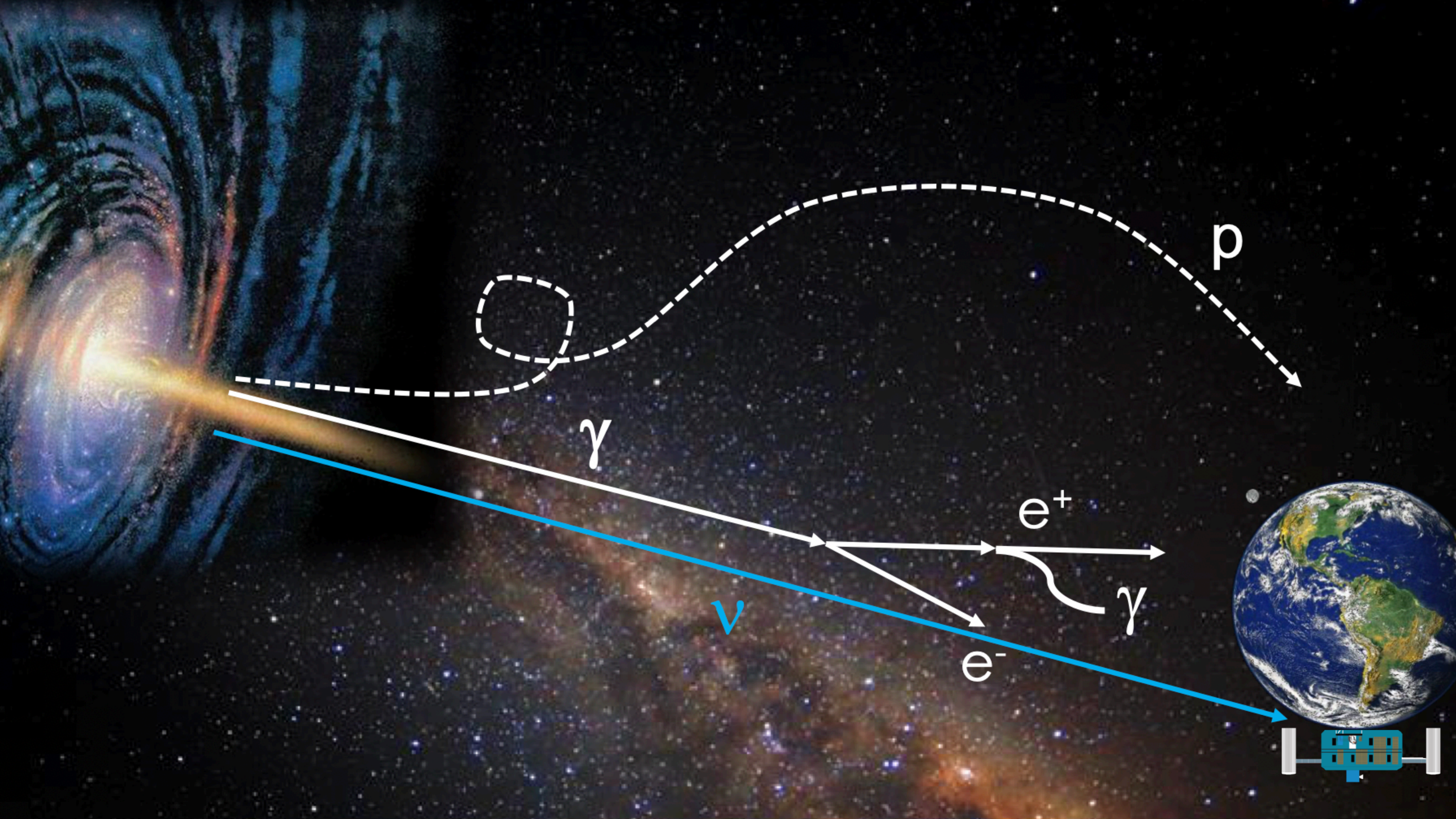
Examining the High-Energy Neutrino Cross Section with the IceCube Neutrino Observatory

Colton Hill for the IceCube Collaboration

EW Moriond 2025

NSF-IceCube/Ilya Bodo


p
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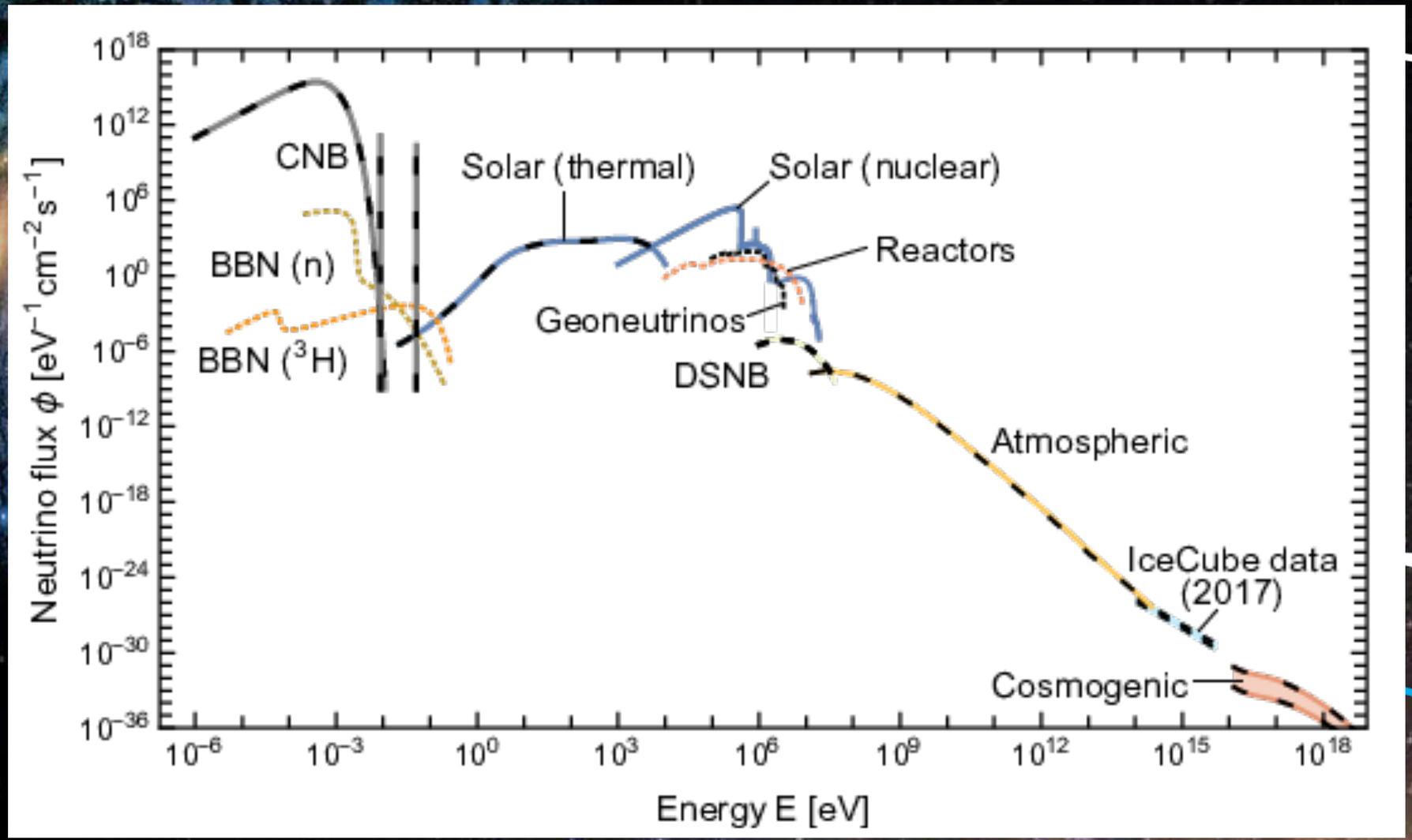
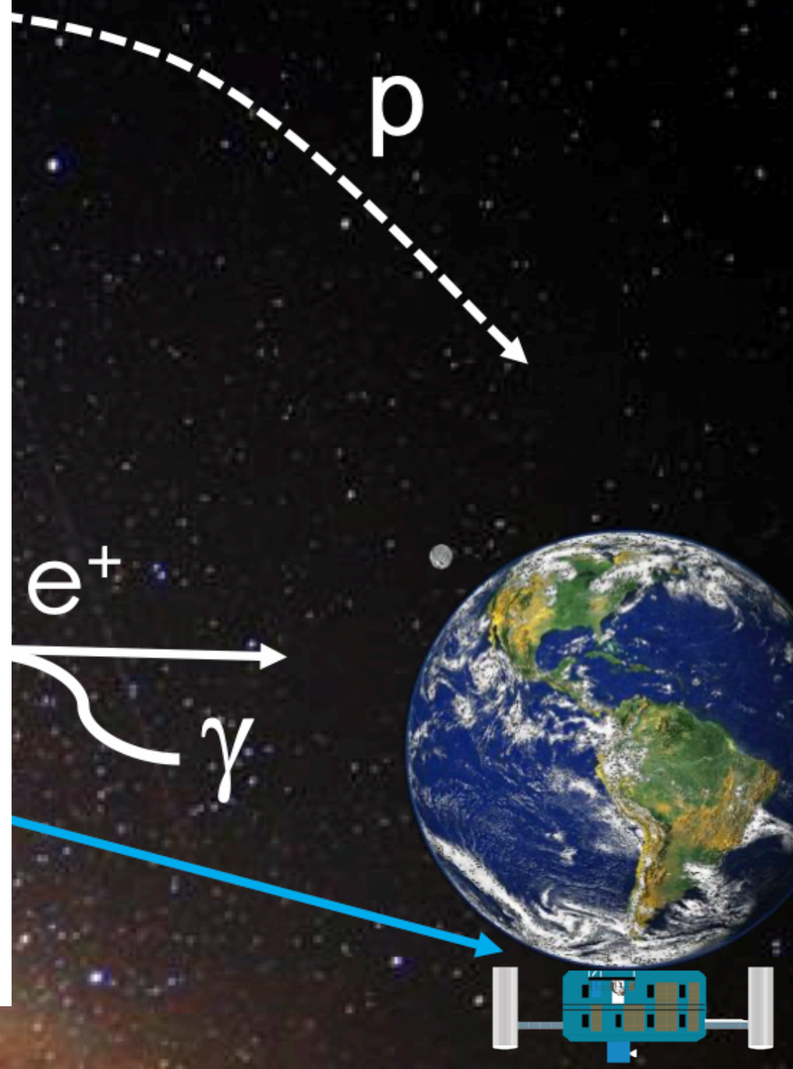




Snowmass Neutrino Frontier Report - Huber, Patrick *et al* - arXiv:2211.08641FERMILAB-FN-1215-ND-PPD-SCD

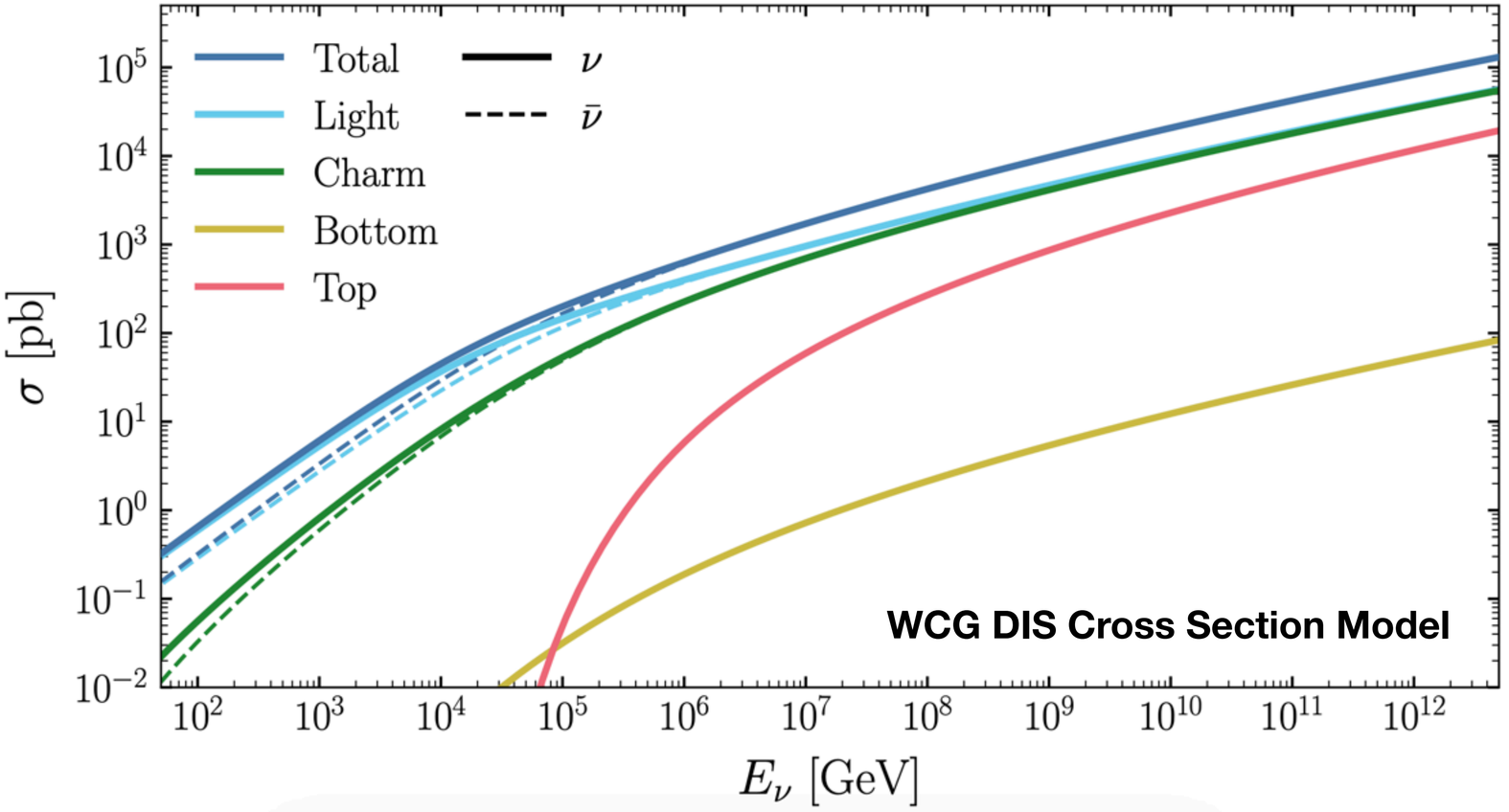
Why Do We Care About Cross Sections?

- The cross section describes the interaction probability ⇒ vital for our Monte Carlo simulations!

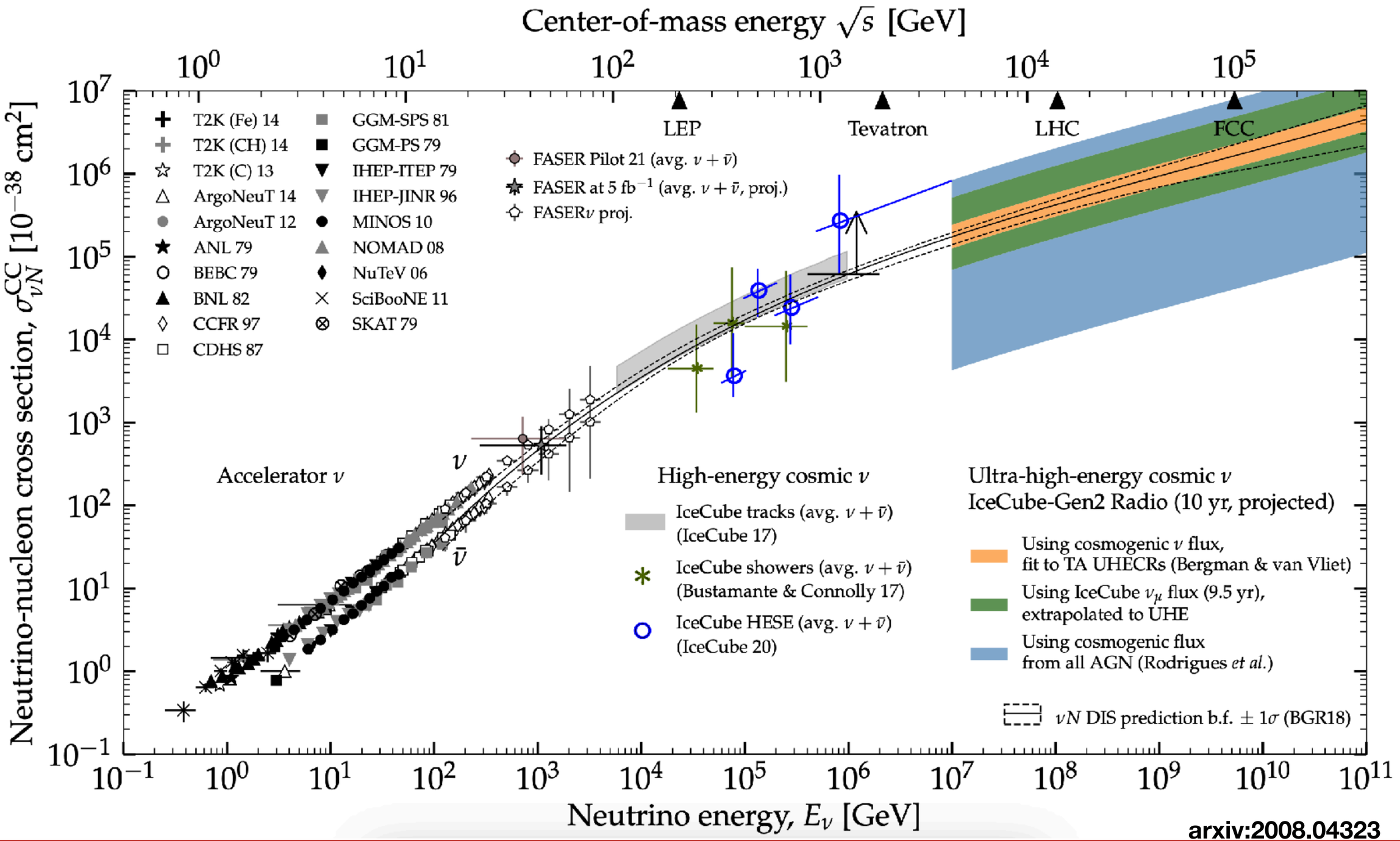
In the simplest case:

$$N = \phi \, \sigma \, n_T \, \varepsilon$$

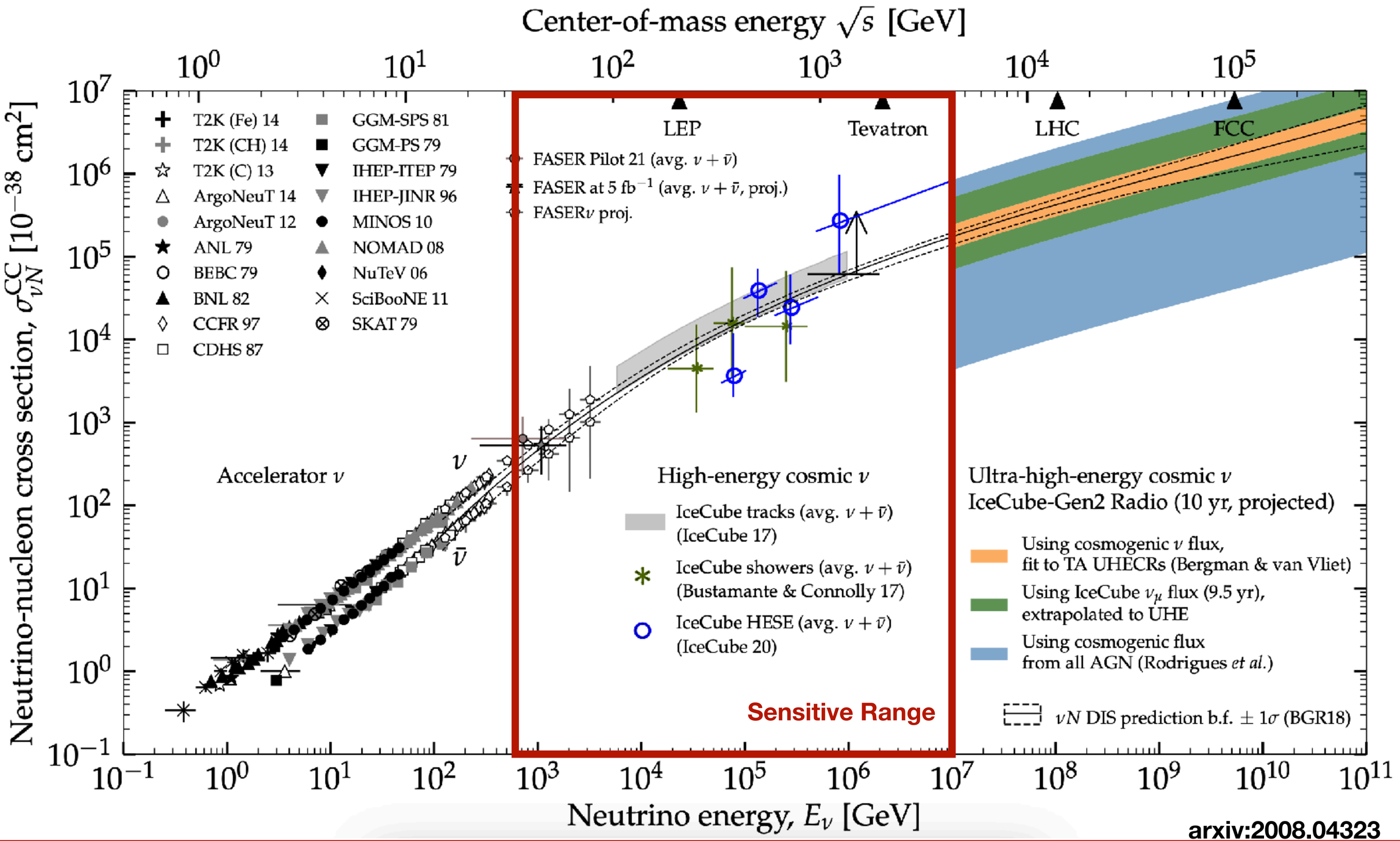
- For deep-inelastic scattering cross section calculations, theoretical calculations rely on parton distribution functions ⇒ directly probe Standard Model.



arXiv:2408.05866v1

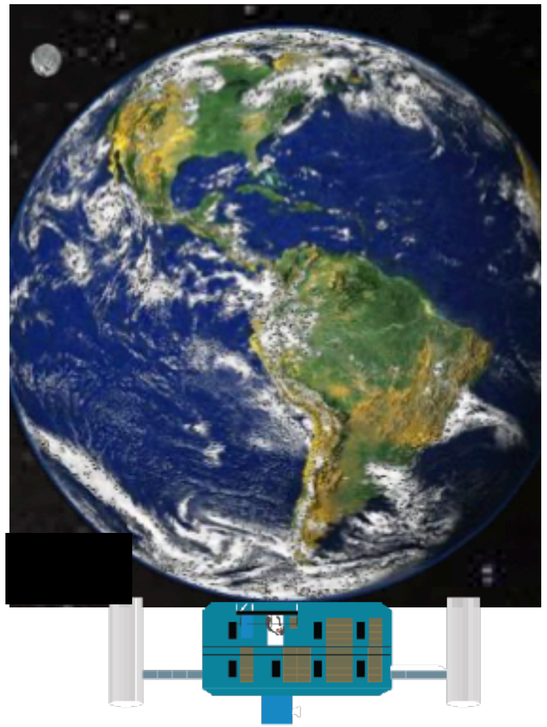


arxiv:2008.04323

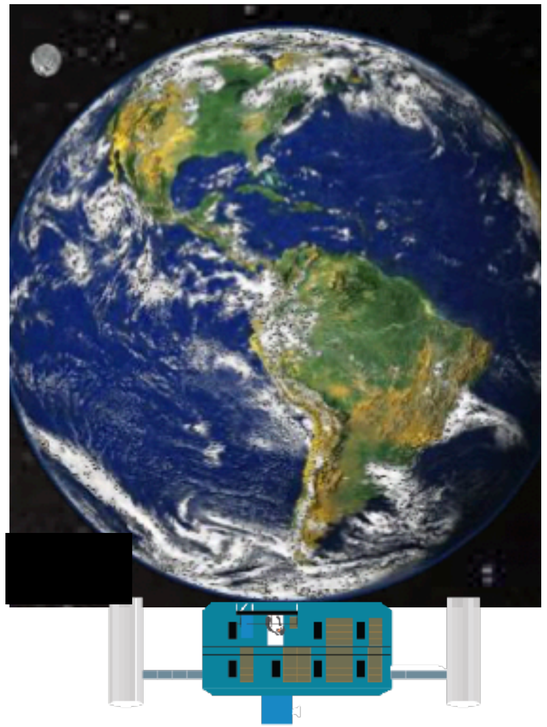


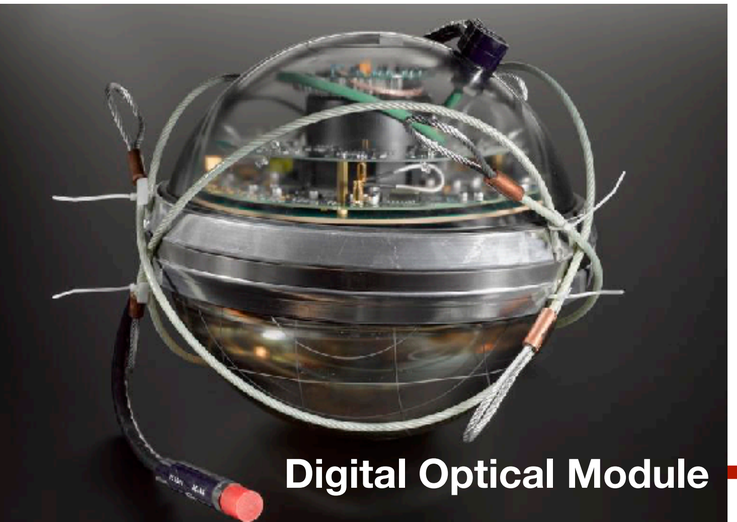
arxiv:2008.04323

The IceCube Neutrino Experiment

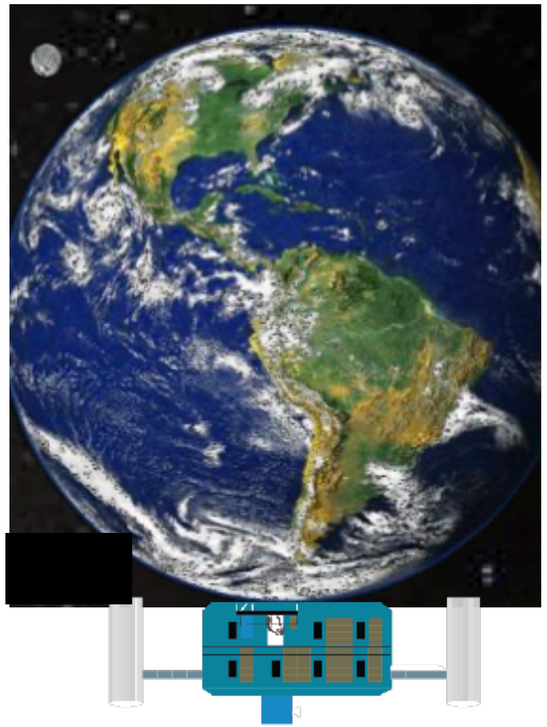


The IceCube Neutrino Experiment

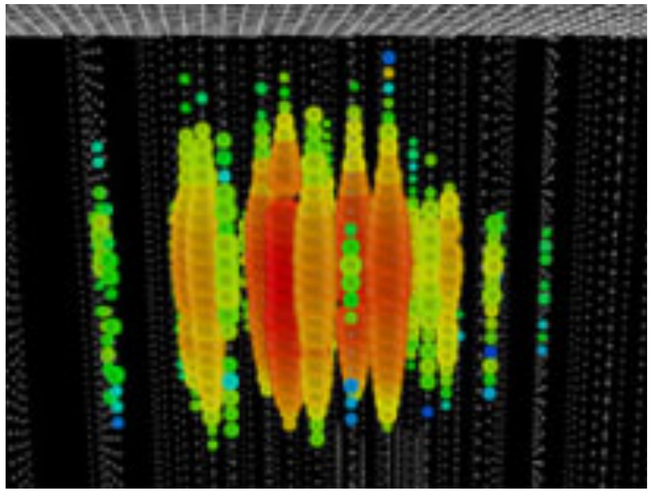




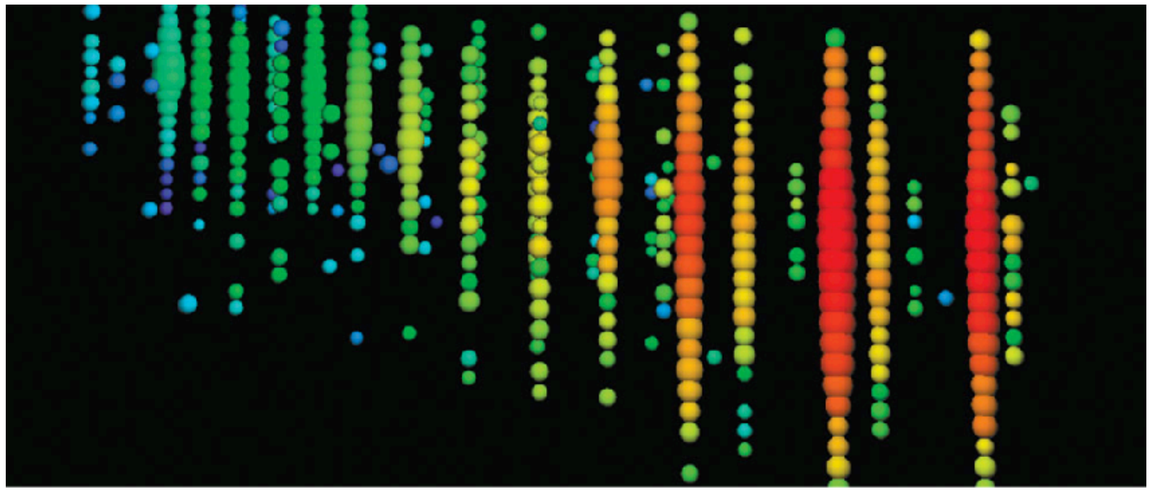
The IceCube Neutrino Experiment

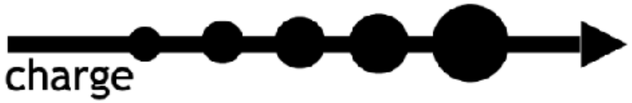


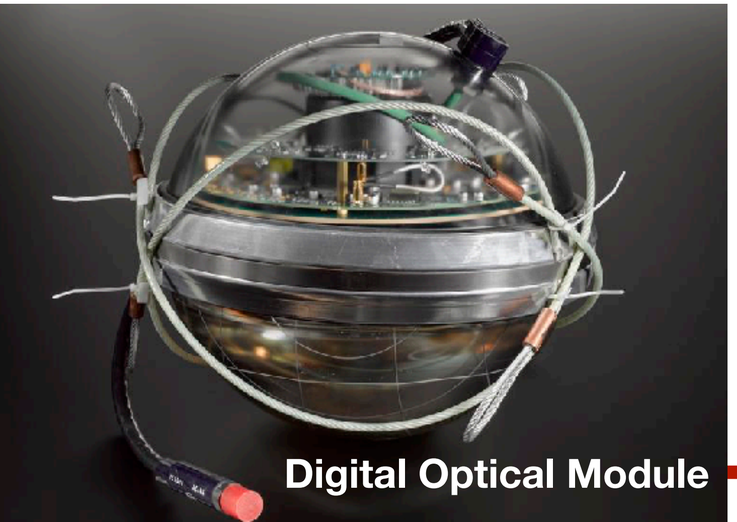
Cascades

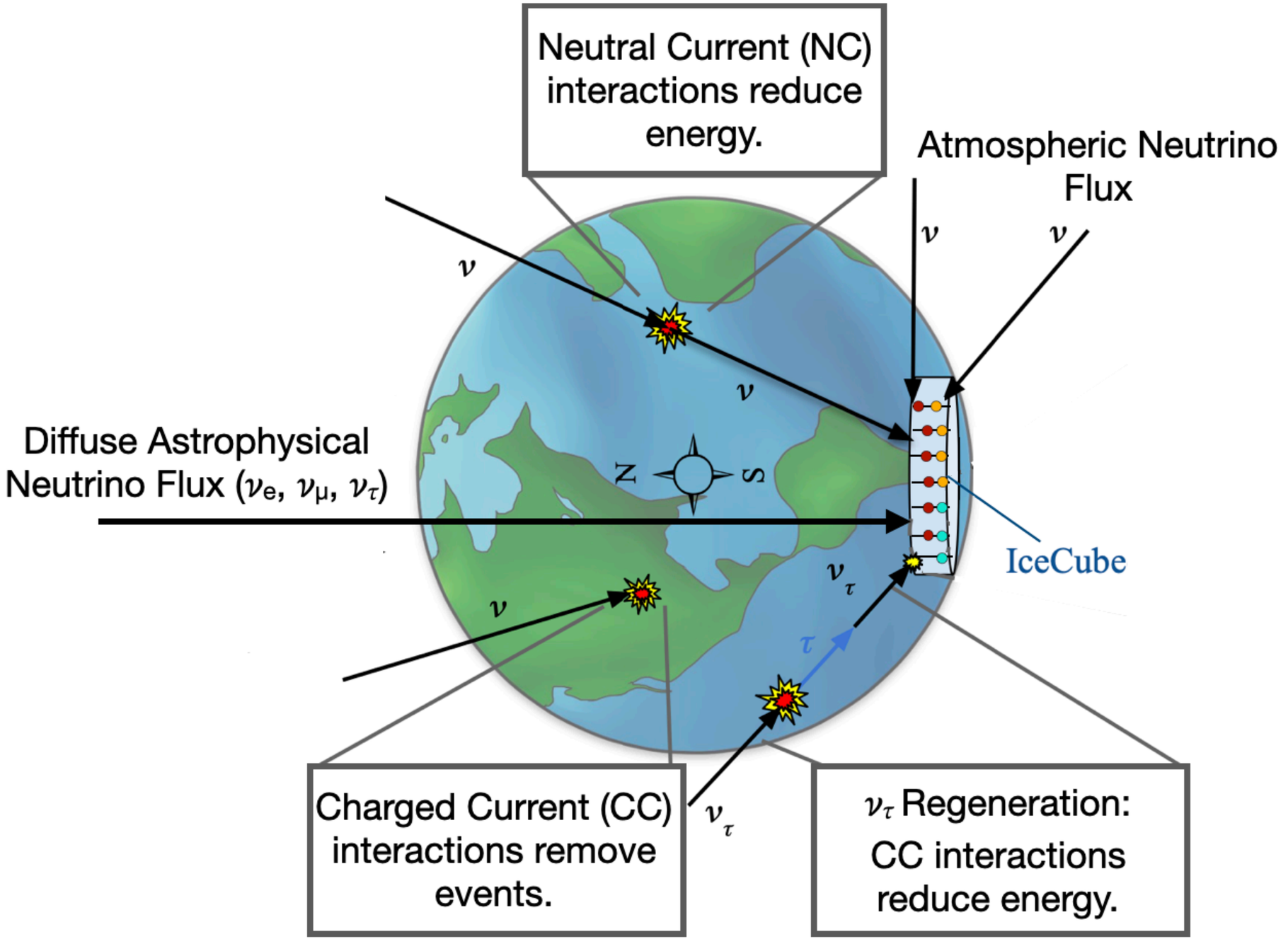


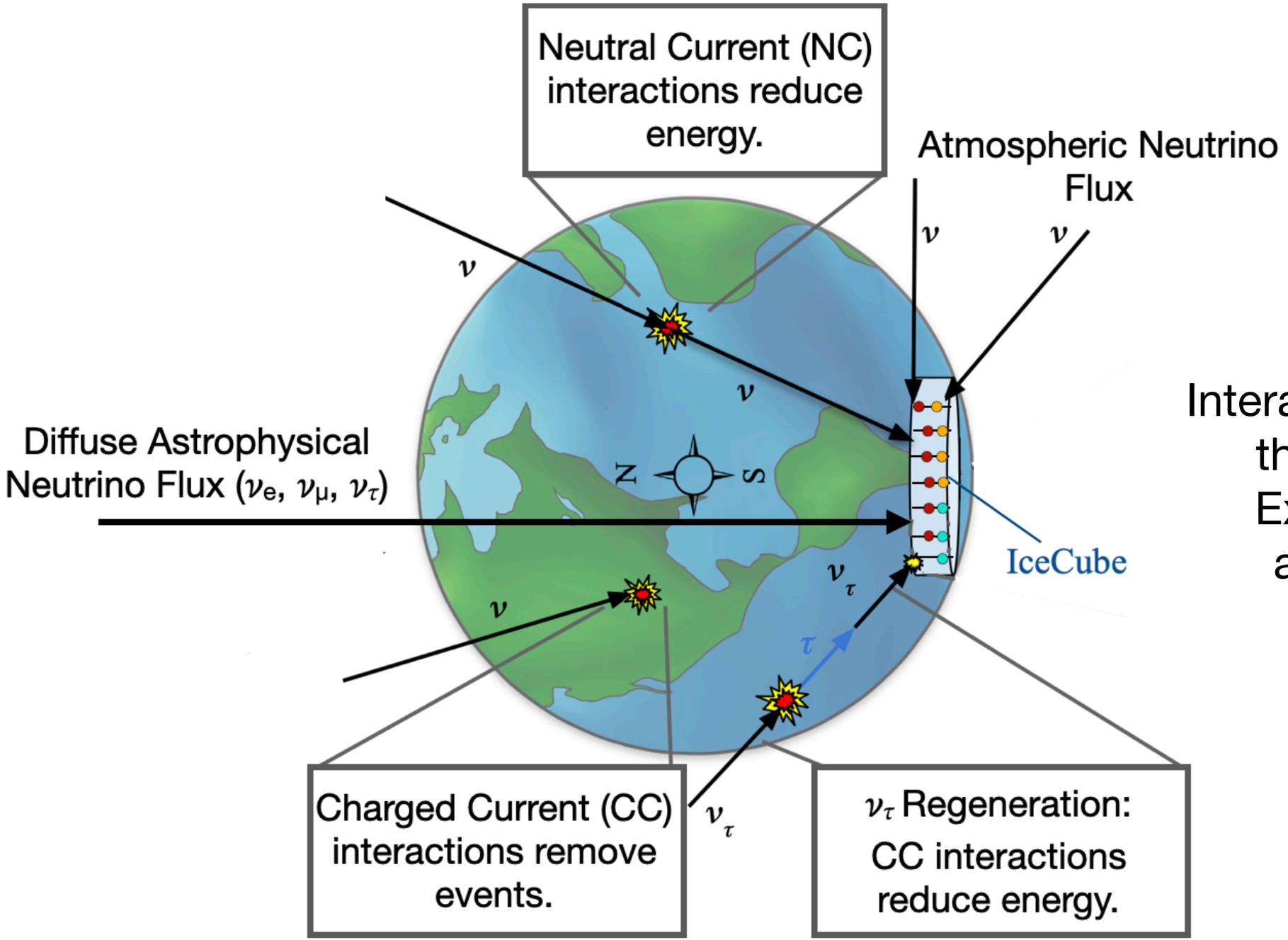
Tracks





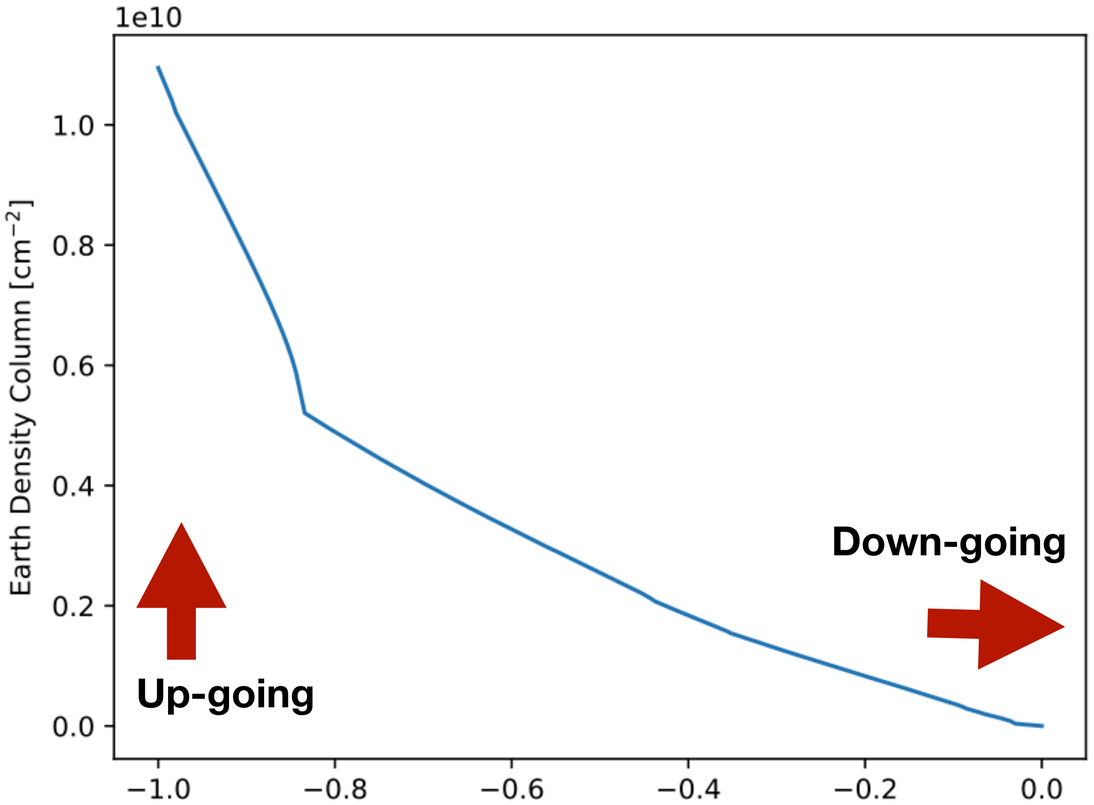



Neutral Current (NC) interactions reduce energy.
Atmospheric Neutrino Flux
Diffuse Astrophysical Neutrino Flux (ν_e, ν_μ, ν_τ)
IceCube
Charged Current (CC) interactions remove events.
ν_τ Regeneration: CC interactions reduce energy.

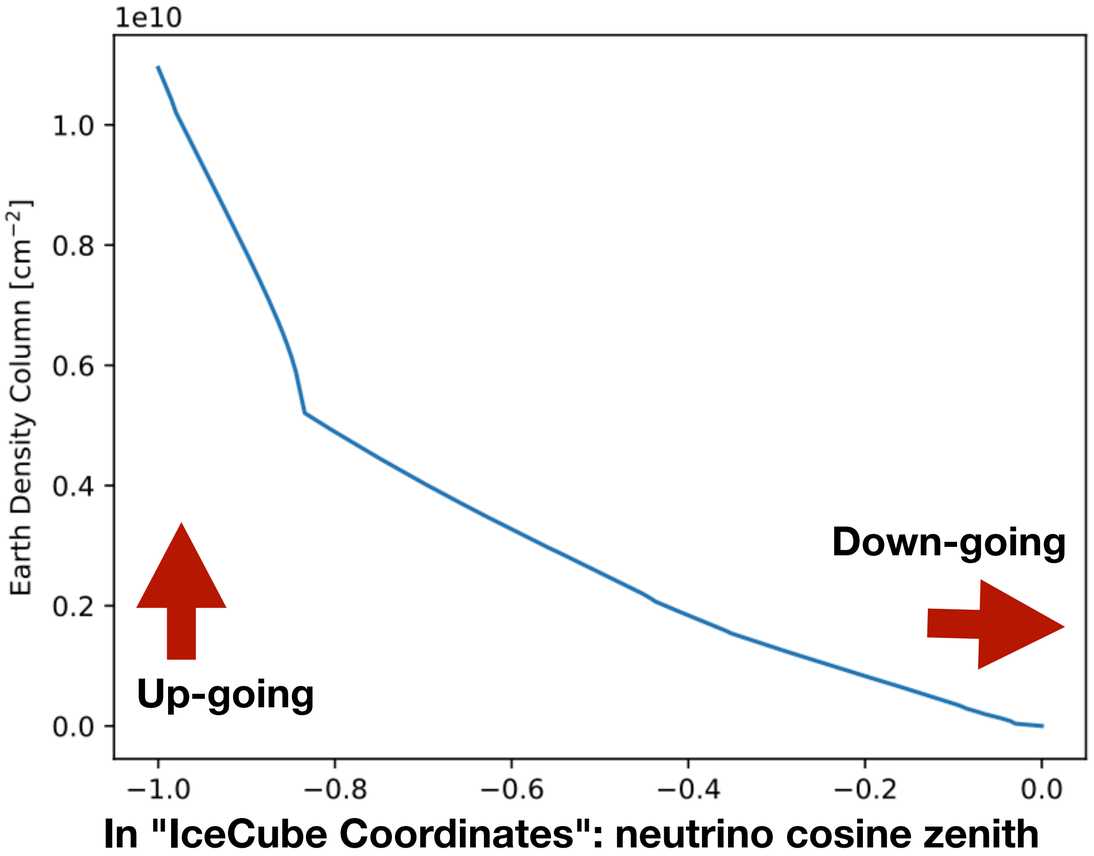


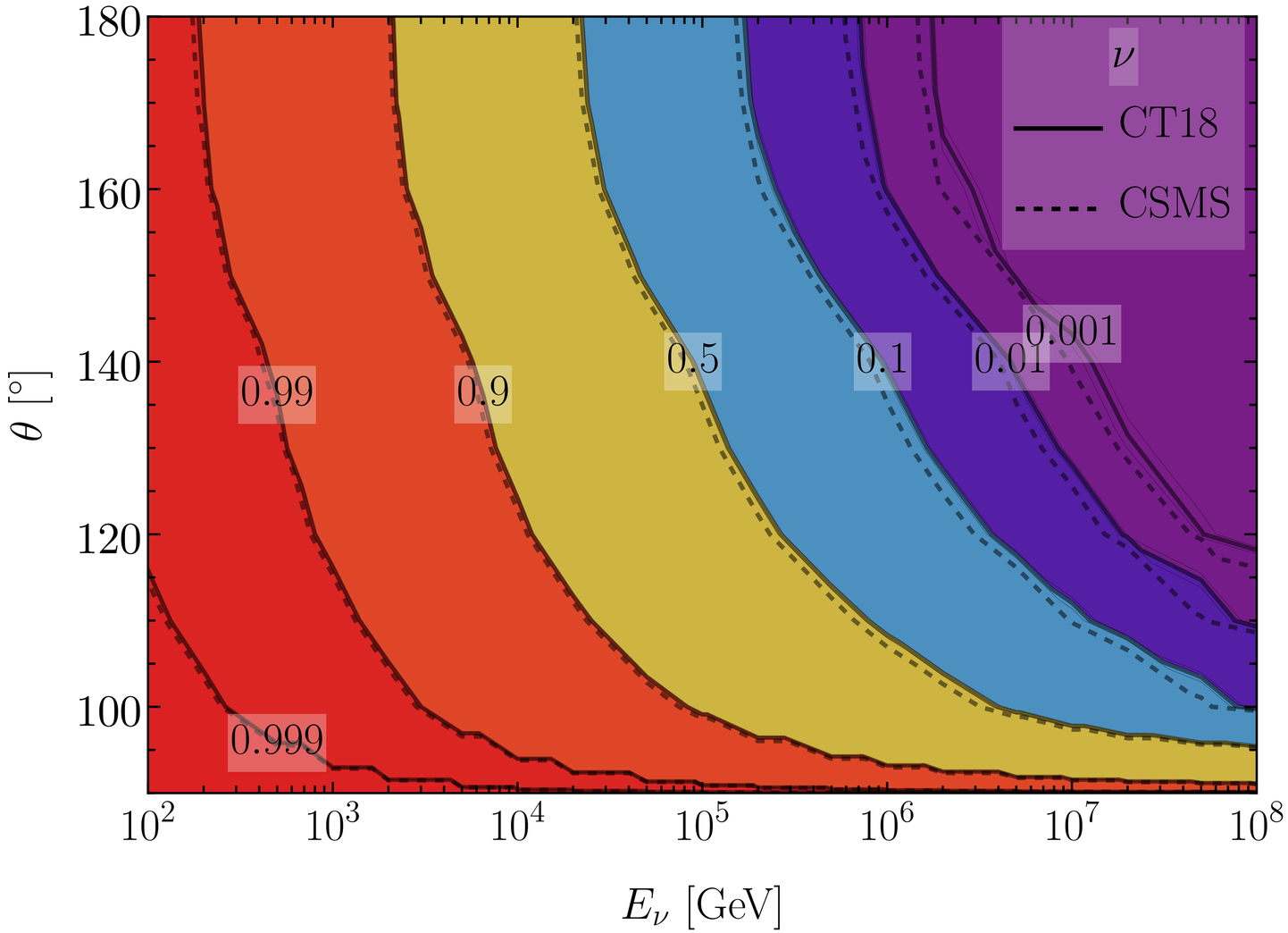
Interaction probability *within* the Earth is non-zero!
Expectation now also a function of zenith!

$N = \phi'(\sigma)\, \sigma\, n_T\, \varepsilon$

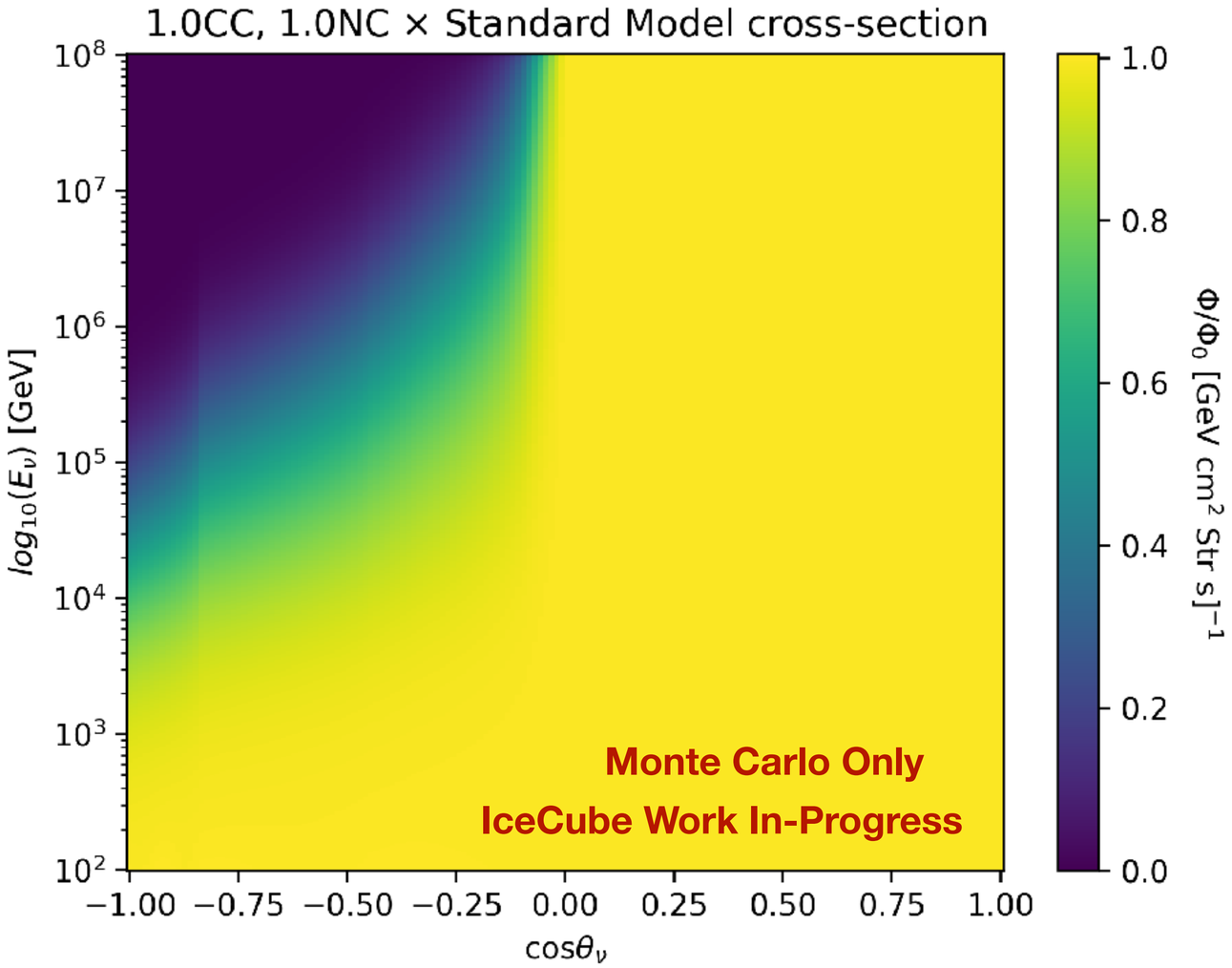


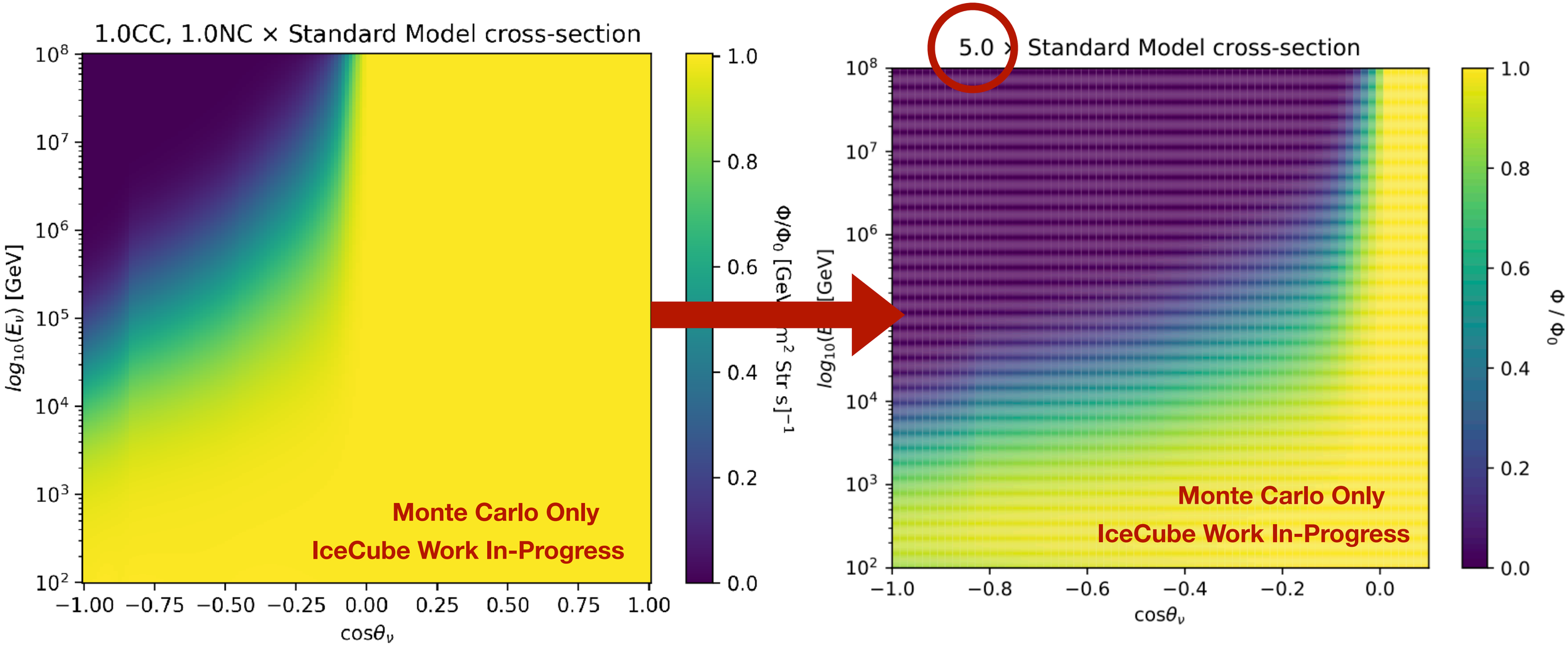
In "IceCube Coordinates": neutrino cosine zenith



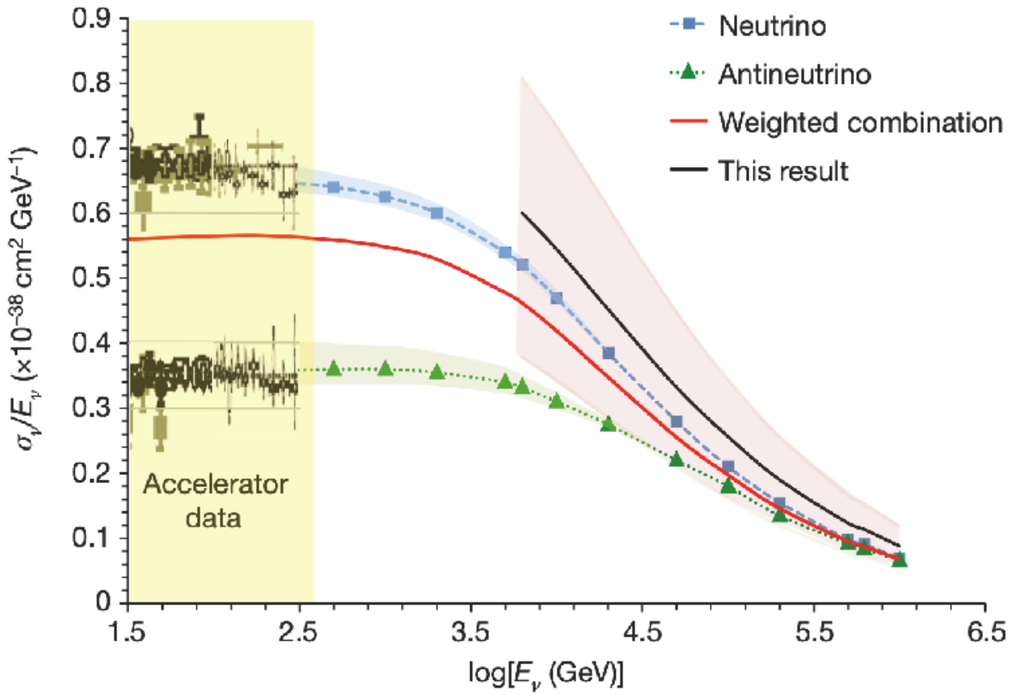


- Observed neutrino flux reaching IceCube is a function of energy ($\Phi_{\text{Atm, Astro}}(E)$ & $\sigma(E)$) & zenith ($\Phi_{\text{Atm}}(\Theta, \rho(\Theta))$).
- IceCube is sensitive to how changes in the cross section modify the observed flux!

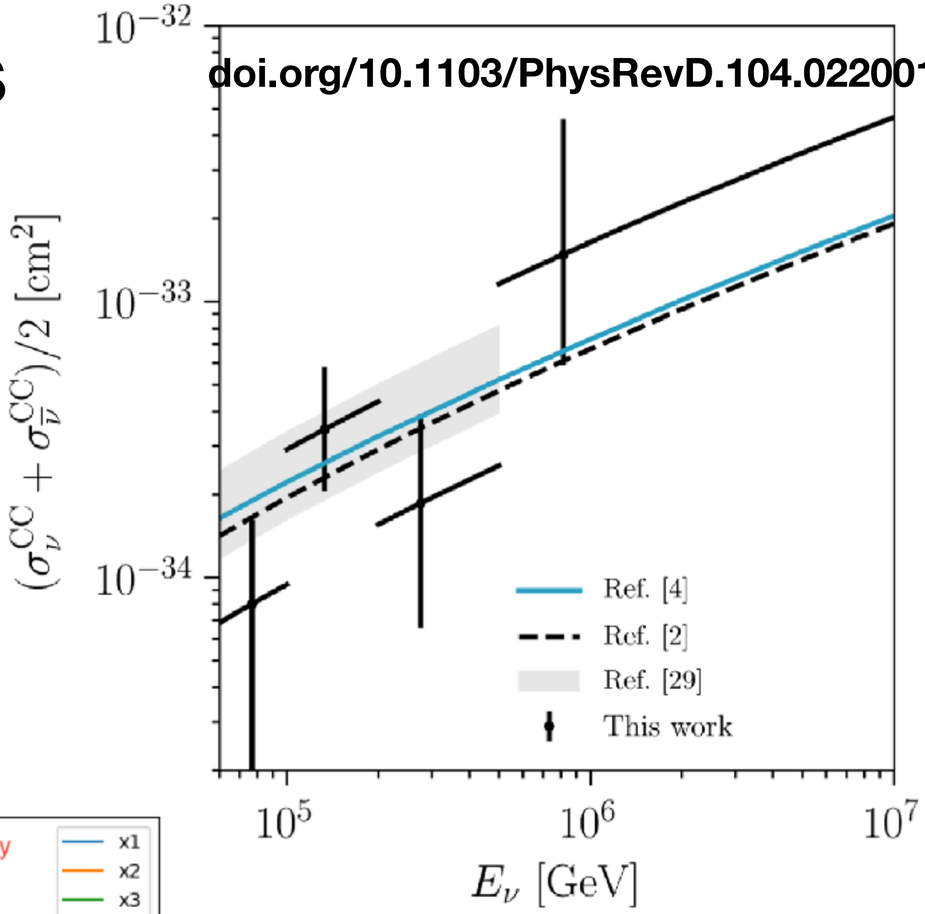

1.0CC, 1.0NC × Standard Model cross-section
10^8
10^7
10^6
10^5
10^4
10^3
10^2
$log_{10}(E_\nu)$ [GeV]
−1.00 −0.75 −0.50 −0.25 0.00 0.25 0.50 0.75 1.00
$cos\theta_\nu$
1.0
0.8
0.6
0.4
0.2
0.0
Φ/Φ_0 [GeV cm^2 Str s]$^{-1}$
Monte Carlo Only
IceCube Work In-Progress


1.0CC, 1.0NC × Standard Model cross-section
$log_{10}(E_\nu)$ [GeV]
$cos\theta_\nu$
Φ/Φ_0 [GeV m^2 Str s]$^{-1}$
Monte Carlo Only
IceCube Work In-Progress
5.0 × Standard Model cross-section
$log_{10}(E$ [GeV]
$cos\theta_\nu$
Φ/Φ_0
Monte Carlo Only
IceCube Work In-Progress

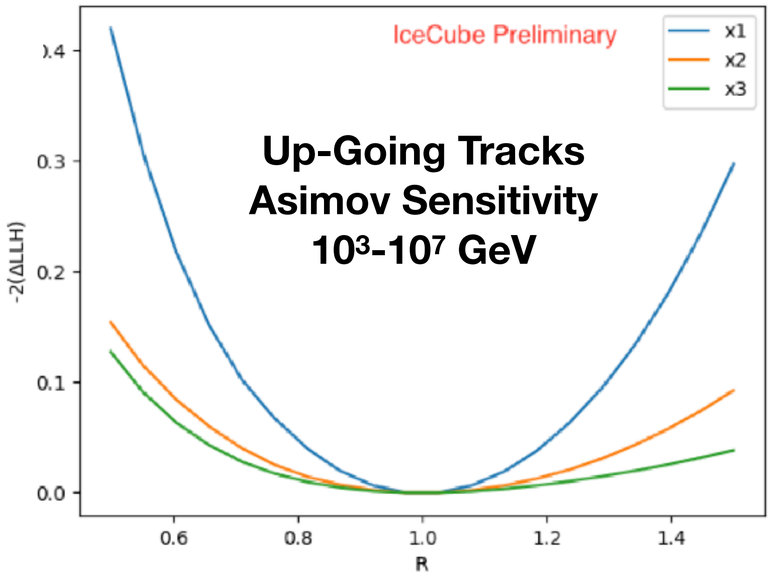
Previous IceCube Cross Section Results



doi.org/10.1038/nature24459

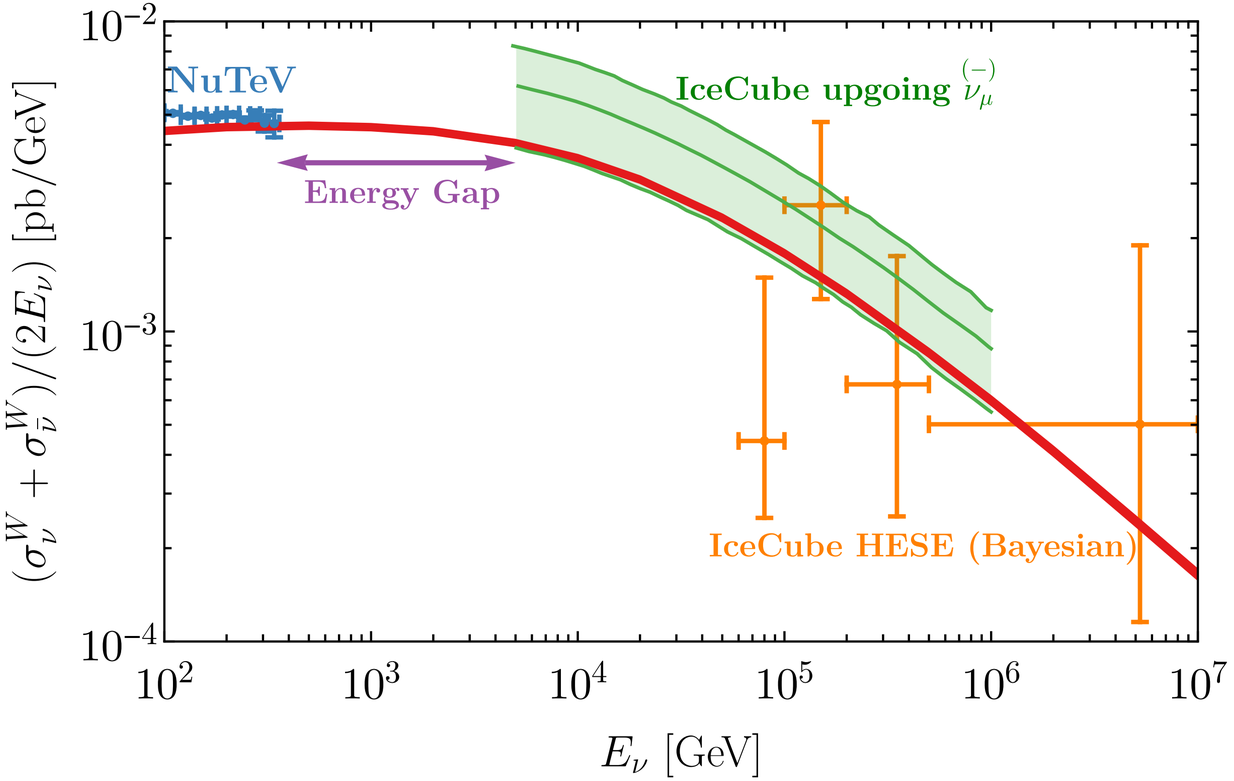


Previous IceCube measurements use this attenuation to perform measurements!

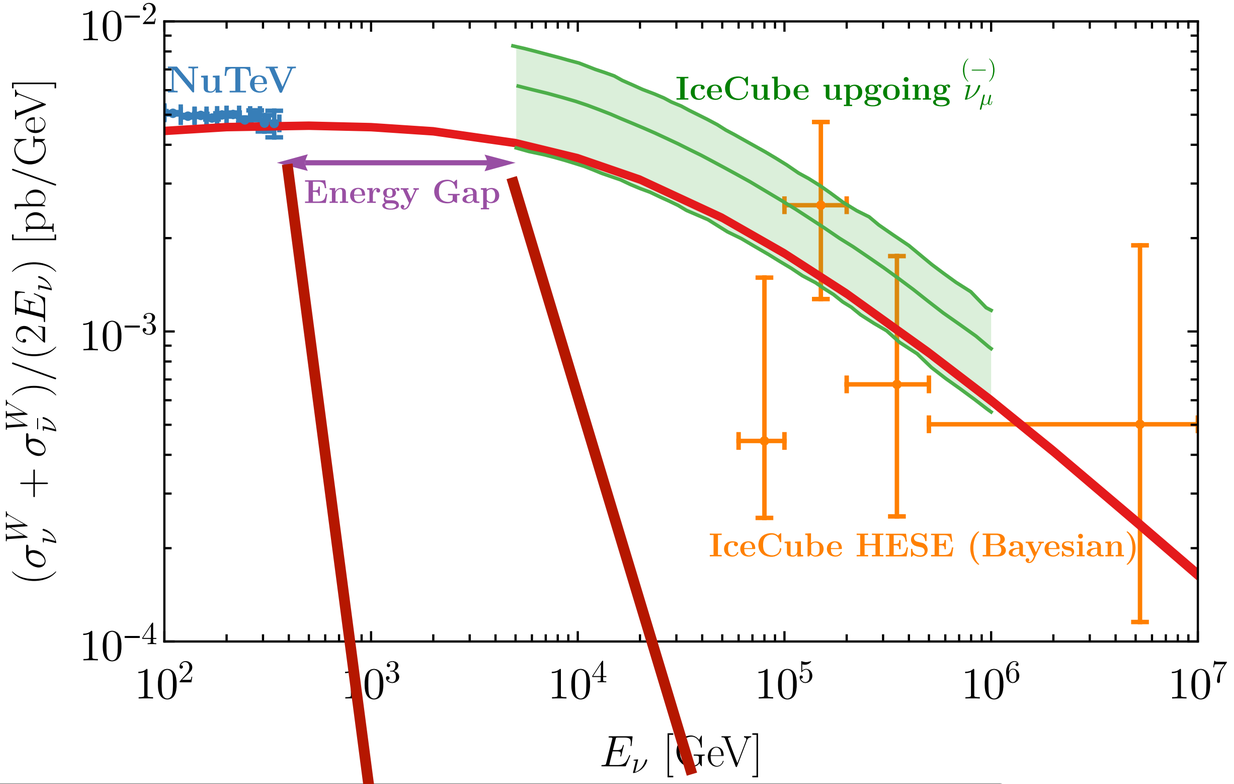


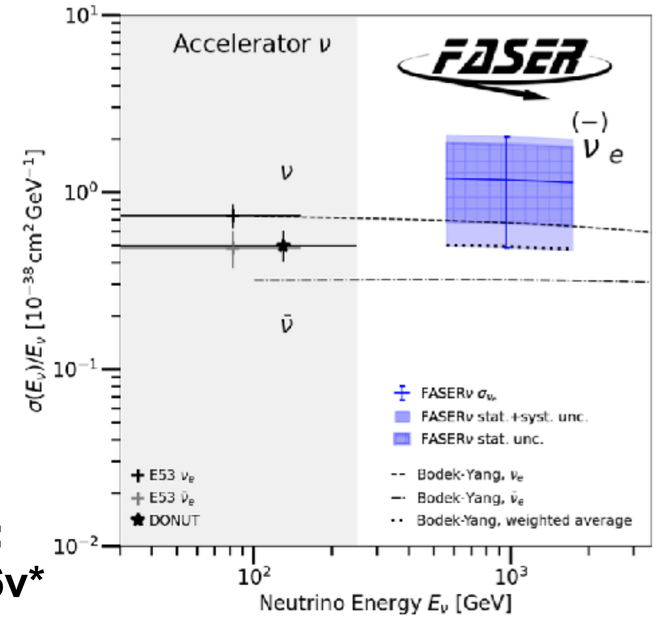
arXiv:2108.04965v1

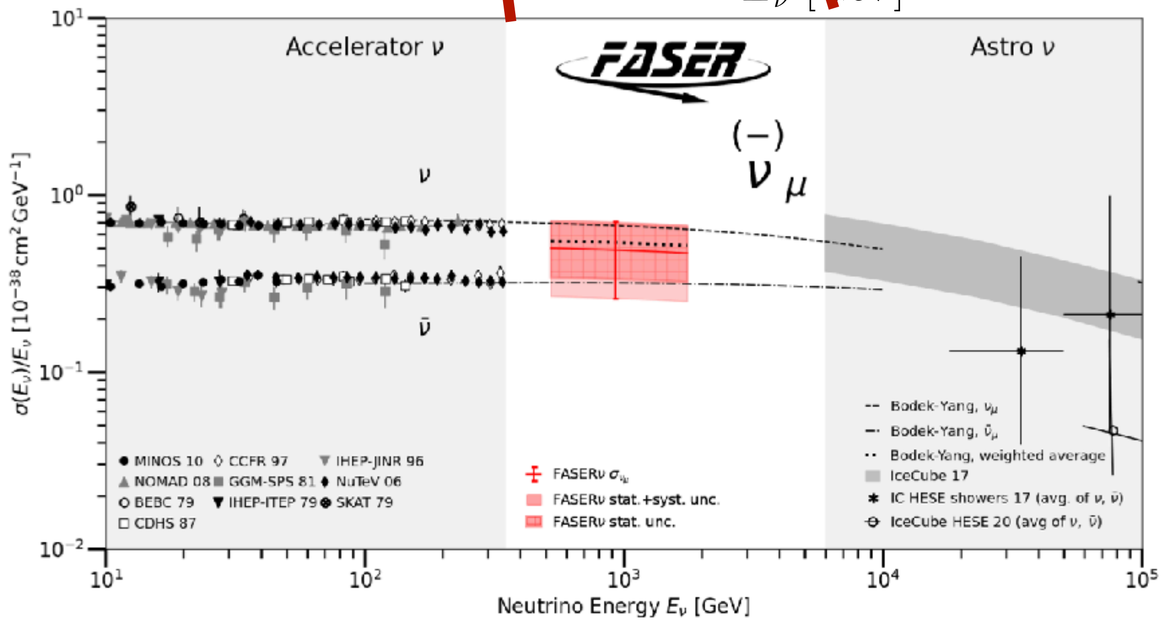
- Until recently, IceCube was the only experiment to measure the DIS cross section above several hundred GeV.



- Until recently, IceCube was the only experiment to measure the DIS cross section above several hundred GeV.
- Recent results from Faser are filling in the "Energy Gap".
- Complimentary measurement: next-generation IceCube cross section with more precision & overlapping energy.



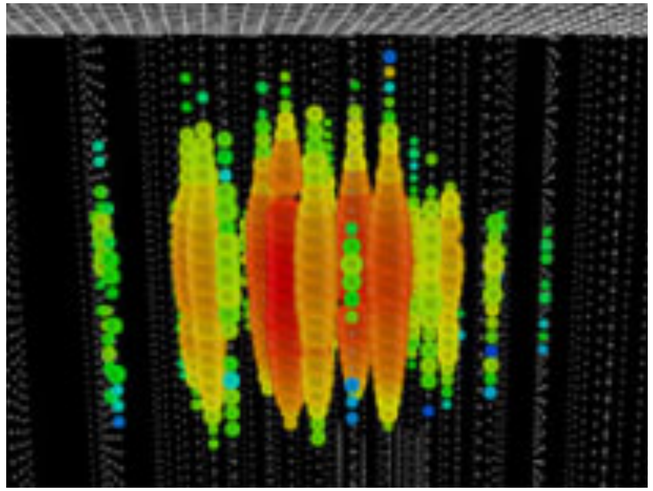




Also new FASER results: arXiv:2412.03186v

A Combined Analysis

Cascades



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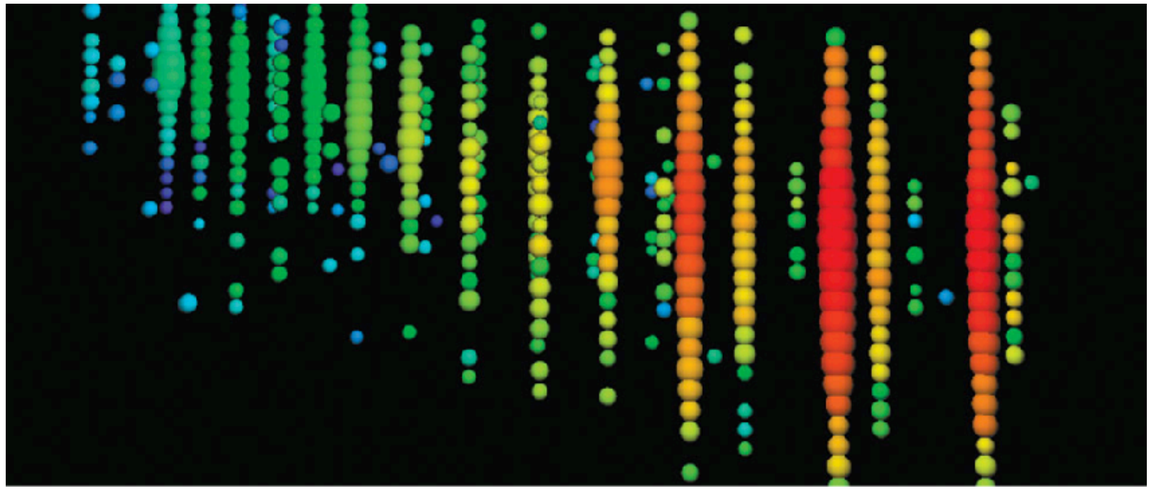
Tracks

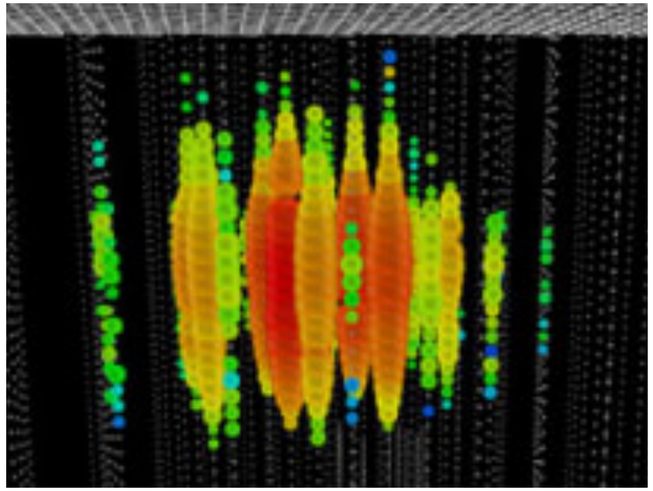


- Calorimetric energy reconstruction.
- 360° reconstructed zenith.

- High statistics.
- Lever-arm-based direction reconstruction.

A Combined Analysis

Cascades



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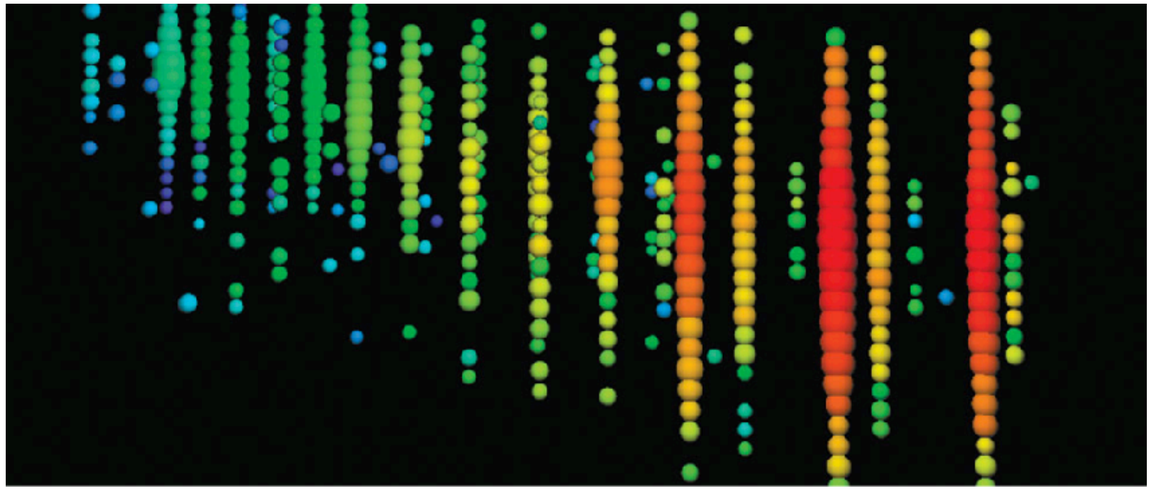
Tracks

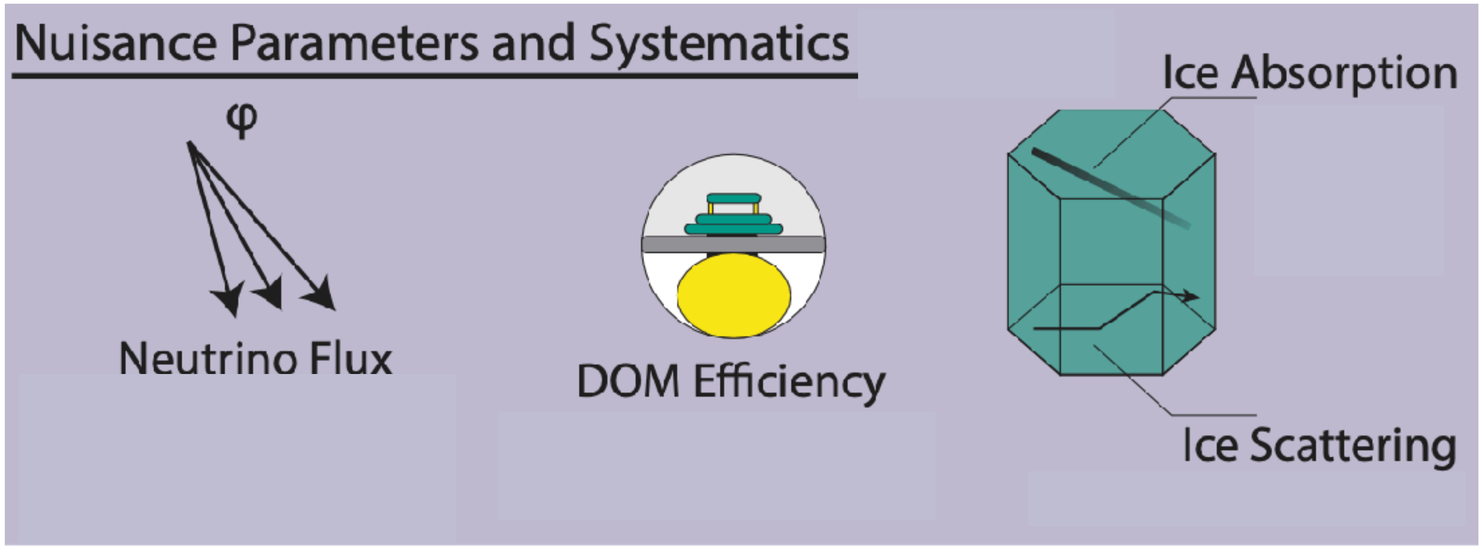


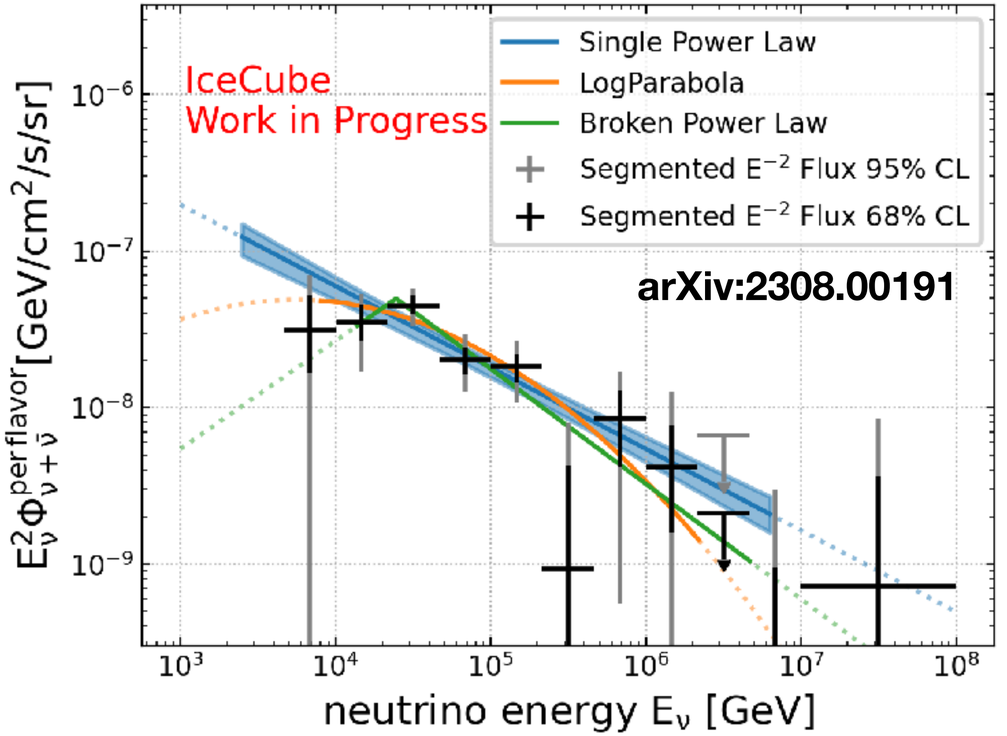
- Calorimetric energy reconstruction.
- 360° reconstructed zenith.

- High statistics.
- Lever-arm-based direction reconstruction.

- Leverage highly-synergistic information in a simultaneous multi-dimensional fit.

Nuisance Parameters & Systematic Uncertainties





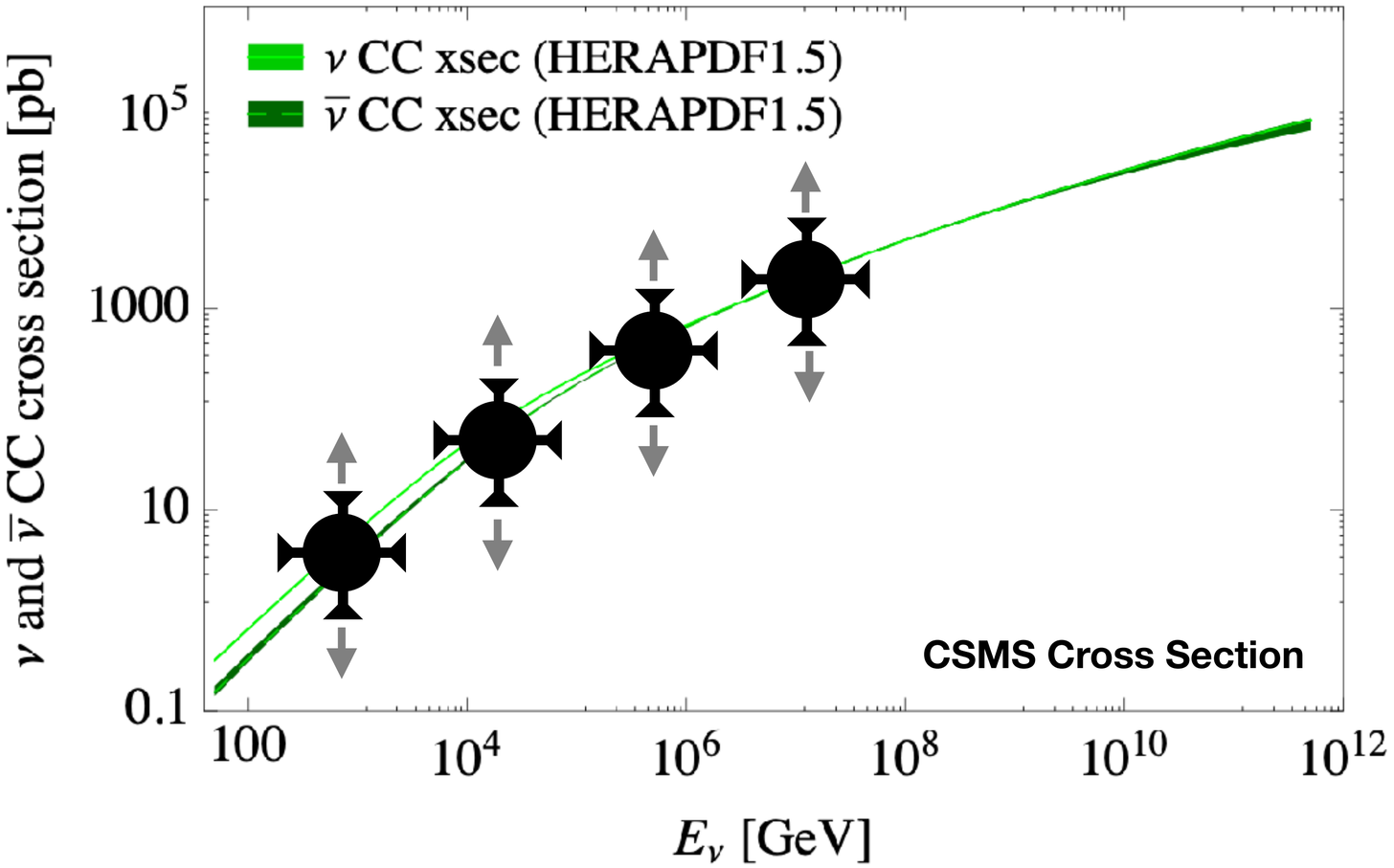
- Consider detector effects like DOM efficiency and ice properties.
- Introduce additional flexibility for astrophysical flux models beyond the traditional single power-law.

Methodology

IceCube's Multi-Dimensional Fitting Tool

icecube / NNMFit

- Construct a binned likelihood with the cross section as free parameters.

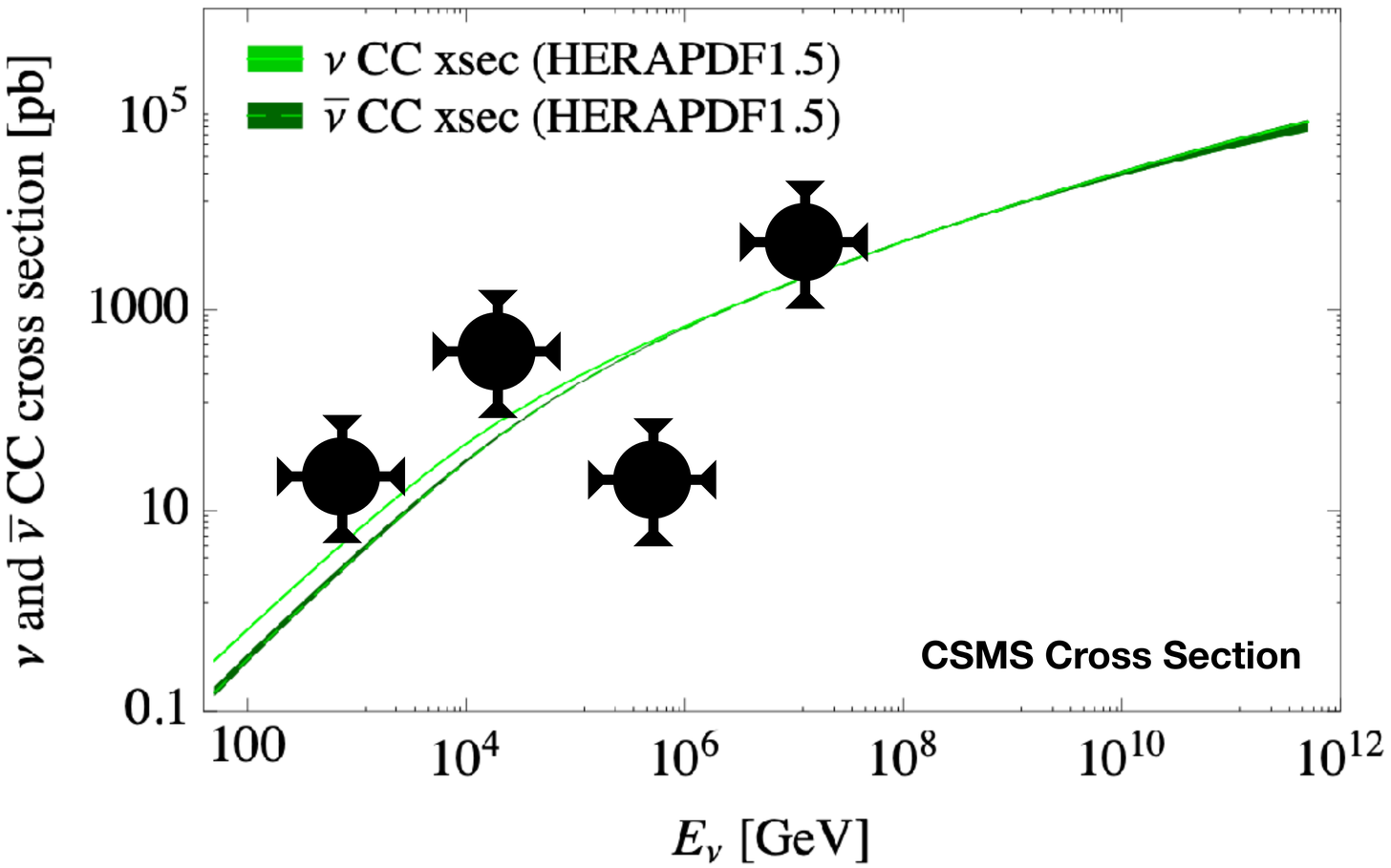


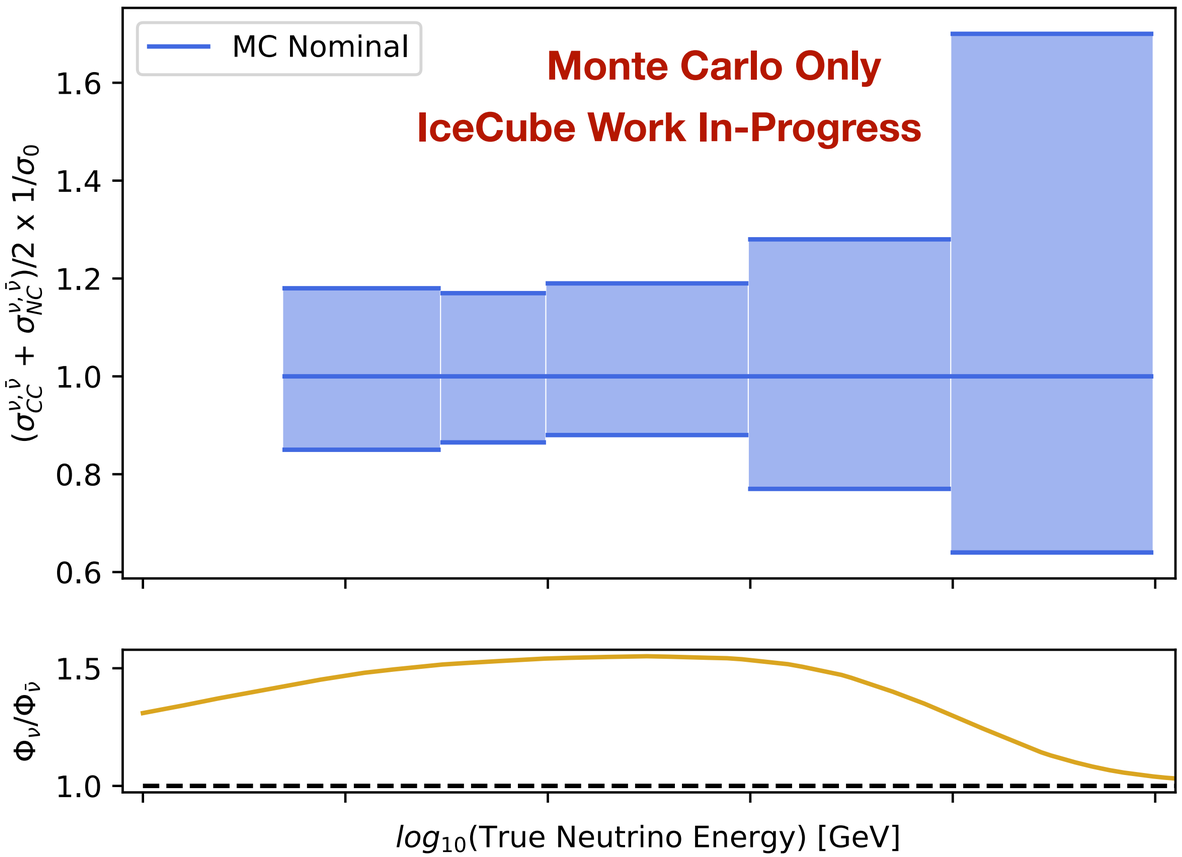
Methodology

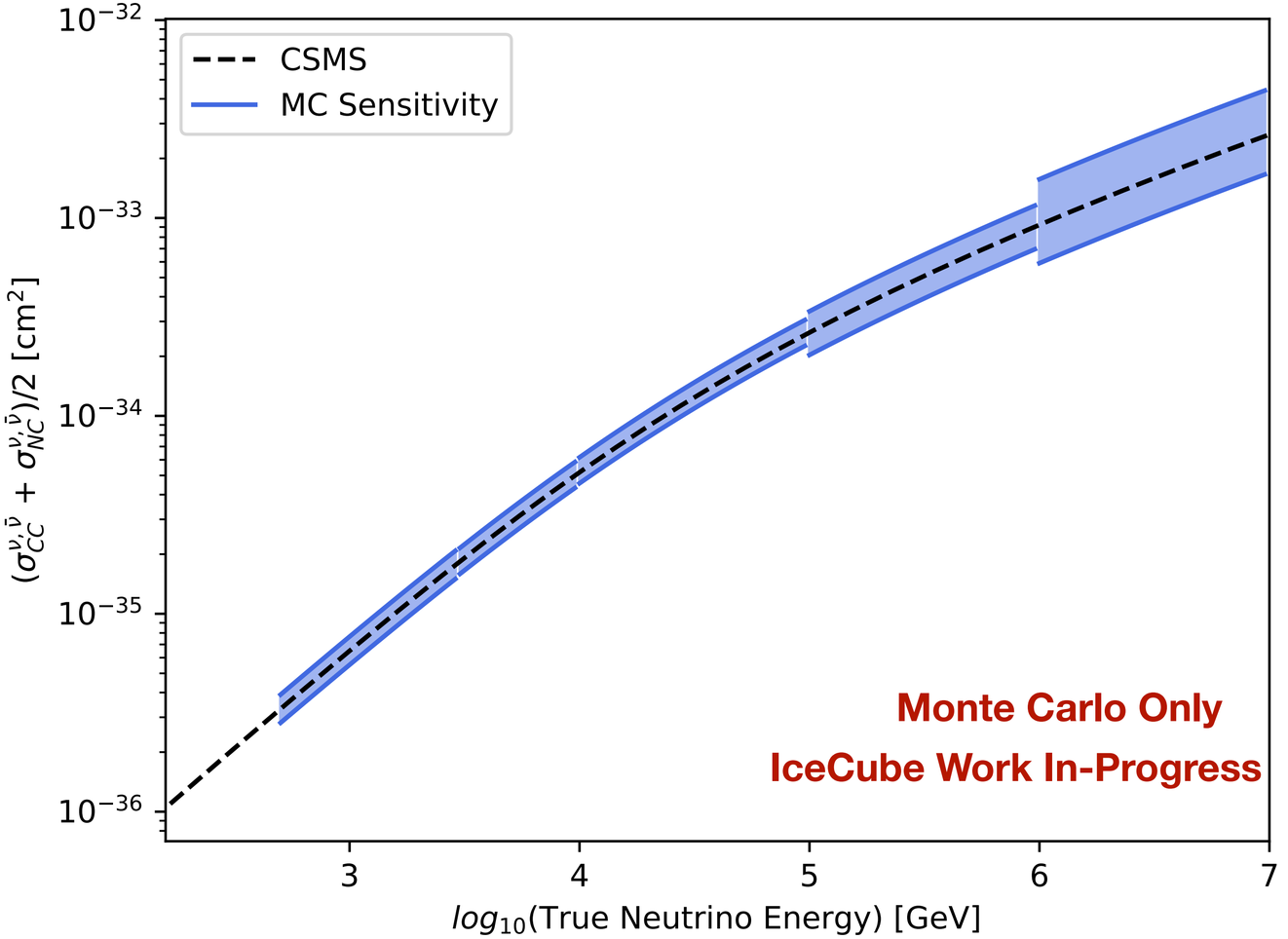
IceCube's Multi-Dimensional Fitting Tool

icecube / NNMFit

- Construct a binned likelihood with the cross section as free parameters.
- Fit the segmented normalisation assuming some cross section model shape and baseline.



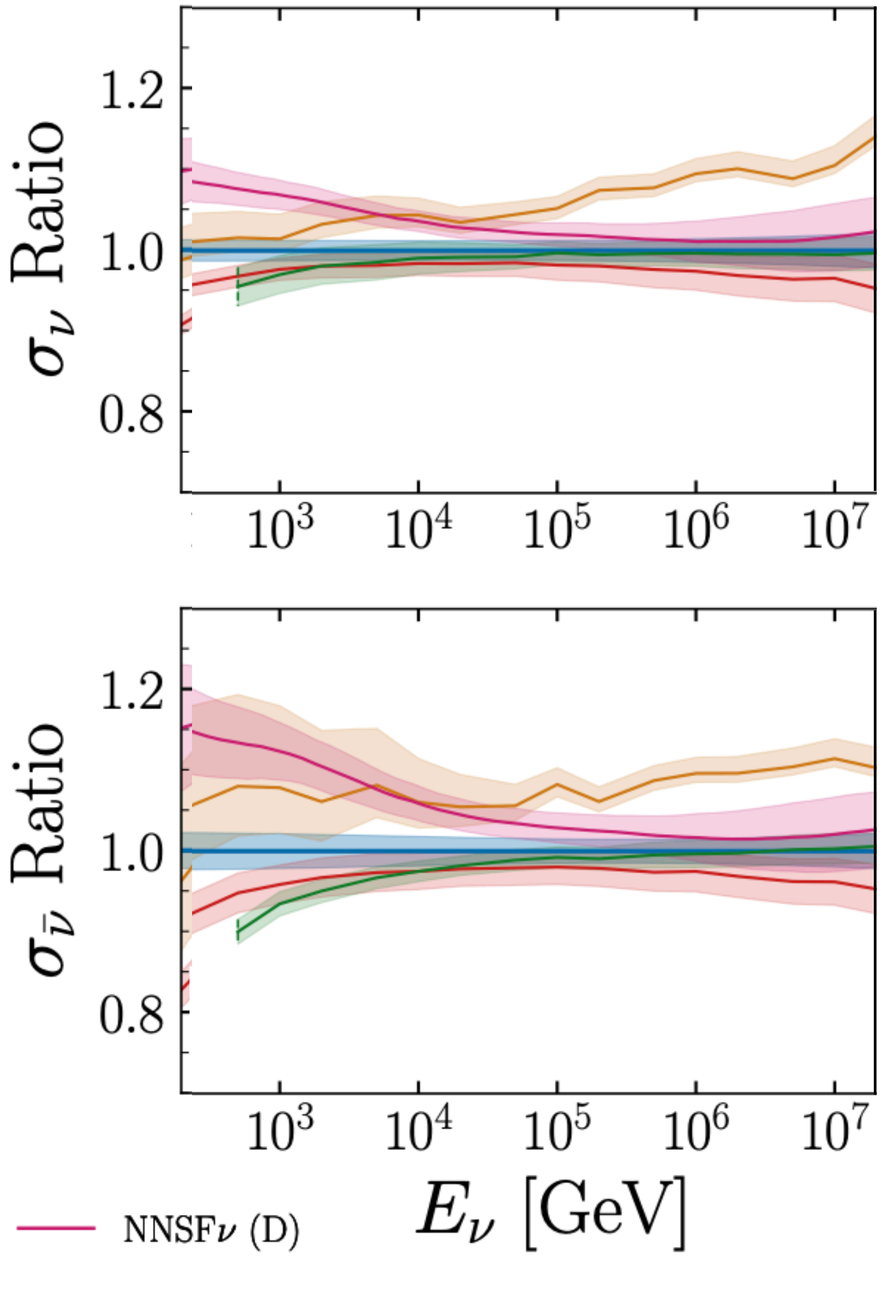




- Leverage synergistic information in a simultaneous multi-dimensional fit.
- Projecting sensitivity in the TeV-range around 20%, around 50% in PeV-range.

Future Potential

- In recent years, the number of theoretical models describing the DIS neutrino cross section has also increased.
- While the differences between these models in the sensitive energy range is on the order of 10% or less, this measurement offers a potential opportunity to compare models to data.

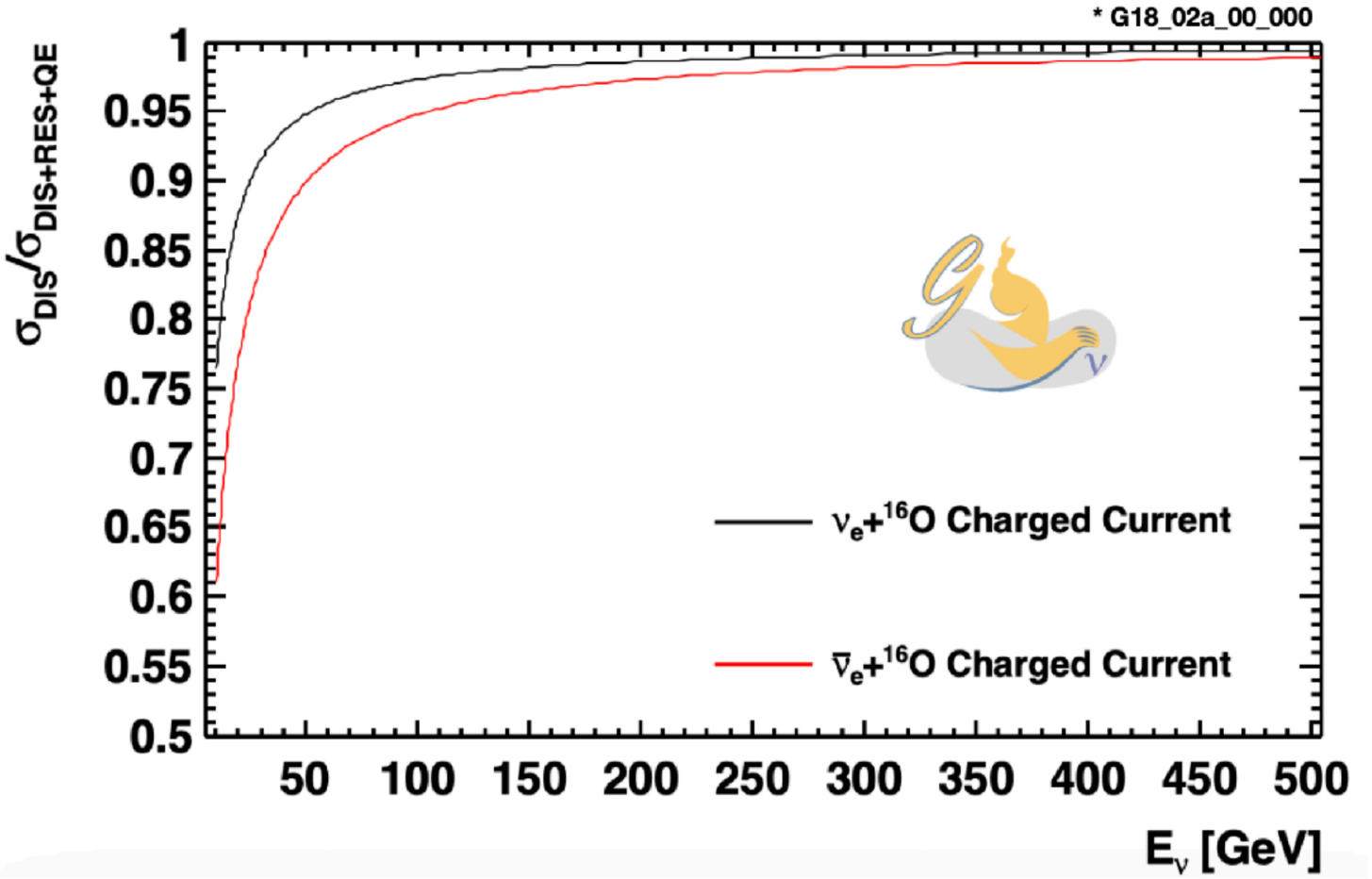


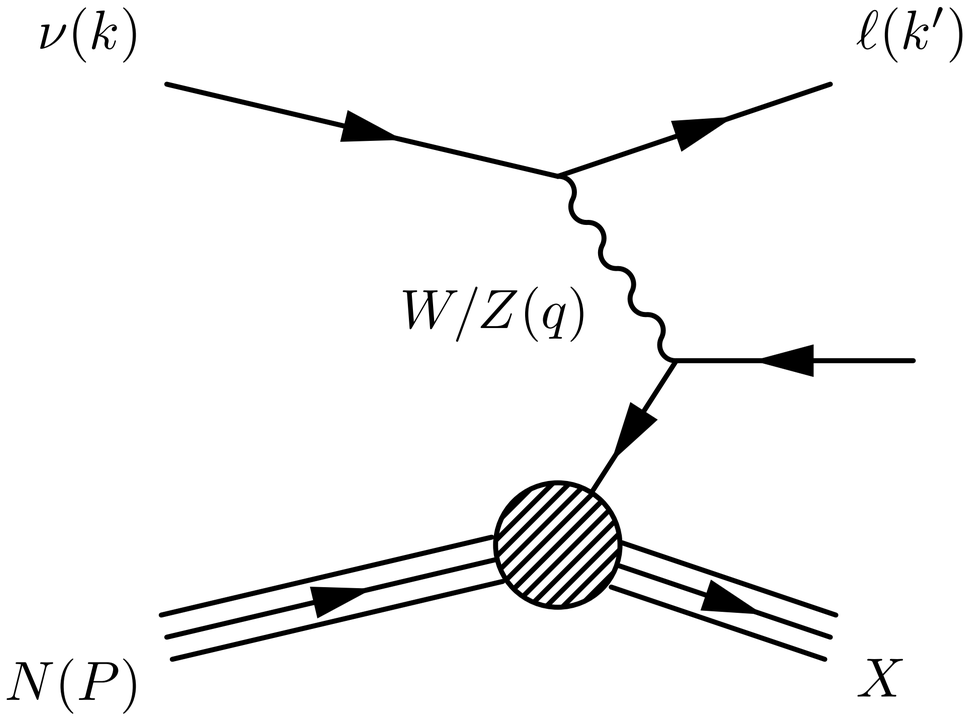
Summary and Outlook

- IceCube has the ability to measure the DIS neutrino cross section across a wide energy-band.
- Using a combined sample of track and cascade type events, we can construct a synergistic event sample.
- The next-generation DIS cross section measurement with the IceCube detector is *nearly* ready to unblind.
- New results expected within just a few months!

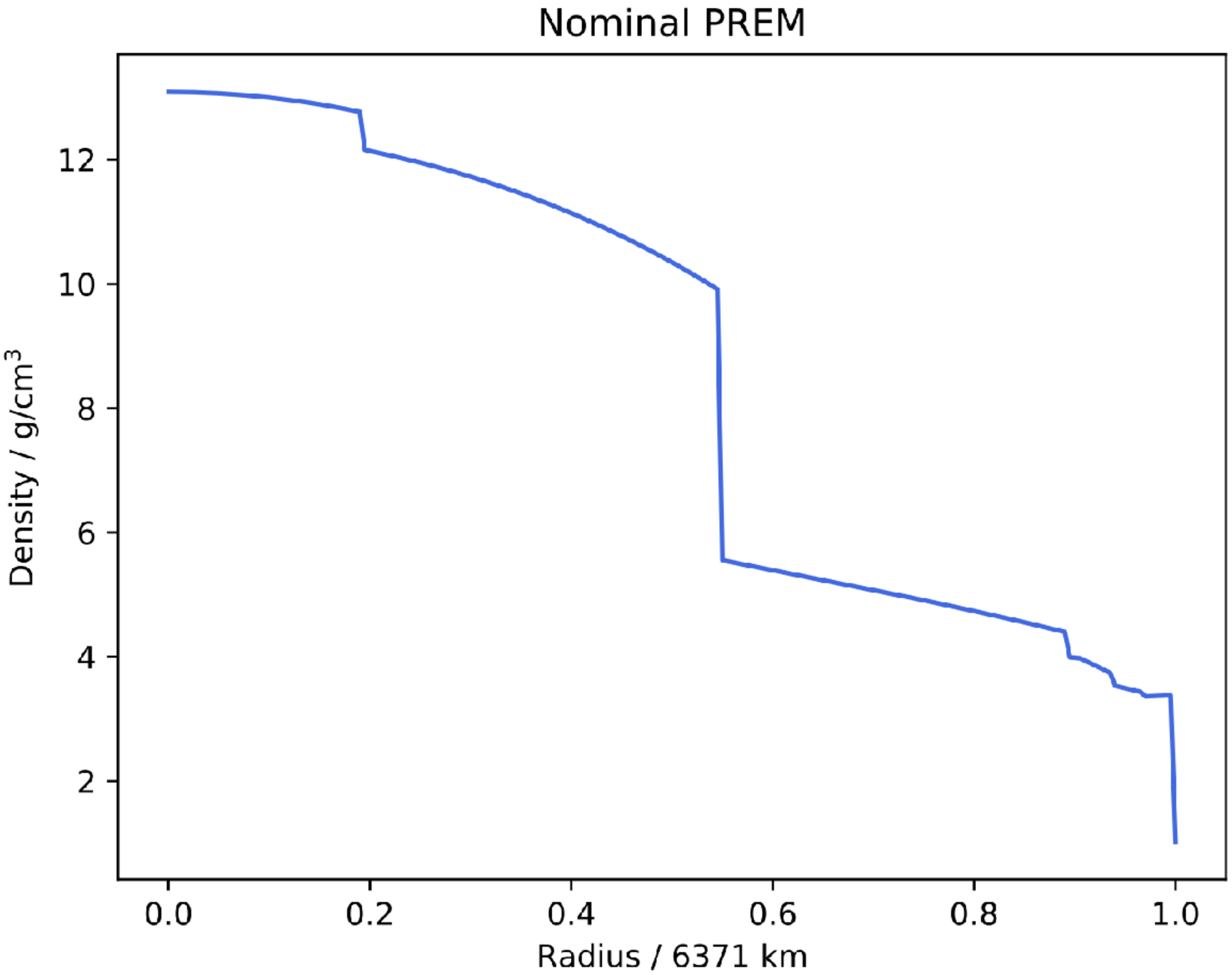
- Backup

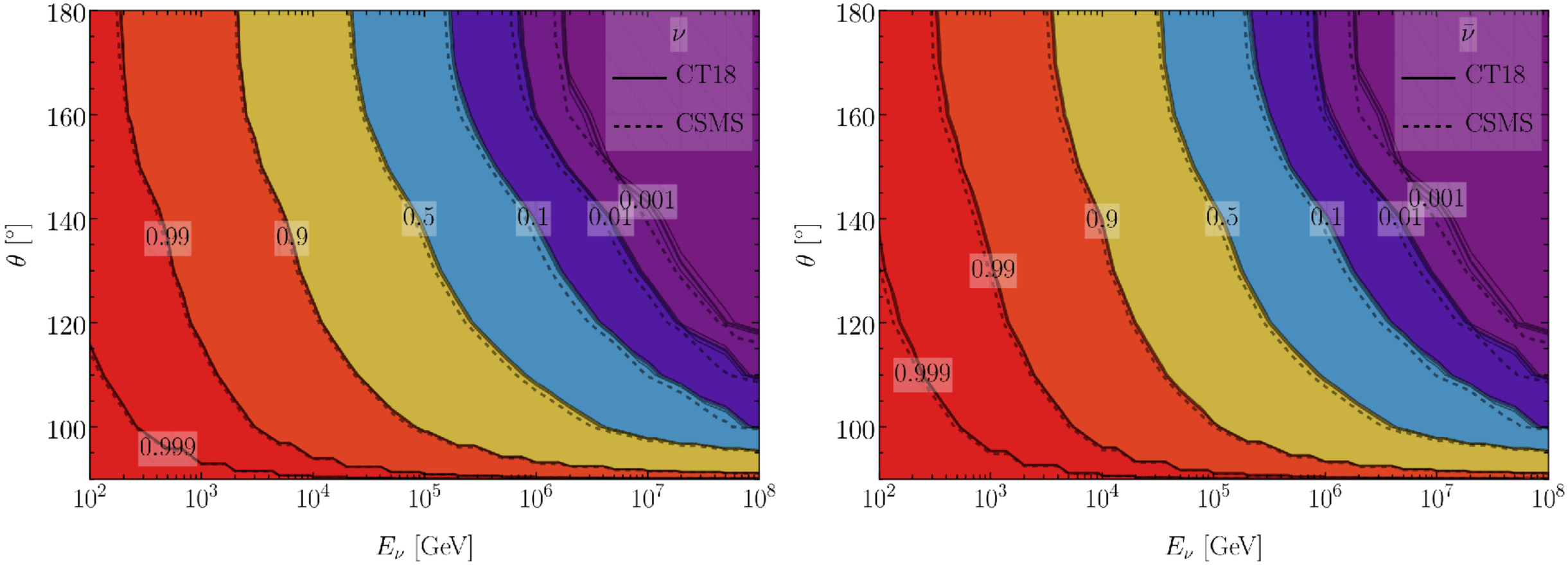
Deep-Inelastic Scattering



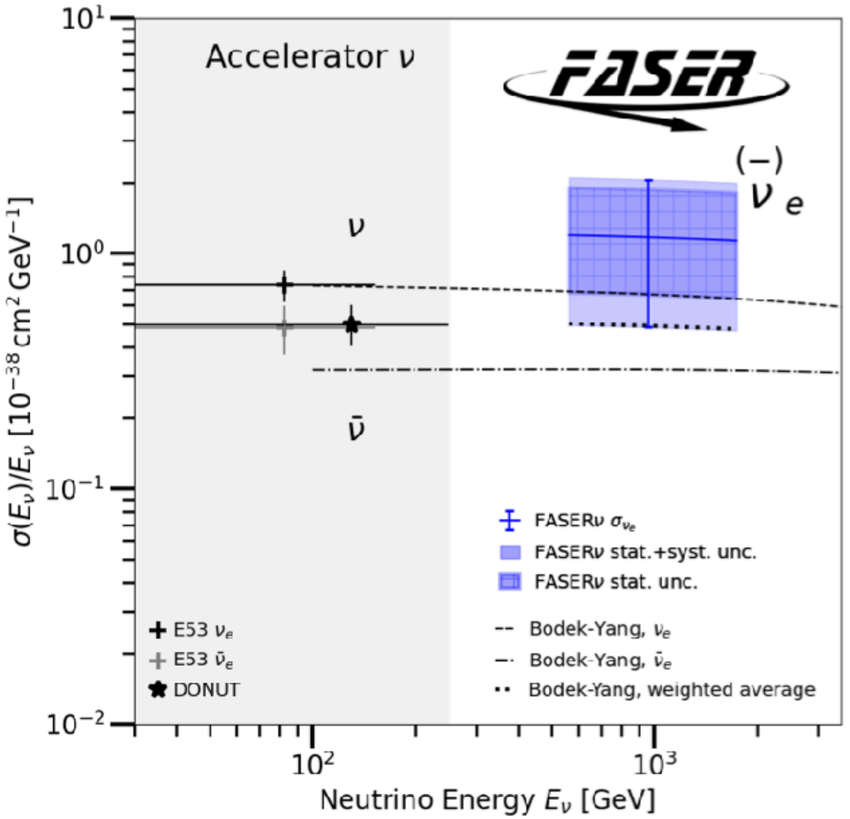


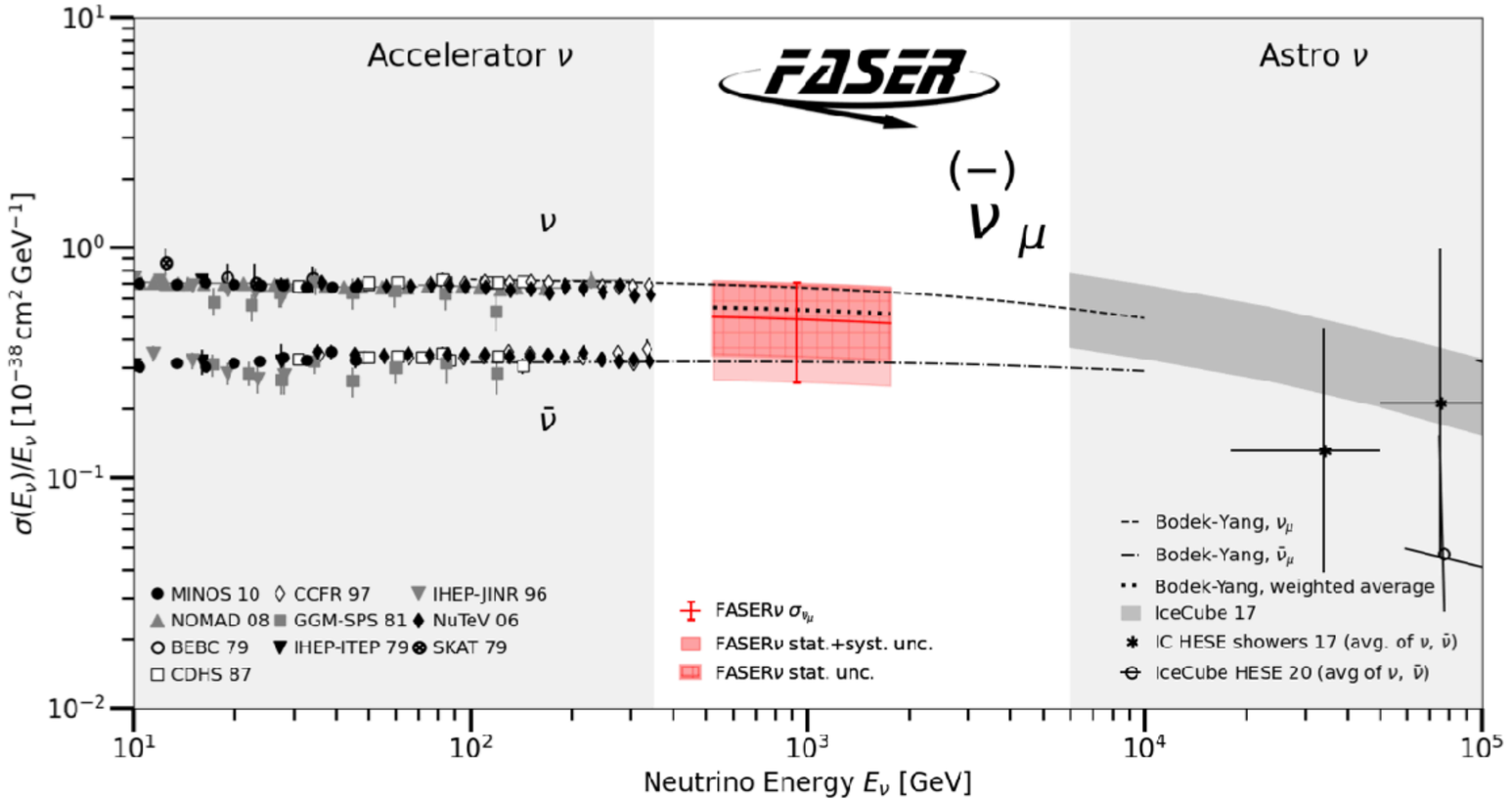
- At IceCube energies - strongly in the DIS regime!


Nominal PREM
Density / g/cm^3
12
10
8
6
4
2
0.0
0.2
0.4
0.6
0.8
1.0
Radius / 6371 km

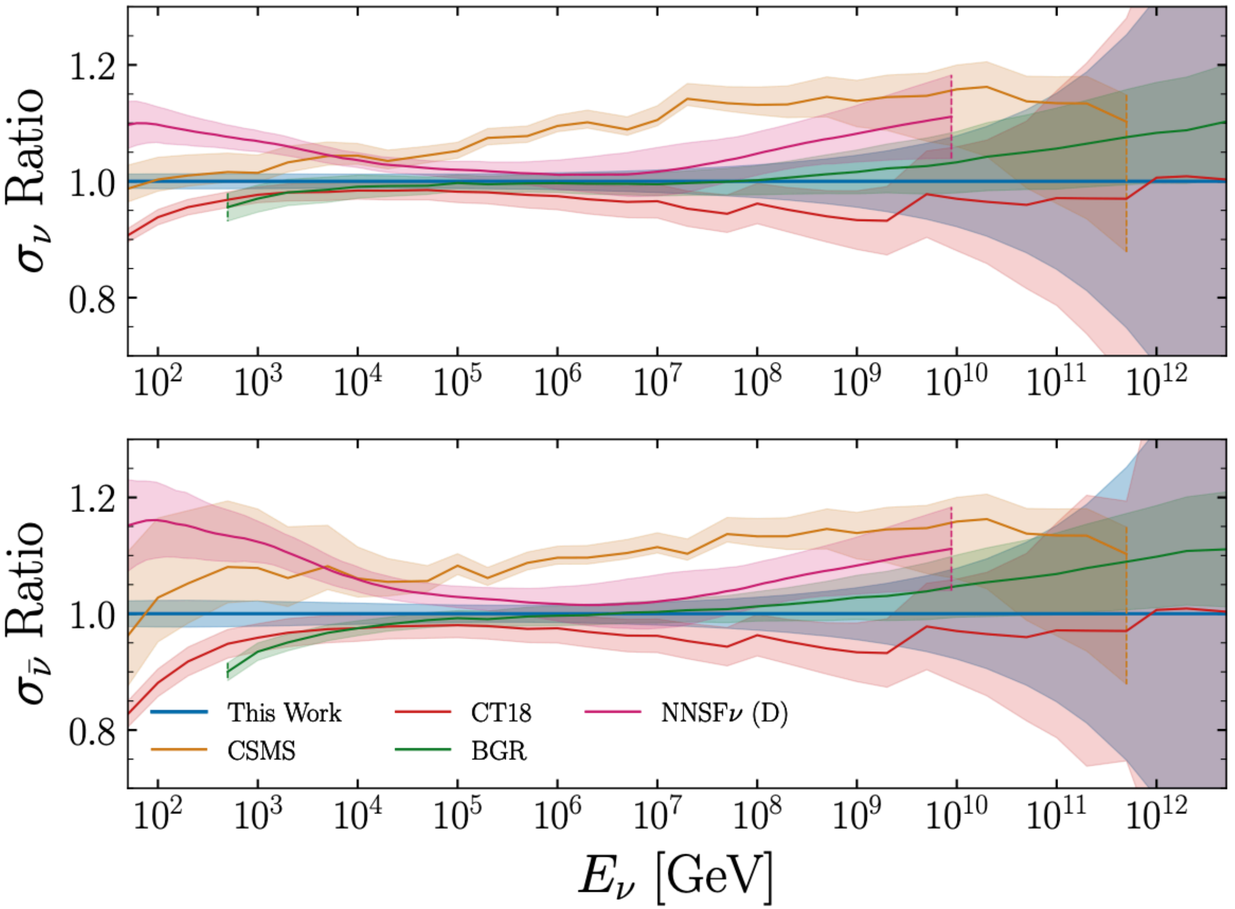


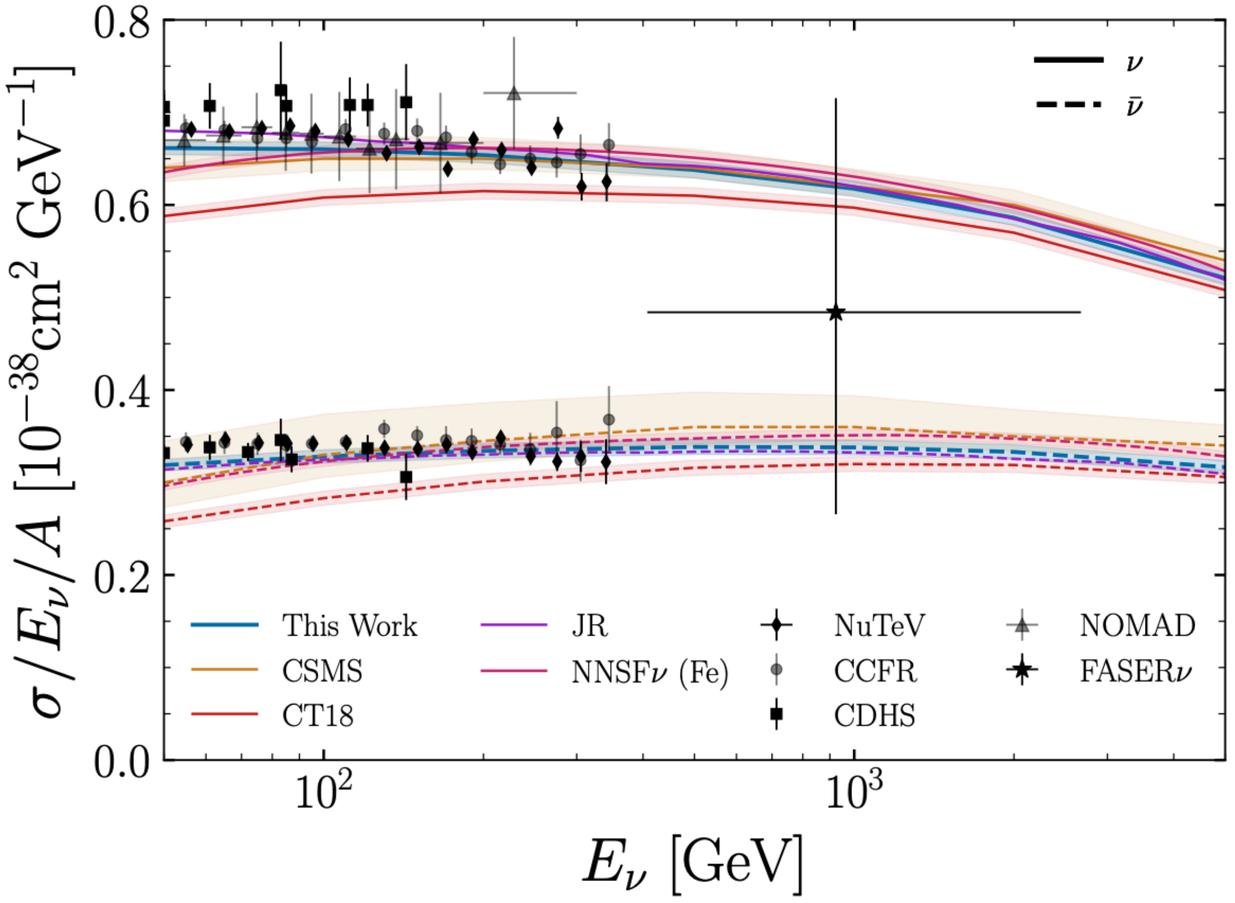
Neutrino vs Anti-Neutrino





https://doi.org/10.48550/arXiv.2403.12520


σ_ν Ratio
$\sigma_{\bar{\nu}}$ Ratio
This Work
CSMS
CT18
BGR
NNSFν (D)
E_ν [GeV]


$\sigma/E_\nu/A$ [10^{-38}cm^2 GeV^{-1}]
ν
$\bar{\nu}$
This Work
CSMS
CT18
JR
NNSFν (Fe)
NuTeV
CCFR
CDHS
NOMAD
FASERν
E_ν [GeV]