UHE neutrino-nucleon cross section from IceCube-Gen2

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In collaboration with
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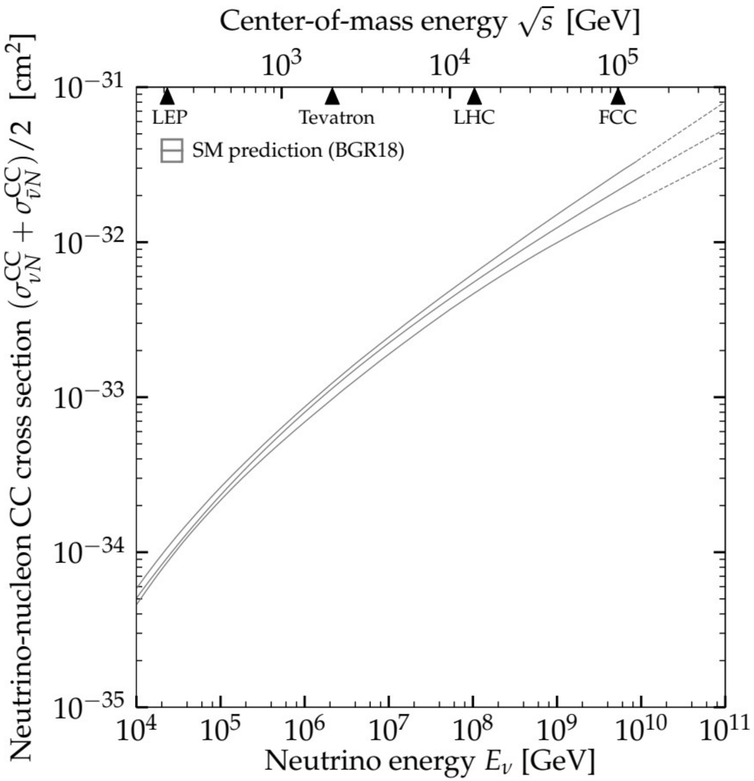
UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

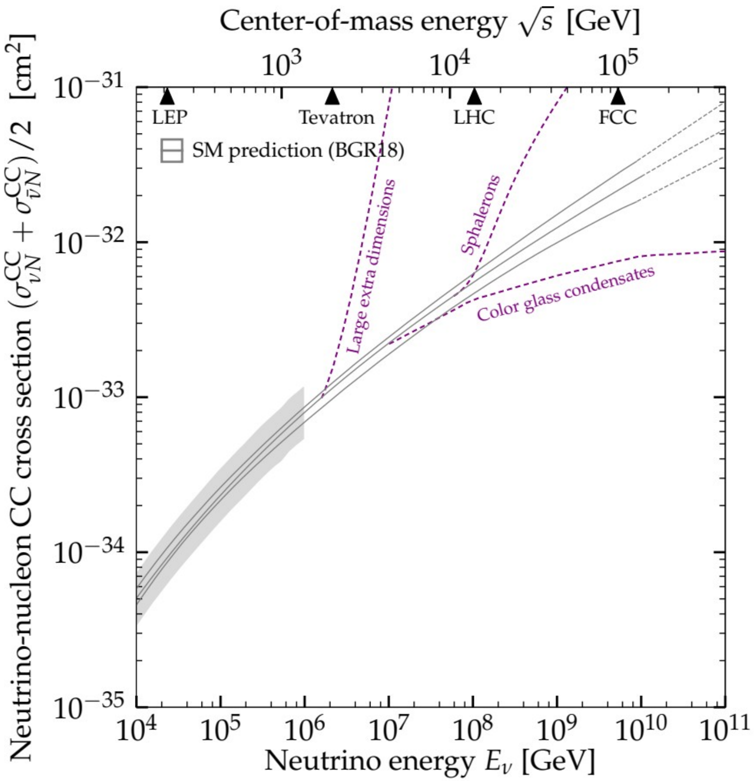
MAIN OBJECTIVES

- **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

Neutrino-nucleon cross section measurements today

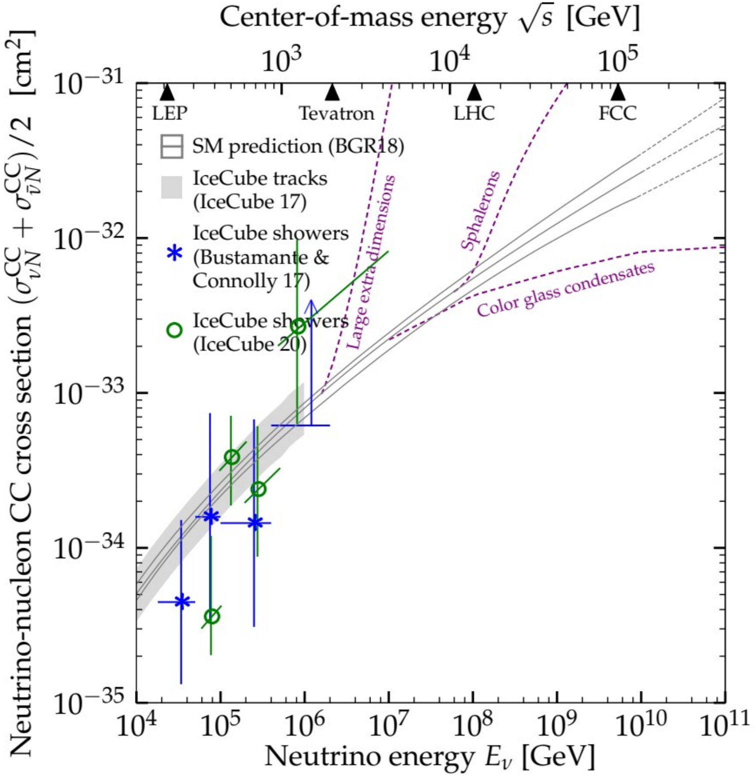


Neutrino-nucleon cross section measurements today



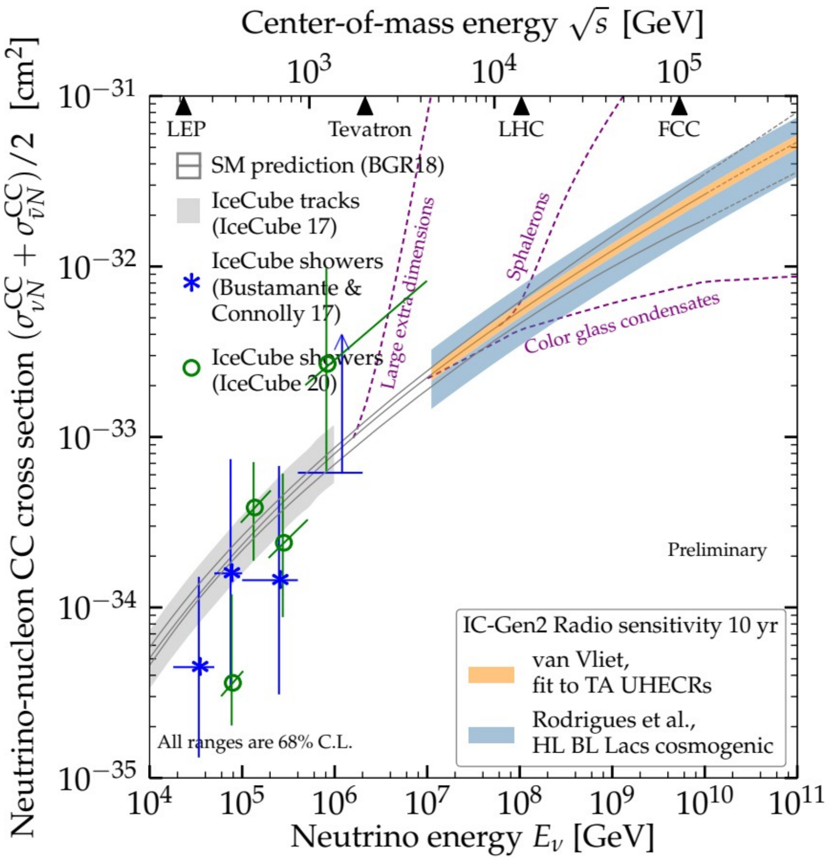
Potential exciting new Physics at ultra-high energies

Neutrino-nucleon cross section measurements today



Relax model dependency in stages:

1) **Perfectly known UHEν** flux.
2) Add a normalization uncertainty to the assumed UHEν.
3) Measure the flux and the cross section simultaneously.



THE METHOD: Model-dependent → independent

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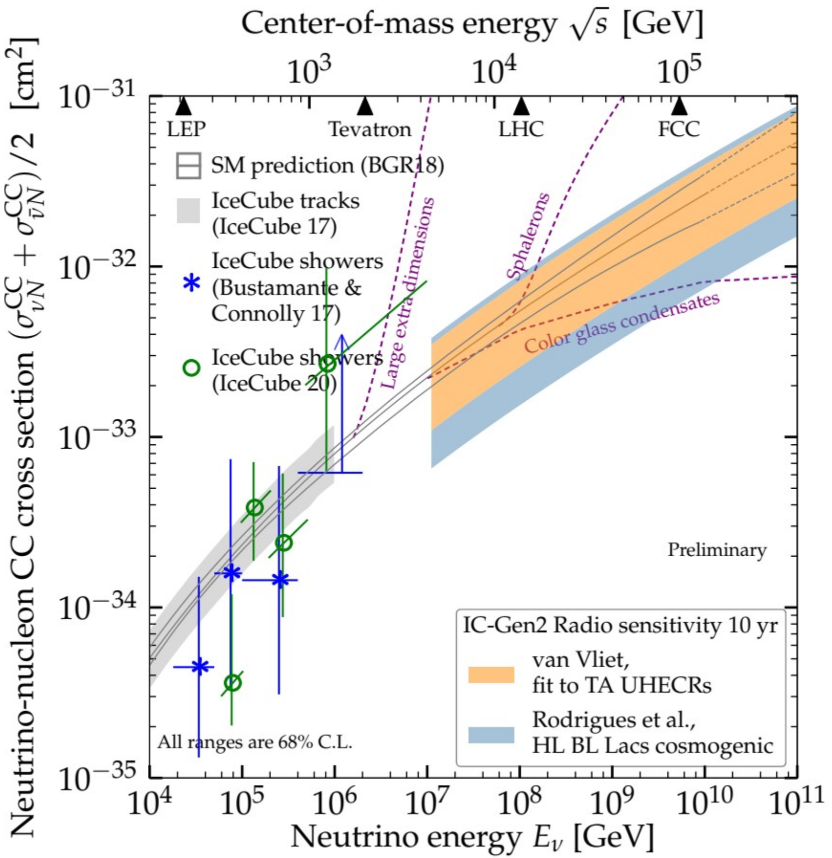

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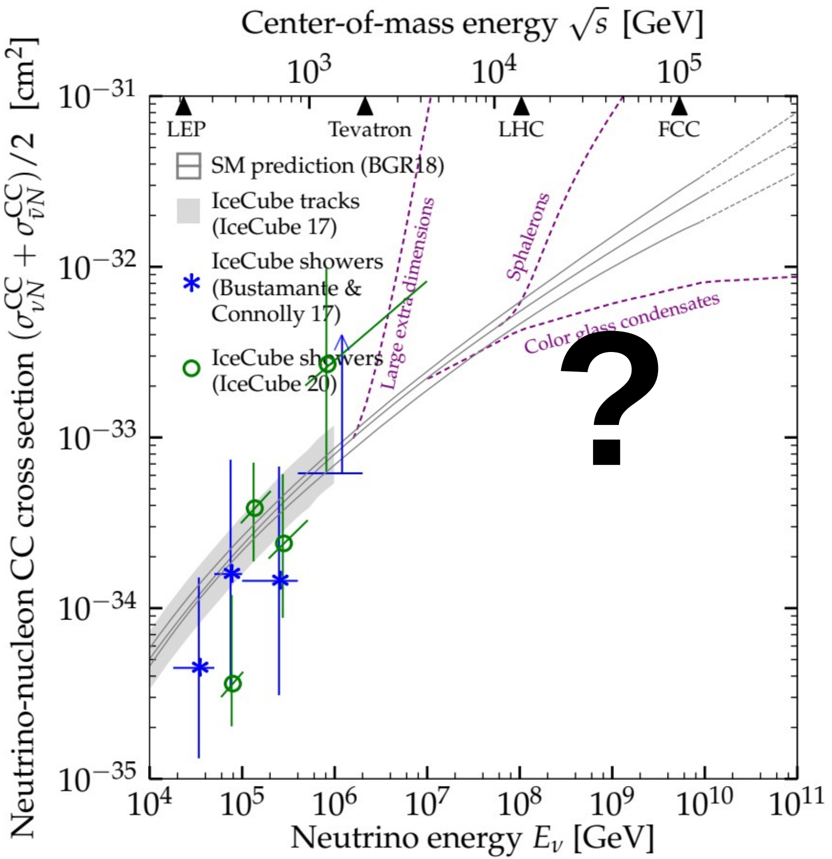
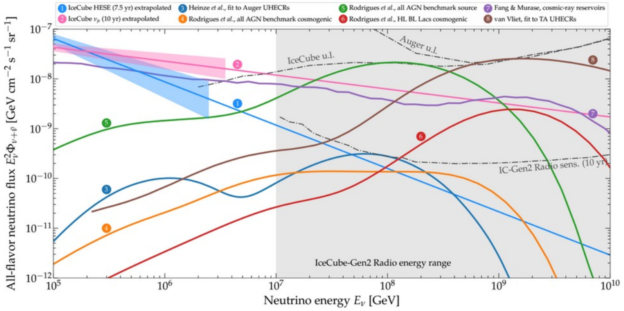
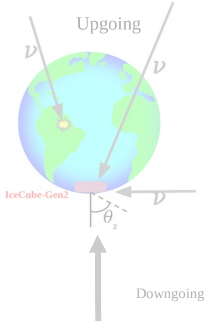
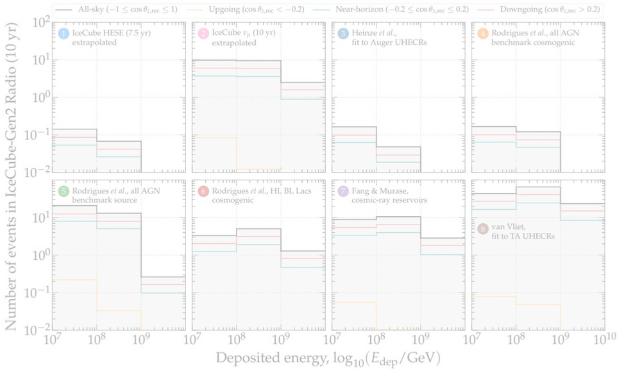
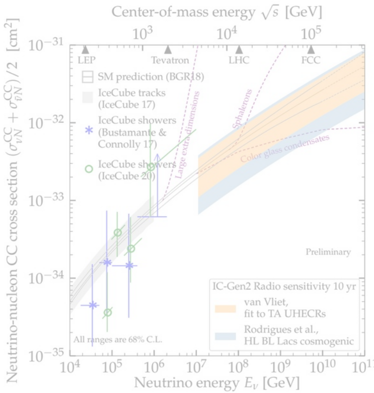


WORKFLOW: Each step of this work









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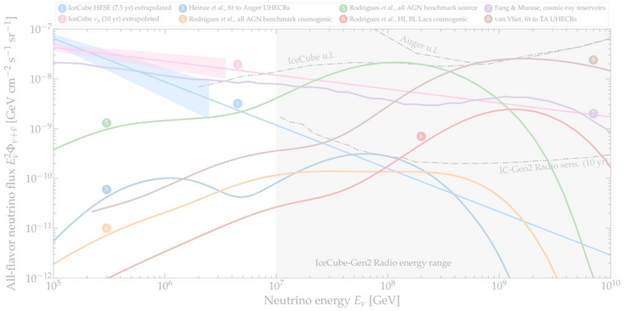
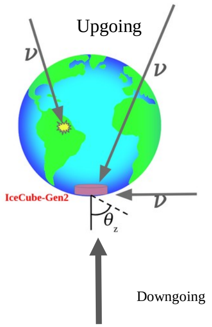
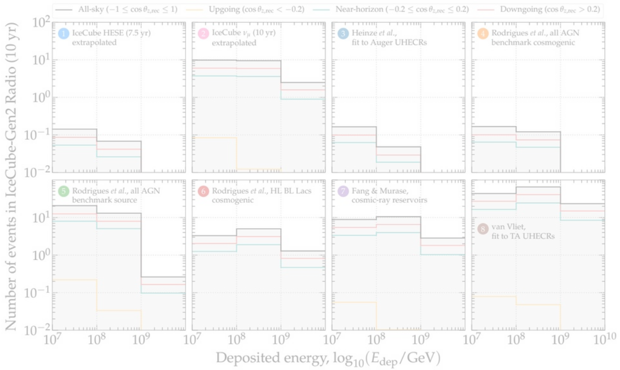
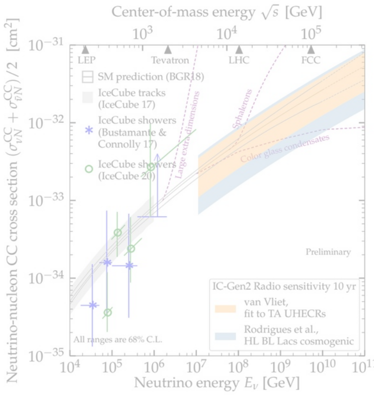
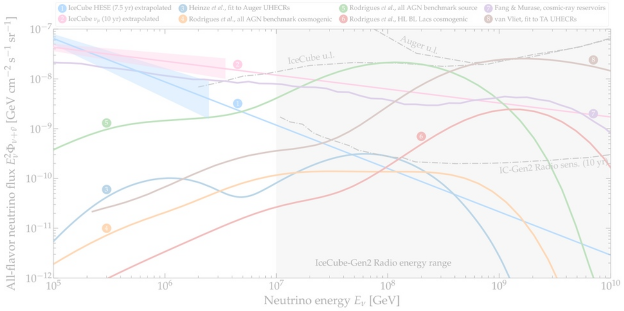
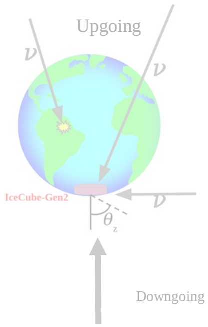


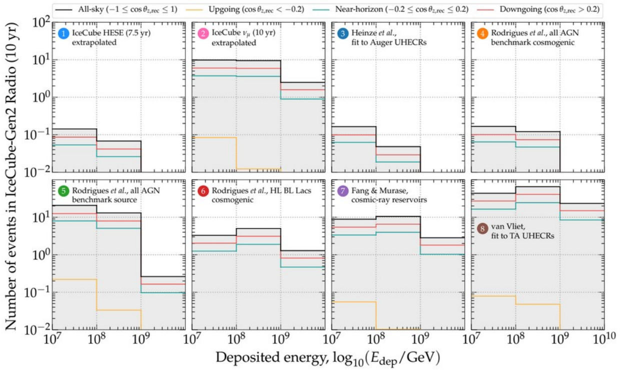


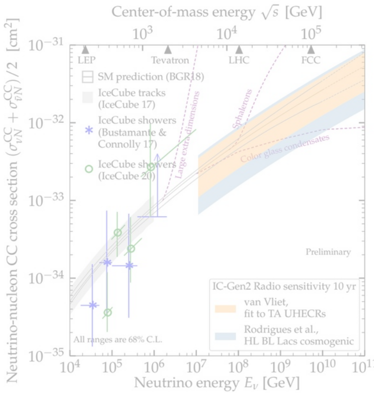





All-flavor neutrino flux
Neutrino energy E_ν [GeV]
IceCube u.l.
Auger u.l.
IC-Gen2 Radio sens. (10 yr)
IceCube-Gen2 Radio energy range


Upgoing
Downgoing
IceCube-Gen2
ν
θ_z


All-sky ($-1 \le \cos\theta_{z,rec} \le 1$)
Upgoing ($\cos\theta_{z,rec} < -0.2$)
Near-horizon ($-0.2 \le \cos\theta_{z,rec} \le 0.2$)
Downgoing ($\cos\theta_{z,rec} > 0.2$)
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (10 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Rodrigues et al., all AGN benchmark cosmogenic
5 Rodrigues et al., all AGN benchmark source
6 Rodrigues et al., HL BL Lacs cosmogenic
7 Fang & Murase, cosmic-ray reservoirs
8 van Vliet, fit to TA UHECRs
Number of events in IceCube-Gen2 Radio (10 yr)
Deposited energy, $\log_{10}(E_{dep}/\mathrm{GeV})$


Center-of-mass energy $\sqrt{s}$ [GeV]
LEP
Tevatron
LHC
FCC
SM prediction (BGR18)
IceCube tracks (IceCube 17)
IceCube showers (Bustamante & Connolly 17)
IceCube showers (IceCube 20)
Large extra dimensions
Sphalerons
Color glass condensates
Preliminary
IC-Gen2 Radio sensitivity 10 yr
van Vliet, fit to TA UHECRs
Rodrigues et al., HL BL Lacs cosmogenic
All ranges are 68% C.L.
Neutrino-nucleon CC cross section
Neutrino energy E_ν [GeV]

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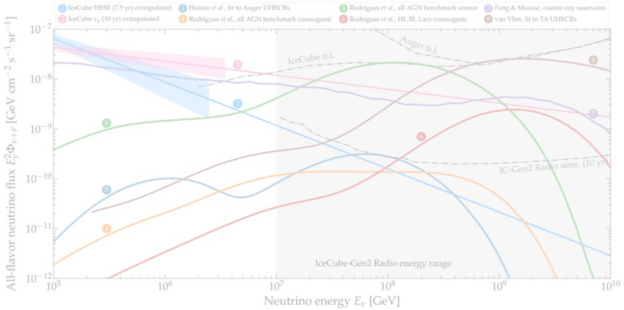
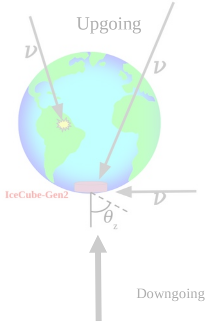
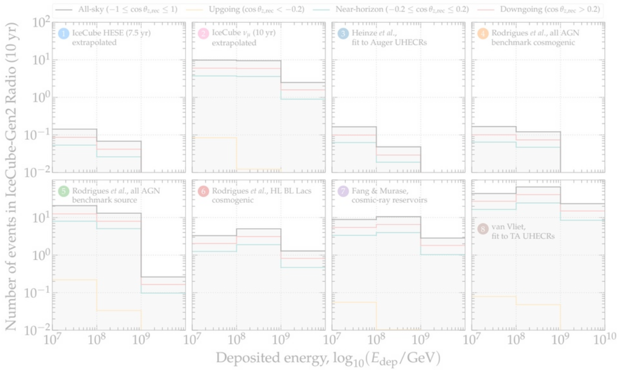
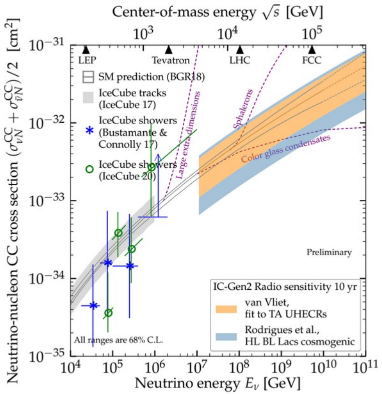
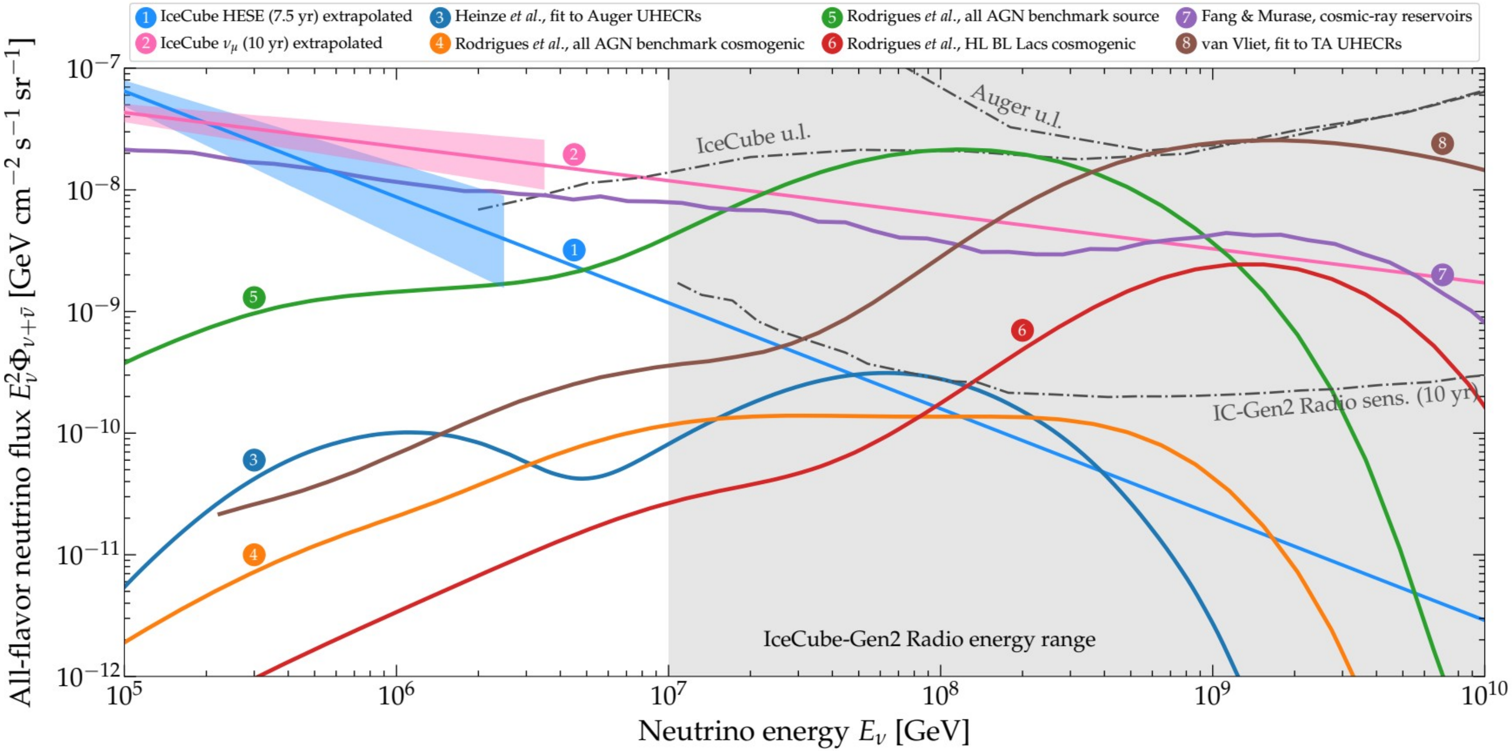








The UHE neutrino flux



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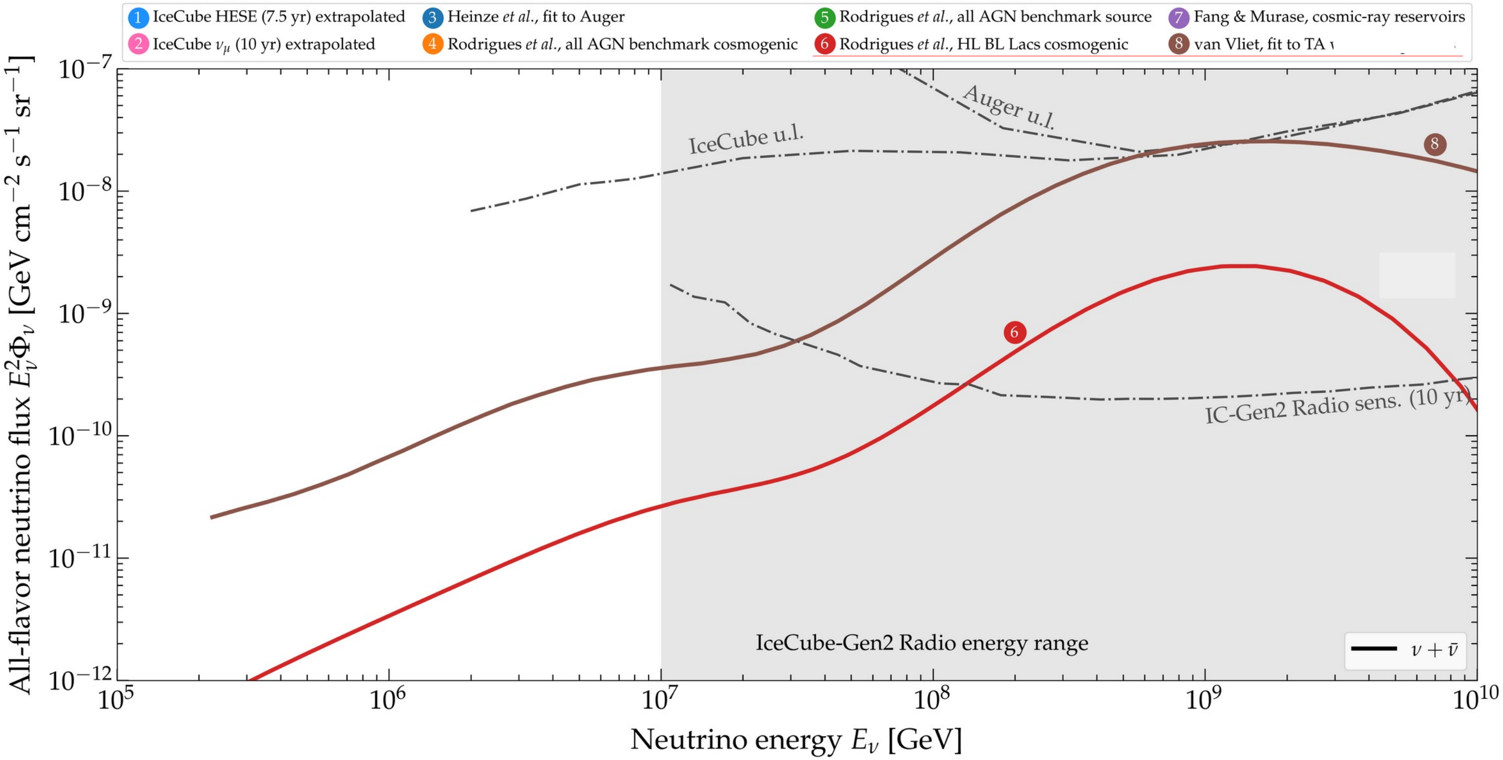
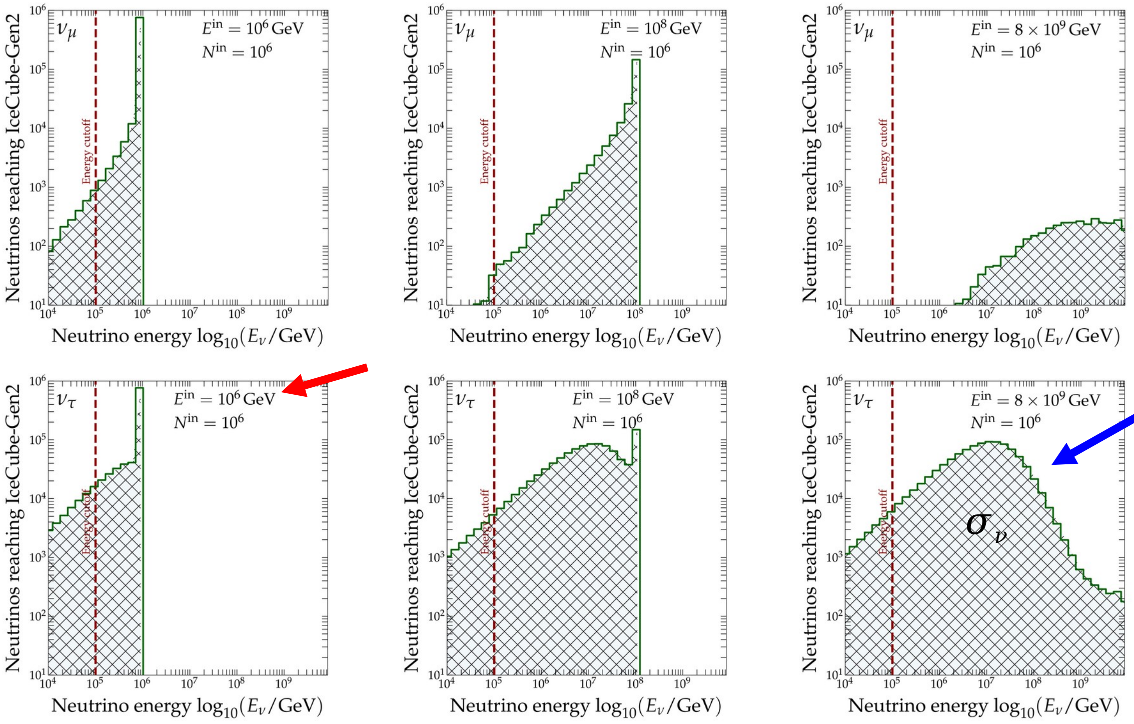


NuPropEarth: an in-Earth neutrino propagation tool

- Monte Carlo neutrino propagation
- Leading interaction DIS
- + sub-leading contributions
- Most updated $\sigma_{\nu N}$ predictions
- Earth density: PREM model

Garcia et. al., *JCAP 2020*



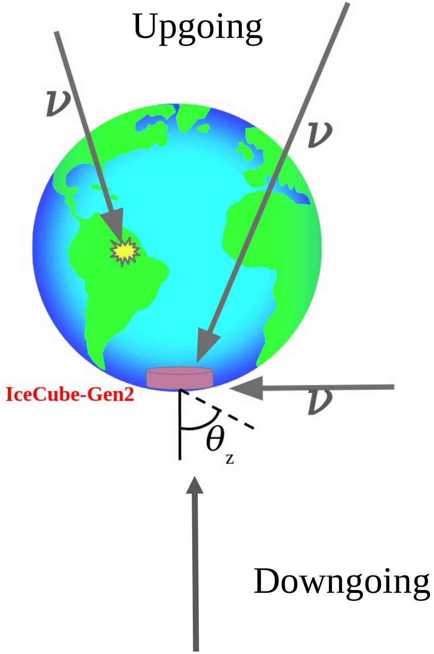
ν_μ

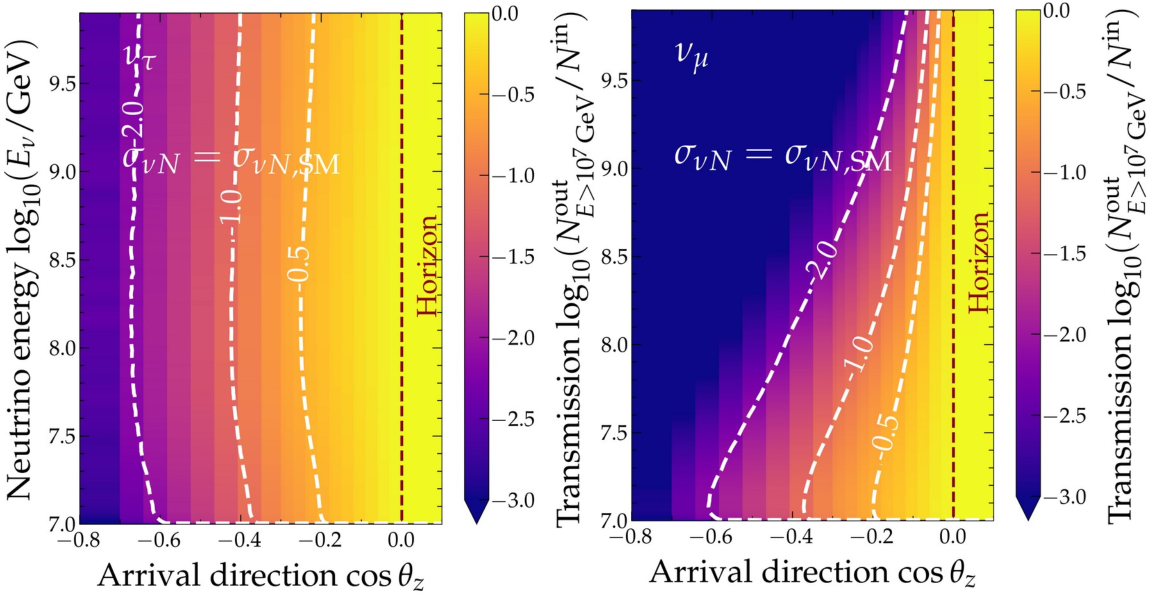
τ

Higher injected neutrino energy

Monochromatic neutrino beam propagation

- Monochromatic neutrino beams
- Various directions at different energies
- Store how they cascade down at the detector.

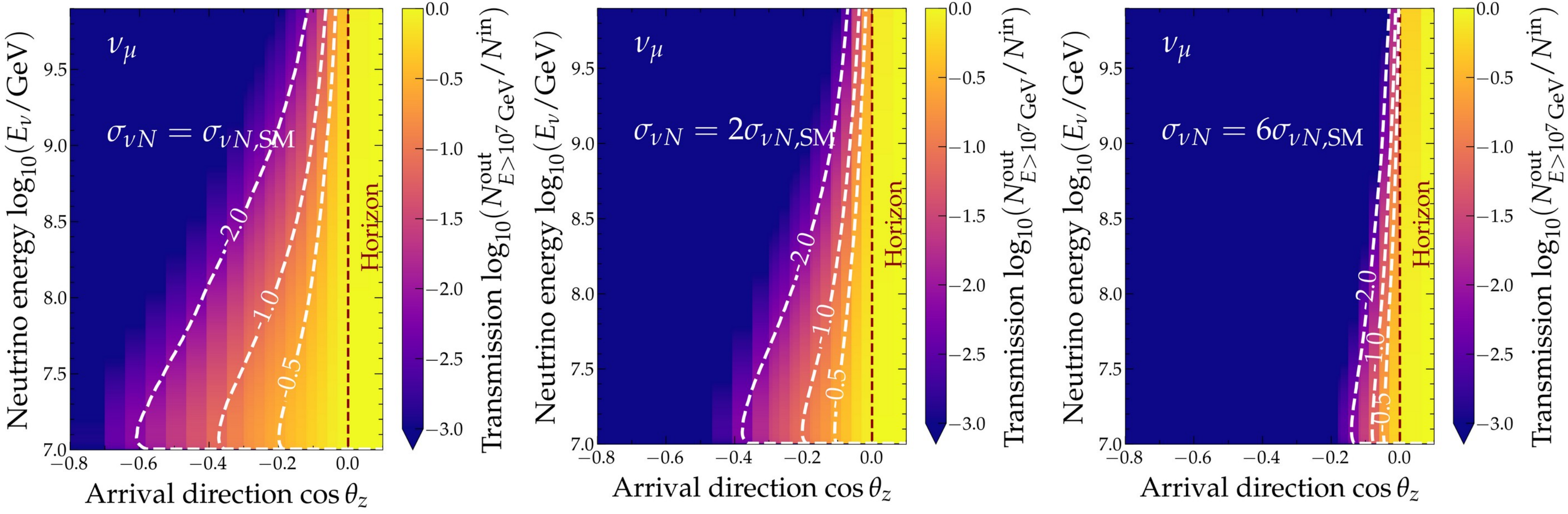




Propagate neutrino for $\sigma \neq \sigma_{SM}$, f = [0.1, 10]

Cross section σ_{SM}

$\sigma = \sigma_{SM}$ $\sigma = 2\sigma_{SM}$ $\sigma = 6\sigma_{SM}$



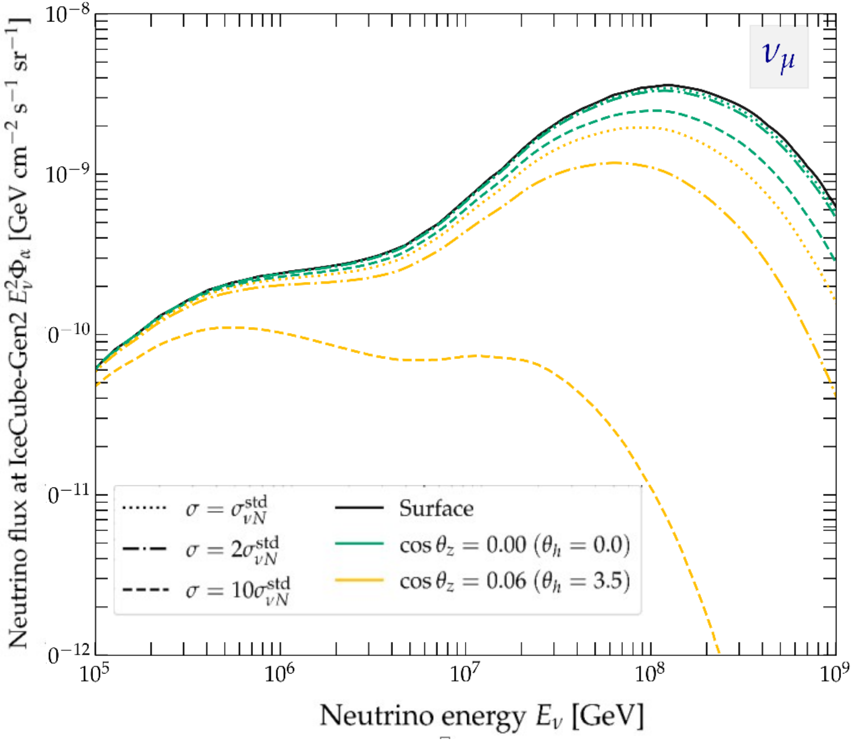
Flux propagation from precomputed tables

Flux propagation:

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

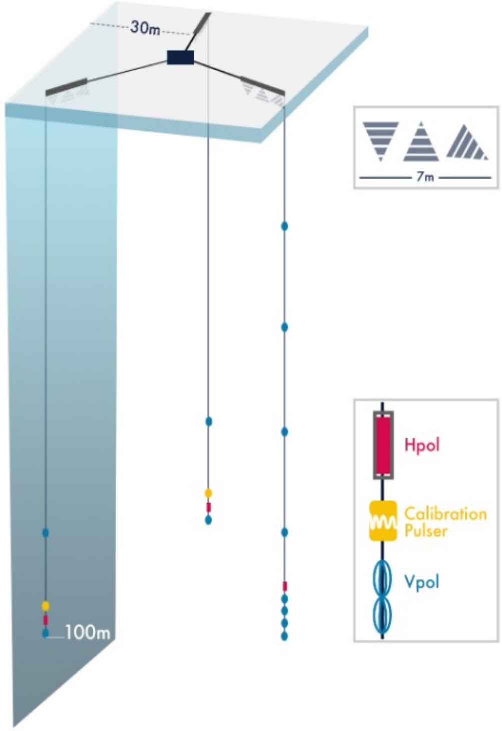
The result:

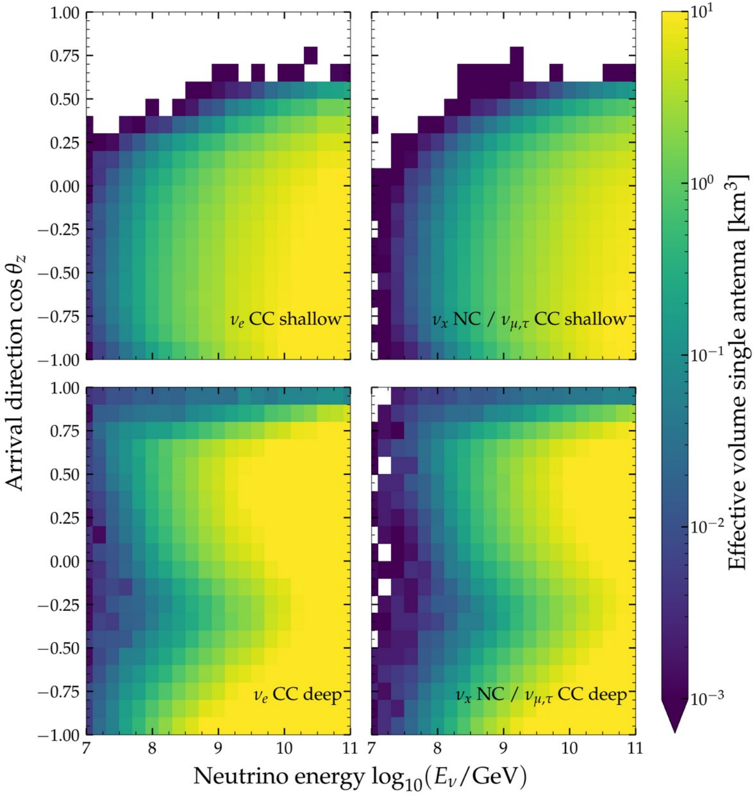
Propagated neutrino flux for each flavor at different directions



IceCube-Gen2 Radio

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





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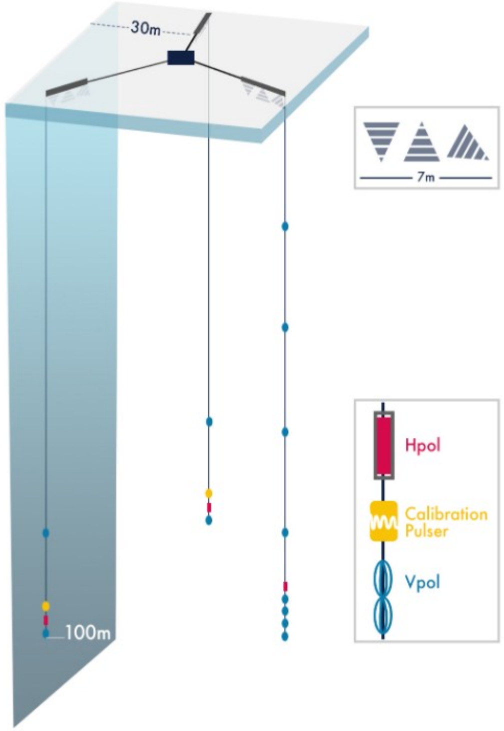
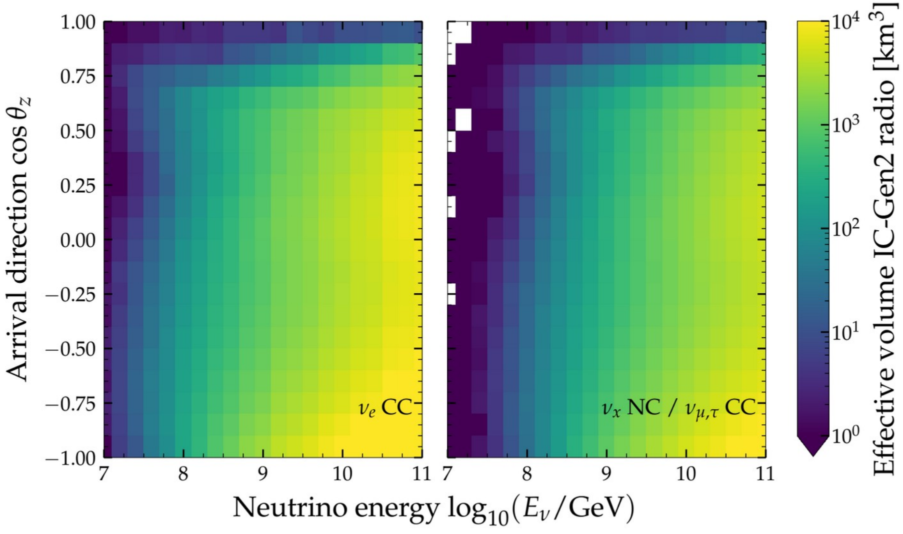


- The full detector is made of a total of 144 hybrid (shallow + deep) and 169 shallow-only stations



Predicted event rate at IceCube-Gen2 radio

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

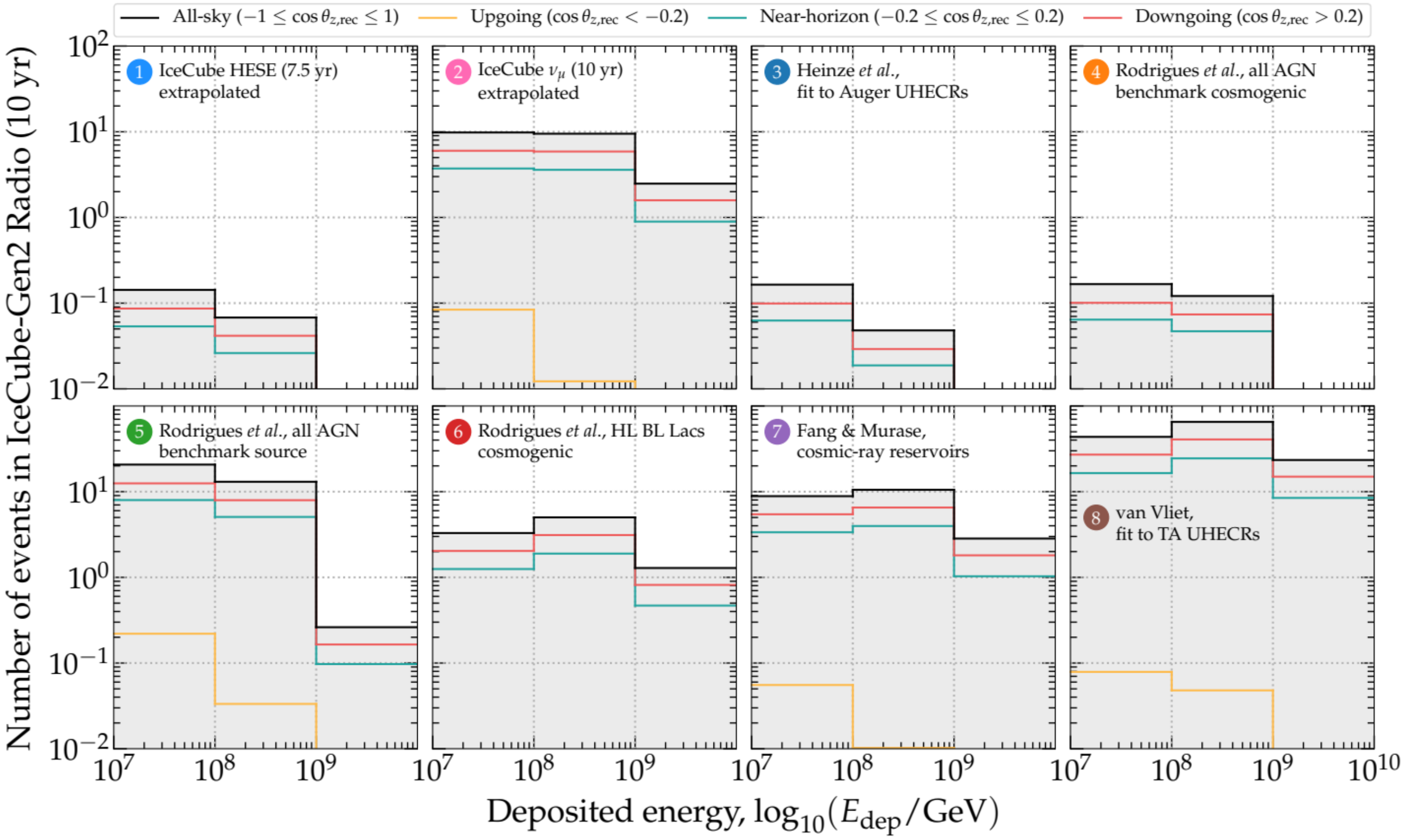
Increases the probability of a neutrino detection

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}, $\cos\theta_{\text{z, rec}}$)
- IC-Gen2 effective volume simulated for this study without Earth attenuation (we include it ourselves)

* See backup for full expression

The predicted event rates after 10 years of IC-Gen2



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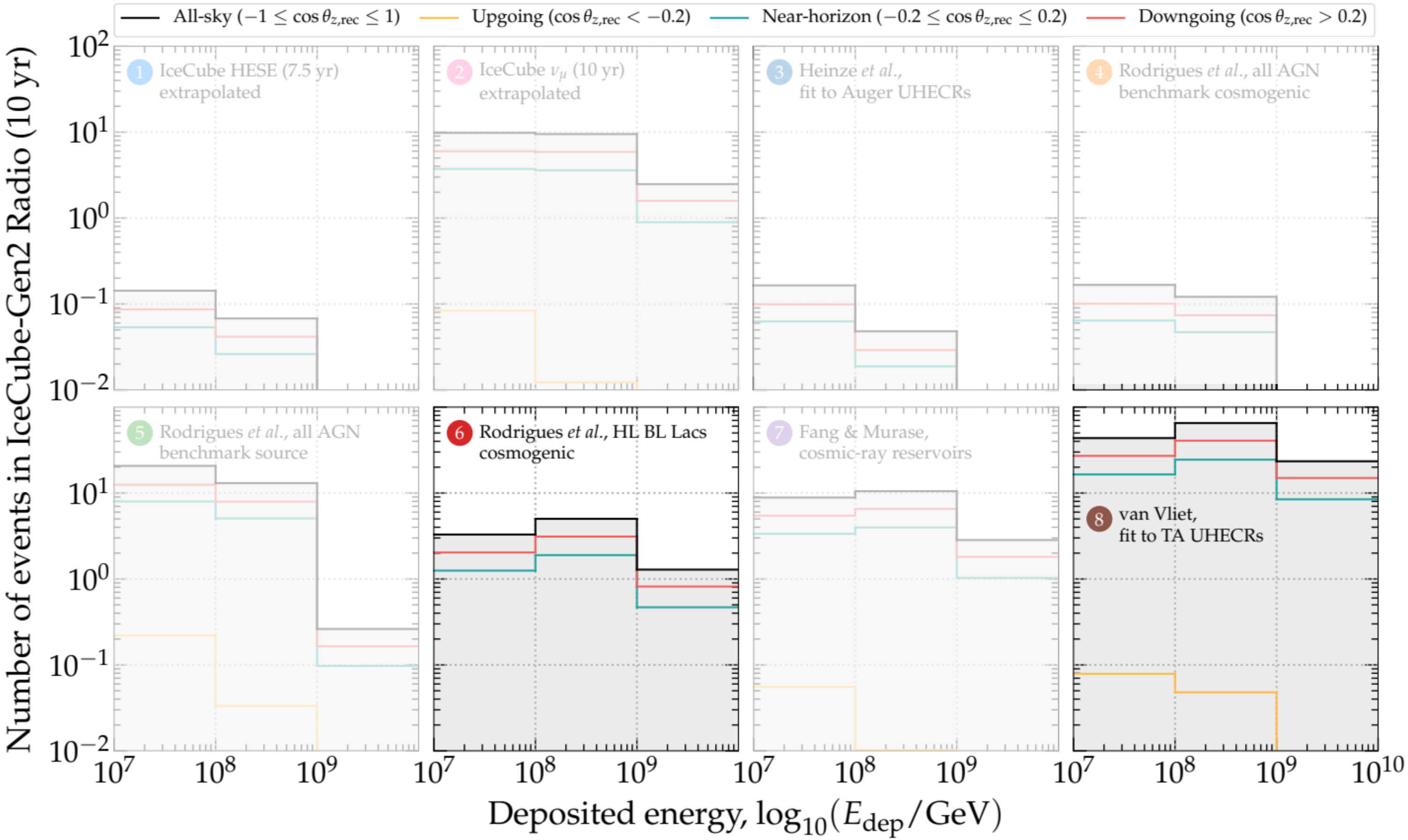


* See backup for full expression

How well can we measure $\sigma_{\nu N}$? - Perfectly known flux

- Bayesian analysis
- Unbinned Poissonian likelihood:

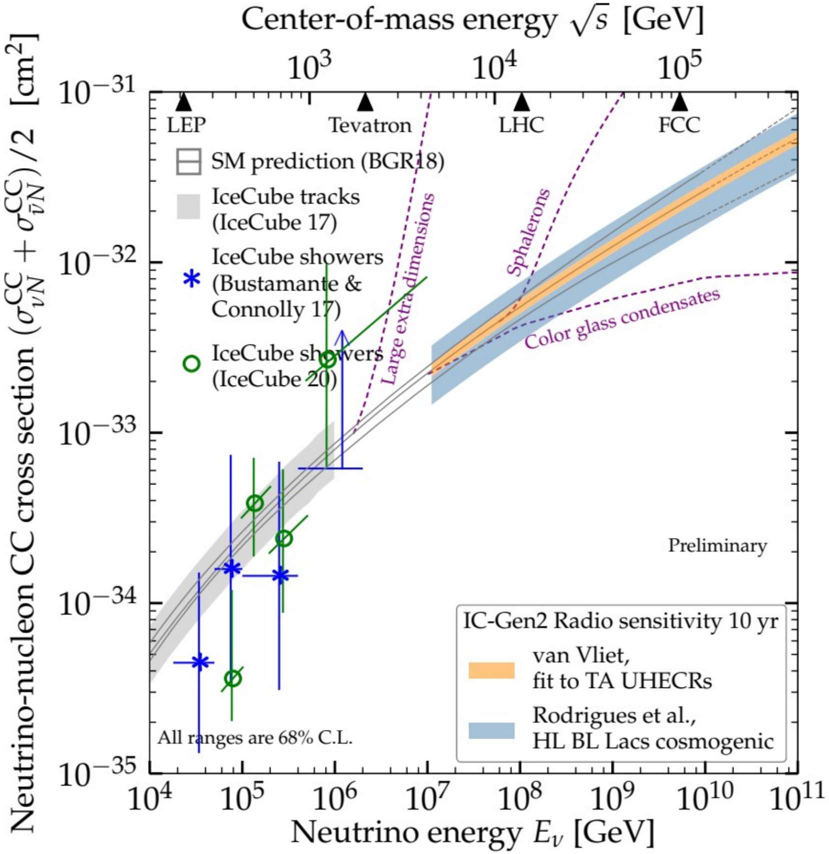
$$\mathcal{L}(f, N_{\text{obs}}) = \frac{e^{-[N(f)+N_{\text{bkg}}]}[N(f) + N_{\text{bkg}}]^{N_{\text{obs}}}}{N_{\text{obs}}!}$$

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

N_{obs} = Observed events assuming f=1

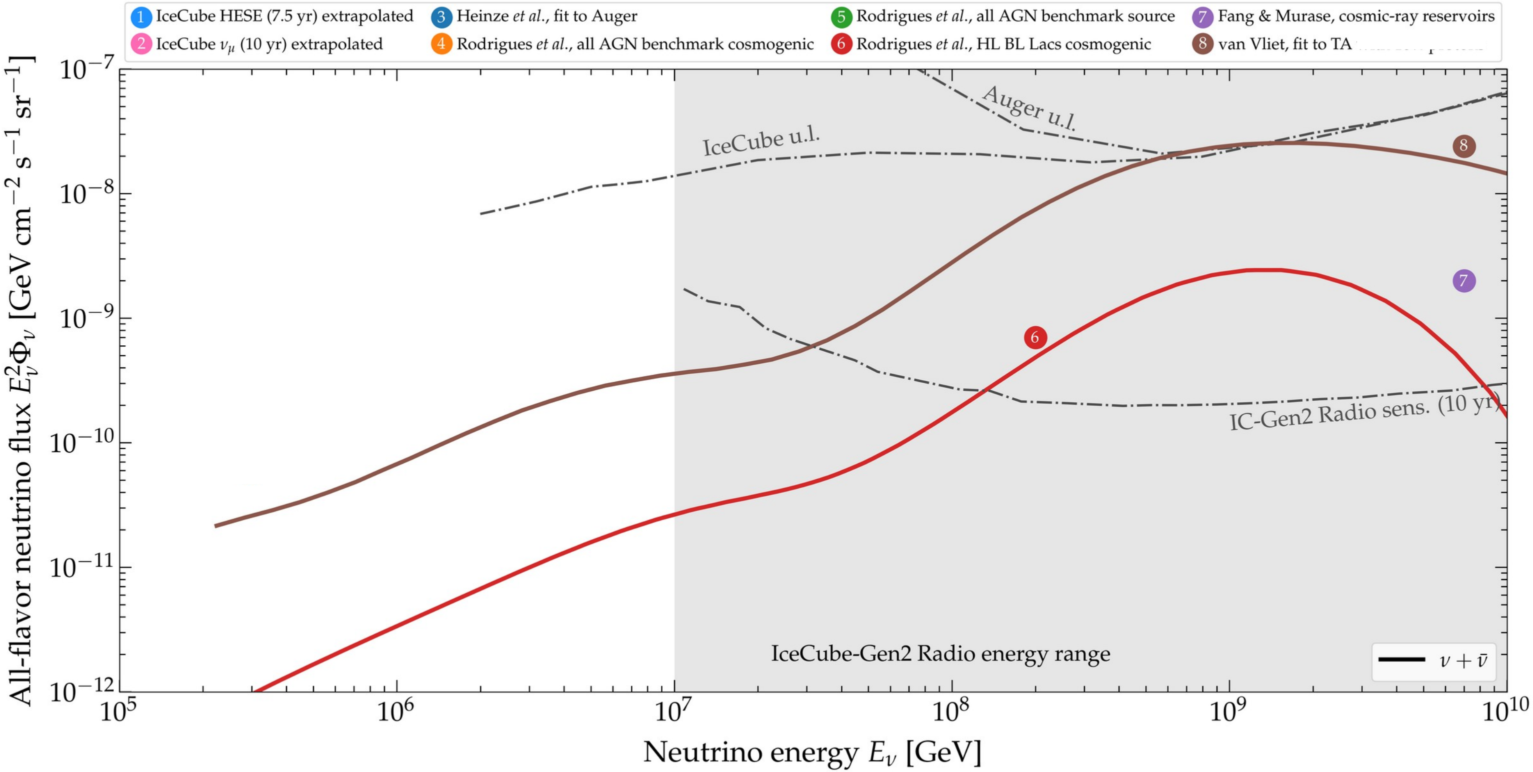
N_{bkg} = Background events **(atm muons)**

N(f) = Predicted number of events for different f



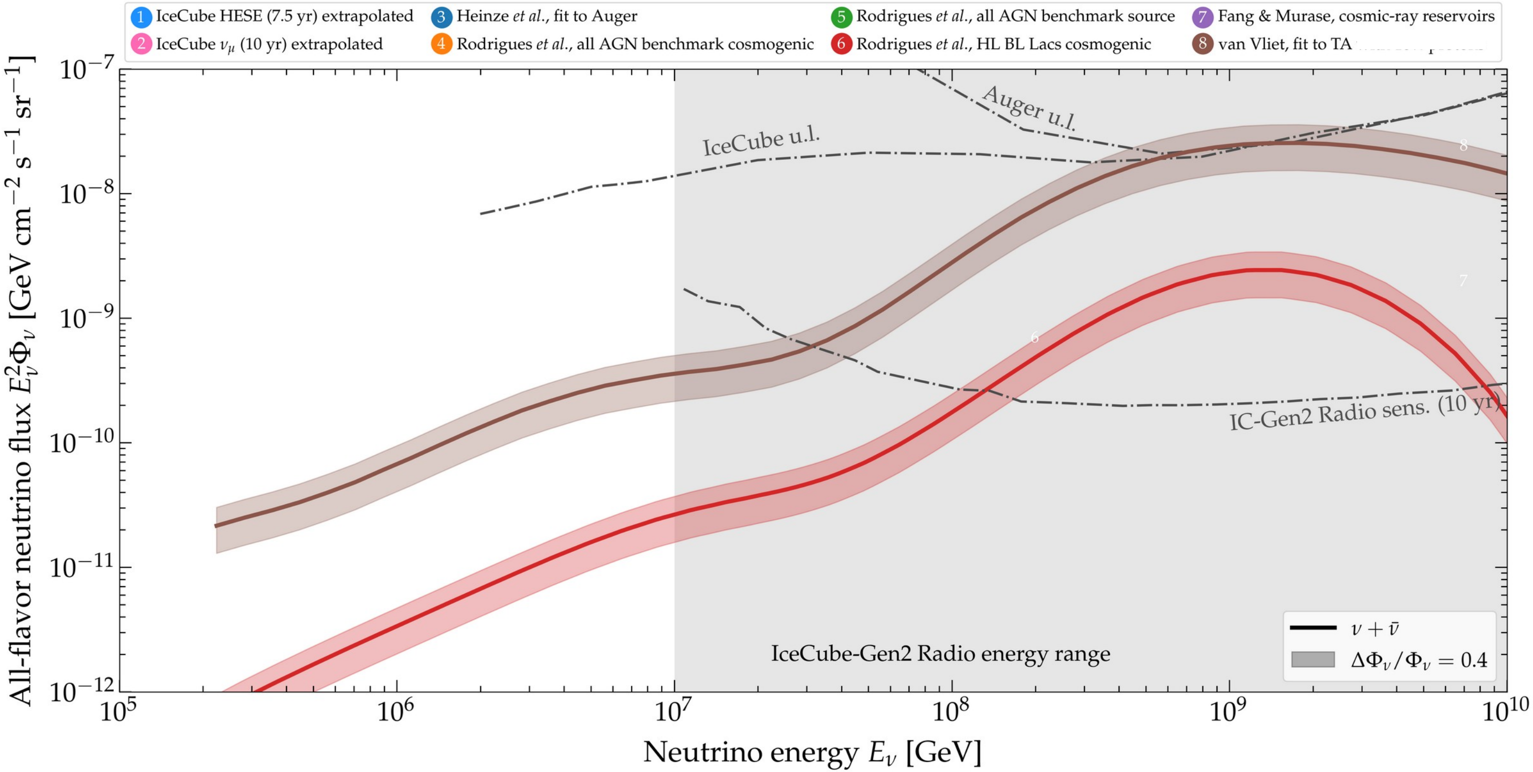
But assuming we know the flux perfectly is aggressive

At this point we have obtained our results under the assumption of a known flux



But assuming we know the flux perfectly is aggressive

We add an error in the flux normalization to account for and unknown flux on a first instance



An analysis binned on reconstructed arrival direction

- The data set is divided in 3 different bins for $\cos \theta_{z,\,rec}$.
- The normalization uncertainty is taken into account as a Gaussian prior.
- As the exposure time increases, the measurement improves but eventually saturates

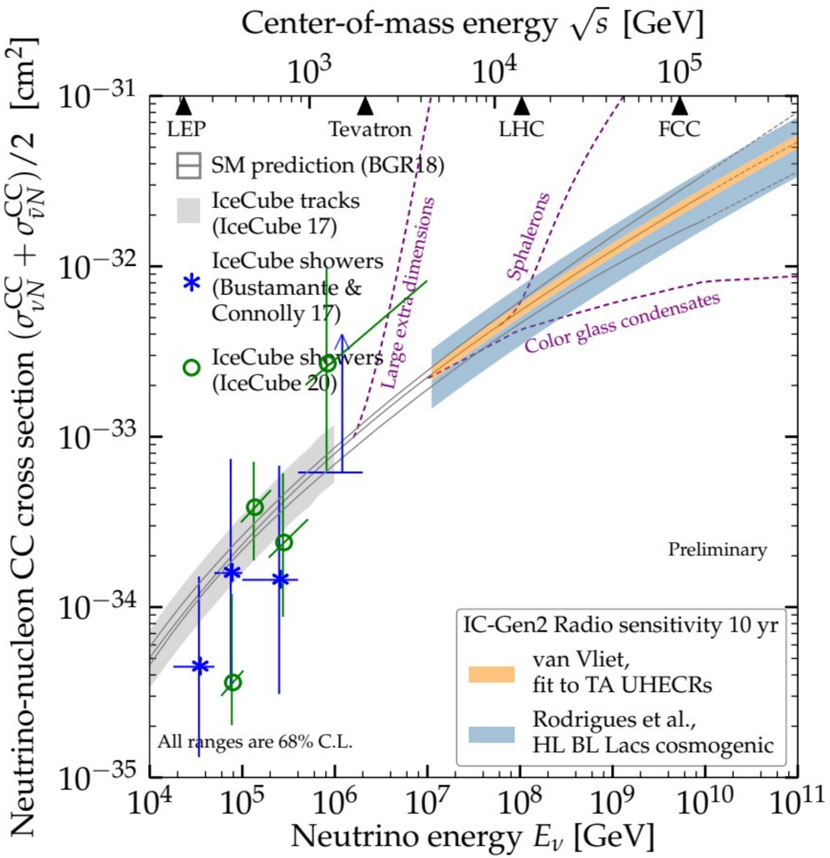
$$\Delta\Phi/\Phi = 0.4$$

An analysis binned on reconstructed arrival direction

- The data set is divided in 3 different bins for cos $\theta_{z,\,rec}$.
- The normalization uncertainty is taken into account as a Gaussian prior.
- As the exposure time increases, the measurement improves but eventually saturates

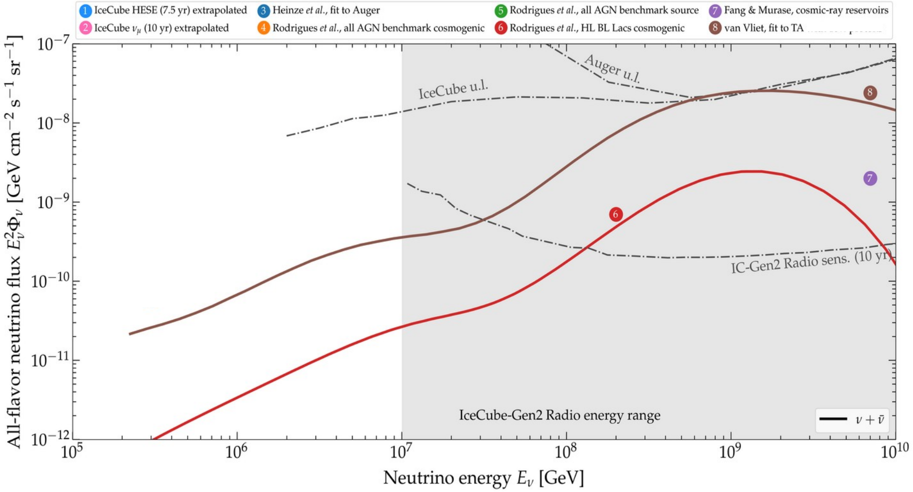
$\Delta\Phi/\Phi = 0.1$

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



$\sigma/\sigma_{SM} = 1 + 0.395 - 0.375$

$\sigma/\sigma_{SM} = 1 + 0.101 - 0.085$



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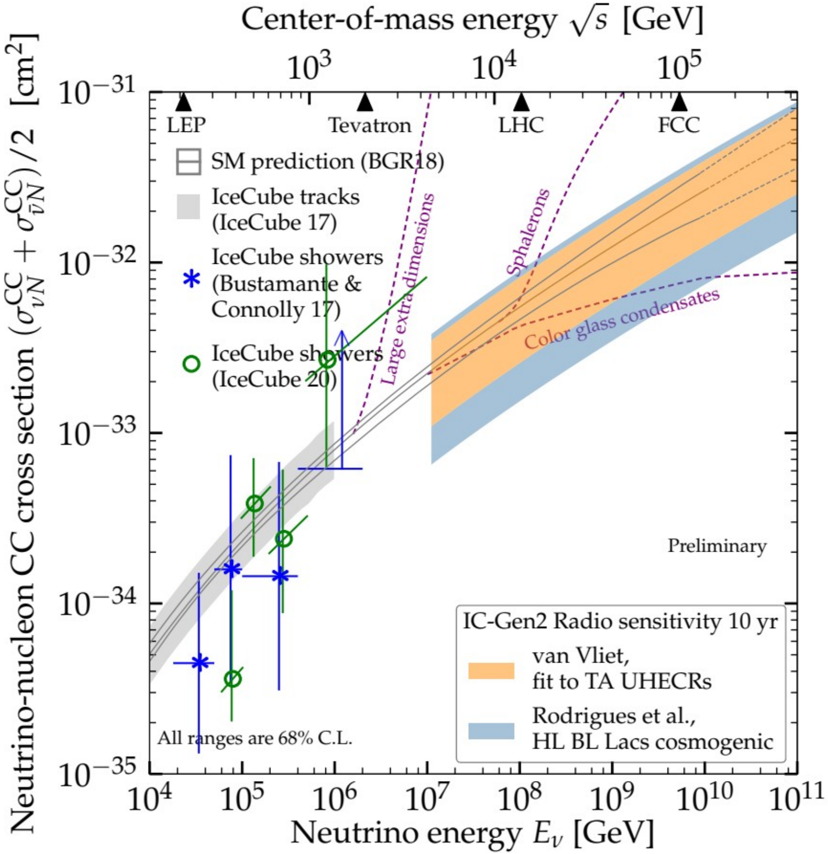
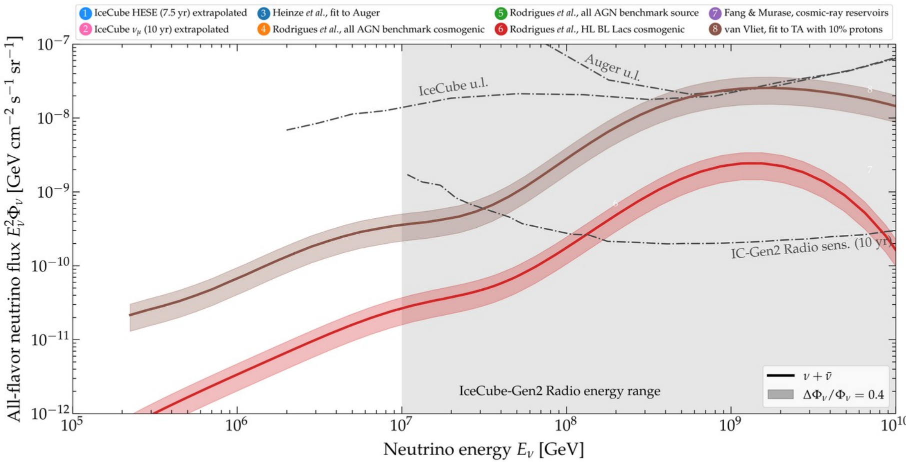


$$\sigma/\sigma_{SM} = 1 + 0.631 - 0.720$$

$$\sigma/\sigma_{SM} = 1 + 0.492 - 0.531$$



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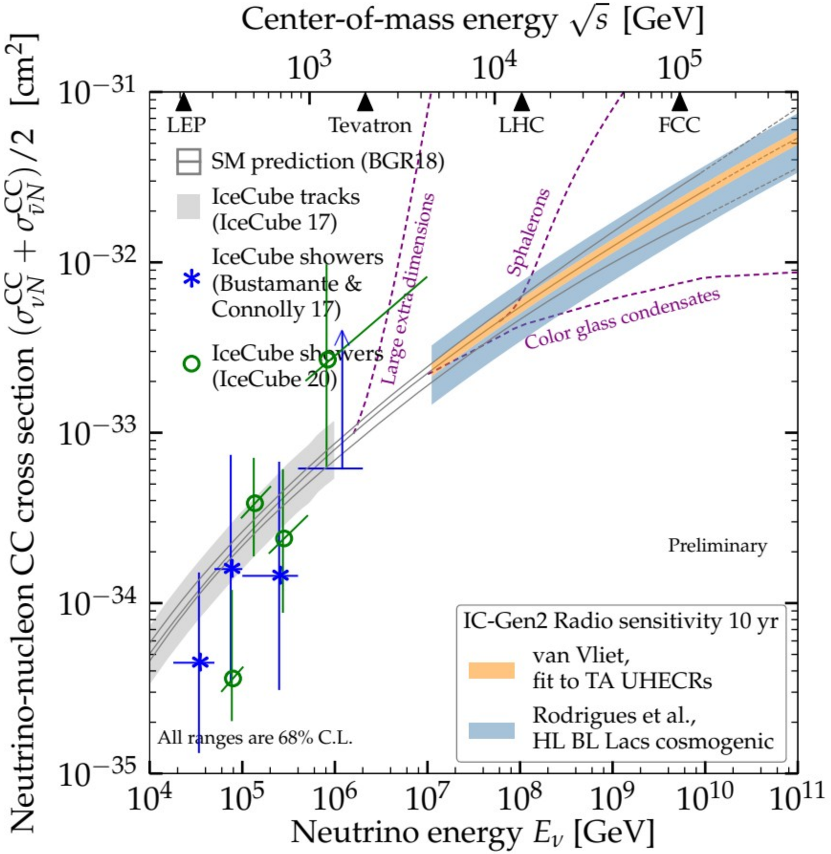

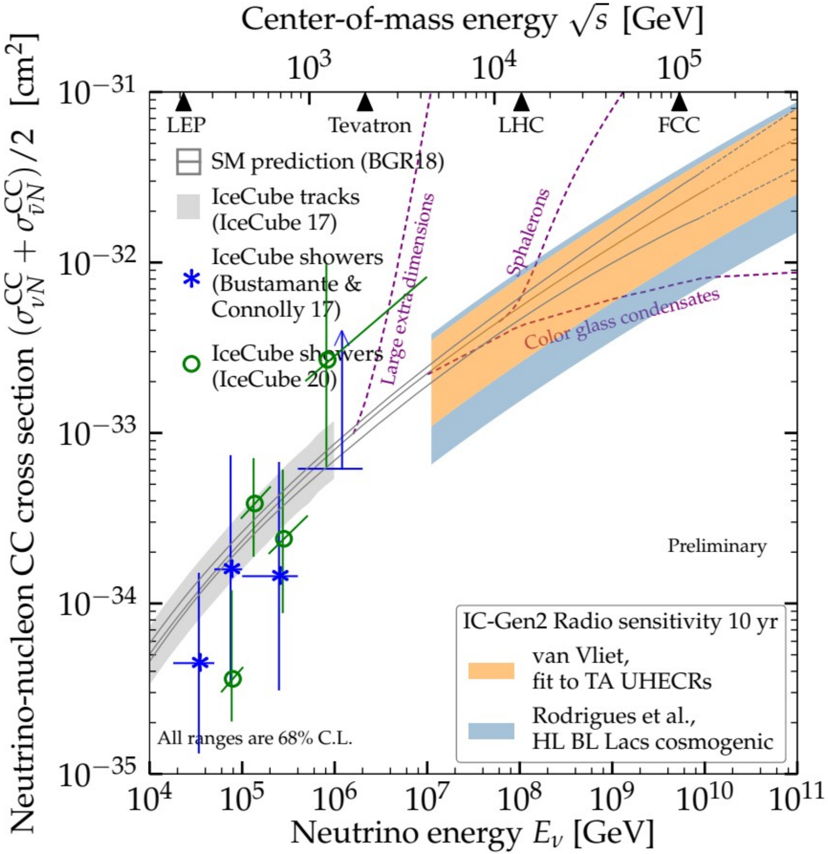

Back to the most general situation

Relax model dependency in stages:

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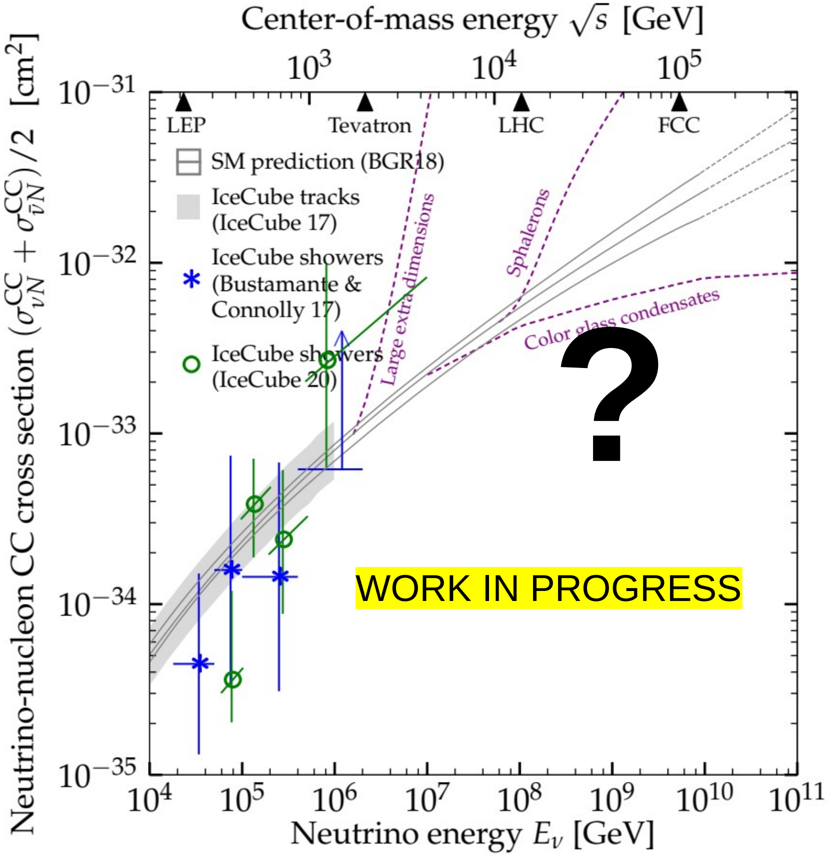
2) Add a normalization uncertainty to the assumed UHEν.
3) Measure the flux and the cross section **simultaneously**.



Conclusions & take-home message

- The radio component of IceCube-Gen2 has good sensitivity to UHE nu.
- Good enough for physics studies if the flux is high enough.
- We have developed a detailed end-to-end machinery for event rates a physics studies.
- Cross section measurement measurement depend on the uncertainty of the flux
- For high fluxes a more clever strategy is being follow to measure cross section and flux simultaneously.

Backup slides

Event rate full computation

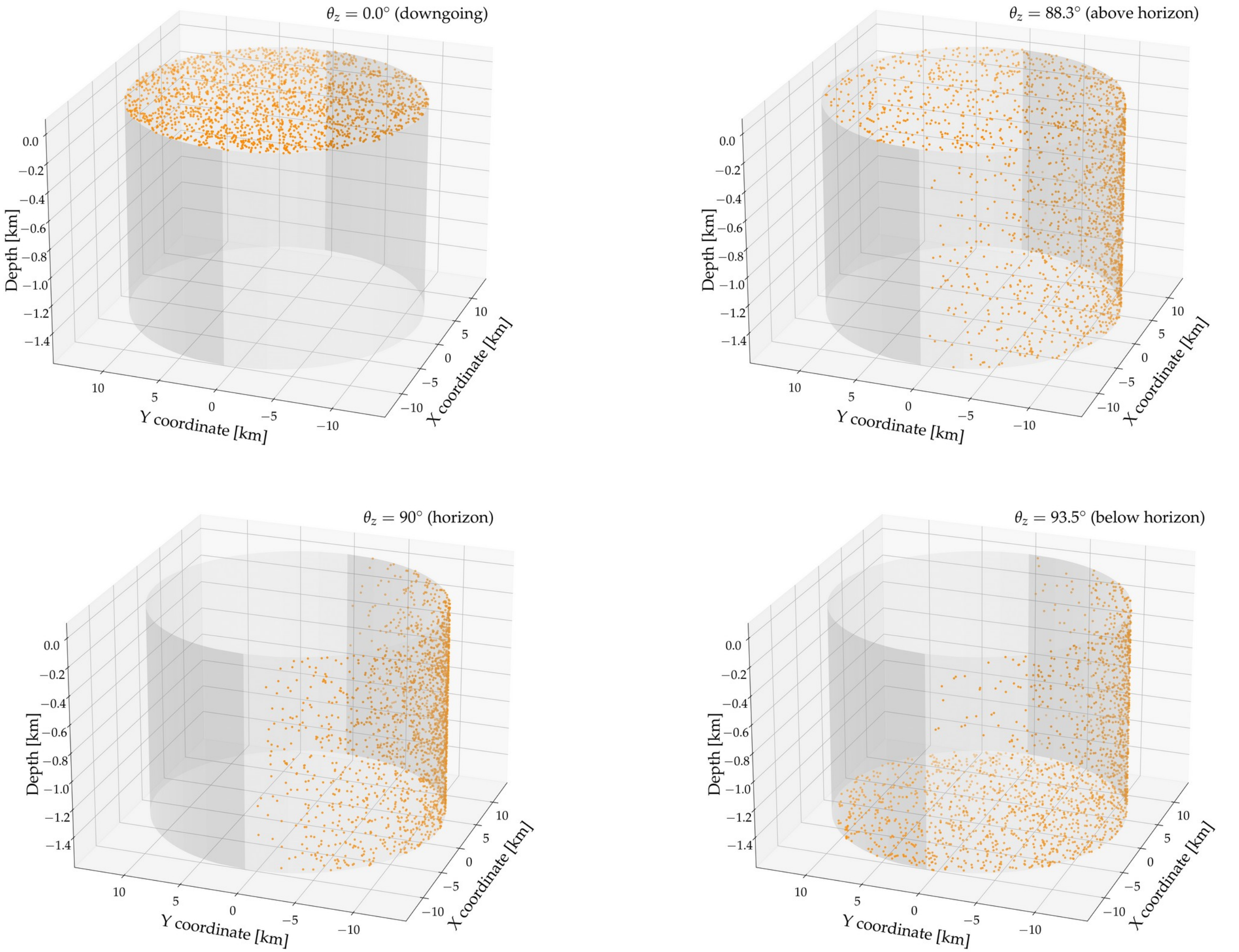
Differential event rate per energy and arrival direction

$$\frac{d^3 N^{\rm CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} = 2\pi T N_{\rm Av} \frac{\rho_{\rm ice}}{M_{\rm ice}} V^{\rm CC}_{{\rm eff},\nu_\alpha}(E_\nu, \cos\theta_z) \times \frac{d\sigma^{\rm CC}_{\nu N}(E_\nu, y)}{dy} \Phi^{\rm det}_{\nu_\alpha}(E_\nu, \cos\theta_z)$$

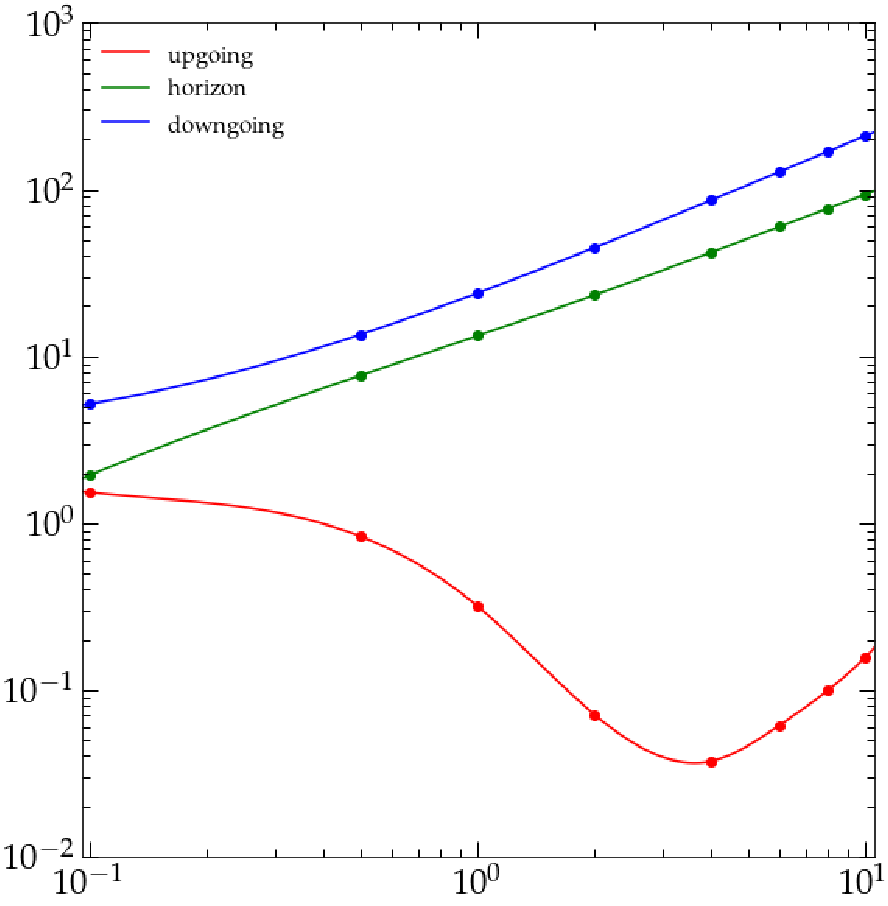
Diff. event rate in terms of deposited energy and reconstructed arrival direction

$$\frac{d^2 N^{\rm CC}_{\nu_\alpha}}{dE_{\rm dep} d\theta_{z,\rm rec}} = \int_{-1}^{+1} d\cos\theta_z \int_{E_{\rm dep}}^{\infty} dE_\nu \int_0^1 dy \frac{d^3 N^{\rm CC}_{\nu_\alpha}}{dE_\nu dy d\cos\theta_z} R_E[E_{\rm dep}, E^{\rm CC}_{{\rm sh},\nu_\alpha}(E_\nu, y)] \; R_{\theta_z}(\theta_{z,\rm rec}, \theta_z)$$

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



$\theta_z = 0.0°$ (downgoing)
$\theta_z = 88.3°$ (above horizon)
$\theta_z = 90°$ (horizon)
$\theta_z = 93.5°$ (below horizon)
Depth [km]
Y coordinate [km]
X coordinate [km]
0.0
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
−1.4
10
5
0
−5
−10



upgoing
horizon
downgoing
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1