EXPLORING NEUTRINO-MATTER INTERACTIONS AT THE EeV ENERGY FRONTIER

Víctor B. Valera Baca
Niels Bohr Institute, University of Copenhagen
vvalera@nbi.ku.dk

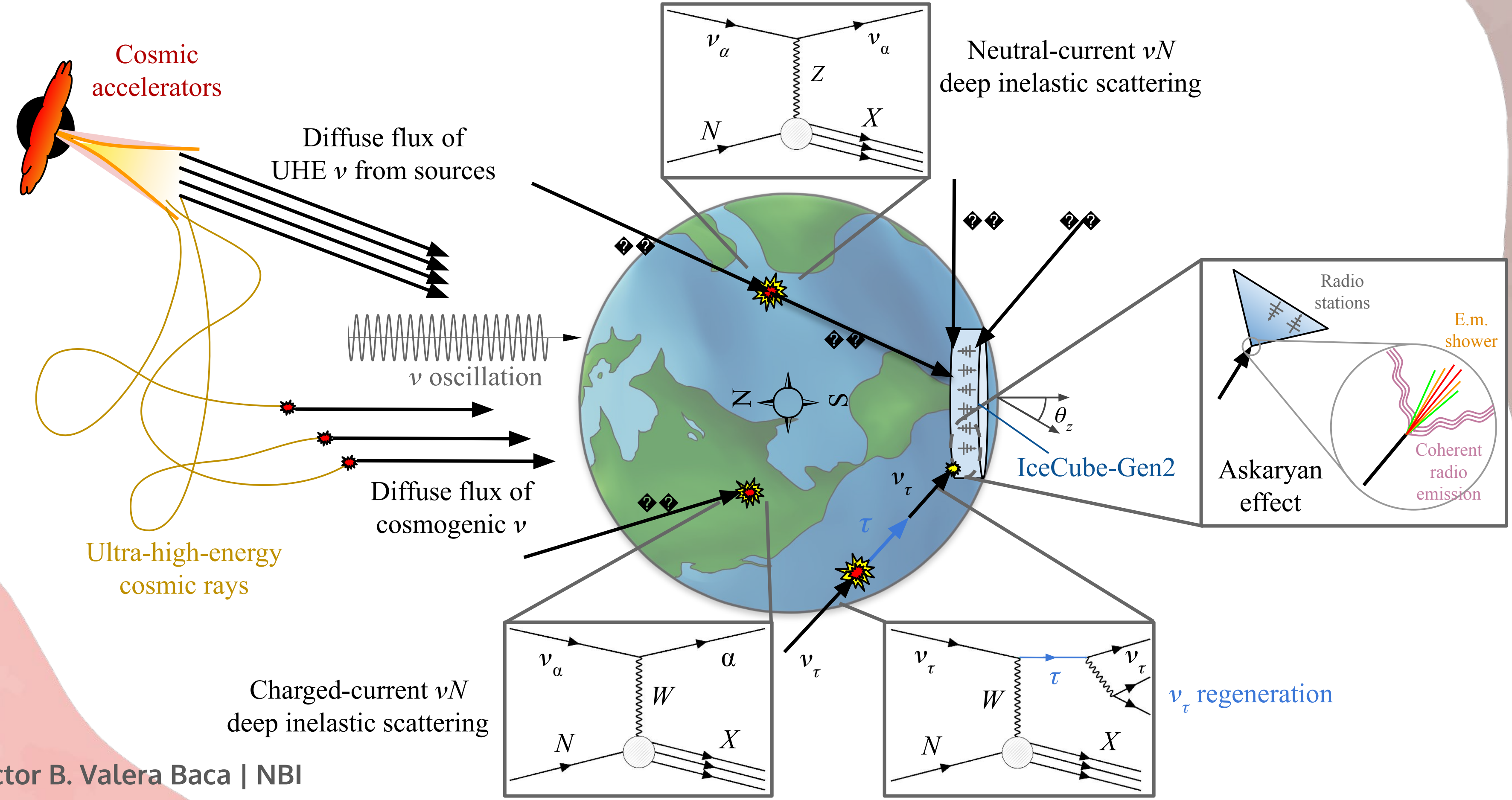
TevPA 2022 - Kingston, ON
August 9th, 2022

UNIVERSITY OF COPENHAGEN

VILLUM FONDEN

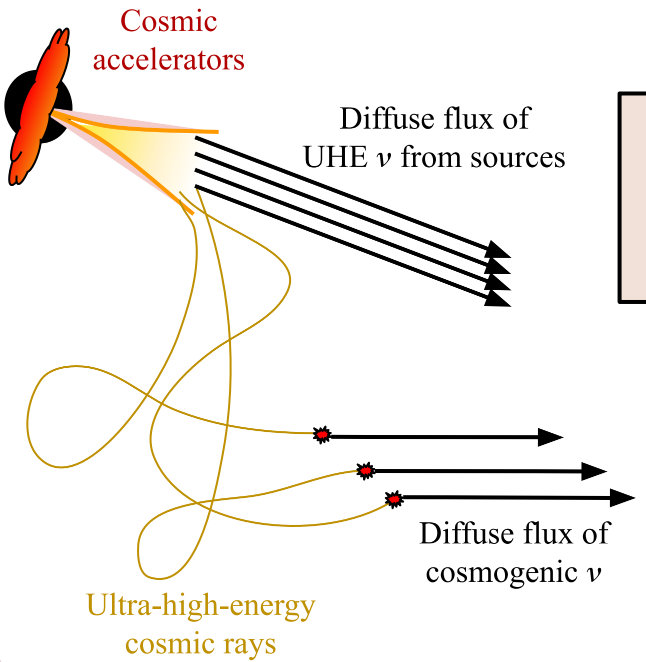
Based on JHEP 06 (2022) 105 [ArXiv:2204.04237]
In collaboration with M. Bustamante and C. Glaser

OVERVIEW



Cosmic accelerators
Diffuse flux of UHE ν from sources
ν oscillation
Diffuse flux of cosmogenic ν
Ultra-high-energy cosmic rays
ν_α
ν_α
Z
N
X
Neutral-current νN deep inelastic scattering
N
S
θ_z
IceCube-Gen2
ν_τ
τ
ν_τ
Radio stations
E.m. shower
Coherent radio emission
Askaryan effect
ν_α
α
W
N
X
Charged-current νN deep inelastic scattering
ν_τ
τ
ν_τ
W
N
X
ν_τ regeneration

IT ALL BEGINS IN COSMIC ACCELERATORS



SOURCE NEUTRINO: PRODUCED IN THE SOURCE ENVIRONMENT

COSMOGENIC NEUTRINOS: PRODUCED EN-ROUTE

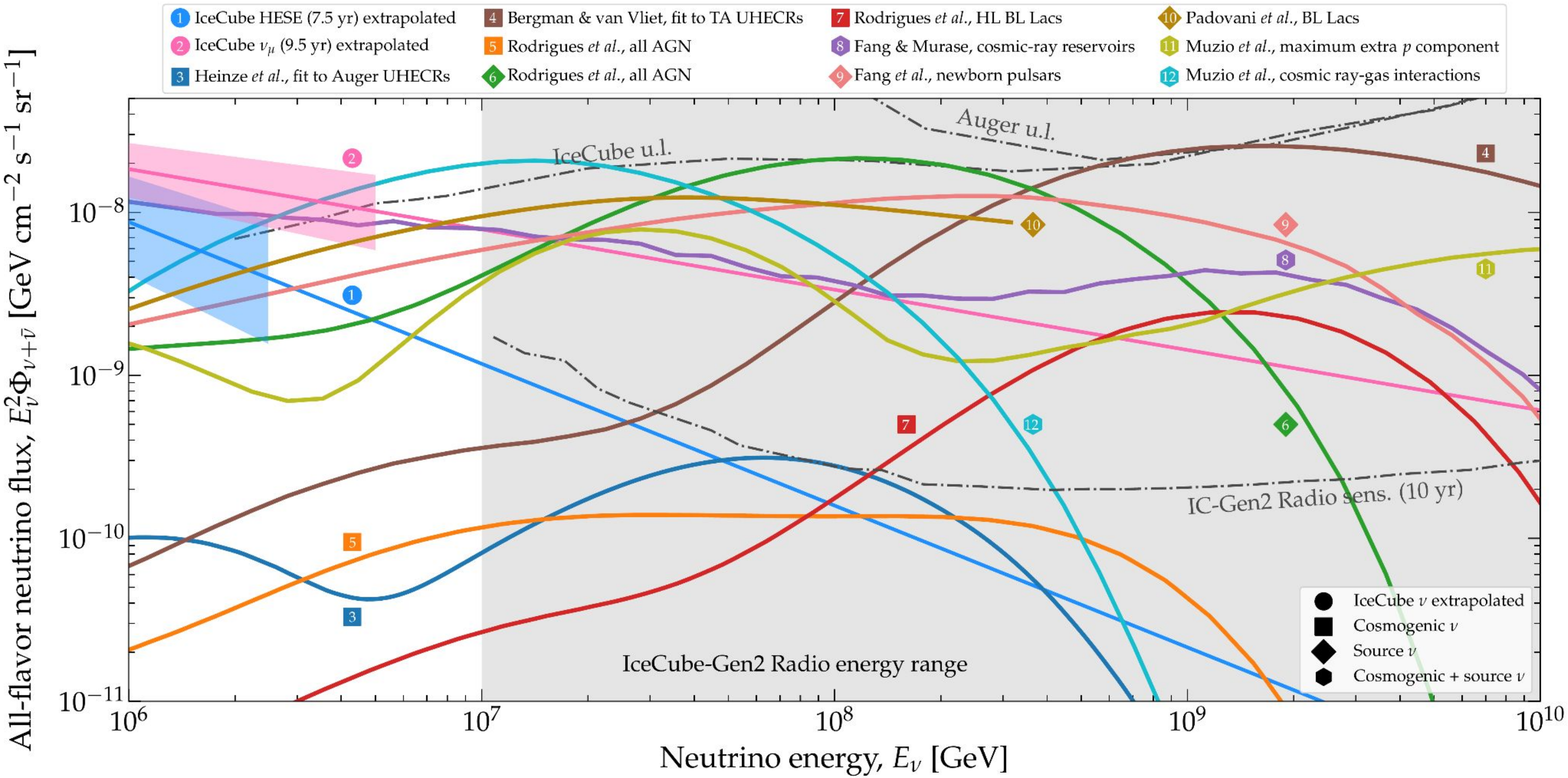
WHAT DO WE KNOW ABOUT THE UHE NEUTRINO FLUX?

Unfortunately… not much

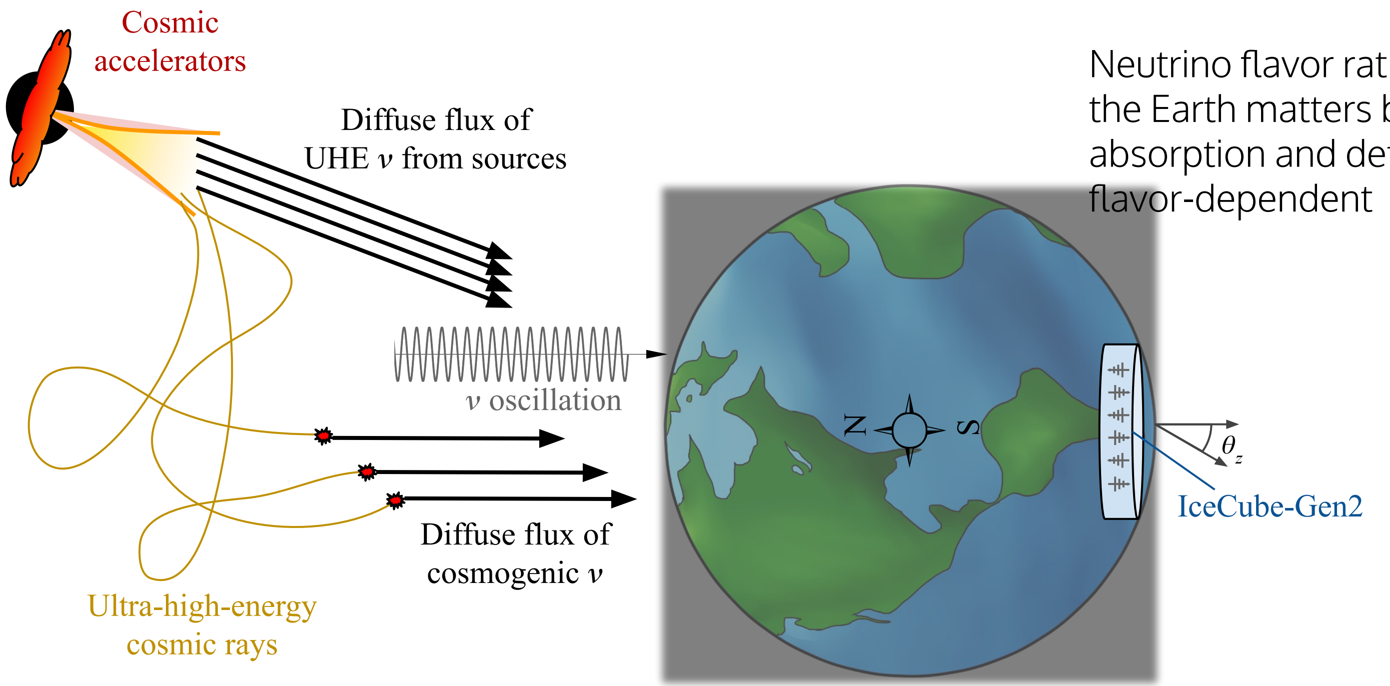
WHAT DO WE KNOW ABOUT THE UHE ν FLUX

- Guaranteed component from UHECRs
- A few experimental upper limits

- Unknown origin (cosmogenic or source?)
- Unknown source properties and production mechanism
- BSM during propagation??

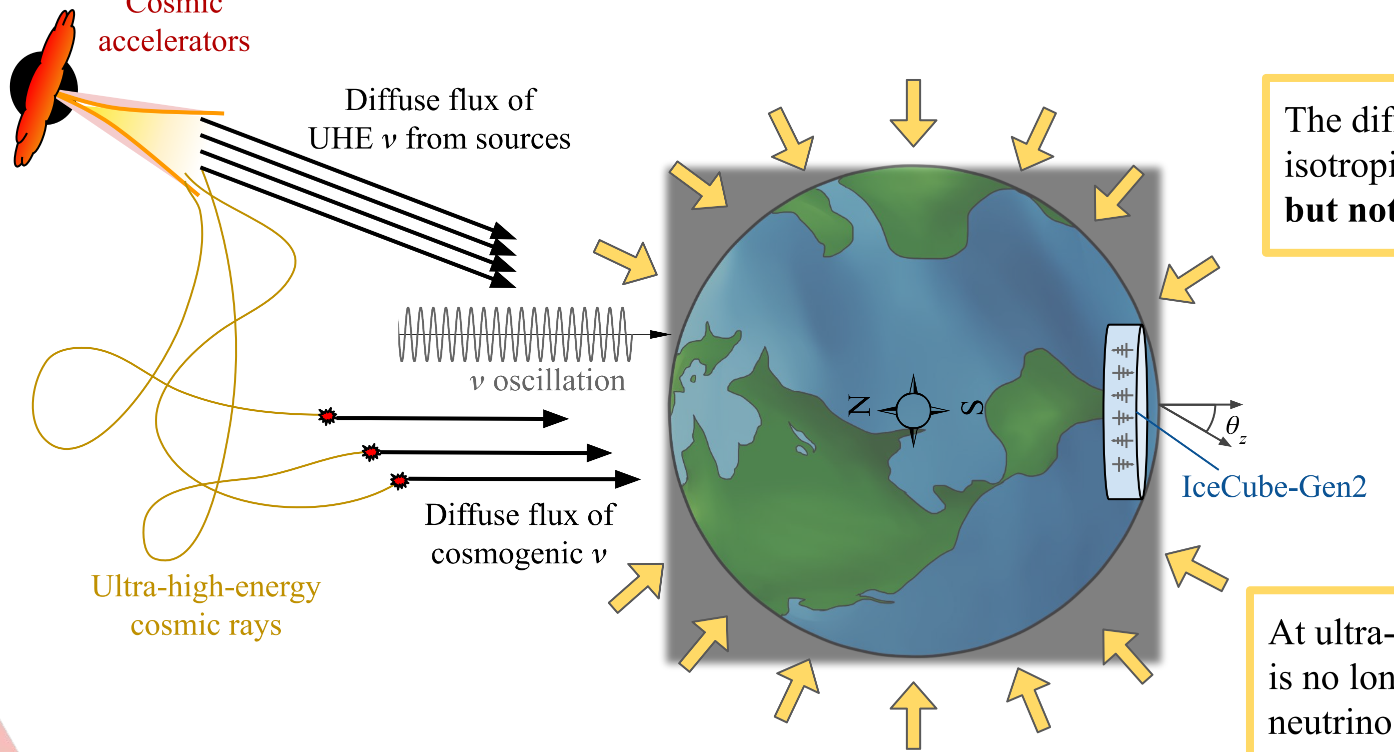


UHE NEUTRINOS REACH THE SURFACE OF THE EARTH



Neutrino flavor ratios at the surface of the Earth matters because both Earth absorption and detector response are flavor-dependent

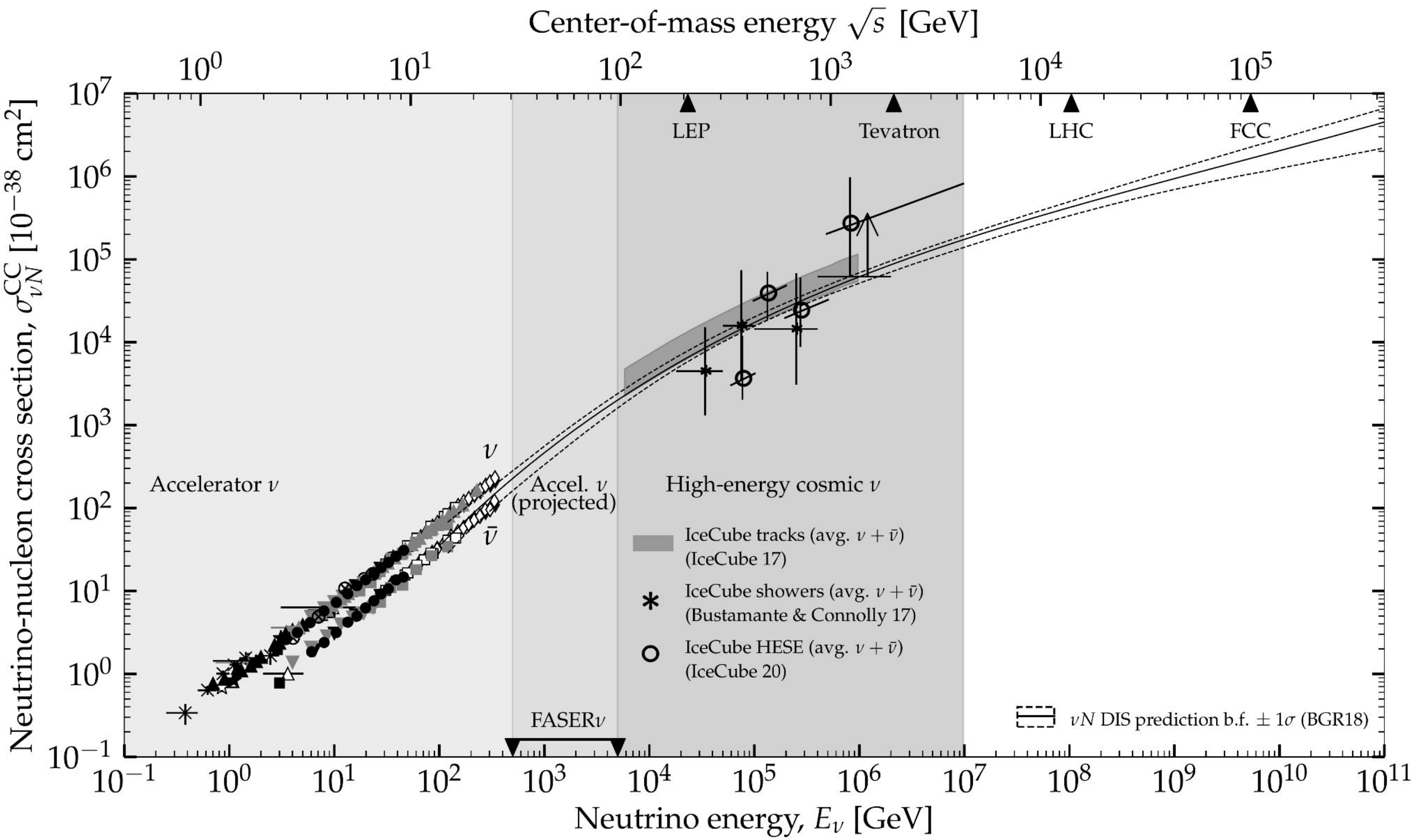
UHE NEUTRINOS REACH THE SURFACE OF THE EARTH



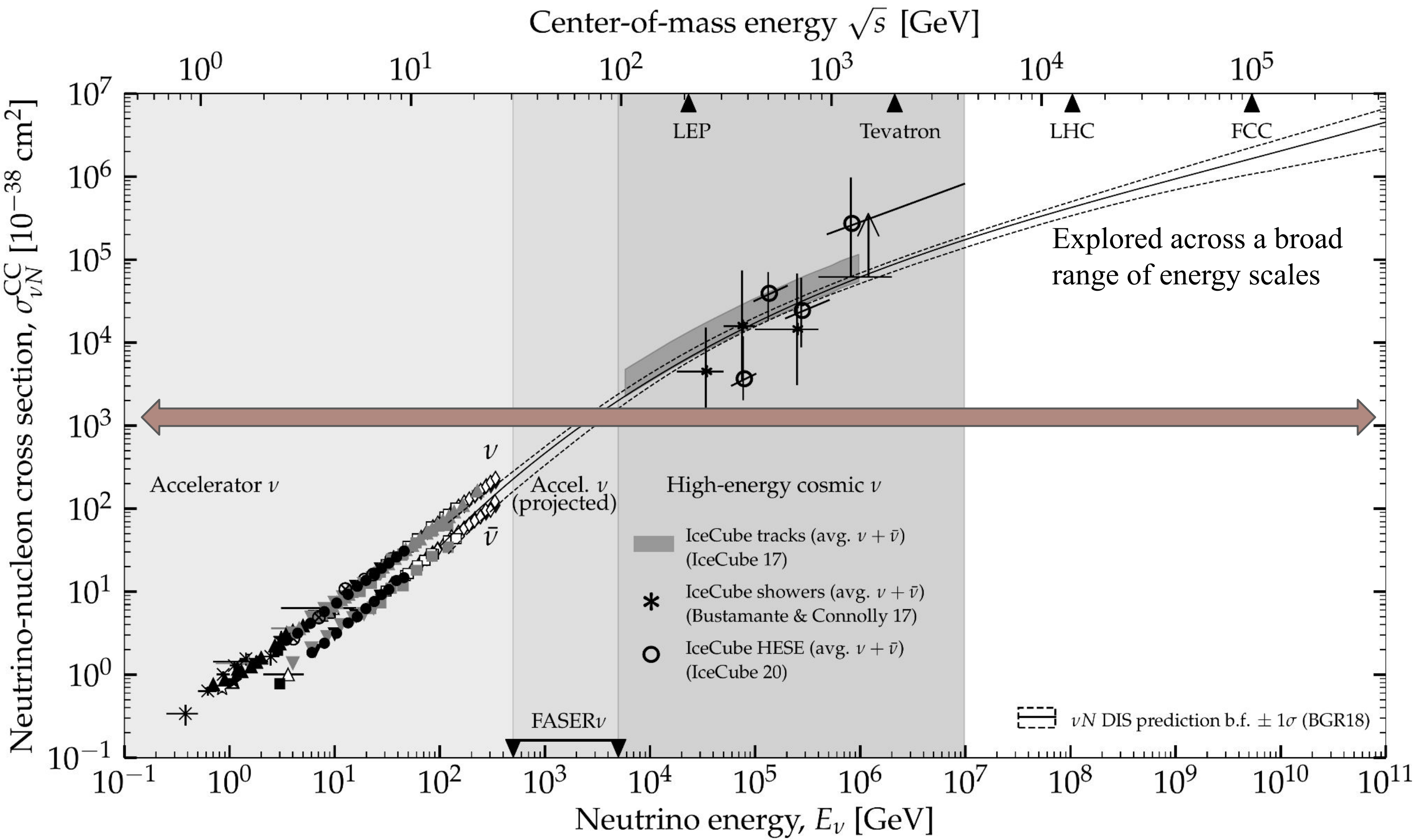
The diffuse neutrino flux is isotropic at surface of the Earth **but not** at the detector

At ultra-high energies the Earth is no longer transparent to neutrinos

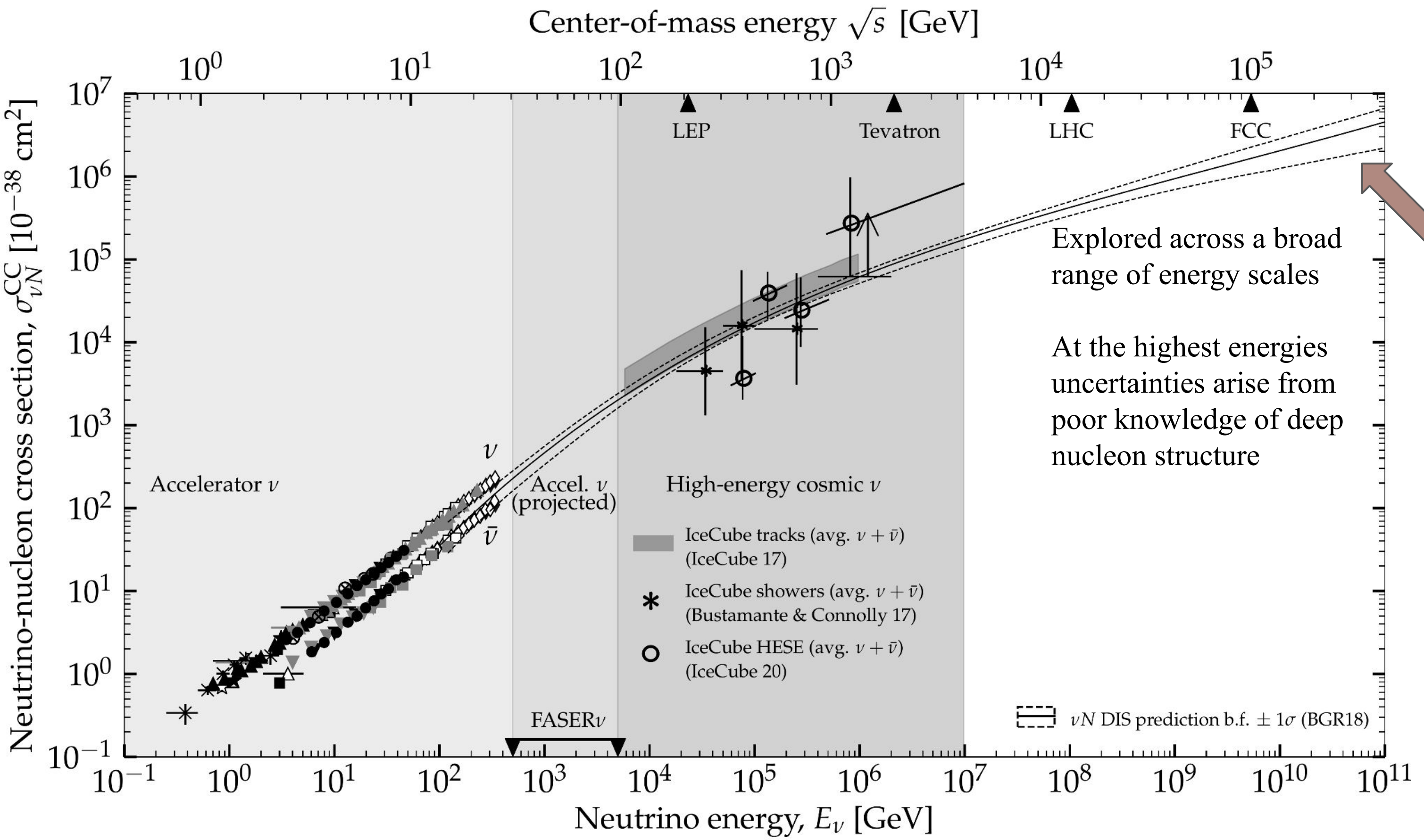
NEUTRINO-MATTER INTERACTIONS GET A LOT OF ATTENTION



NEUTRINO-MATTER INTERACTIONS GET A LOT OF ATTENTION



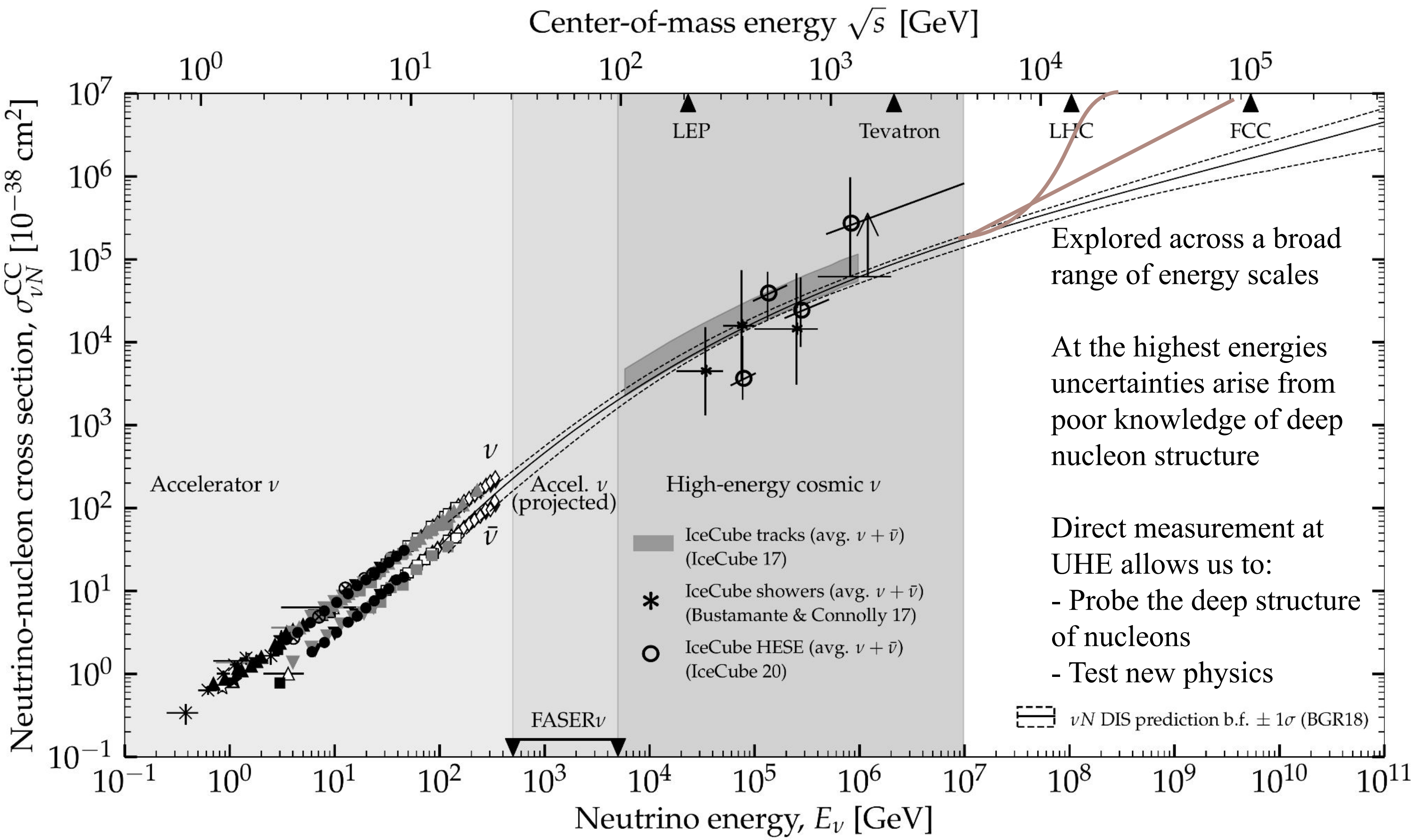
NEUTRINO-MATTER INTERACTIONS GET A LOT OF ATTENTION



Explored across a broad range of energy scales

At the highest energies uncertainties arise from poor knowledge of deep nucleon structure

NEUTRINO-MATTER INTERACTIONS GET A LOT OF ATTENTION

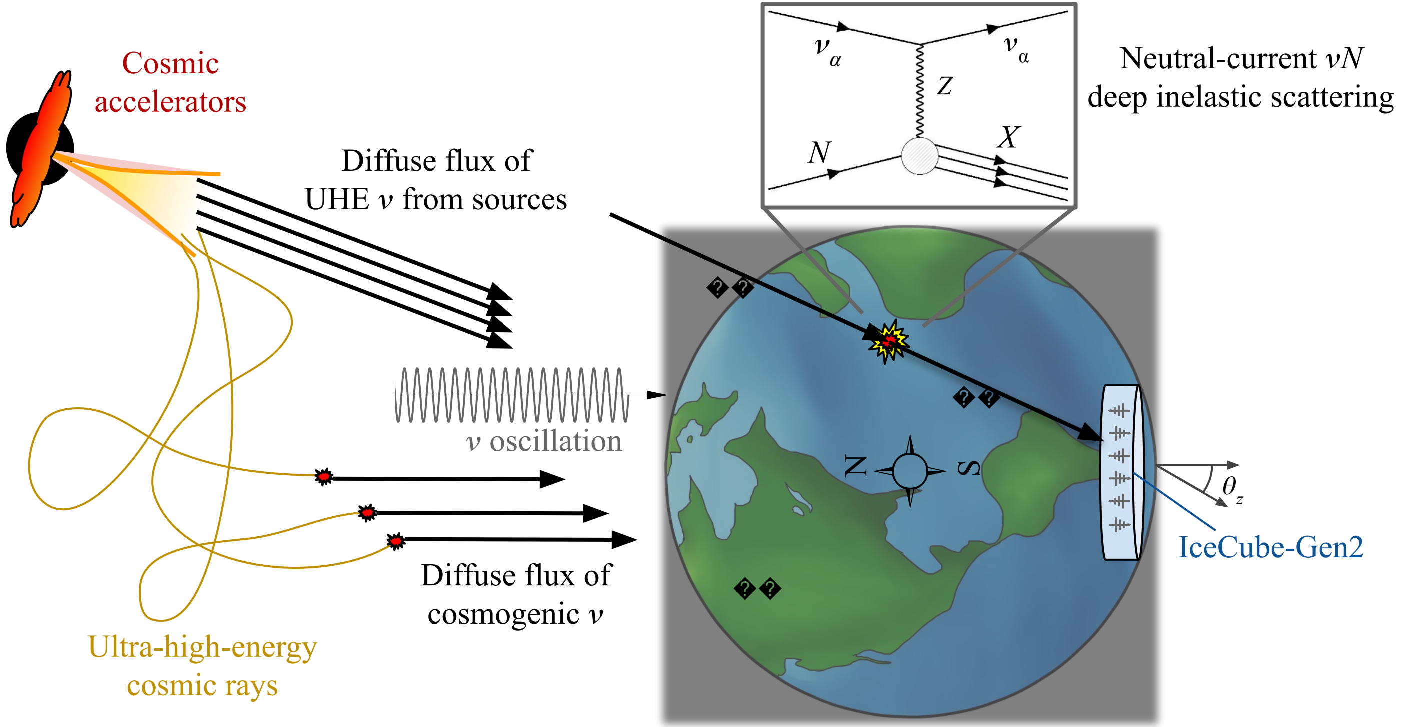


Explored across a broad range of energy scales

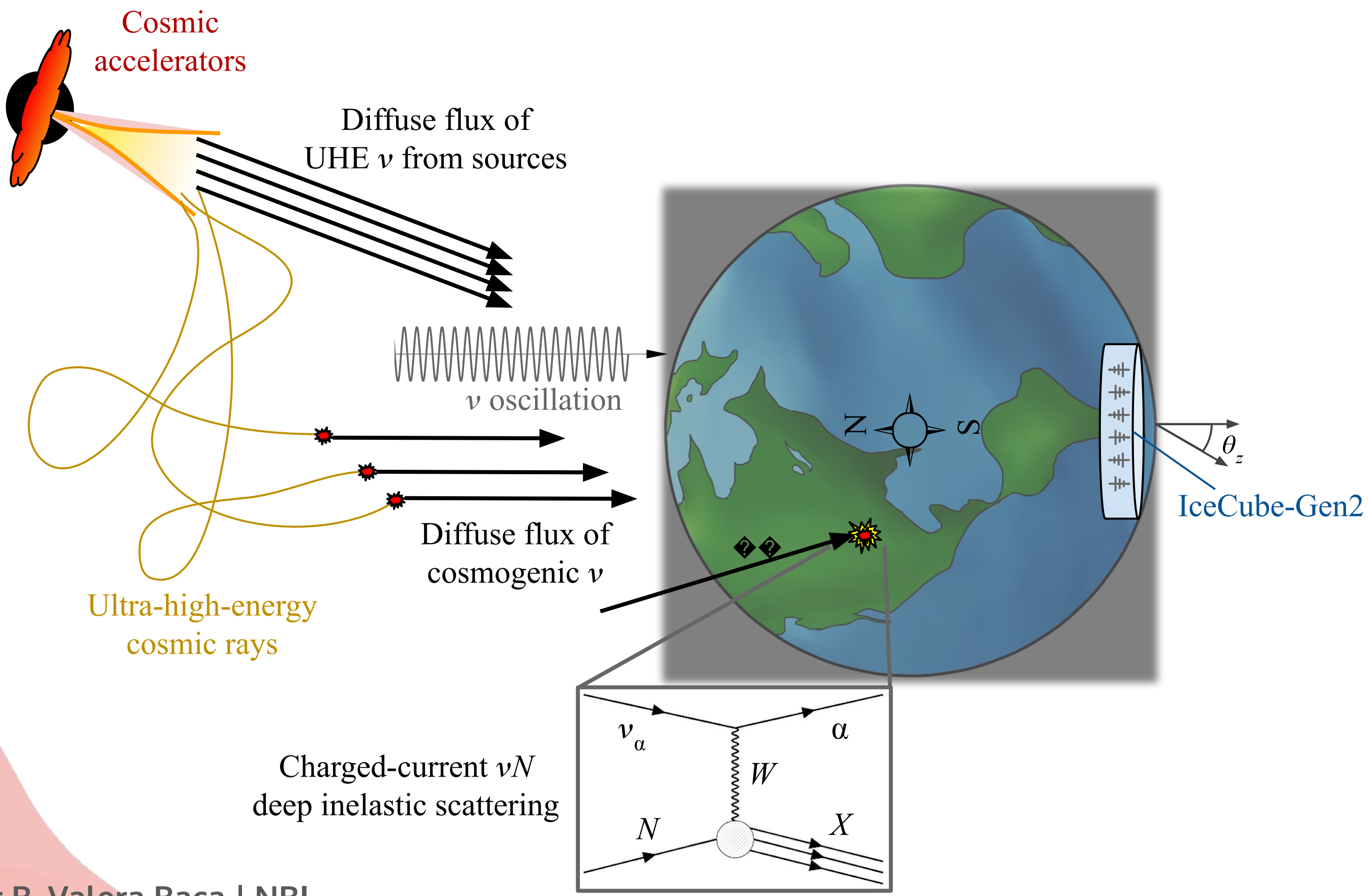
At the highest energies uncertainties arise from poor knowledge of deep nucleon structure

Direct measurement at UHE allows us to:
- Probe the deep structure of nucleons
- Test new physics

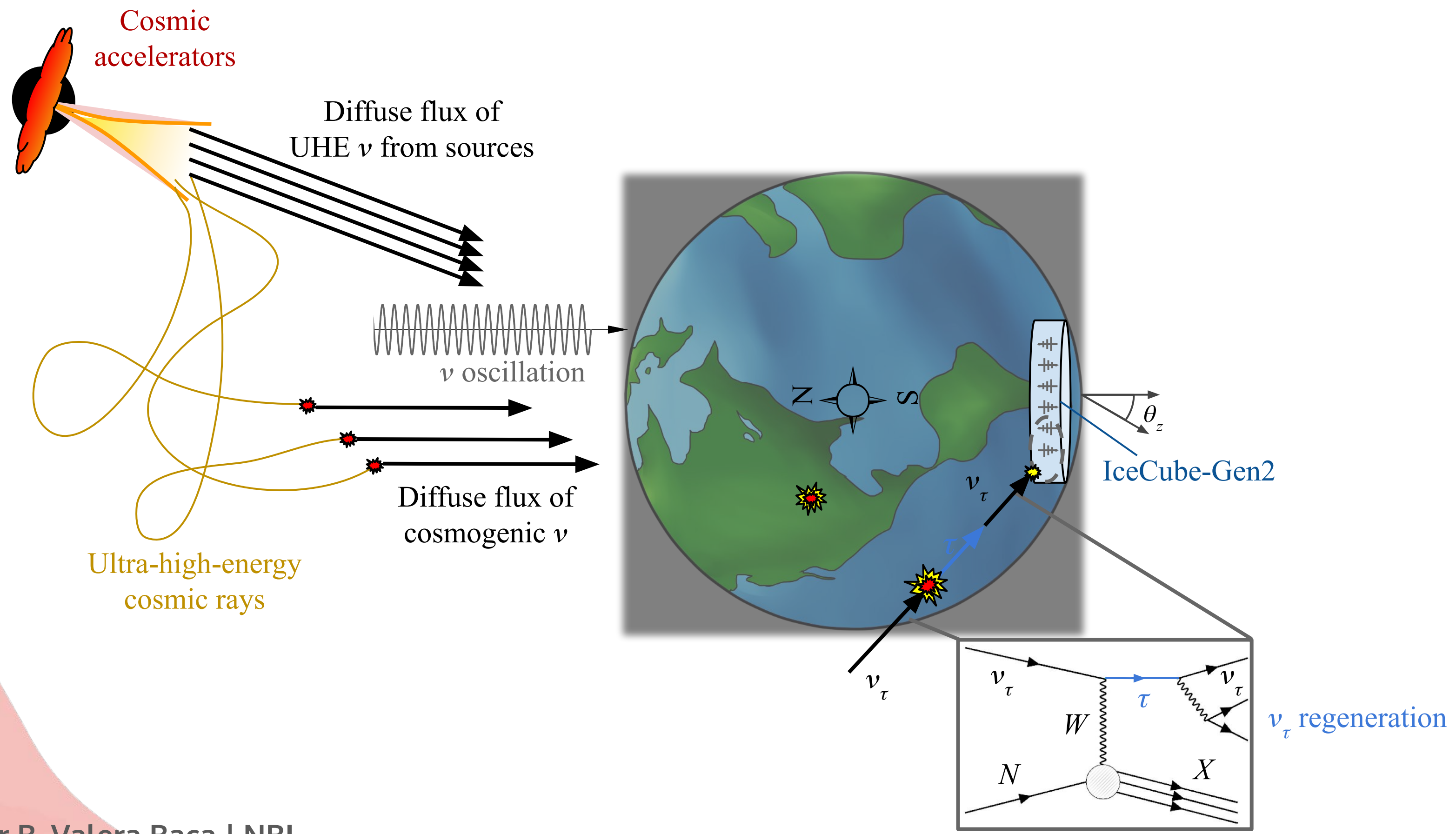
NEUTRAL CURRENT DIS: ENERGY DAMPING



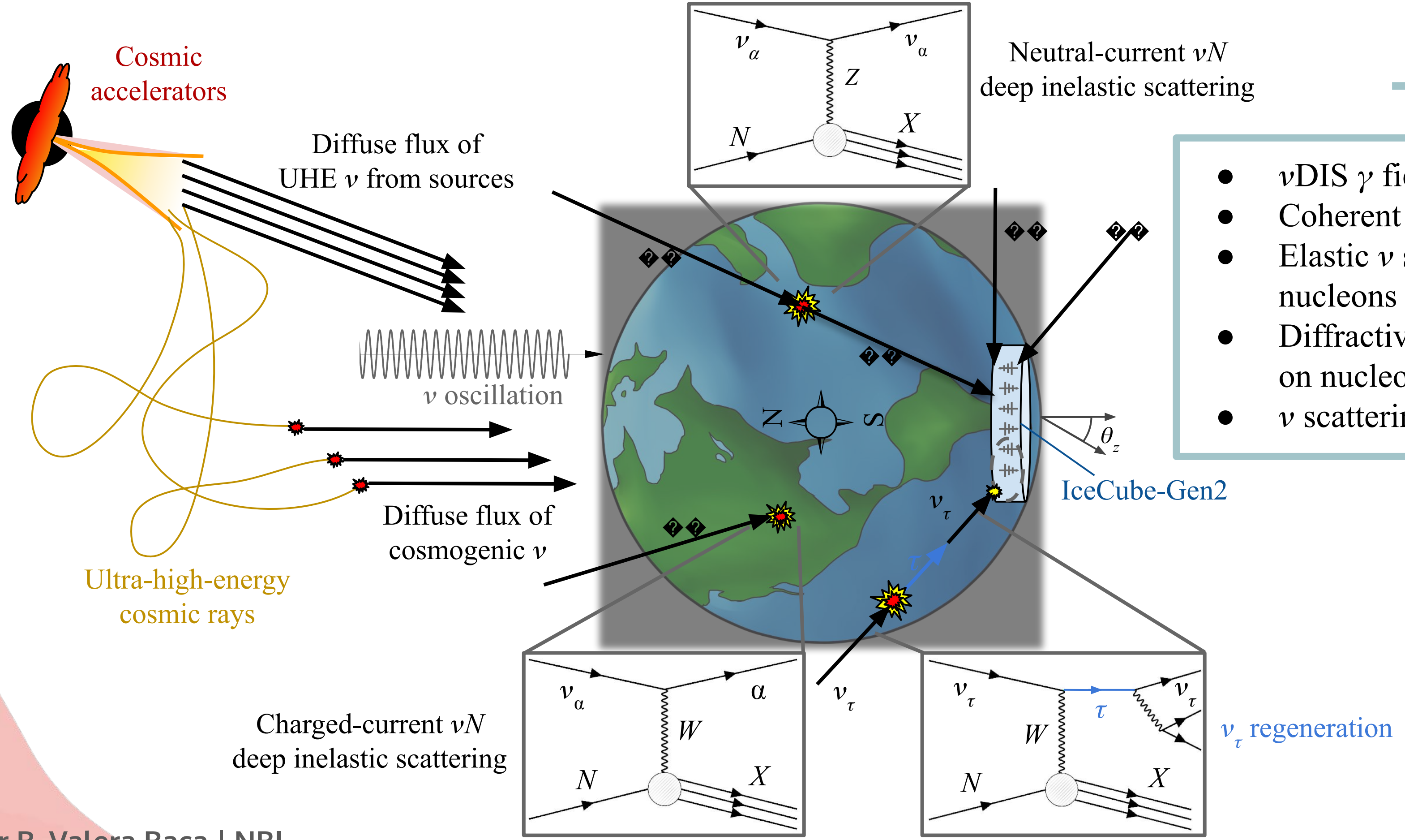
NON-ν_τ CHARGED CURRENT DIS: NEUTRINO DISAPPEARANCE



ν_τ CHARGED CURRENT DIS: ν_τ REGENERATION



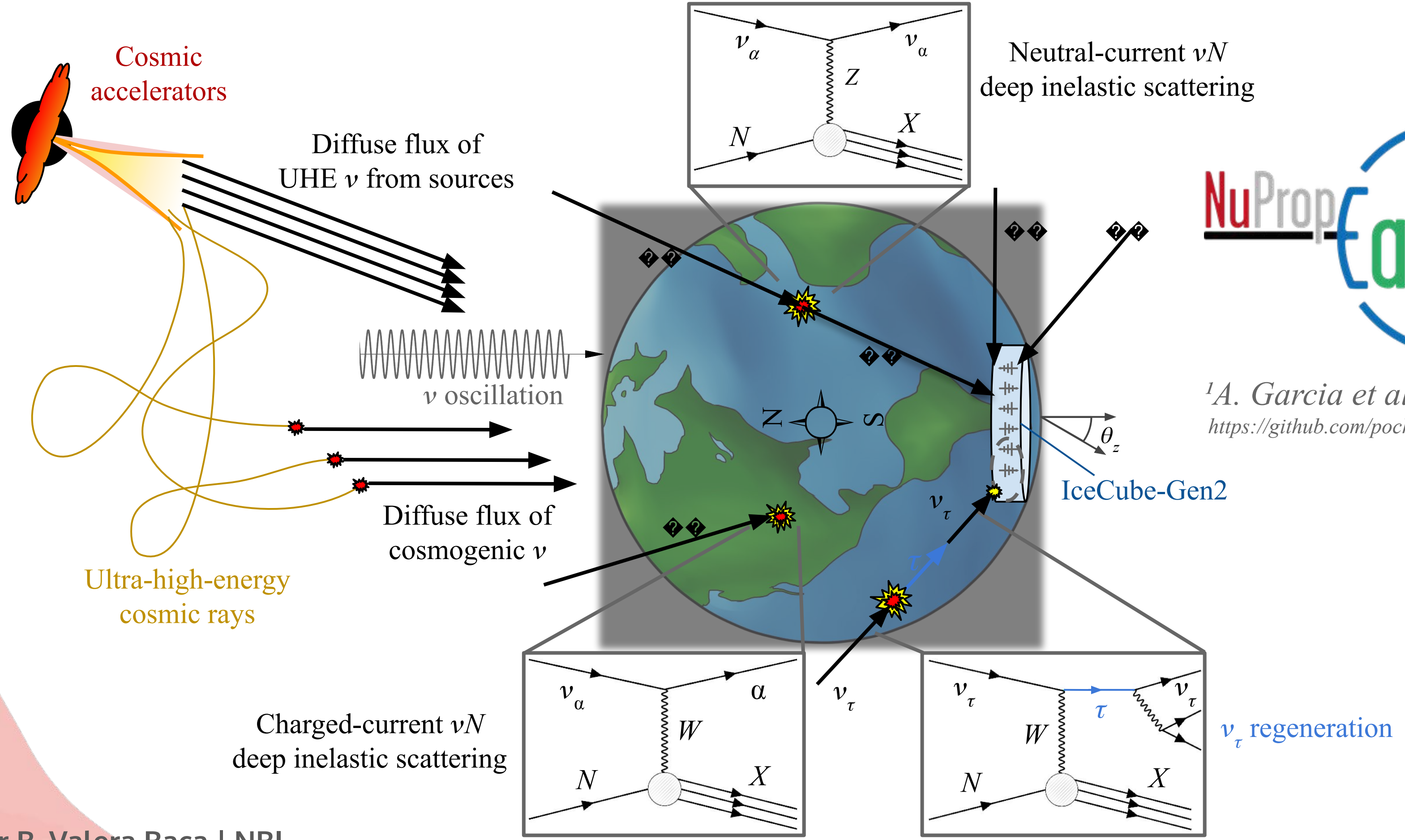
WE ALSO ACCOUNT FOR NEXT-TO-LEADING ORDER INTERACTIONS



+

- νDIS γ field of nucleon
- Coherent νN scattering
- Elastic ν scattering on nucleons
- Diffractive ν scattering on nucleons
- ν scattering on atomic e

WE ALSO ACCOUNT FOR NEXT-TO-LEADING ORDER INTERACTIONS



[1]A. Garcia et al. JCAP 2020

https://github.com/pochoarus/NuPropEarth

A SIMPLIFIED EXPRESSION FOR DIDACTICAL PURPOSES

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

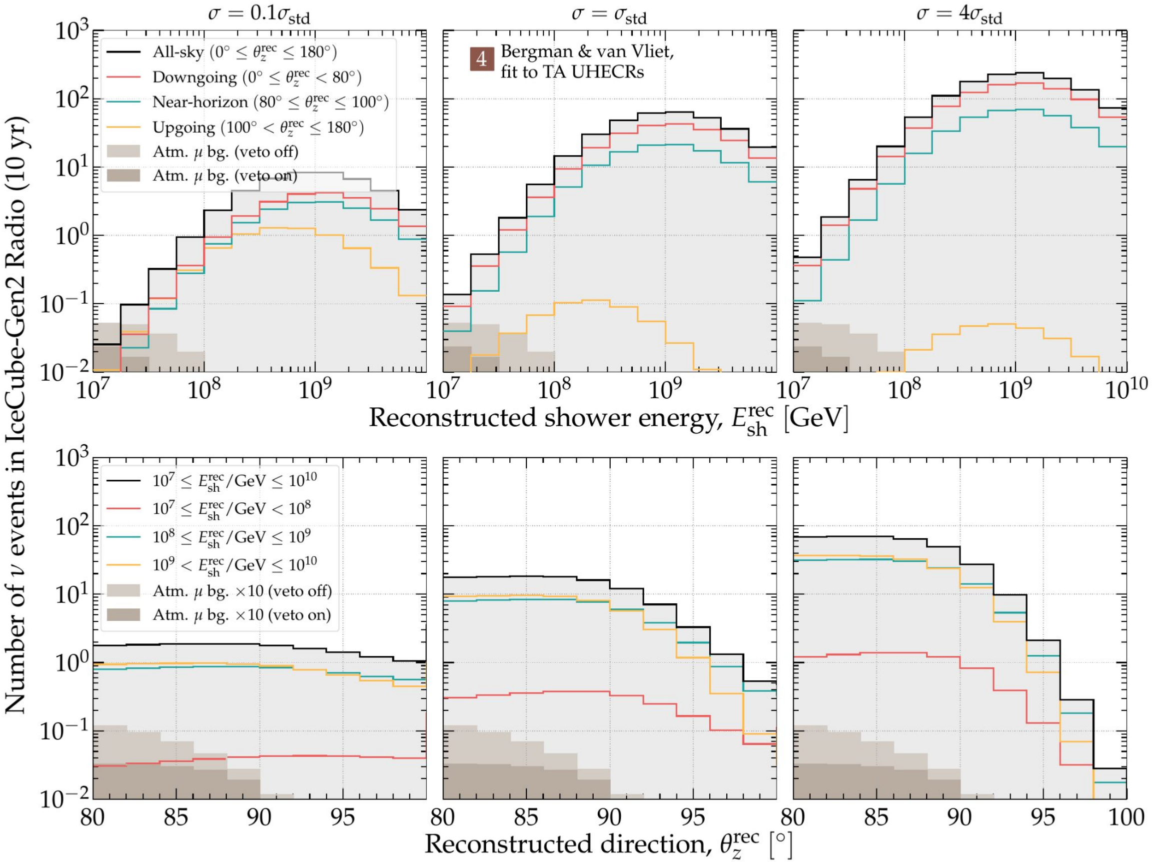
Increases the probability of a neutrino detection

Decreases probability of a neutrino transmission

Goldilocks situations:

- Downgoing neutrinos: Negligible attenuation, degeneracy between cross section and flux
- Upgoing neutrinos: Strong attenuation, unlikely for most of the flux models to reach the detector
- Horizontal: Just right to break the degeneracy 👌

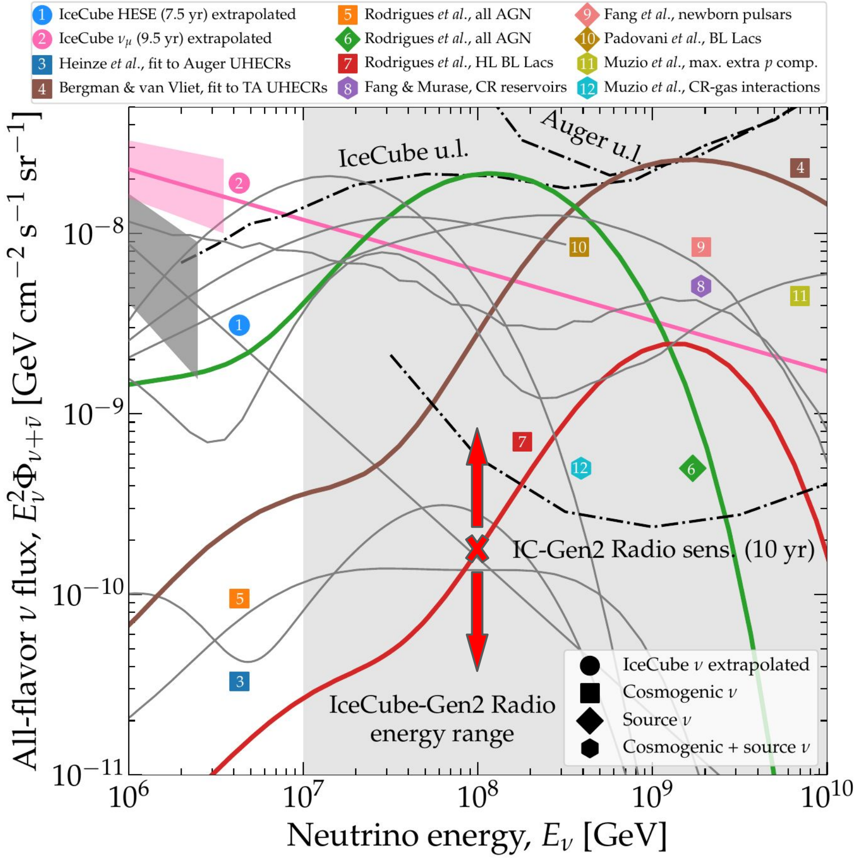
NEUTRINO EVENT RATE AS A FUNCTION OF OBSERVABLE VARIABLES



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

- Small σ flattens the θ distribution
- Large σ leads to a more pronounced cut at the horizon
- Atm. μ background mainly in the lowest energy bin
- Energy binning matters

THE PARAMETERS OF THE MODEL

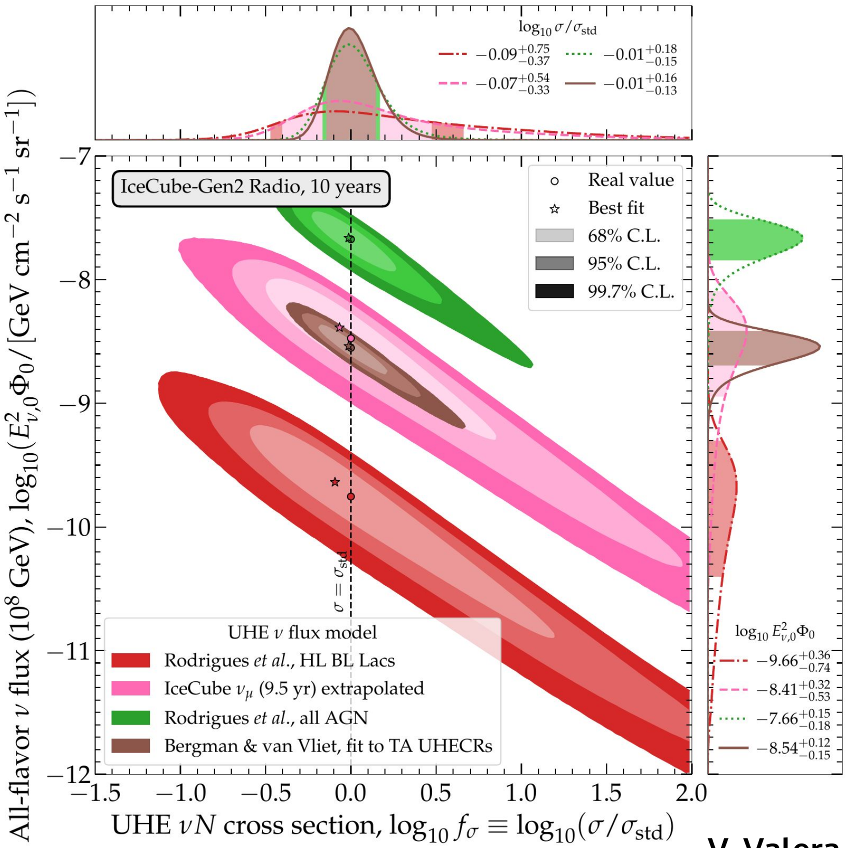


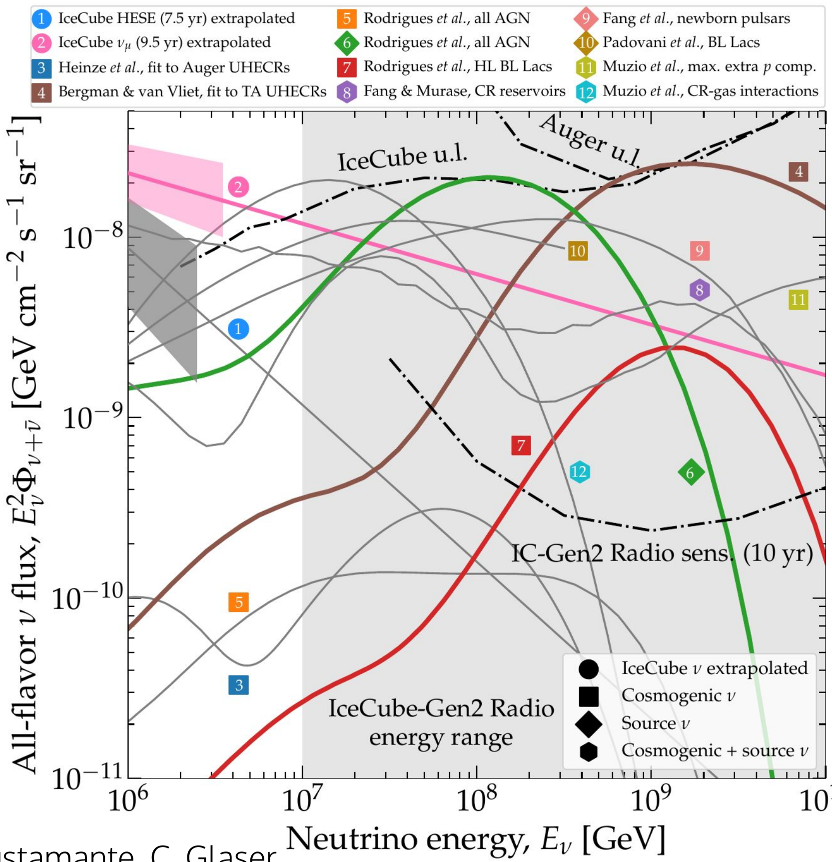
$$f_\sigma \equiv \frac{\sigma}{\sigma_{std}}, \quad f_\Phi \equiv \frac{\Phi_0}{\Phi_{0,\ std}}$$

- The parameters of the model are $\boldsymbol{\theta} = (f_\sigma, f_\Phi)$
- f_σ : energy-independent deviations from the BGR cross section central value
- f_Φ : energy-independent deviations of the flux normalization relative to the nominal flux at 1e8 GeV
- Flat priors in log-scale

$$\mathcal{L}_{ij}(\boldsymbol{\theta}) = \frac{\bar{N}_{\mathrm{test},ij}(\boldsymbol{\theta})^{N_{\mathrm{obs},ij}} e^{-\bar{N}_{\mathrm{test},ij}(\boldsymbol{\theta})}}{N_{\mathrm{obs},ij}!}$$

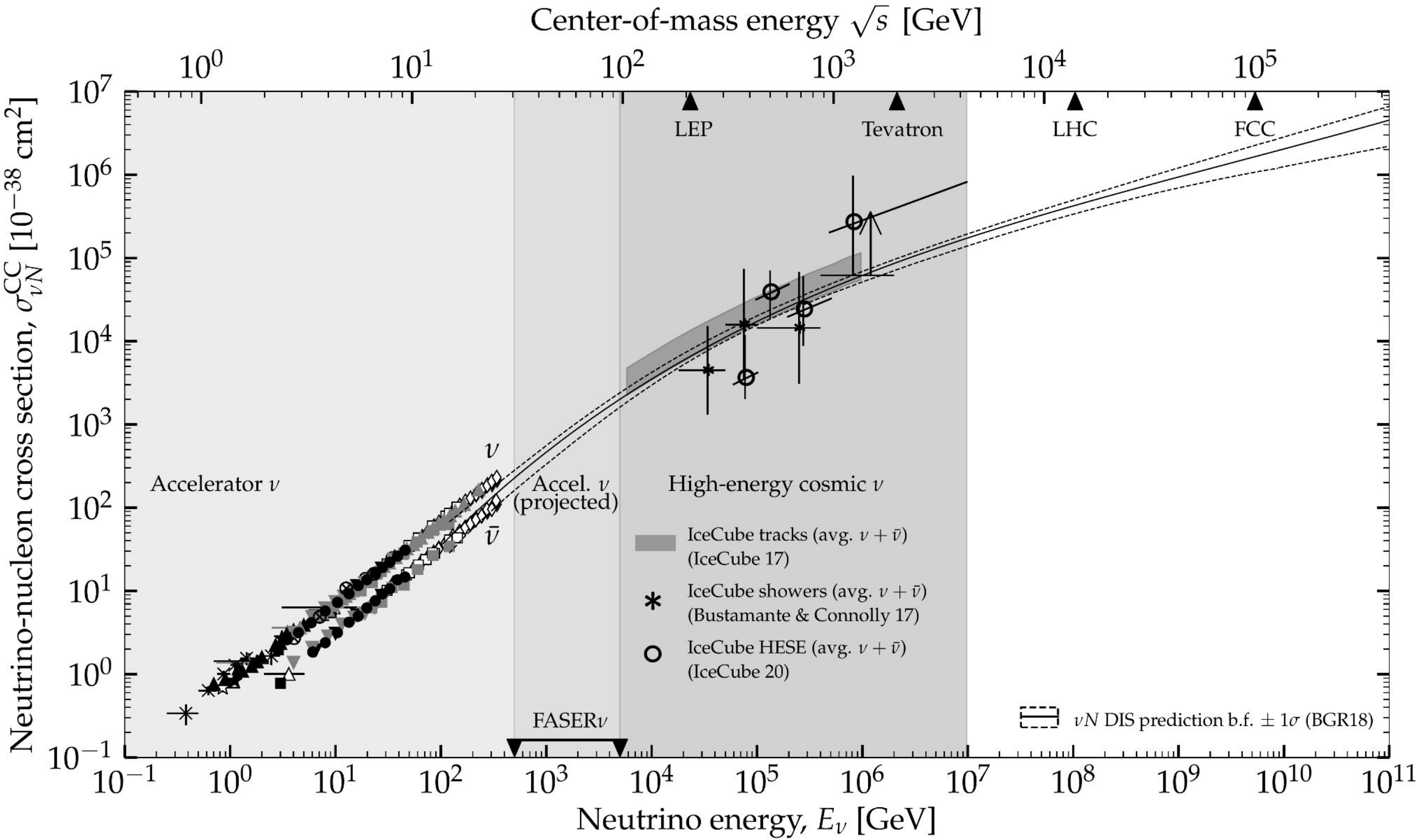
BASELINE RESULTS FOR BENCHMARK FLUXES



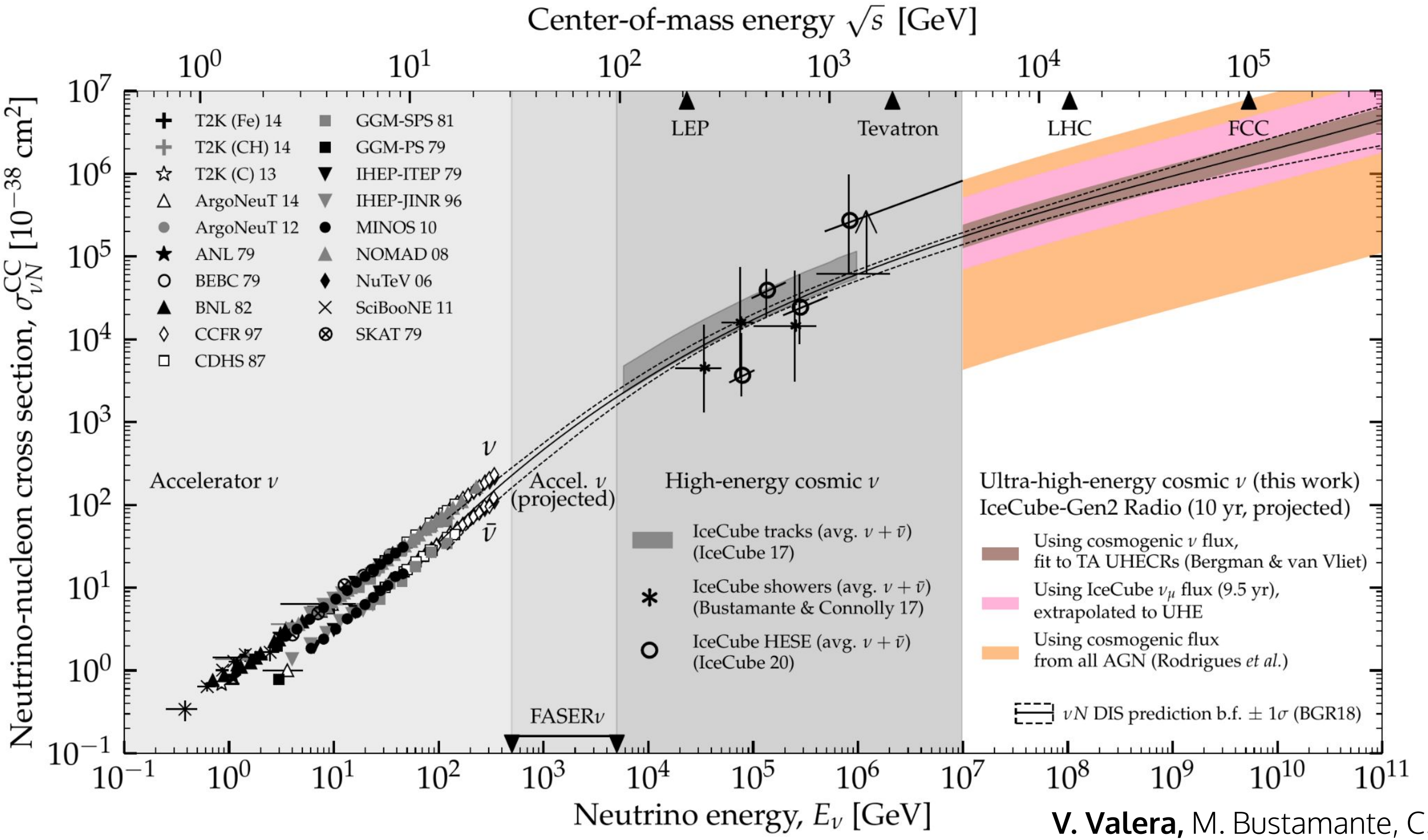


V. Valera, M. Bustamante, C. Glaser
ArXiv:2204.04237

OUR RESULTS IN THE CONTEXT OF ν-MATTER INVESTIGATIONS



OUR RESULTS IN THE CONTEXT OF ν-MATTER INVESTIGATIONS



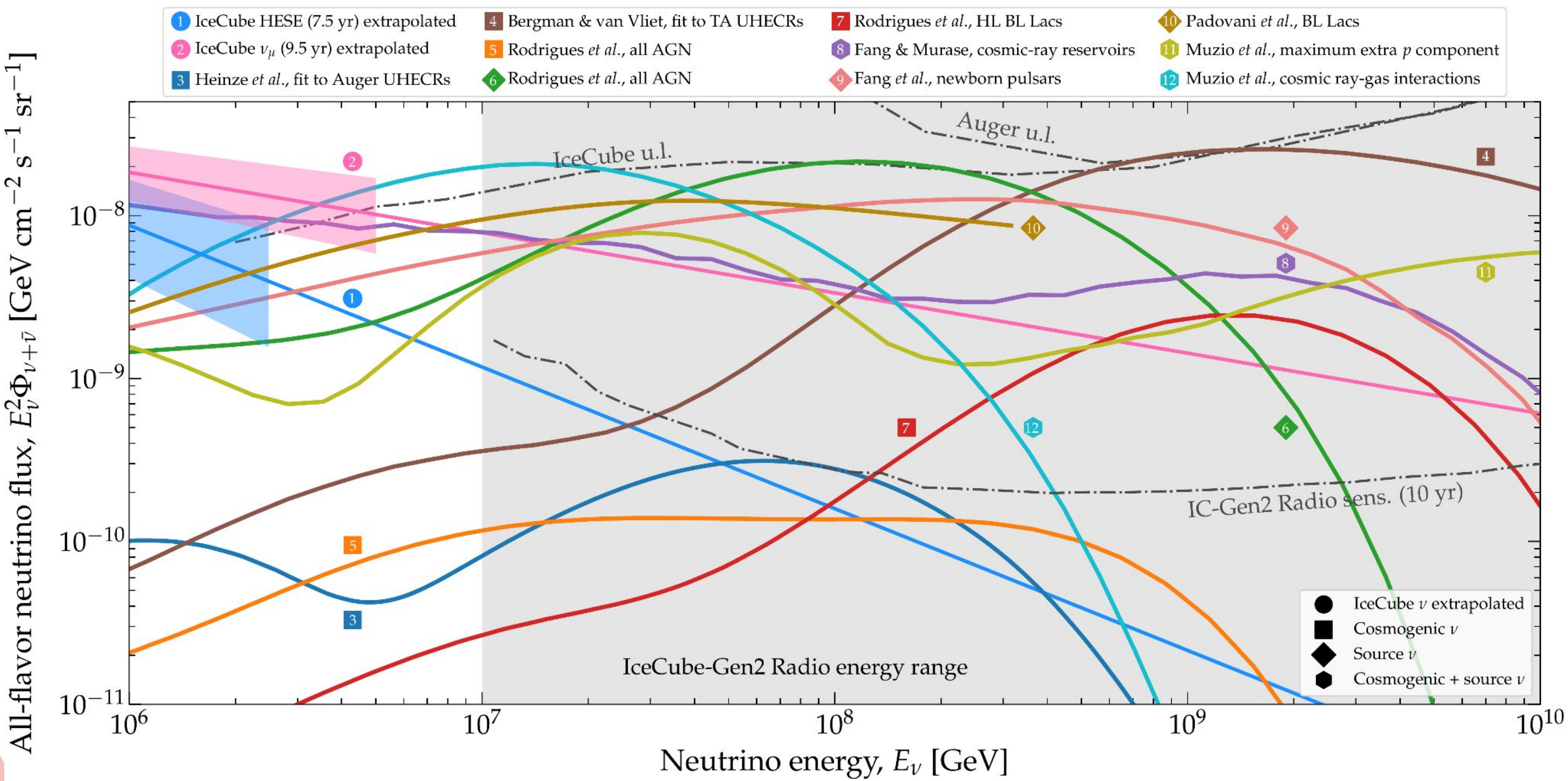
V. Valera, M. Bustamante, C. Glaser
ArXiv:2204.04237

Good! Cross section measurements are possible with a few tens of events.

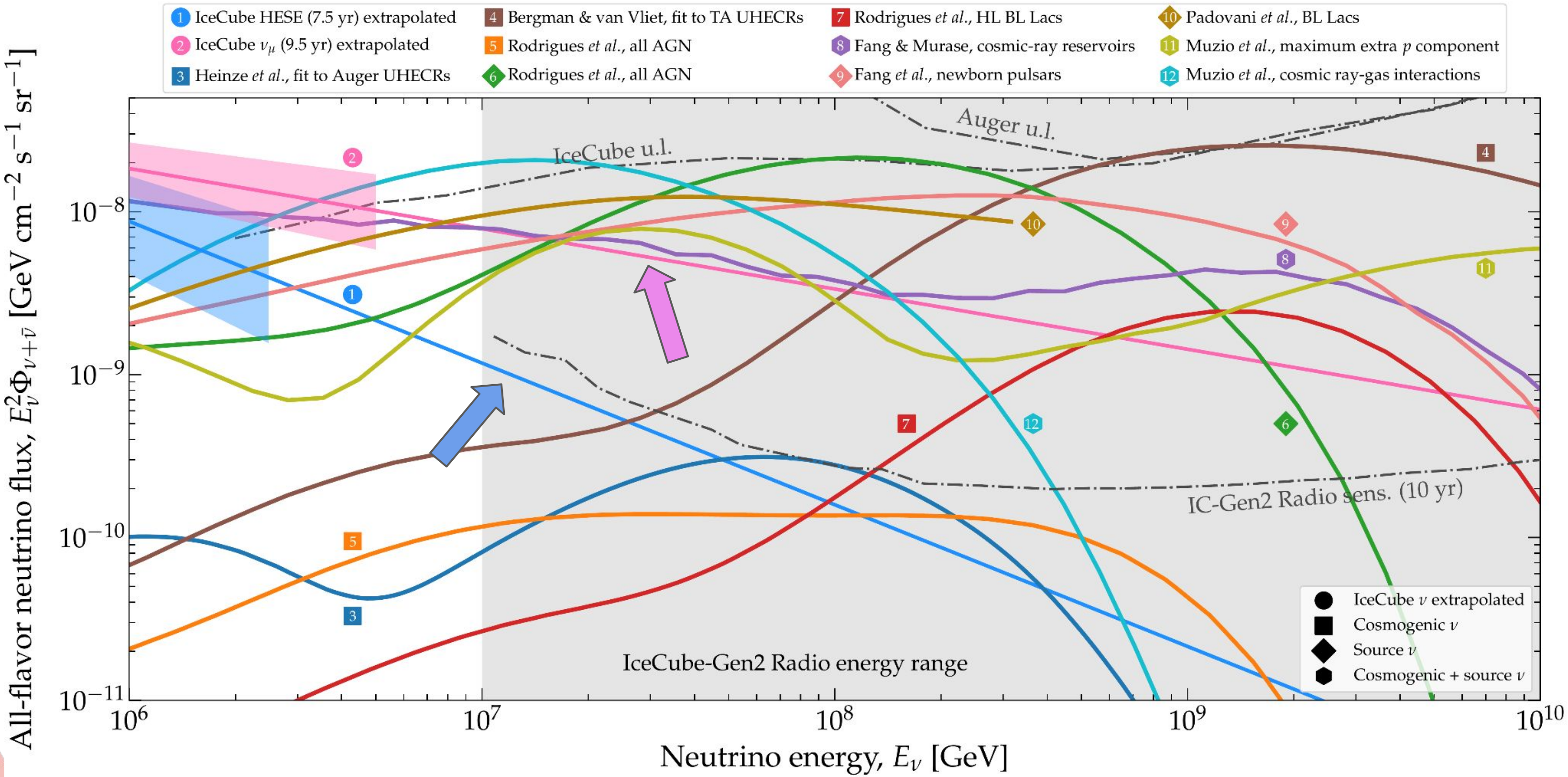
But that is assuming we know the spectral shape of the UHE neutrino flux.

If we relax that?

WE NEED TO DISTINGUISH ~~AND RECONSTRUCT~~ THE TRUE UHE FLUX



THE IceCube FLUX WOULD BE A SOURCE OF BACKGROUND



HYPOTHESIS A: THE BACKGROUND HYPOTHESIS

The observed signal is produced by

- Atmospheric muon +
- Neutrinos from the UHE tail of one of the IceCube flux parametrizations with and exponential cutoff somewhere > 10^7 GeV

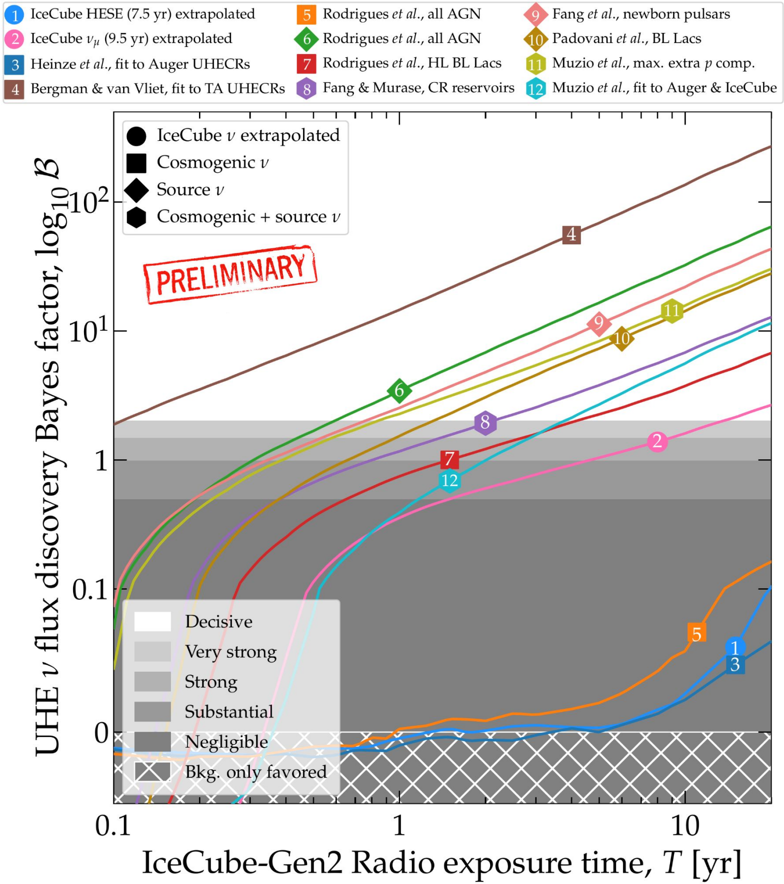
HYPOTHESIS B: THE SIGNAL HYPOTHESIS

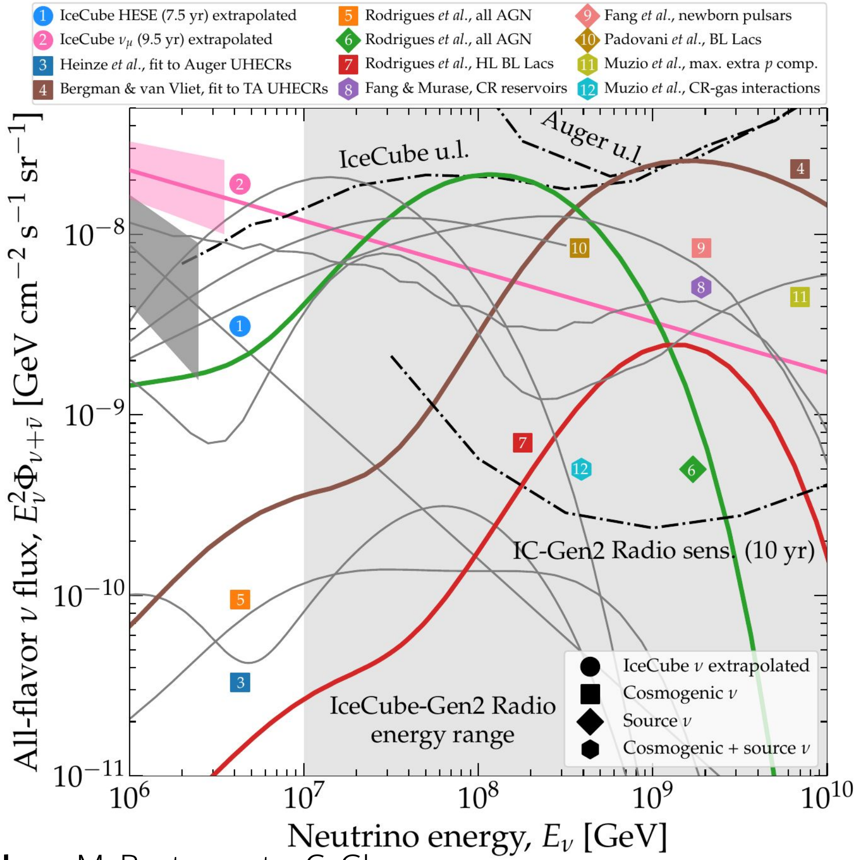
The observed signal is produced by

- Atmospheric muon +
- Neutrinos from the UHE tail of one of the IceCube flux parametrizations with and exponential cutoff somewhere > 10^7 GeV +
- **Neutrinos from a given UHE flux model**

WE OBTAIN THE BAYESIAN EVIDENCES $\mathcal{Z}_A$ AND $\mathcal{Z}_B$ INTEGRATING THE LIKELIHOOD OVER THE PARAMETER SPACE AND FROM THERE THE BAYES FACTOR $\mathcal{B} = \mathcal{Z}_B/\mathcal{Z}_A$

MOST OF THESE SCENARIOS WOULD BE DISCOVERED IN ONE DECADE





V. Valera, M. Bustamante, C. Glaser
(In preparation)

OK COOL, BUT OUR ORIGINAL GOAL WAS TO DISTINGUISH AMONG FLUX MODELS

WE SIMPLY CHANGE THE QUESTION

The following results correspond to a work in progress.

HYPOTHESIS A: UHE FLUX MODEL A HYPOTHESIS

The observed signal is produced by

- Atmospheric muon +
- Neutrinos from the UHE tail of one of the IceCube flux parametrizations with and exponential cutoff somewhere > 10^7 GeV
- **Neutrinos from UHE flux model A**

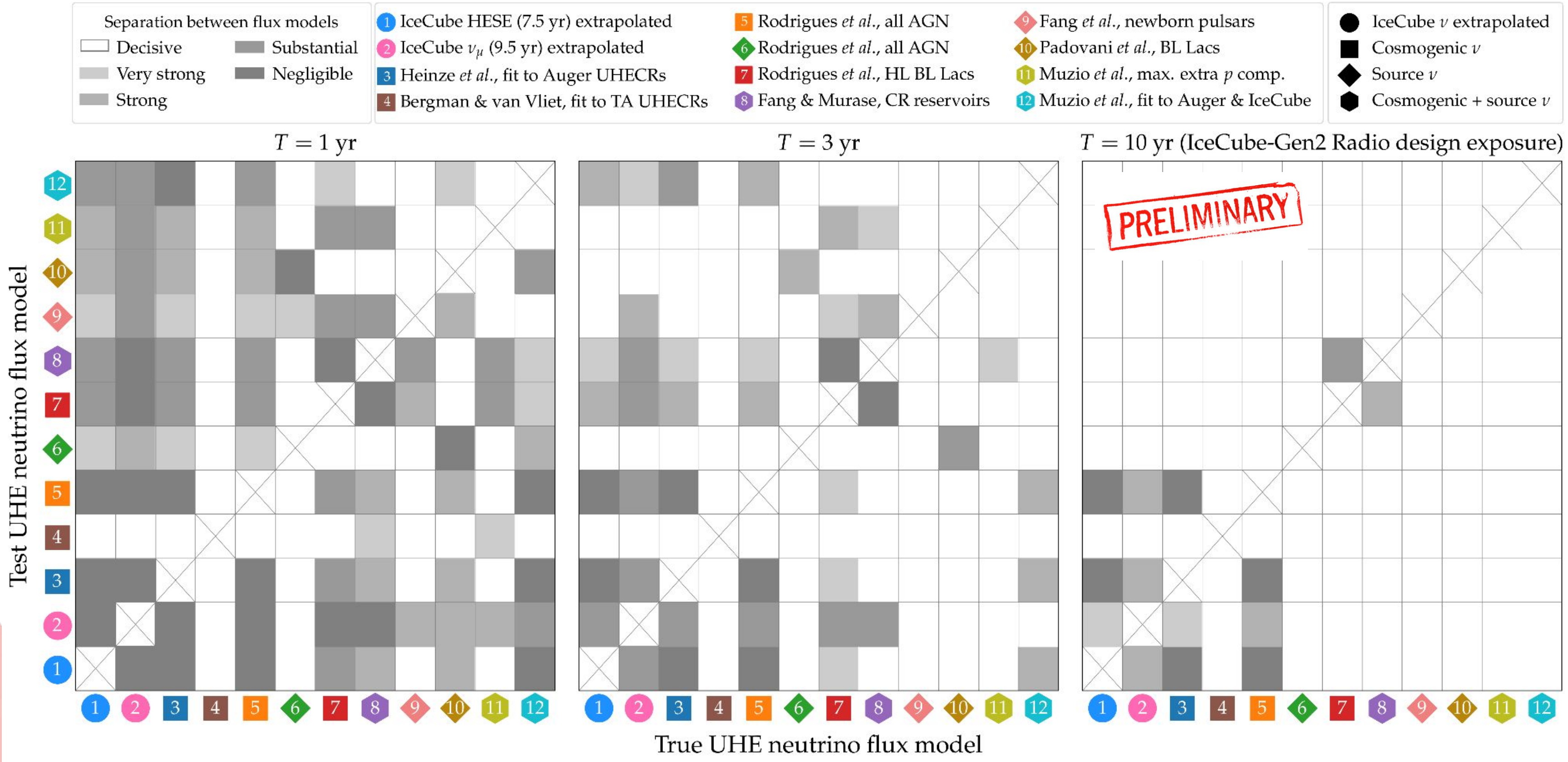
HYPOTHESIS B: UHE FLUX MODEL B HYPOTHESIS

The observed signal is produced by

- Atmospheric muon +
- Neutrinos from the UHE tail of one of the IceCube flux parametrizations with and exponential cutoff somewhere > 10^7 GeV +
- **Neutrinos from UHE flux model B**

AND AGAIN OBTAIN THE BAYES FACTOR $\mathcal{B} = \mathcal{Z}_A / \mathcal{Z}_B$

WE QUANTIFY THE CAPABILITY TO DISTINGUISH DIFFERENT SPECTRAL SHAPES



V. Valera, M. Bustamante, C. Glaser
(In preparation)

SO MOST OF THE FLUXES CAN BE DISTINGUISHED FROM BACKGROUND SOURCES WITHIN A DECADE

AND THOSE CAN ALSO BE DISTINGUISHED FROM ALTERNATIVE UHE FLUX MODELS

THESE RESULTS ARE ENCOURAGING!!!

CONCLUSIONS

With the next generation of neutrino telescopes we can go beyond the discovery of the first EeV neutrino

- **Particle Physics:** Next energy frontier through neutrino-matter interactions.
- **Neutrino Astronomy:** Distinguish the UHE flux signal over the most conservative backgrounds. (see talk by Damiano Fiorillo on point sources)
- **Astroparticle Physics:** Discern between different predictions for the UHE neutrino flux model and therefore learn more about the sources of most energetic particles in the Universe.

Special thanks to Mauricio Bustamante and Christian Glaser, co-authors of this work.

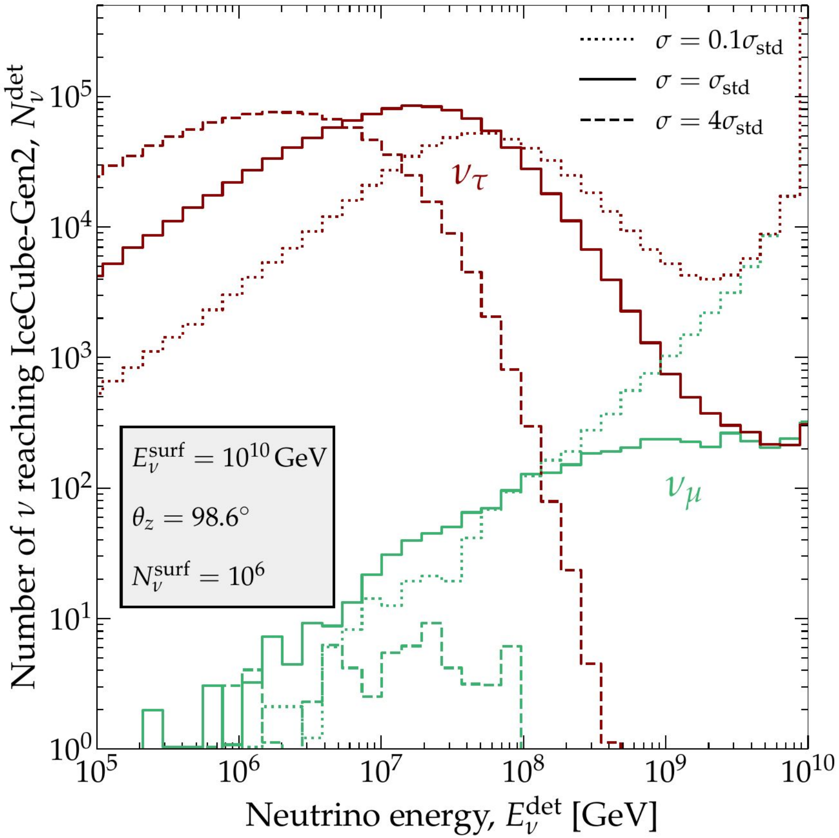
THANKS

Feel free to reach out if you have any question!

vvalera@nbi.ku.dk

BACKUP

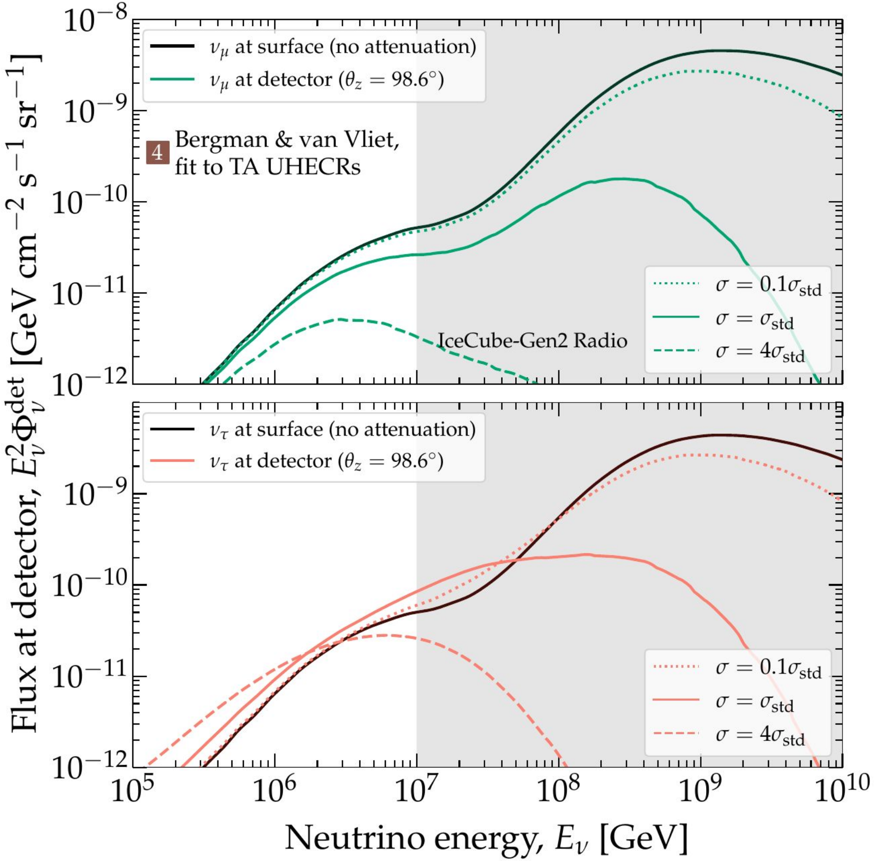
MONOCHROMATIC NEUTRINO BEAM REACHING THE DETECTOR



- Central value of the BGR computation of the DIS as $\sigma_{\rm std}$ [*Bertone et al. JHEP 2019*]
- Consider energy-independent deviations of $\sigma_{\rm std}$ by a constant factor
- Cross section deviations strongly impact the flux reaching the detector
- Effect of tau regeneration

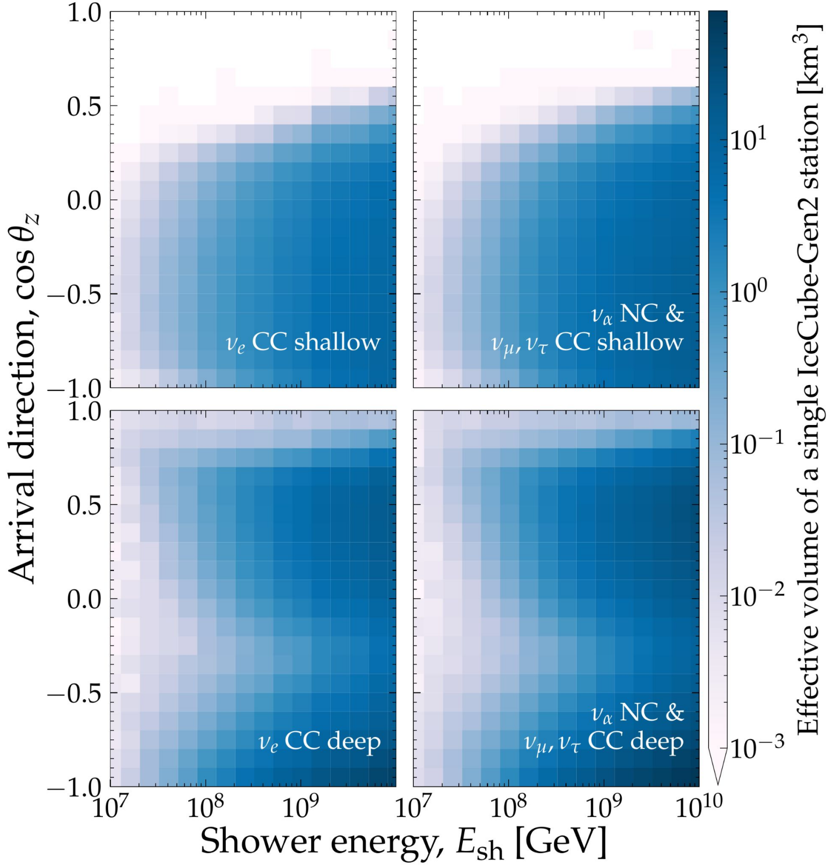
PROPAGATE THE NEUTRINO FLUXES THROUGH THE EARTH

- To propagate neutrinos we use NuPropEarth[1]
- Per-flavor propagation
- We get the angle-dependent diffuse flux at the detector



[1] *A. Garcia et al. JCAP 2020*
https://github.com/pochoarus/NuPropEarth

ICECUBE-GEN2 RADIO ARRAY EFFECTIVE VOLUME



- Baseline design[1]:
  - 144 hybrid + 169 shallow-only stations
- Effective volume depends on
  - Arrival direction
  - **Shower energy**
  - Interaction type
  - Neutrino flavor
  - Antenna type
- Non-Earth-attenuated effective volume
- Obtained with NuRadioMC[2] & NuRadioReco[3]

We can easily test the performance of different detector configurations!

[1] *Hallmann et al. ICRC 2021*

[2] *Glaser et al. Eur. Phys. J. C 80, 77 (2020)*

[3] *Glaser et al. Eur. Phys. J. C 79, 464 (2019)*

NEUTRINO SHOWER DIFFERENTIAL RATE (see text for details)

Real shower spectrum:

$$\frac{d^2 N_{\nu_\alpha}}{dE_{\rm sh}\, d\cos\theta_z} = 2\pi T n_t \int_0^1 dy \left(\frac{E^{\rm NC}_{\nu_\alpha}(E_{\rm sh}, y)}{E_{\rm sh}} V^{\rm NC}_{{\rm eff},\nu_\alpha}(E_{\rm sh}, \cos\theta_z) \times \frac{d\sigma^{\rm NC}_{\nu_\alpha {\rm w}}(E_\nu, y)}{dy} \Phi^{\rm det}_{\nu_\alpha}(E_\nu, \cos\theta_z)\Big|_{E_\nu = E^{\rm NC}_{\nu_\alpha}(E_{\rm sh}, y)} + {\rm NC} \to {\rm CC} \right),$$

exposure (T)

# of targets (n_t)

Effective Volume

Diff. cross section

Attenuated flux

FACTOR IN DETECTOR LIMITATIONS WITH RESOLUTION FUNCTIONS

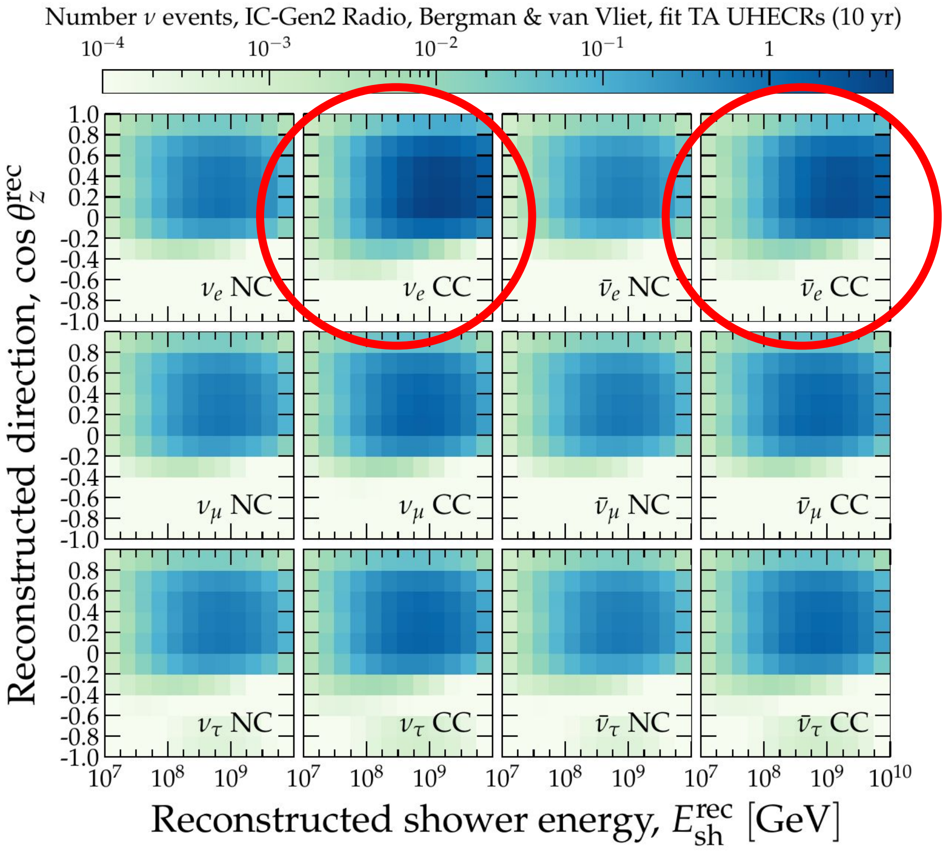
Real shower spectrum:

$$\frac{d^2 N_{\nu_\alpha}}{dE_{\rm sh} d\cos\theta_z} = 2\pi T n_t \int_0^1 dy \left(\frac{E_{\nu_\alpha}^{\rm NC}(E_{\rm sh}, y)}{E_{\rm sh}} V_{{\rm eff},\nu_\alpha}^{\rm NC}(E_{\rm sh}, \cos\theta_z) \times \frac{d\sigma_{\nu_\alpha {\rm w}}^{\rm NC}(E_\nu, y)}{dy} \Phi_{\nu_\alpha}^{\rm det}(E_\nu, \cos\theta_z) \Big|_{E_\nu = E_{\nu_\alpha}^{\rm NC}(E_{\rm sh}, y)} + {\rm NC} \to {\rm CC} \right),$$

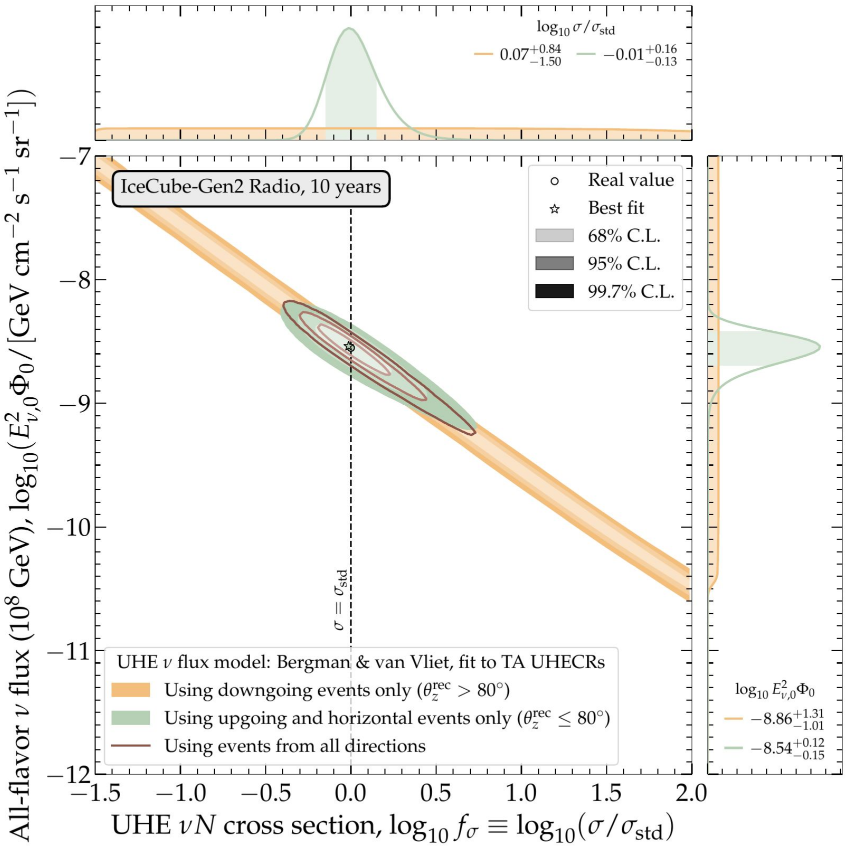
Reconstructed shower spectrum (what we use):

$$\frac{d^2 N_{\nu_\alpha}}{dE_{\rm sh}^{\rm rec} d\theta_z^{\rm rec}} = \int_{-1}^{+1} d\cos\theta_z \int_0^\infty dE_{\rm sh} \frac{d^2 N_{\nu_\alpha}}{dE_{\rm sh} d\cos\theta_z} \mathcal{R}_{E_{\rm sh}}(E_{\rm sh}^{\rm rec}, E_{\rm sh})\, \mathcal{R}_{\theta_z}(\theta_z^{\rm rec}, \theta_z)$$

NEUTRINO SHOWER EVENT RATE PER CHANNEL

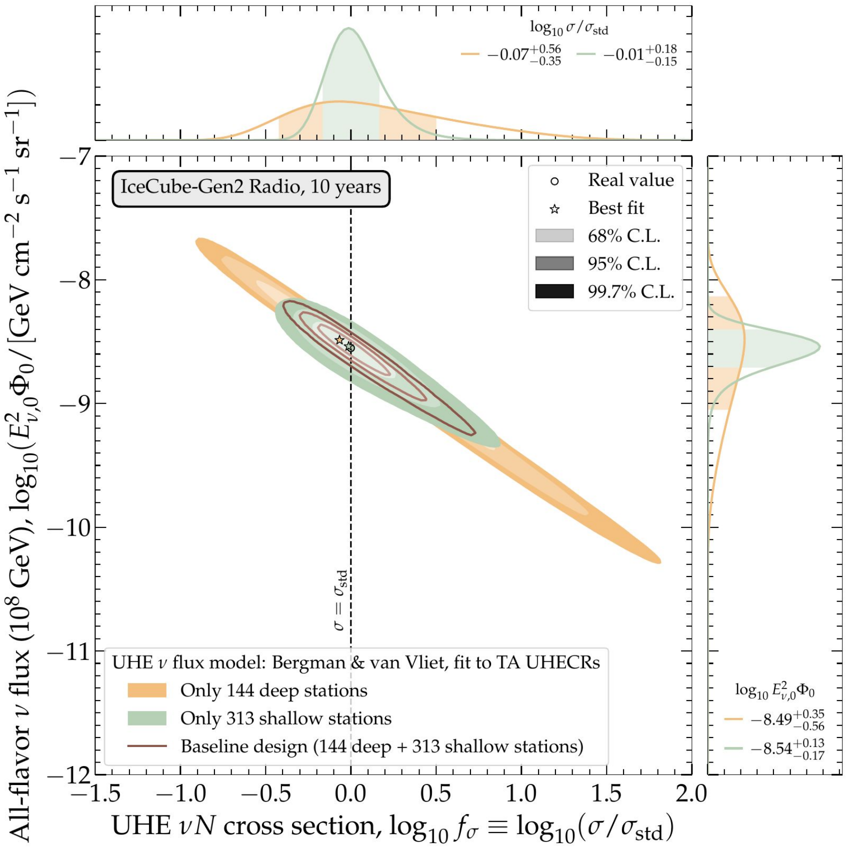


THE IMPORTANCE OF EARTH-SKIMMING NEUTRINOS



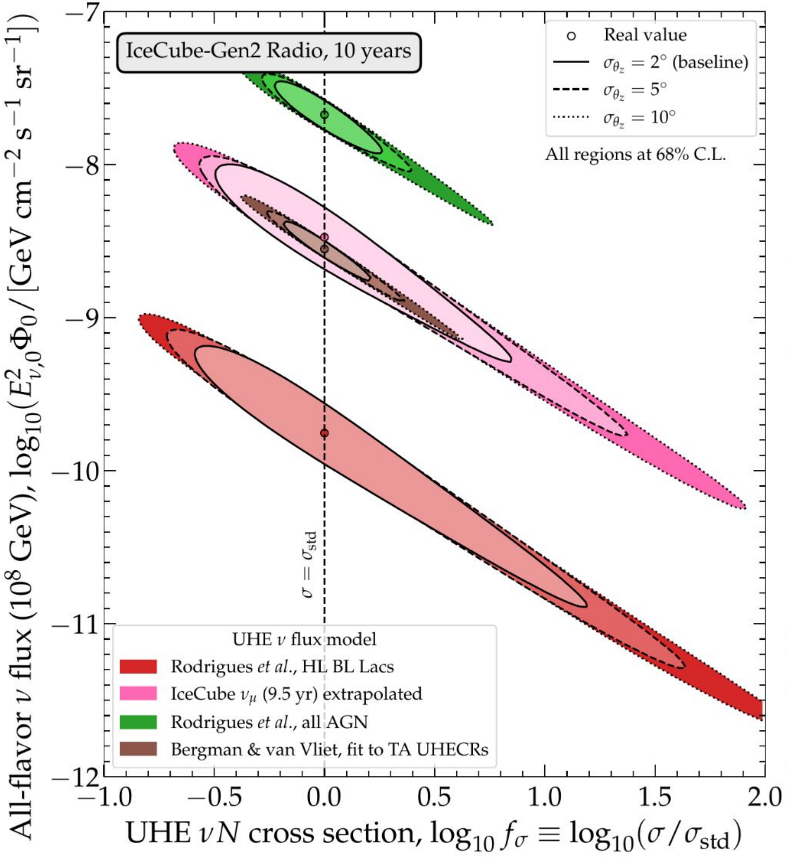
- Sensitivity to the cross section comes predominantly from near-horizontal showers.
- Neutrinos undergo significant, but not complete, attenuation inside the Earth.
- Using only downgoing showers is sensitive only to the product of the cross section and flux normalization
- The numerous downgoing events can be used for flux shape reconstruction

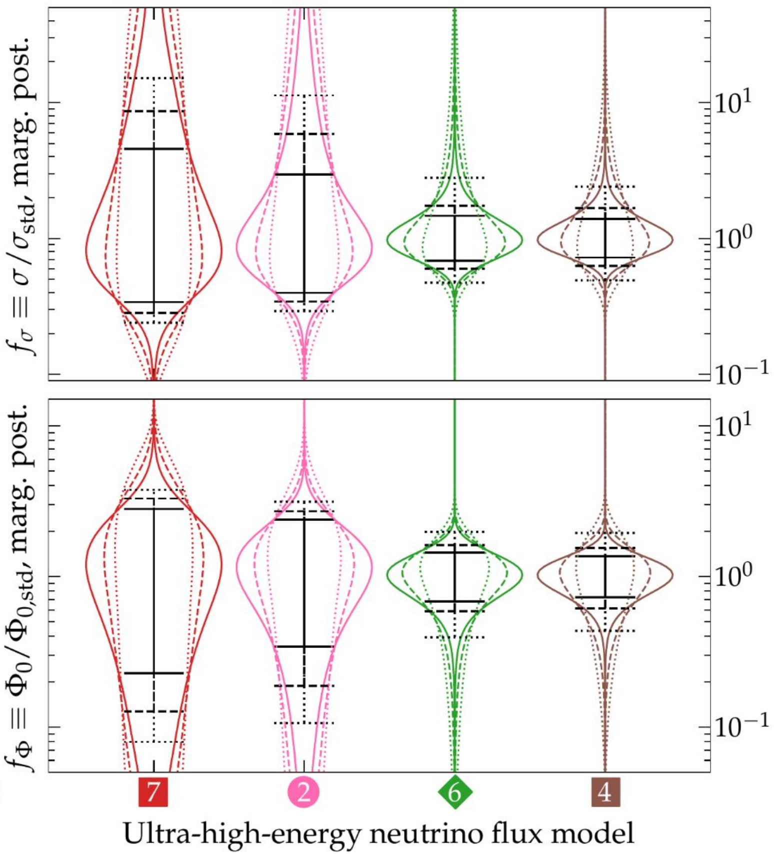
SHALLOW-ONLY VS DEEP-ONLY CONFIGURATIONS



- Baseline sensitivity dominated by shallow stations.
- Shallow antennas are more (313 vs 144).
- We assume the same 2º resolution for both types stations.
- Real measurement resolution will depend on the single-event quality.
- Also on which component (shallow or deep) is detected
- Possible multiple component coincidence

BEYOND THE $\sigma_\theta = 2^o$ BENCHMARK RESOLUTION





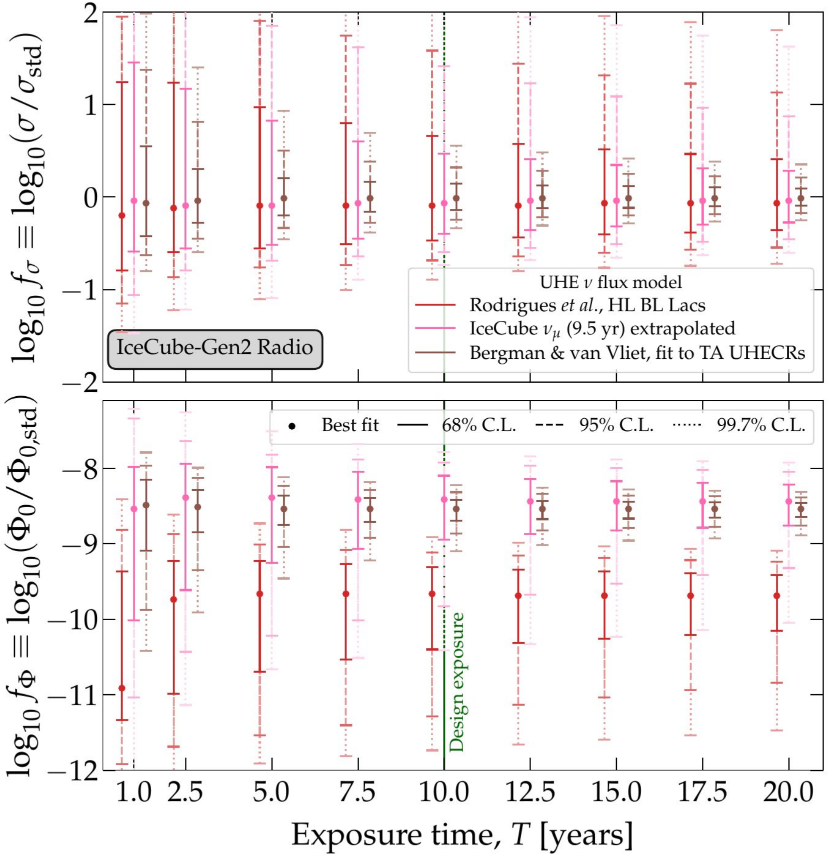
Good angular resolution is of great importance.

We obtained and increased of

- 50% ($\sigma_\theta = 5^o$)
- 178% ($\sigma_\theta = 10^o$)

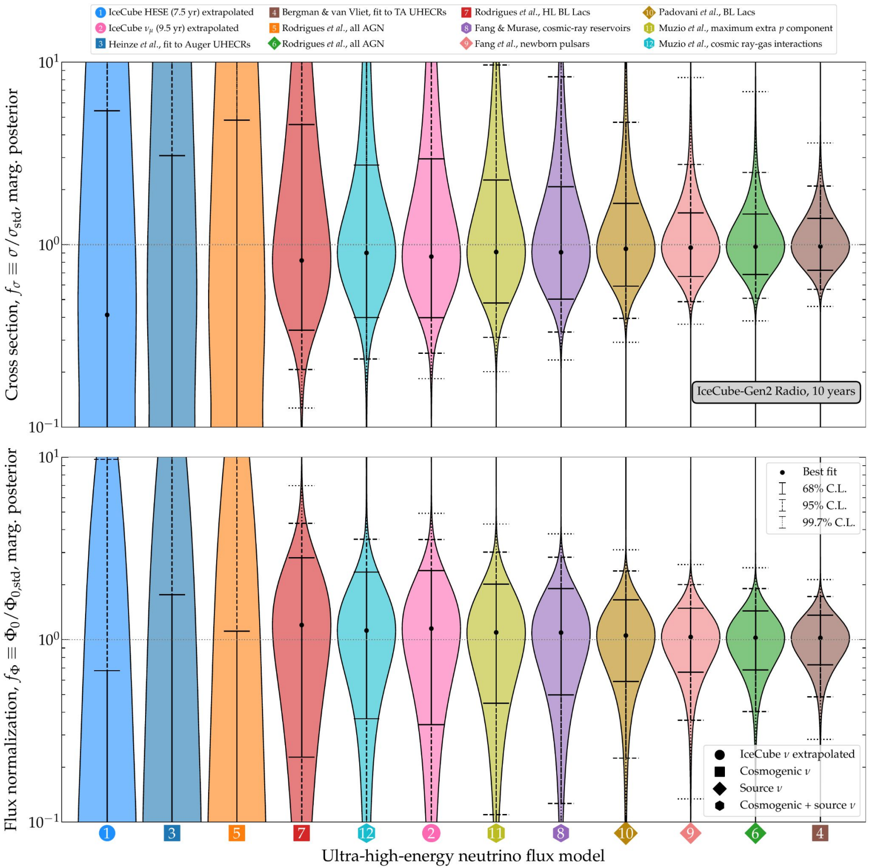
in the measurement error Δf_σ compared to the baseline resolution of $\sigma_\theta = 2^o$.

THE EVOLUTION OF THE SENSITIVITY OVERTIME



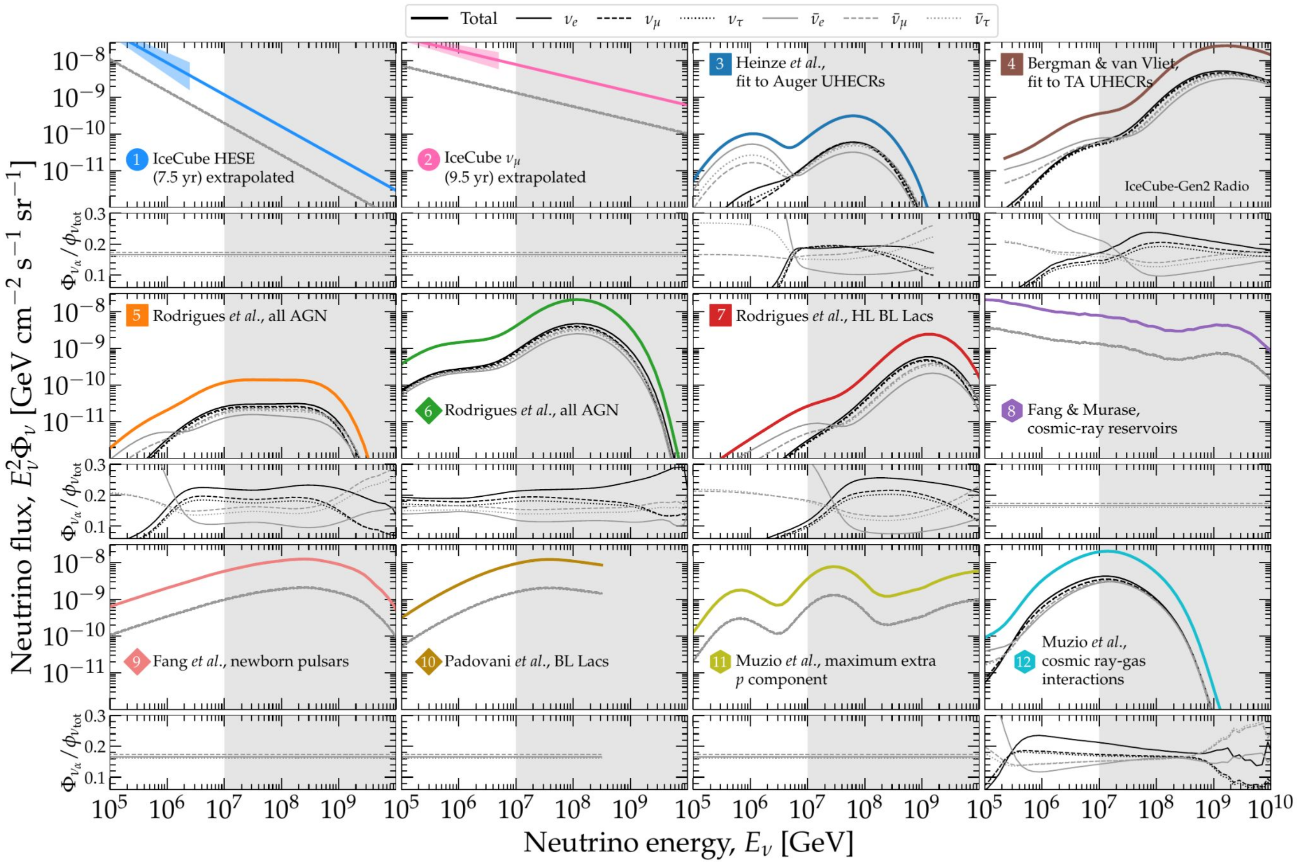
- Expected improvements in the measurement over time
- In the most optimistic scenario the sensitivity after 2.5 years is comparable to 10 years of exposure
- And after 20 years we are at the level of the theoretical uncertainty
- A similar situation occurs for the IceCube power law extrapolation

SLIDE TITLE



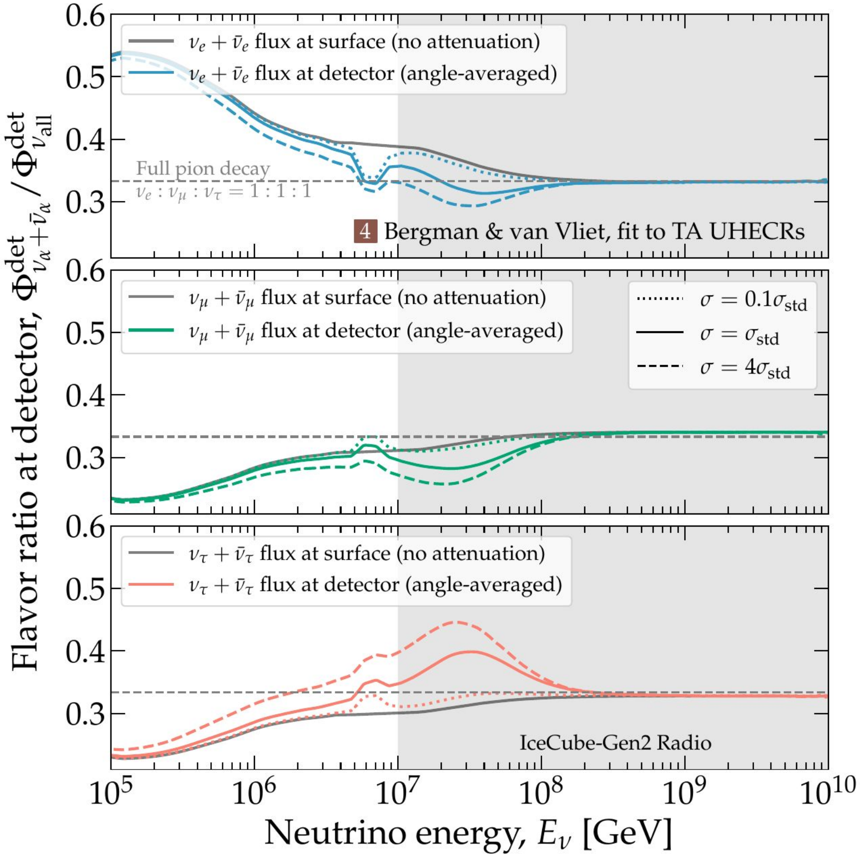
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
12 Muzio et al., cosmic ray-gas interactions
Cross section, $f_\sigma \equiv \sigma/\sigma_{\rm std}$, marg. posterior
IceCube-Gen2 Radio, 10 years
Flux normalization, $f_\Phi \equiv \Phi_0/\Phi_{0,\rm std}$, marg. posterior
Best fit
68% C.L.
95% C.L.
99.7% C.L.
IceCube ν extrapolated
Cosmogenic ν
Source ν
Cosmogenic + source ν
Ultra-high-energy neutrino flux model

SLIDE TITLE



Total
ν_e
ν_μ
ν_τ
$\bar{\nu}_e$
$\bar{\nu}_\mu$
$\bar{\nu}_\tau$
1 IceCube HESE (7.5 yr) extrapolated
2 IceCube ν_μ (9.5 yr) extrapolated
3 Heinze et al., fit to Auger UHECRs
4 Bergman & van Vliet, fit to TA UHECRs
IceCube-Gen2 Radio
5 Rodrigues et al., all AGN
6 Rodrigues et al., all AGN
7 Rodrigues et al., HL BL Lacs
8 Fang & Murase, cosmic-ray reservoirs
9 Fang et al., newborn pulsars
10 Padovani et al., BL Lacs
11 Muzio et al., maximum extra p component
12 Muzio et al., cosmic ray-gas interactions
Neutrino flux, $E_\nu^2\Phi_\nu$ [GeV cm^{-2} s^{-1} sr^{-1}]
$\Phi_{\nu_\alpha}/\phi_{\nu_{tot}}$
Neutrino energy, E_ν [GeV]

SLIDE TITLE



$\nu_e + \bar{\nu}_e$ flux at surface (no attenuation)
$\nu_e + \bar{\nu}_e$ flux at detector (angle-averaged)
Full pion decay
$\nu_e : \nu_\mu : \nu_\tau = 1:1:1$
4 Bergman & van Vliet, fit to TA UHECRs
$\nu_\mu + \bar{\nu}_\mu$ flux at surface (no attenuation)
$\nu_\mu + \bar{\nu}_\mu$ flux at detector (angle-averaged)
$\sigma = 0.1\sigma_{\rm std}$
$\sigma = \sigma_{\rm std}$
$\sigma = 4\sigma_{\rm std}$
$\nu_\tau + \bar{\nu}_\tau$ flux at surface (no attenuation)
$\nu_\tau + \bar{\nu}_\tau$ flux at detector (angle-averaged)
IceCube-Gen2 Radio
Flavor ratio at detector, $\Phi^{\rm det}_{\nu_\alpha+\bar{\nu}_\alpha} / \Phi^{\rm det}_{\nu_{\rm all}}$
Neutrino energy, E_ν [GeV]
0.6
0.5
0.4
0.3
10^5
10^6
10^7
10^8
10^9
10^{10}