What to expect for the flavor composition of high-energy astrophysical neutrinos

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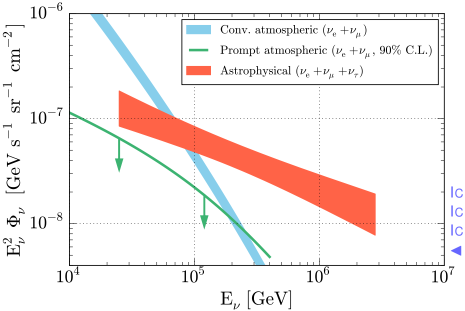
CCAPP

High-energy astrophysical neutrinos: they exist!

The era of neutrino astronomy has begun!

– IceCube has reported 54 events with 30 TeV – 2 PeV in 4 years



IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, 1507.03991

Diffuse per-flavor astrophysical flux [IceCube, 1507.03991]:

$$\Phi_\nu = \left(6.7^{+1.1}_{-1.2} \cdot 10^{-18}\right) \left(\frac{E}{100\ \text{TeV}}\right)^{-(2.5\pm0.09)} \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$$

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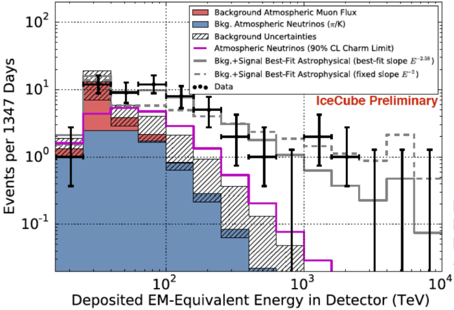

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IceCube, *PRL* **113**, 101101 (2014)
◀ O. Botner, IPA 2015

Diffuse flux compatible with extragalactic origin [Waxman & Bahcall 1997]:

$$E^2\Phi_\nu = (0.95 \pm 0.3) \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{(per flavor)}$$

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Arrival directions compatible with an isotropic distribution –

IceCube, *PRL* **111**, 021103 (2013)
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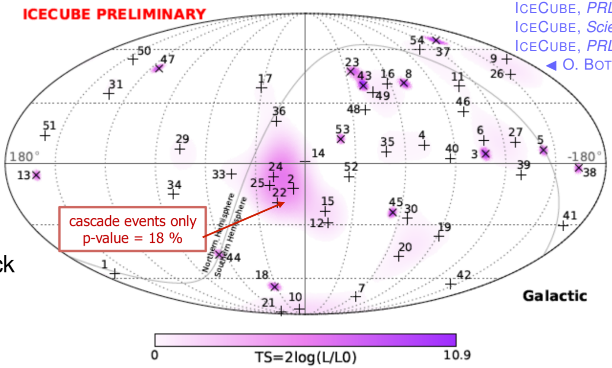
◀ O. Botner, IPA 2015



$+$: shower
$\times$: muon track

– no association with sources found yet

What we know / don't know

What we know

- compatible with isotropy
- power-law $\propto E^{-2.5}$
- not coincident with transient sources (*e.g.*, GRBs)
- not correlated with known sources
- **flavor composition: compatible with equal proportion of ν_e, ν_μ, ν_τ**
- also: no prompt atmospheric neutrinos

What we don't know

- what are the sources?
- what is the production mechanism?
- is there a cut-off at 2 PeV?
- what is the Galactic contribution, if any?
- what is the precise relation to UHE cosmic rays?
- is there new physics?
- **what is the precise flavor composition of the flux?**

. . . but we have good ideas on all

Flavor composition of neutrinos: an open question

Arguably the second most important question to answer is:

What is the proportion of ν_e, ν_μ, ν_τ in the diffuse flux?

Knowing this can reveal two important pieces of information:

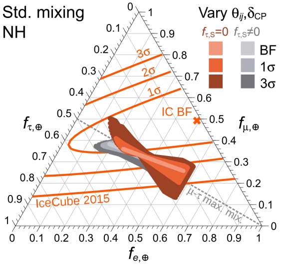
- the physical conditions at the neutrino sources; and
- whether there is new physics, and of what kind

So it will pay off to explore what to expect from theory

[Barenboim, Quigg, *PRD* **67**, 073024 (2003)]
[Winter, *PRD* **88**, 083007 (2013)]
[Mena, Palomares, Vincent, *PRL* **113**, 091103 (2014)]
[Palomares, Vincent, Mena, *PRD* **91**, 103008 (2015)]
[Palladino, Pagliaroli, Villante, Vissani, *PRL* **114**, 171101 (2015)]

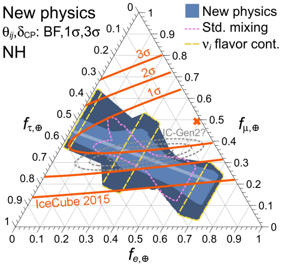
Mapping the theoretical landscape – three regions

1. With standard neutrino oscillations, only $\sim$ 10% of the flavor composition space can be accessed



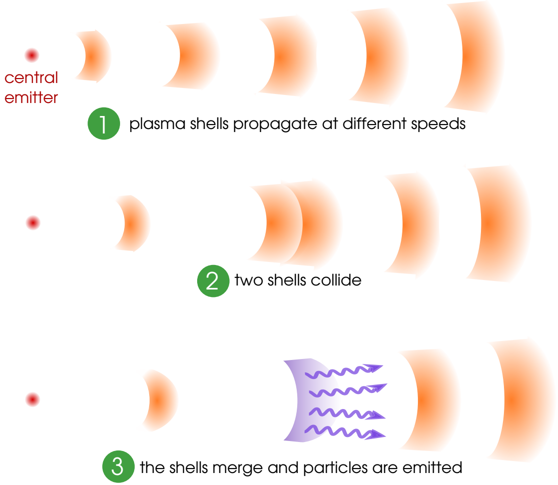
2. With new physics that affects the incoherent mix of mass eigenstates (*e.g.*, ν decay), still only $\sim$ 25%

3. A broader class of new physics is required to access the rest of the flavor space (*e.g.*, CPT violation)



UHE particle production in astrophysical sources

Relativistically-expanding blobs of plasma containing e's, p's, and γ's collide with each other, merge, and emit UHE particles (*e.g.*, in a GRB)



Why do we expect UHE neutrinos?

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

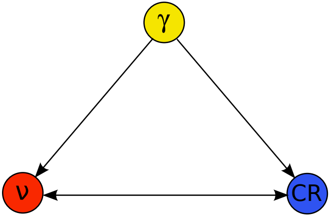
power law $\sim E^{-\alpha p}$ broken power law

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

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

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

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



After propagation, with flavor mixing:

$$\nu_e : \nu_\mu : \nu_\tau : p = 1 : 1 : 1 : 1$$

("one ν_μ per cosmic ray")

This neutron model of CR emission is now strongly disfavored

[Ahlers *et al.*, *Astropart. Phys.* **35**, 87 (2011)] [IceCube Coll., *Nature* **484**, 351 (2012)]

But we can do better by letting the p's escape without interacting

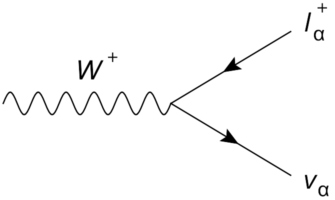
[Baerwald, MB, Winter, *ApJ* **768**, 186 (2013)] [Baerwald, MB, Winter, *Astropart. Phys.* **62**, 66 (2015)]
[MB, Baerwald, Murase, Winter, *Nat. Commun.* **6**, 6783 (2015)]

A quick review of neutrino mixing

- Two bases:

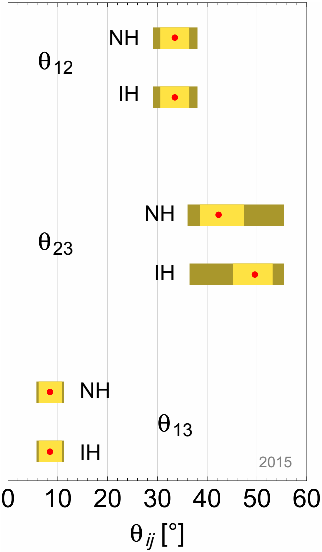
$$\underbrace{\{\nu_e, \nu_\mu, \nu_\tau\}}_{\text{flavor eigenstates}} \quad \neq \quad \underbrace{\{\nu_1, \nu_2, \nu_3\}}_{\text{mass eigenstates}}$$

- Flavor eigenstate ν_α ($\alpha = e, \mu, \tau$): accompanies the charged anti-lepton l_α^+ that is created in a charged-current weak interaction:



- Mass eigenstate ν_i ($i = 1, 2, 3$): has a definite mass
- Bases connected by a rotation U: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

Normal vs. inverted mass hierarchy



PMNS matrix U depends on θ_{12}, θ_{23}, θ_{13}, δ_{CP}.

The neutrino mass hierarchy is unknown:

- Normal hierarchy (NH): ν_1 is lightest
- Inverted hierarchy (IH): ν_3 is lightest

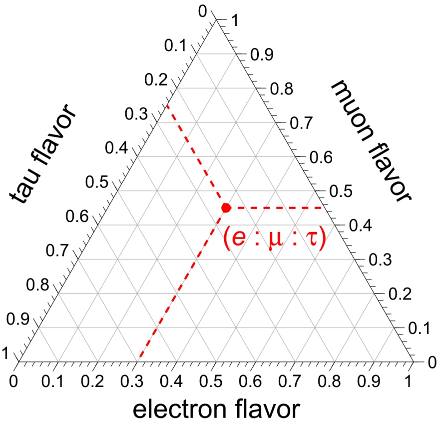
Using the latest fits from González-García *et al.*, *JHEP* **1411**, 052 (2014):

- θ_{12} and θ_{13} are well-determined
- Little NH/IH difference for θ_{12} and θ_{13}
- Large error and NH/IH difference for θ_{23}
- At 3σ, NH and IH regions are equal

"Flavor triangle" or Dalitz/Mandelstam plot

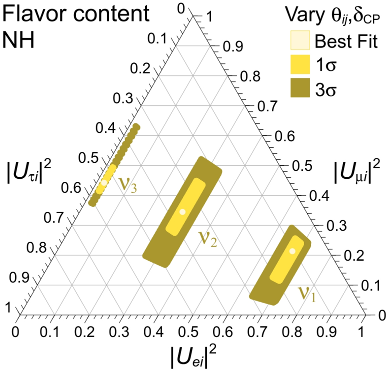
Assumes underlying unitarity: sum of projections on each axis is 1

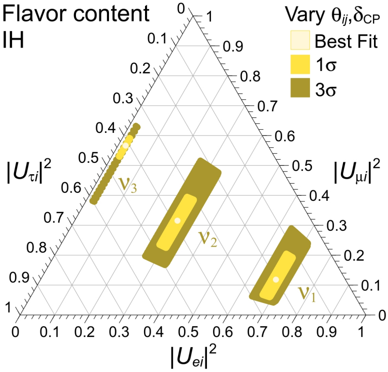
How to read it: follow the tilt of the tick marks, *e.g.*,



Flavor content of the mass eigenstates ν_1, ν_2, ν_3

Show the e, μ, and τ content of the ν_i via ternary plots:





[MB, Beacom, Winter, 1506.02645, *PRL*]

Flavor mixing in high-energy astrophysical neutrinos

Probability of $\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta$ transition:

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}\left(J_{\alpha\beta jk}\right) \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) \pm 2 \sum_{k>j} \mathrm{Im}\left(J_{\alpha\beta jk}\right) \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

$$\text{For } \begin{cases} E \sim 1 \text{ PeV} \\ \Delta m_{kj}^2 \sim 10^{-4} \text{ eV}^2 \end{cases} \Rightarrow L_{\text{osc}} \sim 10^{-10} \text{ Mpc} \ll L = 10 \text{ Mpc} - \text{few Gpc}$$

- 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:

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$ ◀ incoherent mixture of mass eigenstates

Flavor ratios

- Neutrino production at the source via pion decay:

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

- Flavor ratios at the source: $(f_e : f_\mu : f_\tau)_{\rm S} \approx (1/3 : 2/3 : 0)$
- At Earth, due to flavor mixing:

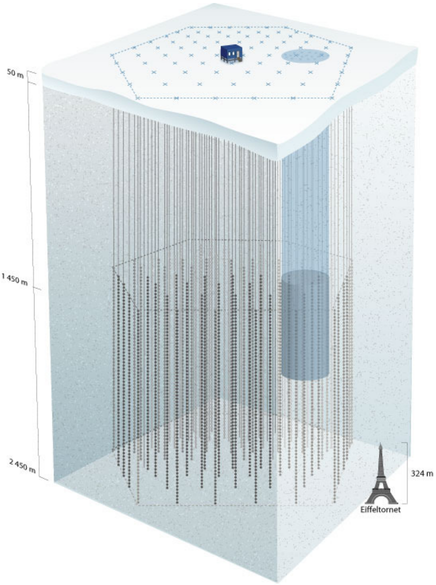
$$f_{\alpha,\oplus} = \sum_\beta P_{\beta\alpha} f_{\beta,{\rm S}} = \sum_\beta \left(\sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \right) f_{\beta,{\rm S}}$$

$$(1/3 : 2/3 : 0)_{\rm S} \xrightarrow{\text{flavor mixing, NH, best-fit}} (0.36 : 0.32 : 0.32)_\oplus$$

- Other compositions at the source:

$$(0 : 1 : 0)_{\rm S} \longrightarrow (0.26 : 0.36 : 0.38)_\oplus \quad \text{("muon damped")}$$
$$(1 : 0 : 0)_{\rm S} \longrightarrow (0.55 : 0.26 : 0.19)_\oplus \quad \text{("neutron decay")}$$
$$(1/2 : 1/2 : 0)_{\rm S} \longrightarrow (0.40 : 0.31 : 0.29)_\oplus \quad \text{("charmed decays")}$$

Detecting the neutrinos: IceCube



IceCube: km^3 in-ice South Pole Čerenkov detector

- νN interactions ($N = n, p$) create particle showers
- 86 strings with 5160 digital optical modules (DOMs)
- depths between 1450 m and 2450 m

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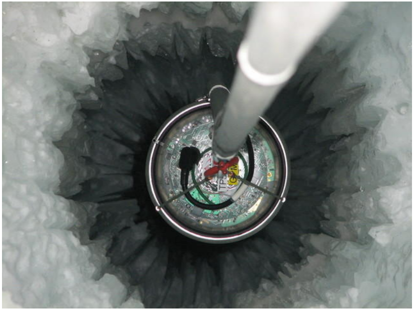

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How does IceCube see flavor?

Below $E_\nu \sim 5$ PeV, there are two event topologies:

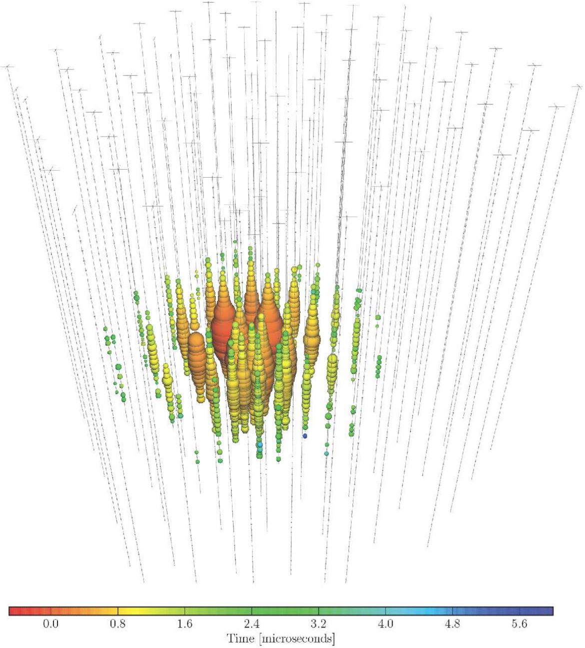
- Showers: generated by CC ν_e or ν_τ; or by NC ν_x
- Muon tracks: generated by CC ν_μ

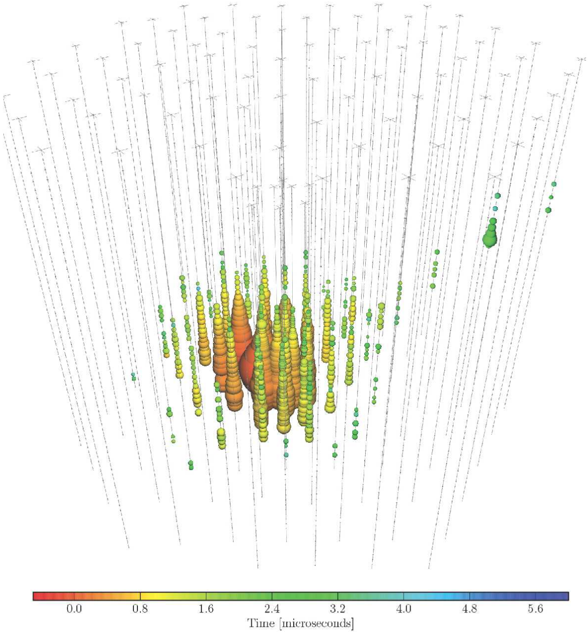
(Some muon tracks can be mis-reconstructed as showers)

At $\gtrsim 5$ PeV (no events so far), all of the above, plus:

- Glashow resonance: CC $\bar{\nu}_e e$ interactions at 6.3 PeV
- Double bangs: CC $\nu_\tau \to \tau \to \nu_\tau$

Flavor ratios must be inferred from the number of showers and tracks


0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]


0.0
0.8
1.6
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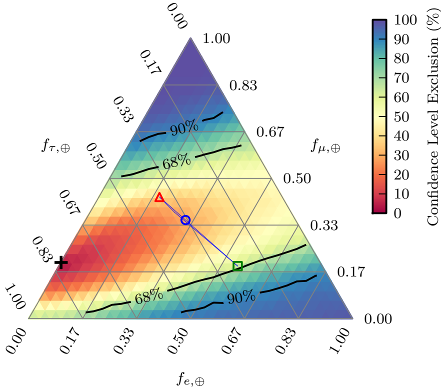
Time [microseconds]

Two IceCube analyses of flavor composition

Using contained events only

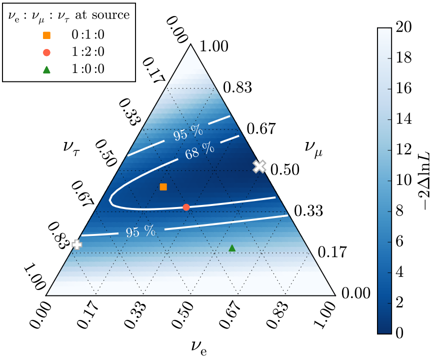
[IceCube Coll., *PRL* **114**, 171102 (2015)]



Best fit: $(0 : 0.2 : 0.8)_\oplus$

Using contained events + throughgoing muons

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

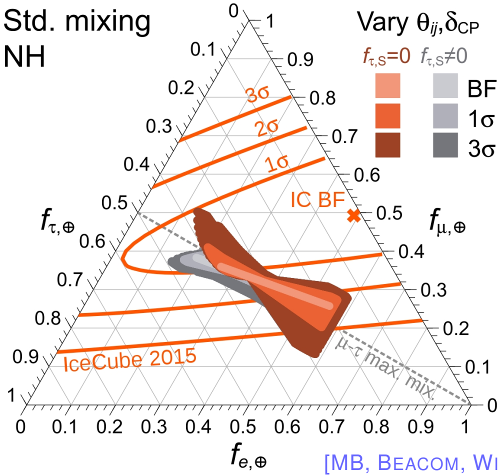


Best fit: $(0.49 : 0.51 : 0)_\oplus$

- Compatible with standard source compositions
- Bounds are weak – need more data and better flavor-tagging

Flavor combinations at Earth from std. mixing

Assume unconstrained flavor composition at source (with and w/o ν_τ):



[MB, Beacom, Winter, 1506.02645]

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

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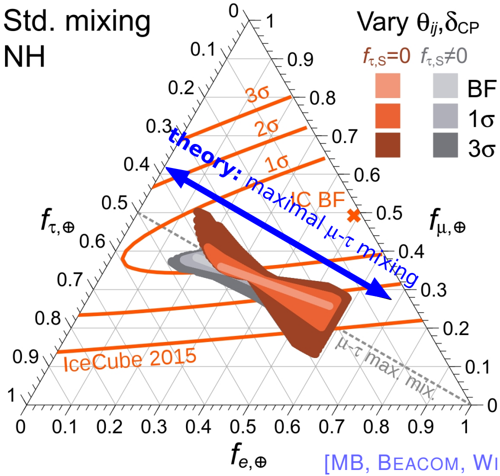

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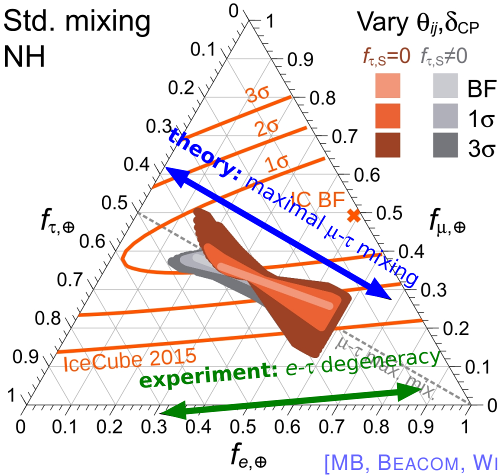
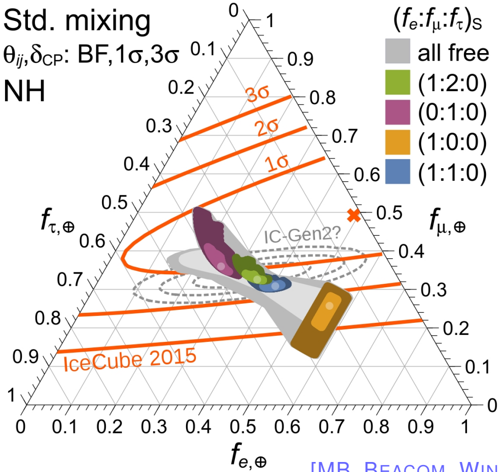


[MB, Beacom, Winter, 1506.02645]

Std. mixing can access *only* ∼ 10% of the possible combinations

Selected source compositions

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

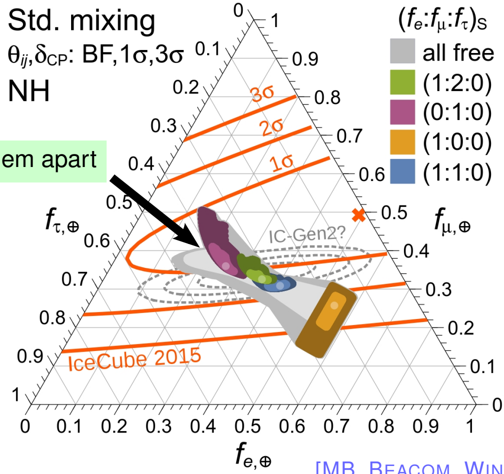


[MB, Beacom, Winter, 1506.02645]

Selected source compositions

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

challenging to tell them apart



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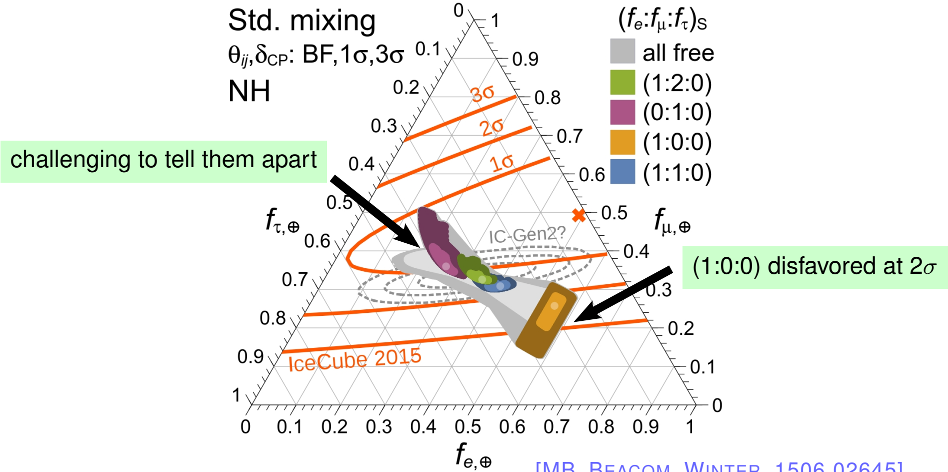
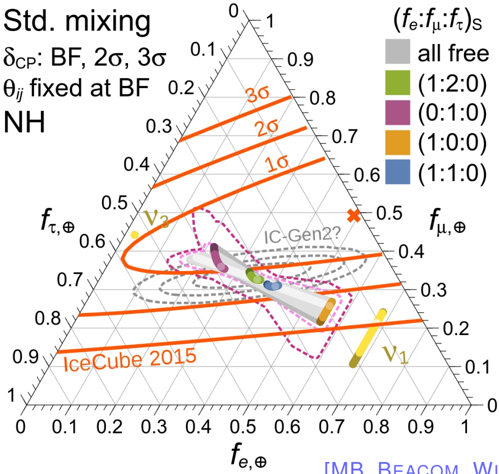


[MB, Beacom, Winter, 1506.02645]

Perfect knowledge of mixing angles

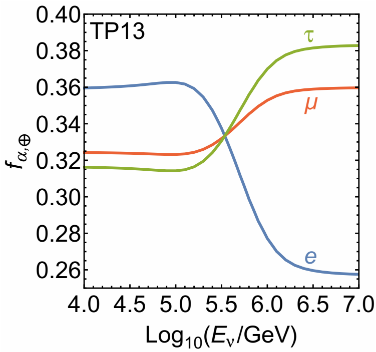
In a few years, we might know all the mixing parameters except δ_{CP}:

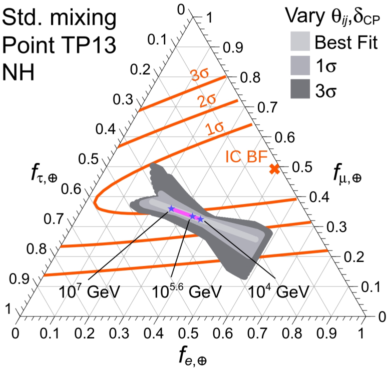


[MB, Beacom, Winter, 1506.02645]

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies





[MB, Beacom, Winter, 1506.02645]

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

New physics: effect on the flavor composition

- New physics in the neutrino sector could affect the
  - production; and/or
  - propagation; and/or
  - detection

- Detection: probe NP in the ν interaction length via the angular dependence of the flux [MARFATIA, MCKAY, WEILER, 1502.06337]

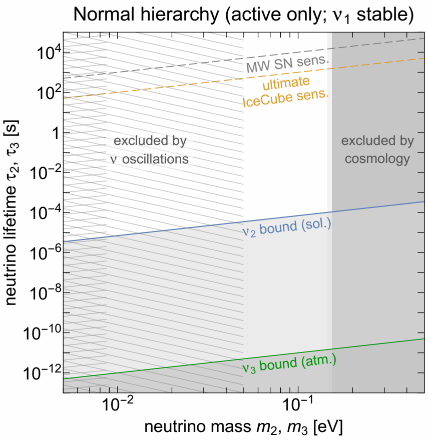
- NP at production and propagation could modify the incoherent mixture of ν_1, ν_2, ν_3

- Example: neutrino decay ►

[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, VISSANI, VILLANTE 1506.02624]

Neutrino decay

- SM: ν lifetimes are $> 10^{36}$ yr
- Via new-physics decay modes, they could be shorter
- Consider two possibilities:
  - NH: $\nu_2, \nu_3 \to \nu_1$
  - IH: $\nu_1, \nu_2 \to \nu_3$
- There are experimental bounds on the lifetime τ_i/m_i



[MB, Beacom, Murase, in prep.]

Decay: effect on flavor ratios

$$f_{\alpha,\oplus}\left(E_0, z, \kappa_j^{-1}\right) = |U_{\alpha l}|^2 + \sum_{j \neq l} \left(|U_{\alpha j}|^2 - |U_{\alpha l}|^2\right) f_{j,S}\, D\left(E_0, z, \kappa_j^{-1}\right)$$

$l = 1$ (NH), 3 (IH)

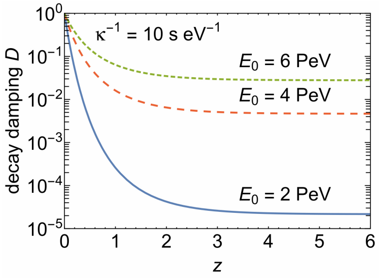
$\nu_{1,2,3}$ ratios at source

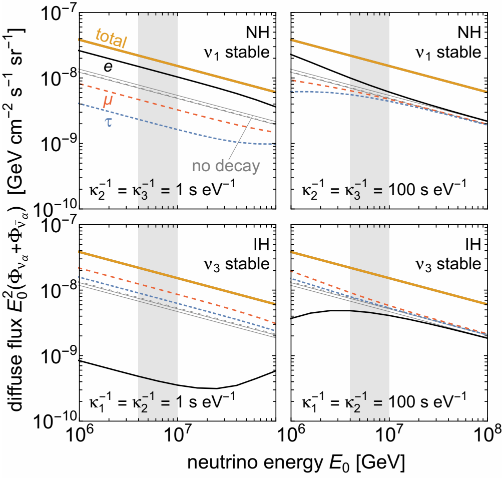
- Damping due to decay:

$$0 < D < 1$$

- Complete decay:

$$D \to 0 \Rightarrow f_{\alpha,\oplus} = |U_{\alpha l}|^2$$

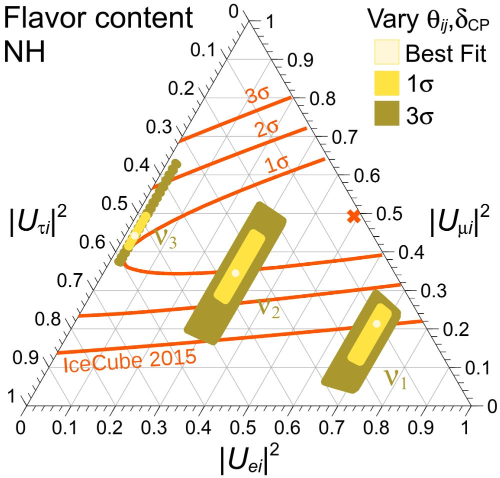




[MB, Beacom, Murase, in prep.]

Decay: using the flavor ratios

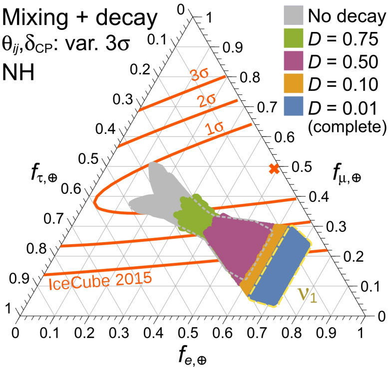
Flavor ratios are currently more sensitive to complete decay in the NH than in the IH:

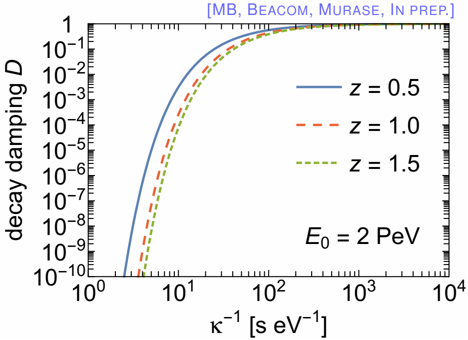


Decay: lifetime bounds with current IceCube data

Flavor ratios with decay in the NH ($\nu_2, \nu_3 \to \nu_1$):

$$f_{\alpha,\oplus}\left(E_0, z, \kappa_j^{-1}\right) = |U_{\alpha 1}|^2 + \sum_{j=2,3} \left(|U_{\alpha j}|^2 - |U_{\alpha 1}|^2\right) f_{j,S}\, D\left(E_0, z, \kappa_j^{-1}\right)$$





$D \lesssim 0.01$ implies a bound of $\kappa_{2,3}^{-1} \gtrsim 10$ s eV^{-1} at $\gtrsim 2\sigma$

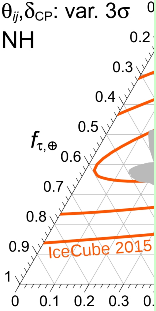
Flavor ratios with decay in the NH ($\nu_2, \nu_3 \to \nu_1$):

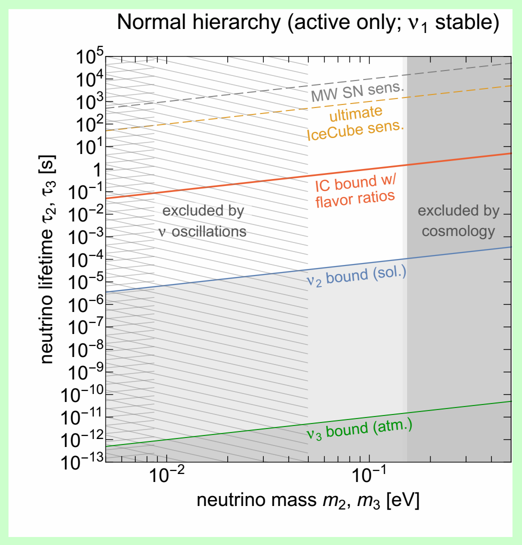
$f_{\alpha,\oplus}\left(E_0, z, \right.$ … $D\left(E_0, z, \kappa_j^{-1}\right)$

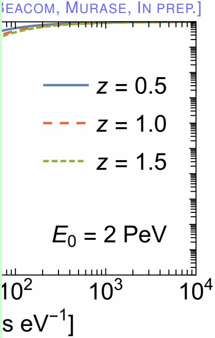
Mixing + decay

θ_{ij}, δ_{CP}: var. 3σ

NH







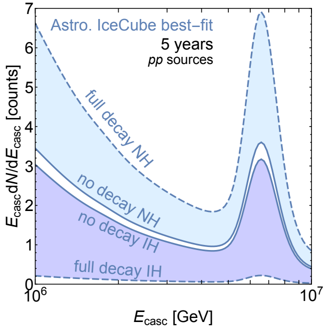
$D \lesssim 0.01$ implies a bound of $\kappa_{2,3} \gtrsim 10$ … s eV … at $\gtrsim 2\sigma$

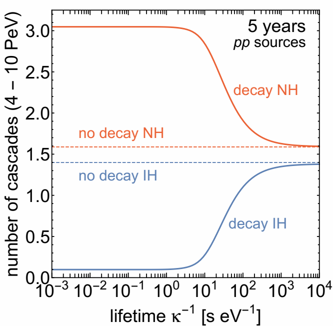
Decay: cascade rate probes the IH

- Around 6.3 PeV, the Glashow resonance is accessible:

$$\bar{\nu}_e + e \to W \to \text{ hadronic shower (BR} = 67\%)$$

- Three scenarios:
  - Neutrinos are stable: we see the GR as a bump in the cascade rate
  - Neutrinos decay in the NH: the bump is larger ($|U_{e1}|^2$ is large)
  - Neutrinos decay in the IH: no or almost no cascades ($|U_{e3}|^2$ is tiny)





[MB, Beacom, Murase, in prep.]

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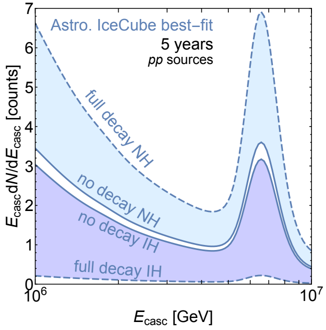

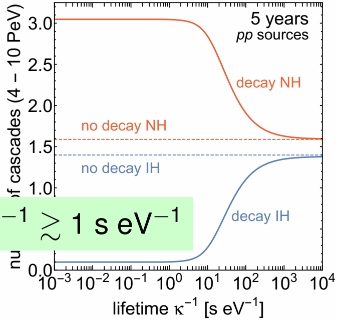

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[MB, Beacom, Murase, in prep.]

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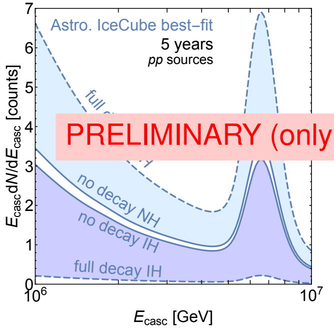
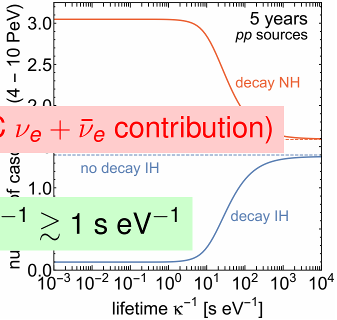


PRELIMINARY (only CC $\nu_e + \bar{\nu}_e$ contribution)



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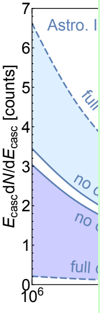
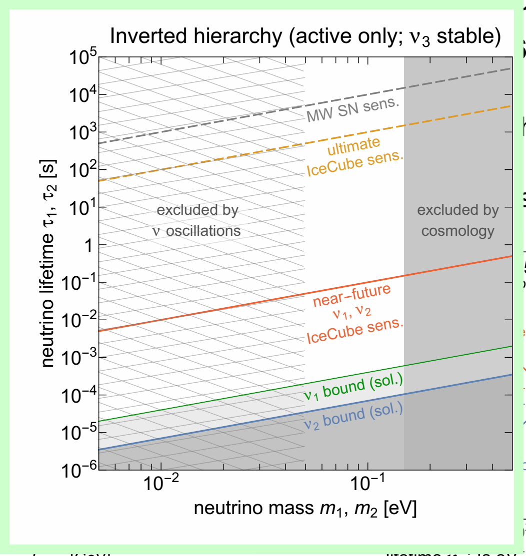
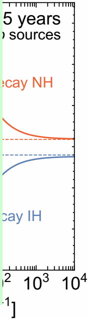


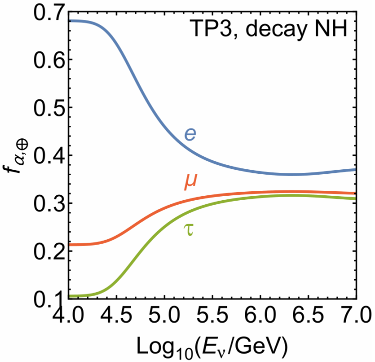


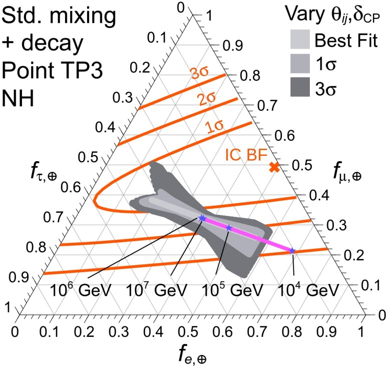


[MB, Beacom, Murase, in prep.]

Decay: seeing the energy dependence?

- The effect of decay shows up at low energies
- *e.g.*, for a model of AGN cores [Hümmer *et al.*, *Astropart. Phys.* **34**, 205 (2010)],

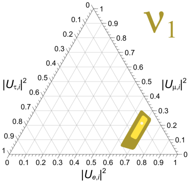




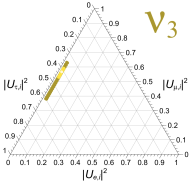
[MB, Beacom, Winter, 1506.02645]

Decay: complete vs. incomplete

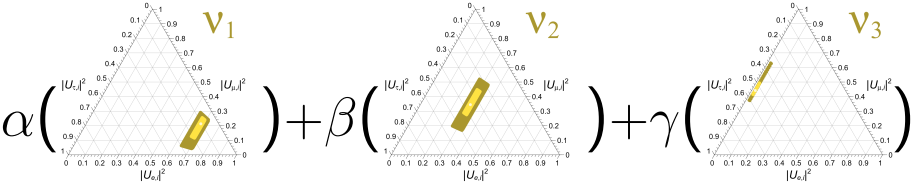
- Complete decay: only ν_1 (ν_3) reach Earth assuming NH (IH)



or

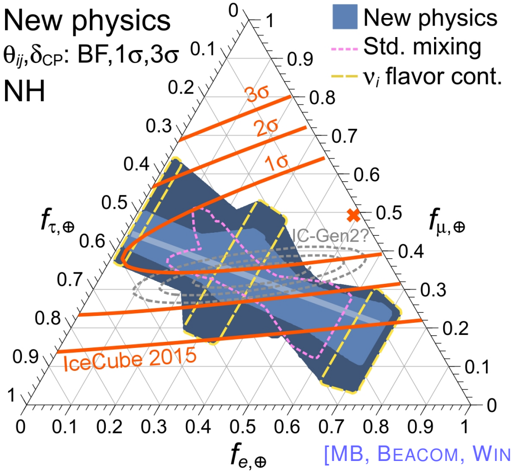


- Incomplete decay: incoherent mixture of ν_1, ν_2, ν_3 reaches Earth



New physics that changes the ν_i mixture

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



[MB, BEACOM, WINTER, 1506.02645]

This class of NP can access *only* $\sim$ 25% of the possible combinations

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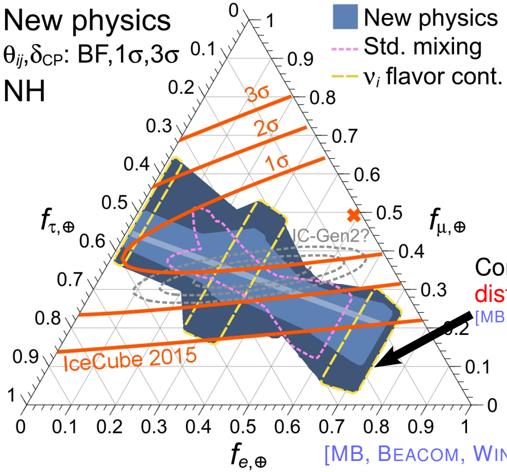

Complete decay in NH
disfavored at $> 2\sigma$
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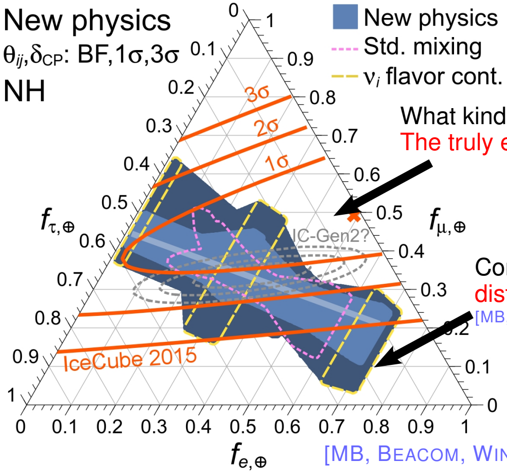

What kind of NP lives outside?
The truly exotic kind!

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[MB, Beacom, Winter, 1506.02645]

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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

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  - 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.*, 1410.0408]
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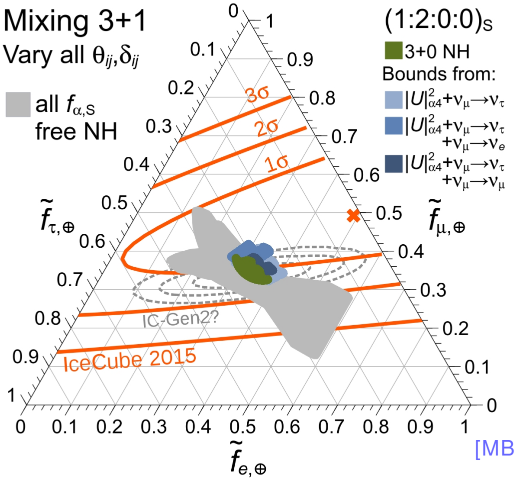
Mixing with a sterile neutrino (3+1) changes the flavor ratios:

- standard parameters: θ_{12}, θ_{23}, θ_{13}, δ_{13}
- sterile parameters: θ_{14}, θ_{24}, θ_{34}, δ_{24}, δ_{34}



Bounds from T2K, SK, Daya Bay

[MB, Coloma]

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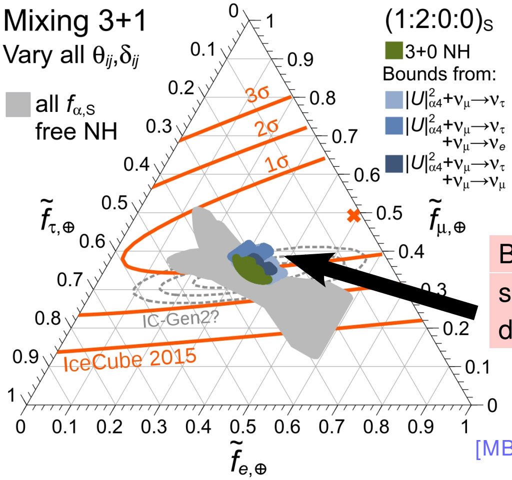

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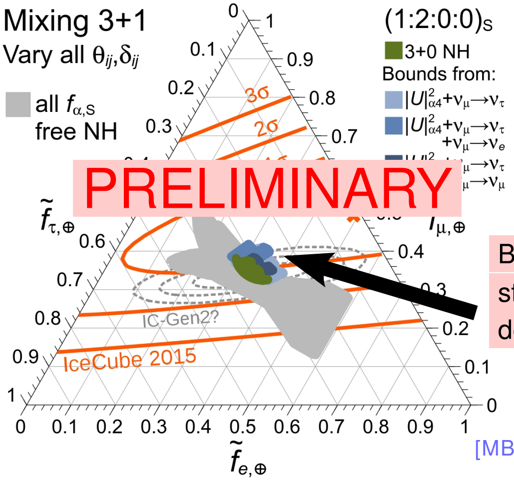

Bounds from T2K, SK, Daya Bay

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[MB, Coloma]

New physics — high-energy effects (I)

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

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

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

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

$n = 0$

- 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 $\quad\quad$ $O_1/\Lambda_1 \lesssim 10^{-27}$ GeV

[MB, Gago, Peña-Garay, *JHEP* **1004**, 005 (2010)]
[Argüelles, Katori, Salvadó, 1506.02043]
[IceCube Coll., *PRD* **82**, 112003 (2010)]
[Super-K Coll., *PRD* **91**, 052003 (2015)]

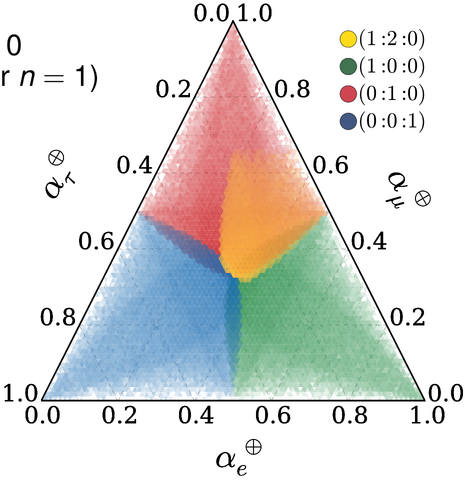
New physics — high-energy effects (II)

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 1506.02043]

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

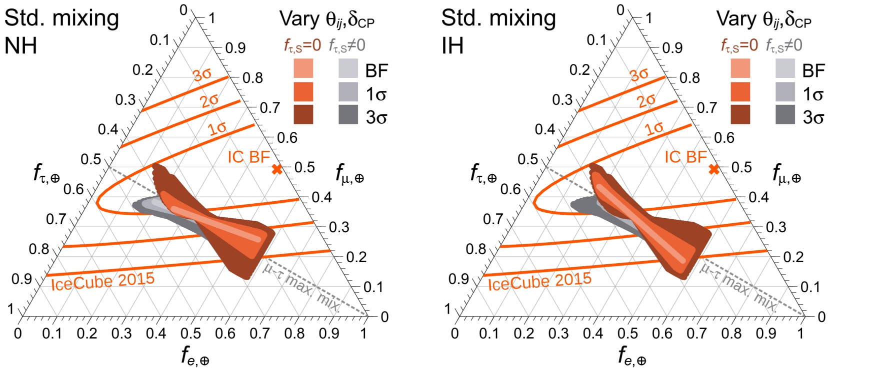


Conclusions . . . and the future

- The flavor composition is arguably the second-most interesting unknown after the identification of sources
- The space of allowed flavor compositions is surprisingly small:
  - Standard mixing: $\sim$ 10% of all possibilities
  - ν_i-mixing new physics: $\sim$ 25% (*e.g.*, decay)
- Only a broader class of new physics (*e.g.*, CPT violation) can access all compositions
- IceCube can improve the lifetime bounds in the NH (now!) and IH (soon!) by several orders of magnitude
- More, better data on the particle-physics *and* astrophysics fronts are needed (*e.g.*, IceCube-Gen2, DUNE)

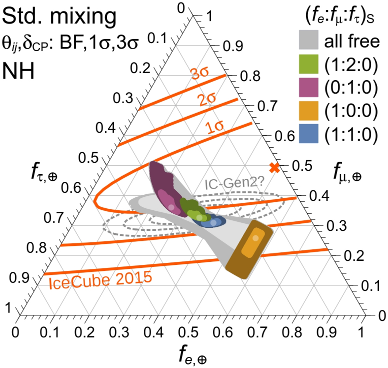
Backup slides

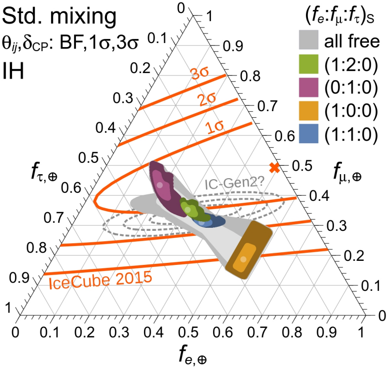
Flavor combinations from std. flavor mixing: NH vs. IH



[MB, BEACOM, WINTER, 1506.02645]

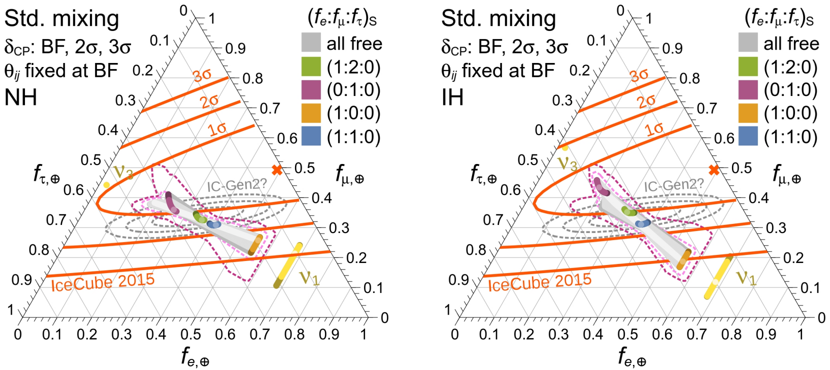
Selected source compositions: NH vs. IH





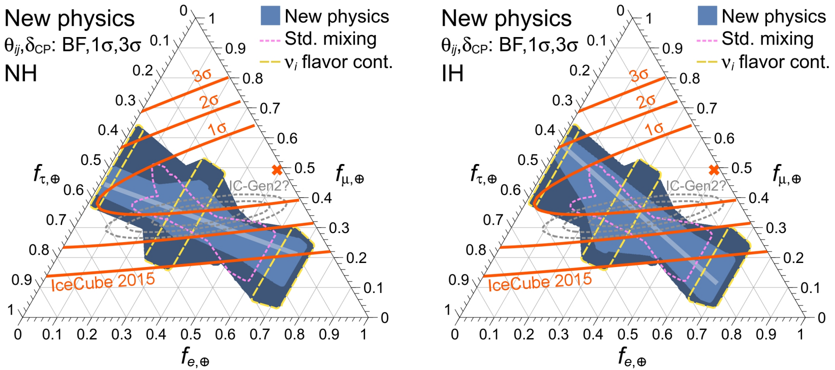
[MB, Beacom, Winter, 1506.02645]

Perfect knowledge of mixing angles: NH vs. IH



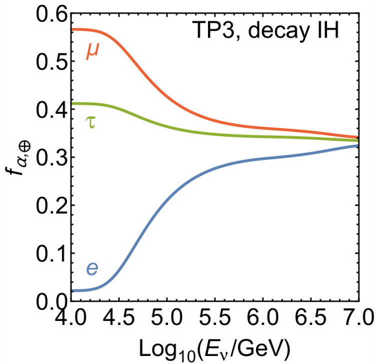
[MB, Beacom, Winter, 1506.02645]

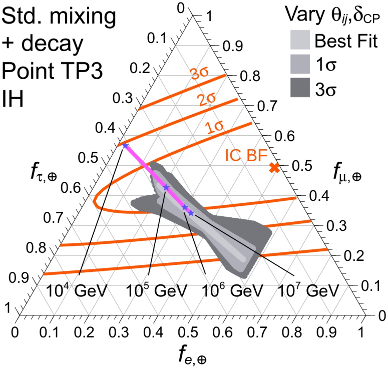
New physics: NH vs. IH



[MB, Beacom, Winter, 1506.02645]

New physics: decay in the IH





[MB, Beacom, Winter, 1506.02645]

The need for km-scale neutrino telescopes

Expected ν flux from cosmological accelerators (Waxman & Bahcall 1997–1998):

$$E^2\Phi_\nu \sim 10^{-8} \frac{f_\pi}{0.2} \left(\frac{\dot{\varepsilon}_{\rm CR}^{[10^{10},10^{12}]}}{10^{44}~\text{erg Mpc}^{-3}~\text{yr}^{-1}} \right)~\text{GeV cm}^{-2}~\text{s}^{-1}~\text{sr}^{-1}$$

Integrated flux above 1 PeV:

$$\Phi_\nu (> 1~\text{PeV}) \sim \int_{1~\text{PeV}}^{\infty} \frac{10^{-8}}{E^2}\, dE \sim 10^{-20}~\text{cm}^{-2}~\text{s}^{-1}~\text{sr}^{-1}$$

Number of events from half of the sky (2π):

$$N_\nu \simeq 2\pi \cdot \Phi_\nu (> 1~\text{PeV}) \cdot 1~\text{yr} \cdot A_{\rm eff} \approx \left(2.4 \times 10^{-10}~\text{cm}^{-2}\right) A_{\rm eff}~,$$

where $A_{\rm eff}$ is the effective area of the detector

To detect $N_\nu > 1$ events per year, we need an area of

$$A_{\rm eff} \gtrsim 0.4~\text{km}^2$$

Therefore, we need km-scale detectors, like IceCube