Laboratori Nazionali del Sud

Neutrinos in the multi-messenger era

PIERA SAPIENZA LNS - INFN Heavy Quarks and Leptons 2025 - 15th September Bejin CHINA

High energy Universe

Ultra High Energy Cosmic Rays

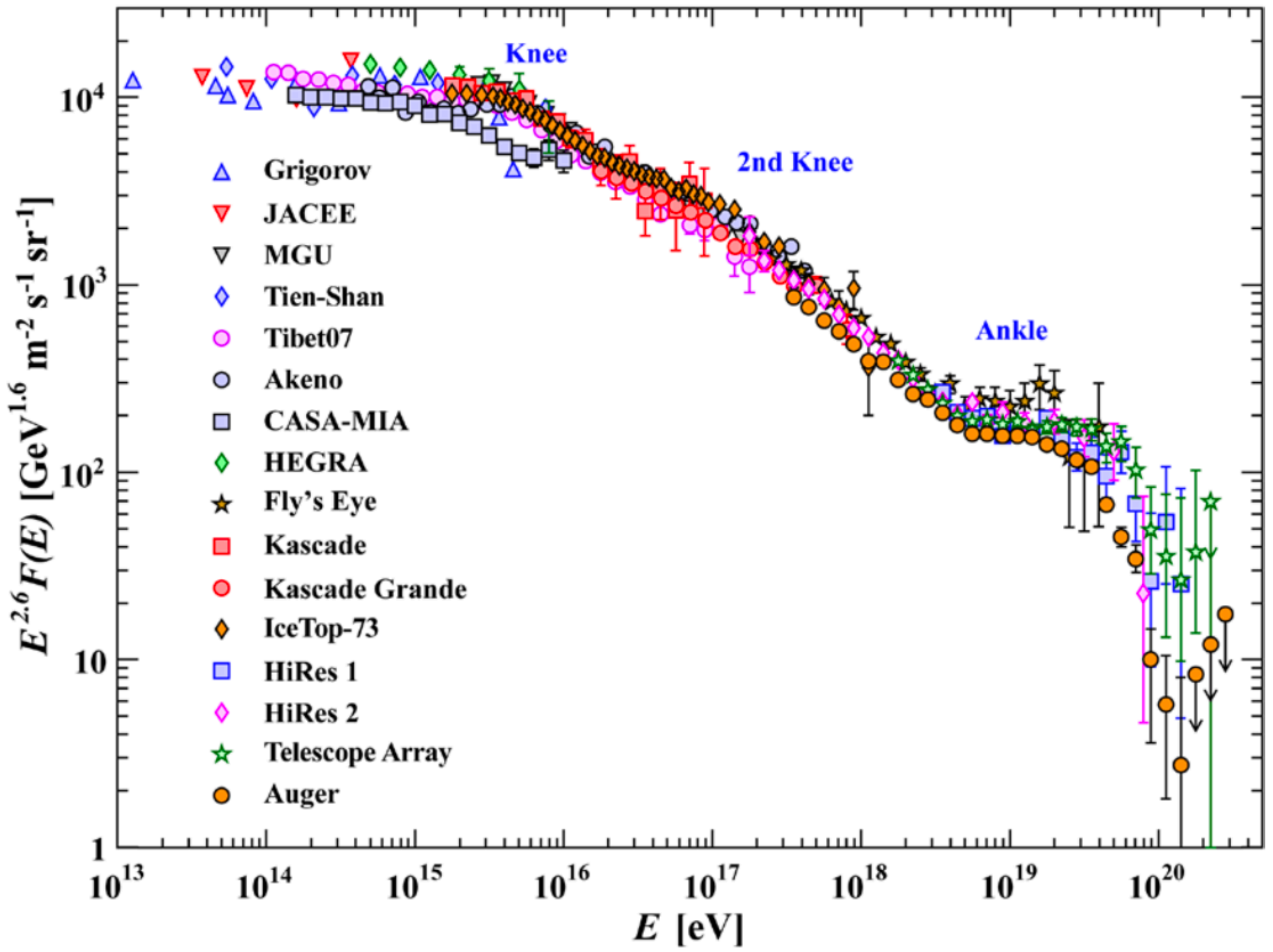
Cosmic particles reach us with energies exceeding 10^{20} eV showing a broken power-law spectrum over many orders of magnitude with some prominent spectral features:

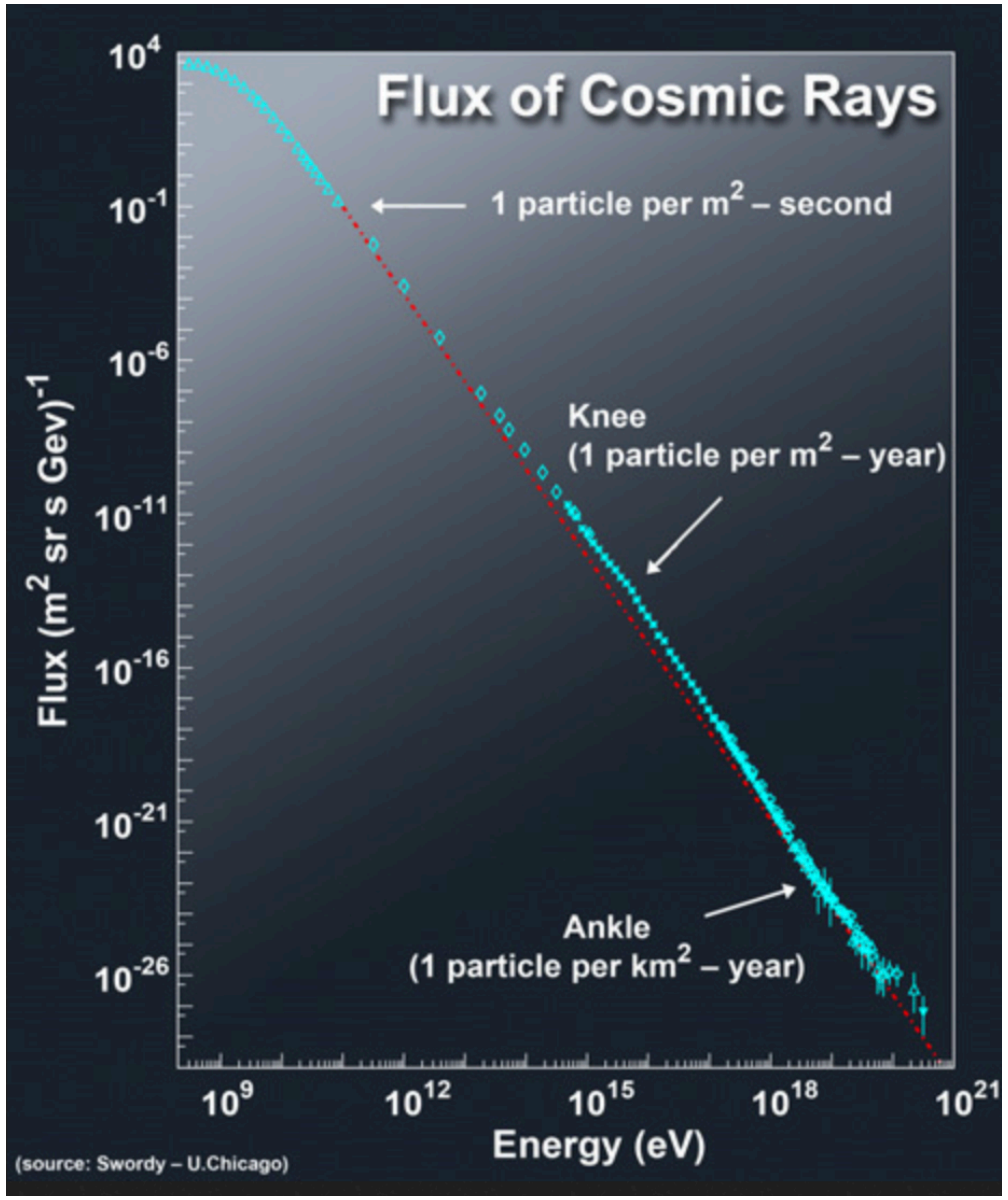
knee: slope change at about 4×10^3 TeV (galactic)

second knee: slope change at about 4×10^3 TeV

ankle: slope change at about 5×10^6 TeV (extra-galactic)

cut-off above 10^{20}



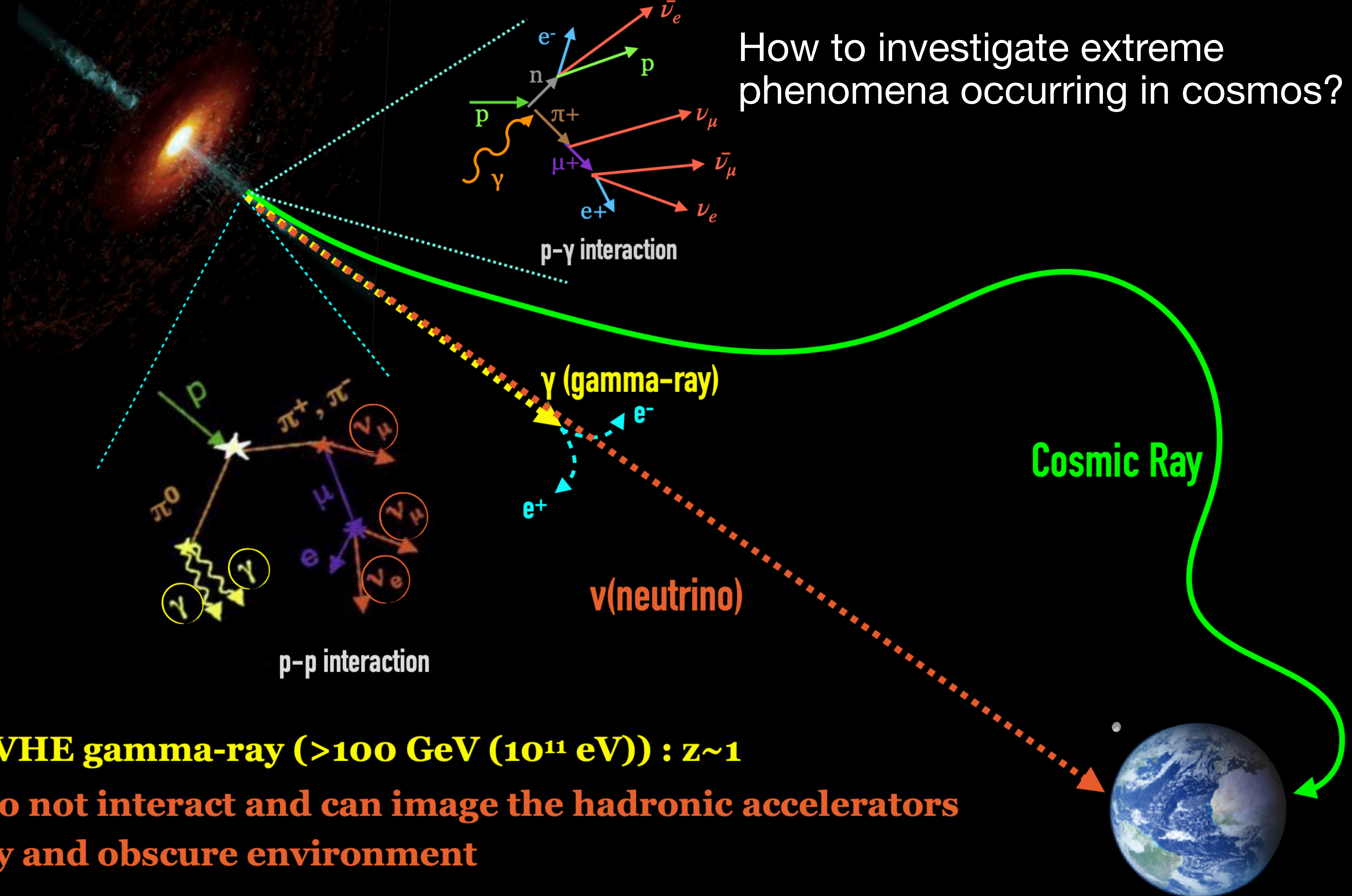


Cosmic rays are scrambled by galactic and extragalactic magnetic fields thus loosing info about their spatial origin

The sources of cosmic rays is still unknown

From energetic considerations possible candidates are SNR for Galactic, AGN, GRB, SBG, TDE… for extragalactic

How to investigate extreme phenomena occurring in cosmos?



Horizon of VHE gamma-ray (>100 GeV (10^{11} eV)) : z~1

Neutrinos do not interact and can image the hadronic accelerators farther away and obscure environment

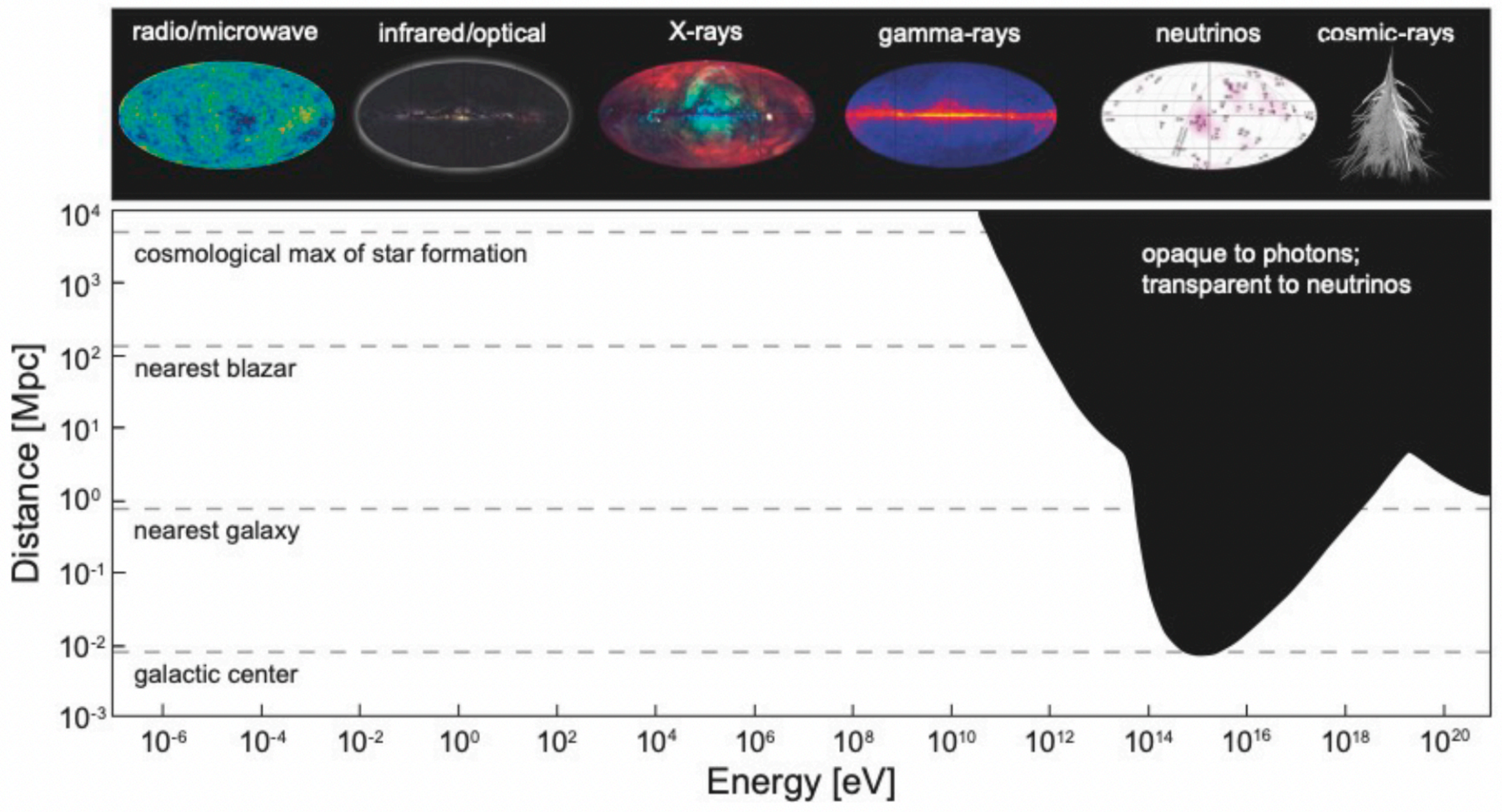
High energy Universe

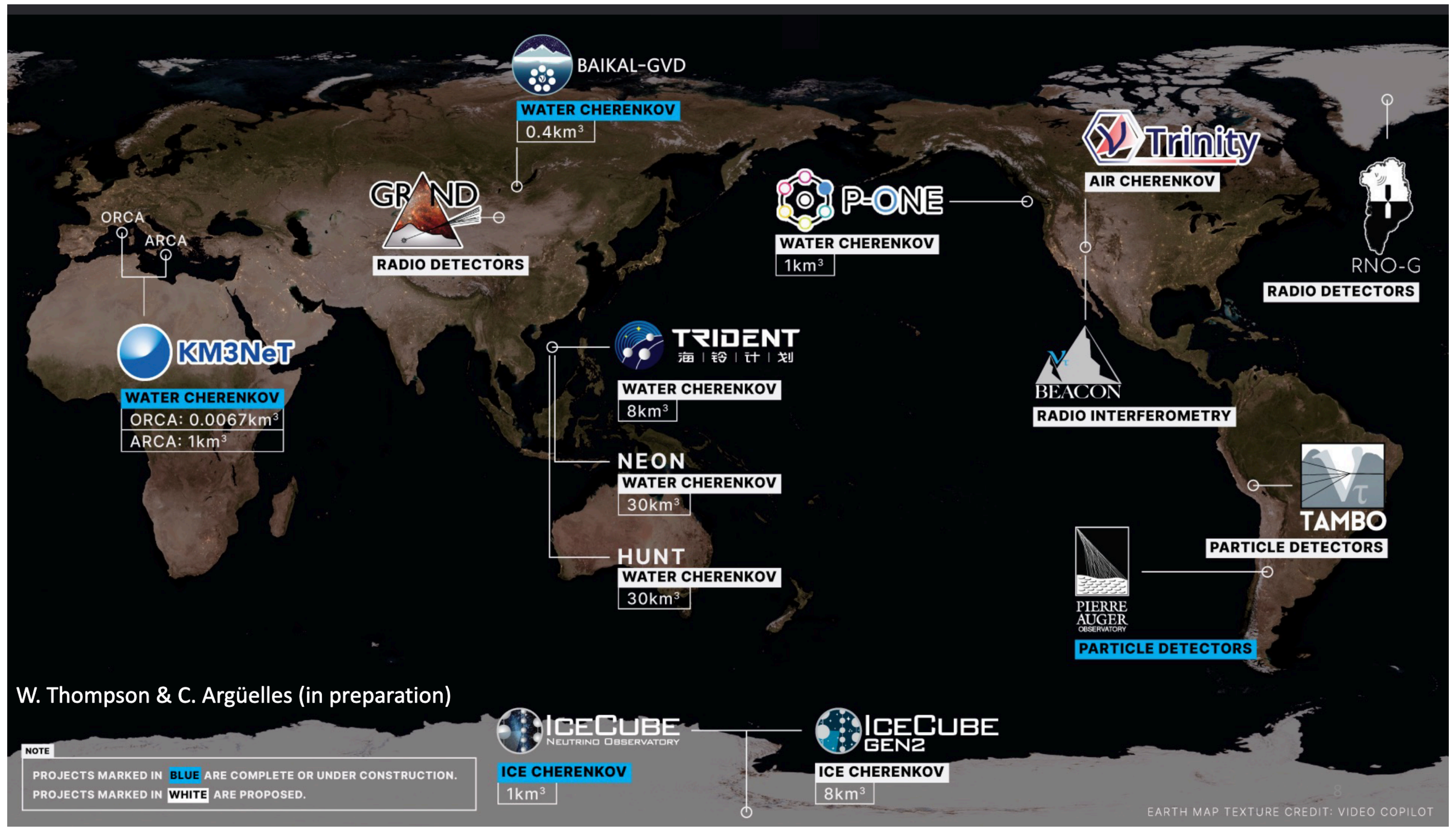
Neutrinos shed a new light on our Universe

- Neutrinos interact very weakly with matter allowing to image distant hadronic accelerators and environments that are otherwise obscured

- High energy neutrinos are expected to be multi-messenger by nature since are produced in hadronic interactions where also very energetic gamma are produced

- Eventually neutrino is the smoking gun of hadronic mechanism since VHE gamma can be produced also from leptonic process like syncroton radiation and inverse Compton



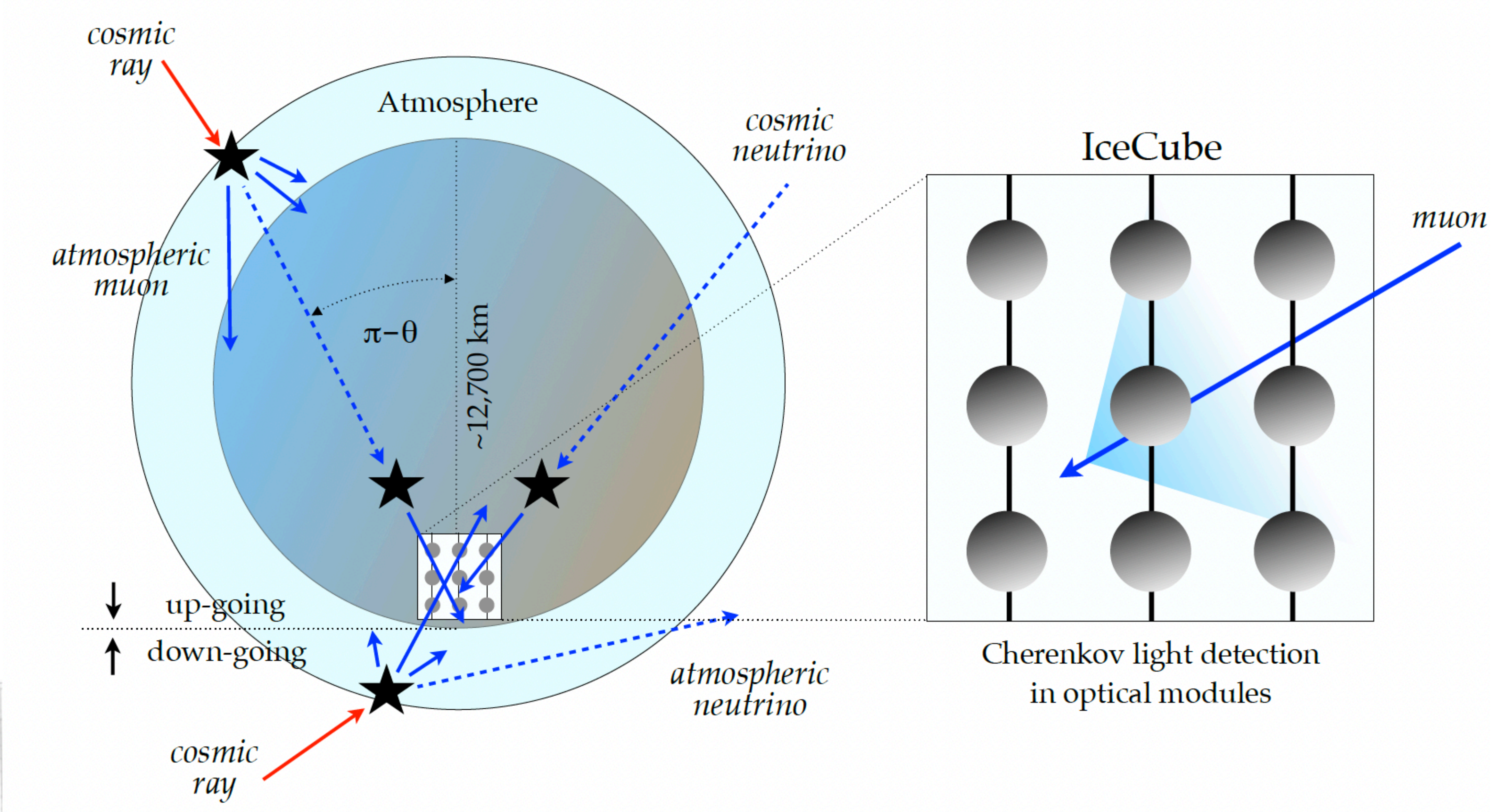


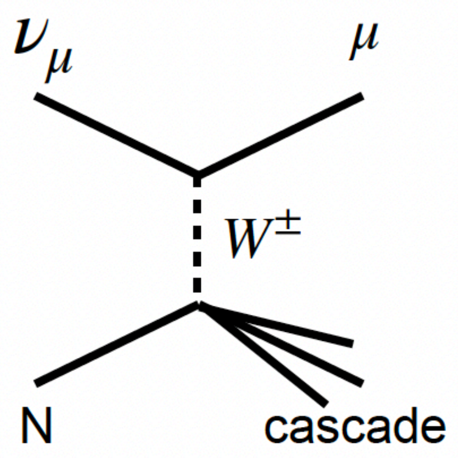
In this talk I will focus on observations by optical Cherenkov neutrino telescopes

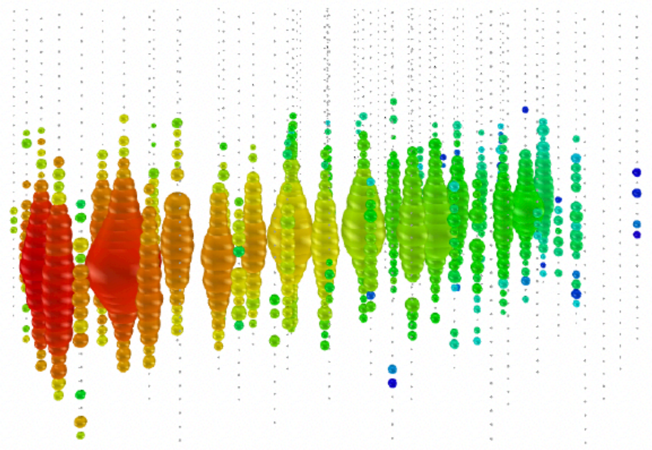
High energy neutrino telescopes

High energy neutrino detection requires volume of km³-scale

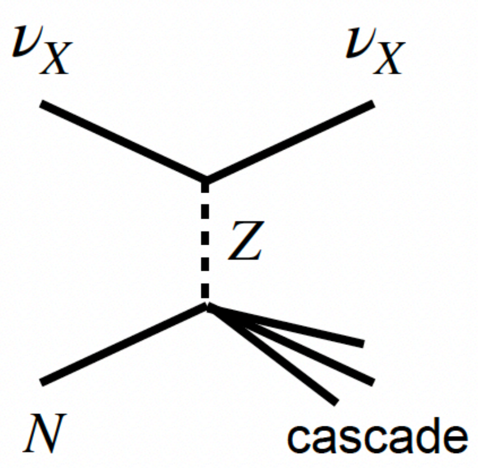
- natural media where exploit optical Cherenkov effect in deep water or antarctic ice
    - threefold function: shield, target, radiator
- all flavor detection, muons neutrinos golden channel for neutrino astronomy due to their superior angular resolution

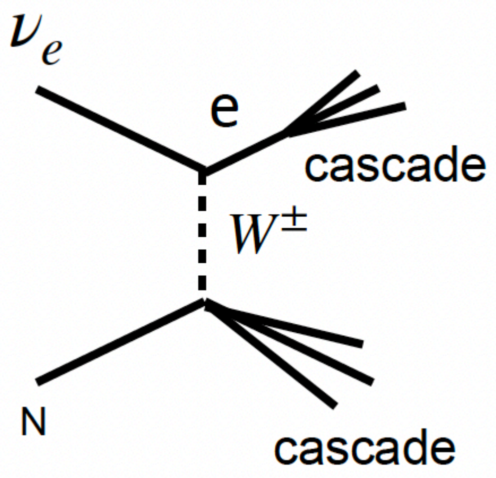


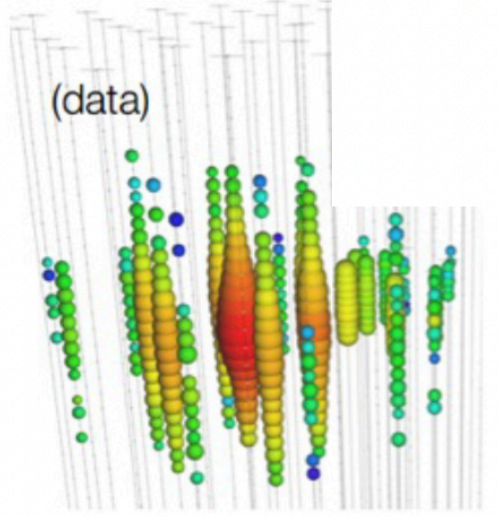




muon in IceCube



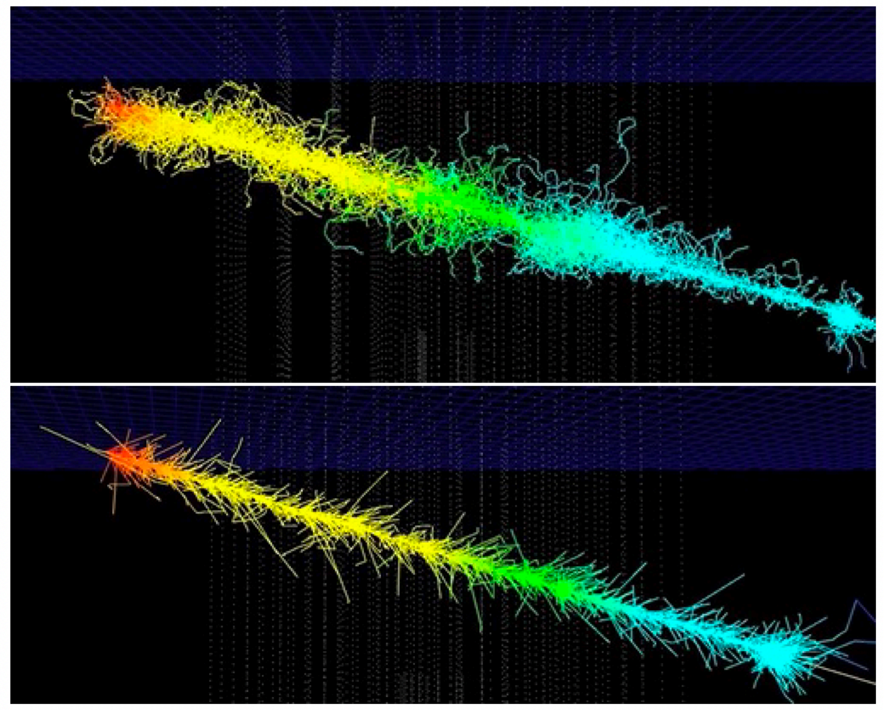


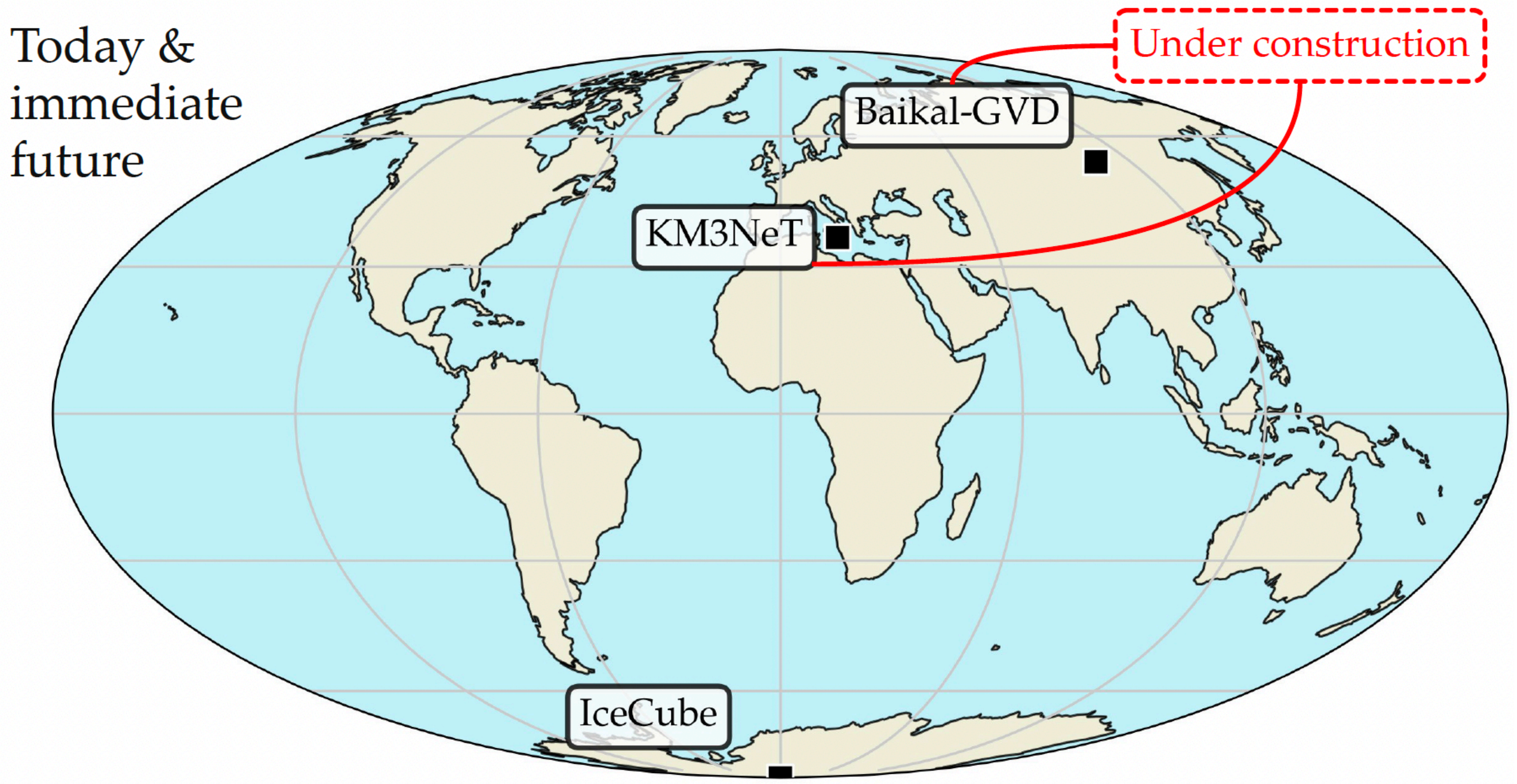


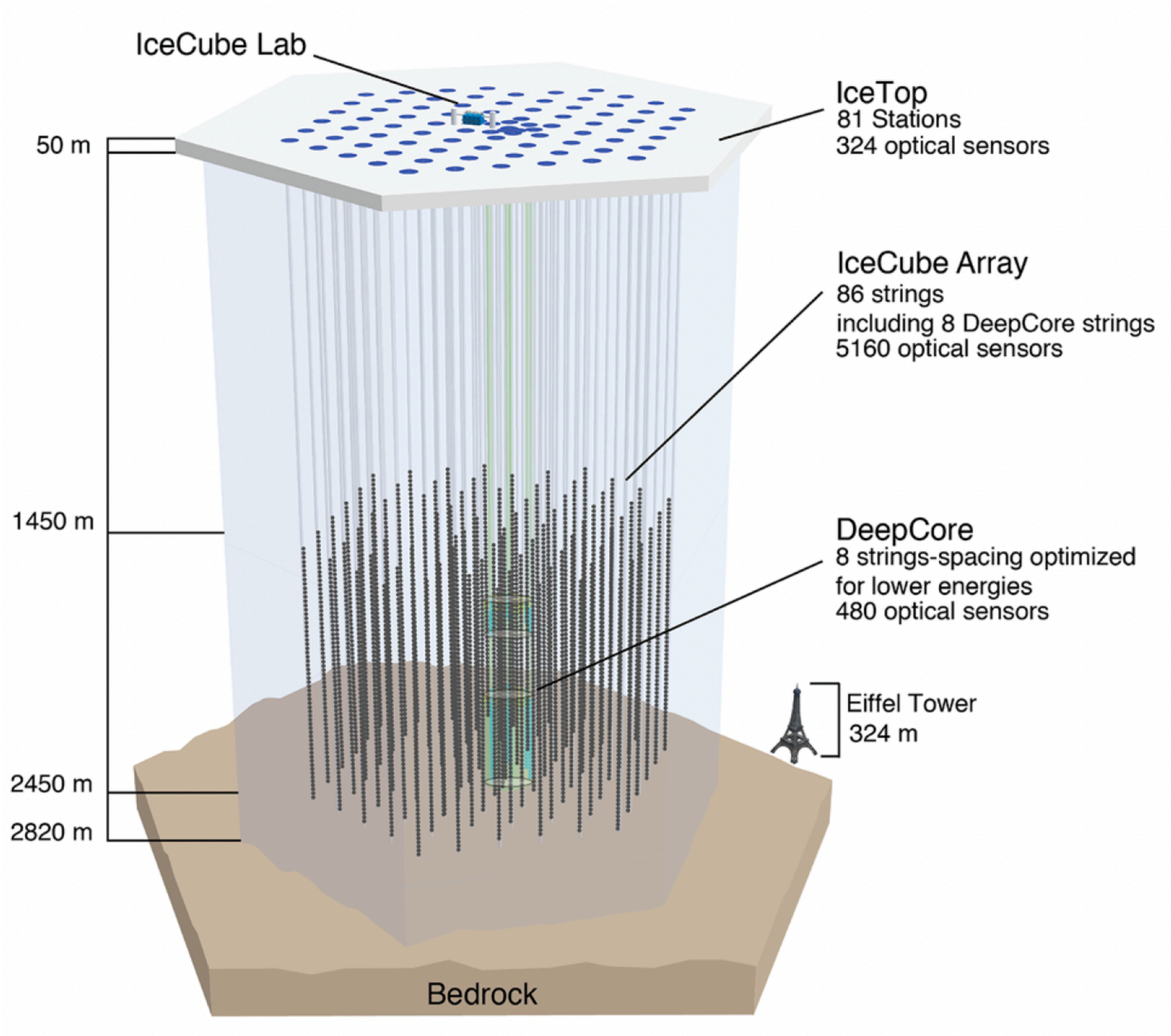
cascade in IceCube

Extremely challenging experiments

- harsh environments
- marginally accessible
- low signal rate and huge background






IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings
including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized
for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

The cosmic neutrinos discovery

IceCube at South Pole is largest neutrino telescope in operation since 2011 with 1 km³ detection volume

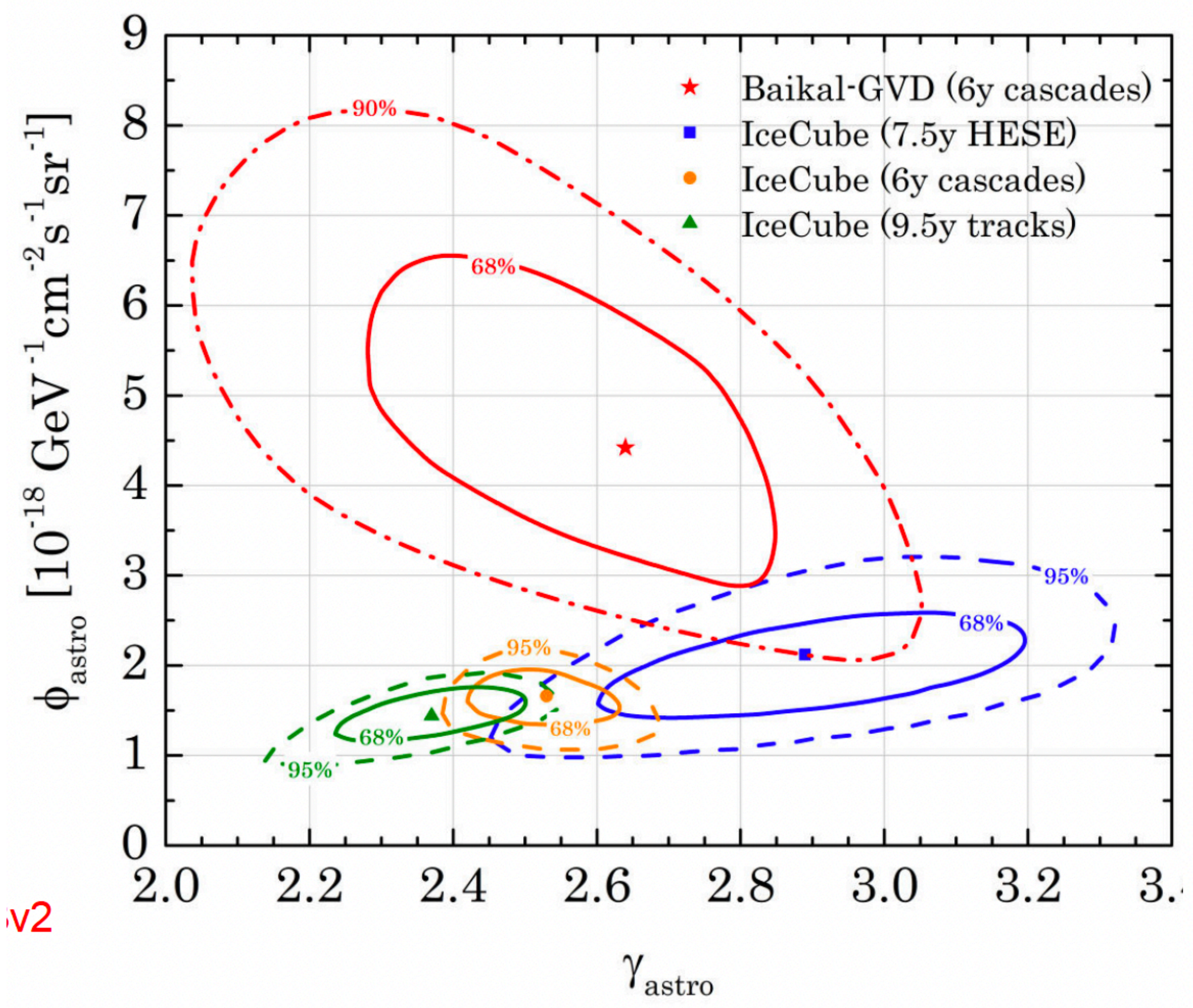
High energy neutrino astronomy *was* born with IceCube discovery of diffuse cosmic neutrino flux (HESE xx years) *Science 342 (2013)*
add fig

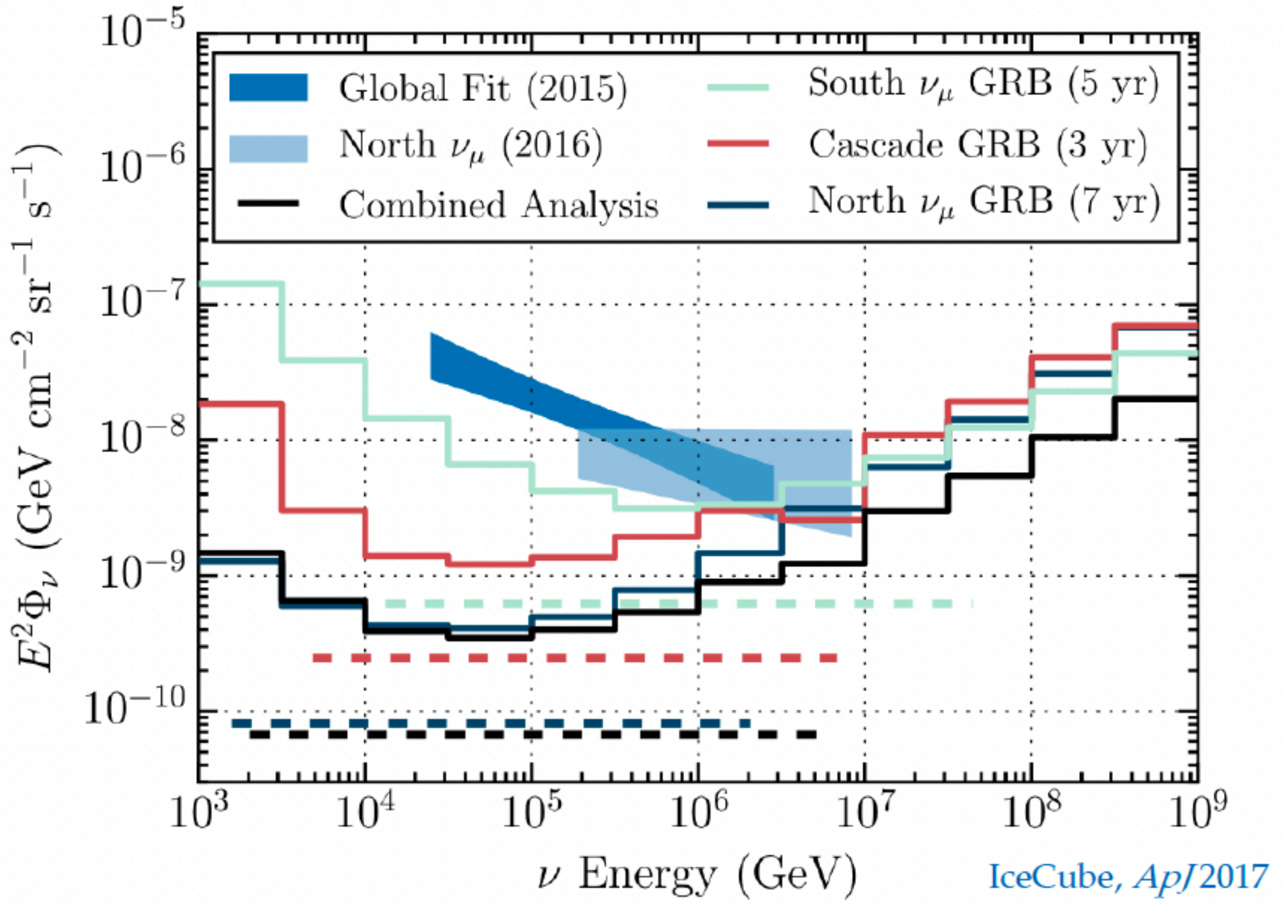
Following observations of diffuse cosmic neutrino flux in different cascade and track analysis

First independent observation of diffuse cosmic neutrinos at 5.1 sigma, flux larger than IceCube

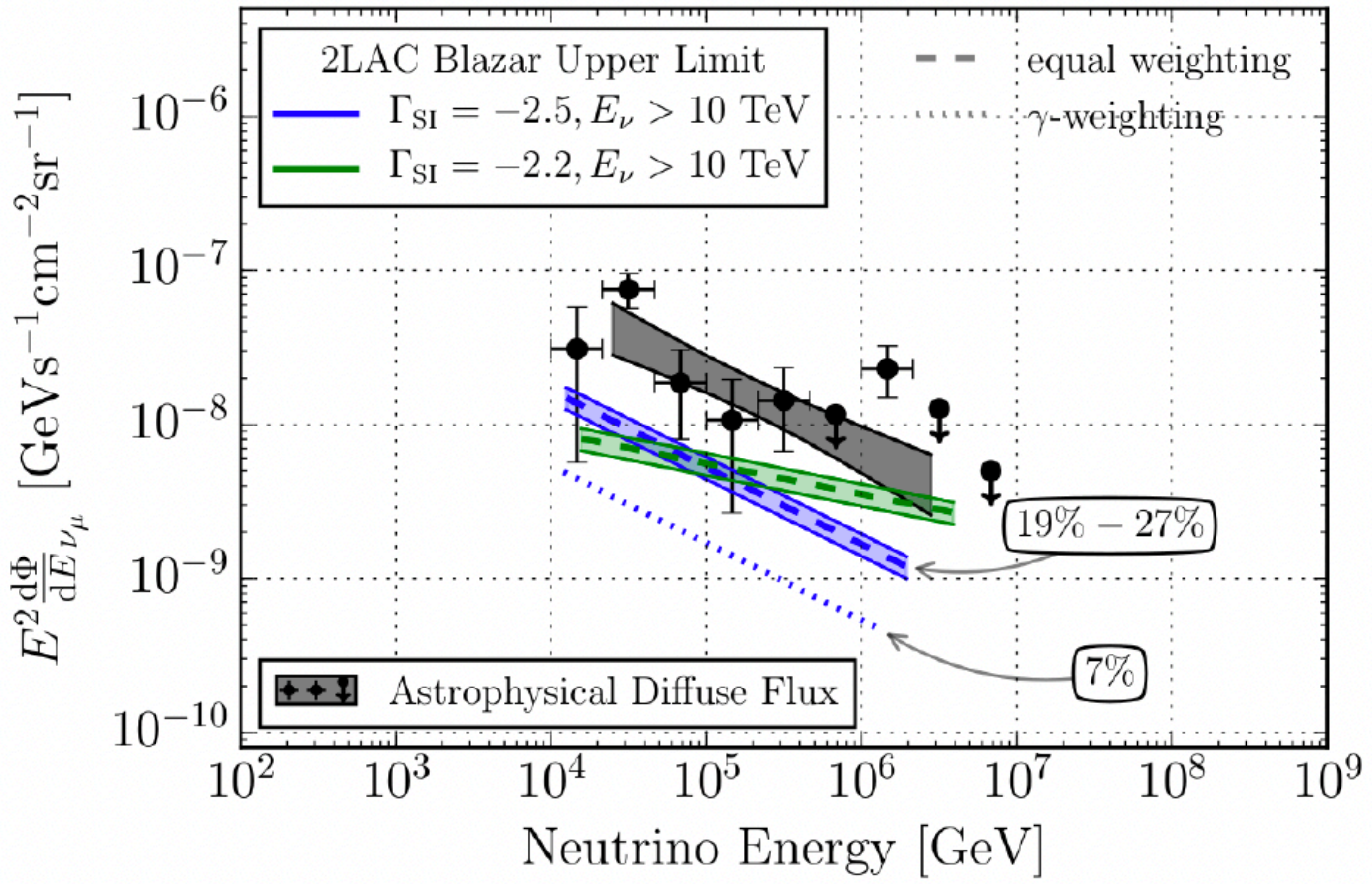
Diffuse cosmic neutrino flux (2013)

v2



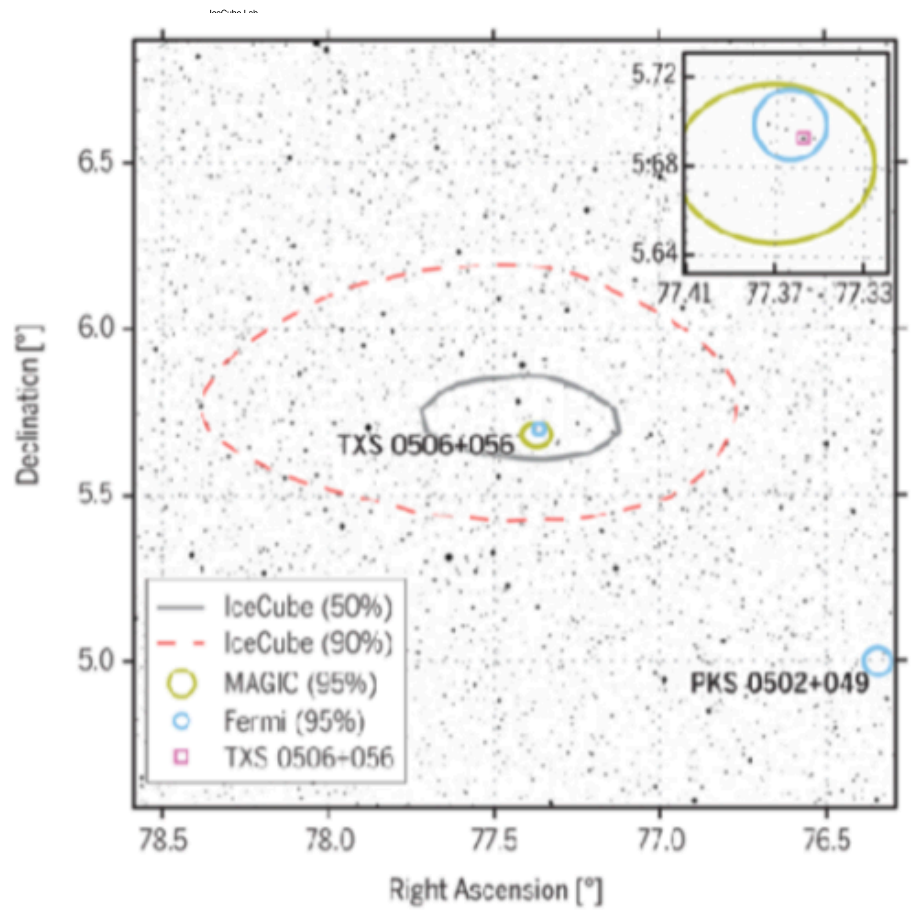


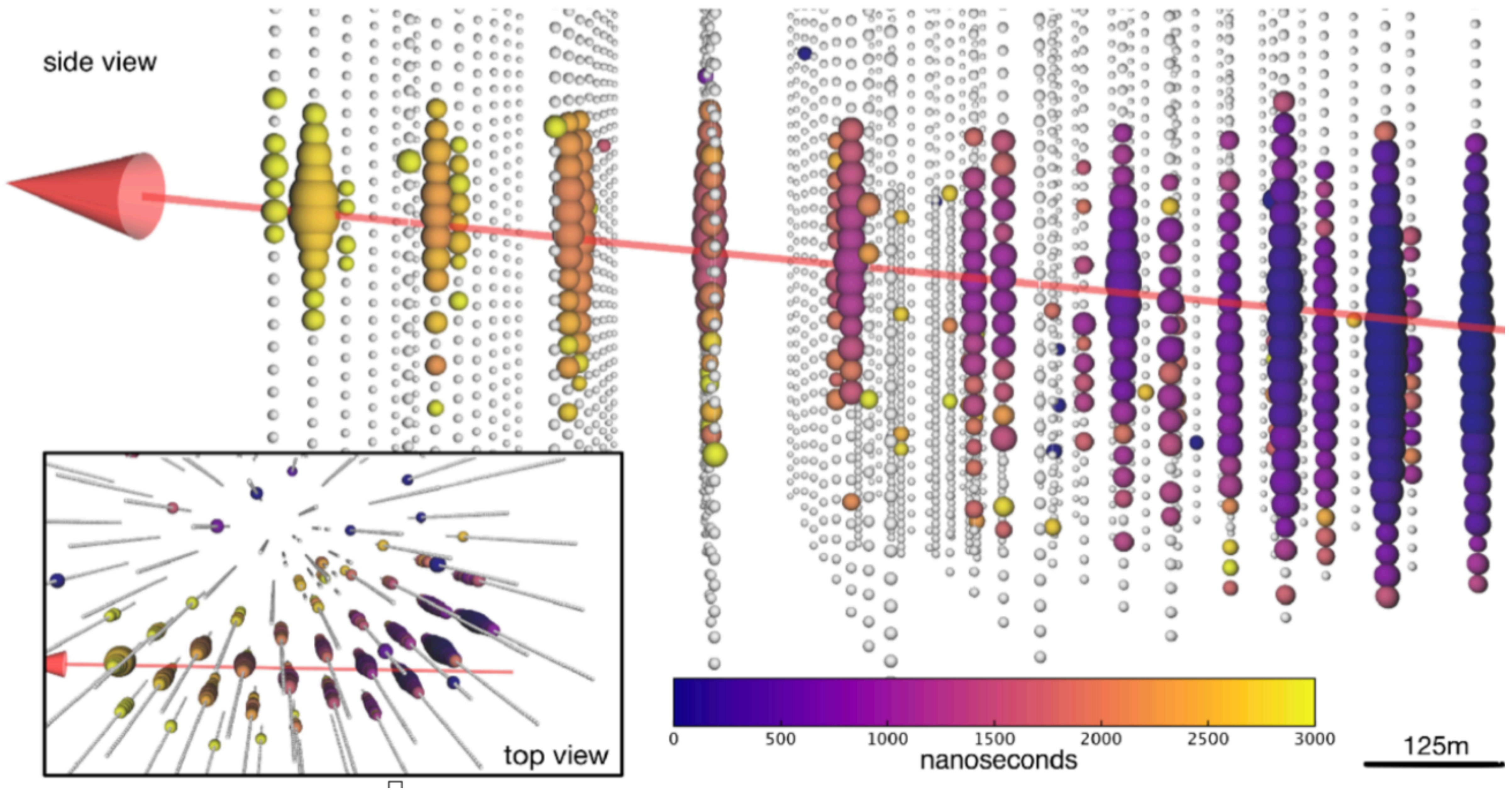
1172 GRBs inspected, no correlation found
< 1% contribution to diffuse flux



862 blazars inspected, no correlation found
< 27% contribution to diffuse flux

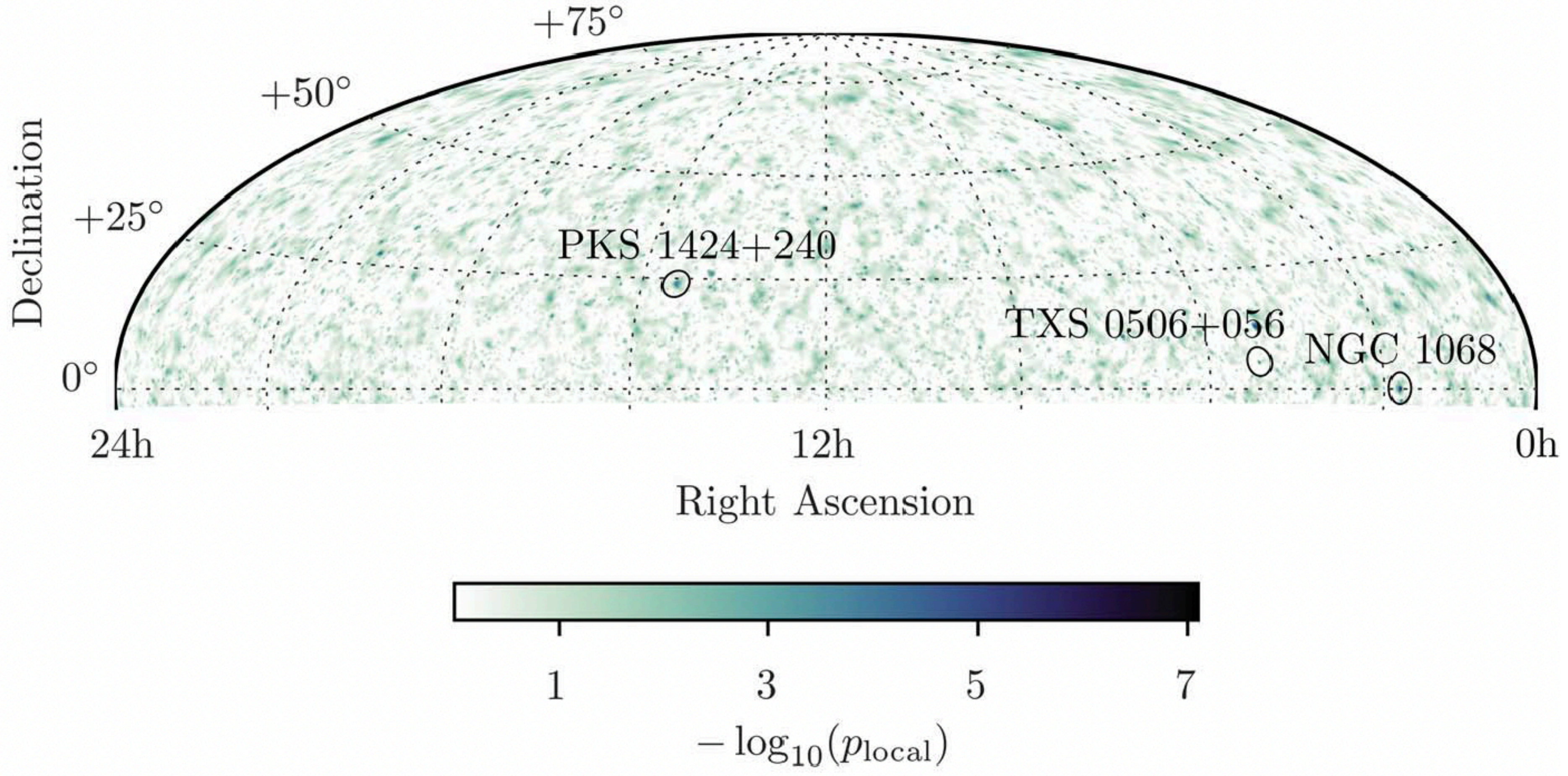
Multimessenger neutrino alert



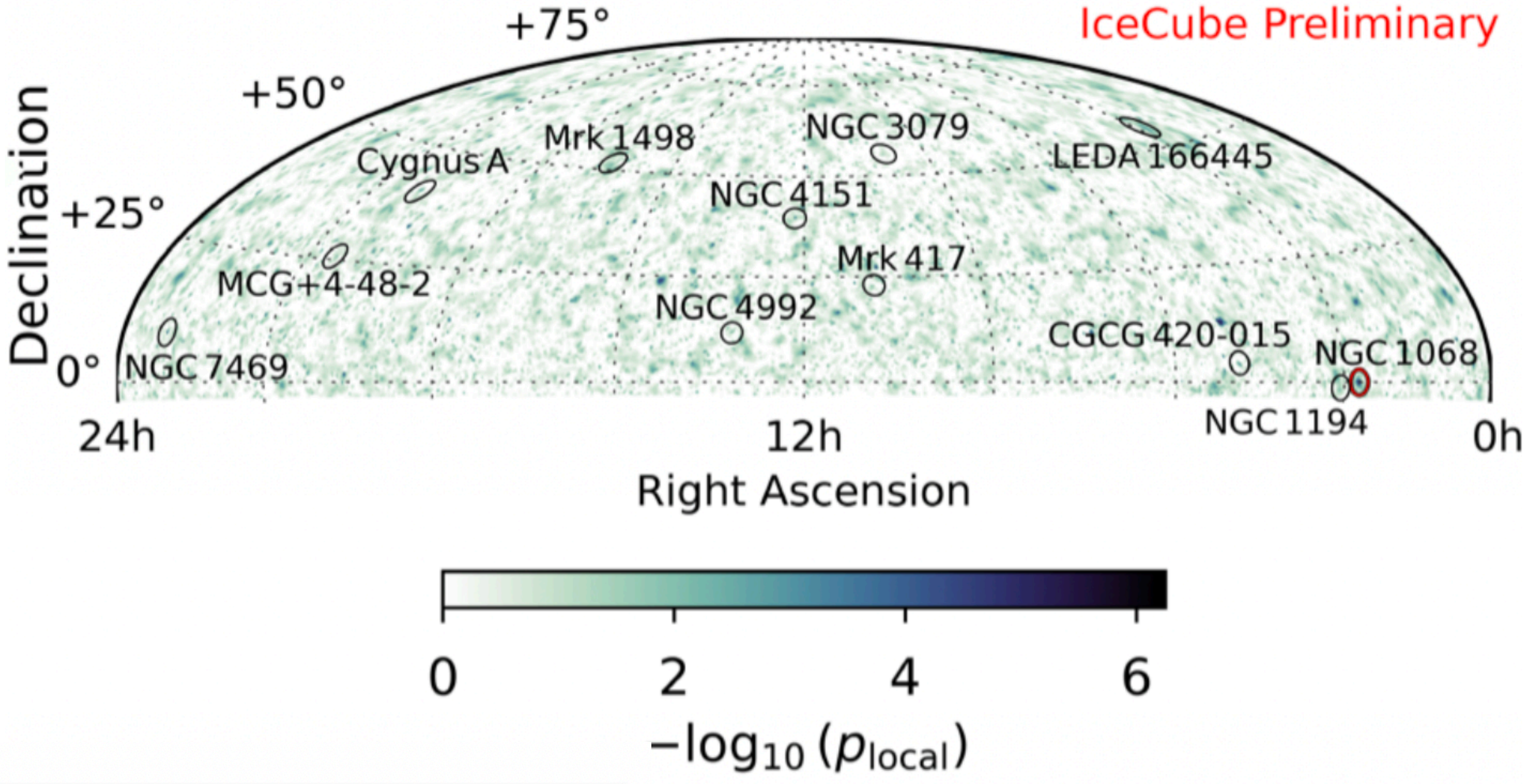


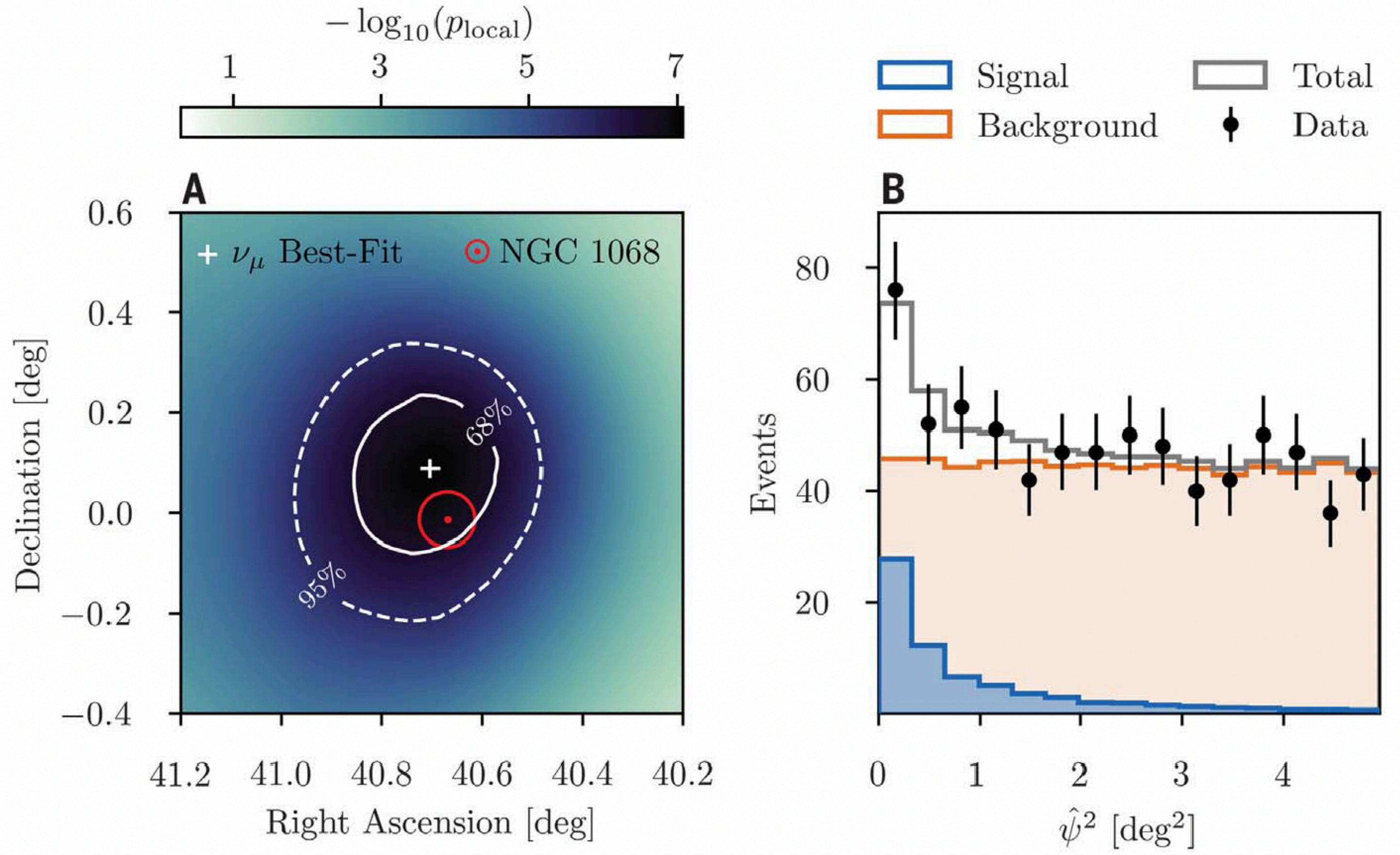
IceCube - Point-like sources

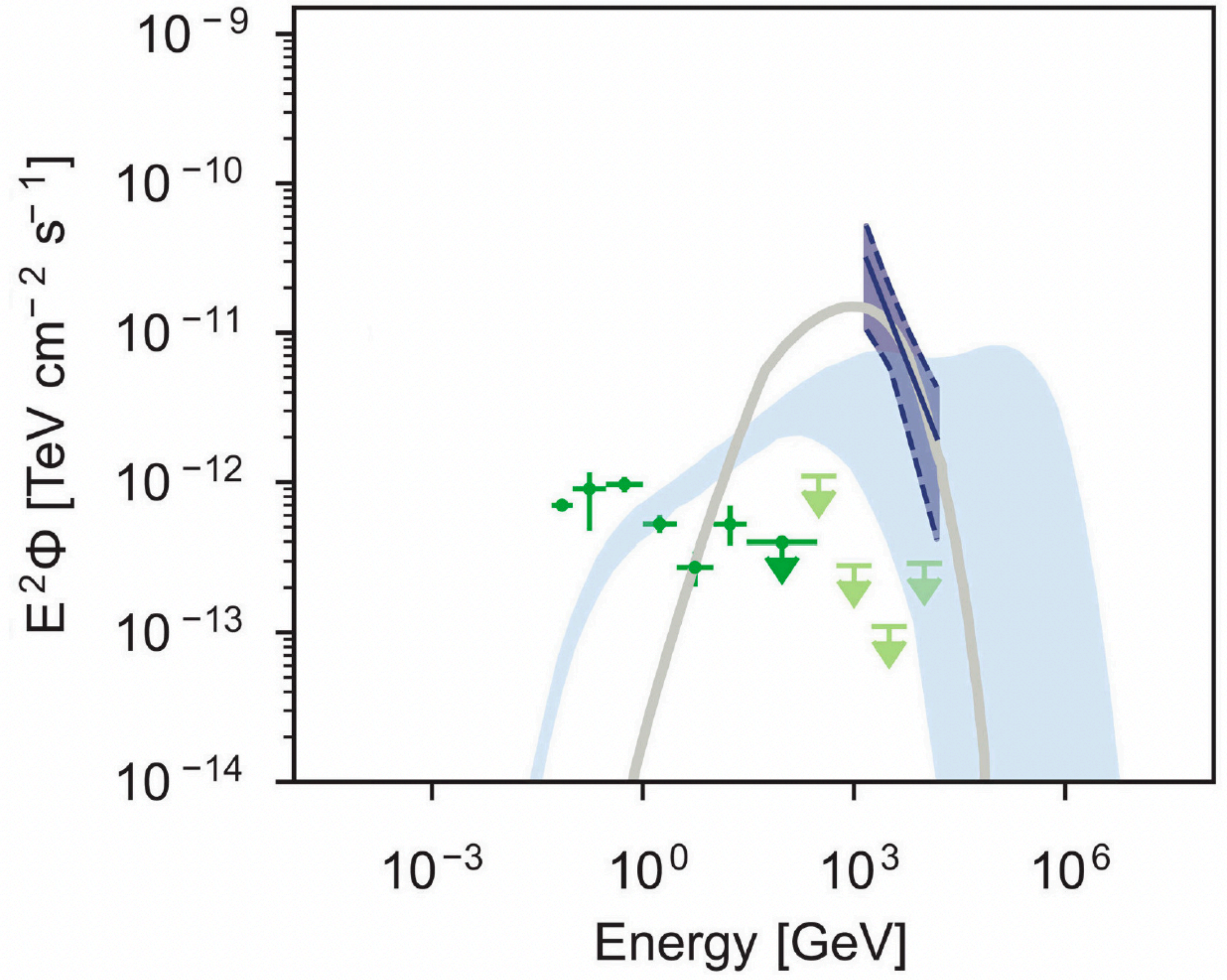
The first neutrino steady source NGC1068, Science 378, 538 (2022)

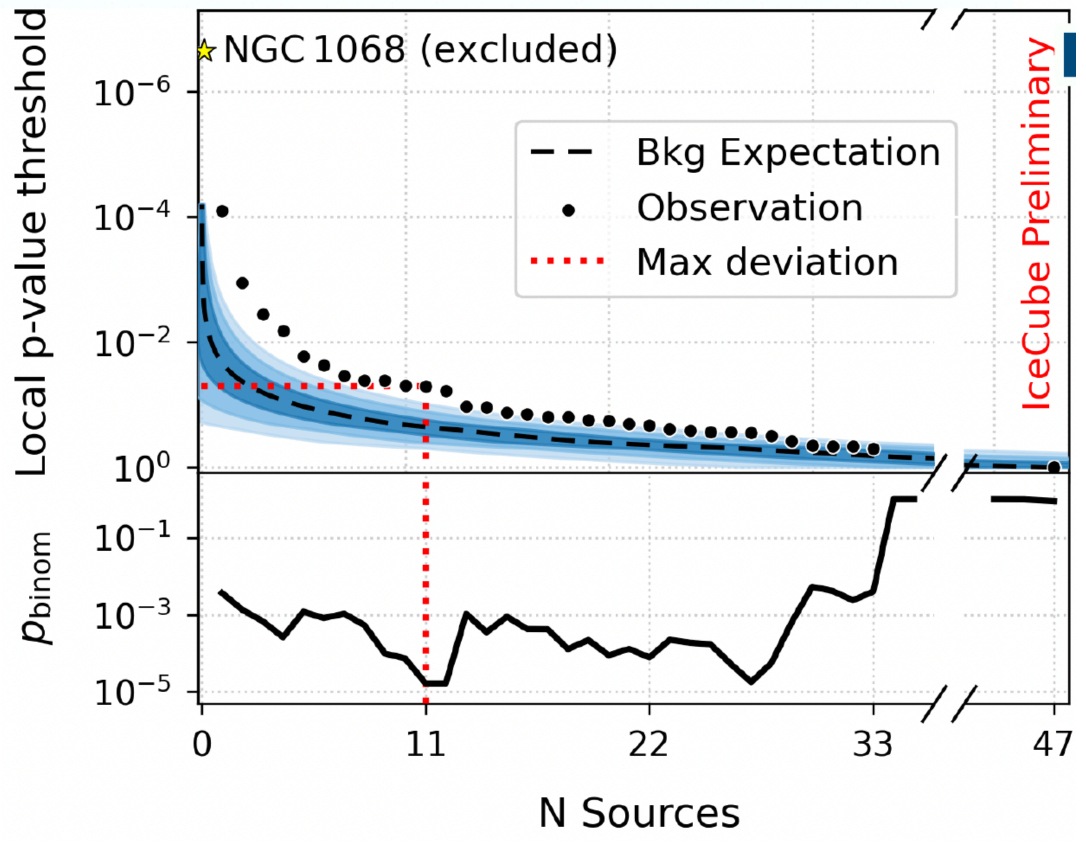


Search for neutrinos from Seyfert Galaxies









High-energy neutrinos detection at 4.2 sigma from active galaxy NGC 1068 powered by supermassive black hole
Flux more than an order of magnitude higher than the upper limit on emissions of TeV gamma rays (Fermi in green)

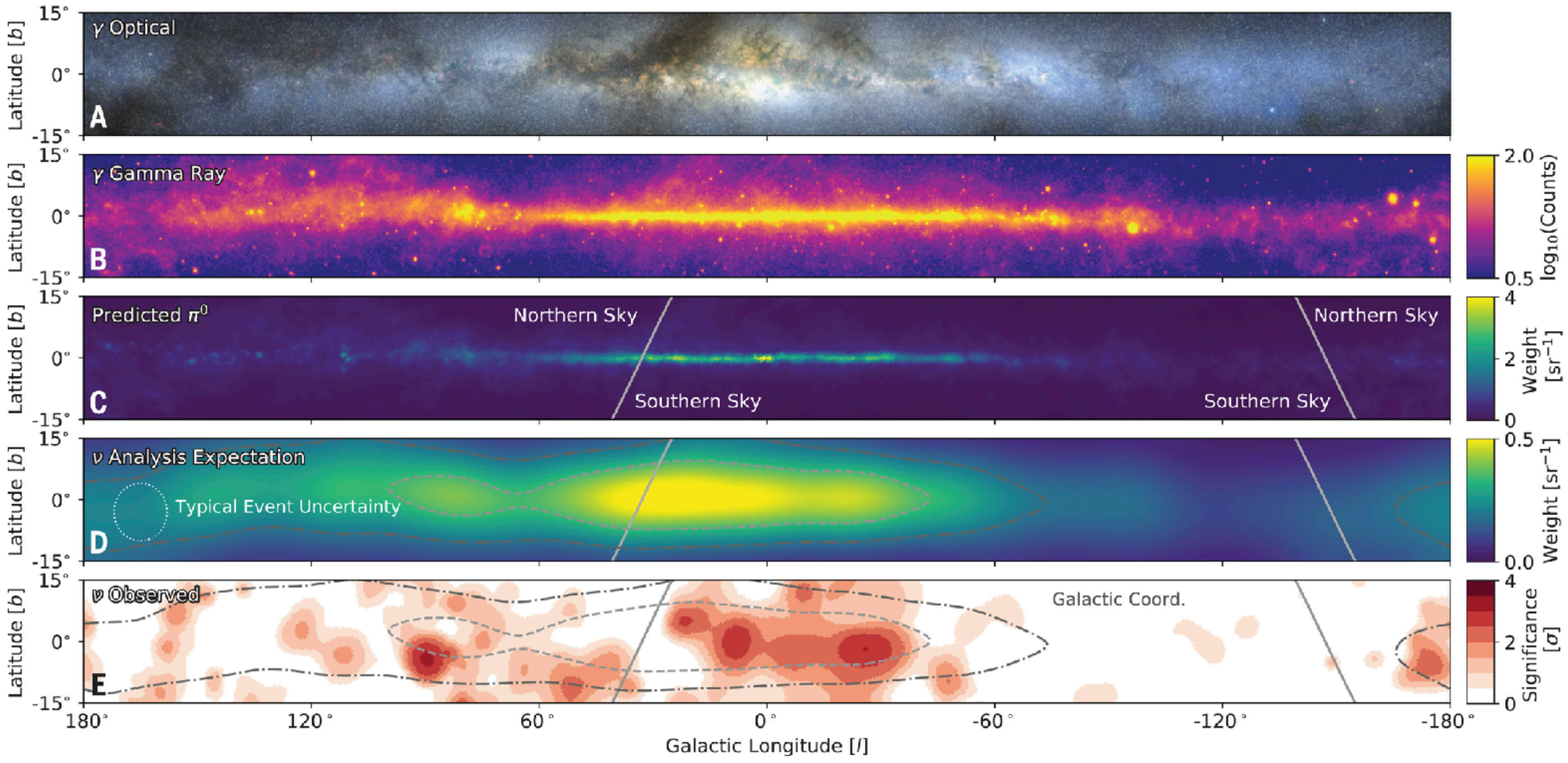
3.3 sigma excess observed stacking 11 sources over 47 (NGC 1068 excluded)

Aguilar-Sanchez Neutrino 2024

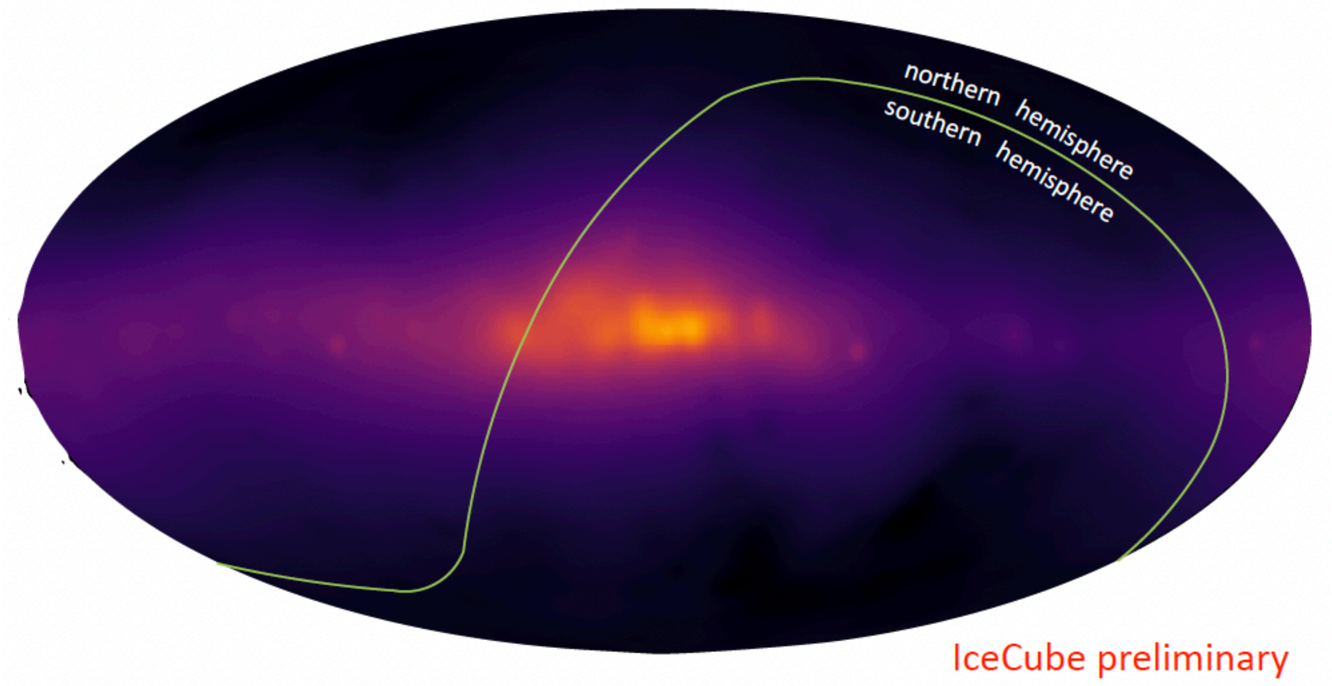
IceCube - Galactic Plane

Neutrino detection from Galactic Plane at 4.5 sigma Science (2023)

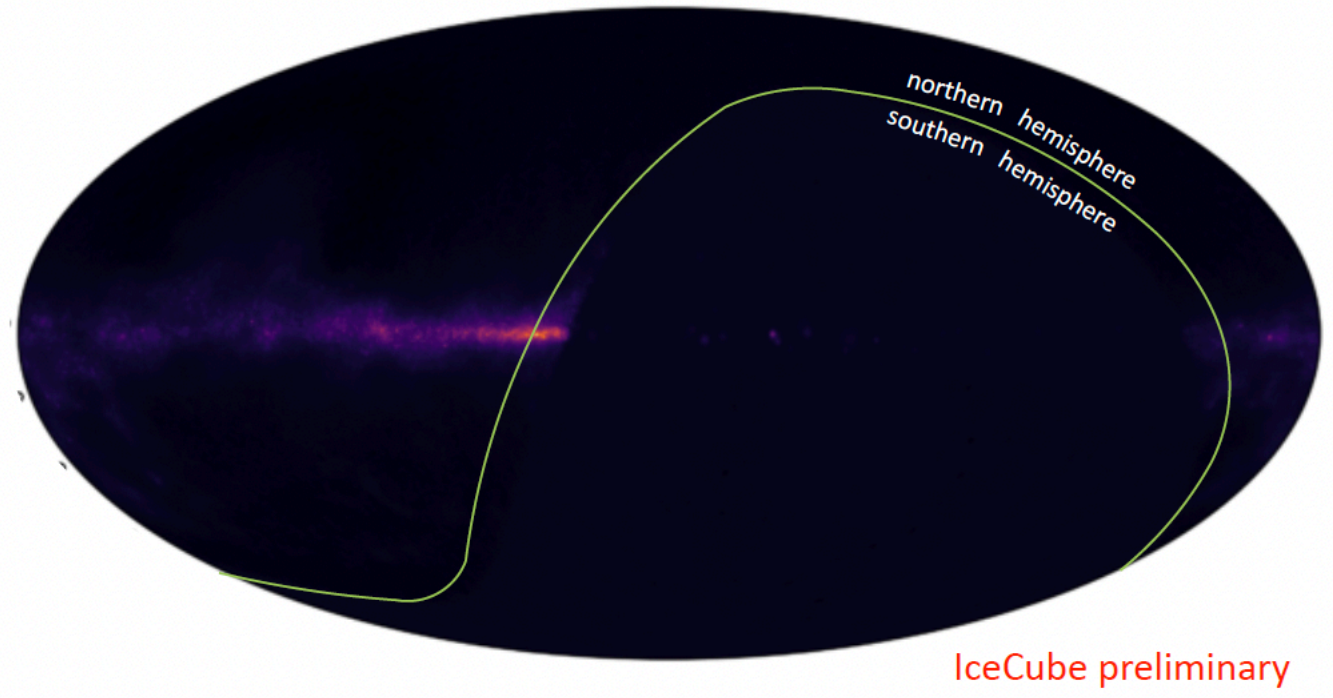
Observed flux does not agree with galactic diffuse models show?



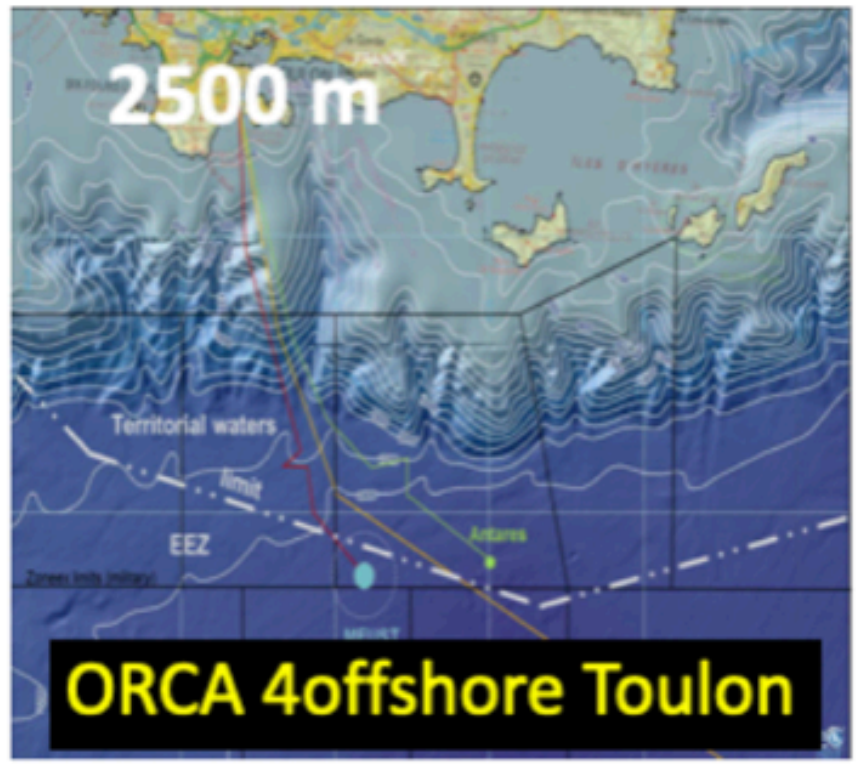
TS cascades (π^0)



TS tracks (π^0)

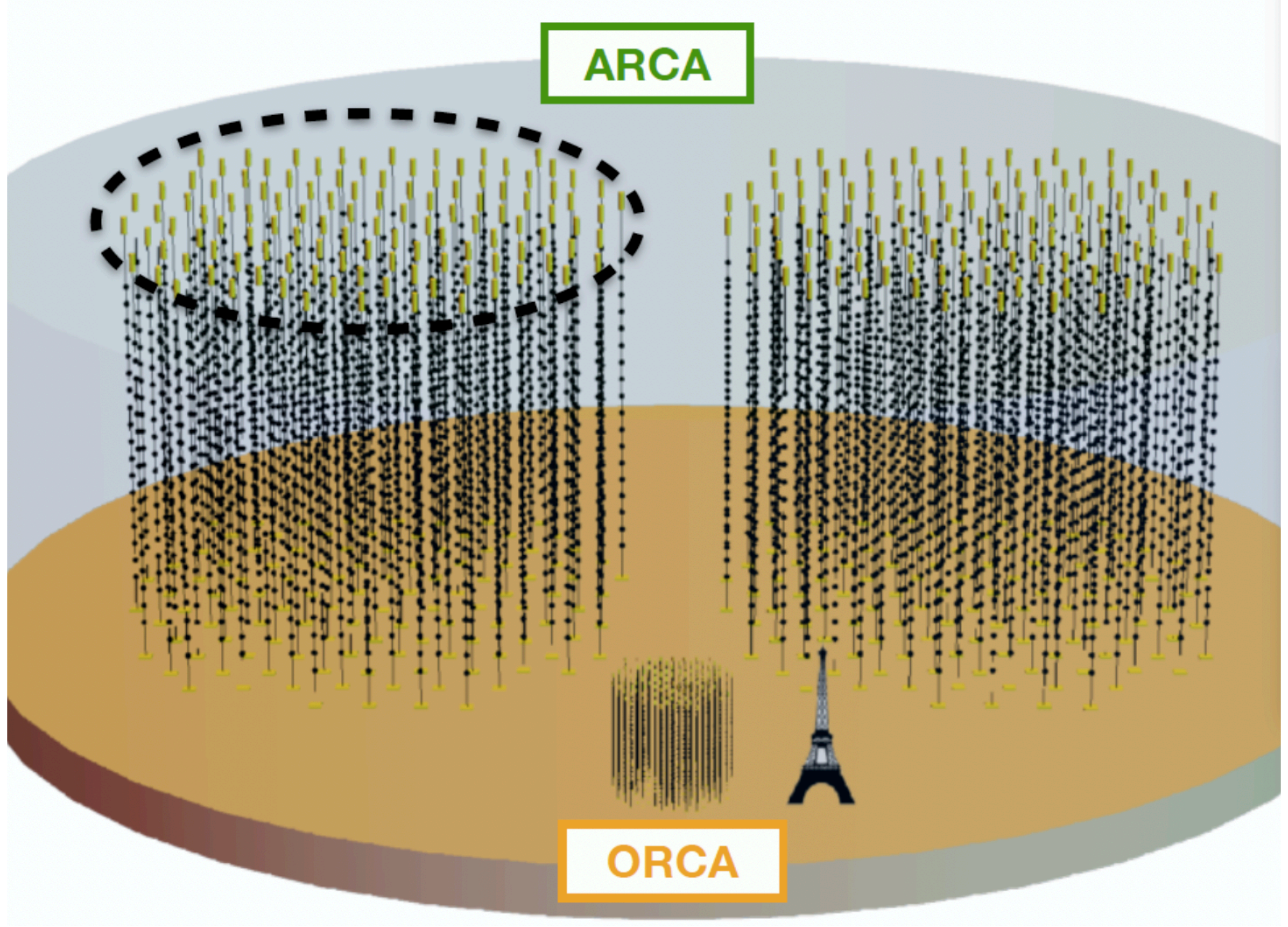


KM3NeT - a distributed infrastructure

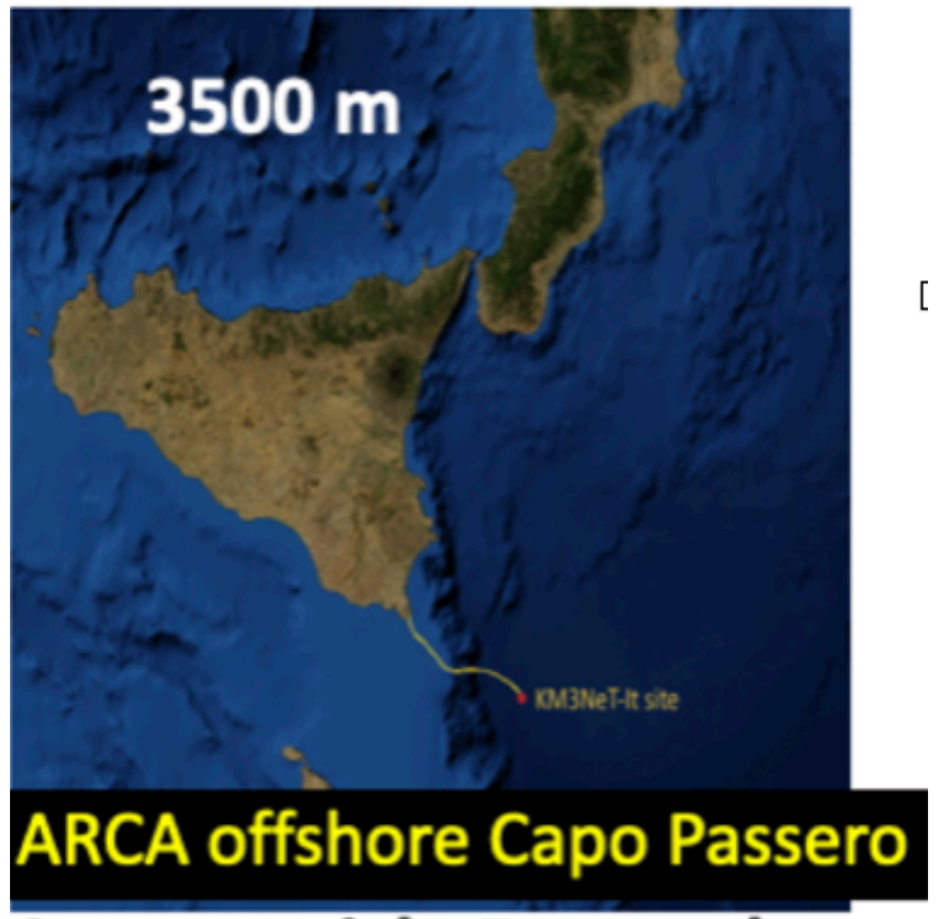


Two telescopes, one technology

- innovative with multi-PMT DOM that inspired several new projects



Oscillation Research with Cosmics In the Abyss

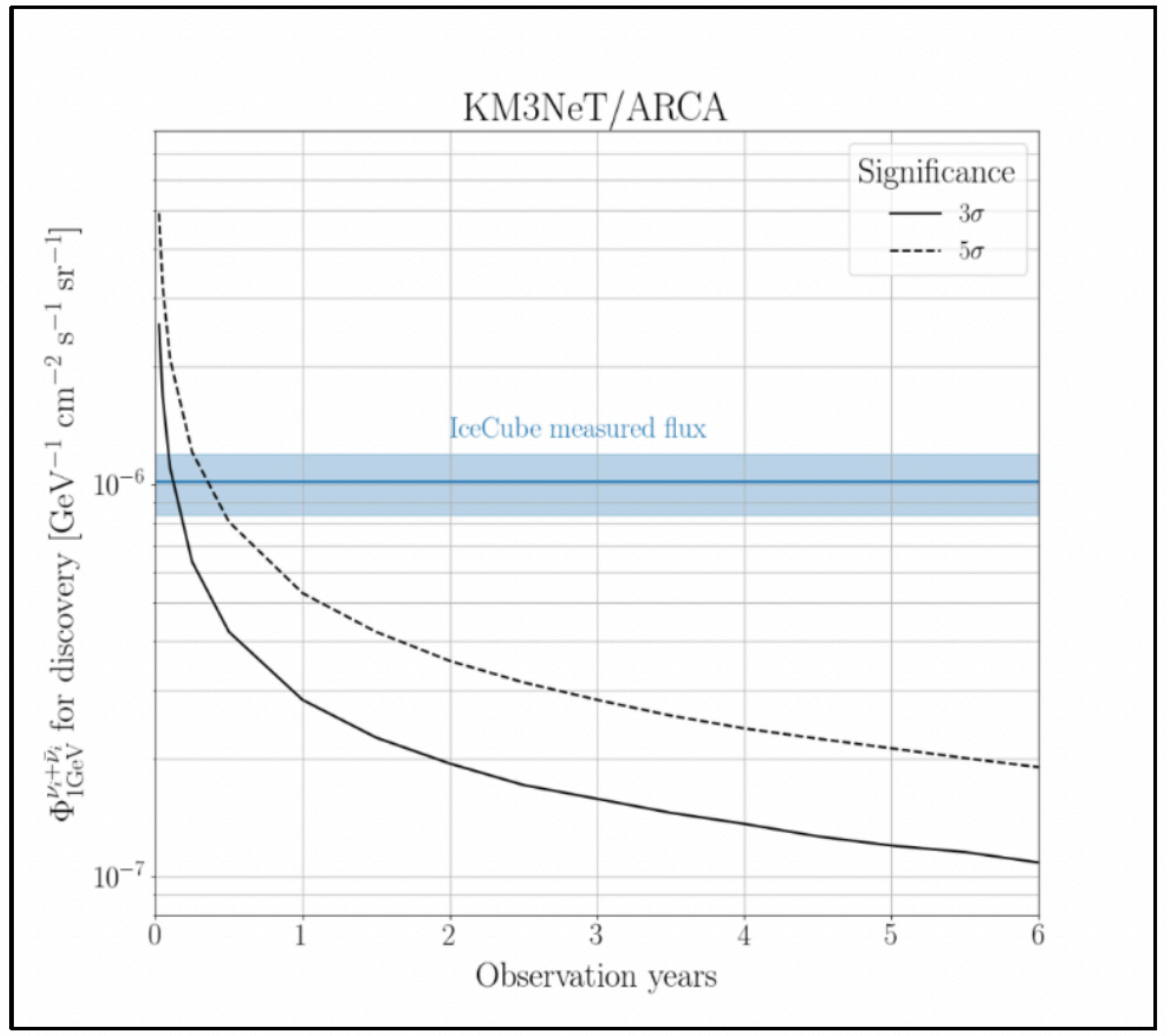


Astroparticle Research with Cosmics In the Abyss

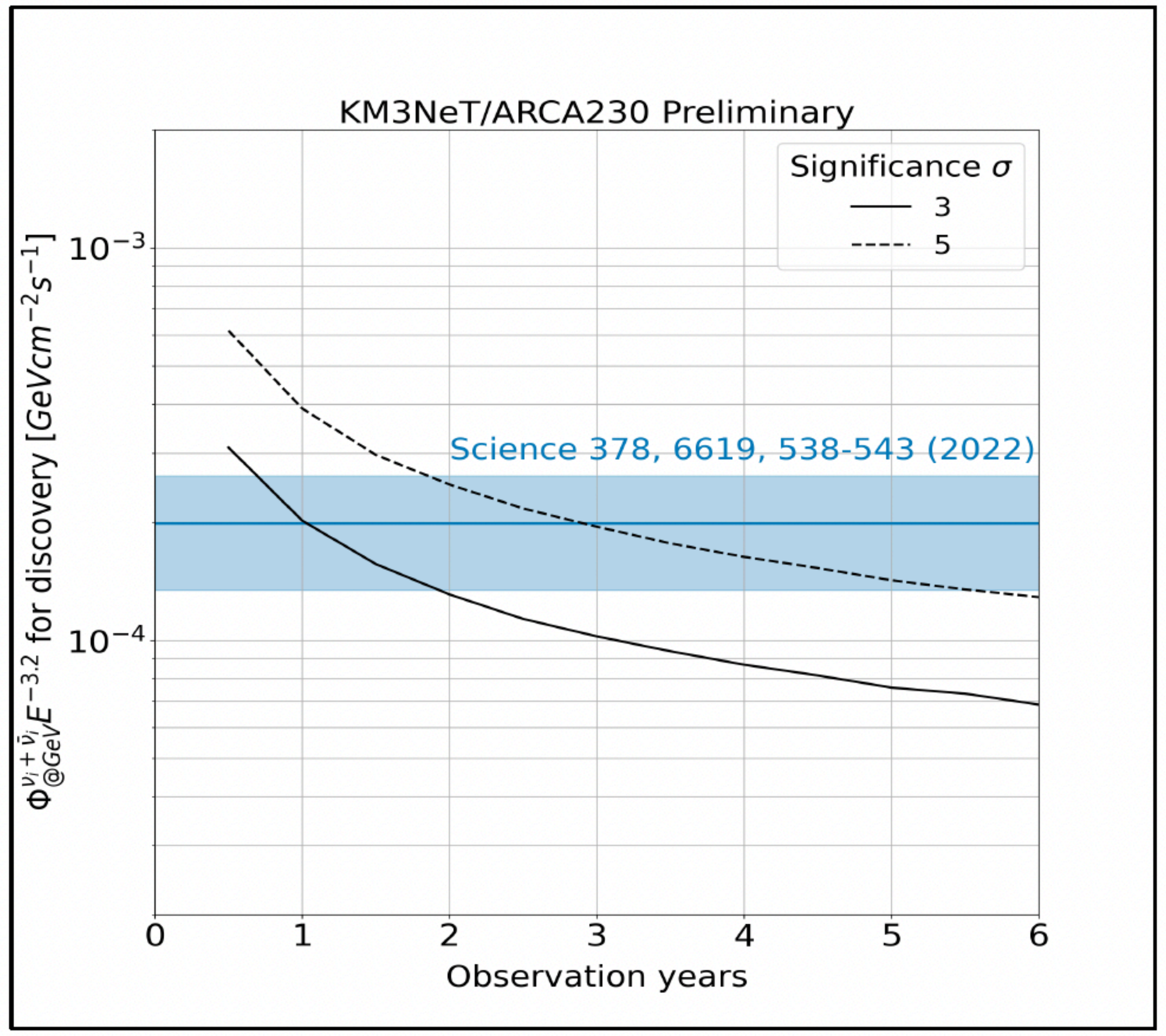
Building blocks of 115 strings
DOM distance => Energy range
ARCA 2BB 1 km^3
51/230 strings deployed
ORCA 1 BB 7 Mton
28/115 strings deployed

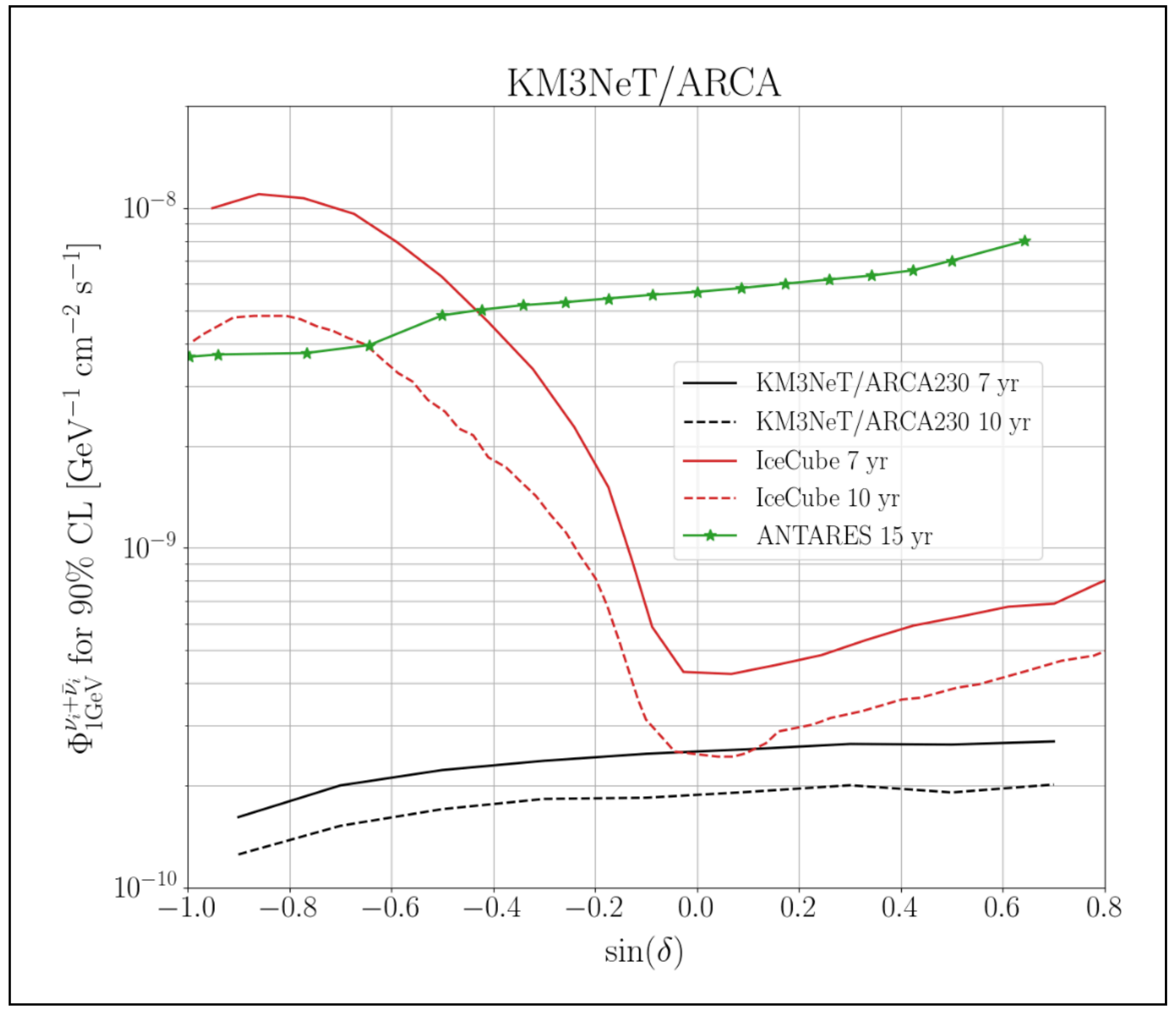
KM3NeT with its large effective area, sky visibility and unprecedented angular resolution will improve neutrino discovery potential especially for point-like sources

Diffuse flux



NGC1068





Eur. Phys. J. C 84, 885 (2024)

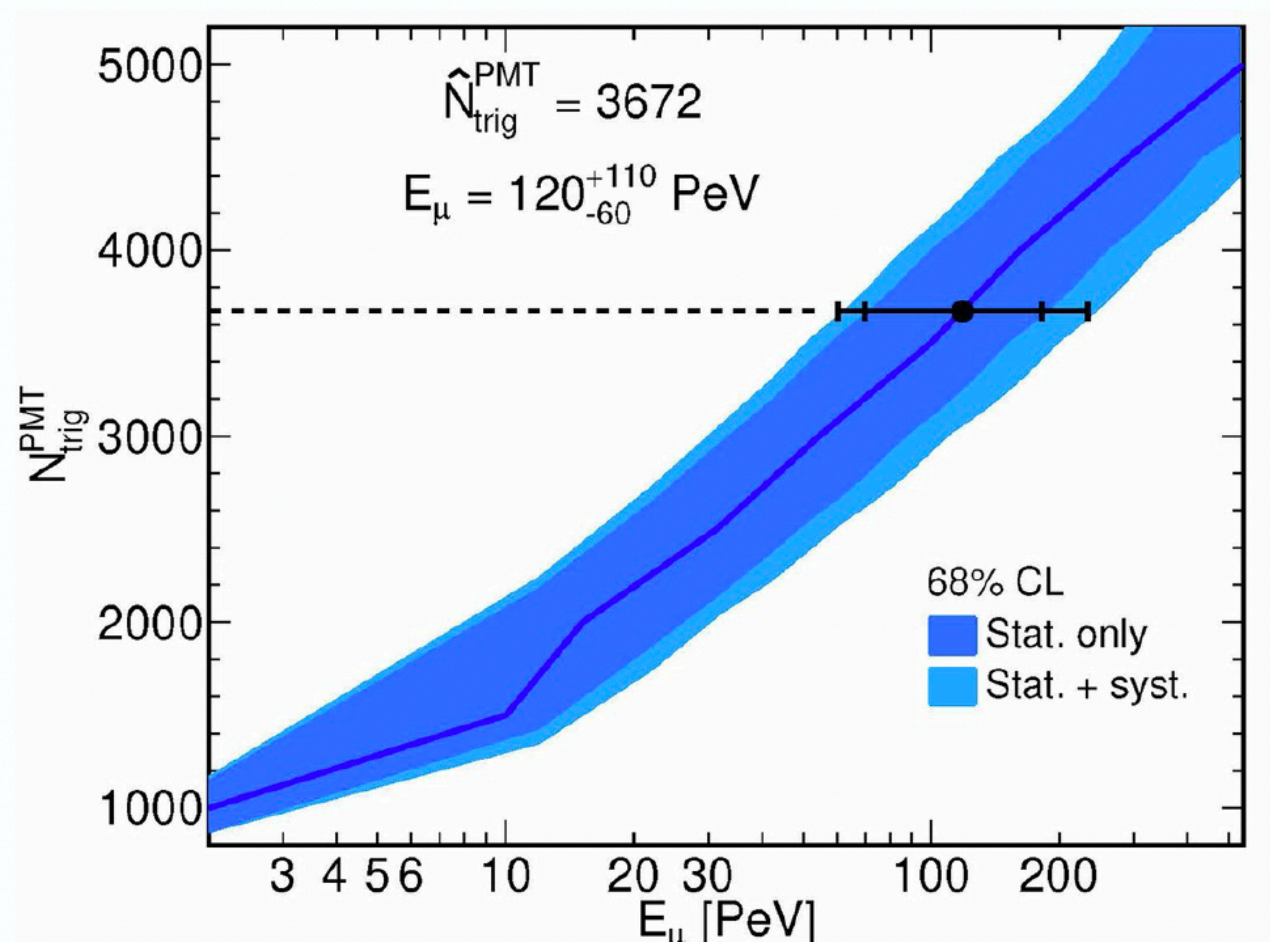
Uncharted territory: breaking into a new energy regime

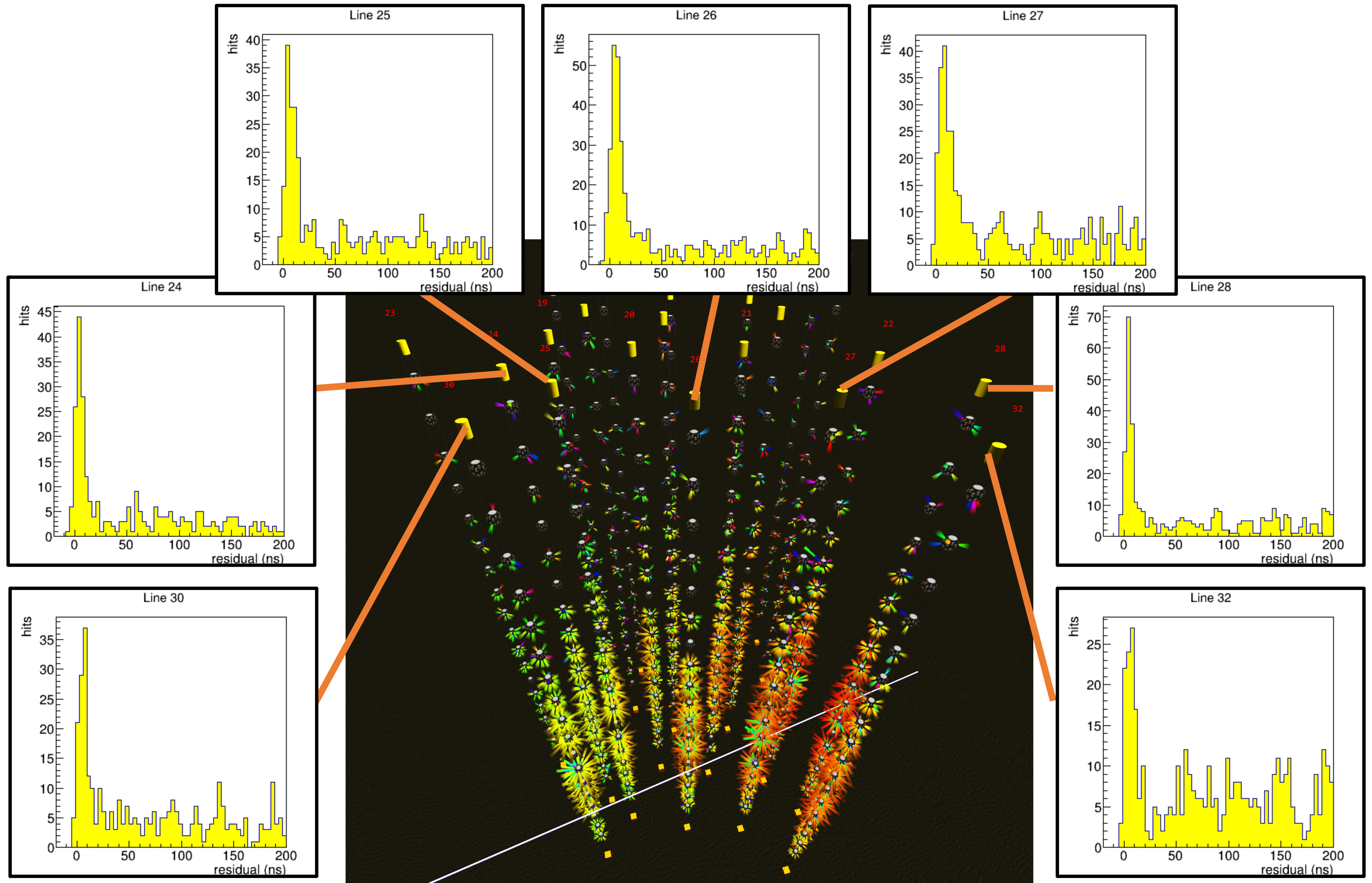
KM3NeT still in construction, detected the most energetic neutrino ever seen *Nature* **638**, 376–382 (2025)

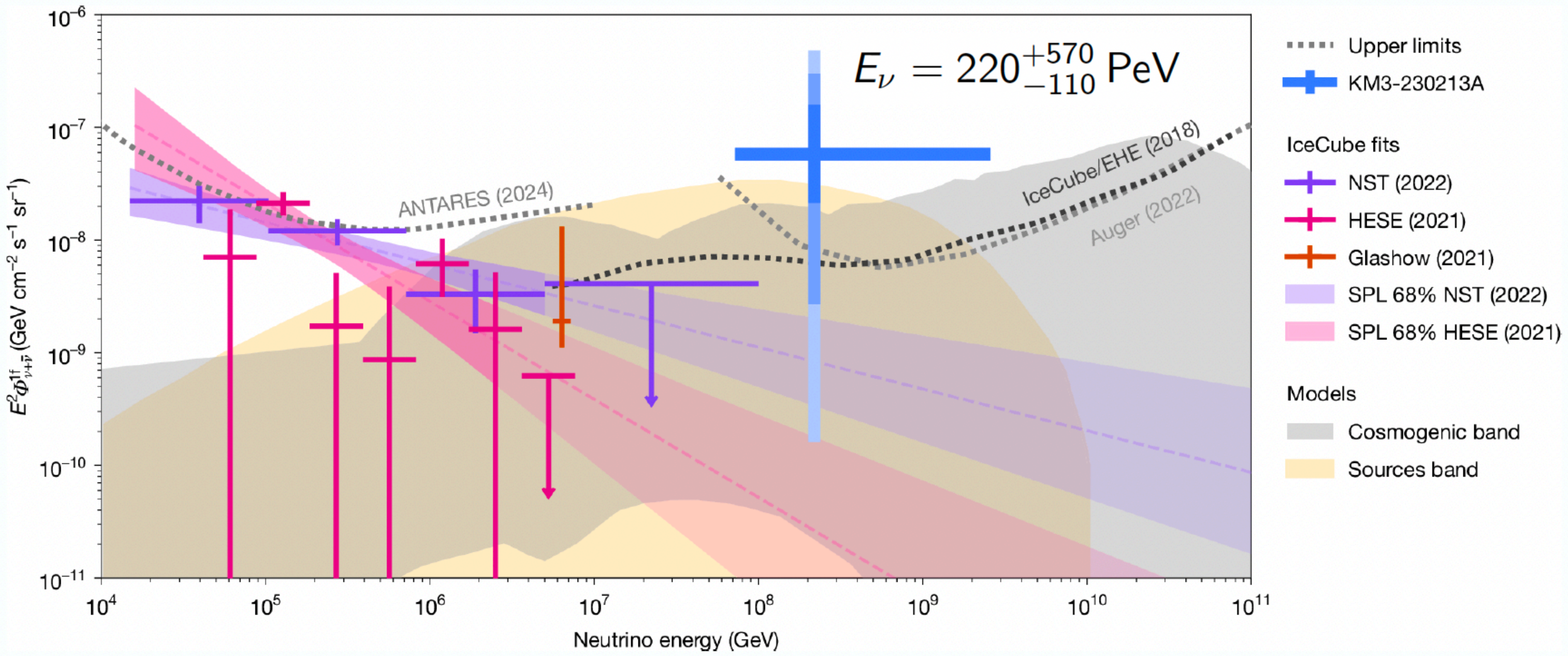
Local coordinates: (zenith, azimuth) = (89.4°, 259.8°):

- **Celestial coordinates: (RA, dec) = (94.3°, –7.8°)**
- R(68%) = 1.5°, R(90%) = 2.2°, R(99%) = 3.0°
- Limited by the absolute positioning of the detection elements (intrinsic reconstruction uncertainty of 0.12°)

A long baseline acoustic array deployed in July 2025 will allow more precise data (re)calibration







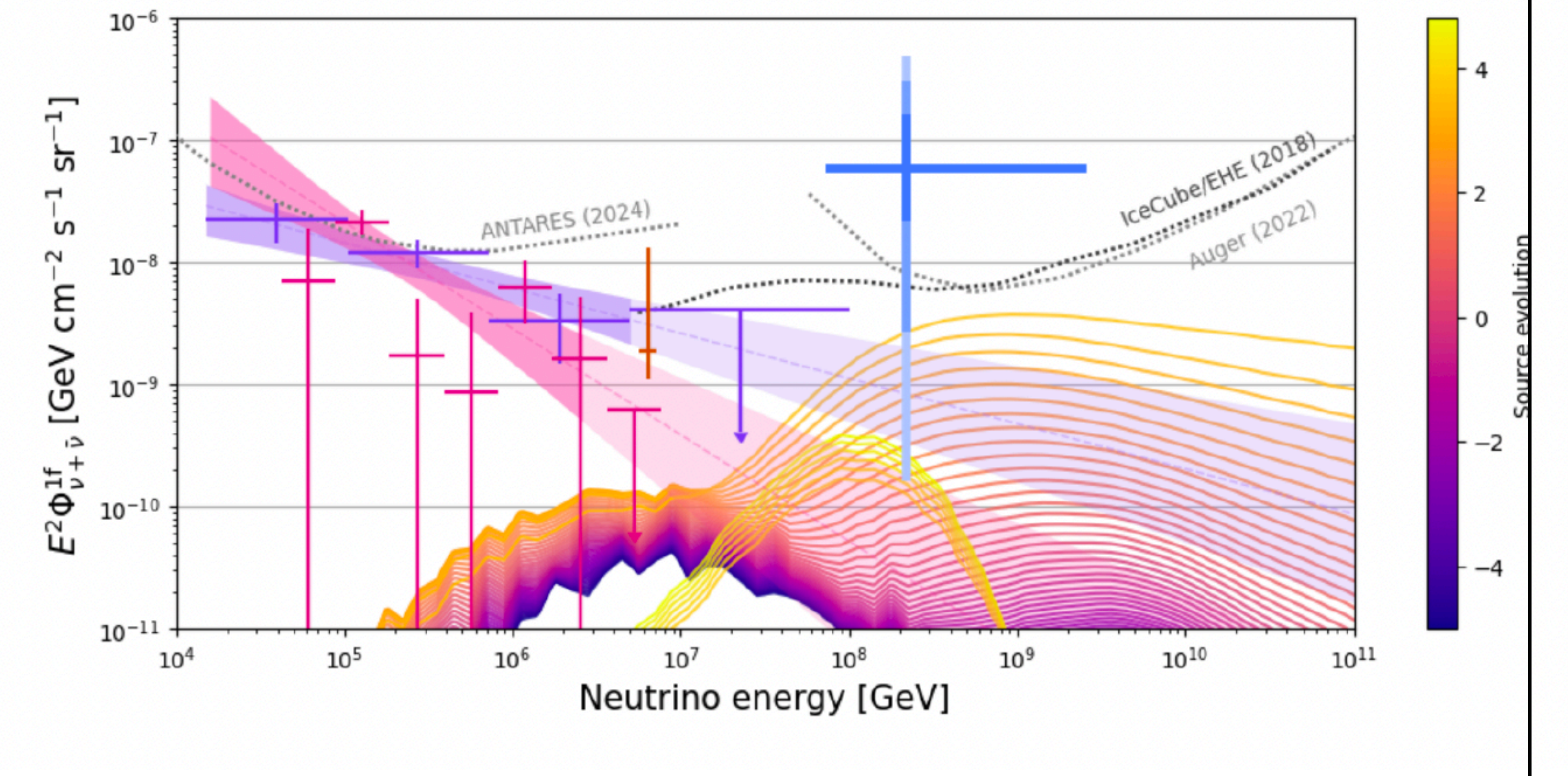
Moderated tension with IceCube and Auger no observations (2.5 sigma)

KM3-230213 1st UHE neutrino

UHE neutrino can be cosmogenic or produced in most powerful accelerators such AGN, GRB, TDE,…

On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A - 2025 *ApJL* **984** L41

- constrains on Auger+ TA UHECR data
- subdominant fraction of proton at UHE
- high z

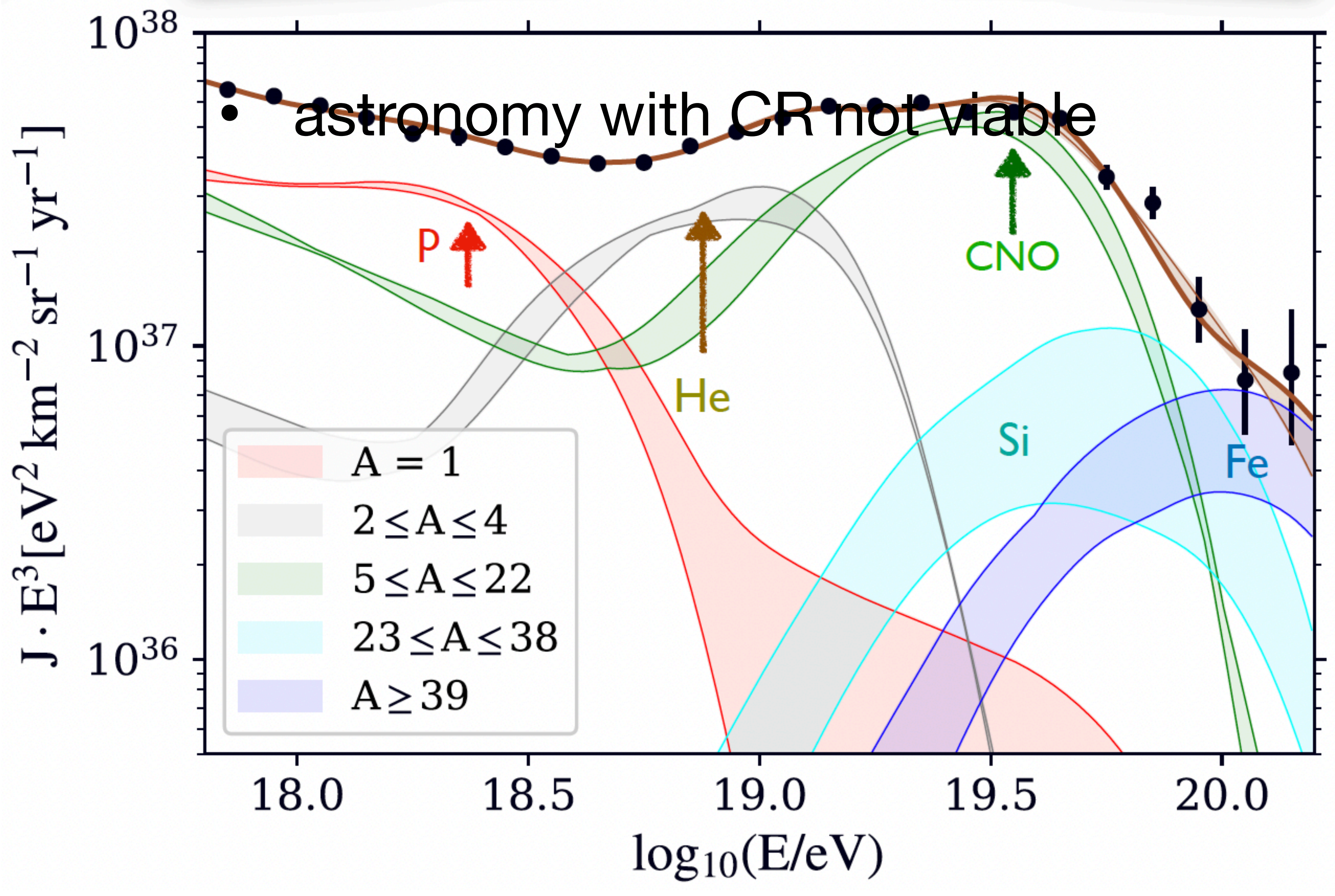


Exotics interpretations have also been proposed….

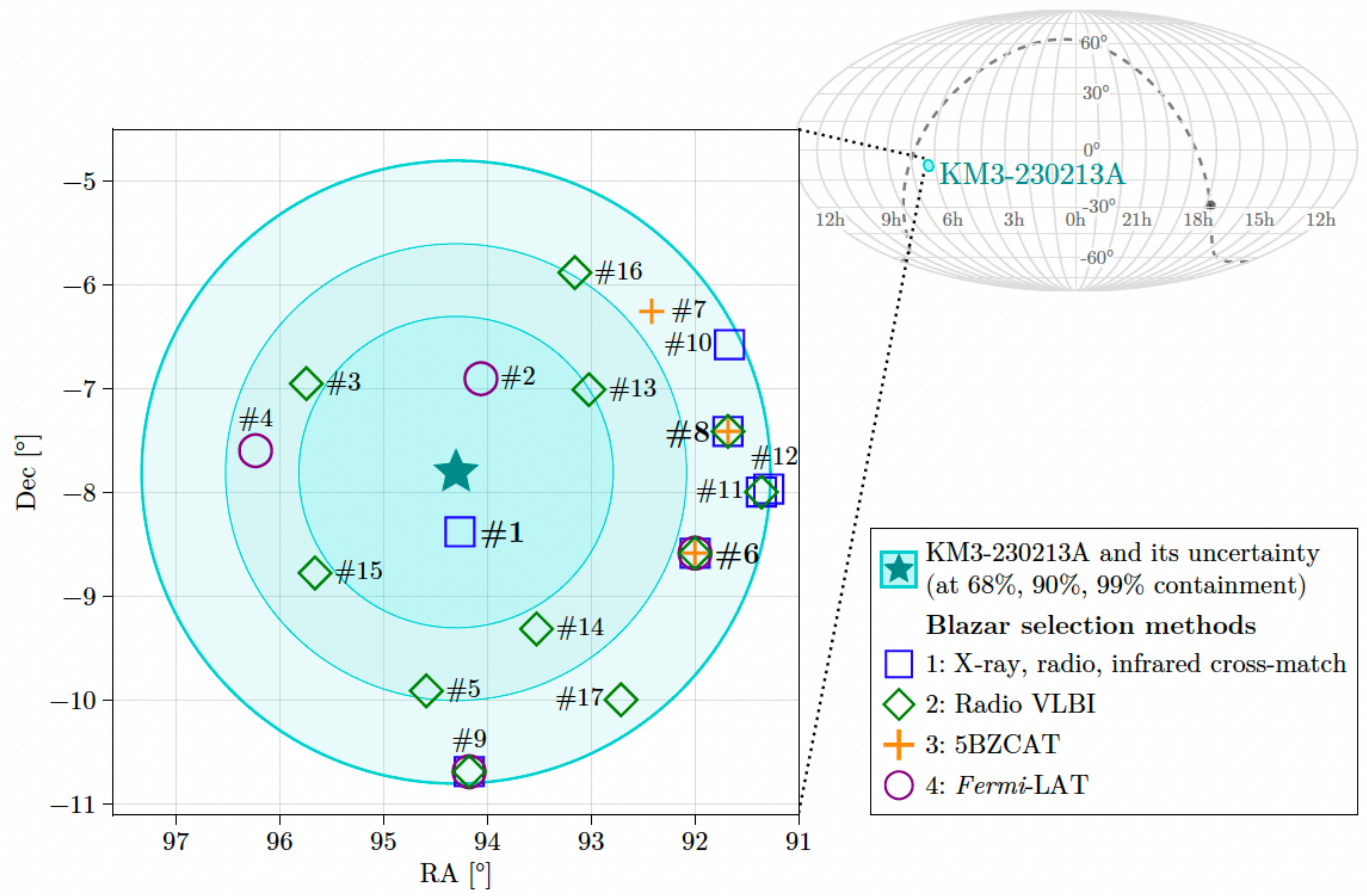
The cut-off observed at the highest energies has been a hot topic for many years

Auger very detailed studies in particular on mass composition studies exclude

- a large fraction of protons at highest energy
- GZK as dominant cause of spectral cut-off
- astronomy with CR not viable

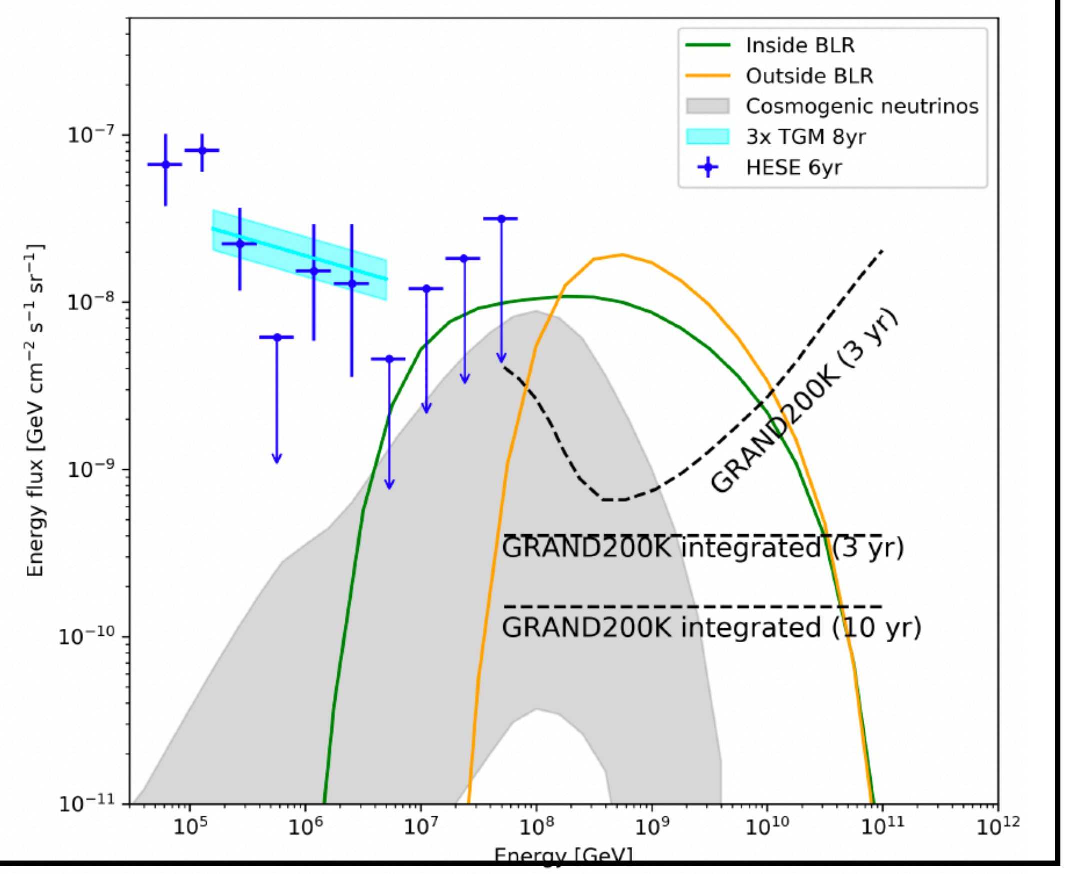


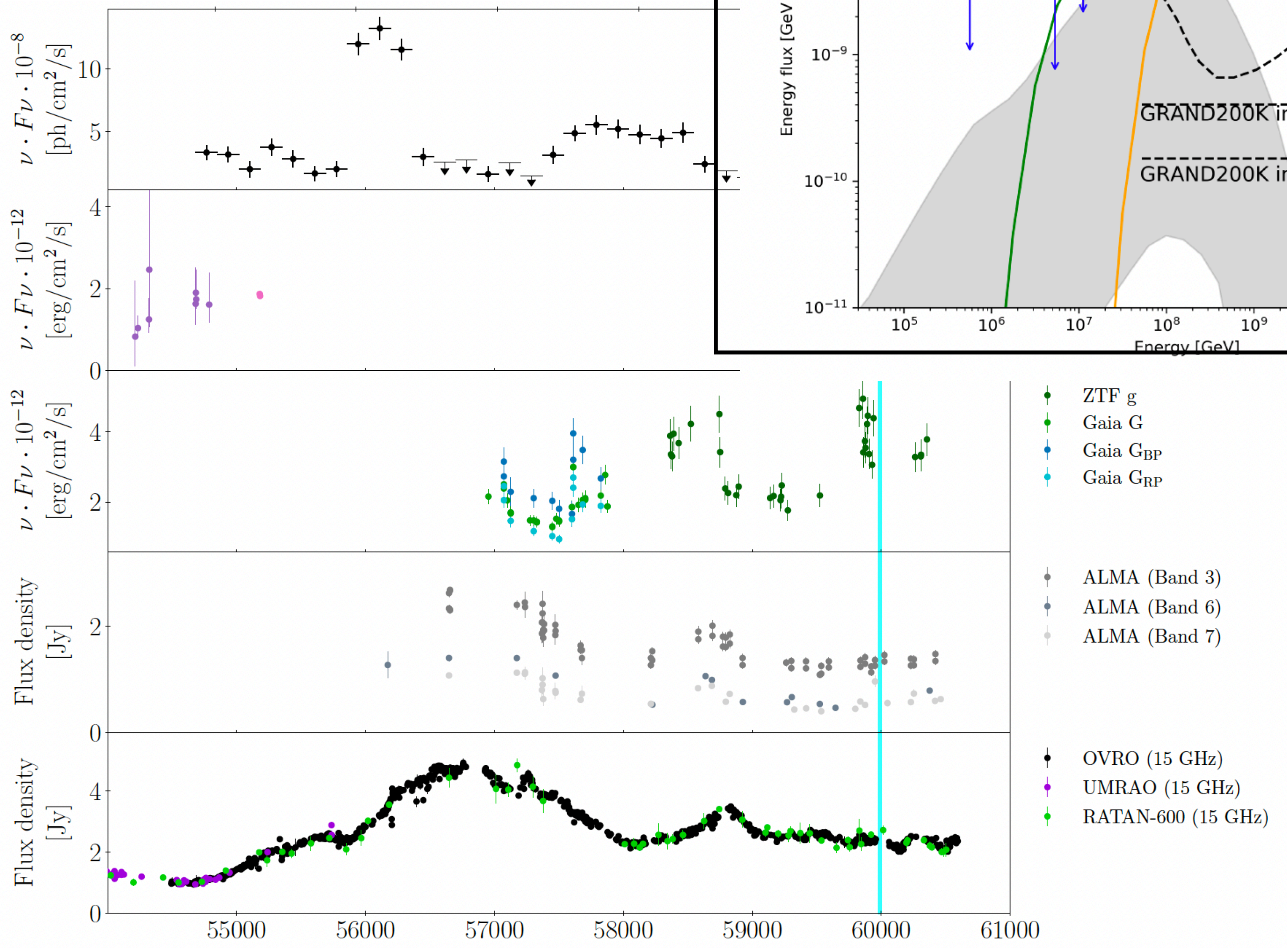
Characterising Candidate Blazar Counterparts of the Ultra-High-Energy Event KM3-230213A



KM3NeT collaboration arXiv: [2502.08484](https://arxiv.org/abs/2502.08484)

EeV Astrophysical neutrinos from FSRQs? C. Righi et al, Astronomy&Astrophysics (2020)

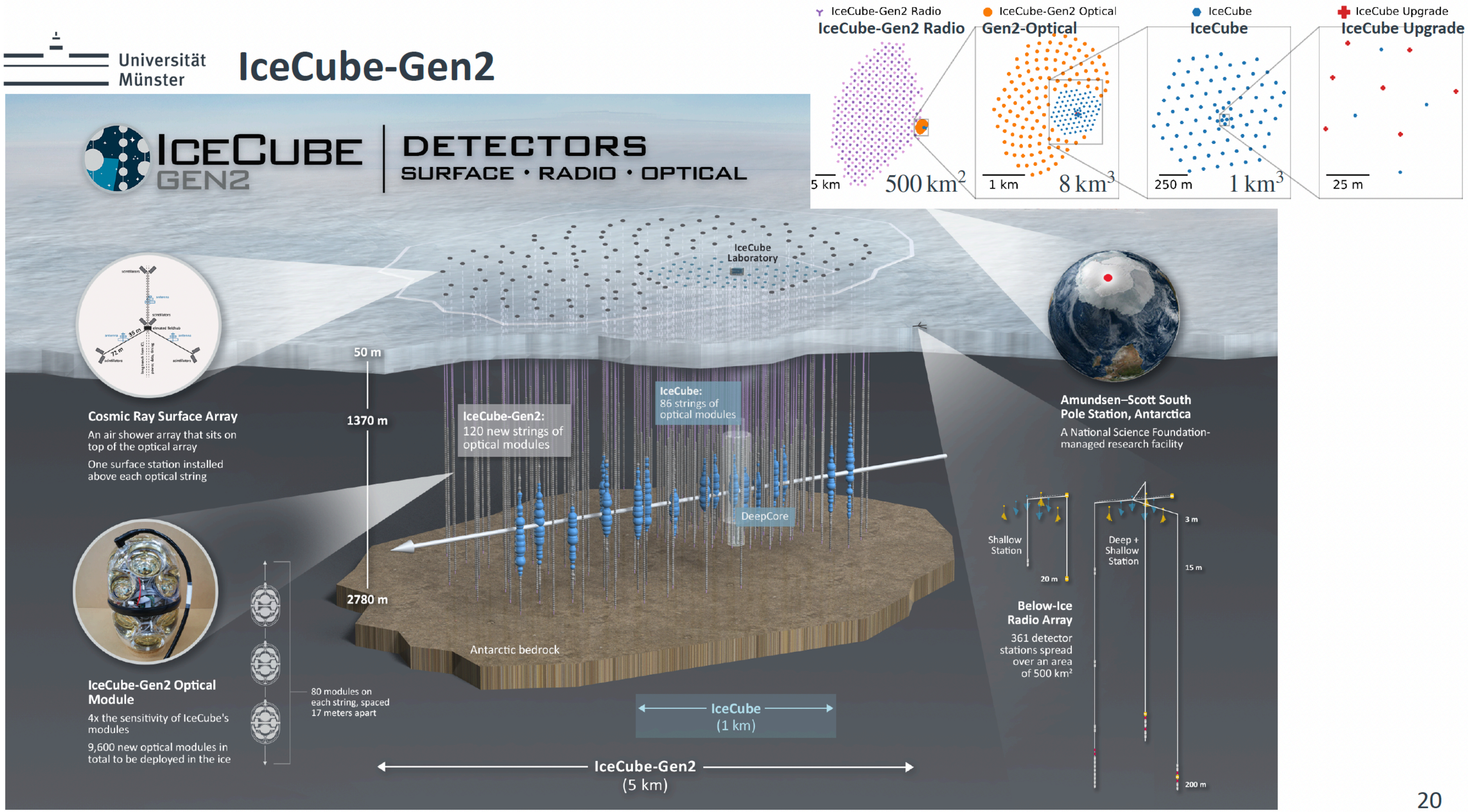




Crossmatch with gamma/X/radio catalogs

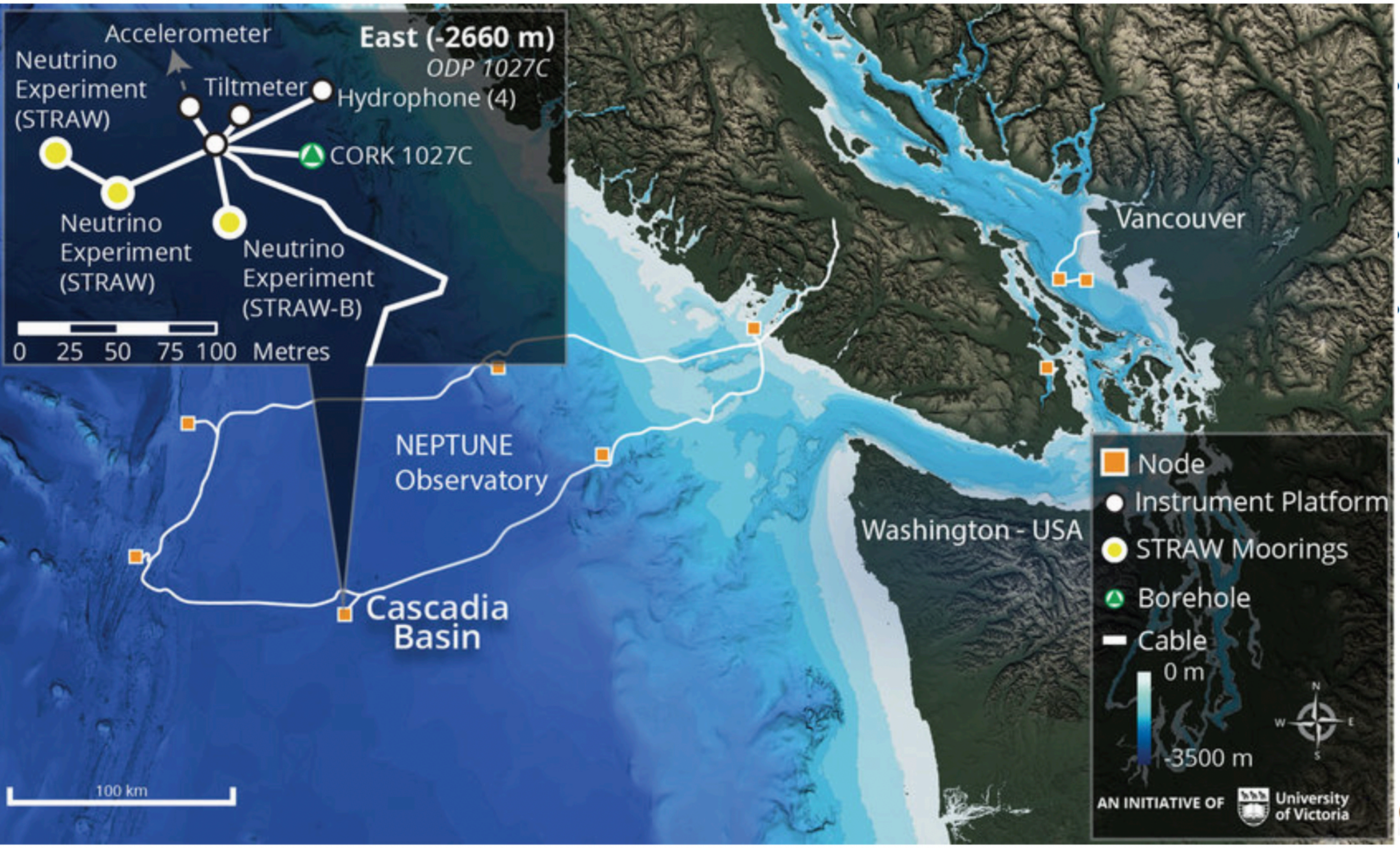
- **17 blazar candidates** identified
- 3 coincidence electromagnetic flares but **nothing conclusive**

Future projects -IceCube-Gen2



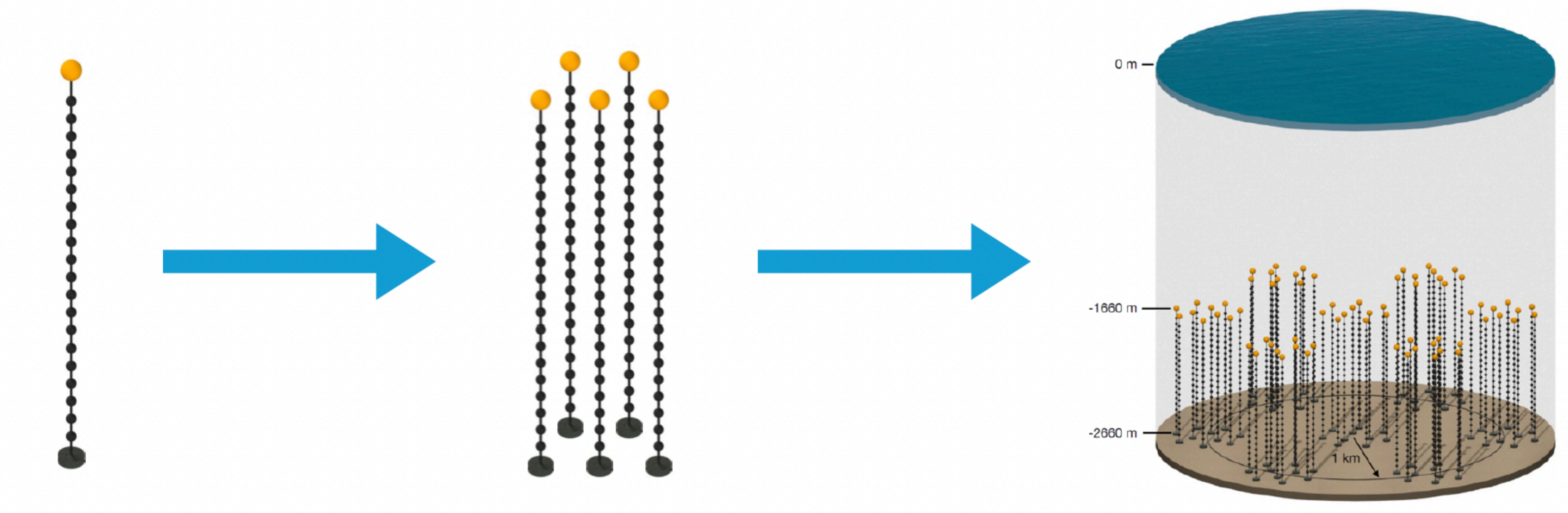
Future projects - P-ONE

1 km^3 project located in Cascadia Basin



Source: Ocean Networks Canada

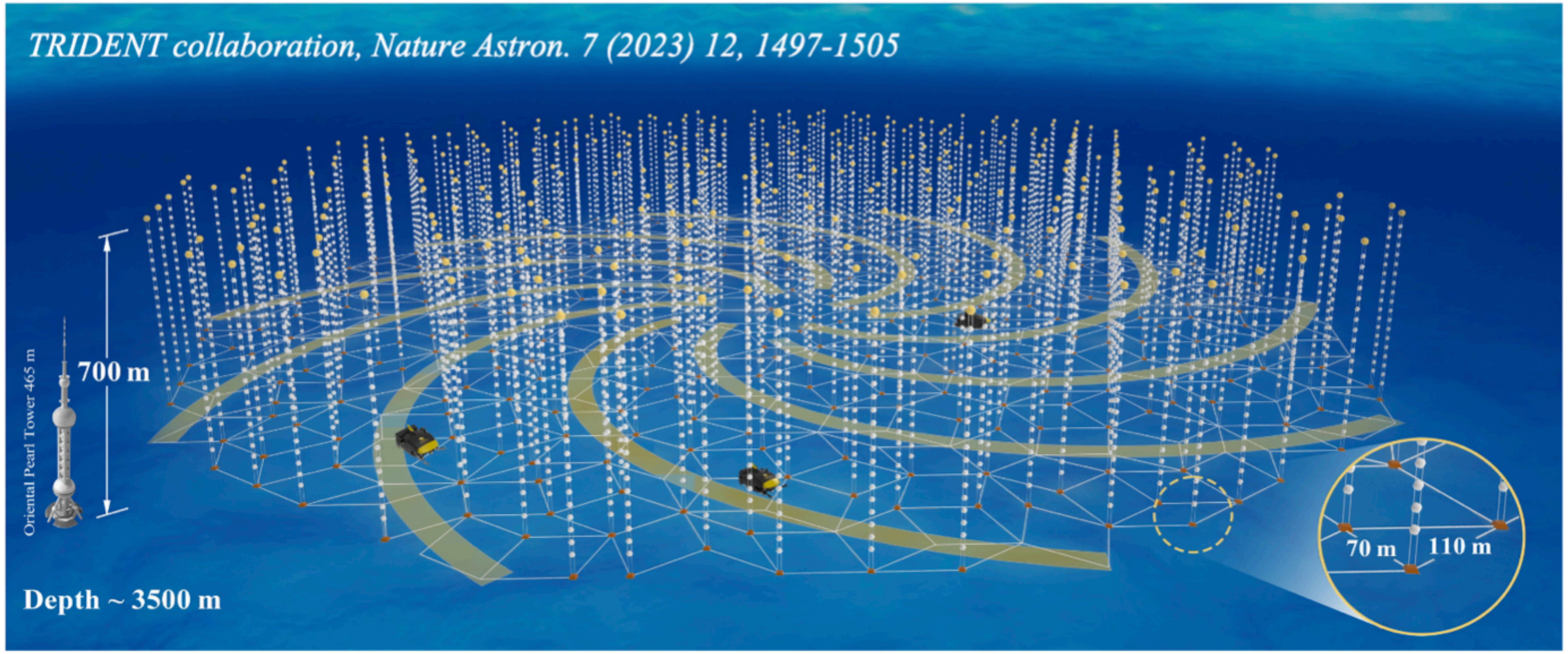
- Significant development milestone already achieved
- Final assembly and testing on-going
- First target of opportunity for deployment in the 2026 season
- First step towards the P-ONE Demonstrator (first ~5 lines, already funded) and P-ONE Array (planned, 80-100 lines)

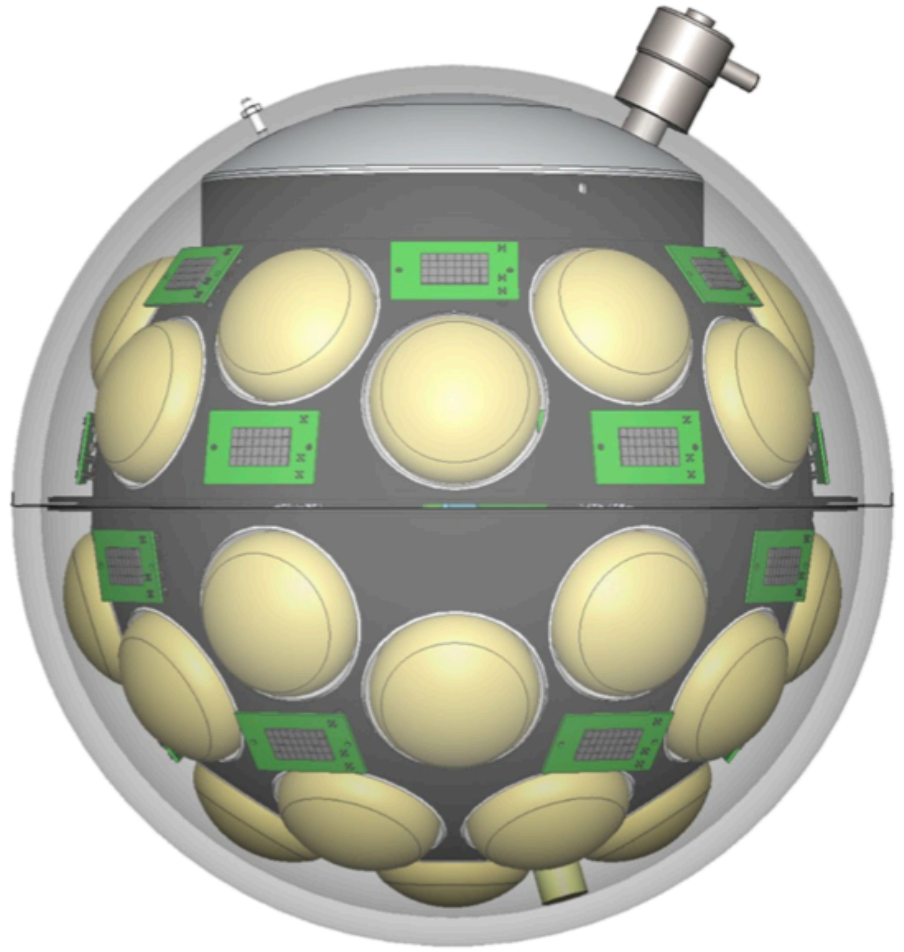


Future projects - TRIDENT

South China Sea

- Water depth: ~3500m
- Number of strings: ~1000, 20,000 hDOMs, Penrose-tiling
- Inter-string distance: 70m/110m Inter-DOM distance: 30m
- Detection Volume: ~8 km^3





Hybrid optical module
multi-PMT + SiPM

see Xin Xiang and Iwan Morton-Blake talks on 28 August

Conclusions - Status of art

Neutrino astronomy is in its discovery phase with exciting observations from the three km^3 optical Cherenkov experiments already running

KM3NeT and Baikal construction to be completed

AUGER provided competitive limits at very high energy

see Piera Luisa Ghia and Rossella Caruso talks today

Several other projects are at design and prototyping phase

- IceCube-Gen2
- P-ONE, TRIDENT, HUNT

see Xin Xiang and Iwan Morton-Blake talks on 28 August

- Radio and particle detectors: GRAND*, RNO-G*, Trinity and BEACON, TAMBO *not covered in this talk*

*see Guoyuan Huang and Jethro Stoffels talks on 28 August

Conclusions - Highlights

- IceCube provided several strong evidences of diffuse cosmic neutrino flux
- IC-170922A alert in coincidence with flaring blazer TX0506+056 inaugurated neutrino multi-messenger astronomy
- Neutrinos from Galactic Plane observed by IceCube at > 4.5 sigma
- IceCube reported first evidence of neutrino emission from steady source NG1068

    - few other steady sources close to detection threshold

- Baikal provided first independent evidence of diffuse cosmic neutrino
- KM3NeT break into a unexplored region detecting a UHE neutrino with 220 PeV energy

Conclusions - Open questions

- **Diffuse neutrino cosmic flux**
    - large power index spread for different IceCube event selection
    - preliminary analysis of IceCube MESE events favor a broken power law
    - Baikal diffuse neutrino cosmic flux overshoot IceCube flux by about a factor two
    - source population not clearly identified
- **Few neutrino sources identified, not always associated with bright gamma sources**
- **Origin of UHE neutrino KM3-230213 cannot be established on the base of a single event**
- **…**

Conclusions - Perspectives

- **IceCube** with its huge exposure and ongoing developments will continue to be a key player increasing significance for several sources already spotted
- **Baikal,** actually largest telescope in the Northern Hemisphere, is expected to be completed around 2030 and will have an important role
- **KM3NeT**, with 51/230 strings already deployed and completion foreseen in 2030, will be a key player with a major role in source identification thanks to its unprecedented angular resolution
- **New generation projects**
- optical Cherenkov with larger volumes, up to tens of km^3 (IceCube-Gen2, TRIDENT, HUNT)
- radio experiments that allow to increase detection volume by two order of magnitude

will strongly increase HE neutrino detection rate enlarging discovery potential for neutrino sources and allowing to investigate the highest energy region where KM3-240213A stemmed out and beyond

High energy neutrino telescope operating in different locations will assure a **complete survey of the sky**, with large overlapping regions at the same time, their c**ooperative efforts** with combined analysis will boost high energy neutrino discovery potential providing a deeper understanding of the high energy Universe

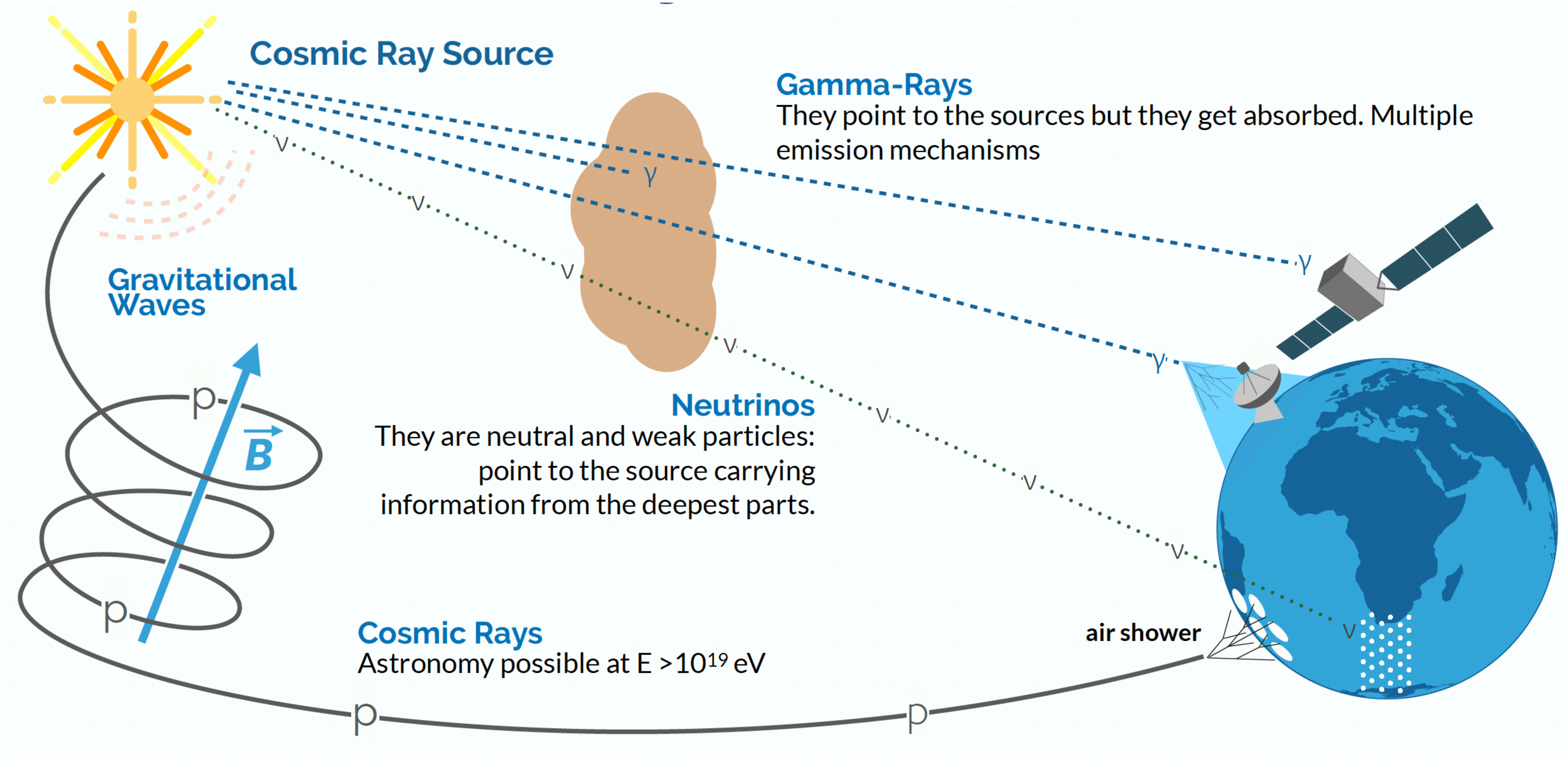
The future of Neutrino Astronomy looks bright!

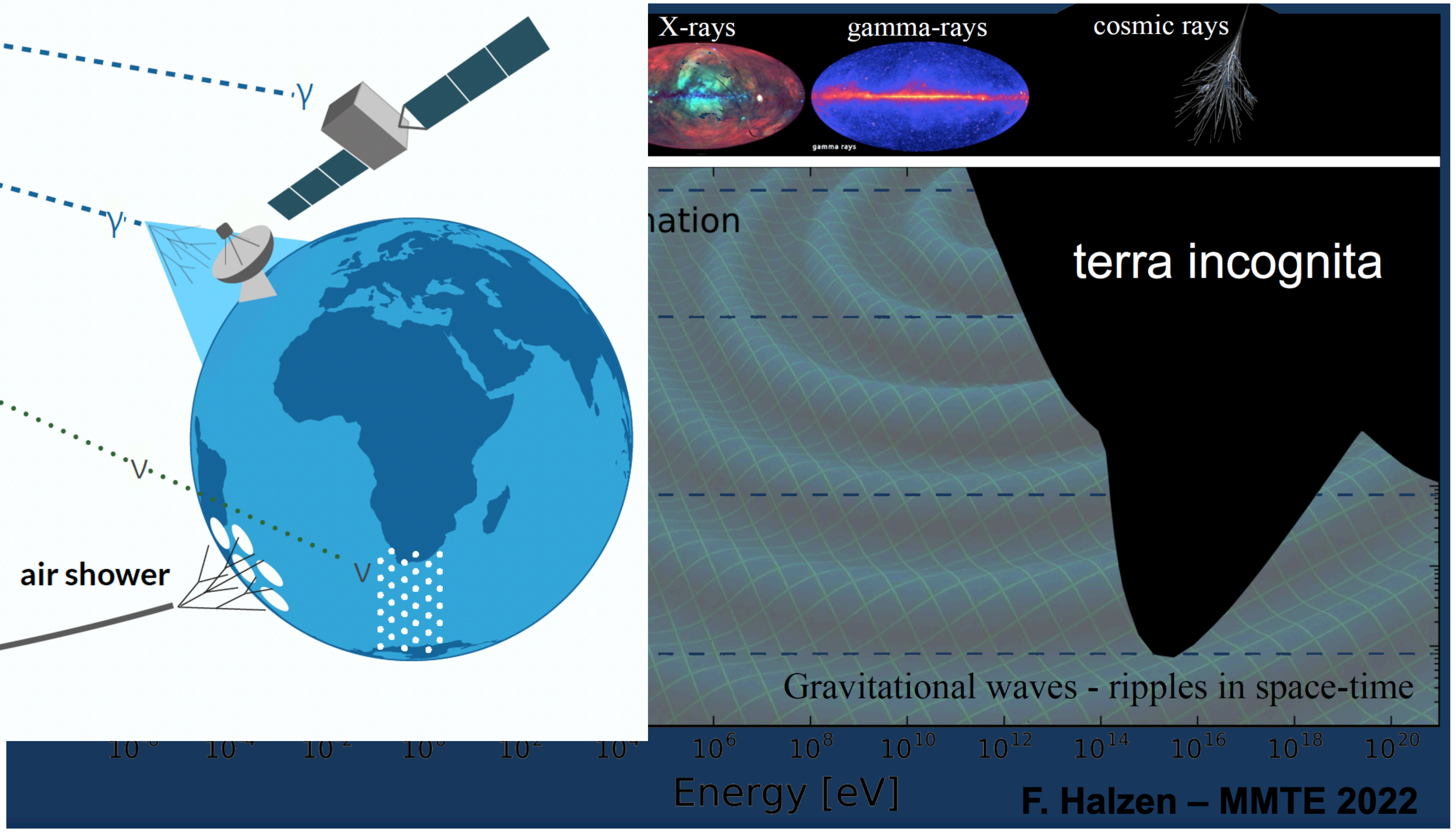
Effective areas

Neutrinos shed a new light on our Universe

High energy Universe

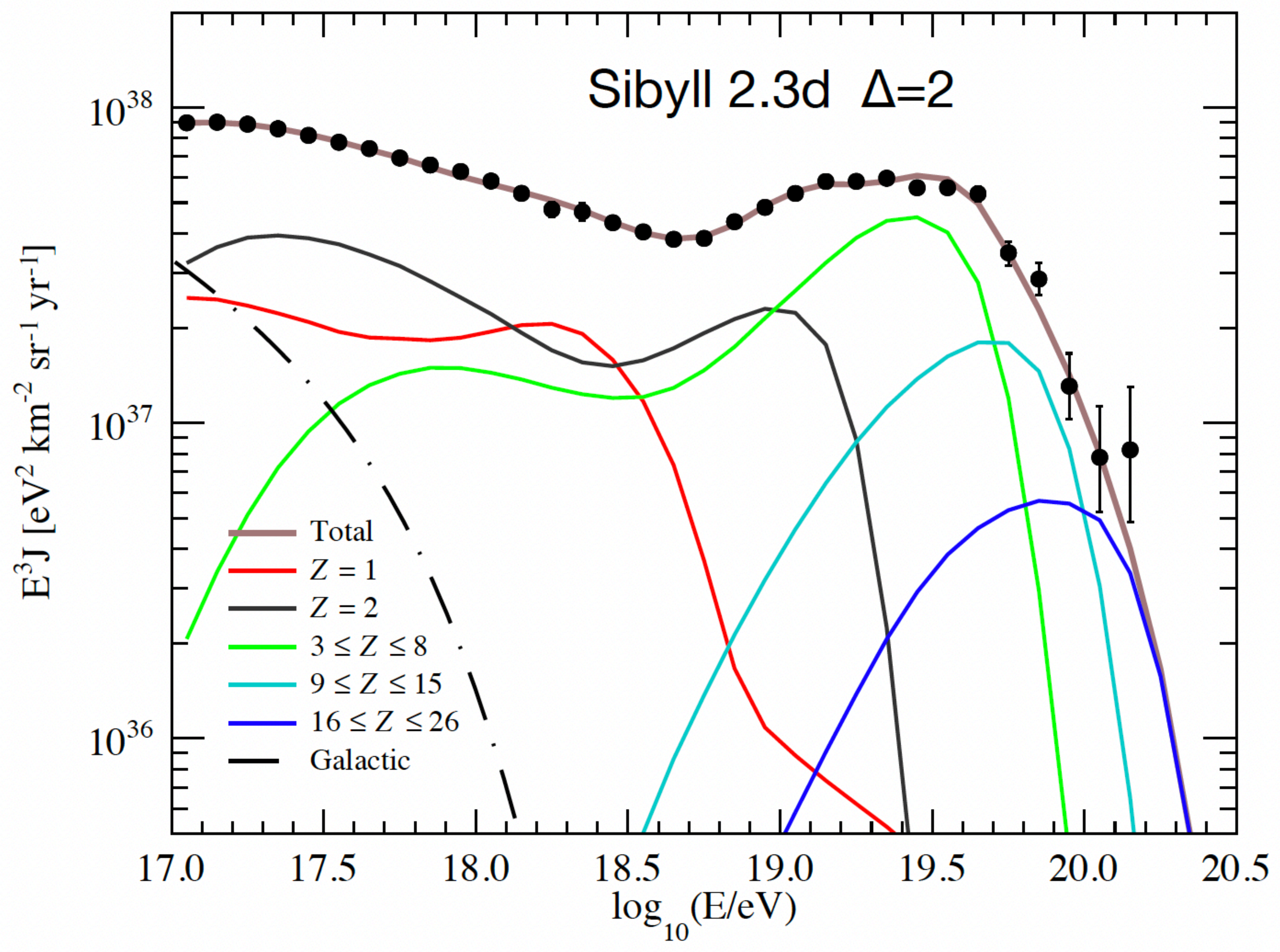
- How to investigate extreme phenomena occurring in cosmos?

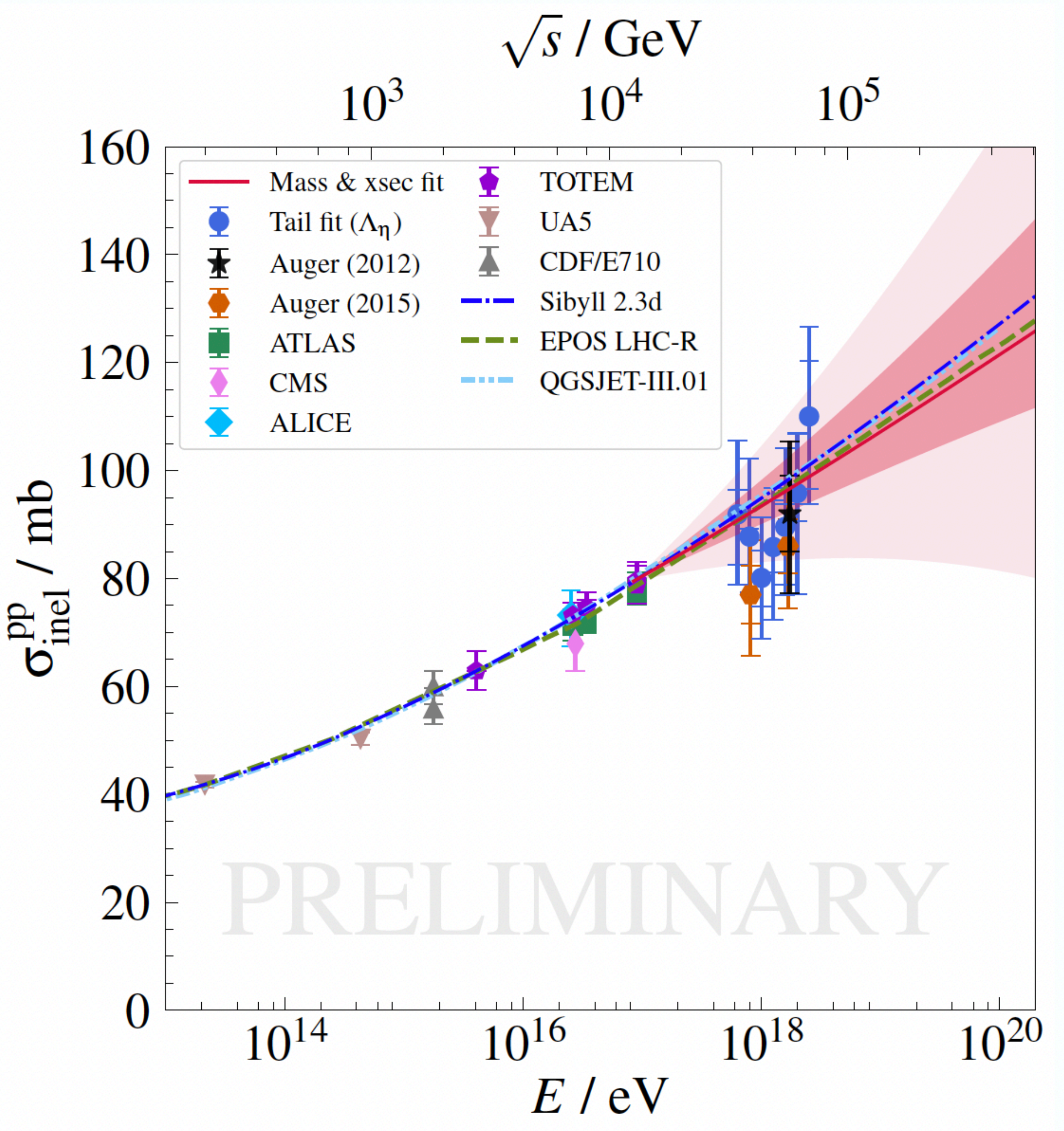




Historical notes Neutrino astronomy

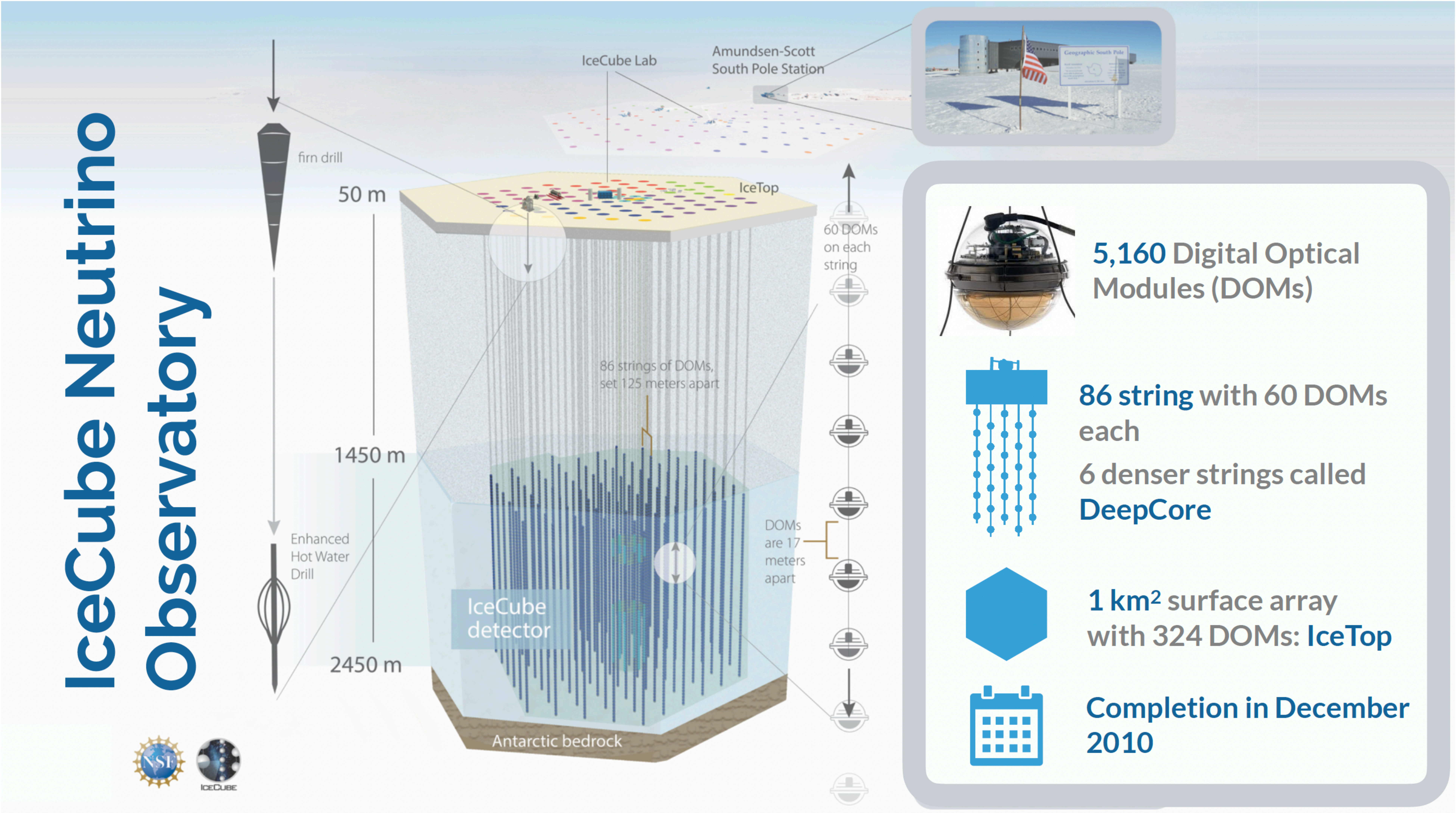
- The SUN
- SN1987A





PoS(ICRC2025)416 O. Tkachenko

Diffuse neutrino Flux



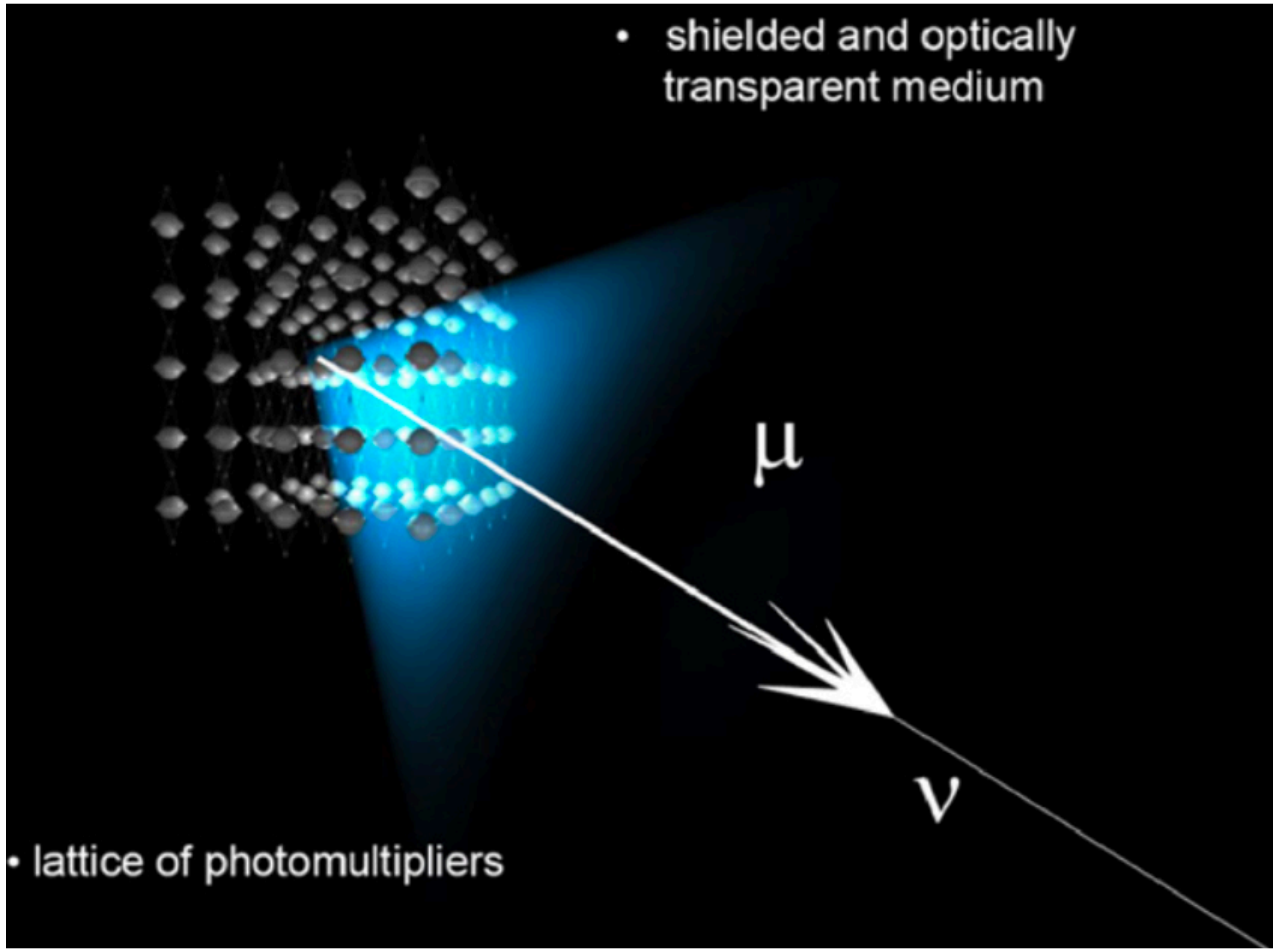
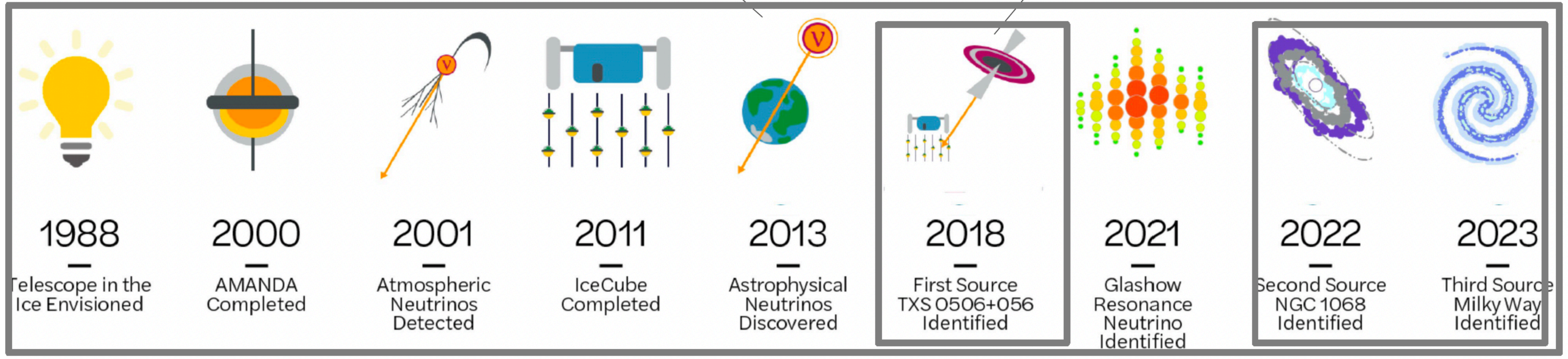


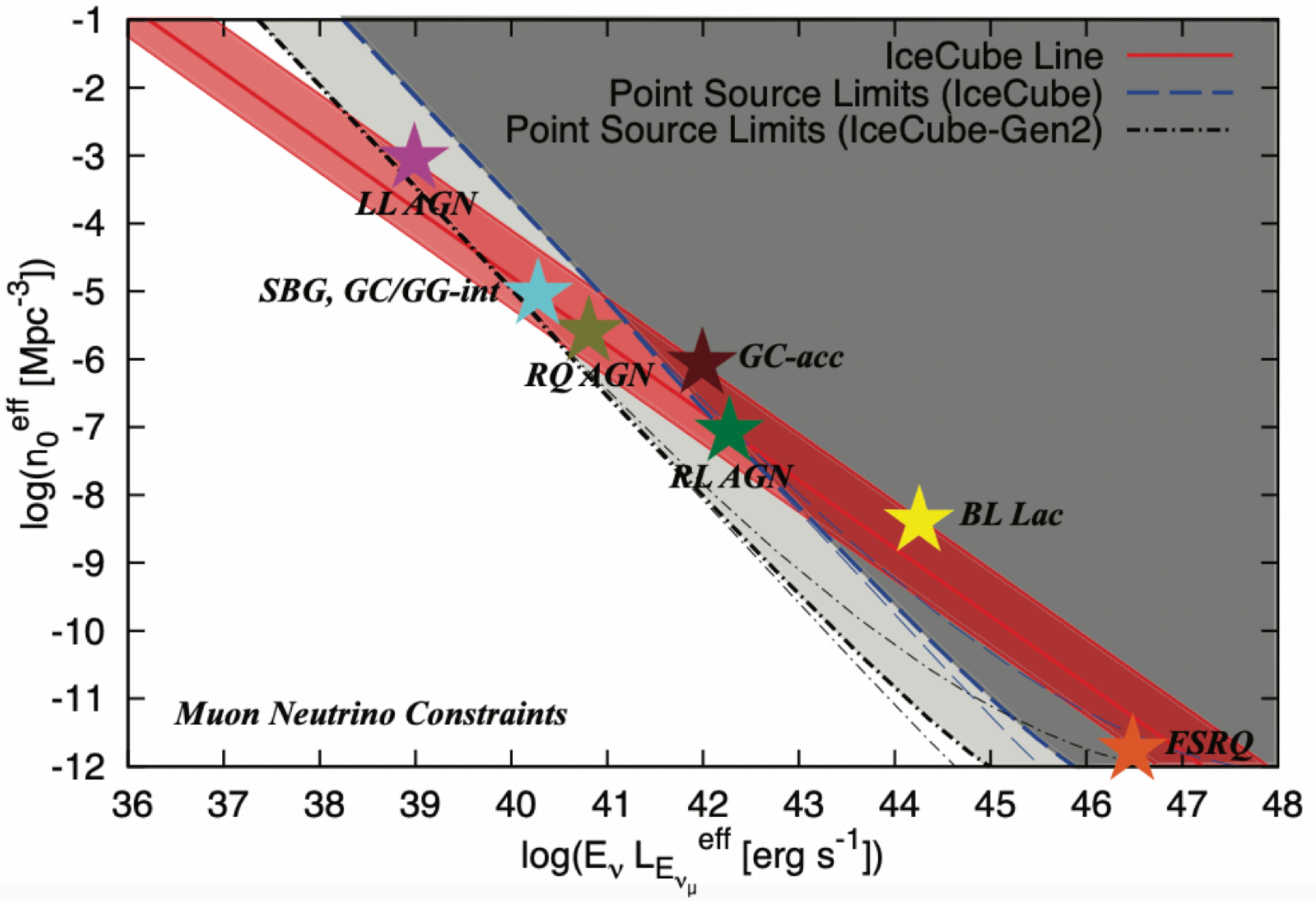
Image Credit: IceCube Collaboration



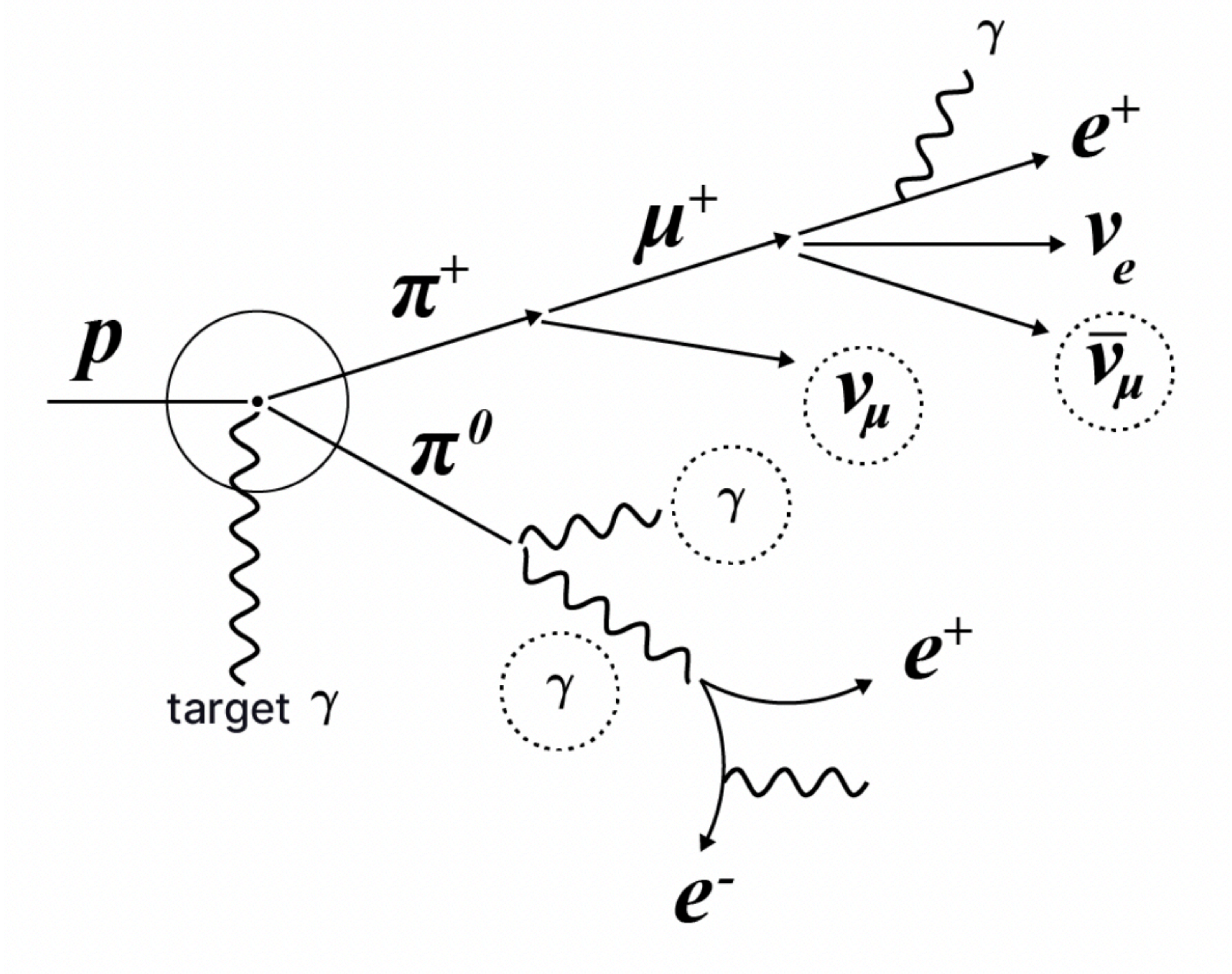
Neutrino telescope	$L_{absorption}$ [488 nm]	$L_{scattering}$ [488 nm]
IceCube	190-200 m	20-26 m
KM3NeT	55-60 m	200 m
Baikal	20-25 m	40-80 m

Introduction and motivation

Murase & Waxman, PRD 2016



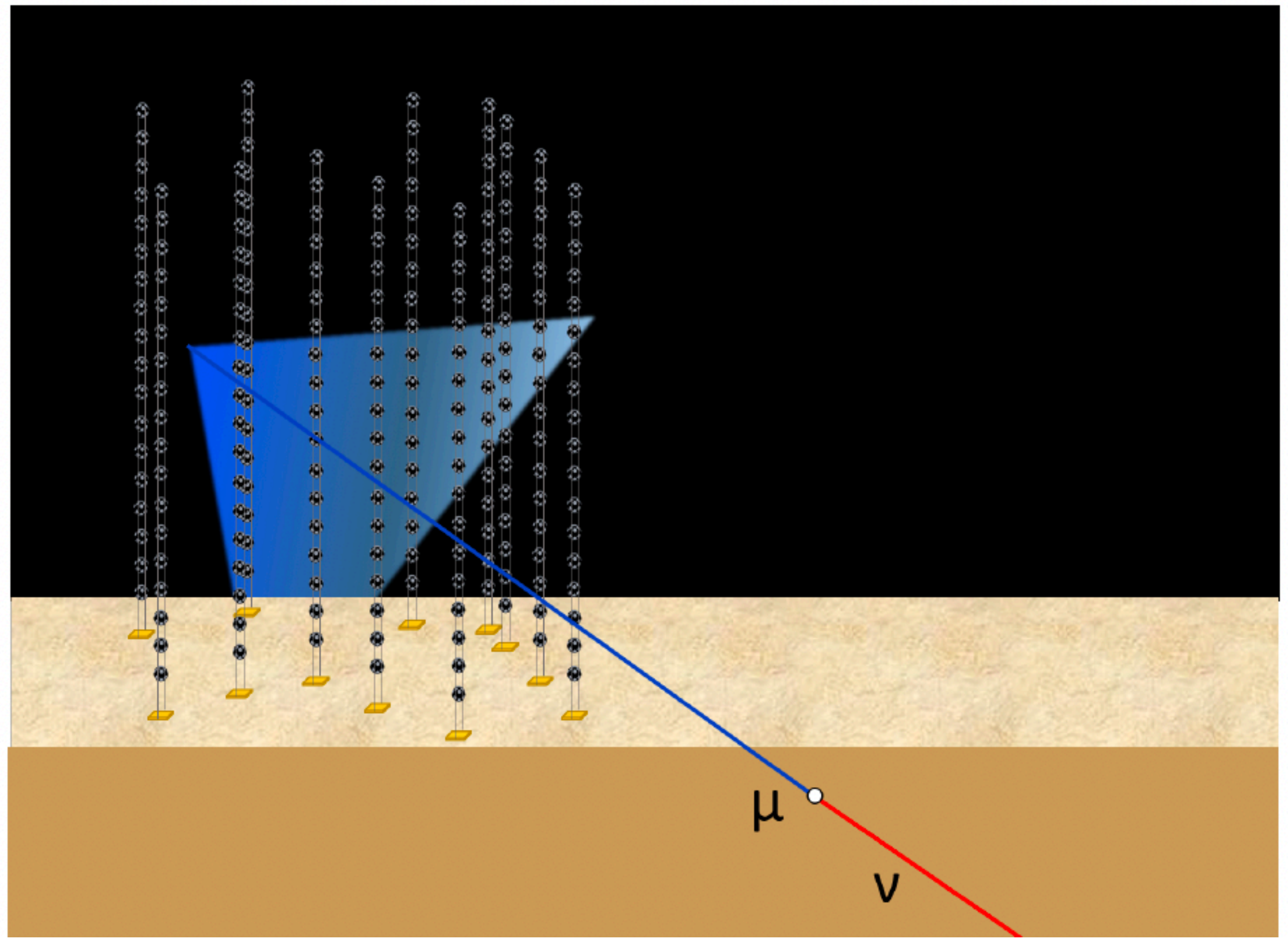
Because cosmic neutrinos are inevitably accompanied in their production by high energy photons, neutrino astronomy is a messenger astronomy

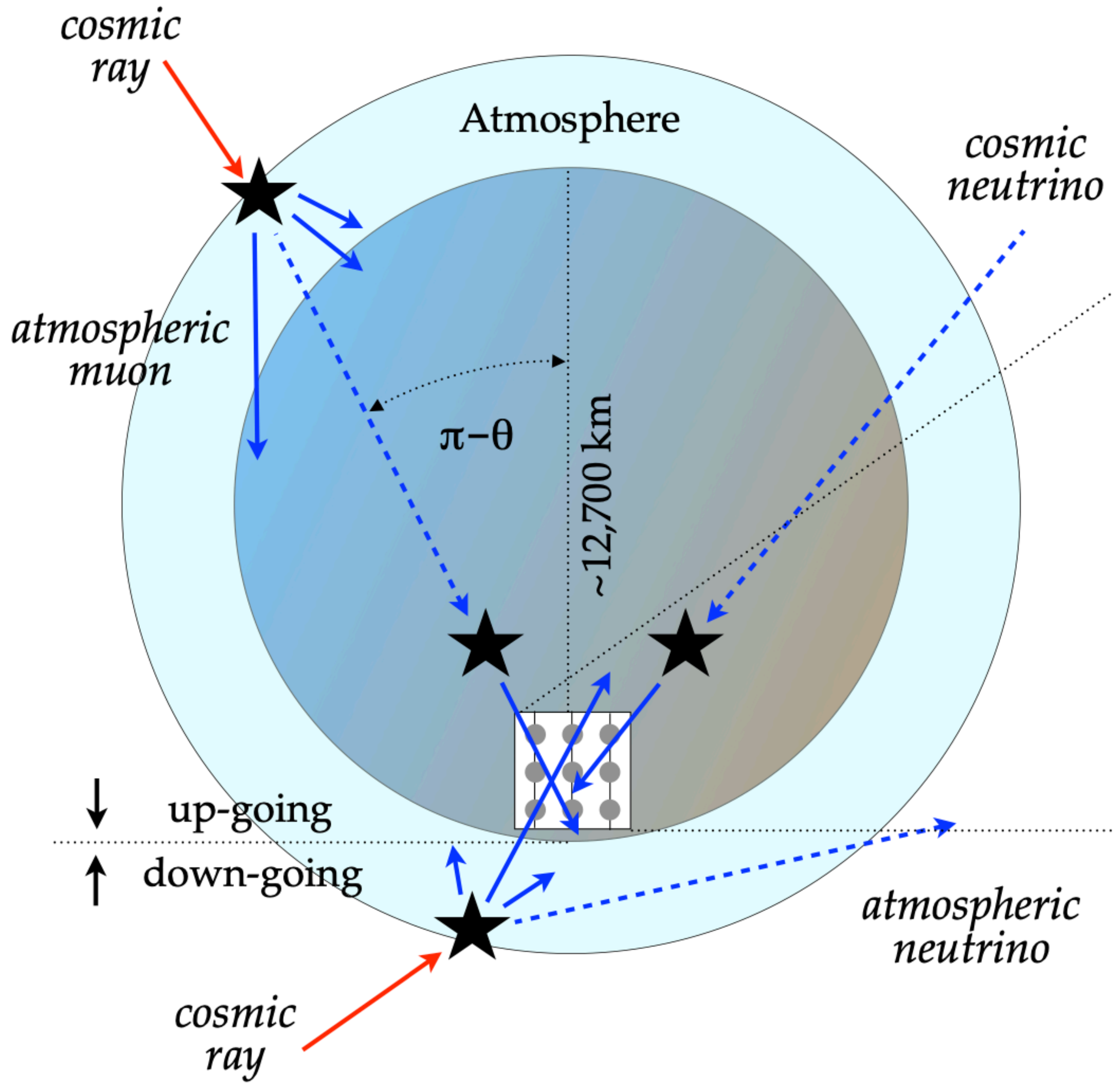


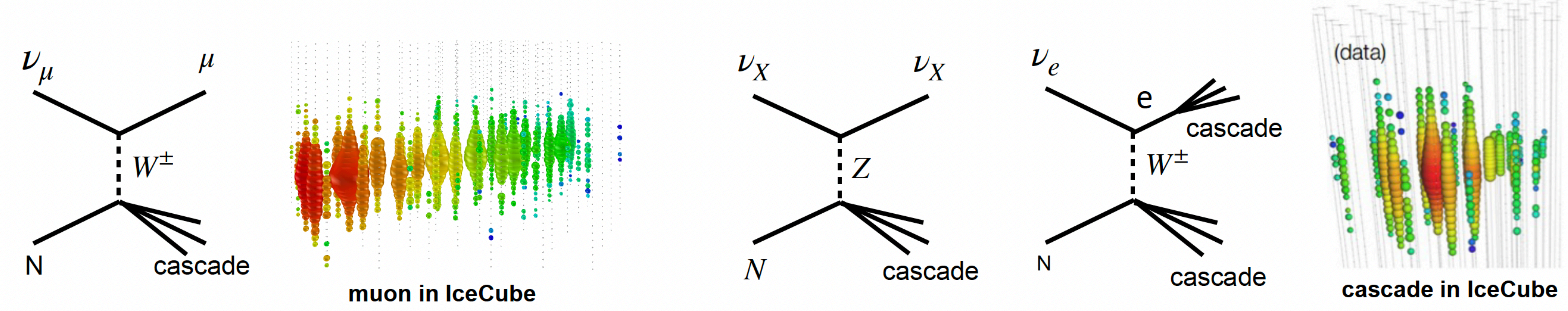
HE neutrino telescopes TeV-PeV

High energy neutrino detection requires volume of km^3-scale

- natural media where exploit optical Cherenkov effect in deep water or antarctic ice
    - threefold function: shield, target, radiator
- all flavor detection, muons neutrinos golden channel for neutrino astronomy due to their superior angular resolution







Extremely challenging experiments

- harsh environments
- low signal rate and huge background