Recent results on the theoretical expectations of the flavor composition of astrophysical neutrinos

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INT 15-2a Program “Neutrino Astrophysics and Fundamental Properties”

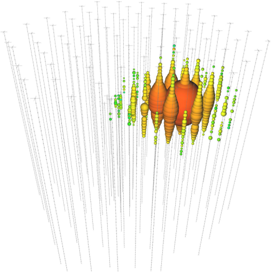
Seattle, June 19, 2015

High-energy astrophysical neutrinos: they exist!

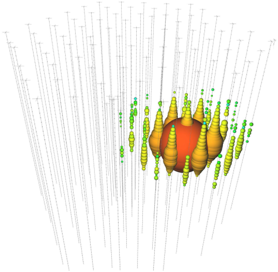
The era of neutrino astronomy has begun!

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

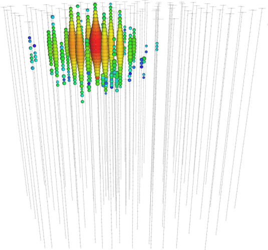
“Bert”, 1.04 PeV



“Ernie”, 1.14 PeV



“Big Bird”, 2 PeV



. . . and 51 more events > 30 TeV

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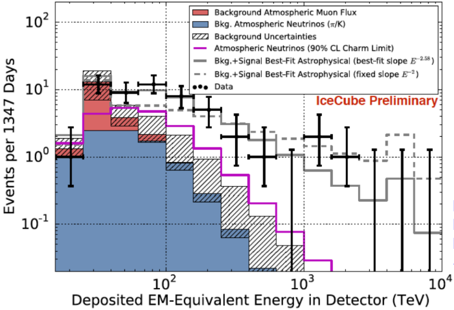

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ O. Botner, IPA 2015

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

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

The era of neutrino astronomy has begun!

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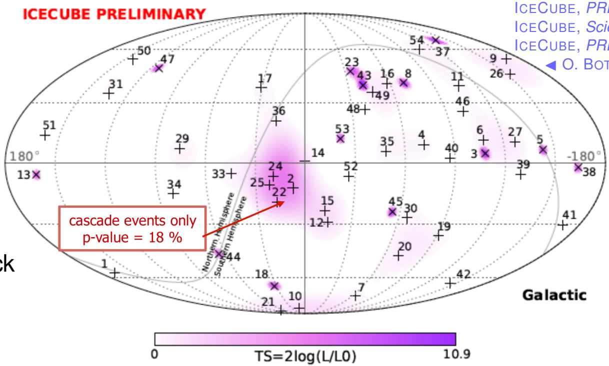
Arrival directions compatible with an isotropic distribution –

ICECUBE, *PRL* **111**, 021103 (2013)
ICECUBE, *Science* **342**, 1242856 (2013)
ICECUBE, *PRL* **113**, 101101 (2014)
◀ O. BOTNER, IPA 2015



+: shower
×: muon track

– no association with sources found yet

Flavor composition of neutrinos: an open question

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

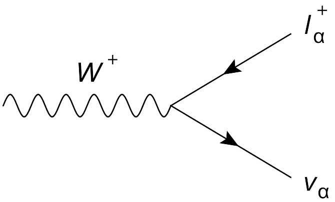
[Barenboim, Quigg, *PRD* **67**, 073024 (2003)]
[Winter, *PRD* **88**, 083007 (2013)]
[Mena, Palomares, Vincent, *PRL* **113**, 091103 (2014)]
[Palomares, Vincent, Mena, *PRD* **91**, 103008 (2015)]
[Palladino, Pagliaroli, Villante, Vissani, *PRL* **114**, 171101 (2015)]

A quick review of neutrino mixing (I)

- Two bases:

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

- 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: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

A quick review of neutrino mixing (II)

- U is a 3×3 rotation matrix (PMNS matrix):

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

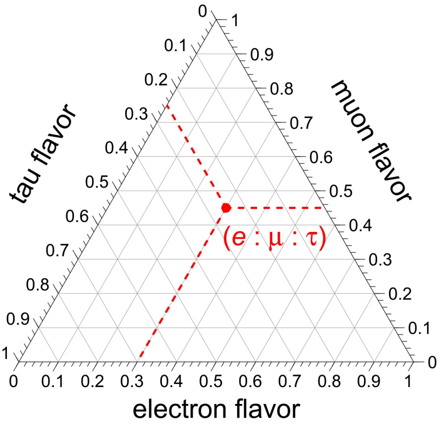
- Parametrise it with three angles and one CP-violating phase
- From solar, atmospheric, reactor, and accelerator experiments:

$$\theta_{12} \approx 37^\circ\,,\ \theta_{23} \approx 45^\circ\,,\ \theta_{13} \approx 9^\circ\,,\ \delta_{\rm CP}\ \text{unknown}$$

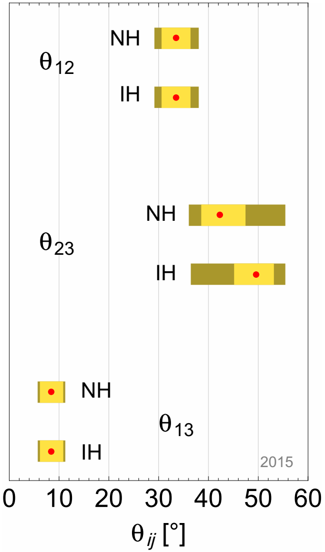
“Flavor triangle” or Dalitz/Mandelstam plot

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

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



Normal vs. inverted mass hierarchy



The mass hierarchy is also unknown:

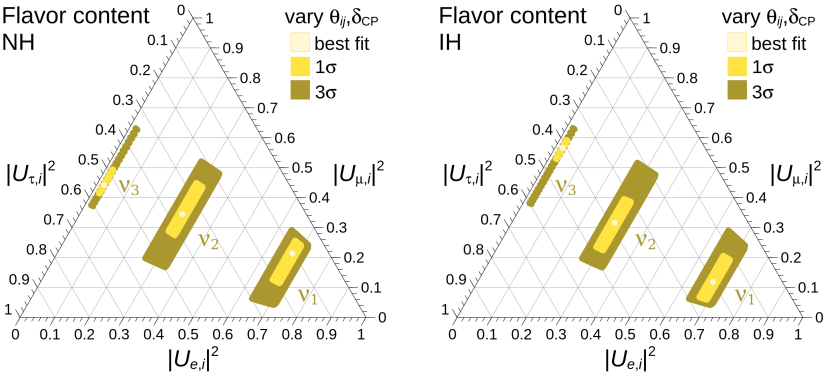
- Normal hierarchy (NH): ν_1 is lightest
- Inverted hierarchy (IH): ν_3 is lightest

Using 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 content of the mass eigenstates ν_1, ν_2, ν_3

A different way to show this information is via ternary plots:



Flavor mixing in high-energy astrophysical neutrinos

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

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

- The Δm_{kj}^2 are very small: $\sim 10^{-4}, 10^{-3}$ eV^2
- 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 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: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$
- At Earth, due to flavor mixing:

$$f_{\alpha,\oplus} = \sum_\beta P_{\beta\alpha} f_{\beta,S}$$

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

- Other compositions at the source:

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

How can IceCube identify flavor?

Below $E_\nu \sim 10$ 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 $\gtrsim 10$ PeV (no events so far), all of the above, plus:

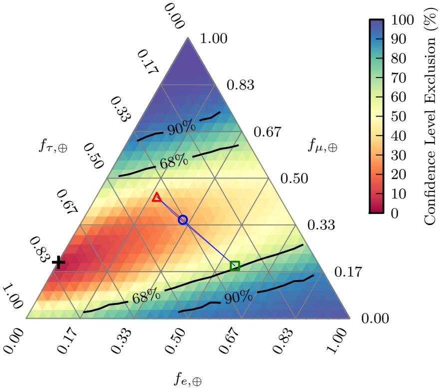
- Glashow resonance: CC $\bar{\nu}_e e$ interactions at 6.3 PeV
- Double bangs: CC $\nu_\tau \to \tau \to \nu_\tau$

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

Two IceCube analyses of flavor composition

Using contained events only

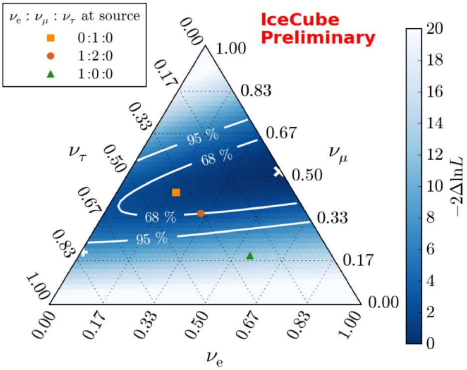
ICECUBE COLL., *PRL* **114**, 171102 (2015)



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

Using contained events +
throughgoing muons

MORIOND 2015, IPA 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 flavor mixing

- But we do not really know the flavor composition at the source
- So let us be agnostic and assume very general compositions:

1. No ν_τ production:

$$(f_{e,\mathrm{S}} : f_{\mu,\mathrm{S}} : 0)$$

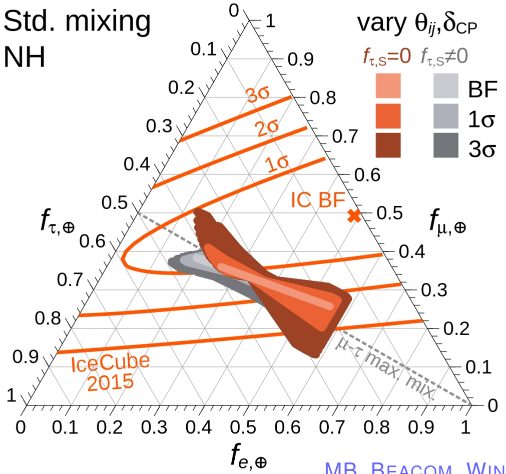
2. Anything goes:

$$(f_{e,\mathrm{S}} : f_{\mu,\mathrm{S}} : 1 - f_{e,\mathrm{S}} - f_{\mu,\mathrm{S}}) \,,$$

with $0 \leq f_{e,\mathrm{S}} \leq 1$ and $f_{\mu,\mathrm{S}} \leq f_{e,\mathrm{S}}$

- And we will calculate the flavor ratios at Earth ▶

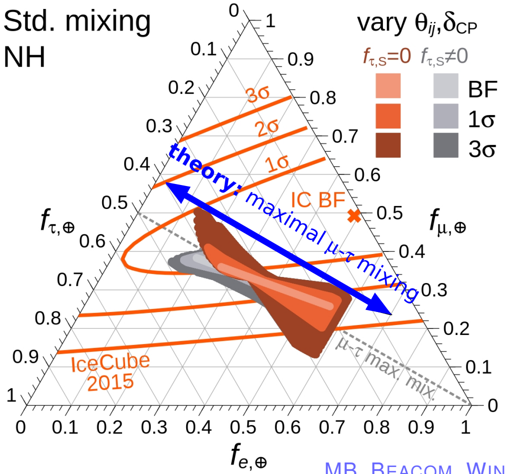
Flavor combinations at Earth from flavor mixing



MB, Beacom, Winter, 1506.02645

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

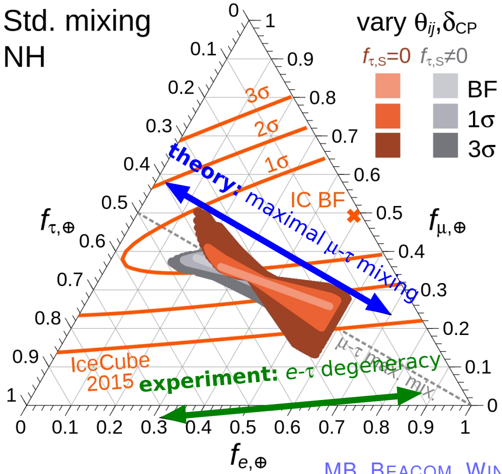
Flavor combinations at Earth from flavor mixing



MB, BEACOM, WINTER, 1506.02645

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

Flavor combinations at Earth from flavor mixing

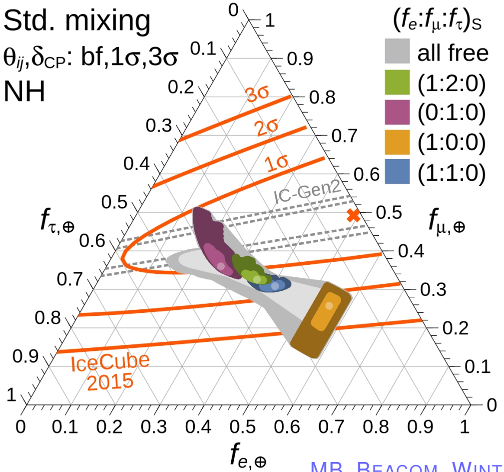


MB, Beacom, Winter, 1506.02645

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

Selected source compositions

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



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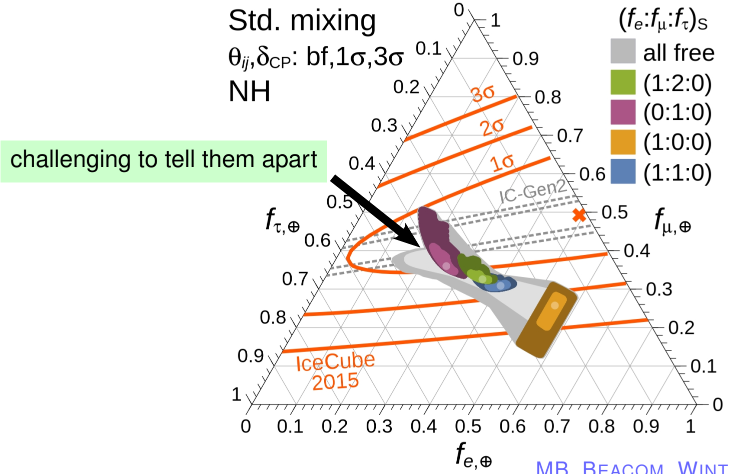

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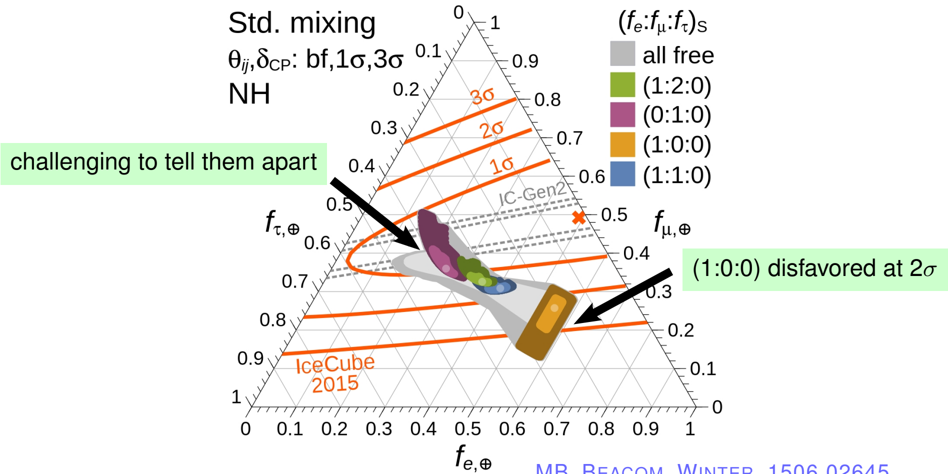
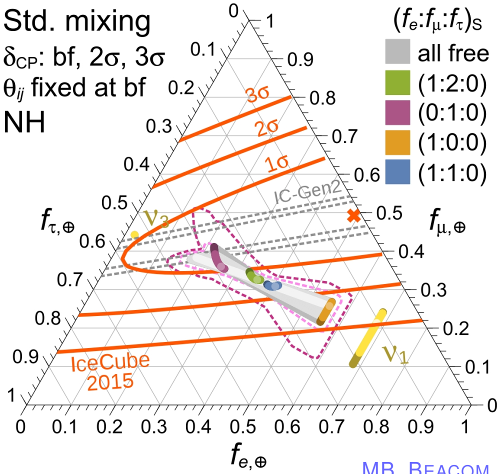


MB, Beacom, Winter, 1506.02645

Perfect knowledge of mixing angles

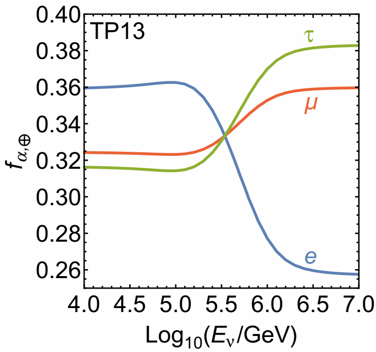
In a few years, we might know all the mixing parameters except δ_{CP}:

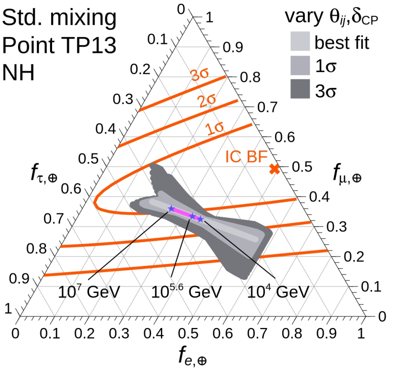


MB, Beacom, Winter, 1506.02645

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)]

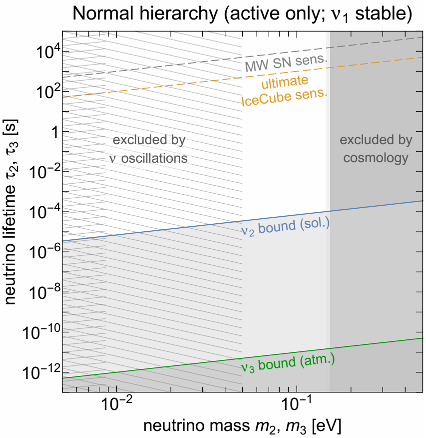
New physics: effect on the flavor composition

- 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: example of *mild* new physics

- SM: ν lifetimes are $> 10^{36}$ yr
- Via new-physics decay modes, they could be shorter
- Consider two possibilities:
  - NH: ν_1 stable; ν_2, ν_3 decay
  - IH: ν_3 stable; ν_1, ν_2 decay
- There are experimental bounds on the lifetime τ_i/m_i



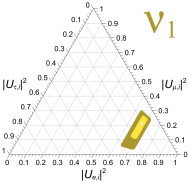
[MB, Beacom, Murase, In prep.]

Decay changes the flavor ratios at Earth:

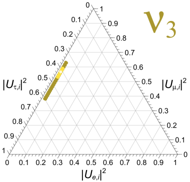
$$f_{\alpha,\oplus} = \sum_{\beta} \sum_{i} |U_{\alpha i}|^2 |U_{\beta i}|^2 e^{-\frac{\tau_i}{m_i} \frac{L}{E}} f_{\beta,S}$$

Neutrino decay: complete vs. incomplete

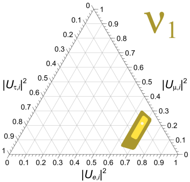
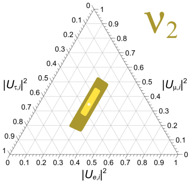
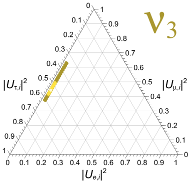
- Complete decay: only ν_1 (ν_3) reach Earth assuming NH (IH)



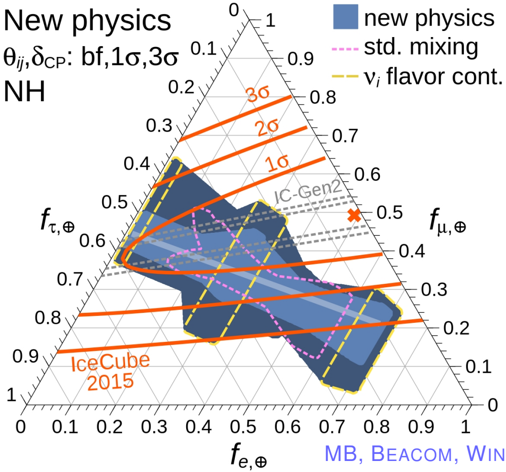
or



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

$\alpha\Big($  $\Big) + \beta\Big($  $\Big) + \gamma\Big($  $\Big)$

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



MB, Beacom, Winter, 1506.02645

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

New physics — of the *mild* kind

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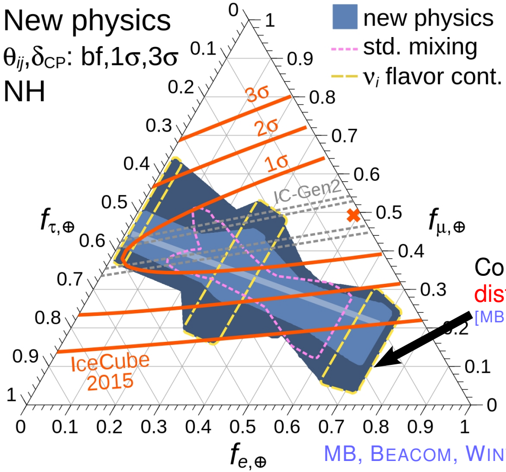

Complete decay in NH
disfavored at $> 2\sigma$
[MB, Beacom, Murase, in prep.]

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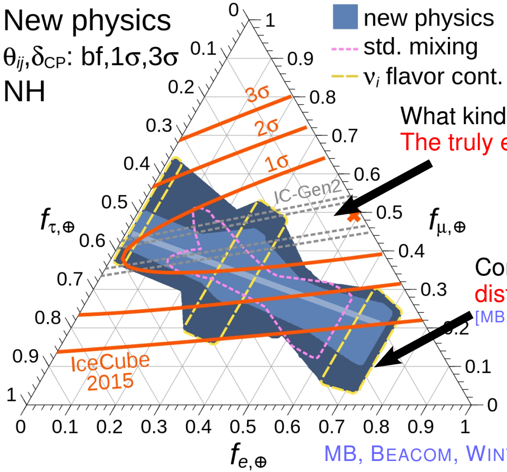


What kind of NP lives outside?
The truly exotic kind!

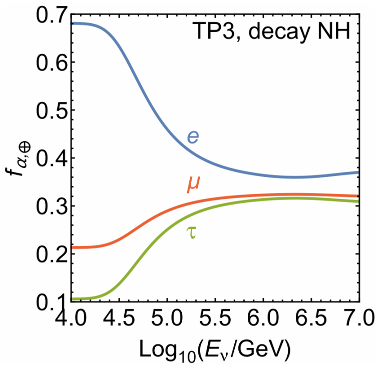
Complete decay in NH
disfavored at $> 2\sigma$
[MB, Beacom, Murase, In prep.]

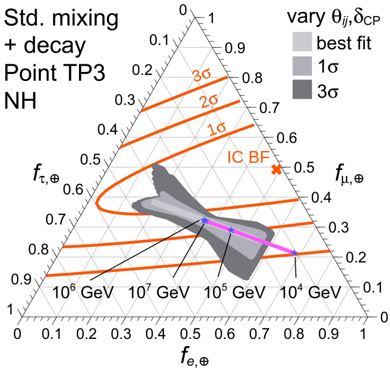
MB, Beacom, Winter, 1506.02645

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

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

New physics — of the *truly exotic* kind (I)

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
    [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.*, 1410.0408]
- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

New physics — of the *truly exotic* kind (I)

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- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

New physics — of the *truly exotic* kind (II)

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

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

- Standard Hamiltonian:

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

  with U the PMNS matrix

- NP Hamiltonian:

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

  with U_n a PMNS-*like* matrix and Λ_n the scale of n-th order NP

New physics — of the *truly exotic* kind (III)

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

$n = 0$

- 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

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

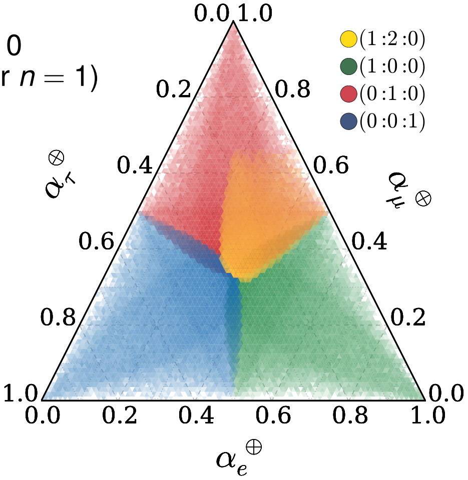
[IceCube Coll., *PRD* **82**, 112003 (2010)]
[Super-K Coll., *PRD* **91**, 052003 (2015)]
[Argüelles, Katori, Salvadó, 1506.02043]

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 $n = 1$)



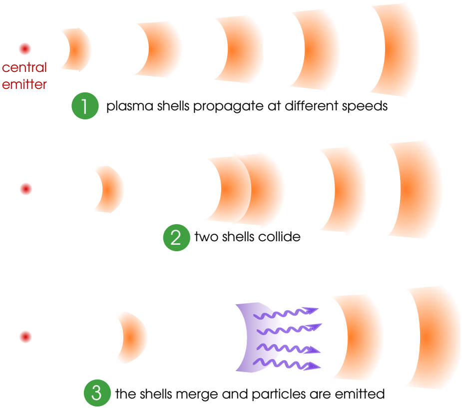
Conclusions . . . and the future

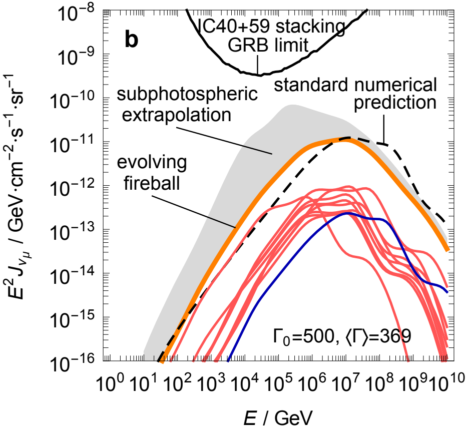
- The flavor composition is arguably the second-most interesting unknown after the identification of sources
- The space of allowed flavor compositions is surprisingly small:
  - Standard mixing: $\sim$ 10% of all possibilities
  - *Mild* new physics: $\sim$ 25% (*e.g.*, decay)
- Only truly exotic new physics (*e.g.*, CPT-violation) can access all compositions
- IceCube searches could use these theoretical considerations to improve constraints
- More, better data on the particle-physics *and* astrophysics fronts are needed (*e.g.*, IceCube-Gen2, DUNE)

Extra: GRB neutrinos from multiple collisions

[MB, BAERWALD, MURASE, WINTER, *Nature Commun.* **6**, 6783 (2015)]

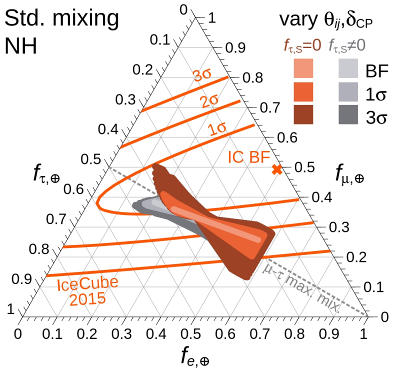
Cumulative UHE ν, CR, γ-ray emission from multiple collisions of plasma shells in a GRB jet

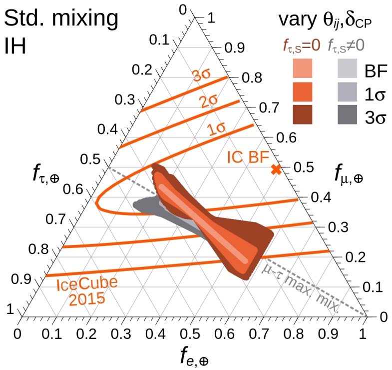




Spoiler: we found a fairly robust minimal GRB diffuse ν flux

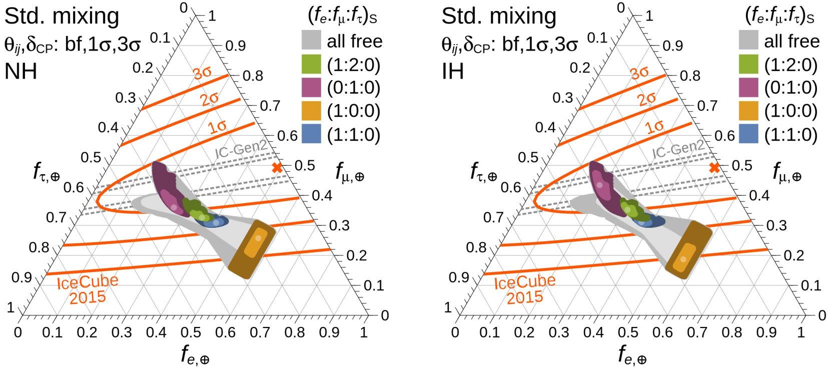
Backup slides





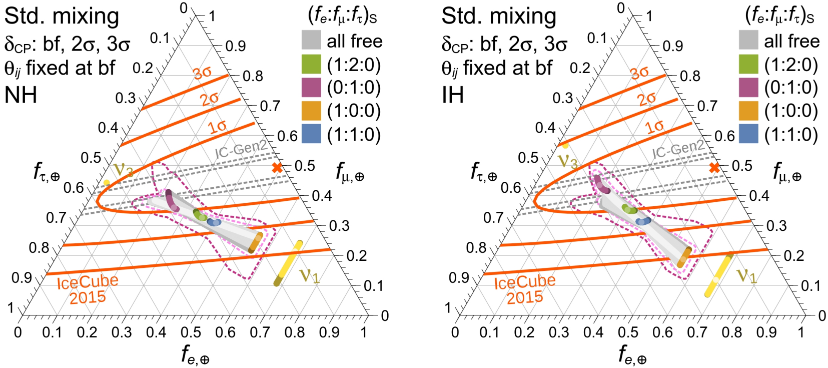
MB, Beacom, Winter, 1506.02645

Selected source compositions: NH vs. IH



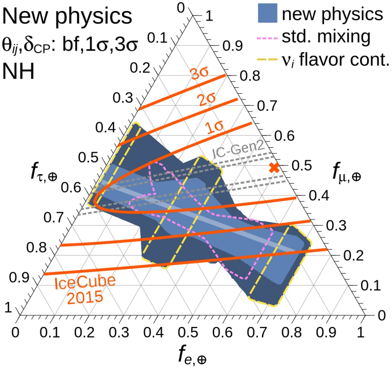
MB, Beacom, Winter, 1506.02645

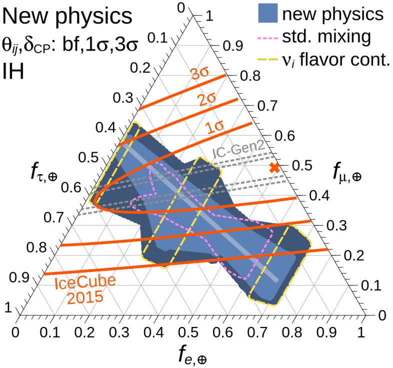
Perfect knowledge of mixing angles: NH vs. IH



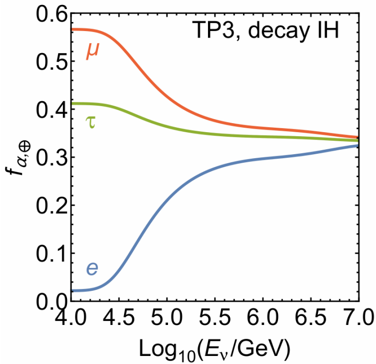
MB, BEACOM, WINTER, 1506.02645

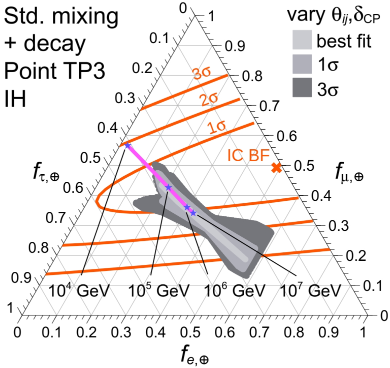
New physics: NH vs. IH





MB, Beacom, Winter, 1506.02645





MB, Beacom, Winter, 1506.02645