Prospecting for new physics with high-energy astrophysical neutrinos

Mauricio Bustamante

Center for Cosmology and AstroParticle Physics (CCAPP)
The Ohio State University

Particle Astrophysics Seminar

Case Western Reserve University

March 21, 2017

THE OHIO STATE UNIVERSITY
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

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

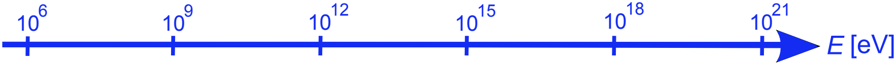
The history of neutrinos is a history of fighting against the odds

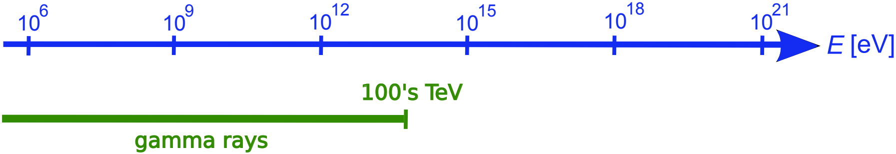
. . . and winning

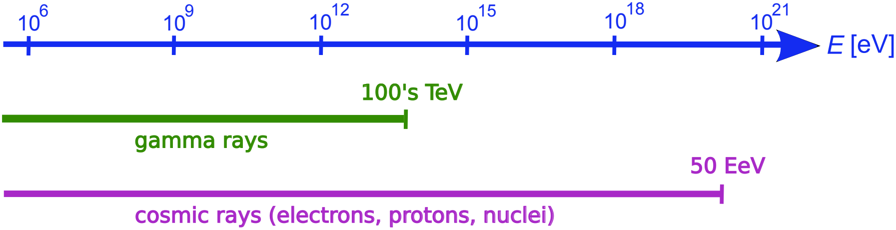
Some reasons why neutrinos are special:

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 us with higher energies than anything else

Let’s talk energy scales...


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


10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]
100's TeV
gamma rays

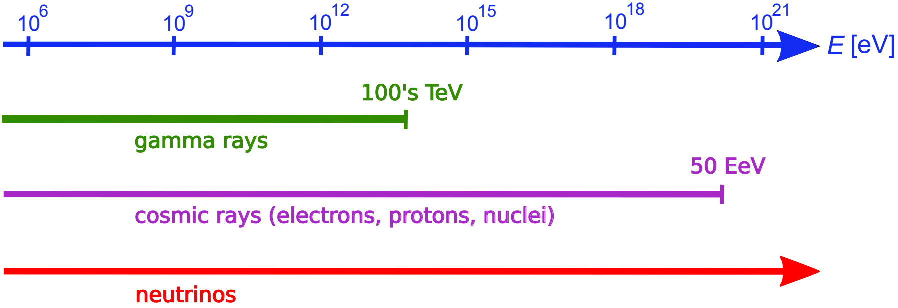


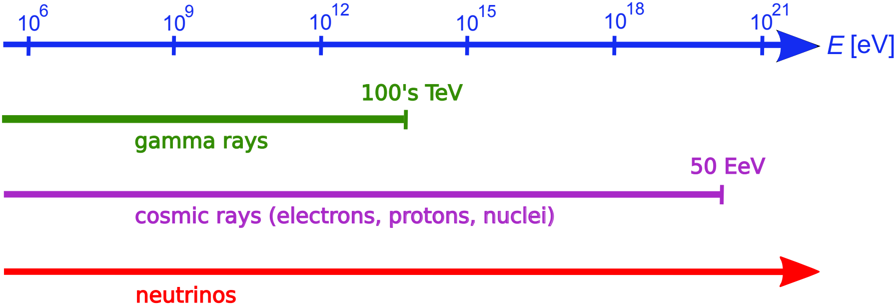
100's TeV

gamma rays

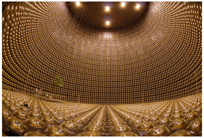
50 EeV

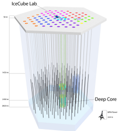
cosmic rays (electrons, protons, nuclei)

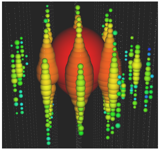

10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]
100's TeV
gamma rays
50 EeV
cosmic rays (electrons, protons, nuclei)
neutrinos



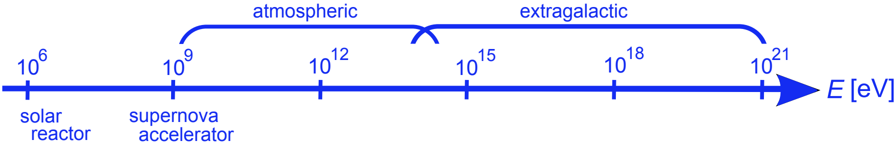
⑤ Unlike gamma rays and cosmic rays, neutrinos have flavor







2013+



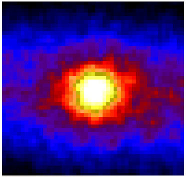
atmospheric

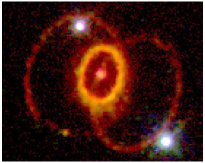
extragalactic

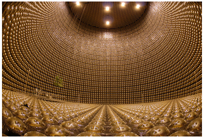
10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21} E [eV]

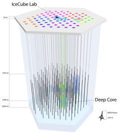
solar
reactor

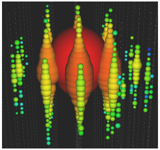
supernova
accelerator



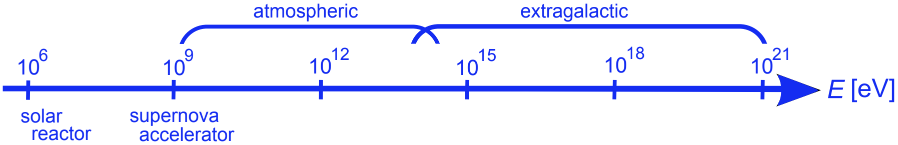








2013+



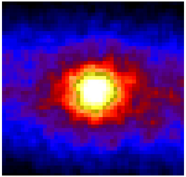
atmospheric

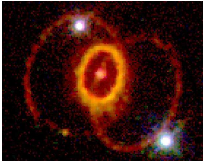
extragalactic

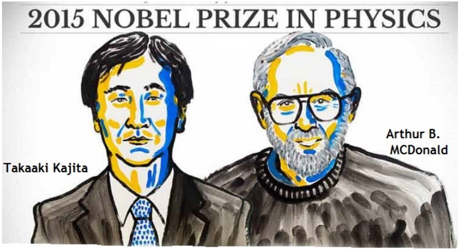
10^6 10^9 10^{12} 10^{15} 10^{18} 10^{21} E [eV]

solar
reactor

supernova
accelerator



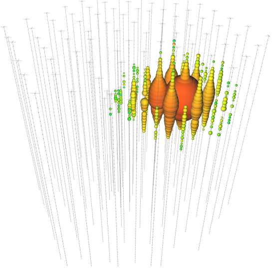


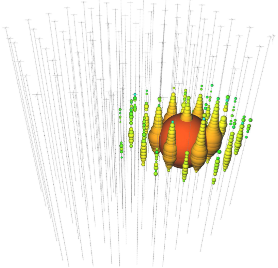


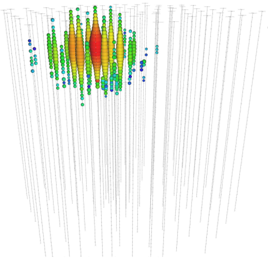
Next ν-Nobel for high-energy ν's?

High-energy astrophysical neutrinos: they exist!

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


“Bert”, 1.04 PeV

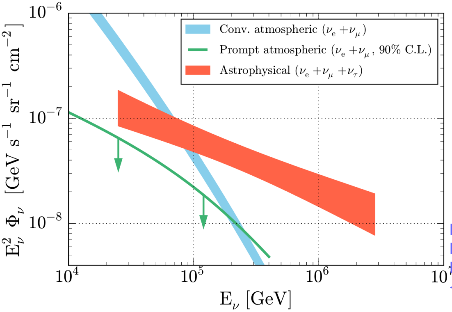

“Ernie”, 1.14 PeV


“Big Bird”, 2 PeV

…and 51 more events > 30 TeV

High-energy astrophysical neutrinos: they exist!

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



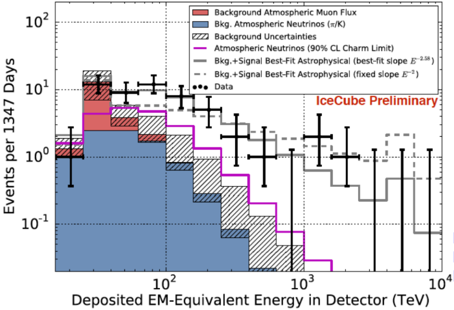
IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, *ApJ* **809**, 98 (2015)

Diffuse per-flavor astrophysical flux [IceCube 2015]:

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

High-energy astrophysical neutrinos: they exist!

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



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

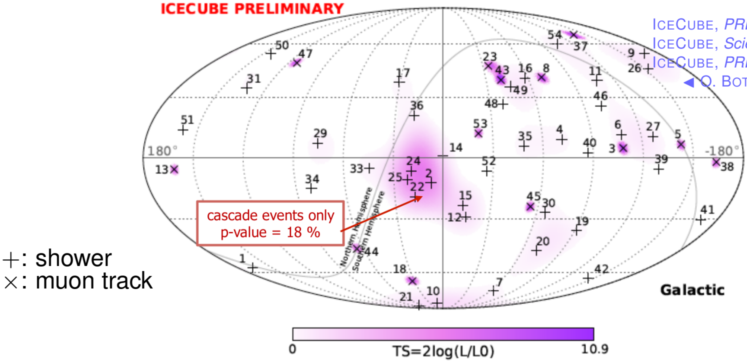
Diffuse flux compatible with extragalactic origin [Waxman & Bahcall 1997]:

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

High-energy astrophysical neutrinos: they exist!

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

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

– no association with sources found yet

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

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

If the effect grows as $\sim \kappa E^n L$ (with κ its strength), then we can probe

$$\kappa \sim 4 \cdot 10^{-47} \left(\frac{E}{\text{PeV}}\right)^{-n} \left(\frac{L}{\text{Gpc}}\right)^{-1} \text{PeV}^{n+1}$$

(Current limits: $\lesssim 10^{-30}$ PeV)

[Barenboim, Quigg, *PRD* **67**, 073024 (2003)]
[Beacom, Bell, Hooper, Pakvasa, Weiler, *PRL* **90**, 181301 (2003)]
[Maltoni, Winter, *JHEP* **07**, 064 (2008)]
[Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012)]
[Pagliaroli, Palladino, Vissani, Villante 1506.02624]

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?

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

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

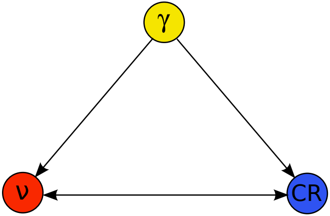
broken power law

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

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

$$\pi^0 \rightarrow \gamma\gamma$$

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



[*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

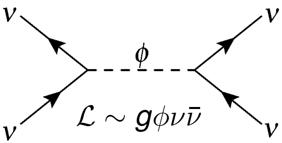
- New physics in the neutrino sector could affect the
    - production; and/or
    - propagation; and/or
    - detection

- Look for modifications in . . .
    - The shape of the neutrino spectrum (*e.g.*, via secret neutrino interactions)
    - The angular distribution of events (*e.g.*, via neutrino-DM 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:

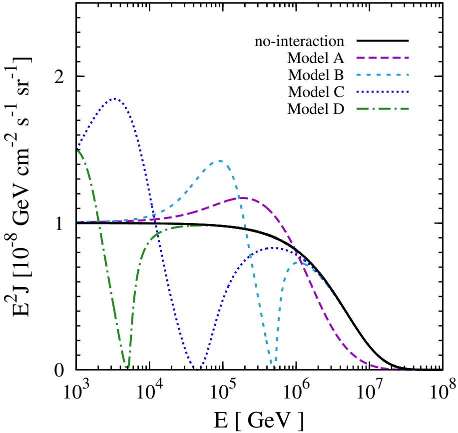


Cross section:

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

Resonance at

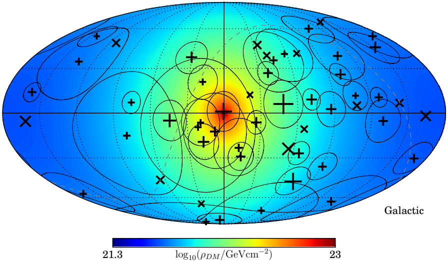
$$E_{\text{res}} = \frac{M^2}{2m_\nu}$$

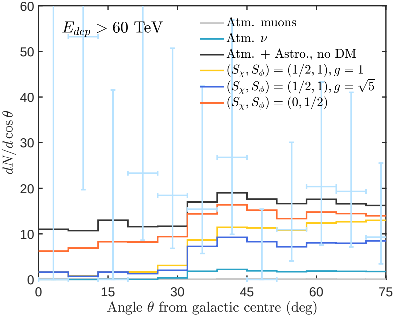


[Ng & Beacom, *PRD* **6**, 065035 (2014)]
[Cherry, Friedland, Shoemaker, 1411.1071]
[Blum, Hook, Murase, 1408.3799]

New physics: effect on the angular distribution

Interaction between astrophysical neutrinos and the Galactic DM profile:



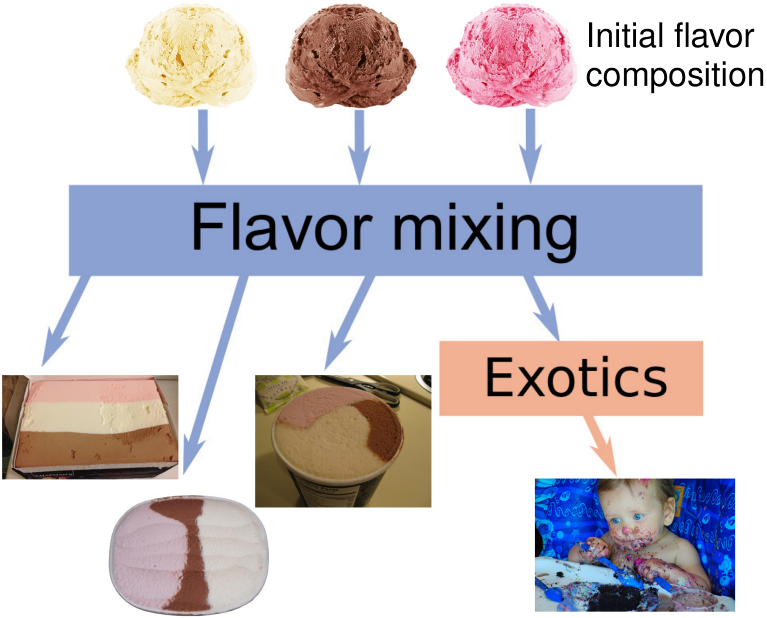


[ARGÜELLES *et al.* 1703.00451]

Expected: fewer events towards the Galactic Center

Observed: Isotropy

New physics: effect on the flavor composition



Initial flavor composition

Flavor mixing

Exotics

Flavor — what is it good for?

1. To reveal the neutrino production mechanism
   Current status: yes, but needs statistics to become interesting

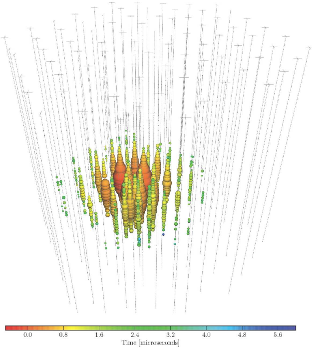
2. To test for new physics *robustly*
   Current status: yes, already today

Flavor is difficult to detect — but the payoff is high!

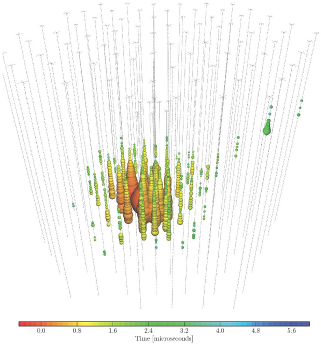
How does IceCube see flavor?

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

Showers:
made by CC ν_e or ν_τ; or by NC ν_x



Tracks:
made (mainly) by CC ν_μ

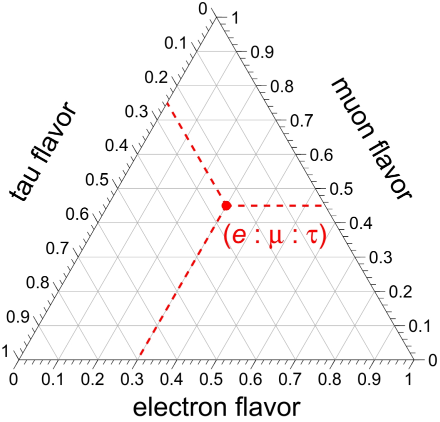


Flavor ratios must be inferred from the number of showers and tracks

“Flavor triangle” or Dalitz/Mandelstam plot

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

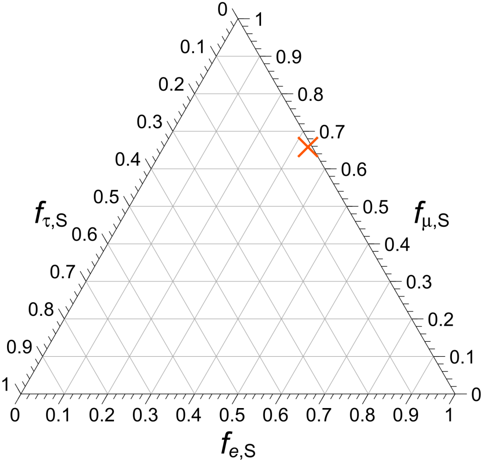
How to read it: follow the tilt of the tick marks, *e.g.*,



Flavor ratios — at the sources

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

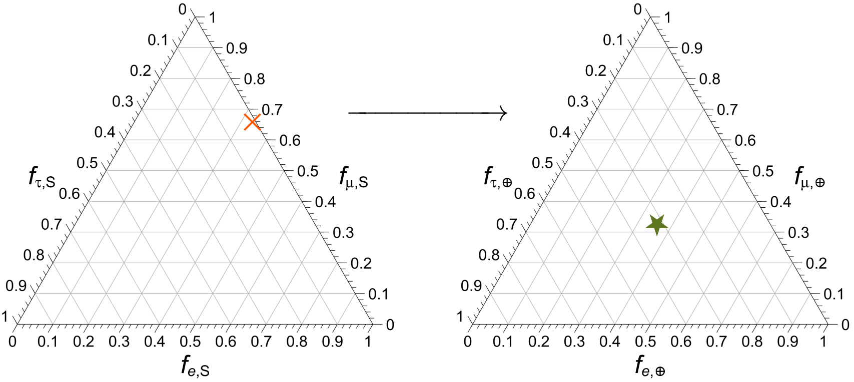
Flavor ratios at the source: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$



Flavor ratios — at Earth

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

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

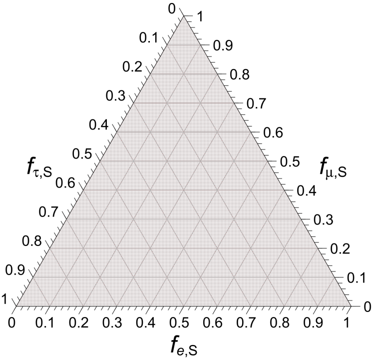


Embracing our ignorance

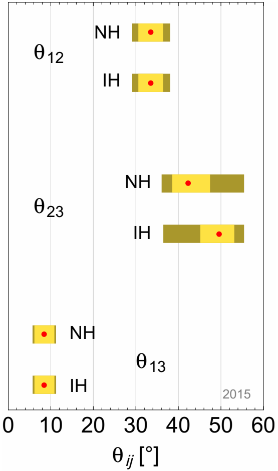
We ignore or do not know perfectly the two key ingredients —

Flavor ratios at the source

$$\begin{aligned} 0 \leq \quad & f_{e,\mathrm{S}} && \leq 1 \\ 0 \leq \quad & f_{\mu,\mathrm{S}} && \leq 1 - f_{e,\mathrm{S}} \\ 0 \leq \quad & f_{\tau,\mathrm{S}} && \leq 1 - f_{e,\mathrm{S}} - f_{\mu,\mathrm{S}} \end{aligned}$$

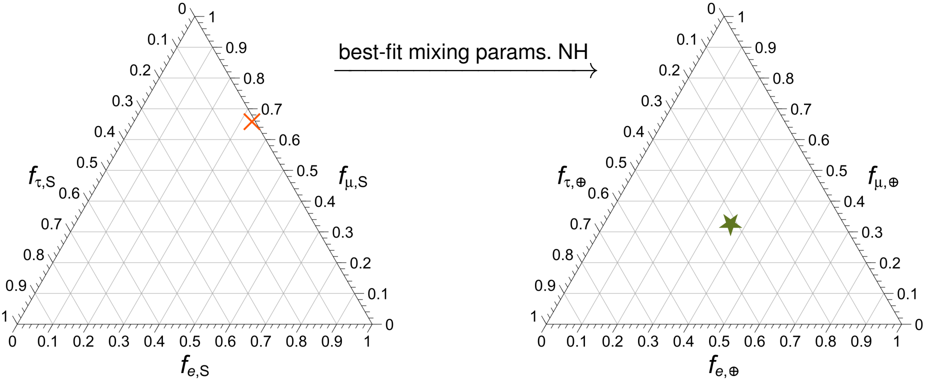


Mixing parameters

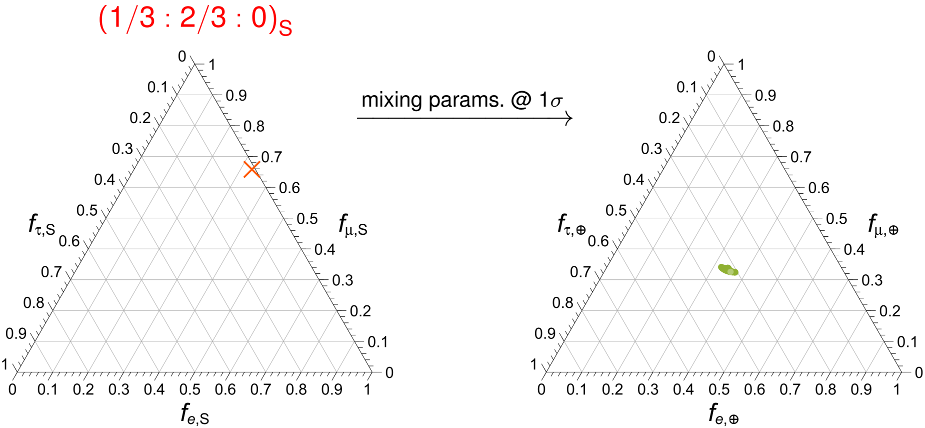


Effect of mixing uncertainty

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

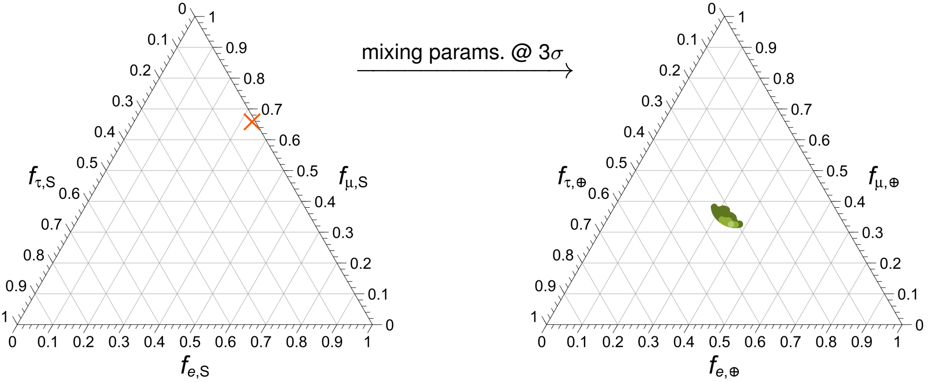


Effect of mixing uncertainty



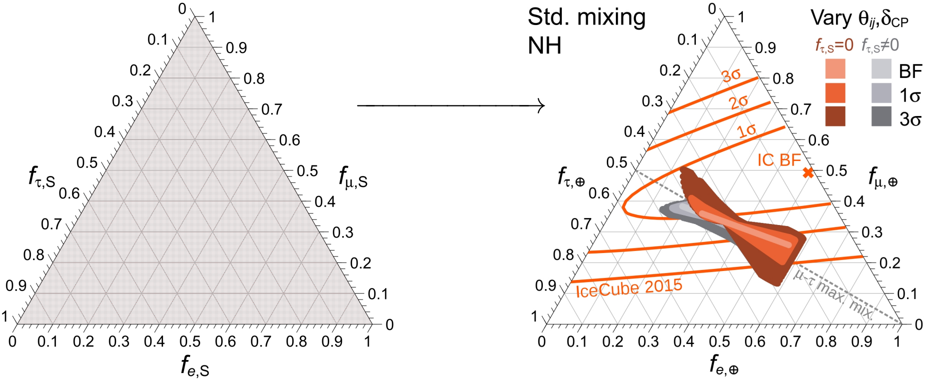
Effect of mixing uncertainty

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



The full monty

All possible source flavor ratios

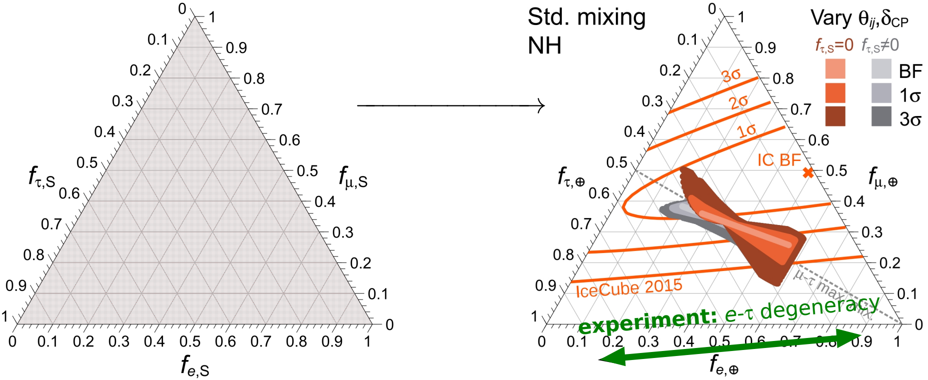


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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

The full monty

All possible source flavor ratios

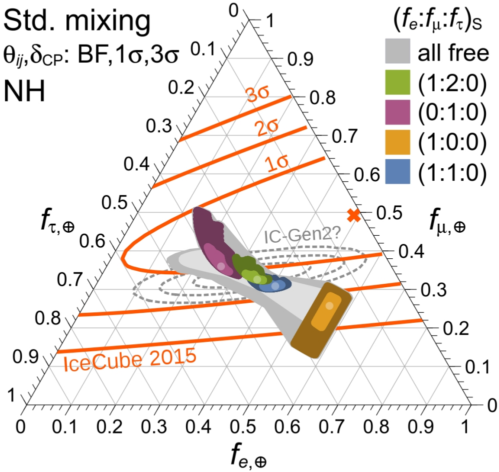


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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:

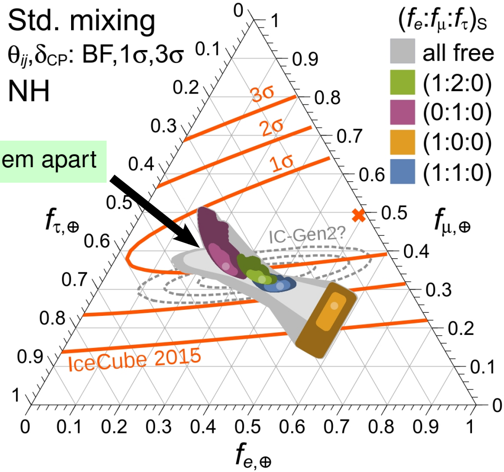


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Selected source compositions

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

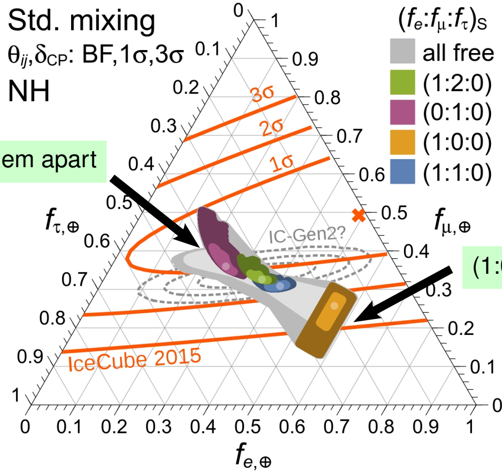
challenging to tell them apart



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

Selected source compositions

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



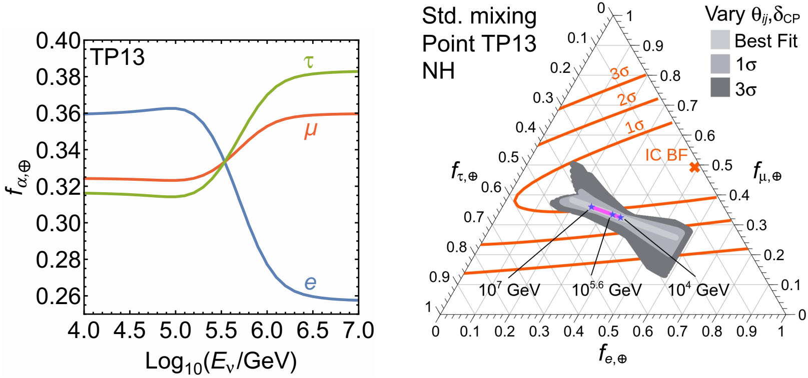
challenging to tell them apart

(1:0:0) disfavored at 2σ

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

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies

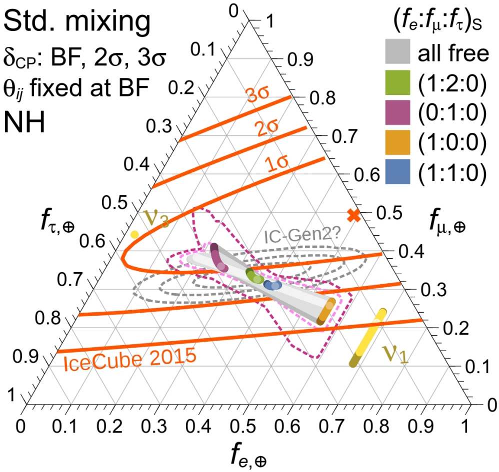


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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

Perfect knowledge of mixing angles

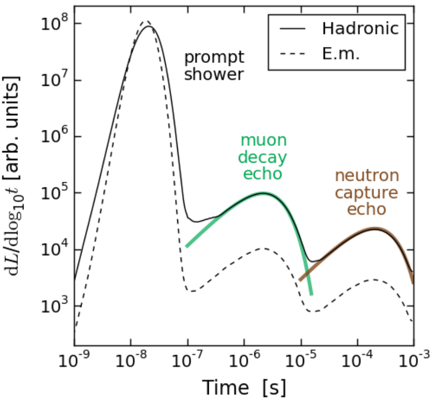
In a few years, we might know all the mixing parameters except δ_{CP}:

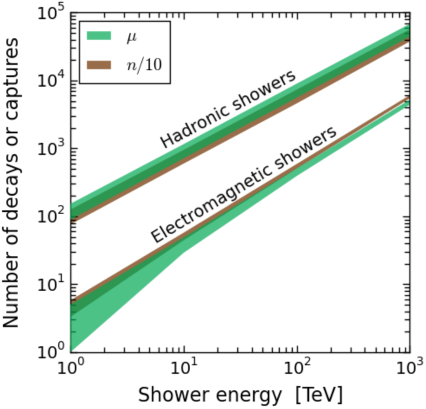


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

How to improve ν_e vs. ν_τ separation?

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



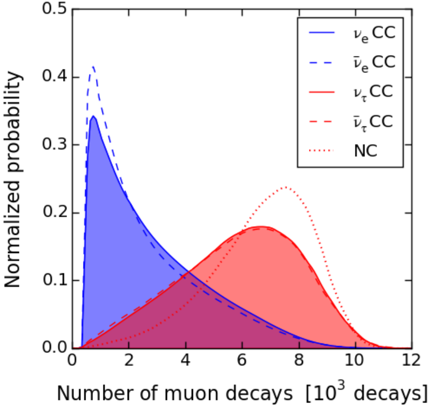


Li, MB, Beacom, 1606.06290

How to improve ν_e vs. ν_τ separation?

ν_e-initiated CC showers: e.m.
ν_τ-initiated CC showers: mostly ($\sim$ 67%) hadronic
ν_x-initiated NC showers: hadronic

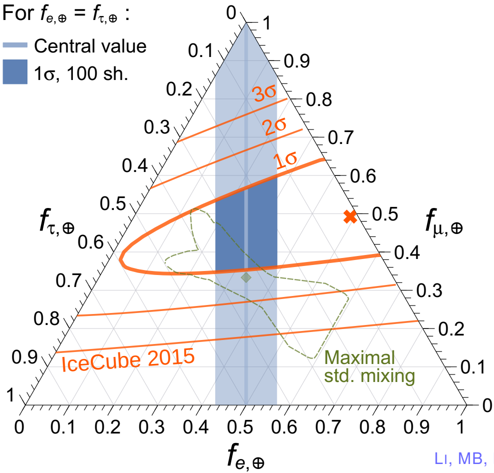
Probability distribution of number of muon decays per 100-TeV shower:



Li, MB, Beacom, 1606.06290

How to improve ν_e vs. ν_τ separation?

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

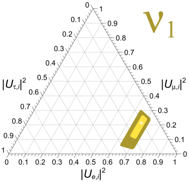


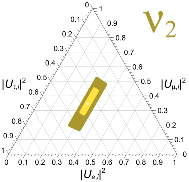
Li, MB, Beacom, 1606.06290

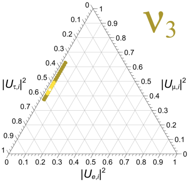
Using echoes: $\sim \times 9$ improvement over current flavor contours

Two classes of new physics

- Neutrinos propagate as incoherent mix of ν_1, ν_2, and ν_3
- Each has a different flavor content:



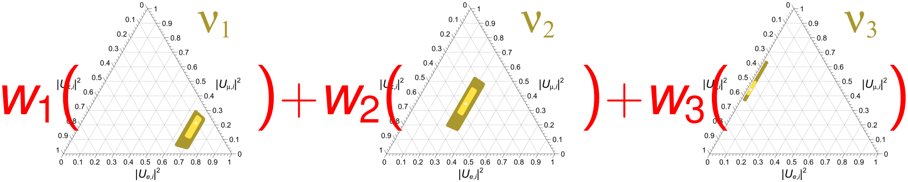




- The flavor ratios at Earth are the result of their combination
- New physics may
  - Reweigh the proportion of each ν_i reaching Earth (*e.g.*, decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Two classes of new physics

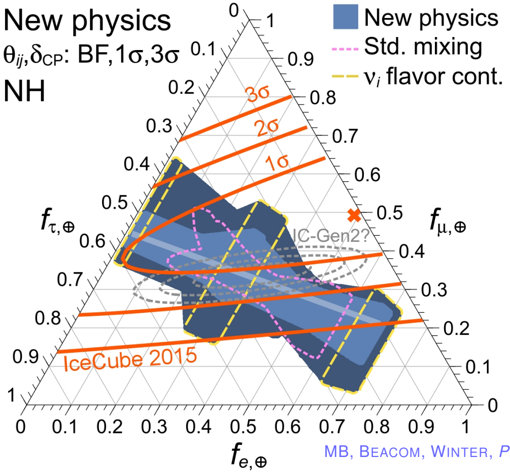
- Neutrinos propagate as incoherent mix of ν_1, ν_2, and ν_3
- Each has a different flavor content:



- The flavor ratios at Earth are the result of their combination
- New physics may
  - Reweigh the proportion of each ν_i reaching Earth (*e.g.*, decay)
  - Redefine the propagation states (*e.g.*, Lorentz-invariance violation)

Region of flavor ratios accessible with decay

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

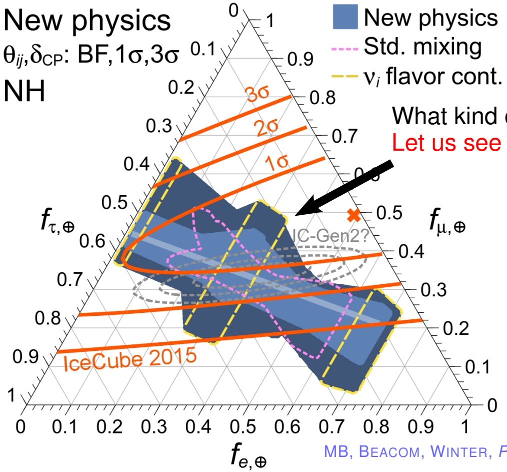


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

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

Region of flavor ratios accessible with decay

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



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.*, *JCAP* **10**, 1510 (2015)] [Brdar *et al.*, 1611.04598]
- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

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* **100**
  - violation of equivalence principle
    [Gasperini, *PRD* **39**, 3606 (1989)] [Glashow *et al.*, *PRD* **56**, 2433 (1997)]
  - coupling to a torsion field
    [De Sabbata, Gasperini, *Nuovo. Cim.* **A65**, 479 (1981)]
  - renormalization-group running of mixing parameters
    [MB, Gago, Jones, *JHEP* **1105**, 133 (2011)]
- active-sterile mixing [Aeikens *et al.*, *JCAP* **10**, 1510 (2015)] [Brdar *et al.*, 1611
- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

New physics — high-energy effects (I)

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

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

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

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

$n = 0$

- coupling to a torsion field
- CPT-odd Lorentz violation

$n = 1$

- equivalence principle violation
- CPT-even Lorentz violation

Experimental upper bounds from atmospheric ν's:

$O_0 \lesssim 10^{-23}$ GeV

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

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

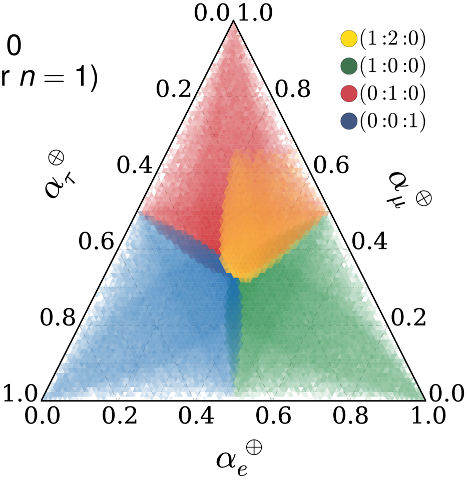
New physics — high-energy effects (II)

Truly exotic new physics is indeed able to populate the white region:

- use current bounds on $O_{n,i}$
- sample the unknown NP mixing angles

[ARGÜELLES, KATORI, SALVADÓ *PRL* **115**, 161303 (2015)]

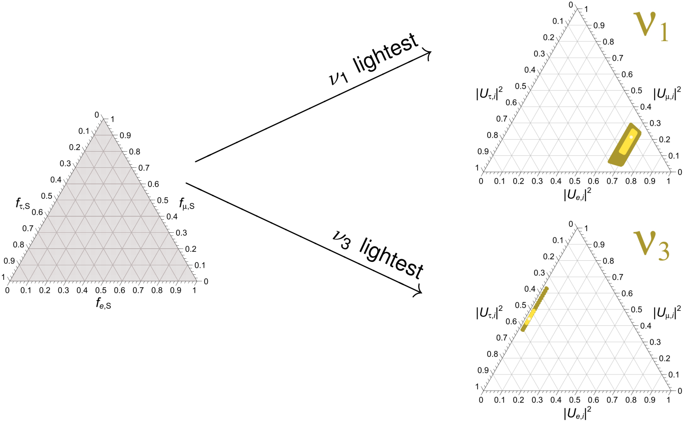
$n = 0$
(similar for $n = 1$)



Tasting complete decay

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

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



Standard Model decay modes

SM decay rates are negligible:

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

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

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

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

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

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

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

New neutrino decay modes

- Models beyond the SM may introduce new decay modes:

$$\nu_i \rightarrow \nu_j + \phi$$

- 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 in the flavor ratios

fraction of ν_i that reach Earth

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

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

Complete decay ($D \ll 1$) —

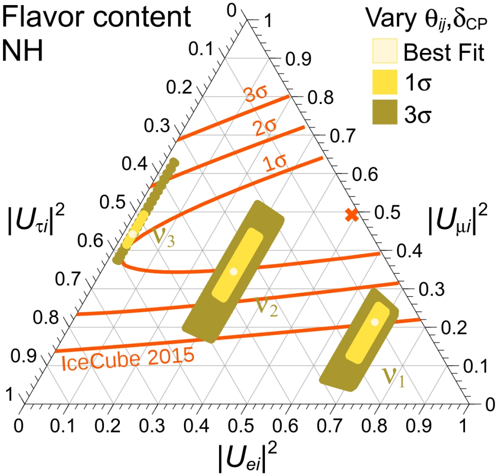
Flavor ratios equal the flavor content of ν_1 (NH) or ν_3 (IH):

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

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

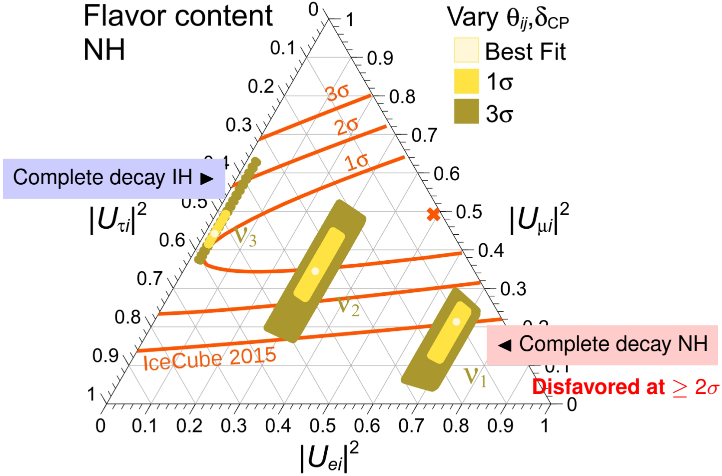
Sensitivity to decay using IceCube flavor contours

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



Sensitivity to decay using IceCube flavor contours

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



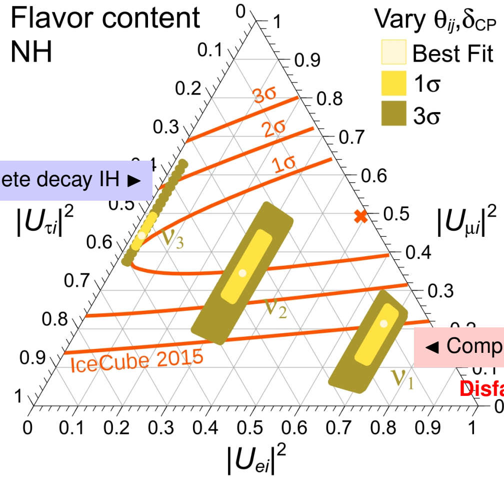
Complete decay IH ▶

◀ Complete decay NH

Disfavored at $\geq 2\sigma$

Sensitivity to decay using IceCube flavor contours

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



Complete decay IH ▶

◀ Complete decay NH

Disfavored at $\geq 2\sigma$

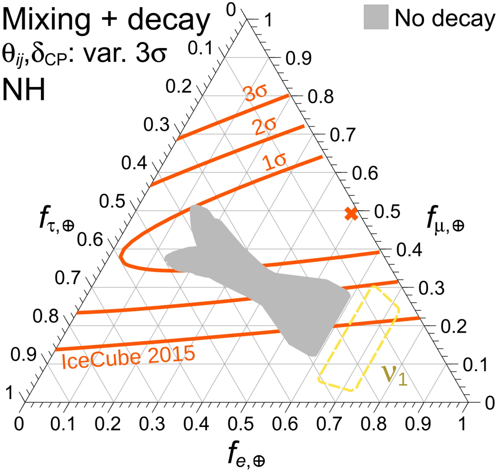
This leads to an improved lifetime sensitivity in the NH case ▶

NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

Assume equal lifetimes of ν_2, ν_3

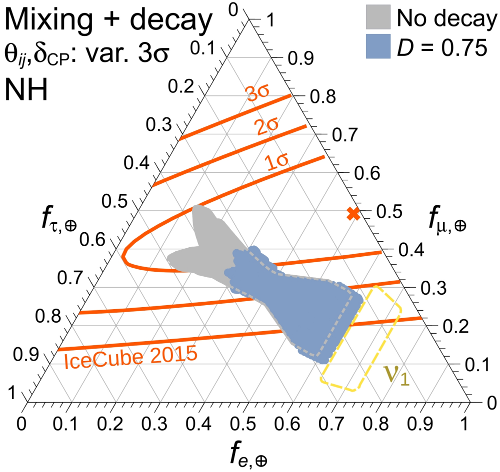


NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

Assume equal lifetimes of ν_2, ν_3

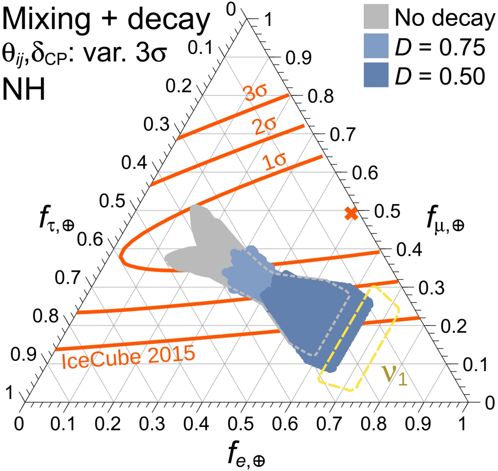


NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

Assume equal lifetimes of ν_2, ν_3

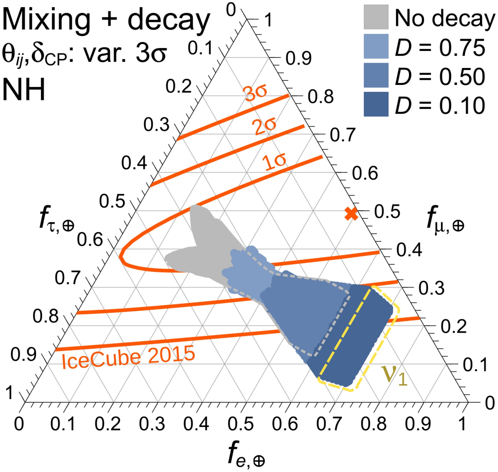


NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

Assume equal lifetimes of ν_2, ν_3

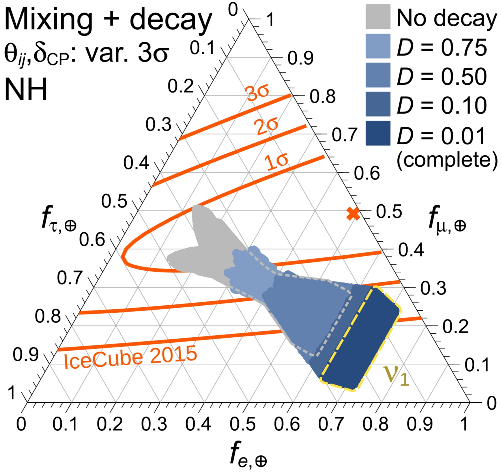


NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

Assume equal lifetimes of ν_2, ν_3

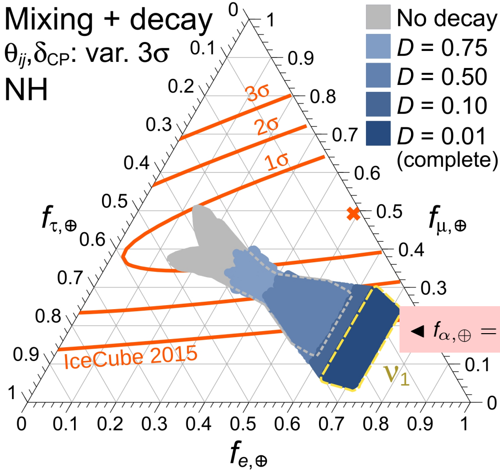


NH: lifetime sensitivity with current IceCube data

Find the value of *D* so that decay is complete, *i.e.*, $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$, for

- *Any* value of mixing parameters; and
- *Any* flavor ratios at the sources

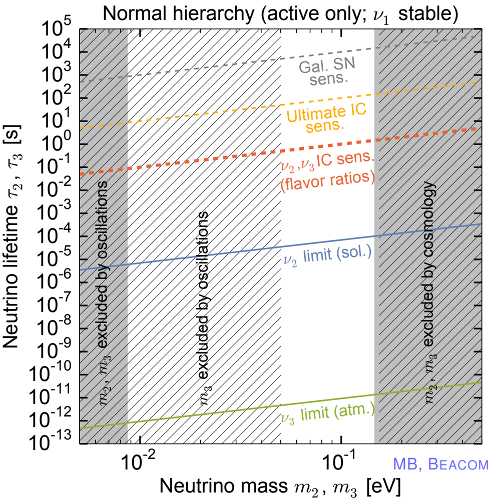
Assume equal lifetimes of ν_2, ν_3



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

Improved lifetime sensitivity in the NH

$D \lesssim 0.01$ implies $\tau_2/m_2, \tau_3/m_3 \gtrsim 10\ \mathrm{s\ eV}^{-1}$ at $\gtrsim 2\sigma$



MB, Beacom, Murase, 1610.02096

Outlook

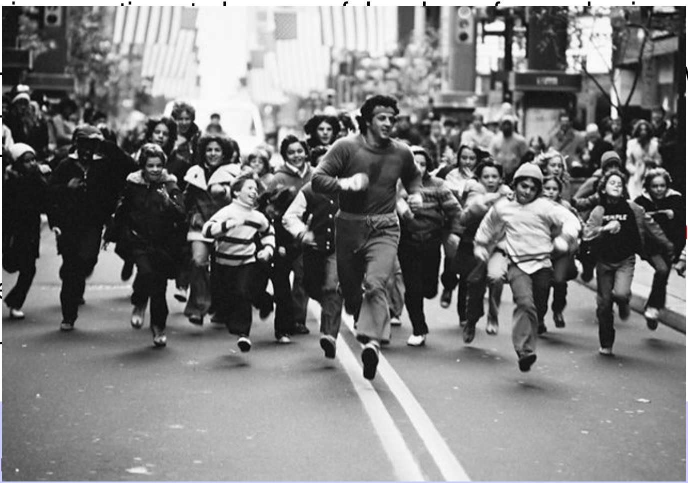
- Neutrinos continue to be powerful probes of new physics
- High-energy astrophysical neutrinos probe a new regime with . . .
  - The highest energies observed
  - The longest baselines observed
- New physics via changes in spectral shape and flavor composition
- Current data already improves lifetime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

Outlook

- Neut
- High-	vith . . .
  -
  -
- New	position
- Curre
- Prom

b



TeVPA 2017

Columbus, OH

August 7-11, 2017

tevpa2017.osu.edu

THE OHIO STATE UNIVERSITY

CENTER FOR COSMOLOGY AND
ASTROPARTICLE PHYSICS

Backup slides

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:

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

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

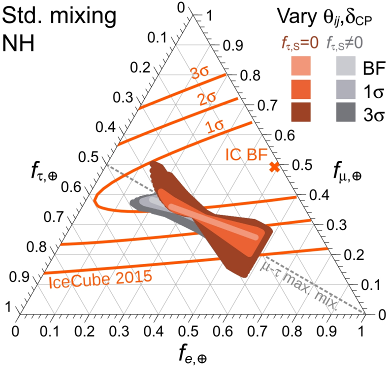
- Other compositions at the source:

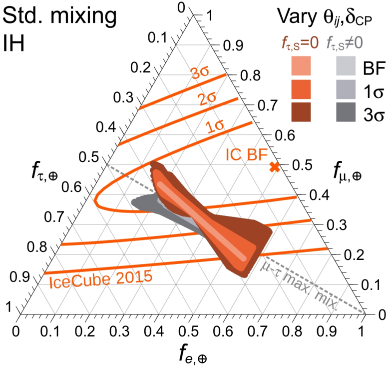
$(0 : 1 : 0)_{\rm S} \longrightarrow (0.26 : 0.36 : 0.38)_\oplus$ (“muon damped”)

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

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

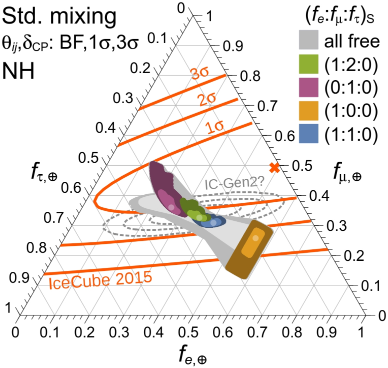
Flavor combinations from std. flavor mixing: NH vs. IH

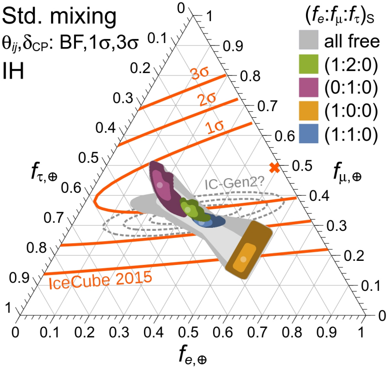




[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

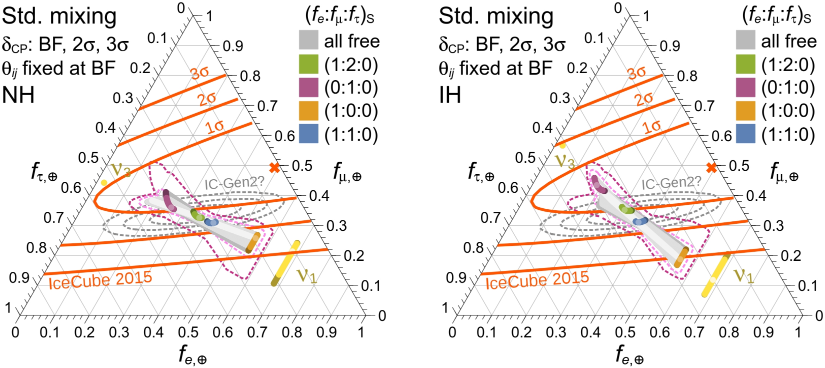
Selected source compositions: NH vs. IH





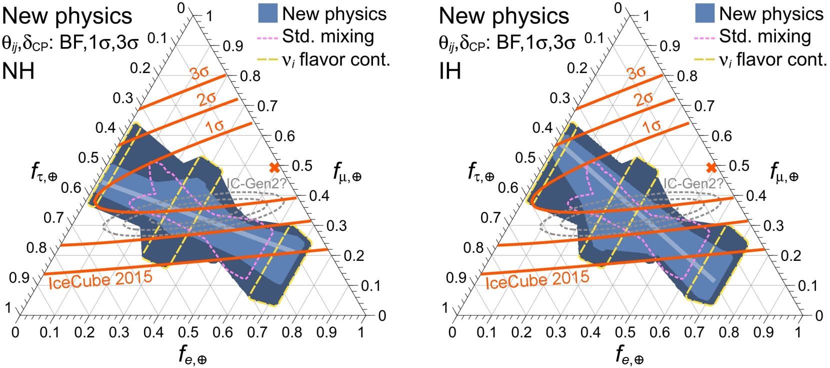
[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Perfect knowledge of mixing angles: NH vs. IH



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

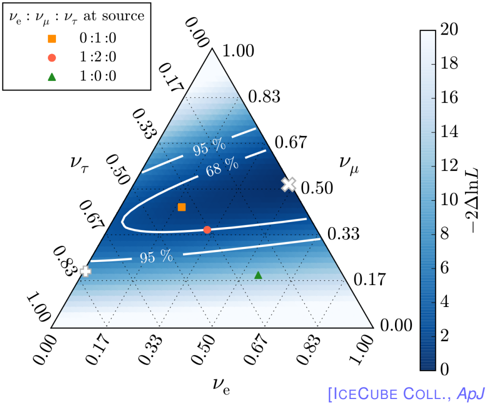
New physics: NH vs. IH



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

IceCube analysis of flavor composition

Using contained events + throughgoing muons:

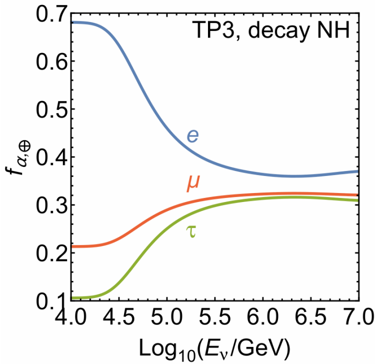


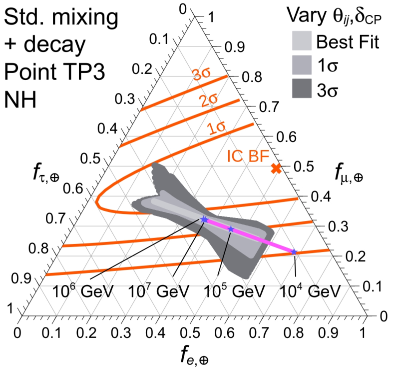
[IceCube Coll., *ApJ* **809**, 98 (2015)]

- Best fit: $(f_e : f_\mu : f_\tau)_\oplus \approx (0.5 : 0.5 : 0)_\oplus$
- Compatible with standard source compositions
- Bounds are weak – need more data and better flavor-tagging

Decay: seeing the energy dependence?

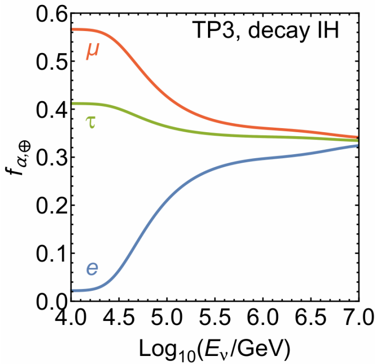
- The effect of decay shows up at low energies
- *e.g.*, for a model of AGN cores [Hümmer *et al.*, *Astropart. Phys.* **34**, 205 (2010)],
- Would require high statistics + exquisite energy resolution

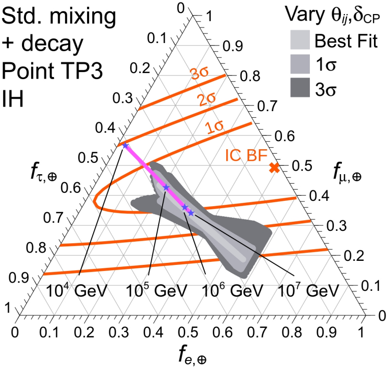




[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Decay in the IH





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

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:

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

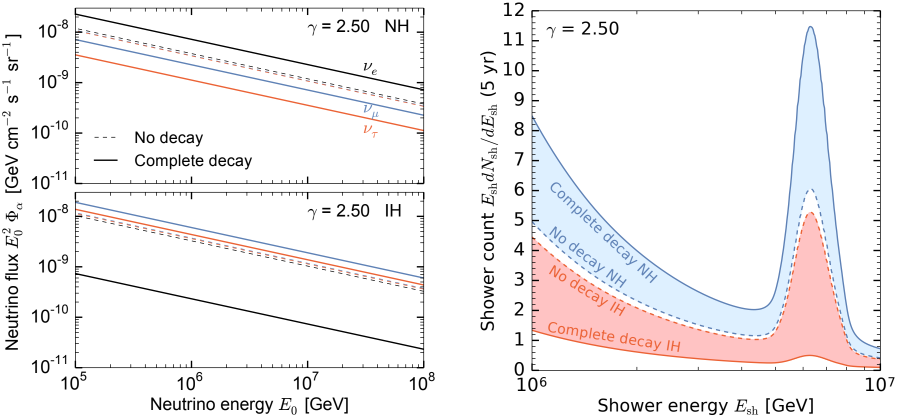
Hence, for high-energy astrophysical neutrinos:

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

Decay and the Glashow resonance

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

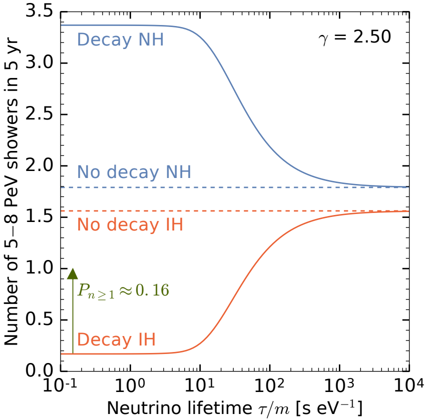
$$\bar{\nu}_e(6.3 \text{ PeV}) + e \rightarrow W \rightarrow \text{hadrons}$$

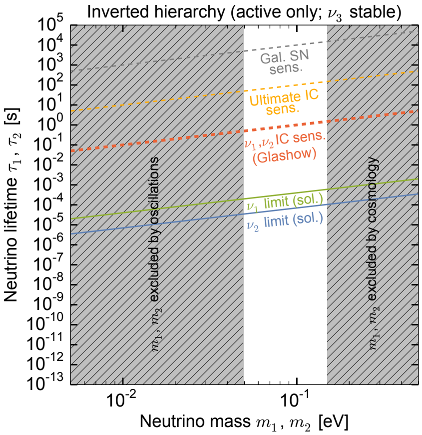


(All-flavor $\nu_\alpha + \bar{\nu}_\alpha$ flux normalized to IceCube combined-likelihood flux.)

IH: probing lifetime with high-energy showers

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





MB, BEACOM, MURASE, 1610.02096

Neutrino decay with flavor — how to do better?

Achievable *now*:

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

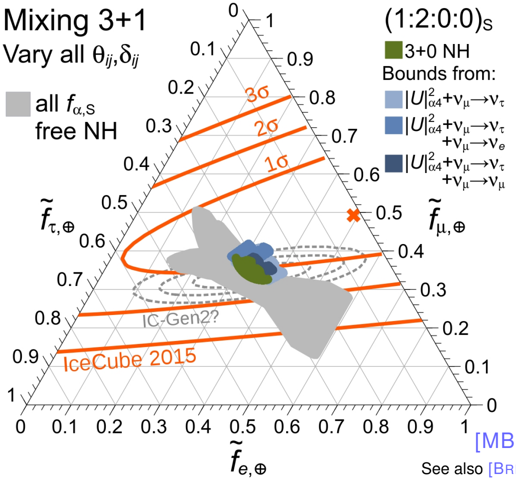
Achievable in the *near future*:

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

New physics — active-sterile mixing

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

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



Bounds from T2K, SK, Daya Bay

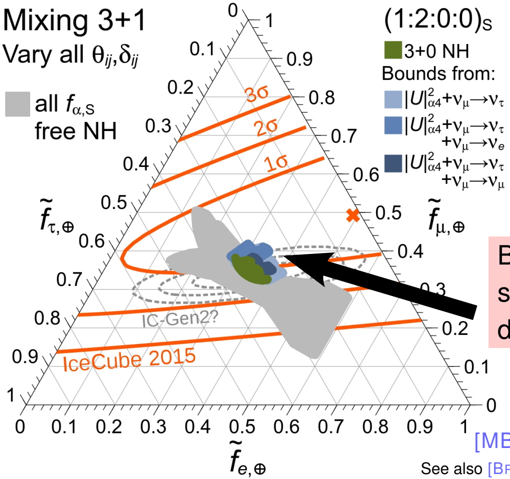
[MB, Coloma]

See also [Brdar, Kopp, Wang 2016]

New physics — active-sterile mixing

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

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



Bounds from T2K, SK, Daya Bay

Bounds are too strong for large deviations

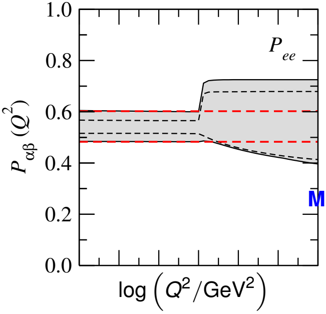
[MB, Coloma]

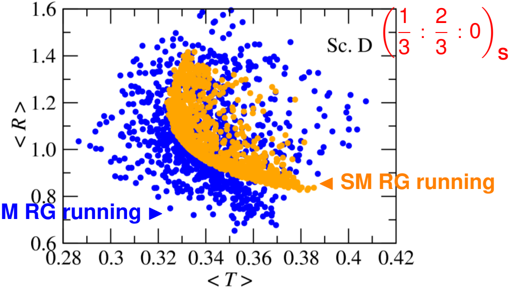
See also [Brdar, Kopp, Wang 2016]

New physics — SUSY renormalization group running

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

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





MSSM RG running ▶

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

Echoes: two (surmountable) obstacles

Obstacle:

Low numbers of photoelectrons (100-TeV shower: muon and neutron echoes have ~ 30 and ~ 6 p.e.)

Solution:

- IceCube *does* see 100-GeV atmospheric events, with ~ 30 p.e.
- Use spatial and temporal information:
  focus on the handful of DOMs closest to the prompt shower

Obstacle:

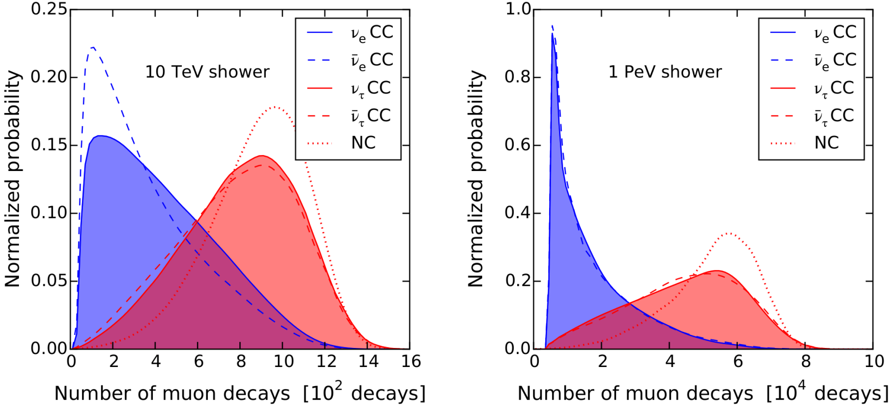
Muon echo time scale (2–5 μs) is plagued by **PMT afterpulsing**

Solution:

- Map afterpulsing curves of individual PMTs
- Use neutron echoes instead
- Use different PMTs in upgraded and next-gen detectors

How to improve ν_e vs. ν_τ separation?

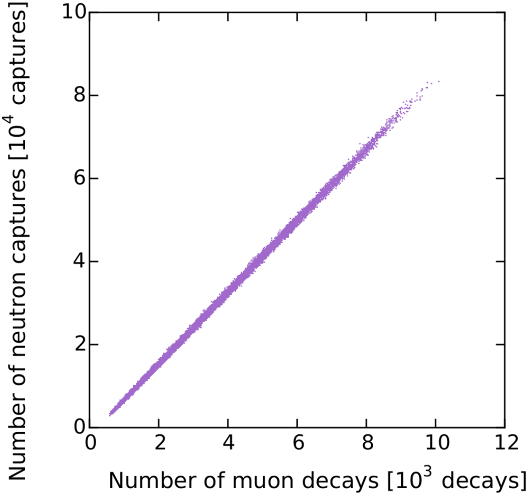
Probability distribution of number of muon decays:



Li, MB, Beacom, 1606.06290

Dispersion: muon decays vs. neutron captures

For 100-TeV showers:

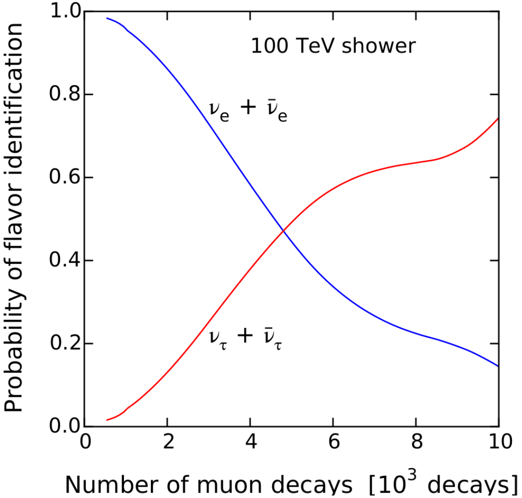


LI, MB, BEACOM, 1606.06290

Probability of flavor identification

Assuming:

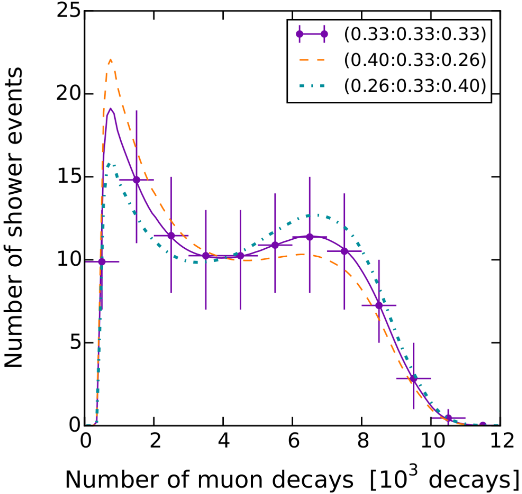
- Flux $\propto E^{-2.5}$
- $\left(\frac{1}{3}:\frac{1}{3}:\frac{1}{3}\right)_\oplus$



Li, MB, Beacom, 1606.06290

Distribution of number of muon decays

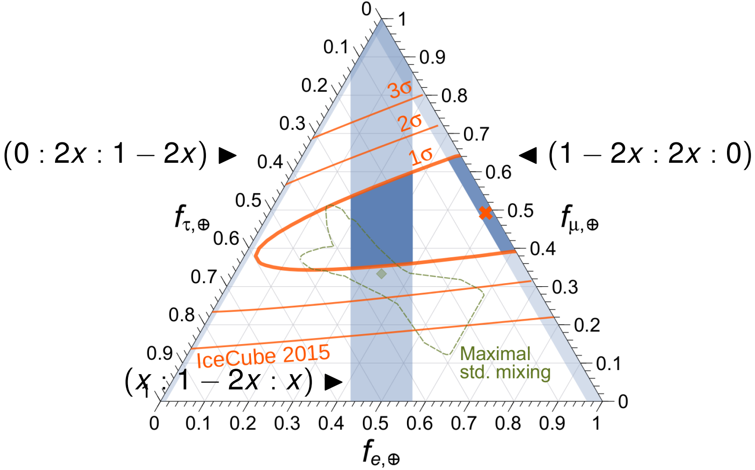
For 100 showers of 100 TeV:



Li, MB, Beacom, 1606.06290

Other flavor assumptions

For 100 showers of 100 TeV ($x \in [0, 0.5]$):



$(0 : 2x : 1 - 2x)$ ▶

◀ $(1 - 2x : 2x : 0)$

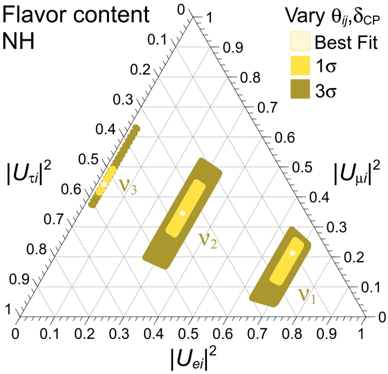
$(x : 1 - 2x : x)$ ▶

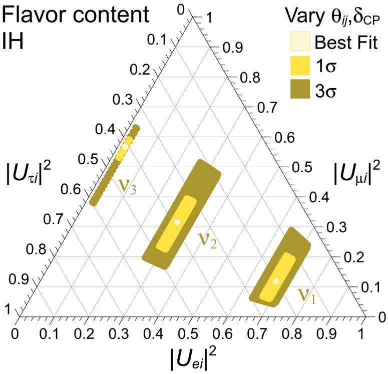
Li, MB, Beacom, 1606.06290

Flavor content of the mass eigenstates

Flavor content for every allowed combination of mixing parameters:

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





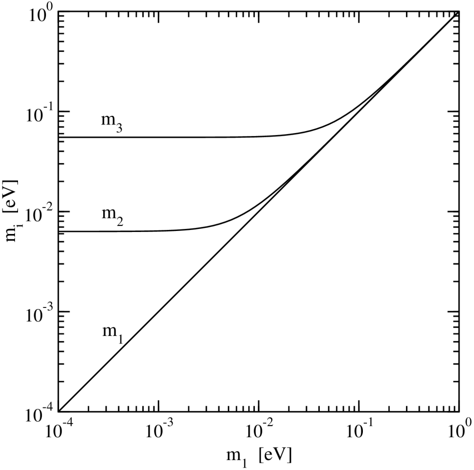
MB, BEACOM, WINTER, *PRL* **115**, 161302 (2015)

Decay with incomplete information

- **Source properties:**
  Distances to the source(s) are known.
  Sources follow star formation rate: most lie 1–4 Gpc away
  Flavor ratios at the sources(s) are known.
  Unnecessary under complete decay
  Energy spectrum at the source(s) is known.
  Unnecessary under complete decay
- **Neutrino properties:**
  Mixing parameters are known.
  Decay can be probed even if parameters vary within 3σ
  Decay modes are known.
  We have model-independent sensitivity
  Neutrino daughter kinematics are known.
  ν masses non-degenerate: daughters get $\sim$ half of parent energy
- **Detection aspects:**
  Negligible contribution from background events.
  Use high-energy ($\gtrsim$ 100 TeV) events away from the Galactic Plane
  Flavor is measured well for each neutrino.
  Suffices to use statistical measurement of flavor ratios of an event sample
  Energy is measured well for each neutrino.
  Not a concern if decay is complete for all relevant energies (0.1–10 PeV)

Support for non-degenerate neutrino masses

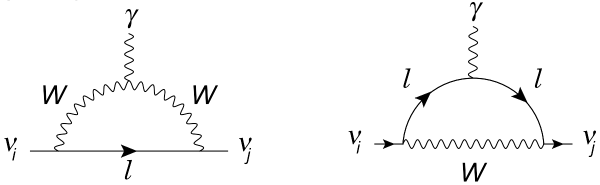
Today: mass limits make non-degenerate scenarios more likely —



Beacom & Bell, *PRD* **65**, 113009 (2002)

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

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

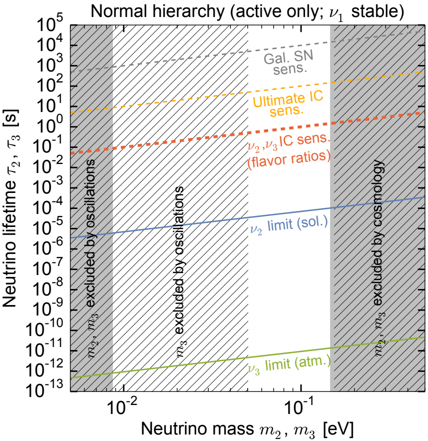
- Taking $U_{\tau i} \sim \mathcal{O}(1)$ and $m_i = 1$ eV $\gg m_j$ yields a lifetime of

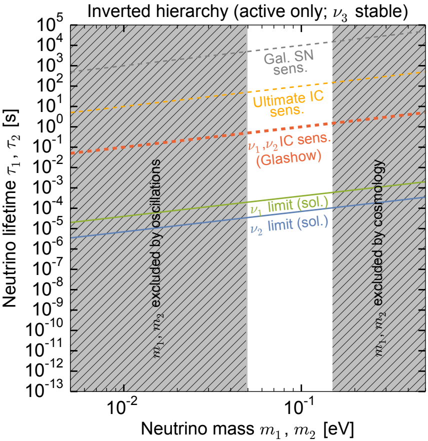
$$\tau \sim 10^{36}\ \text{yr} \gg 13.8 \cdot 10^9\ \text{yr (age of the Universe)}$$

Lifetime limits and sensitivities

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

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


Normal hierarchy (active only; ν_1 stable)


Inverted hierarchy (active only; ν_3 stable)

Decay fundamentals

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

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

- 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

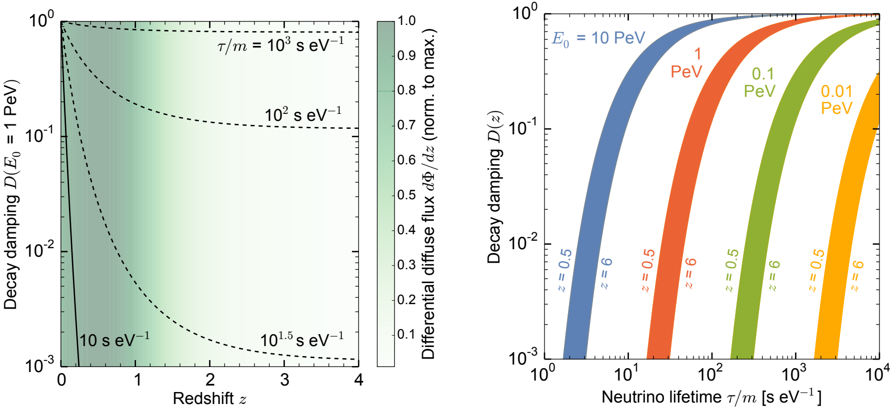
- Neutrinos with known L and E_ν are sensitive to "lifetimes" of

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

Two necessary cosmological corrections

1. Energy at production = $(1+z)\times$ energy at detection
2. Maximum propagated distance is the Hubble horizon ($\sim$4 Gpc)

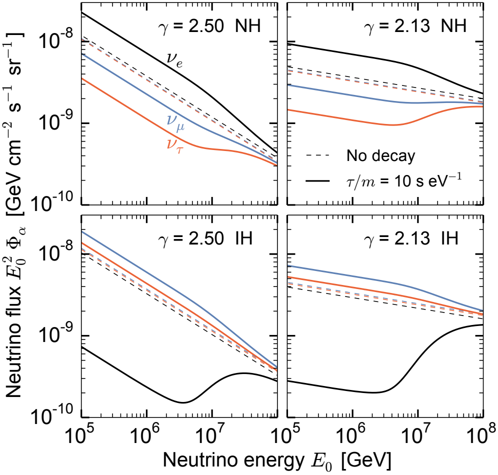
The cosmologically-correct survival fraction D behaves like this:



Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012) + MB, Beacom, Murase, 1610.02096

How to look for decay?

Depletes flux of heavy eigenstates and enhances flux of lightest one



What are the decay signatures?

- Complete decay
- Transition region

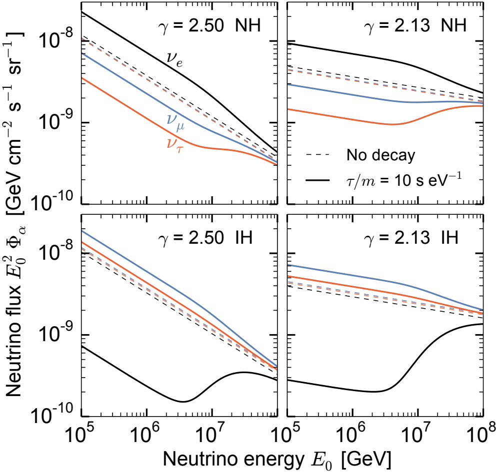
Where to look for it?

- Flavor ratios
- Absolute number of events of each flavor

MB, Beacom, Murase, 1610.02096

How to look for decay?

Depletes flux of heavy eigenstates and enhances flux of lightest one



What are the decay signatures?

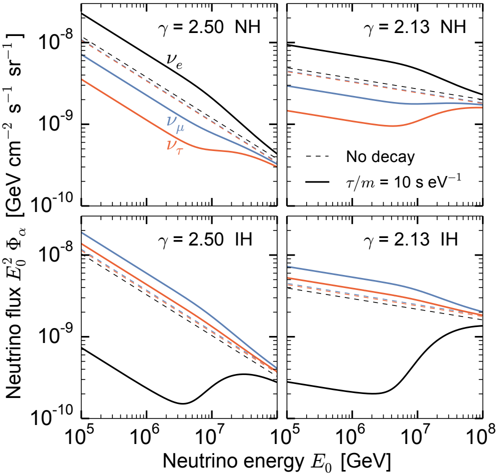
- Complete decay ◀
- Transition region

Where to look for it?

- Flavor ratios ◀
- Absolute number of events of each flavor ◀

MB, BEACOM, MURASE, 1610.02096

Decay in the high-energy shower rate



MB, Beacom, Murase, 1610.02096

What are the decay signatures?

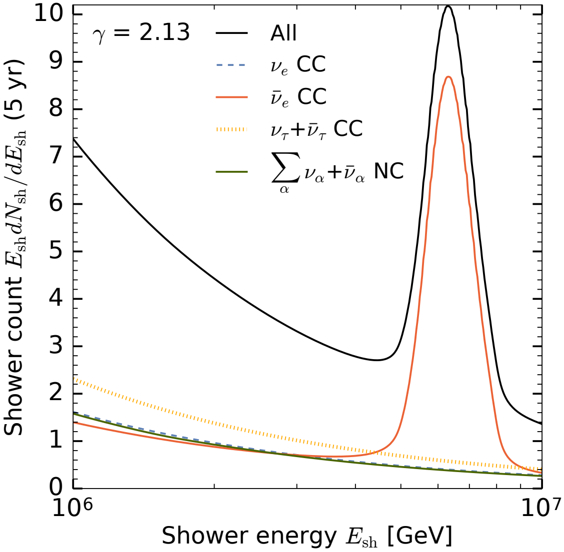
- Complete decay ◄
- Transition region

Where to look for it?

- Flavor ratios
- Absolute number of events of each flavor ◄

The ν_e flux changes the most:
IH, complete decay

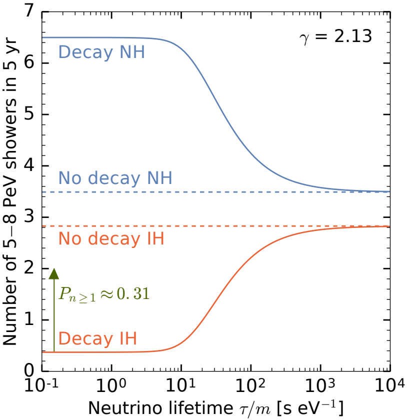
Shower spectrum components

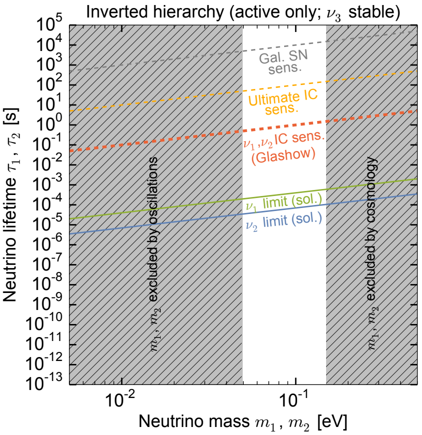


MB, Beacom, Murase, 1610.02096

IH: lifetime with high-energy showers ($\gamma = 2.13$)

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





MB, Beacom, Murase, 1610.02096