

High-energy astrophysical neutrinos: theoretical aspects

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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
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... and winning

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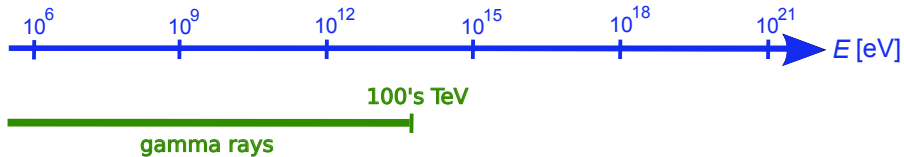


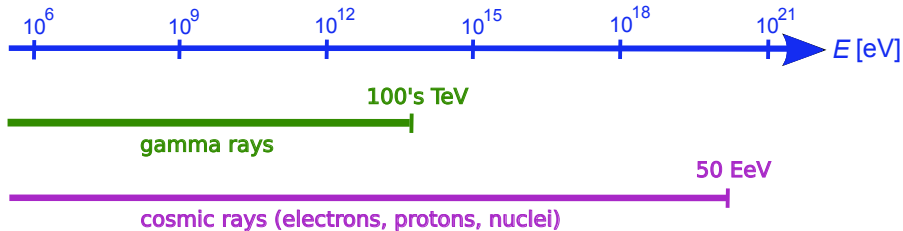
Some reasons why neutrinos are special:

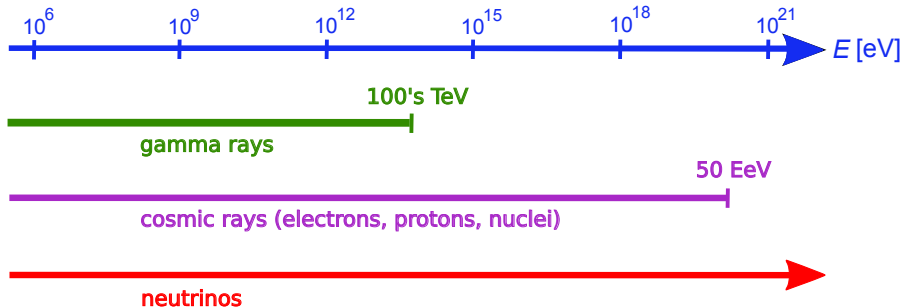
- 1 They are lighter than any other massive particle we know of
- 2 They retain their quantum nature over long distances
- 3 They are notoriously anti-social
- 4 (We believe) they reach us with higher energies than anything else

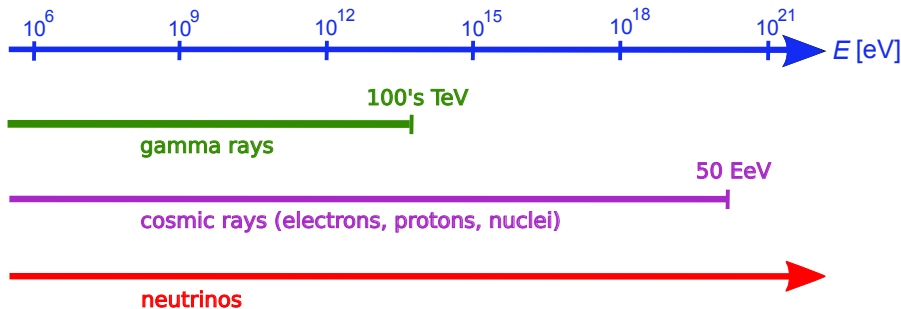
Let's talk energy scales...



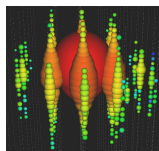
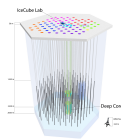
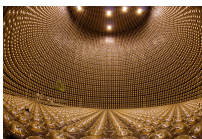




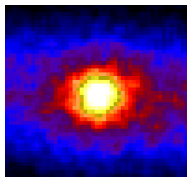
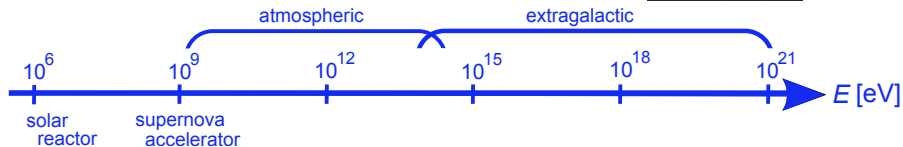


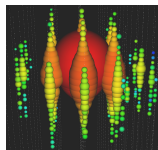
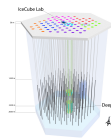
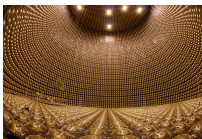


- ⑤ Unlike gamma rays and cosmic rays, neutrinos have flavor

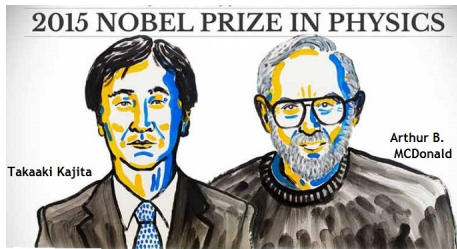
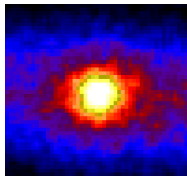
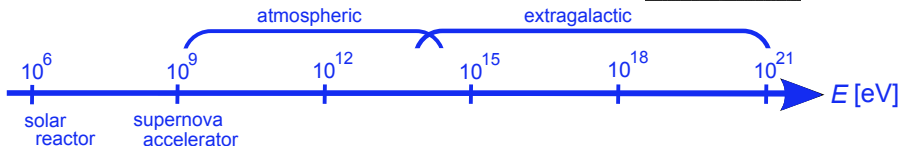


2013+





2013+



Next ν -Nobel for high-energy ν 's?

High-energy astrophysical neutrinos: they exist!

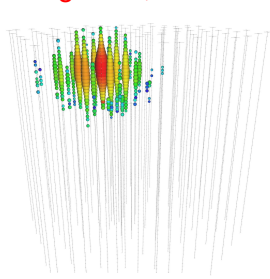
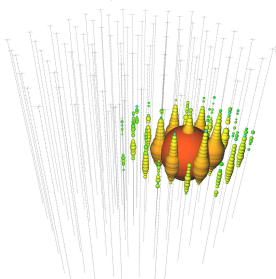
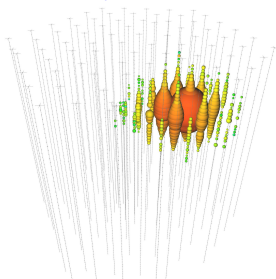
The era of neutrino astronomy has begun!

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



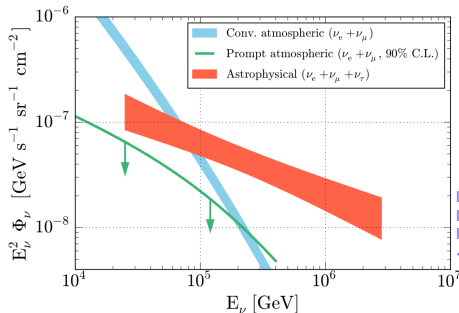
...and 51 more events > 30 TeV



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

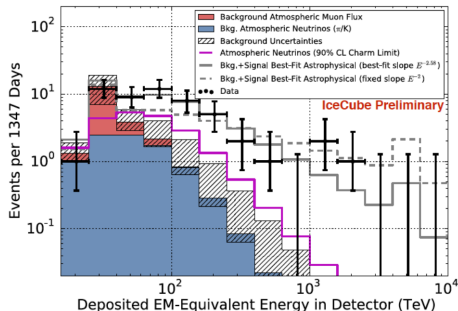
Diffuse per-flavor astrophysical flux [IceCube 2015]:

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

High-energy astrophysical neutrinos: they exist!

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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]:

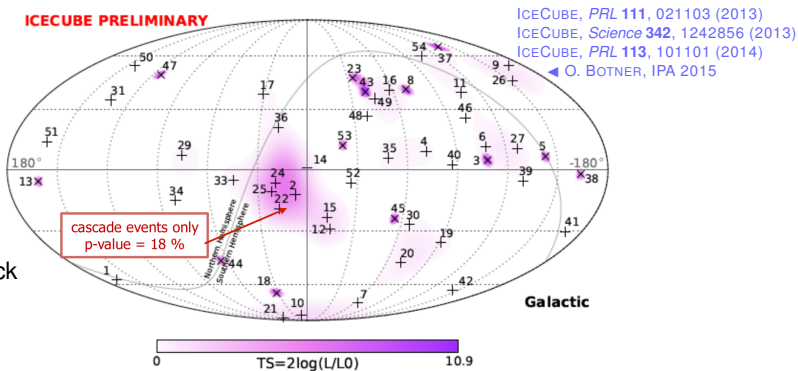
$$E^2 \Phi_\nu = (0.95 \pm 0.3) \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ (per flavor)}$$

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**

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

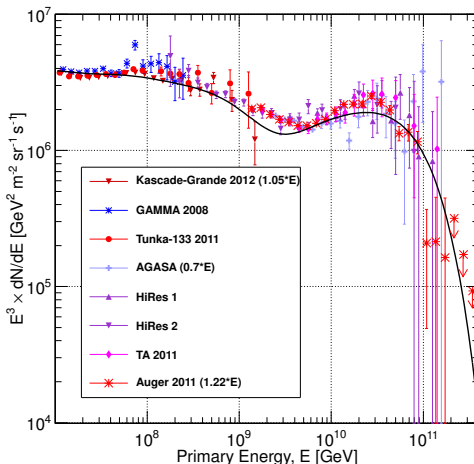
What we don't know

- ▶ 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 —

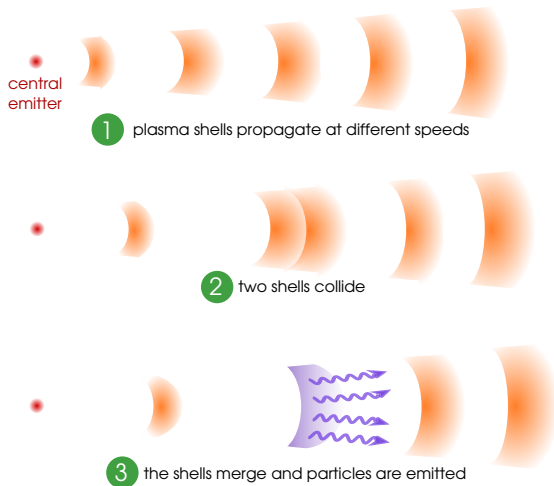


GAISSER, STANEV, TILAV,
Front. Phys. China **8**, 748 (2013)

Cosmic-ray accelerators should also produce neutrinos ►

HE particles from astrophysical sources

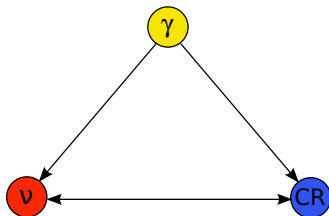
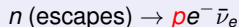
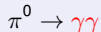
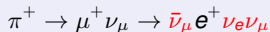
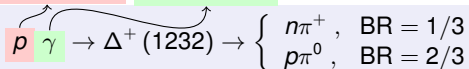
Relativistically-expanding blobs of plasma containing e 's, p 's, and γ 's collide with each other, merge, and emit HE particles (e.g., in a GRB)



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

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

broken power law



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

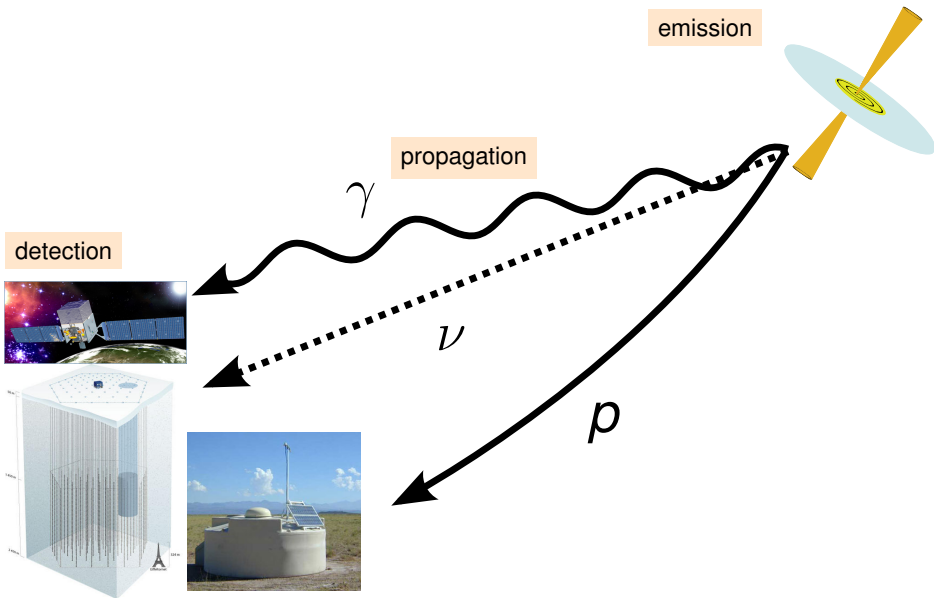
[AHLERS *et al.*, *Astropart. Phys.* **35**, 87 (2011)] [ICECUBE COLL., *Nature* **484**, 351 (2012)]

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

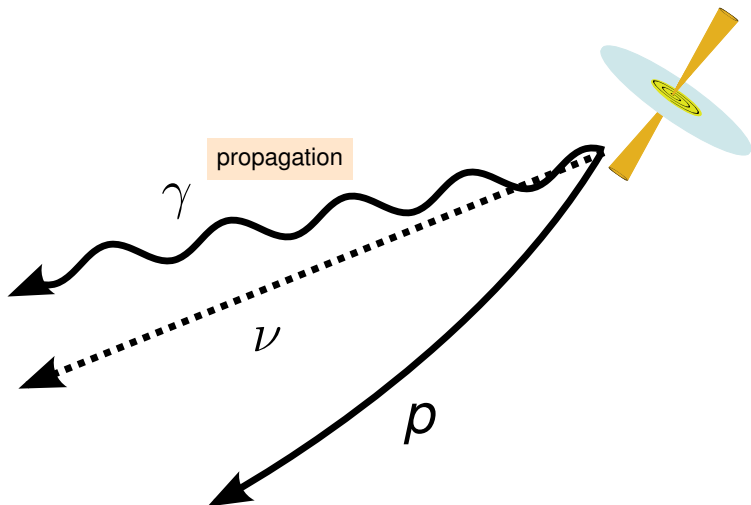
[BAERWALD, MB, WINTER, *ApJ* **768**, 186 (2013)] [BAERWALD, MB, WINTER, *Astropart. Phys.* **62**, 66 (2015)]

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

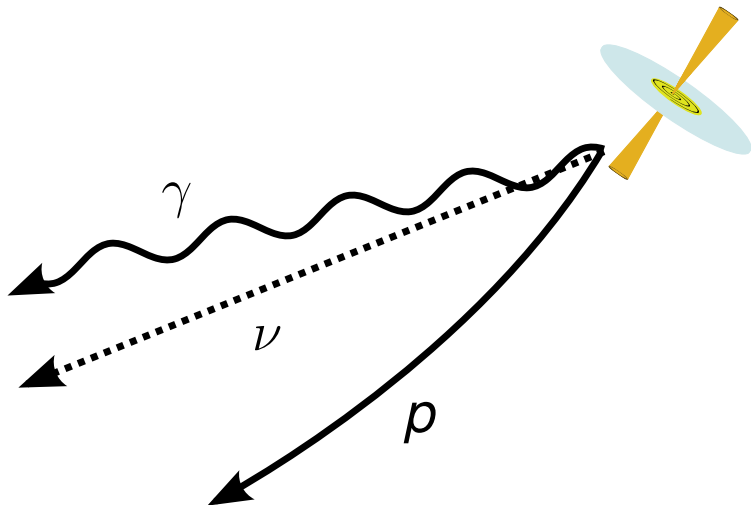
From the sources to us



From the sources to us



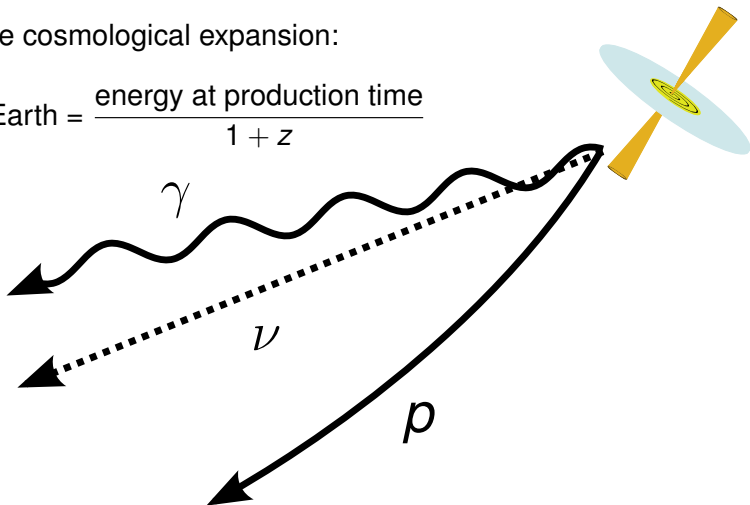
From the sources to us



From the sources to us

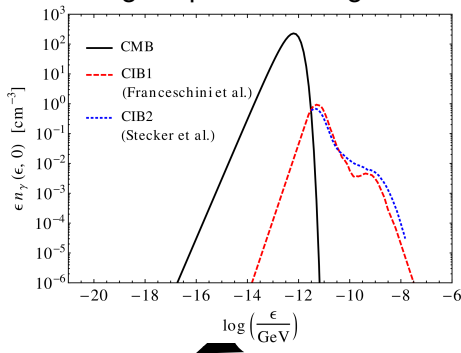
Because of the cosmological expansion:

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

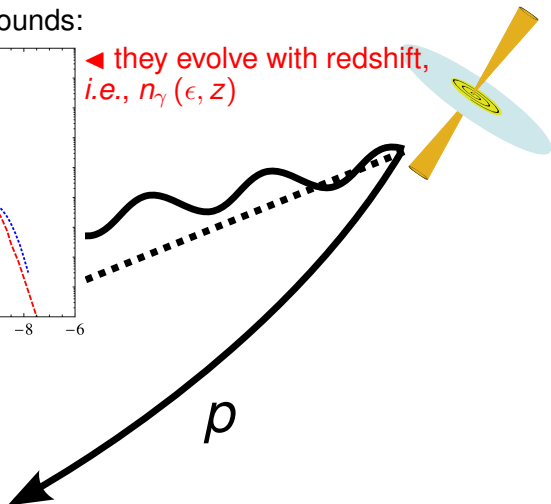


From the sources to us

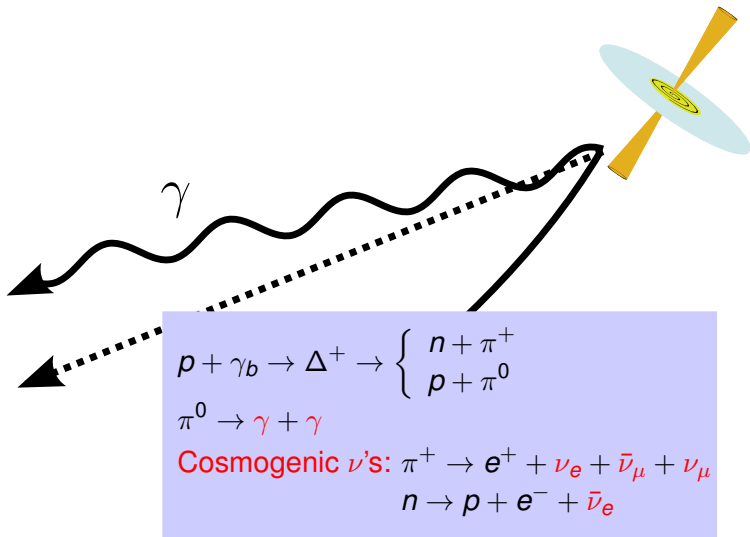
Cosmological photon backgrounds:



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



From the sources to us

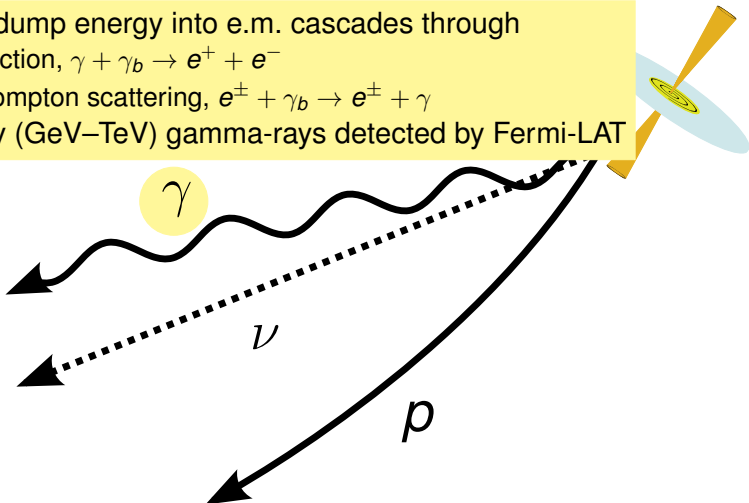


From the sources to us

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

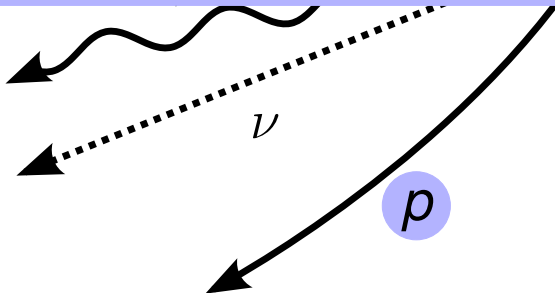
⇒ except for the most energetic ones, they are **not** expected to point back to the sources

} Pierre Auger found weak correlation with known AGN positions

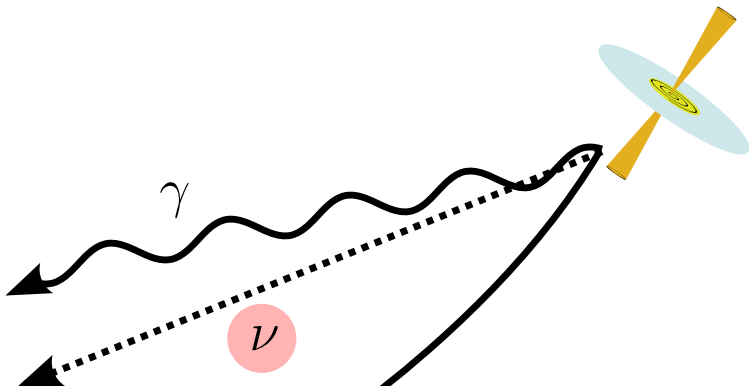
They lose energy through:

- ▶ 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: $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

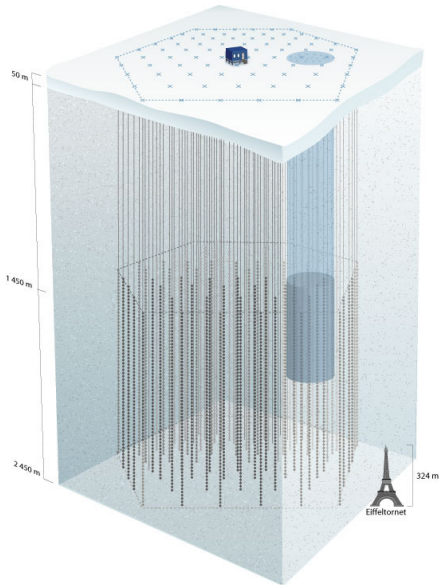
Probability of $\nu_\alpha \rightarrow \nu_\beta$ transition: $P_{\alpha\beta}(E_0, z)$

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)

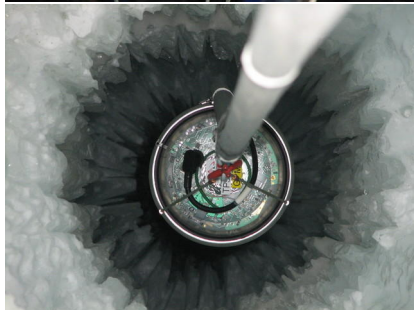
Detecting the neutrinos: IceCube



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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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):

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

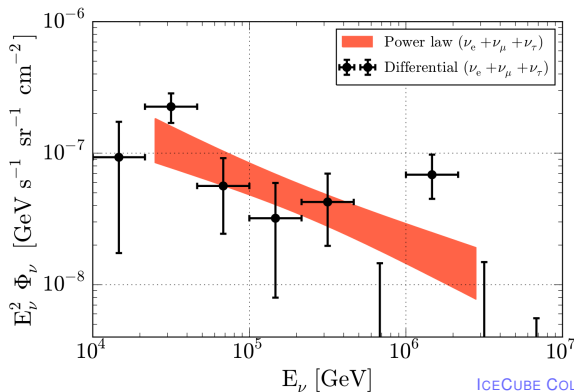
To detect $N_\nu > 1$ events per year, we need a detector area of

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

Therefore, we need km-scale detectors, like IceCube

Spectral shape

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



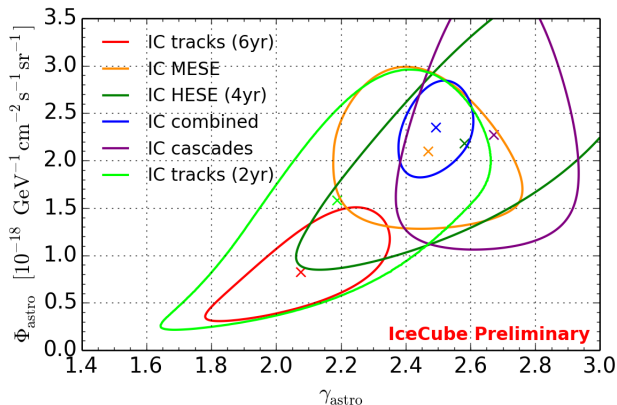
Per-flavor flux:

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

Spectrum from different data sets

The spectral shape $E^{-\gamma}$ varies depending on the data set used —

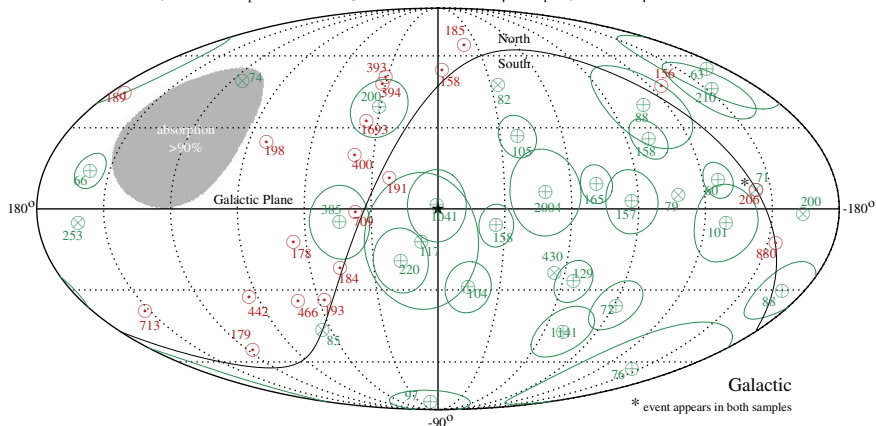
- ▶ With through-going muon tracks: $\gamma = 2.0 - 2.2$
- ▶ With high-energy starting events: $\gamma \approx 2.6$



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]

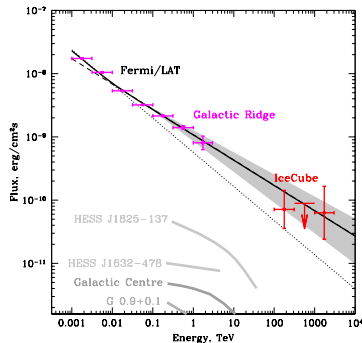
- ▶ **Heavy dark matter decay**

[Feldstein, Kusenko, 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

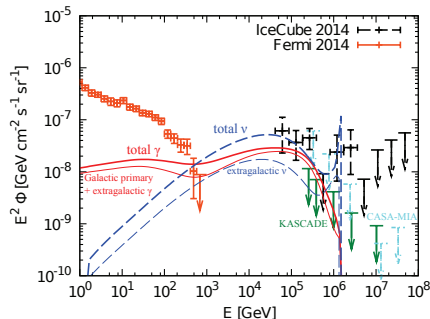
Hard Galactic diffuse emission



[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



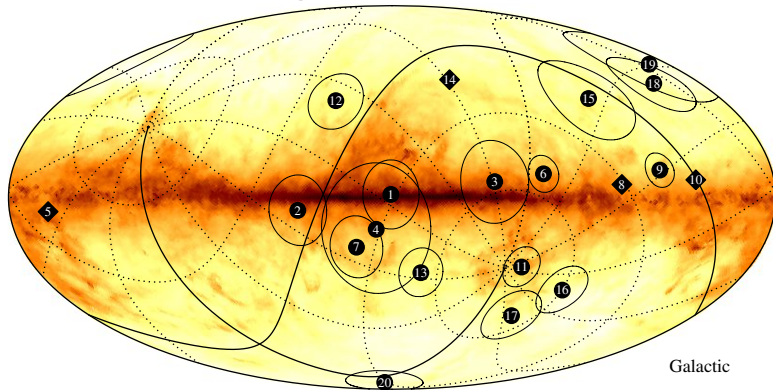
[Murase, Laha, Ando, Ahlers 15]

- 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, $n_{\text{tot}} = 20$, $\hat{f}_{\text{iso}} = 0.81$, $\lambda = 0.74$



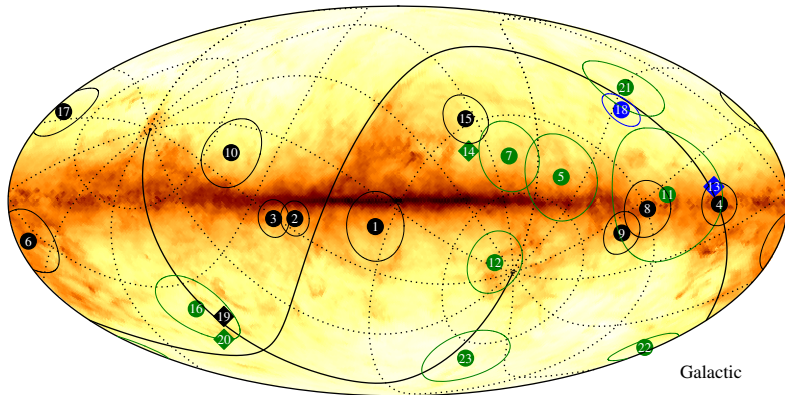
Galactic
[Ahlers, Bai, Barger, Lu 15]

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

Galactic diffuse emission

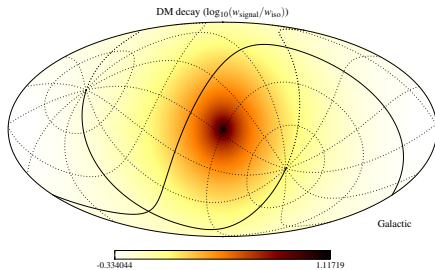
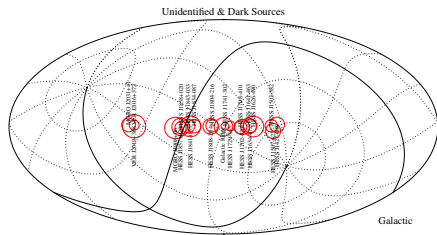
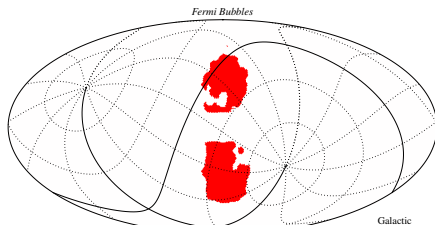
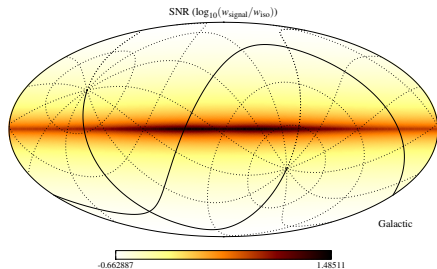
Simulated map with 50% isotropic + 50% Galactic components —

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

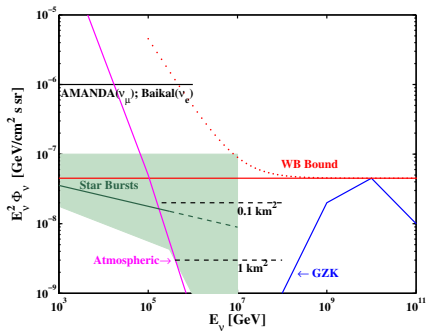
[Murase, Ahlers, Lacki 13; Zandanel, Tamborra, Gabici, Ando 14]

► ?

(Compilation by M. Ahlers)

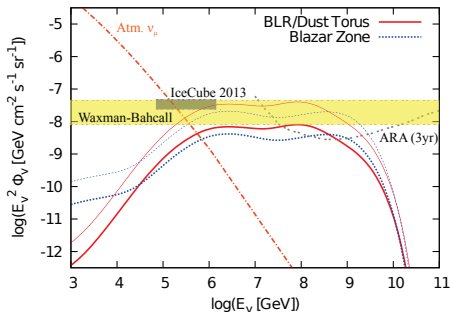
Two extragalactic source examples

pp production: starburst galaxies



[Loeb & Waxman 06]

$p\gamma$ production: active galactic nuclei



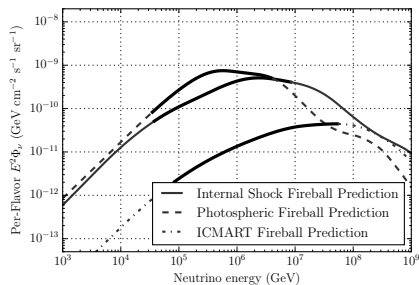
[Mannheim 96; Halzen & Zas 97]

[▲ 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

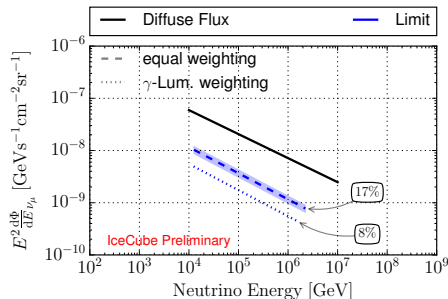
GRB stacking



[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

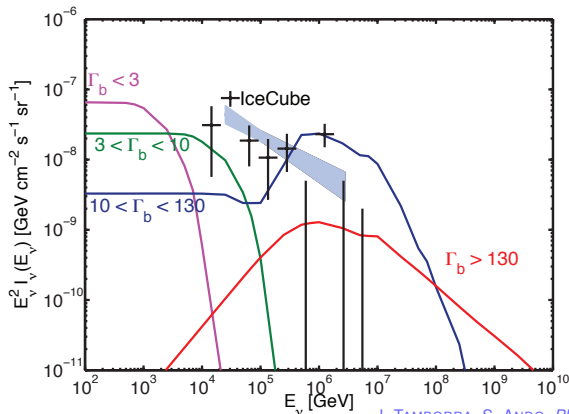


[IceCube 1502.03104]

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

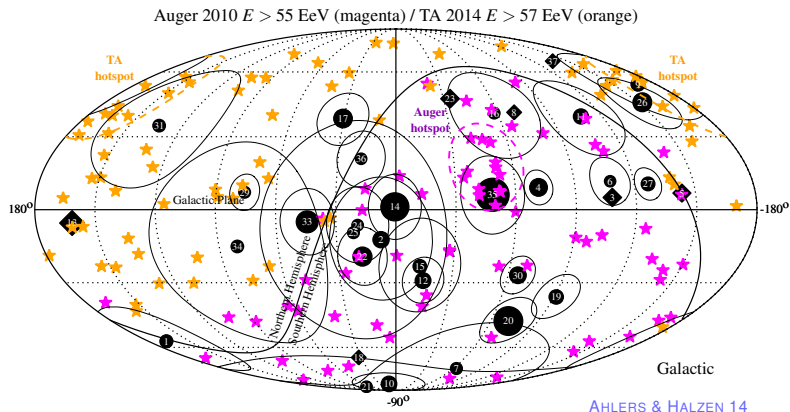
What about low-luminosity and choked GRBs?

- ▶ 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?

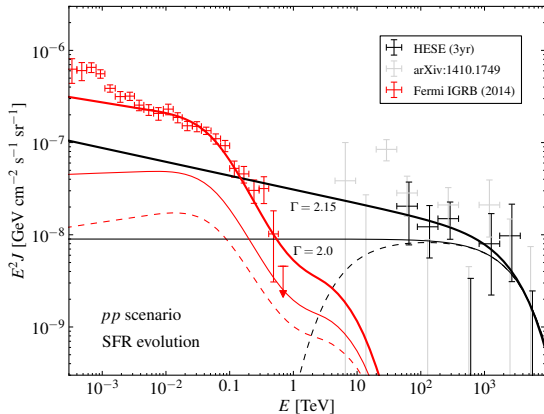
- ▶ UHECRs trace sources within $\lambda_{\text{GZK}} \approx 200$ Mpc
- ▶ Neutrinos come from anywhere inside Hubble horizon $D_{\text{H}} \approx 4$ Gpc
- ▶ Maximal overlap:

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

- ▶ 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 $\propto E^{-\Gamma}$
- ▶ Gamma rays pile up in GeV range due to interactions with CMB
- ▶ Fermi gamma-ray background satisfied only if $\Gamma \lesssim 2.2$
- ▶ IceCube favors $\Gamma \approx 2.6$
- ▶ *pp* production disfavored



AHLERS & MURASE 14

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:

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

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

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

How does IceCube see neutrinos?

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

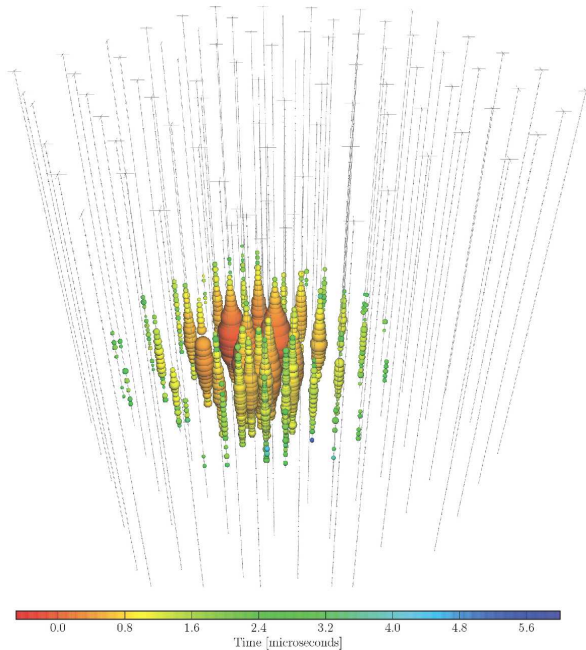
- ▶ **Showers:** generated by CC ν_e or ν_τ ; or by NC ν_X
- ▶ **Muon tracks:** generated by CC ν_μ

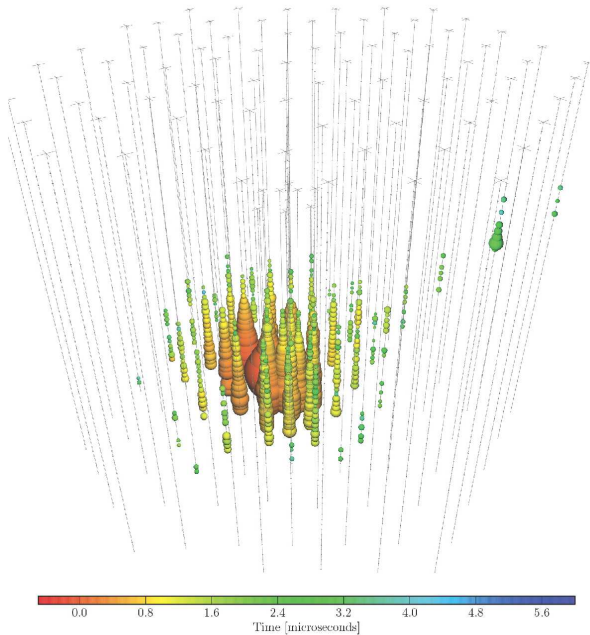
(Some muon tracks can be mis-reconstructed as showers)

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 composition is inferred from the number of showers and tracks

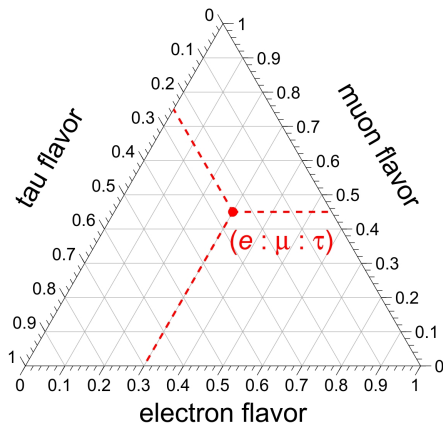




“Flavor triangle” or Dalitz/Mandelstam plot

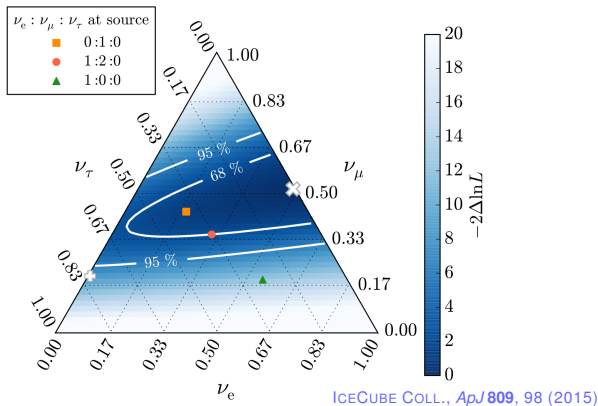
Assumes underlying unitarity: sum of projections on each axis is 1

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



IceCube analysis of flavor composition

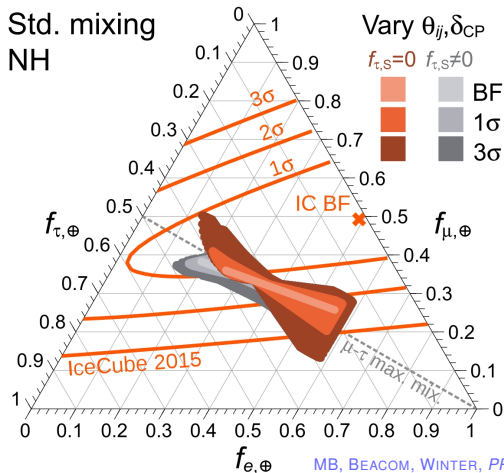
Using contained events + throughgoing muons:



- ▶ 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

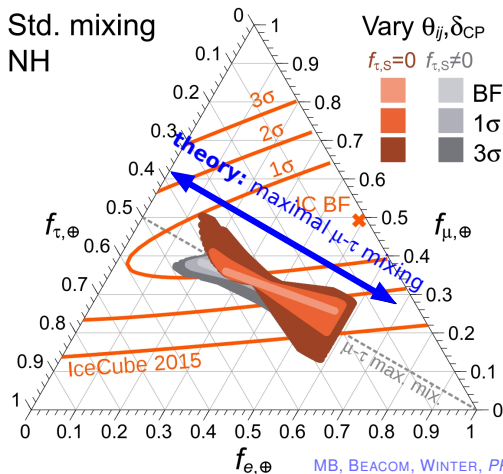
All possible flavor combinations accessible with standard mixing?



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

Flavor combinations at Earth from std. mixing

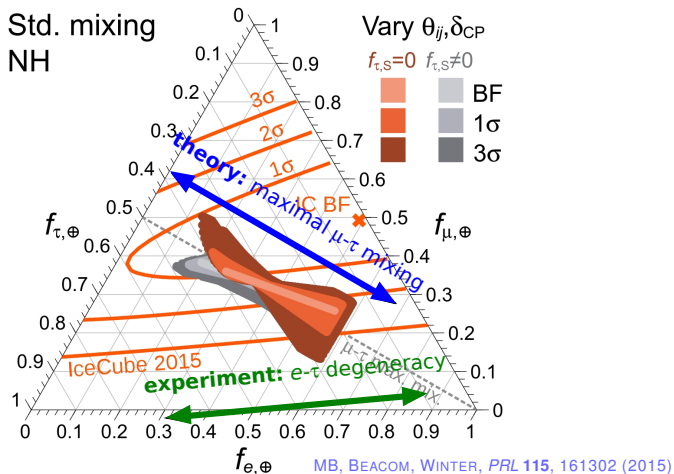
All possible flavor combinations accessible with standard mixing?



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Flavor combinations at Earth from std. mixing

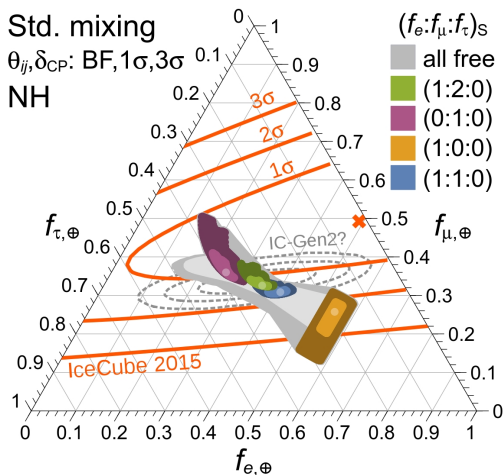
All possible flavor combinations accessible with standard mixing?



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

Selected source compositions

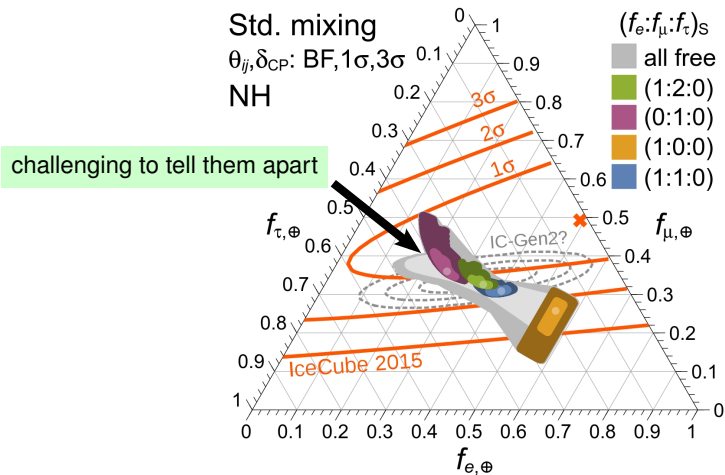
We can look at results for particular choices of ratios at the source:



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

Selected source compositions

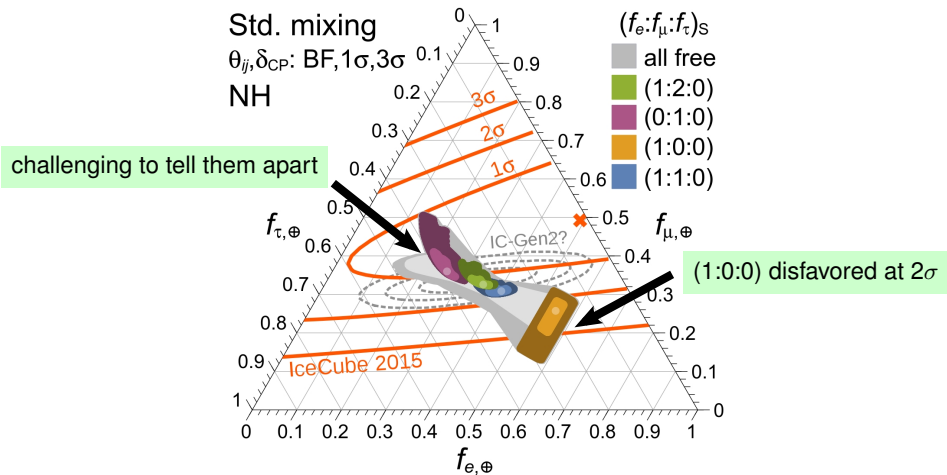
We can look at results for particular choices of ratios at the source:



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

Selected source compositions

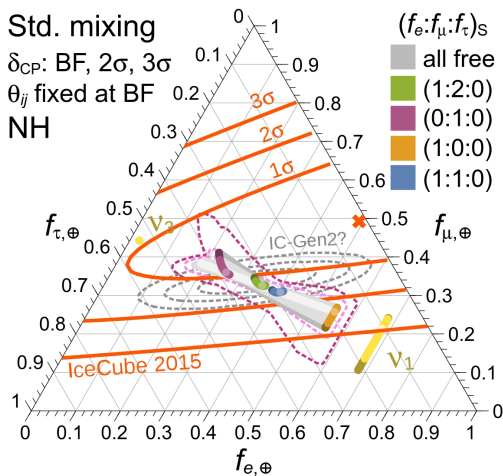
We can look at results for particular choices of ratios at the source:



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

Perfect knowledge of mixing angles

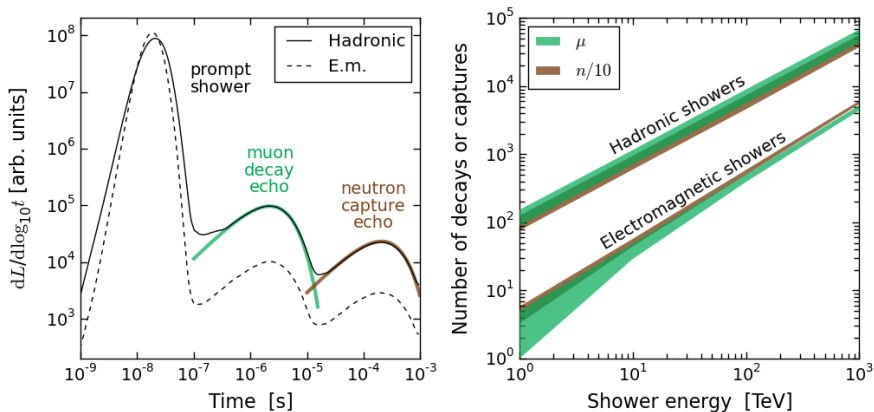
In a few years, we might know all the mixing parameters except δ_{CP} :



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

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

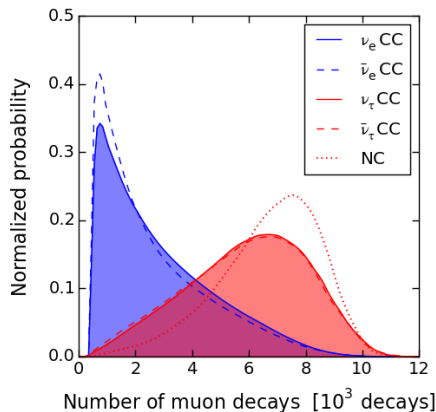
How to improve ν_e vs. ν_τ separation?

ν_e -initiated CC showers: e.m.

ν_τ -initiated CC showers: mostly ($\sim 67\%$) hadronic

ν_X -initiated NC showers: hadronic

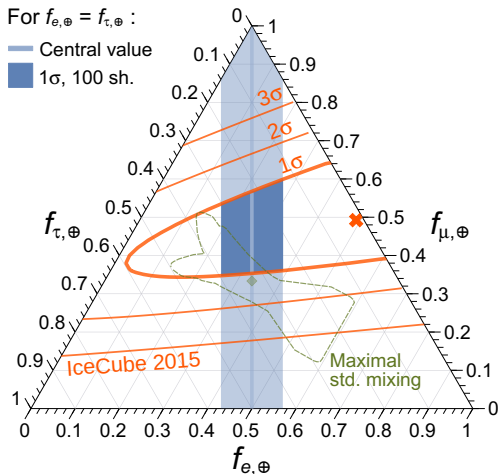
Probability distribution of number of muon decays per 100-TeV shower:



Li, MB, BEACOM, 1606.06290

How to improve ν_e vs. ν_τ separation?

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



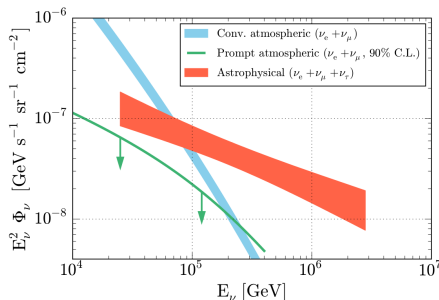
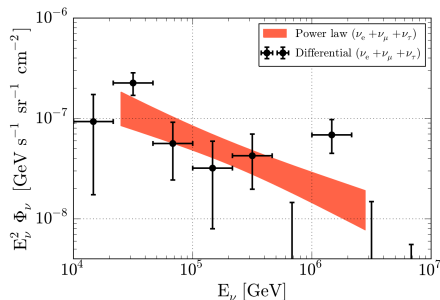
Using echoes: $\sim \times 9$ improvement over current flavor contours

LI, MB, BEACOM, 1606.06290

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

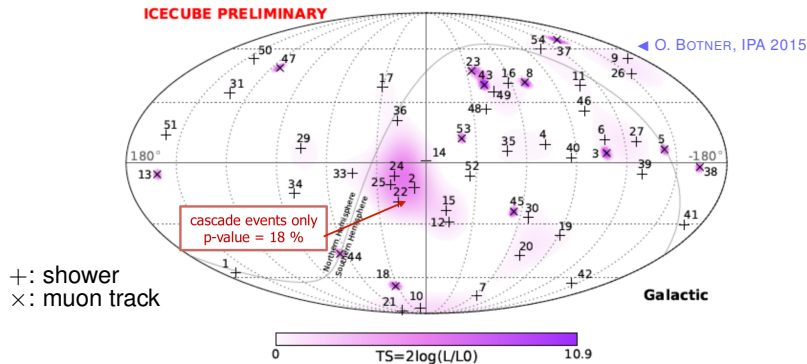


[IceCube Coll., *ApJ* **809**, 98 (2015)]

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



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)]

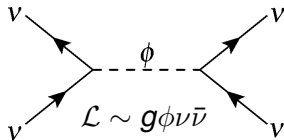
[MALTONI, WINTER, *JHEP* **07**, 064 (2008)]

[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

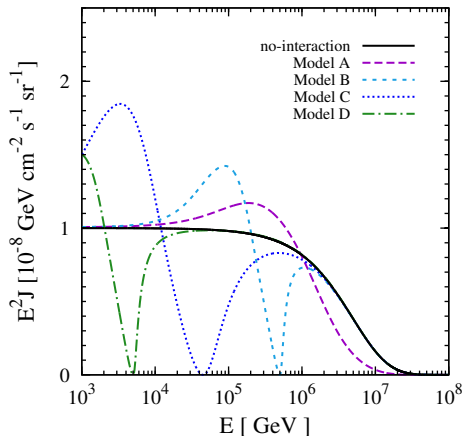


Cross section:

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

Resonance at

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

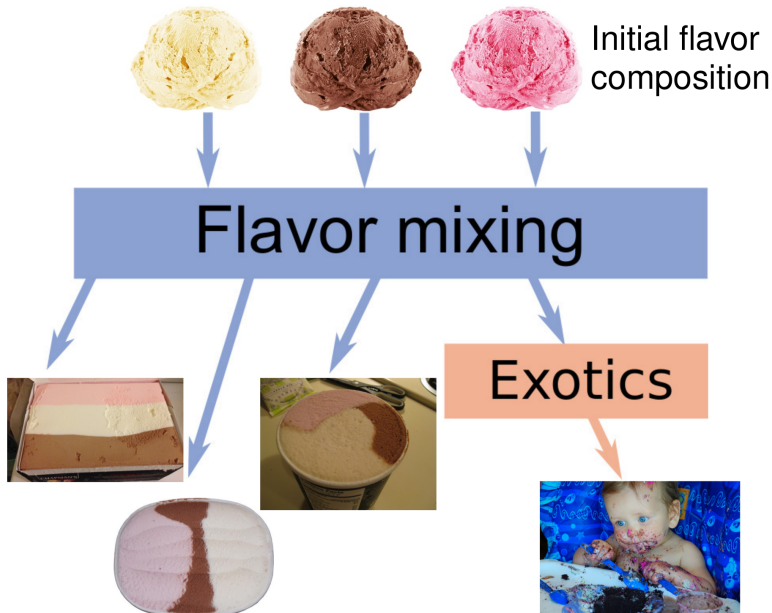


[NG & BEACOM, *PRD* **6**, 065035 (2014)]

[CHERRY, FRIEDLAND, SHOEMAKER, 1411.1071]

[BLUM, HOOK, MURASE, 1408.3799]

New physics: effect on the flavor composition



Can neutrinos decay?

In principle, yes

Why? Because different neutrinos have different masses:

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

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

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

- ▶ 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
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

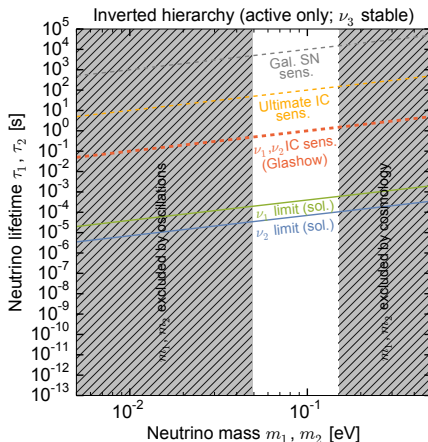
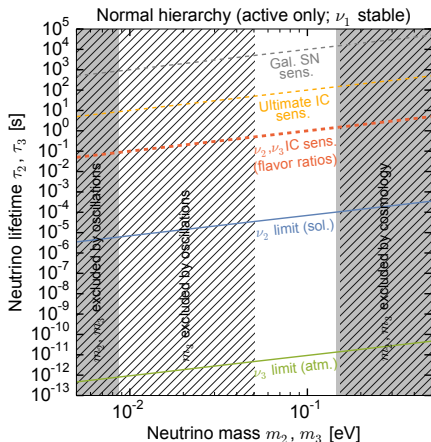
Lifetime limits and sensitivities

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

$\nu_2, \nu_3 \rightarrow \nu_1$

or

$\nu_1, \nu_2 \rightarrow \nu_3$



Decay in the flavor ratios

$$f_{\alpha,\oplus}(E_0, z, \tau_i/m_i) = \sum_{\beta=e,\mu,\tau} \left(\sum_{i=1}^3 |U_{\alpha i}|^2 |U_{\beta i}|^2 \overset{\text{fraction of } \nu_i \text{ that reach Earth}}{\downarrow} D(E_0, z, \tau_i/m_i) \right) f_{\beta,s}$$

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

Complete decay ($D \ll 1$) —

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

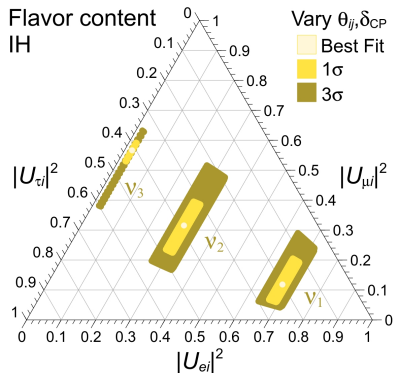
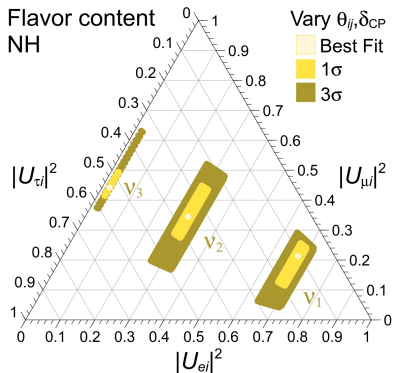
$$f_{\alpha,\oplus} = \begin{cases} |U_{\alpha 1}|^2, & \text{for NH} \\ |U_{\alpha 3}|^2, & \text{for IH} \end{cases}$$

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

Flavor content of the mass eigenstates

Flavor content for every allowed combination of mixing parameters:

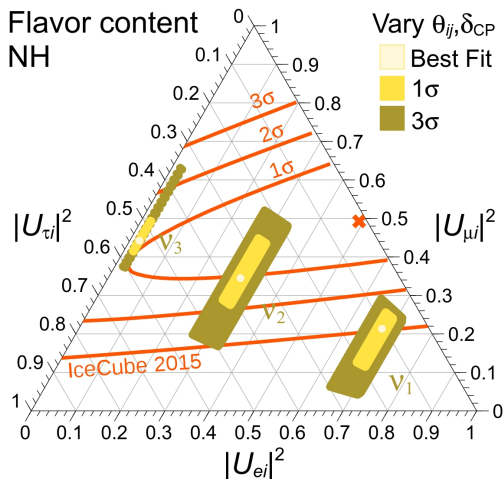
$$|U_{\alpha i}|^2 = |U_{\alpha i}(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}})|^2$$



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

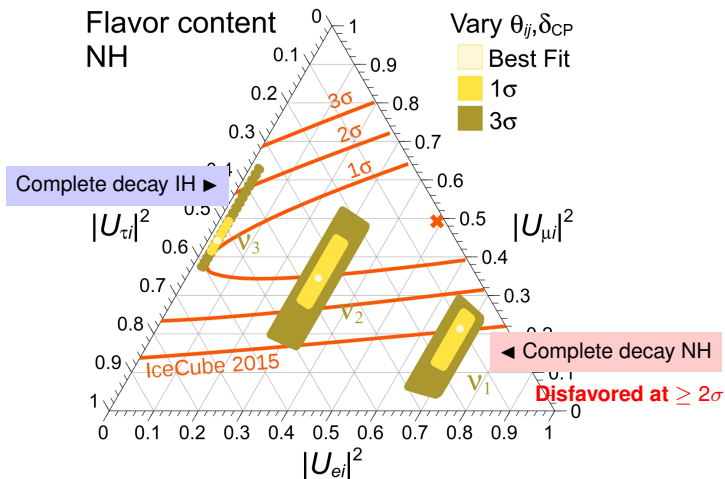
Sensitivity to decay using IceCube flavor contours

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



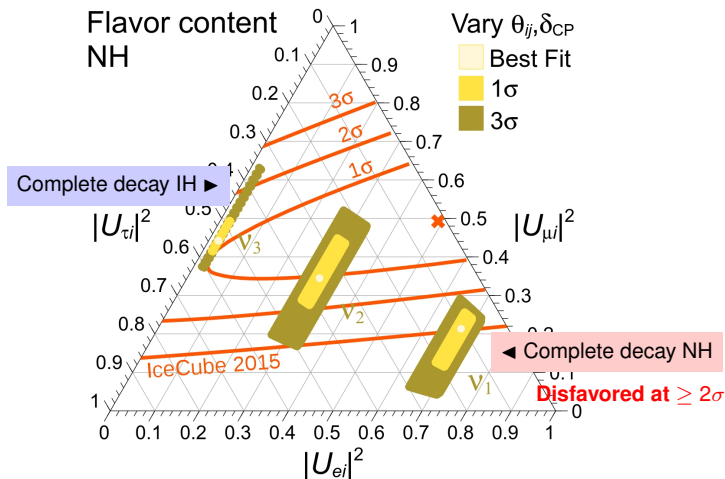
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Sensitivity to decay using IceCube flavor contours

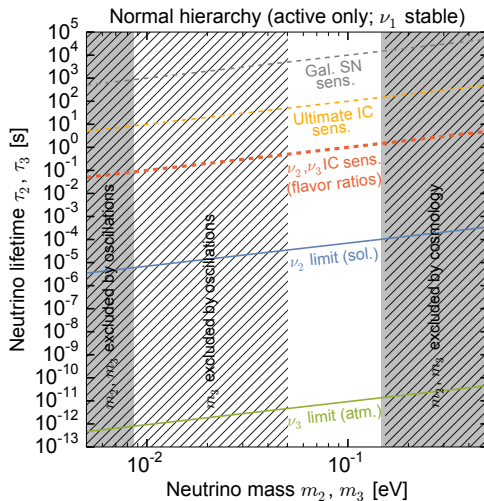
Overlay the IceCube flavor-ratio contours on the flavor-content regions:



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

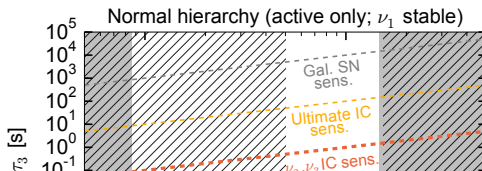
Improved lifetime sensitivity in the NH

$$\kappa_2^{-1}, \kappa_3^{-1} \gtrsim 10 \text{ s eV}^{-1} \text{ at } \gtrsim 2\sigma$$

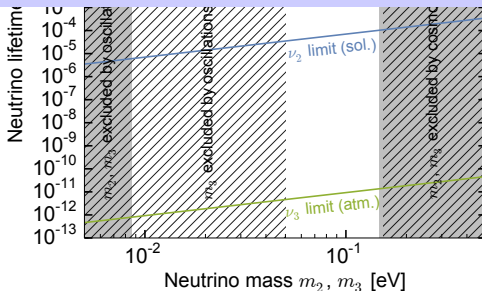


Improved lifetime sensitivity in the NH

$$\kappa_2^{-1}, \kappa_3^{-1} \gtrsim 10 \text{ s eV}^{-1} \text{ at } \gtrsim 2\sigma$$

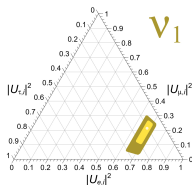


(Similar for IH, using the Glashow resonance — see [MB](#), [BEACOM](#), [MURASE](#), 1610.02096)

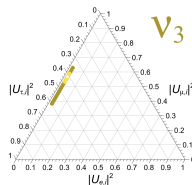


Decay: complete vs. incomplete

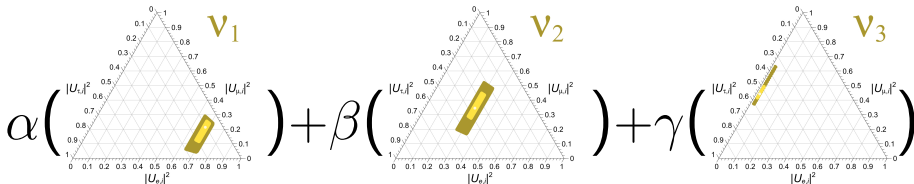
- **Complete decay:** only ν_1 (ν_3) reach Earth assuming NH (IH)



or

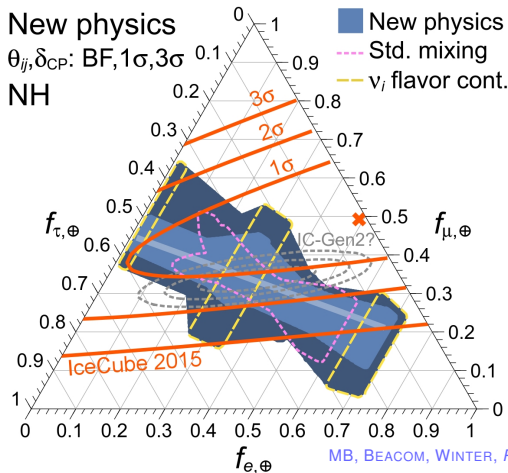


- **Incomplete decay:** incoherent mixture of ν_1 , ν_2 , ν_3 reaches Earth



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

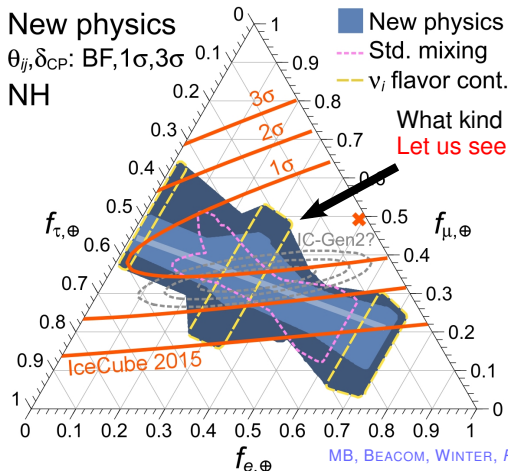
Region of flavor ratios accessible with decay

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

New physics

θ_{ij}, δ_{CP} : BF, $1\sigma, 3\sigma$

NH



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

New physics — of the *truly exotic* kind

What kind of NP lives outside the blue region?

- ▶ NP that changes the values of the mixing parameters, *e.g.*,
 - ▶ violation of Lorentz and CPT invariance
[BARENBOIM, QUIGG, *PRD* **67**, 073024 (2003)] [MB, GAGO, PEÑA-GARAY, *JHEP* **1004**, 005 (2010)]
 - ▶ violation of equivalence principle
[GASPERINI, *PRD* **39**, 3606 (1989)] [GLASHOW *et al.*, *PRD* **56**, 2433 (1997)]
 - ▶ coupling to a torsion field
[DE SABBATA, GASPERINI, *Nuovo. Cim.* **A65**, 479 (1981)]
 - ▶ renormalization-group running of mixing parameters
[MB, GAGO, JONES, *JHEP* **1105**, 133 (2011)]
- ▶ active-sterile mixing [AEIKENS *et al.*, 1410.0408]
- ▶ flavor-violating physics
- ▶ ν – $\bar{\nu}$ mixing (if ν , $\bar{\nu}$ flavor ratios are considered separately)

New physics — of the *truly exotic* kind

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 - ▶ 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)



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)]

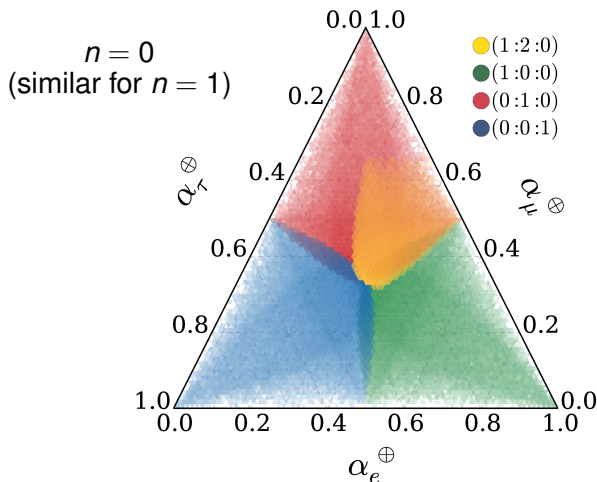
[SUPER-K COLL., *PRD* **91**, 052003 (2015)]

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

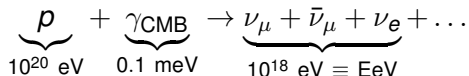
[ARGÜELLES, KATORI, SALVADÓ
PRL **115**, 161303 (2015)]



What lies beyond — cosmogenic neutrinos

We expect the $> \text{PeV}$ ν sky to be populated: cosmogenic neutrinos

They are produced in proton (or nuclei) interactions with CMB photons:



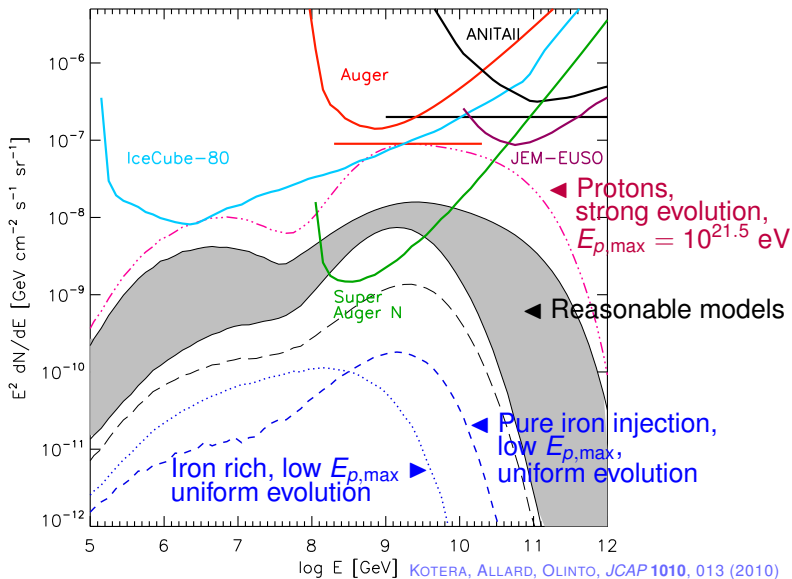
We have not seen them — why are they worth looking for?

- ▶ They are sensitive to the UHECR composition (fewer ν 's if nuclei)
- ▶ They probe the high-redshift UHECR evolution
- ▶ Probe ν properties at previously unexplored energies

CMB photons are abundant but UHECRs are much less so

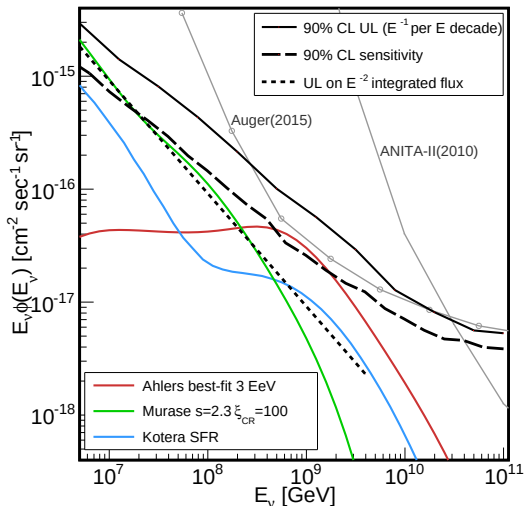
$\therefore$ The cosmogenic neutrino flux is low

How low can low be?



The present-day picture

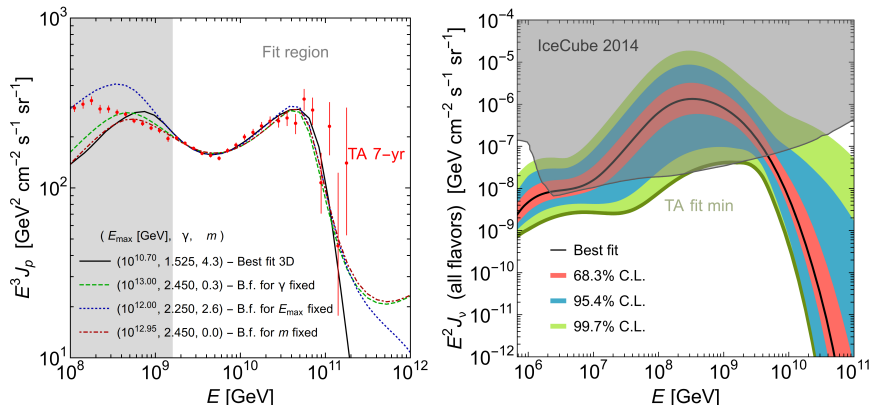
The latest IceCube search (7 years) disfavors optimistic flux predictions —



IceCUBE, 1607.05886

Challenging the UHECR “proton dip” model

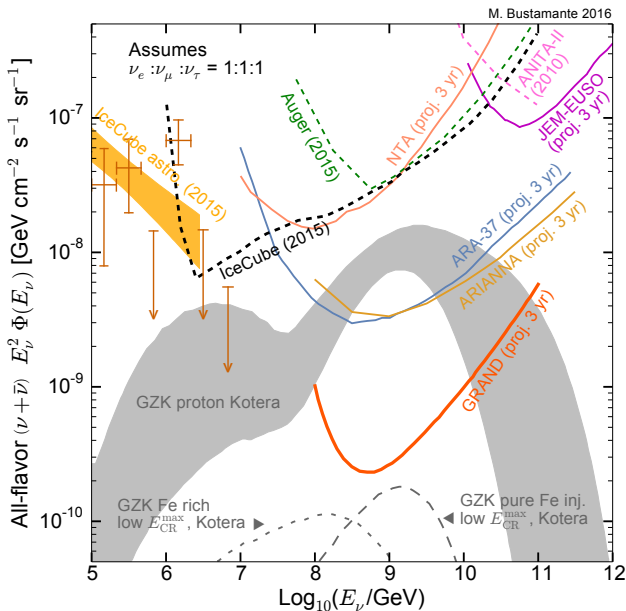
Fit UHECR pure-proton fluxes to 7-year TA spectrum — *all* associated cosmogenic ν fluxes overshoot the IceCube bound:



This challenges a pure-proton UHECR composition

J. HEINZE, D. BONCIOLI, MB
W. WINTER, *ApJ* 825, 122 (2016)

Discovering cosmogenic neutrinos



Sensitivity to pessimistic scenarios of cosmogenic neutrinos can realistically be achieved only with dedicated EAS detectors

How can the nightmare scenario be overcome?

- 1 Build big. Really big.
- 2 Use radio emission — attenuation length is ~ 100 km in air

GRAND: Giant Radio Array for Neutrino Detection



- ▶ Detects Earth-skimming ν_τ 's with $10^{8.5}$ – $10^{11.5}$ GeV
- ▶ Via radio emission of τ -initiated extensive air showers
- ▶ $\sim 10^5$ antennas covering 2×10^5 km²

A win-win-win situation

For cosmogenic neutrinos, GRAND is ...

- ▶ ... a discovery *and* precision instrument for **optimistic** fluxes:
600–1400 events yr^{-1}
- ▶ ... a discovery instrument for **pessimistic** fluxes:
6–15 events yr^{-1}
- ▶ ... and a strong-exclusion instrument, if < 1 event yr^{-1}



Summary and outlook

- ▶ High-energy (10 TeV – 2 PeV) astrophysical neutrinos exist
- ▶ IceCube measures spectral shape, arrival directions, flavor composition
- ▶ No sources found yet:
 - ▶ **Galactic component:** $\lesssim$ few 10%
 - ▶ **Extragalactic component:** multi-messenger studies provide clues
- ▶ Definitive new-physics tests can be performed already with current data
- ▶ Proposed upgrades (IceCube-Gen2, KM3NeT) will provide more data
- ▶ Next frontier: EeV cosmogenic neutrinos

Summary and outlook

- ▶ High-
- ▶ IceCube
- ▶ No so
- ▶
- ▶
- ▶ Defin
- ▶ Propo
- ▶ Next



position

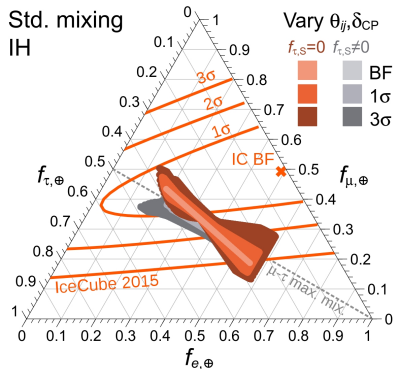
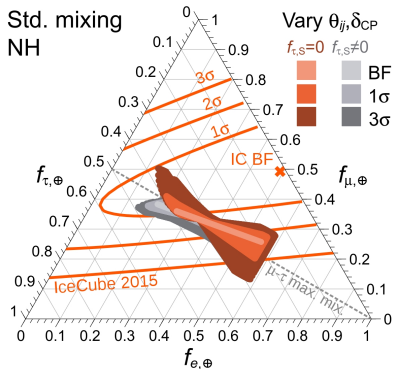
clues

ent data

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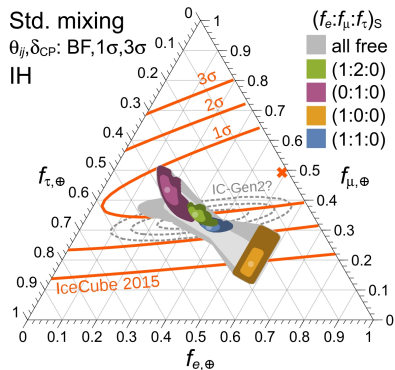
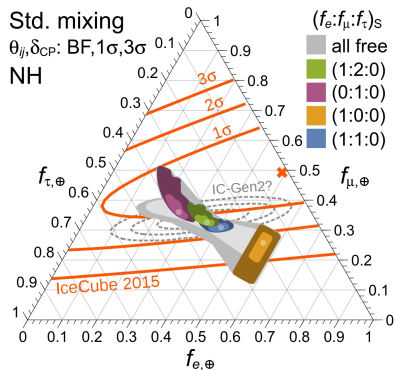
Backup slides

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



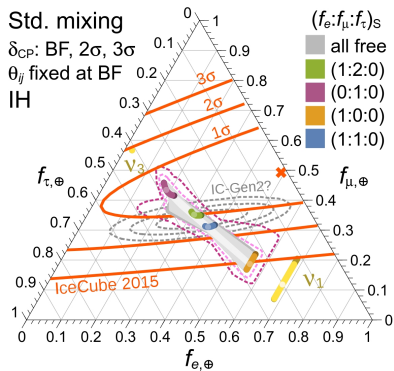
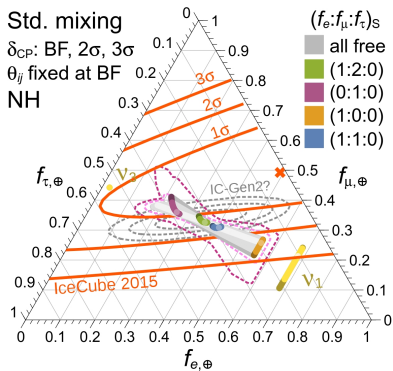
[MB, BEACOM, WINTER, *PRL* **115**, 1611302 (2015)]

Selected source compositions: NH vs. IH



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

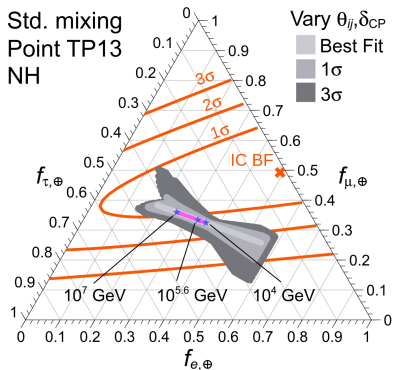
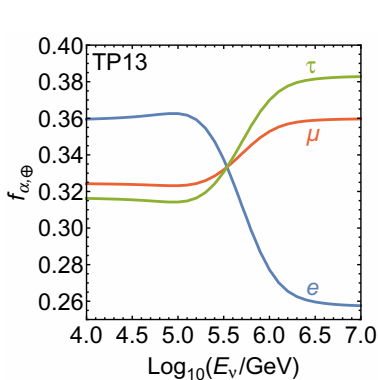
Perfect knowledge of mixing angles: NH vs. IH



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

Energy dependence of the composition at the source

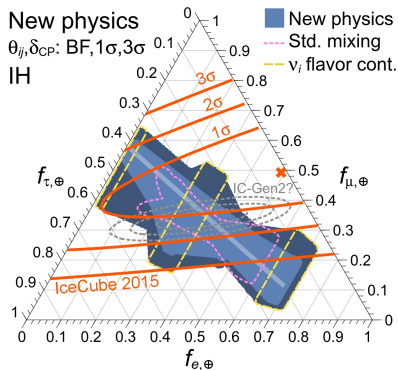
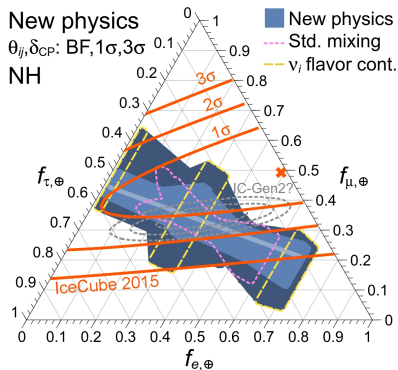
Different ν production channels are accessible at different energies



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)]

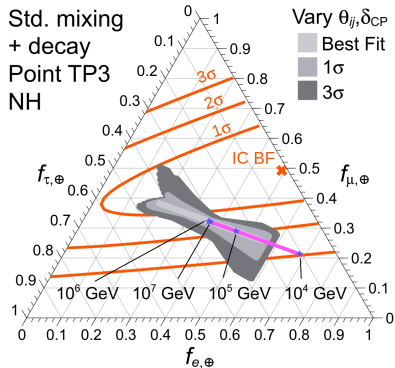
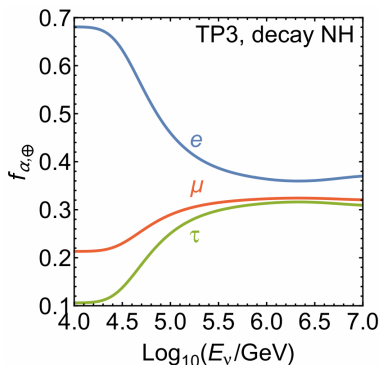
New physics: NH vs. IH



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

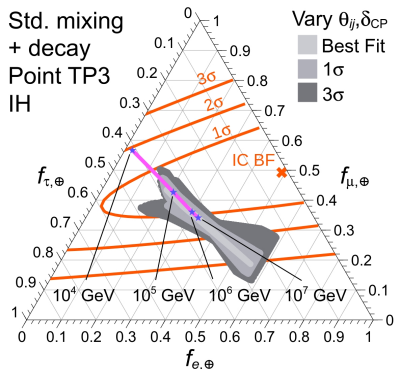
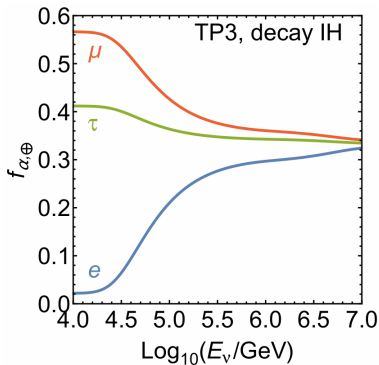
Decay: seeing the energy dependence?

- ▶ 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)]

Flavor mixing in high-energy astrophysical neutrinos

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

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

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:

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

Echoes: two (surmountable) obstacles

Obstacle:

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

Solution:

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

Obstacle:

Muon echo time scale ($2\text{--}5\ \mu\text{s}$) 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

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 source(s) are known.

Unnecessary under complete decay

Energy spectrum at the source(s) is known.

Unnecessary under complete decay

► **Neutrino properties:**

Mixing parameters are known.

Decay can be probed even if parameters vary within 3σ

Decay modes are known.

We have model-independent sensitivity

Neutrino daughter kinematics are known.

ν masses non-degenerate: daughters get $\sim$ half of parent energy

► **Detection aspects:**

Negligible contribution from background events.

Use high-energy ($\gtrsim 100$ TeV) events away from the Galactic Plane

Flavor is measured well for each neutrino.

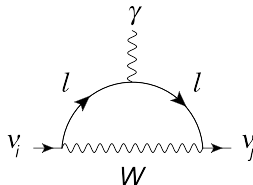
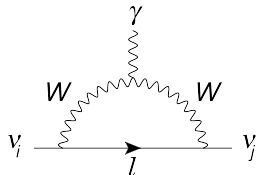
Suffices to use statistical measurement of flavor ratios of an event sample

Energy is measured well for each neutrino.

Not a concern if decay is complete for all relevant energies (0.1–10 PeV)

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

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

Decay fundamentals

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

$\underbrace{\nu_2, \nu_3 \rightarrow \nu_1}$
normal mass hierarchy (NH)

or

$\underbrace{\nu_1, \nu_2 \rightarrow \nu_3}$
inverted mass hierarchy (IH)

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

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

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

▲ For very long L ,
this will have redshift corrections

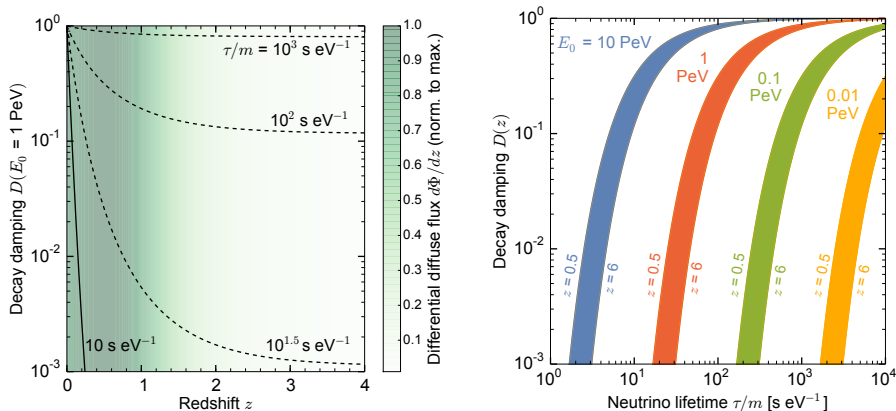
- ▶ Neutrinos with known L and E_ν are sensitive to “lifetimes” of

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

Two necessary cosmological corrections

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

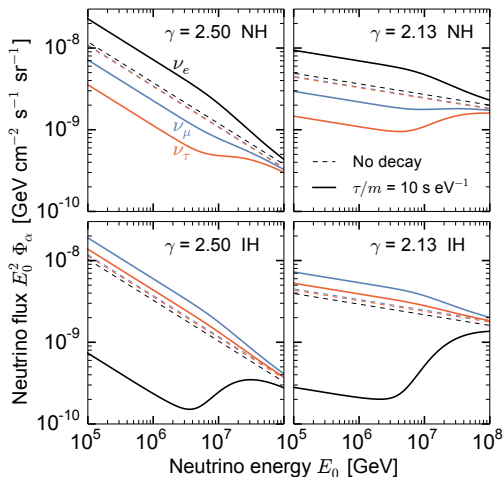
The cosmologically-correct survival fraction D behaves like this:



BAERWALD, MB, WINTER, *JCAP* **1210**, 020 (2012) + MB, BEACOM, MURASE, 1610.02096

How to look for decay?

Depletes flux of heavy eigenstates and enhances flux of lightest one



What are the decay signatures?

- ▶ Complete decay
- ▶ Transition region

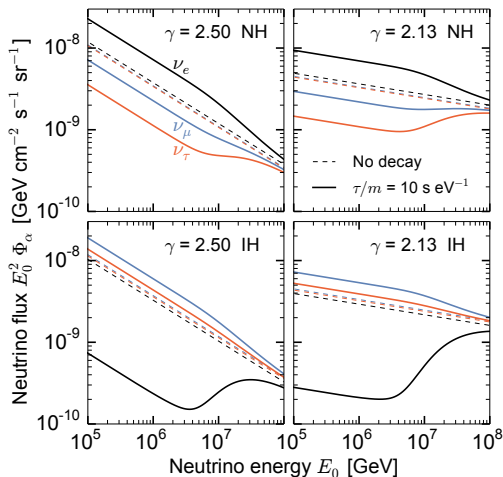
Where to look for it?

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

MB, BEACOM, MURASE, 1610.02096

How to look for decay?

Depletes flux of heavy eigenstates and enhances flux of lightest one



What are the decay signatures?

- ▶ Complete decay ◀
- ▶ Transition region

Where to look for it?

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

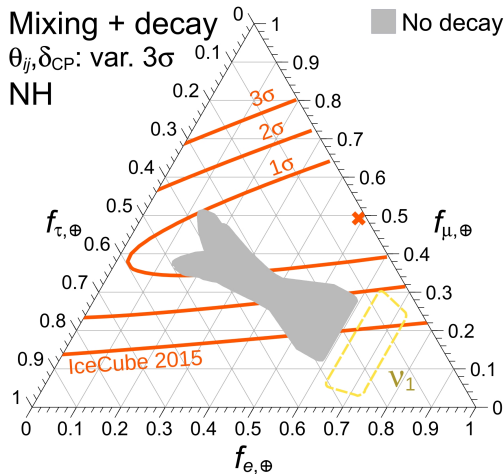
MB, BEACOM, MURASE, 1610.02096

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

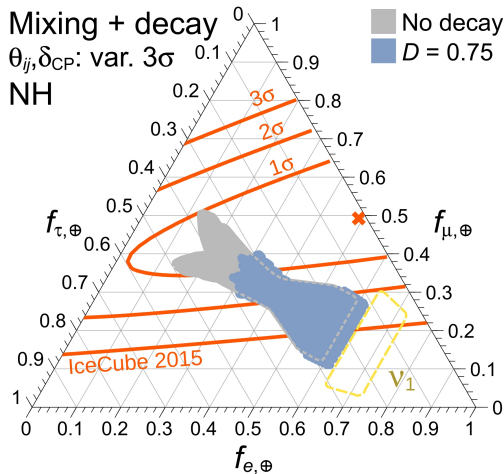


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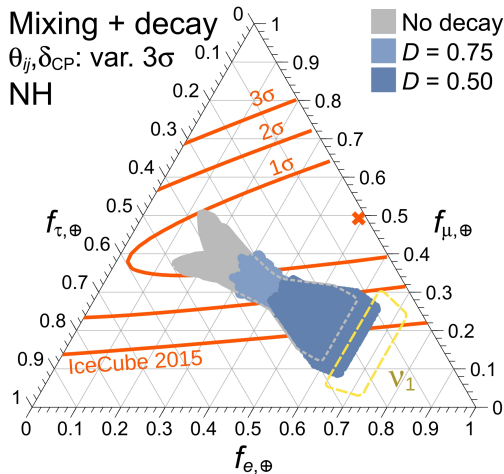


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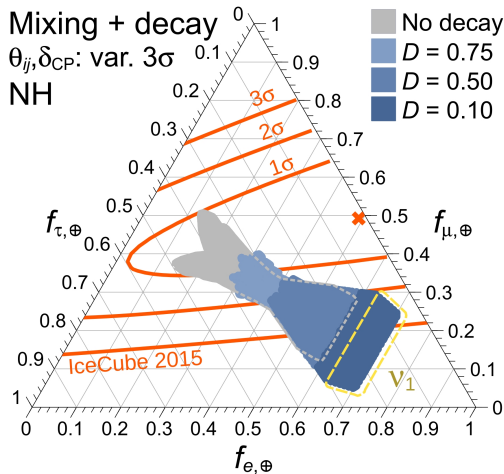


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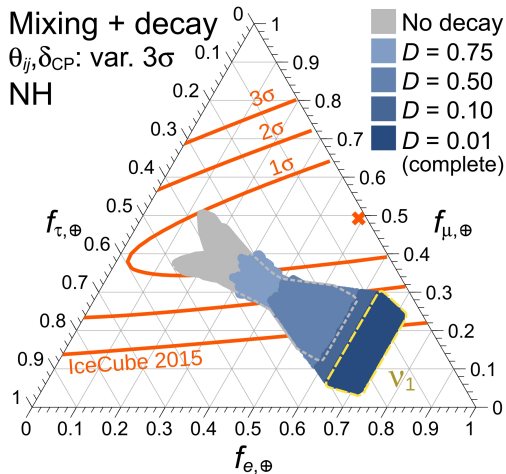


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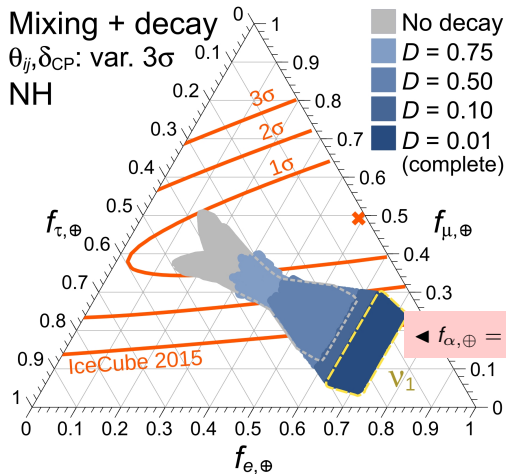


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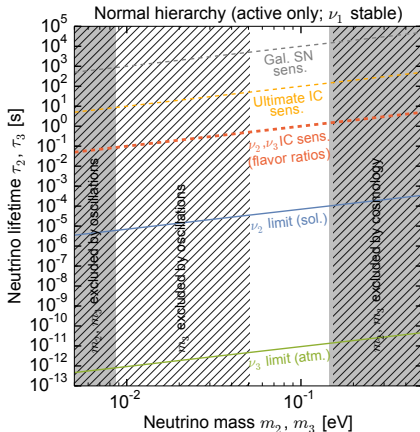
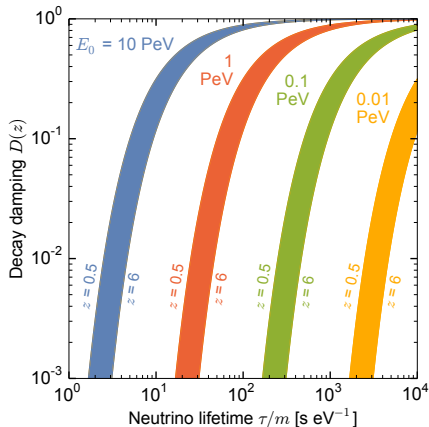
Assume equal lifetimes of ν_2, ν_3



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

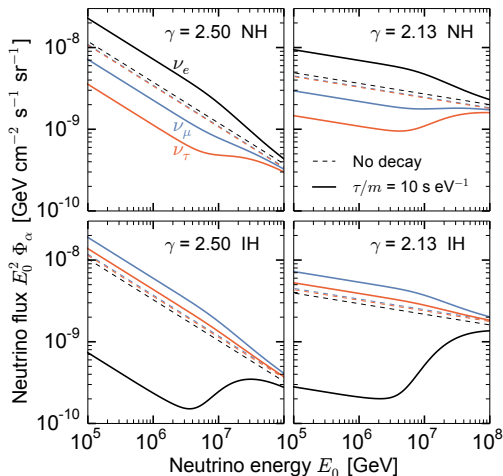
NH: lifetime sensitivity with **current** IceCube data (II)

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



MB, BEACOM, MURASE, 1610.02096

Decay in the high-energy shower rate



What are the decay signatures?

- ▶ Complete decay ◀
- ▶ Transition region

Where to look for it?

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

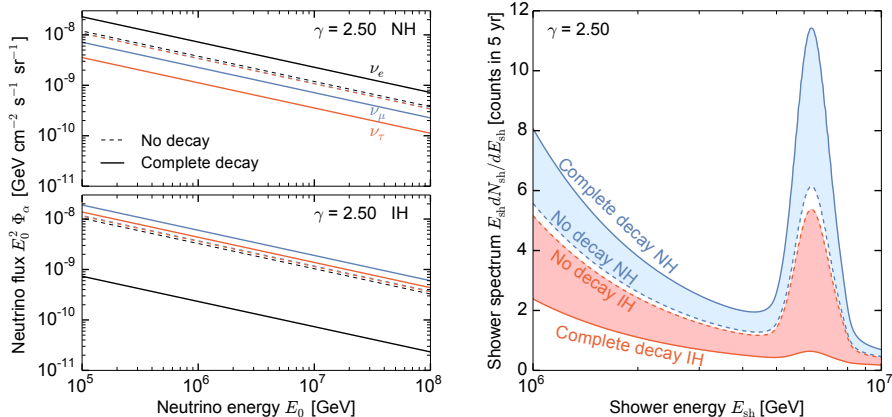
The ν_e flux changes the most:
IH, complete decay

MB, BEACOM, MURASE, 1610.02096

Decay and the Glashow resonance

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

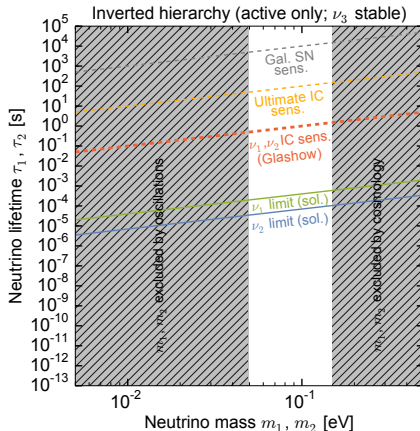
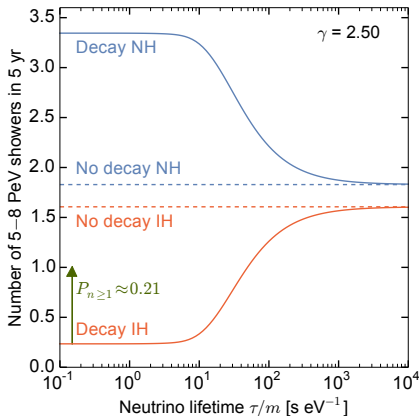
$$\bar{\nu}_e(6.3 \text{ PeV}) + e \rightarrow W \rightarrow \text{hadrons}$$



(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: $\kappa_1^{-1}, \kappa_2^{-1} \gtrsim 1 \text{ s eV}^{-1}$



MB, BEACOM, MURASE, 1610.02096

Neutrino decay with flavor — how to do better?

Achievable *now*:

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

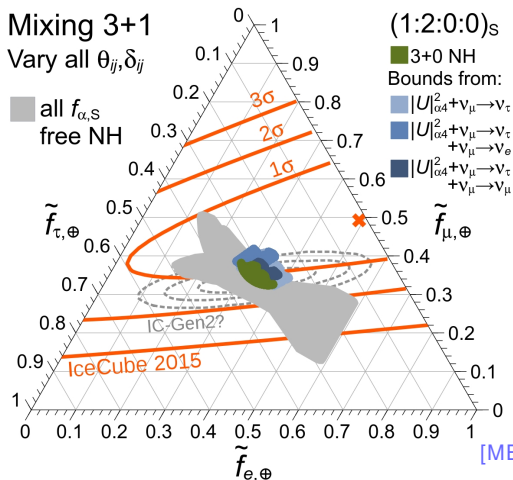
Achievable in the *near future*:

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

New physics — active-sterile mixing

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

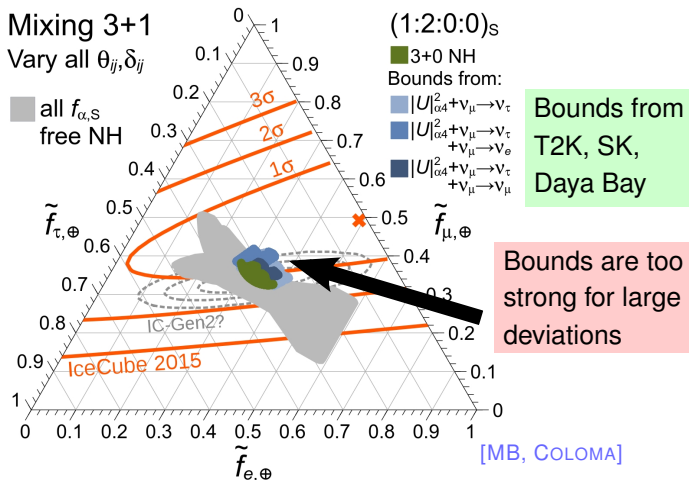
- ▶ standard parameters: $\theta_{12}, \theta_{23}, \theta_{13}, \delta_{13}$
- ▶ sterile parameters: $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{24}, \delta_{34}$



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: $\theta_{14}, \theta_{24}, \theta_{34}, \delta_{24}, \delta_{34}$



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:

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

