

High-energy astrophysical neutrinos: testing ground for new physics

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THE OHIO STATE UNIVERSITY



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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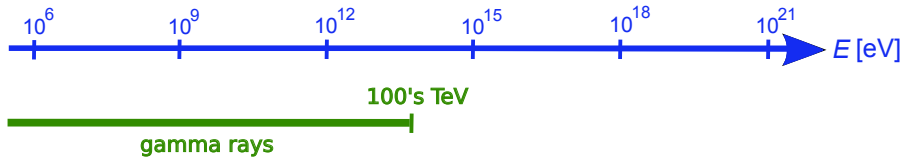


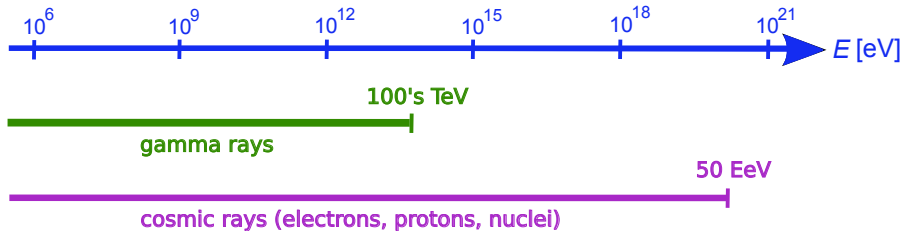
Some reasons why neutrinos are special:

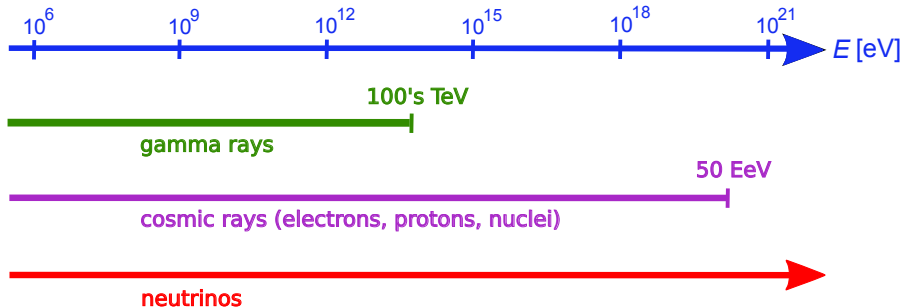
- 1 They are lighter than any other massive particle we know of
- 2 They retain their quantum nature over long distances
- 3 They are notoriously anti-social
- 4 (We believe) they reach higher energies than anything else

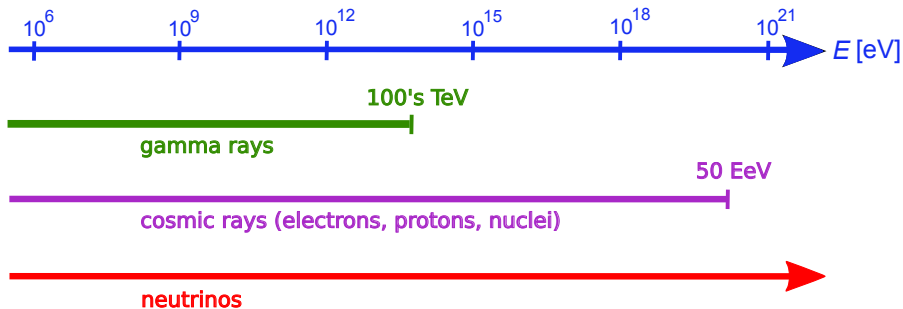
Let's talk energy scales...



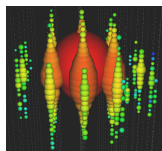
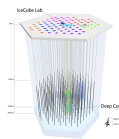




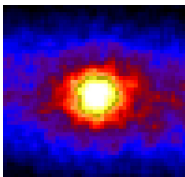
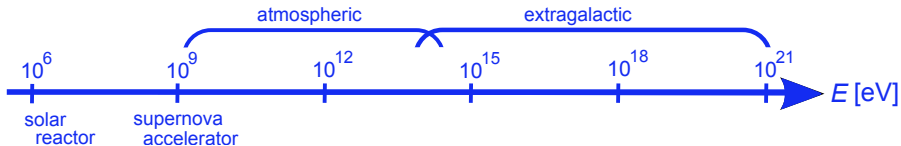


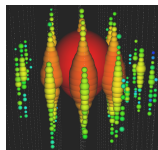
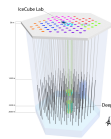
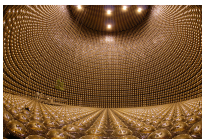


- ⑤ Unlike gamma rays and cosmic rays, neutrinos have flavor

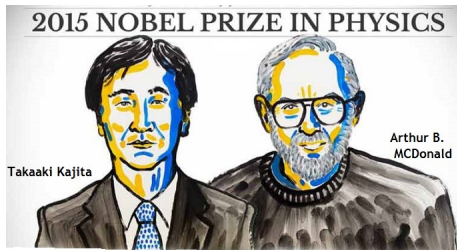
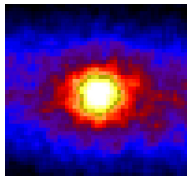
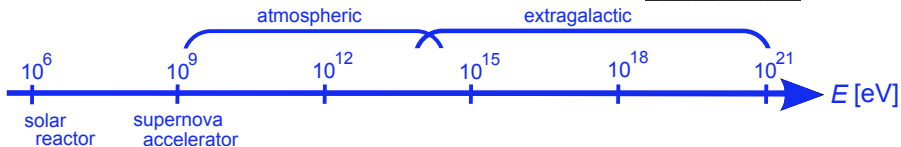


2013+





2013+



Next ν -Nobel for high-energy ν 's?

High-energy astrophysical neutrinos: they exist!

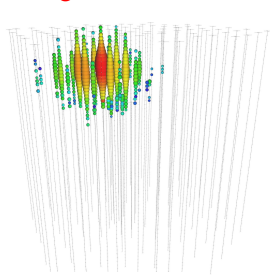
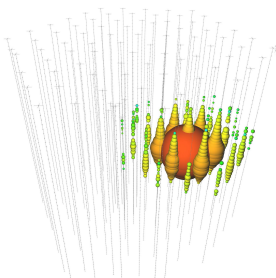
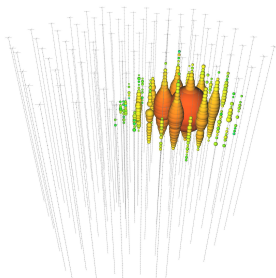
The era of neutrino astronomy has begun!

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



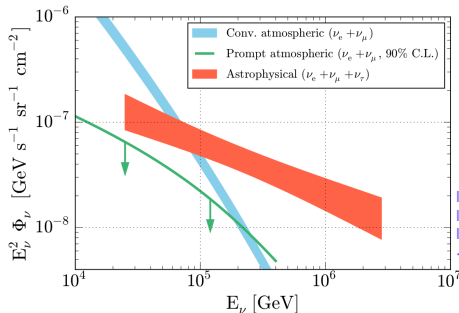
...and 51 more events > 30 TeV



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

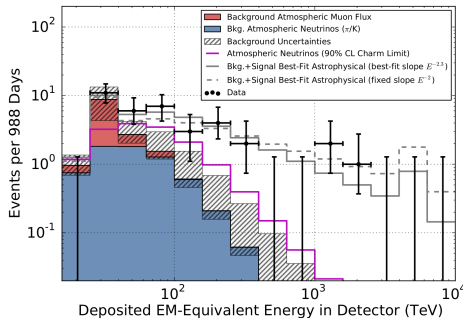
Diffuse per-flavor astrophysical flux [IceCube 2015]:

$$\Phi_\nu = \left(6.7^{+1.1}_{-1.2} \cdot 10^{-18}\right) \left(\frac{E}{100 \text{ TeV}}\right)^{-(2.5 \pm 0.09)} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

High-energy astrophysical neutrinos: they exist!

The era of neutrino astronomy has begun!

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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]:

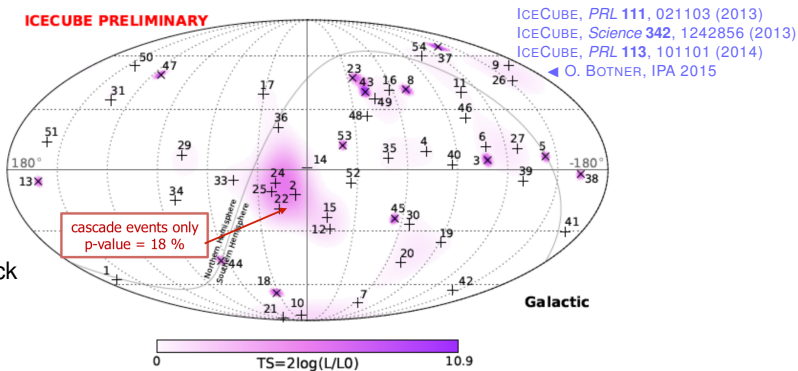
$$E^2 \Phi_\nu = (0.95 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (per flavor)}$$

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

Arrival directions compatible with an **isotropic** distribution –

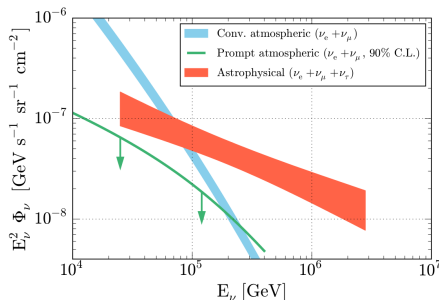
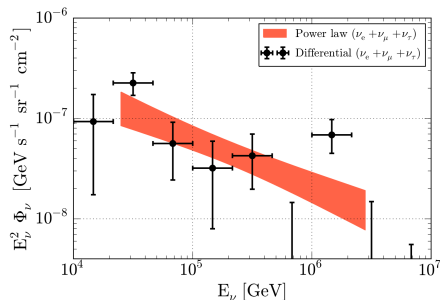


– no association with sources found **yet**

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

1 They are the **most energetic** ones observed

- ▶ 10s TeV to few PeV (vs. $\lesssim 350$ GeV man-made)
- ▶ Probe new physics at scales that cannot be produced at Earth

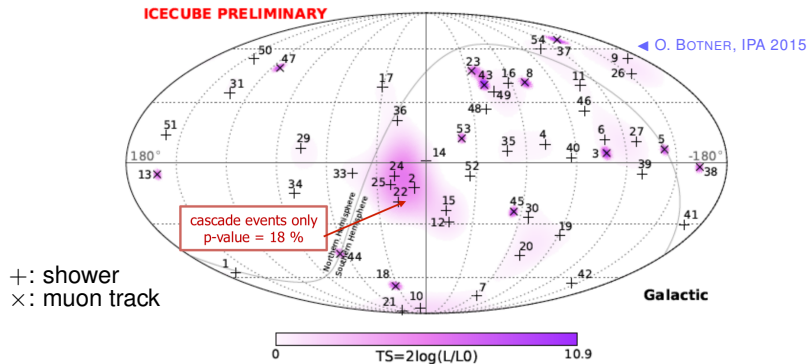


[IceCube Coll., *ApJ* **809**, 98 (2015)]

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

② They have the **longest baselines** observed

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



What we know / don't know

What we know

- ▶ compatible with isotropy
- ▶ power-law $\propto E^{-2.5}$
- ▶ not coincident with transient sources (*e.g.*, GRBs)
- ▶ not correlated with known sources
- ▶ flavor composition:
compatible with equal proportion of ν_e , ν_μ , ν_τ
- ▶ also: no prompt atmospheric neutrinos

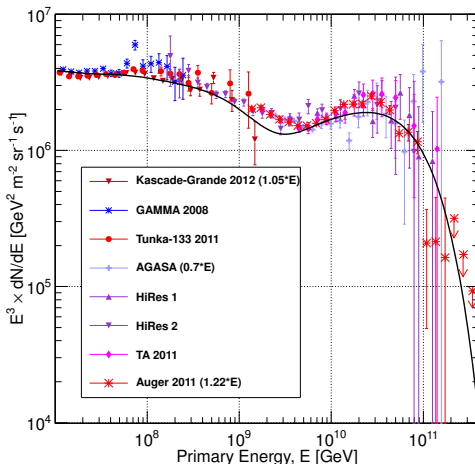
What we don't know

- ▶ what are the sources?
- ▶ what is the production mechanism?
- ▶ is there a cut-off at 2 PeV?
- ▶ what is the Galactic contribution, if any?
- ▶ what is the precise relation to UHE cosmic rays?
- ▶ **what is the precise flavor composition of the flux?**
- ▶ **is there new physics?**

...but we have good ideas on all

Why did we expect high-energy neutrinos?

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

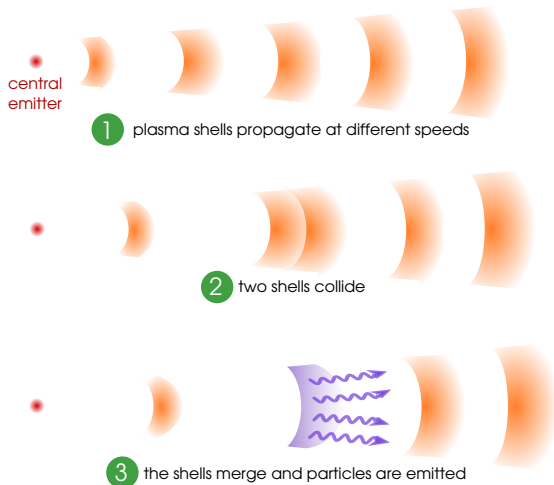


GAISSER, STANEV, TILAV,
Front. Phys. China **8**, 748 (2013)

Cosmic-ray accelerators should also produce neutrinos ►

HE particles from astrophysical sources

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



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

power law $\sim E^{-\alpha p}$

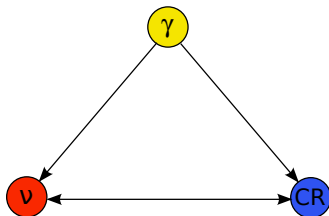
broken power law

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

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

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

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



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

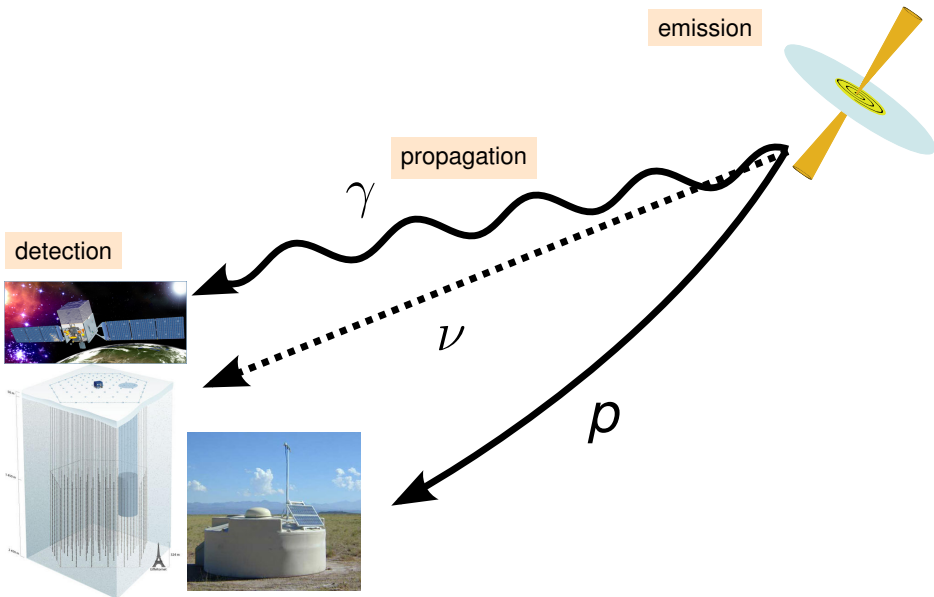
[AHLERS *et al.*, *Astropart. Phys.* **35**, 87 (2011)] [ICECUBE COLL., *Nature* **484**, 351 (2012)]

But we can do better by letting the p 's escape without interacting

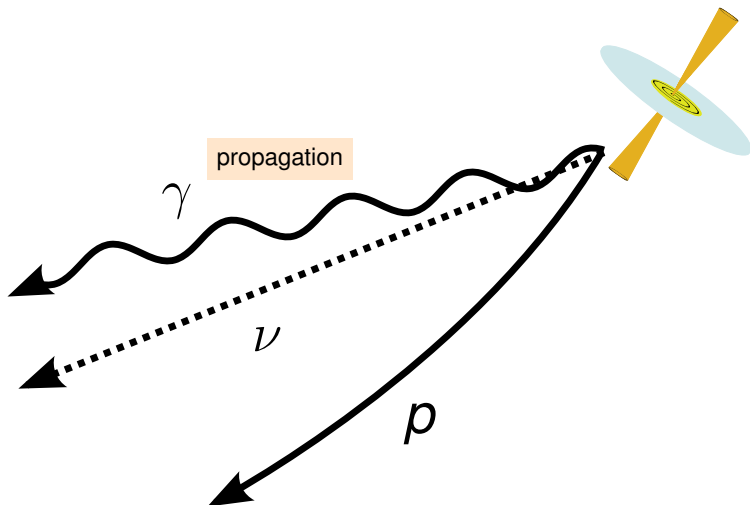
[BAERWALD, MB, WINTER, *ApJ* **768**, 186 (2013)] [BAERWALD, MB, WINTER, *Astropart. Phys.* **62**, 66 (2015)]

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

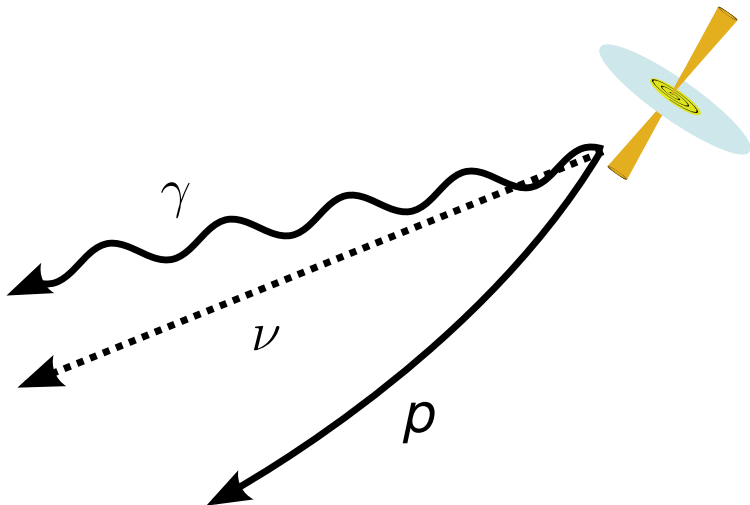
From the sources to us



From the sources to us



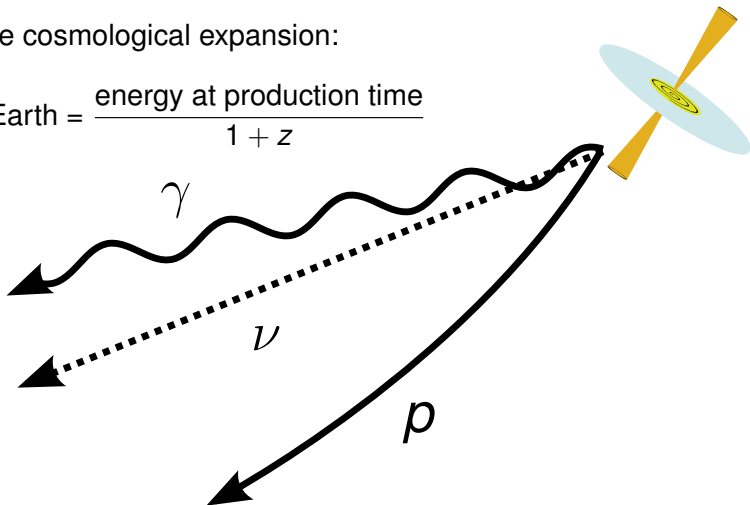
From the sources to us



From the sources to us

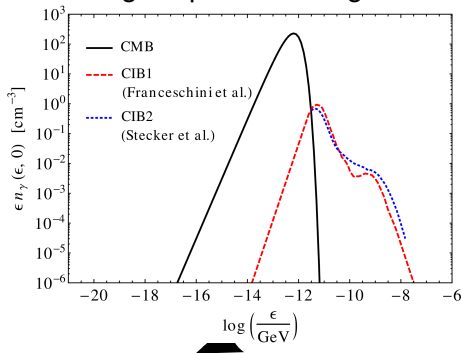
Because of the cosmological expansion:

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

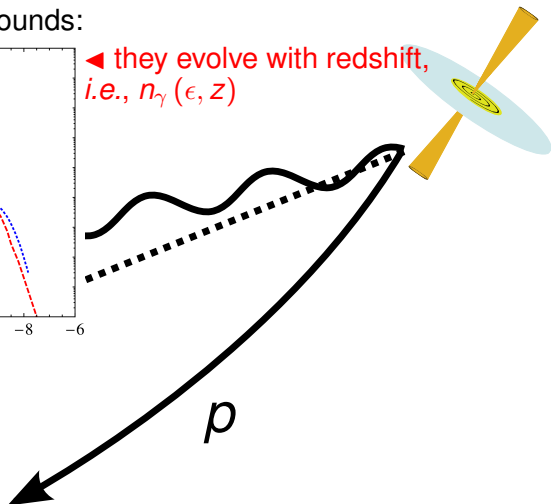


From the sources to us

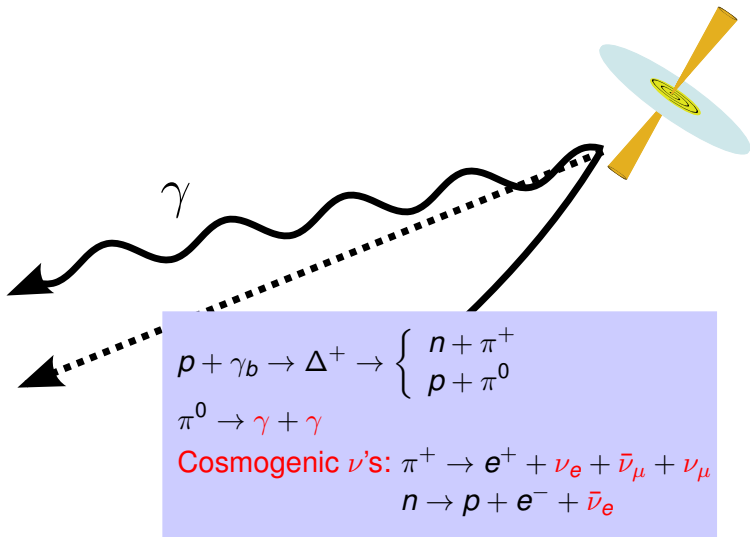
Cosmological photon backgrounds:



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



From the sources to us

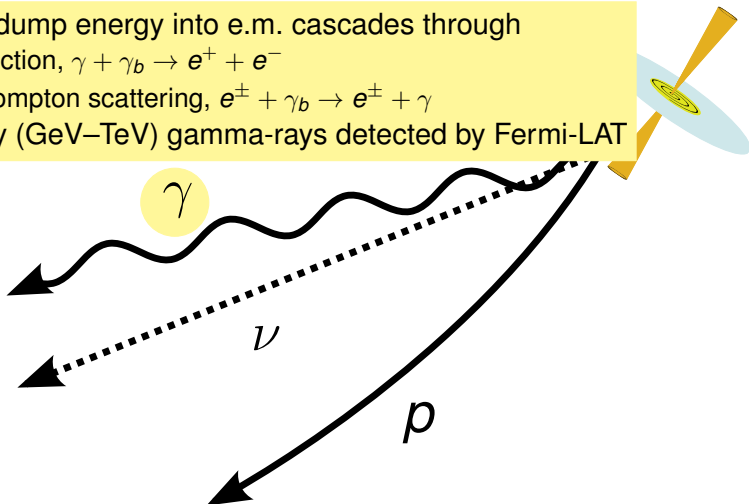


From the sources to us

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

- ▶ pair production, $\gamma + \gamma_b \rightarrow e^+ + e^-$
- ▶ inverse Compton scattering, $e^\pm + \gamma_b \rightarrow e^\pm + \gamma$

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



From the sources to us

p 's are deflected by extragalactic magnetic fields

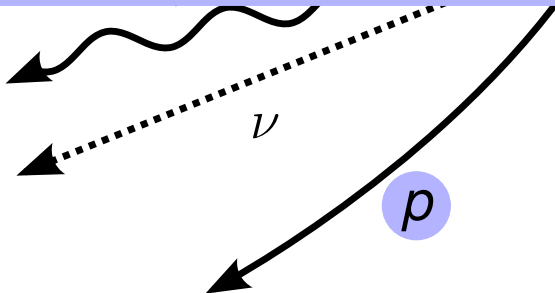
⇒ except for the most energetic ones, they are **not** expected to point back to the sources

} Pierre Auger found weak correlation with known AGN positions

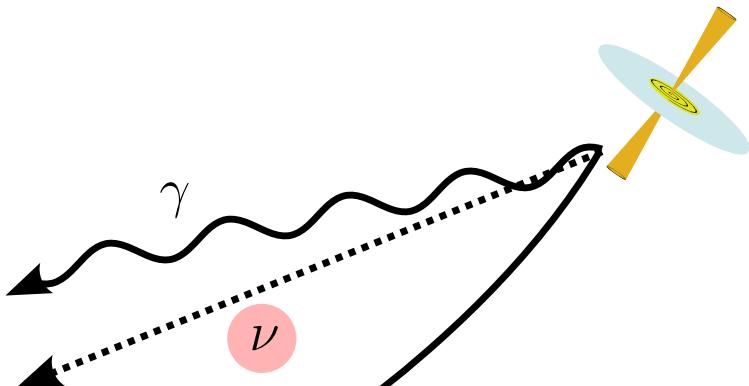
They lose energy through:

- ▶ pair production, $p + \gamma_b \rightarrow p + e^+ + e^-$
- ▶ 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 $\nu_\alpha \rightarrow \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

Flavor oscillations redistribute the fluxes

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

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

The need for km-scale neutrino telescopes

Expected ν flux from accelerators of UHECRs (WAXMAN & BAHCALL 97–98):

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

Diagram annotations:

- A green box labeled "pion production efficiency" points to f_π .
- A red box labeled " $\dot{\epsilon}_{\text{CR}} [10^{10}, 10^{12}]$ " is part of the fraction.
- A red box labeled "local UHECR energy density" points to the fraction.

Integrated flux above 1 PeV:

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

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

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

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

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

Therefore, we need km-scale detectors, like IceCube

Where to look for new physics

- ▶ New physics in the neutrino sector could affect the
 - ▶ **production**; and/or
 - ▶ **propagation**; and/or
 - ▶ detection
- ▶ Look for modifications in . . .
 - ▶ The **shape** of the neutrino spectrum
(e.g., via secret neutrino interactions)
 - ▶ The **flavor composition** of the spectrum
(e.g., via neutrino decay, Lorentz invariance violation, . . .)

[BARENBOIM, QUIGG, *PRD* **67**, 073024 (2003)]

[BEACOM, BELL, HOOPER, PAKVASA, WEILER, *PRL* **90**, 181301 (2003)]

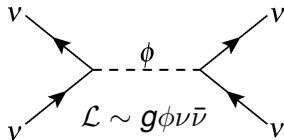
[MALTONI, WINTER, *JHEP* **07**, 064 (2008)]

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

[PAGLIAROLI, PALLADINO, VISSANI, VILLANTE 1506.02624]

New physics: effect on the spectral shape

Secret neutrino interactions between astrophysical neutrinos and the cosmic neutrino background

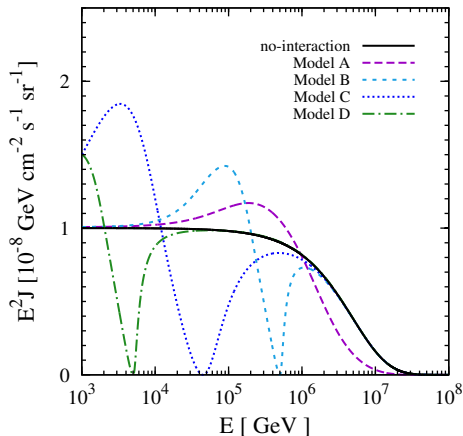


Cross section:

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

Resonance at

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

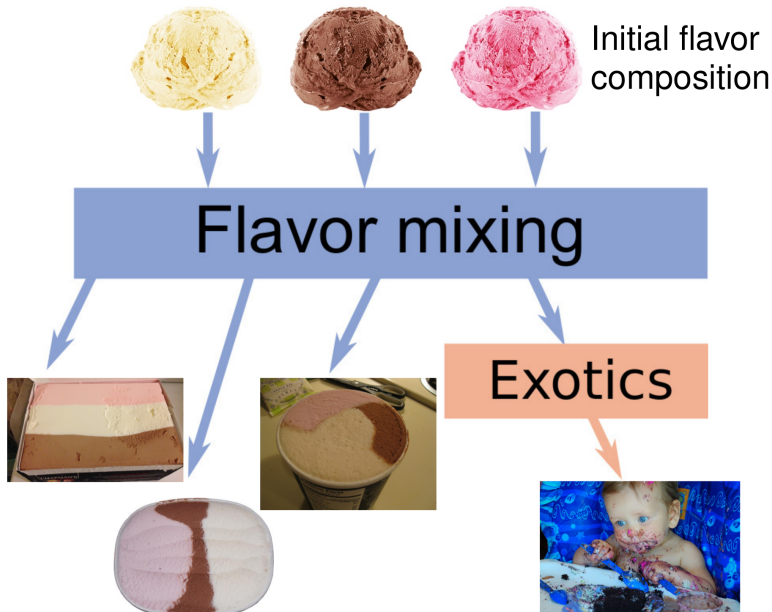


[NG & BEACOM, *PRD* **6**, 065035 (2014)]

[CHERRY, FRIEDLAND, SHOEMAKER, 1411.1071]

[BLUM, HOOK, MURASE, 1408.3799]

New physics: effect on the flavor composition



Flavor mixing in high-energy astrophysical neutrinos

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

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

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

- ▶ Therefore, oscillations are very rapid
- ▶ They average out after only a few oscillations lengths:

$$\sin^2(\dots) \rightarrow 1/2, \quad \sin(\dots) \rightarrow 0$$

Hence, for high-energy astrophysical neutrinos:

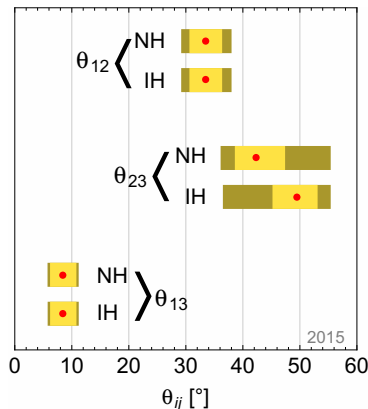
$$\langle P_{\alpha\beta} \rangle = \sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2 \quad \blacktriangleleft \text{ incoherent mixture of mass eigenstates}$$

Flavor content of the mass eigenstates (I)

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

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

- ▶ 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

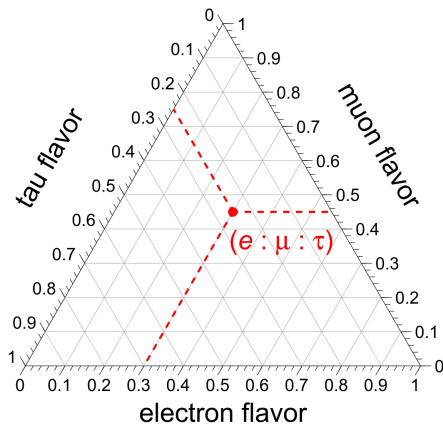
ν_2 : $\sim$ equal proportion of each

ν_3 : 3% ν_e , 40 – 60% ν_μ , 40 – 60% ν_τ

“Flavor triangle” or Dalitz/Mandelstam plot

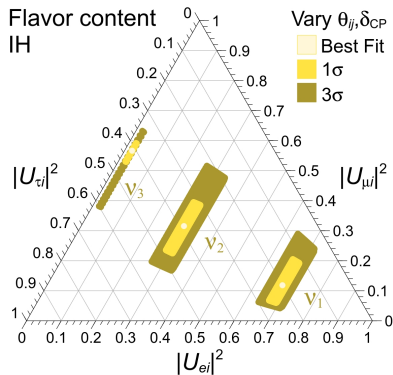
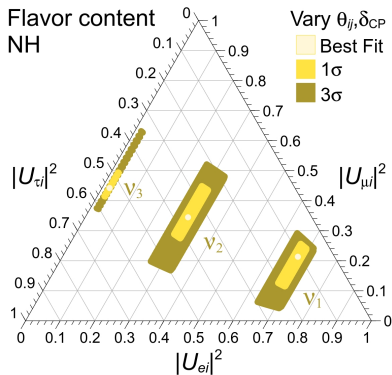
Assumes underlying unitarity: sum of projections on each axis is 1

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:

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

- ▶ Flavor ratios at the **source**: $(f_e : f_\mu : f_\tau)_S \approx (1/3 : 2/3 : 0)$
- ▶ At **Earth**, due to flavor mixing:

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

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

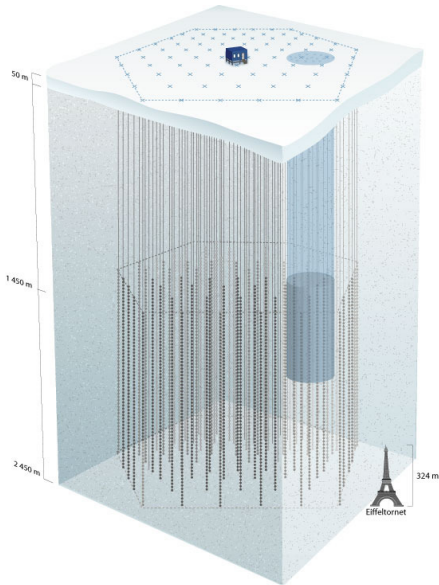
- ▶ Other compositions at the source:

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

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

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

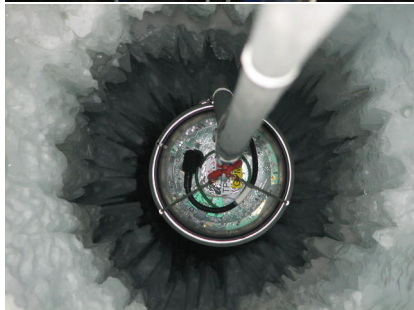
Detecting the neutrinos: IceCube



IceCube: km³ 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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IceCube: km³ in-ice South Pole
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- ▶ νN interactions ($N = n, p$)
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- ▶ depths between 1450 m and
2450 m

How does IceCube see flavor?

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

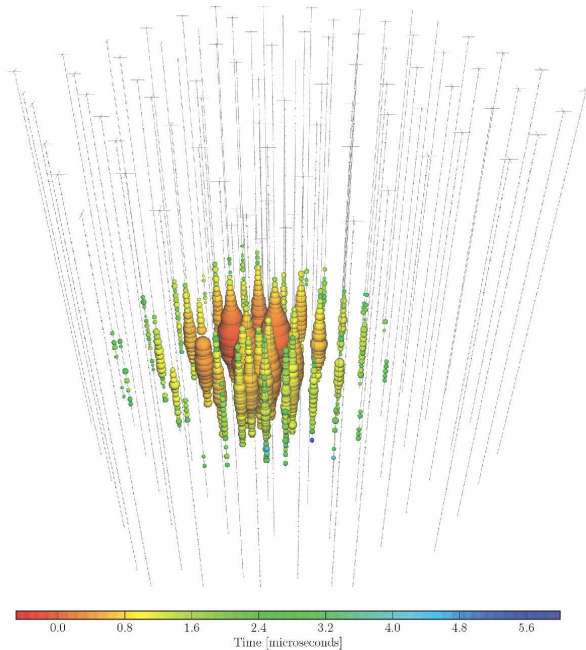
- ▶ **Showers:** generated by CC ν_e or ν_τ ; or by NC ν_X
- ▶ **Muon tracks:** generated by CC ν_μ

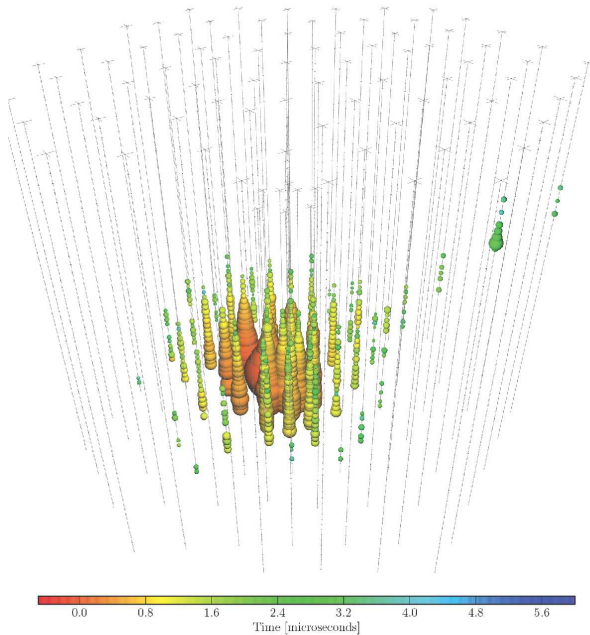
(Some muon tracks can be mis-reconstructed as showers)

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

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

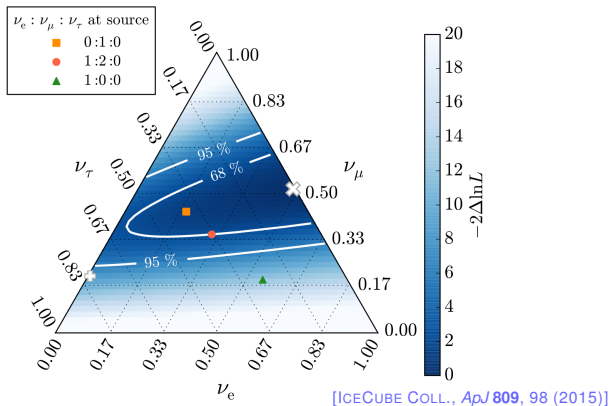
Flavor ratios must be inferred from the number of showers and tracks





IceCube analysis of flavor composition

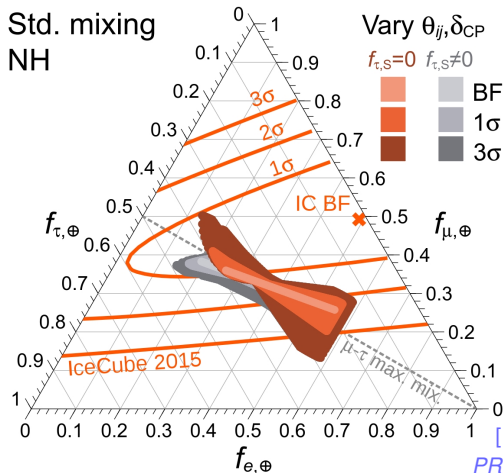
Using contained events + throughgoing muons:



- ▶ 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

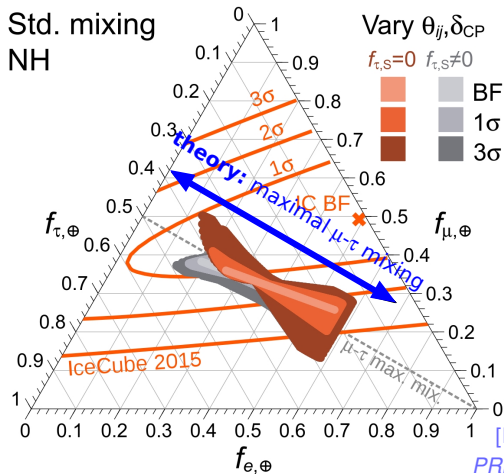
But first: what flavor region is accessible with standard mixing?



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

Flavor combinations at Earth from std. mixing

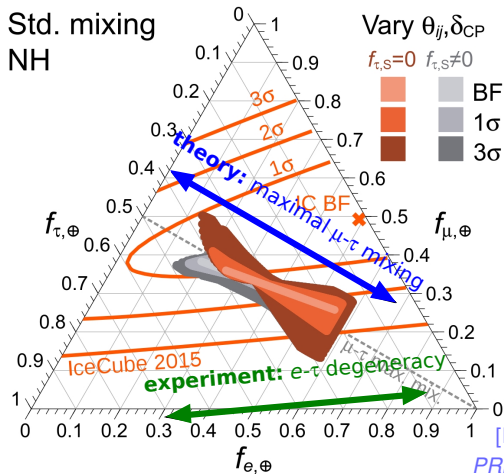
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Flavor combinations at Earth from std. mixing

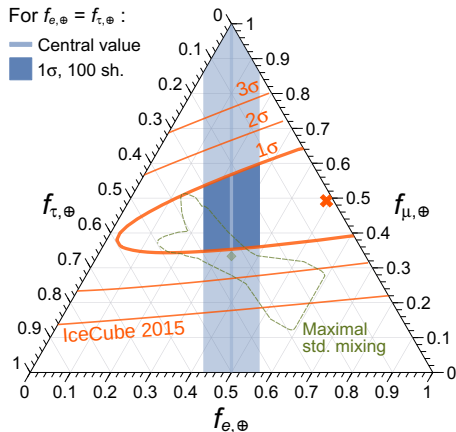
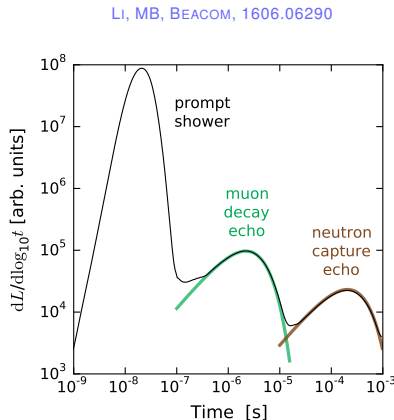
But first: what flavor region is accessible with standard mixing?



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

Side note: improving the flavor measurements

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



Using 100 showers of 100 TeV, this achieves $\times 9$ improvement
— Otherwise, $\times 81$ exposure is needed (320 yr of IceCube or 54 yr of Gen2)

Standard Model decay modes

SM decay modes are negligible:

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

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

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

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

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

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

All lifetimes $\gg$ age of Universe

– therefore, it is hopeless to look for 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 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

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

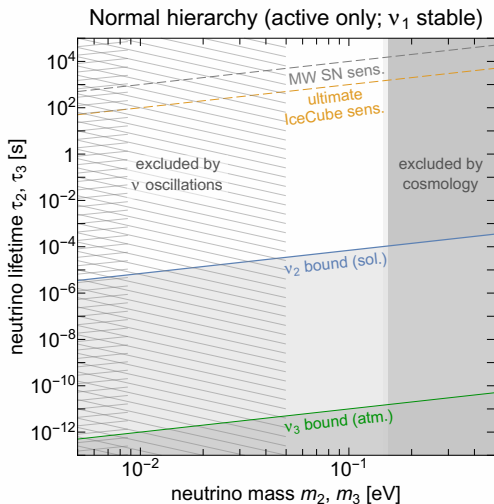
m_i, τ_i are the mass and (rest-frame) lifetime of ν_i ▲ For very long L , this will have redshift corrections

- ▶ Neutrinos with known L and E_ν are sensitive to “lifetimes” of

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

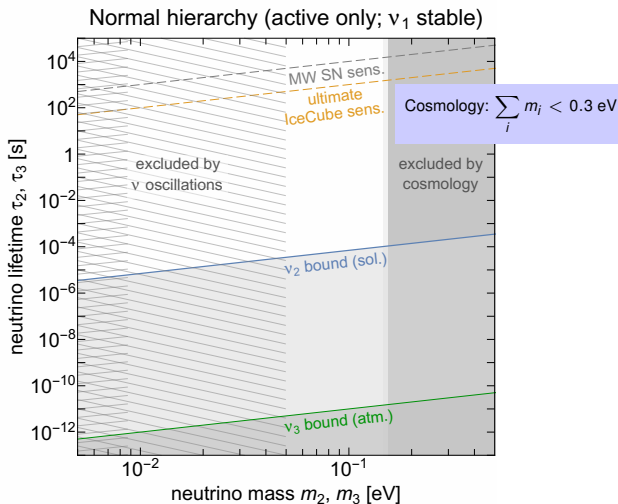
Current lifetime limits

- ▶ ν_1 : $\gtrsim 4 \cdot 10^{-3} \text{ s eV}^{-1}$ (solar, [BERRYMAN et al. 2014](#))
- ▶ ν_2 : $\gtrsim 7 \cdot 10^{-3} \text{ s eV}^{-1}$ (solar, [BERRYMAN et al. 2014](#))
- ▶ ν_3 : $\gtrsim 7 \cdot 10^{-11} \text{ s eV}^{-1}$ (atmospheric, [GONZÁLEZ-GARCÍA & MALTONI 2008](#))



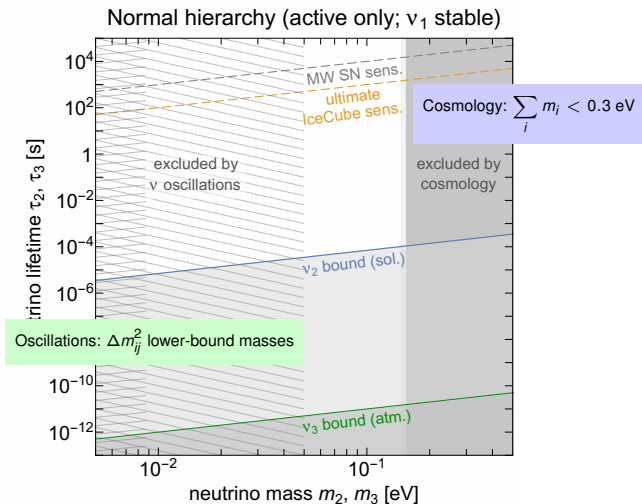
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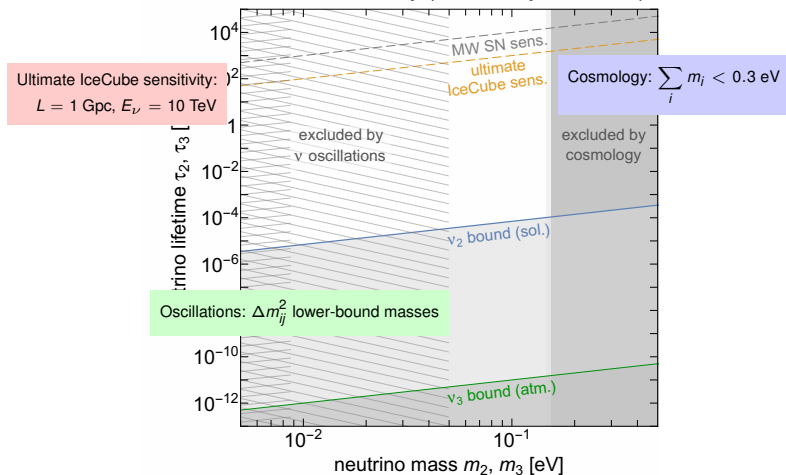
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Normal hierarchy (active only; ν_1 stable)

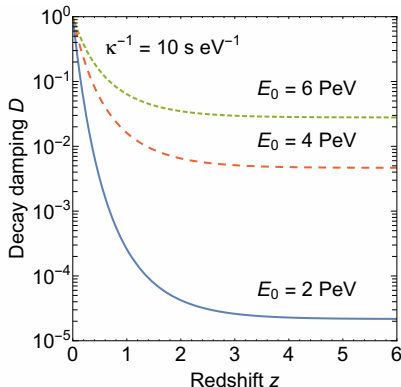


Decay affects the flavor ratios

fraction of ν_i that reach Earth

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

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



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

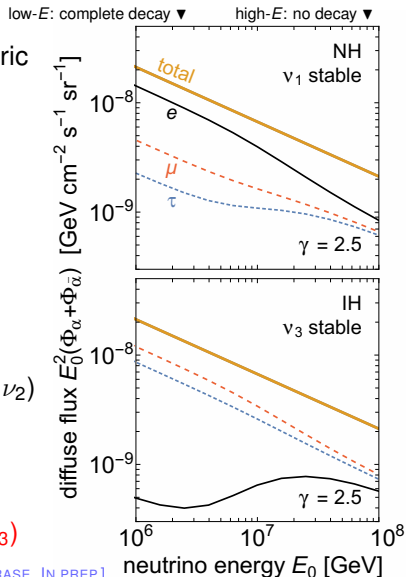
$$f_{\alpha,\oplus} = \begin{cases} |U_{\alpha 1}|^2, & \text{for NH} \\ |U_{\alpha 3}|^2, & \text{for IH} \end{cases}$$

Flavor ratios equal flavor content of the one stable eigenstate

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

Seeing decay in the flavor fluxes

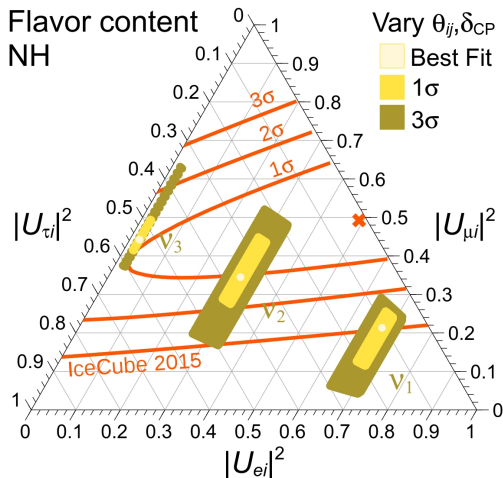
- ▶ Diffuse $\nu + \bar{\nu}$ flux from population of generic sources, normalized to IceCube flux
- ▶ Assuming $(f_{e,S} : f_{\mu,S} : f_{\tau,S}) = \left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)$
- ▶ Fixed lifetime of 10 s eV^{-1}
- ▶ Decay NH: $\nu_2, \nu_3 \rightarrow \nu_1$
 - ▶ ν_μ, ν_τ depleted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



[MB, BEACOM, MURASE, IN PREP.]

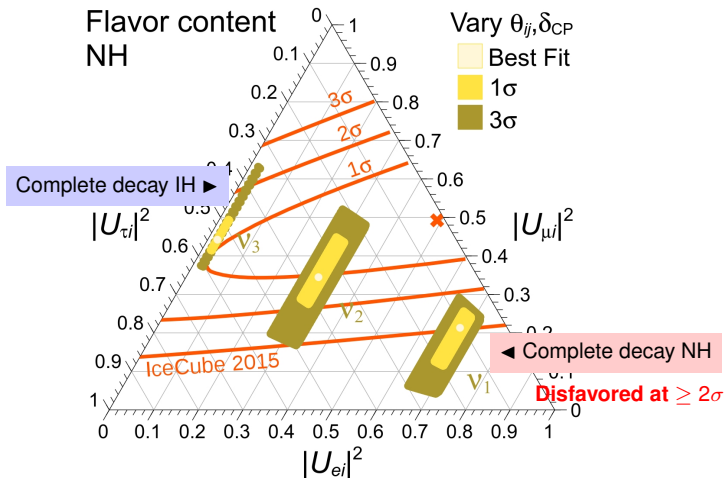
Is complete decay allowed by IceCube?

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



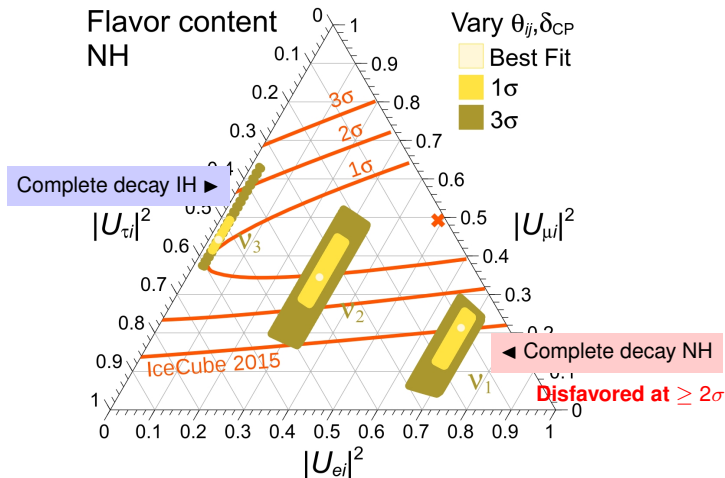
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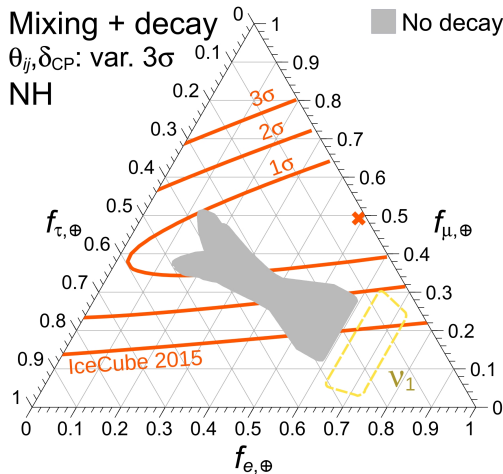
Let us calculate the lifetime bounds in the NH case ►

NH: lifetime limits with **current** IceCube data (I)

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

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

Assume equal lifetimes of ν_2, ν_3

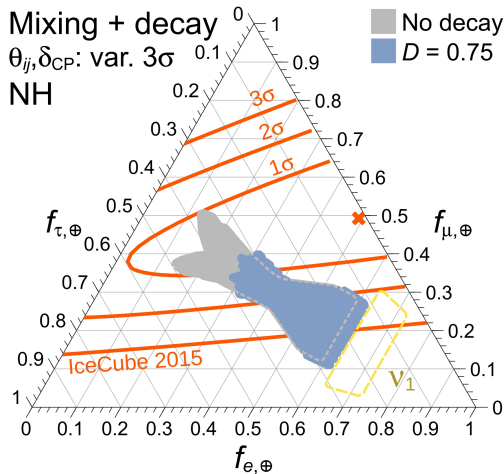


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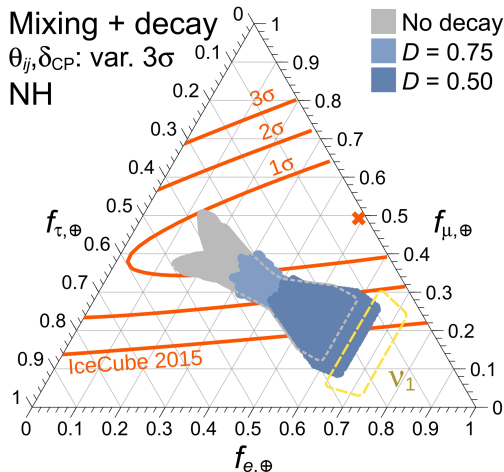


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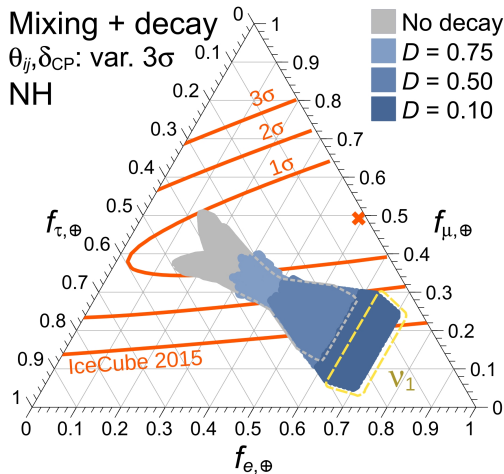


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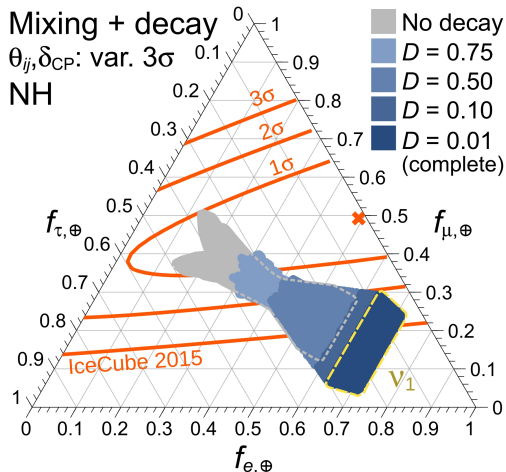


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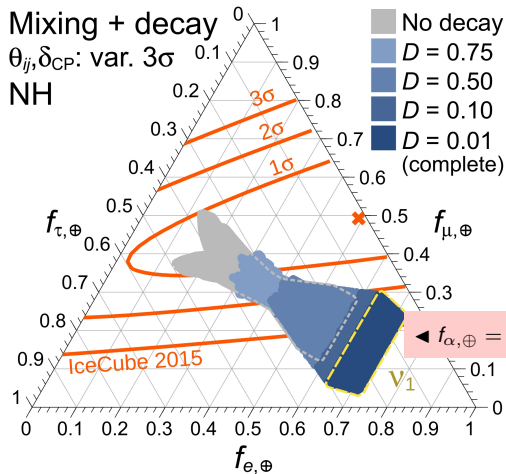


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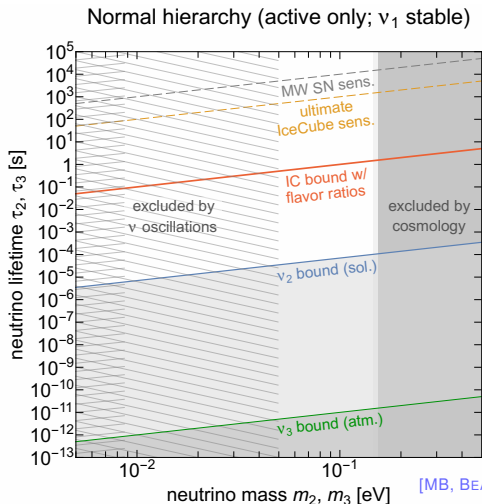
Assume equal lifetimes of ν_2, ν_3



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

NH: lifetime limits with **current** IceCube data (II)

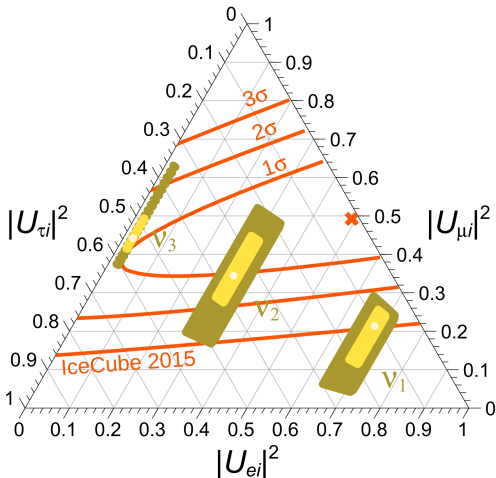
$D \lesssim 0.01$ implies a bound of $\kappa_{2,3}^{-1} \gtrsim 10 \text{ s eV}^{-1}$ at $\gtrsim 2\sigma$



[MB, BEACOM, MURASE, IN PREP.]

What will higher-energy events do for us?

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



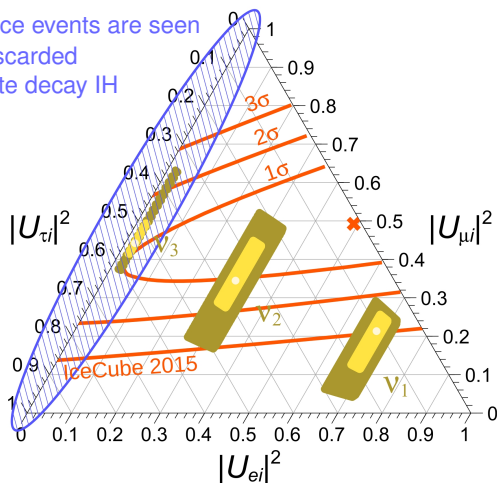
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If Glashow resonance events are seen

⇒ small $f_{e,\oplus}$ are discarded

⇒ discards complete decay IH



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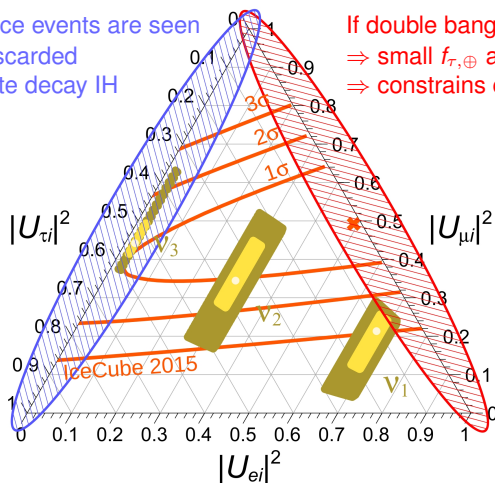
⇒ small $f_{e,\oplus}$ are discarded

⇒ discards complete decay IH

If double bangs are seen

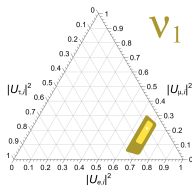
⇒ small $f_{\tau,\oplus}$ are discarded

⇒ constrains complete decay NH

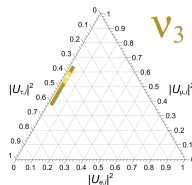


Decay: complete vs. incomplete

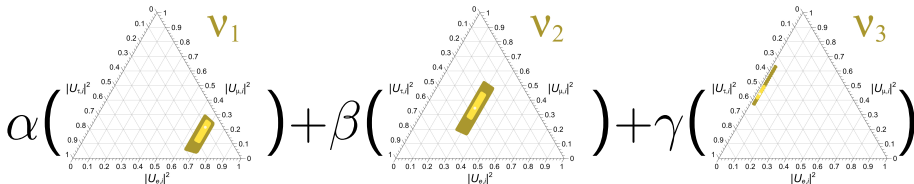
- **Complete decay:** only ν_1 (ν_3) reach Earth assuming NH (IH)



or

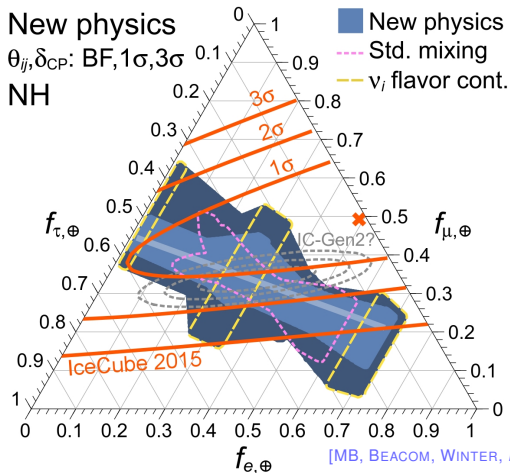


- **Incomplete decay:** incoherent mixture of ν_1 , ν_2 , ν_3 reaches Earth



Region of flavor ratios accessible with decay

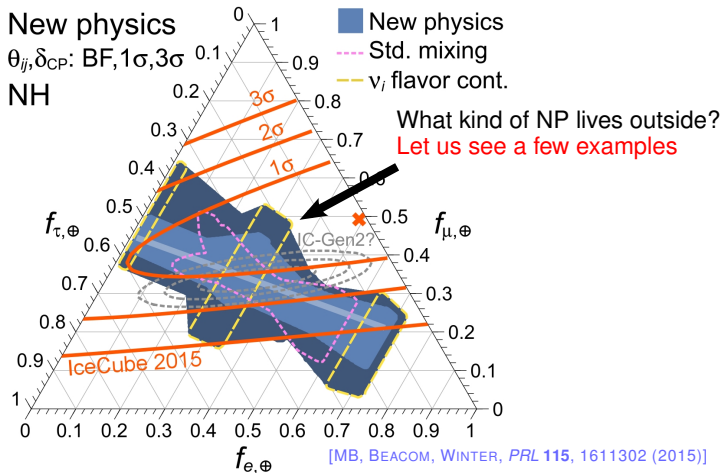
Region of all linear combinations of ν_1, ν_2, ν_3 :



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

Region of flavor ratios accessible with decay

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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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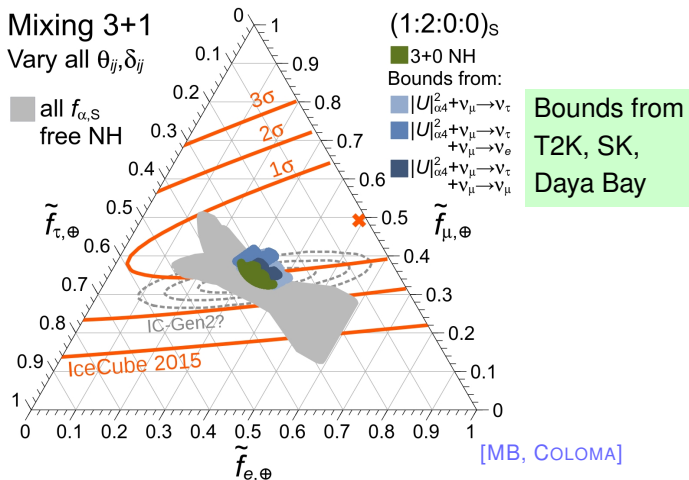
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New physics — active-sterile mixing

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

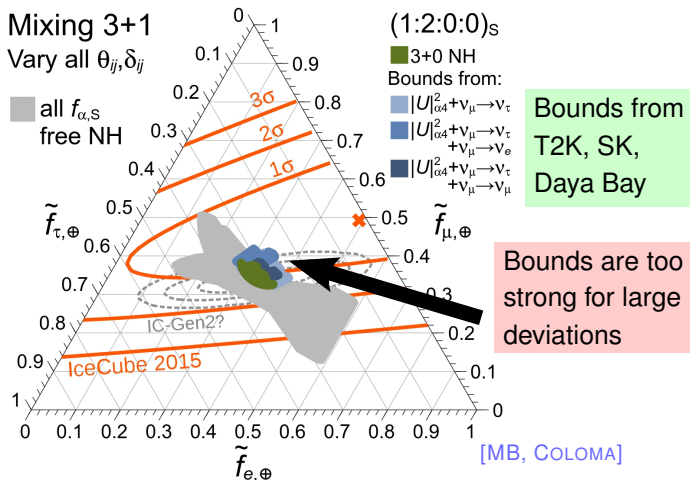
- ▶ standard parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$
- ▶ sterile parameters: $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{24}, \delta_{34}$



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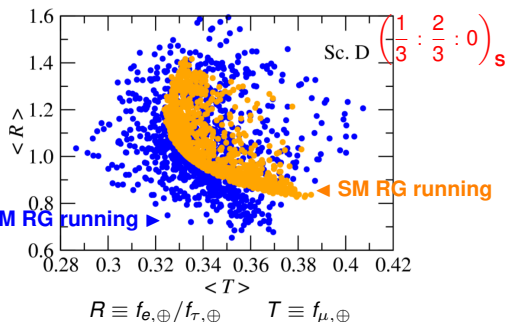
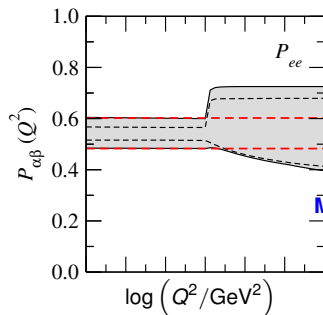


SUSY renormalization group running

- ▶ The MSSM introduces loop corrections in the ν interaction vertices
- ▶ Renormalization scale $\mu = Q = \sqrt{-q^2}$ (transferred momentum)
- ▶ Two energy scales:
 - ▶ At production: $Q = m_\pi$
 - ▶ At detection (via ν -nucleon): $Q \propto \sqrt{E_\nu}$
- ▶ RG running between the scales changes the mixing probability:

[MB, GAGO, JONES, *JHEP* **05**, 133 (2011) [1012.2728]]

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



New physics — high-energy effects (I)

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

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

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

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

$n = 0$

- ▶ 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:

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

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

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

[MB, GAGO, PEÑA-GARAY, *JHEP* **1004**, 005 (2010)]

[IceCube COLL., *PRD* **82**, 112003 (2010)]

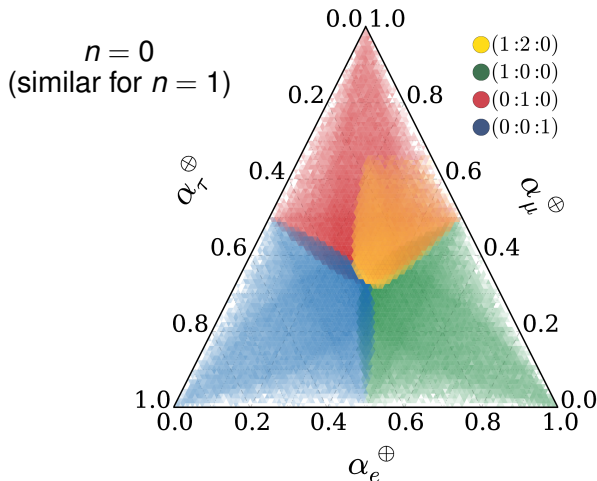
[SUPER-K COLL., *PRD* **91**, 052003 (2015)]

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)]



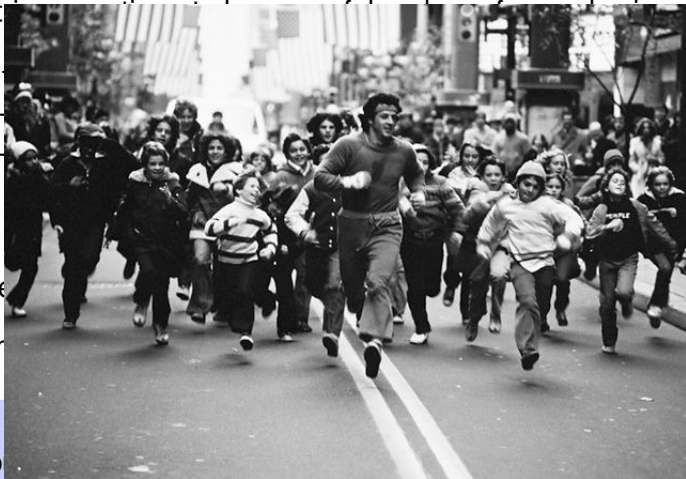
Conclusions

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

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

Conclusions

- ▶ Neutrinos
- ▶ High energy
- ▶ New physics
- ▶ Current
- ▶ Promising



with ...

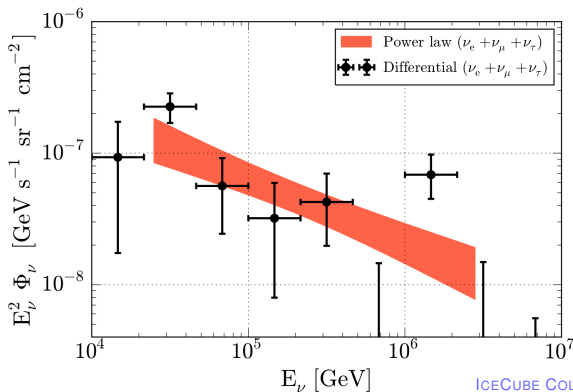
position

b

Backup slides

Spectral shape

High-energy astrophysical neutrinos follow a power law $\propto E^{-2.5}$ —



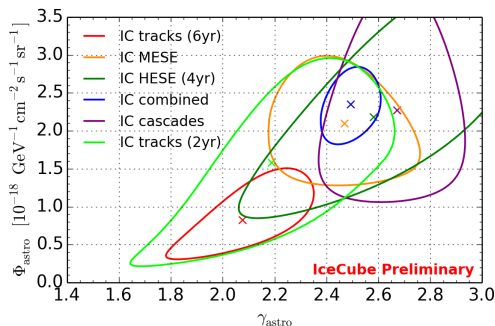
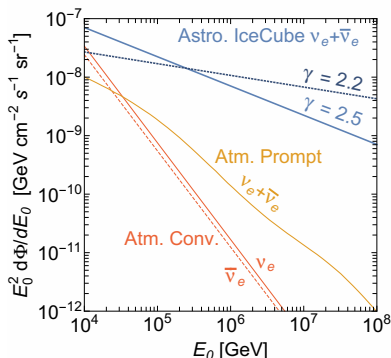
Per-flavor flux:

$$\Phi_\nu = \left(6.7^{+1.1}_{-1.2} \cdot 10^{-18}\right) \left(\frac{E}{100 \text{ TeV}}\right)^{-(2.5 \pm 0.09)} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

Spectrum from different data sets

The spectral shape varies depending on the data set used —

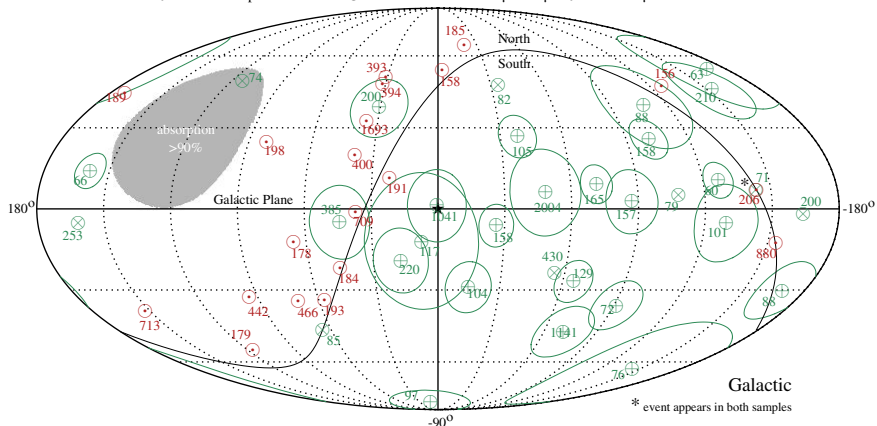
- ▶ With through-going muon tracks: 2.0–2.2
- ▶ With high-energy starting events: ~ 2.6



Neutrinos from the Galactic Center?
Atmospheric neutrino contamination at low E ?

Arrival directions

HESE 4yr with $E_{\text{dep}} > 60$ TeV (green) / Classical $\nu_{\mu} + \bar{\nu}_{\mu}$ 2yr with $E_{\mu} > 50$ TeV (red)



- ▶ 24 cascade events (⊕) + 8 tracks (⊗) with $E_{\text{dep}} > 60$ TeV
- ▶ 20 upgoing tracks with $E_{\mu} \gtrsim 50$ TeV
- ▶ No significant spatial or temporal correlation of events

Sources inside the Galaxy

Full or partial contribution:

- ▶ **Diffuse Galactic gamma-ray emission**

[Ahlers & Murase 13; Joshi, Winter, Gupta 13] [Kachelriess & Ostapchenko 14; Neronov, Semikoz, Tchernin 13]
[Neronov & Semikoz 14, 16; Guo, Hu, Tian 14; Gaggero, Grasso, Marinelli, Urbano, Valli 15]

- ▶ **Unidentified Galactic gamma-ray emission**

[Fox, Kashiyama, Meszaros 13] [Gonzalez-Garcia, Halzen, Niro 14]

- ▶ **Fermi bubbles**

[Ahlers & Murase 13; Razzaque 13] [Lunardini, Razzaque, Theodoseau, Yang 13; Lunardini, Razzaque, Yang 15]

- ▶ **Supernova remnants**

[Mandelartz & Tjus 14]

- ▶ **Pulsars**

[Padovani & Resconi 14]

- ▶ **Microquasars**

[Anchordoqui, Goldberg, Paul, da Silva & Vleck 14]

- ▶ **Sagittarius A***

[Bai, Barger, Barger, Lu, Peterson, Salvado 14; Fujita, Kimura, Murase 15, 16]

- ▶ **Galactic halo**

[Taylor, Gabici, Aharonian 14]

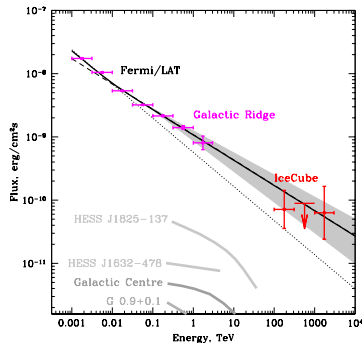
- ▶ **Heavy dark matter decay**

[Feldstein, Kusenkov, Matsumoto, Yanagida 13] [Esmaili & Serpico 13; Bai, Lu, Salvado 13]
[Cherry, Friedland, Shoemaker 14] [Murase, Laha, Ando, Ahlers 15; Boucenna 15; Chianese, Miele, Morisi, Vitagliano 16]

(Compilation by M. Ahlers)

Two Galactic source examples

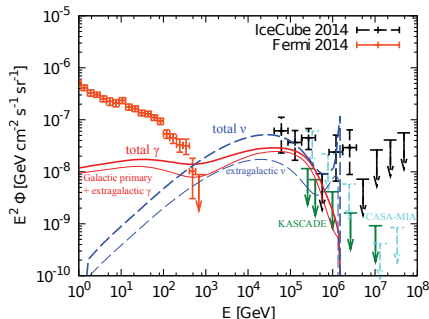
Hard Galactic diffuse emission



[Neronov, Semikoz, Tchernin 14]

- ▶ **Red:** neutrinos above 100 TeV
- ▶ **Magenta:** associated gamma rays in $-30^\circ < l < 30^\circ$, $-4^\circ < b < 4^\circ$ of the Galactic Plane
- ▶ Solid (dotted) line: $\Gamma = 2.4$ (2.5)

PeV dark matter decay



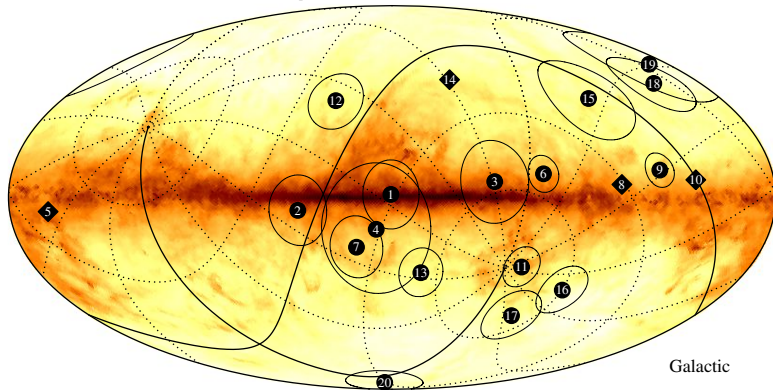
[Murase, Laha, Ando, Ahlers 15]

- ▶ DM lifetime: $3 \cdot 10^{27}$ s
- ▶ $\text{DM} \rightarrow \begin{cases} \nu_e \bar{\nu}_e, & \text{BR} = 12\% \\ q\bar{q}, & \text{BR} = 88\% \end{cases}$
- ▶ NFW DM density profile

Galactic diffuse emission

Neutrino production via pp on gas in the Galaxy —

HESE 3yr with $E_{\text{dep}} > 60$ TeV, $n_{\text{tot}} = 20$, $\hat{f}_{\text{iso}} = 0.81$, $\lambda = 0.74$



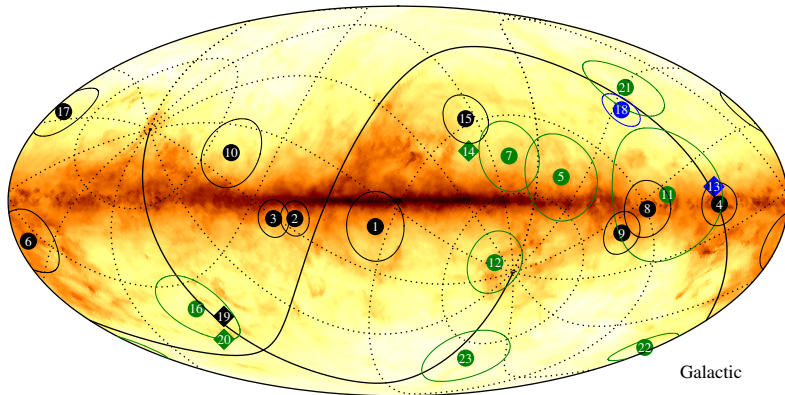
Galactic
[Ahlers, Bai, Barger, Lu 15]

Observed HESE events with $E_{\text{dep}} > 60$ TeV: tracks ($\diamond$), showers ($\circ$)

Galactic diffuse emission

Simulated map with 50% isotropic + 50% Galactic components —

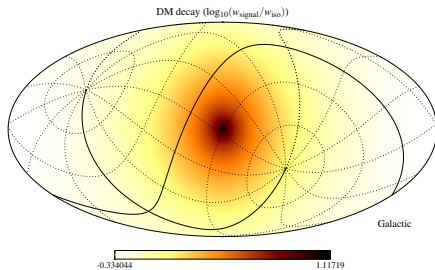
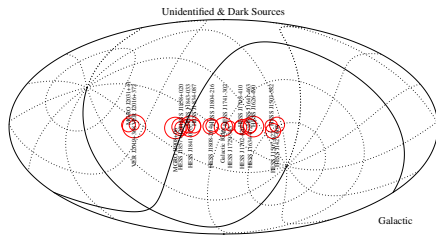
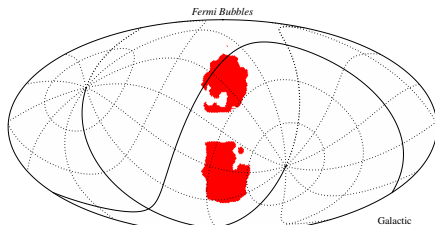
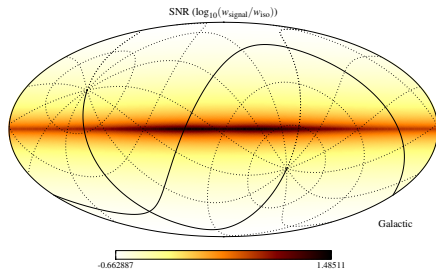
sample with $f_{\text{iso}} = 0.50$, $n_{\text{tot}} = 23$, $\hat{f}_{\text{iso}} = 0.76$, $\lambda = 0.86$



► Tracks: $\diamond$; showers: $\circ$

► Galactic ν : $\diamond/\circ$; isotropic: $\diamond/\circ$; atmospheric: $\diamond/\circ$

Different diffuse emission templates



Comparing observed arrival directions and directions from pseudo-experiments obtained with different templates —

- ▶ Diffuse Galactic emission: $\lesssim 50\%$
- ▶ Quasi-diffuse emission (SNRs, PWN): $\lesssim 65\%$
- ▶ *Fermi* bubbles: $\lesssim 25\%$
- ▶ Unidentified TeV gamma-ray sources: $\lesssim 25\%$
- ▶ Dark matter decay: unconstrained

[Ahlers, Bai, Barger, Lu 15]

Sources outside the Galaxy

► Association with UHECR sources

[Kistler, Stanev, Yuksel 13] [Katz, Waxman, Thompson, Loeb 13; Fang, Fujii, Linden, Olinto 14]
[Moharana & Razzaque 15]

► Association with gamma-ray background

[Murase, Ahlers, Lacki 13] [Chang & Wang 14; Ando, Tamborra, Zandanel 15]

► Active galactic nuclei (AGN)

[Stecker 13; Kalashev, Kusenko, Essey 13] [Murase, Inoue, Dermer 14; Kimura, Murase, Toma 14]
[Kalashev, Semikoz, Tkachev 14] [Padovani & Resconi 14; Petropoulou+ 15; Padovani+ 16; Kadler+16]

► Gamma-ray bursts (GRBs)

[Murase & Ioka 13; Dado & Dar 14; Tamborra & Ando 15] [Bustamante, Baerwald, Murase, Winter 15]
[Senno, Murase, Meszaros 16]

► Starburst galaxies

[He+ 13; Yoast-Hull, Gallagher, Zweibel, Everett 13; Murase, Ahlers, Lacki 13]
[Anchordoqui, Paul, da Silva, Torres, Vitek 14; Tamborra, Ando, Murase 14; Chang & Wang 14]
[Liu, Wang, Inoue, Crocker, Aharonian 14; Senno+ 15]
[Chakraborty & Izaguirre 15; Emig, Lunardini, Windhorst 15; Bechtol+ 15]

► Galaxy clusters

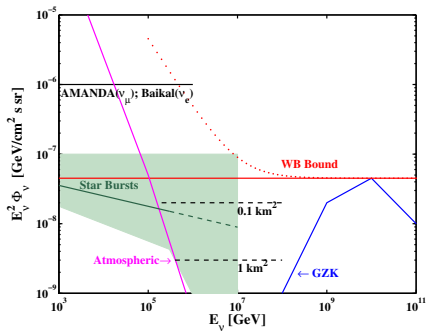
[Murase, Ahlers, Lacki 13; Zandanel, Tamborra, Gabici, Ando 14]

► ?

(Compilation by M. Ahlers)

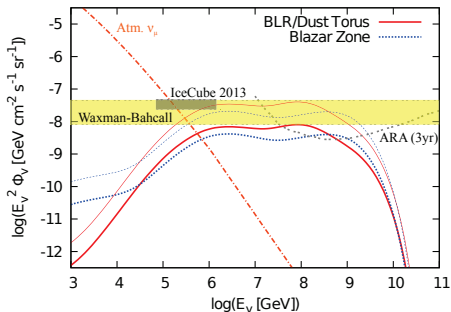
Two extragalactic source examples

pp production: starburst galaxies



[Loeb & Waxman 06]

$p\gamma$ production: active galactic nuclei



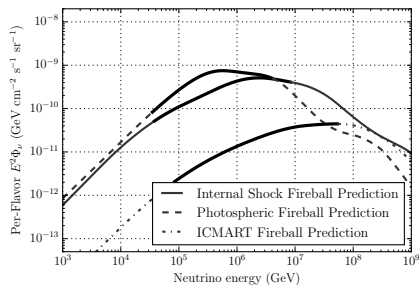
[Mannheim 96; Halzen & Zas 97]

[▲ Murase, Inoue, Dermer 14]

- ▶ CR-gas (pp) interactions: broken power-law neutrino spectra
- ▶ CR-photon ($p\gamma$) interactions: spectral features from γ spectrum

Stacking searches

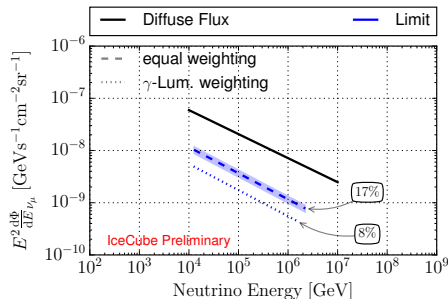
GRB stacking



[IceCube 1601.06484]

- ▶ 807 GRBs (2008-2016)
- ▶ 3 yr of showers (all flavors) + 4 yr of upgoing tracks > 1 TeV
- ▶ Six coincidences, low significance
- ▶ $\lesssim 1\%$ of diffuse flux due to prompt GRB emission

Blazar stacking

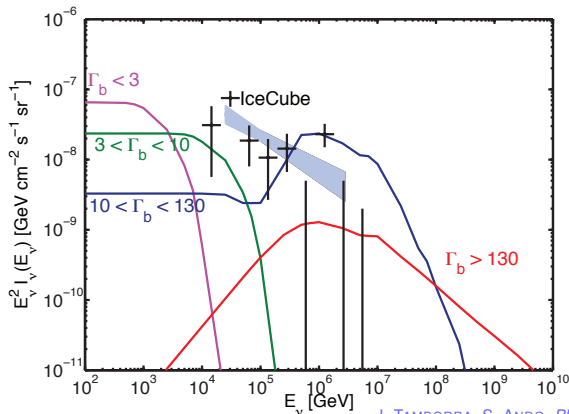


[IceCube 1502.03104]

- ▶ 862 blazars from the 2nd Fermi-LAT AGN catalog (2LAC)
- ▶ Blazars emit gamma-rays up to tens of TeV

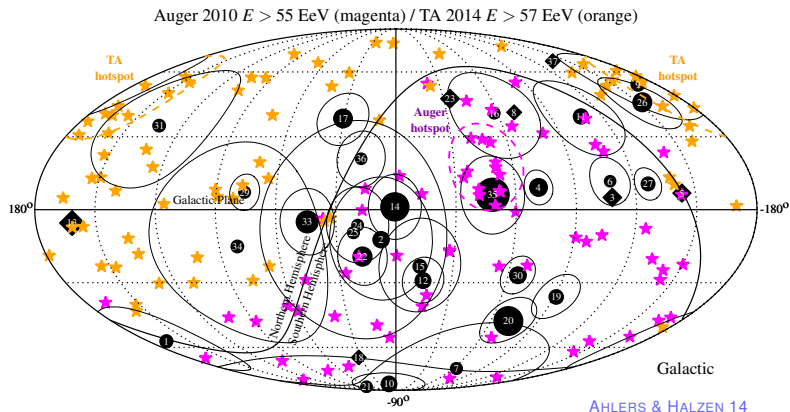
What about low-luminosity and choked GRBs?

- ▶ Low-luminosity and choked GRBs might be in the same family as high-luminosity long GRBs
- ▶ Due to lower jet speeds (Γ_b), they do not break out
- ▶ They might explain the TeV region of the IceCube diffuse ν flux:



I. TAMBORRA, S. ANDO, *PRD* **93**, 053010 (2016)

Correlation with UHECRs?



- ▶ Angular deflection of CRs on extragalactic magnetic field:

$$\theta_{\text{rms}} \simeq 1^\circ \left(\frac{D}{L_{\text{coh}}} \right)^{\frac{1}{2}} \left(\frac{E}{55 \text{ EeV}} \right)^{-1} \left(\frac{L_{\text{coh}}}{1 \text{ Mpc}} \right) \left(\frac{B}{1 \text{ nG}} \right)$$

- ▶ No significant correlation with Auger and Telescope Array data

Identifying extragalactic point sources

How many neutrinos should be correlated with UHECR sources?

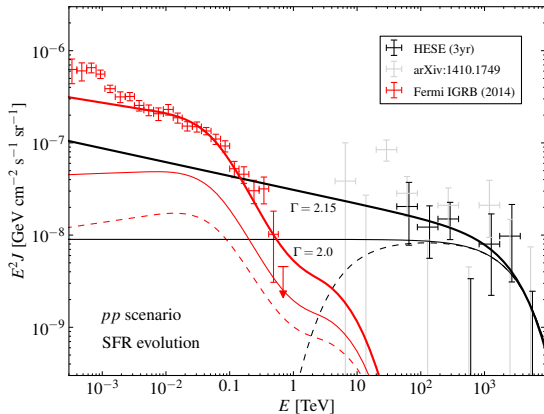
- ▶ UHECRs trace sources within $\lambda_{\text{GZK}} \approx 200 \text{ Mpc}$
- ▶ Neutrinos come from anywhere inside Hubble horizon $D_{\text{H}} \approx 4 \text{ Gpc}$
- ▶ Maximal overlap:

$$\frac{\lambda_{\text{GZK}}}{D_{\text{H}}} \approx 5\%$$

- ▶ Current HESE data: ~ 30 signal events
- ▶ $\therefore$ **Expected correlations with 1–2 neutrinos**
- ▶ Weaker signal due to magnetic deflection, angular resolution, catalog incompleteness, *etc.*

Constraints from the isotropic gamma-ray background

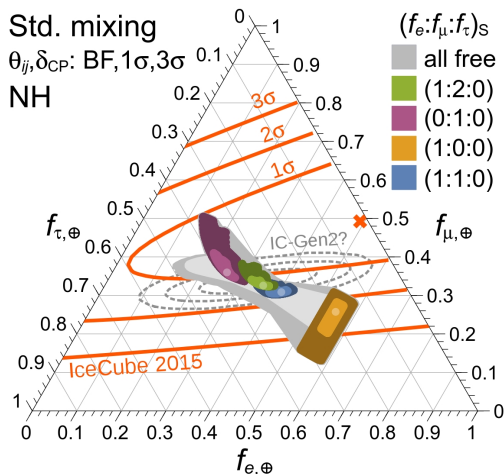
- ▶ *pp* production: ν and gamma-ray spectra follow the CR spectrum $\propto E^{-\Gamma}$
- ▶ Interactions of gamma rays with CMB make them pile up in GeV range
- ▶ Fermi gamma-ray background satisfied only if $\Gamma \lesssim 2.2$
- ▶ IceCube favors $\Gamma \approx 2.6$
- ▶ *pp* production disfavored



AHLERS & MURASE 13

Selected source compositions

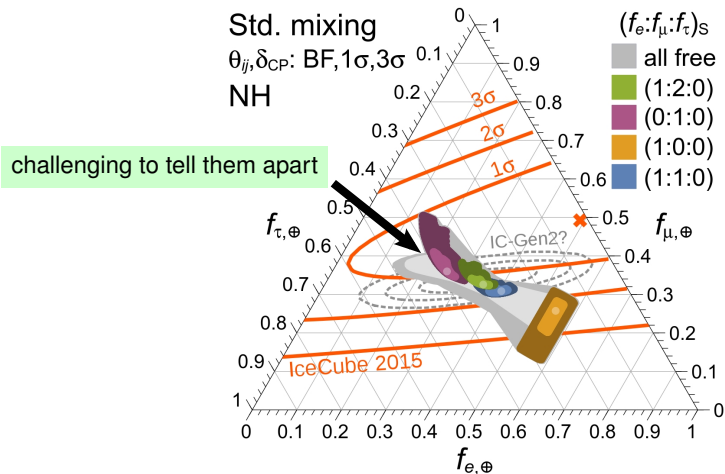
We can look at results for particular choices of ratios at the source:



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

Selected source compositions

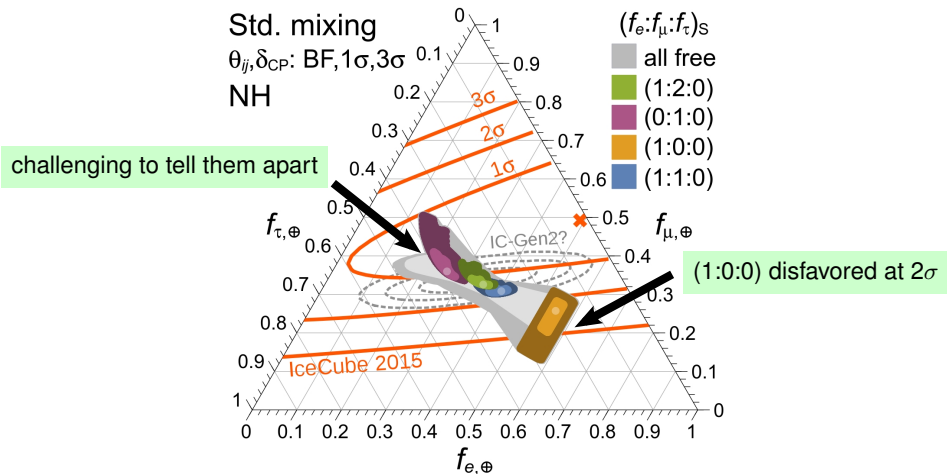
We can look at results for particular choices of ratios at the source:



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

Selected source compositions

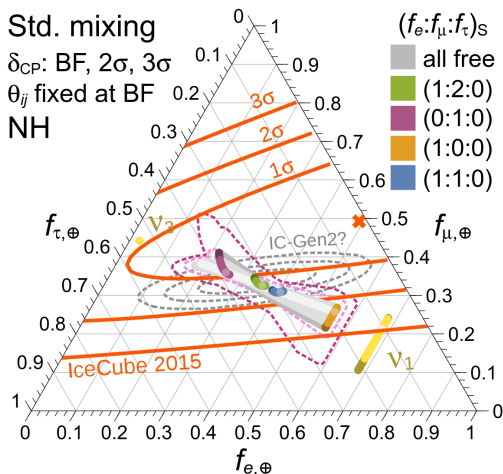
We can look at results for particular choices of ratios at the source:



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

Perfect knowledge of mixing angles

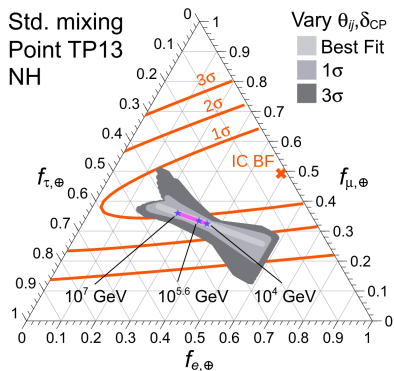
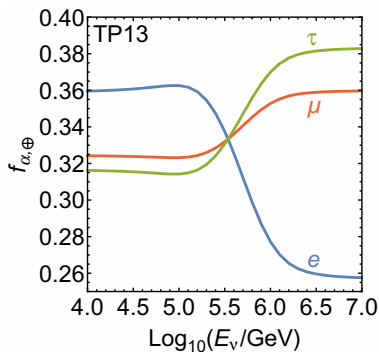
In a few years, we might know all the mixing parameters except δ_{CP} :



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

Energy dependence of the composition at the source

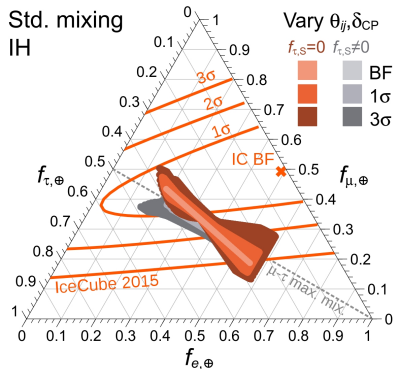
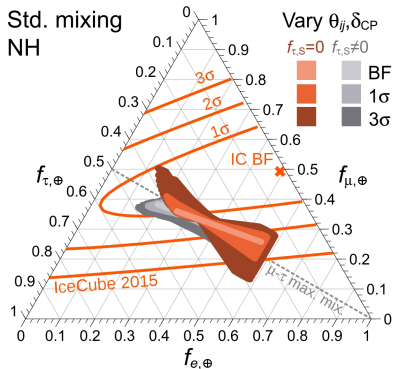
Different ν production channels are accessible at different energies



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

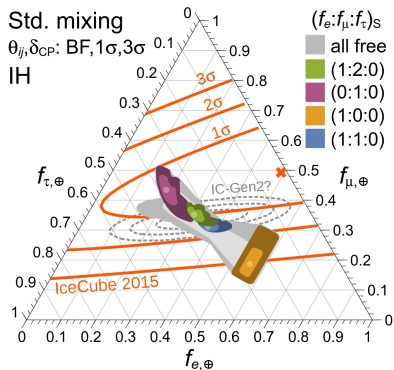
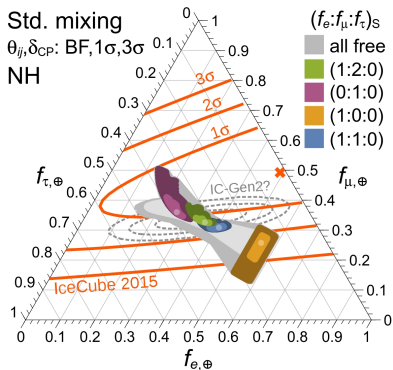
- ▶ TP13: $p\gamma$ model, target photons from co-accelerated electrons
[HÜMMER *et al.*, *Astropart. Phys.* **34**, 205 (2010)]
- ▶ Equivalent to different sources types contributing to the diffuse flux
- ▶ Will be difficult to resolve
[KASHTI, WAXMAN, *PRL* **95**, 181101 (2005)] [LIPARI, LUSIGNOLI,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

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



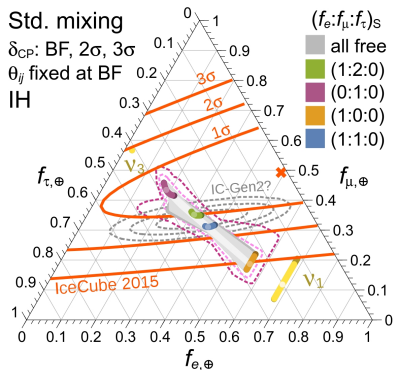
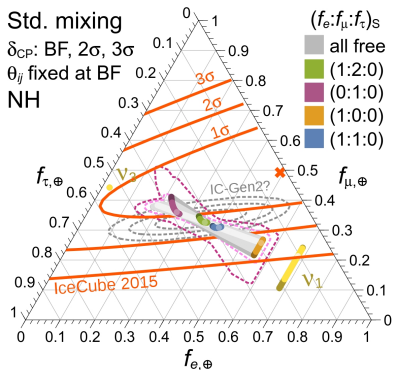
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Selected source compositions: NH vs. IH



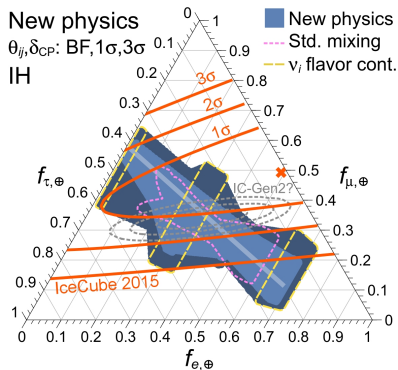
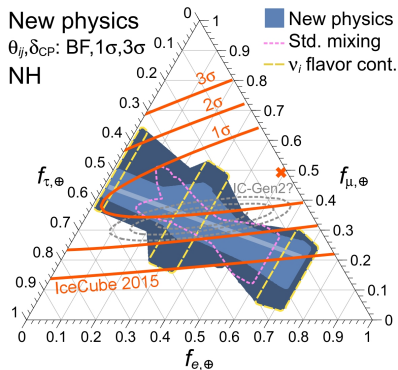
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Perfect knowledge of mixing angles: NH vs. IH



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

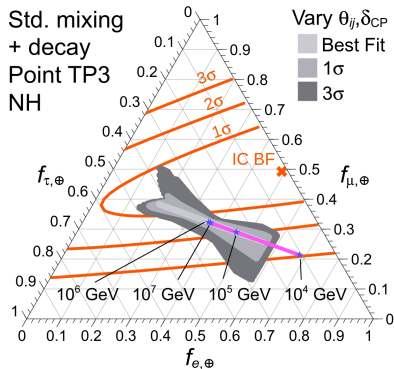
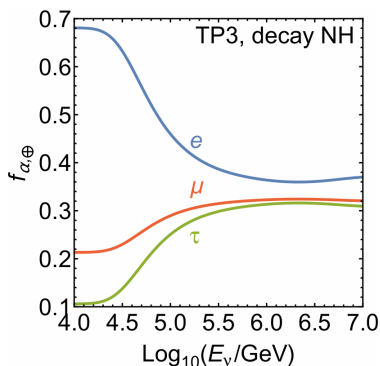
New physics: NH vs. IH



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

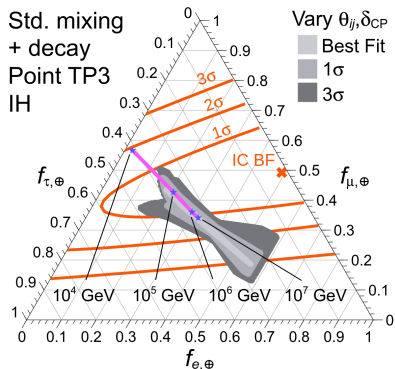
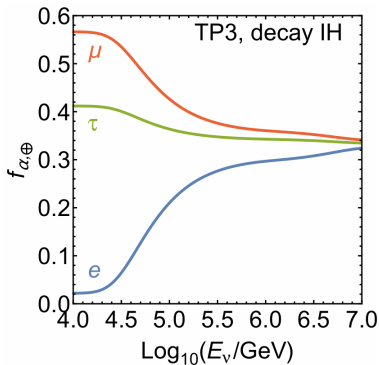
Decay: seeing the energy dependence?

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



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

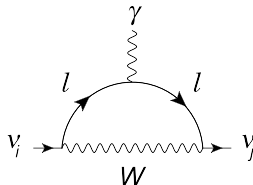
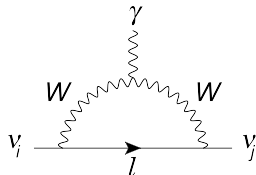
Decay in the IH



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

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

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

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

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

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

Neutrino decay: caveats and improvements

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

Cosmological effects on decay

There are two cosmological effects:

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

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

Fraction of remaining ν_i at Earth:

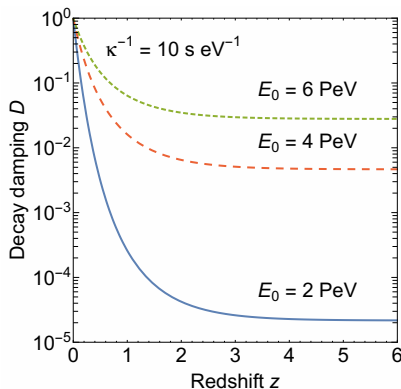
$$D(E_0, z, \kappa_i^{-1}) = (a + b e^{-cz})^{-\frac{\kappa_i L_H}{E_0}}$$

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

$$\text{for } \Lambda\text{CDM with } (\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$$

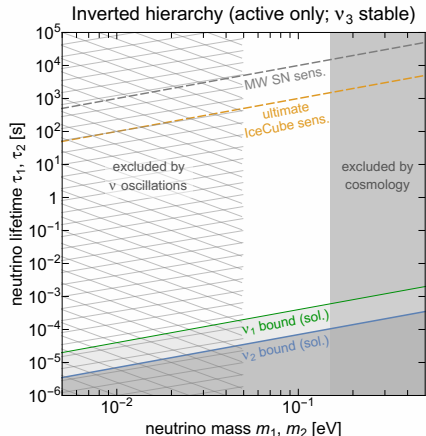
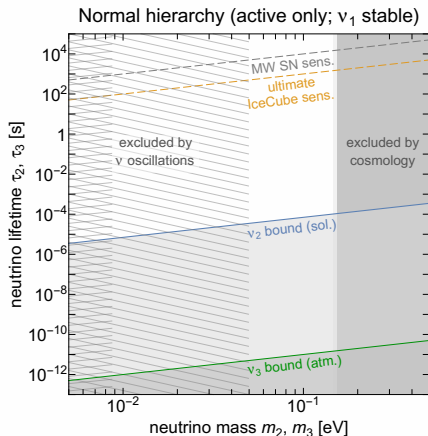
$$\langle P_{\alpha\beta} \rangle \rightarrow \underbrace{D(E_0, z, \kappa_i^{-1})}_{0 < D < 1} \langle P_{\alpha\beta} \rangle$$

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



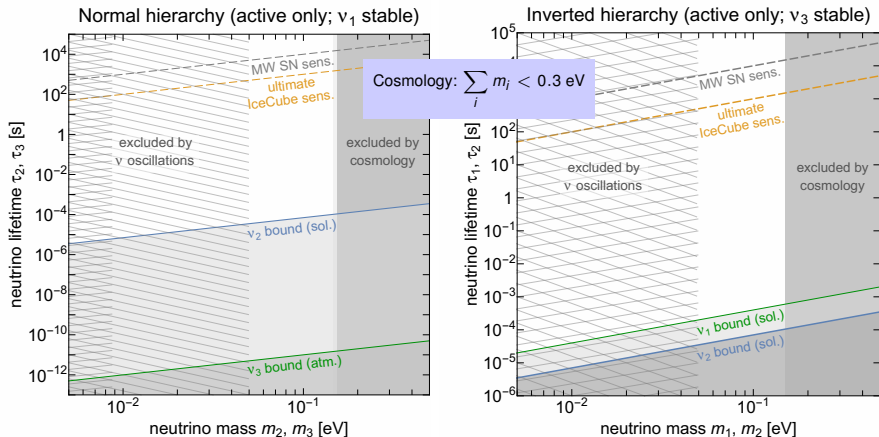
Current lifetime limits

- ▶ ν_1 : $\gtrsim 4 \cdot 10^{-3} \text{ s eV}^{-1}$ (solar, [BERRYMAN et al. 2014](#))
- ▶ ν_2 : $\gtrsim 7 \cdot 10^{-3} \text{ s eV}^{-1}$ (solar, [BERRYMAN et al. 2014](#))
- ▶ ν_3 : $\gtrsim 7 \cdot 10^{-11} \text{ s eV}^{-1}$ (atmospheric, [GONZÁLEZ-GARCÍA & MALTONI 2008](#))



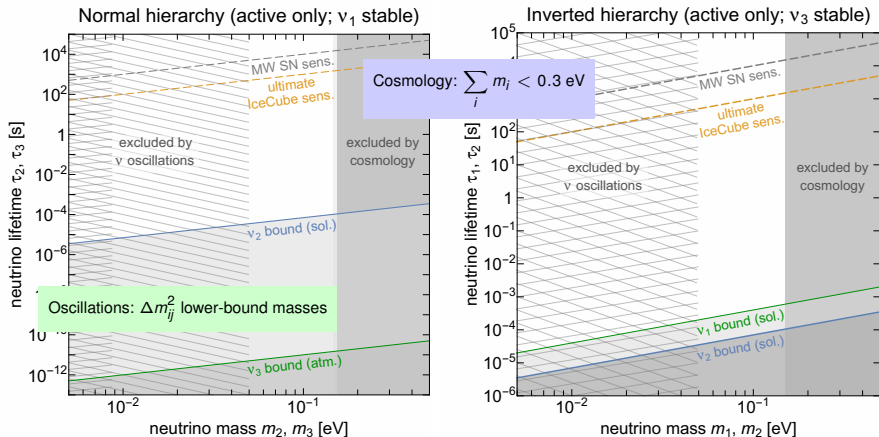
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Current lifetime limits

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- ▶ $\nu_2: \lambda \gtrsim 7 \cdot 10^{-3} \text{ s eV}^{-1}$ (solar, BERRYMAN *et al.* 2014)
- ▶ $\nu_3: \lambda \gtrsim 7 \cdot 10^{-11} \text{ s eV}^{-1}$ (atmospheric, GONZÁLEZ-GARCÍA & MALTONI 2008)



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- ▶ $\nu_3: \lambda \gtrsim 7 \cdot 10^{-11} \text{ s eV}^{-1}$ (atmospheric, [GONZÁLEZ-GARCÍA & MALTONI 2008](#))

