A Model Independent Framework for Measuring the UHE neutrino Cross Section

(based on 2205.09763)

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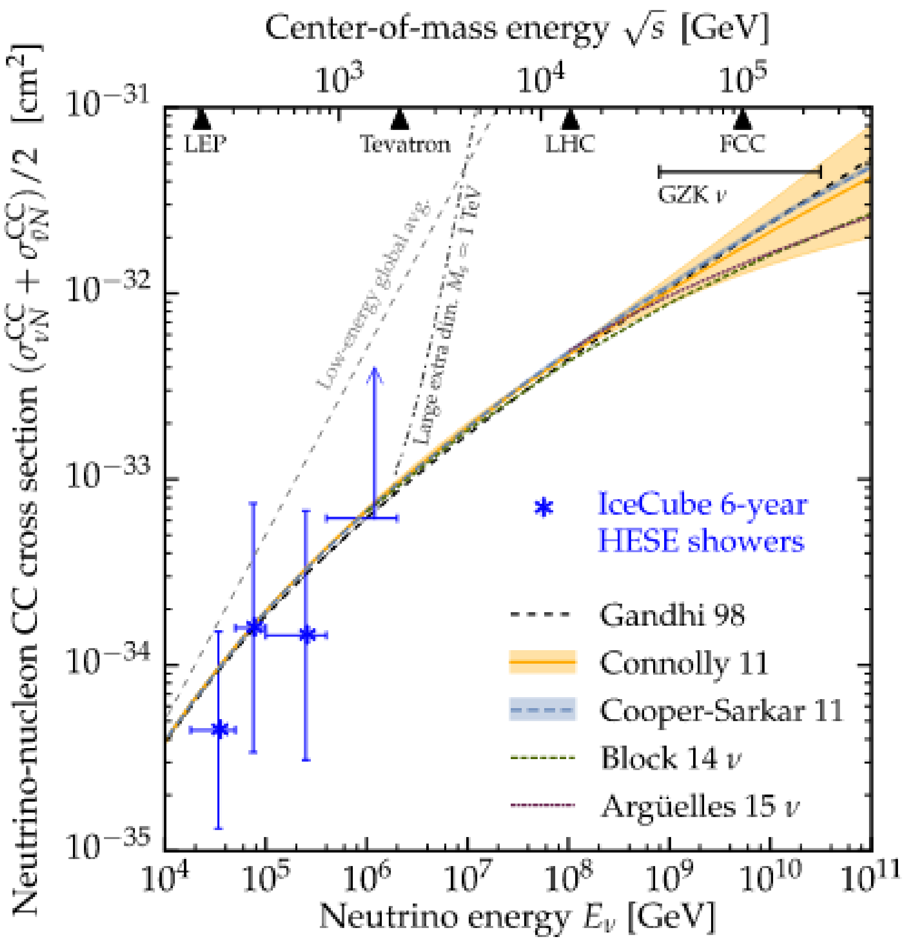
Motivation

- The UHE neutrino cross section is interesting for several reasons:
  - Neutrinos are the **only observed particle with known beyond-standard-model properties,** and **xSec has yet to be measured!**
  - New physics is expected at high energies!
  - UHE regime is beyond collider reach in energy!
- No one has measured it because no one has measured neutrinos in the UHE range.
- We want to answer 3 questions:
  1) Can the UHE cross section be measured?
  2) How many neutrinos would you need to detect?
  3) What would the detector requirements be to make the measurement?

UHE xSec at "lower" energies

- Bustamante and Connolly in 2017 made a measurement of the neutrino-nucleon σ at IceCube
- Here they show data (blue) and a range of SM σ uncertainty (and some theory curves)
- Things start to get interesting at UHE, just beyond IceCube range



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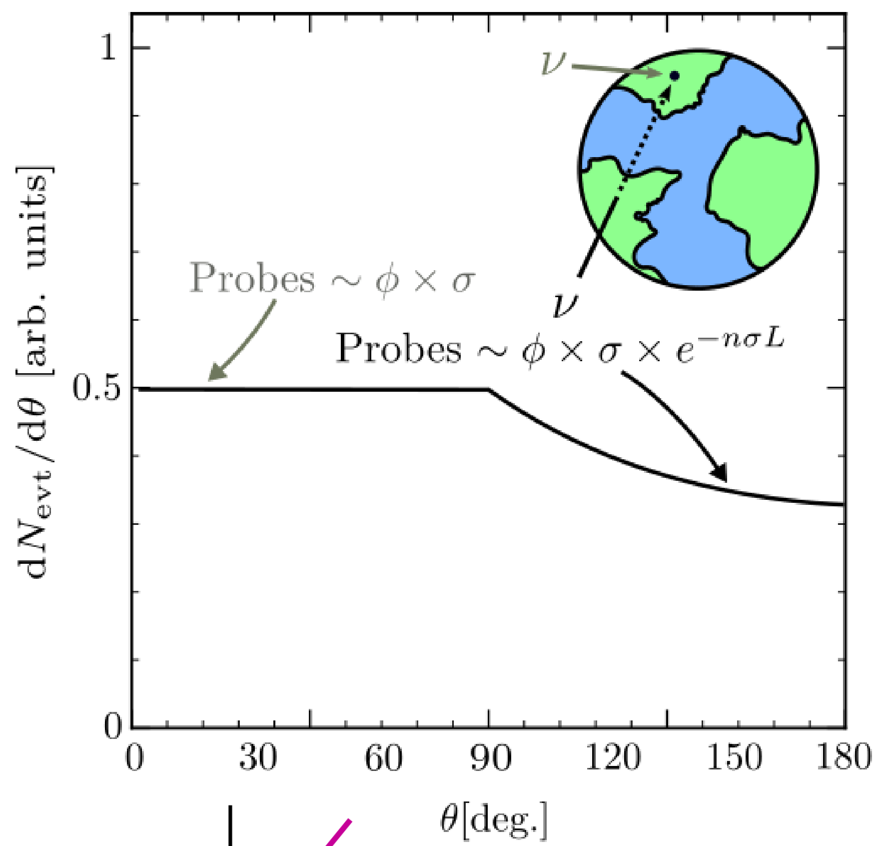
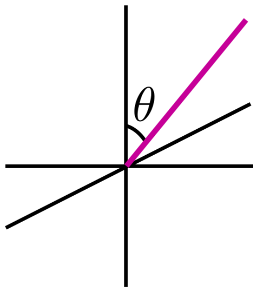
How is the cross section measured at IceCube?

- At higher energies, the earth becomes more opaque to neutrinos.
- neutrinos coming down through the air to your detector (that is, traversing very little material, θ<90) measure flux times cross section, φσ
- neutrinos coming up through the earth are absorbed by the amount of earth they traverse L(θ), which is dependent on arrival direction zenith angle θ, so this probes $\phi\sigma e^{-n\sigma L(\theta)}$
- The ratio of upcoming to downgoing lets you measure the cross section.

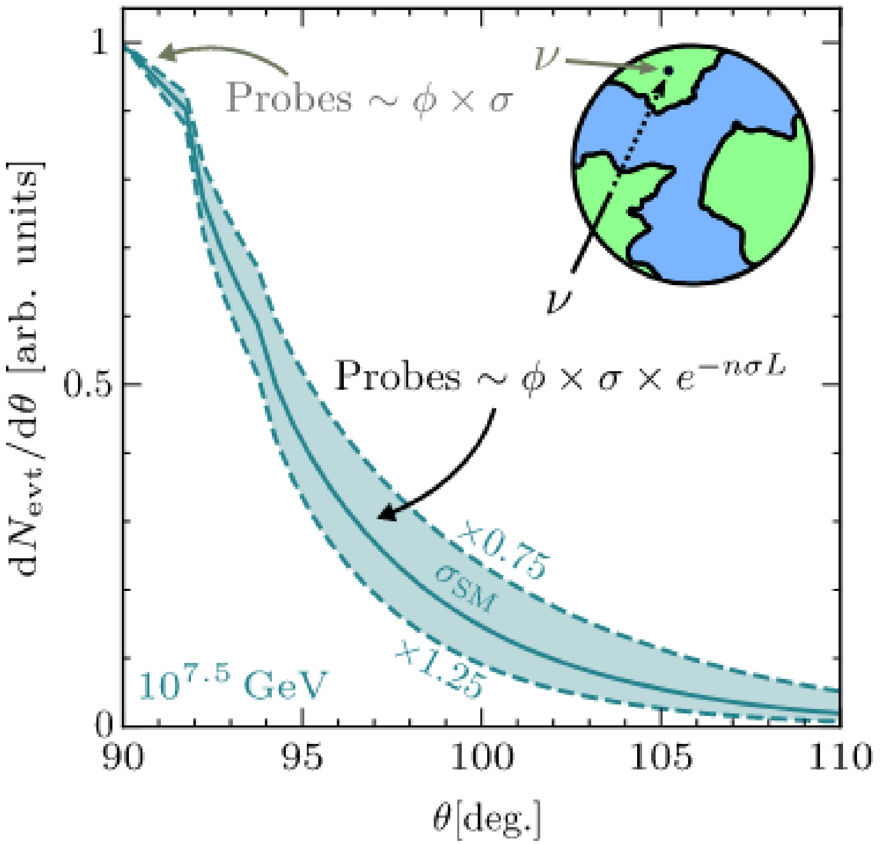
Not to scale, just for illustration





What about the UHE range?

- In the UHE range, the absorption is so strong that basically all neutrinos get absorbed when they interact with some amount of earth en route to the detector.
- Does this make it easier or harder to measure the cross section?

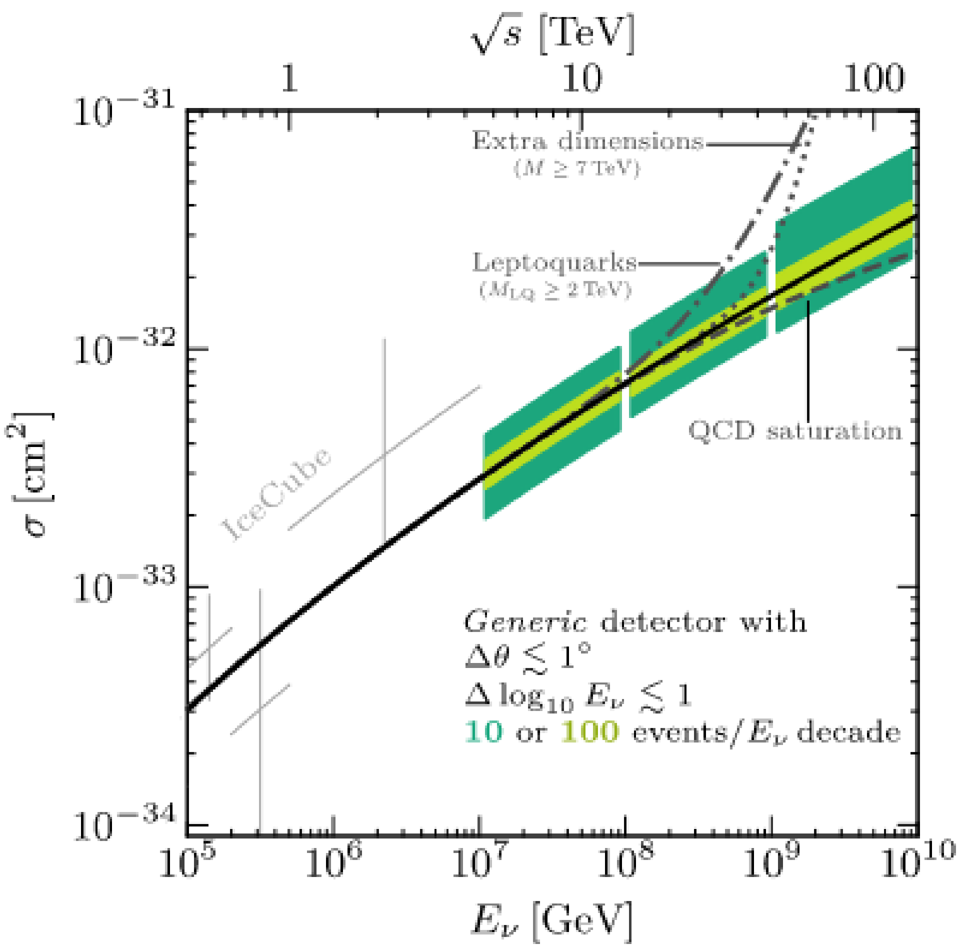


note the x axis spans only 20 deg!

What about the UHE range?

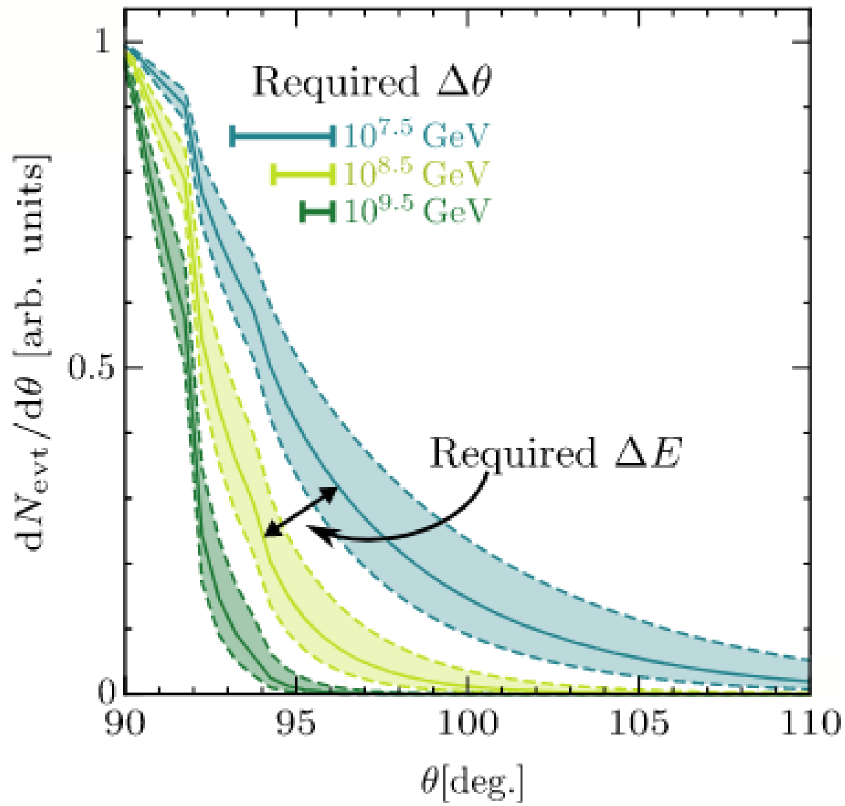
Result in brief:

- If we assume a **generic flux** and a **generic detector** with a ~1 degree resolution in arrival angle and a ~1 decade resolution in energy, the measurements are as shown:
  - darker green band, 10 events per decade
    - Maybe doable in our careers!
  - light green band, 100 events per decade
    - Maybe doable in several consecutive careers!

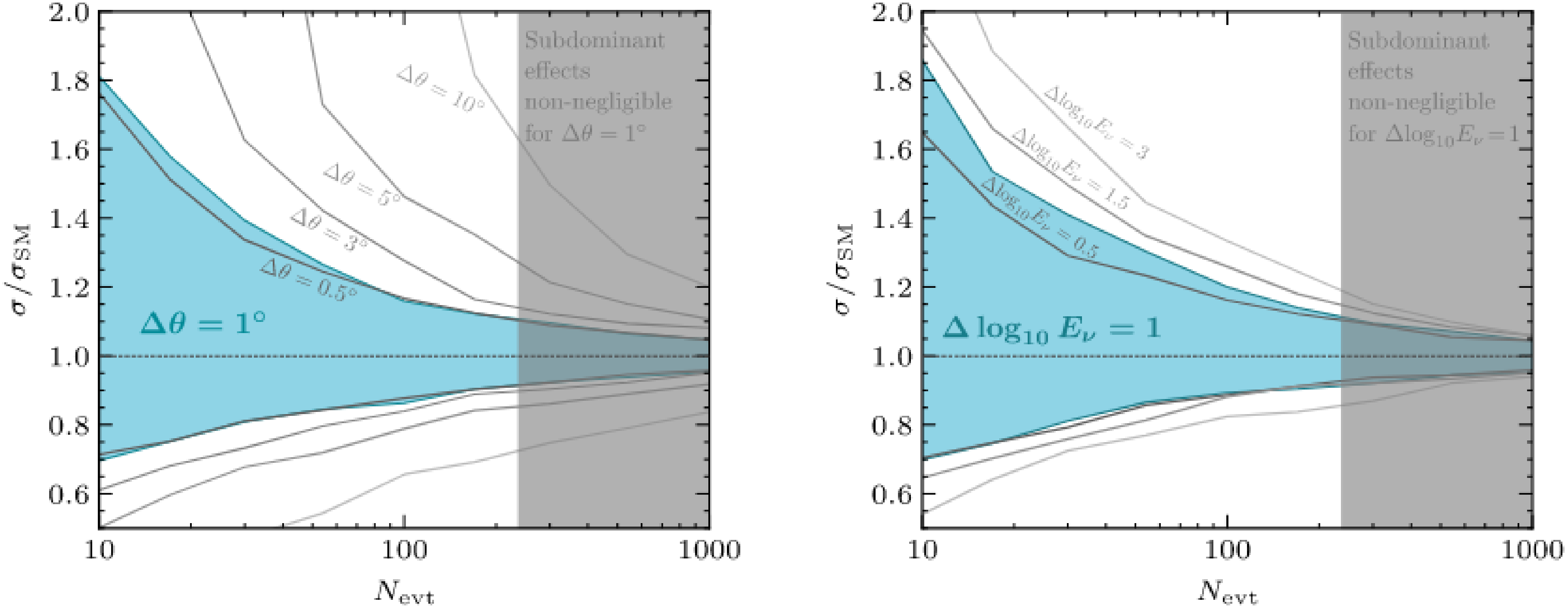


What are the detector requirements?

- Many experimental papers discuss their capabilities, and what can be done with them (e.g. Denton et al. 2007.10334 and Valera et al. 2204.04237 [*and this session!*])
- What about instead asking, what capabilities should experiments aim for in order to make physics measurements? And how many neutrinos would be needed at those resolutions?

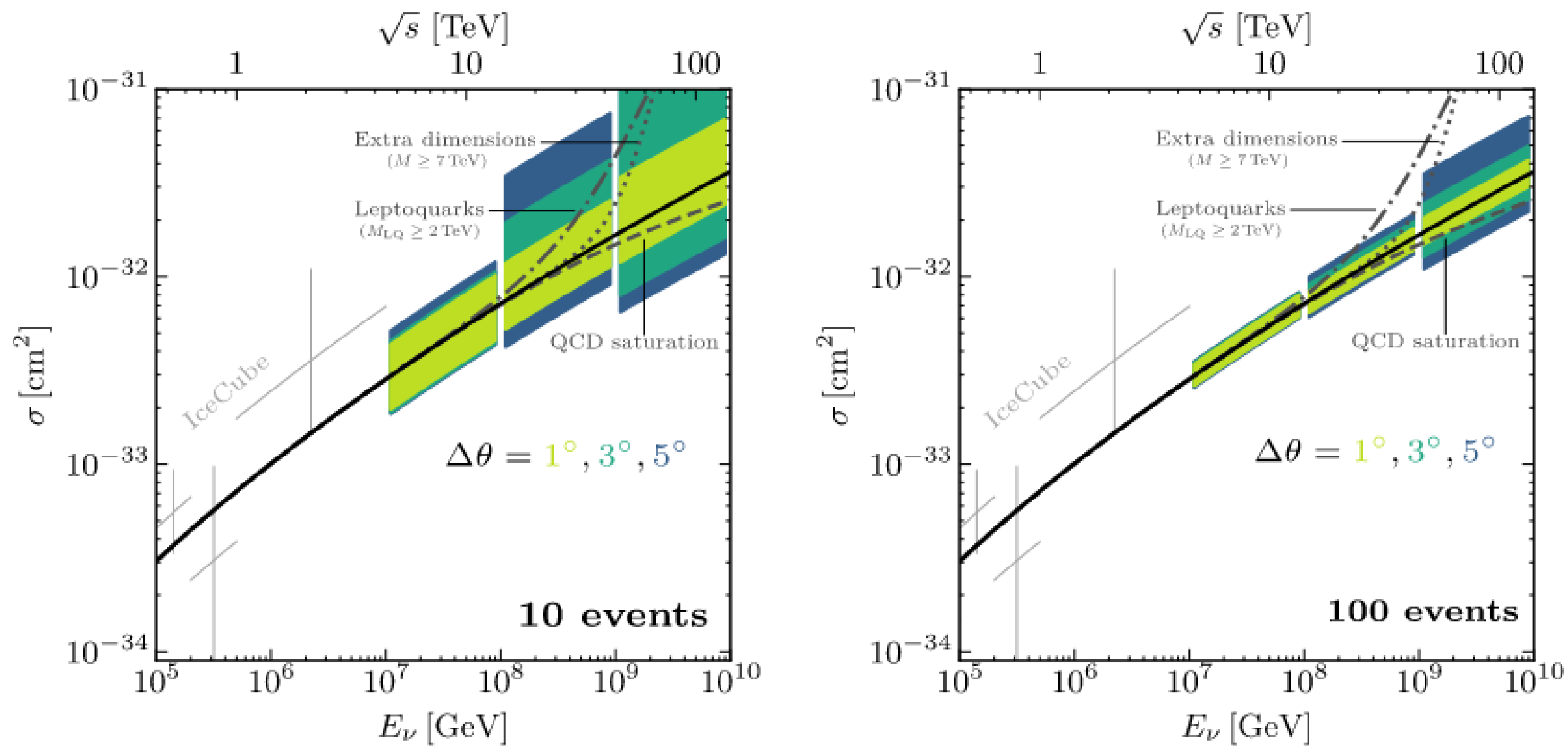


What are the detector requirements?



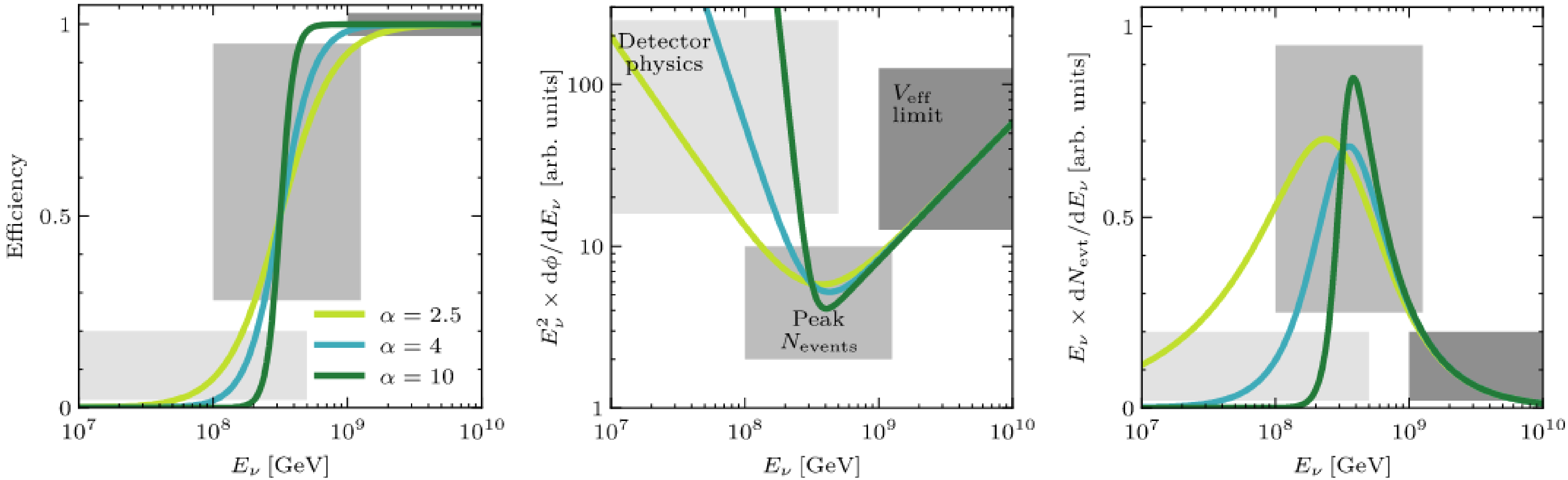
- **Left:** one sigma constraining power contours on the ratio of measured σ to the SM σ for various detector resolutions in zenith angle θ. **Right:** same, but for energy resolution.
- Interesting observation: ***once you hit a benchmark resolution in angle and energy, improvement does not really help!***

A global measurement



- Cool thing is, once a detector is capable of hitting these requirements, nothing else really matters! (detection strategy, location, etc).
- Multiple measurements can be combined to hit the required statistics: **a global measurement.**
- Above: Left: how the measurement changes with 10 events per bin, with different resolutions. Right: same, with 100 events per bin.

Understanding experimental capabilities

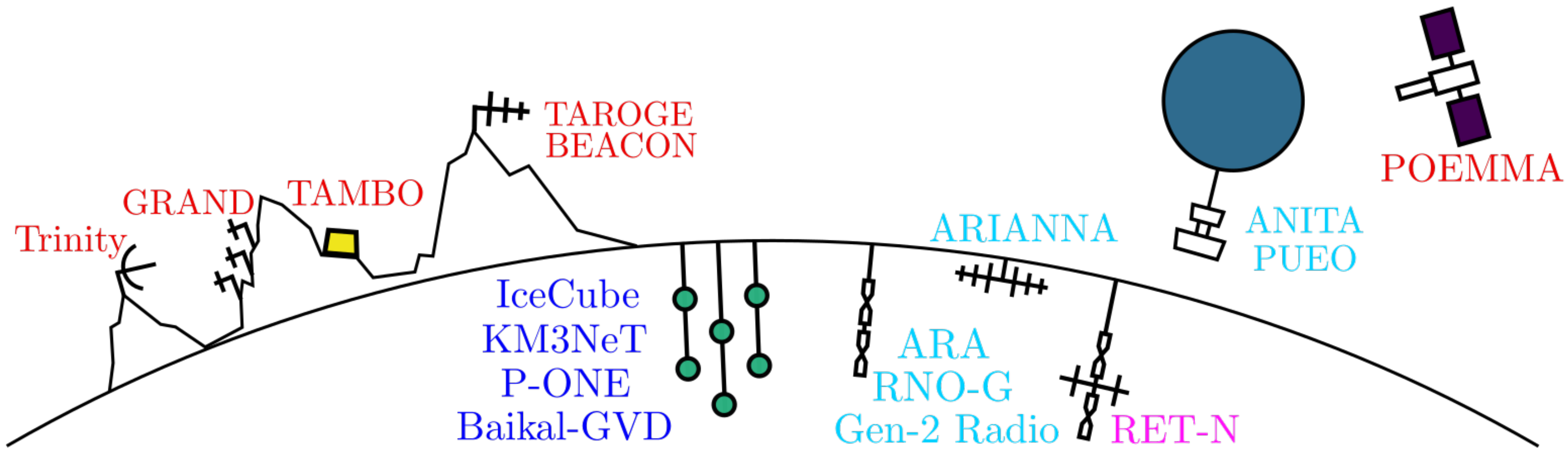


- **Left:** Generic experimental efficiency curves. The experiment's sensitivity turns on at some energy with some slope. Detector geometry + physics.
- **Middle:** Typical sensitivity curves in E^2 flux units. These curves come directly from the efficiency curves convolved with an exponentially falling flux.
- **Right:** number of neutrinos as a function of energy.
- Things to note: **1)** The minimum in the sensitivity curve (center) represents the peak sensitivity of a detector (right). **2)** A slower turn on (for the same characteristic energy) increases the statistics drastically. **3)** Very few events come from the most efficient region (because flux).

Big picture:

- As long as a detector hits the requirements for E and θ, a robust measurement of σ can be made.
- The shape of the experiment's sensitivity curve doesn't matter (so long as it hits the requirements, and has enough exposure/effective volume to be sensitive to a flux)
- Different experiments live in different energy bins; combining them for a global measurement is a powerful way to measure σ in a region where amassing statistics is very challenging!

The experiment zoo



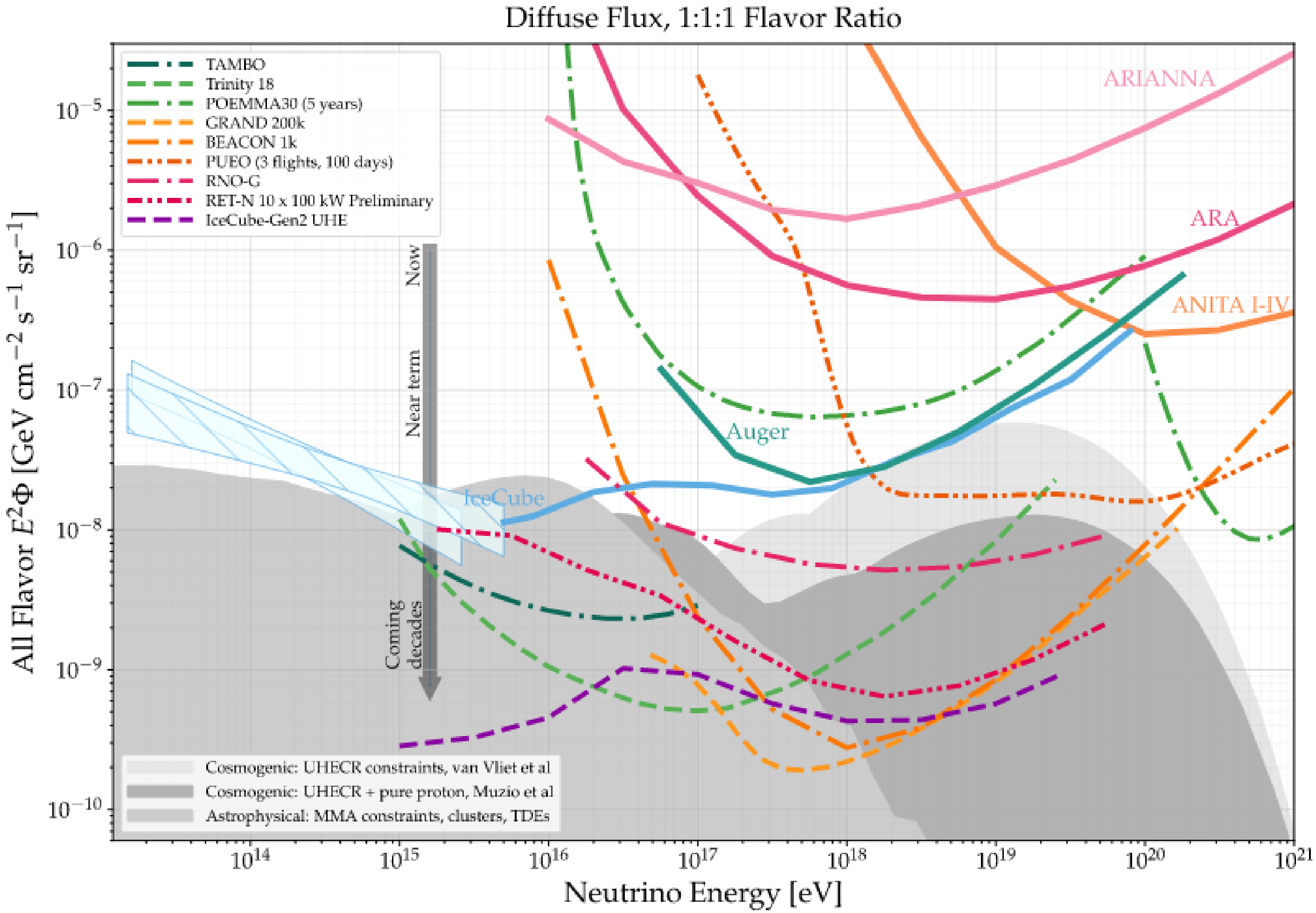
Adapted from Esteban et al. arXiv:2205.09763

Tau neutrino (optical+radio)
Askaryan (radio Cherenkov)
In-ice Optical Cherenkov
Radar

This cartoon shows many of the current and proposed experiments to measure VHE and UHE neutrinos.

Each has strengths and weaknesses, but the different physics underlying each method provides **different observables.**

The experiment zoo



- Many experimental curves with different shapes and different peak sensitivities
- Opportunity for **complementary physics measurements** in the next decade
- ***Your experiment can use our framework!***

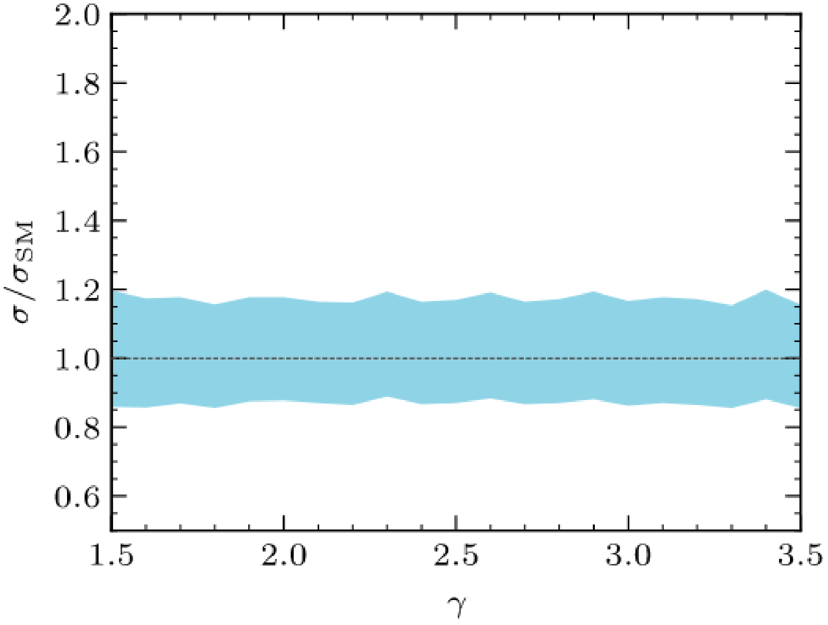
Summary

- Cross sections *can* be measured in the UHE range with modest statistics (~10 neutrinos), enough to constrain new physics models
- **Do you have a UHE neutrino experiment? *You can use our framework!*** Basically, plug-and-play
- Detector requirements are a challenge, but achievable
- Once benchmarks are met, **combination of experiments can allow robust measurement of σ across energies**
- Measurement possible within our lifetimes probably!

backup

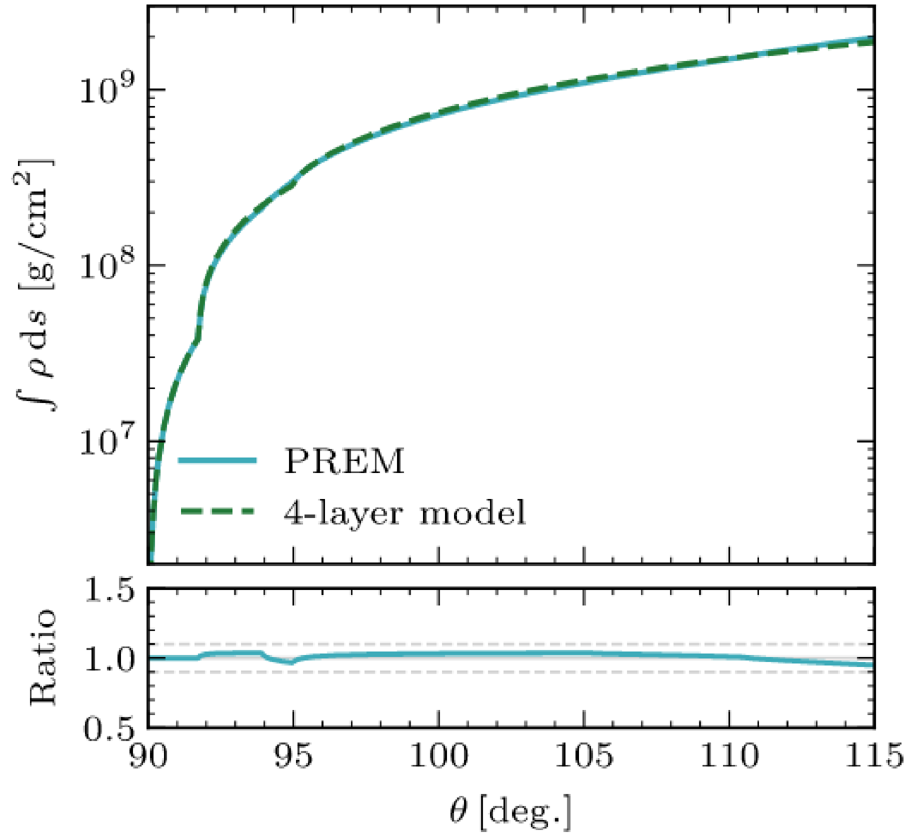
Model independence

- This study is model independent, meaning, we don't care about the flux. the right side shows the constraining power on the cross section (for fixed resolution and N events) for different shapes of the underlying flux.
- Because, a falling flux coupled with basically any efficiency gives you basically the same information: most of your events come from the lower energy end of your sensitvity.

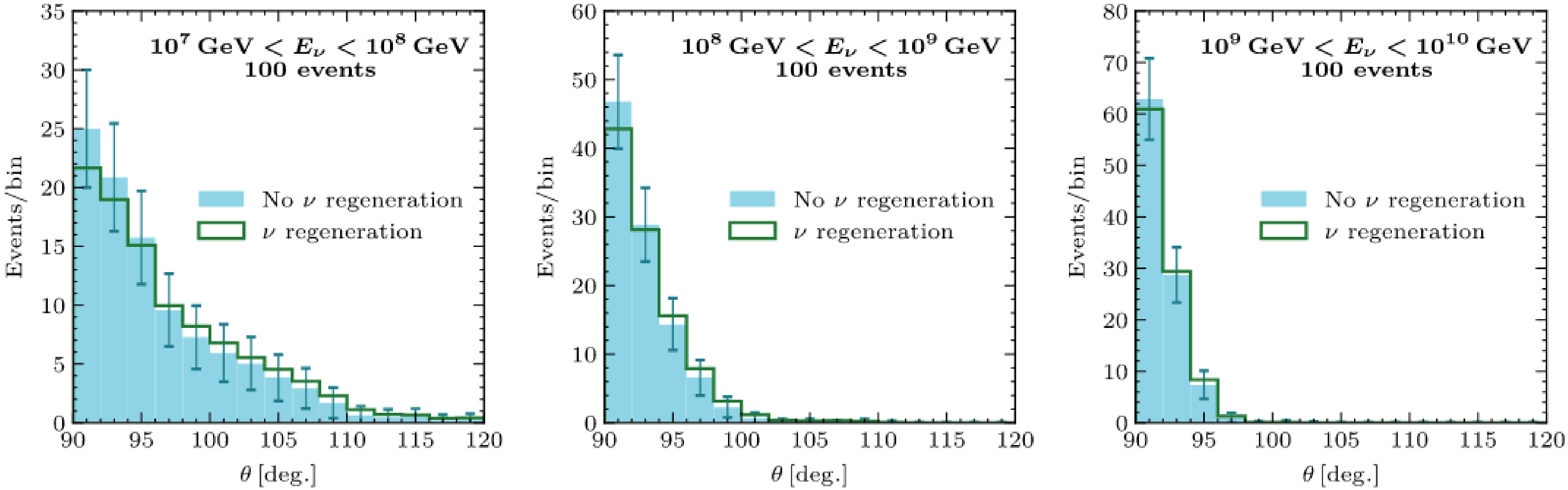


Earth profile

- Doing things simply: the Earth profile can be approximated by the PREM model, but even that can be approximated by a 4 layer model: ice, crust, upper mantle, lower mantle.
- We find that the profile really doesn't matter; the changes are largely irrelevant on the length scales traversed.



Does tau regeneration help?



- **Tau regeneration is a cool idea.** tau neutrino->tau lepton->tau neutrino->tau lepton. In this way, a very high energy neutrino that would normally never make it to your detector could in principle be detected
- BUT, this signal is buried in the far larger flux of lower energy stuff (each round of regeneration loses ~ decade in energy, so more than that in flux).
- won't be important until you hit the very high statistics regime (I'll be dust)