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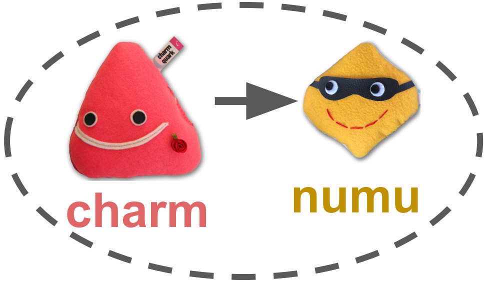
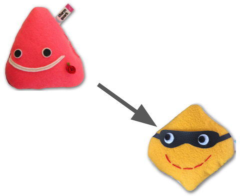
Search for Prompt Atmospheric Neutrinos with IceCube

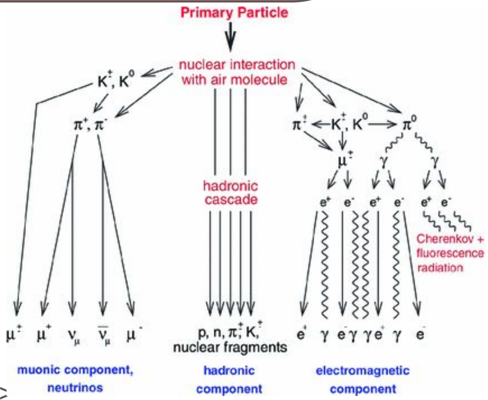
Jakob Böttcher on behalf of the IceCube Collaboration





Prompt Atmospheric Neutrinos

- Atmospheric neutrinos dominate the neutrino flux from GeV to 100s of TeV
  - Decay product of mesons in cosmic-ray air showers
  - The components of atmospheric neutrinos
    - Conventional flux from kaon and pion decays
    - Neutrinos from prompt decays of heavy hadrons (charm mesons, …) prompt (atmospheric) neutrino flux
- Model predictions (BERSS, SIBYLL, …) on prompt neutrino flux have large uncertainties
  - Large uncertainties in forward production of heavy mesons
  - Small coverage by collider experiments
  - Further uncertainty from primary flux models
- Prompt atmospheric neutrino flux not measured so far
- Significant background in the analysis of the astrophysical neutrino energy spectrum
- Measurement of prompt atmospheric neutrinos will decrease uncertainties in heavy hadron production



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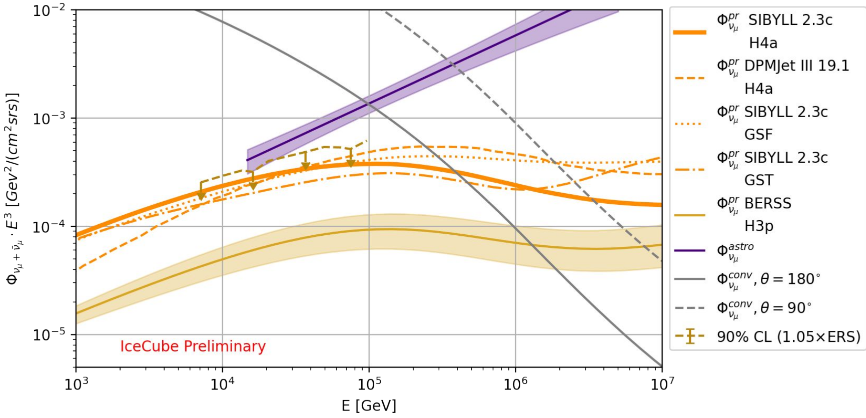
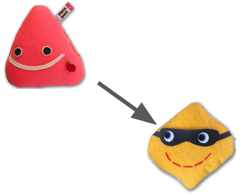
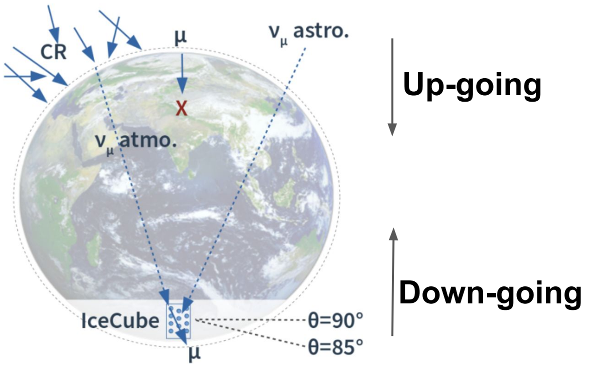
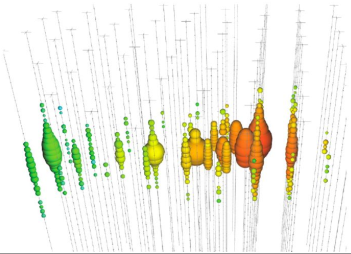


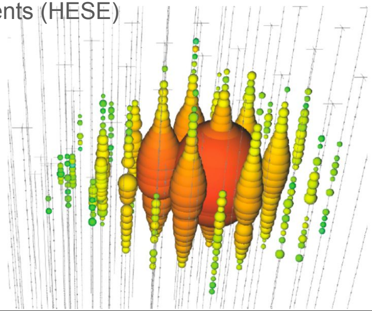


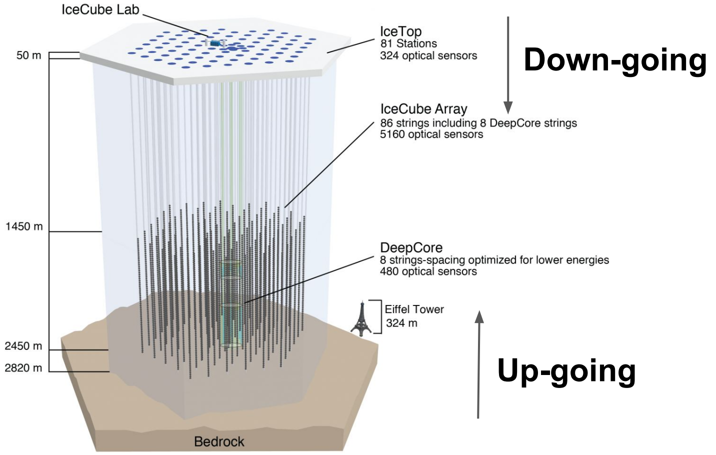
IceCube Neutrino Observatory



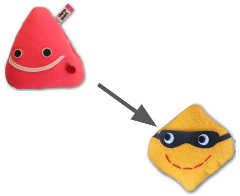
- IceCube observes light of secondary particles of high energy neutrinos with 5160 optical modules in the Antarctic ice
- Search for astrophysical neutrinos and their sources + spectrum
- Event topologies in IceCube:
  - Muon Tracks (muon neutrino CC interactions)
  - Hadronic/EM cascades (NC/CC interactions)
  - Double cascades (Tau decays)
- Events can start inside or outside the detector
- Several event selections based on these topologies:
  - Up-going muon tracks (Northern tracks)
  - Hadronic cascades (Cascades)
  - High energy starting events (HESE)
  - …

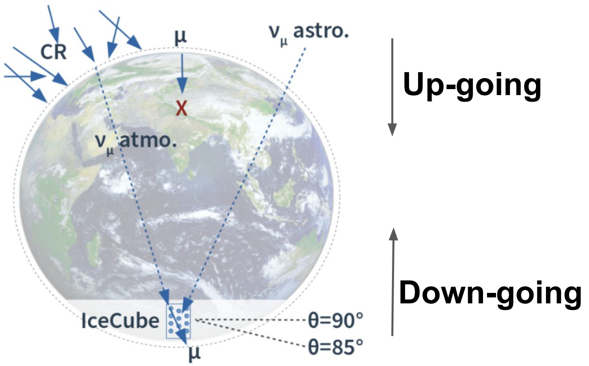




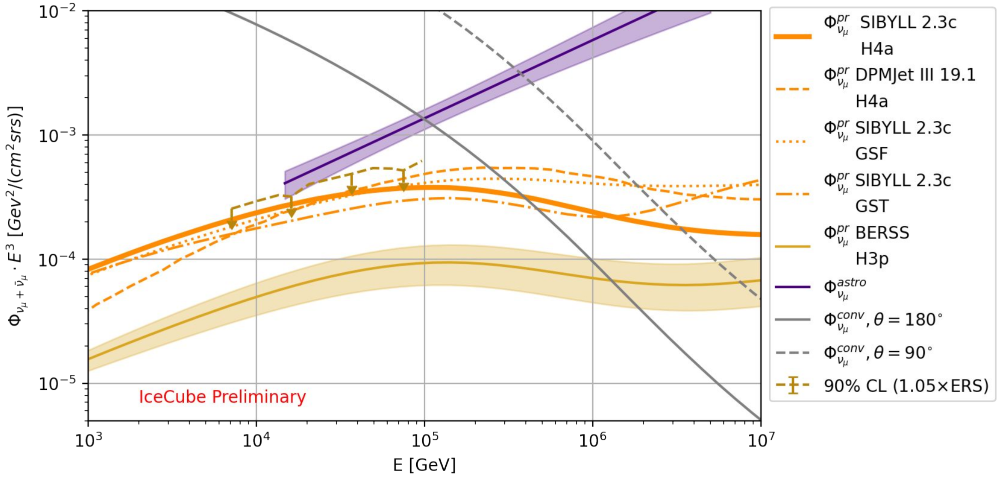


Prompt Neutrino Flux in IceCube





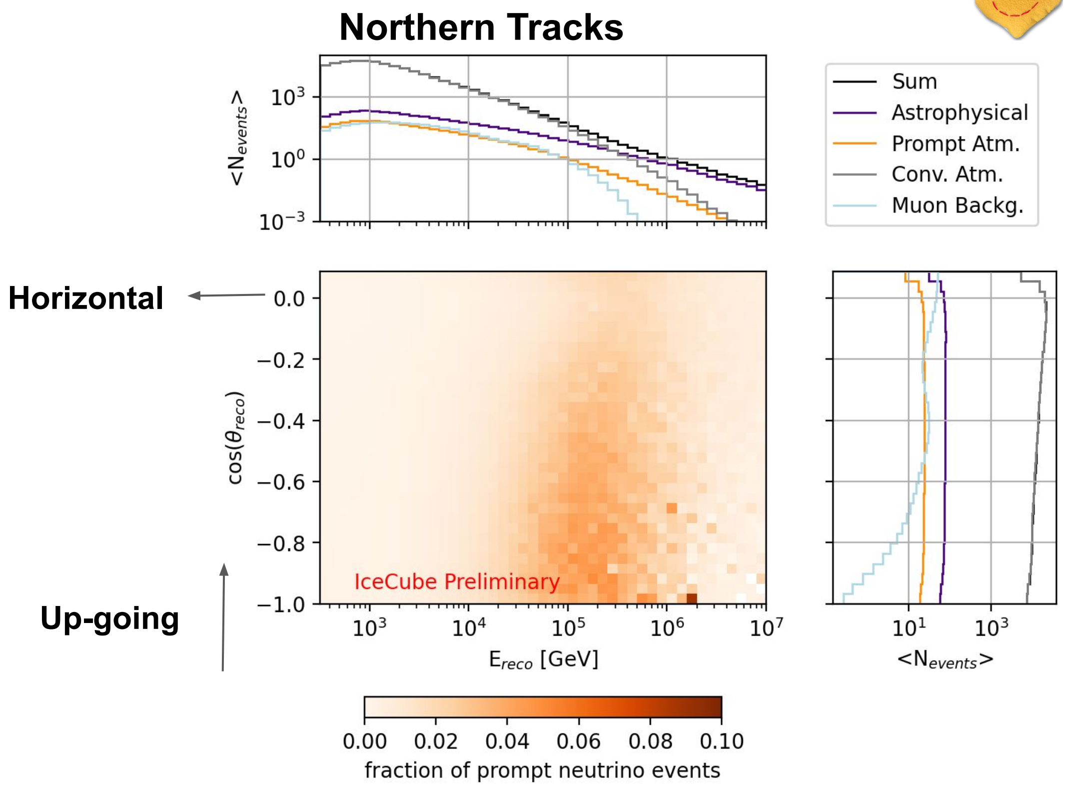
- Event selections differ in sensitivity to prompt neutrino flux
- Published IceCube 90% limits on prompt atmospheric neutrino flux
  - 7.5 year HESE [arXiv:2011.03545]:
    - 9.82 x BERSS
  - 6 years Northern Tracks [arXiv:1607.08006]:
    - 1.05 x ERS
  - 6 years Cascades [arXiv:2001.09520]:
    - 5 x BERSS
- Sensitivity of single selections not good enough to find prompt flux



=> Combine selections to Global analysis

Global Fit Analysis

- Ongoing efforts to combine event selections
- So far combined Northern Tracks and Cascades
- First results shown at ICRC [proceeding]
- Expect improved sensitivity to prompt atmospheric neutrino flux
  - Increase in statistics
  - Decrease in uncertainties of astrophysical flux
  - Region with decreased (prompt) atmospheric neutrino flux (Downgoing self-veto)



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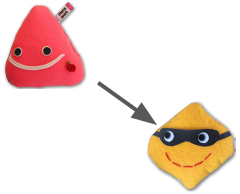
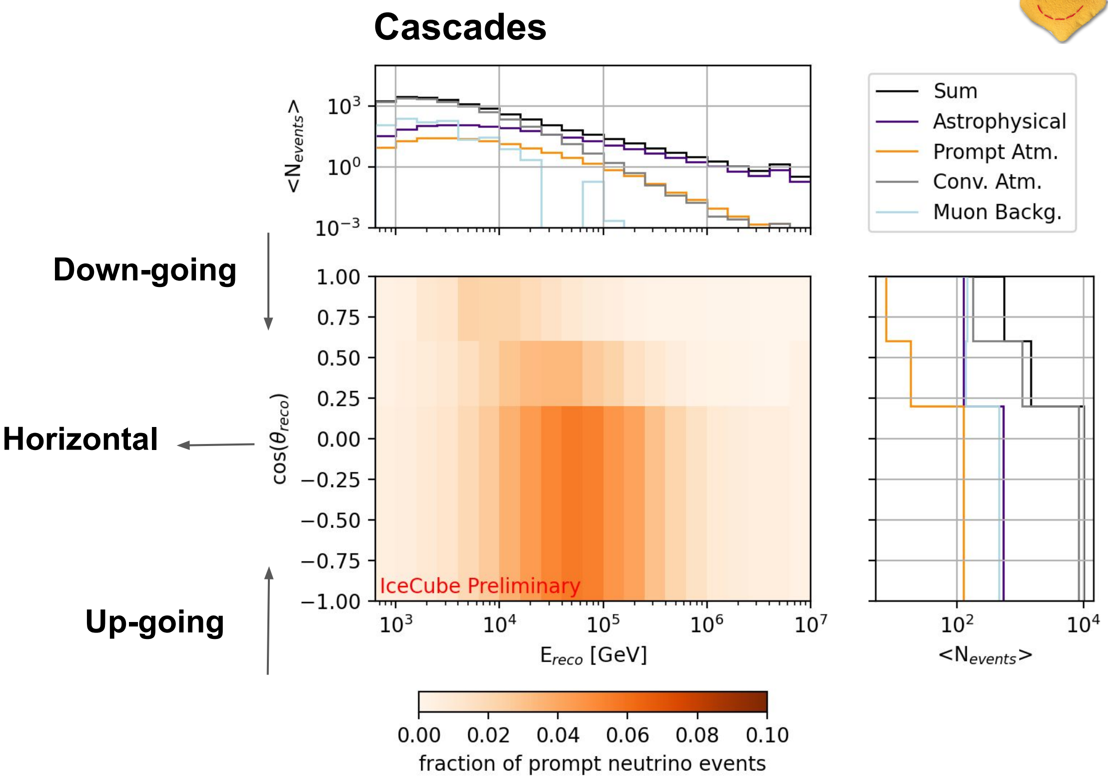
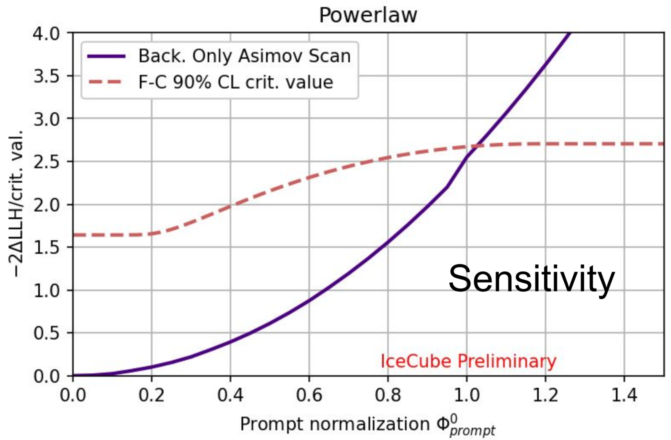
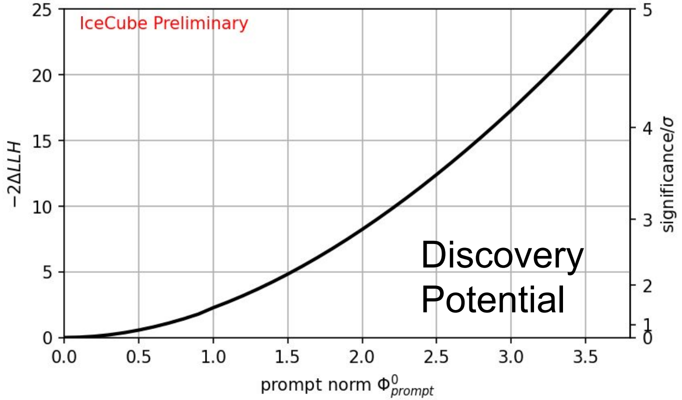


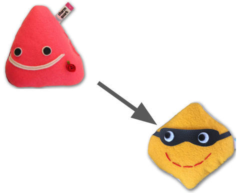


Sensitivity Study

- Analysis method:
  - Forward folding of MC with detector response into zenith, energy bins
  - Binned Poisson Log-Likelihood
  - Minimize signal and nuisance parameters (detector systematics and background flux uncertainties)
  - Each flux component is scaled by independent normalization
- Sensitivity:
  - 90% expected Central Limit: ~1 x SIBYLL 2.3c
  - Analysis will likely not exclude current models (BERSS etc.)
- Discovery potential:
  - Significance will be at the 1 or 2 sigma level

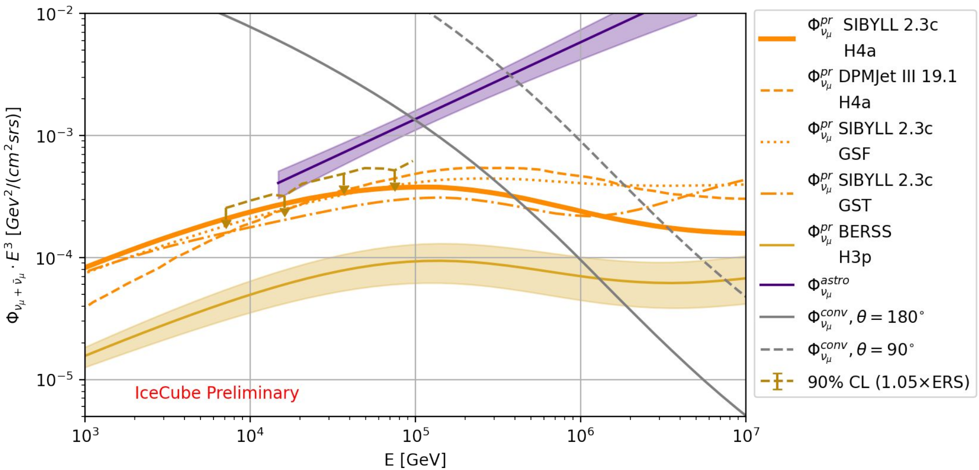






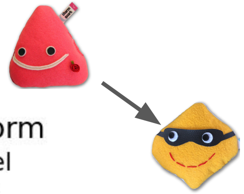
Systematic Biases

- Prompt neutrino flux is sub-dominant (< 10% of expected neutrino rate)
- Minor variations in “background” lead to large variation in fitted prompt flux
- Prone to systematic effects in other flux components
  - Assumptions on astrophysical flux model (e.g. SPL, Log-P, BPL, …) (see ICRC proceeding)
  - Undercoverage of conventional flux uncertainties (primary flux variation)
  - Unaccounted anisotropy in Astrophysical flux component (e.g. galactic plane)
- Test robustness of the prompt flux fit by injecting variations of astrophysical and conventional neutrino fluxes

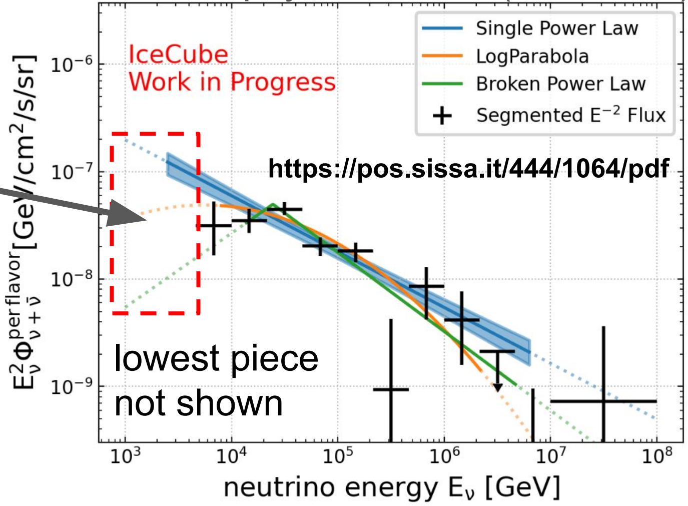


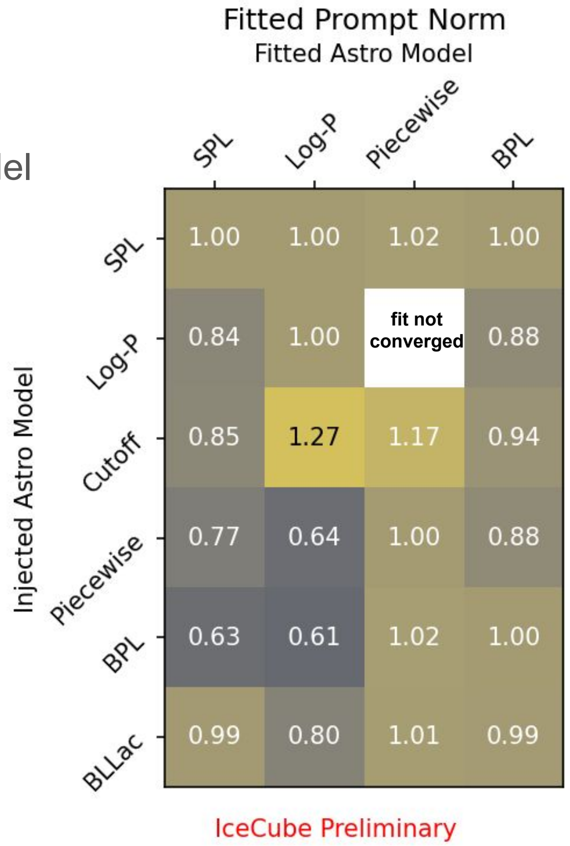
Astrophysical Model Bias

- Spectral shape of astrophysical flux is not well known
- Extrapolation to TeV region strongly depends on assumed model description
- Sensitivity to prompt neutrino flux starts at a few TeVs
- Analysis with SPL introduces bias of up to 40%
- Smallest bias by most flexible astrophysical model (Piecewise)



Extrapolation region





Additionally:

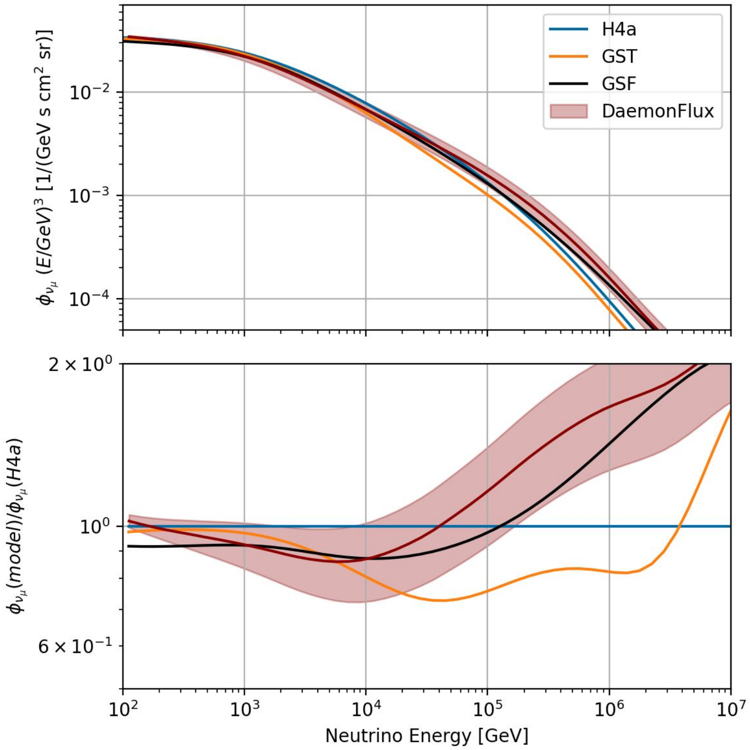
Change in prompt sensitivity by variation of astrophysical model

Conventional Flux Coverage

- Conventional Flux uncertainties from hadronic and primary CR models
  - Hadronic uncertainties modeled by Barr scheme
  - Primary CR model uncertainty based on interpolation between H4a and GST
- Injecting GSF leads to in 10%-20% bias on prompt normalization

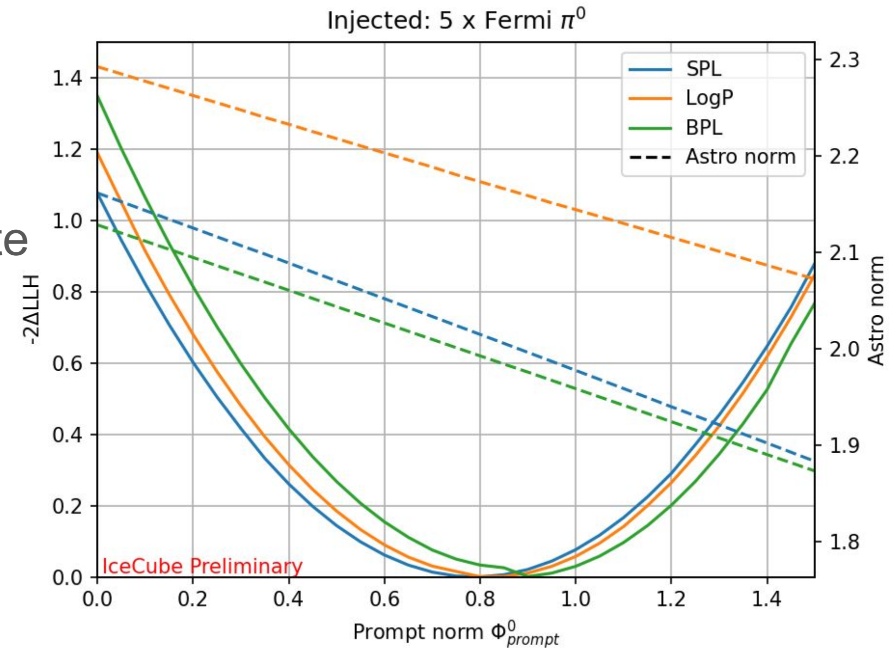
=> Not all primary flux variations are fully covered

Future update: data-based conventional flux modeling (daemonflux)



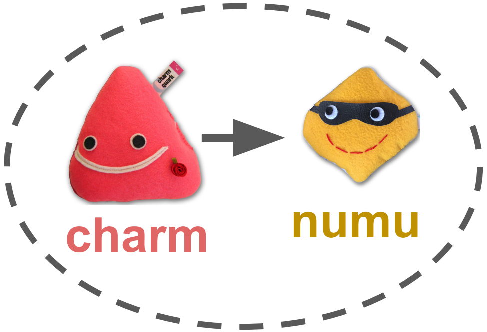
Diffuse Galactic Neutrino Flux

- Astrophysical flux is not completely isotropic
- Current results show that a fraction of diffuse astrophysical neutrinos originate from the milky way [Science paper]
- Unaccounted anisotropy causes mismatch in zenith dependence
- Injecting 5 x Fermi-Pi0 as galactic neutrino flux leads to ~20% bias on prompt norm



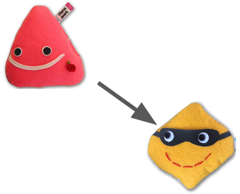
Conclusion and Outlook

- IceCube's Global Fit efforts result in improved sensitivity regarding the prompt atmospheric neutrino flux
- Combined large atmospheric neutrino statistics of northern tracks with decreased atmospheric flux of cascades
- 90% sensitivity is close to the SIBYLL 2.3c prompt flux prediction
- Mismodelings of other components can lead to biases on prompt neutrino flux measurement
  - Astrophysical bias can be avoided by piecewise model parametrization
  - Undercoverage of primary flux uncertainty leads to 10%-20% uncertainty
  - Disregard of galactic flux leads to a 20% bias

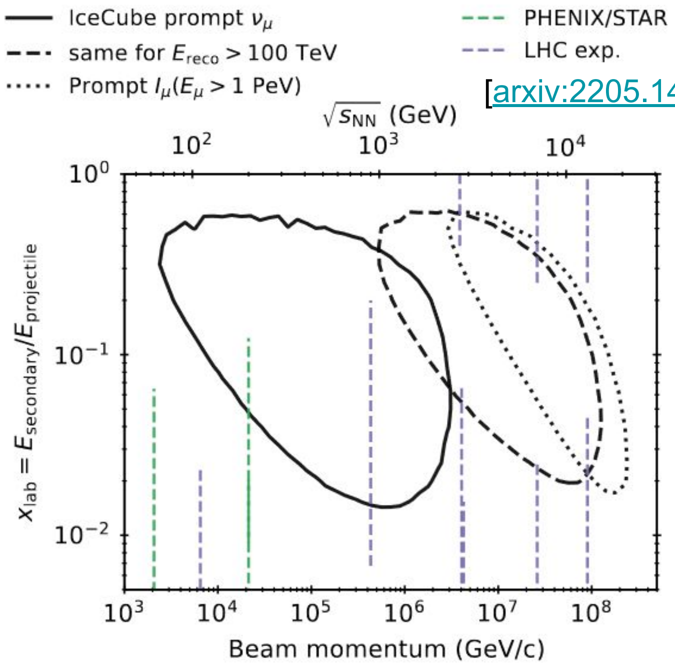


- Future update to data-based conventional flux modeling (daemonflux)
- Include galactic diffuse model in global fit analysis

Backup

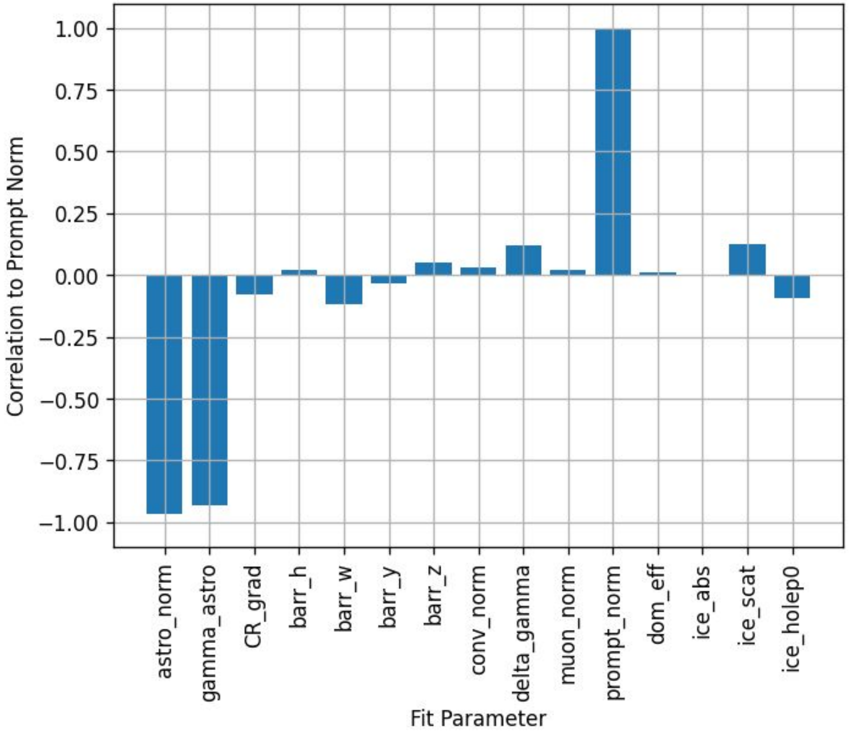


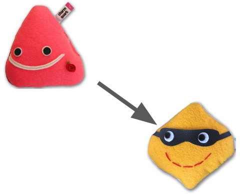
Production Phase Space



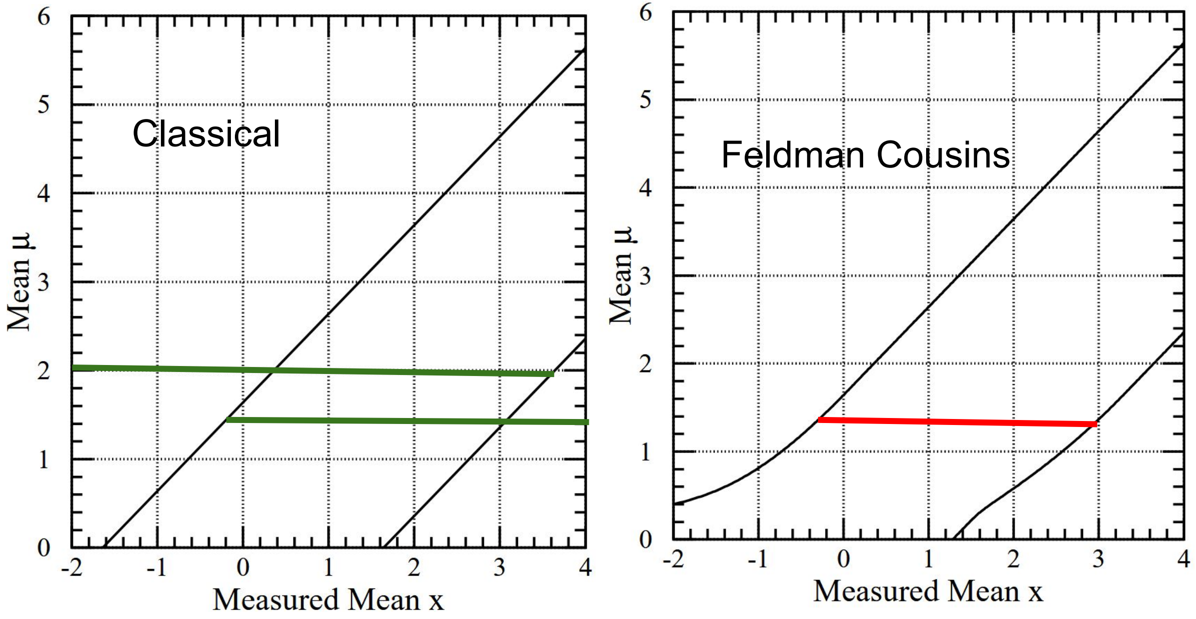
[arxiv:2205.14766]

Correlations





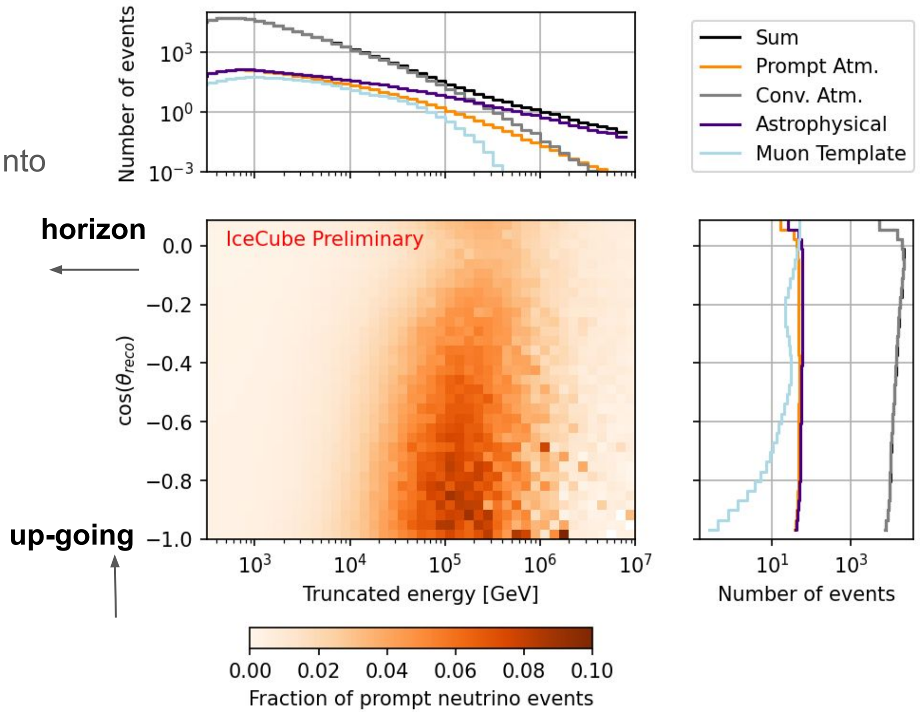
Feldman-Cousins



Up-Going Muon Track Analysis

$$\mathcal{L}(D|\vec{\theta},\vec{\xi}) = \prod_{\text{bin}}^{N_{\text{bins}}} \frac{\mu_{\text{bin}}^{n_{\text{bin}}}}{n_{\text{bin}}!} e^{-\mu_{\text{bin}}}$$

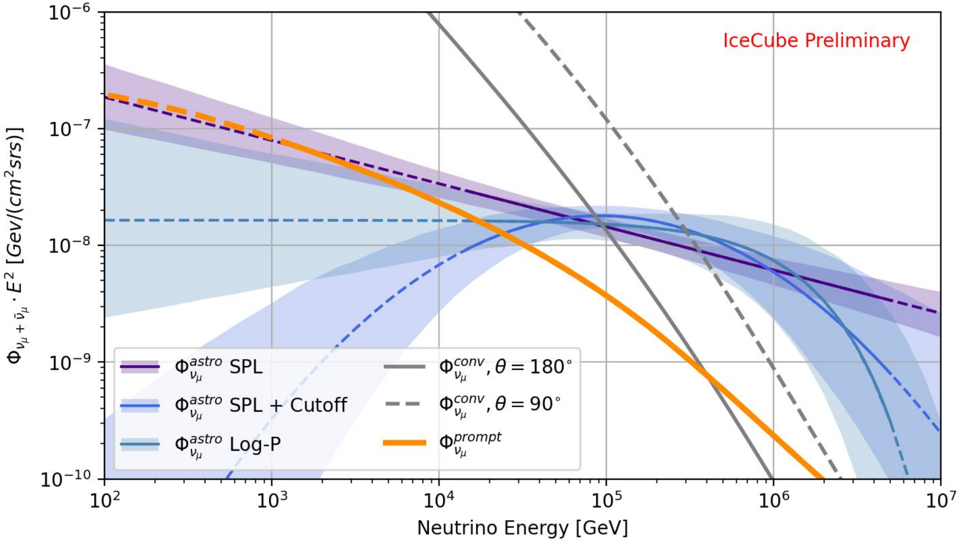
- Analysis of the high energy astrophysical neutrino spectrum
- Current analysis method:
  - Forward folding of MC with detector response into zenith, energy bins
  - Binned Poisson Log-Likelihood
  - Minimize 3 signal (astro x 2 + prompt) and 13 nuisance parameters
- Atmospheric neutrino flux treatment:
  - Based on calculations with MCEq
  - SIBYLL 2.3c + Parameters from Barr et. al.
  - Primary CR model based on H4a and GST (interpolation)
  - Spectral shape adjusted by delta gamma
  - Constant scaling with normalization factor
- Probability intervals by scaling of prompt normalization (norm=0 => H_0)

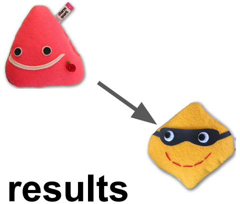


Astrophysical Model Bias

- Shape of astrophysical neutrino flux unknown at low energies
- Northern tracks sensitive energy range starts at 15 TeV
- Flux below 15 TeV driven by choice of parametrization
- Sensitivity to prompt neutrino flux extends to 1 TeV

=> Measurement of prompt neutrino flux is biased by astrophysical model choice



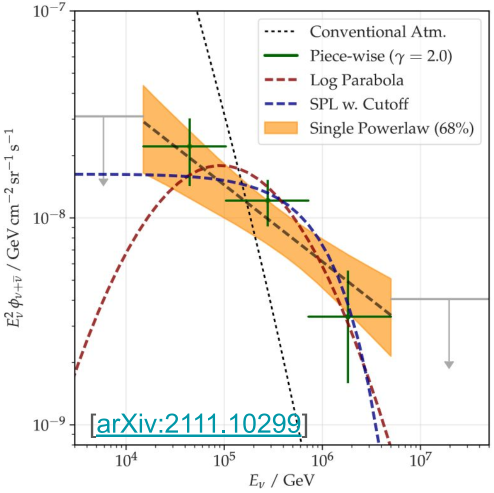


Astrophysical Model Bias

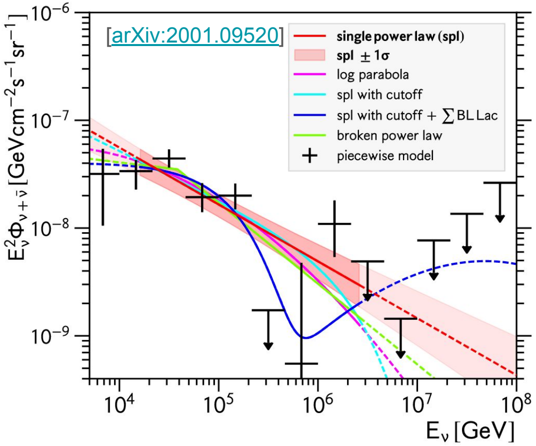
- Various astrophysical models have been fitted in previous analyses
- Test magnitude of bias by varying assumed and tested astrophysical models
- Inject astrophysical models
- Vary model parameters according to published uncertainties

Astrophysical Model	Function	Assumed Values
Powerlaw	$\Phi^0_{\mathrm{astro}}/C_0(\frac{E}{100\,\mathrm{TeV}})^{-\gamma}$	$\Phi^0_{\mathrm{astro}} = 1.44 \pm 0.26$, $\gamma = 2.37 \pm 0.09$
Log-Parabola	$\Phi^0_{\mathrm{astro}}/C_0(\frac{E}{100\,\mathrm{TeV}})^{-\alpha-\beta\log_{10}(\frac{E}{100\,\mathrm{TeV}})}$	$\Phi^0_{\mathrm{astro}} = 1.79 \pm 0.4$, $\alpha = 2.03 \pm 0.22$, $\beta = 0.45 \pm 0.29$
Piecewise	$\sum_i^5 \chi(E)\ \Phi^0_i/C_0\ (\frac{E}{100\,\mathrm{TeV}})^{-2}$	Piecewise fit results in [7]
Cascades	$\sum_i^{13} \chi(E)\ \Phi^0_i/C_0\ (\frac{E}{100\,\mathrm{TeV}})^{-2}$	Piecewise fit results as prior [13]
Cutoff	$\Phi^0_{\mathrm{astro}}/C_0(\frac{E}{100\,\mathrm{TeV}})^{-\gamma}\ e^{-\frac{E}{E_{\mathrm{cutoff}}}}$	$\Phi^0_{\mathrm{astro}} = 1.64 \pm 0.39$, $\gamma = 2.0 \pm 0.4$, $\log_{10}(E_{\mathrm{cutoff}}) = 6.1 \pm 0.3$
Astro BL-Lac	$\Phi_{\mathrm{Cutoff}}(E) + \Phi_{\mathrm{BL-Lac}}(E)$	Adding the BL-Lac astrophysical model [13, 18]

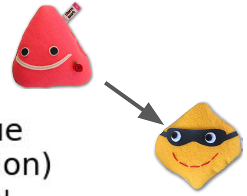
9.5 years Northern Tracks



6 year Cascade results



- Fit with:
  - Powerlaw
  - Log-Parabola
  - Piecewise
  - Cascades



Astrophysical Model Bias

- Distribution of fitted prompt normalizations shows bias (std) caused by variation of astrophysical models
- Results:
  - Large bias in Powerlaw fit
  - LogParabola and Piecewise are less biased
  - Using priors from cascades sample analysis reduces bias significantly
- Sensitivities:
  - Sensitivity of SPL/LogP/Piecewise comparable (prompt norm ~2.4-2.9)
  - Cascade priors improve sensitivity (prompt norm ~1.45)