High-energy astrophysical neutrinos: where do we stand, where do we go?

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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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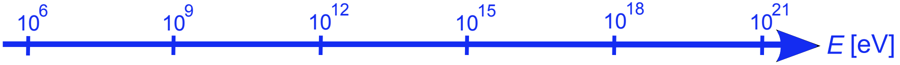
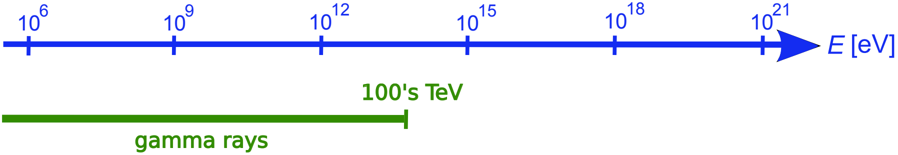
Some reasons why neutrinos are special:

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

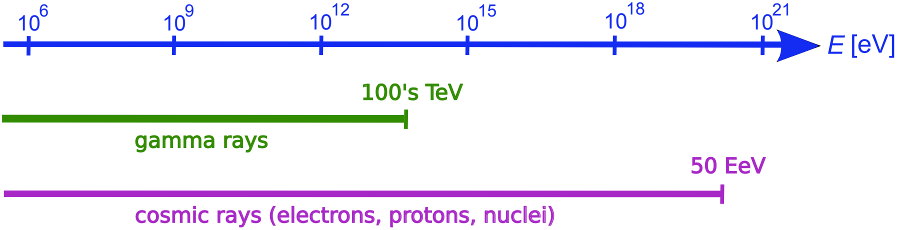
Let's talk energy scales...



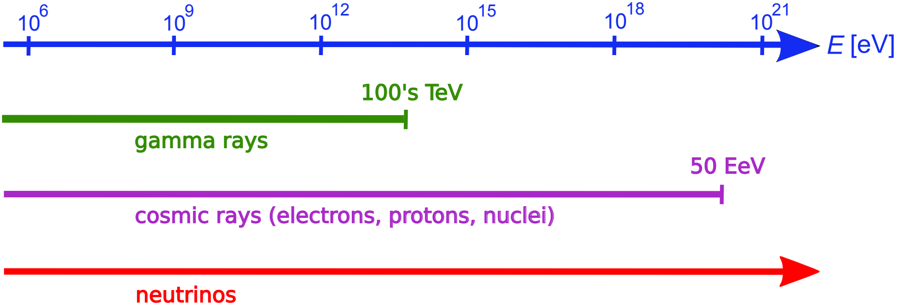
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]



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



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


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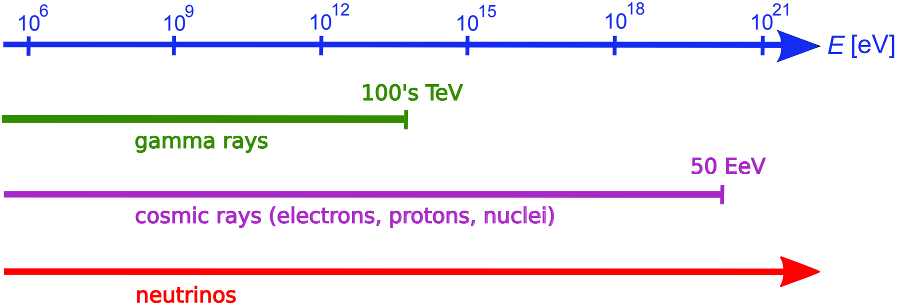
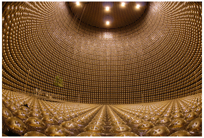
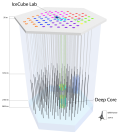
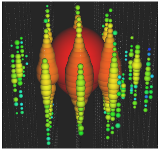
50 EeV
cosmic rays (electrons, protons, nuclei)
neutrinos



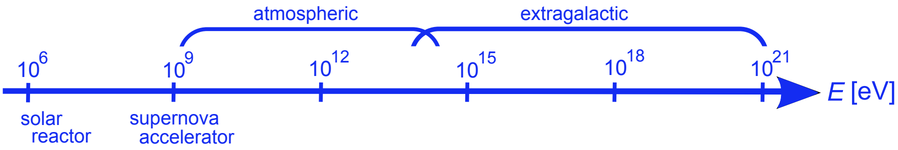
5 Unlike gamma rays and cosmic rays, neutrinos have flavor

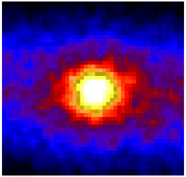


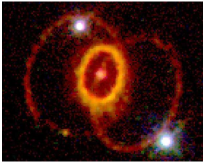

IceCube Lab
Deep Core

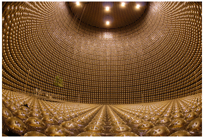


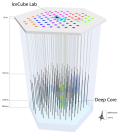
2013+

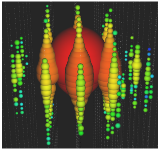

atmospheric
extragalactic
10^6
10^9
10^{12}
10^{15}
10^{18}
10^{21}
E [eV]
solar
reactor
supernova
accelerator



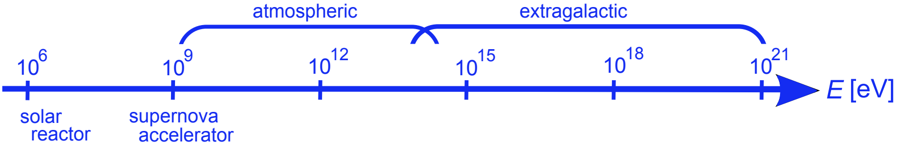


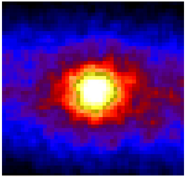


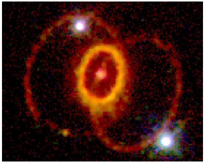


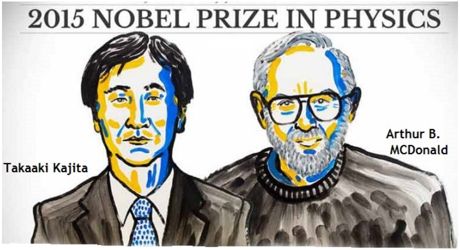


2013+









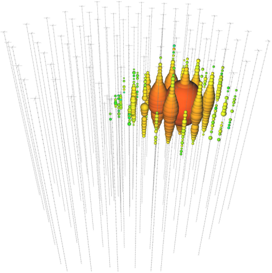
Next ν-Nobel for high-energy ν's?

High-energy astrophysical neutrinos: they exist!

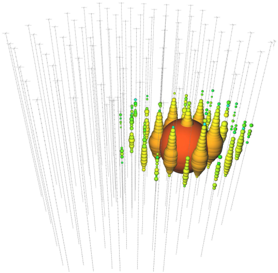
The era of neutrino astronomy has begun!

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

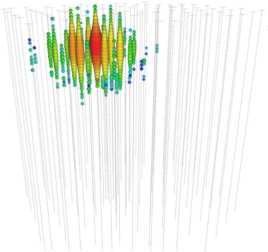
"Bert", 1.04 PeV



"Ernie", 1.14 PeV



"Big Bird", 2 PeV



...and 51 more events > 30 TeV

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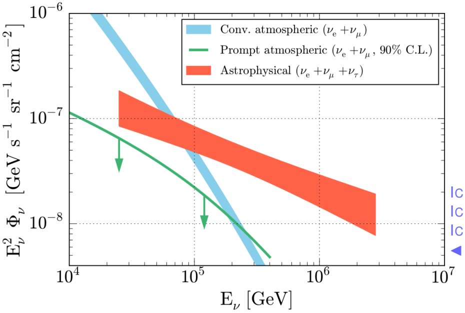

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ IceCube, *ApJ* **809**, 98 (2015)

Diffuse per-flavor astrophysical flux [IceCube 2015]:

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

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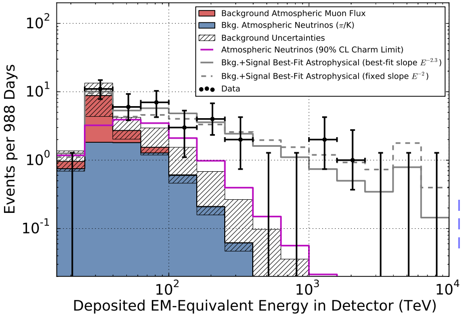

IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)

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

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

High-energy astrophysical neutrinos: they exist!

The era of neutrino astronomy has begun!

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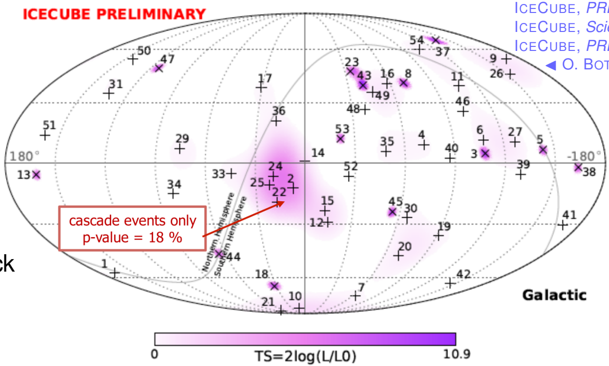
Arrival directions compatible with an isotropic distribution –

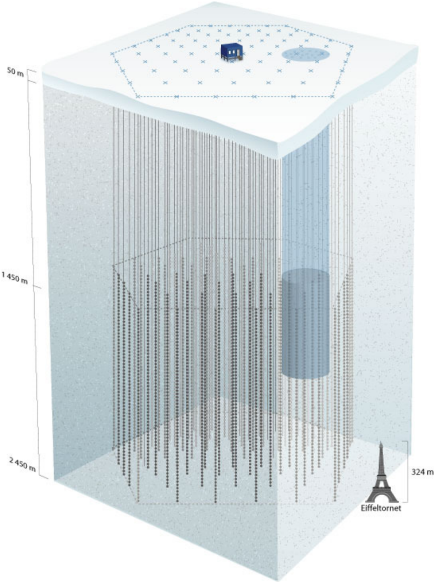
IceCube, *PRL* **111**, 021103 (2013)
IceCube, *Science* **342**, 1242856 (2013)
IceCube, *PRL* **113**, 101101 (2014)
◀ O. Botner, IPA 2015



+: shower
×: muon track

– no association with sources found yet

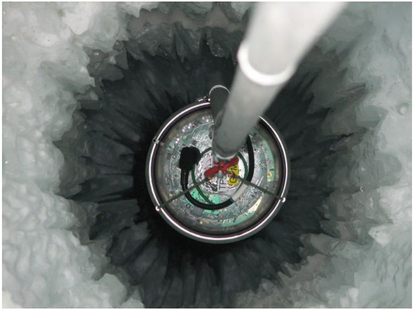
Detecting the neutrinos: IceCube



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

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

Detecting the neutrinos: IceCube



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

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

How does IceCube see neutrinos?

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

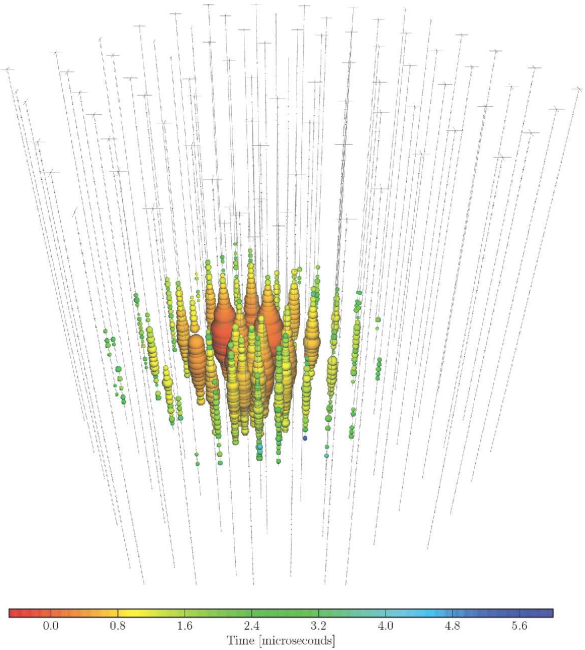
- Showers: generated by CC ν_e or ν_τ; or by NC ν_x
- Muon tracks: generated by CC ν_μ

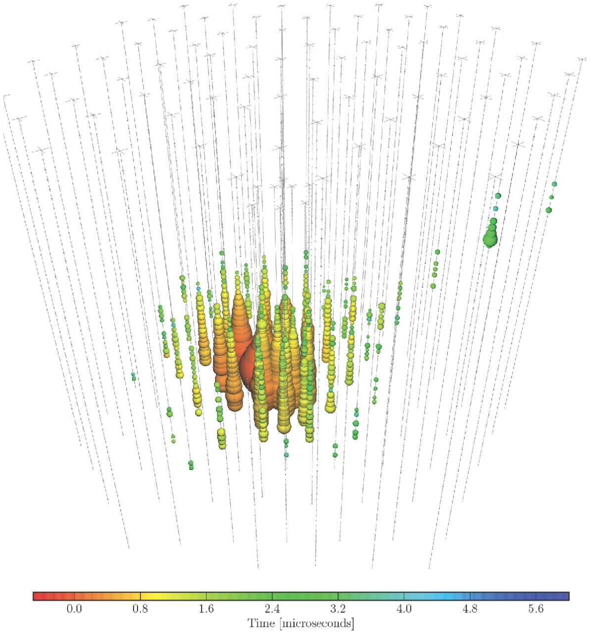
(Some muon tracks can be mis-reconstructed as showers)

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

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

Flavor composition is inferred from the number of showers and tracks


0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]


0.0
0.8
1.6
2.4
3.2
4.0
4.8
5.6
Time [microseconds]

What we know / don't know

What we know

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

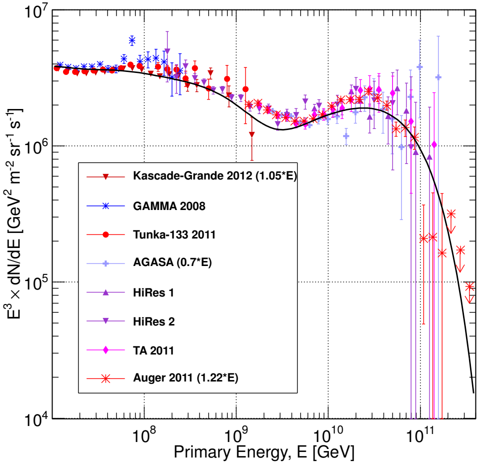
What we don't know

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

. . . but we have good ideas on all

Why did we expect high-energy neutrinos?

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

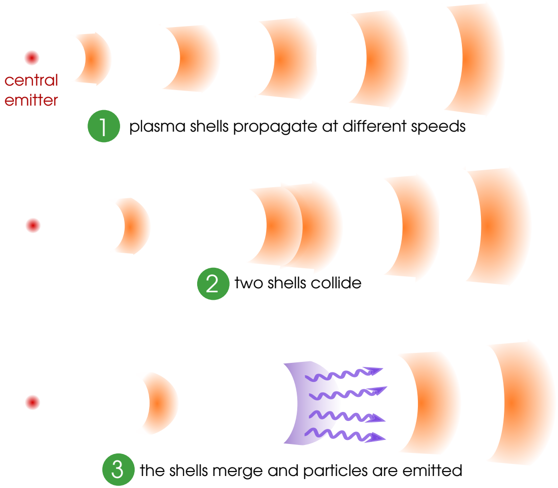


Gaisser, Stanev, Tilav, *Front. Phys. China* **8**, 748 (2013)

Cosmic-ray accelerators should also produce neutrinos ▶

HE particles from astrophysical sources

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



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

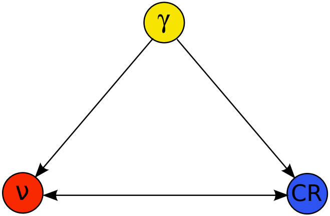
power law $\sim E^{-\alpha_p}$ broken power law

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

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

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

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

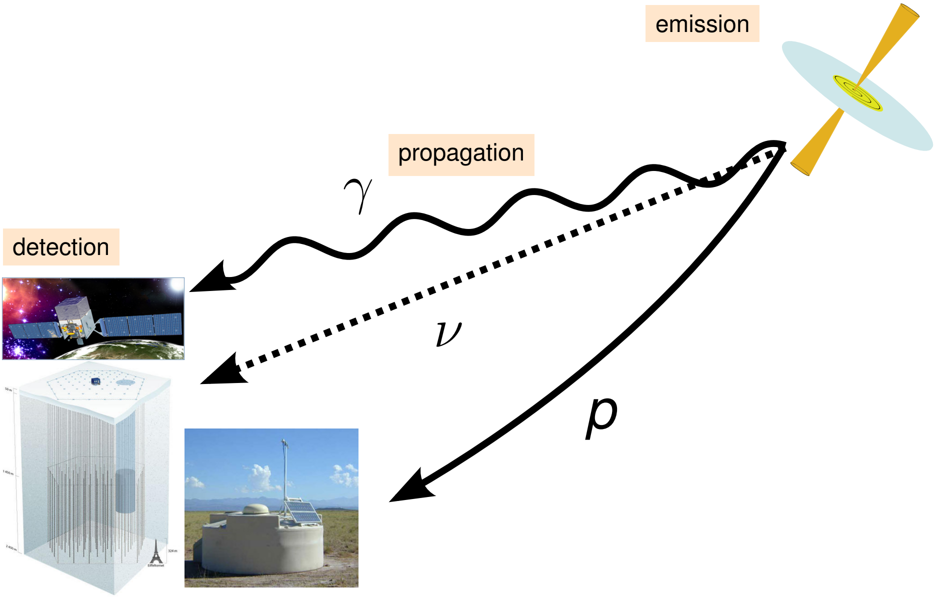


neutrino energy $\simeq$ proton energy / 20

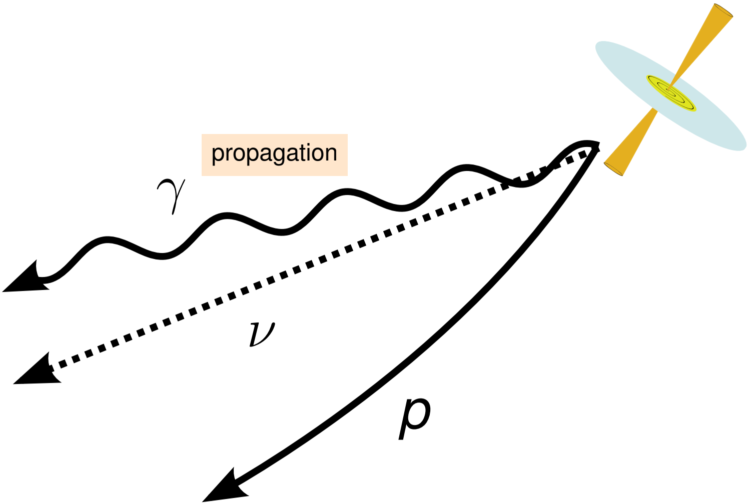
neutrino energy $\simeq$ gamma-ray energy / 2

[*Actually*, it is more complicated . . .
This neutron model of CR emission is now strongly disfavored
[Ahlers *et al.*, *Astropart. Phys.* **35**, 87 (2011)] [IceCube Coll., *Nature* **484**, 351 (2012)]
But we can do better by letting the p's escape without interacting
[Baerwald, MB, Winter, *ApJ* **768**, 186 (2013)] [Baerwald, MB, Winter, *Astropart. Phys.* **62**, 66 (2015)]
[MB, Baerwald, Murase, Winter, *Nat. Commun.* **6**, 6783 (2015)]]

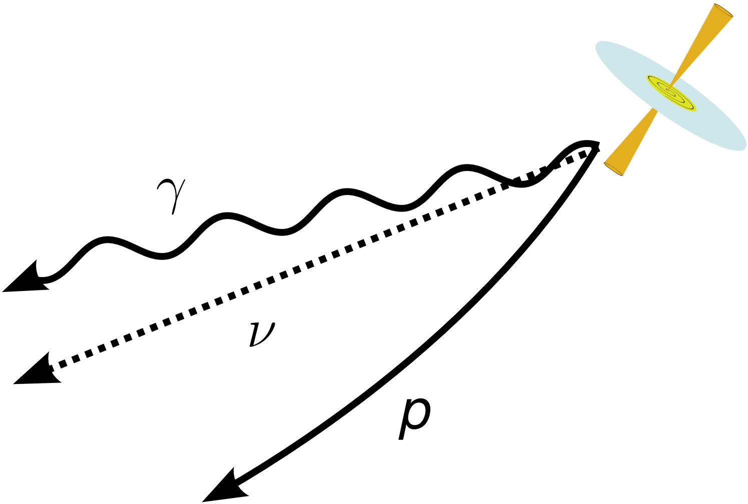
From the sources to us



From the sources to us

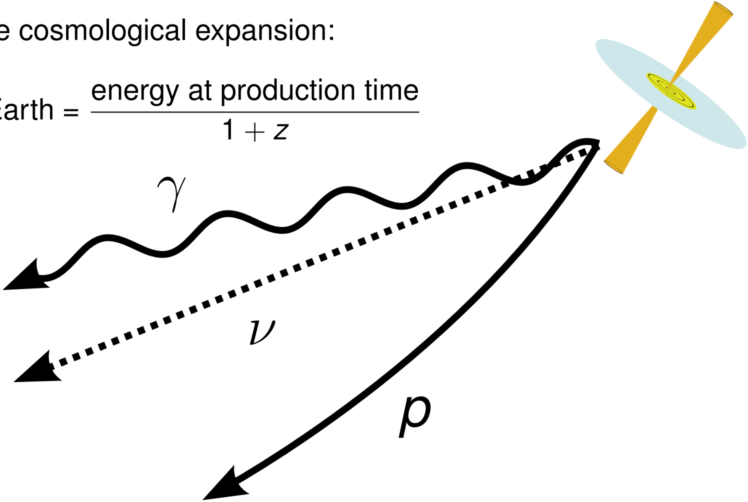


From the sources to us

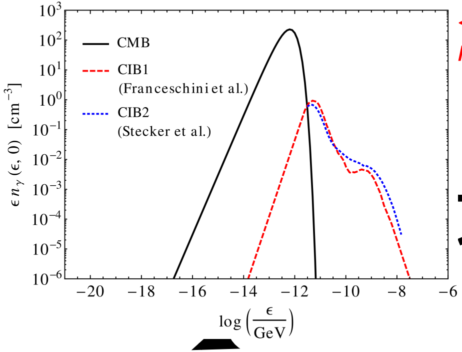


Because of the cosmological expansion:

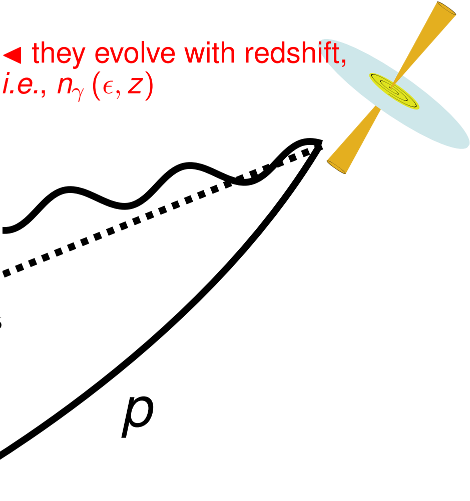
$$\text{energy at Earth} = \frac{\text{energy at production time}}{1+z}$$



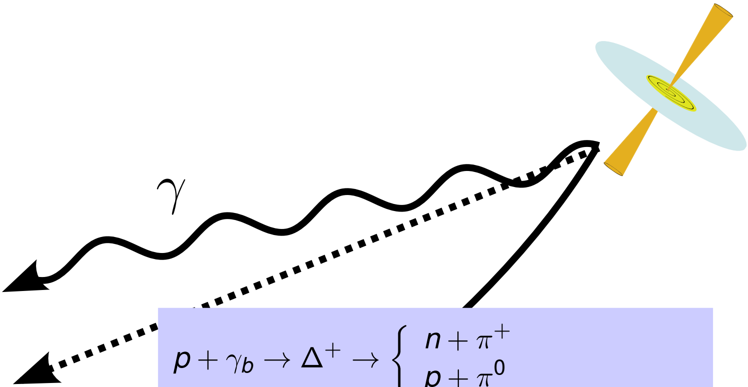
Cosmological photon backgrounds:



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



From the sources to us



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

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

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

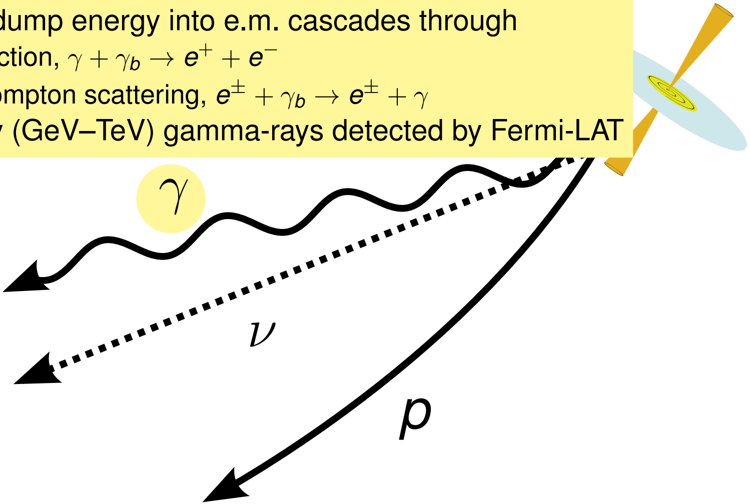
$$n \to p + e^- + \bar{\nu}_e$$

From the sources to us

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

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

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



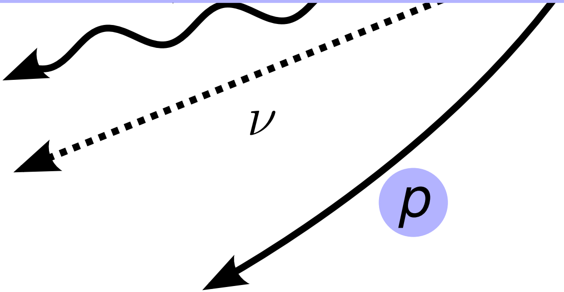
From the sources to us

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

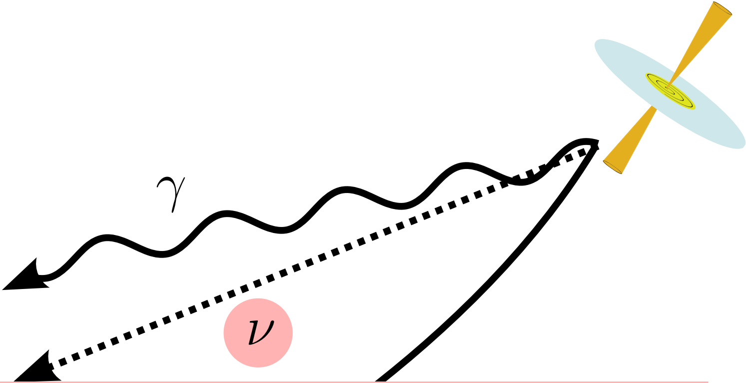
They lose energy through:

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

} depend on the redshift evolution of the cosmological γ backgrounds



From the sources to us



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

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

Flavor oscillations redistribute the fluxes

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

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

The need for km-scale neutrino telescopes

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

pion production efficiency

local UHECR energy density

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

Integrated flux above 1 PeV:

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

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

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

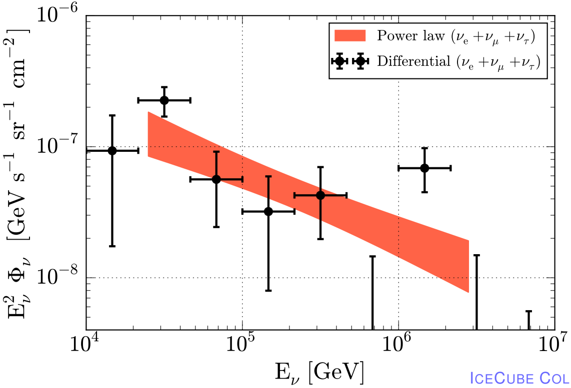
To detect $N_\nu > 1$ events per year, we need a detector area of

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

Therefore, we need km-scale detectors, like IceCube

Spectral shape

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



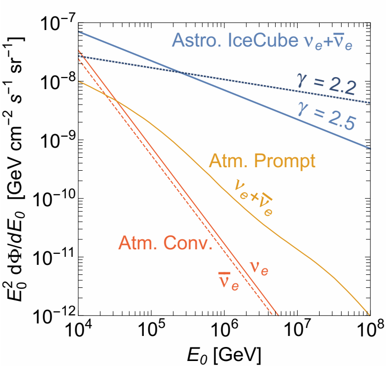
IceCube Coll., *ApJ* **809**, 98 (2015)

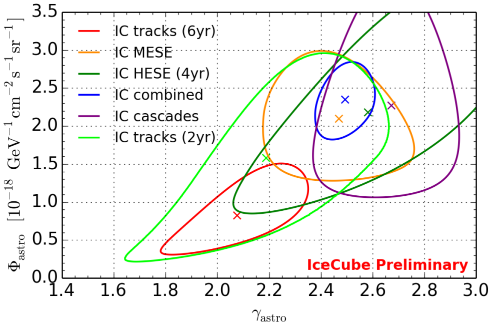
Per-flavor flux:

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

The spectral shape varies depending on the data set used —

- With through-going muon tracks: 2.0–2.2
- With high-energy starting events: $\sim$ 2.6

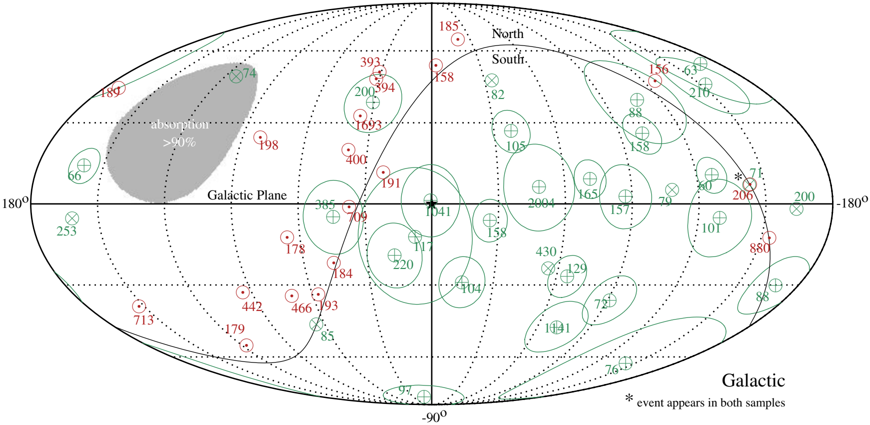




Neutrinos from the Galactic Center?
Atmospheric neutrino contamination at low E?

Arrival directions

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



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

Flavor ratios — at the sources and Earth

- Neutrino production at the astrophysical source via pion decay:

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

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

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

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

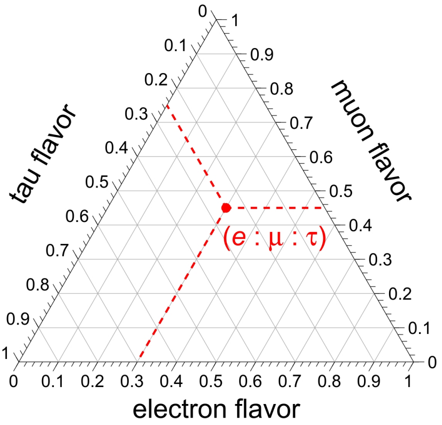
- Other compositions at the source:

$$(0 : 1 : 0)_S \longrightarrow (0.26 : 0.36 : 0.38)_\oplus \quad \text{(“muon damped”)}$$
$$(1 : 0 : 0)_S \longrightarrow (0.55 : 0.26 : 0.19)_\oplus \quad \text{(“neutron decay”)}$$
$$(1/2 : 1/2 : 0)_S \longrightarrow (0.40 : 0.31 : 0.29)_\oplus \quad \text{(“charmed decays”)}$$

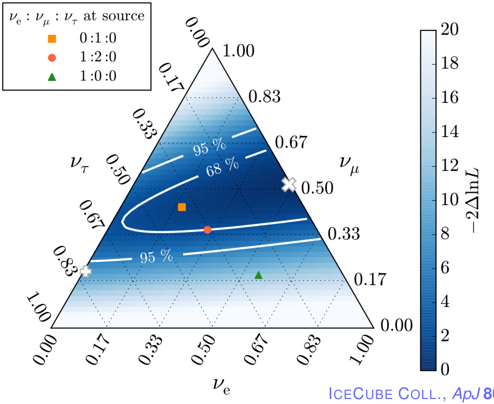
“Flavor triangle” or Dalitz/Mandelstam plot

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

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



Using contained events + throughgoing muons:

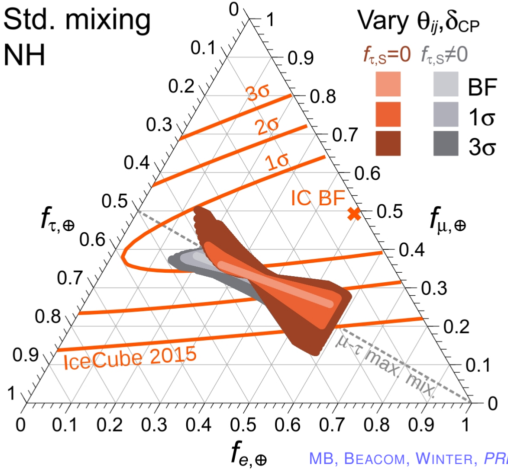


ICECUBE COLL., *ApJ* **809**, 98 (2015)

- Best fit: $(f_e : f_\mu : f_\tau)_\oplus = (0.49 : 0.51 : 0)_\oplus$
- Compatible with standard source compositions
- Bounds are weak – need more data and better flavor-tagging

Flavor combinations at Earth from std. mixing

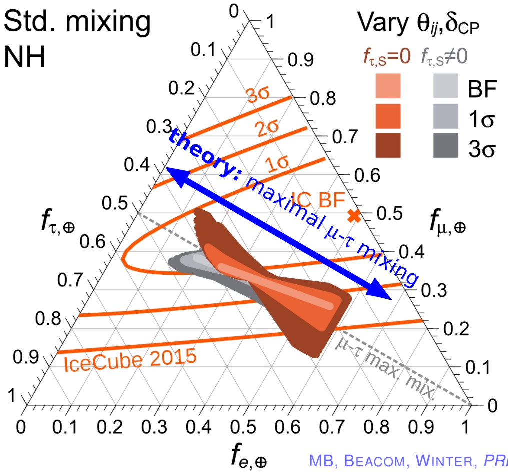
All possible flavor combinations accessible with standard mixing?



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

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

All possible flavor combinations accessible with standard mixing?



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

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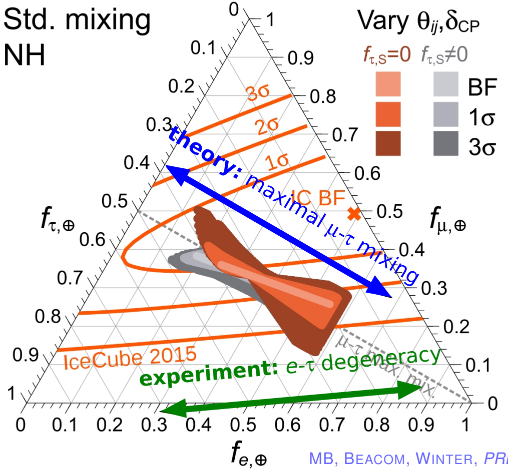
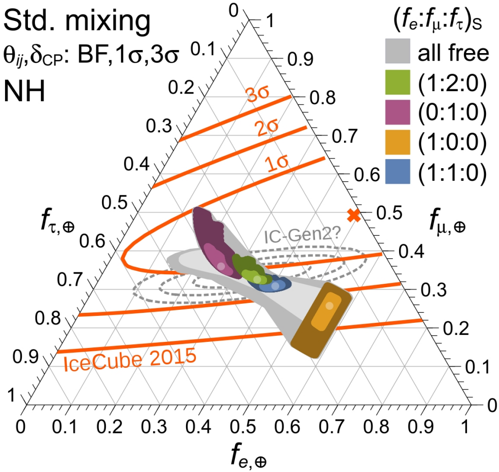


MB, Beacom, Winter, *PRL* **115**, 161302 (2015)

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

Selected source compositions

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

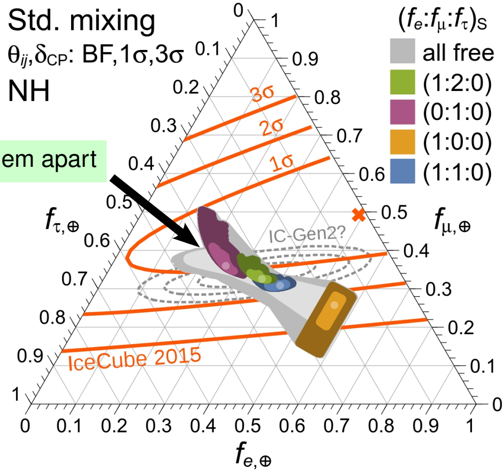


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

Selected source compositions

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

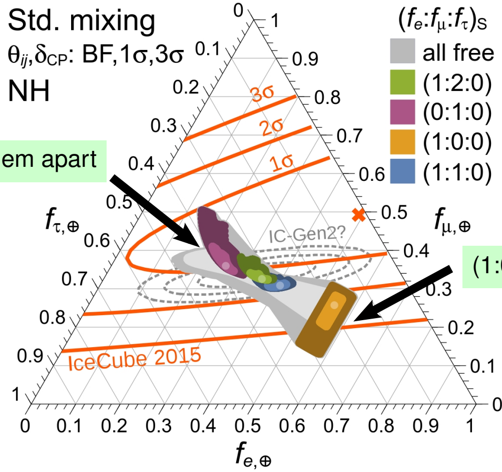
challenging to tell them apart



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

Selected source compositions

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



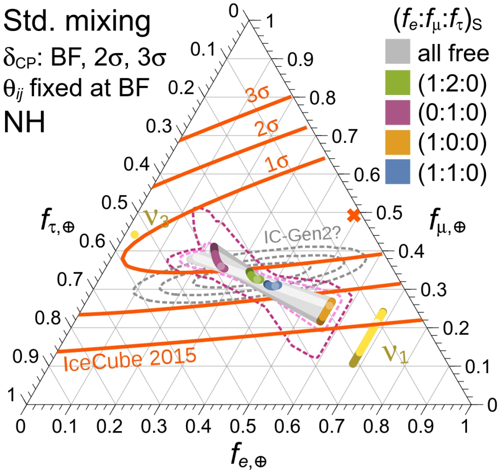
challenging to tell them apart

(1:0:0) disfavored at 2σ

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

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)

New physics? Neutrino decay affects flavor ratios

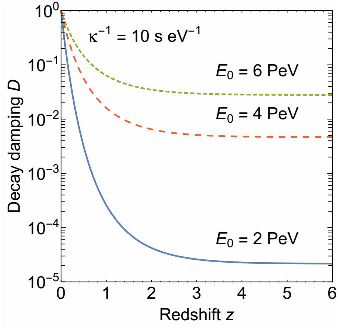
En route, unstable neutrino mass eigenstates might decay via

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

fraction of ν_i that reach Earth

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

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



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

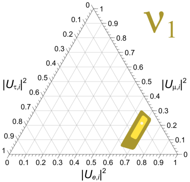
$$f_{\alpha,\oplus} = \begin{cases} |U_{\alpha 1}|^2 \,, & \text{for NH} \\ |U_{\alpha 3}|^2 \,, & \text{for IH} \end{cases}$$

Flavor ratios equal flavor content of the one stable eigenstate

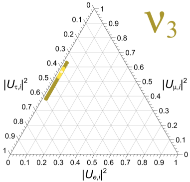
Baerwald, MB, Winter, *JCAP* **1210**, 020 (2012)

Decay: complete vs. incomplete

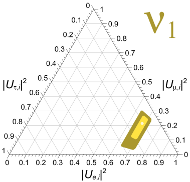
- **Complete decay:** only ν_1 (ν_3) reach Earth assuming NH (IH)

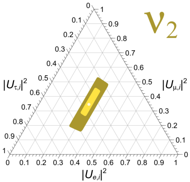


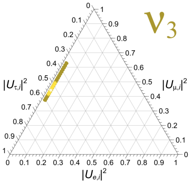
or



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

$\alpha\Big($


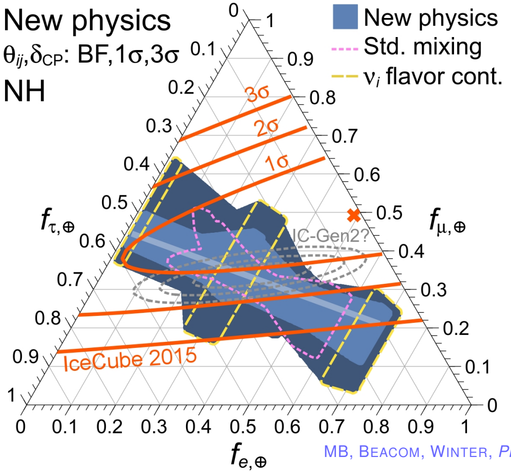
$\Big) + \beta\Big($


$\Big) + \gamma\Big($


$\Big)$

Region of flavor ratios accessible with decay

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



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

Decay can access *only* ~ 25% of the possible combinations

Region of flavor ratios accessible with decay

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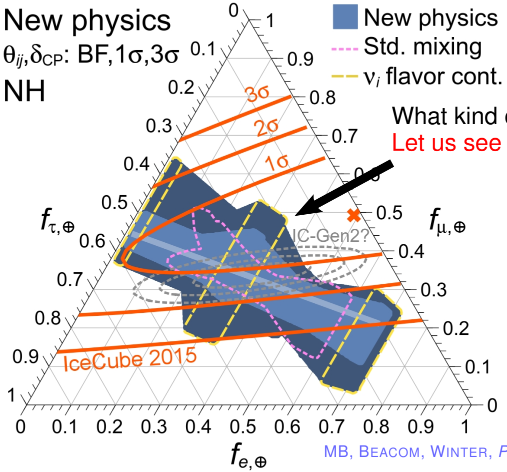

What kind of NP lives outside?

Let us see a few examples

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

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

New physics — of the *truly exotic* kind

What kind of NP lives outside the blue region?

- NP that changes the values of the mixing parameters, *e.g.*,
  - violation of Lorentz and CPT invariance

    [Barenboim, Quigg, *PRD* **67**, 073024 (2003)] [MB, Gago, Peña-Garay, *JHEP* **1004**, 005 (2010)]
  - violation of equivalence principle

    [Gasperini, *PRD* **39**, 3606 (1989)] [Glashow *et al.*, *PRD* **56**, 2433 (1997)]
  - coupling to a torsion field

    [De Sabbata, Gasperini, *Nuovo. Cim.* **A65**, 479 (1981)]
  - renormalization-group running of mixing parameters

    [MB, Gago, Jones, *JHEP* **1105**, 133 (2011)]
- active-sterile mixing [Aeikens *et al.*, 1410.0408]
- flavor-violating physics
- ν–$\bar{\nu}$ mixing (if ν, $\bar{\nu}$ flavor ratios are considered separately)

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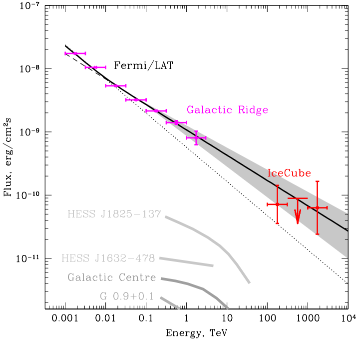
Sources inside the Galaxy

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 & Vlcek 14]
- Sagitarius 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)

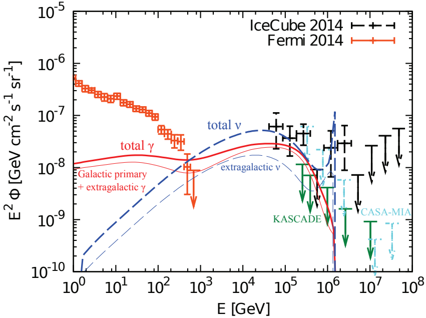
Hard Galactic diffuse emisssion



[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

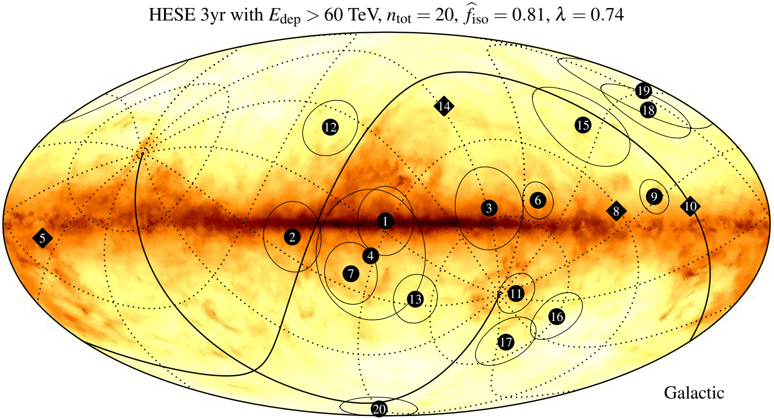


[Murase, Laha, Ando, Ahlers 15]

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

Galactic diffuse emission

Neutrino production via *pp* on gas in the Galaxy —

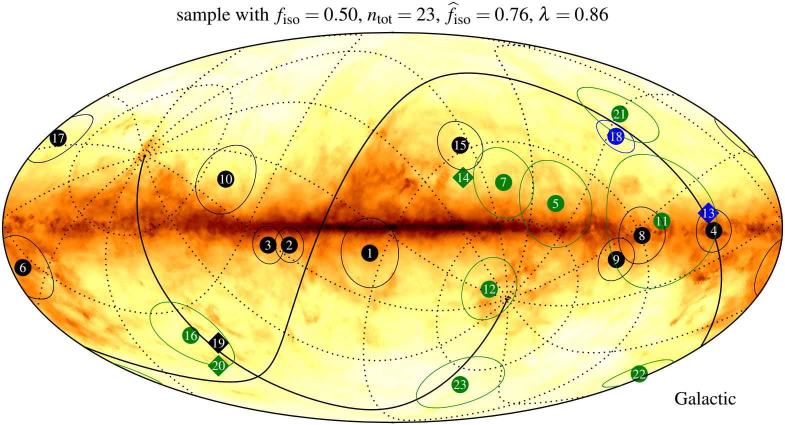


[Ahlers, Bai, Barger, Lu 15]

Observed HESE events with $E_{\rm dep} > 60$ TeV: tracks (◇), showers (○)

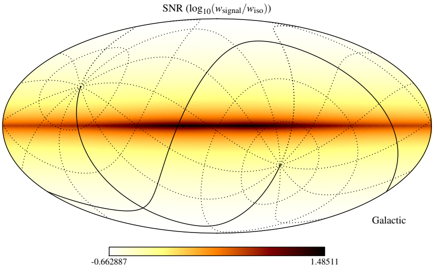
Galactic diffuse emission

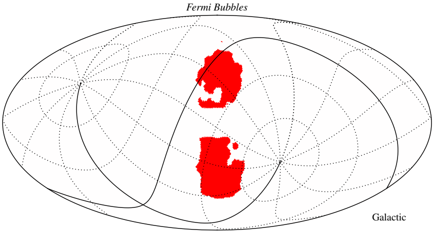
Simulated map with 50% isotropic + 50% Galactic components —

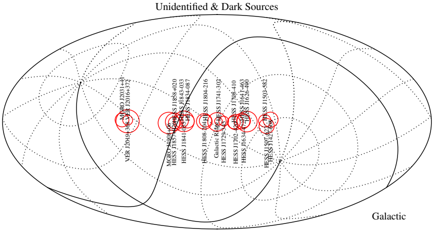


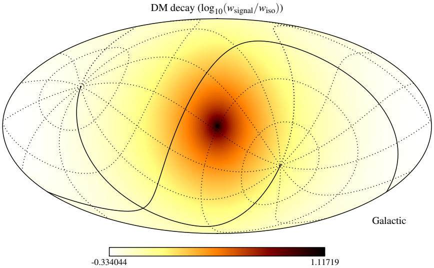
- Tracks: ◇ ; showers: ○
- Galactic ν: ◇/○ ; isotropic: ◇/○ ; atmospheric: ◇/○

Different diffuse emission templates









Galactic contribution

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]

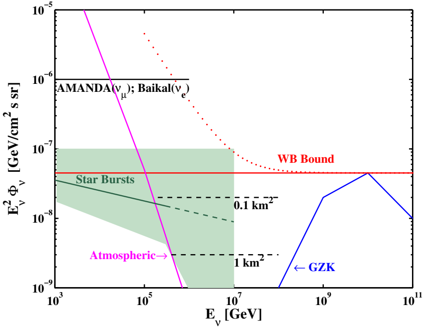
Sources outside the Galaxy

- 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, Vlcek 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)

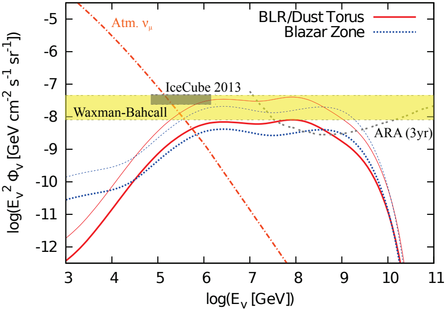
Two extragalactic source examples

pp production: starburst galaxies



[Loeb & Waxman 06]

$p\gamma$ production: active galactic nuclei



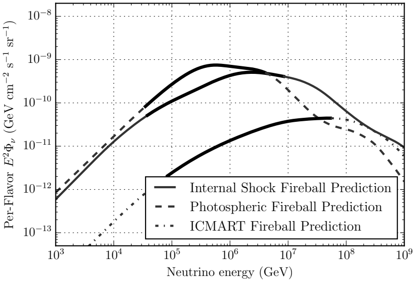
[Mannheim 96; Halzen & Zas 97]

[▲ 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

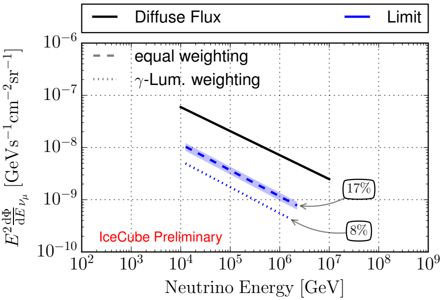
GRB stacking



[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

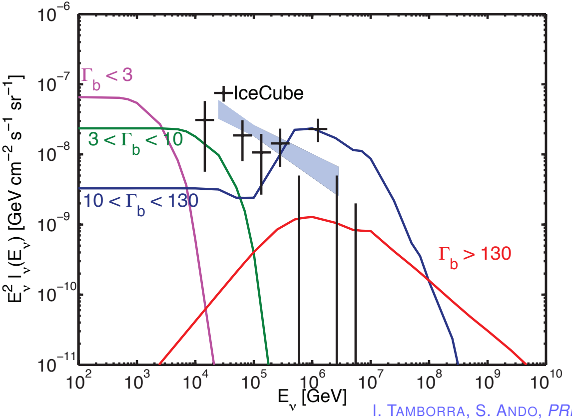


[IceCube 1502.03104]

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

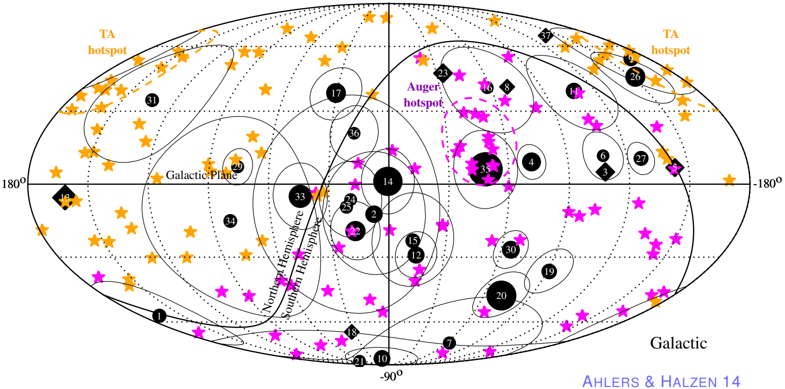
What about low-luminosity and choked GRBs?

- 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?



AHLERS & HALZEN 14

- Angular deflection of CRs on extragalactic magnetic field:

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

- No significant correlation with Auger and Telescope Array data

Identifying extragalactic point sources

How many neutrinos should be correlated with UHECR sources?

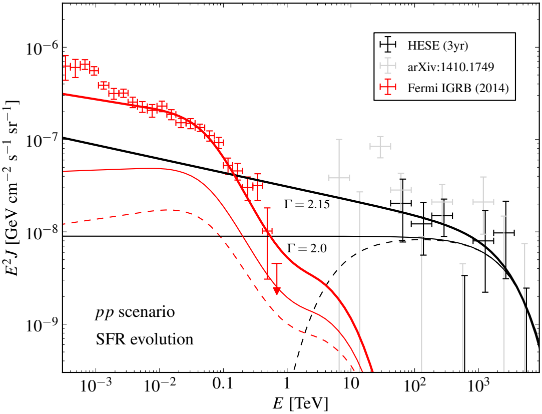
- UHECRs trace sources within $\lambda_{\text{GZK}} \approx 200$ Mpc
- Neutrinos come from anywhere inside Hubble horizon $D_{\text{H}} \approx 4$ Gpc
- Maximal overlap:

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

- 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 $\propto E^{-\Gamma}$
- 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

What lies beyond — cosmogenic neutrinos

We expect the > PeV ν sky to be populated: cosmogenic neutrinos

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

$$\underbrace{p}_{10^{20}\ \mathrm{eV}} + \underbrace{\gamma_{\mathrm{CMB}}}_{0.1\ \mathrm{meV}} \to \underbrace{\nu_\mu + \bar{\nu}_\mu + \nu_e}_{10^{18}\ \mathrm{eV}\ \equiv\ \mathrm{EeV}} + \ldots$$

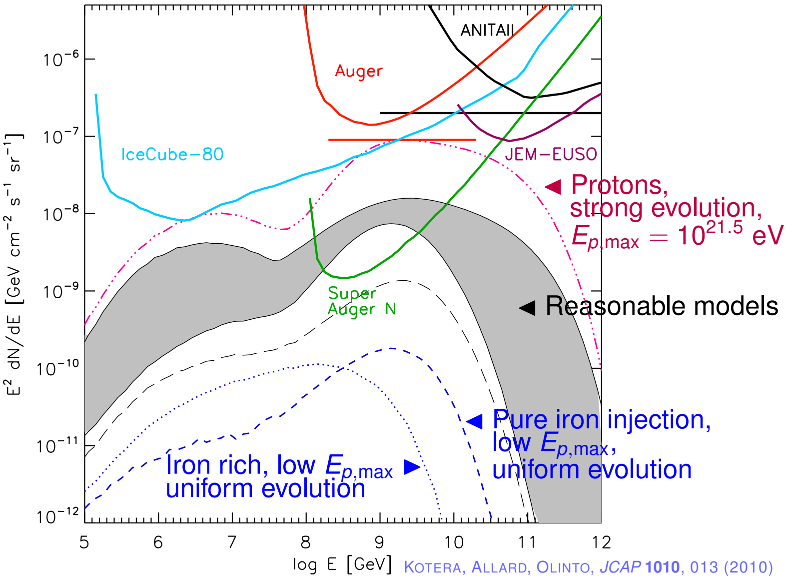
We have not seen them — why are they worth looking for?

- 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

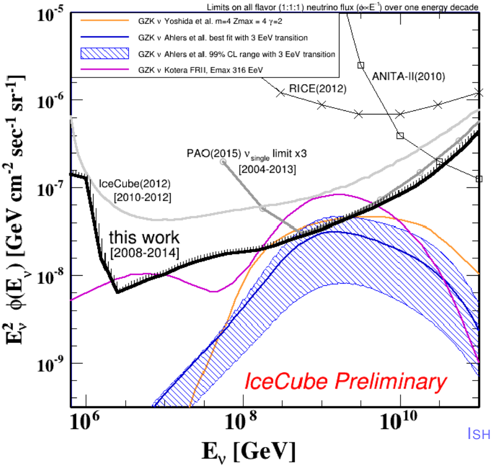
How low can low be?



KOTERA, ALLARD, OLINTO, *JCAP* **1010**, 013 (2010)

The present-day picture

The latest IceCube search (6 years) found only one candidate event — the most optimistic predictions are disfavored

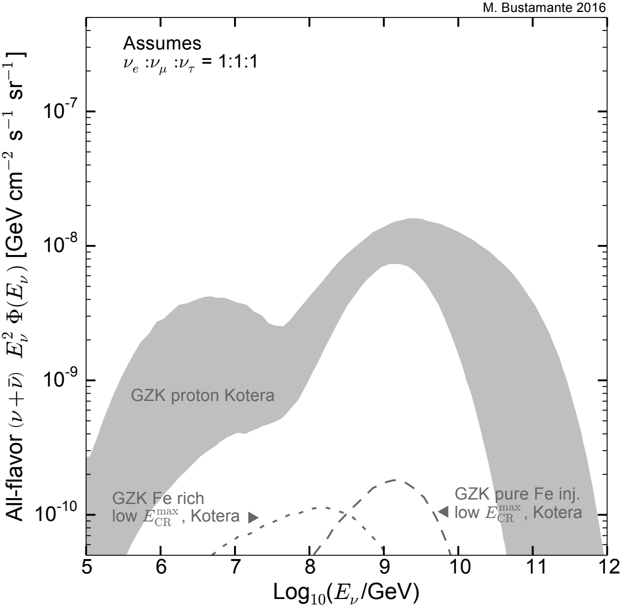


Ishihara, TeVPA 2015

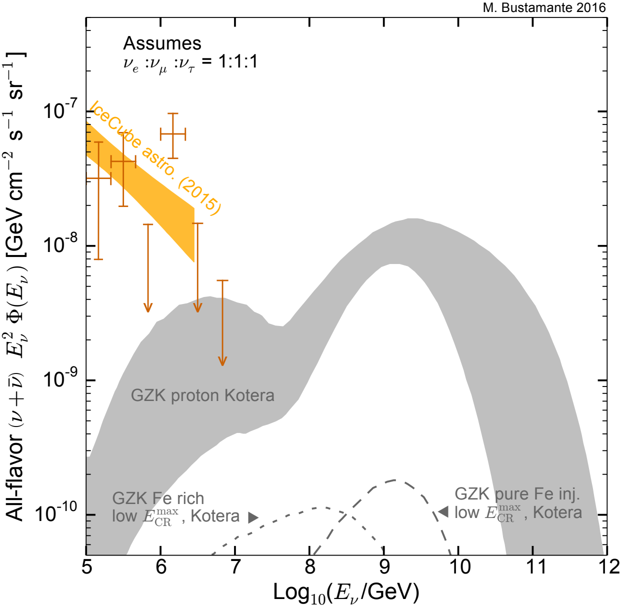
This limit already disfavors the proton dip model of UHECRs

[Heinze, Boncioli, MB, Winter, 1512.05988]

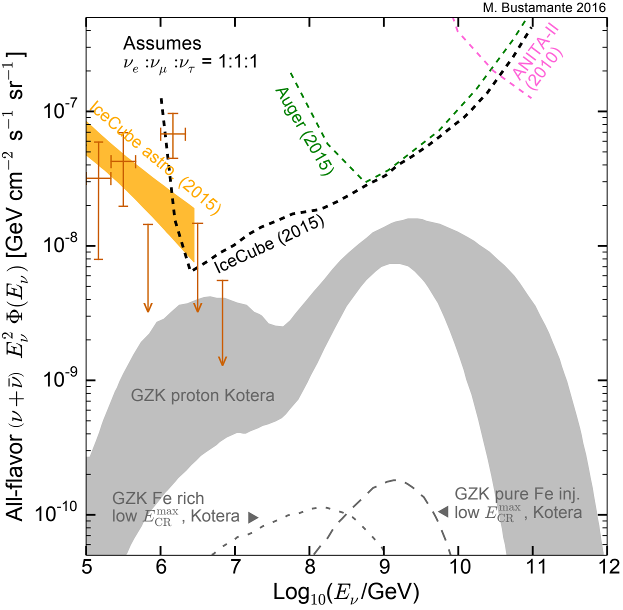
Predictions vs. detectors — now



Predictions vs. detectors — now



Predictions vs. detectors — now



The solution: build larger and/or build different

Two philosophies:

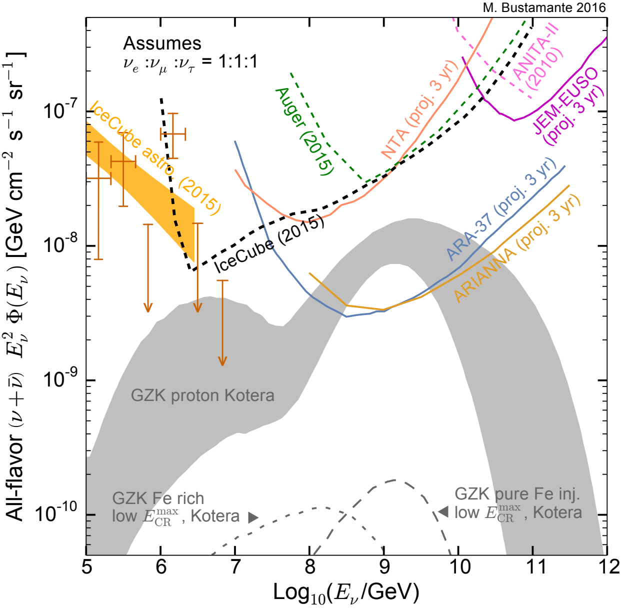
1 — Build larger water/ice Cherenkov detectors

- Pro: the technique is mature (IceCube-Gen2, KM3NeT)
- Con: unfeasible to cover very large area

2 — Use more suitable techniques: EAS detection

- Pro: surface arrays can cover large areas (*e.g.*, Auger, ANITA)
- Con: limited exposure, technique has not been as developed

Predictions vs. detectors — future



Enter GRAND

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

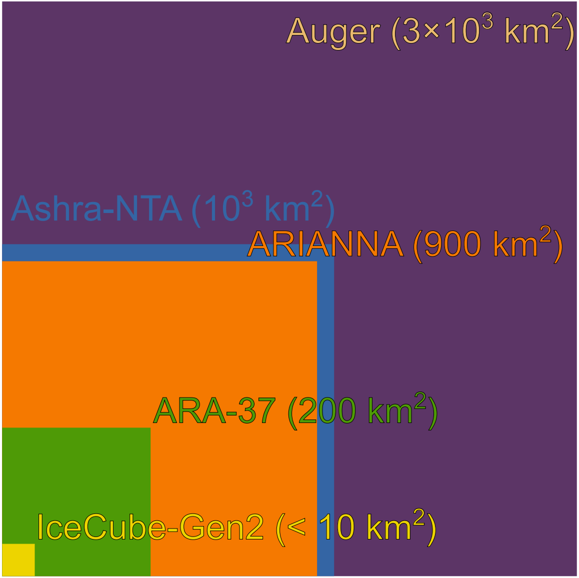
How can the nightmare scenario be overcome?

1. Build big. Really big.
2. Use radio emission — attenuation length is $\sim$ 100 km in air

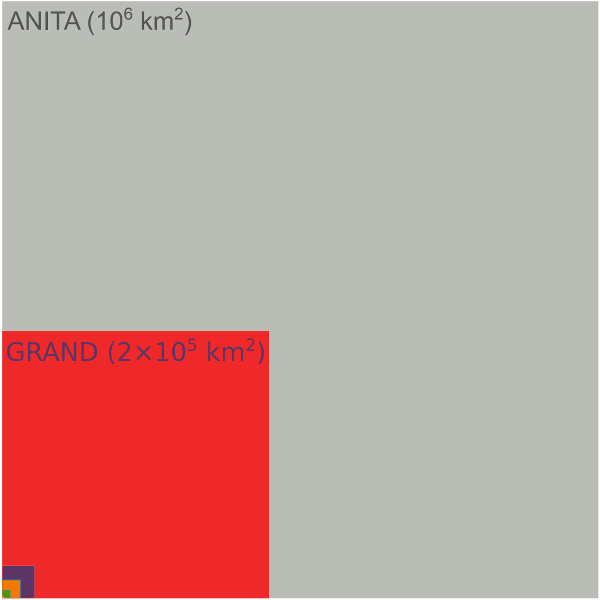
GRAND: Giant Radio Array for Neutrino Detection

- 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 km^2

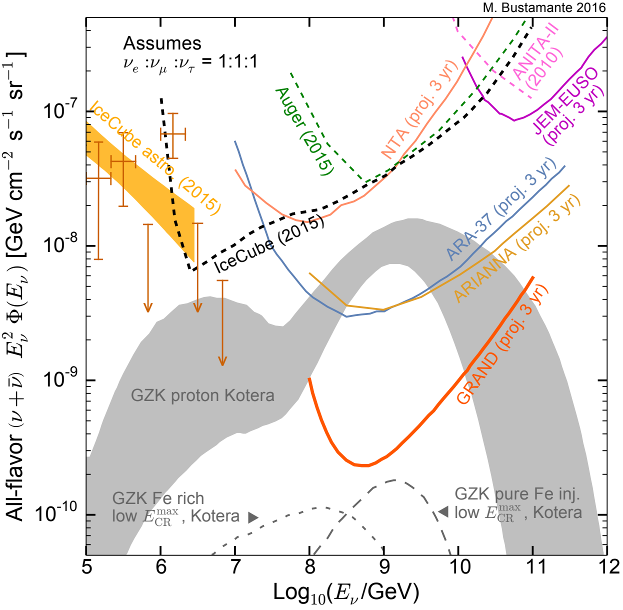
Building big — comparing the surface areas



Building big — comparing the surface areas



GRAND cuts deep



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}

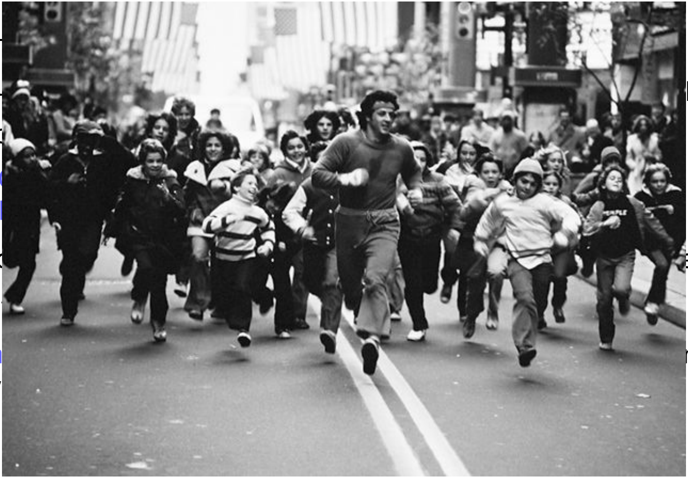
- ... and a strong-exclusion instrument, if < 1 event yr^{-1}

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
- Proposed upgrades (IceCube-Gen2, KM3NeT) will provide more data
- Next frontier: EeV cosmogenic neutrinos
- Promising technology: detection of radio signals from neutrino-induced showers in ice (ARA, ARIANNA) and in air (GRAND)

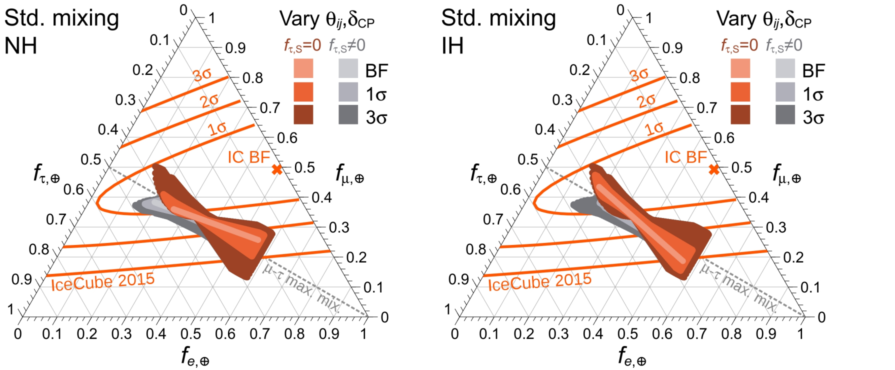
Summary and outlook

- High-
- IceCu … position
- No sc
    - …
    - … clues
- Propo … e data
- Next
- Prom … nduced show



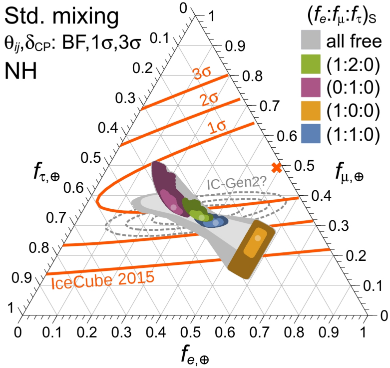
Backup slides

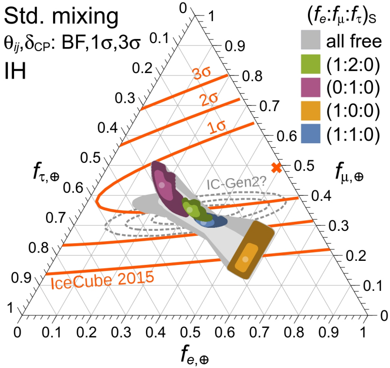
Flavor combinations from std. flavor mixing: NH vs. IH



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

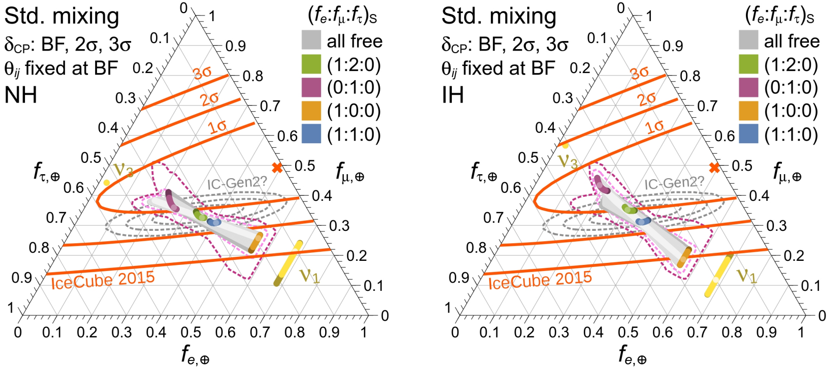
Selected source compositions: NH vs. IH





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

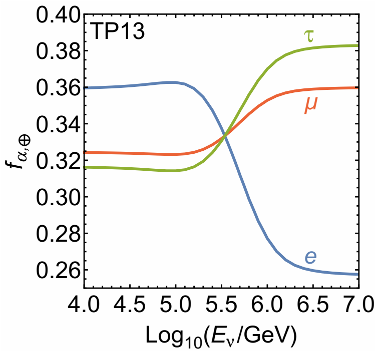
Perfect knowledge of mixing angles: NH vs. IH

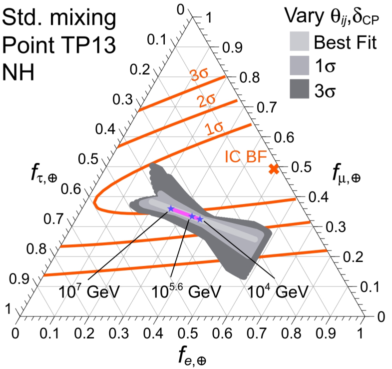


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Energy dependence of the composition at the source

Different ν production channels are accessible at different energies

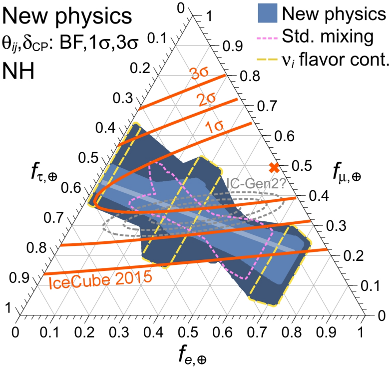


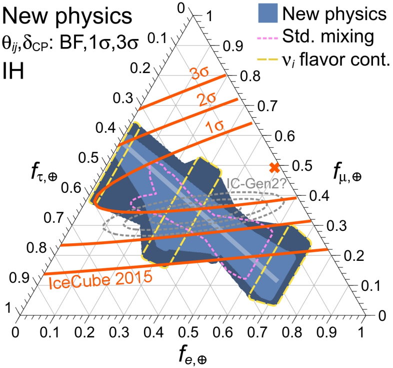


MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)

- 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

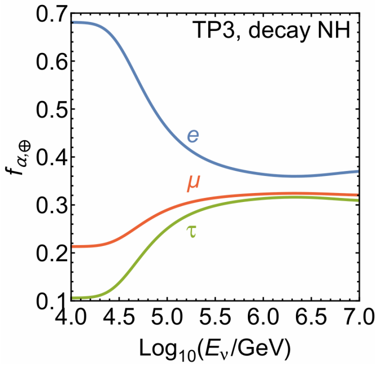


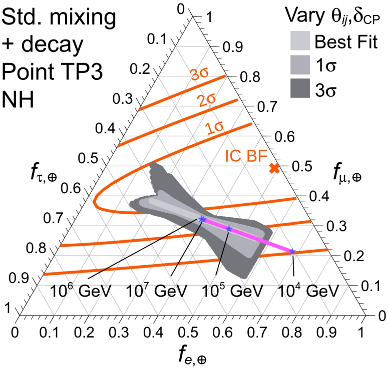


[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Decay: seeing the energy dependence?

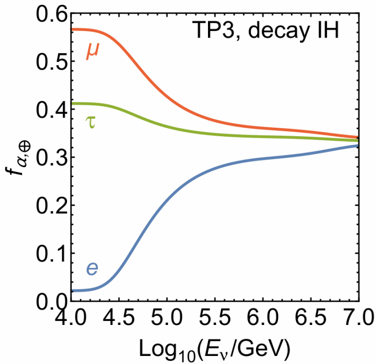
- The effect of decay shows up at low energies
- *e.g.*, for a model of AGN cores [Hümmer *et al.*, *Astropart. Phys.* **34**, 205 (2010)],
- Would require high statistics + exquisite energy resolution

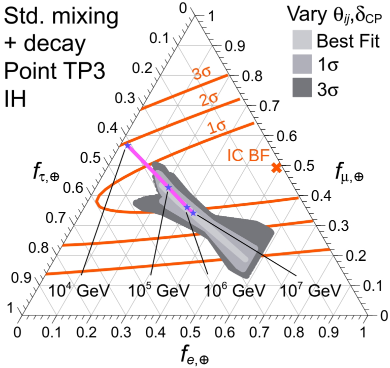




[MB, Beacom, Winter, *PRL* **115**, 1611302 (2015)]

Decay in the IH





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

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:

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

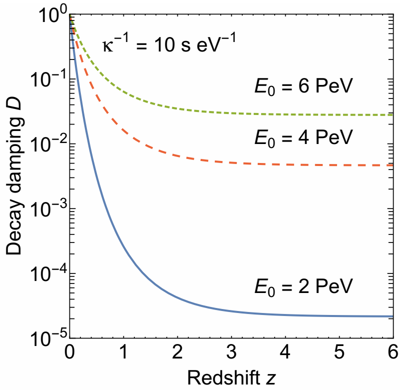
Fraction of remaining ν_i at Earth:

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

$a \approx 1.71$, $b = 1 - a$, $c \approx 1.27$
for ΛCDM with $(\Omega_m, \Omega_\Lambda) = (0.27, 0.73)$

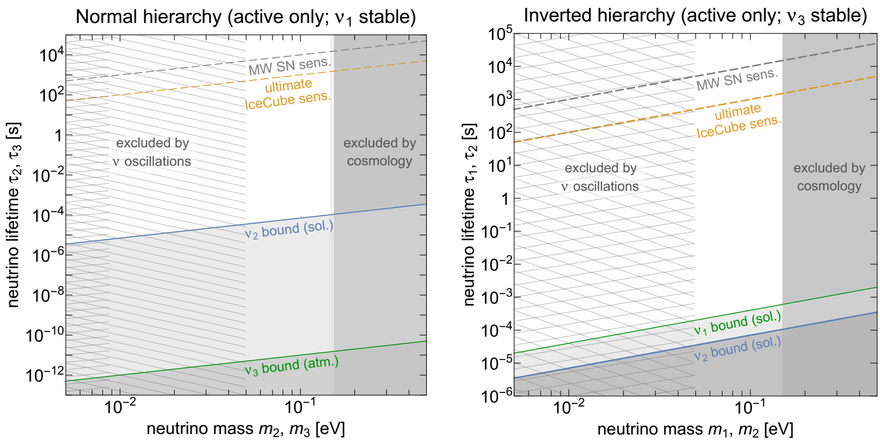
$$\langle P_{\alpha\beta}\rangle \to \underbrace{D\left(E_0, z, \kappa_i^{-1}\right)}_{0<D<1}\langle P_{\alpha\beta}\rangle$$

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



Current lifetime limits

- ν_1: $\gtrsim 4 \cdot 10^{-3}$ s eV^{-1} (solar, Berryman *et al.* 2014)
- ν_2: $\gtrsim 7 \cdot 10^{-3}$ s eV^{-1} (solar, Berryman *et al.* 2014)
- ν_3: $\gtrsim 7 \cdot 10^{-11}$ s eV^{-1} (atmospheric, González-García & Maltoni 2008)



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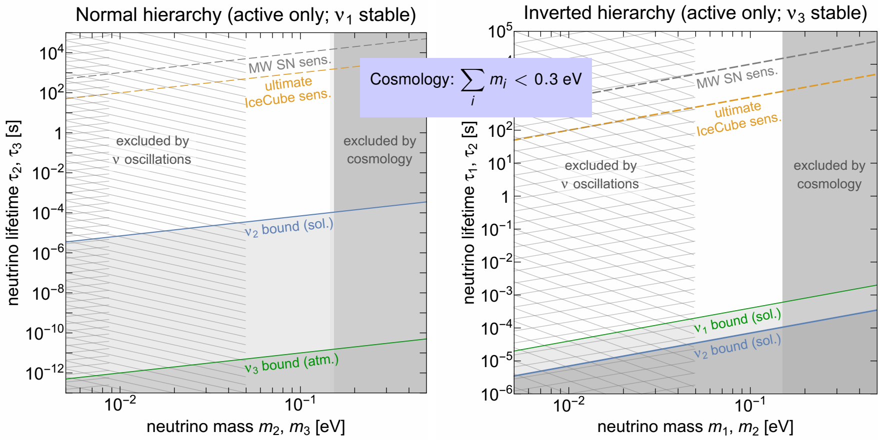

Cosmology: $\sum_i m_i < 0.3$ eV

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- ν_1: $\gtrsim 4 \cdot 10^{-3}$ s eV^{-1} (solar, Berryman *et al.* 2014)
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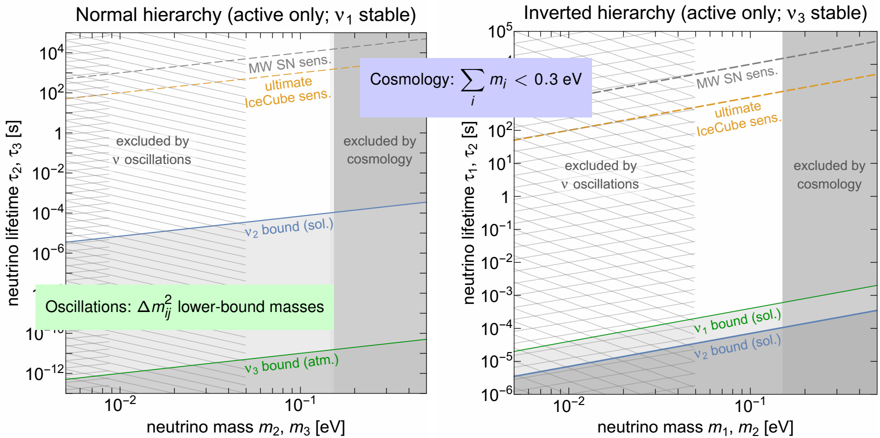

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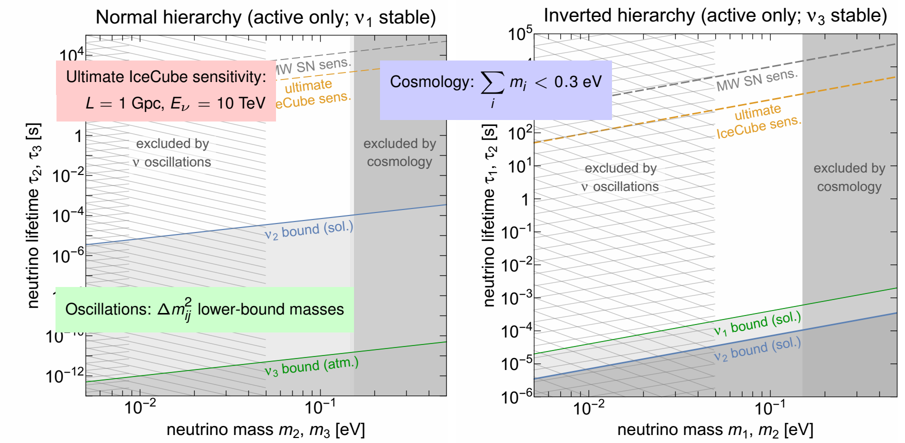


Flavor mixing in high-energy astrophysical neutrinos

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

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

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

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

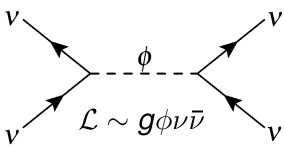
$$\sin^2(\ldots) \to 1/2 \,, \quad \sin(\ldots) \to 0$$

Hence, for high-energy astrophysical neutrinos:

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

New physics: effect on the spectral shape

Secret neutrino interactions between astrophysical neutrinos and the cosmic neutrino background

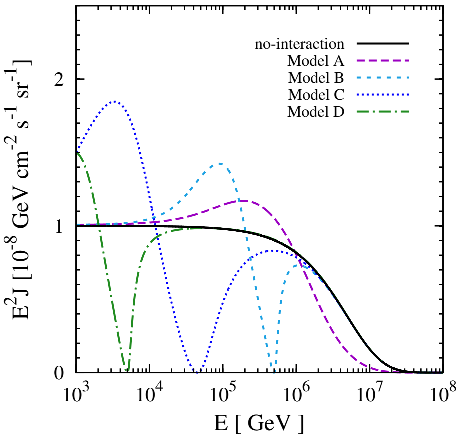


Cross section:

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

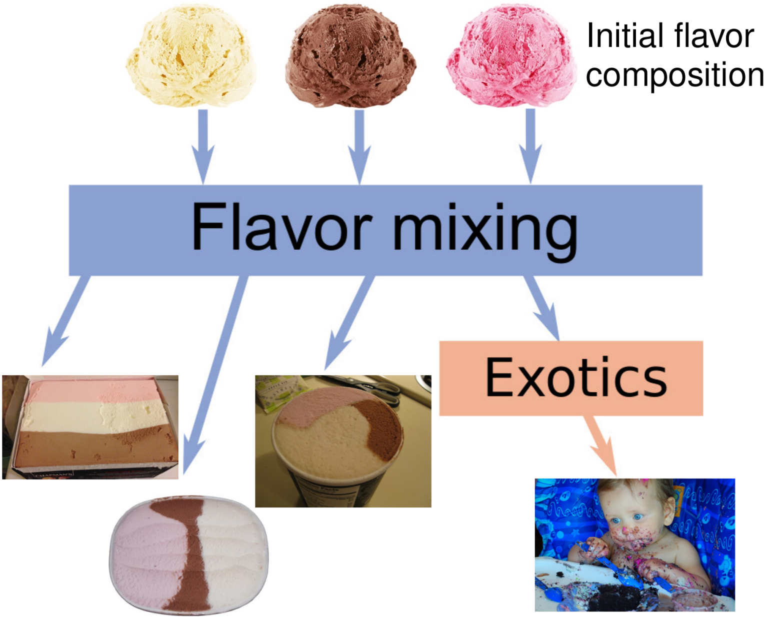
Resonance at

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



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

New physics: effect on the flavor composition

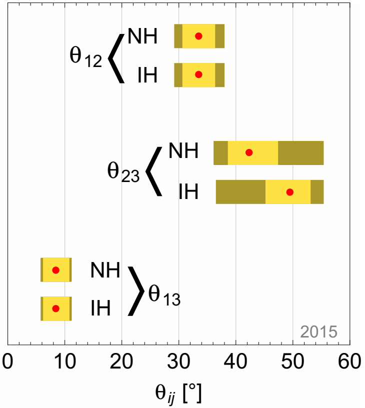


Flavor content of the mass eigenstates (I)

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

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

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



Using the best-fit values:

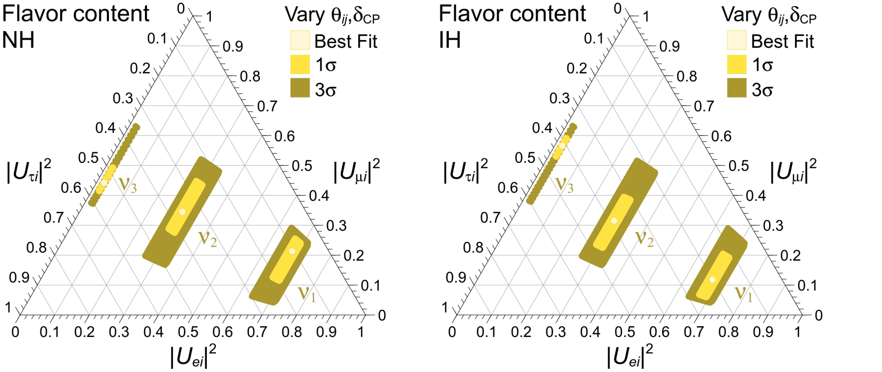
ν_1 : 70% ν_e, 10 – 20% ν_μ, 10 – 20% ν_τ

ν_2 : $\sim$ equal proportion of each

ν_3 : 3%ν_e, 40 – 60%ν_μ, 40 – 60%ν_τ

Flavor content of the mass eigenstates (II)

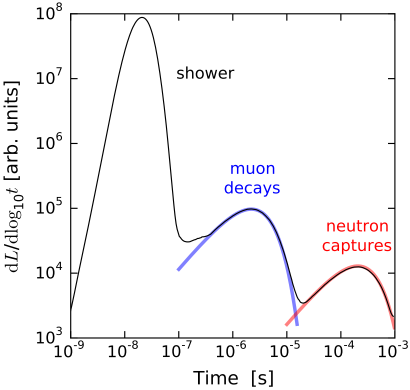
Flavor content for every allowed combination of mixing parameters:

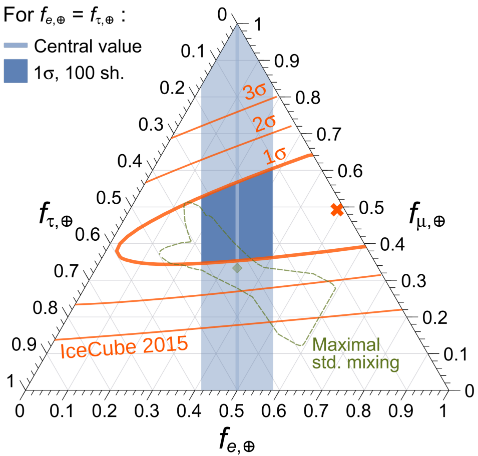


MB, Beacom, Winter, *PRL* **115**, 161302 (2015)

Side note: improving the flavor measurements

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





Li, MB, Beacom, in prep.

Standard Model decay modes

SM decay modes are negligible:

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

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

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

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

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

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

All lifetimes $\gg$ age of Universe
– 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

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

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

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

▲ For very long L, this will have redshift corrections

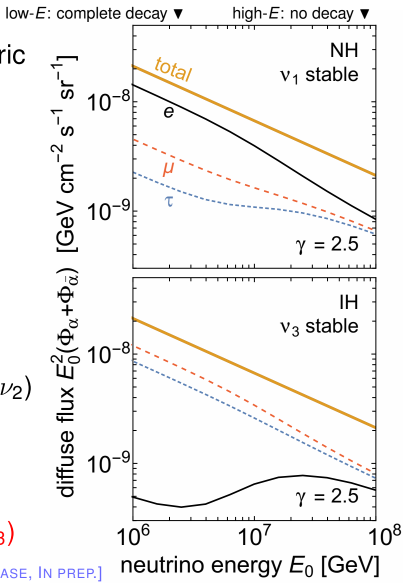
m_i, τ_i are the mass and (rest-frame) lifetime of ν_i

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

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

Seeing decay in the flavor fluxes

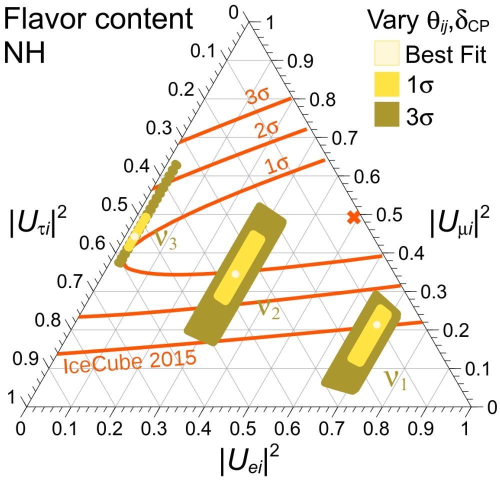
- Diffuse $\nu + \bar{\nu}$ flux from population of generic sources, normalized to IceCube flux
- Assuming $(f_{e,S} : f_{\mu,S} : f_{\tau,S}) = \left(\frac{1}{3} : \frac{1}{3} : \frac{1}{3}\right)$
- Fixed lifetime of 10 s eV^{-1}
- Decay NH: $\nu_2, \nu_3 \to \nu_1$
  - ν_μ, ν_τ depleted
  - ν_e doubled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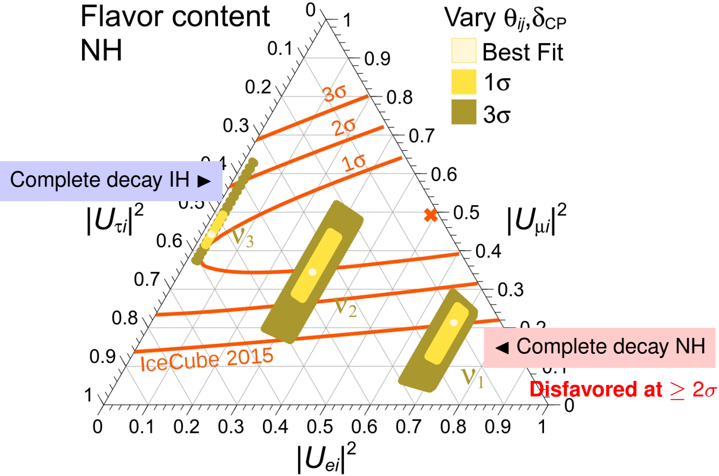

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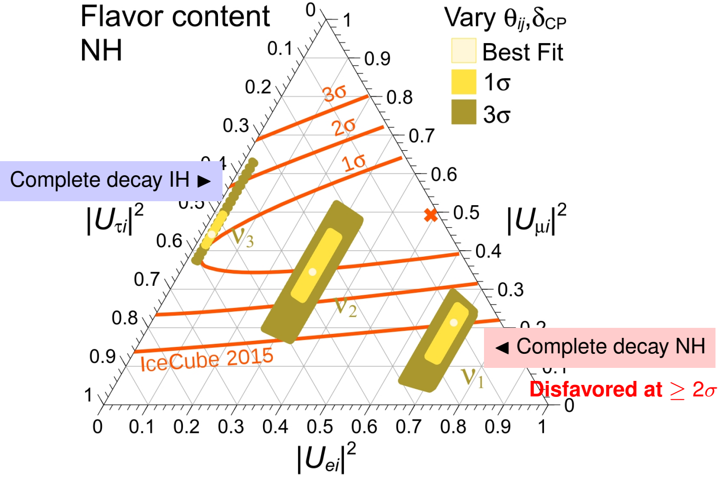


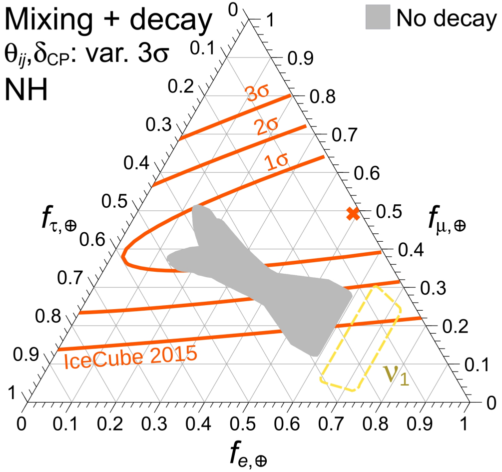
Let us calculate the lifetime bounds in the NH case ▶

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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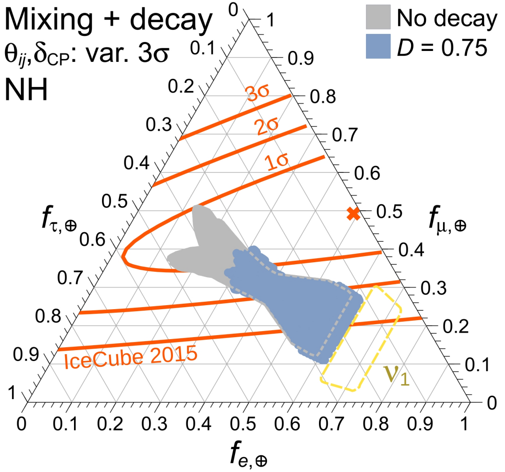

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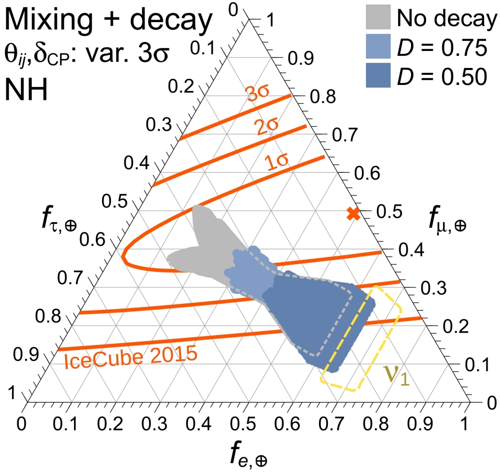

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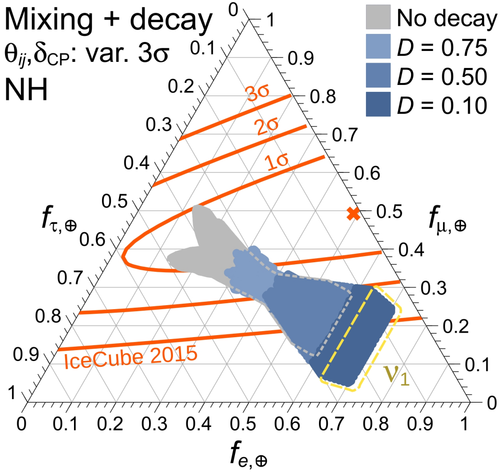

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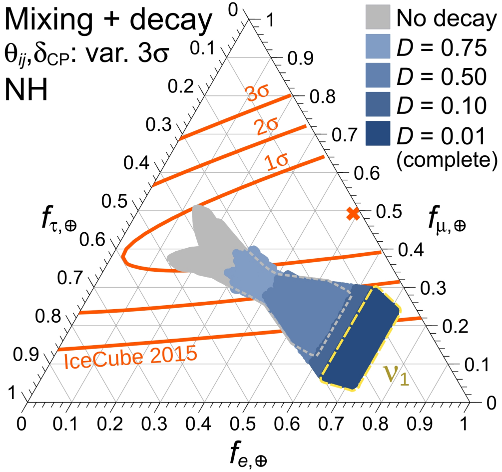
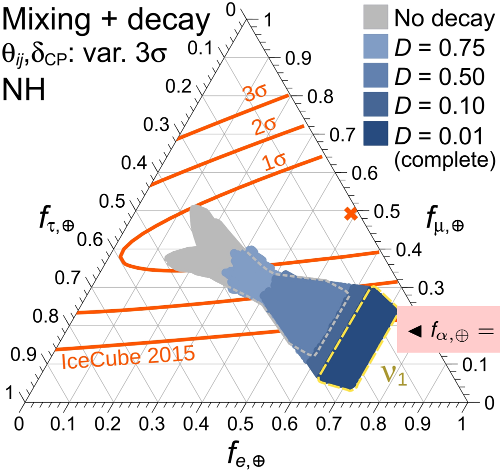


NH: lifetime limits with current IceCube data (I)

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

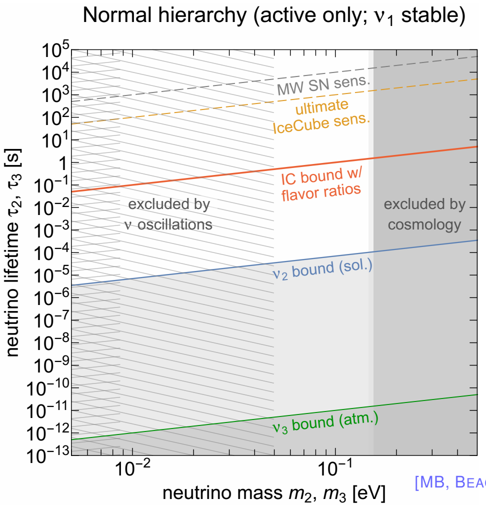
Assume equal lifetimes of ν_2, ν_3



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

NH: lifetime limits with current IceCube data (II)

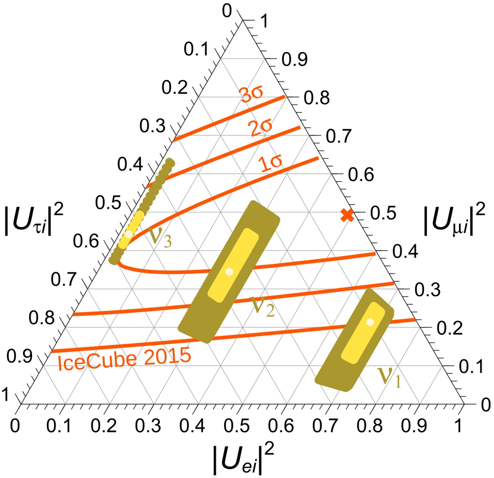
$D \lesssim 0.01$ implies a bound of $\kappa_{2,3}^{-1} \gtrsim 10$ s eV^{-1} at $\gtrsim 2\sigma$



[MB, Beacom, Murase, in prep.]

What will higher-energy events do for us?

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



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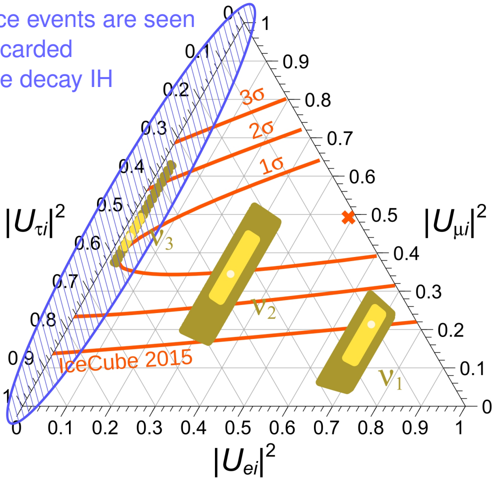
If Glashow resonance events are seen
⇒ small $f_{e,\oplus}$ are discarded
⇒ discards complete decay IH

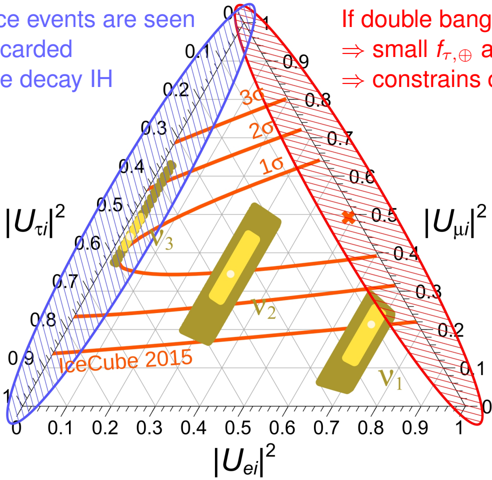


What will higher-energy events do for us?

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

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

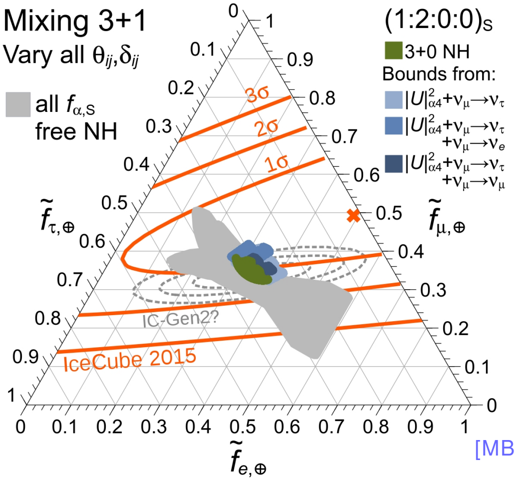
If double bangs are seen
⇒ small $f_{\tau,\oplus}$ are discarded
⇒ constrains complete decay NH



New physics — active-sterile mixing

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

- standard parameters: θ_{12}, θ_{23}, θ_{13}, δ_{13}
- sterile parameters: θ_{14}, θ_{24}, θ_{34}, δ_{24}, δ_{34}



Bounds from T2K, SK, Daya Bay

[MB, Coloma]

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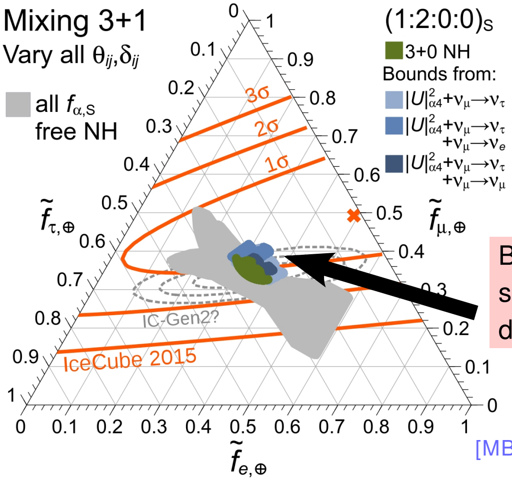


Bounds from T2K, SK, Daya Bay

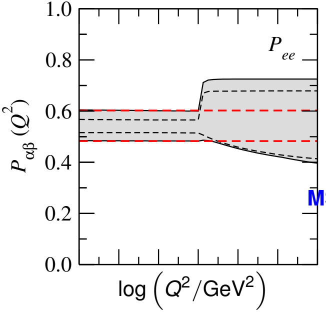
Bounds are too strong for large deviations

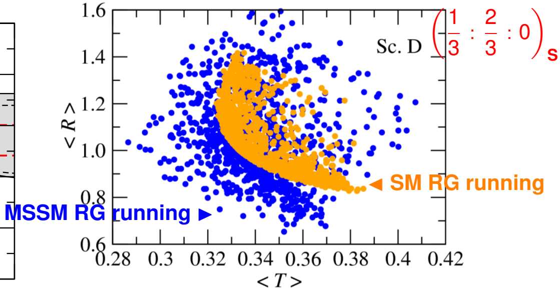
[MB, Coloma]

SUSY renormalization group running

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

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





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

New physics — high-energy effects (I)

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

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

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

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

$n = 0$

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

$n = 1$

- equivalence principle violation
- CPT-even Lorentz violation

Experimental upper bounds from atmospheric ν's:

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

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

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

New physics — high-energy effects (II)

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

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

[Argüelles, Katori, Salvadó *PRL* **115**, 161303 (2015)]

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