Flavor Probes the Production of High-Energy Astrophysical Neutrinos

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Based on:
PRL 122, 241101 (2019) [1901.10087]

At a glance

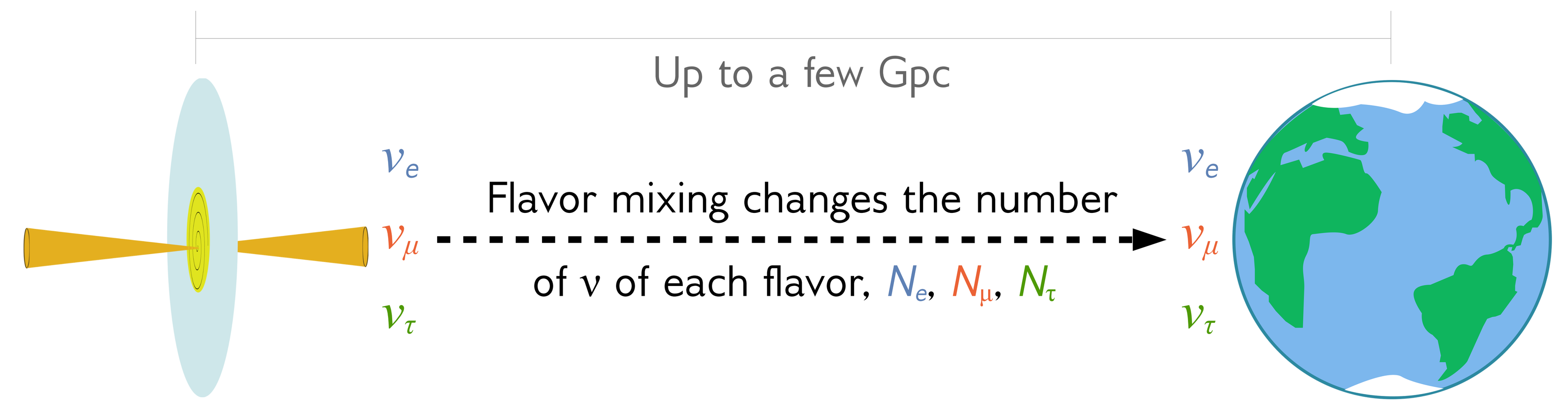
- The sources of TeV–PeV astrophysical neutrinos are unknown
- Goal: Find the process by which the sources produce neutrinos
- How: Use the flavor composition — the relative number of ν_e, ν_μ, ν_τ — to infer the production process and the source properties
- Results:
  1 — Today, flavor data show preference for ν production via pion decay
  2 — Future detectors may single out the production mechanism

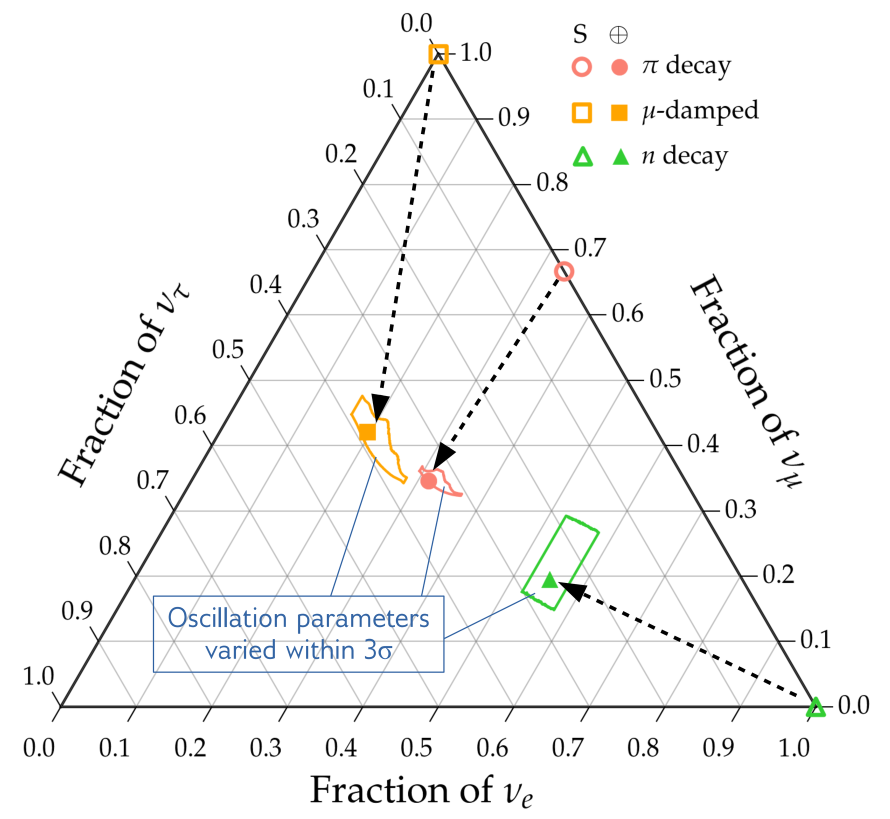
Flavor basics: From the sources to Earth

- We do not know where and how TeV–PeV neutrinos are made
- Likely scenario: Protons of 10s of PeV interact with matter or photons,
  $p + \gamma \to \pi^+ \to \mu^+ + \nu_\mu$ followed by $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
- The production process depends on the conditions at the sources
- Different processes yield different ratios $(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) \equiv (N_{e,\mathrm{S}}, N_{\mu,\mathrm{S}}, N_{\tau,\mathrm{S}})/N_{\mathrm{tot}}$ of neutrinos of each flavor, *e.g.*, the benchmarks

Full π decay chain	π decay + μ synchrotron cooling	Neutron decay
$(1:2:0)_\mathrm{S}$	$(0:1:0)_\mathrm{S}$	$(1:0:0)_\mathrm{S}$

- Then neutrino oscillations en route to Earth change the flavor ratios:





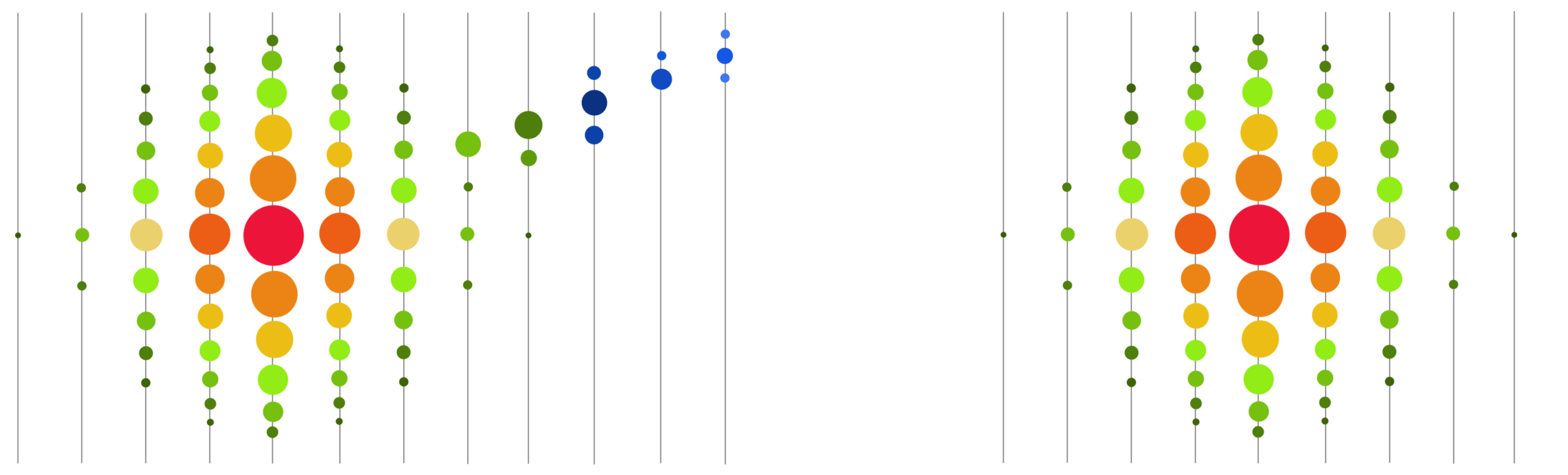
- Flavor ratios at Earth (α = e, μ, τ):

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} \underbrace{P_{\nu_\beta \to \nu_\alpha}}_{\text{The flavor-changing probability depends on three mixing angles } \theta_{12},\, \theta_{23},\, \theta_{13} \text{, and one CP phase } \delta_{\mathrm{CP}}} f_{\beta,\mathrm{S}}$$

- These parameters are known from oscillation experiments

Our goal: From the Earth back to the sources

- Solve the inverse problem: From the flavor ratios $f_{\alpha,\oplus}$ measured at Earth, reconstruct the flavor ratios $f_{\alpha,\mathrm{S}}$ at the sources
- Complication: The flavor ratios at Earth and the oscillation parameters are not measured perfectly — but we can account for that
- How does IceCube see flavor? Using TeV–PeV contained events, which are either tracks (from ν_μ) or showers (mostly from ν_e and ν_τ)

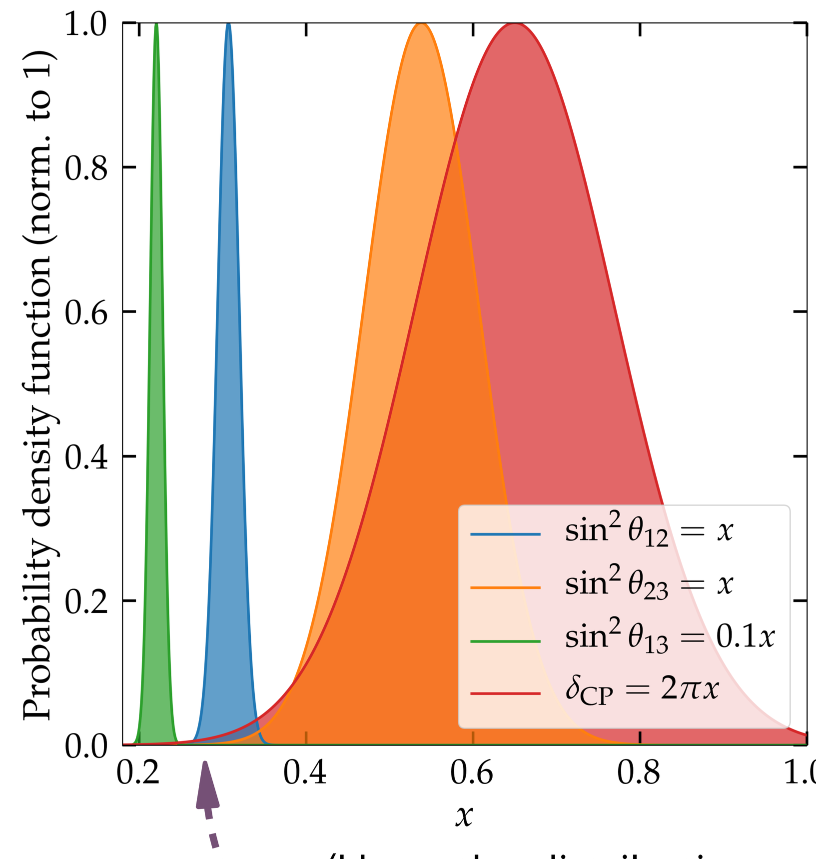


Identifiable due to km-long muon track — Can separate ν_e from ν_τ statistically

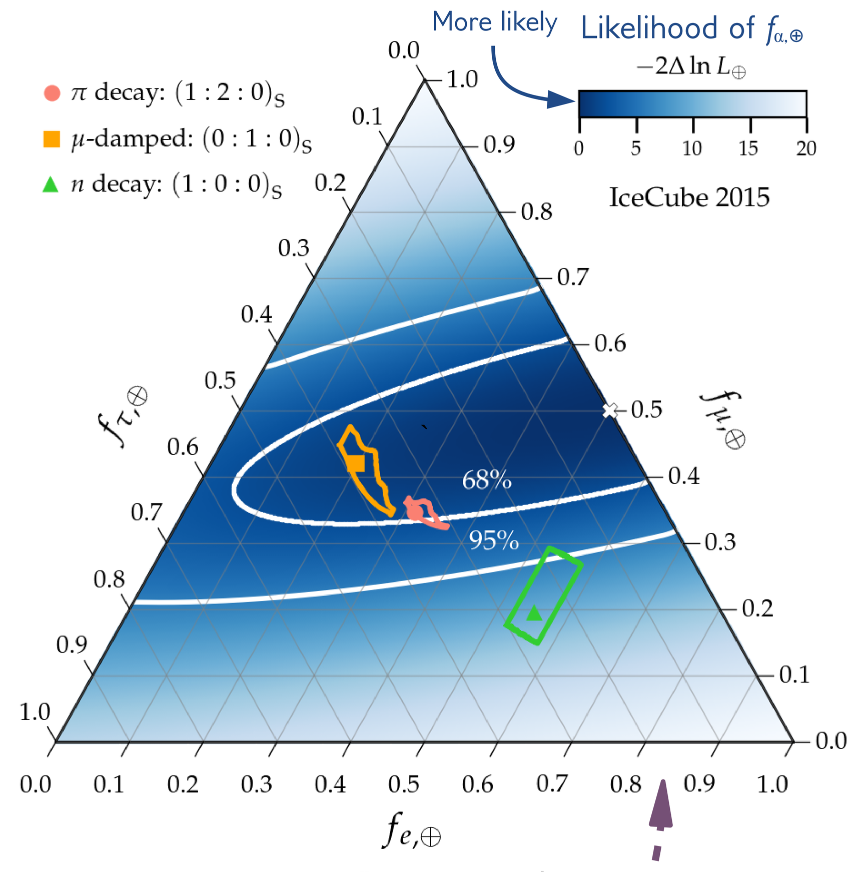
Inferring flavor at the astrophysical sources

The ingredients: Flavor measured at Earth + oscillations

PDFs of oscillation parameters:



IceCube flavor measurements:



(Here, the distributions are approximated by Gaussians)

The method: Bayesian inference

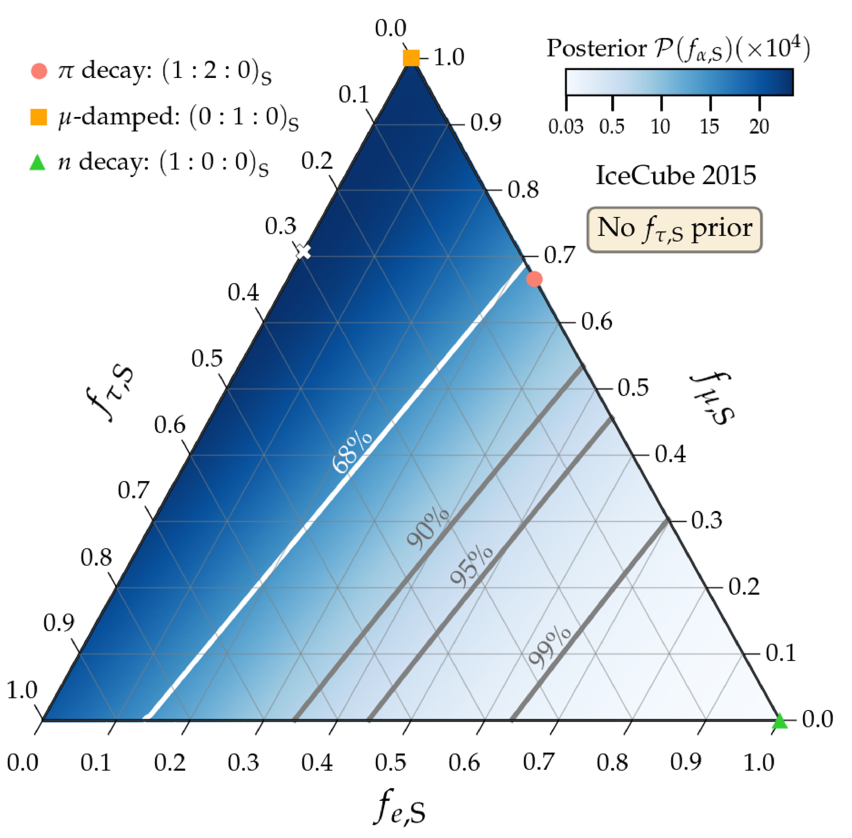
Posterior probability density of $f_{\alpha,\mathrm{S}}$ being the flavor ratios at the sources:

$$\mathcal{P}(f_{\alpha,\mathrm{S}}) \equiv \int d\boldsymbol{\theta}\, \frac{\mathcal{P}(\boldsymbol{\theta})}{\mathcal{N}(\boldsymbol{\theta})} \mathcal{L}_\oplus\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$$

$$\boldsymbol{\theta} \equiv (\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\mathrm{CP}})$$

Normalization: $\mathcal{N}(\boldsymbol{\theta}) \equiv \int_0^1 df_{e,\mathrm{S}} \int_0^{1-f_{e,\mathrm{S}}} df_{\mu,\mathrm{S}}\, \mathcal{L}_\oplus\left[f_{e,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta}), f_{\mu,\oplus}(f_{\alpha,\mathrm{S}}, \boldsymbol{\theta})\right]$

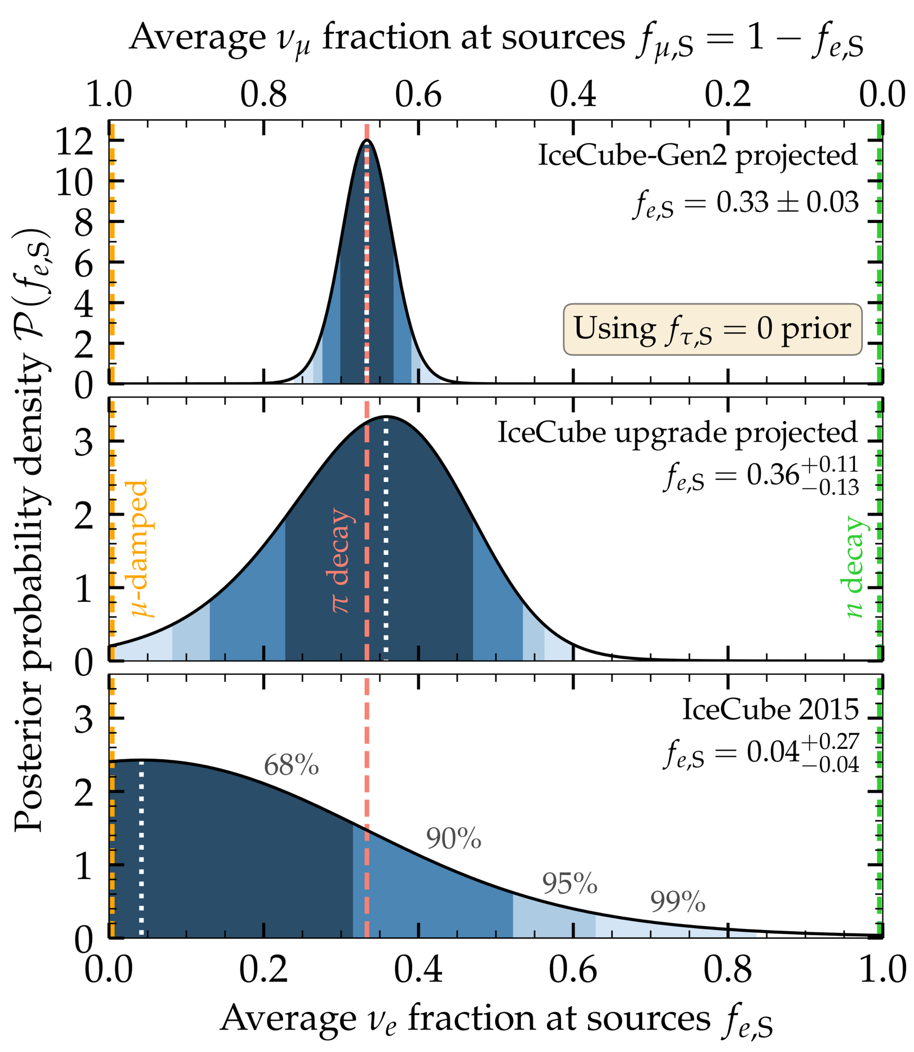
The result: Flavor composition at the sources



- Using present data, the most likely ratios at the sources are $(f_{e,\mathrm{S}}, f_{\mu,\mathrm{S}}, f_{\tau,\mathrm{S}}) = (0, 0.7, 0.3)$
- Compatible with neutrino production via pion decay
- Hint of muon synchrotron cooling
- Neutron decay ruled out
- Large uncertainties in $f_{\alpha,\mathrm{S}}$ echo the uncertainties in $f_{\alpha,\oplus}$ measurement

The future: The IceCube upgrade and Gen2

- The IceCube upgrade (2022) and IceCube-Gen2 (2030) will measure flavor more precisely
- We focus on the likely case where sources do not produce ν_τ
- For projections, we assume:
  - ν production via π decay chain
  - Gen2: negligible uncertainties on $\boldsymbol{\theta}$
- Uncertainty in $f_{e,\mathrm{S}}$ reduced by
  - IceCube upgrade: factor of 2.5
  - IceCube-Gen2: factor of 10
- They will be able to single out the ν production mechanism



Conclusions

We have inferred the flavor composition of high-energy astrophysical neutrinos at their sources, based on their flavor composition measured at Earth, and accounting for measurement uncertainties. Using our procedure, upcoming detectors will be able to single out the neutrino production process.

Selected references

A combined maximum-likelihood analysis of the high-energy astrophysical neutrino flux measured with IceCube, IceCube Collab., ApJ 2015 [1507.03991] • *On the flavor composition of the high-energy neutrino events in IceCube*, O. Mena, S. Palomares-Ruiz, A.C. Vincent, PRL 2014 [1404.0017] • *Theoretically palatable flavor combinations of astrophysical neutrinos*, M. Bustamante, J.F. Beacom, W. Winter, PRL 2015 [1506.02645]

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