What do we know so far of cosmic neutrinos?

Highlights of the cosmic discoveries

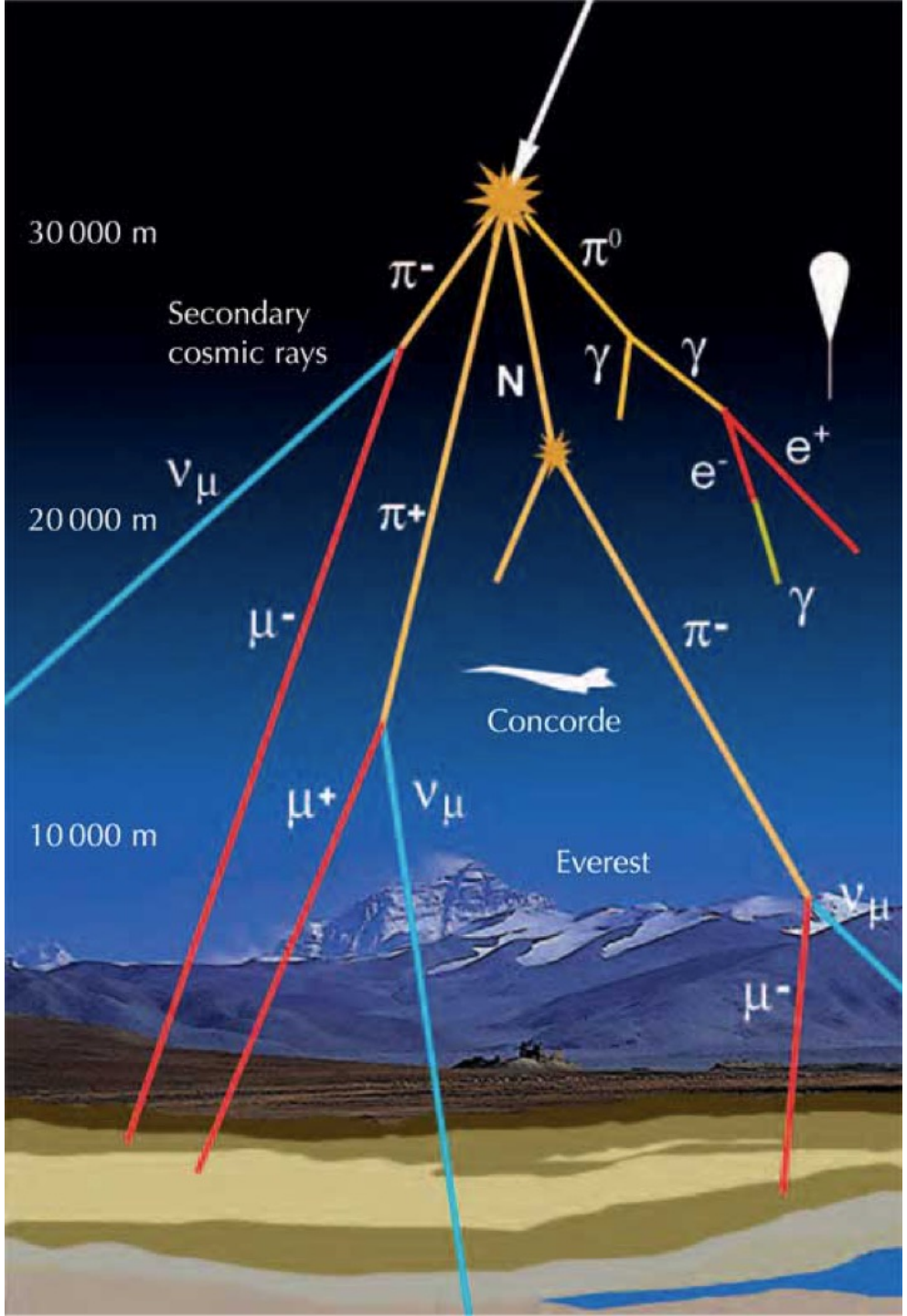
- Diffuse Cosmic Neutrino Flux
- Cosmic Sources
- Galactic Neutrinos
- The Unexpected

A neutrino beam ‘for free’

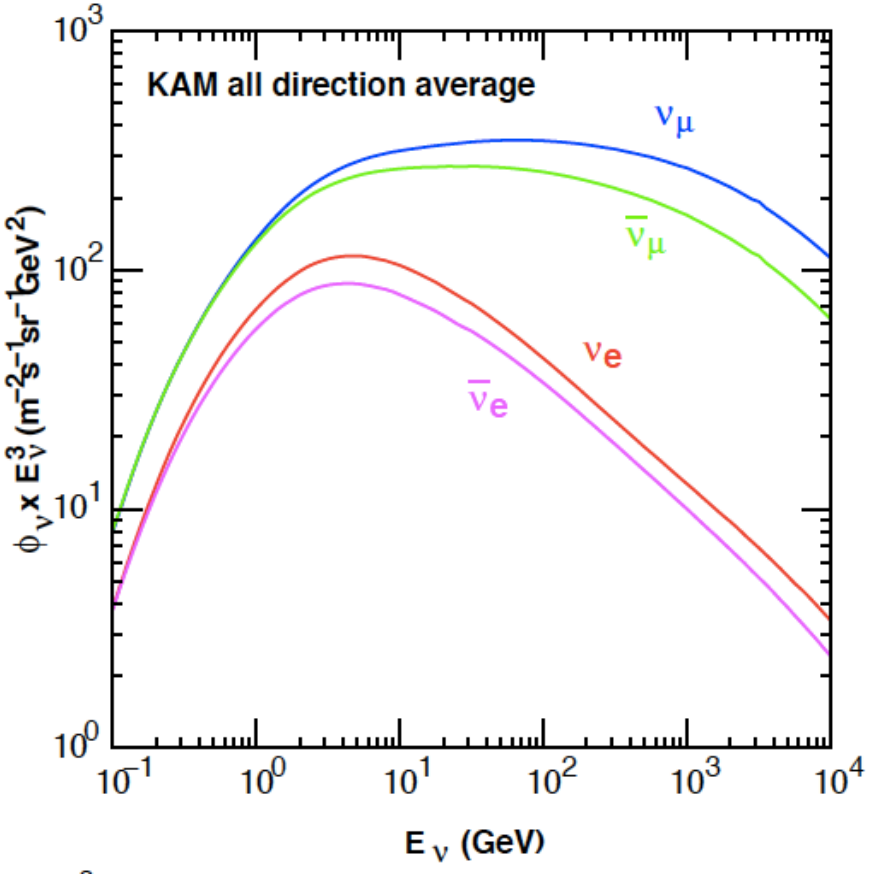
Cosmic rays hit the atmosphere
=> particle showers

Particles decays
=> Muon/Electron neutrinos
created in ratio 2:1

Backgrounds for cosmic neutrino searches, but useful
for neutrino ocillation studies



Flavors and neutrino/antineutrinos



Honda et al, Phys. Rev. D92 (2015) 023004

Conventional atmospheric neutrino flux
from kaon and pion decays

- Mainly muon neutrinos
- More neutrinos than anti-neutrinos
- Fluxes depend on atmospheric seasonal changes
  -> slight annual flux changes

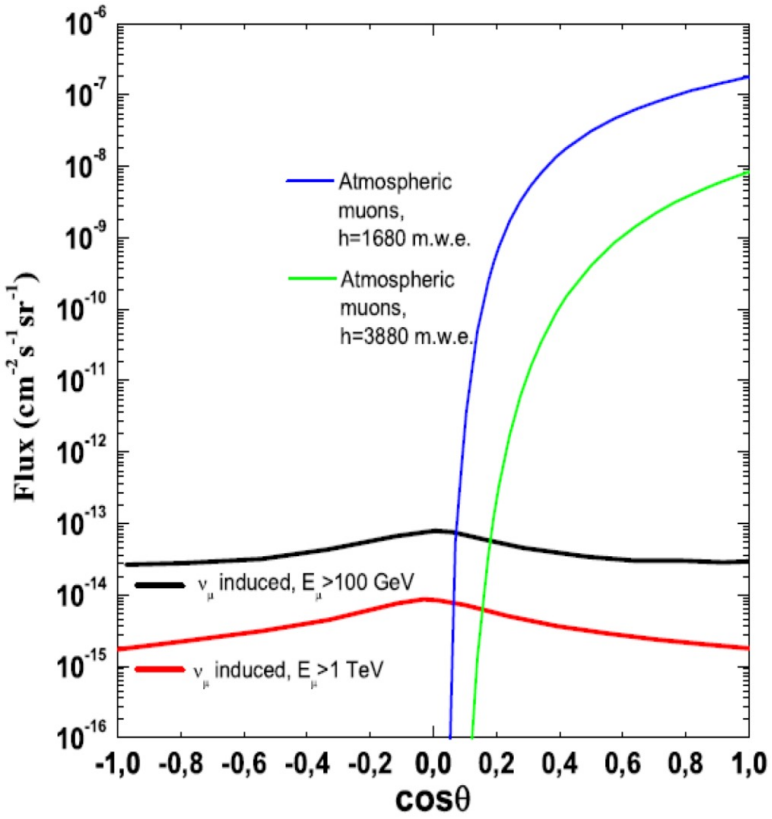
In addition '**prompt flux**':
Neutrinos from decay of heavy mesons (D-mesons)

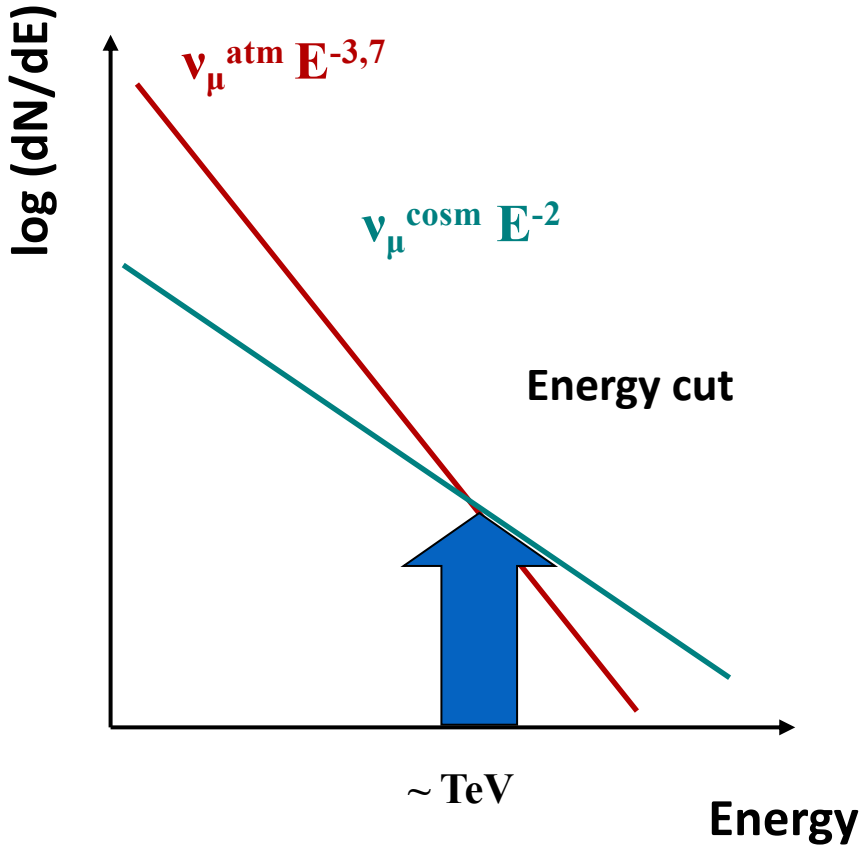
- Higher energies, harder energy spectrum
- First hint of this flux component seen by now in IceCube

Atmospheric background & cosmic neutrinos

~1km3 detector:

Atmospheric μ 10^9 per year
Atmospheric ν 10^4 per year
Cosmic ν ~100 per year





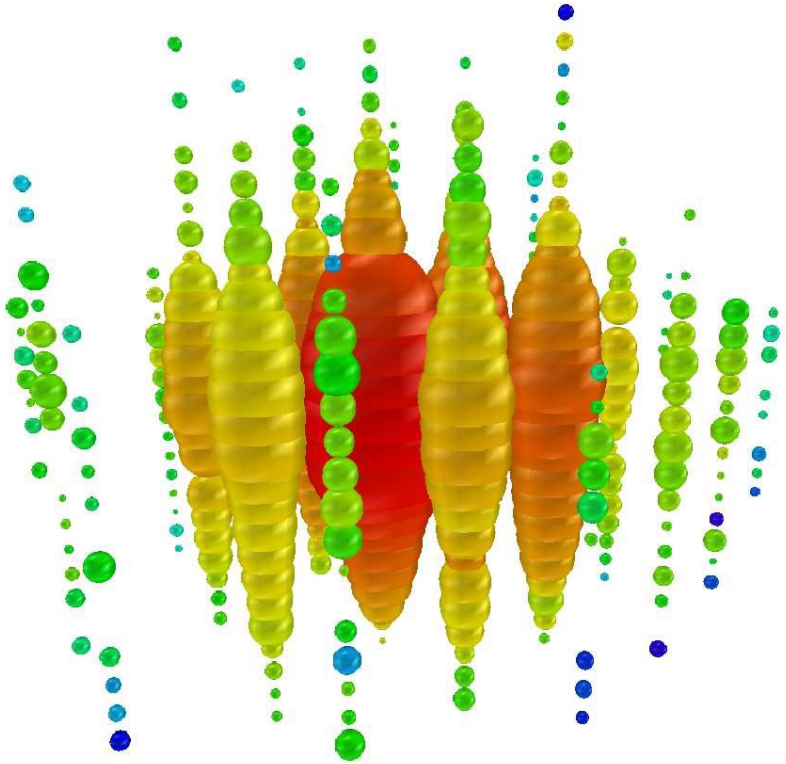
High energies -> Cosmic neutrinos dominate
In order to identify sources: Time / space coincidence with other cosmic probes

Diffuse cosmic neutrino flux

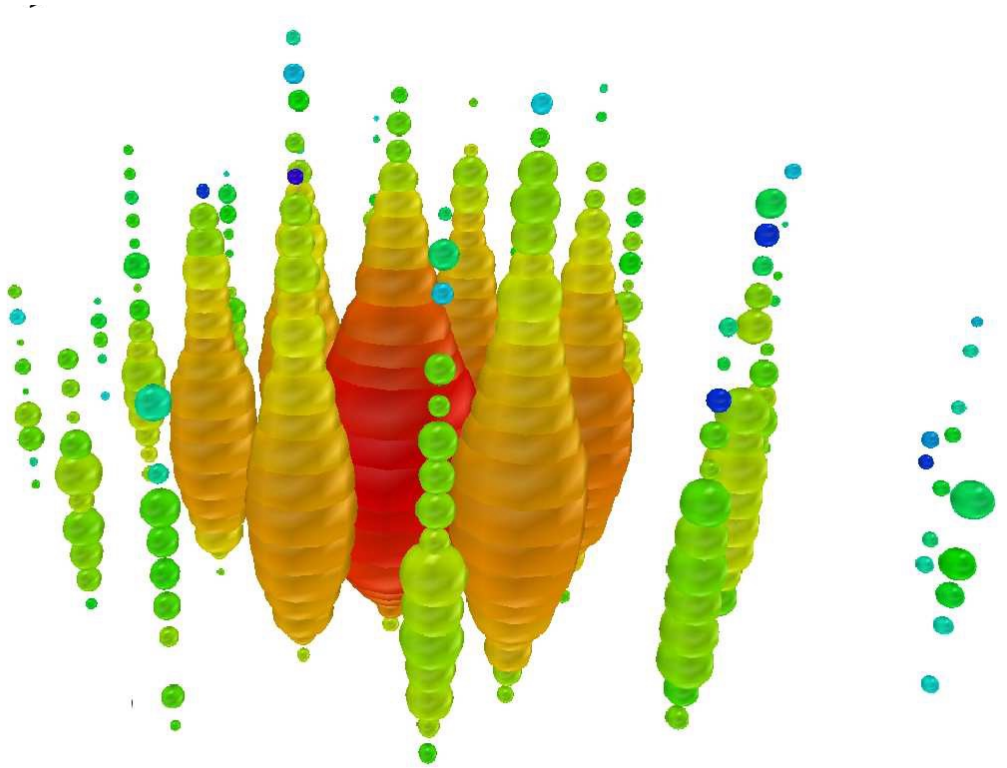
The two first cosmic neutrinos detected by IceCube

Light detection in the detector

1.04 ± 0.16 PeV

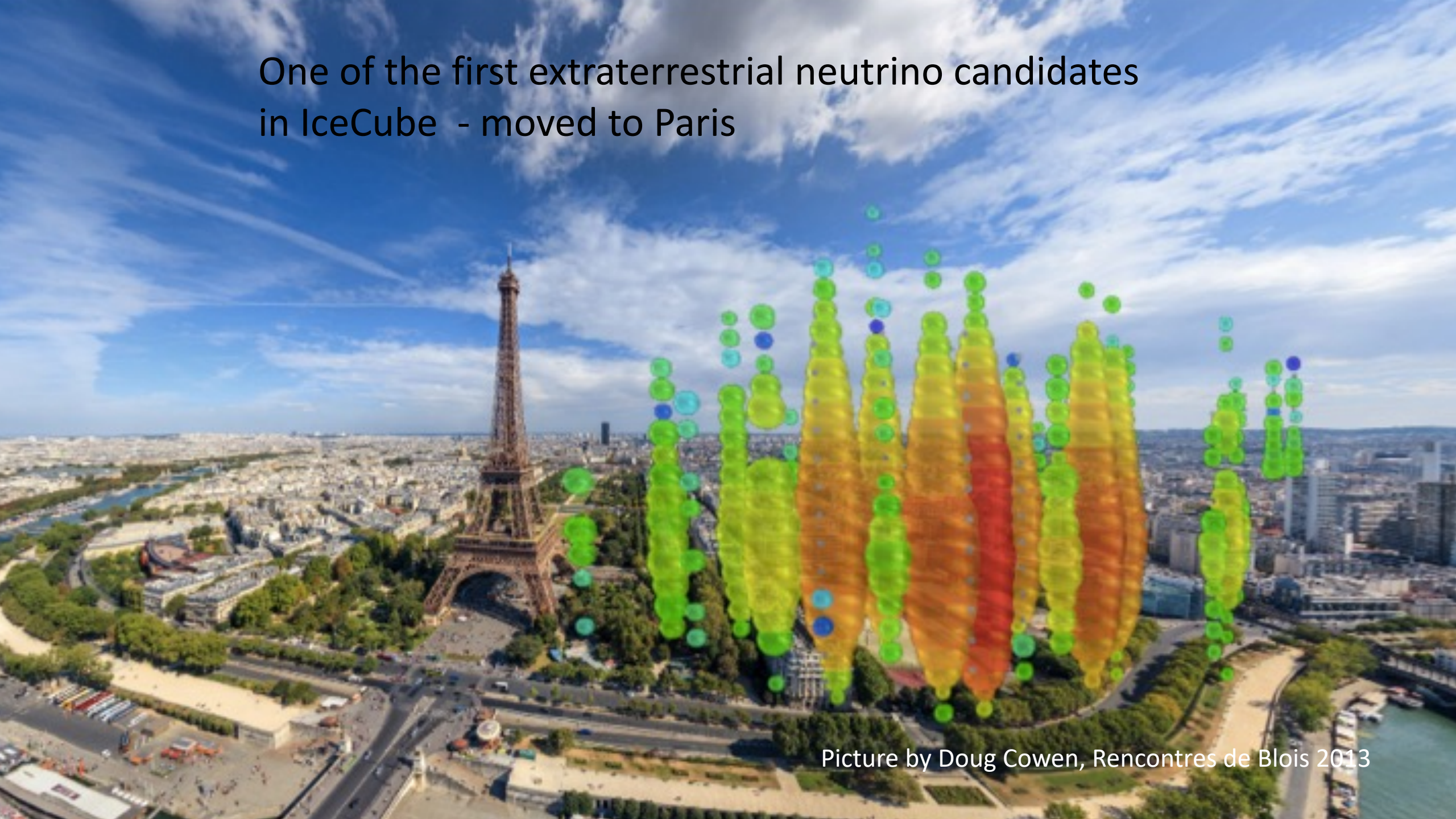


1.14 ± 0.17 PeV

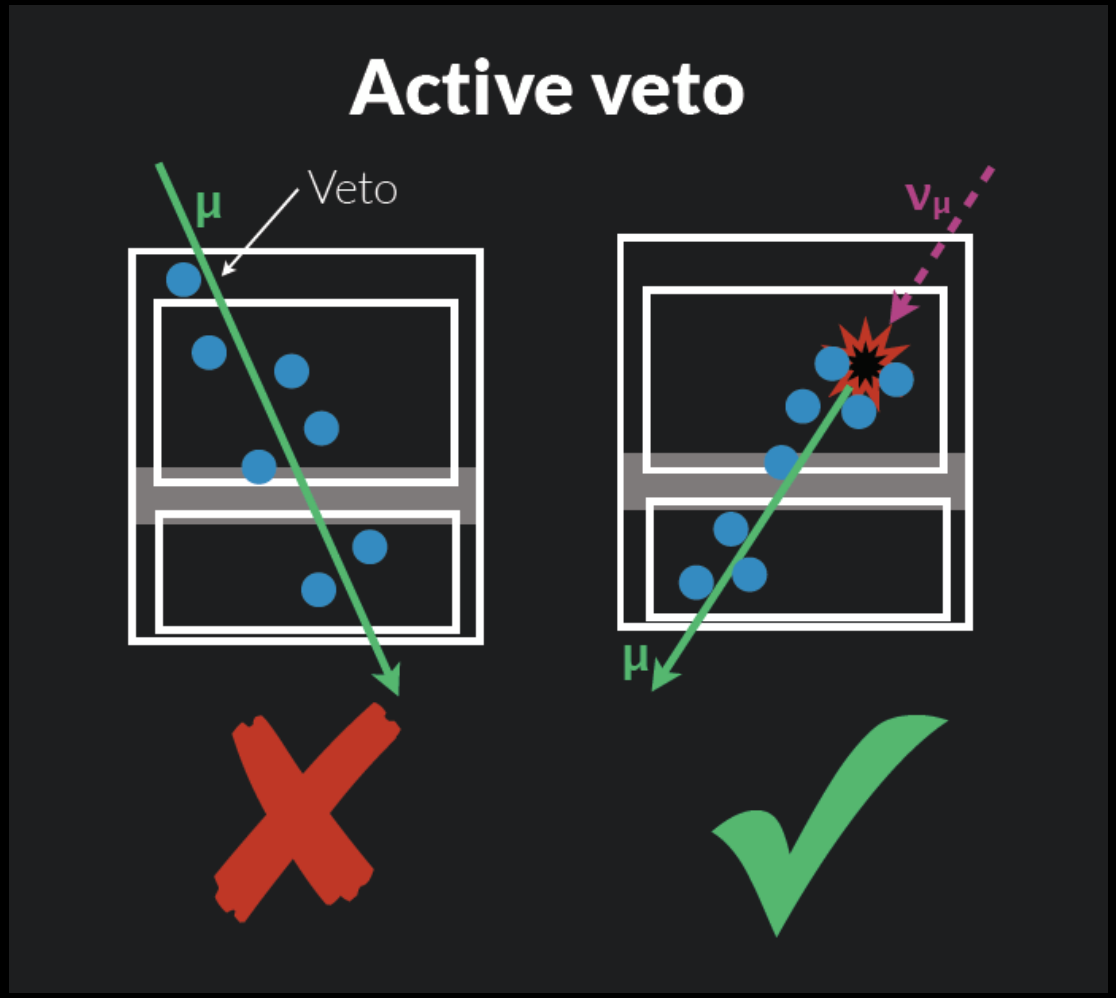


High energy events could not be explained by atmospheric background

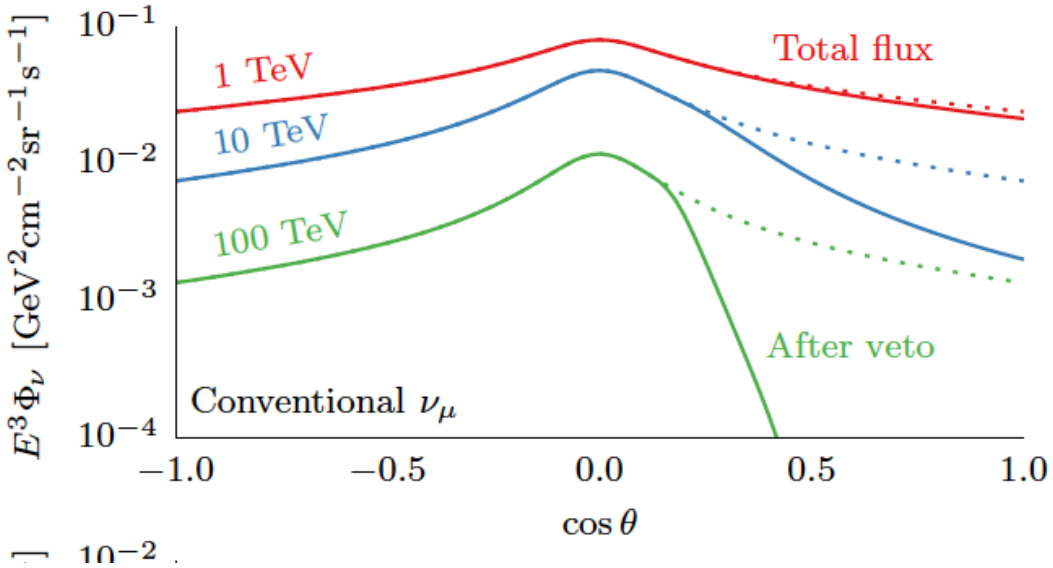
One of the first extraterrestrial neutrino candidates in IceCube - moved to Paris



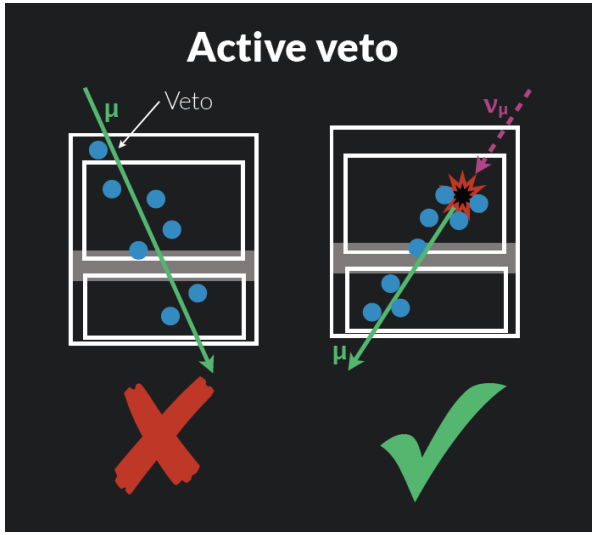
Picture by Doug Cowen, Rencontres de Blois 2013



Veto allows to cleanly identify neutrino interactions



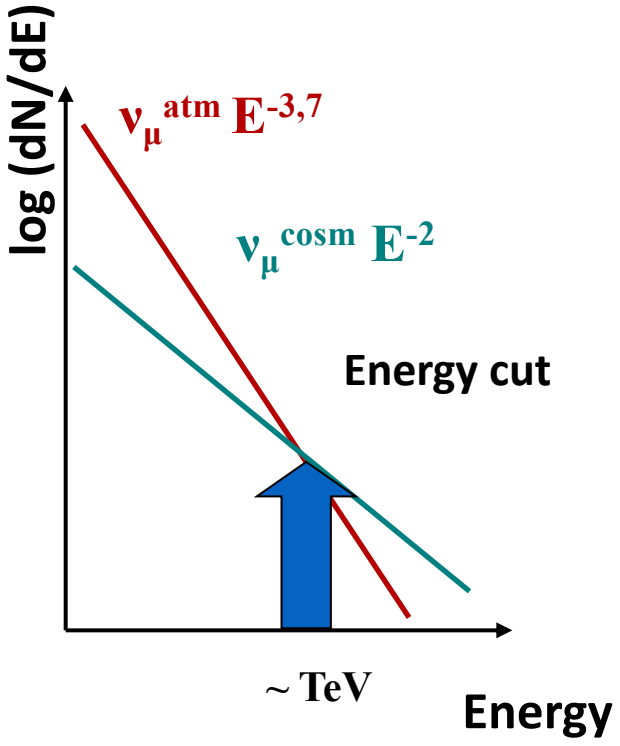
Gaisser et al, PhysRevD, 90:023009 (2014)



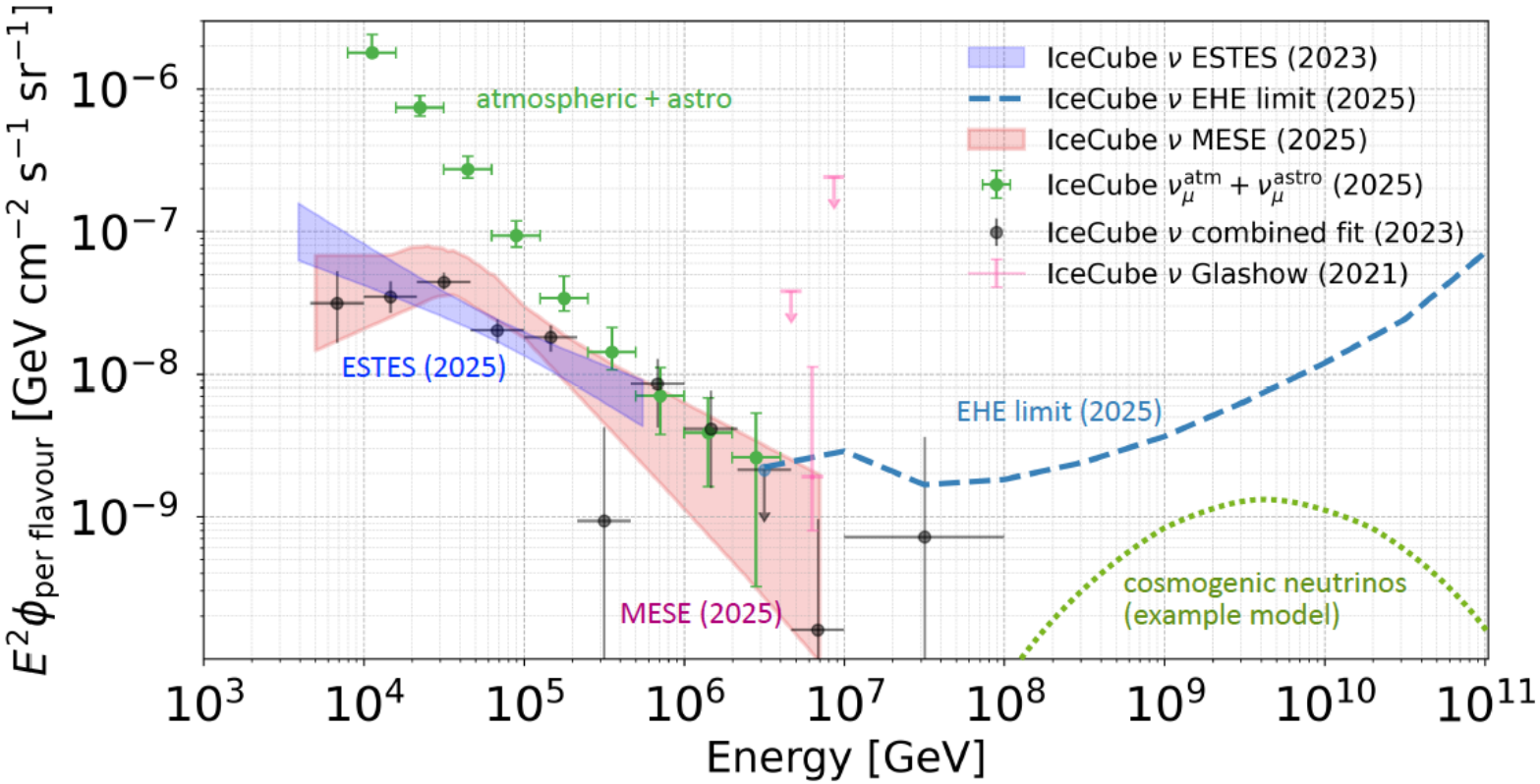
- Veto allows to cleanly identify neutrino interactions
- Reduces atmospheric neutrino 'background' from above due to signals of high-energy muon accompanying neutrino production

Led to discovery of many more cosmic neutrino candidates
HESE: High Energy Starting Events

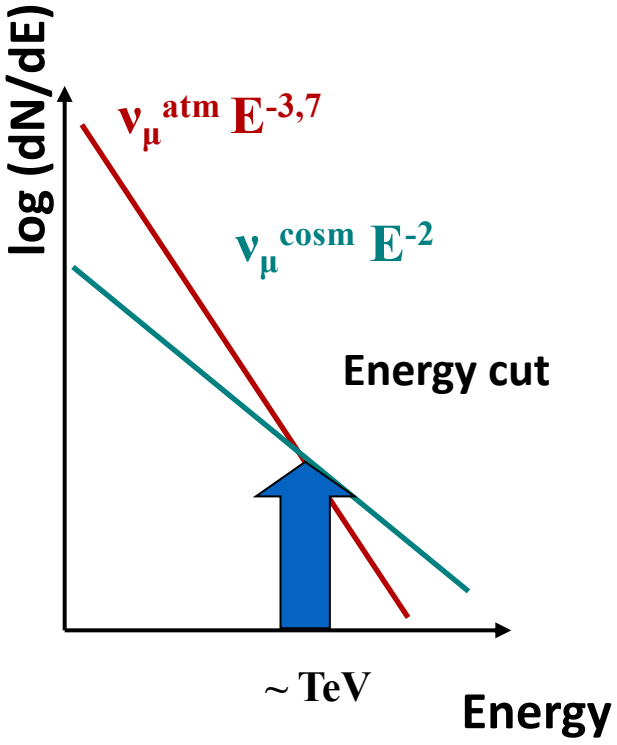
High energy diffuse neutrino flux



Many more searches established the cosmic diffuse neutrino flux



High energy diffuse neutrino flux



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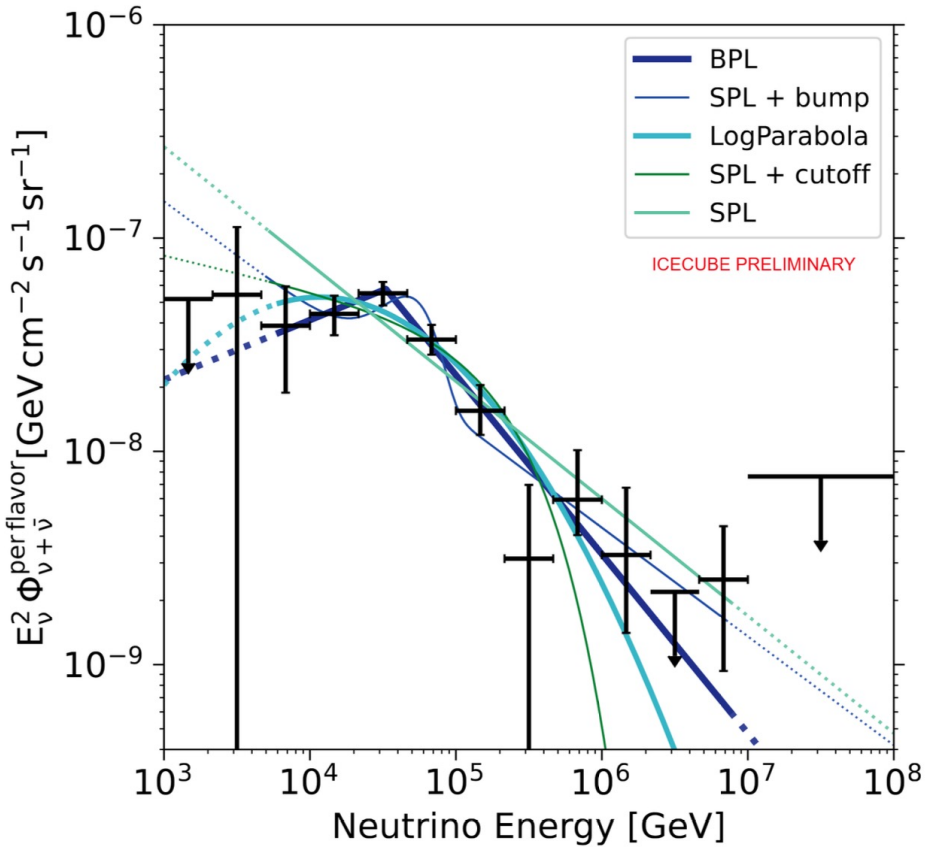
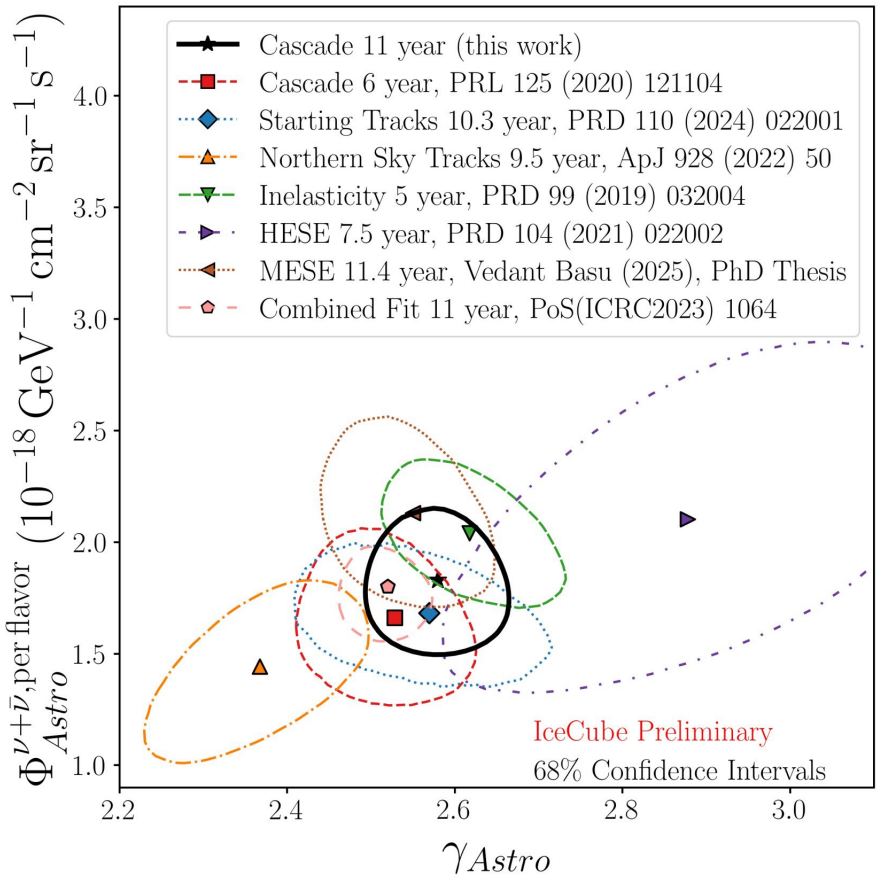
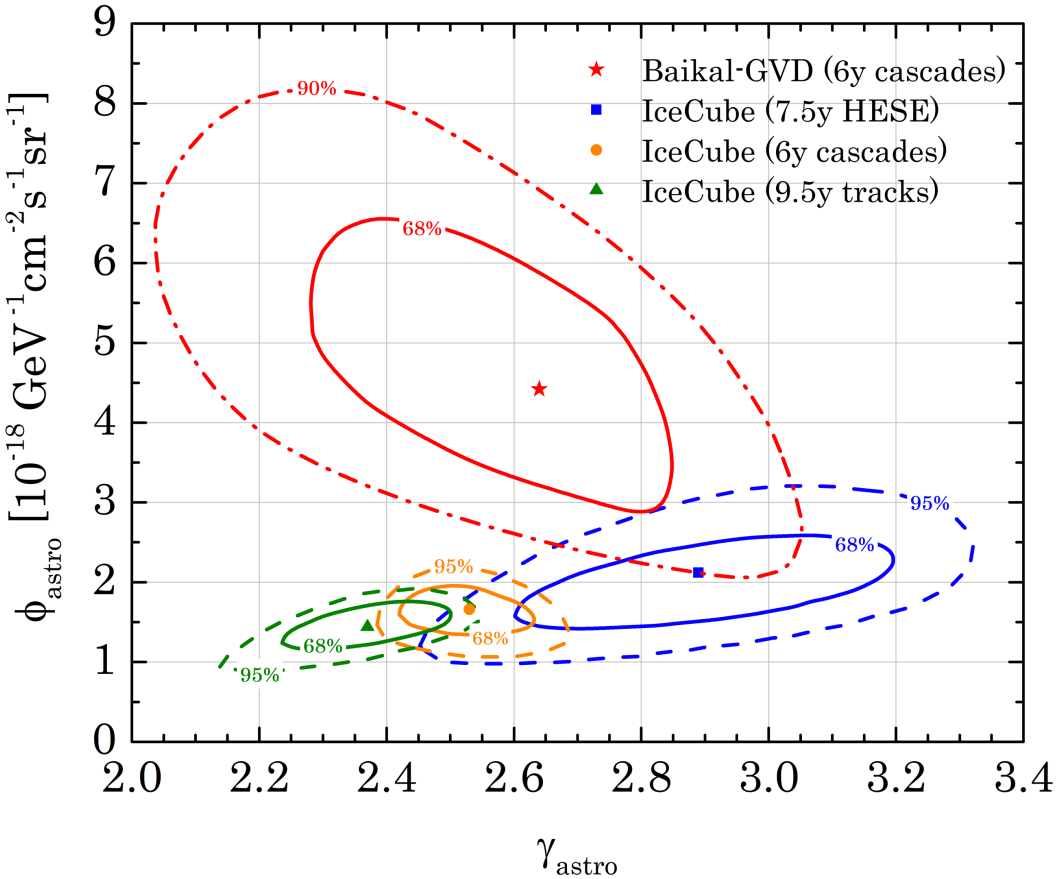


	$-2\Delta\ln\mathscr{L}$ compared to SPL
Single PL	0
SPL + Cutoff	1.8 (0.9σ)
Log Parabola	19.8 (4.2σ)
SPL + Bump	22.3 (3.9σ)
Broken PL	27.3 (4.7σ)

New: A ‘broken power law’ clearly identified





Z. Chen, Z. Zhang, J. Kiryluk (for IceCube)
PoS(ICRC2025)1011

GVD, arXiv.2507.01893

Potential differences could be expected from different event samples:

- Different sky regions probed
- Different energy ranges probed
- Different flavors

Different source scenarios

$$p + \gamma \rightarrow \Delta^{+} \begin{cases} \rightarrow p + \pi^{0} \\ \rightarrow n + \pi^{+} \end{cases}$$

$$\pi^{0} \rightarrow \gamma\gamma$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$$

$$\hookrightarrow e^{+} + \bar{\nu}_{\mu} + \nu_{e}$$

$$n \rightarrow e^{-} + p + \bar{\nu}_{e}$$

Neutron lifetime: 881 s

$$p + p \rightarrow \pi^{\pm} + X$$

$$\hookrightarrow \mu^{\pm} + \nu_{\mu}(\bar{\nu}_{\mu})$$

$$\hookrightarrow e^{\pm} + \bar{\nu}_{\mu}(\nu_{\mu}) + \nu_{e}(\bar{\nu}_{e})$$

Different cosmic source scenarios

$$\nu_e : \nu_\mu : \nu_\tau$$

'Standard '

-> charged pion decay, muon decay

1 : 2 : 0

Muon damped source

-> strong magnetic fields, muon decay suppressed

-> pion decay dominant

0 : 1 : 0

Neutron beam source

-> extremely strong magnetic field

-> cosmic rays heavy nuclei

1 : 0 : 0

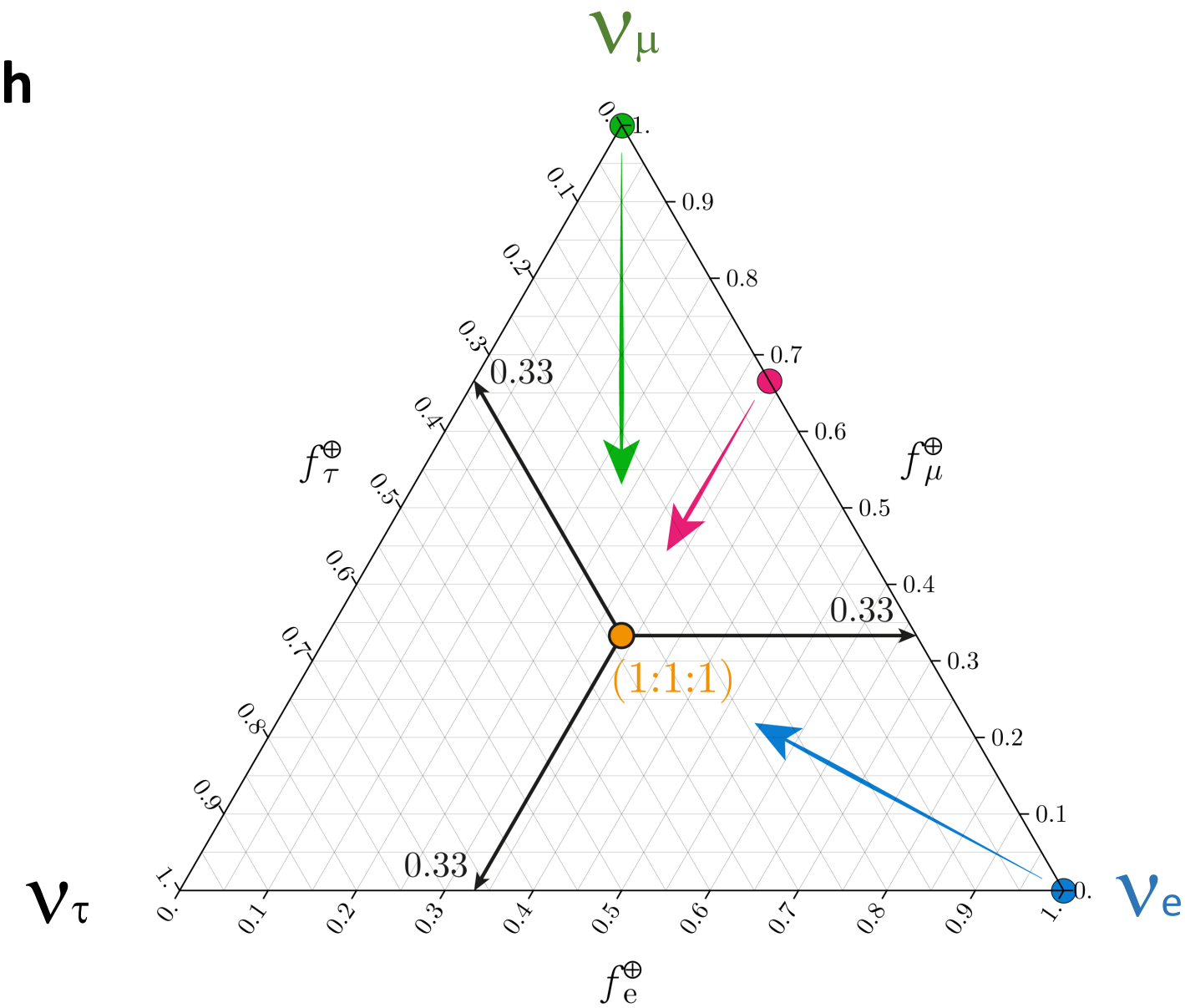
Note: *Also different neutrino/antineutrino ratios*

Neutrino flavor ratio at Earth

- Different astrophysical scenarios will lead to different observed flavor compositions
- Potential to find new physics effects

- Flavor ratio can be energy dependent
- In neutron decay scenario only antineutrinos

neutrino telescopes don't distinguish neutrinos and antineutrinos, but Glashow resonance occurs only for antineutrinos



C. A. Argüelles , K. Farrag, T. Katori, S. Mandalia, ICRC2019

Neutrino flavor ratio at Earth

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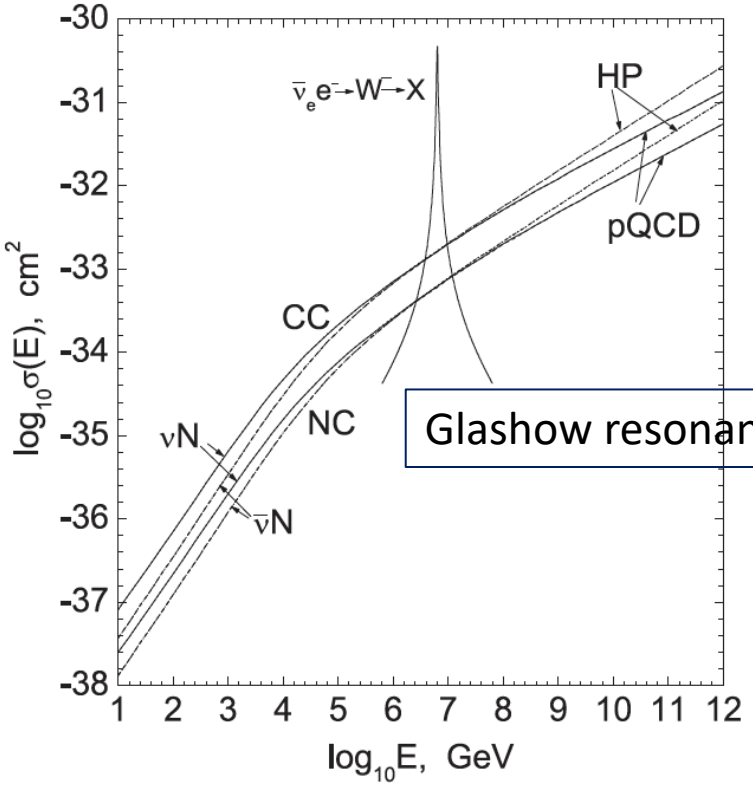
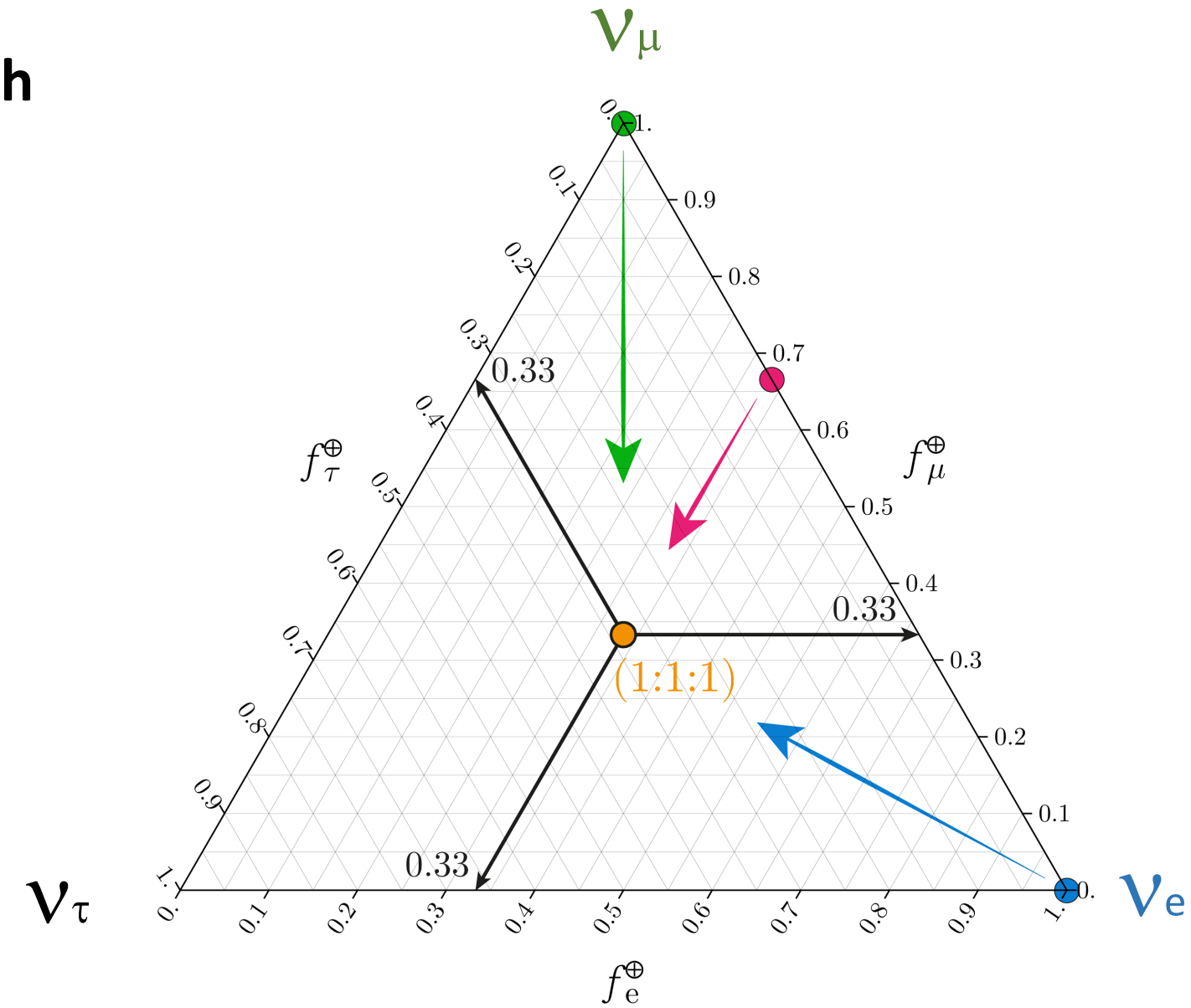


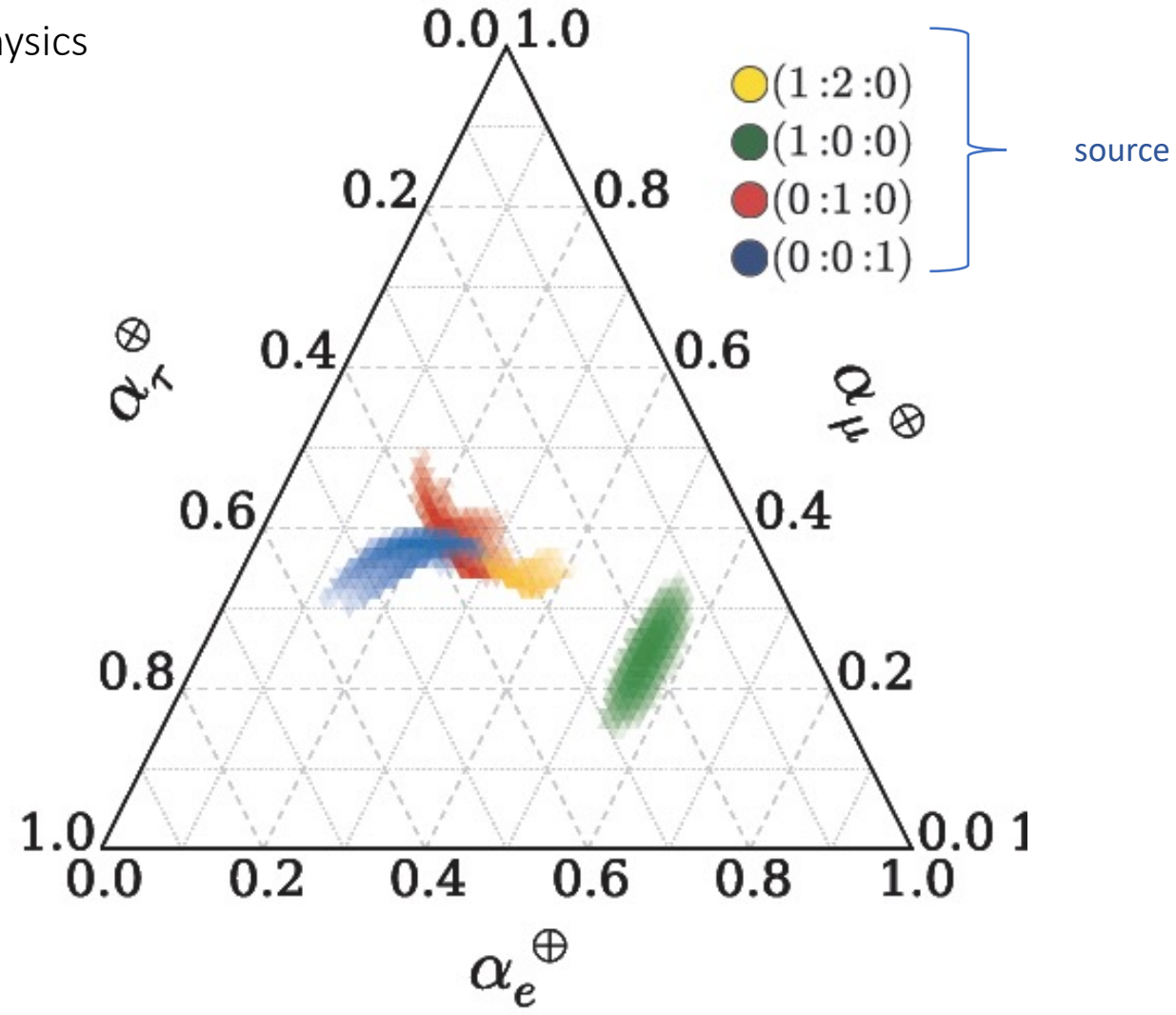


(0 : 1 : 0) (1 : 2 : 0) (1 : 0 : 0) (1 : 1 : 1)

C. A. Argüelles , K. Farrag, T. Katori, S. Mandalia, ICRC2019

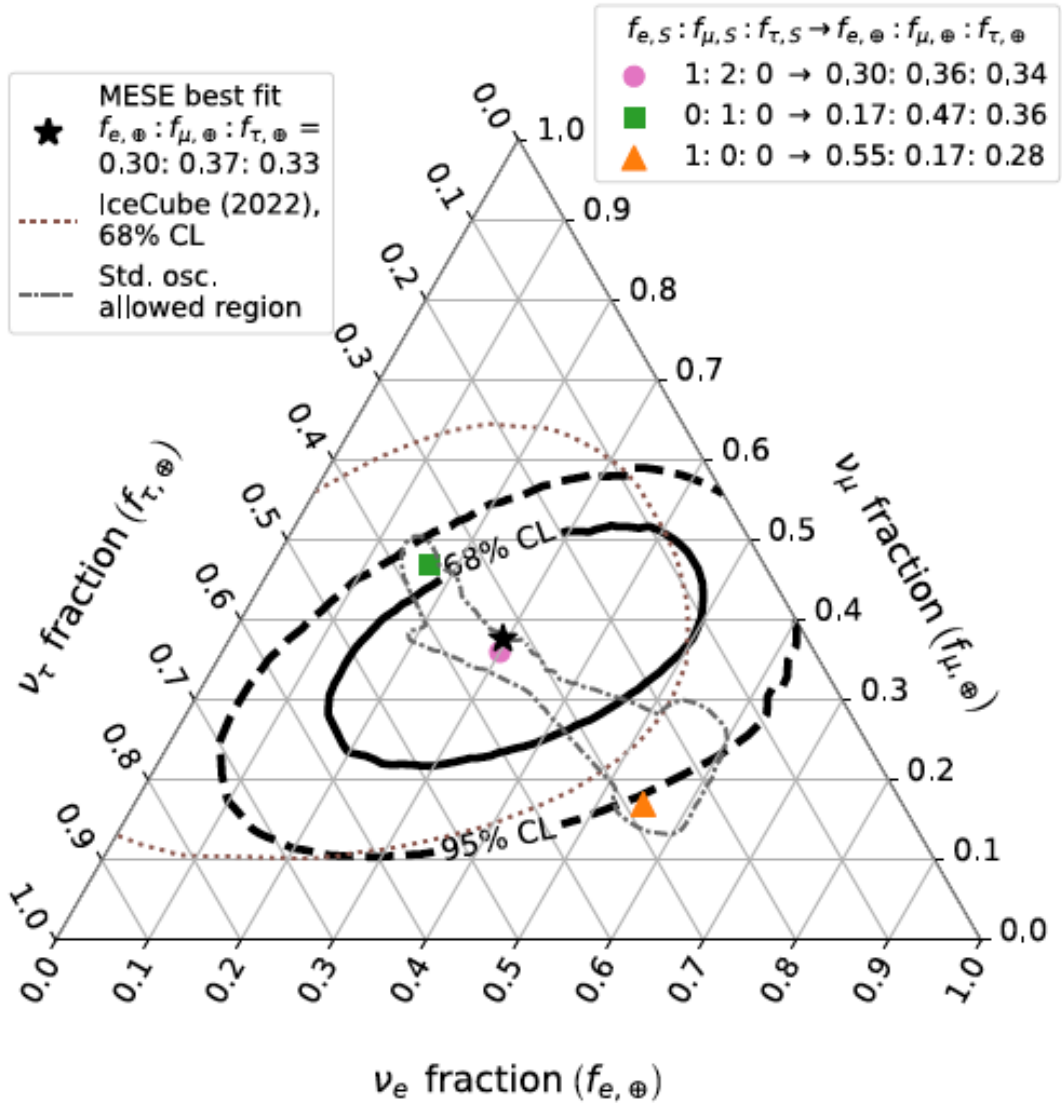
Neutrino flavor ratio at Earth

‘Standard’ phase space
-> Deviations indicate new physics

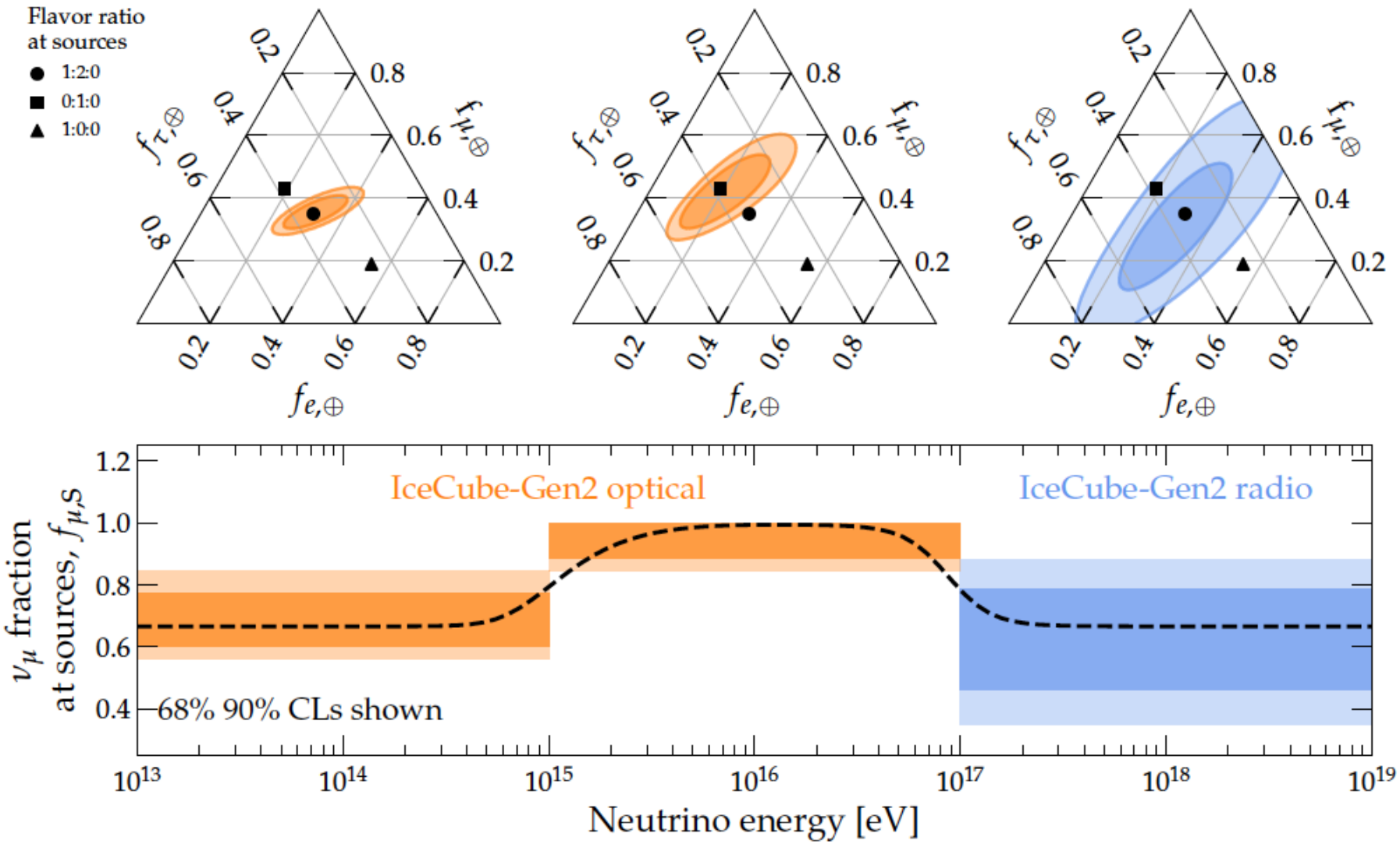


C. Arg⍰uelles, T. Katori and J. Salvado, Phys.Rev.Lett. 115 (2015) 161303

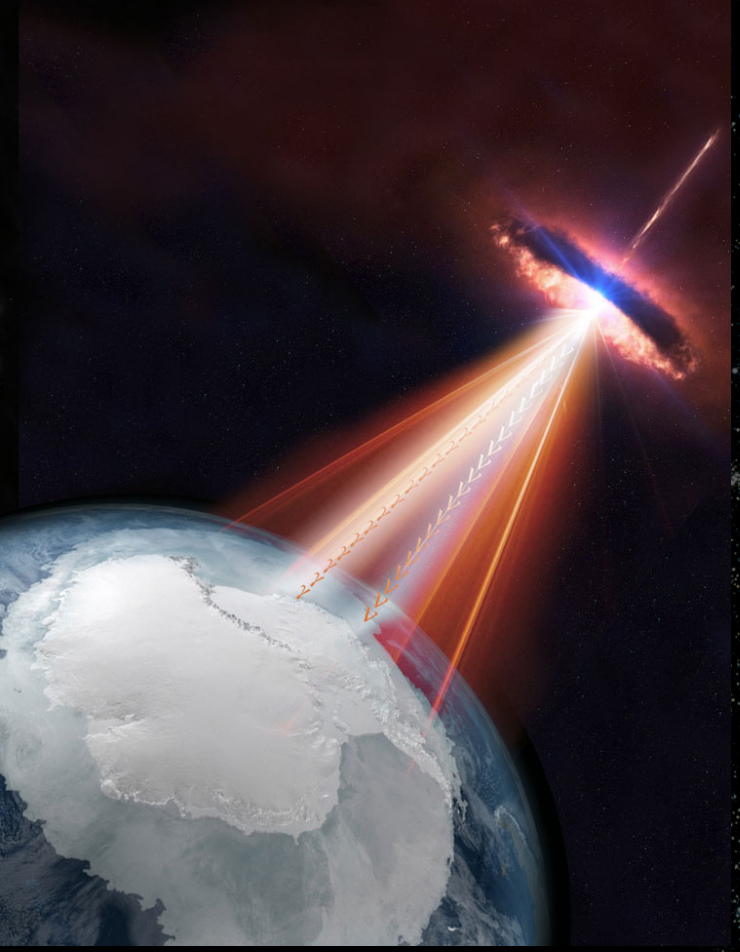
IceCube measurement

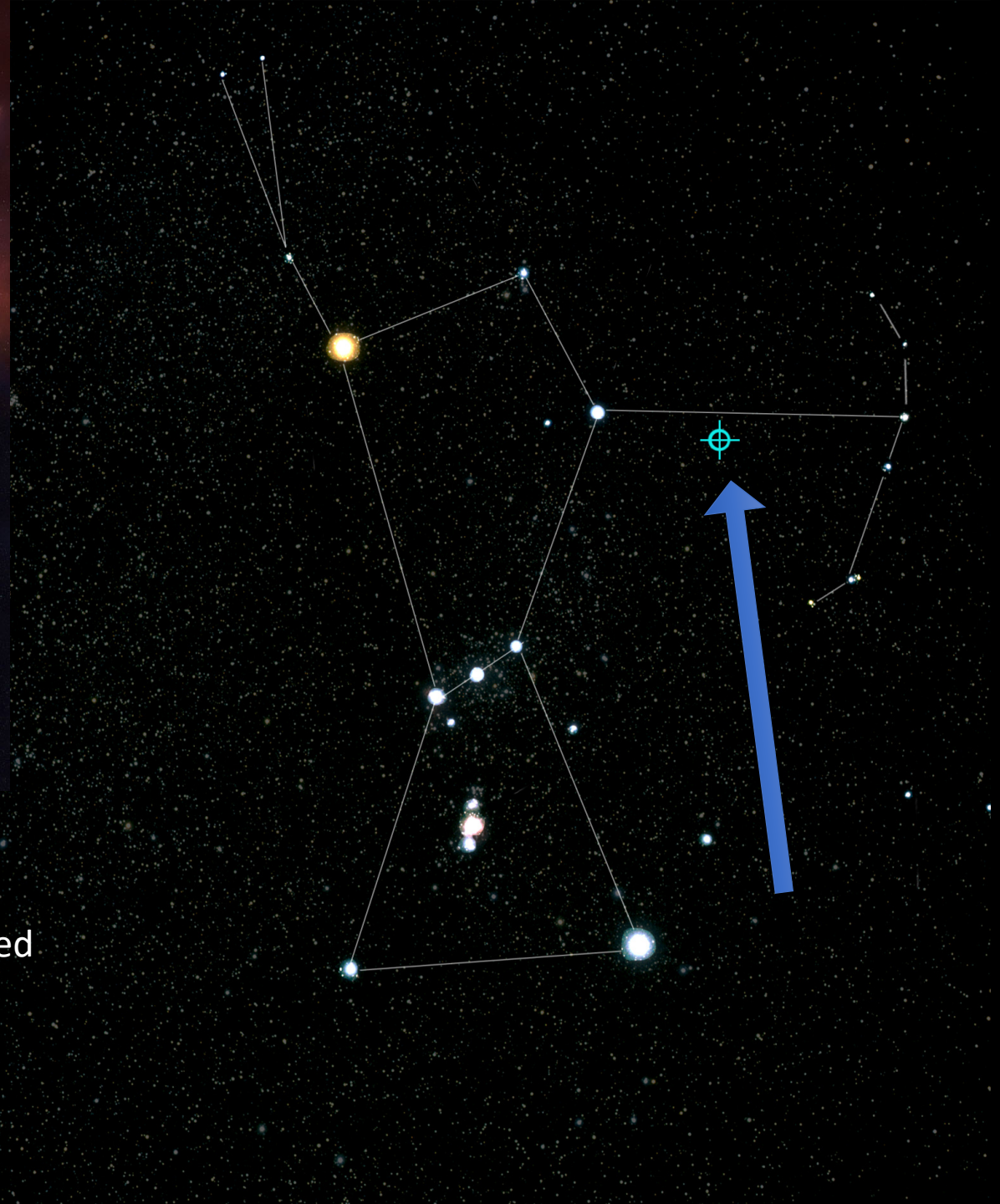


Prospects for measurements – energy dependence



Cosmic neutrino sources



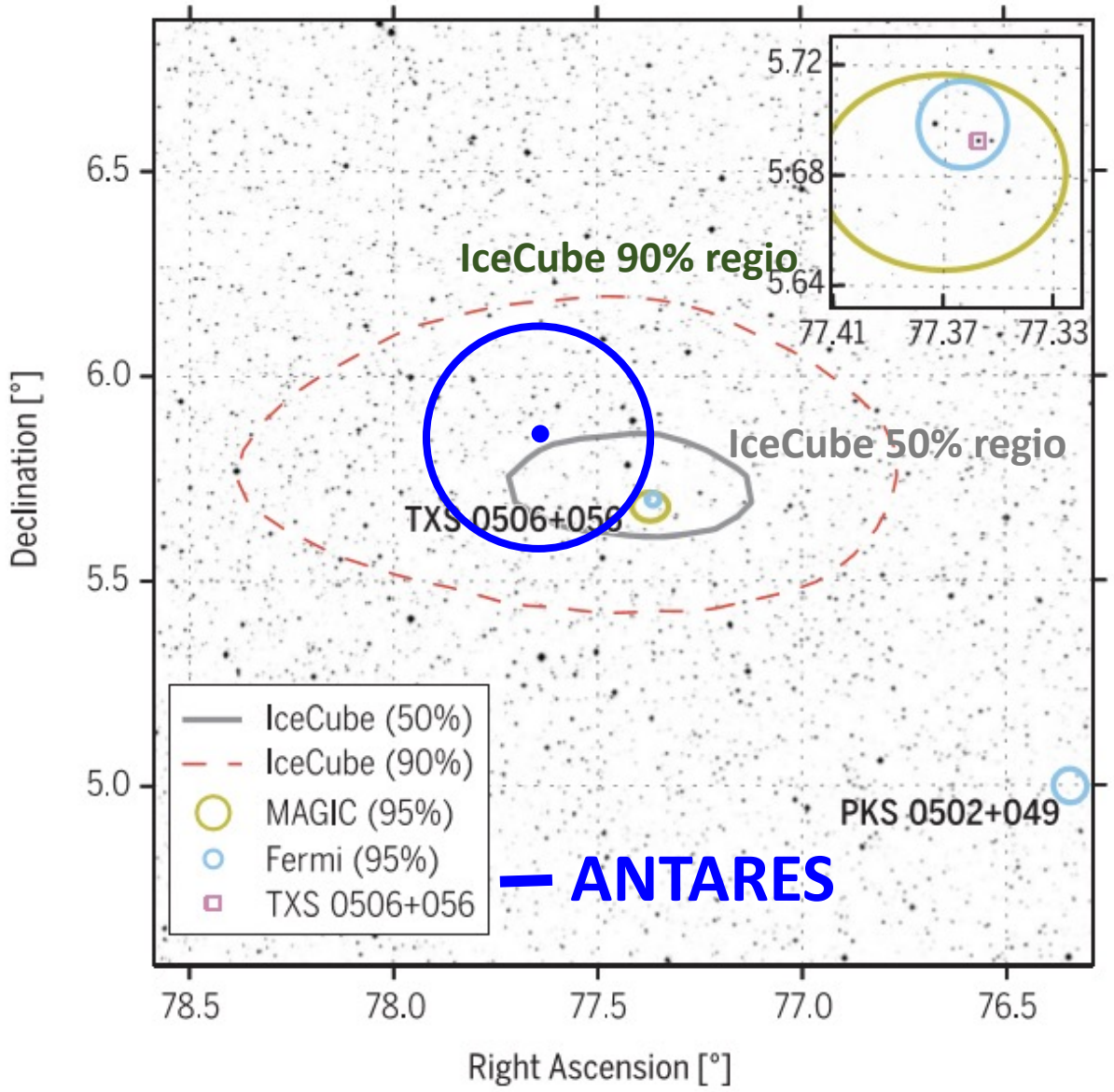


22 September 2017
Blazar TXS 0506 in flaring state
-> High energy neutrino detected

Optical sky observations around the IceCube observation

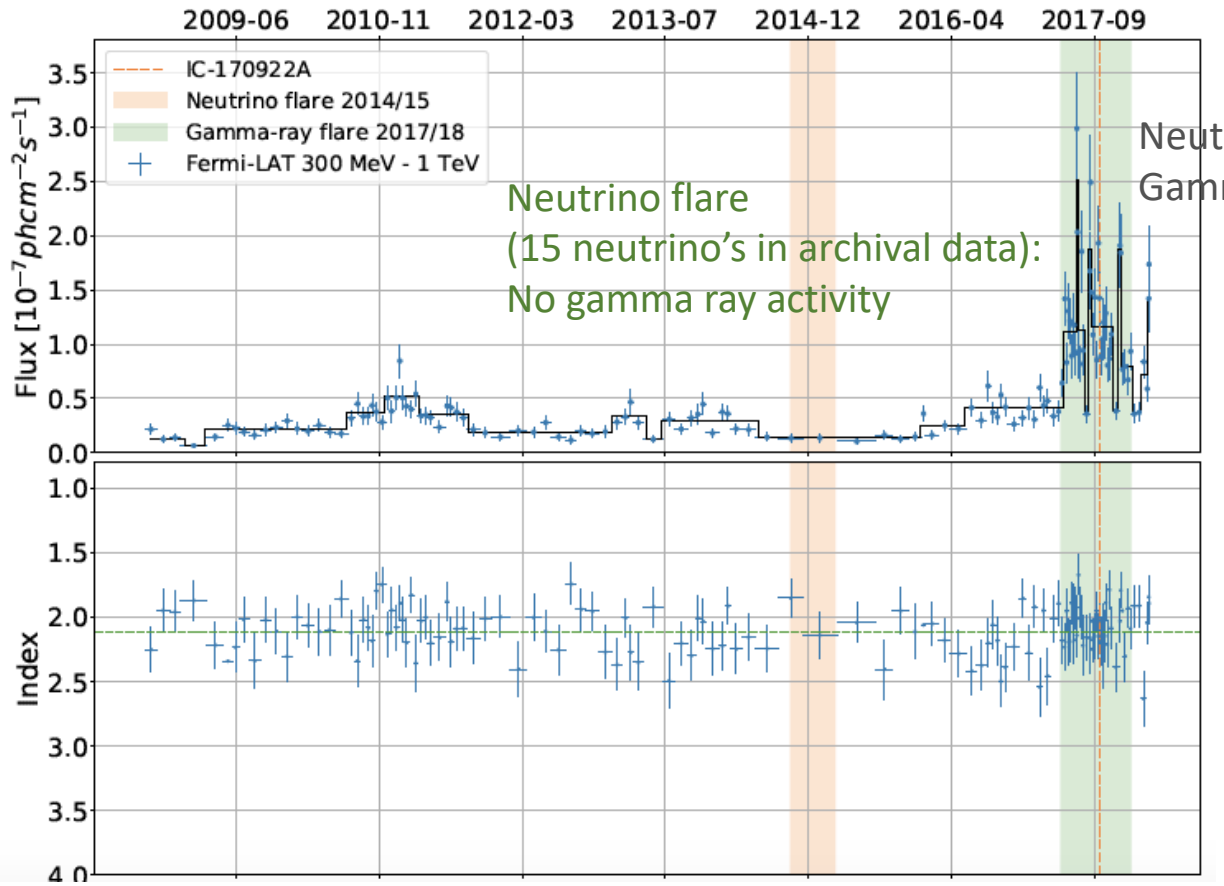
Blazar TXS 0506+056

Angular resolution crucial to identify neutrino sources



Science 13 Jul 2018: Vol. 361, Issue 6398, 1378

γ ray observations



Neutrino alert:
Gamma flare closeby

Puzzling: Neutrino coincidence with γ ray alert,
but no enhanced γ ray flaring in 2014

γ ray absorption?

3 November 2022 Announcement by IceCube,

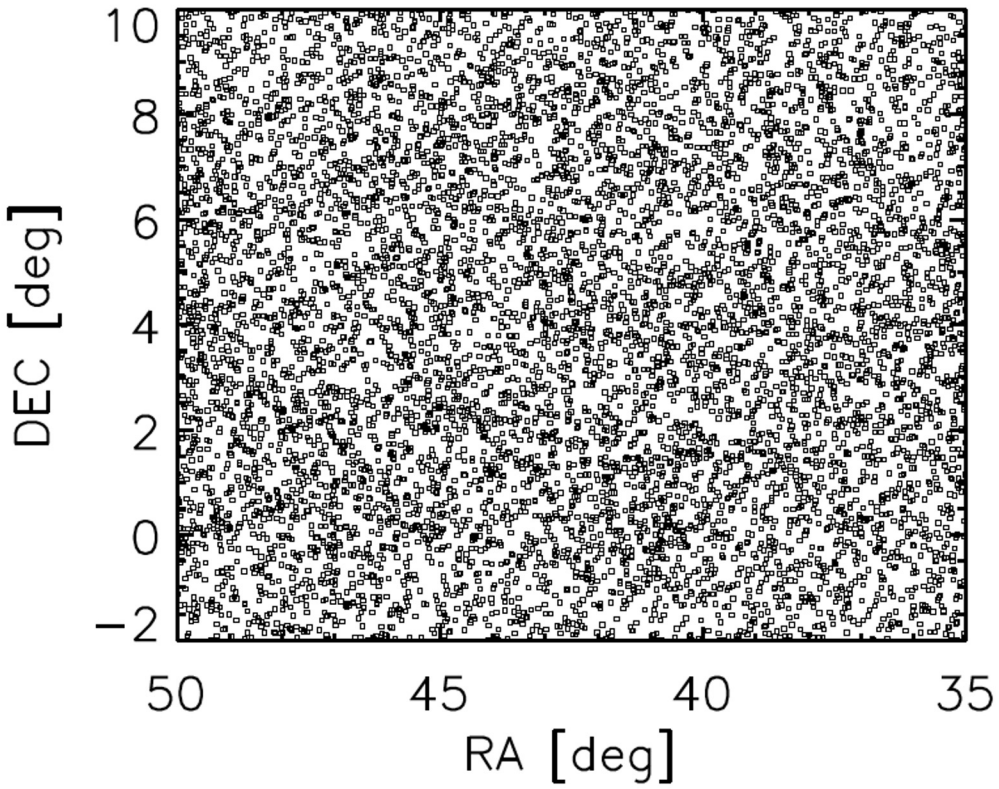
Publication in ‘Science’ journal

Evidence (>4 σ) of neutrino emission from NGC 1068 (Messier 77)

IceCube events around NGC 1068C

Events close to NGC 1068

Can you spot a source with
80 events (excess over background)?



Evidence for neutrino emission from the nearby active galaxy NGC1068, ***SCIENCE*** 2022, Vol 378, Issue 6619
Dataset. DOI: 10.21234/03fq-rh11

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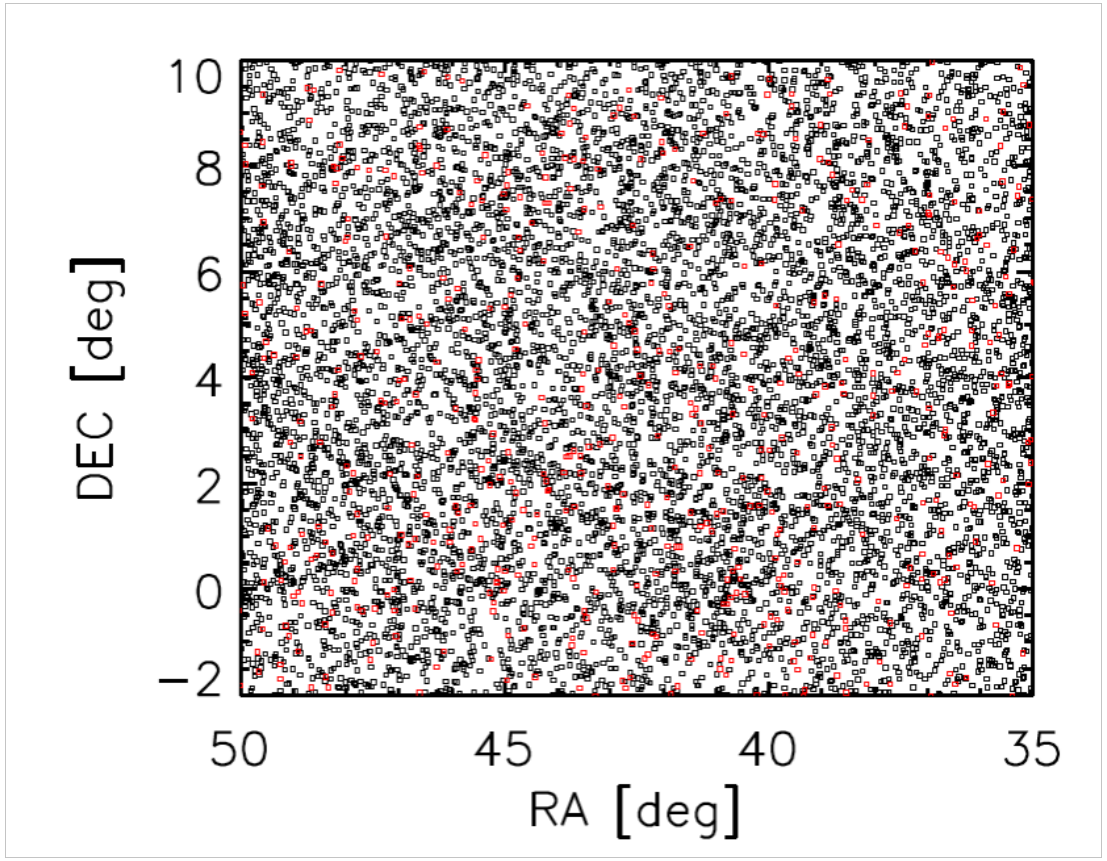

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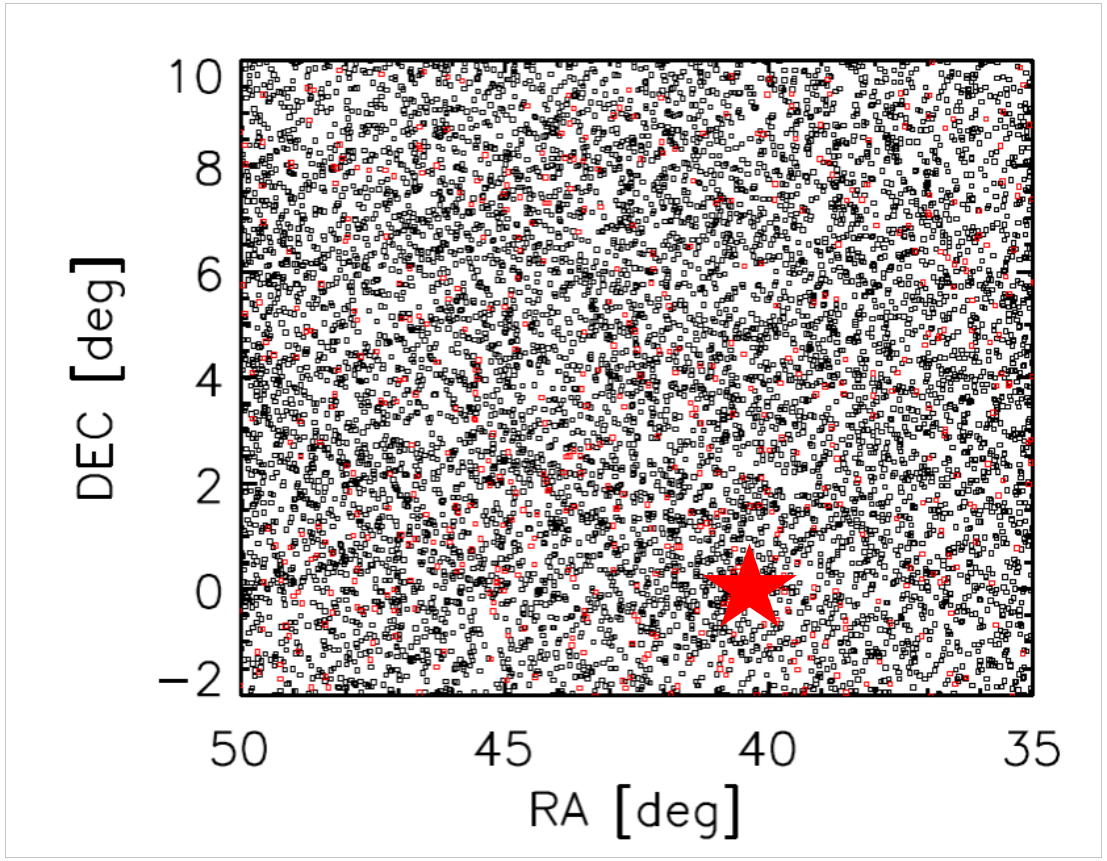

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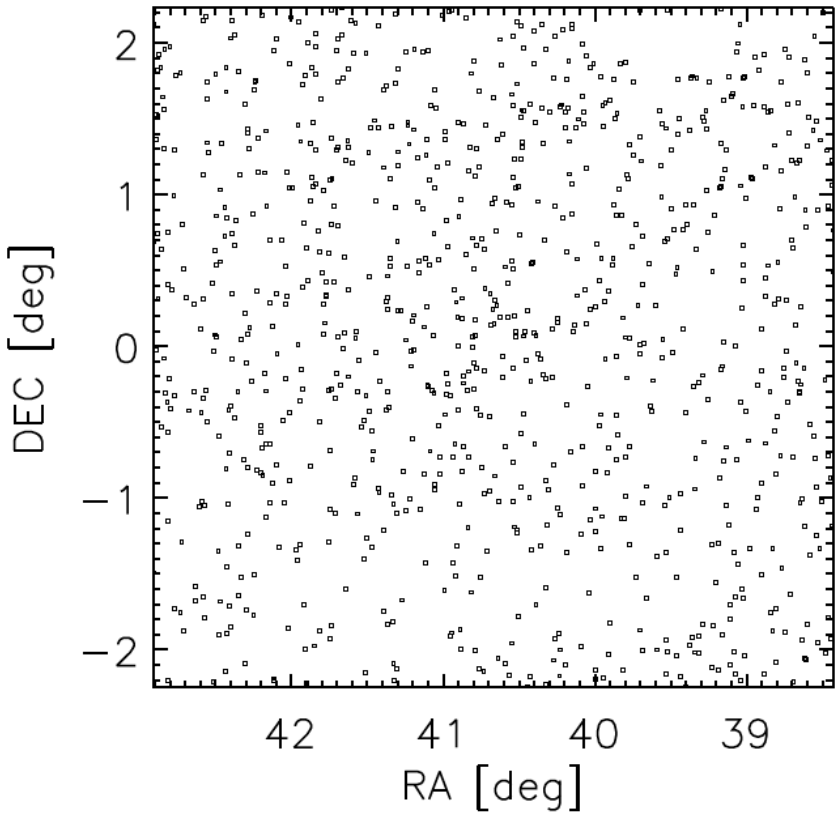

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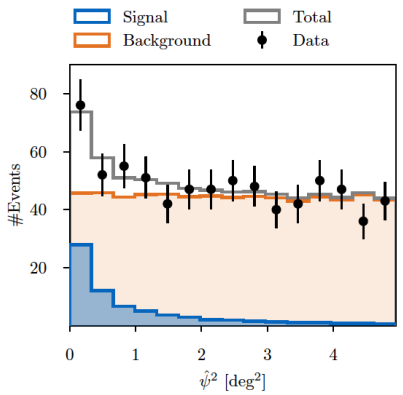
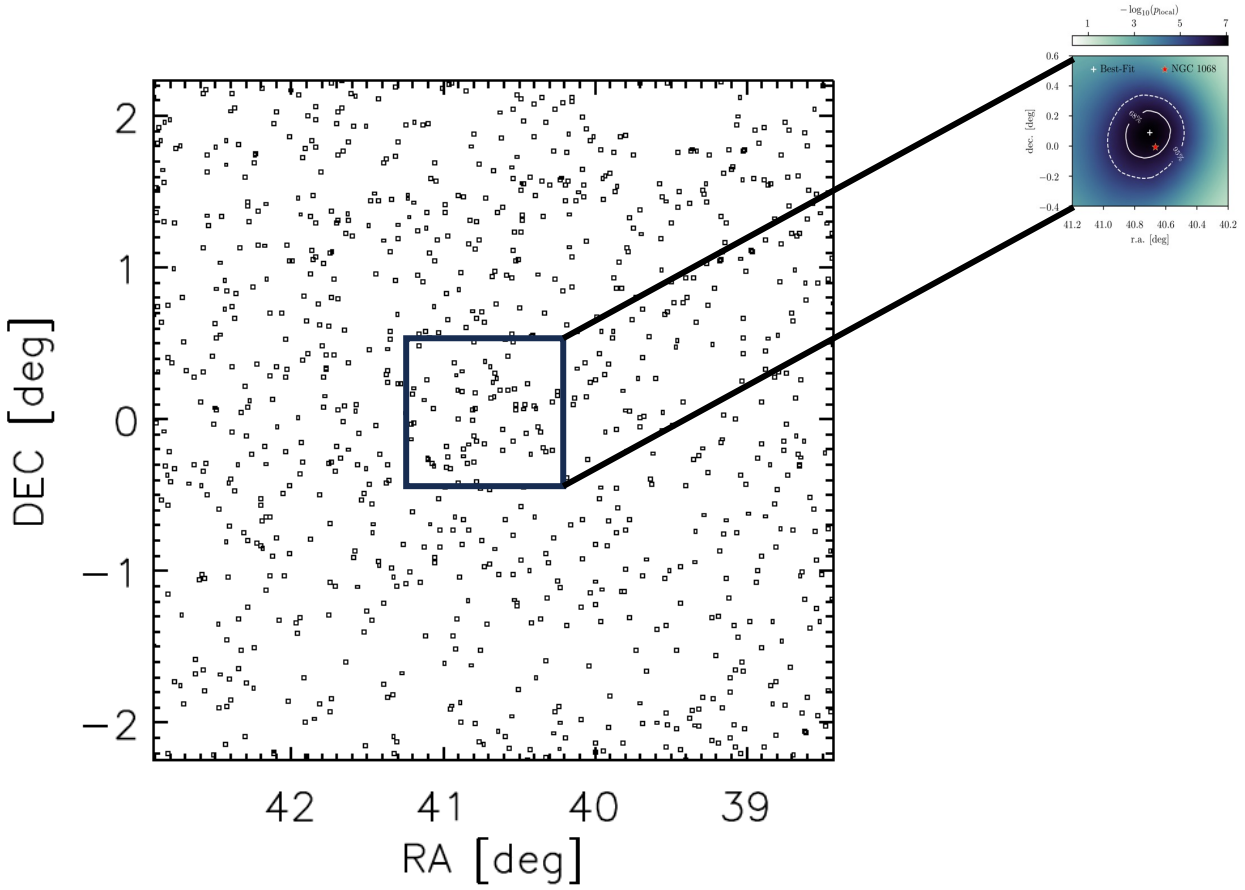




Evidence for neutrino emission from the nearby active galaxy NGC1068, ***SCIENCE*** 2022, Vol 378, Issue 6619 Dataset. DOI: [10.21234/03fq-rh11](https://doi.org/10.21234/03fq-rh11)

Search for event excess by use of likelihood evaluation:

- Maximize likelihood L at each point in the sky
- Signal and background PDFs contain spatial and energy terms

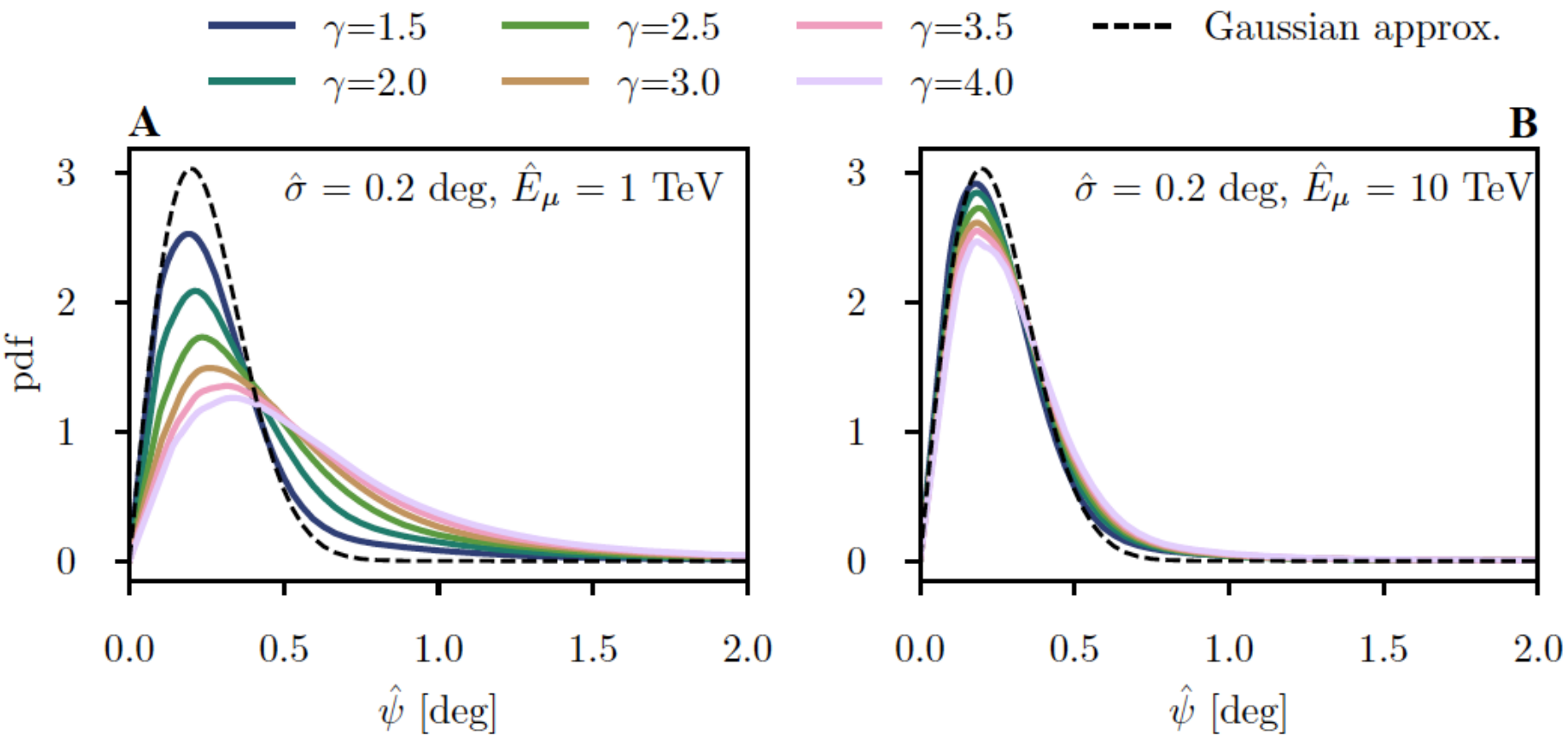
$$L(n_s, x_s, \gamma) = \prod_{i}^{events} \left(\frac{n_s}{N} S_i(|x_i - x_s|\sigma_i, E_i, \gamma) + \frac{N - n_s}{N} B_i(\delta_i, E_i)\right)$$

Spatial term for likelihood was:

$$S_i(|\vec{x}_i - \vec{x}_s|, \sigma_i) = \frac{1}{2\pi\sigma_i^2} \exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\sigma_i^2}\right)$$

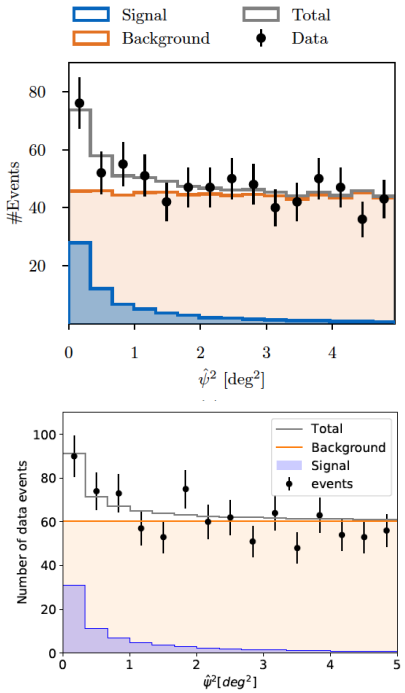
Assumes here Gaussian shape of resolution,
but can be replaced also by non-gaussian shape

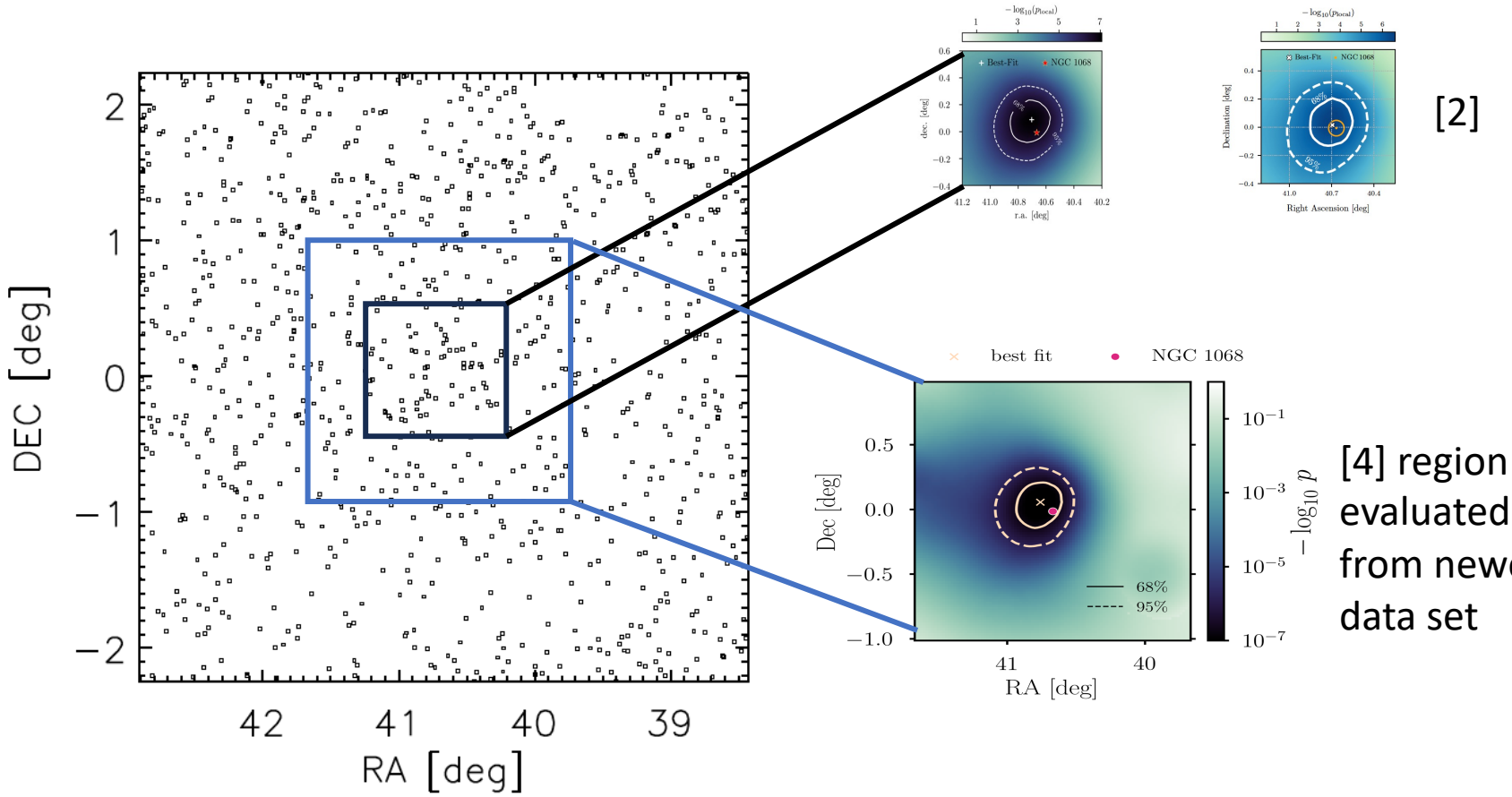
Refined resolution for the NGC 1068 analysis



IceCube events around NGC 1068

[3]





[2]

[4] region evaluated from newer data set

1) Evidence for neutrino emission from the nearby active galaxy NGC1068, ***SCIENCE*** 2022, Vol 378, Issue 6619 Dataset. DOI: 10.21234/03fq-rh11

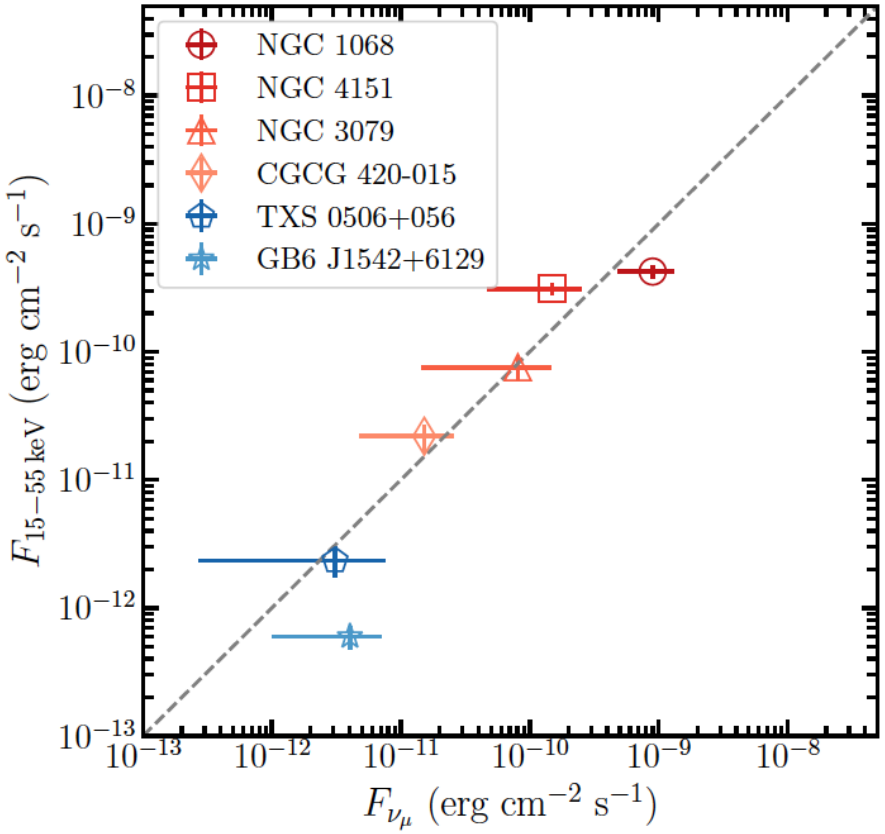
]2] IceCube Search for Neutrino Emission from X-ray Bright Seyfert Galaxies, 2025 *ApJ* **988** 141

[3] Search for neutrino emission from hard X-ray AGN with IceCube, 2025 ApJ **981** 131

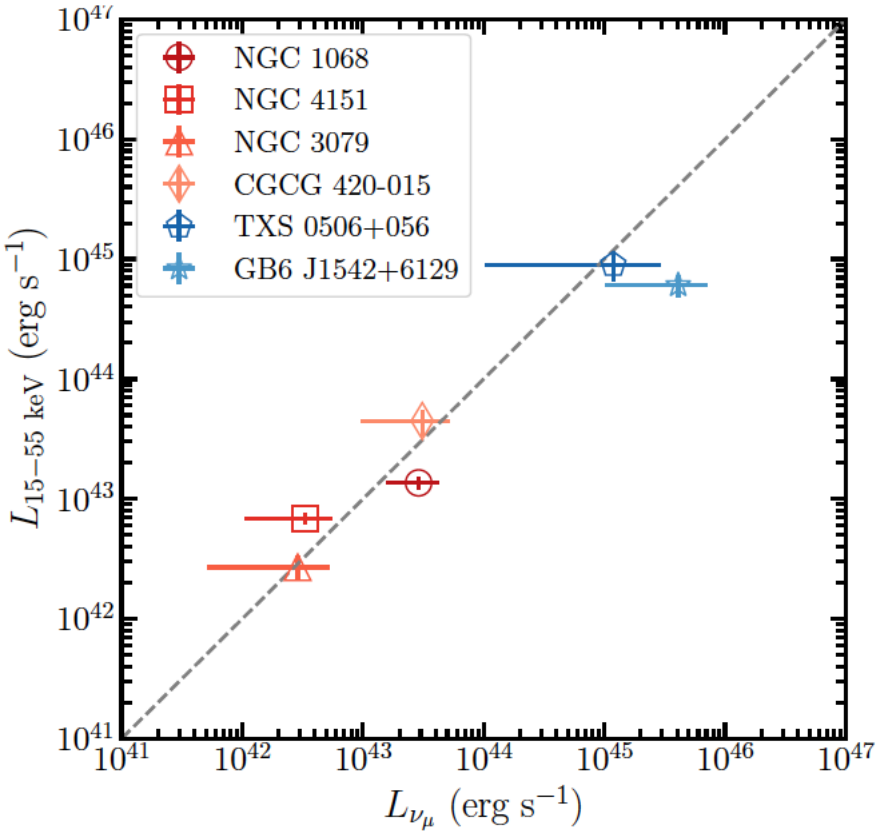
[4] Evidence for Neutrino Emission from X-ray Bright Active Galactic Nuclei with IceCube, *arXiv:2510.13403*

Correlation with X-ray flux/luminosity

Flux



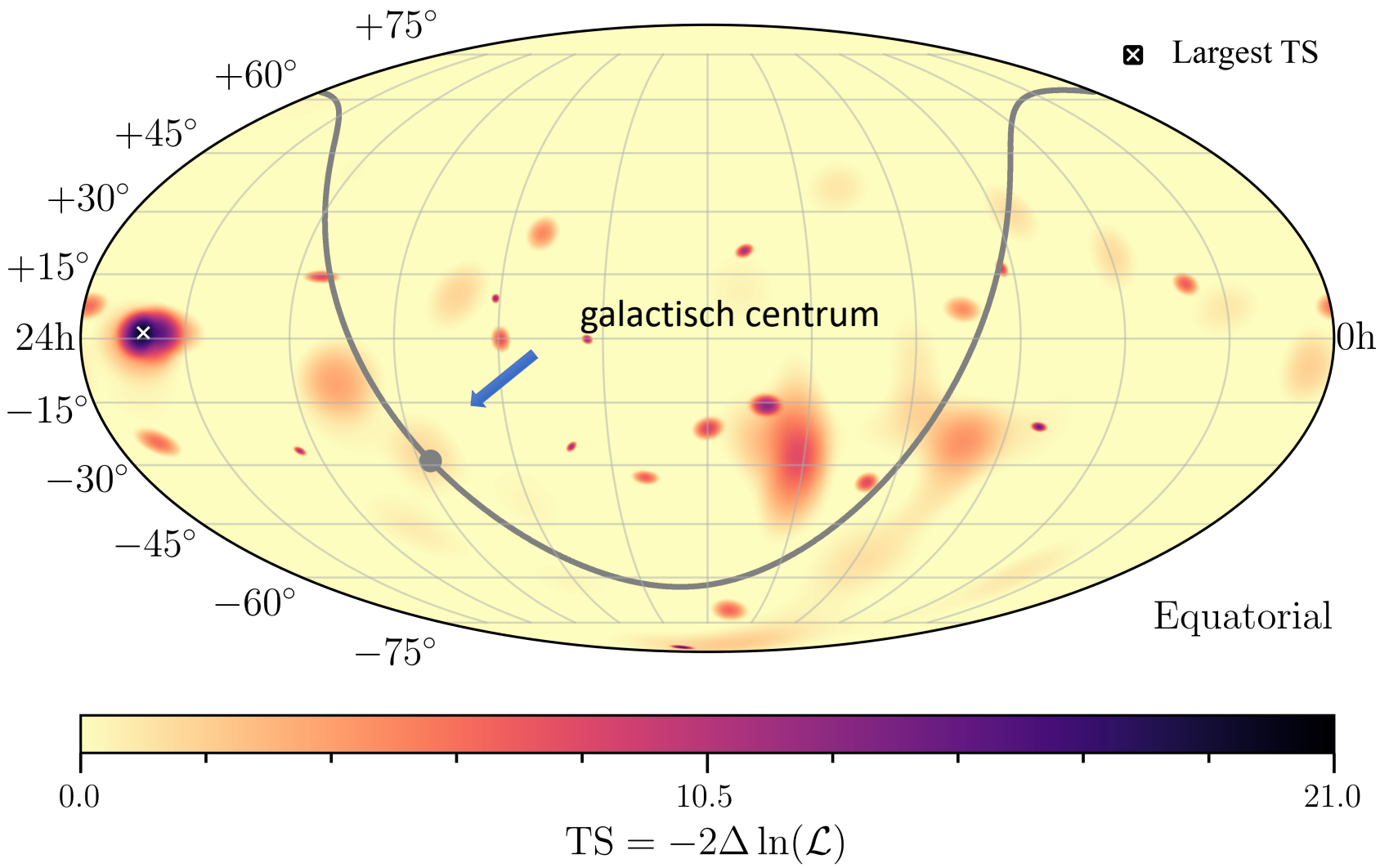
Luminosity



Galactic neutrino flux

One of the first neutrino skies from IceCube

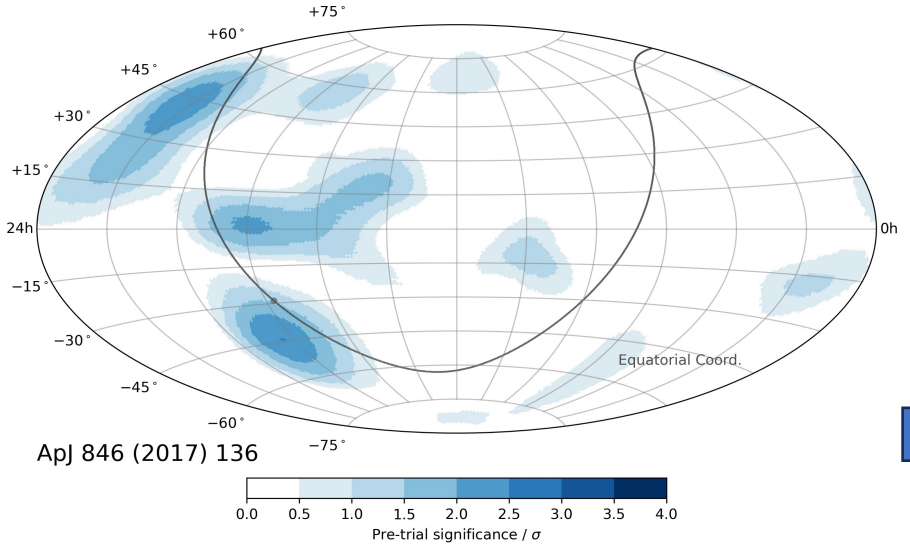
7.5 years data (102 events)



Many events high energy cascades

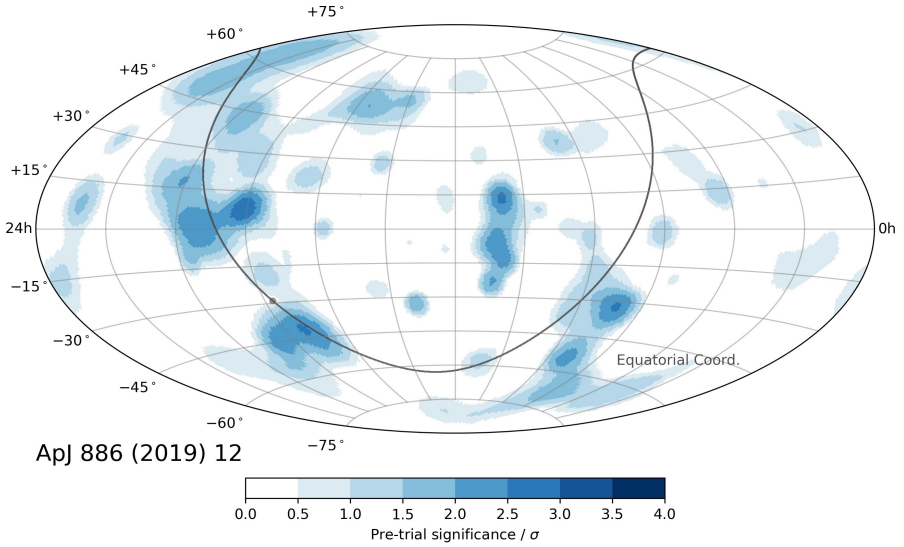
➔ large angular uncertainty

2017 paper



ApJ 846 (2017) 136

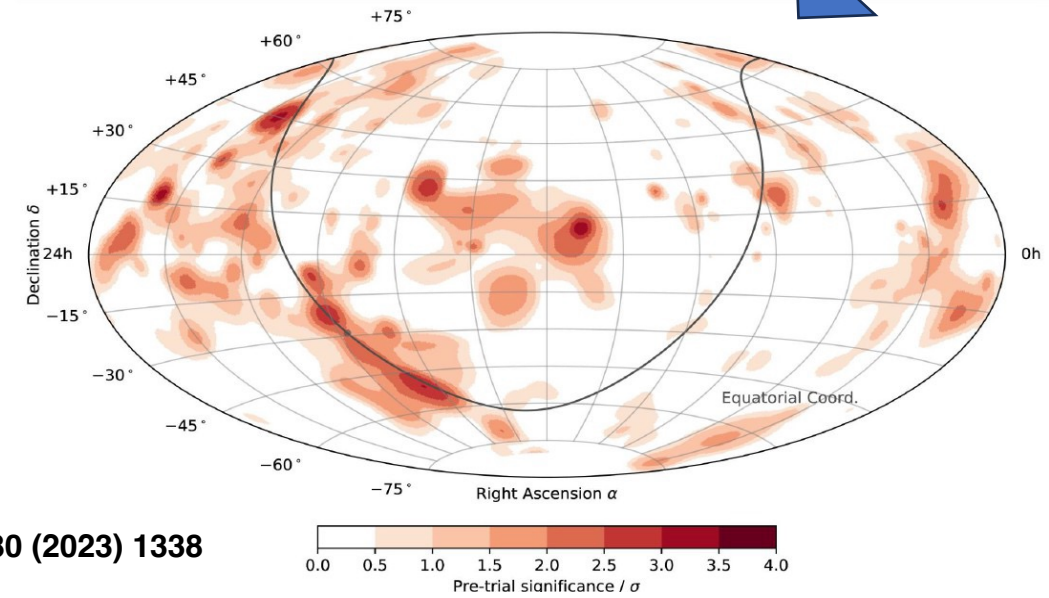
2019 paper



ApJ 886 (2019) 12

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

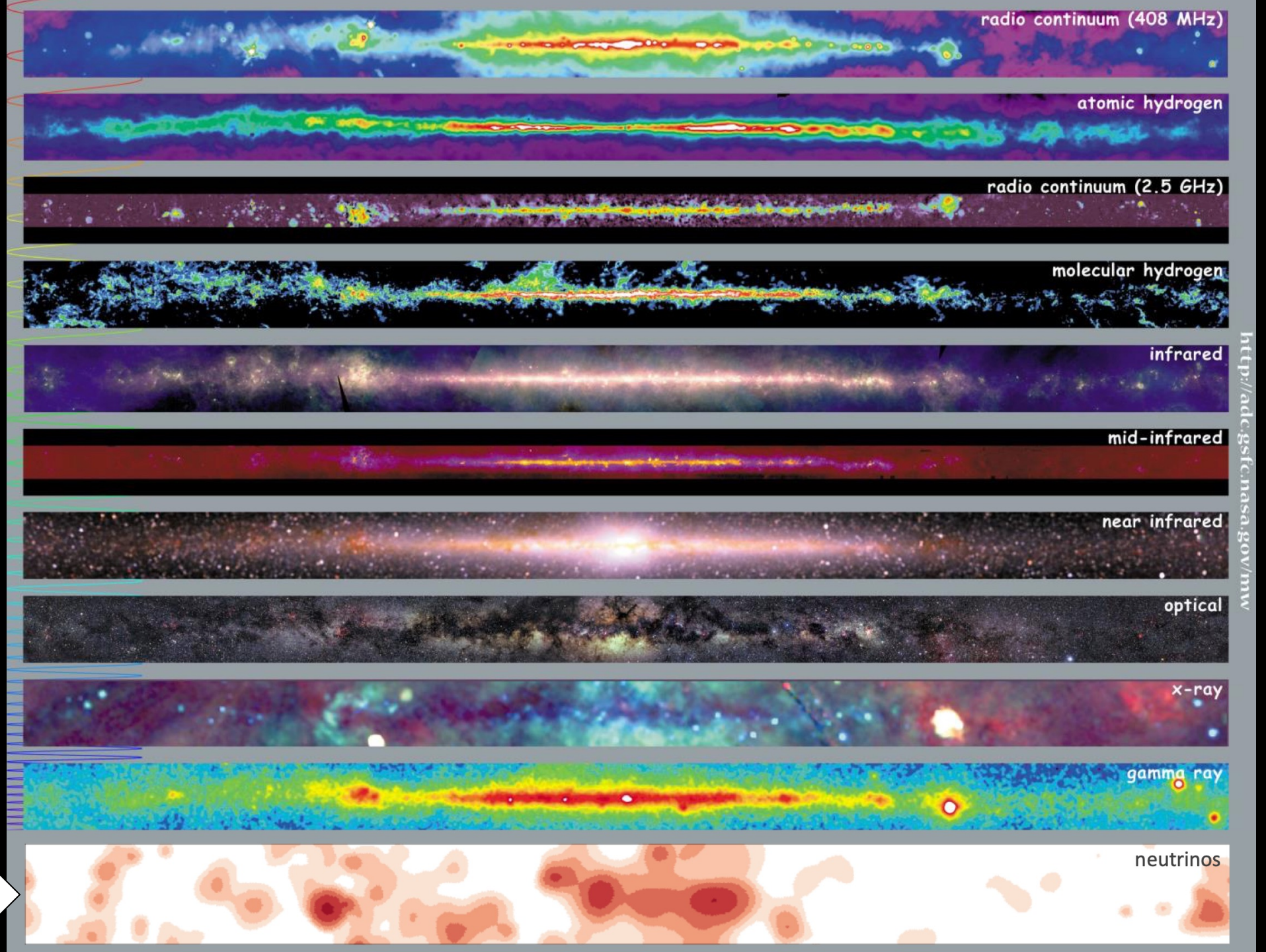
7 years of data
Galactic Plane p-value: 2.1% (2σ)



Science 380 (2023) 1338

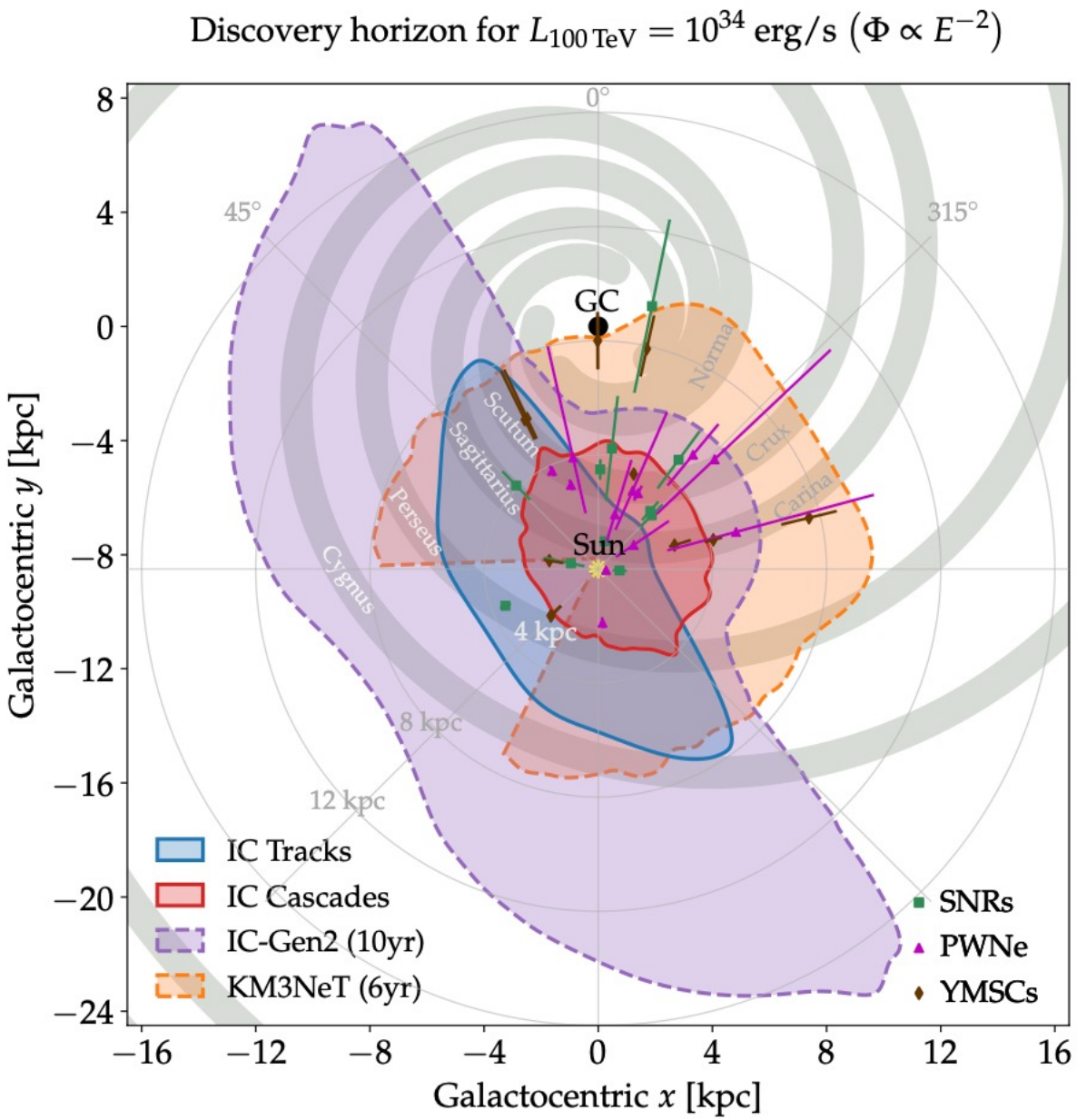
- Deep learning improved resolution by 2, sensitivity by 3
- **13 years of data Galactic Plane: 5.7σ post trial (Lepton-Photon 2025, Madison)**

Halzen, Neutel 2025



Milky Way viewed in neutrinos

Halzen, Neutel 2025

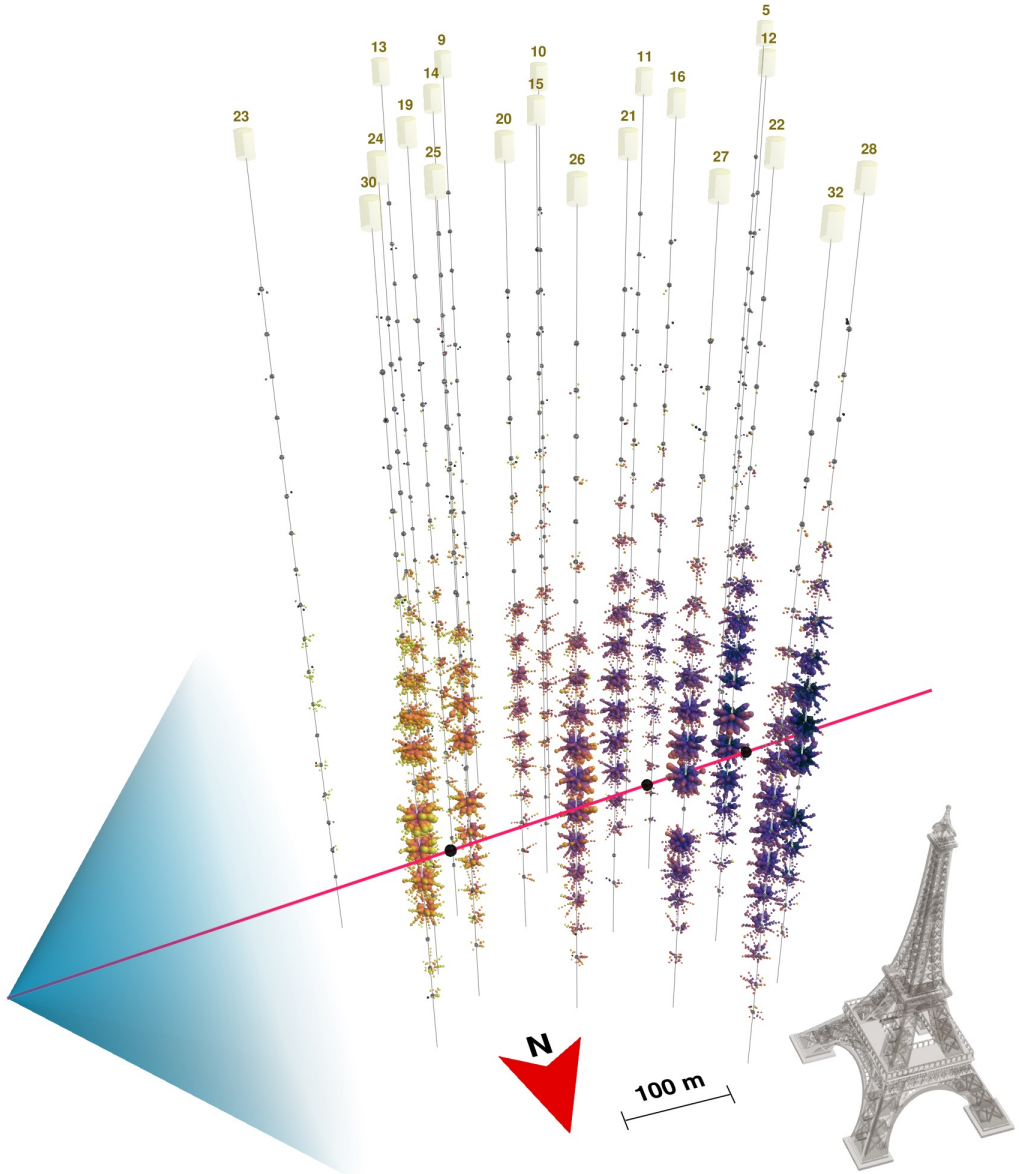


- Complementary galactic regions to be probed by future detectors

The Unexpected

Nikhef

Universiteit Leiden


23
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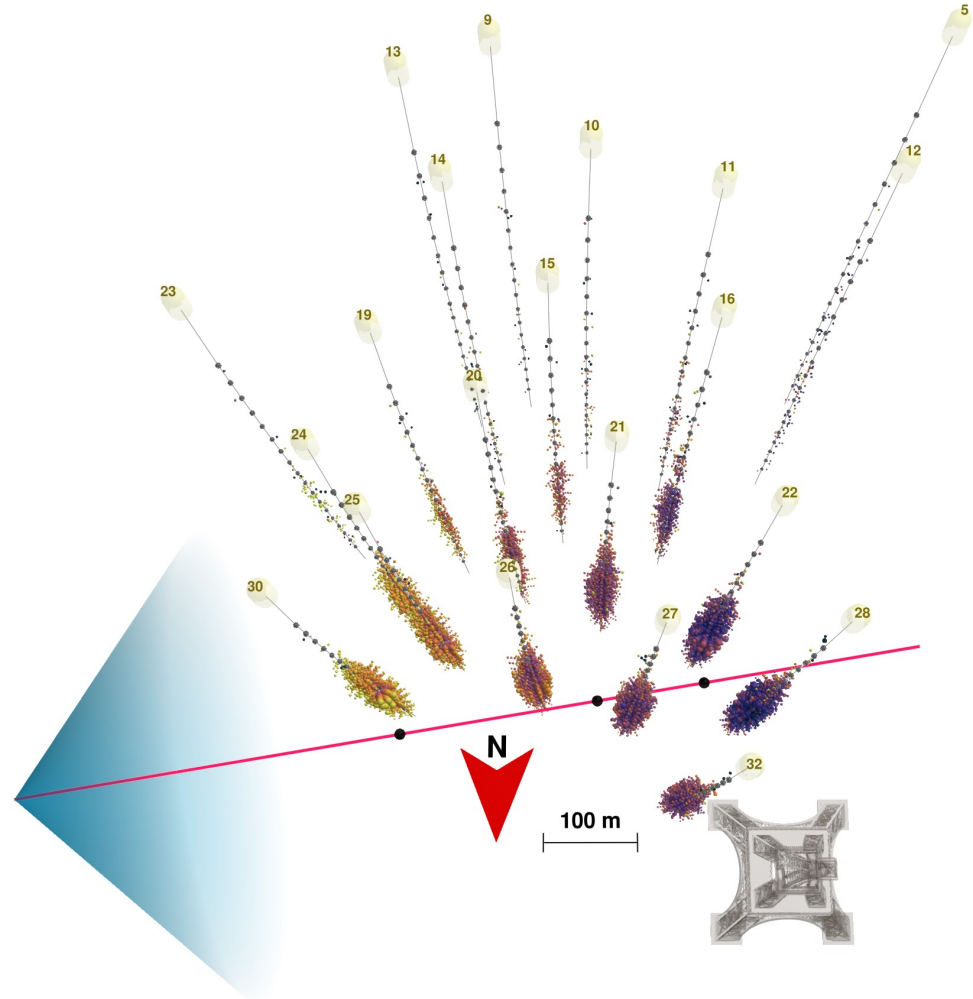
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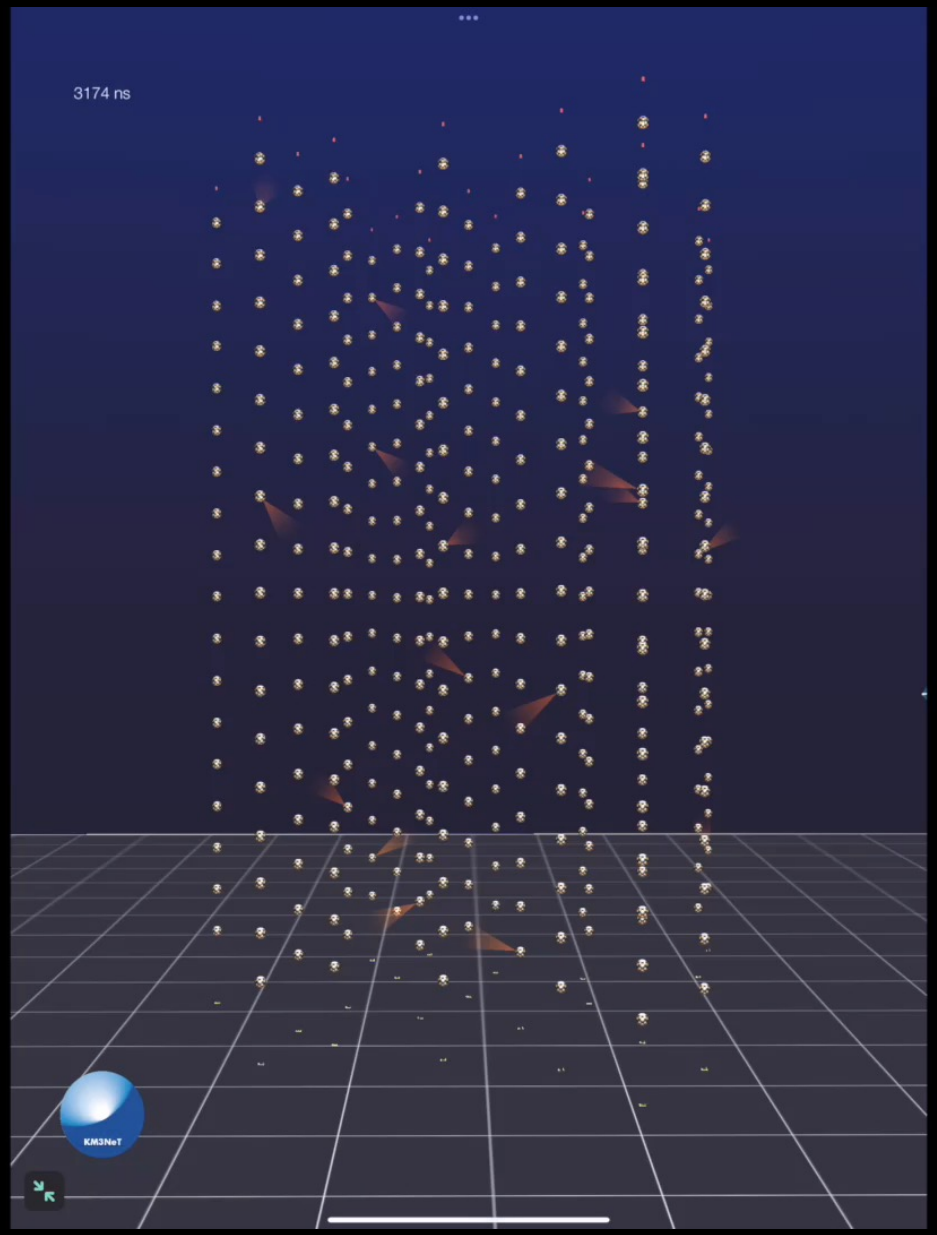
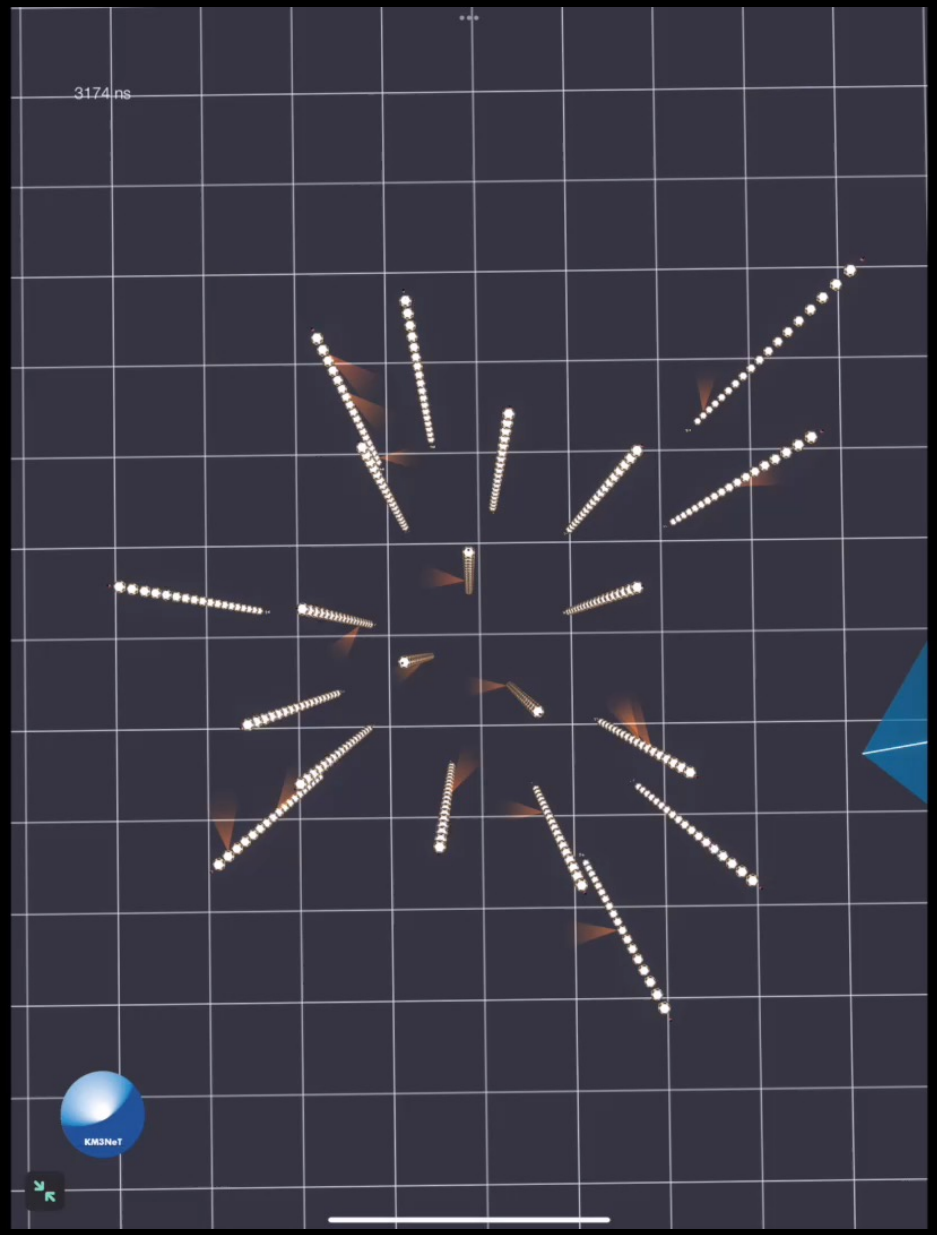
100 m

Unique event

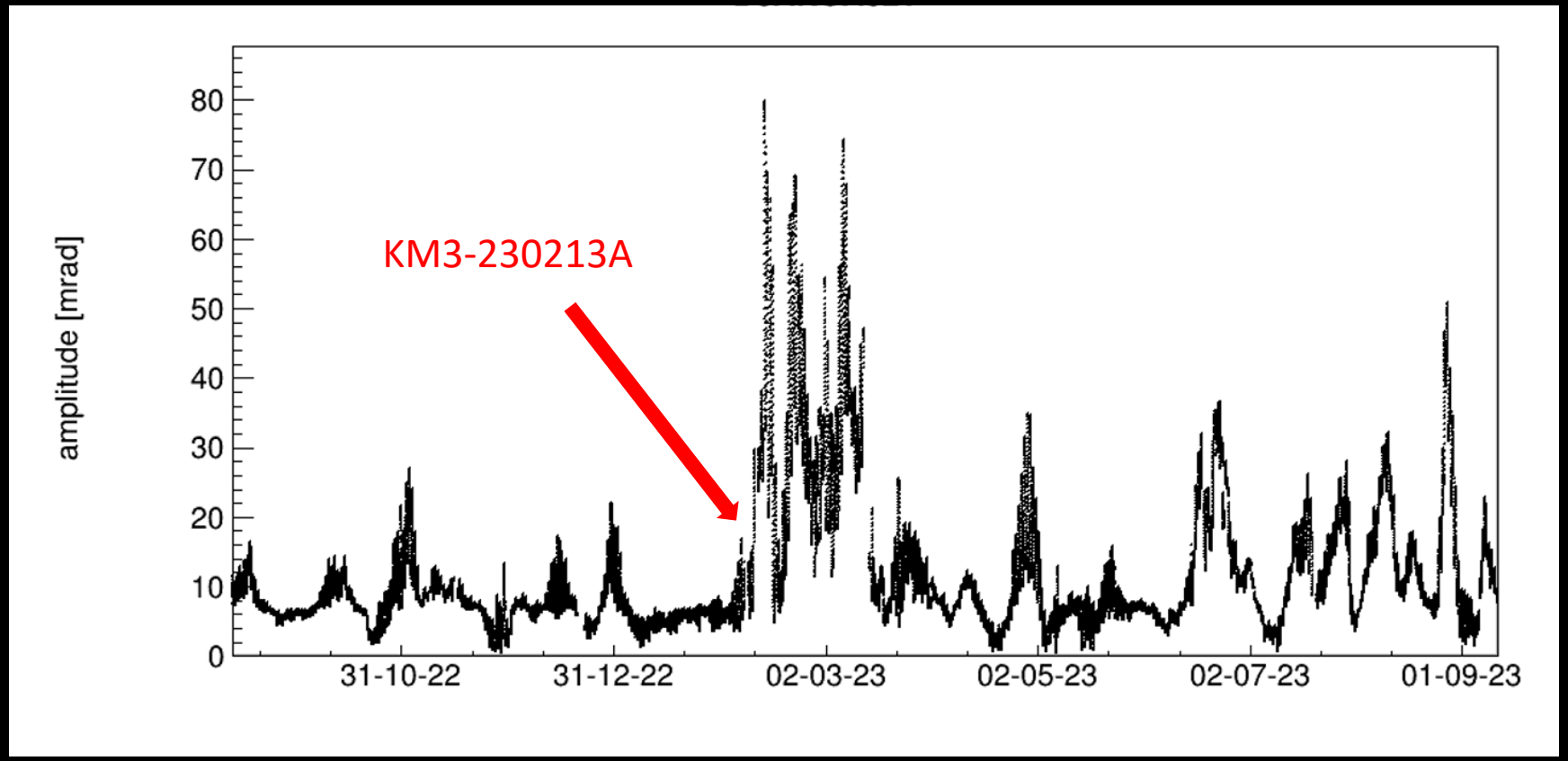




A moving detector

Tilt Compared to tilt of tower of Pisa?

Tower of Pisa:
~4 degrees



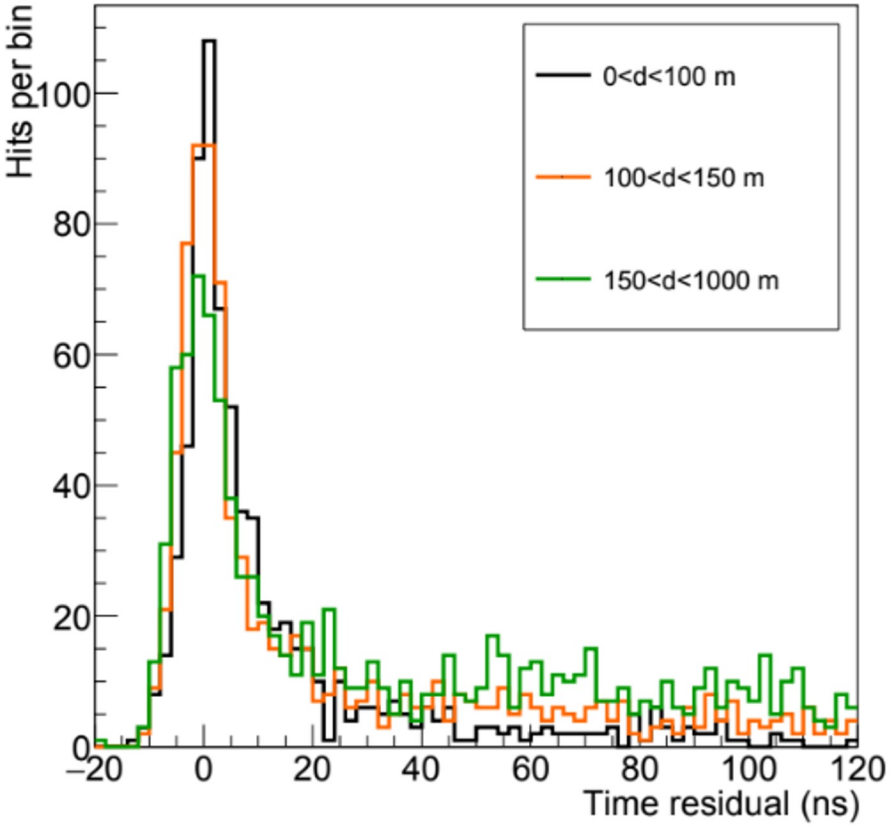
4.5deg

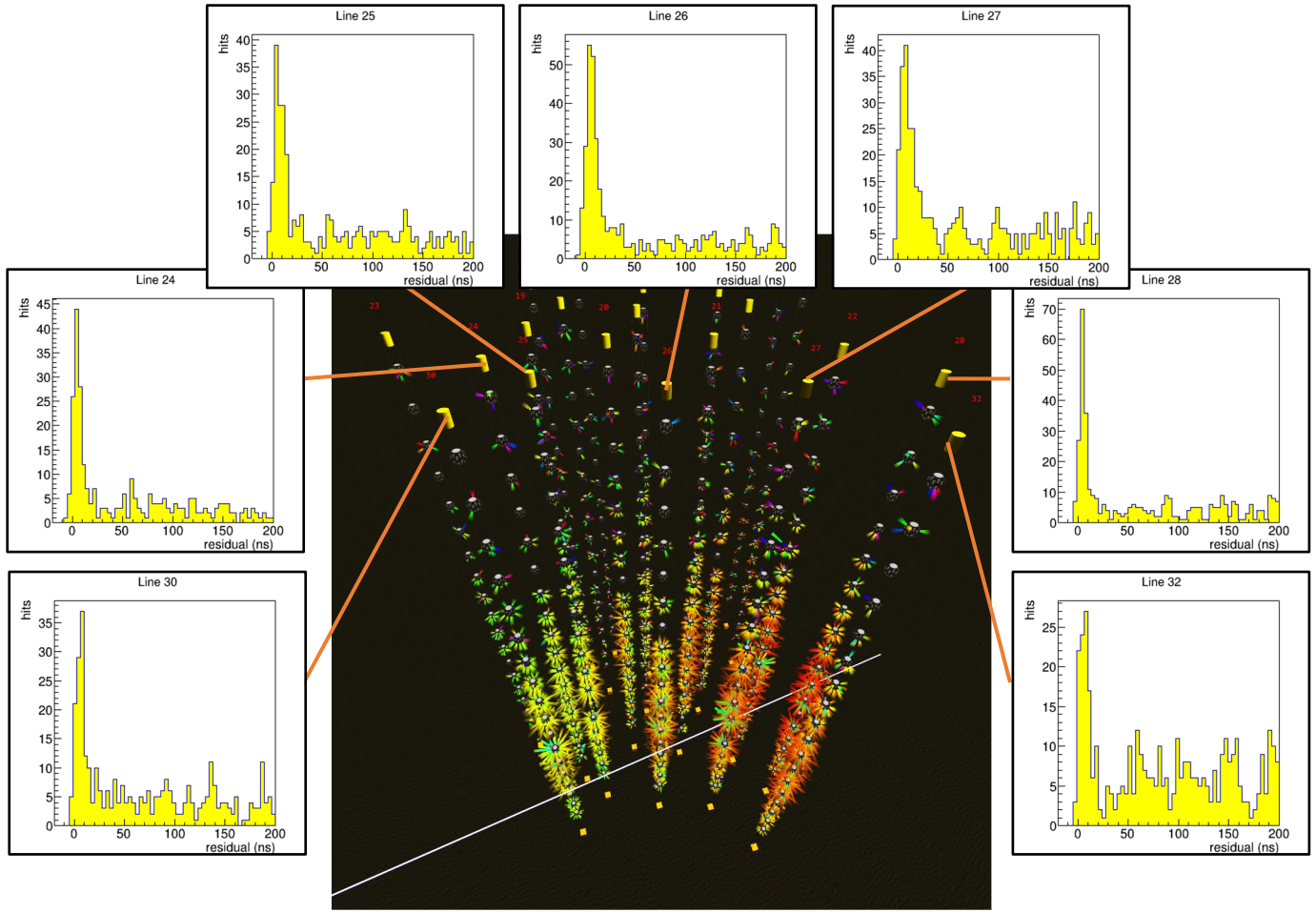
1 year of data

- Detector positions monitored every 10 minutes with acoustic signals
- Position accuracy: ~20cm

A very well reconstructed muon

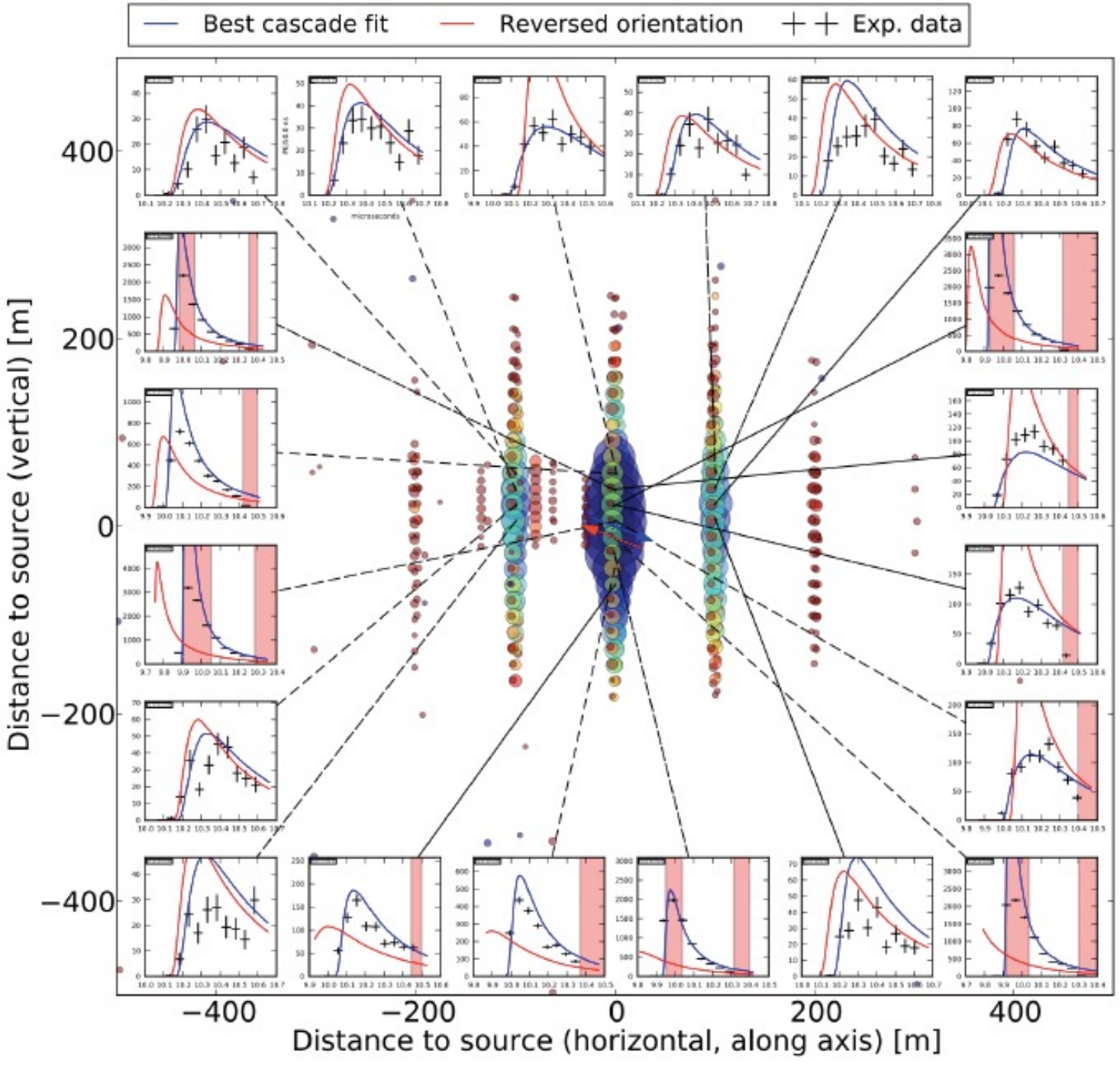
Intrinsic reconstruction uncertainty: ~0.1deg





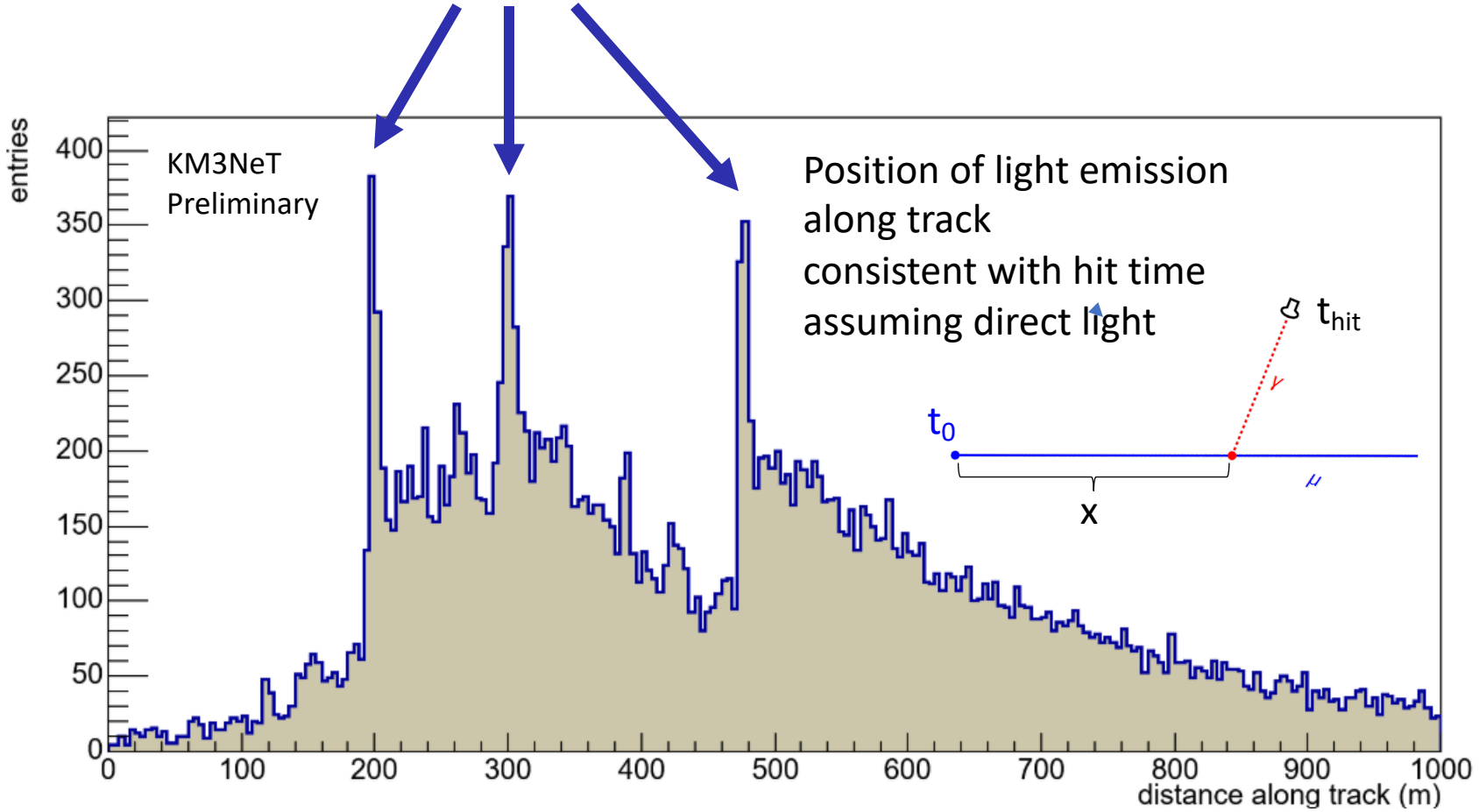
IceCube
High energy cascade ‘Bert’

- Likelihood fit on the waveforms
- Shaded areas disregarded (saturation/ systematics)
- High energy events direction resolution 7-25 degrees



Unique Event

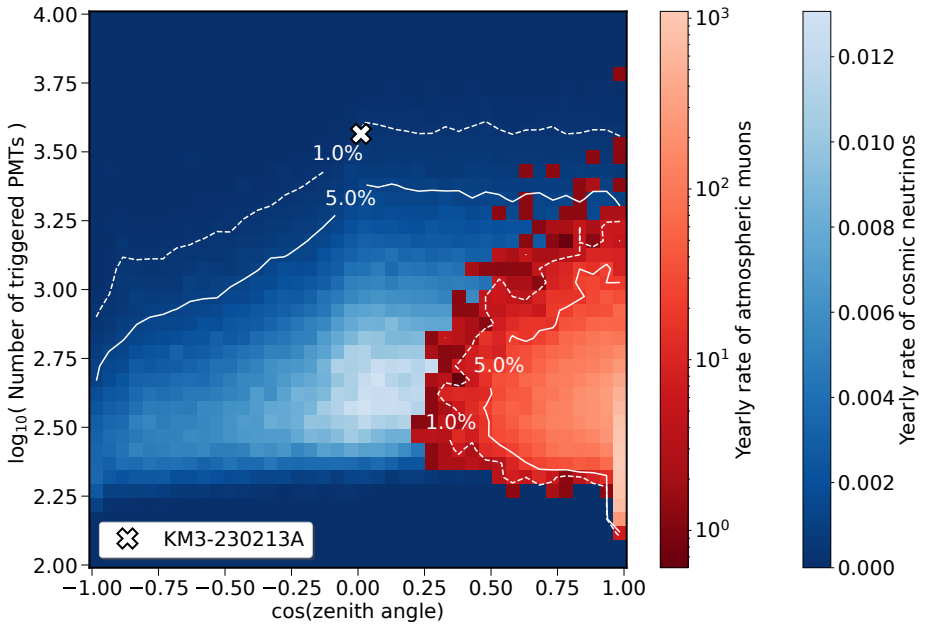
- Light profile consistent with at least 3 large energy depositions along the muon track
- Characteristic of stochastic losses from very high energy muons



Unique Event

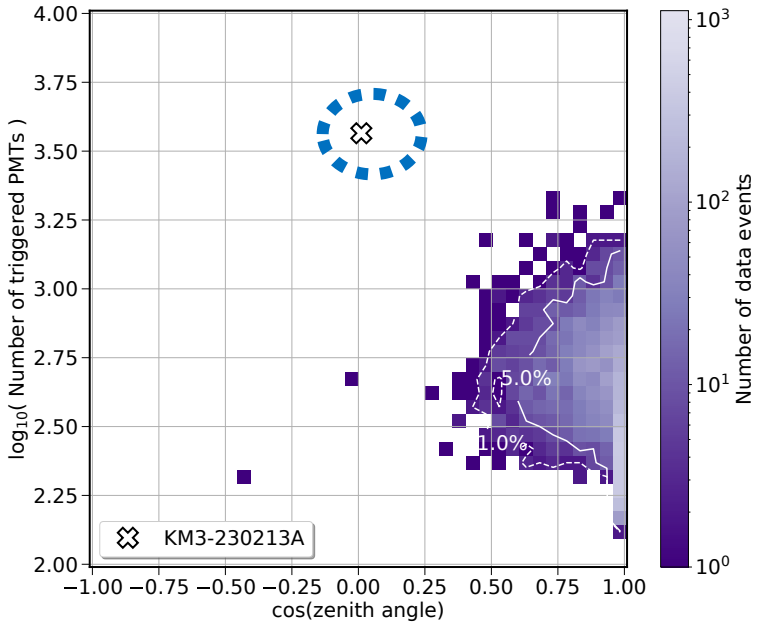
Aantal PMTs

Simulation



direction – cos θ

Data

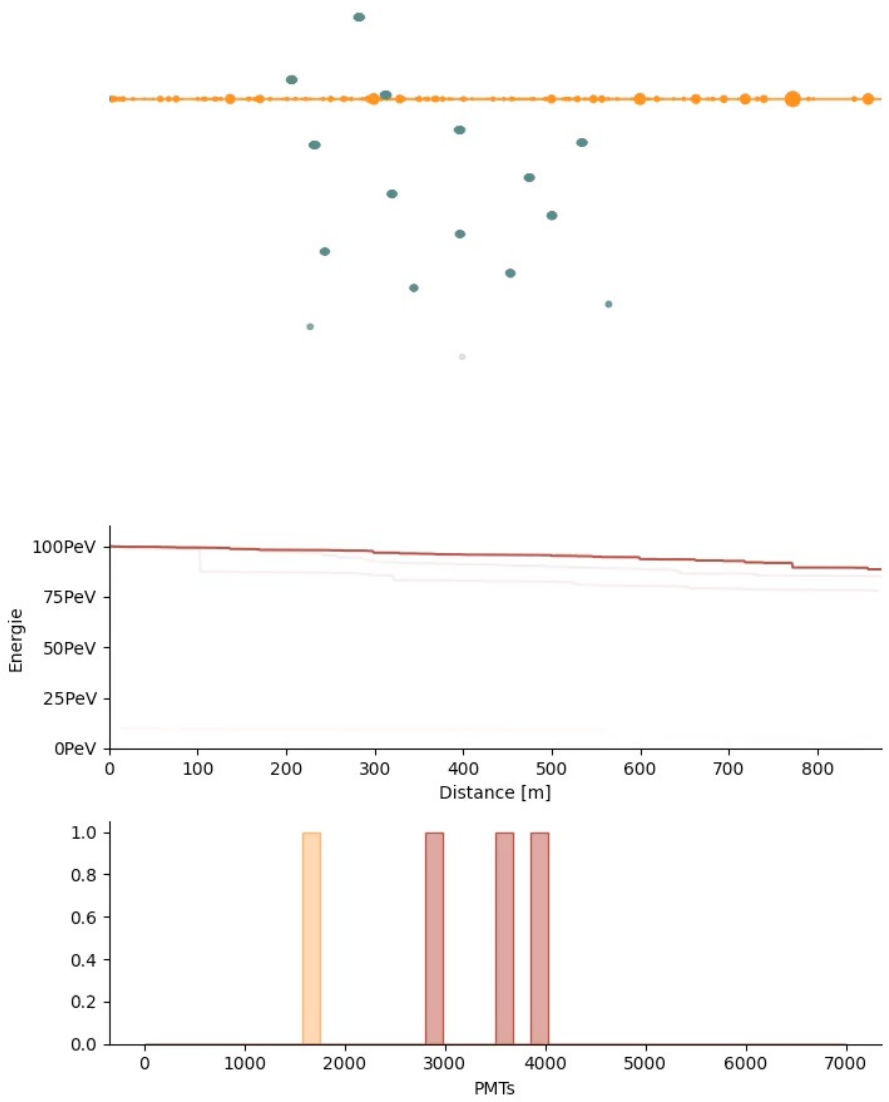


direction – cos θ

Red: atmospheric muons

Blue: cosmic neutrinos

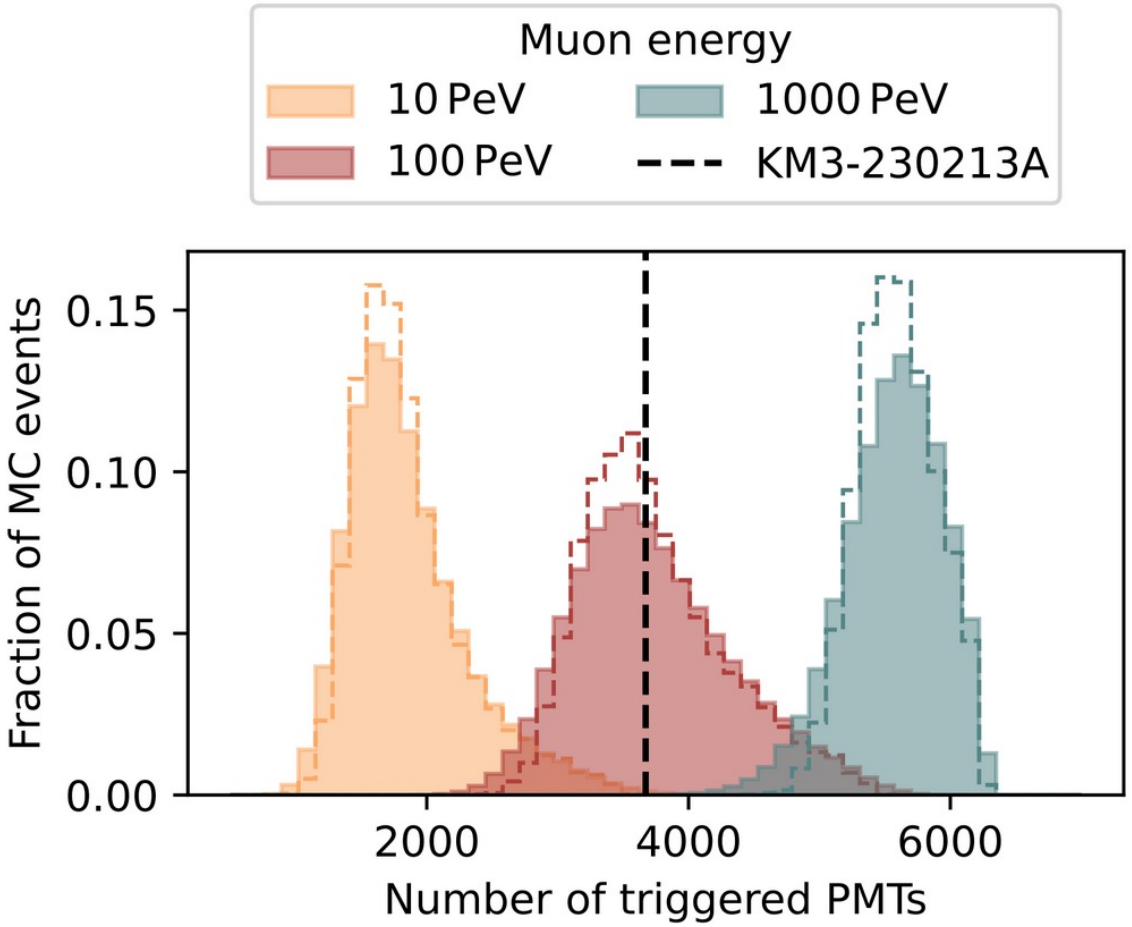
Energy estimate



- Energy loss simulated for 10 PeV and 100 PeV muons with the very same location
- 3672 PMTs (35%) were triggered in the detector
- Muons simulated at 10 PeV almost never generate this much light

Simulations *Valentin Pestel (Caen)*

Energy estimate



- Estimate of the muon energy:

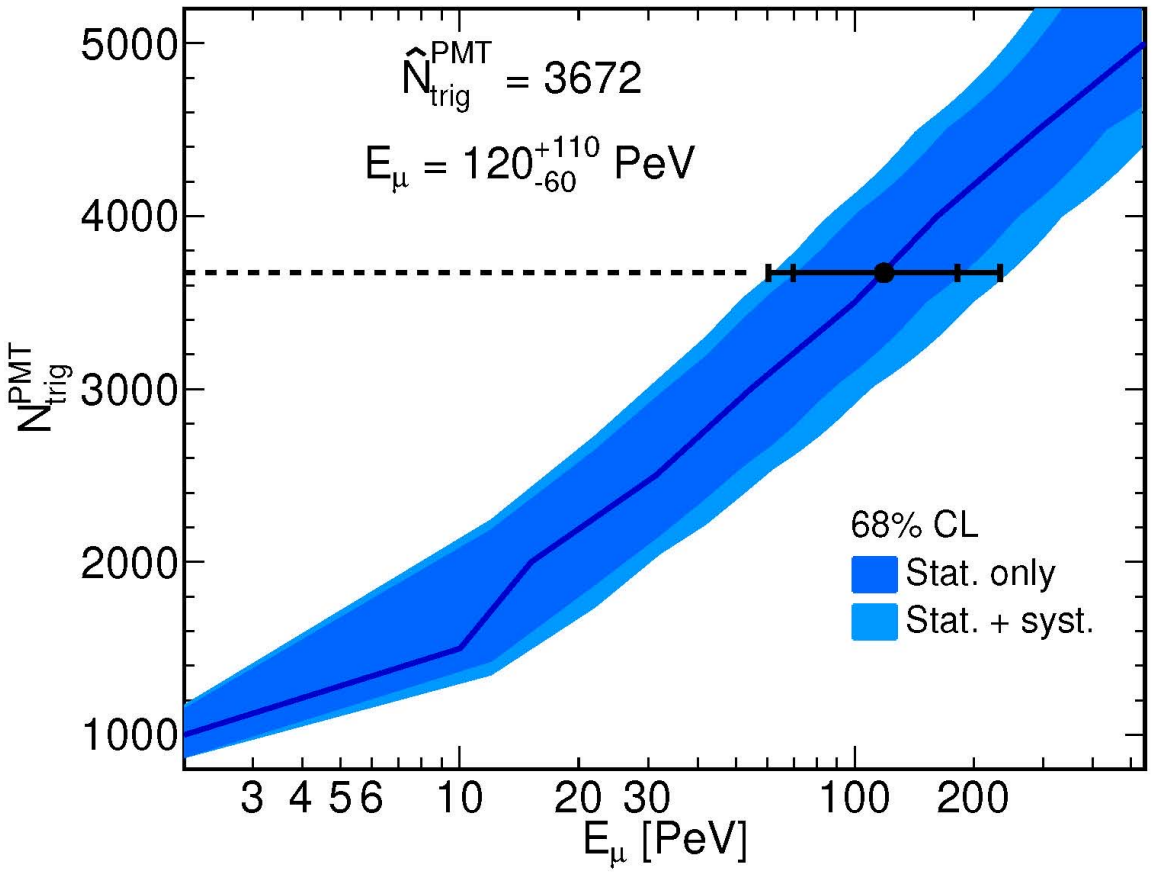
$$E_\mu = 120^{+110}_{-60}\ \text{PeV}$$

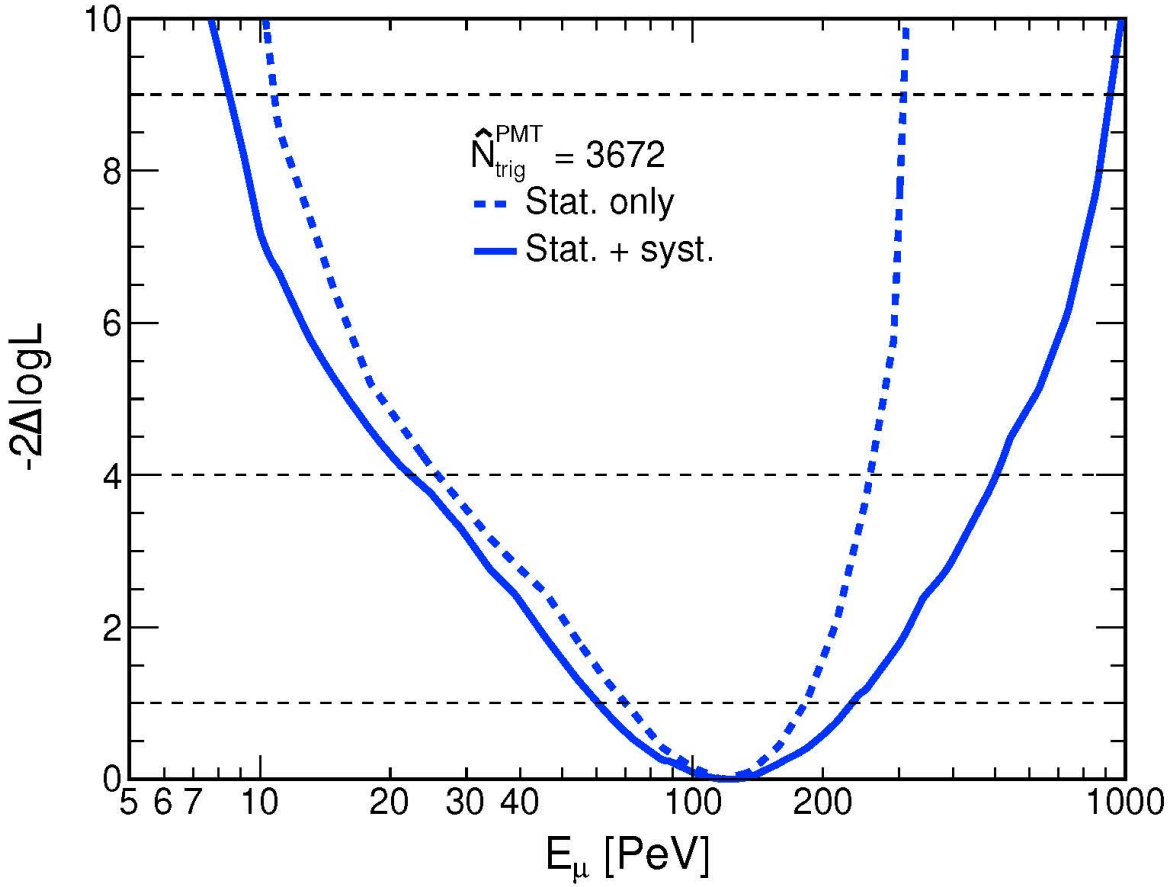
- Estimate of neutrino energy:

$$E_\nu = 220^{+570}_{-100}\ \text{PeV}$$

(assumption: E^{-2} spectrum)

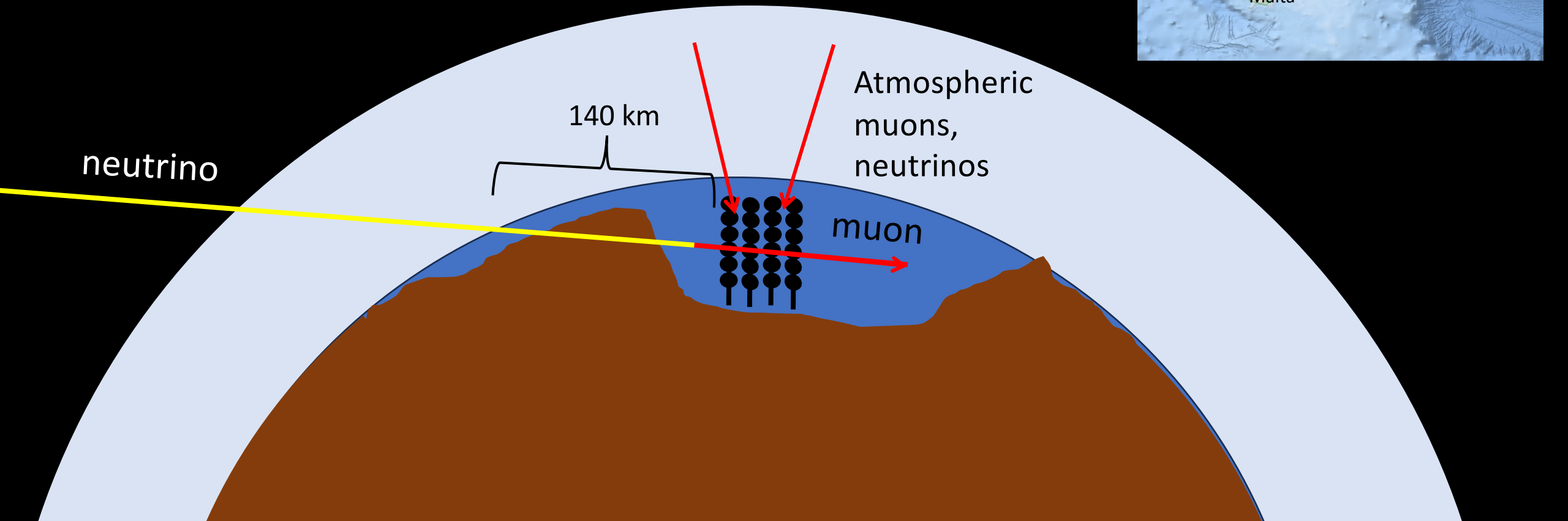
Energy estimate

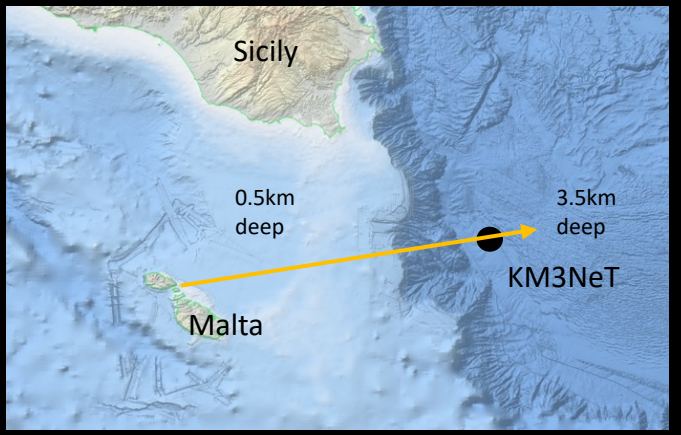




Where did it come from?

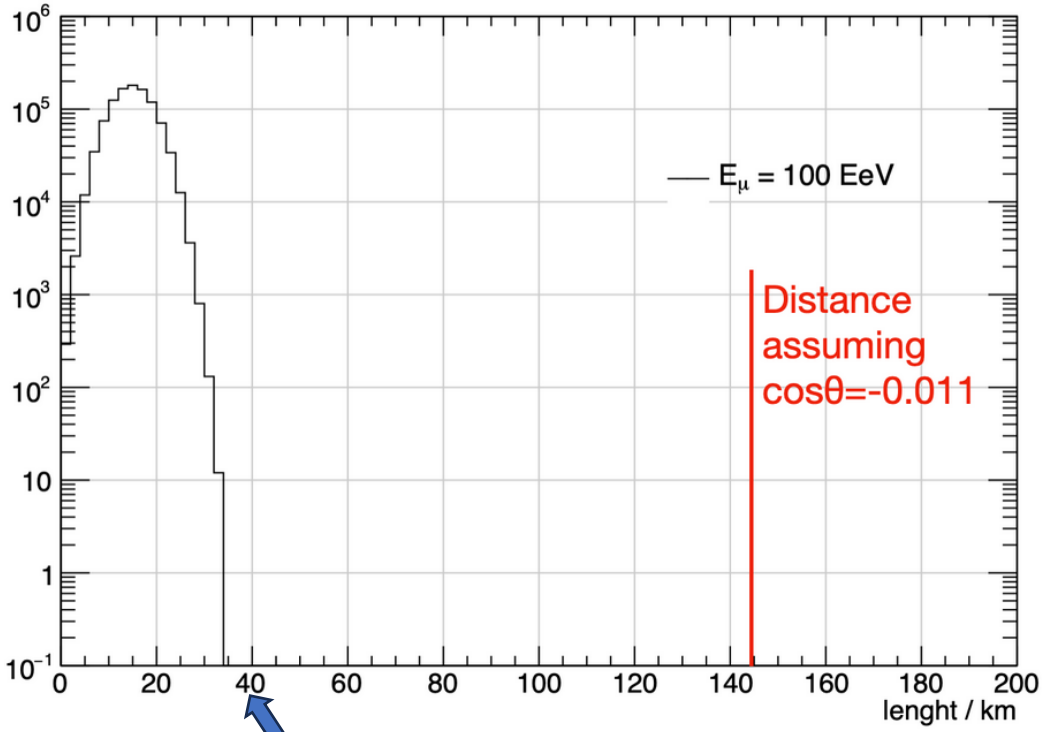
Horizontal muon from a neutrino interaction

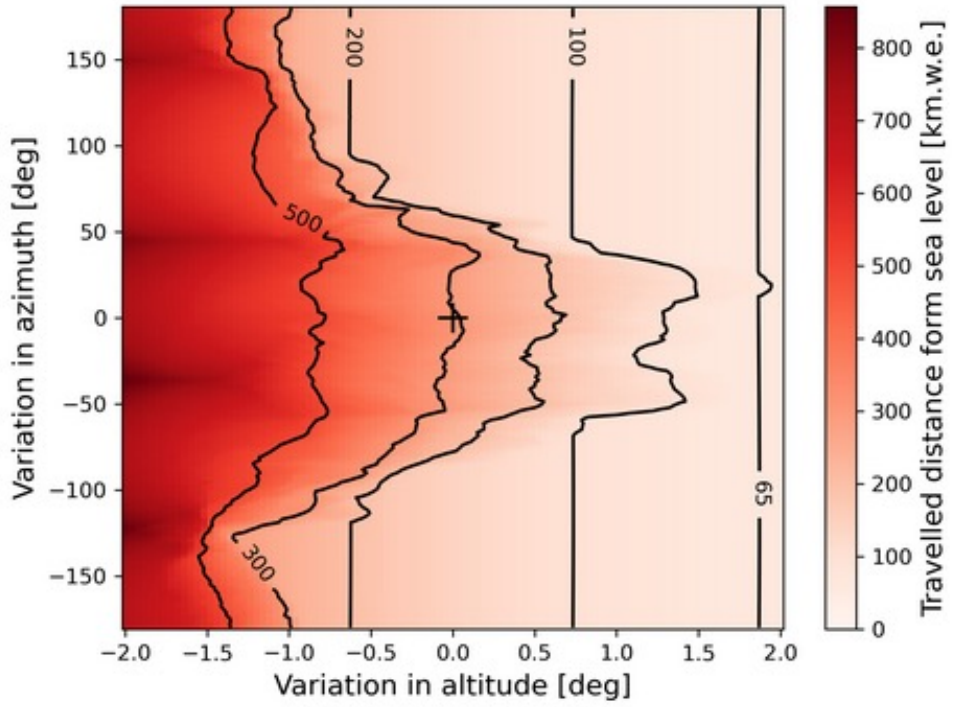




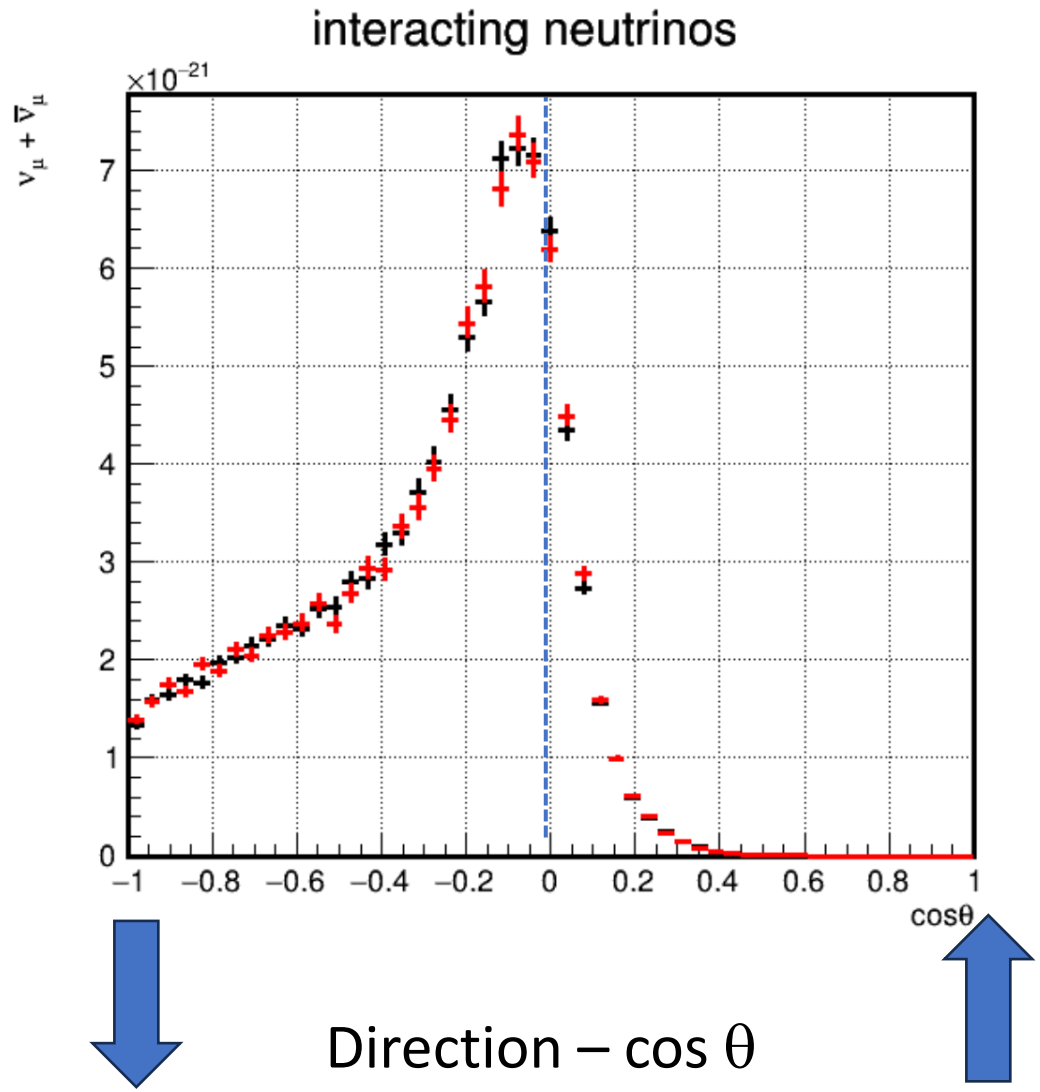
It can’t be an atmospheric muon

Distance travelled by 100 EeV muons



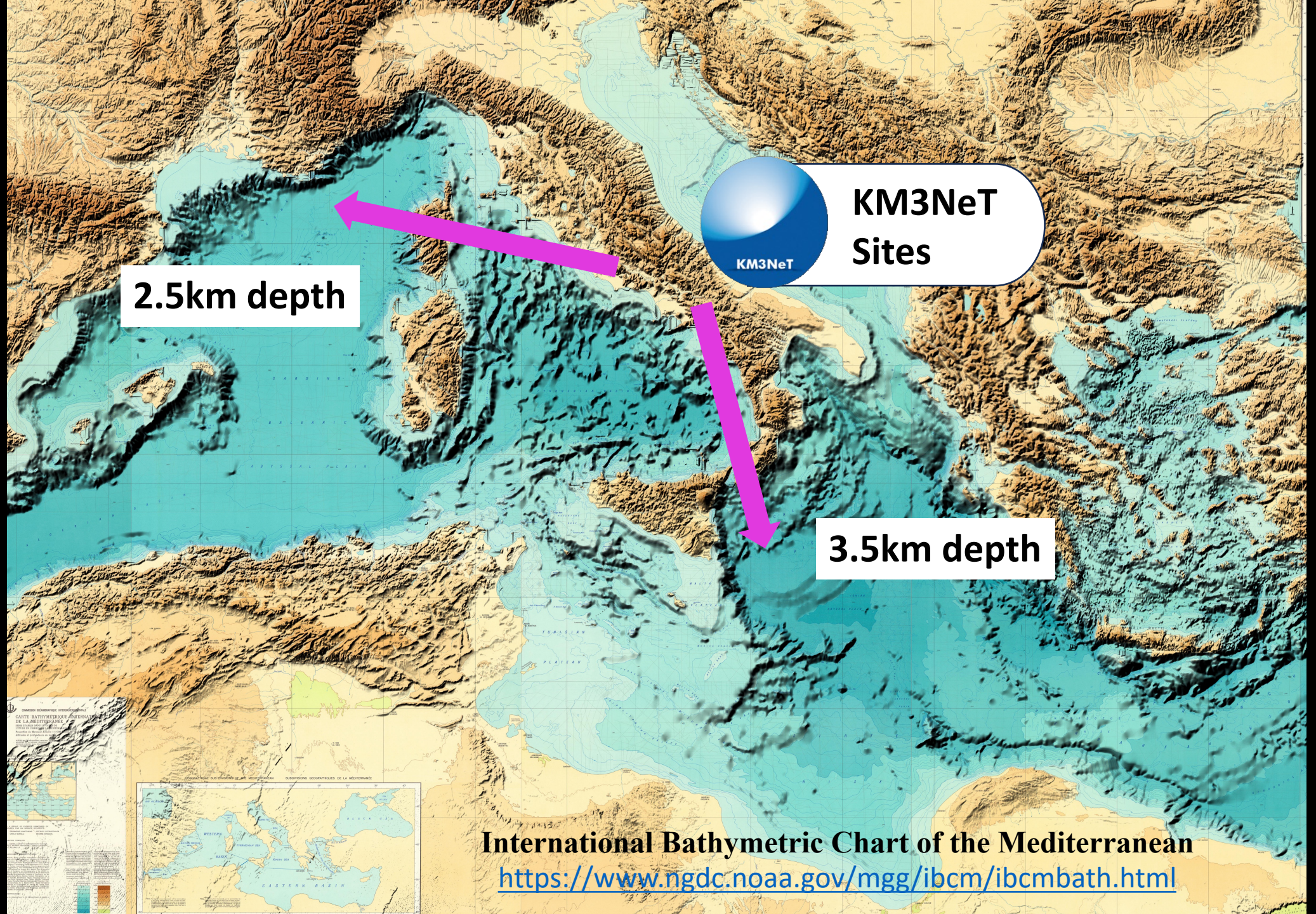


Simulations: Isotropic 100 PeV neutrino flux



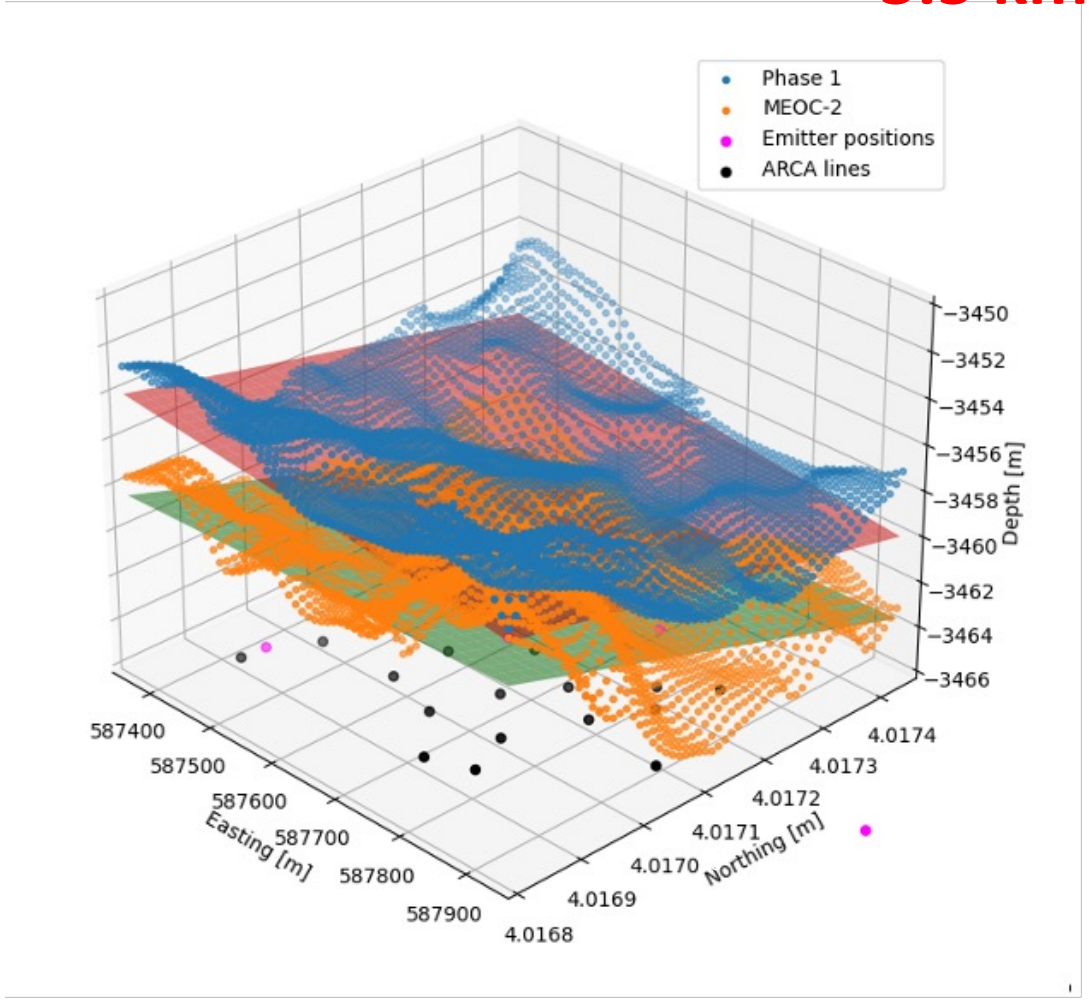
Direction – cos θ

Most likely detection
Is from a horizontal direction!


KM3NeT
KM3NeT
Sites
2.5km depth
3.5km depth
International Bathymetric Chart of the Mediterranean
https://www.ngdc.noaa.gov/mgg/ibcm/ibcmbath.html

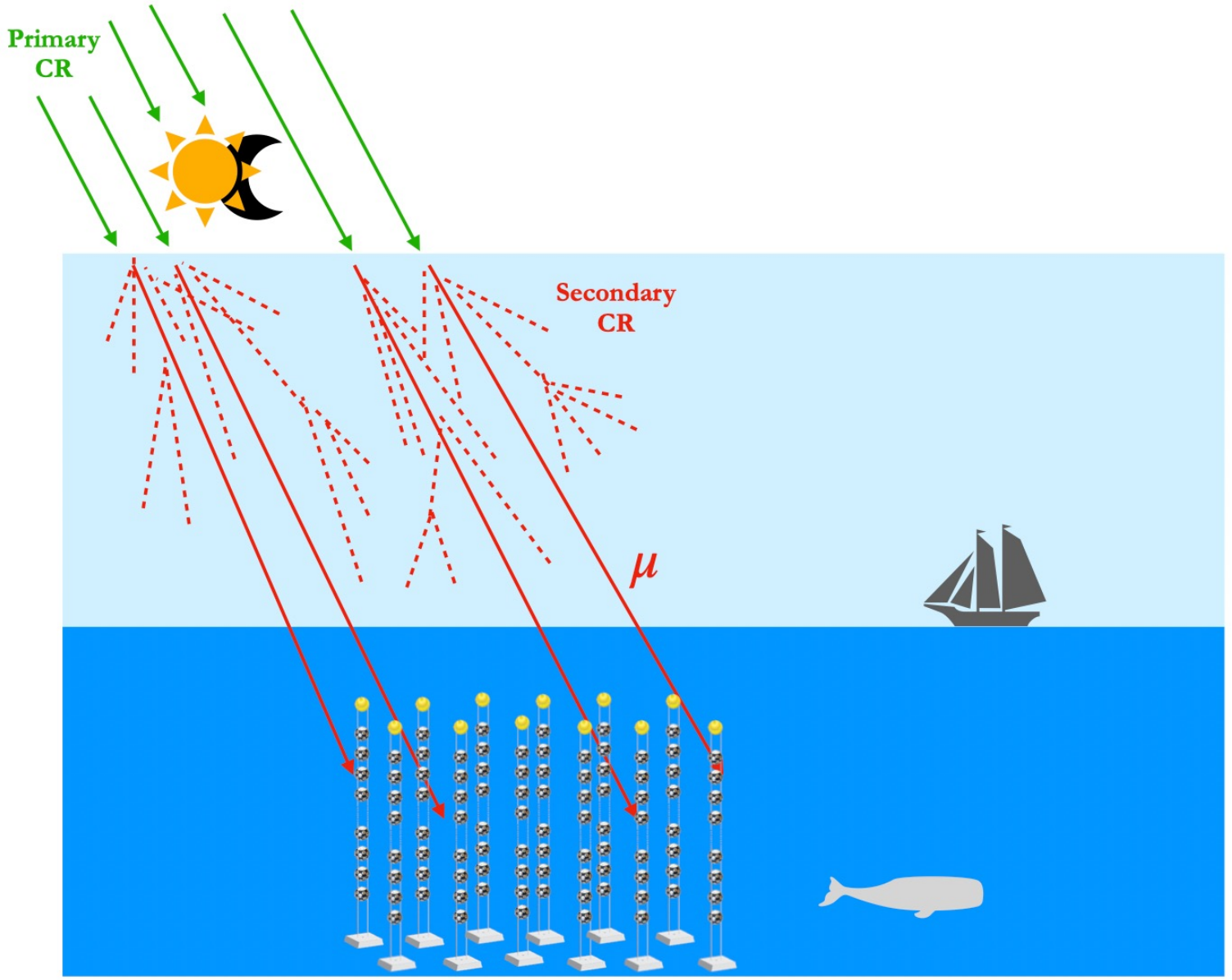
How accurate do we know the absolute orientation/tilt of the detector?

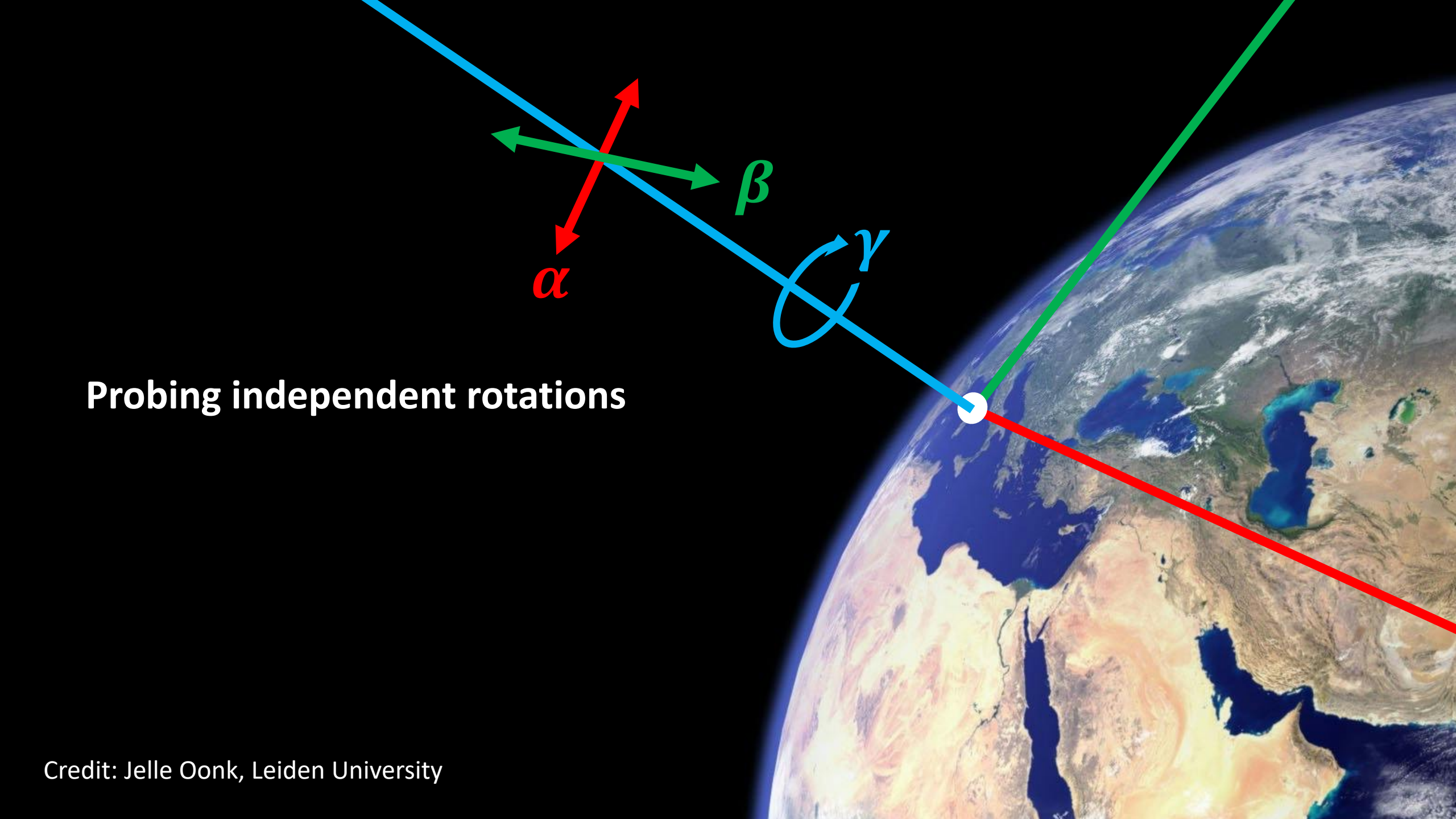
3.5 km deep!



- Transfer of GPS coordinates from Sea Surface during deployments with acoustic signals
- Comparison of 2 existing bathymetric data sets
- Check average tilt of the lines
- Evaluation of the cosmic ray shadow of the moon/sun

Check the shadow of the moon/sun in cosmic rays

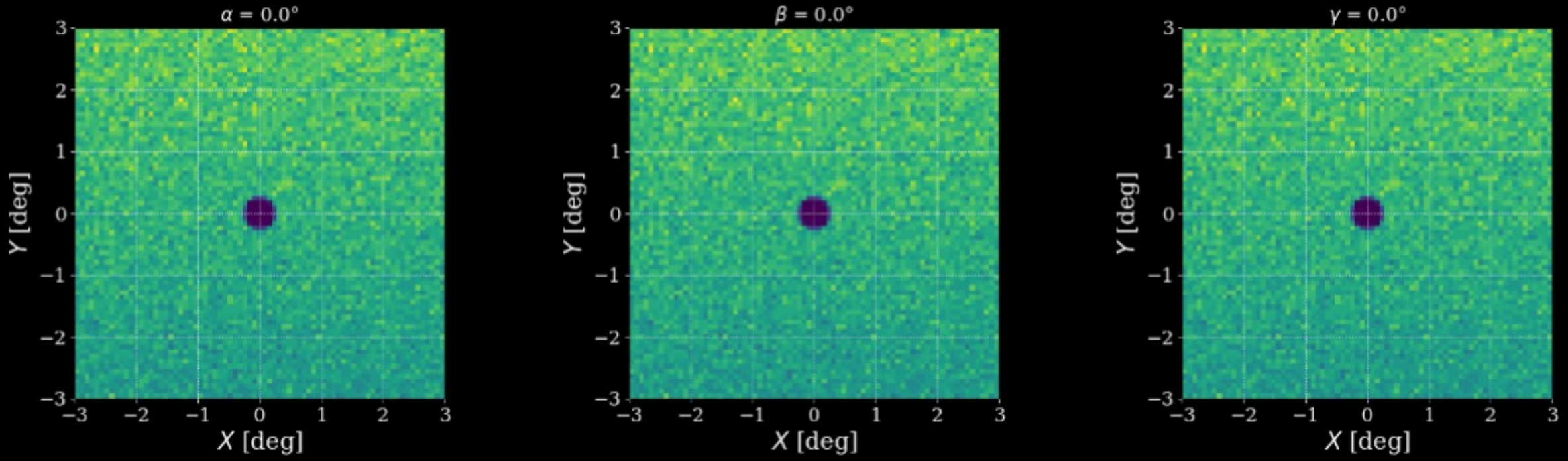




Probing independent rotations

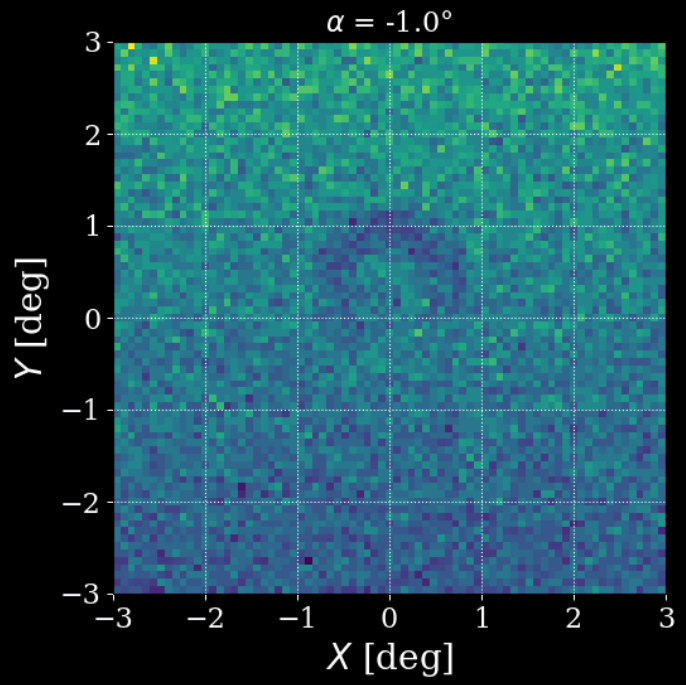
Credit: Jelle Oonk, Leiden University

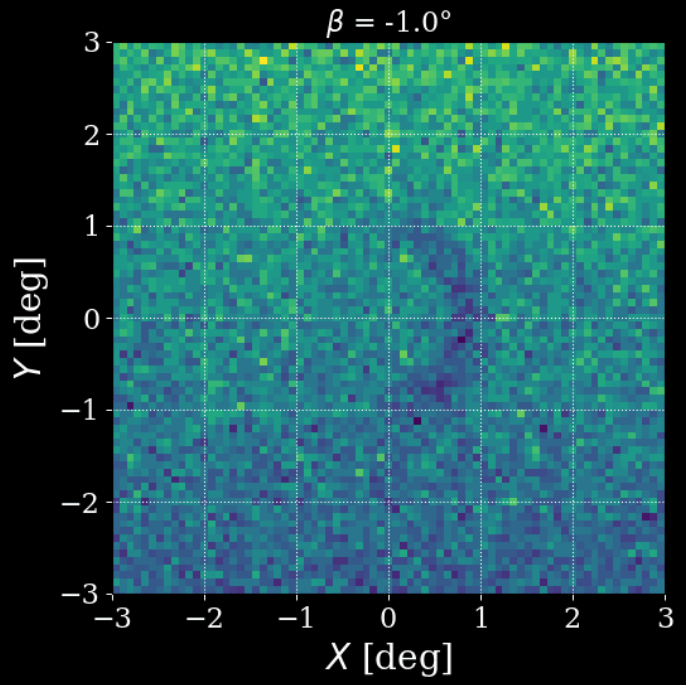
Effects of Misalignment

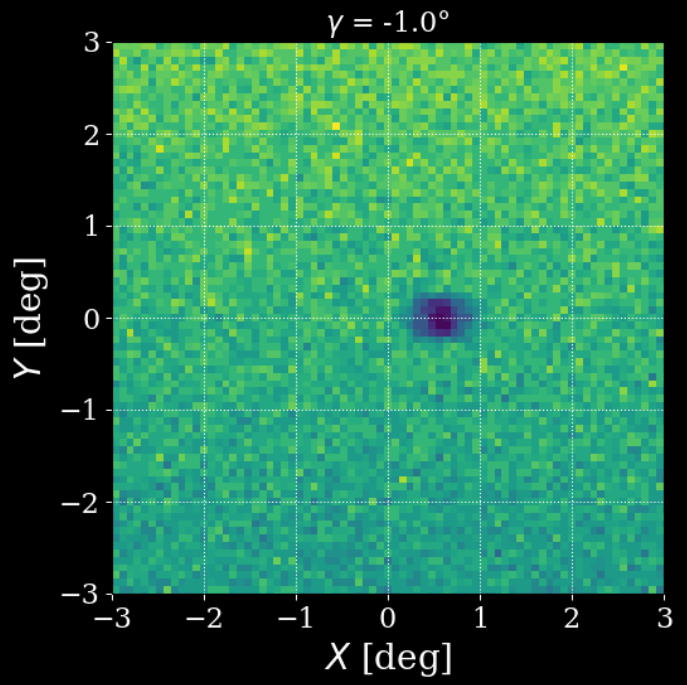


Credit: Jelle Oonk, Leiden University

Effects of Misalignment

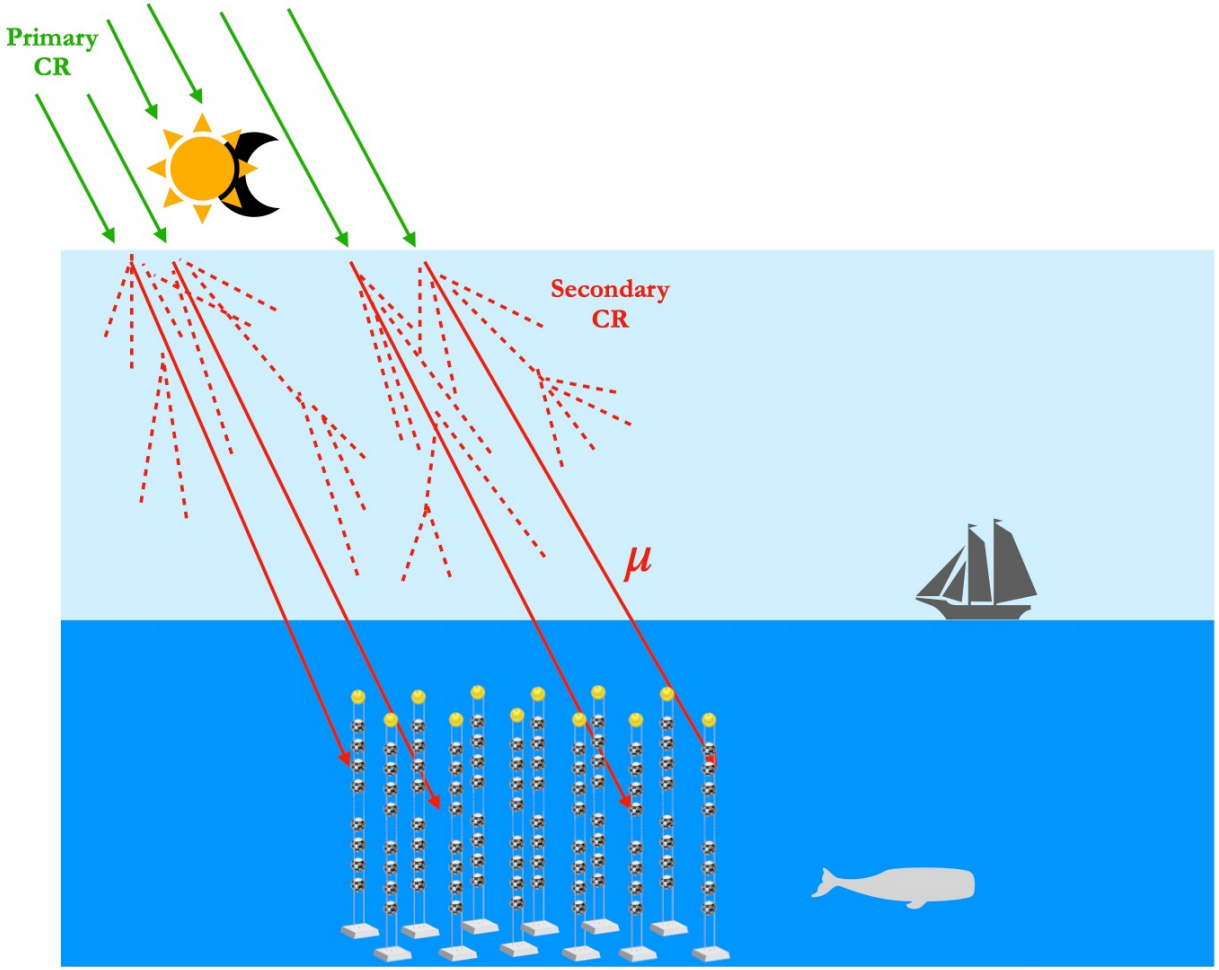


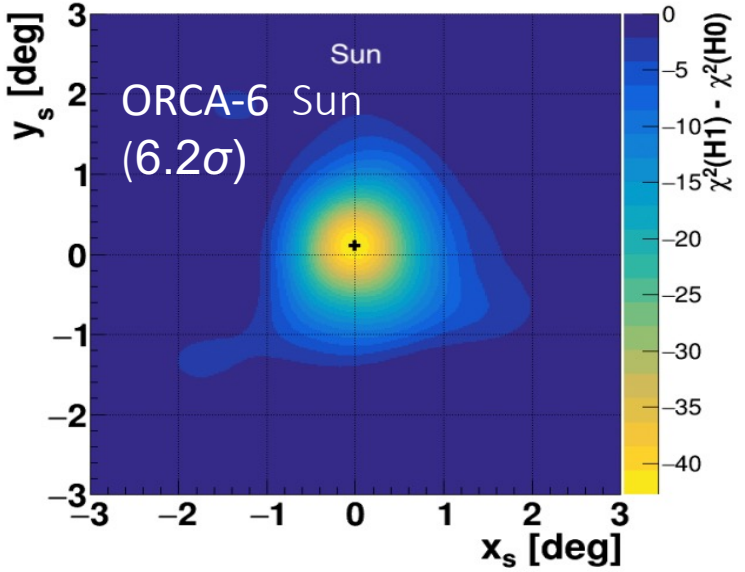


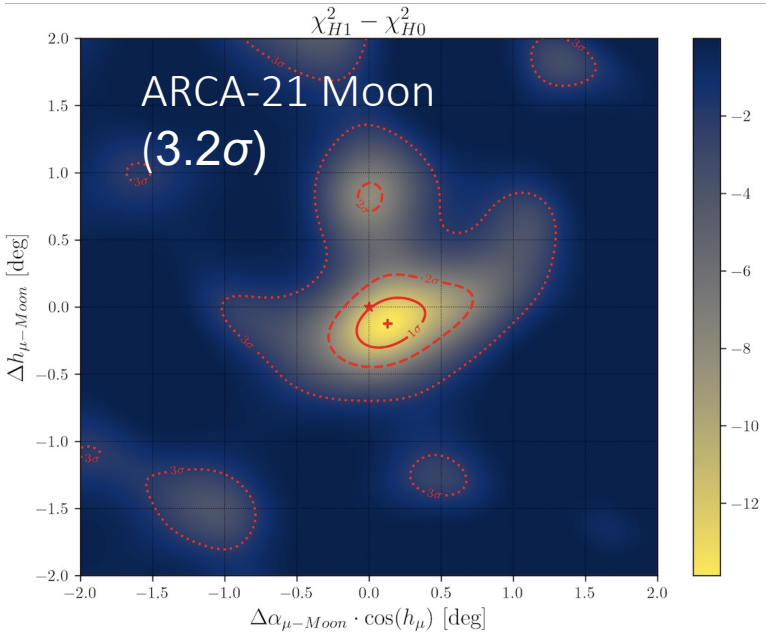


Credit: Jelle Oonk, Leiden University

Check the shadow of the moon/sun in cosmic rays

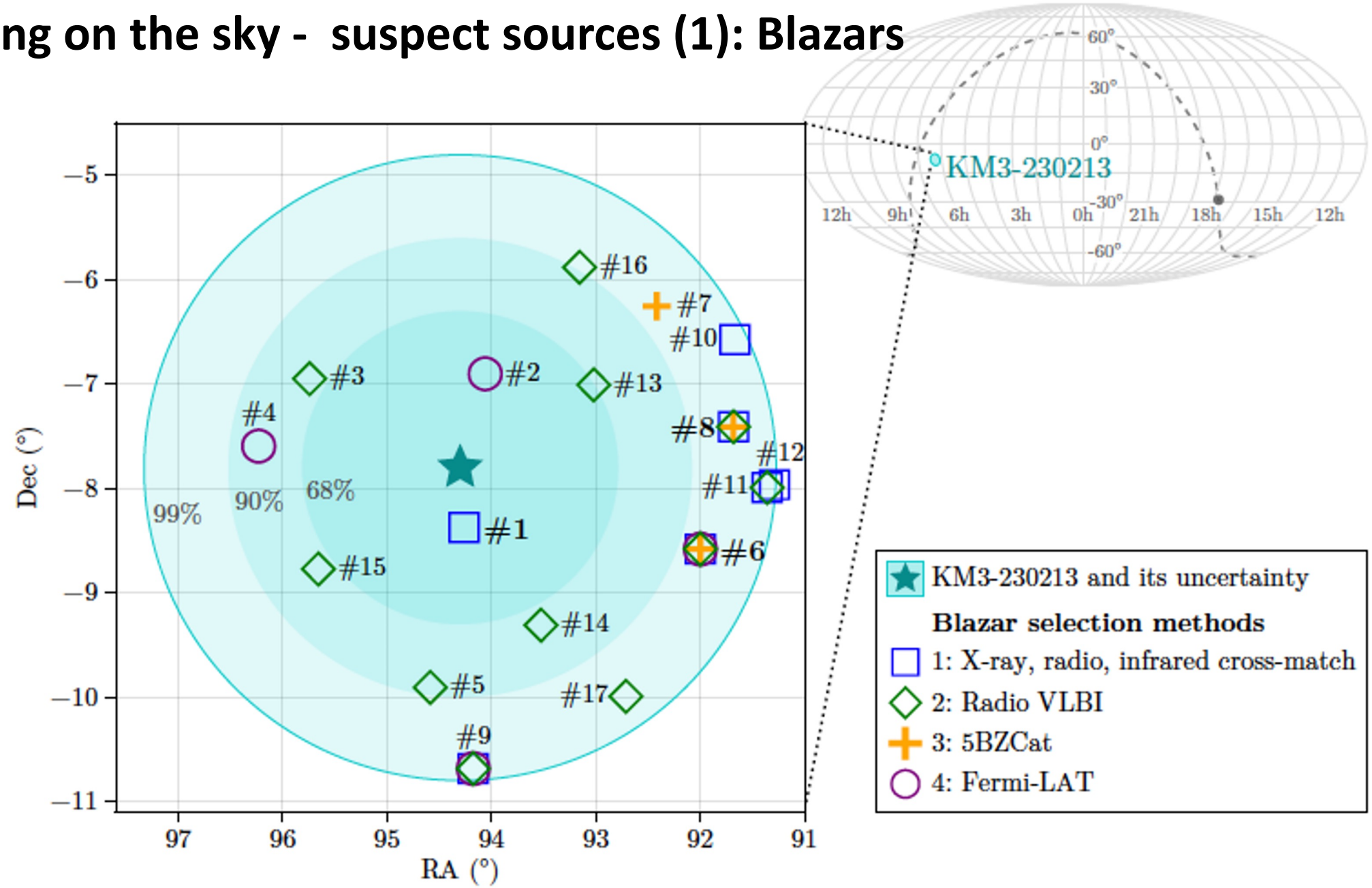




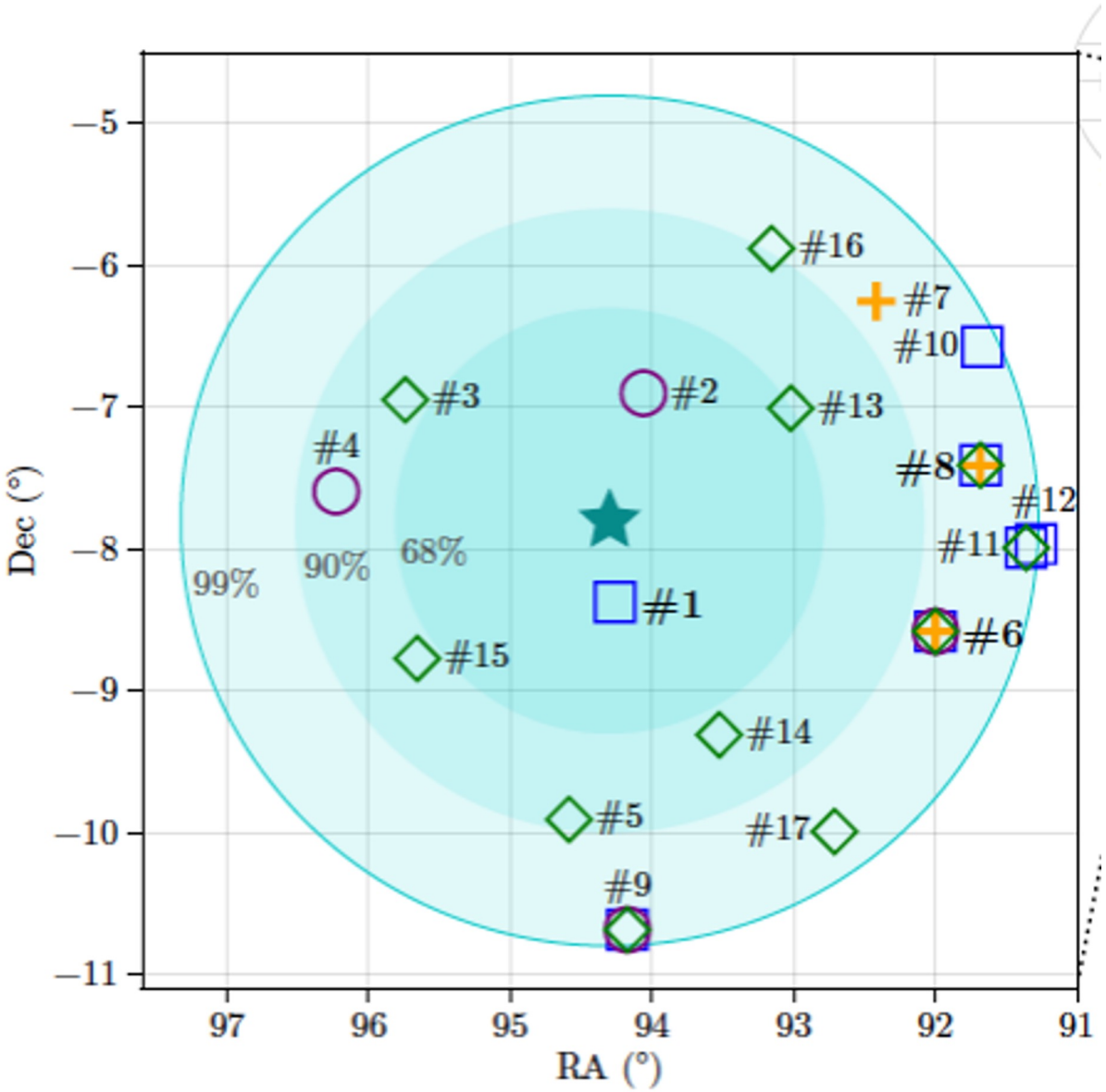


Confirmation of good data filtering,calibration, reconstruction!

Pointing on the sky - suspect sources (1): Blazars



Pointing on the sky - suspect sources (1): Blazars



- Large uncertainy region
- Intrinsic reconstruction uncertainty ~0.1deg
- Current uncertainty dominated by uncertainty in absolute detector orientation

- New acoustic beacon deployments with high accuracy (1m) will enable to measure absolute orientation
- Moon shadow analysis will serve as cross check

=> We will in the future improve on the direction information of this event!

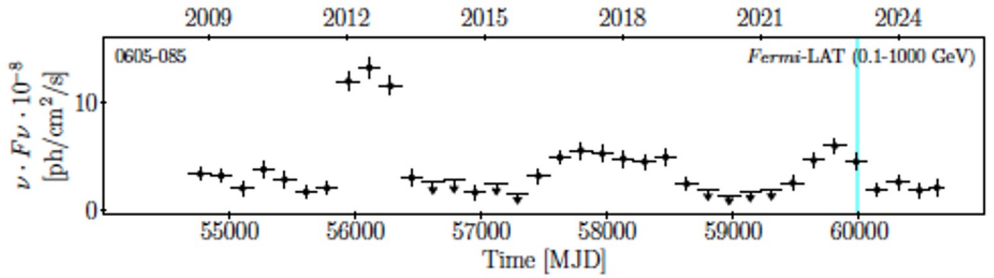
KM3-230213A Blazar candidates

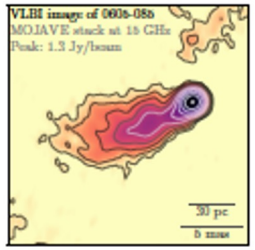
#6 0605-085
Fermi-LAT
γ-ray observations
1-100 GeV

#8: PMN J0606-0724
OVRO/RATAN
radio observations
15GHz

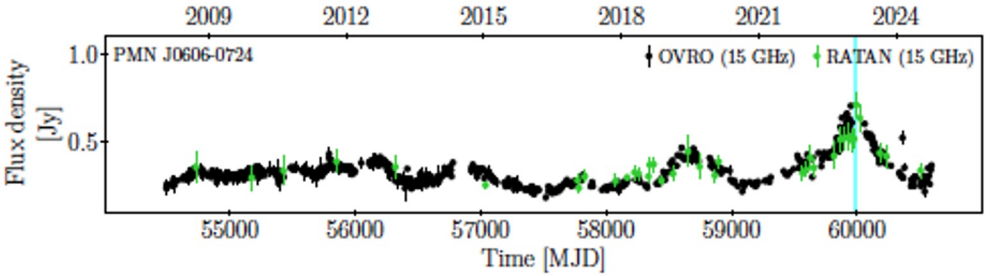
#1: MRC 0614-083
eROSITA/Swift-XRT
X-ray observations
0.2-2.3 keV

KM3-230212A Blazar Counterparts

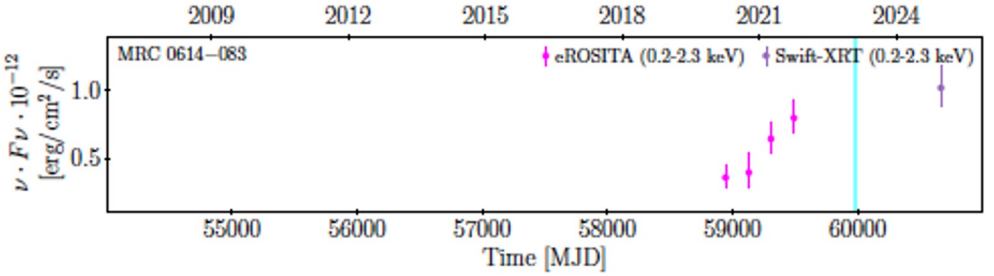




(a) The *Fermi*-LAT light curve and a VLBI image of 0605-085: the brightest radio source in the neutrino localization region that experiences a gamma-ray flaring activity around the neutrino arrival (Section 5.1).

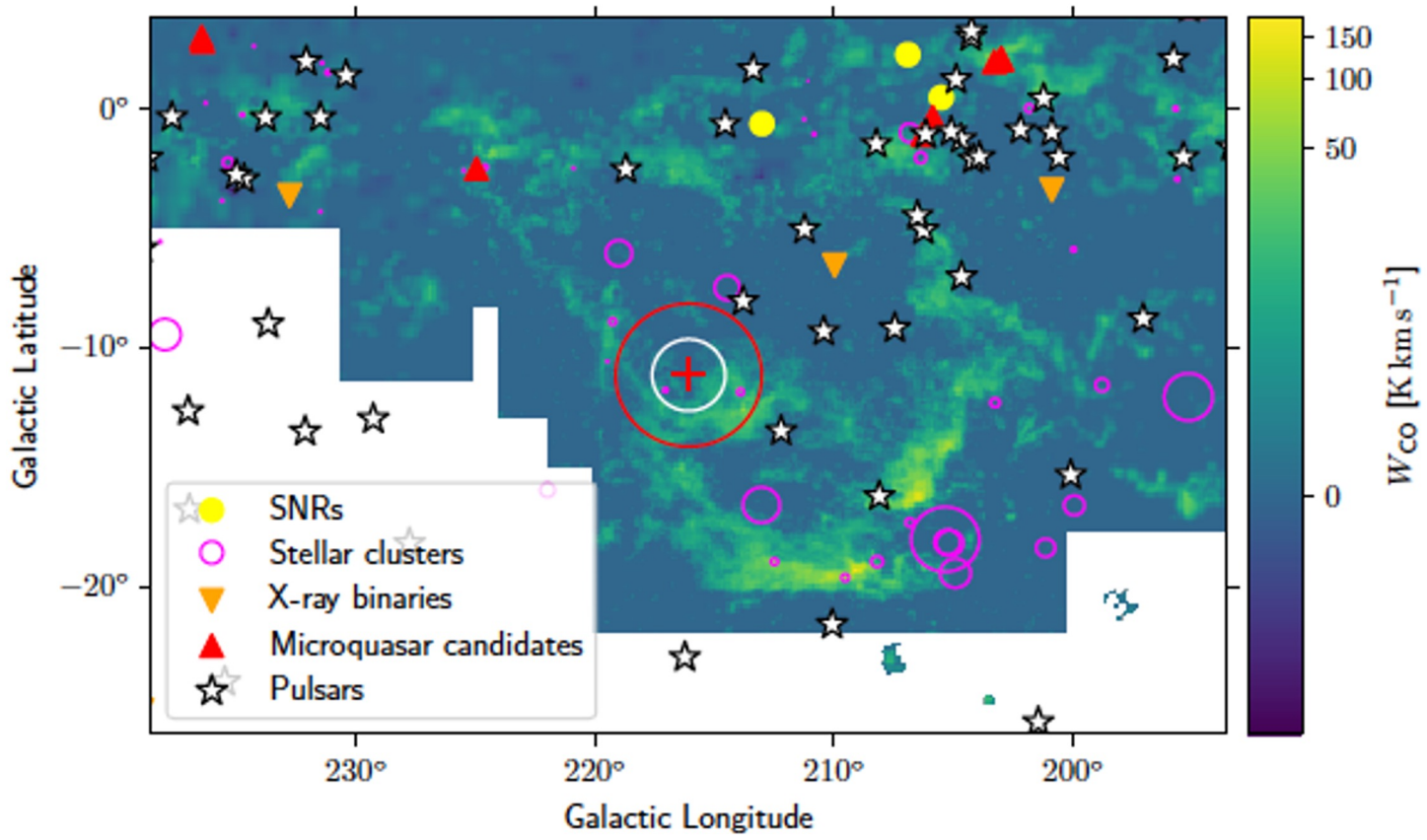


(b) The radio light curve for PMN J0606-0724 that experiences a major flare in close coincidence to the neutrino arrival (Section 5.2).



(c) The X-ray light curve for MRC 0614-083 that indicates a flaring activity around the neutrino arrival (Section 5.3).

Pointing on the sky - suspect sources (2): Galactic?



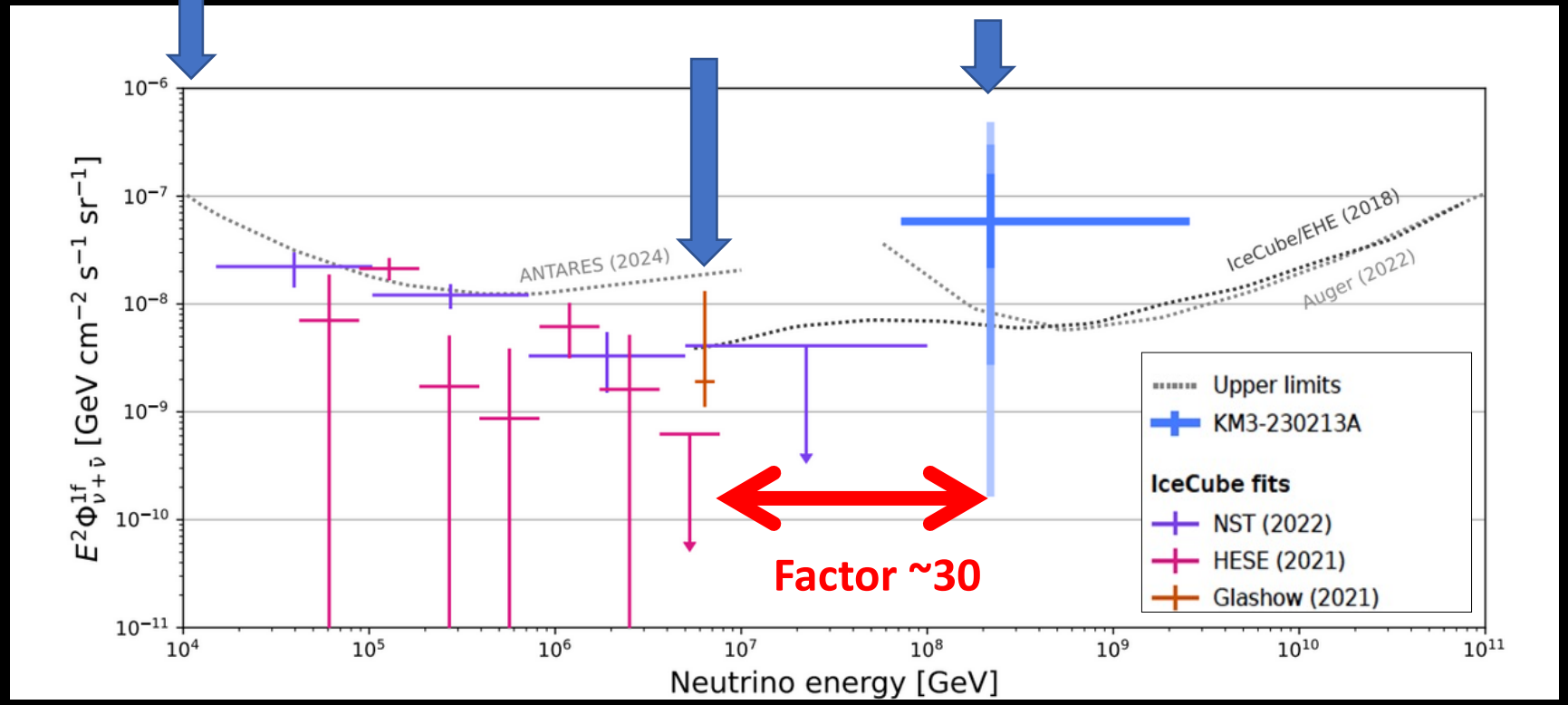
No obvious suspect, generally hard to achieve this high energy

Unexplored energy regime

LHC@CERN

Previous highest energy neutrino

This observation

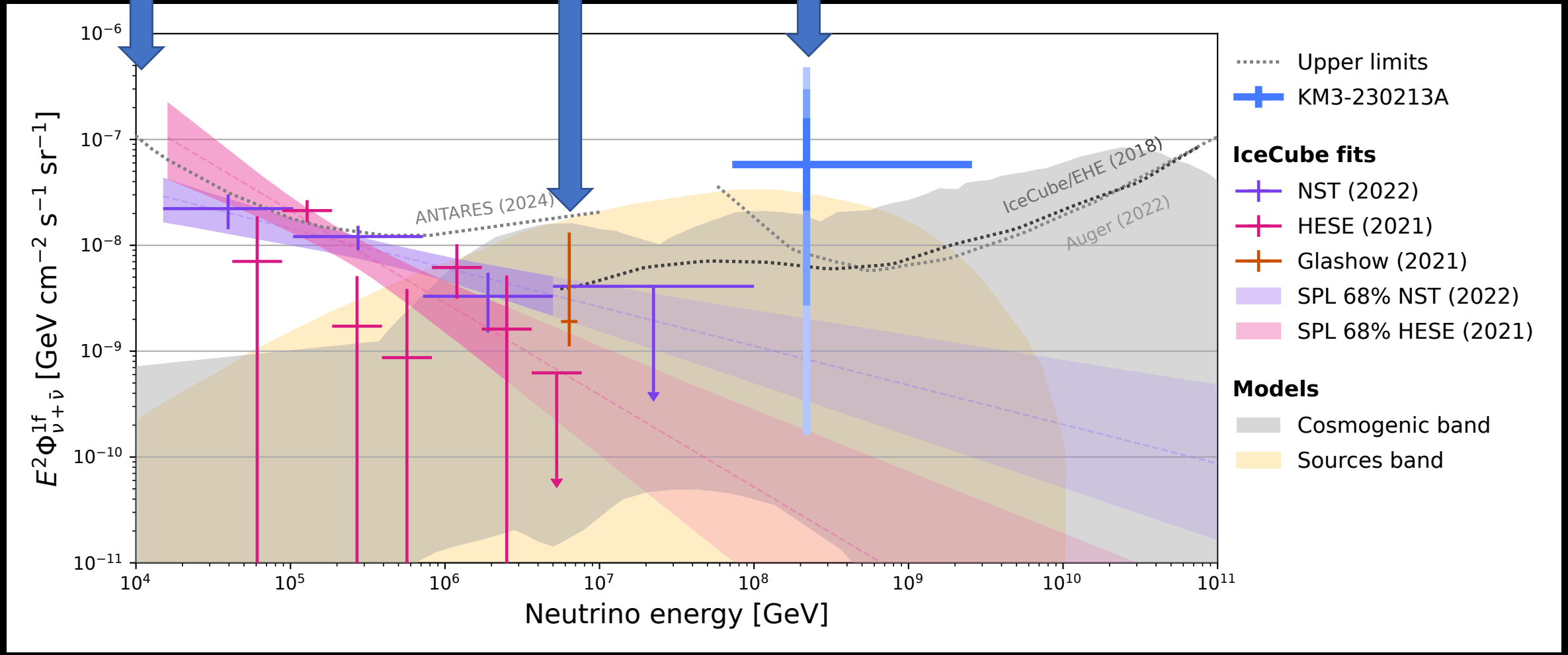


Neutrino energy (logarithmic scale)

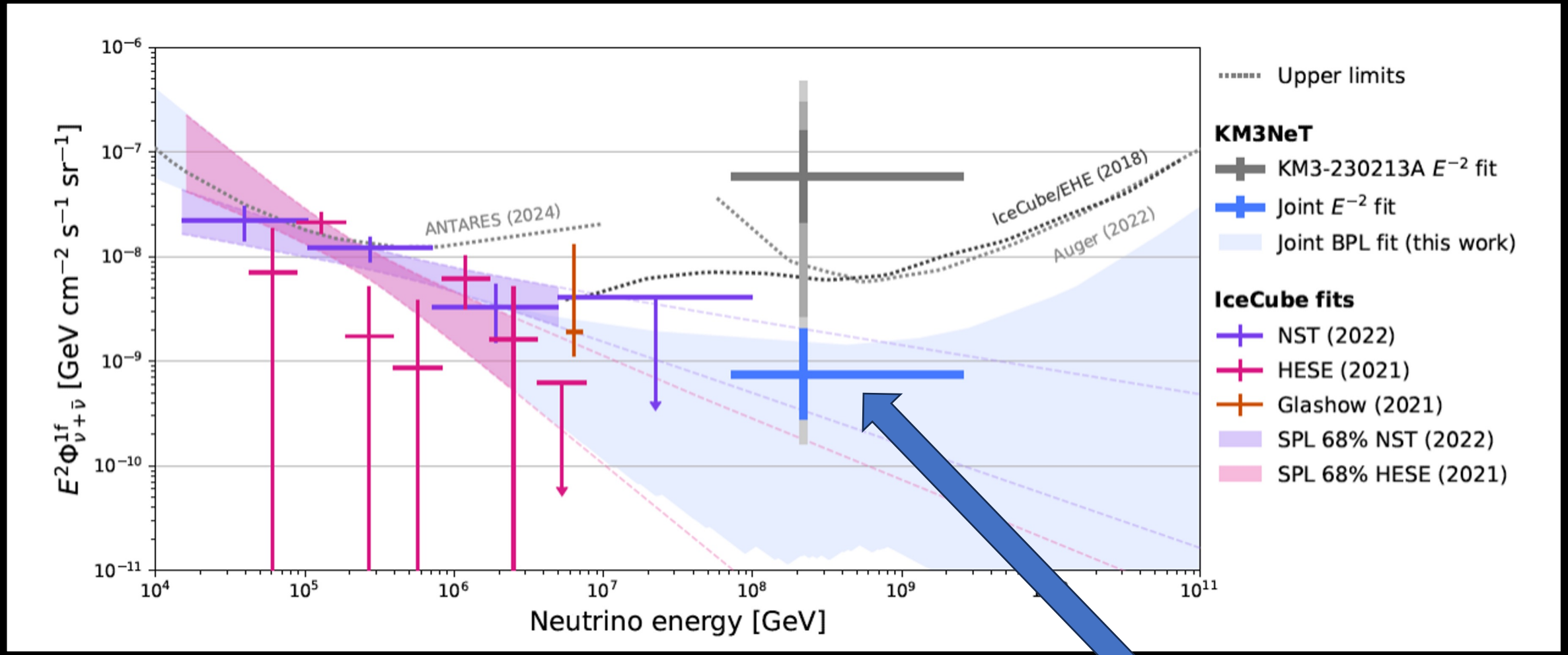
LHC@CERN

Previous highest energy neutrino

This observation

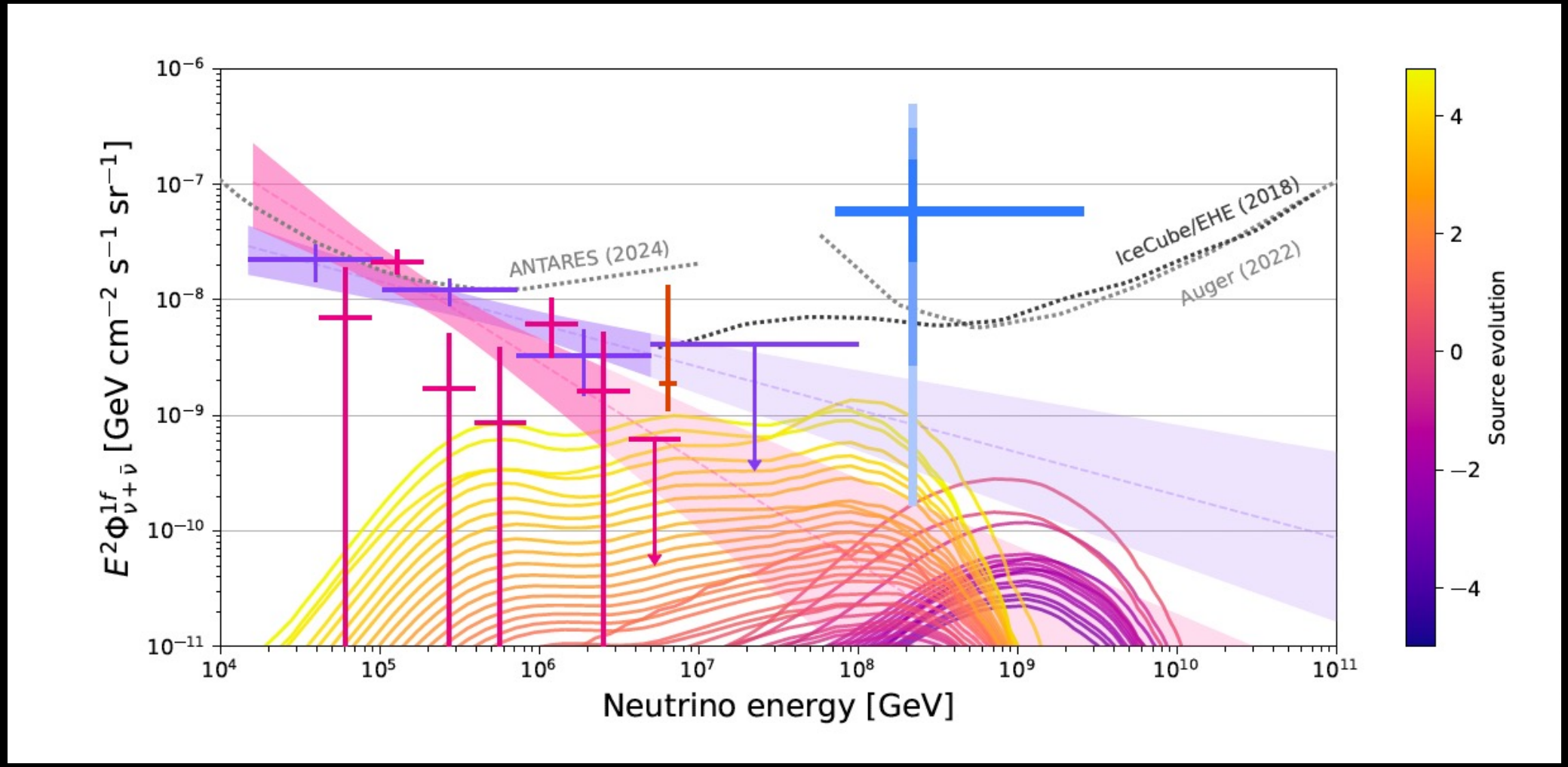


Unexplored energy regime



Best-fit flux taking into account non-observations from IceCube and Auger

Varying the cosmogenic neutrino models



Moving forward

Many neutrino observatories substantially growing, coming online

- Angular resolution crucial
  -> expect improvements from refined reconstructions & lower intrinsic uncertainties (water)

- Multi - messenger observations key to unravel the actual high energy cosmic sources
  -> connection between observatories essential

The neutrino sky has surprised us several times before
-> exciting decades ahead!

’Draw me a neutrino’ contest 2020
winner:: Evangelos Zacharopoulos