Decay of high-energy astrophysical neutrinos: present and near future

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Neutrinos *can* decay

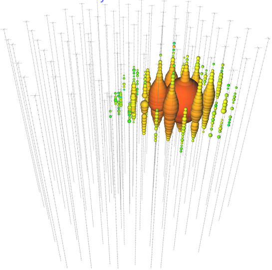
- Fact: neutrinos change flavor – they oscillate
- Therefore ...
  1. Neutrinos have mass; and
  2. Different neutrino types have different masses
- Heavier neutrinos may decay into lighter ones
- However, expected decay rates are *low*
- The effect on a neutrino beam is typically tiny ...
- ... but cumulative effects over long baselines might be detectable

What are the longest baselines we have access to? ▶

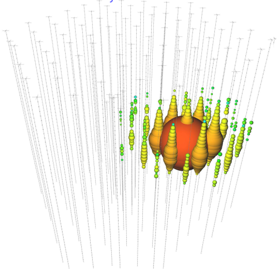
High-energy astrophysical neutrinos

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

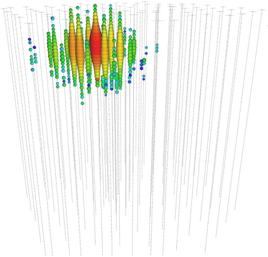
"Bert", 1.04 PeV



"Ernie", 1.14 PeV



"Big Bird", 2 PeV

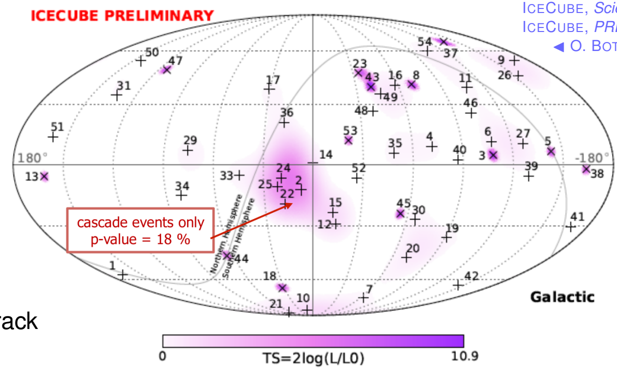


…and 51 more events > 30 TeV

Astrophysical neutrinos: the longest baselines

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
$\times$: muon track

- No sources identified, but isotropy hints at extragalactic origin
- If extragalactic, estimated baselines are 10 Mpc – few Gpc

Neutrino decay in the SM

- Consider the SM minimally extended to include massive neutrinos
- We will consider three active neutrinos only:

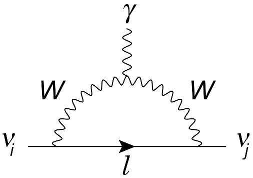
$$\underbrace{\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}}_{\text{flavor eigenstates}} = U_{\text{PMNS}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}}_{\text{mass eigenstates}}$$

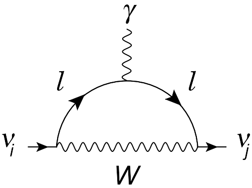
- SM decay modes:
  - One-photon radiative decay: $\nu_i \to \nu_j + \gamma$
  - Two-photon: $\nu_i \to \nu_j + \gamma + \gamma$
  - Three-neutrino: $\nu_i \to \nu_j + \nu_k + \bar{\nu}_k$
  - Pair production: $\nu_i \to \nu_j + e^+ + e^-$ (unavailable – needs too high ν masses)

Let us look at one mode in some detail ▶

One-photon radiative decay

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





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

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

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

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

$$\tau \sim 10^{36} \text{ yr} \gg 13.3 \cdot 10^9 \text{ yr (age of the Universe)}$$

Other SM decay modes

The situation is worse for other decay modes:

- 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
– therefore, it is hopeless to look for SM decay channels

New neutrino decay modes

- 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 in lepton number violation via neutrino mass [Chikashige *et al.* 1980, Gelmini *et al.* 1982]
- Bounds from $0\nu\beta\beta$ decay and supernovae [Tomas *et al.* 2001], and precision CMB measurements [Hannestad & Raffelt 2005]
- We work in a model-independent way
  – nature of ϕ unimportant as long as invisible to neutrino detectors

Decay fundamentals

- A neutrino source emits known numbers of ν_1, ν_2, ν_3
- En route, they decay via

$$\underbrace{\nu_2, \nu_3 \to \nu_1}_{\text{normal mass hierarchy (NH)}} \quad \text{or} \quad \underbrace{\nu_1, \nu_2 \to \nu_3}_{\text{inverted mass hierarchy (IH)}}$$

- At time t (= baseline L), the fraction of surviving unstable ν_i's is

$$\frac{N_i(L)}{N_{i,\text{emit}}} = \exp\left[-\left(\frac{m_i}{\tau_i}\right)\left(\frac{L}{E_\nu}\right)\right]$$

◀ For very long L, this will have redshift corrections

m_i, τ_i are the mass and (rest-frame) lifetime of ν_i

- Neutrinos with known L and E_ν are sensitive to "lifetimes" of

$$\kappa^{-1}\left[\frac{\text{s}}{\text{eV}}\right] \equiv \frac{\tau\,[\text{s}]}{m\,[\text{eV}]} \lesssim 10^2\,\frac{L\,[\text{Mpc}]}{E_\nu\,[\text{TeV}]}$$

Decay changes flavor oscillations

- Consider ordinary two-flavor oscillations (*e.g.*, $\nu_e \to \nu_\mu$)
- Probability of flavor change $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = \frac{1}{2} \sin^2(2\theta) \sin^2\left(1.27 \Delta m^2 \, [\mathrm{eV}^2] \frac{L \, [\mathrm{km}]}{E_\nu \, [\mathrm{GeV}]}\right)$$

- Decay damps this exponentially $P_{\alpha\beta} \to \left(N_i(L)/N_{i,\mathrm{emit}}\right) P_{\alpha\beta}$, *i.e.*,

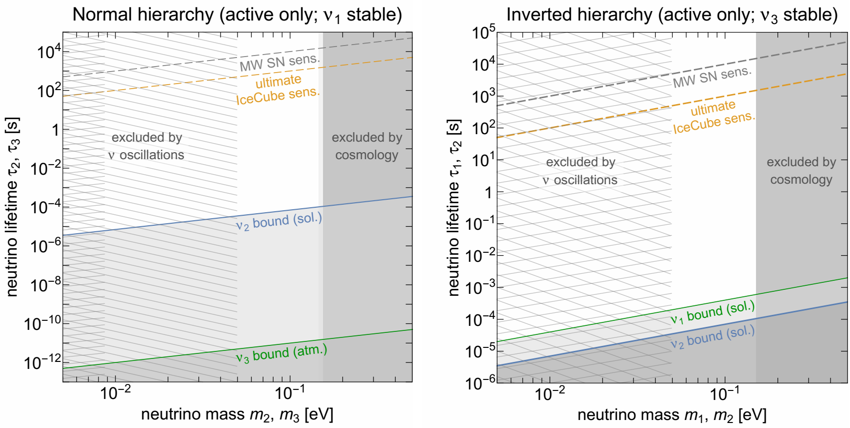
$$P_{\alpha\beta} = \frac{1}{2} \exp\left(-\frac{L}{L_{\mathrm{dec}} \, [\mathrm{Mpc}]}\right) \sin^2(2\theta) \sin^2\left(2\pi \frac{L}{L_{\mathrm{osc}} \, [\mathrm{km}]}\right)$$

- The length scales are vastly different:

$$\frac{L_{\mathrm{dec}}}{\mathrm{Mpc}} \simeq 0.01 \cdot \left(\frac{\kappa^{-1}}{\mathrm{s \; eV}^{-1}}\right) \left(\frac{E_\nu}{\mathrm{TeV}}\right) \gg \frac{L_{\mathrm{osc}}}{\mathrm{km}} \simeq \left(10^3 - 10^4\right) \cdot \left(\frac{E_\nu}{\mathrm{TeV}}\right)$$

Current lifetime limits

- Different ν experiments probe different L/E_ν values and lifetimes
- From the tiny decay-induced modifications of oscillations:
  - ν_1: $\gtrsim 4 \cdot 10^{-3}$ s eV^{-1} (solar, Berryman *et al.* 2014)
  - ν_2: $\gtrsim 7 \cdot 10^{-3}$ s eV^{-1} (solar, Berryman *et al.* 2014)
  - ν_3: $\gtrsim 7 \cdot 10^{-11}$ s eV^{-1} (atmospheric, González-García & Maltoni 2008)



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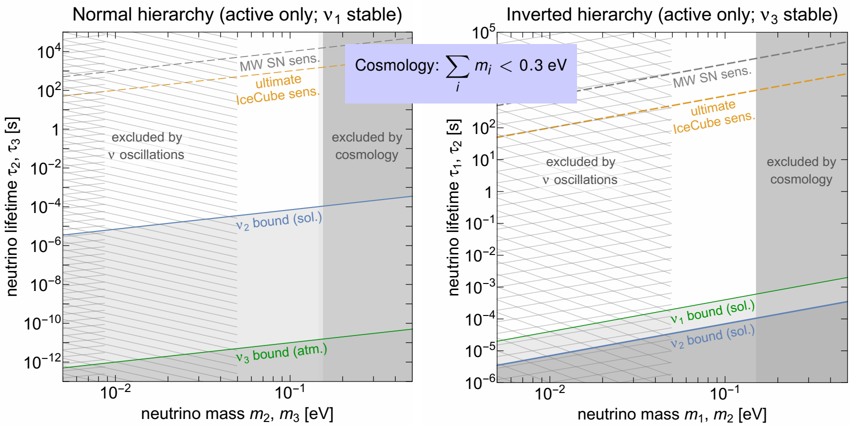

Cosmology: $\sum_i m_i < 0.3$ eV

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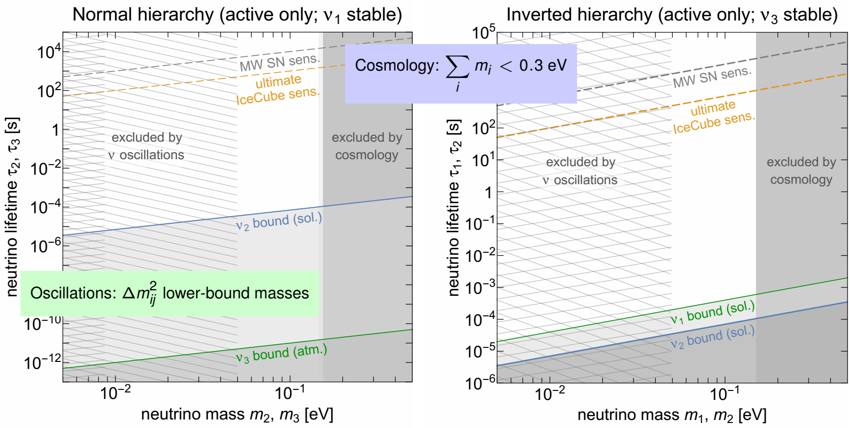

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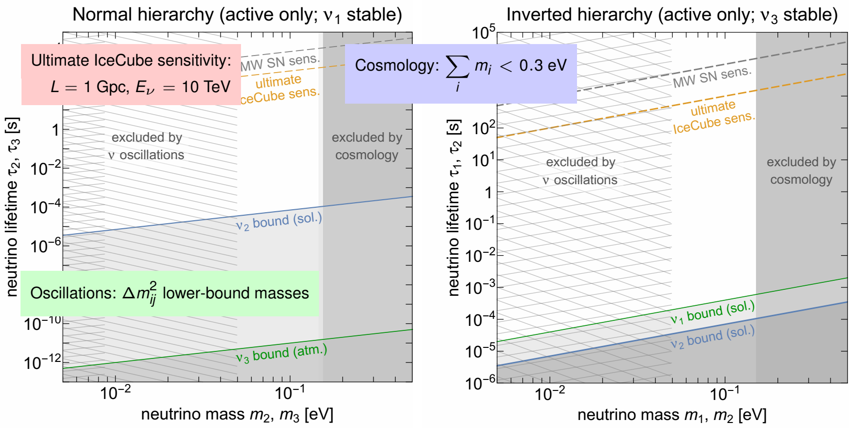


Flavor mixing in high-energy astrophysical neutrinos

Probability of $\overleftrightarrow{\nu}_\alpha \to \overleftrightarrow{\nu}_\beta$ transition (three generations):

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

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

- 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:

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

Flavor ratios

- Neutrino production at the astrophysical 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:

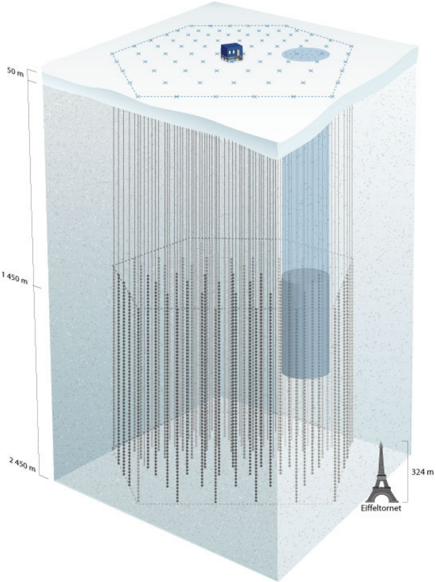
$$f_{\alpha,\oplus} = \sum_\beta \langle P_{\beta\alpha}\rangle f_{\beta,S} = \sum_\beta \left(\sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 \right) f_{\beta,S}$$

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

- Other compositions at the source:

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

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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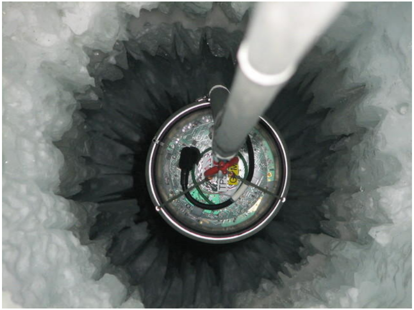

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- νN interactions ($N = n, p$) create particle showers
- 86 strings with 5160 digital optical modules (DOMs)
- depths between 1450 m and 2450 m

How does IceCube see flavor?

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

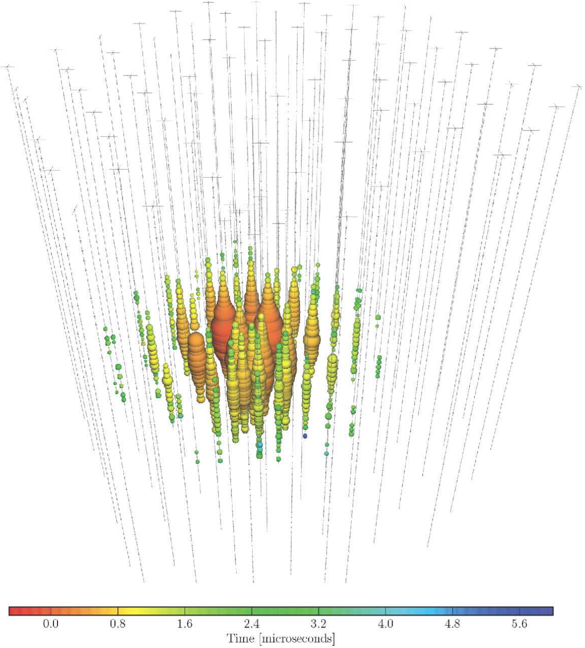
- Showers: generated by CC ν_e or ν_τ; or by NC ν_x
- Muon tracks: generated by CC ν_μ

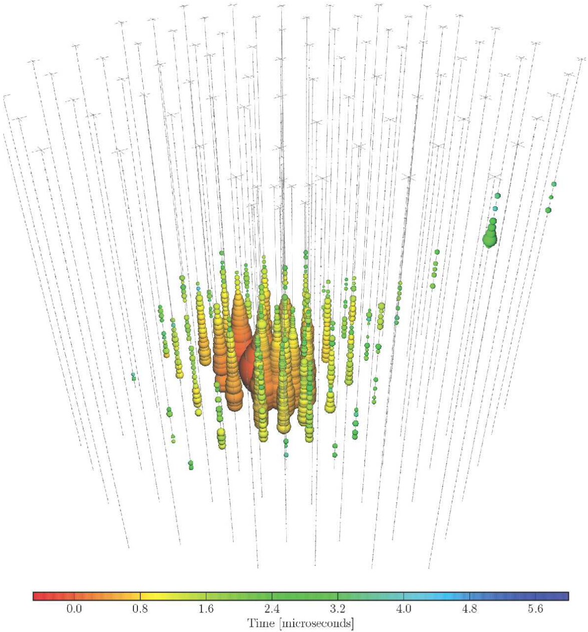
(Some muon tracks can be mis-reconstructed as showers)

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

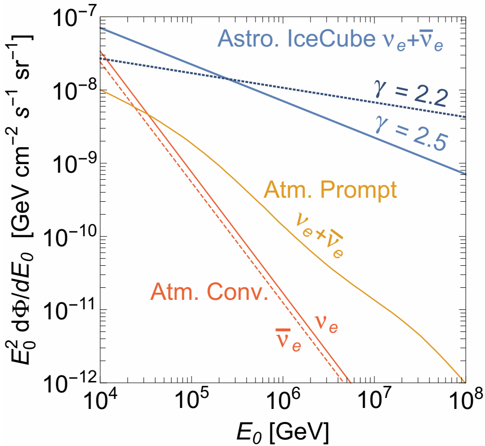

0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]


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

Astrophysical fluxes

IceCube events are fit by a power law $\sim E^{-\gamma}$:

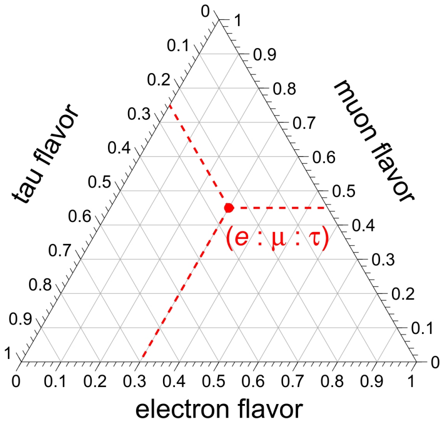
- Using contained events + through-going muons: $\gamma = 2.5 \pm 0.09$
- Using through-going muons only: $\gamma = 2.2 \pm 0.2$



“Flavor triangle” or Dalitz/Mandelstam plot

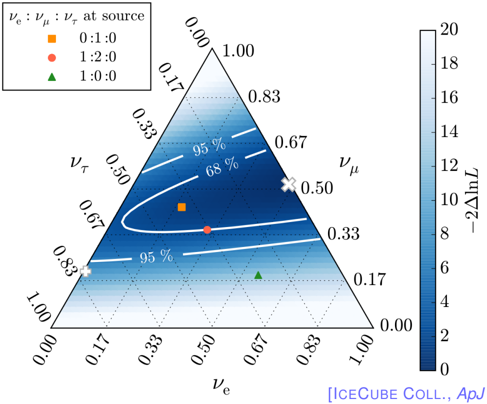
Assumes underlying unitarity: sum of projections on each axis is 1

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



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

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]

Cosmological effects on decay

There are two cosmological effects:

1. Lookback distance as a function of redshift z: $L = L(z)$
2. Adiabatic cosmological expansion:

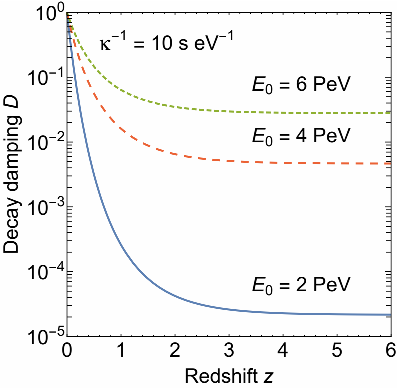
$$\text{energy at production}\,(E) = (1+z)\cdot\text{energy at detection}\,(E_0)$$

Fraction of remaining ν_i at Earth:

$$D\left(E_0, z, \kappa_i^{-1}\right) = \left(a + be^{-cz}\right)^{-\frac{\kappa_i L_H}{E_0}}$$

$a \approx 1.71$, $b = 1 - a$, $c \approx 1.27$
for ΛCDM with $(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$

$$\langle P_{\alpha\beta}\rangle \to \underbrace{D\left(E_0, z, \kappa_i^{-1}\right)}_{0<D<1}\langle P_{\alpha\beta}\rangle$$



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

Flavor ratios with decay

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

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

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

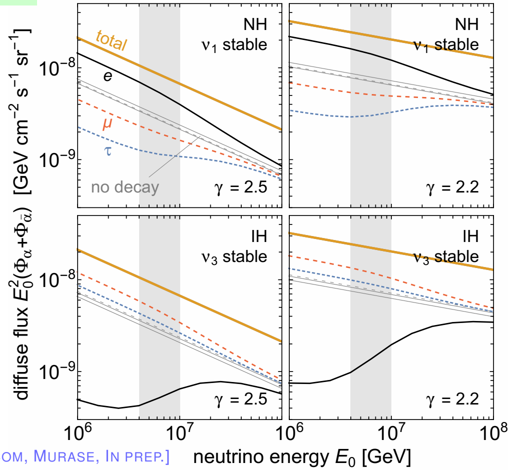
- Standard mixing ($D \to 1$):

$$f_{\alpha,\oplus} = \sum_\beta \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2 f_{\beta,S}$$

as before

- Complete decay ($D \to 0$):

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

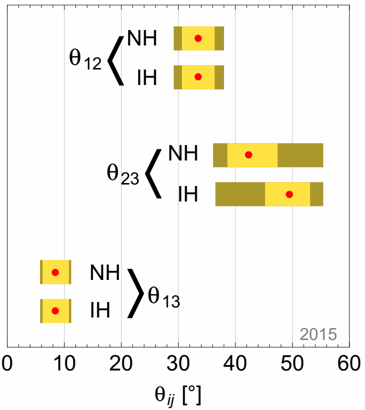


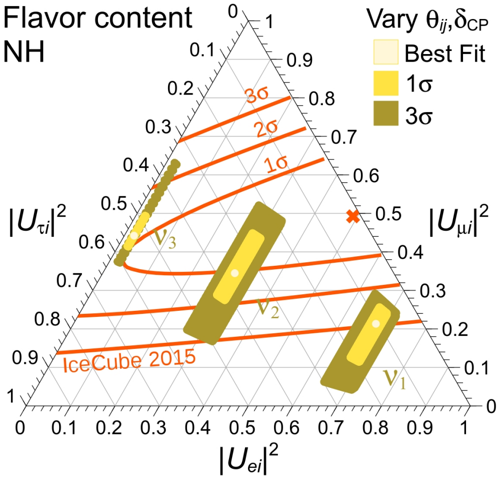
[MB, Beacom, Murase, in prep.]

IceCube sensitivity to complete decay

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

Ranges from GONZÁLEZ-GARCÍA *et al.* 2014





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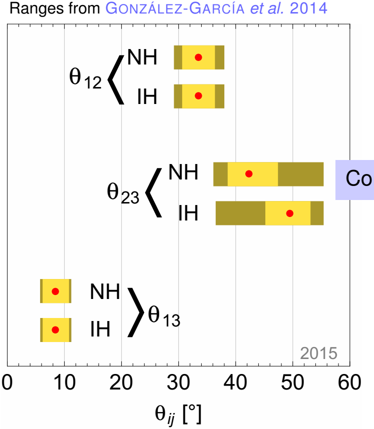
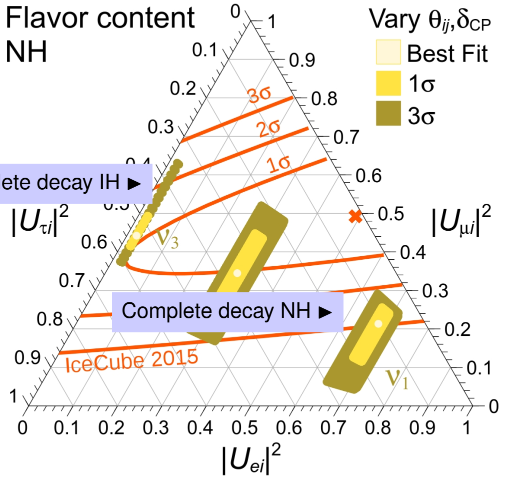


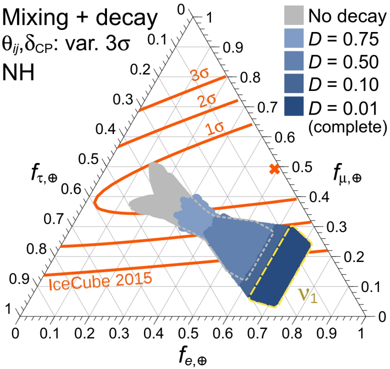


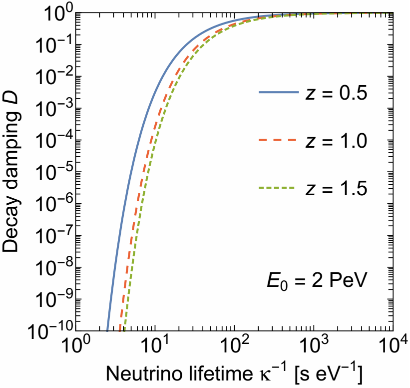
[MB, BEACOM, MURASE, IN PREP.]

NH: lifetime limits 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





[MB, Beacom, Murase, in prep.]

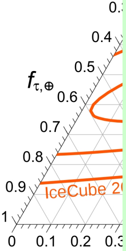
$D \lesssim 0.01$ implies a bound of $\kappa_{2,3}^{-1} \gtrsim 10$ s eV^{-1} at $\gtrsim 2\sigma$

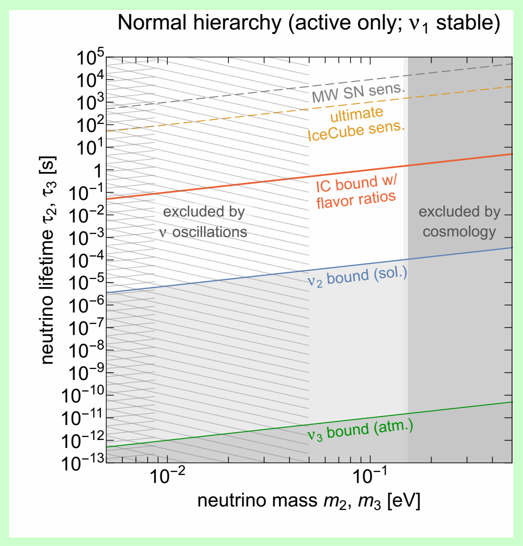
NH: lifetime limits with current IceCube data

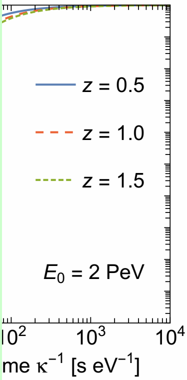
Find the valu… $= |U_{\alpha 1}|^2$, for

- *Any* valu…
- *Any* flavo…

Mixing + dec…
θ_{ij}, δ_{CP}: var. 3σ…
NH







[…BEACOM, MURASE, IN PREP.]

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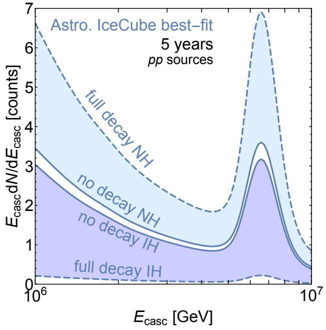
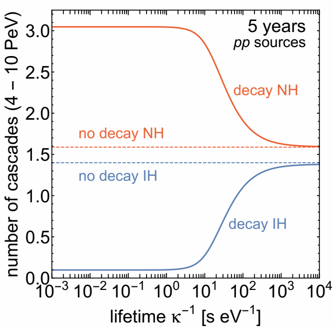
IH: lifetime limits with near-future IceCube data

- 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)





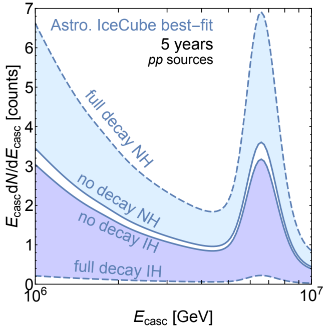
[MB, Beacom, Murase, in prep.]

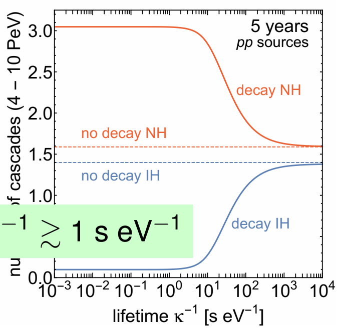
IH: lifetime limits with near-future IceCube data

- 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)





$\kappa^{-1} \gtrsim 1$ s eV^{-1}

[MB, Beacom, Murase, in prep.]

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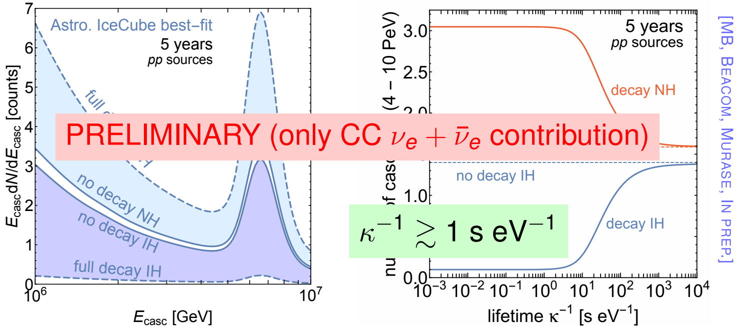

PRELIMINARY (only CC $\nu_e + \bar{\nu}_e$ contribution)

$\kappa^{-1} \gtrsim 1$ s eV^{-1}

IH: lifetime limits with near-future IceCube data

- Around 6.3 PeV, the Glashow resonance is accessible:

  $\bar{\nu}$ … 7%)

- Three scen…
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  - Neutrin… ^{2} is large)
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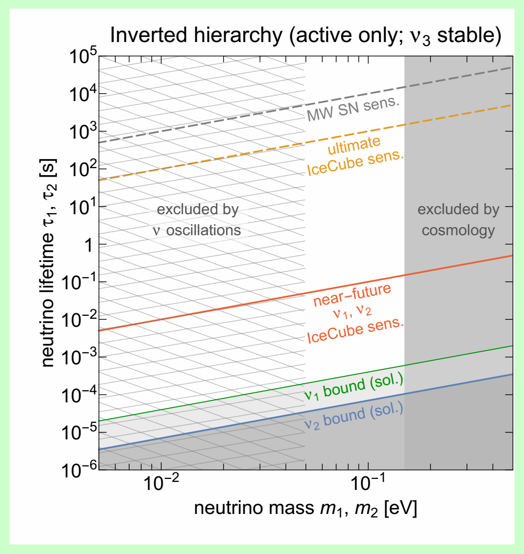
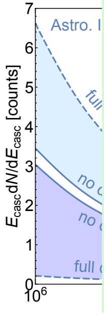
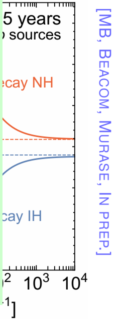
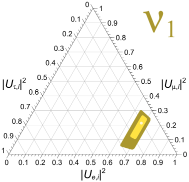




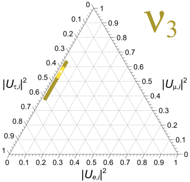


Decay: complete vs. incomplete

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

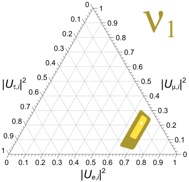


or



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

$\alpha\Big($



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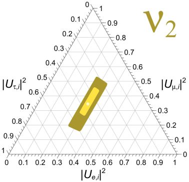
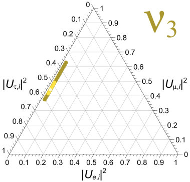


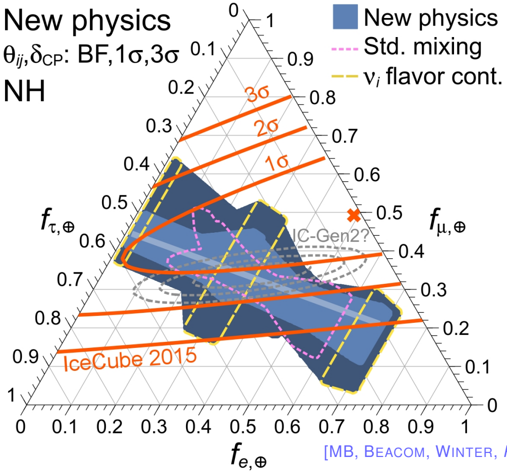
$\Big)+\gamma\Big($



$\Big)$

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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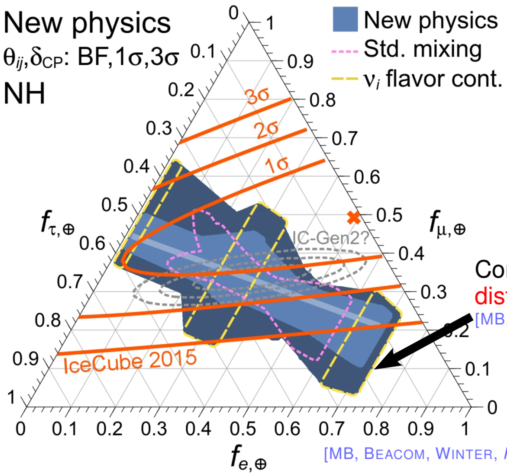

[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

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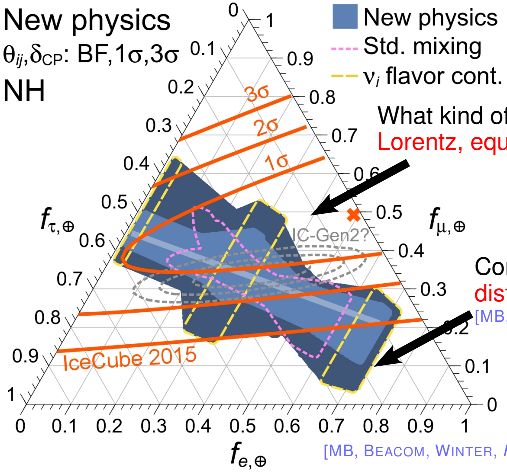


What kind of NP lives outside?
Lorentz, equiv. principle violation

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

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

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

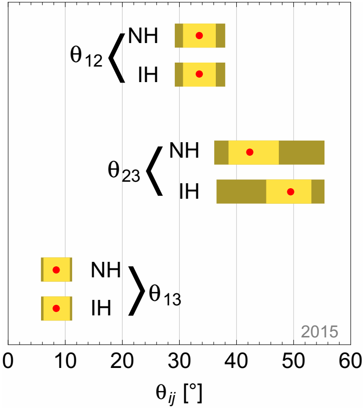
Conclusions

- Decay may imprint on flux of high-energy astrophysical neutrinos
- Their probing power is their huge baselines: 10 Mpc – few Gpc
- NH: current flavor ratios improve limits to $\gtrsim$ 10 s eV^{-1} for ν_2, ν_3 – improvement factor of 10^4, 10^7
- IH: future $>$ 4 PeV showers improve limits to $\gtrsim$ 1 s eV^{-1} for ν_1, ν_2 – improvement factor of 10^2, 10^3

IceCube is not only an astrophysics instrument,
but also an instrument for fundamental particle physics

Backup slides

Mixing parameters: mass hierarchy



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

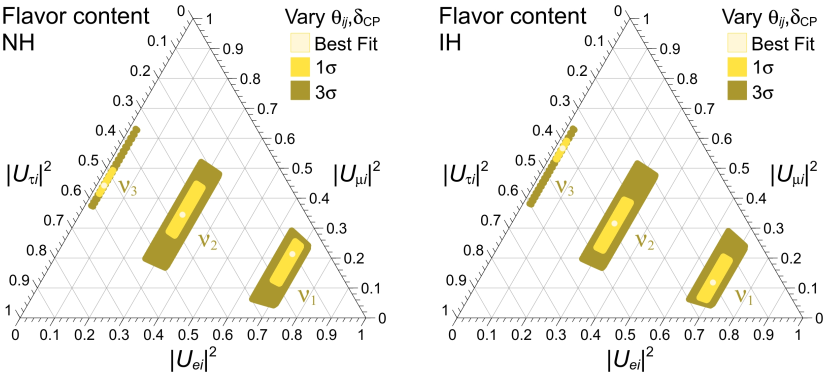
The neutrino mass hierarchy is unknown:

- 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):

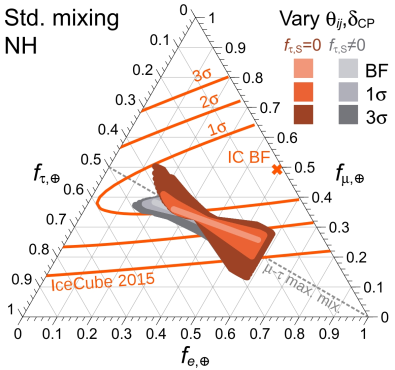
- θ_{12} and θ_{13} are well-determined
- Little NH/IH difference for θ_{12} and θ_{13}
- Large error and NH/IH difference for θ_{23}
- At 3σ, NH and IH regions are equal

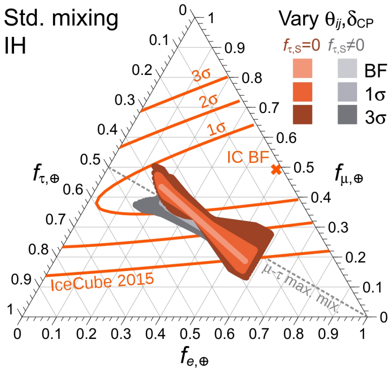
Show the e, μ, and τ content of the ν_i via ternary plots:



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

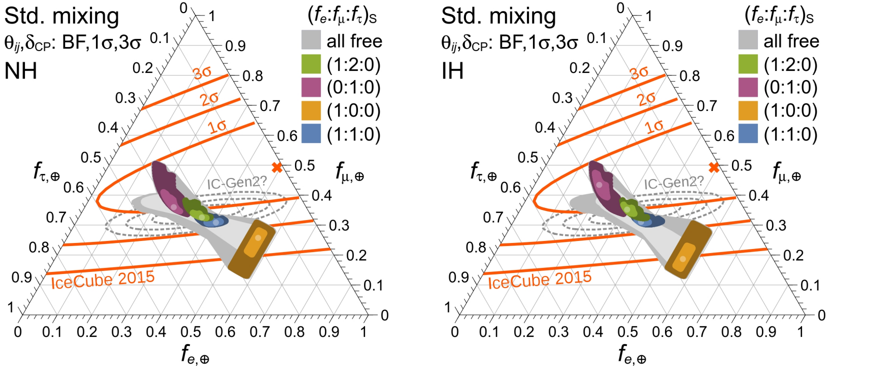
Flavor combinations from std. flavor mixing: NH vs. IH





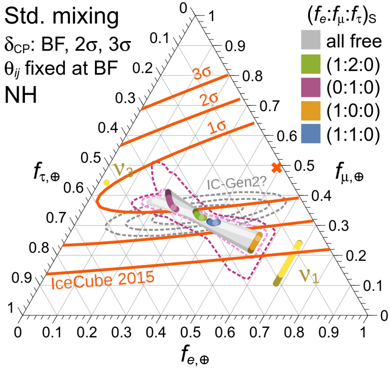
[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Selected source compositions: NH vs. IH



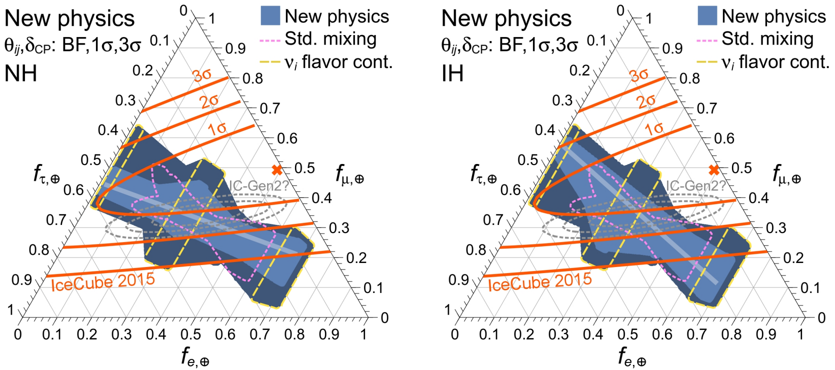
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Perfect knowledge of mixing angles: NH vs. IH



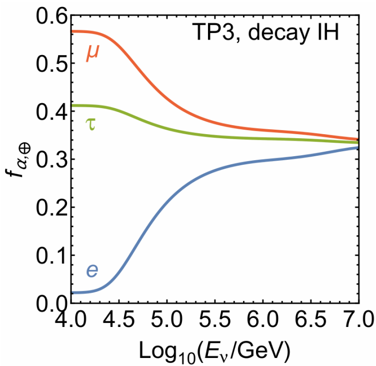
[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

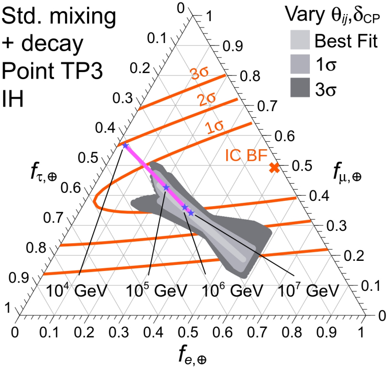
New physics: NH vs. IH



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

New physics: decay in the IH





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

The need for km-scale neutrino telescopes

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

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

Integrated flux above 1 PeV:

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

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

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

where A_{eff} is the effective area of the detector

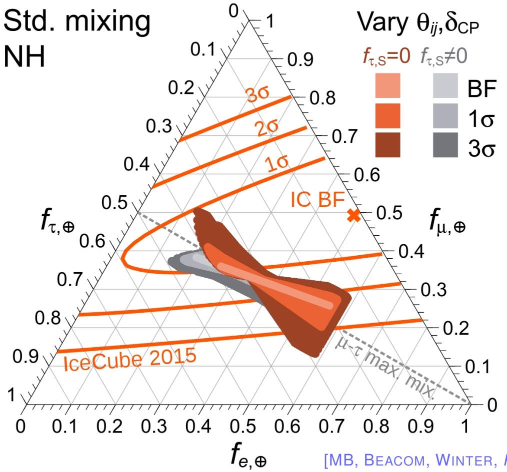
To detect $N_\nu > 1$ events per year, we need an area of

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

Therefore, we need km-scale detectors, like IceCube

Flavor combinations at Earth from std. mixing

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



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

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

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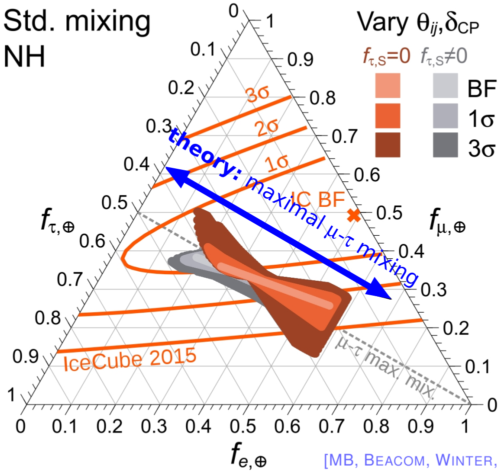

[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

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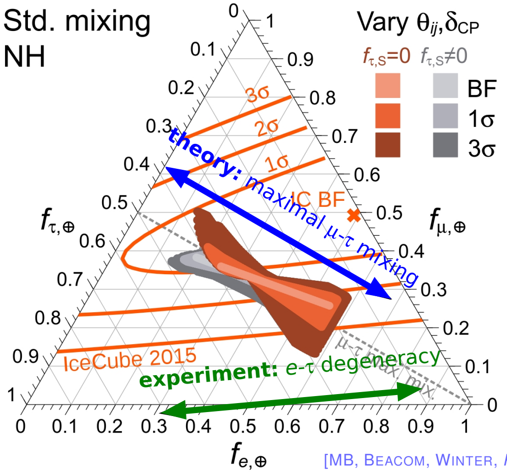
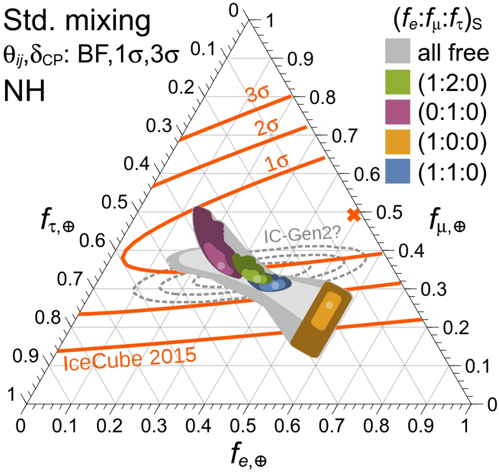


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

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, *PRL* **115**, 1611302 (2015)]

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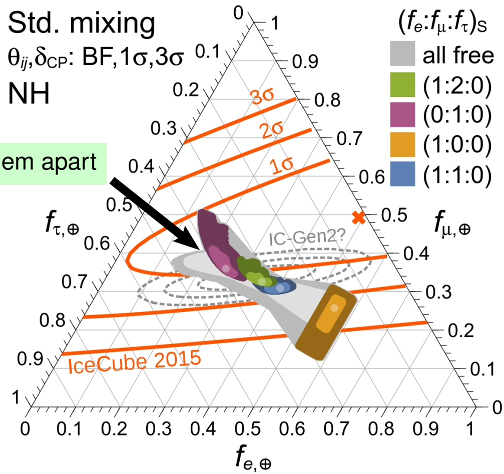

challenging to tell them apart

[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

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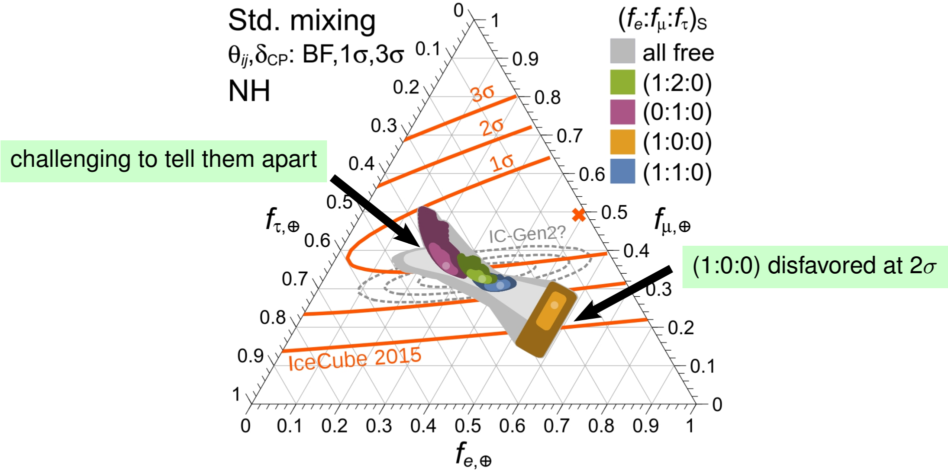
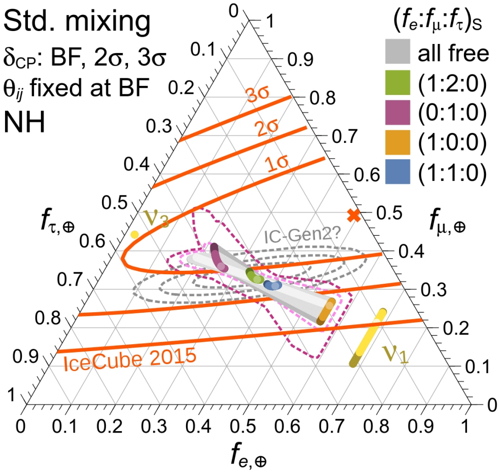


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Perfect knowledge of mixing angles

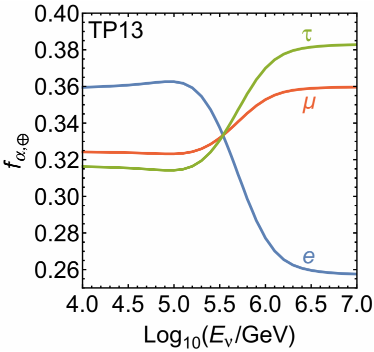
In a few years, we might know all the mixing parameters except δ_{CP}:

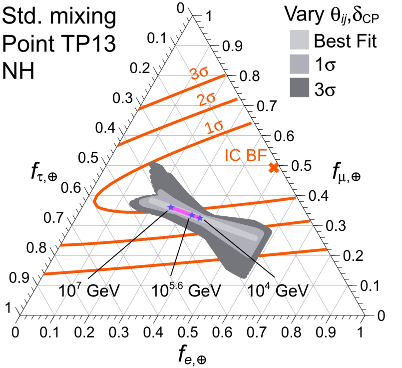


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies



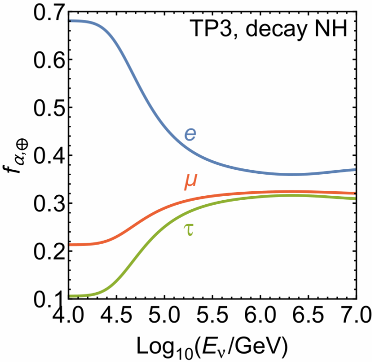


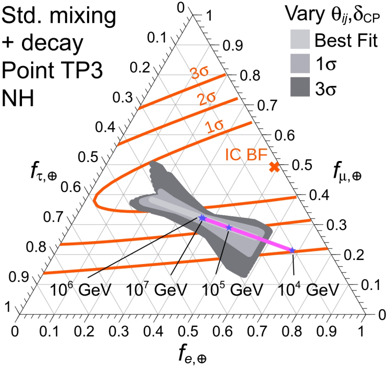
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

- TP13: $p\gamma$ model, target photons from co-accelerated electrons
  [HÜMMER *et al.*, *Astropart. Phys.* **34**, 205 (2010)]
- 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)]

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, *PRL* **115**, 1611302 (2015)]

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

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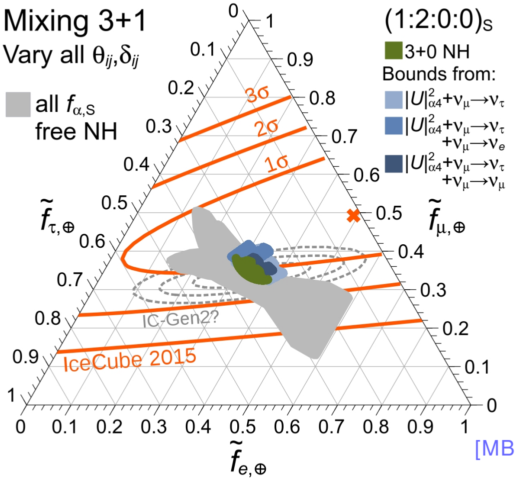
Mixing with a sterile neutrino (3+1) changes the flavor ratios:

- 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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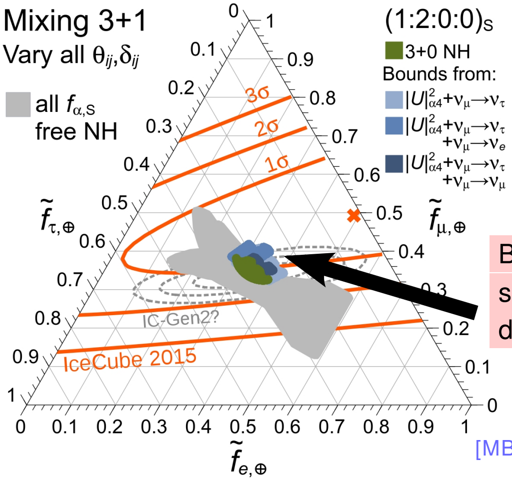

Bounds from T2K, SK, Daya Bay

Bounds are too strong for large deviations

[MB, Coloma]

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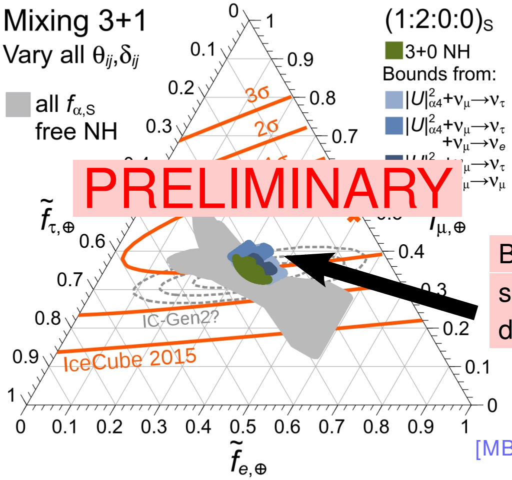

Bounds from T2K, SK, Daya Bay

Bounds are too strong for large deviations

[MB, COLOMA]

New physics — high-energy effects (I)

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

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

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

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

$n = 0$

- 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

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

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 $n = 1$)