Characterization of the Diffuse Astrophysical Neutrino Spectrum with IceCube All-Flavor Starting Events

TeV Particle Astrophysics
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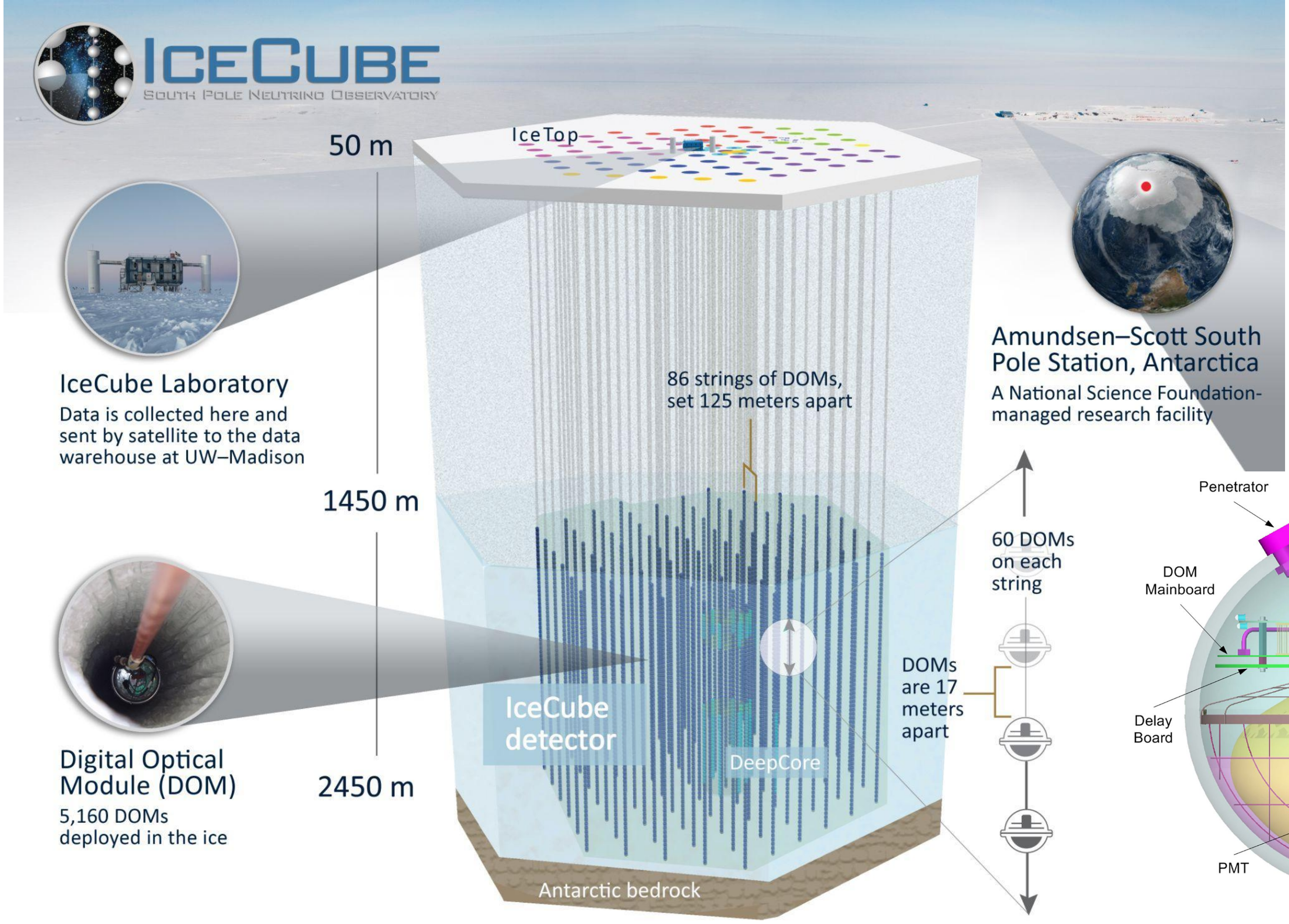
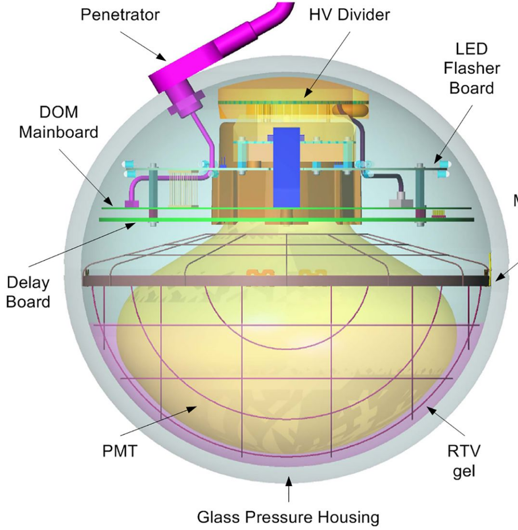
On behalf of the IceCube Collaboration

Outline

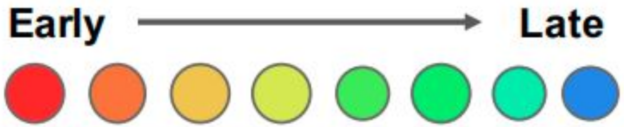
- **The Medium Energy Starting Event (MESE) event selection**
- Measurement of the Diffuse Astrophysical Neutrino Flux
- Measurement of the Astrophysical Neutrino Flavor Composition
- IC190331:The Highest Energy IceCube Event
- Summary



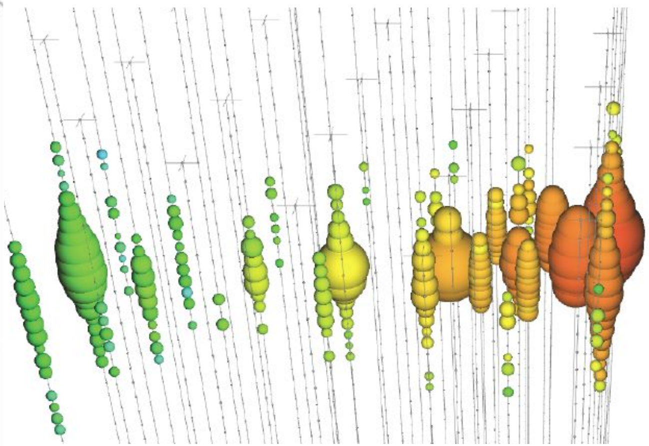
Digital **O**ptical **M**odule



IceCube Event Morphologies



Tracks

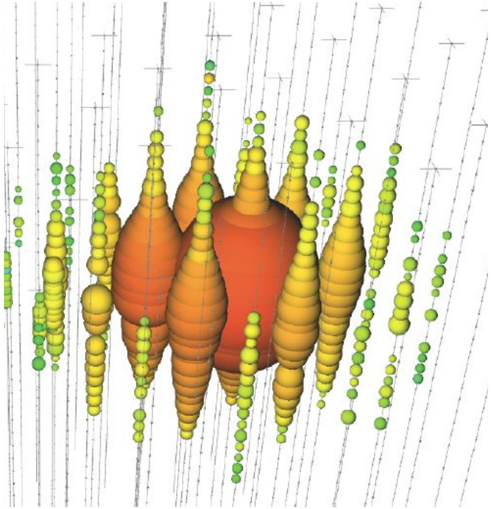


$\nu_\mu + \mathrm{X} \rightarrow \mu^- + \mathrm{Hadrons}$

$\mathrm{Energy\ Res.} : 0.3 \text{ in } \mathrm{Log}\frac{\mathrm{E}}{\mathrm{TeV}}$

$\mathrm{Angular\ Res.} : 0.3^\circ$

Cascades



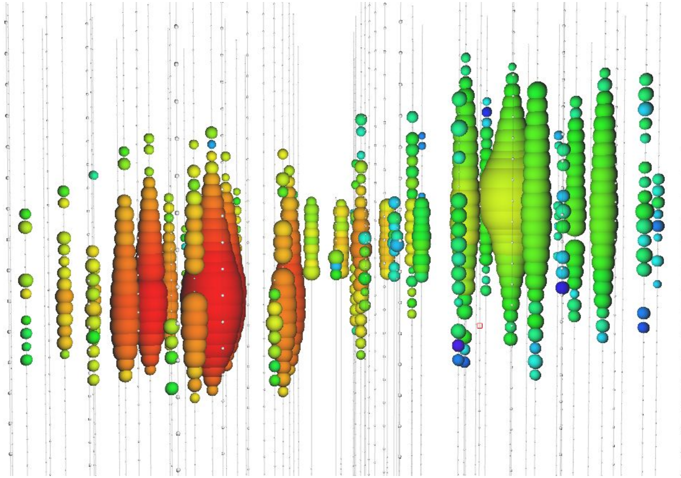
$\nu_e + \mathrm{X} \rightarrow e^- + \mathrm{Hadrons}$

$\nu_l + \mathrm{X} \rightarrow \nu_l + \mathrm{Hadrons}$

$\mathrm{Energy\ Res.} : 15\%@100\mathrm{TeV}$

$\mathrm{Angular\ Res.} : 4^\circ$

Double Cascades



$\nu_\tau + \mathrm{X} \rightarrow \tau^- + \mathrm{Hadrons}$

$\tau^- \rightarrow \nu_\tau + \ldots$

$\mathrm{Decay\ Length} : 50\mathrm{m/PeV}$

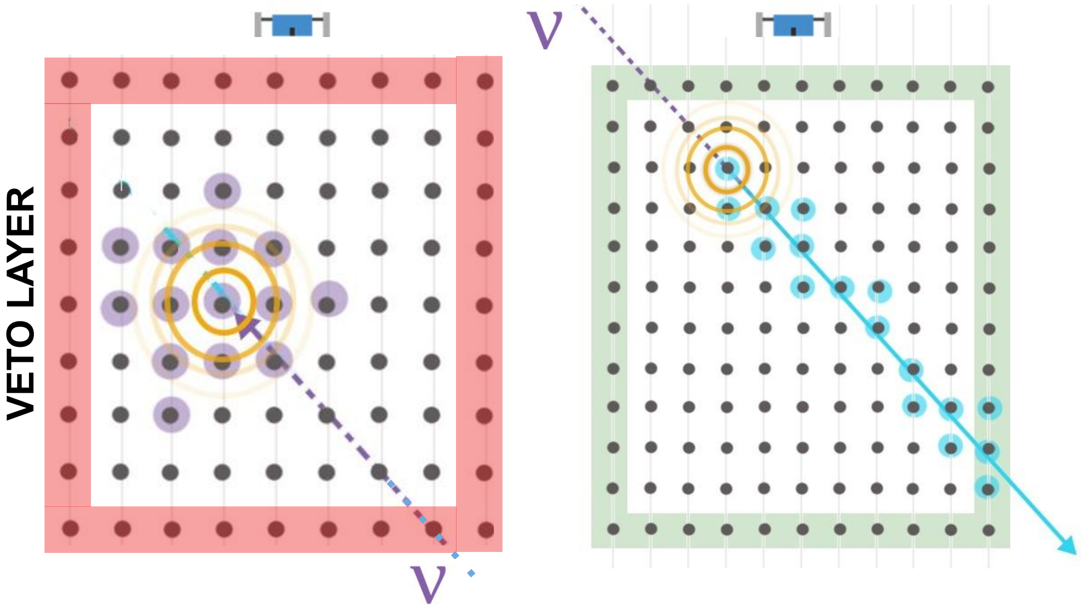
Ref.

IceCube Starting Events

- Identify neutrinos with interaction vertex contained within the detector (Starting Events)

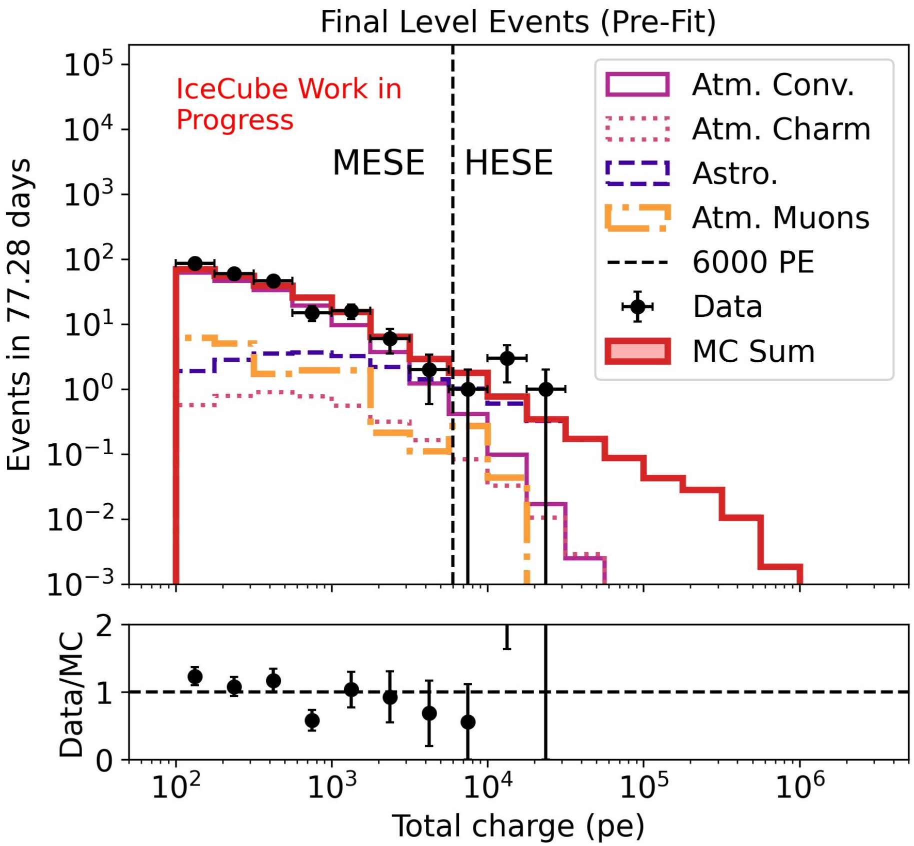
- Sensitive to all neutrino flavours with different event topologies, from the entire sky

- Published analyses using starting events include **HESE** (High Energy Starting Events) and **ESTES** (Enhanced Starting Track Event Selection)

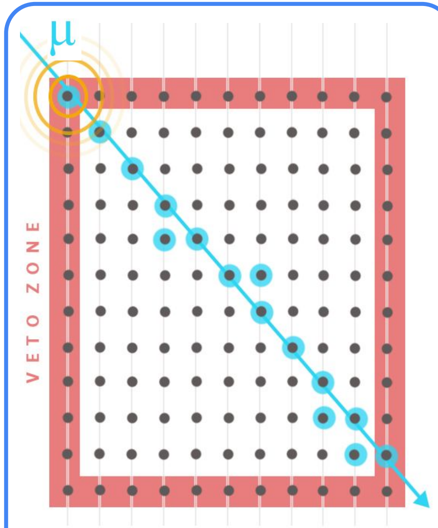


Medium Energy Starting Events (MESE)

- Extend HESE concept to lower energies, while retaining high signal purity, with additional veto steps
- Neutrinos of all flavors and the whole sky included in this dataset with events having energy > 1 TeV
- Use the dataset to measure astrophysical neutrino spectrum and astrophysical flavor ratio

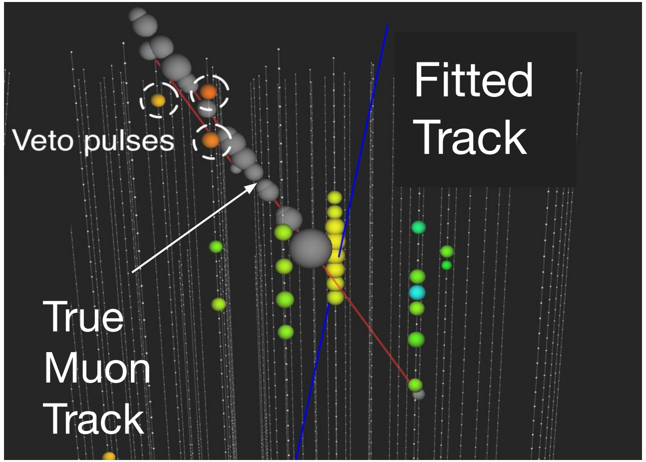


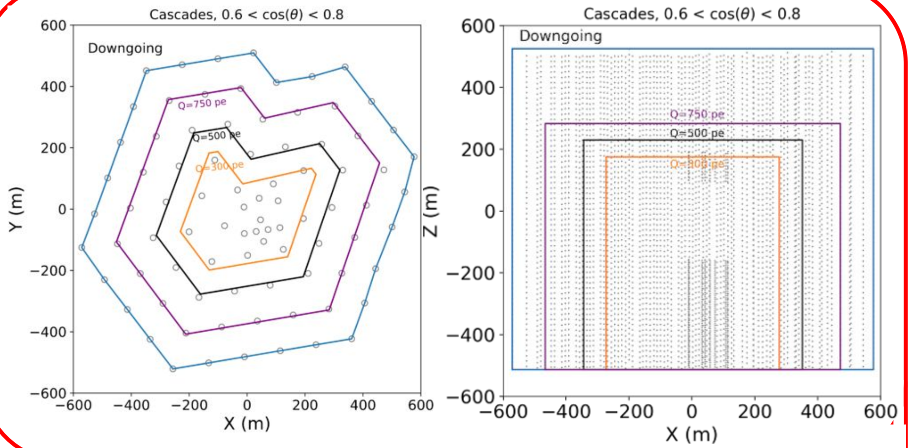
Event Selection



L3: **Outer Layer Veto**, reject atmospheric muons starting outside detector

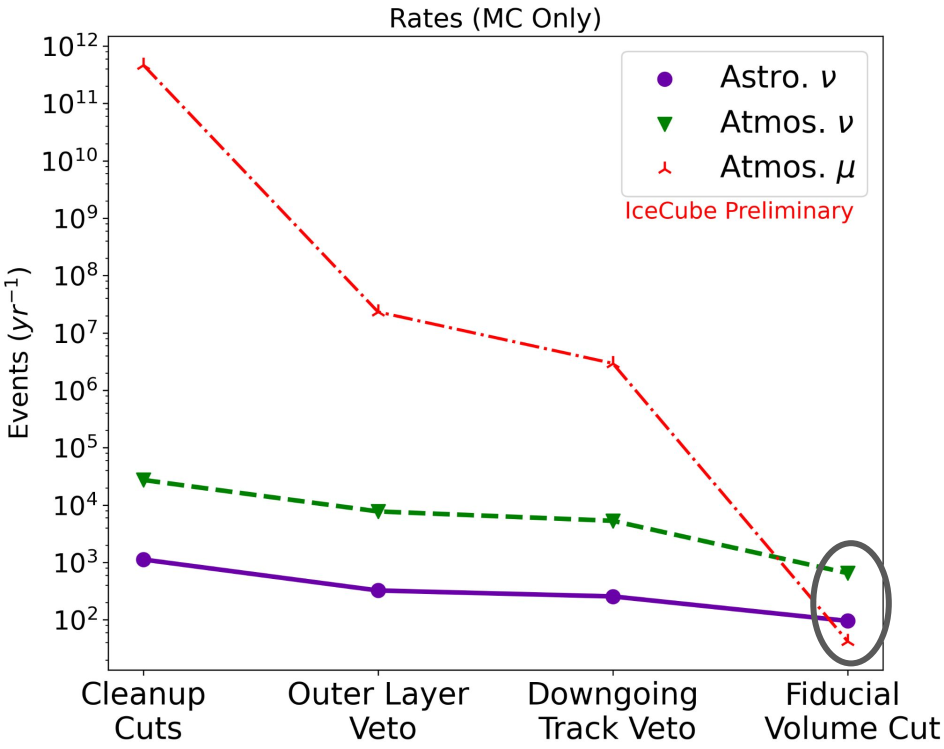
L4: **Downgoing Track Veto**, link isolated hits with muon hypotheses





L5: **Fiducial Volume Scaling** for dim events, veto hits closer to the reconstructed vertex.

Expected Rates



Astro Flux model: $\Phi_{astro,}$=2.06, γ_{astro}= 2.46 (from 2-year MESE analysis)

Atm. Flux model: GaisserH4a +SIBYLL 2.3

Rates (yr^{-1}) (MC)	Astro. ν	Atm. ν	Atm. μ
Total	95.3	644.3	40.9

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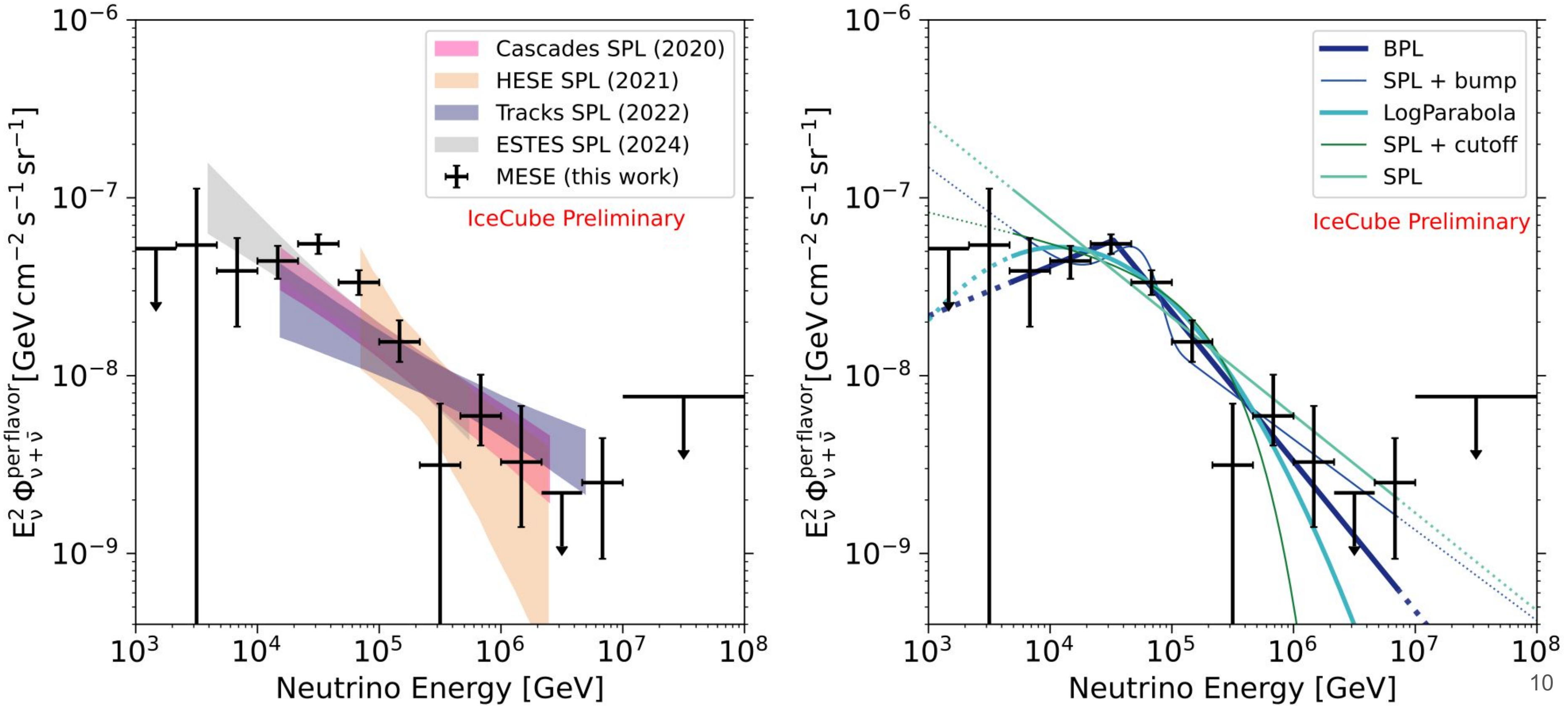
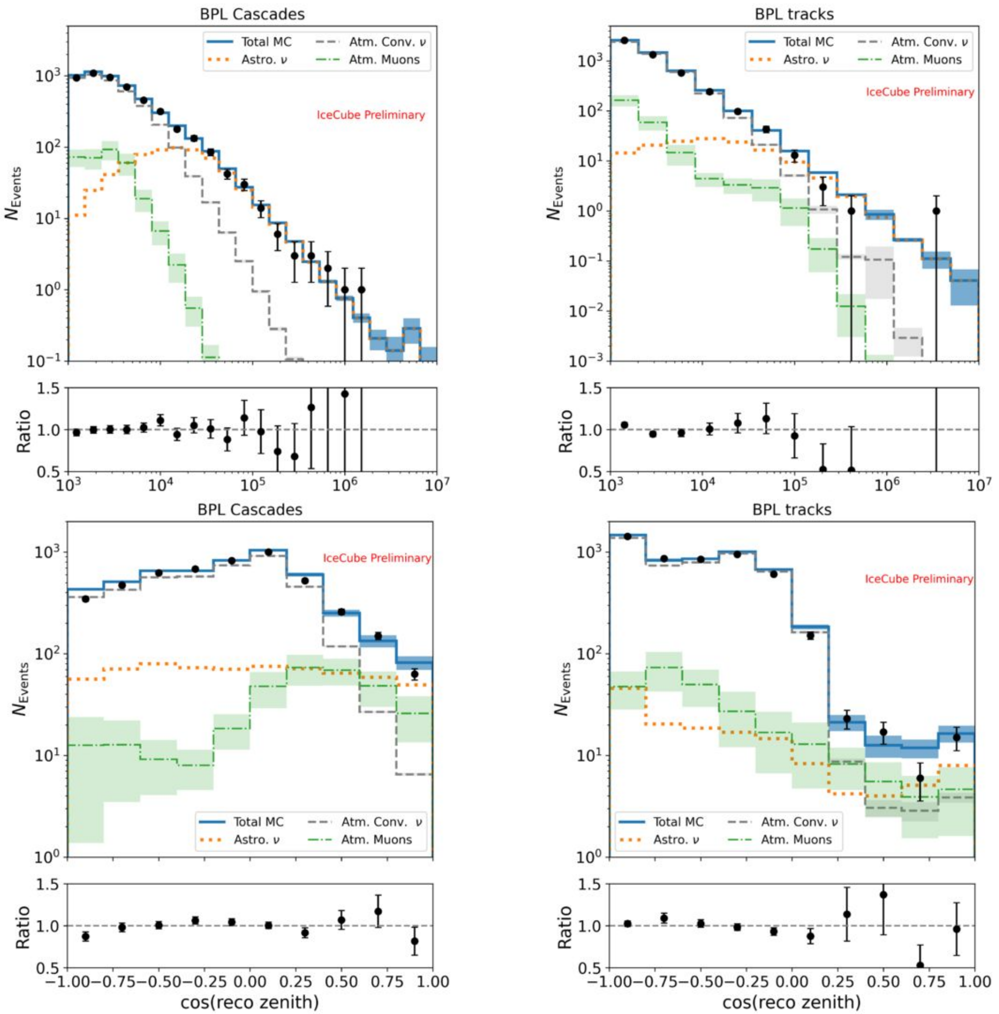
Observed neutrino spectrum

Best fit model: Broken Power Law, followed by SPL+ Bump and then LogParabola.
We reject SPL with respect to BPL with 4.7σ with MESE



Data-MC comparison

Event Counts (11.4 yr)	Expected	Data
Cascades	4947.7	4949
Tracks	4859.9	4908
Total	9807.6	9857



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Tau neutrino identification

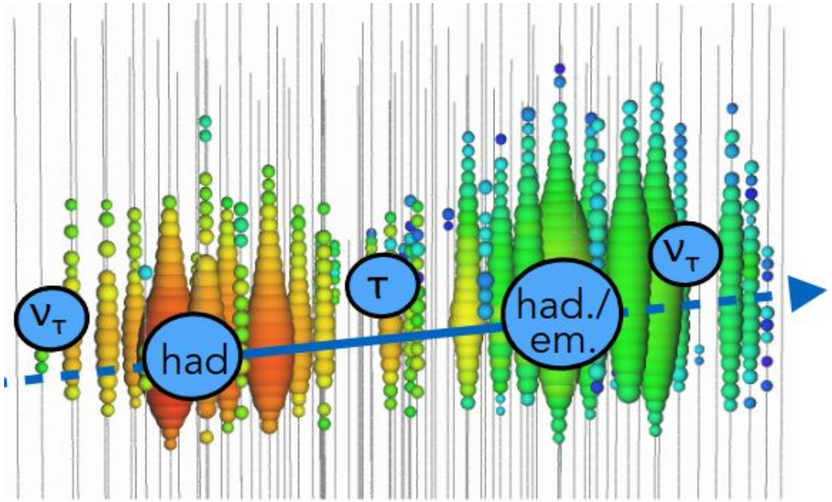
Selection strategy focused on double-cascade identification

- Perform likelihood-based reconstruction

- Additional cuts to select double cascades based on reconstructed energy in both cascades and their relative magnitudes

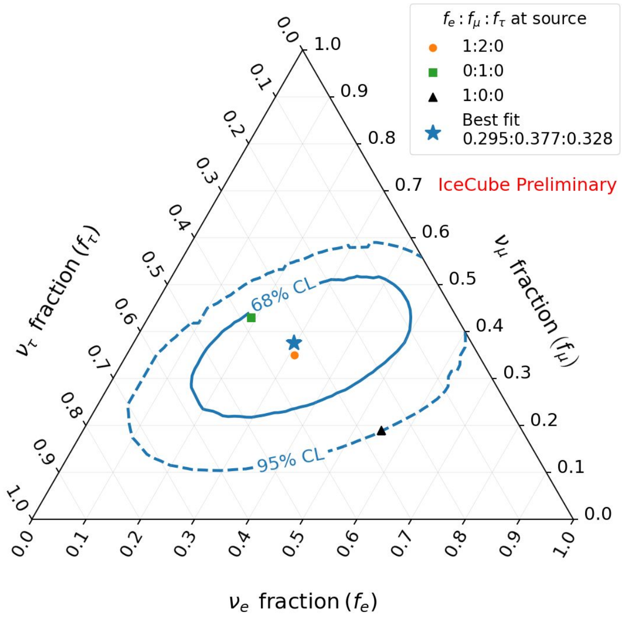
- Retain events that pass the cuts with tau-decay length > 10 m and energy > 30 TeV as double cascades

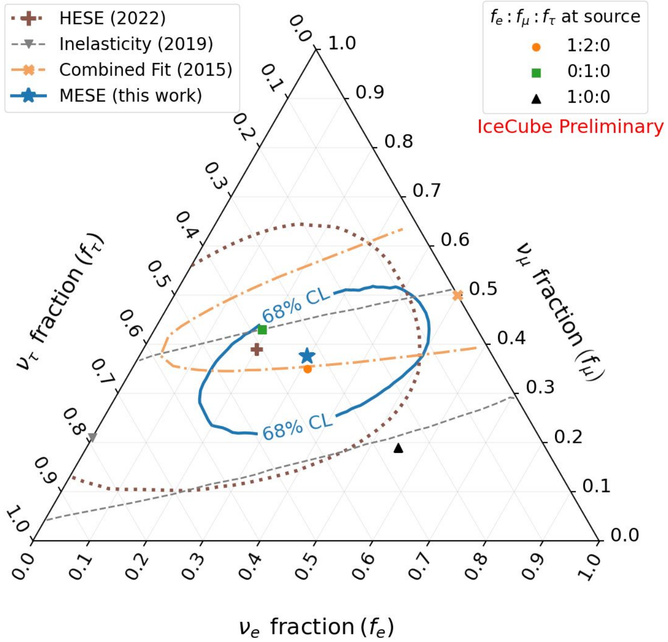
- Remaining events are cascades or tracks (based on a DNN)



Measurement of the flavor ratio

- BPL assumed as the flux model for the measurement of the flavor ratio
- IceCube obtains a closed 1σ contour for the first time
- ν_e-only at source (neutron decay) excluded with 94.8% CL





Comparison of MESE results with previous IC results

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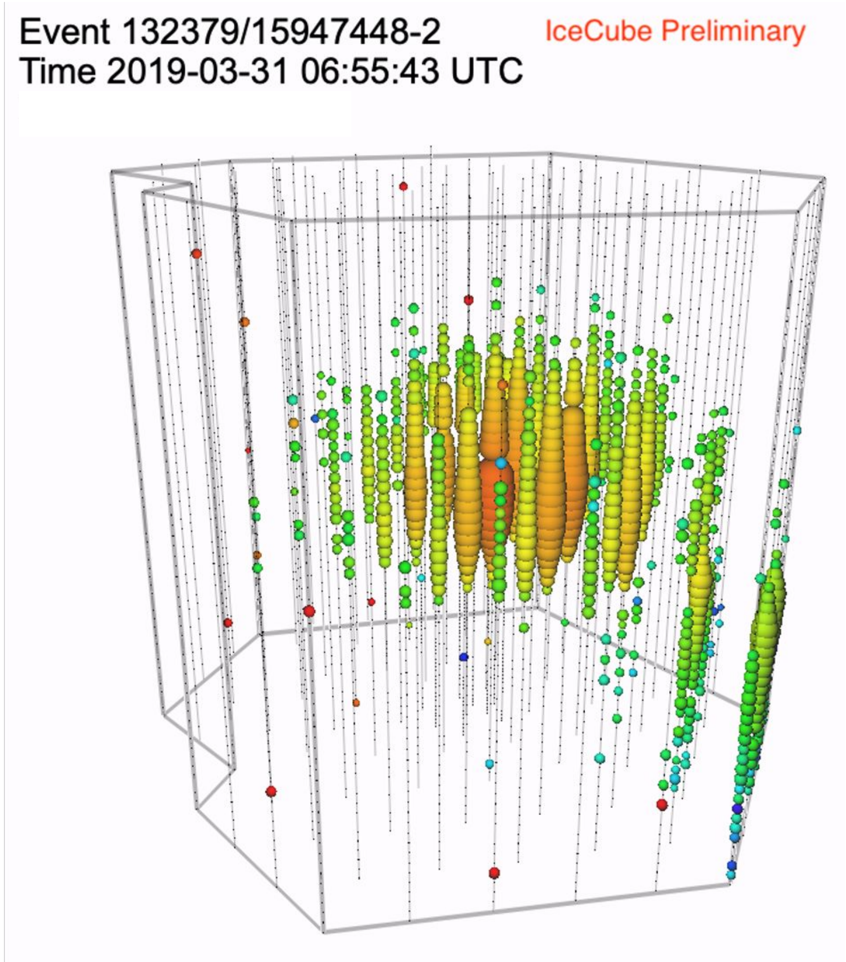
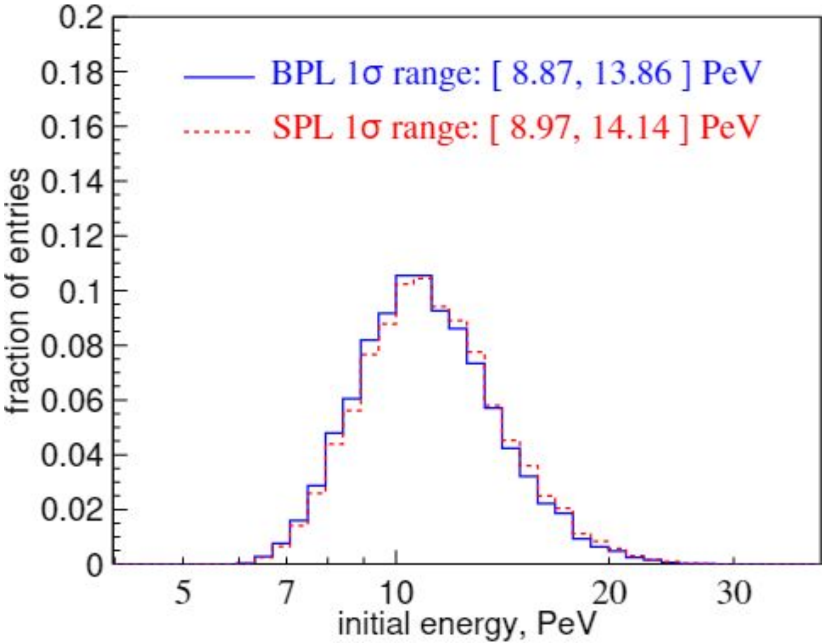
IceCube's Highest Energy Event



- Starting Track in MESE sample, reconstructed energy 4.8 PeV
- Primary neutrino energy*:11.4 PeV



*Most probable neutrino energy when assuming a BPL spectrum (γ_1 ,γ_2)=(1.72,2.84) [Data Release]

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Summary

- A study of starting events with 11.4 years of IceCube data reveals evidence for features in the spectrum of astrophysical neutrinos beyond the single power law.

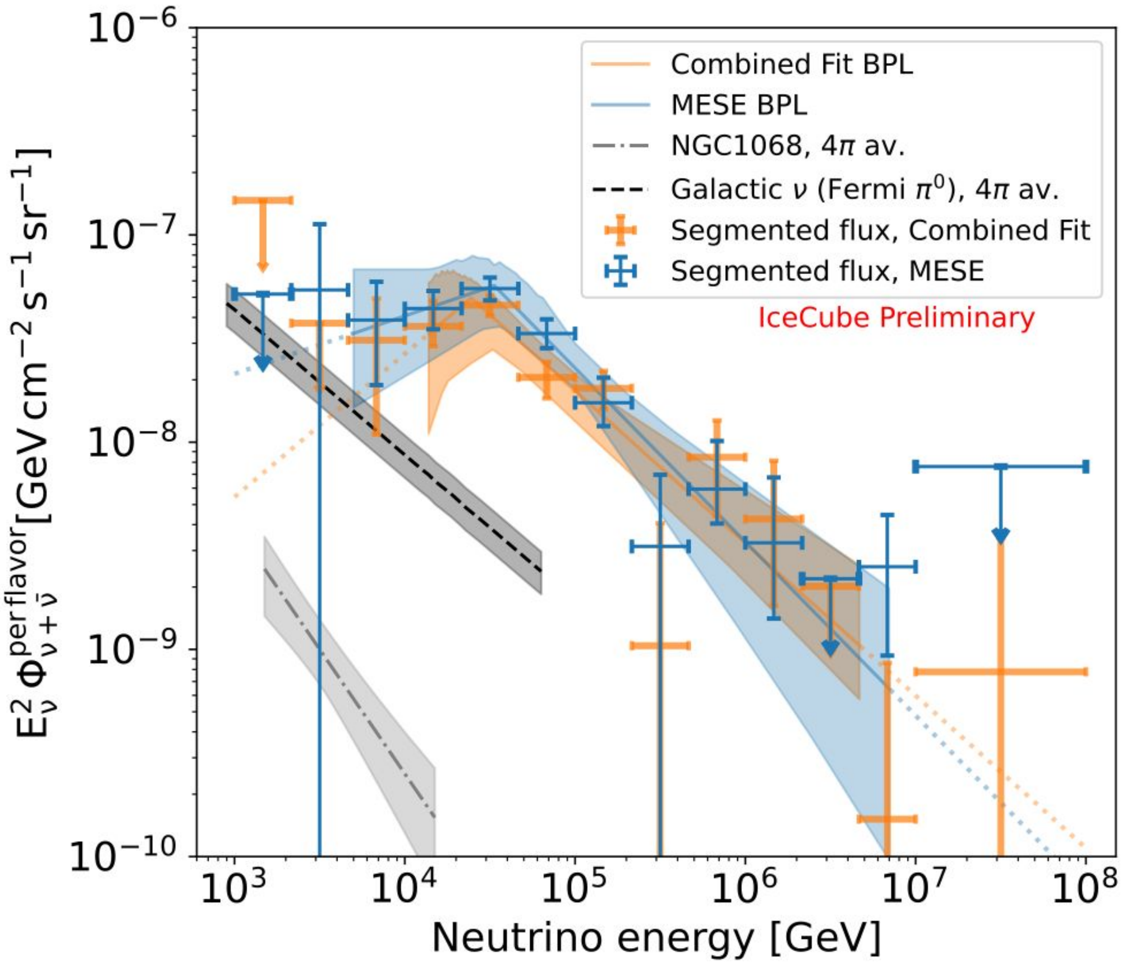
- IceCube observes a steeper spectrum at higher energies, while below ~30 TeV a harder spectrum is measured.

- Flavor ratio of extragalactic neutrinos measured to be consistent with SM, with a closed contour at 68% CL.
  We reject production of cosmic neutrinos via neutron-decay with 94.8% CL.

- In addition, a muon neutrino with energy 11. 4 PeV has been observed, IceCube’s highest energy event to date

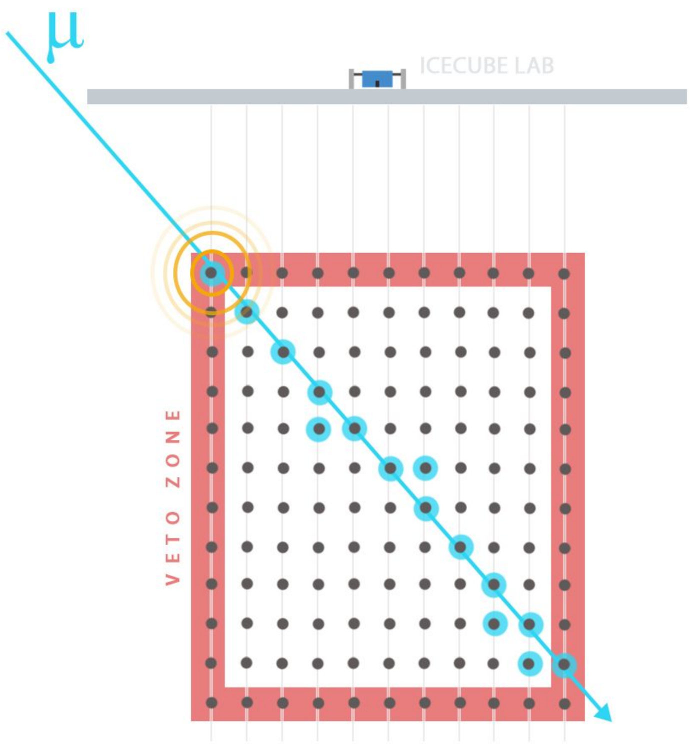
Backup

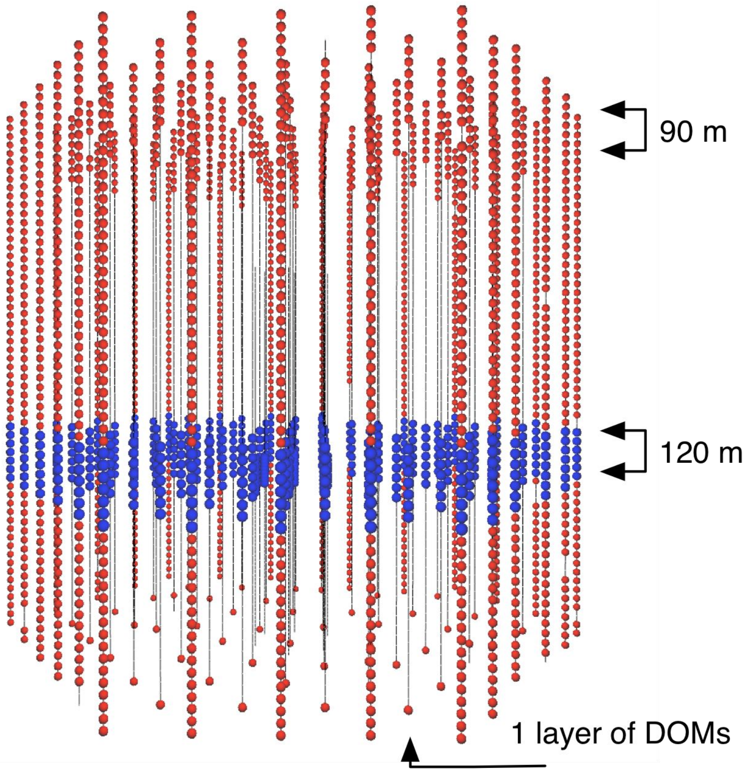
IceCube Fits



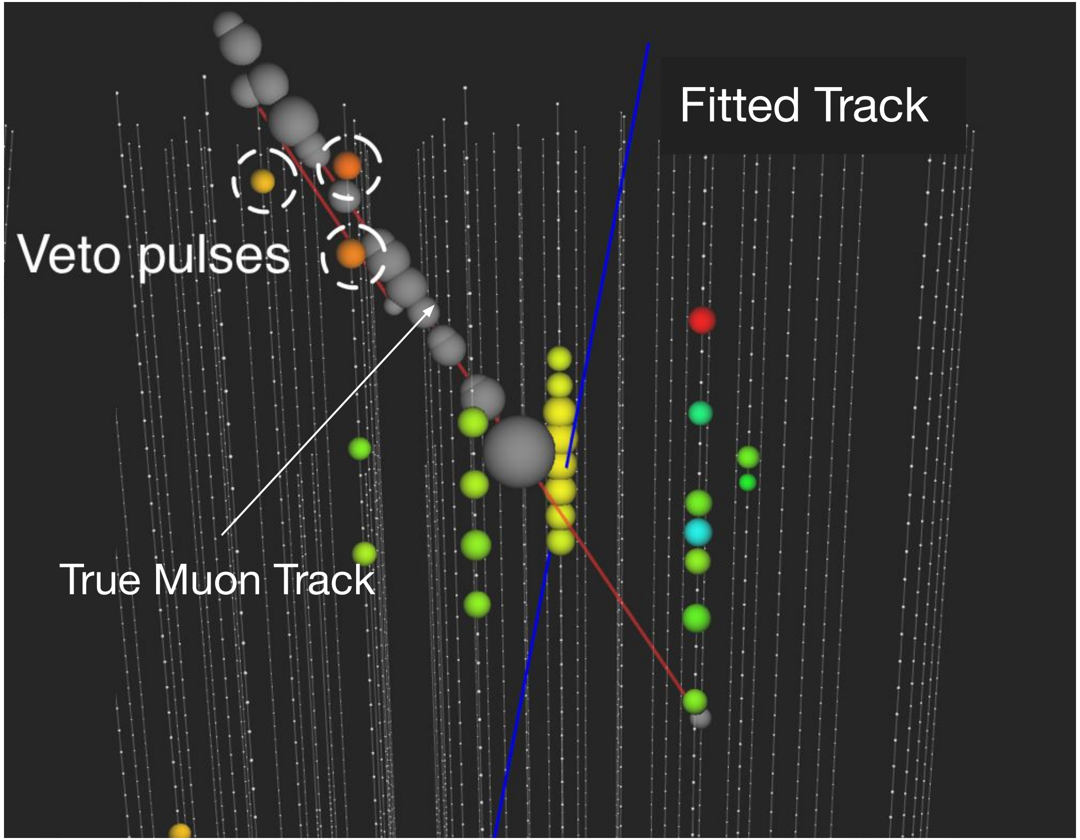
L3: Outer Layer Veto

Outer Layer Veto helps reject events starting outside detector, mostly background muons





L4: Downgoing Track Veto

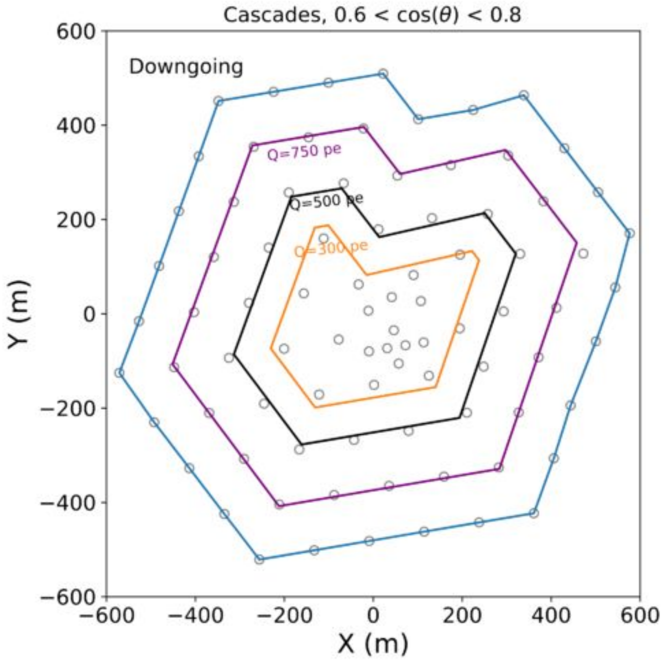


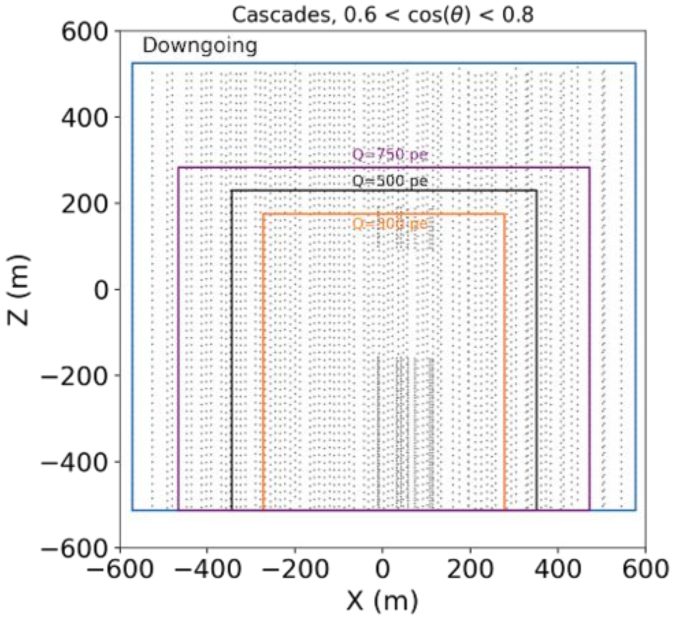
- Post outer-layer veto, muon background dominated by lower energy muons sneaking through veto layer

- Try to associate isolated boundary hits with track hypotheses to veto dim muons

L5: Fiducial Volume Scaling

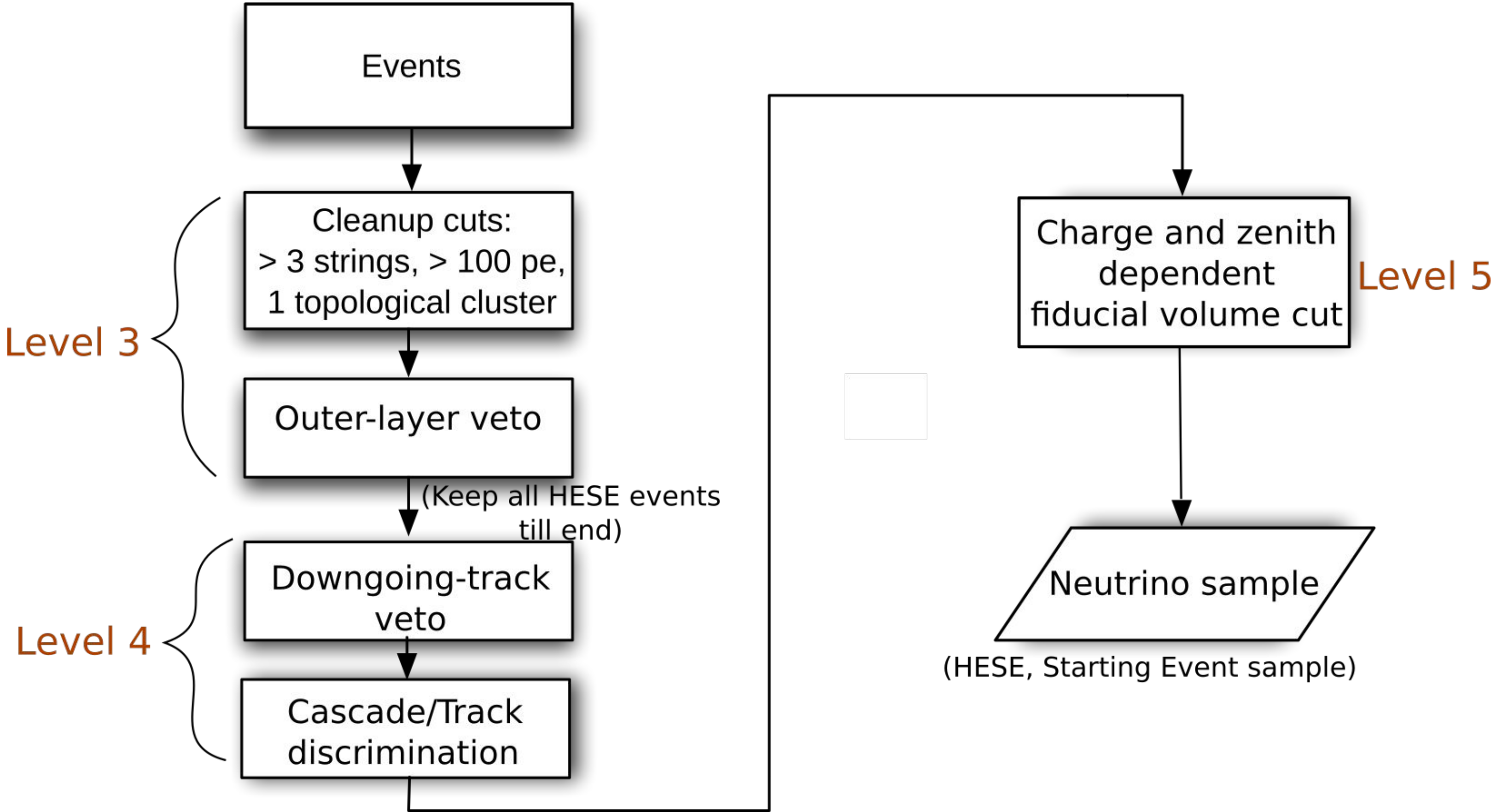
- Downgoing track veto less efficient as muon energy decreases
- For dim events, search for hits closer to the reconstructed vertex
- Zenith and morphology dependent cuts

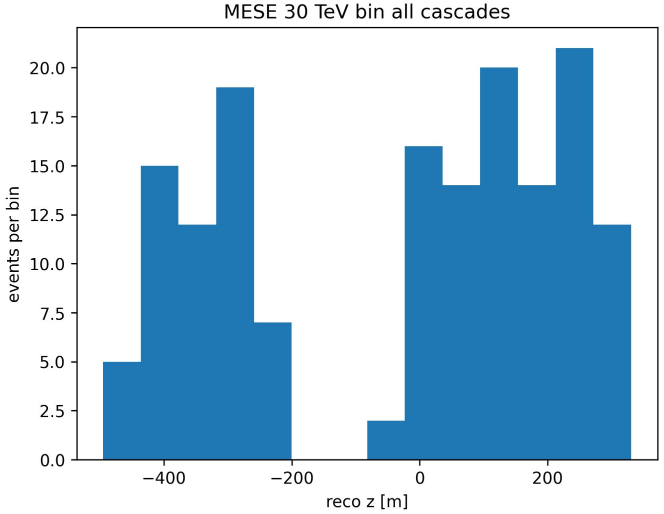


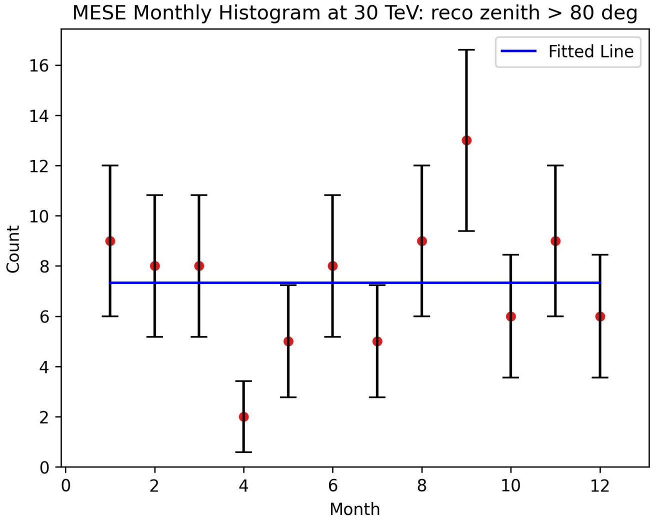


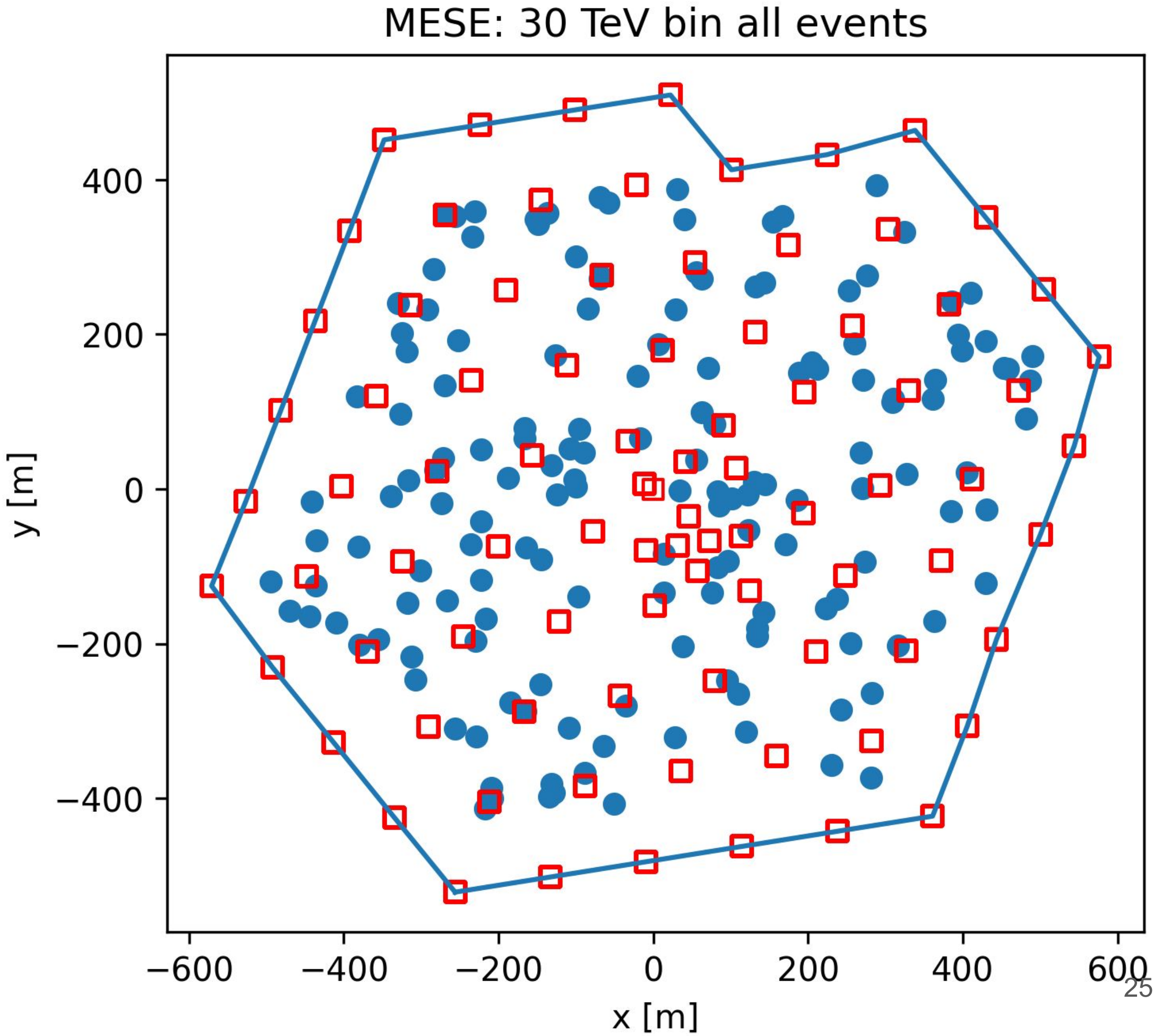
Event Selection

We select starting cascades and starting tracks from the whole sky and with energies above 1 TeV

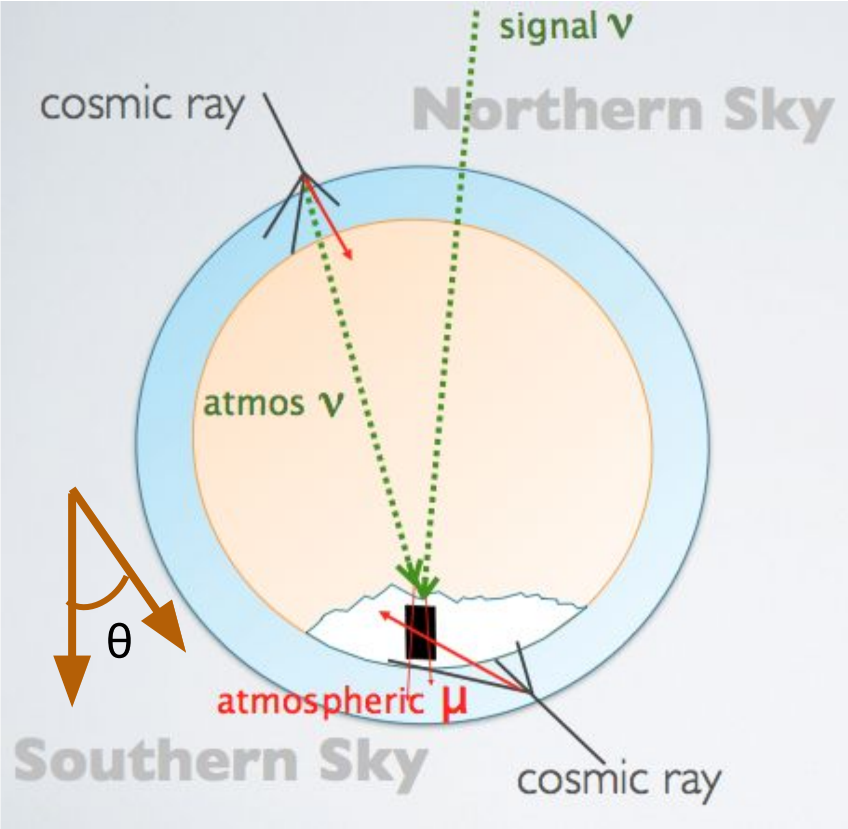


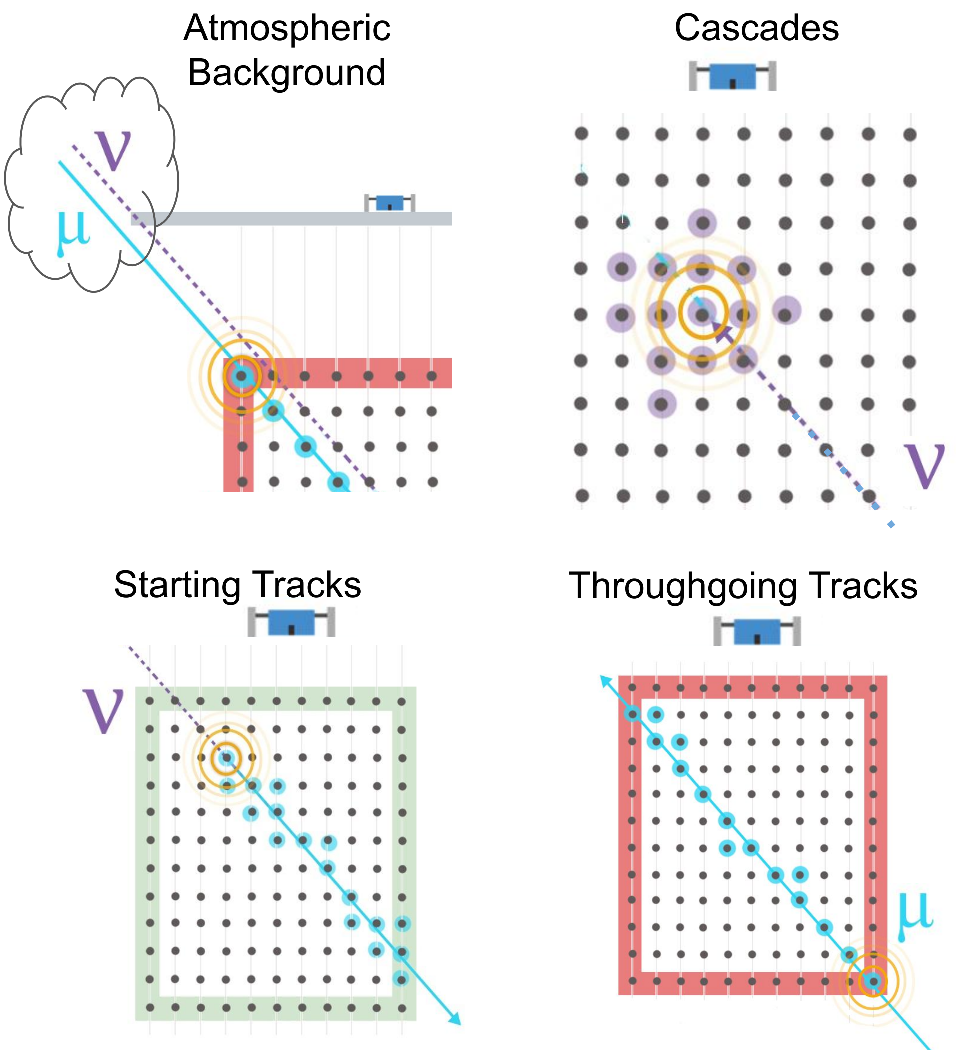

MESE 30 TeV bin all cascades
events per bin
reco z [m]
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0
−400
−200
0
200


MESE Monthly Histogram at 30 TeV: reco zenith > 80 deg
Fitted Line
Count
Month
0
2
4
6
8
10
12
14
16


MESE: 30 TeV bin all events
y [m]
x [m]
400
200
0
−200
−400
−600
600

Event Selections





Cosmic Messengers

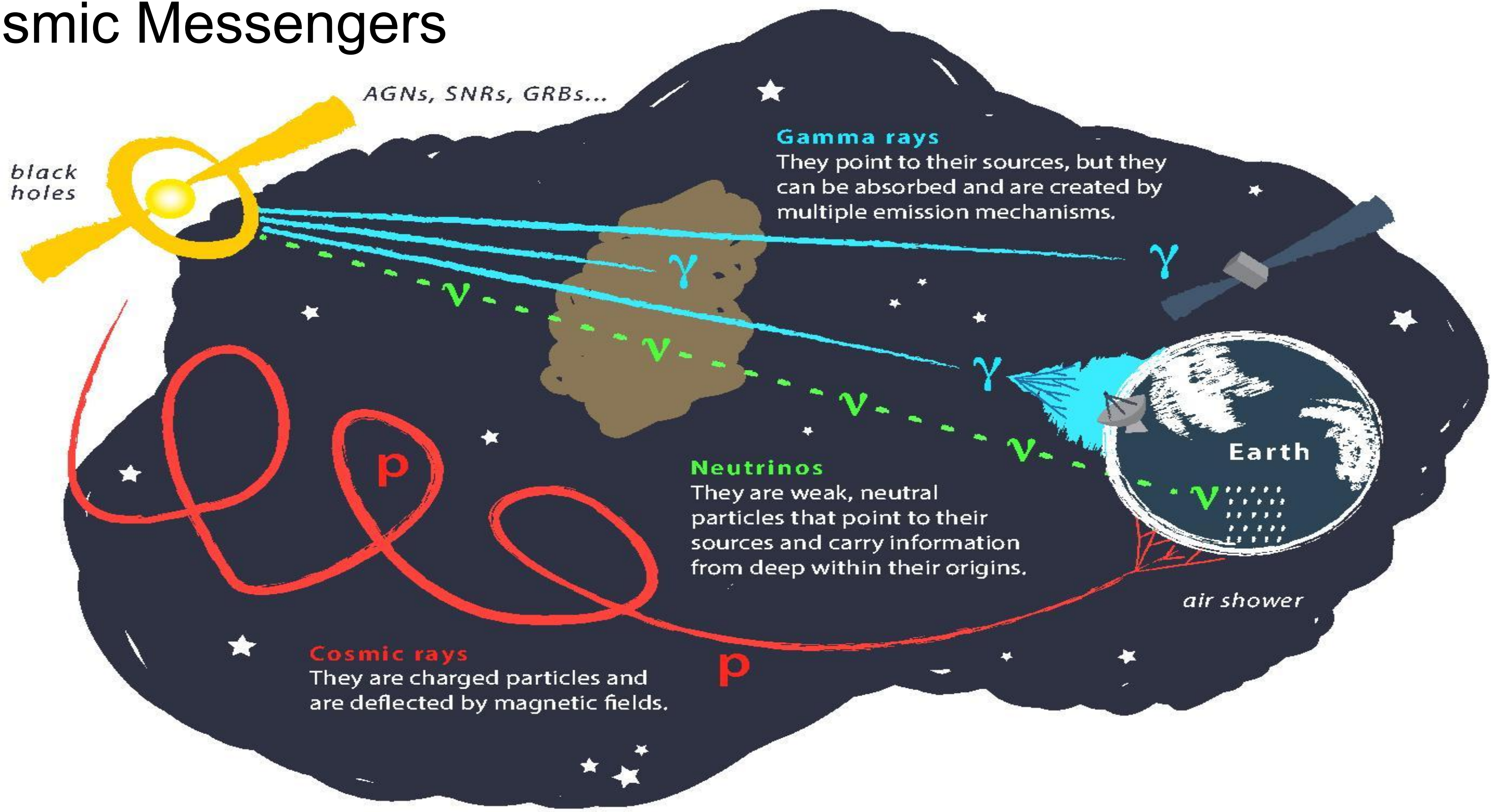
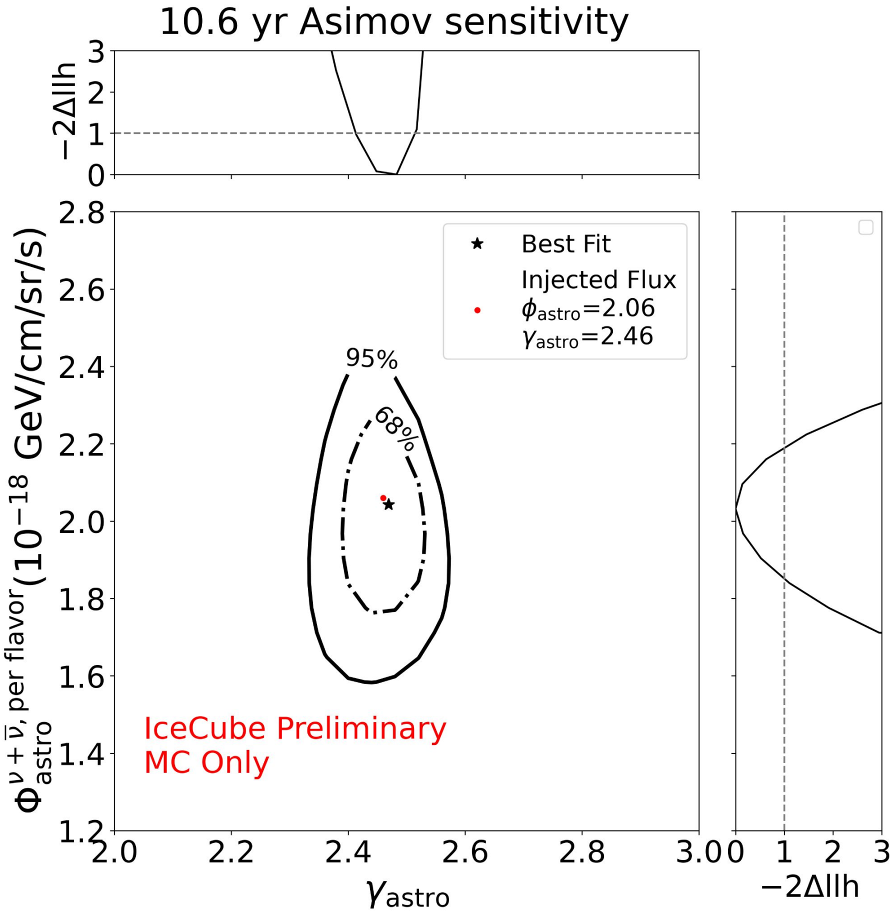


Fig: J. Aguilar and J. Yang for the IceCube Collaboration

Single Power Law (SPL) Sensitivity

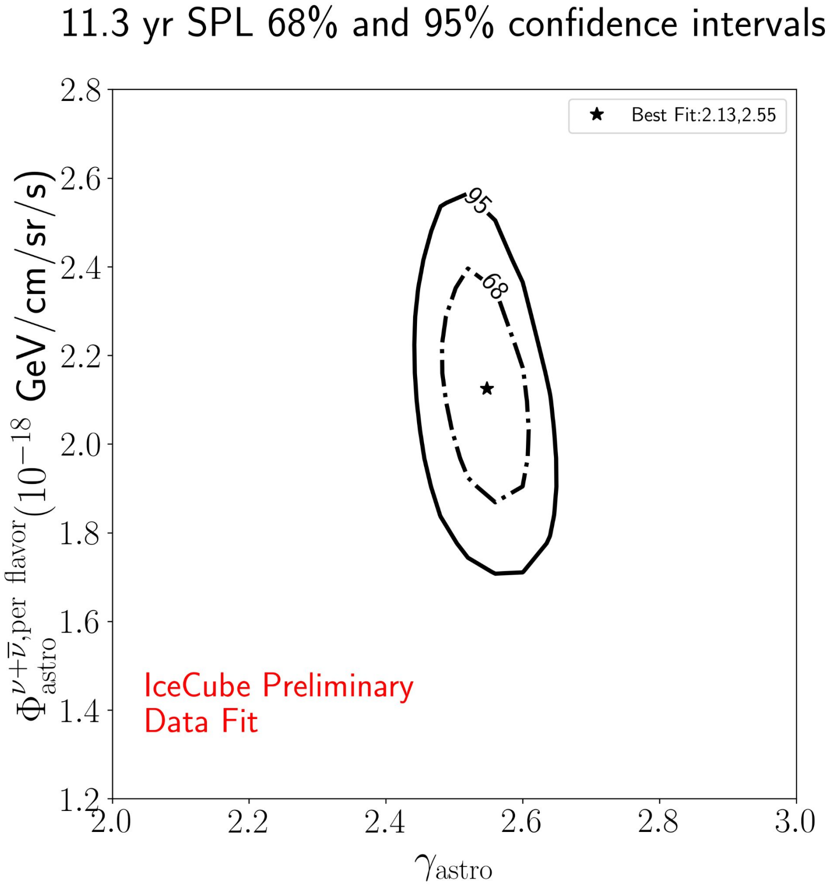


Physics parameters: Assuming Single Power Law Flux (SPL)

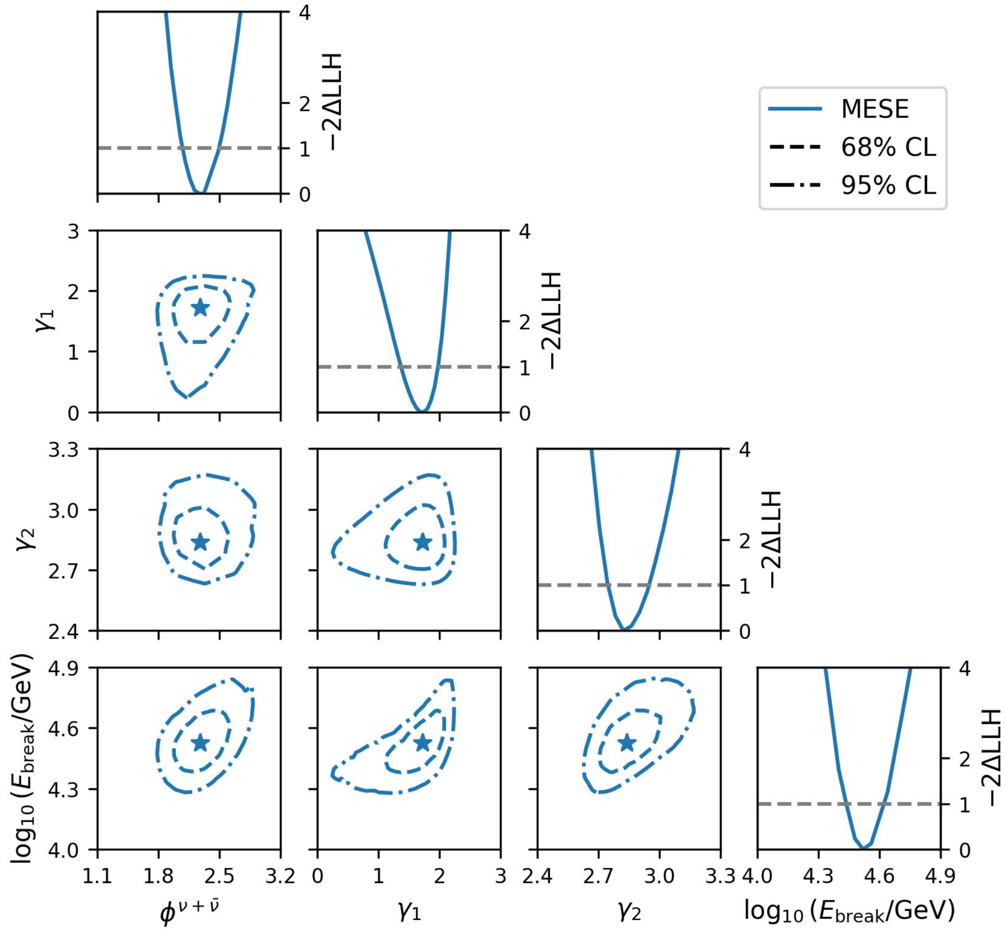
- $\Phi_{astro,}\gamma_{astro}$: The normalization and spectral index
- $\Phi_{\mu:}$: Scaling factor for the atmospheric muon flux assuming GaisserH4a + SIBYLL2.3c
- Φ_{conv} ,Φ_{prompt} : Atmospheric neutrino flux normalisation

Systematics modelled using the SnowStorm method
(M.G. Aartsen et al JCAP10(2019)048)

SPL Fit Contour



BPL Spectral Indices



Models tested

Astrophysical Flux Models:

- Single Power Law (SPL):

$$\Phi_{\text{astro}} \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\gamma}$$

- Broken Power Law (BPL):

$$\Phi_{\text{astro,br}} \begin{cases} \left(\frac{E_\nu}{E_{\text{break}}} \right)^{-\gamma_1} \\ \left(\frac{E_\nu}{E_{\text{break}}} \right)^{-\gamma_2} \end{cases}$$

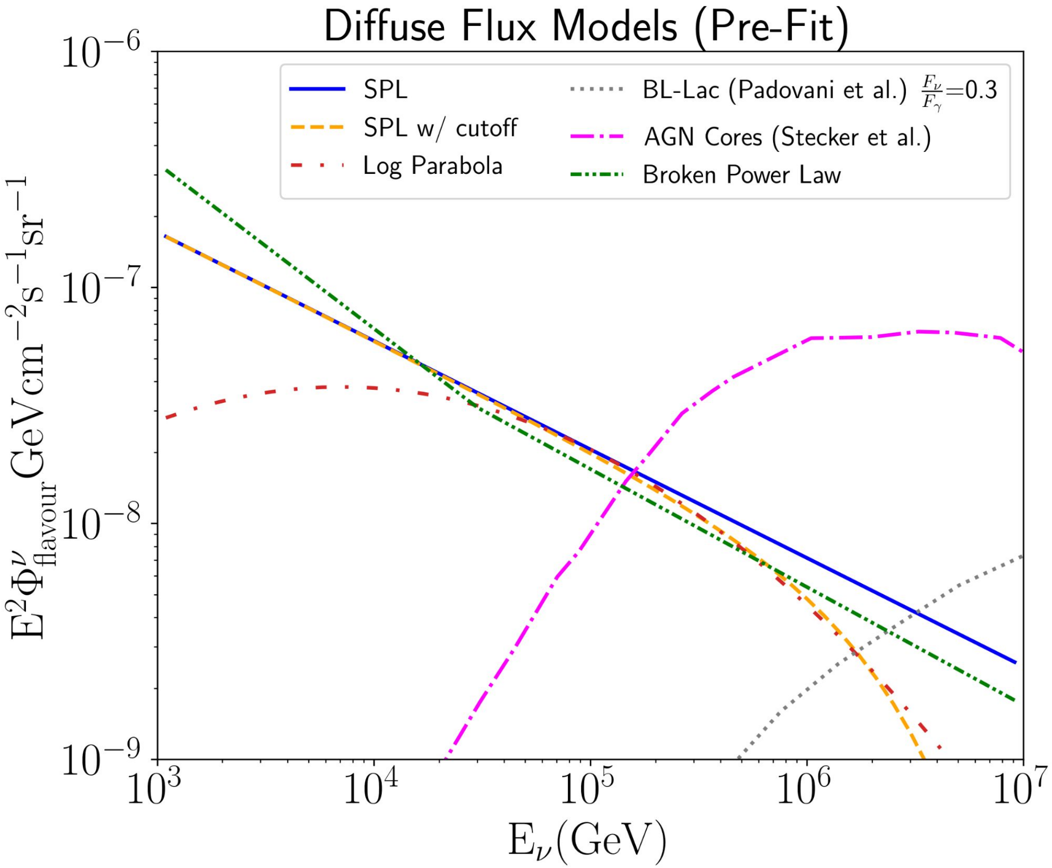
- Log-parabola:

$$\Phi_{\text{astro}} \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\alpha-\beta \log_{10}\left(\frac{E_\nu}{100\text{TeV}} \right)}$$

- SPL+Cutoff:

$$\Phi_{\text{astro}} \left(\frac{E_\nu}{100\text{TeV}} \right)^{-\gamma} e^{-\left(\frac{E_\nu}{E_{\text{cutoff}}} \right)}$$

- AGN core neutrino emission
- Neutrino emission from BLLac objects

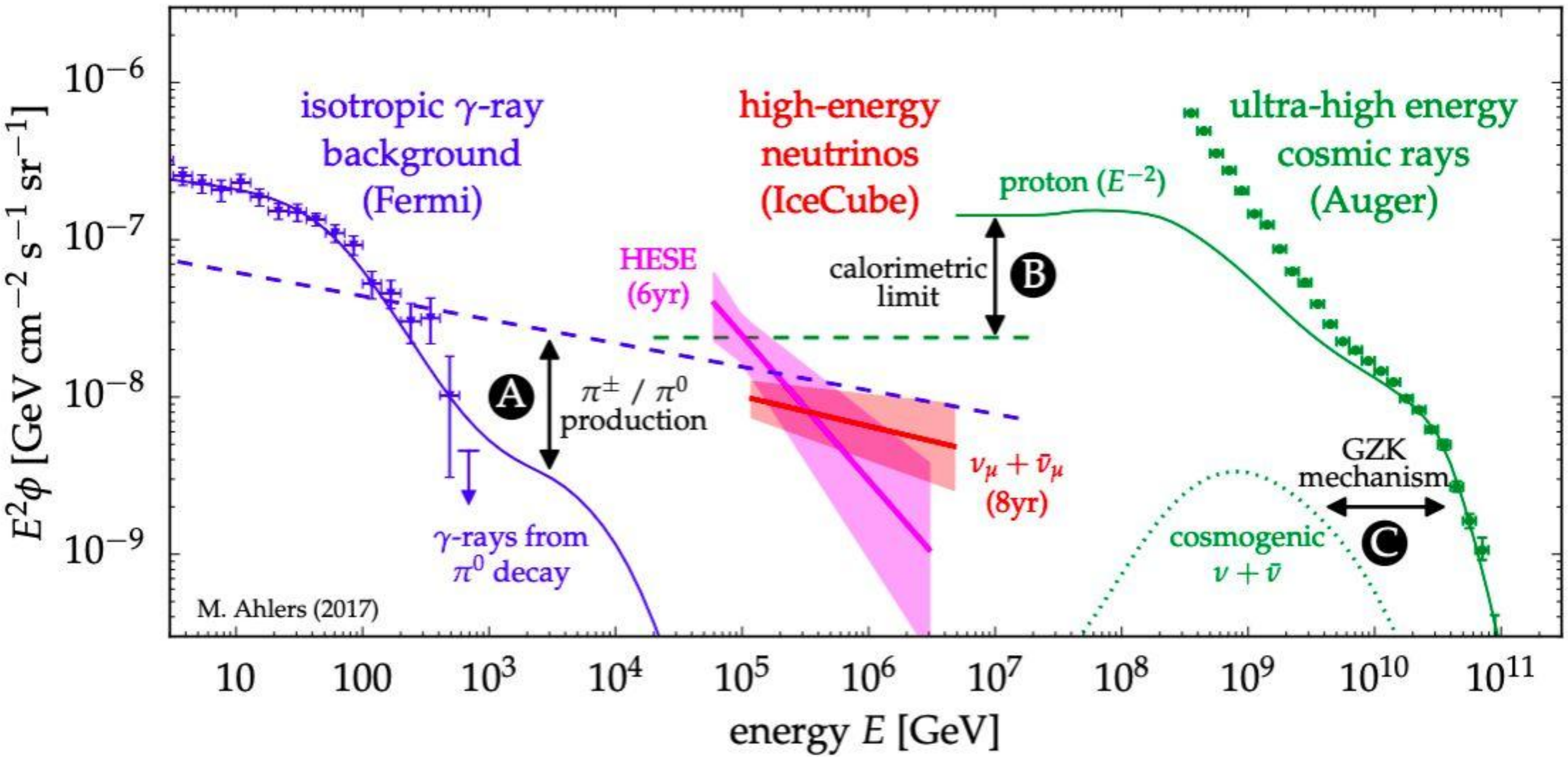


Fit results

- Broken Power Law is the best fit model, followed by SPL+ Bump and then Log Parabola flux.
- We reject single power law by 4.7σ with MESE

Flux Model	Fit Parameters	-2 $\Delta\log\mathcal{L}$
Single Power Law (SPL) $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma}\right]$	$\Phi^{\nu+\bar{\nu}}/C = 2.13^{+0.18}_{-0.17}$ $\gamma = 2.55^{+0.04}_{-0.04}$	0
SPL + AGN $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma}\right]$	$\Phi^{\nu+\bar{\nu}}/C = 2.13^{+0.18}_{-0.17}$ $\gamma = 2.55^{+0.04}_{-0.04}$ $\Phi_{\mathrm{model}} = 0^{+0.002}$	0
SPL + BLLac $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma}\right]$	$\Phi^{\nu+\bar{\nu}}/C = 2.13^{+0.18}_{-0.17}$ $\gamma = 2.55^{+0.04}_{-0.04}$ $\Phi_{\mathrm{model}} = 0^{+0.002}$	0
SPL + Cutoff $\left[\Phi^{\nu+\bar{\nu}}(\Lambda)^{-\gamma}e^{\frac{-E_\nu}{E_{\mathrm{cutoff}}}}\right]$ $\Lambda = \frac{E_\nu}{100\mathrm{TeV}}$	$\Phi^{\nu+\bar{\nu}}/C = 3.975^{+1.14}_{-1.32}$ $\gamma = 2.16^{+0.23}_{-0.16}$ $\log_{10}\left(\frac{E_{\mathrm{cutoff}}}{\mathrm{GeV}}\right) = 5.40^{+0.51}_{-0.23}$	1.8
Log Parabola $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\alpha_{\mathrm{LP}}-\beta_{\mathrm{LP}}\log_{10}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)}\right]$	$\Phi^{\nu+\bar{\nu}}/C = 2.58^{+0.26}_{-0.26}$ $\alpha_{\mathrm{LP}} = 2.67^{+0.13}_{-0.06}$ $\beta_{\mathrm{LP}} = 0.36^{+0.10}_{-0.08}$	18.84
SPL + Bump $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{100\mathrm{TeV}}\right)^{-\gamma} + \Phi_{\mathrm{bump}}e^{\frac{-(E_\nu-E_{\mathrm{bump}})^2}{2\sigma^2_{\mathrm{bump}}}}\right]$	$\Phi^{\nu+\bar{\nu}}/C = 1.42^{+0.21}_{-0.20}$ $\gamma = 2.51^{+0.05}_{-0.07}$ $\log_{10}\left(\frac{E_{\mathrm{bump}}}{\mathrm{GeV}}\right) = 4.30^{+0.13}$ $\log_{10}\left(\frac{\sigma_{\mathrm{bump}}}{\mathrm{GeV}}\right) = 4.42^{+0.12}_{-0.13}$ $\Phi_{\mathrm{bump}}/C = 24.79^{+13.55}_{-7.95}$	22.3
Broken Power Law $\left[\Phi^{\nu+\bar{\nu}}\left(\frac{E_\nu}{E_{\mathrm{break}}}\right)^{-\gamma_{\mathrm{BPL}}}\left(\frac{E_{\mathrm{break}}}{100\mathrm{TeV}}\right)^{-\gamma_1}\right]$ $\gamma_{\mathrm{BPL}} = \begin{cases}\gamma_1\ (E_\nu < E_{\mathrm{break}})\\ \gamma_2\ (E_\nu > E_{\mathrm{break}})\end{cases}$	$\Phi^{\nu+\bar{\nu}}/C = 2.28^{+0.22}_{-0.20}$ $\gamma_1 = 1.72^{+0.26}_{-0.35}$ $\gamma_2 = 2.84^{+0.11}_{-0.09}$ $\log_{10}\left(\frac{E_{\mathrm{break}}}{\mathrm{GeV}}\right) = 4.52^{+0.11}_{-0.09}$	27.3

Energy density of high energy neutrinos similar to γ-ray flux, and Ultra High Energy Cosmic Rays (UHECRs) -> could indicate related production mechanisms

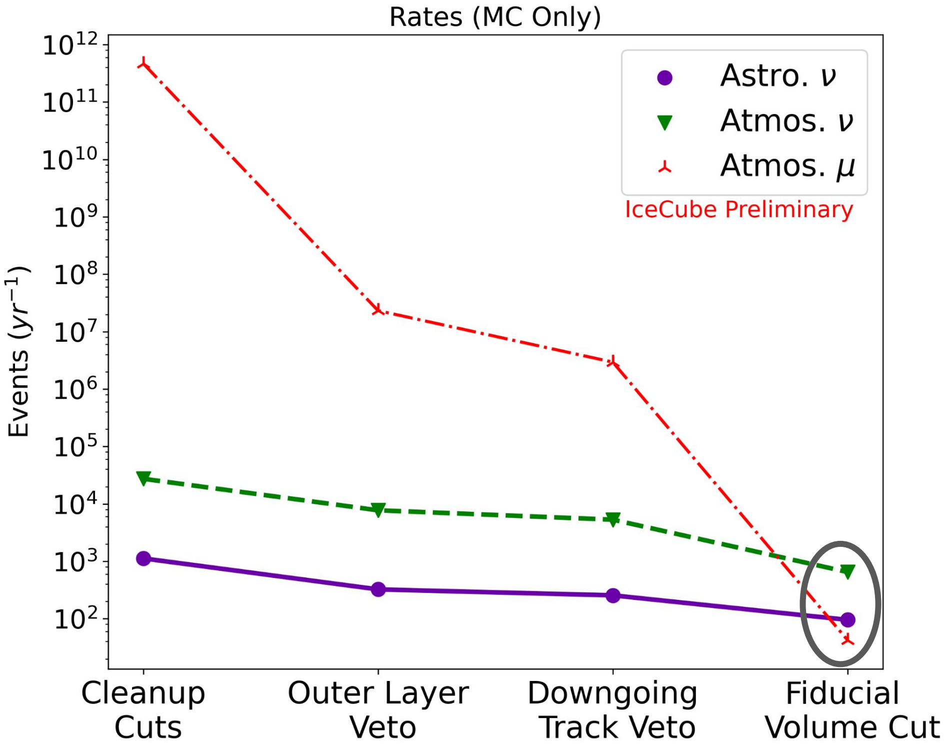


Ref: M. Ahlers, and F. Halzen (arXiv:1805.11112, 2018)

Expected Rates

Astro Flux model: $\Phi_{astro,}$=2.28, γ_1= 1.72, γ_2= 2.84, Log(E_{break}/GeV)= 4.52 (Best Fit Flux Model)

Atm. Flux model: GaisserH4a +SIBYLL 2.3

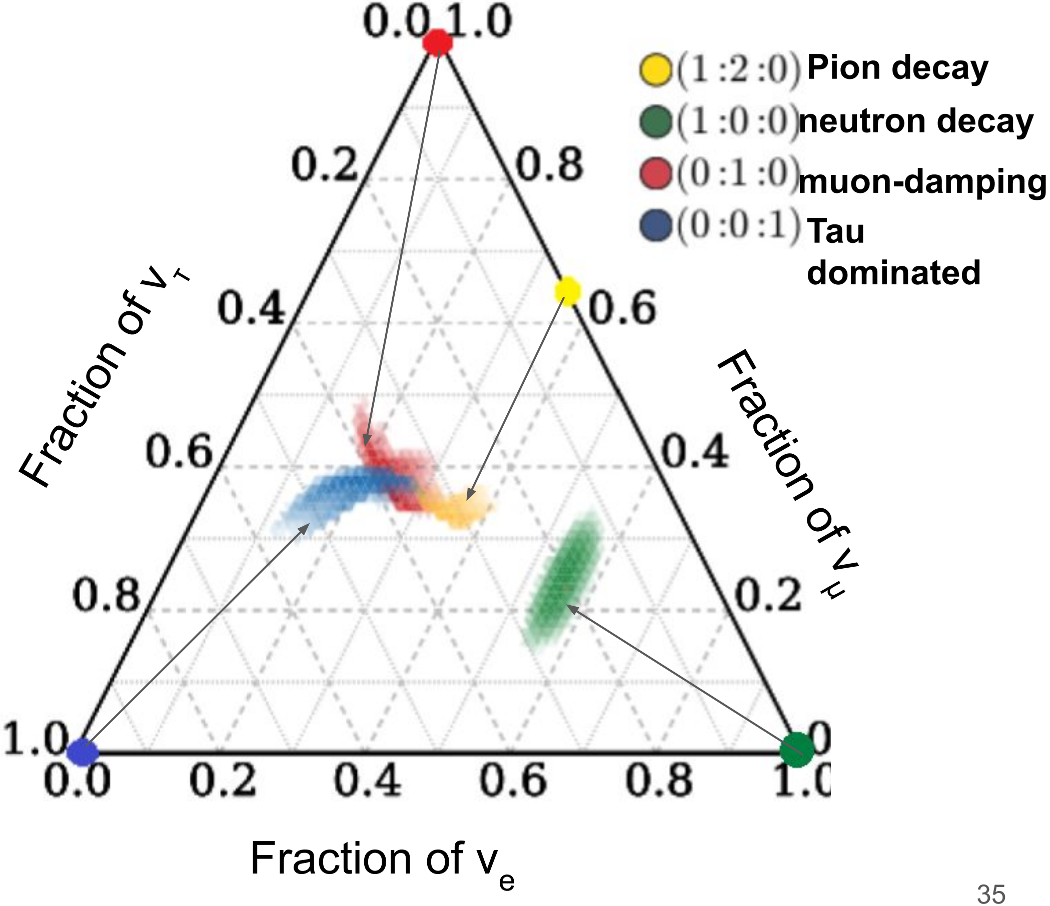


Rates (yr^{-1})	Astro. ν	Atm. ν	Atm. μ
Cascades	58.87	367.68	28.52
Tracks	12.83	412.21	21.91
Total	71.71	779.89	50.43

Motivation: Flavour Studies

- With tracks, cascades and tau discrimination, we can study the flavour composition of cosmic neutrinos.

- These observations help constrain the source production mechanisms and possible new physics



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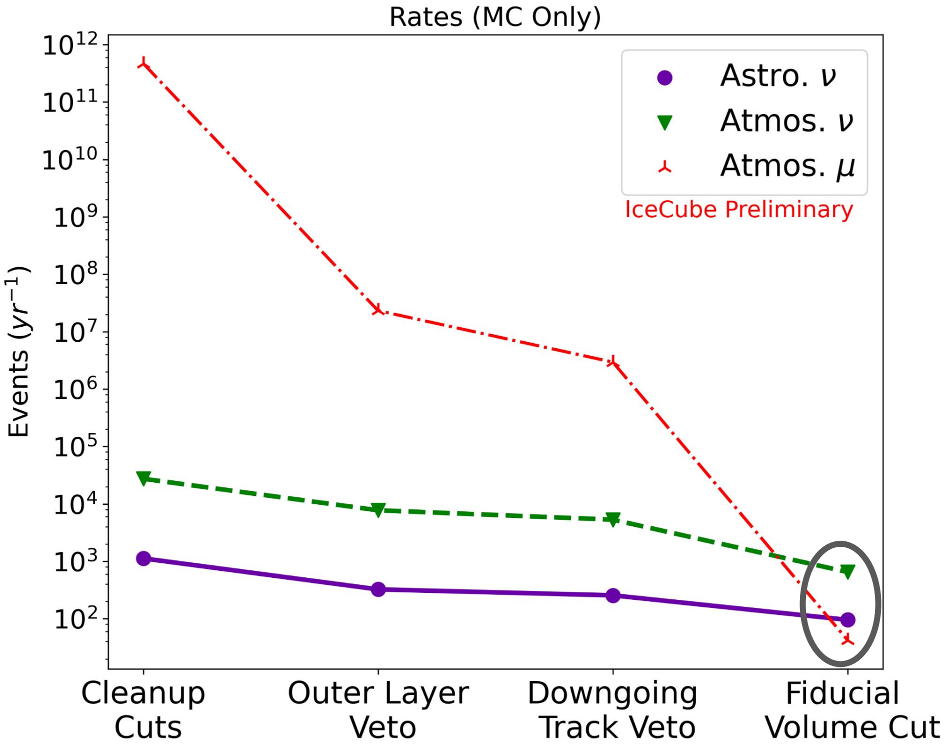
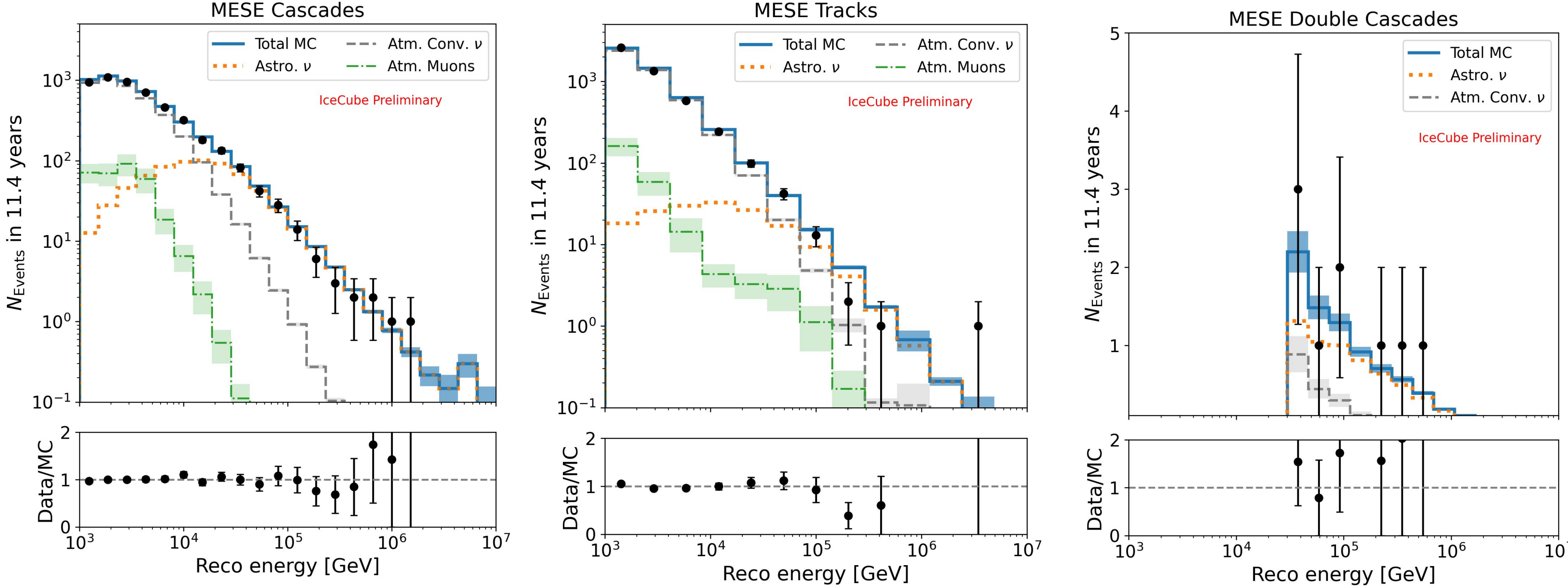


Rates (yr^{-1})	Astro. ν	Atm. ν	Atm. μ
Cascades	80.2	321.1	24.3
Tracks	15.05	323.2	16.6
Total	95.25	644.3	40.9

Energy distributions

- Selected 4960 cascades, 4919 tracks and 9 double cascades
- MC expectations with best fit BPL model
- Shown here: distributions for the flavor measurement*



*cascade and track distributions for spectral measurement looks similar