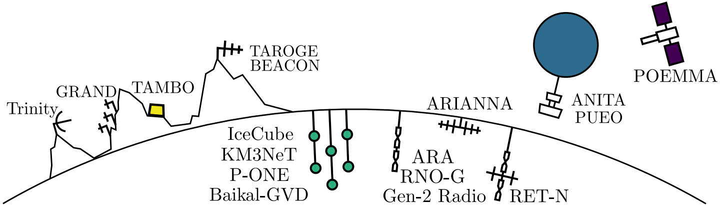
Ultra-high energy neutrinos and physics opportunities



Ivan Esteban

22th February 2023

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The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

Introduction

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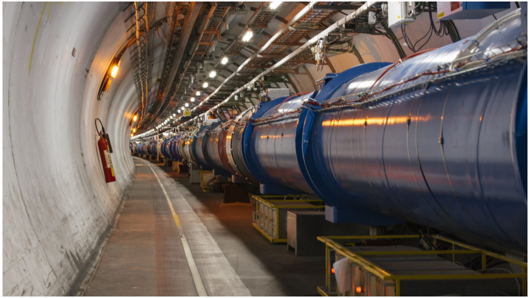
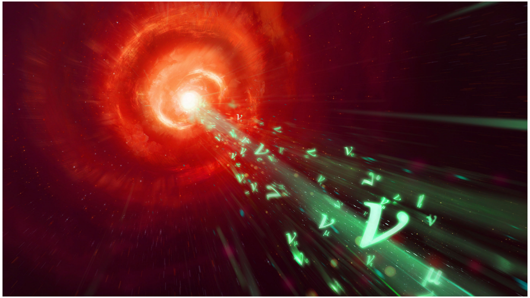
See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

Take-home ideas

We anticipate new physics at **high energies**



$\sqrt{s} \lesssim 10$ TeV



Source: Quanta Magazine

Ultra-High Energy **astrophysical neutrinos** will offer a **novel window**

Despite unknown flux, despite novel experimental techniques, despite low statistics

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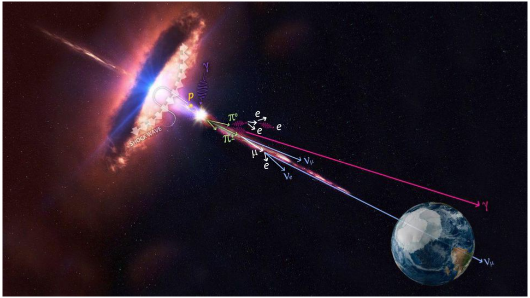
Some context

Probing high energies at Earth is technology- and investment-limited
Can we use astrophysical accelerators?



Source: IceCube/NASA

In principle yes!

$$\sqrt{s} = \sqrt{2\,E\,m_{\rm p}} \gtrsim 10\,\mathrm{TeV}\ \text{for}\ E > 5\times 10^7\,\mathrm{GeV}$$

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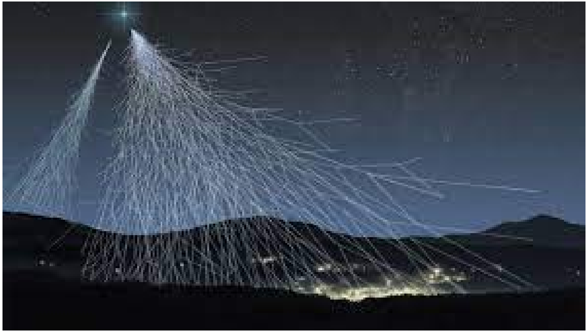
Some context: Auger

Auger (& TA) detects protons and other nuclei.



E up to $10^{11}\,\mathrm{GeV}$. But novel physics competes with strong interactions!
Let's use **neutrinos**!

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What about neutrinos?

The idea is simple:
Ultra-high energy proton flux ⇒ **Ultra-High Energy neutrino flux**

$$p + \gamma_{\text{bkg}} \Rightarrow \Delta^+ \Rightarrow n + \pi^+$$

$$n \Rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \Rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \Rightarrow \bar{\nu}_\mu + e^+ + \nu_e$$

Greisen–Zatsepin–Kuzmin, 1966

For $E_p \gtrsim 10^9\,\mathrm{GeV}$, we **expect** this flux at $E_\nu \sim 10^7$–$10^{10}\,\mathrm{GeV}$

$$\phi_\nu \sim 1\text{–}100\,\nu/\mathrm{km}^2/\mathrm{year}$$

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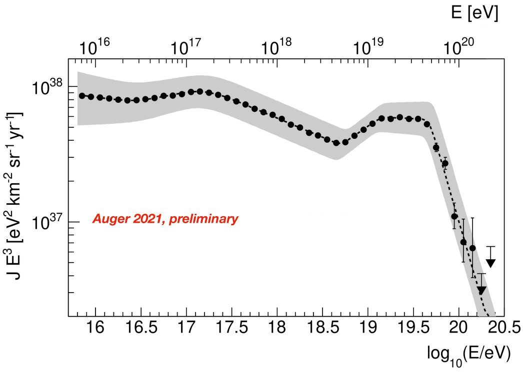
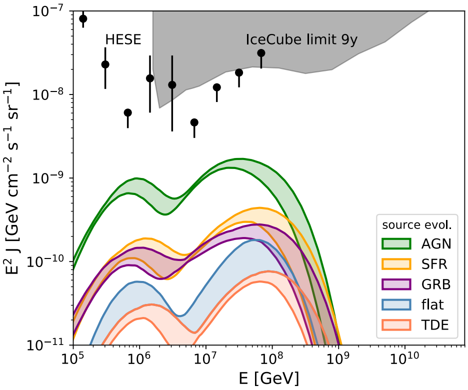
What about neutrinos?

Ultra-high energy proton flux ⇒ **Ultra-High Energy neutrino flux**



Auger, ICRC2021



Heinze et al, 1901.03338

(Of course, sources could also directly produce neutrinos)

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Why do we want to detect them?

Astrophysics

- Multimessenger
- UHE cosmic ray sources
- UHE cosmic ray composition
- High redshift ($z \sim 2$–4)

Particle physics

Largely unexplored, but

- Largest energies
- Largest distances

Let's look for this! What if we instrument ice, like IceCube?

$$N_{\mathrm{evt}} \sim \phi \times \sigma \times N_{\mathrm{targets}} \sim 6 \times 10^{-4} \, \frac{\mathrm{evts}}{\mathrm{yr}} \, \frac{\mathrm{M}}{\mathrm{M}_{\mathrm{IceCube}}}$$

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How can we instrument huge volumes?

Optical Cherenkov attenuates after $\sim 200\,\mathrm{m}$ (on Antarctic ice) 😔

Radio attenuates after $\sim 1\,\mathrm{km}$! 🙂

How do neutrinos emit radio?

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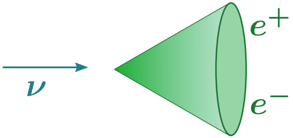
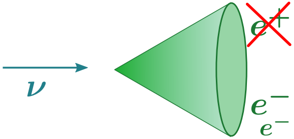
How do neutrinos emit radio?

Large instrumented volume makes radio a natural choice

Askaryan effect





$q \sim 10^6 e$

If $\lambda \gtrsim 10\,\mathrm{cm}$, **coherent**!

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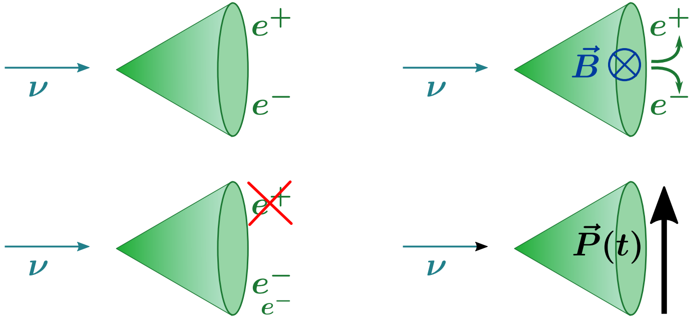
Askaryan effect **Geomagnetic effect**



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$\vec{P}(t) \Rightarrow$ radio

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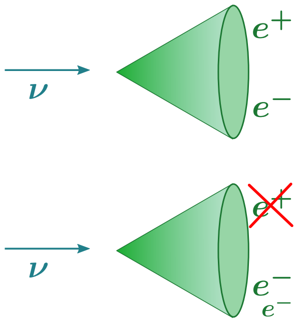

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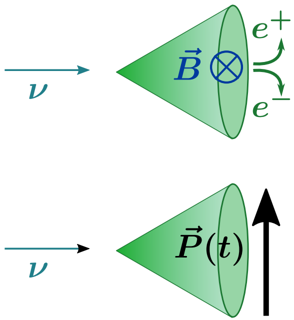
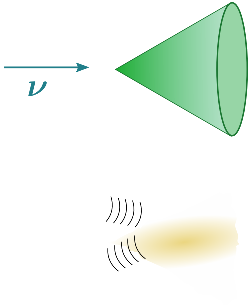
Geomagnetic effect



$\vec{P}(t) \Rightarrow$ radio

Radar



Radar can bounce off the ionization cloud

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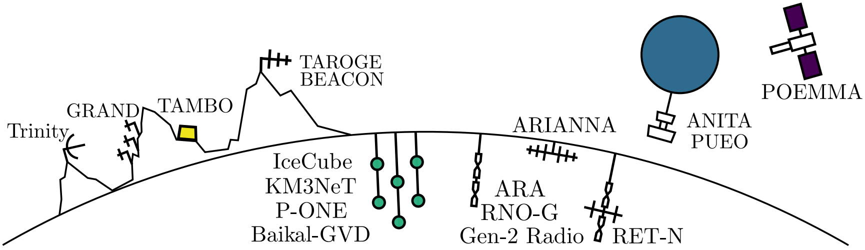
Overall view



UHE neutrinos

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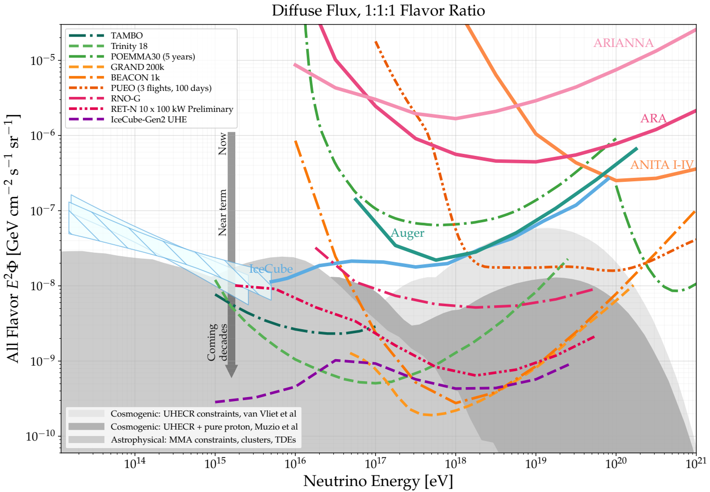
Overall view



UHE white paper, 2203.08096

- Real potential!
- Many opportunities!
- Unexplored regime!
- Experiments **will be there**!

but

- few events
- different experiments
- unknown flux

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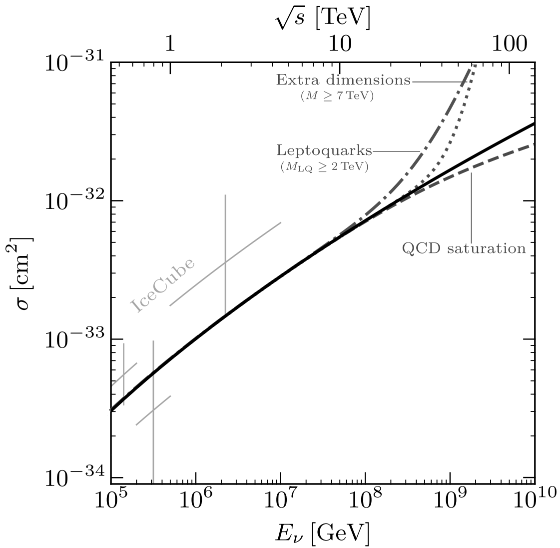
Large $\sqrt{s}$

As a first step, let's look at the **neutrino-nucleon cross section**.

UHE regime, $E_\nu \sim 10^7$–$10^{10}\,\mathrm{GeV}$.

When they hit a nucleon in our detector,
$\sqrt{s} = \sqrt{2E_\nu m_\mathrm{N}} \sim 5$–$100\,\mathrm{TeV}$
beyond collider reach!



Measuring σ

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See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

Let's get to business. A priori σ can be measured from

$$N_{\mathrm{evt}} = \phi \times \sigma \times N_{\mathrm{target}}$$

but we don't know ϕ!

But $\sigma \sim 10^{-32}\,\mathrm{cm}^2$; $\lambda \sim \frac{1}{n\sigma} \sim 1000\,\mathrm{km}$!
Neutrinos get attenuated by Earth with a **characteristic scale set by σ**.
Model-independent handle!

UHE neutrinos probe the Earth **crust**, which is well-understood.

Kusenko & Weiler, 2002; Anchordoqui et al, 2002; Jain et al, 2002; Hooper, 2002 ...

Measuring σ

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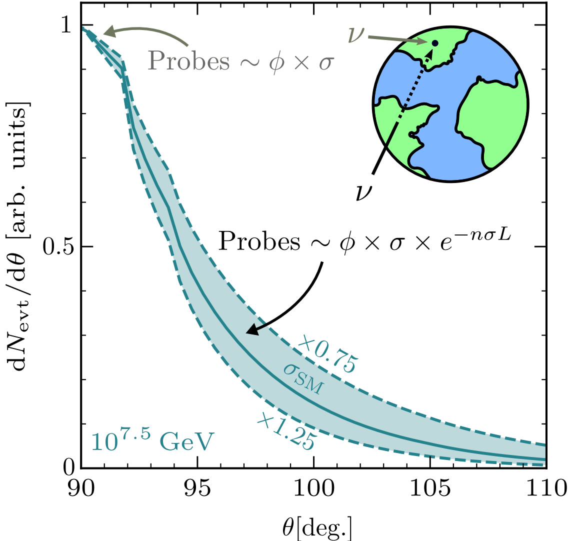
Earth attenuation



Even few events at the tail contain a lot of information

We don't need huge statistics!

Goals of our work

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Given the *many proposals*, *diverse techniques* and *complementarity*, what **detector properties** and **what statistics** gives us what physics?

Are these achievable? By different detectors?
Success in astrophysics will require

- Tens of events
- Good angular resolution
- Acceptable energy resolution

Are the results independent of the flux?

Encouraging prospects for specific fluxes and specific large detectors. See 2007.10334, 2112.09476, 2204.04237.

Measuring σ

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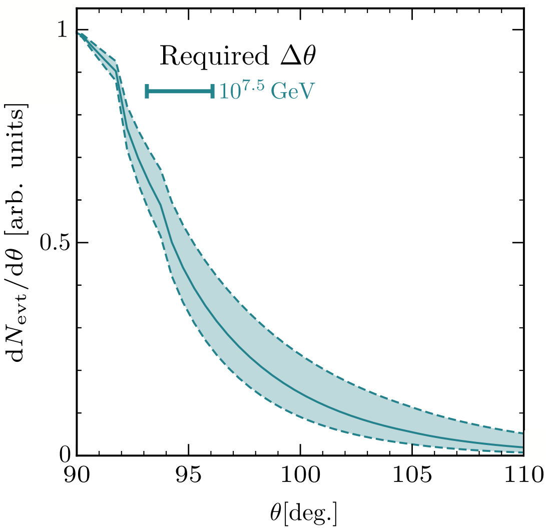

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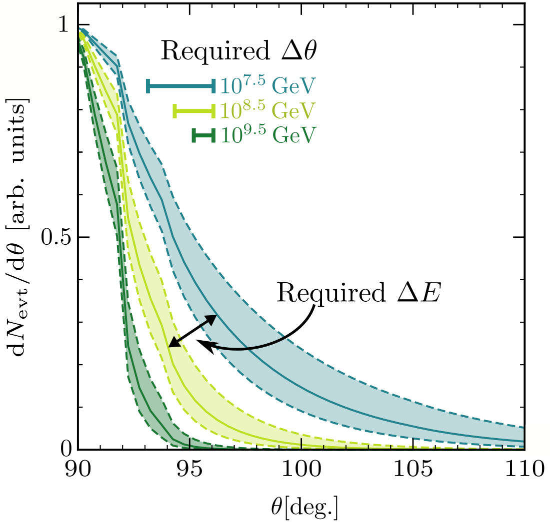

Simplified illustration

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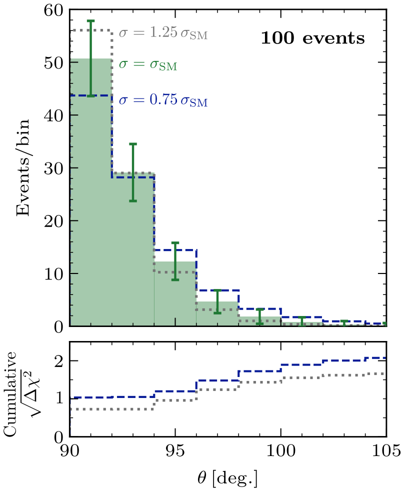
$E_\nu = 10^{8.5}$ GeV



[When doing the analysis, we include energy and **allow the flux to float freely**]

Results

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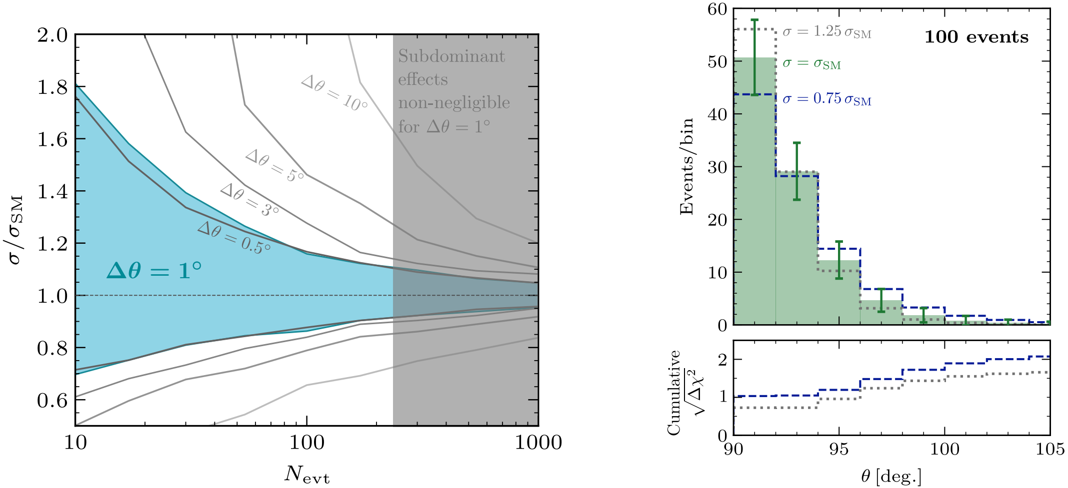
Angular resolution: benchmark $\Delta\theta = 1°$. $[E_\nu = 10^{8.5}\,\text{GeV}]$



Already required for astrophysics goals.

Results

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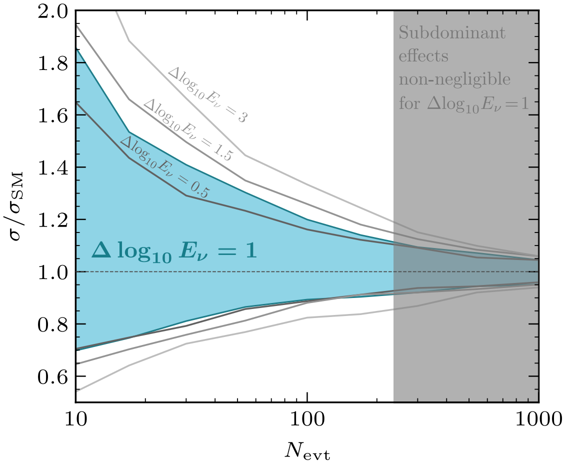
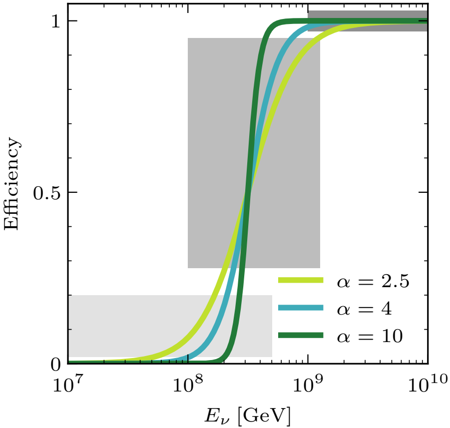
Energy resolution: benchmark $\Delta \log_{10} E_\nu = 1$. $[E_\nu = 10^{8.5}\ \mathrm{GeV}]$





Energy resolution not as critical due to the sharp efficiency and steep flux.

Results

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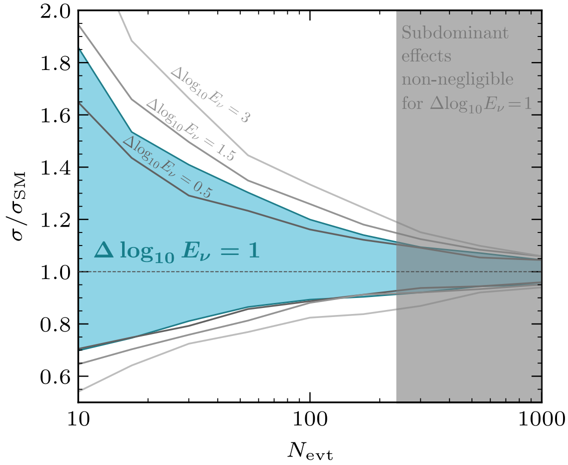

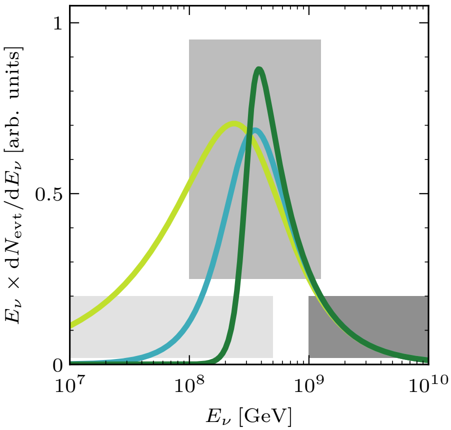

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Take-home messages

- The critical parameters are
  - **Angular resolution**
  - **Statistics**
  - Energy resolution
- We have checked detector response, depth, angular acceptance . . . Nothing matters (for constant below-horizon N_{evt}).
- We can combine data!

Results

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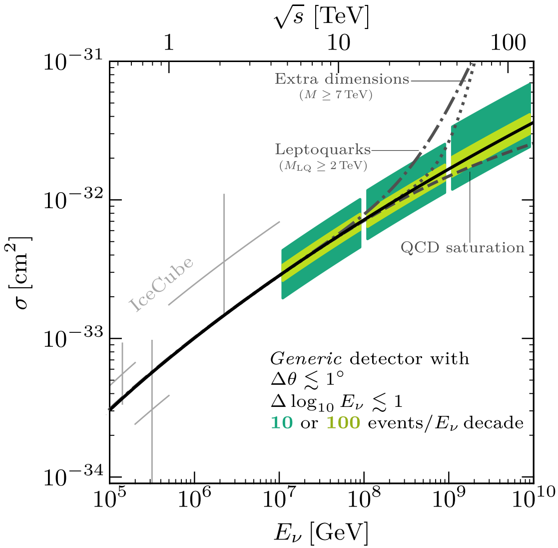
See `arXiv:2205.09763`, with S. Prohira and J. F. Beacom!

Putting everything together



- New physics **within reach** with modest statistics and resolution

Results

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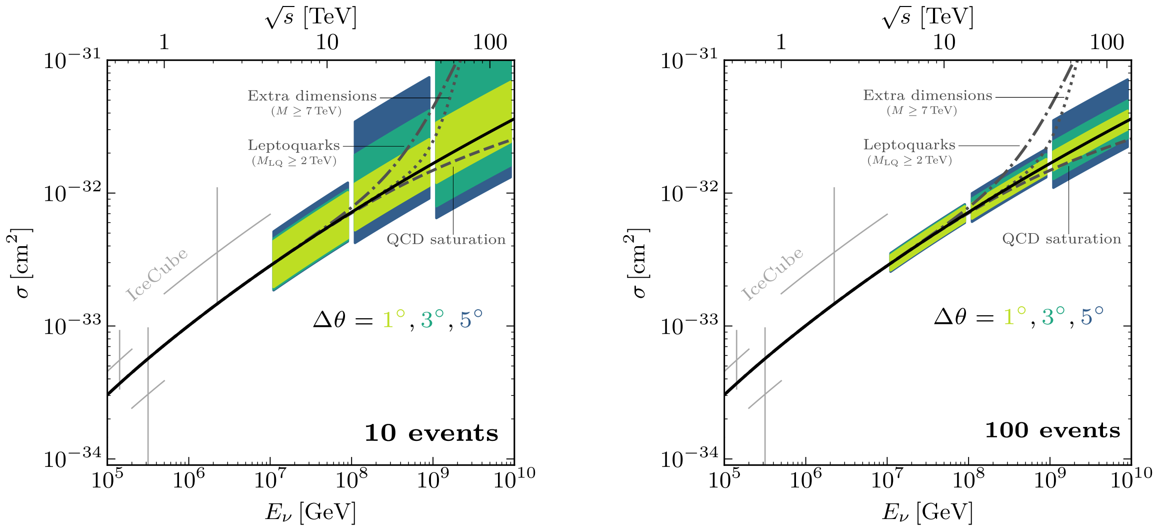
Different $\Delta\theta$



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Conclusions and ways forward

See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

- UHE neutrinos have triggered high astrophysics interest.
  It's time to explore the particle physics!
- We find that, with modest requirements,
  - $\sigma_{\nu \mathrm{N}}$ can be measured without knowing the flux
  - Allowed novel-physics can be tested even with low statistics

  And this can happen relatively soon!
- It's the largest energies and distances, but also
  - Diverse detectors
  - Unique topologies
  - Characteristic angular distributions
- As experiments are being planned, we can have a more active voice.
  And a phenomenological description is easy!
- Stay tuned for the first events within $\sim$ decade!

Backup: the technical slide

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1. We throw N_{evt} events in energy and angle from an *isotropic* flux $\propto E_\nu^{-2.5}$, including absorption with $\sigma = \sigma_{\mathrm{SM}}^{\mathrm{DIS}}$. Subleading effects can be ignored.

   Our results don't depend on the assumed spectral index

2. We include detector efficiency

3. We add energy and angular resolution

4. We fit for σ, *marginalizing over flux and spectral index*

5. We repeat many times to take into account small statistics fluctuations

Backup: efficiency

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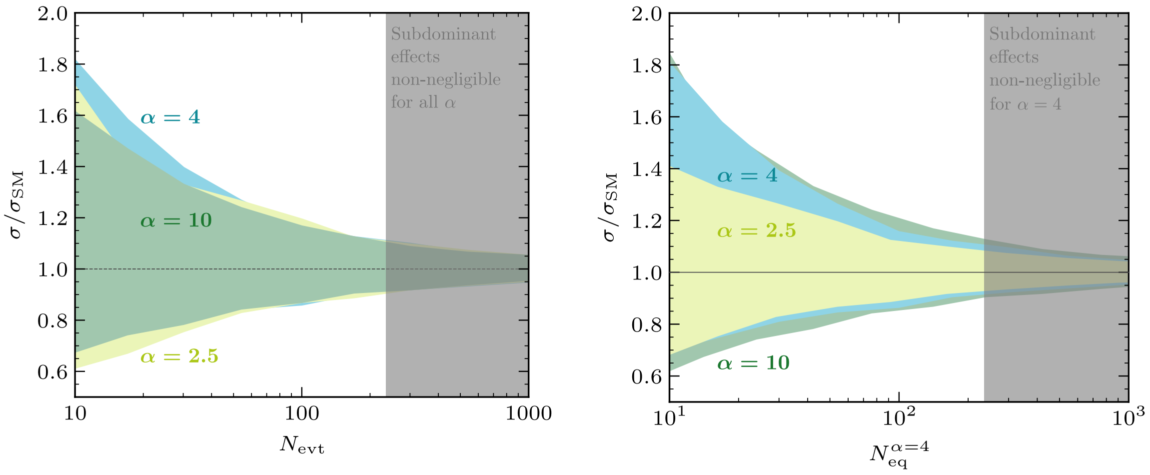

Backup: angular aperture

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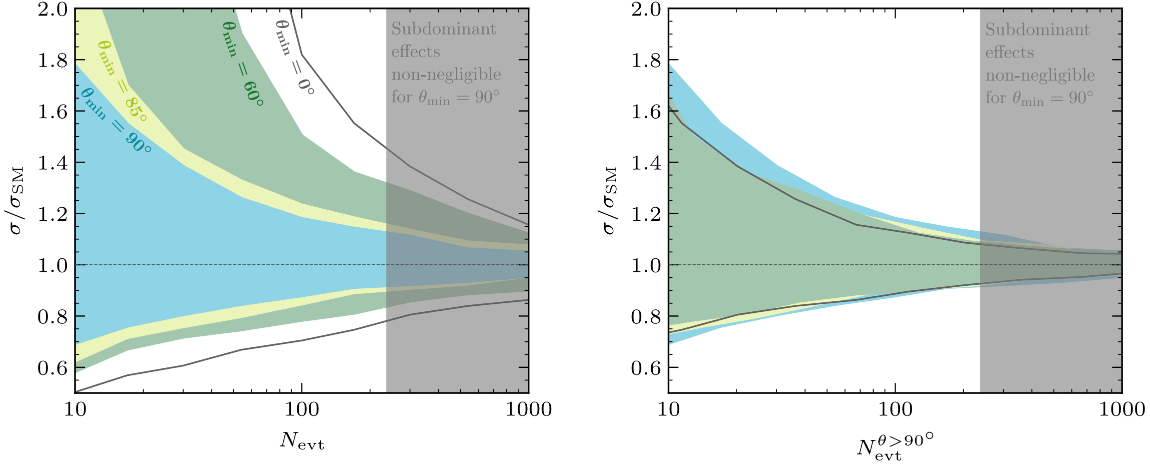

Backup: regeneration

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