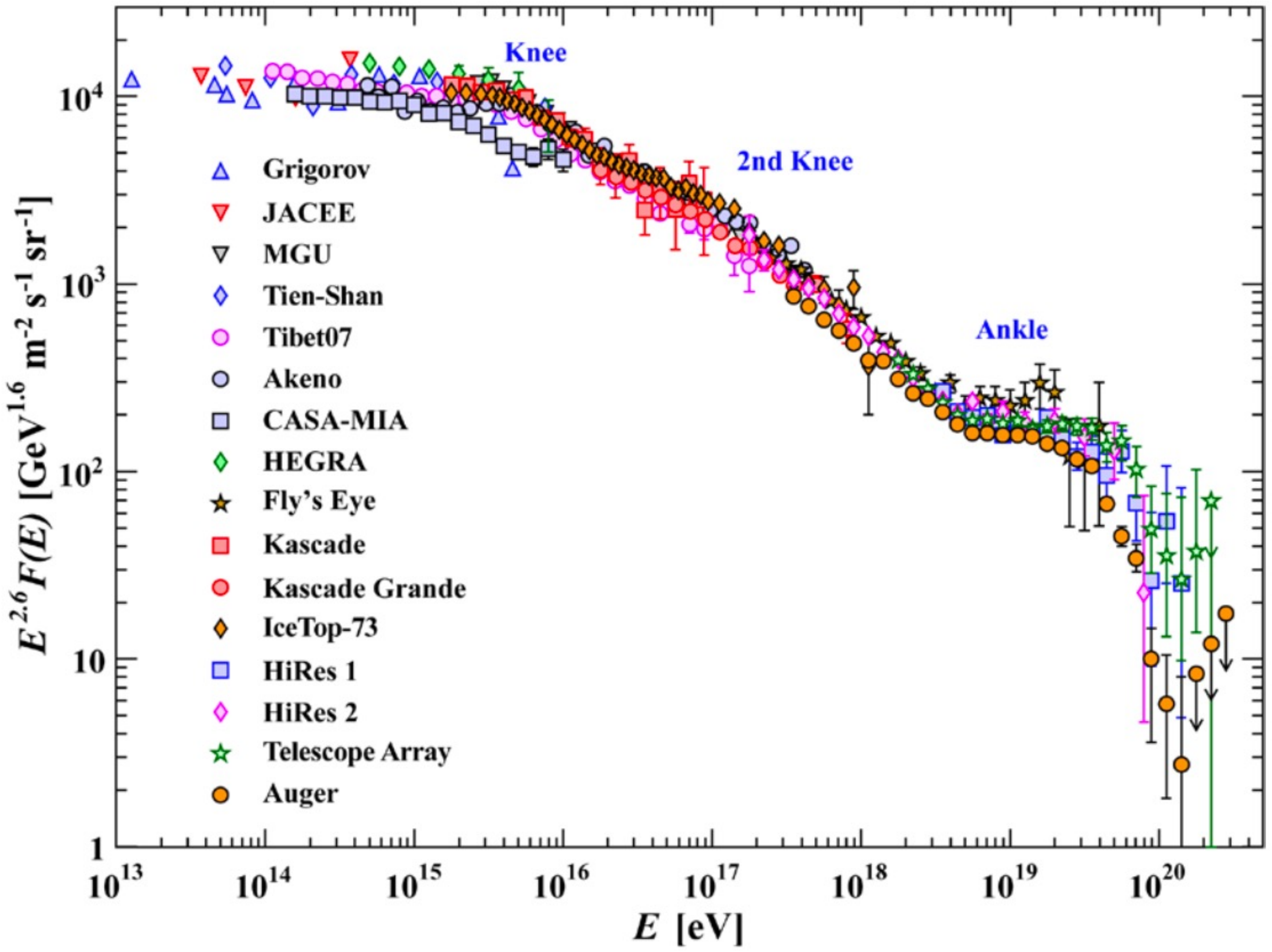
Neutrino Astronomy

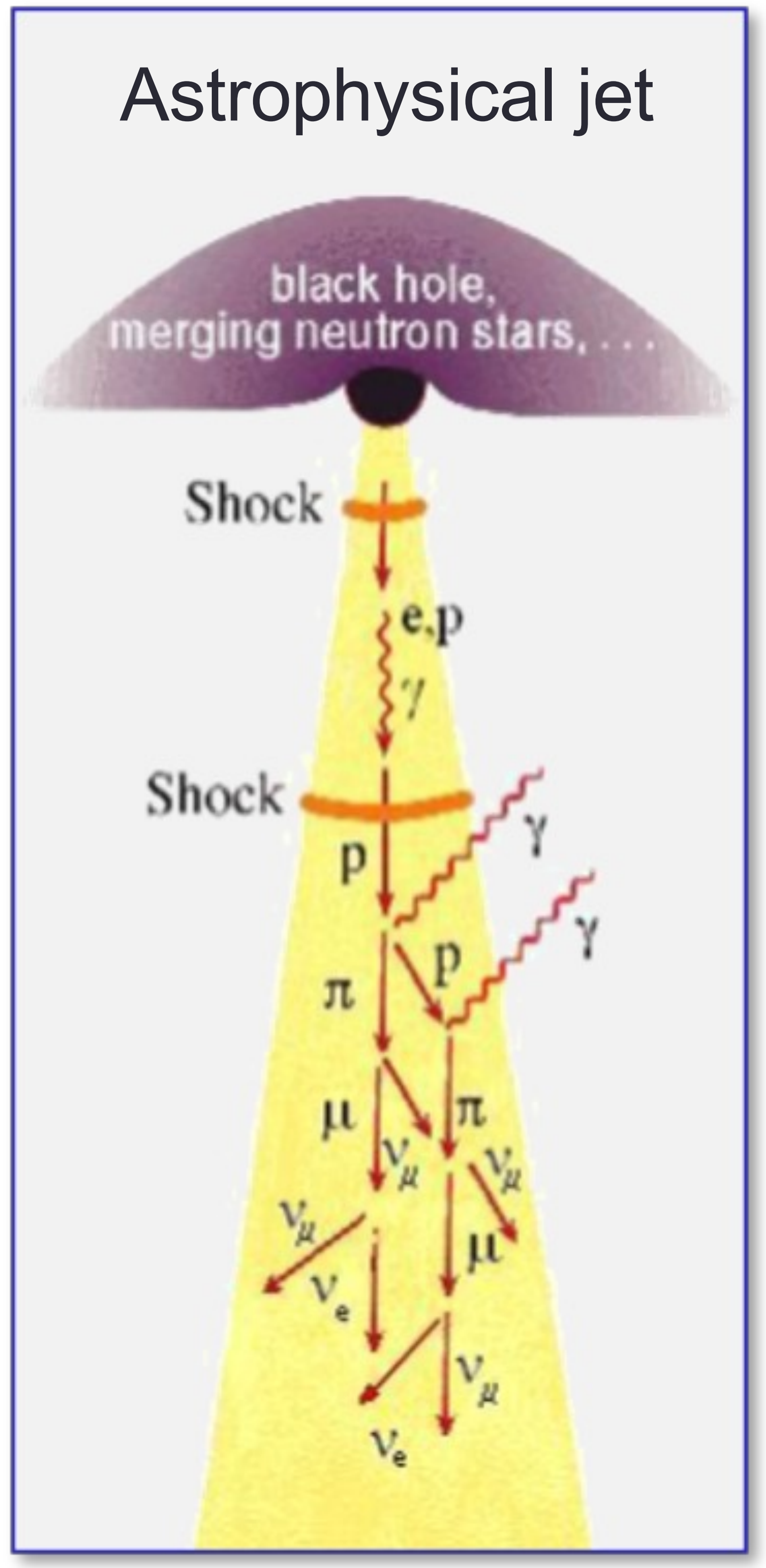
Piera Sapienza, Laboratori Nazionali del Sud, INFN - PIC2023, 12 October 2023 - Arica (Chile)

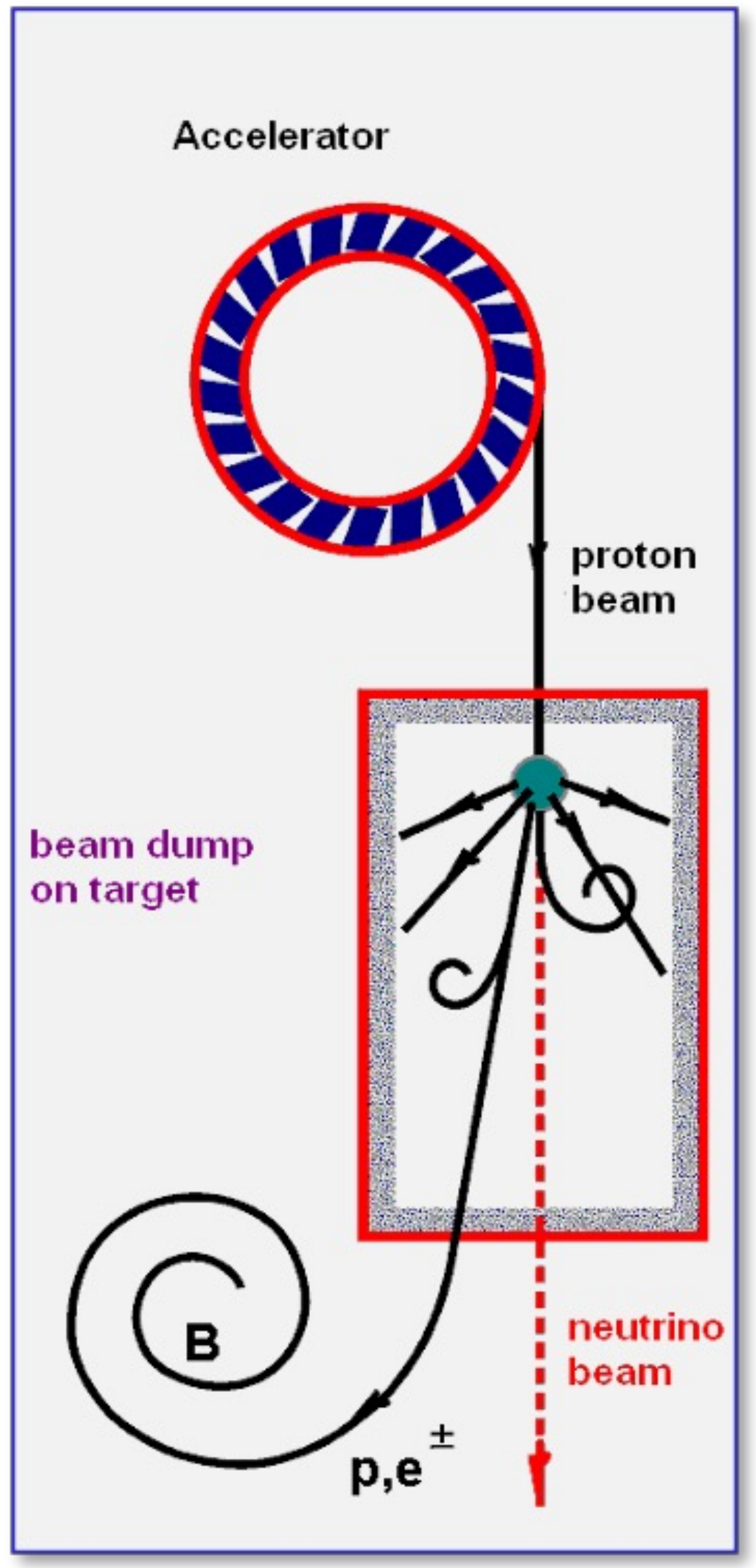
Cosmics Rays

Cosmic particles are produced with energies in excess of 10^8TeV: we still do not know where and how!

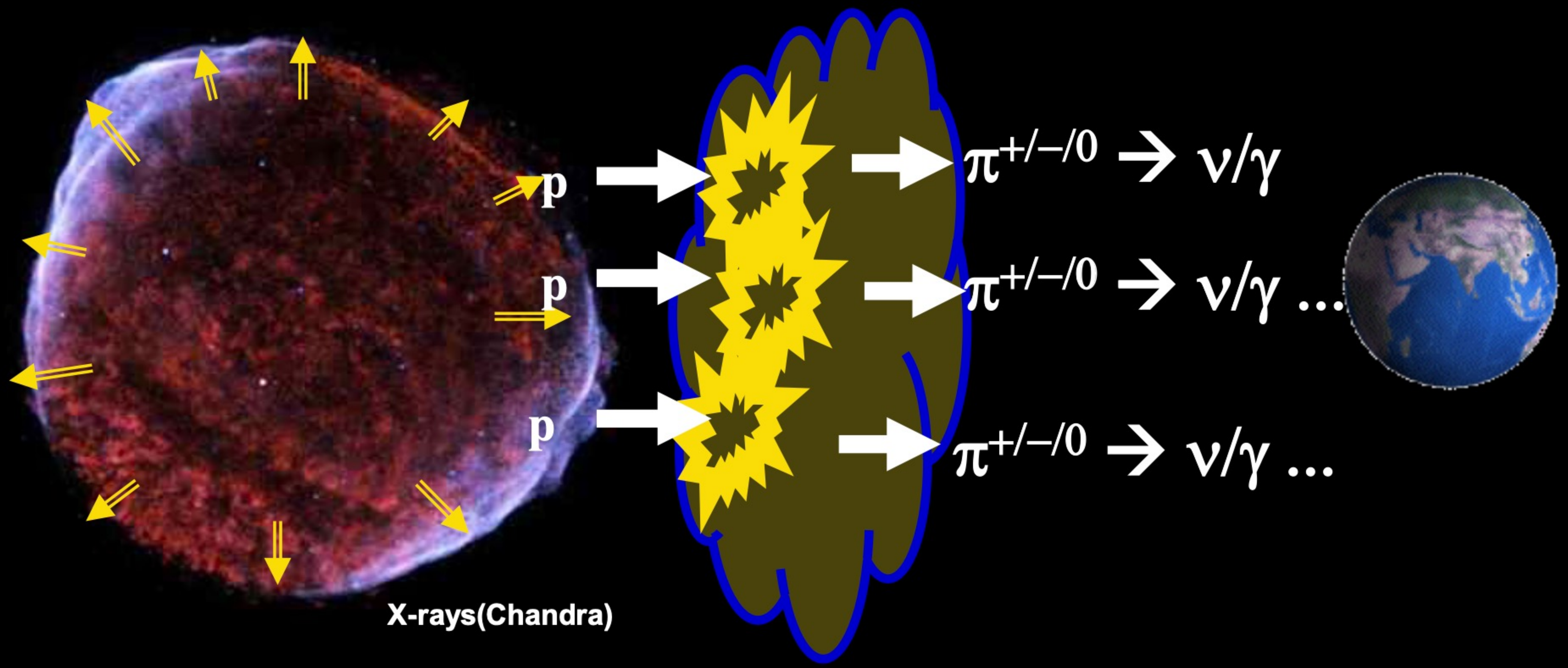
Spectrum follows a broken power-law over many orders of magnitude with a break at about 4×10^3 TeV, called the *knee* and another break, at about 5×10^6 TeV, called the *ankle*





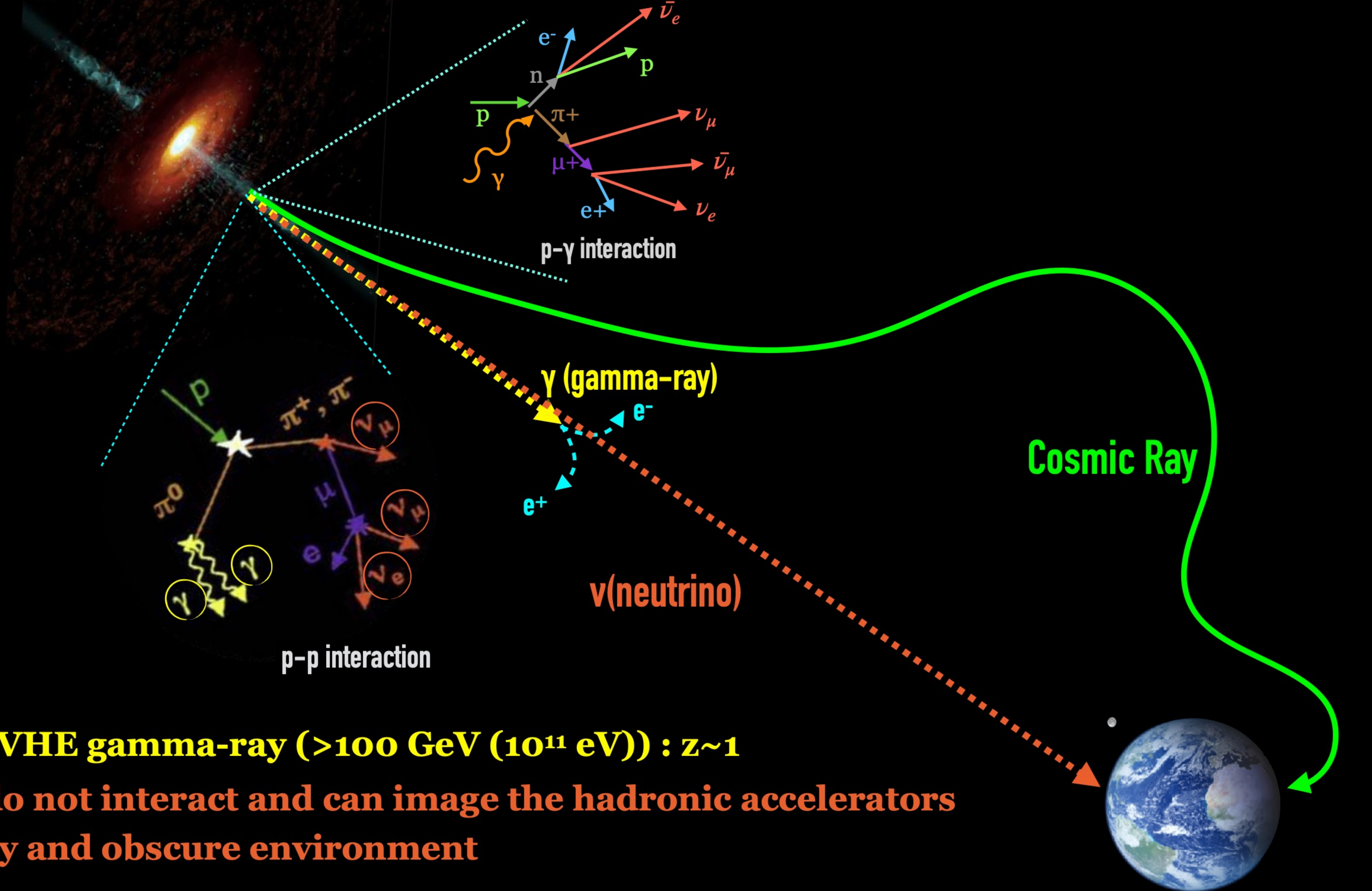


1.) CR acceleration   2.) CR interaction   3.) Detection



$dN_{CR}/dE_{CR} \sim E_{CR}^{-2}$ $dN_{\nu/\gamma}/dE_{\nu/\gamma} \sim E_{\nu/\gamma}^{-2}$

E_{max} E_{max} /20 (ν)

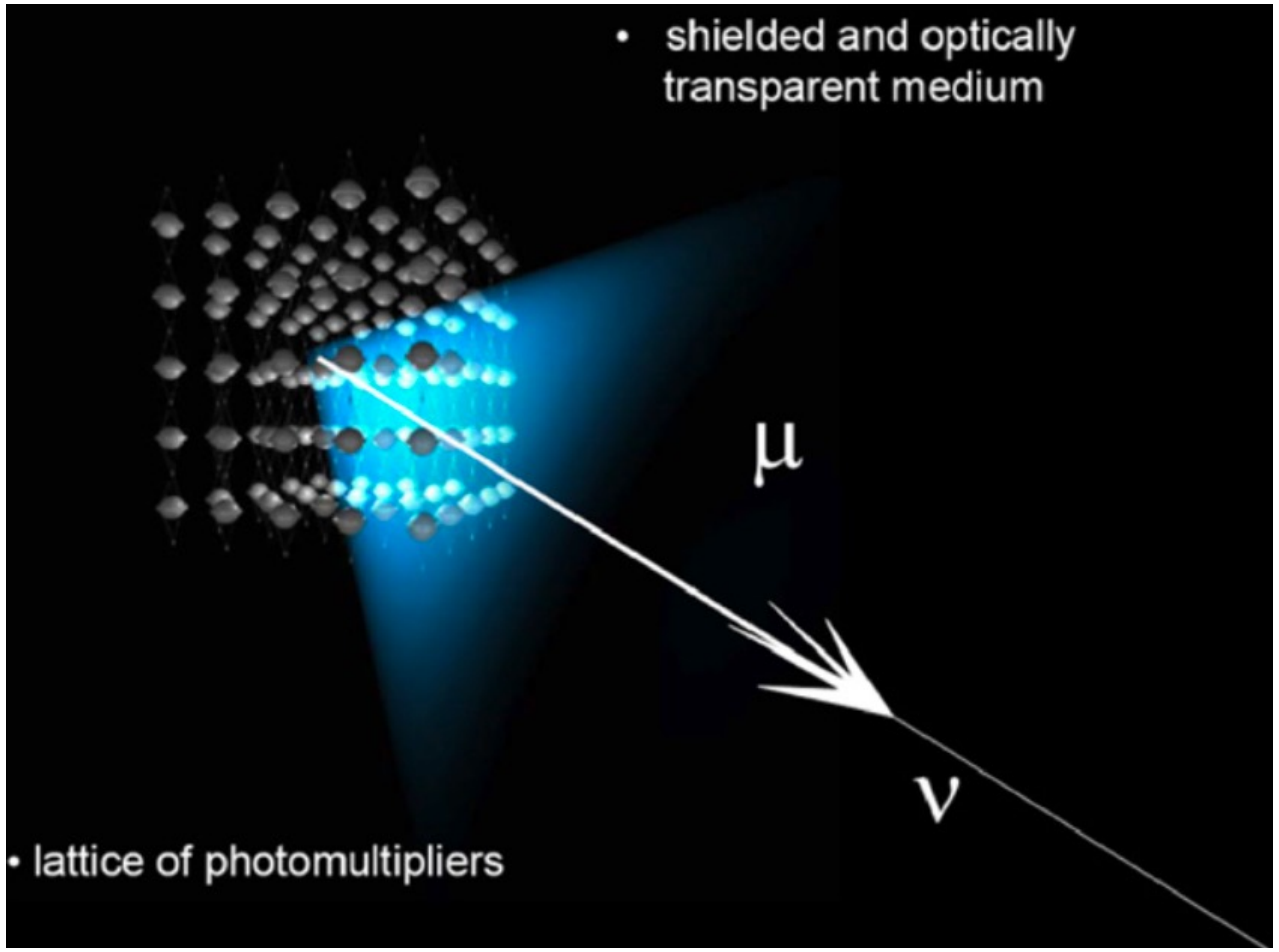


Horizon of VHE gamma-ray (>100 GeV (10^{11} eV)) : z~1

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

High energy neutrino detection principle

- Flux estimates indicate that the volume needed for high energy neutrino detection is in the **km^3-scale**
- Exploit optical Cherenkov effect in deep sea water or antarctic ice
  - threefold function (shield, target, radiator)
- Extremely challenging experiments
  - the first project, DUMAND at Hawaii sea, failed after many year efforts due to connection issues

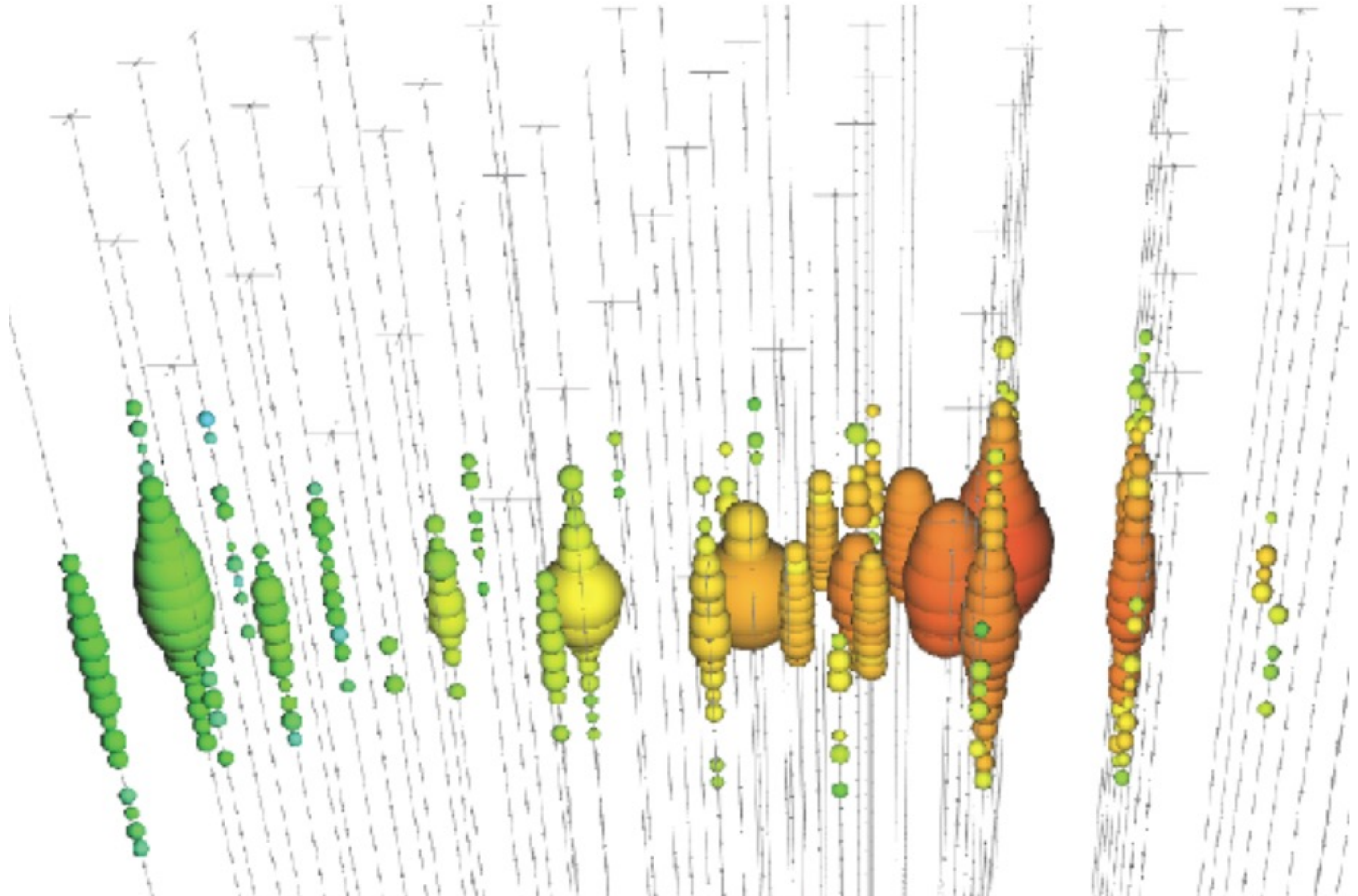


Event Morphology

High-energy neutrinos interact with matter via deep inelastic scattering off nucleons. In this process, a neutrino flavor state scatters off quarks via the exchange of a *Z* boson (*neutral current* (NC)) or *W* boson (*charged current* (CC)). Whereas the former interaction leaves the neutrino flavor state intact, the latter creates a charged lepton corresponding to the initial neutrino flavor.

Track

CC ν_μ interactions



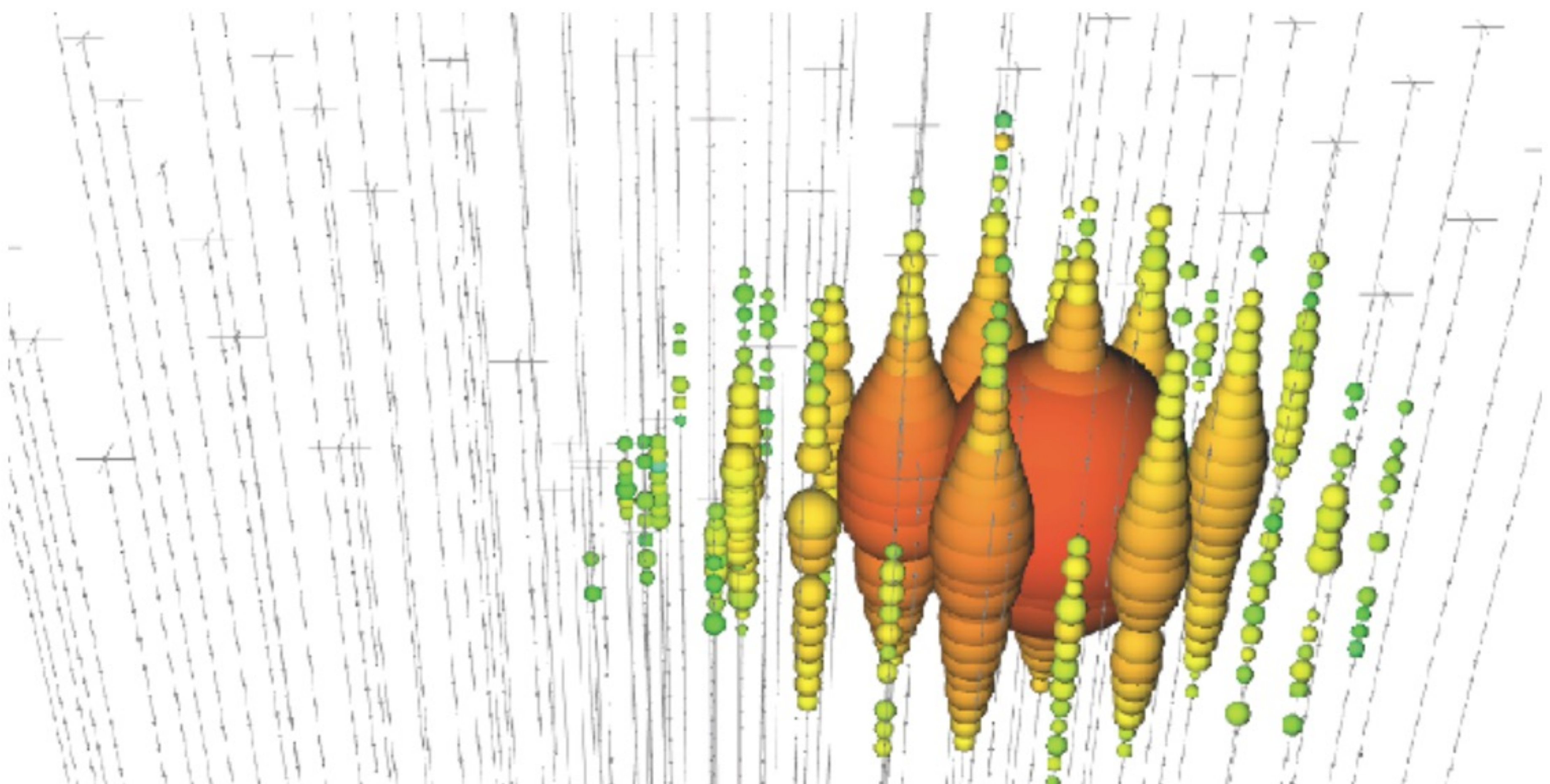
Track (data)

Cascade

NC interactions

CC ν_e interactions

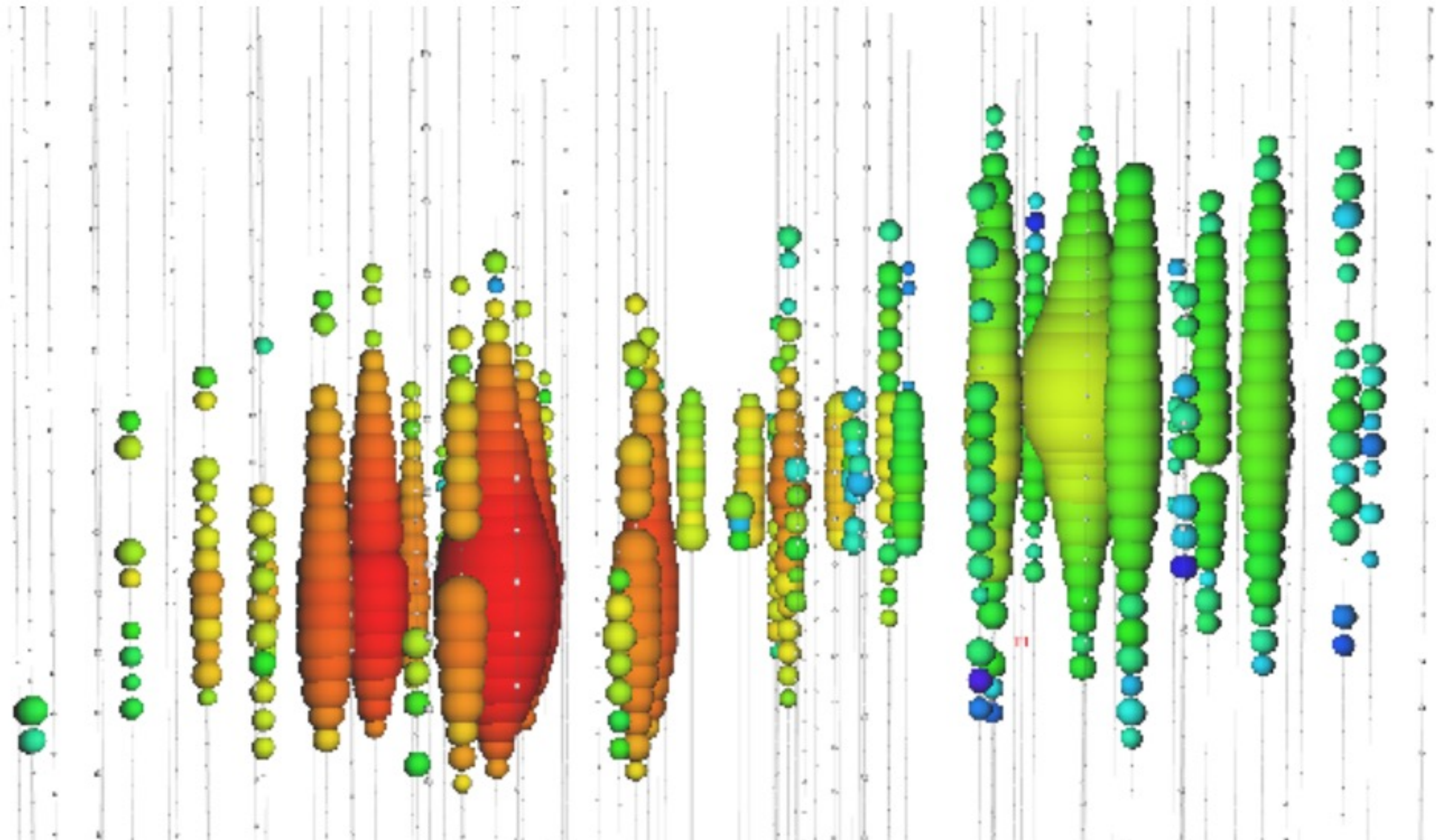
Most of CC ν_τ interactions



Cascade (data)

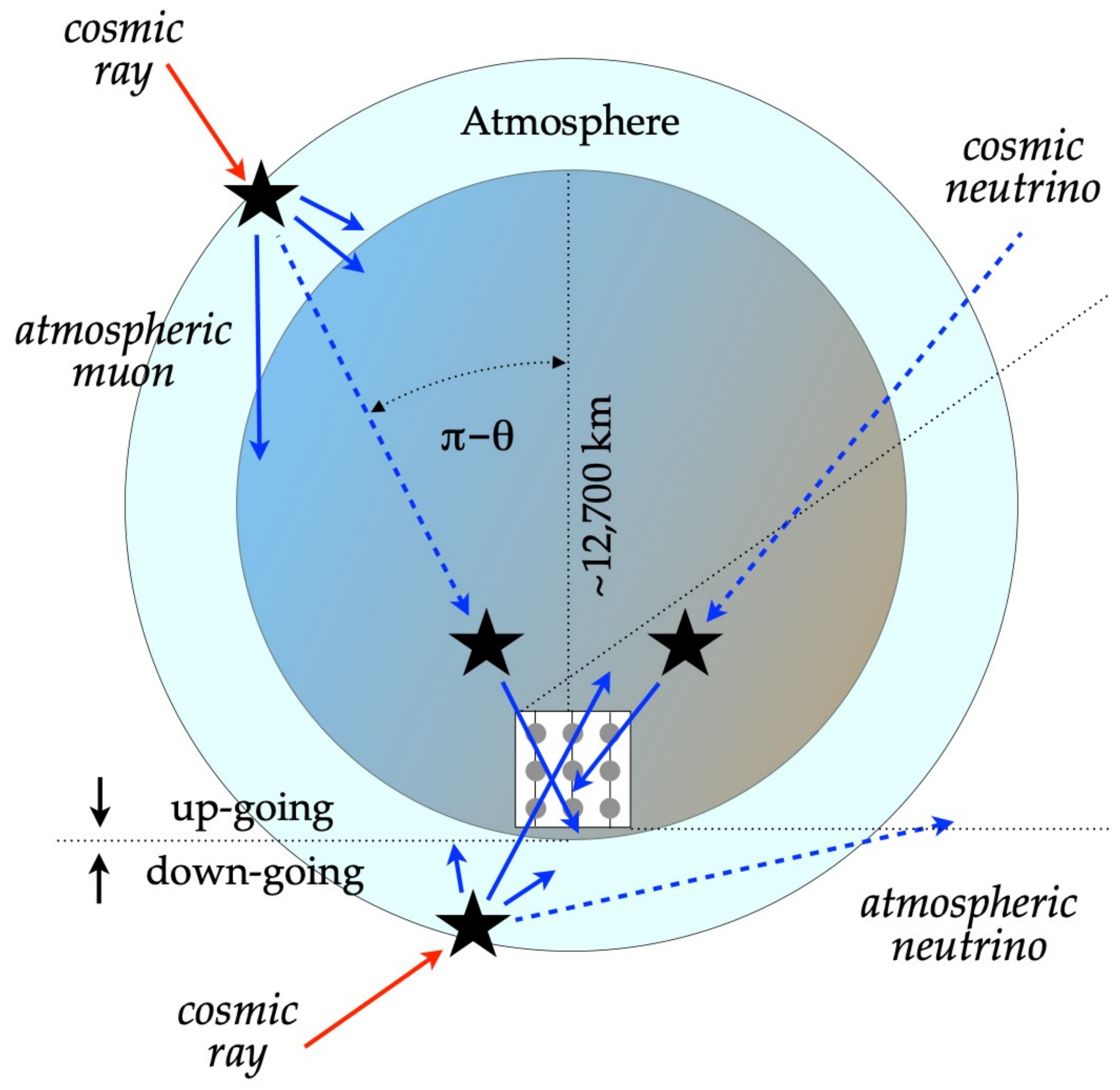
Double Cascade

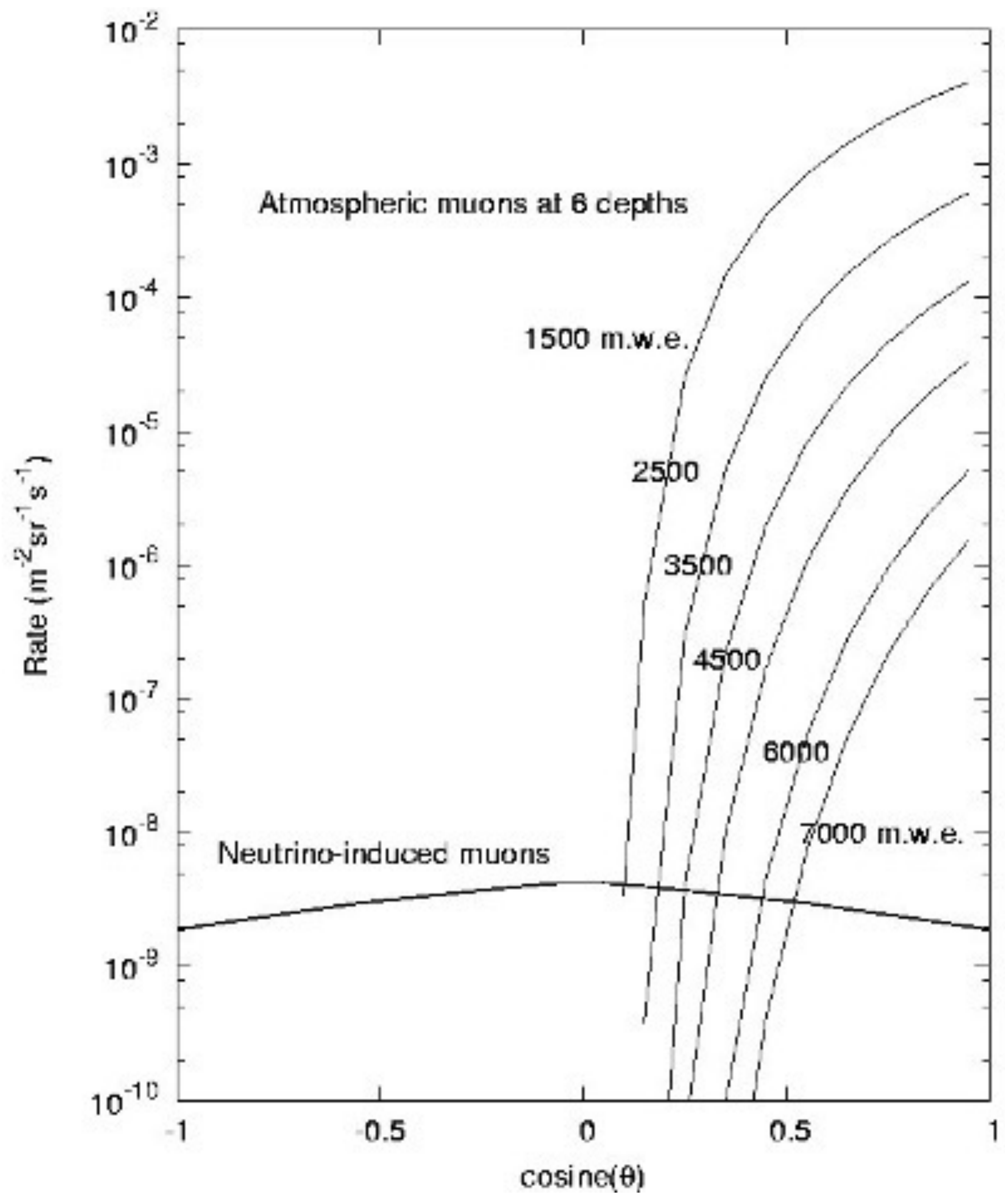
CC ν_τ interactions



Double cascade (MC)

Signal and background

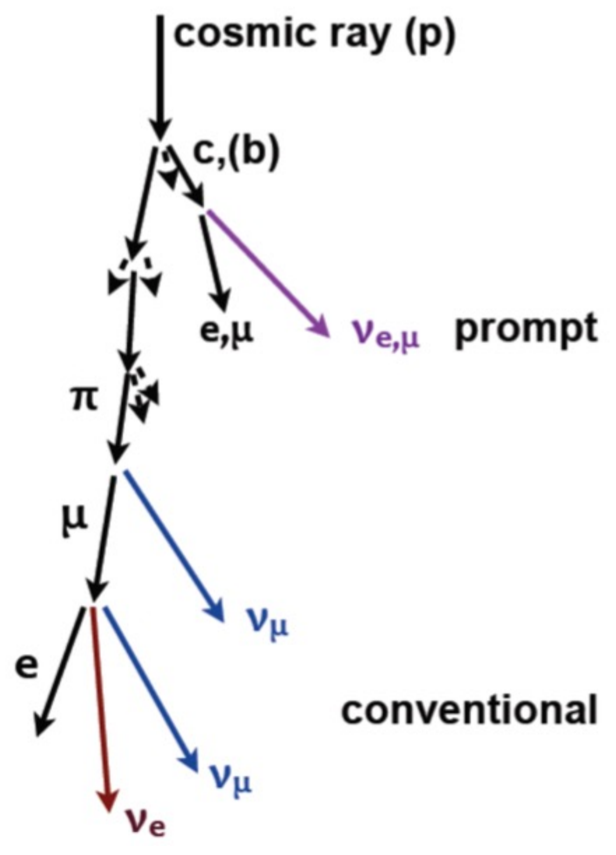




atmospheric muons : ~ 10^{11} year^{-1} (3000 per second)

atmospheric neutrinos : ~ 10^{5} year^{-1} (1 every 6 minutes)

astrophysical : ~ few -100 year^{-1}

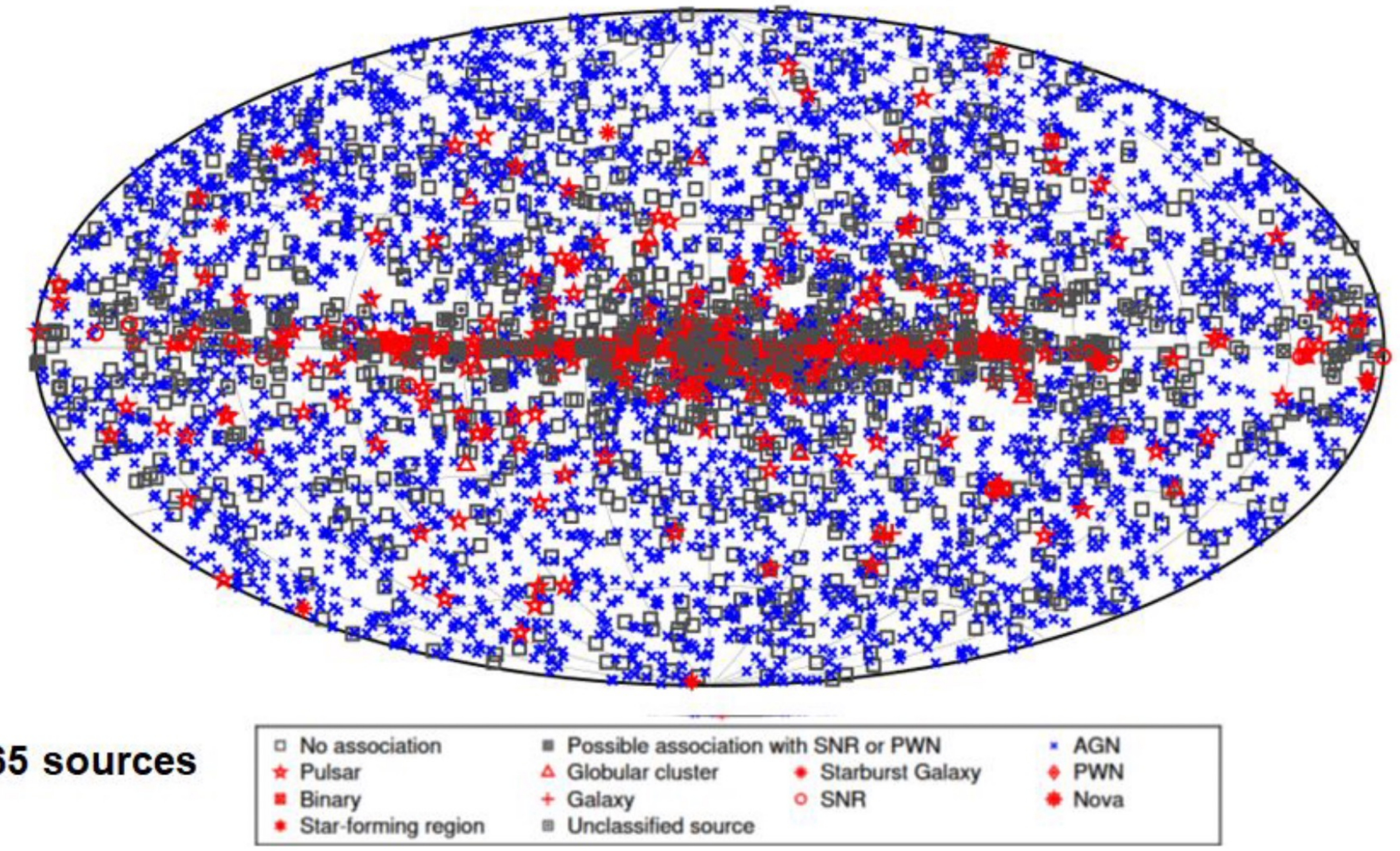


Visibility of the neutrino sky

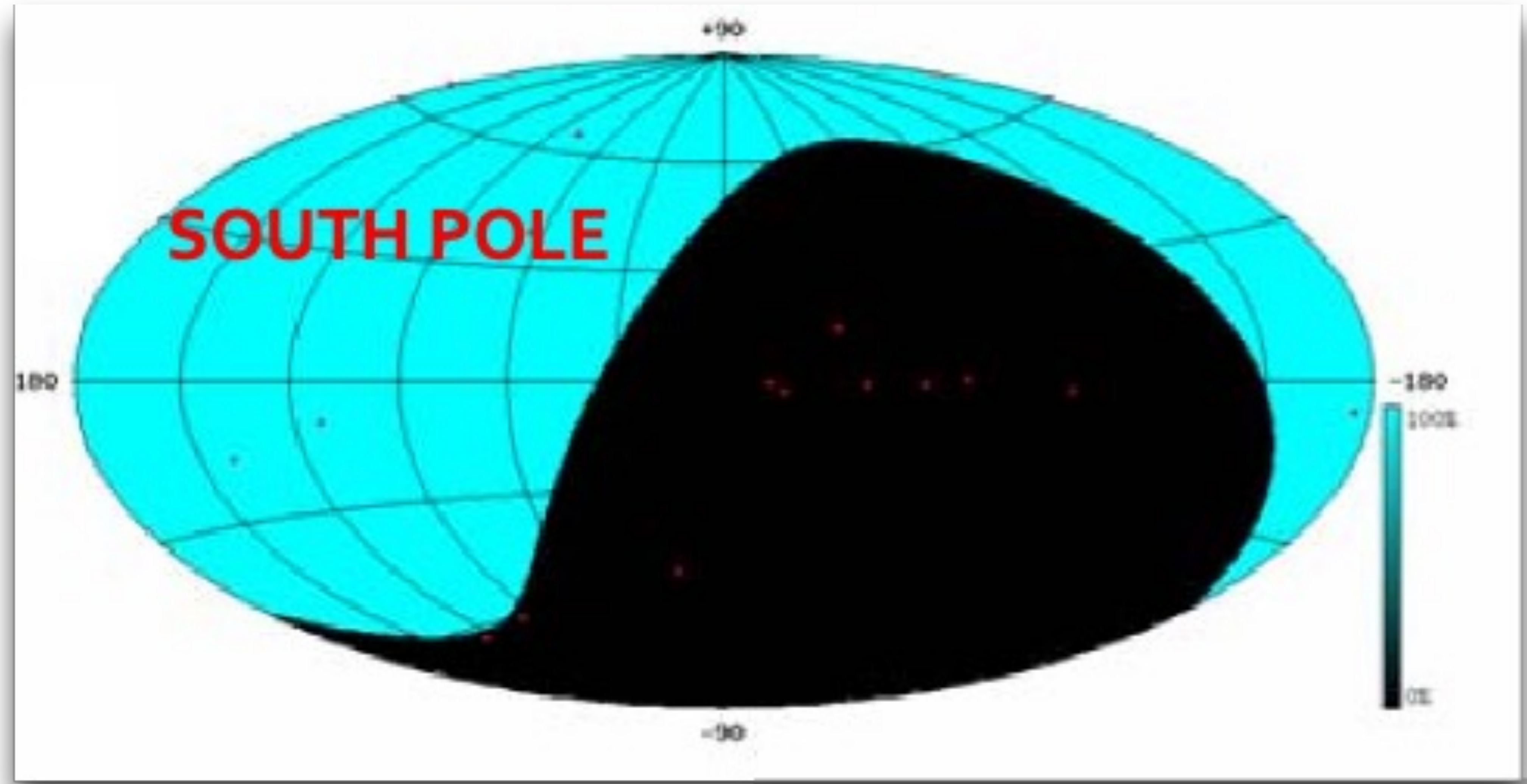
The Fermi Sky map provides a survey of high energy gamma sources

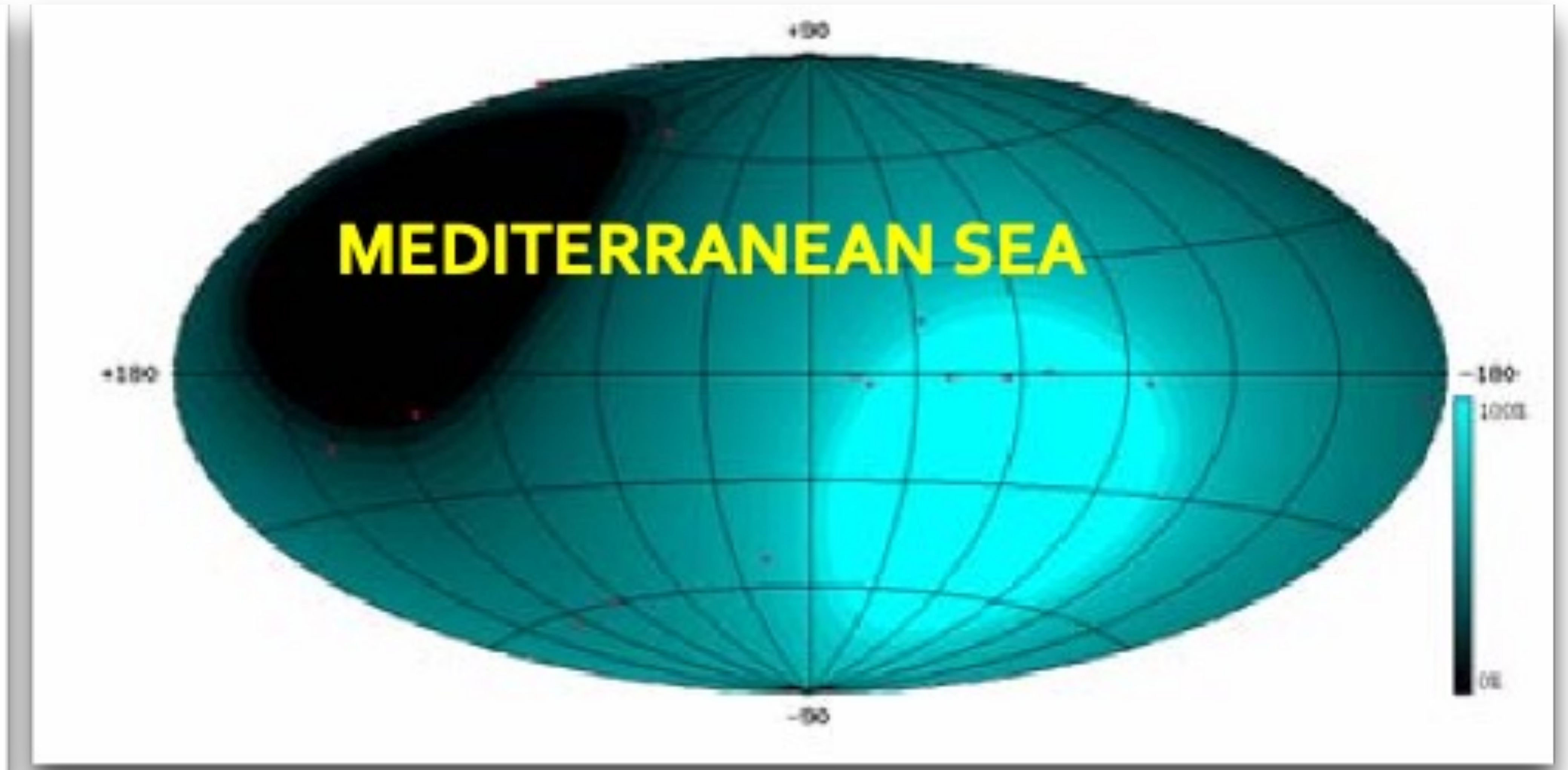
How many neutrino sources, where?

How many telescopes?



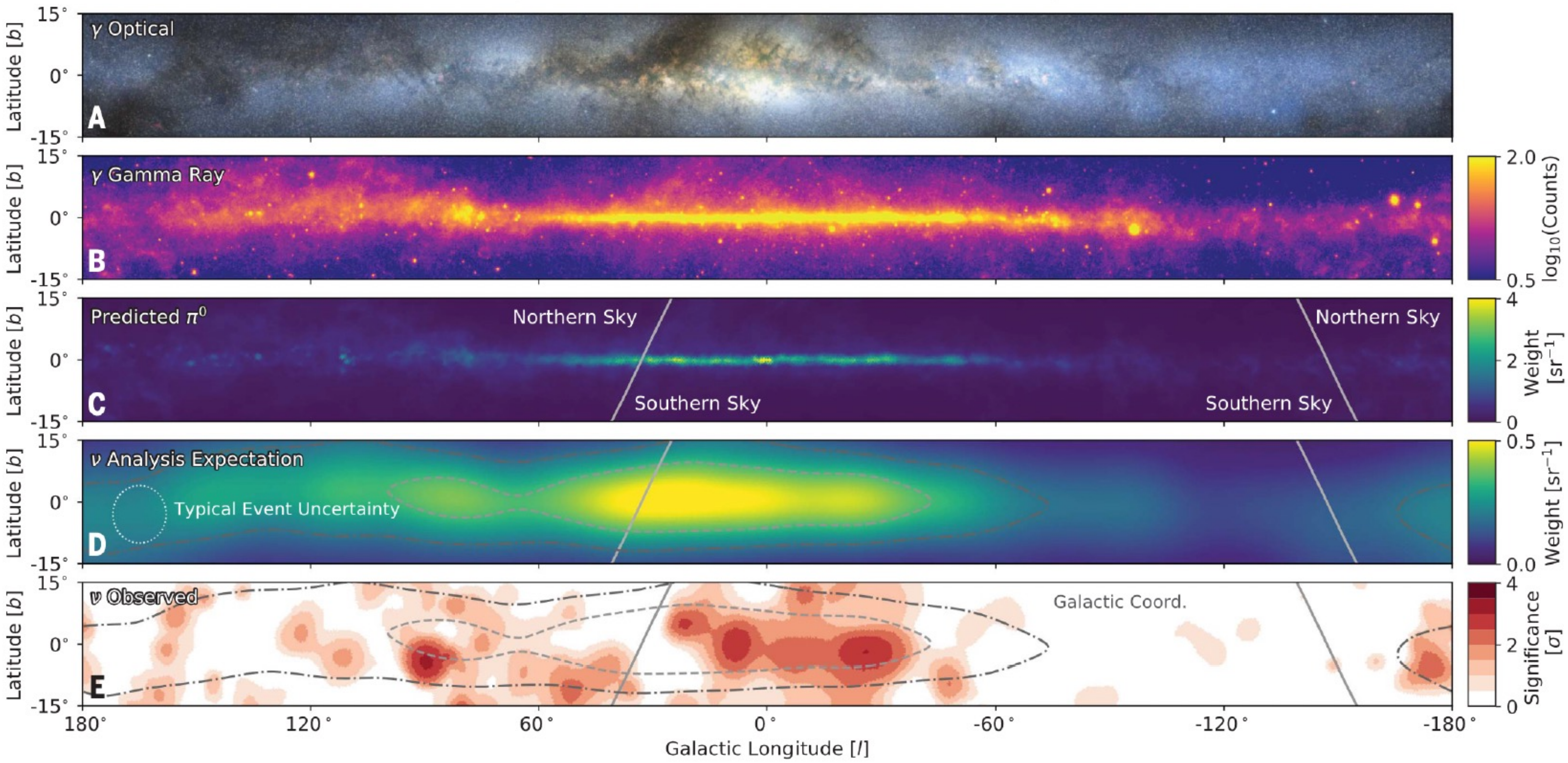
5065 sources



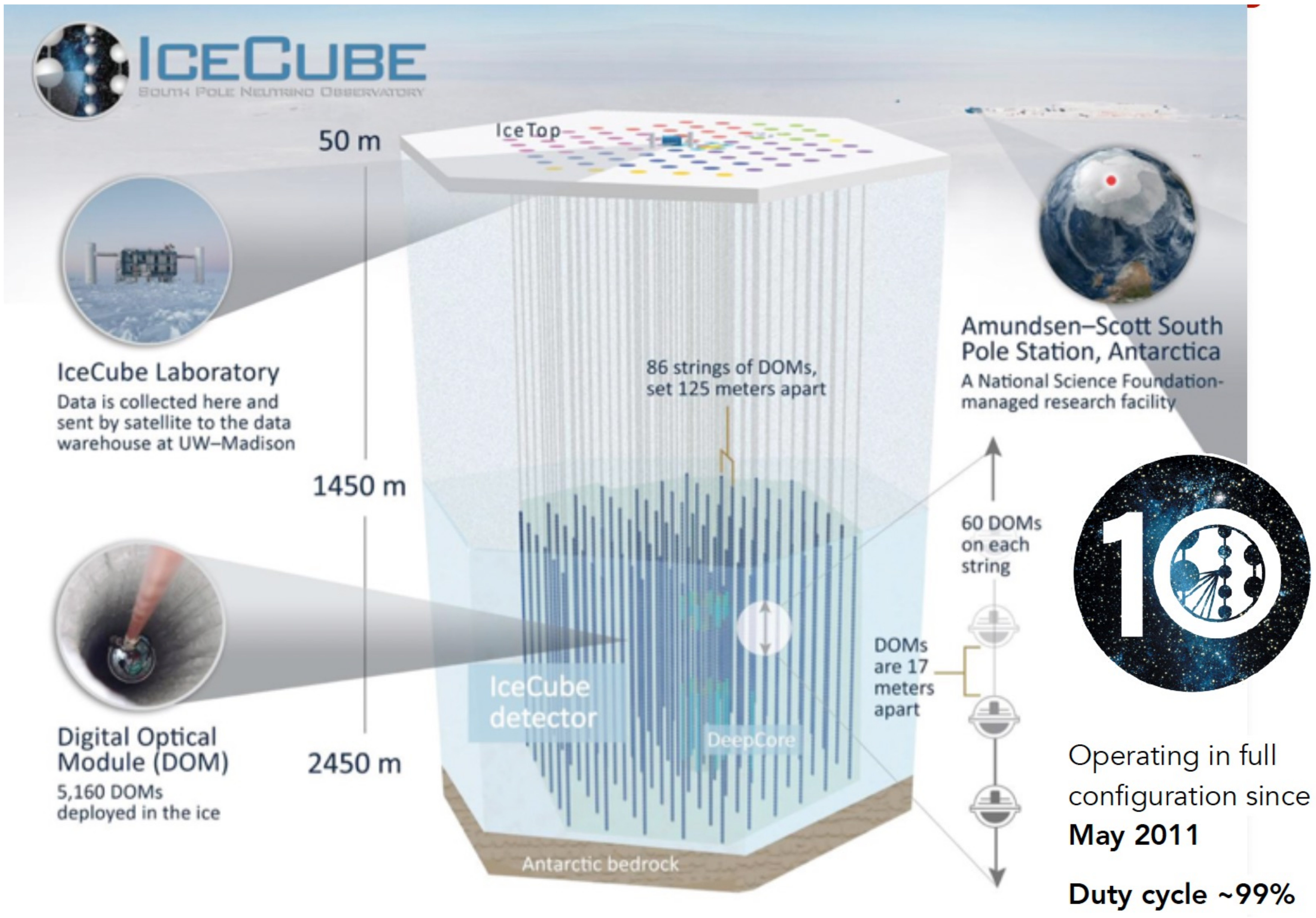


Visibility for up-going neutrinos

The Galactic Plane

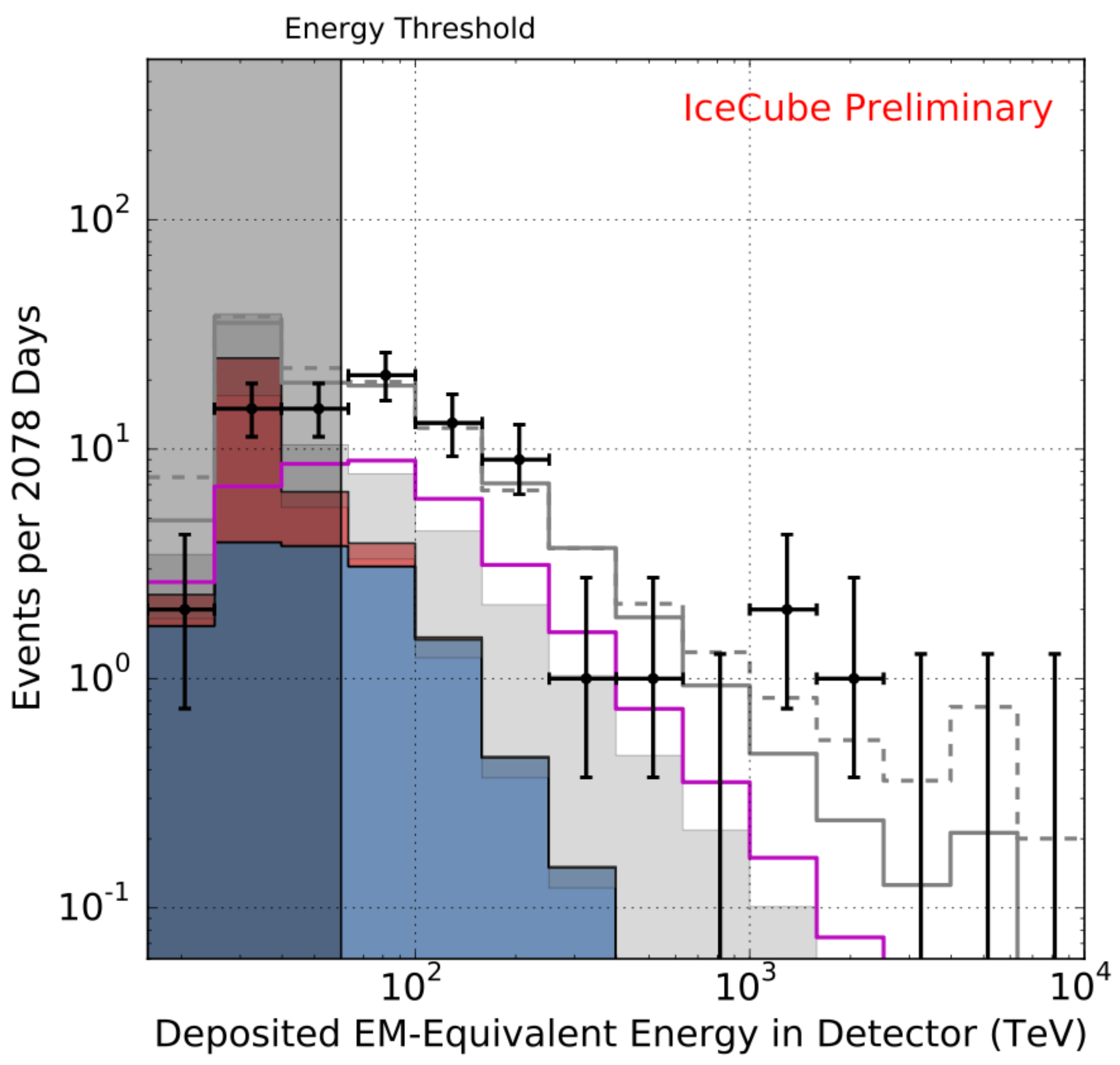


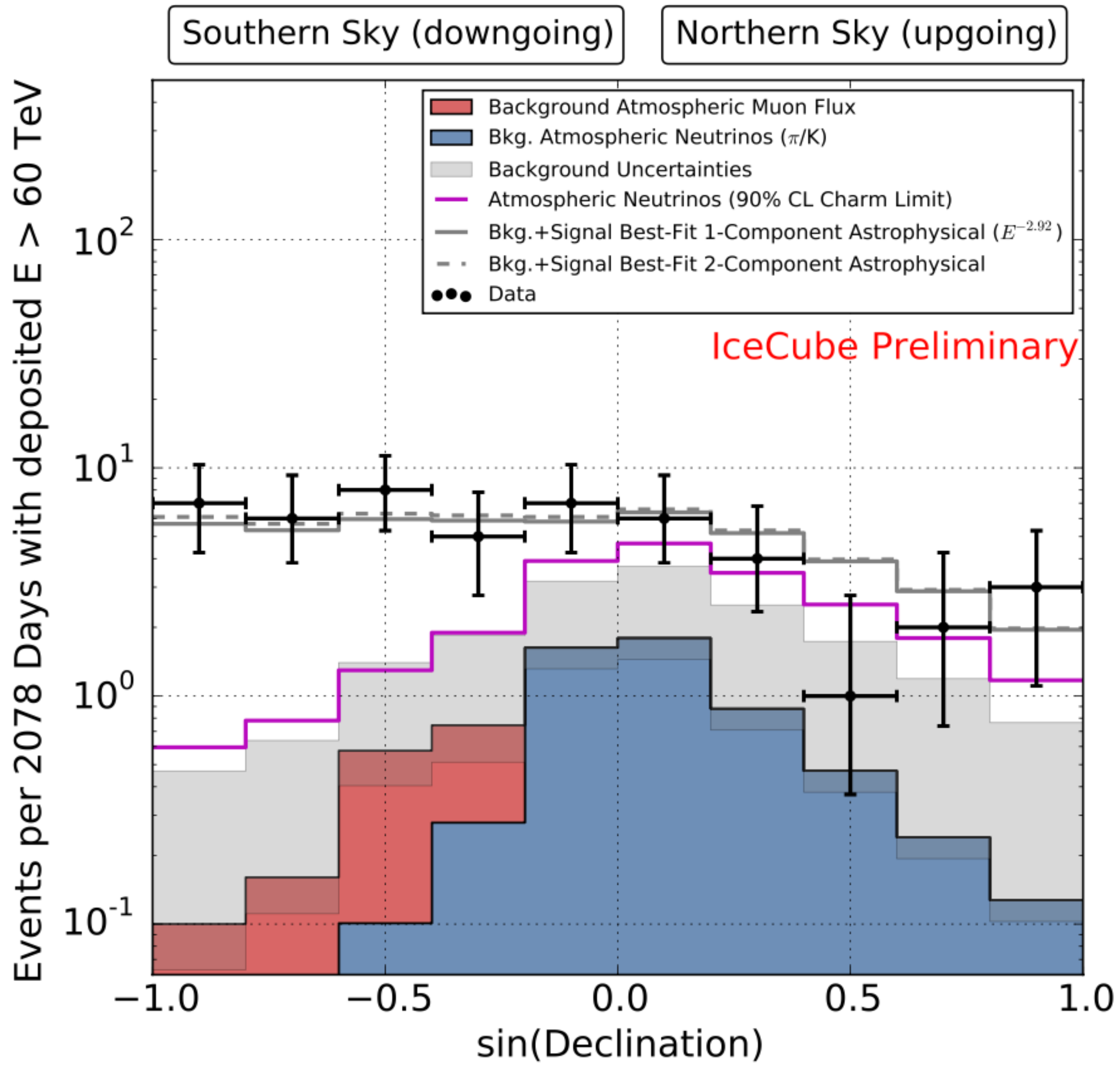
The IceCube Neutrino Observatory



IceCube

The discovery of cosmic neutrinos and the birth of neutrino astronomy

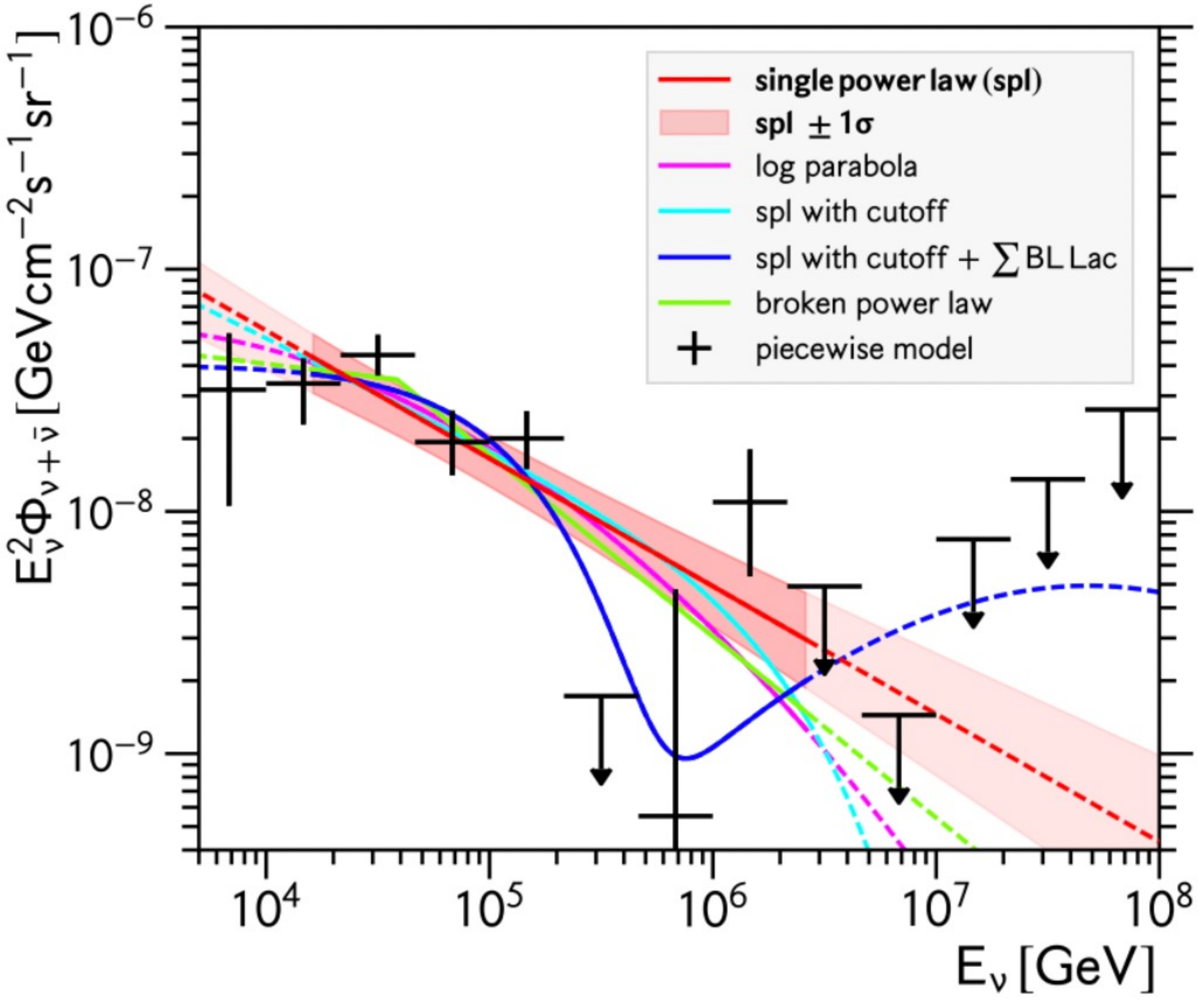




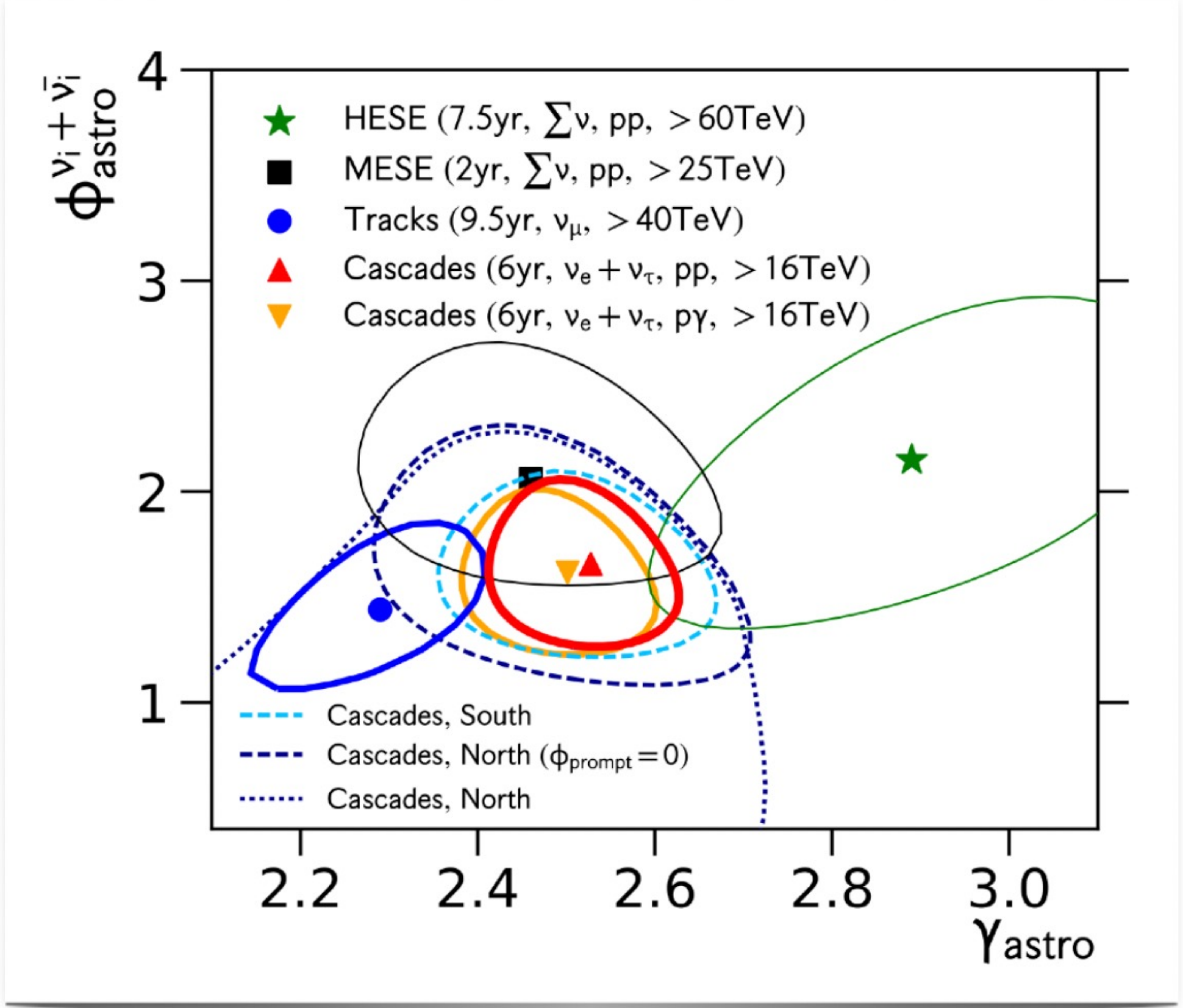
7 years of data

IceCube, Science 342, 1242856 (**2013**)

Diffuse neutrino flux



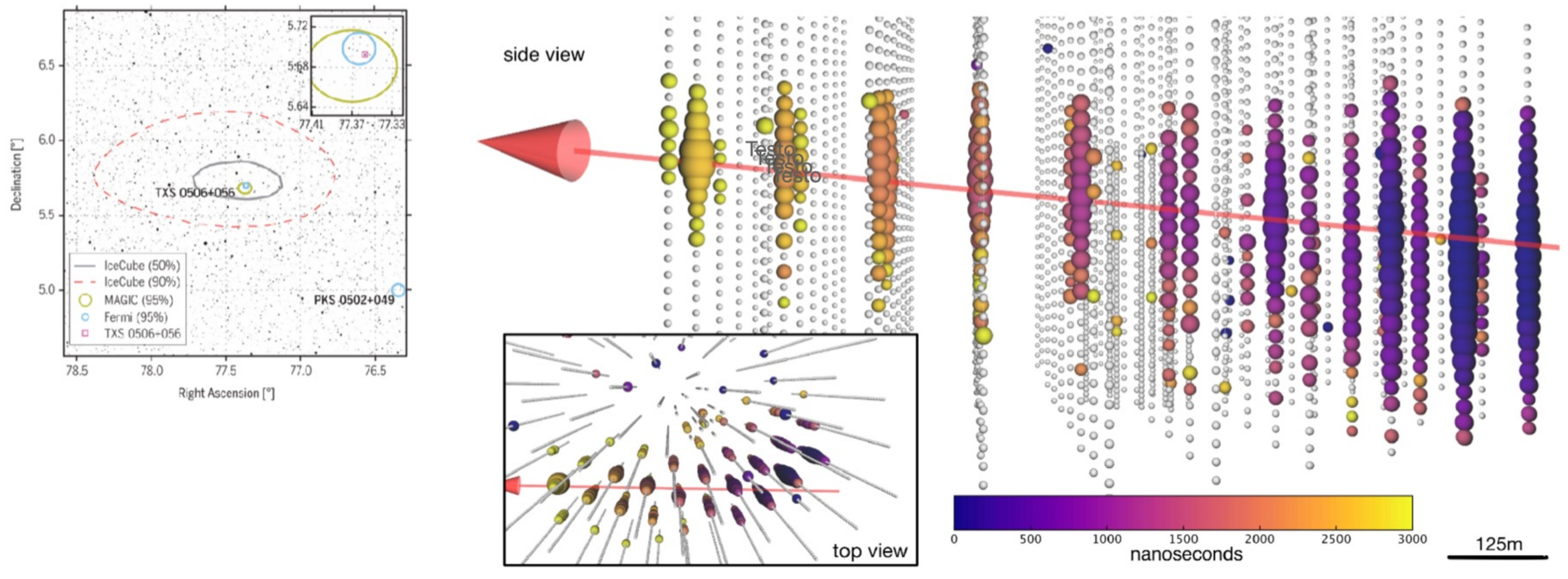
IceCube, Phys. Rev. Lett. 125, 121104 (2020)



Looking for point-like neutrino sources

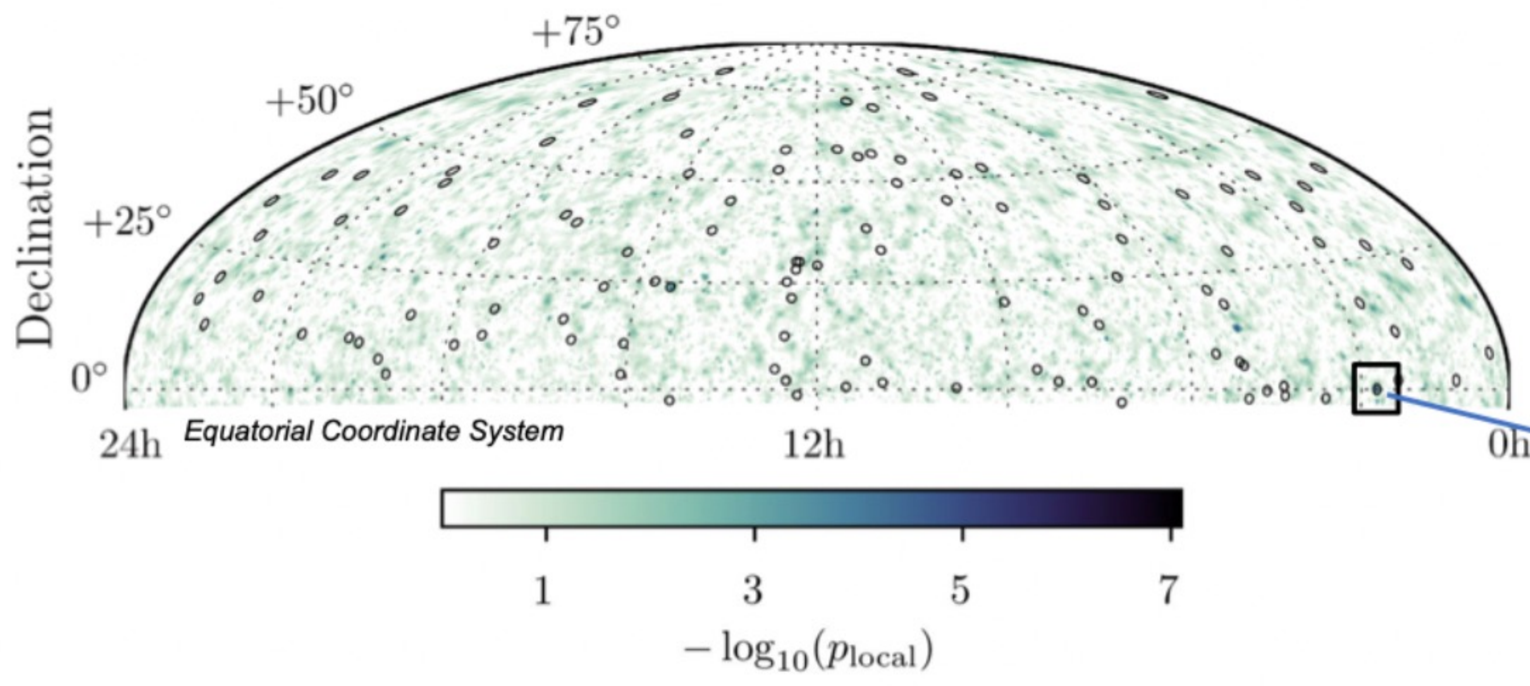
The detection of IceCube-170922 event coincident TX0506+056 flaring blazar inagurated the hera of multimessenger astronomy (E = 290 TeV signalness 56.5%)

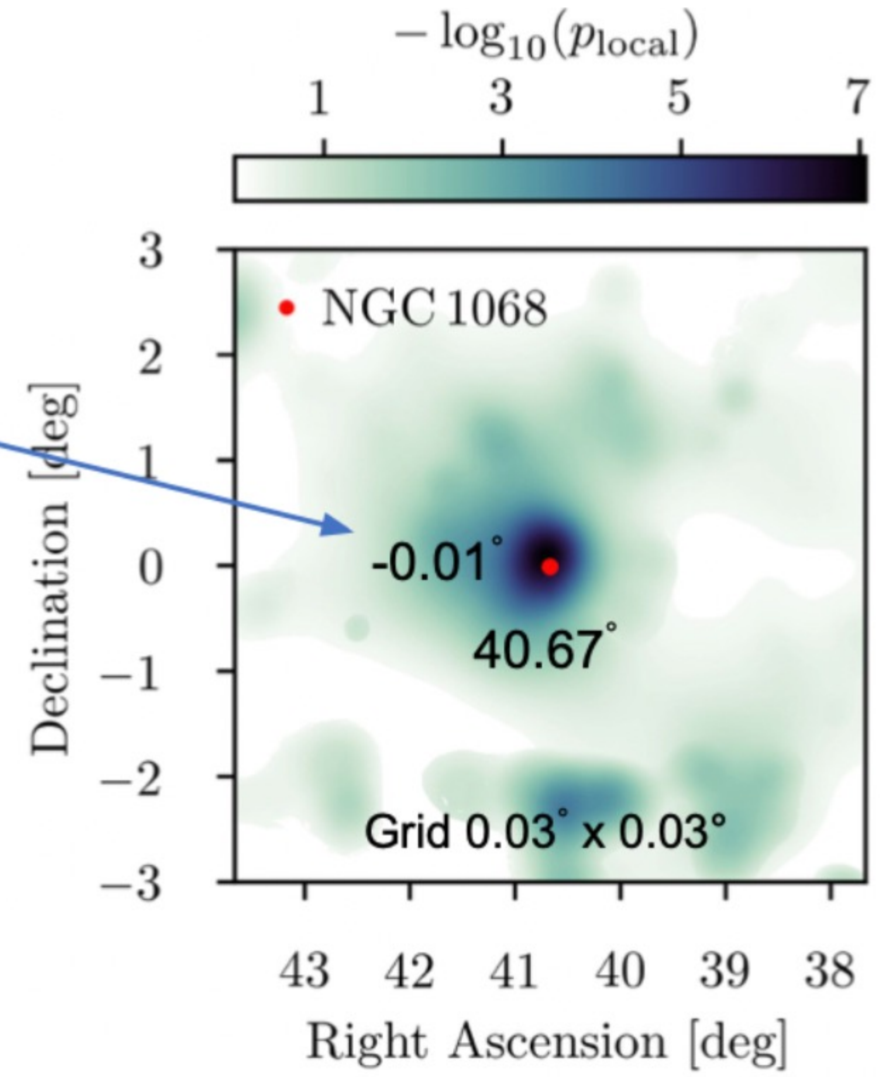
Analysis of neutrino events before 2017 in coincidence with flaring periods gives 3 sigma significance



IceCube, FERMI, MAGIC, ++., Science 361, 146 (**2018**)

Hottest point in IC neutrino sky coincide with AGN NGC 1068 (2011-2020), neutrino flux higher by one order of magntude w.r.t. gamma observation



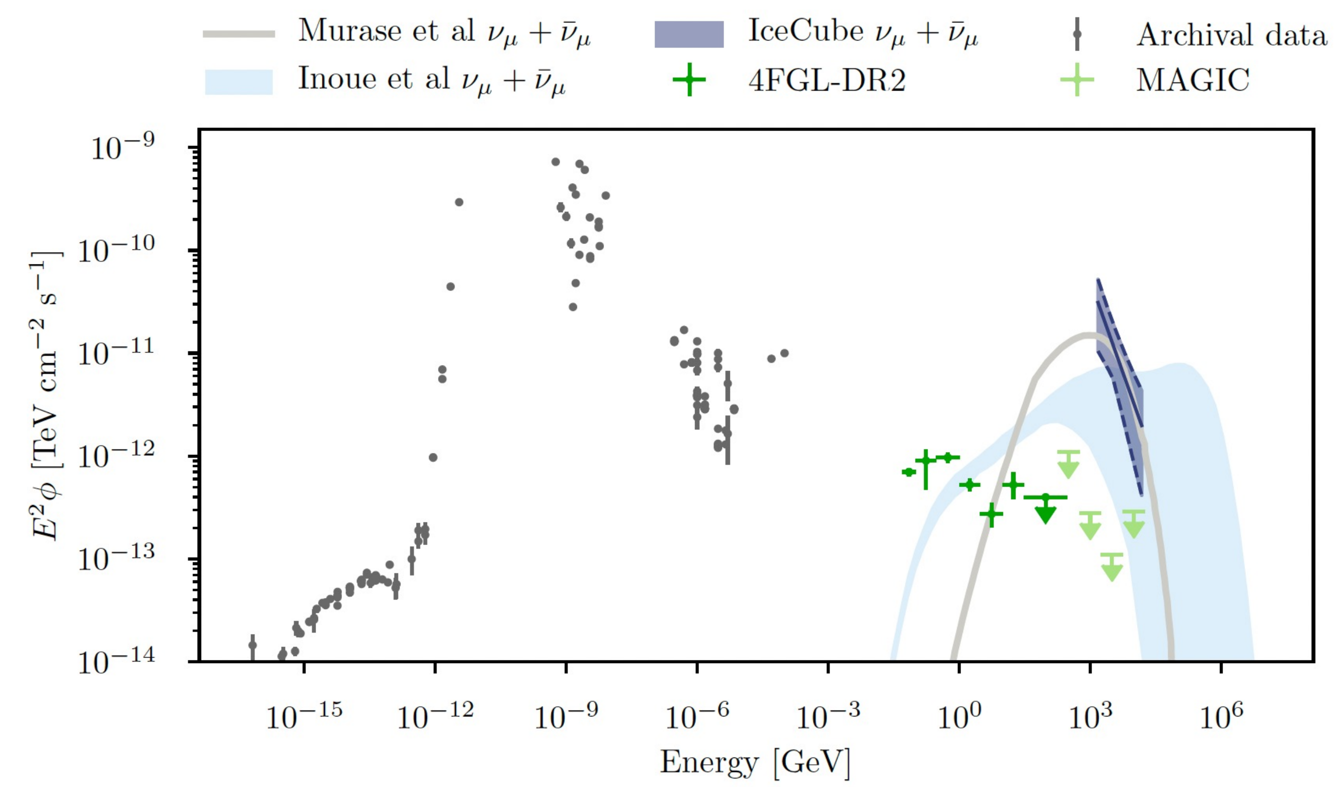


NGC 1068 (Seyfert 2) is the most significant source

$$\hat{\gamma} = 3.2^{+0.2}_{-0.2} \pm 0.07(\textbf{sys}) \qquad \hat{\mu}_{ns} = 79^{+22}_{-20} \pm 2(\textbf{sys})$$

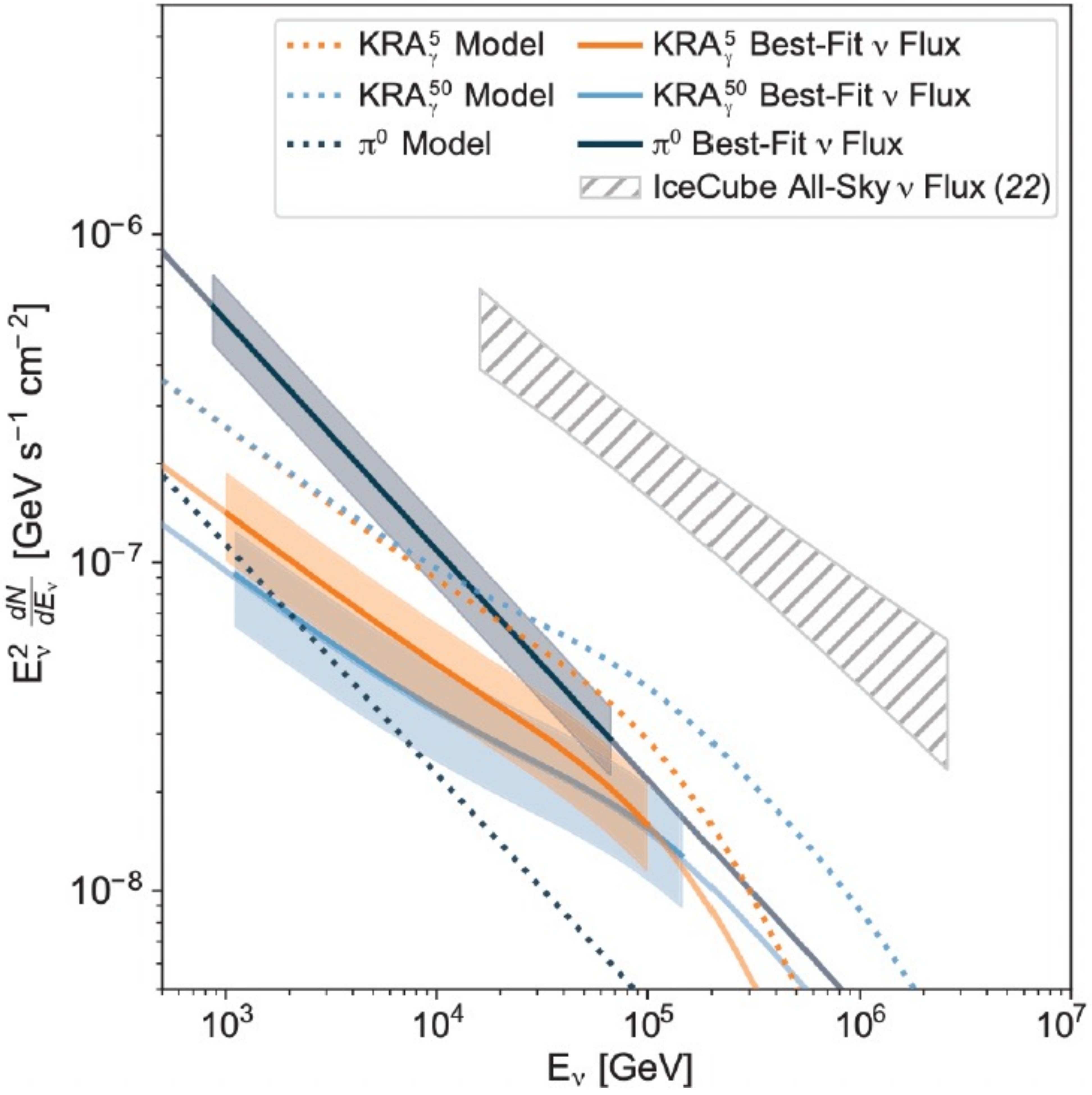
global significance: 4.2σ

IceCube, Science 378, 6619 (2022)



Observation of high energy neutrino from the Galactic Plane

IceCube Collaboration, Science, 2023, 380



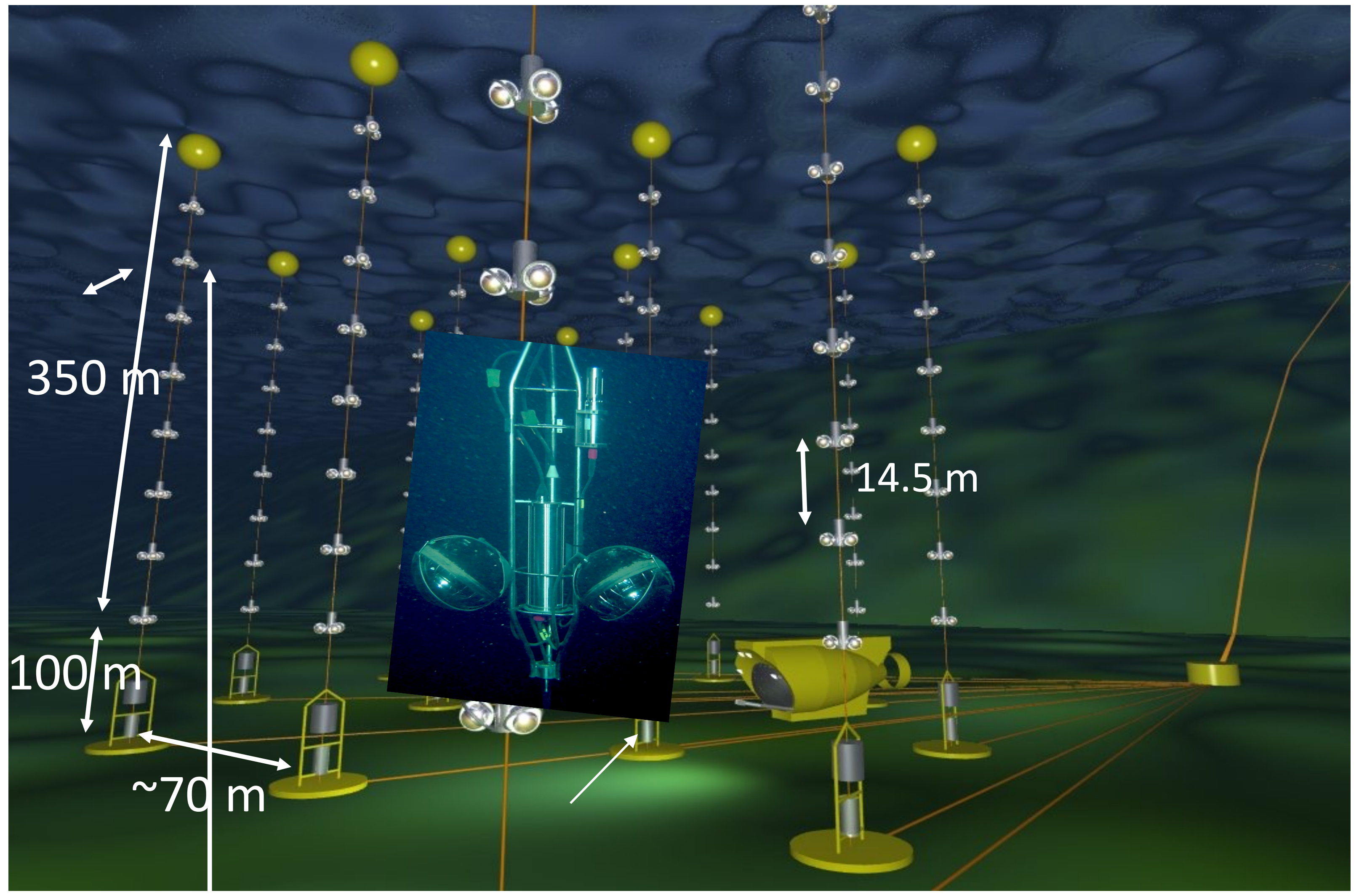
	Flux sensitivity Φ	*P* value	Best-fitting flux Φ
		Diffuse Galactic plane analysis	
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA$_\gamma^5$	0.16 × MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}$ × MF
KRA$_\gamma^{50}$	0.11 × MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}$ × MF
		Catalog stacking analysis	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	
		Other analyses	
Fermi bubbles		0.06 (1.52σ)	
Source list		0.22 (0.77σ)	
Hotspot (north)		0.28 (0.58σ)	
Hotspot (south)		0.46 (0.10σ)	

*Significance values that are consistent with the diffuse Galactic plane template search results.

Antares: the first neutrino telescope in Mediterranean Sea

Optical Cherenkov telescope in sea water

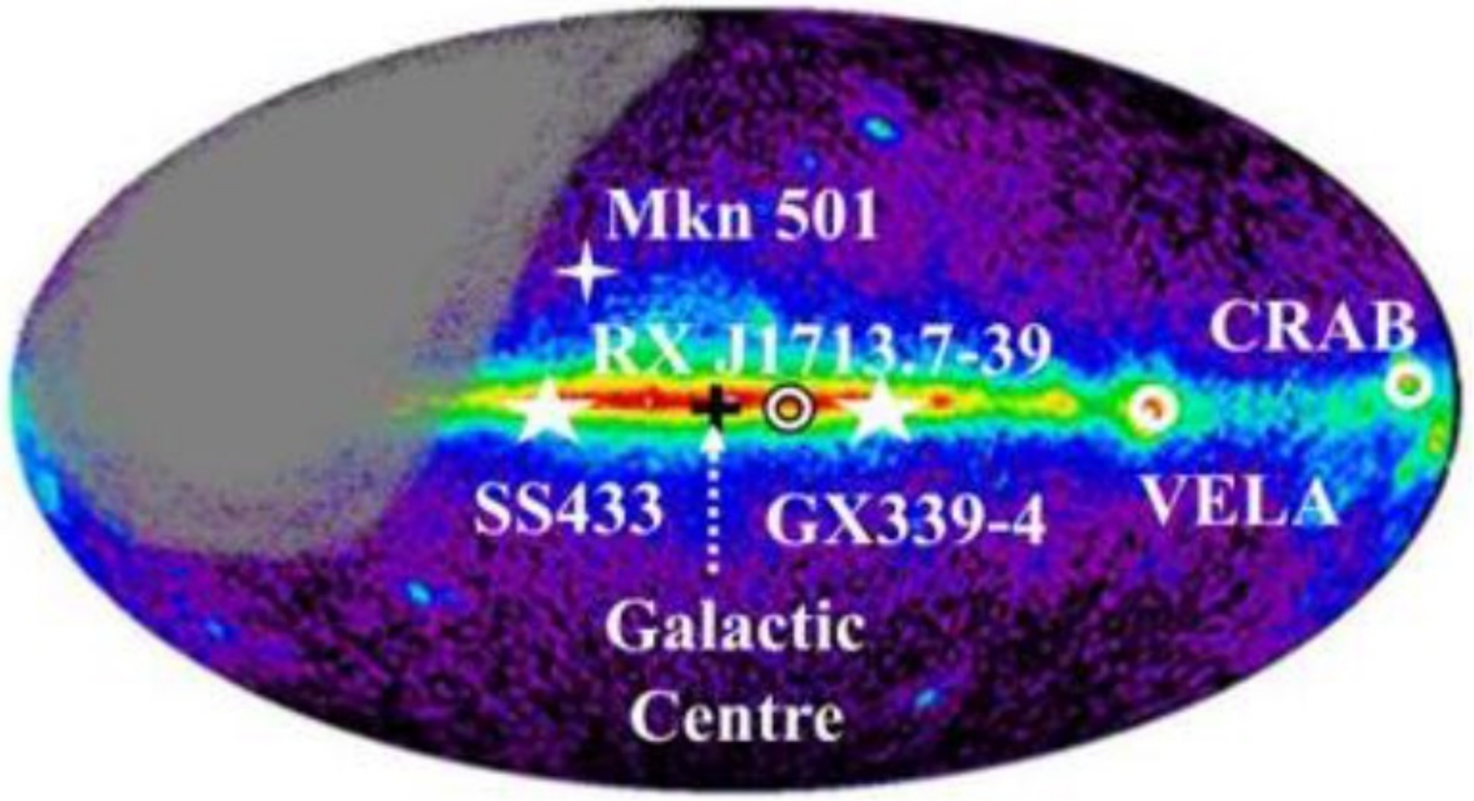
- 12 lines offshore Toulon at 2500 m depth
- 25 storeys / line
- 3 10” PMTs / storey
- 900 PMTs
- 0.01 km3
- Data taking 2008-2022



Survey of Southern neutrino sky

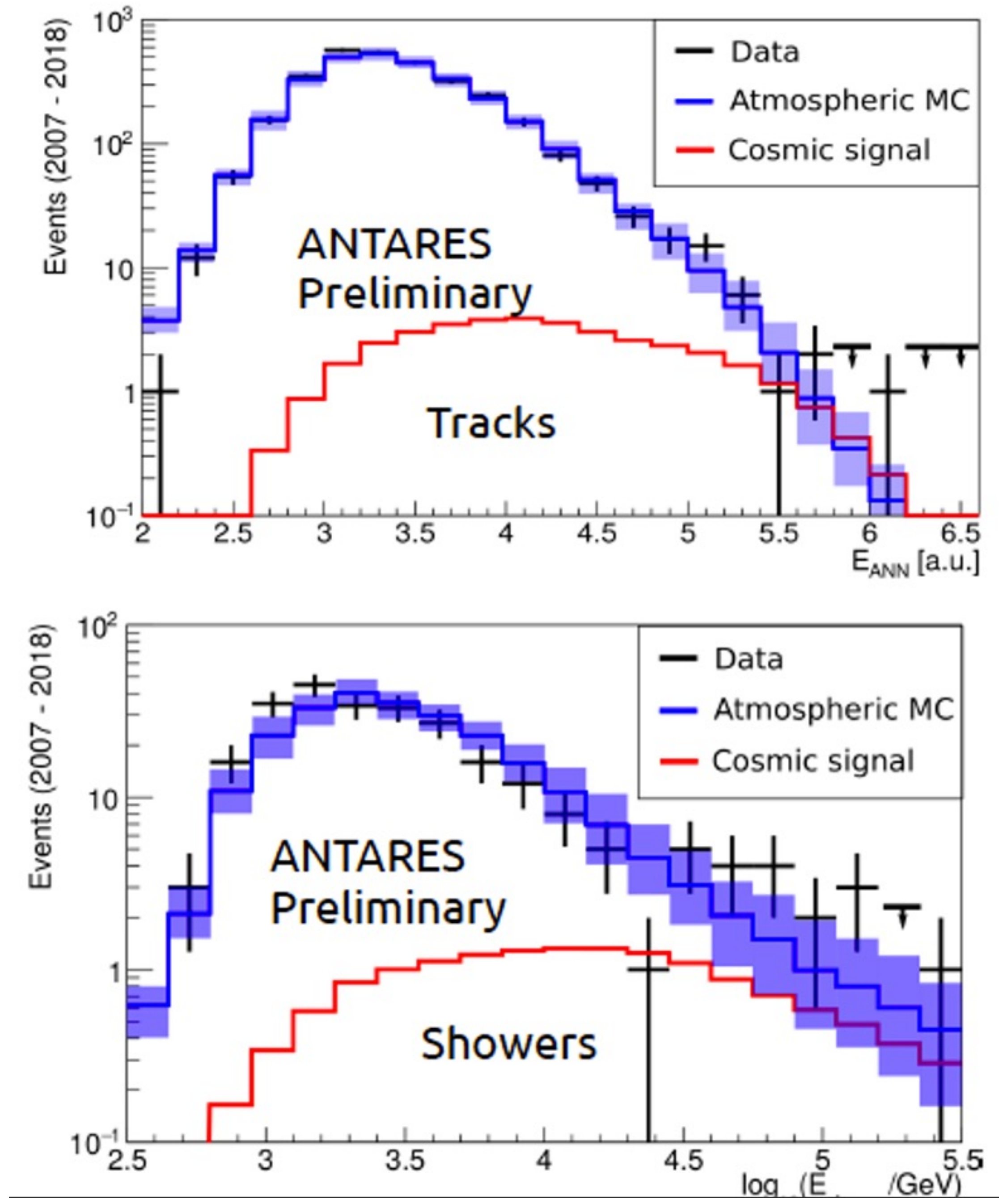
- Best limits on several candidate sources
- no cosmic neutrino discovery due to small size/sensitivity
- synergy with IceCube multimessenger
- indirect DM search

Field of View

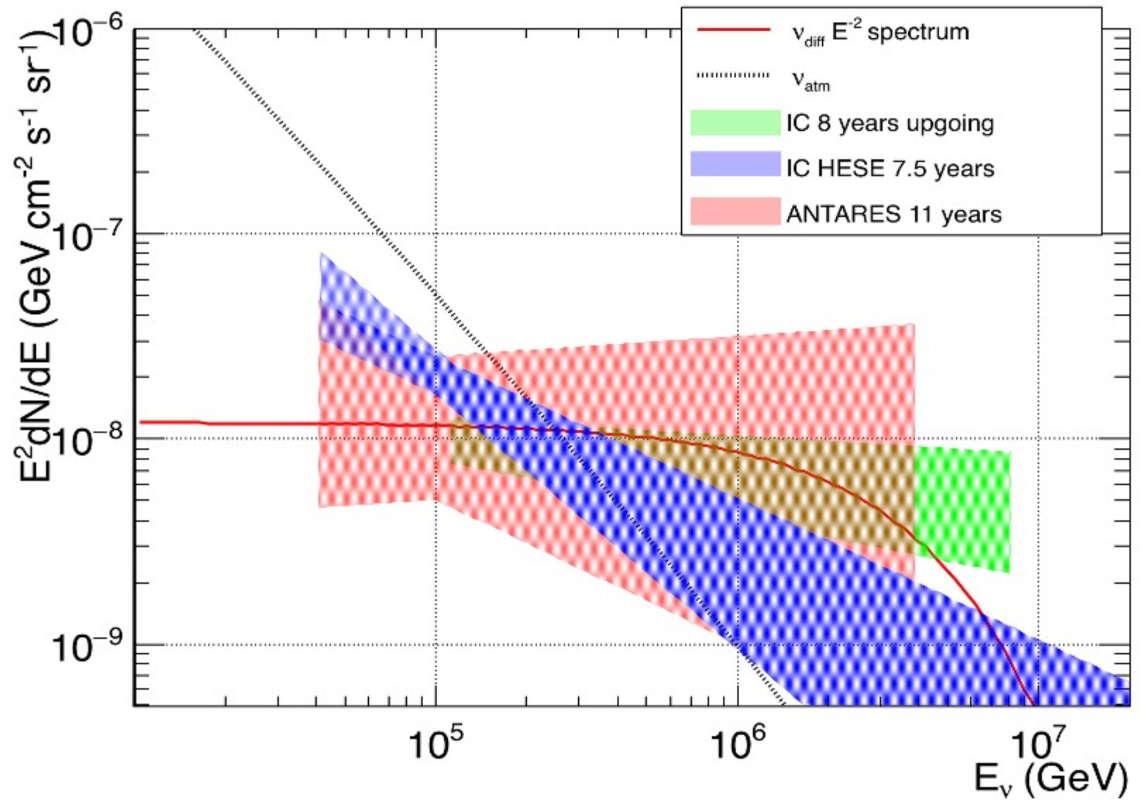


Paved the way to KM3NeT

Antares Diffuse Flux Search



Data: 50 events (27 tracks + 23 showers)
Background expectation (atm. flux, incl. prompt) :
36.1 ± 8.7 (19.9 tracks & 16.2 showers) stat. + syst.



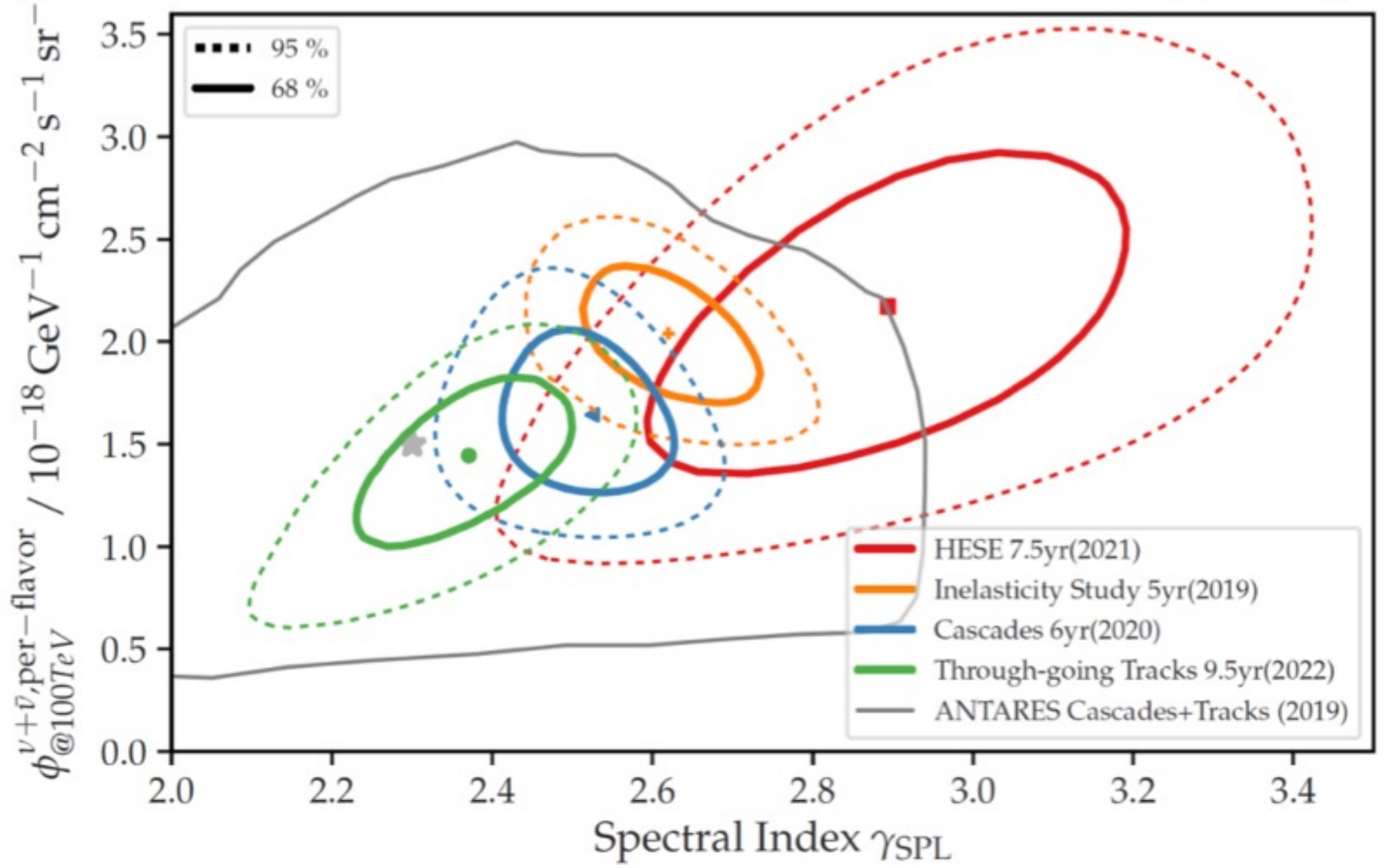
$\Phi_{100\mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

$\Gamma = 2.3 \pm 0.4$

1.8 sigma

Ap.J.Lett. 853 (2018) 1, L7

arXiv: 2203.08096



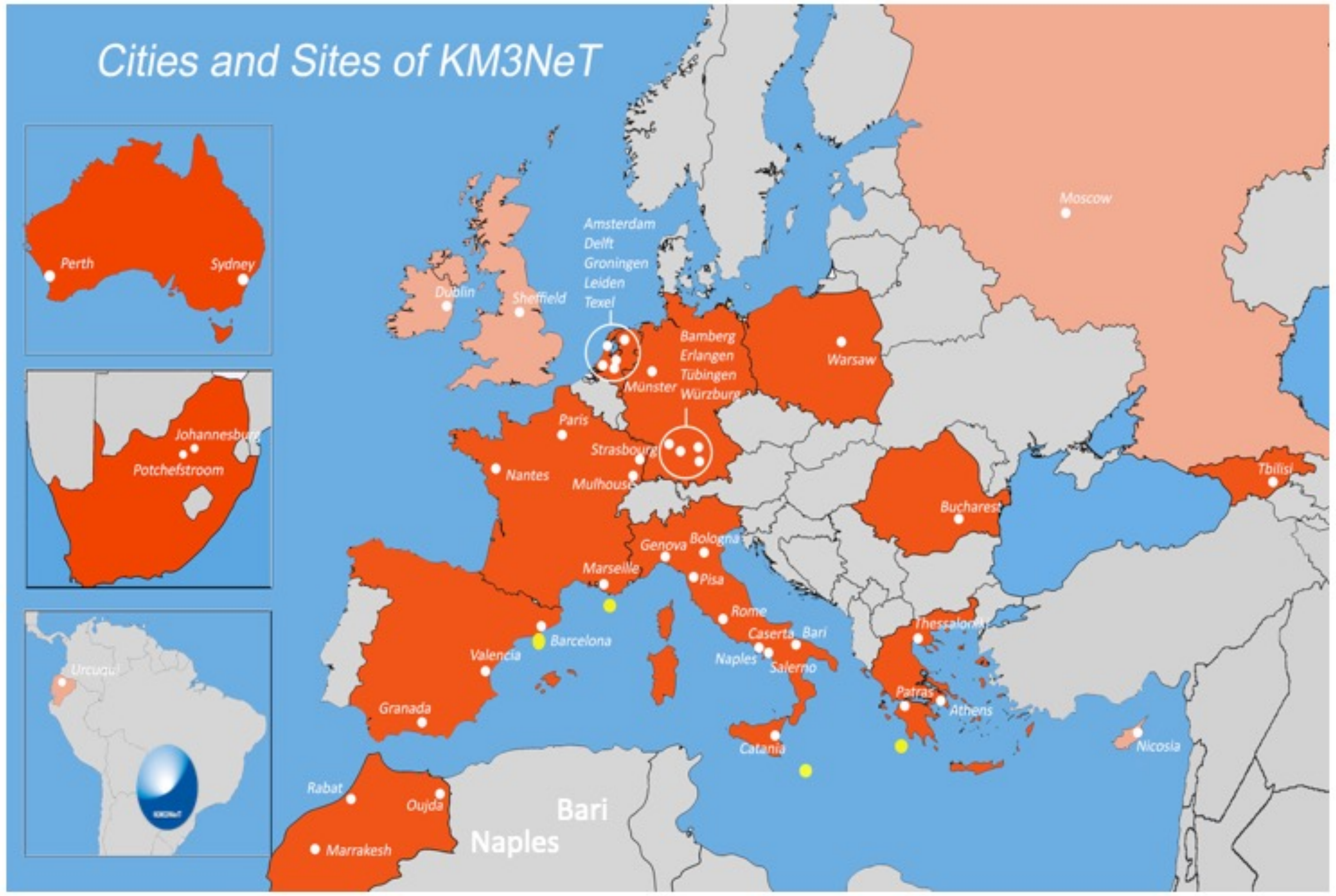
KM3NeT

Multi-site telescope network with two main physics cases

- discovery and subsequent observation of high-energy neutrino sources in the Universe - ARCA
- study of neutrino properties and determination of neutrino mass hierarchy - ORCA

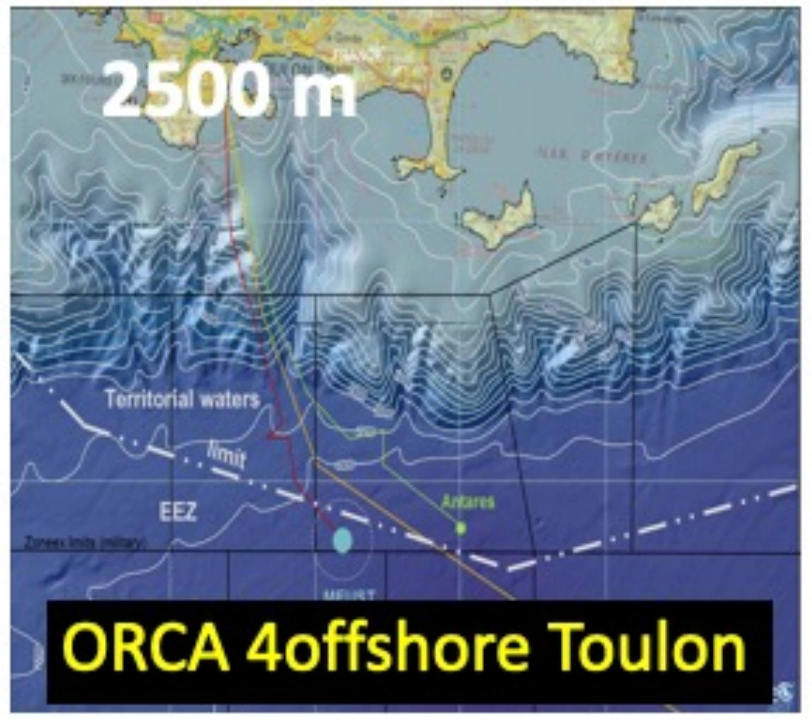
One collaboration and one technology!

Full coverage of the sky with unprecedented angular resolution

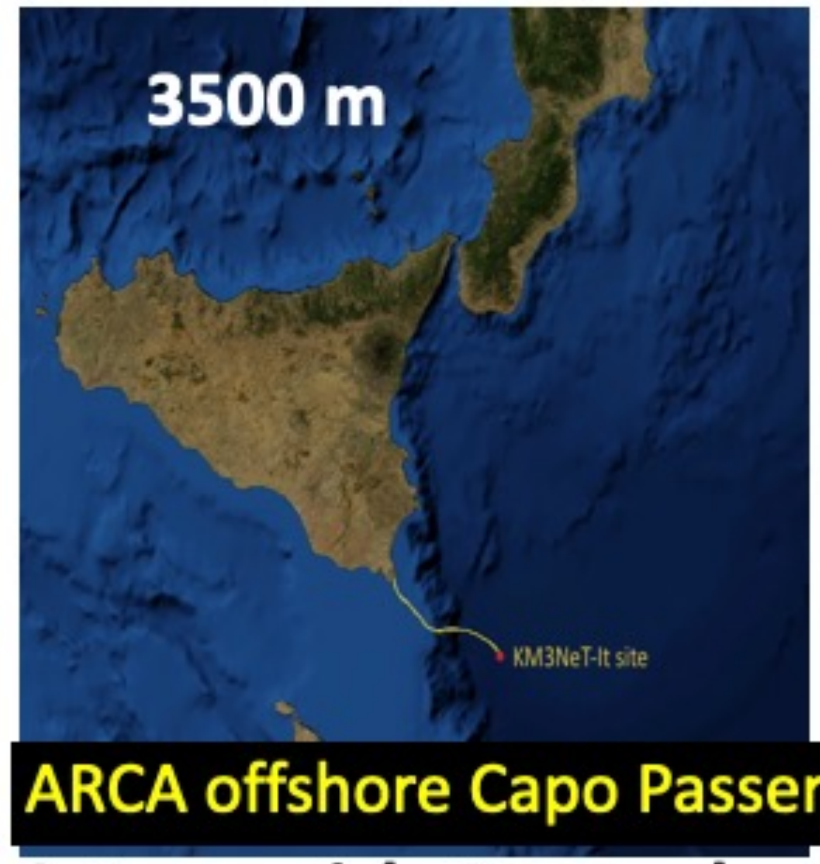


KM3NeT 2.0: Letter of Intent1

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



Oscillation **R**esearch with **C**osmics **I**n the **A**byss



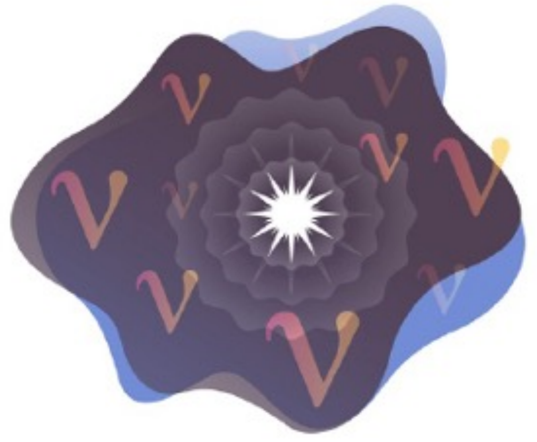
Astroparticle **R**esearch with **C**osmics **I**n the **A**byss

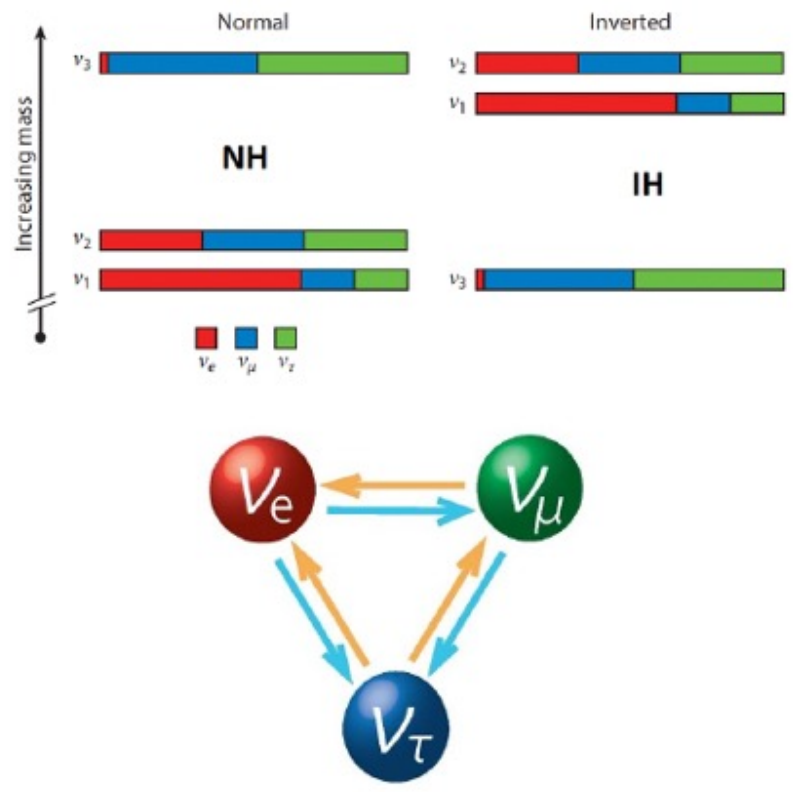
Connection nodes of

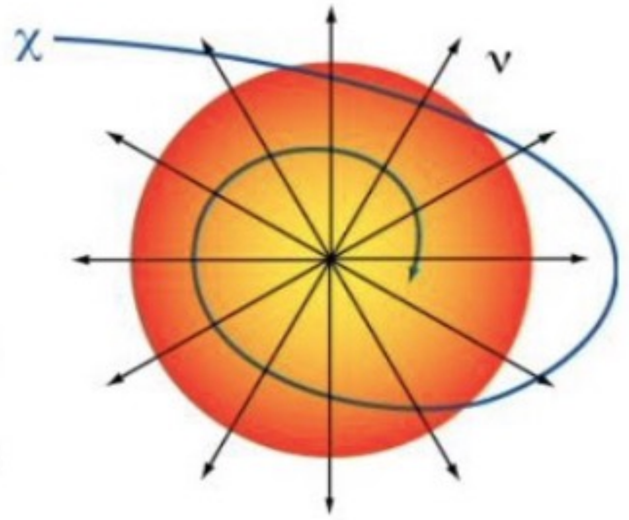
european multidisciplinary seafloor & water column observatory emso

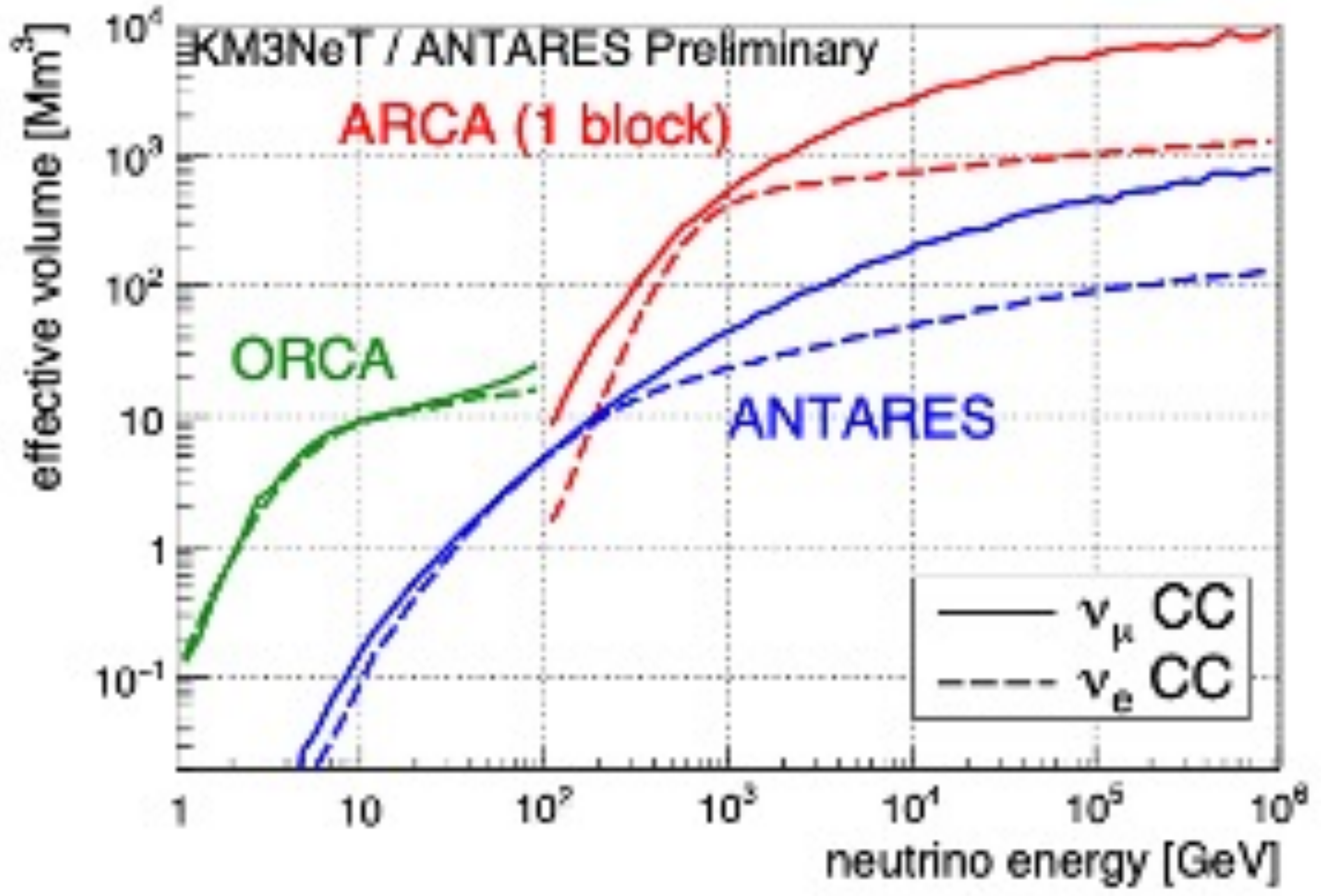
The Physics

Supernovae Explosion	Neutrino Physics	Dark Matter & Exotic searches	Cosmic neutrinos Multi-messenger program
MeV	GeV	TeV	PeV









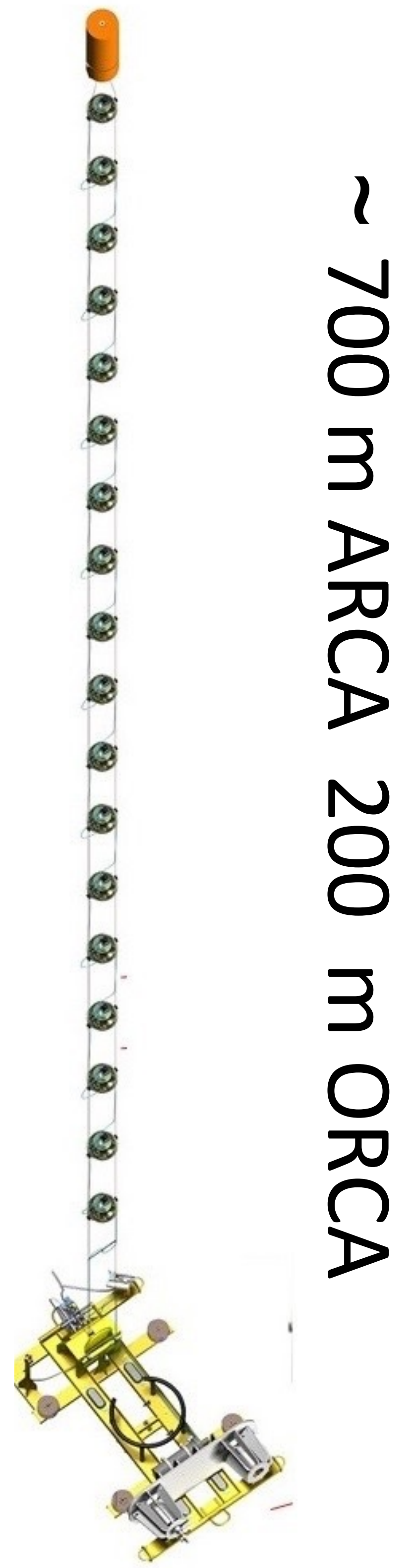
KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

KM3NeT technology

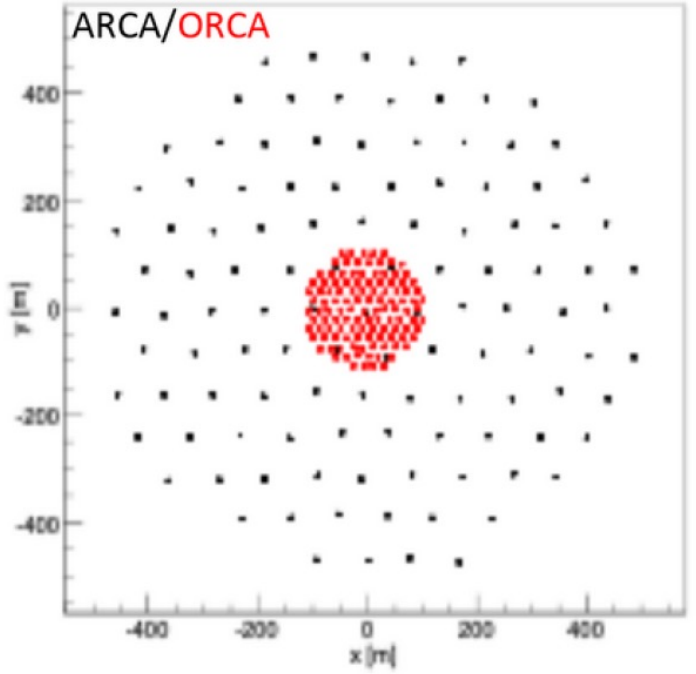
A very challenging project
- 100 x Antares volume
- O(10) strings
- innovative technology & cost

effective detector design
- compact deployment
- larger depth (ARCA @3500)

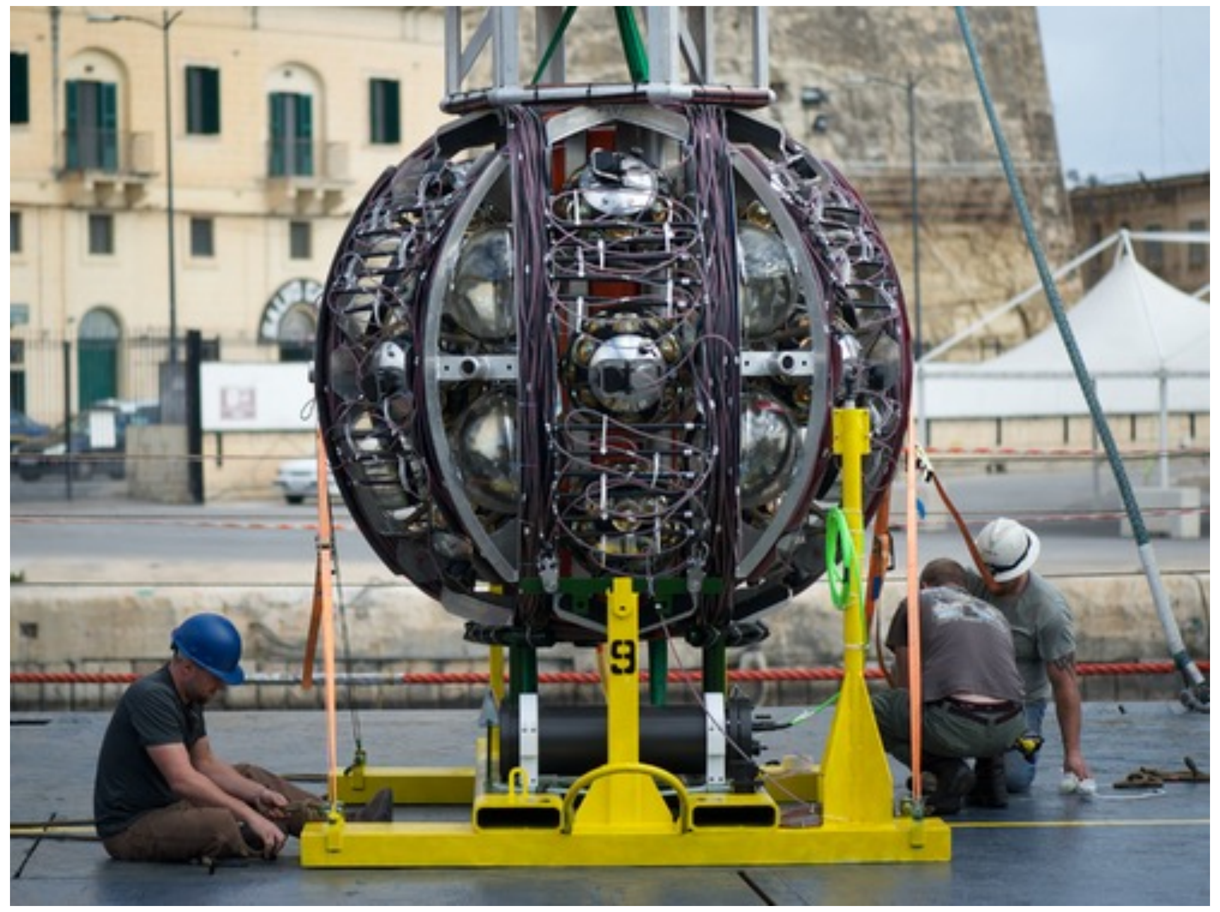
Digital Optical Module (DOM)
Multi-PMT : 31 x 3” PMTs
directional info
wide angle of view
Gbit/s on optical fiber
positioning & timing



Detection Unit (DU)
18 DOMs
Low-drag design
Building block of 115 DUs
- 2 for ARCA
- 1 for ORCA



	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mton	~ 2 × 0,5 Gton

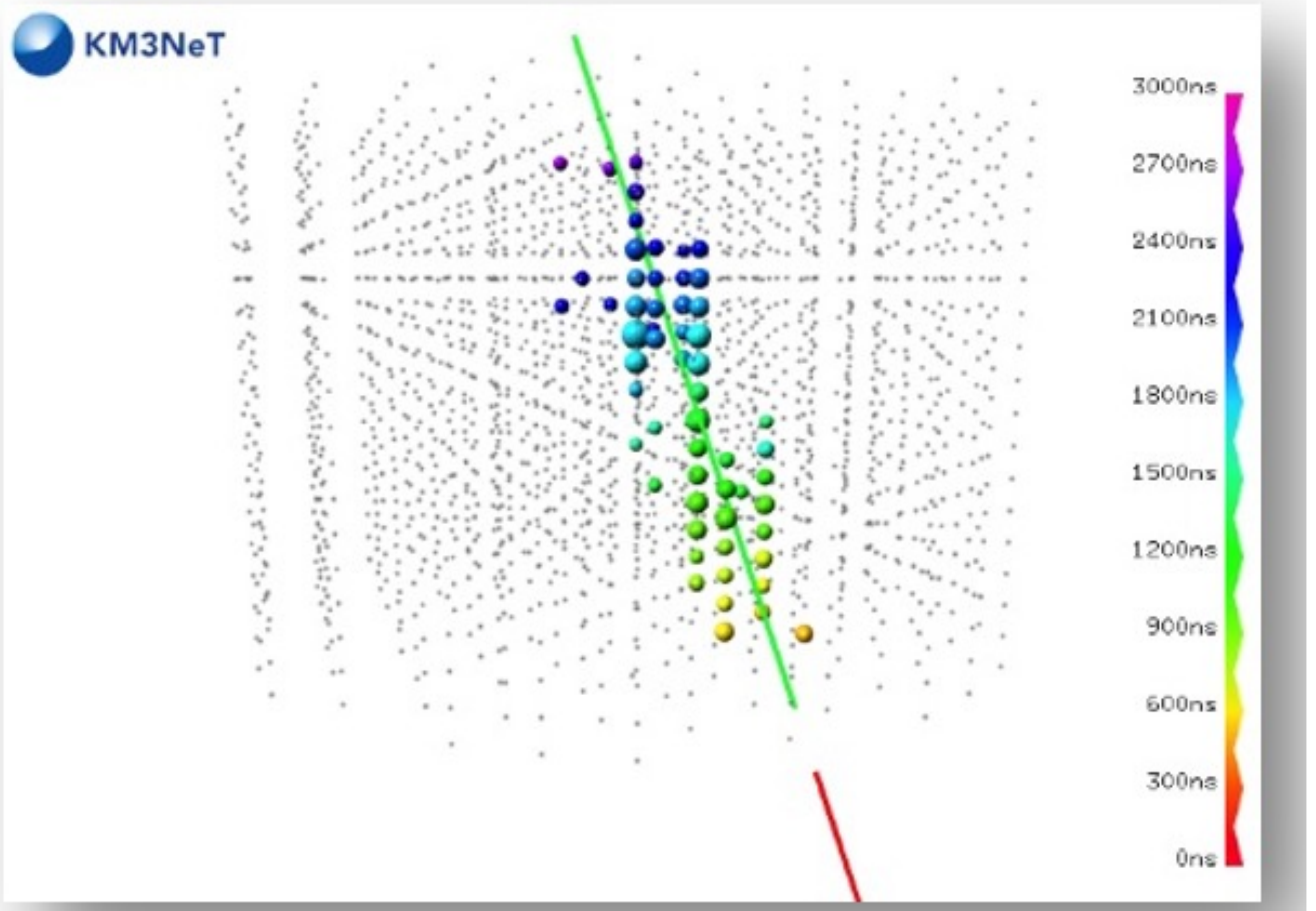


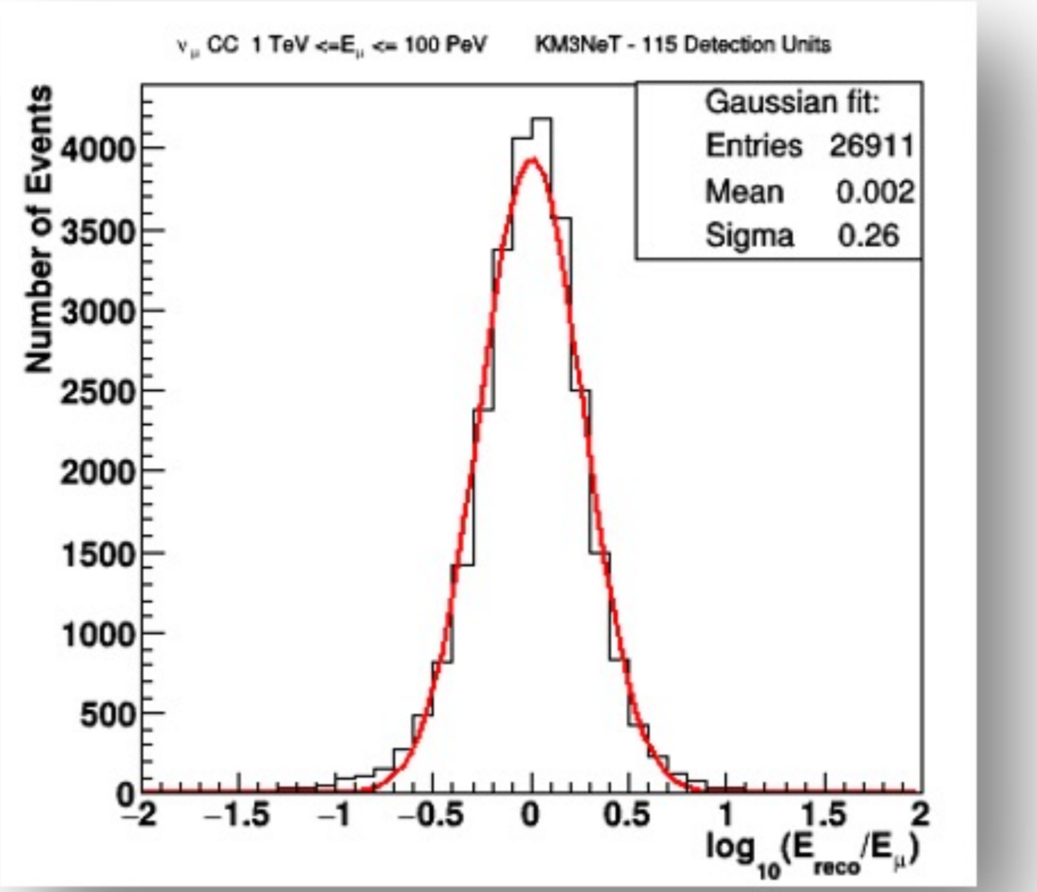
Installation with LOM
Rapid deployment
Multiple strings/sea campaign
Autonomous/ROV unfurling
Reusable

28 (18) strings already deployed in ARCA (ORCA)
Antares acceptance overcome (about x4) by ARCA

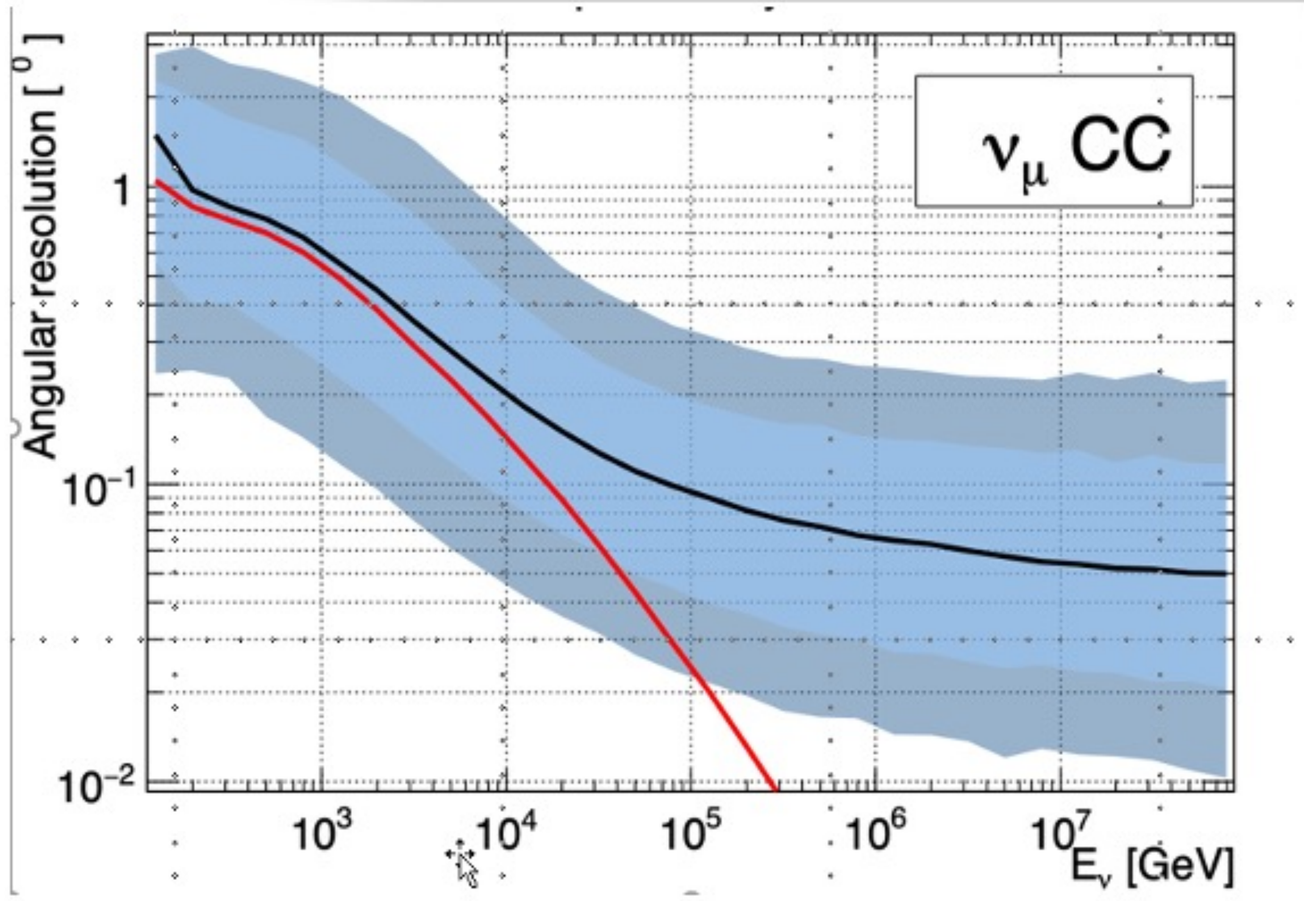
Event Topologies and Detector Response

- ν_μ are the golden channel for neutrino astronomy
- Deep sea water properties, i.e. long scattering length allow to achieve very good angular resolution

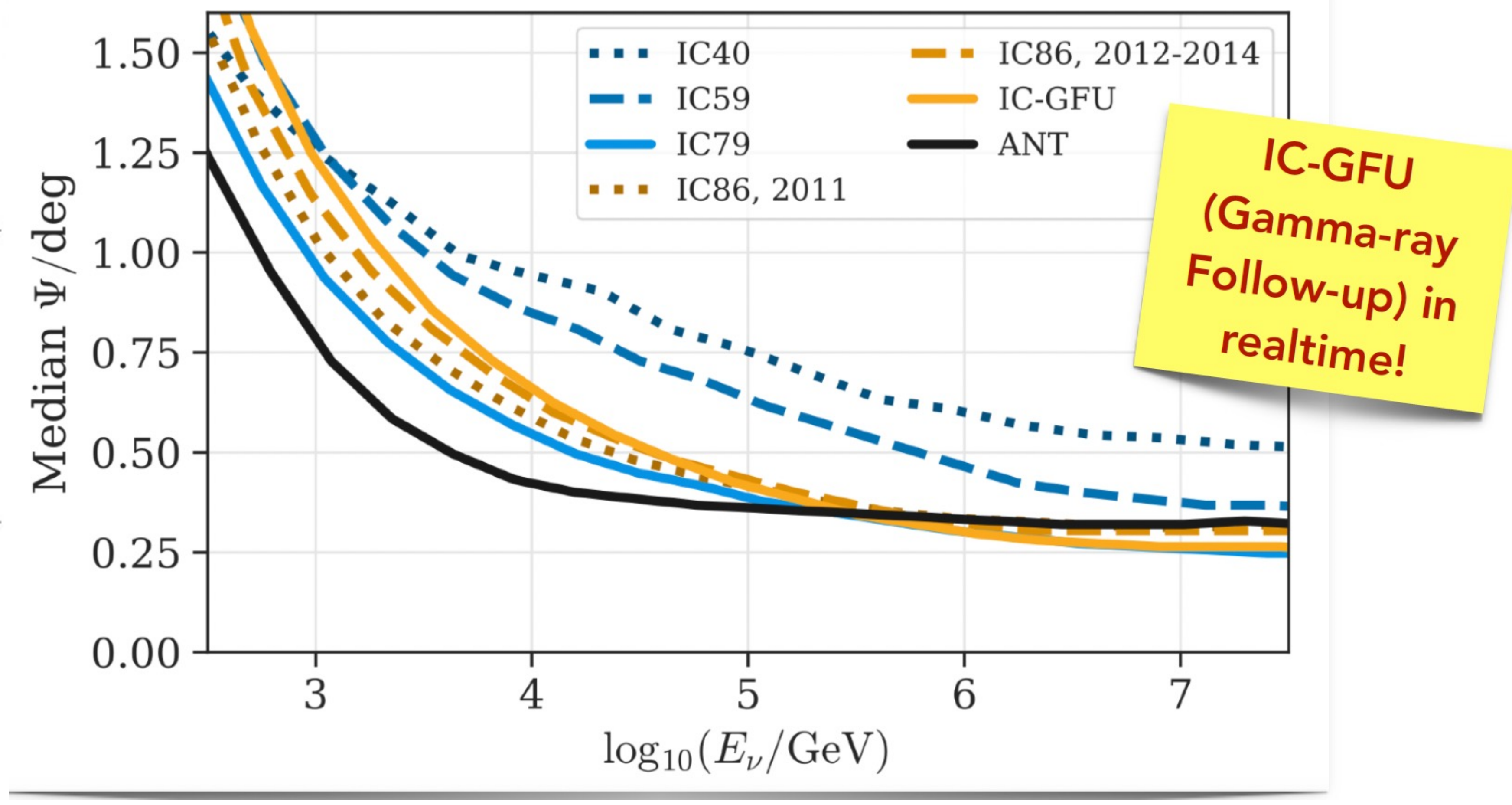




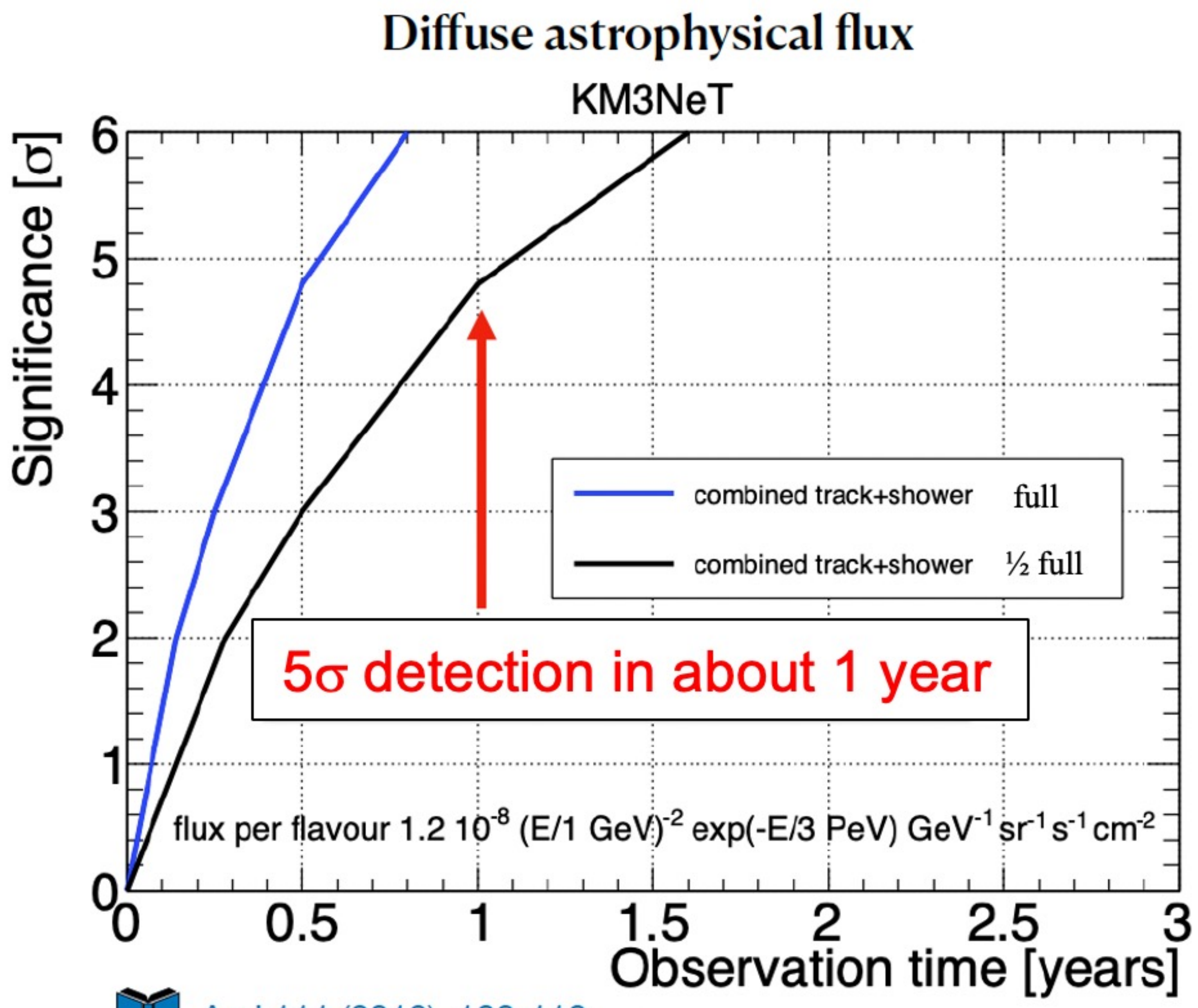
Energy resolution about 0.3 in $\log E_\mu$



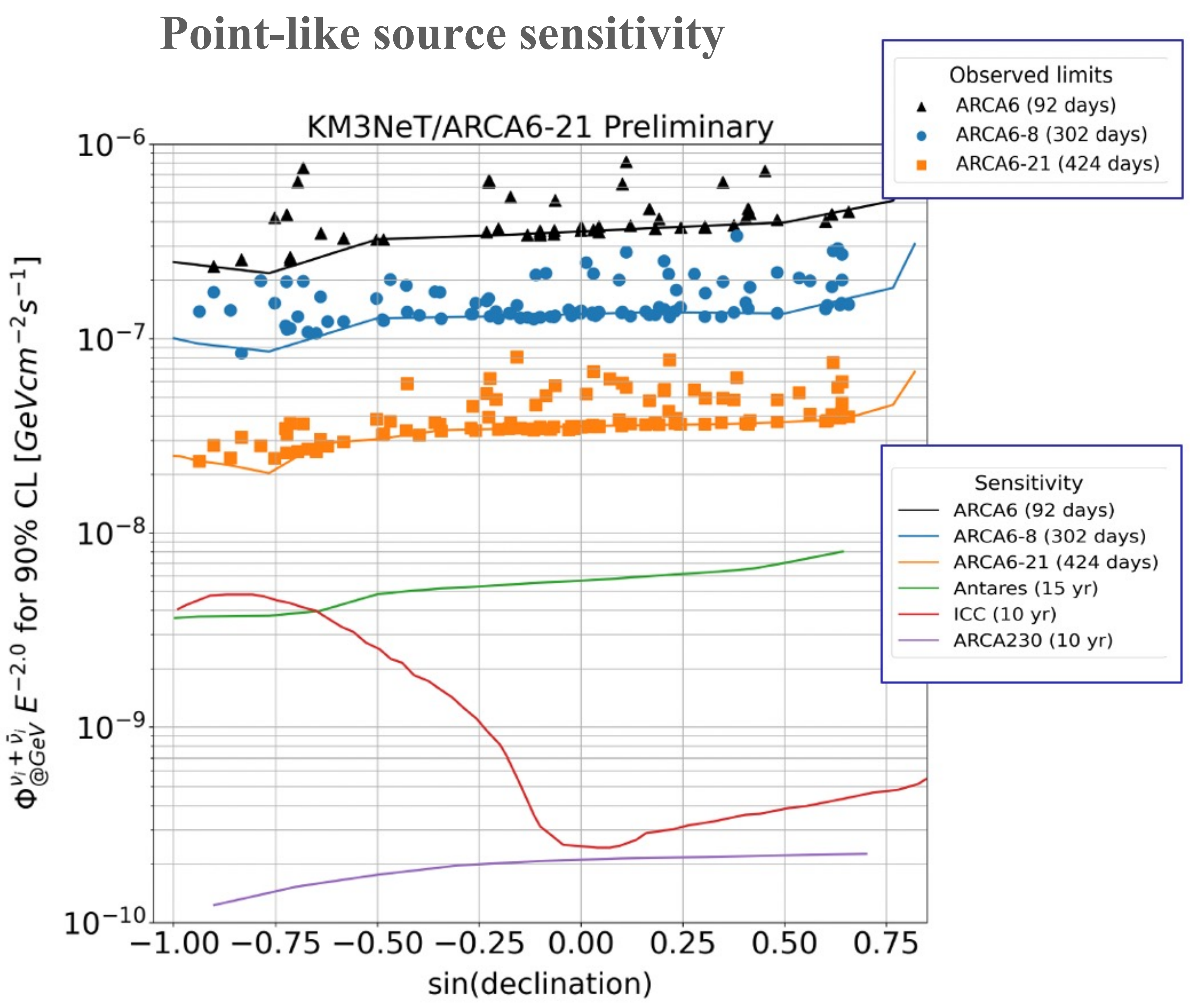
Angular resolution about 0.1° (E_ν>10 TeV)



KM3Net sensitivity



ApJ 111 (2019), 100-110



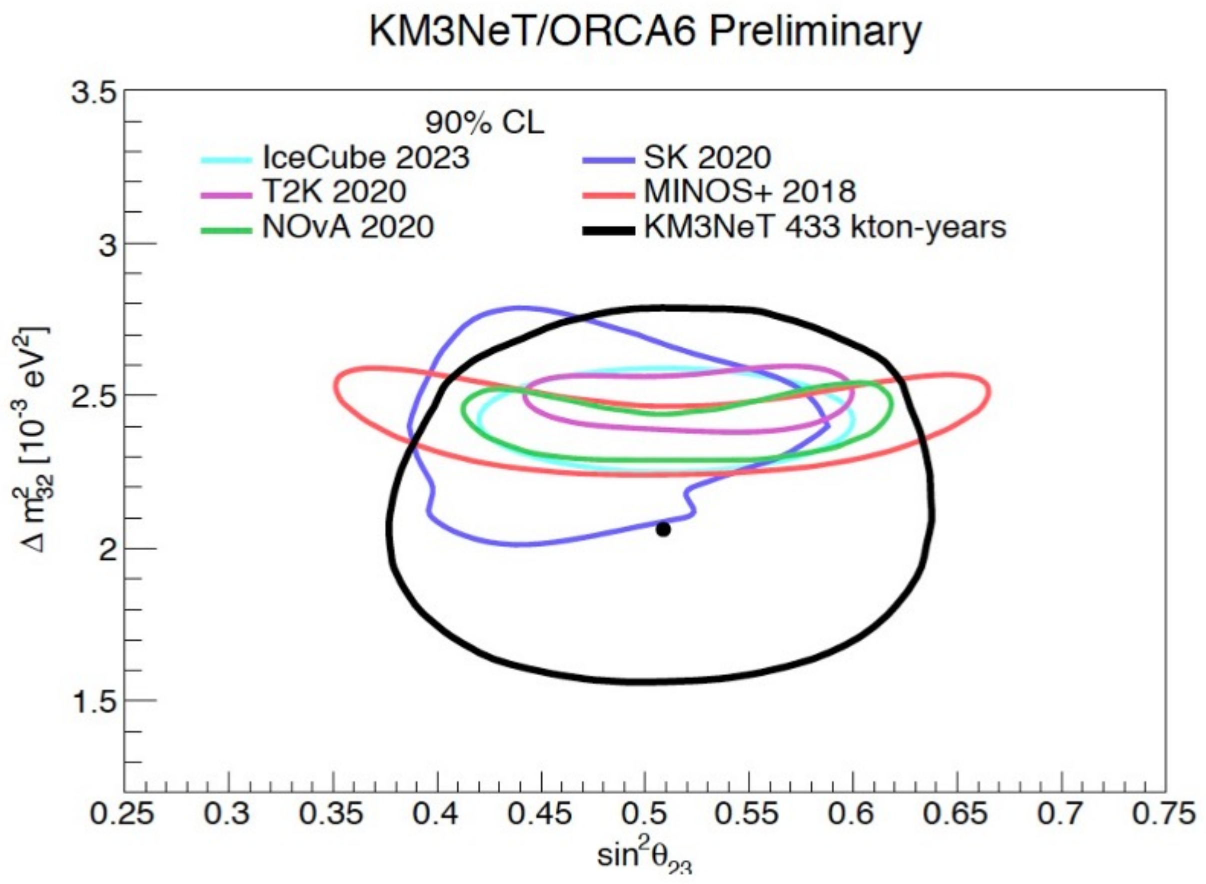
Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

☞ *PoS(ICRC2023)1018 & 1075*

Oscillation studies with KM3NeT/ORCA

ANTARES: No-oscillation hypothesis excluded at 4.6σ
📖 J. High Energ. Phys. (2019) 2019: 113

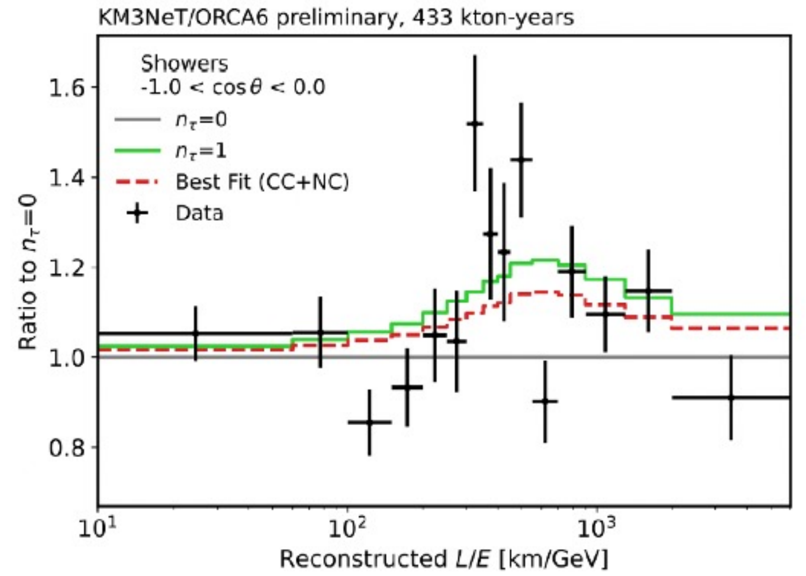
→ Huge improvement with ORCA6 (510 days only)

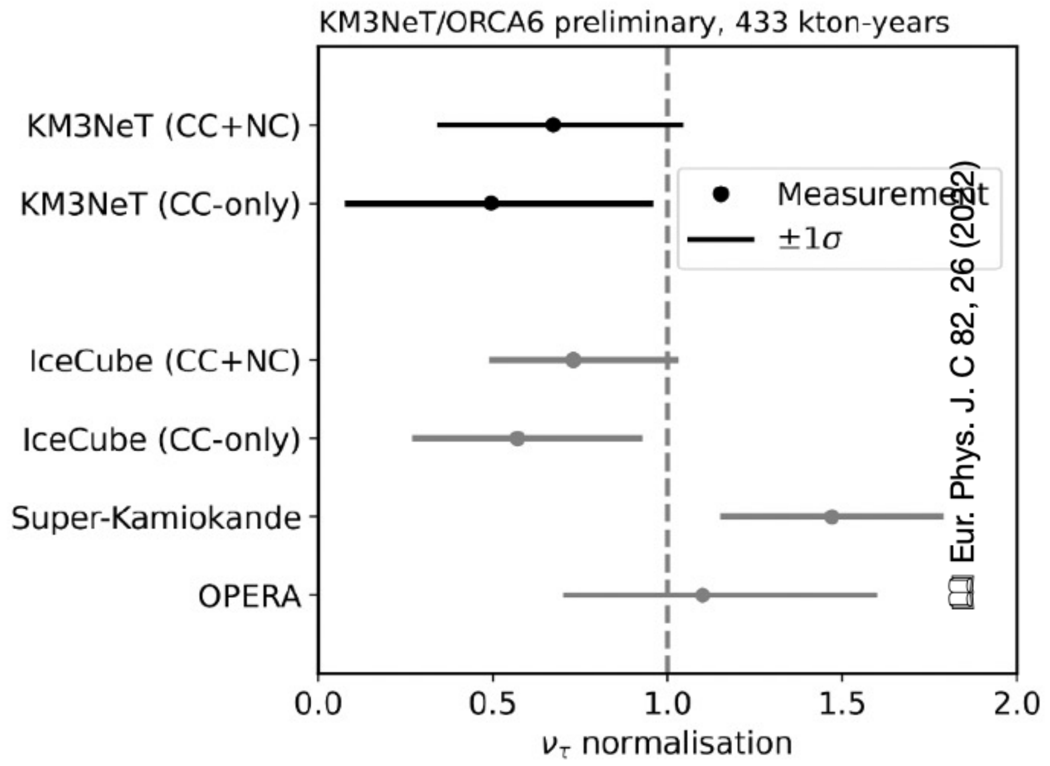


☞ PoS(ICRC2023)996

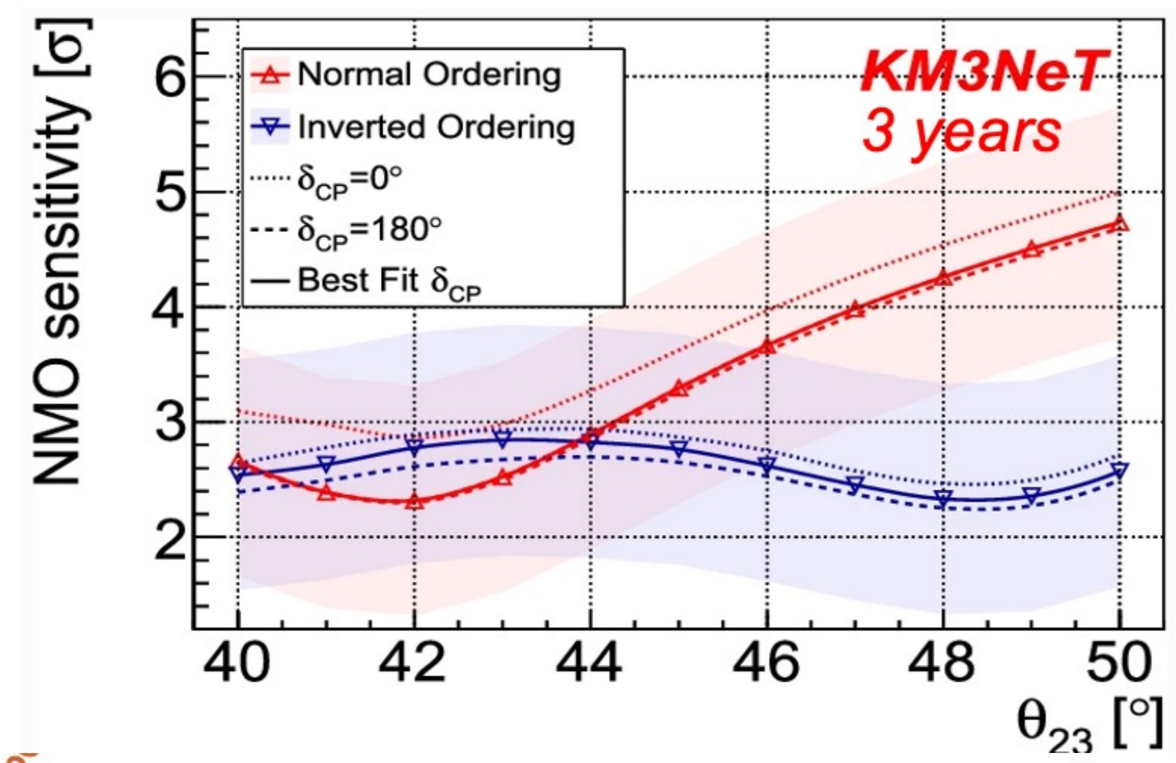
For results on constraints on: ν NSI, ν decoherence, ν decay refer to:
☞ PoS(ICRC2023)998 & PoS(ICRC2023)1025 & PoS(ICRC2023)997

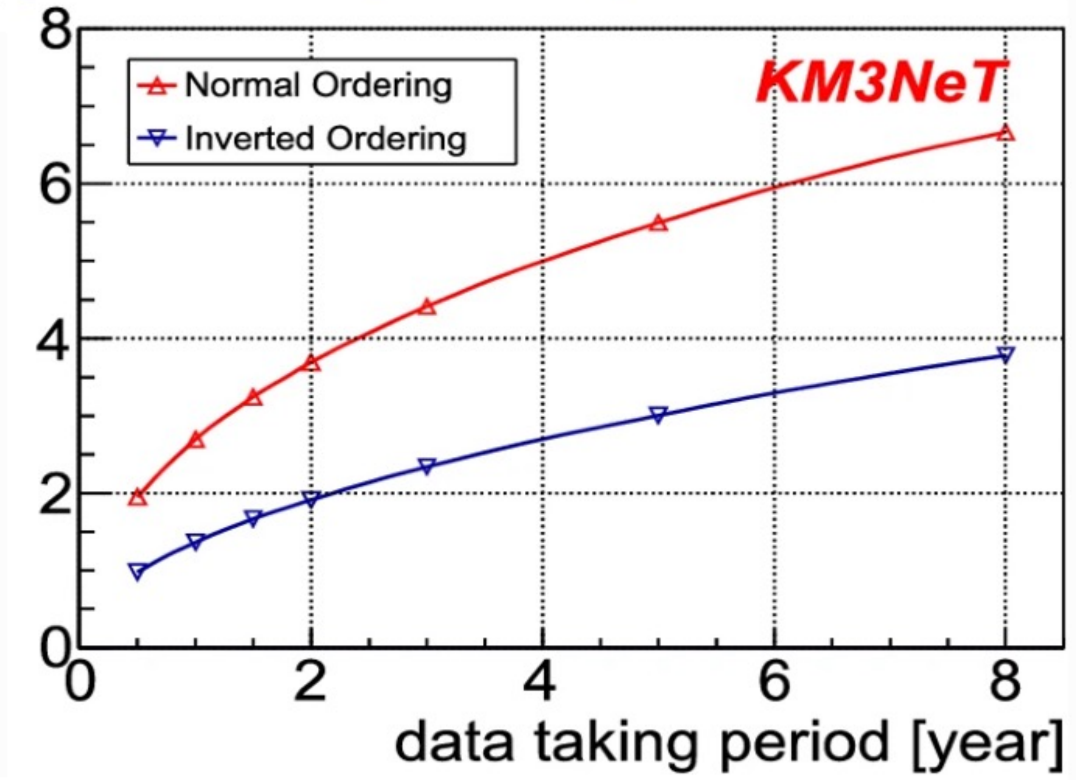
Excess of showers (osc. max.) consistent with tau appearanc-





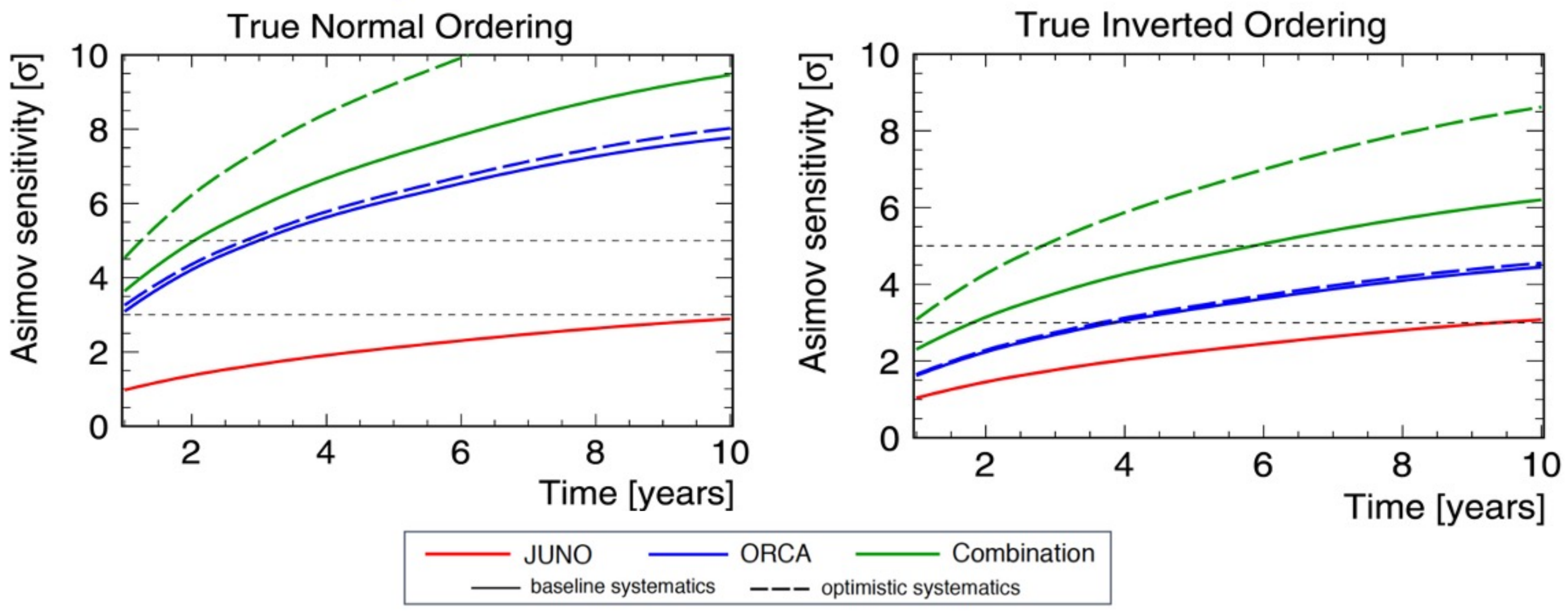
Neutrino Mass Ordering can be measured exploiting Earth matter effect on atmospheric neutrinos





📖 Eur. Phys. J. C 82, 26 (2022)

Combing events with reactor experiment can strongly improve sensitivity

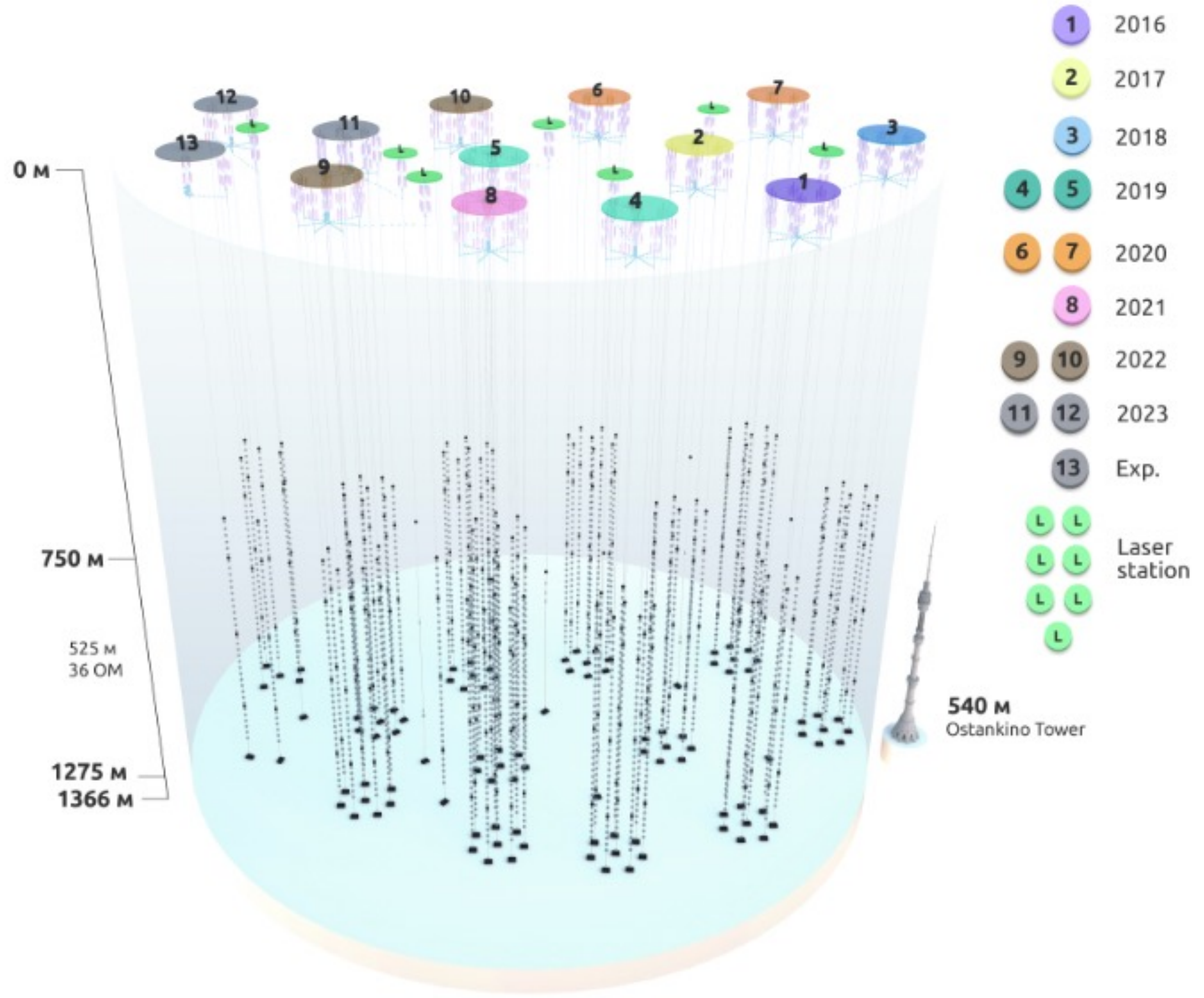


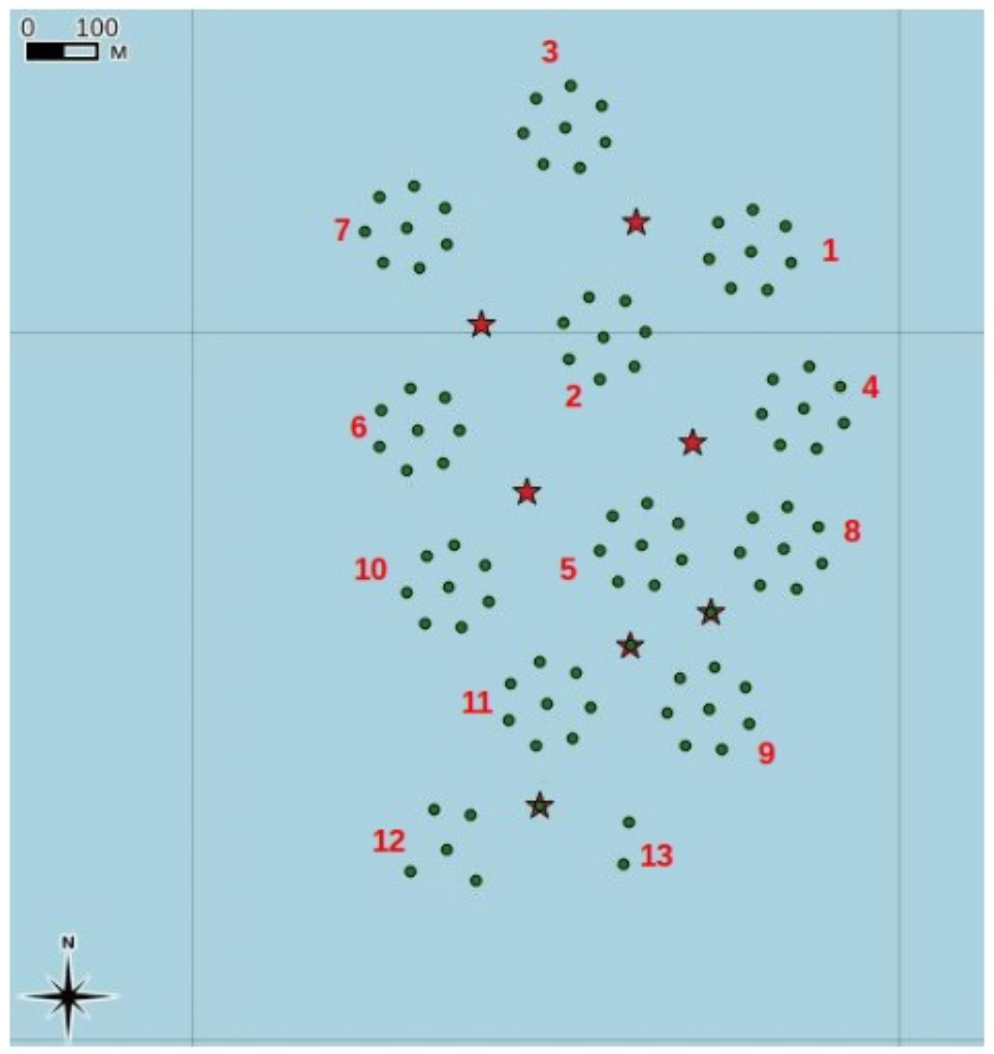
📖 J. High Energ. Phys. 2022, 55 (2022)

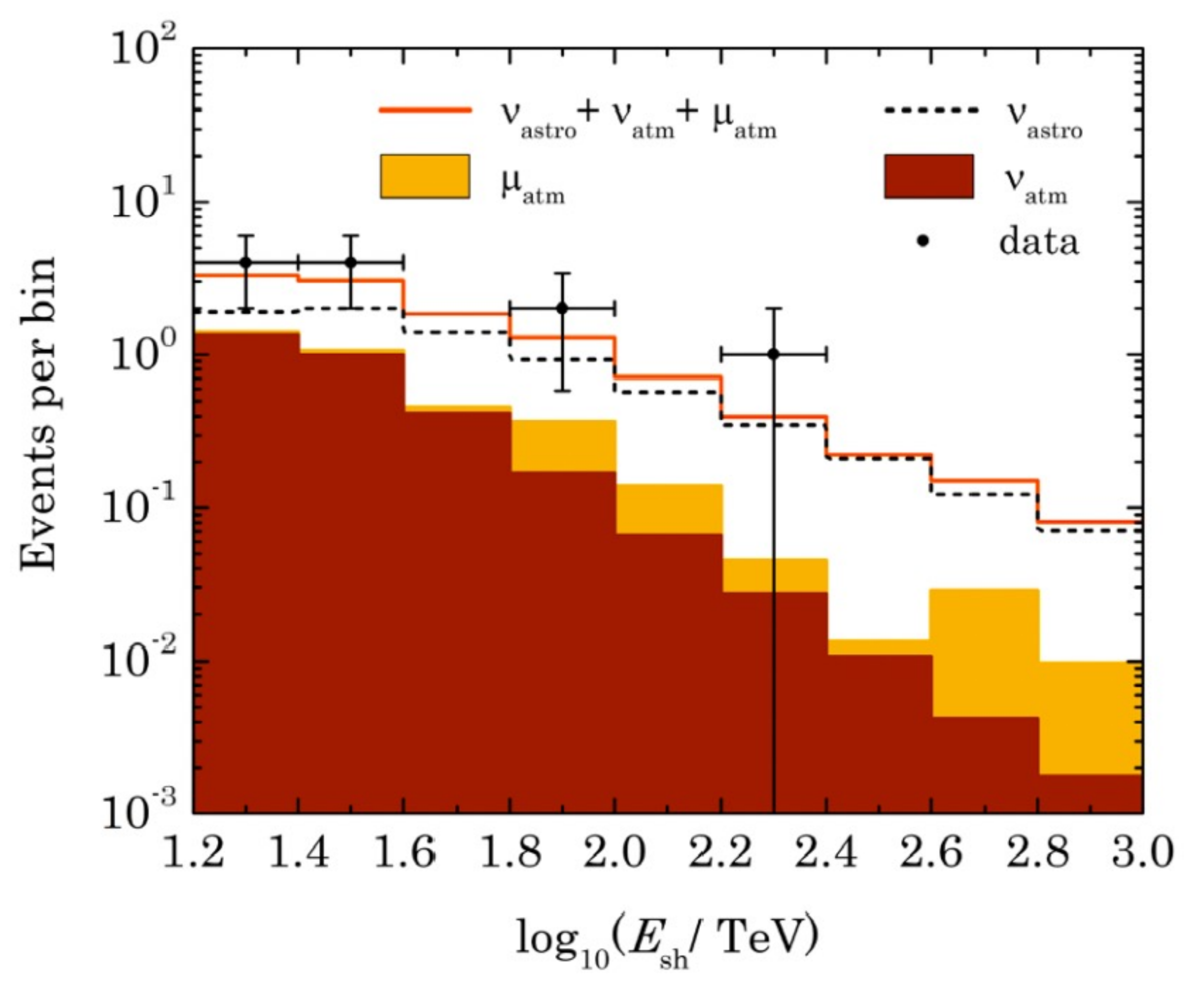
Large neutrino telescope GVD at lake Baikal

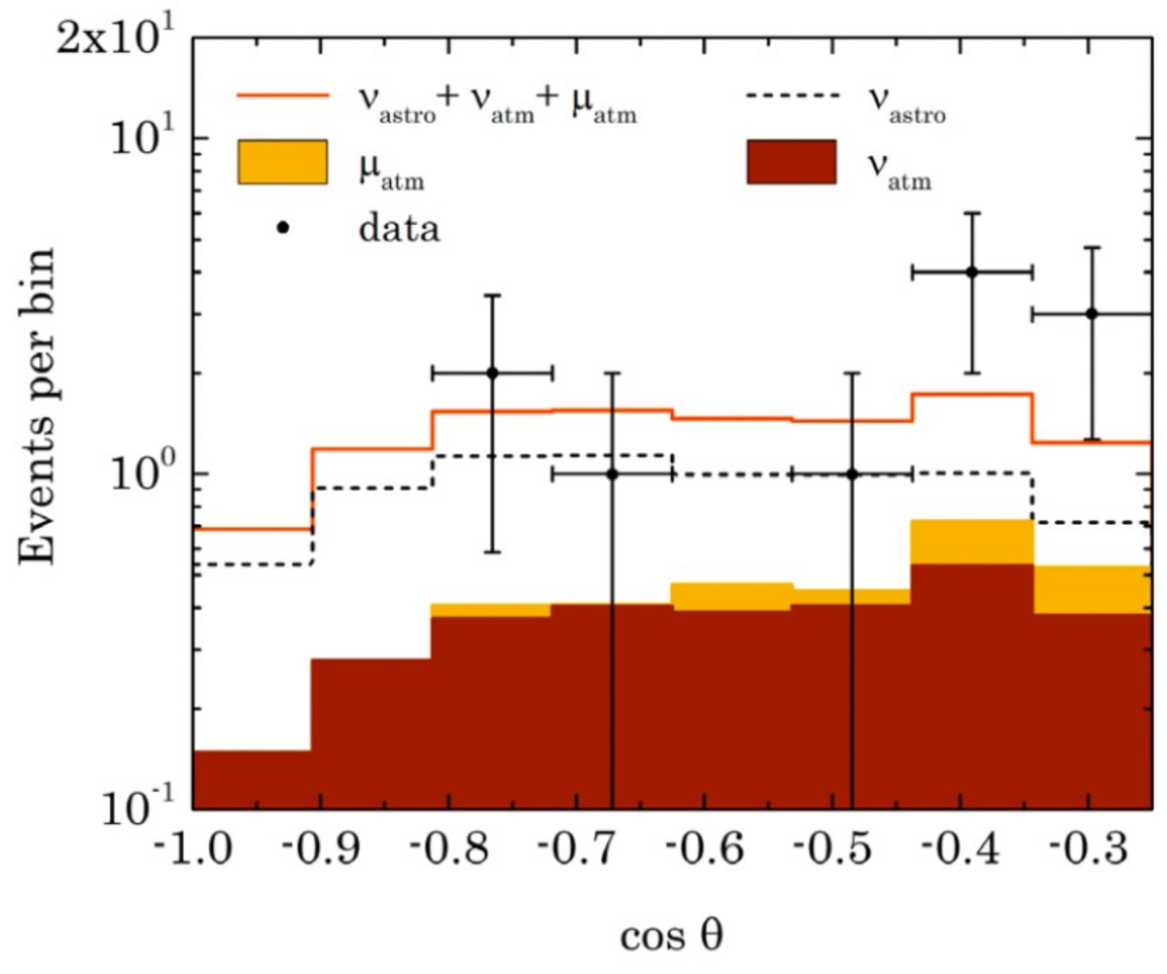
In construction, final volume 1 km3. Depth of lakebed 1366 m. 10’’ PMT Optical Modules

Diffuse neutrino flux search: 11 cascade events observed background only hypothesis excluded at 3.05 sigma level









$$\Phi_0 = 3.04 \text{ and } \gamma_{astro} = 2.58$$

Conclusions

- A lot of exciting results from IceCube, but still many open questions
- IceCube is the first telescope to observe cosmic neutrinos and it provides strong hint on neutrinos sources
- Baikal confirmed IC diffuse flux at 3 sigma level with cascade events
- KM3NeT with its large visibility (including our Galaxy and Galactic Center), high sensitivity and unprecedented angular resolution will give an important boost to neutrino astronomy
- IceCube with KM3NeT and Baikal will ensure full coverage of neutrino sky allowing complete survey for steady and transient phenomena
- A couple of additional future projects, but not (fully) funded and/or in early stage
- Very exciting perspective for neutrino astronomy!

Timeline