Laboratori Nazionali del Sud

Neutrinos in the multi-messenger era

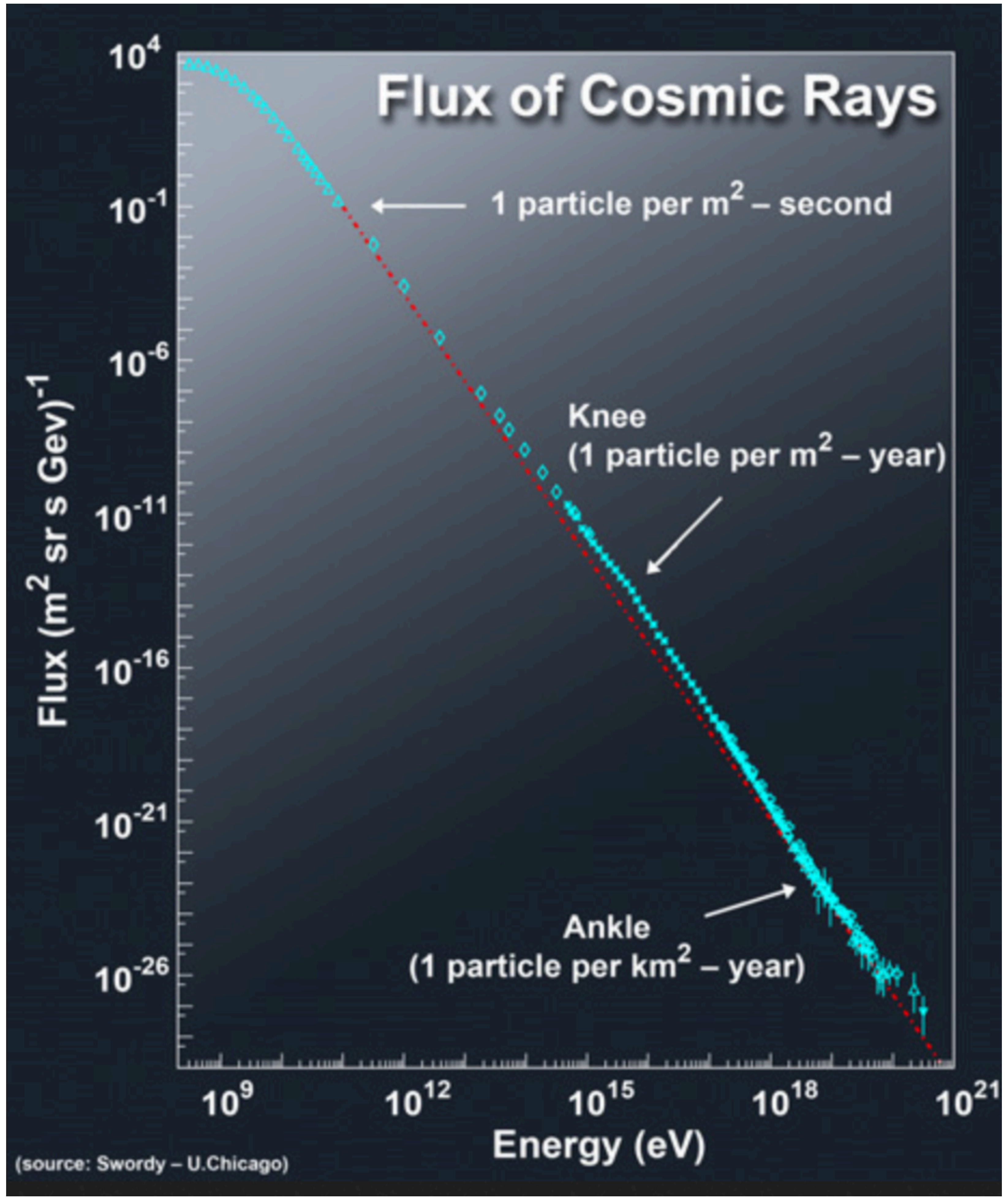
Piera Sapienza LNS - INFN Heavy Quarks and Leptons 2025 - 15th September 2025Bejing CHINA

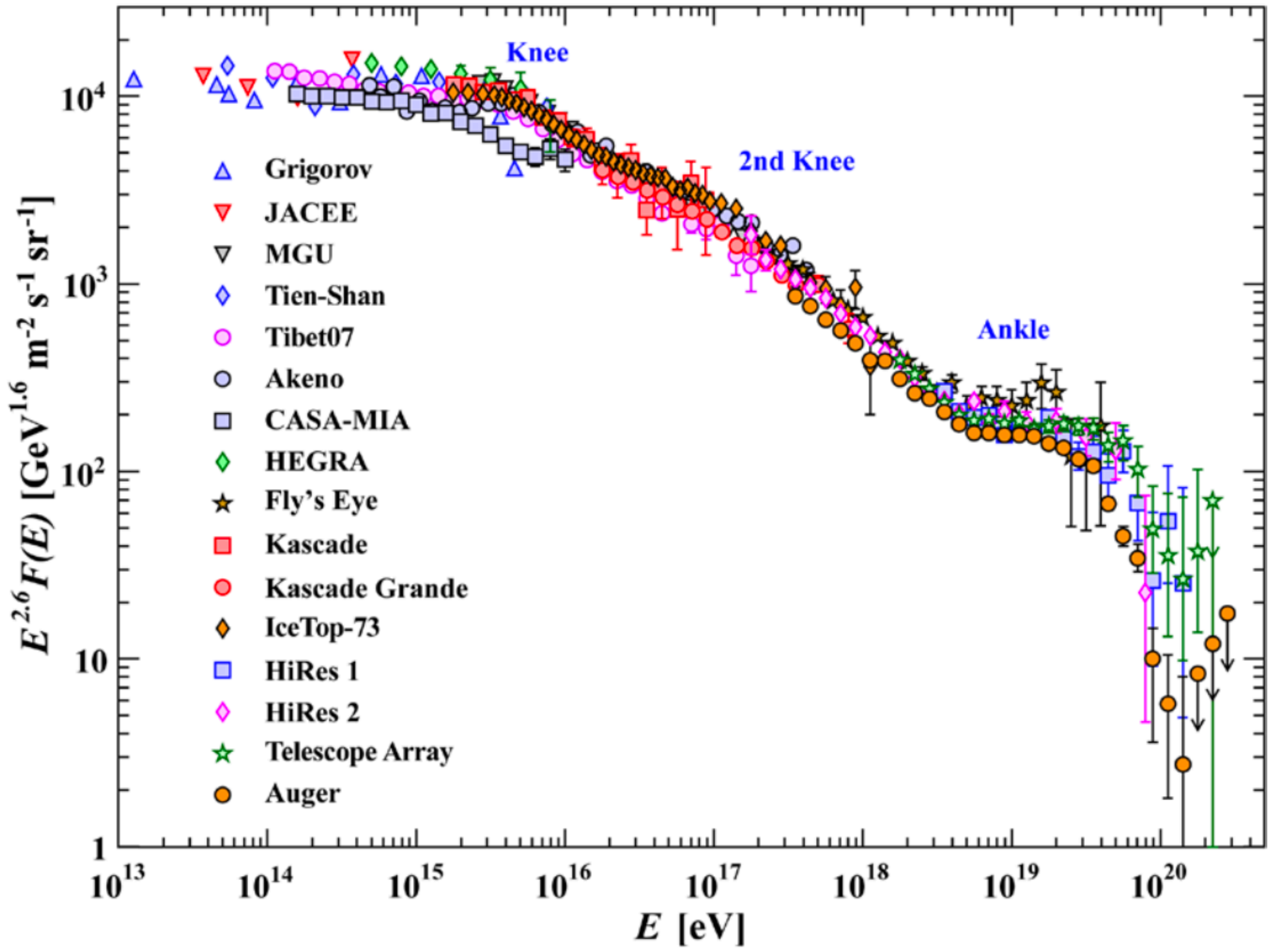
High energy Universe

Neutrino astronomy aims at studying the extreme phenomena occurring in the Universe

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}





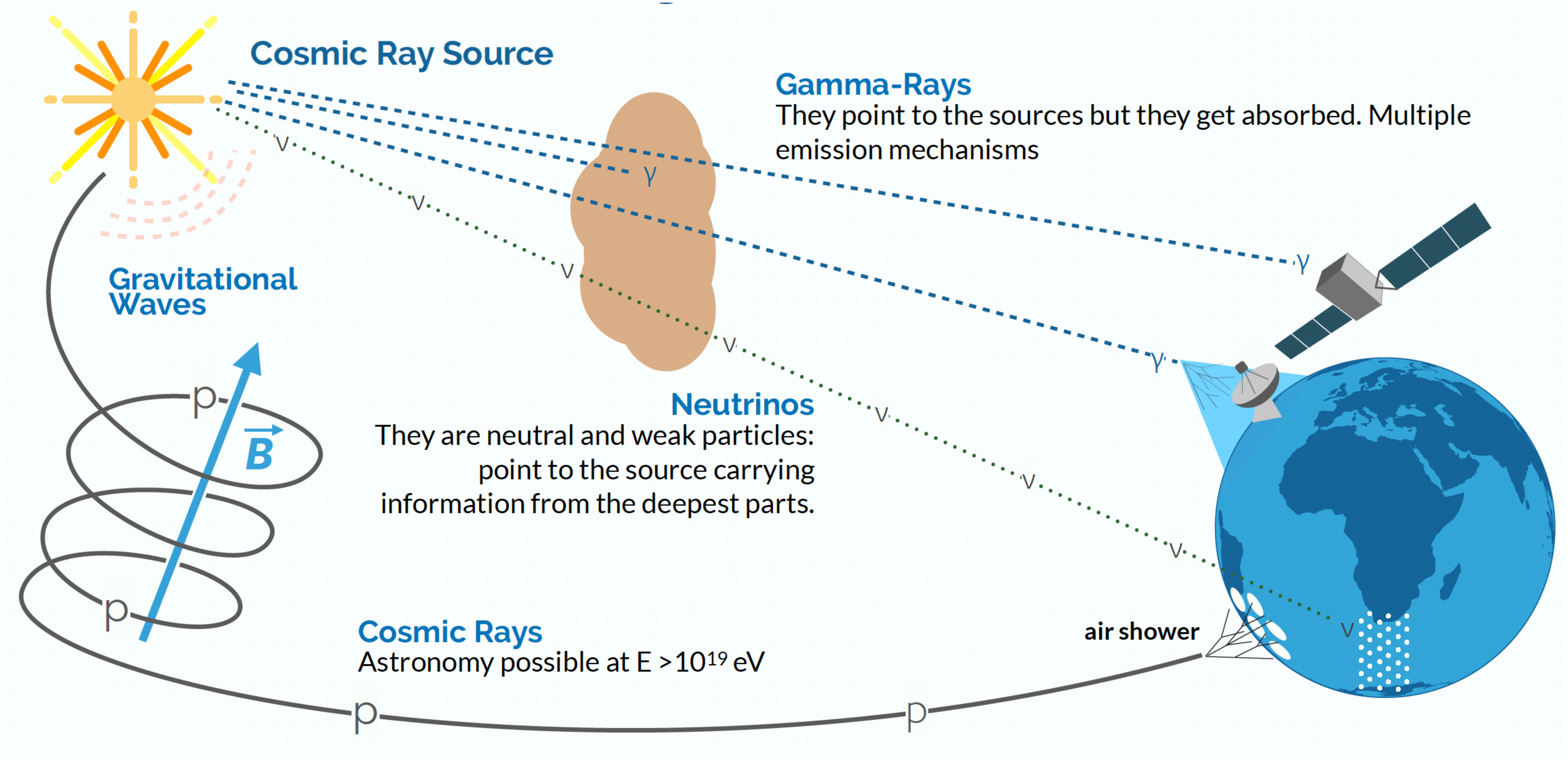
Cosmic rays are scrambled by galactic and extragalactic magnetic fields thus loosing info about their spatial origin

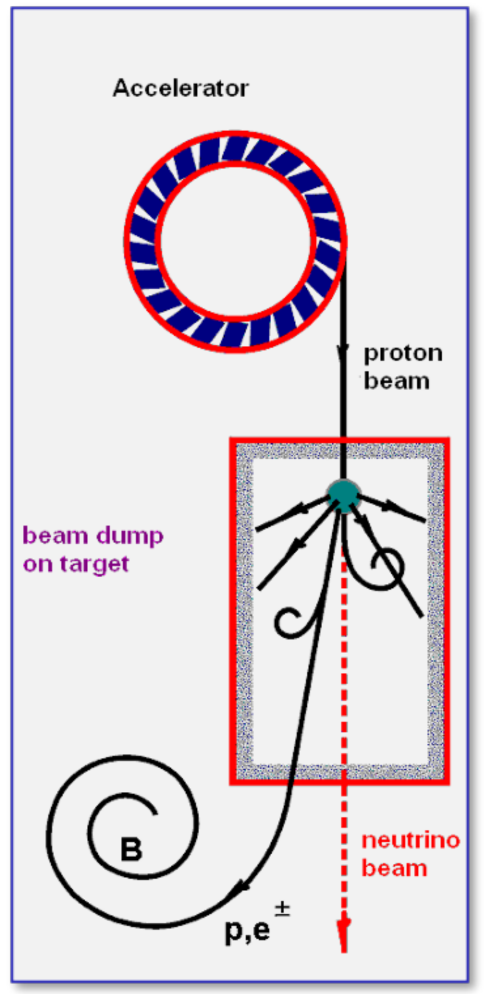
The sources of cosmic rays is still unknown

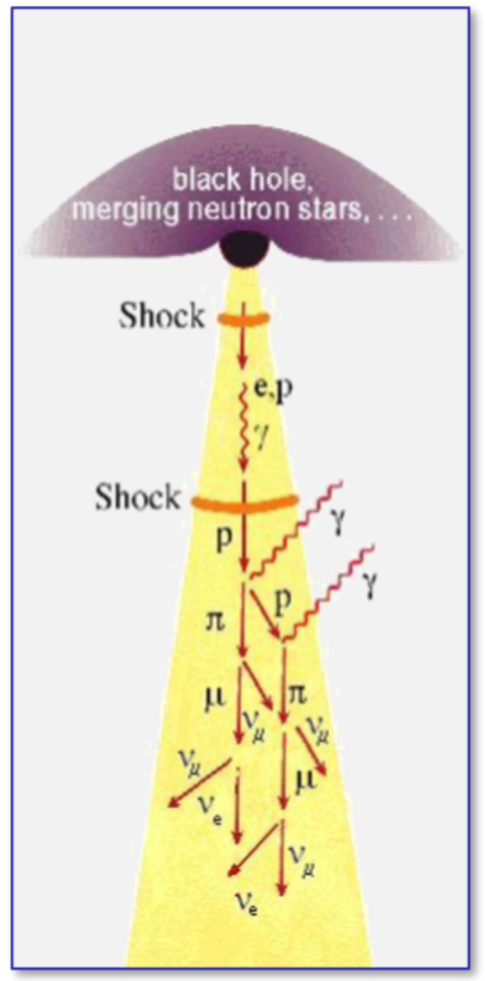
- energetic considerations indicate as possible candidates are SNR for Galactic, AGN, GRB, SBG, TDE… for extragalactic

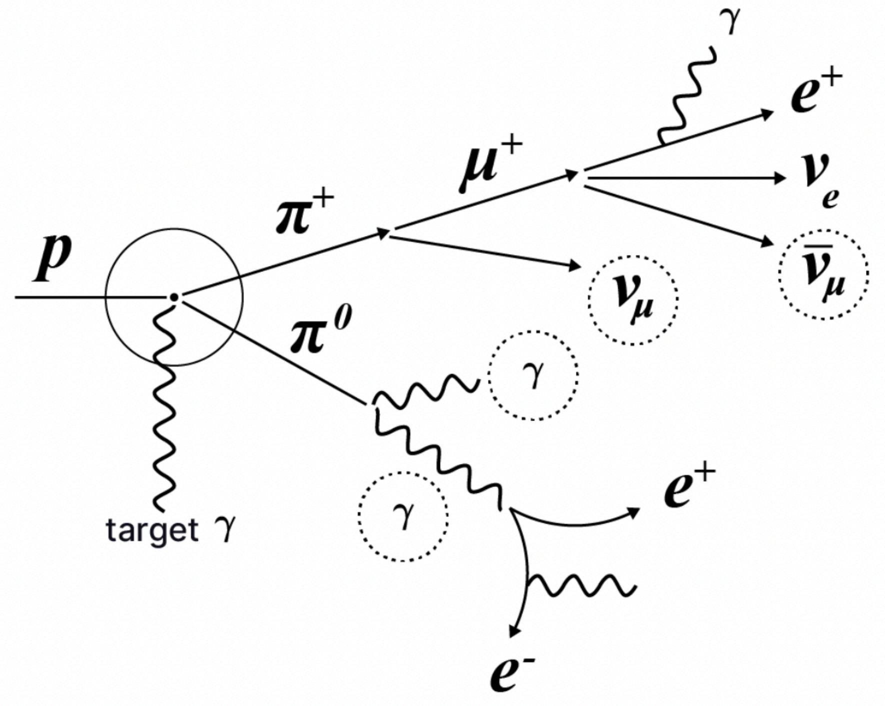
Messengers from high energy Universe

How to investigate extreme phenomena occurring in cosmos?









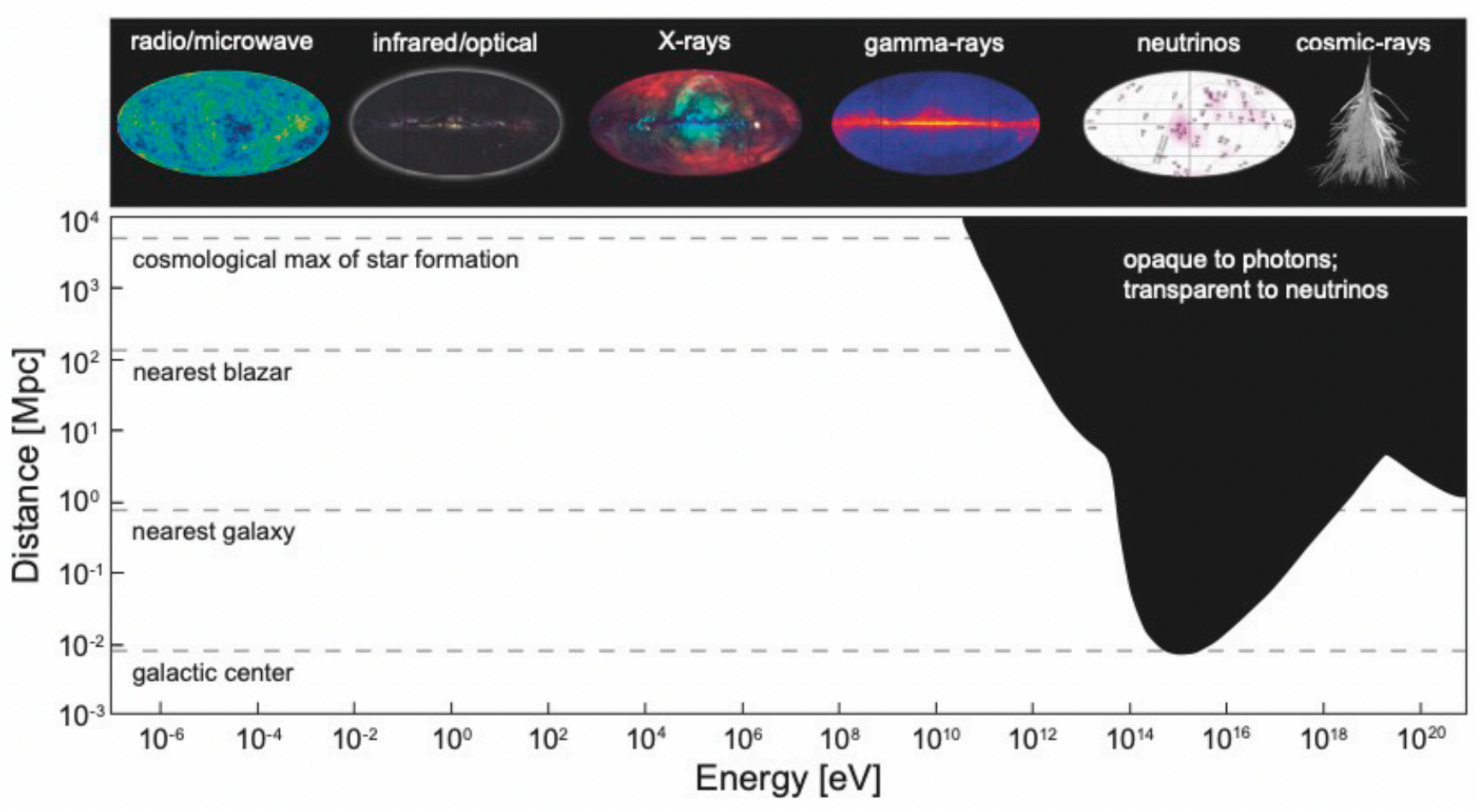
Because cosmic neutrinos are inevitably accompanied in their production by high energy photons, neutrino astronomy is a messenger astronomy

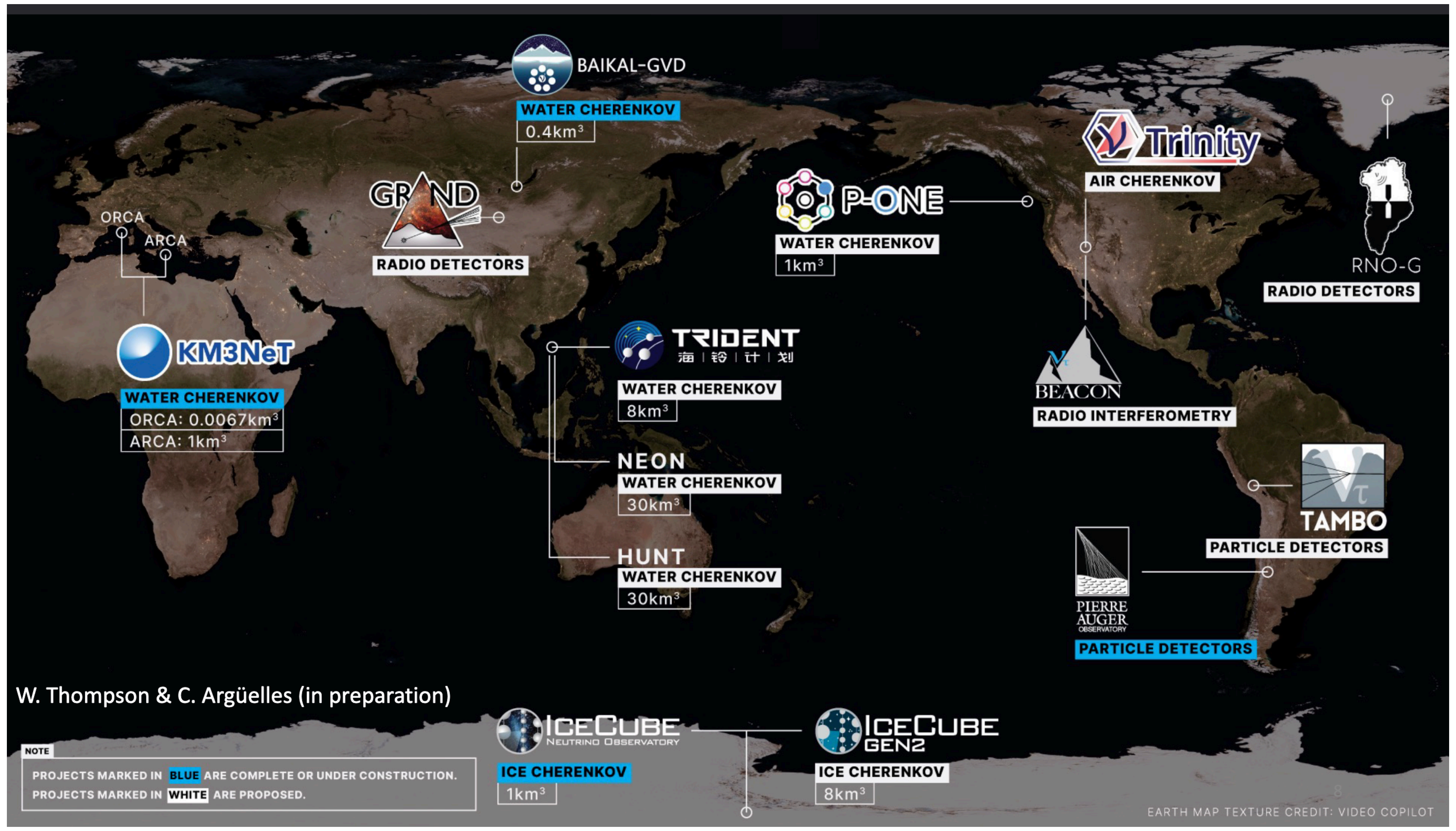
High energy Universe

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

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



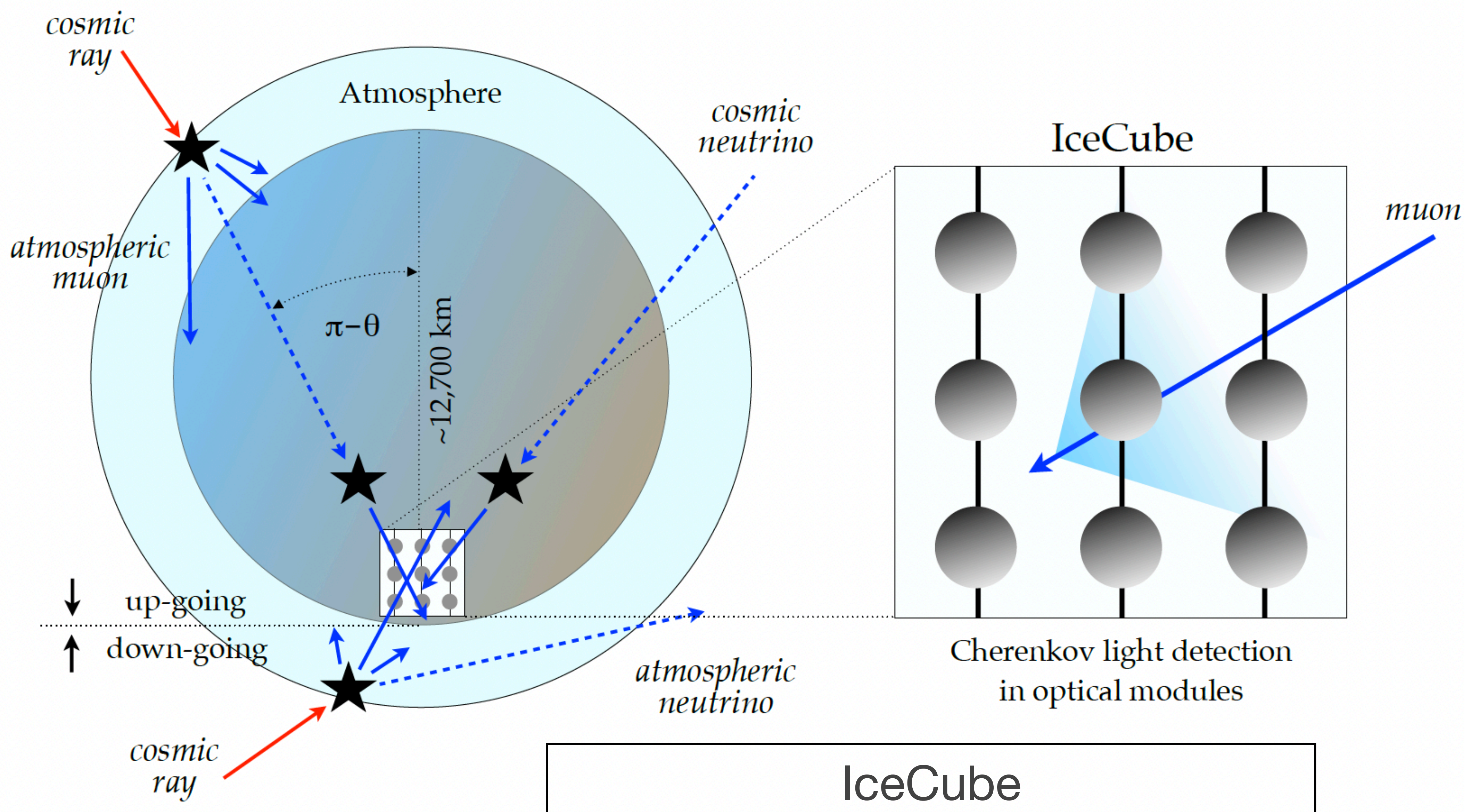


In this talk I will focus on observations by optical Cherenkov neutrino telescopes

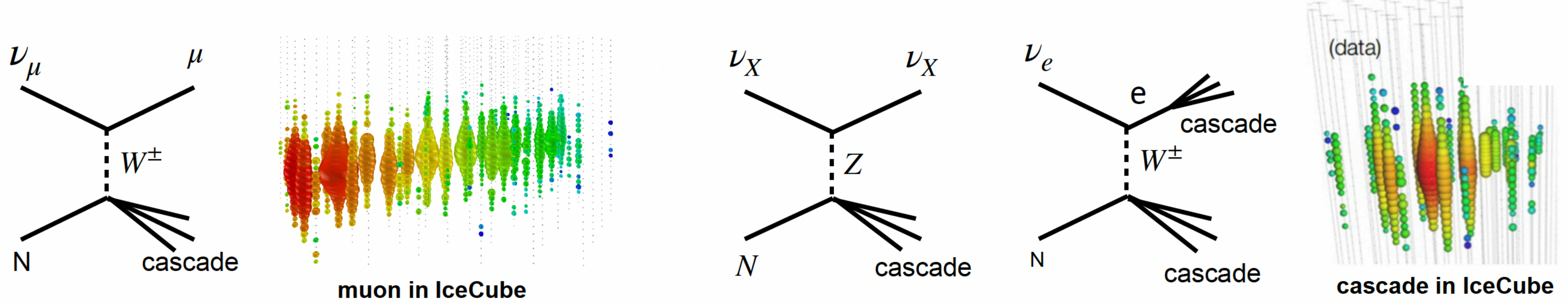
High energy neutrino telescopes

High energy neutrino detection requires volume of 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

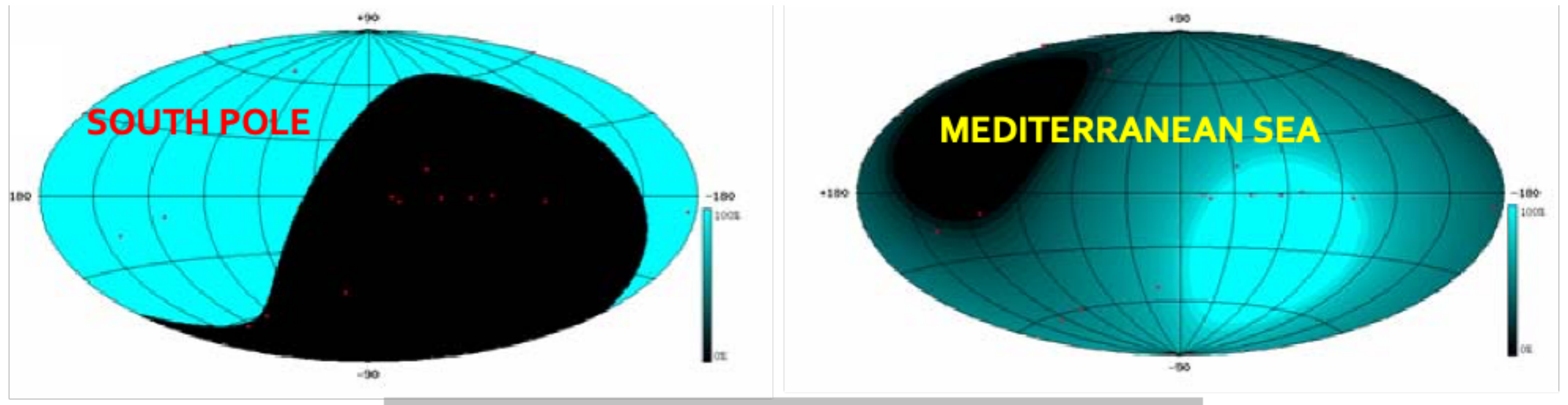


IceCube
Cosmic neutrinos O(100)/year
Atmospheric neutrinos O(105)/year
Atmospheric muons O(1011)/year



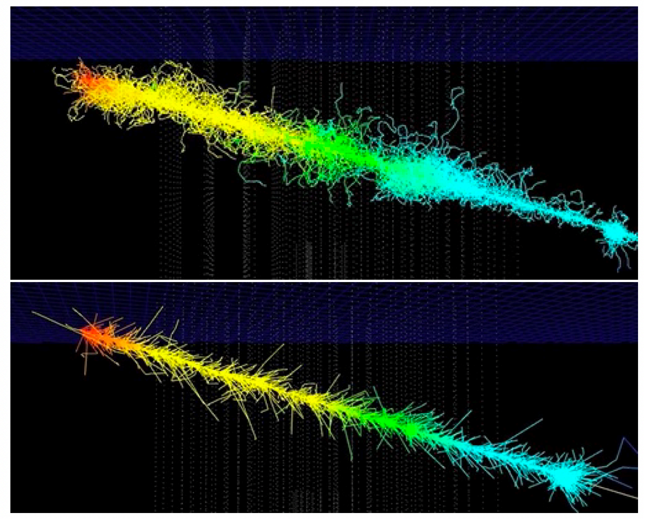
Extremely challenging experiments

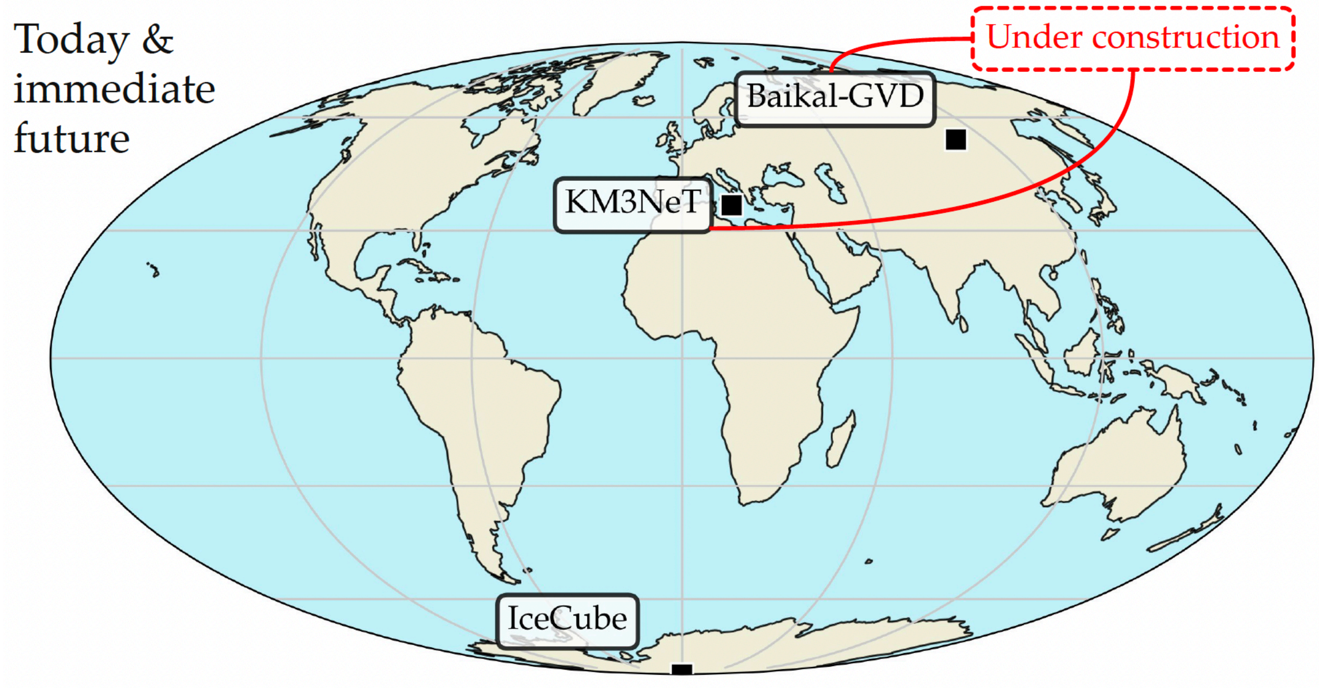
- harsh environments
- marginally accessible
- low signal rate and huge background



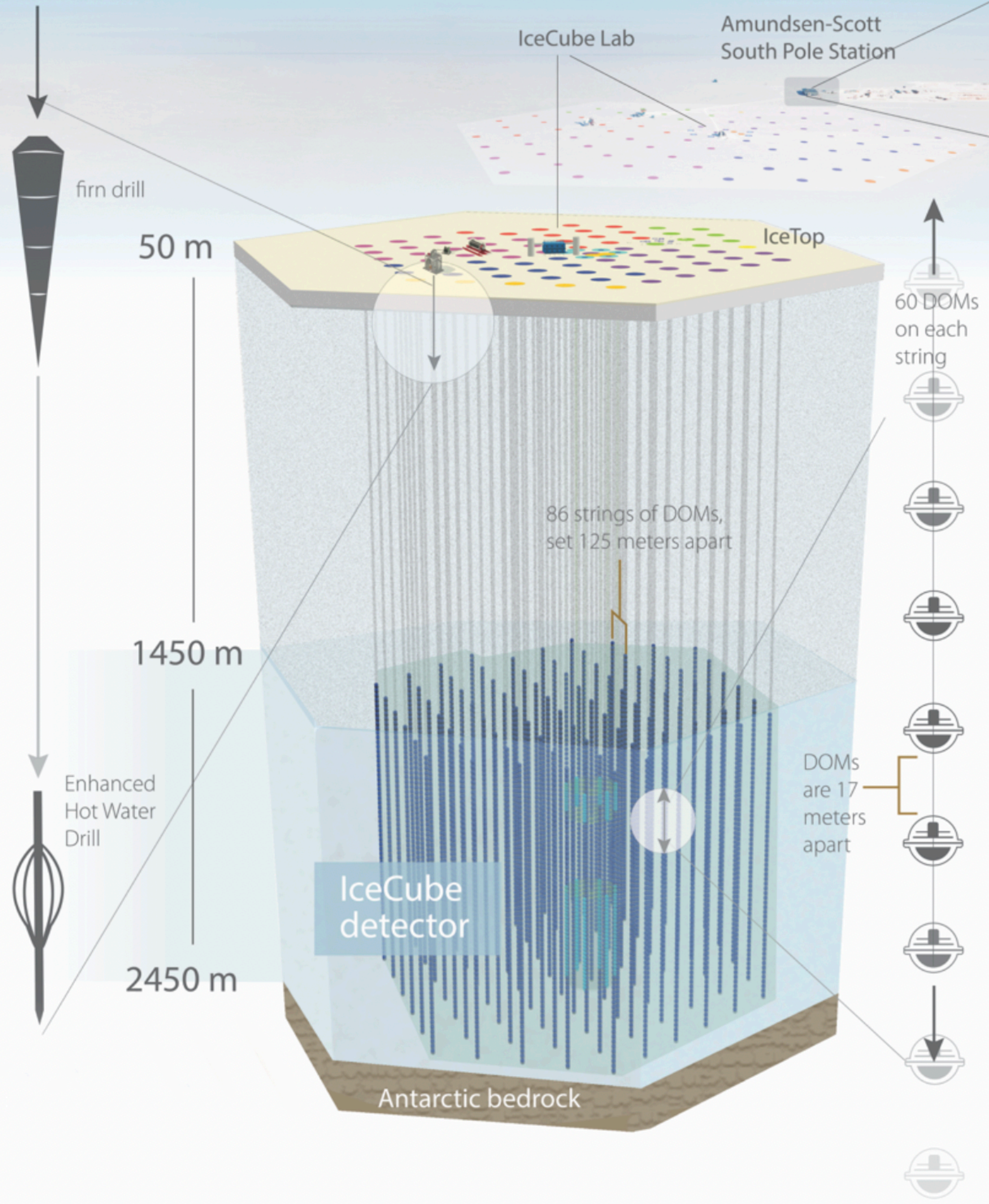
Visibility for up-going neutrinos

muon track: ice vs sea water





IceCube Neutrino Observatory



5,160 Digital Optical Modules (DOMs)

86 string with 60 DOMs each

6 denser strings called **DeepCore**

1 km² surface array with 324 DOMs: **IceTop**

Completion in December 2010

The cosmic neutrinos discovery

IceCube at South Pole is largest neutrino telescope in operation since 2011 with 1 km^3 detection volume

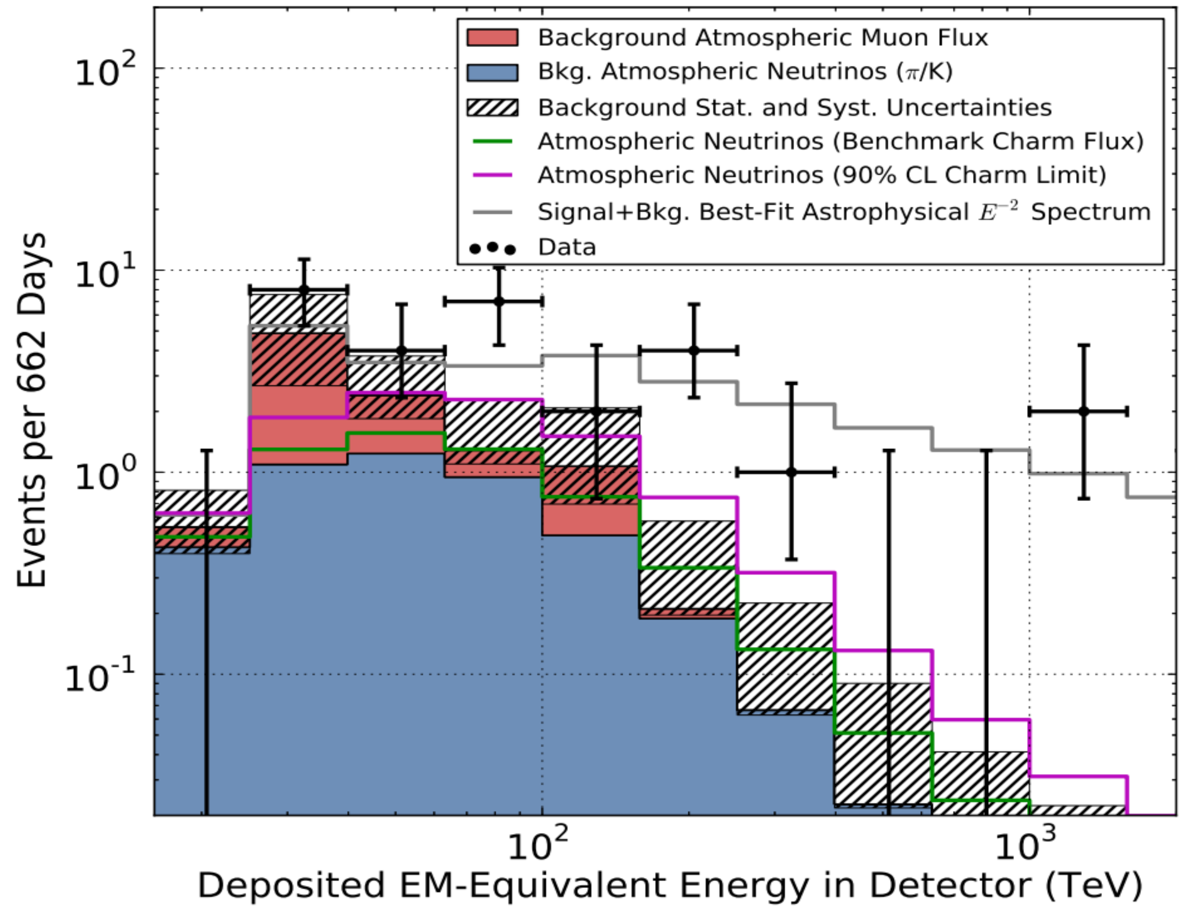
High energy neutrino astronomy *was* born with IceCube discovery of diffuse cosmic neutrino flux

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

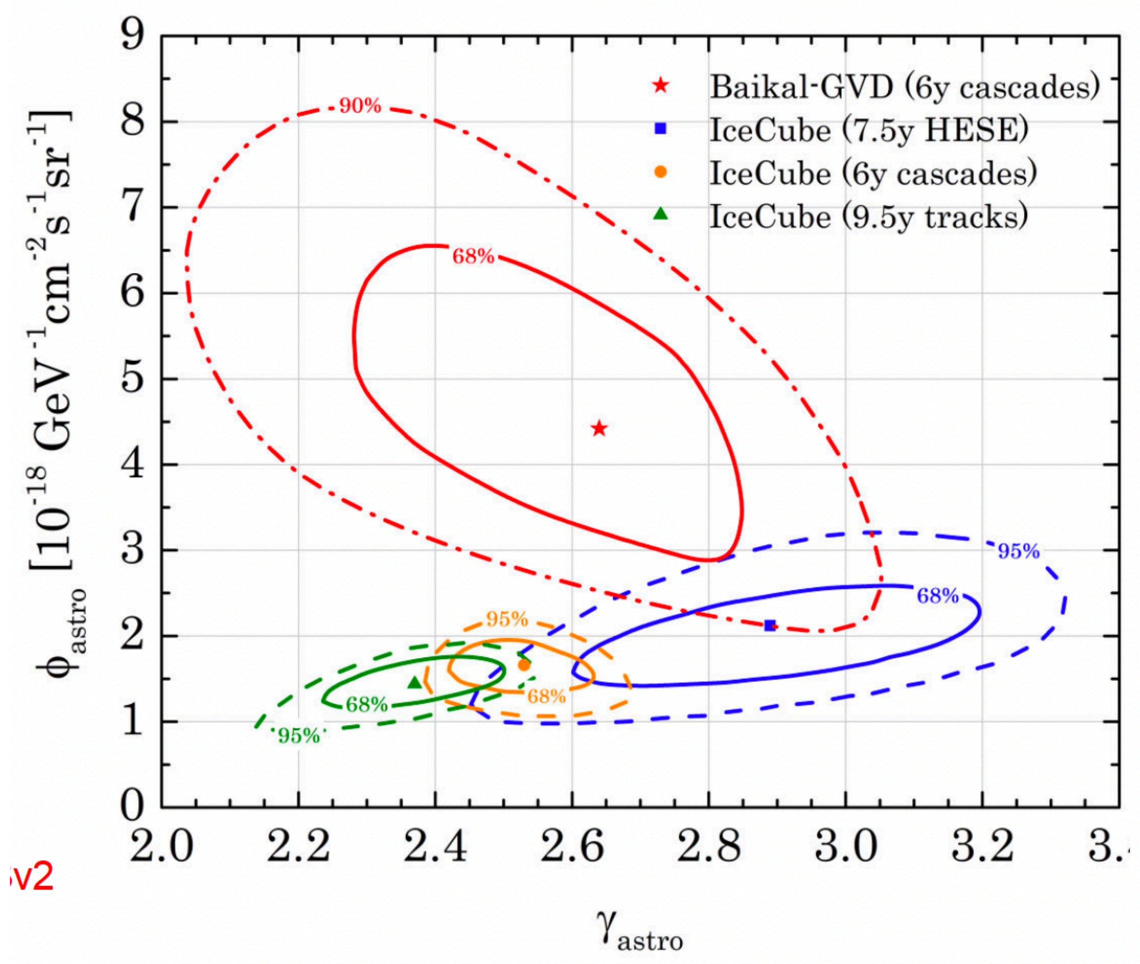
First independent observation of diffuse cosmic neutrinos at 5.1 sigma by Baikal -GVD

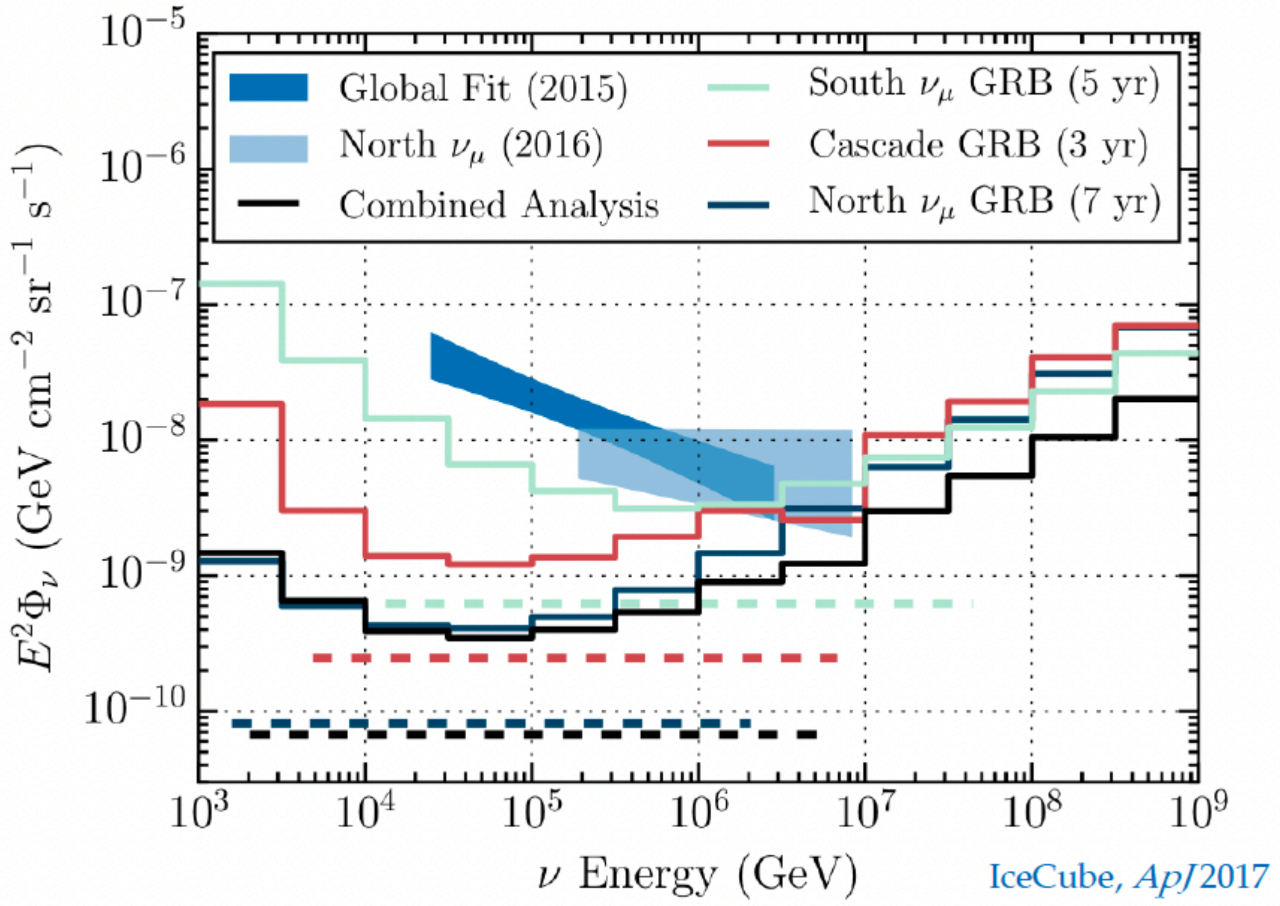
- flux larger than IceCube

Diffuse cosmic neutrino flux discovery



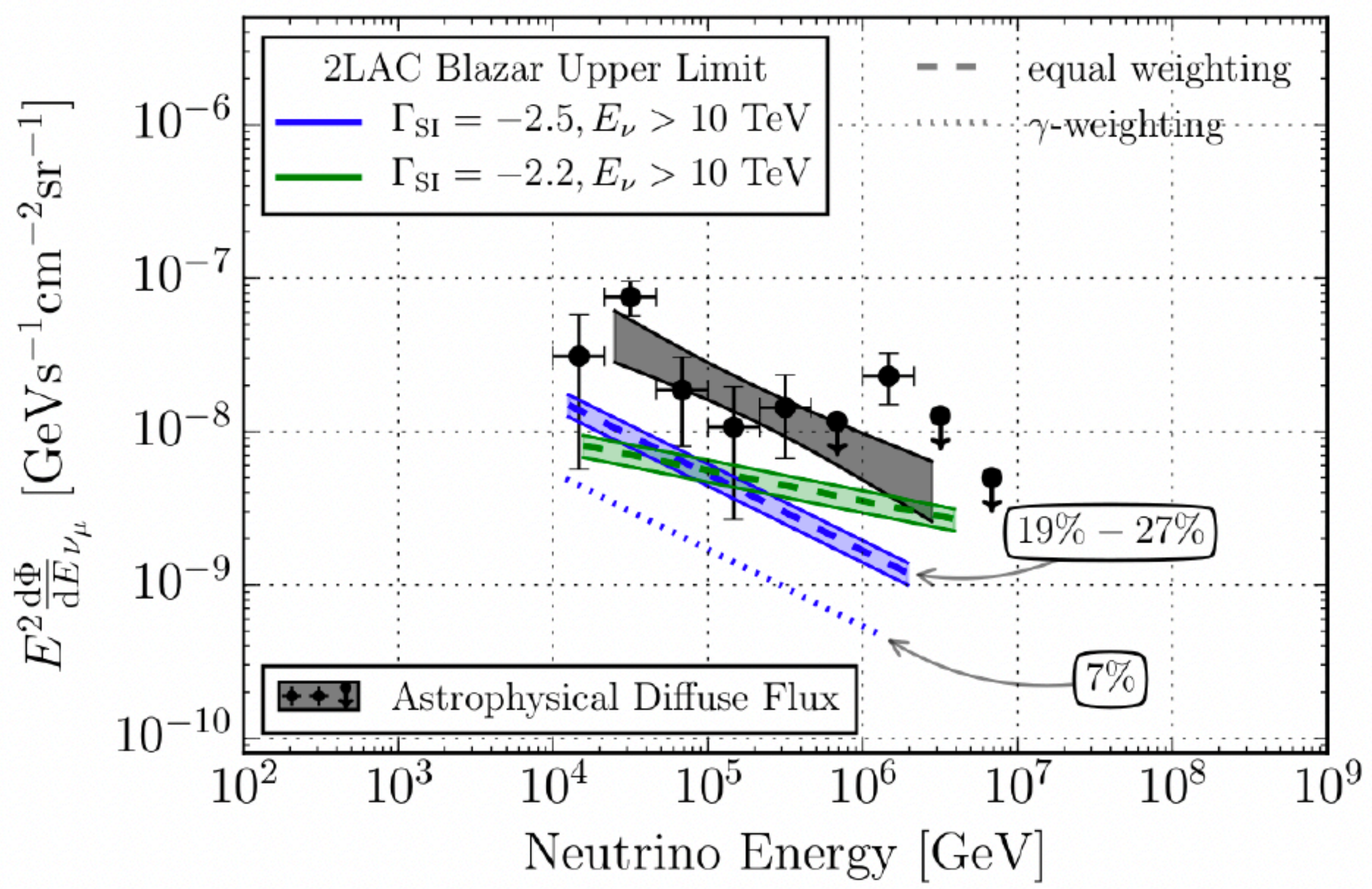
Science. 342 6161 (2013)





1172 GRBs inspected, no correlation found

< 1% contribution to diffuse flux



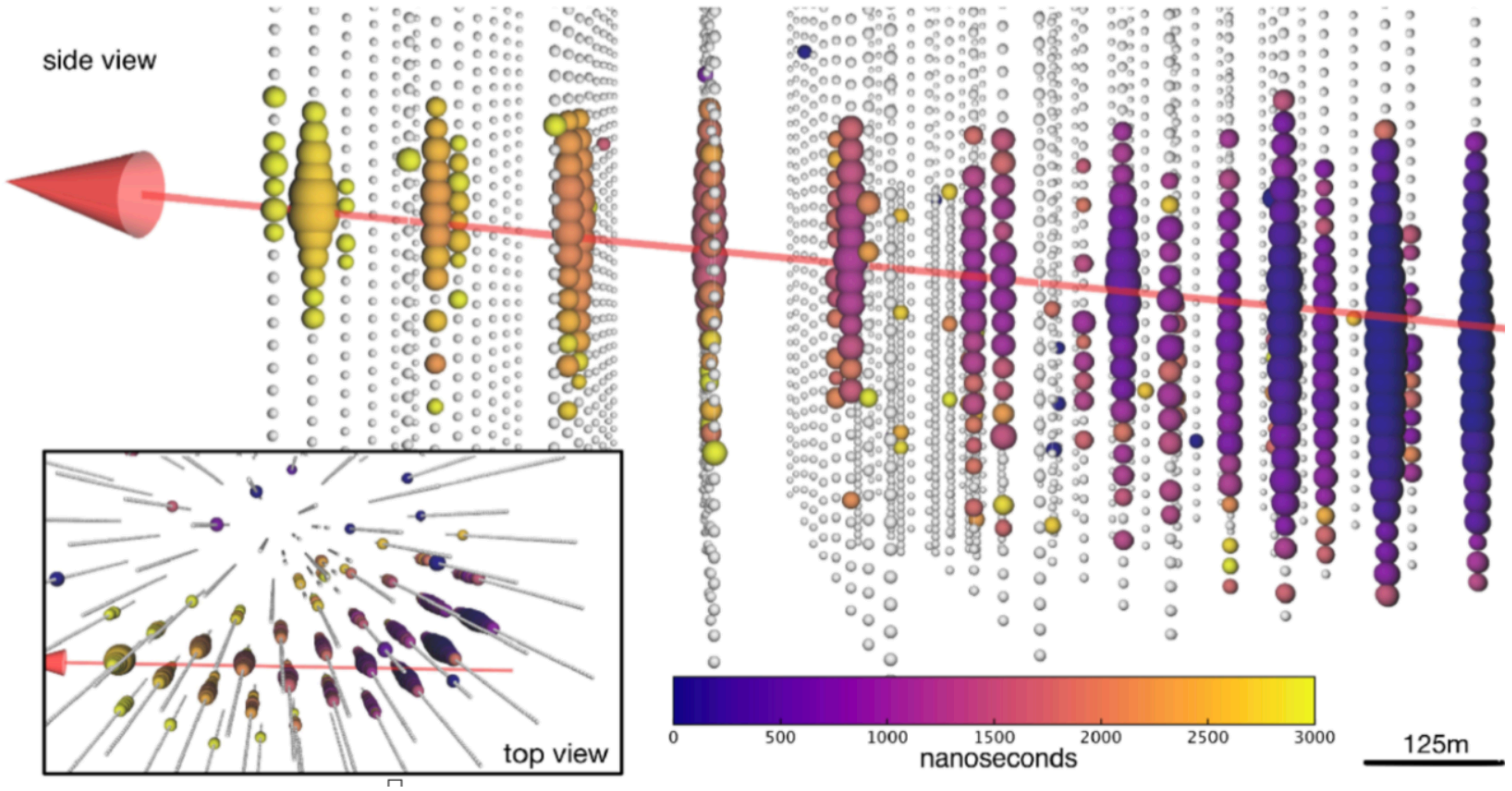
862 blazars inspected, no correlation found

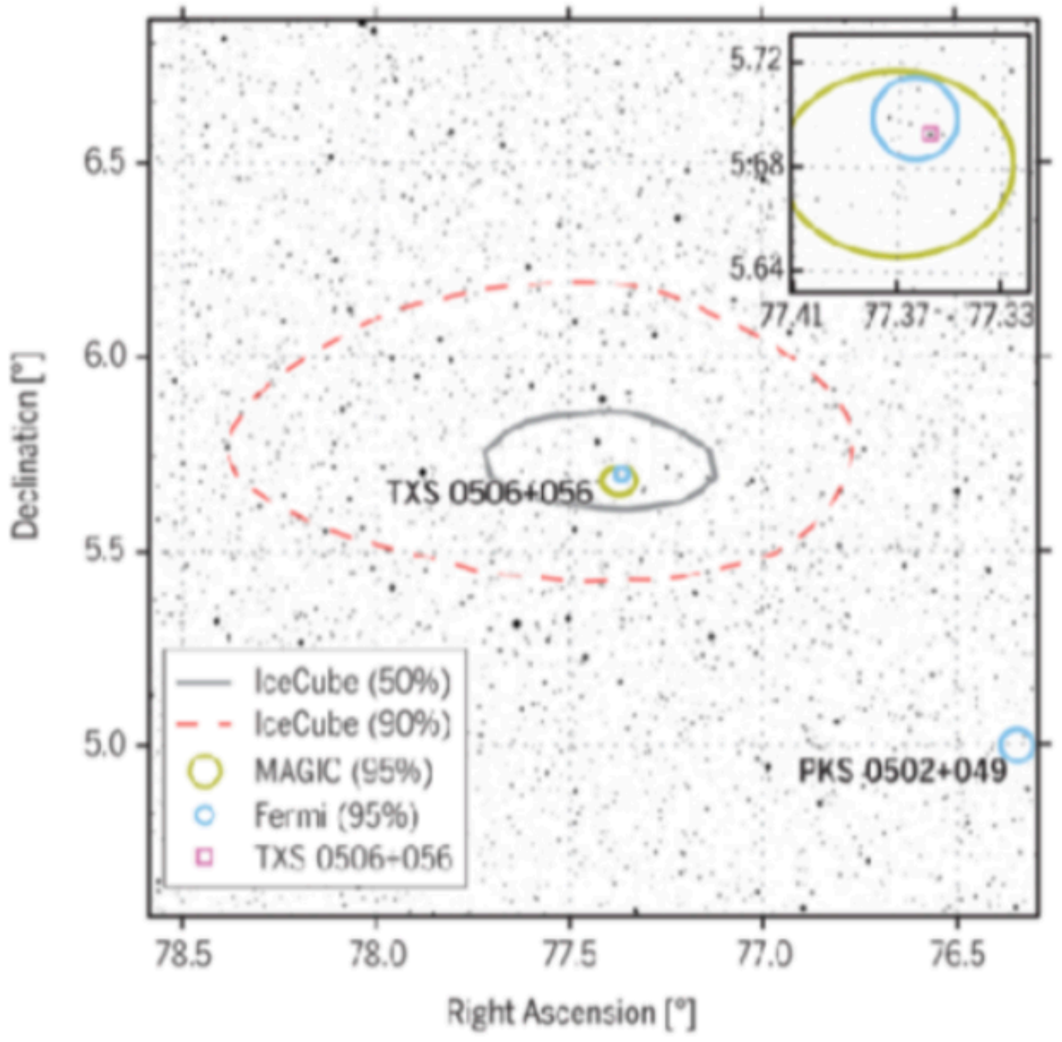
< 27% contribution to diffuse flux

Multimessenger neutrino alert

High neutrino IceCube alert followed by MAGIC detection of very high photons from TXS 0506+056 flaring blazar

- follow up by several other observatories (gamma, optical, radio, …)

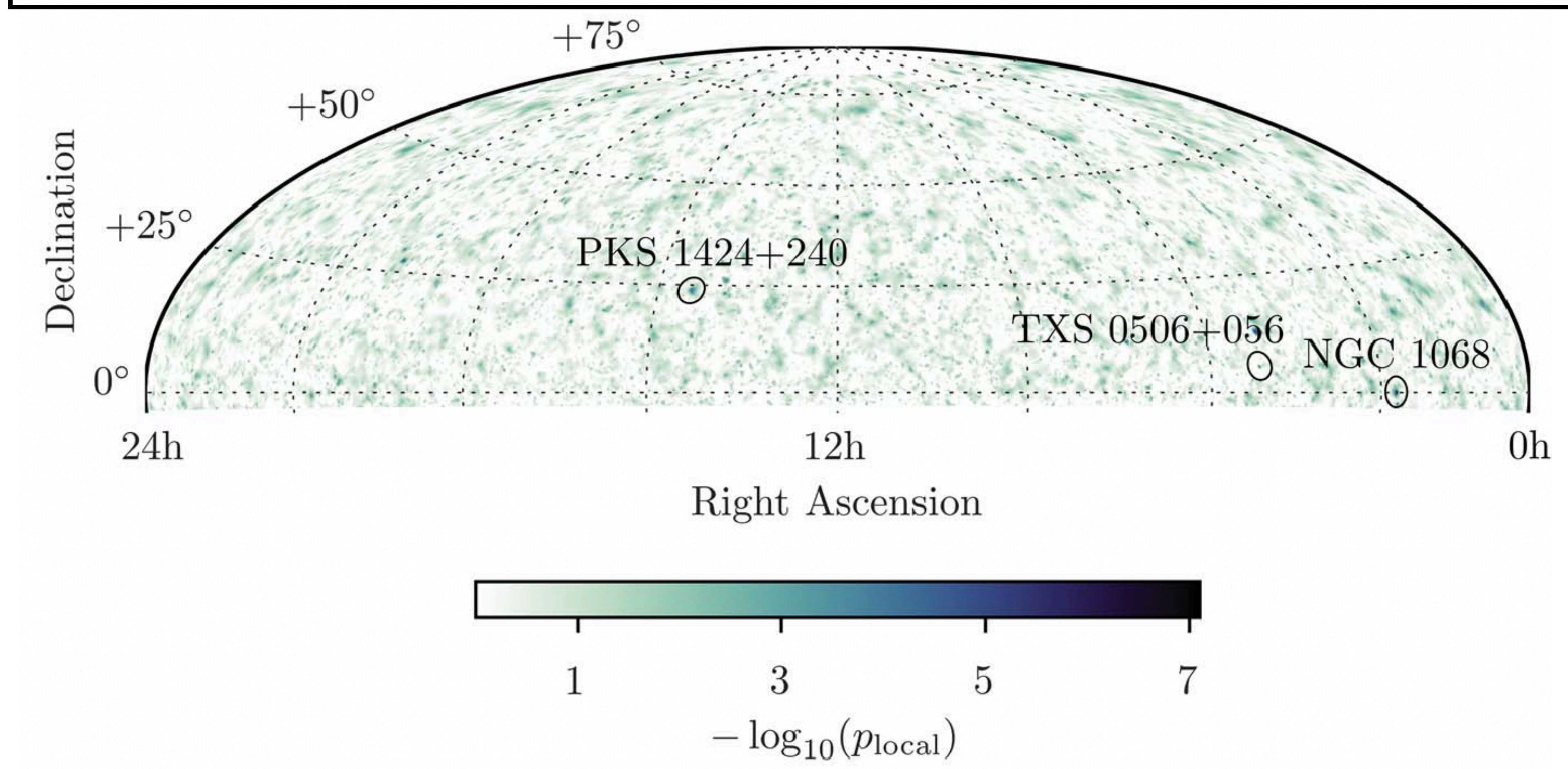




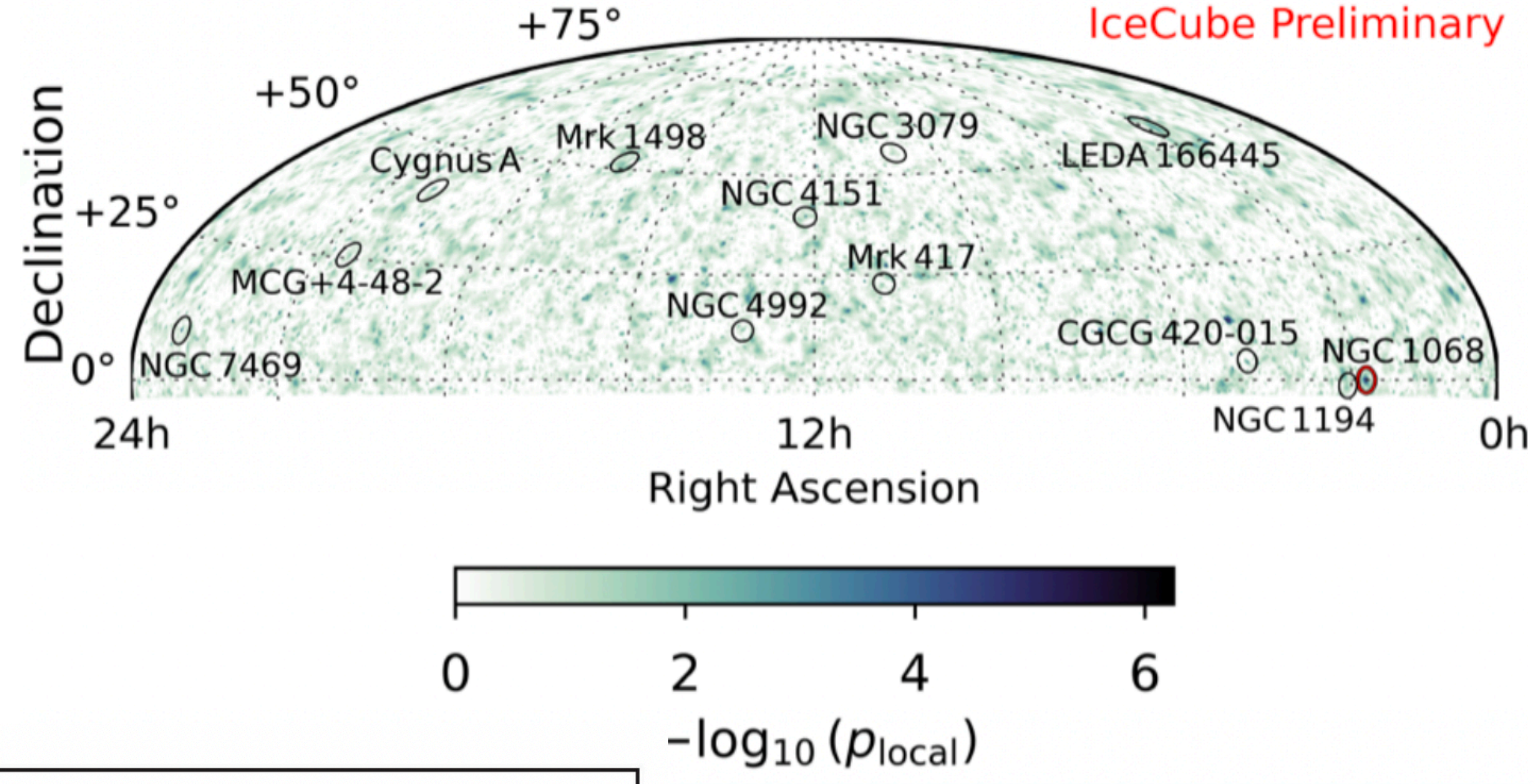
Science. 361 6398 (2018)

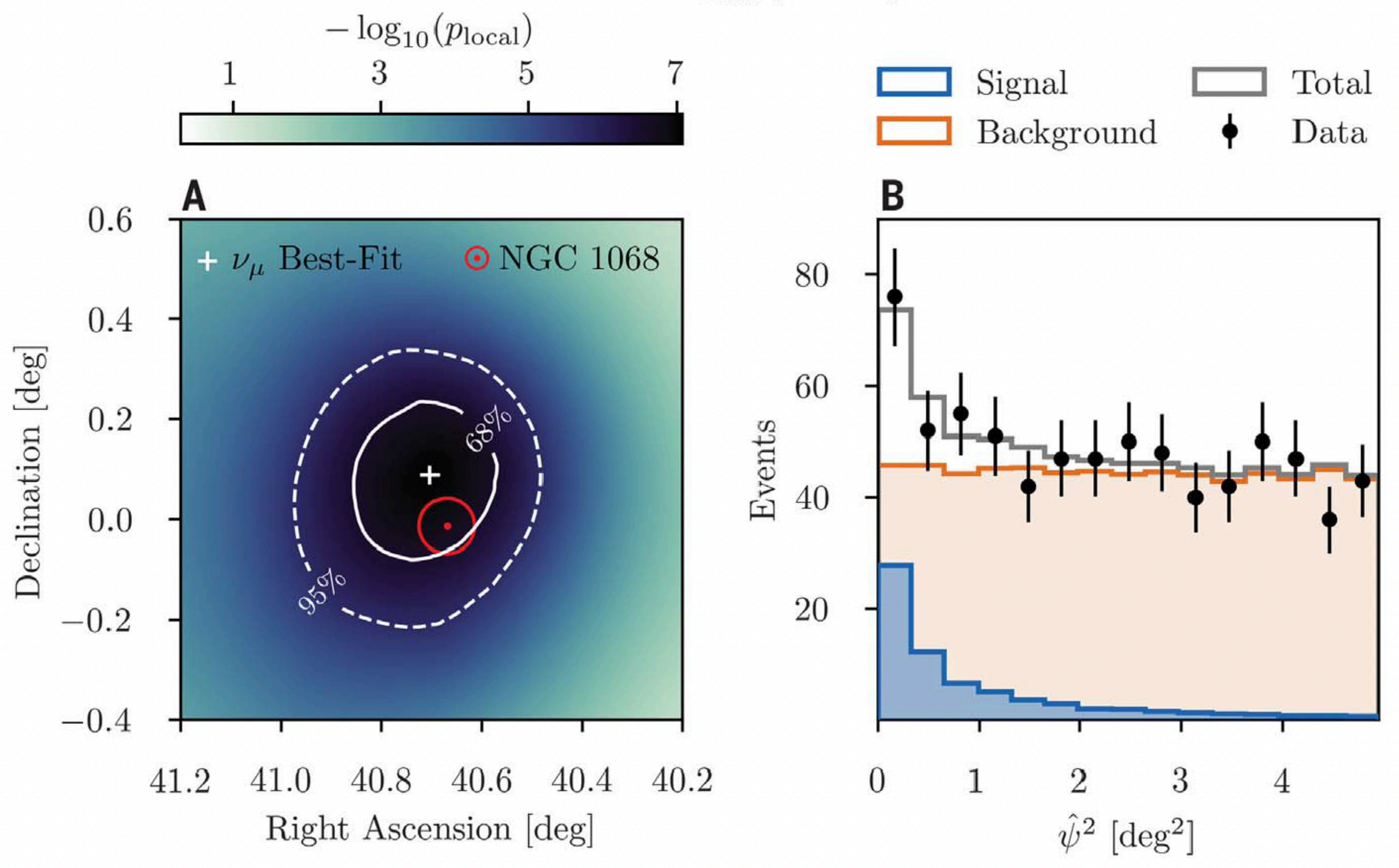
IceCube - Point-like sources

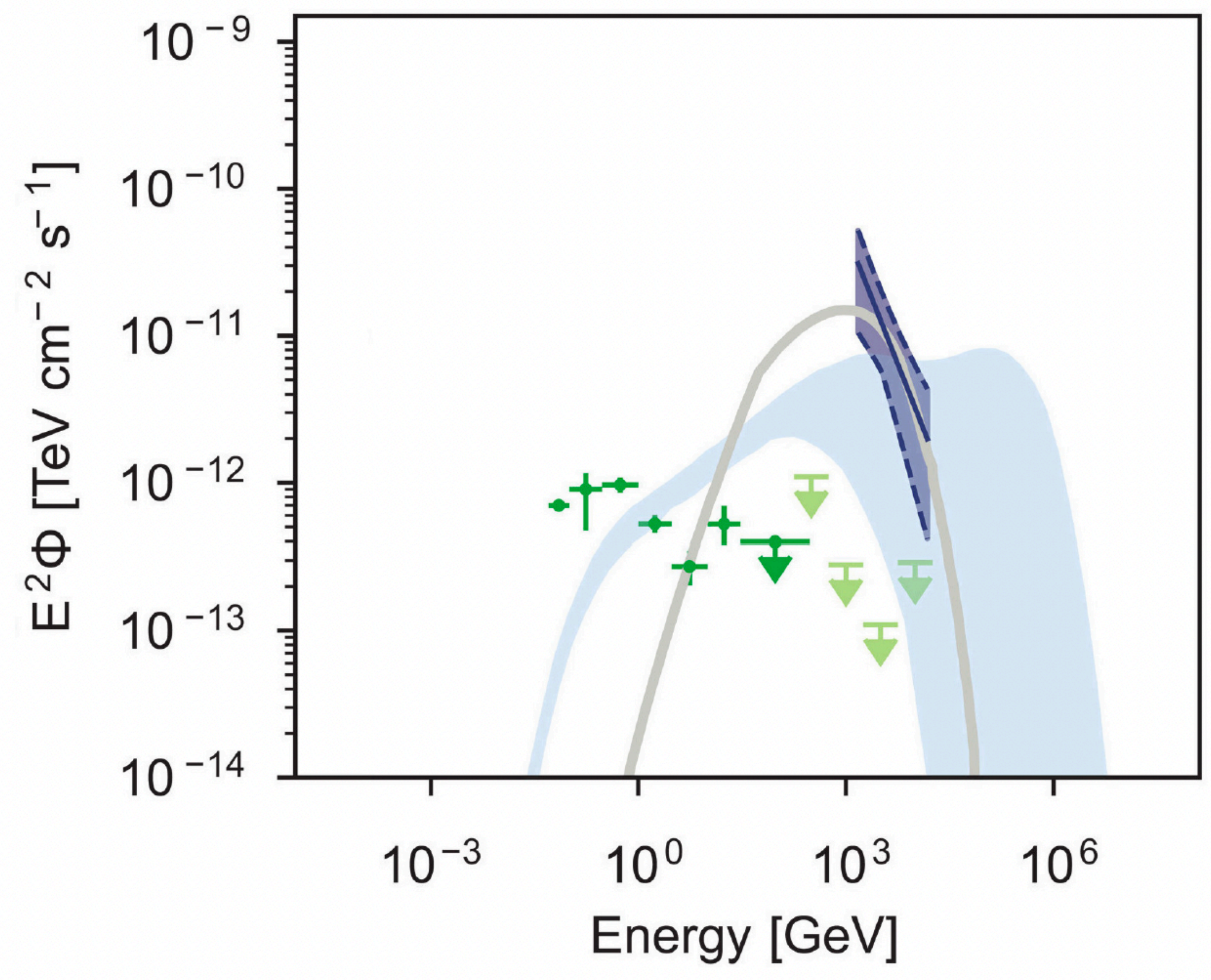
The first neutrino steady source NGC1068, Science 378, 538 (2022)

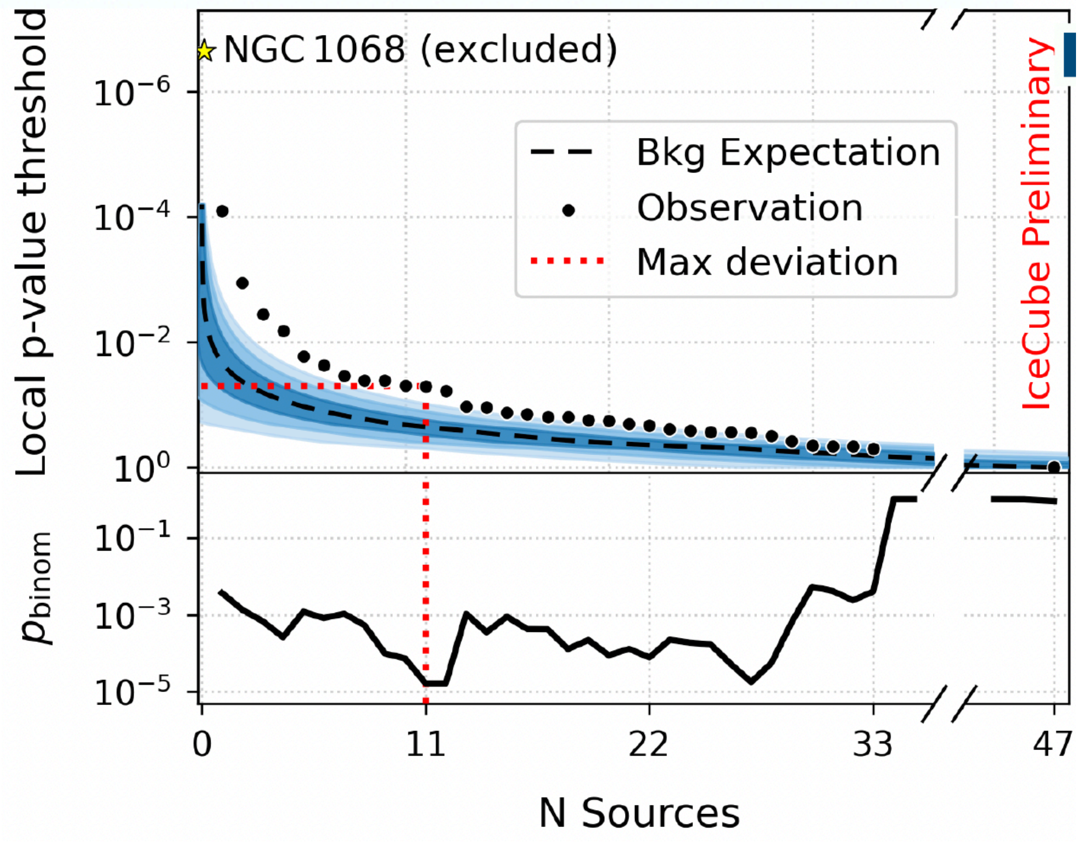


Search for neutrinos from Seyfert Galaxies









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)

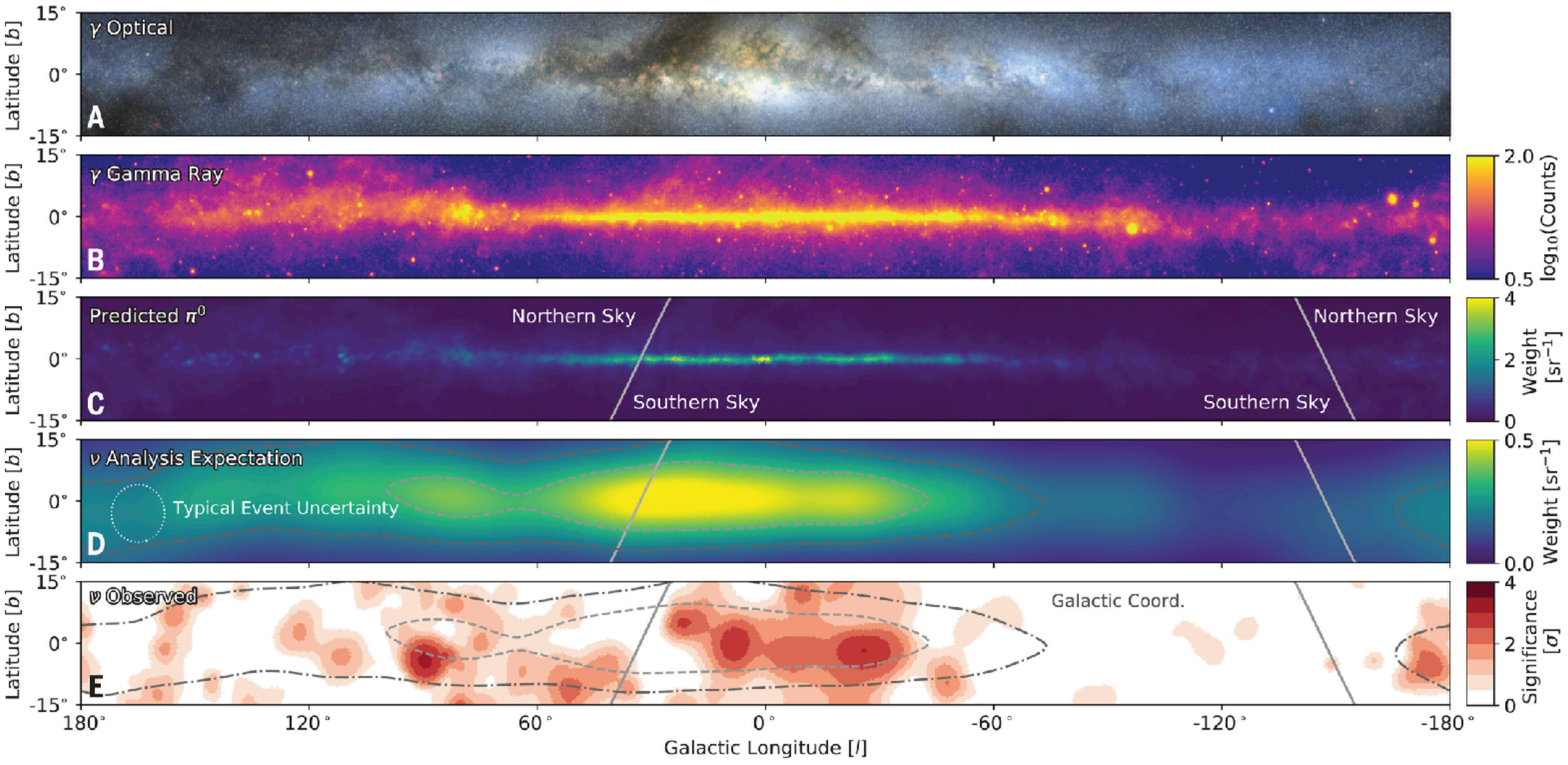
3.3 sigma excess observed stacking 11 sources over 47 (NGC 1068 excluded)

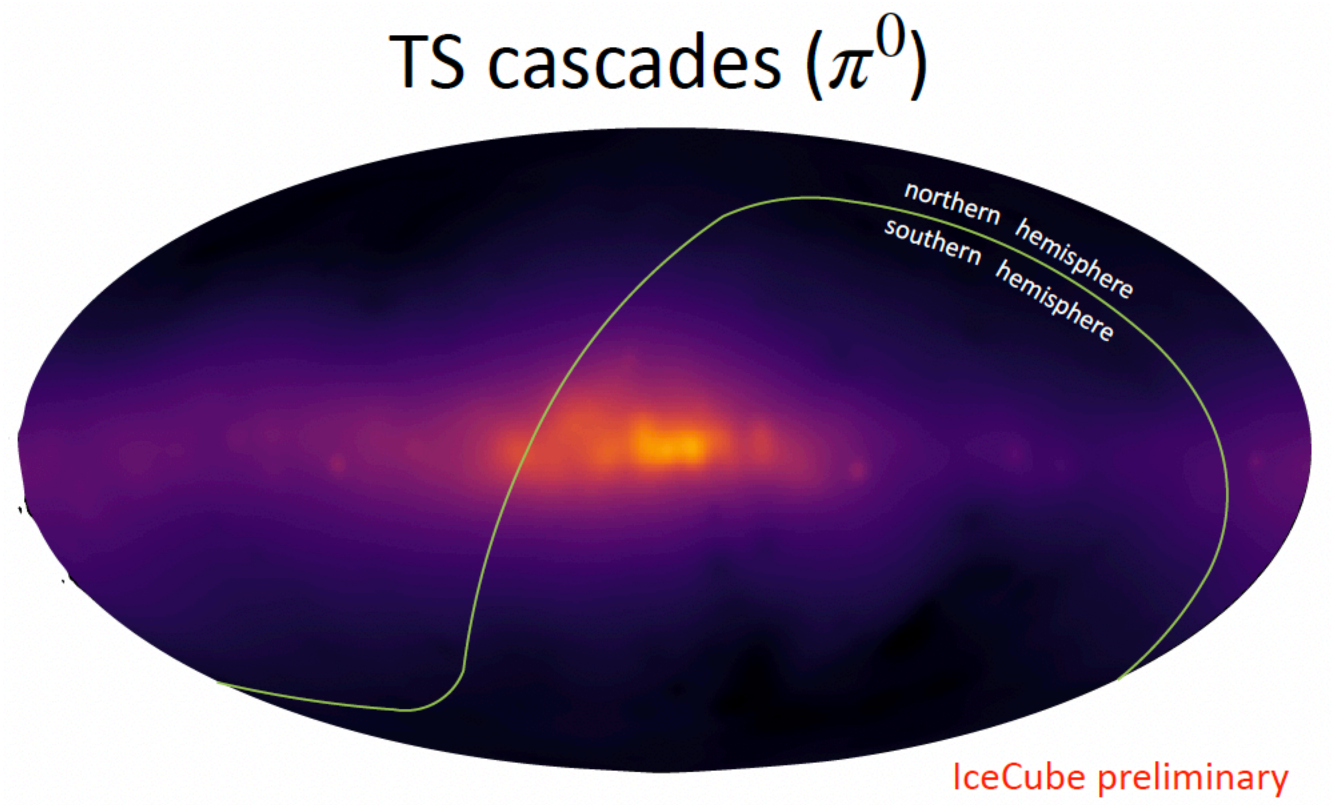
Aguilar-Sanchez Neutrino 2024

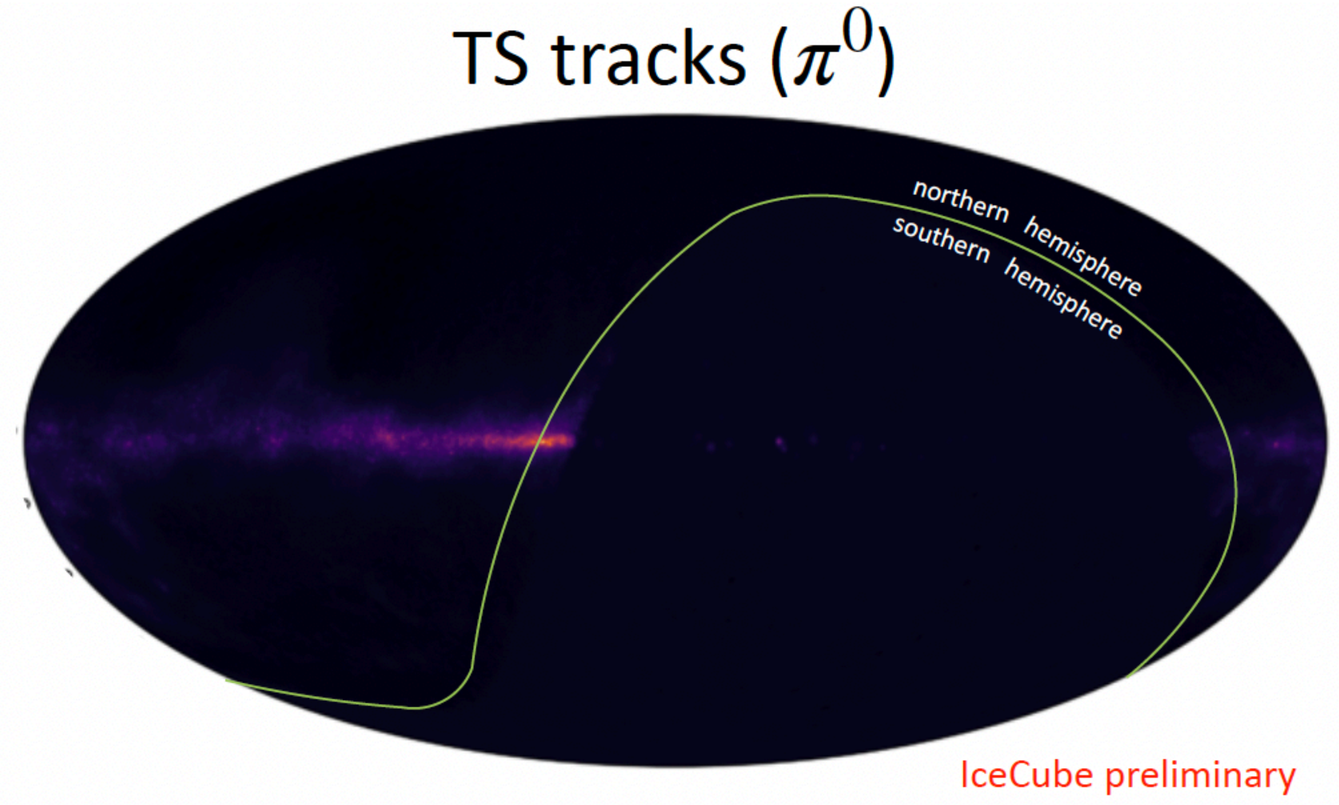
IceCube - Galactic Plane

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

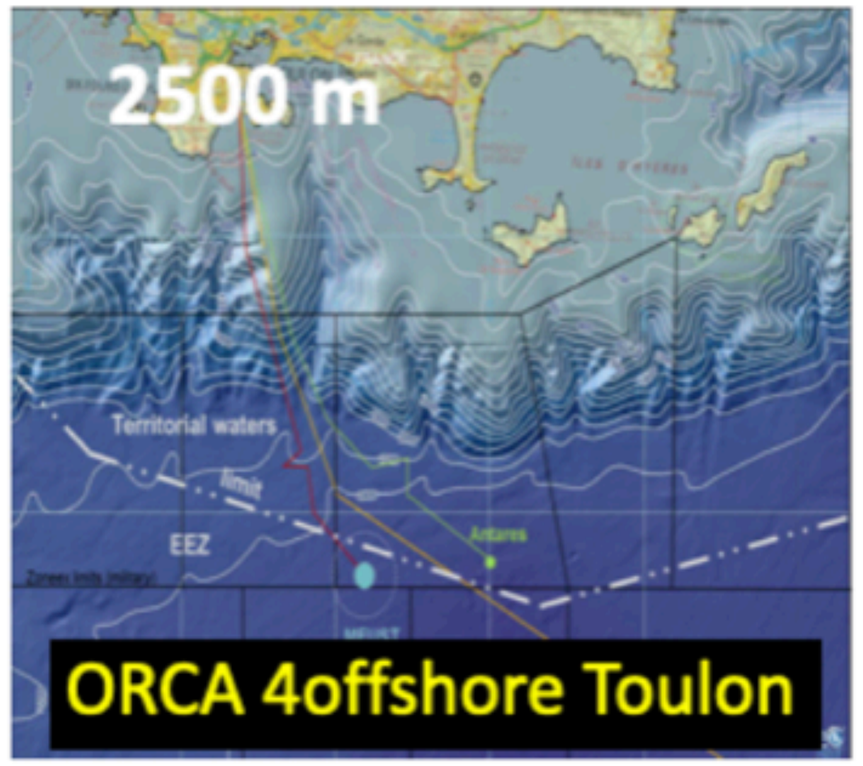
Observed flux does not agree with galactic diffuse models







KM3NeT - a distributed infrastructure

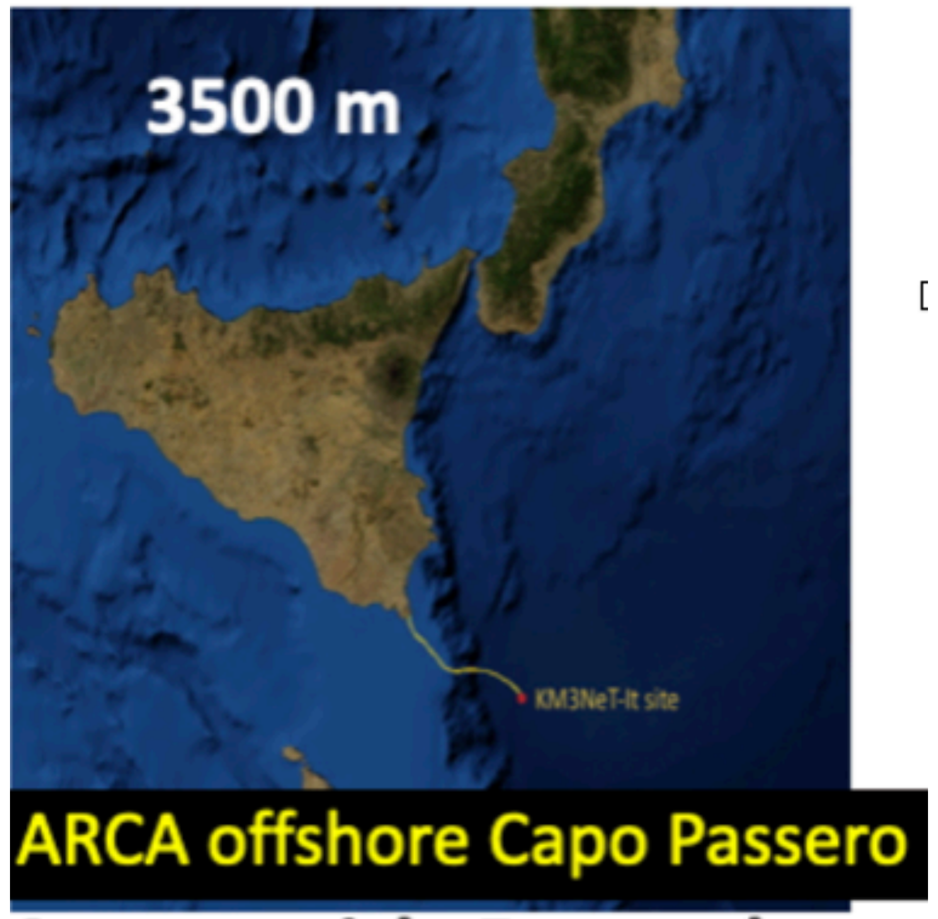


Two telescopes, one technology

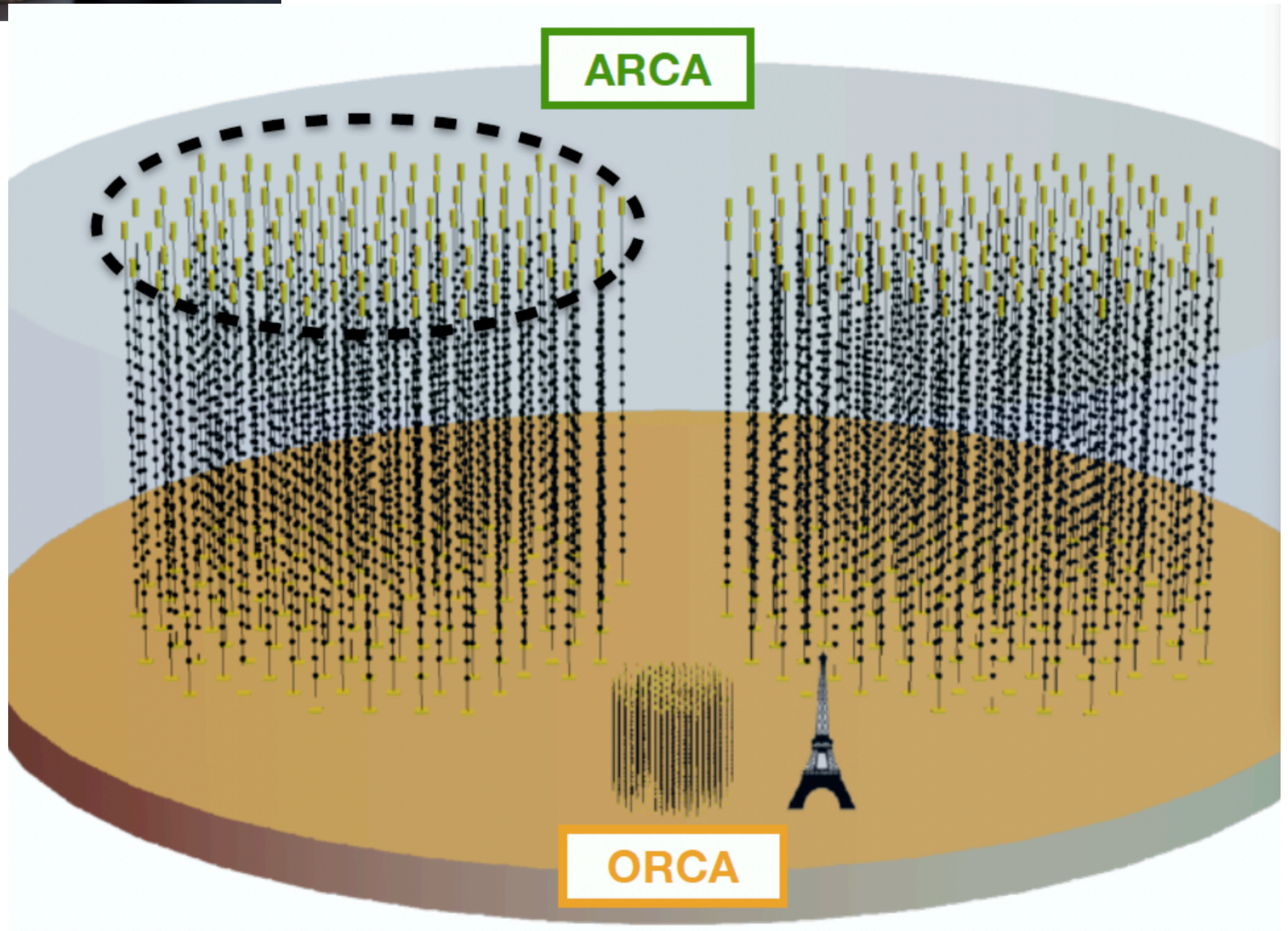
- innovative with multi-PMT DOM that inspired several new projects

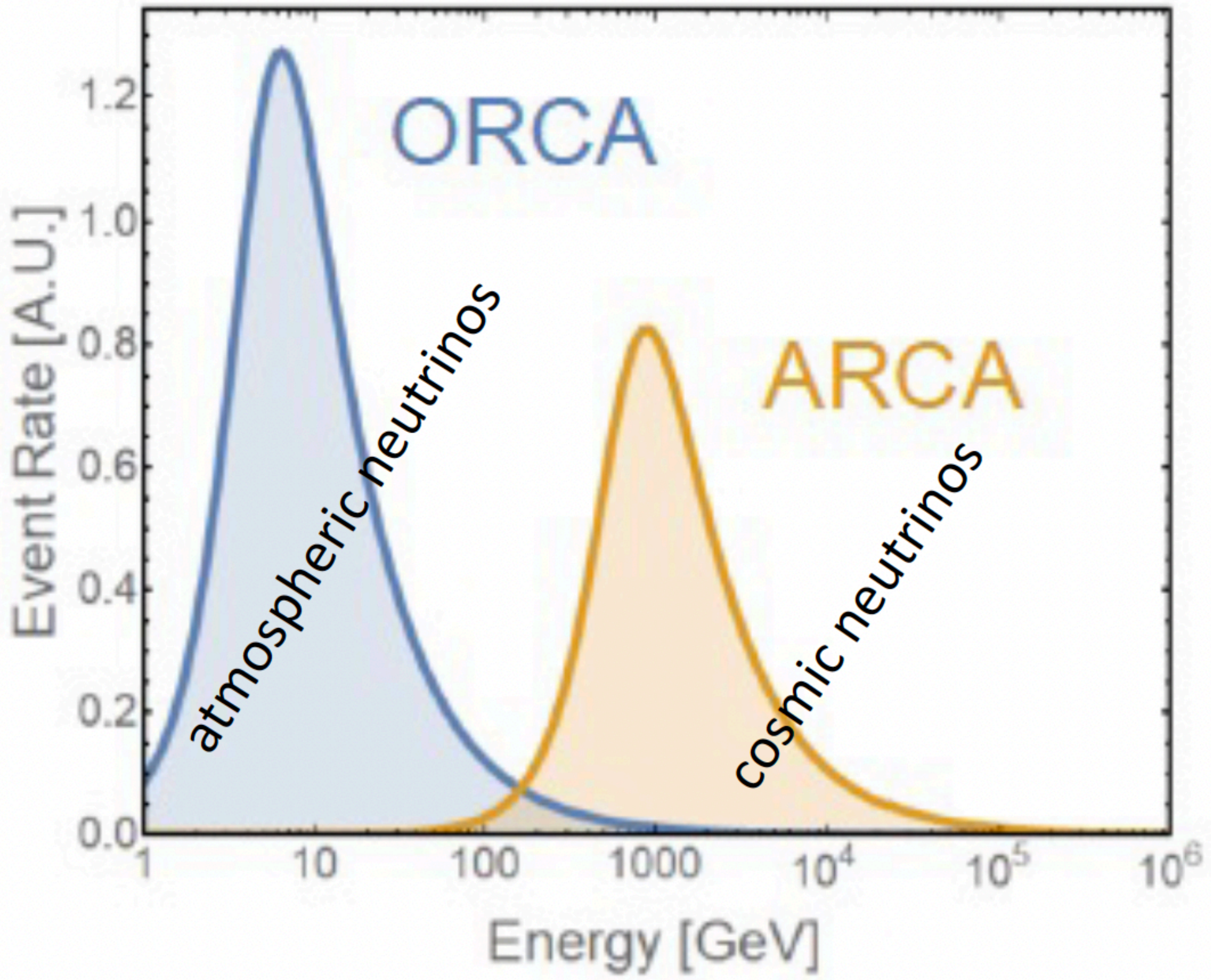
Building blocks of 115 strings
DOM distance => Energy range
ARCA 2BB 1 km^3
51/230 strings deployed
ORCA 1 BB 7 Mton
28/115 strings deployed

Oscillation Research
with Cosmics In the Abyss



Astroparticle Research
with Cosmics In the Abyss

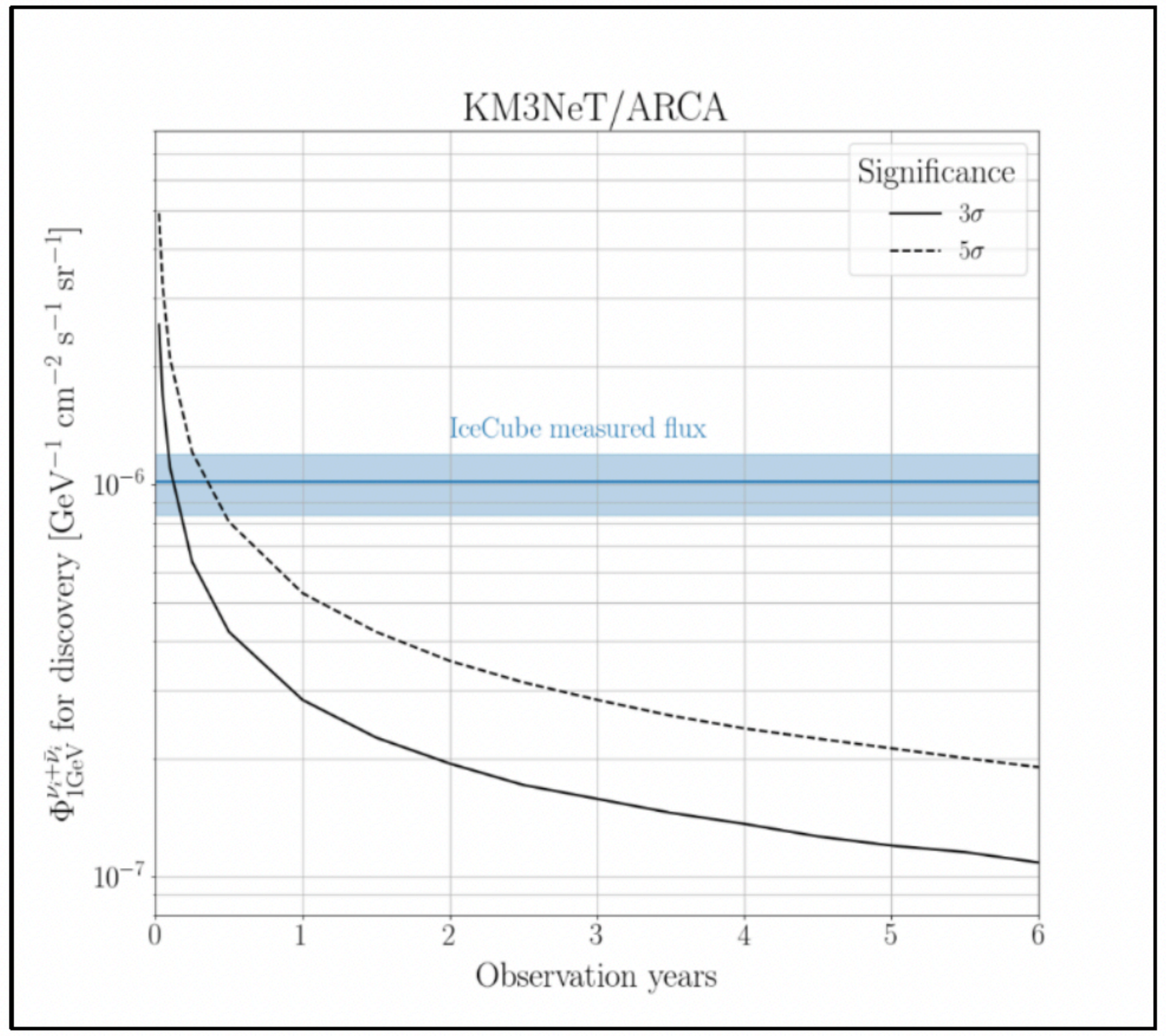




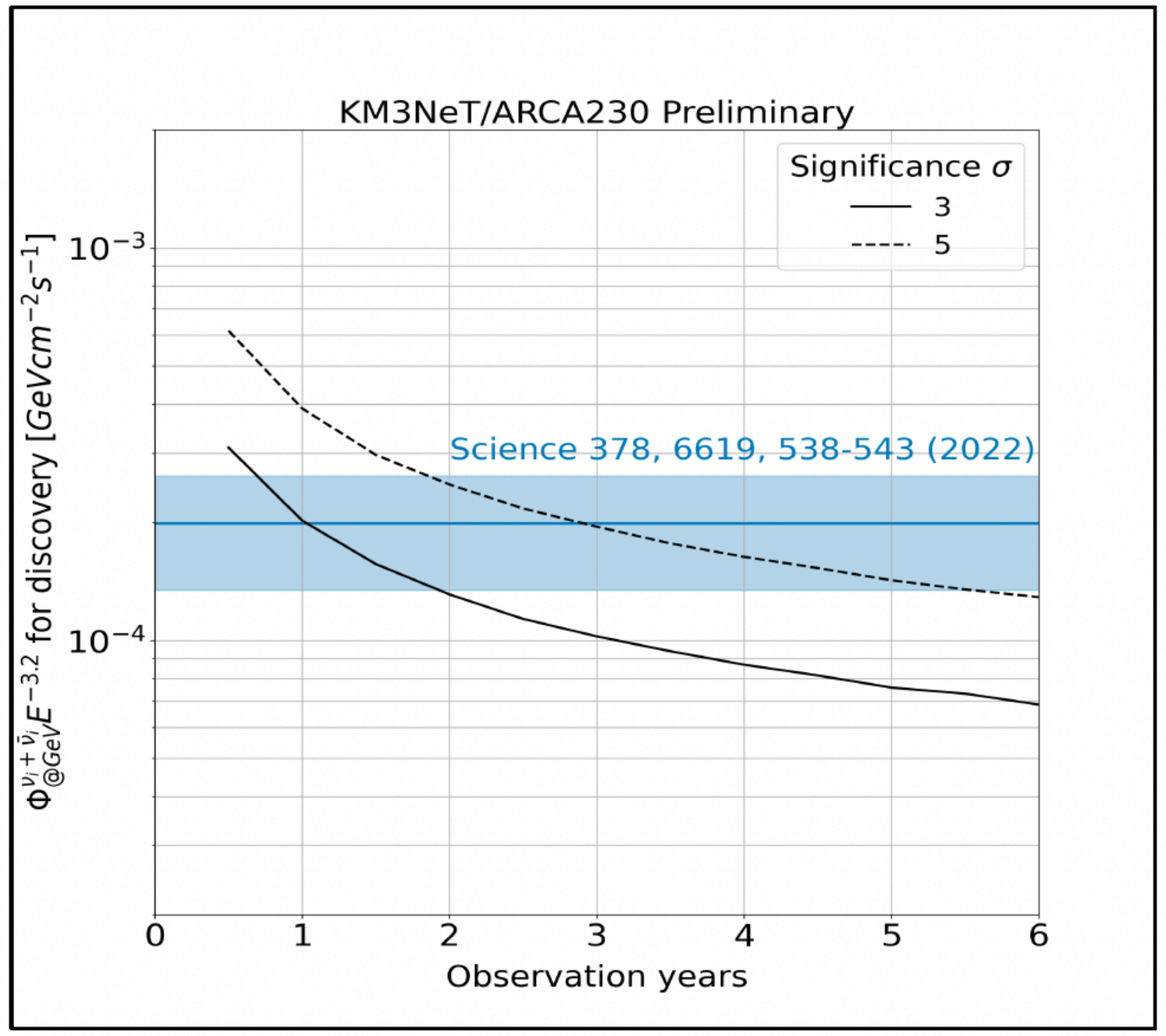
KM3NeT with its large effective area, sky visibility and unprecedented angular resolution will improve neutrino discovery potential especially for point-like sources

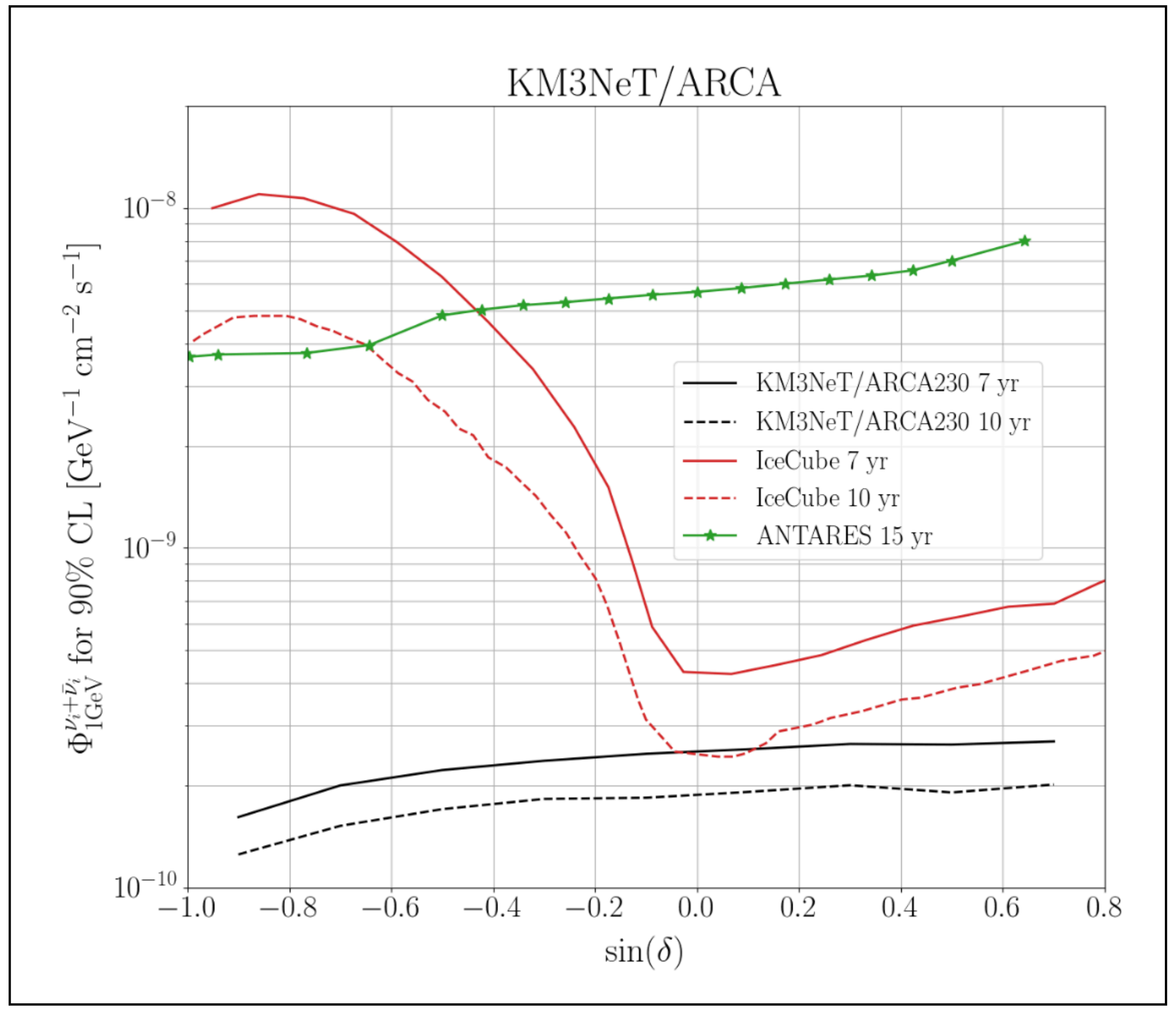
KM3NeT - Expected sensitivity

Diffuse flux



NGC1068





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

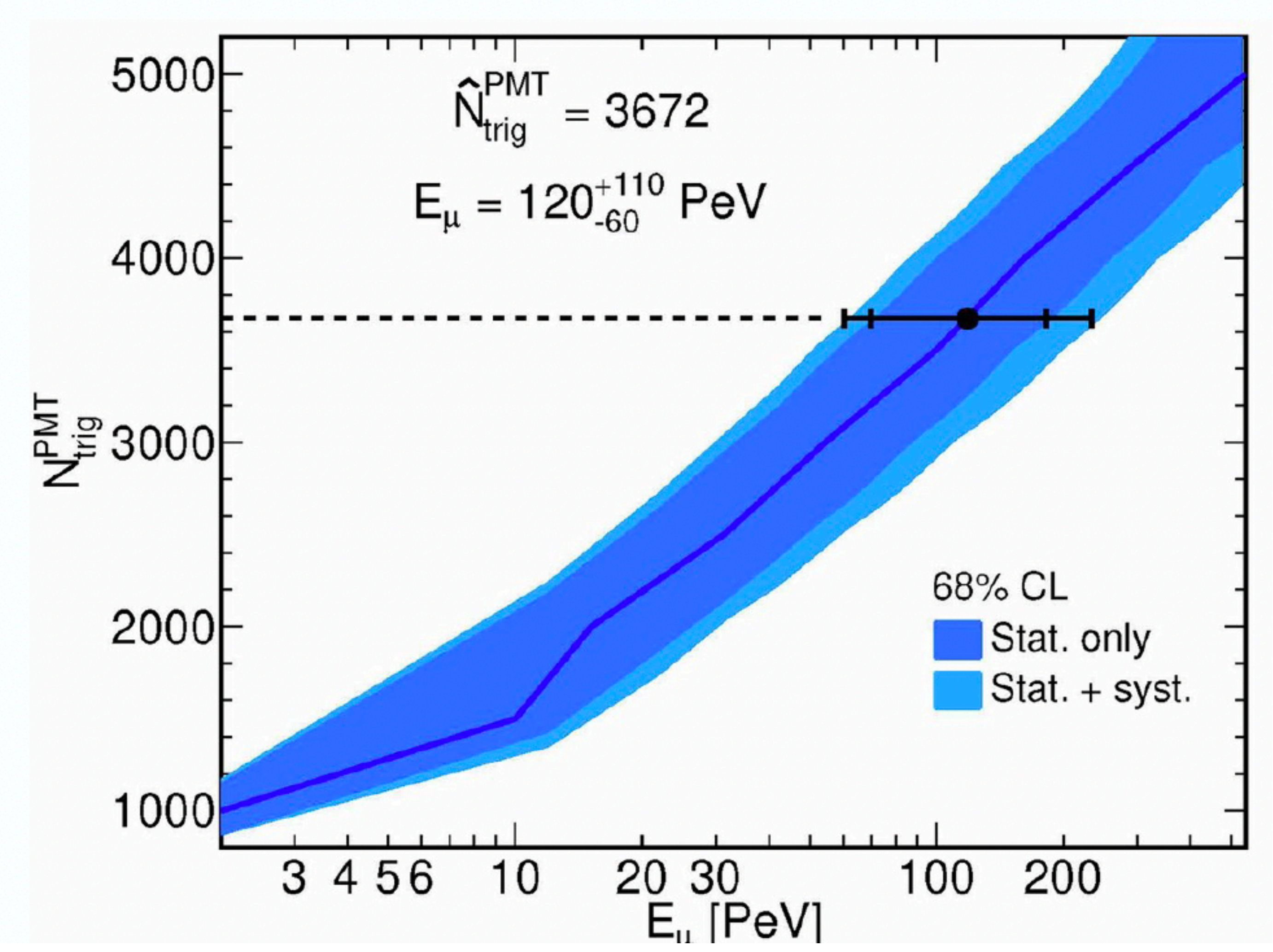
Uncharted territory: breaking into a new energy regime

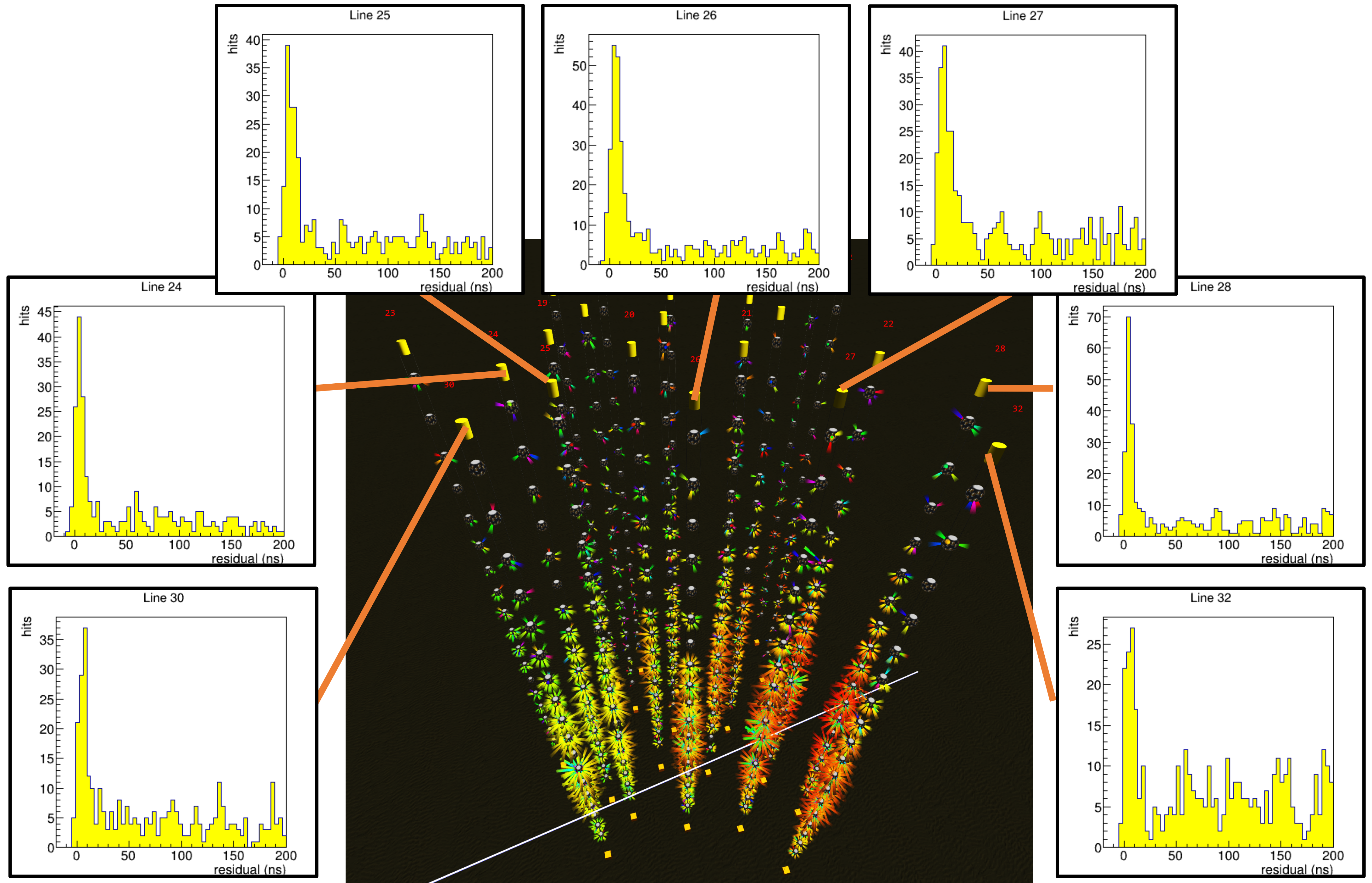
KM3NeT still in construction, detected the most energetic neutrino ever seen
Nature 638, 376–382 (2025)

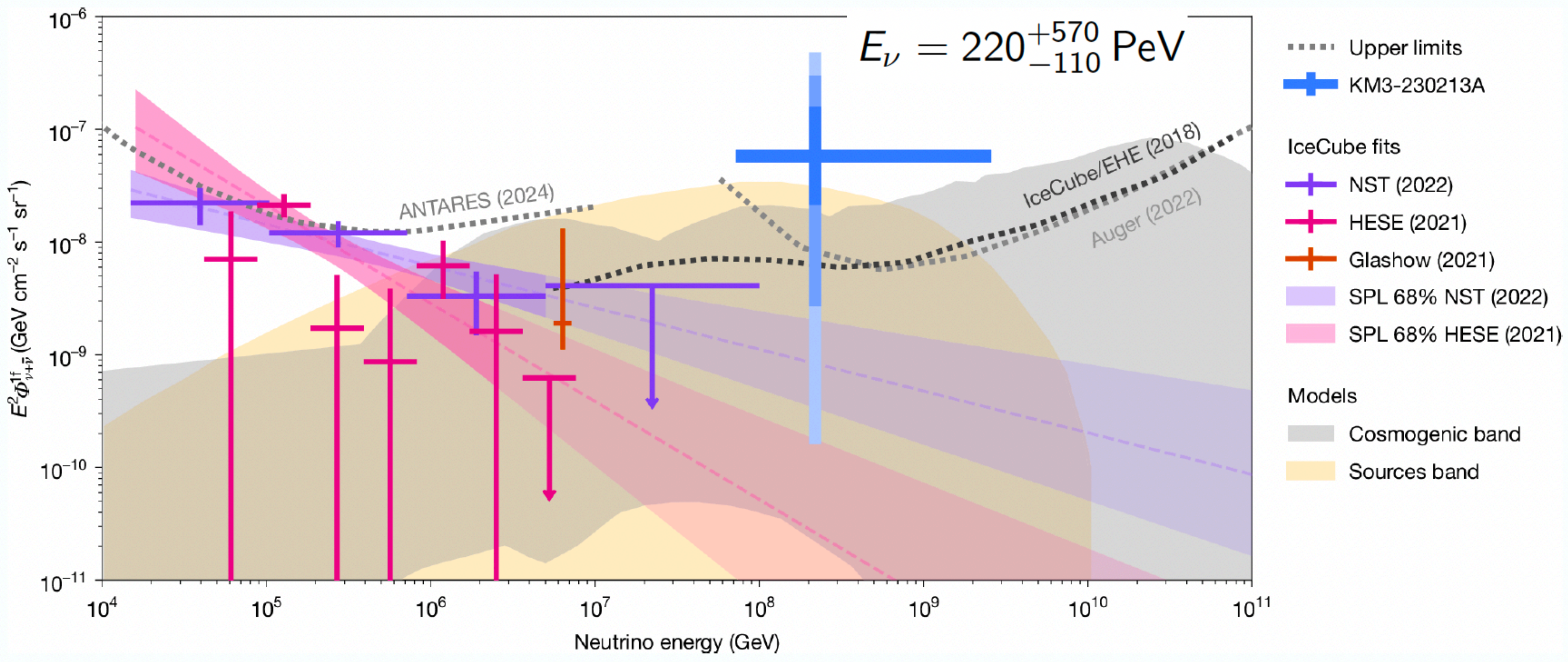
Local coordinates: (zenith, azimuth) = (89.4°, 259.8°):

- **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)

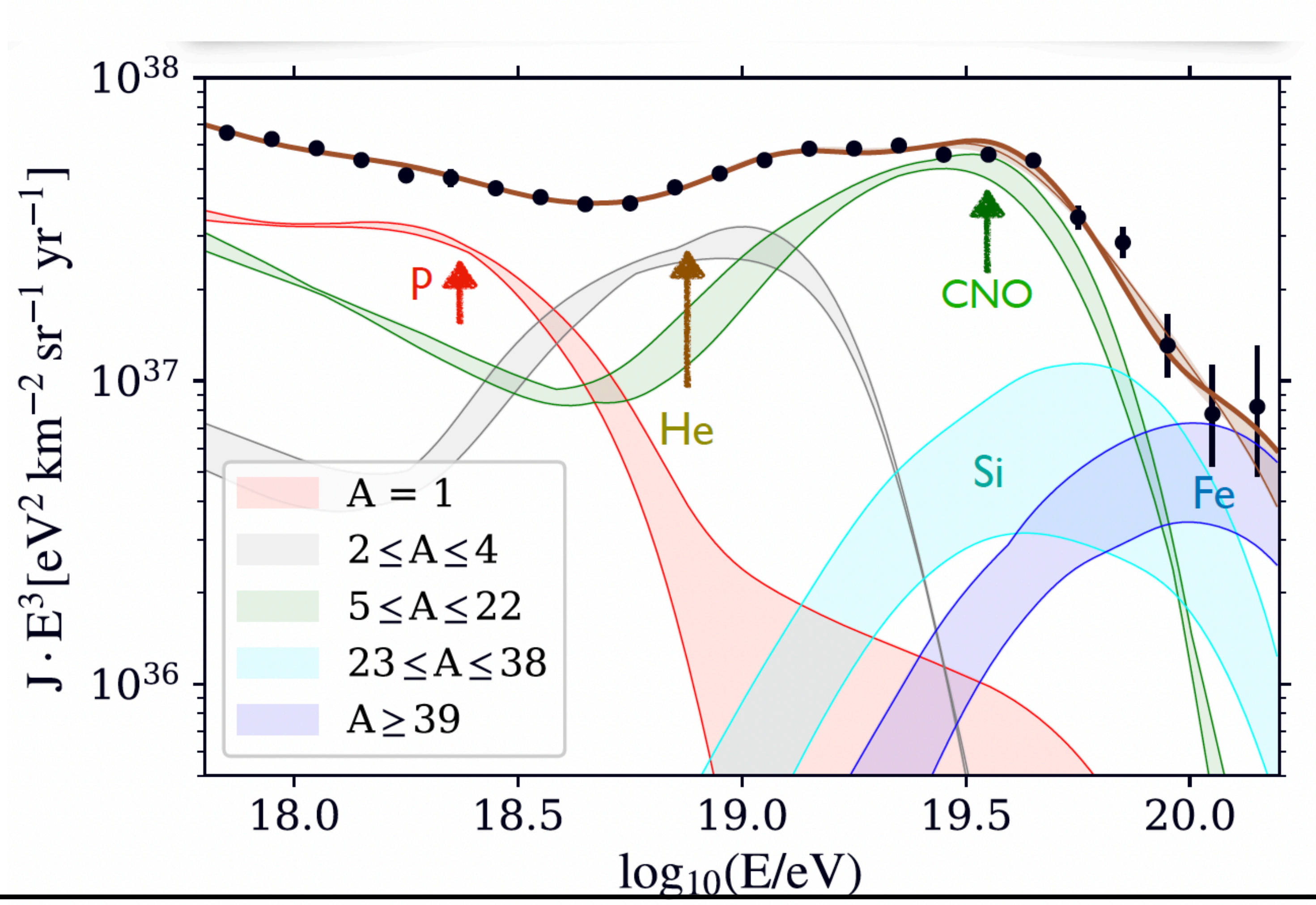
KM3-230213A - 1st UHE neutrino

Can be the first cosmogenic neutrino detected ?

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

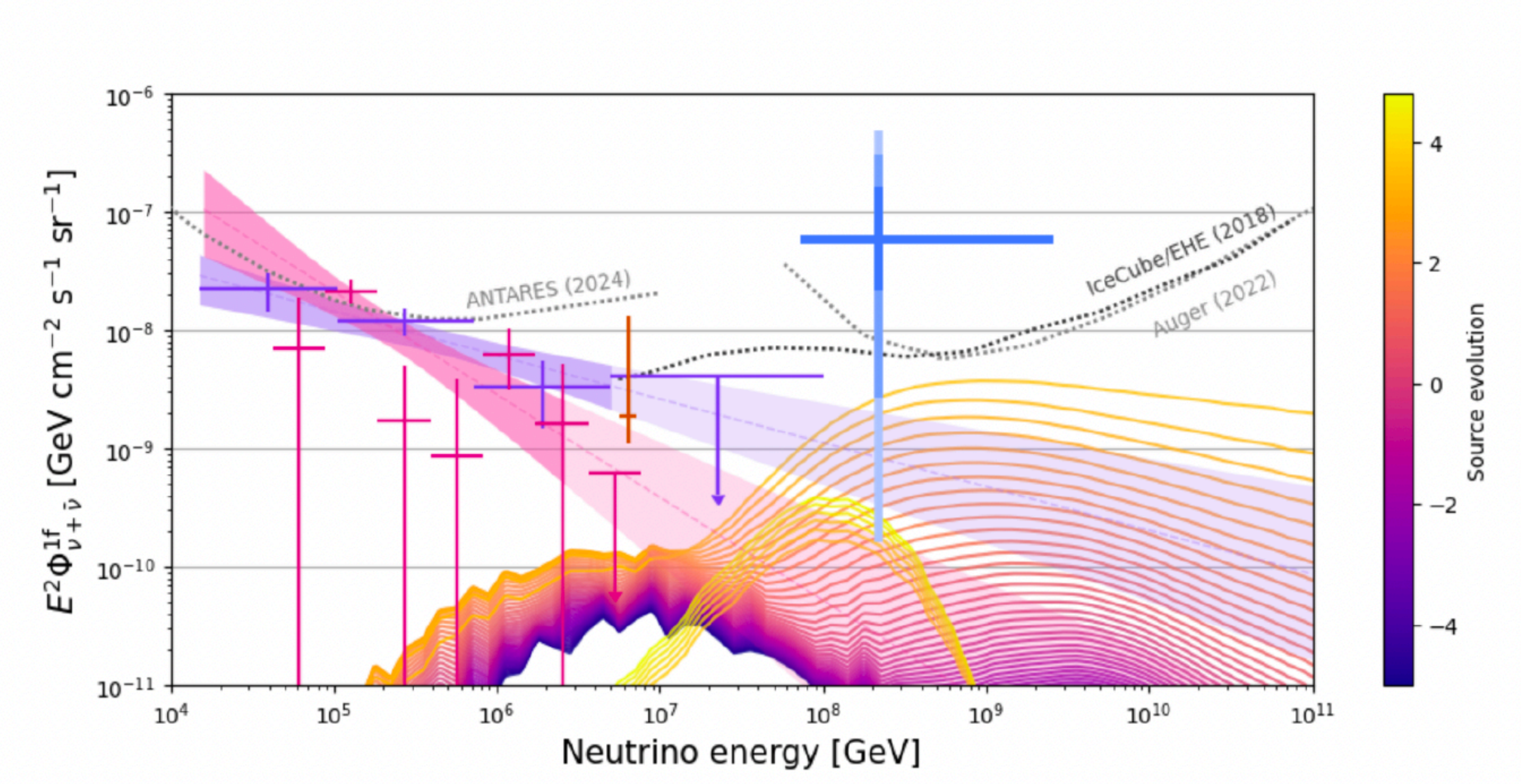
Very detailed studies by Auger exclude

- a large fraction of protons at highest energy
- GZK as dominant cause of spectral cut-off
- astronomy with CR

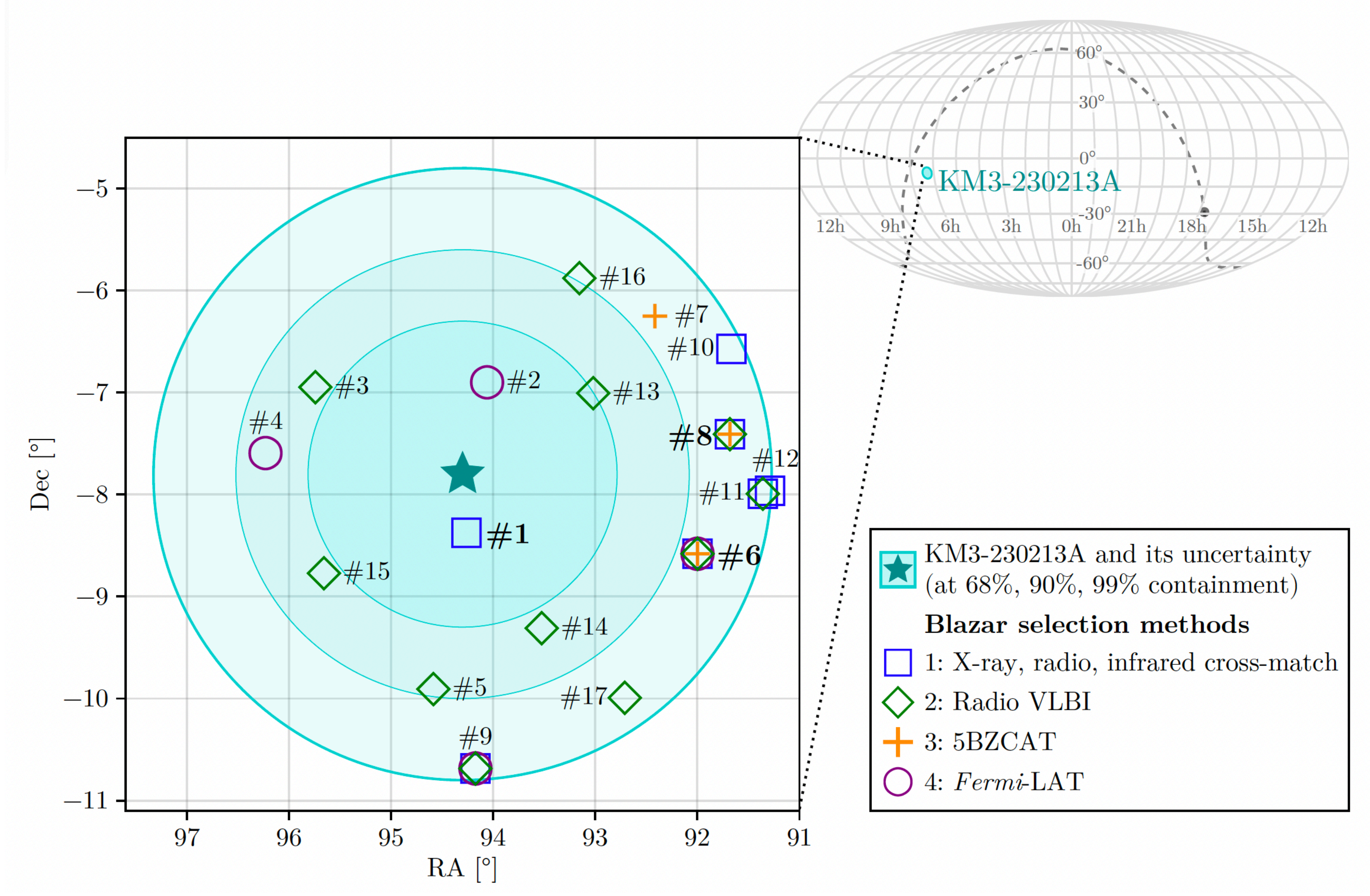


On the potential cosmogenic origin of the ultra-high-energy event KM3-230213A - 2025 *ApJL* **984** L41

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



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



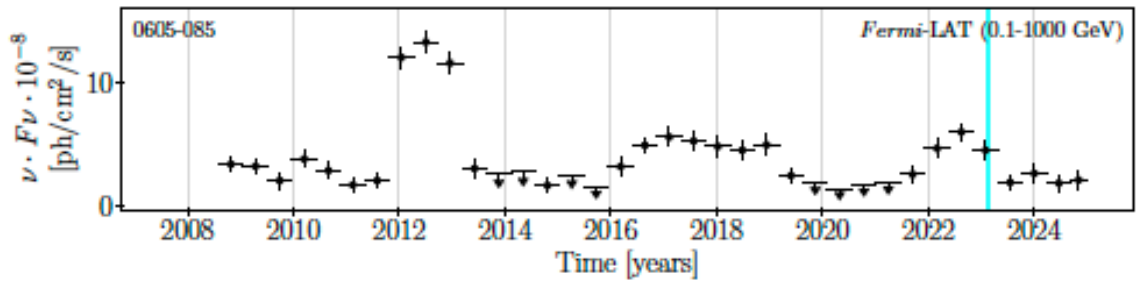
Crossmatch with gamma/X/radio catalogs

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

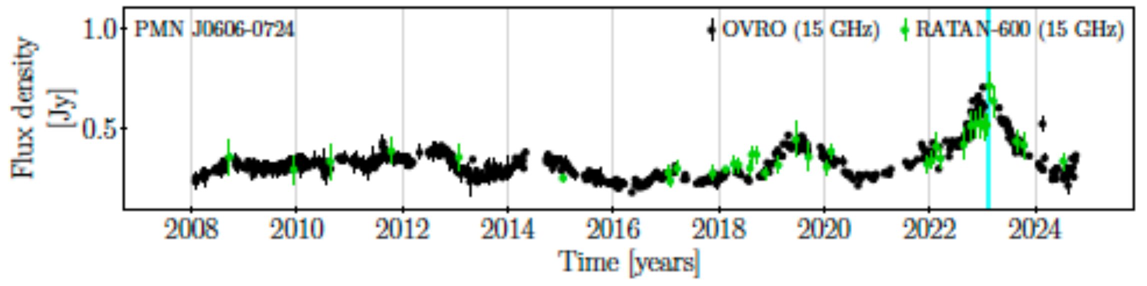
More observations on counterparts will be interesting

KM3NeT collaboration arXiv: 2502.08484

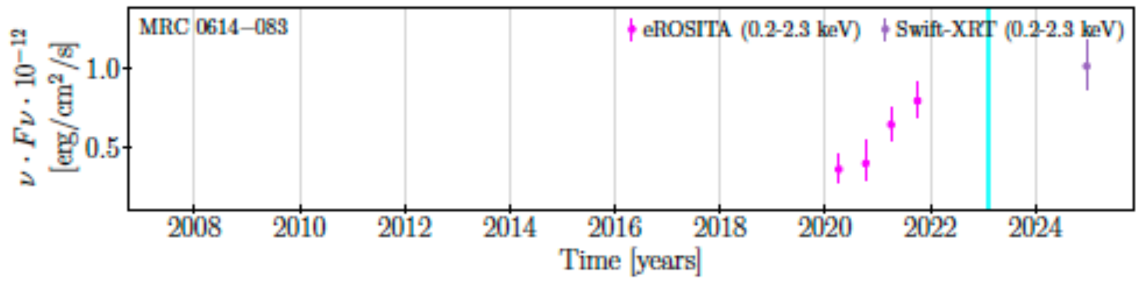
	Name	Sep.	RA	Dec	z	$S_{VLBI}^{8\,GHz}$	X-ray
		[°]	[°] J2000	[°] J2000		[mJy]	$[10^{-13}$ erg cm^{-2} s$^{-1}]$
#1	**MRC 0614-083**	0.6	94.2623	-8.3749	–	–	$5.58^{+1.16}_{-0.99}$
#2	**4FGL J0616.2-0653**	0.9	94.06	-6.90	–	–	≤ 0.89
#3	**PMN J0622-0657**	1.7	95.7419	-6.9478	–	87 ± 9	$0.62^{+1.48}_{-0.39}$
#4	**NVSS J062455-073536**	1.9	96.2306	-7.5936	–	50 ± 5	$0.37^{+1.82}_{-0.21}$
#5	**PMN J0618-0954**	2.1	94.5861	-9.9071	–	100	≤ 0.93
#6	**0605-085**	2.4	91.9987	-8.5805	0.87	2240 ± 226	$11.6^{+9.25}_{-2.89}$
#7	**PMN J0609-0615**	2.4	92.41656	-6.25163	2.219	48 ± 5	≤ 1.45
#8	**PMN J0606-0724**	2.6	91.68144	-7.40840	1.277	306 ± 31	$0.09^{+0.53}_{-0.06}$
#9	**PMN J0616-1040**	2.9	94.17420	-10.68568	–	248 ± 25	$2.82^{+1.5}_{-0.89}$
#10	**NVSS J060639-063421**	2.9	91.6667	-6.5721	–	–	$0.23^{+0.65}_{-0.09}$
#11	**PMN J0605-0759**	2.9	91.35911	-7.99216	–	67 ± 7	$1.99^{+1.04}_{-0.67}$
#12	**NVSS J060509-075747**	3.0	91.28843	-7.96308	–	–	$1.93^{+1.94}_{-0.88}$
#13	**PMN J0612-0700**	1.5	93.02018	-7.00635	–	62 ± 7	≤ 0.98
#14	**PMN J0614-0918**	1.7	93.52517	-9.31053	–	55 ± 6	≤ 0.85
#15	**PMN J0622-0846**	1.7	95.65833	-8.77174	–	109 ± 12	≤ 1.13
#16	**NVSS J061237-055244**	2.2	93.15567	-5.87900	–	45 ± 5	≤ 1.17
#17	**NVSS J061050-095934**	2.7	92.71130	-9.99277	–	94 ± 10	$0.19^{+0.75}_{-0.09}$



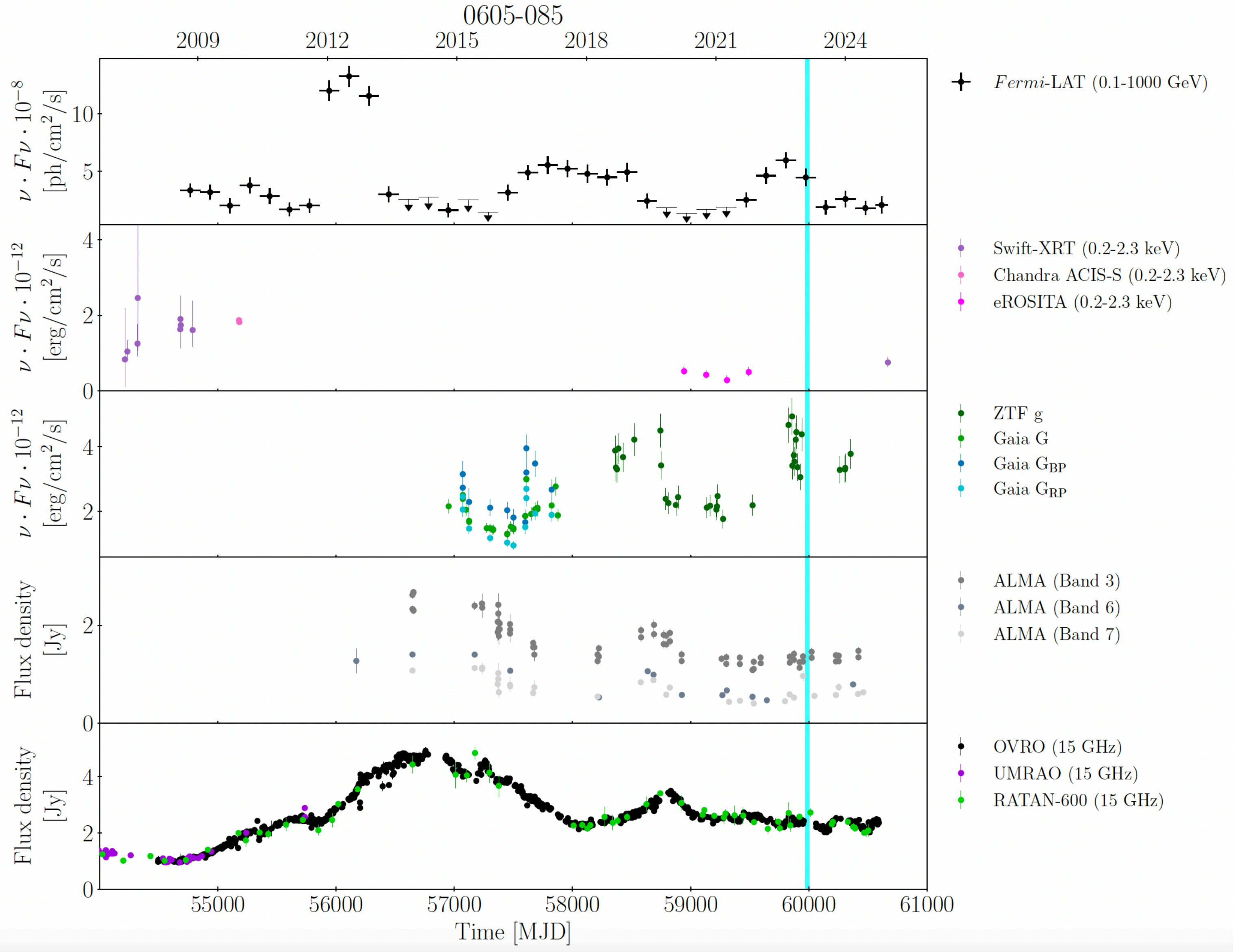
(a) The *Fermi*-LAT light curve of 0605-085, the brightest radio source in the neutrino localization region that experiences gamma-ray flaring activity around the neutrino arrival.



(b) The radio light curve for PMN J0606-0724, which shows a major flare in close coincidence with the neutrino arrival.



(c) The X-ray light curve for MRC 0614-083, indicating flaring activity around the neutrino arrival.

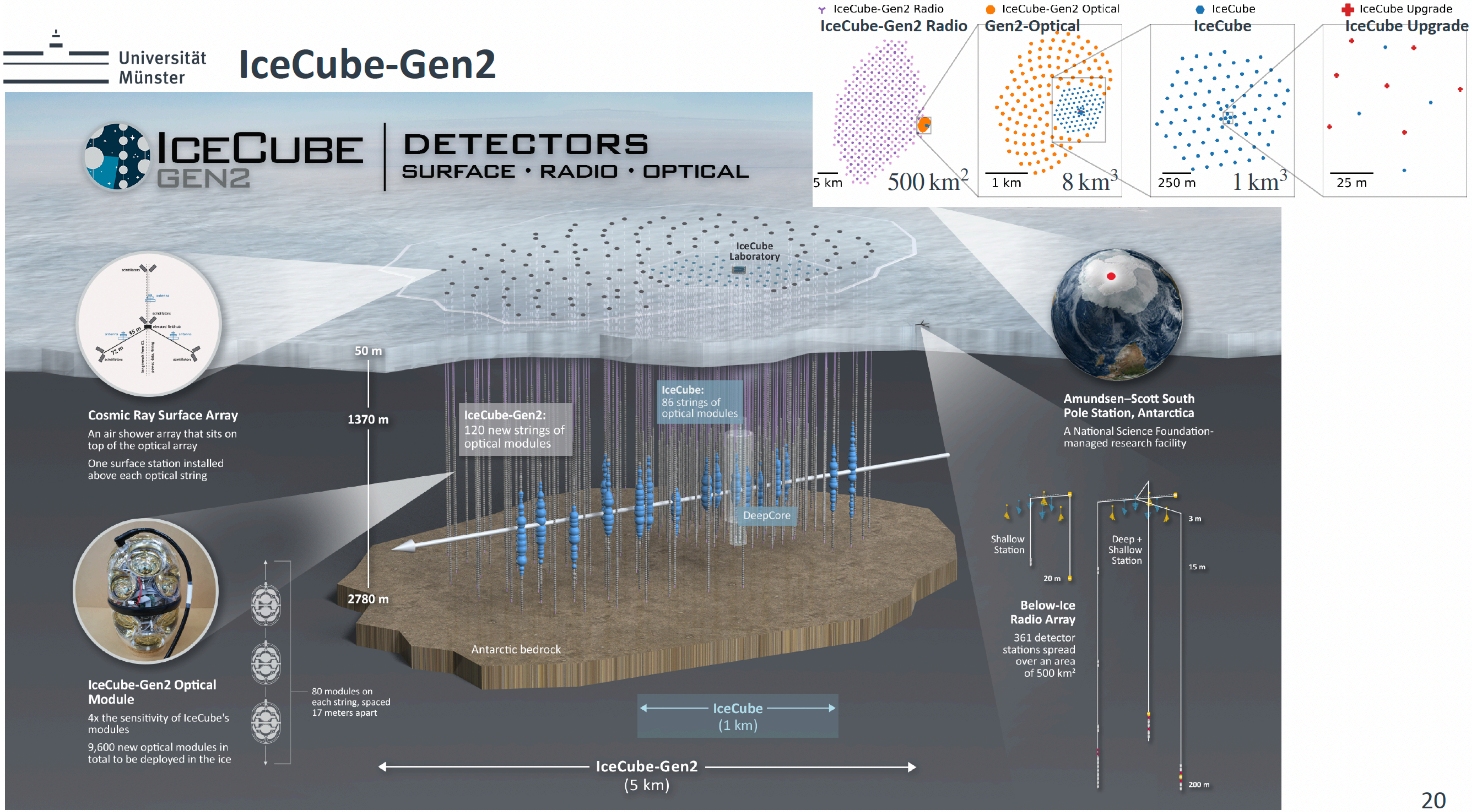


0605-085 is one of the fifty brightest radio blazar in the sky

Future projects

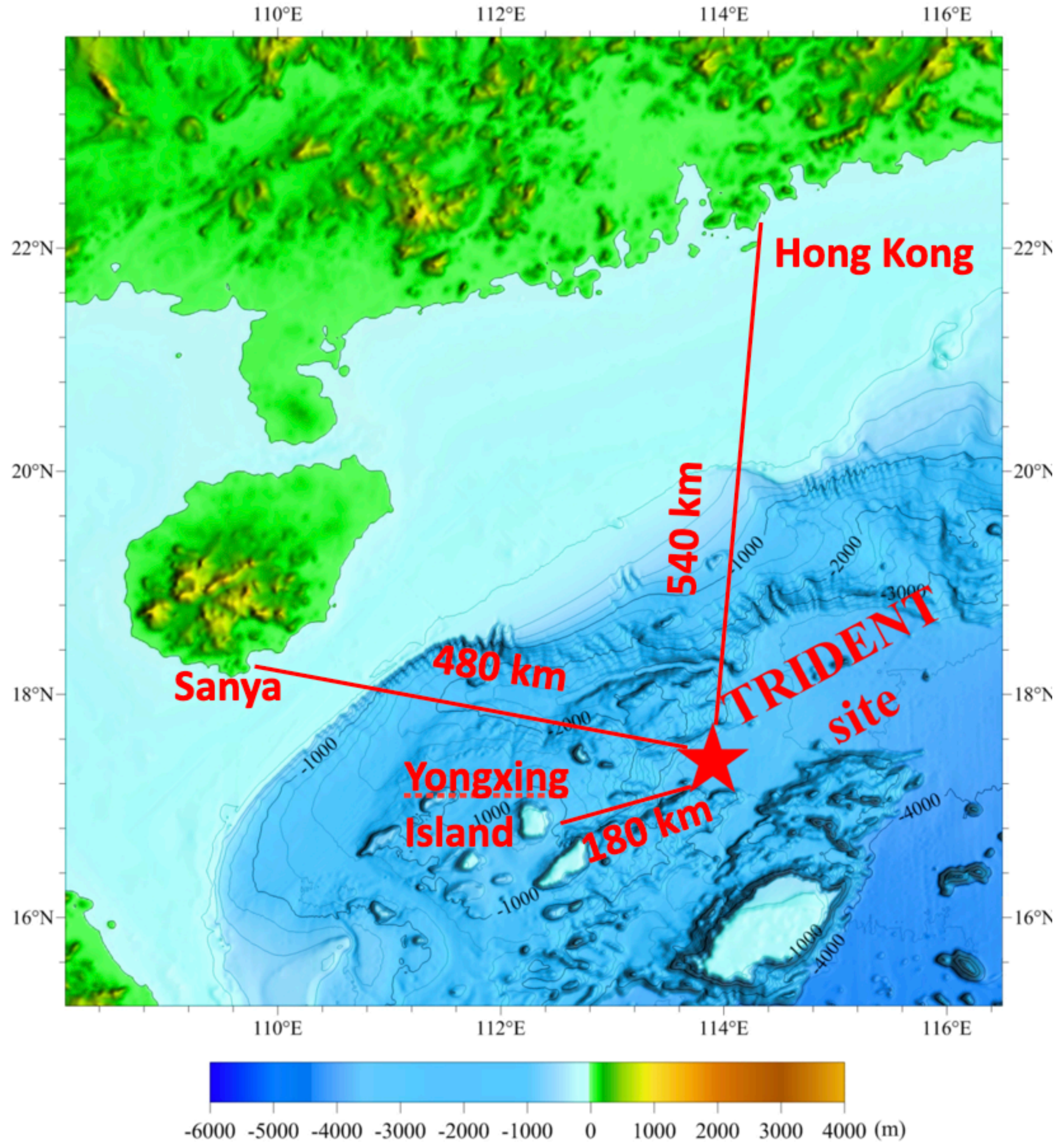
Universität Münster

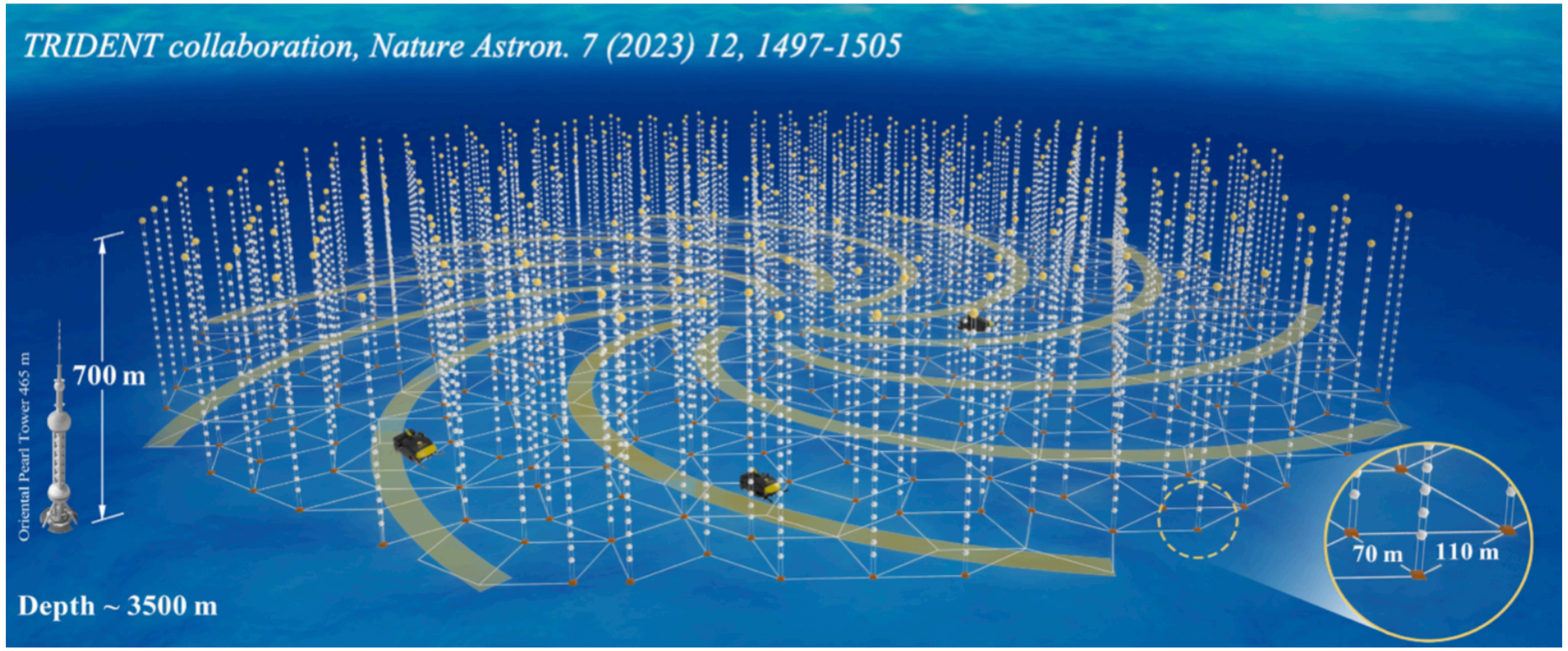
IceCube-Gen2

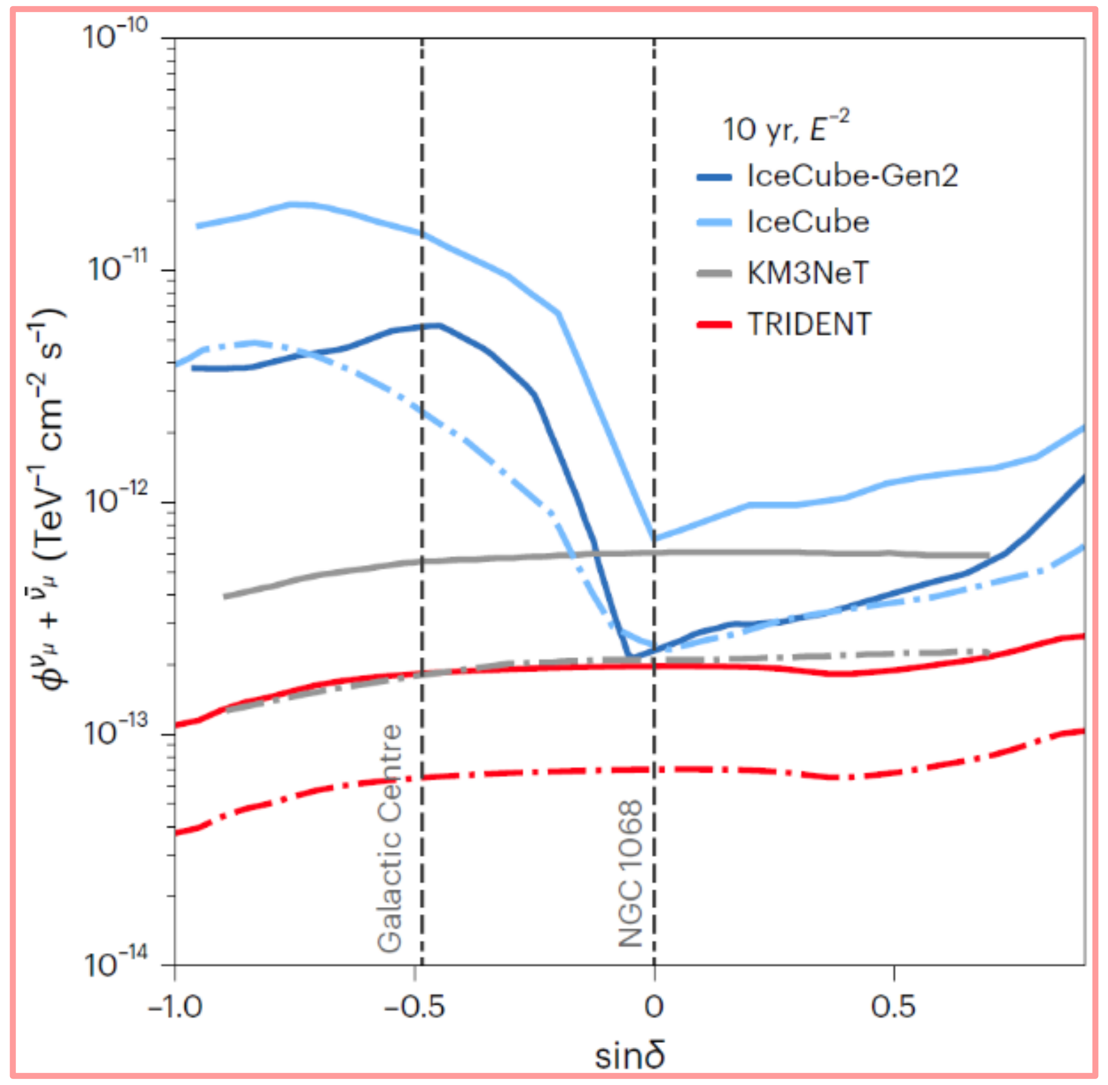


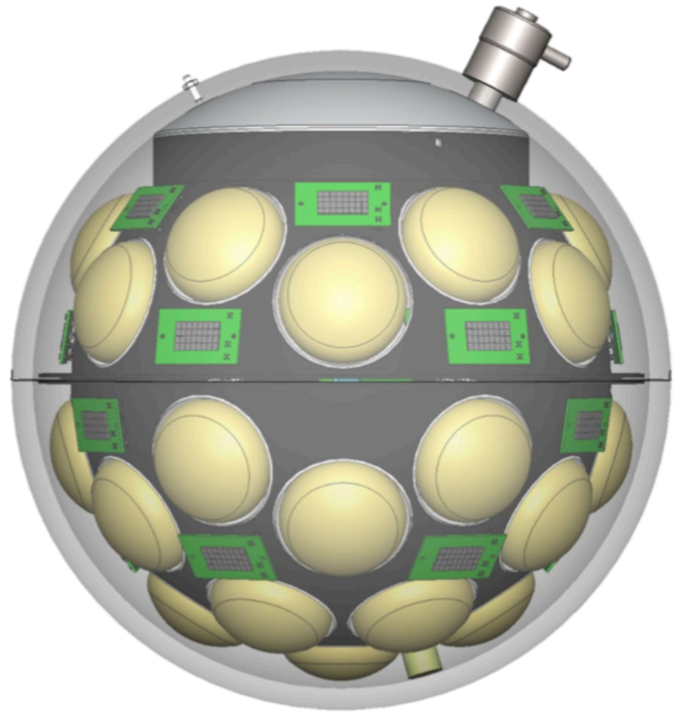
Future projects - TRIDENT

South China Sea, near equator, 3.5 km depth, about 8 km³





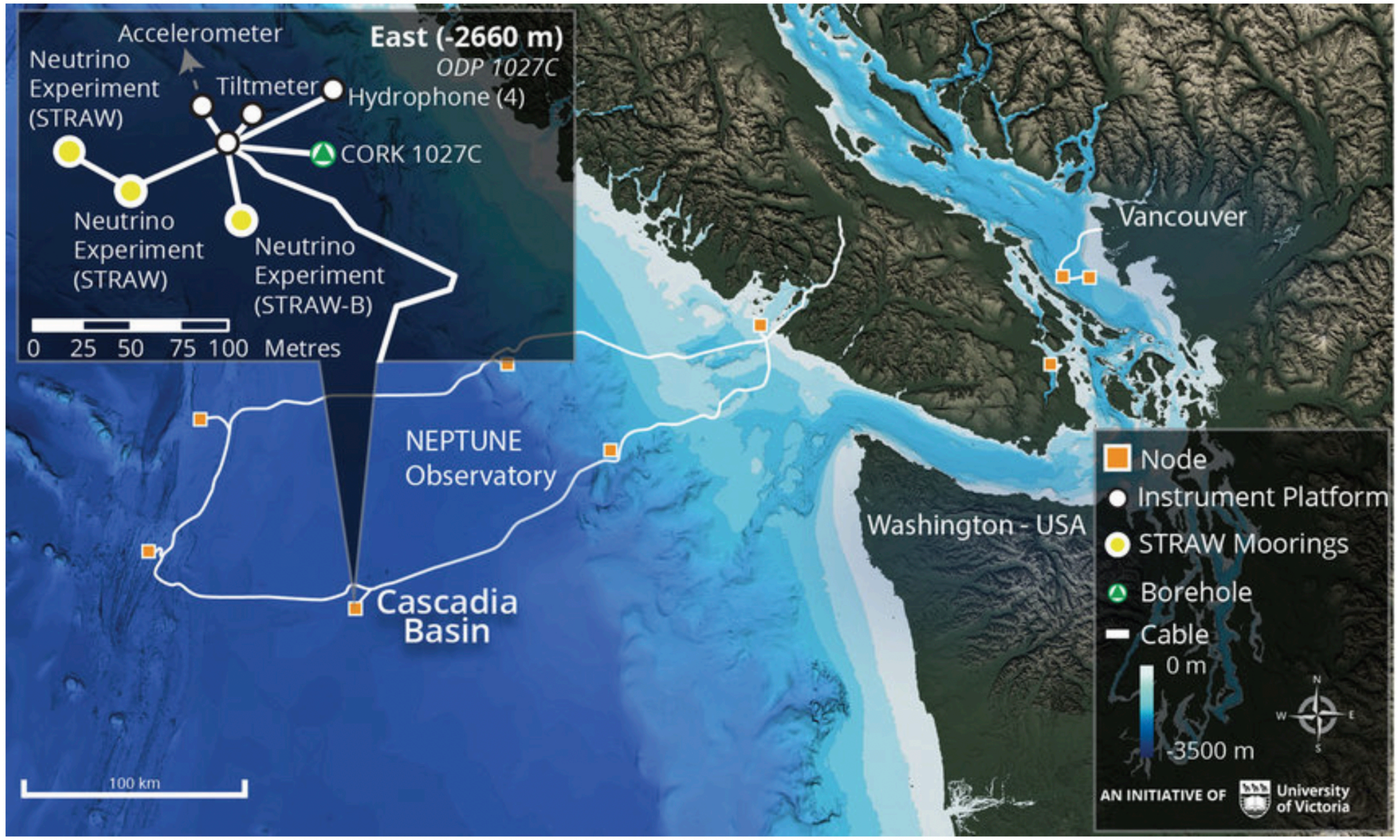




Hybrid optical module
multi-PMT + SiPM

- TRIDENT is an upcoming neutrino telescope expected to reach next-generation size and performance
- Prototype phase ongoing
- Phase-1 of the experiment expected to start next year - *TAUP2025*

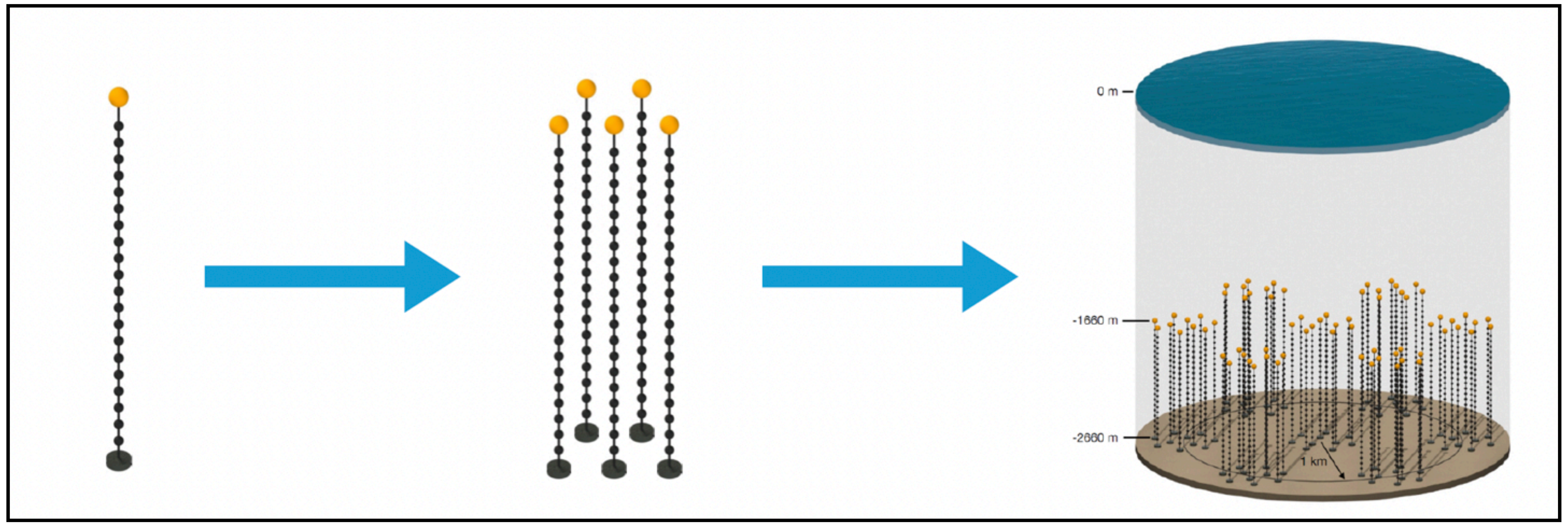
Future projects - P-ONE



Source: Ocean Networks Canada

1 km³ project located at 2600 m depth in Cascadia Basin

- First string to be deployed in 2026
- Demonstrator of 5 strings already funded
- Complete 1 km3 array about 80 strings



Conclusions - Highlights

Neutrino astronomy is in its discovery phase with exciting observations

IceCube provided several evidences of neutrino emission

- diffuse cosmic neutrino flux

- neutrino emission from point-like sources
  - IC-170922A alert in coincidence with flaring blazer TX0506+056
  - steady blazar NG1068 (few other steady sources close to detection threshold)

- neutrinos from Galactic Plane
- …

- **KM3NeT**, still under construction, break into a unexplored region detecting a UHE neutrino with 220 PeV energy, more 20 times higher in energy than any neutrino ever detected

Conclusions - Open questions

- Uncertainties on cosmic neutrino diffuse flux
  - large power index spread for different IceCube event sele ction
  - Baikal data confirm IceCube discovery, but overshoot 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
  - Cosmogenic, powerful flaring source, exotic explanation,…
- …

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** 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 and TRIDENT)
- radio experiments that are expected to increase detection volume by two order of magnitude (GRAND, RNO-G, IceCube-Gen2 radio …)

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 **cooperative efforts** with combined analysis will boost high energy neutrino discovery potential providing a deeper understanding of the high energy Universe

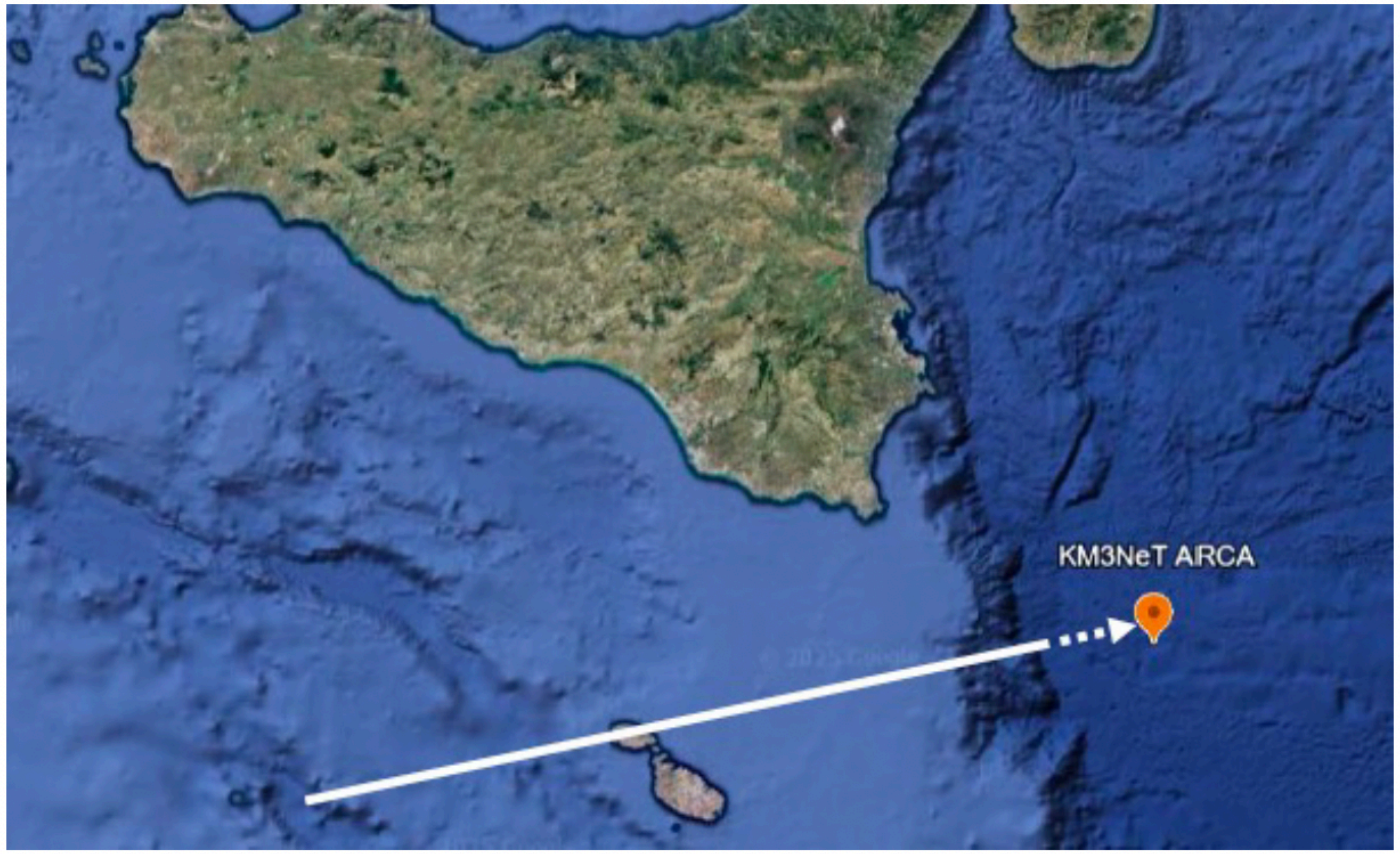
A strong increase of HE neutrino detection rate will enlarge discovery potential for neutrino sources and allow to investigate the highest energy region where KM3-230213A stemmed out and beyond

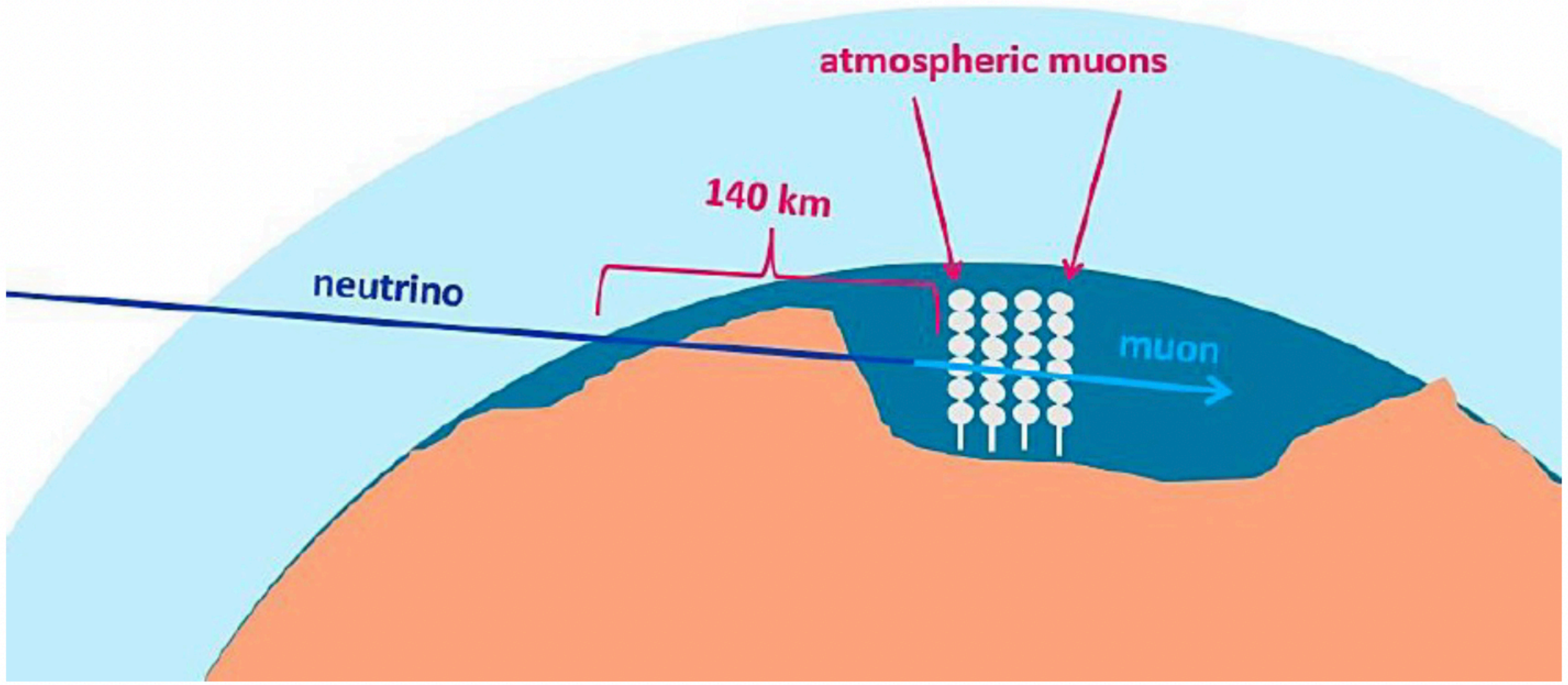
The future of Neutrino Astronomy looks bright!

Back up

Not an atmospheric muon or neutrino

It would have had to traverse 300 km water-equivalent of matter; an EeV muon gets to 60 km

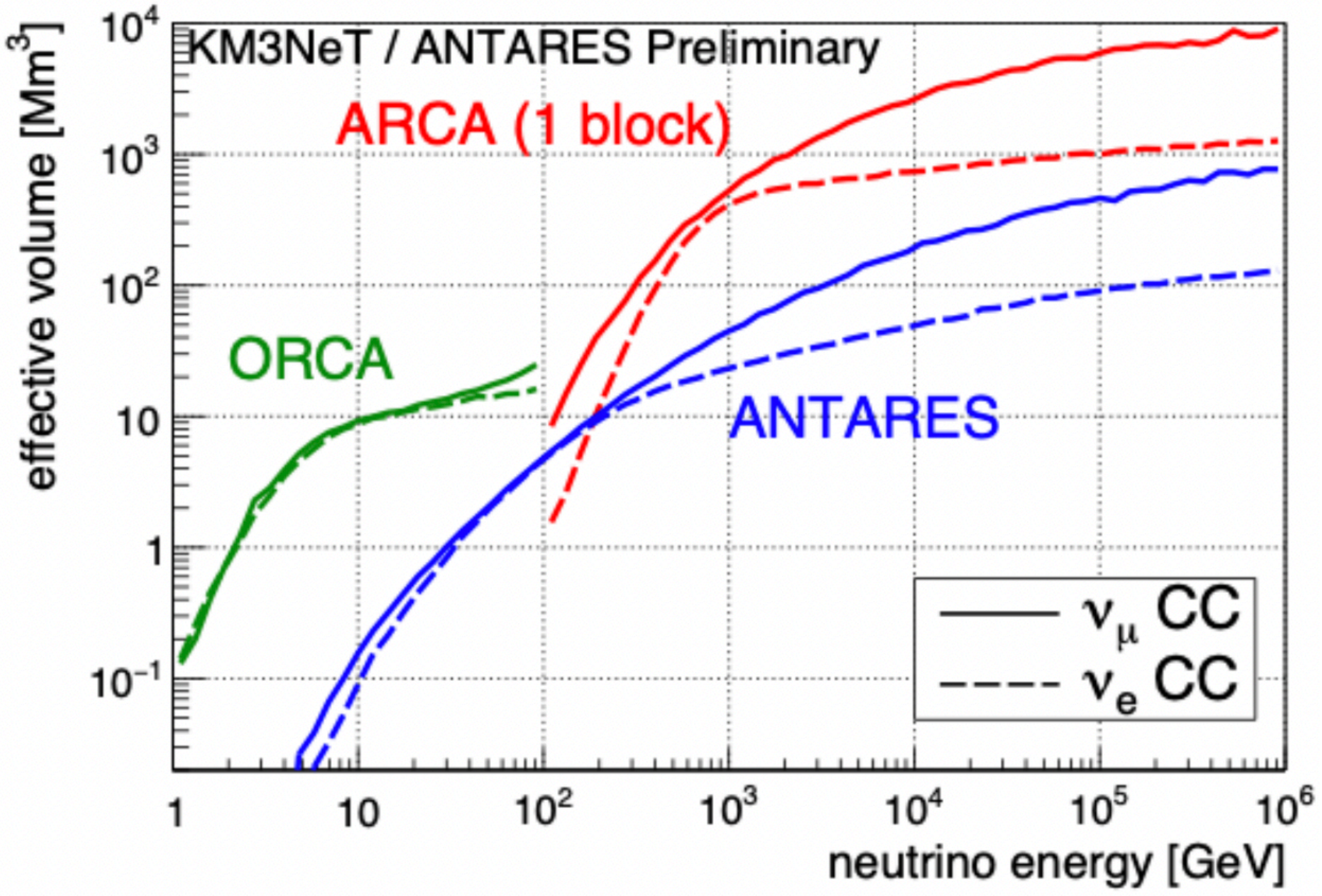


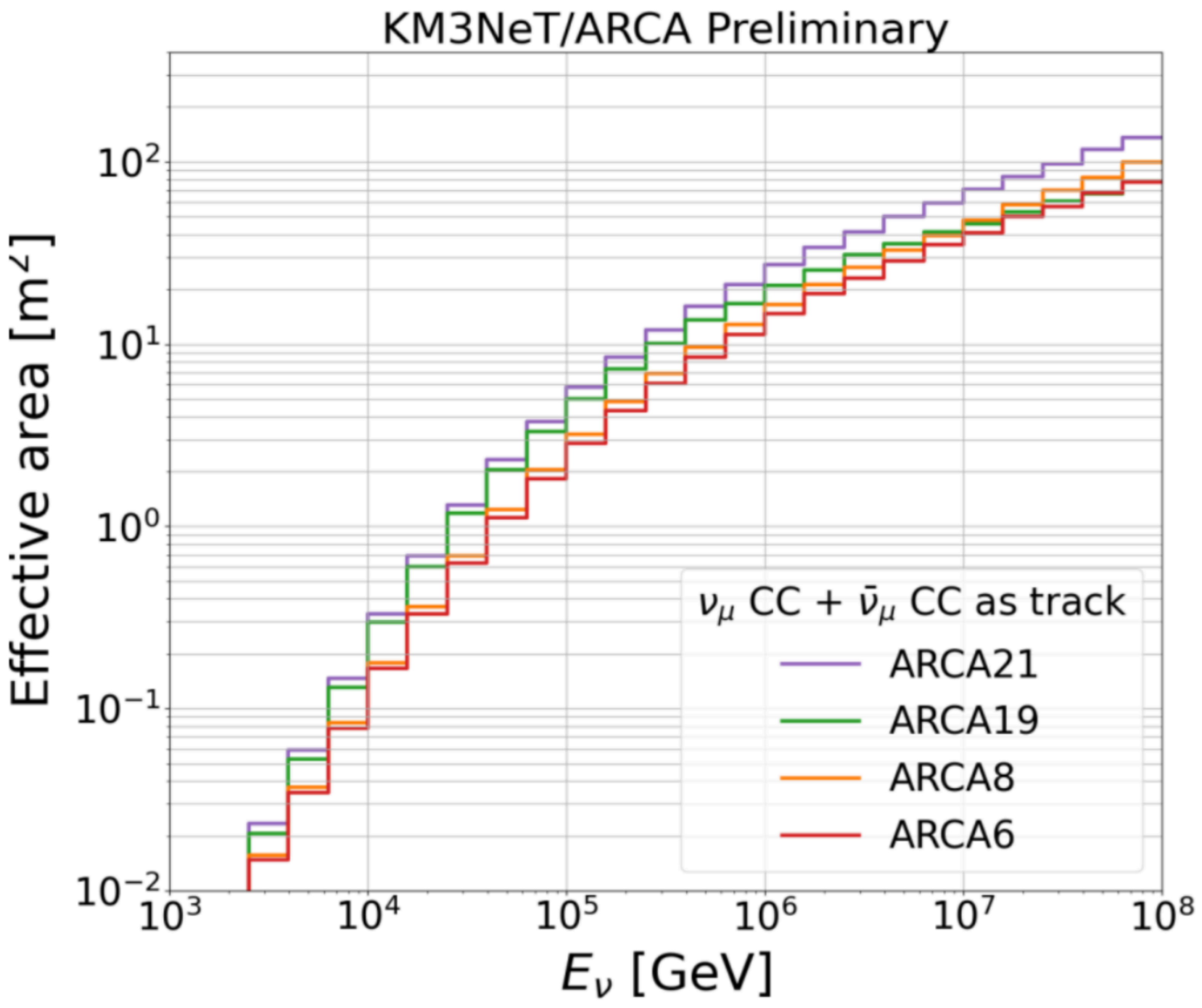


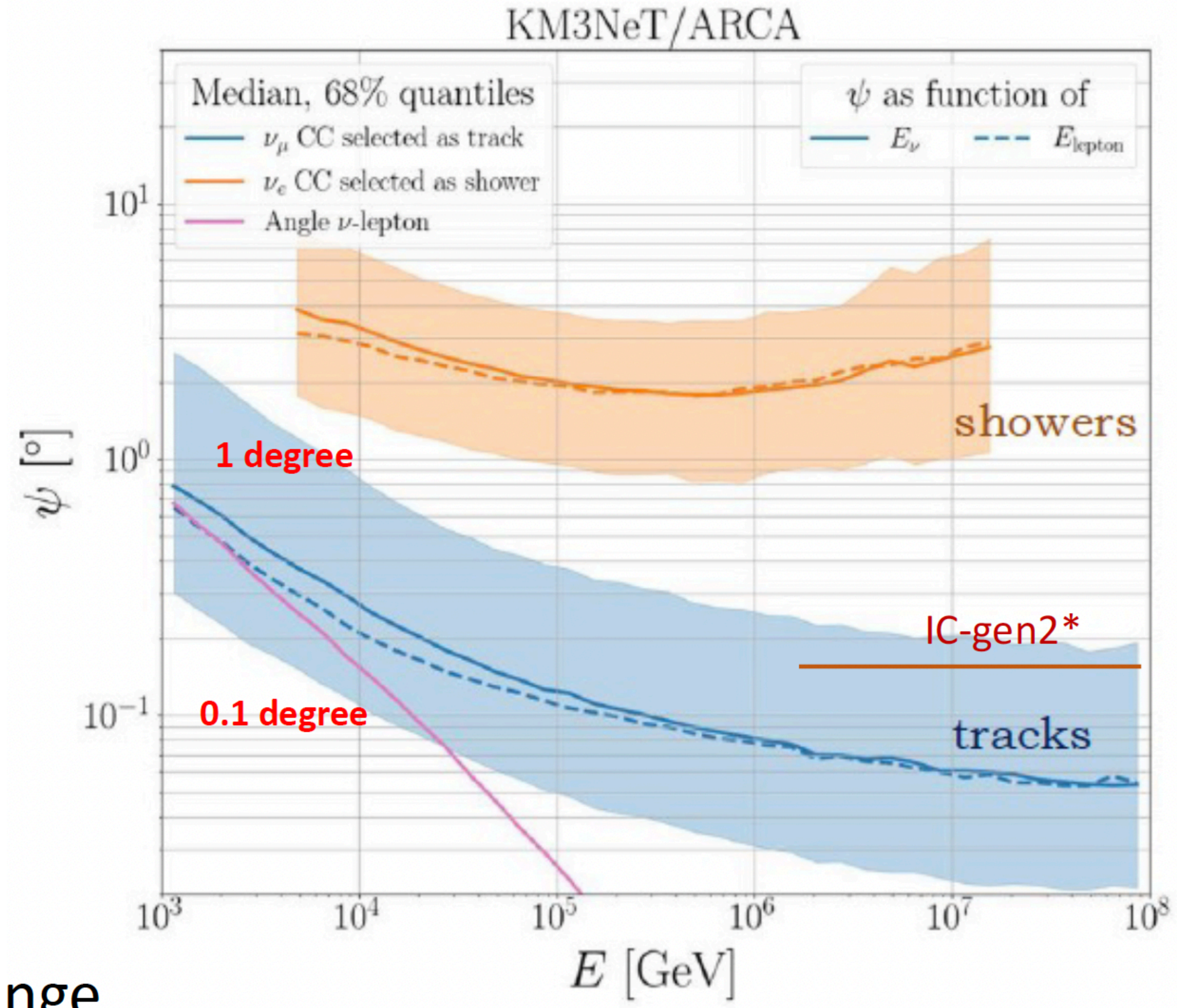
Estimated muon rate: < 10^{-10} events per year within 2 sigma directional uncertainty
Extrapolating atmospheric flux: < 10^{-5} events per year

Most likely interpretation: neutrino. Assuming an E^{-2} spectrum, energy estimate 220^{+570}_{-110} PeV

Effective areas and resolutions







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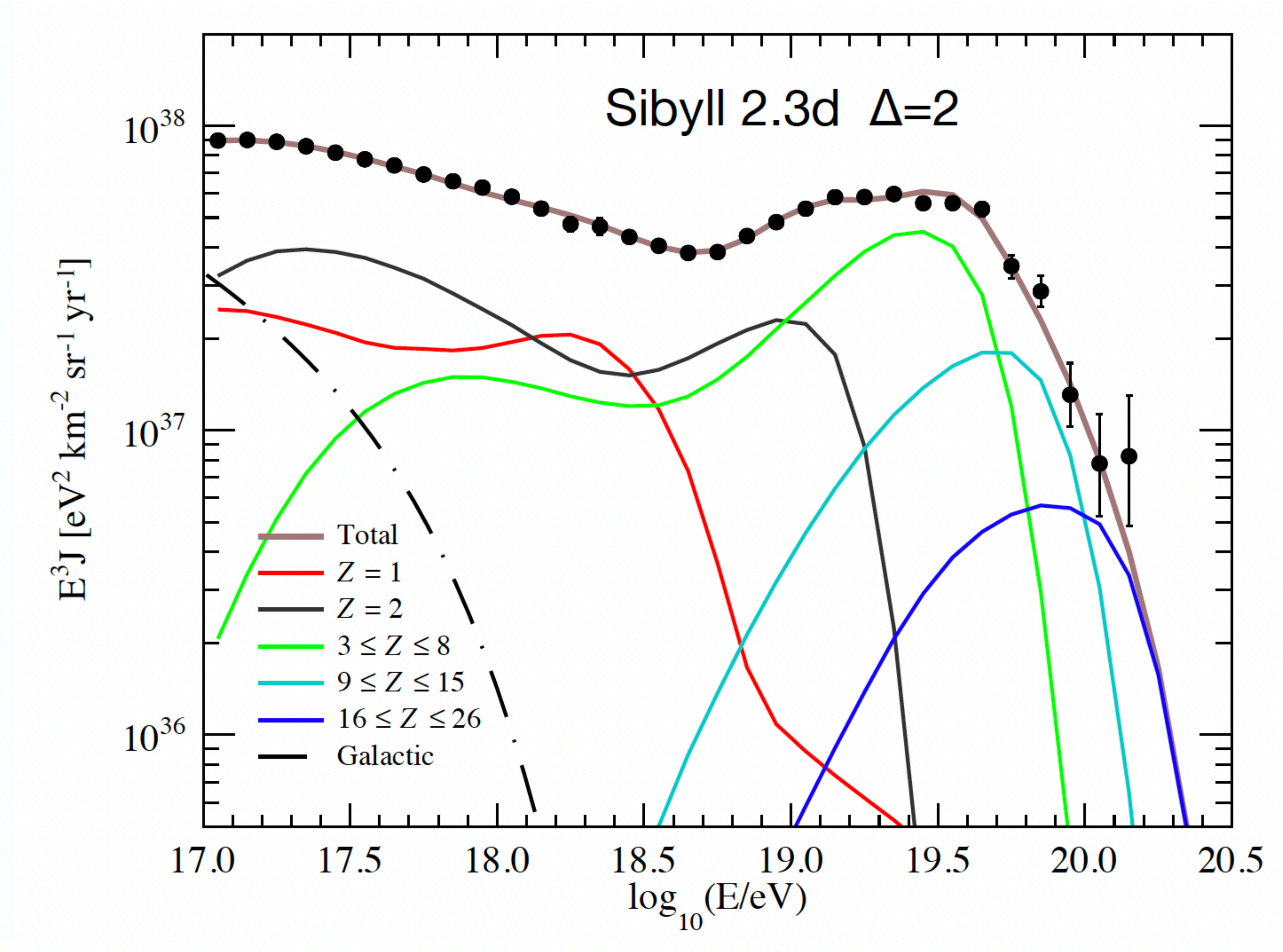

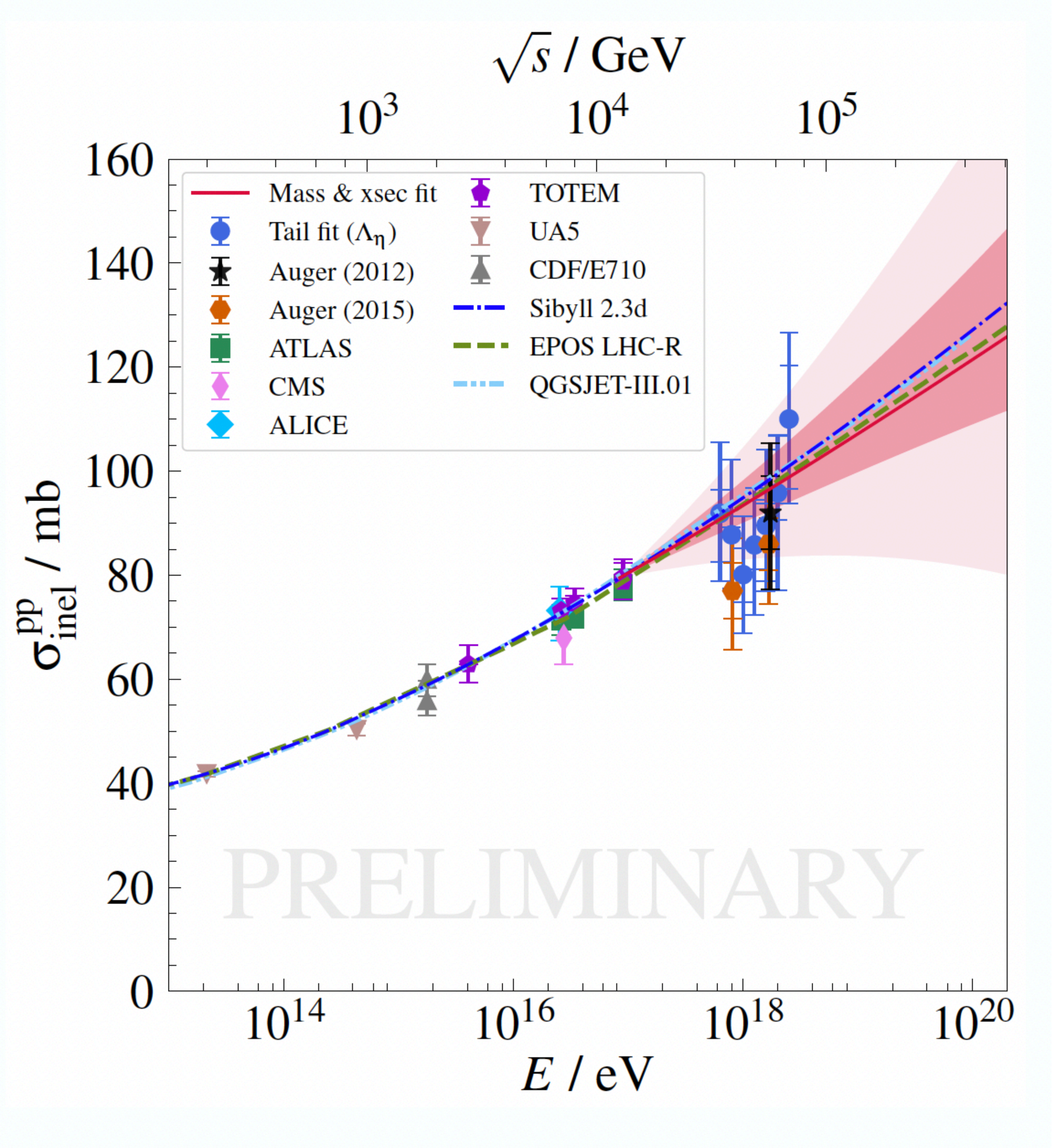

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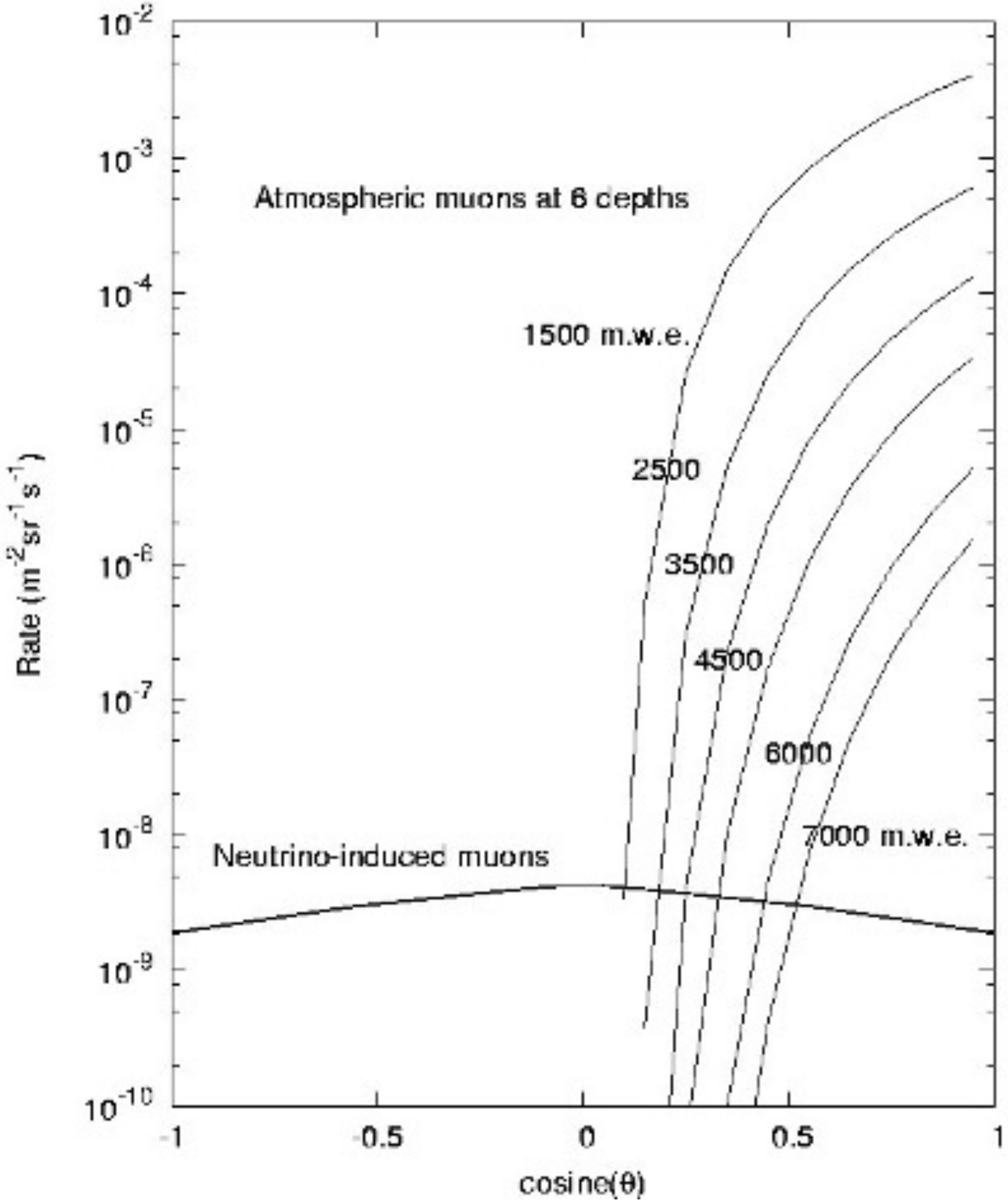

Atmospheric muons at 6 depths
1500 m.w.e.
2500
3500
4500
6000
7000 m.w.e.
Neutrino-induced muons
Rate (m^{-2}sr^{-1}s^{-1})
cosine(θ)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
-1
-0.5
0
0.5
1