IceCube Starting Events For Diffuse Astrophysical Neutrino Measurements

On IceCube Events With Contained Vertices

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for the IceCube collaboration

TeVPA 2023

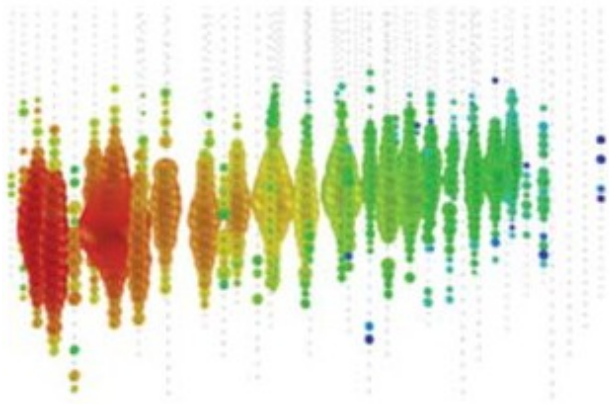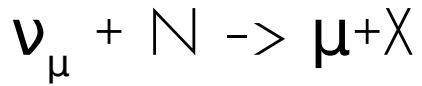# The IceCube Neutrino Observatory

- Located at the South Pole
- Detects Cherenkov light from the interaction of neutrinos in the ice shelf
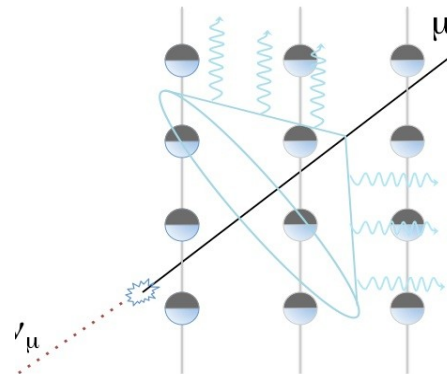
Neutrino Event Signatures in IceCube
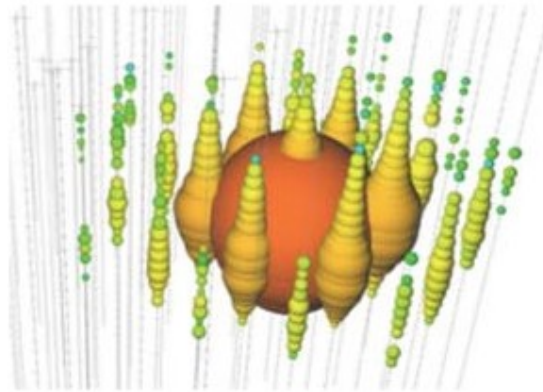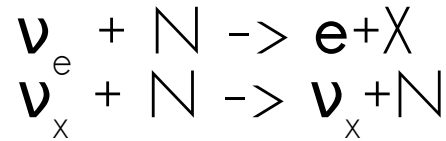

Track-like event

$$\nu_\mu + N \to \mu + X$$

Angular resolution $\leq 1°$
Energy resolution ~ 29%

Shower-like (cascade) event

$$\nu_e + N \to e + X$$
$$\nu_x + N \to \nu_x + N$$

Angular resolution ~ 8°
Energy resolution ~ 15%
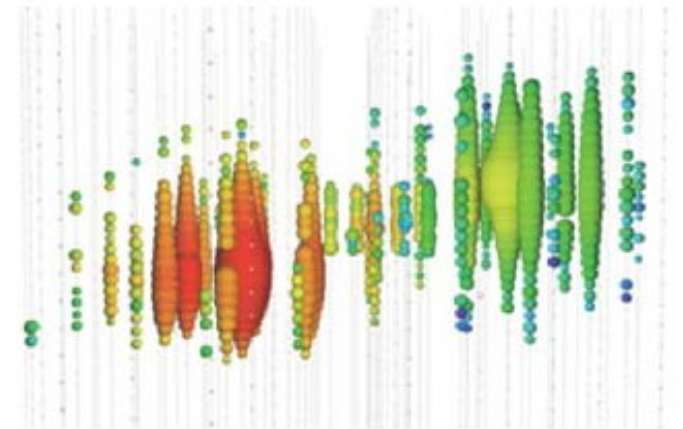
Double-bang (double cascade) event

$$\nu_\tau + N \to \tau + X$$
$$\tau \to X \text{ or } e$$
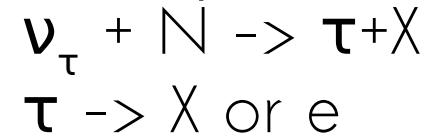
Decay length ~ 50 m E_τ/PeV

Length resolution ~ 2 m

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Background suppression
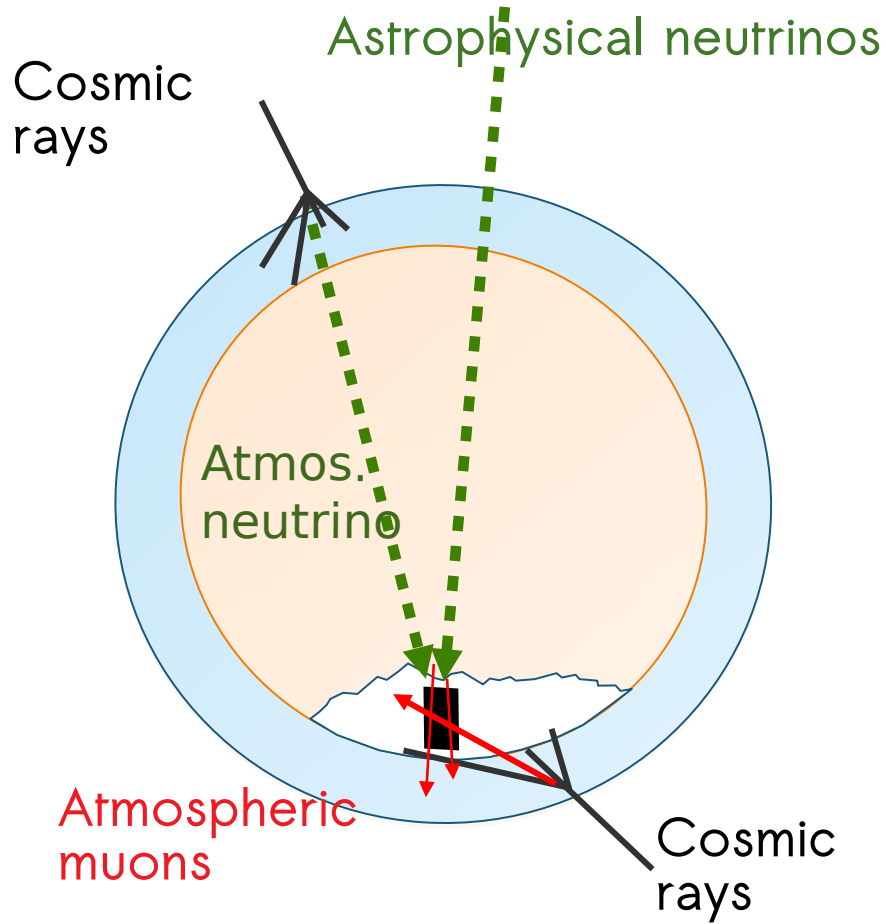
~ 3000 cosmic ray muons/sec
~1 atmospheric neutrino/4 min
~1 astrophysical neutrino/month

Southern hemisphere more challenging than the Northern hemisphere due to the muons

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Starting Events

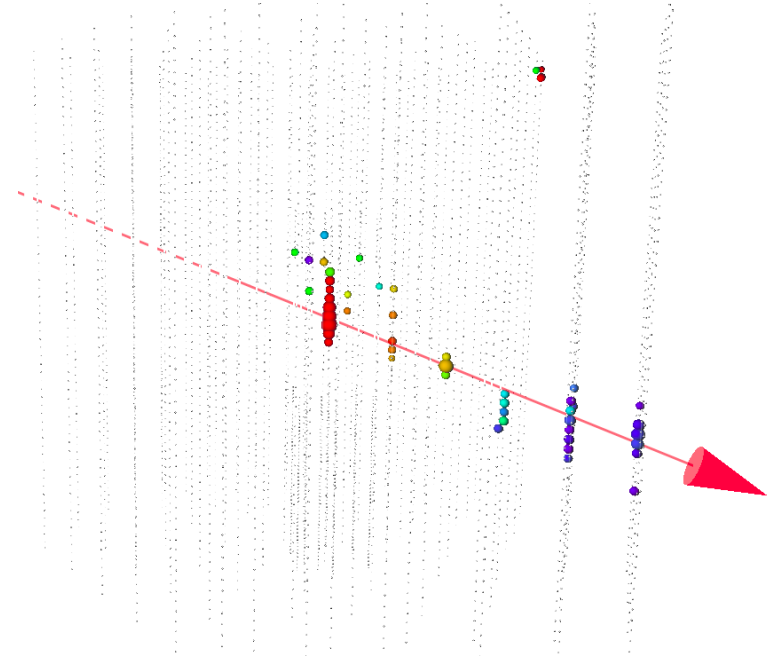Neutrino events with "contained vertices", starting inside the detector

Have a better energy resolution than throughgoing tracks due to the initial hadronic cascade

Can be distinguished from atmospheric muons

Selection strategies use an active veto layer to achieve this

Additional gain in the Southern hemisphere

Several event selections utilize starting events: HESE (High Energy Starting Events), MESE (Medium Energy Starting Events), ESTES (Enhanced Starting Tracks Event Selection)

An ESTES event of 11 TeV

Diffuse astrophysical flux measurements with IceCube
(with events with contained vertices)

HESE: Dataset to make the first ever measurement of the diffuse astrophysical flux using the highest energy starting events detected by IceCube

Northern sky   Southern sky
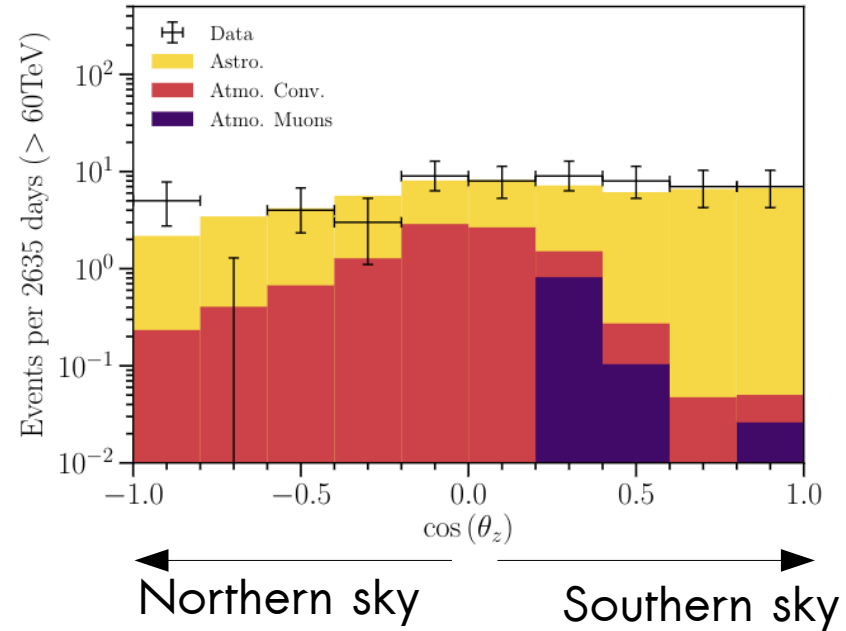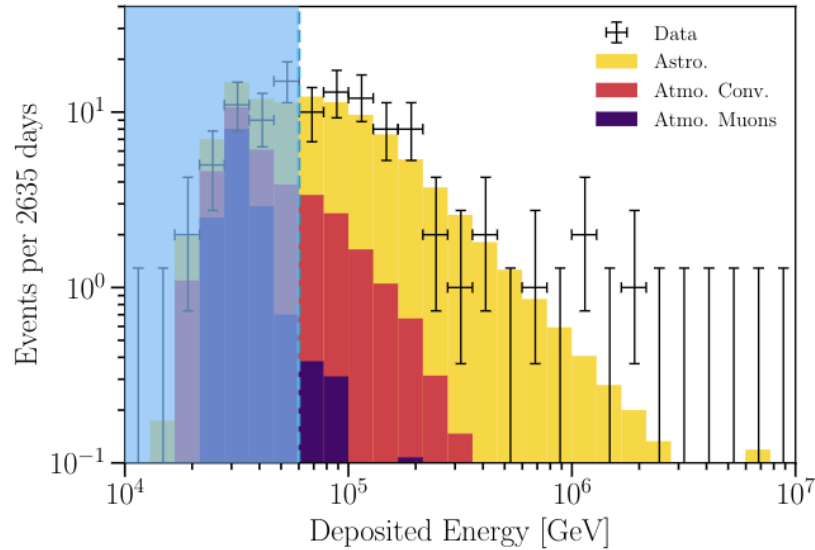
HESE 7.5 years measurement[*Phys. Rev. D 104, 022002 (2021)*] including both Northern and Southern sky events
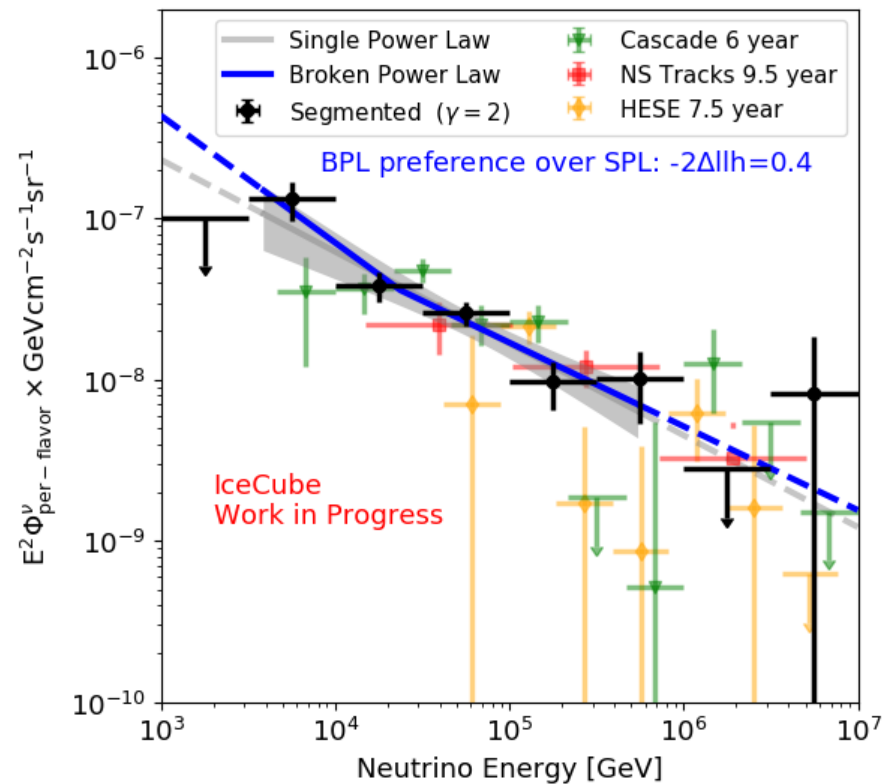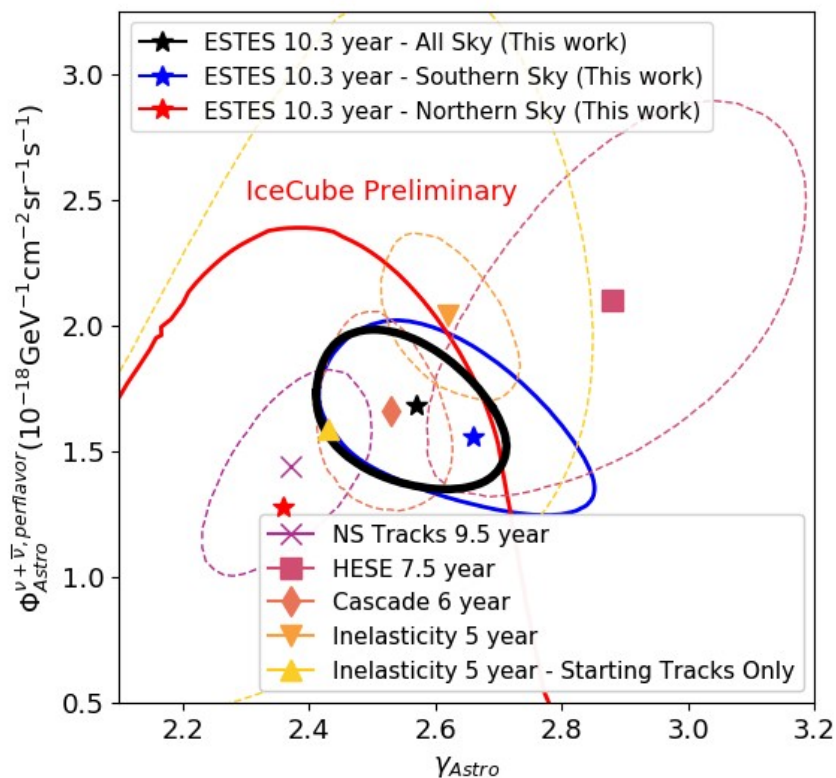
Diffuse astrophysical flux measurements with IceCube
(with events with contained vertices)

ESTES: New measurements above a TeV in energy using starting tracks!

~1365 events in the Southern hemisphere and ~10798 events in the Northern hemisphere

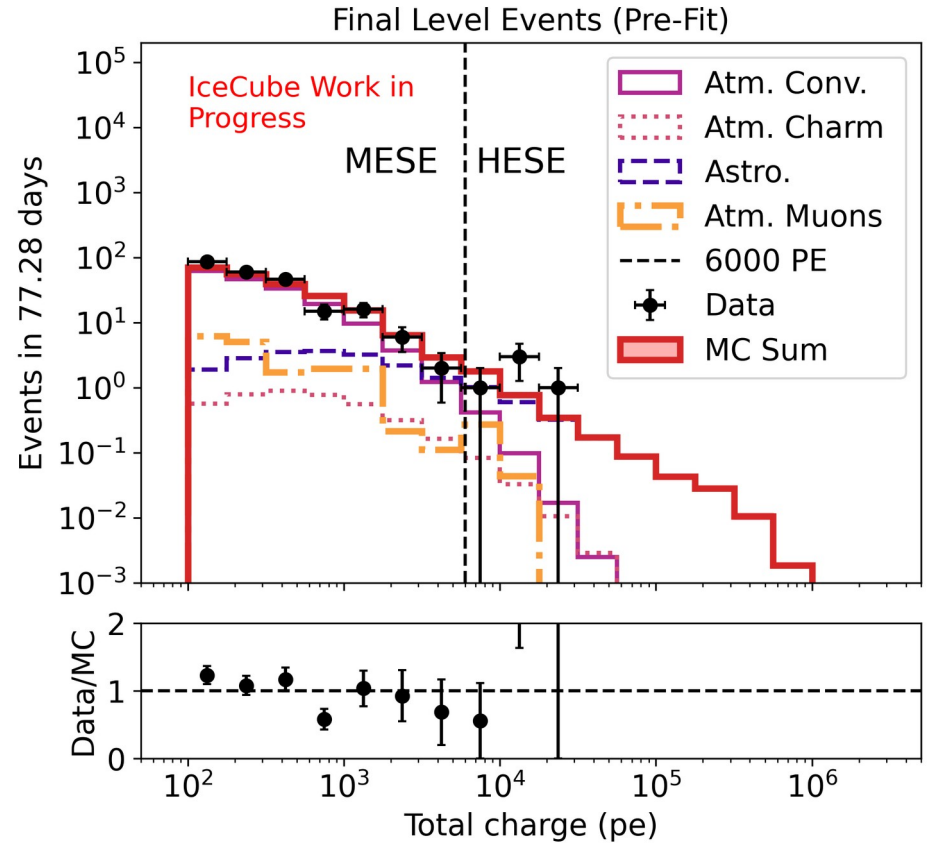A comparison of ESTES measurements with other IceCube results
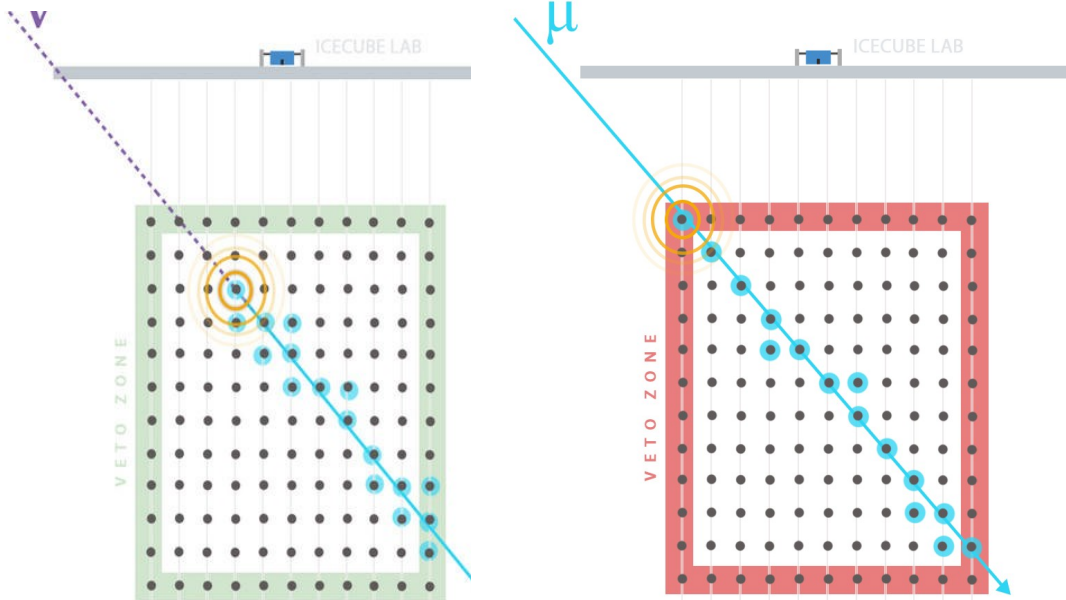[M. Silva, PoS(ICRC2023)1008]

[See talk by S. Mancina, M. Moulai]

Medium Energy Starting Events (MESE)

Uses a series of vetos for reducing the muon background
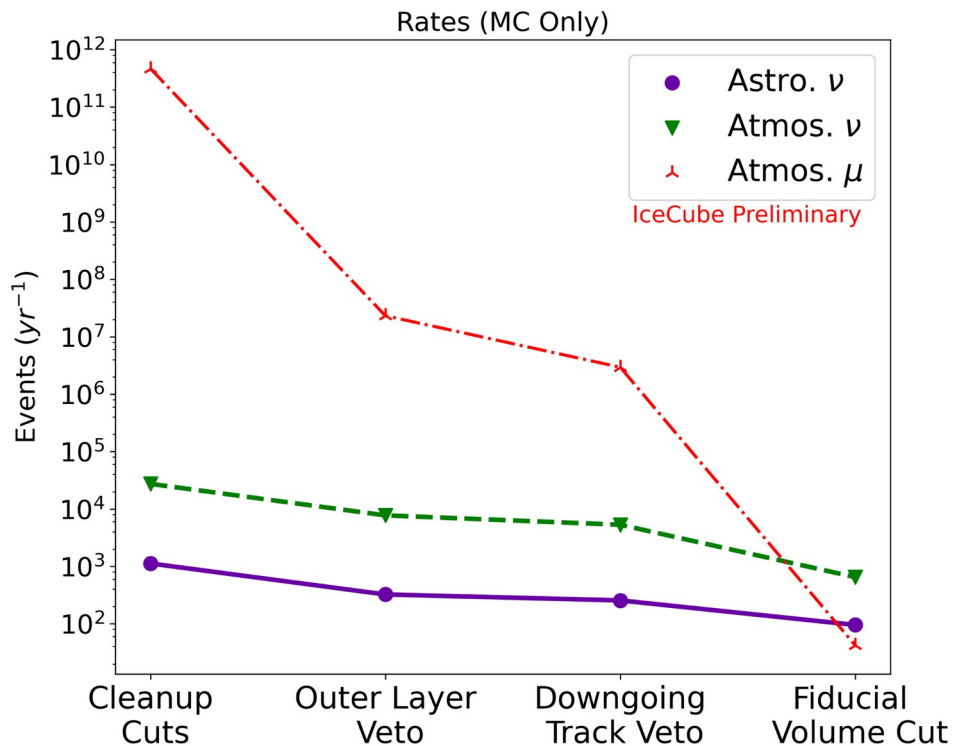
All flavours above 1 TeV included


*MESE is not a strict superset of HESE

MESE Expected Rates

Assuming an astro. flux of $2.06 \times E^{-2.46}$ (2-year MESE [Phys. Rev. D 91, 02200])
Atm. Flux model: GaisserH4a + Sibyll 2.3c

Rates (MC Only)

| Rates (yr^{-1})	Astro. ν	Atm. ν	Atm. μ
Cascades	80.2	321.1	24.3
Tracks	15.05	323.2	16.6
Total	95.25	644.3	40.9

MESE Pre-Fit Data/MC Comparison

Assuming an astro. flux of 2.06 x E$^{-2.46}$ (2-year MESE [Phys. Rev. D 91, 02200])
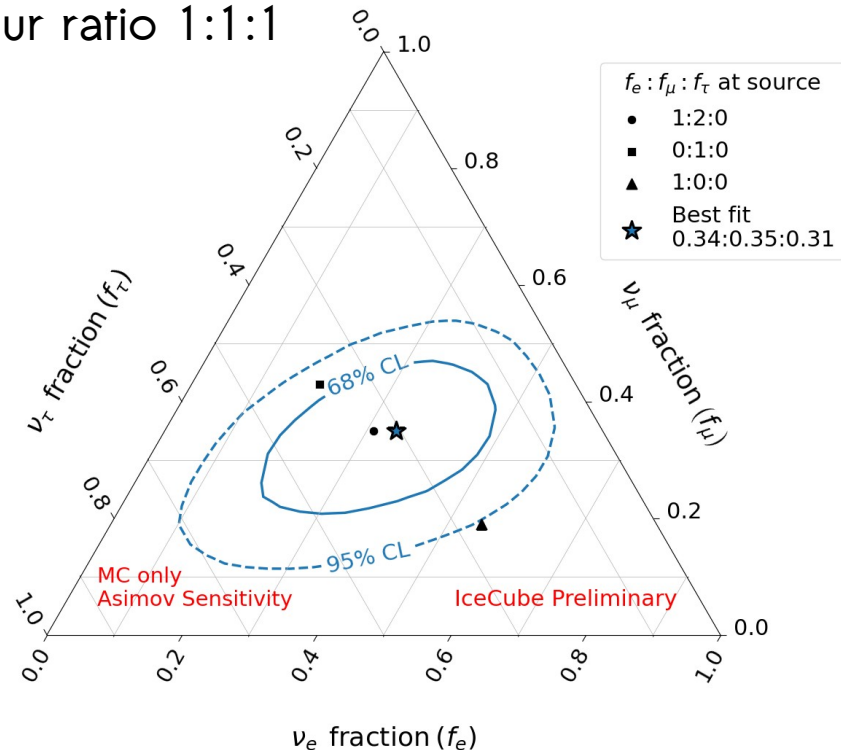Atm. Flux model: GaisserH4a + Sibyll 2.3c
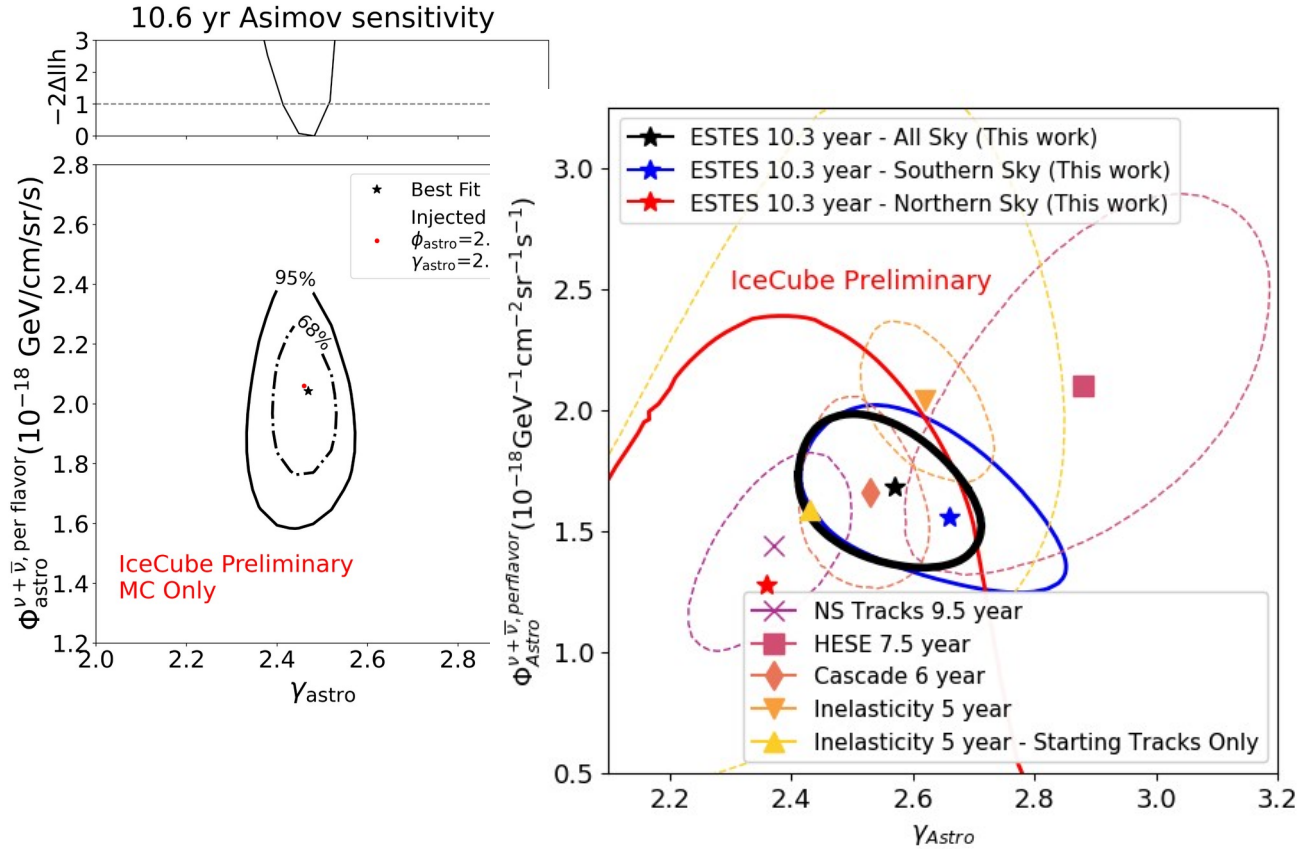Using burnsample data
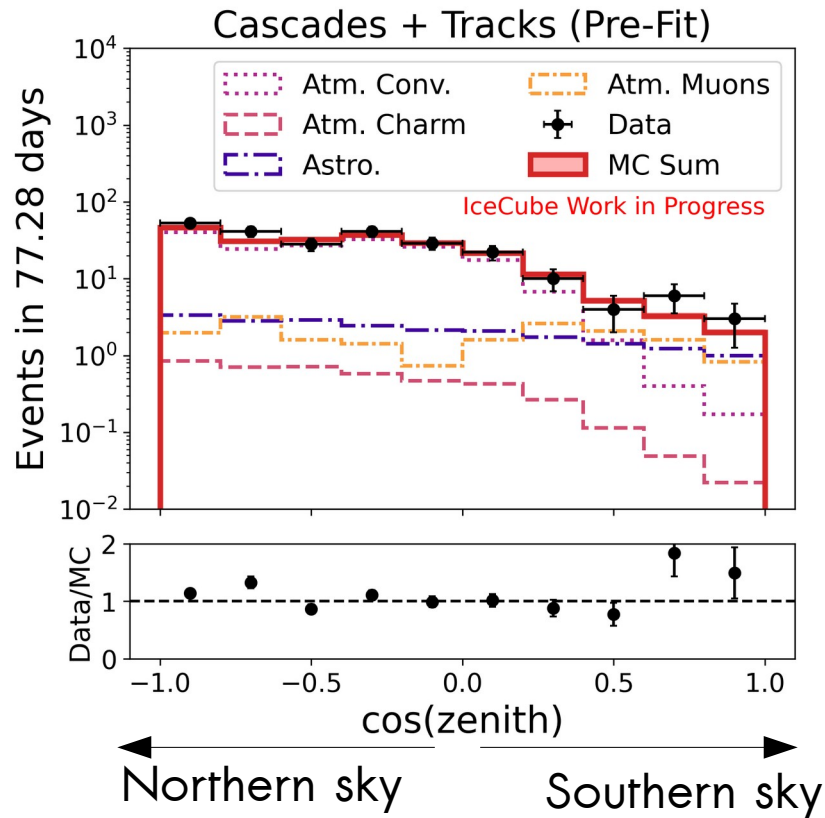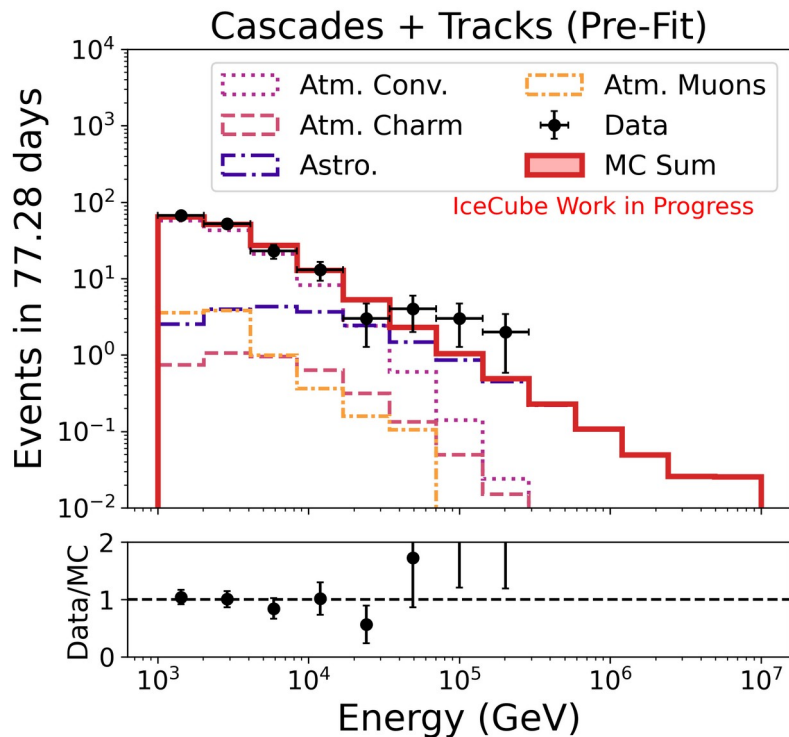
MESE Sensitivities

- Cascades and tracks classified using a DNN
- Likelihood based classification for double cacscade events with E> 30 TeV for 3-flavour measurement
- Snowstorm-based systematics method used [(M.G. Aartsen et al JCAP10 (2019) 048)]
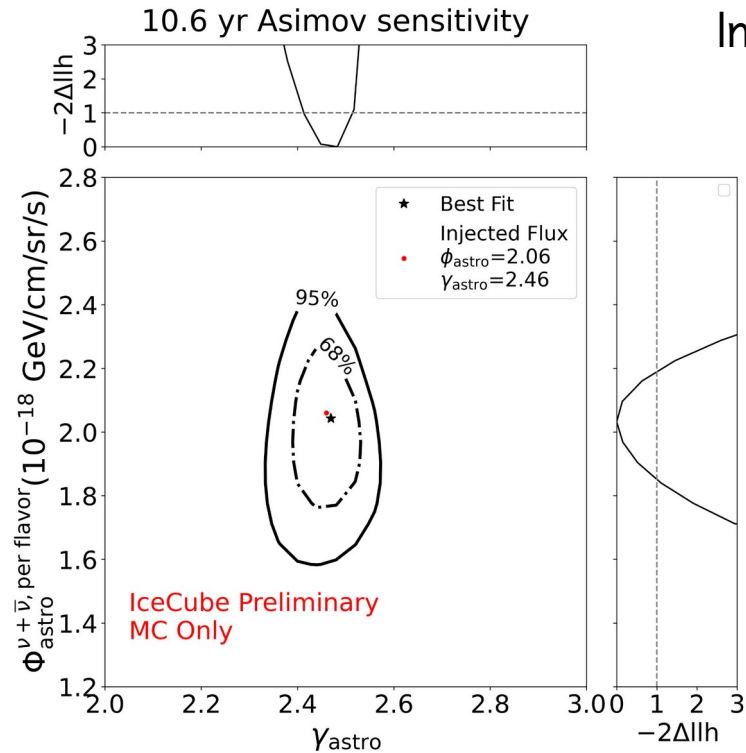
Diffuse Outlook

- IceCube has conducted independent measurements with cascades and tracks
- Since MESE contains both tracks and cascades it can test the consitency between various IceCube measurements!
- MESE: a miniature version of combined fit with various event selections
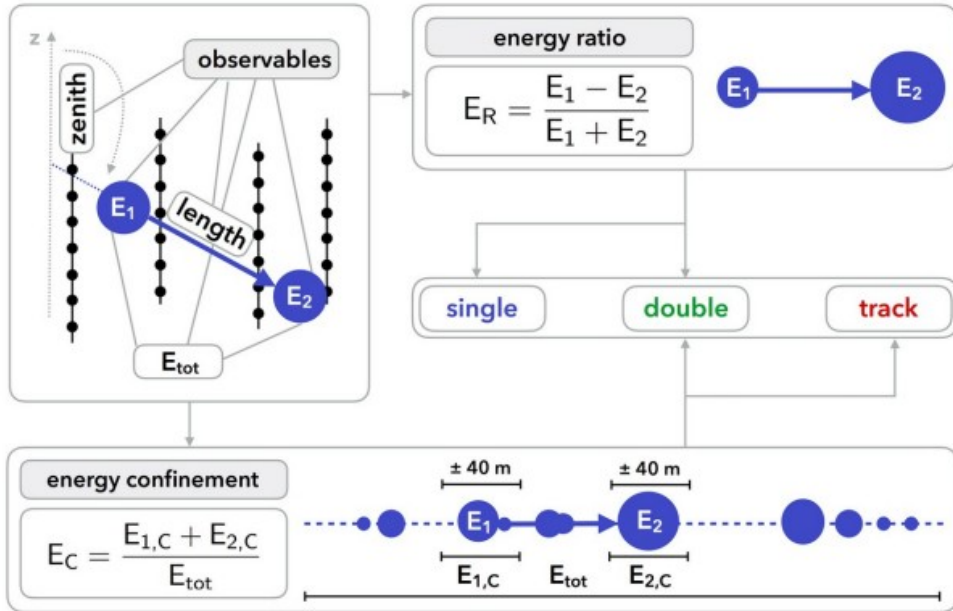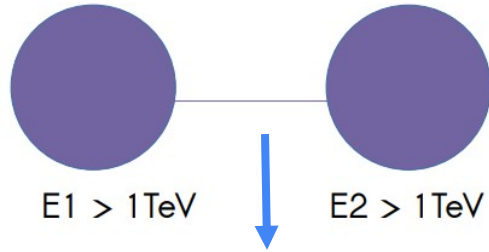- Diffuse Global Fit with IceCube in the works (See talk by N. Lad)

Summary

- Starting Events: a special class of events with contained neutrino vertex
- New unblinded measurements from starting tracks: ESTES
- Results consistent with other IceCube measurements
- Upcoming measurements using all types of starting events: MESE
- MESE and ESTES include measurements below 10 TeV, this is of interest in the multi messenger context in comparison with the Fermi GeV diffuse gamma ray flux.
- We are moving towards a global fit that combines all event selections for a combined measurement of the astrophysical flux and the astrophysical flavour ratio

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Backup

Tau neutrino tagging

E1 > 1TeV   E2 > 1TeV

observables

zenith

E_1 length E_2

E_{tot}

energy ratio

$$E_R = \frac{E_1 - E_2}{E_1 + E_2}$$

$E_1 \rightarrow E_2$

single   double   track

energy confinement

$$E_C = \frac{E_{1,C} + E_{2,C}}{E_{tot}}$$

± 40 m   ± 40 m

E_1 E_2

$E_{1,C}$ E_{tot} $E_{2,C}$

- Using Taupede: likelihood-based fitter for double cascades (DC), previously used in HESE (M. Usner DOI:10.18452/19458
  J. Stachurska DOI:10.18452/21611)

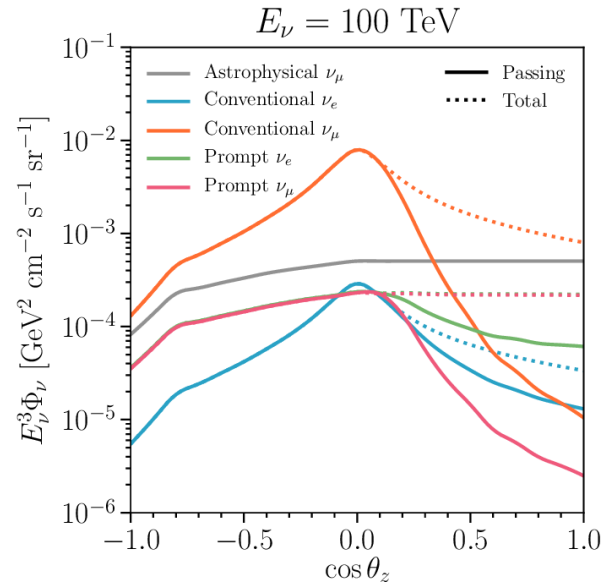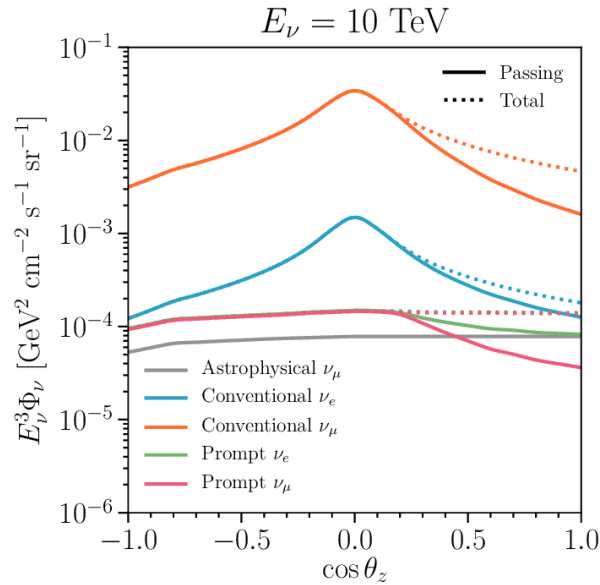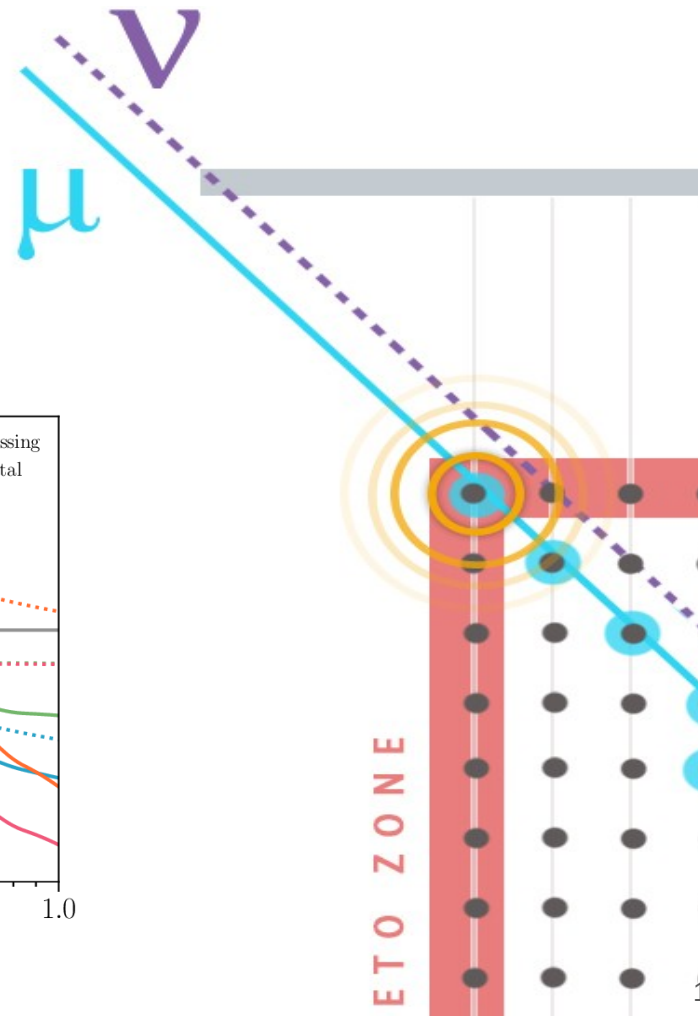- MESE has a DNN-based cascade/track classifier, we use only the DC selection with Taupede

(EC≥0.99)

ER ϵ (0.98,0.3)

(E_{tot}≥ 30TeV)
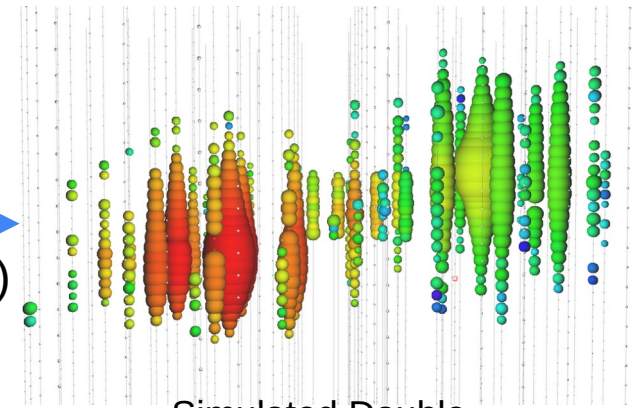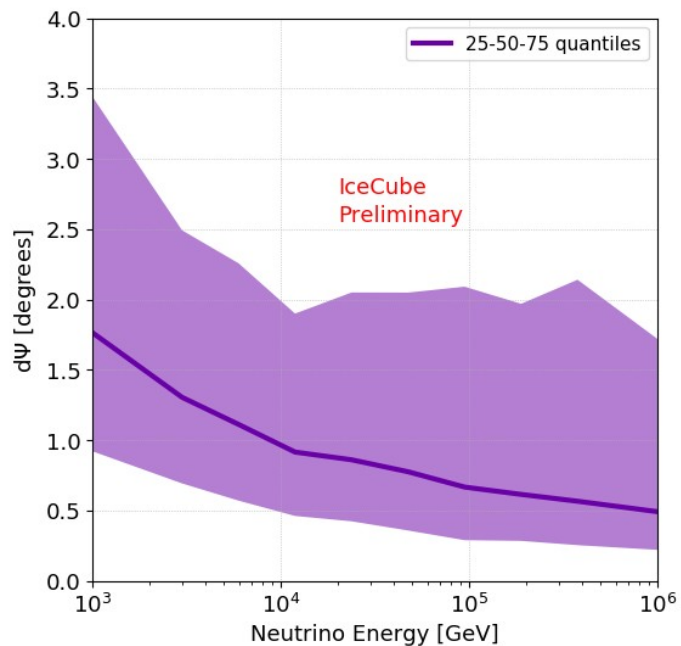

Simulated Double Cascade Event

Neutrino self-veto

- Neutrinos from CR showers often accompanied by muons.
- Vetoing these muons suppresses atm. neutrino background
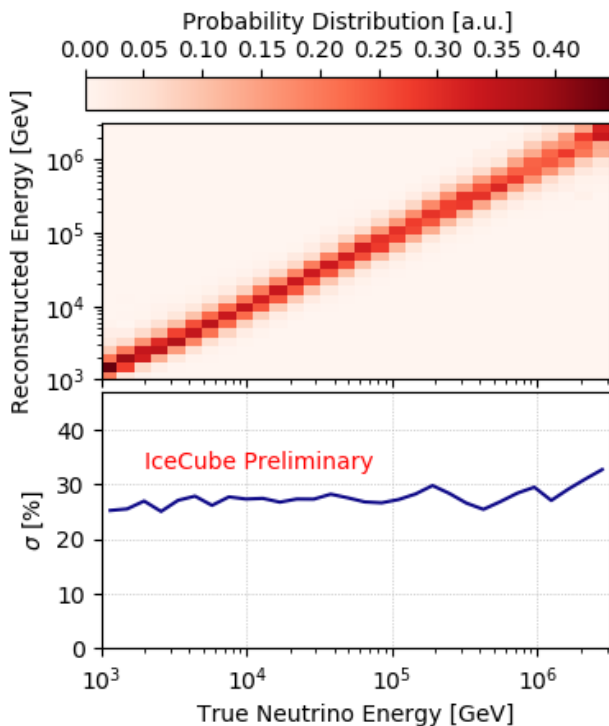- Accurate modeling of the self-veto suppression via muon bundle injection.

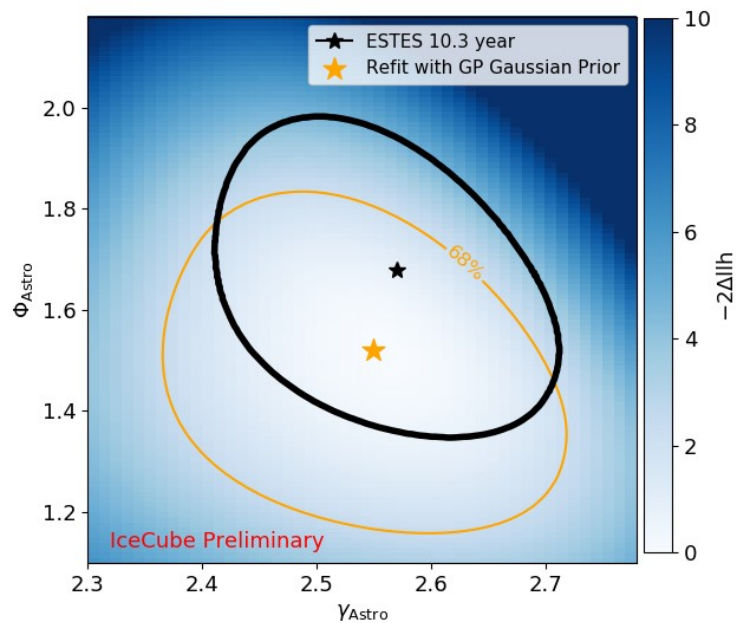Argüelles, Carlos A., et al.*Journal of Cosmology and Astroparticle Physics* 2018.07 (2018): 047.

ESTES Fit

Angular resolution

Energy resolution

ESTES diffuse fit compared to a fit including the Galactic Plan as an additional component

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