Reaching the EeV frontier of neutrino-nucleon cross section

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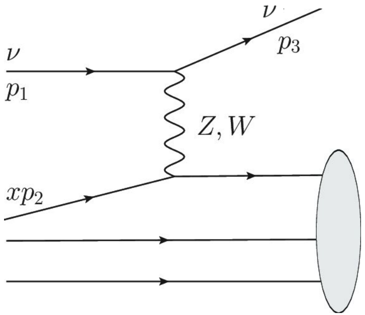
VILLUM FONDEN

MAIN OBJECTIVES

- **Our main goal** is to prepare the most **detailed prediction** of the measurement capabilities of the **neutrino-nucleon cross section at the ~EeV** scale with the next generation of neutrino telescopes

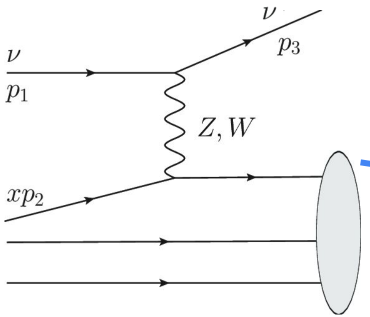
- We assume the flux is known and present our results for 3 benchmark scenarios: cosmogenic, astrophysical source, extrapolation of IceCube flux



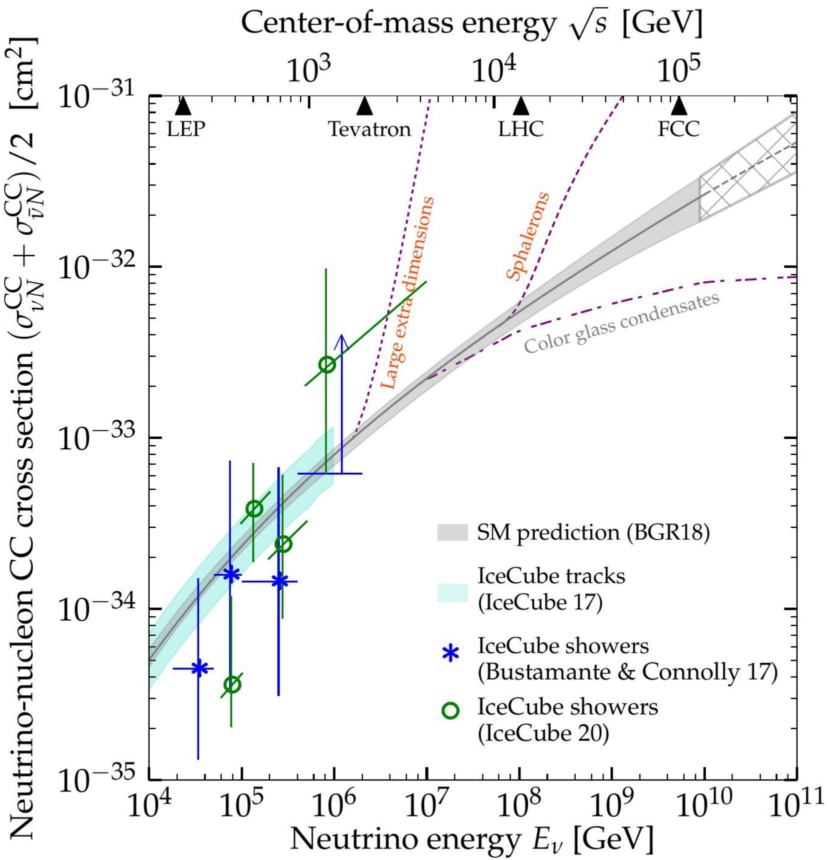
Why should we measure νN cross sections ($\sigma_{\nu\mathrm{N}}$)?

- Important for particle/astroparticle physics
- Precision tests of the SM and nucleon structure
- Probes of BSM physics

- $\sigma_{\nu\mathrm{N}}$ has been measured up to the PeV scale
- The next-gen of ν telescopes could go further
- **In preparation we perform a detailed study of the measurement capabilities in IceCube-Gen2 radio**



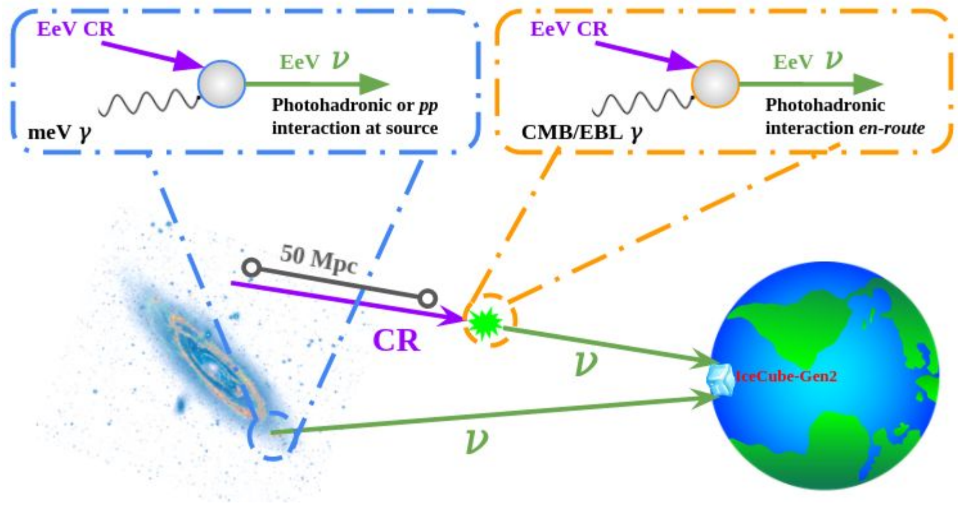
DIS: Deep Inelastic Scattering

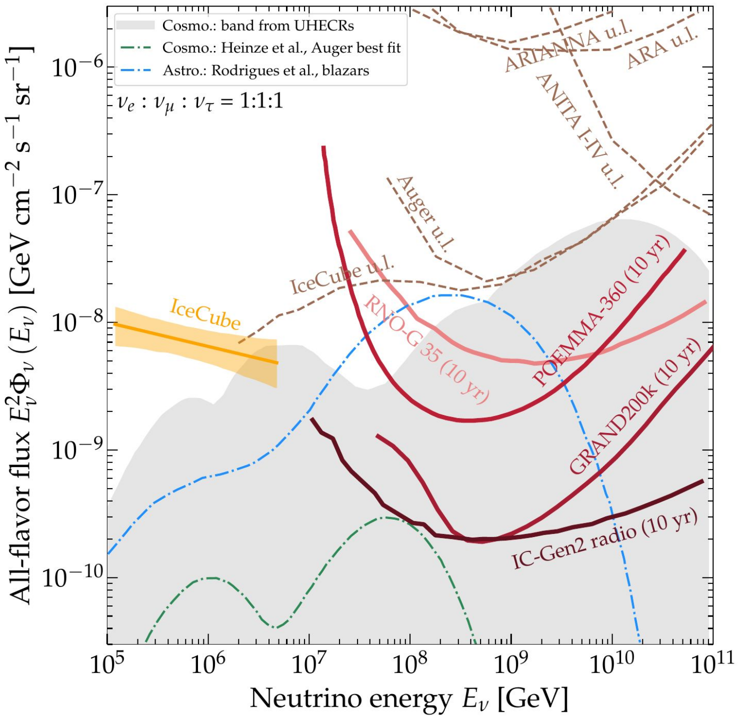


Where do ultra-high-energy (UHE) neutrinos come from?

Astrophysical source flux

Cosmogenic flux





UHE neutrinos = EeV-scale neutrinos (EeV = 10^9 GeV)

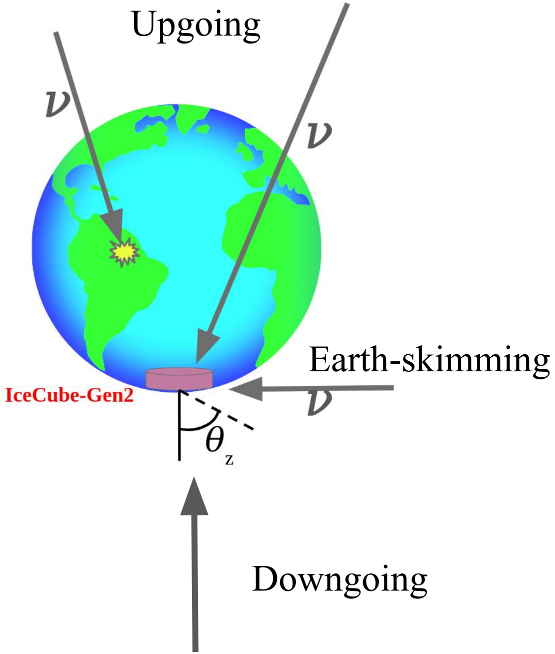
Rodrigues, Heinze, Palladino, van Vliet, Winter, 2003.08392
Heinze, Fedynitch, Boncioli, Winter, *Apj 2019*
POEMMA, 2012.07945
RNO-G, *JINST 2021*
IceCube-Gen2, *J. Phys. G 2021*
GRAND, *Sci. China Phys. Mech. Astron. 2020*

How to extract $\sigma_{\nu N}$ from UHE neutrinos?

At high neutrino energies the **Earth is opaque** to neutrino nucleon (νN) interactions (N = p,n)

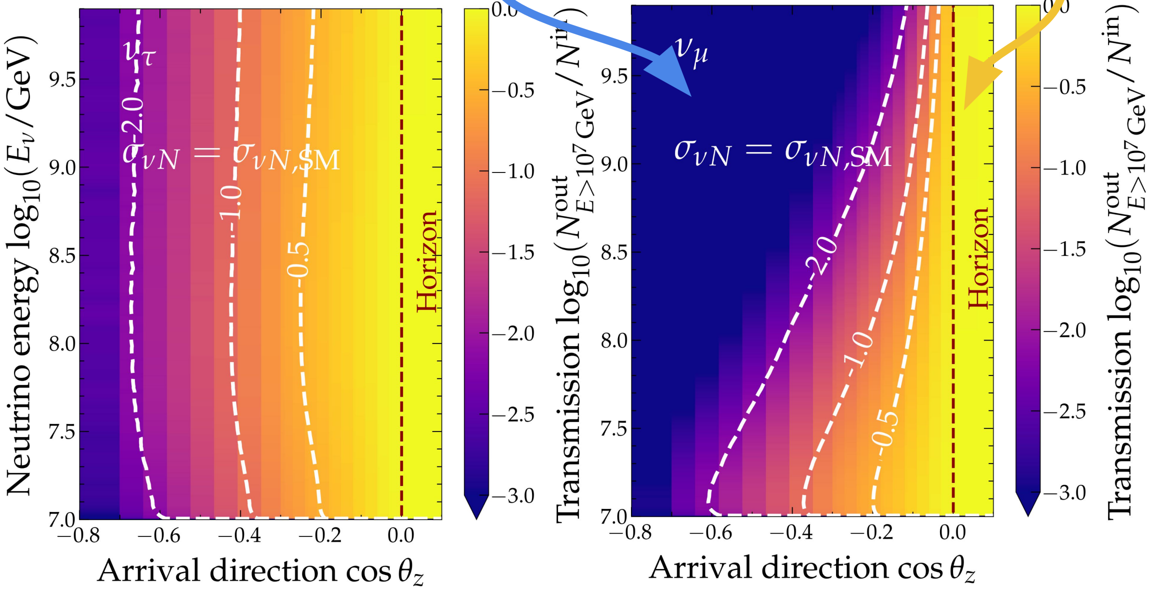
Attenuation factor: $e^{-\tau_{\nu N}} \rightarrow \tau_{\nu N}(E_\nu, \theta_z)$ = Distance traveled in the Earth(θ)/Interaction length(θ,$\sigma_{\nu N}$)

Rate of detected neutrinos at IceCube-Gen2: $N \sim T\Phi_\nu \sigma_{\nu N} e^{-\tau_{\nu N}(E_\nu,\theta_z)}$



Opaque

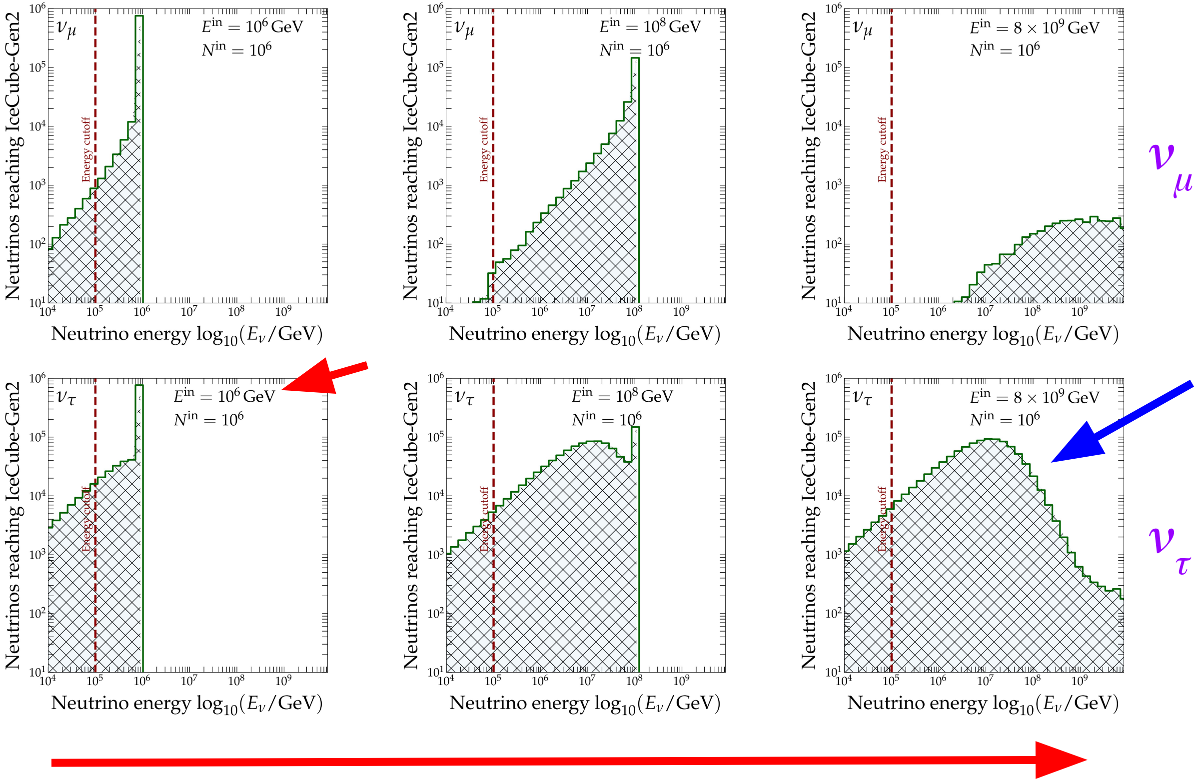
Transparent



NuPropEarth: an in-Earth neutrino propagation tool

- Monte Carlo in-Earth neutrino propagation tool
- Leading interaction DIS + subleading contributions
- Most updated $\sigma_{\nu N}$ predictions
- Earth density: PREM model
- Tau neutrino regeneration
- Propagates each ν state separately

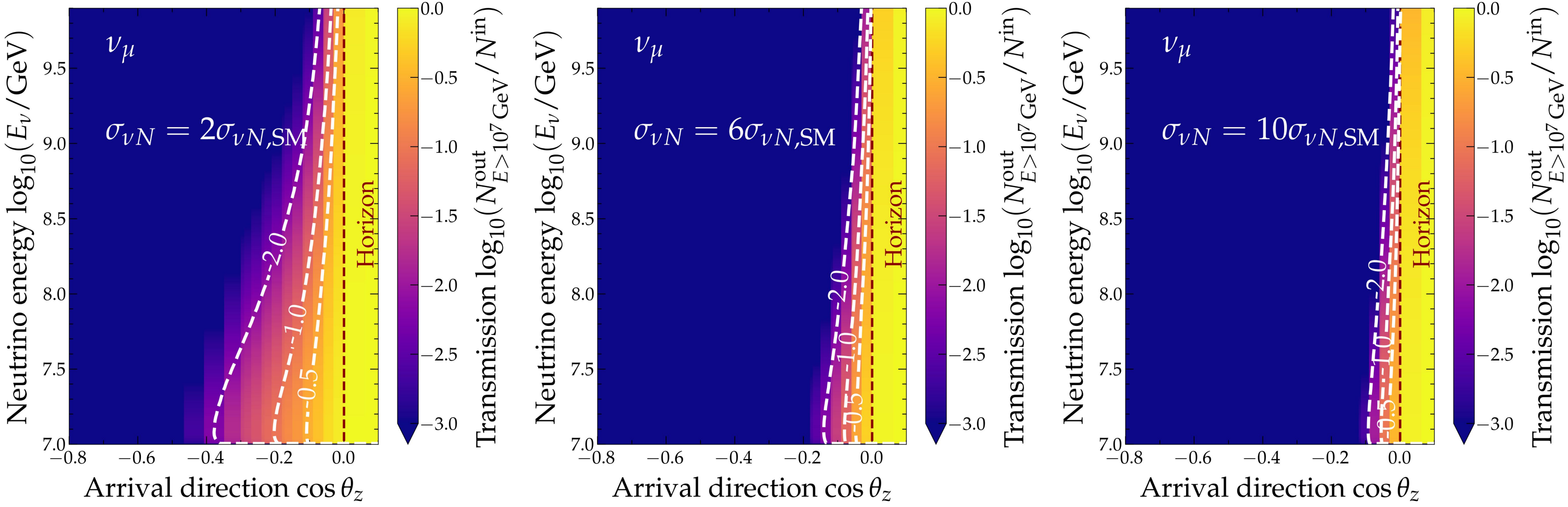
Garcia et. al., *JCAP 2020*



Higher injected neutrino energy

But, what if $\sigma \neq \sigma_{\mathrm{SM}}$?

- BSM physics might manifest as a deviation of the predicted value of the σ_{SM} (*e.g.*, νNSI)
- In that case the attenuation profiles might be modified → signature of BSM physics



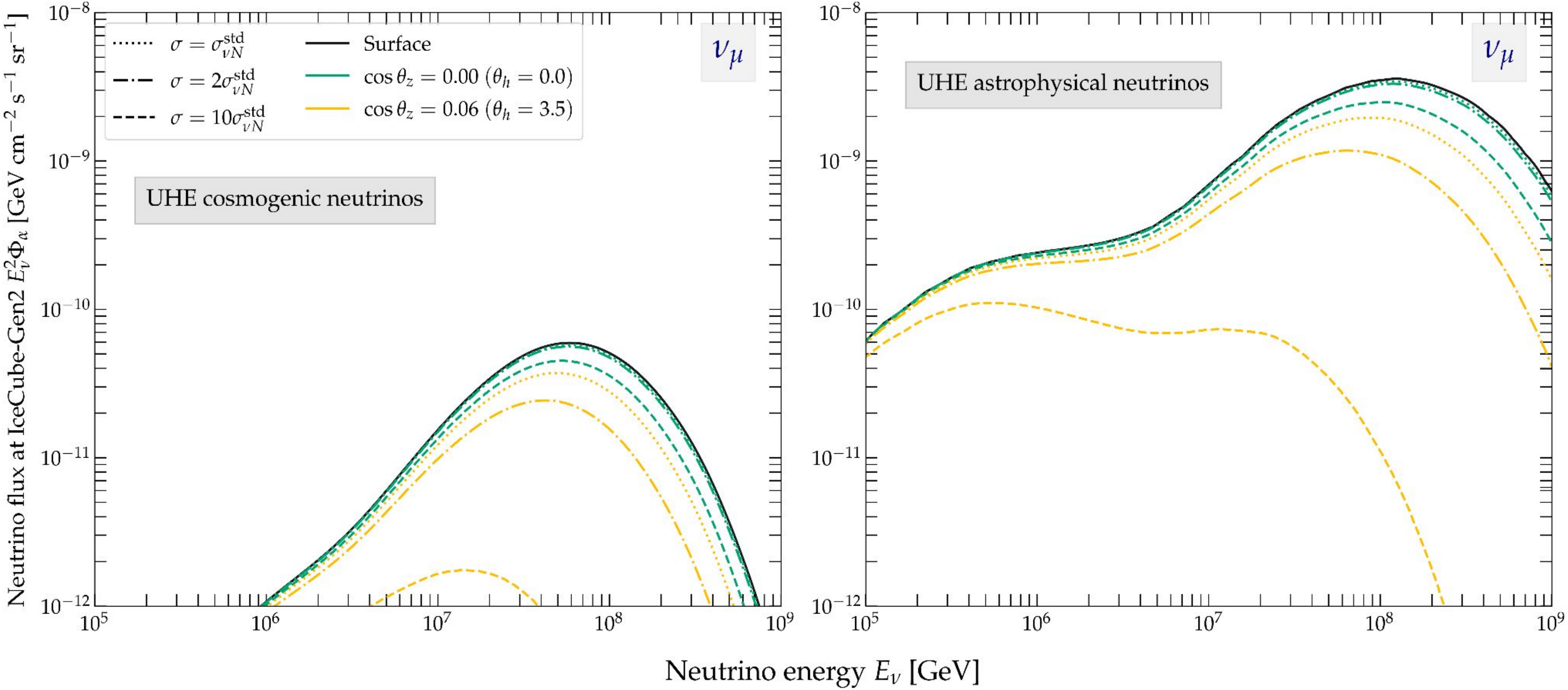
Flux propagation from precomputed tables

Flux propagation:

We sum the transmission histograms for every energy weighted by the value of the flux at each energy

The result:

Propagated neutrino flux for each flavor at different directions



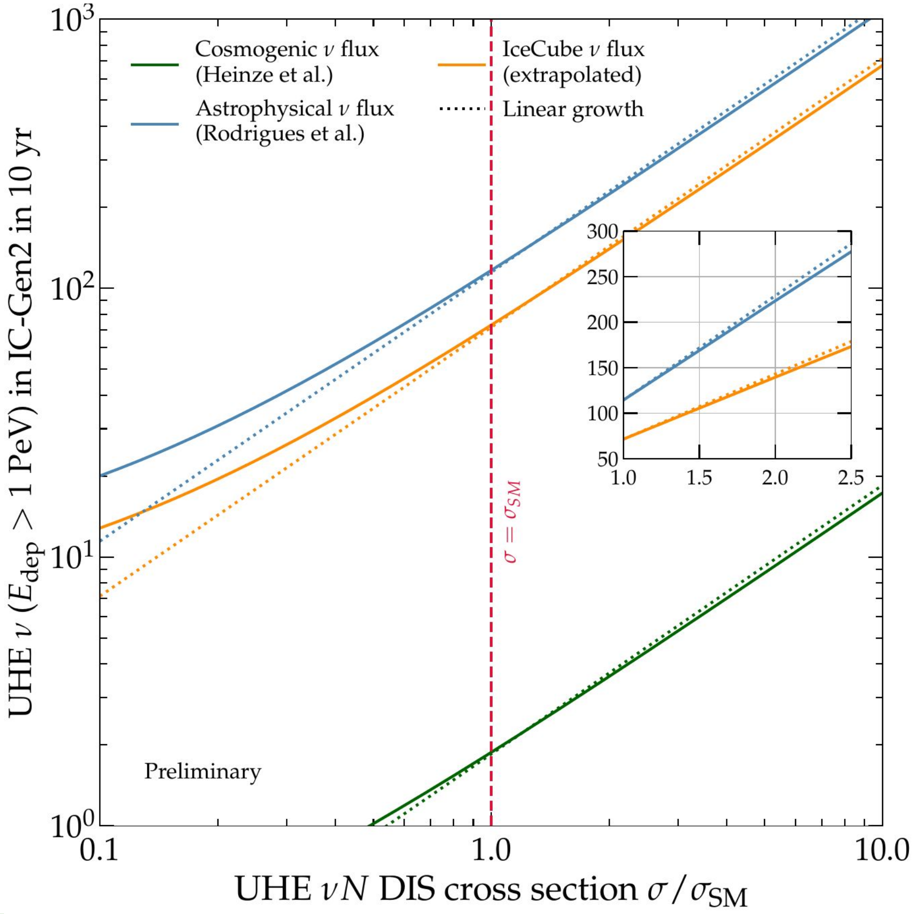
Predicted event rate at IceCube-Gen2 radio

Event rate: $N \sim T\Phi_\nu \underbrace{\overbrace{\sigma_{\nu N}}} e^{-\underbrace{\overbrace{\tau_{\nu N}}}(E_\nu,\theta_z)}$

Increases the probability of a neutrino detection

Decreases probability of a neutrino transmission

- We account for energy and direction smearing through the resolution functions*
- We write the event rate in terms of experimentally measurable quantities (E_{dep}, $\cos\theta_{z,\,\mathrm{rec}}$)
- IC-Gen2 effective volume scaled up from RNO-G volume (García-Fernández, Nelles, Glaser, *PRD 2020*)

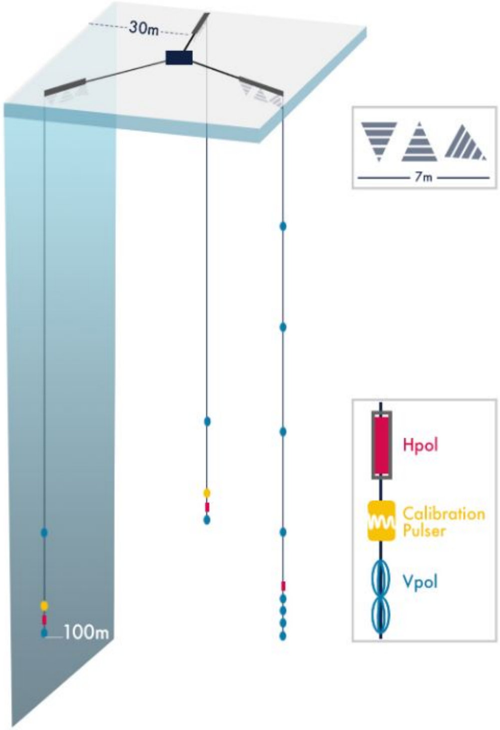


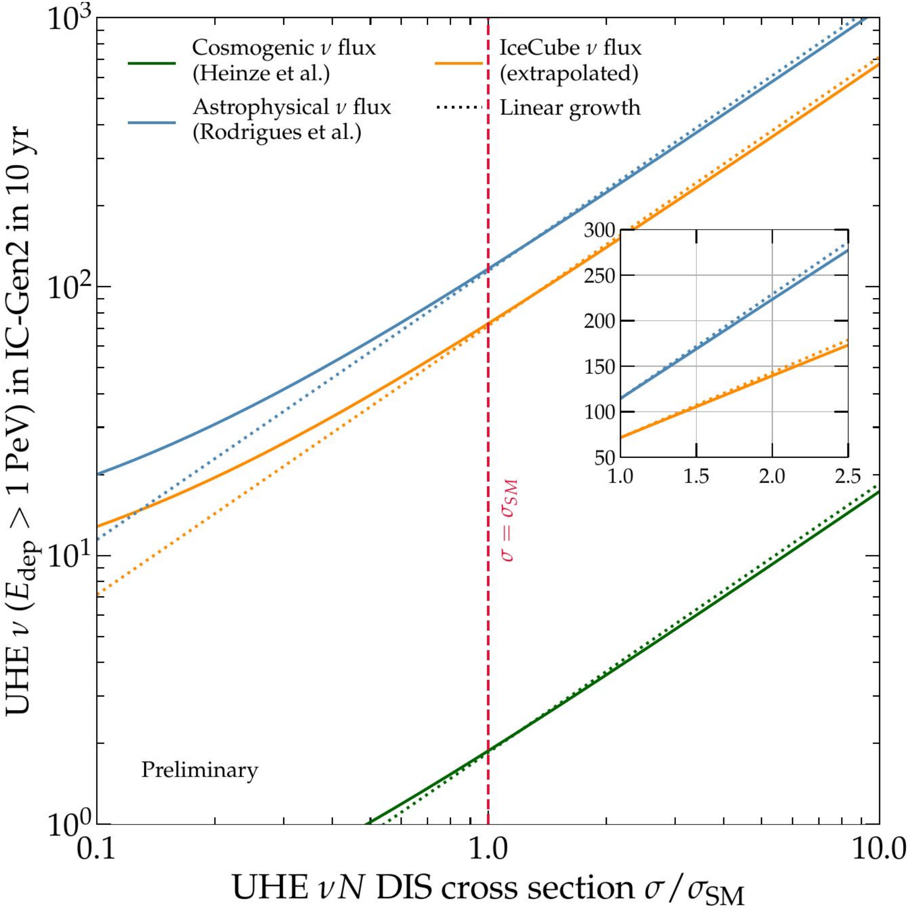
* See backup for full computation

Predicted event rate at IceCube-Gen2 radio

IceCube-Gen2 Radio

M.G. Aartsen et. al., *J. Phys. G. 2021*





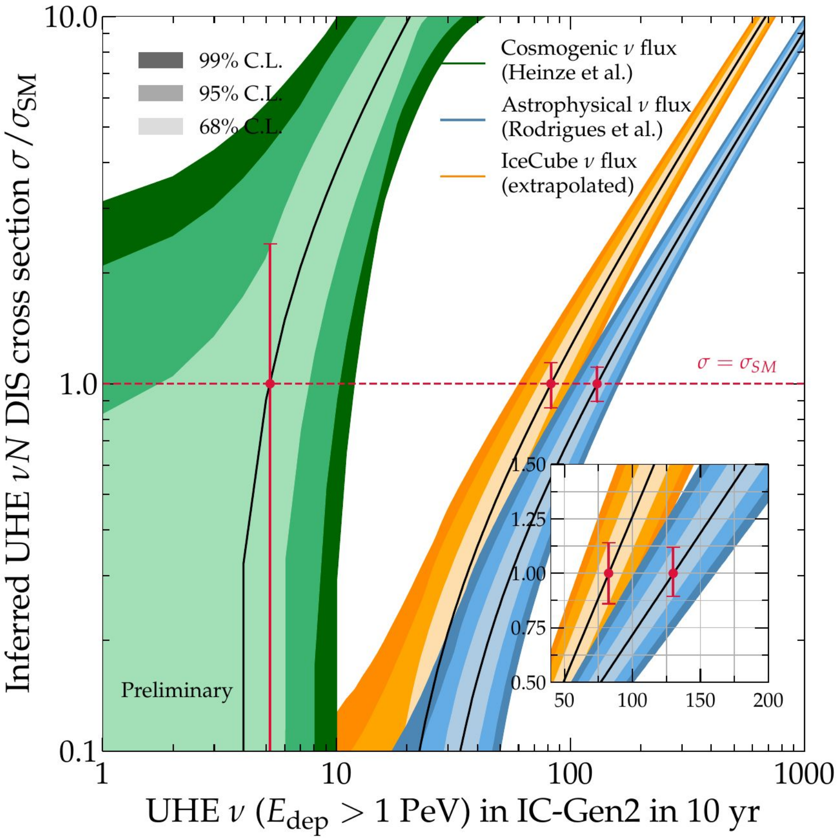
How well can we measure $\sigma_{\nu N}$ in the next decade?

- We perform a Bayesian analysis with an unbinned Poissonian likelihood:

$$\mathcal{L}(f, N_{\text{obs}}) = \frac{e^{-[N(f)+N_{\text{bkg}}]}[N(f) + N_{\text{bkg}}]^{N_{\text{obs}}}}{N_{\text{obs}}!}$$

- Fix N_{obs} and maximize for $f = \sigma/\sigma_{SM}$
- Credible regions from the posterior assuming flat f prior

N_{obs} = Number of observed events by IC-Gen2
N_{bkg} = Background events **(atm muons)**
$N(f)$ = Predicted number of events



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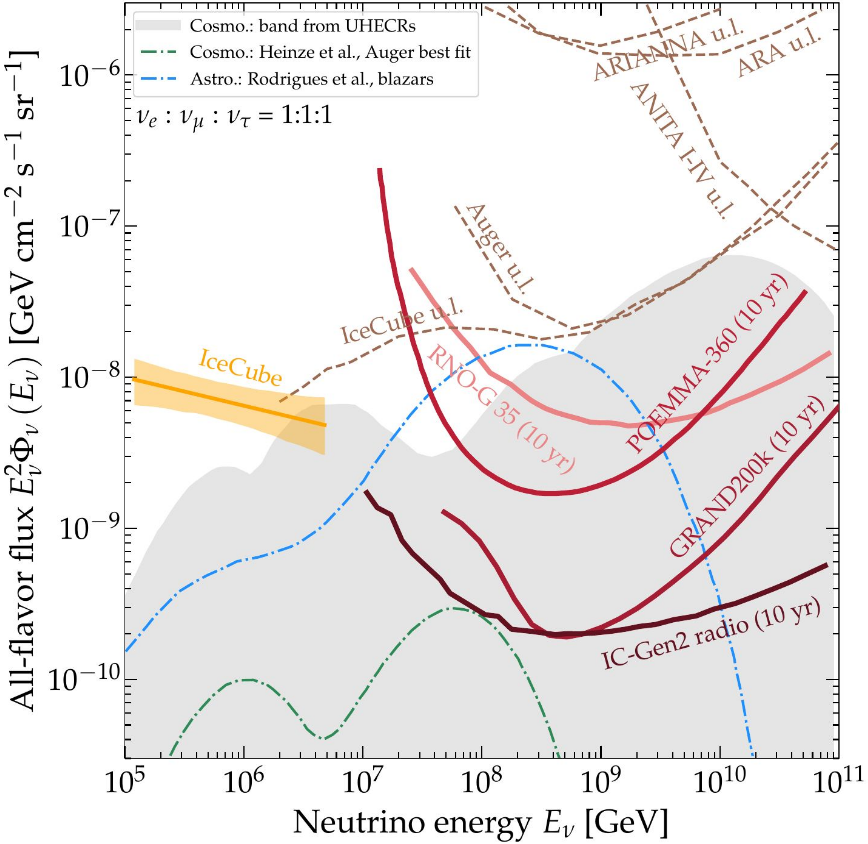
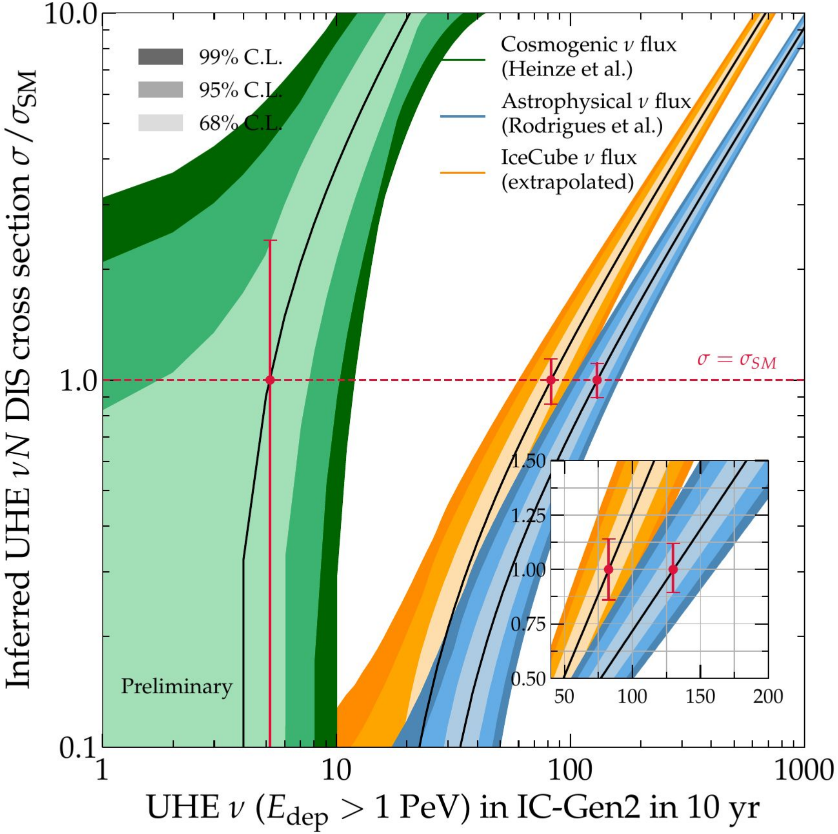
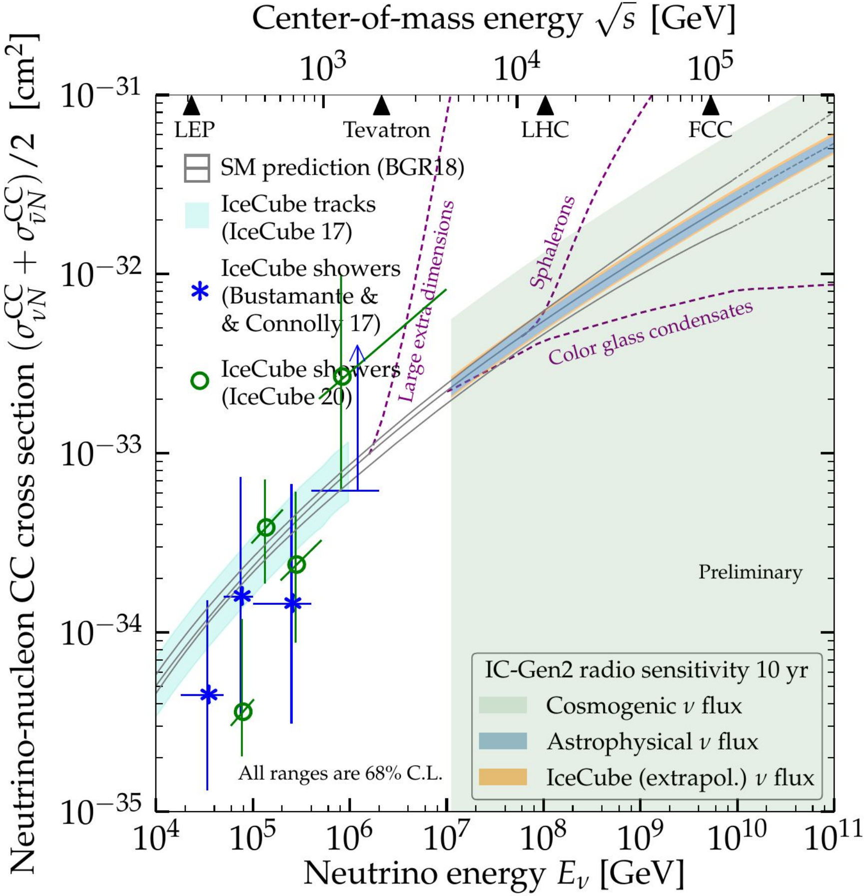




How well can we measure $\sigma_{\nu N}$ in the next decade?

Sensitivity to $f = \sigma/\sigma_{SM}$ in IceCube-Gen2 in 10 years		
	68% C.L.	**99% C.L.**
Cosmogenic ν flux (Heinze et al.)	$1^{+1.40}_{-1.00}$	$1^{+5.00}_{-1.00}$
IceCube ν flux (extrapolated)	$1^{+0.15}_{-0.13}$	$1^{+0.38}_{-0.32}$
Astrophysical ν flux (Rodrigues et al.)	$1^{+0.10}_{-0.11}$	$1^{+0.31}_{-0.26}$



Conclusions & take-home message

- The radio component of IceCube-Gen2 has good chances of finally observing the UHE neutrino flux
- UHE neutrinos represent an excellent window to explore new physics
- Measurements of $\sigma_{\nu N}$ are possible at the EeV frontier is possible, if the UHEν flux is high (i.e., astrophysical)
- If the UHEν is low (predominantly cosmogenic), no measurement is possible
- With an astrophysical UHEν flux $\sigma_{\nu N}$ can be measured within 15%

Backup slides

Event rate full computation

Differential event rate per energy and arrival direction

$$\frac{d^2 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu \, d\cos\theta_z} = 2\pi T N_{\mathrm{Av}} \rho_{\mathrm{ice}} V_{\mathrm{eff},\nu_\alpha}^{\mathrm{CC}}(E_\nu) \sigma_{\nu N}^{\mathrm{CC}}(E_\nu) \phi_{\nu_\alpha}^{\mathrm{det}}(E_\nu, \cos\theta_z)$$

Diff. event rate in terms of deposited energy and reconstructed arrival direction

$$\frac{d^2 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_{\mathrm{dep}} \, d\cos\theta_{z,\mathrm{rec}}} = \int_{-1}^{+1} d\cos\theta_z \int dE_\nu \int dE_{\mathrm{true}} \frac{d^2 N_{\nu_\alpha}^{\mathrm{CC}}}{dE_\nu \, d\cos\theta_z} R_{E_{\mathrm{true}}}(E_{\mathrm{true}}, E_\nu) R_{E_{\mathrm{dep}}}(E_{\mathrm{dep}}, E_{\mathrm{true}}, E_\nu) R_{\theta_z}(\cos\theta_{z,\mathrm{rec}}, \cos\theta_z)$$

The total number of events is obtained from integration
over deposited energy and reconstructed arrival direction