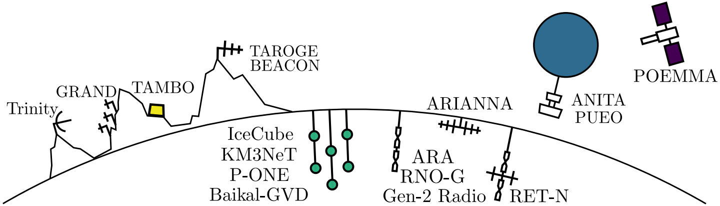
Ultra-high energy neutrinos and physics opportunities

NuTs Extended Workshop



Ivan Esteban

26th May 2022

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The Ohio State University
CENTER FOR COSMOLOGY AND ASTROPARTICLE PHYSICS

Introduction

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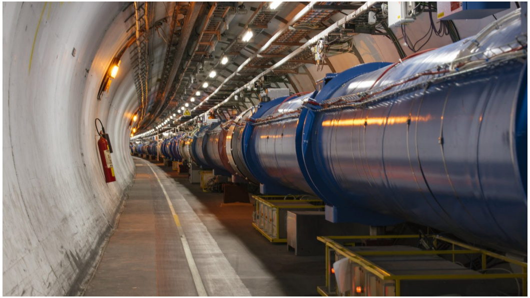
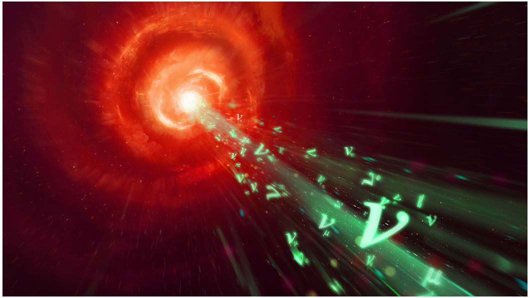
See `arXiv:2205.09763`!

Take-home ideas

We anticipate new physics at **high energies**





Source: Quanta Magazine

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

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

Introduction

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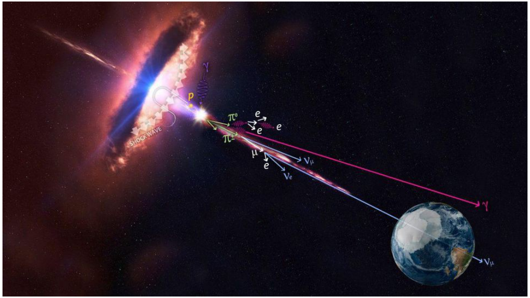
See arXiv:2205.09763!

Some context

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



Source: IceCube/NASA

In principle yes!

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

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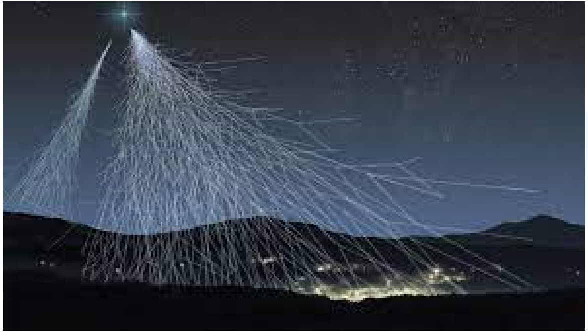
See arXiv:2205.09763!

Some context: Auger

Auger (& TA) detects protons and other nuclei.



E up to $10^{11}\,\mathrm{GeV}$. But novel physics competes with strong interactions!

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What about neutrinos?

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

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

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

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

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

Greisen–Zatsepin–Kuzmin, 1966

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

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

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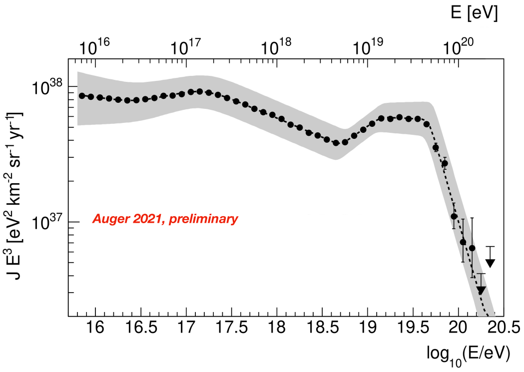
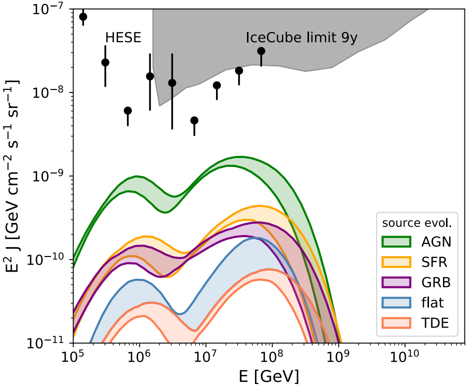
What about neutrinos?

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!

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

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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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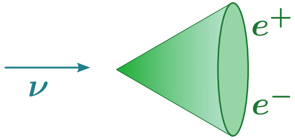
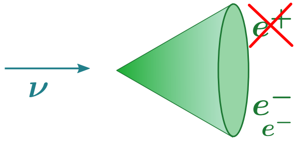
See arXiv:2205.09763!

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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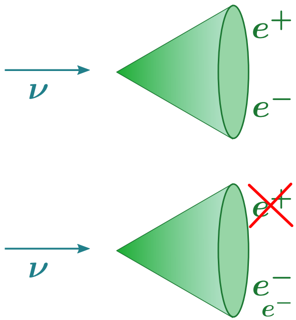
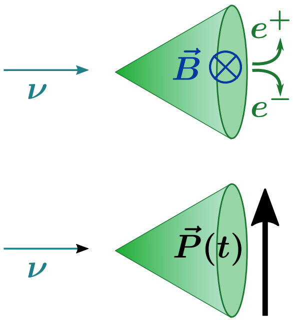
Askaryan effect **Geomagnetic effect**





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

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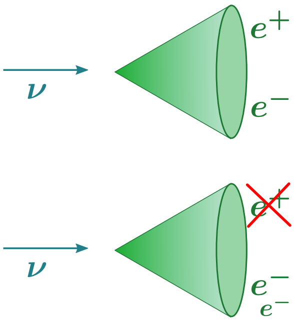
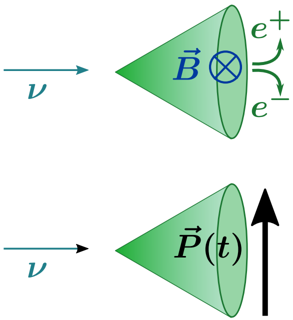


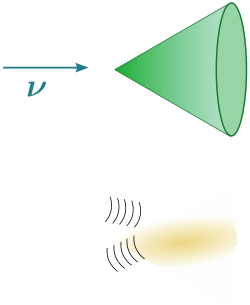
$q \sim 10^6 e$
If $\lambda \gtrsim 10\,\mathrm{cm}$, **coherent**!

Geomagnetic effect



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

Radar



Radar can bounce off the ionization cloud

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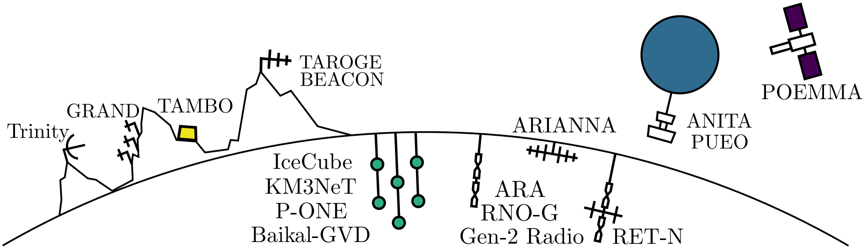
Overall view



UHE neutrinos

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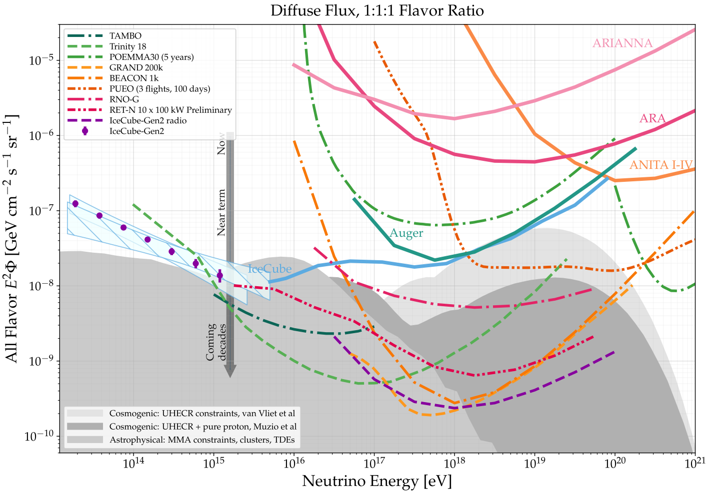
See arXiv:2205.09763!

Overall view



- Real potential!
- Many opportunities!
- Unexplored regime!

but

- few events
- different experiments
- unknown flux

UHE white paper, 2203.08096 [RET curve updated]

Physics opportunities

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See arXiv:2205.09763!

The experiments **will be there**

Success in astrophysics requires

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

what opportunities does this open?

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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!

Physics opportunities

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See arXiv:2205.09763!

Large $\sqrt{s}$

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

Are these achievable? By different detectors?

Is this independent of the flux? And of the physics model?

Encouraging prospects for specific fluxes and specific large detectors.

See 2007.10334, 2112.09476, 2204.04237.

Measuring σ

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See arXiv:2205.09763!

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!

Measuring σ

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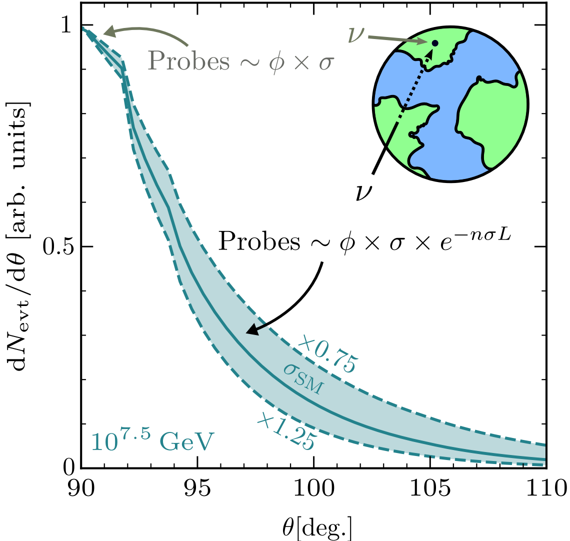
See arXiv:2205.09763!

Earth attenuation



Even few events at the tail contain a lot of information

We don't need huge statistics!

Measuring σ

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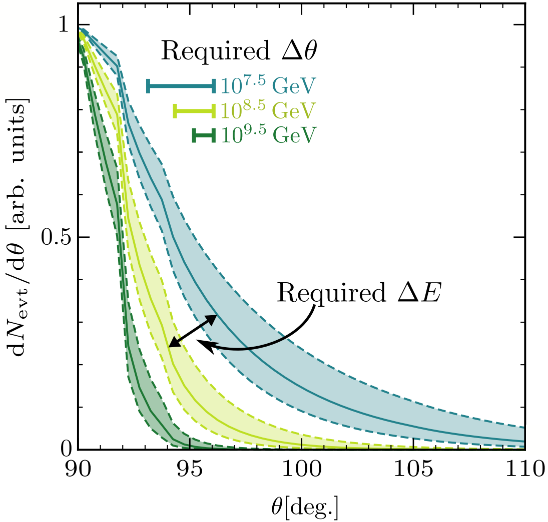
Earth attenuation



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 $\sigma = \sigma_{\text{SM}}^{\text{DIS}}$. 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

Simplified illustration

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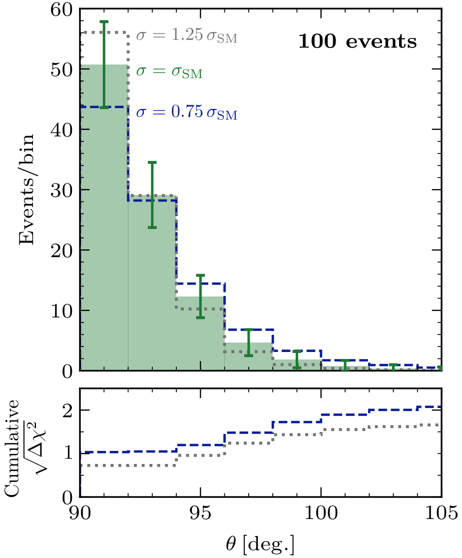
$E_\nu = 10^{8.5}$ GeV



Results

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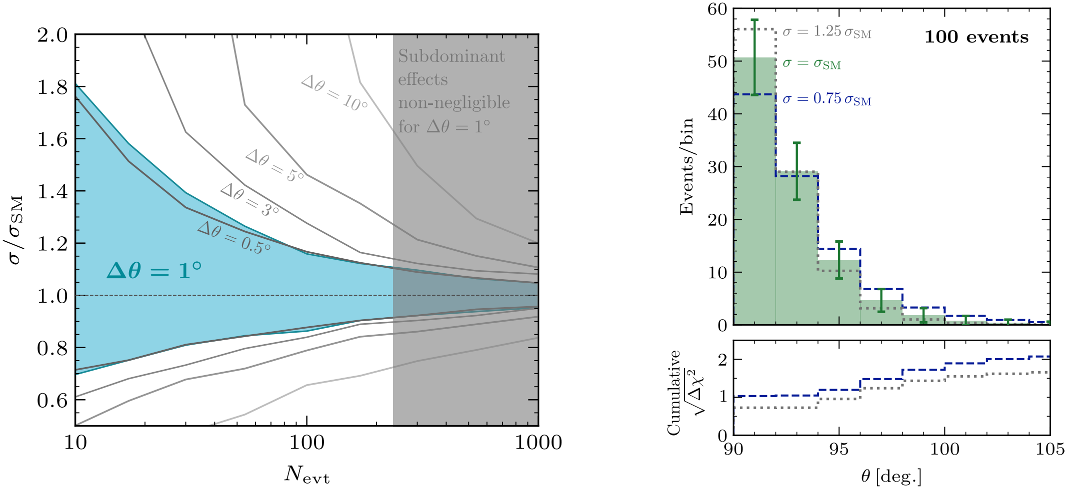
See arXiv:2205.09763!

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



Already required for astrophysics goals.

Results

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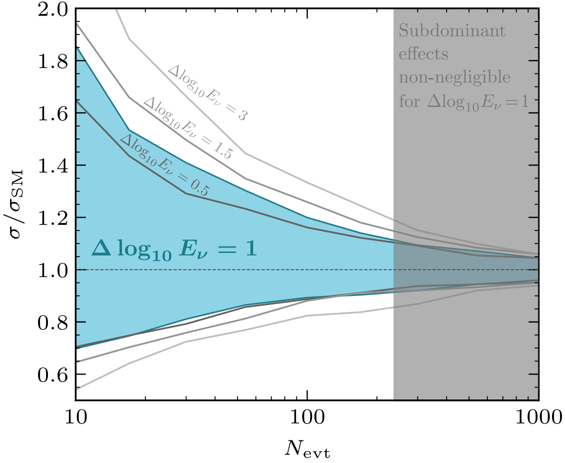
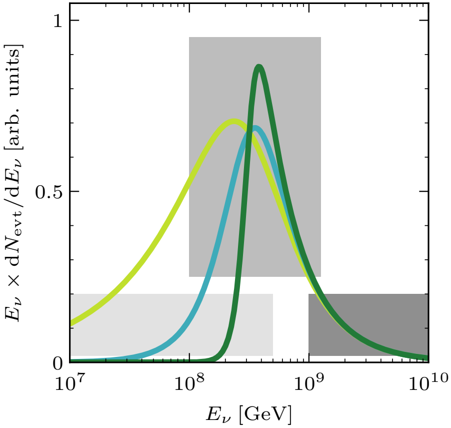
Energy resolution: benchmark $\Delta\log_{10} E_\nu = 1$. $[E_\nu = 10^{8.5}\,\mathrm{GeV}]$





Energy resolution not as critical due to the steep flux.

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See arXiv:2205.09763!

Take-home messages

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

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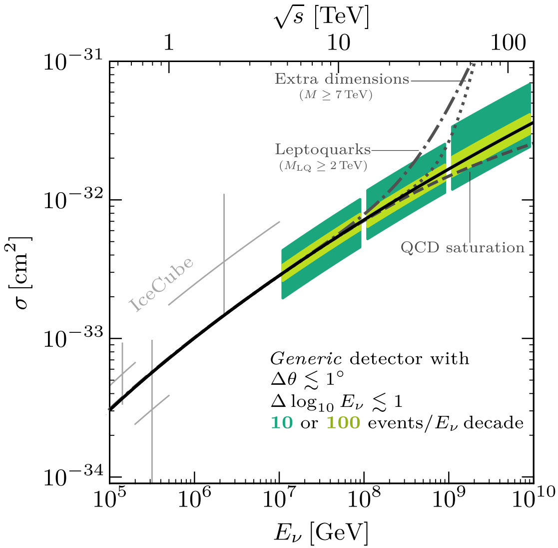
See arXiv:2205.09763!

Putting everything together



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

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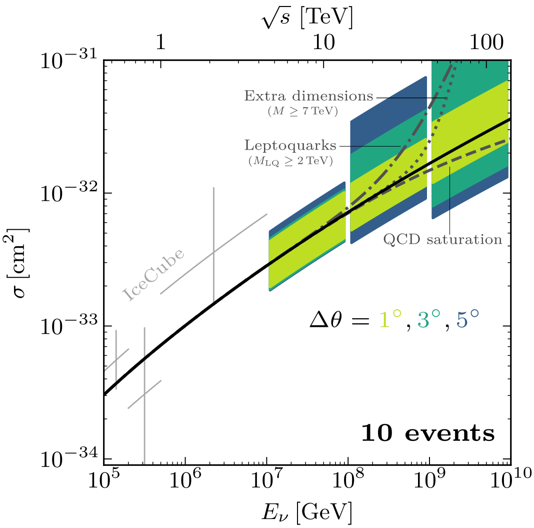
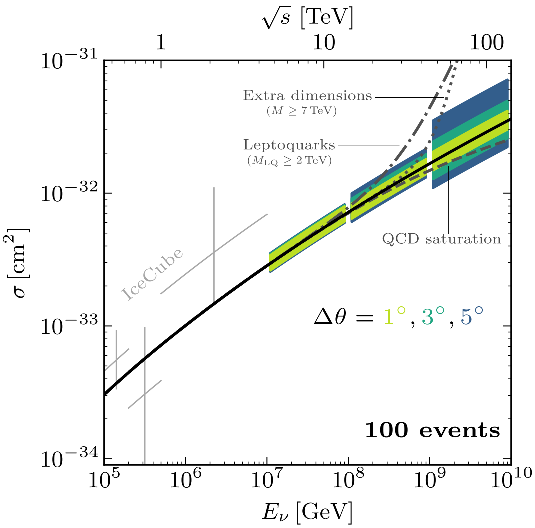
See arXiv:2205.09763!

Results

Different $\Delta\theta$





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Conclusions and ways forward

See arXiv:2205.09763!

- 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: efficiency

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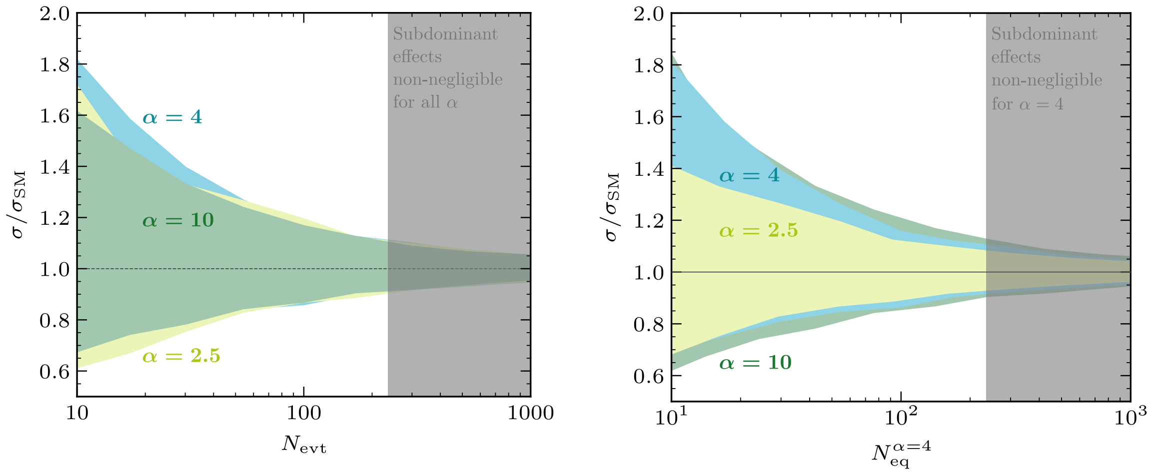
See arXiv:2205.09763!



Backup: angular aperture

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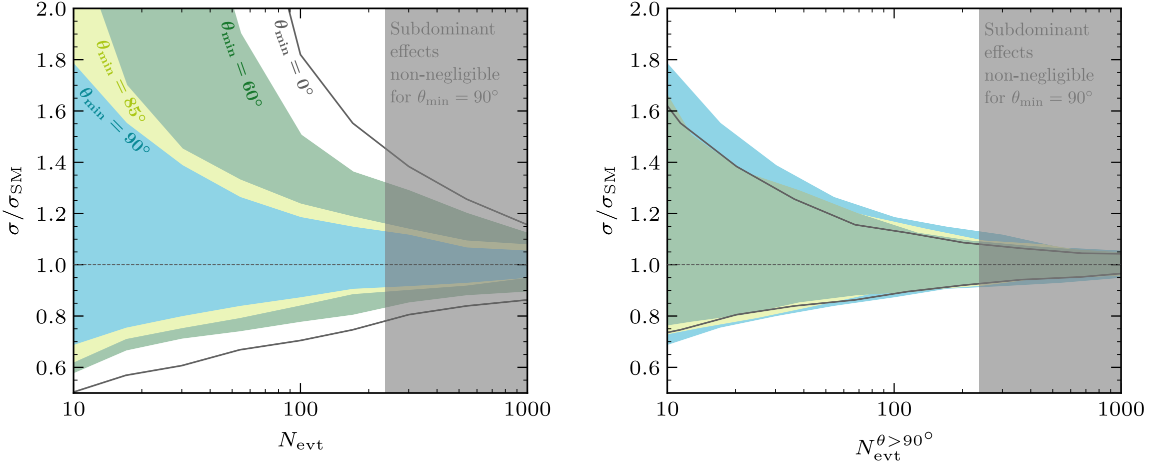
See arXiv:2205.09763!



Backup: regeneration

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