Km3NeT

Neutrino Physics and Astronomy with Km3NeT

ISAPP School
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Outline

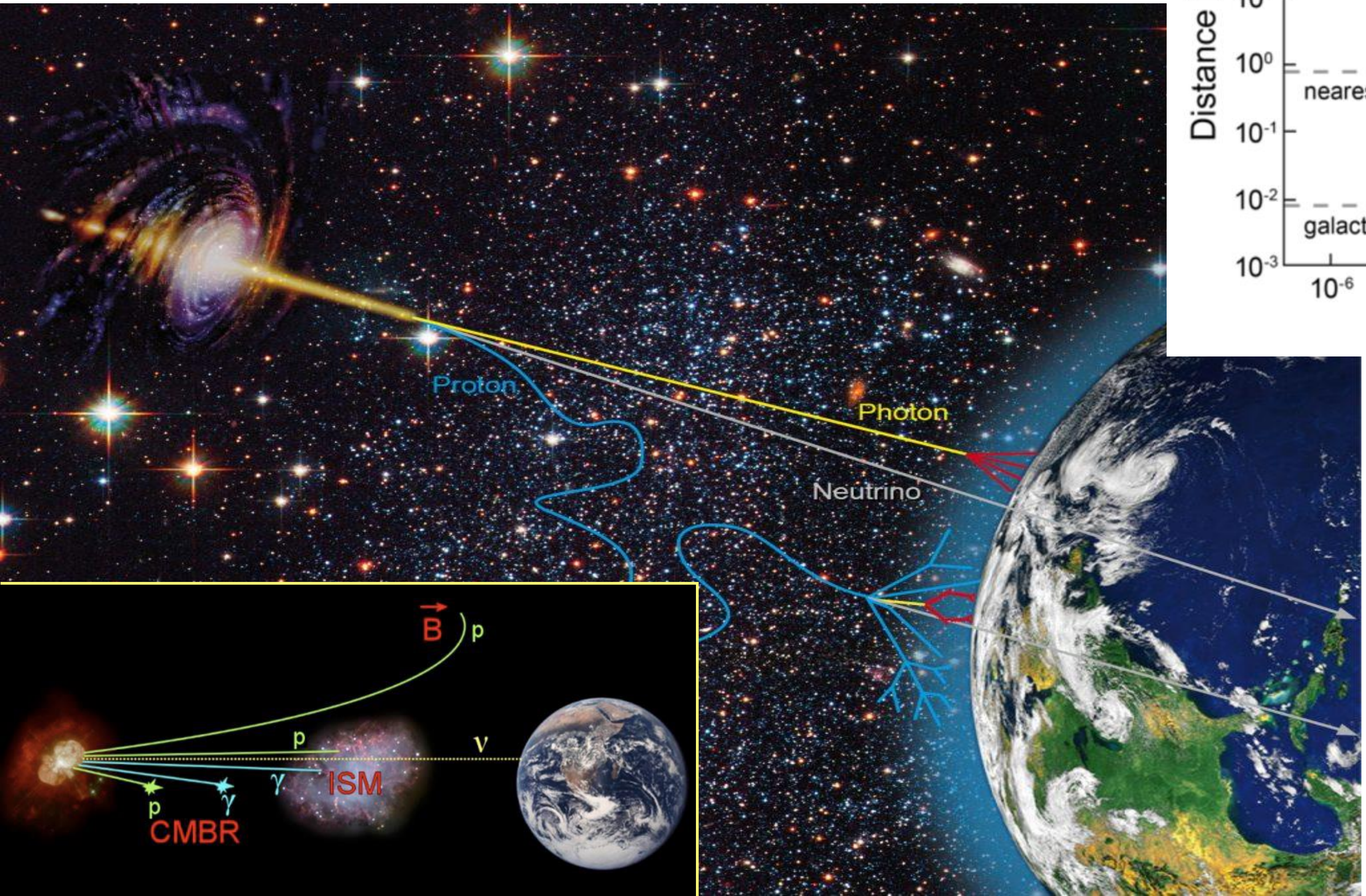
The scope of this talk is getting an understanding of

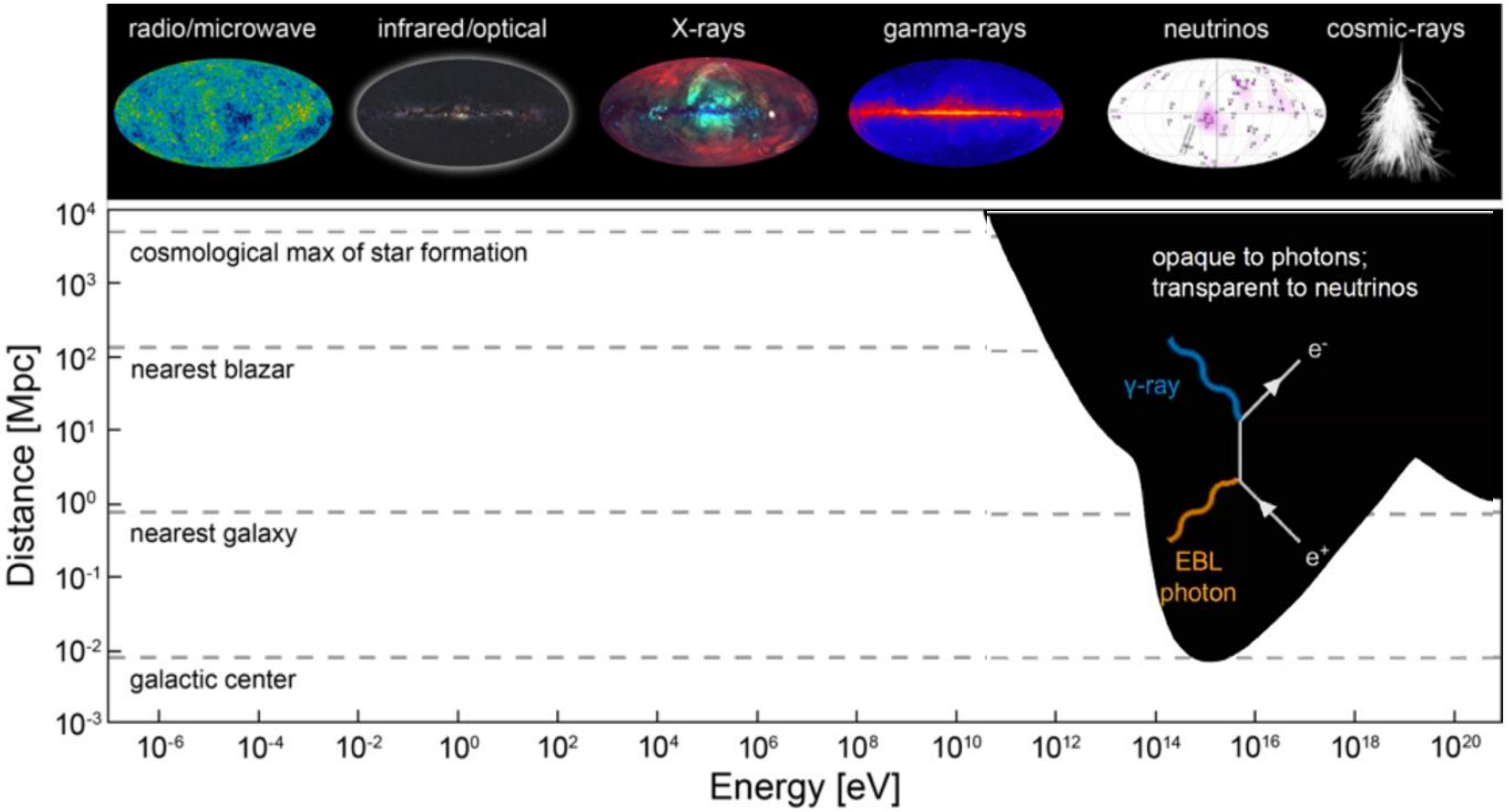
- Neutrino telescopes → physics goals
  → what they do
- Km3Net → what it does
  → the involved technologies
  → how it works and its performances
- ARCA UHE → what we have seen (KM3-230213A)
  → how it was seen

Introduction

A new window into the Universe

- Photons can be absorbed by ISM
- Charged are affected by B-fields and interact w/ CMB





Galactic

Supernovae, SN relics, Pulsar Wind Nebulae, Dark Matter particle annihilation?

Extragalactic

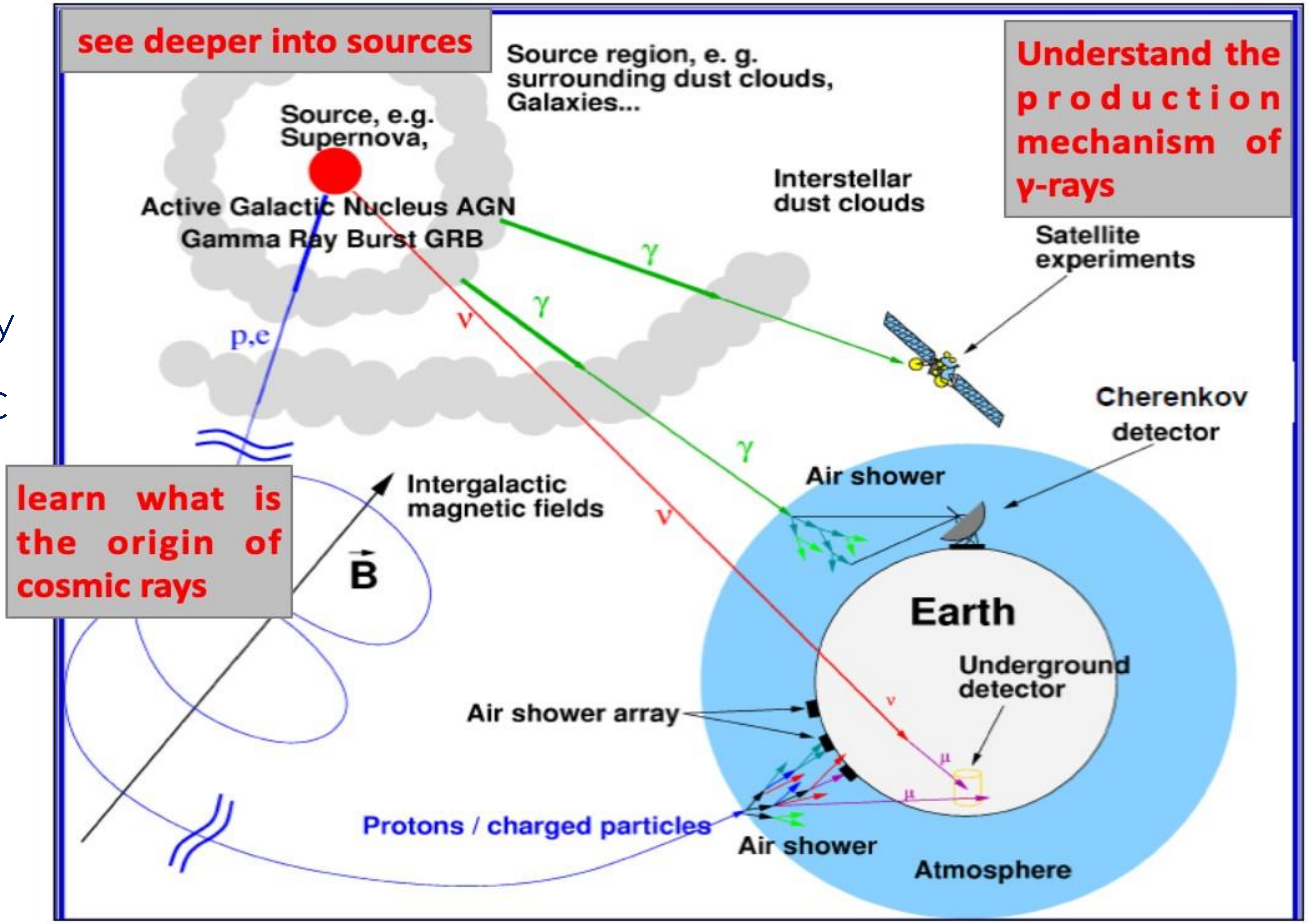
Active Galactic Nuclei, Black hole mergers?

Multi-messenger approach

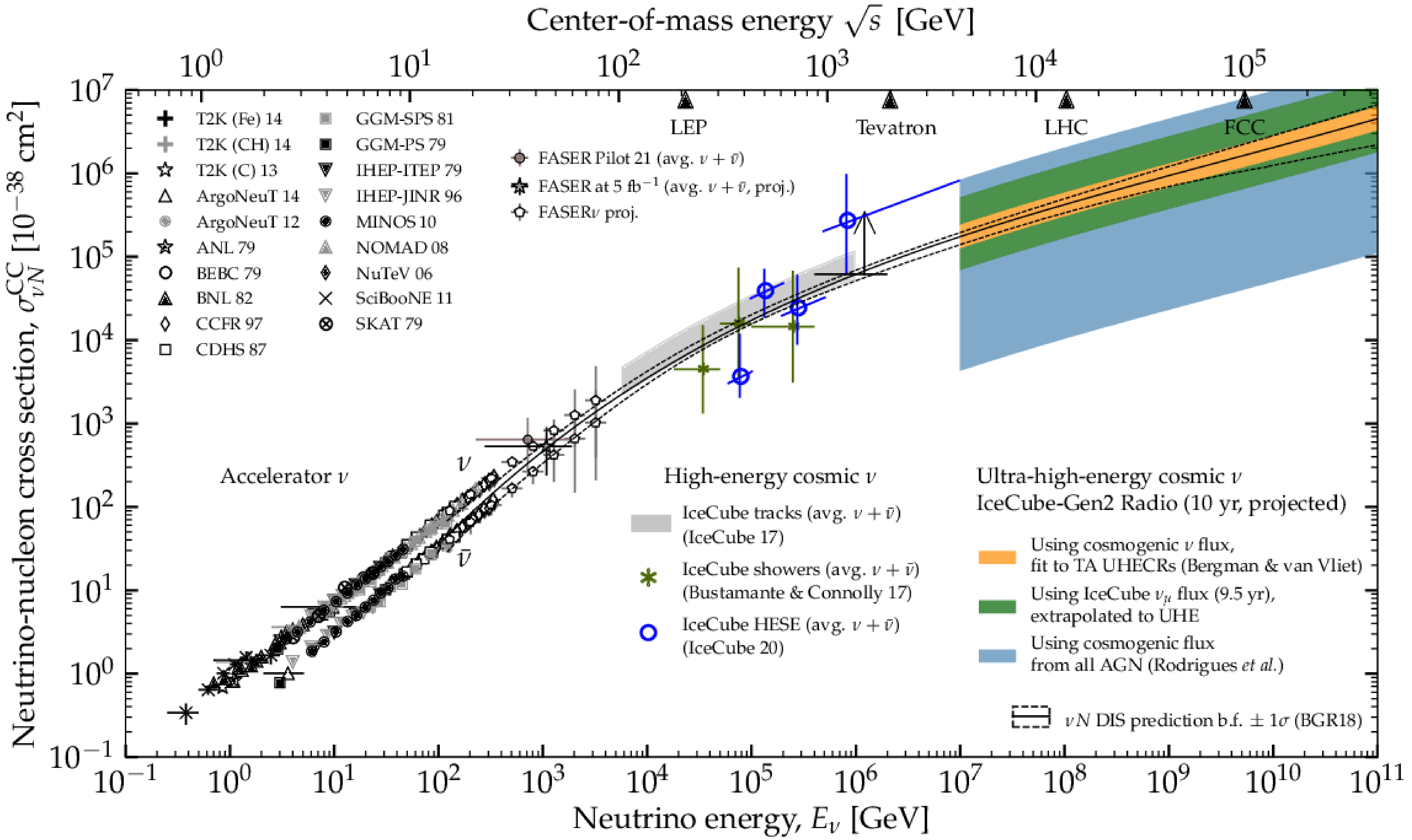
Multi-messenger astronomy is becoming the most sensitive approach to astrophysical event detection, especially for transient events

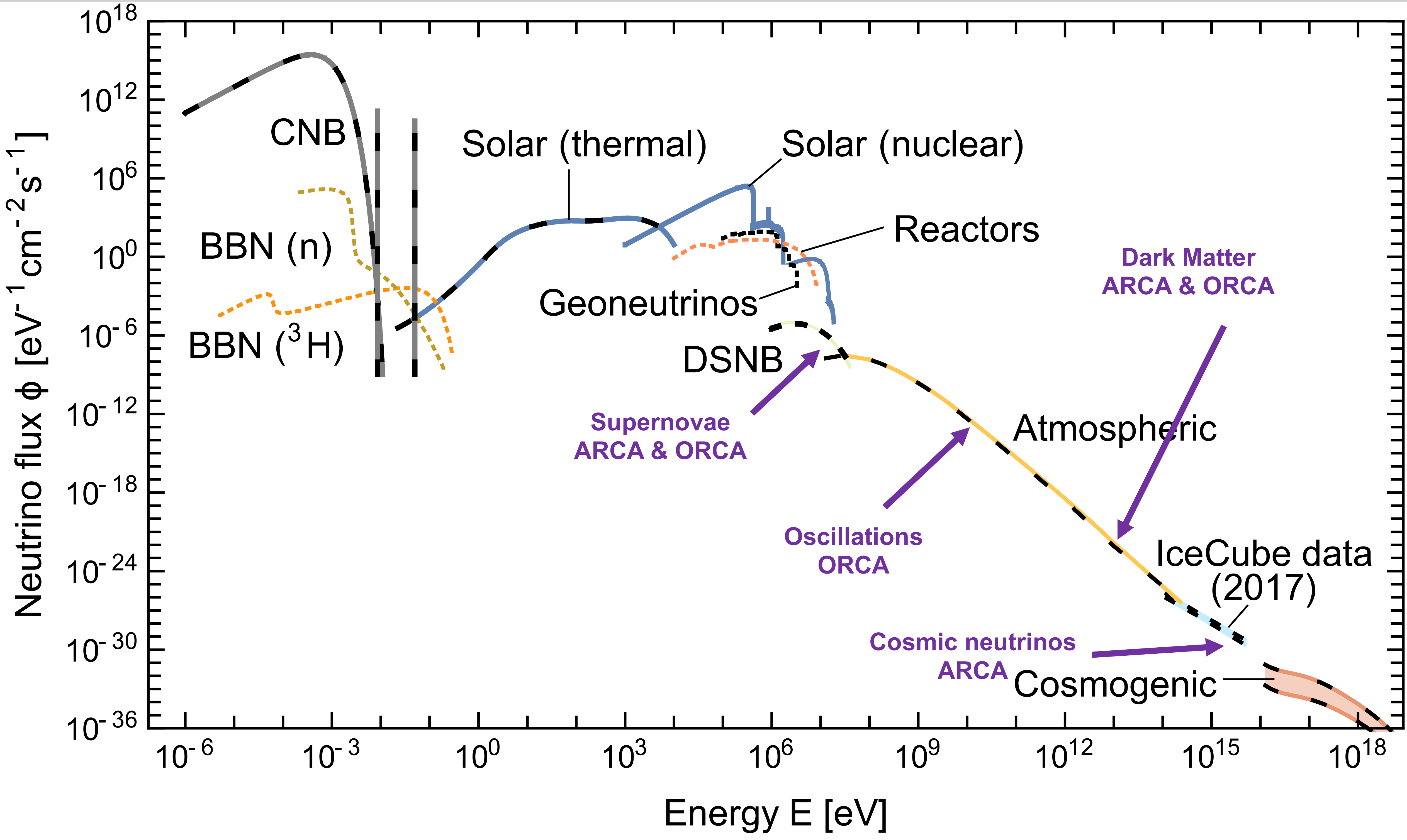
→ KM3NeT actively monitors and analyses a variety of external triggers in real-time, including alerts due to IceCube neutrinos, Fermi/Swift GRB, HAWC gamma-ray transients, LIGO-Virgo-KAGRA gravitational waves, SNEWS neutrino alerts, and others

→ KM3NeT has a real-time analysis framework making it possible to send HE neutrino alerts

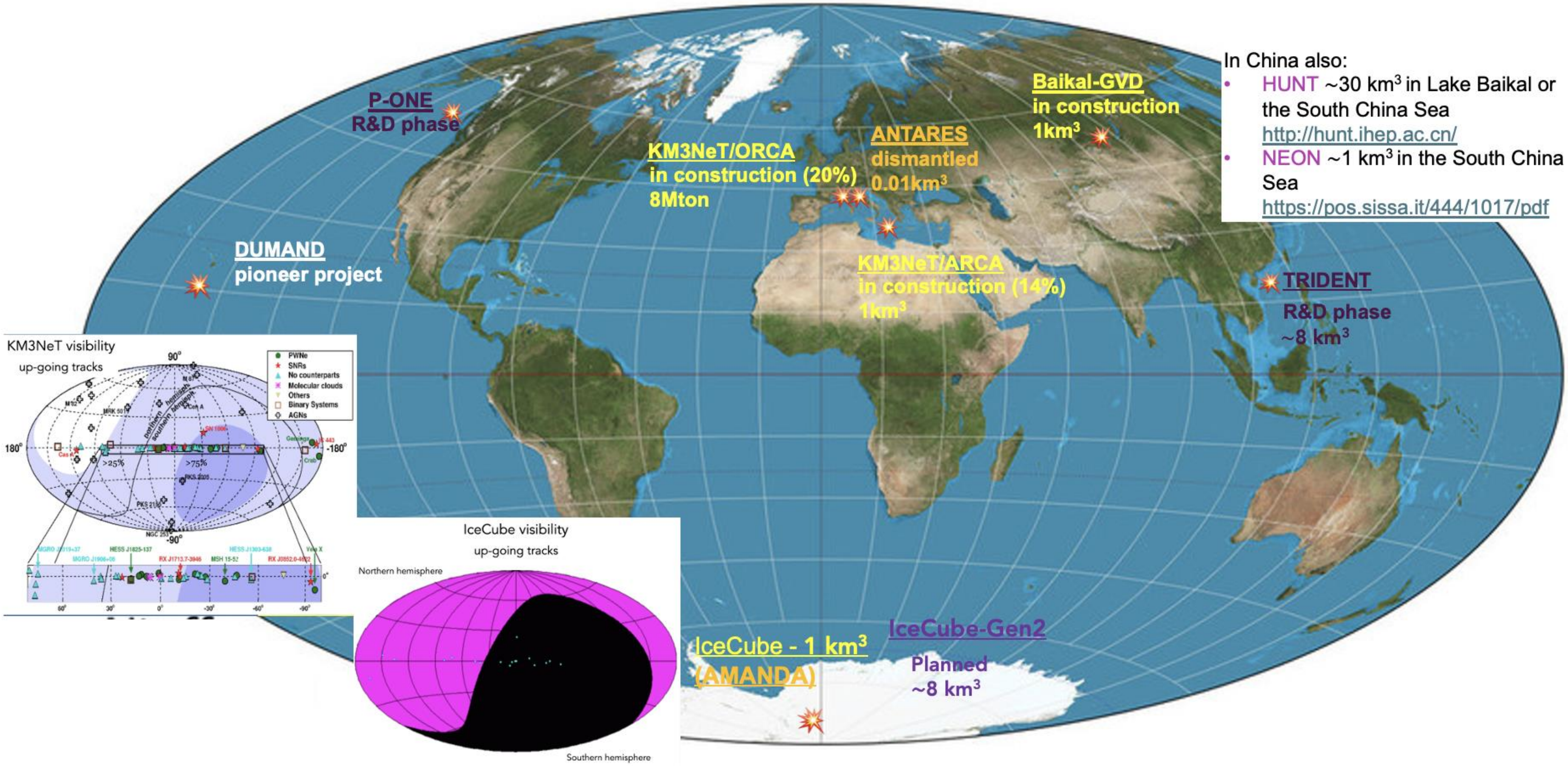


Neutrino detection





Underwater telescopes in the world



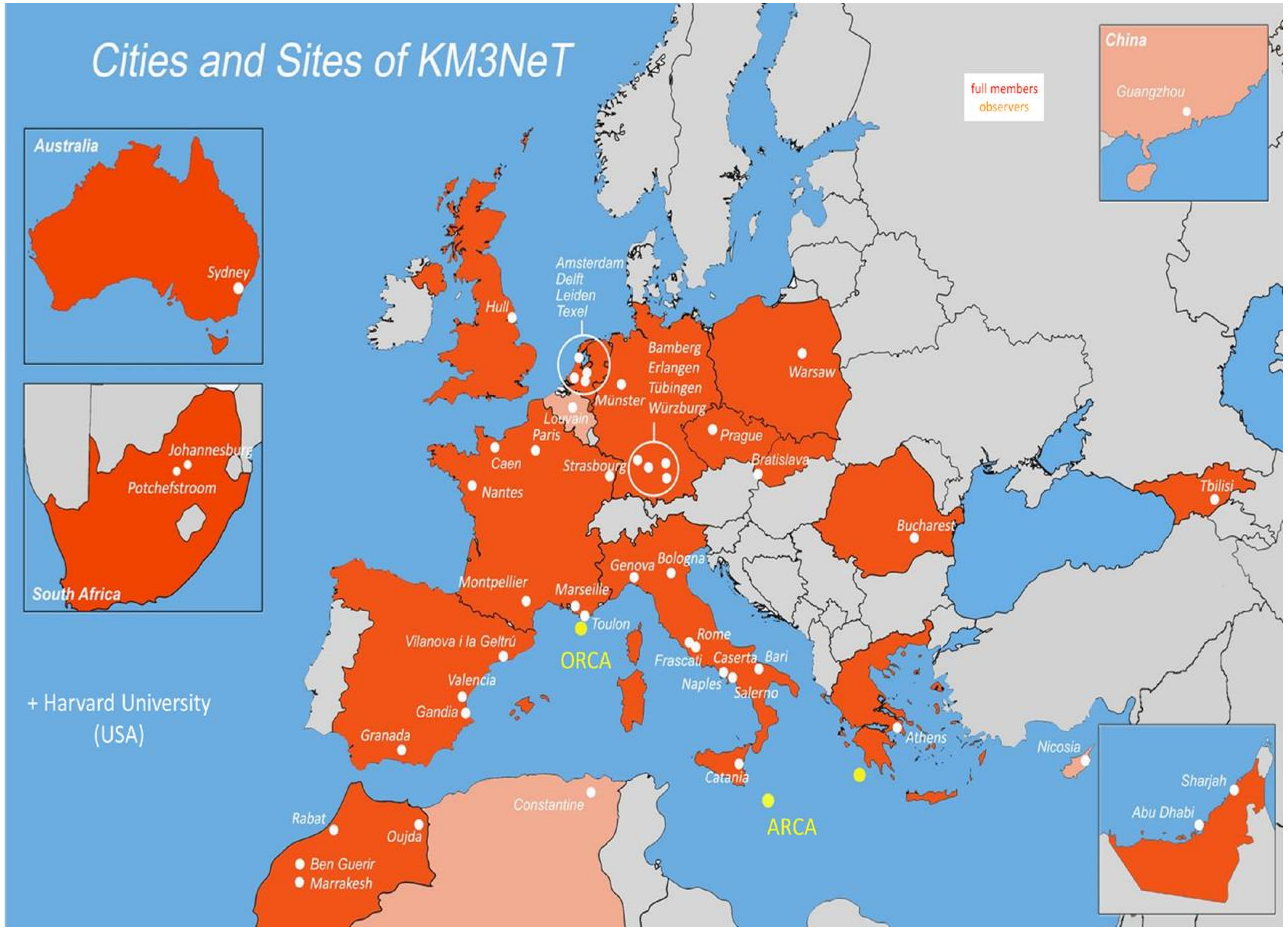
In China also:

- HUNT ~30 km^3 in Lake Baikal or the South China Sea http://hunt.ihep.ac.cn/
- NEON ~1 km^3 in the South China Sea https://pos.sissa.it/444/1017/pdf

Km3NeT

Km3NeT

KM3NeT is a Mediterranean research infrastructure hosting two neutrino detectors and instrumentations for earth and sea sciences



65+ institutes, 22 countries, 5 continents

Km3NeT/ARCA

Astroparticle Research with Cosmics in the Abyss

→ Observation of high energy (GeV ÷ PeV) neutrino sources with a telescope offshore Capo Passero (Sicily-Italy) at a depth of ~3500 m

Km3NeT/ORCA

Oscillation Research with Cosmics in the Abyss

→Neutrino oscillations with a detector offshore Toulon (France) able to detect neutrinos of tens of GeV at a depth of ~ 2500 m

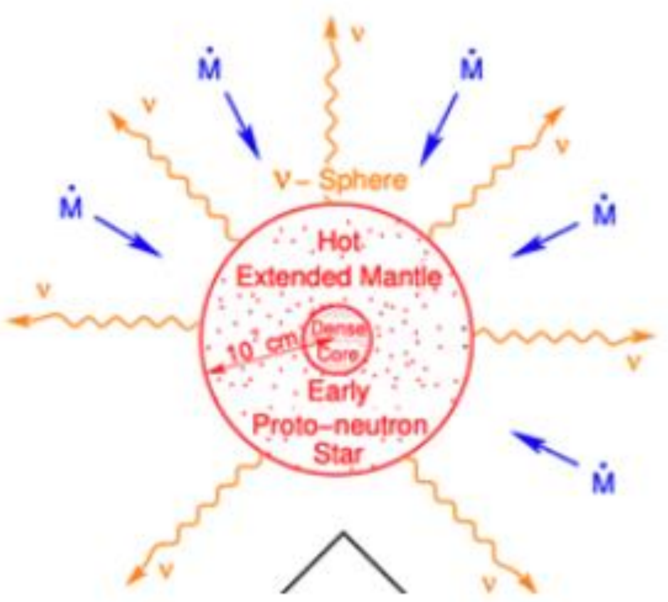
Physics programme

- Cosmic neutrinos
- Intense multi-messenger activity
- Atmospheric neutrino oscillations:
  - Oscillation parameters
  - Neutrino mass hierarchy
  - Non-standard physics
  - Particle physics properties
- Indirect search of Dark Matter
- Exotic particles
- Beyond the SM Physics

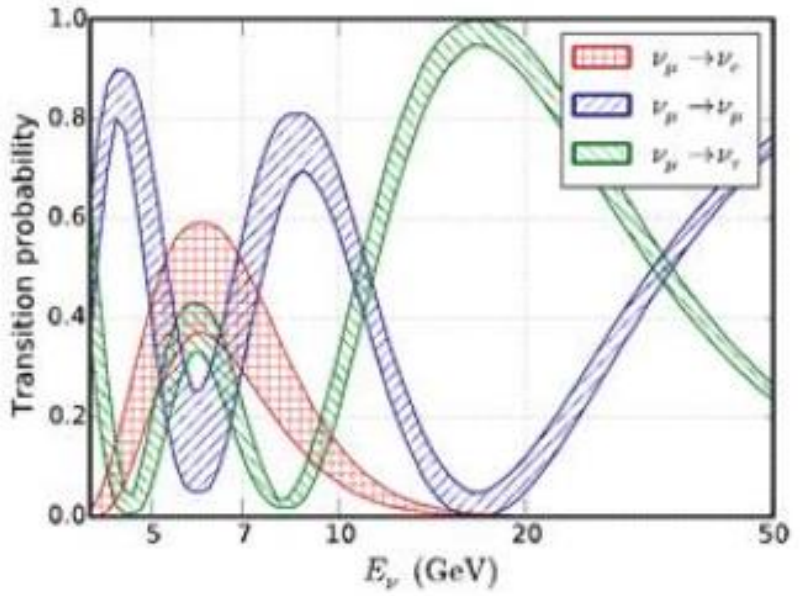
+ oceanology, biology, seismology and more!

Low Energy ~ MeV	Low Energy > 10 GeV	Medium Energy 10 GeV < E_ν < 10 TeV	High Energy E_ν > 1 TeV

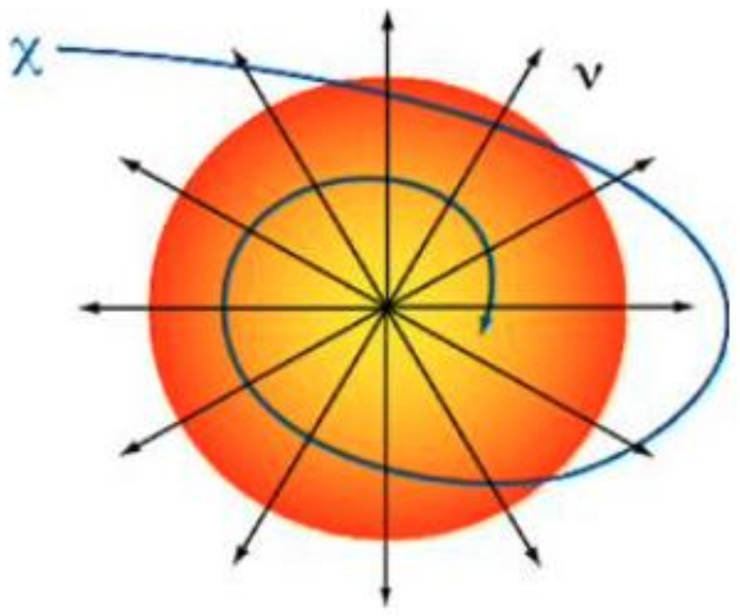
E



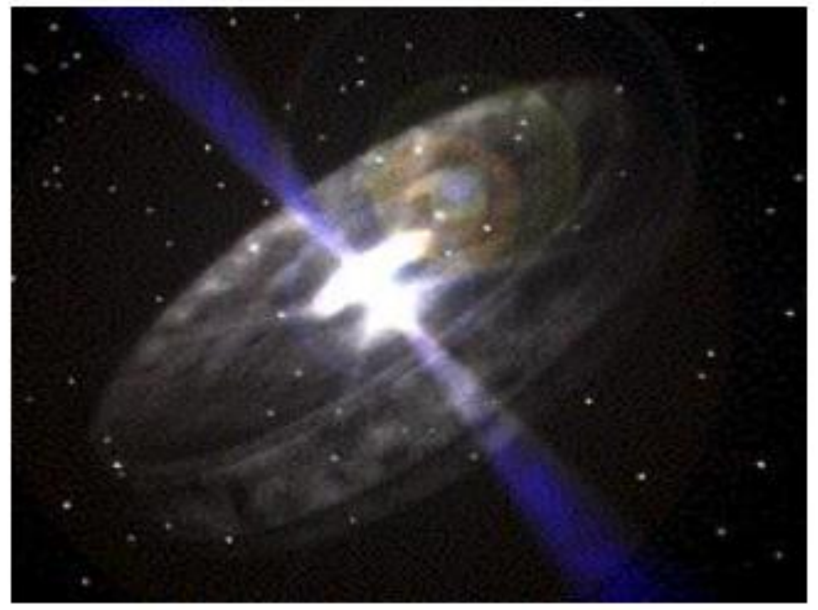
CCSN detection



ν oscillations



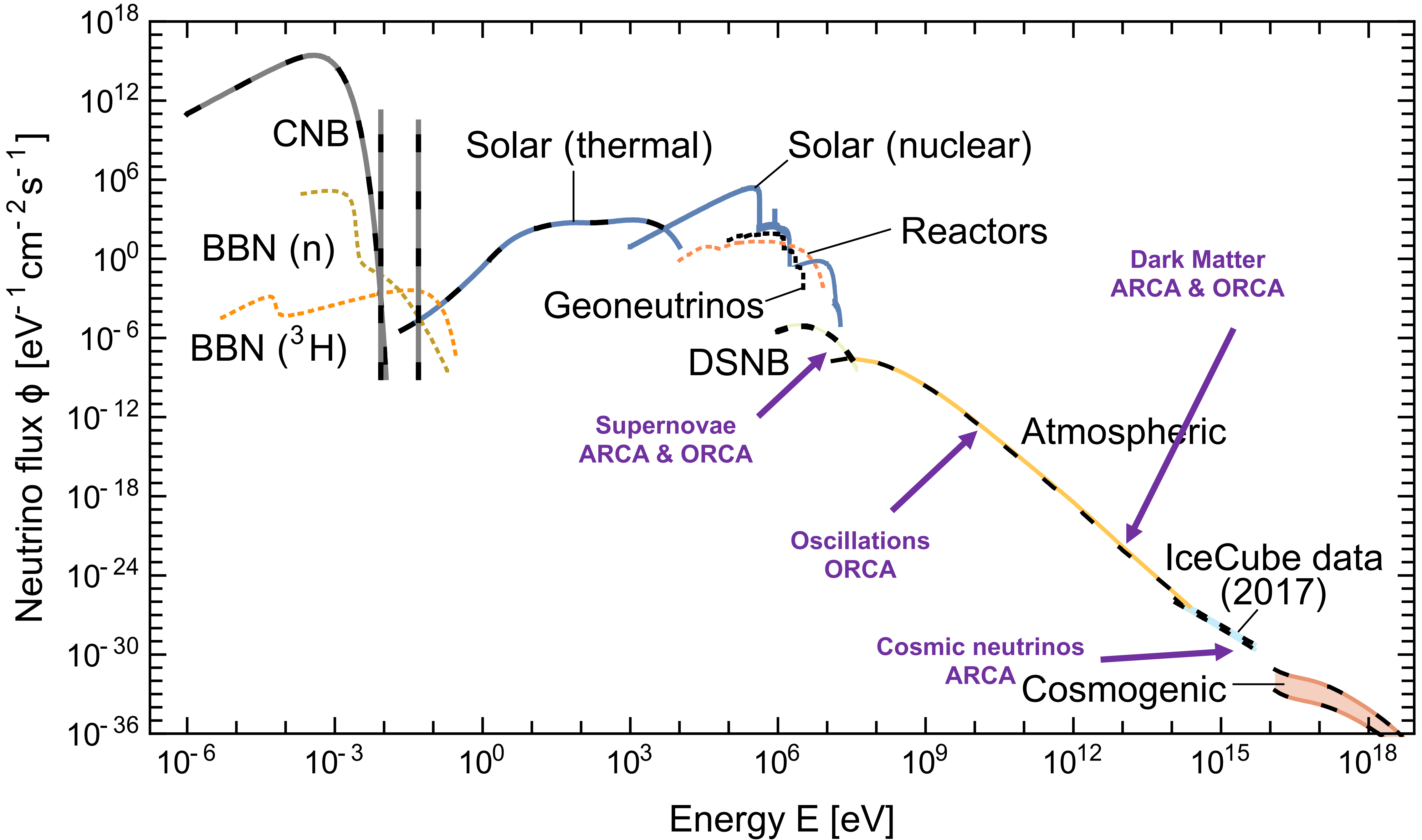
dark matter + exotics

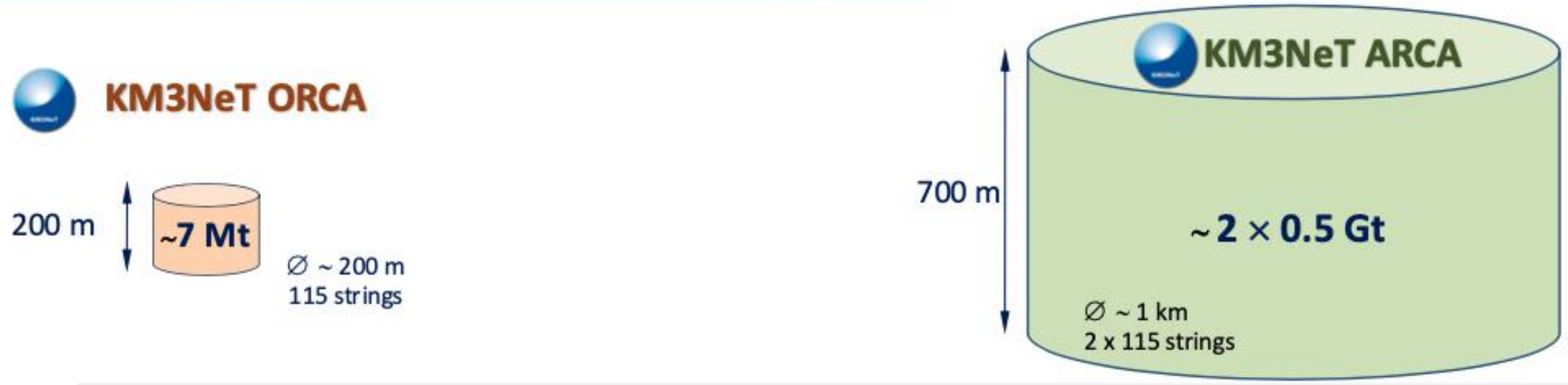


Cosmic ν

ARCA (CCSN detection) — ARCA (dark matter + exotics) — ARCA (Cosmic ν)

ORCA (CCSN detection) — ORCA (ν oscillations) — ORCA (dark matter + exotics)





The idea

Exploit Cherenkov light to detect (and track) charged particles ensuing neutrino interactions in large masses of instrumented water

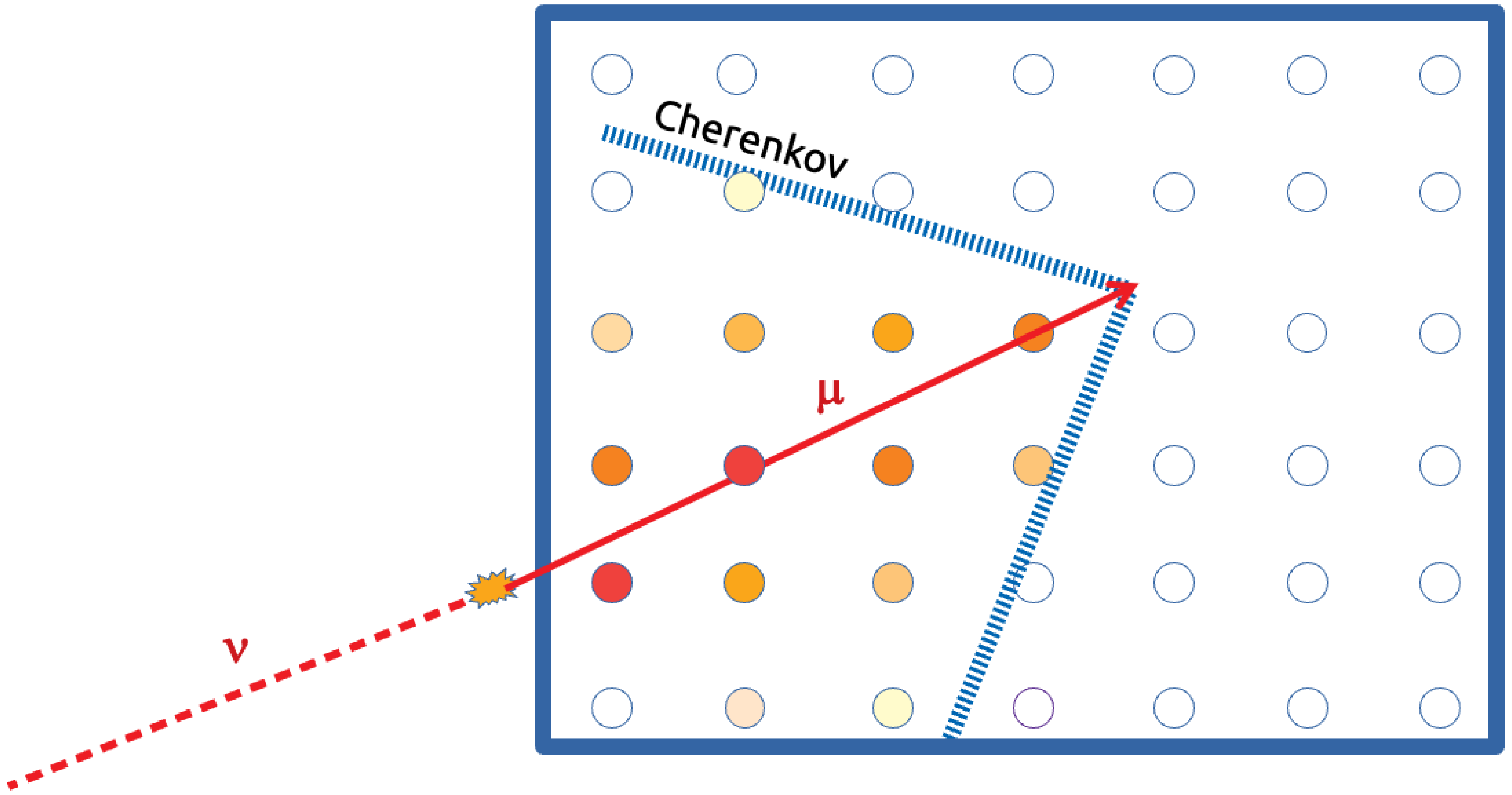
Pavel A. Cherenkov
1904-1990

Moisey Markov, 1908-1994

Bruno Pontecorvo 1913-1993

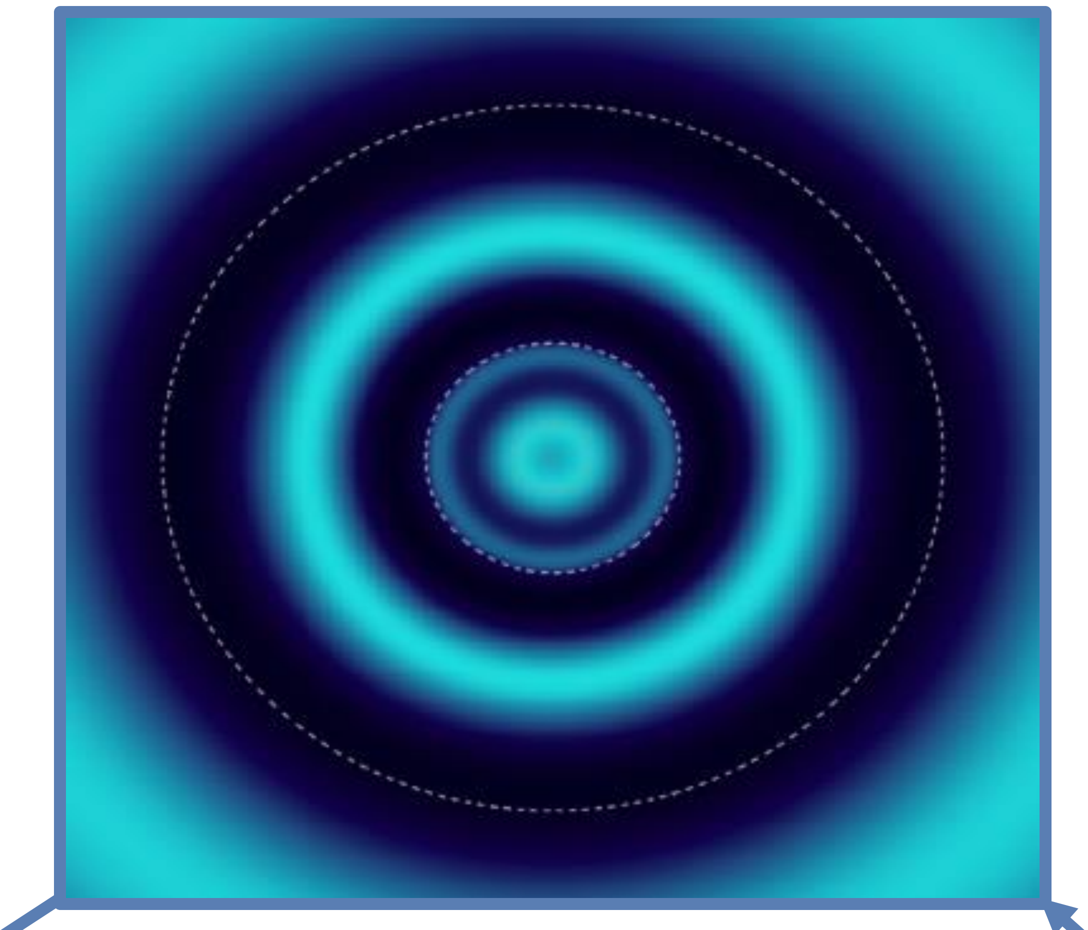
M. Markov:
"Proponiamo di installare rivelatori in profondità in un lago o in mare e di determinare la direzione delle particelle cariche con l'aiuto della radiazione Cherenkov."

1960, Rochester Conference

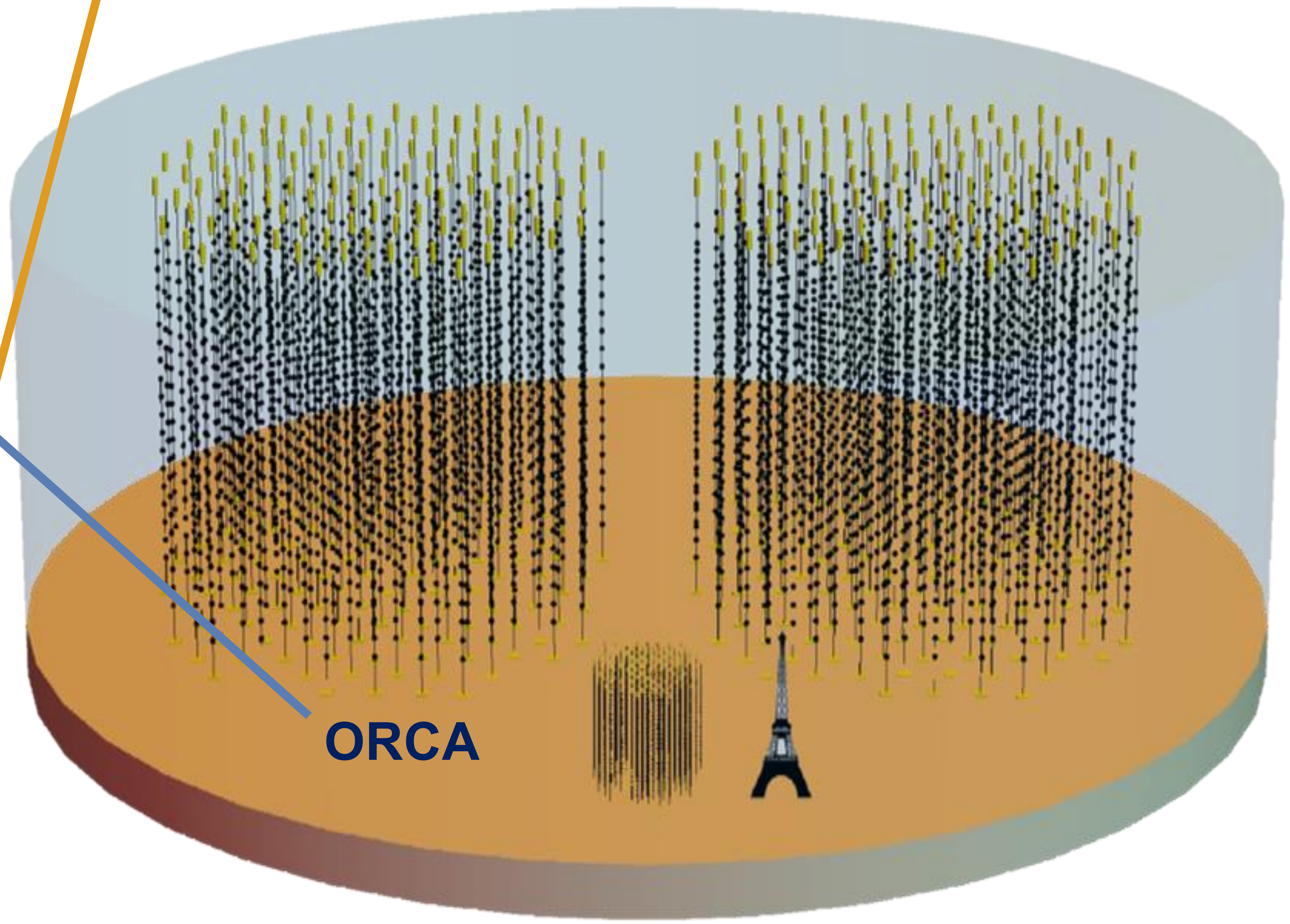


ARCA and ORCA

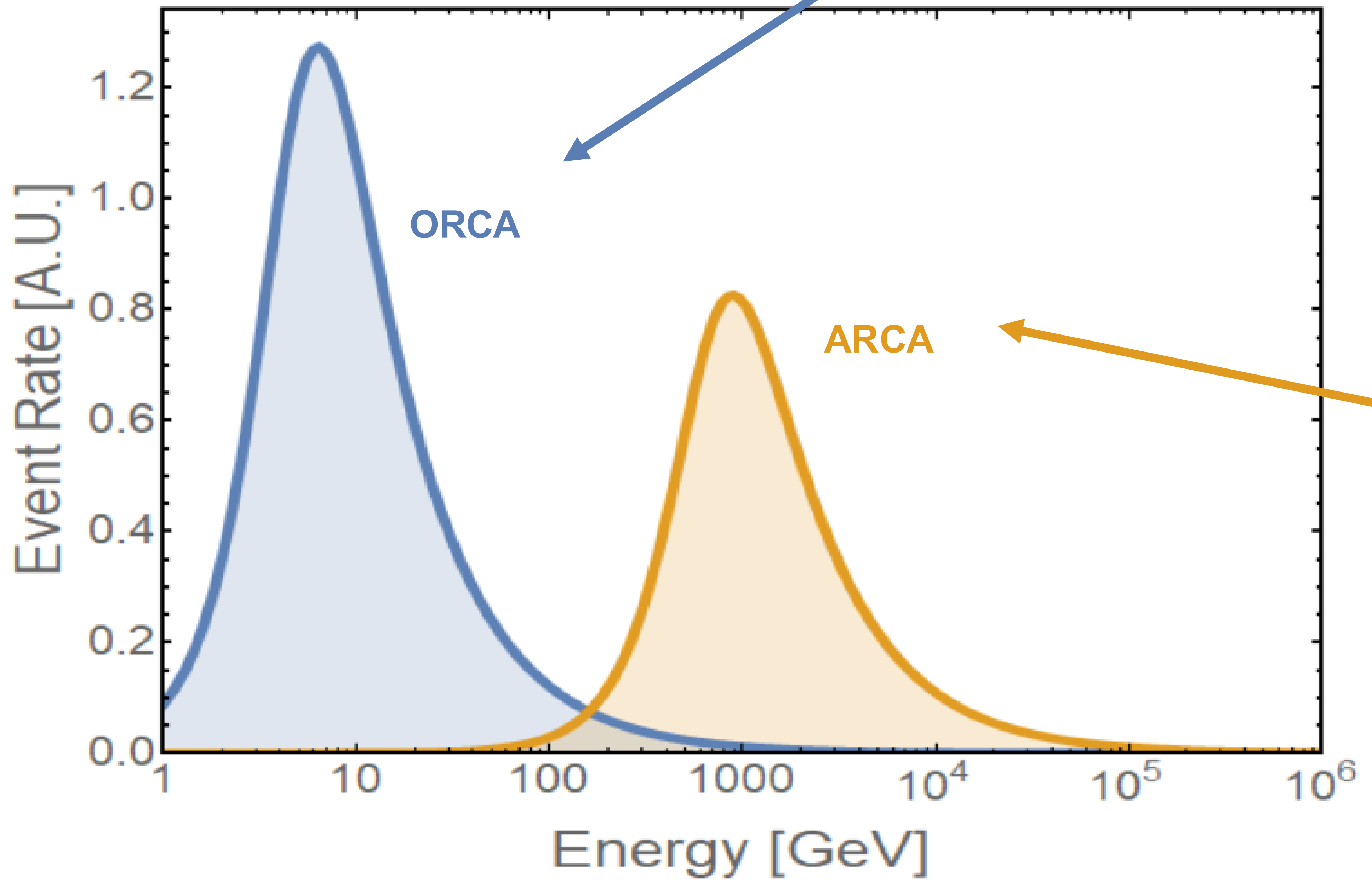
	ARCA	ORCA
Location	Sicily (IT)	Toulon (FR)
Depth	3450m	2450m
No. of DUs	2 x 115	115
DU horizontal spacing	90 m	20 m
DOM Vertical Spacing	36 m	9 m
DOMs/DU	18	18
PMTs/DOM	31	31
Instrumented water mass	1 Gton	7 Mton
DUs deployed	**21**	**18**

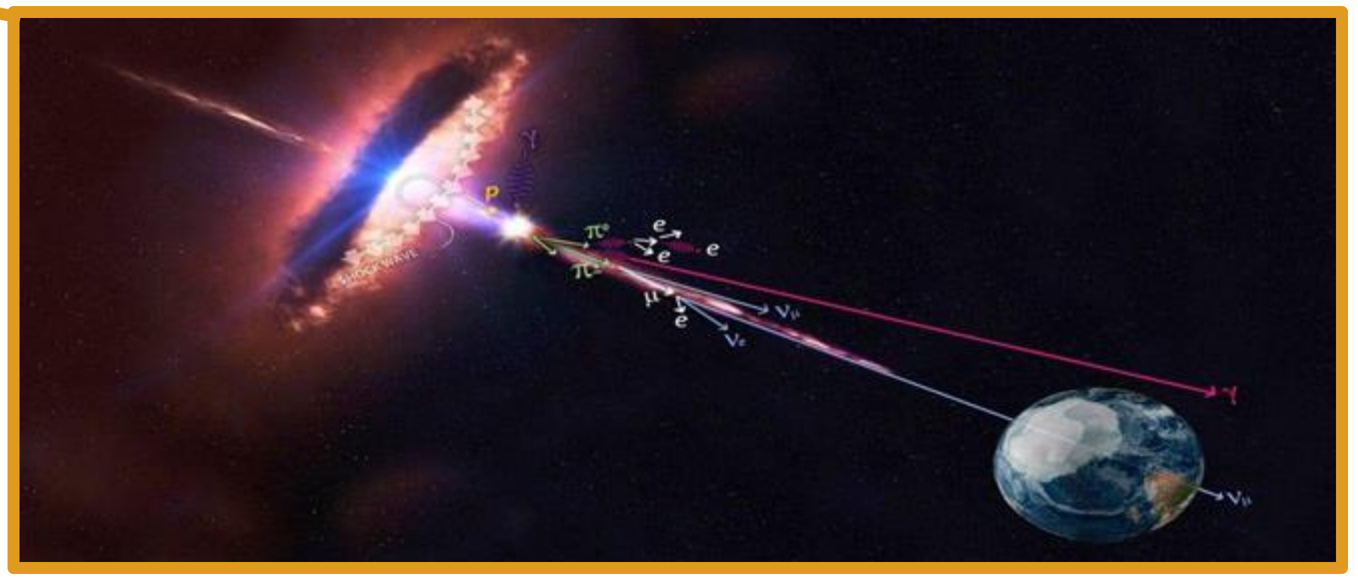


ARCA → 36m vert. x 90m horiz. Spacing → TeV-PeV

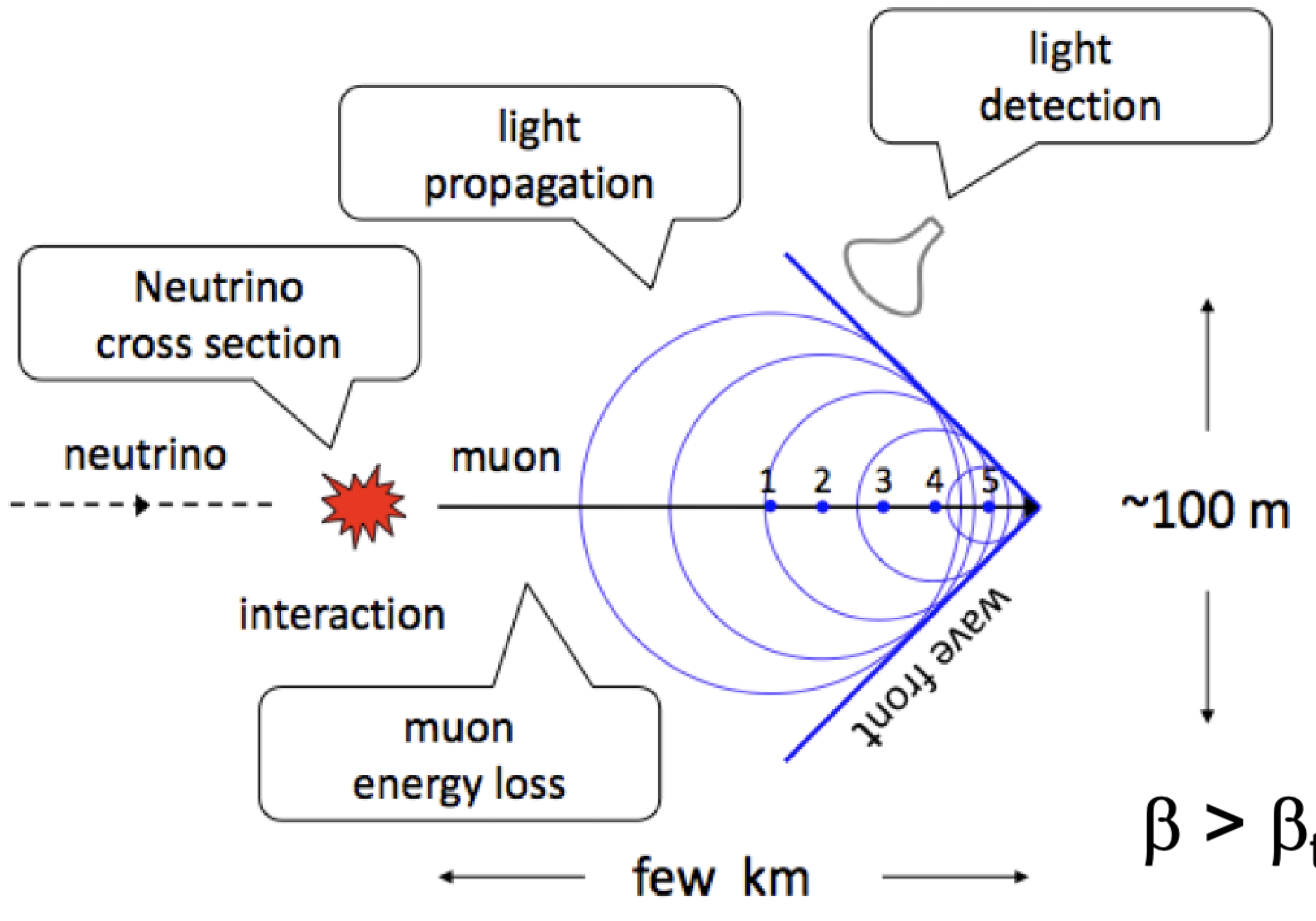


ORCA → 9m vert. x 20m horiz. Spacing → GeV-TeV





Cherenkov emission and propagation



$\beta > \beta_{thr} = 1/n$

Cherenkov emission

Electromagnetic radiation emitted when a charged particle traverses a medium with a velocity higher than the phase velocity of the light in the medium

$$\frac{d^2N}{d\lambda dx} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right) \qquad v > \frac{c}{n}$$

The number of Cherenkov photons N emitted by a charged particle of charge ze per unit wavelength interval dλ and unit distance travelled dx

The number of photons in the wavelength between 300 and 600 nm and distance unit:

$$\frac{dN}{dx} = 76500 \cdot \sin^2\theta_{ch} \approx 34500\, fotoni/m$$

High numbers of photons at low wavelength (blue)

Huge amount of photons

Photons emitted at θ_{ch} w.r.t the track direction

$$\cos\theta_{ch} = \frac{1}{\beta n}$$

n water/ice refractive index

$$n = 1.35 \qquad \theta_{ch} = 42.2°$$

Emission angle defined

Cherenkov emission and propagation

Ilya M. Frank
1908 -1990

Igor Tamm
1895 -1971

Frank-Tamm formula

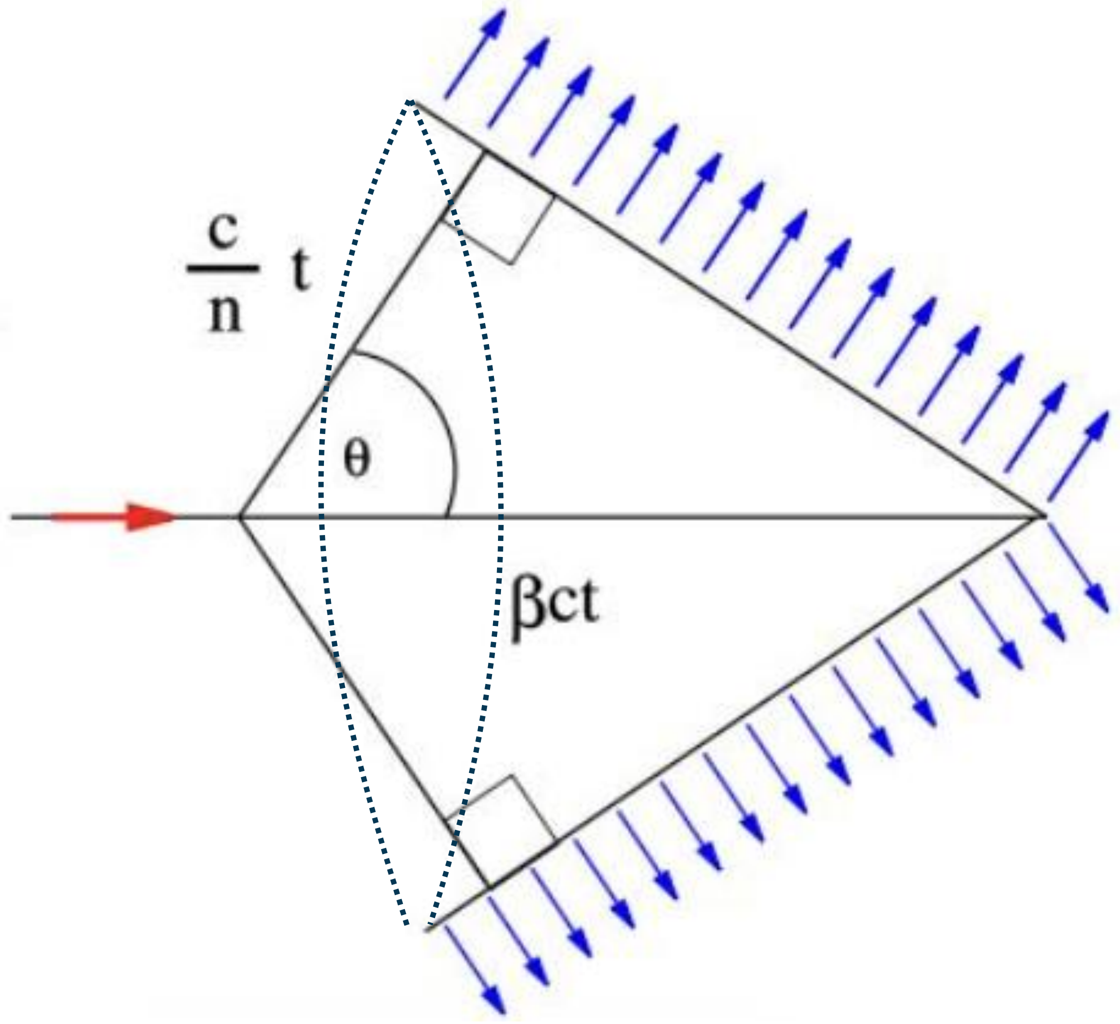
$$\frac{\partial^2 E}{\partial x\, \partial \omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2 n^2(\omega)}\right)$$

N. γ_{Ch}/cm ~ 200

Within acceptance range

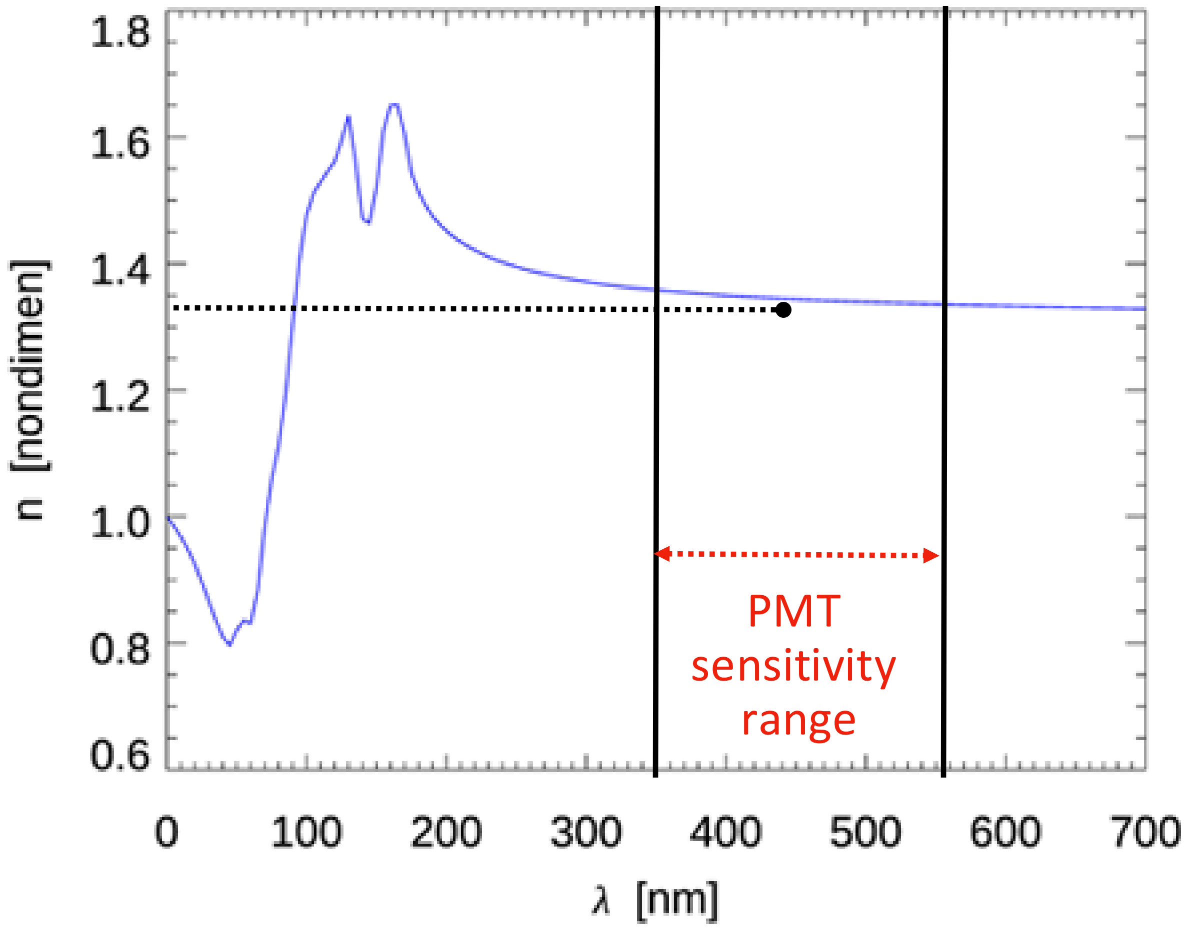
$350nm \leq \lambda \leq 550nm$

$\beta > \beta_{thr} = 1/n$



Assuming $n(\lambda)$ = constant = 1.33 in water

Water refr. index vs λ



In seawater:

$I = I_0 e^{-\frac{\Delta x}{L_{att}}}$

PMT Q.E. <30%

PMT ø O(1-10) inches

$L_{track} \sim O(1)\ km$

$L_{att} \sim 50m$

$N_{points} \sim O(100)$

O(5000) of photo-sensors

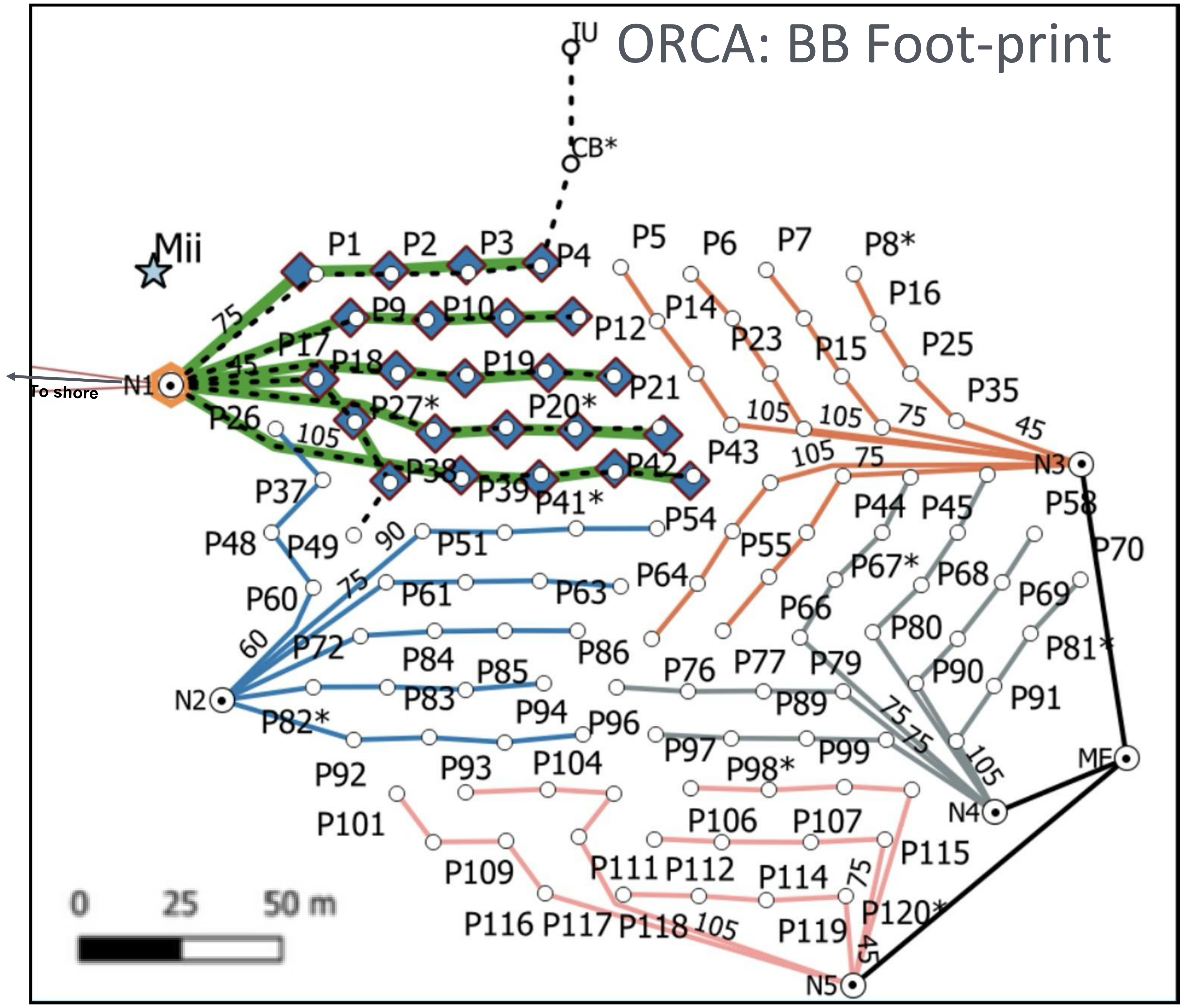
Deployment

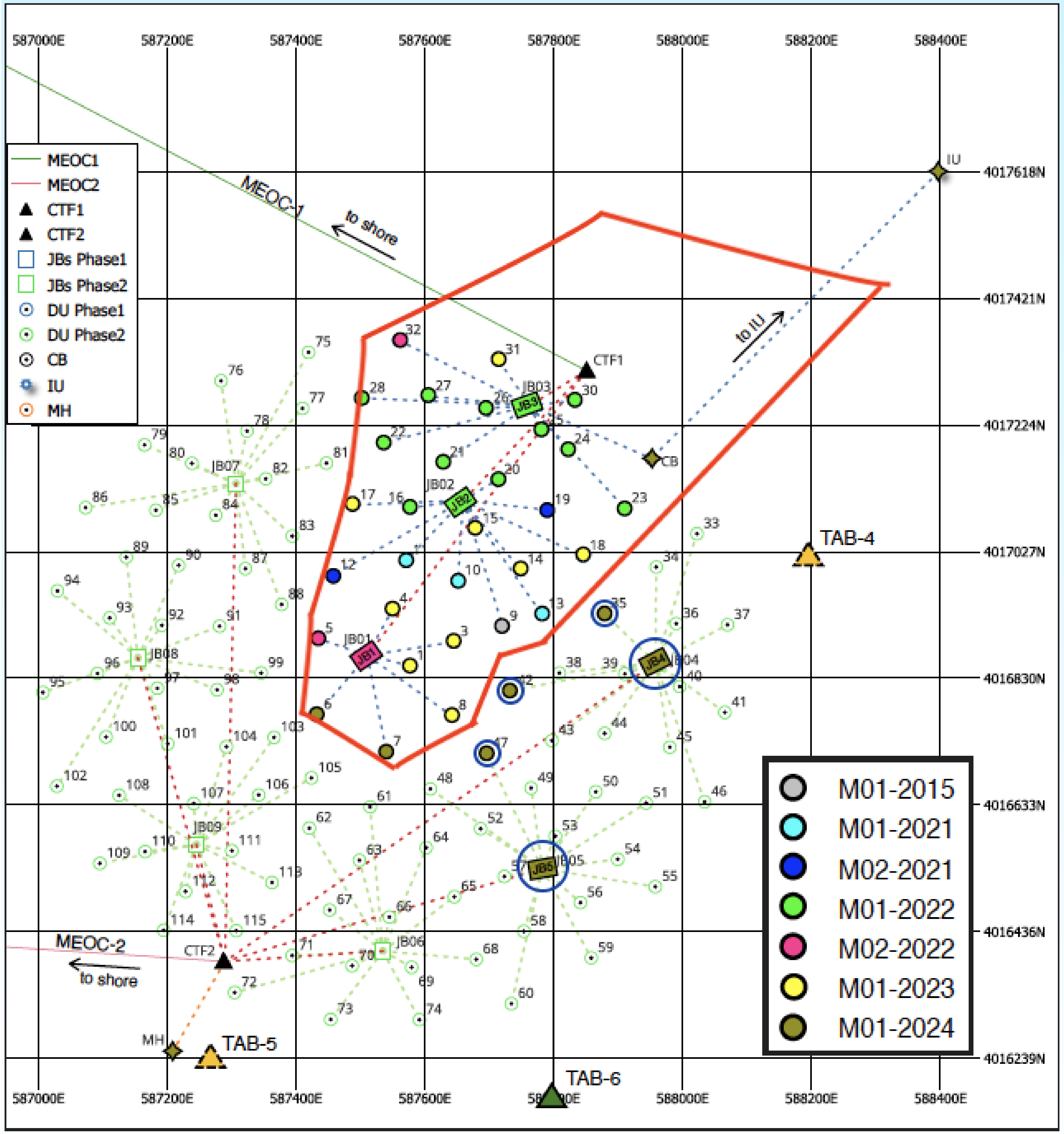
DU deployment

Construction status

33 strings @ARCA site ~0.14 km^3 →

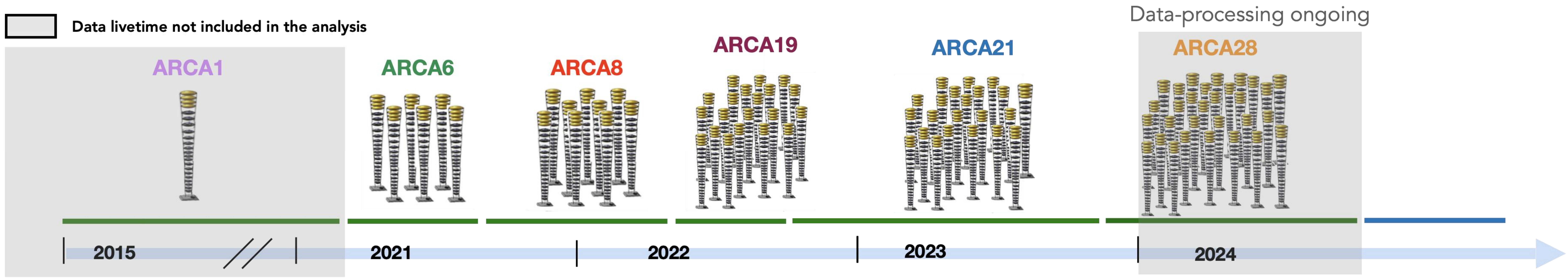
24 strings @ORCA site



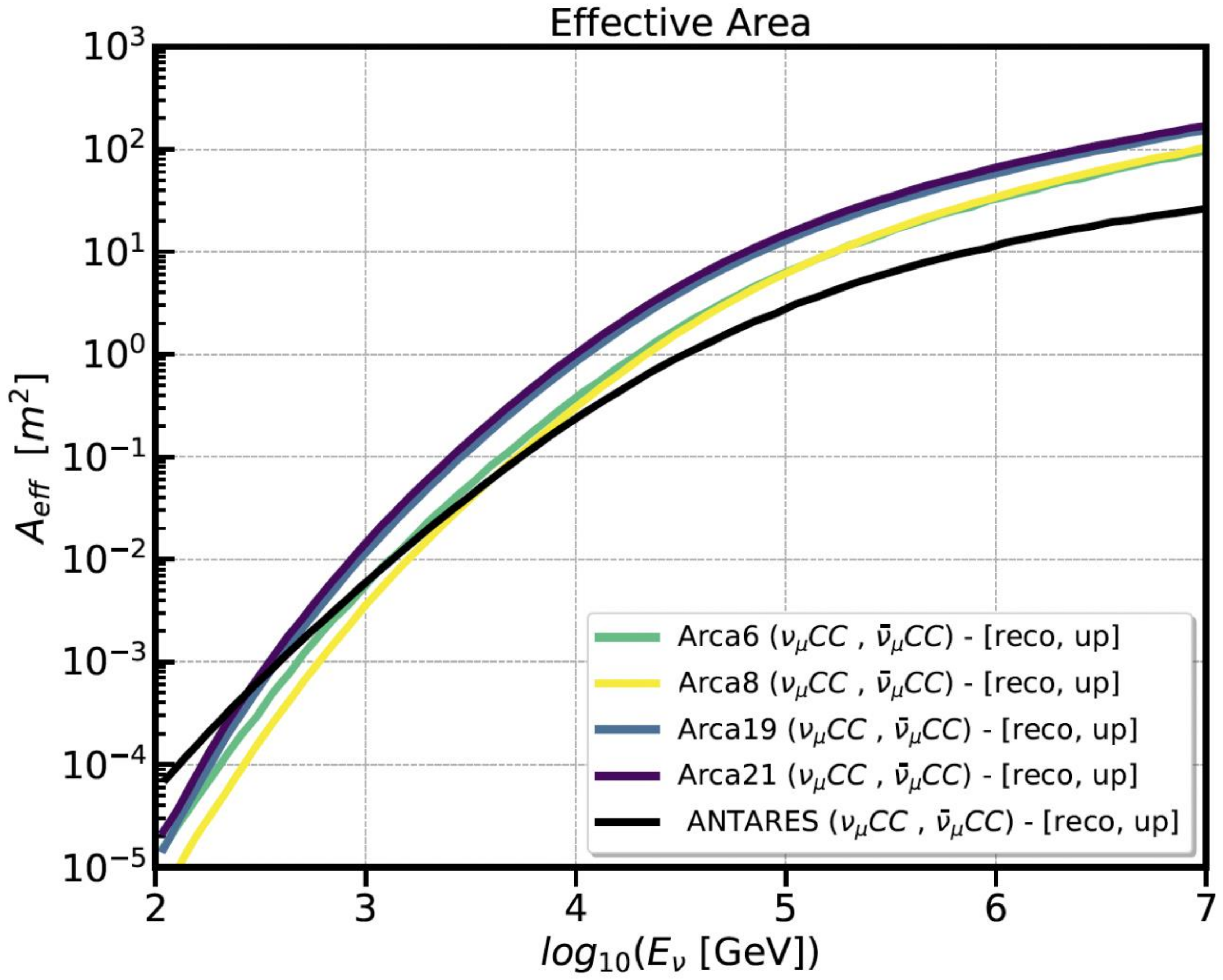


Almost completed the first node ~ 20% ORCA

Construction status - ARCA



KM3NeT/ARCA21 × 3 effective area of KM3NeT/ARCA6



How it works

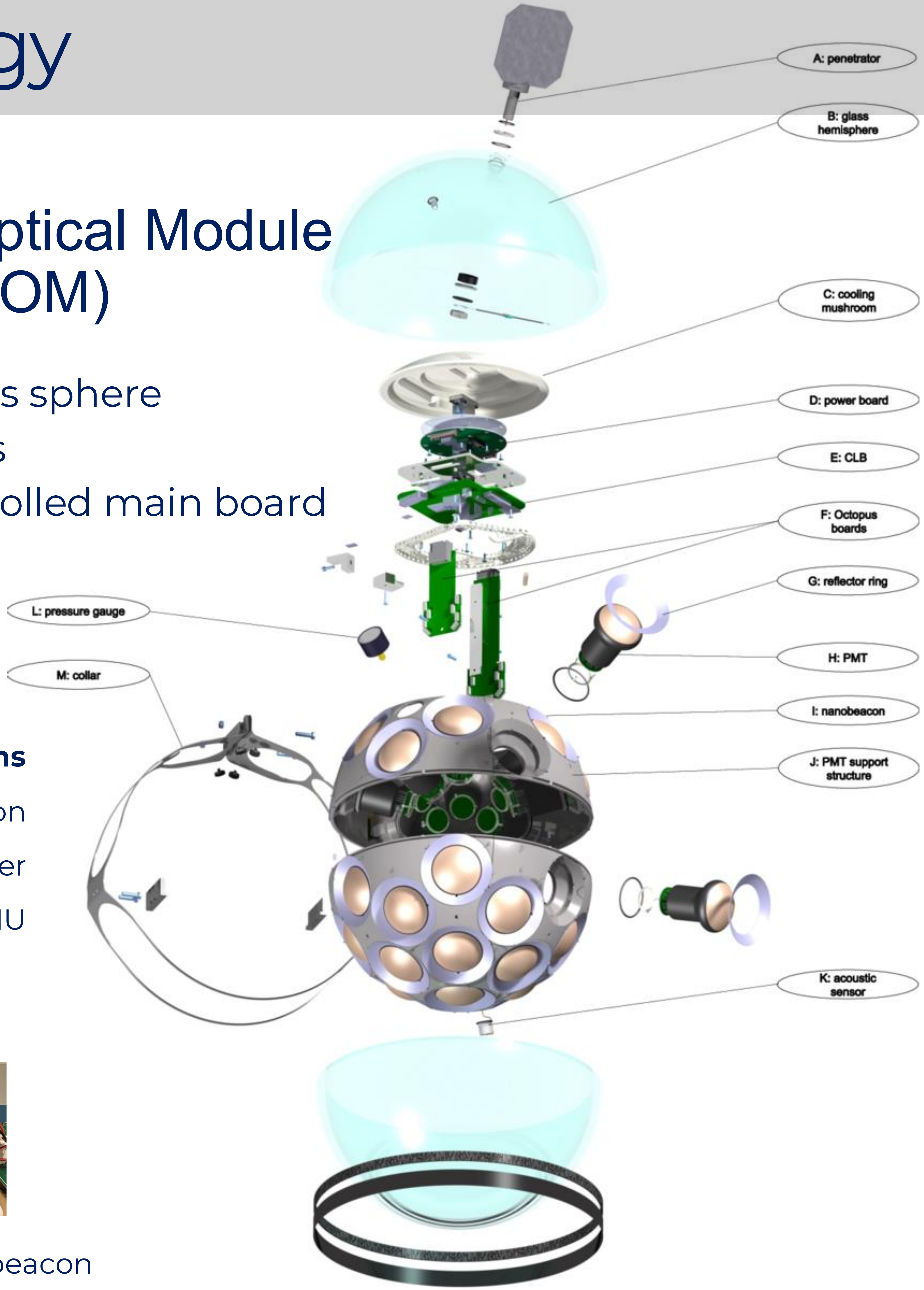
INFN KM3NeT

Technology

Detection Unit (DU)

Detector Optical Module (DOM)

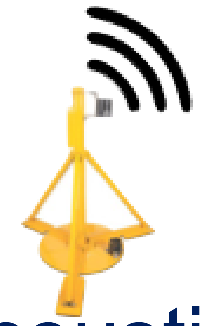
- 17-inch glass sphere
- 31 x 3'' PMTs
- FPGA controlled main board



Built-in positioning and timing calibration systems

- nanosecond LED beacon
- Piezo transducer
- Compass + IMU

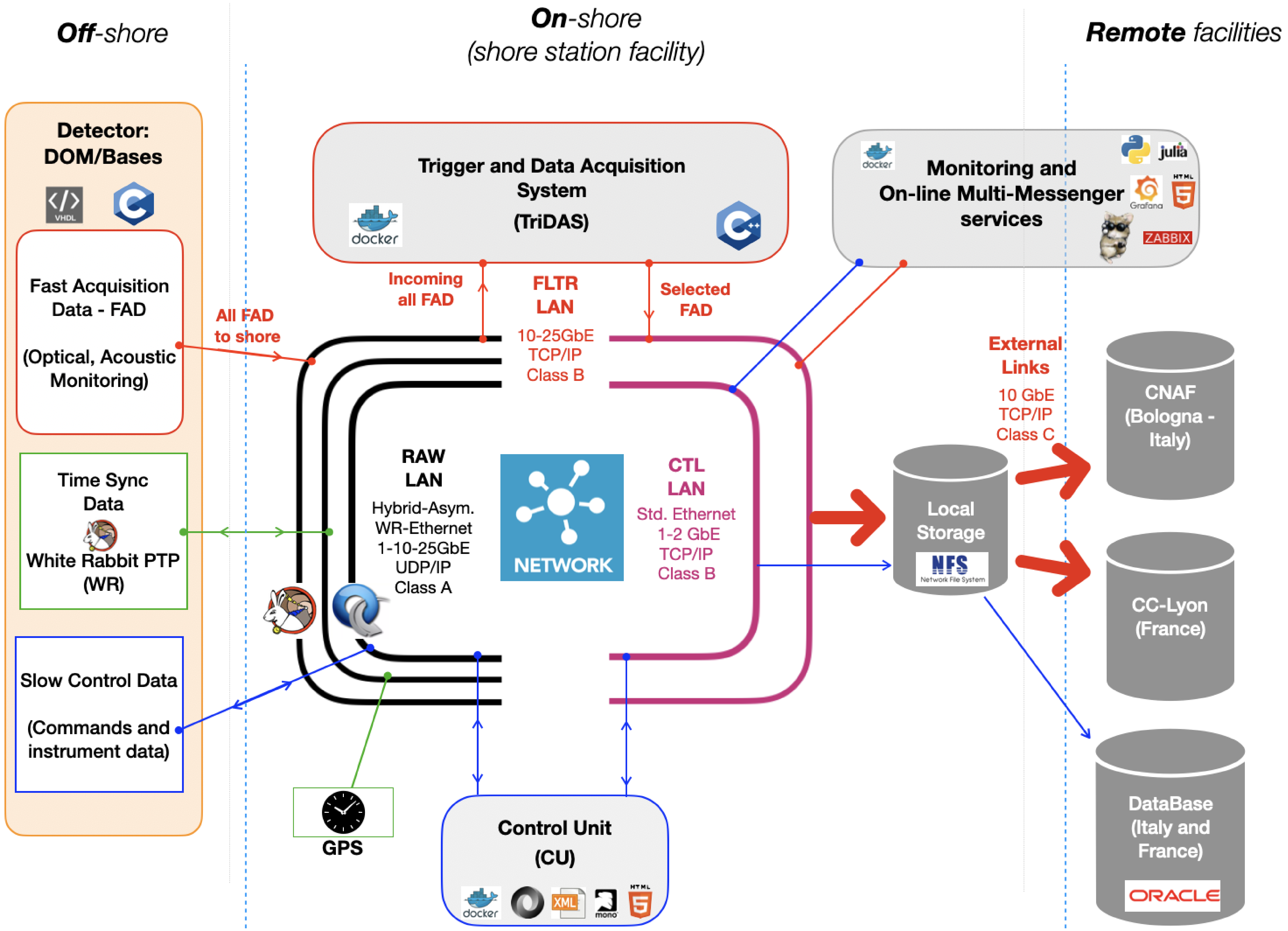
Base Module (BM) with hydrophone + acoustic beacon



acoustic beacon

DAQ overview

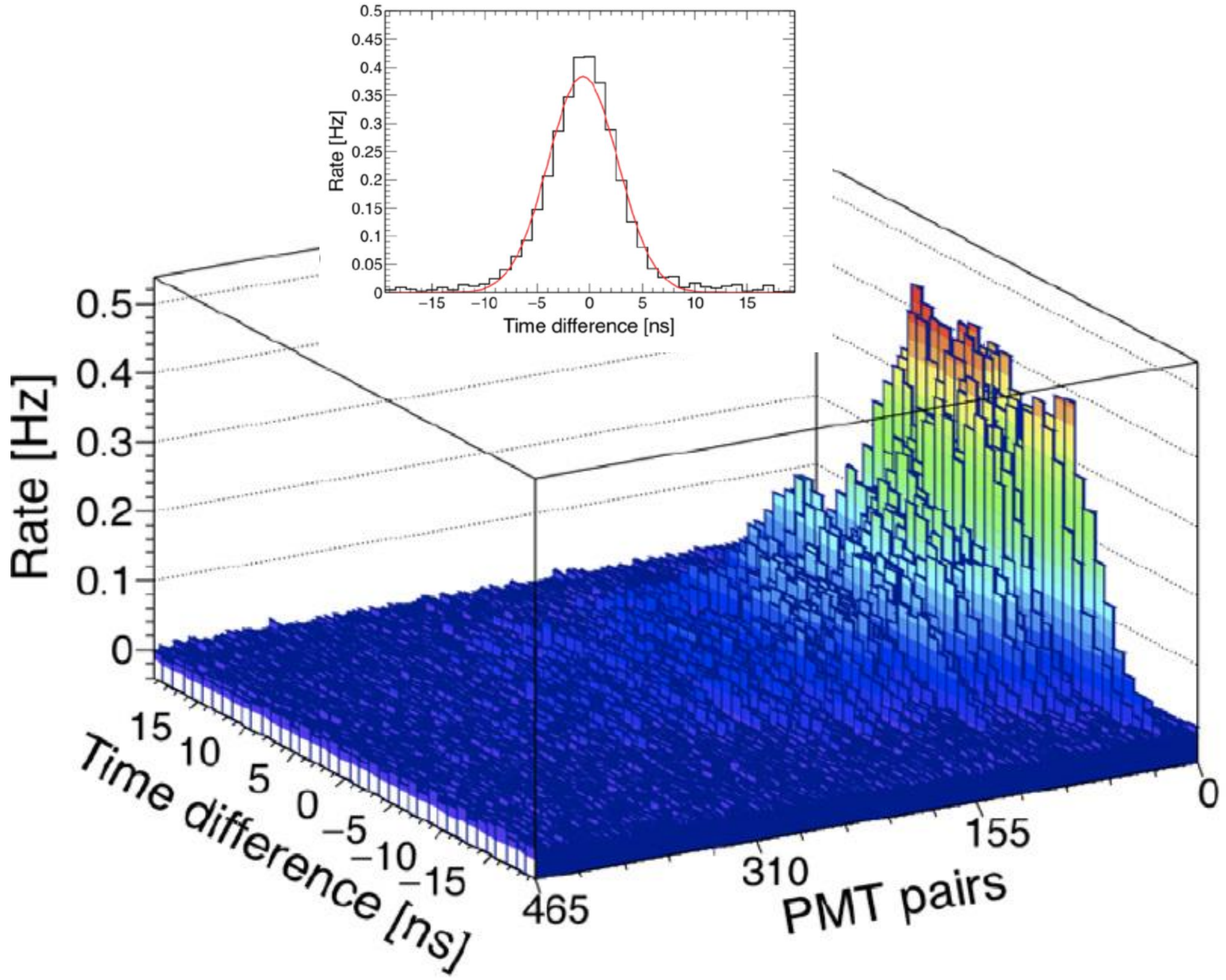
→ **Trigger-less streaming readout** DAQ model → ***all data to shore* approach**
→ All complexity of data-filtering performed onshore in the computing resources in the shore station

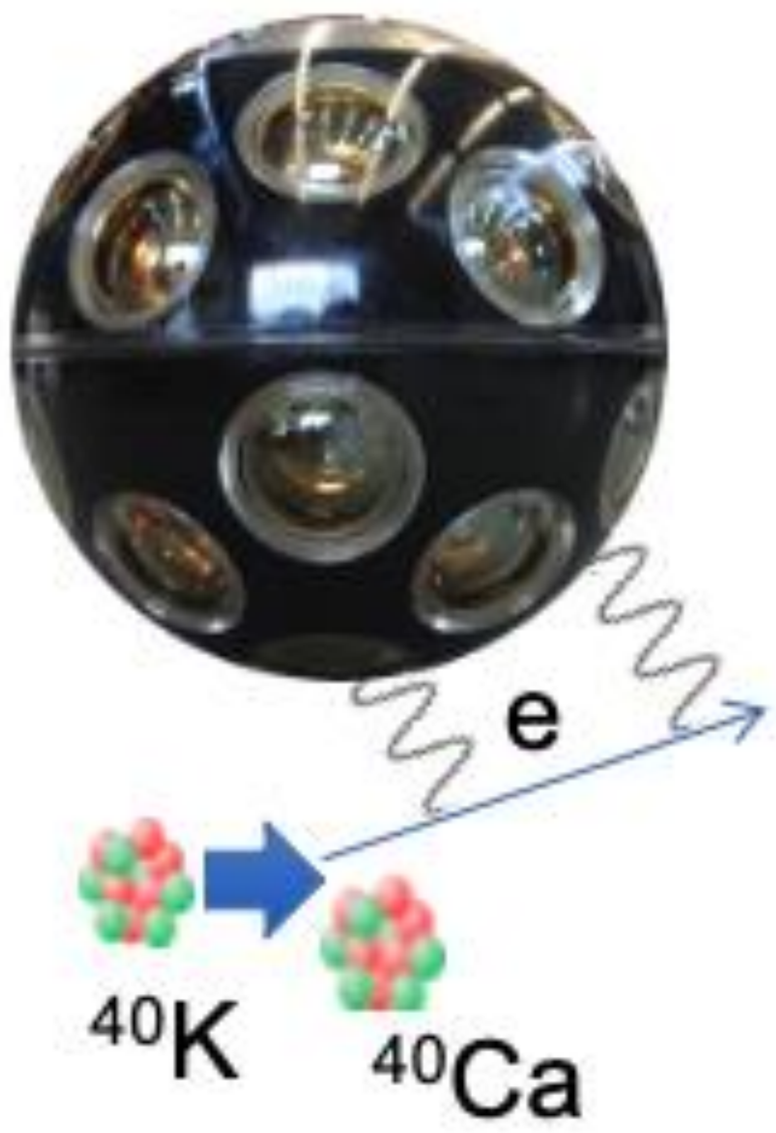


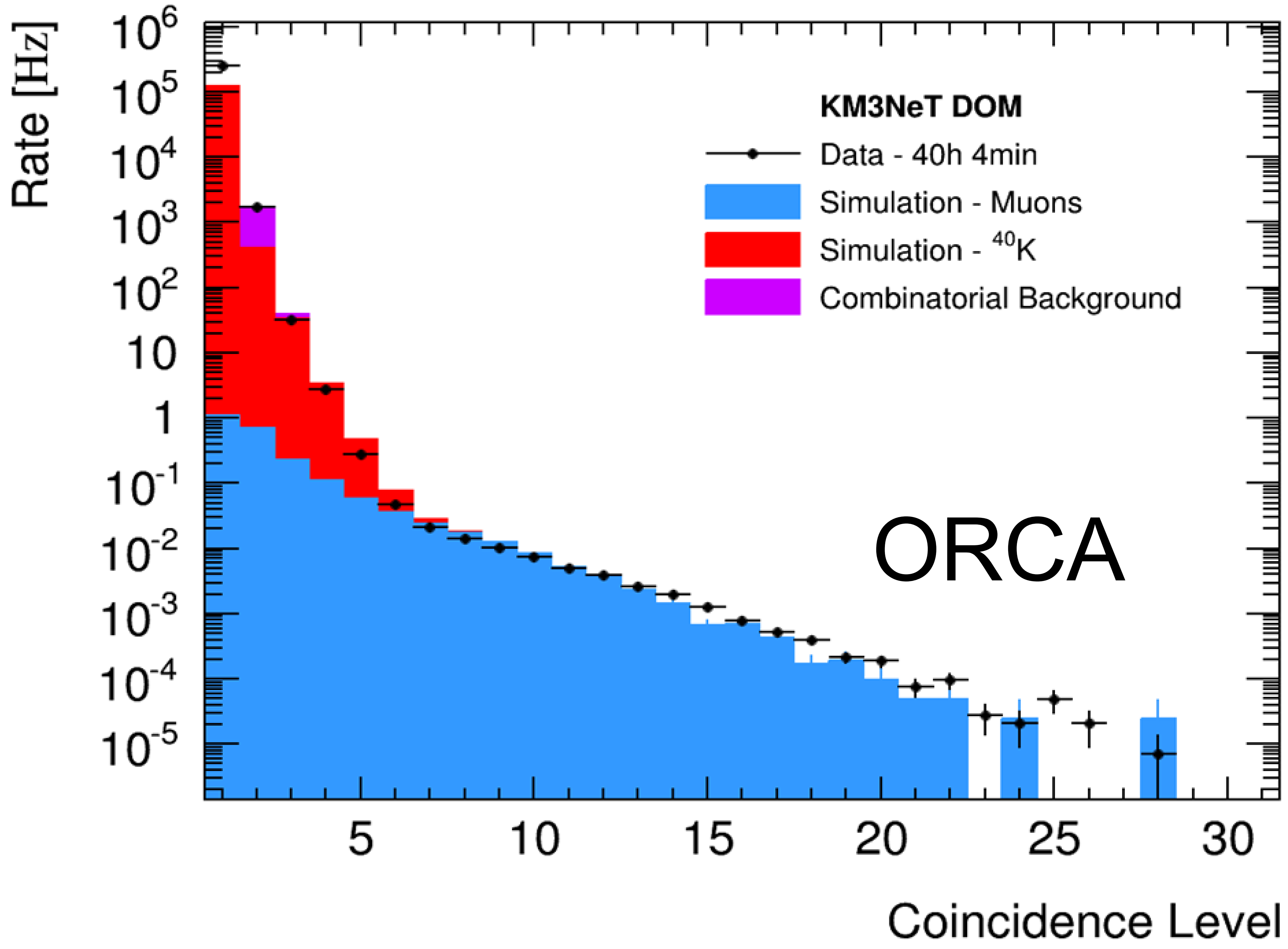
- DOMs are **1GbE submersed ethernet nodes** connected to shore via optical fibres
- **Timing distribution with < 1 ns accuracy and 100 ps precision** across all DOMs via *White Rabbit* Technology
- Large throughput from the detector **O(100) Gbps**
- Large band - high performance network infrastructure on shore
- Scalable on-shore computing facility growing along with detector stages of installation.
- On-shore data reduction by 1:10^3 → recorded data to disk: O(1) TB/day

L0 trigger and noise

- Each PMT is readout using a 0.3 photoelectron threshold
- Hit timing and charge (Time-Over-Threshold) are digitised with 1 ns precision
- Timing resolution of single PMT approx. 1 ns (dominated by PMT TTS)
- Coincidence between PMTs using timing and direction-based causality filters

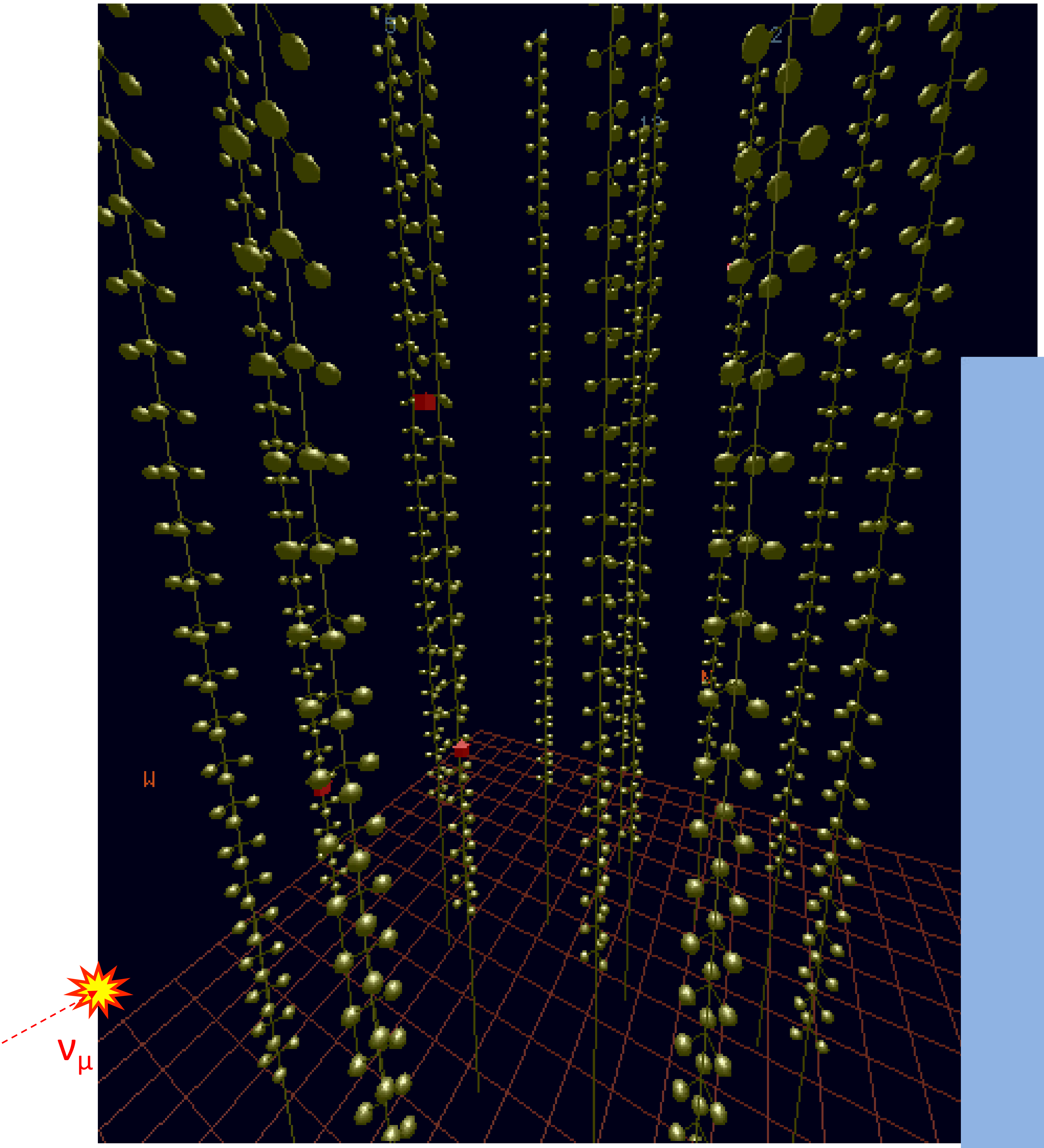






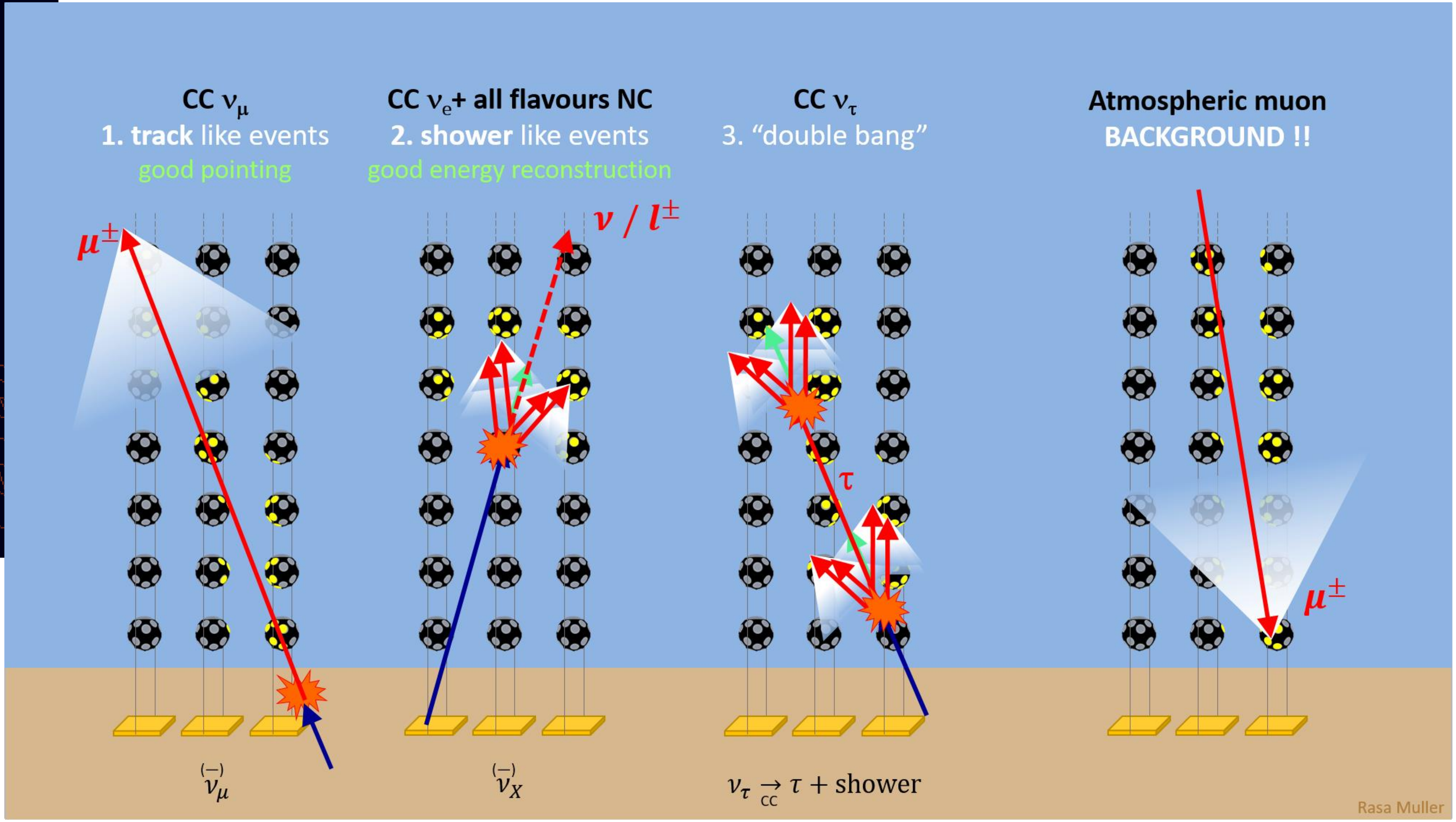
- Optical bkg mostly from K-40 decay: 8 kHz/PMT → 340 Hz 2-fold coincidence
- K-40 decays → 150 Cherenkov photons / decay → also used for pair-wise timing offset equalisation between PMTs

Main event topologies



Track-like events → angluar resolution < 0.1° at En>100 TeV E resolution ~ factor 2

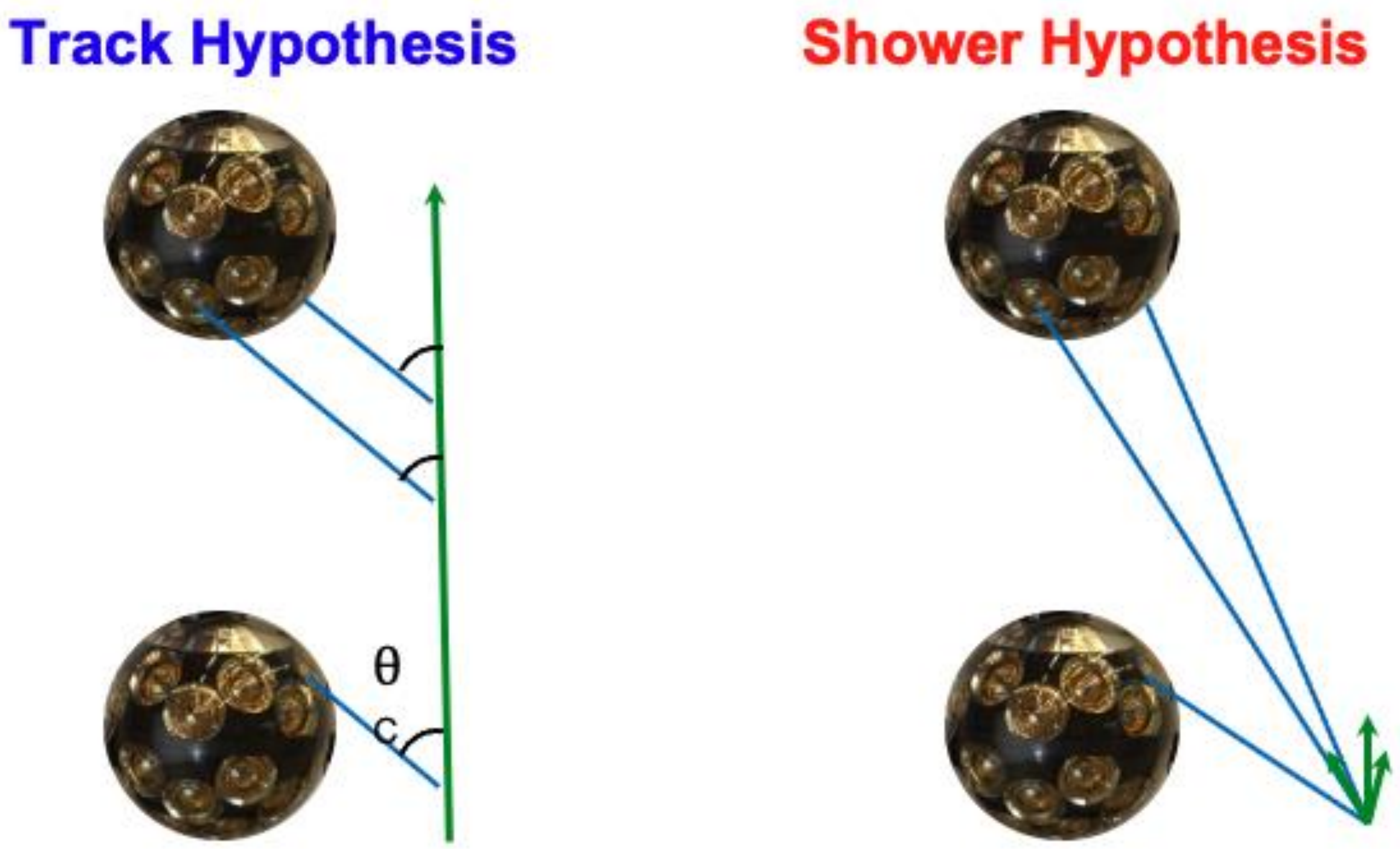
Shower-like events → angular resolution < 2 ° at En>100 TeV E resolution ~6%

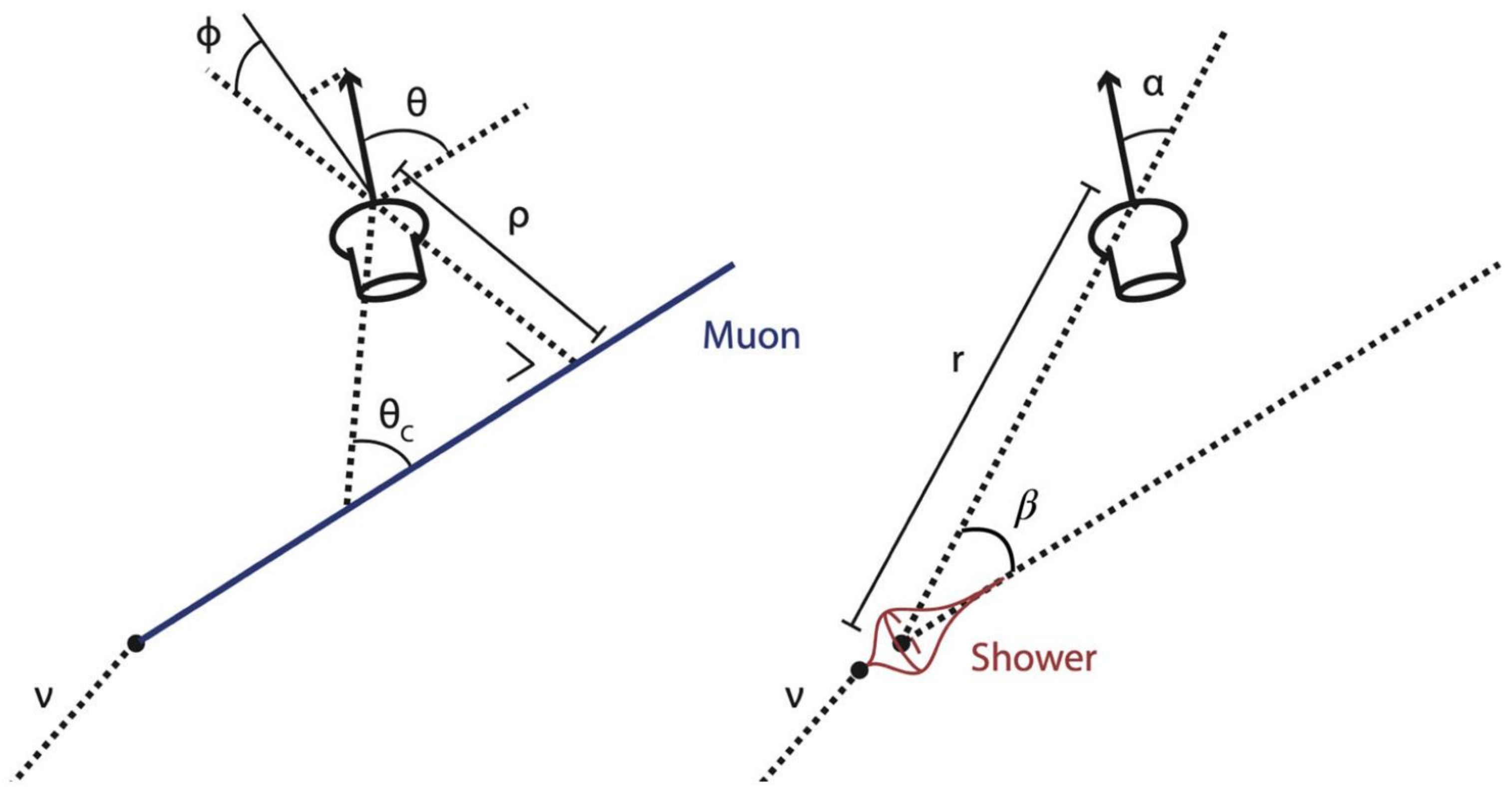


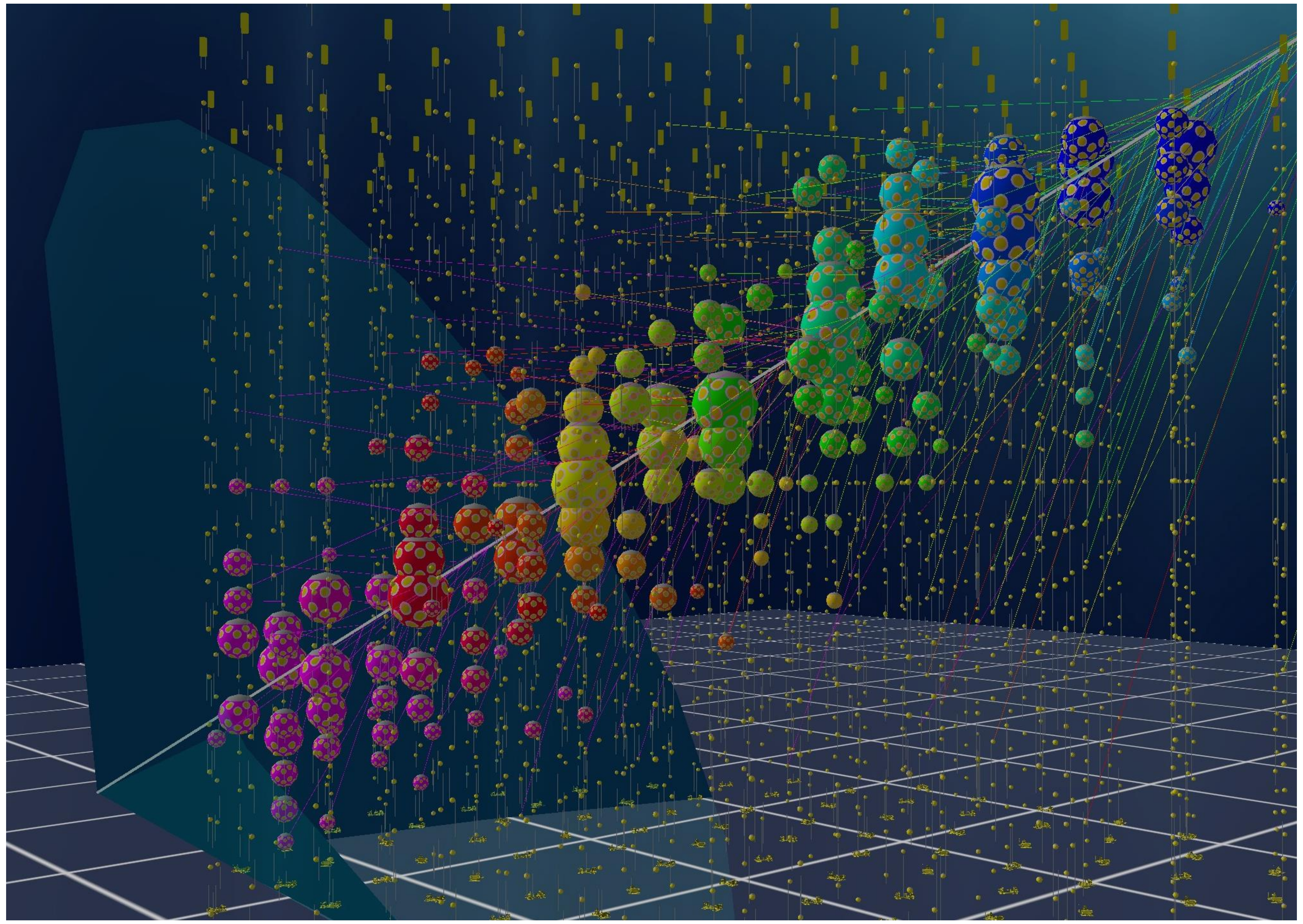
+ SN neutrino detection

Reconstruction

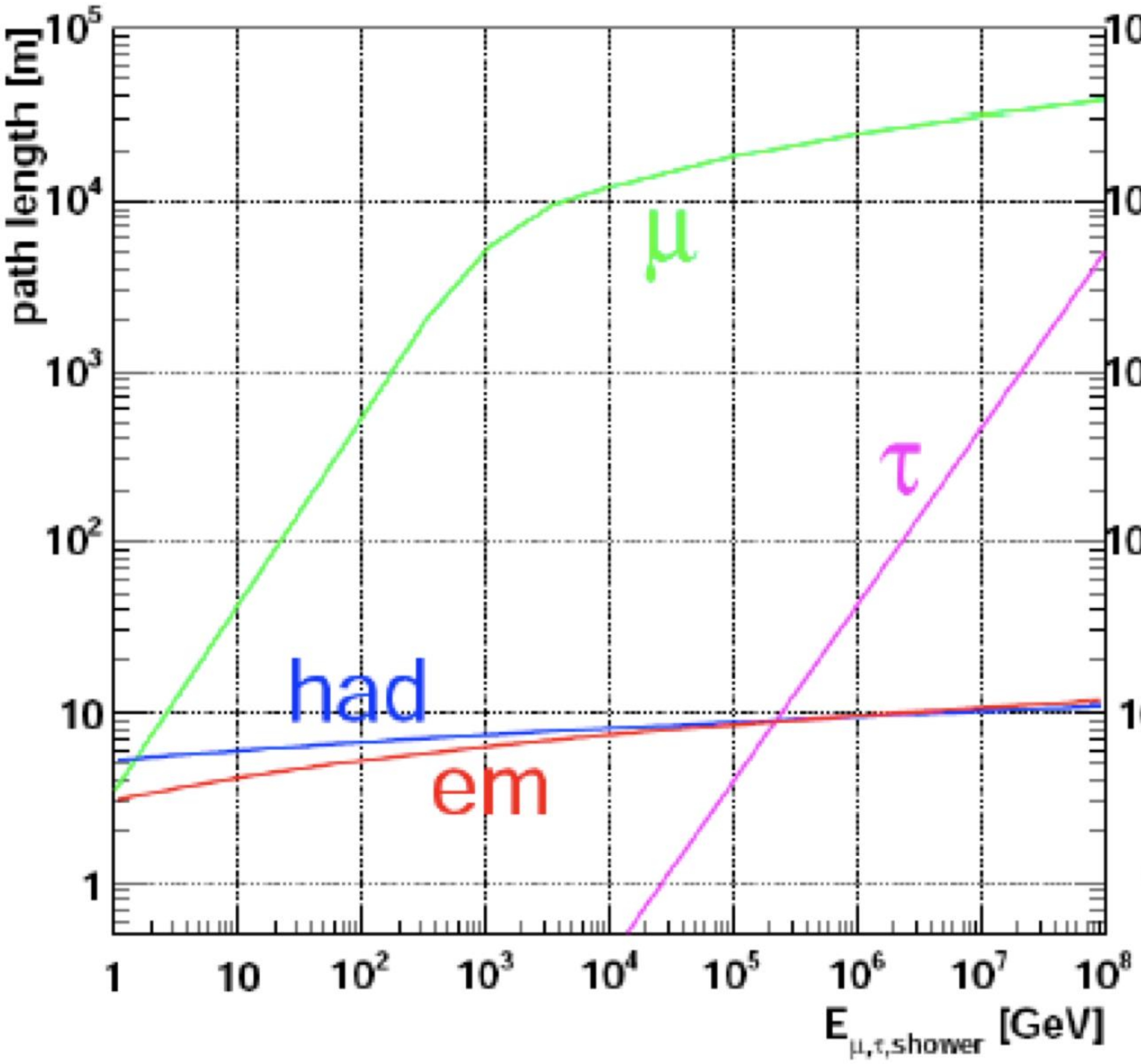
1. Use track or shower hypothesis to select hits is a robust coincidence window
2. Reconstruct **vertex** and **direction** of event
3. Estimate track (dE/dX) or shower (deposited) energy, given reconstructed track or vertex

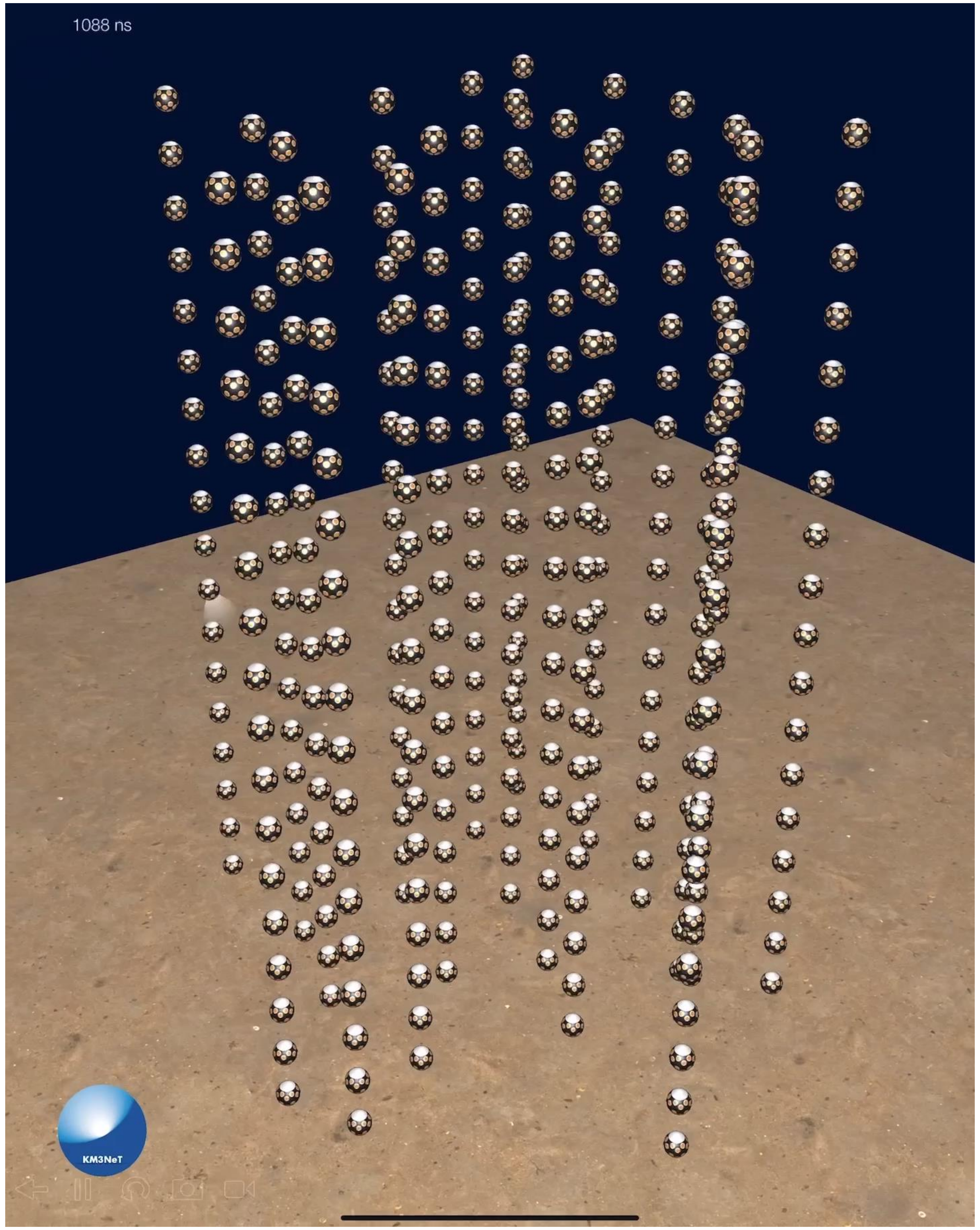




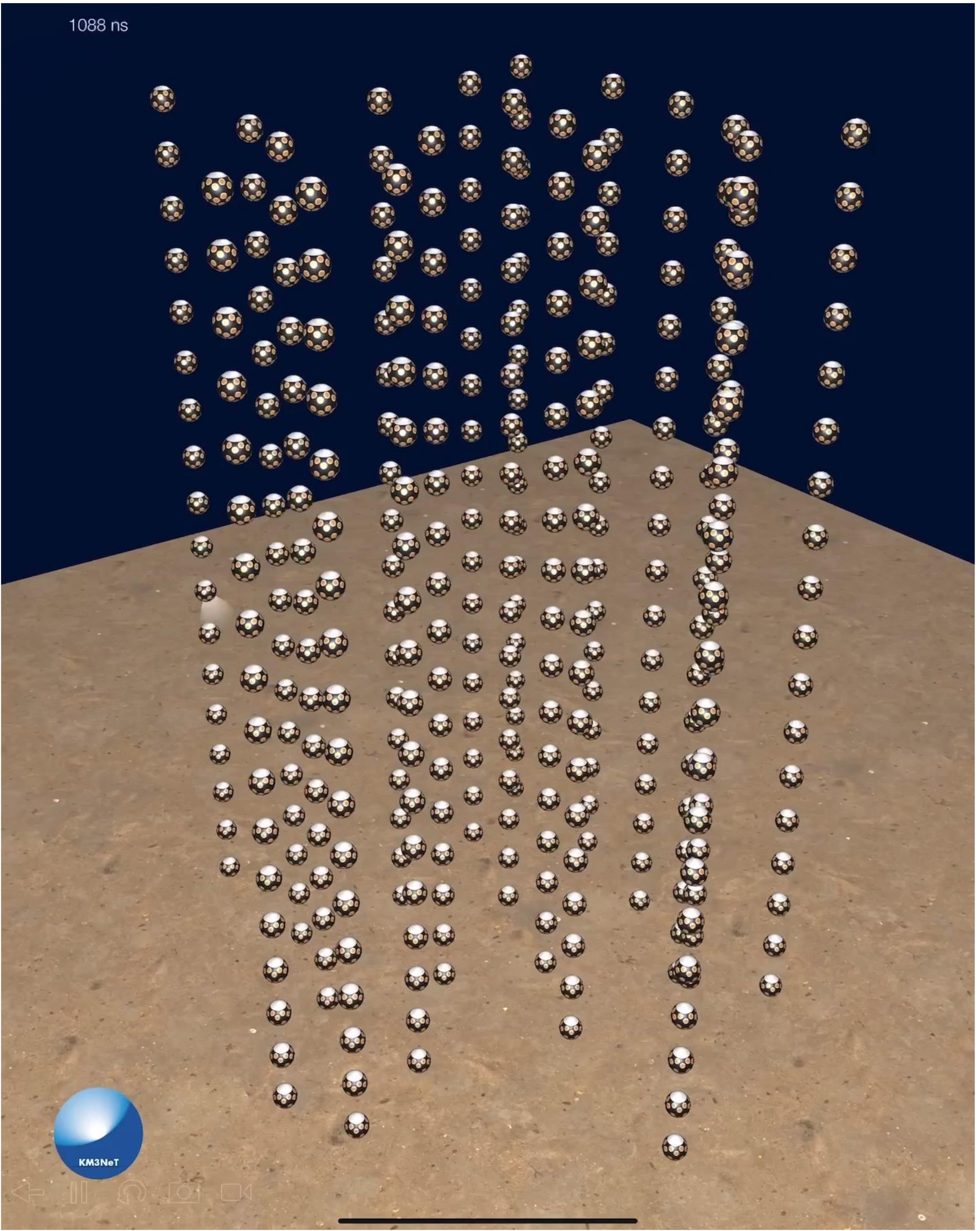


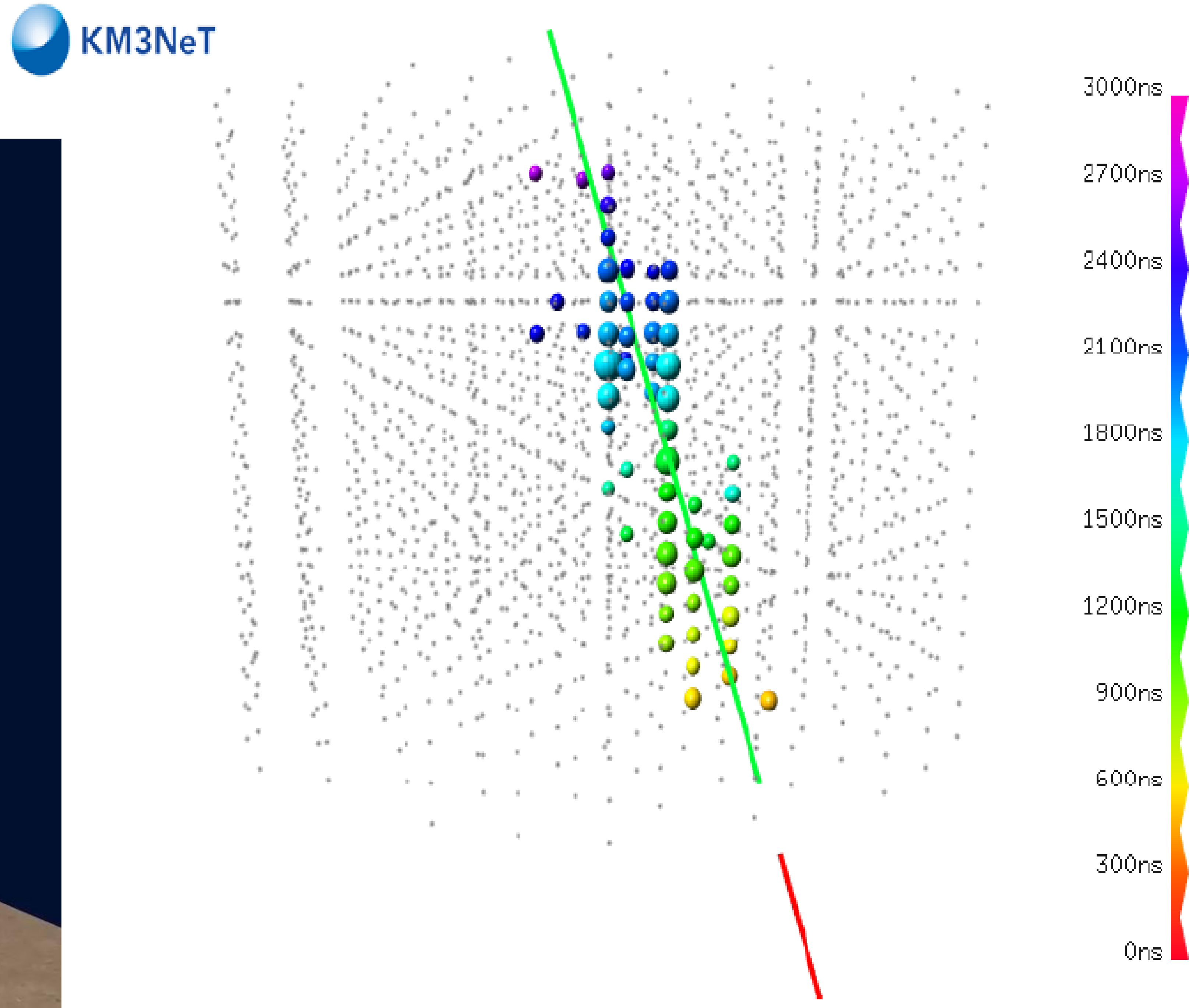
Path lengths in water

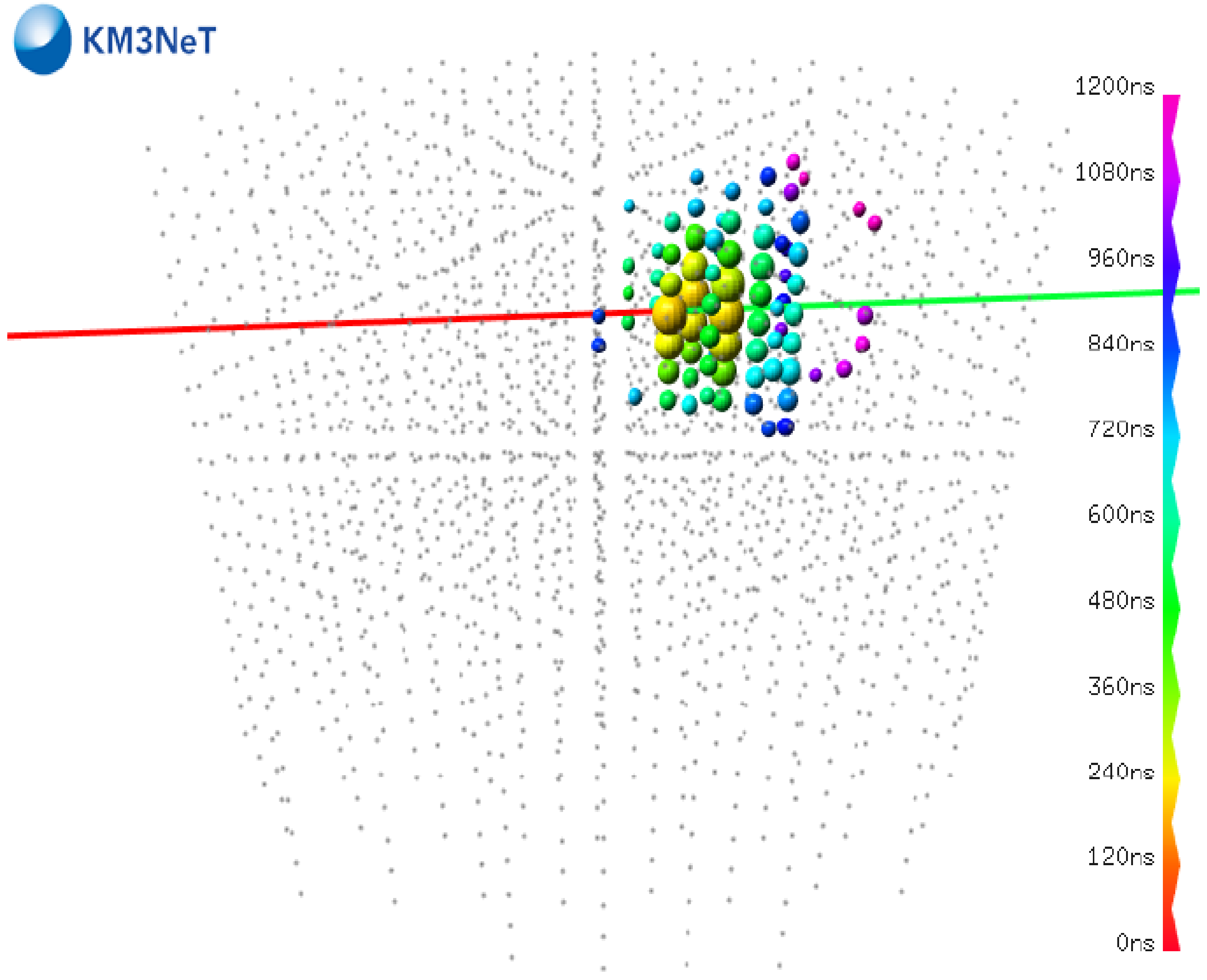


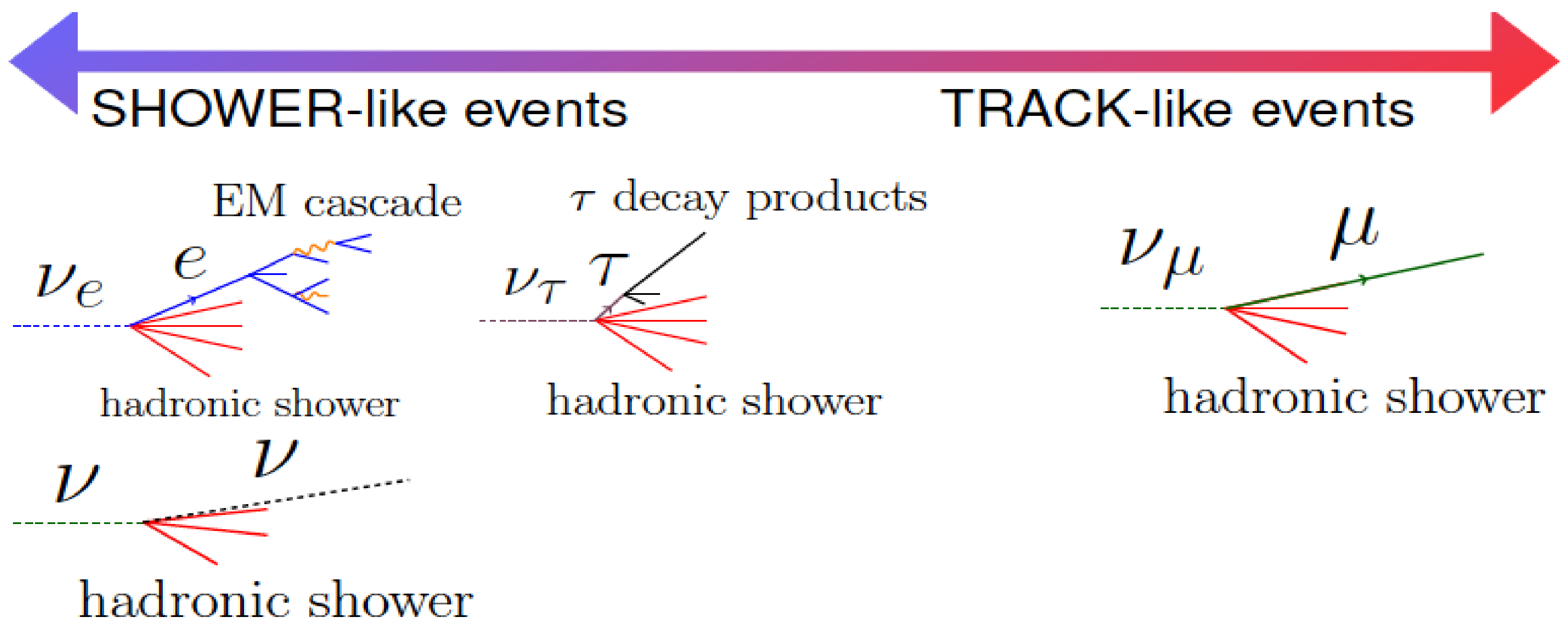


Event display

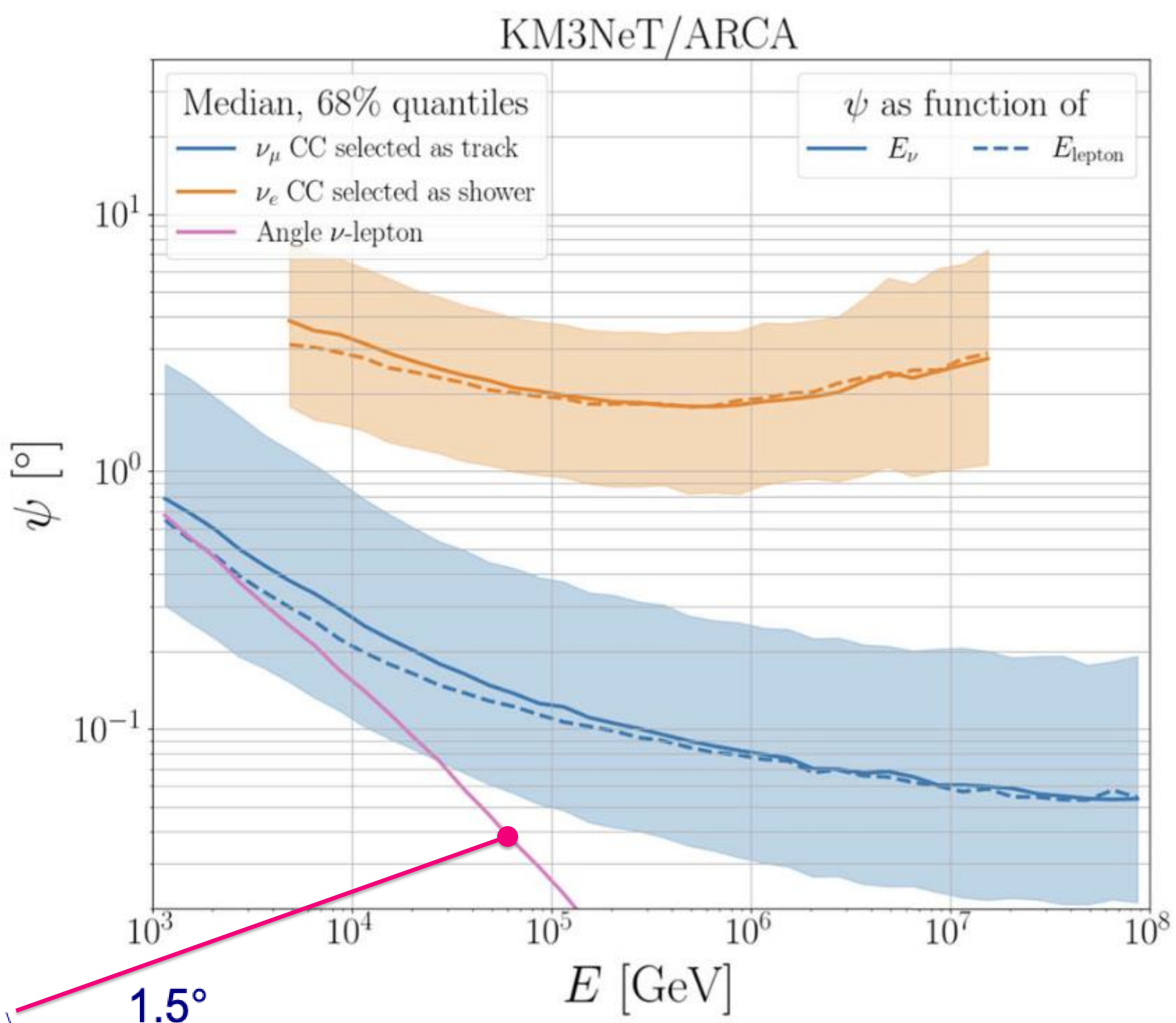


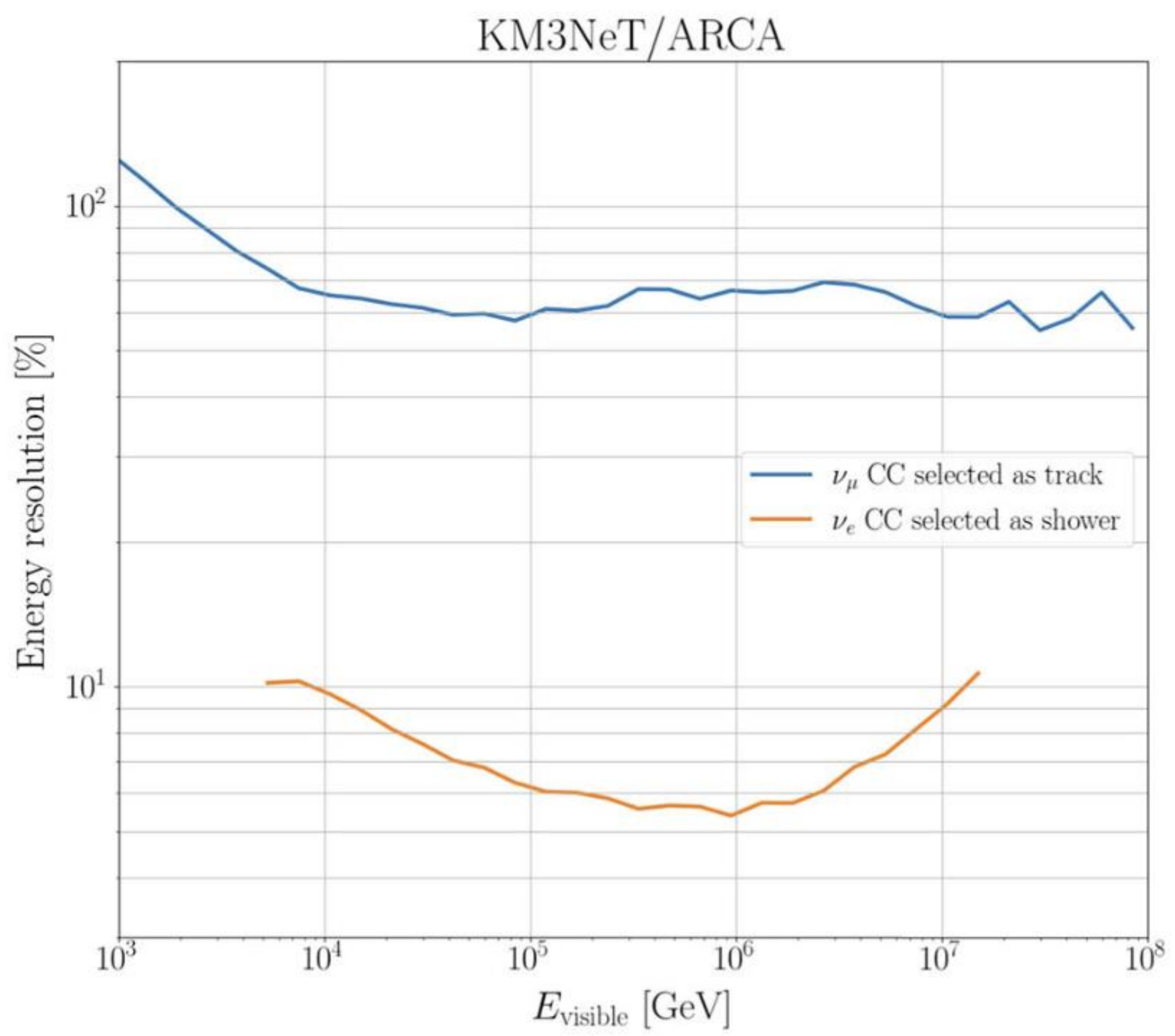






ARCA performances





$$\langle\theta\rangle \approx \frac{1.5°}{\sqrt{E_\nu[\mathrm{TeV}]}}$$

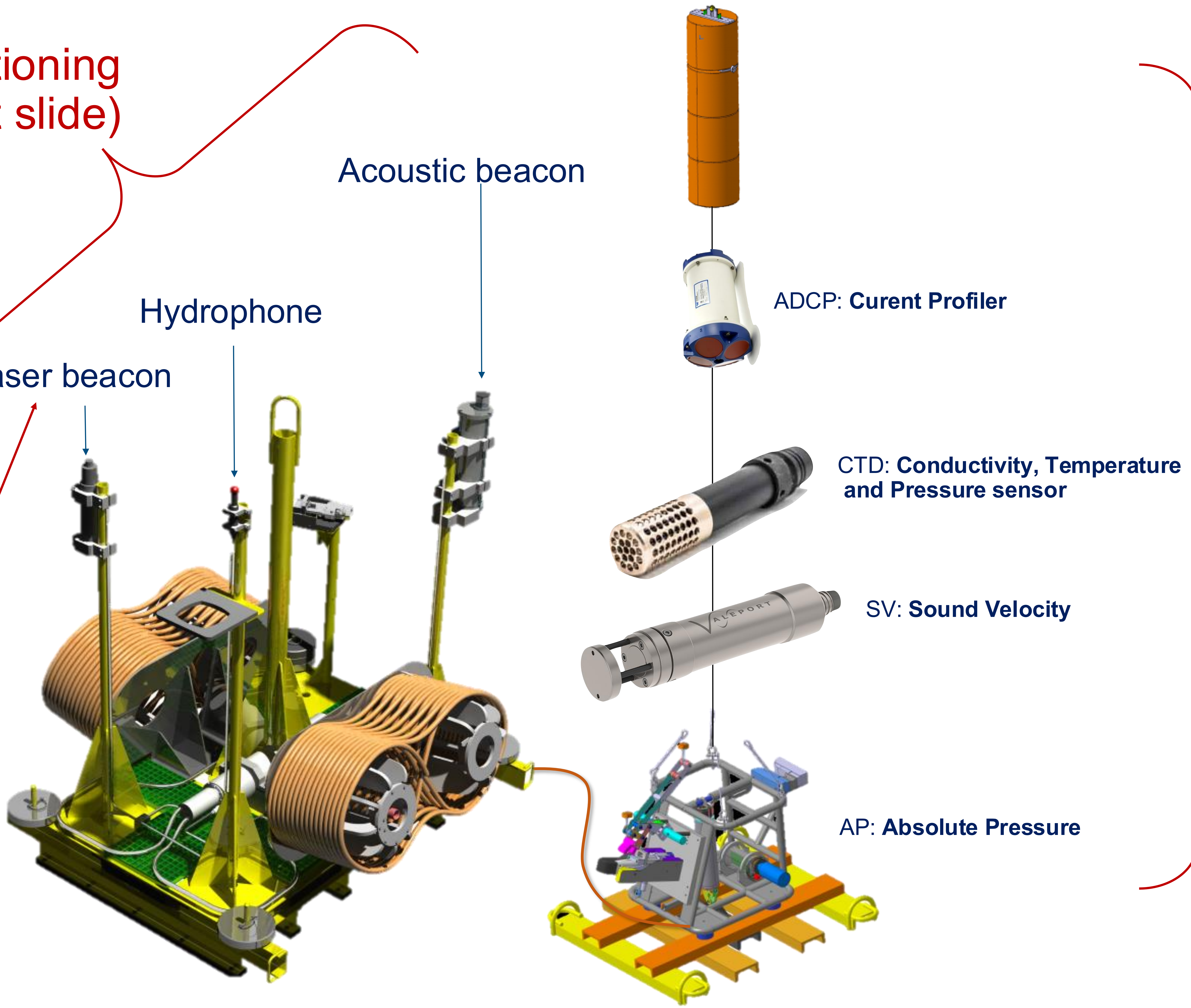
from ARCA MC →

	Trigger [year^{-1}]	Track selection [year^{-1}]	Shower selection [year^{-1}]
Atmospheric μ (> 10 TeV)	8.1×10^7	714	110
Atmospheric ν	1.9×10^5	8.5×10^4	290
Cosmic ν	730	220	60
Neutrino purity		99%	77%

Some calibration systems

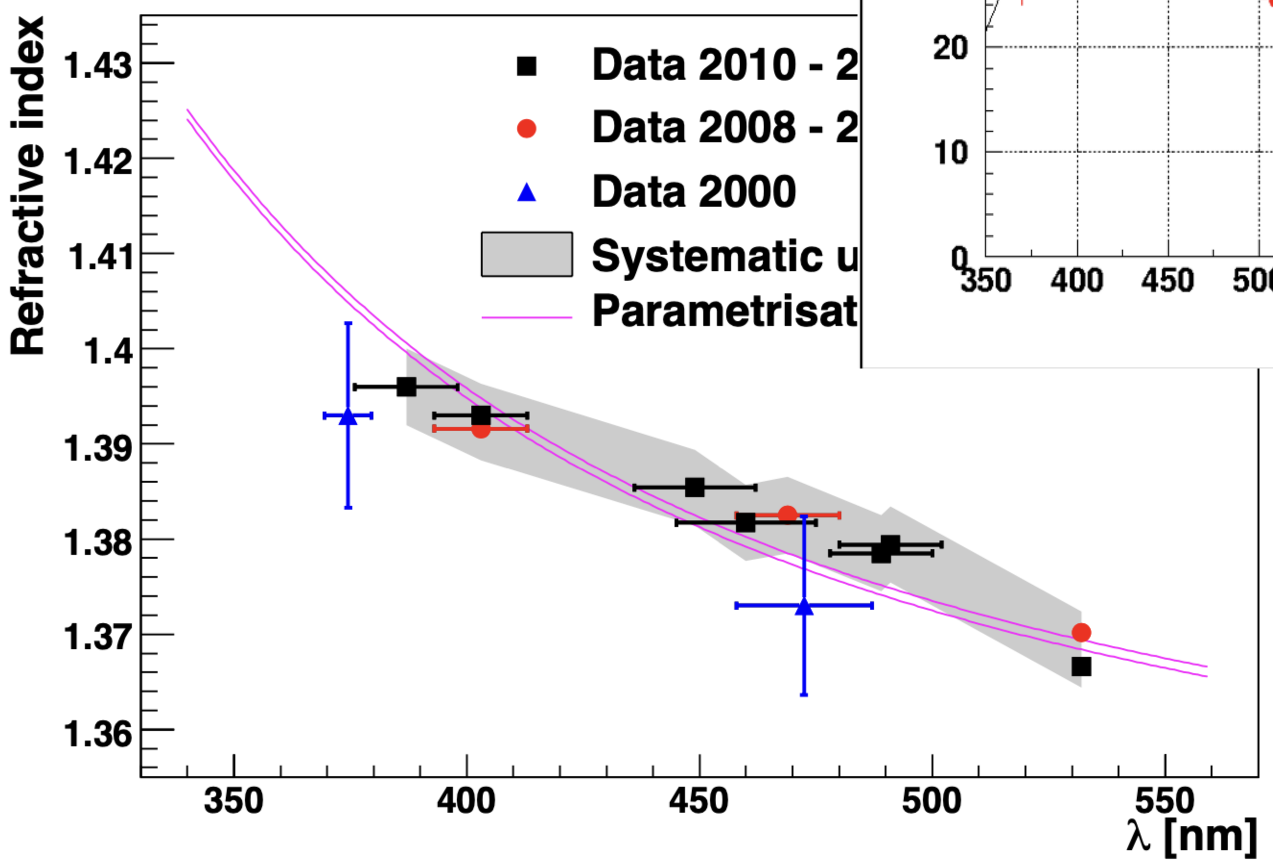
Positioning (next slide)

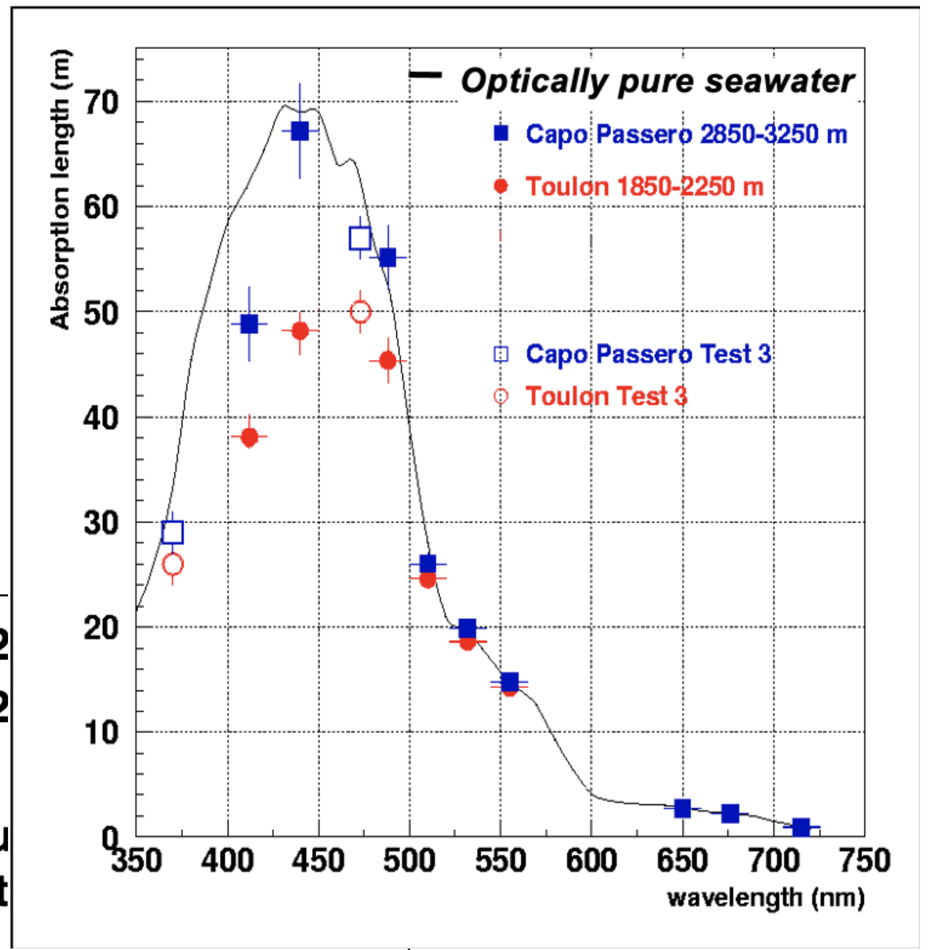
and Timing



It is crucial to correctly model seawater

- **Acoustic properties** for accurate positioning
- **Optical properties** for accurate Cherenkov light transport dynamics in simulation and event reconstruction





Atmospheric background

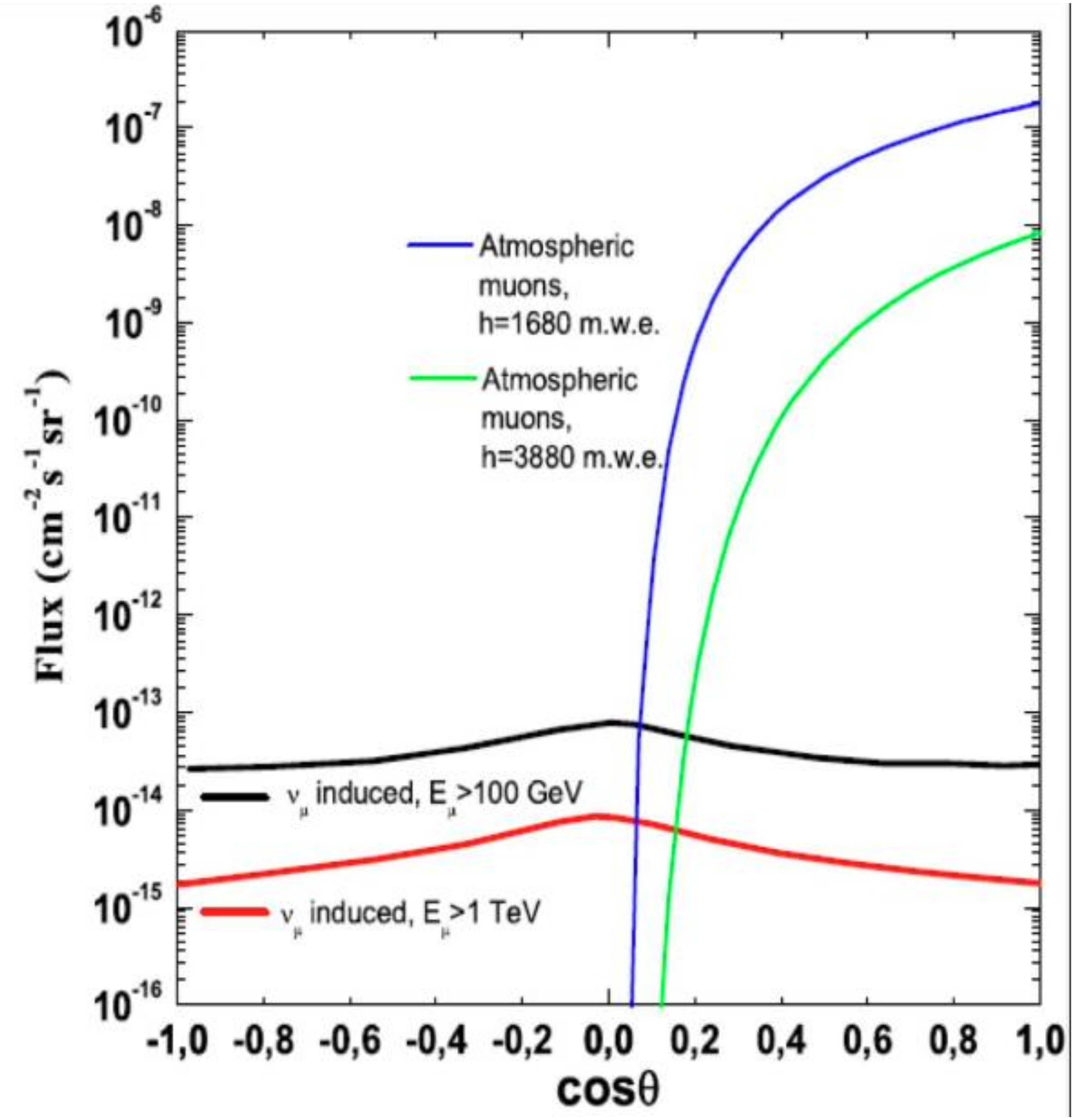
In KM3NeT/ARCA - 3500m depth:

expected per year at reconstruction level:

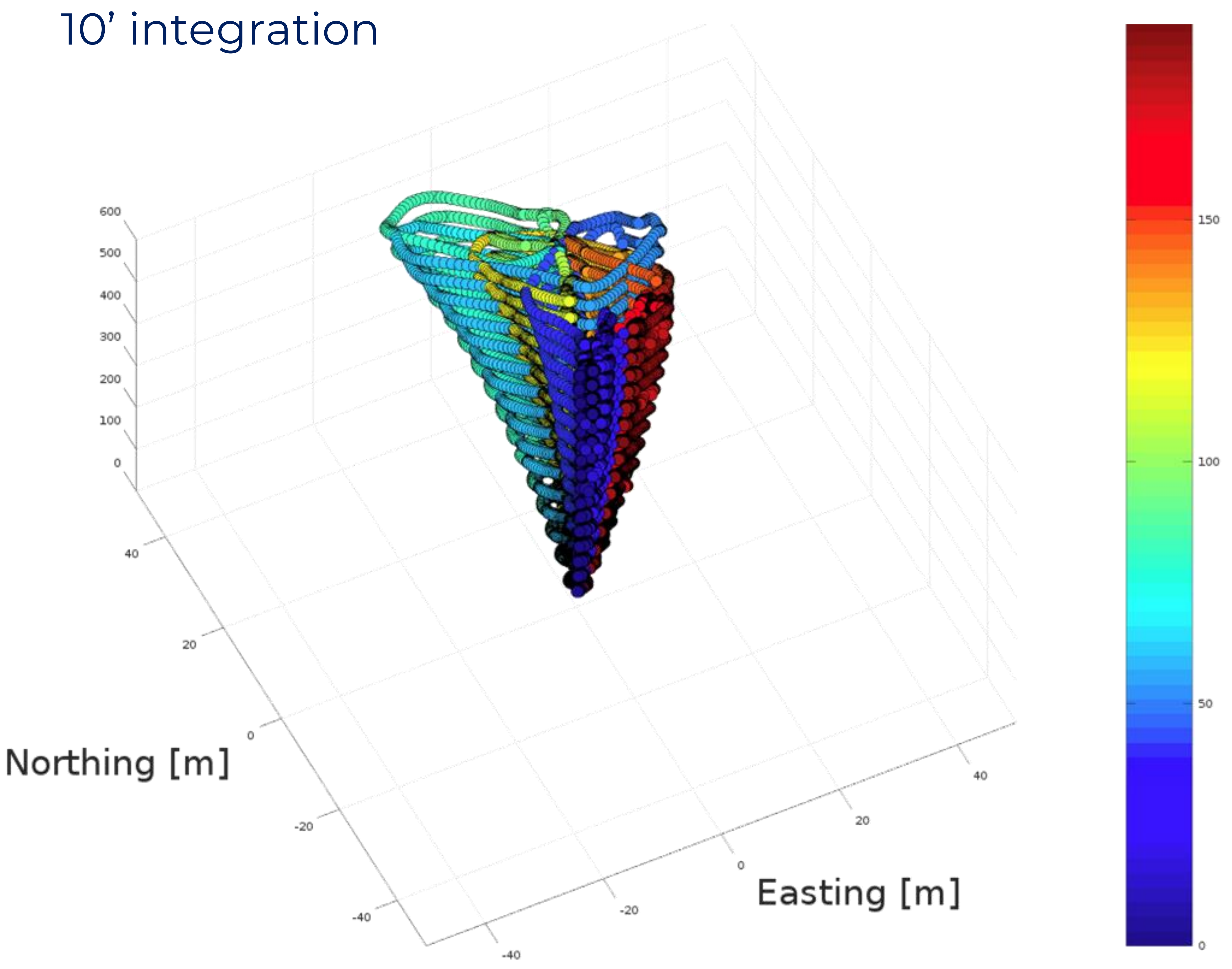
~ 50 million of μ_{atm} (E_μ>10TeV)

~ 0.3 million of ν_{atm} (E_ν>100GeV)

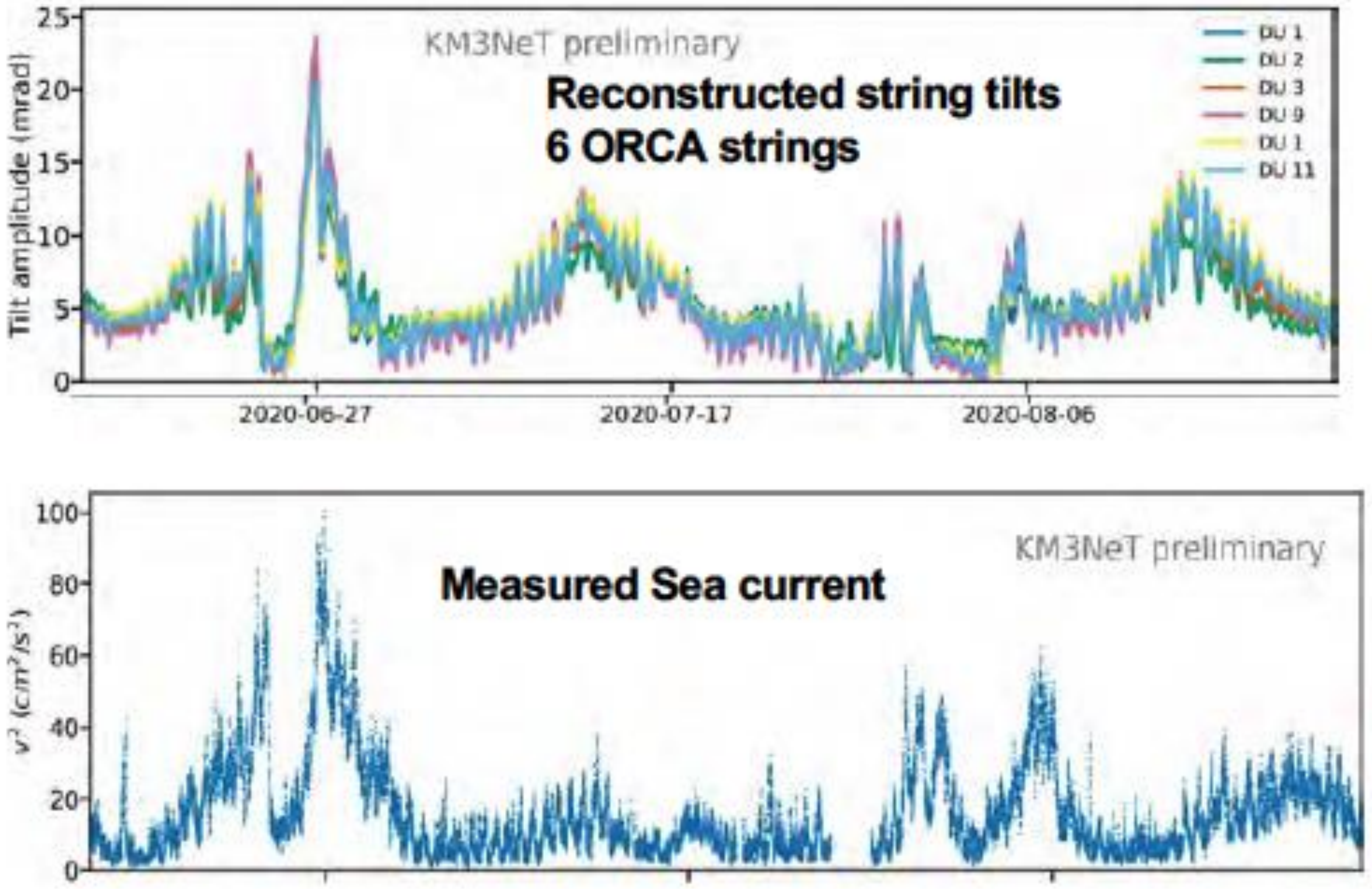
600 of cosmic ($\propto E^{-2}$) (E_ν>100GeV)



Positioning system

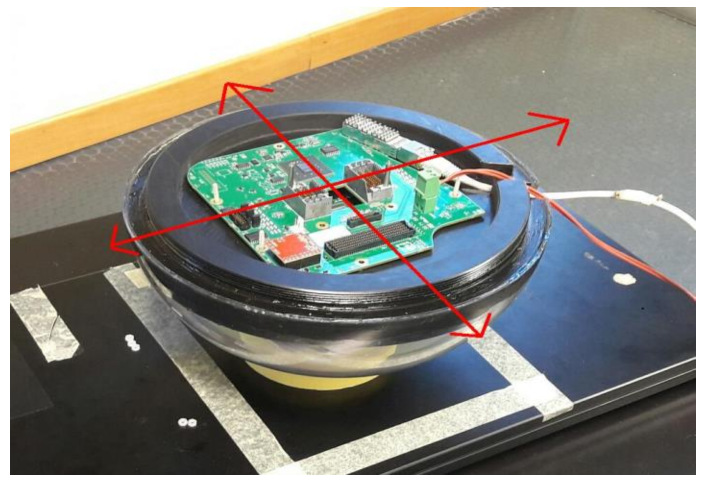


Positioning vs sea current (ORCA)

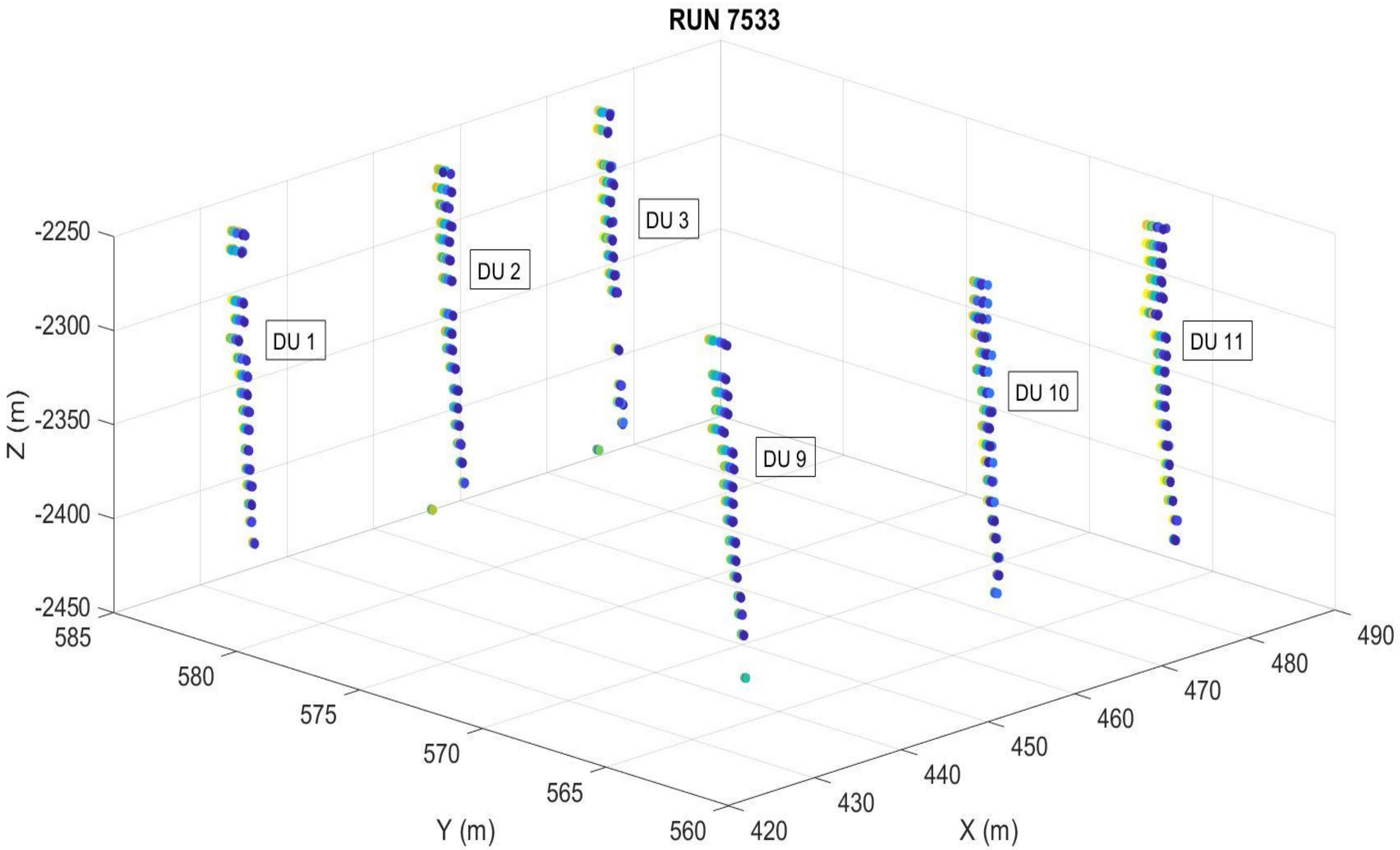


← Single DU over a 24h rotation (Coriolis)

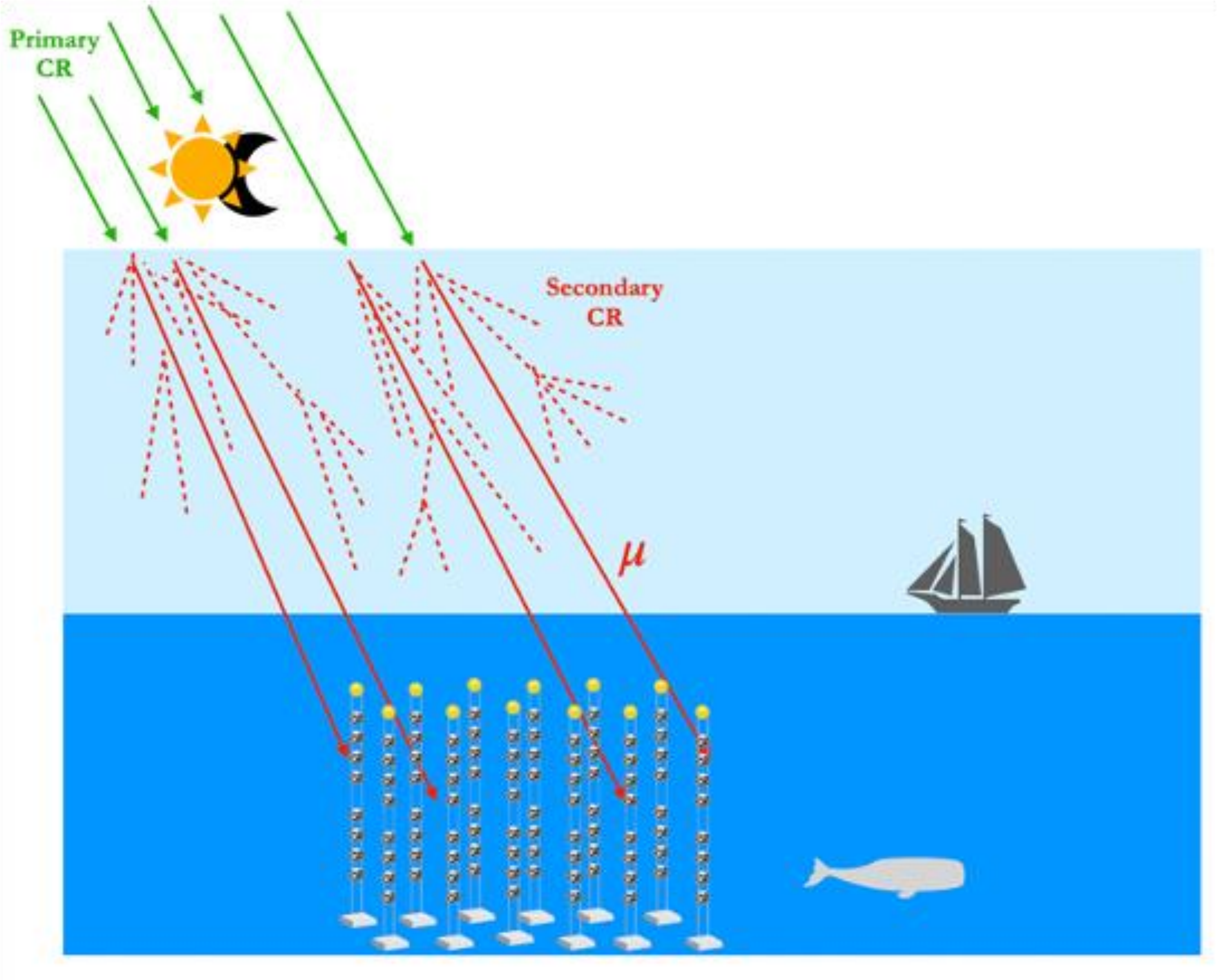
- **Methods:** acoustic beacon ToE + DOM ToA + multi-lateration / global fit of beacon ToAs
- **Target accuracy: 20 cm** (approx. 1 ns / DOM radius)
- Used in conjunction with **DOM compass + accelerometer system** to provide (yaw, pitch and roll) →



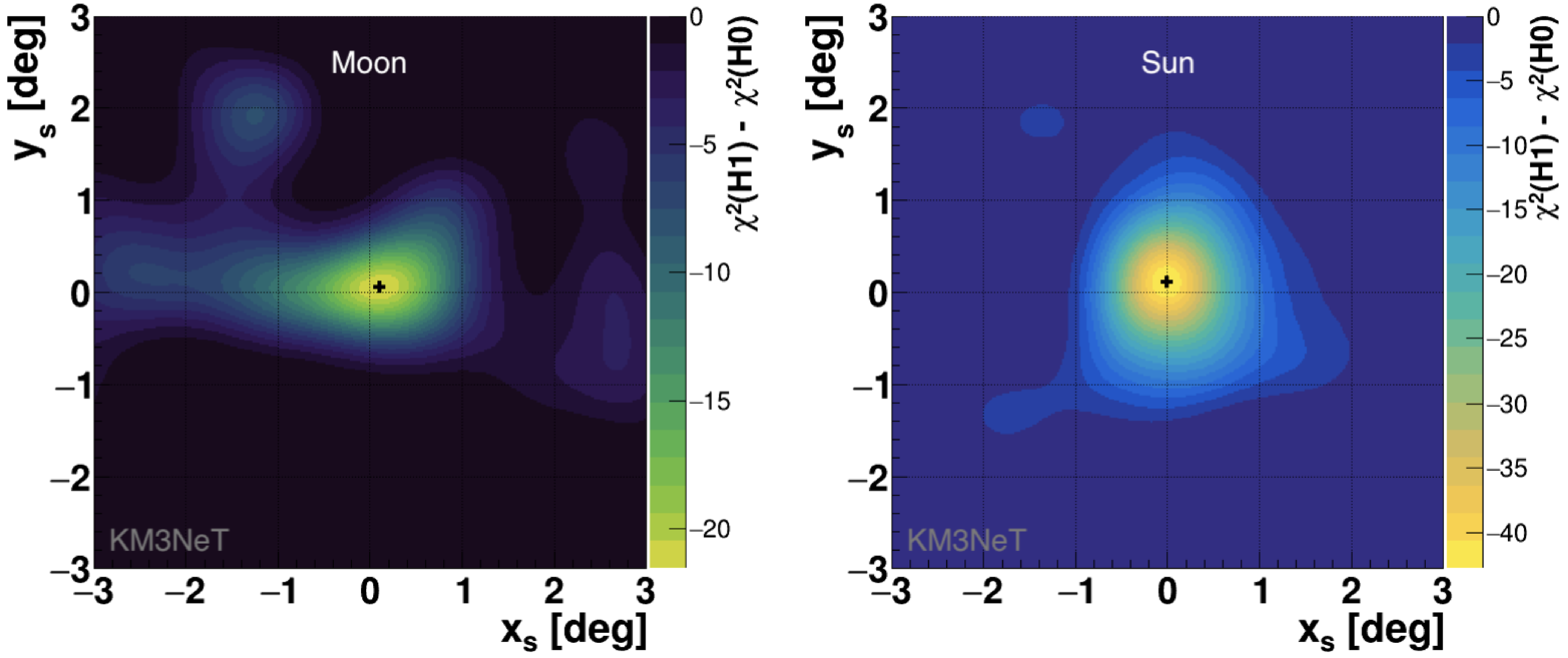
Positioning system



Pointing



ORCA6 (500 days) Eur.Phys.J. C 83 (2023) 3, 344	Sun	Moon
Statistical Significance	6.2 σ	4.2 σ
Resolution	0.65° ± 0.13°	0.49° ± 0.15°



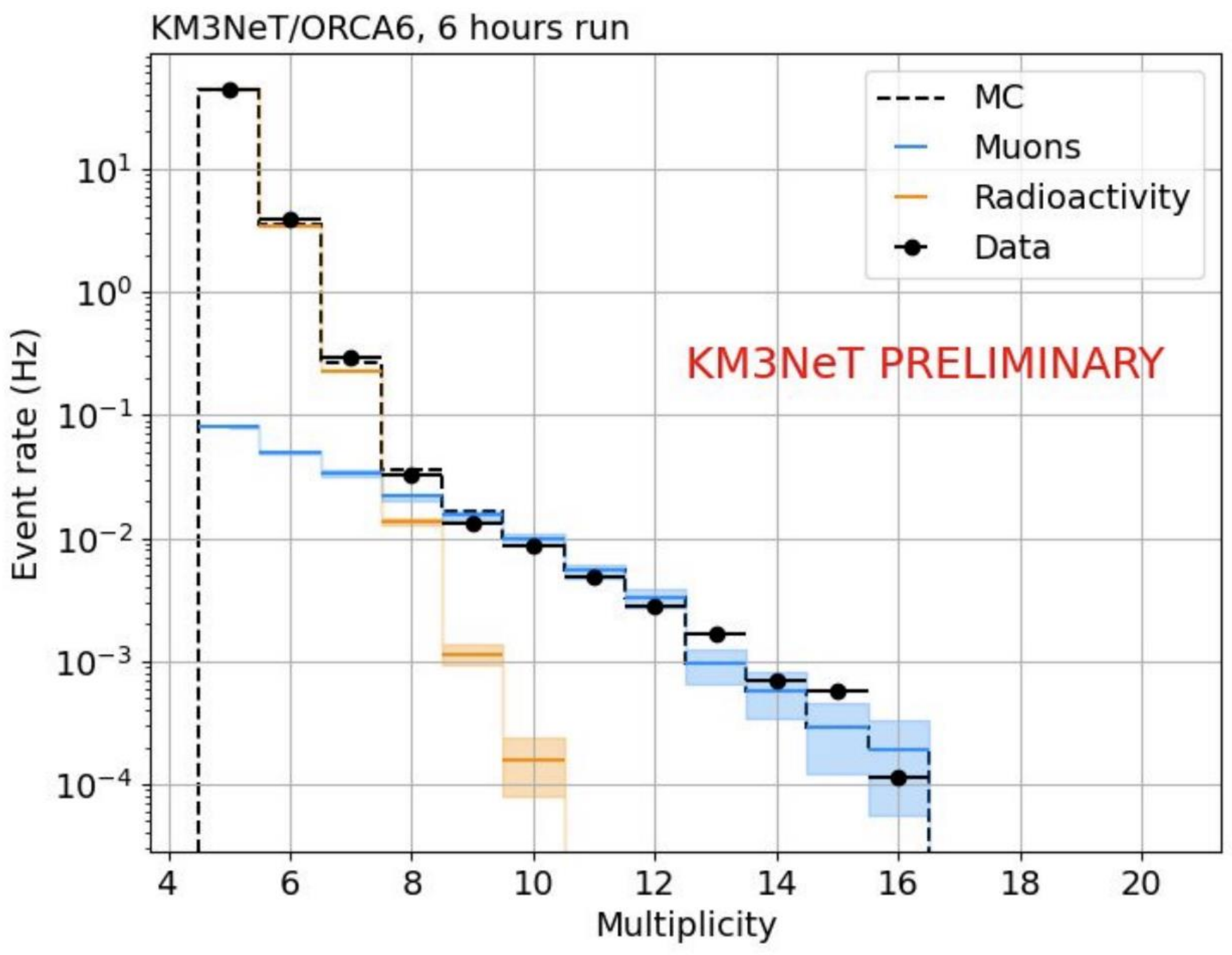
- Cosmic rays are excellent source of particles for calibration
- Timing calibration between DOMs and DUs
- Absolute orientation calibration and positioning calibration check → Moon/Sun
- Measurement of water properties (from stopping muons)

Some highlights

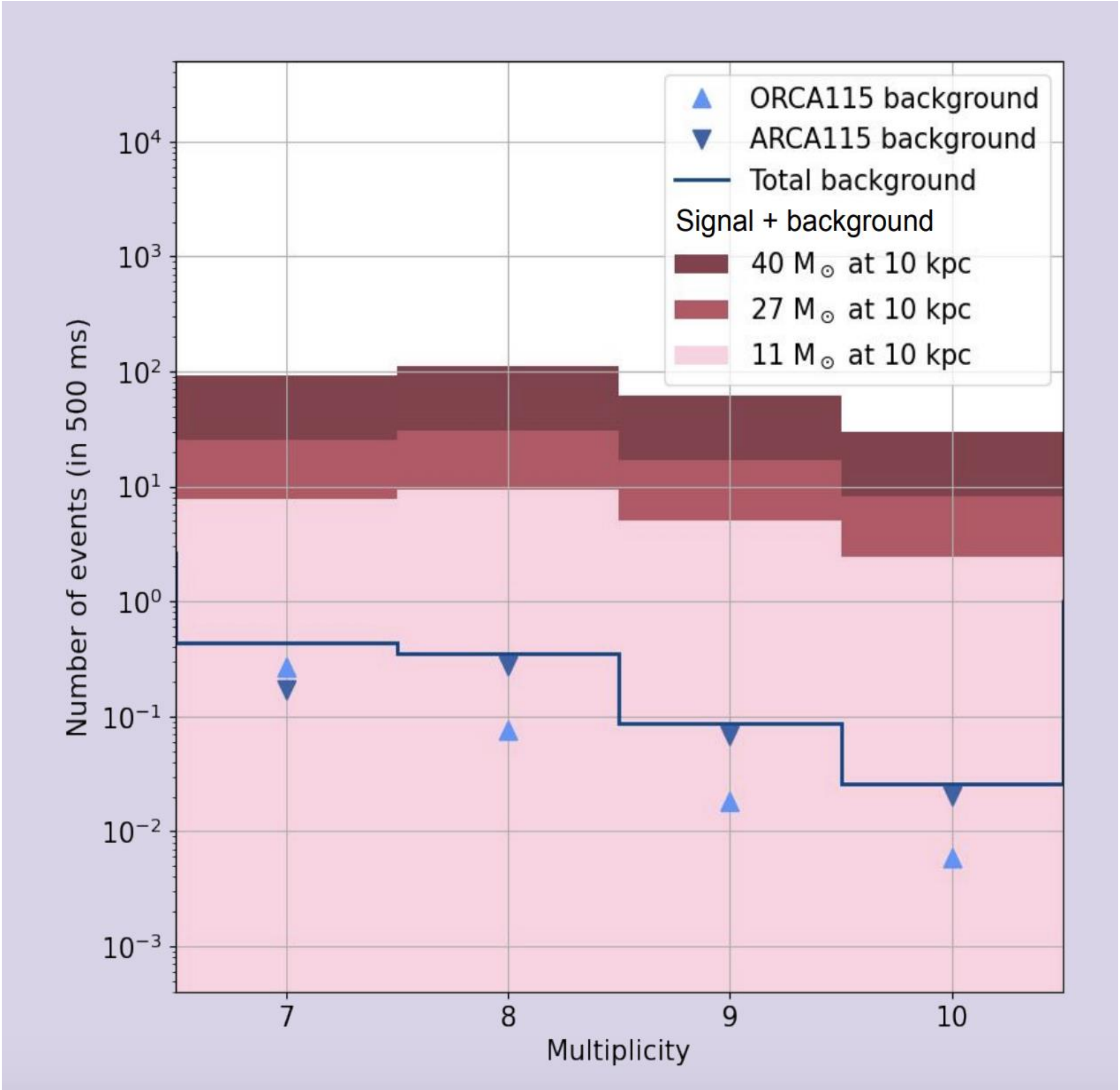
Supernova explosion – ARCA+ORCA

- Each DOM used as single detector
- Discrimination using average direction, signal concentration, multiplicity and Time-over-Threshold (signal intensity)
- on-line alert system for CCSN integrated in SNEWS
- >5σ for ARCA+ORCA for 27M⊙ at a distance <50kpc

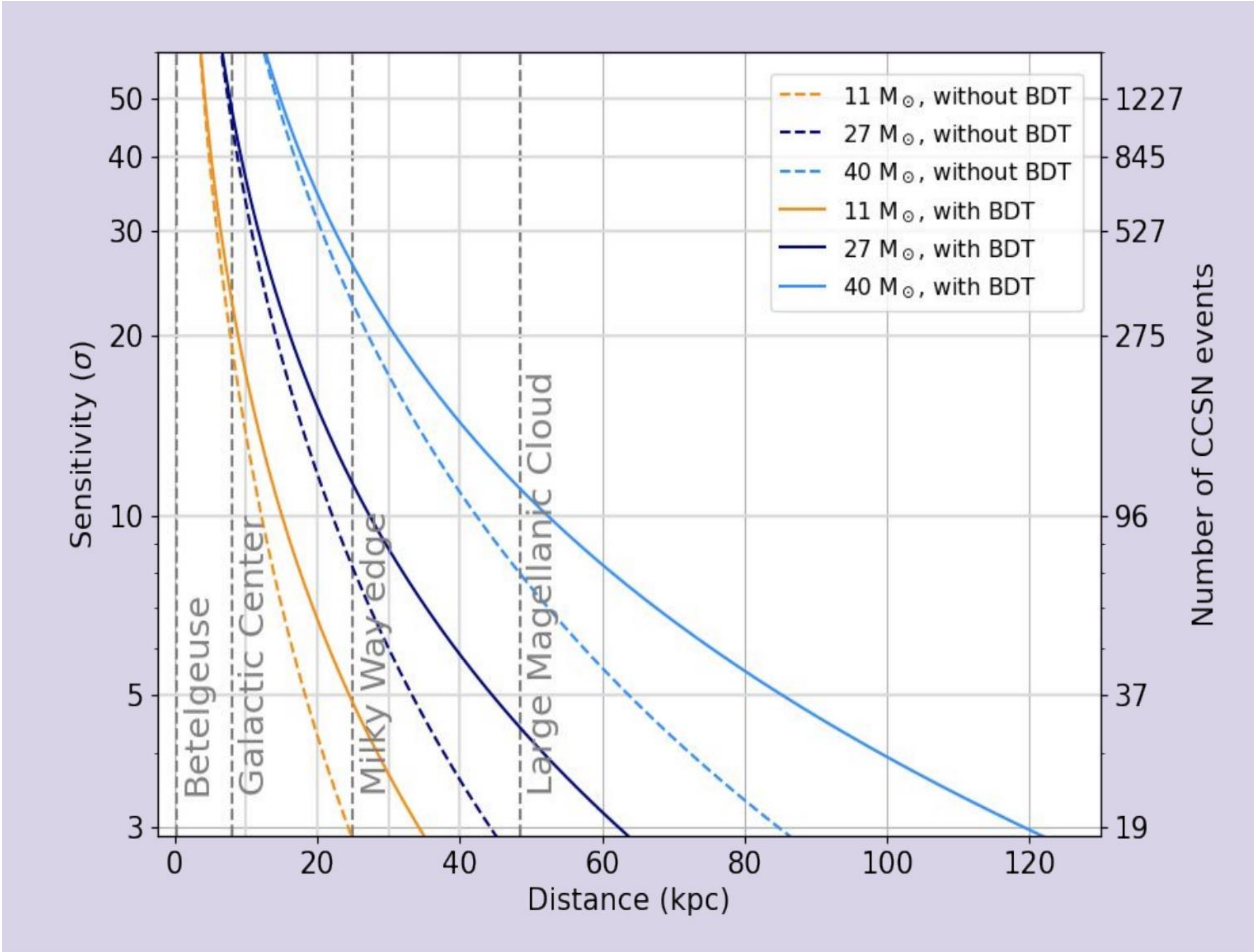
Multiplicity plot



expected S vs B

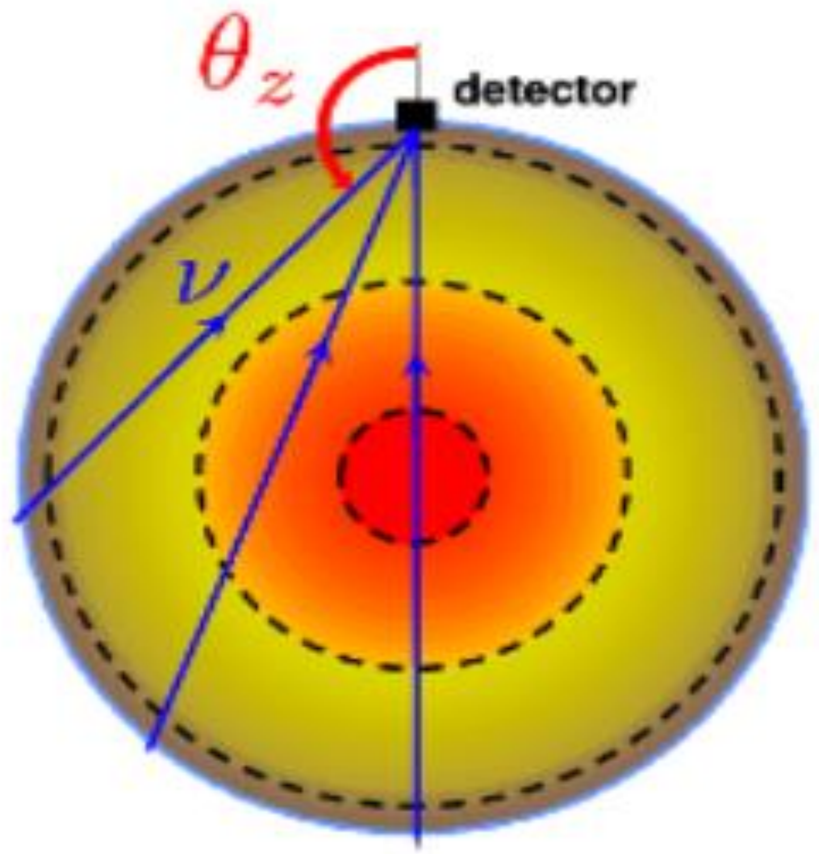


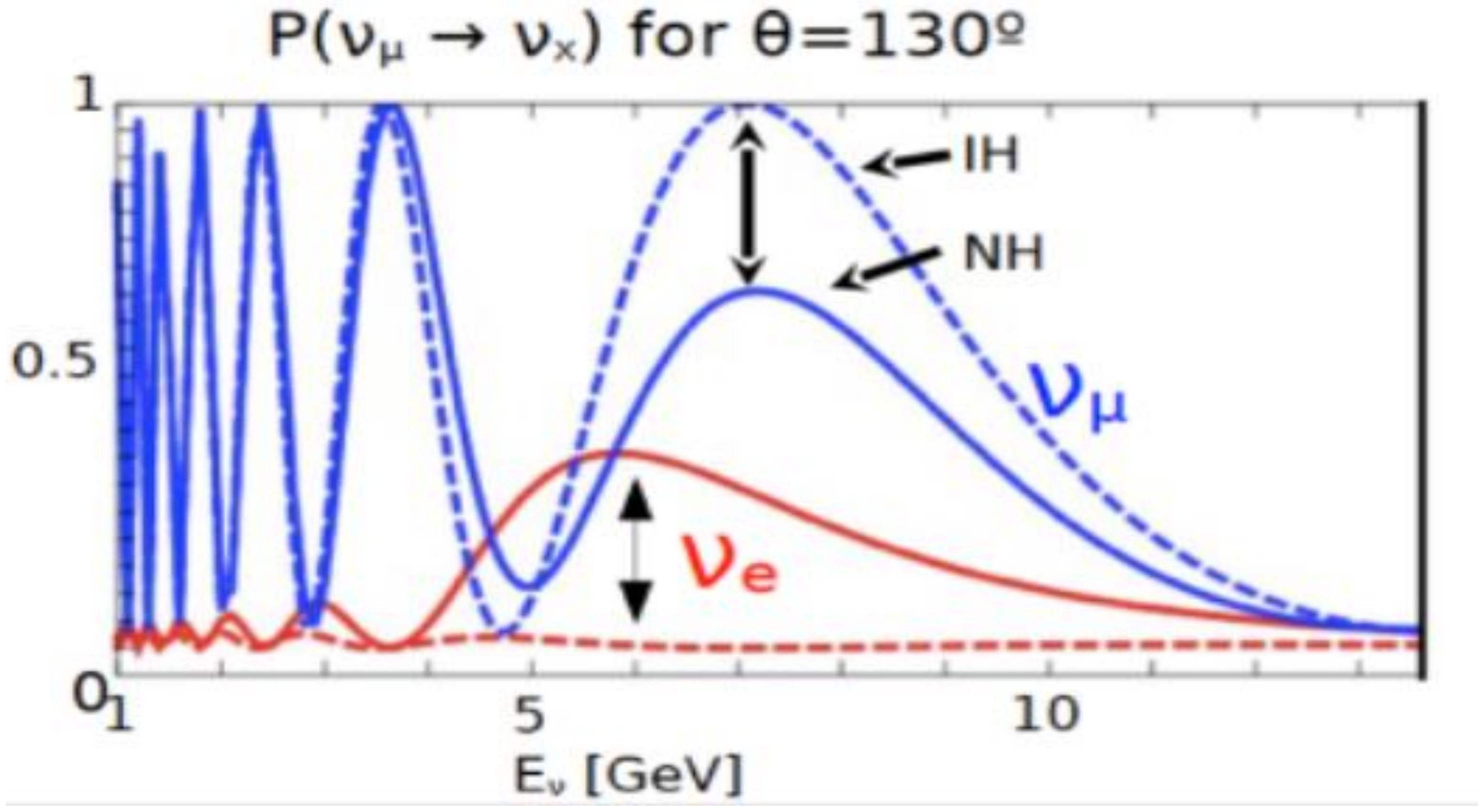
significance

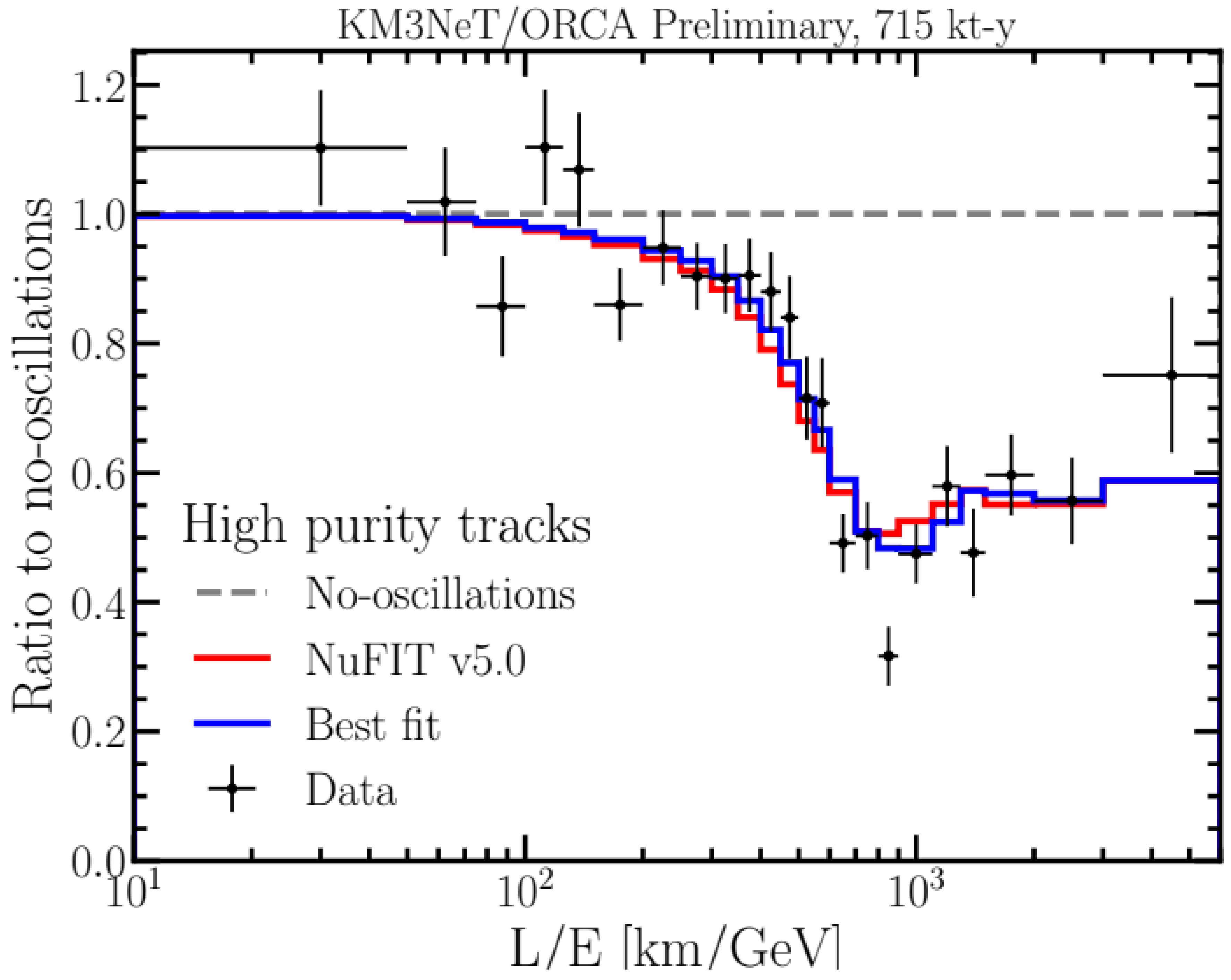


Neutrino oscillations - ORCA

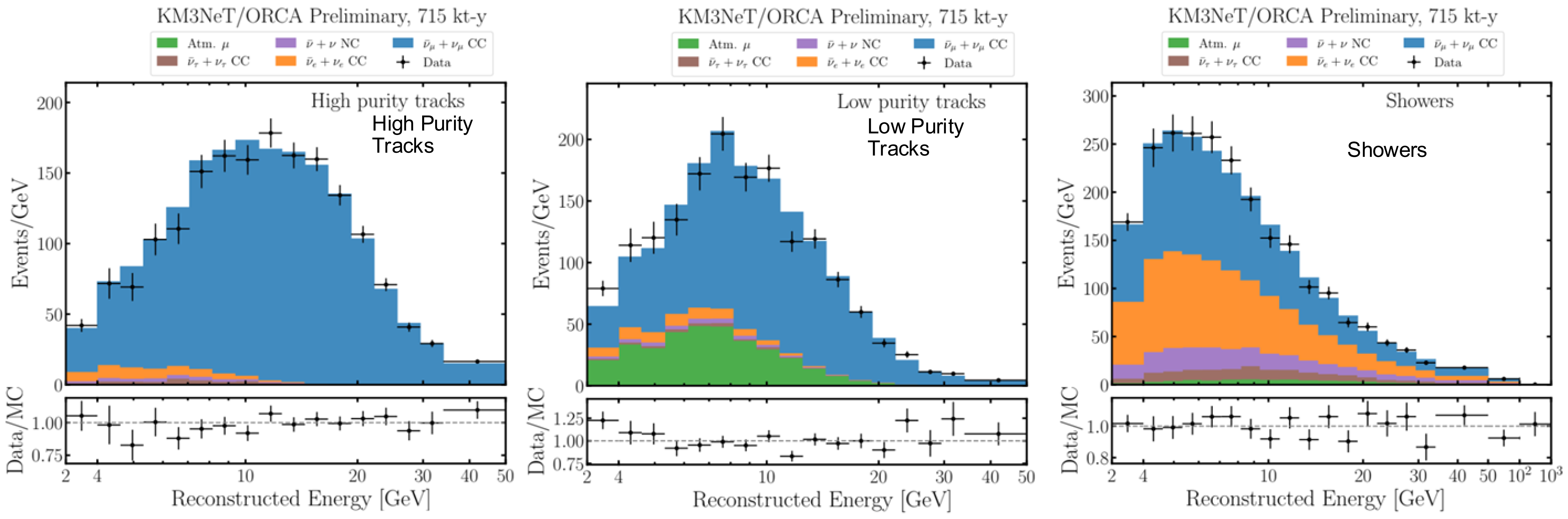
- Baseline from 50 to 12800 km
- Clear oscillation pattern in L/E
- 9751 neutrino candidates
- 97% pure ν_μ-CC sample in high purity track-like class
- 91% accuracy in classifying ν_e-CC events as showers
- ~1300 νe-CC events expected in shower-like sample







datasets



NMO - ORCA

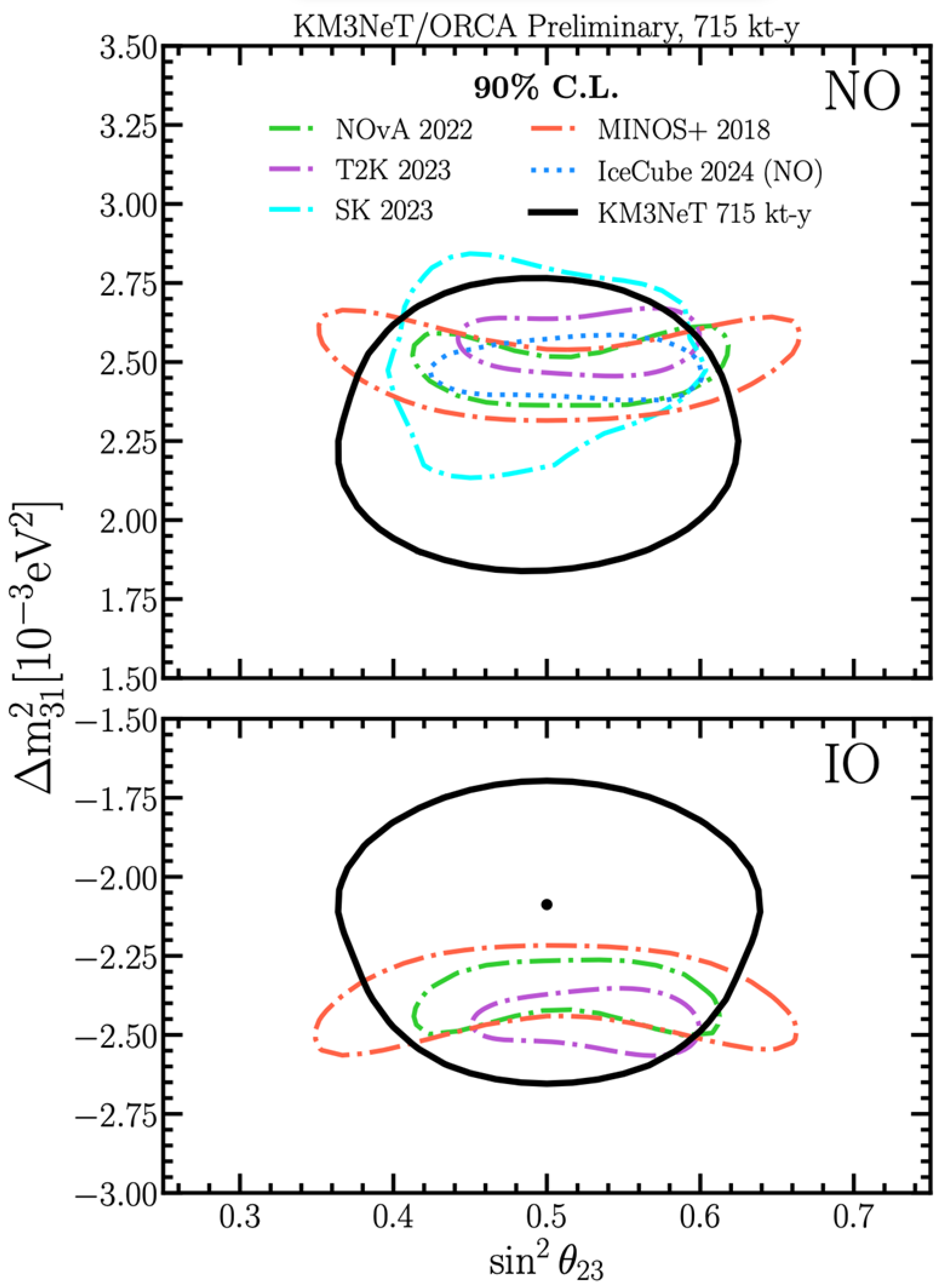
- Fully consistent with world data
- NO slightly disfavoured at 1.7 sigma
- ORCA6-10-11 data

$$\Delta m^2_{31} = \begin{cases} -2.09^{+0.17}_{-0.21} \times 10^{-3}\mathrm{eV}^2, & \mathrm{IO} \\ [2.10, 2.37] \times 10^{-3}\mathrm{eV}^2, & \mathrm{NO} \end{cases}$$

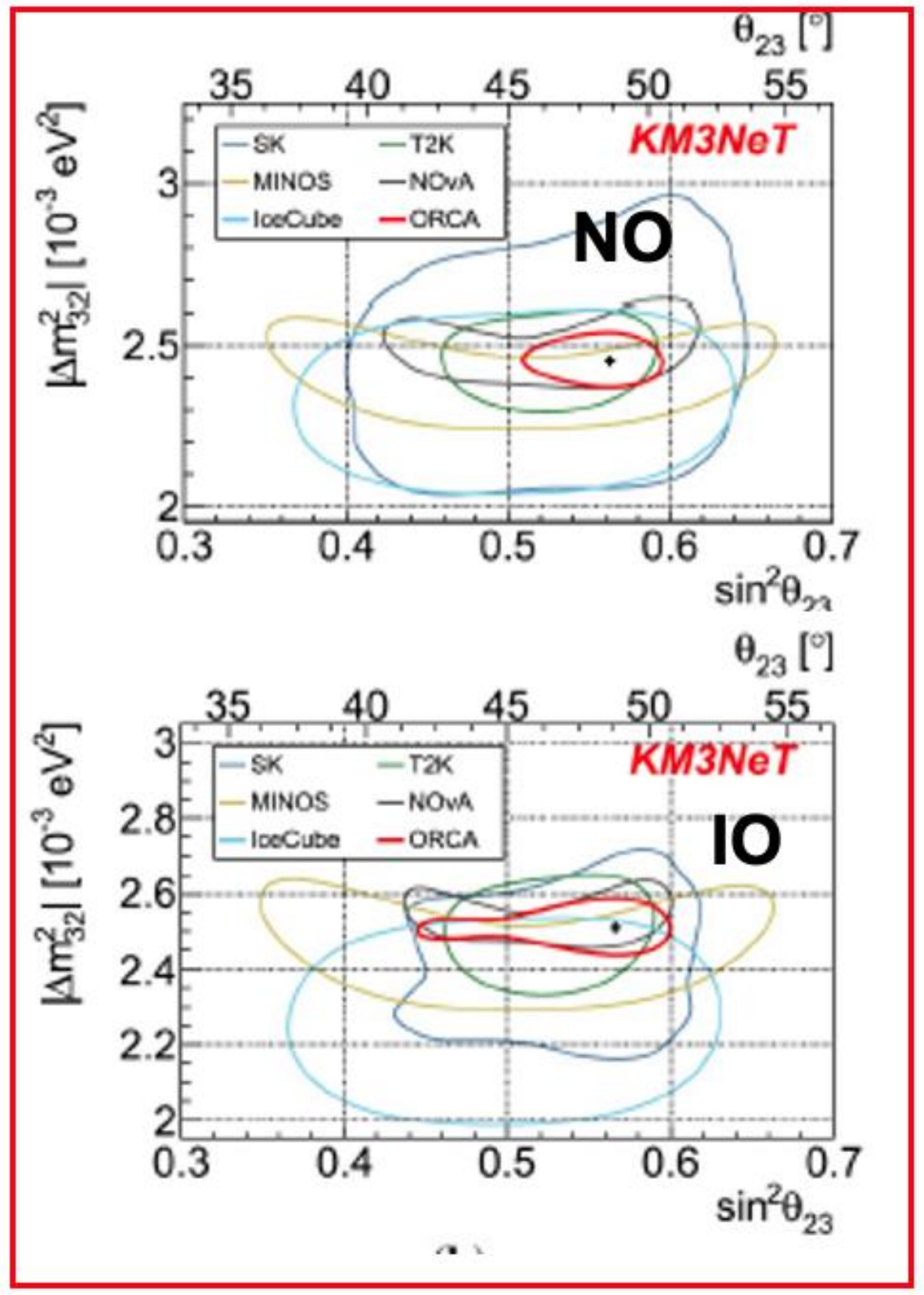
$$\sin^2\theta_{23} = 0.50 \pm 0.07$$

$$2\log(\mathcal{L}_{IO}/\mathcal{L}_{NO}) = 0.61$$

Δm^2_{31} vs $\sin^2\theta_{23}$



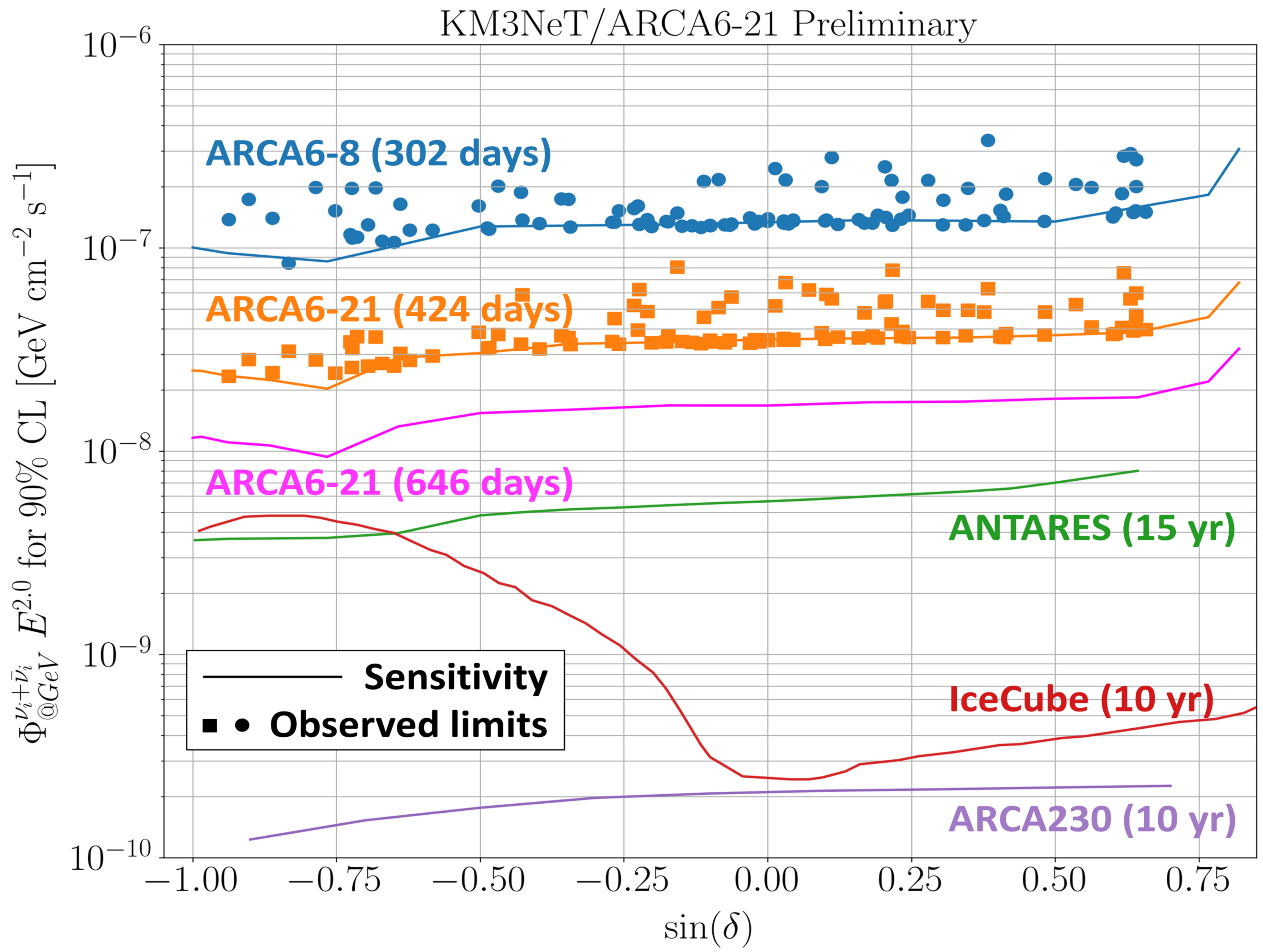
Full detector expectations



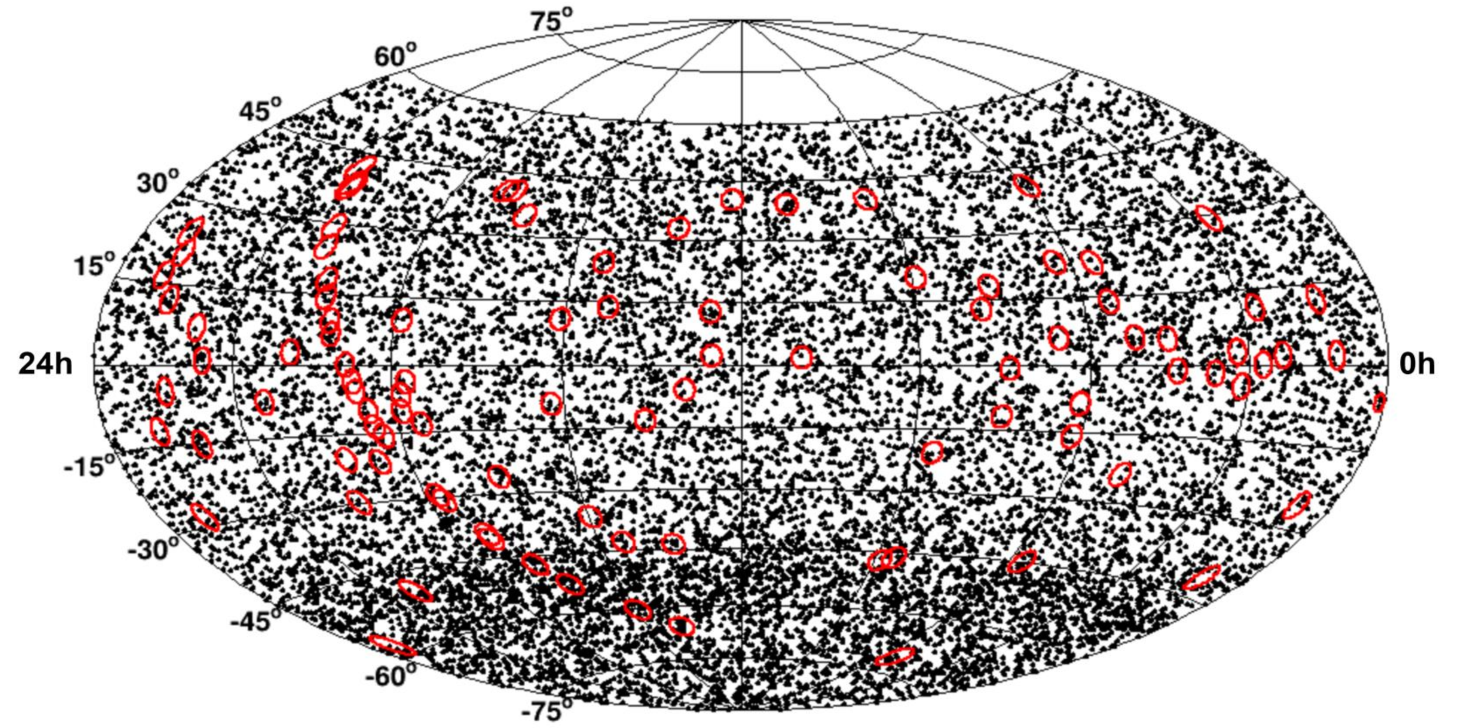
Search for point-like sources - ARCA

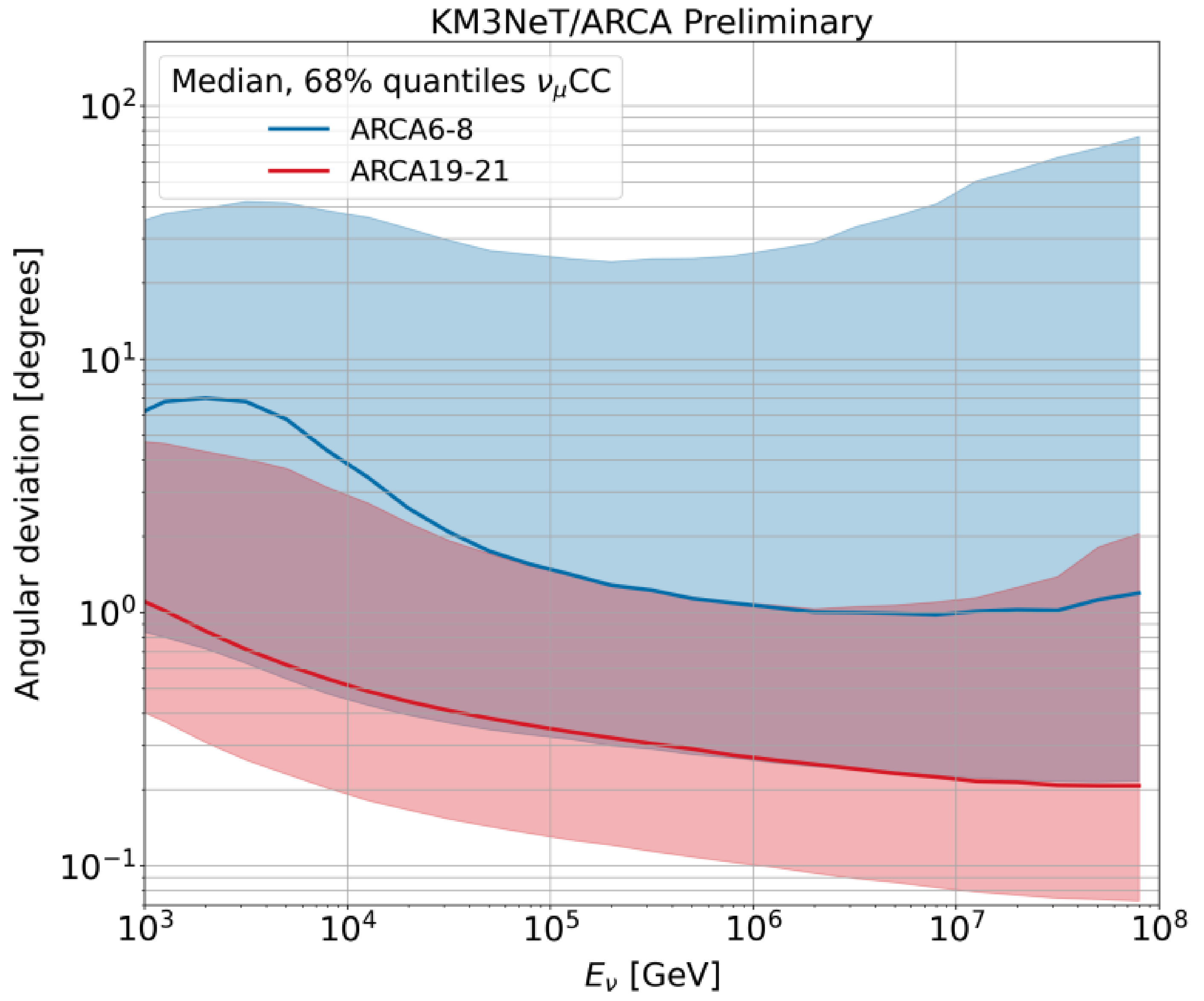
- Search for an excess ν (w.r.t E^{-2}) from the direction of a list of 101 candidate sources (Galactic (TeVCat - γ) + AGN)
- JOINT ARCA-ANTARES searches ongoing → ANTARES (15y) contributes most significantly, enhancement by 10% observed adding ARCA data (424d) → Km3NeT upper limits quickly reaching ANTARES

- Improved angular resolution in ARCA
- Analysis done in 2D space of energy and distance from source
- Background dominated by mis-reconstructed atmospheric μ → no source above BKG yet



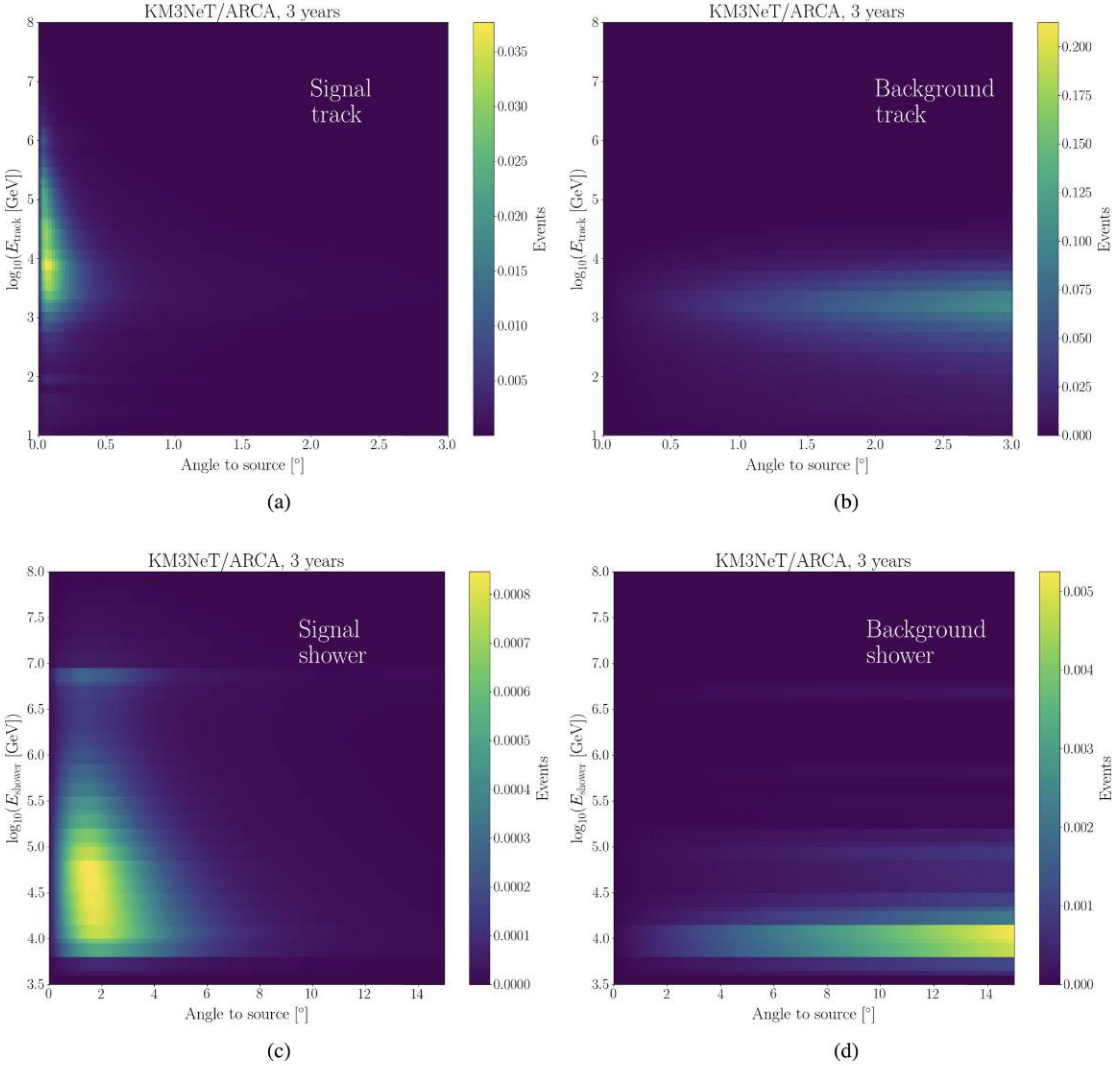
source catalogue (2.5° dot)





Search for point-like sources - ARCA

point source + bkg simulation: showers + tracks



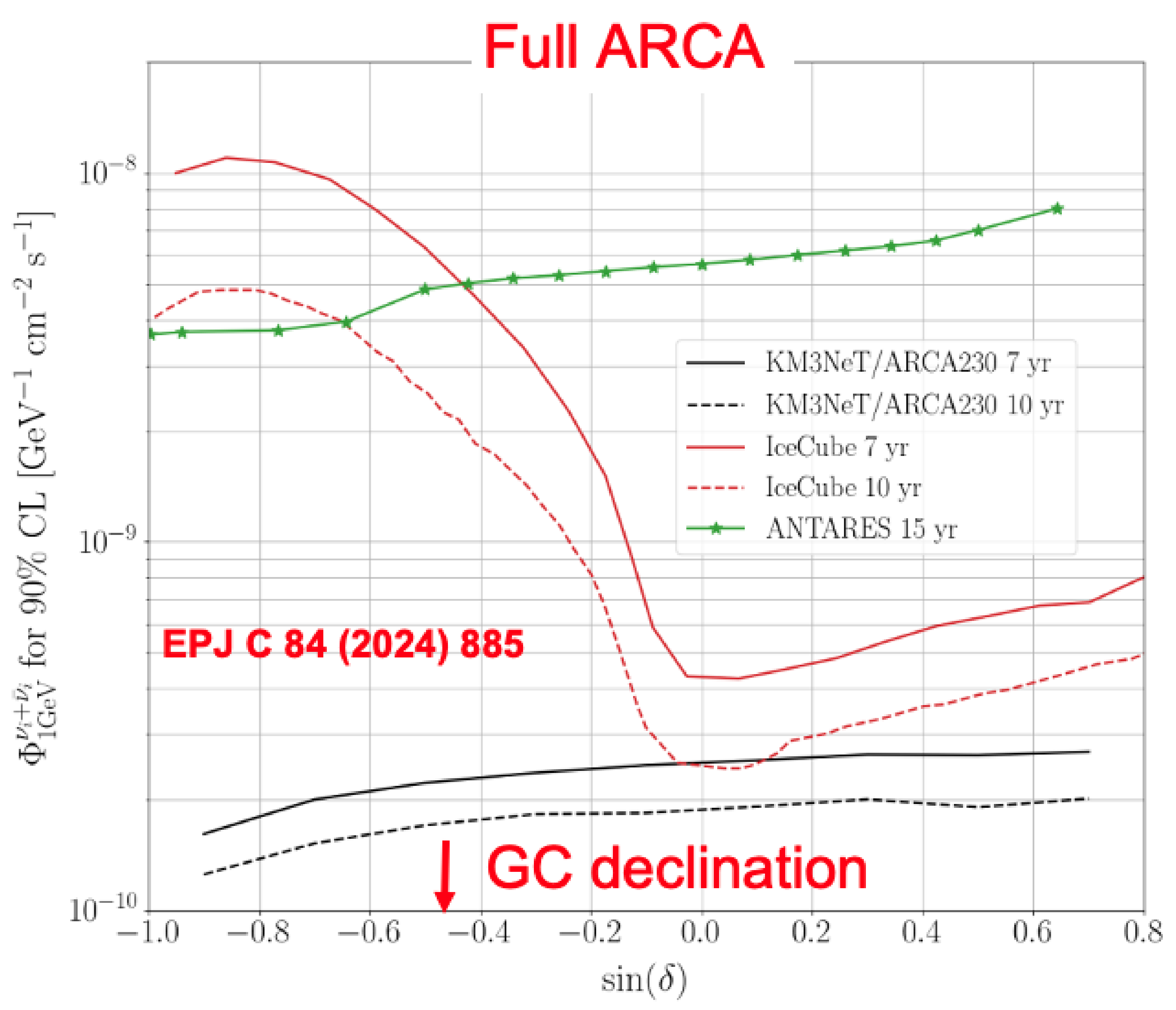
- SPL source flux spectrum

$$\Phi^{\nu_i+\bar{\nu}_i} = \Phi_0\left(\frac{E}{\mathrm{GeV}}\right)^{-\gamma}$$

- $\sin(\delta) = 0.1$, $\gamma = 2.0$, $\Phi_0 = 4 \times 10^{-9}\ \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}$
- 3 years of simulated data taking
- The flux models convolved with the effective area, the simulated point spread function and energy response

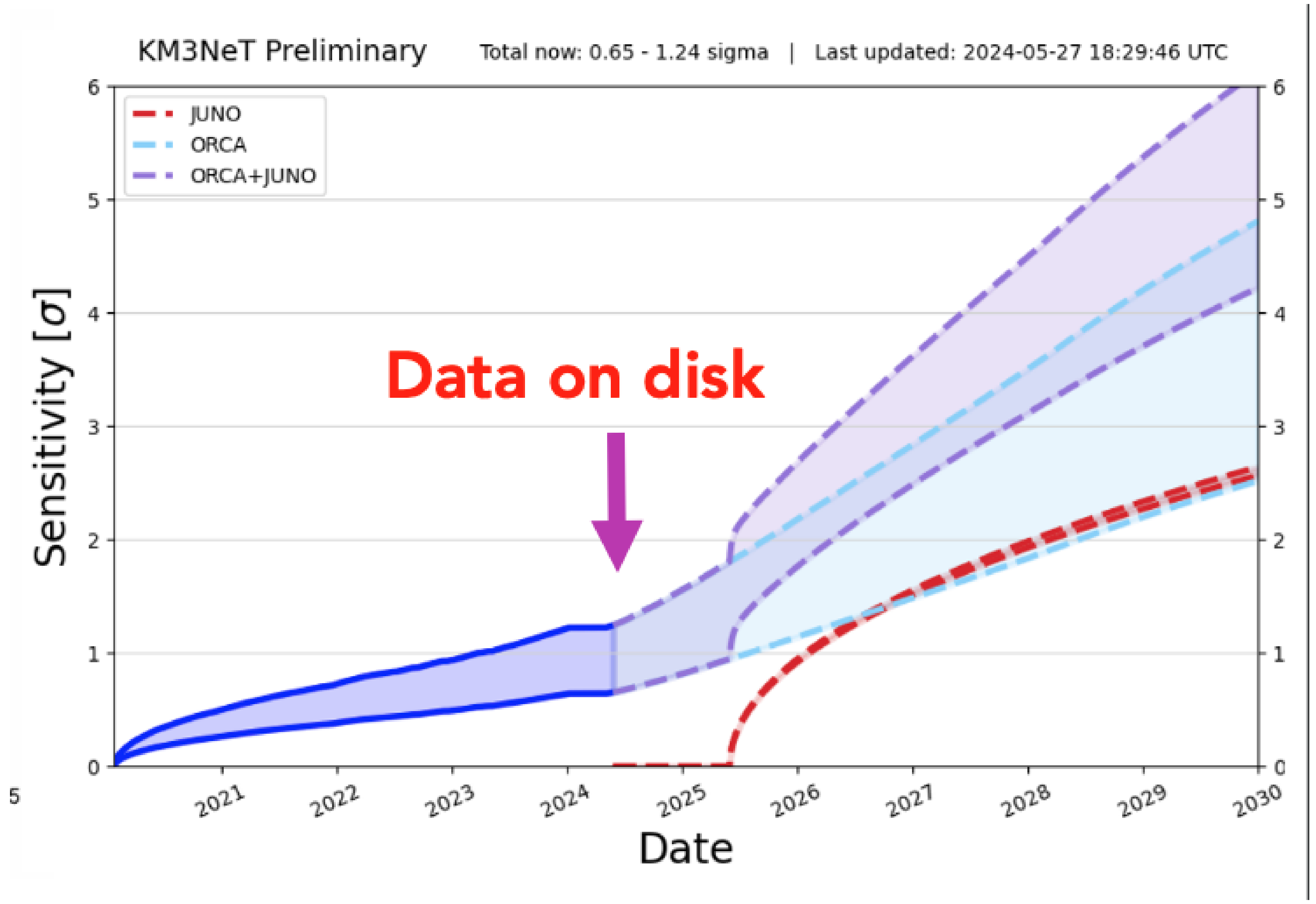
Perspectives

ARCA - Sensitivity to point-like sources



Unprecedented performance for the southern sky

ORCA - Neutrino mass ordering



5σ can be reached in the next 5-6 years if combined with Juno

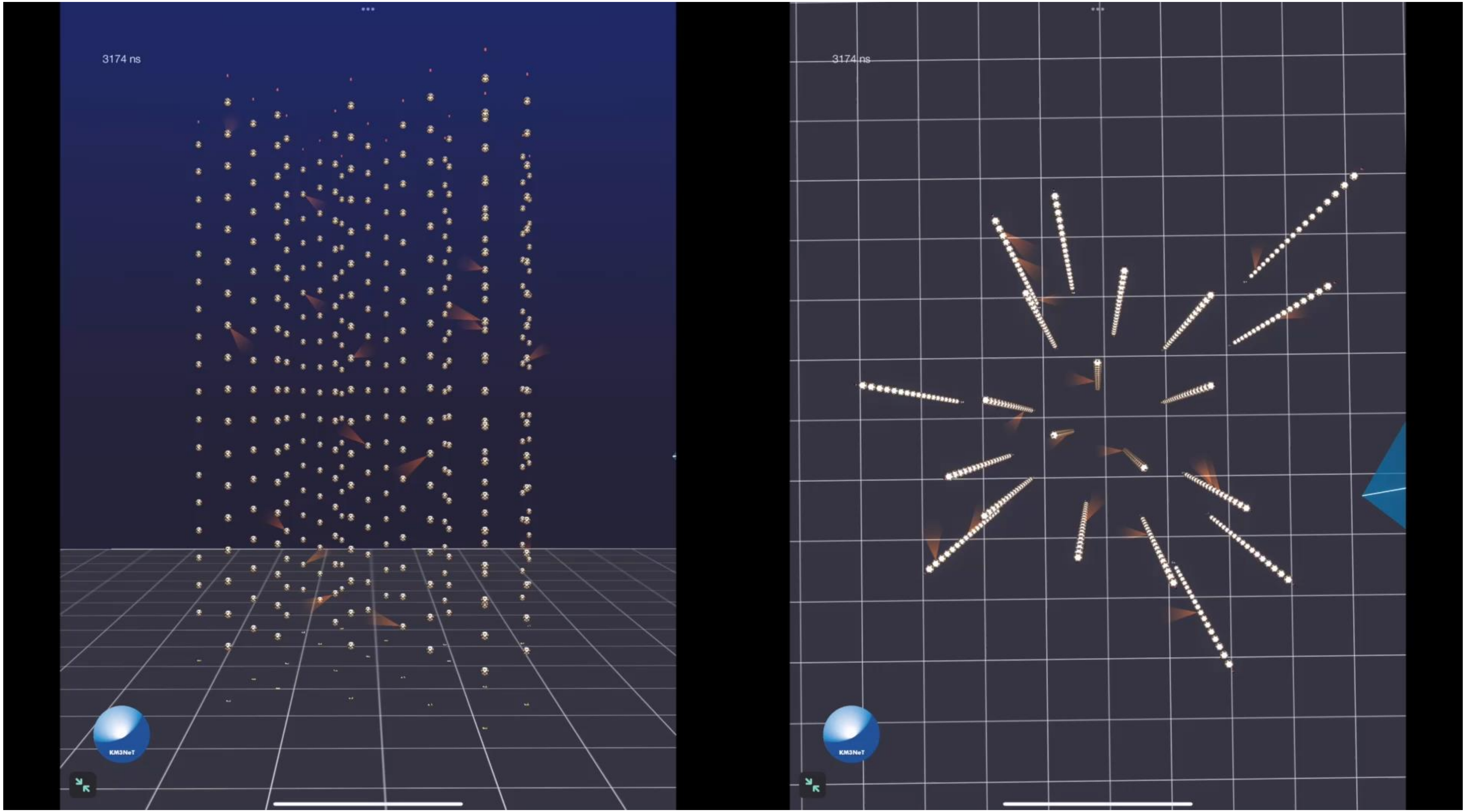
Predictions based on the current construction plan.

2008	2015-17	2022	TODAY	2028
full ANTARES	ARCA 6 DUs ORCA 6 DUs	ANTARES stop ARCA 21 DUs ORCA 10 DUs	ARCA 33 DUs ORCA 24 DUs	Full ARCA & ORCA

The most energetic neutrino

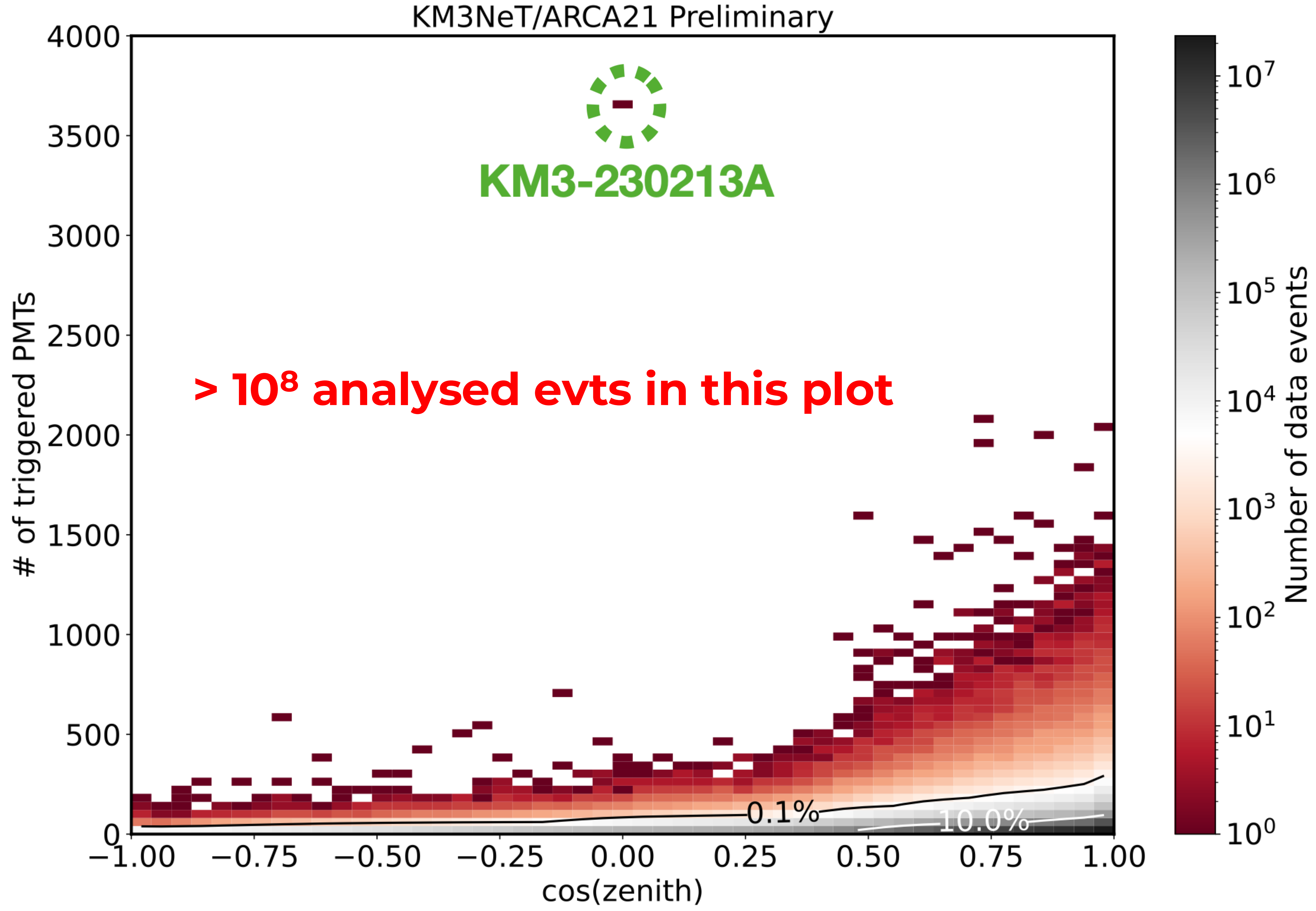
KM3NeT. *Nature* **638**, 376–382 (2025).
https://doi.org/10.1038/s41586-024-08543-1

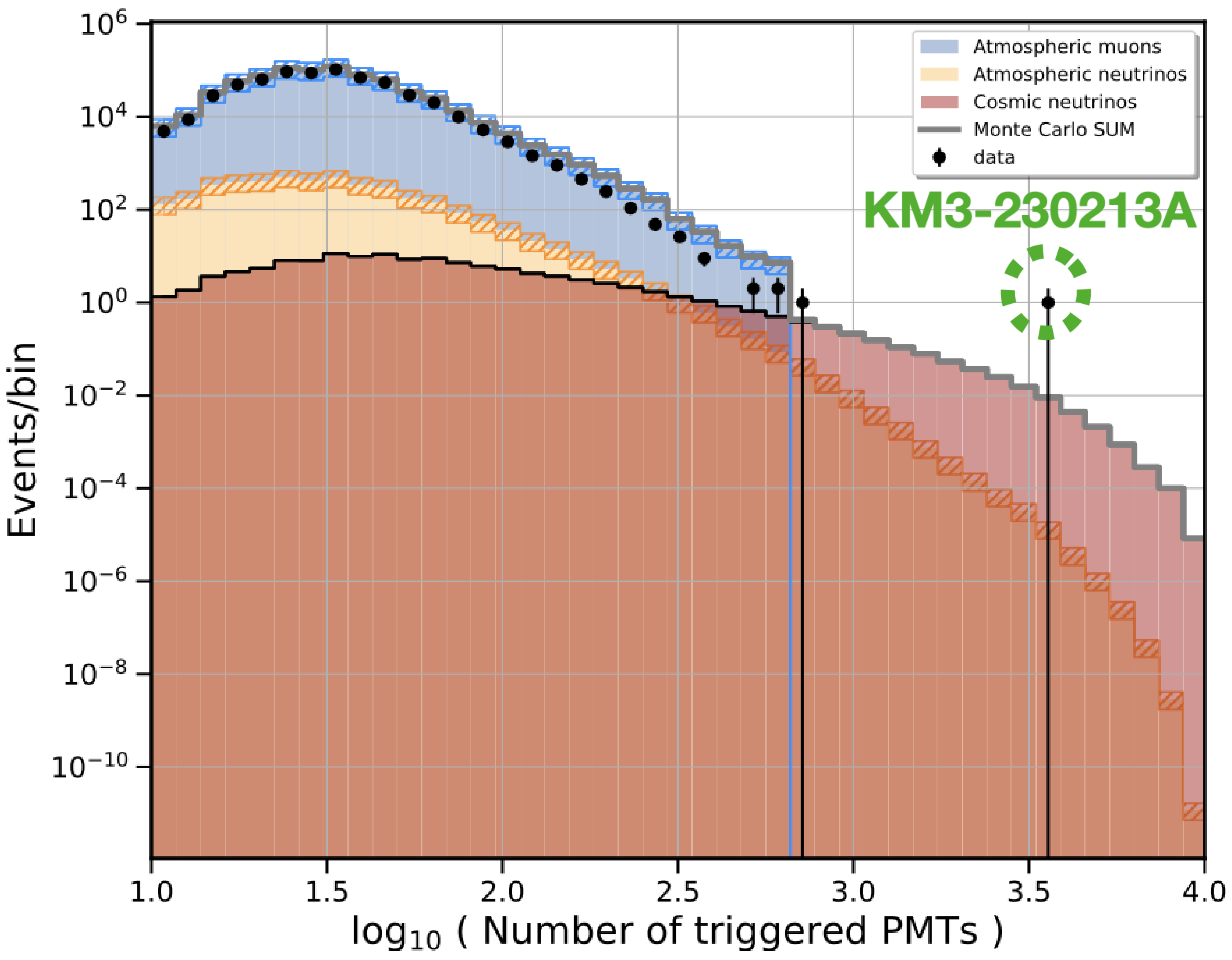
KM3-230213A



What happened

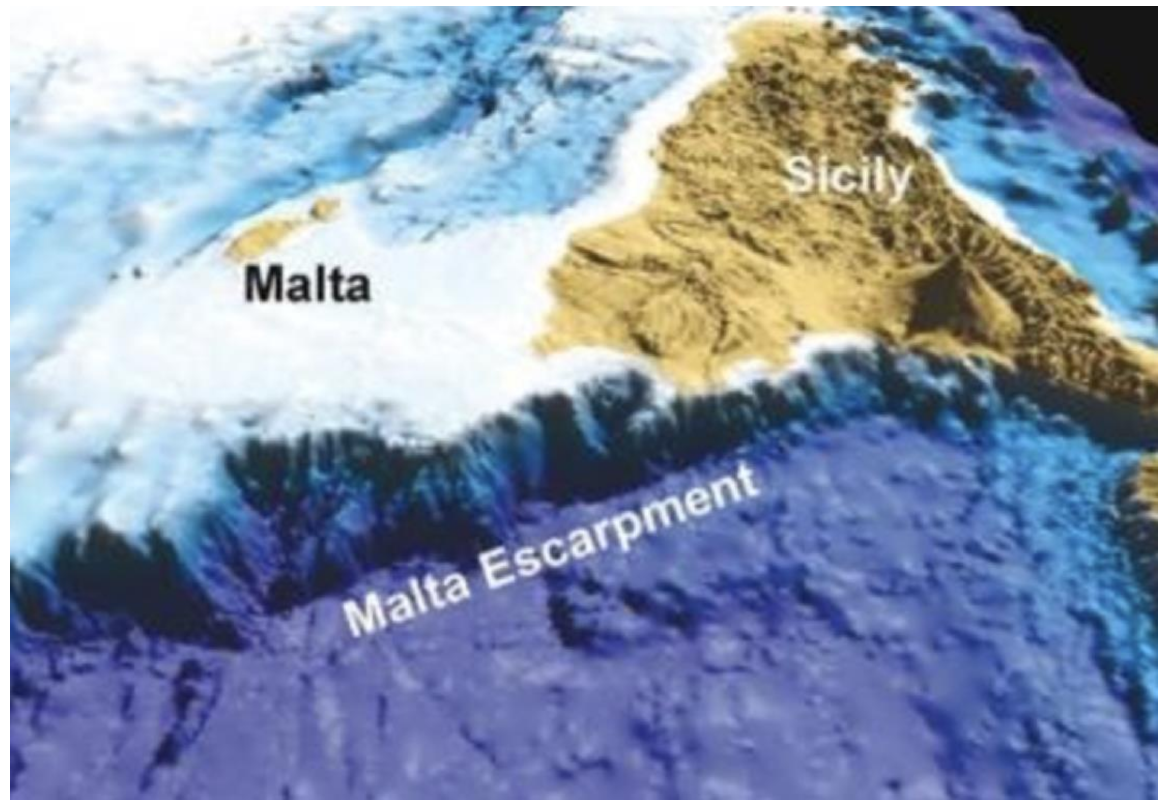
- 3672 PMTs (35 %) triggered → $28*10^3$ hits
- Likelihood of reco event = 1415 (aka it's good!)
- Reconstructed direction of 0.6°

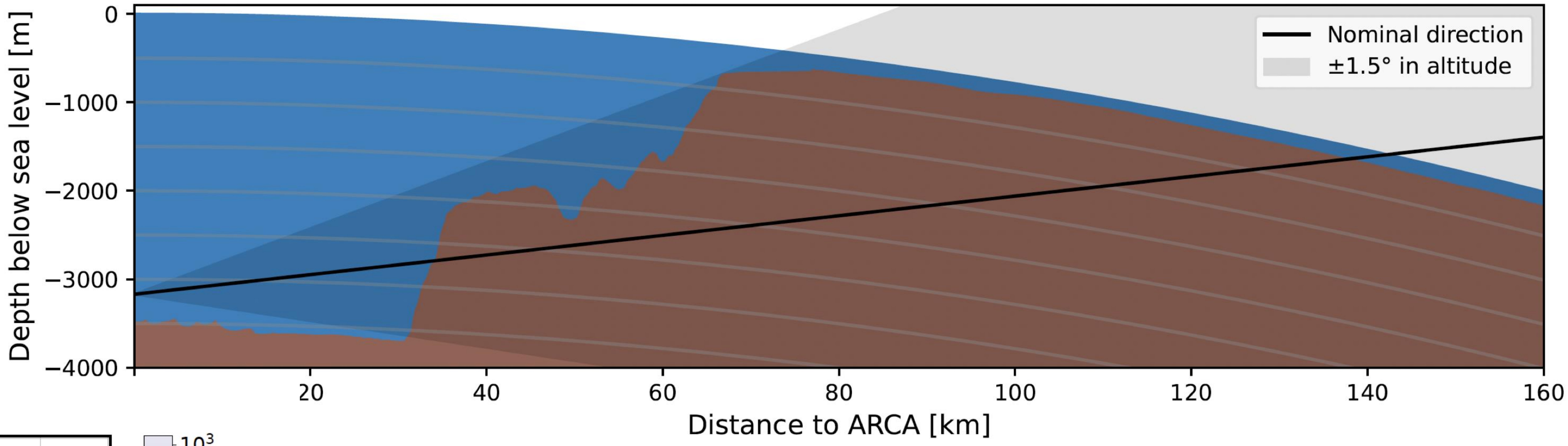


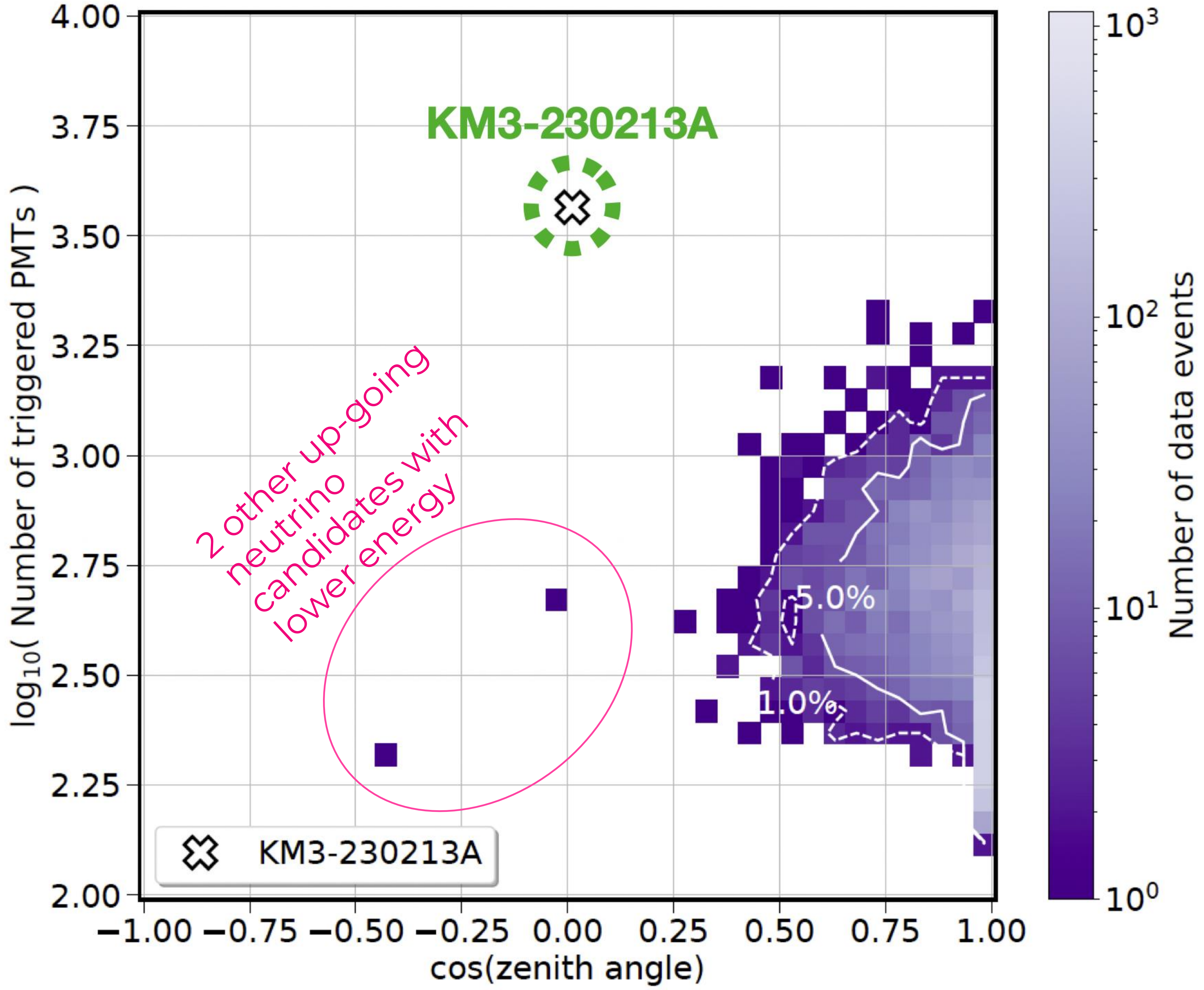


- **Atmospheric muons**
- **Atmospheric neutrinos**
- **Cosmic neutrino flux (from IceCube)**

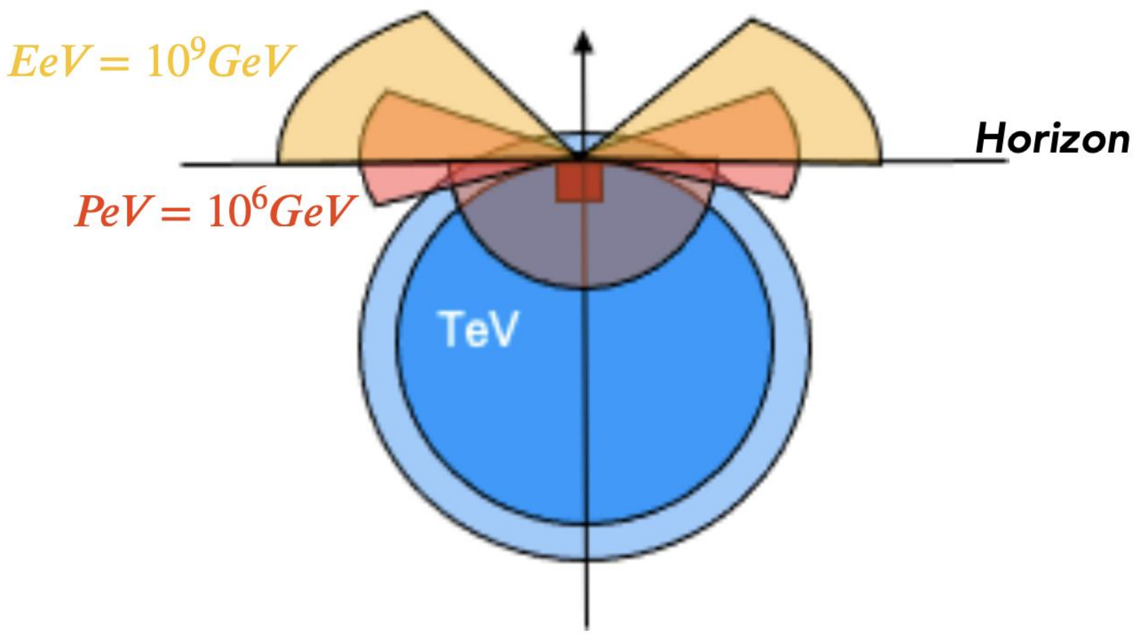
Direction







earth becomes opaque $E_\nu > 200$ TeV
→ UHE candidates expected from the horizon



- Reconstructed direction of 0.6° → slightly above the horizon
- 14 km of crossed material
- The track points towards the *Malta Escarpment*

- clear signature with negligible contribution of atmospheric muons (< 10^{-10} / year) and prompt atmospheric neutrinos (< 10^{-5} / year)
- multi-muon from coincident air-showers also unlikely given the quality of reconstruction

Background

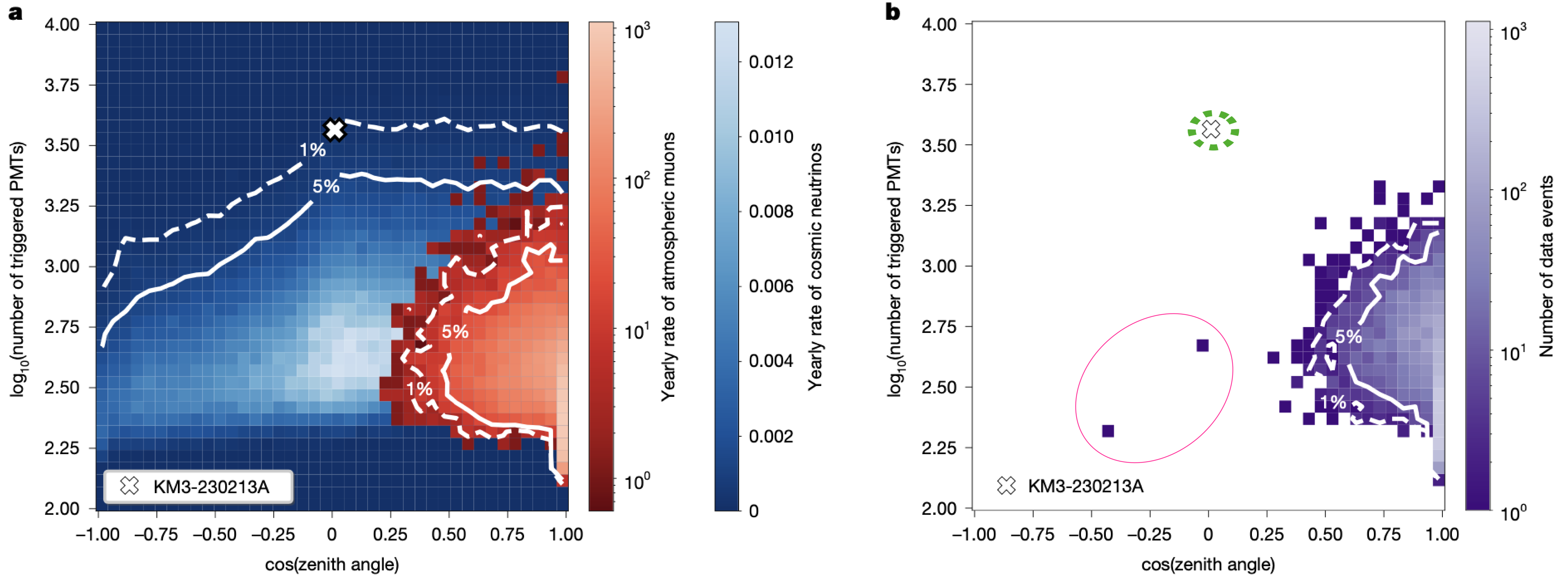
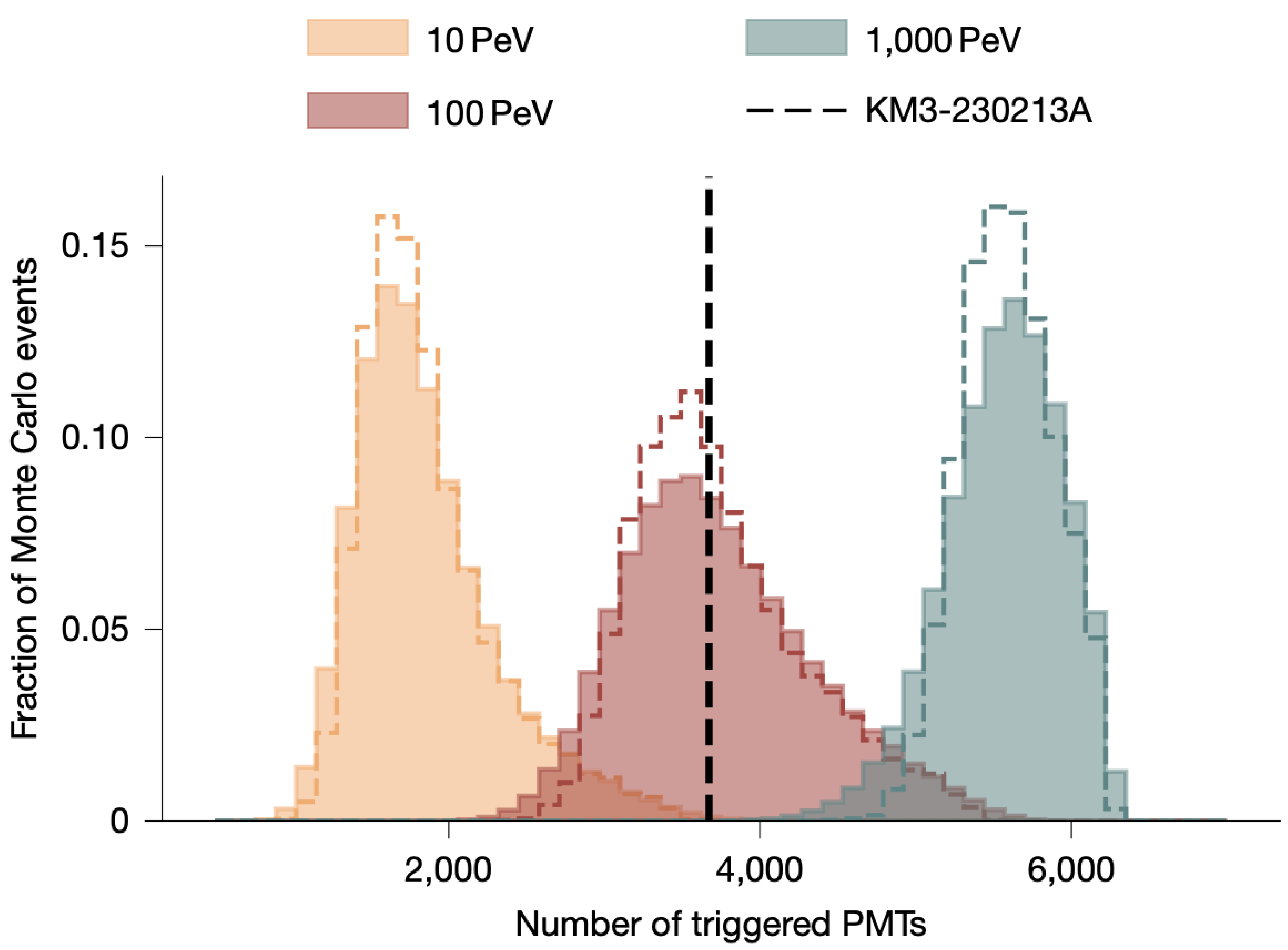


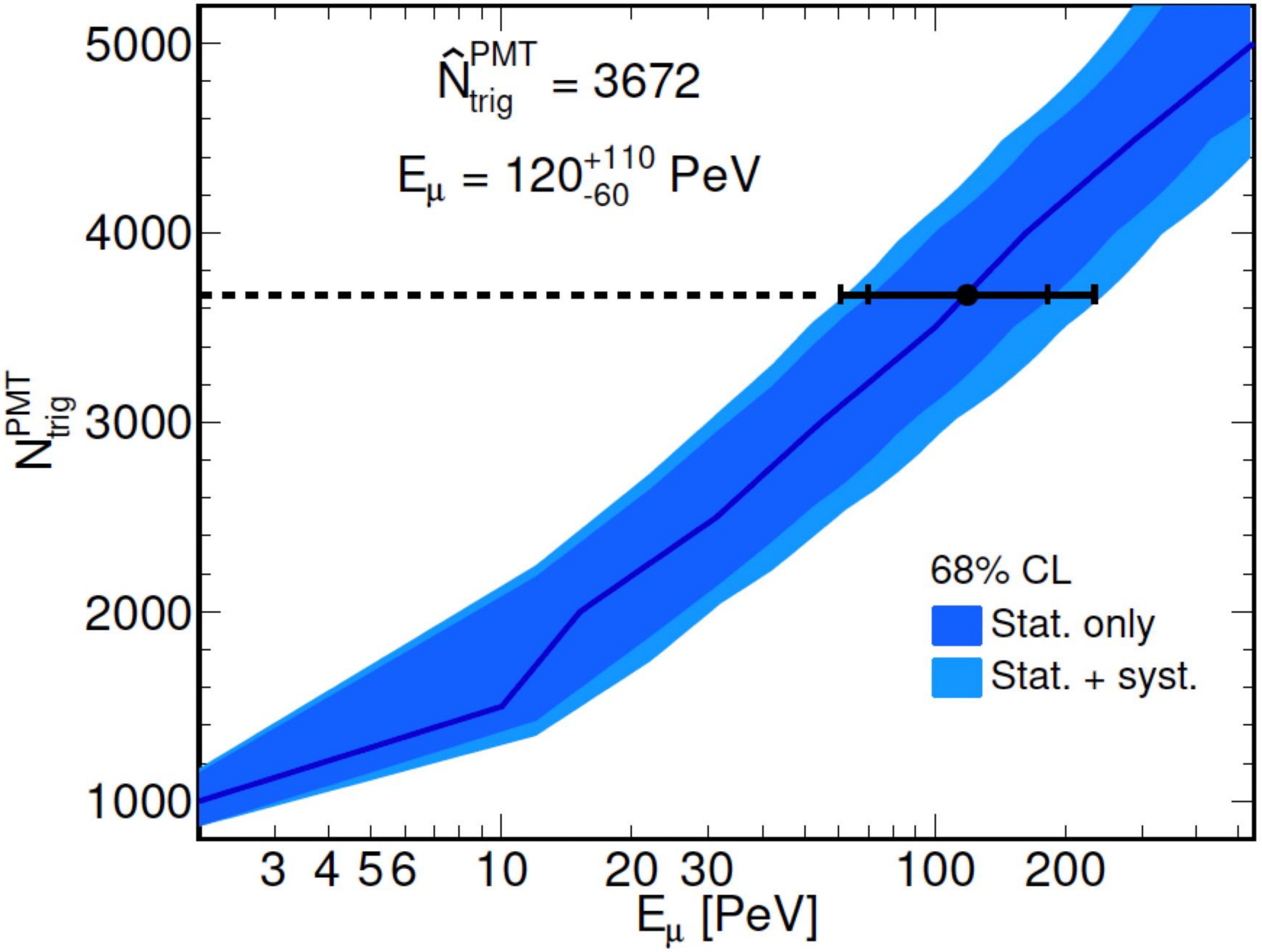
Fig. 3 | Background rates. a, Expected yearly rate of atmospheric muons and cosmic neutrinos (according to the best-fit flux of ref. 5) in ARCA per bin of $\mathcal{N}_{\mathrm{trig}}^{\mathrm{PMT}}$ and cos(zenith angle). The solid (dashed) lines mark the boundary of the phase space outside which 5% (1%) of the muon and neutrino distributions are contained. KM3-230213A is shown by the cross. **b**, Number of events collected in the ARCA detector over the 287 days of data taking with 21 detection lines, with the same selection cuts. Two upgoing, lower-energy events are visible as well as KM3-230213A, which are candidate neutrino events, subject to future analysis.

Energy estimation

At these energies, we must trust our Monte Carlo, light propagation models and water properties …

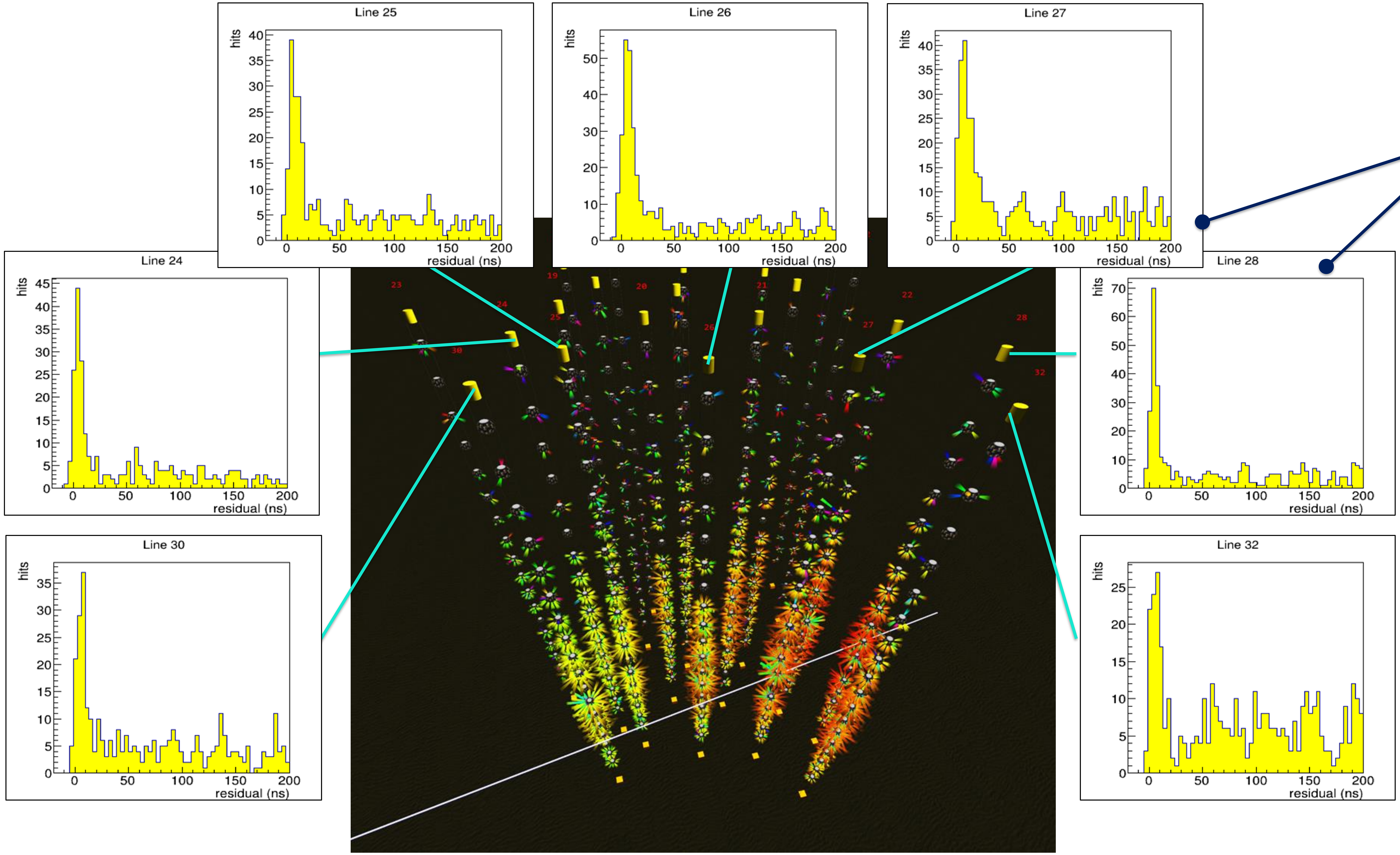
- E estimation via standard MC framework + independent GPU-based photon tracking code → agreement is within 10 %
- True E_{mu} that maximises the likelihood for a given N_{pmt} is shown in blue





$E_\mu = 120^{+110}_{-60}$ PeV consistent with interaction of a ν_μ with $E_\nu = 220^{+570}_{-110}$ PeV

Reconstructed track

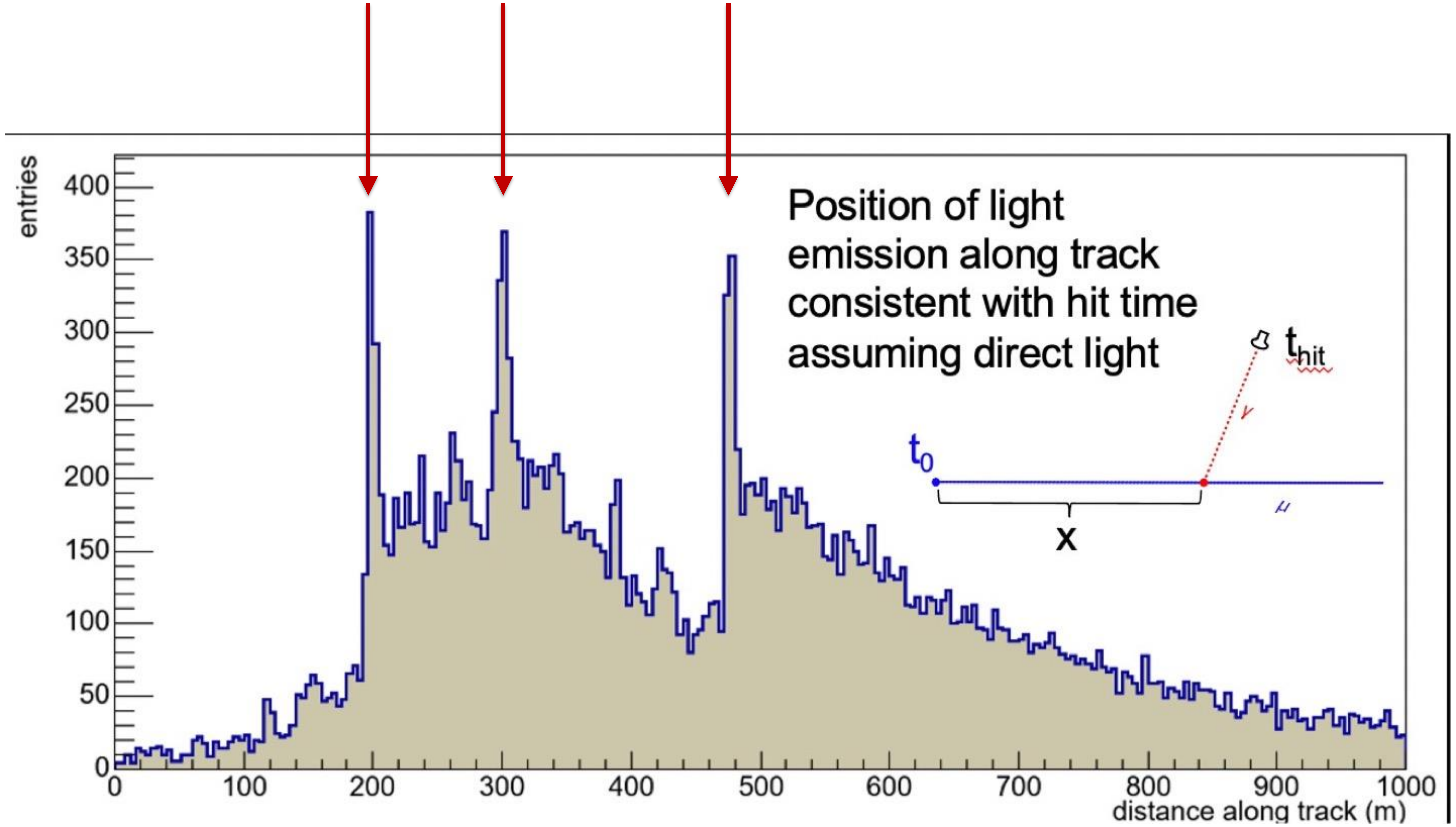


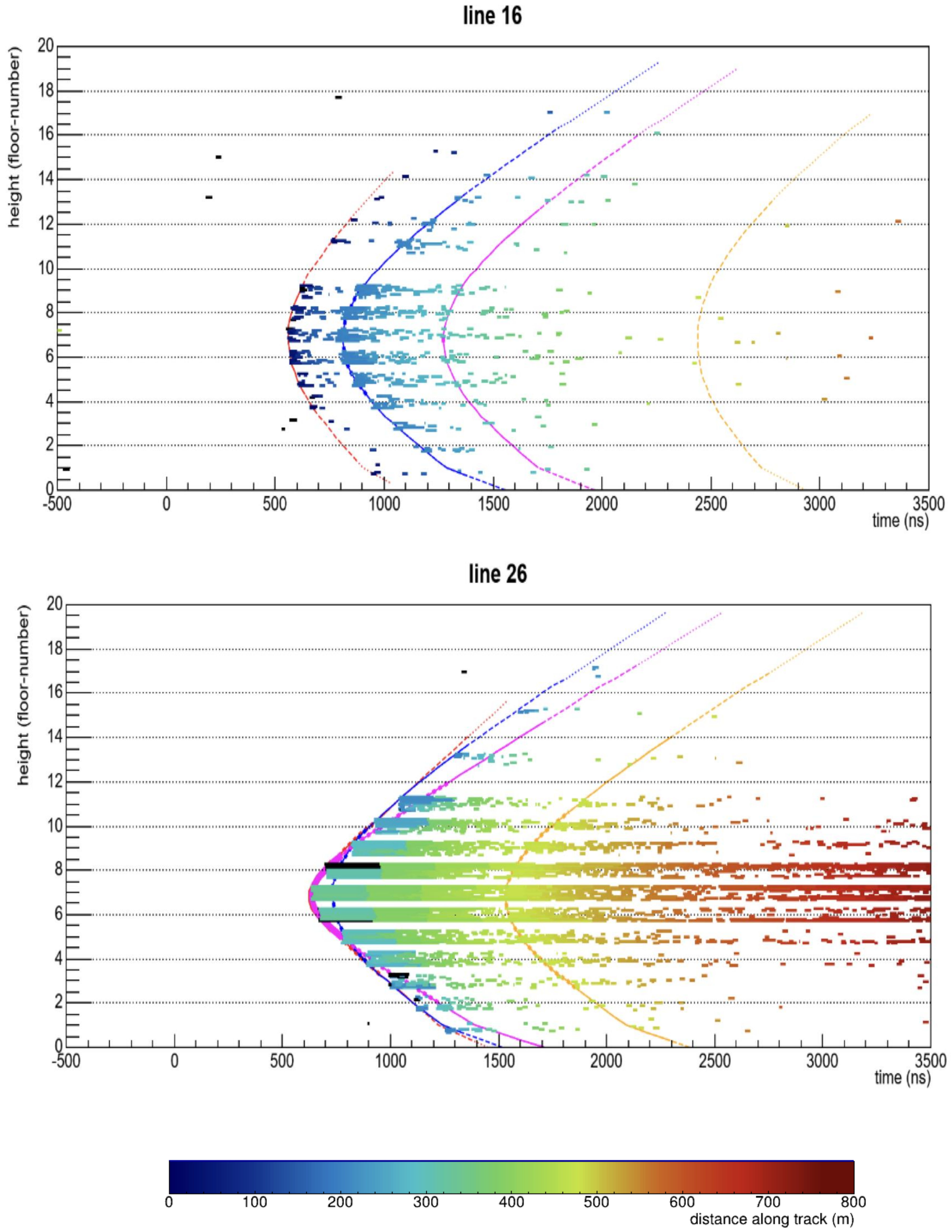
time residuals for a single DU

Only first hit per PMT considered

Deposited energy profile

- Profile of deposited energy along track shows at least **3 large localised energy deposits** along track
- Consistent with **stochastic losses** from highly-energetic muons
- Space-time light correlation consistent with 3 corresponding showers

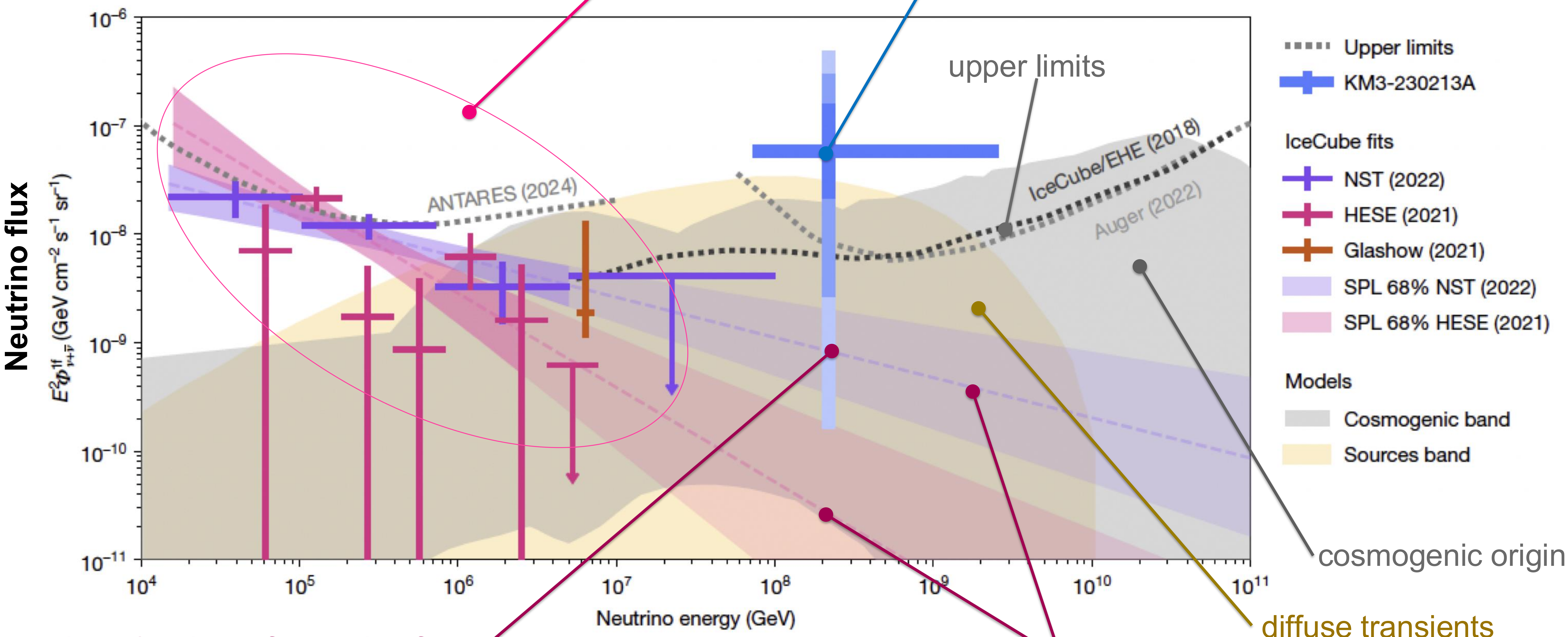




Comparison with expected fluxes

HE neutrinos from IceCube

Neutrino flux that would yield one neutrino in our data, with energy compatible with the observed one + FC CIs



cosmogenic origin

diffuse transients

Under SPL model, ~2.5sigma fluctuation from the global landscape

extrapolation of fits to higher energies
→ 0.12 events expectation in ARCA
→ different cosmic origin for UHE

neutrino flavour equipartition is assumed in the plot

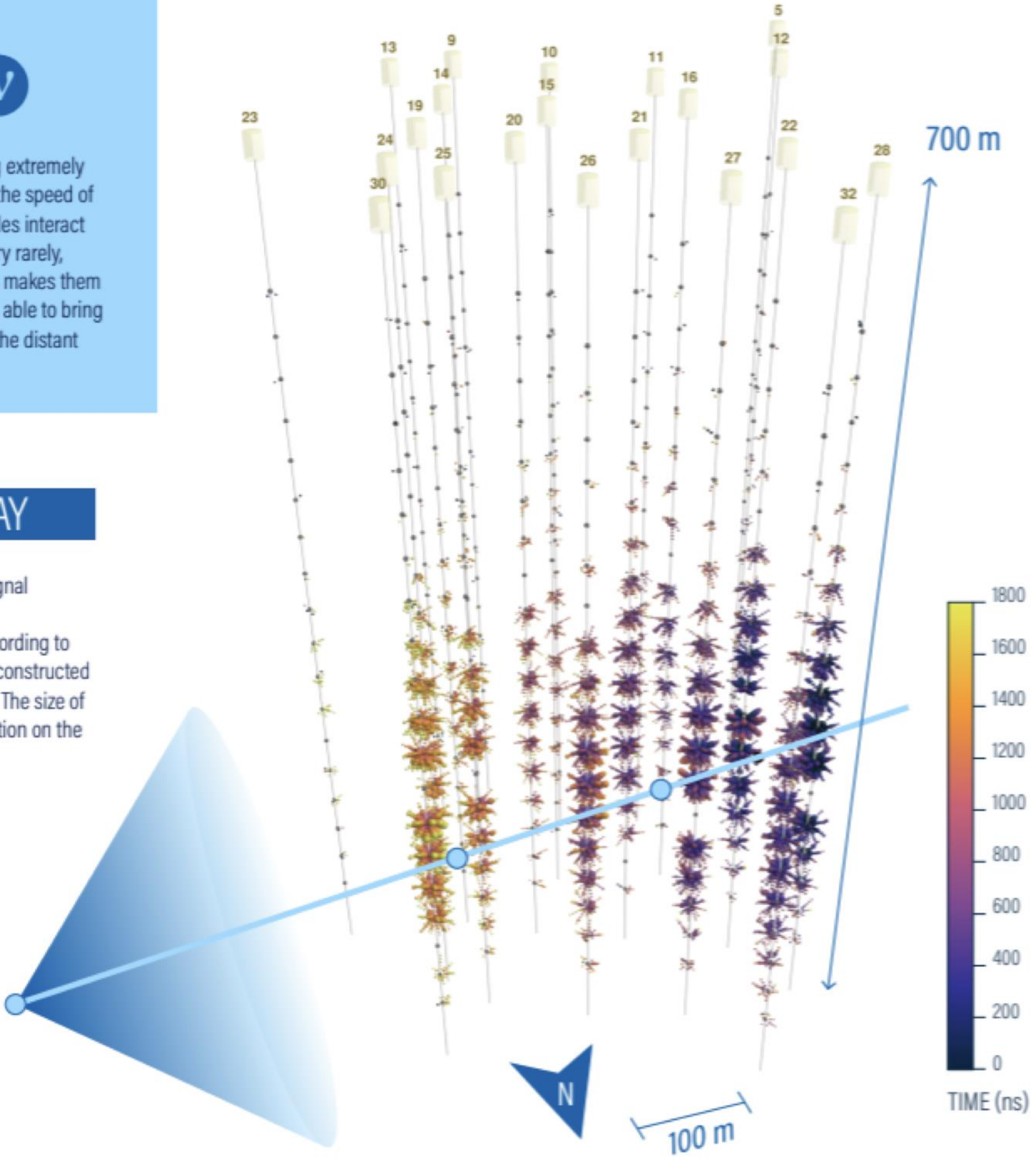
THE RECORD NEUTRINO

NEUTRINOS

With no electric charge, being extremely light and travelling almost at the speed of light, these elementary particles interact only weakly, and therefore very rarely, with matter. Their elusiveness makes them valuable cosmic messengers, able to bring us unique information about the distant universe.

THE EVENT DISPLAY

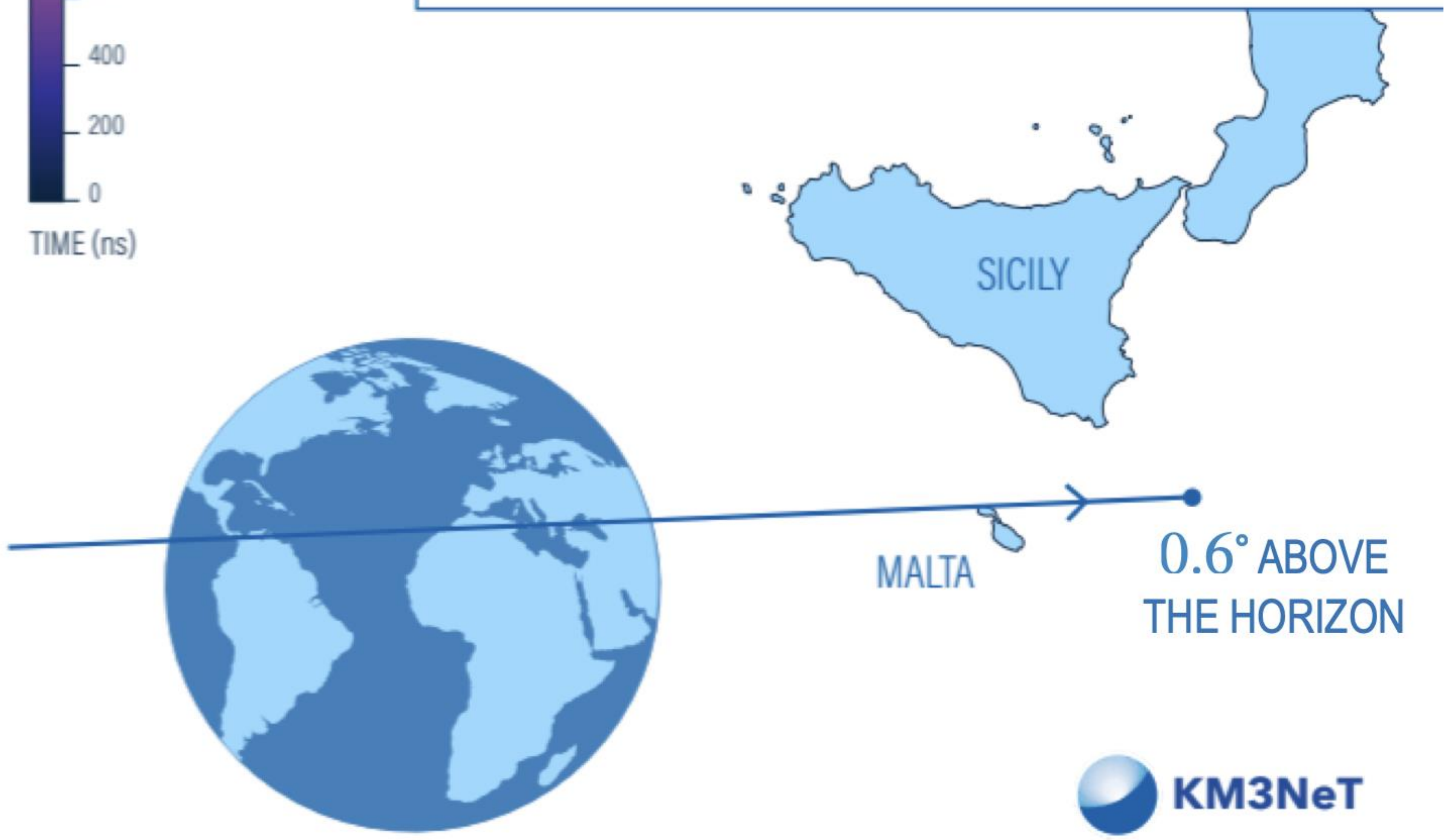
A view of the KM3-230213A signal detected by KM3NeT.
The spheres are coloured according to the detection time and the reconstructed track of the particle is shown. The size of the blue cone gives an indication on the amplitude of the signal.



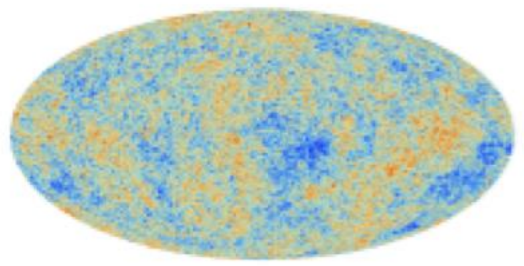
On 13 February 2023, at a depth of 3450 metres off the coast of Sicily, in Italy, the ARCA detector of the KM3NeT submarine neutrino telescope recorded an extraordinary signal: produced by a neutrino with a record energy of about 220 PeV, corresponding to 220 million billion electronvolts. This signal, named KM3-230213A, provides the first evidence that neutrinos with such extreme energies exist in the universe.

KM3-230213A IDENTIKIT

The cosmic neutrino plunged into the Mediterranean Sea and crossed the Malta continental shelf with an inclination of 0.6° above the horizon. During this journey, it travelled almost at the speed of light and interacted with an atomic nucleus, generating an ultra-relativistic muon, which crossed the whole detector.



THE SOURCES



The origin of the ultra-high energy neutrino could have been one of the cataclysmic events that animate our universe, such as an active galactic nucleus or a gamma-ray burst. Or it could be a neutrino generated by the interaction of an ultra-high energy cosmic-ray particle with the cosmic background radiation that permeates the universe.

KM3NeT

Co-funded by the European Union

Backup

Sky map

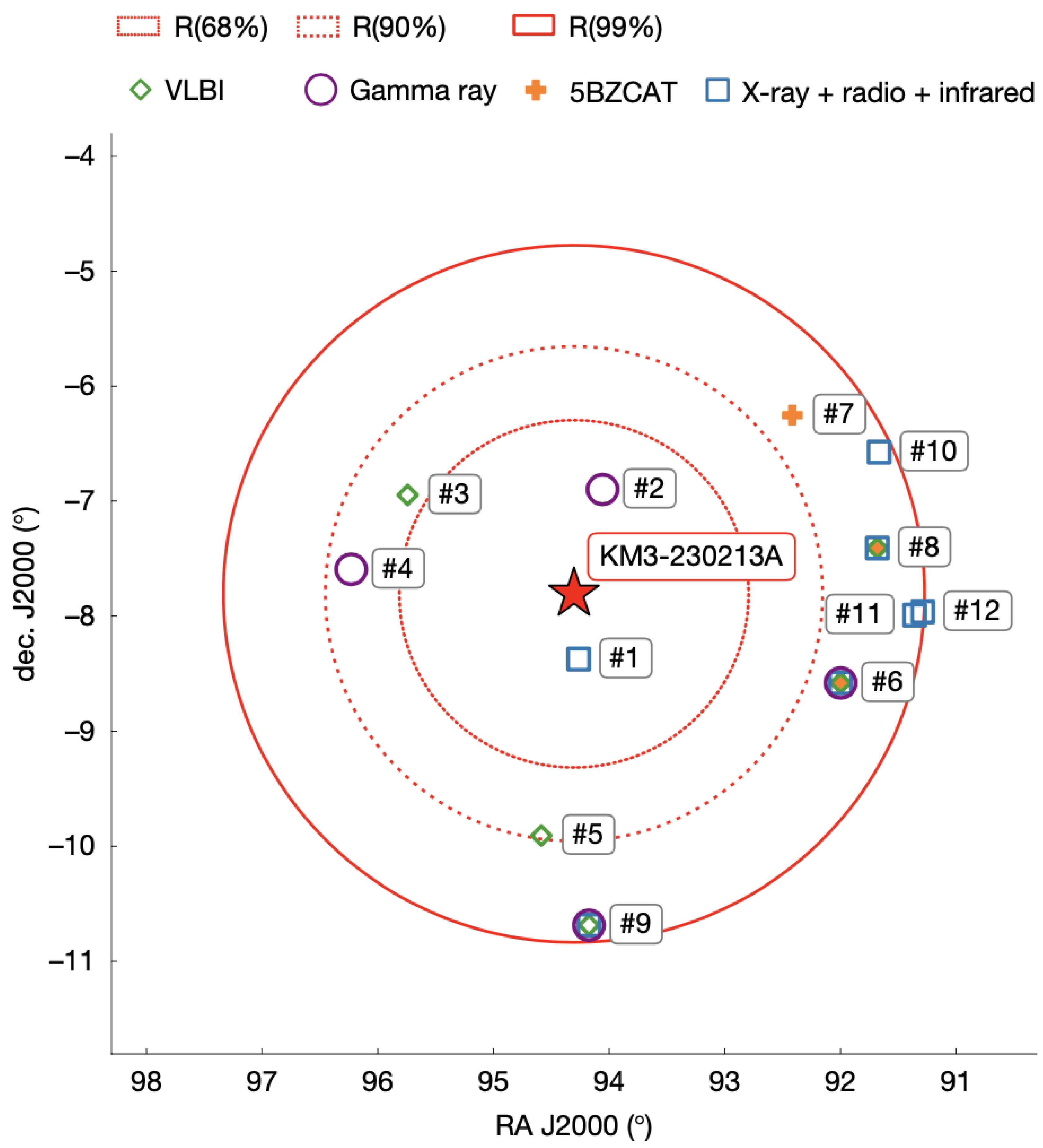
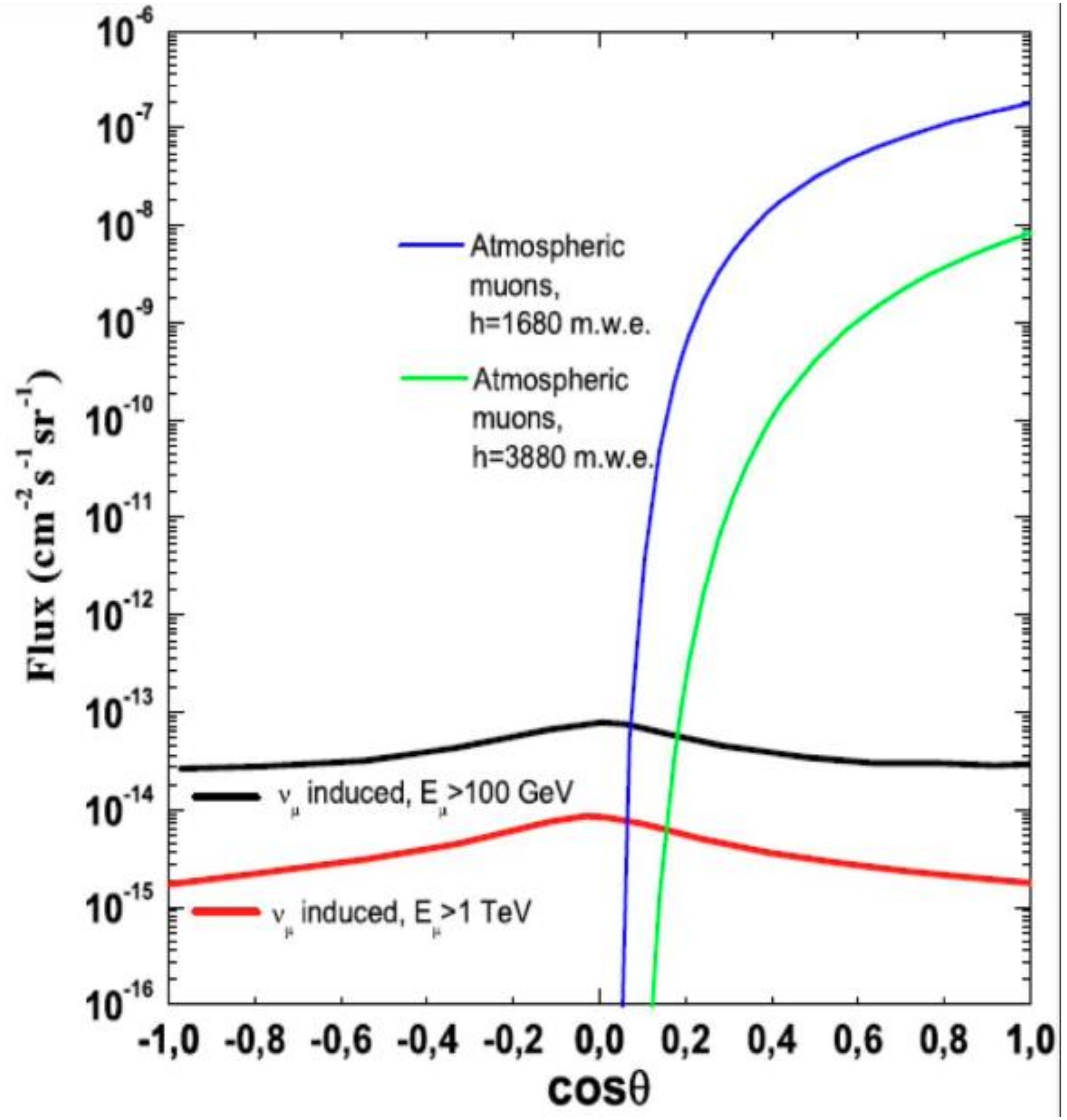
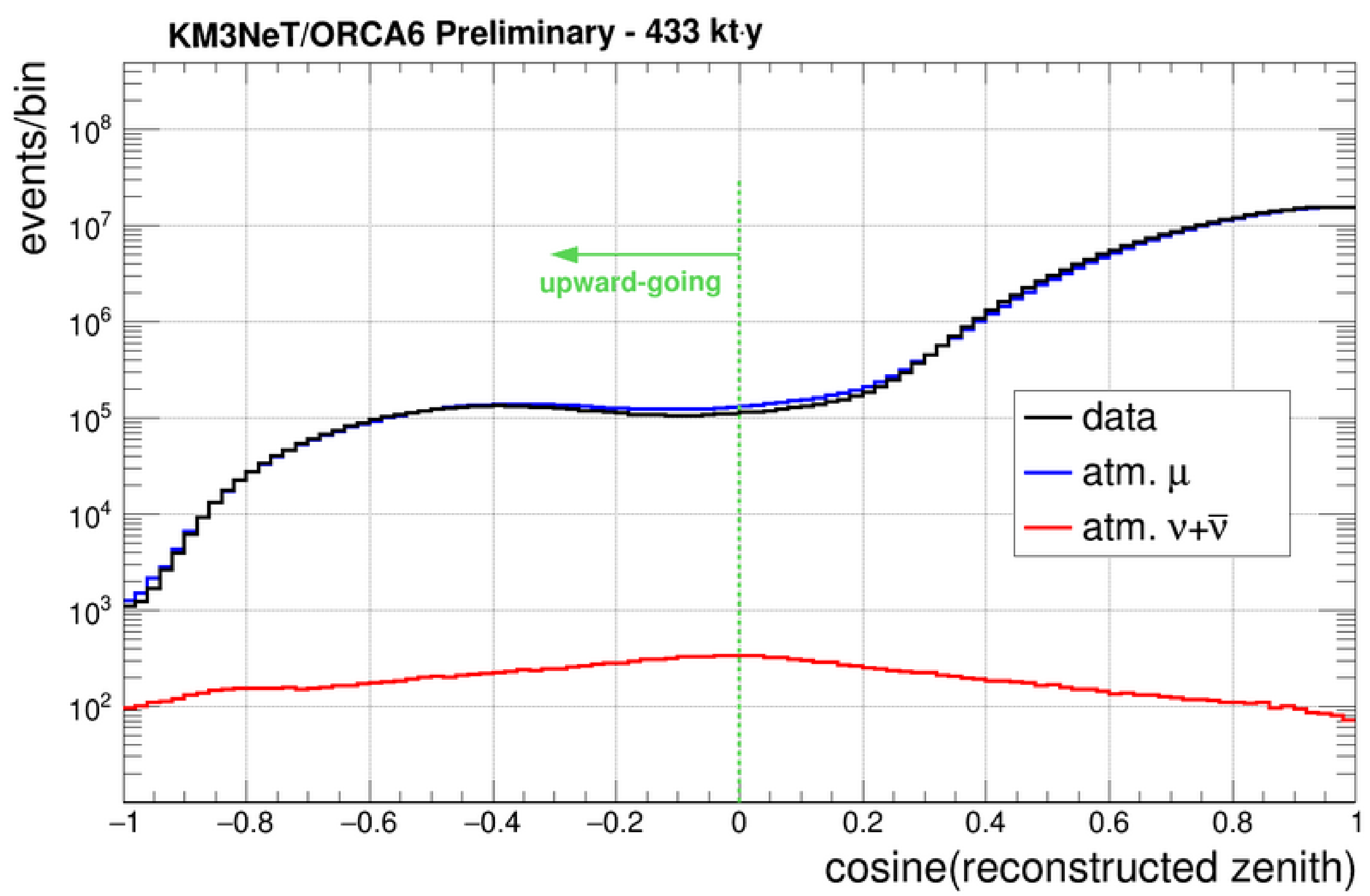


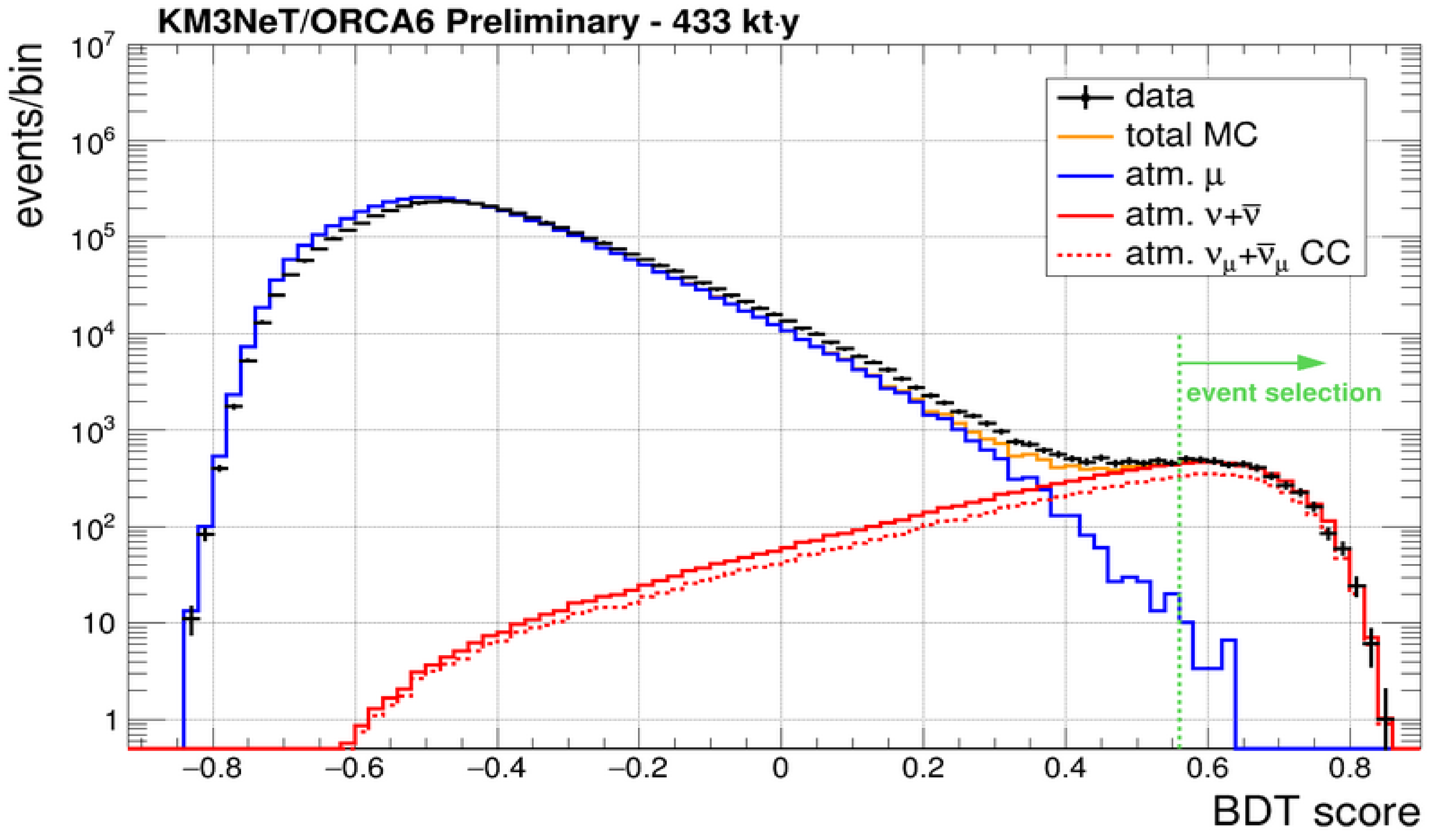
Fig. 4 | Sky map in the direction of KM3-230213A. KM3-230213A is indicated by the red star, with the error regions within R(68%), R(90%) and R(99%) shown as dotted, dashed and solid contours, respectively. The directions of the selected source candidates are shown as coloured markers, whose colours and marker type indicate the criterion according to which the source was selected. The sources are numbered according to their proximity to KM3-230213A, as reported in Methods.

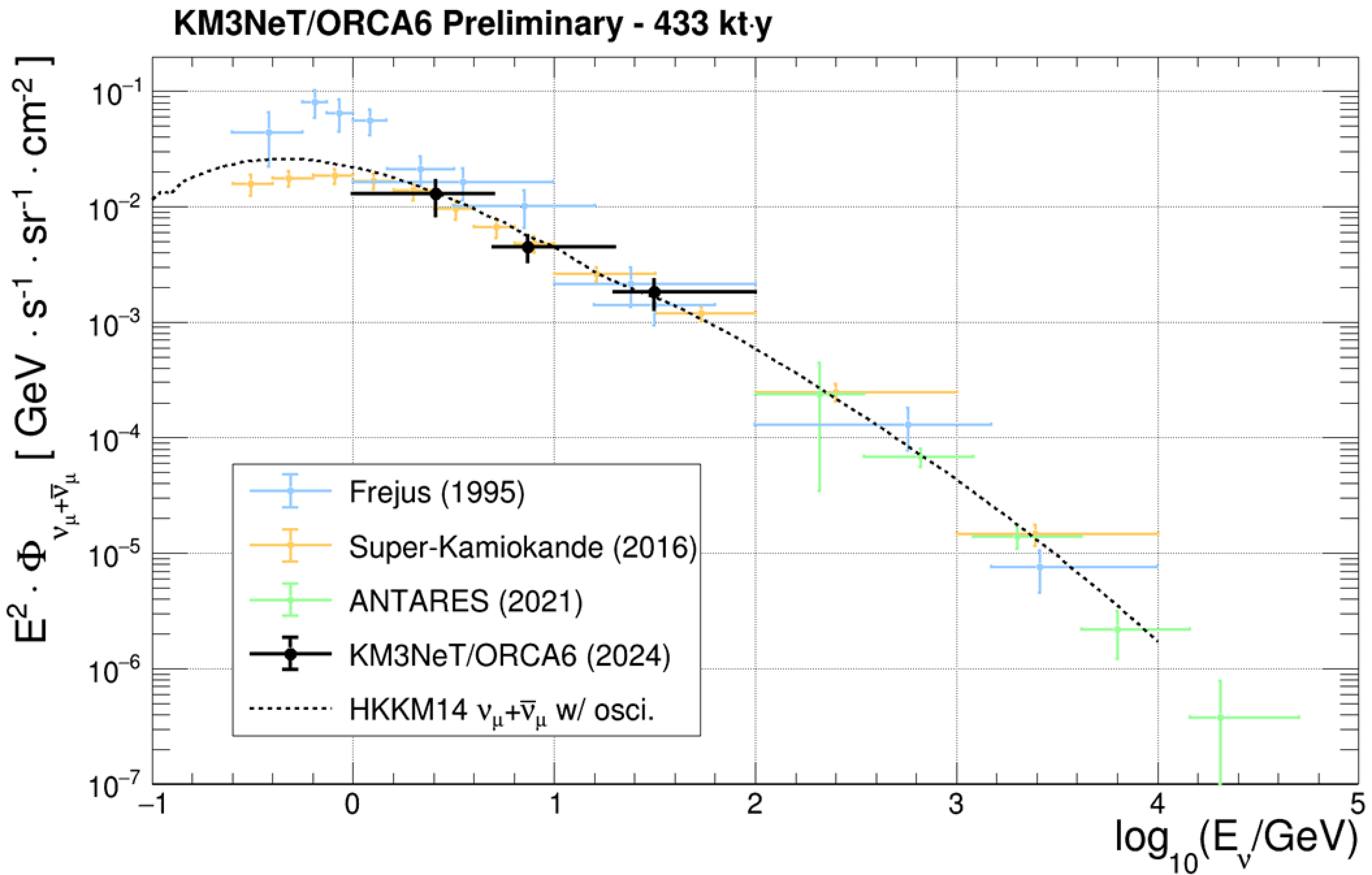

Flux (cm^{-2} s^{-1} sr^{-1})
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Atmospheric muons, h=1680 m.w.e.
Atmospheric muons, h=3880 m.w.e.
ν_μ induced, E_μ>100 GeV
ν_μ induced, E_μ>1 TeV
-1,0 -0,8 -0,6 -0,4 -0,2 0,0 0,2 0,4 0,6 0,8 1,0
cosθ

Atmospheric neutrinos

- Measurement consistent with world data
- BDT selection
- ORCA6 data shown



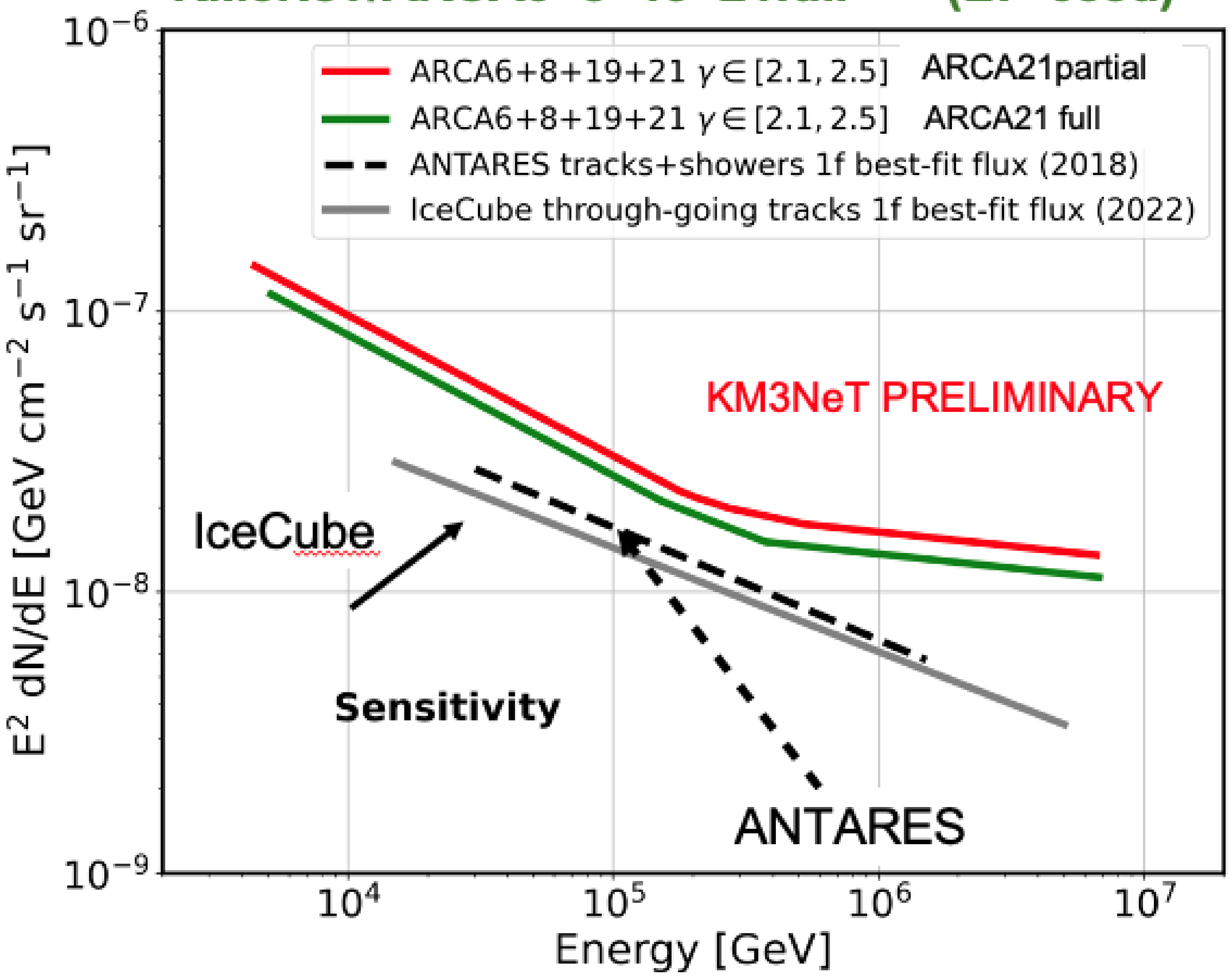




Search for diffuse flux - ARCA

From the full sky

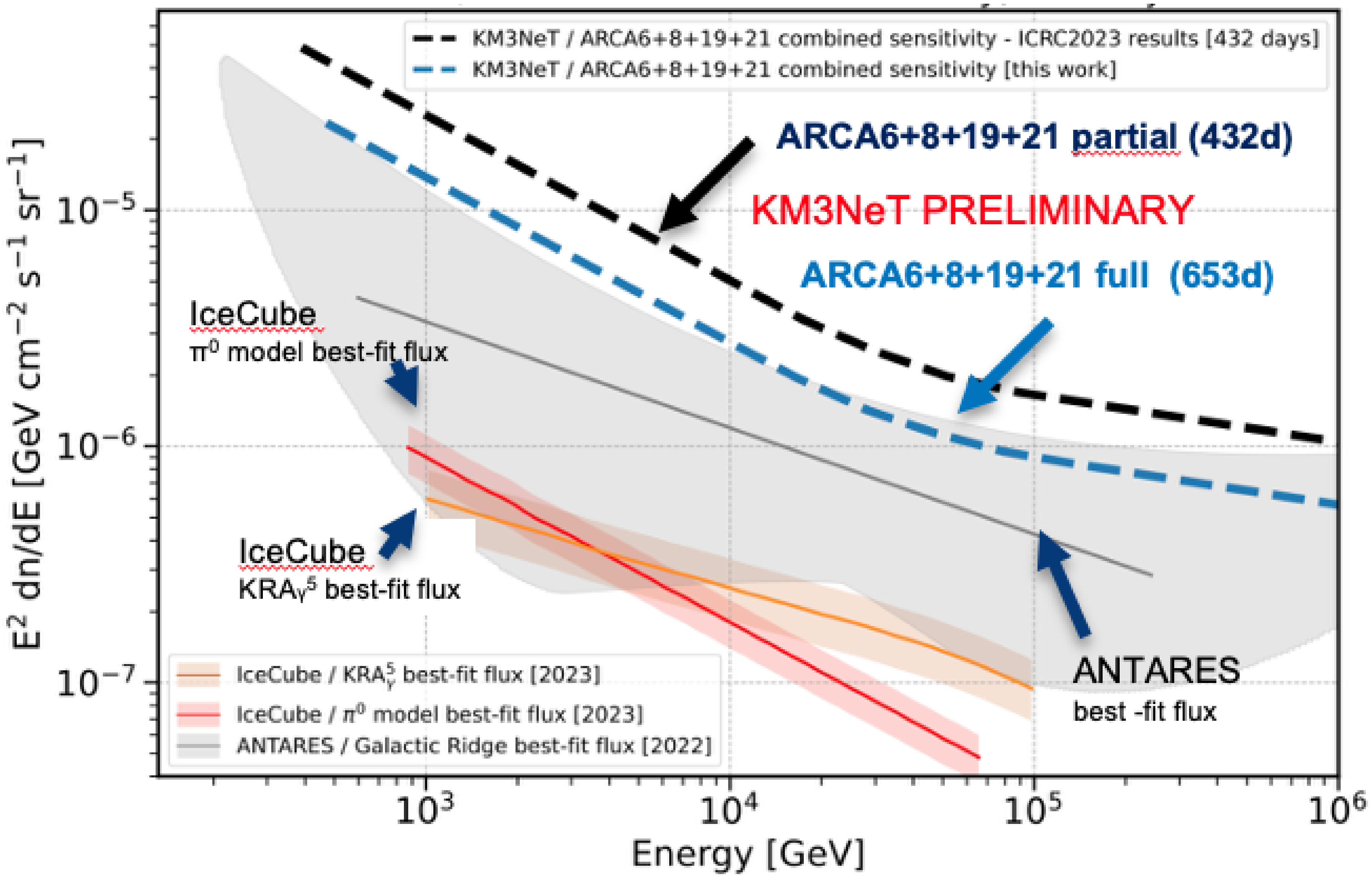
KM3NeT/ARCA6+8+19+21partial (LT=432d)
KM3NeT/ARCA6+8+19+21full (LT=653d)



On-Off zone analysi

From the Galactic plane

KM3NeT/ARCA6+8+19+21partial (LT=432d)
KM3NeT/ARCA6+8+19+21full (LT=653d)



|l| < 31° and |b| < 5° for ARCA6-8 & |l| < 31° and |b| < 4° for ARCA19-21

Km3NeT

Status and Perspectives

ISAPP School
Daniele Paesani
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud

INFN LNS
Istituto Nazionale di Fisica Nucleare
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KM3NeT

Km3NeT

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KM3NeT

Supernova explosion – ARCA+ORCA