Honing in on the flavor composition of high-energy astrophysical neutrinos: the view from theory

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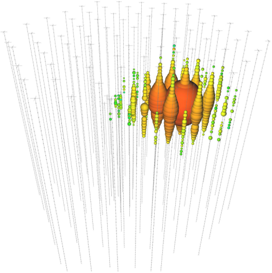
High-energy astrophysical neutrinos: they exist!

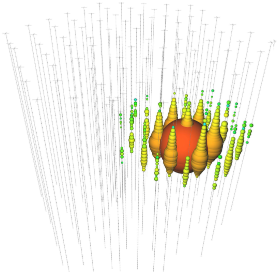
The era of neutrino astronomy has begun!

– IceCube (2010-2013) detected 37 events with 30 TeV – 2 PeV

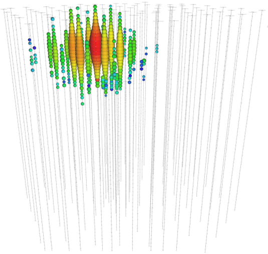
“Bert”, 1.04 PeV



“Ernie”, 1.14 PeV



“Big Bird”, 2 PeV



. . . and 34 more events < 385 TeV

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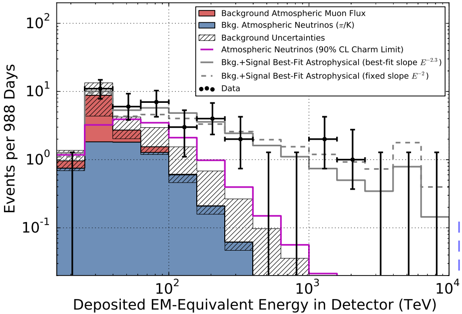

ICECUBE, *PRL* **111**, 021103 (2013)
ICECUBE, *Science* **342**, 1242856 (2013)
ICECUBE, *PRL* **113**, 101101 (2014)

Diffuse flux compatible with extragalactic origin (Waxman & Bahcall 1997):

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

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Arrival directions compatible with an isotropic distribution –

ICECUBE, *PRL* **111**, 021103 (2013)
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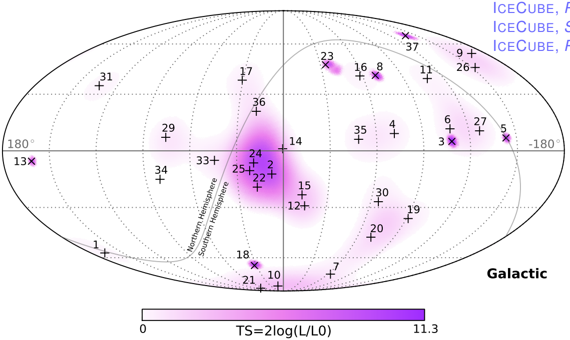


+: shower
×: muon track

– no association with sources found yet

Flavor composition of neutrinos: an open question

What is the proportion of ν_e, ν_μ, ν_τ in the diffuse flux?

Knowing this can reveal two important pieces of information:

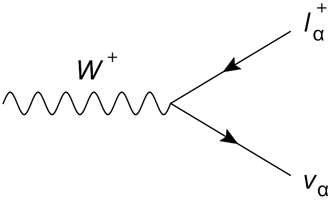
- the physical conditions at the neutrino sources; and
- whether there is new physics, and of what kind

A quick review of neutrino mixing (I)

- Two bases:

$$\underbrace{\{\nu_e, \nu_\mu, \nu_\tau\}}_{\text{flavor eigenstates}} \neq \underbrace{\{\nu_1, \nu_2, \nu_3\}}_{\text{mass eigenstates}}$$

- Flavor eigenstate ν_α ($\alpha = e, \mu, \tau$): accompanies the charged anti-lepton l_α^+ that is created in a charged-current weak interaction:



- Mass eigenstate ν_i ($i = 1, 2, 3$): has a definite mass
- Bases connected by a rotation U: $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$

A quick review of neutrino mixing (II)

- U is a 3×3 rotation matrix (PMNS matrix):

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

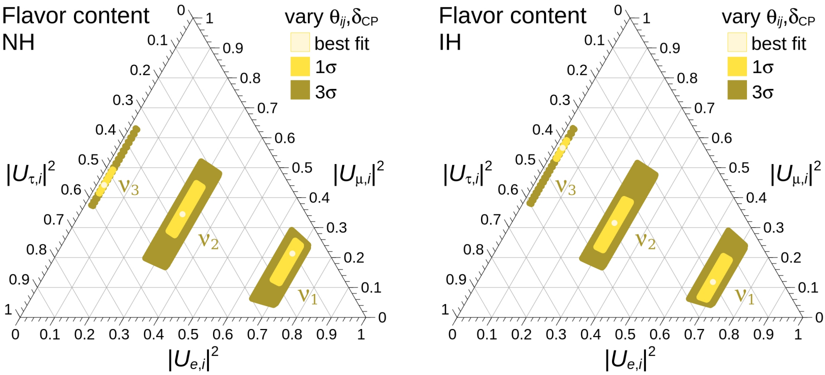
- Parametrise it with three angles and one CP-violating phase
- From solar, atmospheric, reactor, and accelerator experiments:

$$\theta_{12} \approx 37^\circ \,,\ \theta_{23} \approx 45^\circ \,,\ \theta_{13} \approx 9^\circ \,,\ \delta_{\rm CP} \text{ unknown}$$

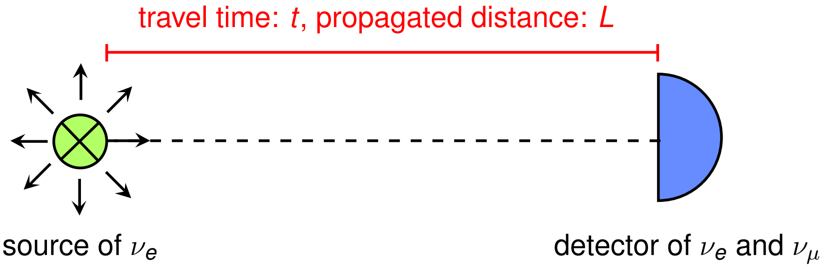
- The mass hierarchy is also unknown:
  - Normal hierarchy (NH): ν_1 is lightest
  - Inverted hierarchy (IH): ν_3 is lightest

  – fits to mixing paramters depend on hierarchy assumption

A different way to show this information is via ternary plots:



Neutrino flavor oscillations (I)



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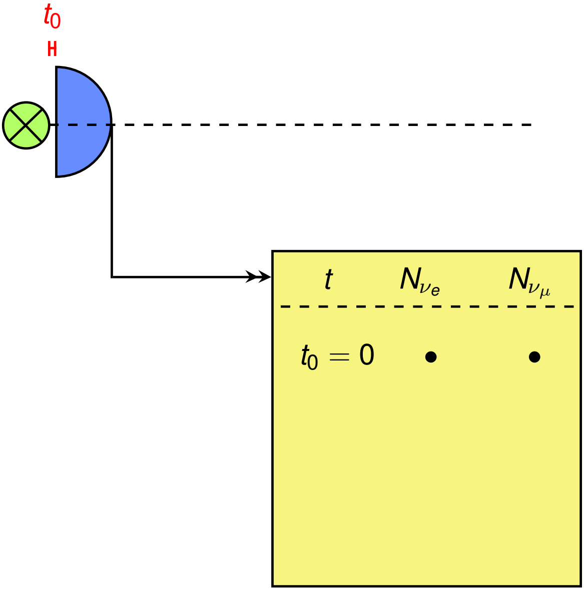

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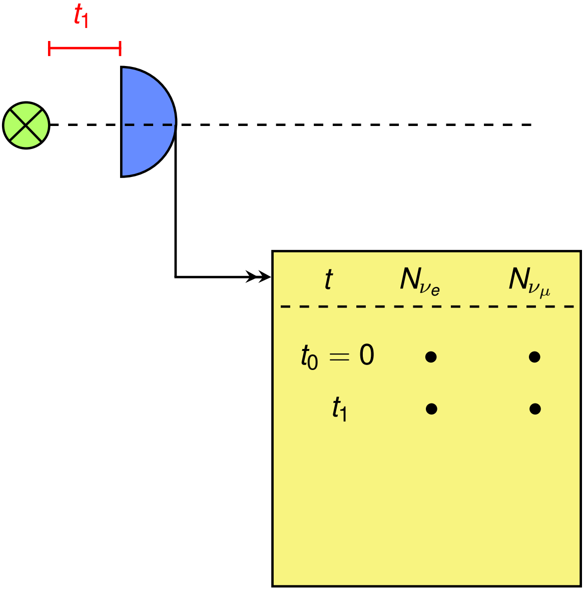

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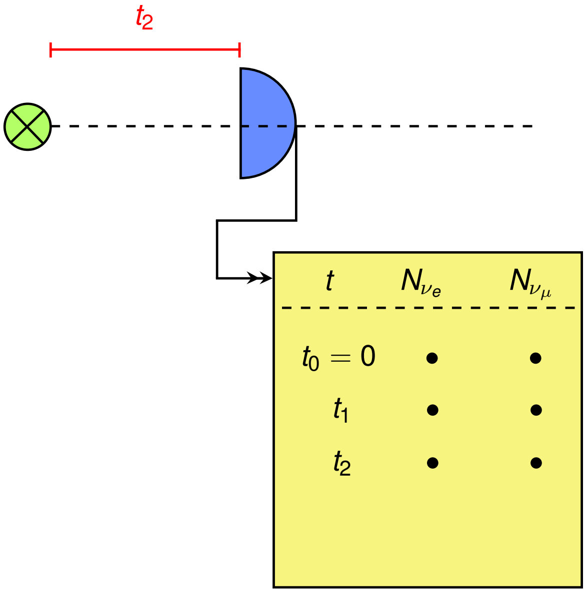

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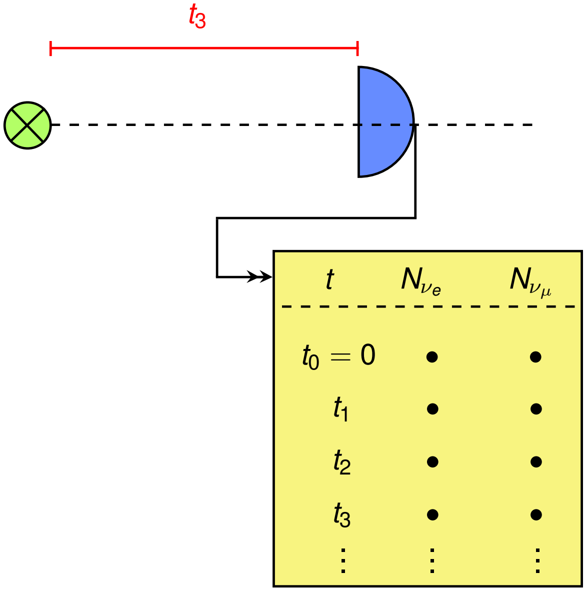
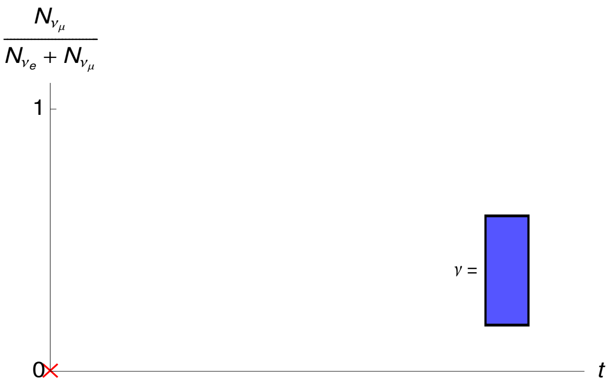


Neutrino flavor oscillations (II)



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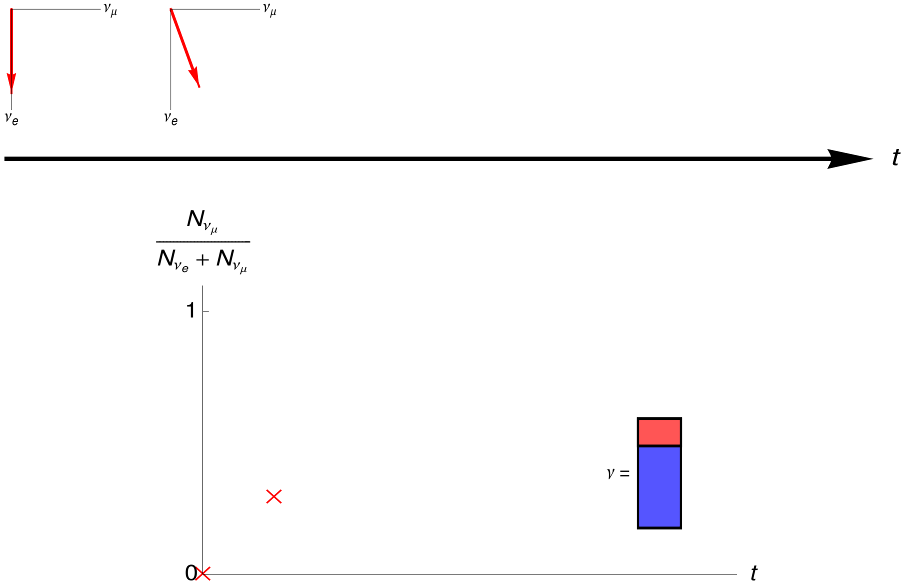

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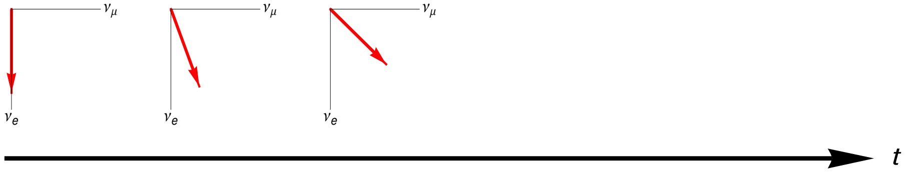

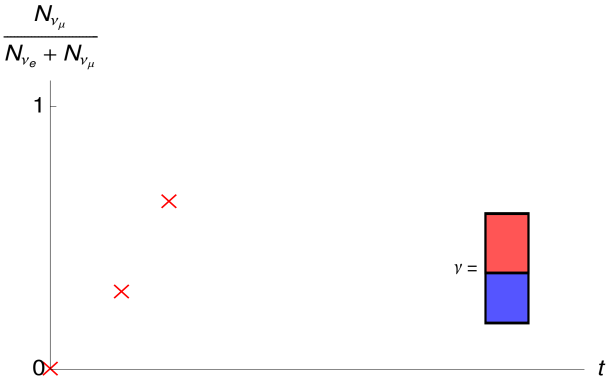

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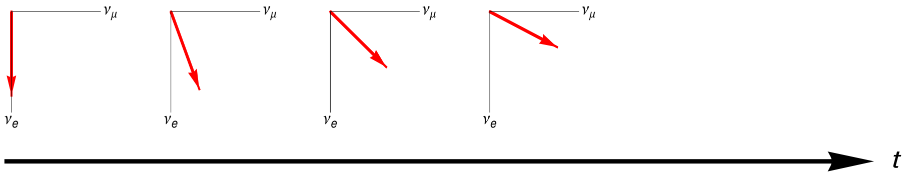

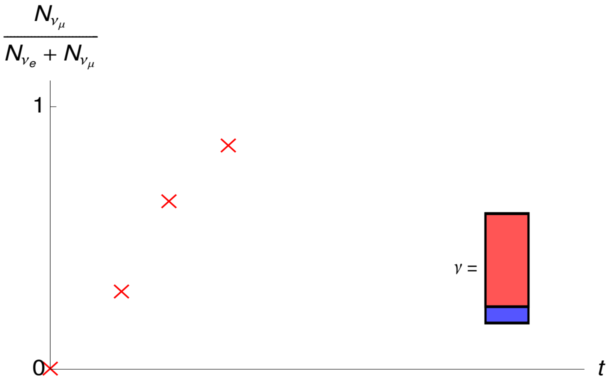

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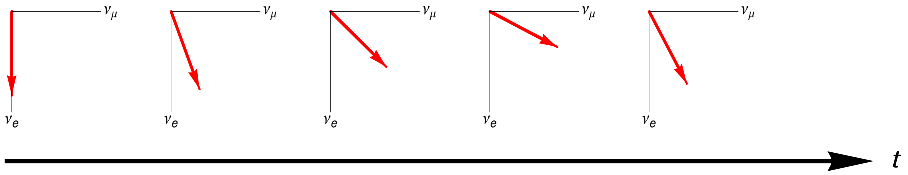

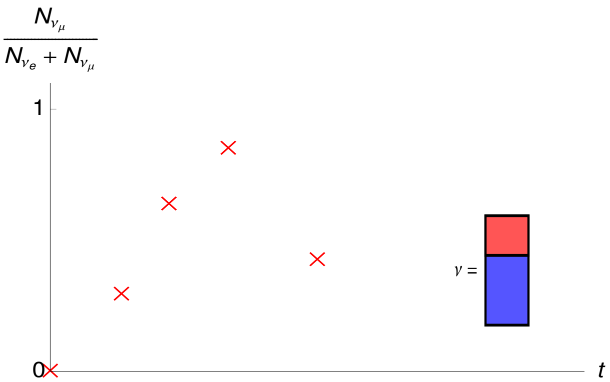

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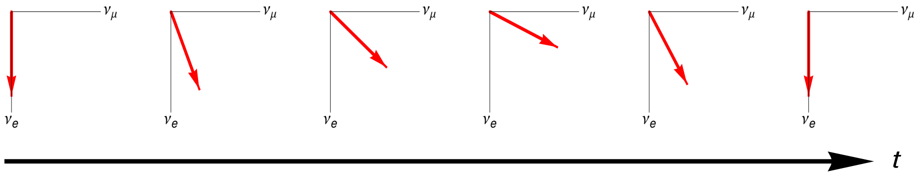

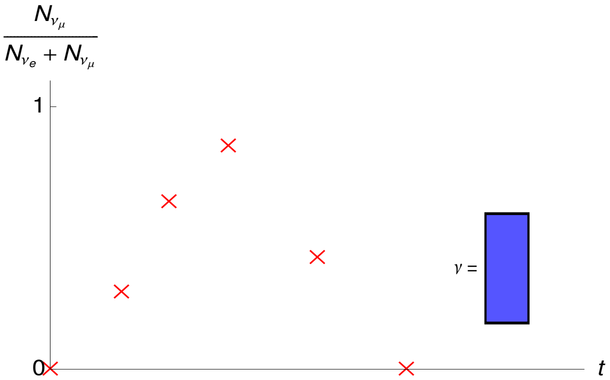

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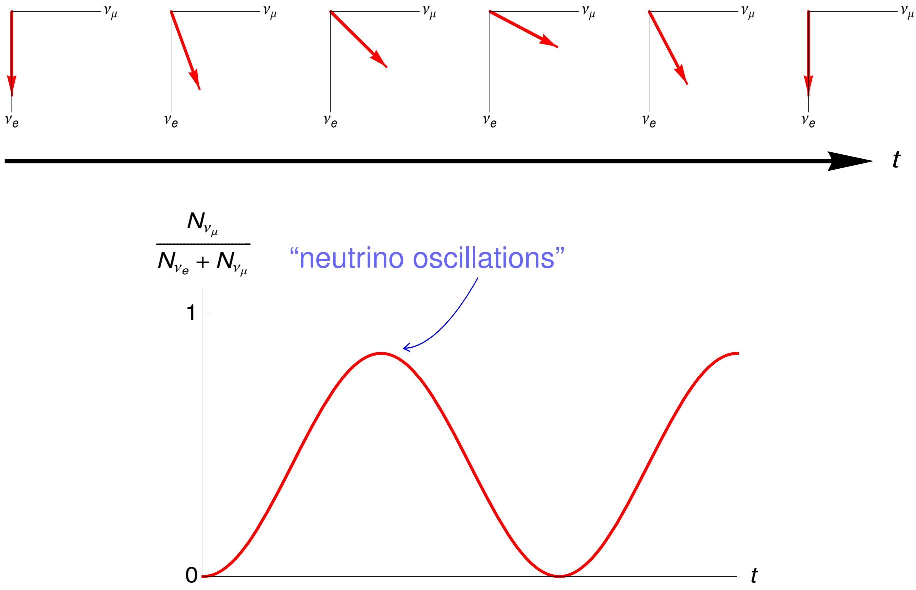


Flavor mixing in high-energy astrophysical neutrinos

A technicality:

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \delta_{\alpha\beta} - 4 \sum_{k>j} \mathrm{Re}\left(J_{\alpha\beta jk}\right) \sin^2\left(\frac{\Delta m_{kj}^2 L}{4E}\right) \pm 2 \sum_{k>j} \mathrm{Im}\left(J_{\alpha\beta jk}\right) \sin\left(\frac{\Delta m_{kj}^2 L}{2E}\right)$$

- The Δm_{kj}^2 are very small: $\sim 10^{-4}, 10^{-3}$ eV^2
- 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 astrophysical neutrinos:

$$P_{\overset{(-)}{\nu}_\alpha \to \overset{(-)}{\nu}_\beta} = \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Flavor ratios

- Neutrino production at the source via pion decay:

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

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

$$f_{\alpha,\oplus} = \sum_\beta P_{\beta\alpha} f_{\beta,\text{S}}$$

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

- Other compositions at the source:

$$(0 : 1 : 0)_\text{S} \longrightarrow (0.26 : 0.36 : 0.38)_\oplus \text{ ("muon damped")}$$
$$(1 : 0 : 0)_\text{S} \longrightarrow (0.55 : 0.26 : 0.19)_\oplus \text{ ("neutron decay")}$$
$$(1 : 1 : 0)_\text{S} \longrightarrow (0.40 : 0.31 : 0.29)_\oplus \text{ ("charmed decays")}$$

How can IceCube identify flavor?

Below $E_\nu \sim 10$ 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)

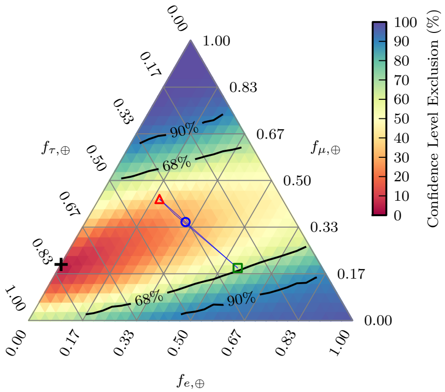
At $\gtrsim 10$ PeV (no events so far), all of the above, plus:

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

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

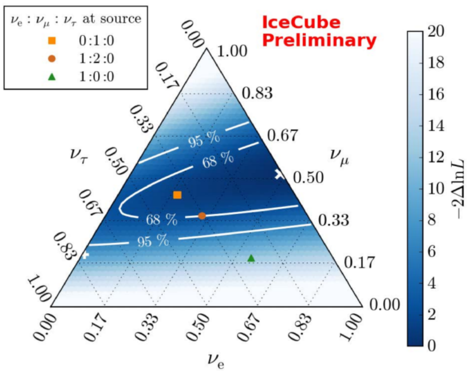
Two IceCube analyses of flavor composition

Using contained events only



Best fit: $(0 : 0.2 : 0.8)_\oplus$

Using contained events + throughgoing muons

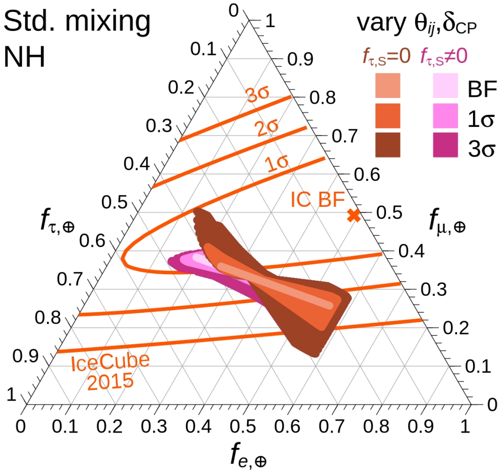


Best fit: $(0.49 : 0.51 : 0)_\oplus$

- Compatible with standard source compositions
- Bounds are weak – need more data and better flavor-tagging

Flavor combinations at Earth from flavor mixing

But we do not really know the flavor composition at the source:



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

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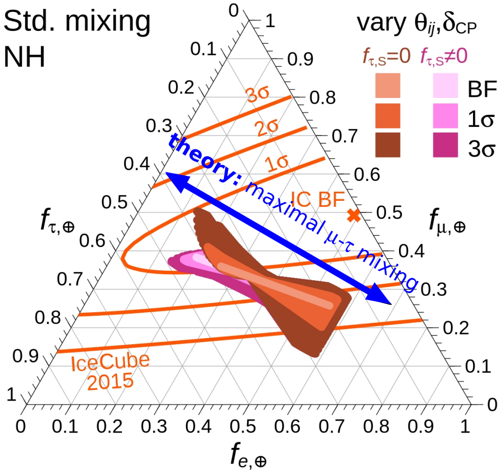

Std. mixing can access *only* ~ 10% of the possible combinations

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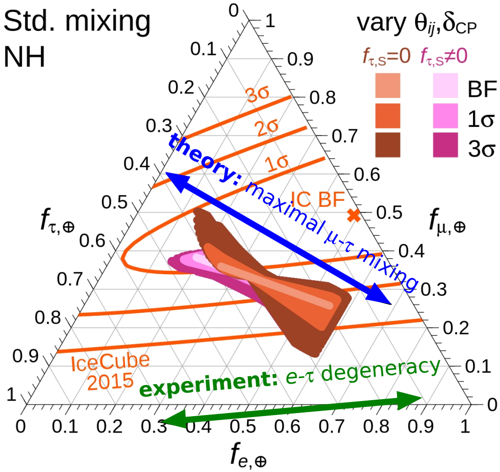

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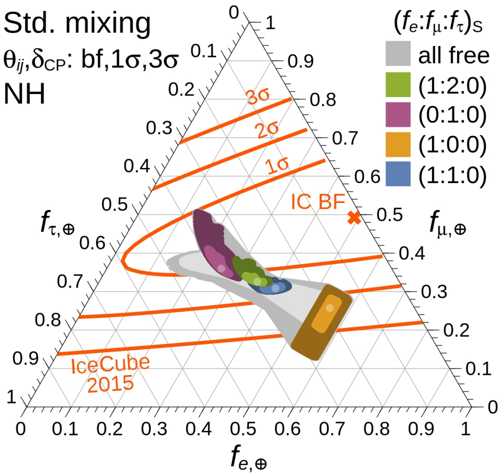
Selected source compositions

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



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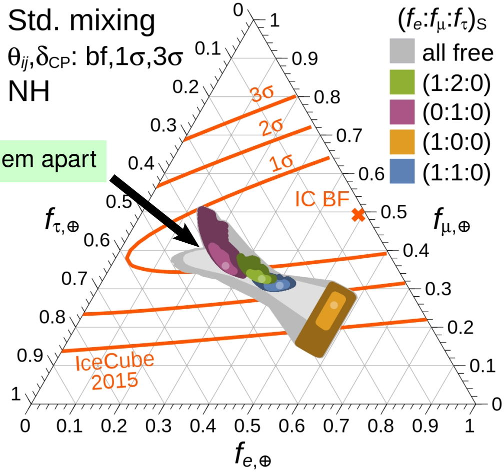

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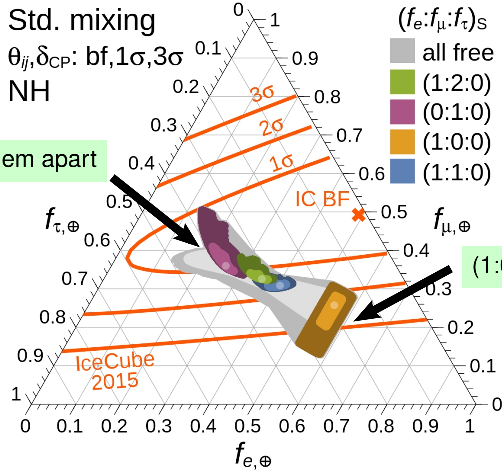
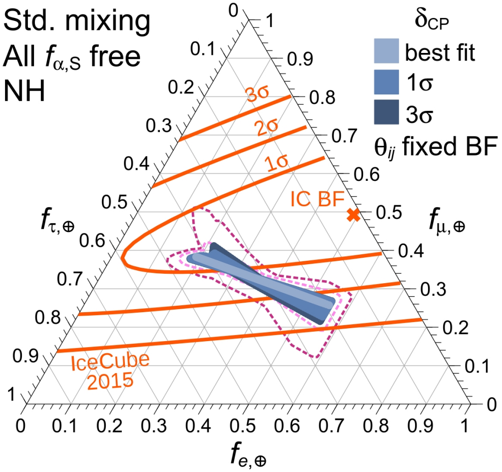


(1:0:0) disfavored at 2σ

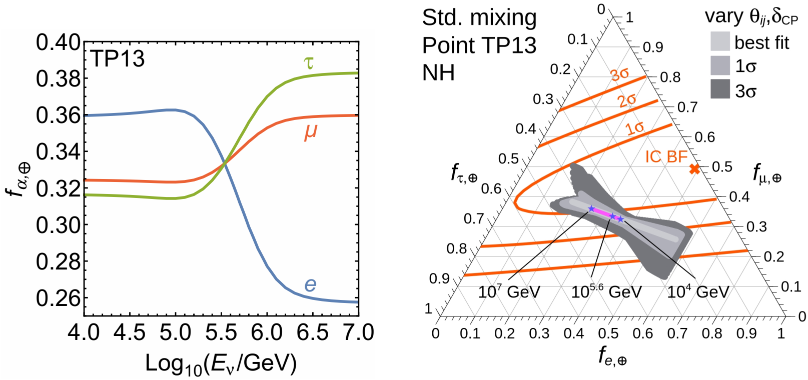
Perfect knowledge of mixing angles

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



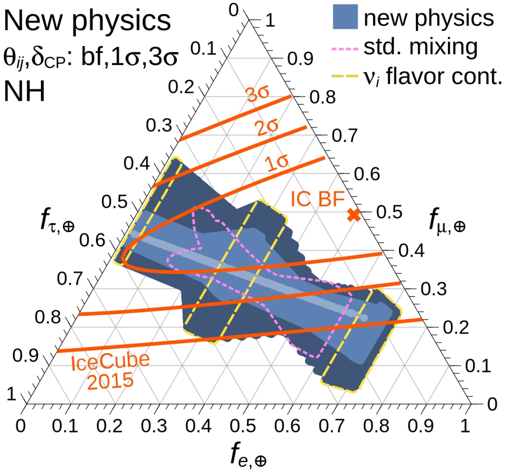
Energy dependence of the composition at the source

Different ν production channels are accessible at different energies:



- Equivalent to different sources types contributing to the diffuse flux
- Will be difficult to resolve

New physics could modify the flavor ratios at Earth:



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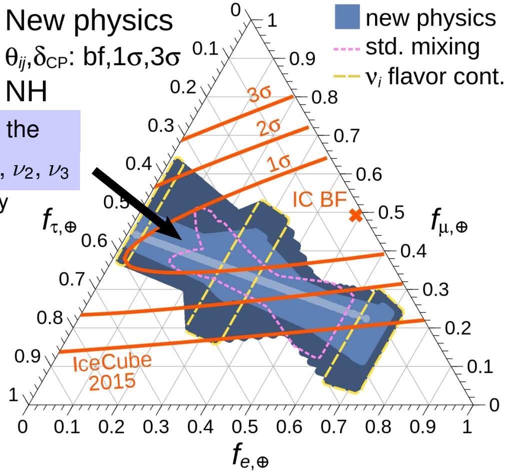
NP that changes the proportions of ν_1, ν_2, ν_3

e.g., neutrino decay



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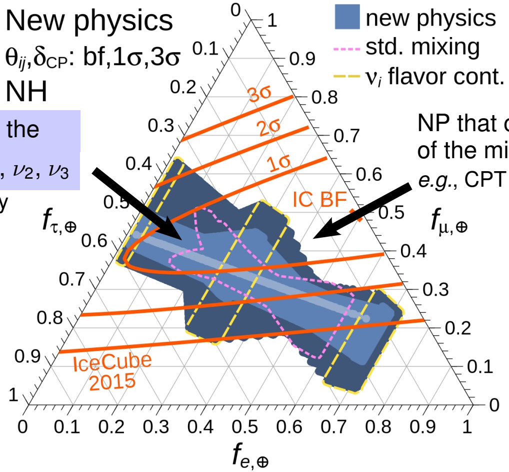


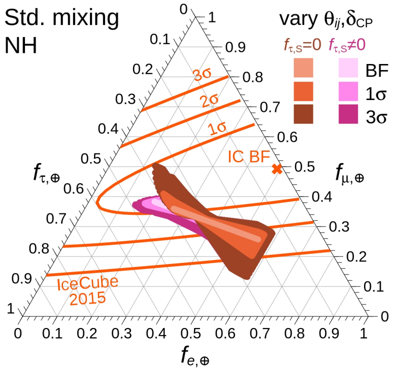
NP that changes the values of the mixing angles

e.g., CPT violation

Conclusions . . . and the future

- Flavor composition provides information about the sources
- Std. mixing can access only $\sim$ 10% of the possible flavor combinations at Earth
- "Milder" new physics can access only 25% of flavor combinations
- It is challenging to think what lies beyond this region
- IceCube searches could use these theoretical considerations to improve constraints

Backup slides


Std. mixing
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vary θ_{ij}, δ_{CP}
$f_{\tau,S}=0$ $f_{\tau,S}\neq0$
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1σ
3σ
3σ
2σ
1σ
IC BF
IceCube 2015
$f_{\tau,\oplus}$
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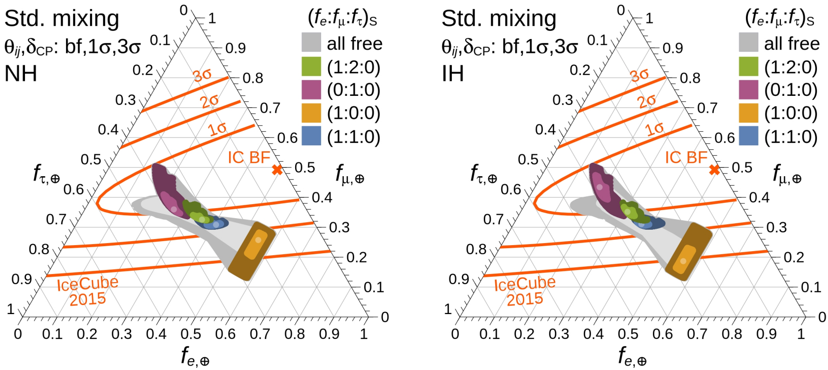
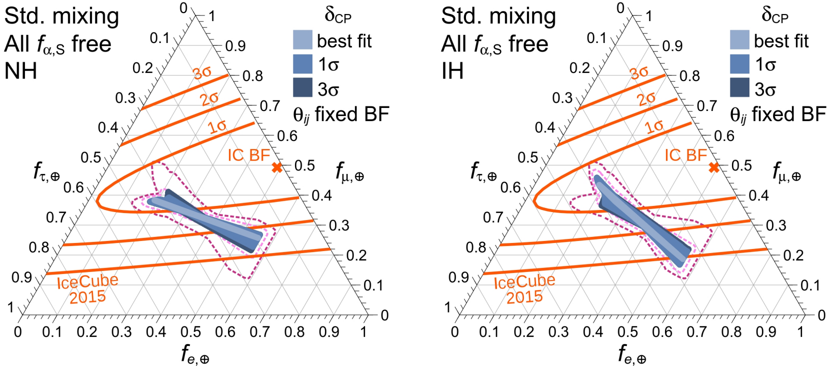
Selected source compositions: NH vs. IH

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