

ICECUBE

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ULB

VUB

Highlights from IceCube

Nhân Châu

on behalf of the IIHE-IceCube group

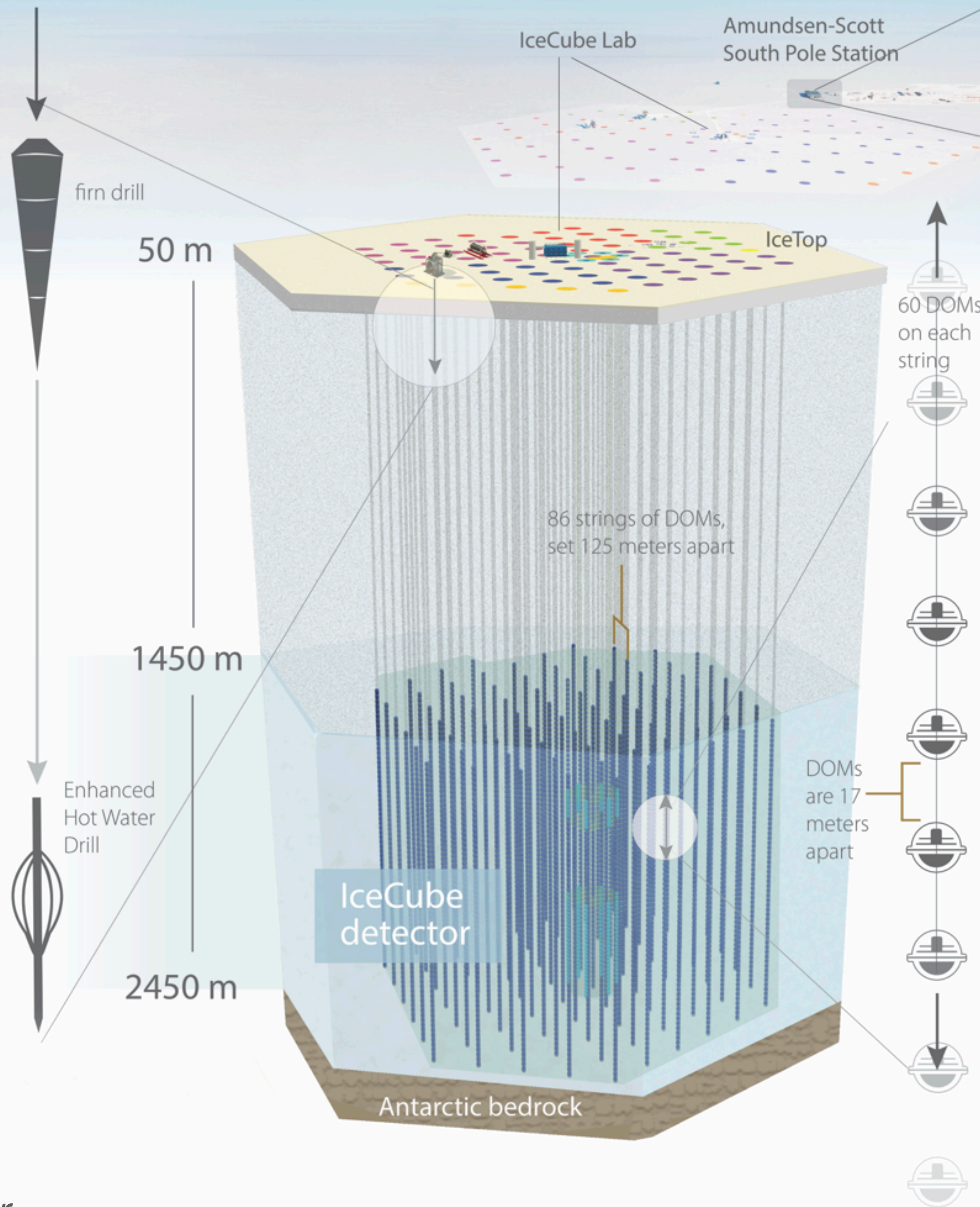
IIHE annual meeting

Brussels - November 15, 2023

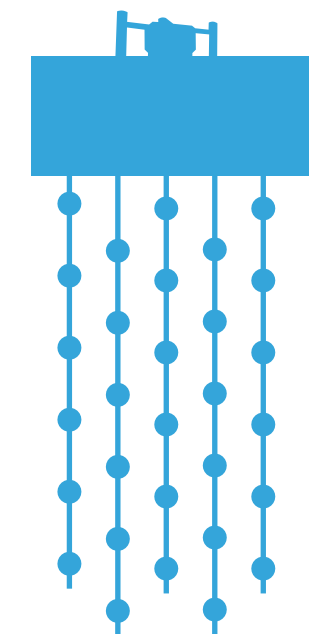
Outlines

- The IceCube Neutrino Observatory
 - Detector design and detection technique
 - Highlights from IceCube (in neutrino astronomy!)
- IceCube activities at IHE
- The future of IceCube: Upgrade and Gen2
 - Gen2 at IHE

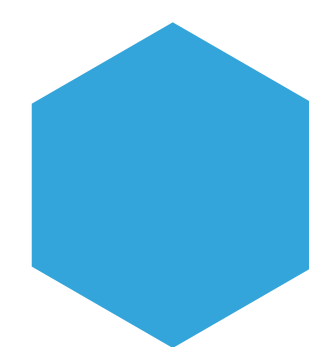
IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)



86 string with 60 DOMs each
6 denser strings called DeepCore



1 km² surface array with 324 DOMs: IceTop

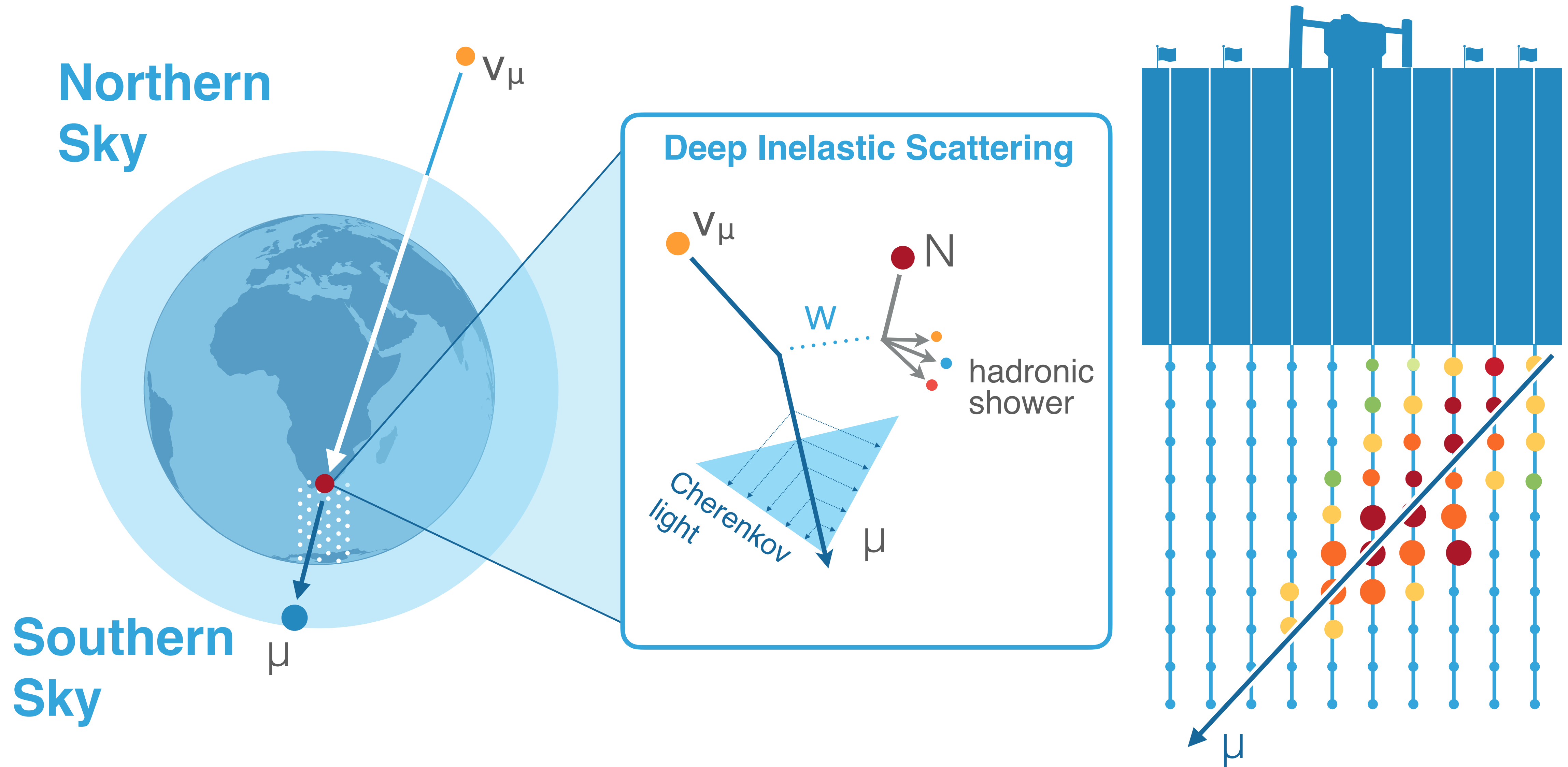


Completion in December 2010

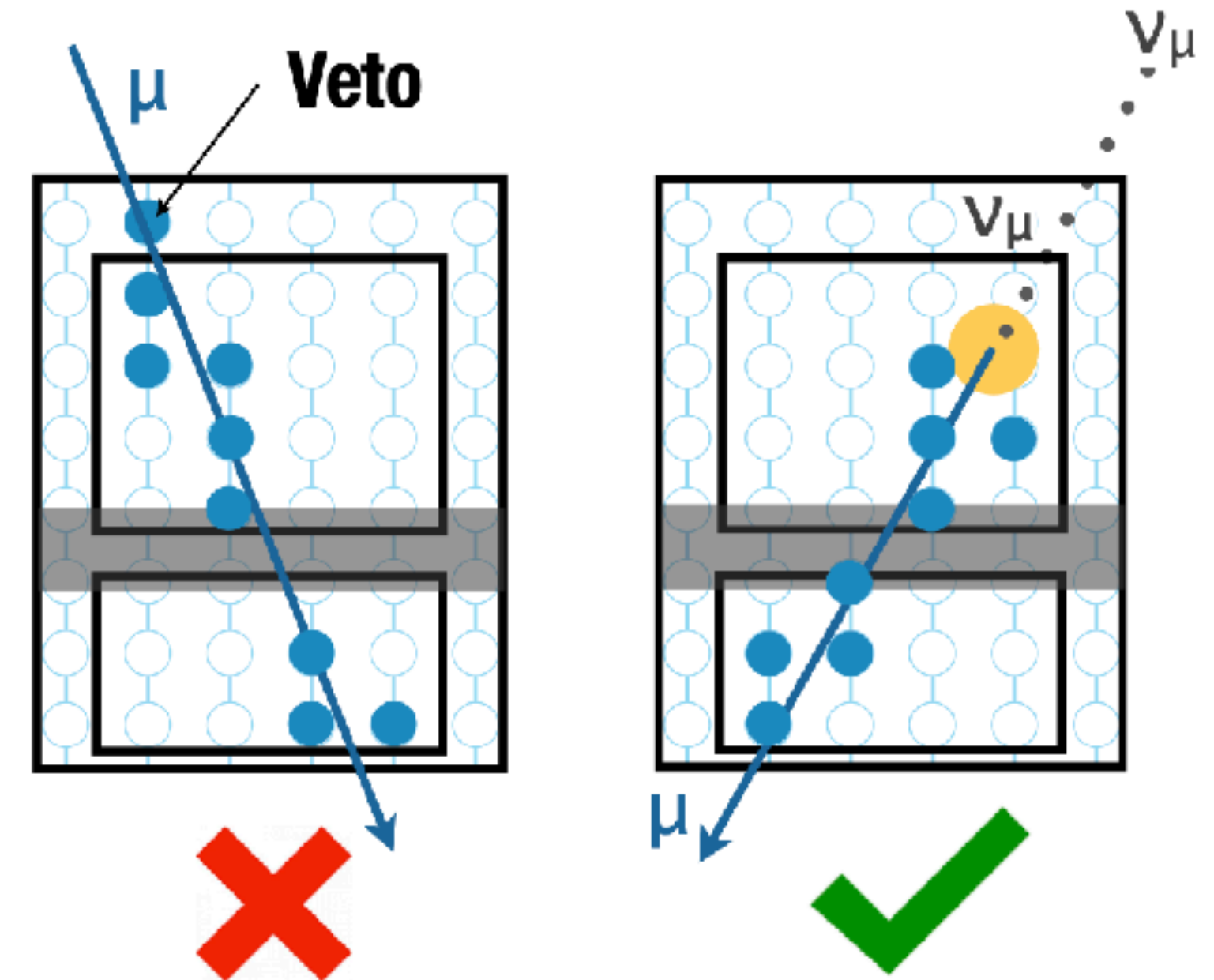
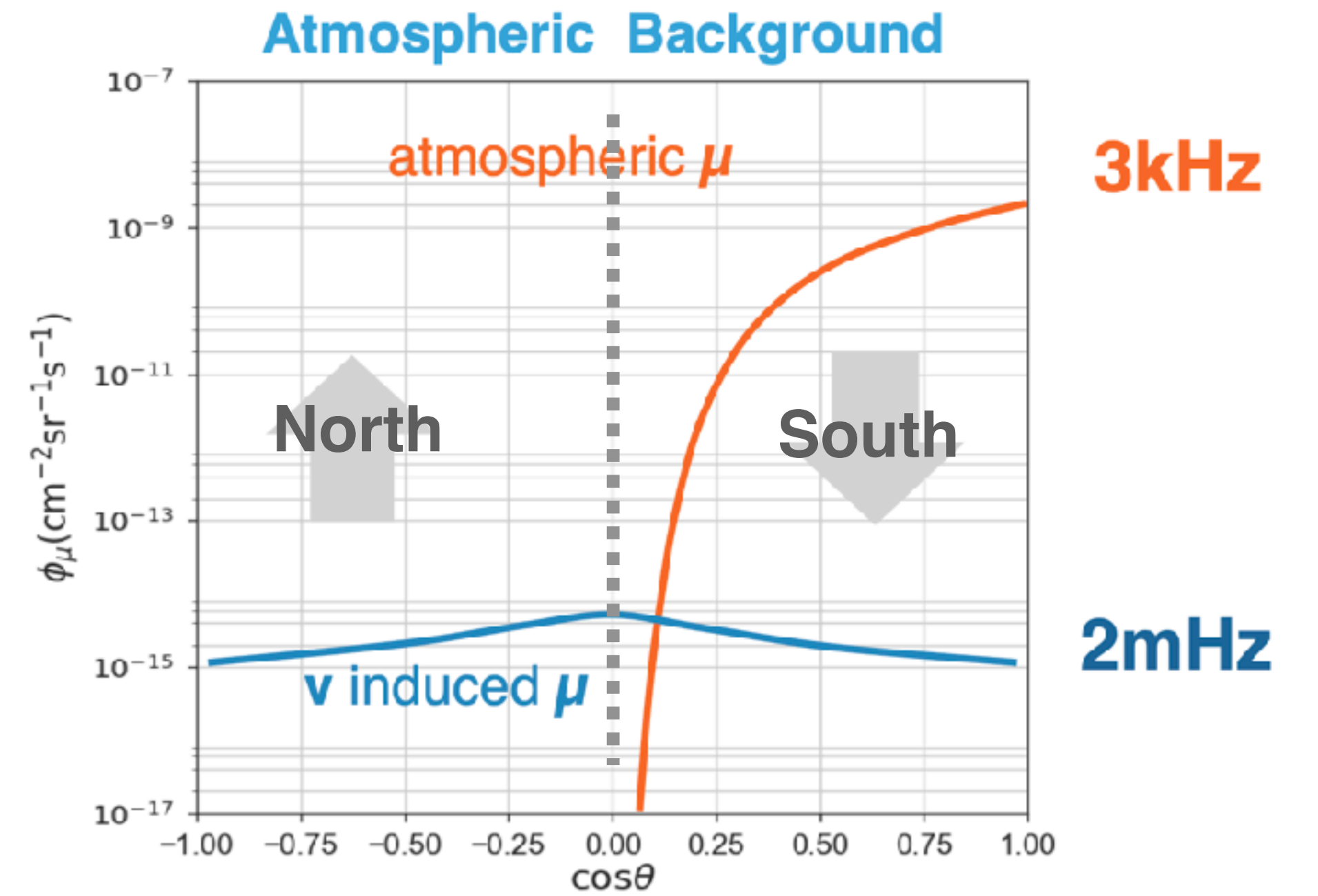
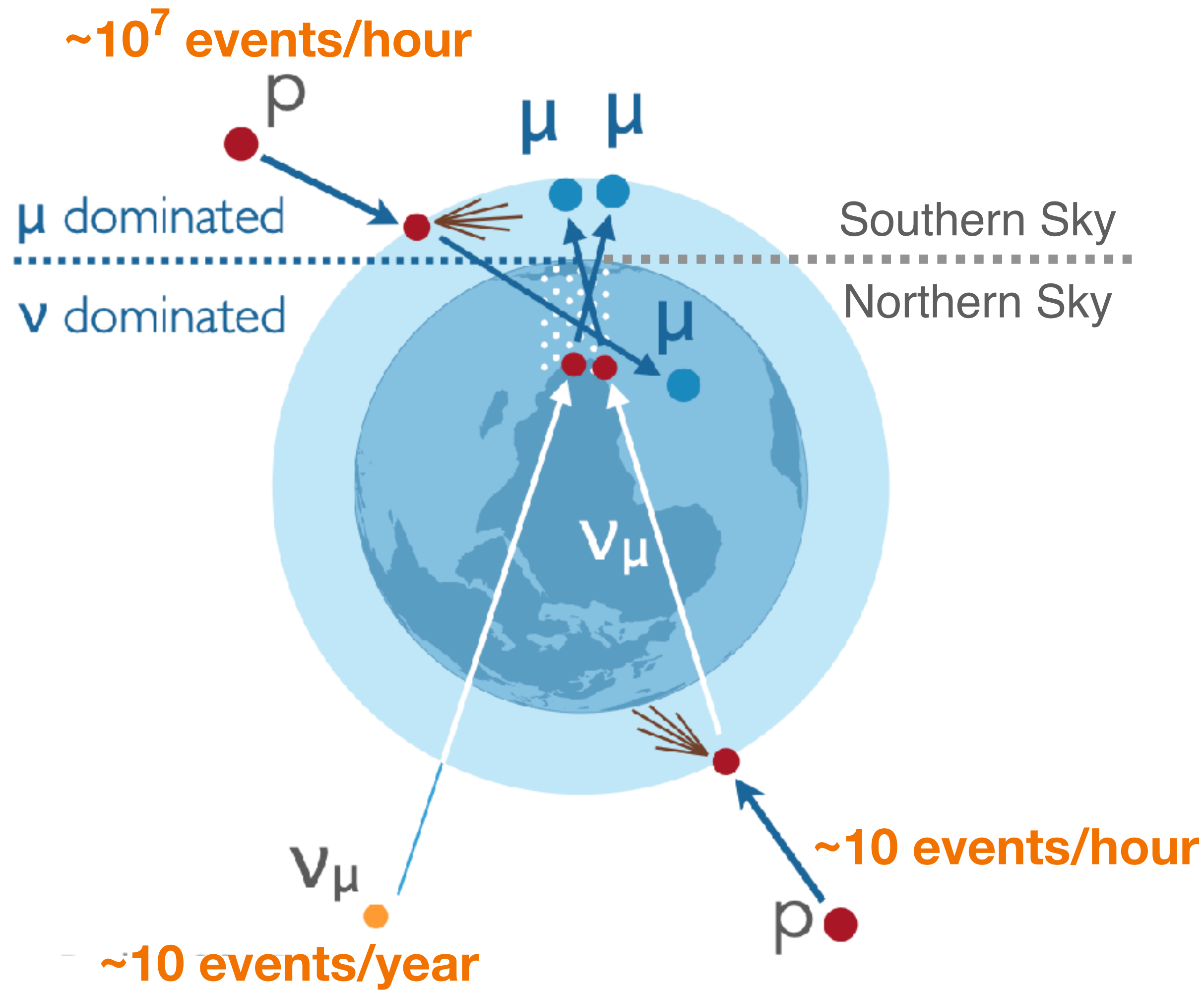


*Credit: Juanan Aguilar

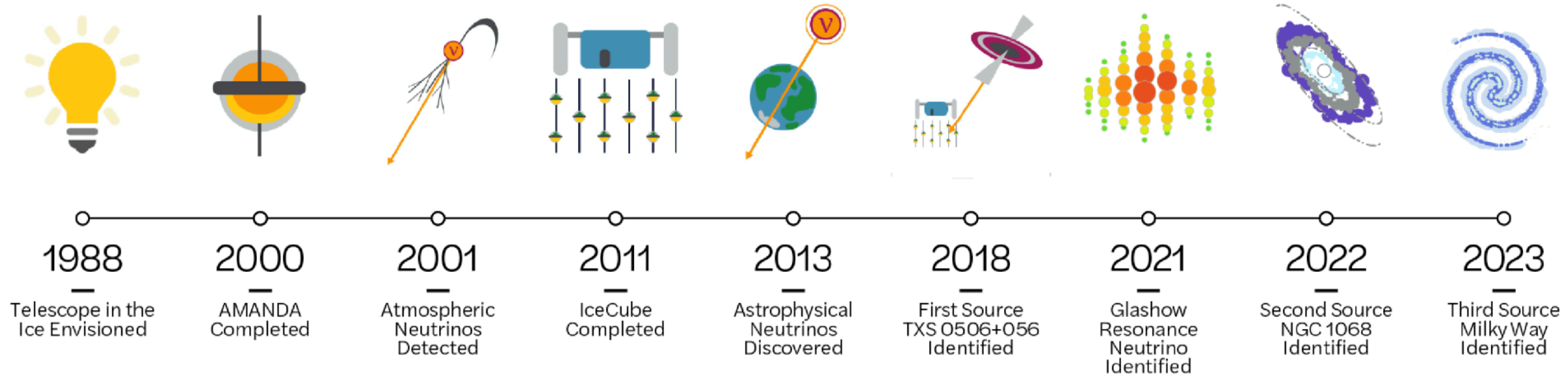
Detection Principle



Detection Principle - background rejection

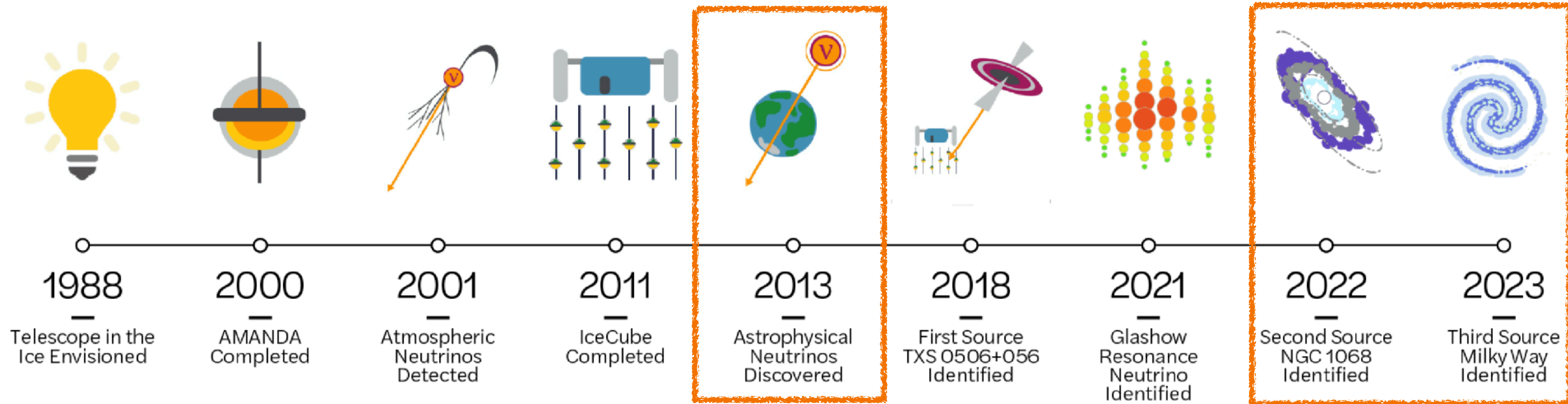


A history of Neutrino Astronomy at Antarctic



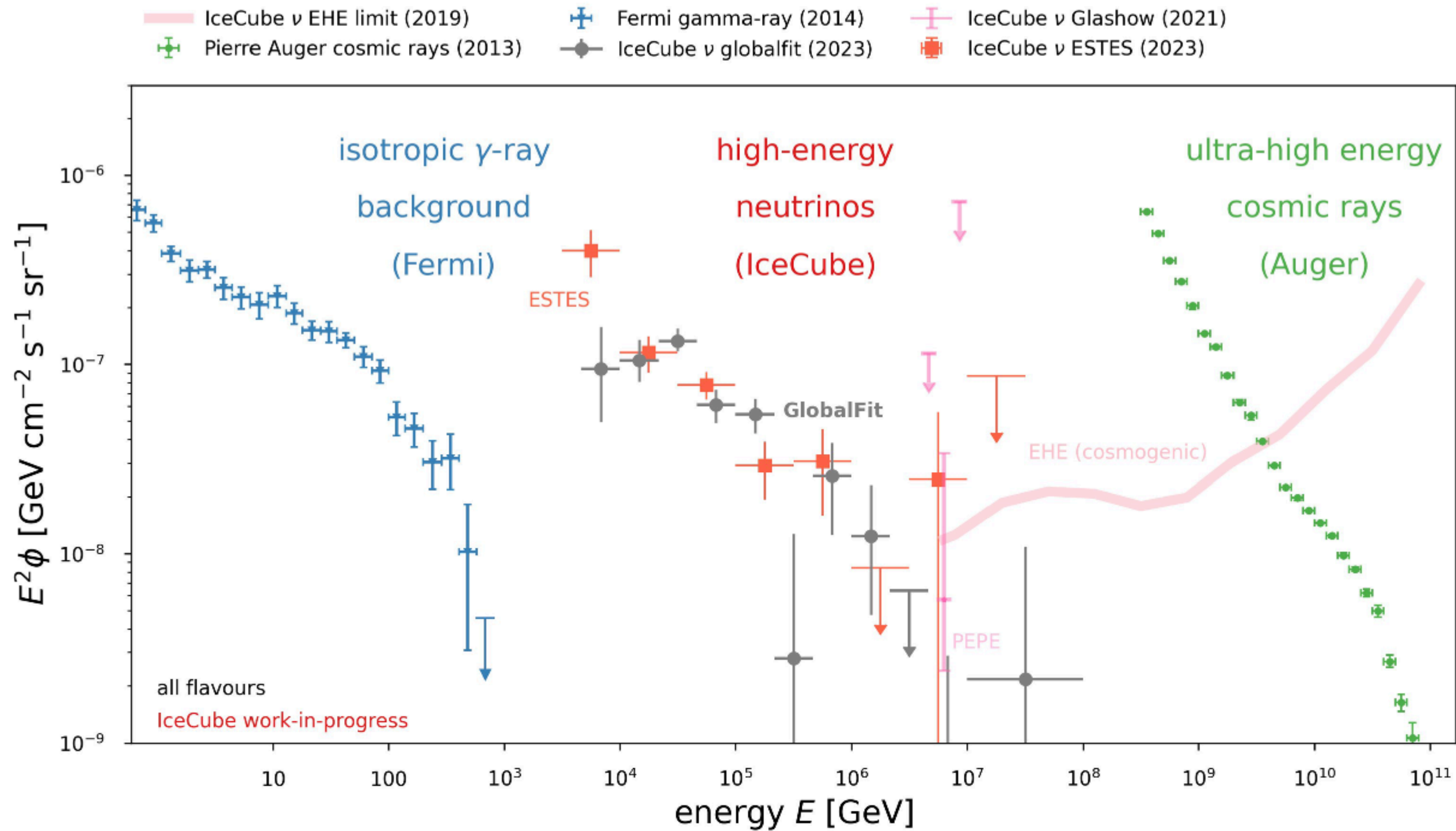
**Credit: IceCube Collaboration/NSF*

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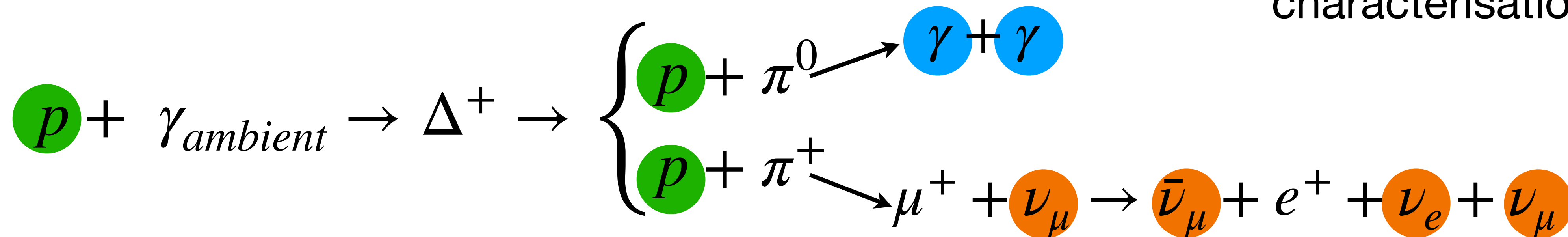


**Credit: IceCube Collaboration/NSF*

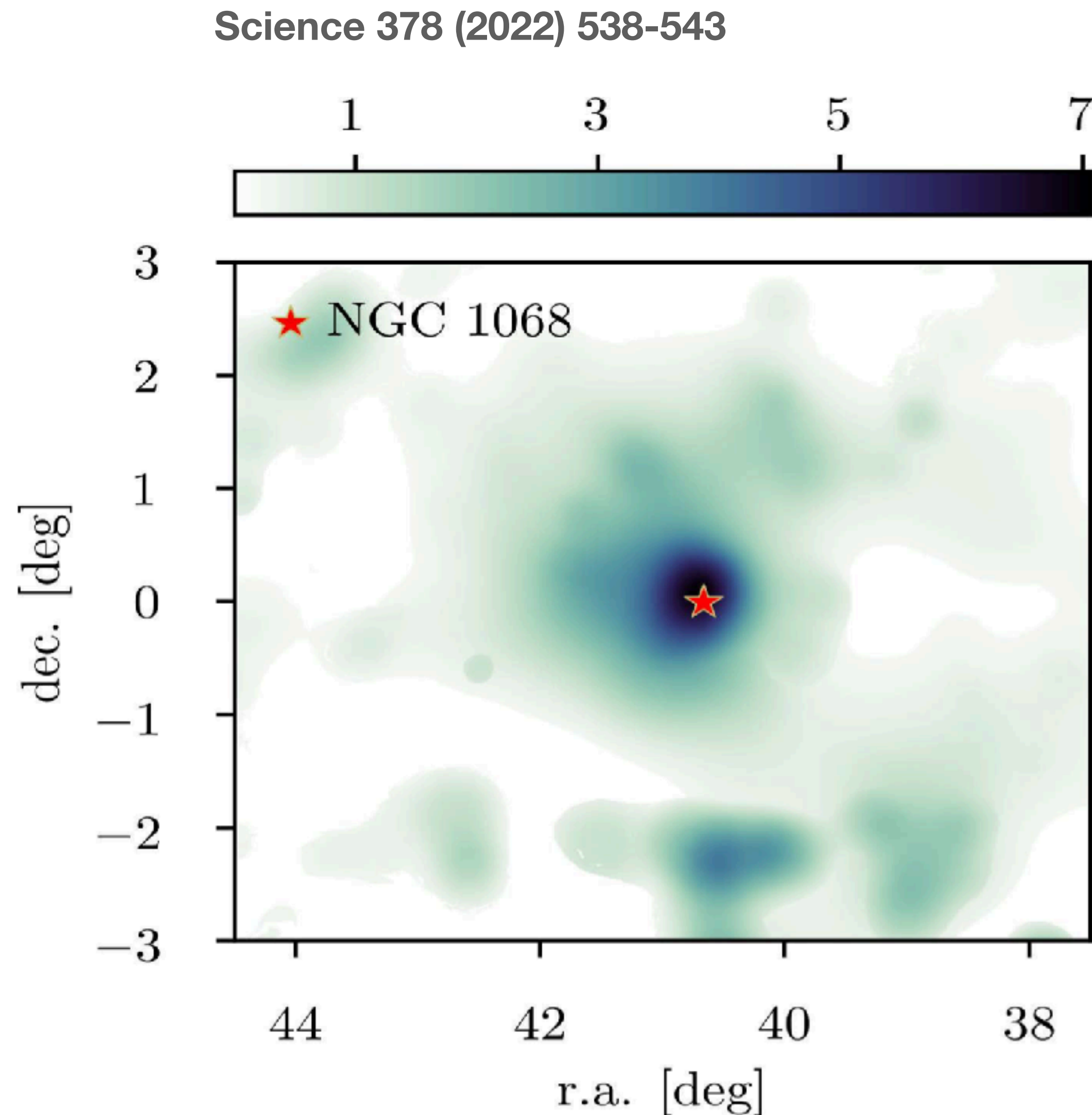
Diffuse Astrophysical Neutrinos



- First observed in 2013
- $\gamma = 2.3 - 2.9$ depends on analysis / energy range
- Consistent energy intensities with other messengers
- Might be the hints for deviation from single power law
- With growing dataset better characterisation is expected



NGC 1068 - first steady point source

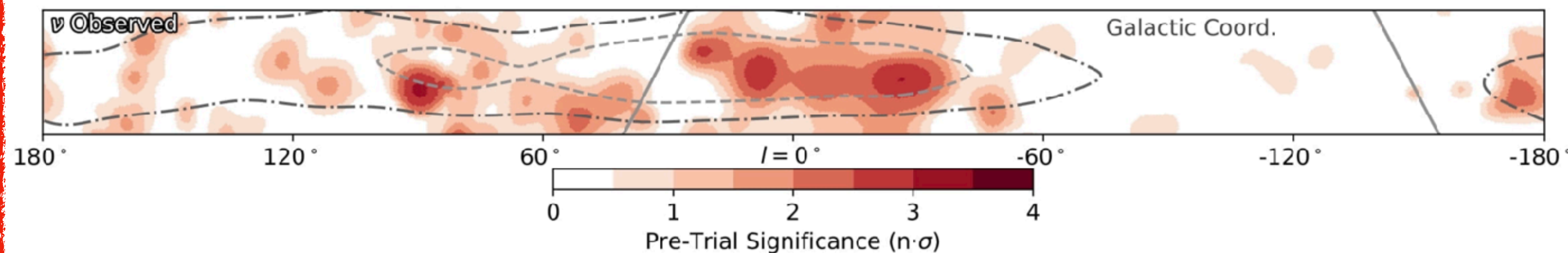
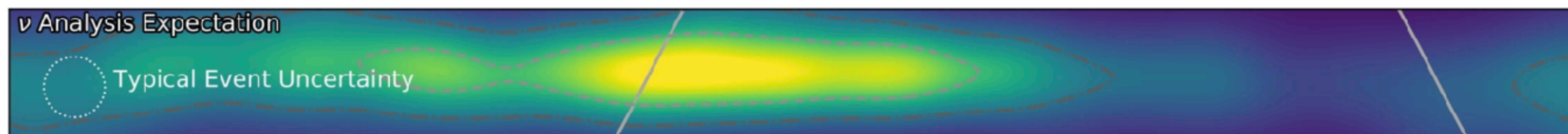
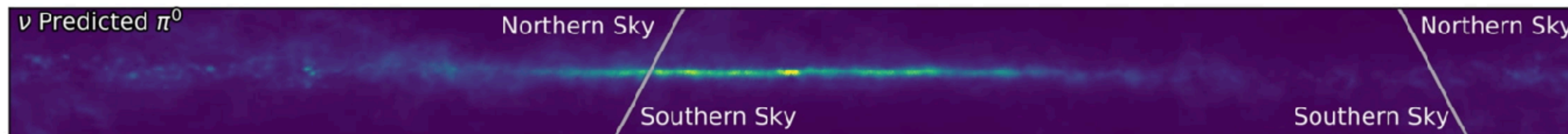
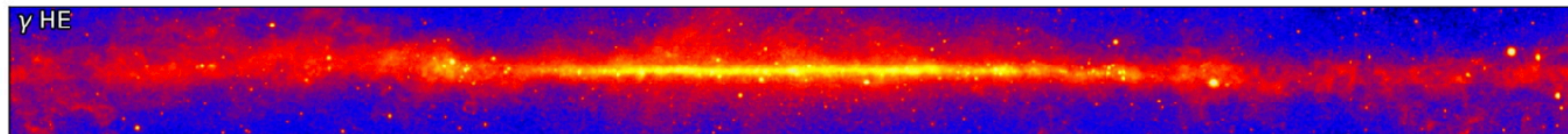
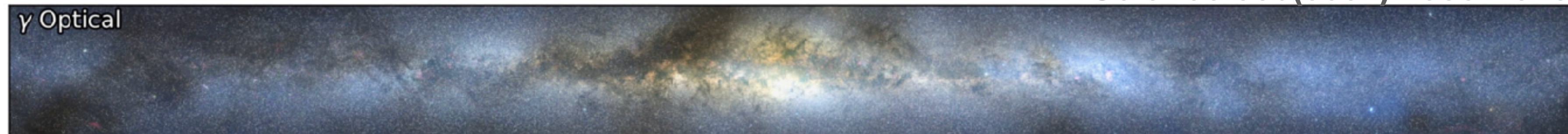


- A nearby active galaxy (Seyfert II, 14 Mpc)
 - Global significance of 4.2σ
 - First hint in 2021 with 2.9σ
- ➔ Improvement thanks to more precise neutrino event characterization (calibration, reconstruction, ..) + 2 additional years of data

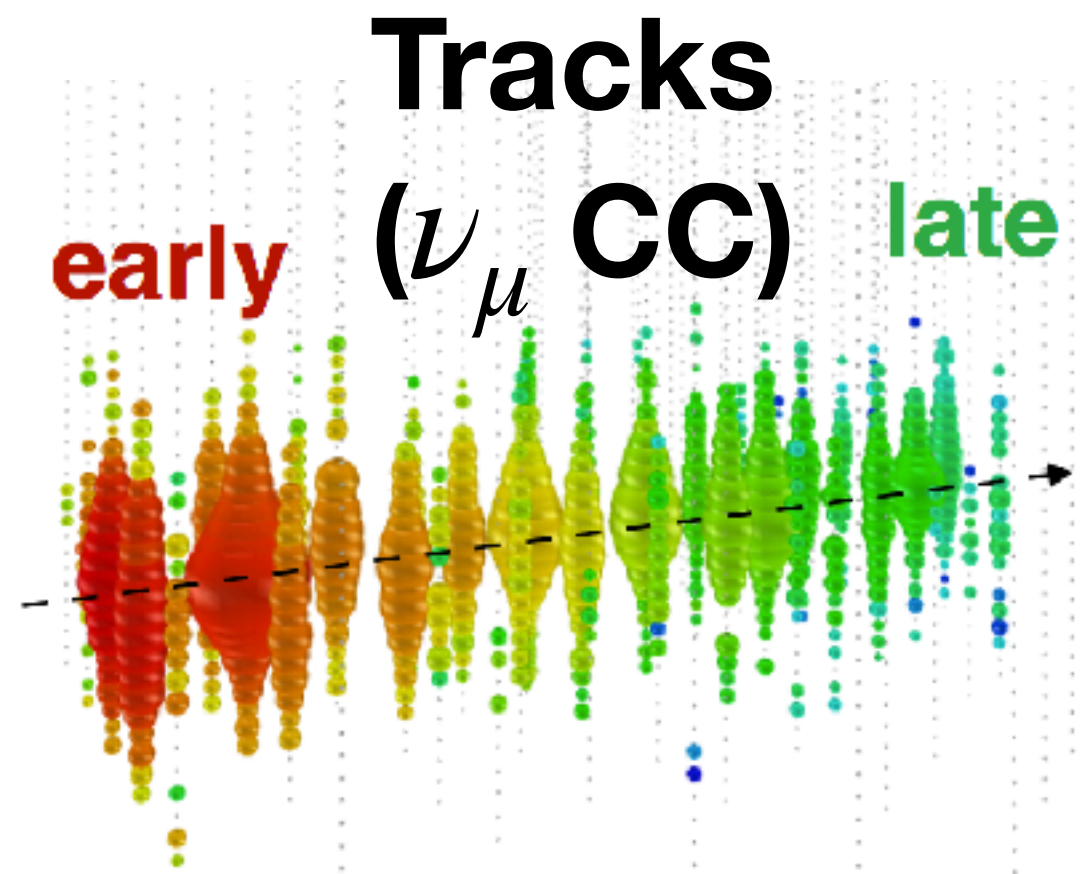
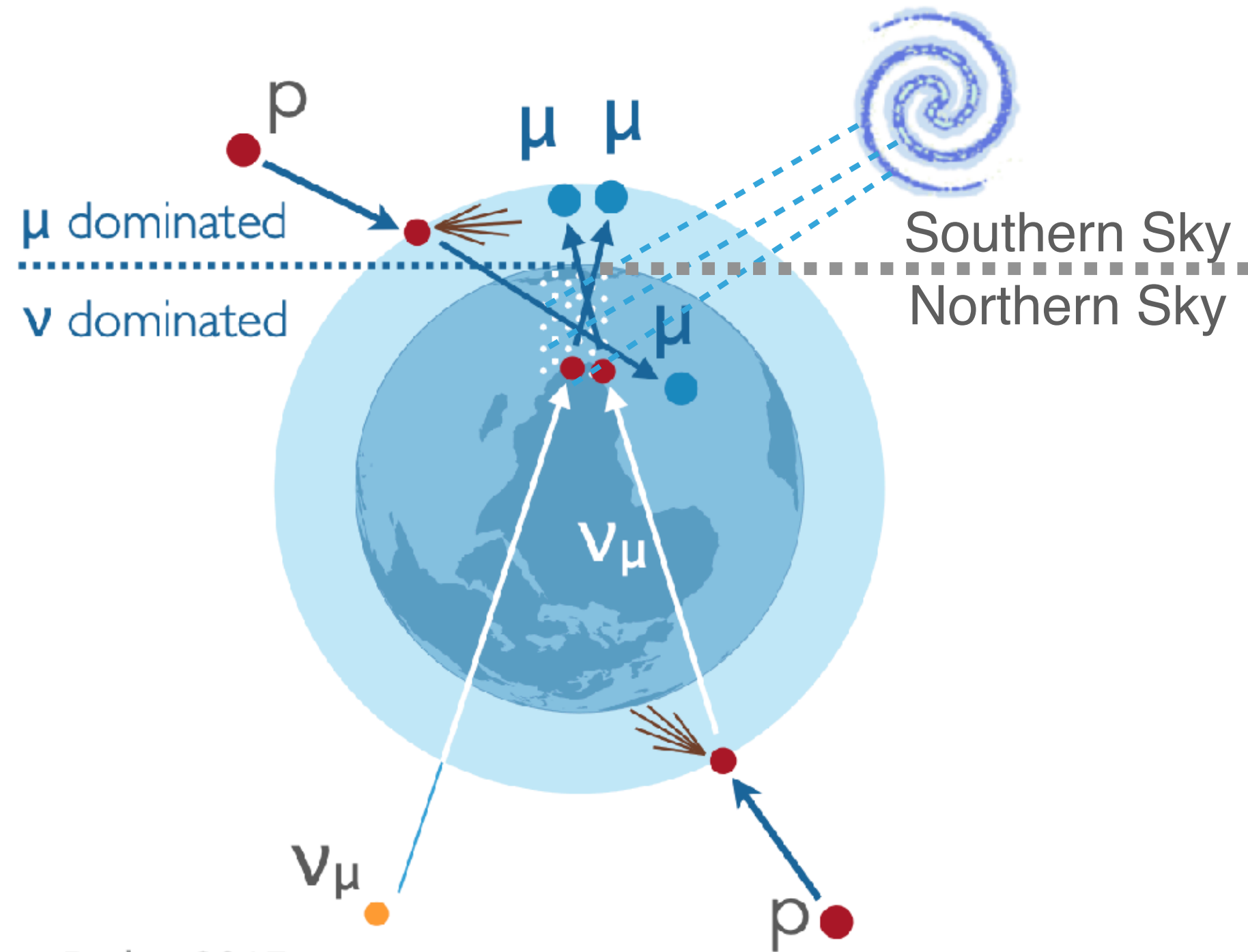
First observation of Galactic Plane in Neutrinos

- First observation of the Milky Way in neutrinos at a statistical significance 4.5σ

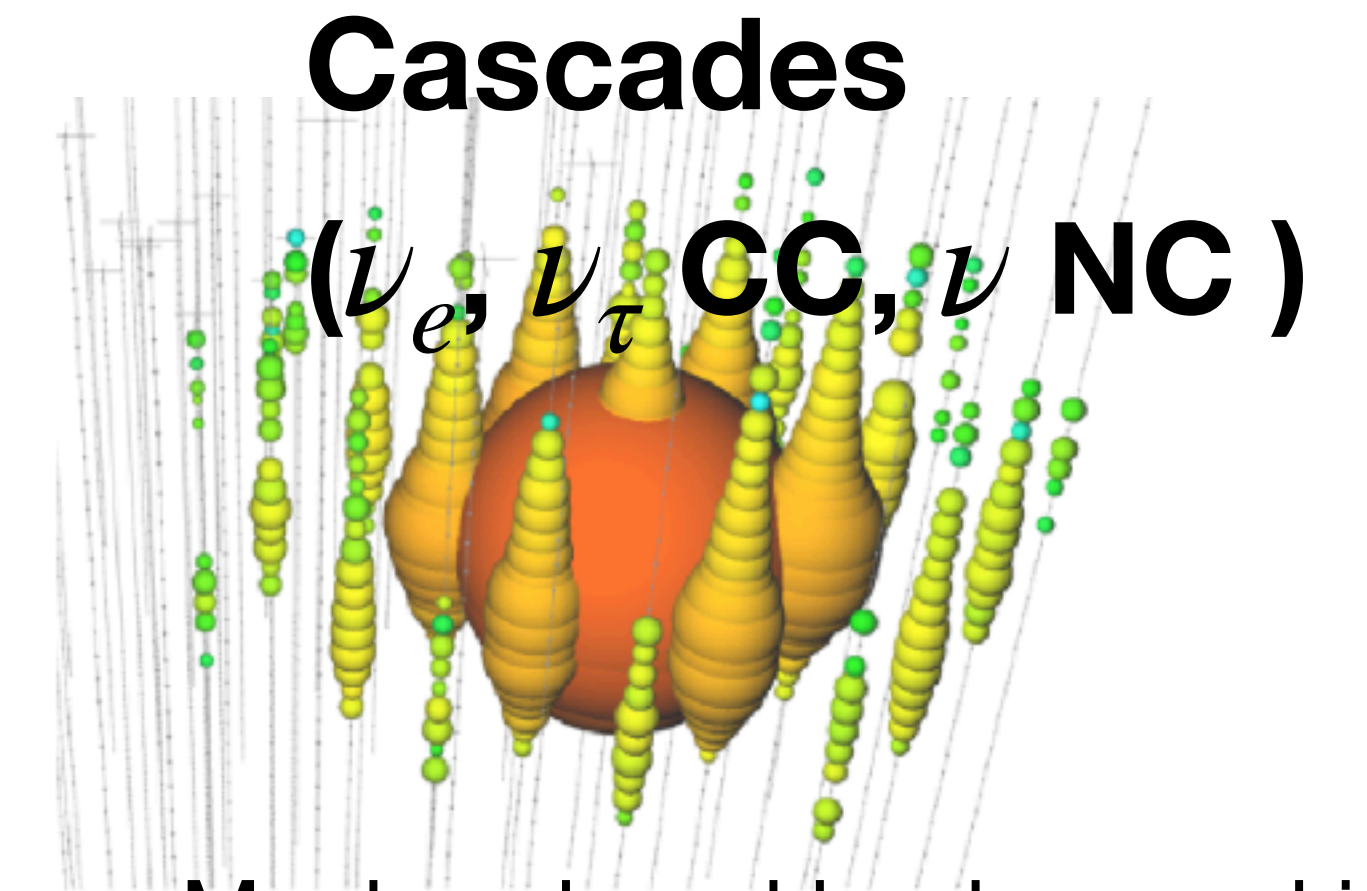
Science 380(6652):1338-1343



First observation of Galactic Plane in Neutrinos

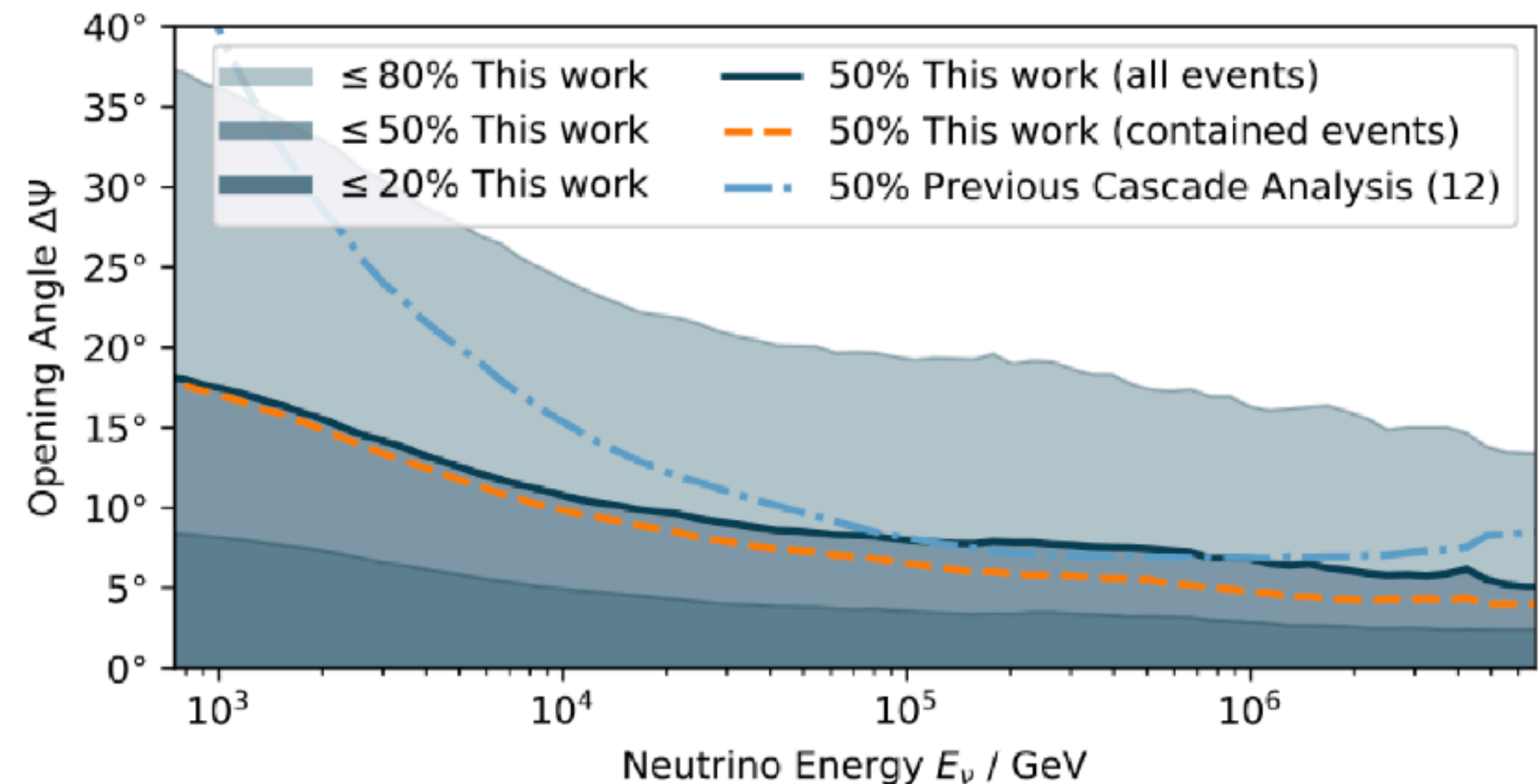


- Good angular resolution.
- But irreducible background in the southern sky.



- Much reduced background in the southern sky
- Large angular resolution..but improved thanks to DNN.

- Observation made possible thanks to **cascade events**:
 - ▶ **Less background** (atm μ, ν) in the southern sky
 - ▶ **Angular resolution improvement** with machine learning.



Recent IceCube activities at IHE

Astrophysical Searches

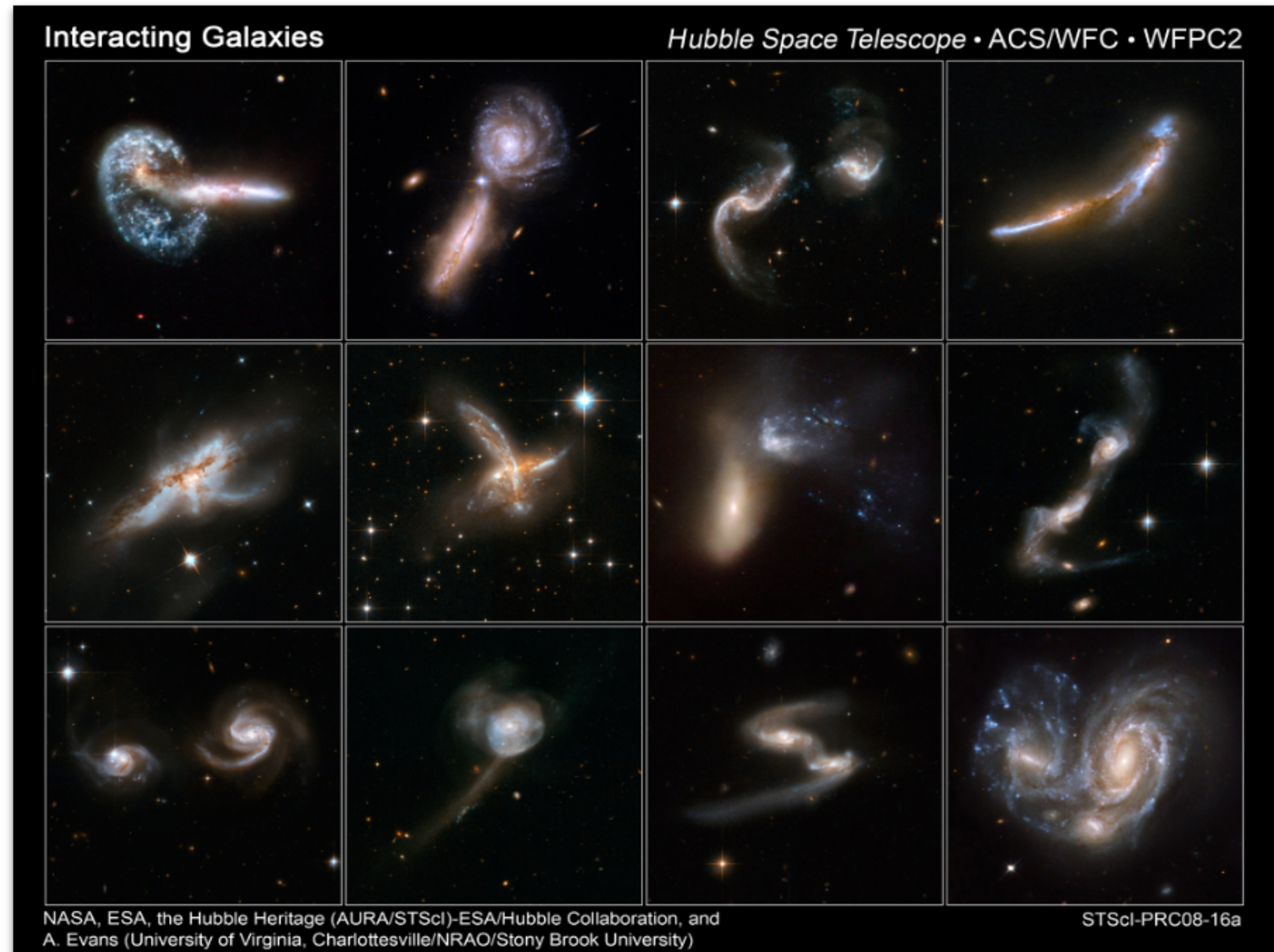
U/LIRGs as ν -sources

- (Ultra)Luminous Infrared Galaxies
(= U/LIRGs)

➤ **ULIRG**: $L_{\text{IR}} \geq 10^{12} L_{\odot}$

➤ **LIRG**: $10^{11} L_{\odot} \leq L_{\text{IR}} < 10^{12} L_{\odot}$

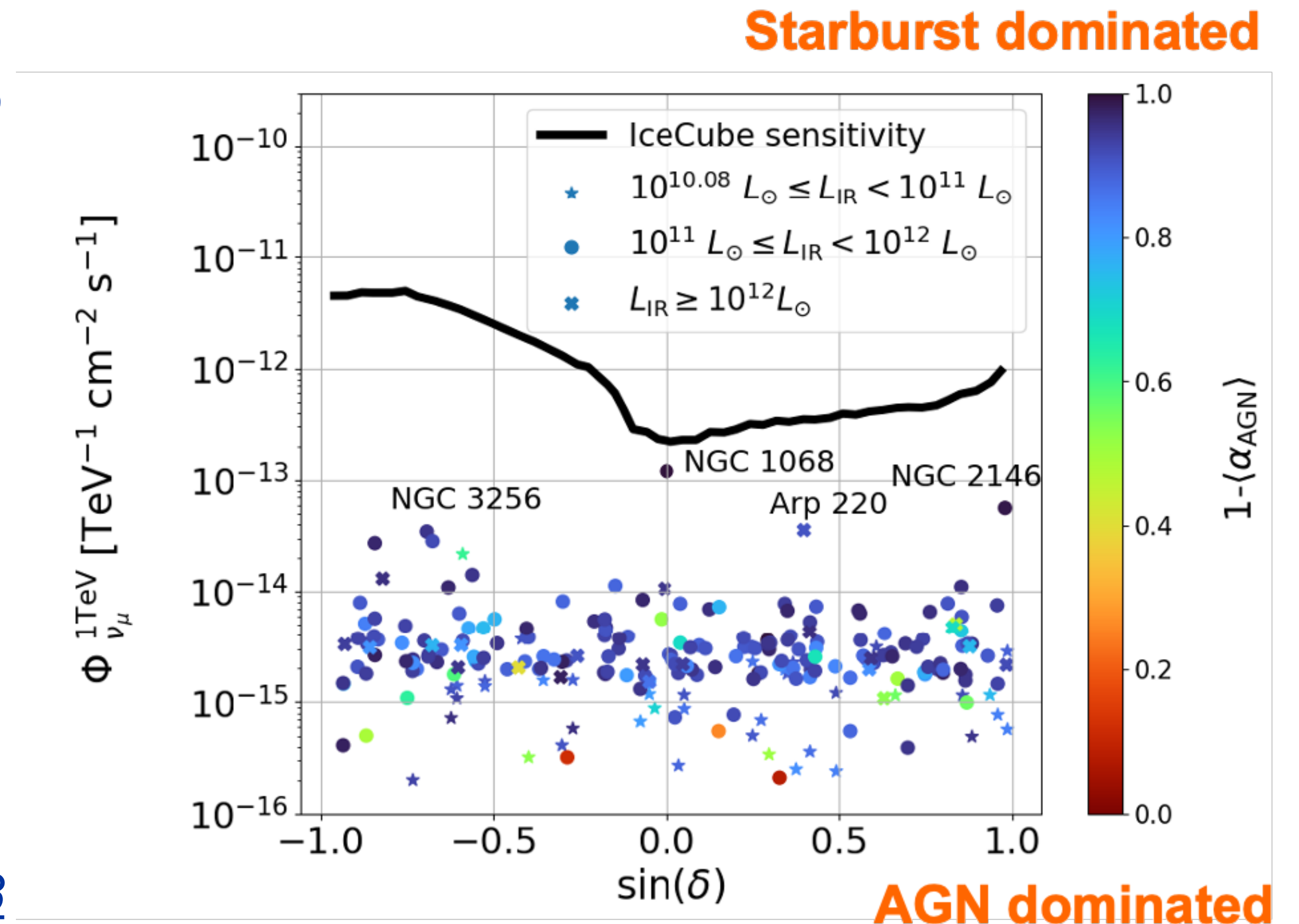
- Primarily interacting galaxies



Astrophysical Searches

U/LIRGs as ν -sources

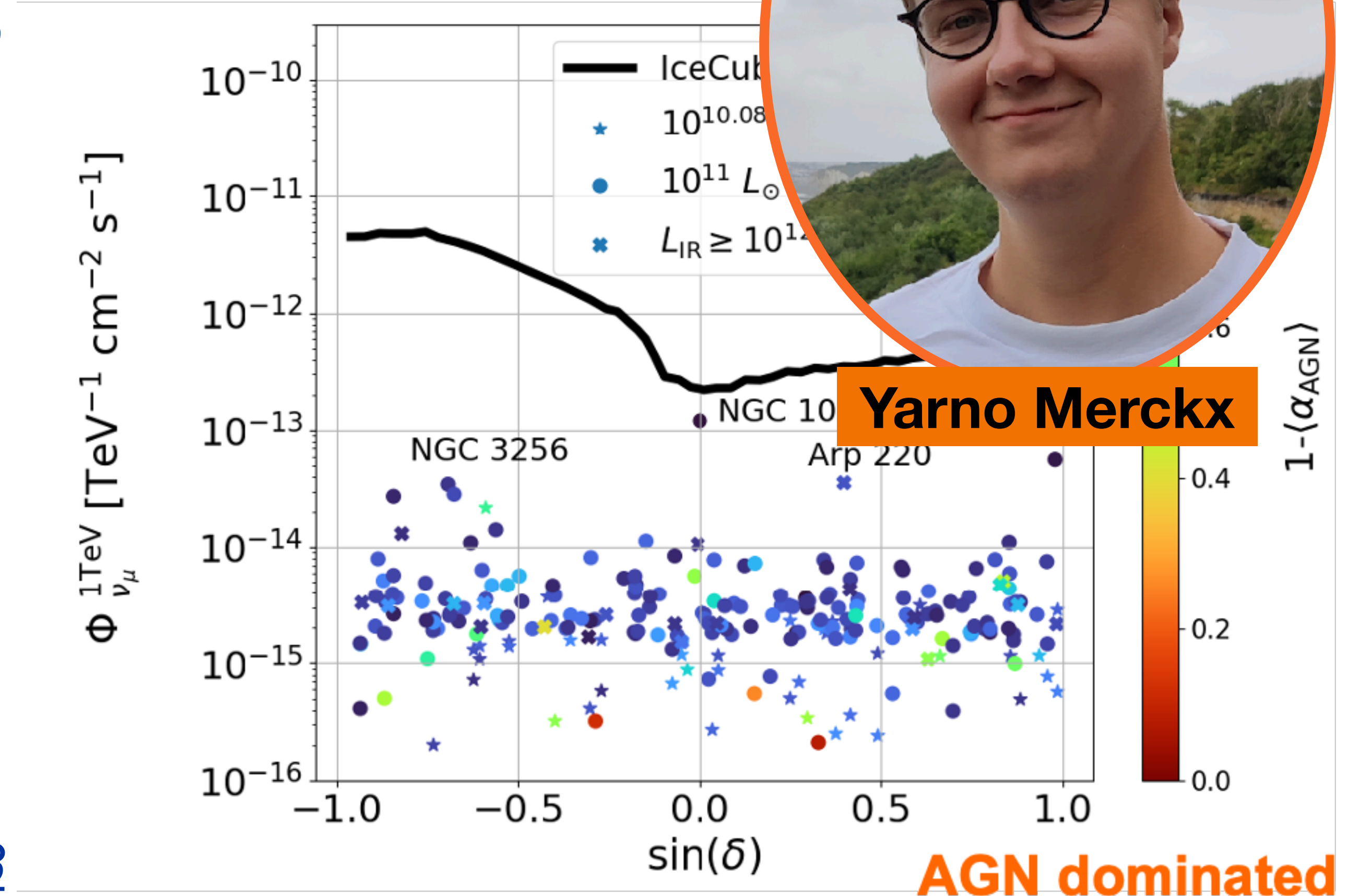
- Pheno framework for high-energy neutrino production in U/LIRGs
 - ✦ Focus on starburst activity
 - ✦ Multi-wavelength data from NASA telescopes as input
 - ✦ Applied to local U/LIRGS (see plot)
- Next up: IceCube analysis targeting promising U/LIRGs
- Motivated by the work in [*Phys. Rev. D* 108 \(2023\) 023015](#)



Astrophysical Searches

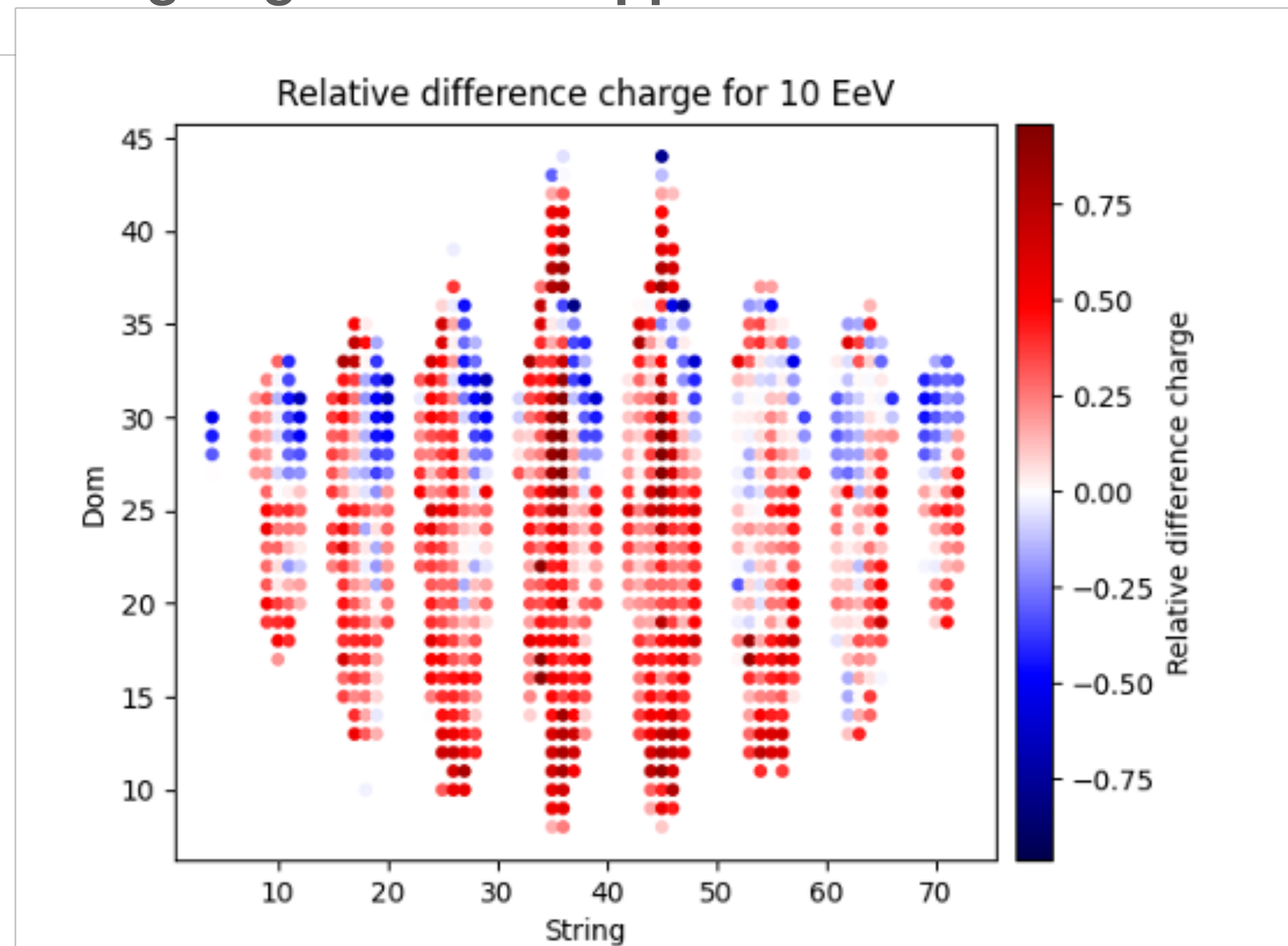
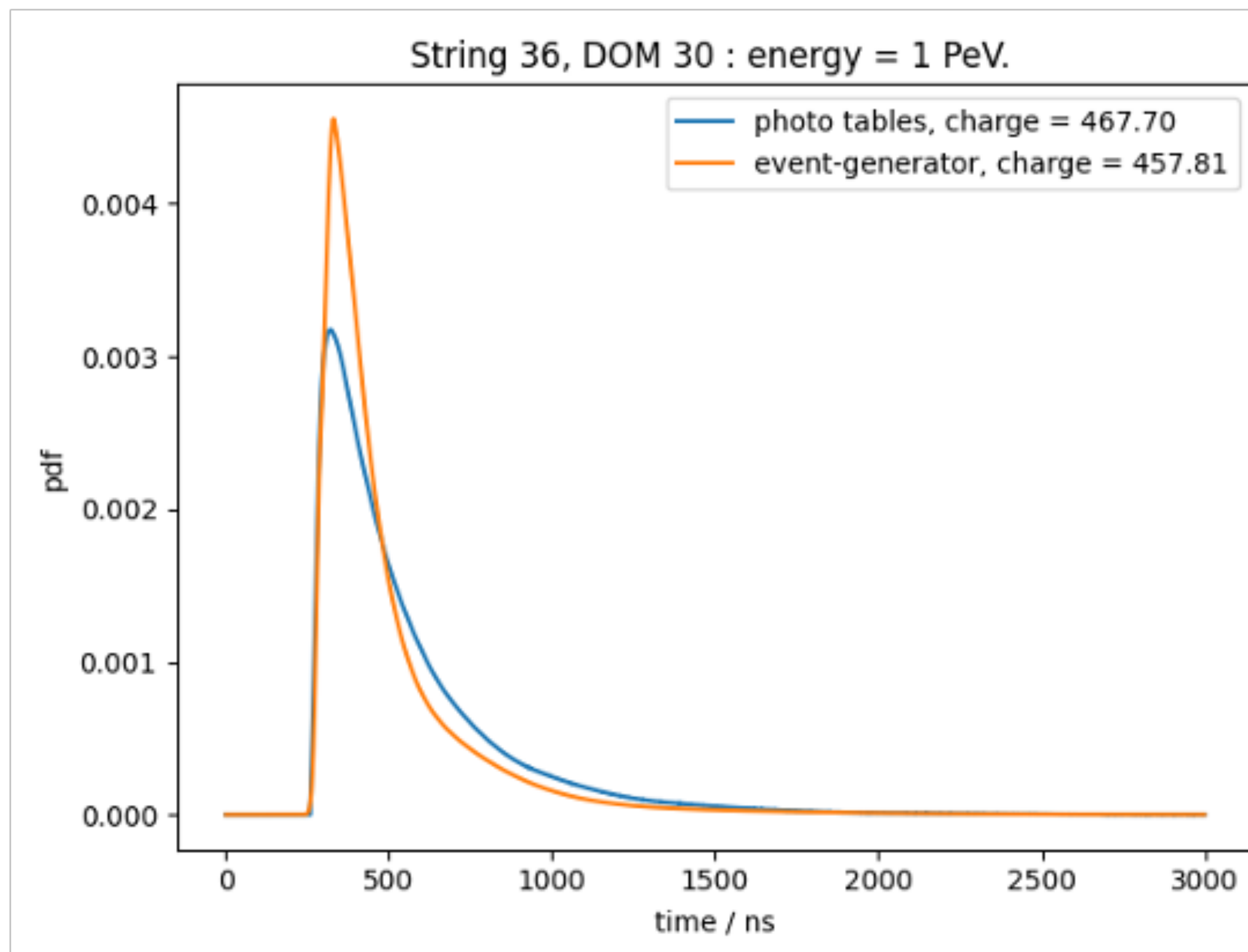
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Improving MC prediction for EHE analysis

- **EHE (Extremely High Energy) Analysis:** events of energies above 1 PeV
- Simulation of photoelectrons in IceCube optical module:
 - ➔ **Photonics Methods:** Simulations based on spline table
 - ➔ **Event-generator Methods:** Deep learning generative model
 - Currently only used for reconstruction → Ongoing works for application to event simulation.

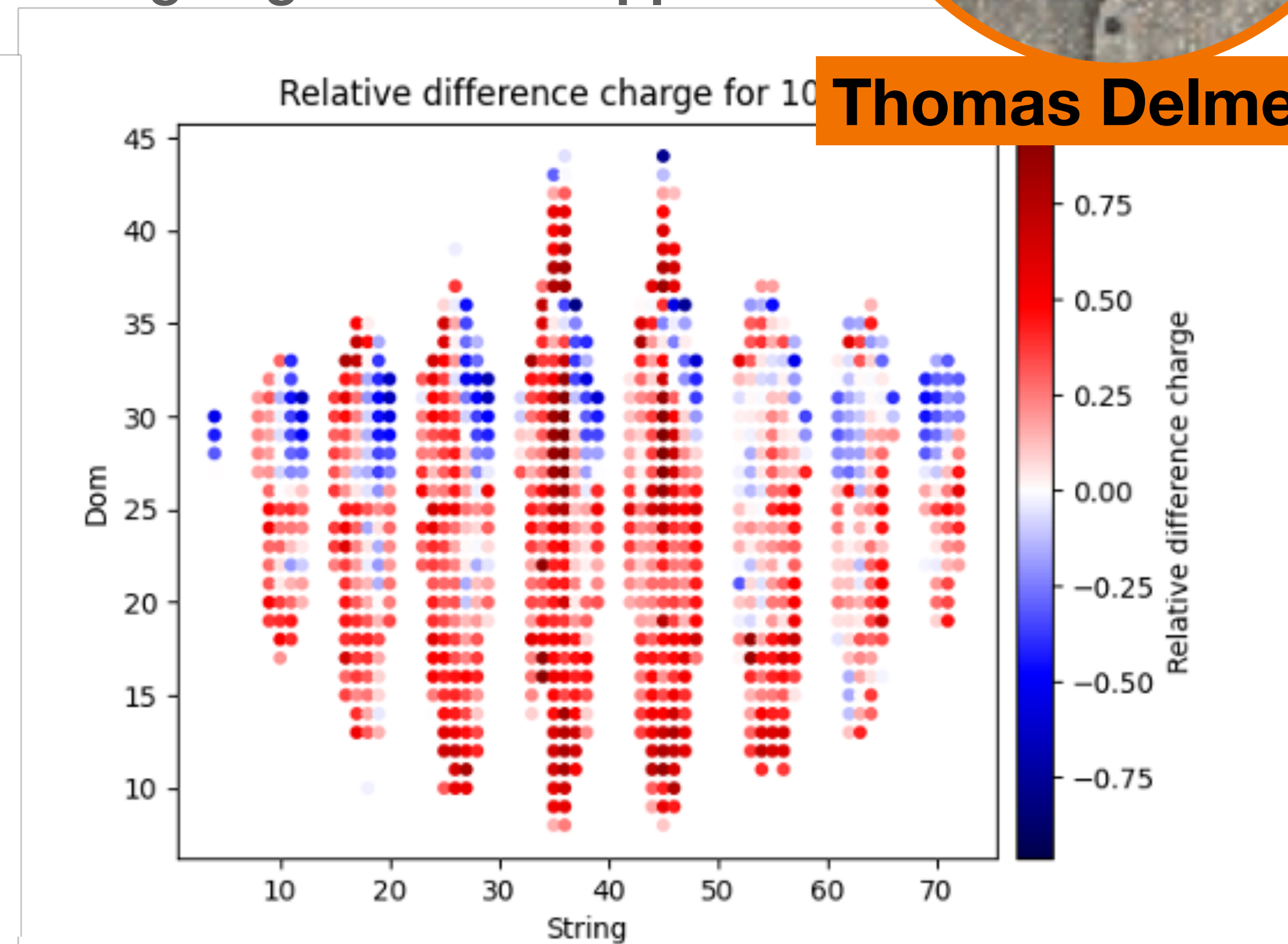
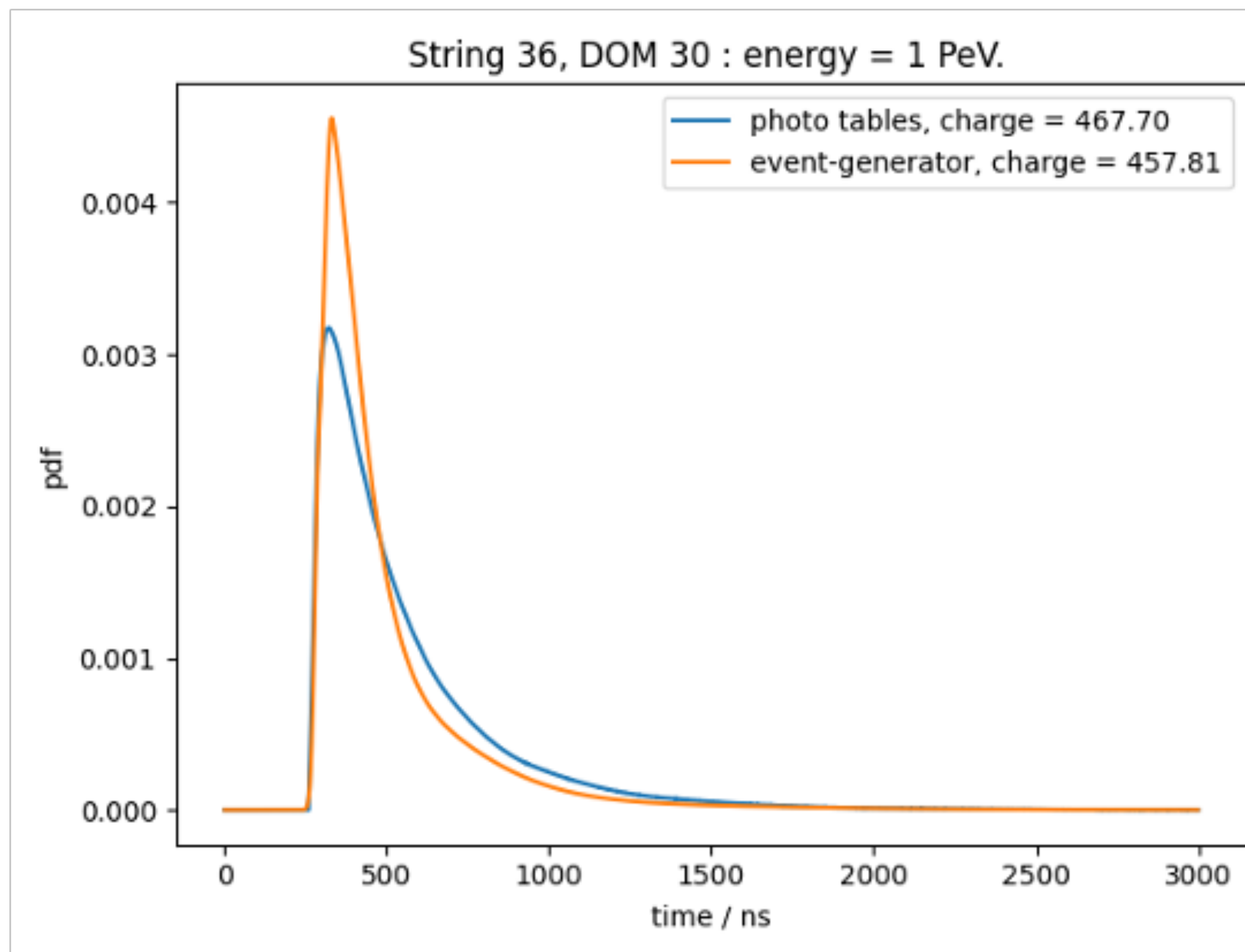


Improving MC prediction for EHE analysis

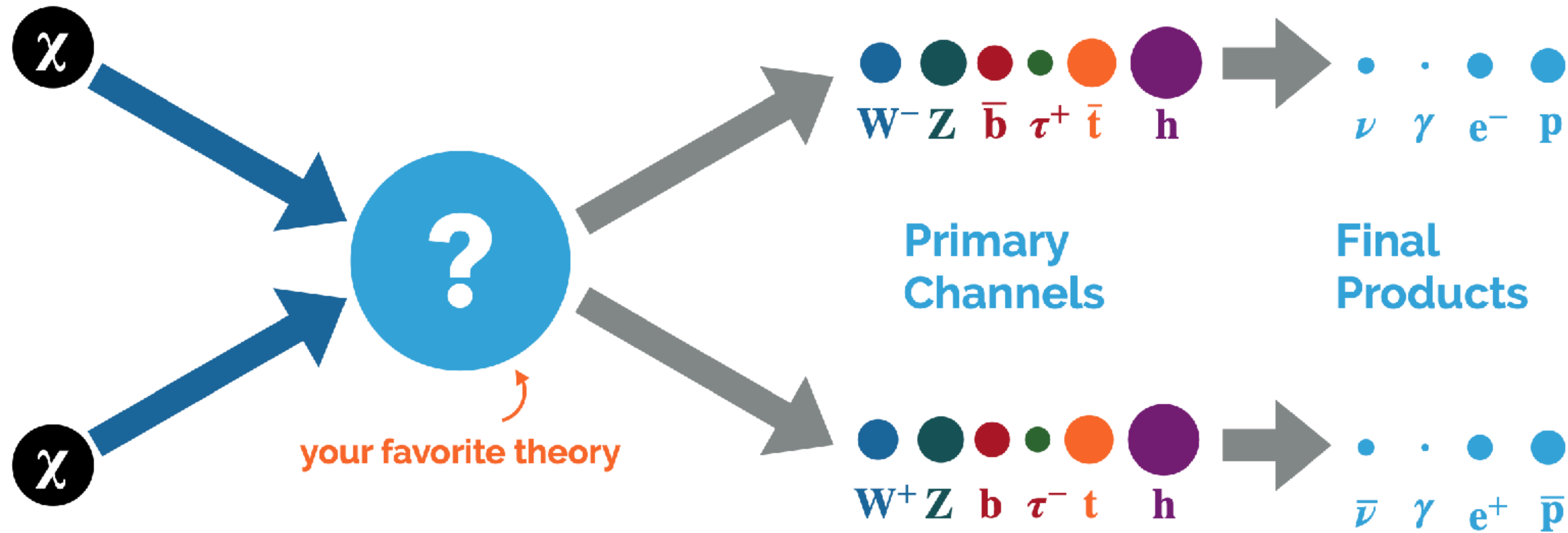
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Thomas Delmeulle



Dark Matter Searches

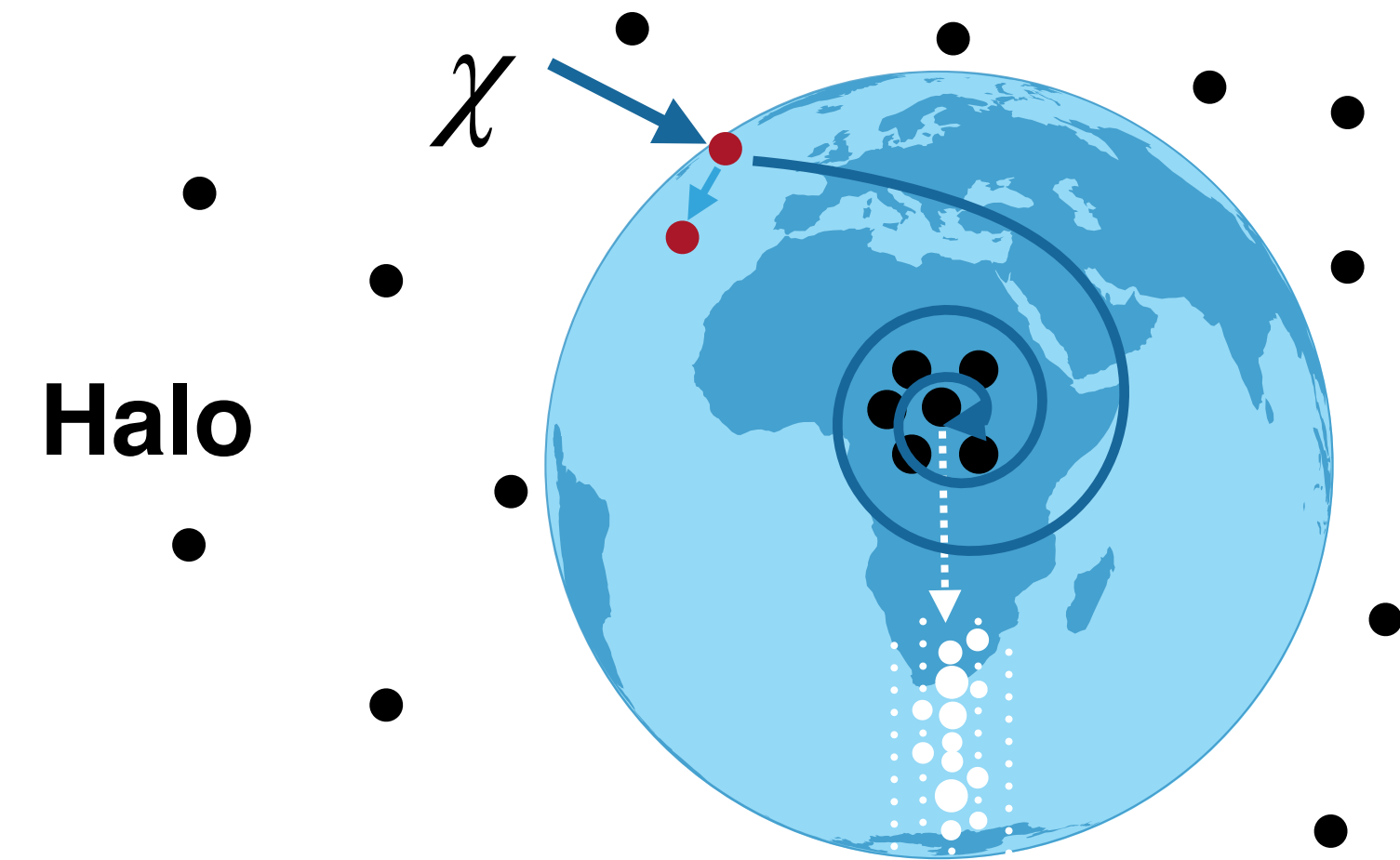


- Indirect searches: look for **anomalous SM flux** from **large reservoir of Dark Matter** (gravitationally trapped by heavy objects).
- Can make use of **the existing telescopes**.

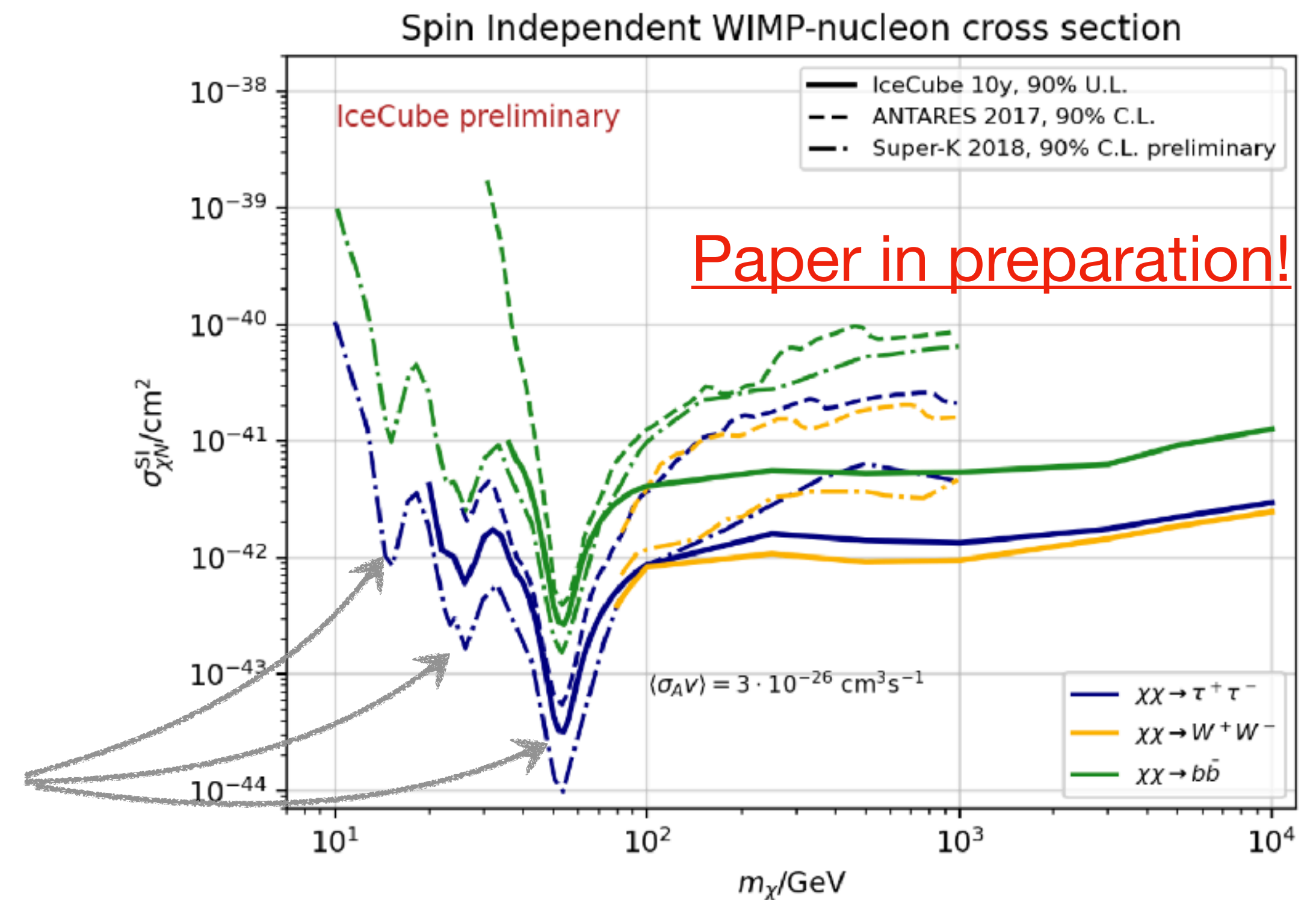
Dark Matter Searches from Earth

$$\frac{dN}{dt} = C_c - C_A N^2 - C_E N$$

C_c (capture) $\sigma_{\chi-N}$
 $C_A N^2$ (annihilation) σ_A
 $C_E N$ ("evaporation")



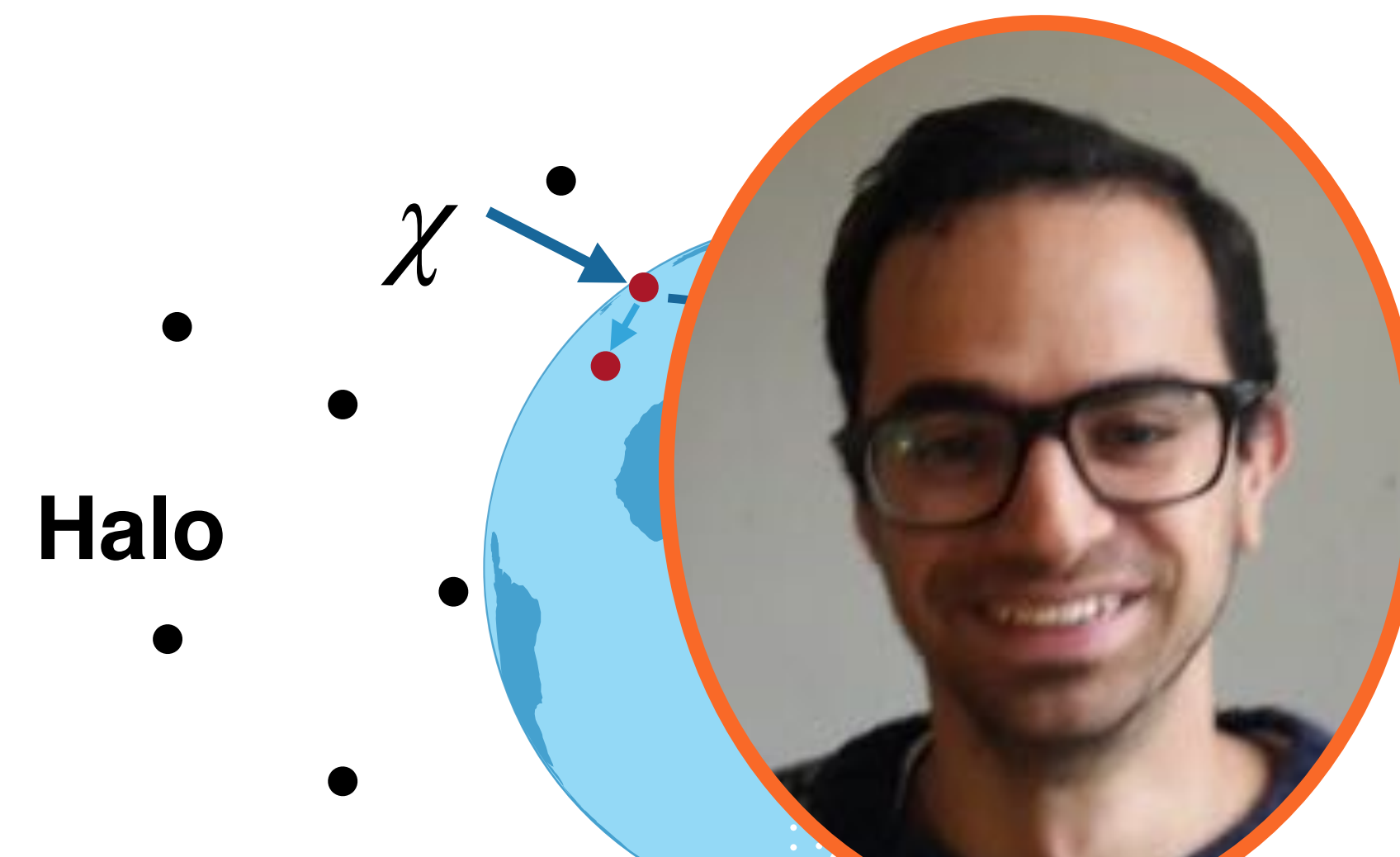
- Dark matter gravitationally trapped inside celestial bodies (Sun, **Earth**)
 - ▶ ν is the only possible messenger!
- Probe dark matter - nucleon cross section:
 - ▶ **Earth** (mainly spin-0 isotopes: ^{56}Fe , ^{28}Si , ^{16}O): spin-independent σ_{SI}
- Mass resonances cause by Earth isotopes



Dark Matter Searches from Earth

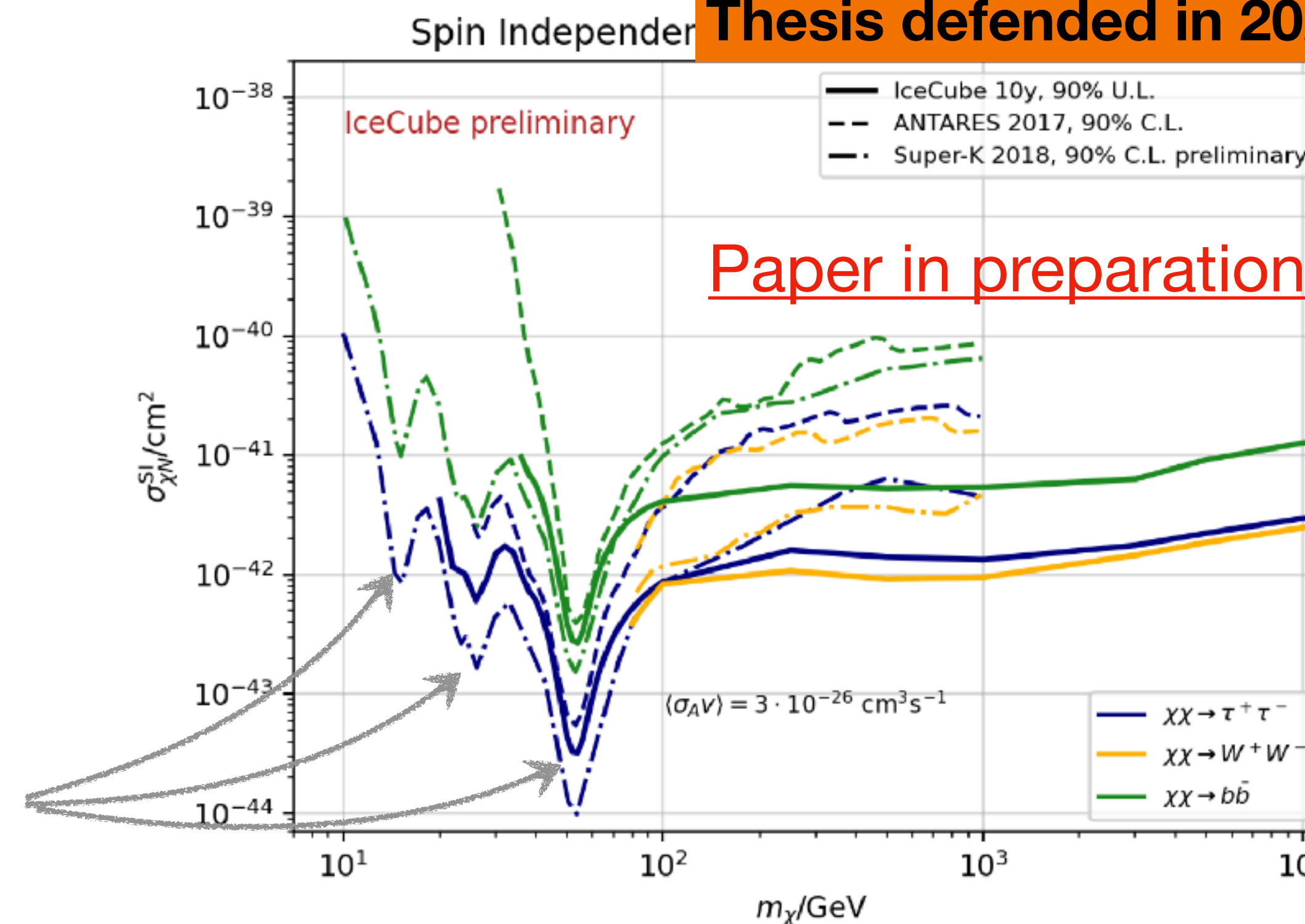
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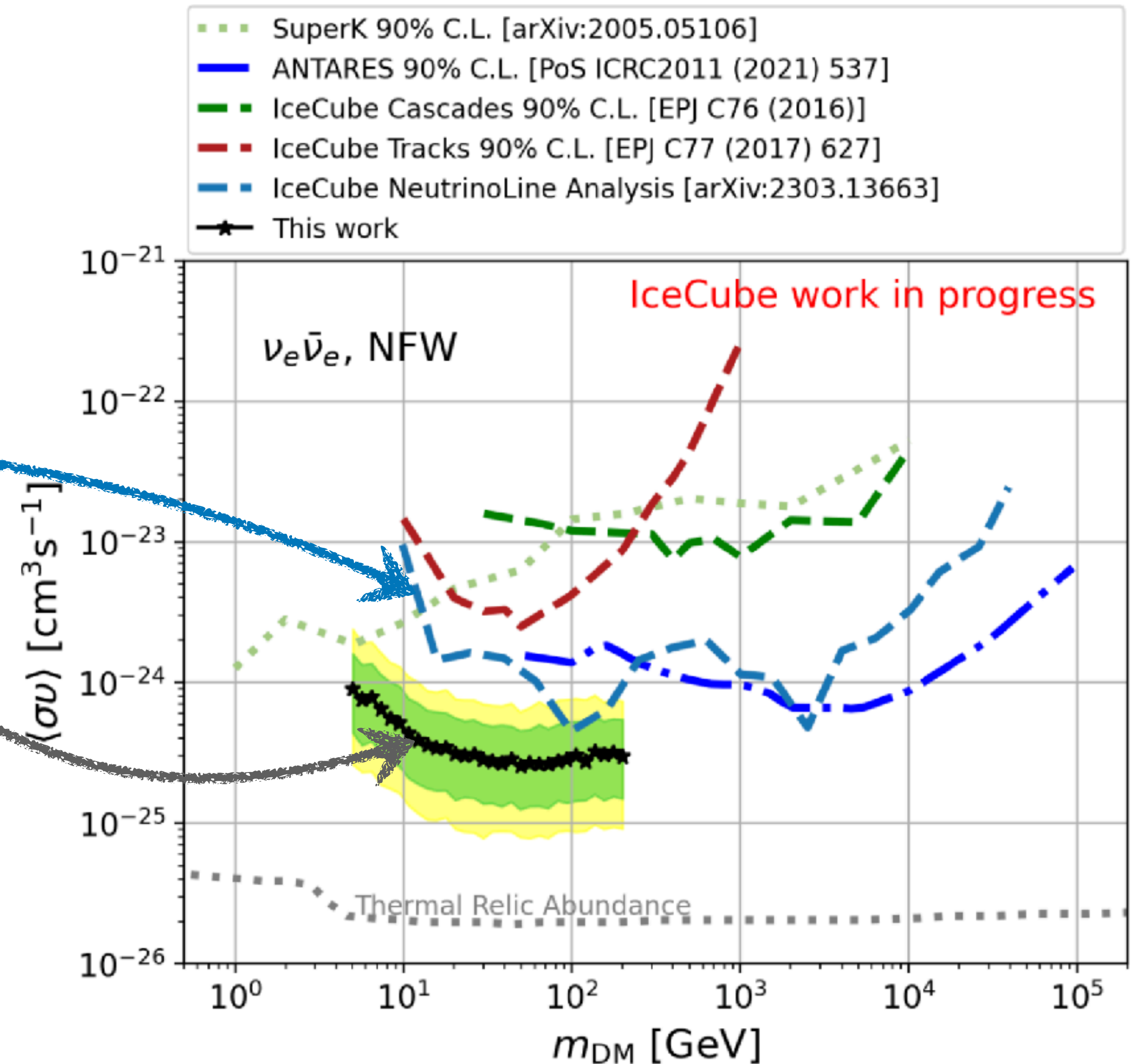
Giovanni Renzi
Thesis defended in 2022

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Dark Matter Searches from Galactic Centre

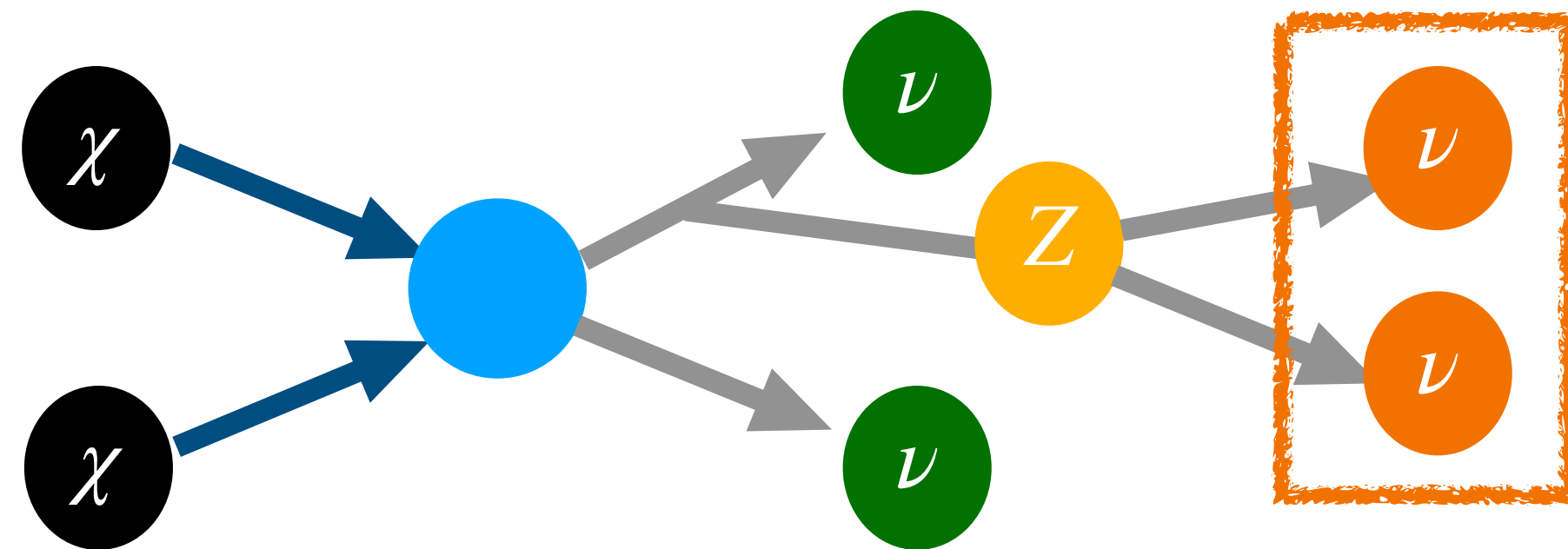
- Neutrino signals from **Dark Matter annihilation/decay in the Galactic Centre**
- First analysis using **energy and the neutrino spectra (Neutrino Lines)** with the theory group @ ULB.
 - Paper published to PRD (*PhysRevD.108.102004*)
- Extended and improved limit at lower masses (**GeV-scale Dark Matter**) with **DeepCore data**
 - Unblinded results (no DM, set 90% limits) and paper in preparation
- **Best limits in neutrino channels**



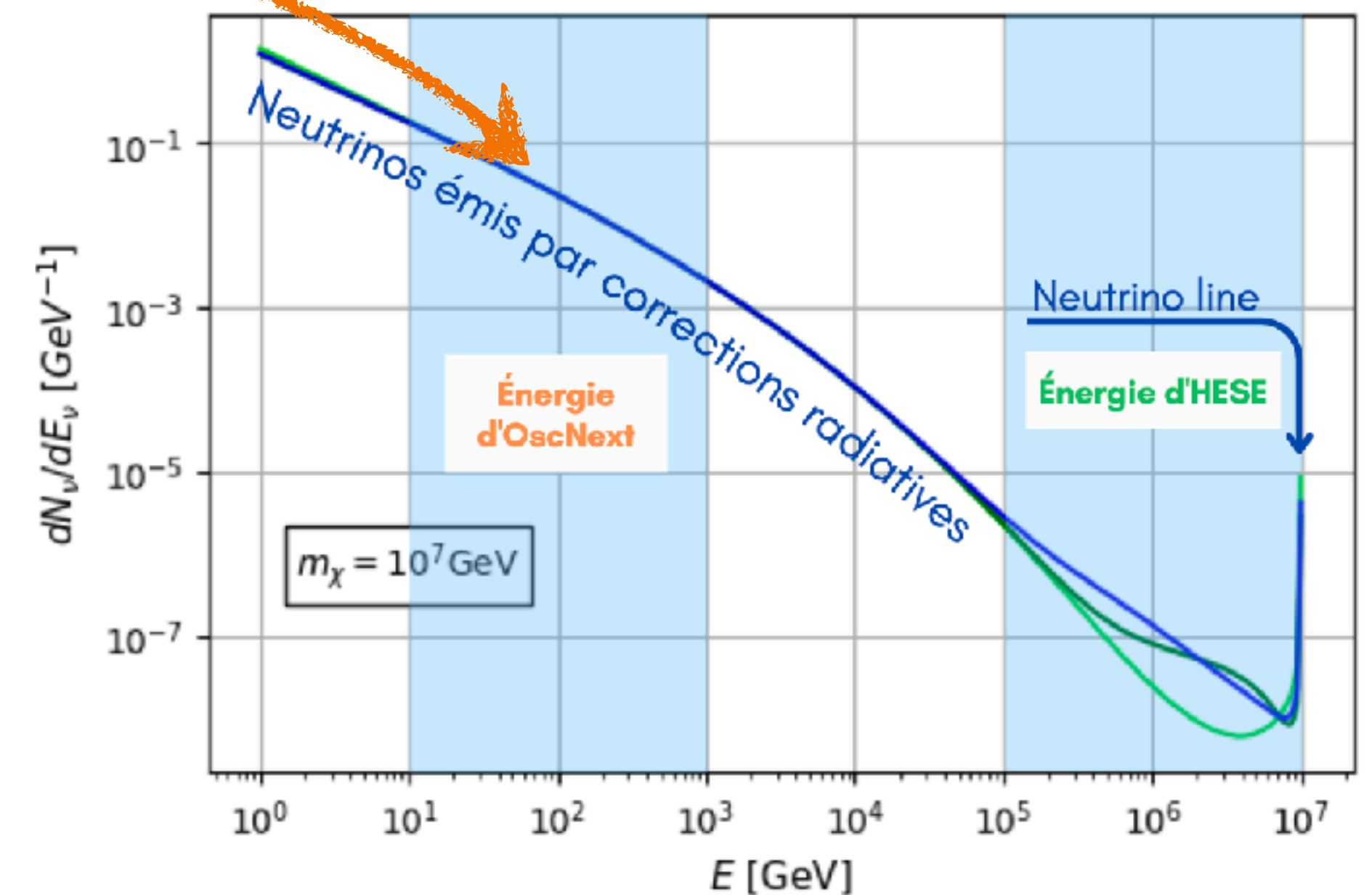
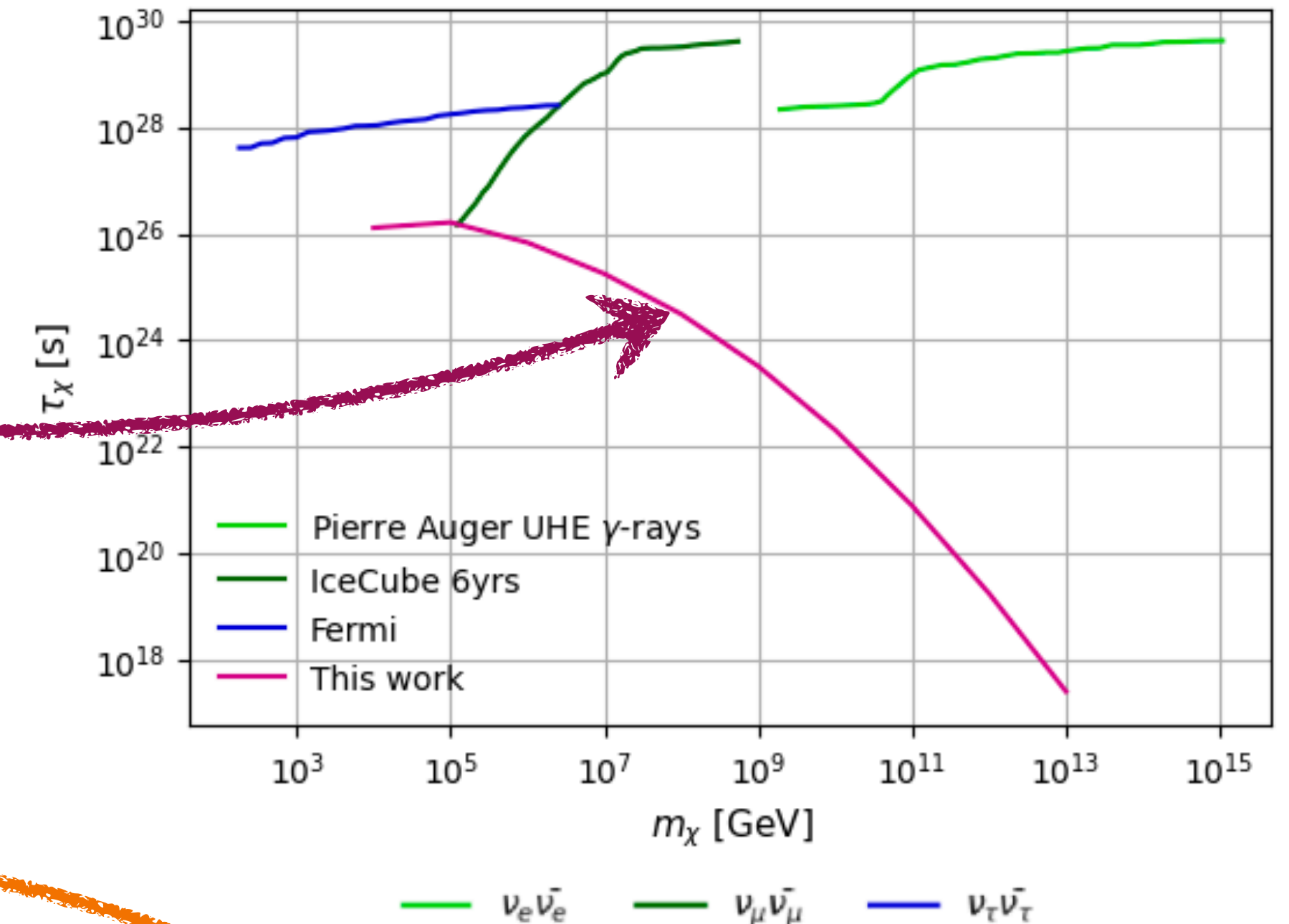
Dark Matter Searches from Galactic Centre

- Ongoing activities with **Super-heavy Dark Matter** ($m > 100 \text{ TeV}$)
- Preliminary sensitivity with DeepCore data i.e low energy events (GeV)

▸ Search for signal from EW correction

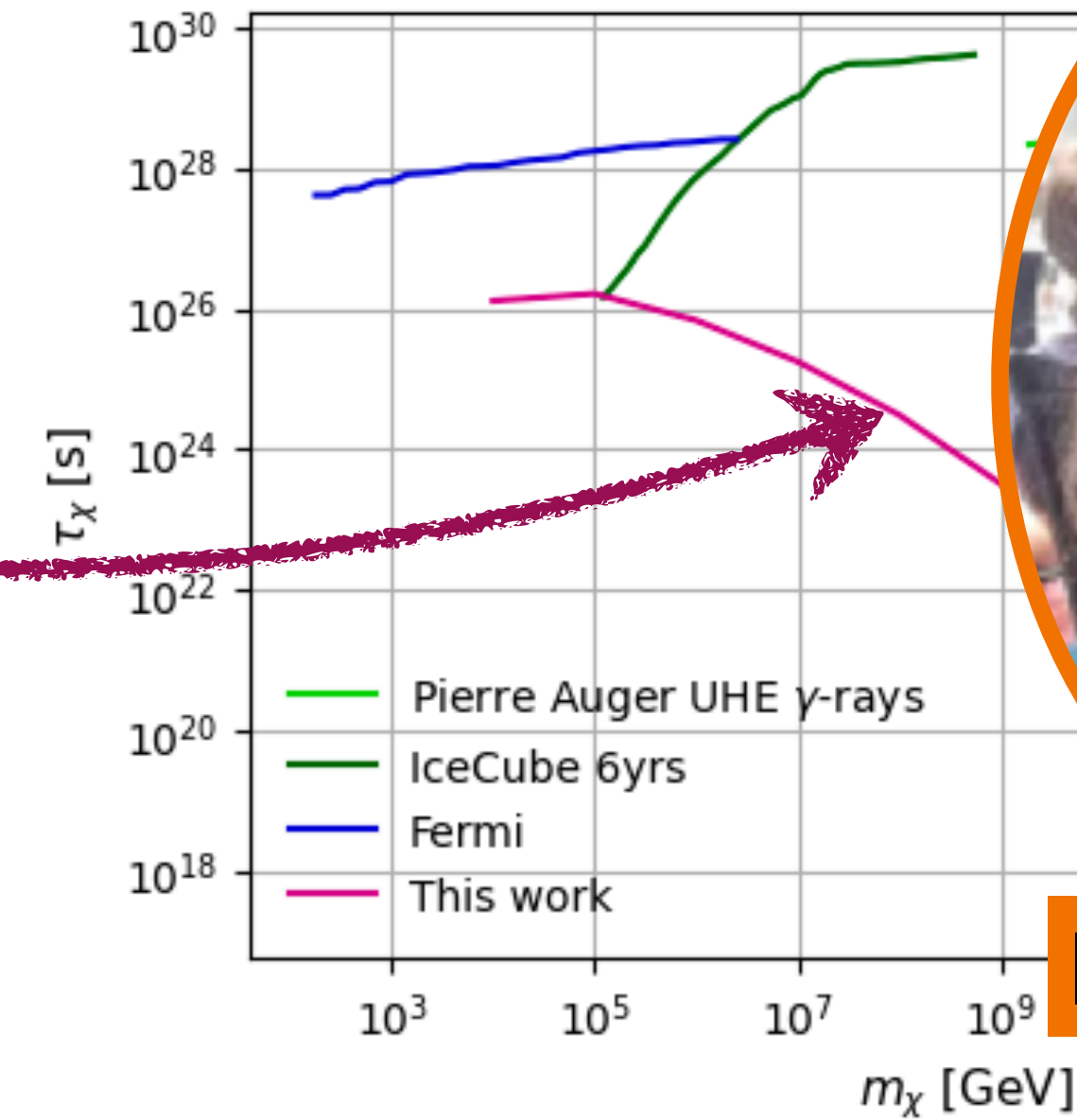
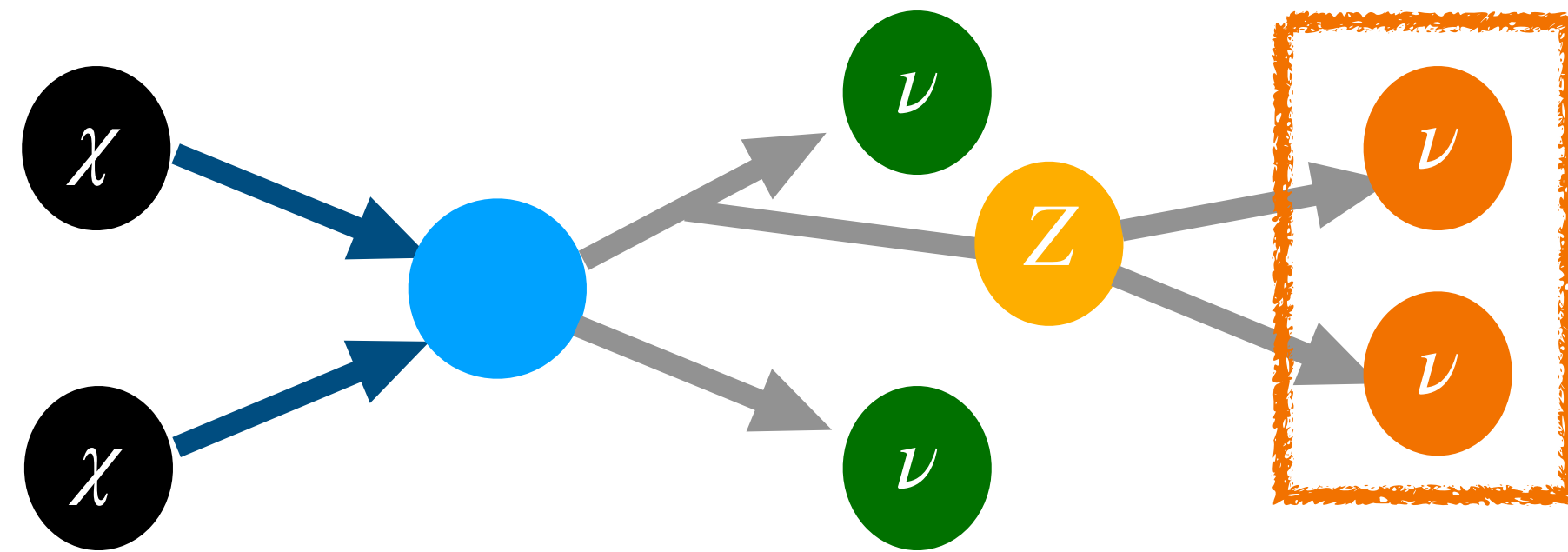


- Follow up works with high energy samples and a combination of both low and high energy data.



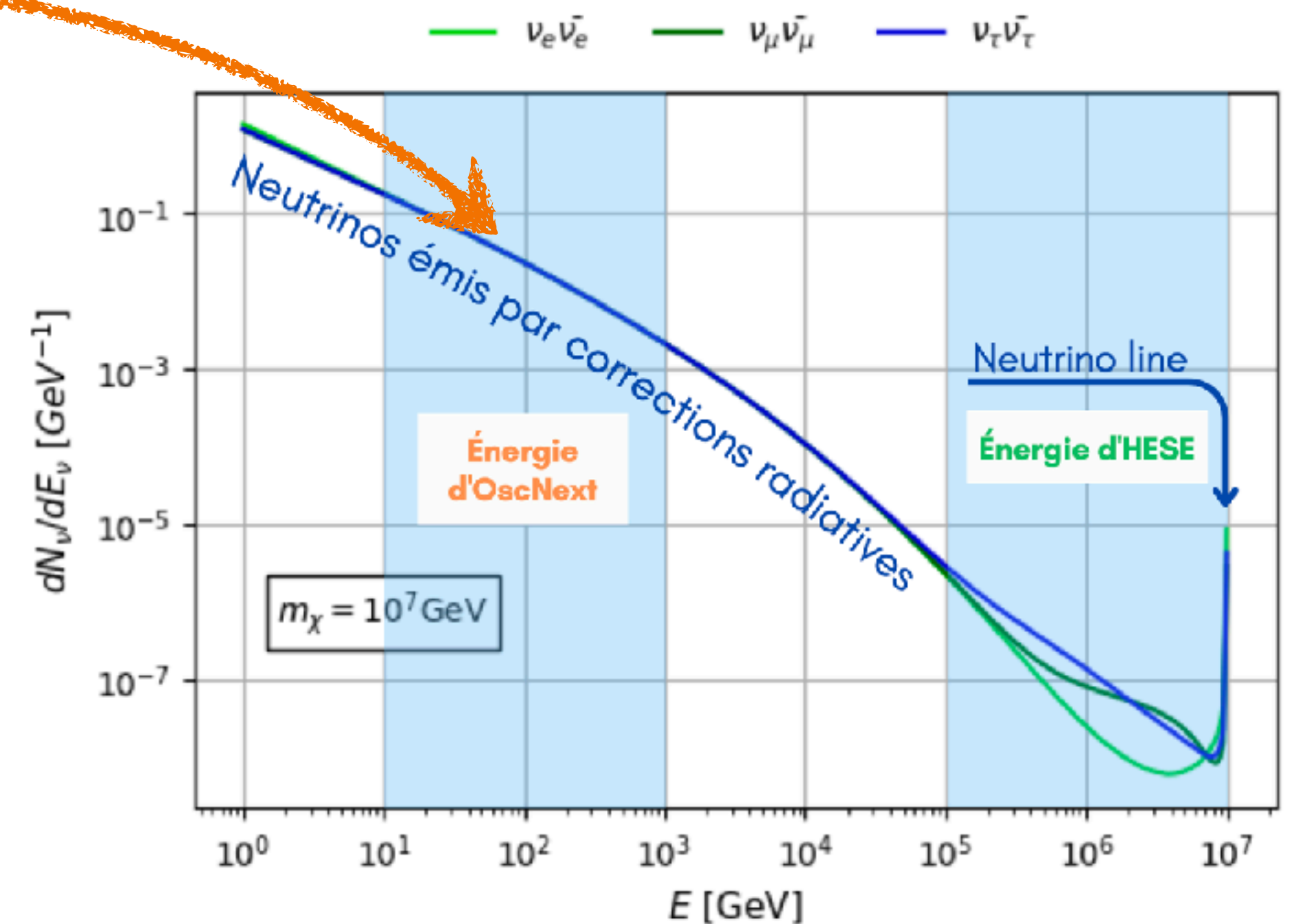
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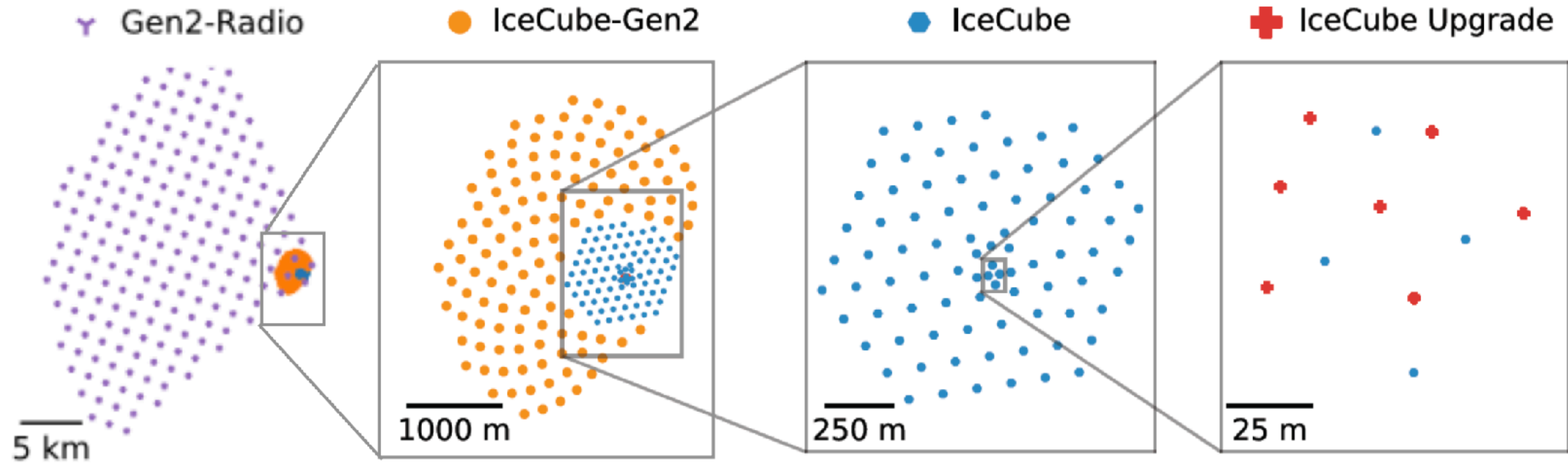


Danaé Valdenaire

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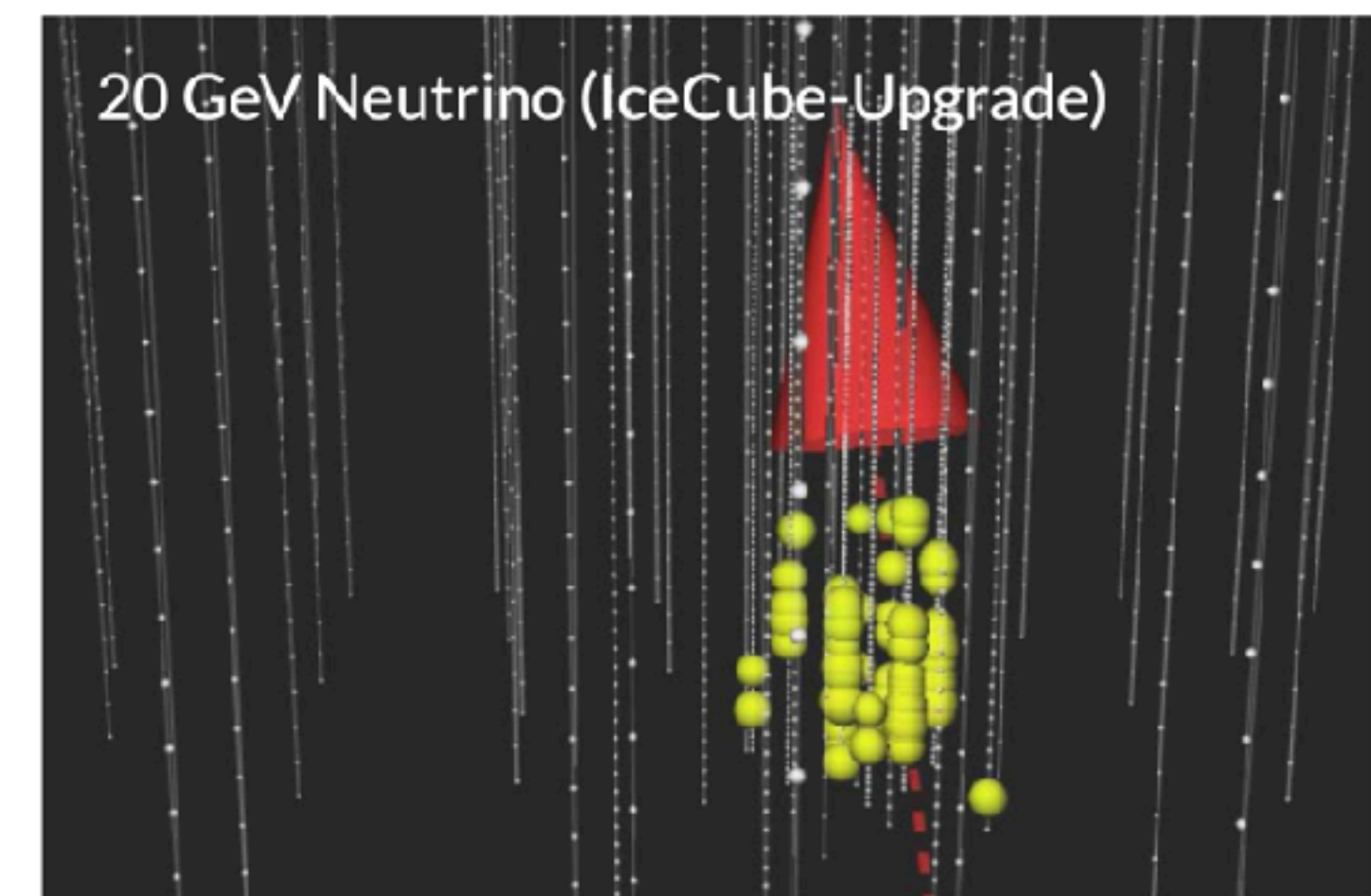
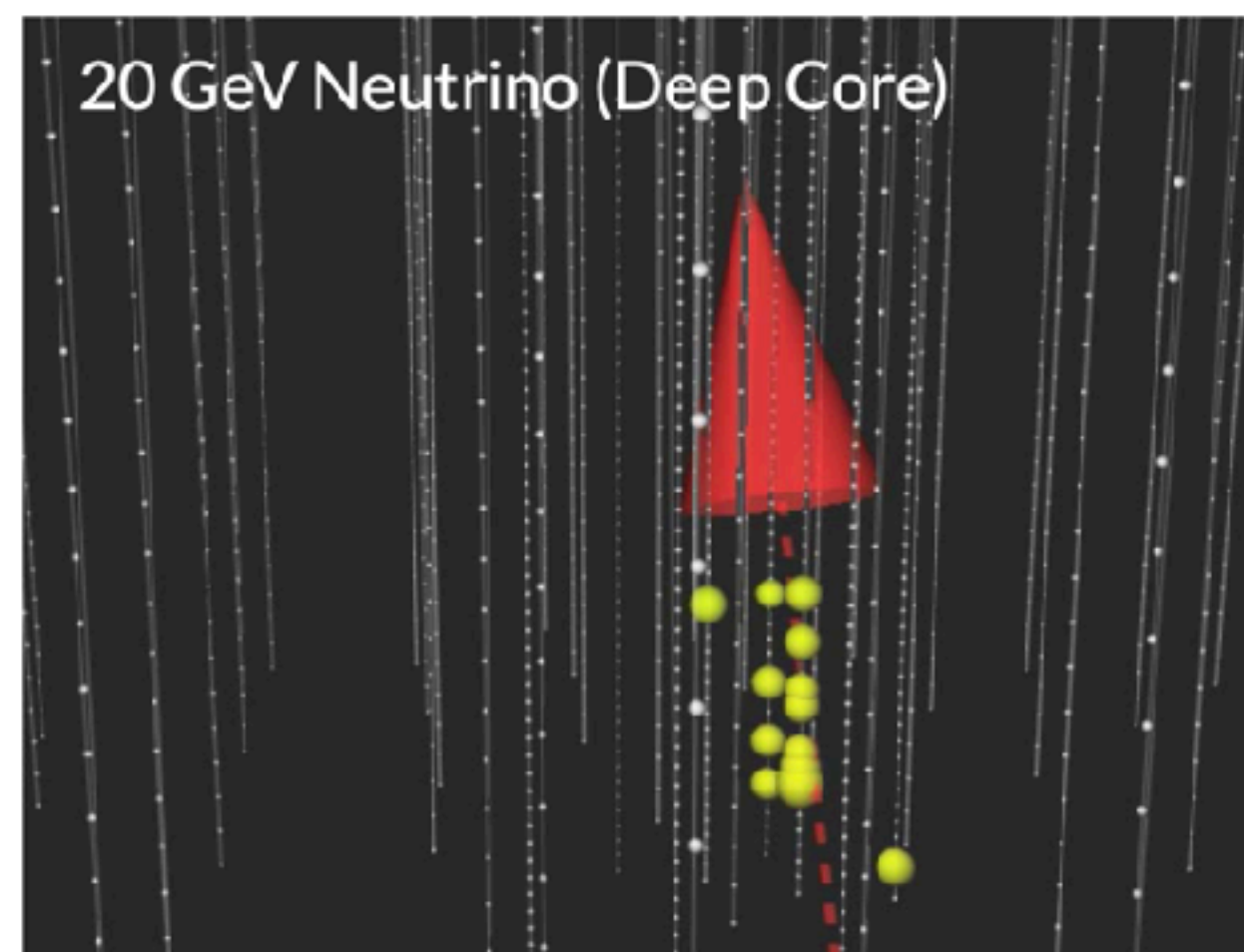
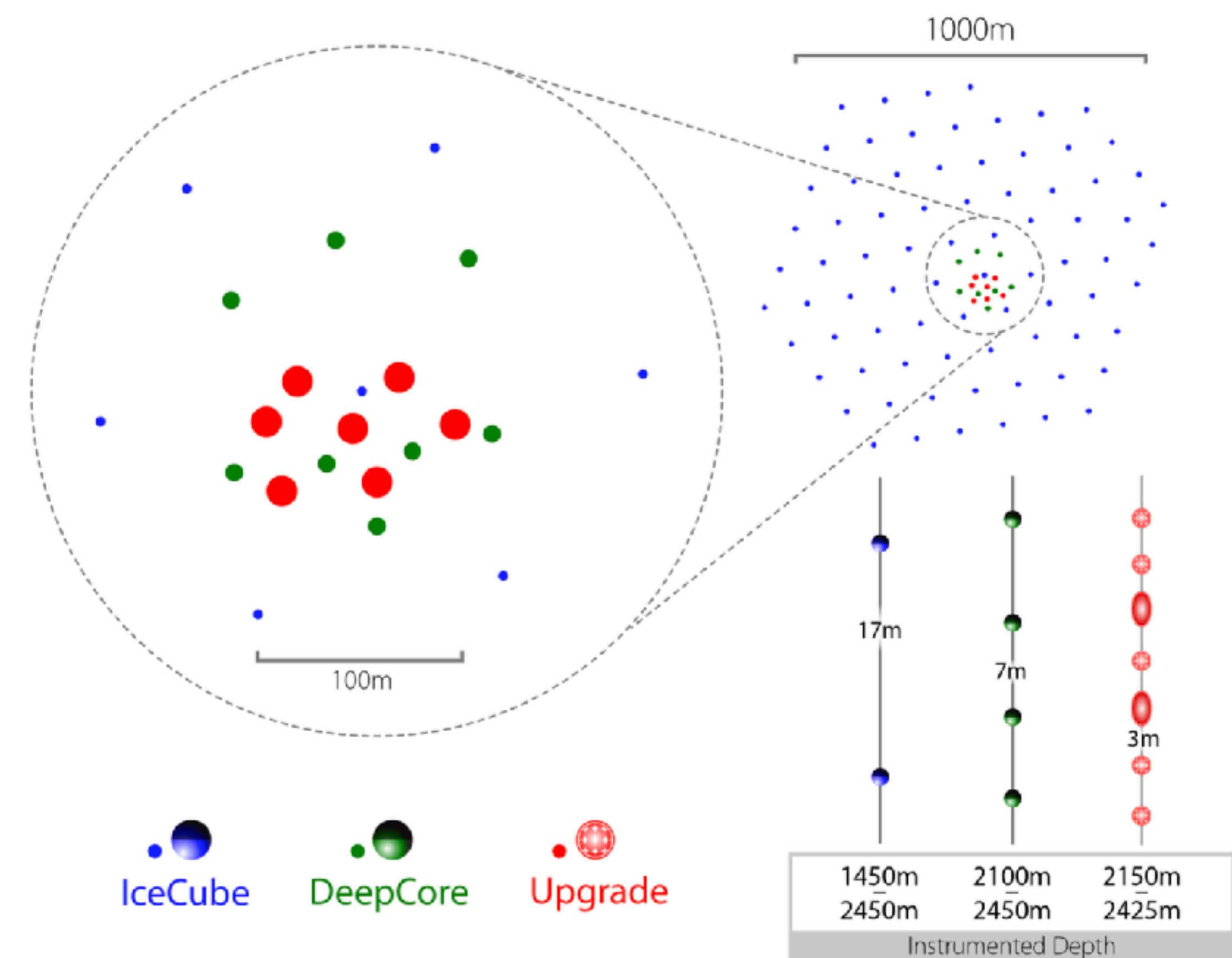


The future of IceCube: Upgrade and Gen2



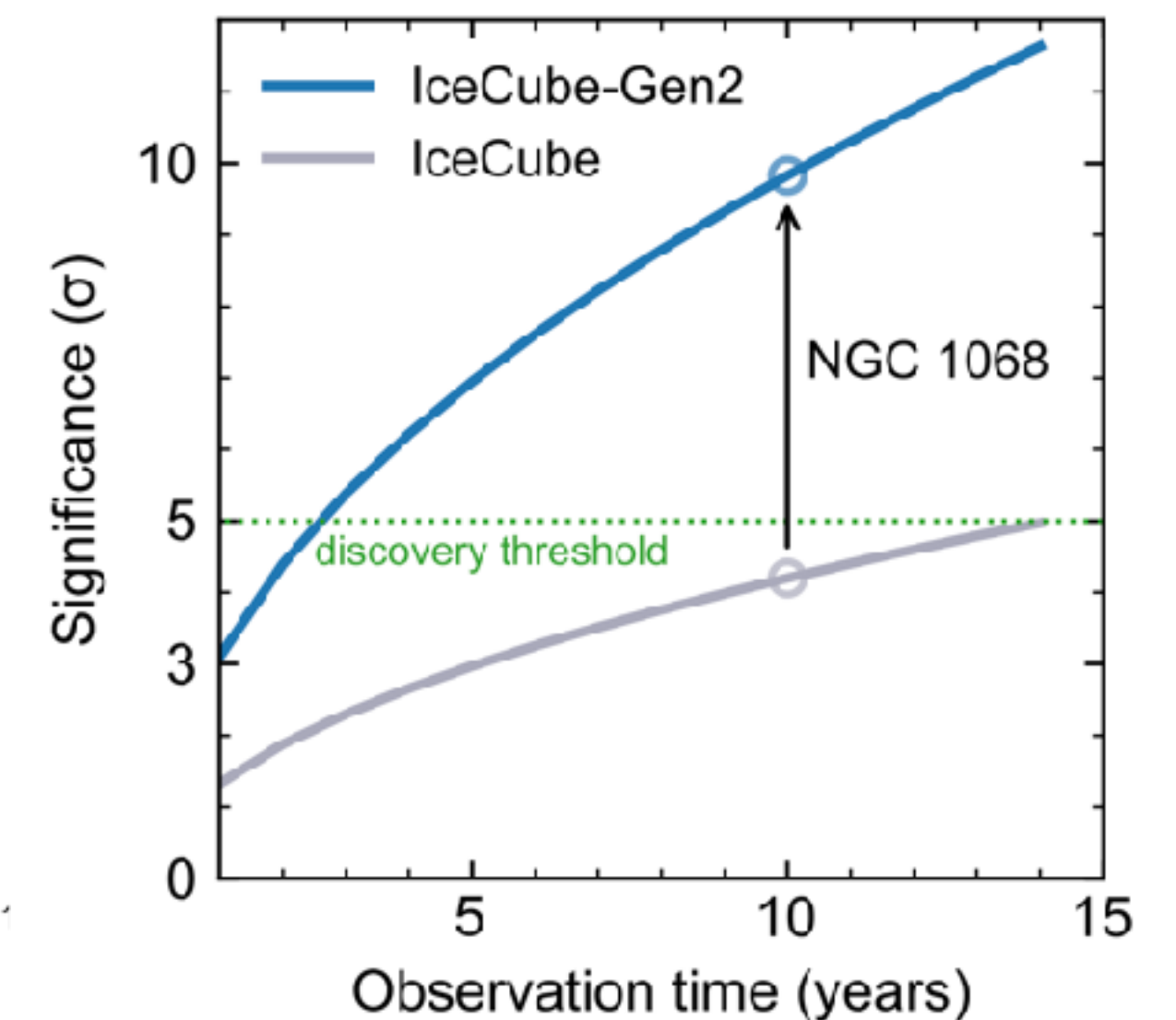
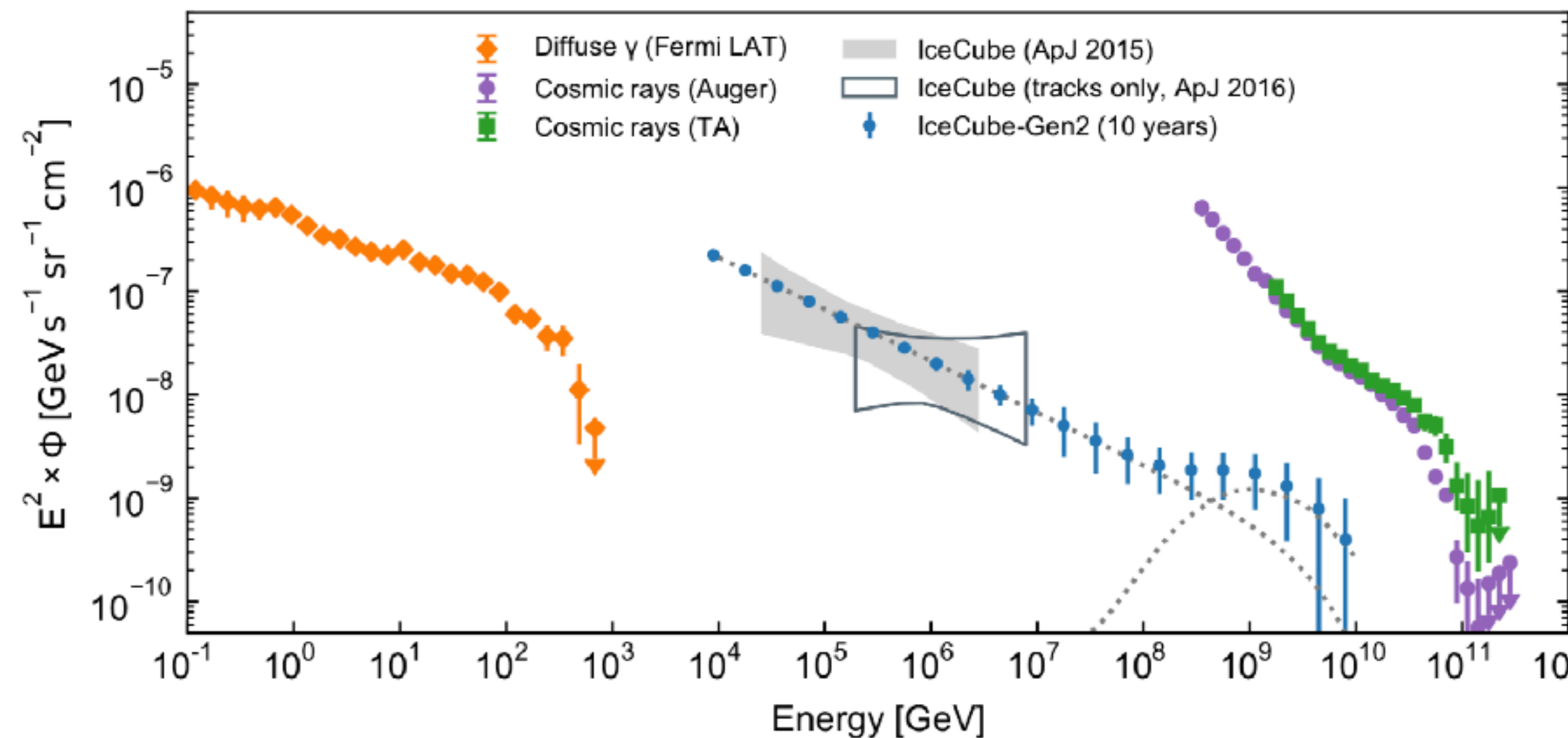
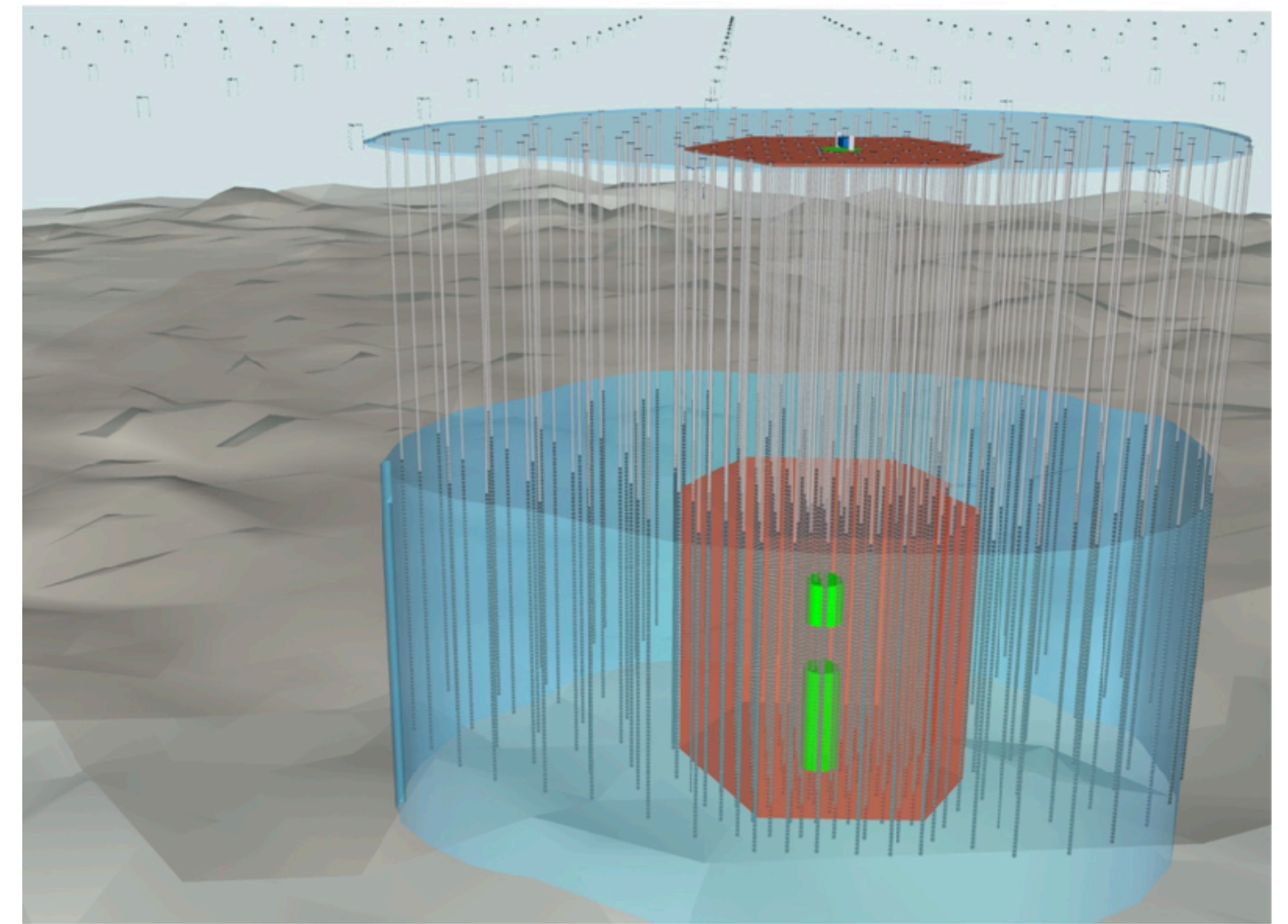
IceCube-Upgrade

- Deployment planned for 2025-2026
- Ice calibration, better control of the systematics
- Improved energy and angular reconstruction
- Reprocess of existing data with new calibration/ice model/reconstruction!
- Precision measurement of atmospheric neutrino oscillations.
- @IIHE: ongoing work for sensitivity with Dark Matter search!



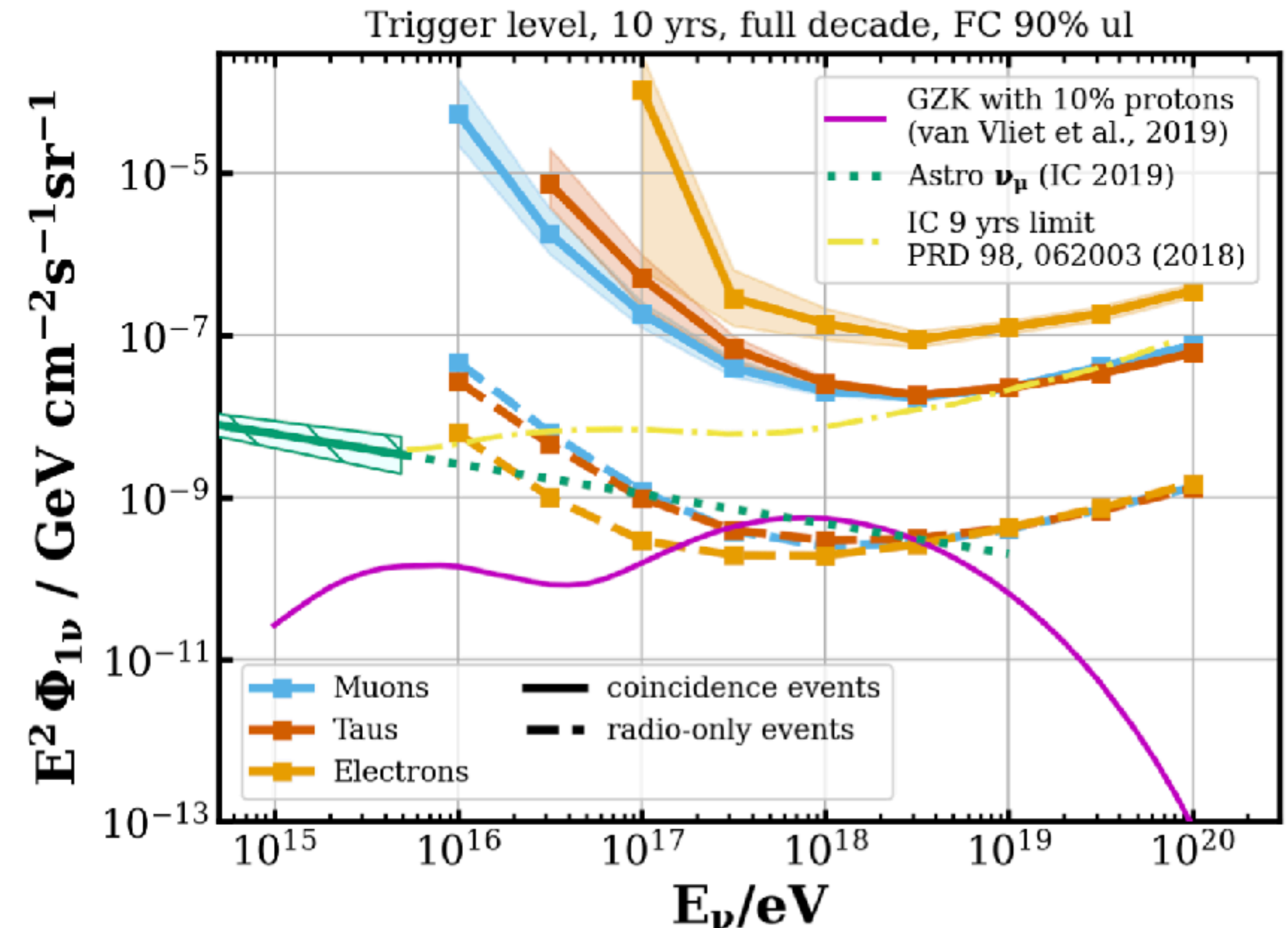
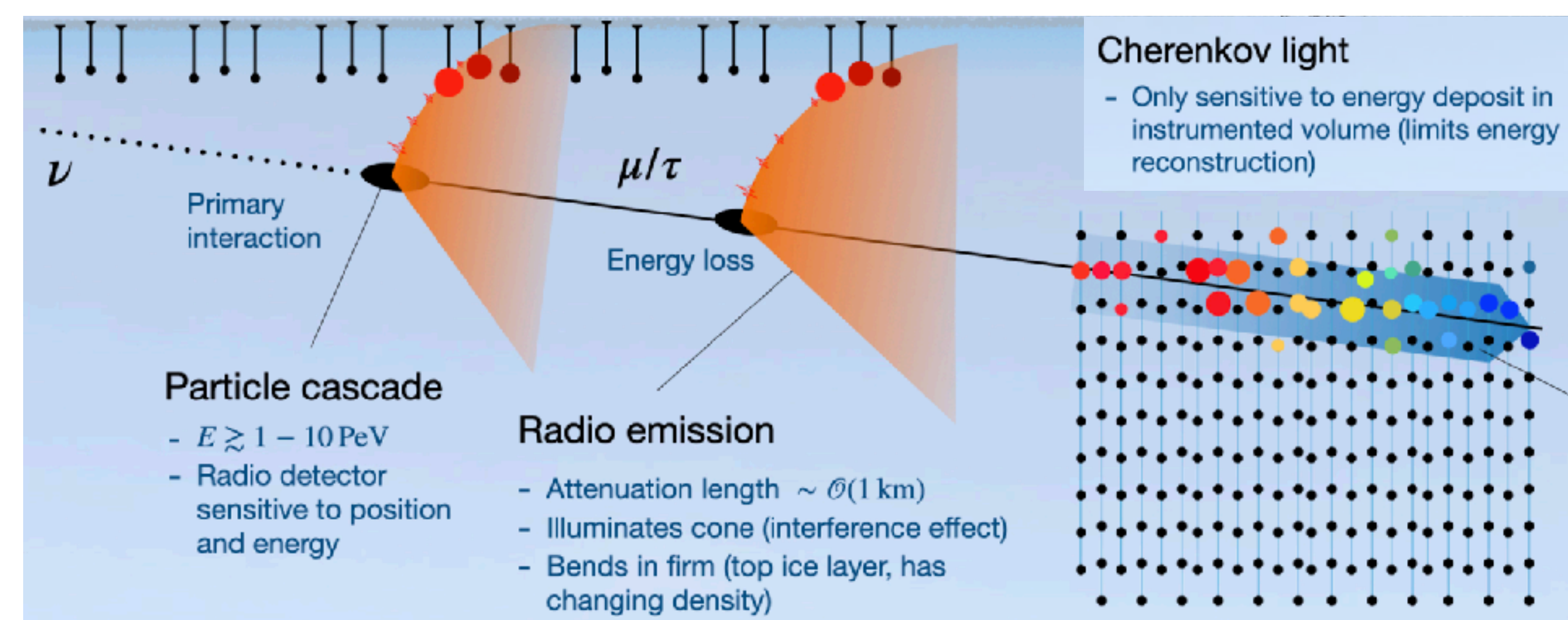
IceCube-Gen2

- Enlarge deep optical array
- Extension of Surface Array
- New shallow Radio Array
- ▶ A sensitivity five times greater than that of IceCube
- ▶ Extend and enhance the sensitivity beyond EeV



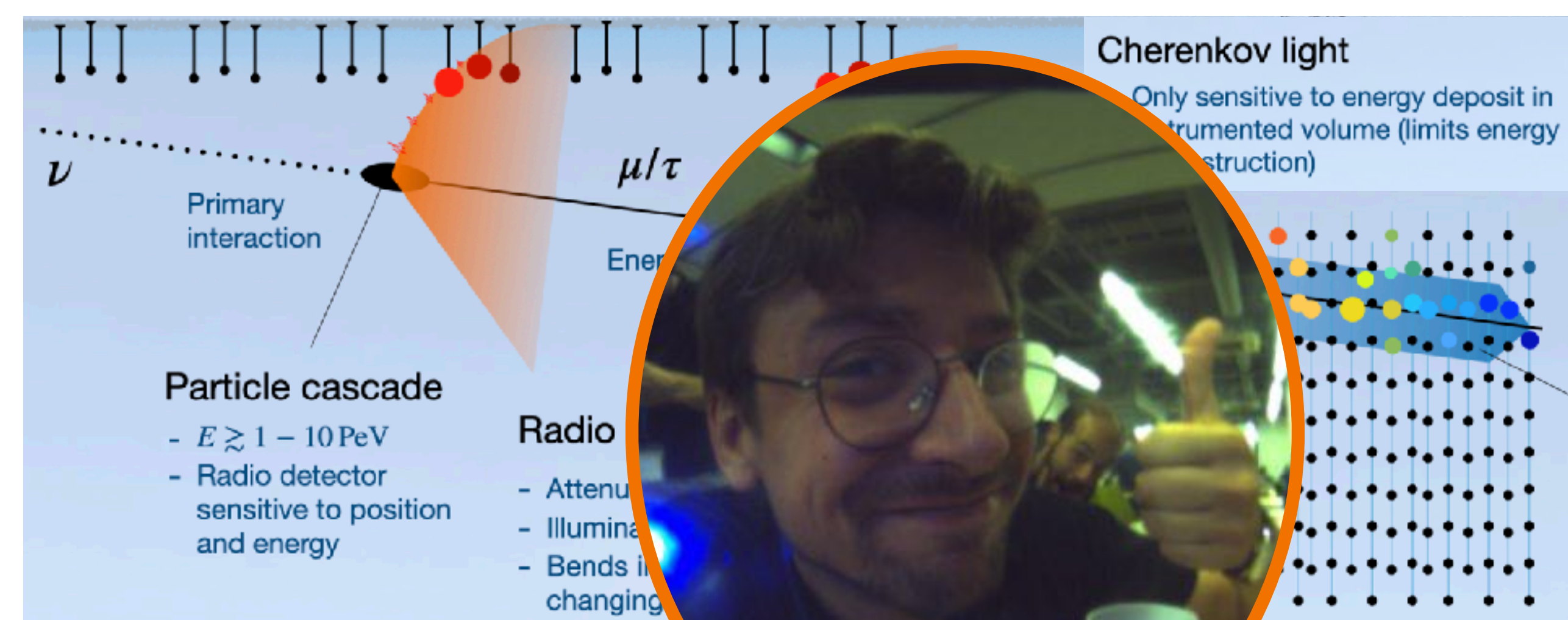
IceCube-Gen2 @ IHE

- Simulation of **radio-optical coincidence events**
- Radio: cascade from ν interaction;
Optical: μ track and tau leptons
- ➔ Complementary information for reconstruction with high fidelity
- ➔ Opportunities for systematics study + cross-calibrate both components

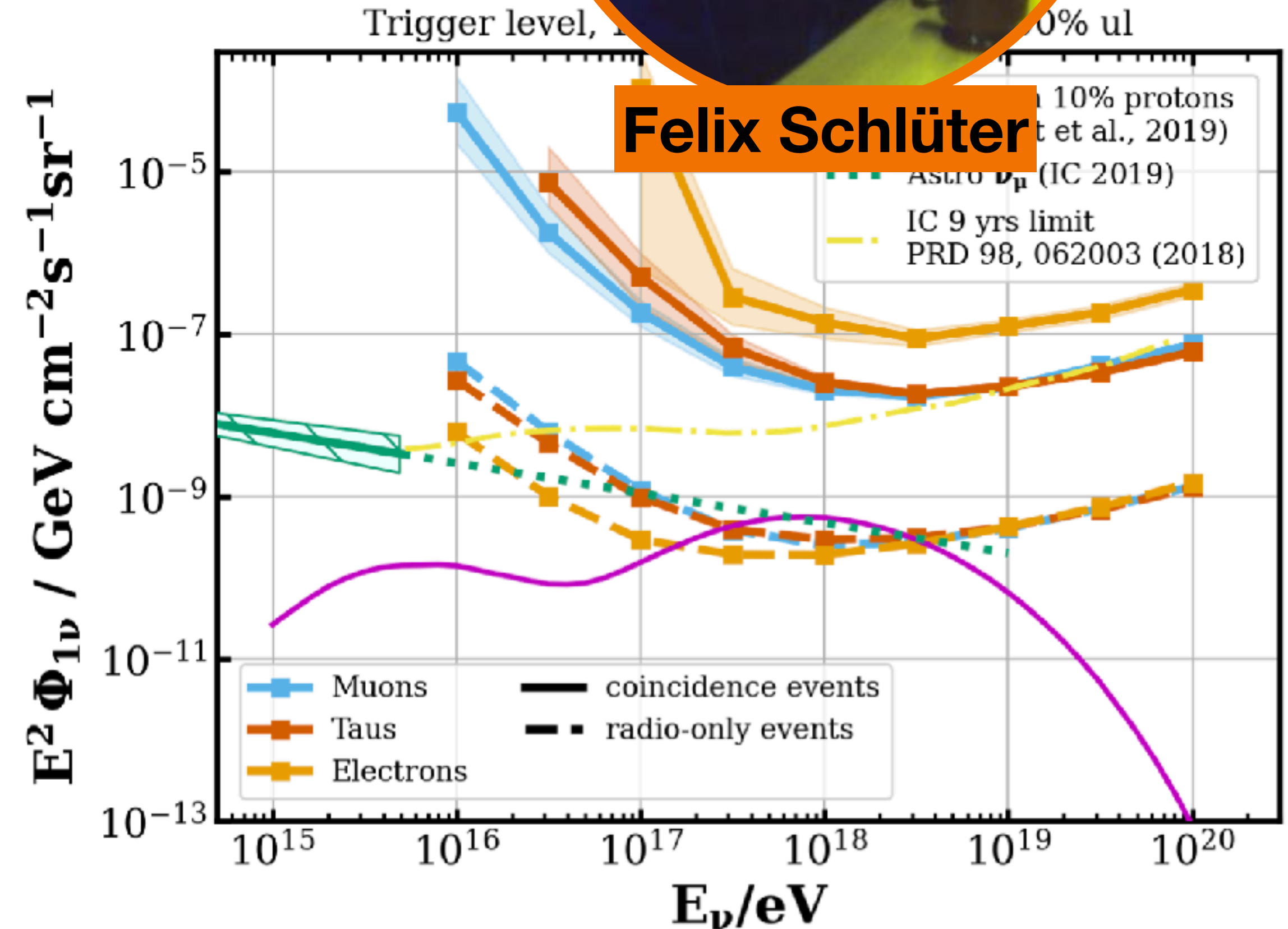


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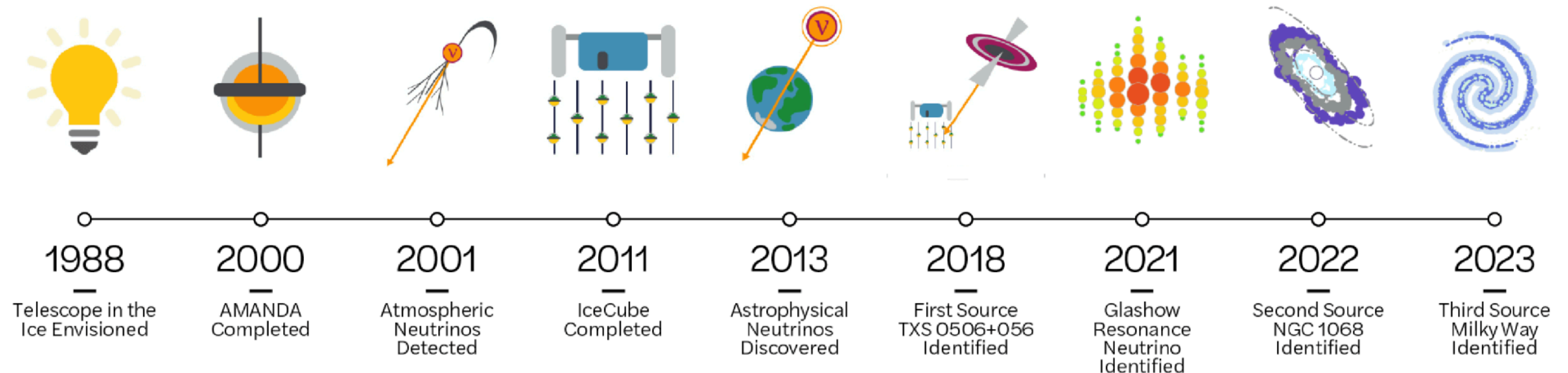
Felix Schlüter

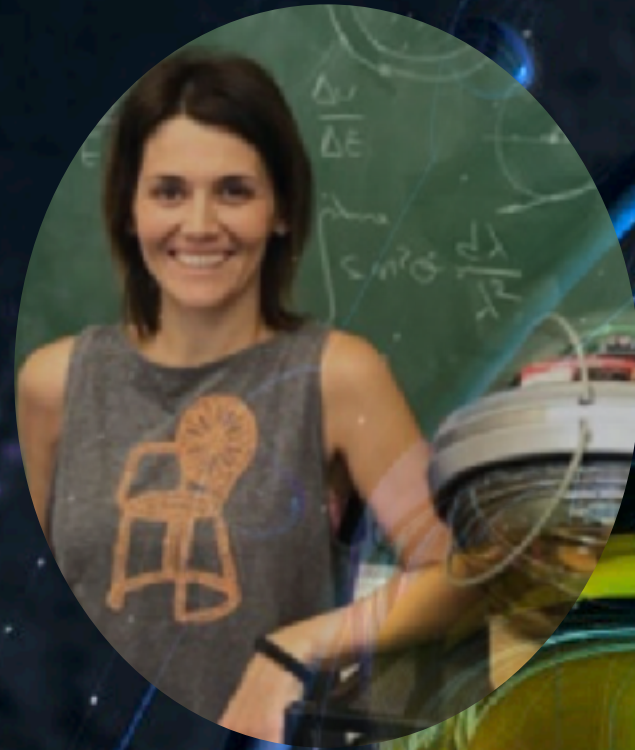


Conclusions

- IceCube has published several important results in the past decade.
- The last 2 wonderful years with 2 sources of astrophysical neutrinos.
- IceCube-Upgrade will come soon and enhance the capabilities of the current IceCube detector.
- IceCube-Gen2 is planned and will further explore the high-energy Universe.

*The era of neutrino astronomy is coming!

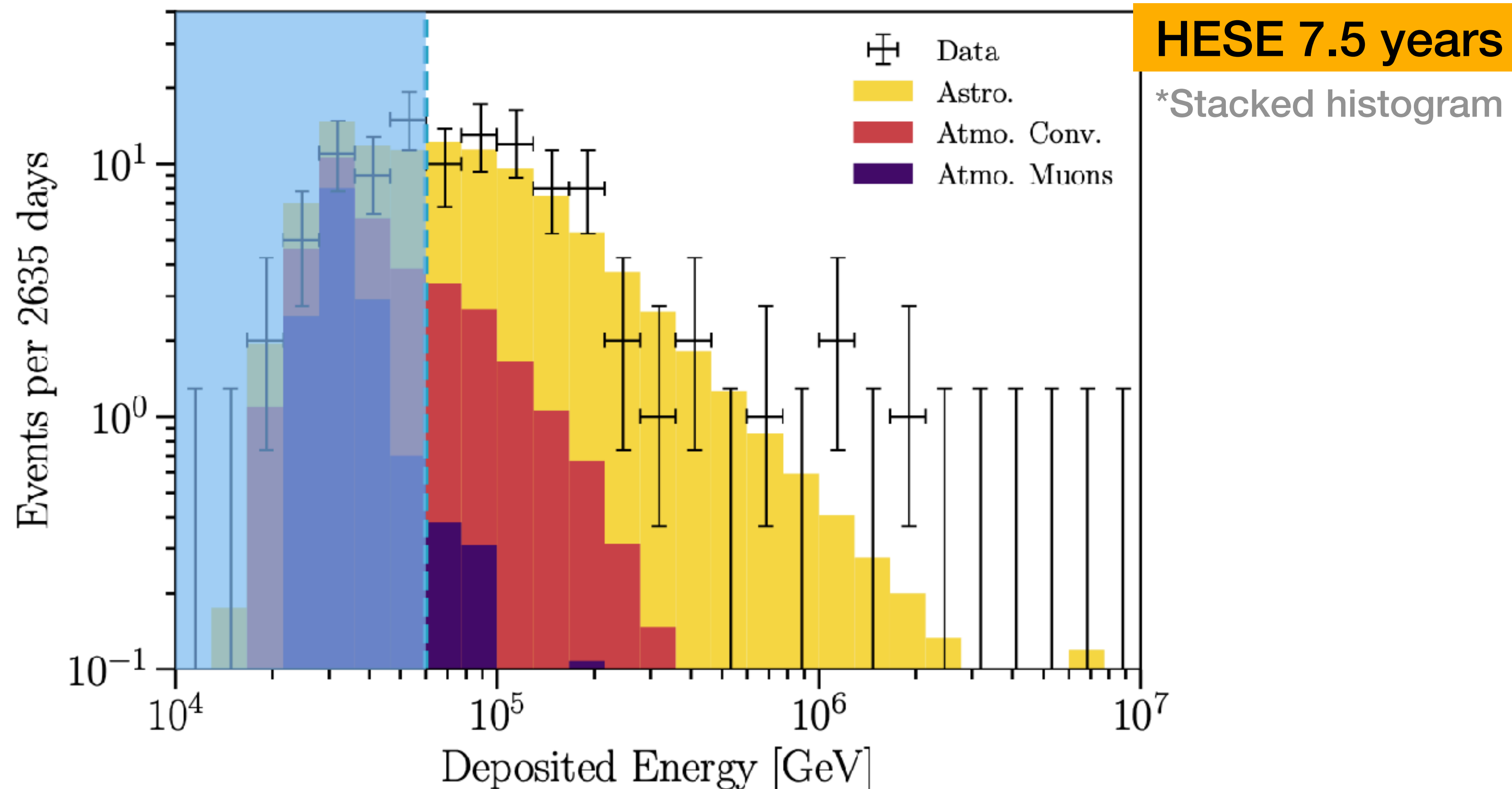




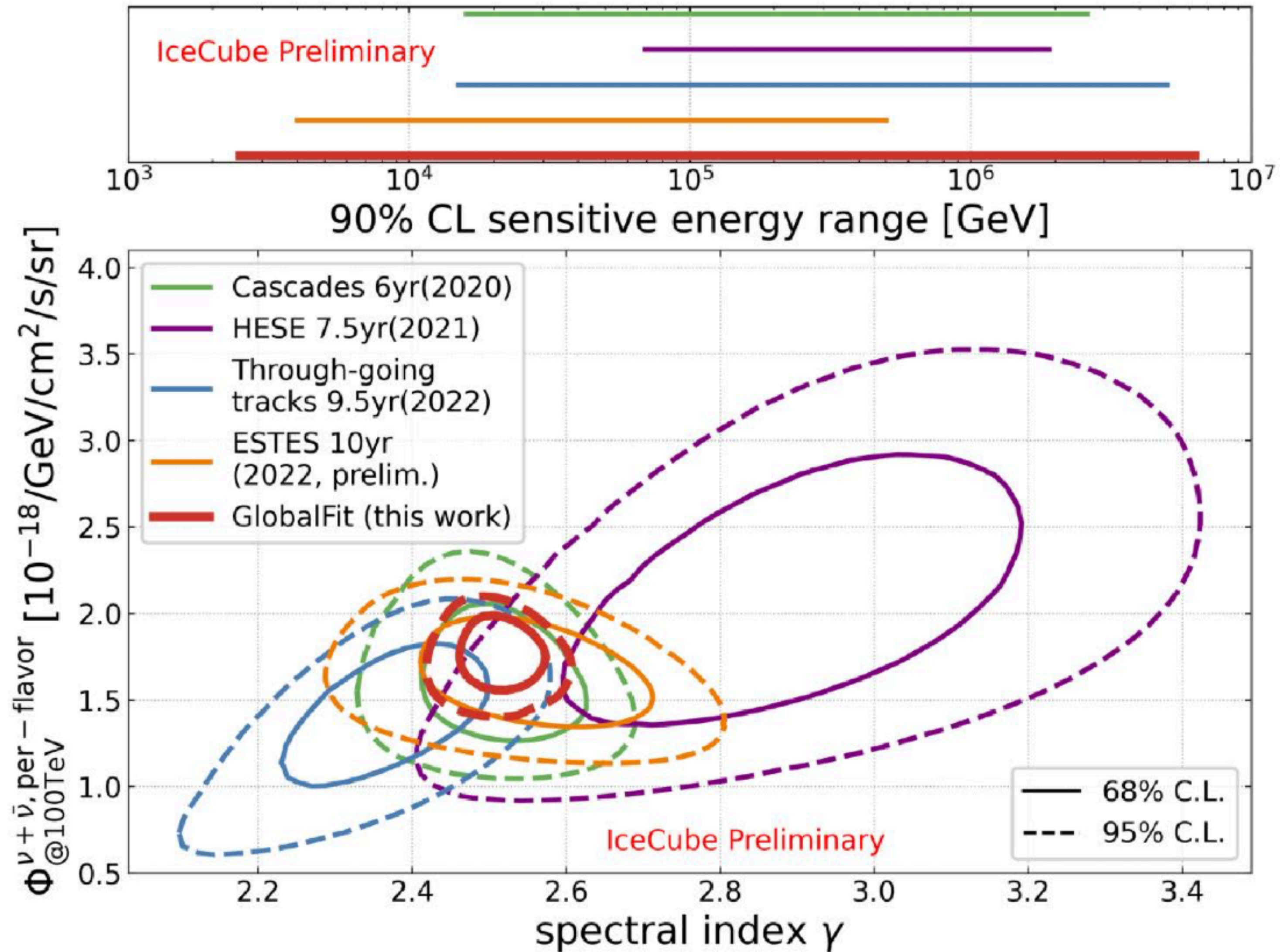
Back up

Astrophysical neutrino flux

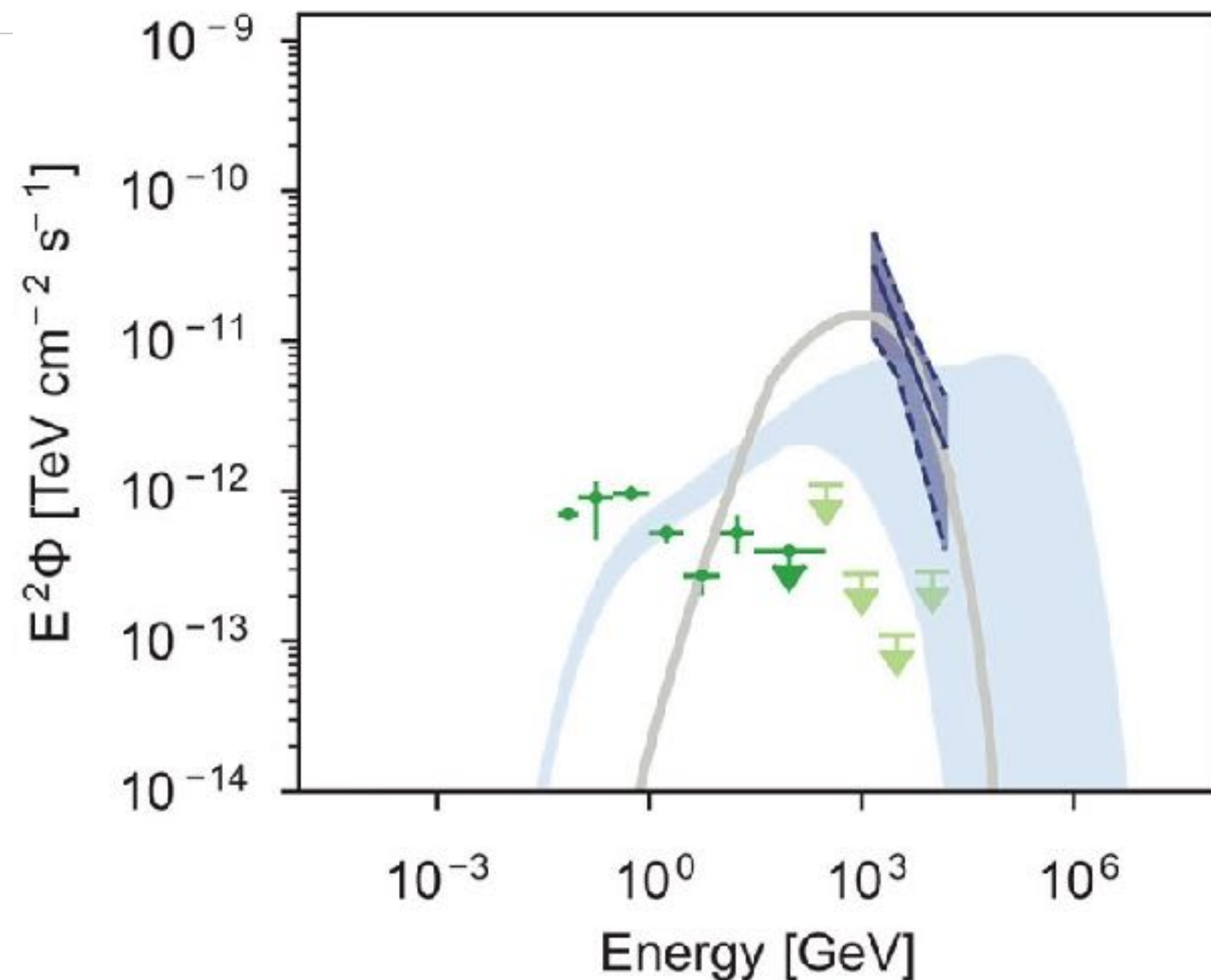
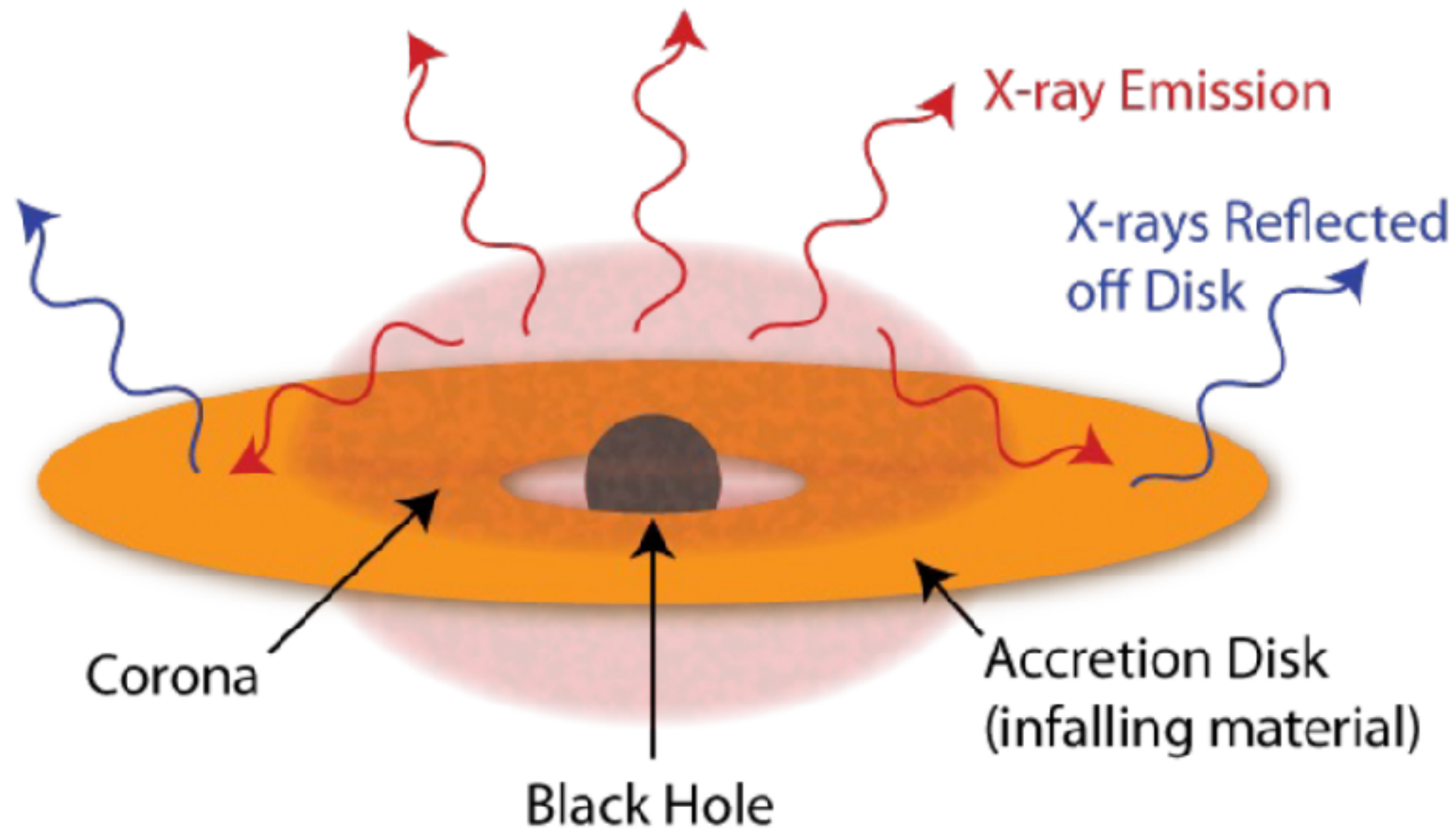
- HESE: High Energy Starting Events
- Muon filter by the Earth + Veto
- Neutrinos: Atmospheric vs Astrophysical!



Astrophysical neutrino flux

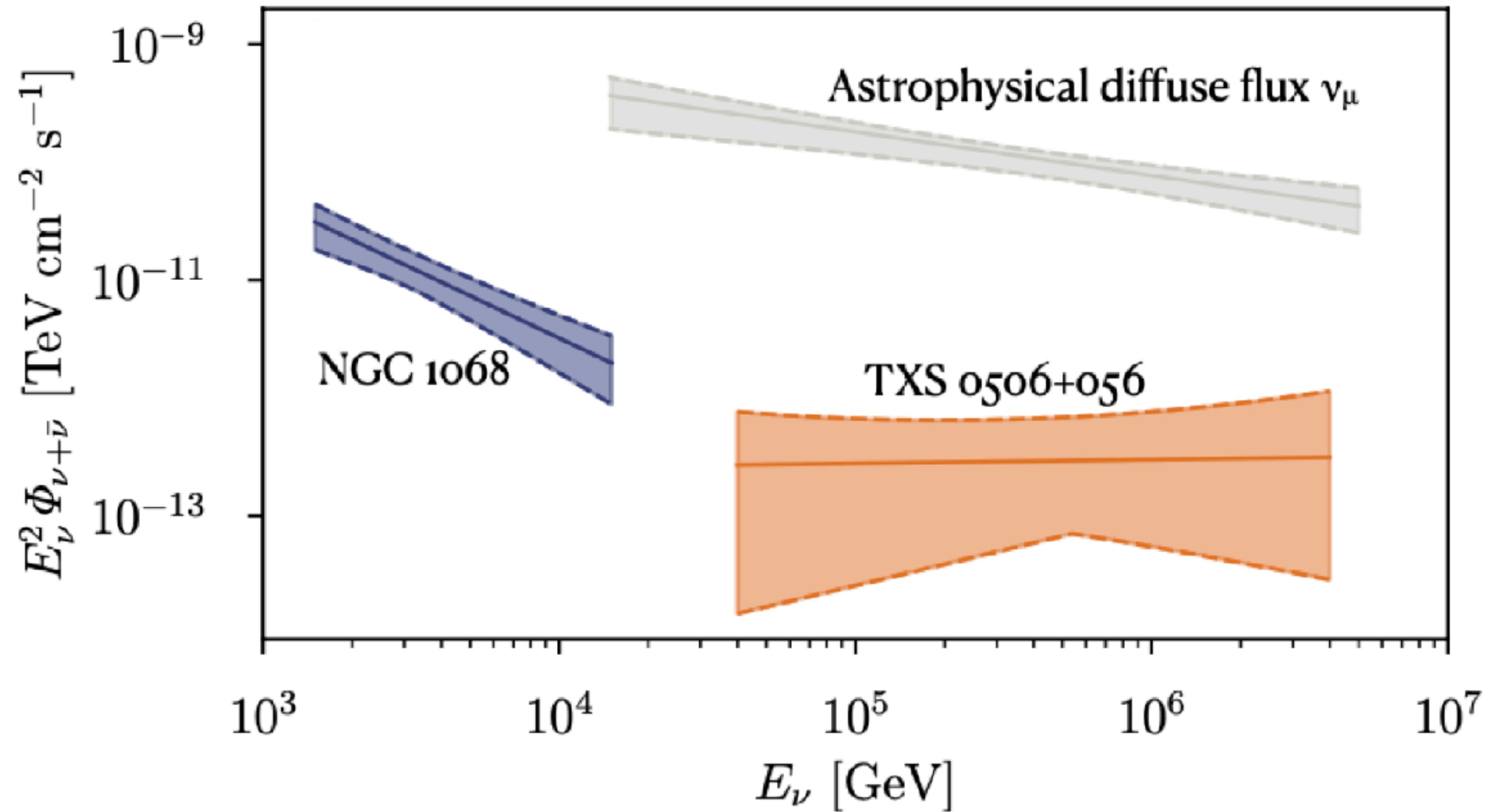


NGC 1068 - disk-corona model



- Host a thick Compton AGN
- Corona - hot plasma above the disk
 - Neutrino produced through $p\gamma$ interaction
 - Strong absorption of gamma ray
- Brightest Seyfert galaxies in X-ray ..but obscured to pionic gamma ray

NGC 1068

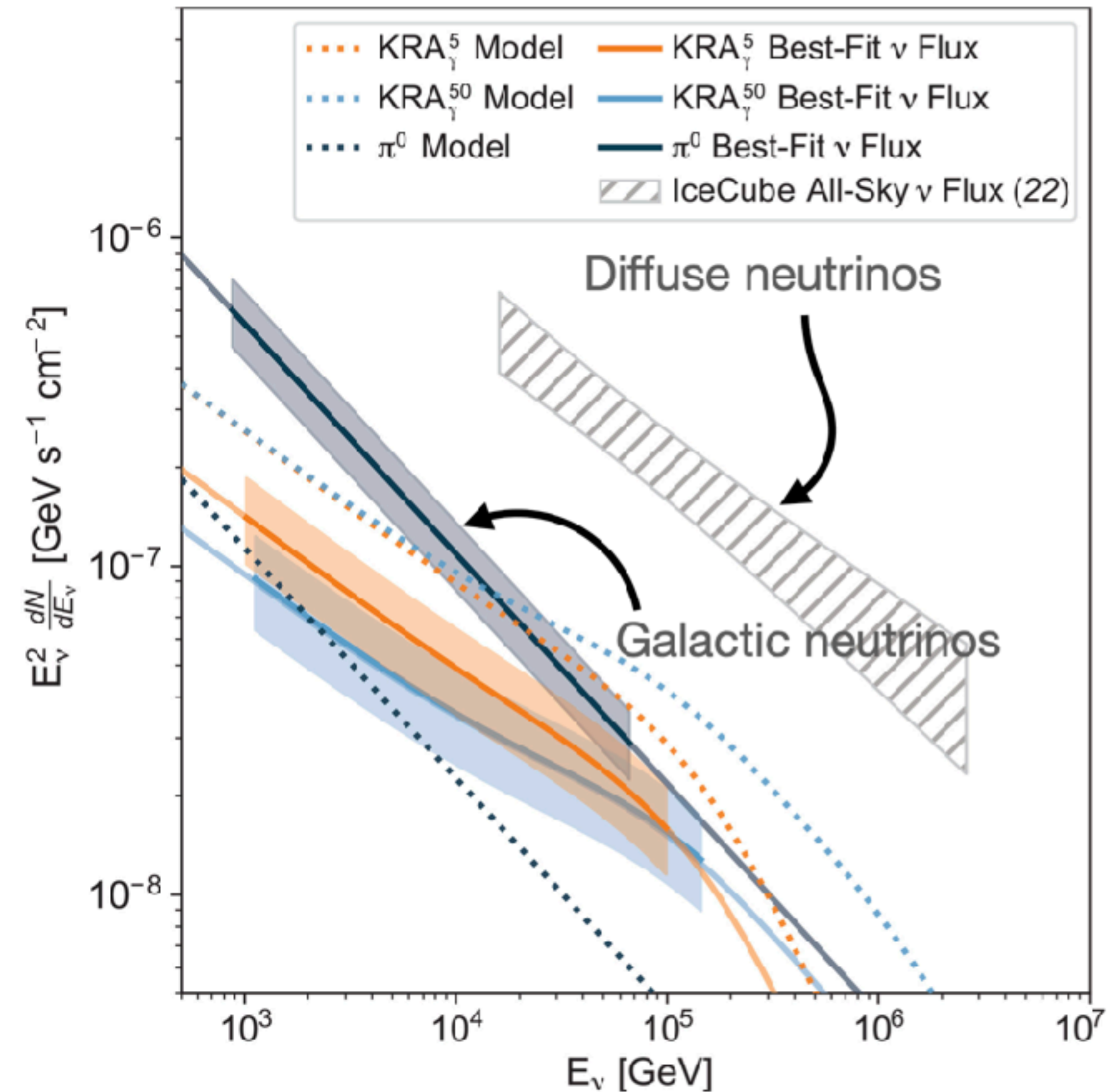


- NGC 1068 and TXS 0506+056 contribute each $\sim 1\%$ to the total diffuse!

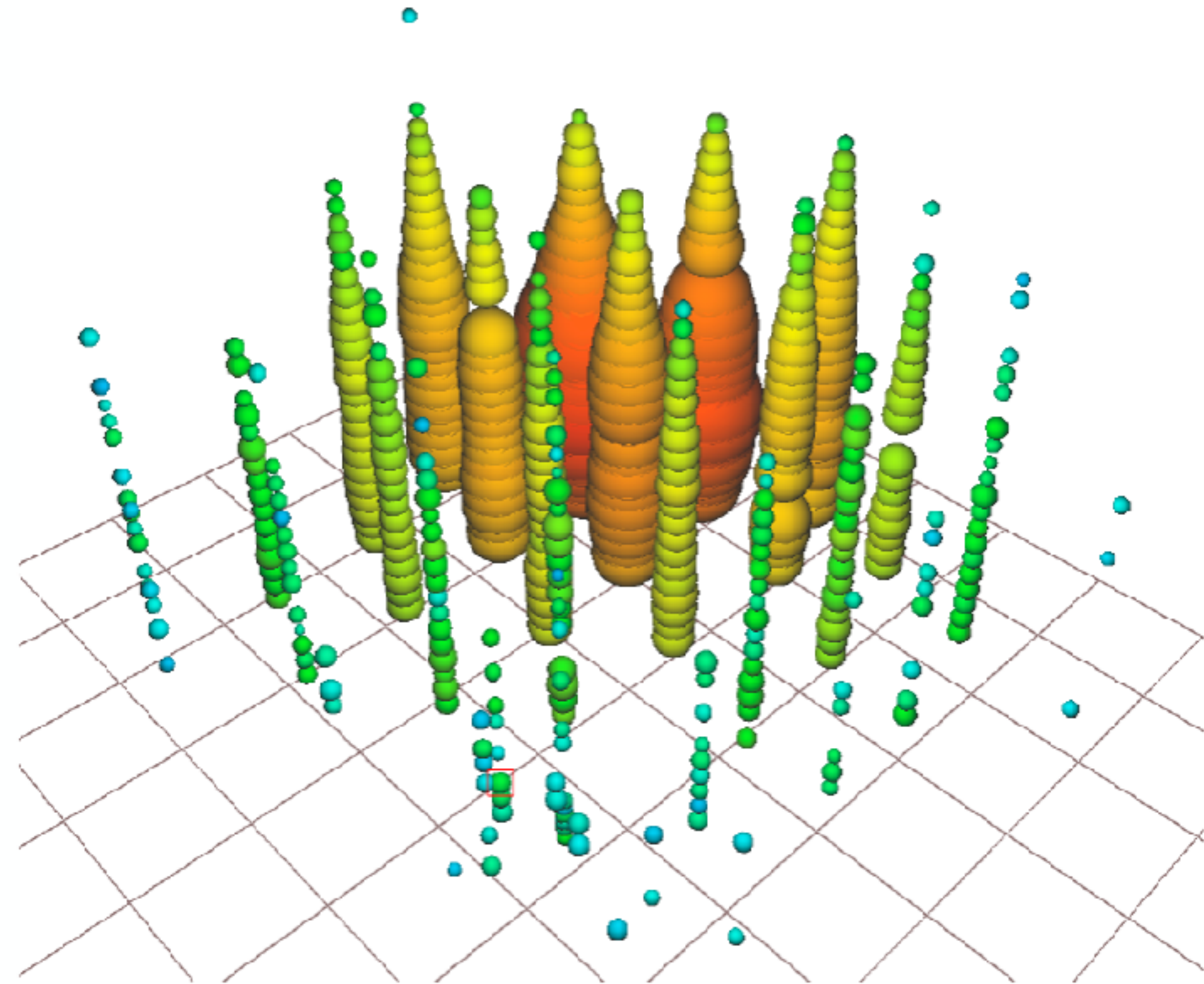
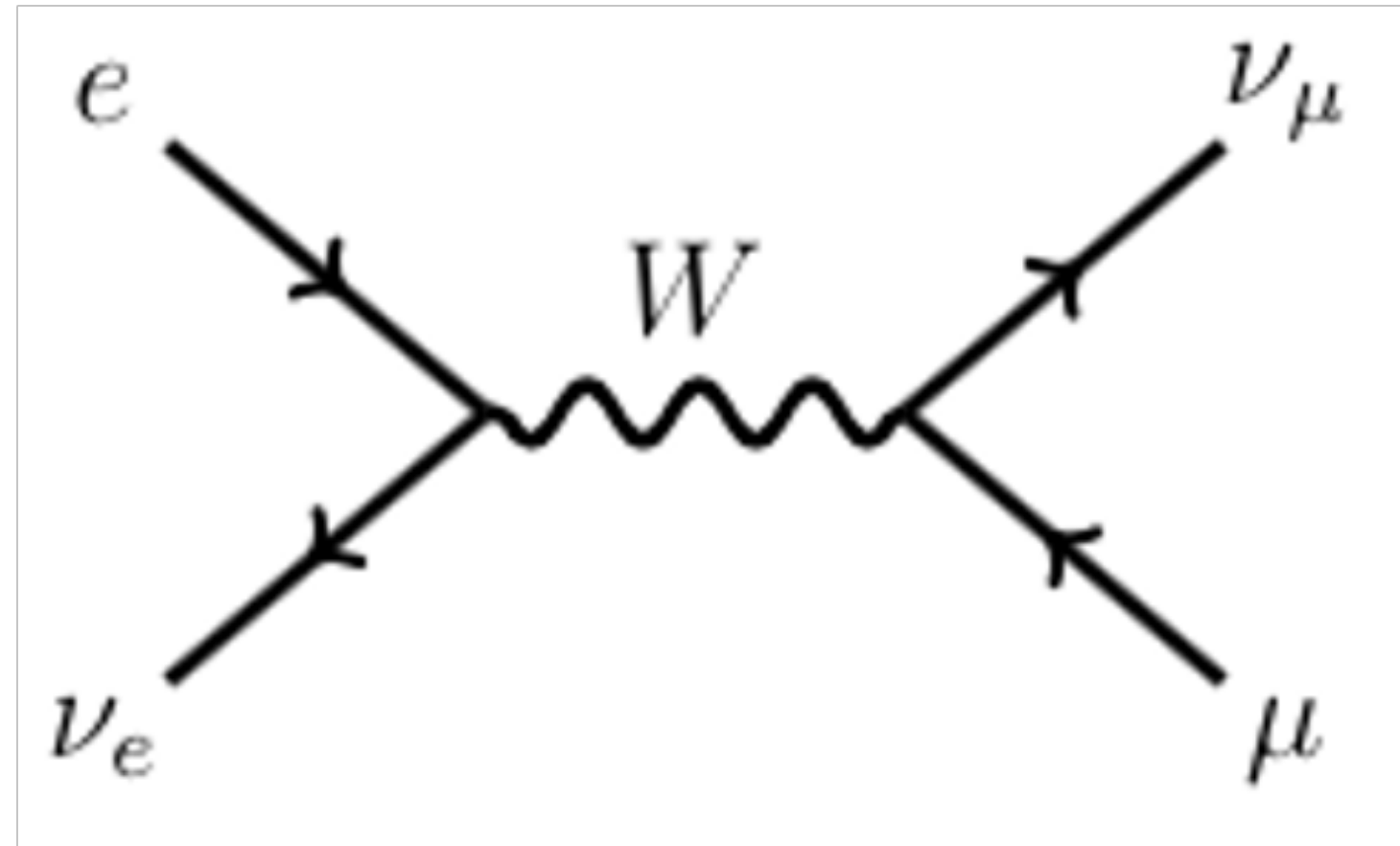
Galactic Plane

Diffuse Galactic plane analyses	Flux Sensitivity Φ	Best-fitting n_s	p-value	Best-fitting flux Φ
π^0	5.98	748	1.3×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA_γ^5	$0.16 \times \text{MF}$	276	6.1×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15} \times \text{MF}$
KRA_γ^{50}	$0.11 \times \text{MF}$	211	3.7×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11} \times \text{MF}$

- 6-13% of total diffuse flux at 30 TeV



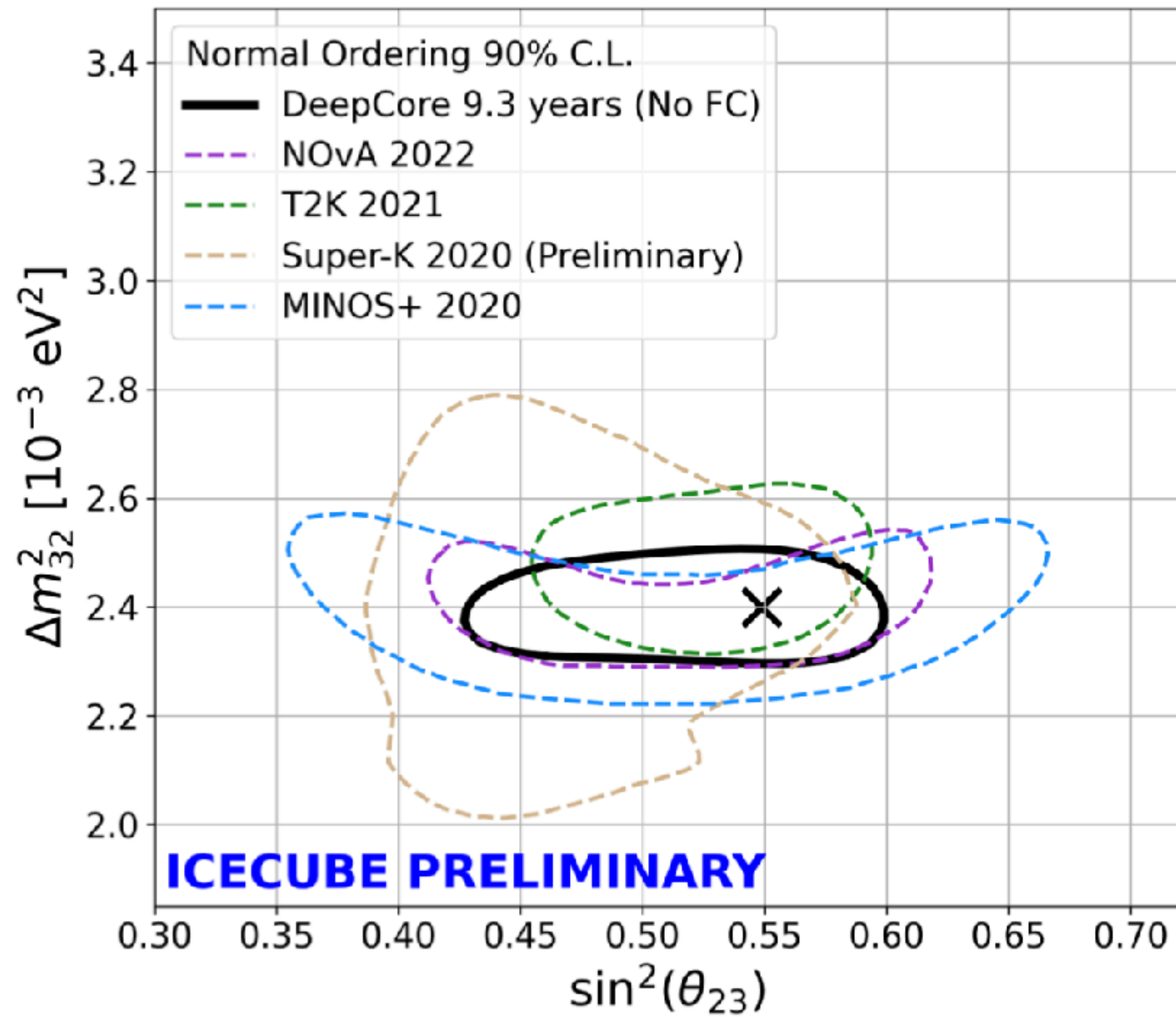
Glashow resonance



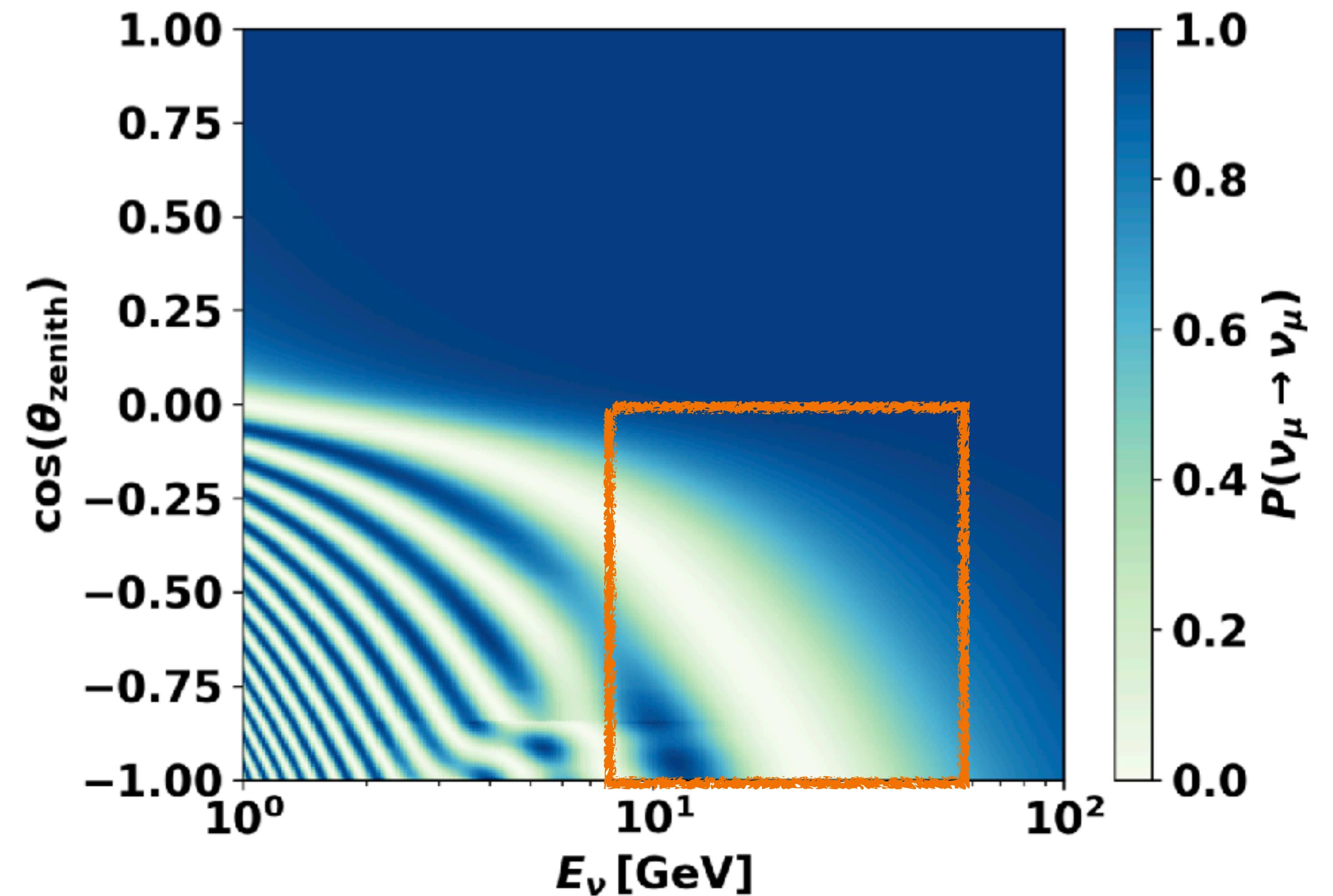
- Resonant production of W boson by an anti electron neutrino interacting with an atomic electron at $E_R = 6.3$ PeV
- Observation of a consistent event with measured energy of ~ 6.05 PeV
- Proof for the presence of anti electron neutrinos in astrophysical flux.

Other interesting topics

Atmospheric Neutrino Oscillations



- Oscillation ‘dip’ give sens. to “23” sector
- Very competitive measurements!



Other interesting topics

Flavour measurement of astrophysical neutrinos

Standard Model

