Probing the High-Energy Universe with Neutrinos and Gamma Rays

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FRIF Day
17 November 2025

The High-Energy Universe

- **Violent processes** in the Universe accelerate particles up to high energies
- **High-energy cosmic messengers** allow us to study these processes

Galactic sources

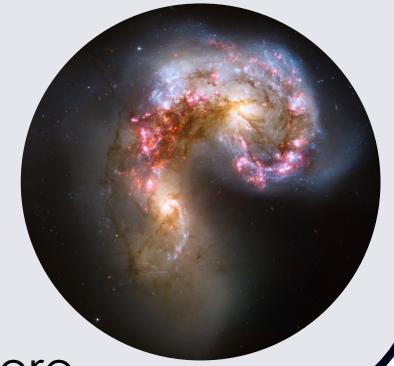
Supernova remnants

Pulsar wind nebulae

and many more

Extragalactic sources

Active galactic nuclei

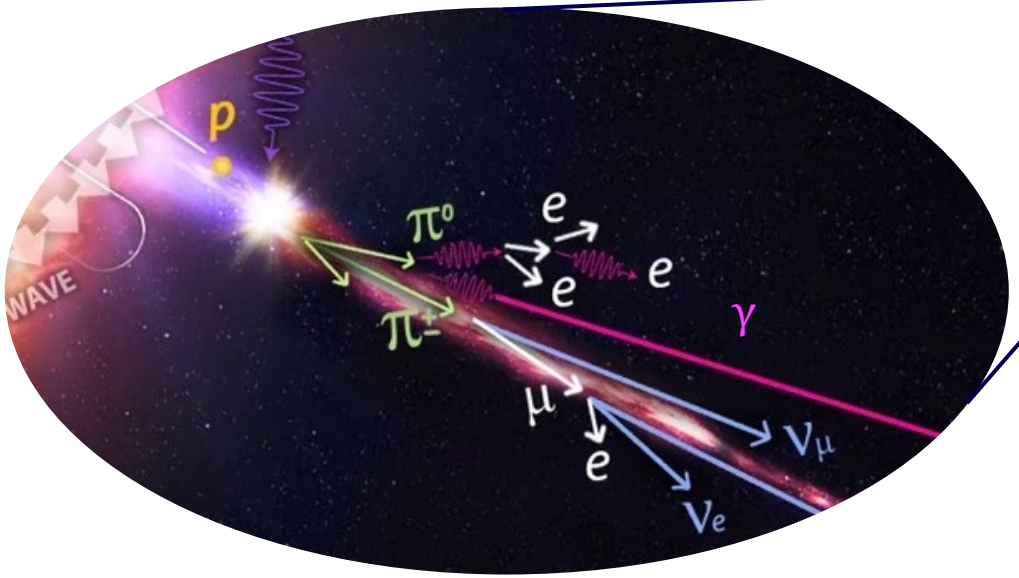


Starburst galaxies

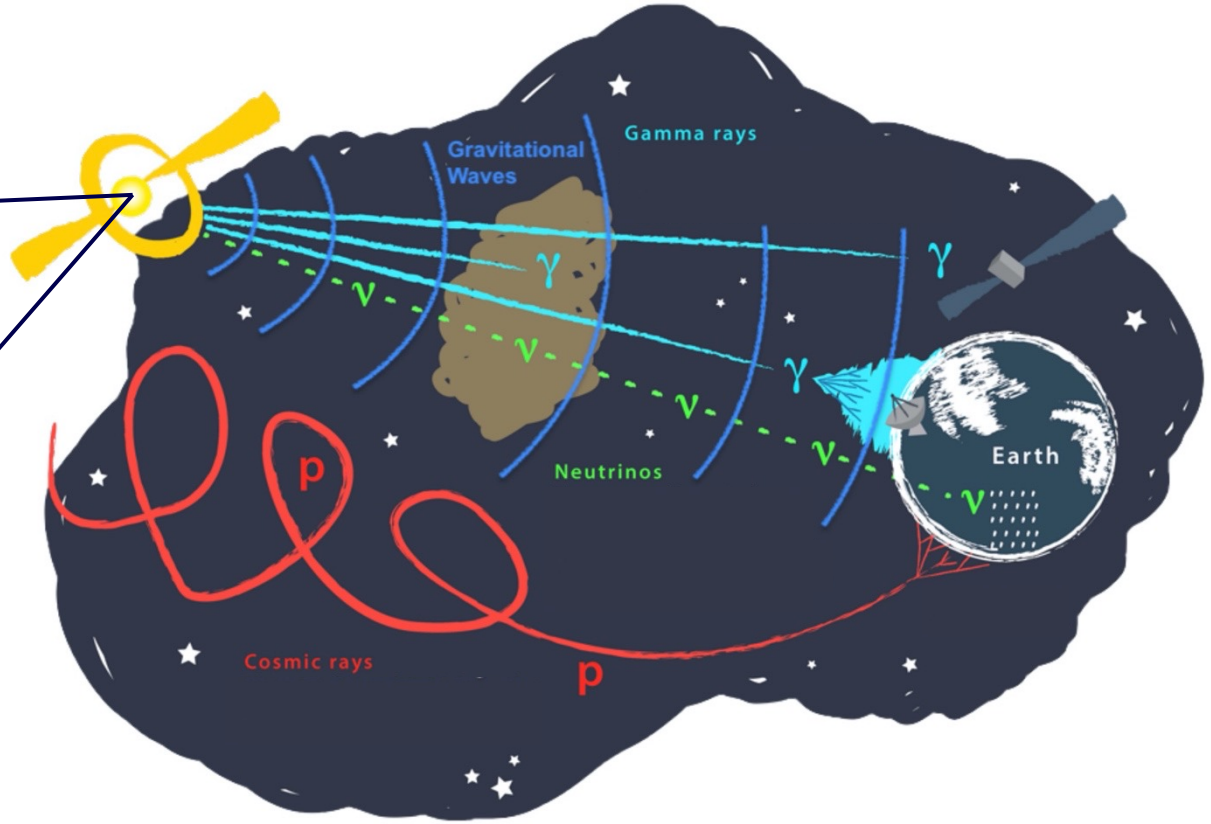
and many more

The Multimessenger Connection

- **Cosmic rays** (p)
  - **Energies** up to 3×10^{20} eV ≈ 48 J
  - **Deflected** by $\vec{B}$ ⟶ **origin unknown!**
- **Gamma rays** (γ)
  - Produced in **leptonic & hadronic** processes
  - **Easy to detect but easily attenuated**
- **Neutrinos** (ν)
  - Smoking gun of **hadronic** interactions
  - **Not attenuated but hard to detect**

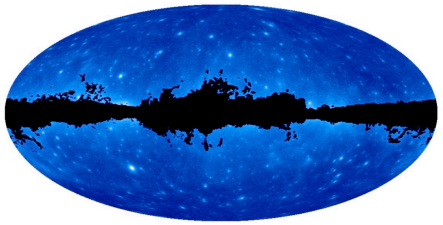


[IceCube/NSF]



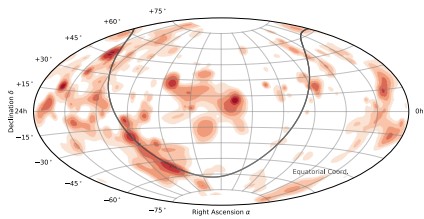
The Diffuse High-Energy Sky

[*Fermi*-LAT (2017) ApJS 232 18]



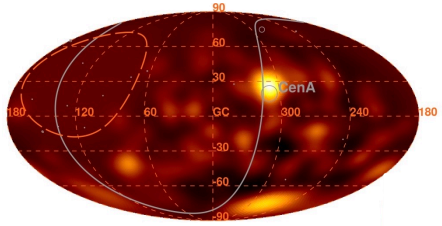
GeV gamma rays

[IceCube (2023) Science 380 1338]

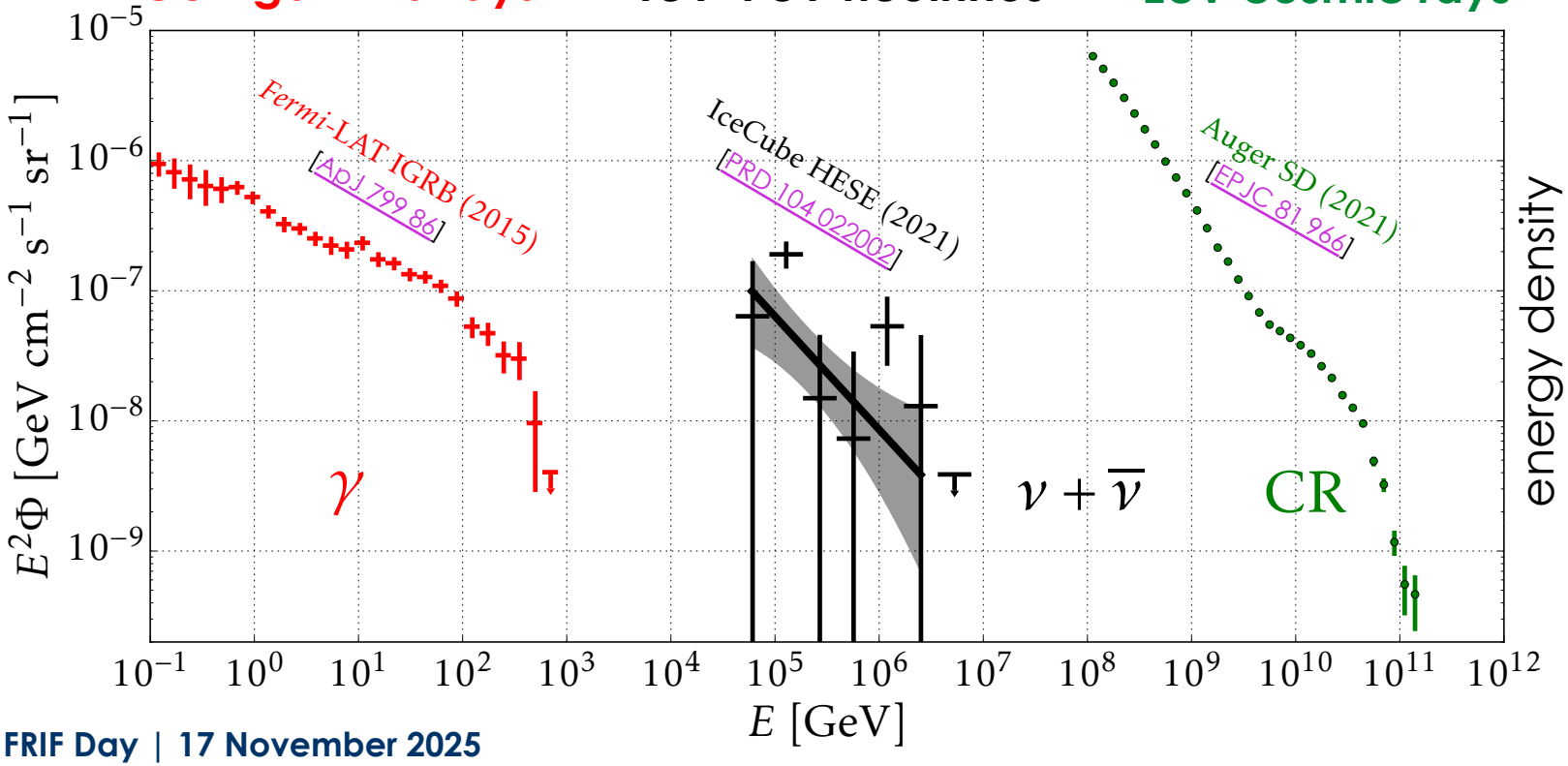


TeV–PeV neutrinos

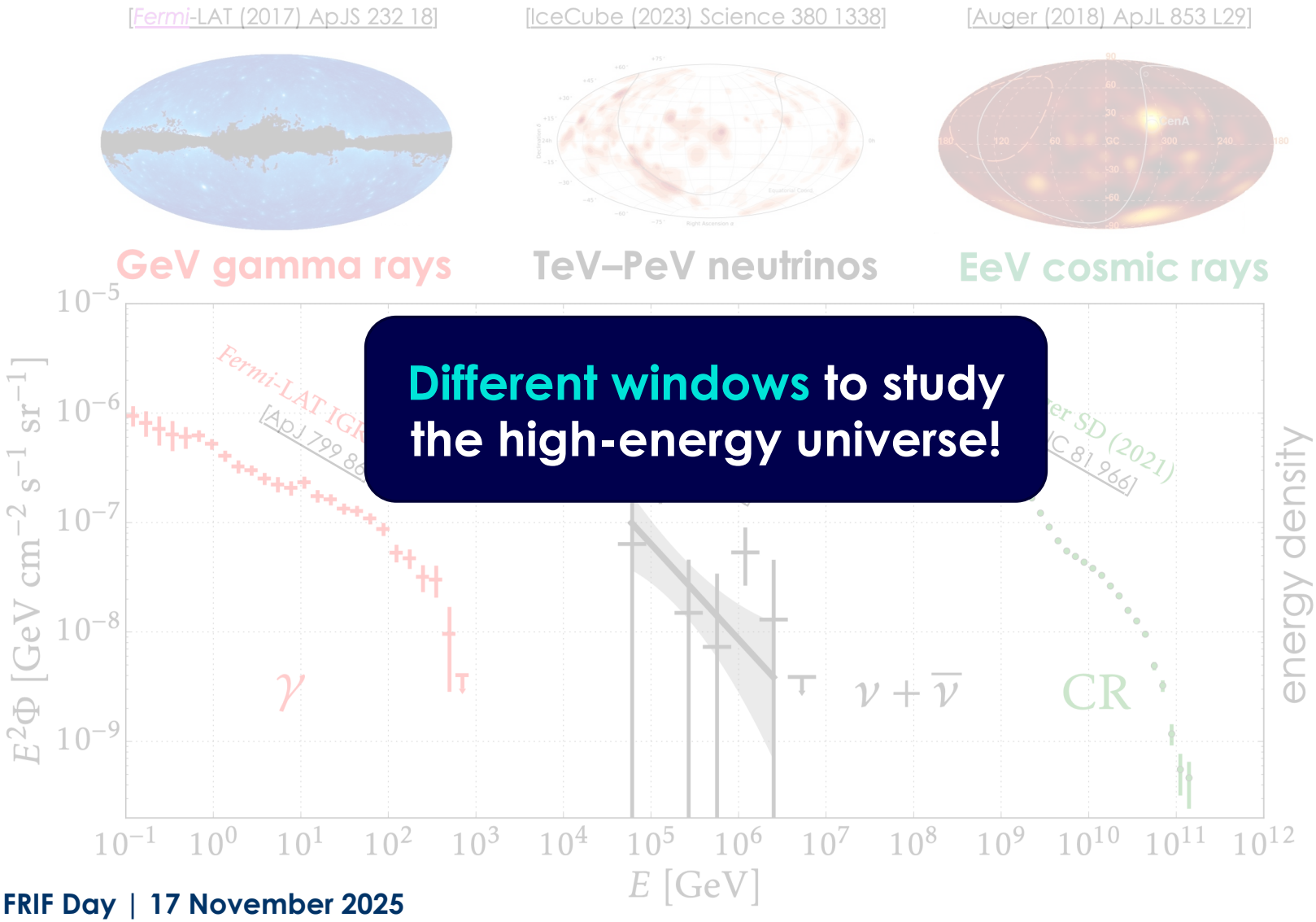
[Auger (2018) ApJL 853 L29]



EeV cosmic rays



Diffuse High-Energy Observations



Career Overview

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High-energy neutrinos & ultra-luminous infrared galaxies

Data analysis & phenomenology


2022–2024 (postdoc)

Towards ultra-high-energy neutrinos

Trigger development & hardware deployment

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Very-high-energy gamma rays with unprecented sensitivity

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CTAO

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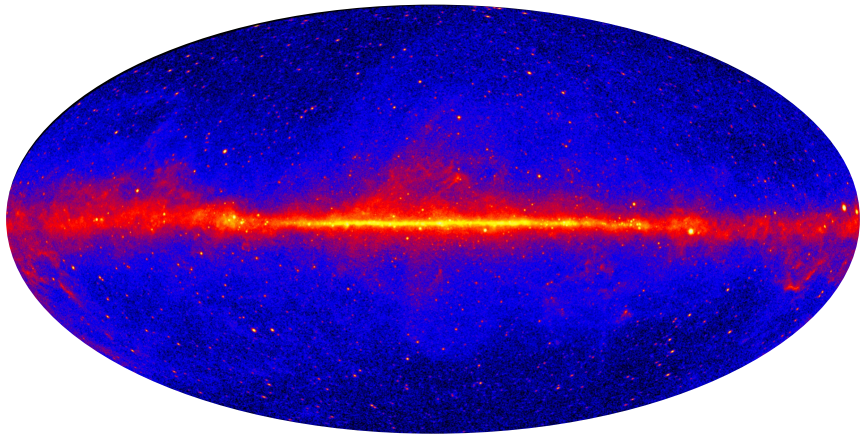
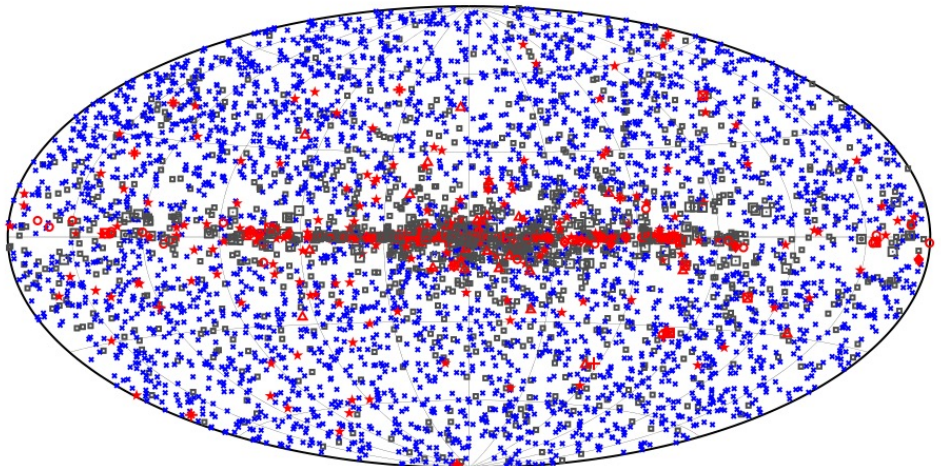
NectarCAM cnrs LPNHE Paris

The Gamma-Ray Sky

- **Wide range** of observations
  - **Satellite** experiments: 100 MeV – 1 TeV
  - **Ground-based** experiments: 100 GeV – 1 PeV
- Various **gamma-ray sources** identified
  - Both **galactic and extragalactic**
  - Hard to distinguish **leptonic vs hadronic** acceleration

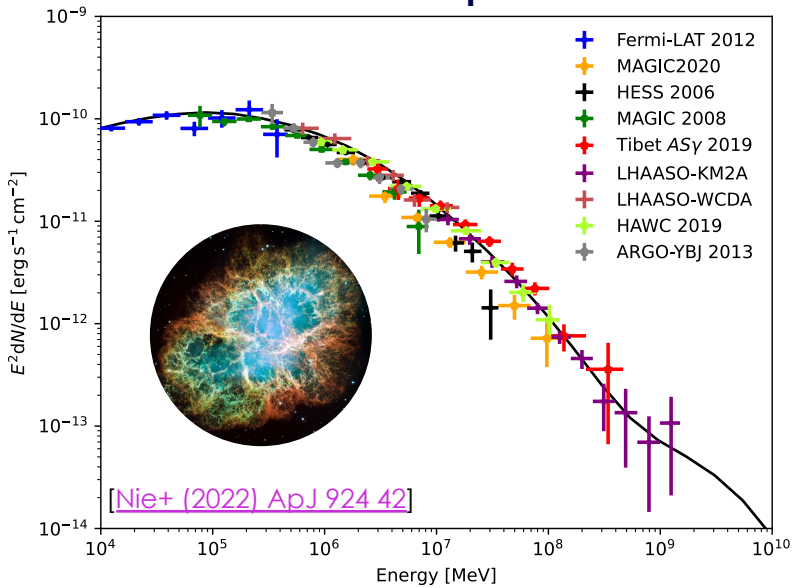
[NASA/DOE/Fermi-LAT (2022)]





[Fermi-LAT (2020) ApJS 247 33]

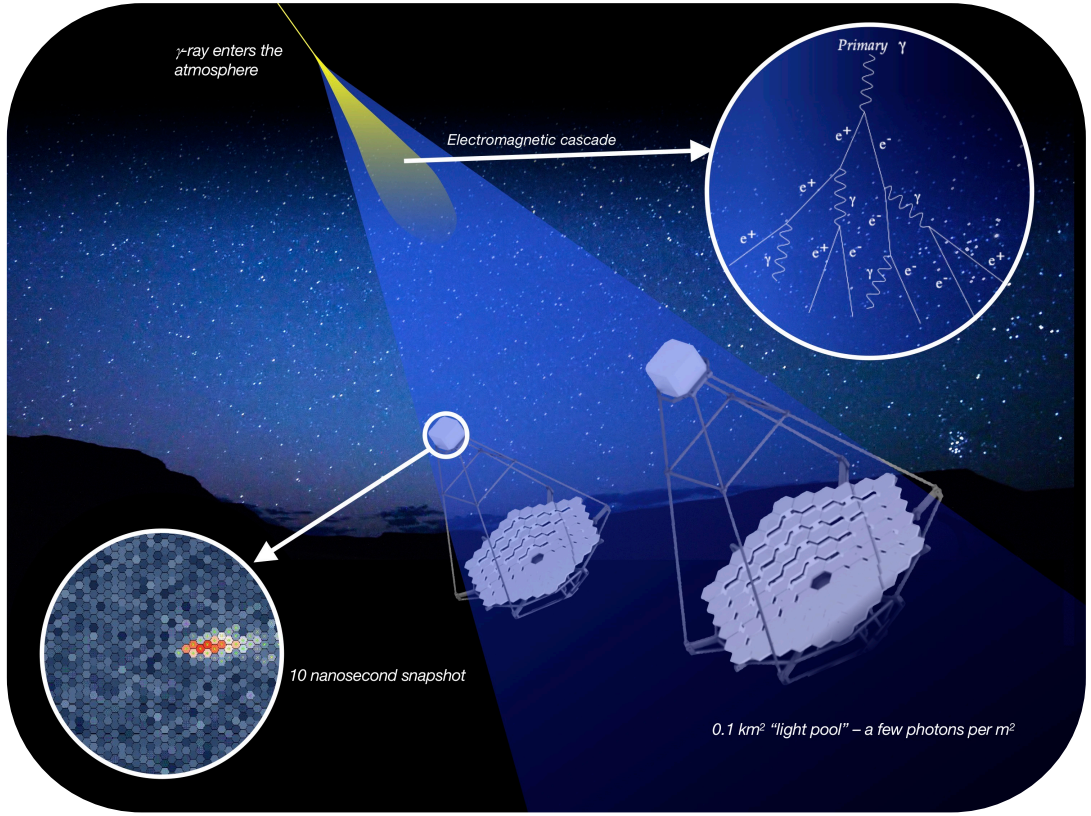
Crab PWN spectrum



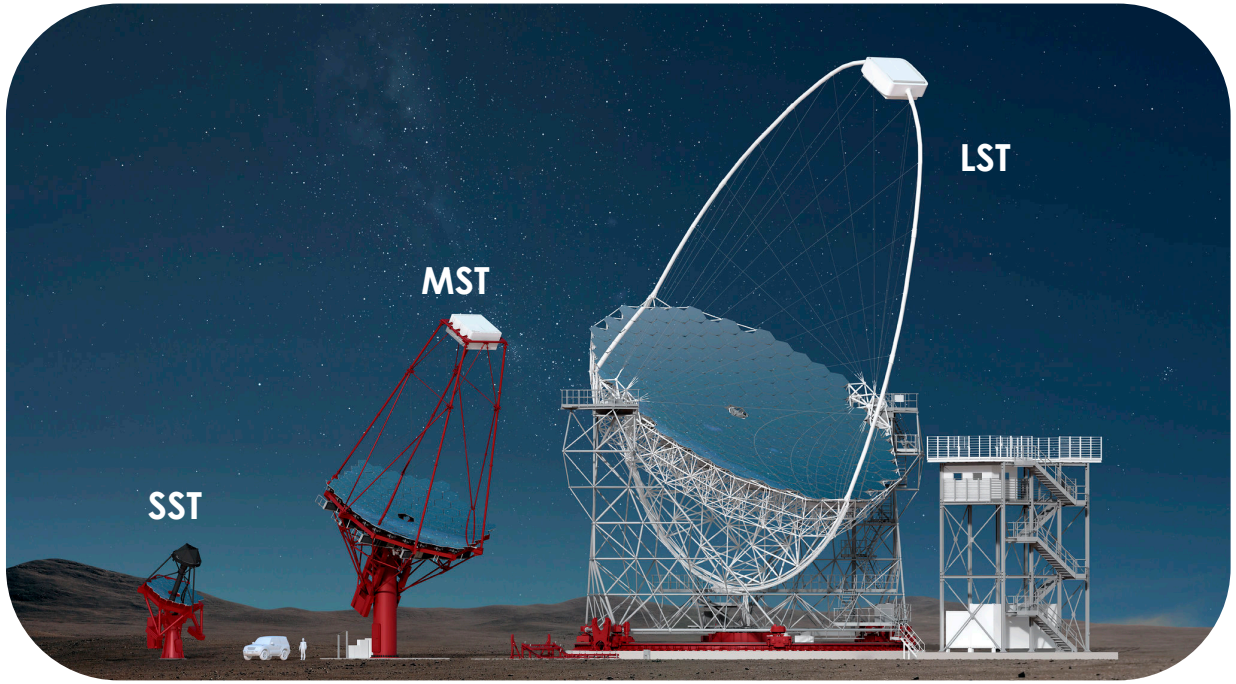
[Nie+ (2022) ApJ 924 42]

Cherenkov Telescope Array Observatory

- Next-generation **imaging air-Cherenkov telescope** (IACT)



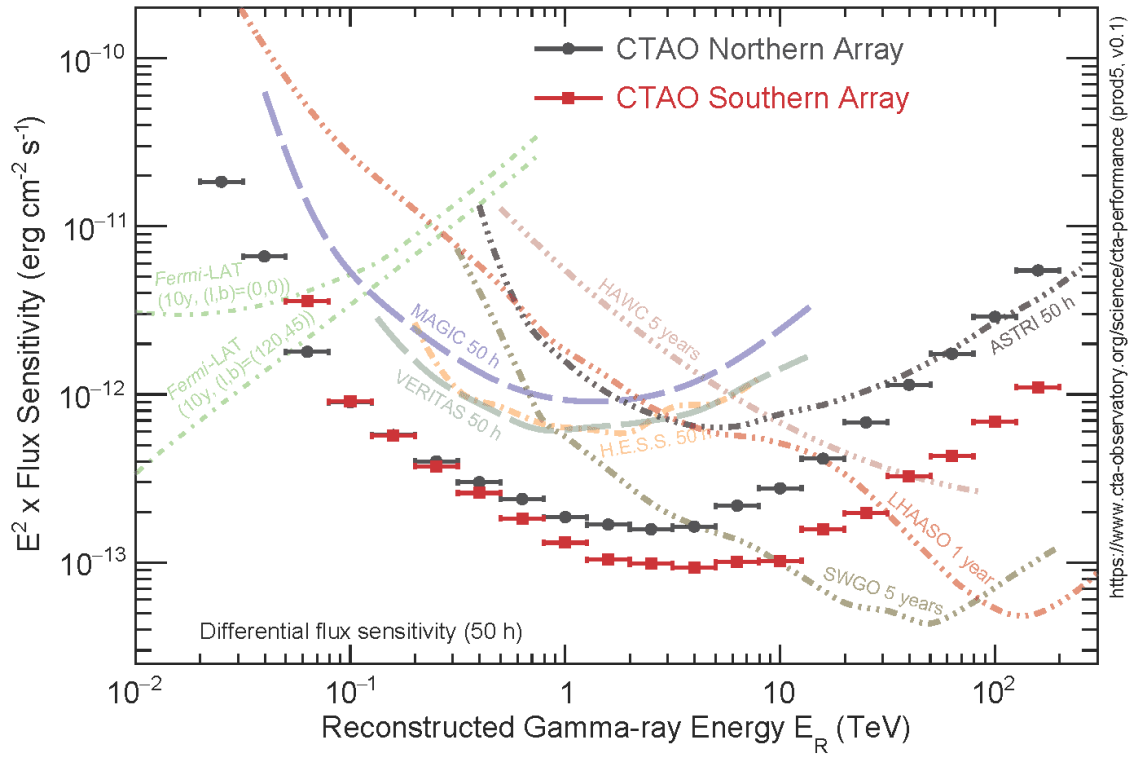
- **Large-sized telescopes** (LSTs): 20–300 GeV
- **Mid-sized telescopes** (MSTs): 0.15–5 TeV
- **Small-sized telescopes** (SSTs): 5–300 TeV

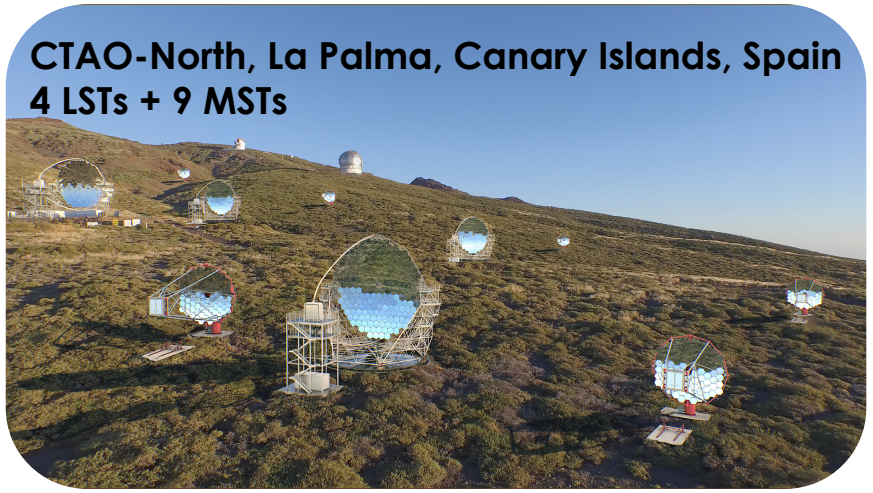


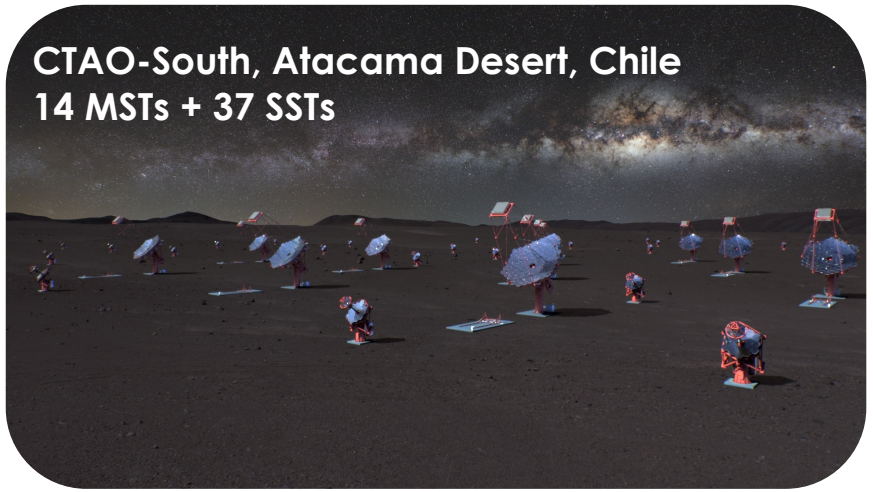
CTAO Alpha Configuration Performance

NectarCAM

- **Unprecented sensitivity** for very-high-energy (0.1–100 TeV) gamma rays
  - Detailed studies of **acceleration mechanisms** (leptonic vs hadronic)

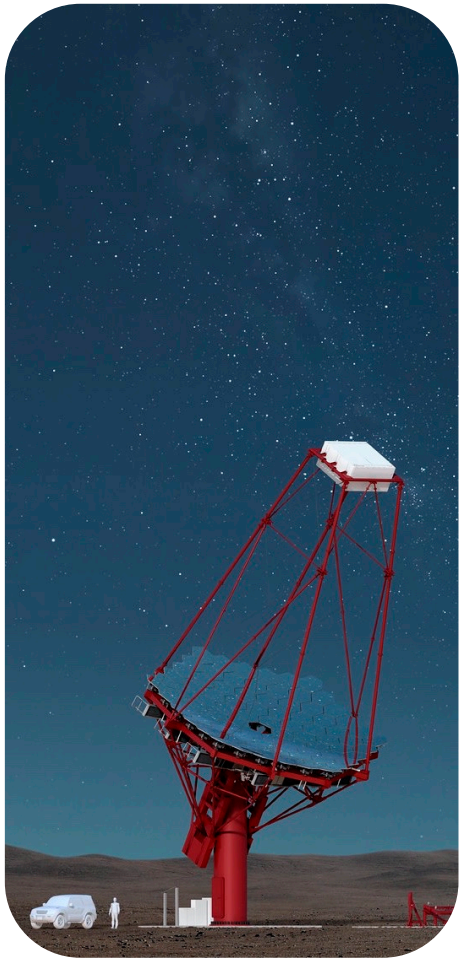




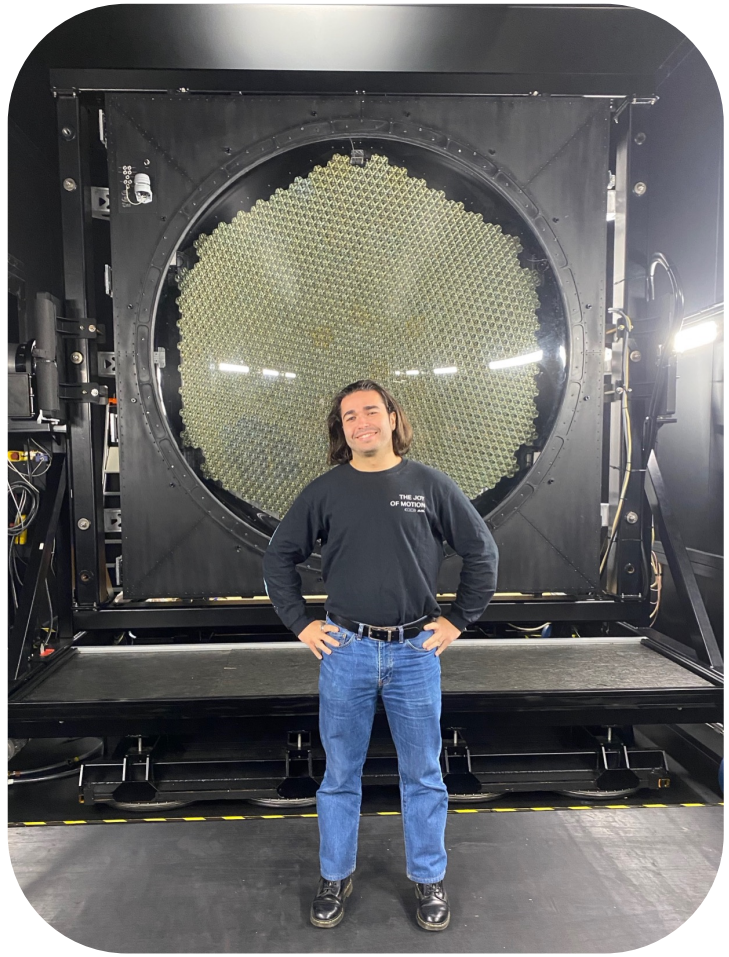


NectarCAM

- One of the **camera** types for the **MST**
  - **1855 pixels** sensitive to single photons
- Currently **2/9 cameras assembled**
  - Undergoing **test-readiness review**
- Cameras need to be **calibrated**
  - Development of **calibration software**
  - `nectarchain` is public!



NectarCAM-2 @ CEA



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First NectarCAM ready for shipment by June 2026

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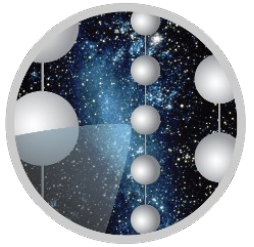
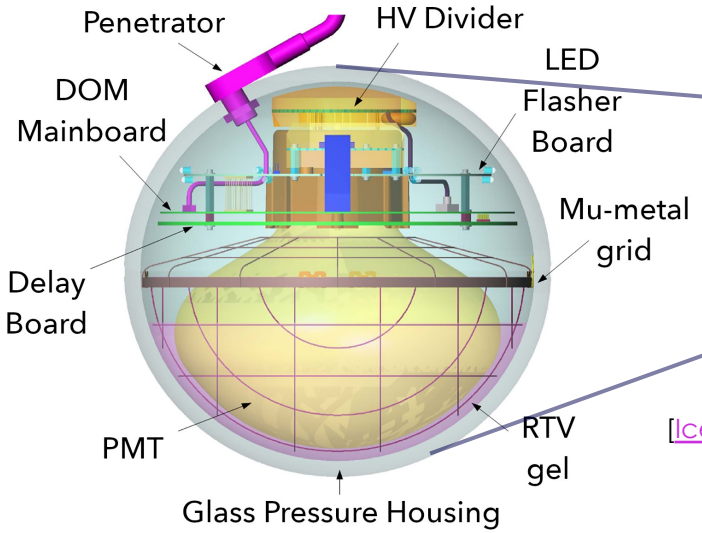
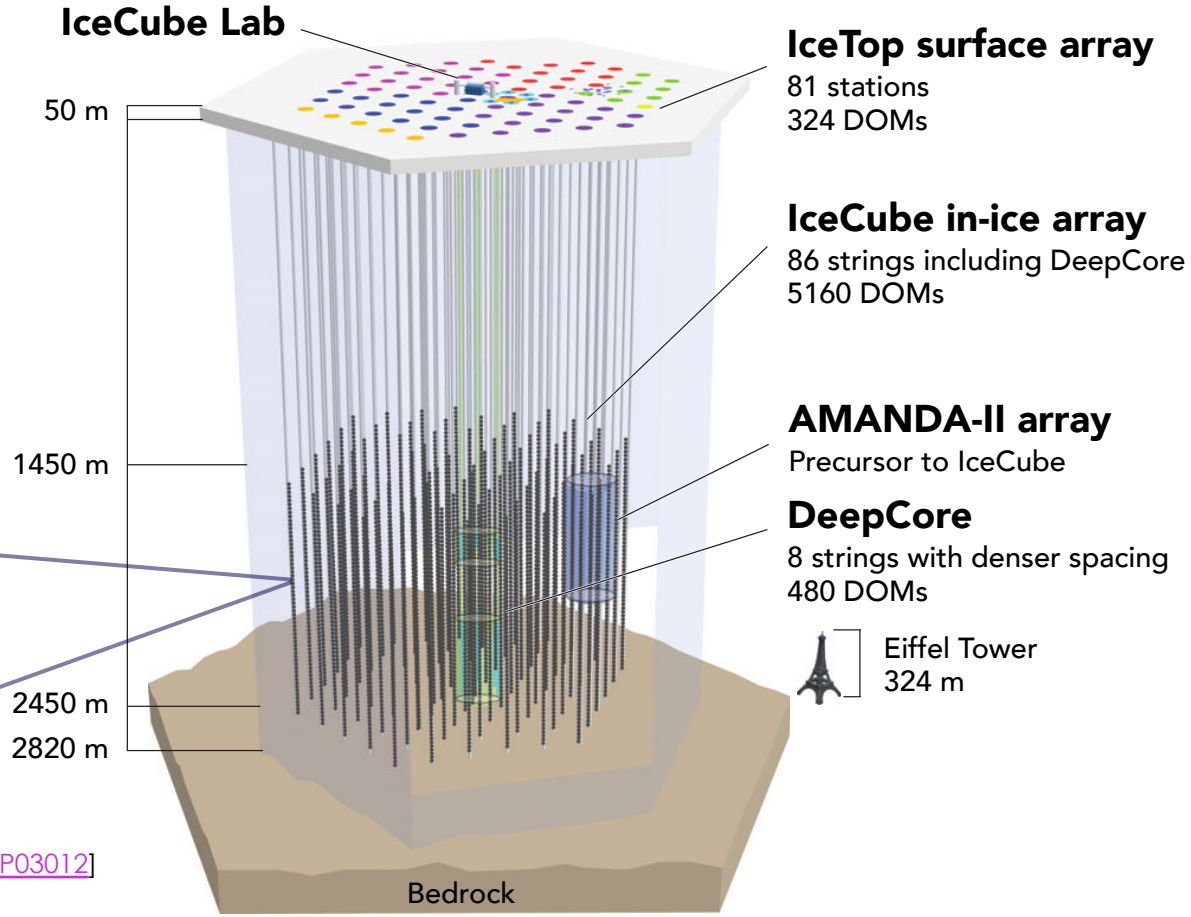


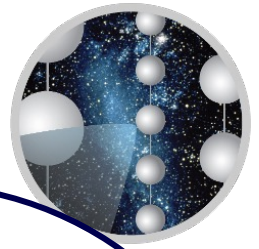
- **1 km³ detector** at the South Pole
- **5160 digital optical modules** (DOMs)
- **86 strings** down to 2.45 km depth



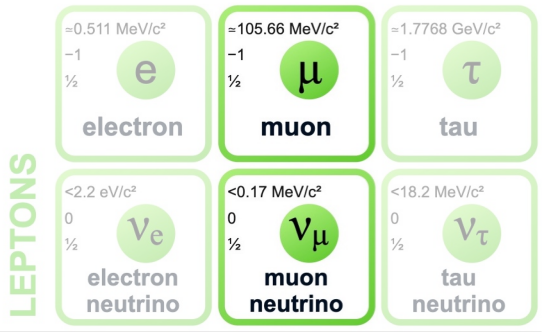
[IceCube (2017) JINST 12 P03012]

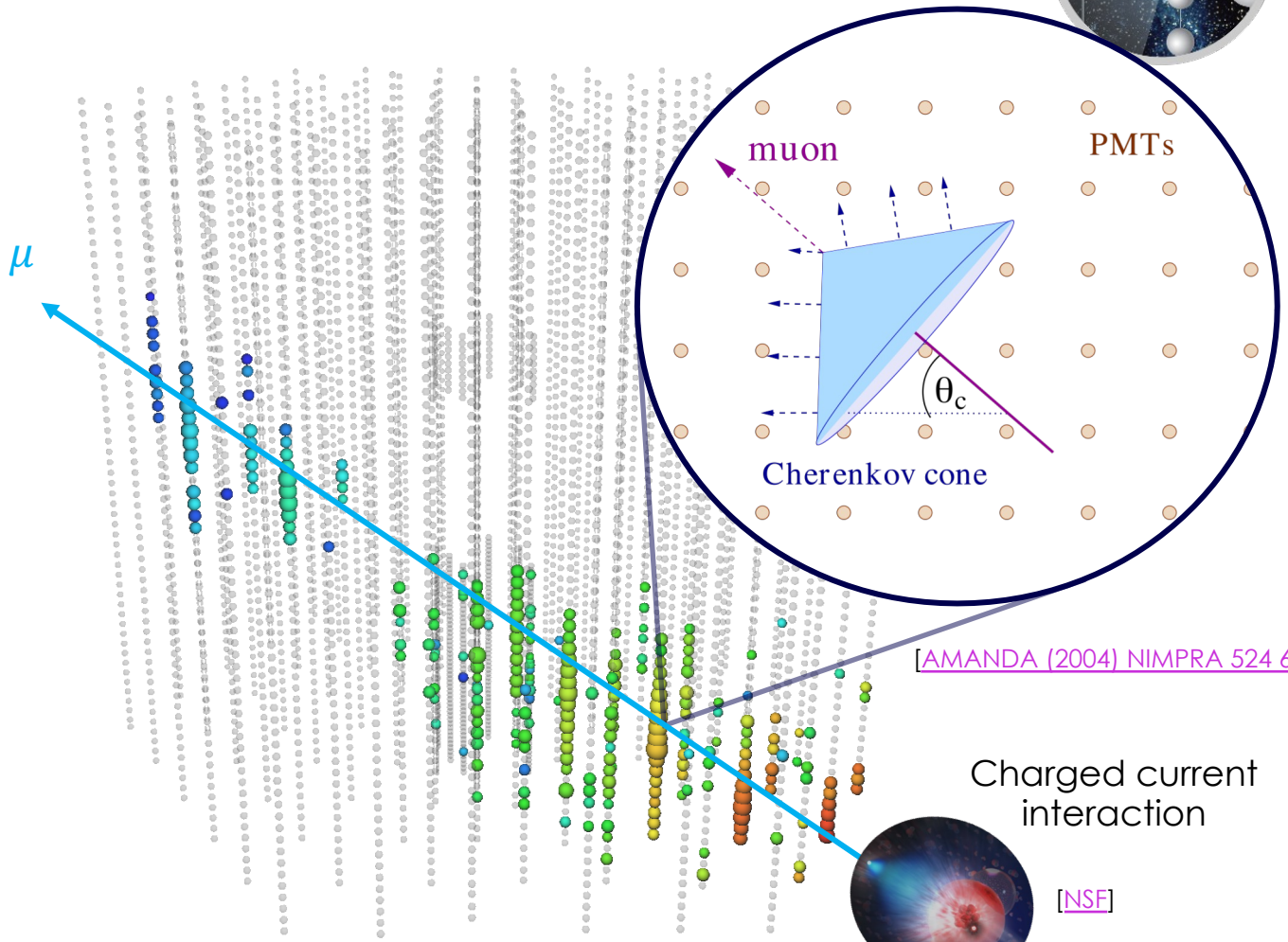


Detecting Neutrinos with IceCube



- Neutrinos can **interact with ice**
  - Produce **secondary charged particles**
  - These emit **Cherenkov radiation**
- Mostly focus on muon (μ) **tracks**
  - Signatures of ν_μ **and** $\bar{\nu}_\mu$
  - Typical **angular resolution** <1°



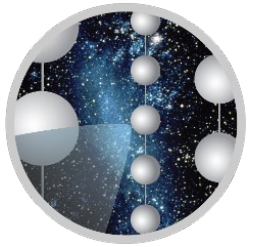


[AMANDA (2004) NIMPRA 524 69]

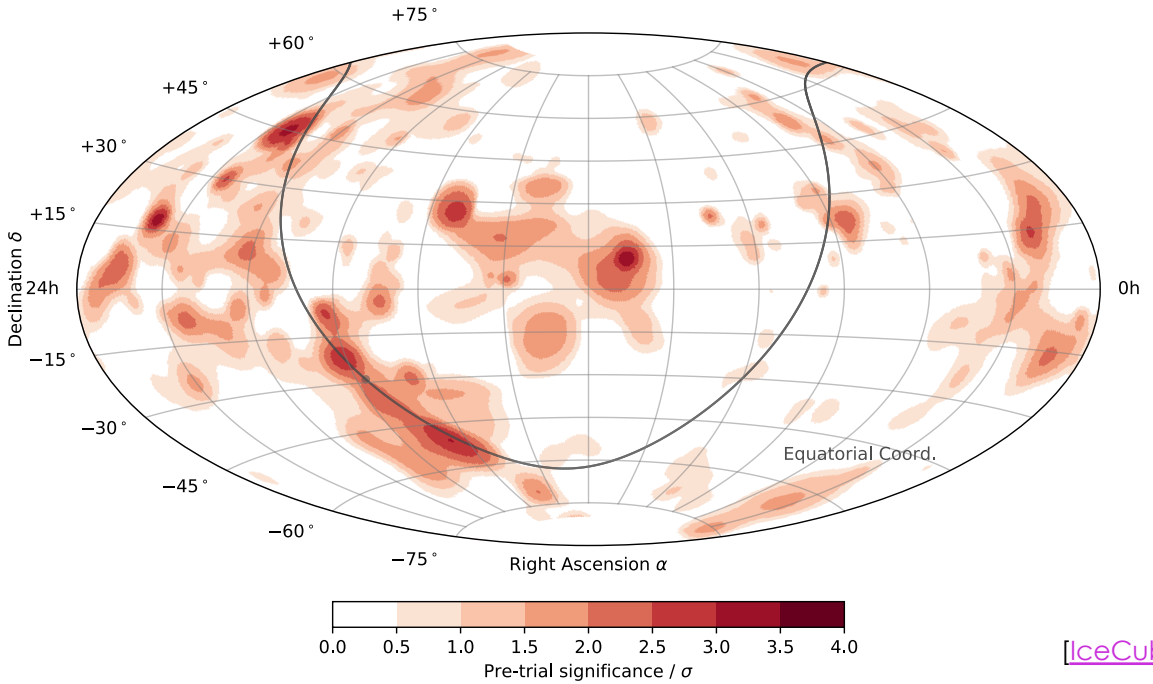
[Kintscher (2020) PhD thesis]

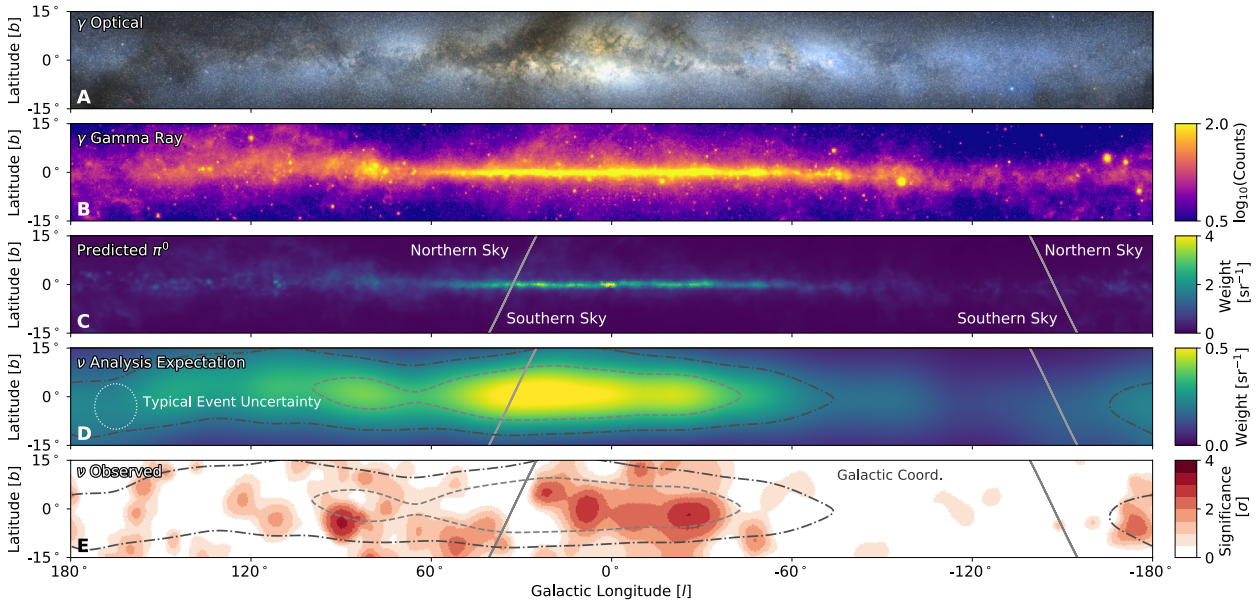
[NSF]

The Diffuse High-Energy Neutrino Sky



- **Diffuse TeV–PeV flux** discovered in 2013
- Evidence of **diffuse emission from Milky Way**

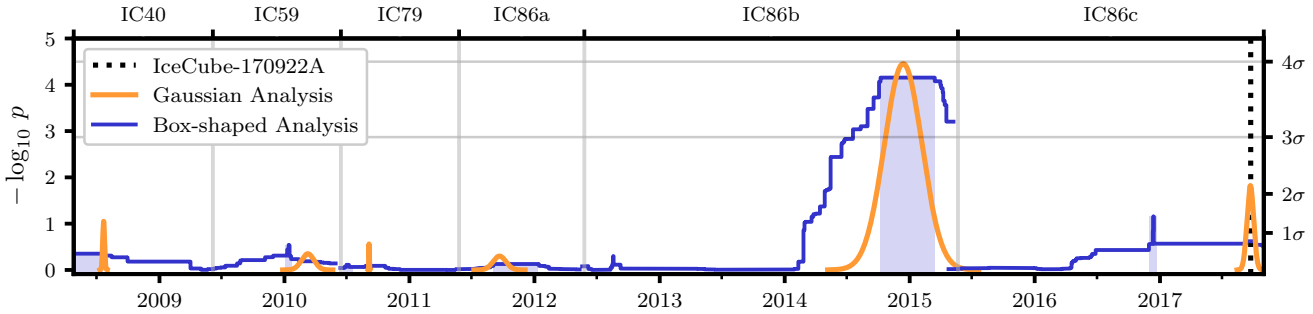




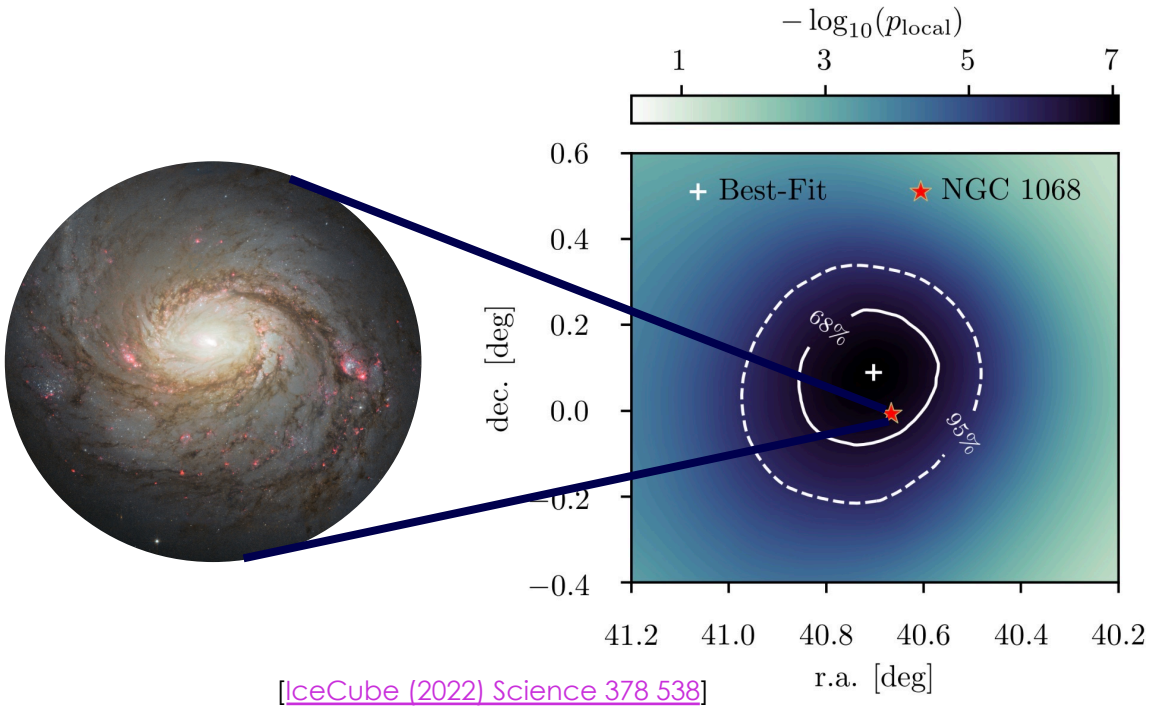
[IceCube (2023) Science 380 1338]

First Sources of High-Energy Neutrinos

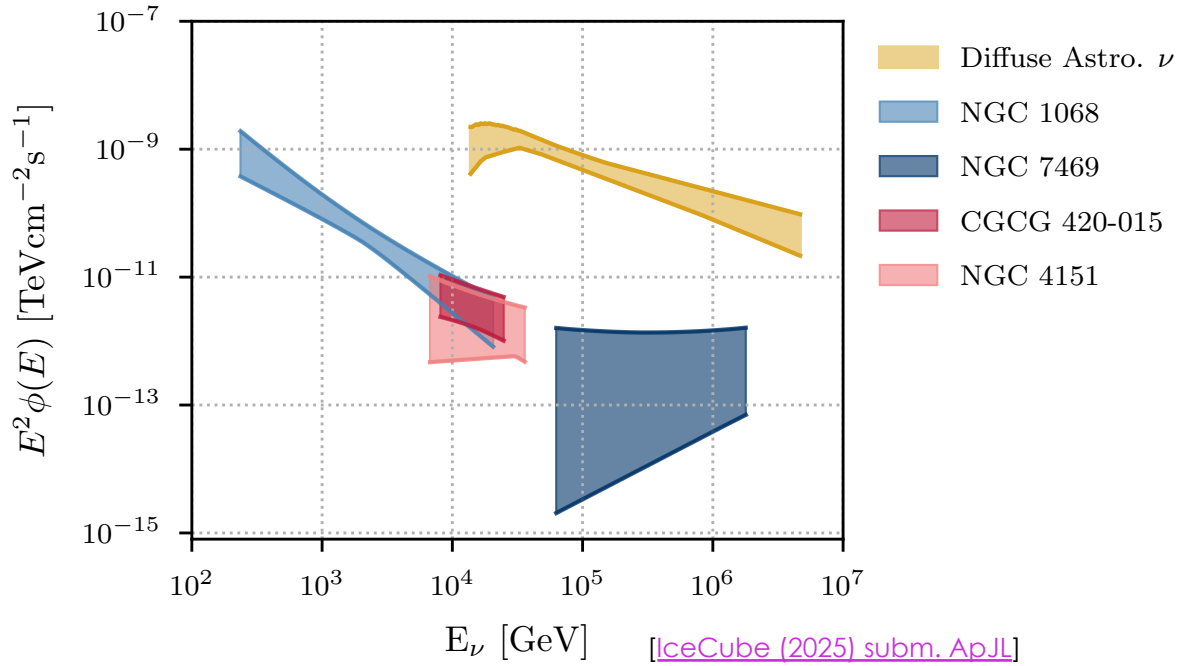
- Evidence for **point sources**
  - **TXS 0506+056**: transient source (blazar)
  - **NGC 1068**: steady source (Seyfert Galaxy)
  - **X-ray galaxies**: steady sources



[IceCube (2018) Science 361 147]



[IceCube (2022) Science 378 538]



[IceCube (2025) subm. ApJL]

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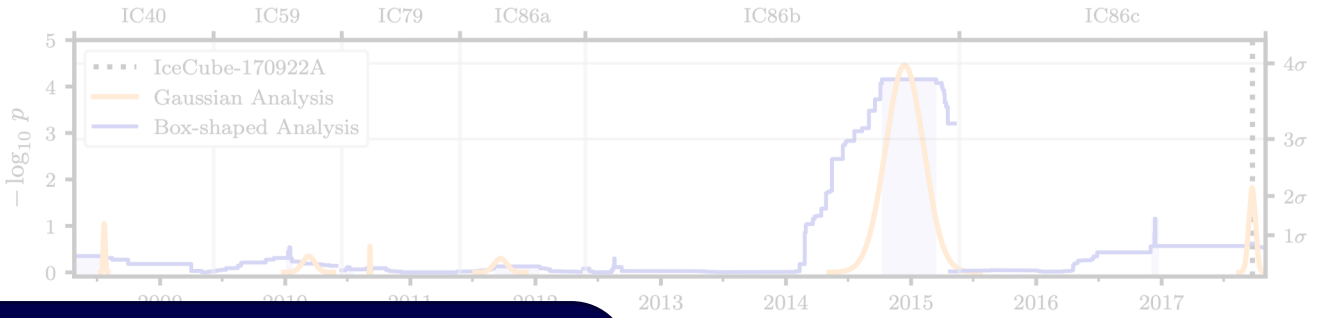
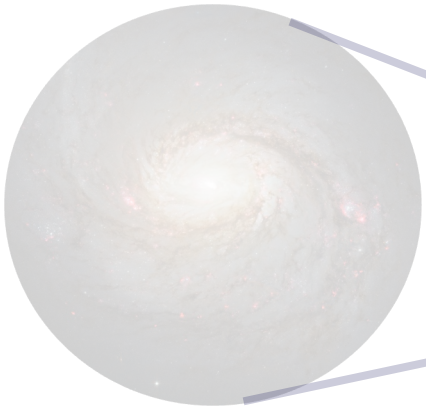
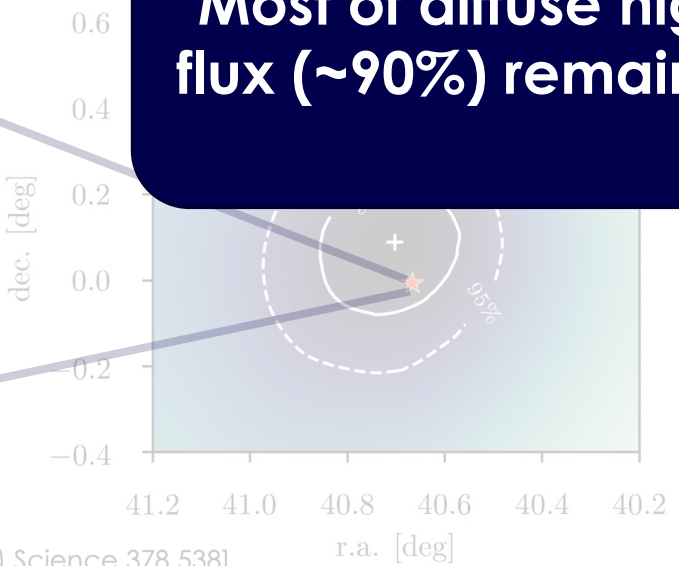


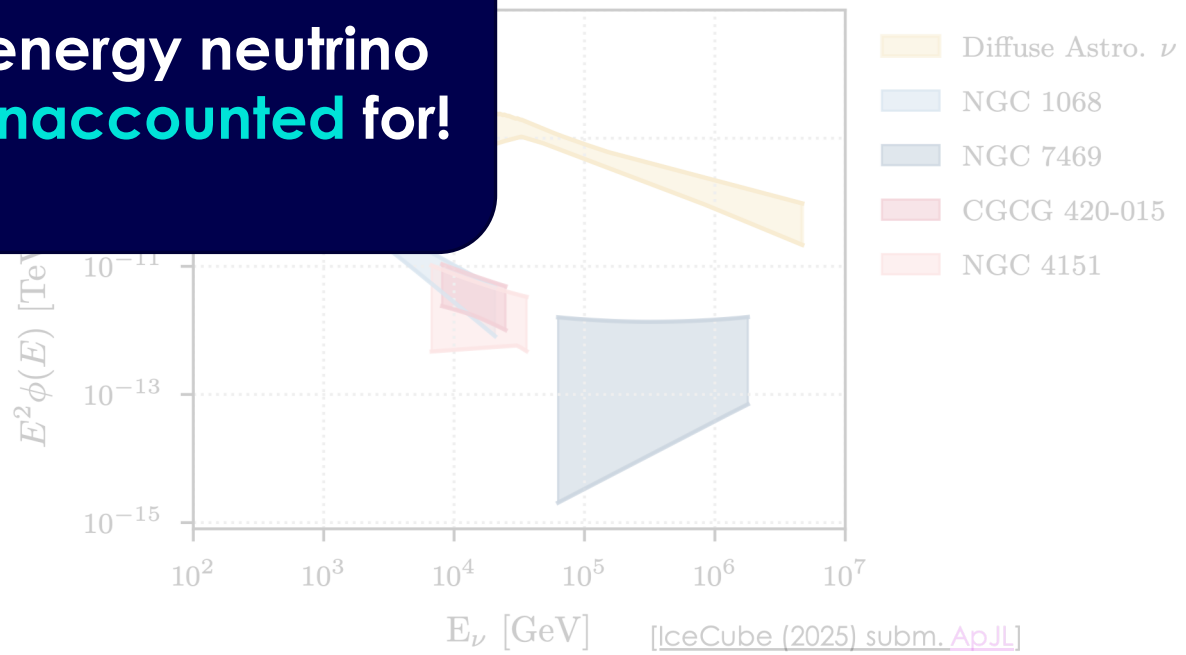
[IceCube (2018) Science 361 147]

Most of diffuse high-energy neutrino flux (~90%) remains unaccounted for!



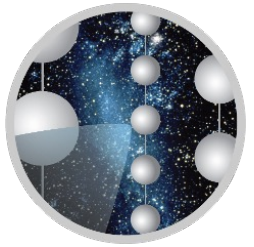


[IceCube (2022) Science 378 538]

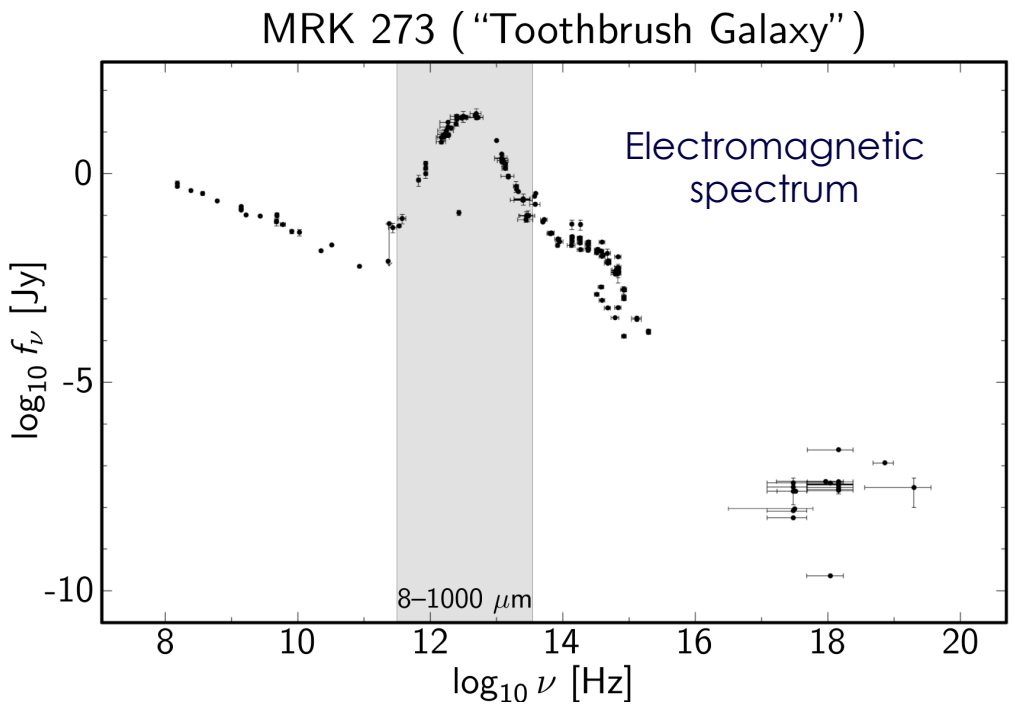


[IceCube (2025) subm. ApJL]

Ultra-Luminous Infrared Galaxies

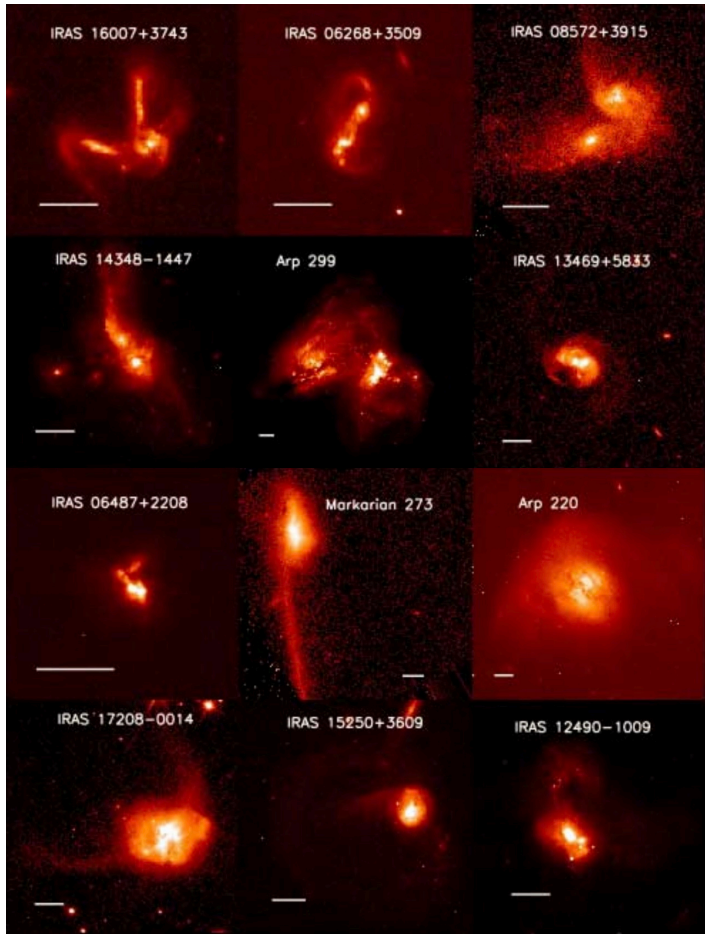


- The **most luminous** objects in the IR sky
  - $L_{IR} \geq 10^{12}\ L_{\odot}$ between 8–1000 micron



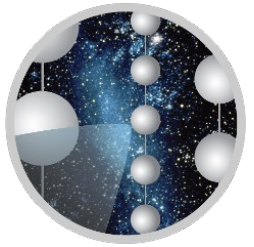
[NASA/IPAC Extragalactic Database]

- **Mergers** of spiral galaxies

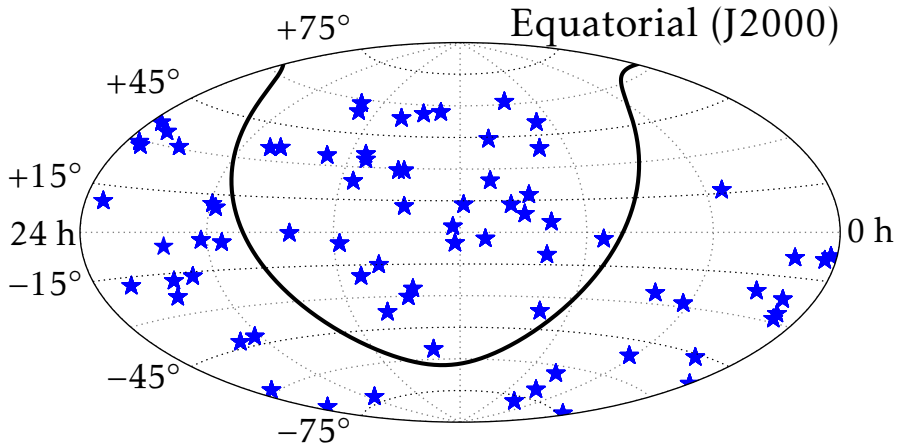


[García-Marín+ (2009) A&A 503 1319]

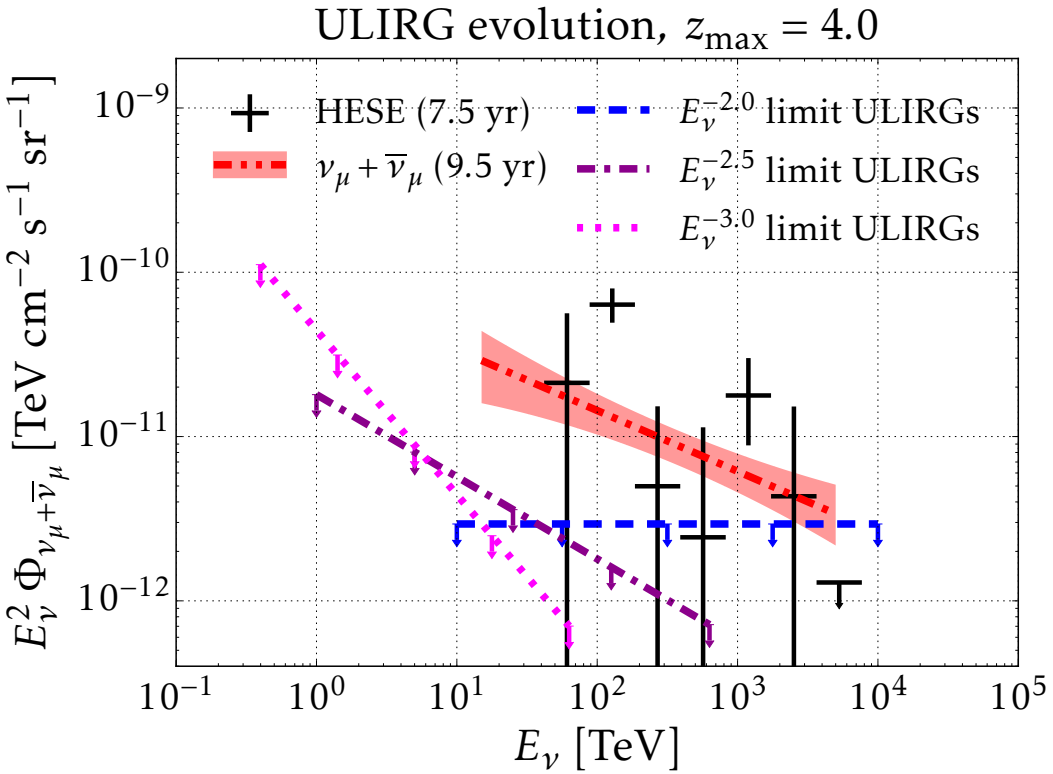
Search for Neutrinos from ULIRGs



- ULIRGs are **candidate neutrino sources**
  - Enhanced **starburst** activity
  - Obscured **active galactic nuclei**
- **IceCube search** performed in 2022
  - **Stacking analysis** on 75 ULIRGs: **null result**
  - Set **limits** on ULIRG contribution to diffuse flux



Upper limits on ULIRG source population
[IceCube [PC] (2022) ApJ 926 59]



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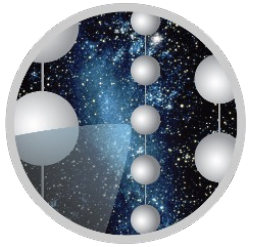

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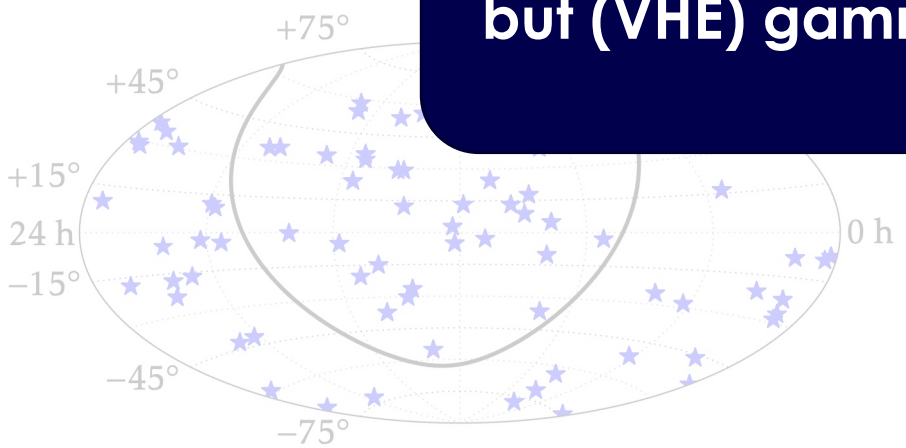
ULIRG neutrino emission constrained
but (VHE) gamma rays to be studied



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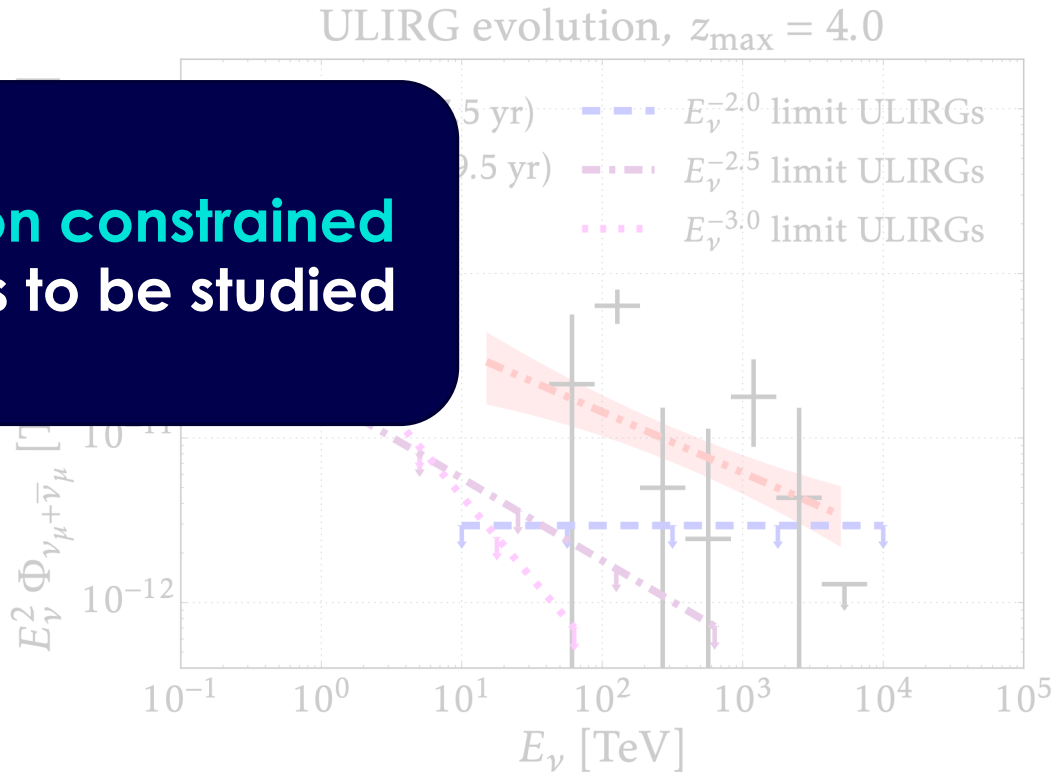

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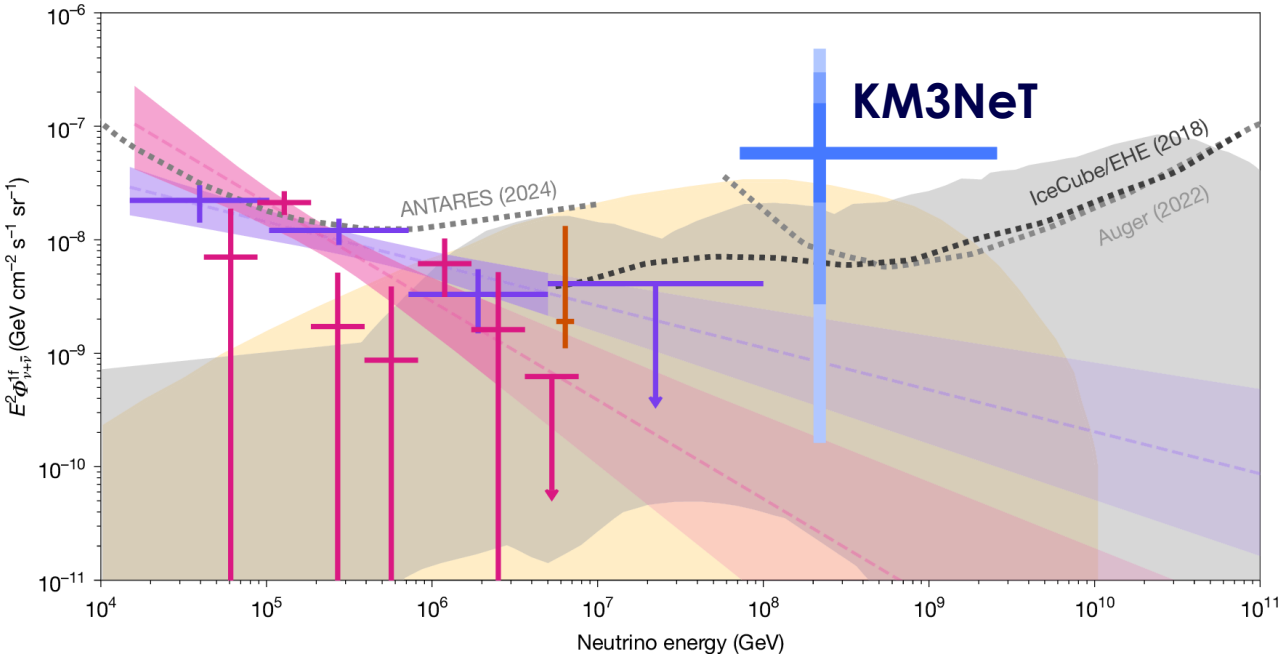
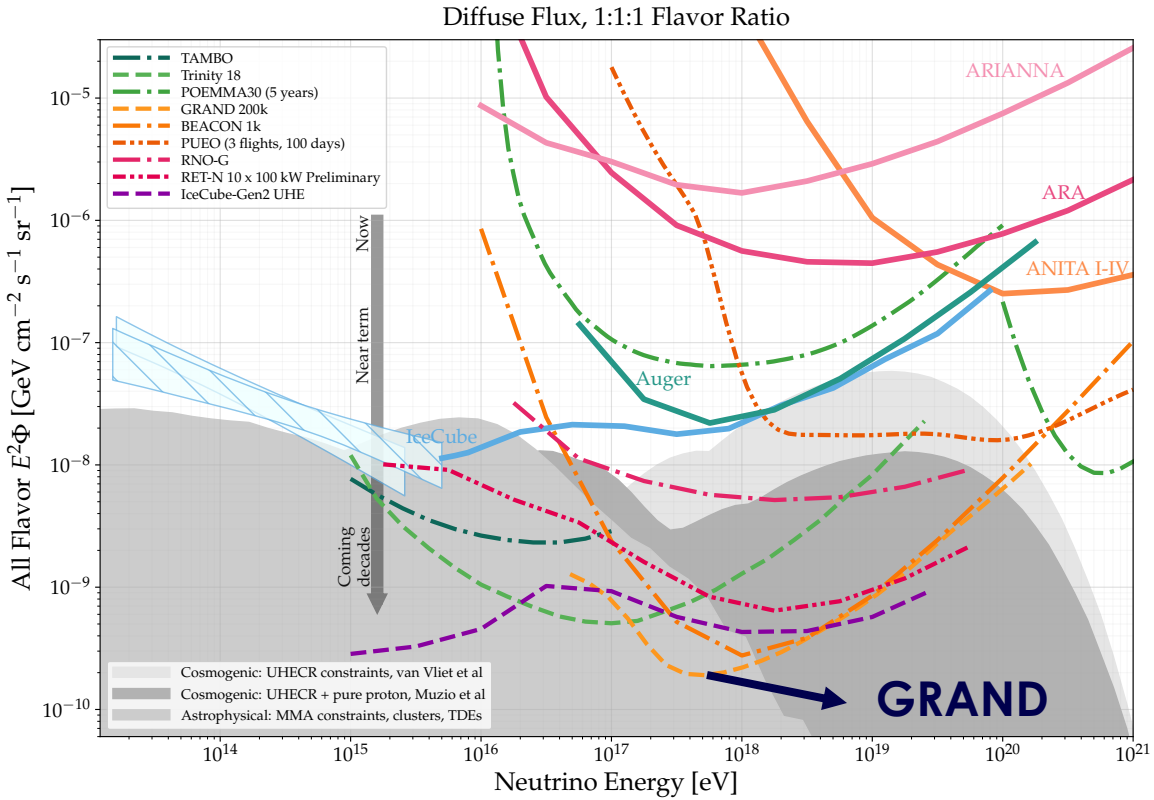
Towards Ultra-High-Energy Neutrinos

- **First UHE neutrino** observed by KM3NeT (~220 PeV)
- Need **other experiments** to further explore UHE energies



[KM3NeT (2025) Nature 638 376]



[Ackermann+ (2022) JHEAp 36 55]

Giant Radio Array for Neutrino Detection

GOAL

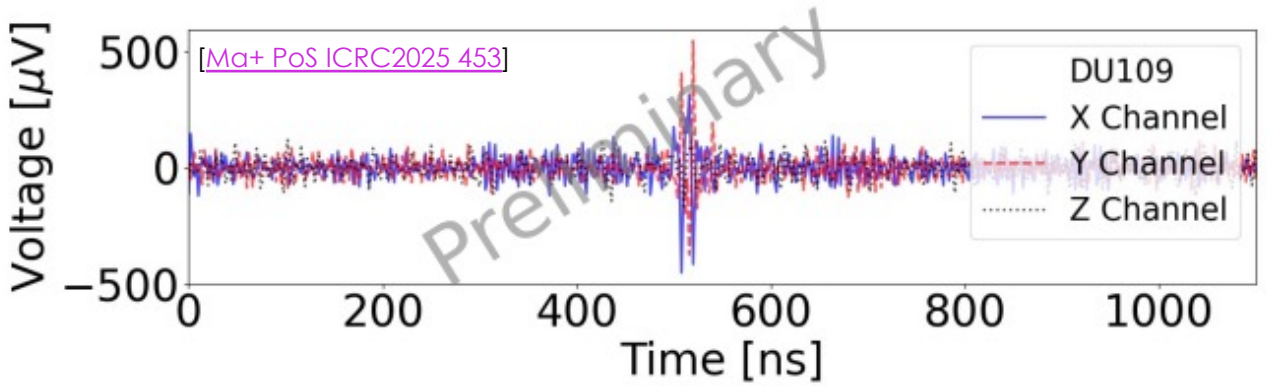
Observe ultra-high-energy (>100 PeV) **neutrinos**

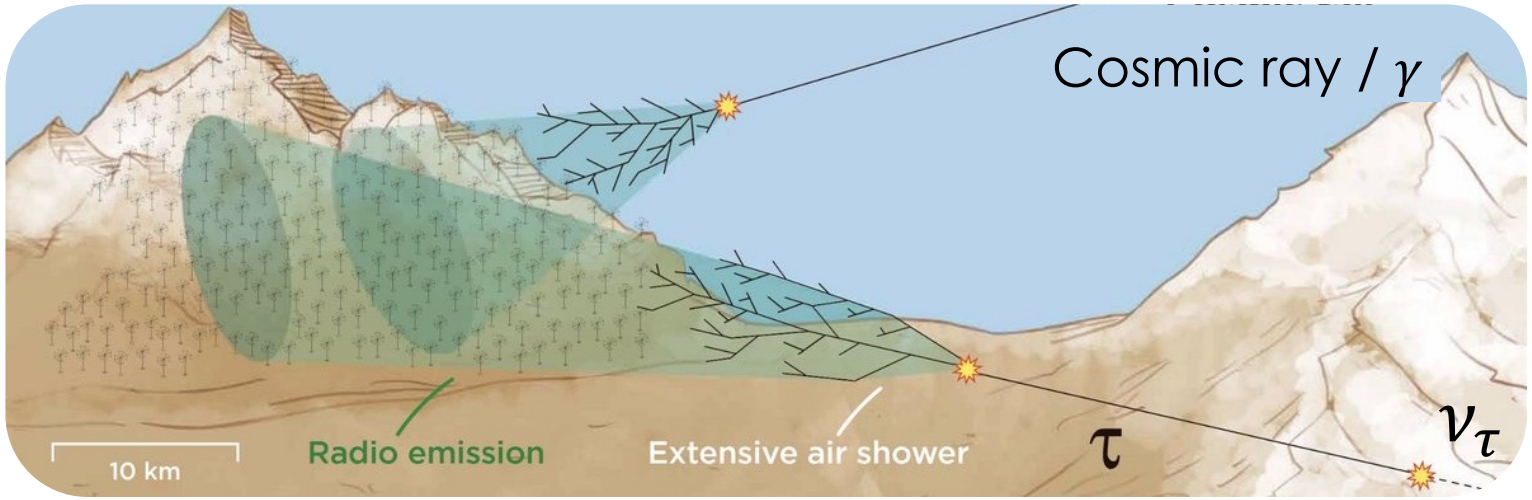
METHOD

Autonomous radio detection of transient (10–100 ns) radio pulses

EXPERIMENT

Distribute **200,000 radio antennas** over 20x10,000 km^2 across the globe

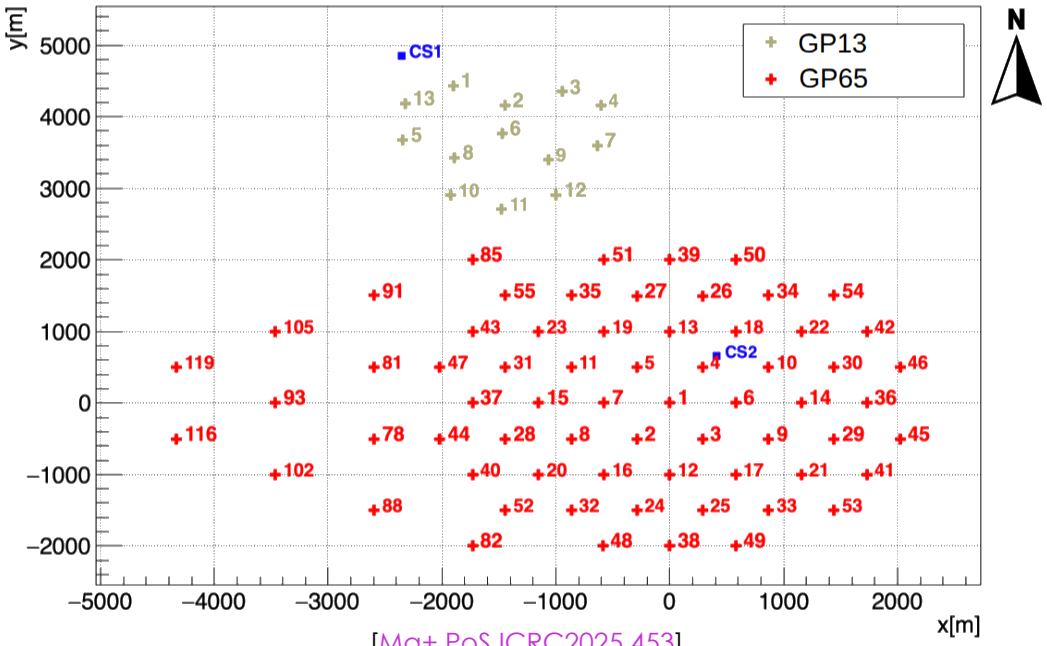




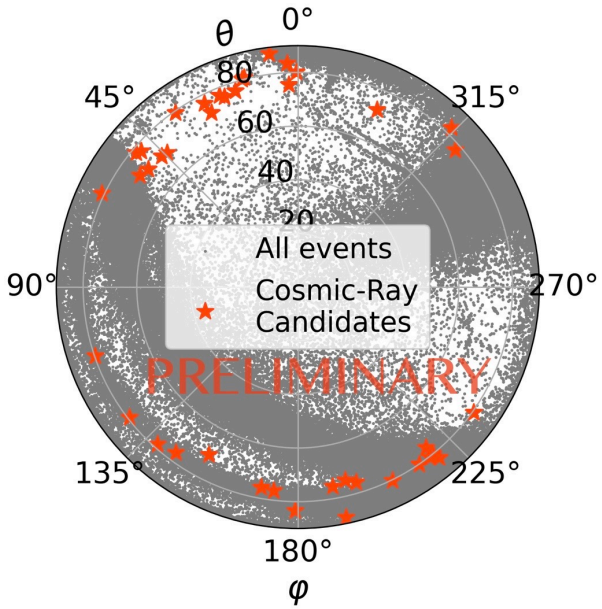
[GRAND (2020) Sci. China Phys. Mech. Astron. 63 219501]

GRANDProto300

- **Pathfinder array** located in Gobi Desert, China
- Currently **65/300 antennas** deployed
- First **cosmic-ray candidates** identified



[Ma+ PoS ICRC2025 453]

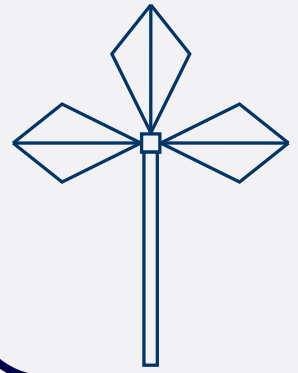


[Lavaoisier+ PoS ICRC2025 314]

The NUTRIG Project

- **Develop scalable radio self-trigger**
  - Maximum **purity & efficiency**
  - Minimum **cost & data bandwidth**
- **First-level trigger** at DU level
  - **GP300**: signal over threshold
  - **NUTRIG**: template matching / CNN [Le Coz+ PoS ICRC2023 224, Correa+ PoS ARENA2024 060]
- **Second-level trigger** at array level
  - **GP300**: time coincidence
  - **NUTRIG**: crude air-shower reconstruction [Köhler+ PoS ARENA2024 061, Correa+ PoS ICRC2025 229]

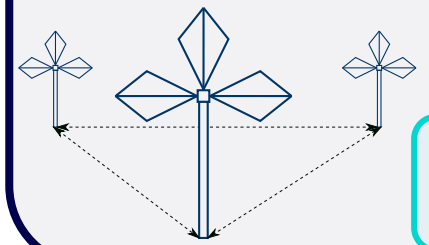
Single detection unit (DU) trigger rate



GP300 nominal: 1kHz

NUTRIG FLT target: 100 Hz

Array of DUs trigger rate

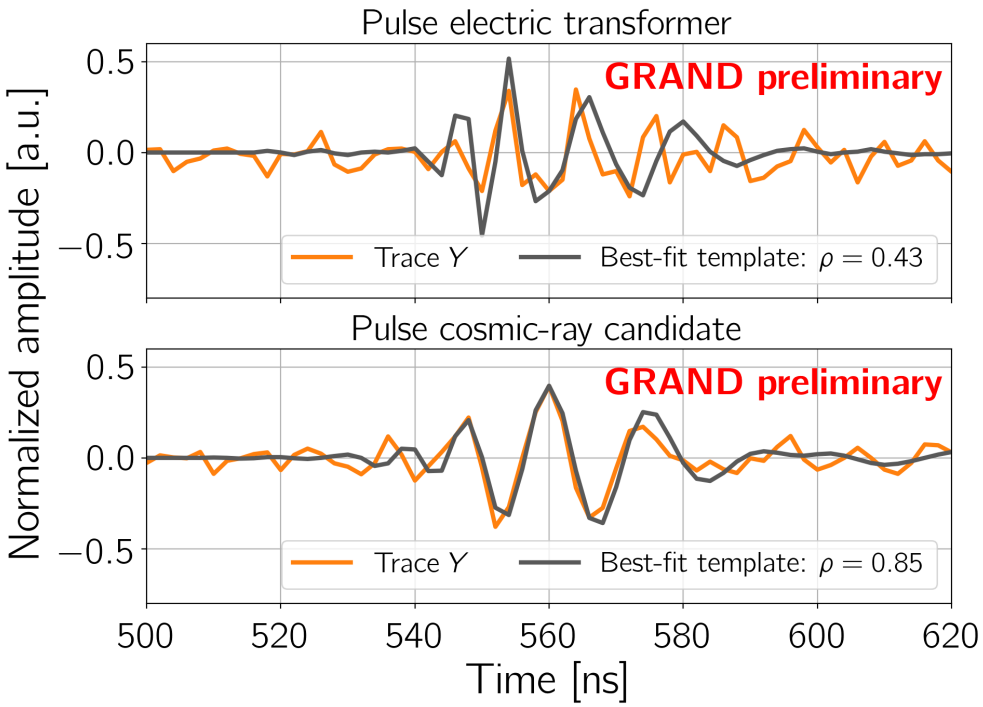


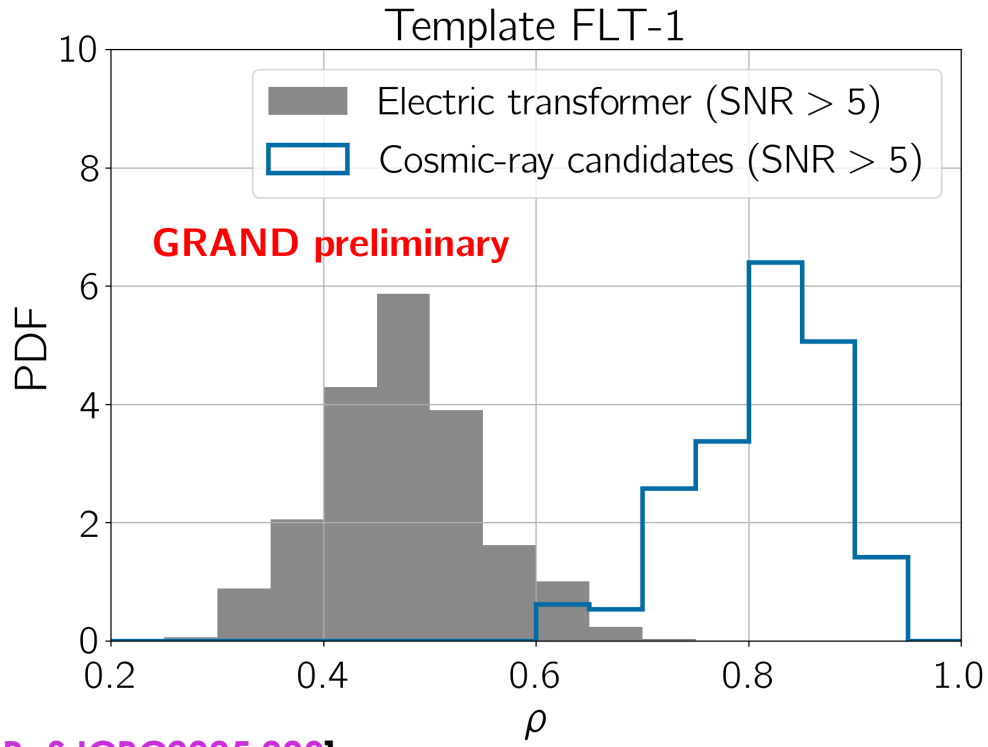
GP300 nominal: 10 Hz

NUTRIG SLT target: 1 Hz

NUTRIG: Template Matching

- Use **templates** of simulated air-shower signal pulses
- **Cross-correlate** with data to separate signal from background



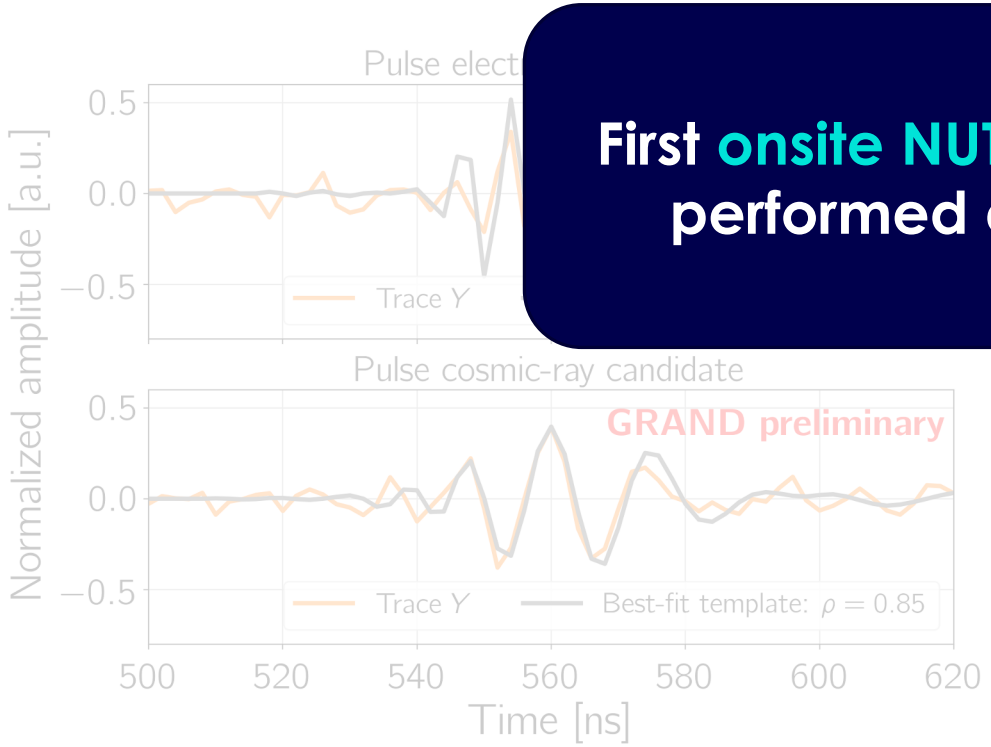


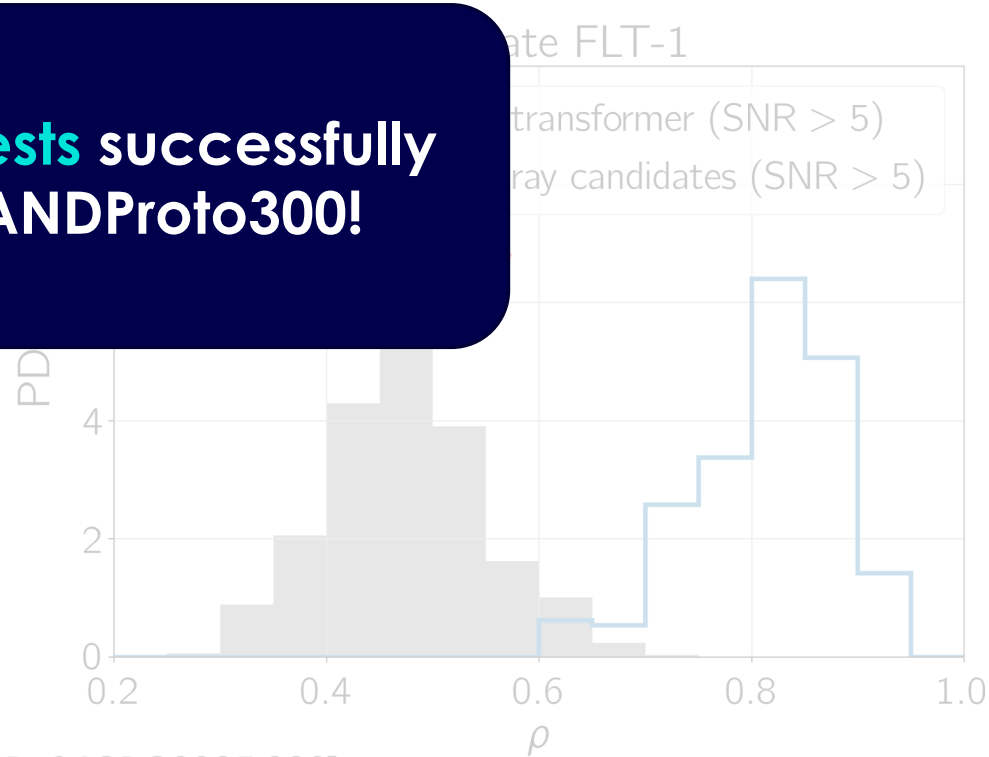
[Correa+ PoS ICRC2025 229]

NUTRIG: Template Matching

- Use **templates** of simulated air-shower signal pulses
- **Cross-correlate** with data to separate signal from background

First onsite NUTRIG tests successfully performed at GRANDProto300!





[Correa+ PoS ICRC2025 229]

Conclusions & Outlook

Summary

- **Multimessenger astronomy** is key to study the high-energy sky
- **CTAO** will study 0.1–100 TeV gamma rays (leptonic vs hadronic)
- **IceCube** discovered TeV–PeV neutrinos and first sources
- **GRAND** aims to observe neutrinos >100 PeV and identify their origin

Outlook

- First **NectarCAM** ship-ready in June
  - Milestone in CTAO-MST construction
- **NUTRIG** to be implemented in GP300
  - Milestone in GRAND's hunt for UHE neutrinos
- Sensitivity study of **ULIRGs** with CTAO
  - Complements IceCube neutrino search