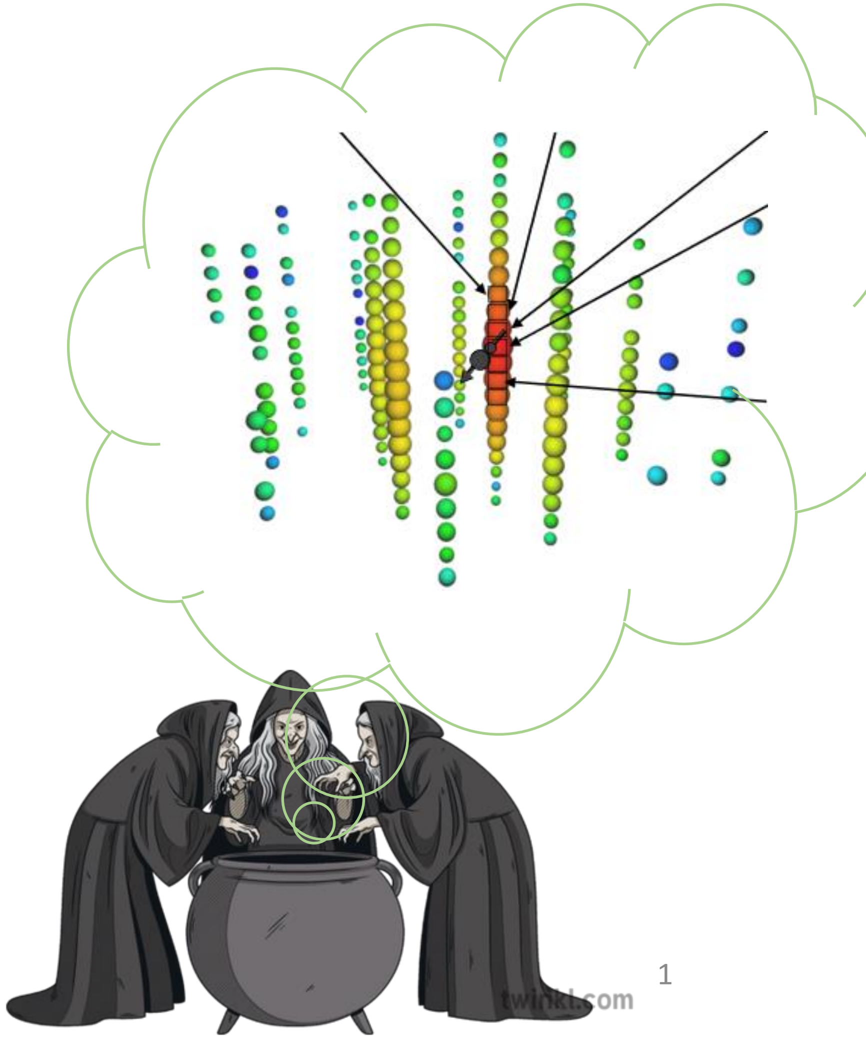
Double Double

Toil and trouble...



Background

- Tau-neutrinos are expected to be produced only at tiny fractions in cosmological neutrino sources

- But neutrino-oscillations give rise to a neutrino-flux close to equipartition on Earth

- Since tau-neutrino production above ~ 100 TeV from rare decays of charmed hadrons make up only ~5%, the observation of high-energy nu-taus can be a smoking gun of cosmic neutrinos

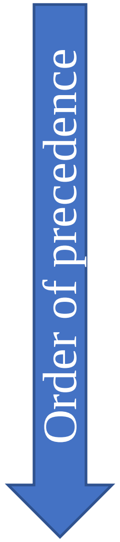
Data selection and reconstruction

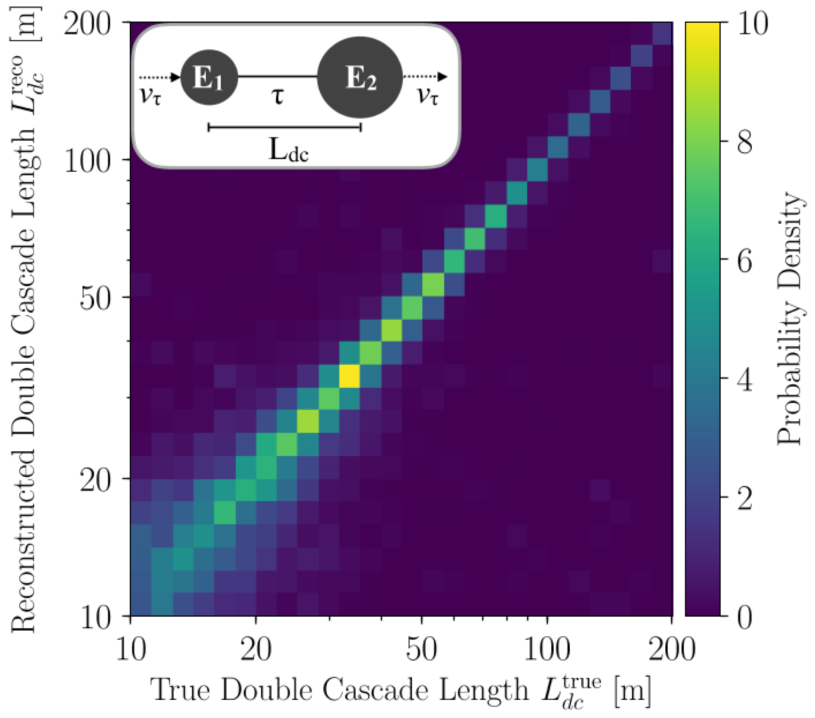
- Data collected between 2010 and 2017 (total livetime 2635 days)
    - New callibration ("pass2") - link
    - Improved ice sheet optical properties model
    - Updated calculation of atmospheric nu self-veto
    - 60 events with Etot > 60 TeV
- All events reconstructed with single cascade, track and double cascade hypothesis
- 9 parameters for double cascade fit:
    - First cascade vertex (4) + direction (2)
    - Energies of first and second cascade
    - Double cascade (separation) length

Double bang classification

- Five criteria:
  1. Total energy
  2. Preselection cuts & fit likelihoods
  3. Double cascade length
  4. Energy confinement
  5. Energy asymmetry

Observable	Requirement for double cascade	Classification if requirement failed
E_{tot}	≥ 60 TeV	Classification not applicable
Preselection	passed	Depending on fit likelihoods
L_{dc}	≥ 10 m	Single cascade
E_C	≥ 0.99	Track
A_E	$\in [-0.98, 0.30]$	Single cascade





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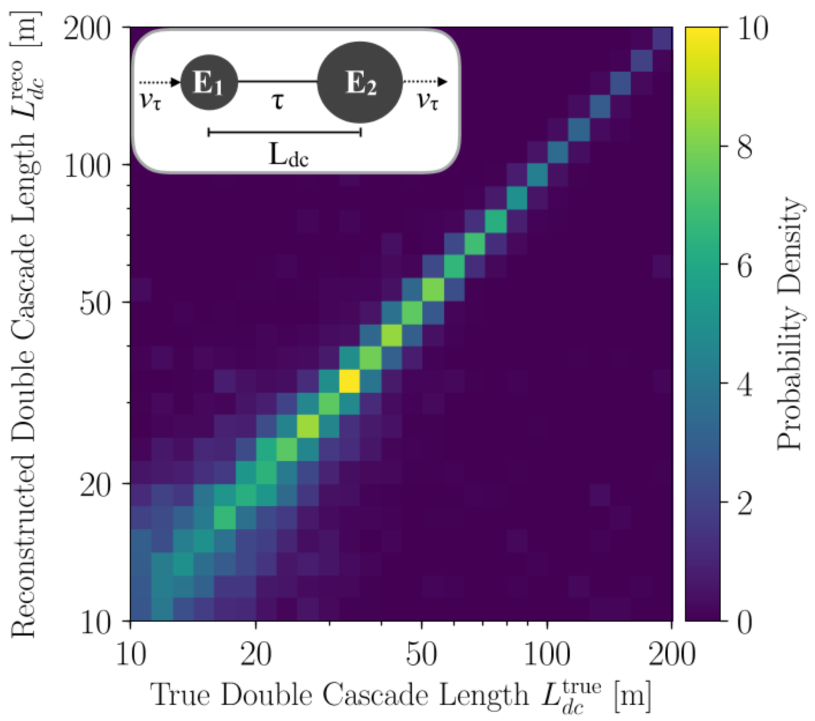
Order of precedence

i. Both cascades > 1TeV
ii. Both cascades within < 50 m radius outside of instrumented volume
iii. Maximum opening angle of 30 deg between best single cascade fit directions and double cascade fit



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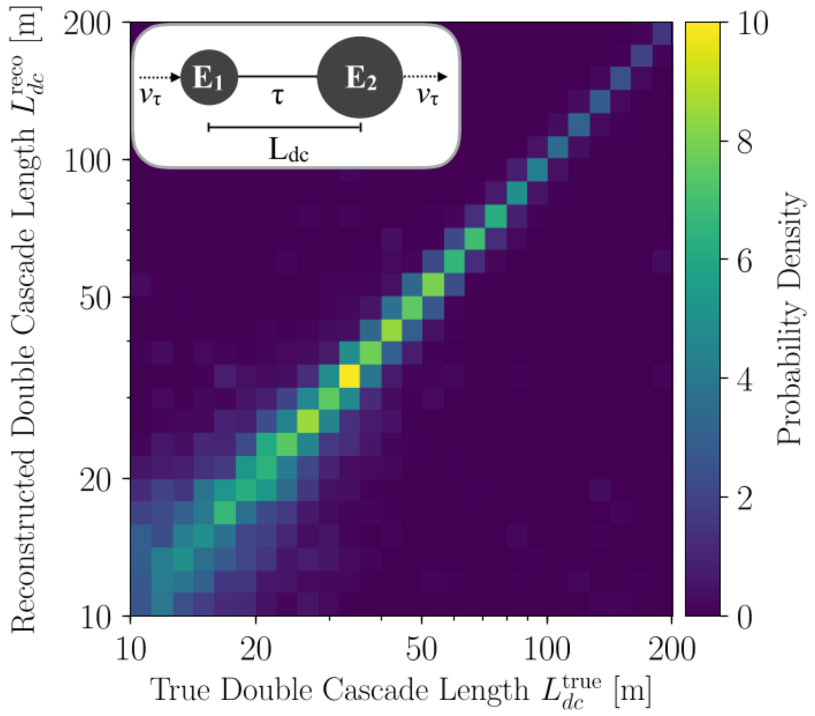


$$E_C = (E_{C1} + E_{C2})/E_{tot} \qquad A_E = (E_1 - E_2)/(E_1 + E_2)$$

Energies obtained from *track-like energy unfolding* within 40 m of the i-th cascade ?

Analysis

- Simple power law assumption for astrophysical neutrino flux

$$\frac{\mathrm{d}\Phi_{\nu_\alpha}}{\mathrm{d}E} = \phi_{\nu_\alpha} \cdot \left(\frac{E}{E_0}\right)^{\gamma_{\mathrm{astro}}}$$

- Multi-component maximum likelihood using PDFs obtained from Monte Carlo

  - Uncertainties due to limited MC-statistics accounted for using effective likelihood (see this paper)

- Individual flavour fractions are fitted as well

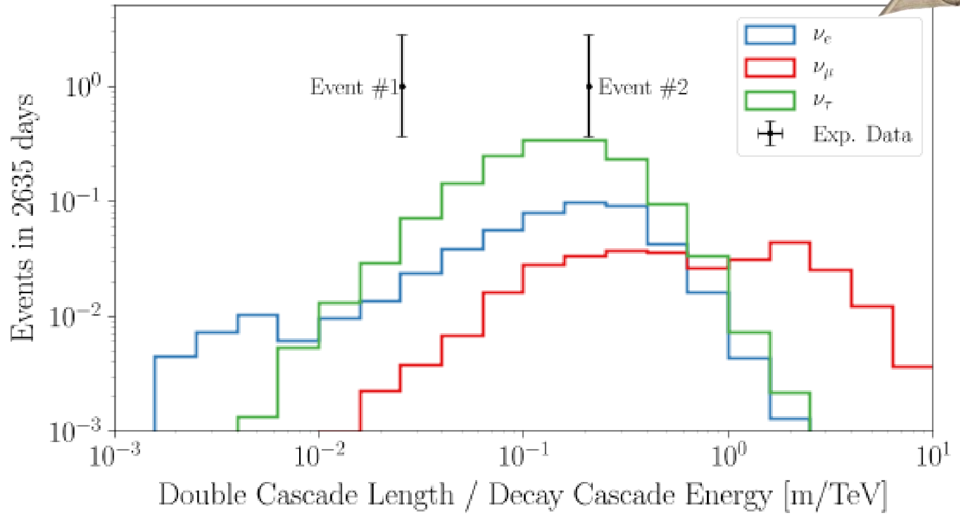
$$f_\alpha = \phi_{\nu_\alpha}/\phi_{6\nu} \qquad f_e + f_\mu + f_\tau = 1$$

- Main background from astrophysical nue and numu

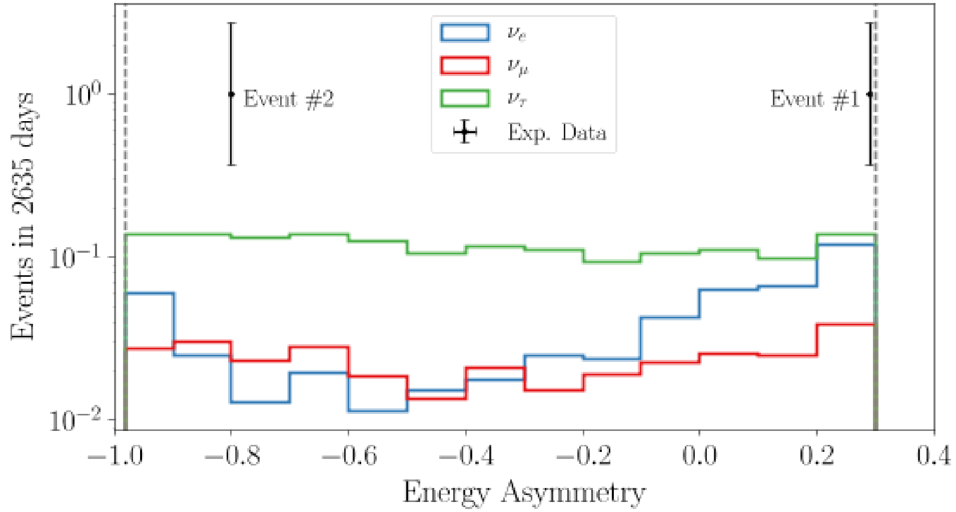
Tau neutrino interaction candidates

- 41 single cascades, 17 tracks and **2 double cascades**

	Event #1	Event #2
Year	2012	2014
Energy of 1st cascade	1.2 PeV	9 TeV
Energy of 2nd cascade	0.6 PeV	80 TeV
Energy Asymmetry	0.29	-0.80
Length	16 m	17 m

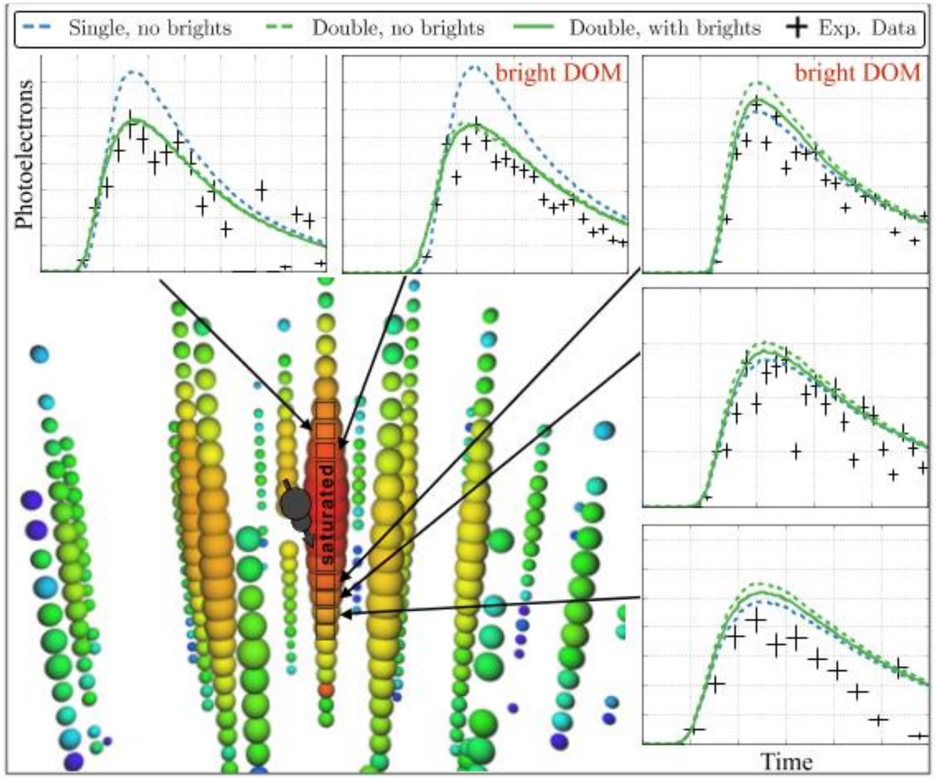


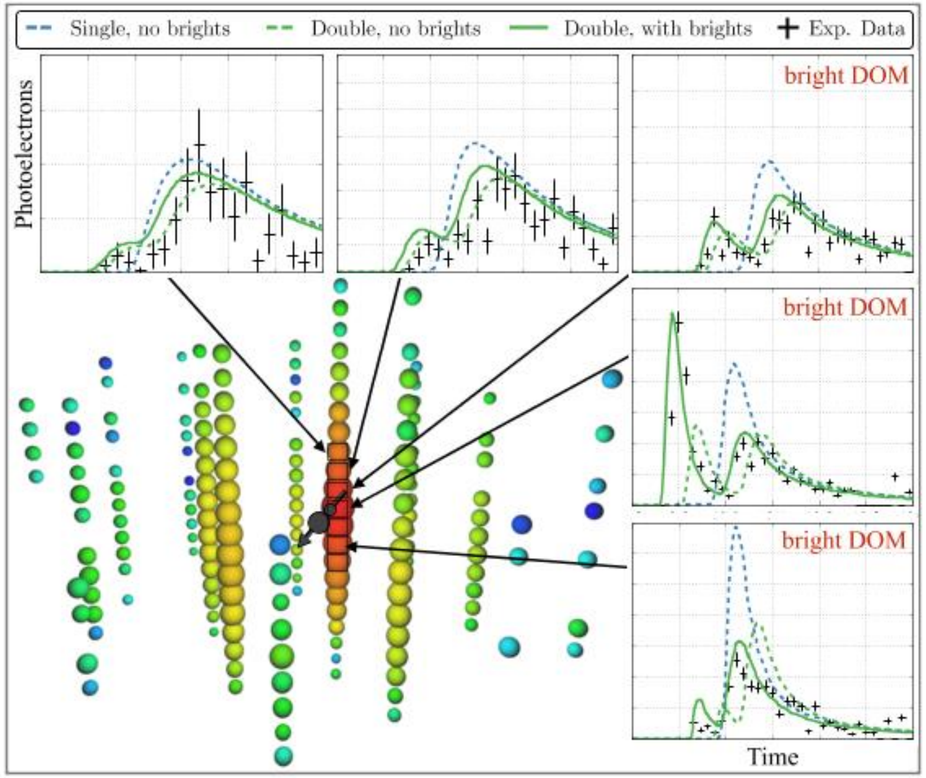
- Event 1 ("Big Bird"):
  - Length-to-energy ratio dominated by nutau contribution
  - Though outside 90% of simulated nutau double bangs
  - High E-asymmetry in region with high background expect.

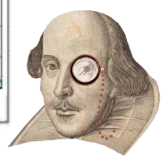


- Event 2 ("Double double"):
  - Length-to-energy ratio around nutau-distribution peak
  - Energy asymmetry in signal-dominated region

Candidate event topologies







- Two cascade vertices (dark grey dots) not spatially resolvable by eye
- **Bright DOMs** (10x more light than average) excluded from analysis
- Significant difference between predicted photon counts for **single** and **double** cascade for event #2

A posteriory analysis

- Targeted MC simulation conducted for both candidates
  - 20 mljn passed "Double Double" events
  - 1 mljn passed "Big Bird" events

Variable	Event #1	Event #2
Primary Energy	> 1.5 PeV	> 65 TeV
Visible Energy	1 - 3 PeV	60 - 300 TeV
Vertex, $r - r_{\text{evt}}$	50 m	50 m
Vertex, $z - z_{\text{evt}}$	± 25 m	± 25 m
Azimuth $\phi - \phi_{\text{evt}}$	$\pm 110(40)^\circ$	$\pm 110^\circ$
Zenith $\theta - \theta_{\text{evt}}$	$\pm 35(17)^\circ$	$\pm 35^\circ$

- Define **"tauness"** as Bayesian posterior prob. for each event originating from a nutau-ineraction
  - 97.5% tauness for "Double Double"
  - 76% tauness for "Big Bird"

$$P(\nu_\tau \mid \vec{\eta}_{\text{evt}}) \approx \frac{N_{\nu_\tau} P_{\nu_\tau}(\vec{\eta}_{\text{evt}})}{N_{\nu_\tau} P_{\nu_\tau}(\vec{\eta}_{\text{evt}}) + N_{\nu_{\not\tau}} P_{\nu_{\not\tau}}(\vec{\eta}_{\text{evt}})} \equiv P_\tau$$

Assuming previously best fit spectra from this study

Estimated from targeted sim. sets using KDE

- Total astrophysical neutrino flux measured at:

$$\frac{d\Phi_{6\nu}}{dE} = 7.4^{+2.4}_{-2.1} \cdot \left(\frac{E}{100\ \text{TeV}}\right)^{-2.87[-0.20,+0.21]} \cdot 10^{-18} \cdot \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1},$$

(in agreement within errors with the study in the link)

- Of which tau-neutrino:

$$\frac{d\Phi_{\nu_\tau}}{dE} = 3.0^{+2.2}_{-1.8} \left(\frac{E}{100\ \text{TeV}}\right)^{-2.87[-0.20,+0.21]} \cdot 10^{-18} \cdot \text{GeV}^{-1}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{sr}^{-1},$$

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  $P(\nu_\tau \mid \vec{\eta}_e$

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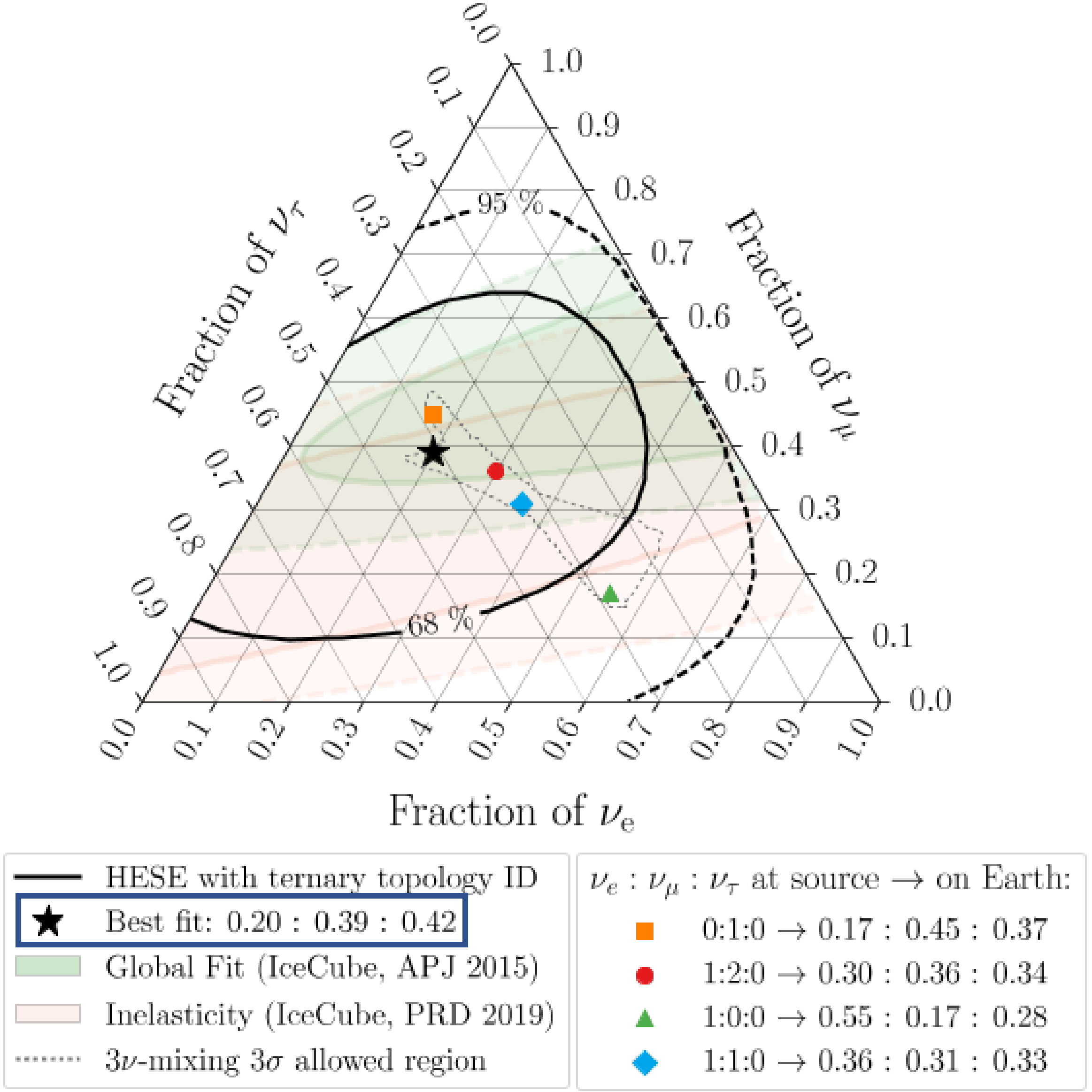

+ Measurement of fitted flavour composition!

Take-home messages

- First two double cascades found, indicative of nu-tau interactions, with expectation of
  - First event ("Big Bird") compatible with single cascade from nu-e at 25% level
  - Second event ("Double Double") ~80 times more likely to be nu-tau than nu-e/mu
- Resultant flavour composition of IceCube HESE events measured at:
  - (nu-e : nu-mu : nu-tau) = (0.20 : 0.39 : 0.42) → First time non-zero in all components!
- First non-zero measurement of the astrophysical nu-tau flux:
  - $$\frac{\mathrm{d}\Phi_{\nu_\tau}}{\mathrm{d}E} = 3.0^{+2.2}_{-1.8} \left(\frac{E}{100\ \mathrm{TeV}}\right)^{-2.87[-0.20,+0.21]} \cdot 10^{-18} \cdot \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1},$$
  - Zero nu-tau flux disfavoured at 2.8 sigma

EXTRA

Systematic uncertainties

Parameter	Prior (constraint)	Range	Description
Astrophysical neutrino flux:			
$\Phi_{\mathtt{astro}}$	-	$[0, \infty)$	Normalization scale
$\gamma_{\mathtt{astro}}$	-	$(-\infty, \infty)$	Spectral index
Atmospheric neutrino flux:			
$\Phi_{\mathtt{conv}}$	1.0 ± 0.4	$[0, \infty)$	Conventional normalization scale
$\Phi_{\mathtt{prompt}}$	-	$[0, \infty)$	Prompt normalization scale
$R_{K/\pi}$	1.0 ± 0.1	$[0, \infty)$	Kaon-Pion ratio correction
$2\nu/\left(\nu+\bar{\nu}\right)_{\mathtt{atmo}}$	1.0 ± 0.1	$[0, 2]$	Neutrino-anti-neutrino ratio correction
Cosmic-ray flux:			
$\Delta\gamma_{\mathtt{CR}}$	0.0 ± 0.05	$(-\infty, \infty)$	Cosmic-ray spectral index modification
Φ_{μ}	1.0 ± 0.5	$[0, \infty)$	Muon normalization scale
Detector:			
$\epsilon_{\mathtt{DOM}}$	0.99 ± 0.1	$[0.80, 1.25]$	Absolute energy scale
$\epsilon_{\mathtt{head\text{-}on}}$	0.0 ± 0.5	$[-3.82, 2.18]$	DOM angular response
$a_{\mathtt{s}}$	1.0 ± 0.2	$[0.0, 2.0]$	Ice anisotropy scale

The main systematic uncertainty affecting the double cascade reconstruction is the anisotropy of the light propagation in the ice [33]. The directional dependence of the photon propagation can cause distortions in the Cherenkov light patterns, leading to an increased misclassification of single cascades as double cascades.