High Energy (TeV-scale) Neutrino Cross Section Sensitivity using the IceCube Neutrino Experiment

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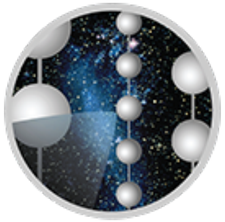
ICEPP Symposium 2023

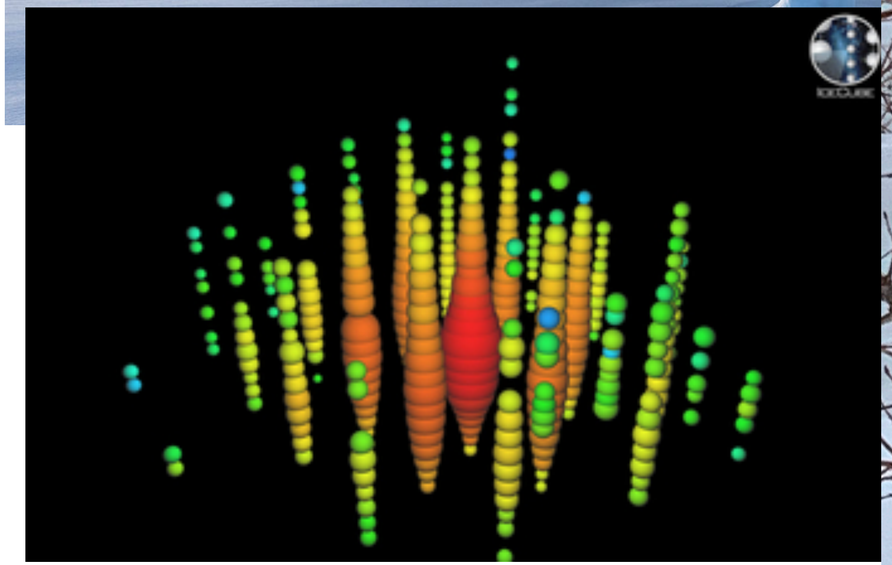
CHIBA UNIVERSITY



IceCube
South Pole Neutrino Observatory

ICEHAP
International Center for Hadron Astrophysics

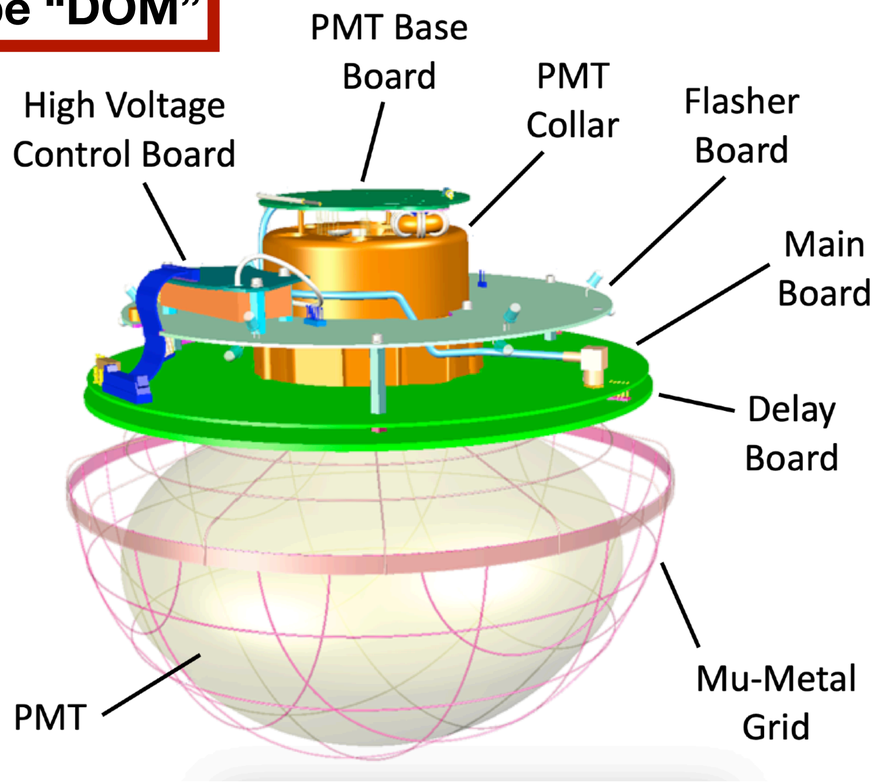
IceCube Neutrino Observatory

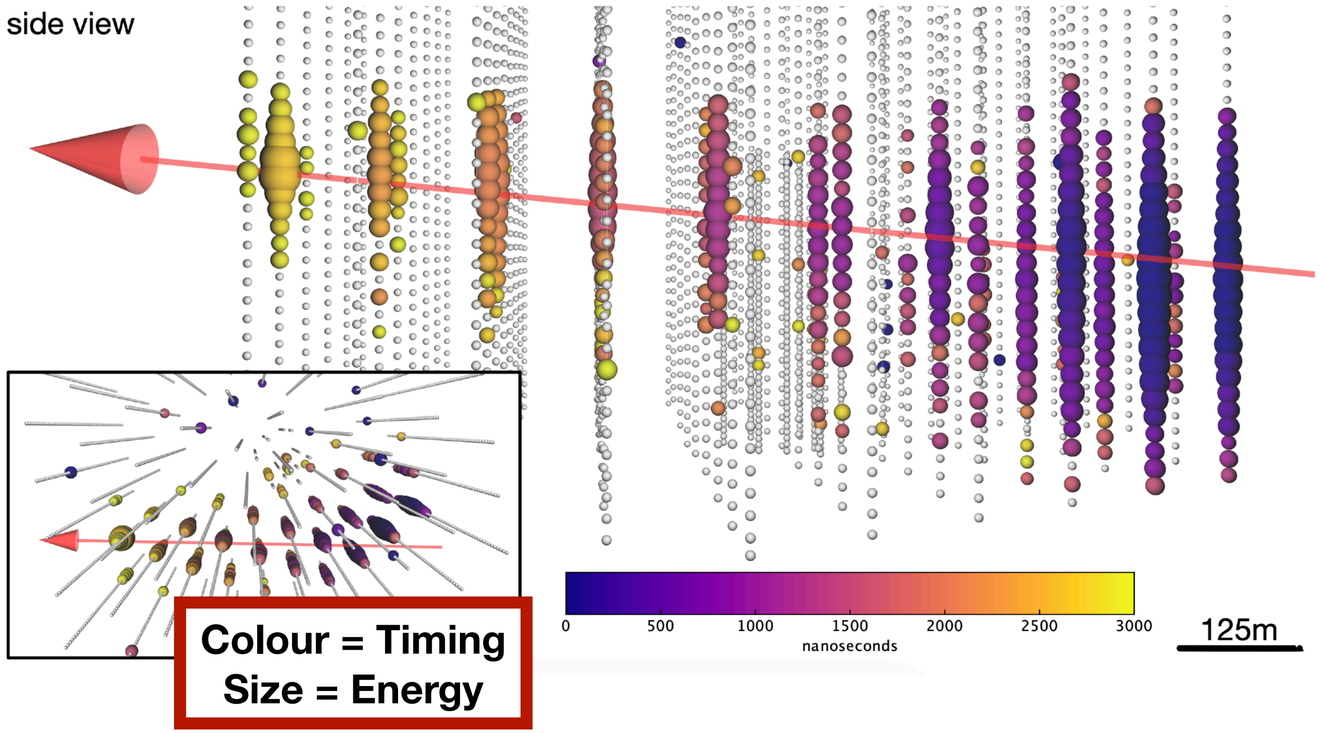


- Located at the geographic South Pole, collecting data for 10+ years.
- IceCube's instrumented volume includes 1 km^3 of ice, making it well suited to detect GeV+ energy neutrinos.
- IceCube detects O(100,000) neutrino interactions per year.
- Higher-level data is transmitted via satellite to the Northern Hemisphere in real-time.

IceCube Neutrino Observatory

IceCube "DOM"

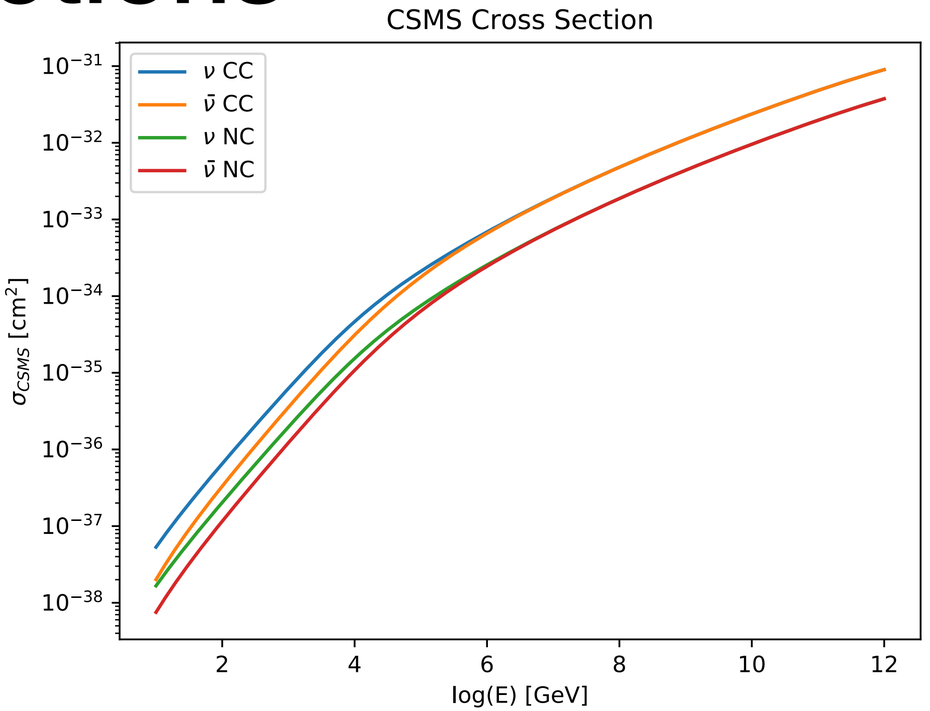




- When charged particles traverse the ice they create Cherenkov radiation, which is detected by Photomultiplier Tubes (PMTs).
- The PMTs are inside 5160 glass optical modules installed in-ice between 1450 m - 2450 m below surface.
- Using timing & charge information, IceCube reconstructs the energy and direction of the neutrino interaction.

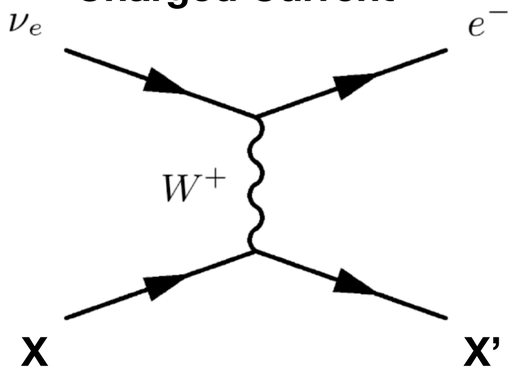
Neutrino Interactions

- Neutrino cross section grows with energy.
- For $E_\nu \gtrsim 40$ TeV Earth is no longer transparent:
  - CC interactions in Earth cause events to range-out before reaching IceCube*.
  - NC interactions in Earth result in a shift towards lower energies.

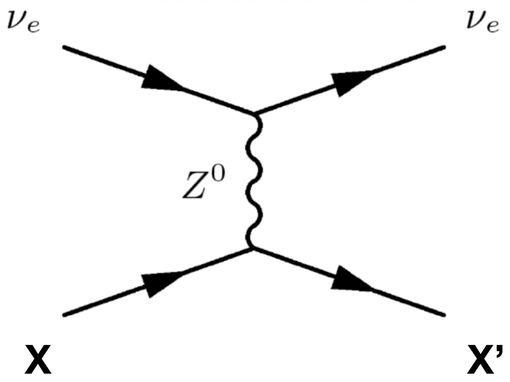


*Tree-level Diagrams

Charged Current



Neutral Current



Nucleon number density

$$e^{-n\,\sigma\,L} < 1$$

Cross Section

Earth Radius

$$L = 2\,R_\oplus\,\cos\theta_z$$

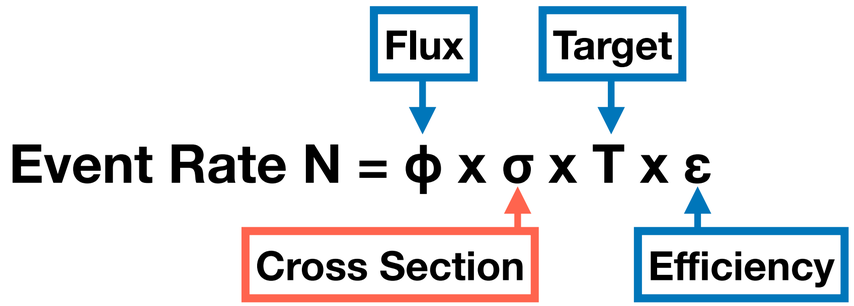
Path length

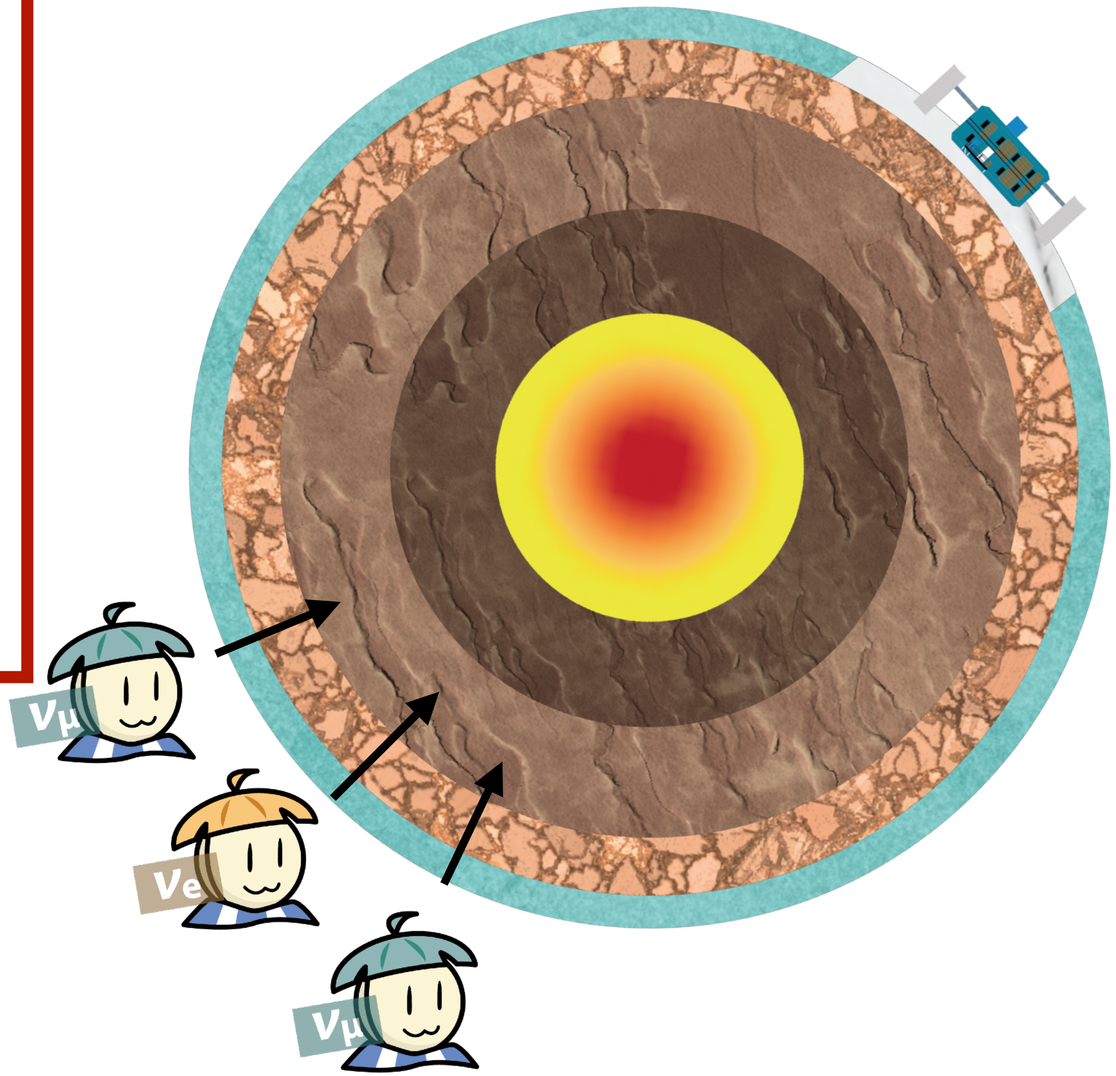
Neutrino Zenith

*Simplified situation

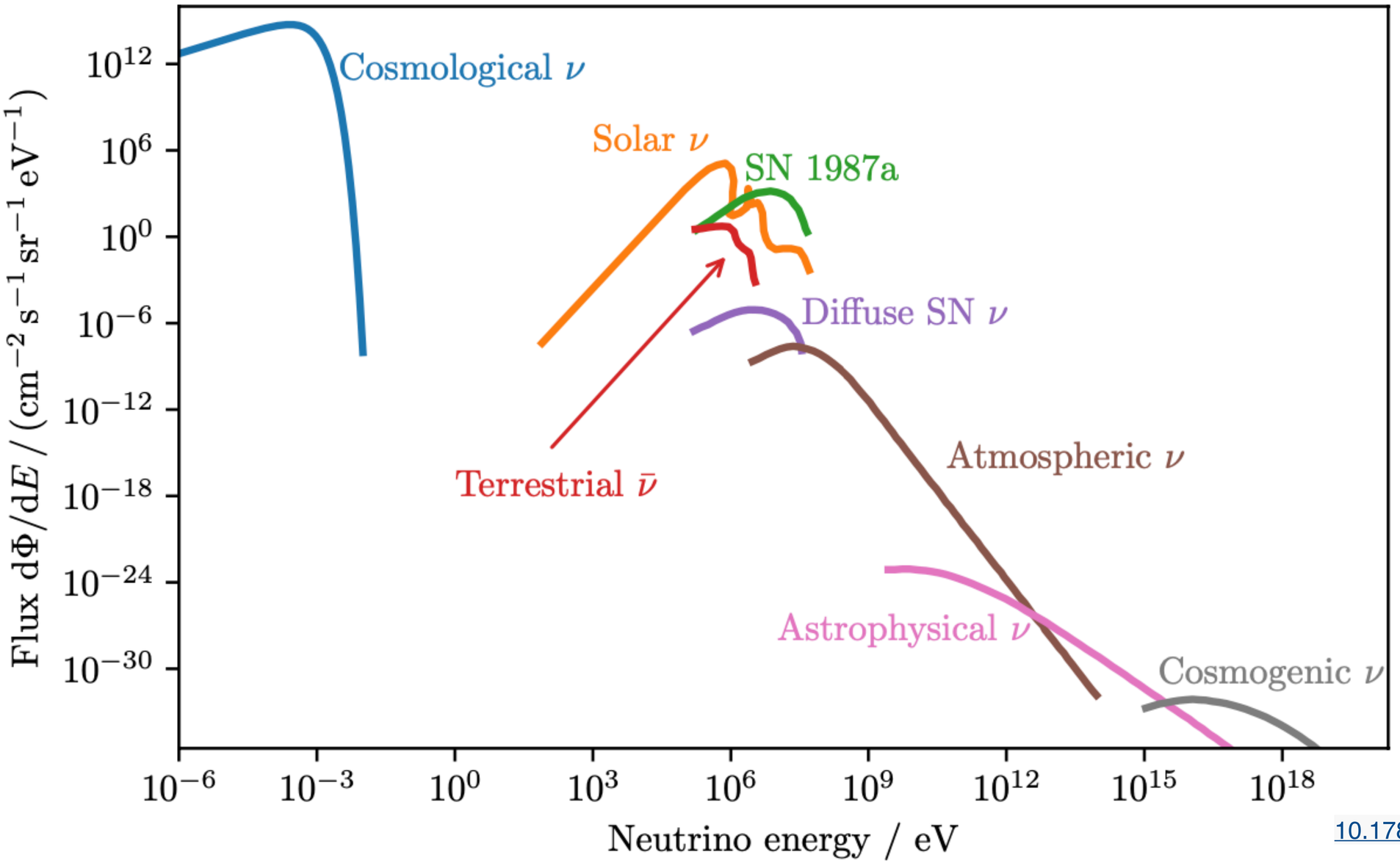
Neutrinos at IceCube

- As exclusively weakly-interacting particles, neutrinos can propagate great distances without interacting.
- IceCube can detect neutrinos which are both “down-going” and “up-going” (propagate through the Earth).
- Flavour tagging possible by identifying the signature for the out-going lepton, but ν/ν-bar extremely challenging on event level.



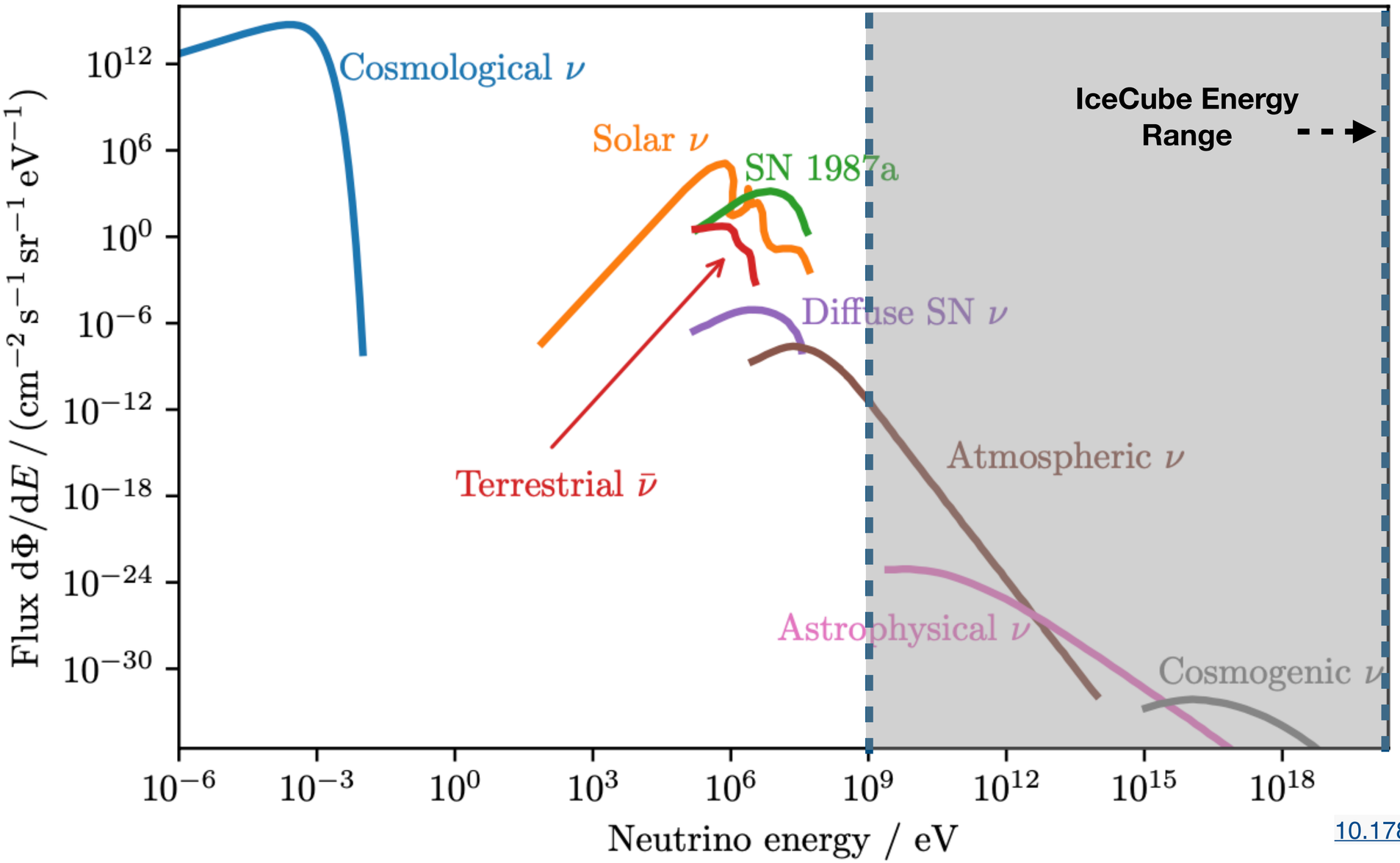


Neutrino Flux Overview



10.17877/DE290R-20335

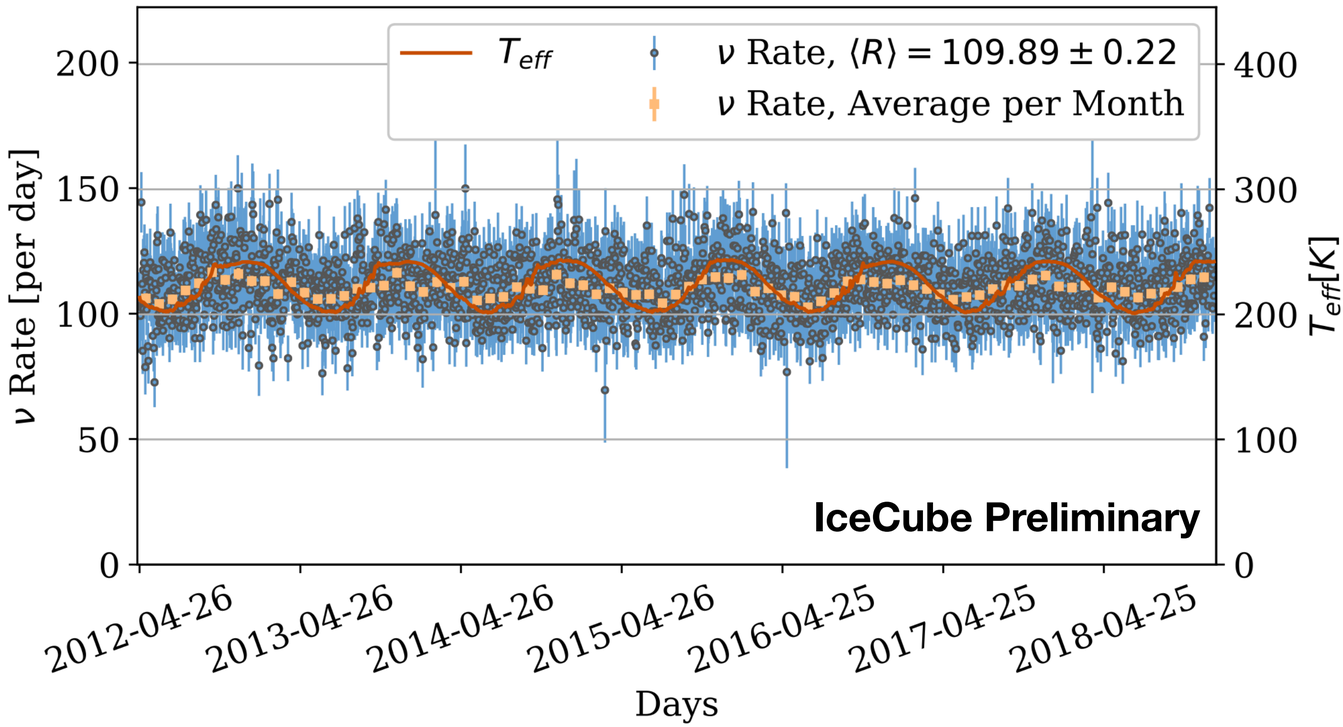
Neutrino Flux Overview



10.17877/DE290R-20335

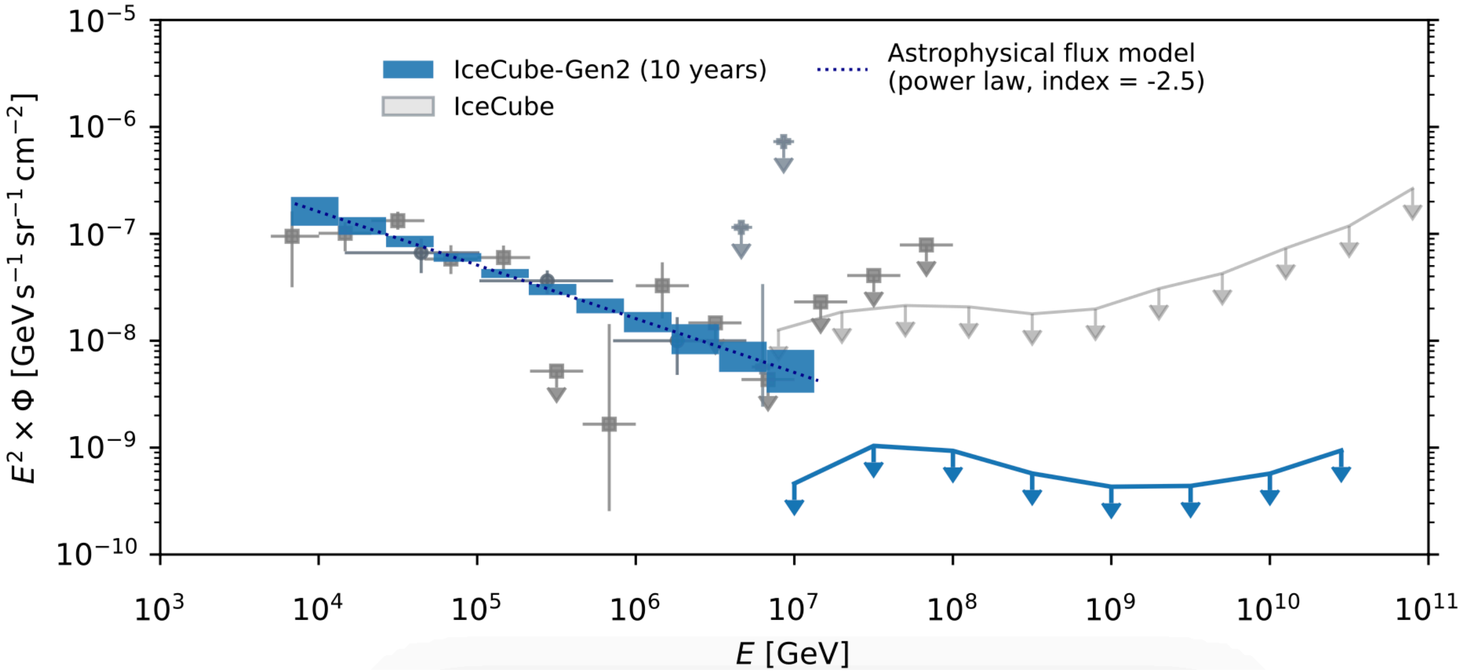
Atmospheric Neutrino Flux

- Atmospheric neutrinos produced primarily by π/K decays.
- Due to the rapidly falling spectrum with energy, the atmospheric neutrino spectrum is the dominant source of neutrinos in IceCube.
- Thanks to its size, IceCube has a large amount of neutrinos to work with - can even observe variations in the seasonal atmospheric neutrino flux.



Astrophysical Neutrino Flux

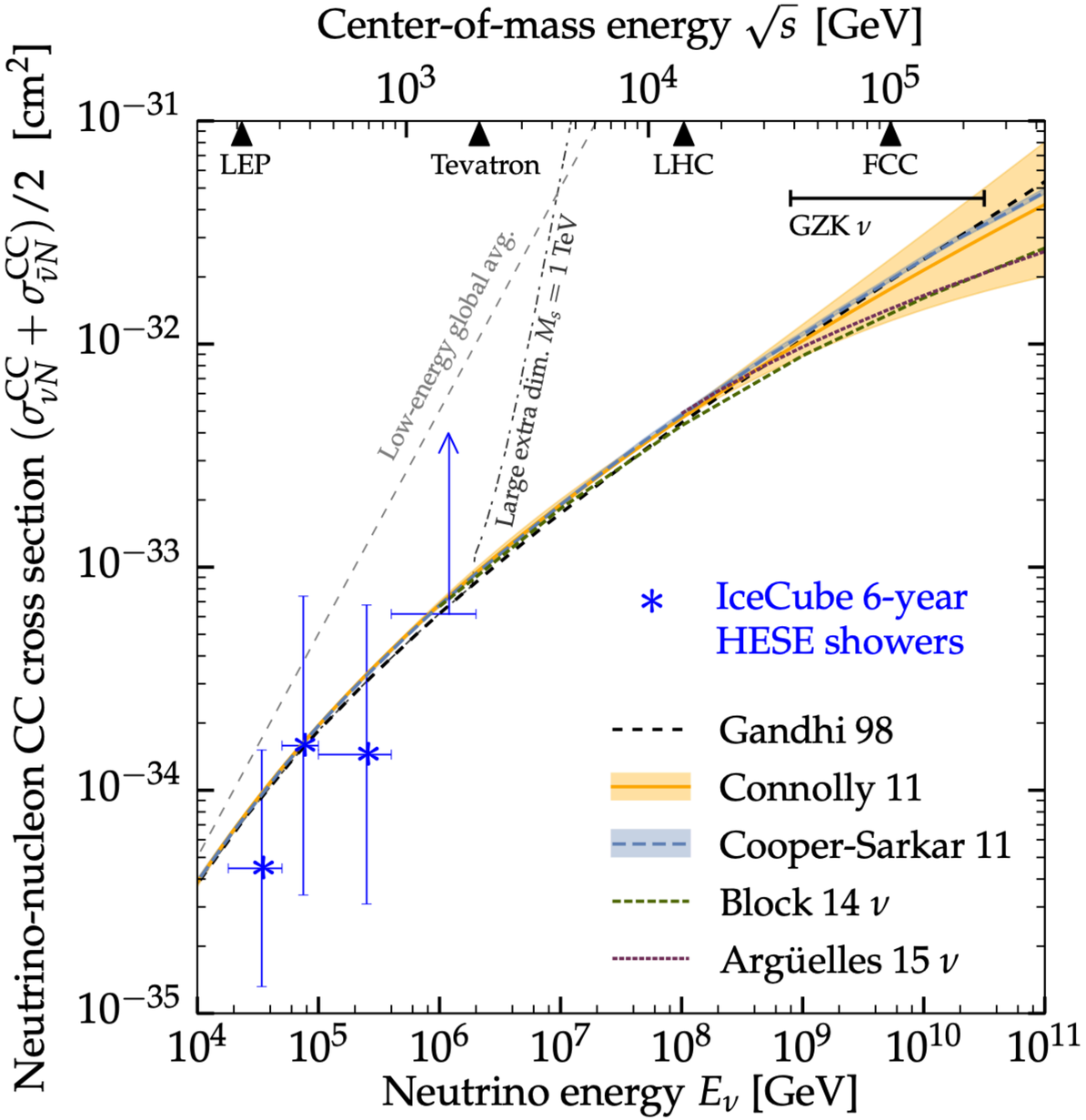
- Astrophysical neutrinos produced in cosmic accelerators up to very high energies.
- Precise sources unknown (“diffuse”).
- Production flavours also unknown - assumed that over long propagation distances mixed to equal amounts of ν_e:ν_μ:ν_τ.
- Number of events observed is small O(100s) in 10+ years of data.

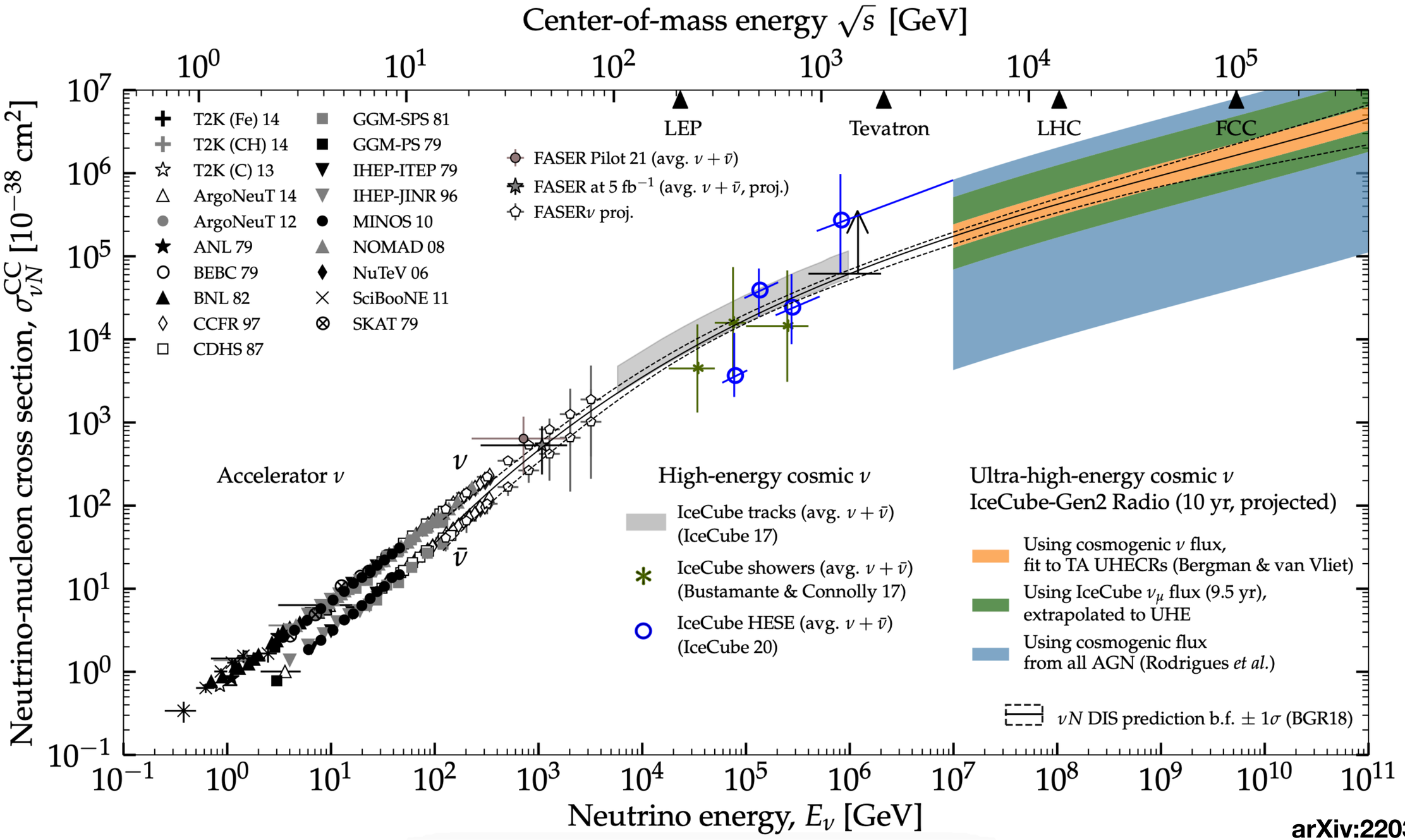


arXiv:2203.08096

Cross Section Measurements with IceCube

- Measurements using IceCube's track (ν_μ CC) & cascade selection have been performed (ν_e CC + ν_τ CC + NC).
- Current results are in agreement with several cross section models (ex. CSMS).
- Results disfavour certain BSM scenarios, but pushing to higher energies probe additional models.
- Significantly more data is available since these measurements were performed! - Better TeV+ limits?





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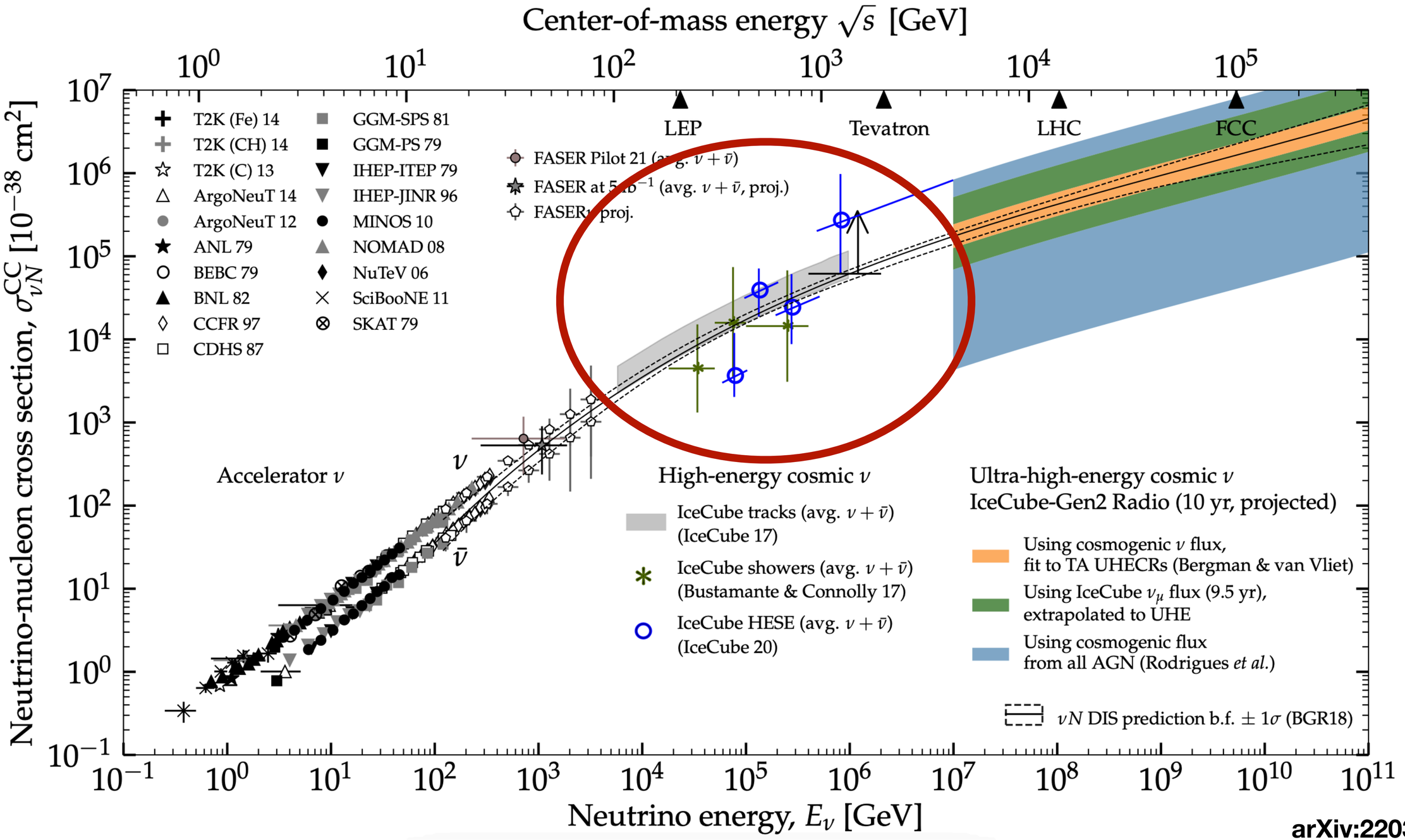

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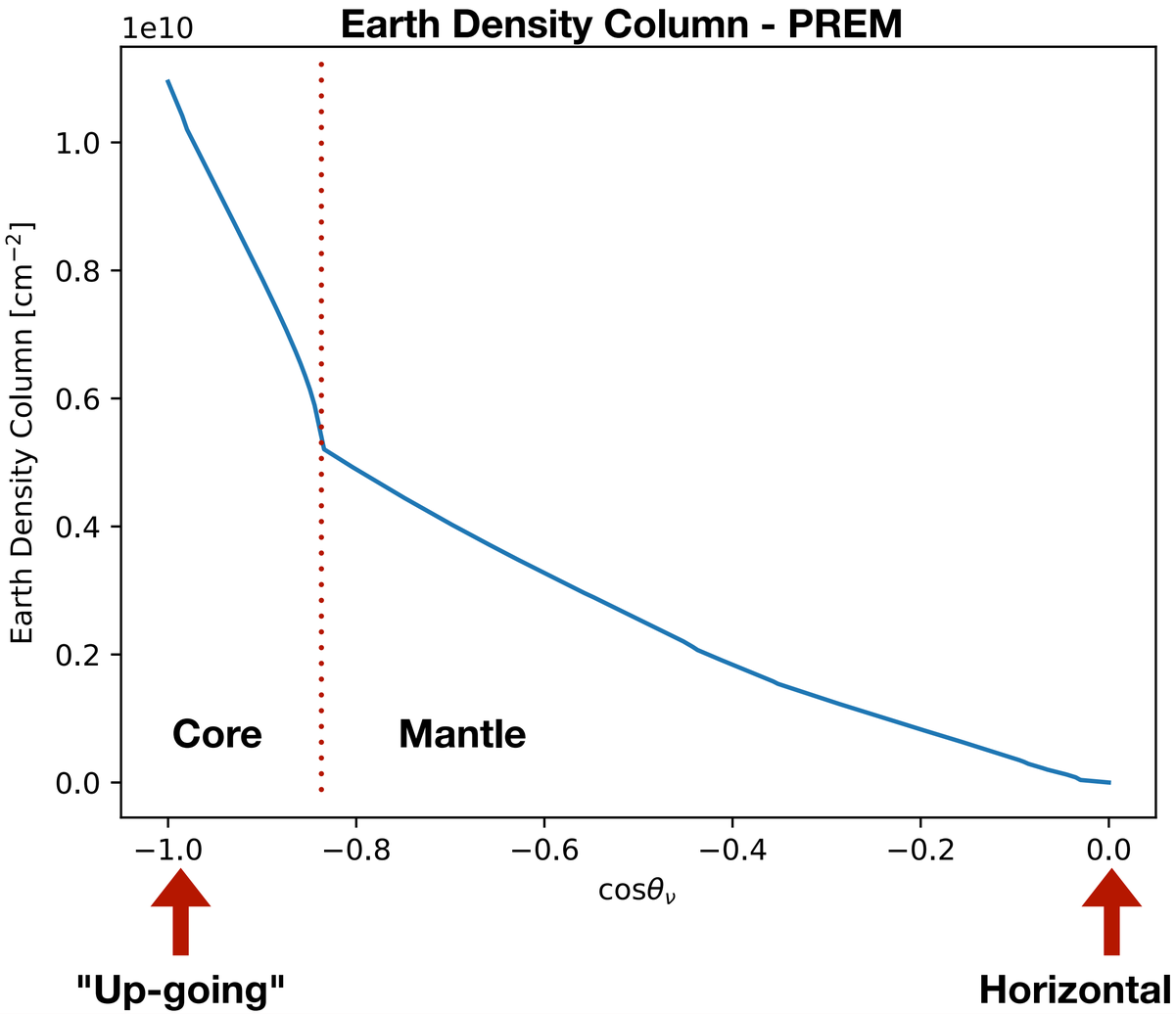
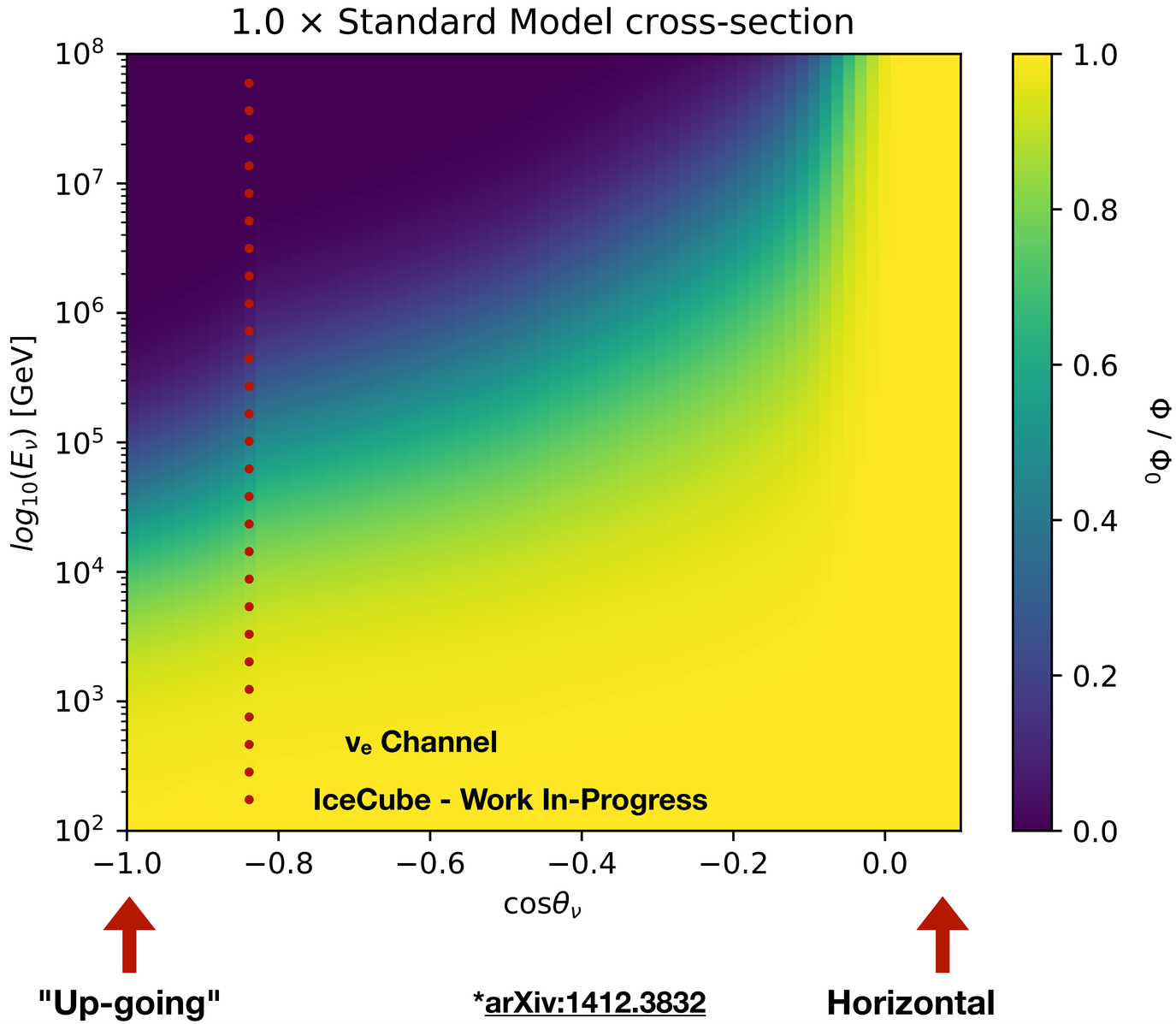
Earth Density Column

- Attenuation experienced by neutrinos is directly related to their propagation distance and density of the matter.
- Because of IceCube's location, the cosine of the neutrino's zenith can be conveniently translated to a column of traversed earth.
- The commonly used Preliminary reference Earth model (PREM) is shown here.
- The impact of the sharp increase in density in the transition region (core to mantle) can be clearly seen on the following slides in the expected flux at IceCube.



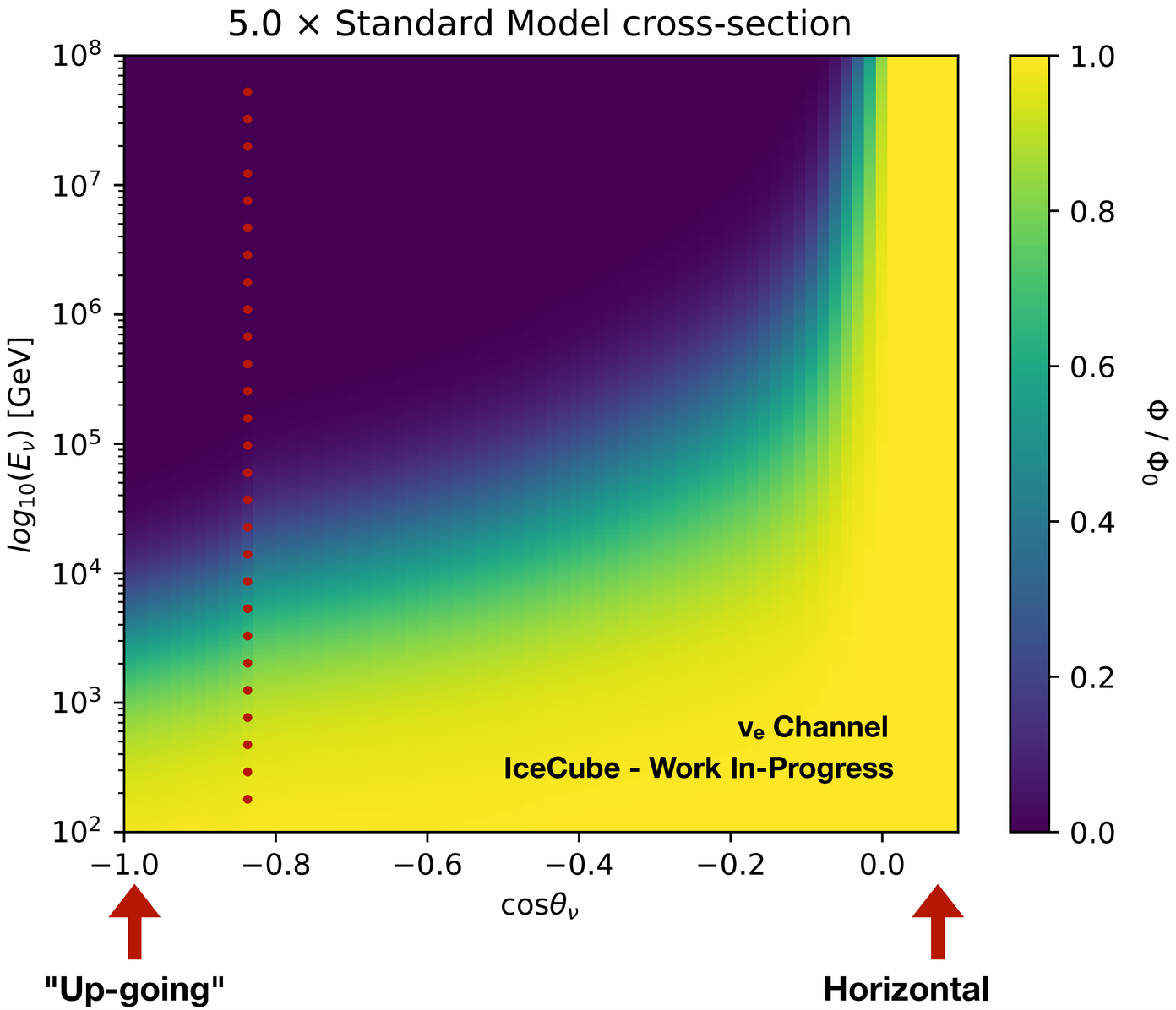
Flux Propagation

- Because of the in-Earth interactions, the flux reaching IceCube is modified.
- To account for effects like NC interactions or τ-regeneration, the flux ϕ_0 must be propagated to the detector.
- A semi-analytical solution from the open-source SQuIDS/nuSQuIDS software packages* is used for the propagation.
- Performing this propagation returns the new flux with respect to energy & $\cos(\theta_z)$ at the detector.
- As E_ν and the size of the density column increase, the contributions from the original flux at those energies decrease.



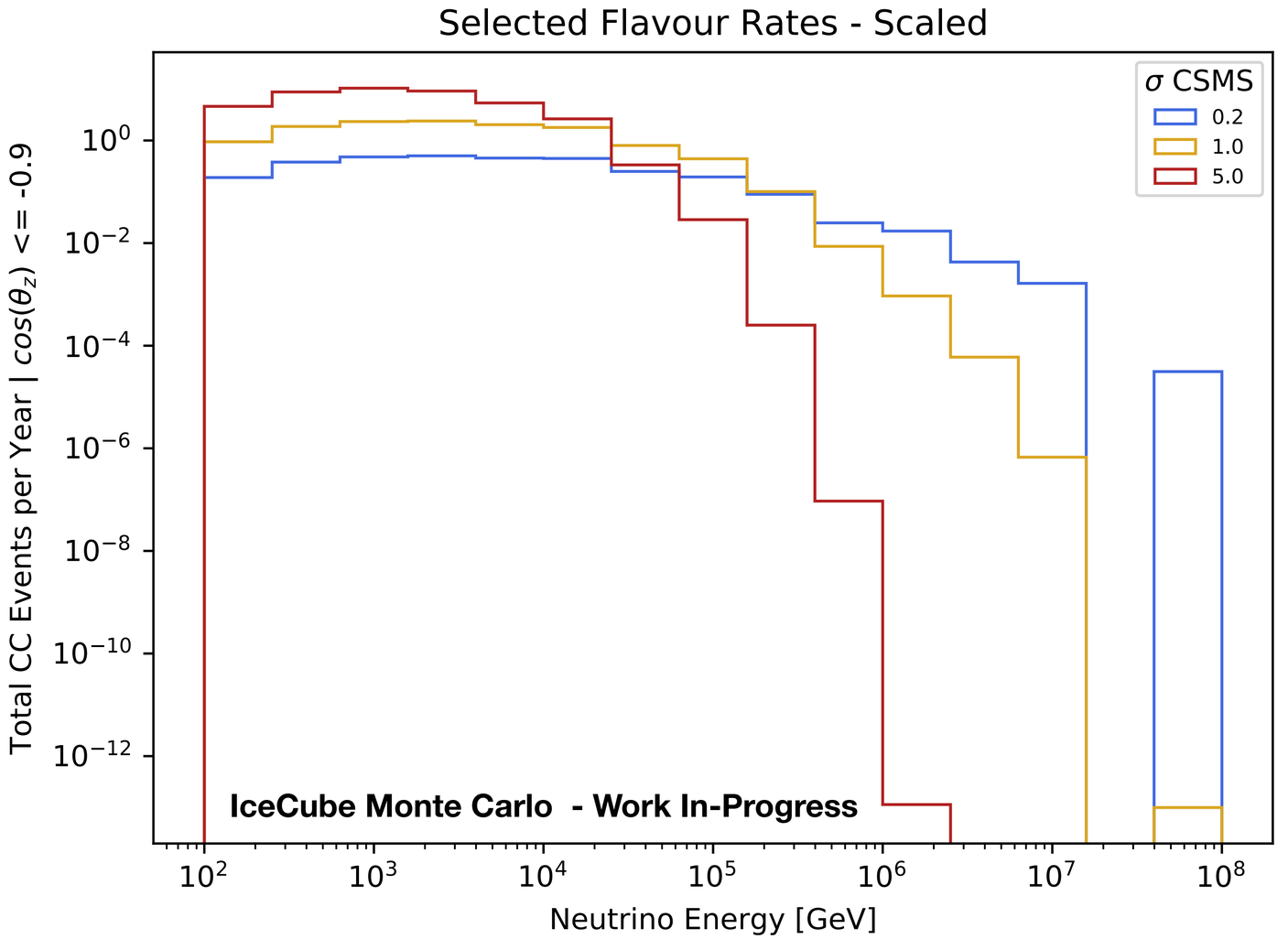
Flux Propagation

- The in-Earth interactions are a function of the neutrino cross section.
- For example, propagating the same flux (ϕ_0) with 5x enhanced cross section results in a reduction of the up-going flux reaching IceCube.
- This is most obvious for higher energy neutrinos or those which pass through more dense regions of the Earth.
- Naturally, interactions from neutrinos which do not pass through the Earth will be enhanced.



Cross Section Measurements with IceCube

- For visualisation, we can choose large scaling factors for the CSMS cross section, and pick events propagating through large amounts of earth.
- ex. an increase in the cross section:
  - Low energy events are enhanced.
  - High energy (up-going) events are suppressed.

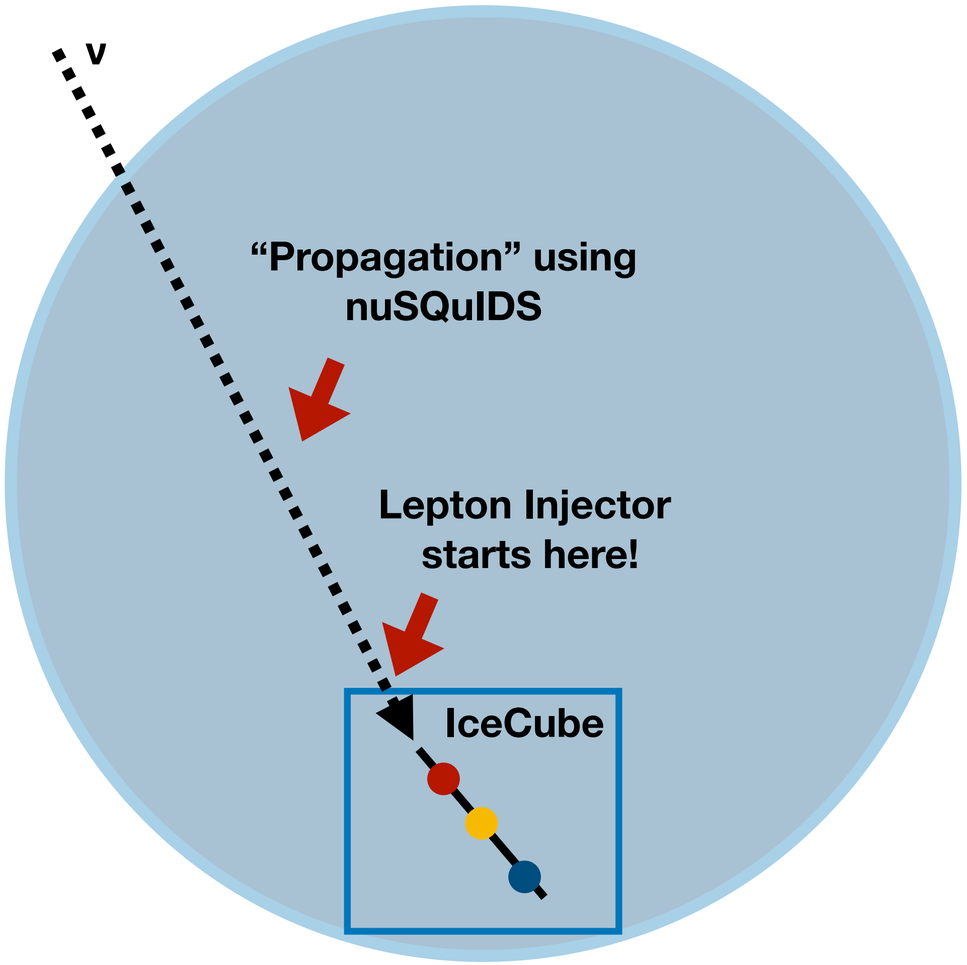


"Global Fit" Cross Section Analysis

- Combine the orthogonal IceCube “track" (νμ CC) and “cascade" (ν_e CC, ν_τ CC/NC) selections.
- Track selection has high efficiency & rate (~2.4 mHz), reconstruction of μ direction very reliable.
- Cascade selection has no zenith cut (up/down-going events), better sensitivity to higher energy events, and robust energy reconstruction.
- Both selections have very low backgrounds.

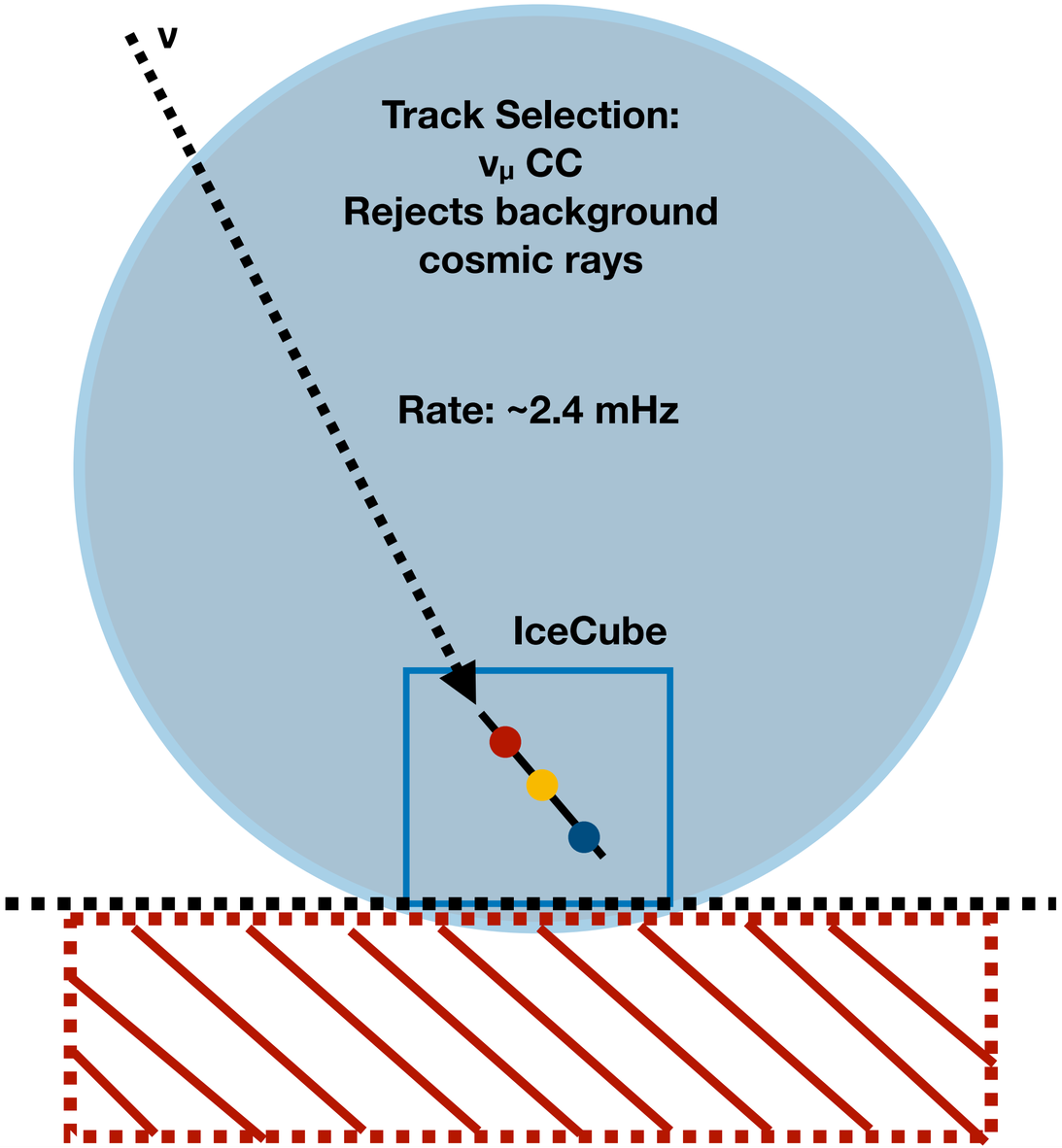
Simulation Approach

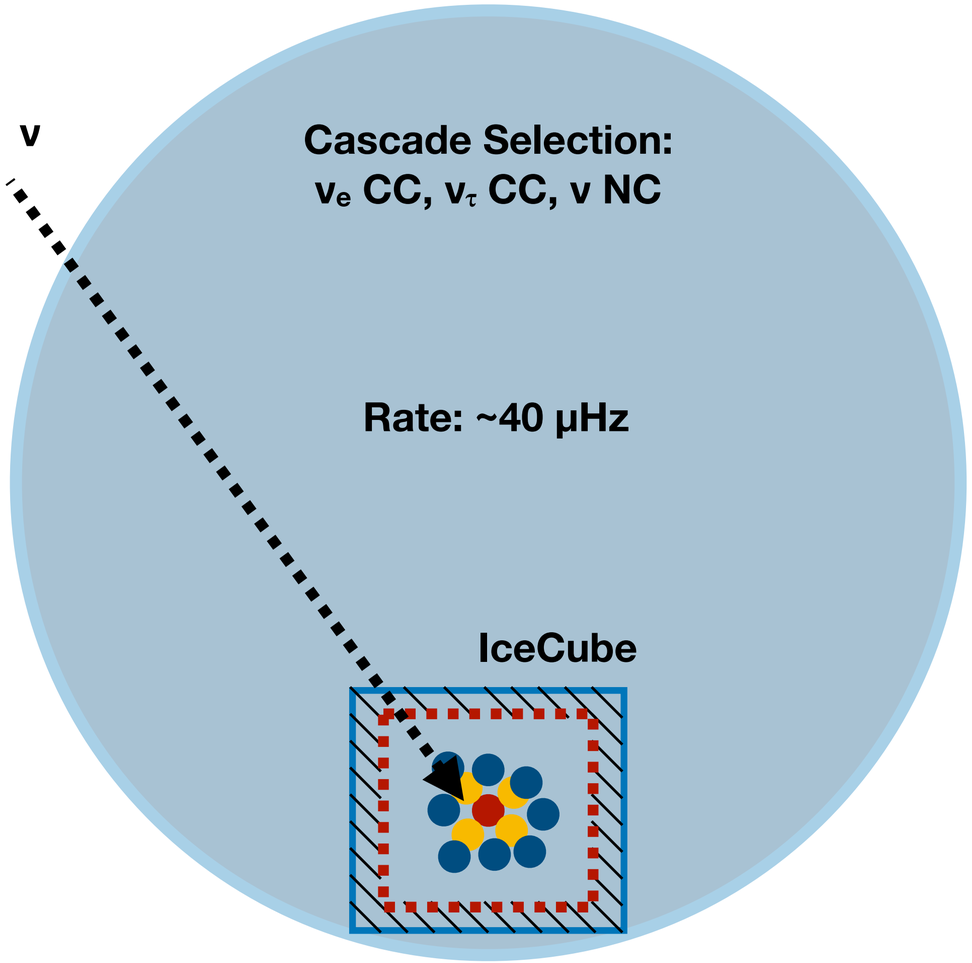
- nuSQuIDS propagates the Atmospheric & Astrophysical ϕ_0 from the Earth's surface to re-weight event by event at the detector.
- Fluxes with a range of cross section normalisations are injected and an event-by-event description of the interaction weight is parameterised.
- This means the propagated ϕ can be modified without needing to re-simulate the entire Monte Carlo.
- Another benefit is correctly handling the treatment of re-interactions within the Earth during propagation as the cross section is modified (not true for other IceCube MC approaches).



At-Detector Injection

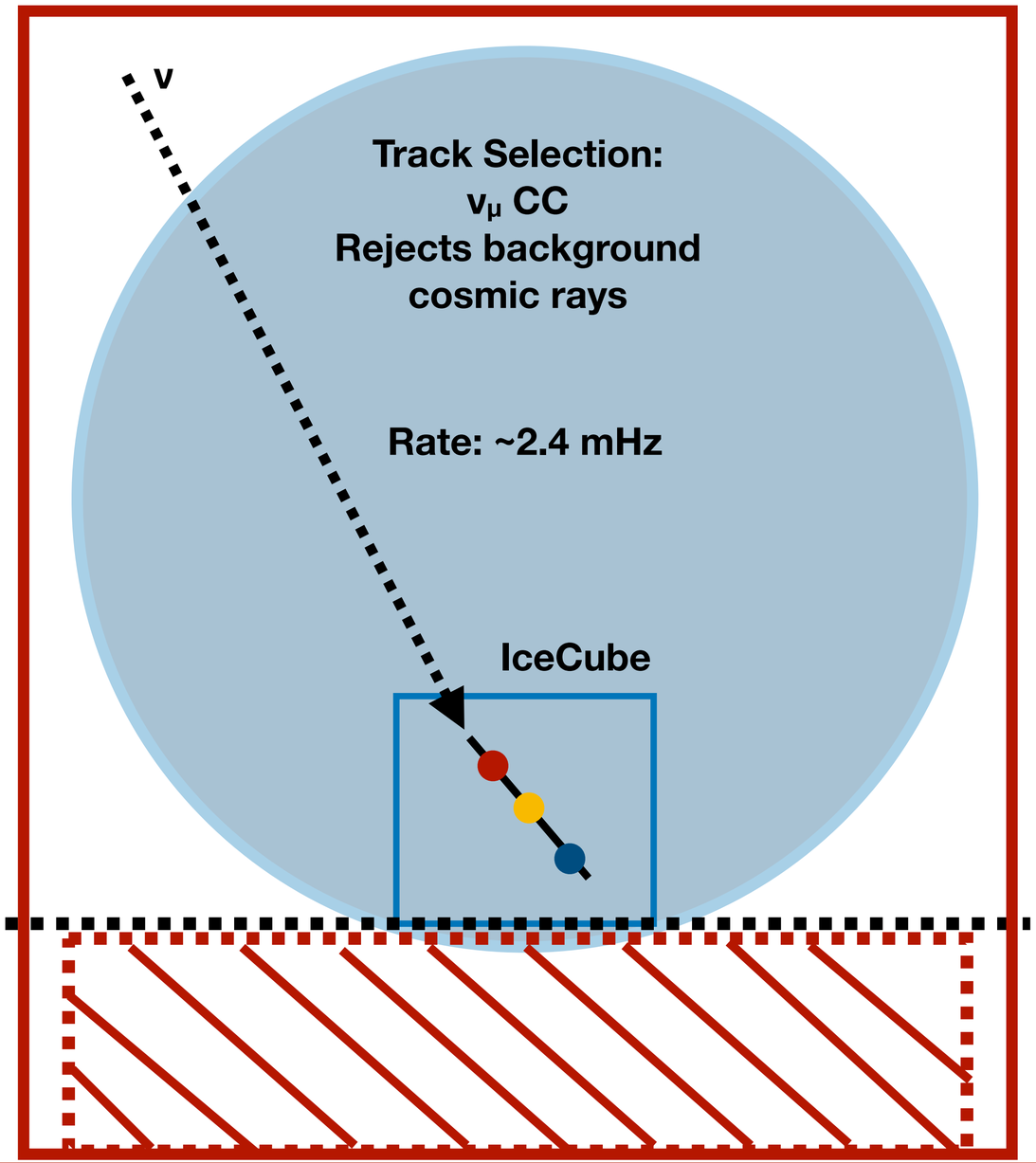
Selections

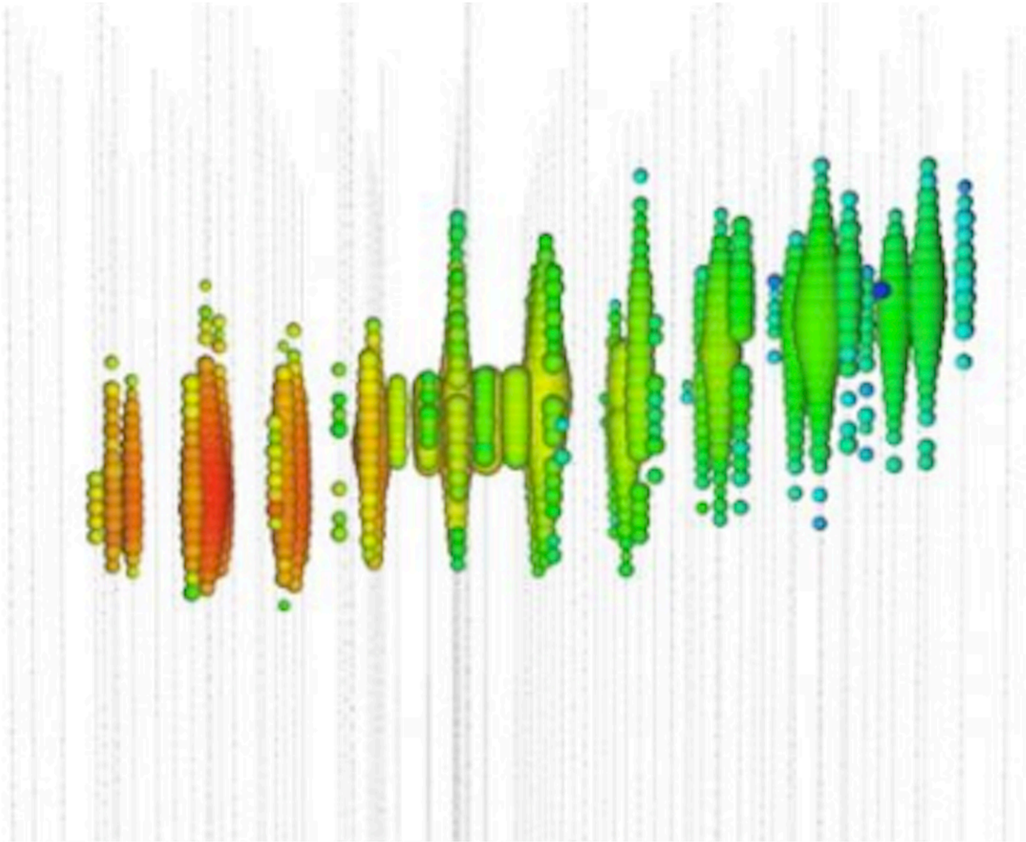




Track: PhysRevD.89.062007
Cascade: arXiv:2001.09520

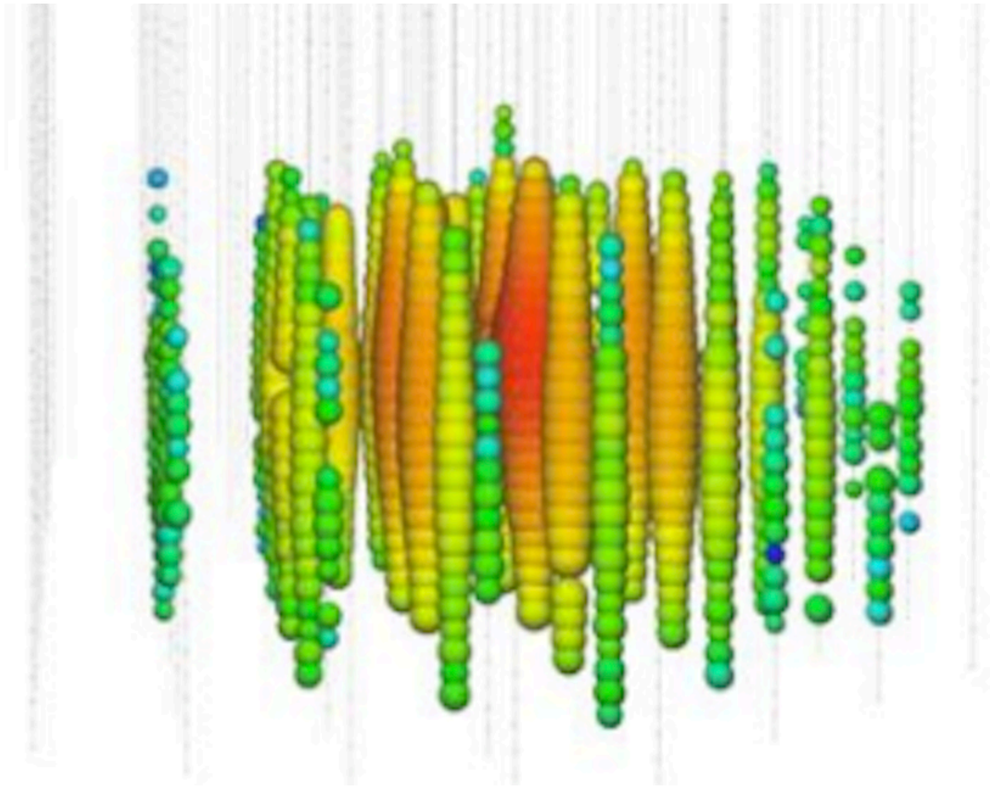
Selections



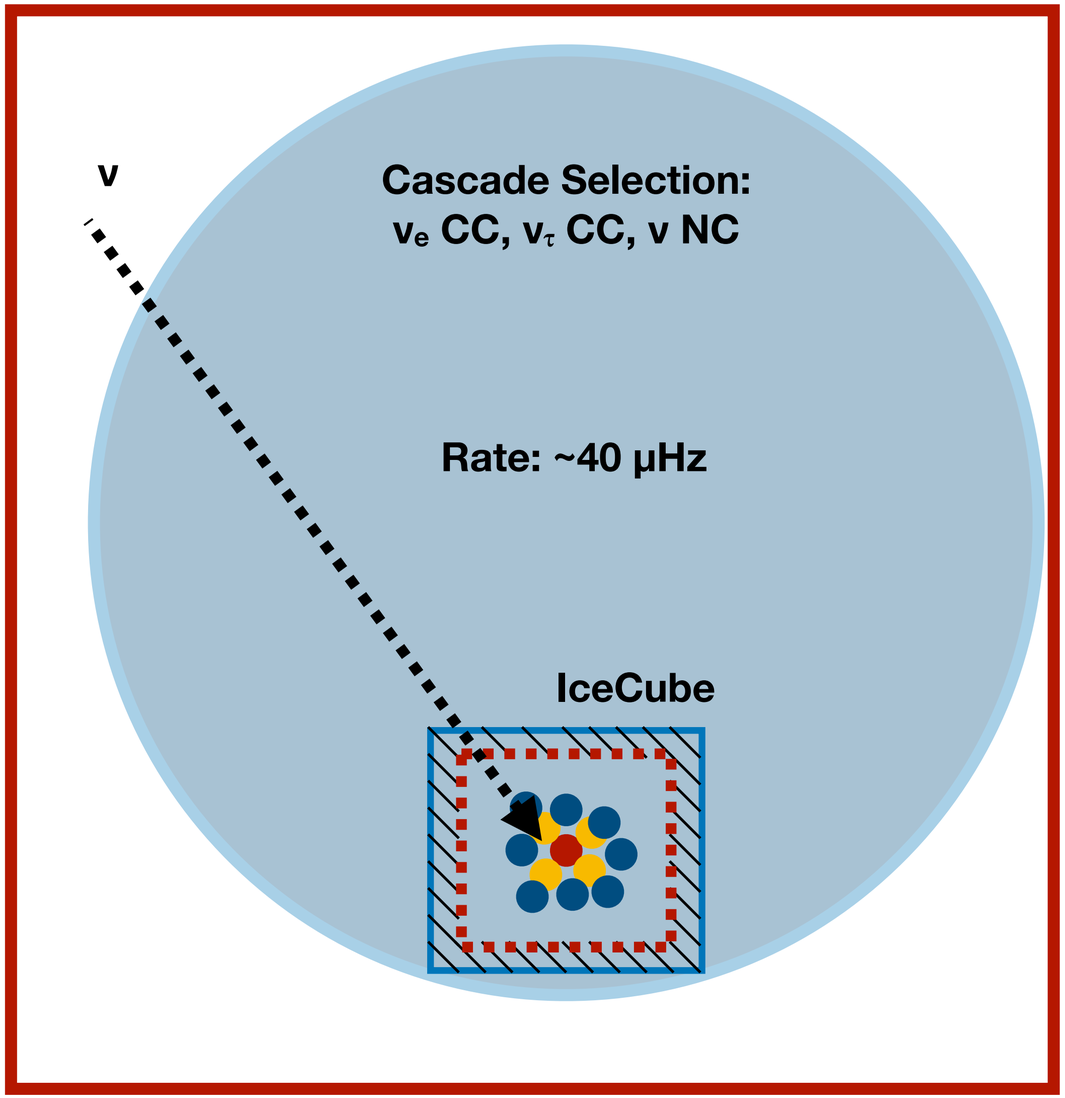


Track Event Display

Selections



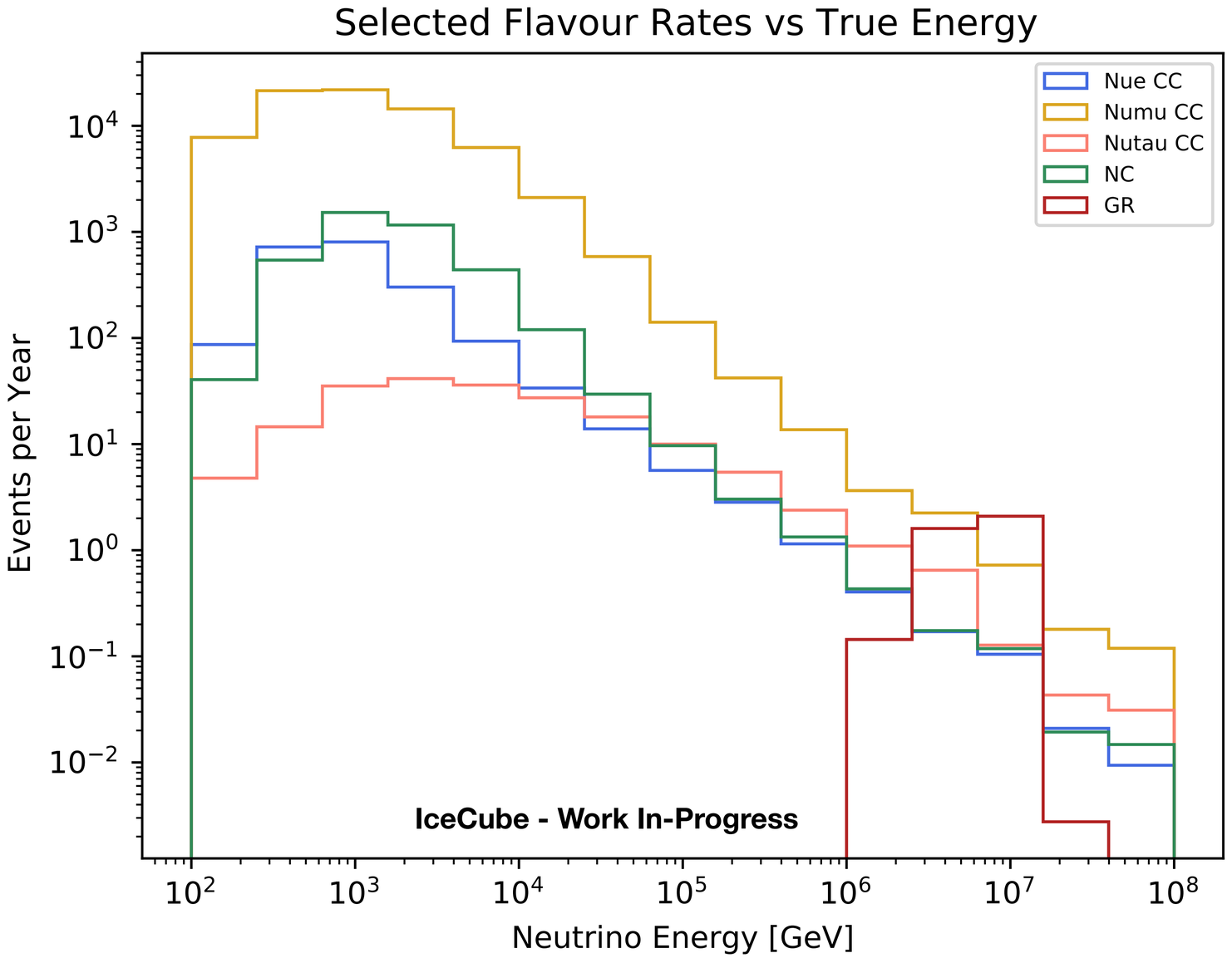
Cascade Event Display



Track: PhysRevD.89.062007
Cascade: arXiv:2001.09520

Selection Rates

- Event rates using combined track & cascade selection.
- ν_μ CC events compose majority of selection, due to high flux contribution.
- At higher energies, ν_e CC ν_τ CC, and NC start to contribute significantly to the total.
- As energy increases:
  - Flux ↓
  - Absorption (Propagation) ↑
  - Interaction Probability ↑



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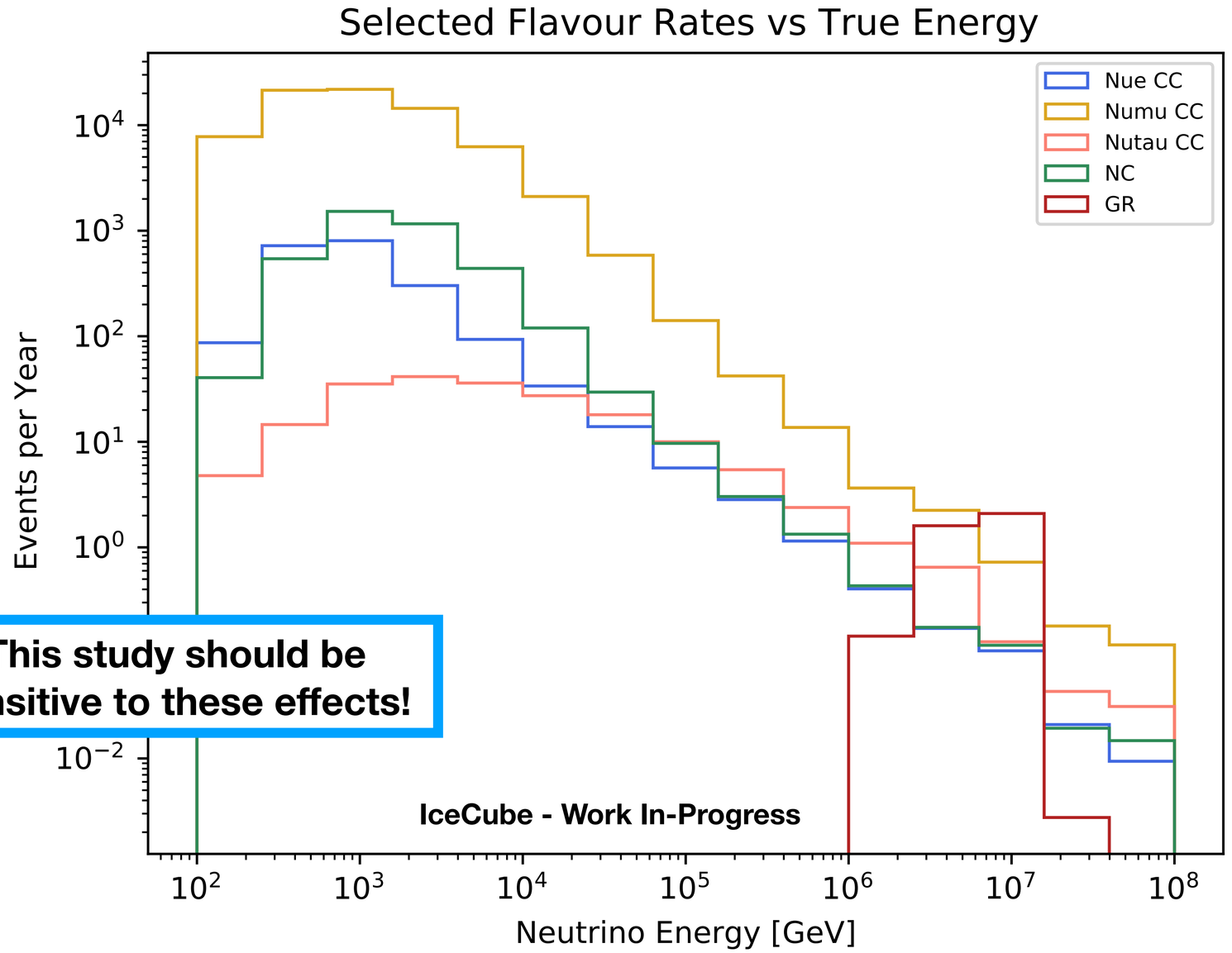

This study should be sensitive to these effects!

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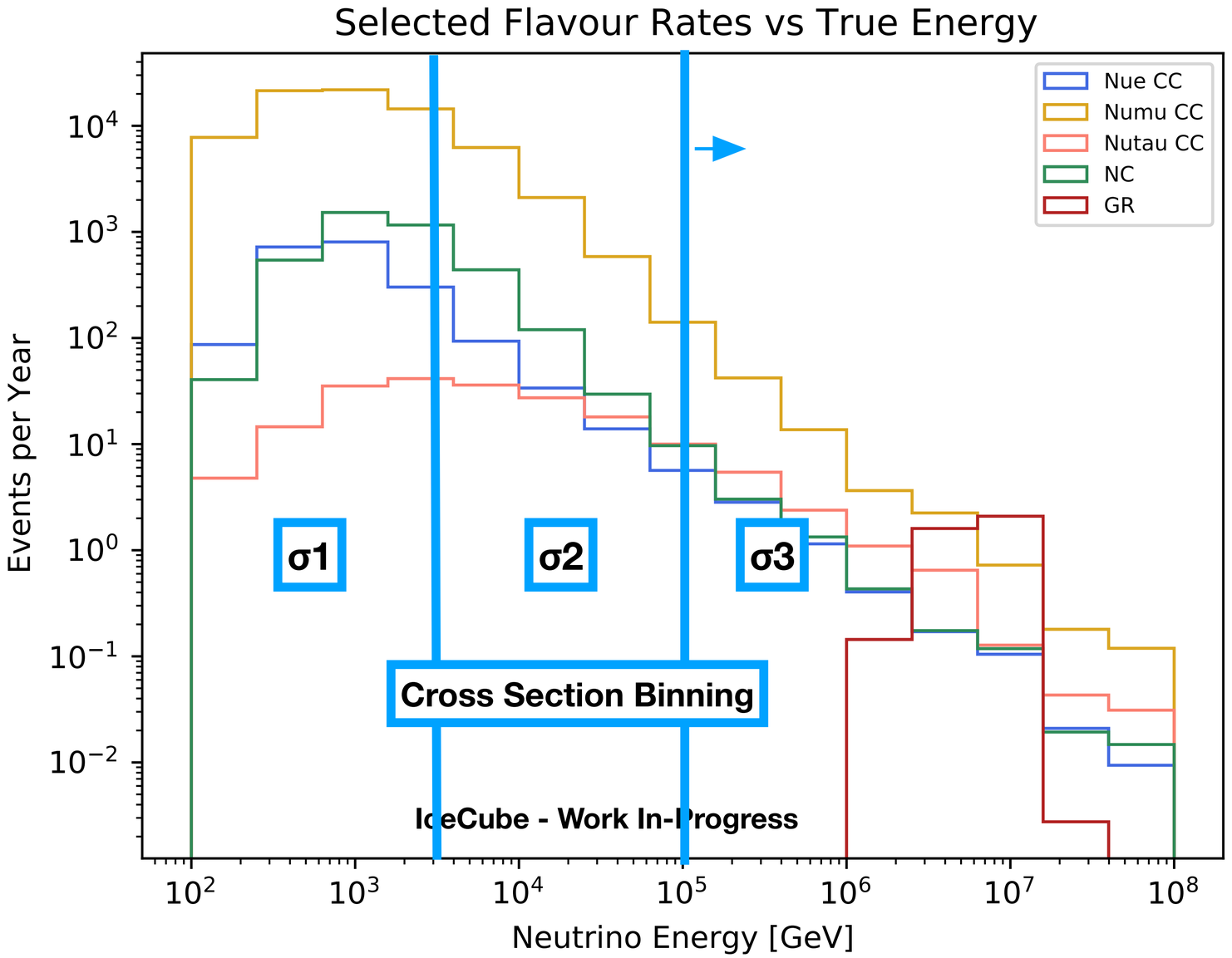
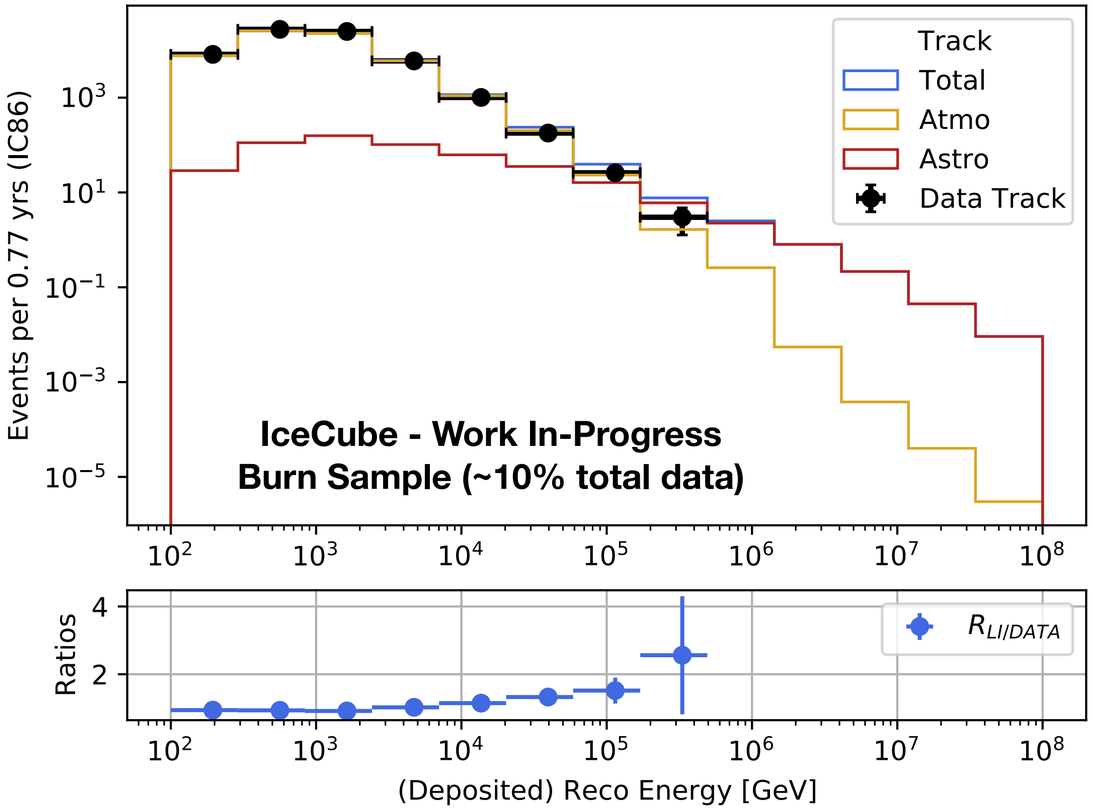
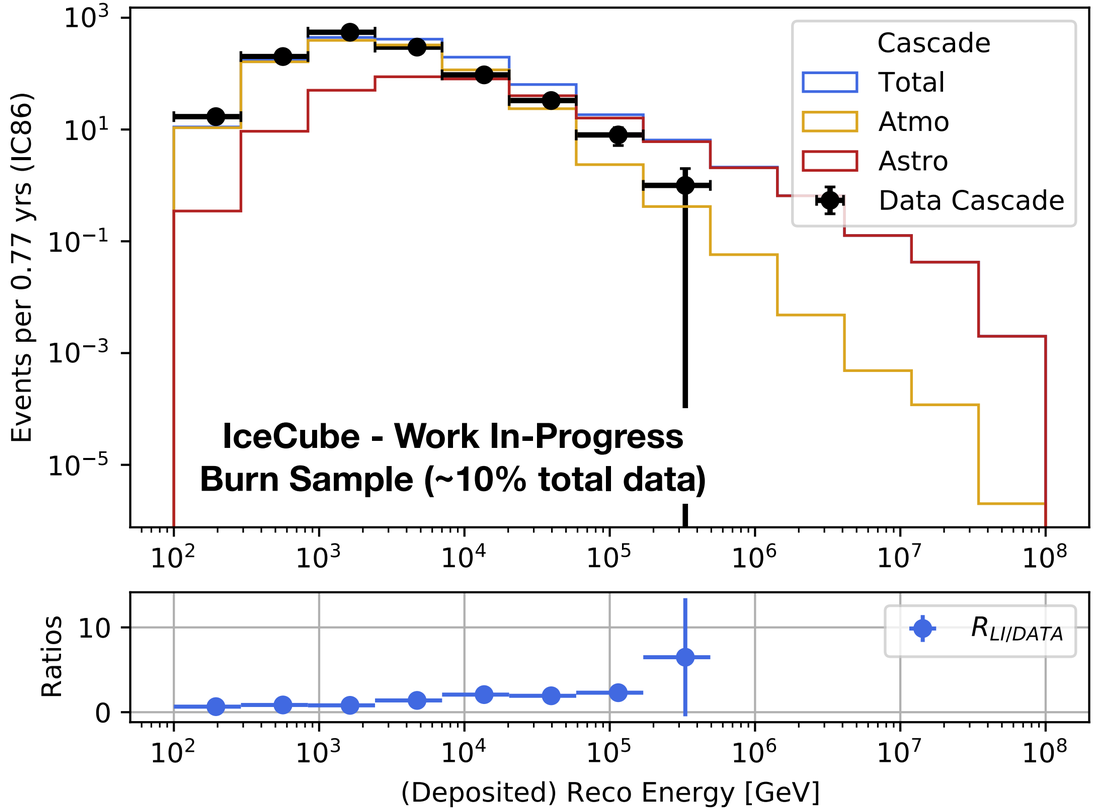




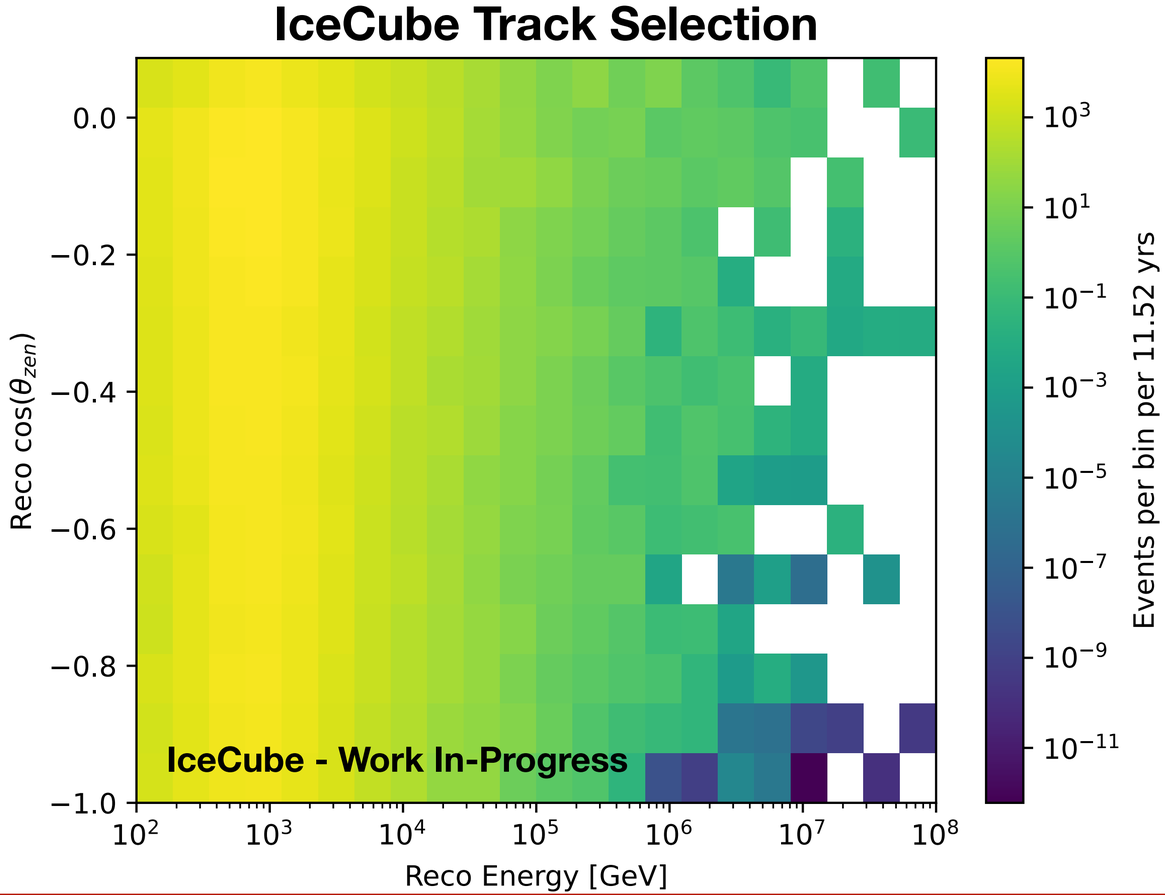


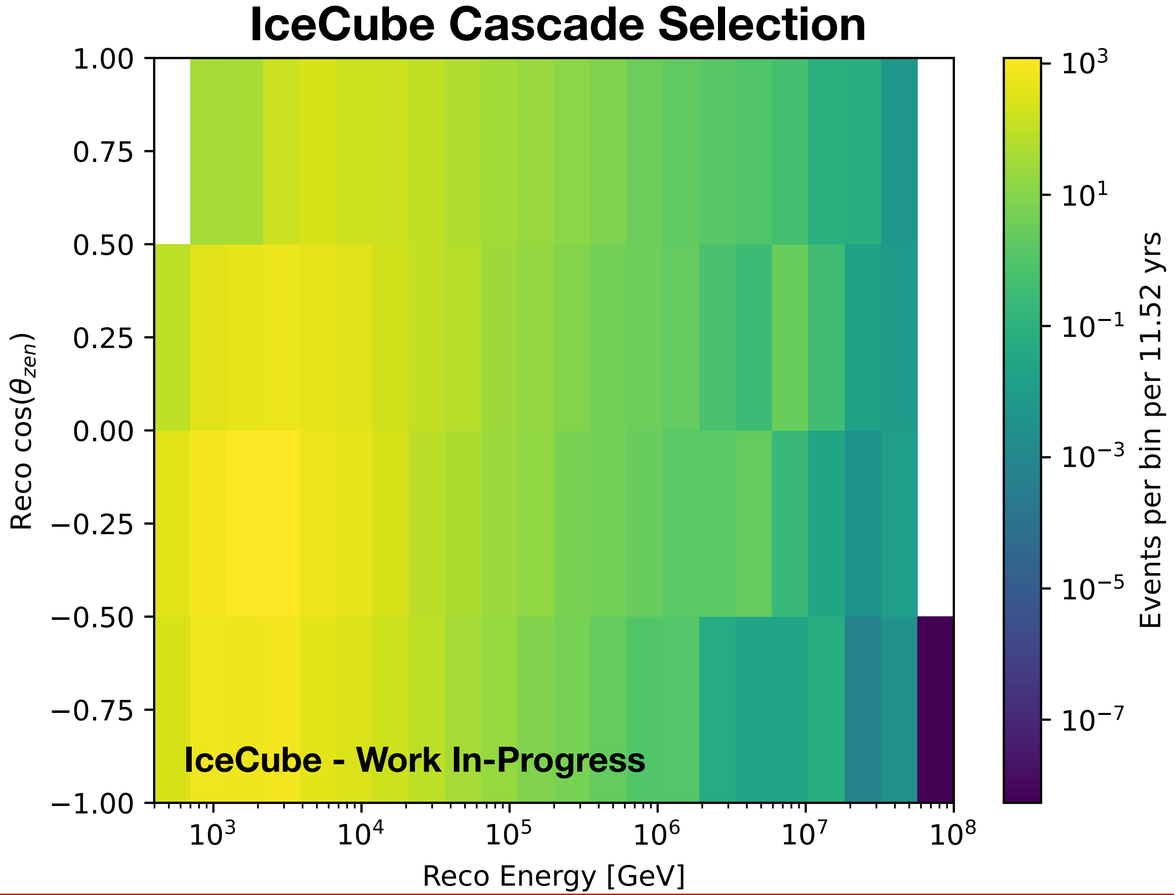
- Contributions from both Atmospheric and Astrophysical fluxes are relevant at different energy ranges. Important for the cross section versus energy.
- Burn sample data comparison to Monte Carlo shows reasonable initial agreement.
- Even in the full IceCube dataset, statistics at higher energies are limited, so final cross section energy bin is wide.

Likelihood-based Approach

- Perform a forward-folding binned likelihood calculation: $\mathcal{L}(\mu_i) = \prod_j \mathcal{L}^j_{bin}(\mu_j; d_j)$.
- From Monte Carlo the bin expectations can be set as μ_j , and determined by data d_j.
- Include my 3 cross section bins, with both normalisation and shape terms for the Atmospheric & Astrophysical fluxes - 7 dimensional minimisation.
- The cross section scaling (how the event weights change) can be de-coupled from the flux normalisations primarily by examining the up-going events. However the parameters are still correlated - more investigation still in progress.

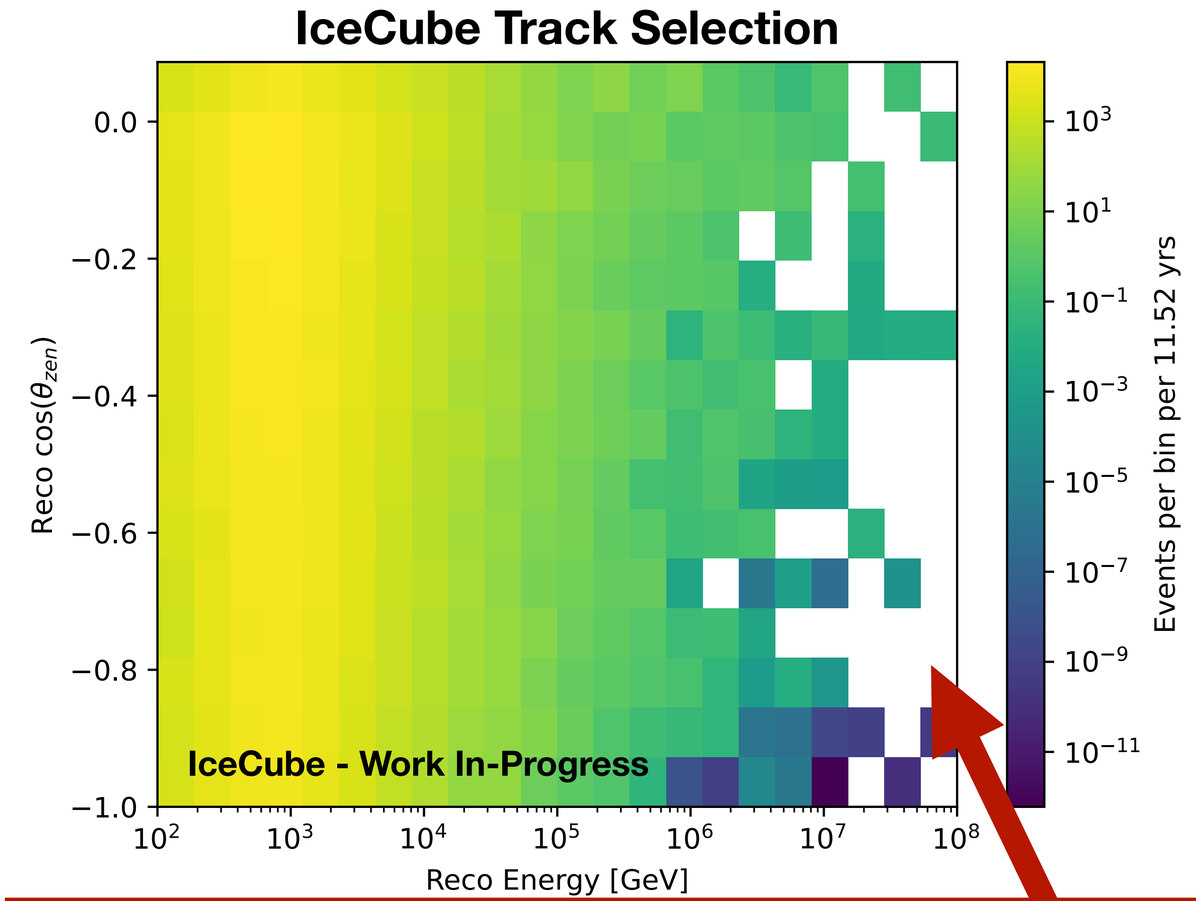
Likelihood-based Approach

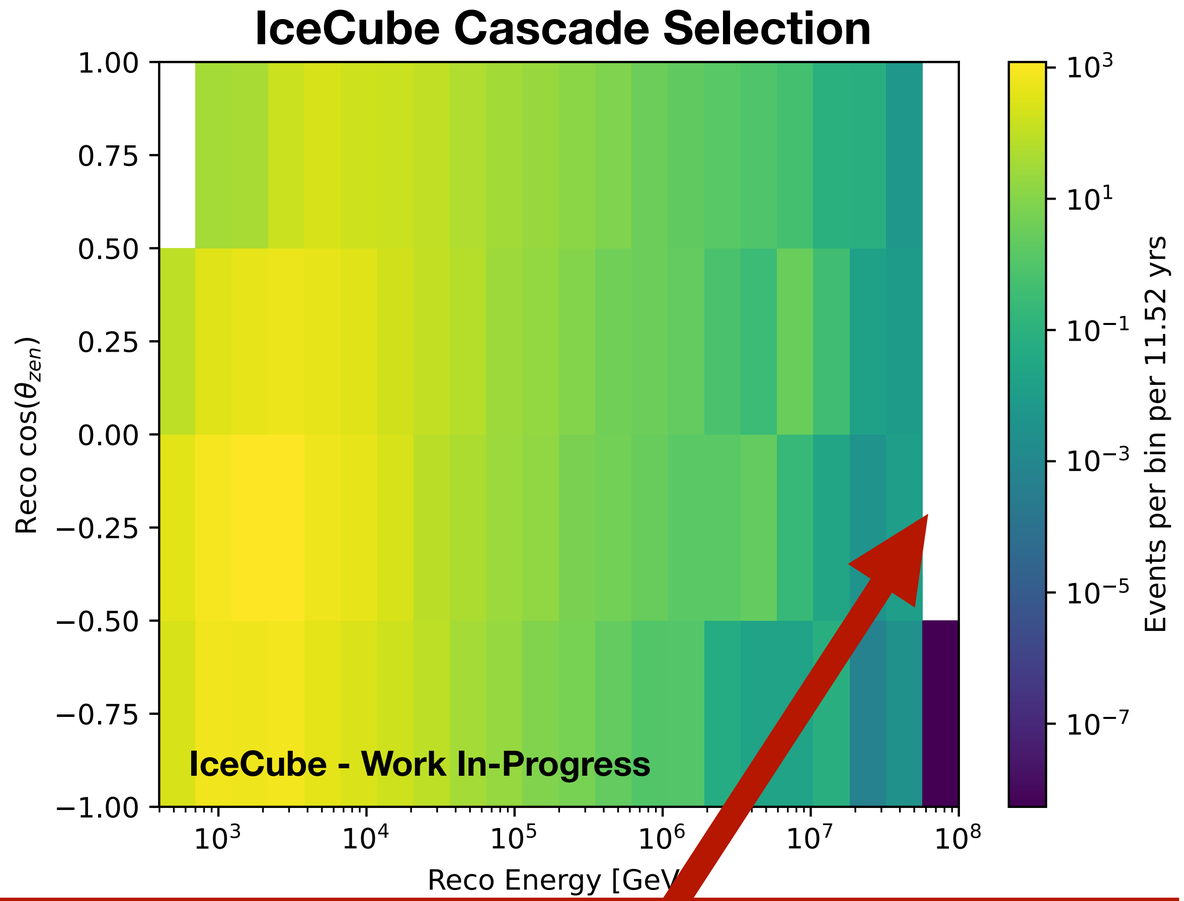




- Binning schemes chosen considering strengths of individual selections & available Monte Carlo.
- Note: additional Monte Carlo to be generated (high energy events are time-intensive).

Likelihood-based Approach





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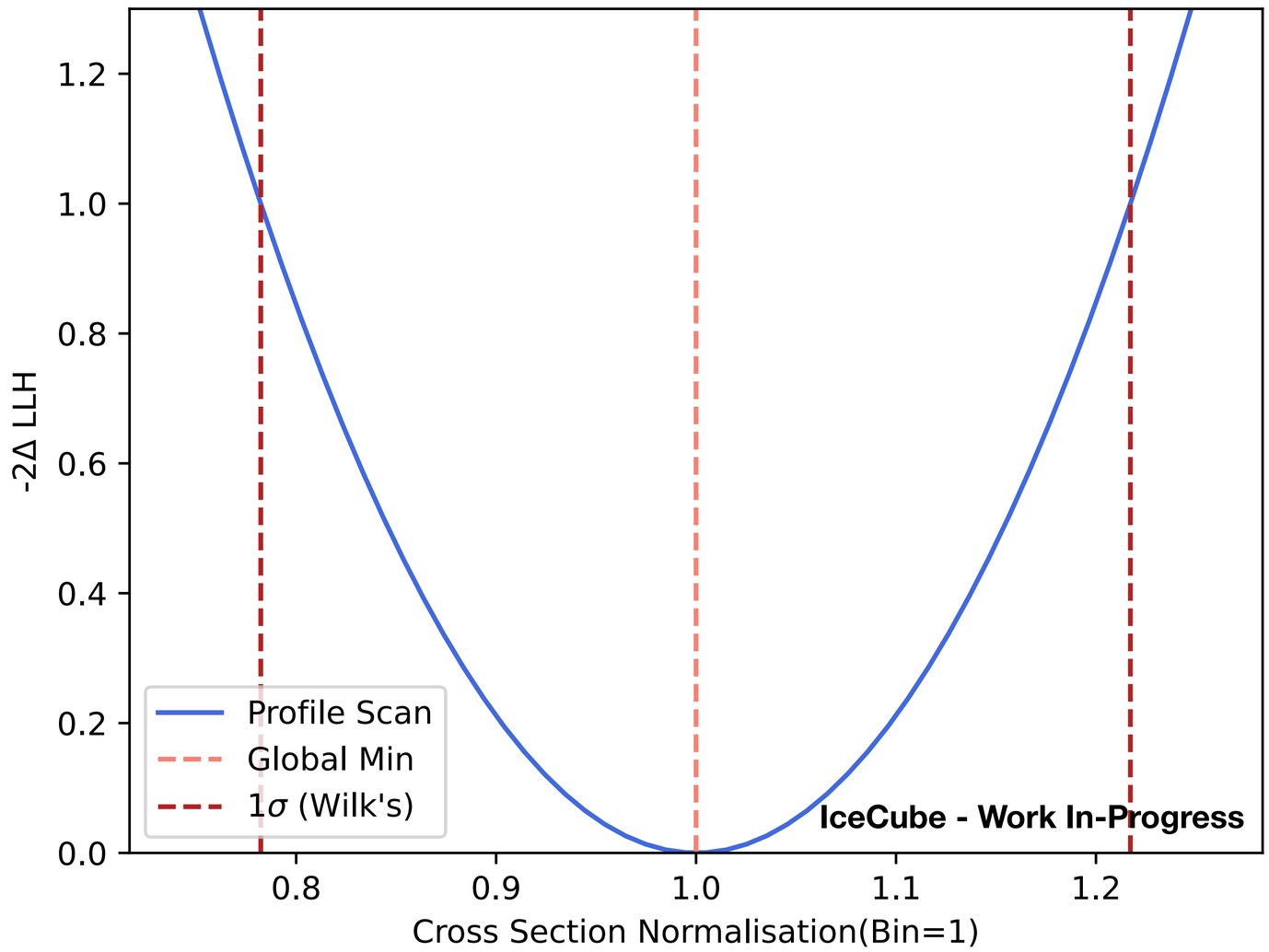
- Note: additional Monte Carlo to be generated (high energy events are time-intensive).

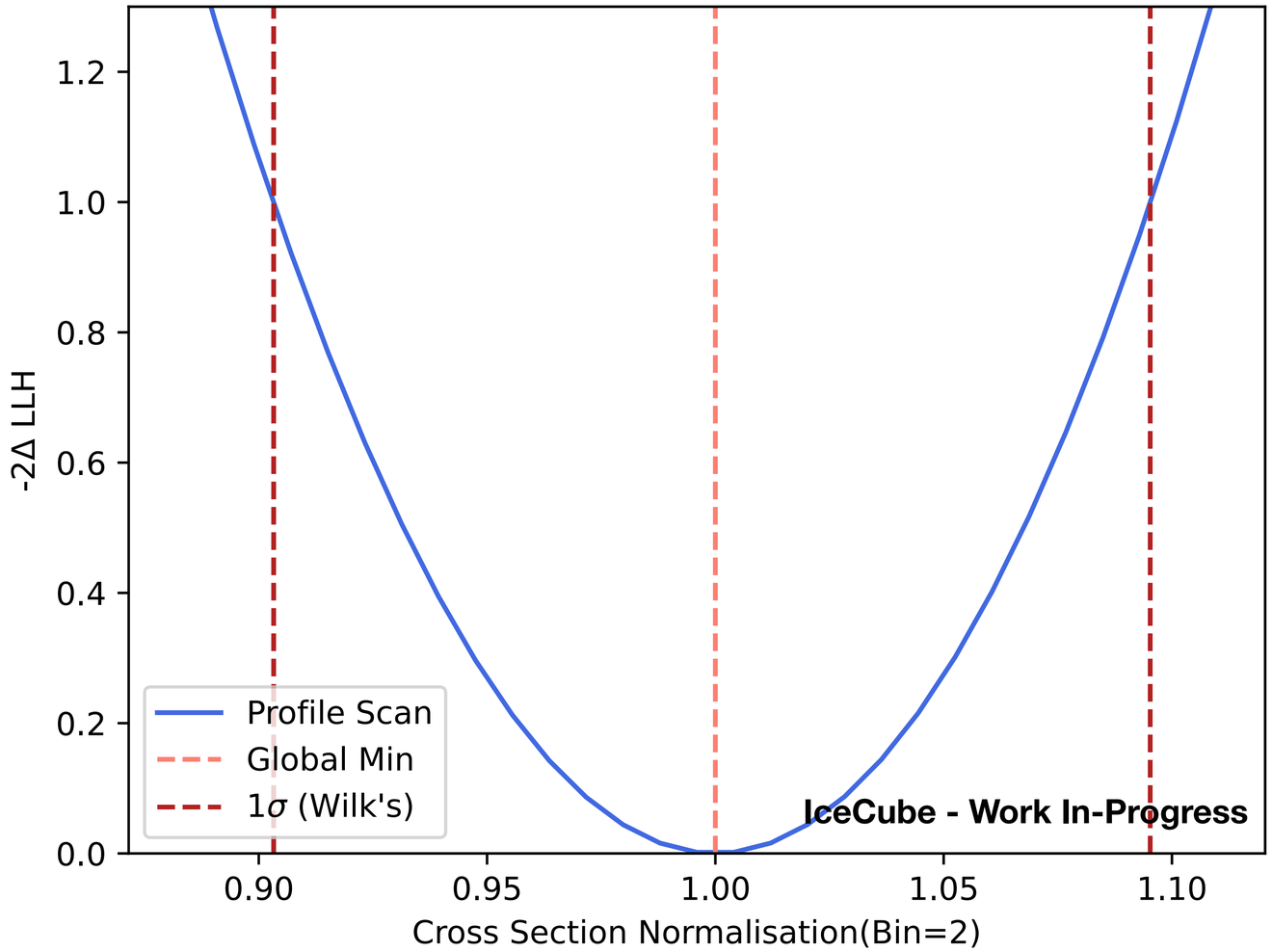
Cross Section Analysis

- Build Asimov likelihood using Monte Carlo for round-trip test of likelihood method.
- Assuming 10 years of data.
- Examine sensitivity in each bin, using Wilks Theorem to set 1σ contour.
- Lowest energy bin mainly includes events from Atmospheric flux.



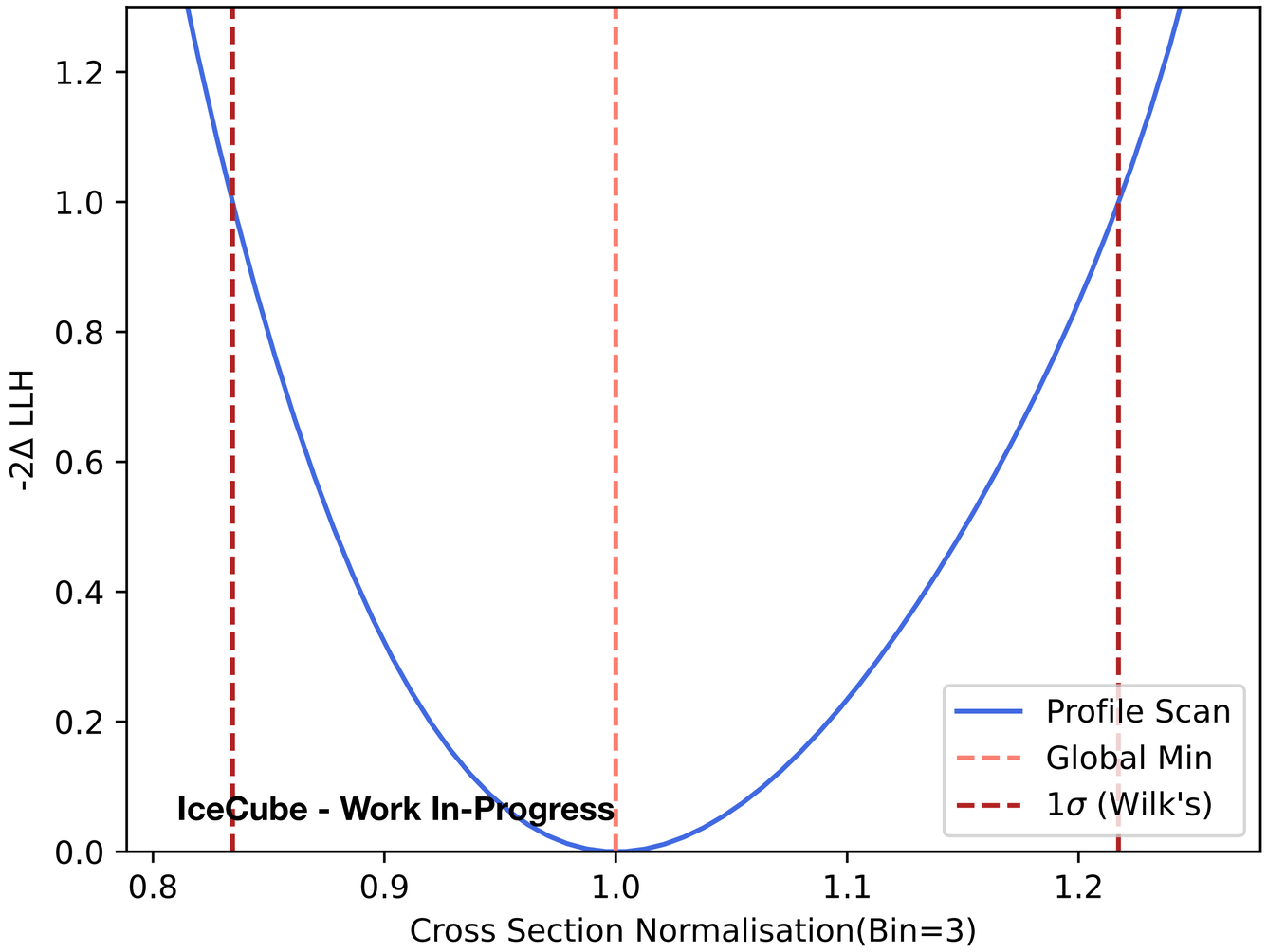
Cross Section Analysis

- Second energy bin also shows agreement with injected values (round-trip).
- Overlap region of Atmospheric and Astrophysical fluxes.
- 1σ sensitivity on the level of 10%.



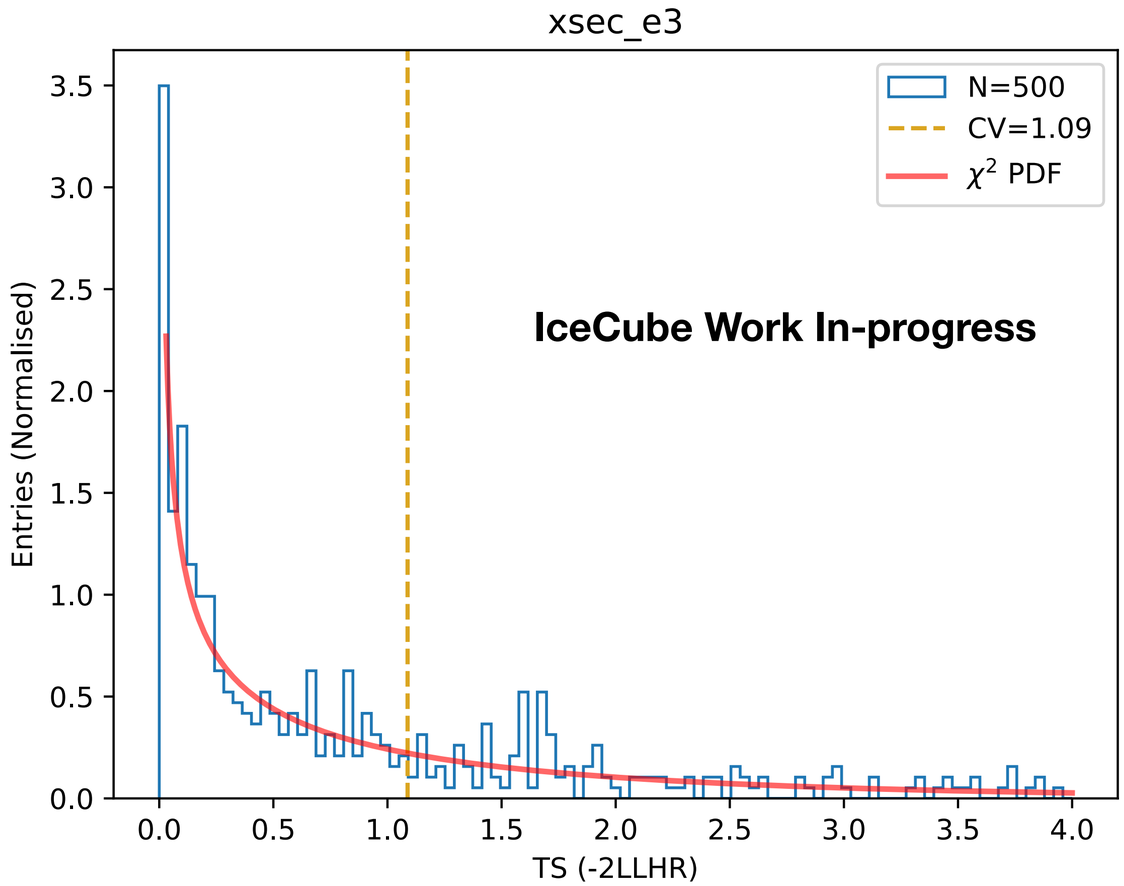
Cross Section Analysis

- While the highest energy bin is the widest, this also includes the most “interesting” events:
- Furthest away from accelerator neutrino regime.
- Least explored region w.r.t. investigating BSM processes.
- Previous IceCube cross section analyses extended sensitivity up to 10 PeV, this analysis plans extending range up to 100 PeV.



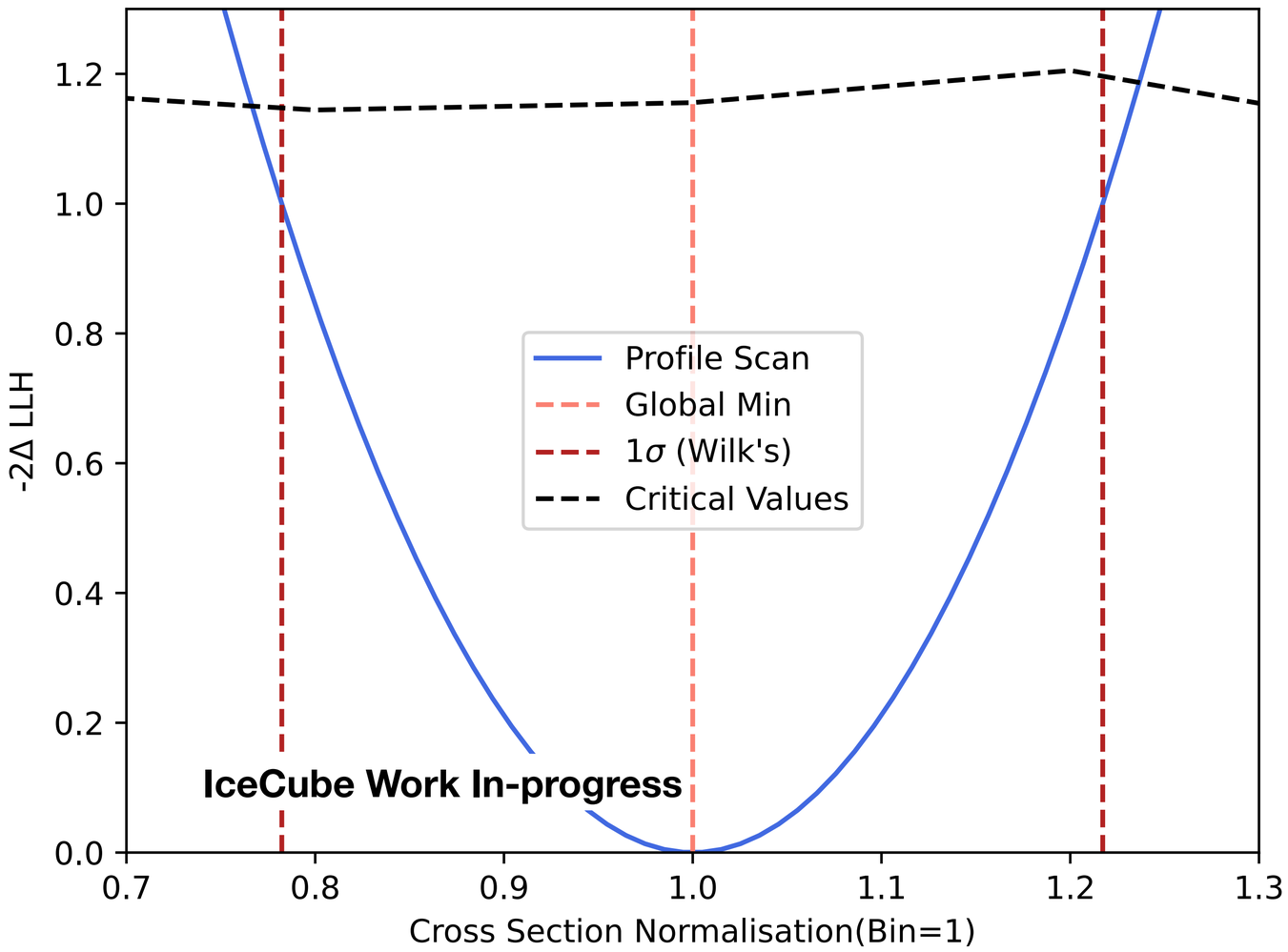
Pseudo-experiment Trials

- Previous IceCube analyses typically simply assume Wilk's Theorem to draw confidence intervals.
- Cross-check confidence intervals by running pseudo-experiments (N=500) and extracting the test statistic for 3 cross section bins.
- Calculating the critical value for 1σ confidence.
- Exploratory scan shows that the TS-distributions follow χ^2 across the profiled likelihood region.



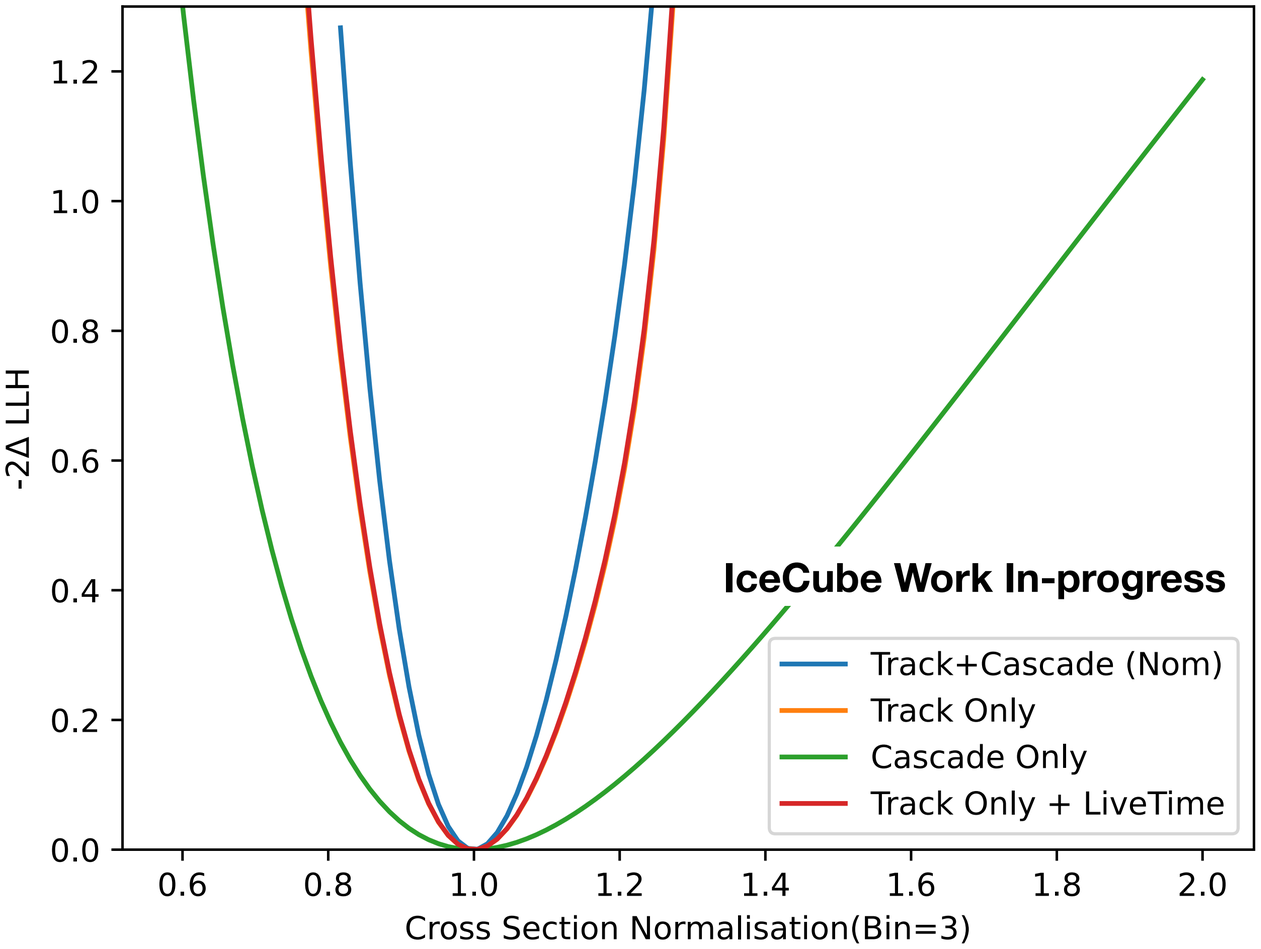
Pseudo-experiment Trials

- Plotting the critical values evaluated at different normalisations gives my new 1σ contour.
- Critical values extracted from pseudo-experiments indicate close agreement w/ Wilk's (~1%) for all 3 energy bins.
- As further systematic effects are included & data injected consistent verification of Wilk's theorem can be important.



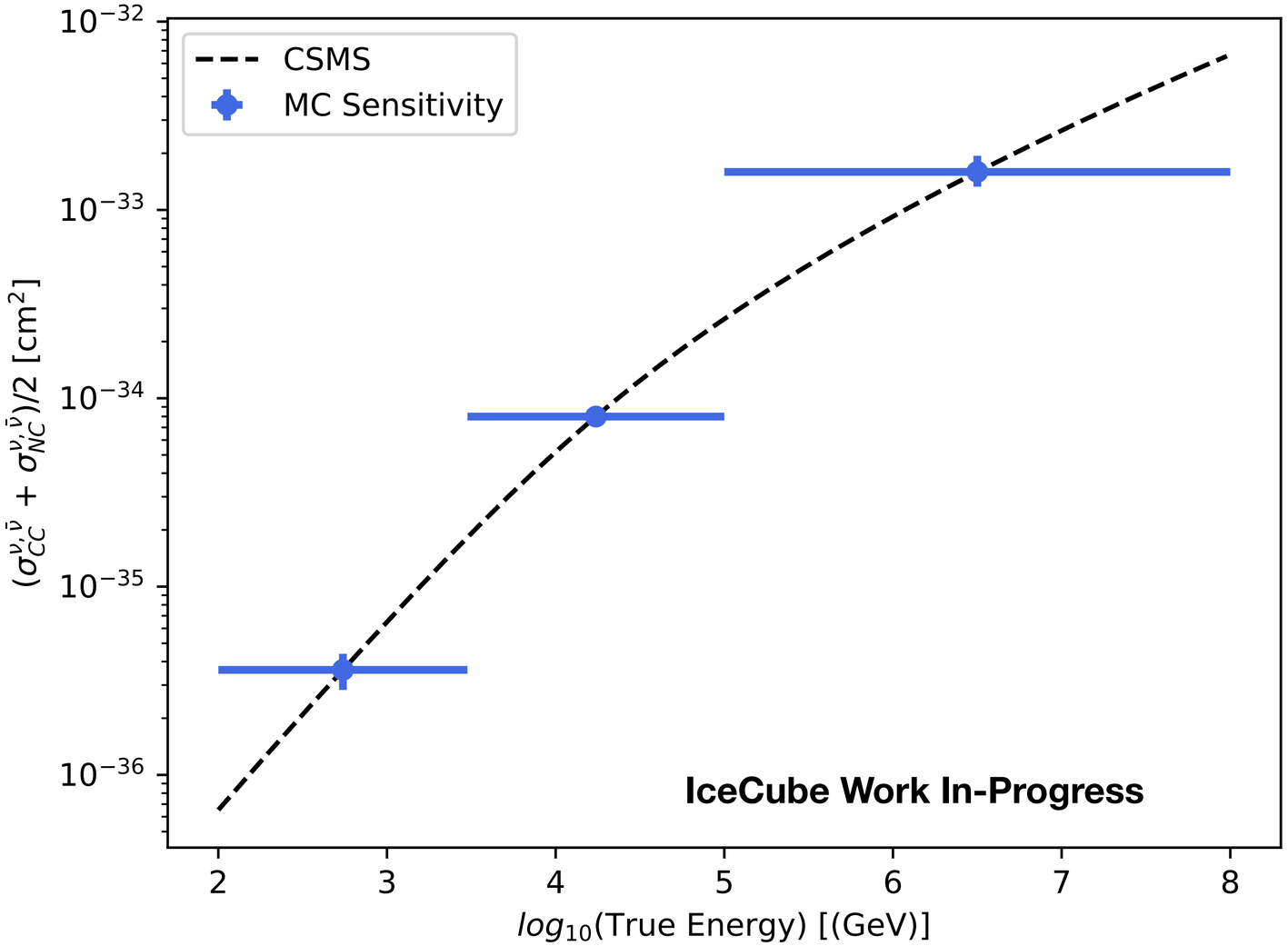
Global Fit Sensitivity

- Evaluating the sensitivity improvement due to combining the track & cascade samples.
- Is using track + cascade more sensitive than *just* enhancing the number of statistics?
- Try scaling the track livetime by the number of cascade events (Track + LiveTime) - only a few %.
- Track Only & Track Only + LiveTime lines almost perfectly overlapping (square-root N scaling).
- Track + Cascade sensitivity better than sqrt(N)!



Monte Carlo Sensitivity

- Extracting the best fit normalisation for each cross section bin to build a sensitivity estimate.
- Uncertainties in the cross section are derived from the likelihood profile contours.
- Current uncertainties indicate competitive sensitivity to contemporary IceCube analyses.
- Uncertainties do not yet include full suite of IceCube systematic effects (ex. ice modelling).



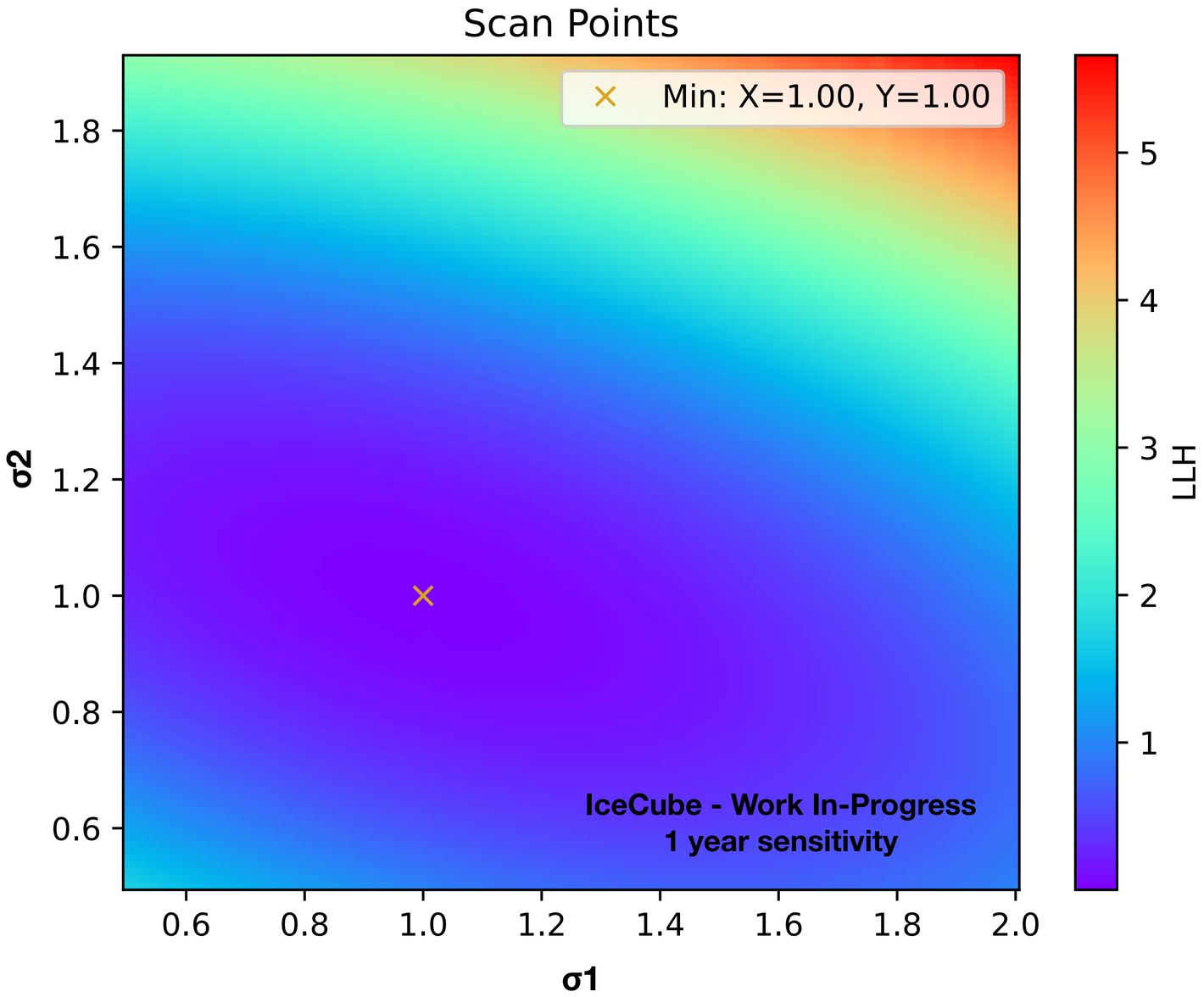
Summary

- IceCube has sensitivity to a wide variety of events available for cross section analyses.
- By considering attenuation of the neutrino flux through the Earth, IceCube has demonstrated unique sensitivity to the DIS neutrino cross section.
- Combining the IceCube track and cascade selections as part of a "global fit" gains additional sensitivity to the σ_ν cross section.
- Careful treatment of the flux prediction and relevant uncertainties will play a key role in determining the accuracy of future IceCube cross section measurements.

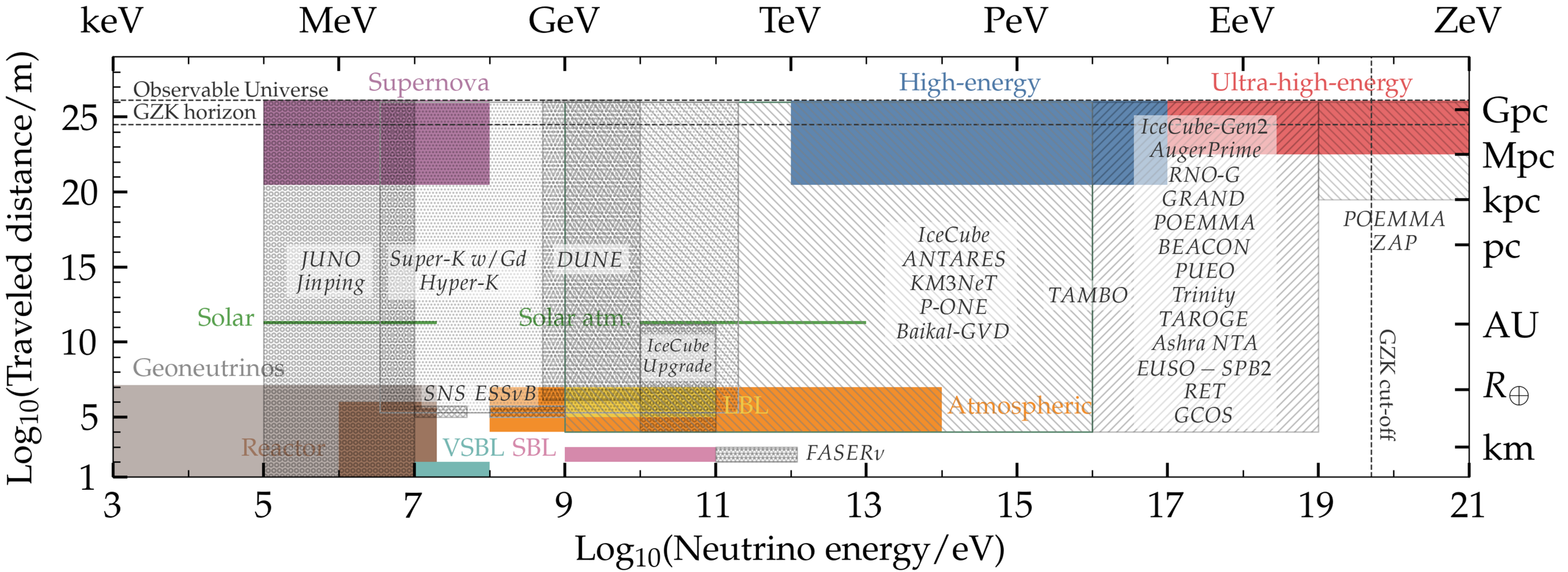
- Backup

Cross Section Analysis

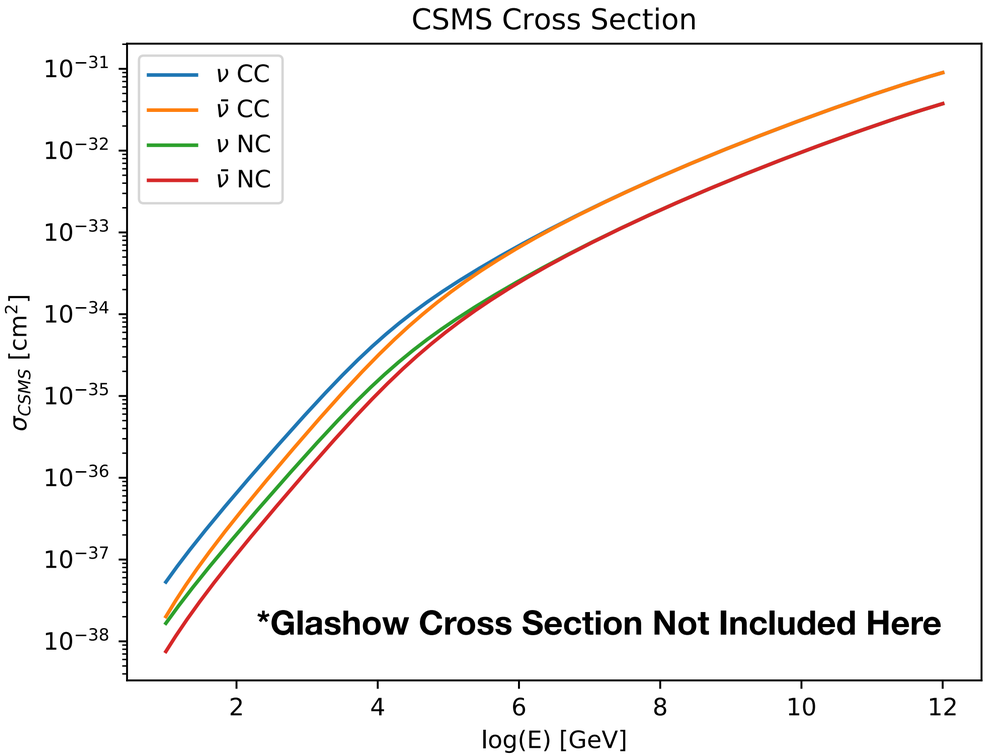
- Additionally examine correlations between the cross section normalisation bins.
- Also in the 2D case, the best fit point is found at 1.0 for both cross section bins (true for all 2D comparisons).
- For σ1 vs σ2, 2D likelihood scans show weak anti-correlation between first and second cross section bin (possibly due to energy reconstruction).

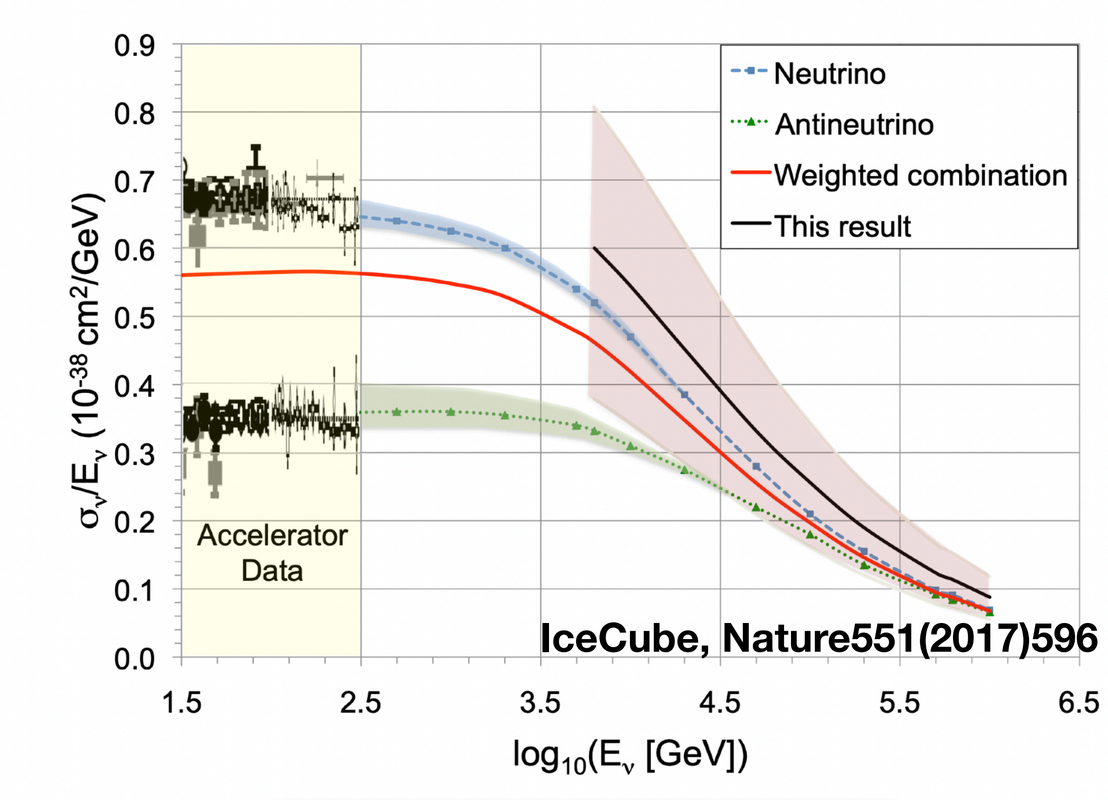


Neutrino Flux Overview

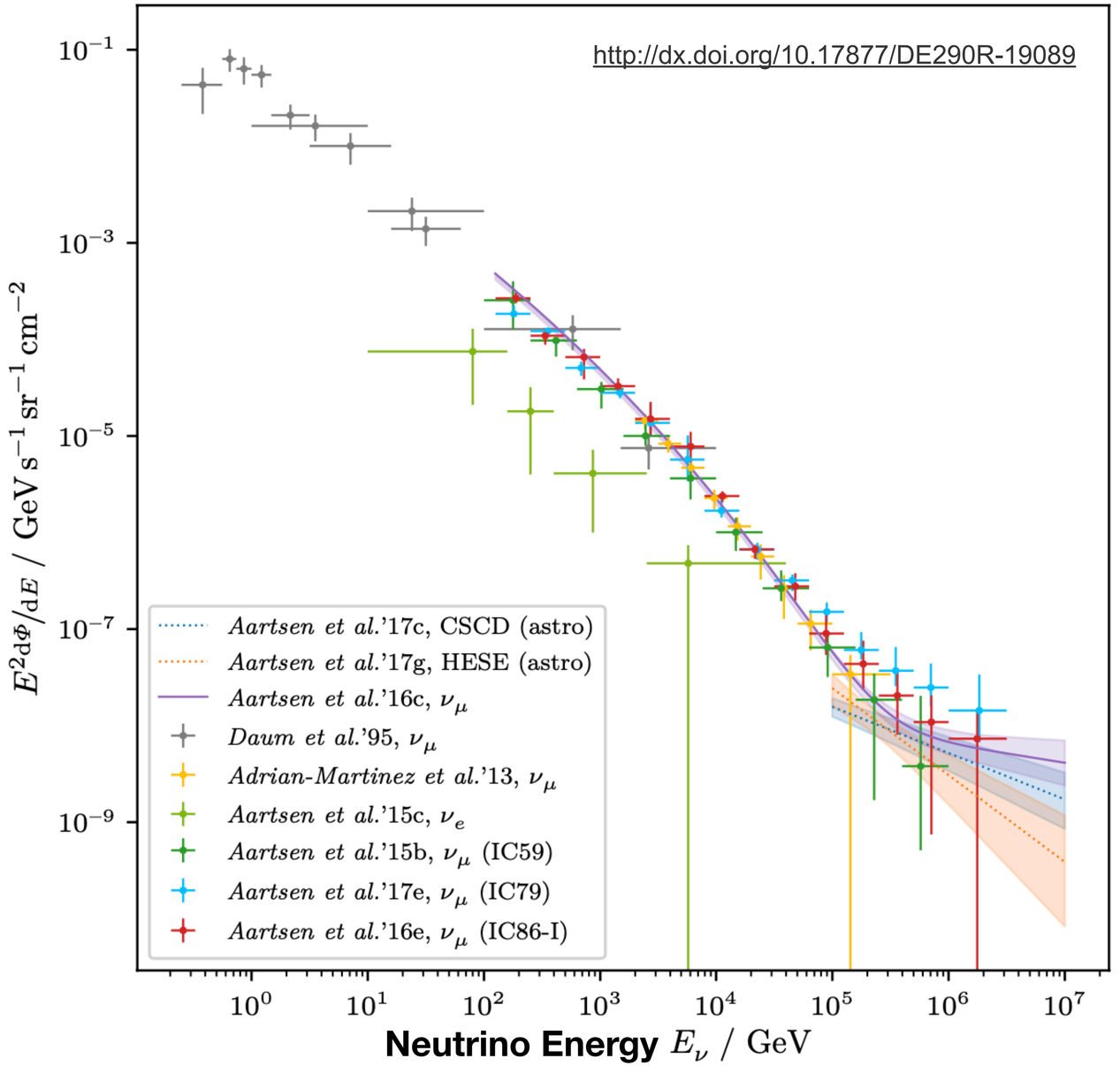


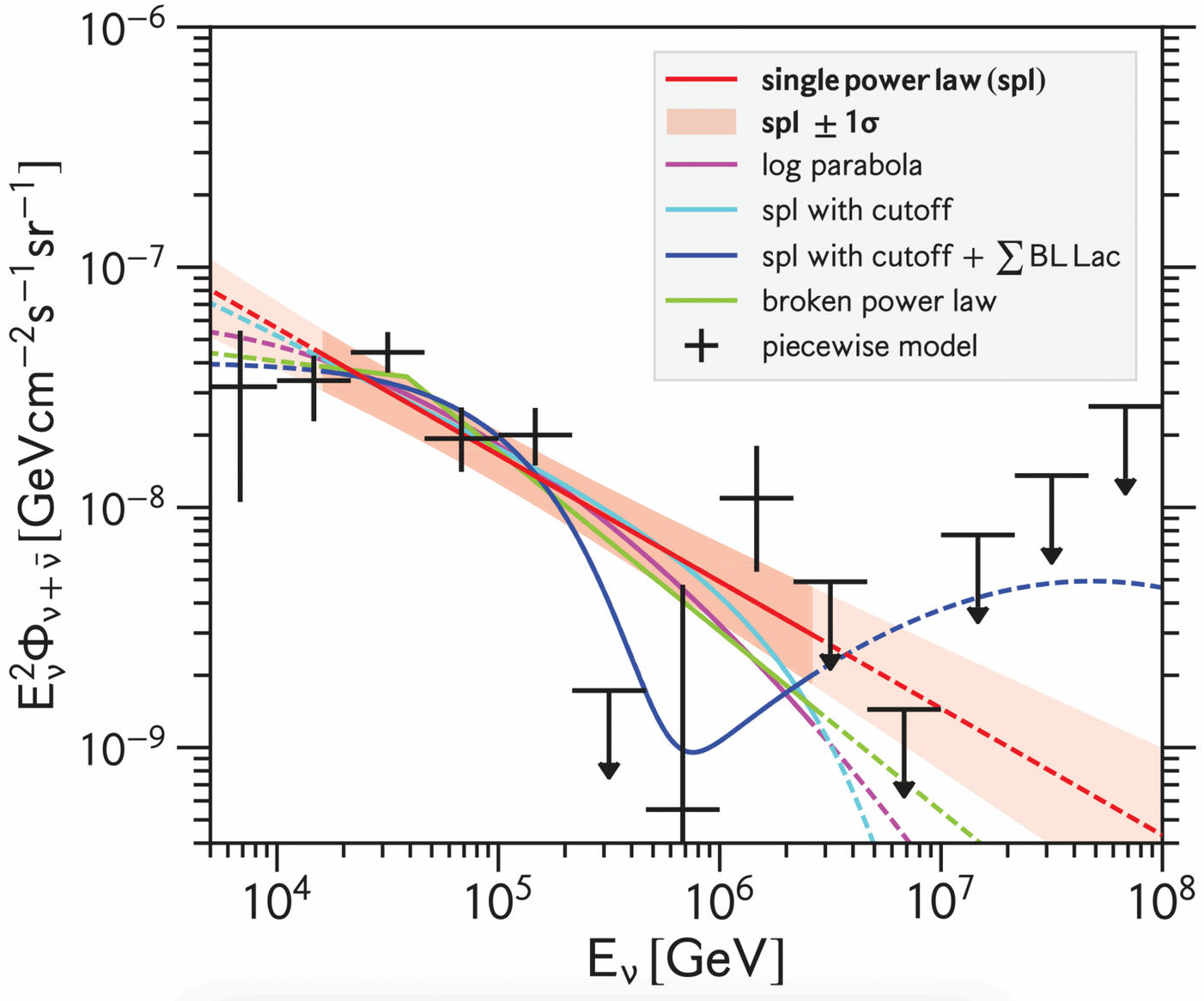
Cross Section Measurements with IceCube





Neutrino Fluxes at IceCube





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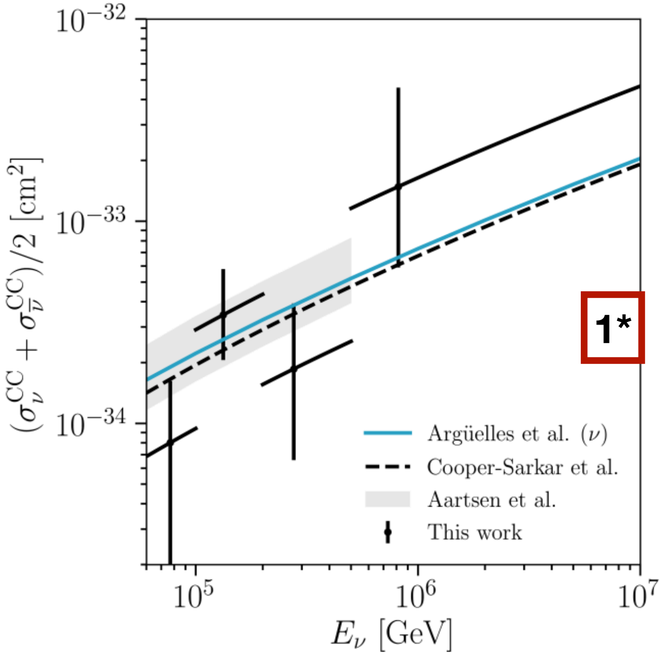
TeV-Scale Cross Section Measurements In IceCube

- IceCube has a varied cross section physics programme, which focuses on a number of different signals and techniques.
- This includes analyses looking for "track-like" or "cascade-like" interactions, or specifically up-going or down-going neutrinos.
- Recent results (1) used "starting" events, measuring the CC all-flavour cross section using the Earth absorption method.
- A number of other new cross section measurements are also in progress and will be released soon.



1: arXiv:2011.03560v1
2: 596 NATURE VOL 551