

ICECUBE

ULB VUB

# Highlights from the IceCube Neutrino Observatory

*Nhân Châu*

*on behalf of the IIHE-IceCube group*

IIHE annual meeting

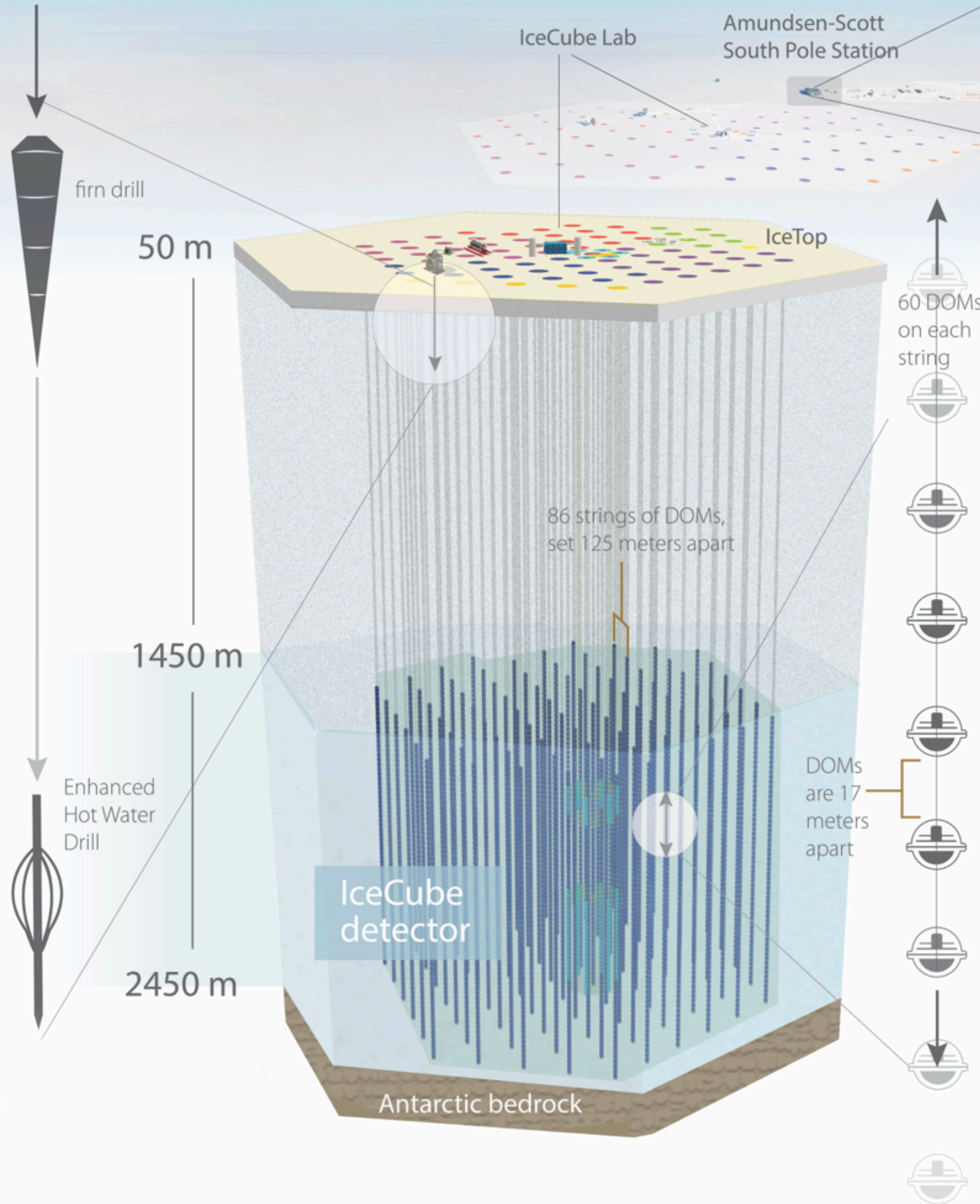
Brussels - November 28, 2024

*iihe*  
BRUXELLES BRUSSEL

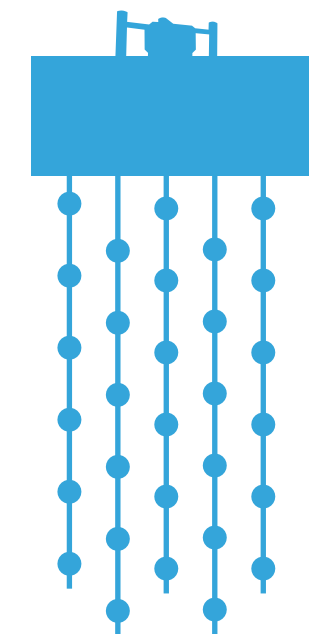
# Outlines

- The IceCube Neutrino Observatory
  - Detector design and detection technique
  - Highlights from IceCube
- IceCube activities at IIHE
- The future of IceCube: Upgrade and Gen2
  - Upgrade at IIHE

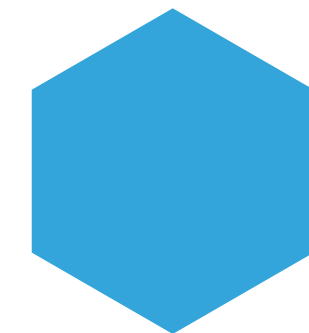
# IceCube Neutrino Observatory



**5,160** Digital Optical Modules (DOMs)



**86** string with 60 DOMs each  
 6 denser strings called **DeepCore**



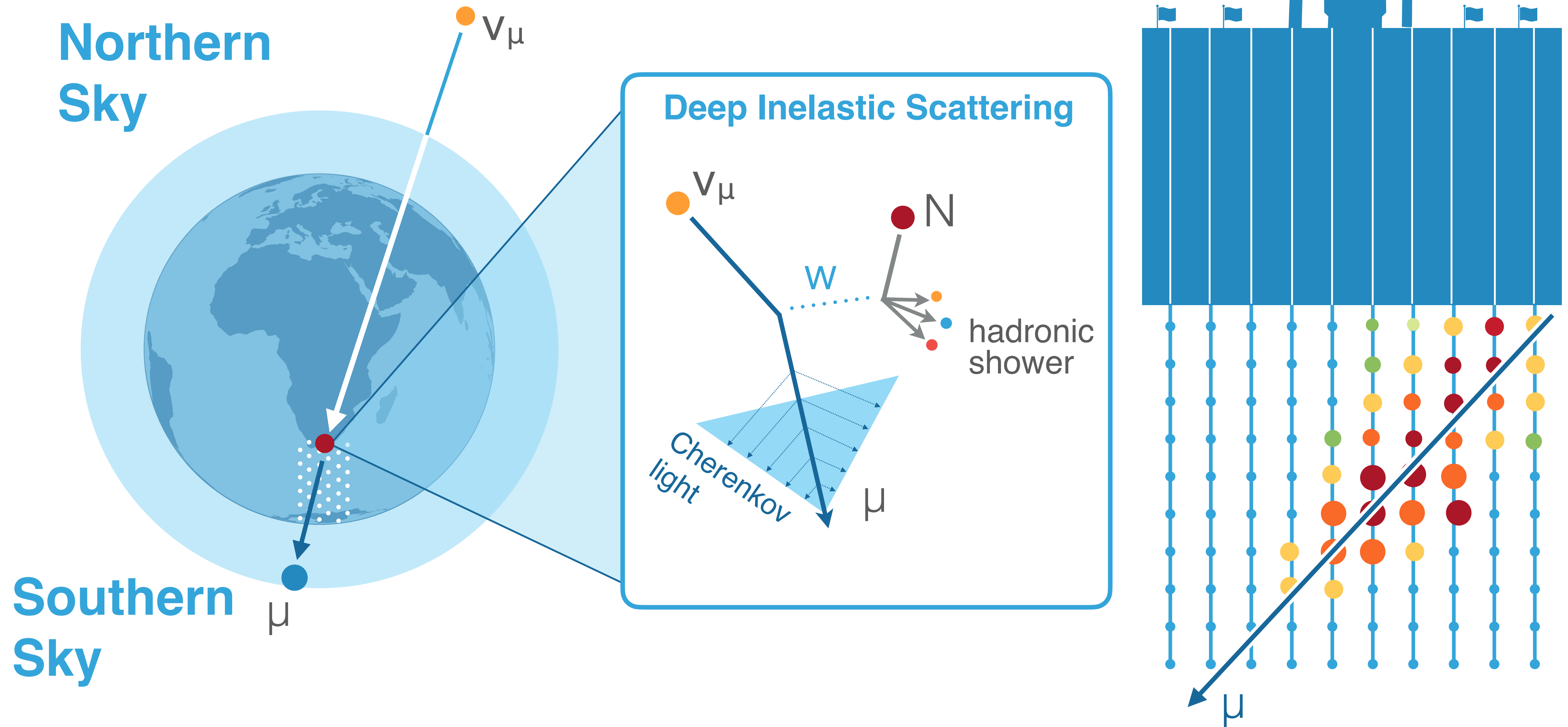
**1 km<sup>2</sup>** surface array with 324 DOMs:  
**IceTop**



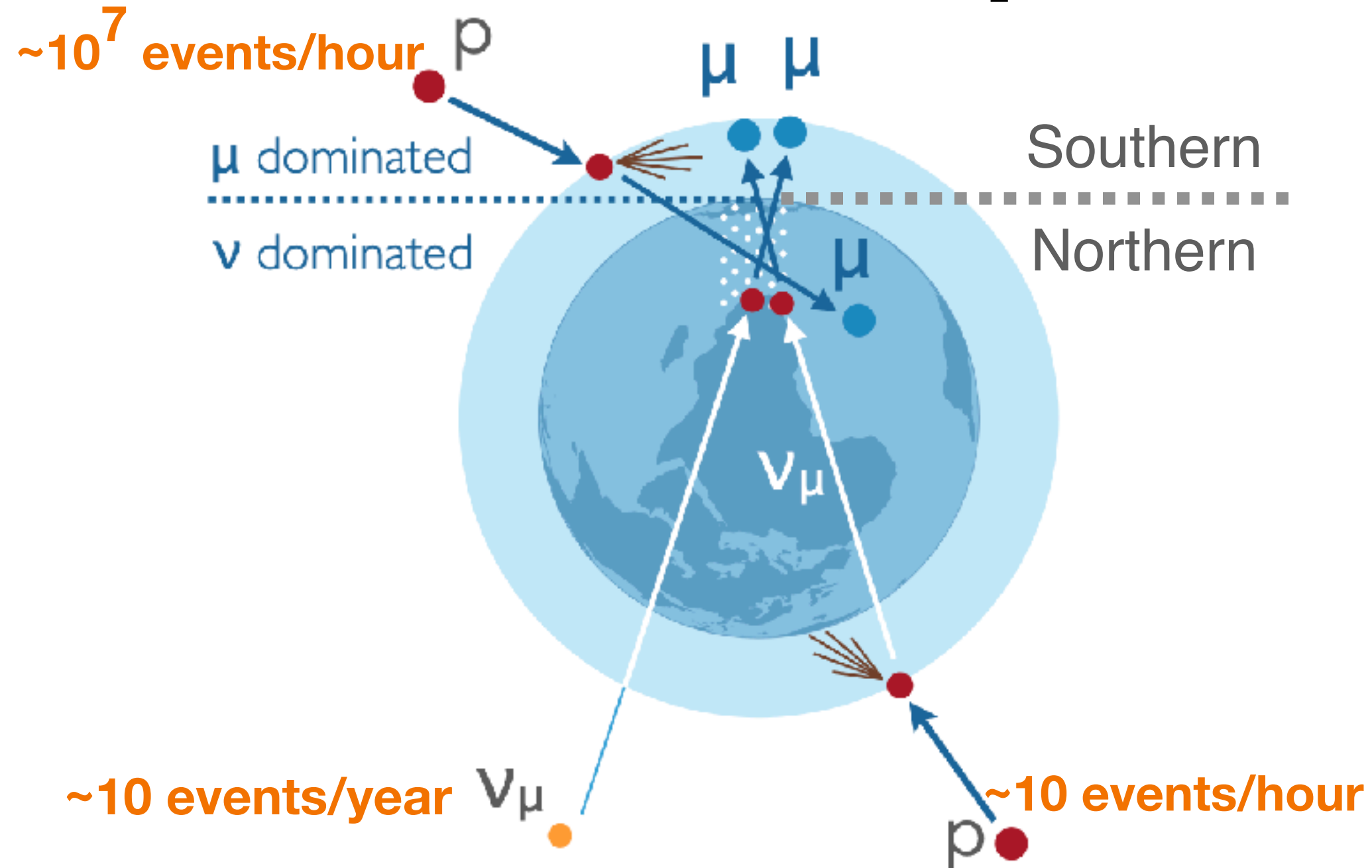
**Completion in December 2010**



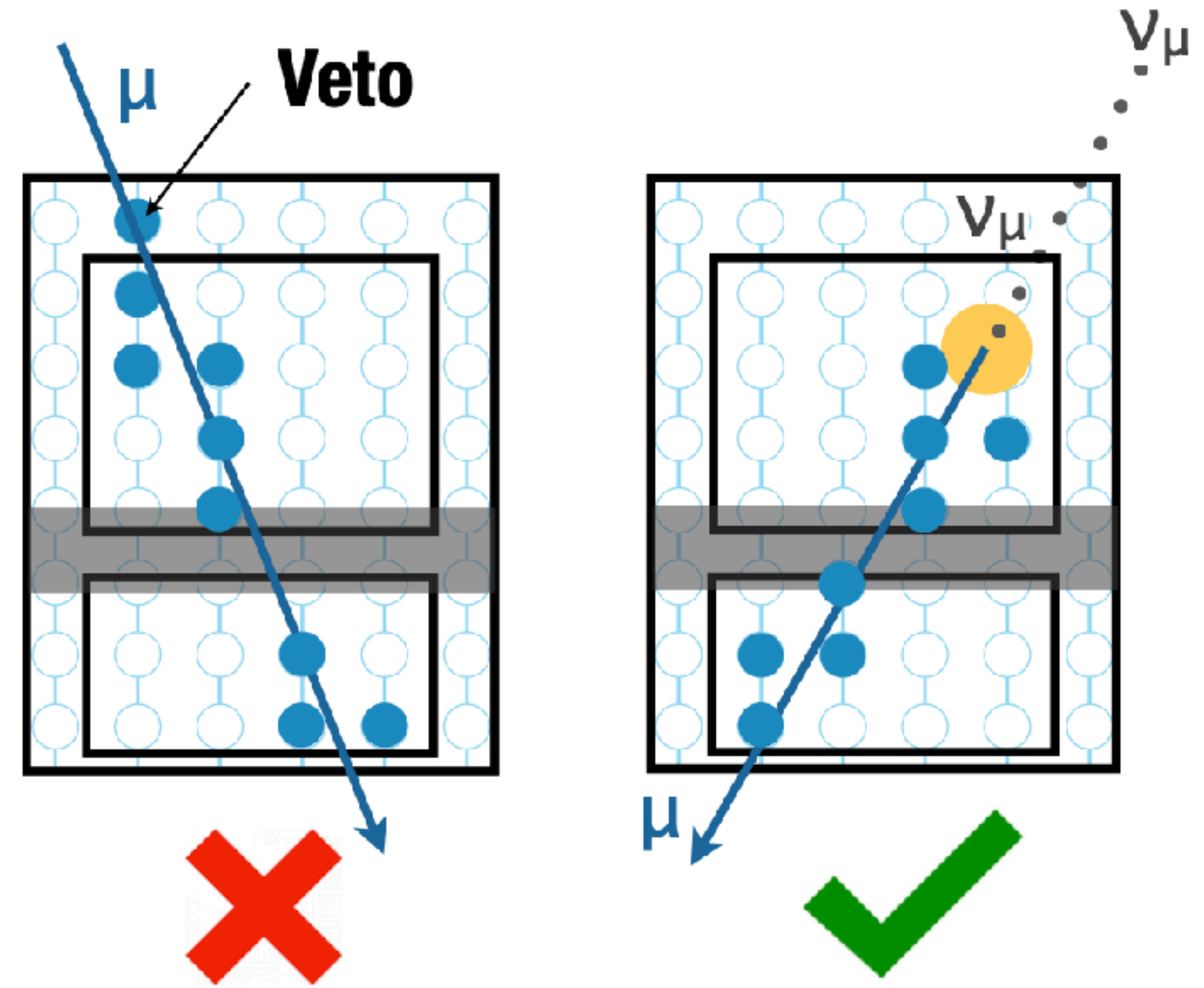
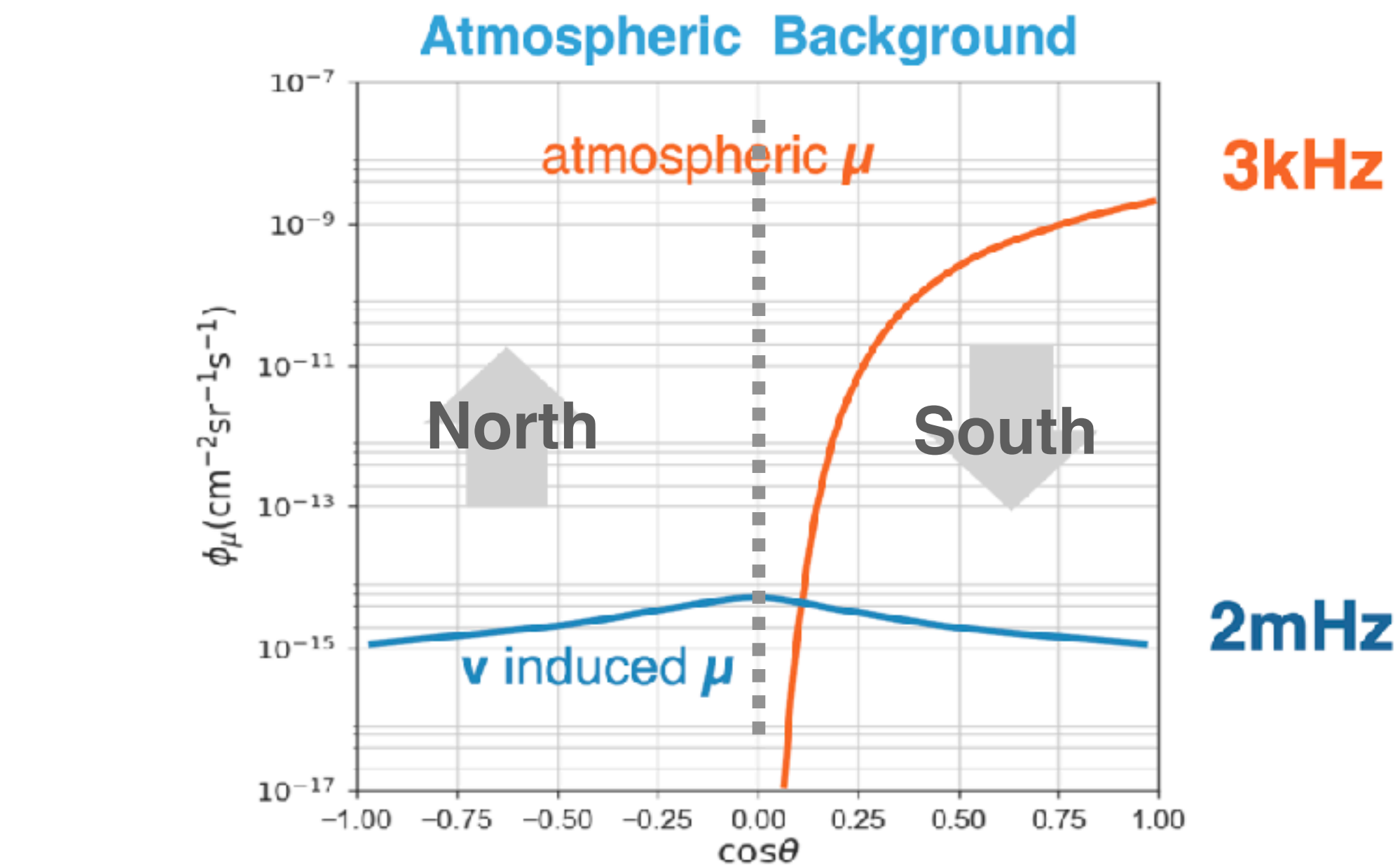
# Detection Principle



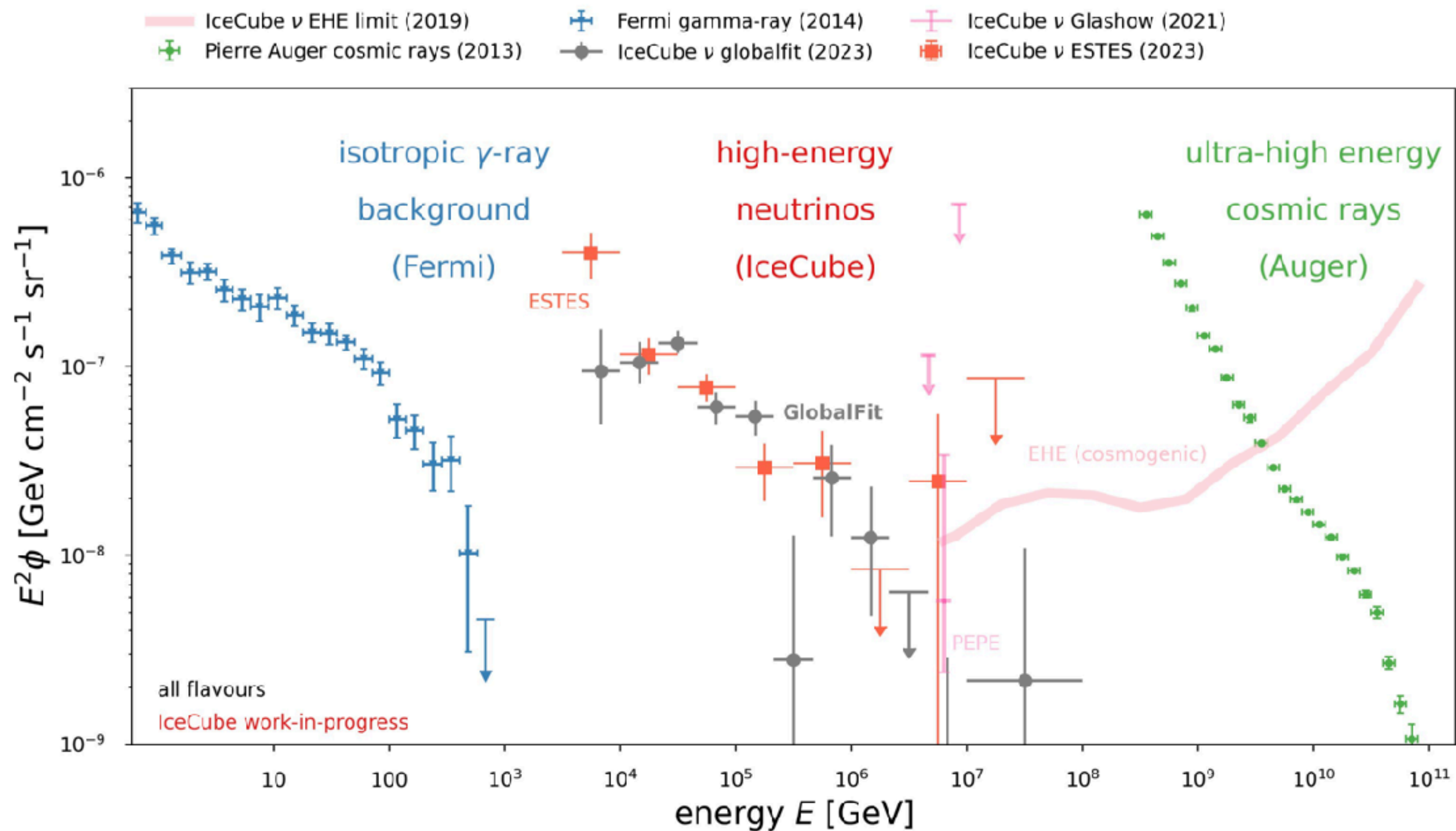
# Detection Principle - background rejection



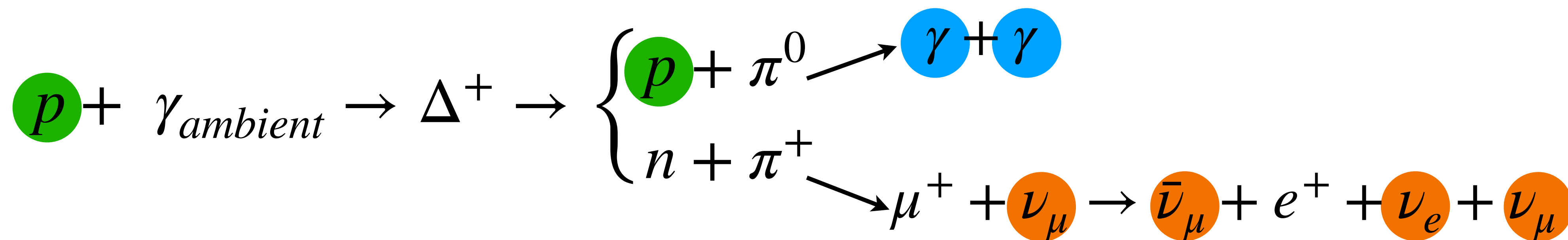
- **In Northern sky:** Earth acts as the natural filter for atm. muons - making use of **up-going events**.
- **In Southern sky:** using outer layer as an active veto for selecting **starting events**.



# Diffuse Astrophysical Neutrinos

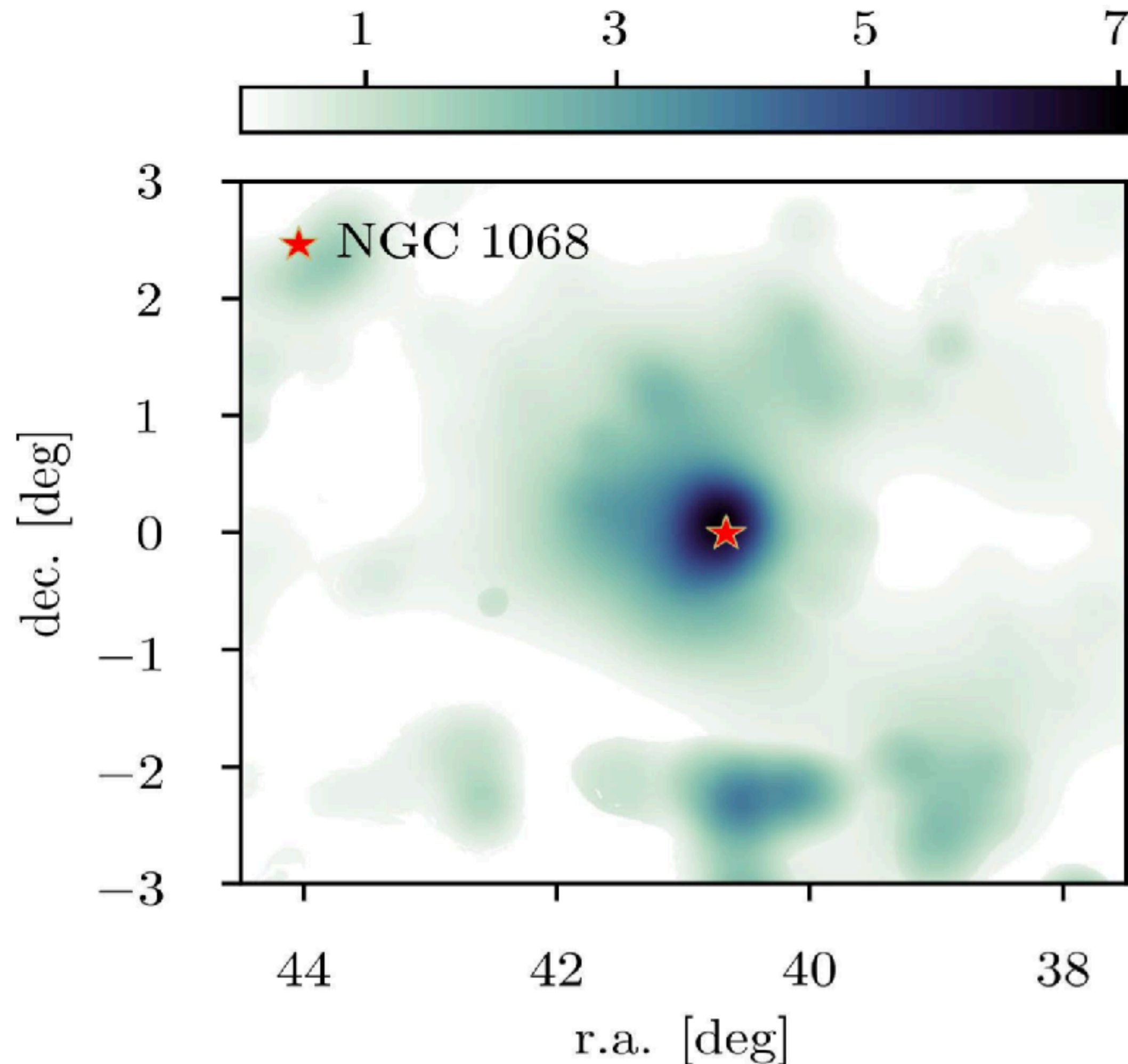


- First observed in 2013
- Spectral index  $\gamma = 2.3 - 2.9$  depends on analysis / energy range
- Consistent energy intensities with other messengers
- Hints for **deviation from single power law**
- With growing dataset better characterisation is expected



# NGC 1068 - first steady point source

Science 378 (2022) 538-543

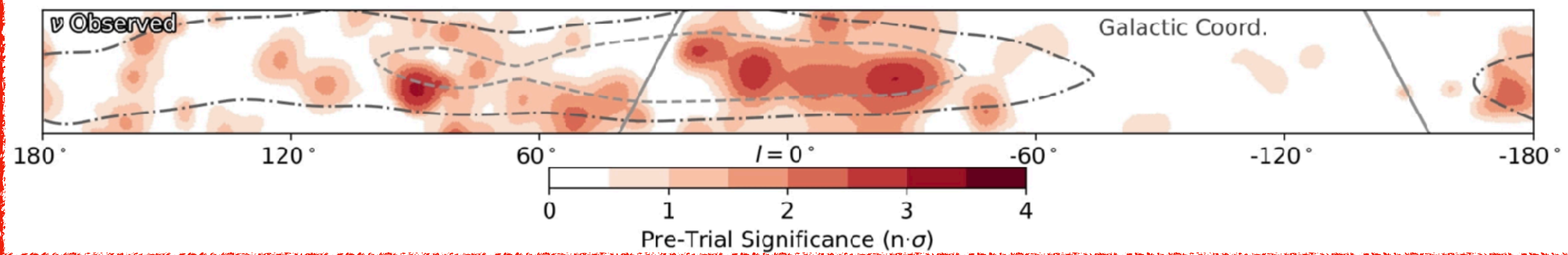
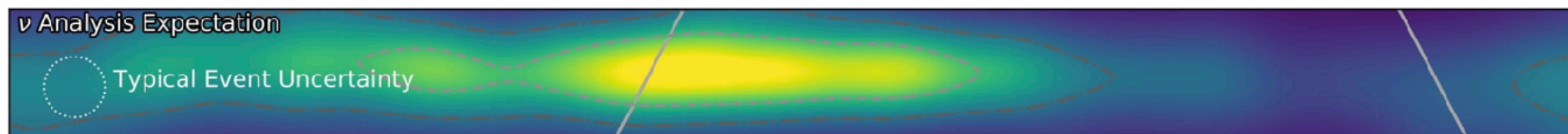
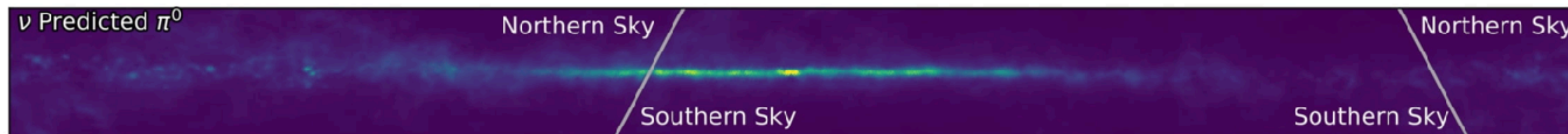
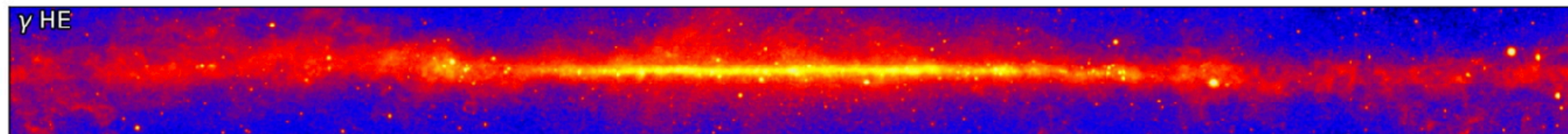
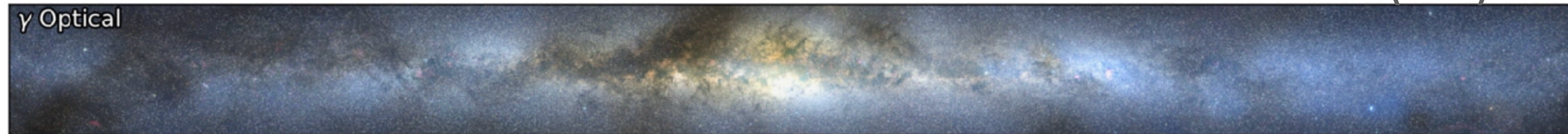


- A nearby active galaxy (Seyfert II, 14 Mpc)
  - Active Galactic Nucleus (AGN) powered by a Super Massive Black Hole (SMBH)
- **Global significance of  $4.2\sigma$**  (2022)
  - First hint in 2021 with  $2.9\sigma$
  - Improvement thanks to more precise neutrino event characterization (calibration, reconstruction, ..) + 2 additional years of data
- **New analysis with 13 years:**  $4.0\sigma$  global significance, hottest spot move closer to NGC1068

# First observation of Galactic Plane in Neutrinos

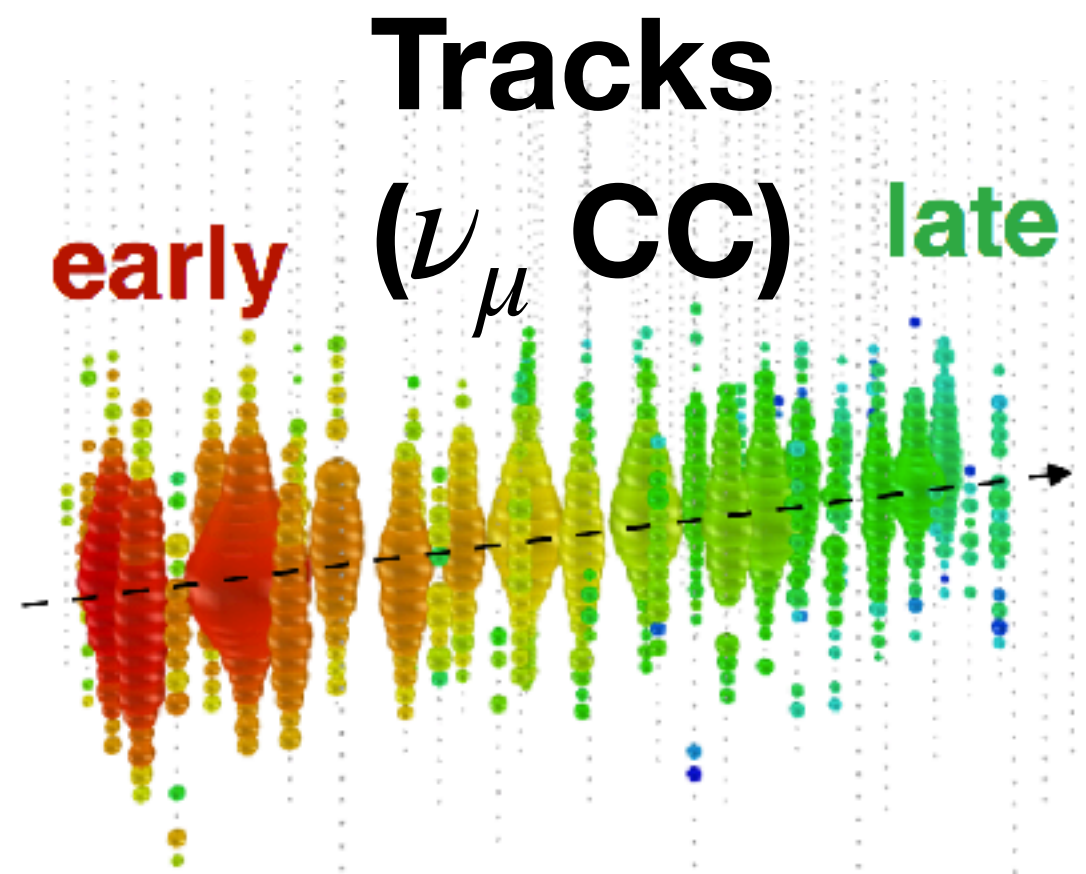
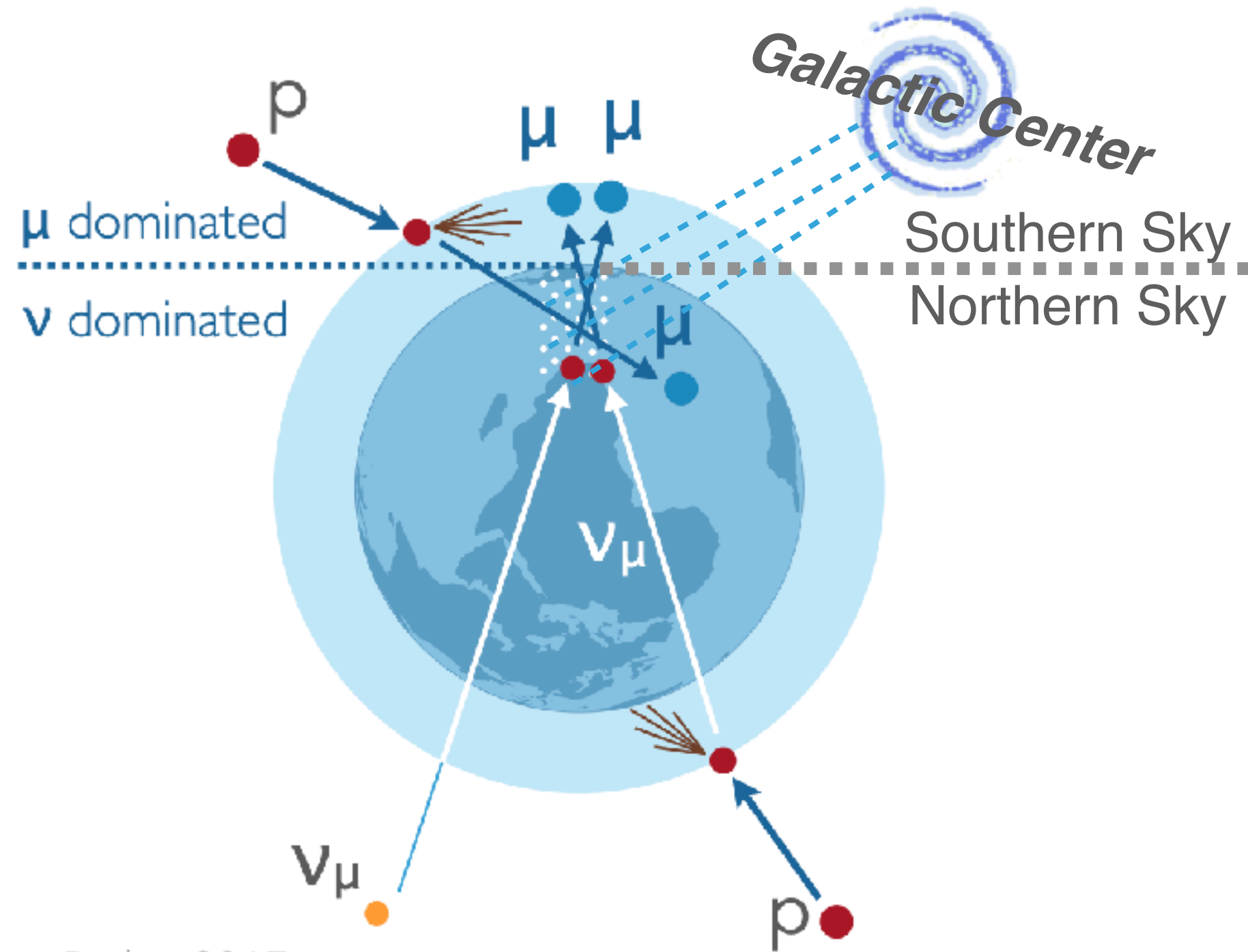
- First observation of the **Milky Way in neutrinos at a statistical significance  $4.5\sigma$**

Science 380 (2023) 6652

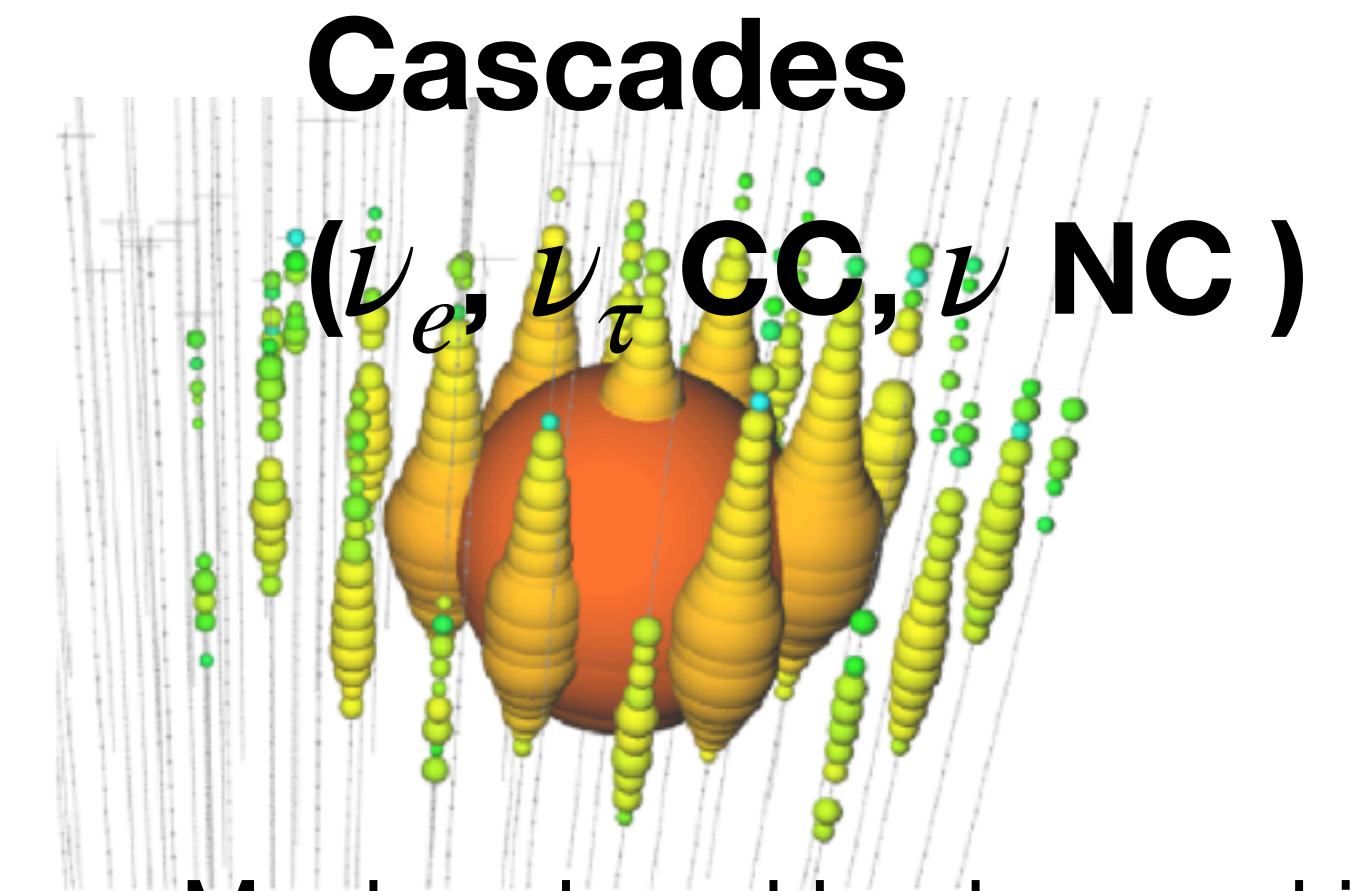




# First observation of Galactic Plane in Neutrinos



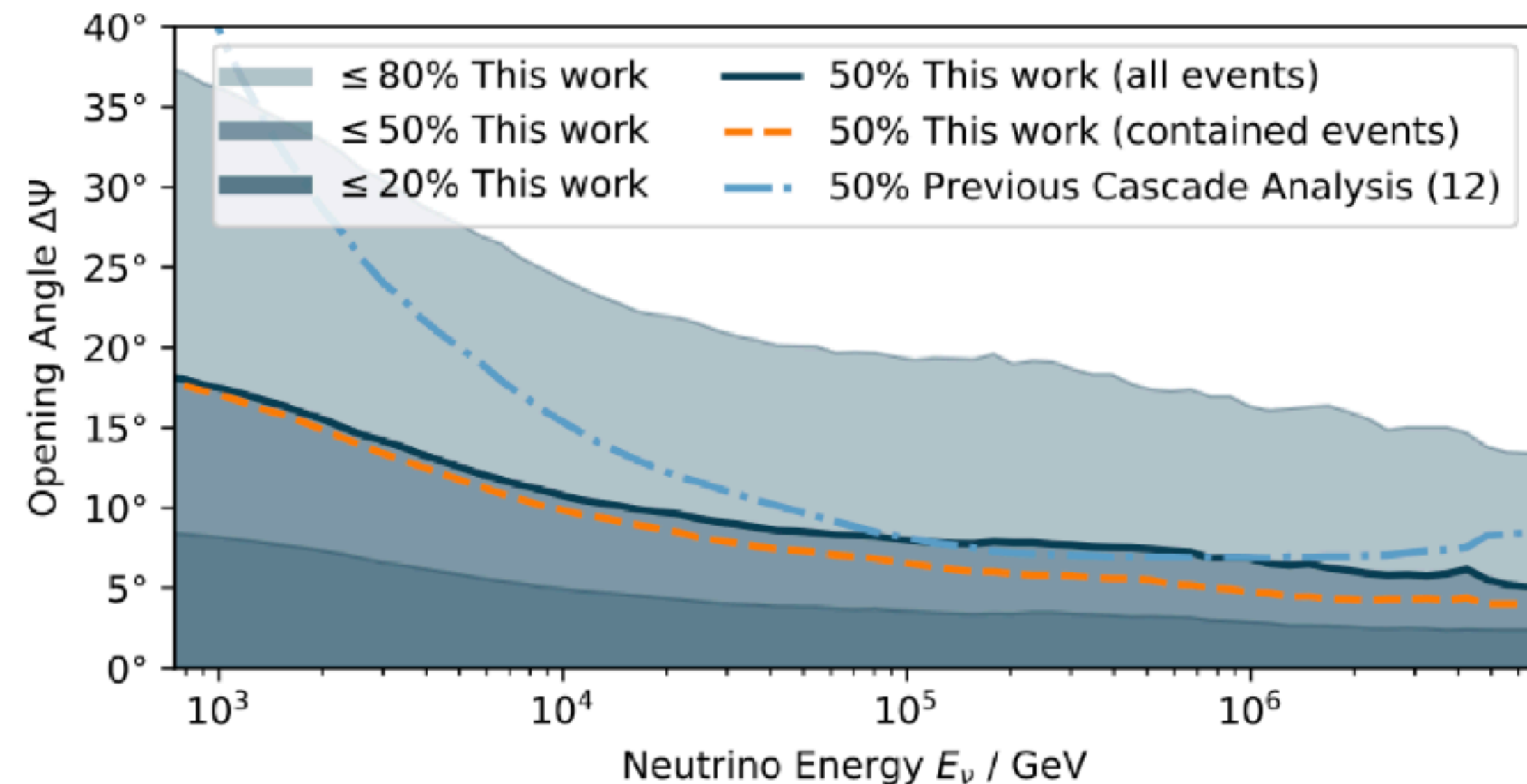
- Good angular resolution.
- But irreducible background in the southern sky.



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

- Observation made possible thanks to **cascade events**:

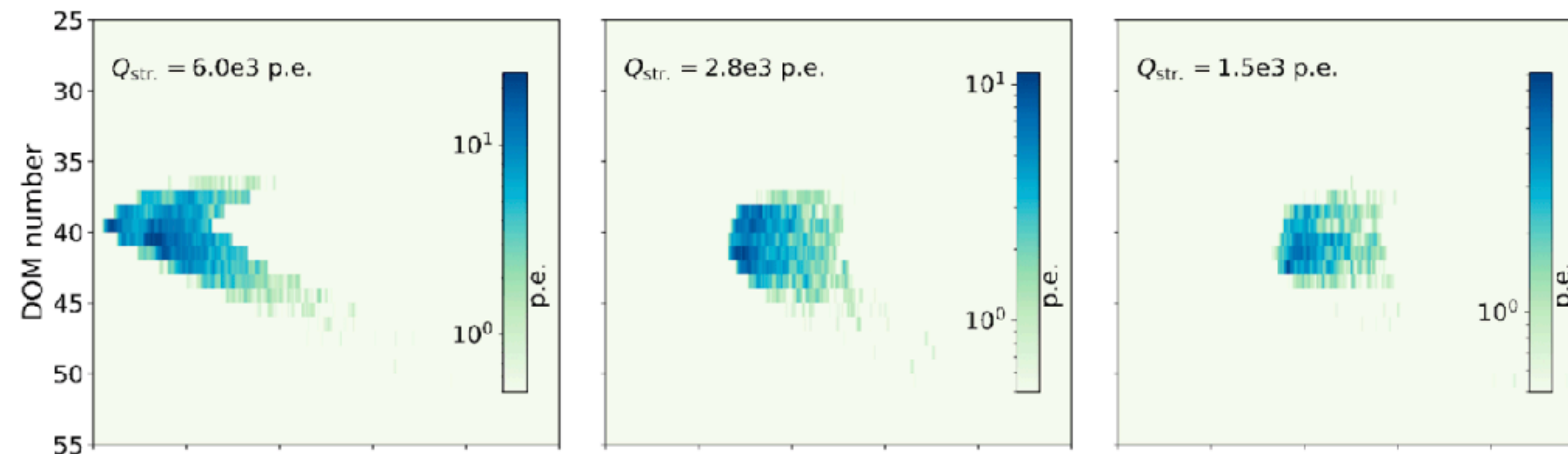
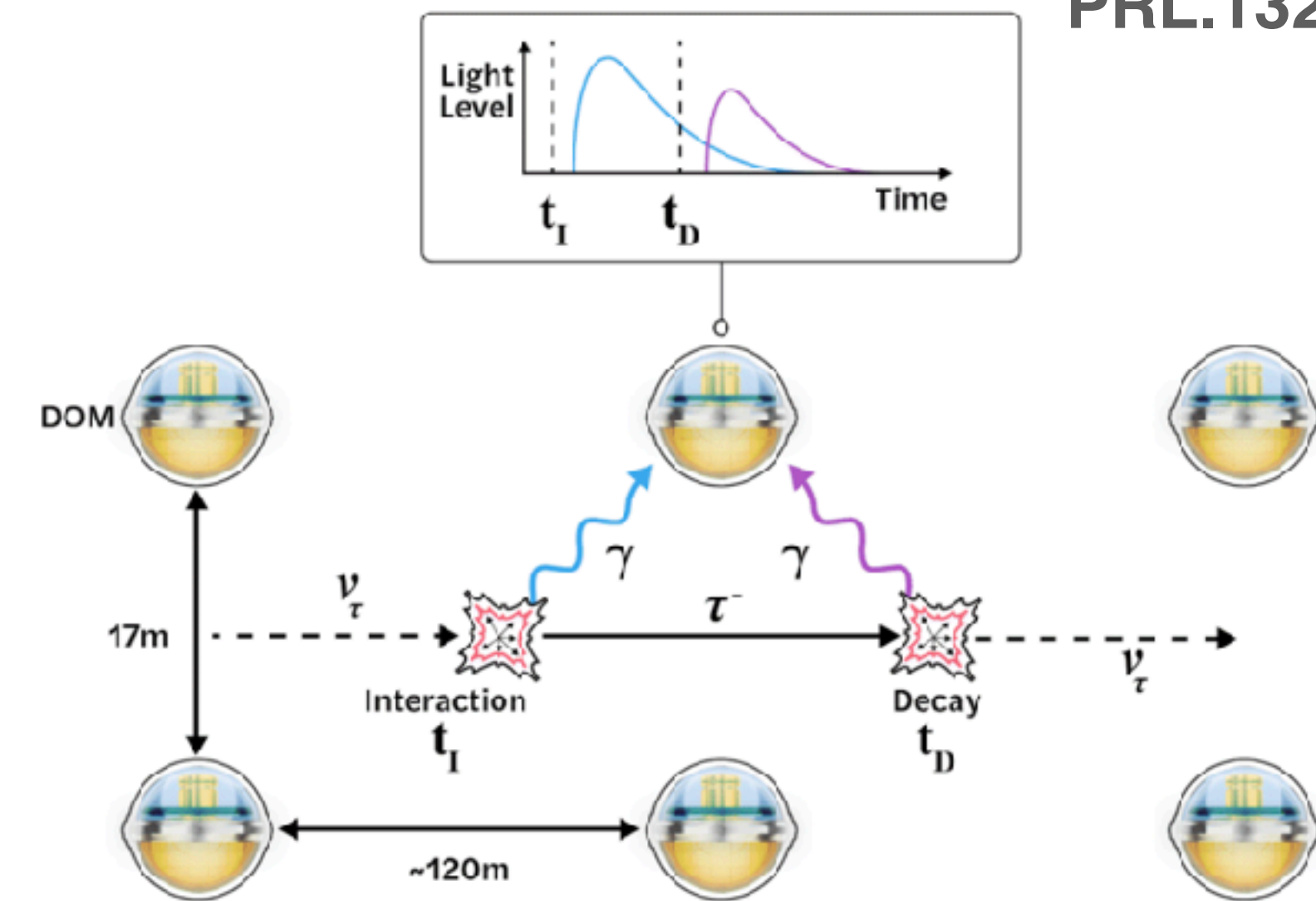
- ▶ **Less background** (atm  $\mu, \nu$ ) in the southern sky
- ▶ **Angular resolution improvement** with machine learning.



# Detection of astrophysical tau neutrinos

PRL.132.151001 (2024)

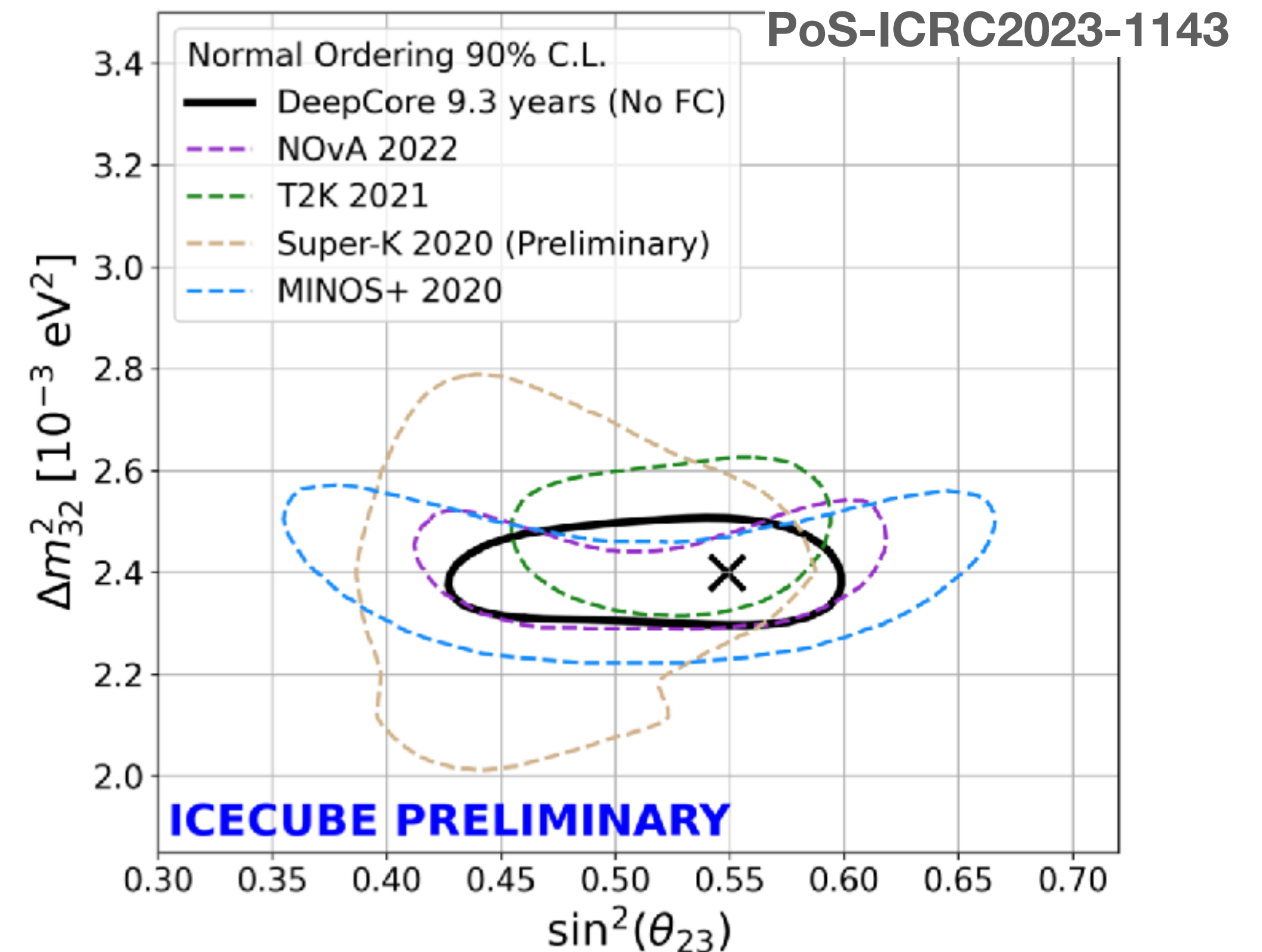
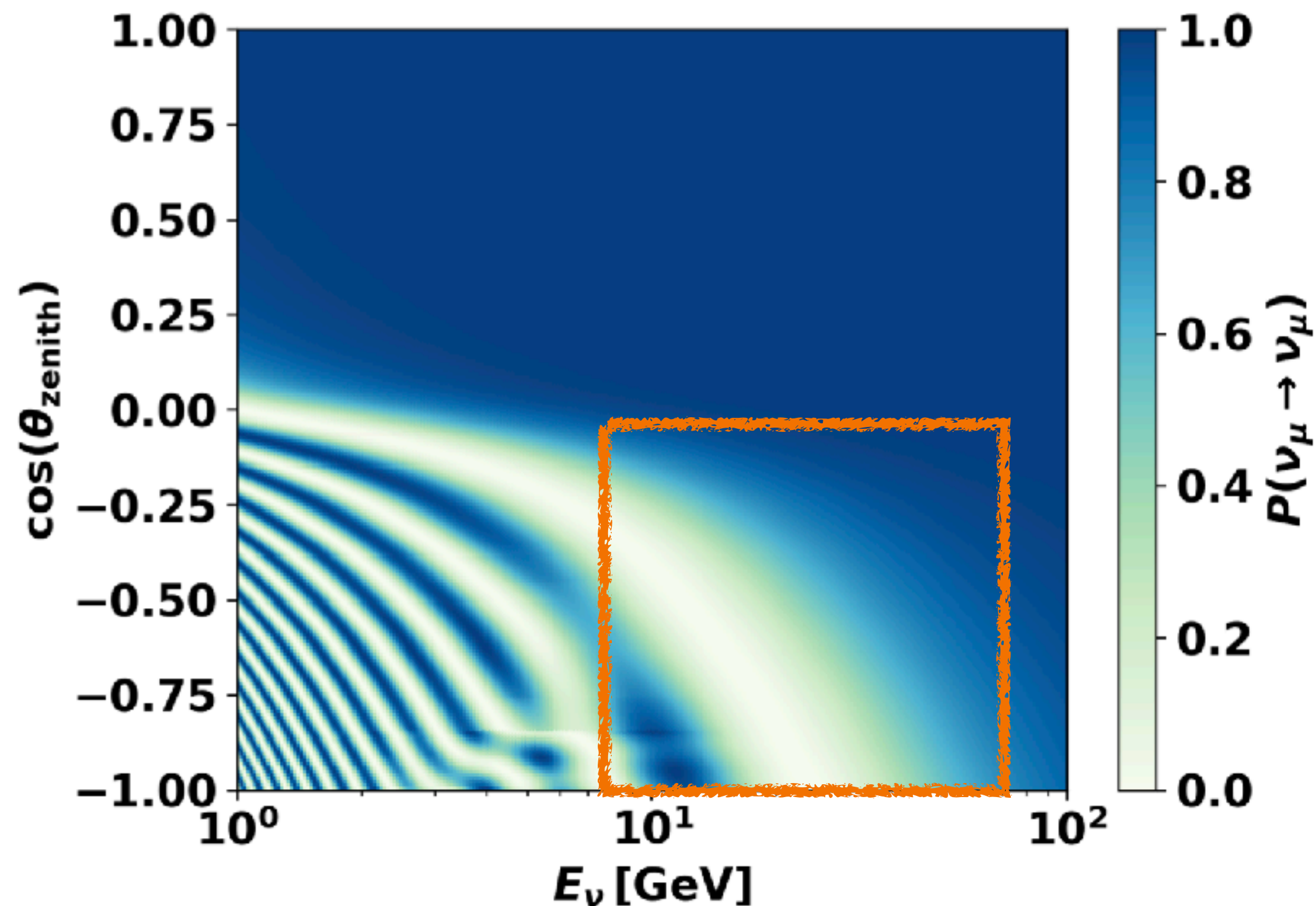
- Looking for **double cascades** event signature at light level
- Study images of most illuminated strings and its 2 neighbors
- 3 independent CNNs trained for distinguish signal from bkg
- **7 astrophysical tau neutrino candidates** found in 9.7 years of data!
- **Rules out absence of astro.  $\nu_\tau$  at  $5.1\sigma$**



# Latest oscillation measurement from DeepCore



- **Neutrino oscillations:** neutrinos changing flavours while propagating
  - **Precision measurement** using **pure and large statistics sample of atm. neutrinos in DeepCore**
- Oscillation ‘dip’ give sensitivity to “23” sector
- **Very competitive results!**



# **Recent and ongoing IceCube activities at IHE**

# Astrophysical Searches

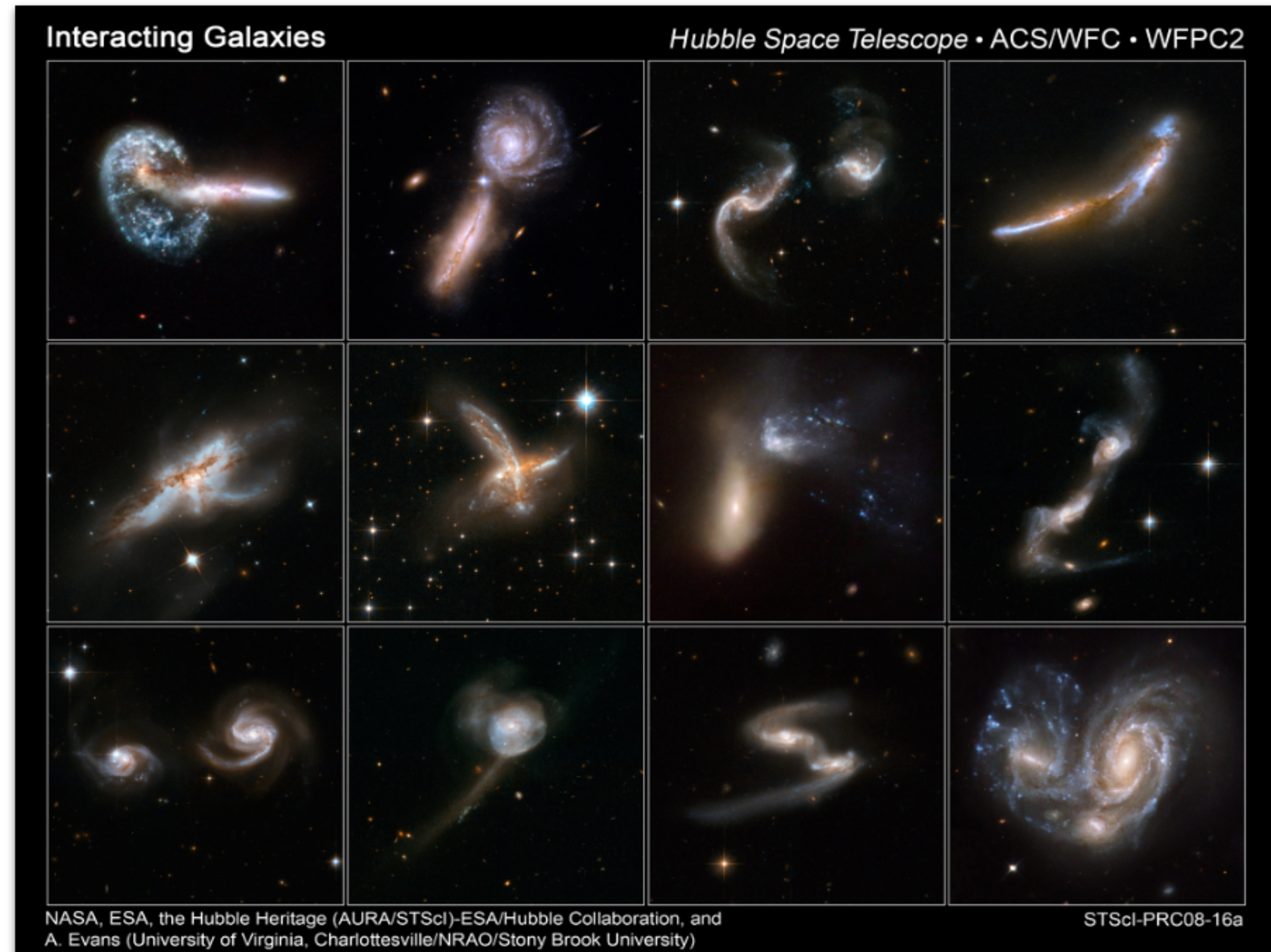
## U/LIRGs as $\nu$ -sources

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

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

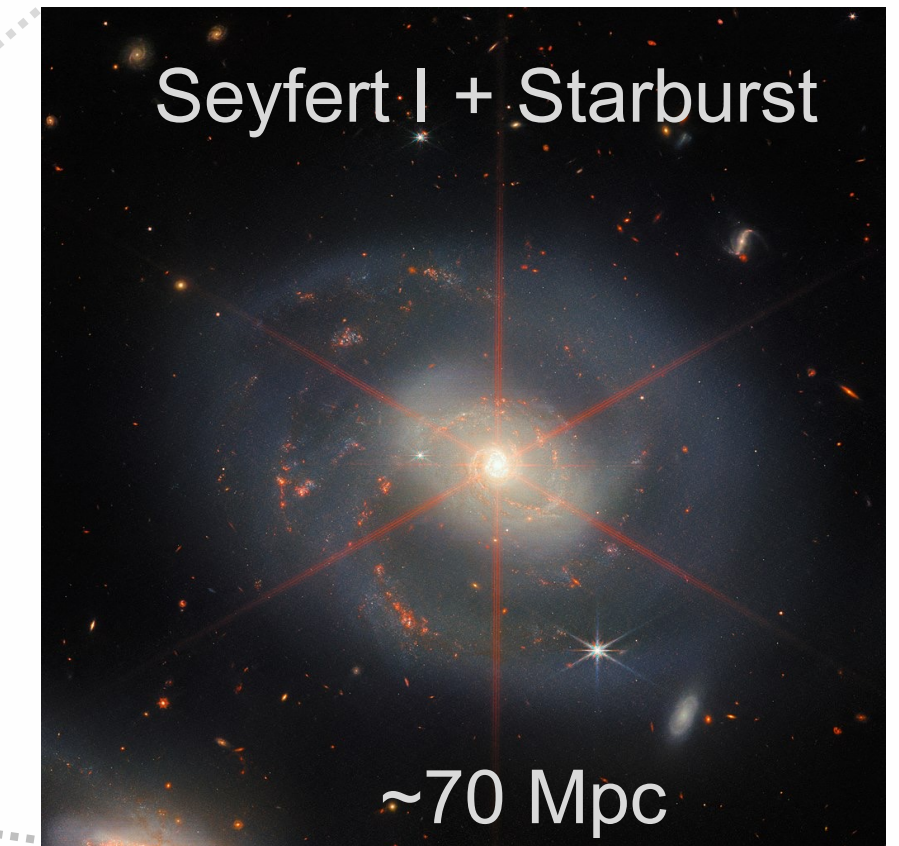
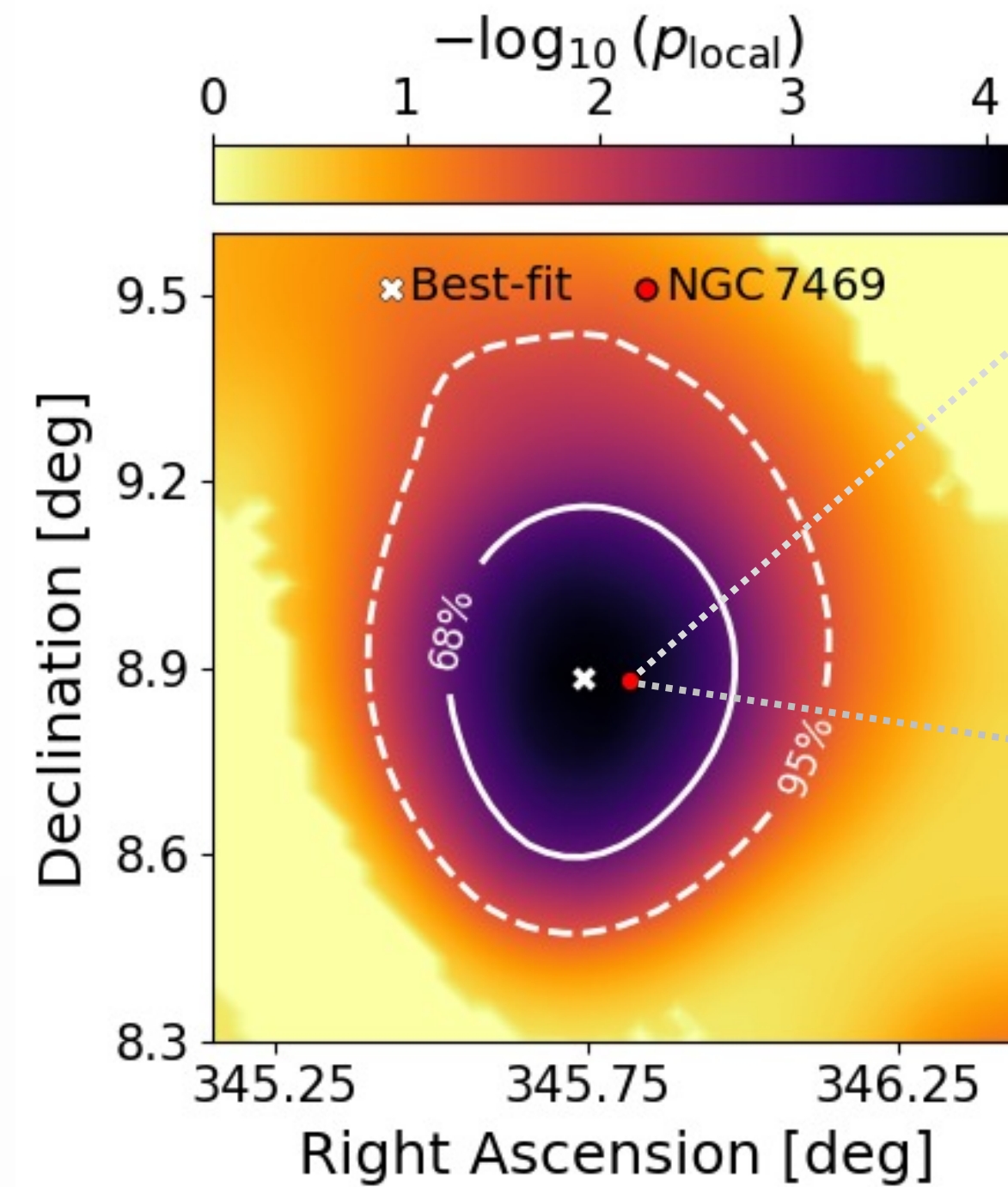
➤ **LIRG**:  $10^{11} L_{\odot} \leq L_{\text{IR}} < 10^{12} L_{\odot}$

- Primarily interacting galaxies



- First IceCube search for high-energy  $\nu$ 's from nearby Luminous Infrared Galaxies (LIRGs)
  - **Dataset:**  $\nu_\mu$ 's from Northern Hemisphere
  - **Catalog:** Northern LIRGs in the Great Observatories All-Sky LIRG Survey (113)
    - Excl. NGC1068
    - Starburst (SB), AGN & AGN+SB
- **Take-home messages:**
  - Excess from NGC7469 (AGN+SB)
  - Starburst galaxies show no excess while hybrid sources (NGC1068 & NGC7469) do

**NGC7469 is the most significant galaxy**



**2.4 $\sigma$  excess** after trial correction

**Driven by two 100 TeV  $\nu$ 's coincident with NGC 7469**



# Investigation of the light curves of gamma-ray bursts

Gamma-ray bursts: Very short pulses of gamma-rays, created when two compact objects merge (e.g. neutron stars) or a massive star explodes (SN Type Ic).

- Emission process still not understood.



**Else Magnus**

🔍 Can we find traces of the underlying processes producing the gamma-rays of GRBs?

- Investigate the **time variability** of an ensemble of GRB light curves by their **average power density spectrum**.

Investigate the shape of the spectrum and

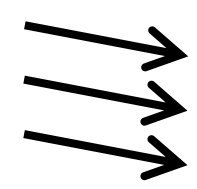
- Compare with earlier research.
- Set new measurements for different types of GRBs.
- Power-law  $\rightarrow$  Hint for turbulent processes?

} Paper in process!

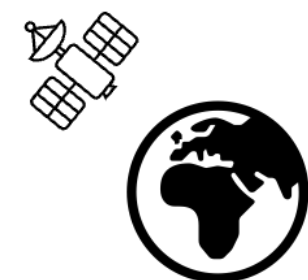
- Goal for next year: **IceCube search** for sources of neutrinos.



Gamma-ray burst



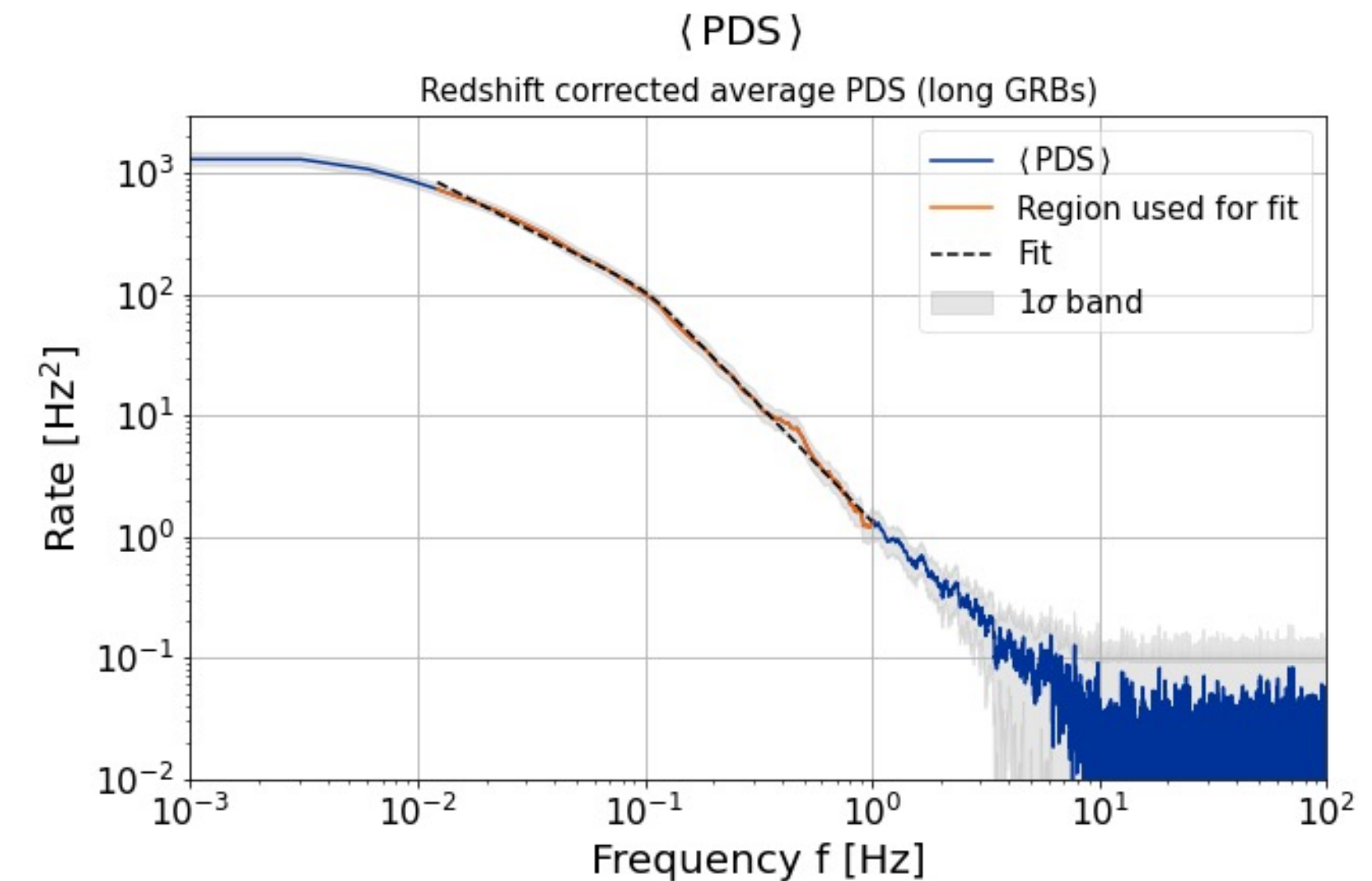
$\gamma$ -rays



Fermi telescope



Else

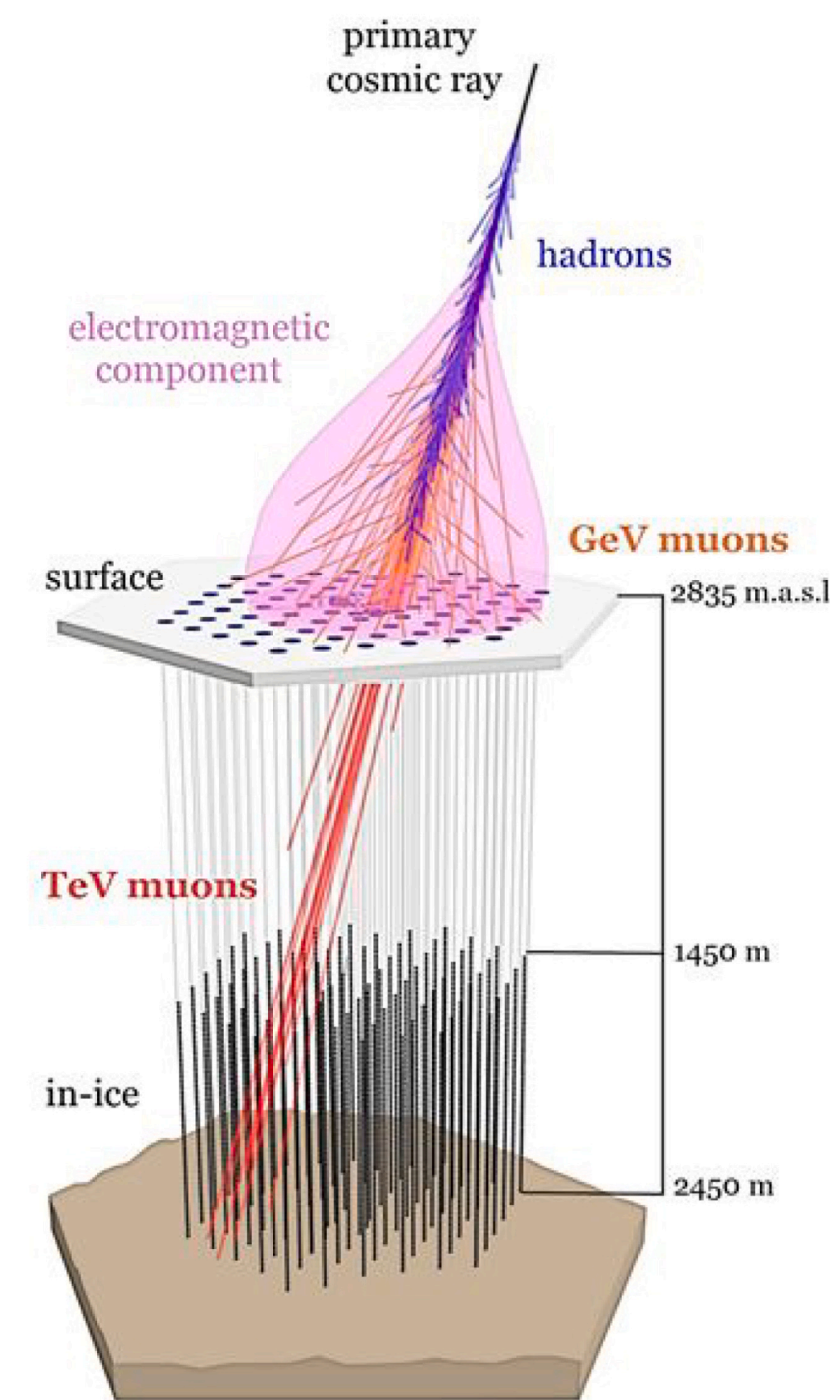




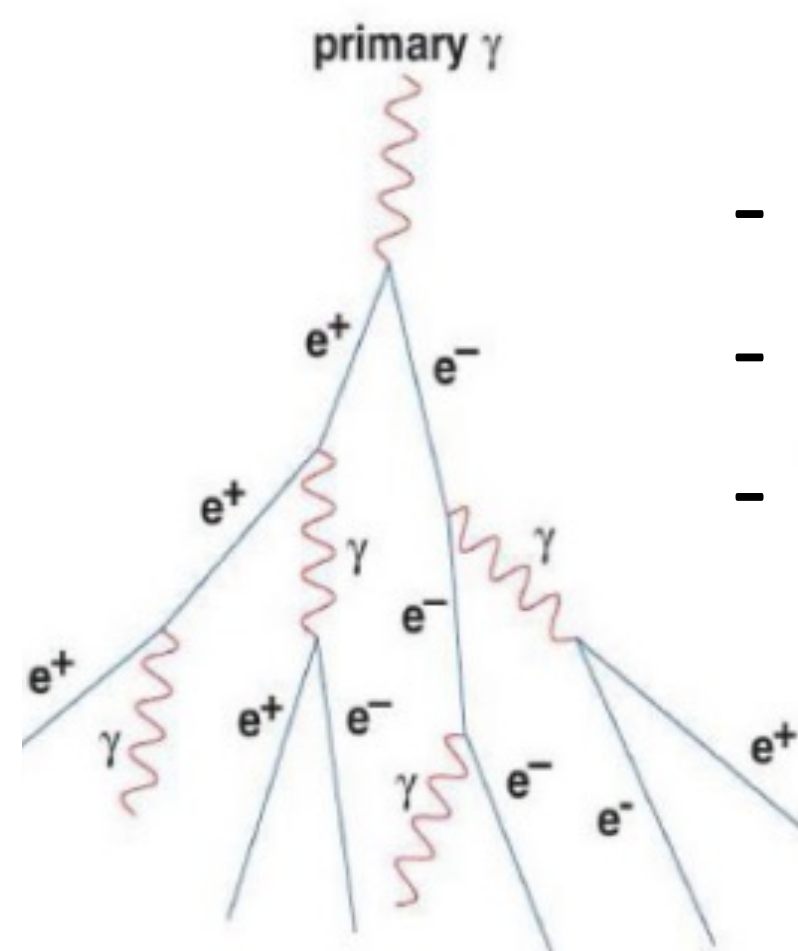
# PeV gamma-ray searches with IceTop

◆ Andrea Parenti, postdoc with Ioana Mariş

- **IceTop** has a unique view of the southern gamma-ray sky in the 1 – 100 PeV energy range
- Measure **diffuse gamma-ray flux** -> limits on lifetime of decaying superheavy dark matter

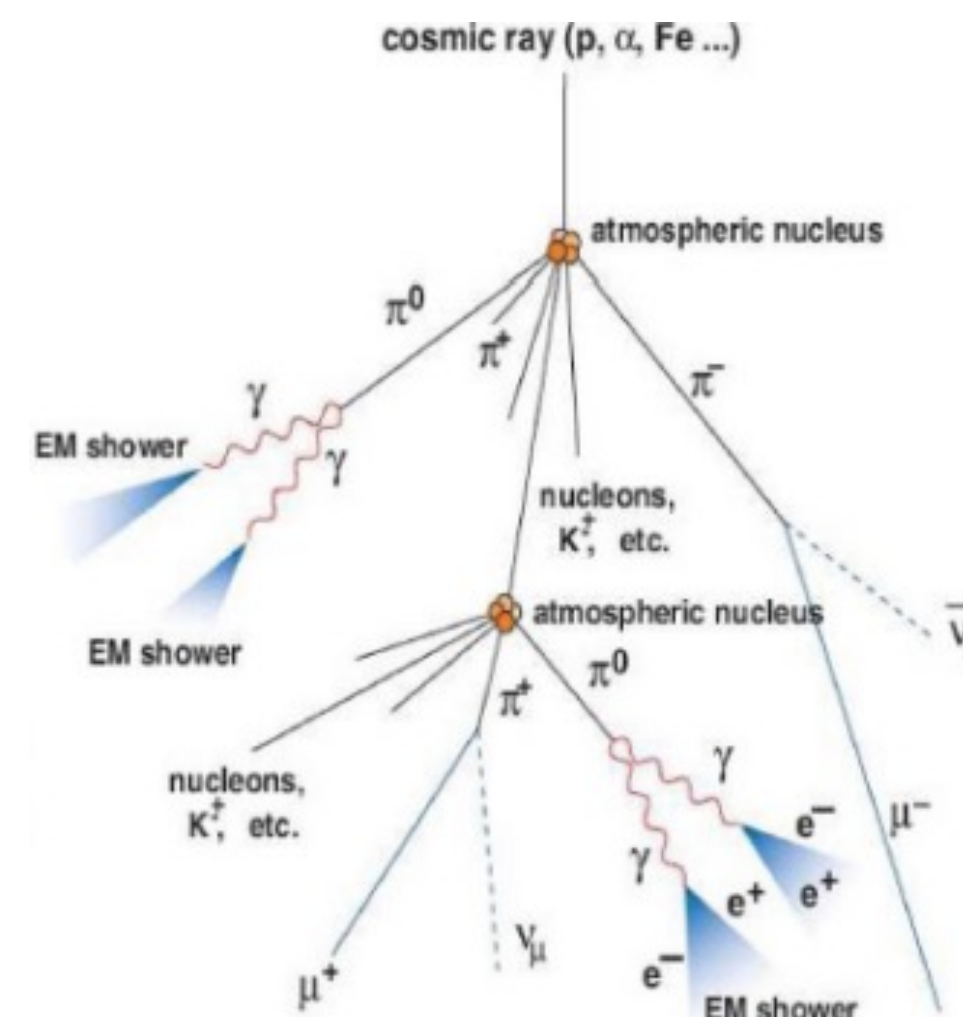


## Gamma-ray shower



- Reduced muon content
- Contained lateral spread
- Initiates deeper in the atmosphere

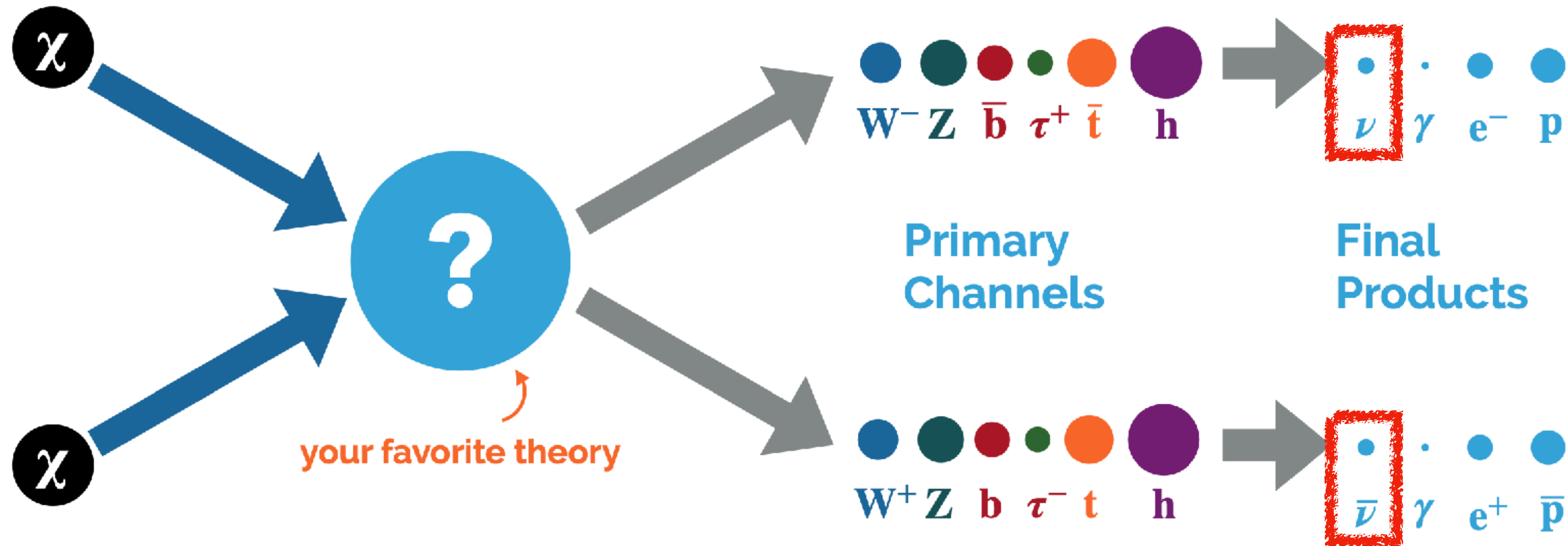
## Cosmic ray shower



- Larger muon content and lateral spread
- Higher shower-to-shower fluctuations
- TeV muons reach the in-ice detector and can be used to tag cosmic rays



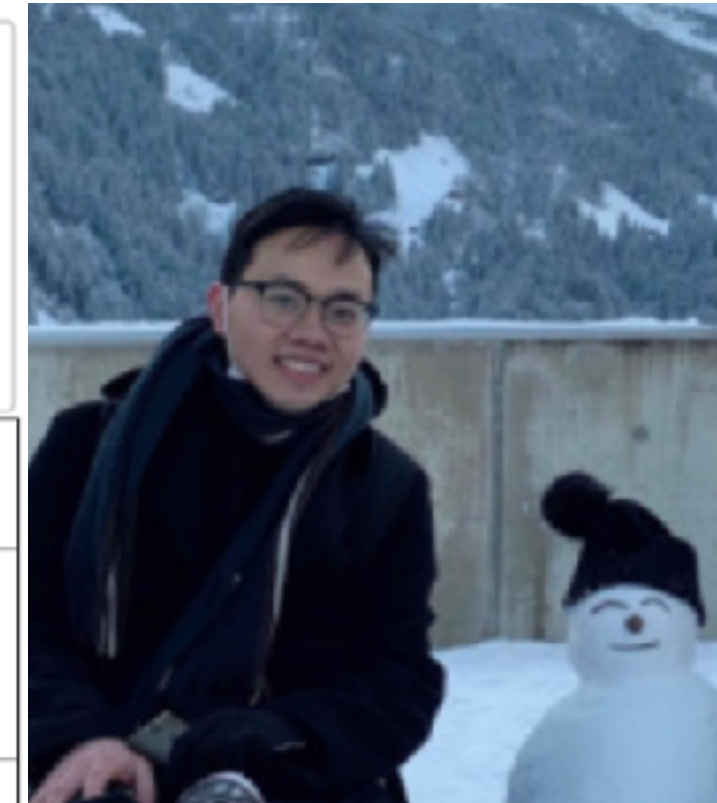
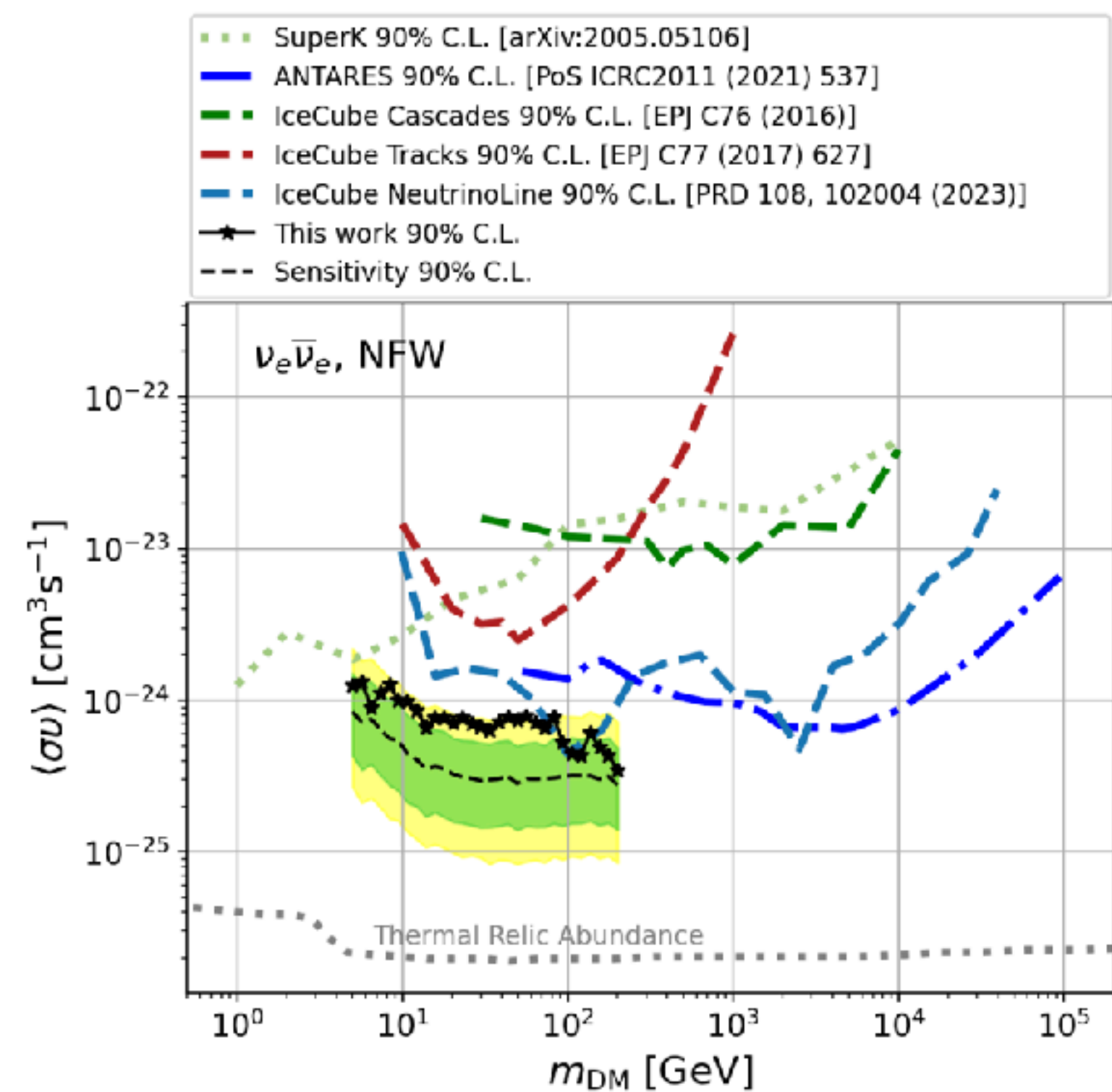
# Indirect Dark Matter Searches



- 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**.

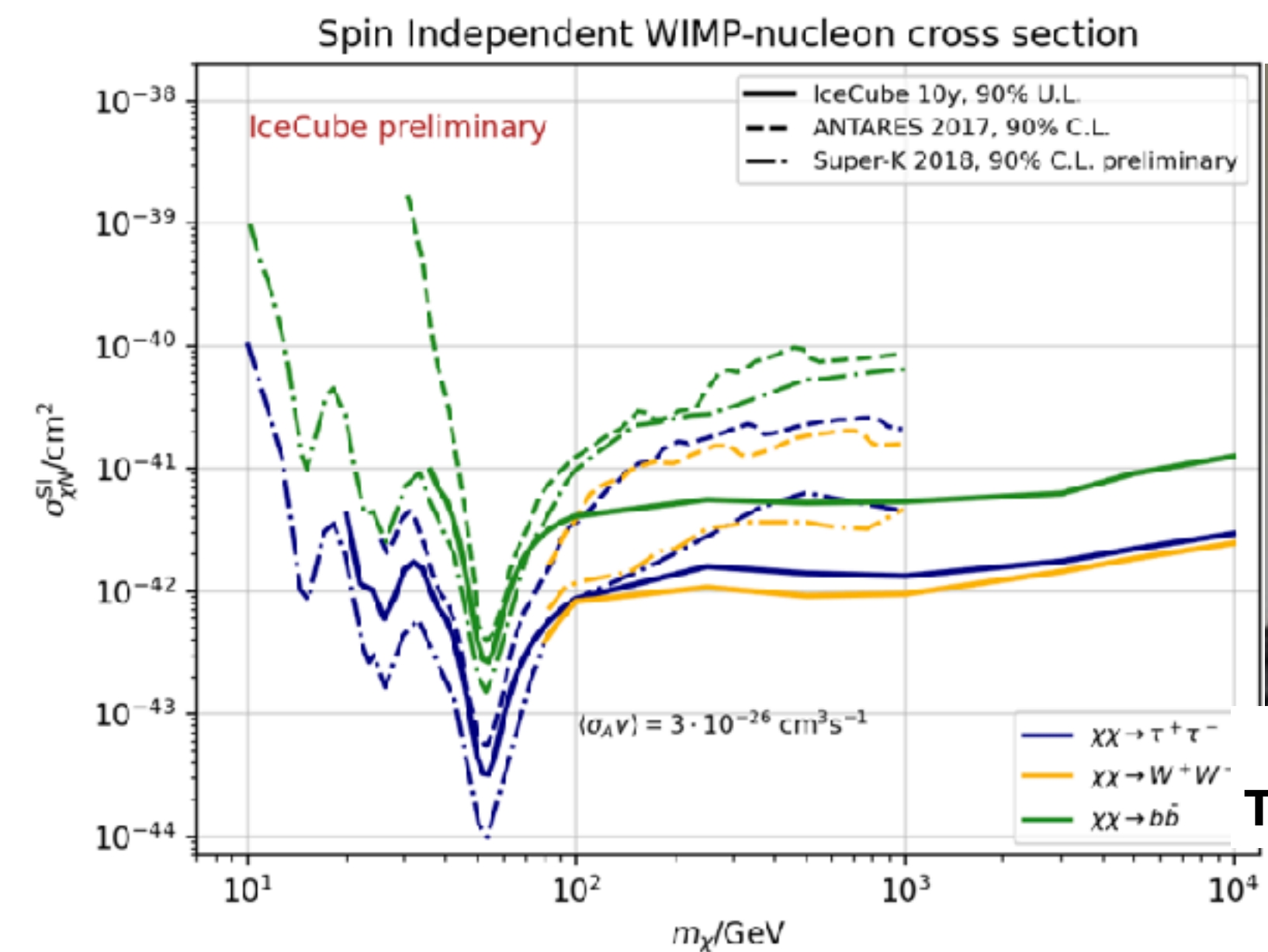
# Indirect Dark Matter Searches

- Neutrino signals from Dark Matter annihilation/decay in the **Galactic Centre:**
  - ▶ Extended and improved limit at low DM masses (GeV-scale Dark Matter) with **most up-to-date DeepCore data. No DM found**, set 90% limits.
  - ▶ Ongoing works for updating full energy range of IceCube



Nhan Chau

- Dark matter gravitationally trapped inside the **Earth:**
  - ▶  $\nu$  is the only possible messenger!
  - ▶ **No DM found.** Probe **dark matter - nucleon spin-independent**  $\sigma_{SI}$



Giovanni Renzi  
Thesis defended in 2022

\* Two papers in preparation

# Other BSM searches starting @ IIHE

- Search for **fractionally charged/milicharged particles** with IceCube: long dim track signatures
- Possible collaboration with milliQan group



**Louise Lallement Arnaud**

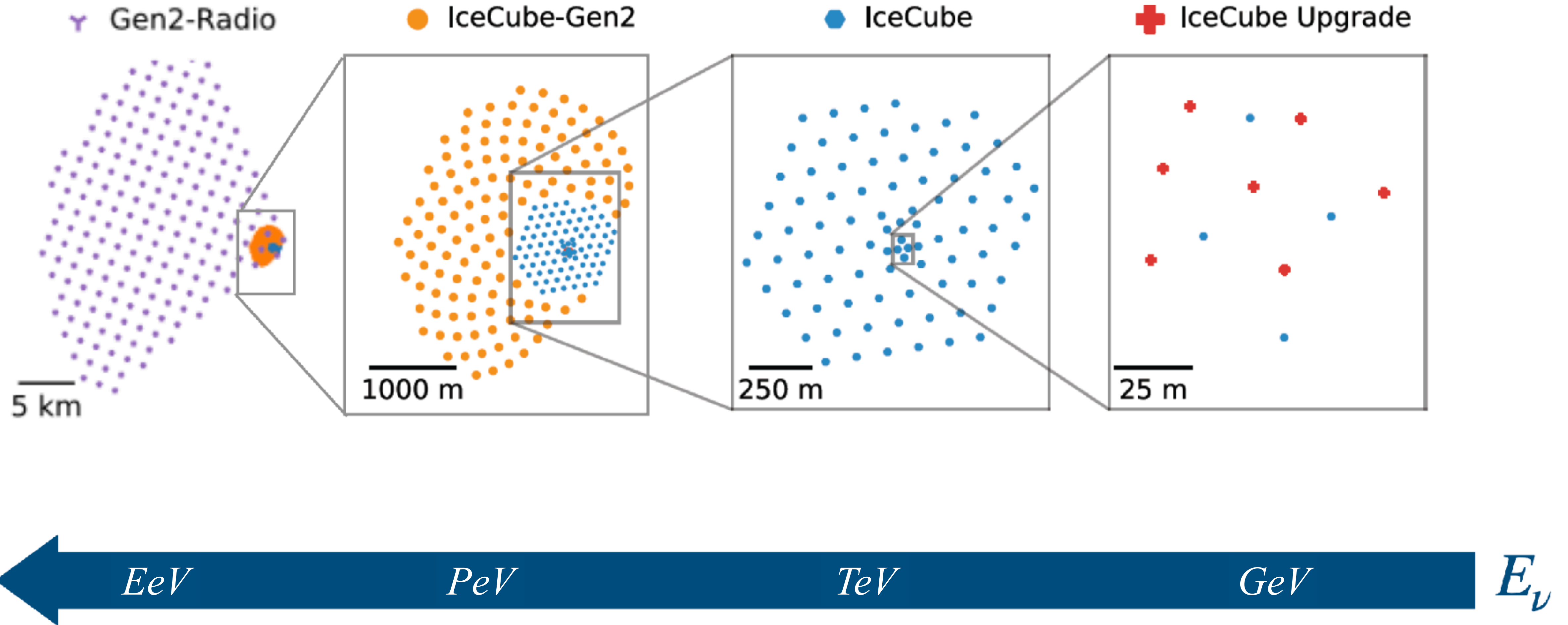
- New PhD student started on October 2024



**Arthur Perce**

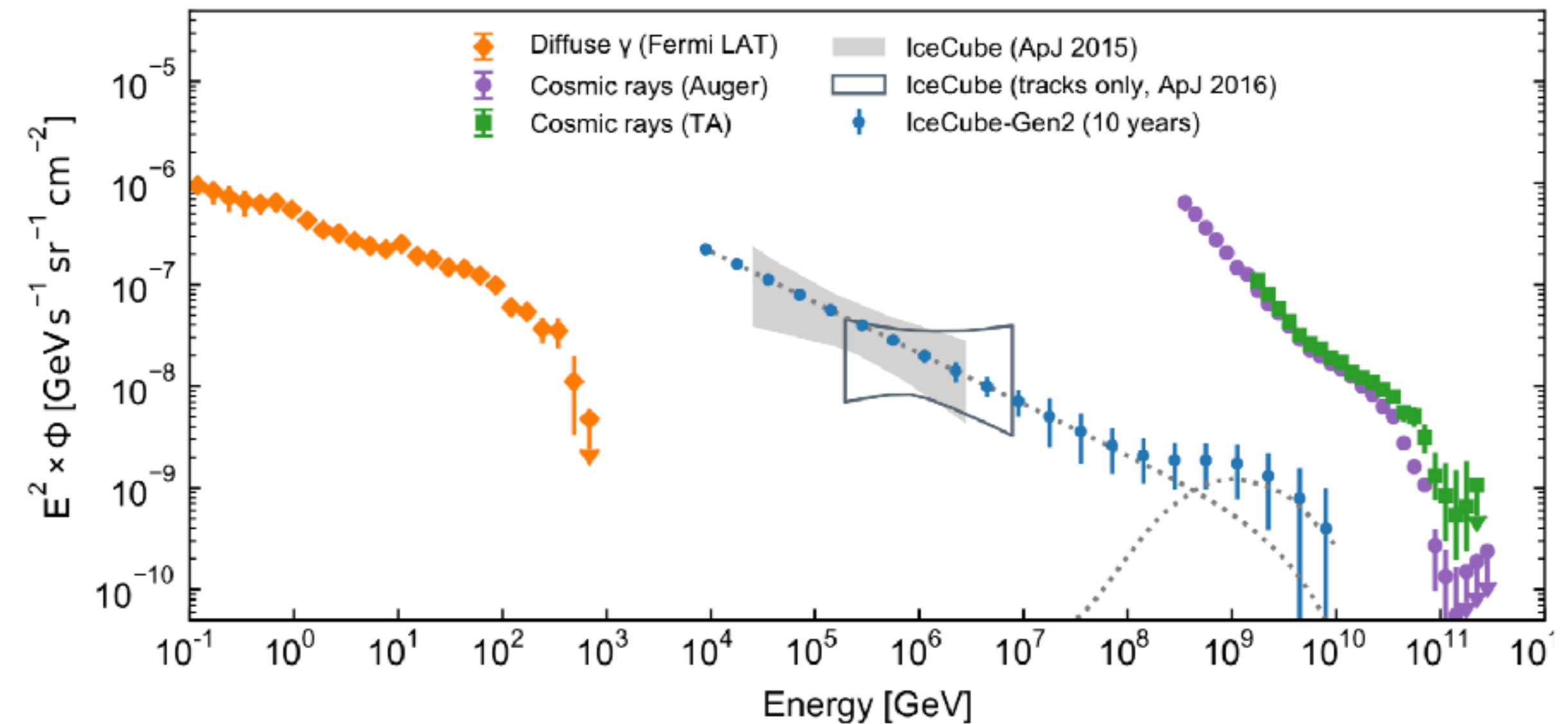
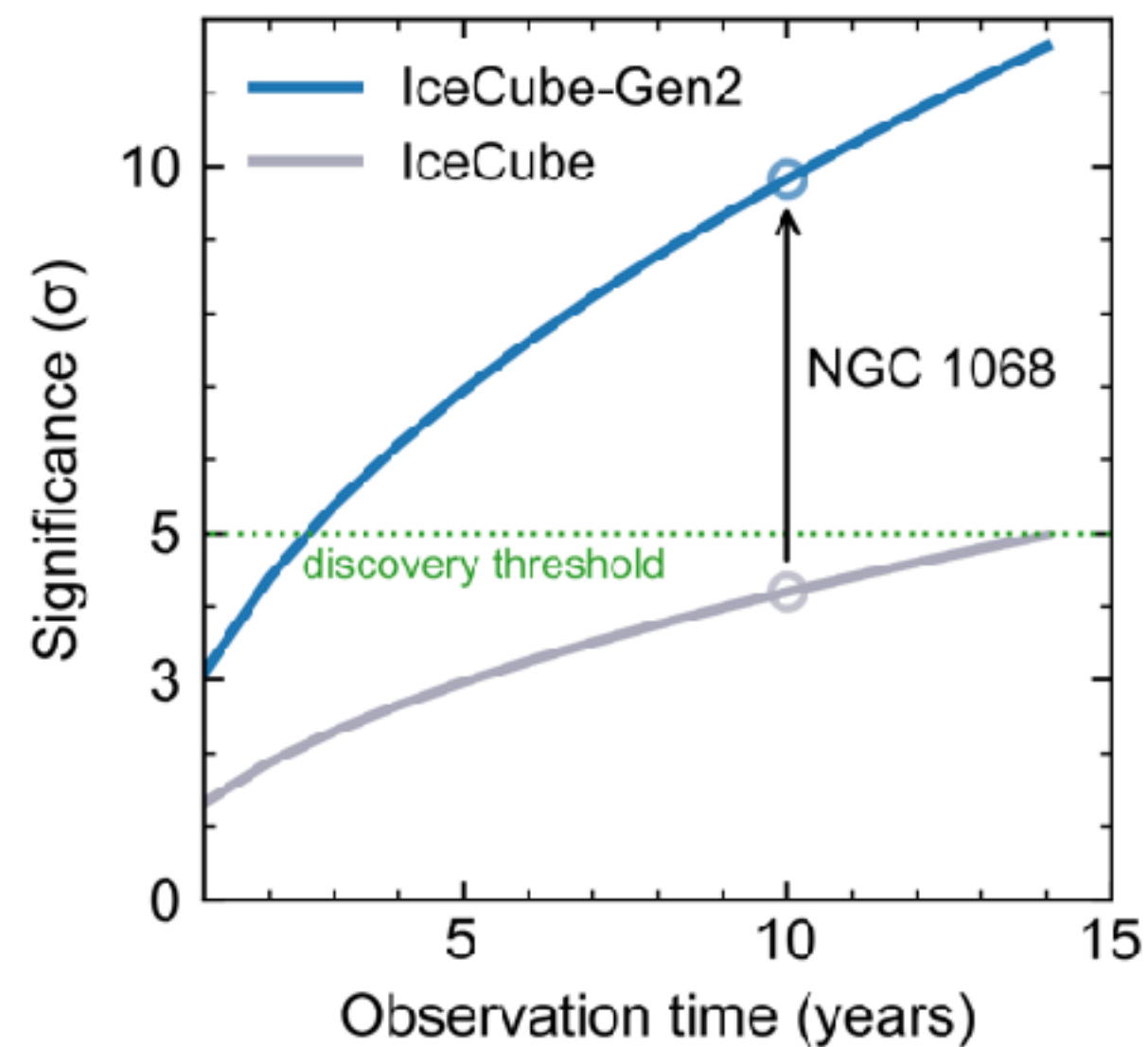
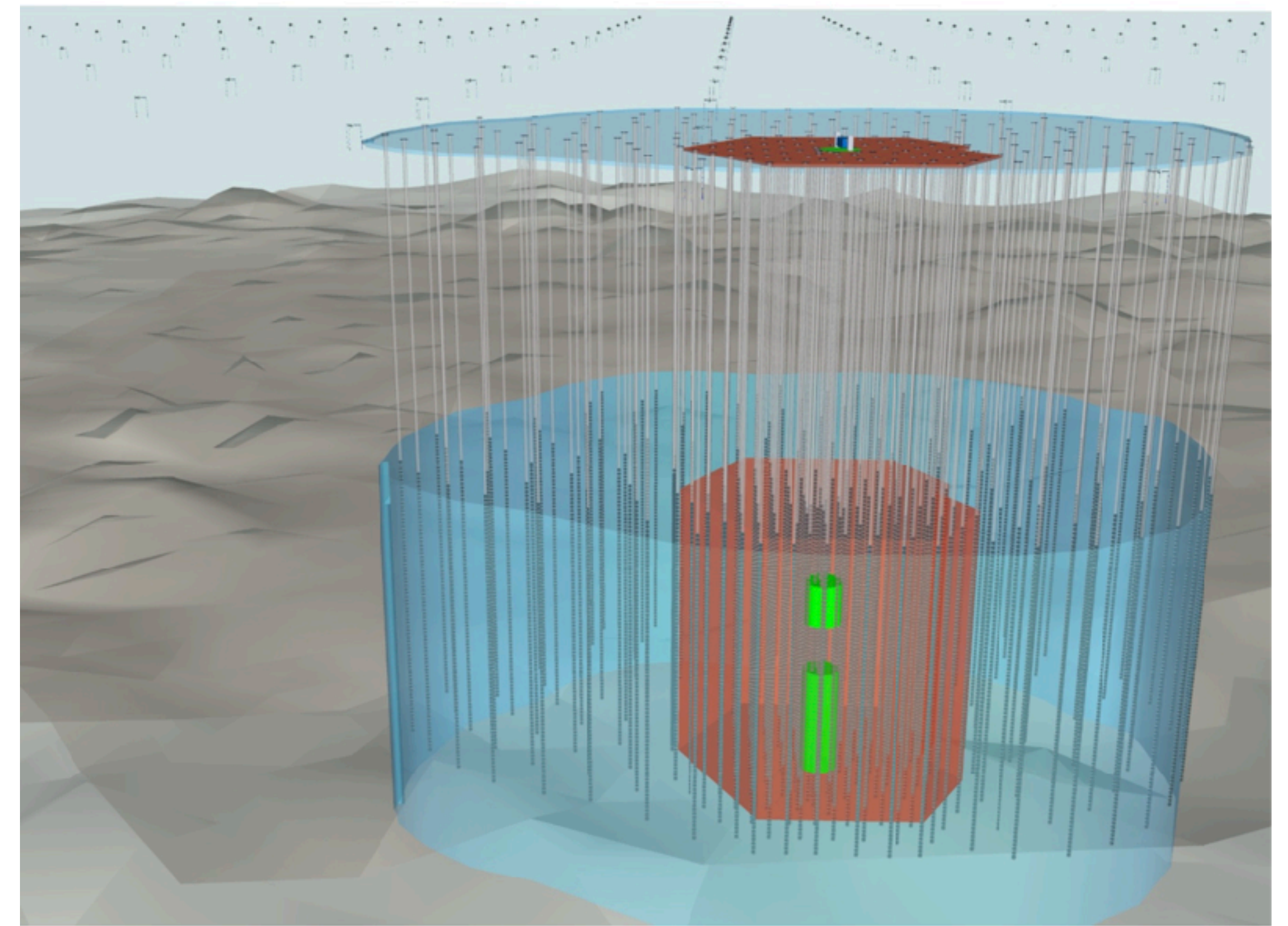
- Master student

# The future of IceCube: Upgrade and Gen2



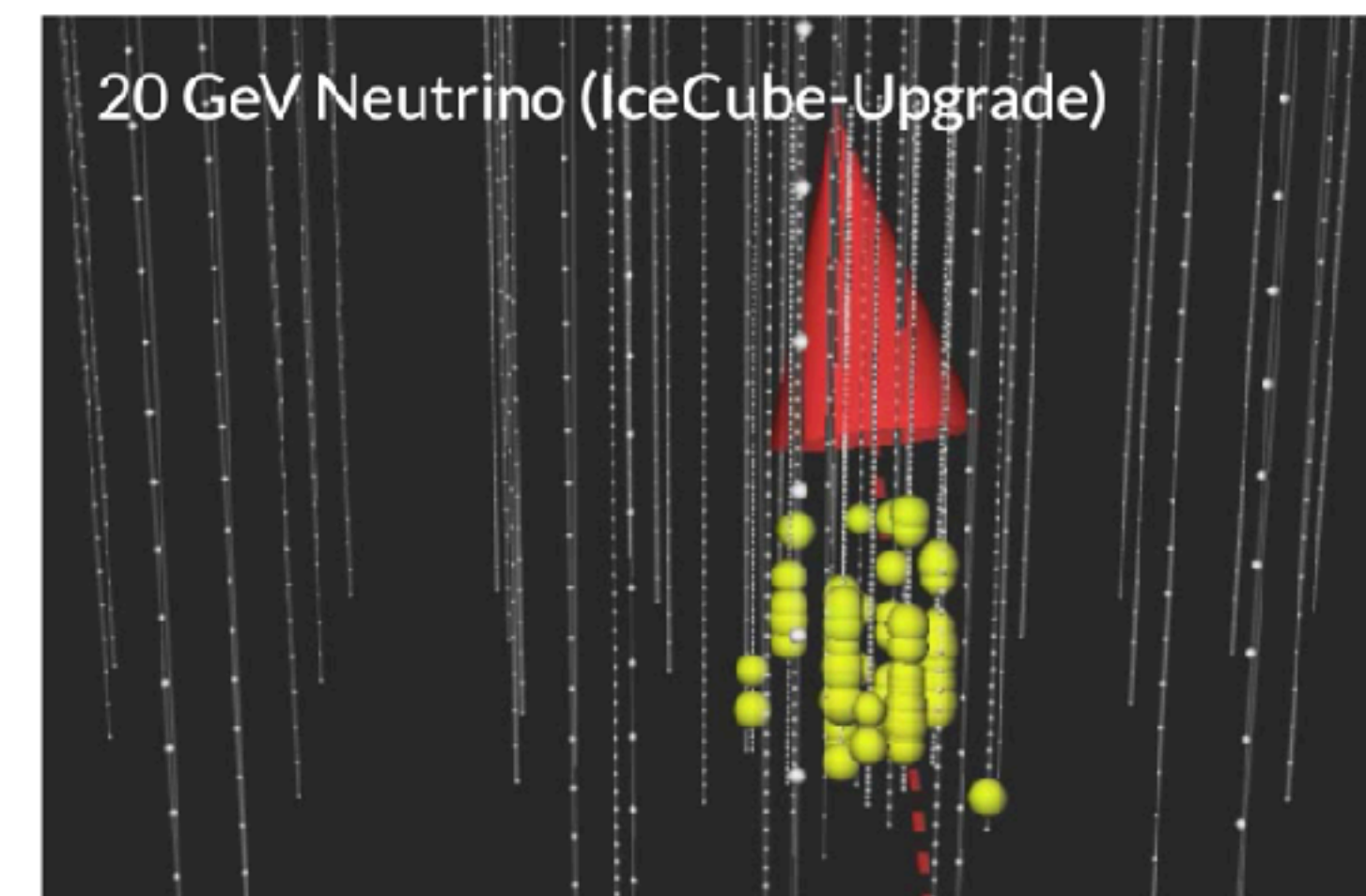
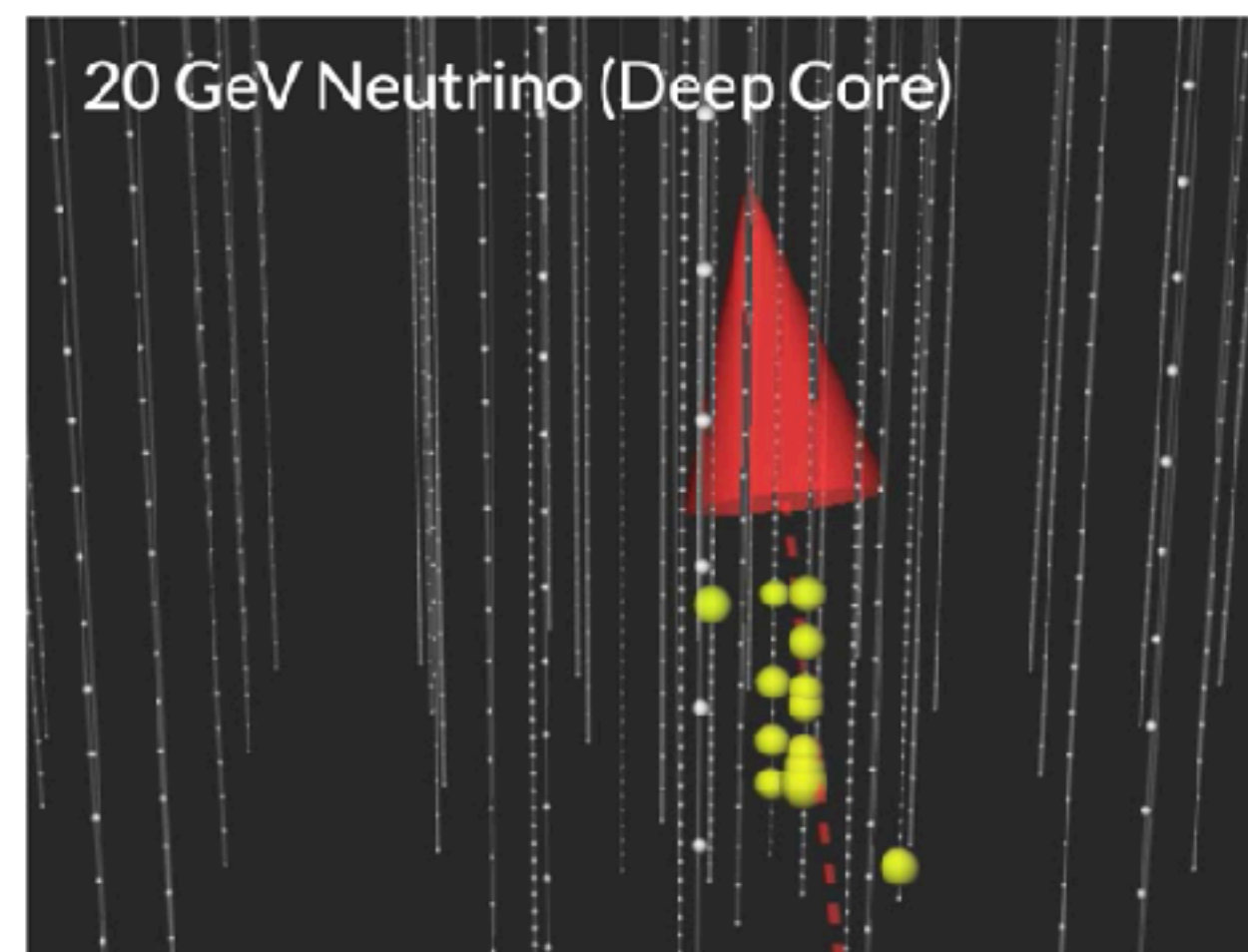
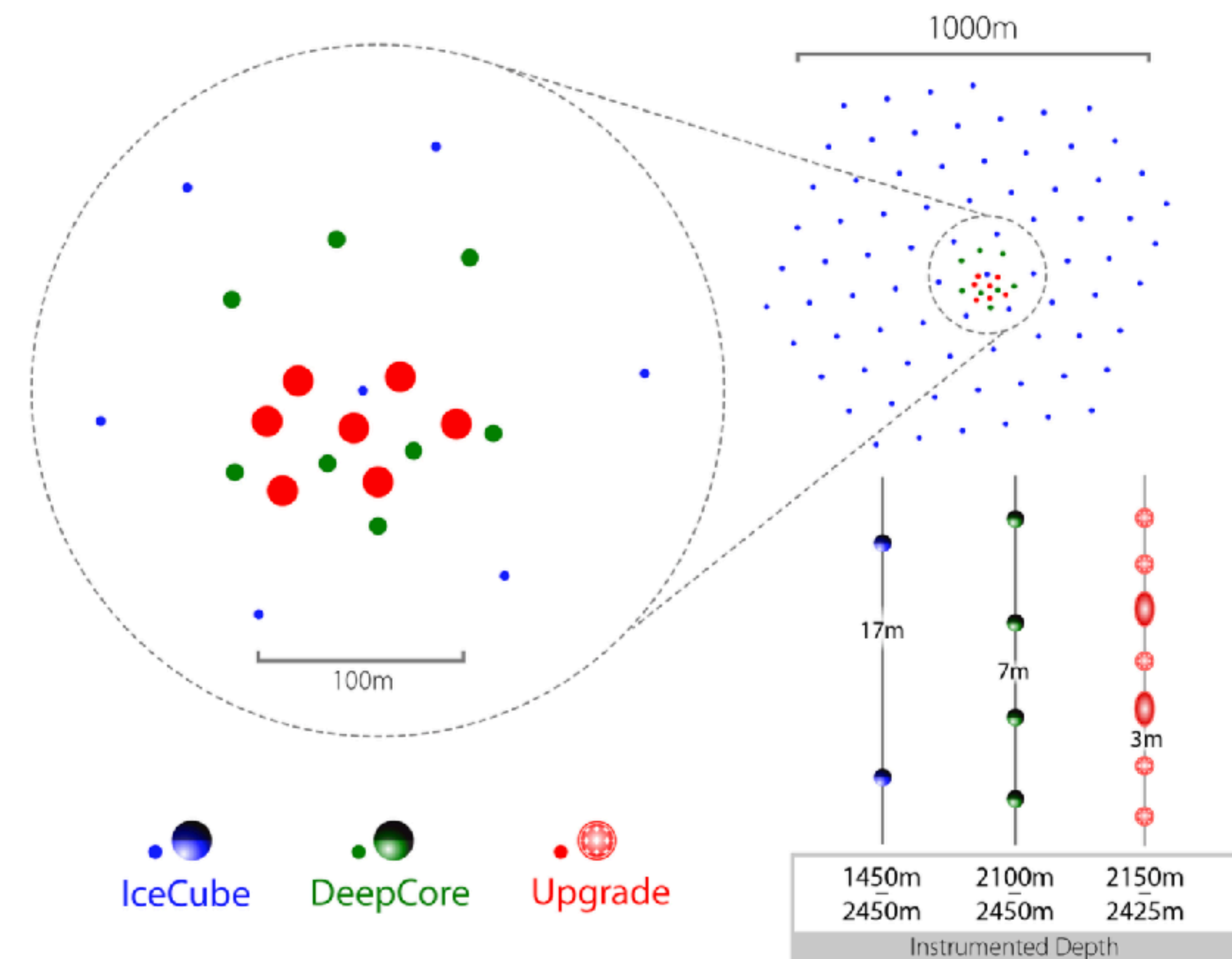
# IceCube-Gen2

- 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-Upgrade

- Deployment planned for 2025-2026
- Extend sensitivity at lower energy
- Ice calibration, better control of the systematics
  - Improved energy and angular reconstruction
- **Objectives:**
  - **Reprocess of existing data** with new calibration/ice model/reconstruction!
  - **Precision measurement of atmospheric neutrino oscillations.**

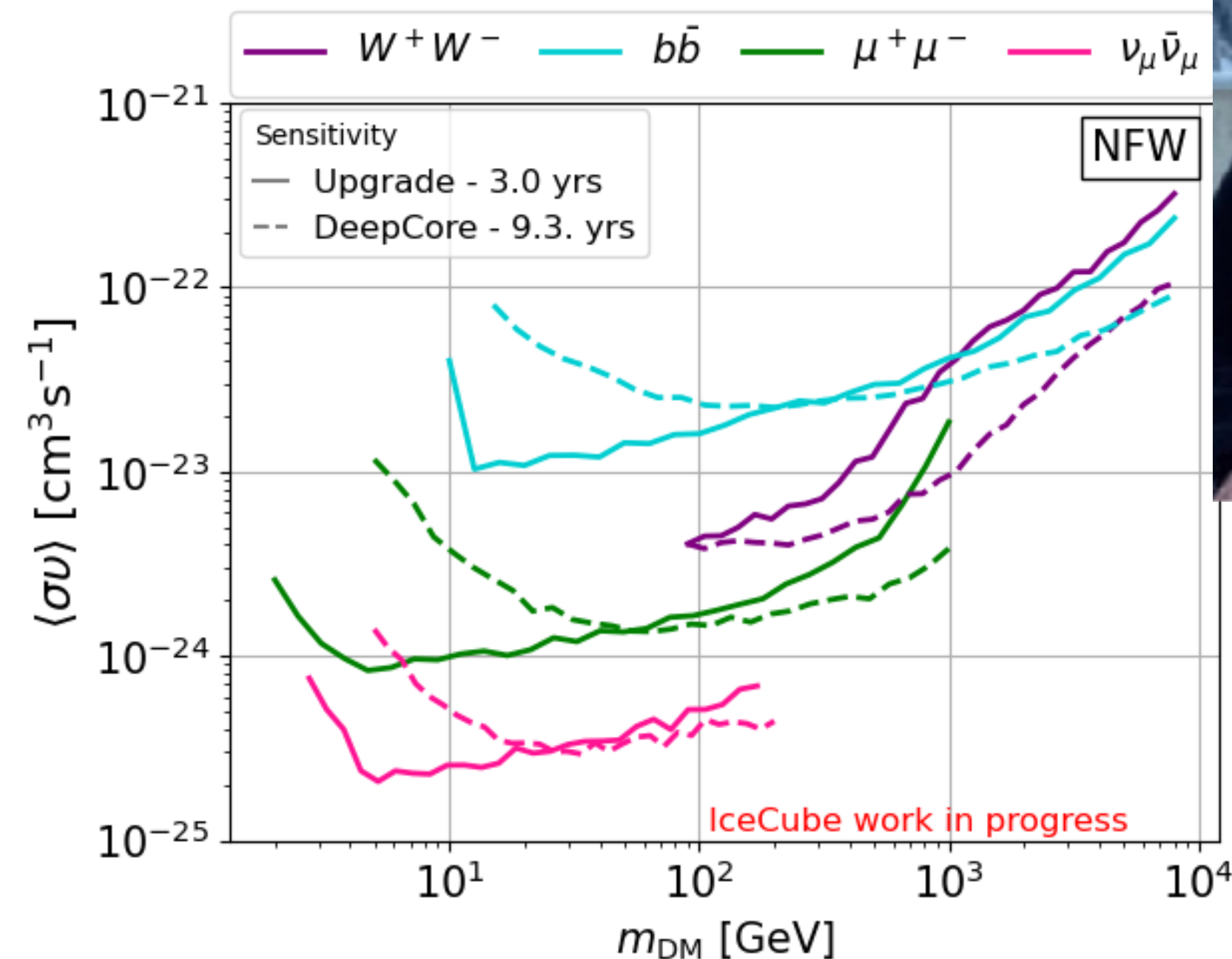


# IceCube-Upgrade @ IIHE

- Exploring the **sensitivity of Upgrade** to the **DM search in the Galactic Center**.
  - ▶ Reach to current level of DeepCore within 3 years.
  - ▶ 1 order of magnitude improvement below 50 GeV.



Louise Lallement Arnaud



Nhan Chau

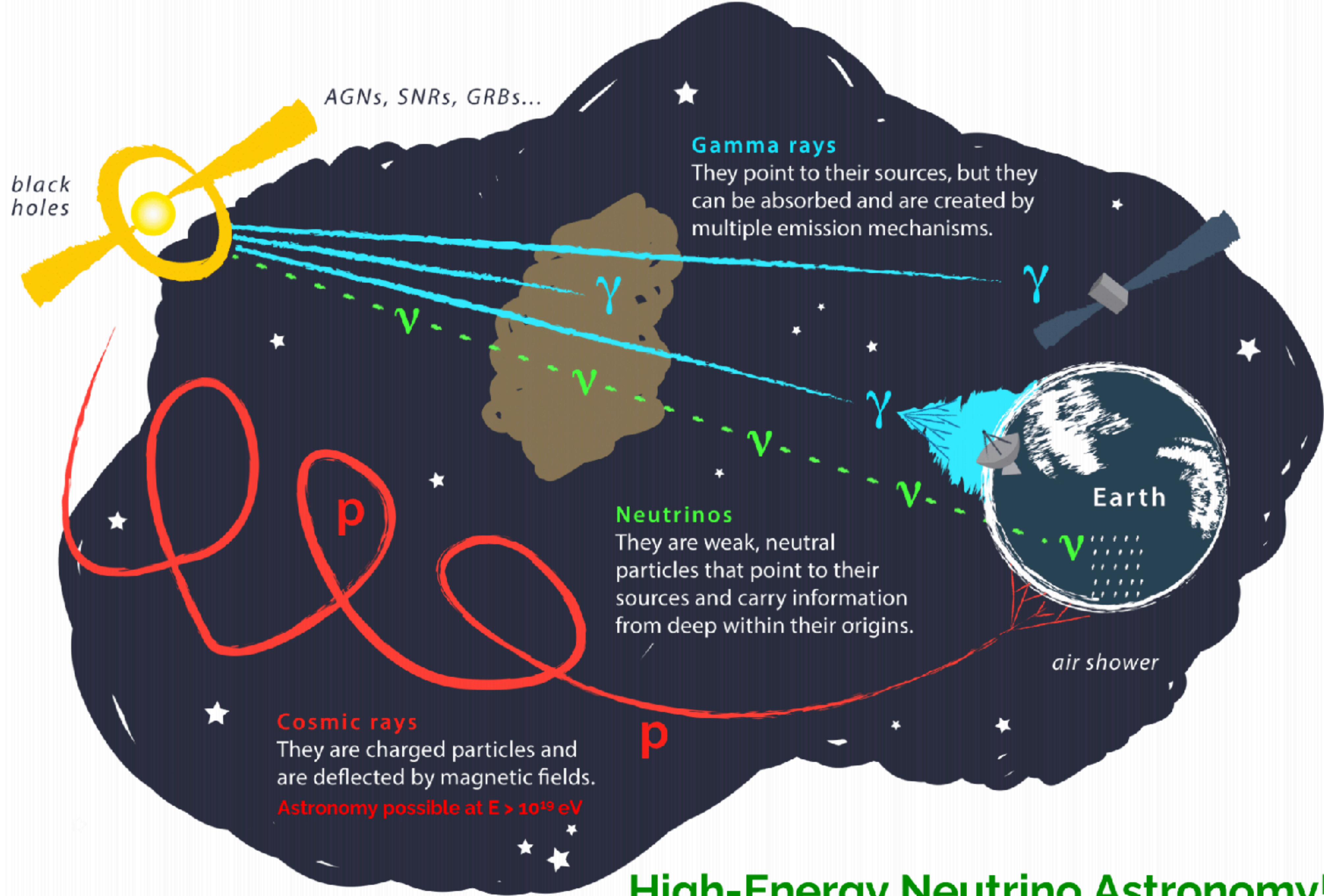
- Joining on-going effort in **Upgrade simulation**.
- Produce new **simulation sets for calibration studies**.

- IceCube has published several important results in the past decade.
  - We have not only pioneered neutrino astronomy but also advancing the frontiers of many other physics topics: neutrino oscillations, dark matter & BSM searches, cosmic rays,...
  - IceCube-Upgrade will come soon and enhance the capabilities of the current IceCube
  - IceCube-Gen2 is planned and will further explore the high-energy Universe.
- ✦ The era of neutrino astronomy is coming!





**Back up**



AGNs, SNRs, GRBs...

black holes

### Gamma rays

They point to their sources, but they can be absorbed and are created by multiple emission mechanisms.

### Neutrinos

They are weak, neutral particles that point to their sources and carry information from deep within their origins.

### Cosmic rays

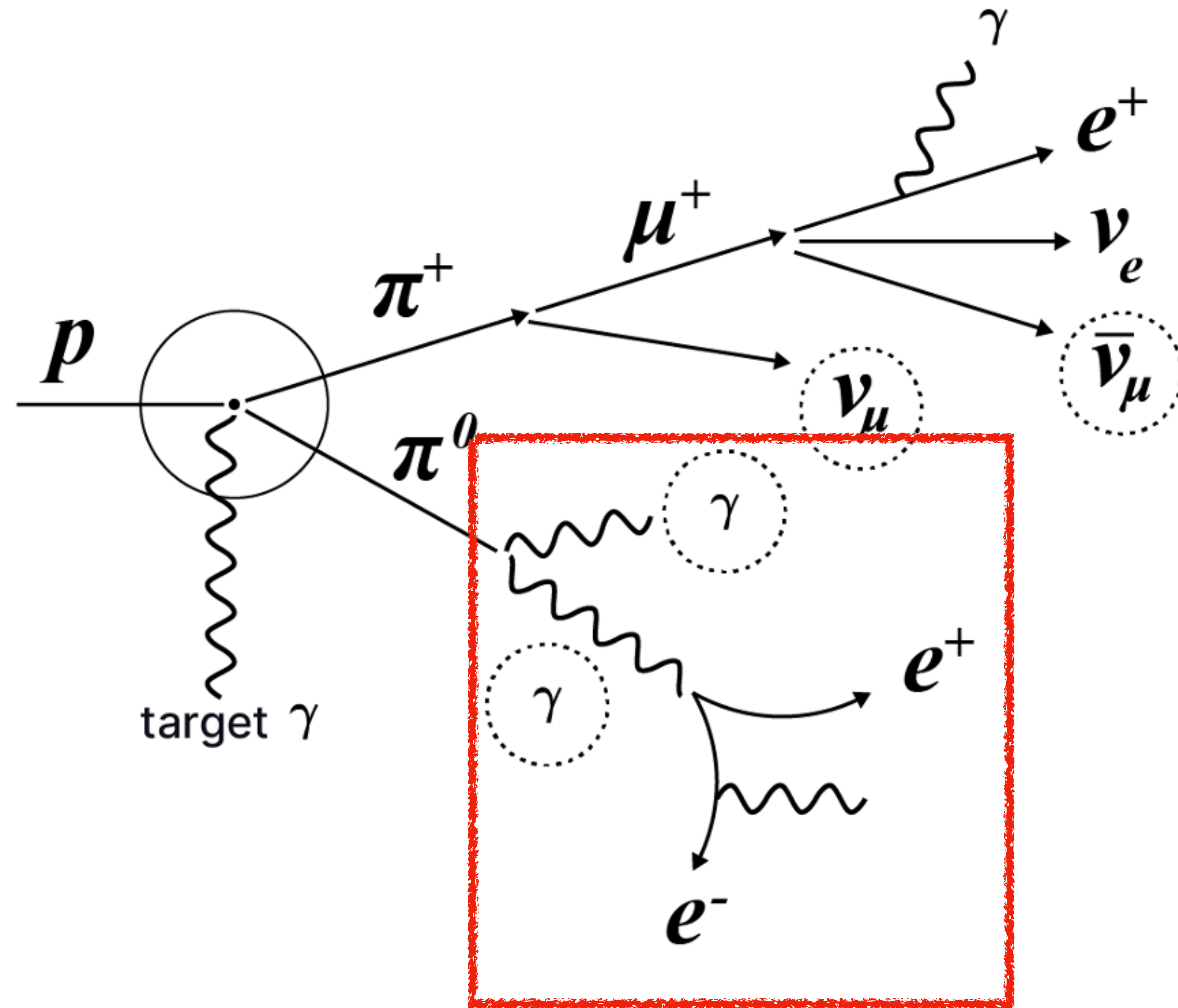
They are charged particles and are deflected by magnetic fields.

Astronomy possible at  $E > 10^{19}$  eV

Earth

air shower

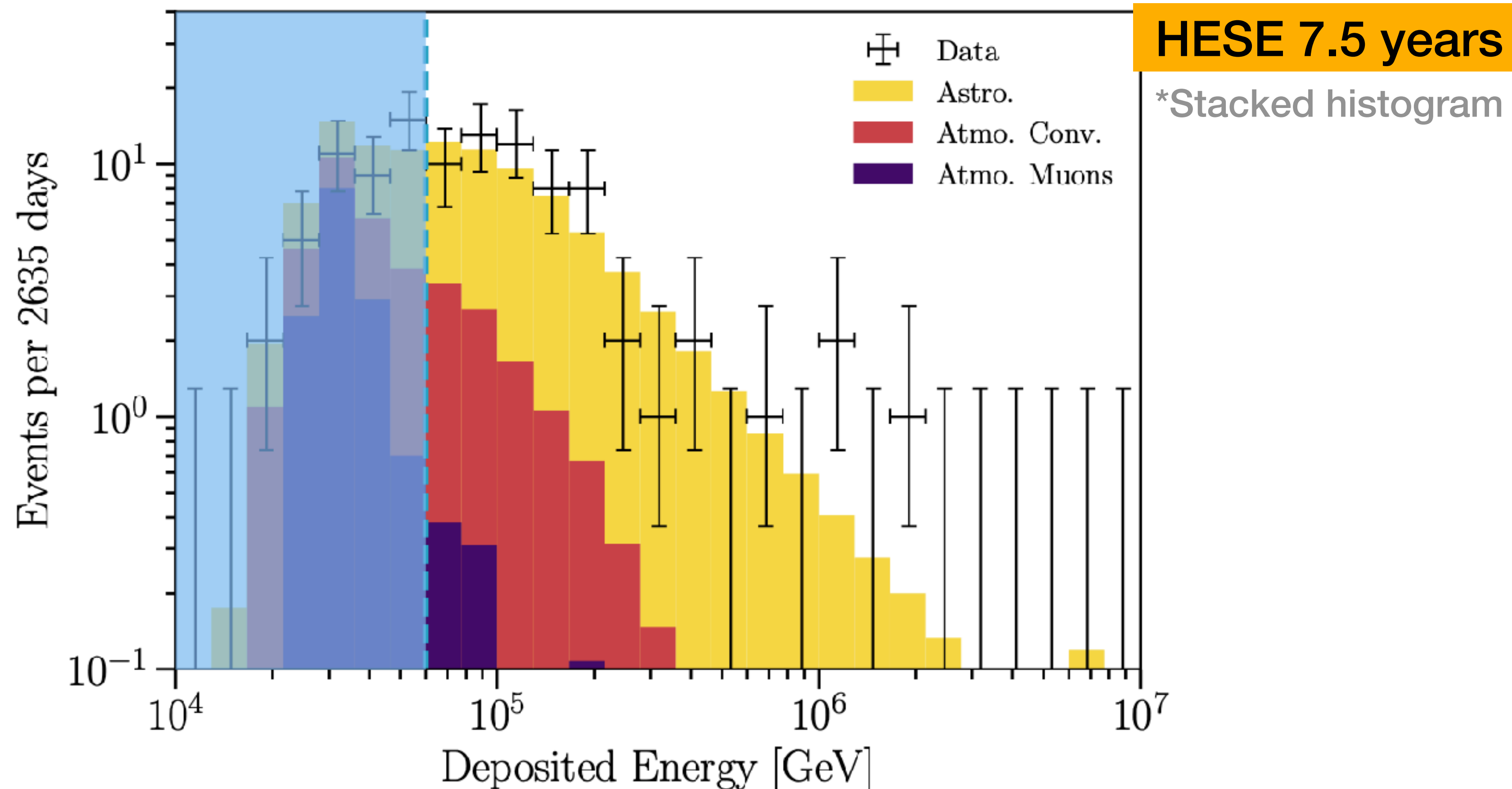
## High-Energy Neutrino Astronomy!



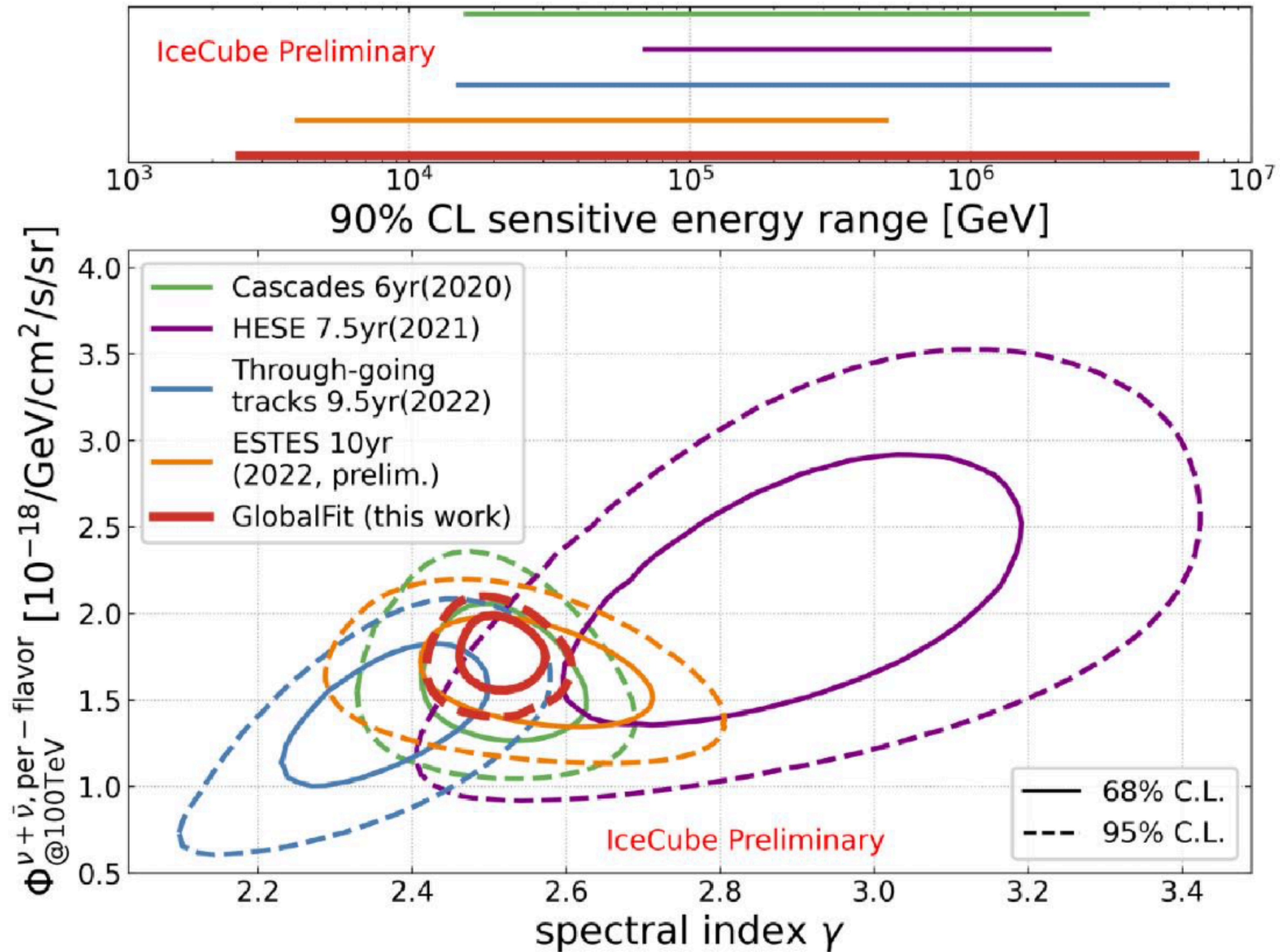
- peV photons cascade down before reach us and appears at GeV

# Astrophysical neutrino flux

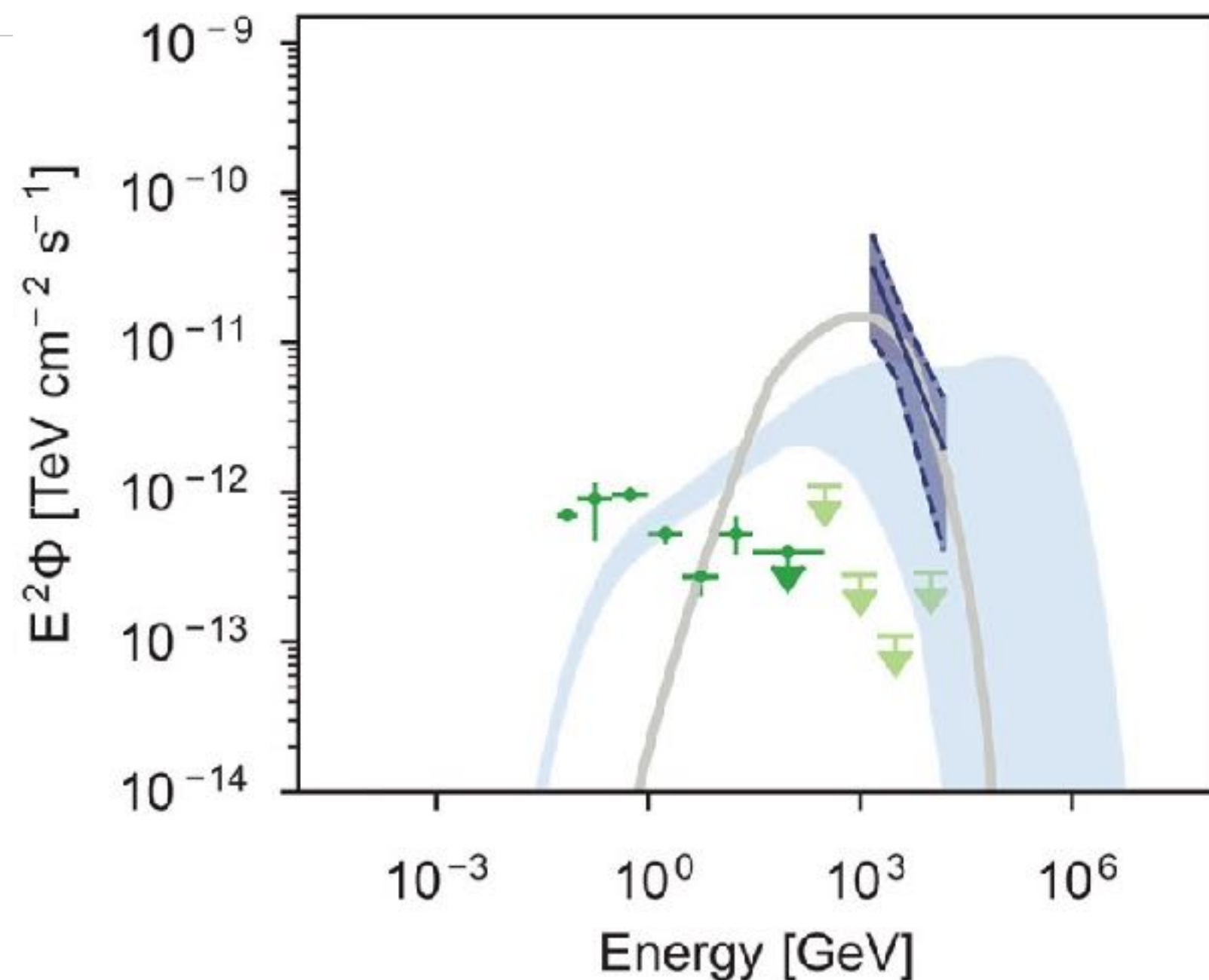
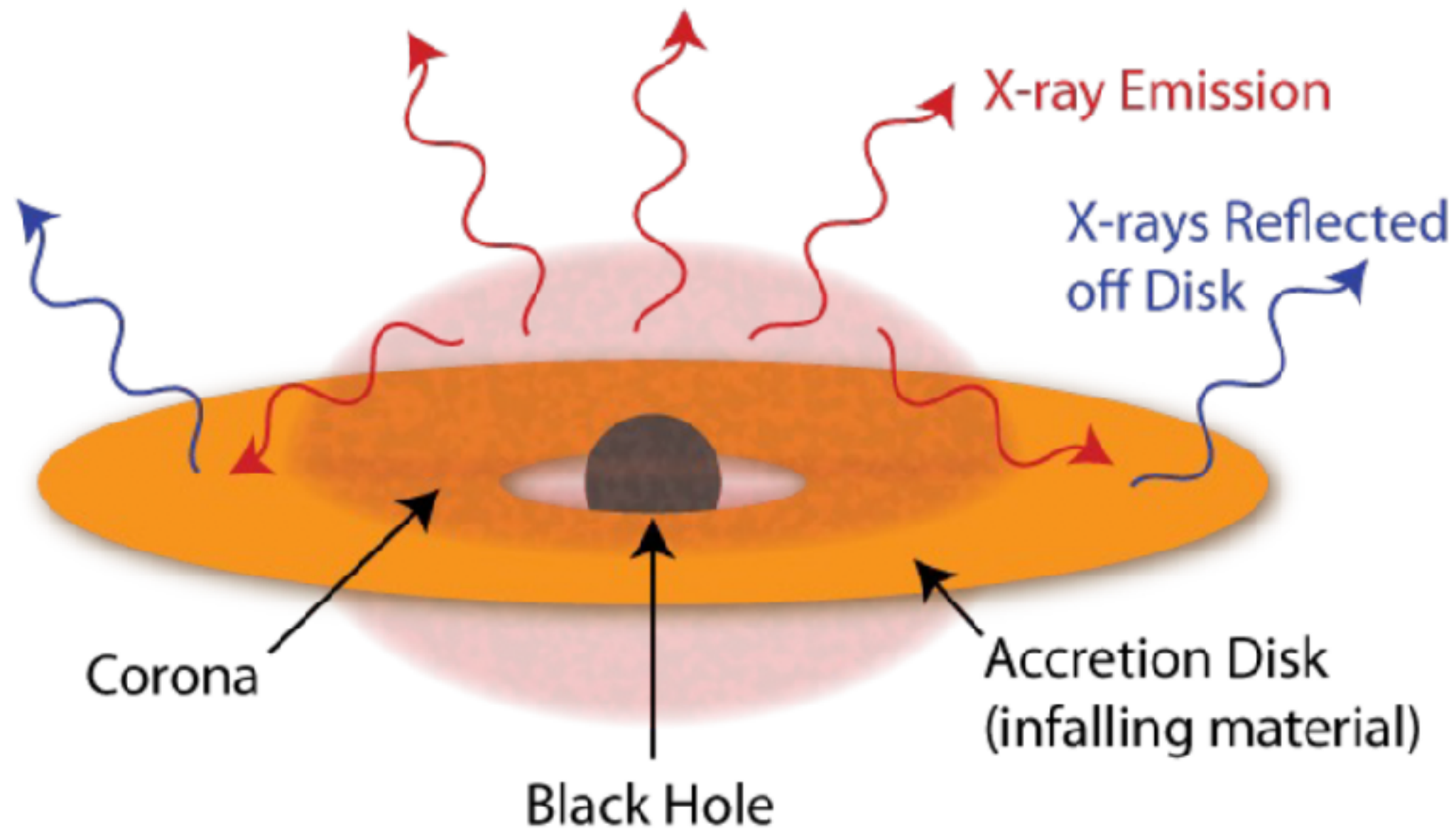
- HESE: High Energy Starting Events
- Muon filter by the Earth + Veto
- Neutrinos: Atmospheric vs Astrophysical!



# Astrophysical neutrino flux

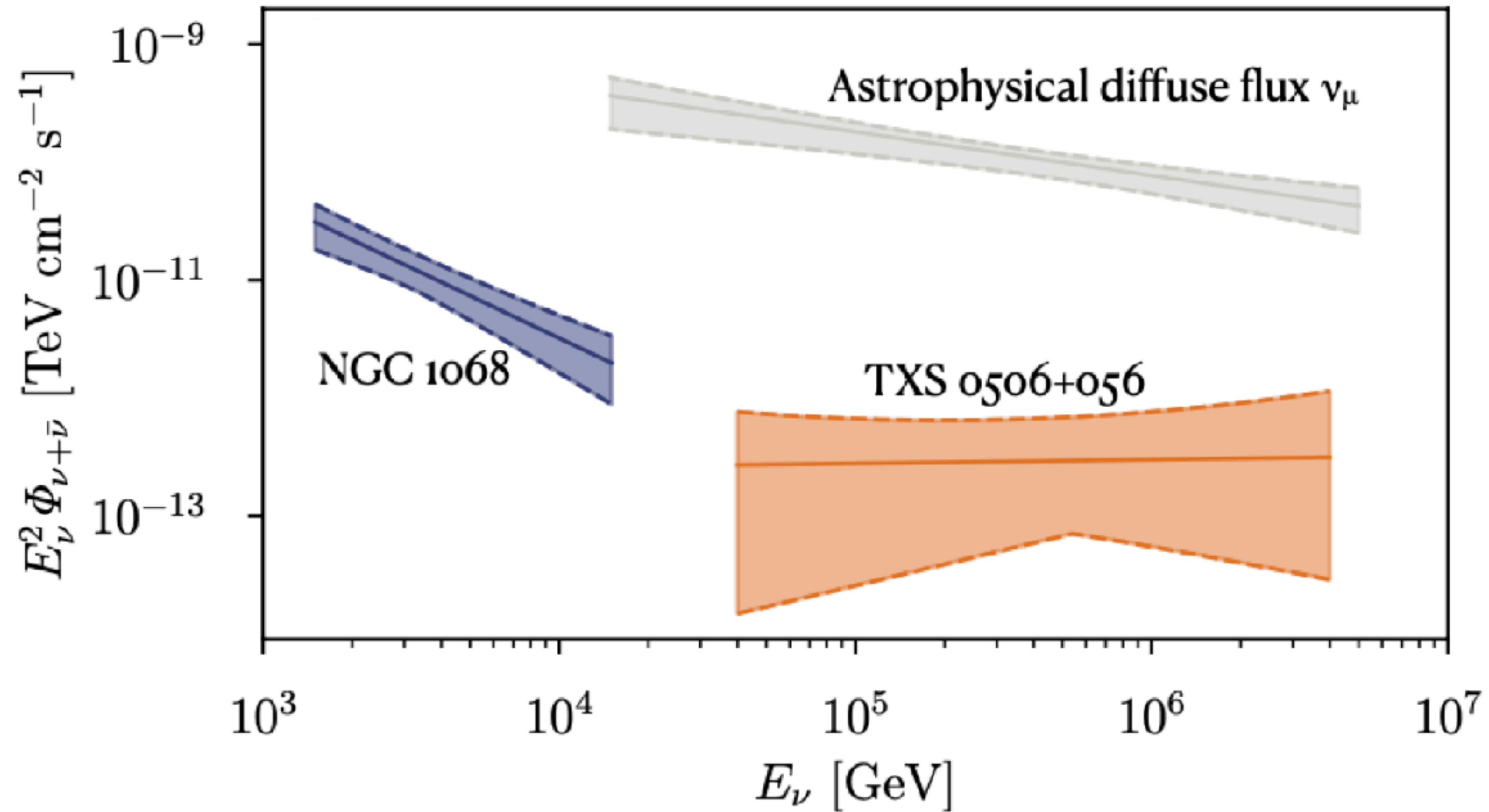


# NGC 1068 - disk-corona model



- 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

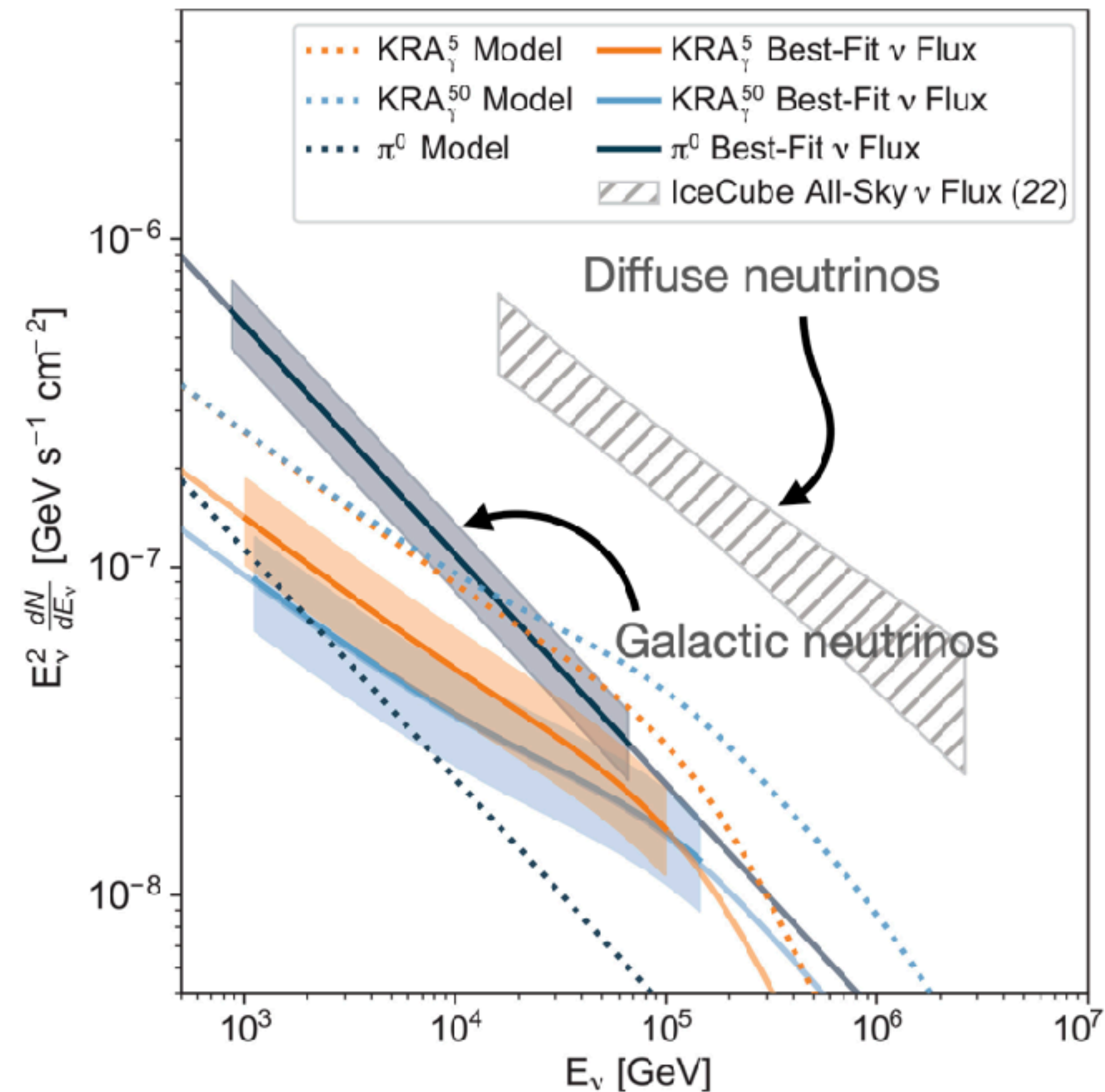


- NGC 1068 and TXS 0506+056 contribute each  $\sim 1\%$  to the total diffuse!

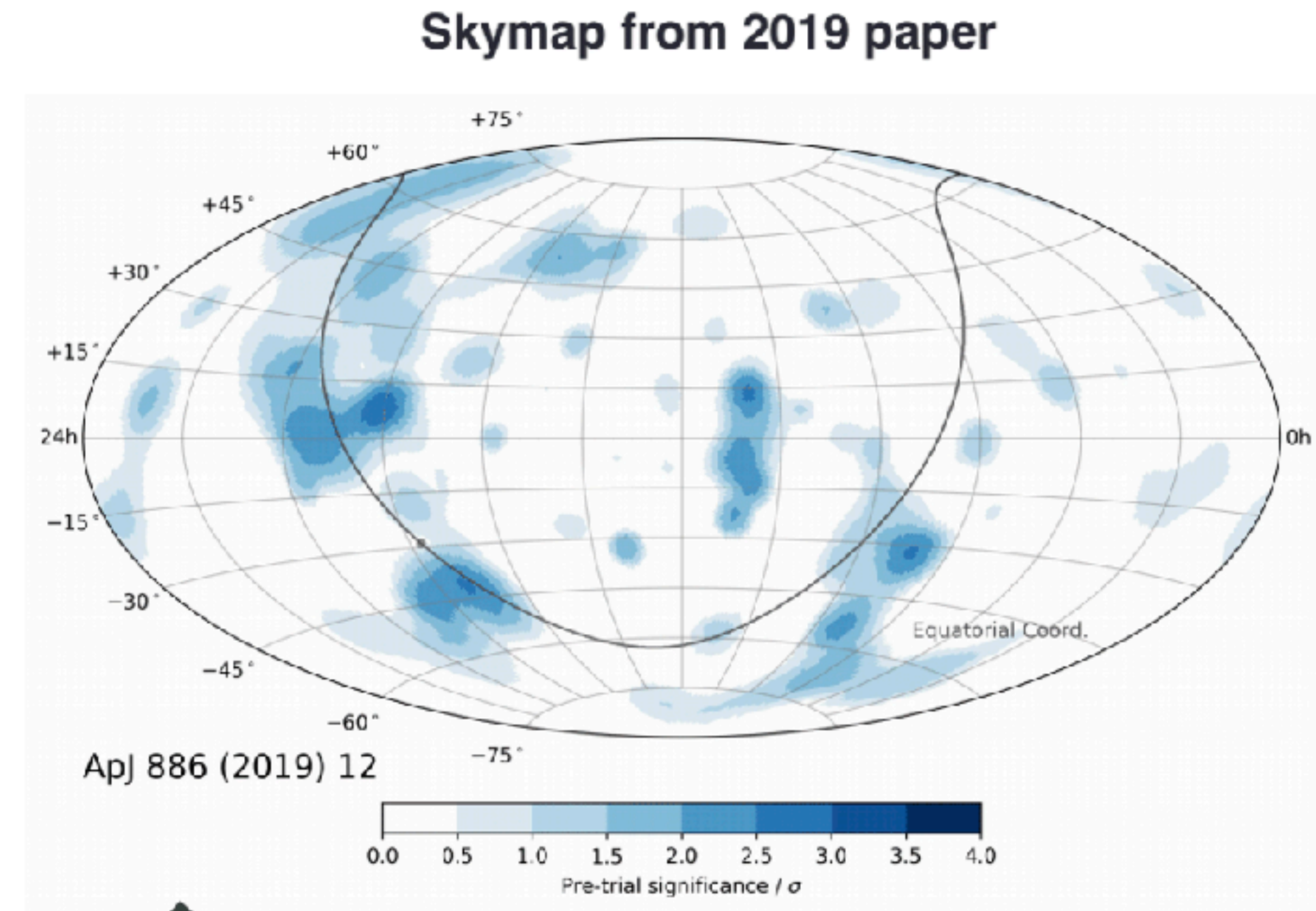
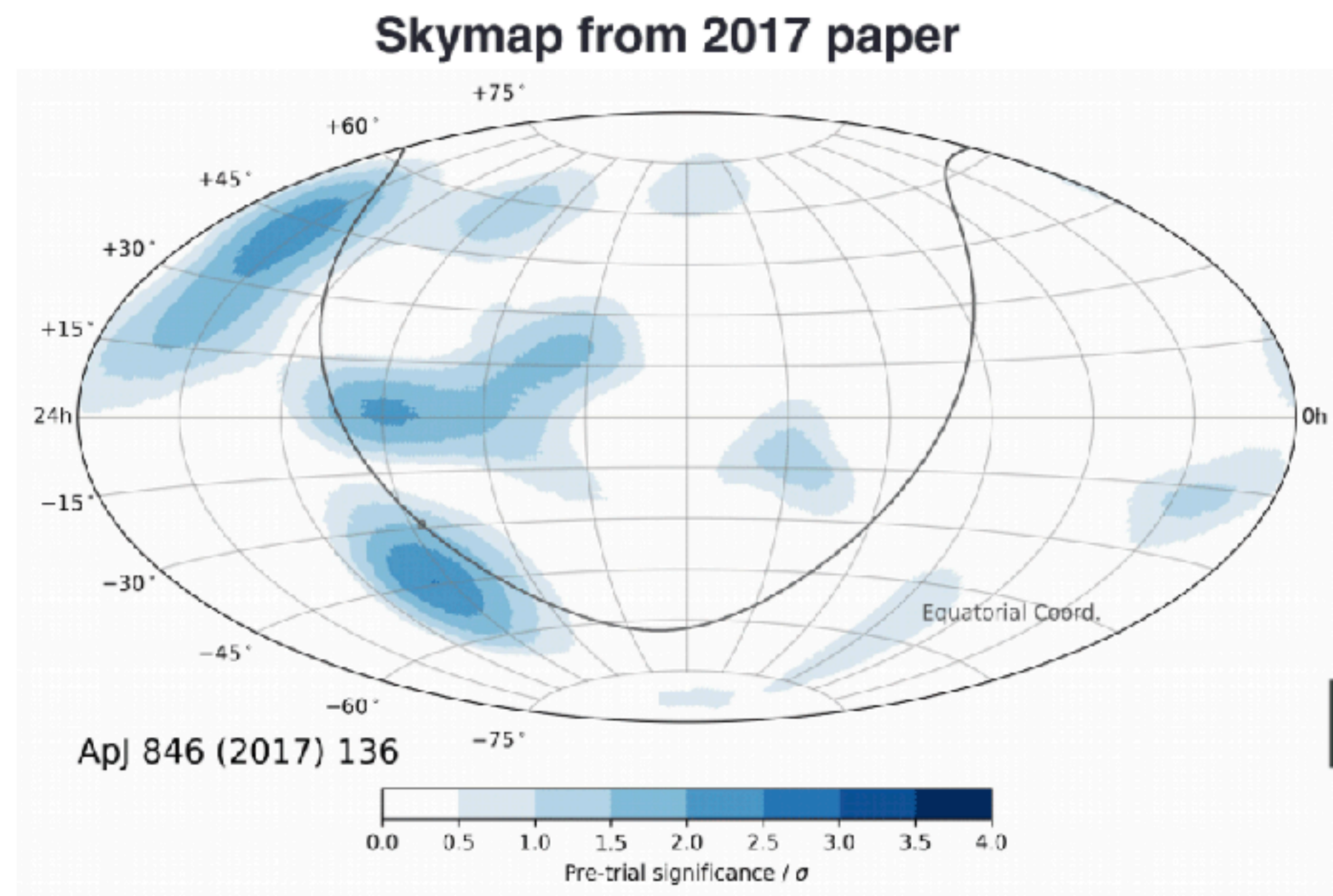
# Galactic Plane

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

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

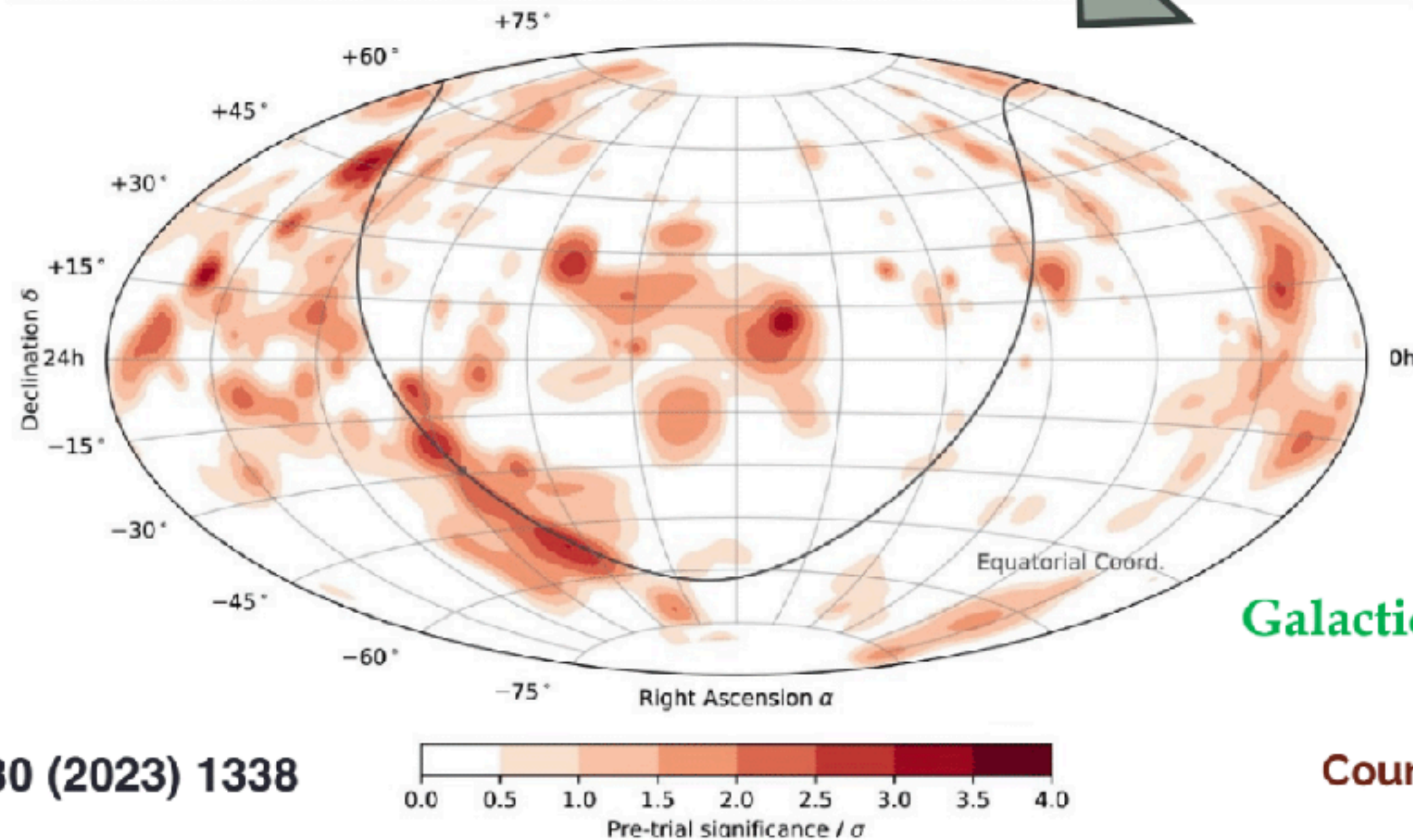






2 years of data  
Galactic Plane p-value: 65%

7 years of data  
Galactic Plane p-value: 2.1% ( $2\sigma$ )

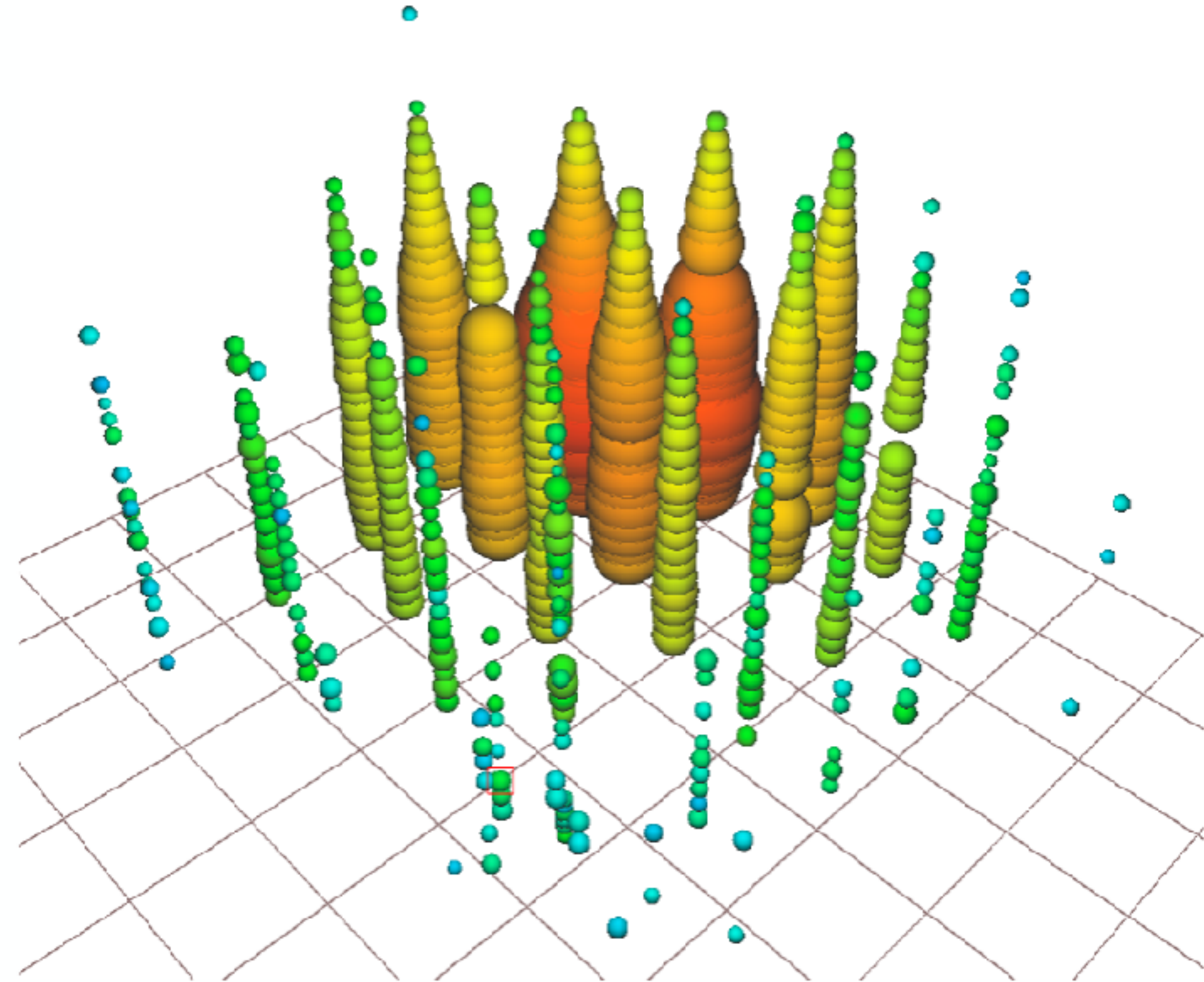
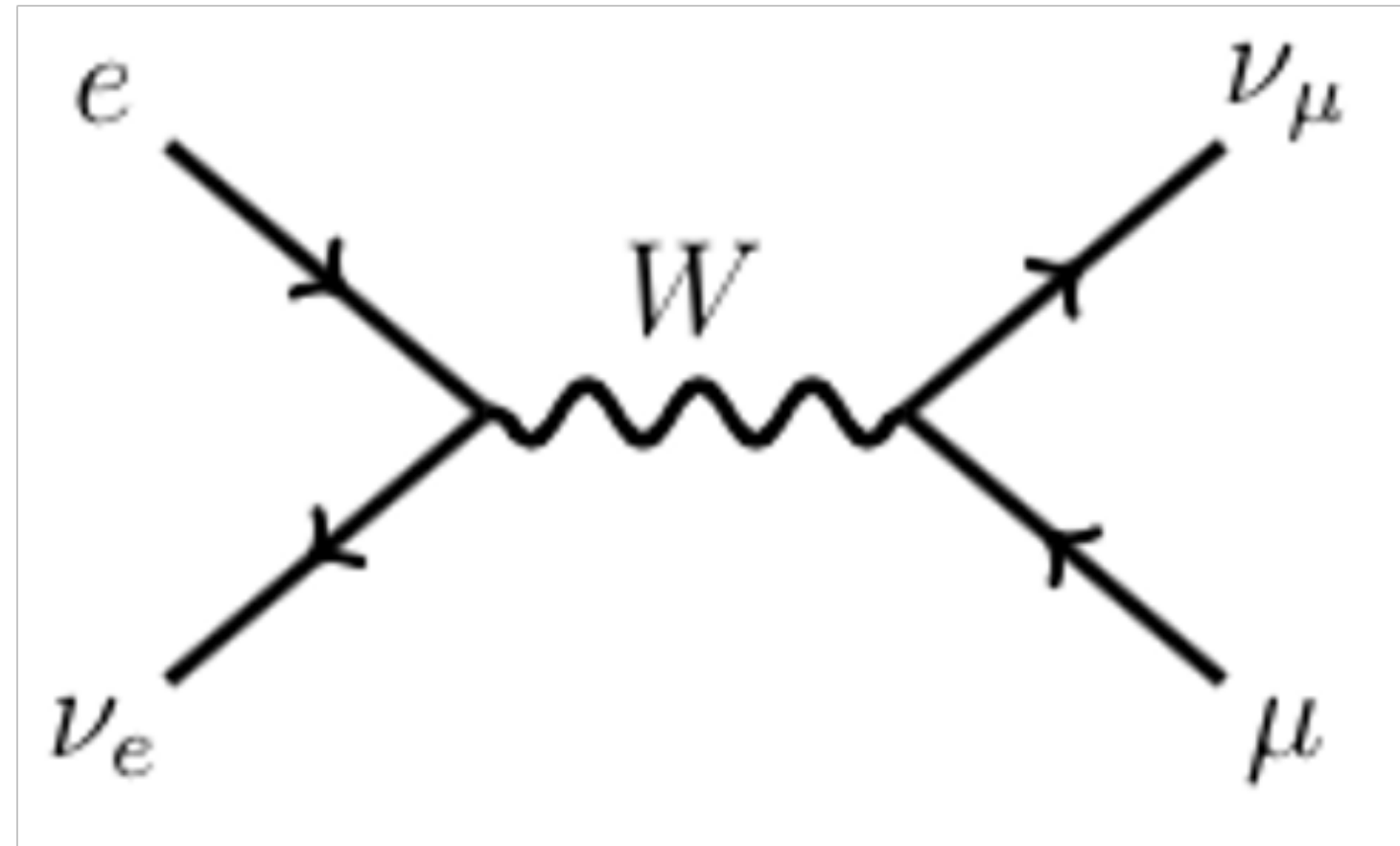


10 years of data  
Galactic Plane p-value: 0.0004% ( $4.5\sigma$ )

Science 380 (2023) 1338

Courtesy Naoko Kurahashi Neilson (ICRC 2023)

# 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  $\sim 6.05$  PeV
- Proof for the presence of **anti-electron neutrinos in astrophysical flux.**

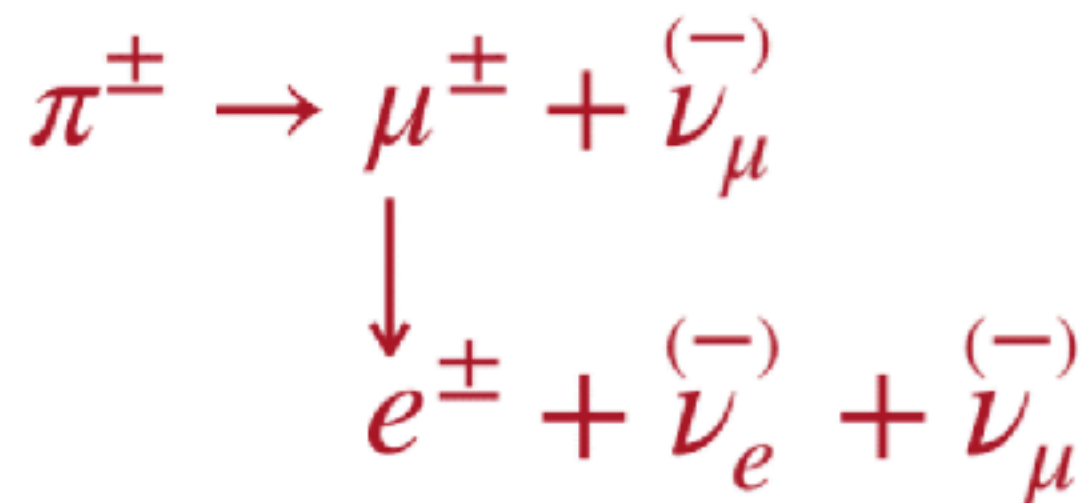
# Astrophysical Neutrinos

## Flavor Ratio

Eur. Phys. J. C 82, 1031 (2022)



### pion production



(1:2:0)

### neutron decay

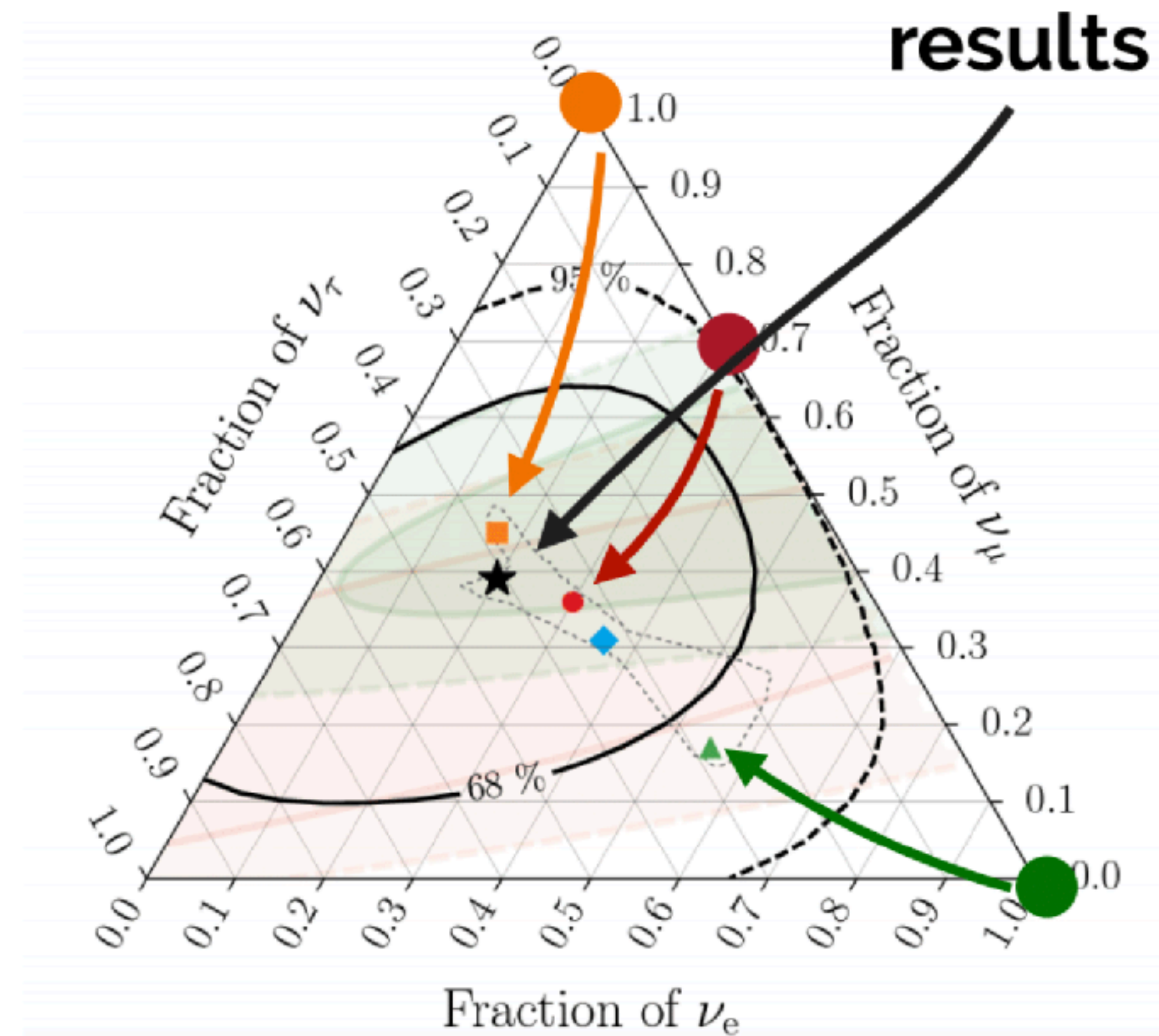


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### muon dumped



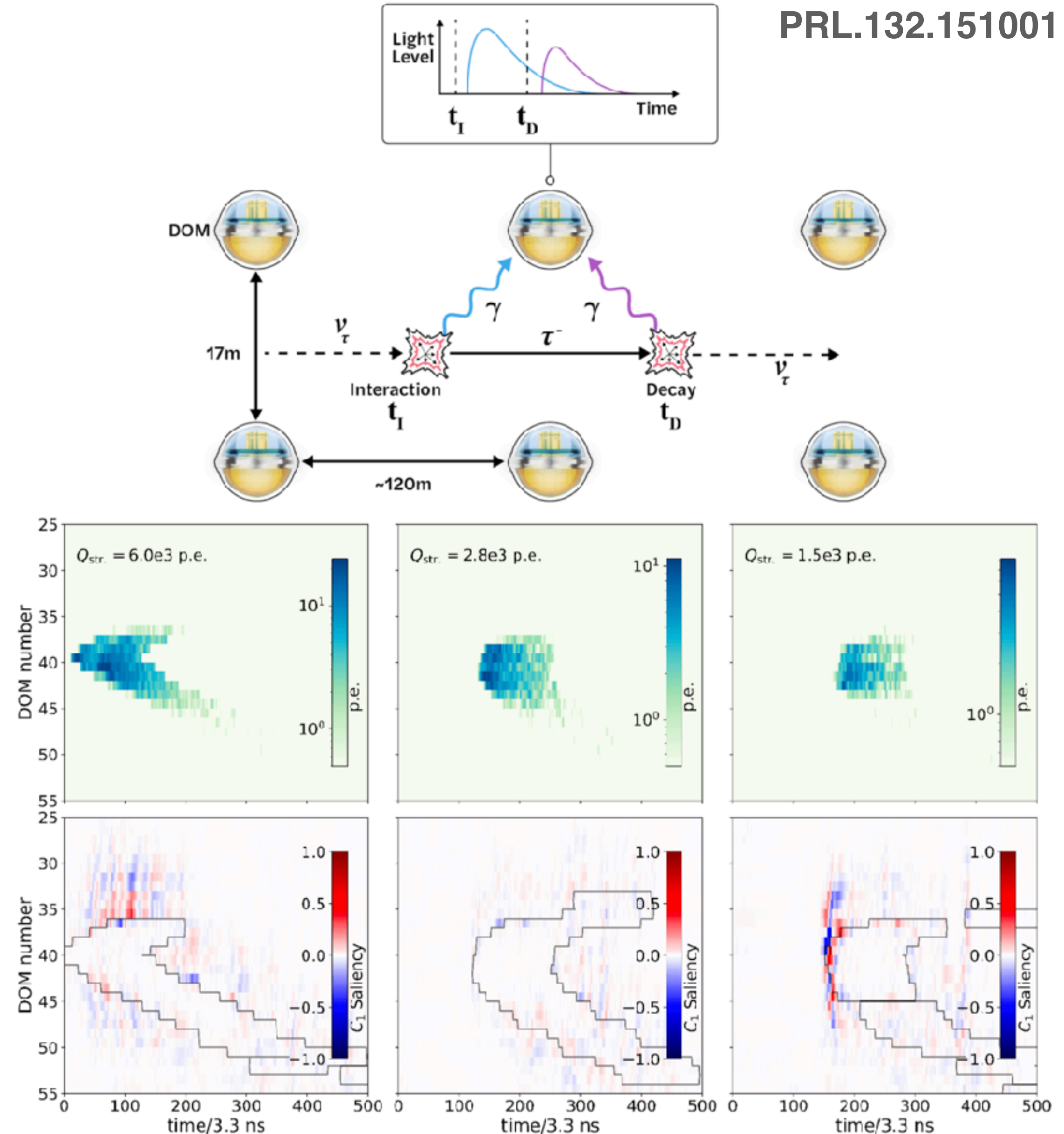
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# Detection of astrophysical tau neutrinos

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- Looking for **double cascades** event signature at light level
- Study images of most illuminated strings and its 2 neighbors
- 3 independent CNNs trained for distinguish signal from bkg
- **7 astrophysical tau neutrino candidates** found in 9.7 years of data!
- **Rules out absence of astro.  $\nu_\tau$  at  $5.1\sigma$**



# 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.

