High-energy astrophysical neutrinos: testing ground for 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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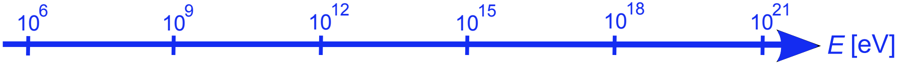
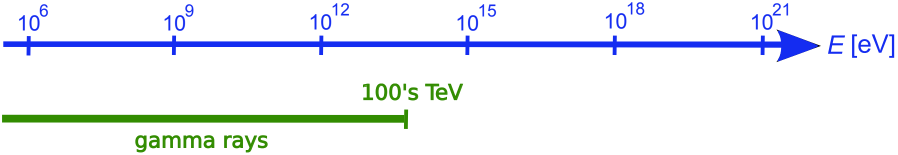
. . . and winning

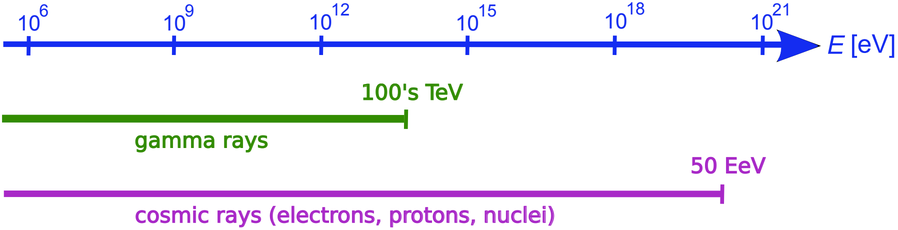
Some reasons why neutrinos are special:

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 us with higher energies than anything else

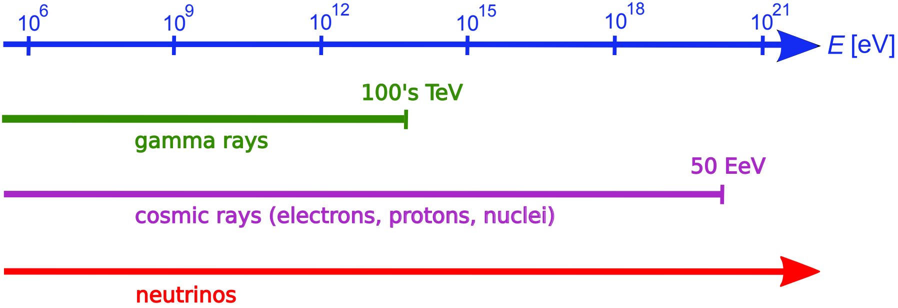
Let's talk energy scales...


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



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)



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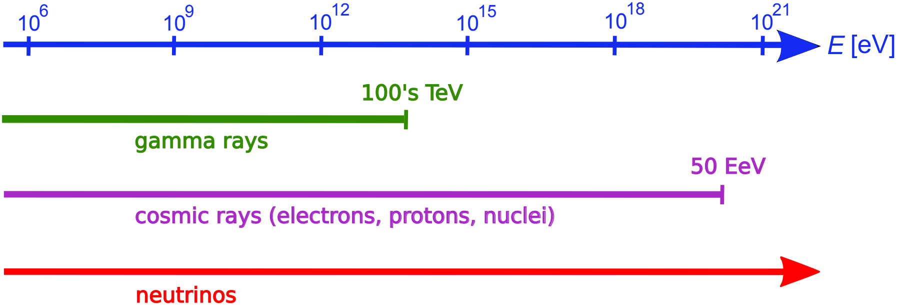
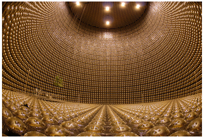
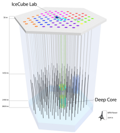
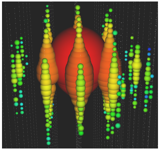
E [eV]
100's TeV
gamma rays
50 EeV
cosmic rays (electrons, protons, nuclei)
neutrinos



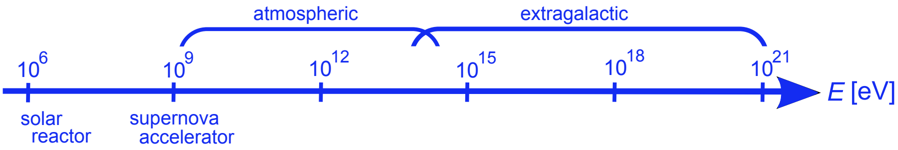
5 Unlike gamma rays and cosmic rays, neutrinos have flavor

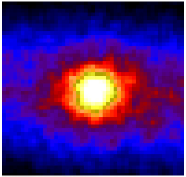


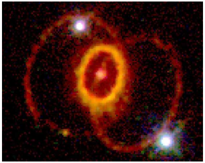

IceCube Lab
Deep Core

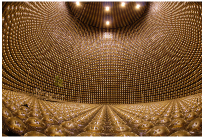


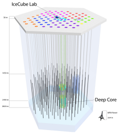
2013+

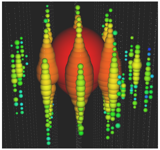

atmospheric
extragalactic
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]
solar
reactor
supernova
accelerator



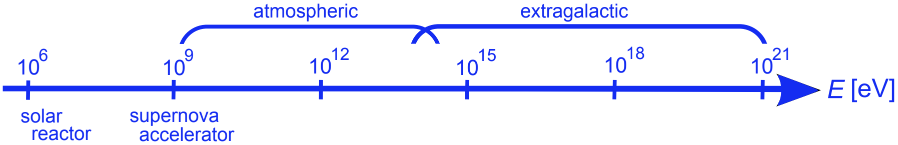


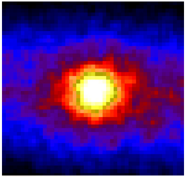


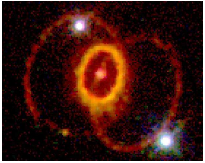


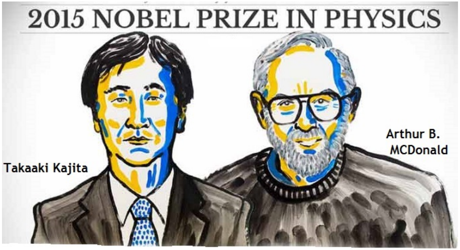


2013+









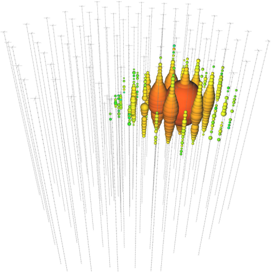
Next ν-Nobel for high-energy ν's?

High-energy astrophysical neutrinos: they exist!

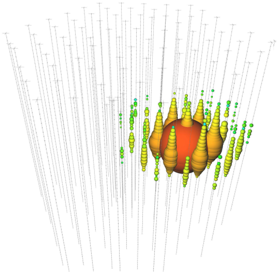
The era of neutrino astronomy has begun!

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

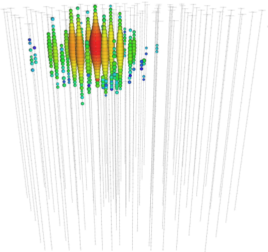
"Bert", 1.04 PeV



"Ernie", 1.14 PeV



"Big Bird", 2 PeV



...and 51 more events > 30 TeV

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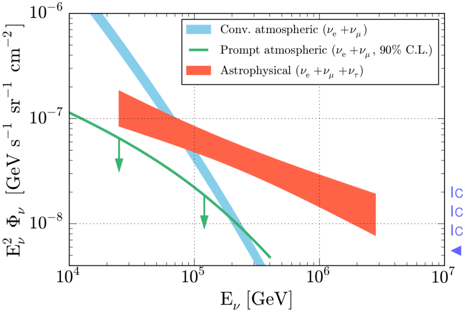

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, *ApJ* **809**, 98 (2015)

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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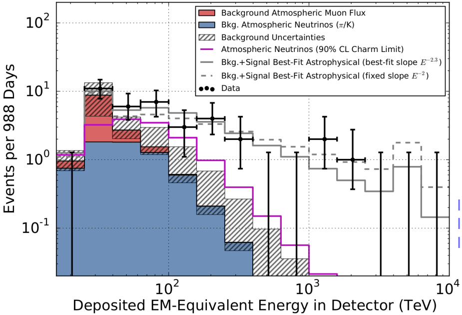


IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

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

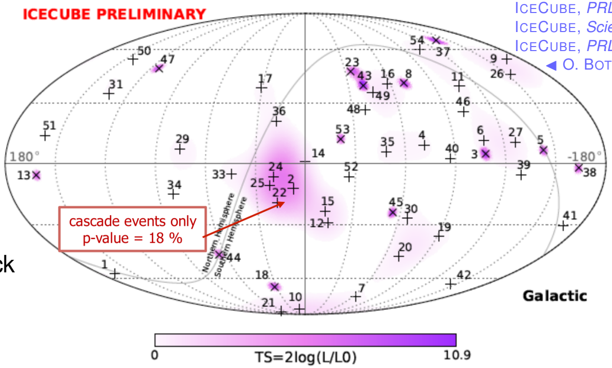
$$E^2\Phi_\nu = (0.95 \pm 0.3) \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{(per flavor)}$$

The era of neutrino astronomy has begun!

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

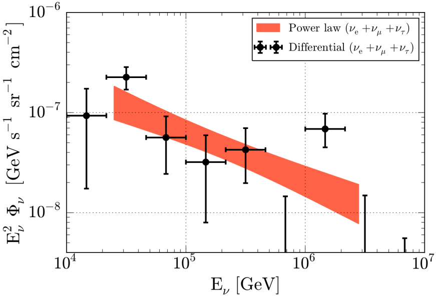


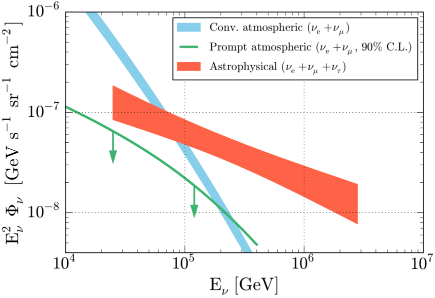
+: shower
×: muon track

– 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



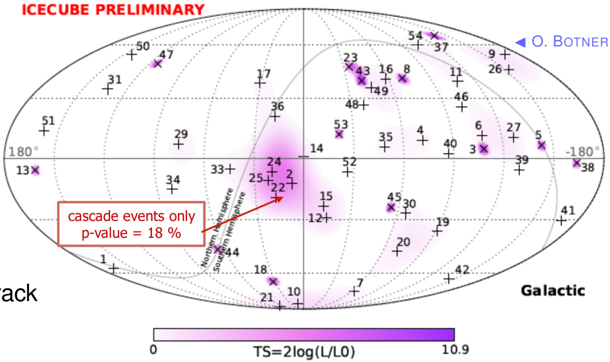


[IceCube Coll., *ApJ* **809**, 98 (2015)]

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

❷ 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

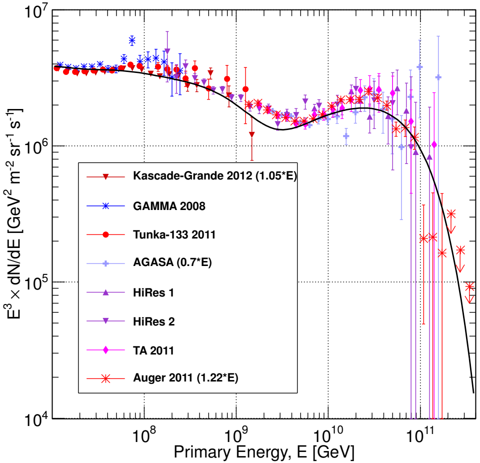
What we don't know

- 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 —

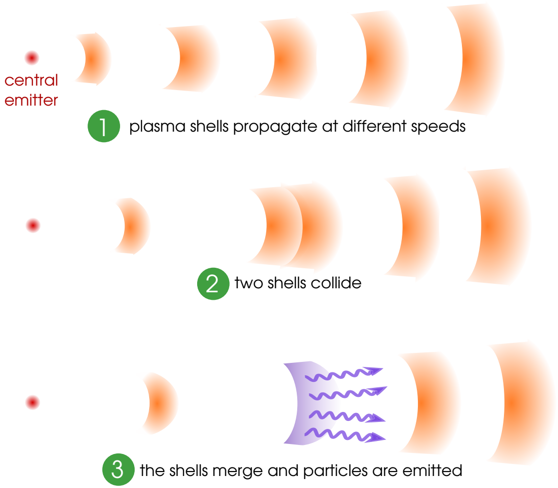


Gaisser, Stanev, Tilav, *Front. Phys. China* **8**, 748 (2013)

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)



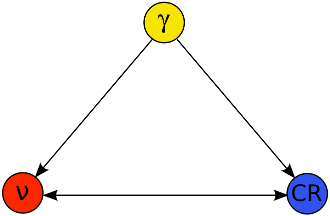
power law $\sim E^{-\alpha_p}$ ← p broken power law ← γ

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

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

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

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



neutrino energy $\simeq$ proton energy / 20

neutrino energy $\simeq$ gamma-ray energy / 2

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

This neutron model of CR emission is now strongly disfavored

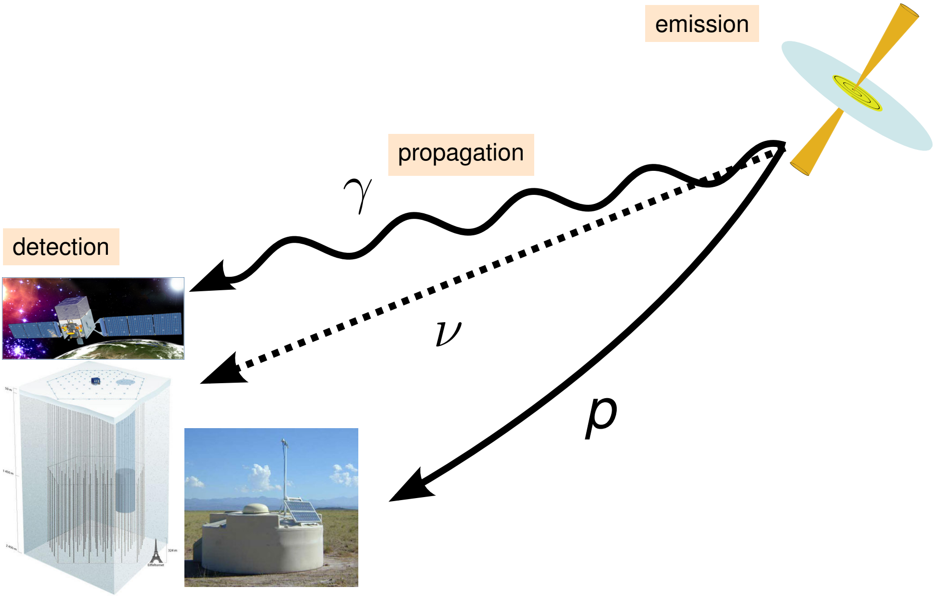
[Ahlers *et al.*, *Astropart. Phys.* **35**, 87 (2011)] [IceCube Coll., *Nature* **484**, 351 (2012)]

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)]]

From the sources to us



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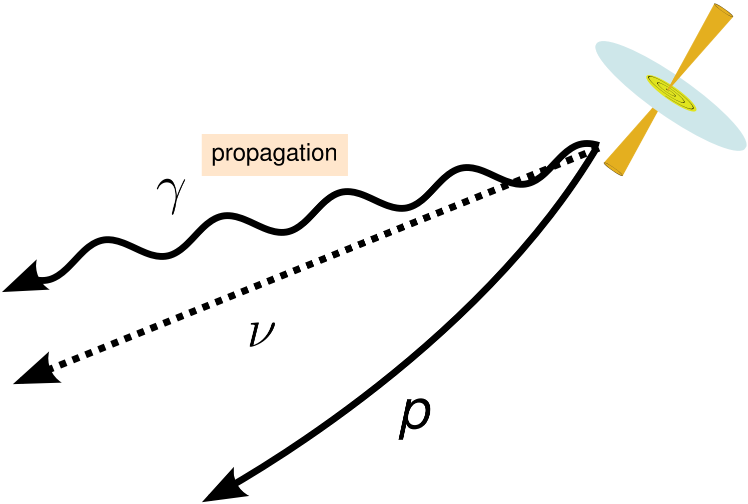
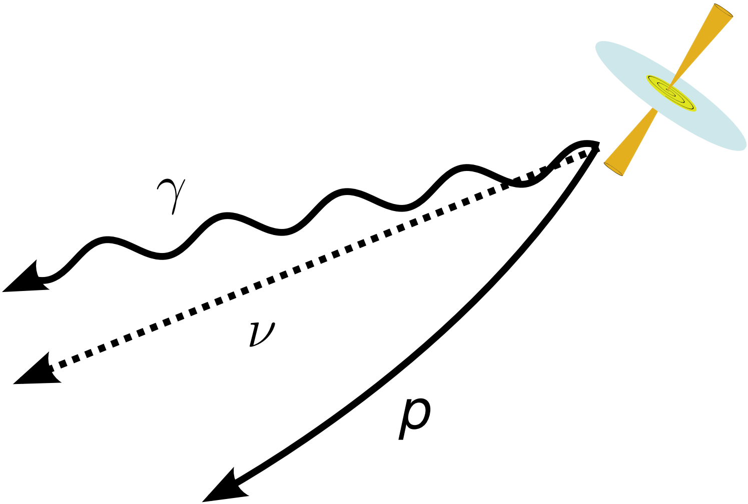


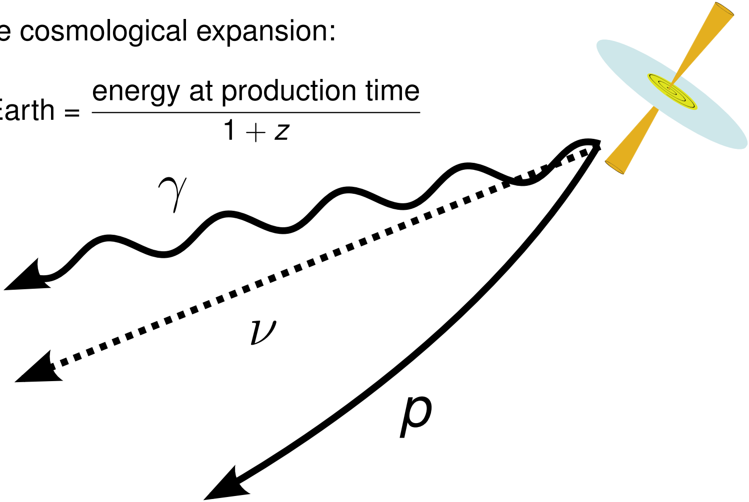
From the sources to us



From the sources to us

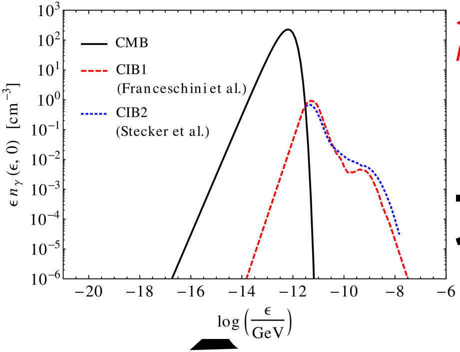
Because of the cosmological expansion:

$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$

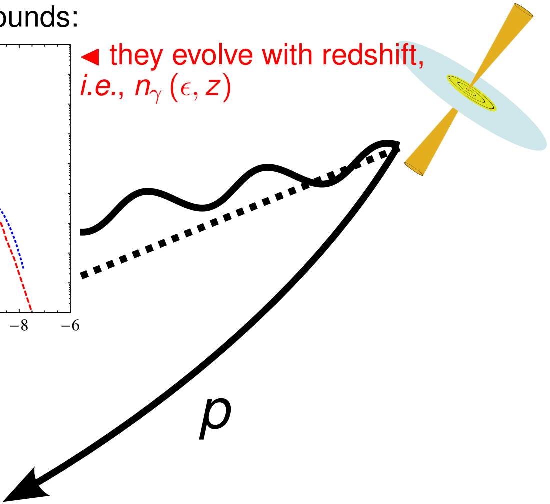


From the sources to us

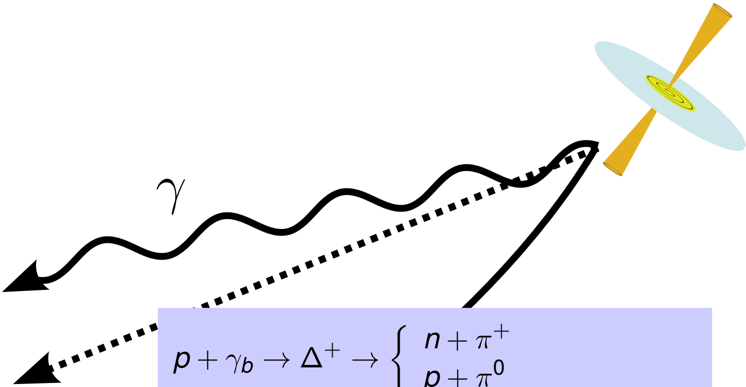
Cosmological photon backgrounds:



◀ they evolve with redshift, *i.e.*, $n_\gamma(\epsilon, z)$



From the sources to us



$$p + \gamma_b \to \Delta^+ \to \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases}$$

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

Cosmogenic ν's: $\pi^+ \to e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

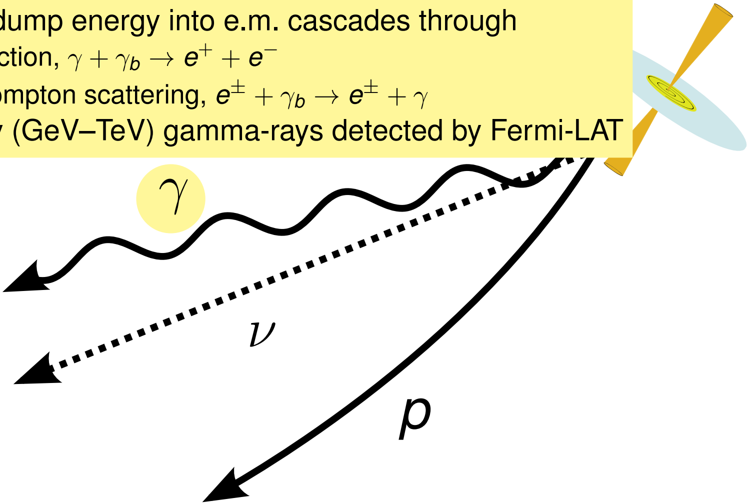
$$n \to p + e^- + \bar{\nu}_e$$

From the sources to us

γ's and $e^{\pm}$'s dump energy into e.m. cascades through

- pair production, $\gamma + \gamma_b \to e^+ + e^-$
- inverse Compton scattering, $e^{\pm} + \gamma_b \to e^{\pm} + \gamma$

Lower-energy (GeV–TeV) gamma-rays detected by Fermi-LAT



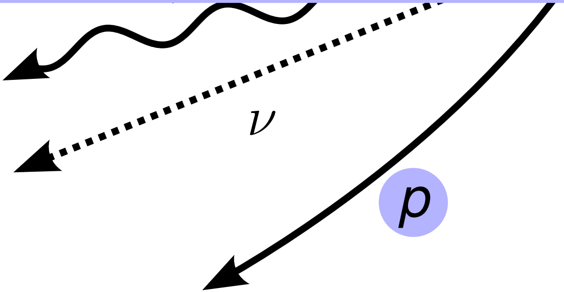
From the sources to us

p's are deflected by extragalactic magnetic fields
⇒ except for the most energetic ones, they are **not** expected to point back to the sources } Pierre Auger found weak correlation with known AGN positions

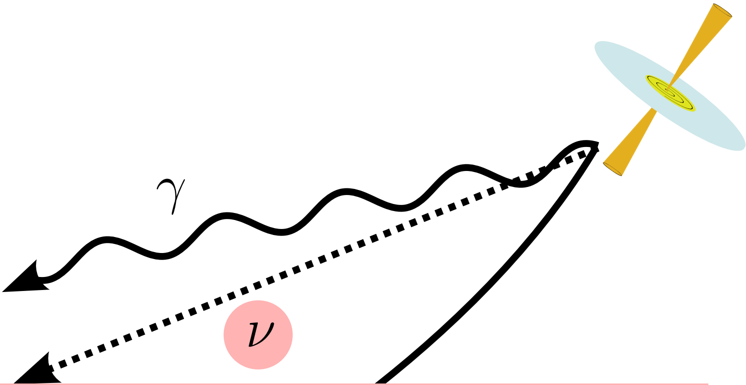
They lose energy through:

- pair production, $p + \gamma_b \to p + e^+ + e^-$
- photohadronic interactions, $p\gamma_b$

} depend on the redshift evolution of the cosmological γ backgrounds



From the sources to us



Initial UHE ν flavor fluxes: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Probability of $\nu_\alpha \to \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

Flavor oscillations redistribute the fluxes

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

– at Earth: $\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$ (might be changed by exotic physics!)

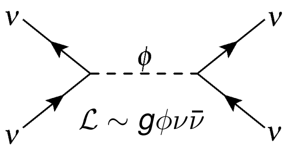
Where to look for new physics

- 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]

Secret neutrino interactions between astrophysical neutrinos and the cosmic neutrino background

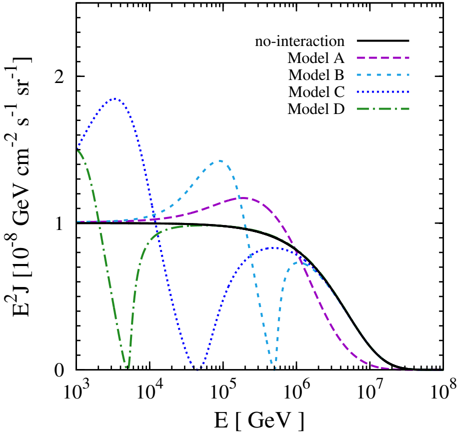


Cross section:

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

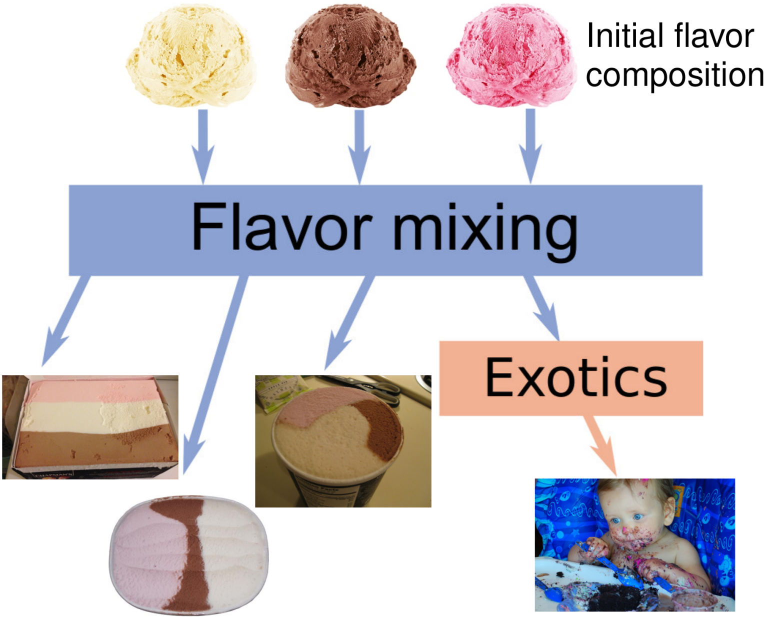
Resonance at

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



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

New physics: effect on the flavor composition



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:

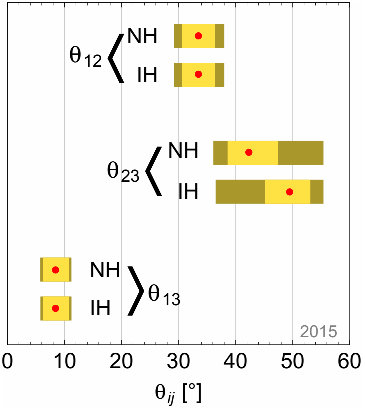
$$\langle P_{\alpha\beta} \rangle = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$ ◀ incoherent mixture of mass eigenstates

Flavor content of the mass eigenstates (I)

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

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

- From global fits [GONZÁLEZ-GARCÍA *et al.* 2014]:



Using the best-fit values:

ν_1 : 70% ν_e, 10 – 20% ν_μ, 10 – 20% ν_τ

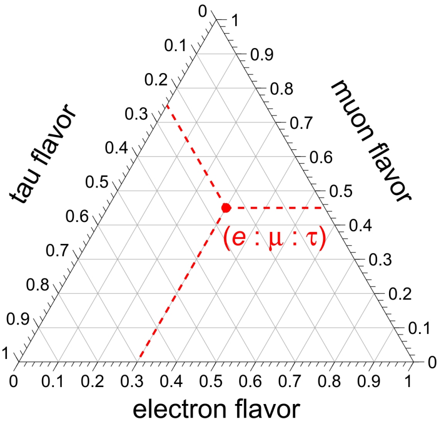
ν_2 : $\sim$ equal proportion of each

ν_3 : 3%ν_e, 40 – 60%ν_μ, 40 – 60%ν_τ

"Flavor triangle" or Dalitz/Mandelstam plot

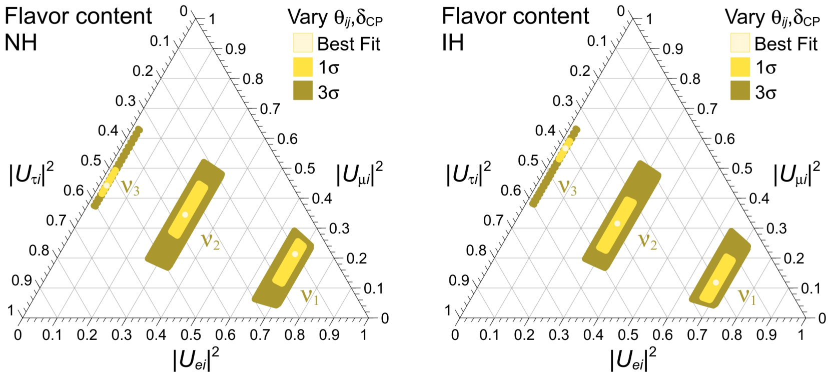
Assumes underlying unitarity: sum of projections on each axis is 1

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

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

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

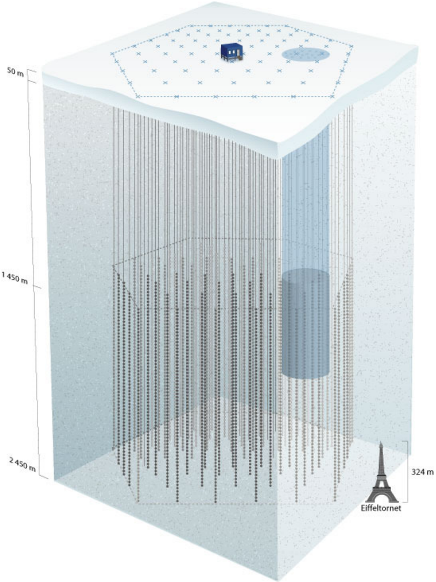
- Other compositions at the source:

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

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

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

Detecting the neutrinos: IceCube



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

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

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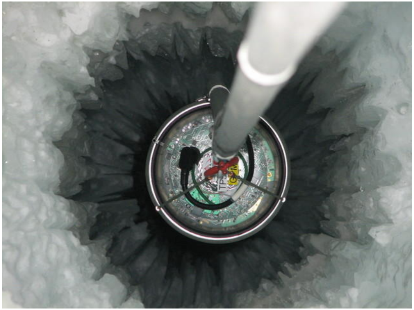

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How does IceCube see flavor?

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

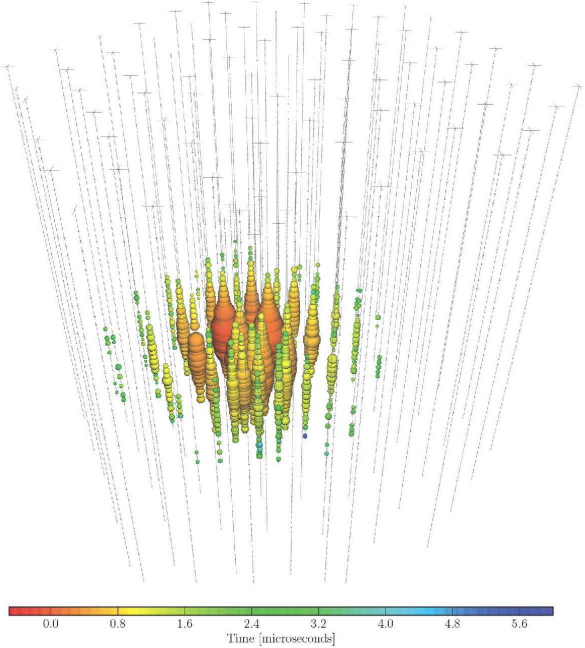
- Showers: generated by CC ν_e or ν_τ; or by NC ν_x
- Muon tracks: generated by CC ν_μ

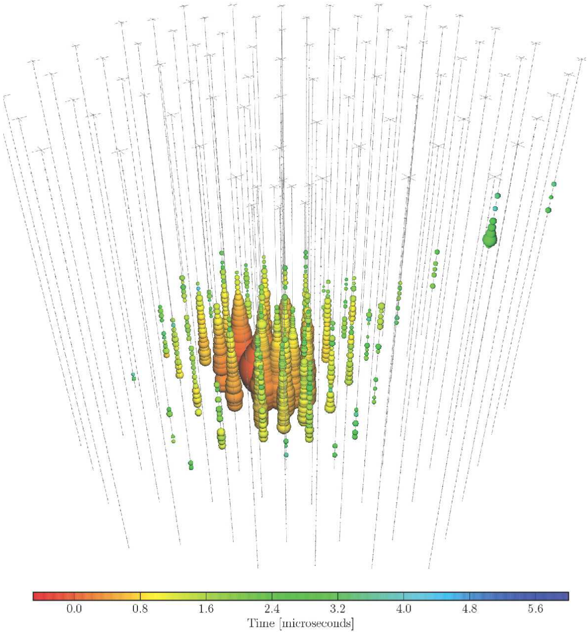
(Some muon tracks can be mis-reconstructed as showers)

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

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

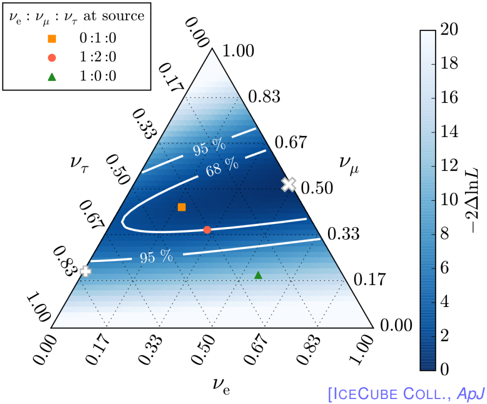
Flavor ratios must be inferred from the number of showers and tracks


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:

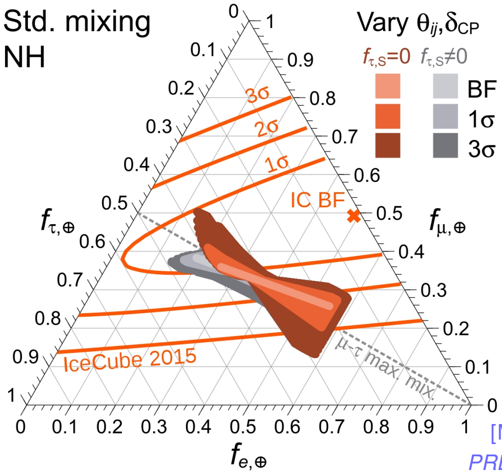


[IceCube Coll., *ApJ* **809**, 98 (2015)]

- 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)]

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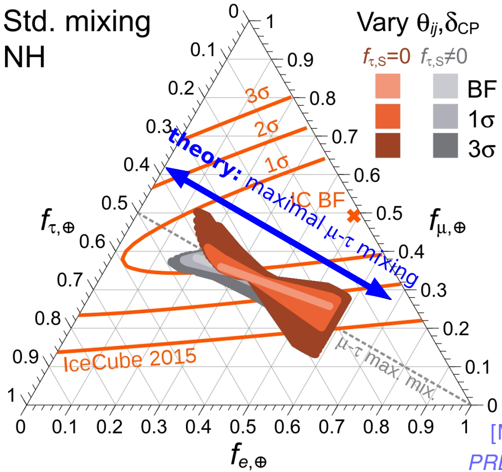

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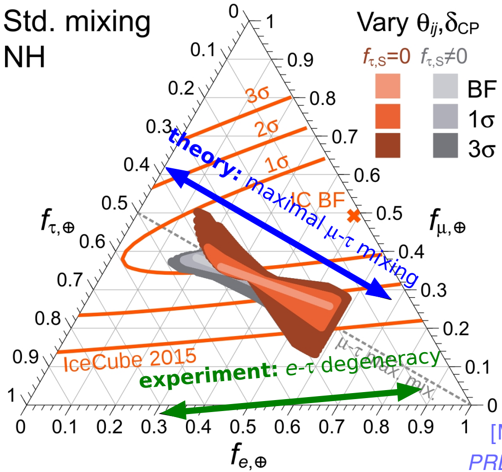
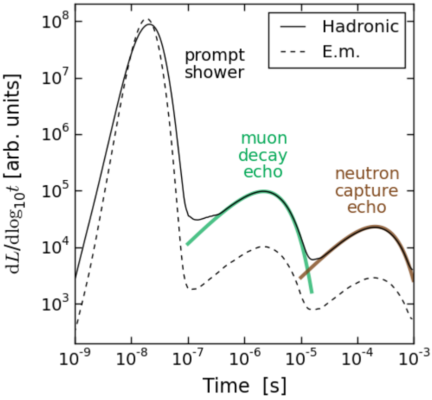


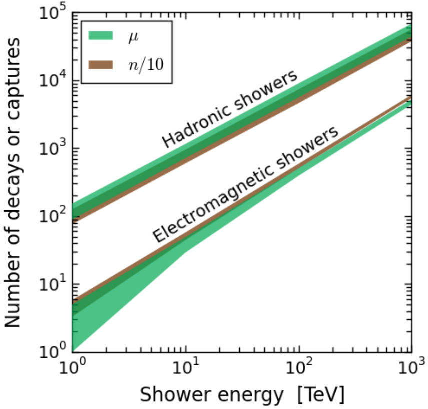
[MB, Beacom, Winter, *PRL* **115**, 161302 (2015)]

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

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 —



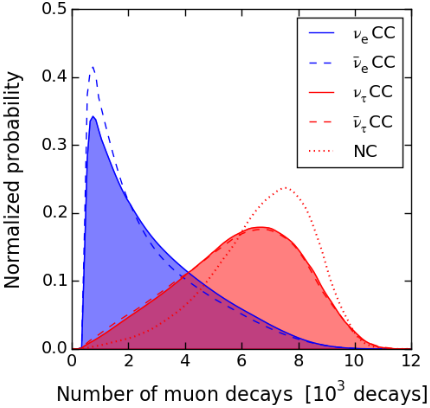


Li, MB, Beacom, 1606.06290

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

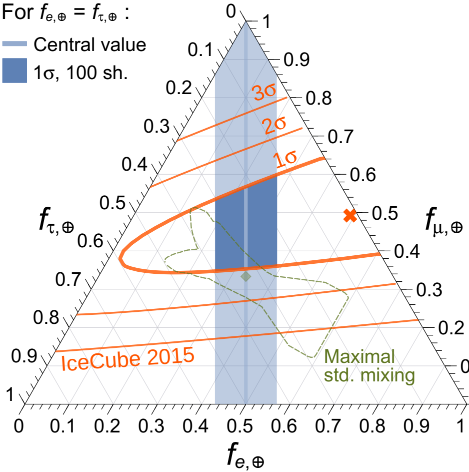
Probability distribution of number of muon decays per 100-TeV shower:



Li, MB, Beacom, 1606.06290

How to improve ν_e vs. ν_τ separation?

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



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

Otherwise, $\times$ 81 exposure is needed (320 yr of IceCube or 54 yr of Gen2)

Two (surmountable) obstacles

Obstacle:

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

Solution:

- IceCube *does* see 100-GeV atmospheric events, with $\sim$ 30 p.e.
- Use spatial and temporal information:
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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

Can neutrinos decay?

In principle, yes

Why? Because different neutrinos have different masses:

$$\begin{aligned} \Delta m_{21}^2 &= m_2^2 - m_1^2 \approx 8 \times 10^{-5}\ \mathrm{eV}^2 \\ |\Delta m_{32}^2| &= |m_3^2 - m_2^2| \approx 3 \times 10^{-3}\ \mathrm{eV}^2 \end{aligned}$$

- Heavier neutrinos decay into lighter ones
- The lightest neutrino is (presumably) stable

How often does this happen? ▶

Standard Model decay modes

SM decay rates are negligible:

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

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

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

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

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

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

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:

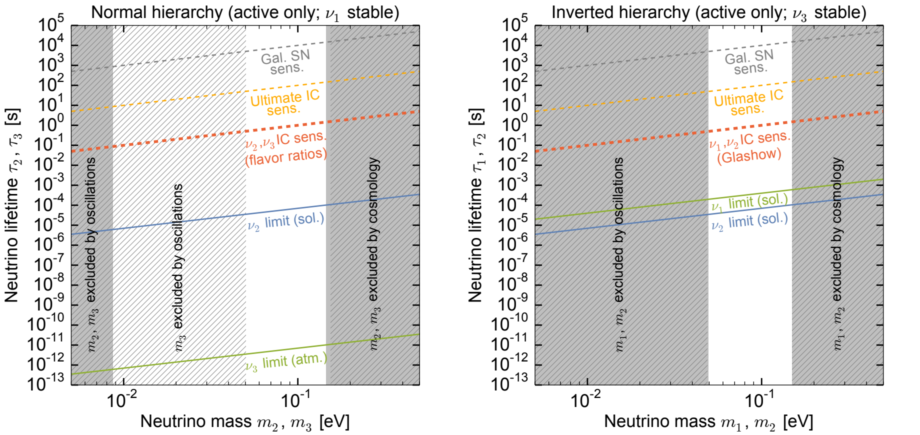
$$\nu_i \rightarrow \nu_j + \phi$$

- 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

Lifetime limits and sensitivities

Neutrino decay rates depend on the factor

$$\exp\left(-\frac{t}{\gamma\tau}\right) = \exp\left(-\frac{L}{E} \times \frac{m}{\tau}\right)$$



Decay: the ideal scenario

To test decay in astro. ν's, typically strong assumptions are made:

- **Source properties:**
  Distances to the source(s) are known.
  Flavor ratios at the sources(s) are known.
  Energy spectrum at the source(s) is known.
- **Neutrino properties:**
  Mixing parameters are known.
  Decay modes are known.
  Neutrino daughter kinematics are known.
- **Detection aspects:**
  Negligible contribution from background events.
  Flavor is measured well for each neutrino.
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With the present IceCube data and analyses, **none** of these are met

But we can still test decay of astro. ν's with incomplete information

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.
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- **Neutrino properties:**
  Mixing parameters are known.
  Decay can 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)

Decay fundamentals

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

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

- At distance $L \approx t$, the fraction of surviving unstable ν_i's is

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

◀ For very long L, this has redshift corrections

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

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

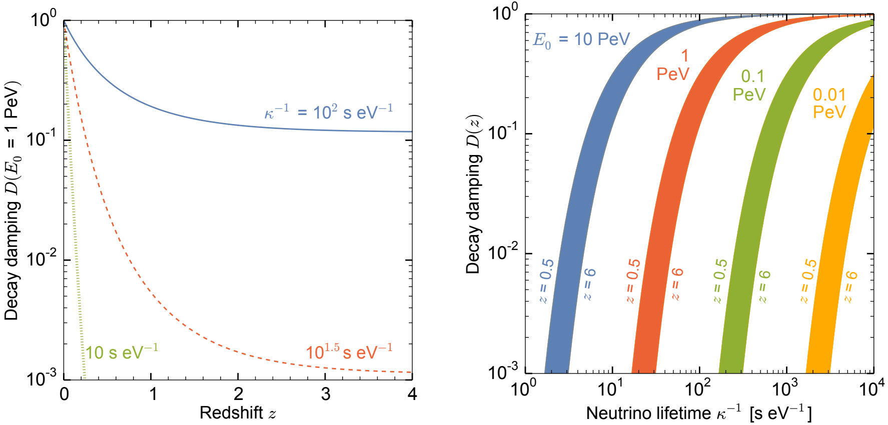
- IceCube is sensitive to

$$\begin{cases} E \sim 0.1\text{–}10\ \text{PeV} \\ L \sim 1\text{–}4\ \text{Gpc} \end{cases} \Rightarrow \kappa^{-1} \sim 10\text{–}10^3\ \text{s eV}^{-1}$$

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, in prep.

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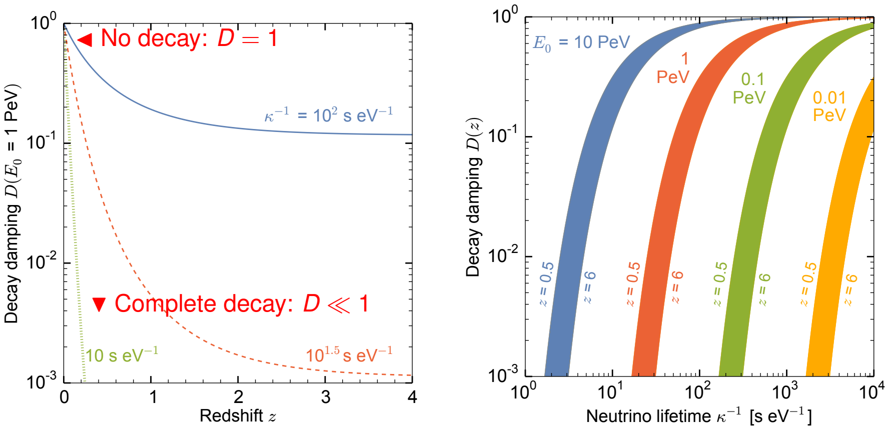

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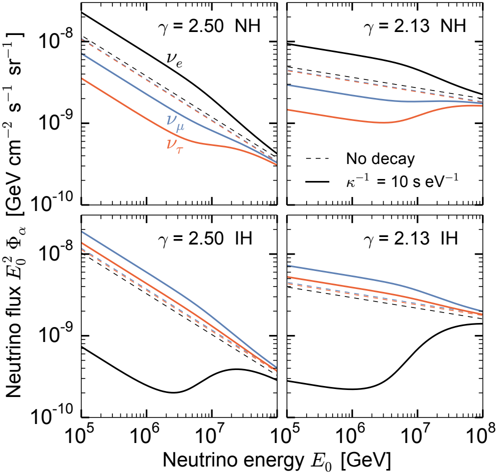
Depletes flux of heavy eigenstates and enhances flux of lightest one



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What are the decay signatures?

- Complete decay
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Where to look for it?

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- Absolute number of events of each flavor

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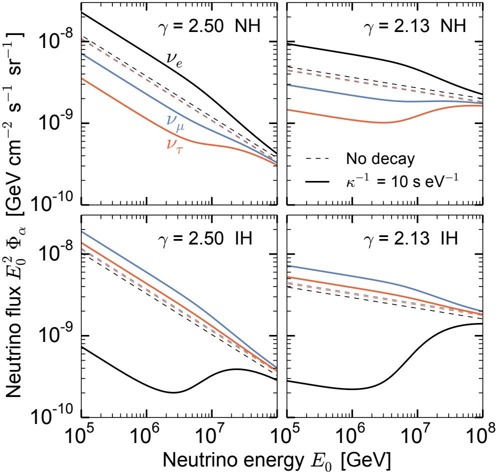

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- Complete decay ◀
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Where to look for it?

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

MB, Beacom, Murase, in prep.

Decay in the flavor ratios

fraction of ν_i that reach Earth

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

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

Complete decay ($D \ll 1$) —

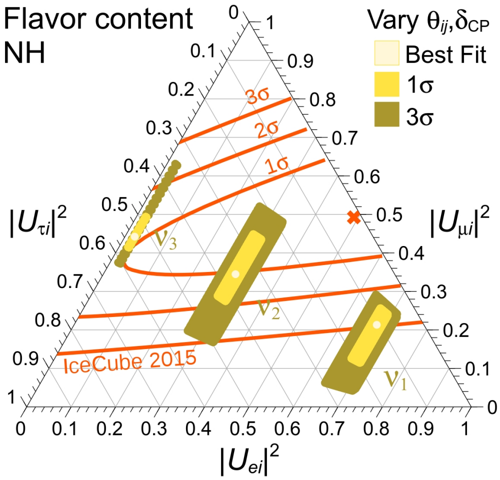
Flavor ratios equal the flavor content of ν_1 (NH) or ν_3 (IH):

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

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:



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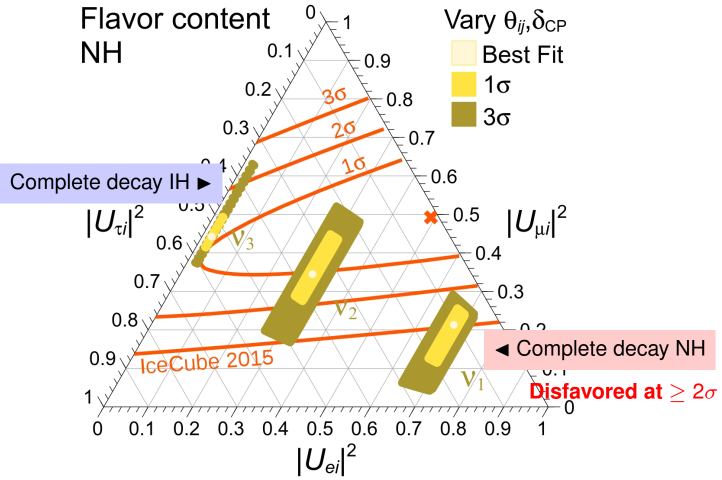

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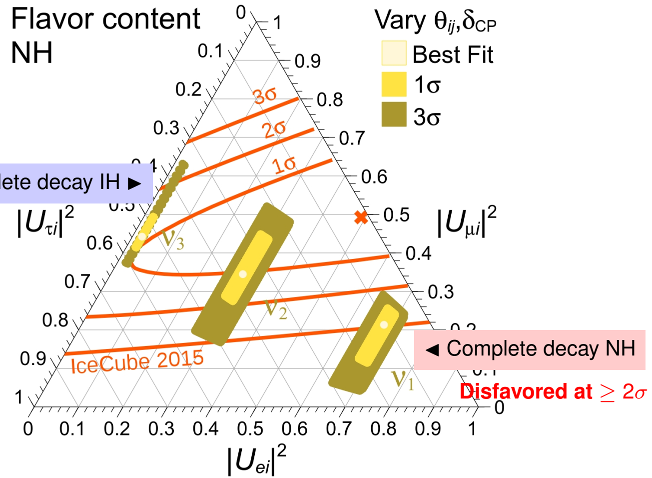


Complete decay IH ▶

◀ Complete decay NH

Disfavored at $\geq 2\sigma$

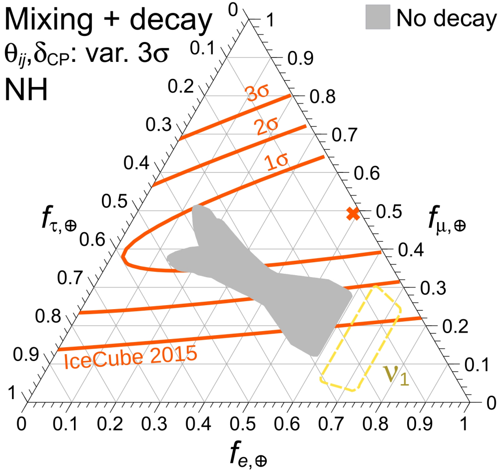
Let us calculate the lifetime bounds in the NH case ▶

NH: lifetime sensitivity 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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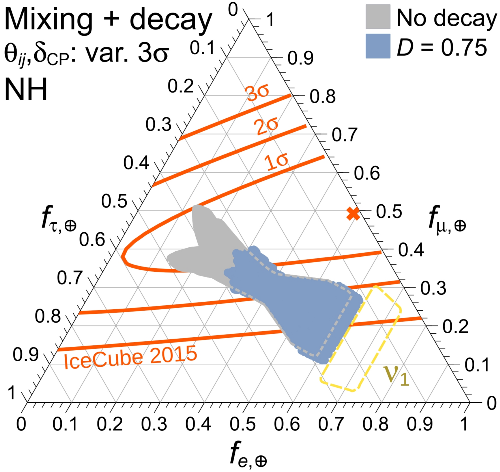

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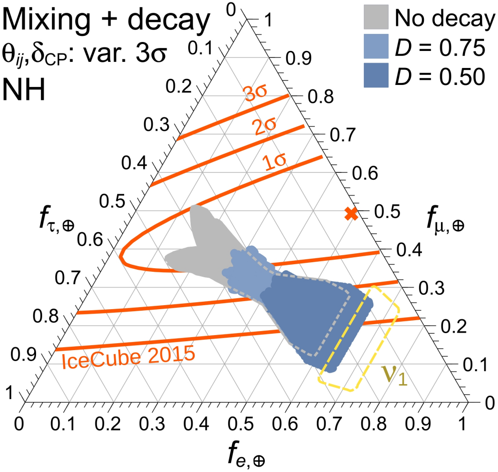

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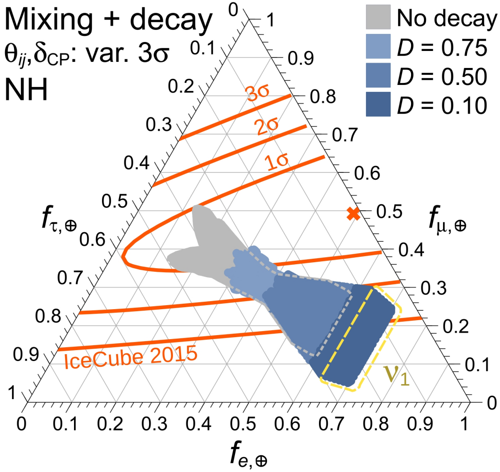

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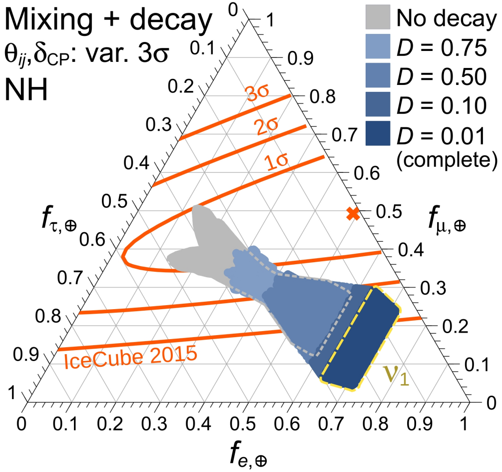

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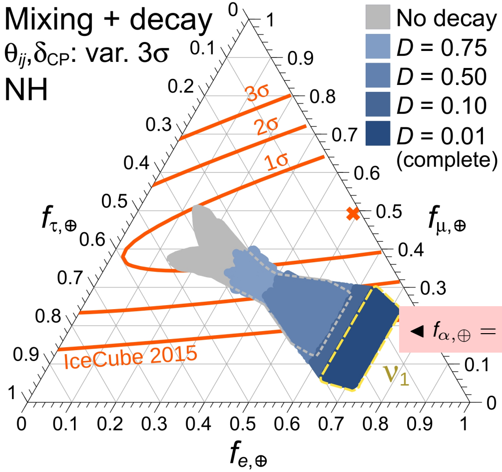
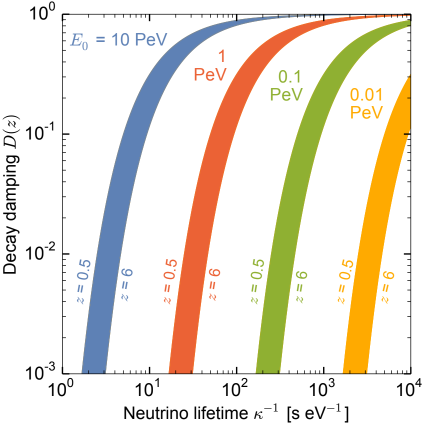
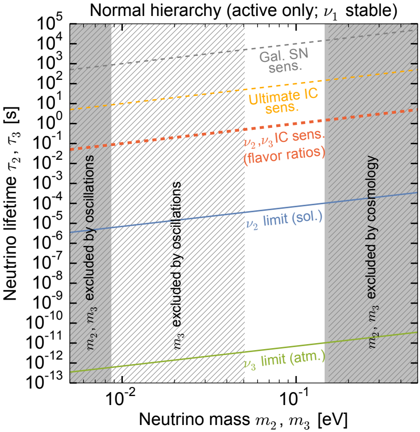


◄ $f_{\alpha,\oplus} = |U_{\alpha 1}|^2$ when $D \lesssim 0.01$

NH: lifetime sensitivity with current IceCube data (II)

$D \lesssim 0.01$ implies $\kappa_2^{-1}, \kappa_3^{-1} \gtrsim 10$ s eV^{-1} at $\gtrsim 2\sigma$

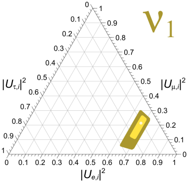




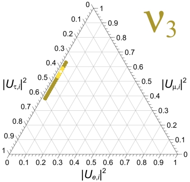
MB, Beacom, Murase, in prep.

Decay: complete vs. incomplete

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

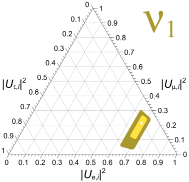


or

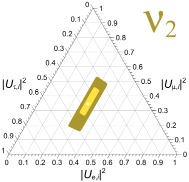


- Incomplete decay: incoherent mixture of ν_1, ν_2, ν_3 reaches Earth

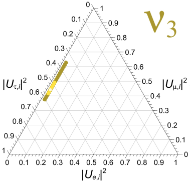
$\alpha\Big($



$\Big) + \beta\Big($



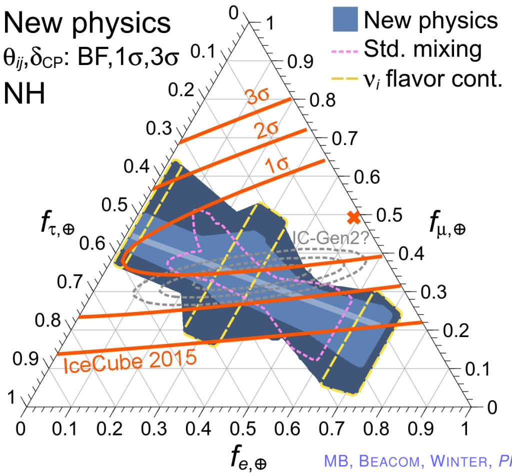
$\Big) + \gamma\Big($



$\Big)$

Region of 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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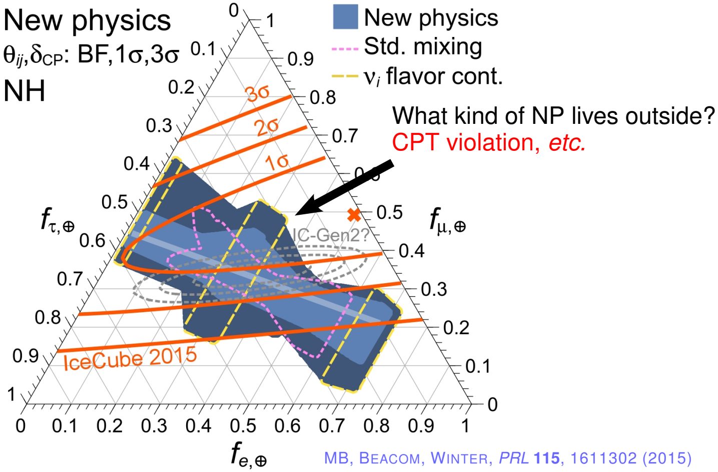

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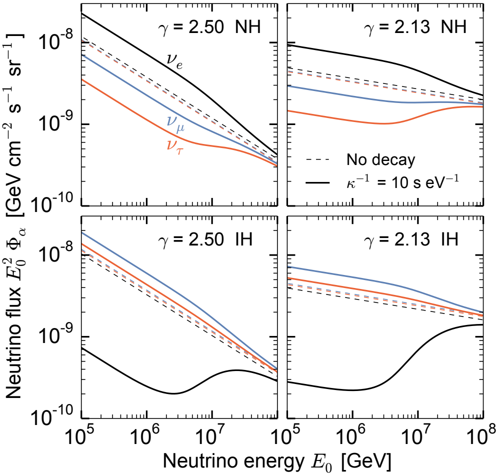


MB, Beacom, Murase, in prep.

What are the decay signatures?

- Complete decay ◄
- Transition region

Where to look for it?

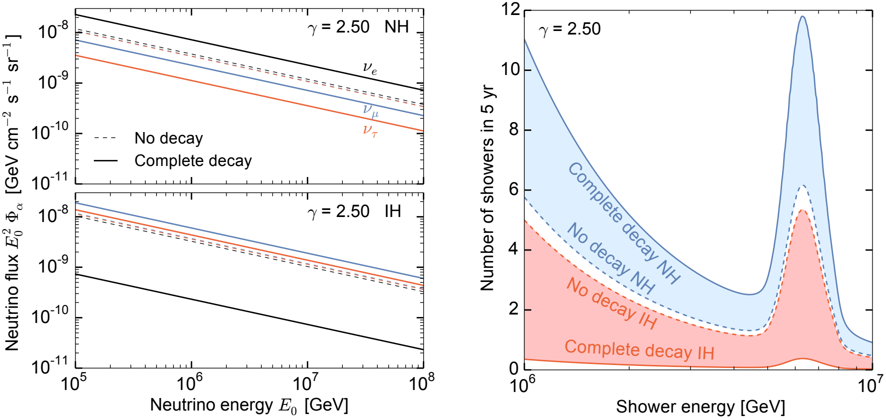
- Flavor ratios
- Absolute number of events of each flavor ◄

The ν_e flux changes the most: IH, complete decay

Decay and the Glashow resonance

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

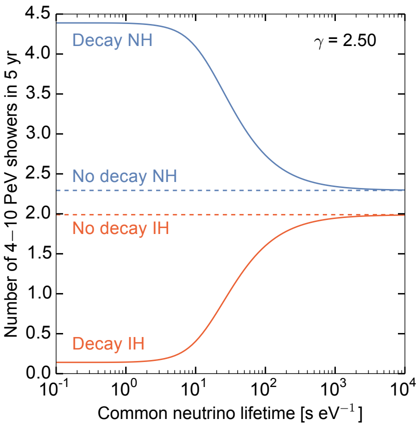
$$\bar{\nu}_e(6.3 \text{ PeV}) + e \rightarrow W \rightarrow \text{hadrons}$$

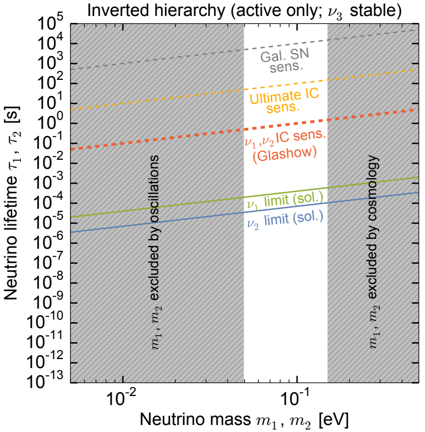


(All-flavor $\nu_\alpha + \bar{\nu}_\alpha$ flux normalized to IceCube combined-likelihood flux.)

IH: lifetime sensitivity with high-energy showers

From observation of even 1 shower: $\kappa_1^{-1}, \kappa_2^{-1} \gtrsim 1$ s eV^{-1}





MB, Beacom, Murase, in prep.

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 — 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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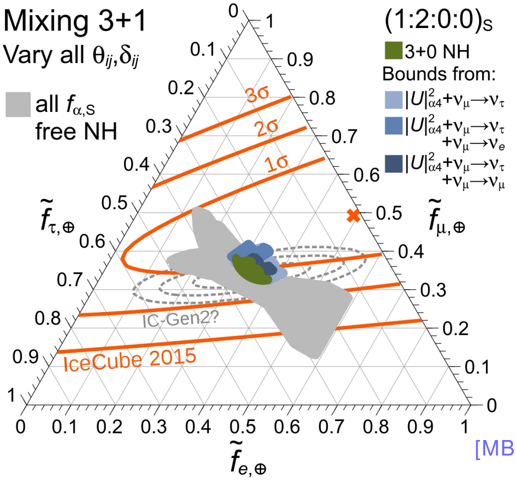
New physics — active-sterile mixing

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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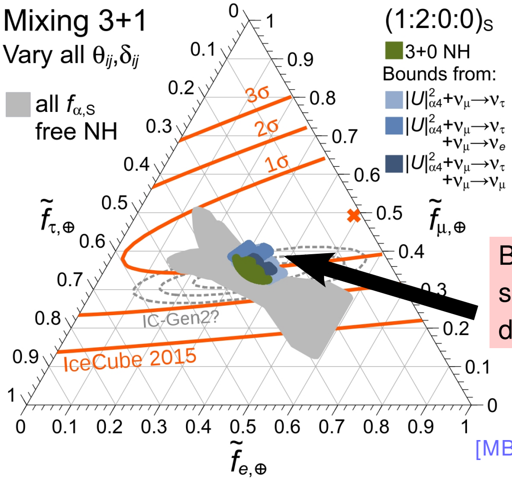


Bounds from T2K, SK, Daya Bay

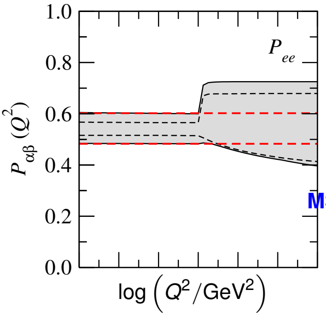
Bounds are too strong for large deviations

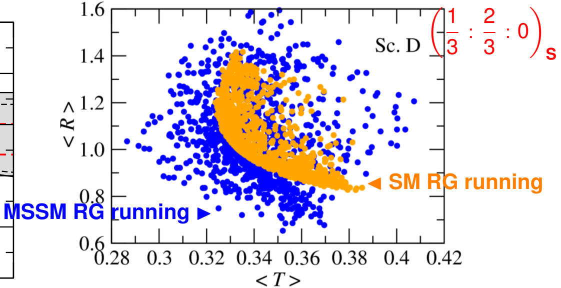
[MB, Coloma]

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:

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





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

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

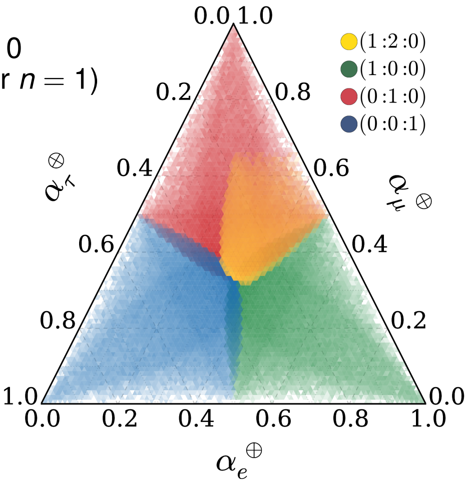
[Argüelles, Katori, Salvadó, *PRL* **115**, 161303 (2015)]
[MB, Gago, Peña-Garay, *JHEP* **1004**, 005 (2010)]
[IceCube Coll., *PRD* **82**, 112003 (2010)]
[Super-K Coll., *PRD* **91**, 052003 (2015)]

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

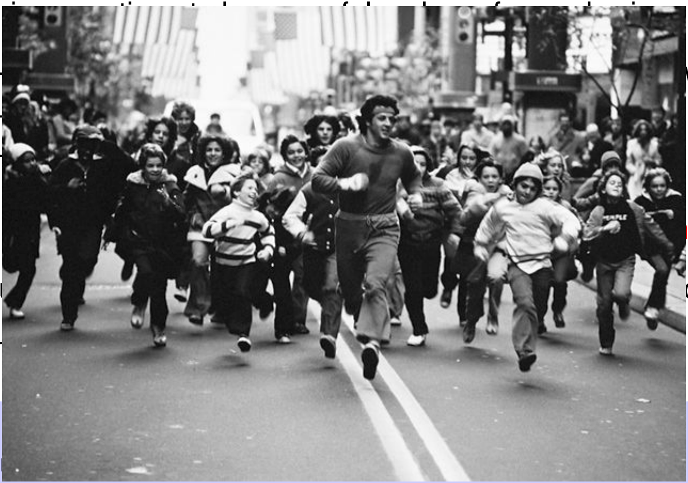
- Neutrinos continue to be powerful probes of new physics
- High-energy astrophysical neutrinos probe a new regime with . . .
  - The highest energies observed
  - The longest baselines observed
- New physics via changes in spectral shape and flavor composition
- IceCube can test neutrino decay with incomplete information
- 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 . . .
  - T
  - T
- New ... position
- IceCu ... on
- Prom

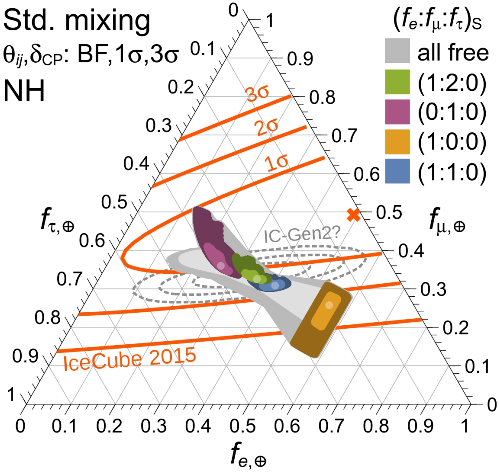
b



Backup slides

Selected source compositions

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



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

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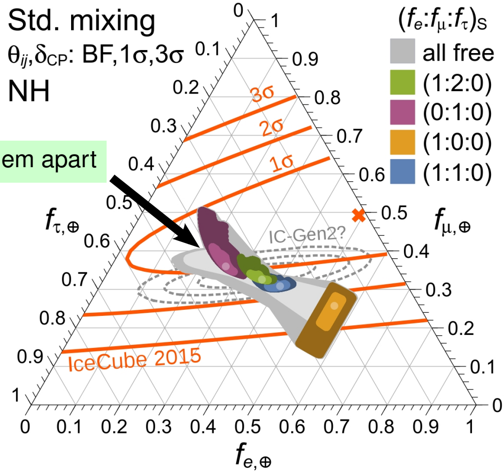

challenging to tell them apart

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

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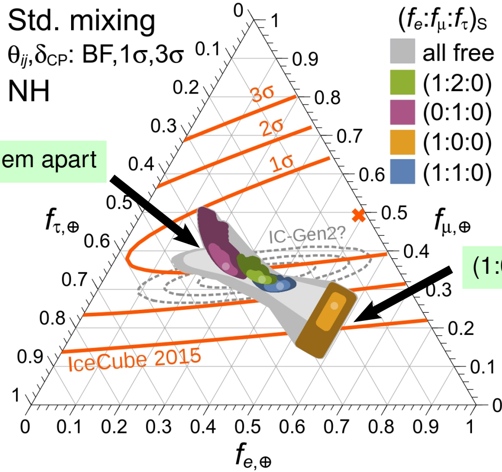
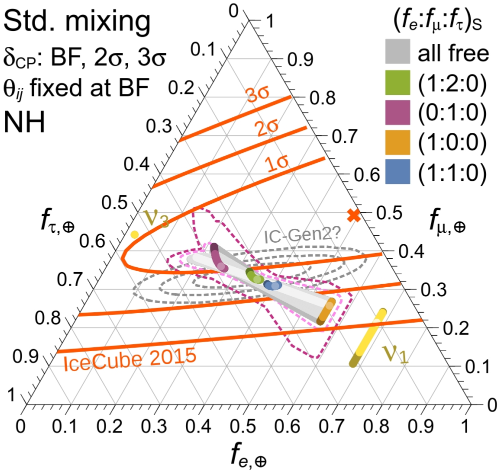


(1:0:0) disfavored at 2σ

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

Perfect knowledge of mixing angles

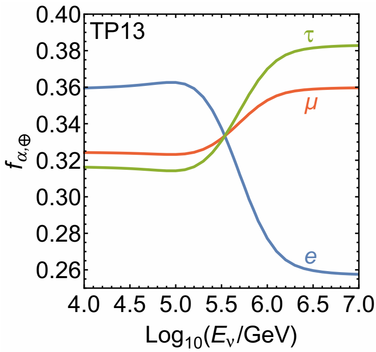
In a few years, we might know all the mixing parameters except δ_{CP}:

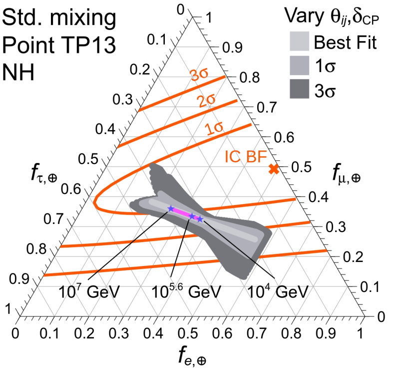


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies

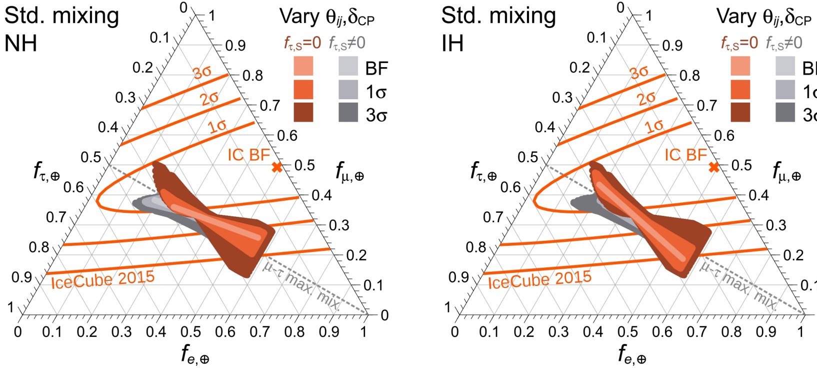




[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

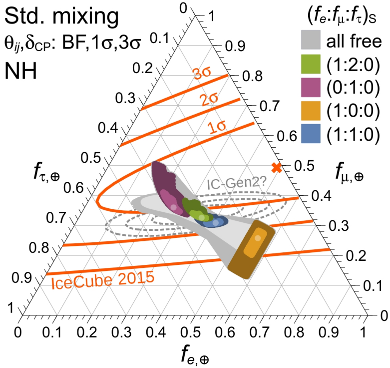
- TP13: $p\gamma$ model, target photons from co-accelerated electrons
  [HÜMMER *et al.*, *Astropart. Phys.* **34**, 205 (2010)]
- Equivalent to different sources types contributing to the diffuse flux
- Will be difficult to resolve
  [KASHTI, WAXMAN, *PRL* **95**, 181101 (2005)] [LIPARI, LUSIGNOLI,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

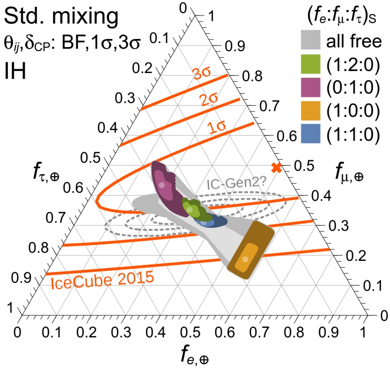
Flavor combinations from std. flavor mixing: NH vs. IH



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

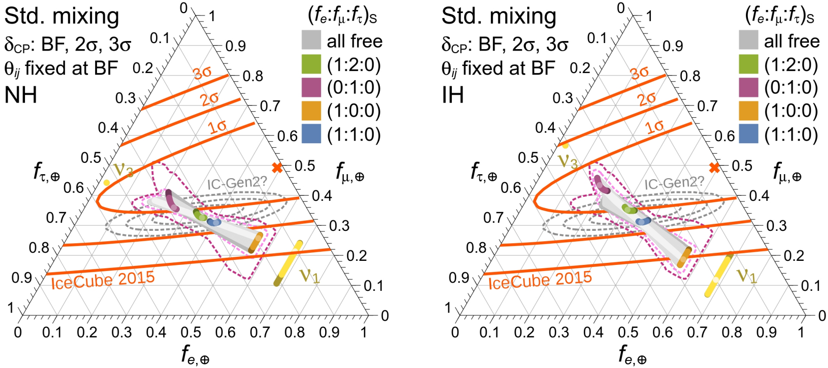
Selected source compositions: NH vs. IH





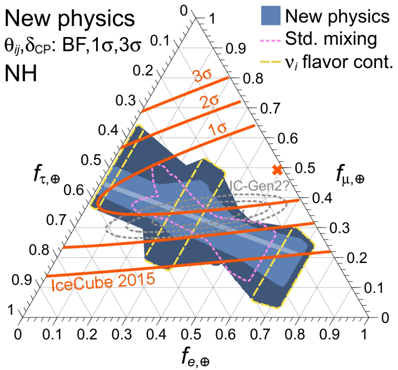
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Perfect knowledge of mixing angles: NH vs. IH



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

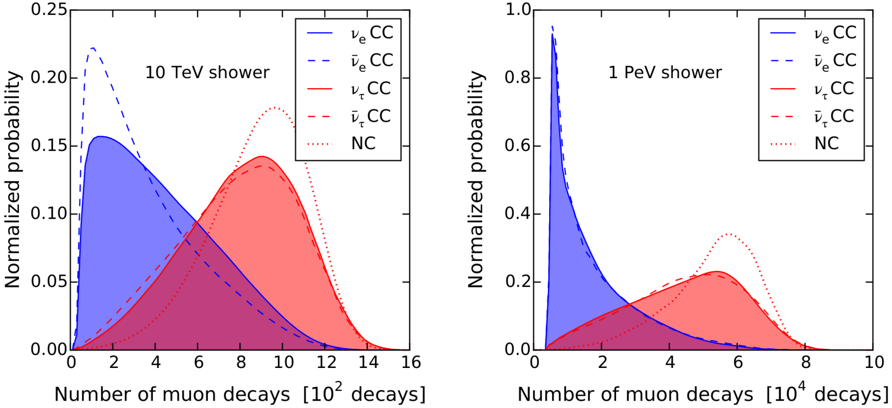
New physics: NH vs. IH



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

How to improve ν_e vs. ν_τ separation?

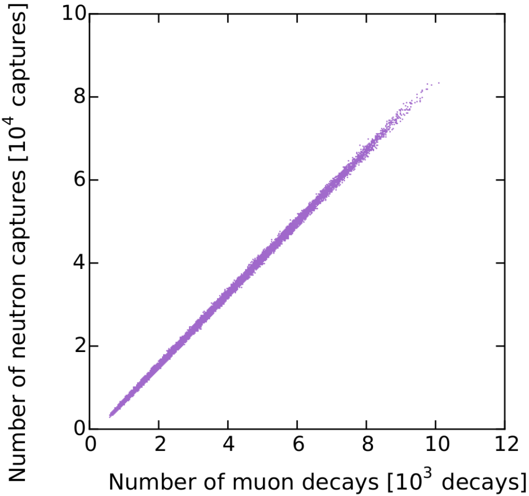
Probability distribution of number of muon decays:



Li, MB, Beacom, 1606.06290

Dispersion: muon decays vs. neutron captures

For 100-TeV showers:

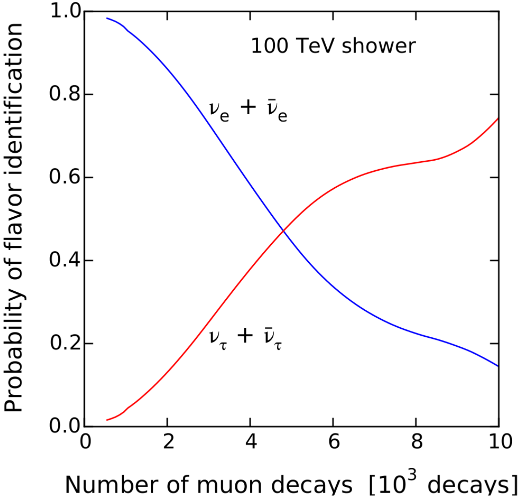


LI, MB, BEACOM, 1606.06290

Probability of flavor identification

Assuming:

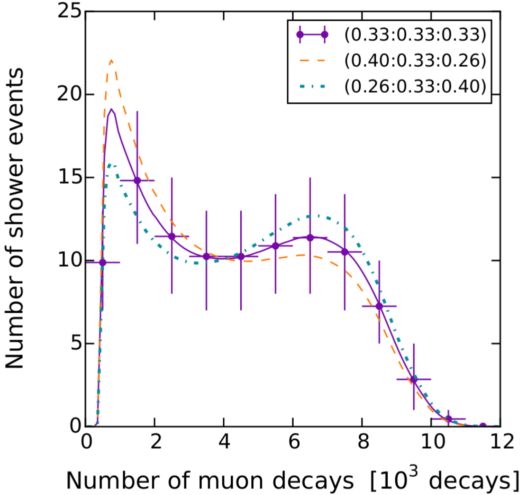
- Flux $\propto E^{-2.5}$
- $\left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)_\oplus$



LI, MB, BEACOM, 1606.06290

Distribution of number of muon decays

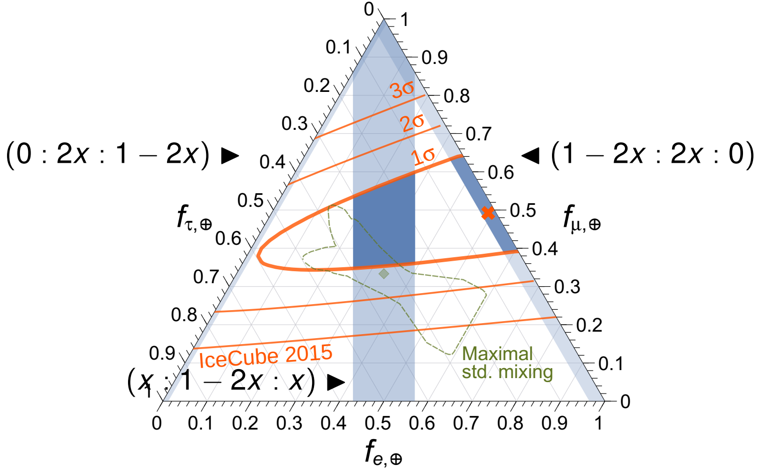
For 100 showers of 100 TeV:



Li, MB, Beacom, 1606.06290

Other flavor assumptions

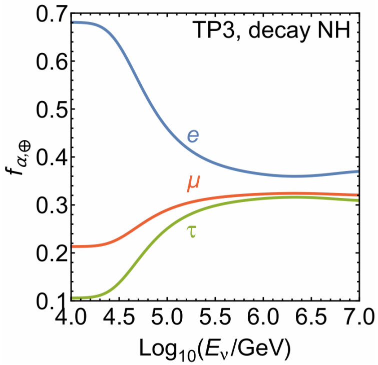
For 100 showers of 100 TeV ($x \in [0, 0.5]$):

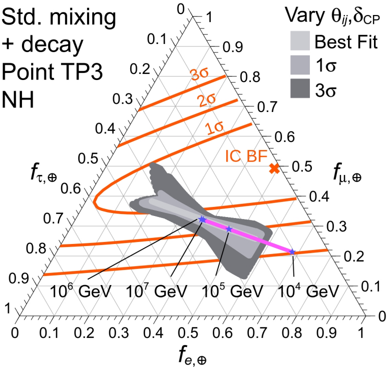


Li, MB, Beacom, 1606.06290

Decay: seeing the energy dependence?

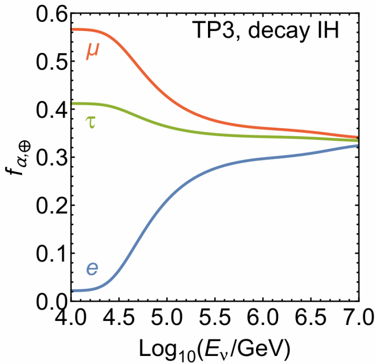
- The effect of decay shows up at low energies
- *e.g.*, for a model of AGN cores [HÜMMER *et al.*, *Astropart. Phys.* **34**, 205 (2010)],
- Would require high statistics + exquisite energy resolution

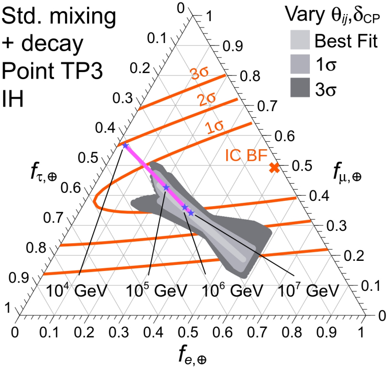




[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Decay in the IH

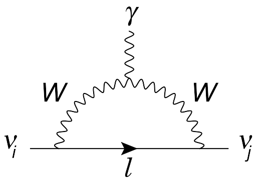


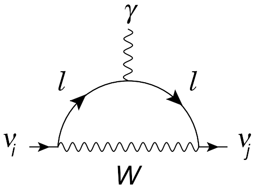


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

One-photon radiative decay

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





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

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

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

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

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

Cosmological effects on decay

There are two cosmological effects:

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

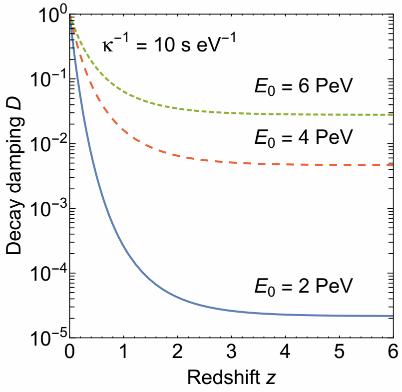
$$\text{energy at production}\,(E) = (1+z)\cdot\text{energy at detection}\,(E_0)$$

Fraction of remaining ν_i at Earth:

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

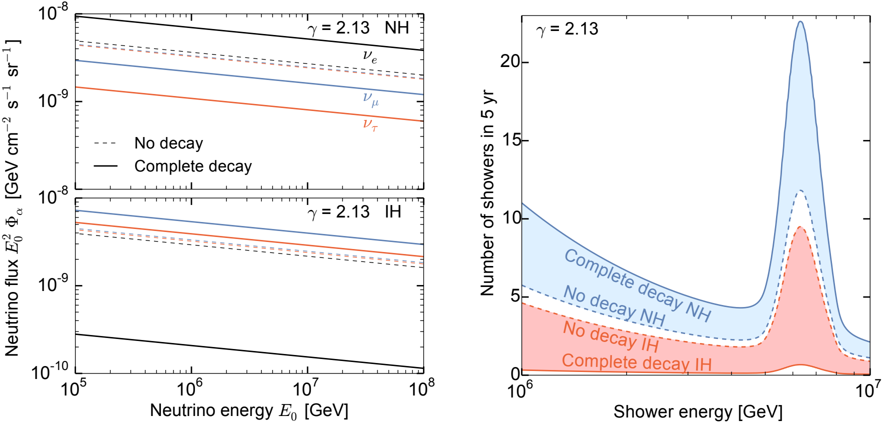
$a \approx 1.71$, $b = 1 - a$, $c \approx 1.27$

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



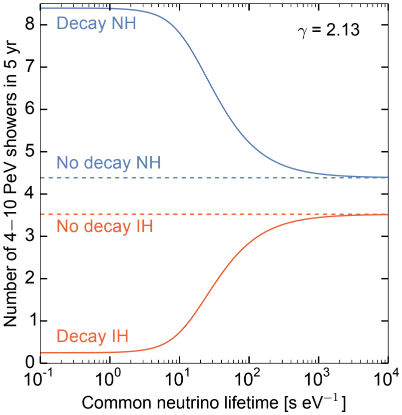
[BAERWALD, MB, WINTER, *JCAP* **1210**, 020 (2012)]

Decay and the Glashow resonance



(No-decay $\nu_\mu + \bar{\nu}_\mu$ flux normalized to IceCube throughgoing 6-yr Northern-hemisphere track flux.)

IH: lifetime sensitivity with high-energy showers



MB, Beacom, Murase, in prep.