High-energy astrophysical neutrinos: probes of new physics

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THE OHIO STATE UNIVERSITY

CCAPP

The history of neutrinos is a history of fighting against the odds

The history of neutrinos is a history of fighting against the odds

. . . and winning

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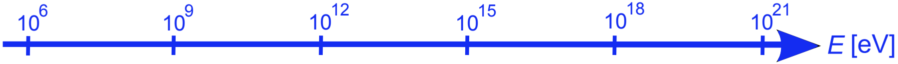
. . . and winning

Some reasons why neutrinos are special:

1. They are lighter than any other massive particle we know of
2. They retain their quantum nature over long distances
3. They are notoriously anti-social
4. (We believe) they reach higher energies than anything else

Let’s talk energy scales...


10^6
10^9
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10^{15}
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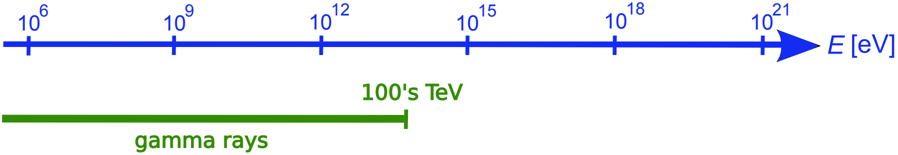
E [eV]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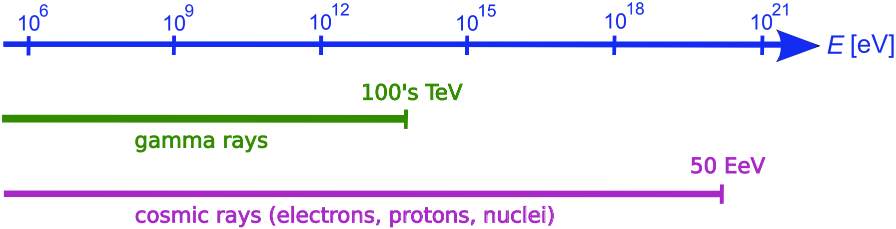
E [eV]
100's TeV
gamma rays

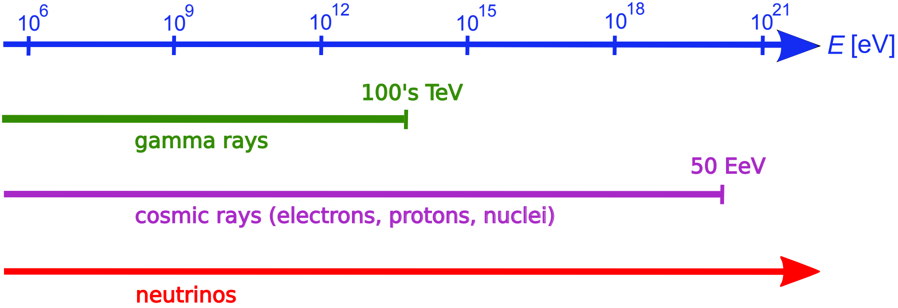


100's TeV

gamma rays

50 EeV

cosmic rays (electrons, protons, nuclei)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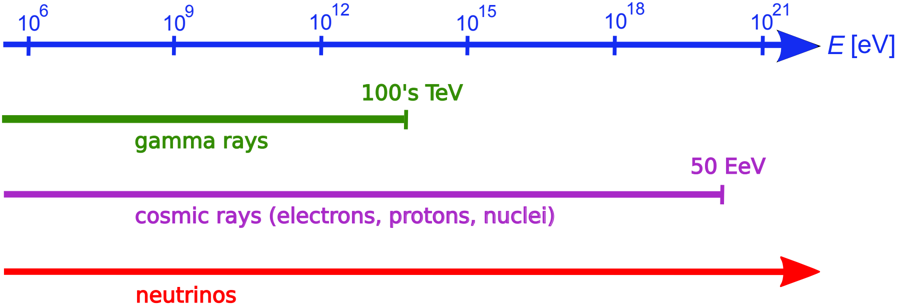
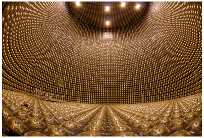
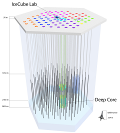
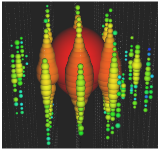
neutrinos



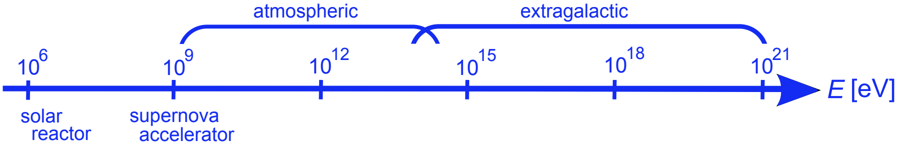
⑤ Unlike gamma rays and cosmic rays, neutrinos have flavor




IceCube Lab
Deep Core



2013+


atmospheric
extragalactic
10^6
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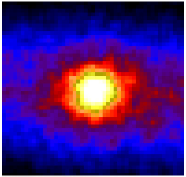
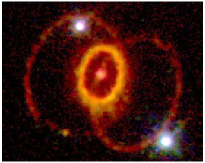
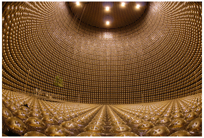
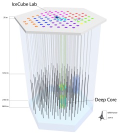
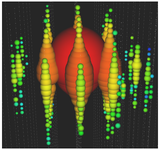
E [eV]
solar
reactor
supernova
accelerator



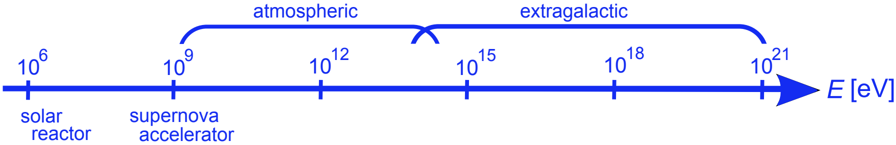








2013+



atmospheric

extragalactic

10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21} E [eV]

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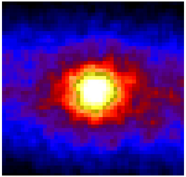
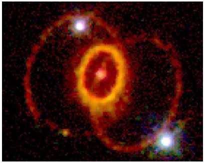
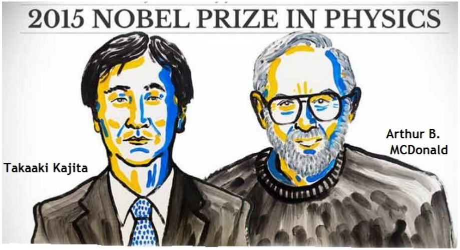




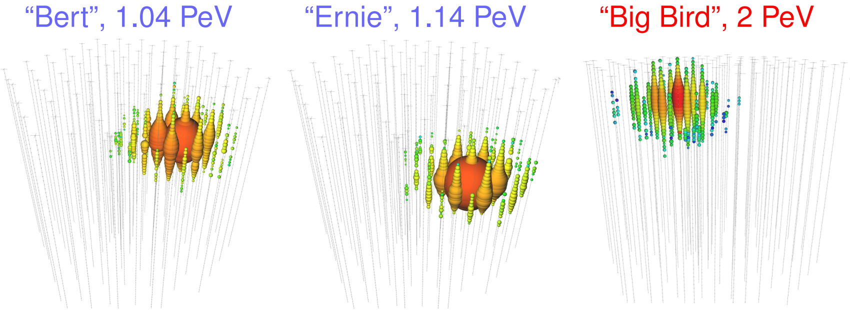


Next ν-Nobel for high-energy ν's?

High-energy astrophysical neutrinos: they exist!

The era of neutrino astronomy has begun!

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



. . . and 51 more events > 30 TeV

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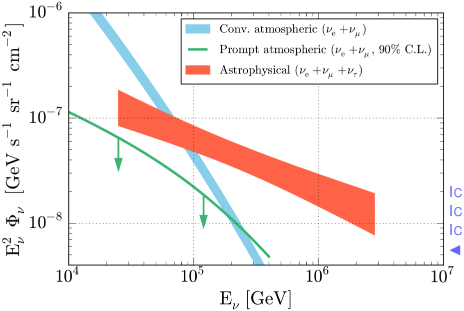

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, *ApJ* **809**, 98 (2015)

Diffuse per-flavor astrophysical flux [IceCube 2015]:

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

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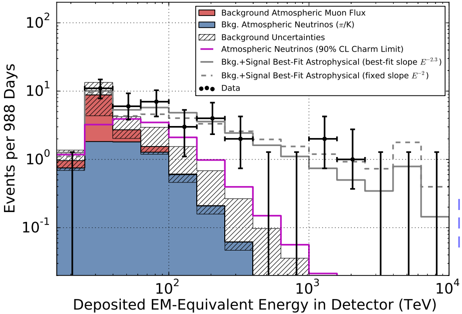

ICECUBE, *PRL* **111**, 021103 (2013)
ICECUBE, *Science* **342**, 1242856 (2013)
ICECUBE, *PRL* **113**, 101101 (2014)

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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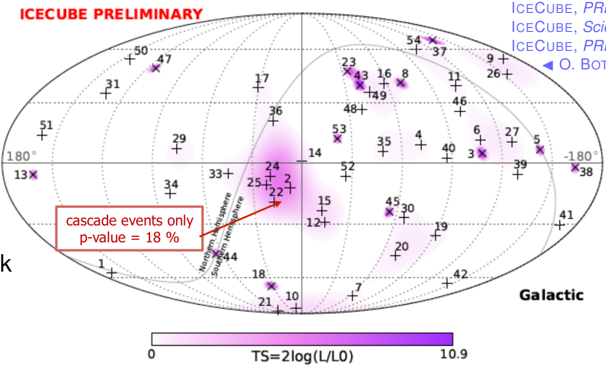
Arrival directions compatible with an isotropic distribution –

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



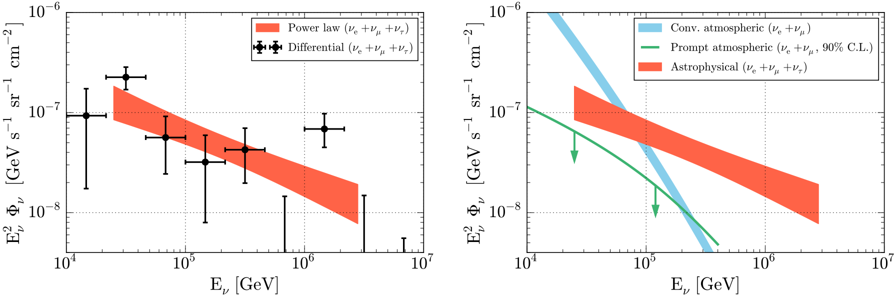
cascade events only
p-value = 18 %

+: shower
×: muon track

– no association with sources found yet

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

1. They are the most energetic ones observed
   - 10s TeV to few PeV (vs. $\lesssim$ 350 GeV man-made)
   - Probe new physics at scales that cannot be produced at Earth

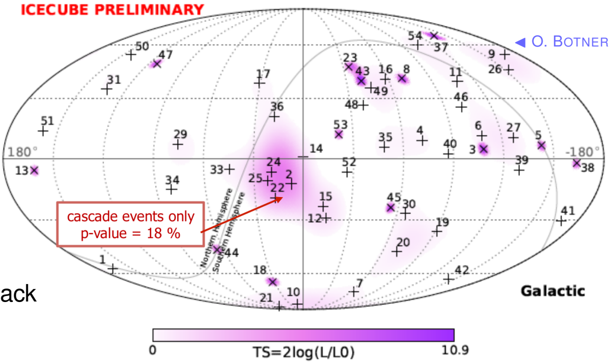


[IceCube Coll., *ApJ* **809**, 98 (2015)]

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

② The have the longest baselines observed

- Isotropic arrivals support extragalactic origin: 10 Mpc to few Gpc (vs. few 1000 km man-made and $\sim$ 50 kpc Galactic SN)
- Tiny new physics effects can accumulate and become observable



◀ O. Botner, IPA 2015

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

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

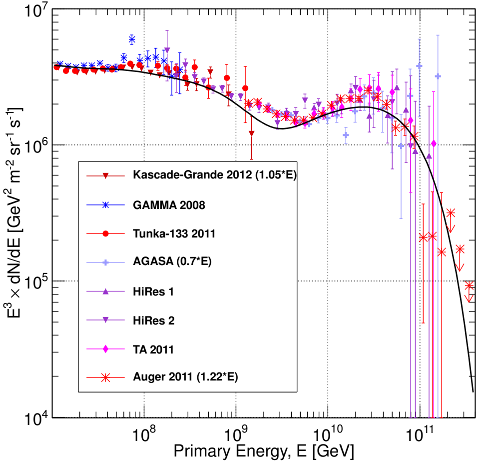
What we don't know

- 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?
- **what is the precise flavor composition of the flux?**
- **is there new physics?**

. . . but we have good ideas on all

Why did we expect high-energy neutrinos?

Because we see loads of ultra-high-energy cosmic rays —

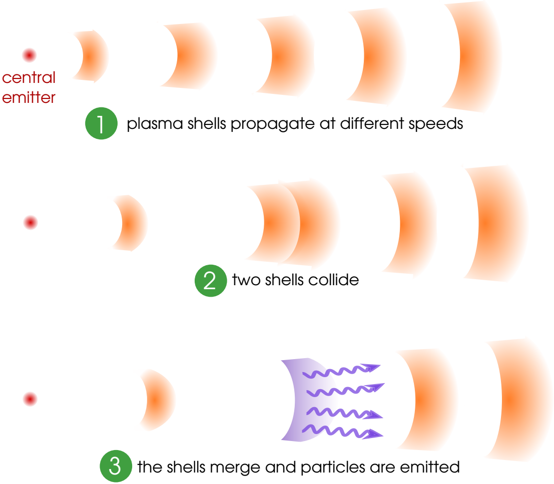


Gaisser, Stanev, Tilav, *Front. Phys. China* **8**, 748 (2013)

Cosmic-ray accelerators should also produce neutrinos ▶

HE particles from astrophysical sources

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



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

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

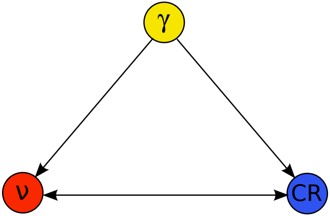
broken power law

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

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

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

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



neutrino energy $\simeq$ proton energy / 20 $\simeq$ photon energy / 2

[*Actually*, it is more complicated . . .

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)]]

Where to look for new physics

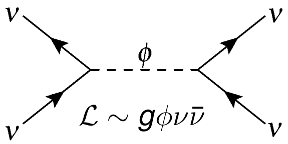
- New physics in the neutrino sector could affect the
  - production; and/or
  - propagation; and/or
  - detection

- Look for modifications in . . .
  - The shape of the neutrino spectrum (*e.g.*, via secret neutrino interactions)
  - The flavor composition of the spectrum (*e.g.*, via neutrino decay, Lorentz invariance violation, . . .)

[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]

New physics: effect on the spectral shape

Secret neutrino interactions between astrophysical neutrinos and the cosmic neutrino background

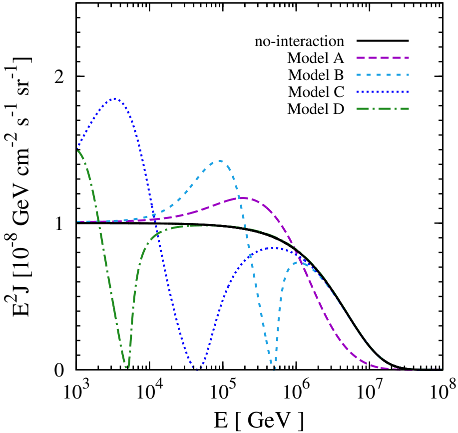


Cross section:

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

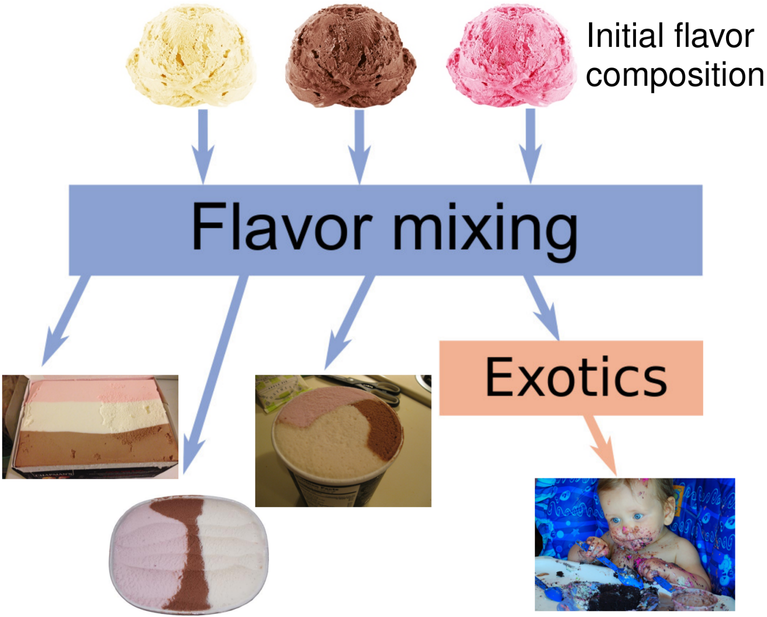
Resonance at

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



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

New physics: effect on the flavor composition



Initial flavor composition

Flavor mixing

Exotics

Flavor mixing in high-energy astrophysical neutrinos

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

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

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

- 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:

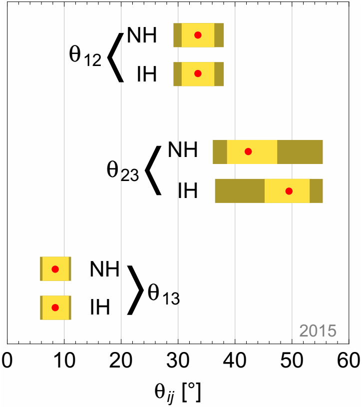
$$\langle P_{\alpha\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$ ◀ incoherent mixture of mass eigenstates

Flavor content of the mass eigenstates (I)

- ν_i ($i = 1, 2, 3$) contains a fraction of flavor $\alpha = e, \mu, \tau$ given by

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

- From global fits [González-García *et al.* 2014]:



Using the best-fit values:

ν_1 : $70\%\ \nu_e, 10-20\%\ \nu_\mu, 10-20\%\ \nu_\tau$

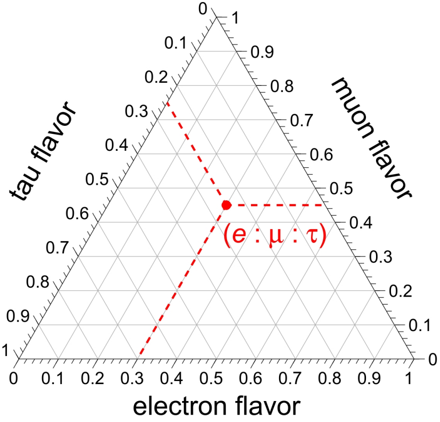
ν_2 : $\sim$ equal proportion of each

ν_3 : $3\%\nu_e, 40-60\%\nu_\mu, 40-60\%\nu_\tau$

“Flavor triangle” or Dalitz/Mandelstam plot

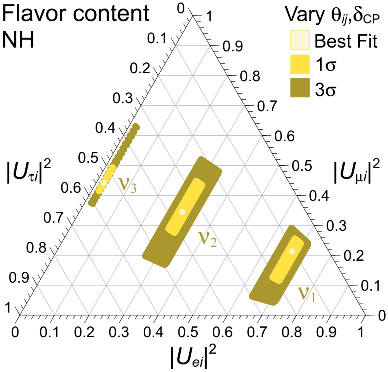
Assumes underlying unitarity: sum of projections on each axis is 1

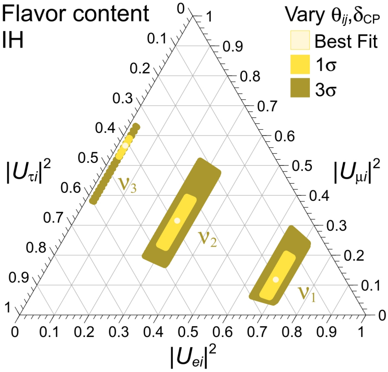
How to read it: follow the tilt of the tick marks, *e.g.*,



Flavor content of the mass eigenstates (II)

Flavor content for every allowed combination of mixing parameters:





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

Flavor ratios — at the sources and Earth

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

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

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

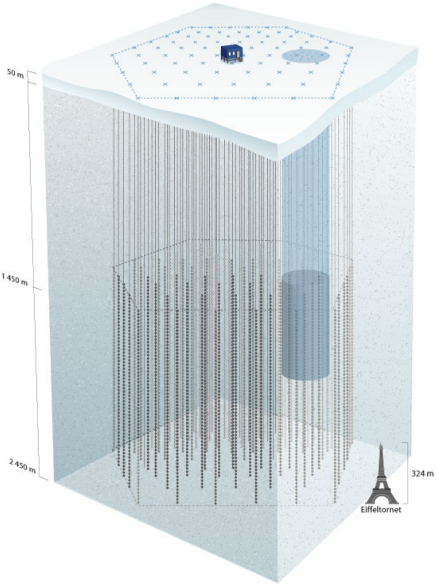
- Other compositions at the source:

$$(0 : 1 : 0)_{\rm S} \longrightarrow (0.26 : 0.36 : 0.38)_\oplus \quad \text{(“muon damped”)}$$

$$(1 : 0 : 0)_{\rm S} \longrightarrow (0.55 : 0.26 : 0.19)_\oplus \quad \text{(“neutron decay”)}$$

$$(1/2 : 1/2 : 0)_{\rm S} \longrightarrow (0.40 : 0.31 : 0.29)_\oplus \quad \text{(“charmed decays”)}$$

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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How does IceCube see flavor?

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

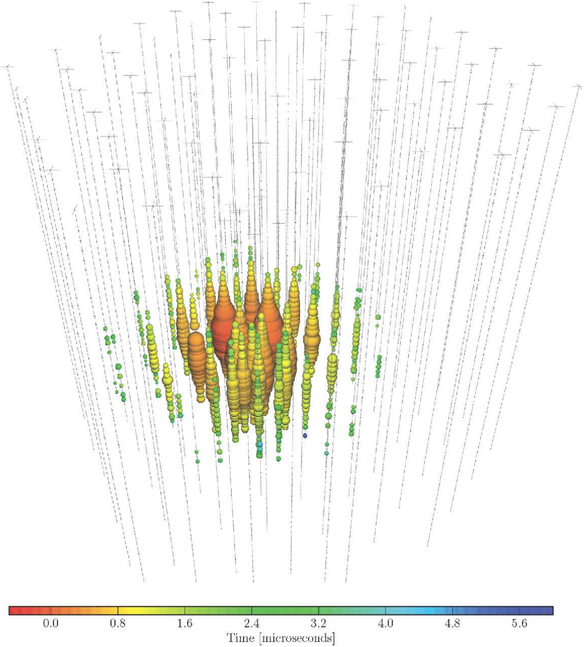
- Showers: generated by CC ν_e or ν_τ; or by NC ν_x
- Muon tracks: generated by CC ν_μ

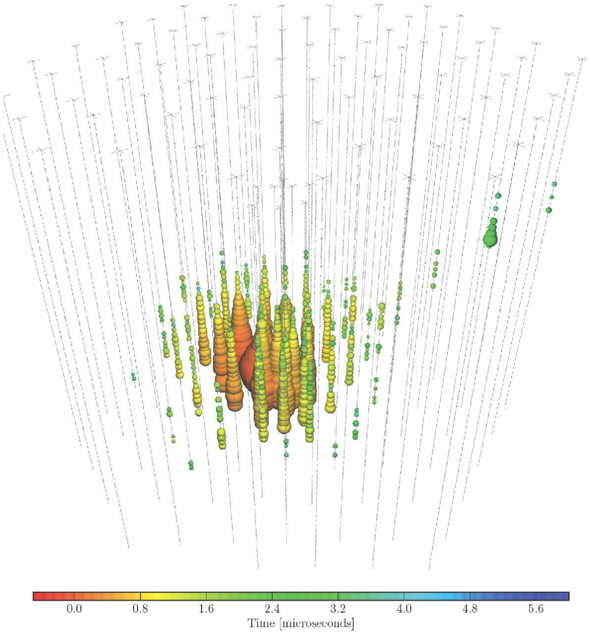
(Some muon tracks can be mis-reconstructed as showers)

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

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

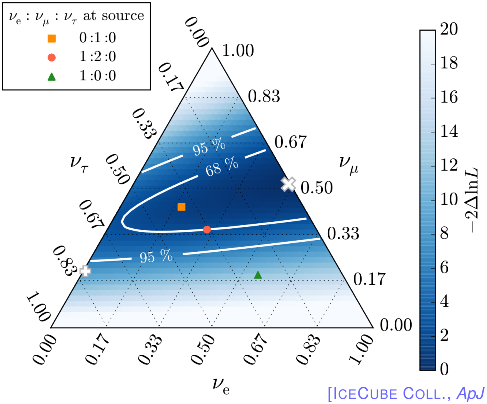
Flavor ratios must be inferred from the number of showers and tracks


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]

IceCube analysis of flavor composition

Using contained events + throughgoing muons:

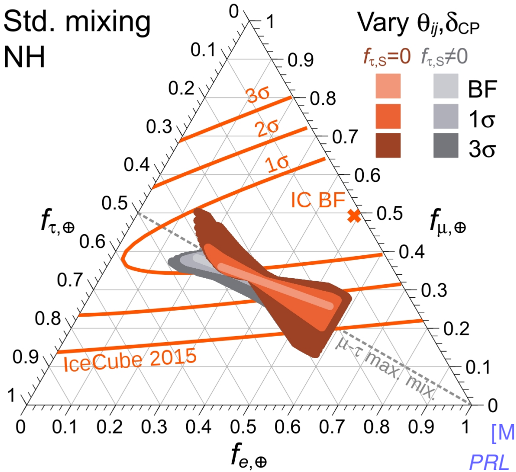


[ICECUBE COLL., *ApJ* **809**, 98 (2015)]

- 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

Flavor combinations at Earth from std. mixing

But first: what flavor region is accessible with standard mixing?

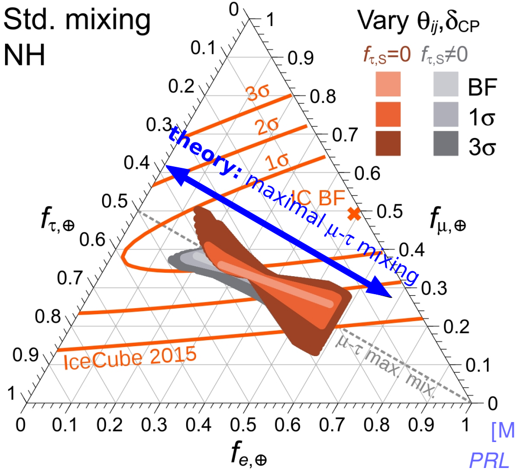


[MB, Beacom, Winter, *PRL* **115**, 161302 (2015)]

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

Flavor combinations at Earth from std. mixing

But first: what flavor region is accessible with standard mixing?



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

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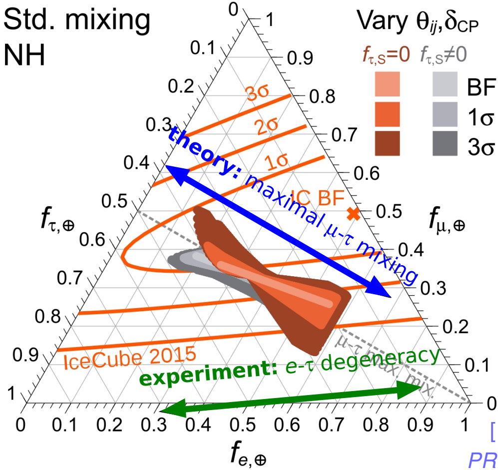
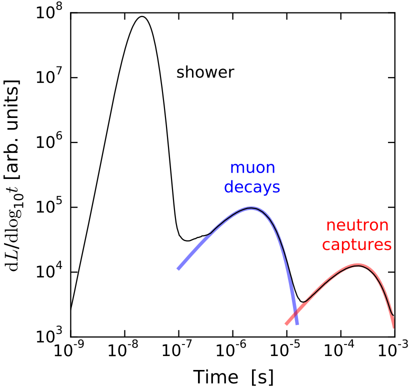


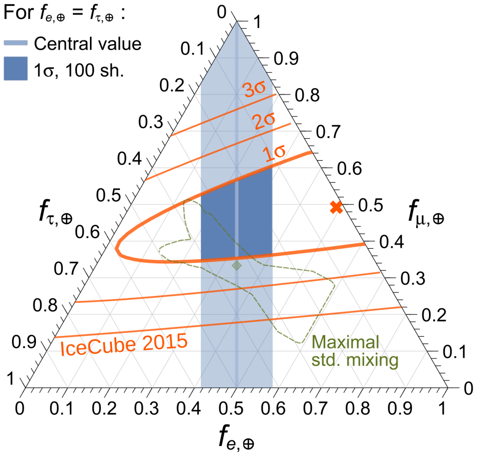
[MB, Beacom, Winter, *PRL* **115**, 161302 (2015)]

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

Side note: improving the flavor measurements

Late-time light ("echoes") from muon decays and neutron captures can separate ν_e-initiated showers from ν_τ-initiated showers —





Li, MB, Beacom, in prep.

Standard Model decay modes

SM decay modes are negligible:

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

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

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

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

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

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

All lifetimes $\gg$ age of Universe
– therefore, it is hopeless to look for effects of 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

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

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

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

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

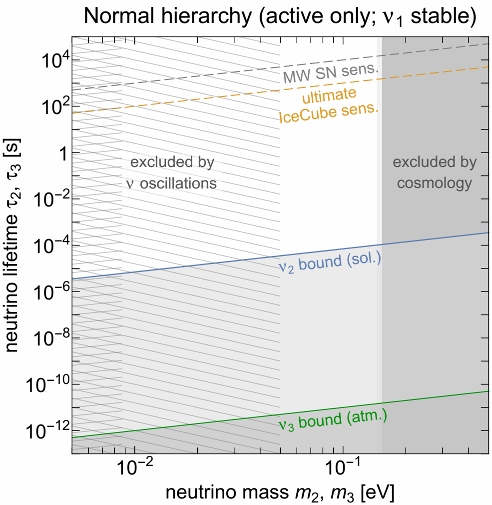
▲ For very long L, this will have redshift corrections

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

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

Current lifetime limits

- 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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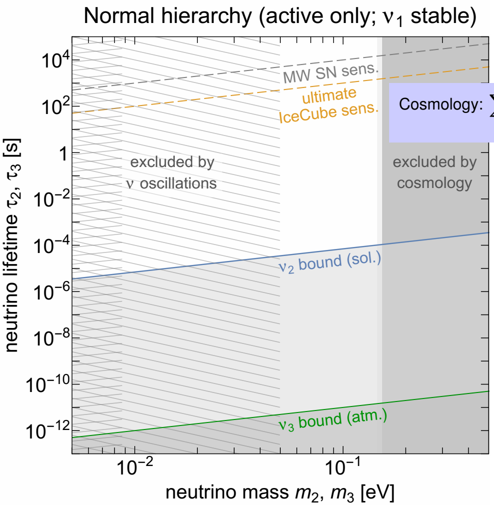

Cosmology: $\sum_i m_i < 0.3$ eV

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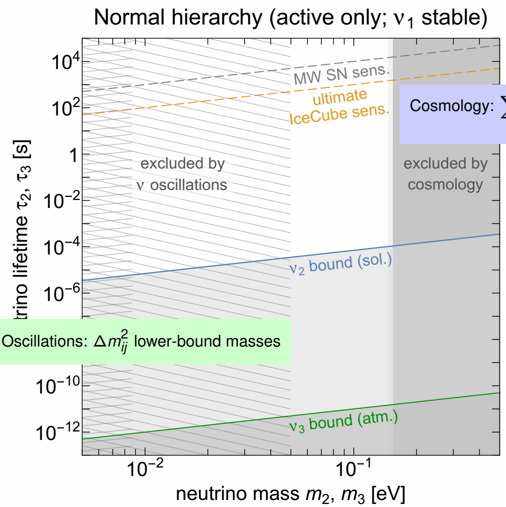

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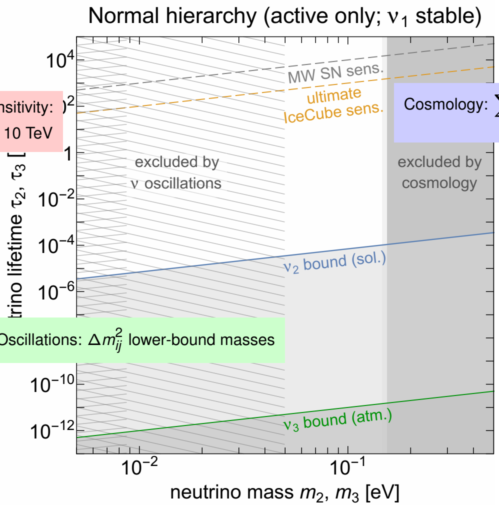


Ultimate IceCube sensitivity: $L = 1$ Gpc, $E_\nu = 10$ TeV

Cosmology: $\sum_i m_i < 0.3$ eV

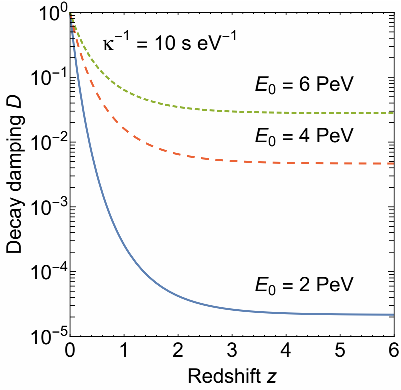
Oscillations: Δm_{ij}^2 lower-bound masses

Decay affects the flavor ratios

fraction of ν_i that reach Earth

$$f_{\alpha,\oplus}\left(E_0, z, \kappa_i^{-1}\right) = \sum_{\beta=e,\mu,\tau}\left(\sum_{i=1}^{3} |U_{\alpha i}|^2 \left|U_{\beta i}\right|^2 D\left(E_0, \overset{\blacktriangledown}{z}, \kappa_i^{-1}\right)\right) f_{\beta,S}$$

(**Note —** NH: $\kappa_1^{-1} \to \infty$; IH: $\kappa_3^{-1} \to \infty$)



Complete decay ($D = 0$): all unstable neutrinos decay en route

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

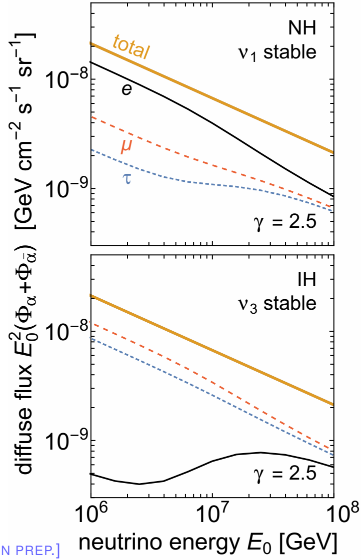
Flavor ratios equal flavor content of the one stable eigenstate

BAERWALD, MB, WINTER, *JCAP* **1210**, 020 (2012)

Seeing decay in the flavor fluxes

- Diffuse $\nu + \bar{\nu}$ flux from population of generic sources, normalized to IceCube flux
- Assuming $\left(f_{e,\mathrm{S}} : f_{\mu,\mathrm{S}} : f_{\tau,\mathrm{S}}\right) = \left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)$
- Fixed lifetime of 10 s eV^{-1}
- Decay NH: $\nu_2, \nu_3 \to \nu_1$
  - ν_μ, ν_τ depleted
  - ν_e doubled (2 × e flavor in ν_1 than in ν_2)
- Decay IH: $\nu_1, \nu_2 \to \nu_3$
  - ν_μ, ν_τ enhanced slightly
  - ν_e greatly depleted (little e flavor in ν_3)

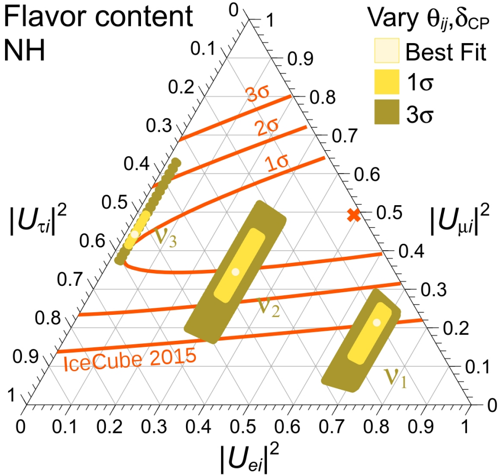
low-E: complete decay ▼ high-E: no decay ▼



[MB, Beacom, Murase, in prep.]

Is complete decay allowed by IceCube?

Overlay the IceCube flavor-ratio contours on the flavor-content regions:



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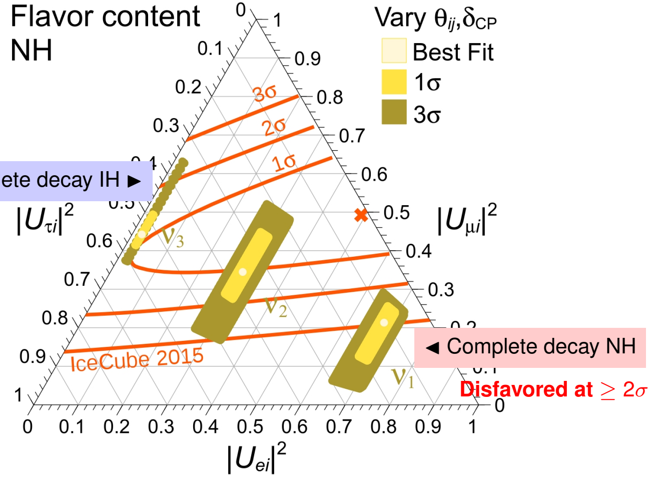

Complete decay IH ▶

◀ Complete decay NH

Disfavored at $\geq 2\sigma$

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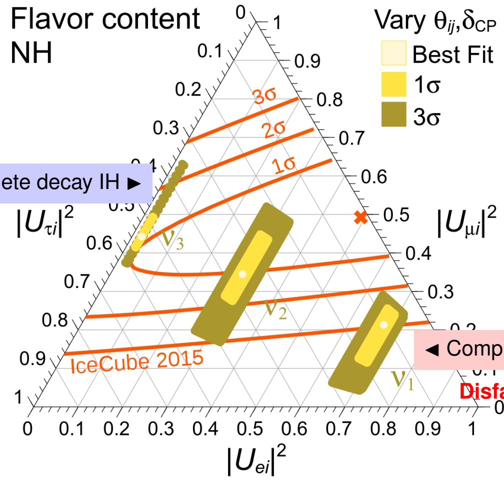


Complete decay IH ►

◄ Complete decay NH

Disfavored at $\geq 2\sigma$

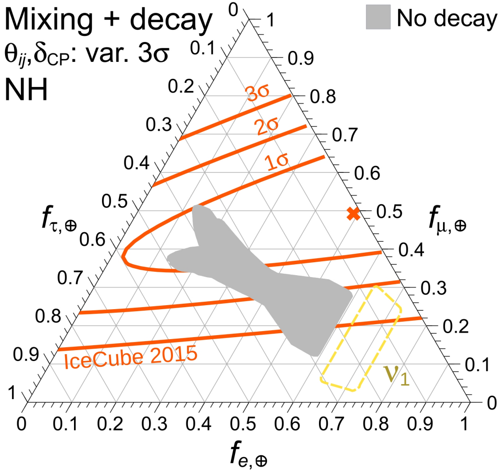
Let us calculate the lifetime bounds in the NH case ►

NH: lifetime limits with current IceCube data (I)

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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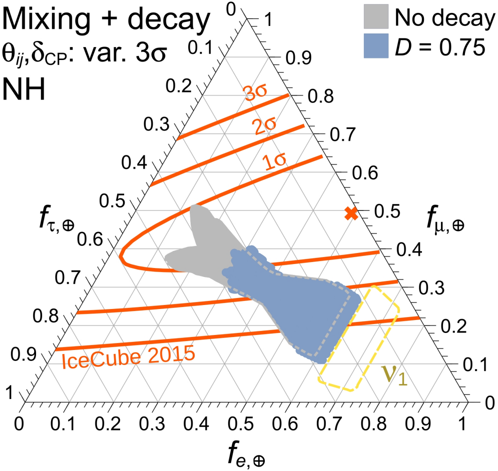

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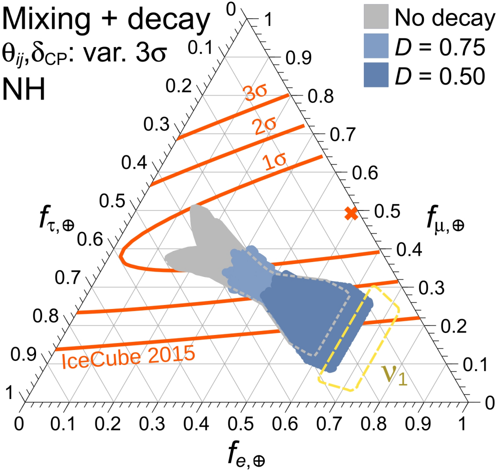

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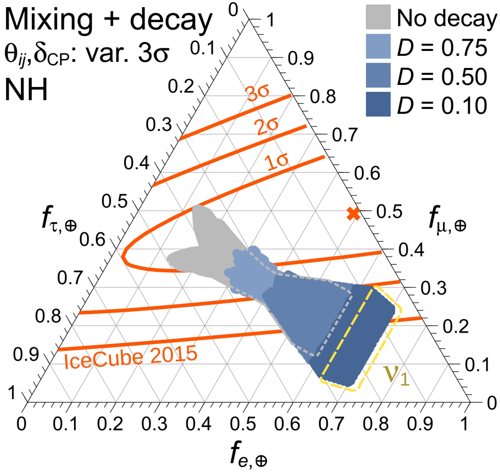

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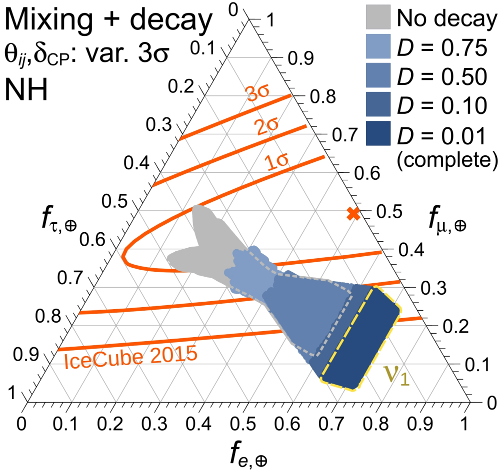

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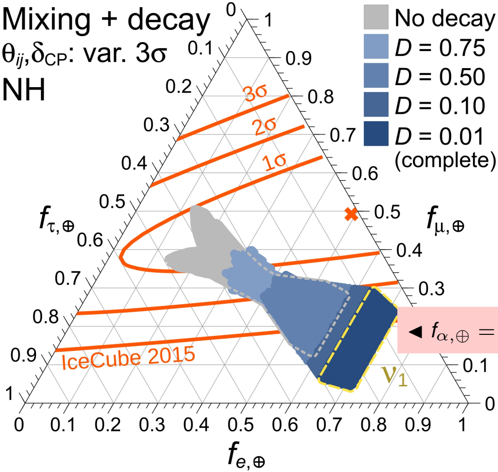
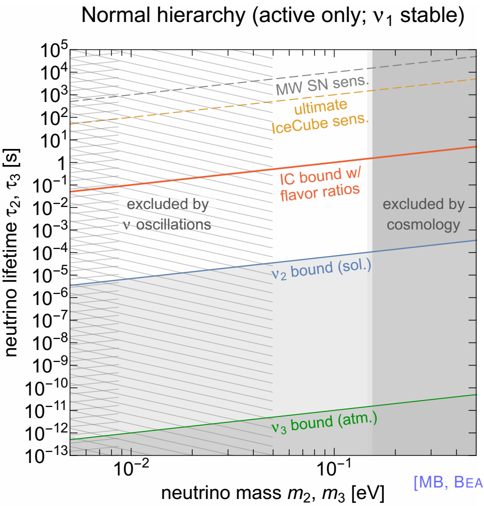


◄ $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D \lesssim 0.01$

NH: lifetime limits with current IceCube data (II)

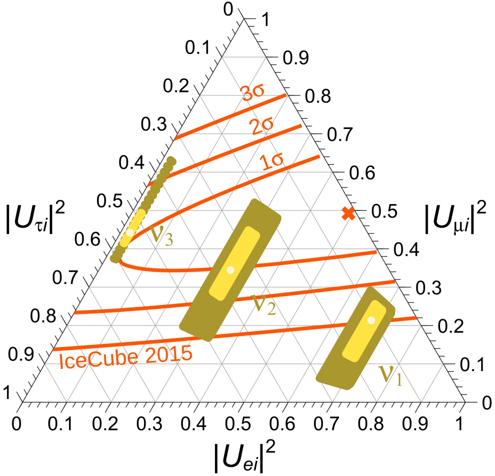
$D \lesssim 0.01$ implies a bound of $\kappa_{2,3}^{-1} \gtrsim 10$ s eV^{-1} at $\gtrsim 2\sigma$



[MB, Beacom, Murase, in prep.]

What will higher-energy events do for us?

Above 5 PeV, IceCube might see flavor-specific signatures:



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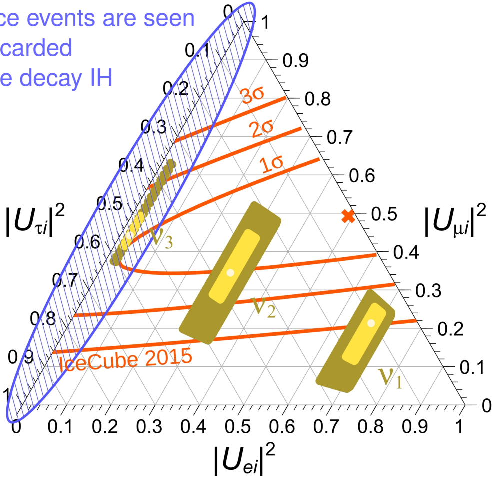
If Glashow resonance events are seen

⇒ small $f_{e,\oplus}$ are discarded

⇒ discards complete decay IH

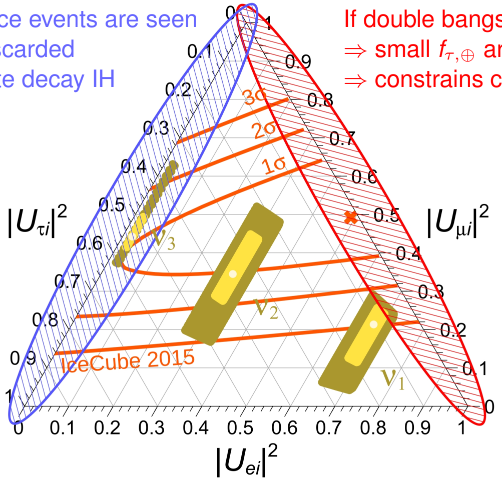


What will higher-energy events do for us?

Above 5 PeV, IceCube might see flavor-specific signatures:

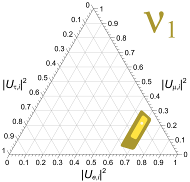
If Glashow resonance events are seen
⇒ small $f_{e,\oplus}$ are discarded
⇒ discards complete decay IH

If double bangs are seen
⇒ small $f_{\tau,\oplus}$ are discarded
⇒ constrains complete decay NH

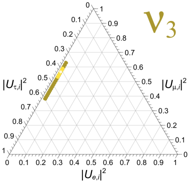


Decay: complete vs. incomplete

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

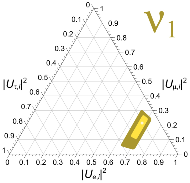


or



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

$\alpha\Big($



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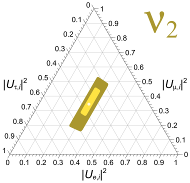

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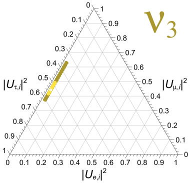

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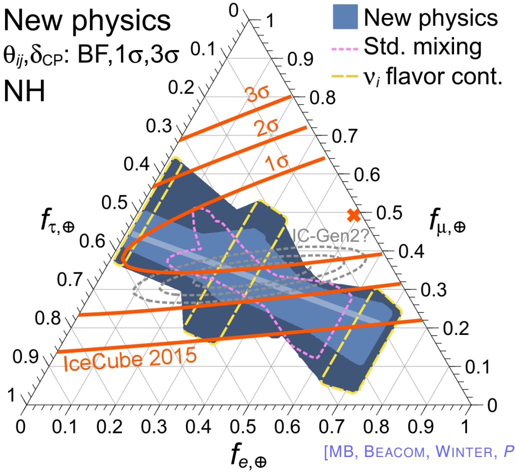
Region of flavor ratios accessible with decay

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



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

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

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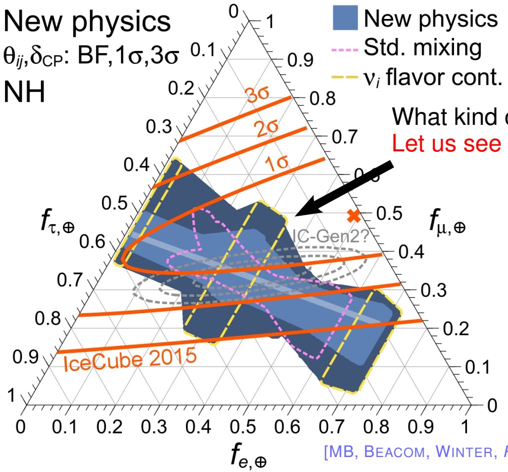

What kind of NP lives outside?

Let us see a few examples

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

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

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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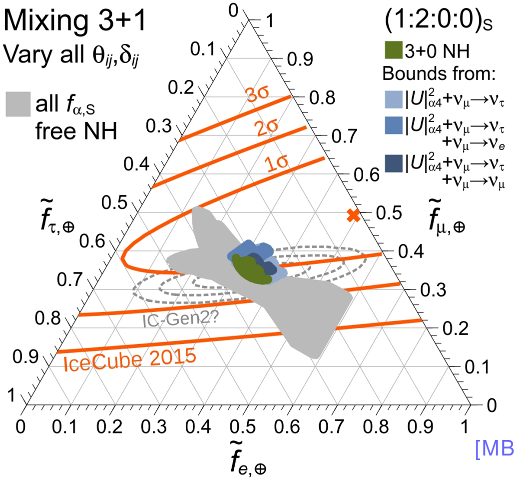
New physics — active-sterile mixing

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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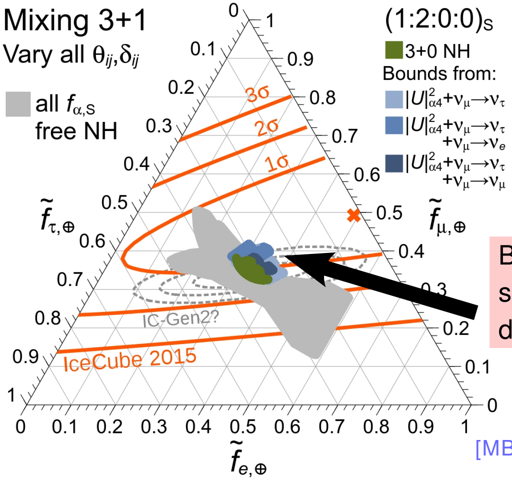


Bounds from T2K, SK, Daya Bay

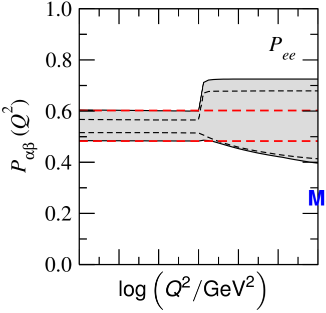
Bounds are too strong for large deviations

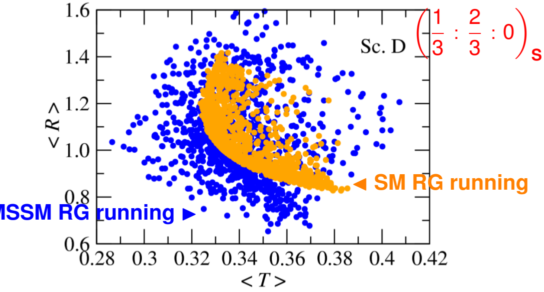
[MB, Coloma]

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 the scales changes the mixing probability:

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





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

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 $\qquad$ $O_1/\Lambda_1 \lesssim 10^{-27}$ 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)]

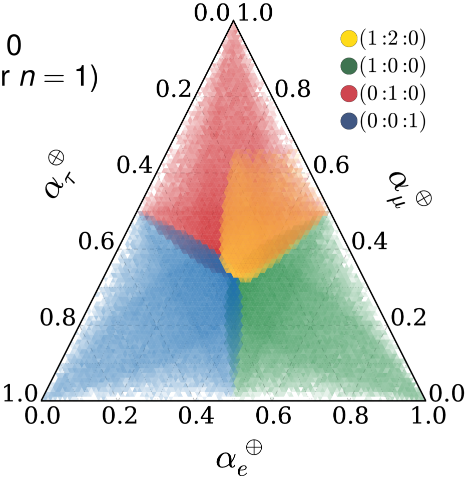
New physics — high-energy effects (II)

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 $n = 1$)

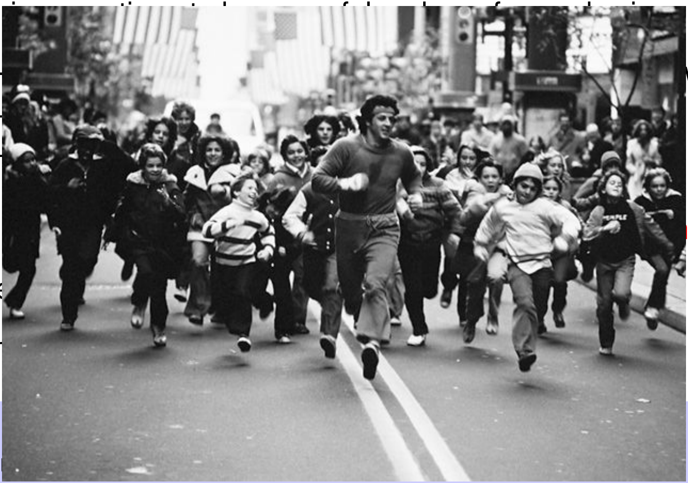


Conclusions

- Neutrinos continue to be powerful probes of new physics
- High-energy astrophysical neutrinos probe a new regime with . . .
    - The highest energies observed
    - The longest baselines observed
- New physics via changes in spectral shape and flavor composition
- Current data already improves lifetime bounds
- Promise of higher sensitivity as more data is gathered

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

Conclusions



- Neut
- High- … with . . .
- New … position
- Curre
- Prom

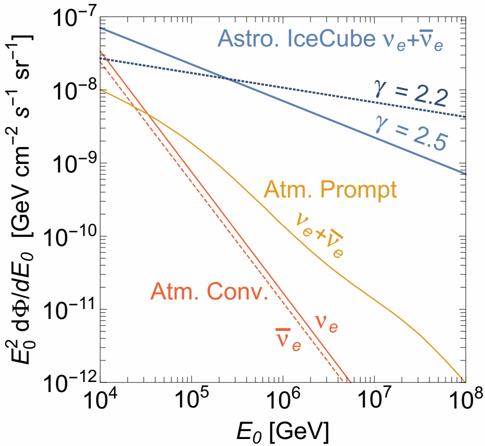
b

Backup slides

Astrophysical fluxes

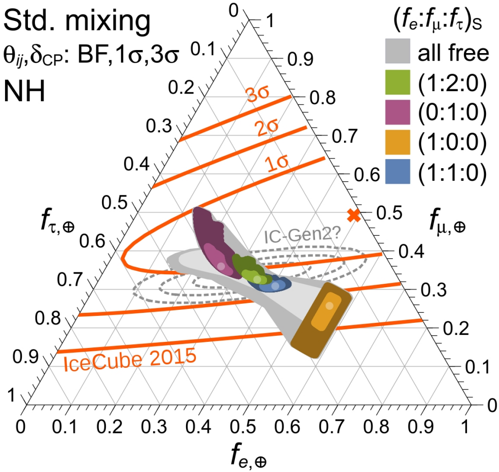
IceCube events are fit by a power law $\sim E^{-\gamma}$:

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



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

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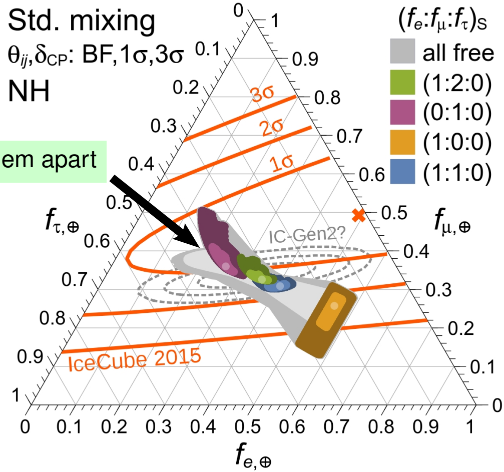
challenging to tell them apart



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

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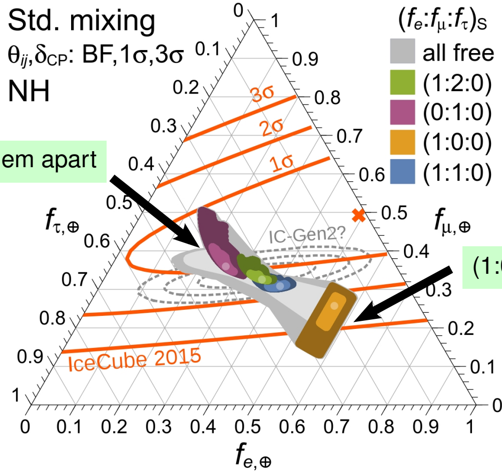


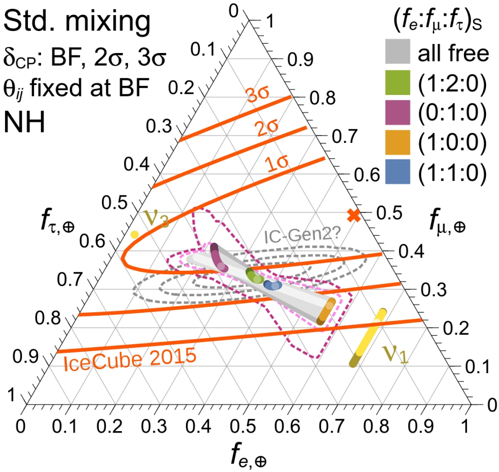
challenging to tell them apart

(1:0:0) disfavored at 2σ

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

Perfect knowledge of mixing angles

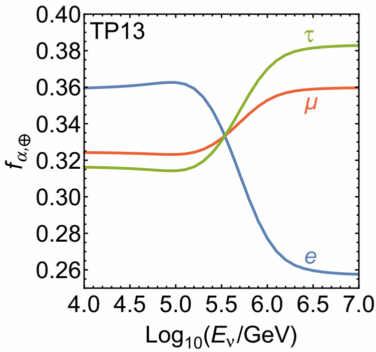
In a few years, we might know all the mixing parameters except δ_{CP}:

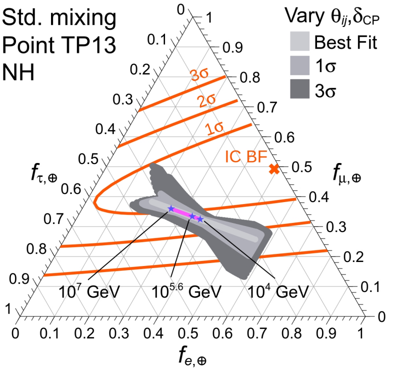


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies

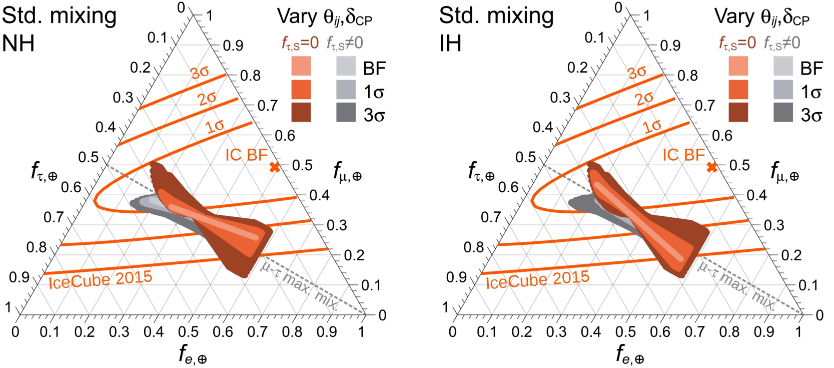




[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

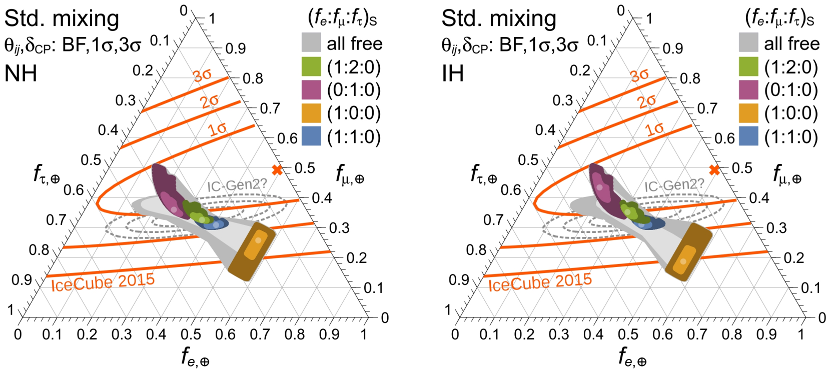
- TP13: $p\gamma$ model, target photons from co-accelerated electrons
  [HÜMMER *et al.*, *Astropart. Phys.* **34**, 205 (2010)]
- Equivalent to different sources types contributing to the diffuse flux
- Will be difficult to resolve
  [KASHTI, WAXMAN, *PRL* **95**, 181101 (2005)] [LIPARI, LUSIGNOLI,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

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



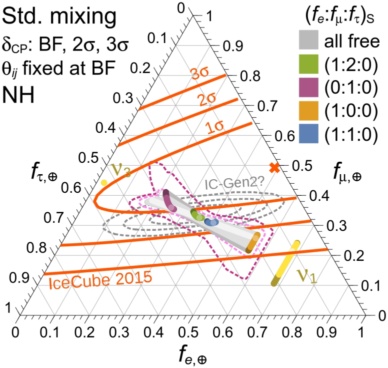
[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

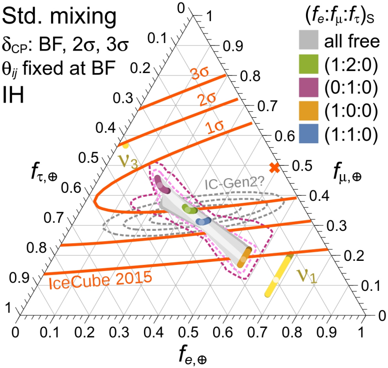
Selected source compositions: NH vs. IH



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

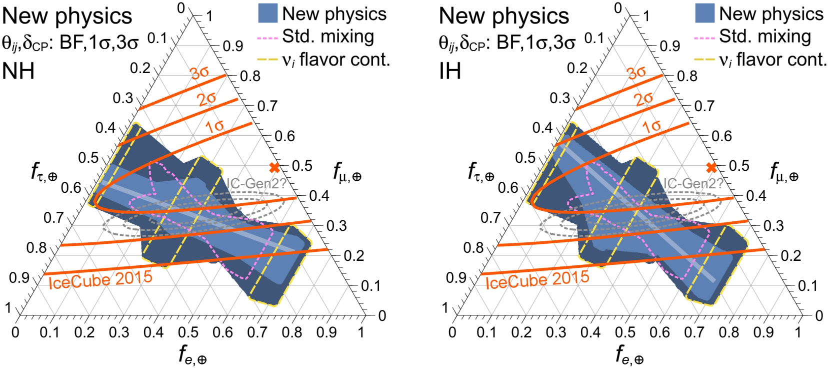
Perfect knowledge of mixing angles: NH vs. IH





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

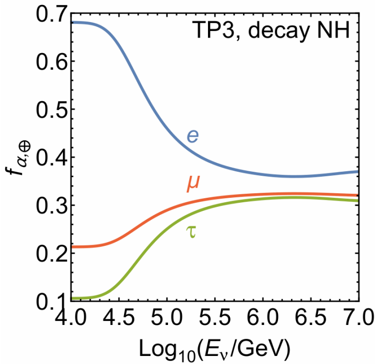
New physics: NH vs. IH

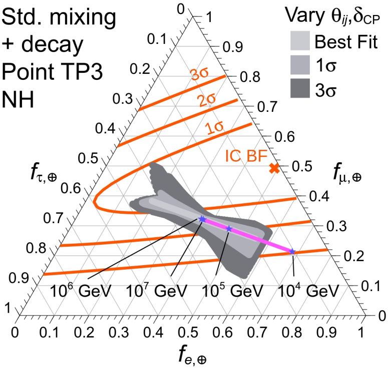


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Decay: seeing the energy dependence?

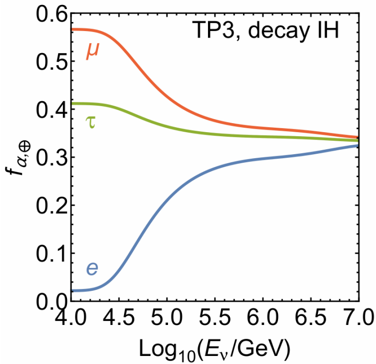
- The effect of decay shows up at low energies
- *e.g.*, for a model of AGN cores [Hümmer *et al.*, *Astropart. Phys.* **34**, 205 (2010)],
- Would require high statistics + exquisite energy resolution

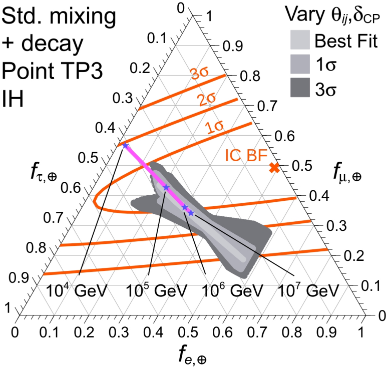




[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

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):

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

Integrated flux above 1 PeV:

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

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

$$N_\nu \simeq 2\pi \cdot \Phi_\nu\left(>1\ \mathrm{PeV}\right) \cdot 1\ \mathrm{yr} \cdot A_{\mathrm{eff}} \approx \left(2.4\times10^{-10}\ \mathrm{cm^{-2}}\right) A_{\mathrm{eff}}\ ,$$

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

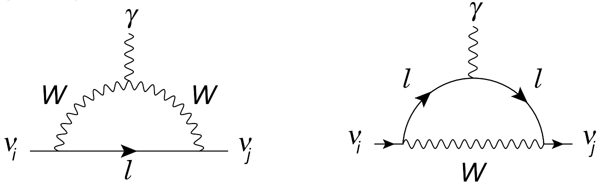
To detect $N_\nu > 1$ events per year, we need an area of

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

Therefore, we need km-scale detectors, like IceCube

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

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

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

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

Neutrino decay: caveats and improvements

- Current IceCube flavor-ratio contours use all recorded data from astrophysical searches:
  - 1 TeV and above
  - all arrival directions
- A more robust lifetime bound should use a curated data set:
  1. Only events with arrival directions off the Galactic Plane
  2. Only events > 100 TeV, to avoid atmospheric contamination
- This would result in a truly extragalactic sample of neutrinos — where decay can act on cosmological scales

Cosmological effects on decay

There are two cosmological effects:

① 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:

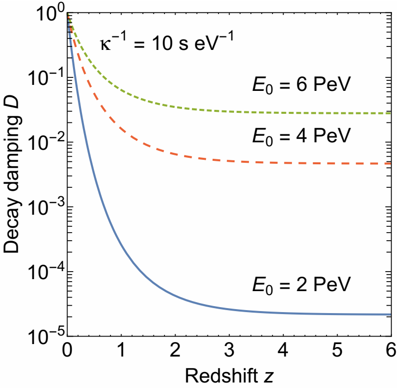
$$\boxed{D\left(E_0, z, \kappa_i^{-1}\right) = \left(a + be^{-cz}\right)^{-\frac{\kappa_i L_H}{E_0}}}$$

$a \approx 1.71$, $b = 1 - a$, $c \approx 1.27$

for ΛCDM with $(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$

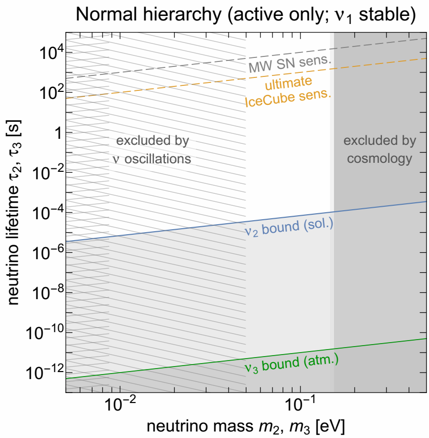
$$\langle P_{\alpha\beta}\rangle \to \underbrace{D\left(E_0, z, \kappa_i^{-1}\right)}_{0<D<1}\langle P_{\alpha\beta}\rangle$$

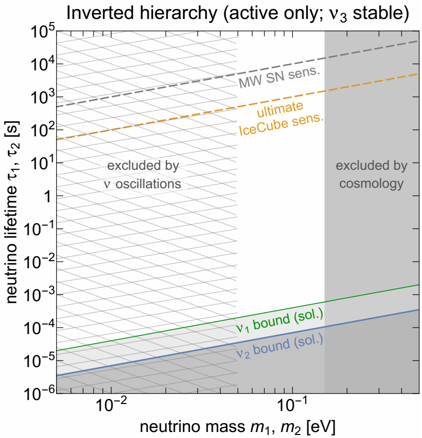
[Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012)]



Current lifetime limits

- 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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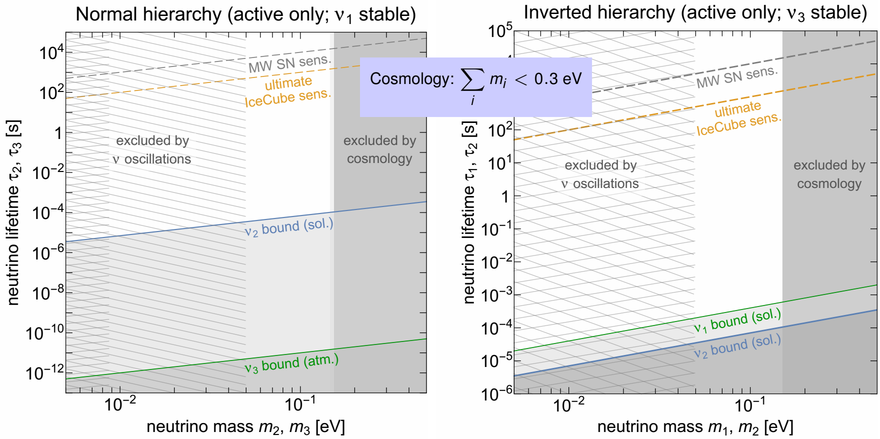

Cosmology: $\sum_i m_i < 0.3$ eV

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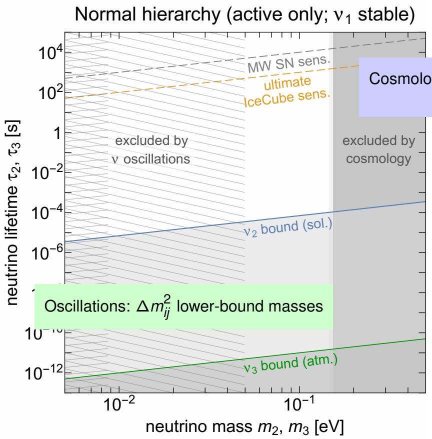

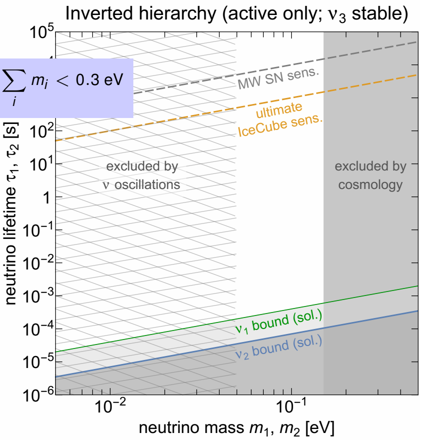

Cosmology: $\sum_i m_i < 0.3$ eV

Oscillations: Δm_{ij}^2 lower-bound masses

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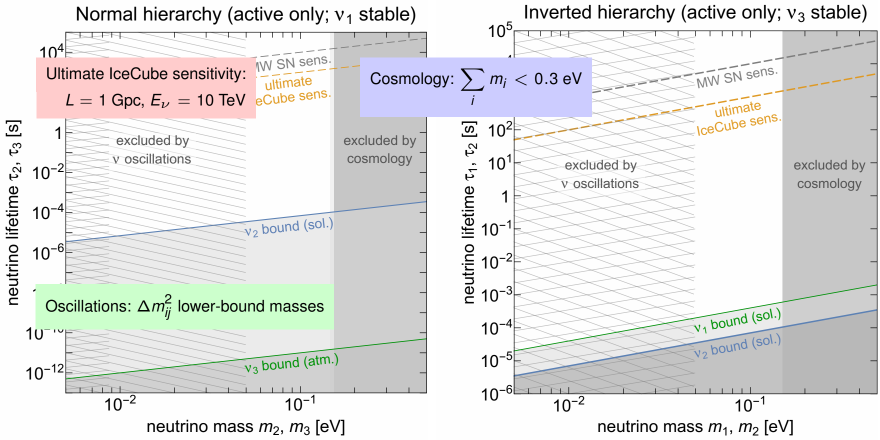

Ultimate IceCube sensitivity:
$L = 1$ Gpc, $E_\nu = 10$ TeV

Cosmology: $\sum_i m_i < 0.3$ eV

Oscillations: Δm_{ij}^2 lower-bound masses