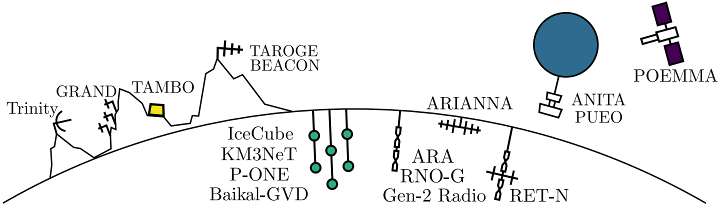
Ultra-high energy neutrinos and physics opportunities

PIKIMO 2022



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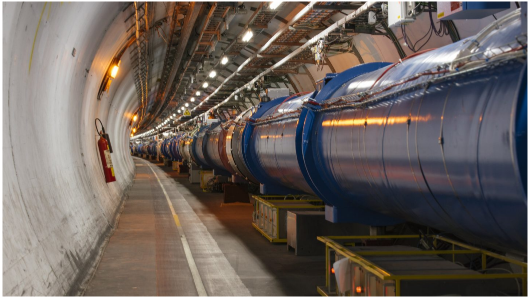
Introduction

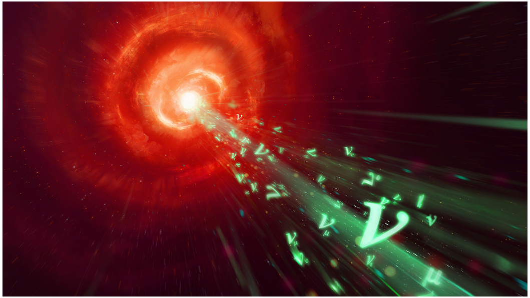
See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

Take-home ideas

We anticipate new physics at **high energies**



$\sqrt{s} \lesssim 10\,\mathrm{TeV}$



Source: Quanta Magazine

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

Introduction

What about neutrinos?

The idea is simple:
Ultra-high energy proton flux $\Rightarrow$ **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 $E_p \gtrsim 10^9\,\text{GeV}$, we **expect** this flux at $E_\nu \sim 10^7$–$10^{10}\,\text{GeV}$
$\phi_\nu \sim 1$–$100\,\nu/\text{km}^2/\text{year}$

Introduction

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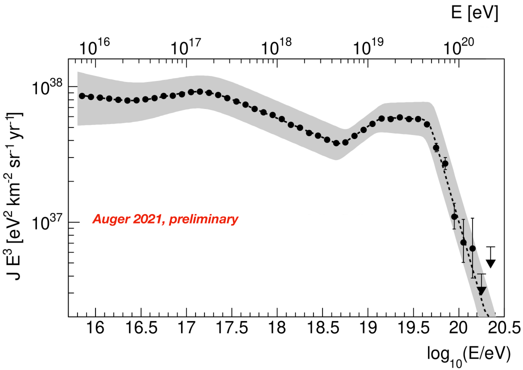
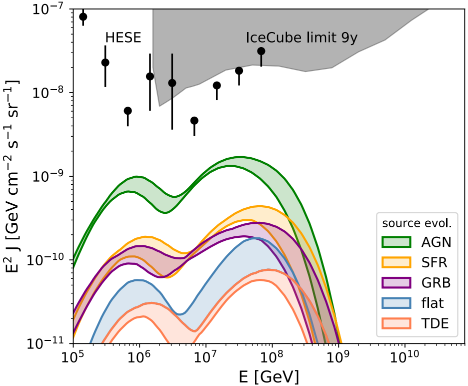
What about neutrinos?

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)

Why do we want to detect them?

Astrophysics

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

Particle physics

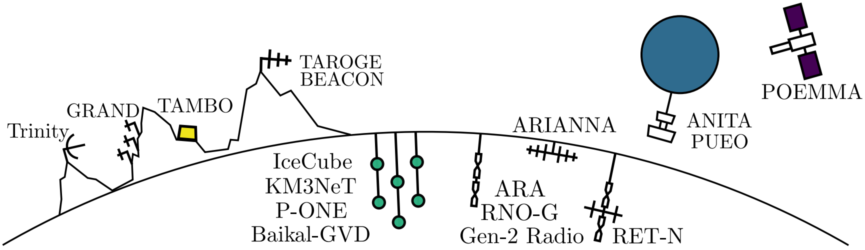
Largely unexplored, but

- Largest distances
- Largest energies

UHE neutrinos

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

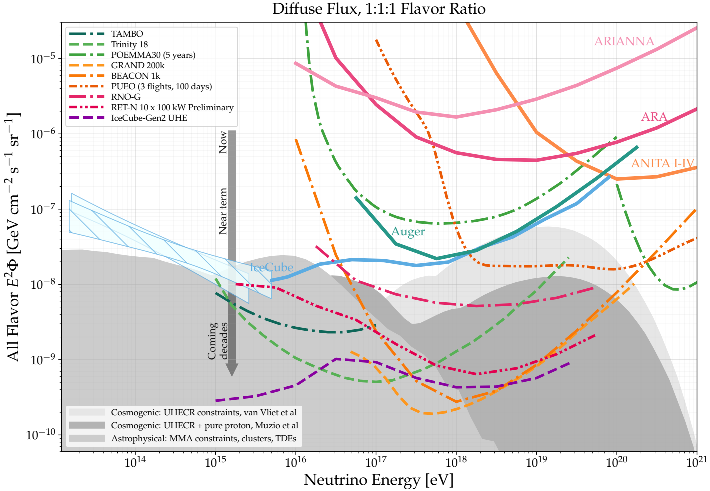
Overall view



UHE neutrinos

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

Overall view



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

UHE white paper, 2203.08096

Physics opportunities

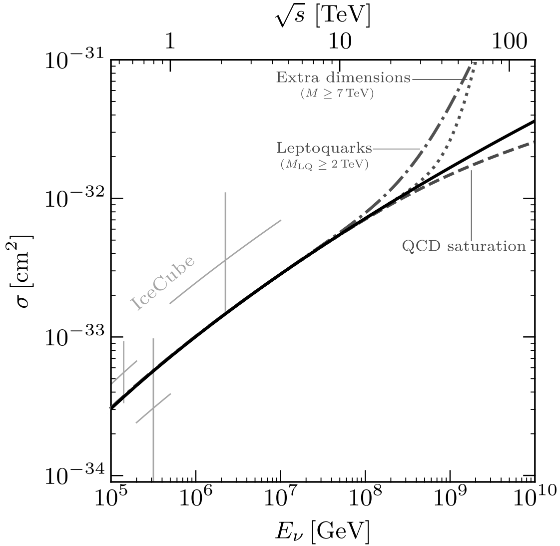
See arXiv:2205.09763, with S. Prohira and J. F. Beacom!

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

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

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

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

but we don't know ϕ!

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

Kusenko & Weiler, 2002; Anchordoqui et al, 2002; Hooper, 2002; Hussain et al, 2002; Borriello et al, 2008; Hussain et al, 2008; Connolly et al, 2011; Marfatia et al, 2015

Measuring σ

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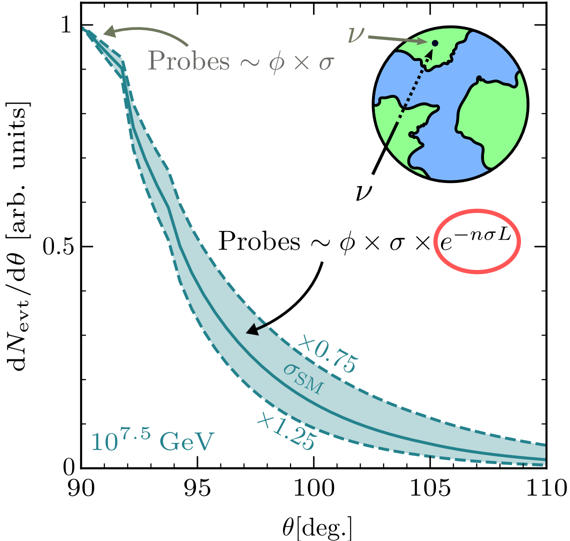
Earth attenuation



Intuitively: *with a single detector*, we measure the flux

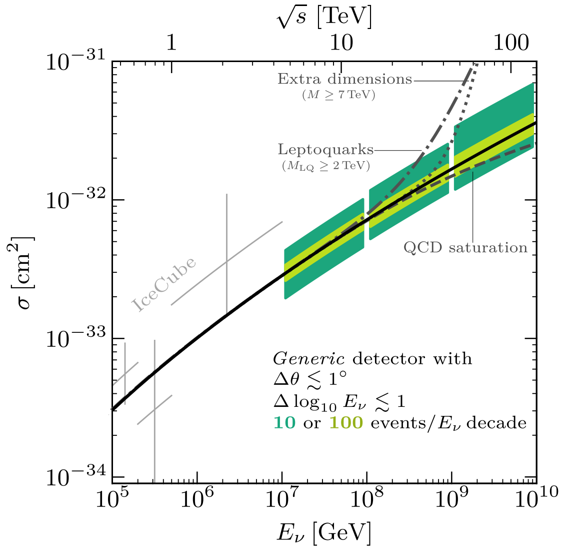
1. Close to the horizon
2. At large zenith angles

The difference tells us how much the Earth absorbed, i.e., σ!

In our paper, we do a shape fit, including relevant experimental details and varying the unknown flux.

Results

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



- New physics **within reach** with modest statistics and resolution
- Requirements are similar to astrophysics!

Results

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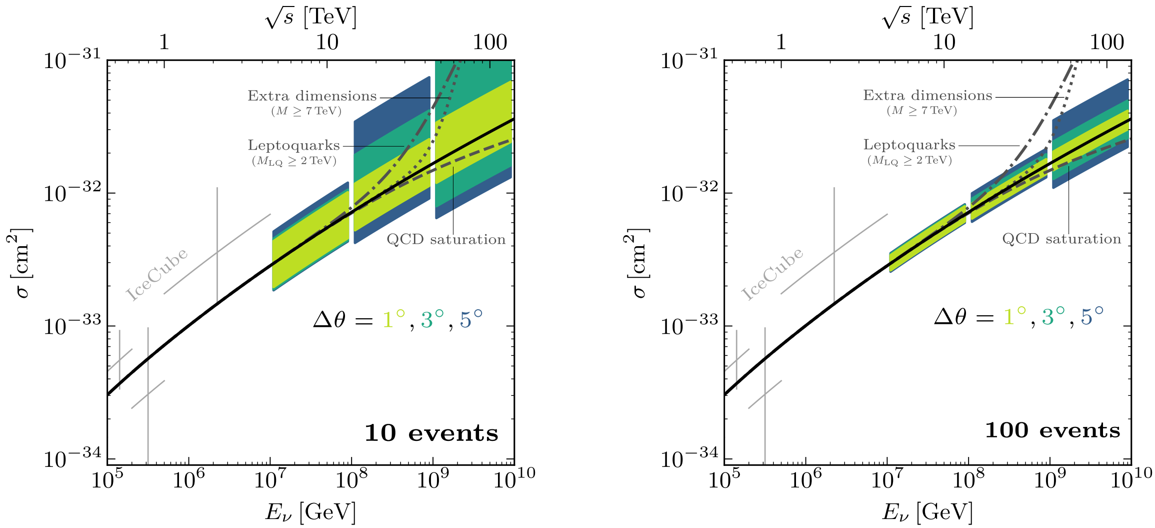
Different $\Delta\theta$



Conclusions and ways forward

- 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!

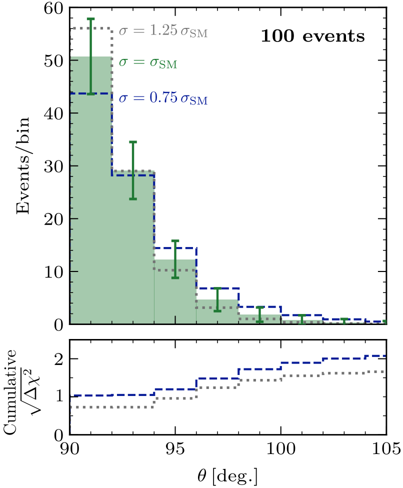
- As experiments are being planned, we can have a more active voice.

- Stay tuned for the first events within $\sim$ decade!

Backup: Simplified illustration

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

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



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