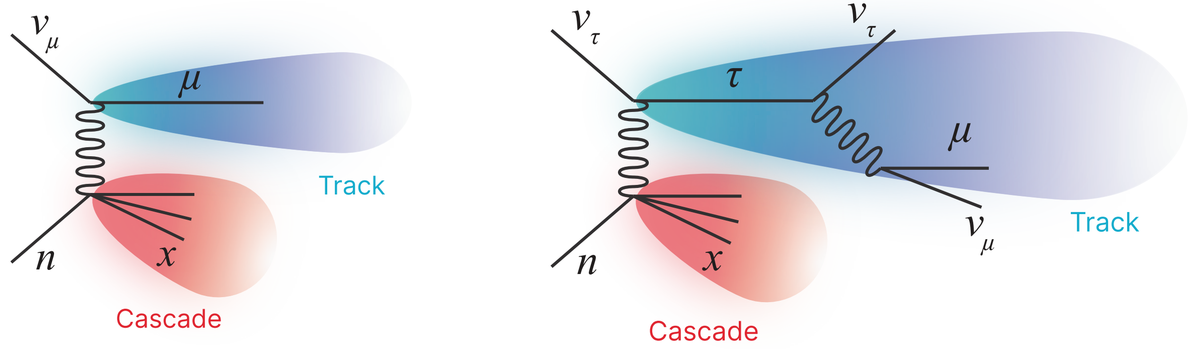


Using inelasticity in neutrino telescopes to measure astrophysical ν_τ

Alex Wen, Carlos Argüelles, Sergio Palomares-Ruiz

31 August 2026

TeVPA - Tendo, Japan

Based on 2605.29105

Graphic: J. Pairin

HARVARD
Department of Physics

NSF
NSERC CRSNG

Theme

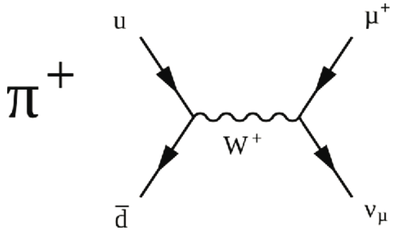
Astrophysical neutrino flavour

Why it's important, especially ν_τ

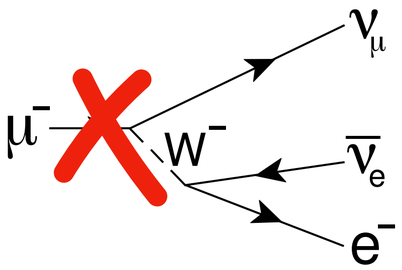
Method to measure it & predictions

Flavours of astrophysical neutrinos

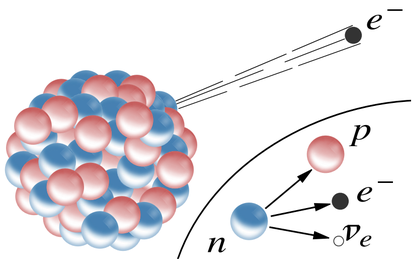
ν source



Pion decay
$(\nu_e : \nu_\mu : \nu_\tau) \sim (1 : 2 : 0)$



Muon-damped
$(\nu_e : \nu_\mu : \nu_\tau) \sim (0 : 1 : 0)$



Beta decay
$(\nu_e : \nu_\mu : \nu_\tau) \sim (1 : 0 : 0)$

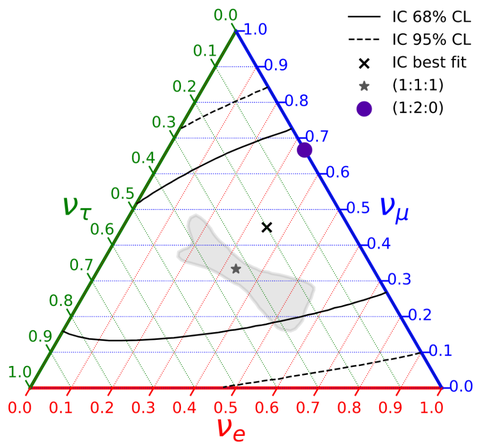
- We don't know exact origin of all astrophysical neutrinos, but there are a few known mechanisms
- Note that the ν_τ is the only one not produced in these common channels

Mixture
$(\nu_e : \nu_\mu : \nu_\tau) \sim (x : 1 - x : 0)$
x in the range [0,1]

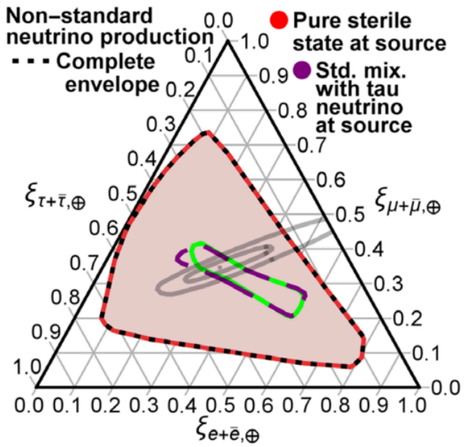
The importance of measuring flavour

- After oscillations over cosmic baselines, known oscillations predict $(\nu_e : \nu_\mu : \nu_\tau) \sim (1 : 1 : 1)$
- Flavour measurement in general is an excellent probe of BSM effects

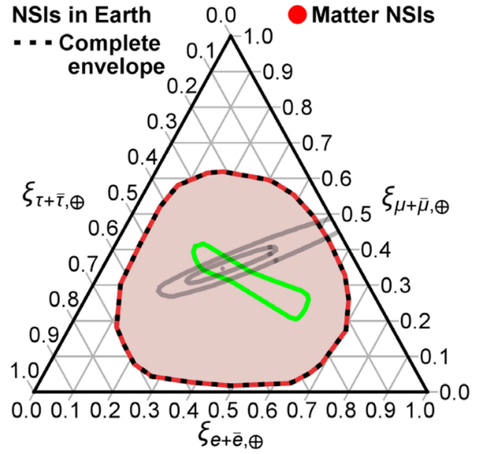
- In particular, the ν_τ component has emerged entirely from oscillation
  - ν_τ is a probe of quantum mechanics at cosmic length scales!



DM couplings



Sterile source composition



Nonstandard interactions

+ many more!

Farzan et al. Phys. Rev. D 99, 051702 (2019)

Rasmussen et al. Phys. Rev. D 96, 083018 (2017)

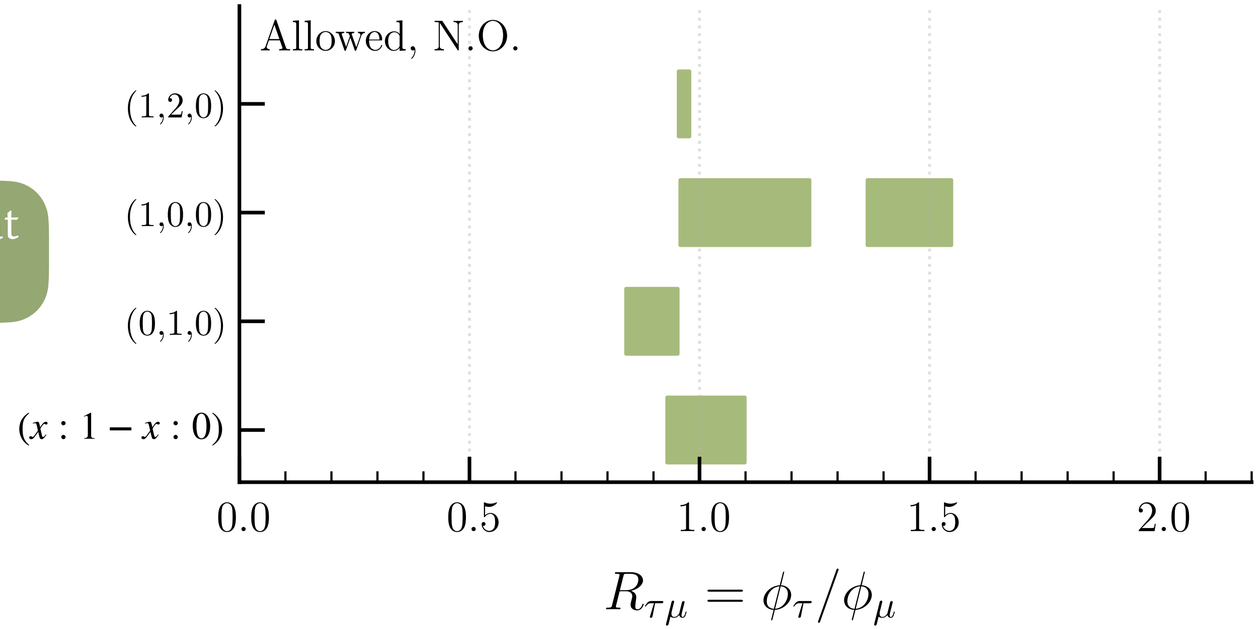
Astrophysical ν_τ expectation at Earth

- In particular, we can predict the $R_{\tau\mu} = \phi_\tau / \phi_\mu$ ratio at Earth
- Accounting for (correlated) uncertainties in the mixing parameters $(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP}, \Delta m^2_{12}, \Delta m^2_{13})$ from, NuFit

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Standard oscillations

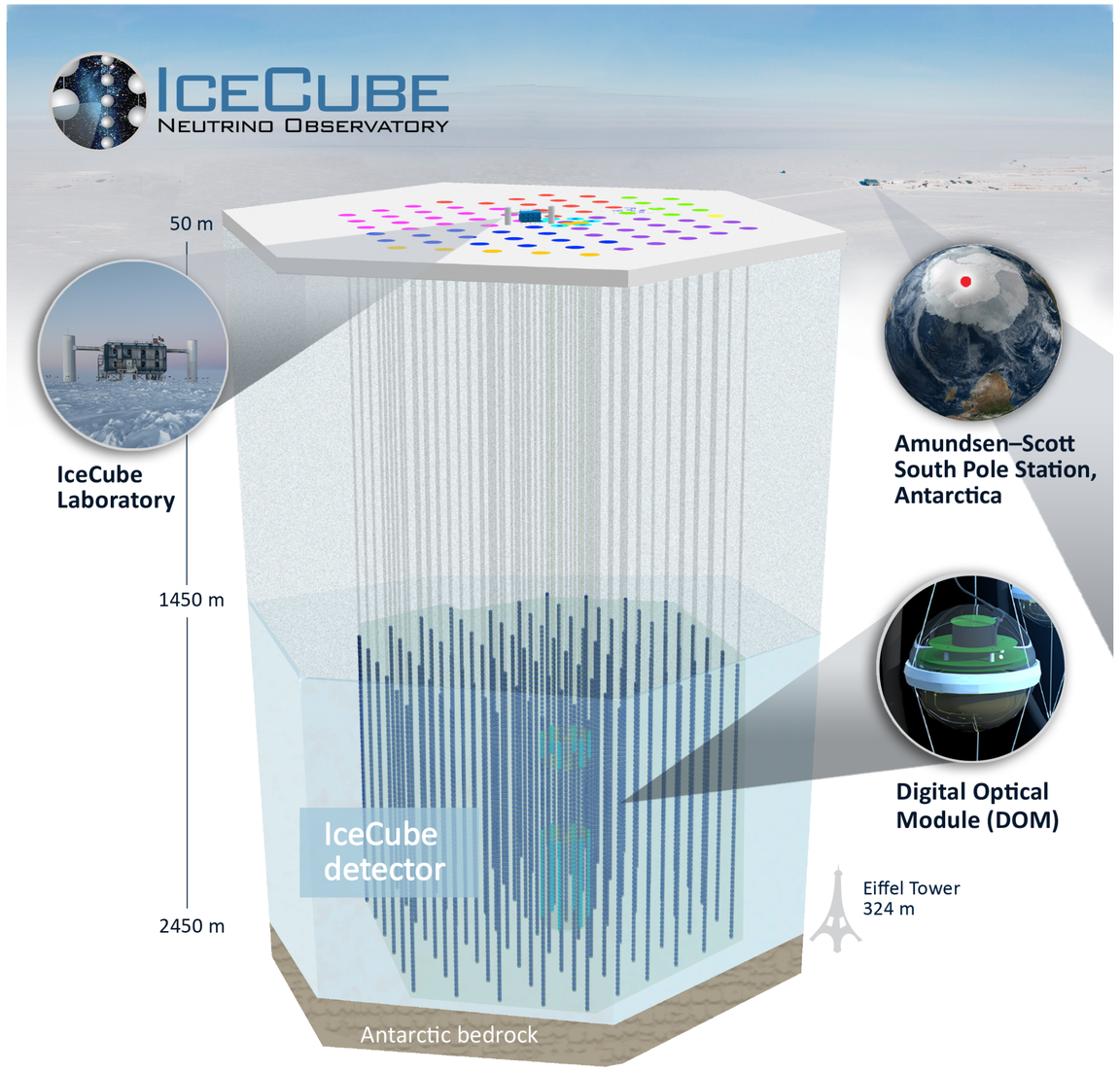
Composition at production



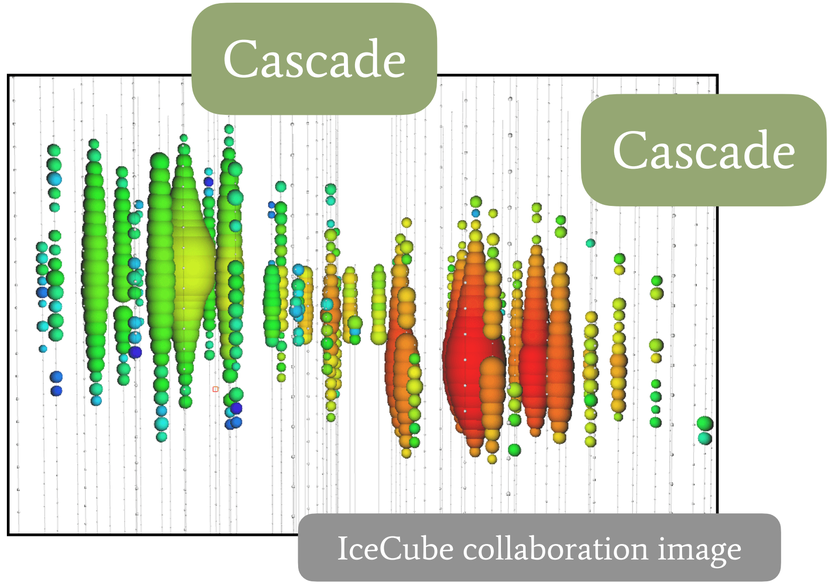
Ratio of ν_τ/ν_μ flux at Earth

NuFit, JHEP 12 (2024) 216

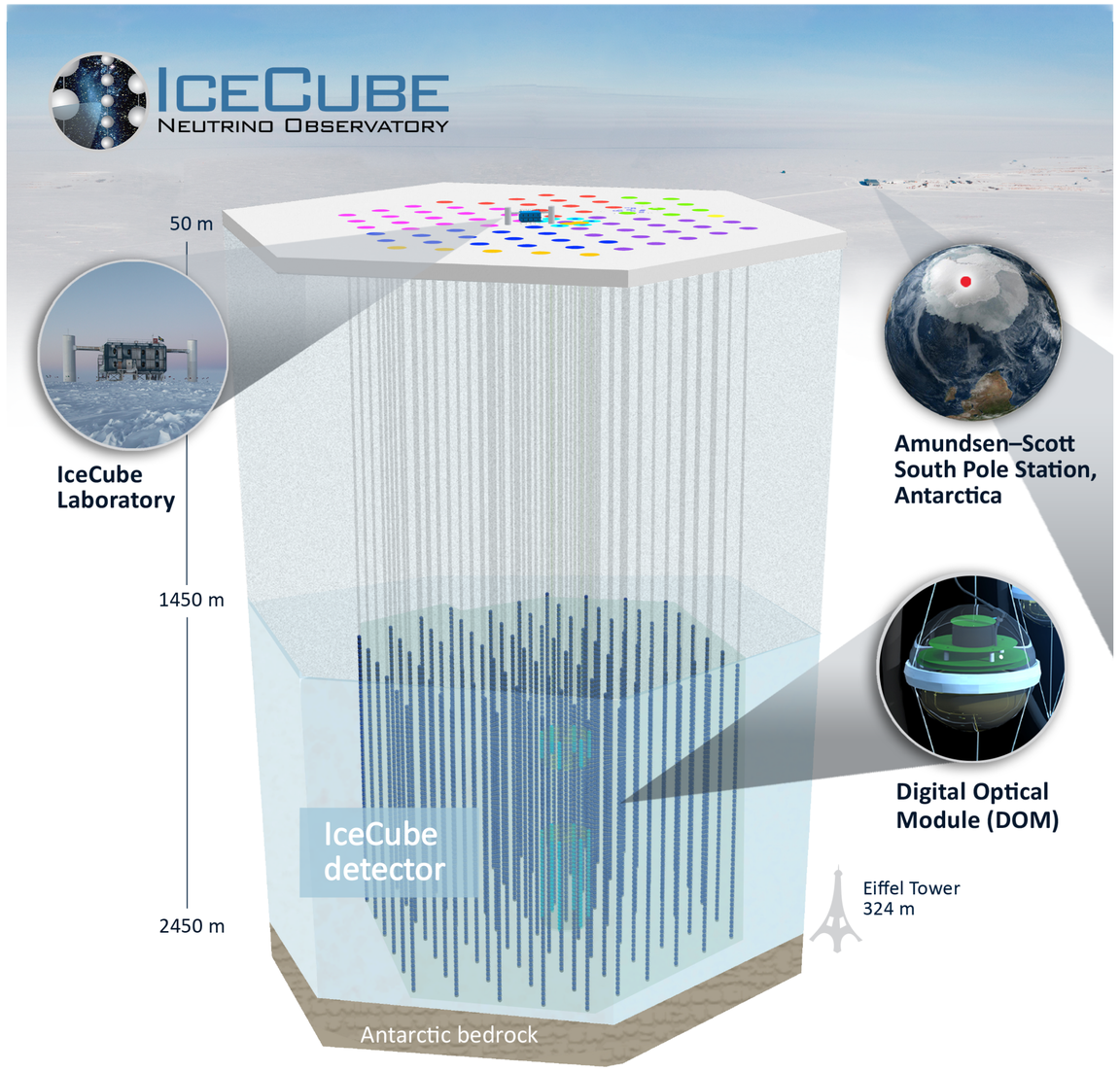
Measurement: relevant nu-tel event morphologies



Measurement: relevant nu-tel event morphologies



- The well-known and proven <u>double-cascade</u> channel: $\nu_\tau \rightarrow \tau \rightarrow$ decay
- Technically very challenging, low event rates, but event-by-event ν_τ label



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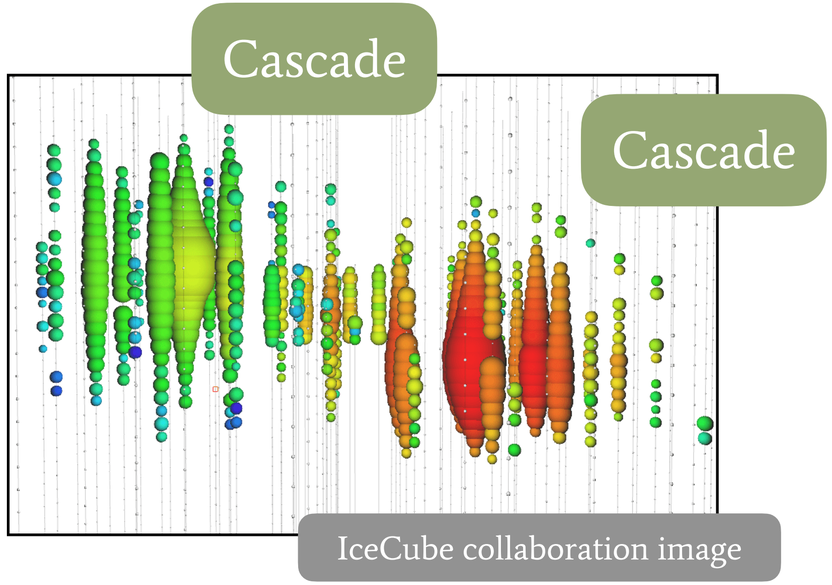
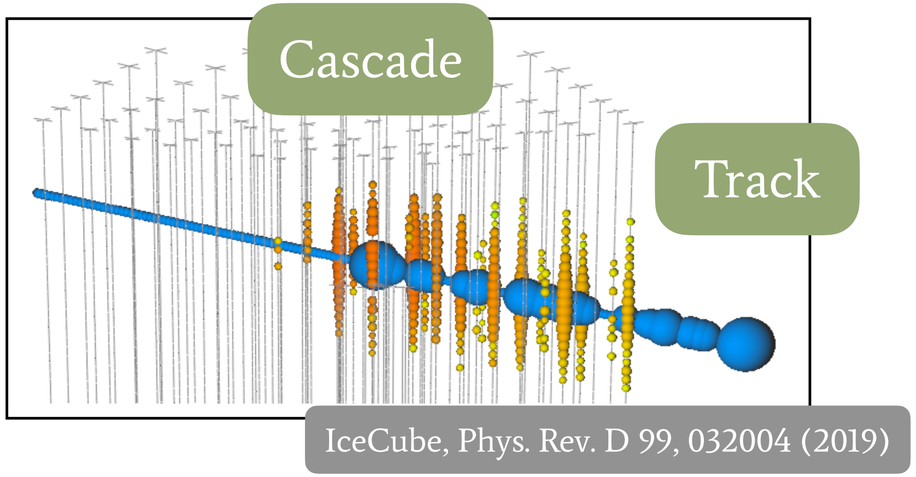




- The well-known and proven <u>double-cascade</u> channel: $\nu_\tau \rightarrow \tau \rightarrow$ decay
- Technically very challenging, low event rates, but event-by-event ν_τ label

- Another prospect: $\nu_\tau \rightarrow \tau \rightarrow \mu$, so find starting tracks, i.e. <u>lollipop</u> events
- Easier time finding them, tracks have good pointing, but only <u>statistical</u> discrimination of ν_τ

Measurement: relevant nu-tel event morphologies

Works with related ideas/ discussions:

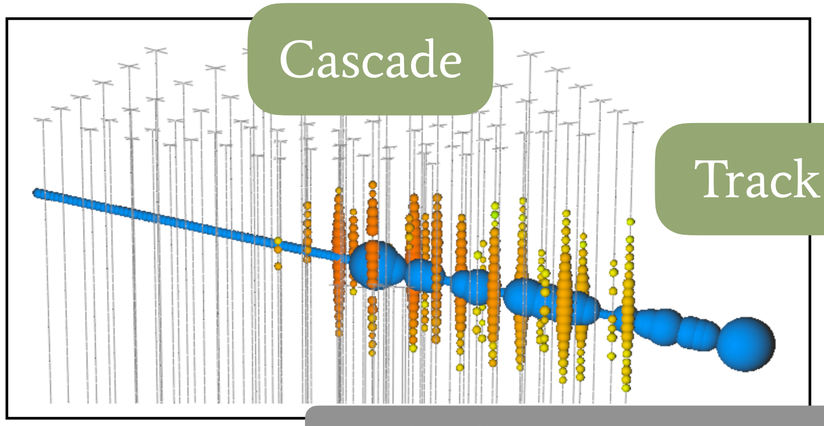
D. F. Cowen for the IceCube Collaboration, J. Phys. Conf. Ser. 60 (2007) 227-230

T. DeYoung et al., Astropart. Phys. 27:238-243 (2007)

IceCube Collaboration, Phys. Rev. D 99, 032004 (2019)

R. Clark, Ph.D. thesis, King's College London (2024)

+ others...



IceCube, Phys. Rev. D 99, 032004 (2019)

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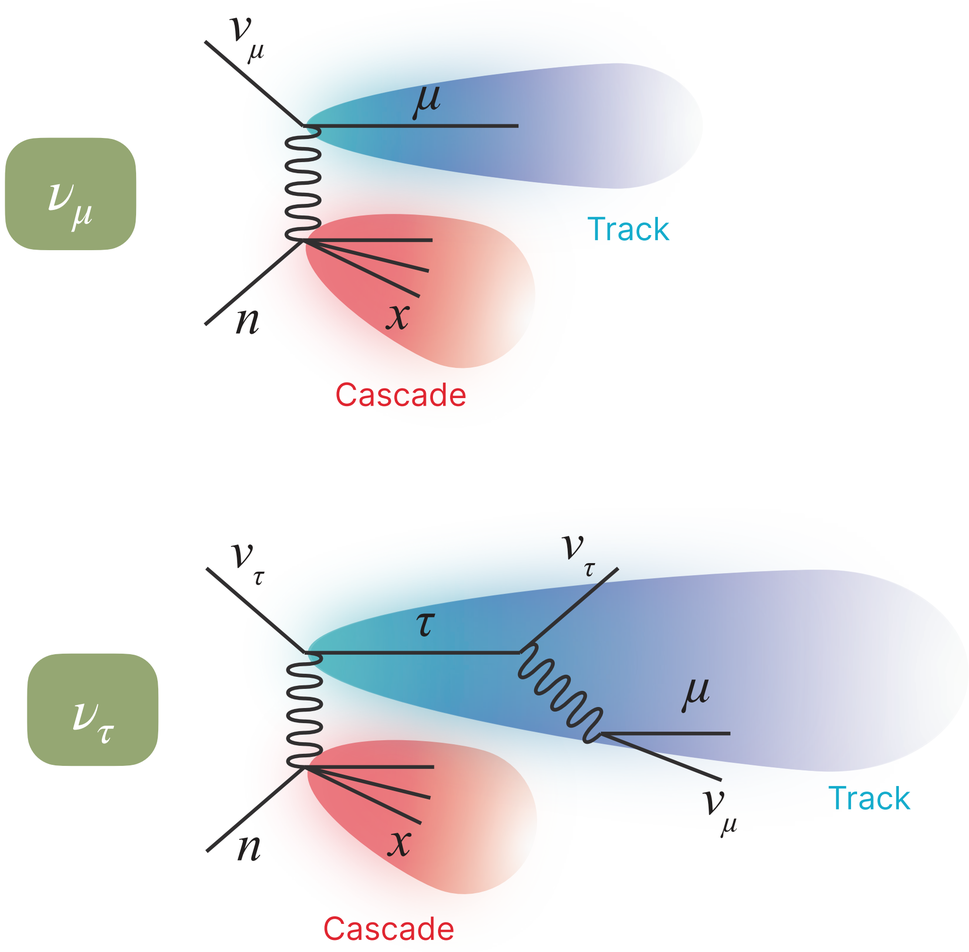
- Easier time finding them, tracks have good pointing, but only statistical discrimination of ν_τ

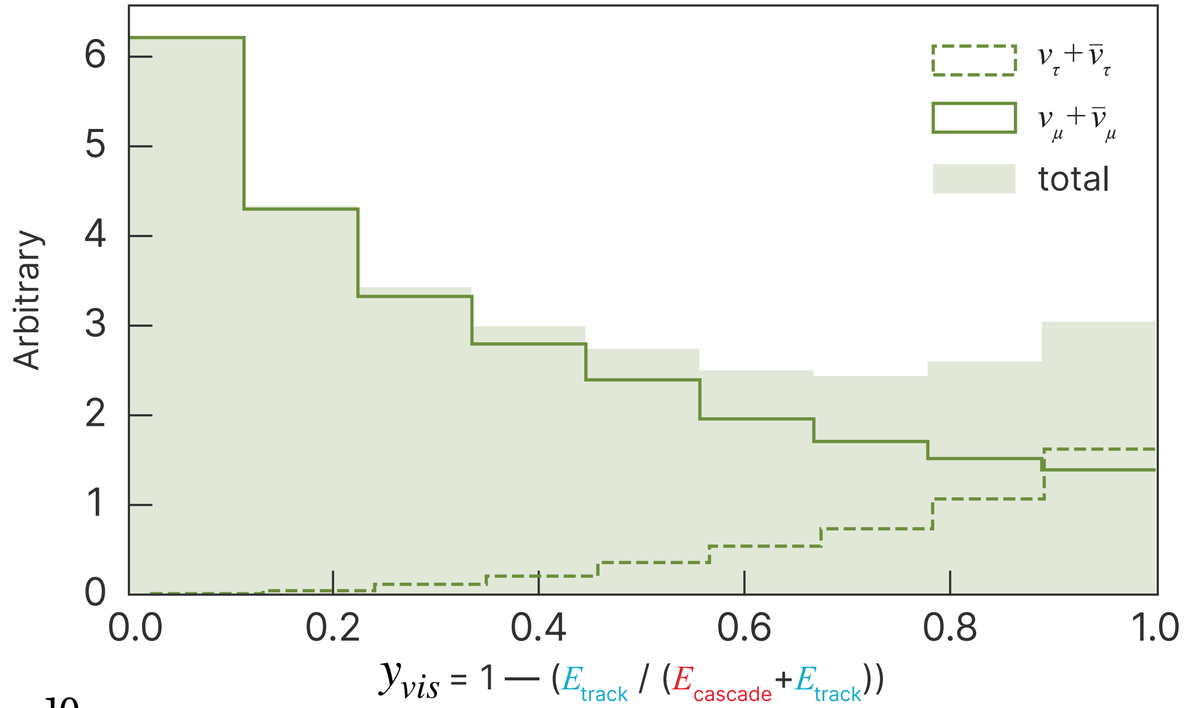
A closer look at starting tracks



- The distribution of visible inelasticity

$$y_{vis} = 1 - (E_{\text{track}} / (E_{\text{cascade}} + E_{\text{track}}))$$

is distinct for ν_τ and ν_μ events

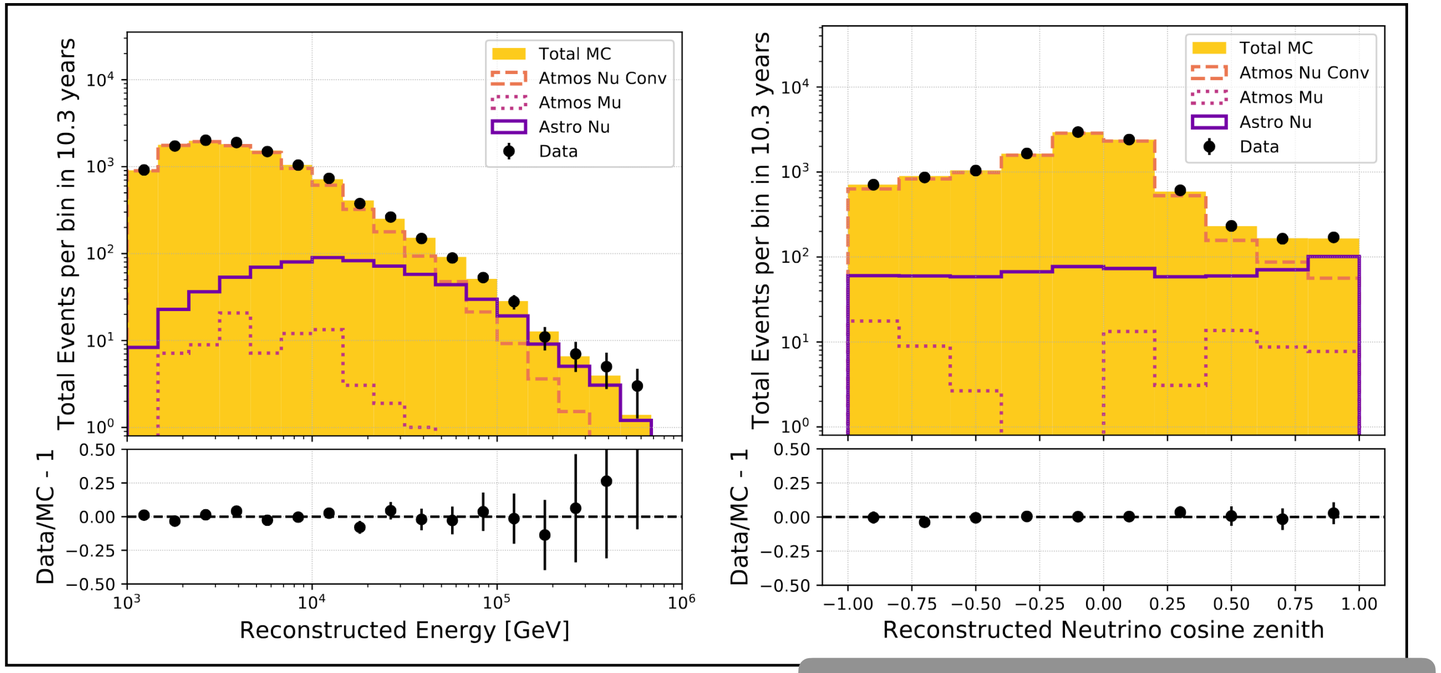


Graphic: J. Pairin

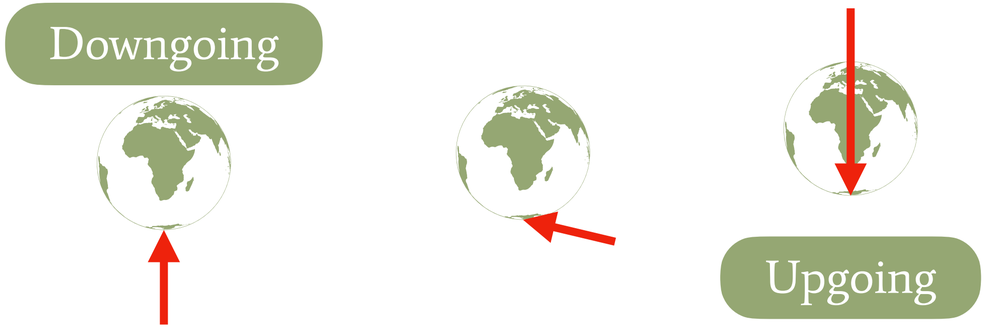
Estimating the effectiveness

Estimating the effectiveness

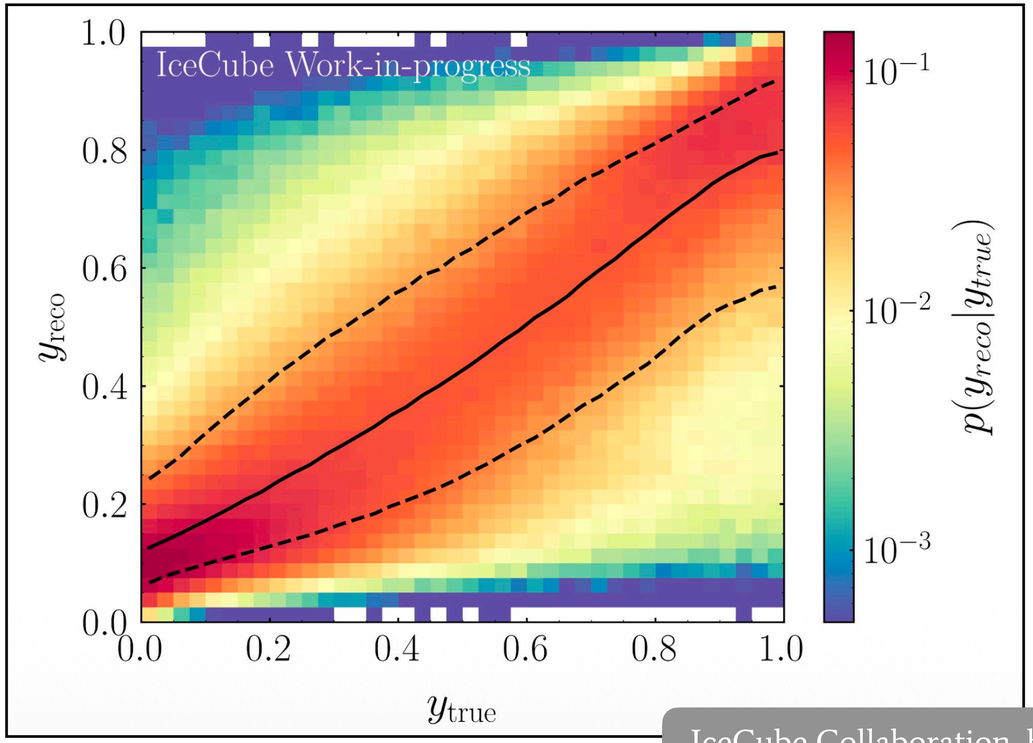
- Assuming an IceCube starting track selection effective area, over 10 years [Phys. Rev. D 110, 022001 (2024)]
  - IceCube is the most mature neutrino telescope, but this would work similarly for others - KM3NeT, etc.
- Tracks from all directions, in the energy range 10 TeV +



IceCube, Phys. Rev. D 110, 022001 (2024)



Estimating the effectiveness



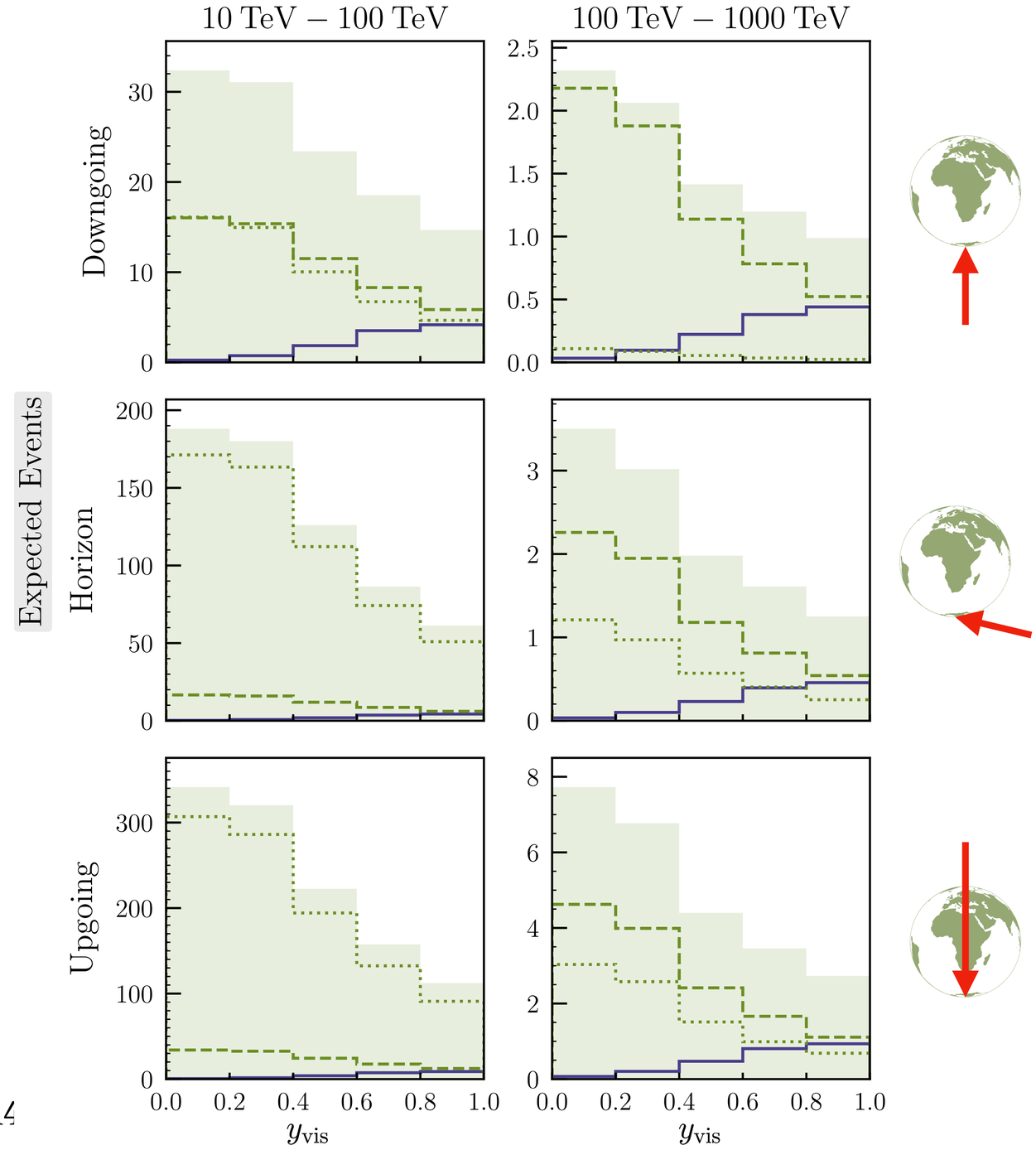
IceCube Collaboration, https://zenodo.org/records/15690410

- Realistic y_{vis} reconstruction uncertainty assumed
- Atmospheric neutrinos - dominant background - partially suppressed by self-veto
- Fitting over astrophysical flux normalization and spectral index
  - 15% wide prior on normalization

For more on the self-veto, see, e.g.:
Carlos A. Argüelles et al., JCAP07(2018)047

Toy analysis

- With these assumptions, we can make a toy analysis
- Binned in energy (2 bins), zenith region (3 bins), and y_{vis} (5 bins)
- Astrophysical ν_τ component contributes most in the downgoing, high energy, high y_{vis} bins

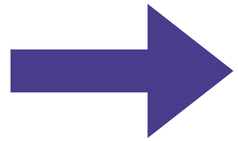


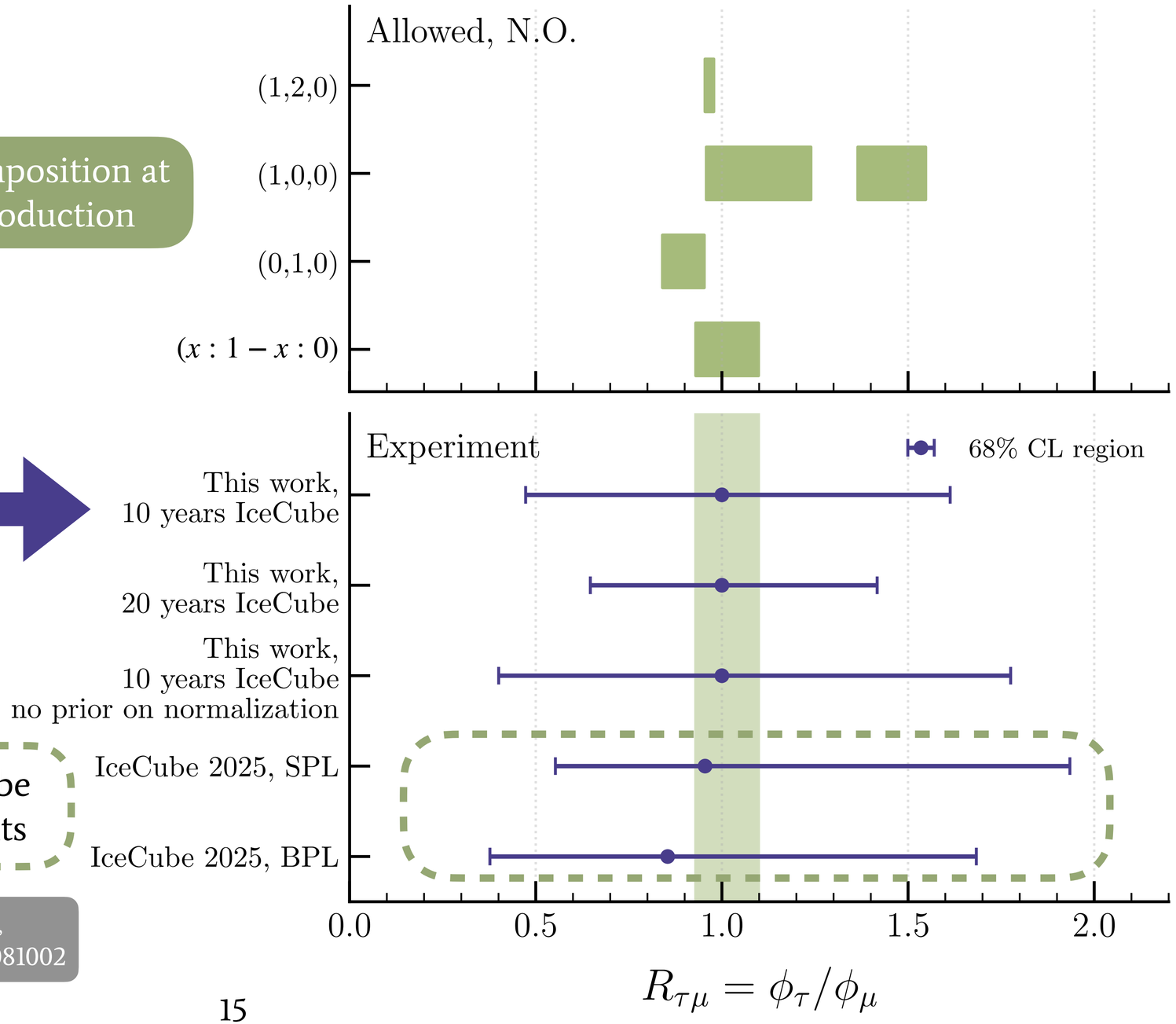
Astrophysical $\nu_\tau + \bar{\nu}_\tau$
Astrophysical $\nu_\mu + \bar{\nu}_\mu$
Atmospheric $\nu_\mu + \bar{\nu}_\mu$
Total

Result

- An estimate, not data
- Using starting tracks, we get comparable performance
- Experiments still much larger than PMNS “allowed” region
- Energy dependence is critical for BSM searches

Composition at production





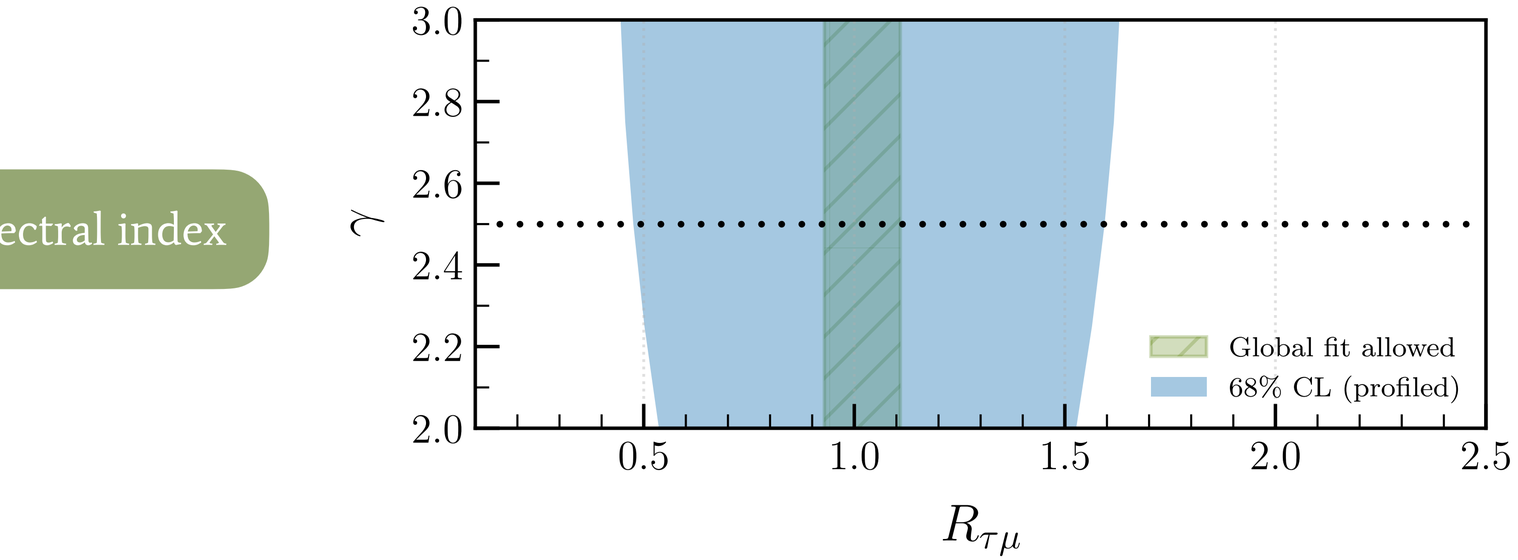
Latest IceCube measurements

IceCube Collaboration,
Phys.Rev.Lett. 137 (2026) 8, 081002

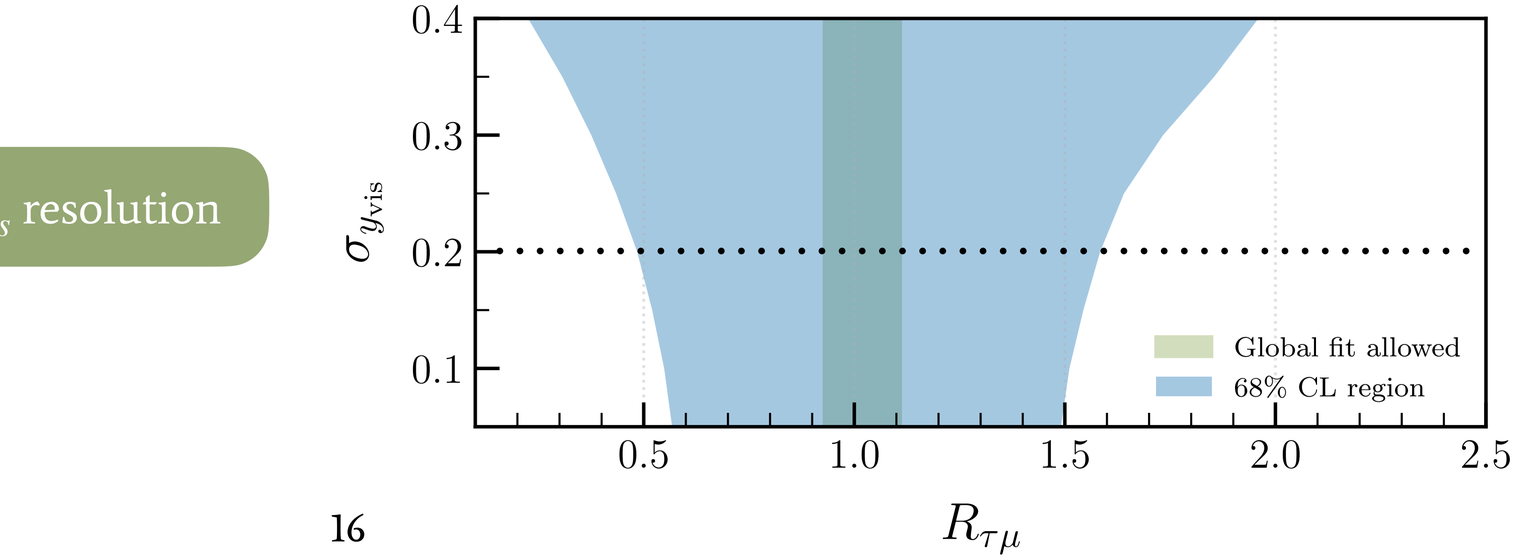
Effect of uncertainty

- What happens if the spectral index is unknown?
- What if y_{vis} resolution is different?
- Both plots: the 10-year IceCube estimate in the blue bands

Spectral index

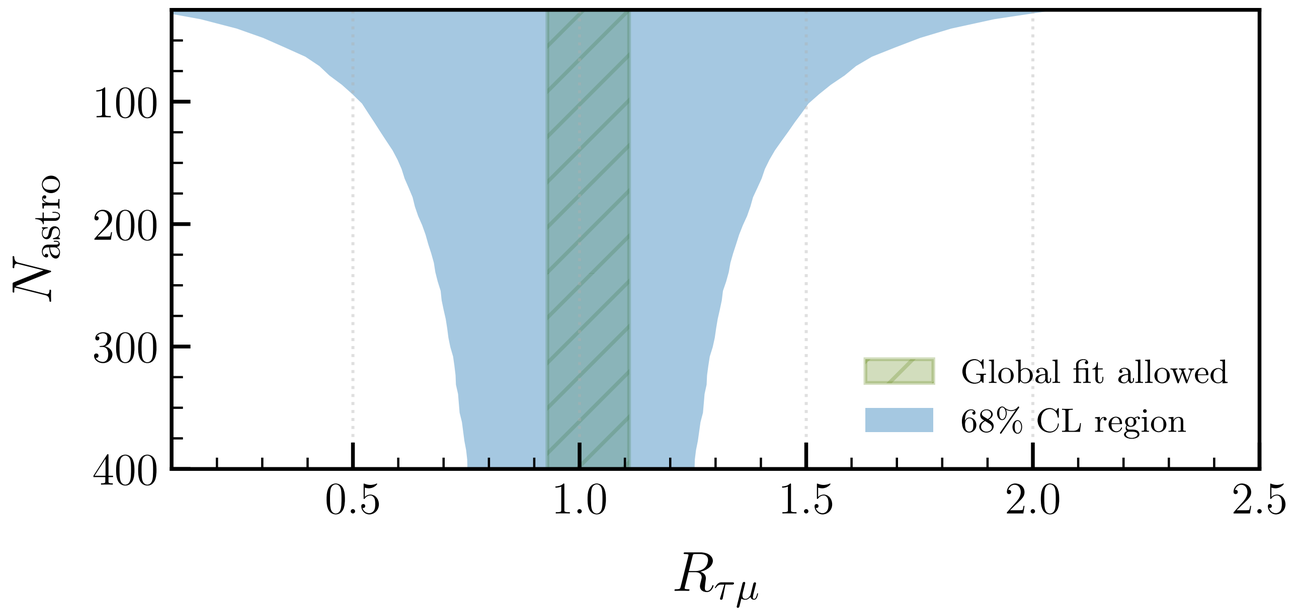


y_{vis} resolution



Far future: source considerations

- If we can measure flavour with just tracks, we can think about measuring the flavour of a single source!
- Shown: the $R_{\tau\mu}$ of a single source given N_{astro} high-energy events from said source
- Not achievable with current detectors/data, but a really exciting prospect!



Summary

- We can measure astrophysical ν_τ content, a powerful BSM probe, in a complementary way using inelasticity of starting track events at neutrino telescopes.

- For more information, check out our preprint: https://arxiv.org/abs/2605.29105

Thanks for listening!

Contact: alexwen@g.harvard.edu

Backup following

What do we expect at Earth?

- Why focus on $R_{\tau\mu} = \phi_\tau / \phi_\mu$ and not $R_{e\mu} = \phi_e / \phi_\mu$?

Composition at production

$$P_{\alpha\beta} = \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

Standard oscillations