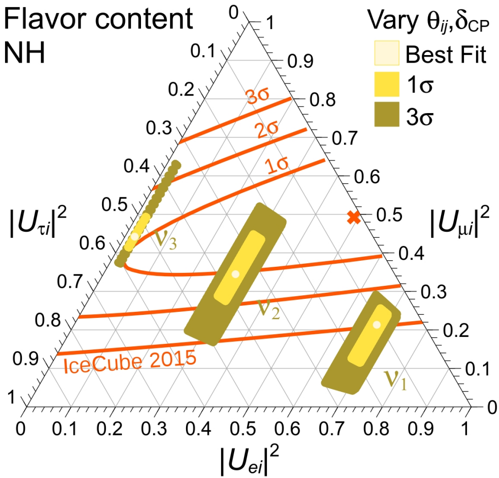
$\underbrace{\nu_2, \nu_3 \to \nu_1}_{}$ ν_1 lightest (normal hierarchy)

$\underbrace{\nu_1, \nu_2 \to \nu_3}_{}$ ν_3 lightest (inverted hierarchy)

Complete decay: only ν_1 or ν_3 reach Earth, so $f_{\alpha,\oplus} = \begin{cases} |U_{\alpha 1}|^2 \,, & \text{for NH} \\ |U_{\alpha 3}|^2 \,, & \text{for IH} \end{cases}$



Sensitivity to decay using IceCube flavor contours



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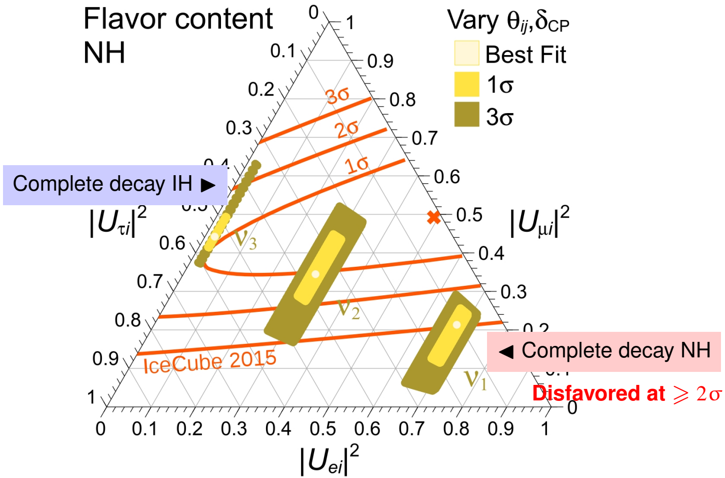

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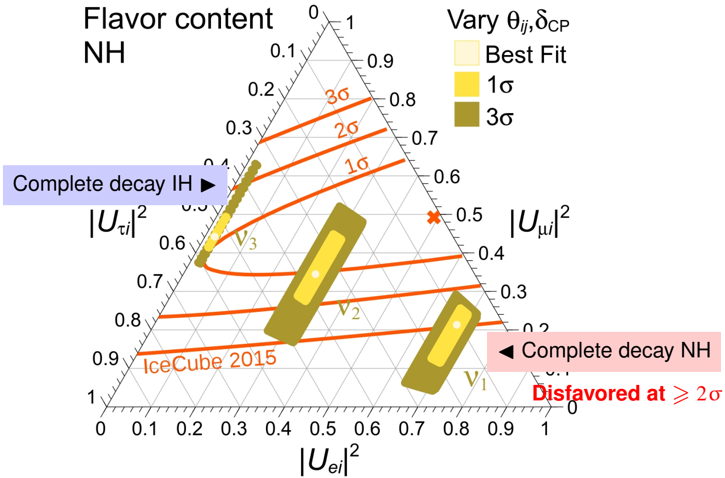
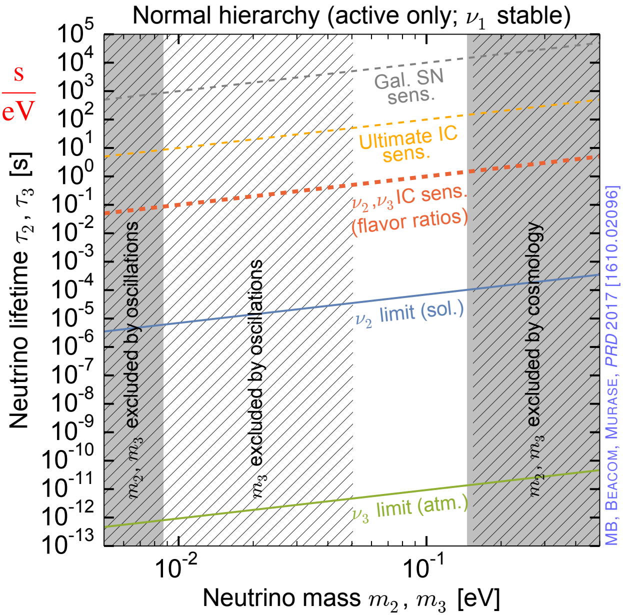


This leads to an improved lifetime sensitivity in the NH case ▶

Improved lifetime sensitivity in the NH

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



How to do better?

Achievable *now*:

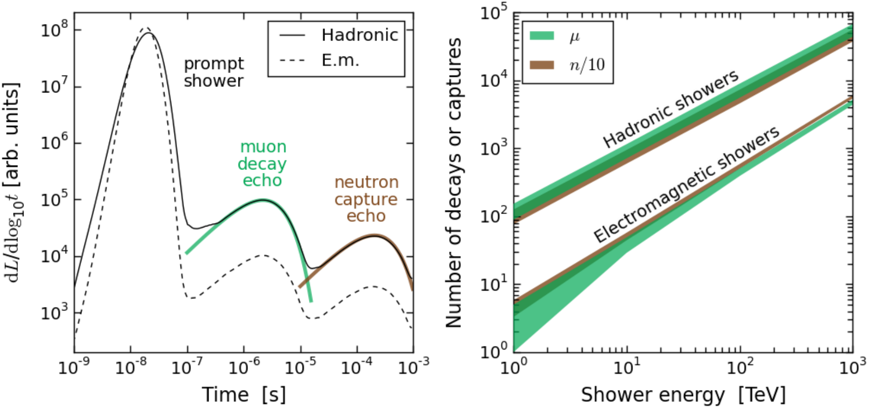
Use flavor contours built with only high-energy events
off the Galactic Plane

Achievable in the *near future*:

- More events
- Improved flavor reconstruction
- Better energy resolution (useful for incomplete decay)
- Smaller uncertainties in mixing parameters

How to improve ν_e vs. ν_τ separation?

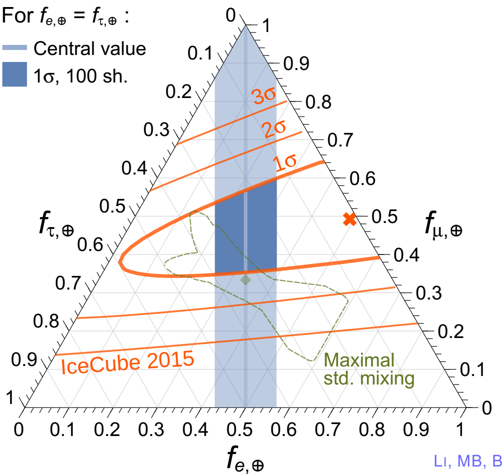
Late-time light (“echoes”) from muon decays and neutron captures is larger in hadronic than in e.m. showers —



Li, MB, Beacom, 1606.06290

How to improve ν_e vs. ν_τ separation?

Using 100 showers of 100 TeV (assuming high efficiency):

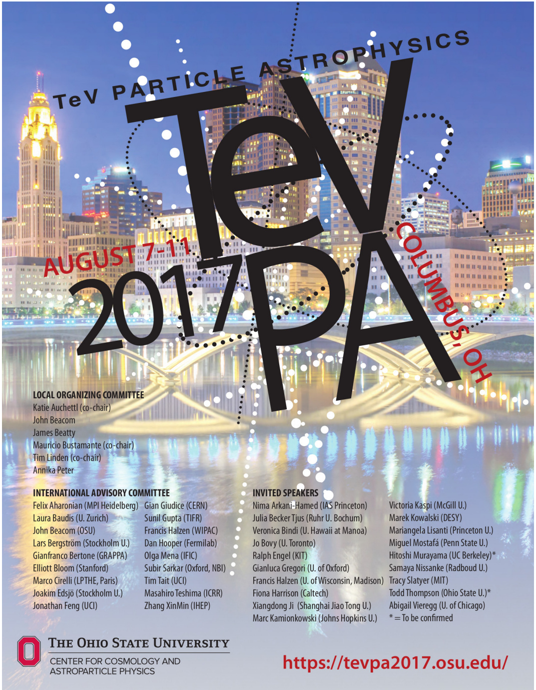


Li, MB, Beacom, 1606.06290

Using echoes: $\sim \times 9$ improvement over current flavor contours

Outlook

- Sensitive new-physics tests can be performed already with current data
- Proposed upgrades (IceCube-Gen2, KM3NeT) will provide more data
- New-physics tests feasible only with diffuse flux, not point-source fluxes
- Better flavor separation would help, *e.g.,* muon and neutron echoes
- Next frontier: cosmogenic neutrinos — new physics at the EeV scale (GRAND!)



TeVPA 2017

tevpa2017.osu.edu

- August 7–11, Columbus, OH
- Deadline for registration and abstract submission: June 2
- Pre-meeting mini-workshops on Sunday, August 7
- Ample room for parallels: *we welcome your talks!*

Backup slides

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

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

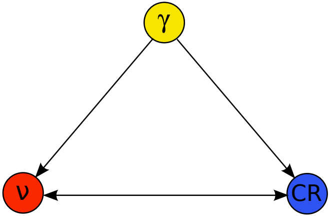
e.g., broken power law

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

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

$$\pi^0 \to \gamma\gamma$$

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



neutrino energy $\simeq$ proton energy / 20

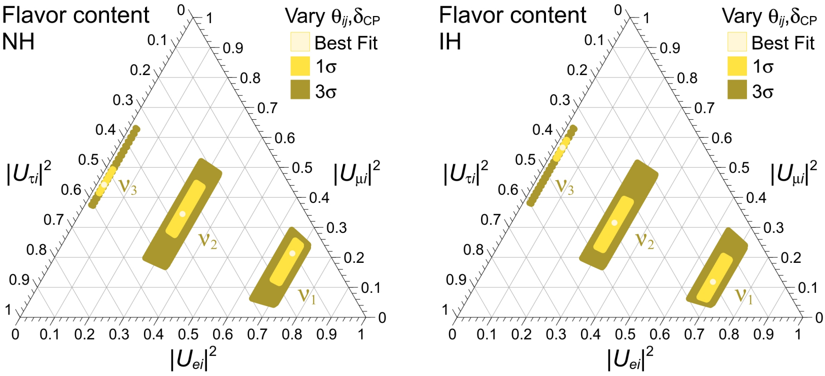
neutrino energy $\simeq$ gamma-ray energy / 2

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:

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

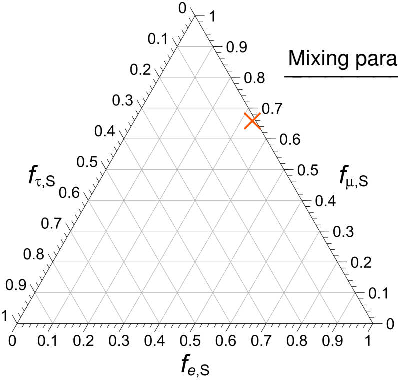
Hence, for high-energy astrophysical neutrinos:

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

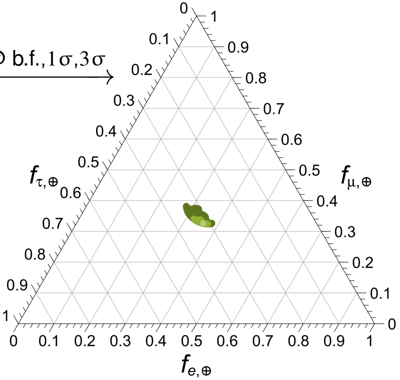
Flavor ratios — at Earth

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

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



Mixing params. @ b.f., 1σ, 3σ →

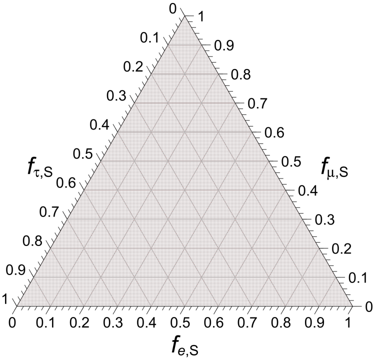


Embracing our ignorance

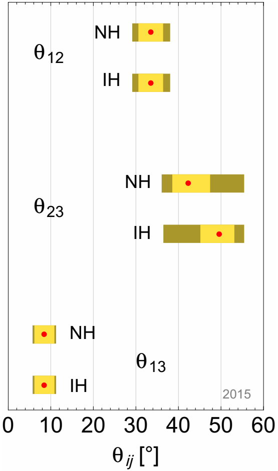
We ignore or do not know perfectly the two key ingredients —

Flavor ratios at the source

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

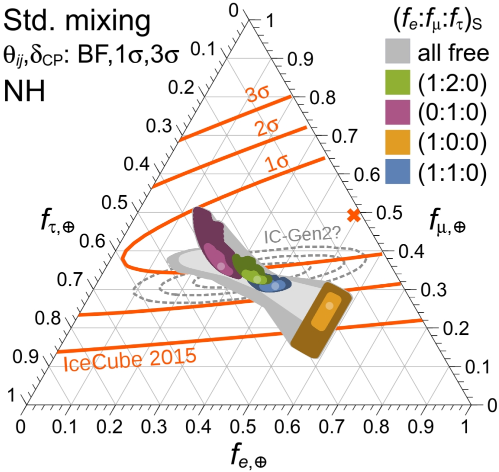


Mixing parameters



Selected source compositions

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

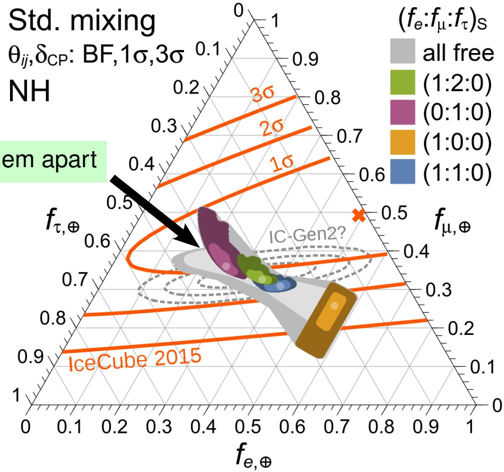


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Selected source compositions

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

challenging to tell them apart



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

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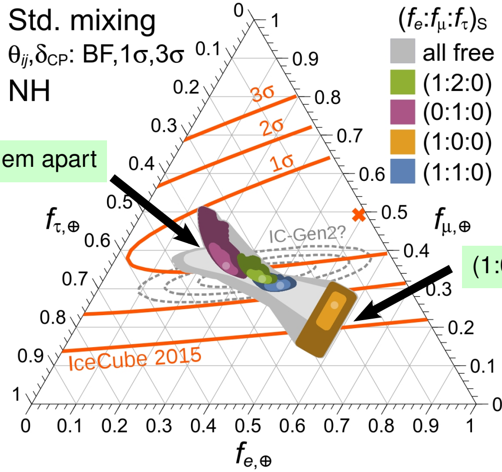


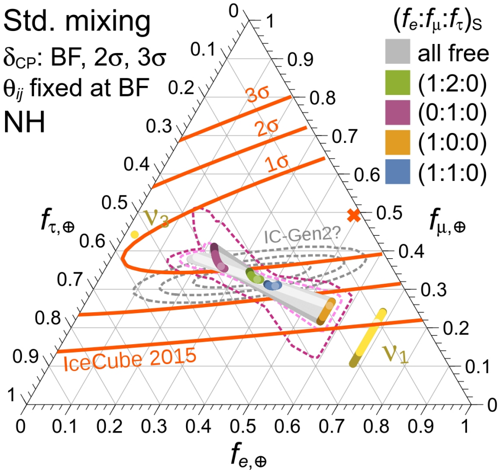
challenging to tell them apart

(1:0:0) disfavored at 2σ

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

Perfect knowledge of mixing angles

In a few years, we might know all the mixing parameters except δ_{CP}:



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

Standard Model decay modes

SM decay rates are negligible:

- One-photon decay ($\nu_i \to \nu_j + \gamma$):

$$\tau \simeq 10^{36} \, (m_i/\text{eV})^{-5} \;\; \text{yr}$$

- Two-photon decay ($\nu_i \to \nu_j + \gamma + \gamma$):

$$\tau \simeq 10^{57} \, (m_i/\text{eV})^{-9} \;\; \text{yr}$$

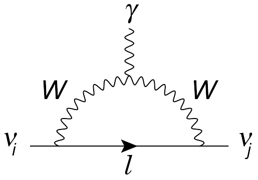
- Three-neutrino decay ($\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$):

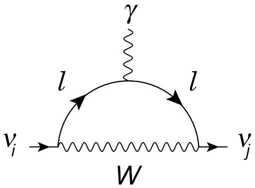
$$\tau \simeq 10^{55} \, (m_i/\text{eV})^{-5} \;\; \text{yr}$$

All lifetimes $\gg$ age of Universe
Hopeless to look for effects of SM decay channels

One-photon radiative decay

- Tree-level suppressed by GIM mechanism (*i.e.*, it has FCNCs)
- One-loop diagrams:





dominated by $l = \tau$ ($m_\tau \gg m_\mu \gg m_e$)

- For $\nu_i \neq \nu_j$, the decay rate is

$$\Gamma = \frac{\alpha}{2}\left(\frac{3G_F}{32\pi^2}\right)^2 \left(\frac{m_i^2 - m_j^2}{m_i}\right)^2 \left(m_i^2 + m_j^2\right) \left| \sum_{l=e,\mu,\tau} U_{li} U_{lj}^* \left(\frac{m_l}{m_W}\right)^2 \right|$$

- Taking $U_{\tau i} \sim \mathcal{O}(1)$ and $m_i = 1$ eV $\gg m_j$ yields a lifetime of

$\tau \sim 10^{36}$ yr $\gg 13.8 \cdot 10^9$ yr (age of the Universe)

New neutrino decay modes

- Standard Model: ν lifetime is 10^{36}–10^{55} yr $\gg$ age of Universe
- Models beyond the SM may introduce new decay modes:

$$\nu_i \to \nu_j + \phi$$

- ϕ: Nambu-Goldstone boson of a broken symmetry
  E.g., Majoron [Chikashige+ 1980, Gelmini+ 1982, Tomas+ 2001, Hannestad & Raffelt 2005]
- Nature of ϕ unimportant as long as invisible to neutrino detectors

Decay in the flavor ratios

fraction of ν_i that reach Earth

$$f_{\alpha,\oplus}\left(E_0, z, \tau_i/m_i\right) = \sum_{\beta=e,\mu,\tau}\left(\sum_{i=1}^{3} |U_{\alpha i}|^2 \left|U_{\beta i}\right|^2 D\left(E_0, z, \tau_i/m_i\right)\right) f_{\beta,\mathrm{S}}$$

(**Note —** NH: $\tau_1/m_1 \to \infty$; IH: $\tau_3/m_3 \to \infty$)

Complete decay ($D \ll 1$) —

Flavor ratios equal the flavor content of ν_1 (NH) or ν_3 (IH):

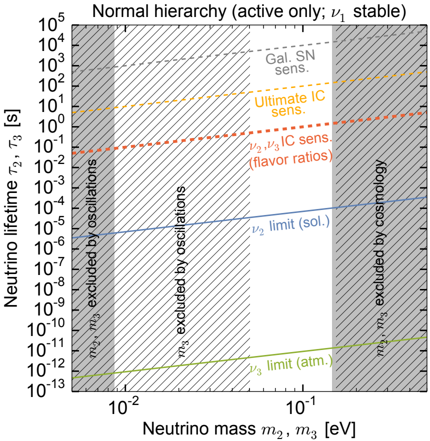
$$f_{\alpha,\oplus} = \begin{cases} |U_{\alpha 1}|^2, & \text{for NH} \\ |U_{\alpha 3}|^2, & \text{for IH} \end{cases}$$

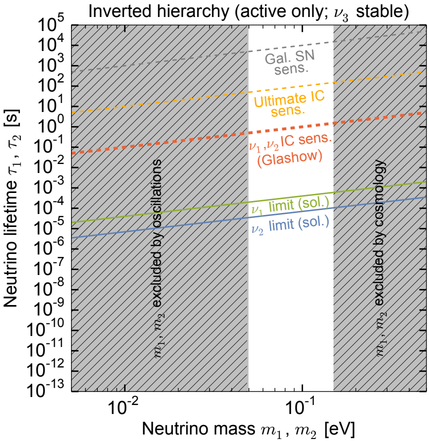
Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012)

Lifetime limits and sensitivities

Decay rates depend on the factor $\exp\left(-\frac{t}{\gamma\tau}\right) = \exp\left(-\frac{L}{E}\times\frac{m}{\tau}\right)$

$\nu_2, \nu_3 \to \nu_1$ or $\nu_1, \nu_2 \to \nu_3$

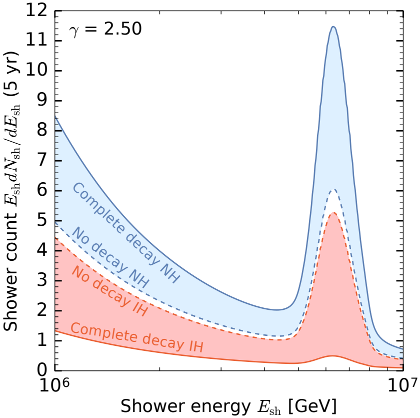




Decay and the Glashow resonance

The $\bar{\nu}_e$ flavor can be probed individually via the Glashow resonance:

$$\bar{\nu}_e(6.3\ \text{PeV}) + e \to W \to \text{hadrons}$$



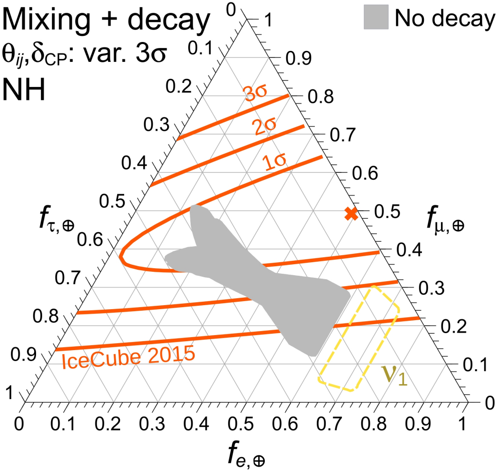
(All-flavor $\nu_\alpha + \bar{\nu}_\alpha$ flux normalized to IceCube combined-likelihood flux.)

NH: lifetime sensitivity with current IceCube data

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



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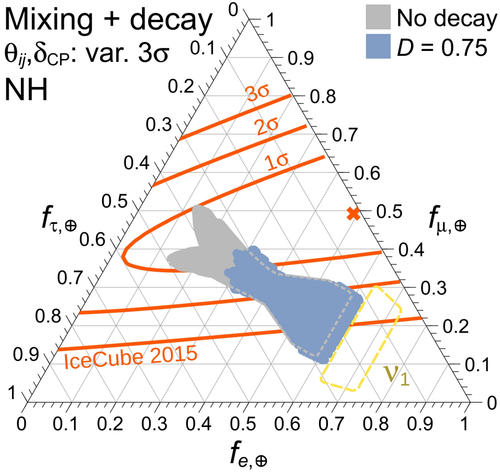

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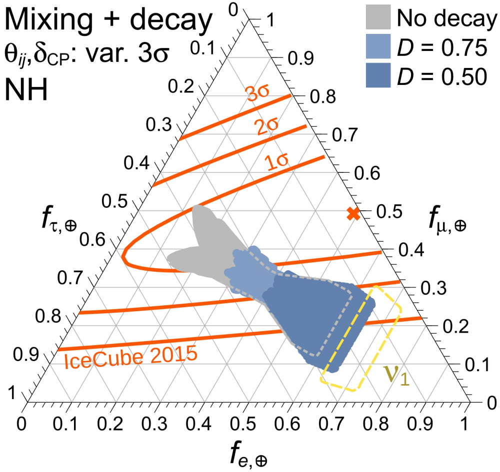

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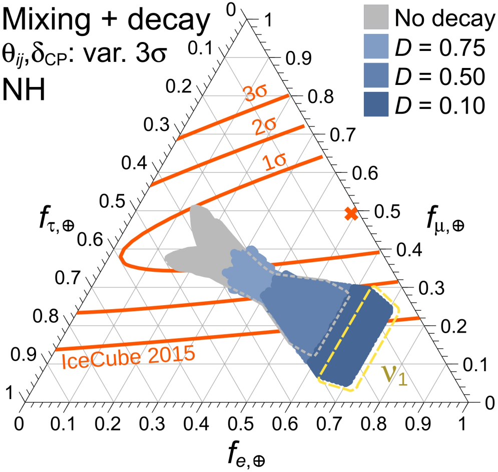

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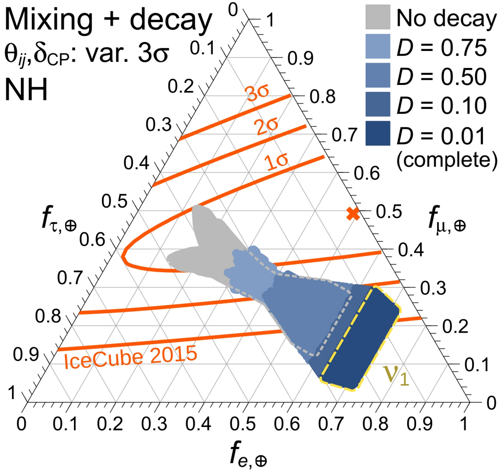

NH: lifetime sensitivity with current IceCube data

↙ 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

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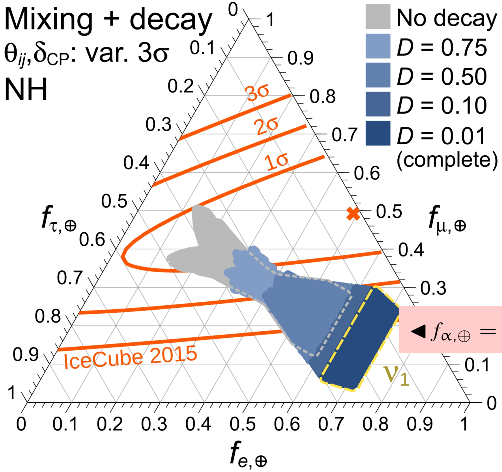
- *Any* flavor ratios at the sources

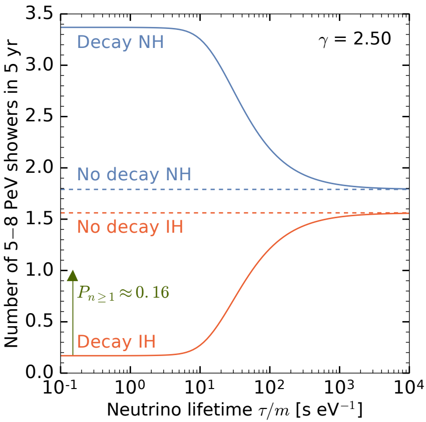
Assume equal lifetimes of ν_2, ν_3

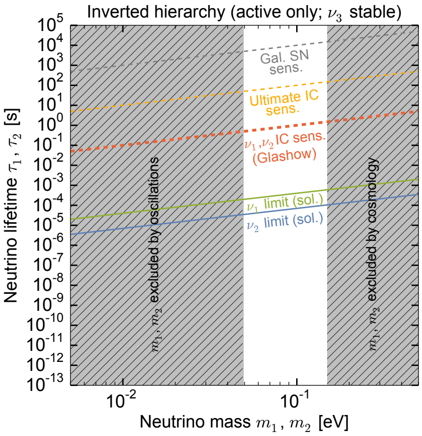


◀ $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D \lesssim 0.01$

IH: probing lifetime with high-energy showers

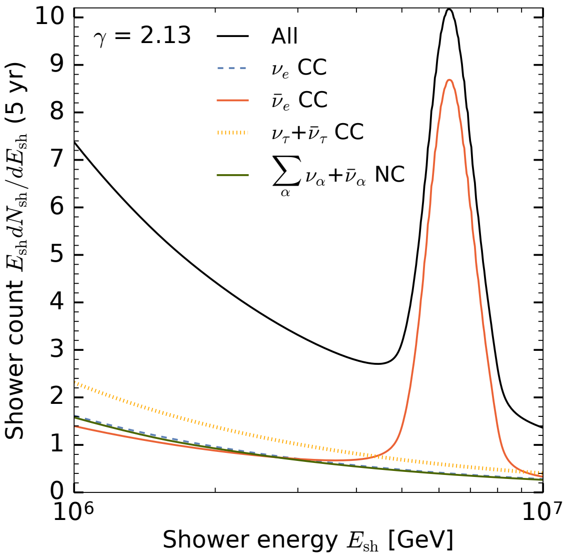
If 1 5–8 PeV shower is seen in 5 yr: $\tau_1/m_1, \tau_2/m_2 \gtrsim 10$ s eV^{-1} at 2σ





MB, Beacom, Murase, *PRD 2017* [1610.02096]

Shower spectrum components

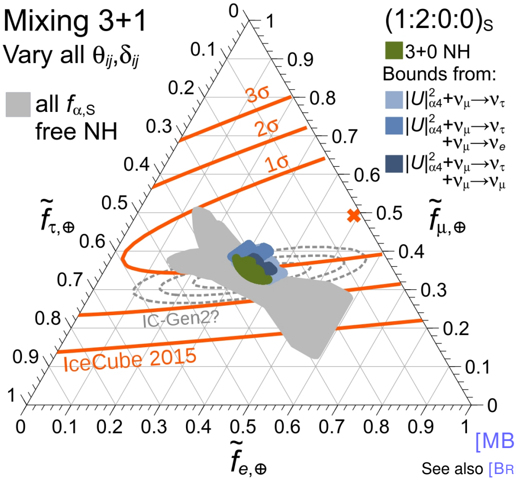


MB, Beacom, Murase, *PRD* 2017 [1610.02096]

New physics — active-sterile mixing

Mixing with a sterile neutrino (3+1) changes the flavor ratios:

- standard parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$
- sterile parameters: $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{24}, \delta_{34}$



Bounds from T2K, SK, Daya Bay

[MB, Coloma]

See also [Brdar, Kopp, Wang 2016]

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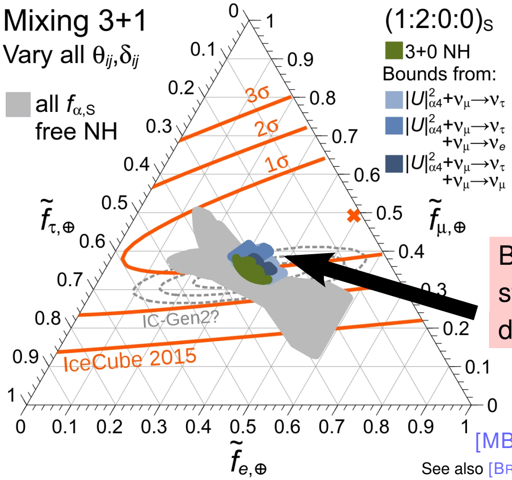


Bounds from T2K, SK, Daya Bay

Bounds are too strong for large deviations

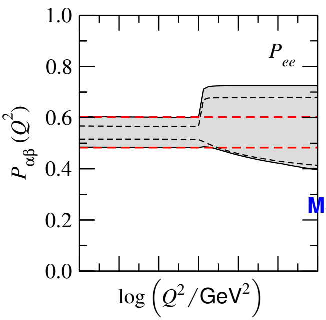
[MB, Coloma]

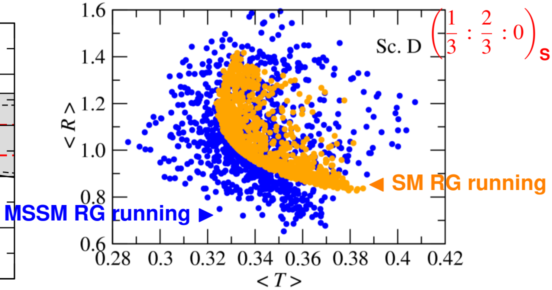
See also [Brdar, Kopp, Wang 2016]

New physics — SUSY renormalization group running

- The MSSM introduces loop corrections in the ν interaction vertices
- Renormalization scale $\mu = Q = \sqrt{-q^2}$ (transferred momentum)
- Two energy scales: [MB, GAGO, JONES, *JHEP* **05**, 133 (2011) [1012.2728]]
  - At production: $Q = m_\pi$
  - At detection (via ν-nucleon): $Q \propto \sqrt{E_\nu}$
- RG running between scales changes the mixing probability:

$$\langle P_{\alpha\beta} \rangle = \sum_{i=1}^{3} |(U_{\text{PMNS}})_{\alpha i}|^2 \left| (U'(Q))_{\beta i} \right|^2$$





$R \equiv f_{e,\oplus}/f_{\tau,\oplus}$ $T \equiv f_{\mu,\oplus}$