Friedrich-Alexander-Universität
Erlangen-Nürnberg

High Energy Neutrino Astronomy and Supernova Neutrinos

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Overview

1. Why neutrino astronomy?
2. Neutrino telescopes
3. High energy neutrino sources
    1. Extragalactic & Galactic sources
4. HE cosmic neutrino detection: where are we now?
5. Supernova neutrinos

1. Why neutrino astronomy?

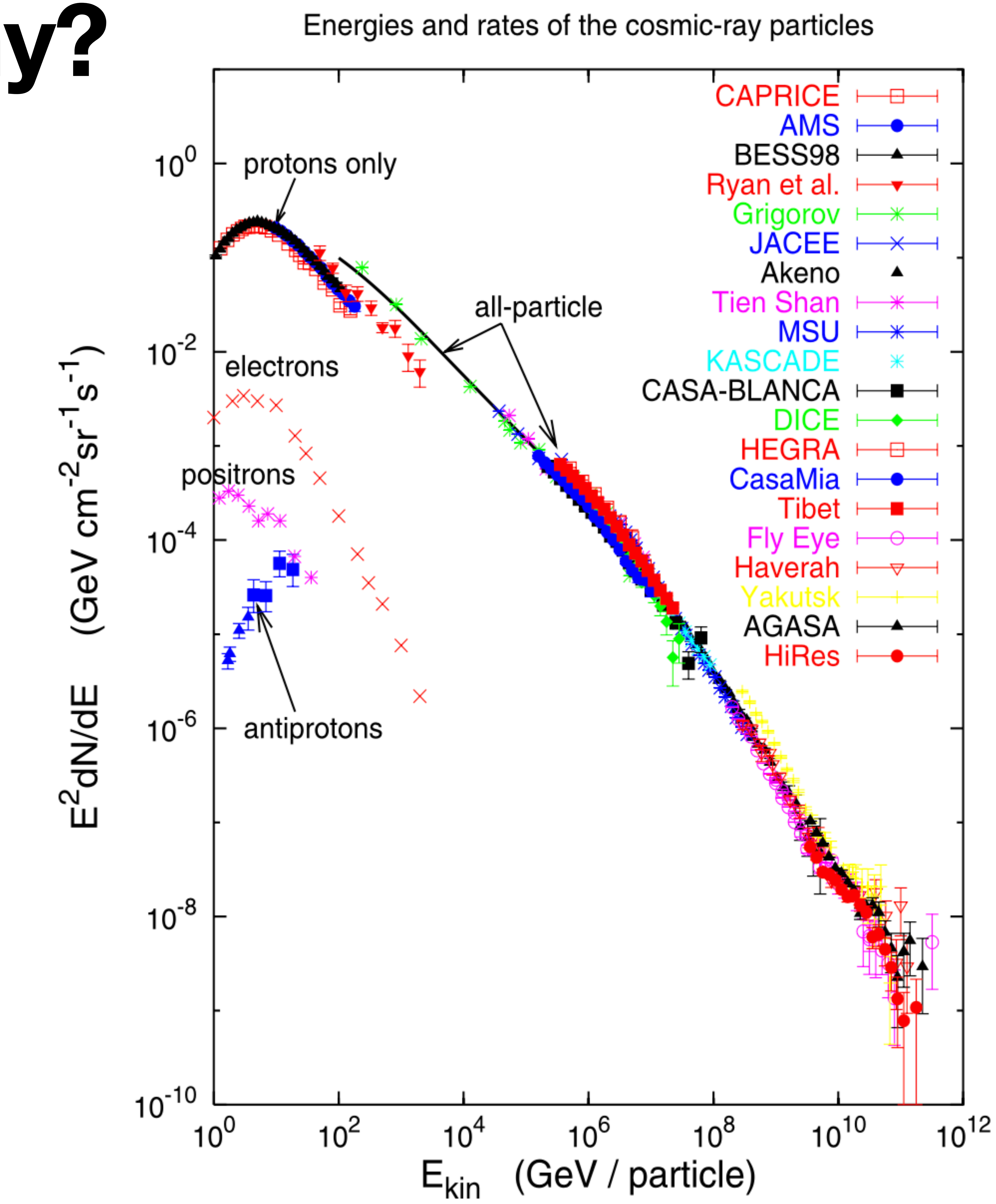
Why neutrino astronomy?

- **Messengers of the Universe:** protons, heavier nuclei, electrons, γ-rays, and neutrinos.

$$\left[\frac{dN_P}{dE}\right]_{\mathrm{obs}} = K \cdot E^{-\alpha} \quad (\mathrm{cm}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{s}^{-1}\,\mathrm{GeV}^{-1})$$

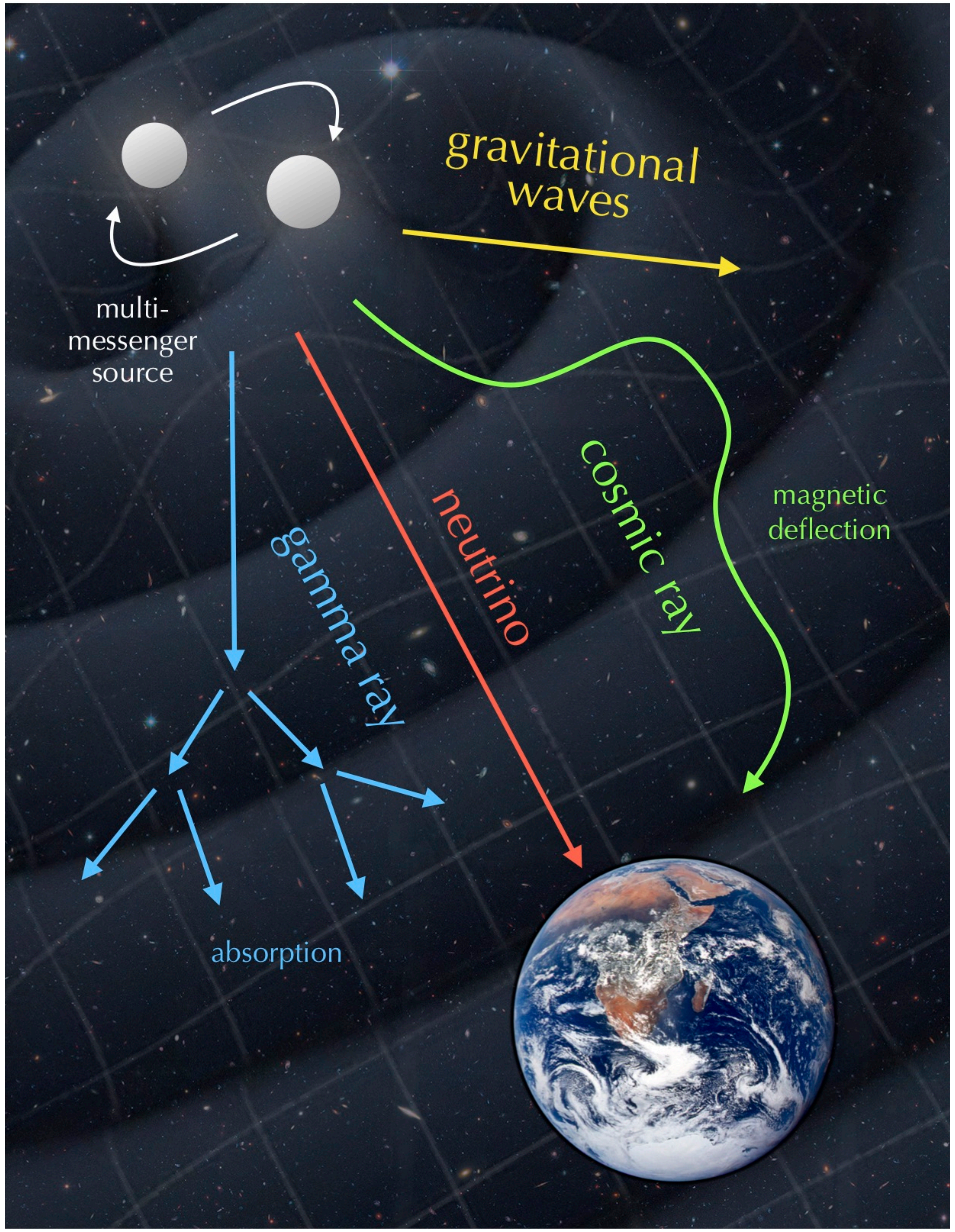
$\alpha = 2.7$ ⟶ Up to ~3x10^6 GeV

$\alpha = 3.1$ ⟶ Higher energies



Why neutrino astronomy?

- **Other probes:**
  - Photons: they interact with CMB (r~10 kpc @100 TeV) and other radiation fields and matter.
  - Protons: interact with CMB and deflected by magnetic fields.
  - Neutrons: are not stable.

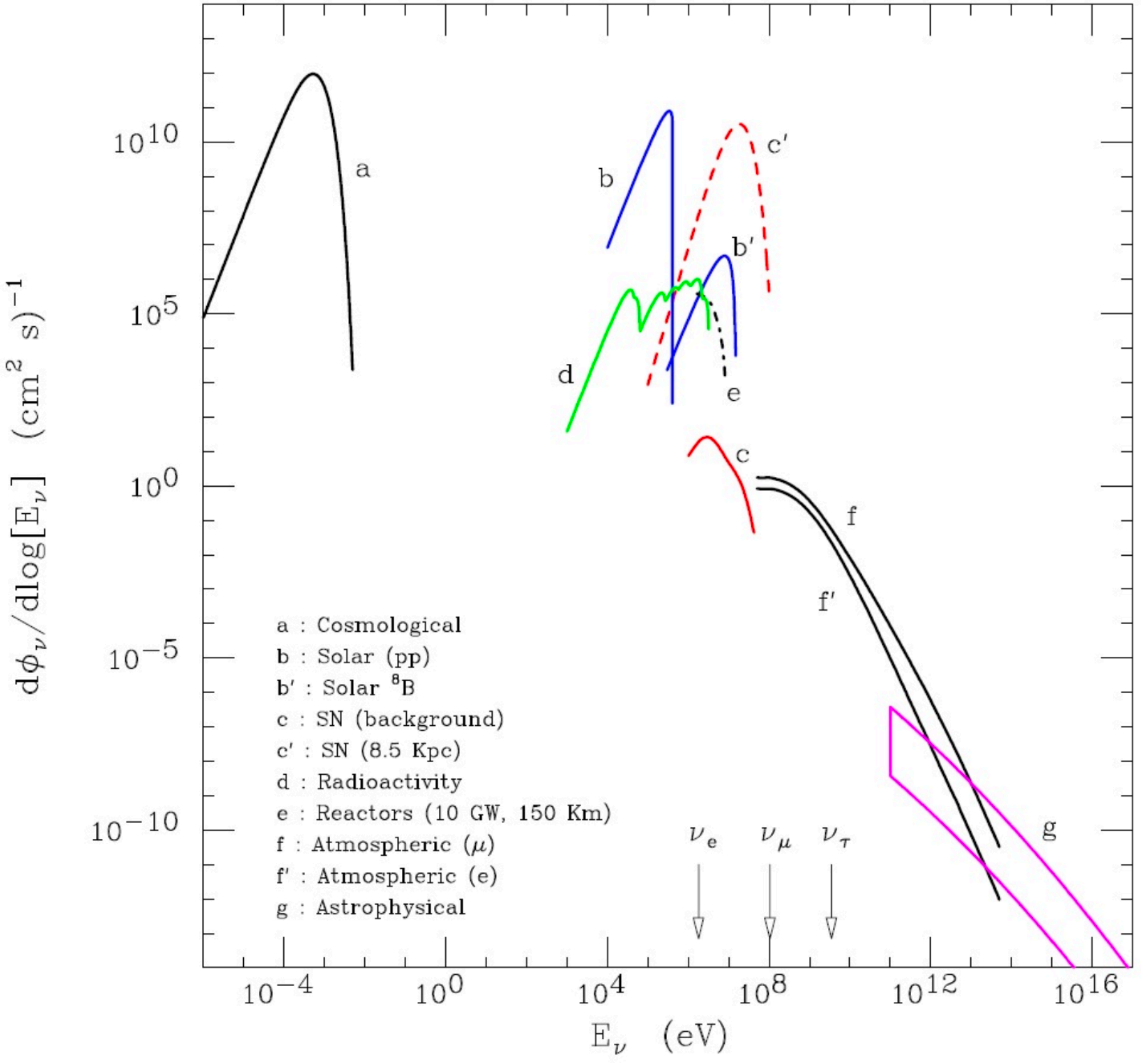


Why neutrino astronomy?

- **Neutrinos are *elusive* particles.**

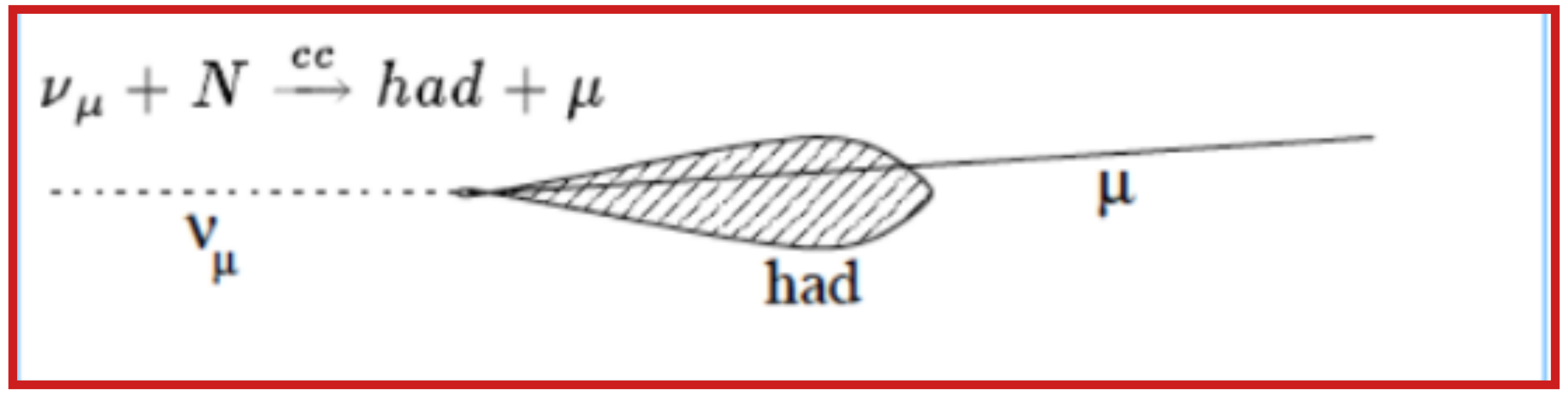
$$\sigma_{\nu p} \sim 10^{-38}\,(E_\nu/\mathrm{GeV})\,\mathrm{cm}^2$$

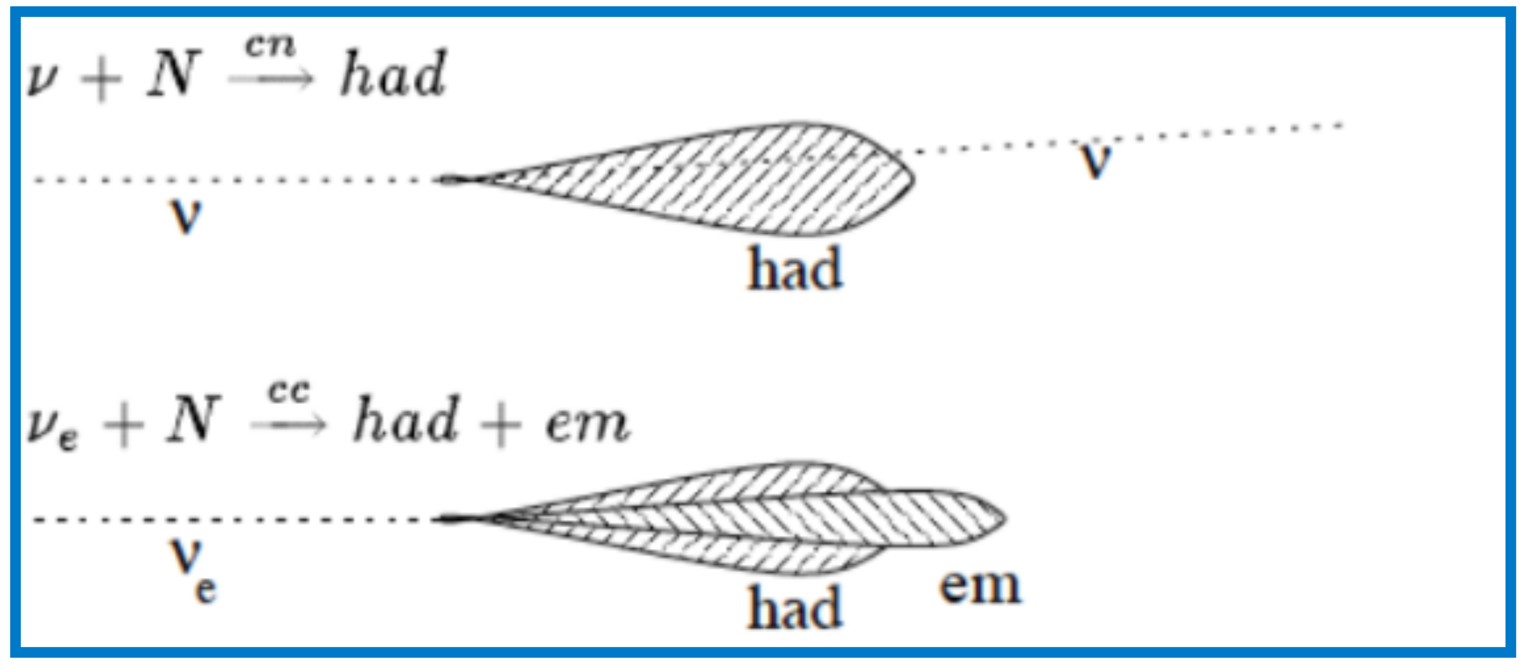
- **Can travel long distances without being deflected nor absorbed:**
  - **They maintain the original information from the source.**
  - **They allow to probe the inner regions of high energy sources.**
- **Very hard to detect.**



2. Neutrino telescopes

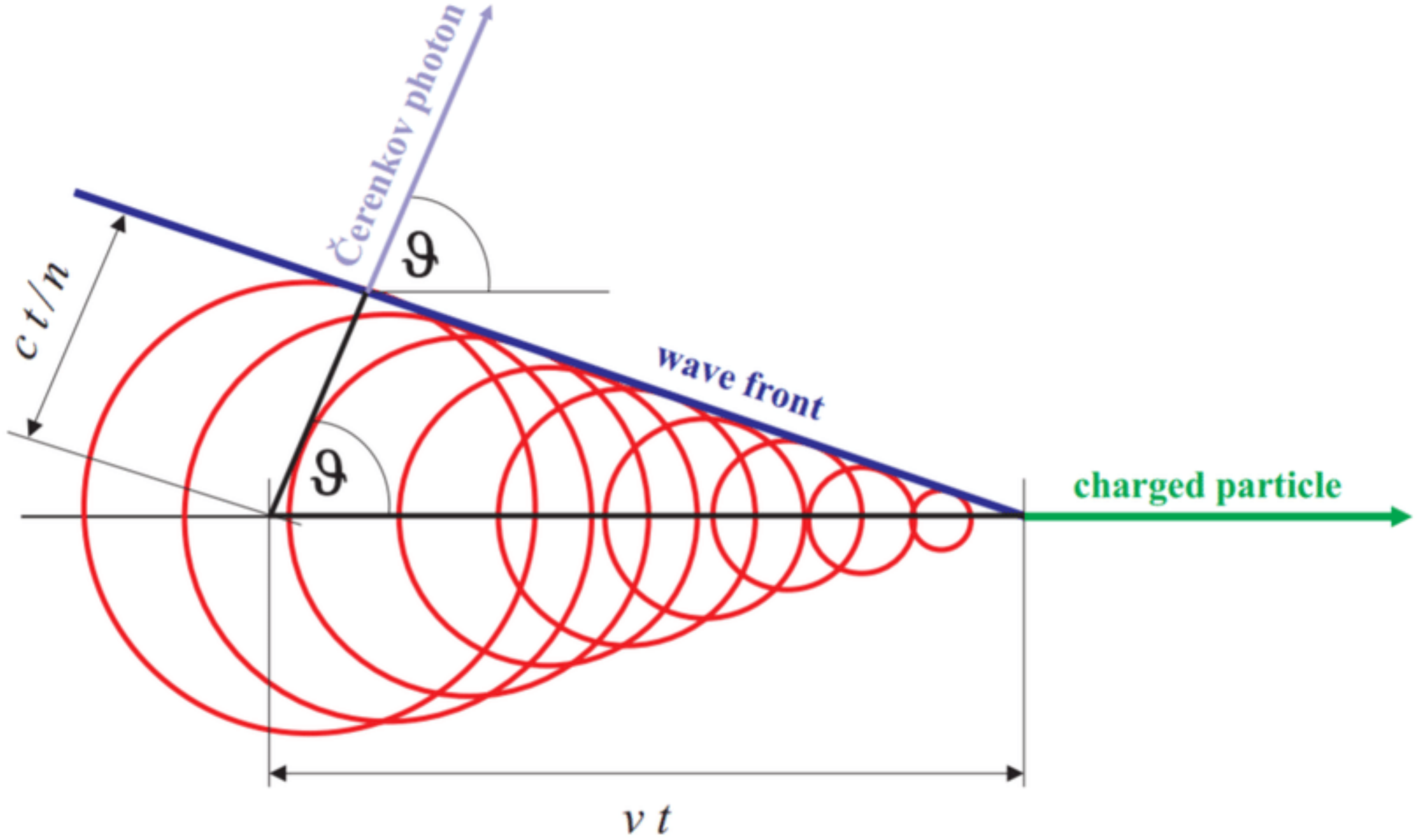
Neutrino detection principle





- Neutrinos can interact with matter via an exchange of Z or W bosons: NC and CC interactions.

- Cherenkov effect: when a charged particle passes with velocity *v > 1/n* through a medium with index of refraction *n*, the particle emits Cherenkov light in a cone around the direction of motion.

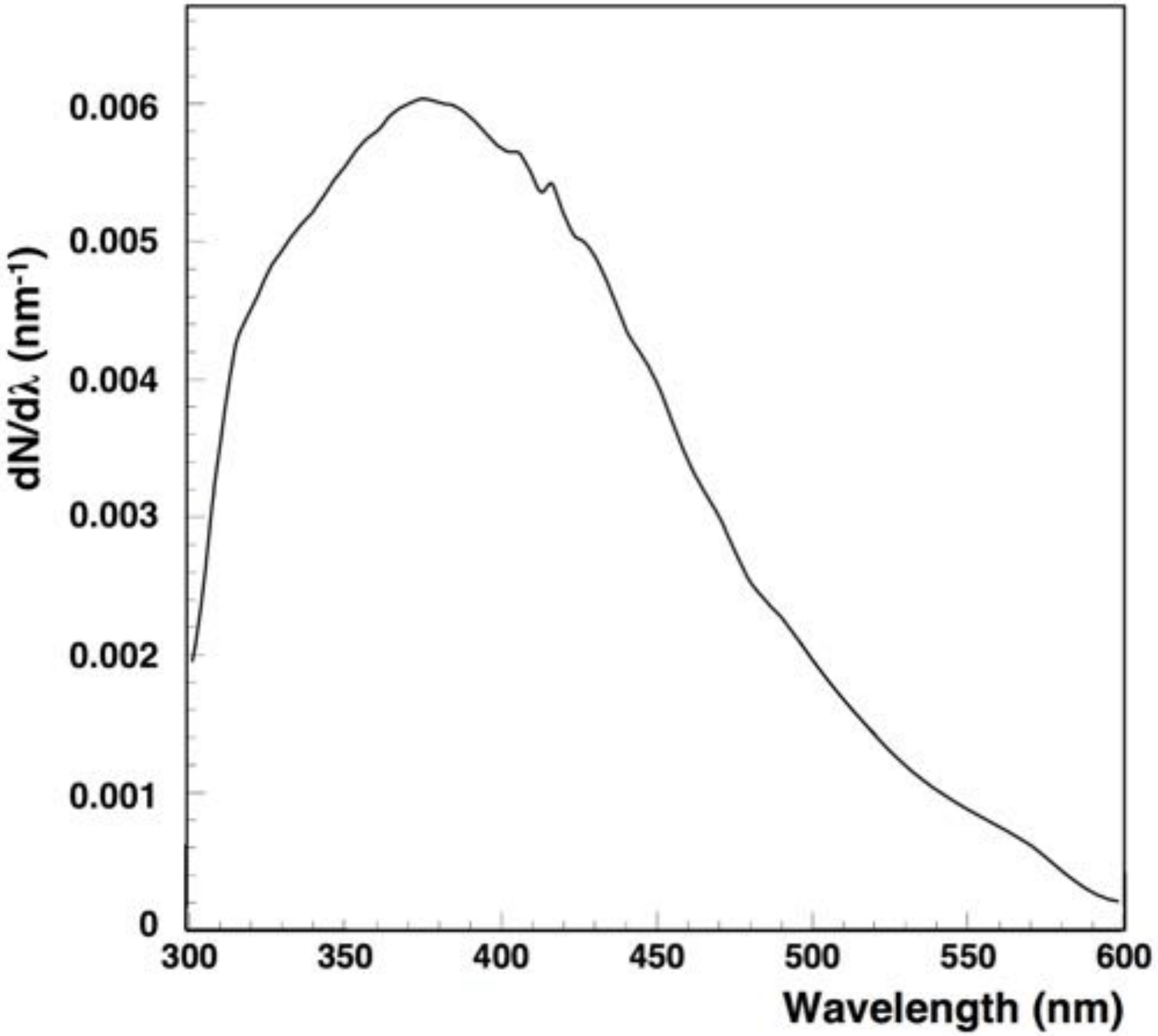


Water Cherenkov detectors

- Cherenkov effect: the spectrum is given by

$$\frac{\mathrm{d}N}{\mathrm{d}\lambda\,\mathrm{d}x} = 2\pi\alpha\left[1 - \left(\frac{1}{nv}\right)^2\right]\lambda^{-2}\,,$$

where N is the number of photons, λ is the wavelength, and x is a coordinate along the track.



Water Cherenkov detectors

- Water has an index of refraction n ≃ 1.33, leading to $\theta \simeq 41^\circ$ for relativistic particles.

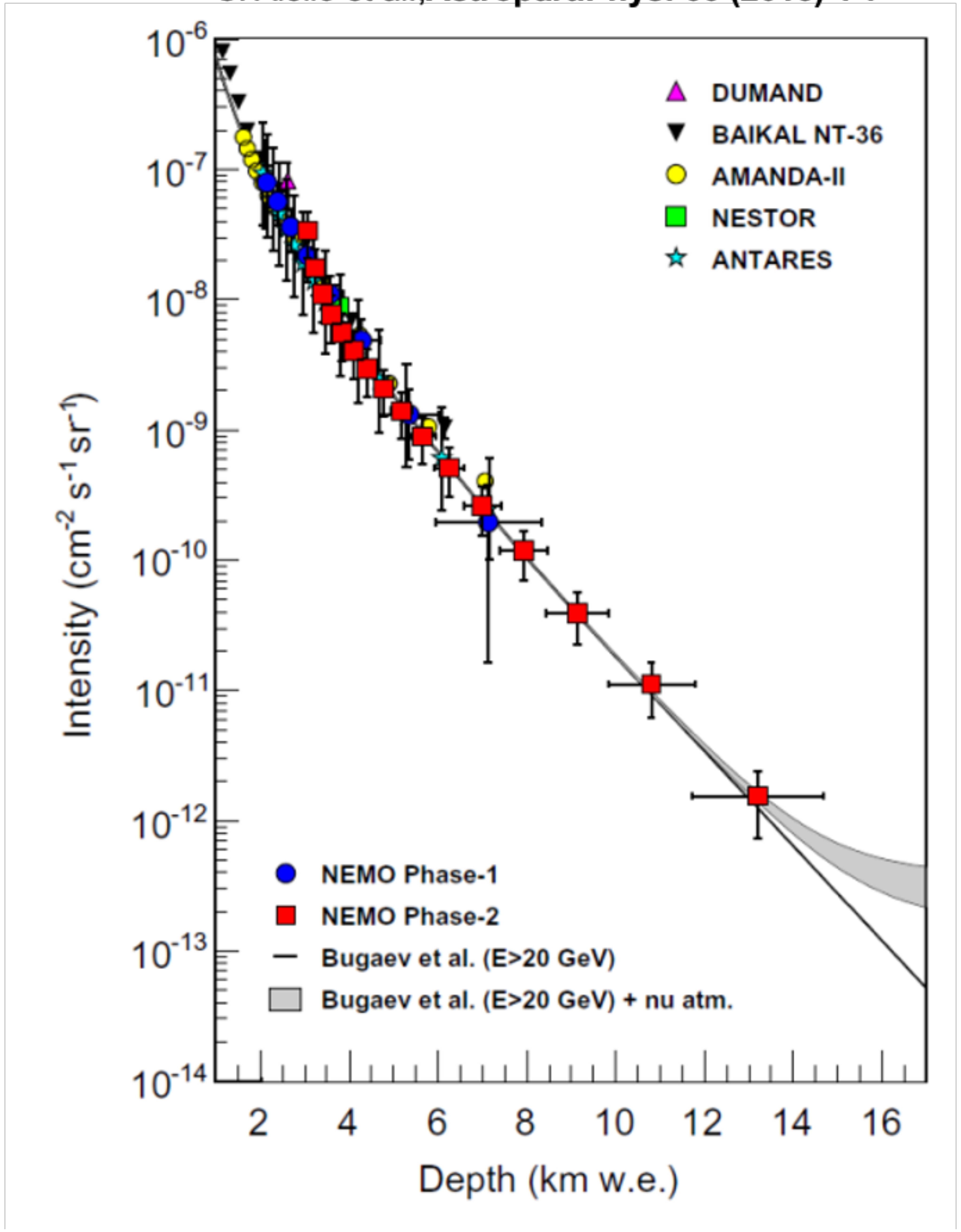
- **For every cm of track length about 340 photons are produced in the wavelength range between 300 and 600 nm**, which is appropriate for detection by photomultiplier tubes (PMT).

- Through observation of these photons, with a precise determination of the arrival time at each PMT, it is possible to determine the neutrino interaction point, the direction of the track of the produced charged lepton and its energy.

Neutrino telescopes

- Built deep in water or ice:
  - large (and inexpensive) target for ν interactions,
  - transparent radiators for Cherenkov light,
  - large deep: protection against the cosmic-ray muon background.

S. Aiello et al., **Astropart.Phys. 66 (2015) 1-7**



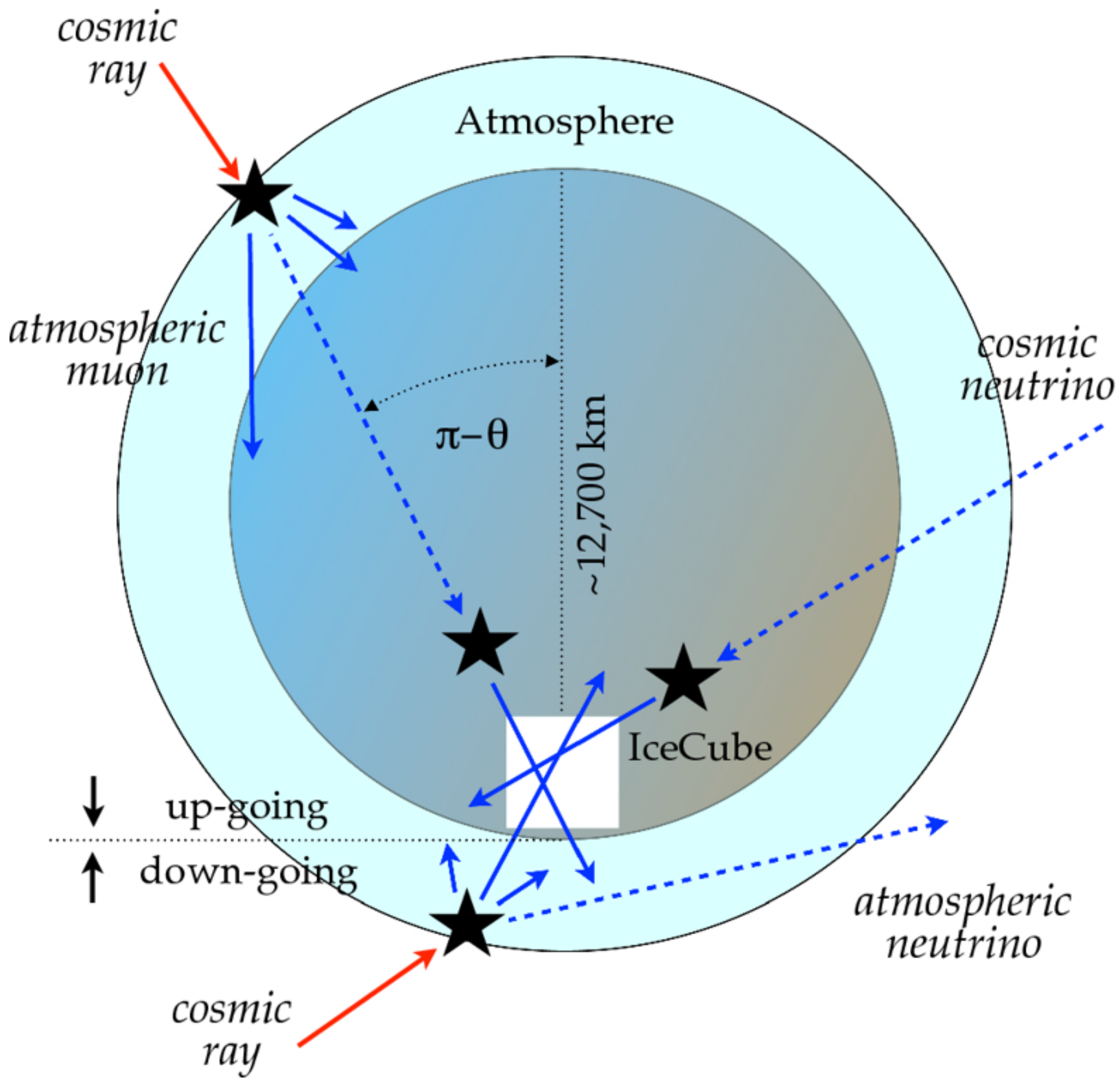
Background

- **Atmospheric neutrinos:** high energy neutrinos (up to >TeV) produced by interactions of primary cosmic rays with the Earth atmosphere. They can travel through the whole Earth up to the neutrino detector.

- **Atmospheric muons:** produced by interactions of primary cosmic rays with the Earth atmosphere. Being charged, they get by the atmosphere and by volumes of rock/ water/ice.

    - Muons cannot cross more than » 15 km.w.e.

    - At 3 km.w.e. the flux is reduced by about 6 order of magnitude



Water vs ice

Cherenkov photons can reach one (or many) **PMT(s)** in an **Optical Module (OM)** and produce a signal.

Water/ice characterized by two quantities (depending on photon wavelength λ)

- ***absorption length, a(λ)***, of the order of 50 m (ice better than water). The absorption reduces the number of photons arriving on OMs.
- ***scattering length, b(λ)***, (water better than ice). The scattering reduces the number of photons arriving in time. It worsening the reconstruction capability.

- Usually, instruments measure the *absorption* and the ***attenuation*** length c(λ) (the combination of scattering and absorption), where

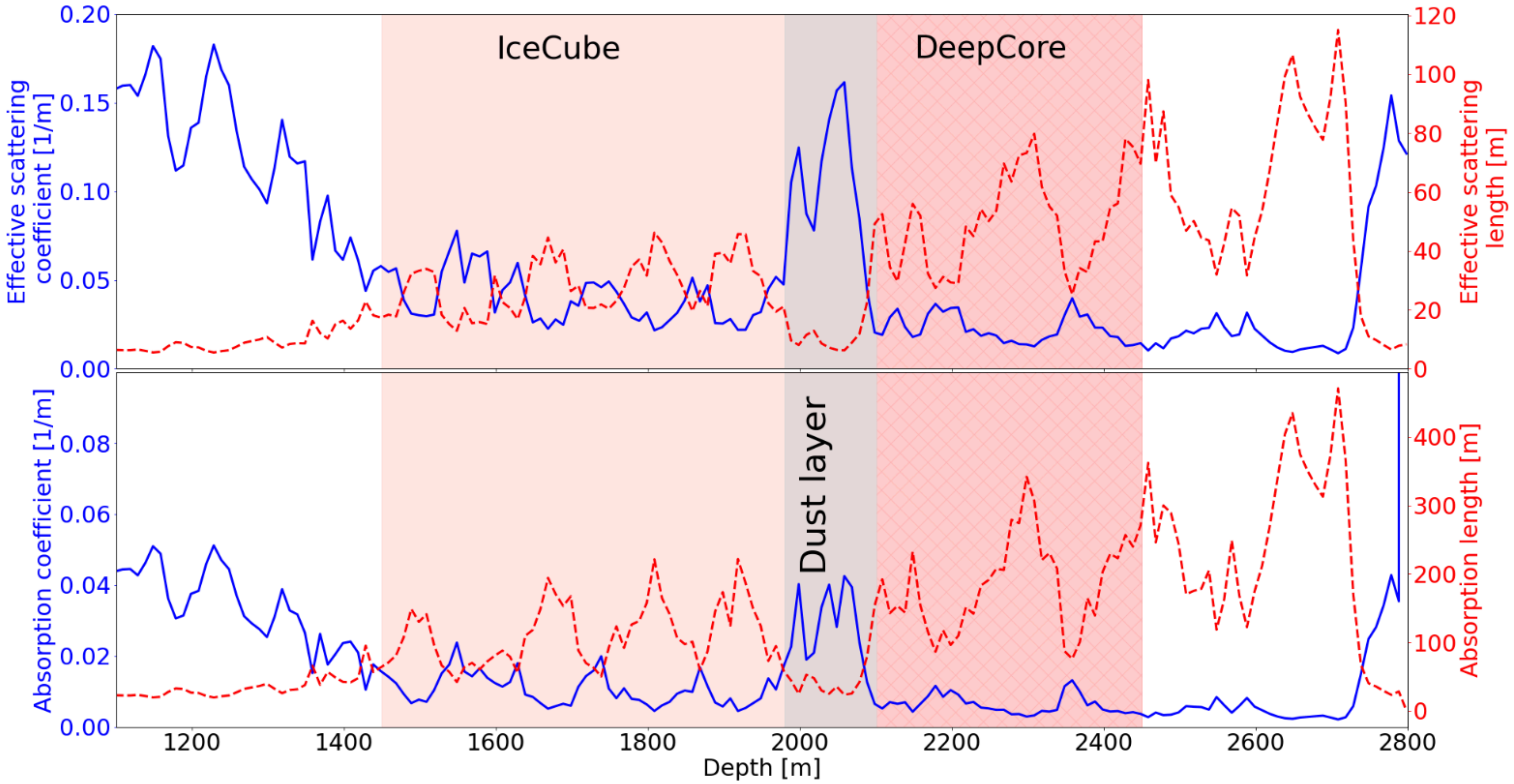
$$c(\lambda) = a(\lambda) + b(\lambda) \ \ [m^{-1}]$$

- The attenuation at a distance x is thus:

$$\mathrm{I}(x,\lambda) = I_o e^{-\,x \cdot c(\lambda)}$$

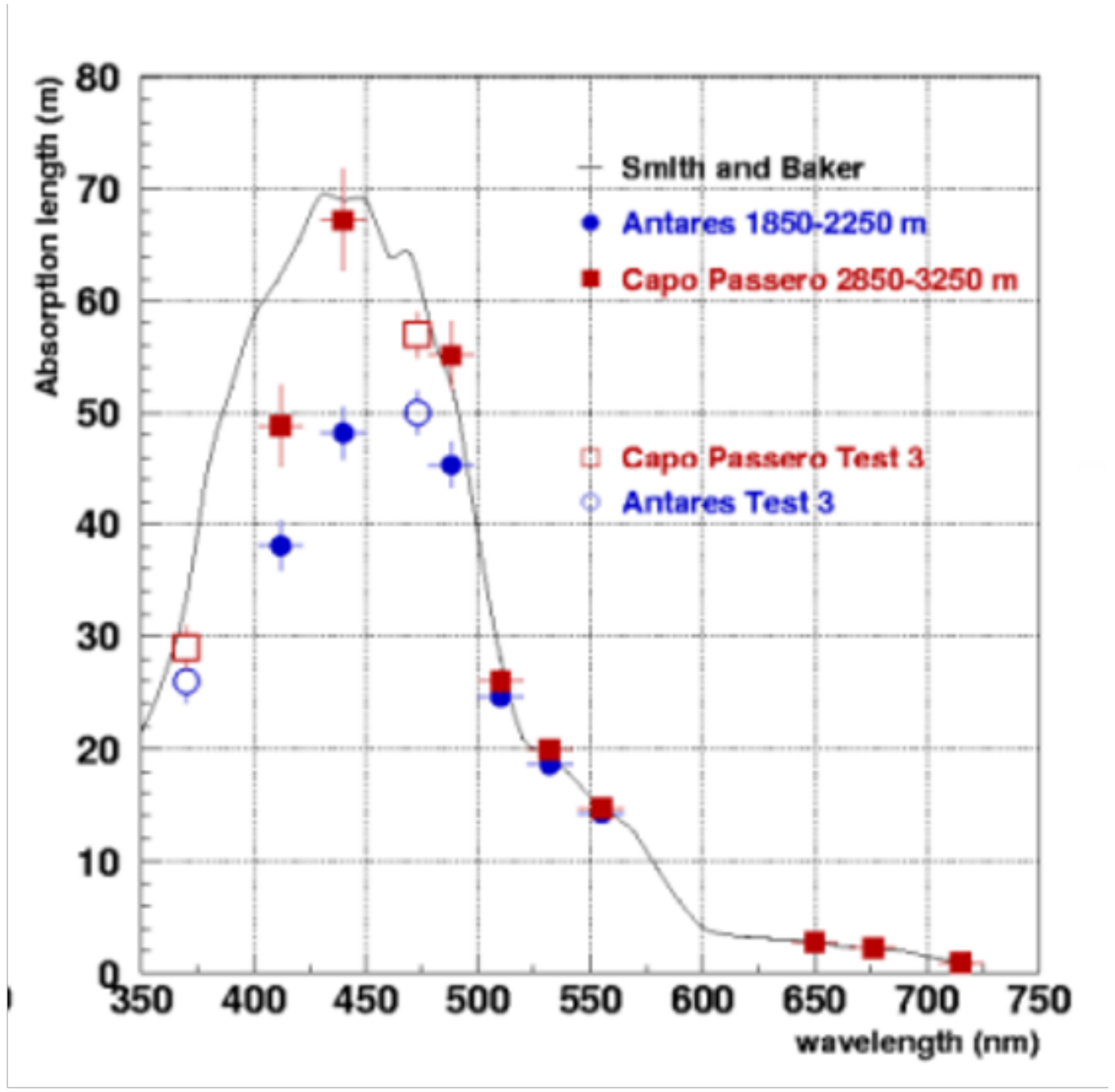
Water vs Ice

Ice



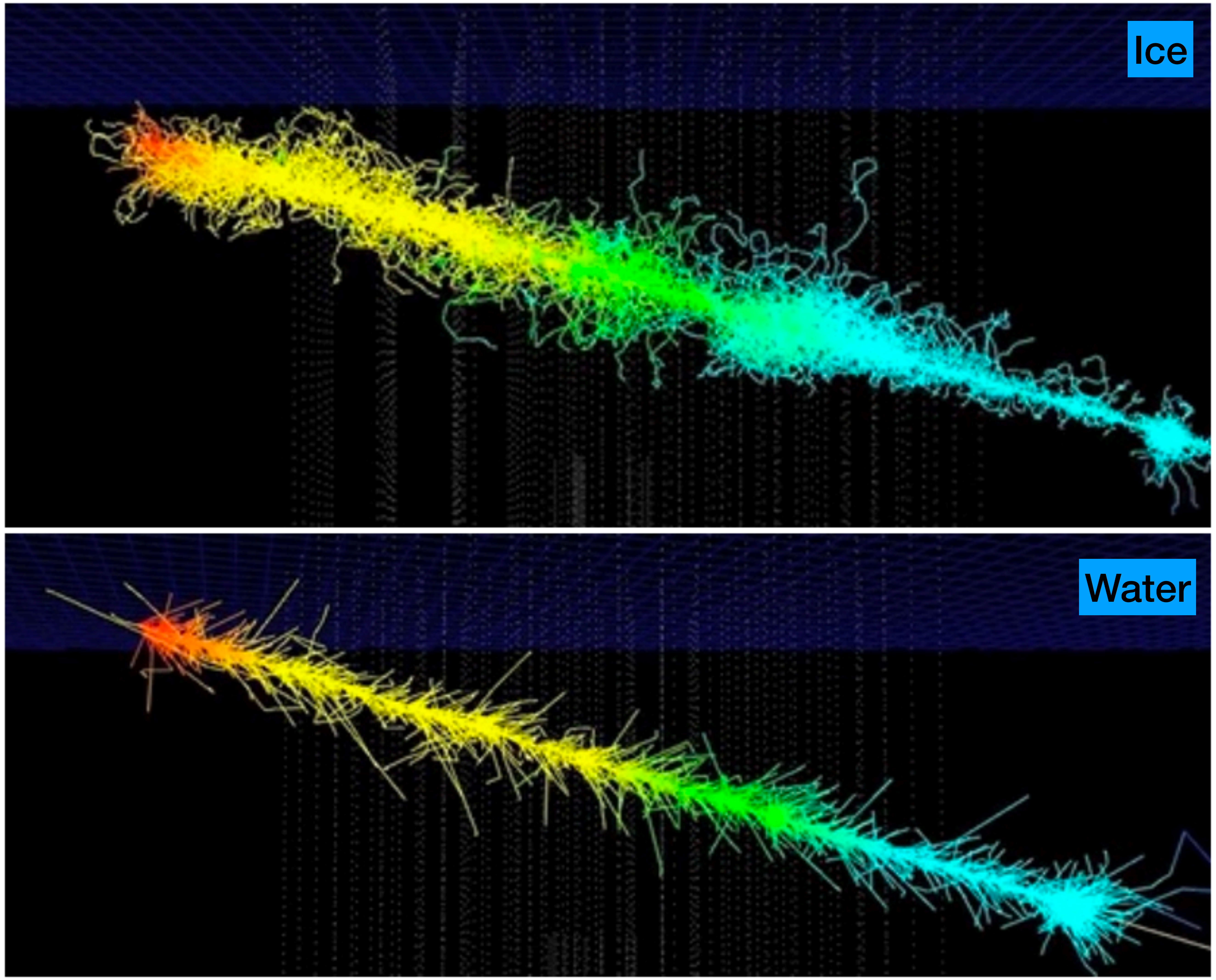
Martin Rongen, IceCube ice tilt, ICRC 2023, Japan

Water



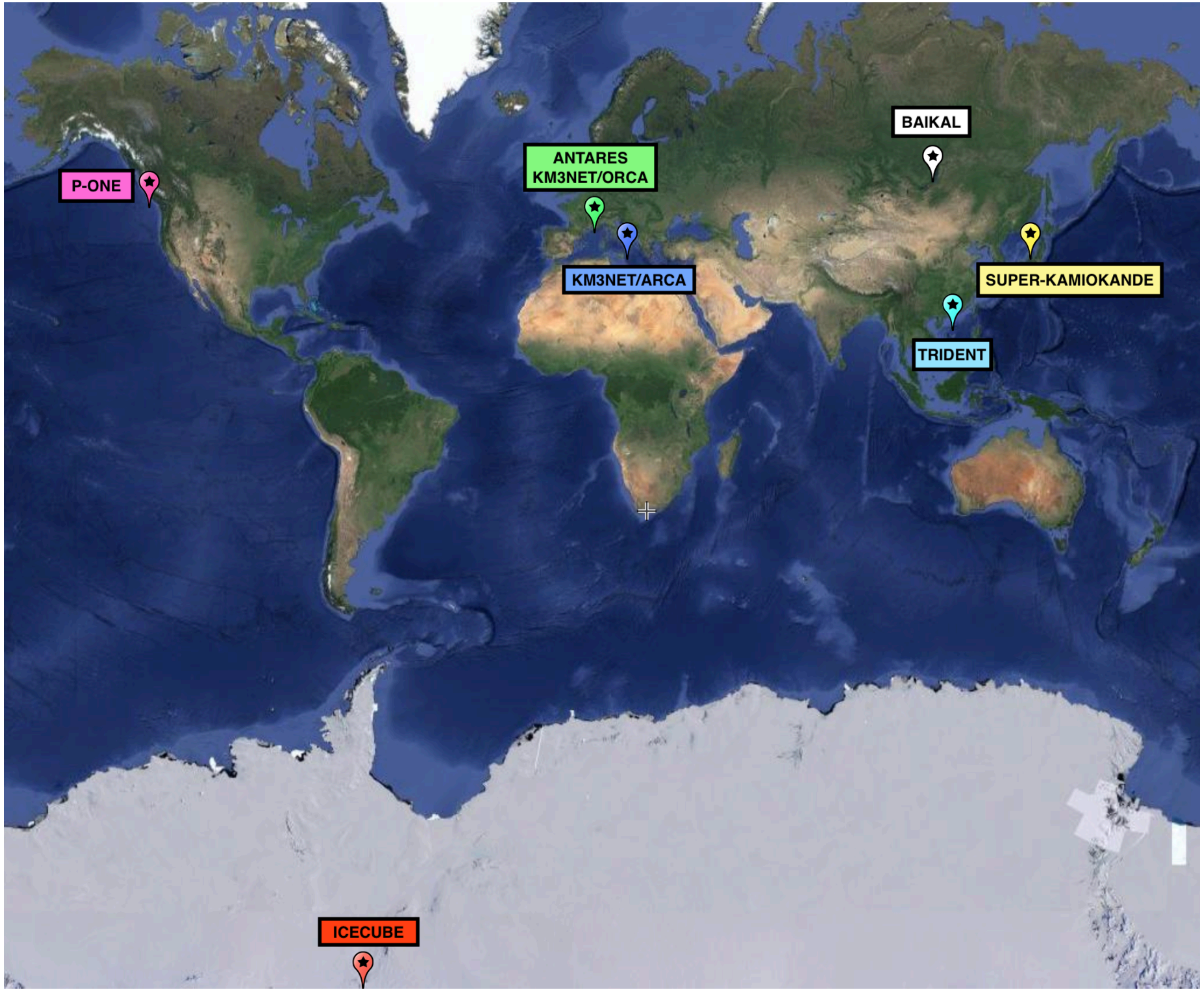
a^{-1} (λ) vs. wavelength for different sites (ANTARES, KM3/ARCA)

Water vs Ice



C. Arguelles et al: arXiv:2405.17623v1 (2024)

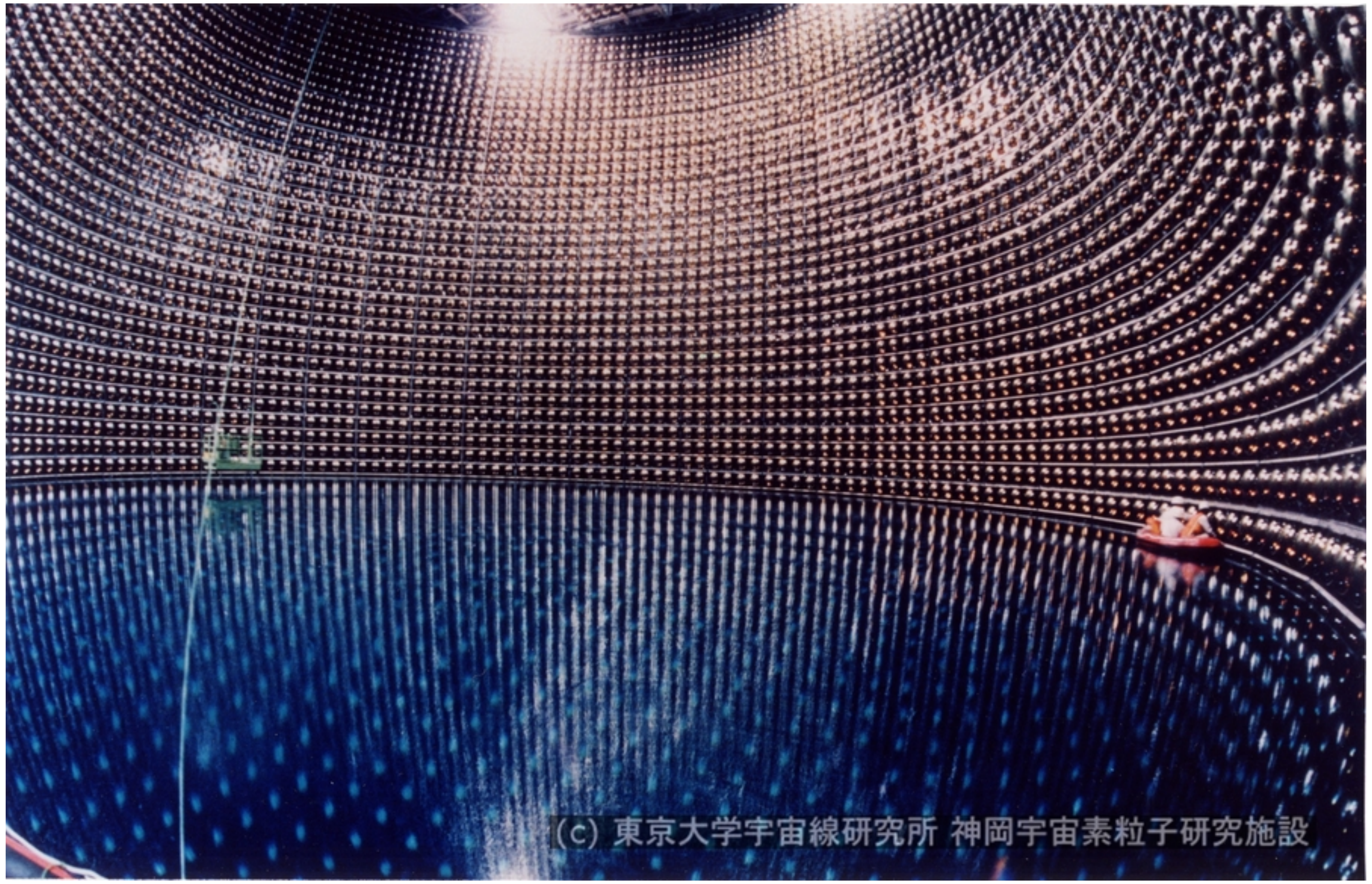
Past, present and future neutrino telescopes



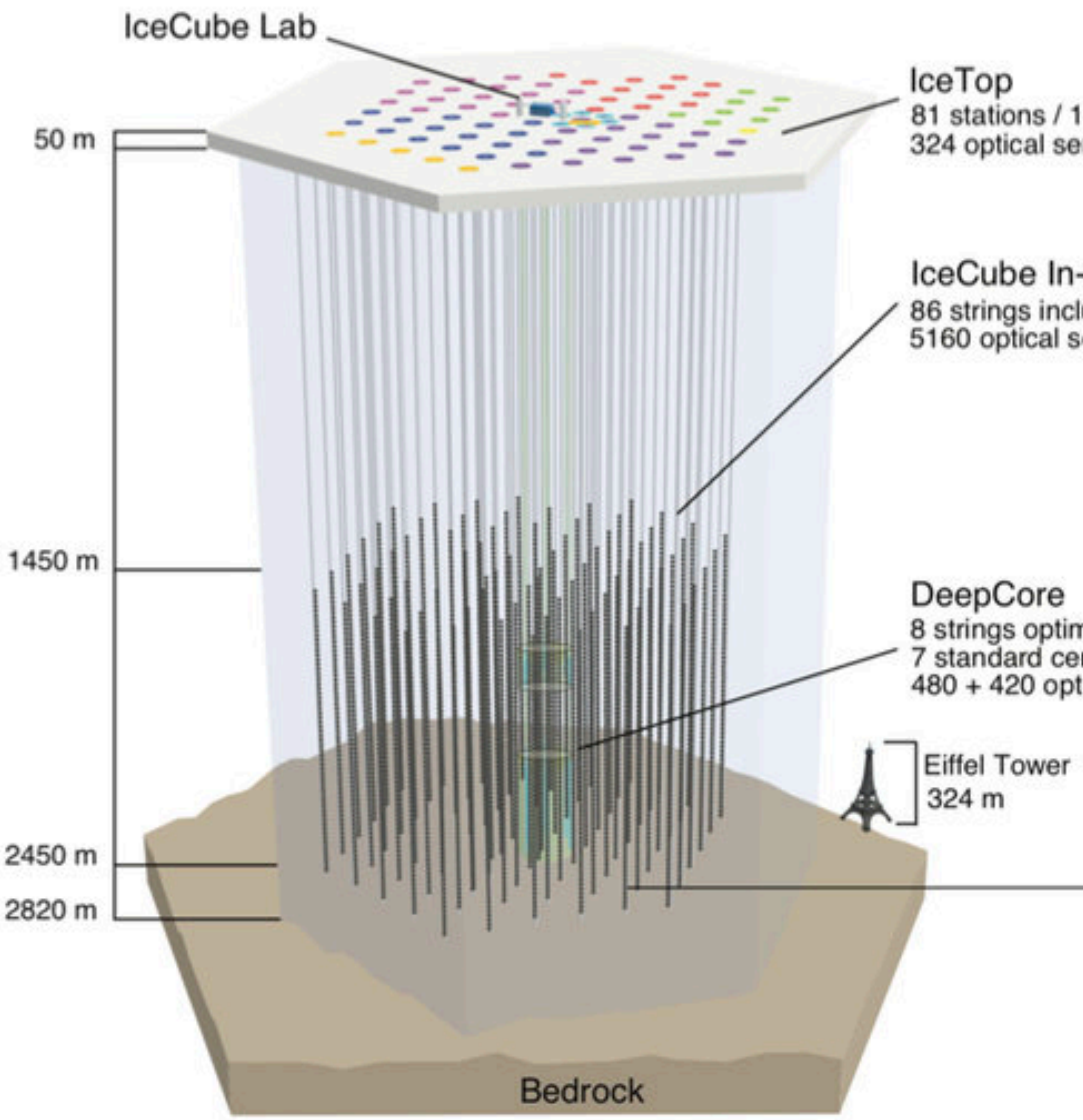
Water Cherenkov detectors

Kamiokande and Super-Kamiokande

- 1000 m underground (2700 m water equivalent)
- **Kamiokande/Super-Kamiokande:**
  - Inner volume ~2.2 kt/32 kt (**purified** water).
  - 948/11146 - 20" photomultiplier tubes.
  - Operation: 1984-1997/1996-2018.


(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

IceCube at South Pole

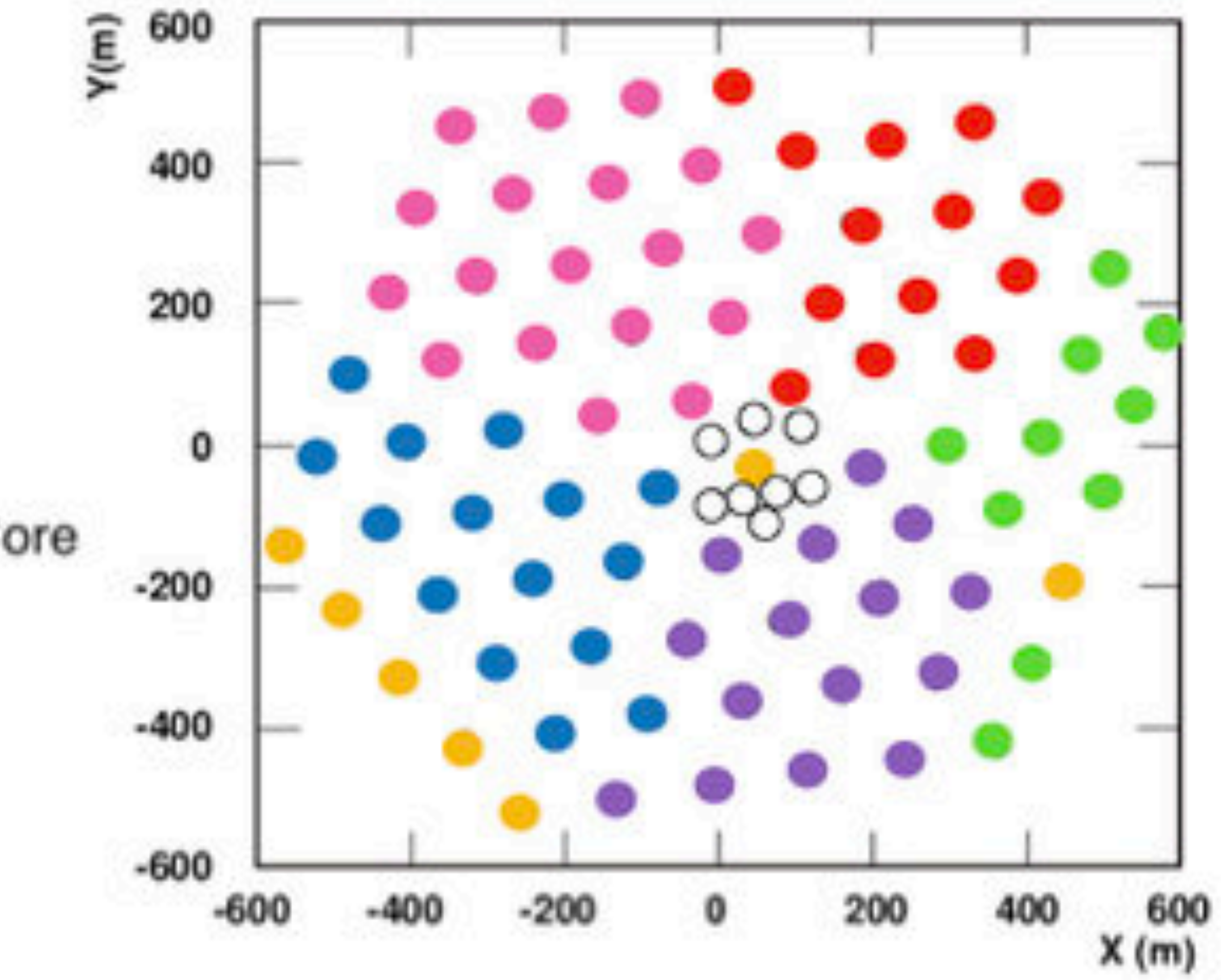


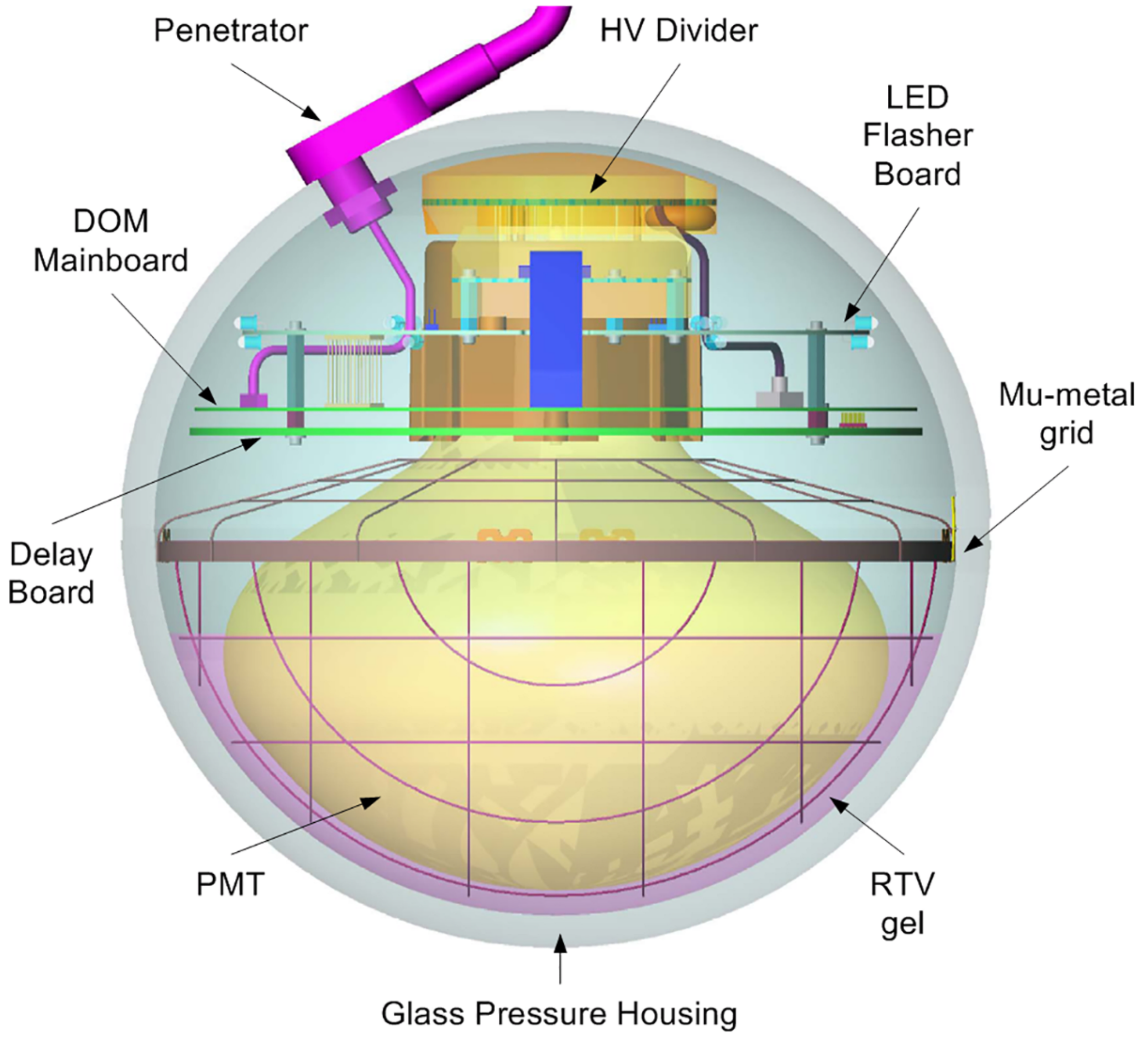
IceTop
81 stations / 162 tanks
324 optical sensors

IceCube In-Ice Array
86 strings including DeepCore
5160 optical sensors

DeepCore
8 strings optimized for lower energies +
7 standard central strings
480 + 420 optical sensors

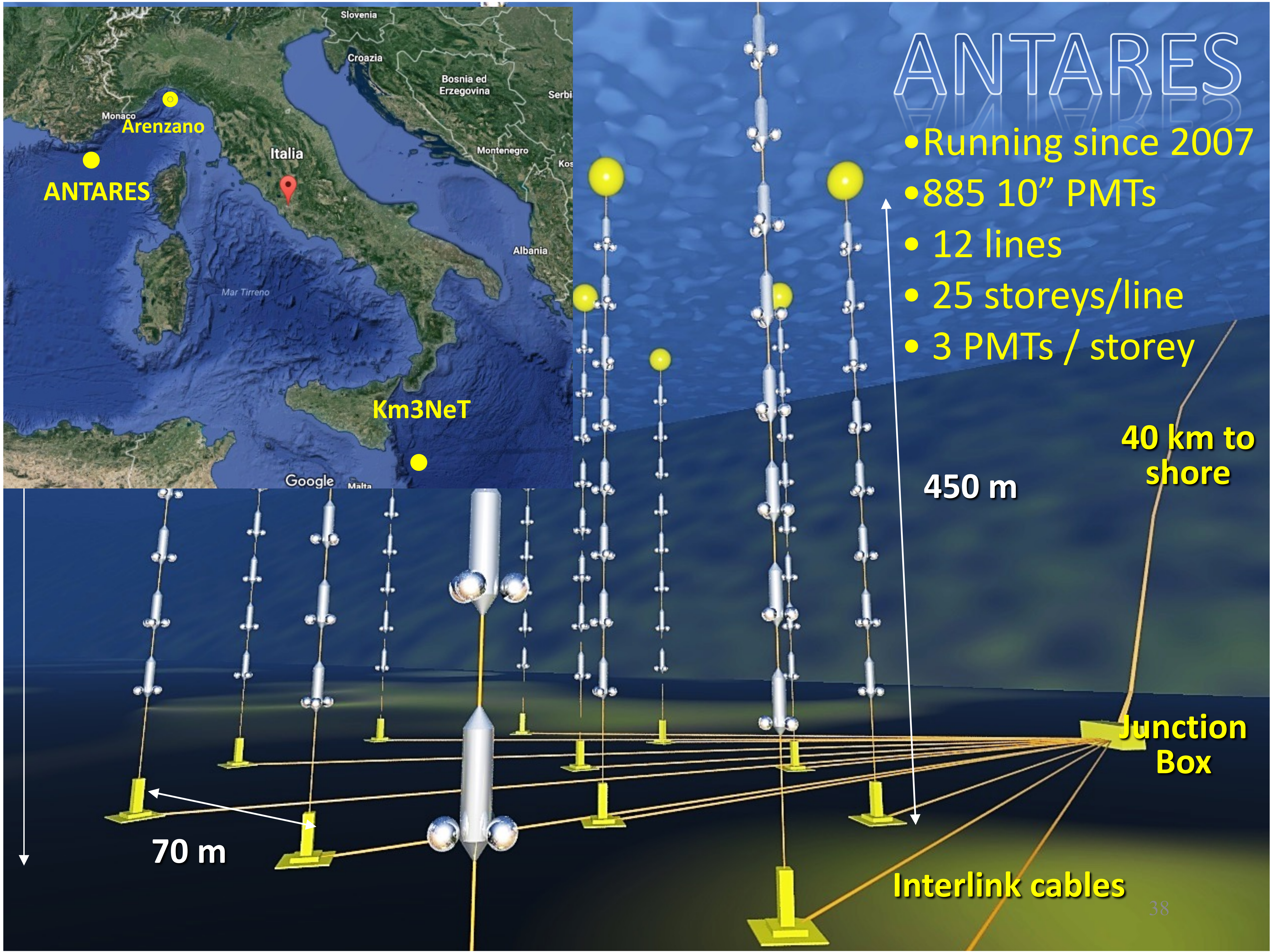
optical sensor

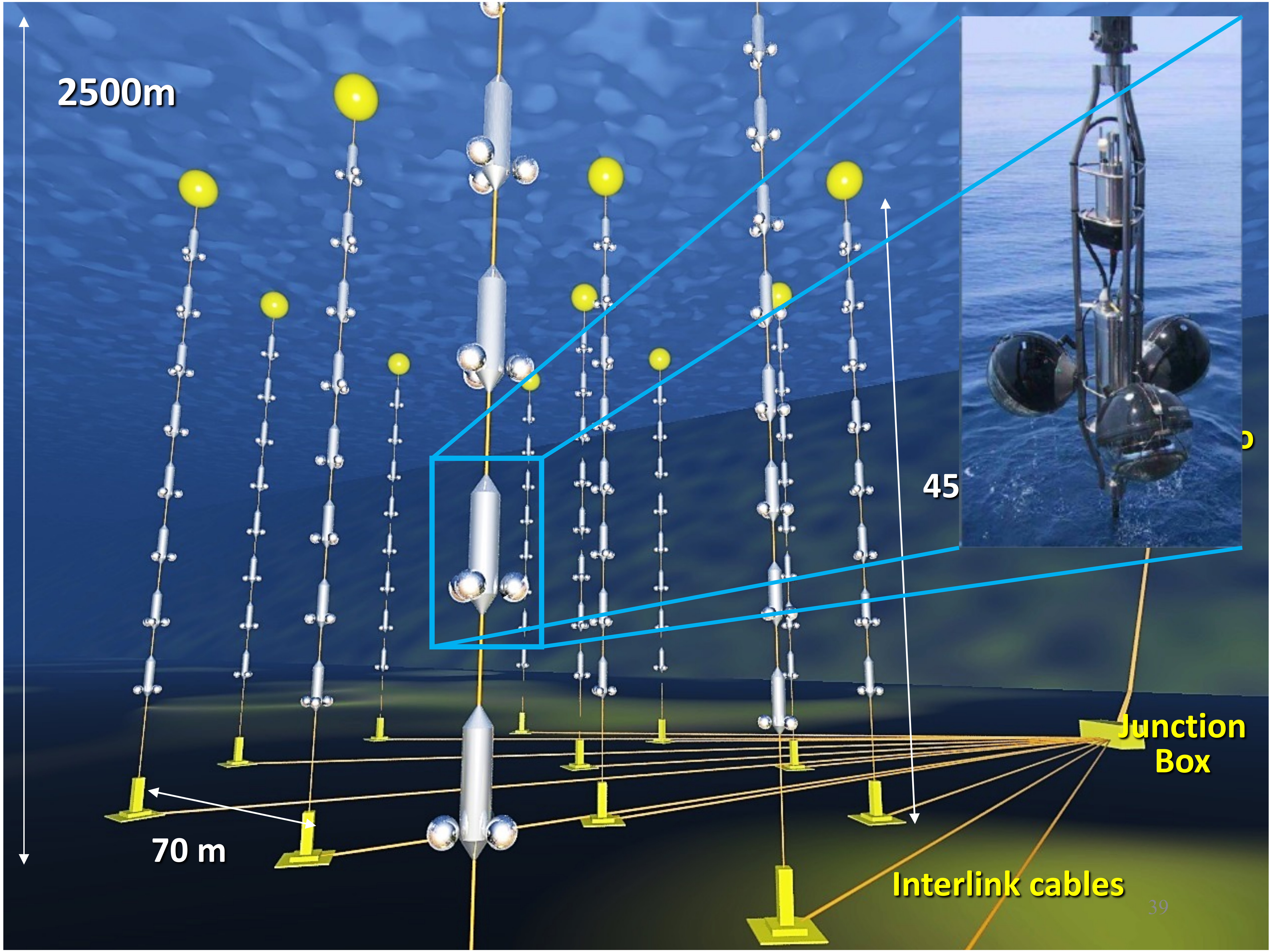




ANTARES

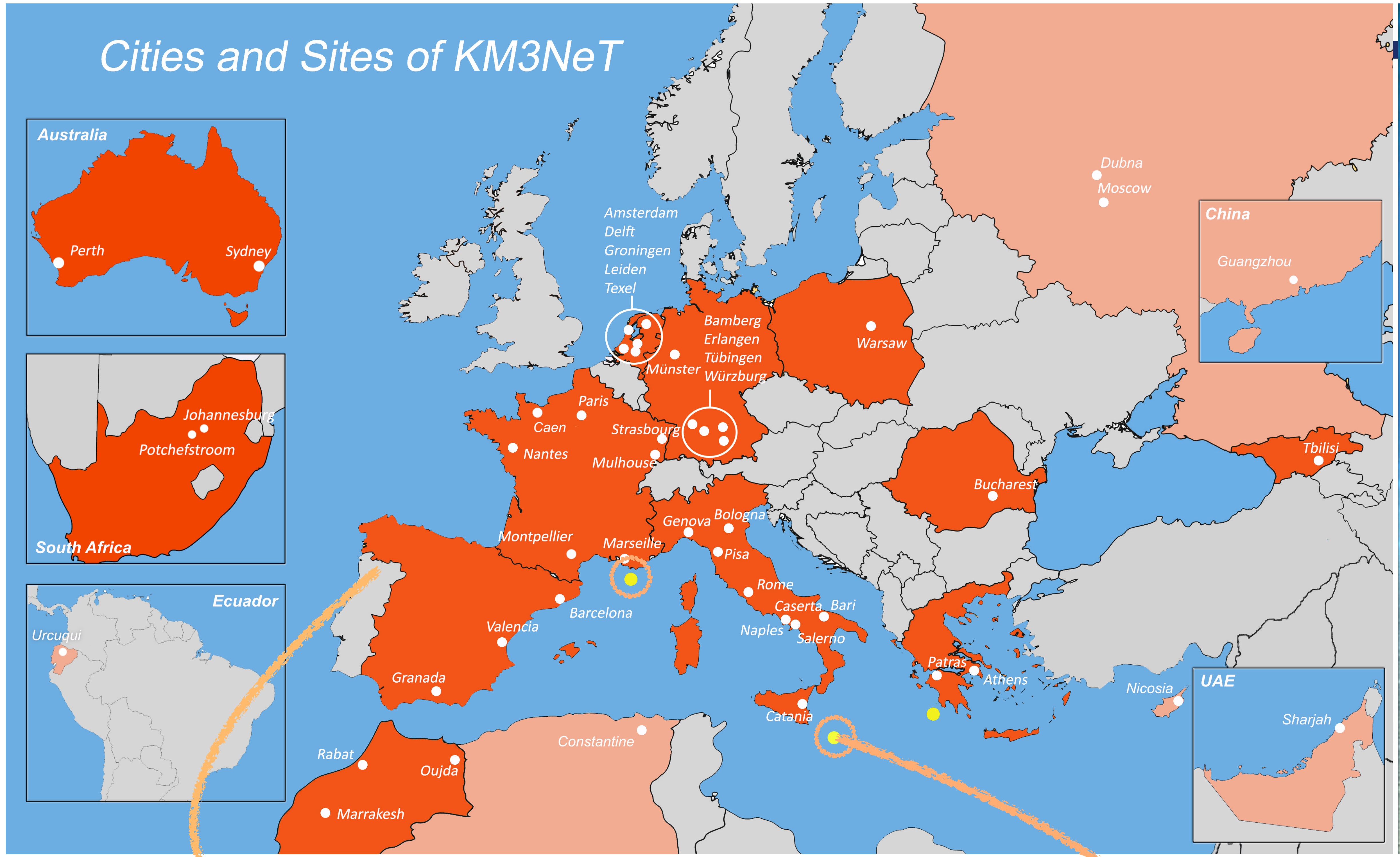
- Running since 2007
- 885 10” PMTs
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

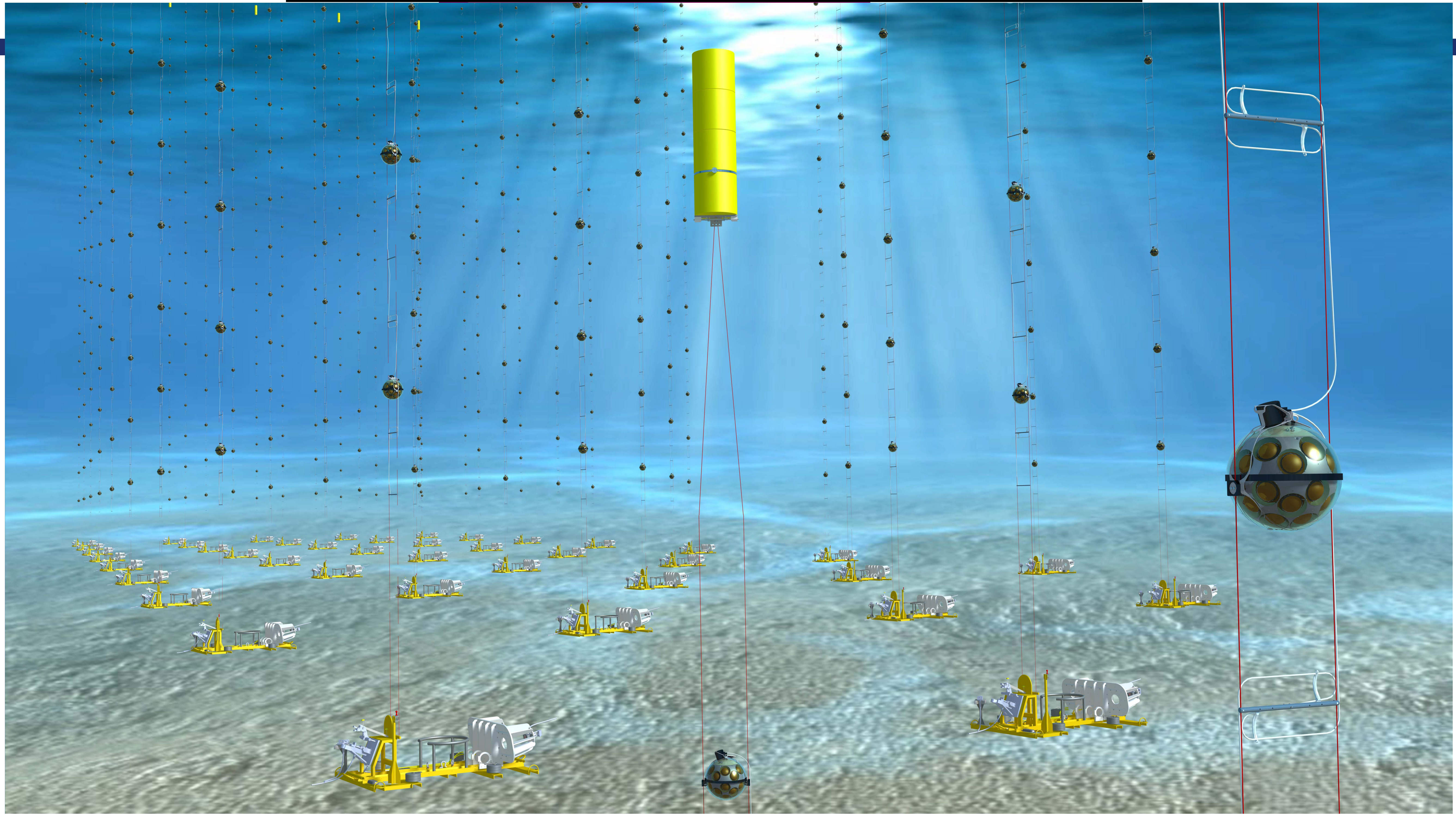



2500m
45
Junction Box
Interlink cables
70 m
39

KM3NeT

18 DOMS with 31 3″ PMTs FOR EACH LINE

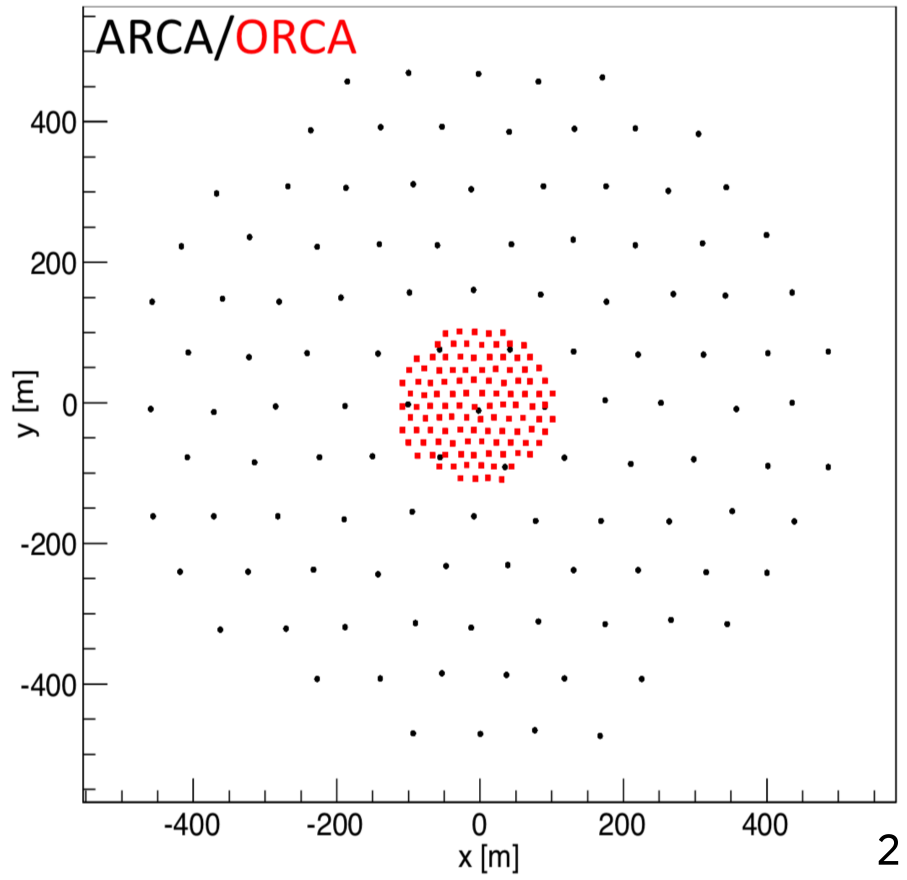




ORCA:
1 dense Building Block
optimised for intermediate energies (1-100 GeV)

ARCA:
2 sparse Building Blocks optimised for high energies (>1 TEV)

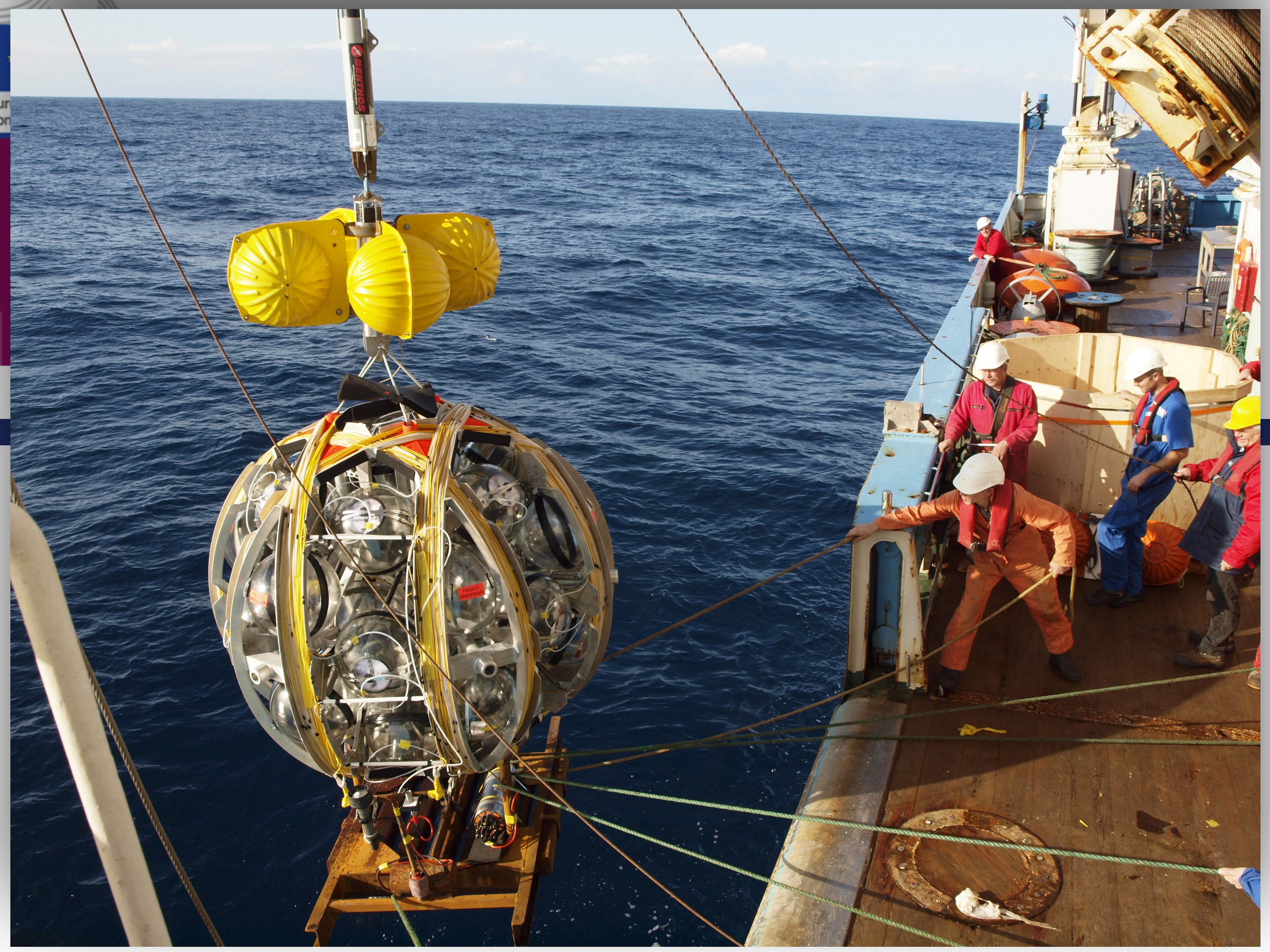
	ORCA	ARCA
String spacing	20 m	90 m
Vertical spacing	9 m	36 m
Depth	2470 m	3500 m

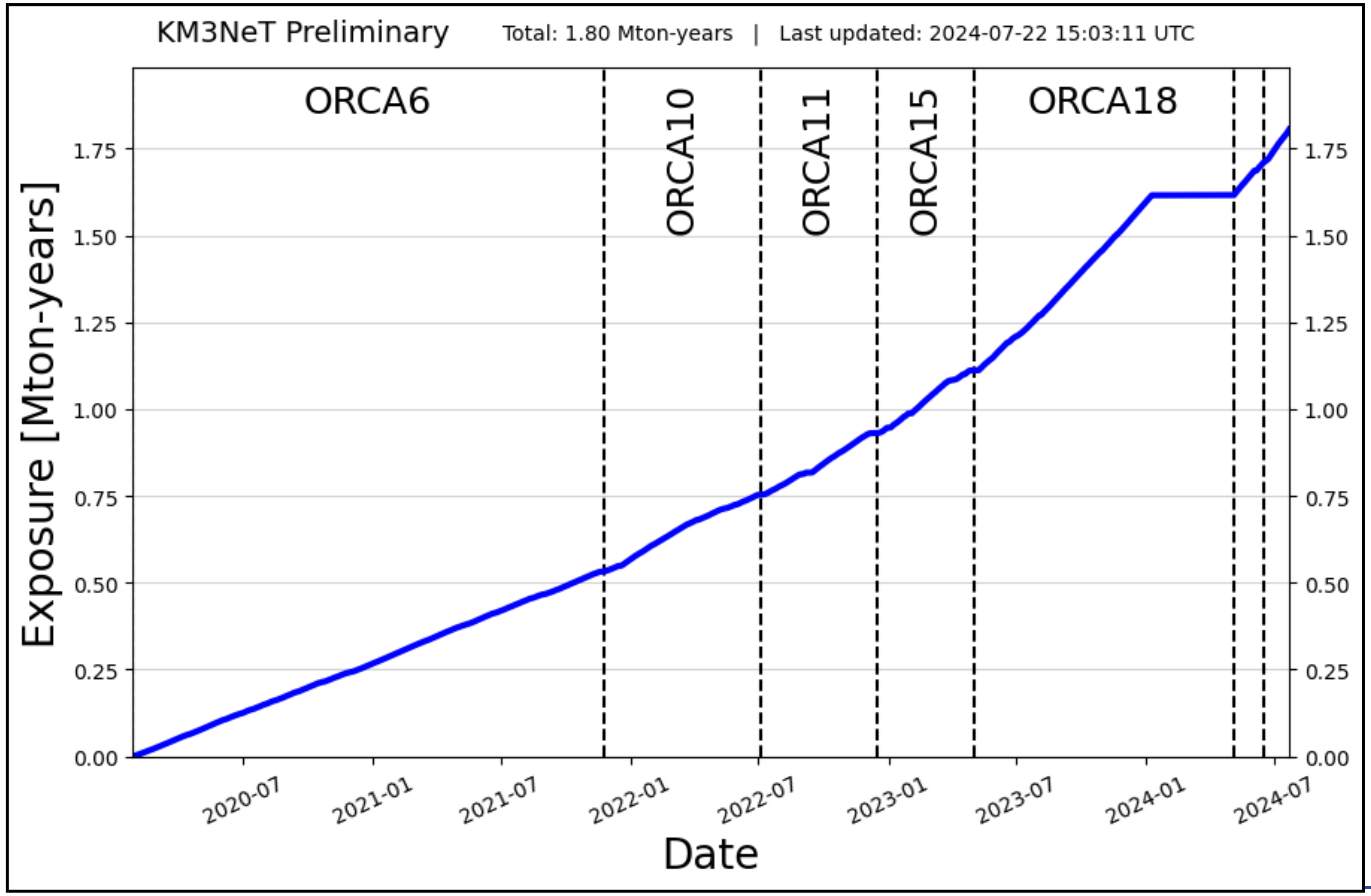


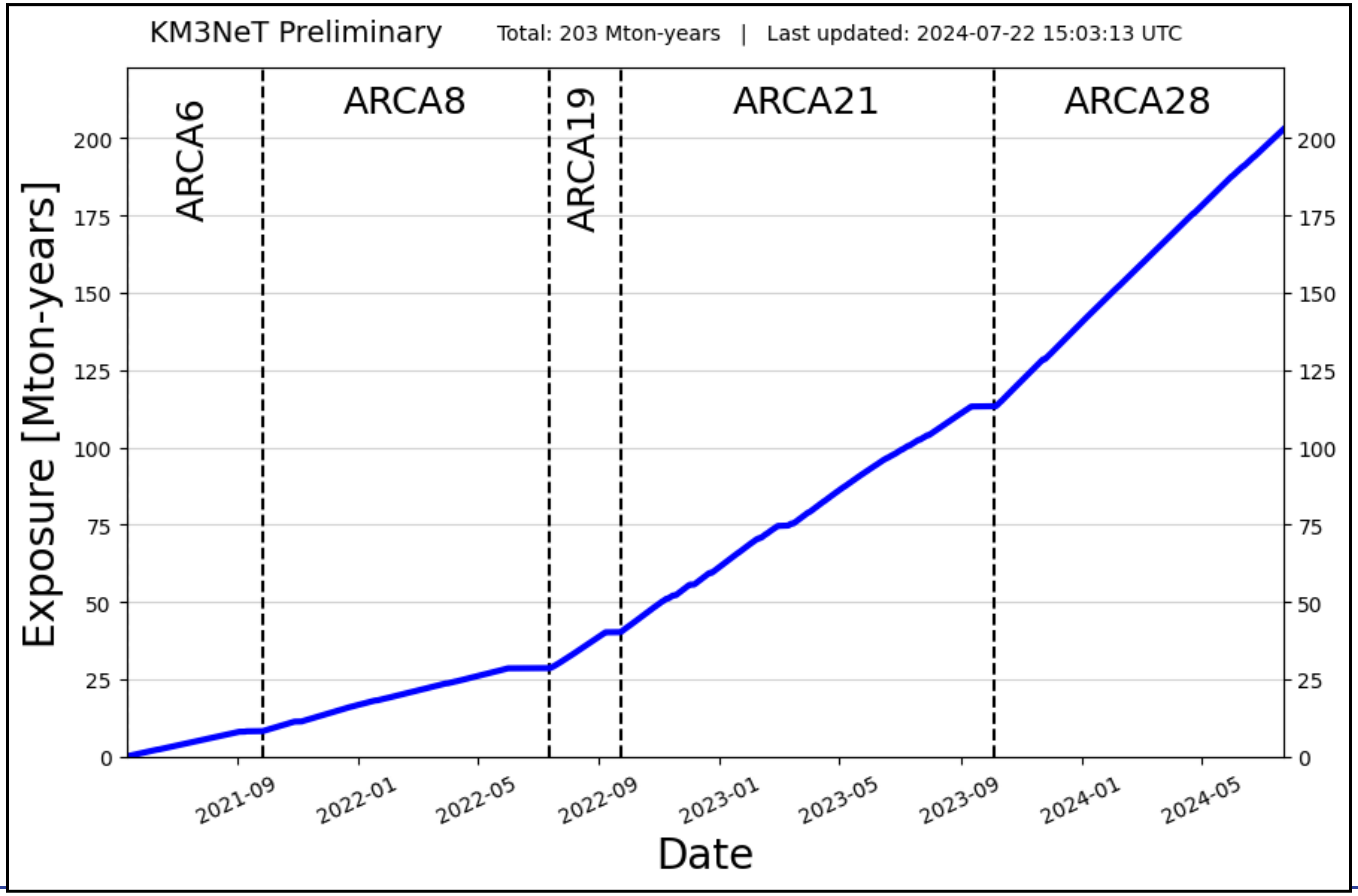
KM3NeT

Modular deployment.

23 ORCA-DUs and 28 ARCA-DUs currently taking data!





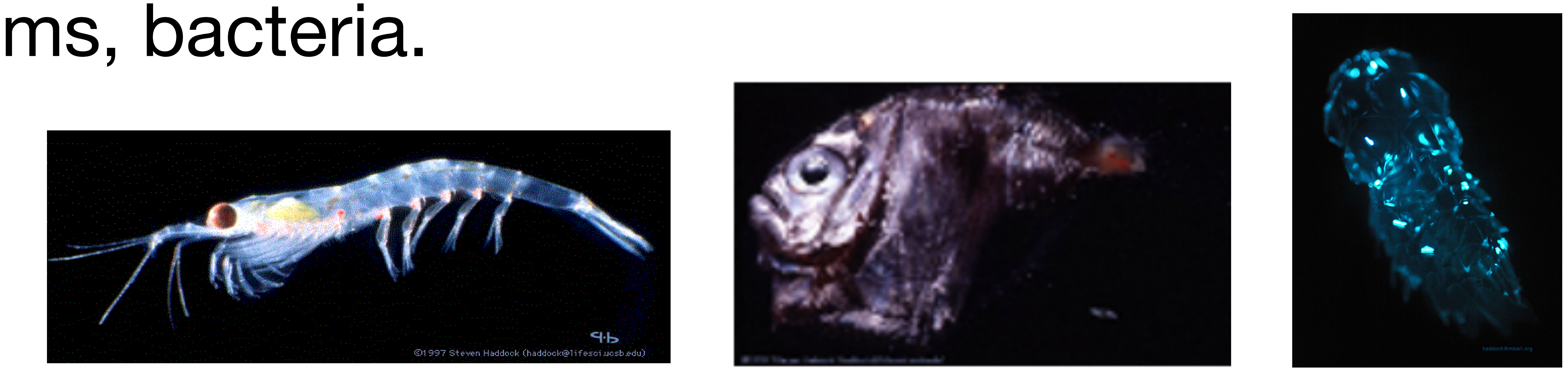


Optical background in water

- K40 decay: most abundant radioactive isotope in sea water.

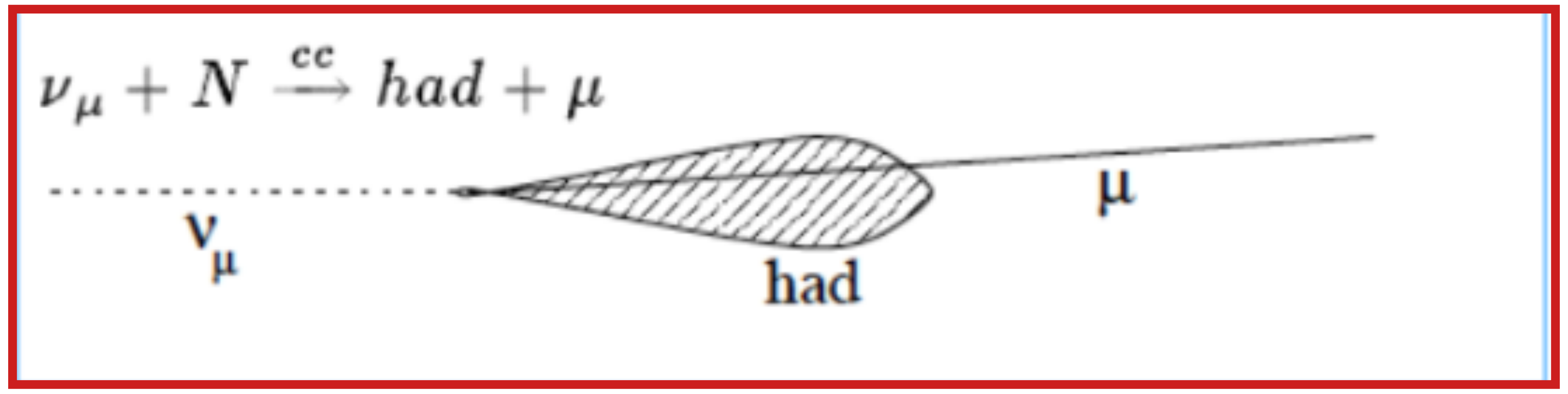
$$
\begin{aligned}
{}^{40}K &\rightarrow {}^{40}Ca + e^- + \overline{\nu}_e && (89.3\%)\\
{}^{40}K + e^- &\rightarrow {}^{40}Ar^* + \nu_e && (10.7\%)\\
&\quad\hookrightarrow {}^{40}Ar + \gamma &&
\end{aligned}
$$

- Bioluminescence: macro organisms, bacteria.

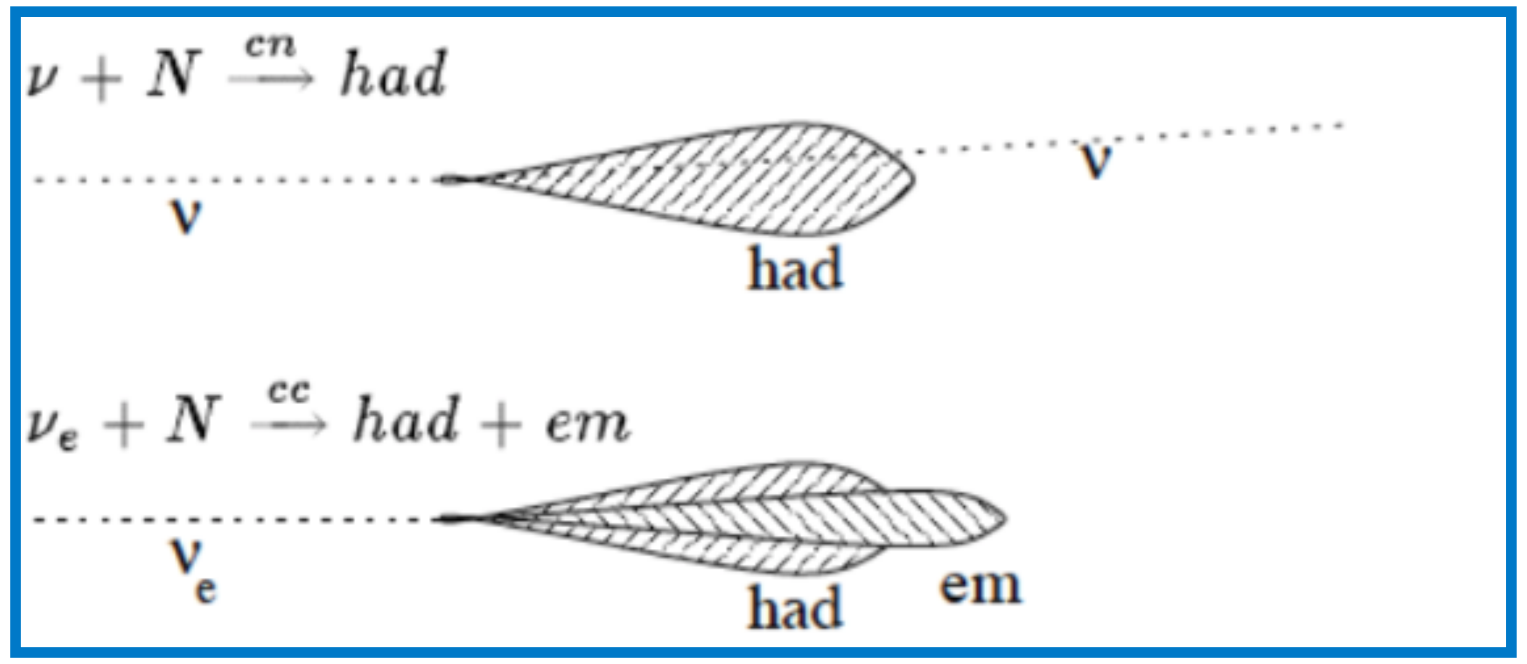


High energy event topologies

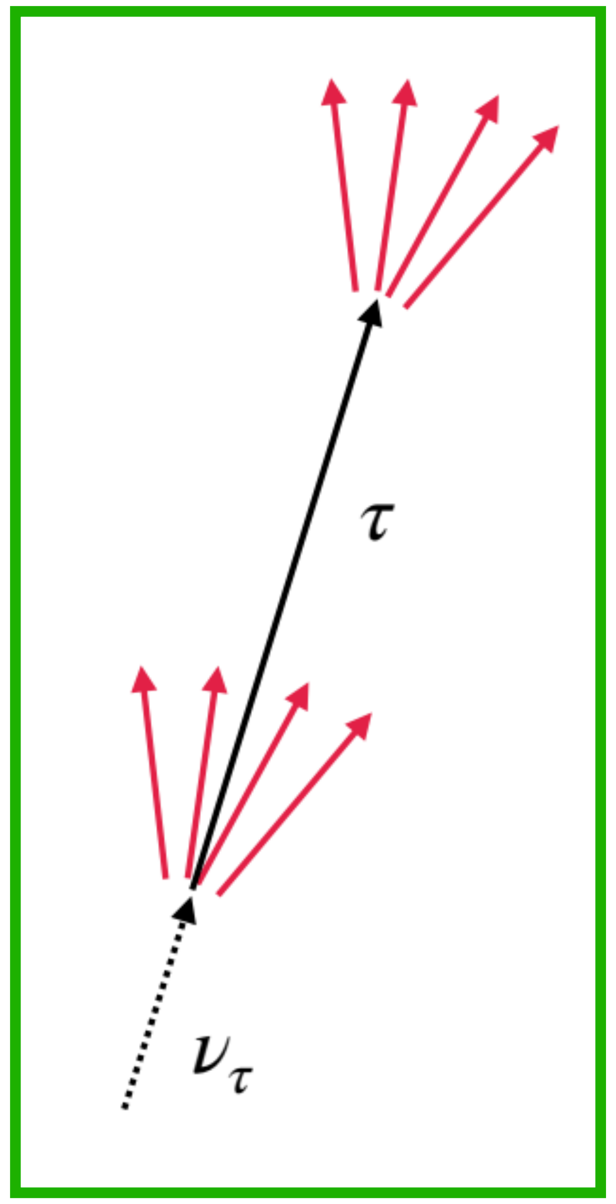
Tracks: ν_μCC, ν_τCC ($\tau \rightarrow \mu$)

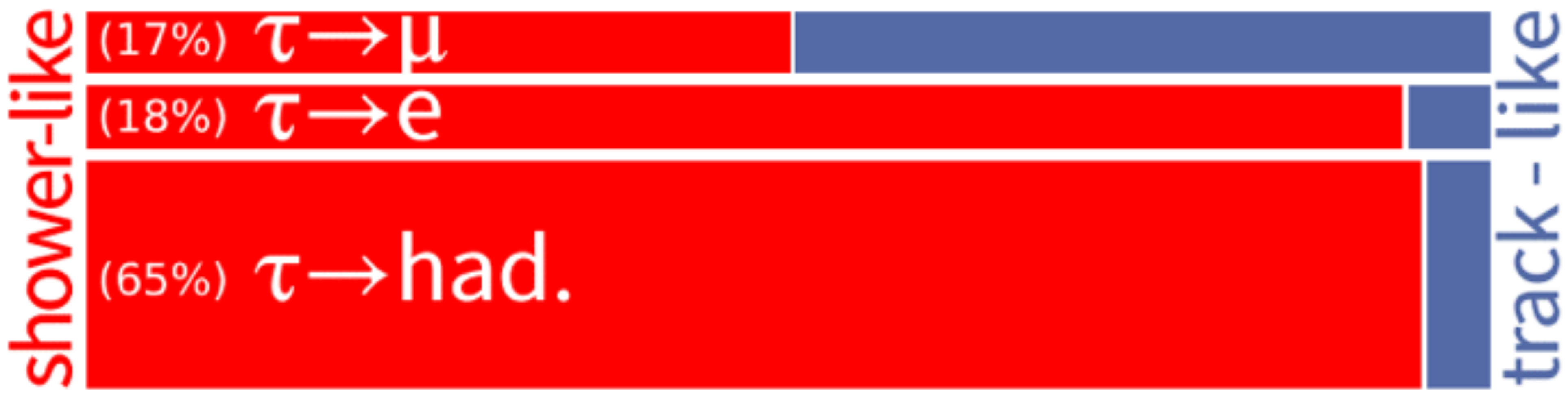


Showers: ν_eCC, νNC, ν_τ



Double showers: ν_τ





Neutrino telescopes

Effective Area

- Figure of merit of neutrino telescopes.

1- PHYSICS: neutrino energy spectrum at source: ν/(cm^2 s GeV)

Event rate (s^{-1})

$$\frac{N_\nu}{T} = \int \mathrm{d}E_\nu \cdot \boxed{\frac{\mathrm{d}\Phi_\nu}{\mathrm{d}E_\nu}(E_\nu)} \cdot \boxed{A_\nu^{\mathrm{eff}}(E_\nu)}$$

2: INSTRUMENT: ν detection effective area (cm^2)

HE cosmic neutrino detection

Effective Area

- Figure of merit of neutrino telescopes.

$$\boxed{A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E_{\mathrm{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}}$$

HE cosmic neutrino detection

Effective Area

- Figure of merit of neutrino telescopes.

$$\boxed{A_{\nu}^{\mathrm{eff}}(E_{\nu}) = \boxed{A} \cdot P_{\nu\mu}(E_{\nu}, E_{\mathrm{thr}}^{\mu}) \cdot \epsilon \cdot e^{-\sigma(E_{\nu})\rho N_{A} Z(\theta)}}$$

- A [cm^2]: geometrical projected detector surface.

HE cosmic neutrino detection

Effective Area

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot \boxed{P_{\nu\mu}(E_\nu, E^\mu_{\mathrm{thr}})} \cdot \epsilon \cdot e^{-\sigma(E_\nu)\rho N_A Z(\theta)}$$

Probability that a ν_μ induces a muon with energy $E>E^\mu_{\mathrm{thr}}$ reaches the detector:

$$\boxed{P_{\nu\mu} = \sigma_{\nu\mu}(cm^2)\times\rho\ (cm^{-3})\times R\ (cm)}$$

$$\sigma_{\nu\mu} \cong 1.5\ 10^{-34}\left(\frac{E}{10\ TeV}\right)^{0.4} (cm^2)$$

- The nucleon number density in ordinary matter

  $\rho \cong 10^{23}\ cm^{-3}$;

- The muon range for $E_\mu > 1$ TeV:

  $R \cong 10^6\ cm$

$$\boxed{P_{\nu\mu} \cong 4\times 10^{-6}\left(\frac{E}{10\ TeV}\right)^{0.4}}$$

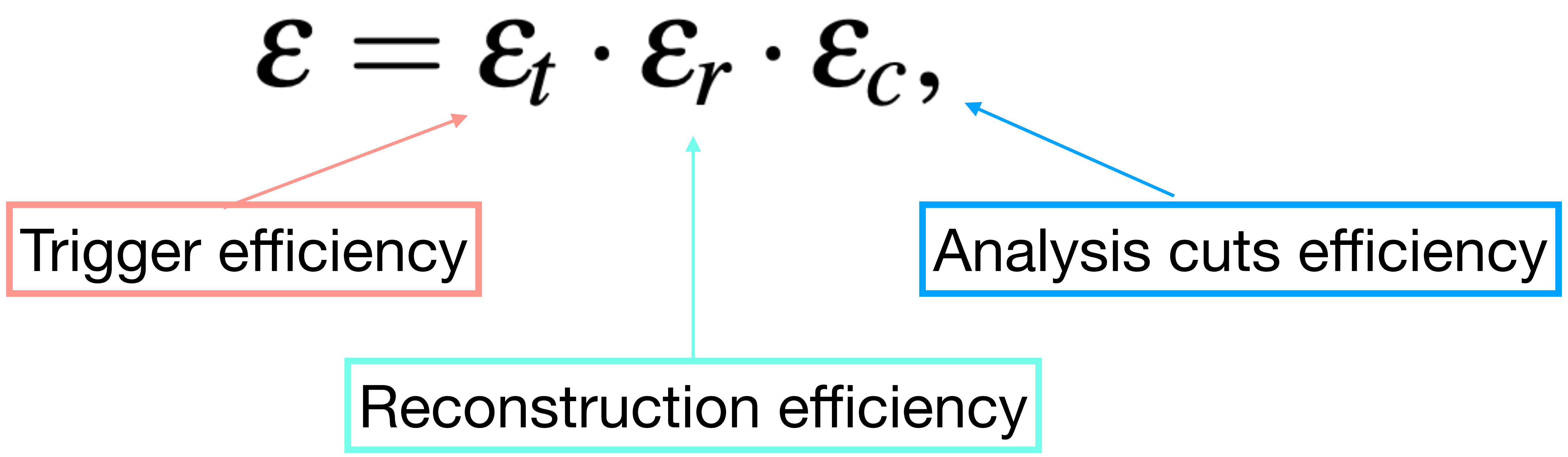
HE cosmic neutrino detection

Effective Area

$$A_{\nu}^{\mathrm{eff}}(E_{\nu}) = A \cdot P_{\nu\mu}(E_{\nu}, E_{\mathrm{thr}}^{\mu}) \boxed{\cdot\ \epsilon\ \cdot} e^{-\sigma(E_{\nu})\rho N_A Z(\theta)}$$

- Detector efficiency: depends on the analysis.
- Fraction of muons with energy Ethr that are detected.

Obtained with MC simulations



$$\varepsilon = \varepsilon_t \cdot \varepsilon_r \cdot \varepsilon_c,$$

Trigger efficiency

Reconstruction efficiency

Analysis cuts efficiency

HE cosmic neutrino detection

Effective Area

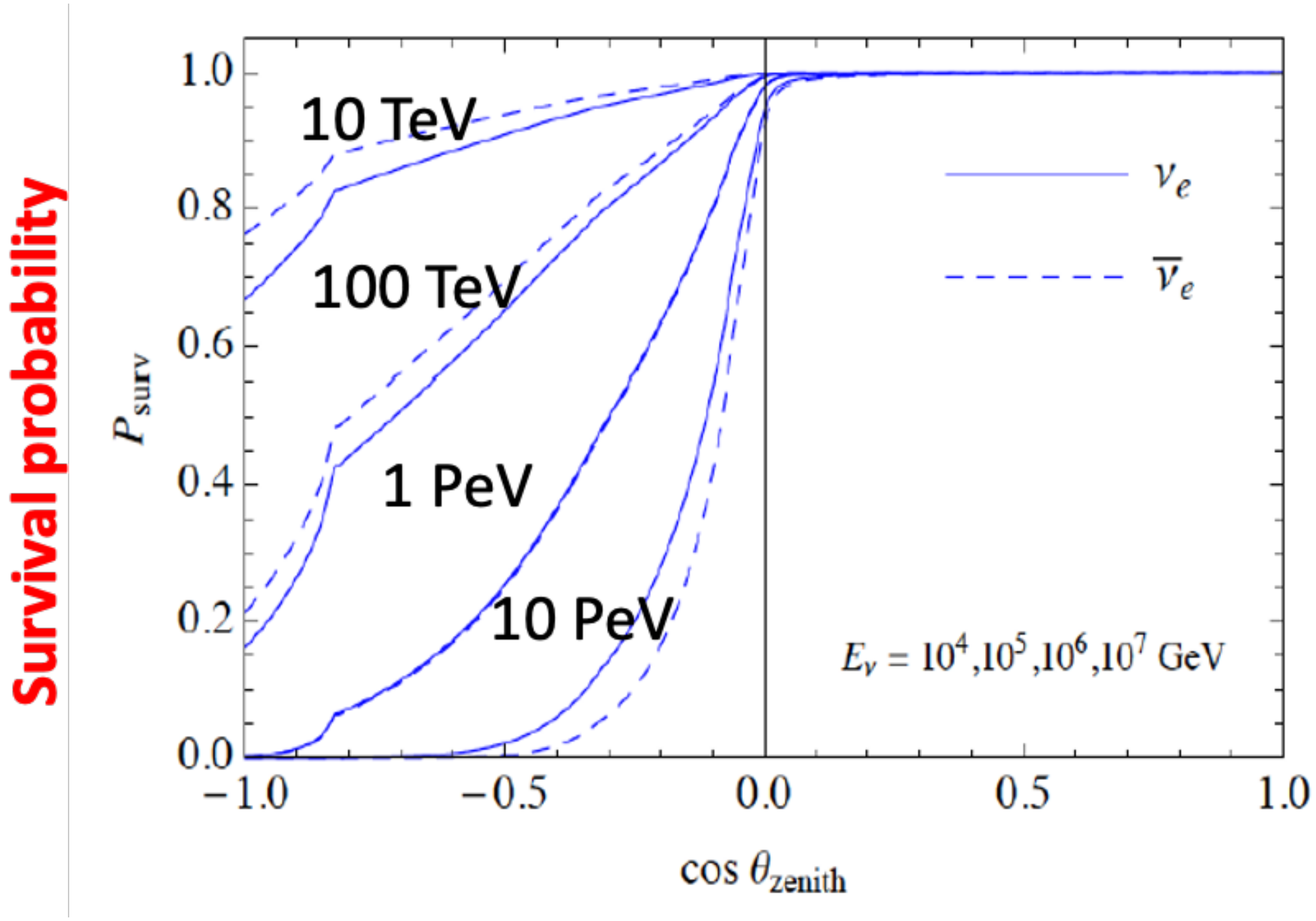
Total neutrino cross section

Target nucleon density

Absorption

$$A_\nu^{\mathrm{eff}}(E_\nu) = A \cdot P_{\nu\mu}(E_\nu, E^\mu_{\mathrm{thr}}) \cdot \epsilon \cdot \boxed{e^{-\sigma(E_\nu)\rho N_A Z(\theta)}}$$

- Earth absorption: the Earth becomes opaque for HE neutrinos.



HE cosmic neutrino detection

Tau neutrino regeneration

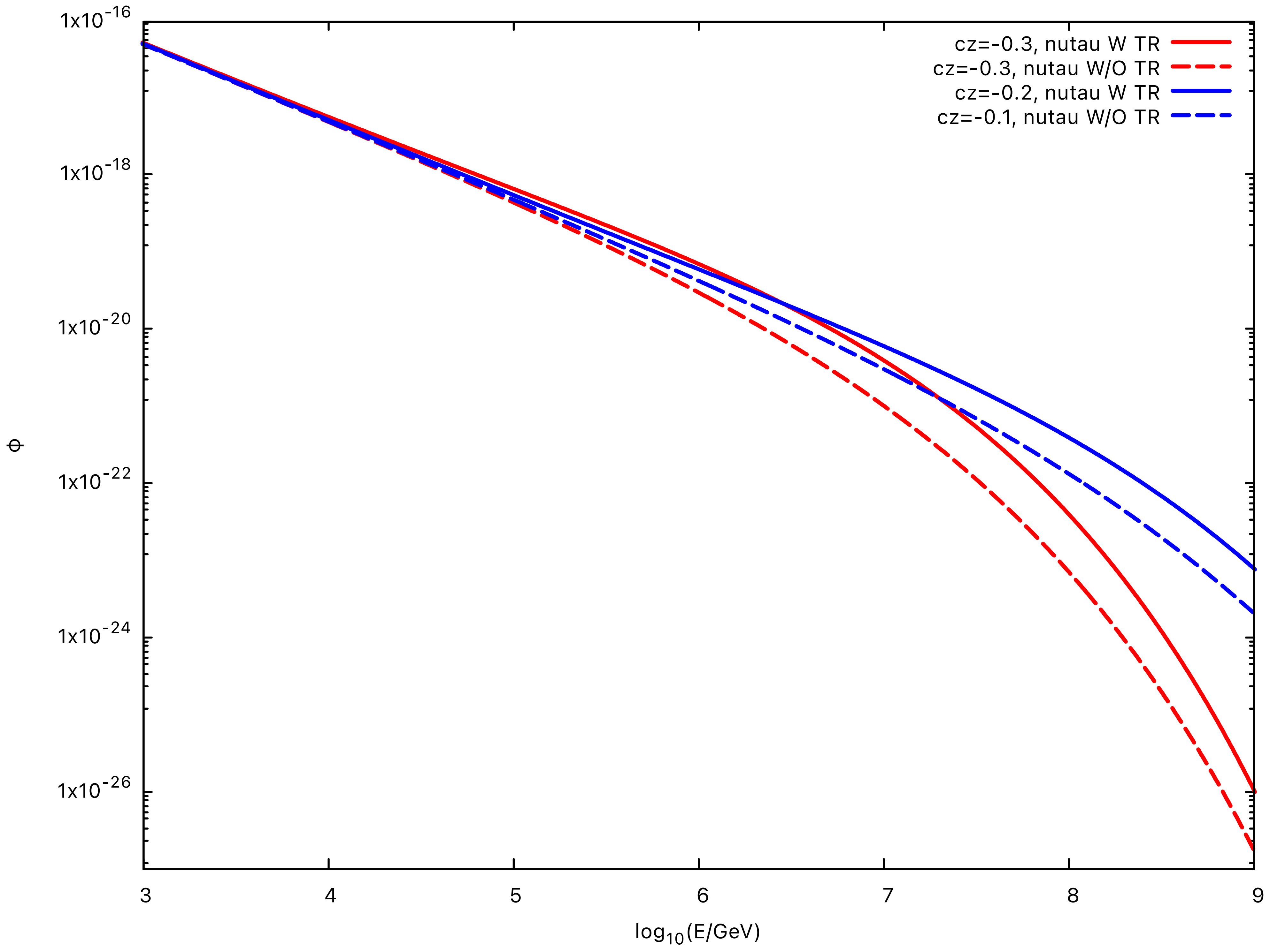
- Generally, the evolution of a neutrino system in the Earth matter includes both coherent flavour changes (oscillations) and non coherent scattering interactions with matter.
- The latter becomes relevant for high energy neutrinos: what is the threshold for HE in this case?
- High-energy neutrinos propagating in the Earth can also interact inelastically with the Earth matter either by CC or NC and as a consequence the neutrino flux is attenuated.
- This attenuation is qualitatively and quantitatively different for ν_τ,ν_μ,ν_e.

HE cosmic neutrino detection

Tau neutrino regeneration

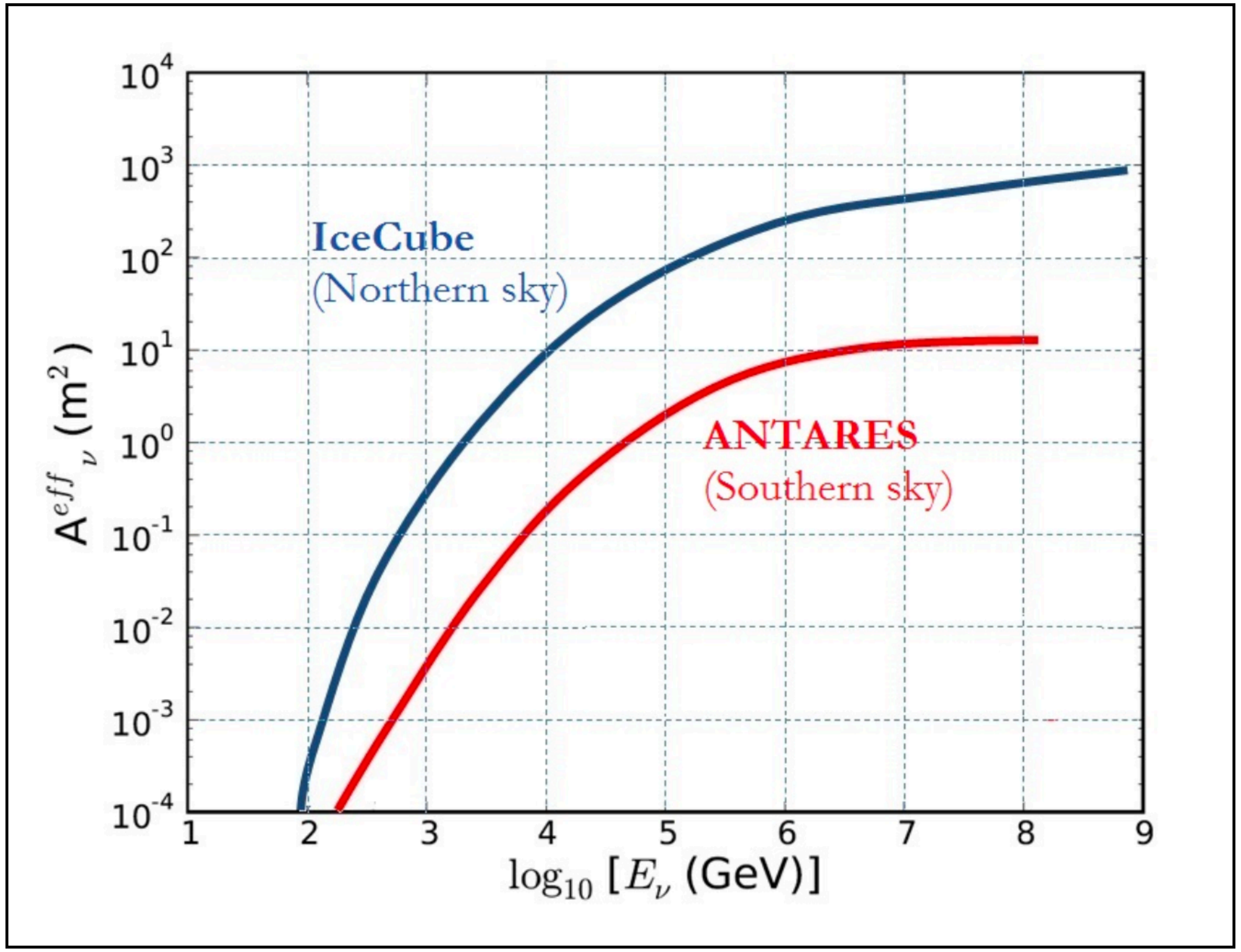
- Muon neutrinos are absorbed by CC interactions while tau neutrinos are regenerated because they produce a τ that decays into another ν_τ before losing energy.
- As a consequence, for each ν_τ lost in CC interactions, another ν_τ appears (degraded in energy) from the τ decay and the Earth never becomes opaque to ν_τ's.
- Moreover, a new secondary flux of anti-ν_τ is also generated in the leptonic decay τ → $\mu\nu_\mu\bar{\nu}_\tau$(BR ~ 17%).

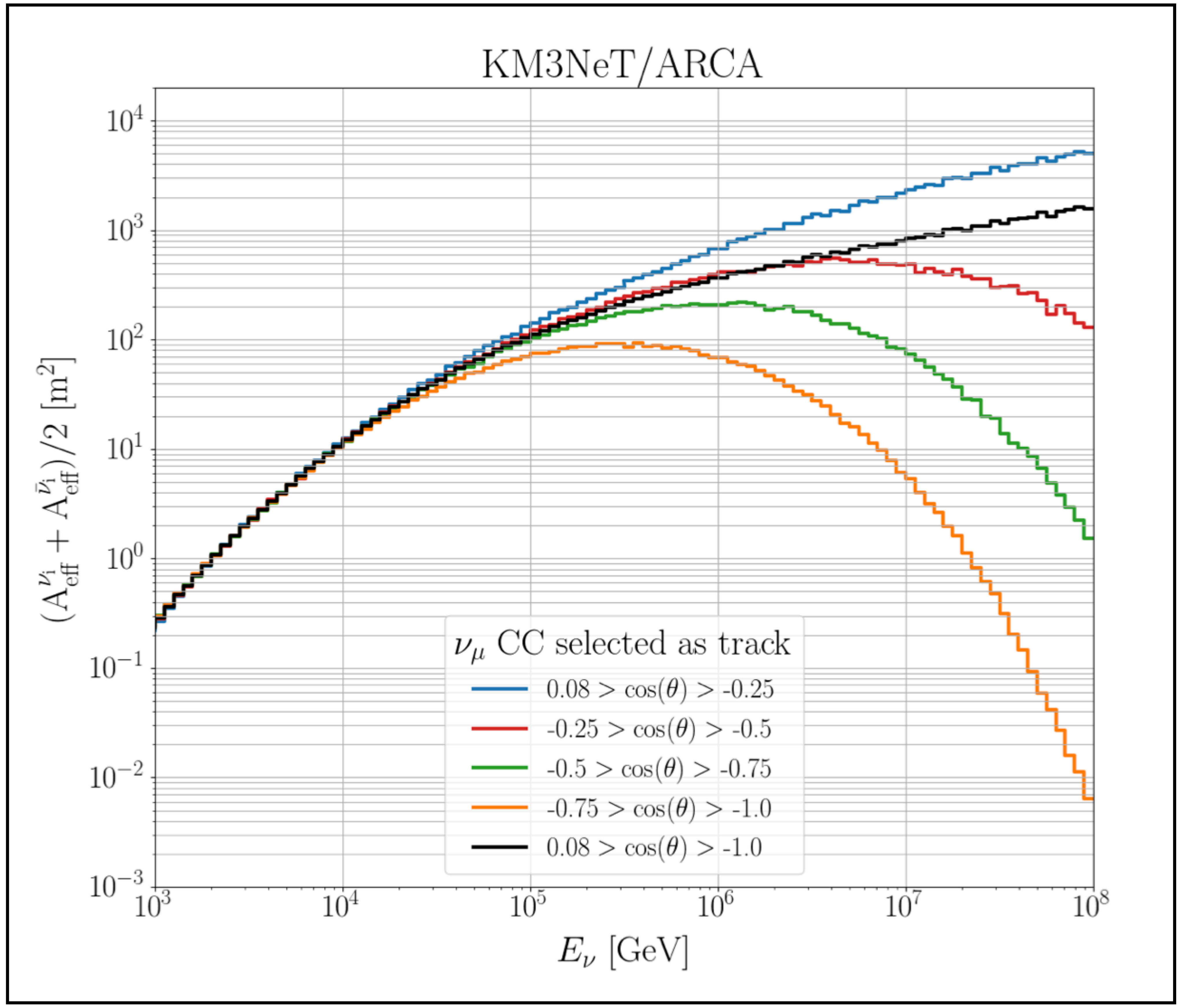
decay mode	fit result (%)	coefficient
$\mu^-\bar{\nu}_\mu\nu_\tau$	17.3937 ± 0.0384	1.0000
$e^-\bar{\nu}_e\nu_\tau$	17.8175 ± 0.0399	1.0000
$\pi^-\nu_\tau$	10.8164 ± 0.0512	1.0000
$K^-\nu_\tau$	0.6964 ± 0.0096	1.0000
$\pi^-\pi^0\nu_\tau$	25.4941 ± 0.0893	1.0000
$K^-\pi^0\nu_\tau$	0.4328 ± 0.0148	1.0000
$\pi^-2\pi^0\nu_\tau$ (ex. K^0)	9.2595 ± 0.0964	1.0021
$K^-2\pi^0\nu_\tau$ (ex. K^0)	0.0647 ± 0.0218	1.0000
$\pi^-3\pi^0\nu_\tau$ (ex. K^0)	1.0429 ± 0.0707	1.0000
$K^-3\pi^0\nu_\tau$ (ex. K^0, η)	0.0478 ± 0.0212	1.0000
$h^-4\pi^0\nu_\tau$ (ex. K^0, η)	0.1118 ± 0.0391	1.0000



HE cosmic neutrino detection

Effective Area

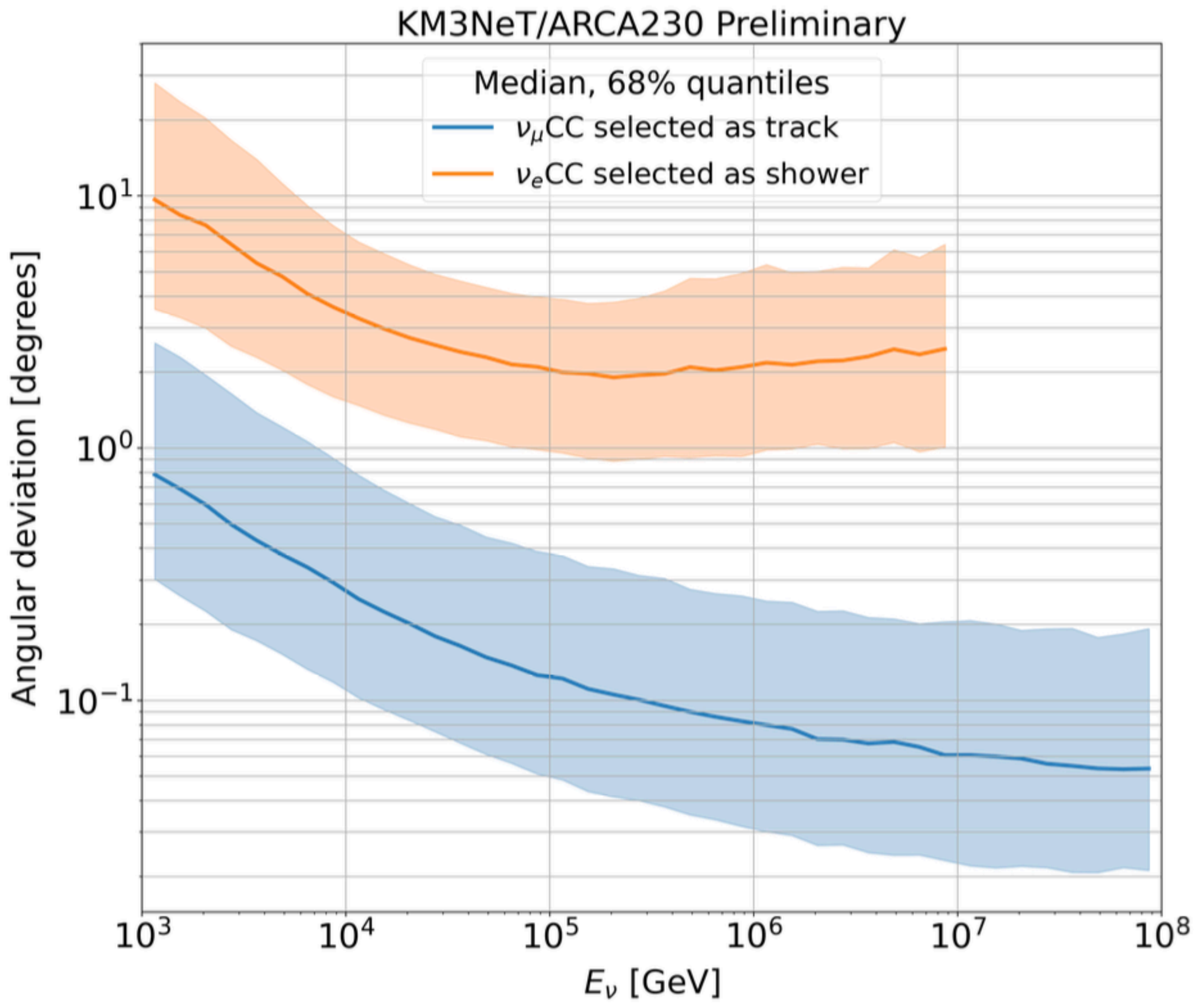


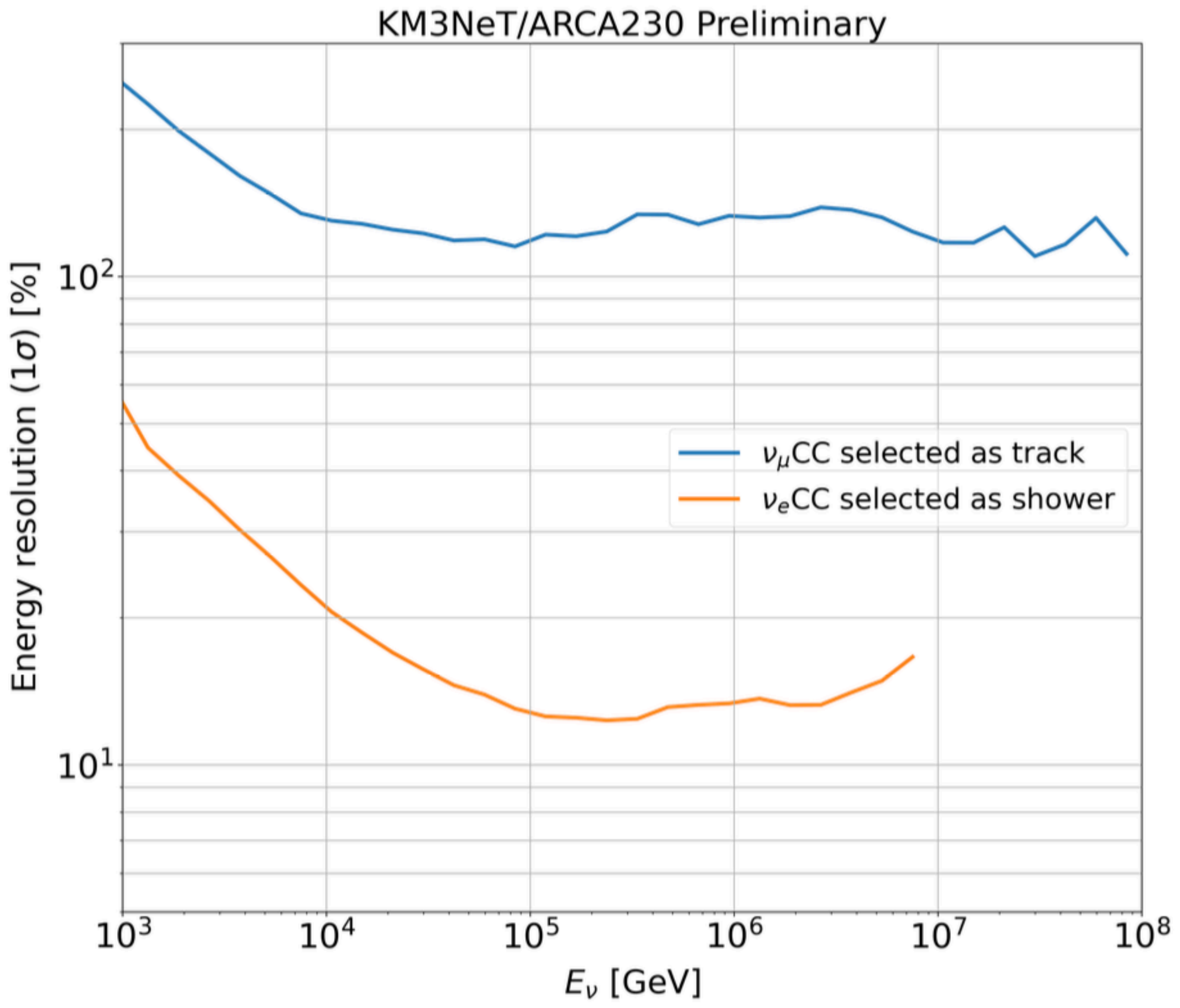


KM3NeT Collaboration, arXiv:2402.08363 (2024)

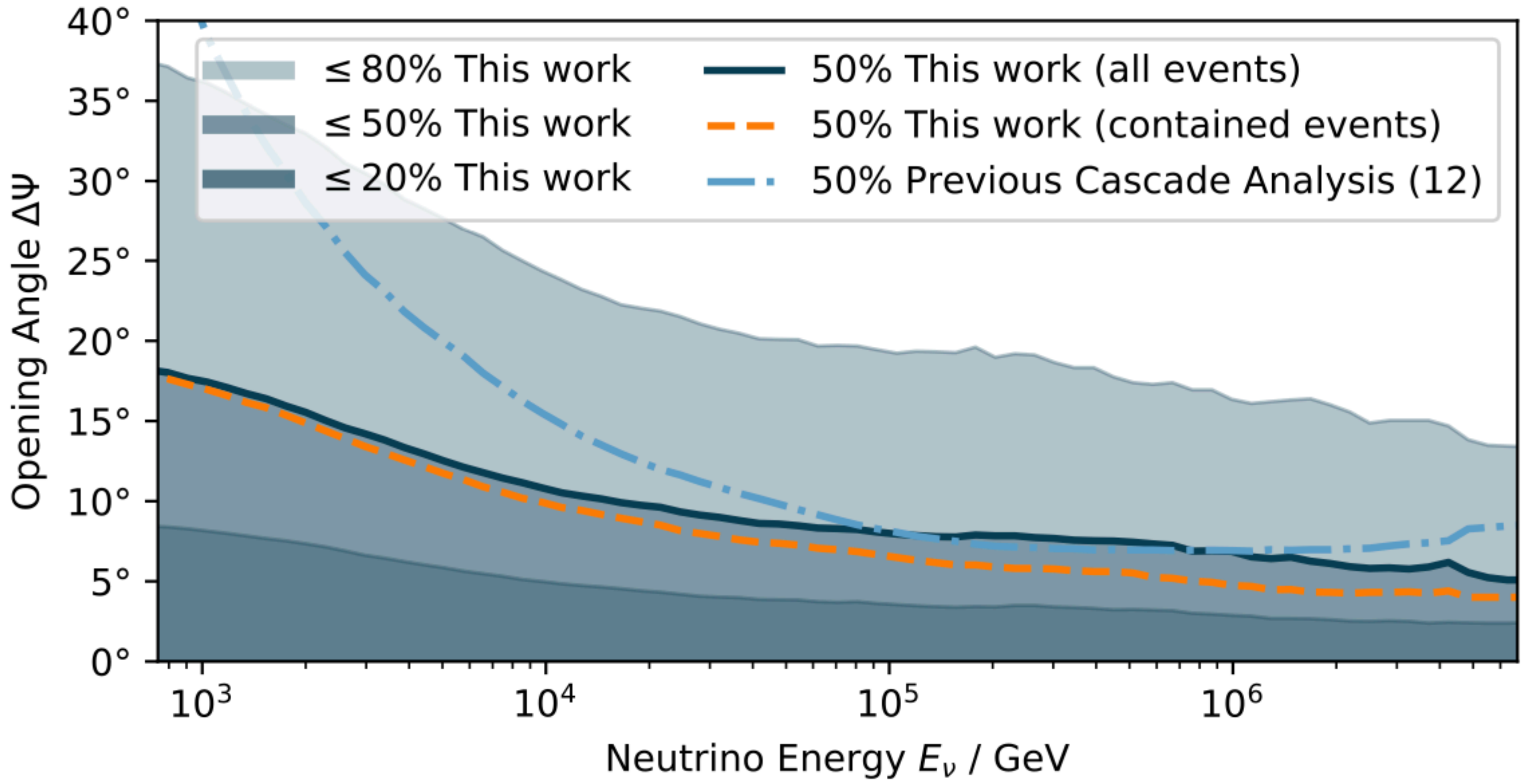
Angular & energy resolution important!

KM3NeT/ARCA





ICECUBE



Cosmic neutrino detection

Method 1) Measuring an excess of events from a given direction (point-sources).

- Mainly ν_μ and upgoing events

Method 2) Measure an excess of high-energy events with respect to the background (diffuse).

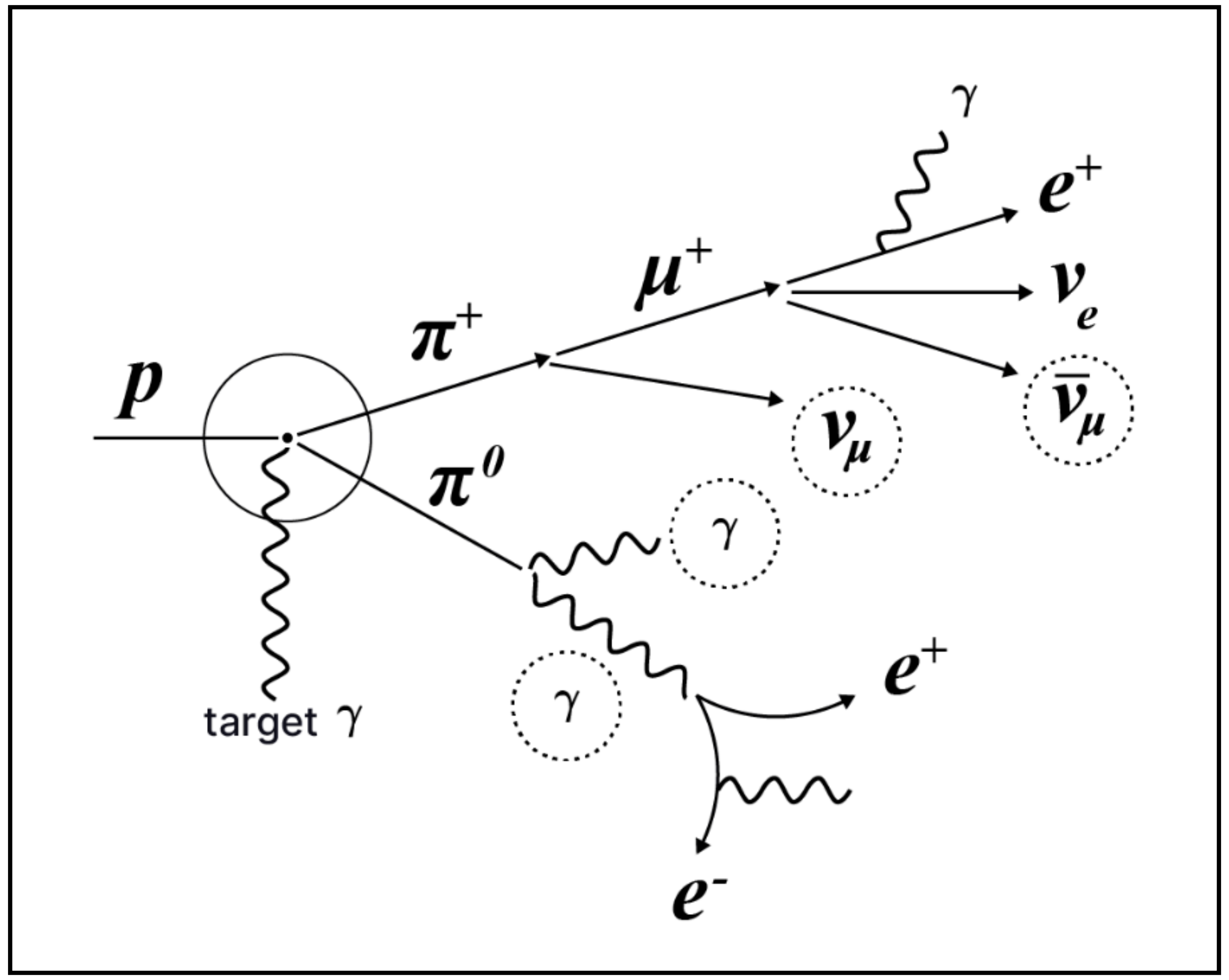
- All flavours. Tracks, showers and partially contained events.

3. High energy neutrino sources

High energy neutrino production

- Gravitational energy in HE sources in the universe (ex. black holes) accelerates protons and heavy nuclei.

- These subsequently interact with the surrounding environment (radiation and/or matter) and produce pions and other secondary particles that decay into neutrinos.



C. Arguelles et al: arXiv:2405.17623v1

We should expect a similar flux of neutrinos and gamma rays

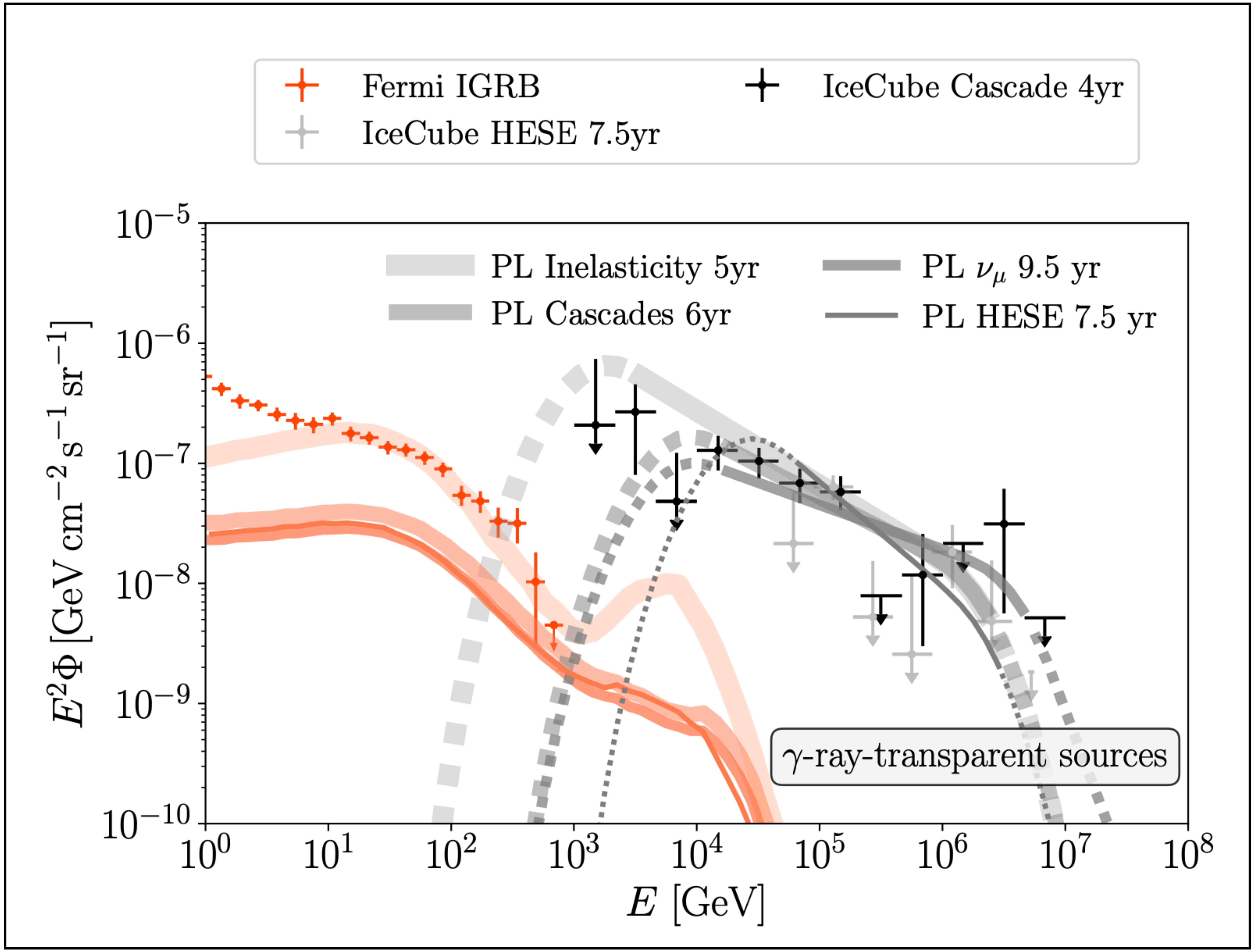
$$\boxed{E_\gamma^2 \frac{dN_\gamma}{dE_\gamma} \approx \frac{4}{K_\pi} \frac{1}{3} E_\nu^2 \frac{dN}{dE_\nu}\Big|_{E_\nu = E_\gamma/2},}$$

Ratio of charged and neutral pions produced: 2(1) for pp(pγ) interactions.

High energy neutrino production

- Unlike neutrinos, gamma rays interact with microwave photons and other diffuse sources of extragalactic background light (EBL) while propagating to Earth.
- They lose energy by pair production and the resulting electromagnetic shower subdivides the initial photon energy into multiple photons with reduced energy reaching our telescopes.
- Observing neutrinos is powerful because the alternative possibility to identify pionic photons has turned out to be challenging -> they must be isolated from photons radiated by, or upscattered to high energy by inverse Compton scattering, by high-energy electrons.

High energy neutrino production



C. Arguelles et al: arXiv:2405.17623v1

High energy neutrino production

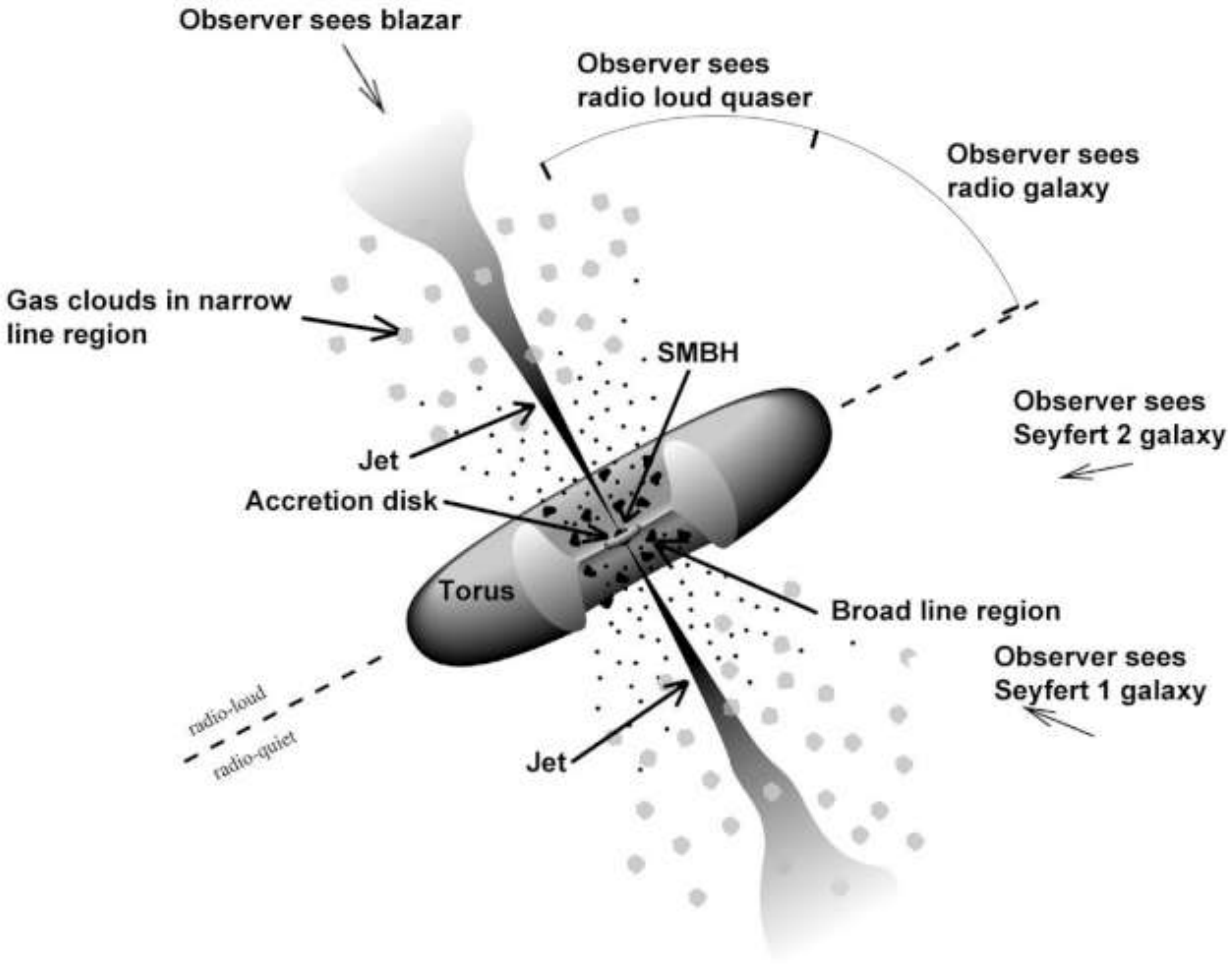
- The observed diffuse neutrino flux originates from γ-ray-obscured sources.
- This should not be a surprise: photon and proton opacities in a neutrino-producing target are related by their cross sections

$$\tau_{\gamma\gamma} \simeq \frac{\sigma_{\gamma\gamma}}{\kappa_{p\gamma}\sigma_{p\gamma}}\,\tau_{p\gamma} \simeq 10^3\,\tau_{p\gamma}\,, \qquad\qquad \kappa_{p\gamma} \sim 0.2$$

- We should not expect neutrinos to be significantly produced in environments that are transparent to very high-energy gamma rays.
- In contrast, the highly obscured dense cores close to supermassive black holes in active galaxies represent an excellent opportunity to produce neutrinos, besides providing opportunities for accelerating protons.

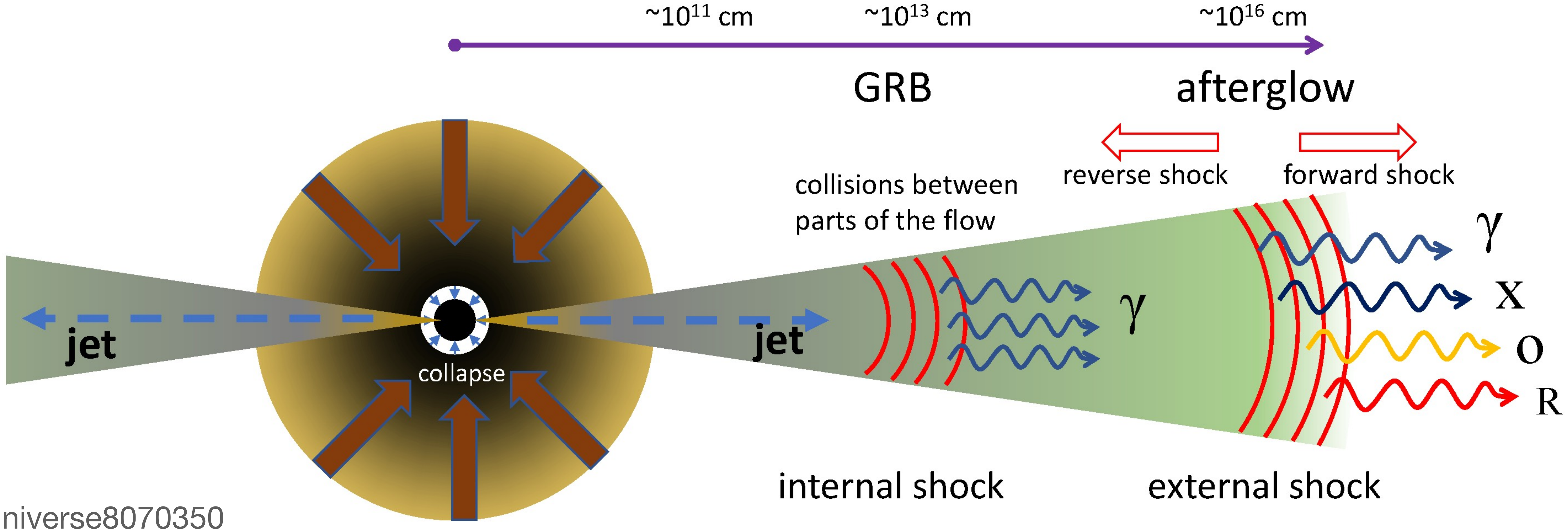
Extragalactic sources

- Extragalactic sources are believed to give the dominant contribution to the high energy neutrino flux.
- AGNs: Active Galactic Nuclei include Seyferts, quasars, radio galaxies and blazars.
  - Standard model: a super-massive (10^6-10^8 M_o) black hole towards which large amounts of matter are accreted.



Extragalactic sources

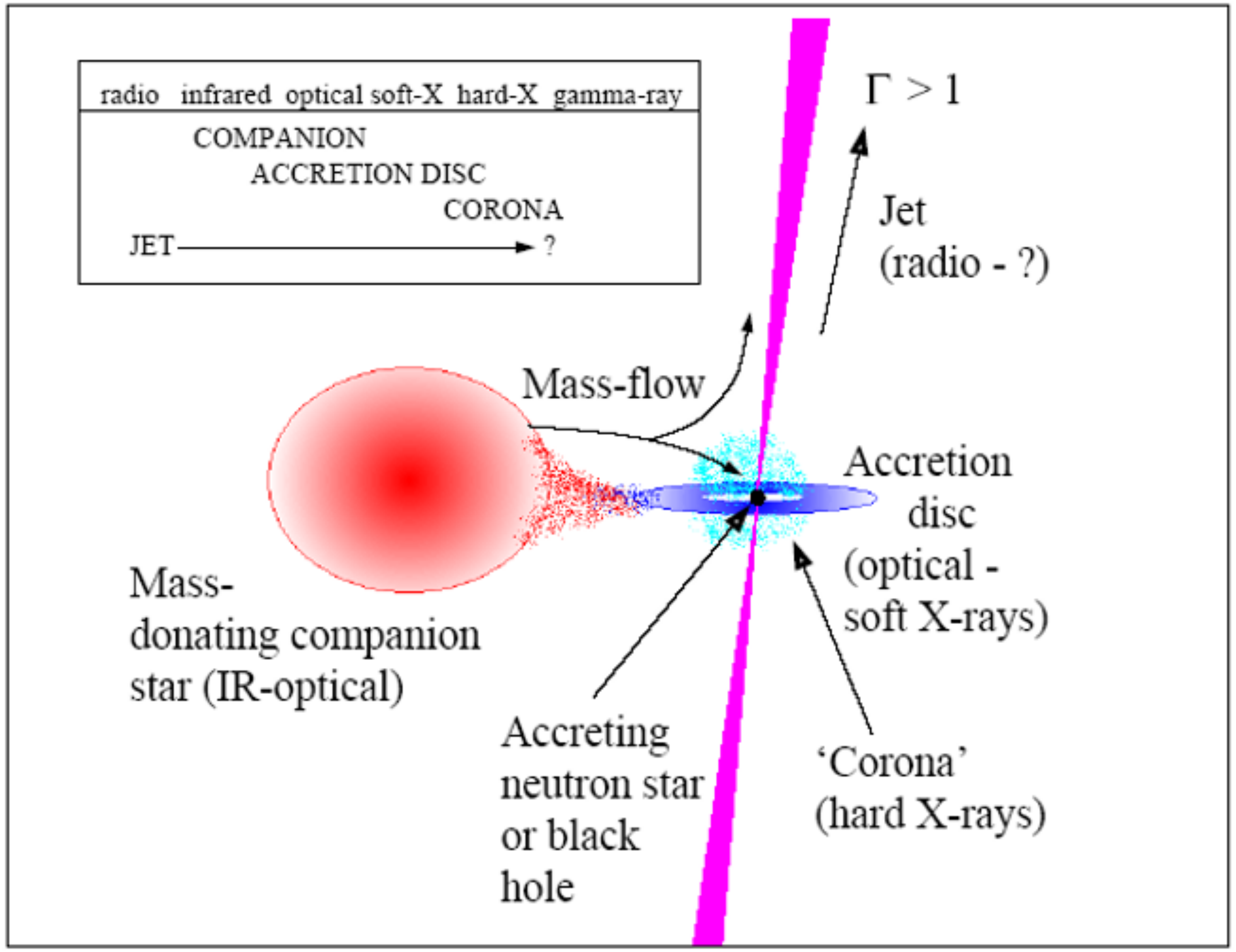
- GRBs: brief explosions of ɣ rays (often + X-ray, optical and radio)
  - Duration: few milliseconds to several hours.
  - Matter moving at relativistic velocities collides with the surrounding material. The progenitor could be a collapsing super-massive star.
  - Time correlation enhances the neutrino detection efficiency.



https://doi.org/10.3390/universe8070350

Galactic sources

- Near objects (few kpc) so the luminosity requirements are much lower.
- Micro-quasars: compact object (BH or NS) towards which a companion star is accreting matter. Neutrino beams could be produced in the Micro-quasar jets.

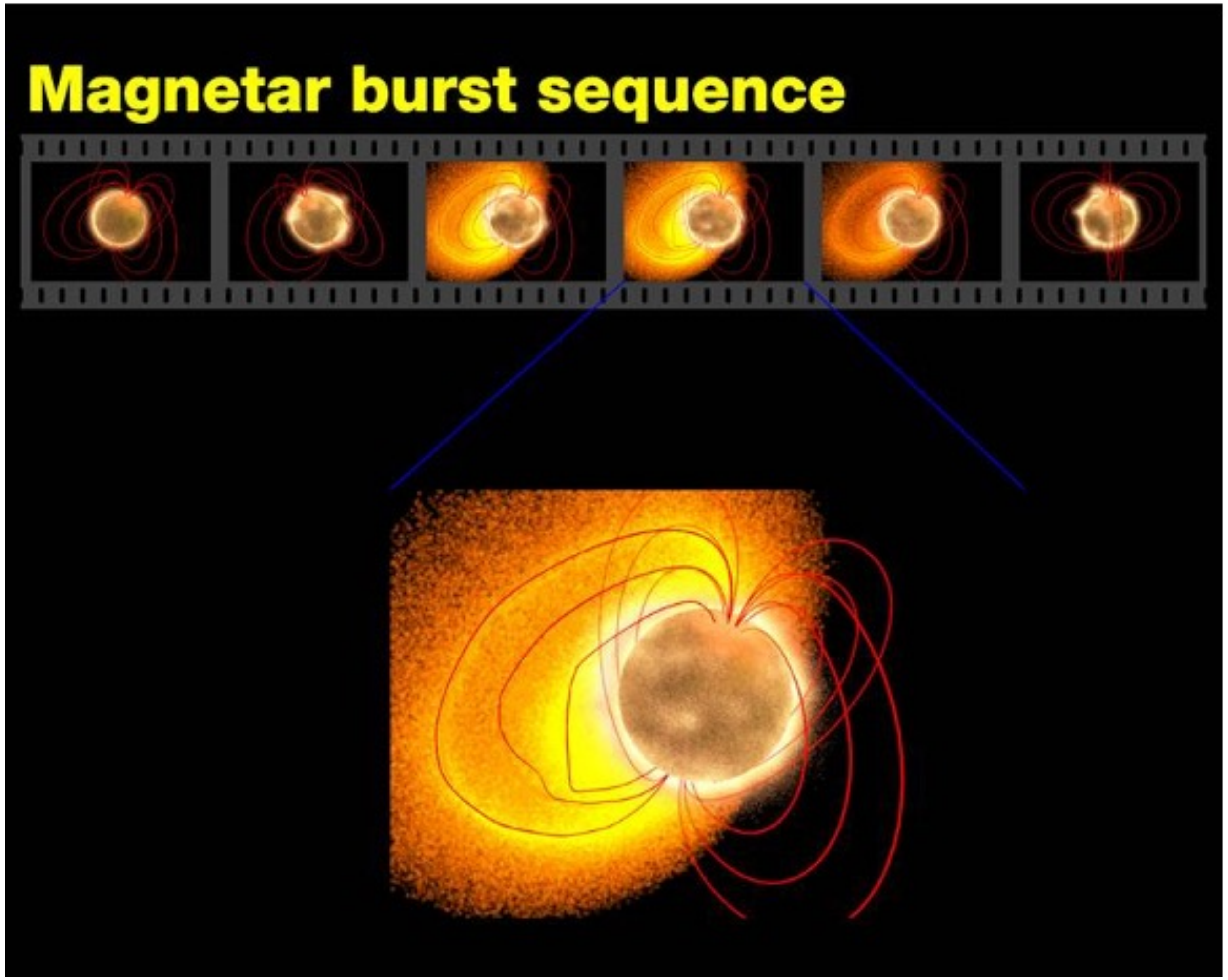


Galactic sources

- Supernova remnants:
- Particles accelerated to relativistic energies through the shock acceleration mechanism.

Galactic sources

- Magnetars: Isolated neutron stars with surface dipole magnetic fields ~10^{15} G, much larger than ordinary pulsars.
    - Seismic activity in the surface could induce particle acceleration in the magnetosphere.



Galactic sources

- Galactic Ridge:
- The Galaxy contains interstellar thermal gas, magnetic fields and CRs which have roughly the same energy density.
- The inhomogeneous magnetic fields confine the CRs within the Galaxy.
- Hadronic interactions of CRs with the interstellar material produce a diffuse flux of γ -rays and neutrinos.

4. HE cosmic neutrino detection: where are we now?

HE cosmic neutrino detection

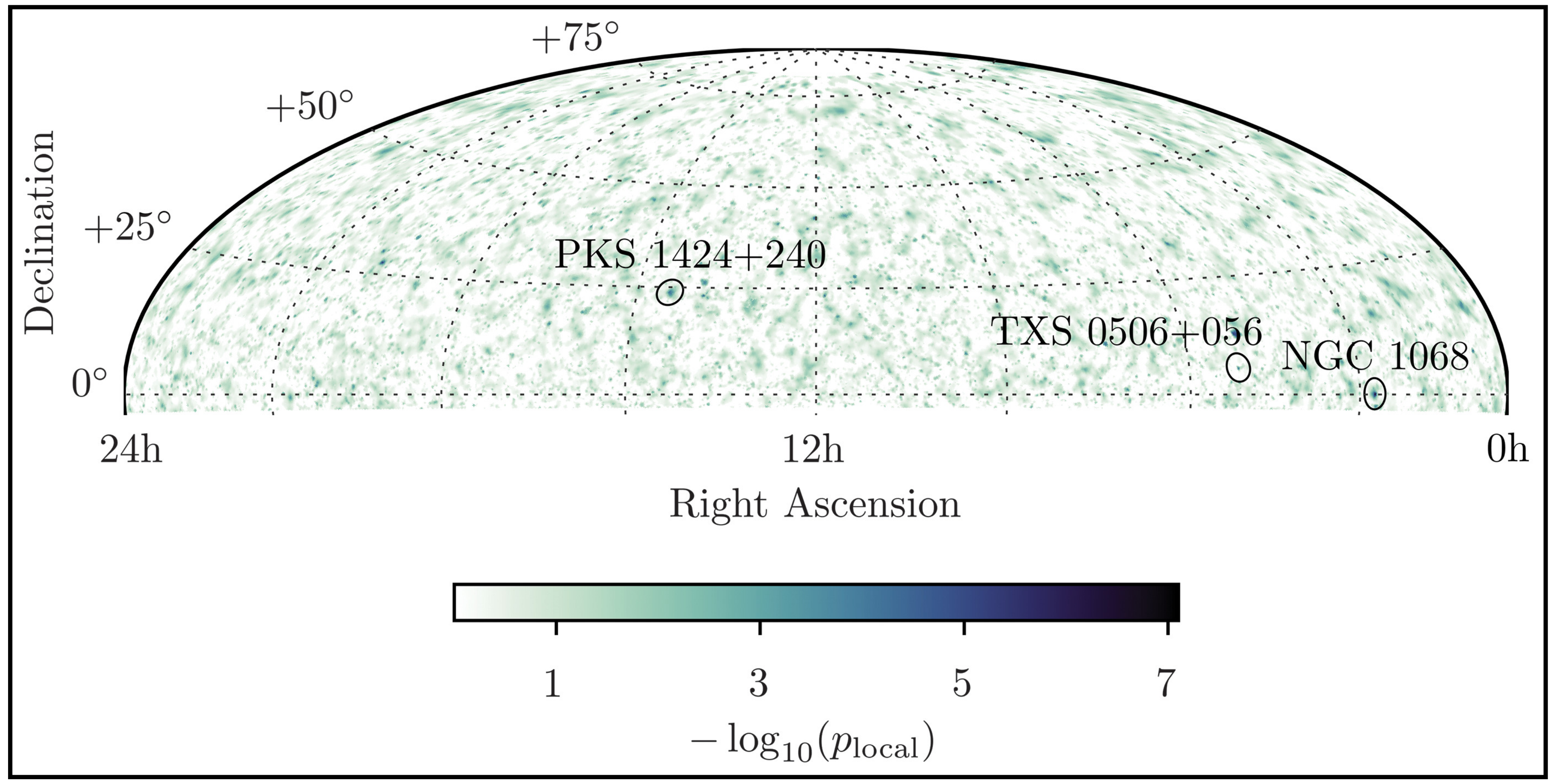
Where are we?

- After a decade of data taking, IceCube has discovered neutrinos in the TeV-PeV range originating outside of our Galaxy.
- The galactic plane only appears at the ten percent level of the extragalactic flux, in sharp contrast with any other wavelength of light where the Milky Way is the dominant feature in the sky.
- This observation implies the existence of sources of high-energy neutrinos in other galaxies that are not present in our own.

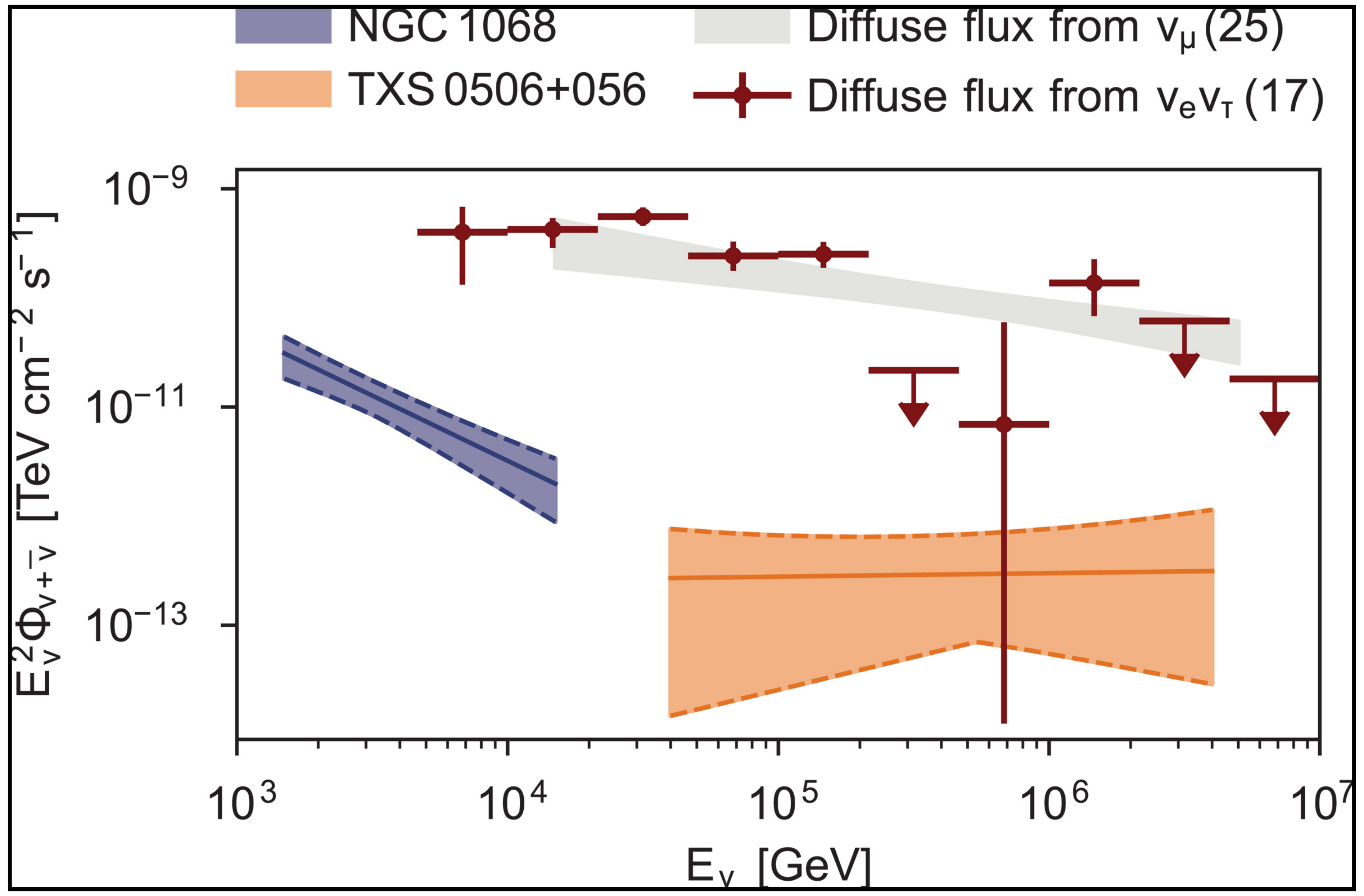
HE cosmic neutrino detection

Where are we? EXTRAGALACTIC

- First high-energy neutrino sources emerged in the neutrino sky:
- Active galaxies
  - NGC 1068: excess of 79(+22,-20) neutrinos at 4.2σ.
  - NGC 4151: excess at 2.7σ.
  - PKS 1424+240: excess at 3.7σ.
  - TXS 0506+056: one neutrino emission together with gamma rays at 3.5σ.

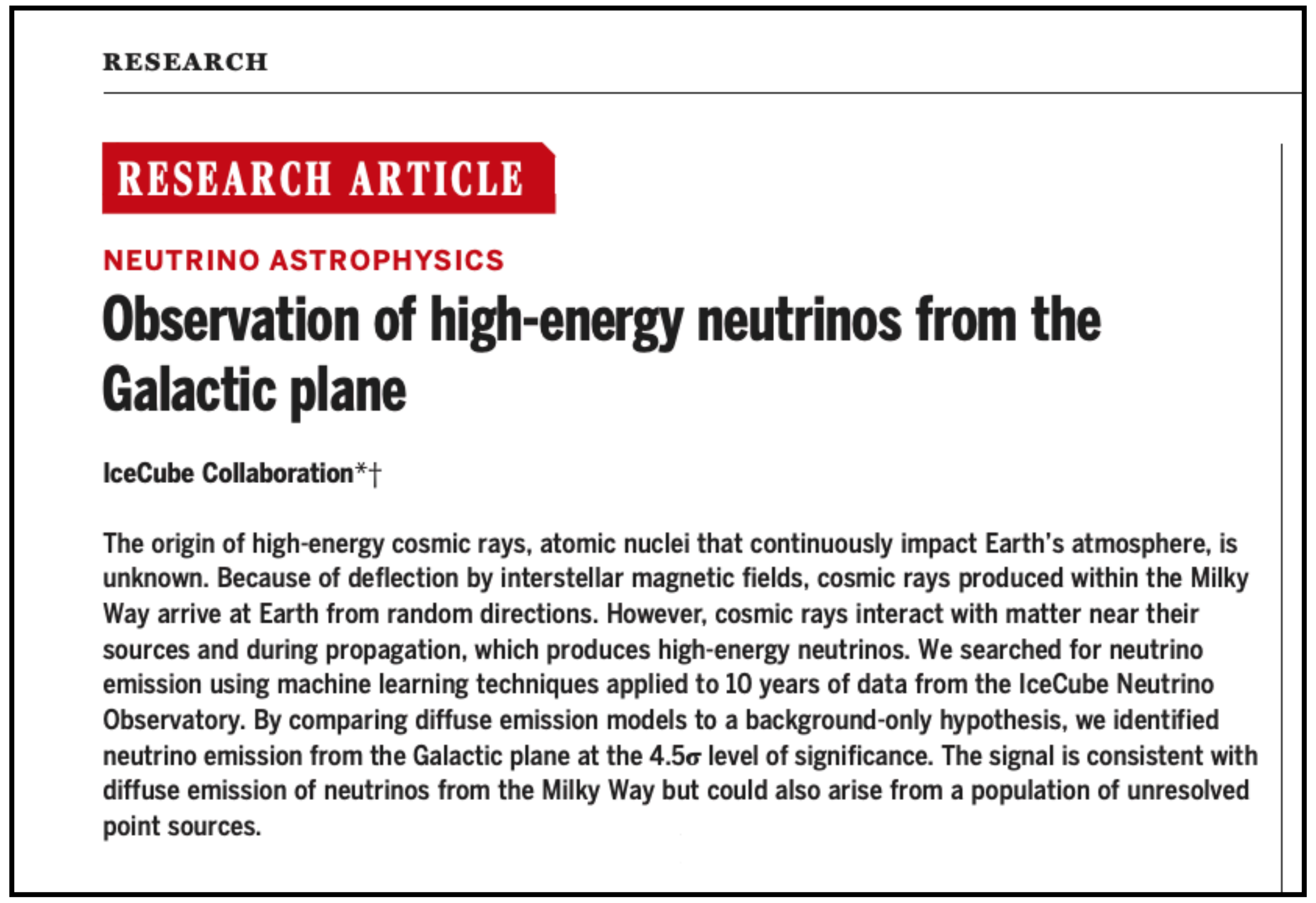


IceCube Collaboration, DOI: 10.1126/science.abg3395 (2022)



HE cosmic neutrino detection

Where are we? GALACTIC



RESEARCH

RESEARCH ARTICLE

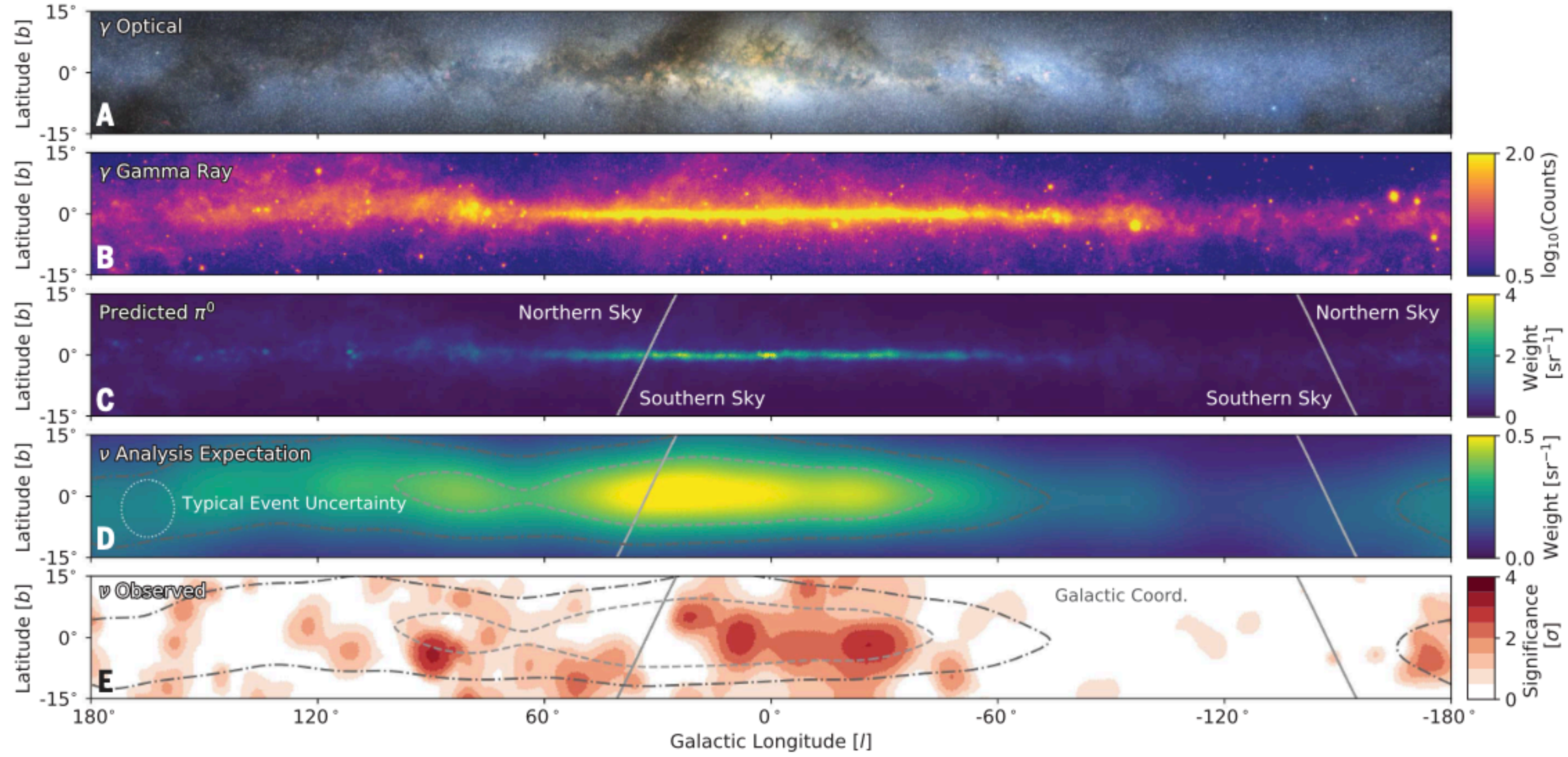
NEUTRINO ASTROPHYSICS

Observation of high-energy neutrinos from the Galactic plane

IceCube Collaboration*†

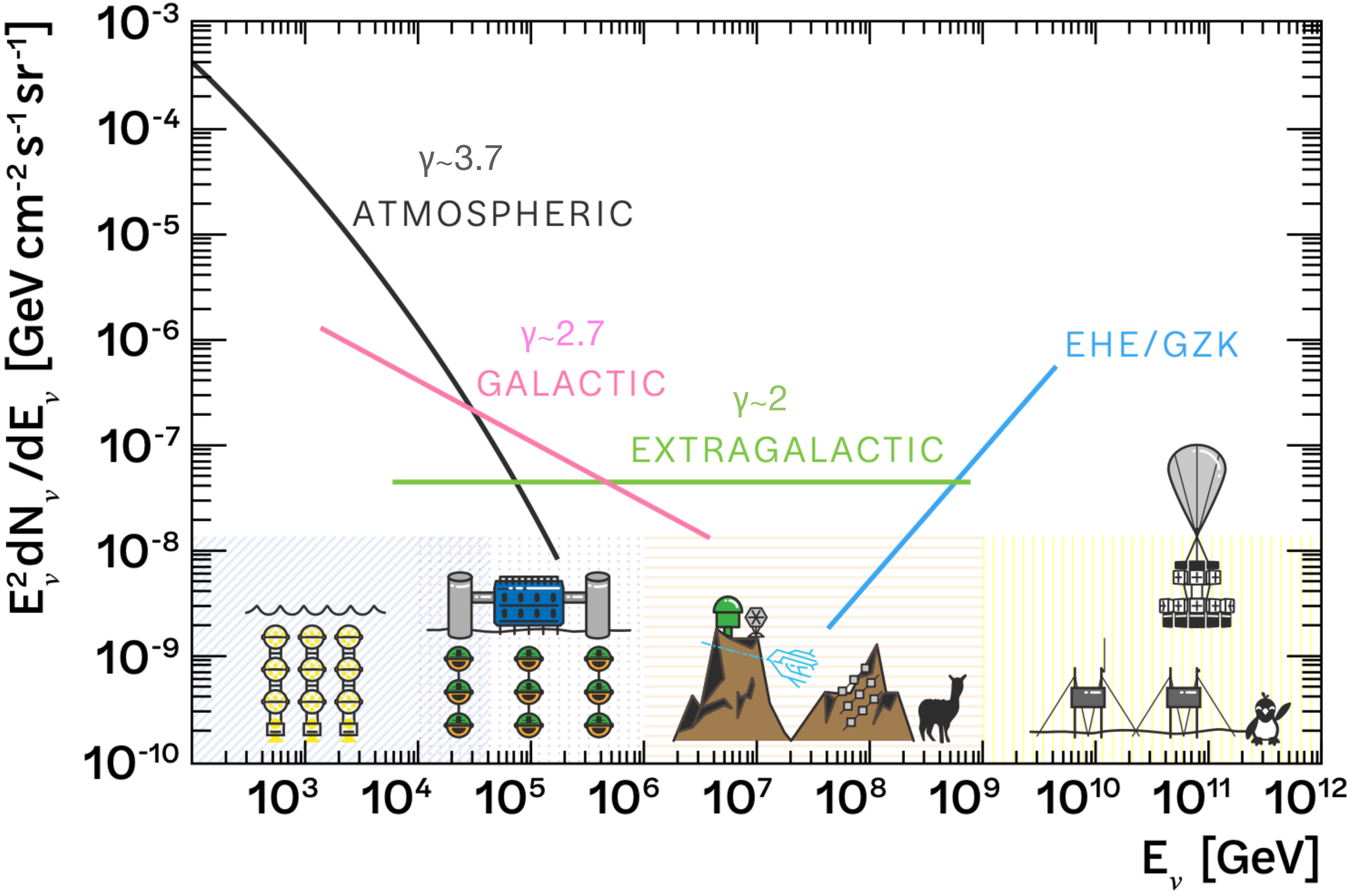
The origin of high-energy cosmic rays, atomic nuclei that continuously impact Earth's atmosphere, is unknown. Because of deflection by interstellar magnetic fields, cosmic rays produced within the Milky Way arrive at Earth from random directions. However, cosmic rays interact with matter near their sources and during propagation, which produces high-energy neutrinos. We searched for neutrino emission using machine learning techniques applied to 10 years of data from the IceCube Neutrino Observatory. By comparing diffuse emission models to a background-only hypothesis, we identified neutrino emission from the Galactic plane at the 4.5σ level of significance. The signal is consistent with diffuse emission of neutrinos from the Milky Way but could also arise from a population of unresolved point sources.

IceCube Collaboration, Science 380, 1338-1343 (2023)



- High energy neutrinos from the Milky Way observed for the first time by IceCube thanks to an improvement in angular resolution due to machine learning.

HE cosmic neutrino detection

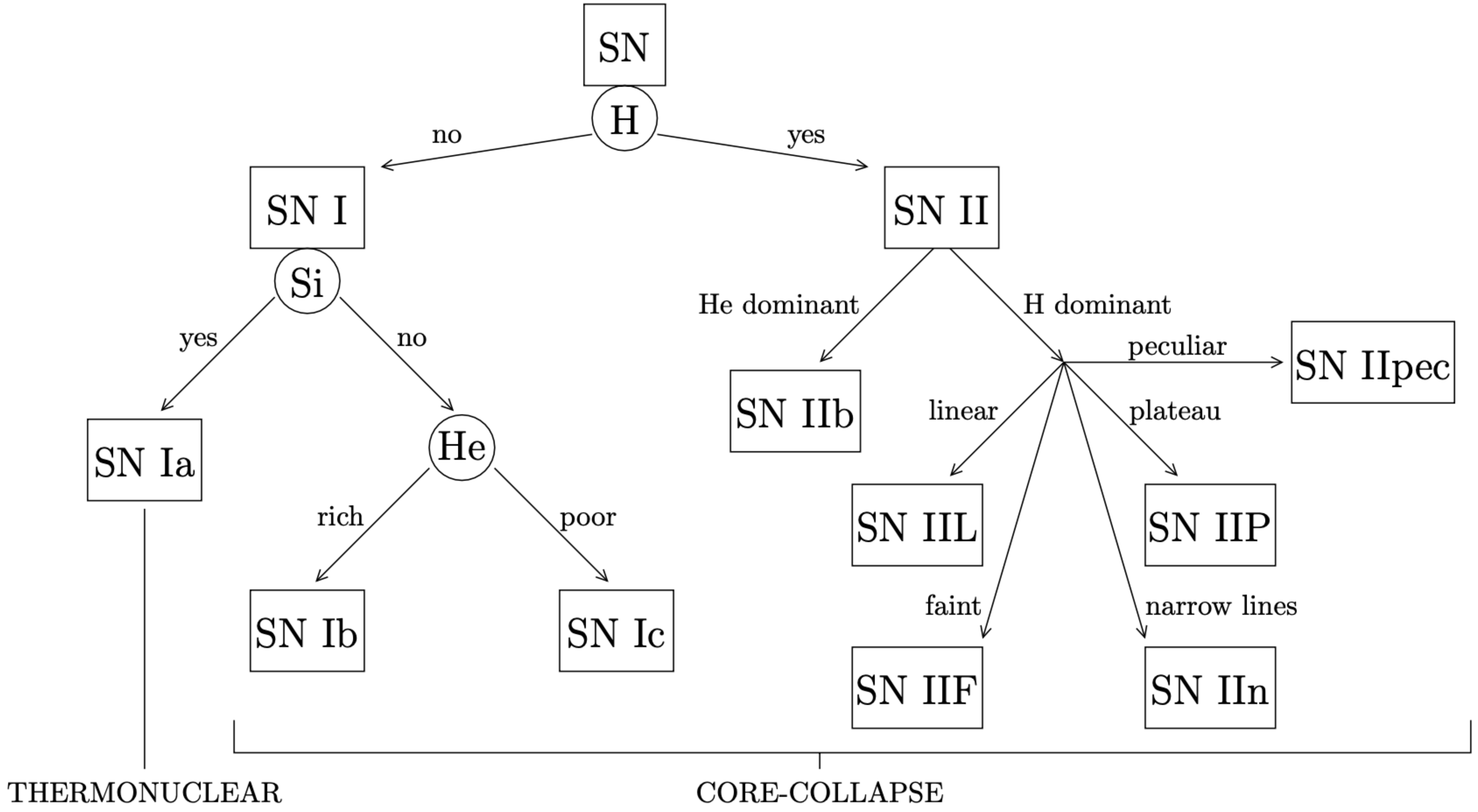


C. Arguelles et al: arXiv:2405.17623v1

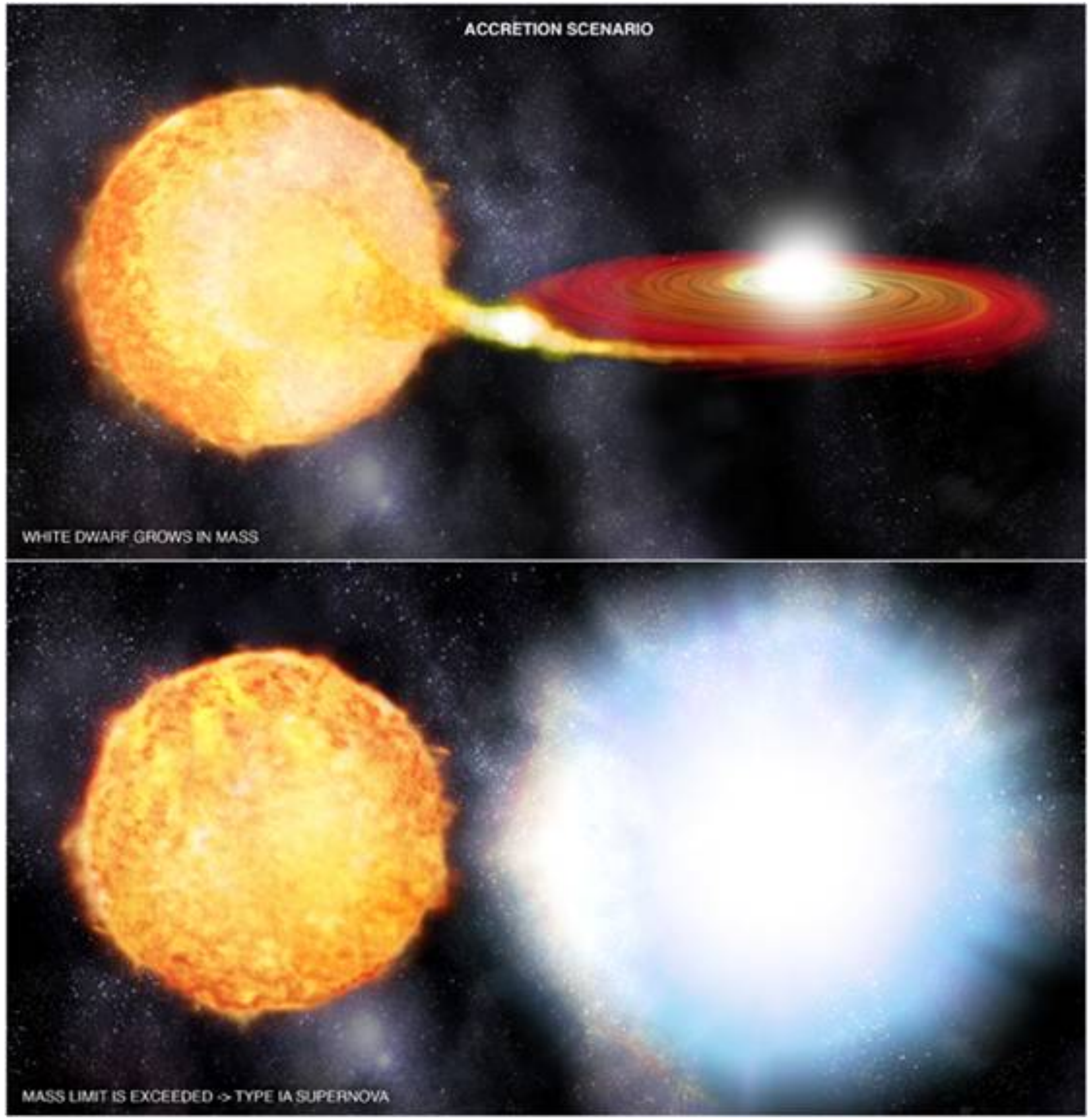
3. Supernova neutrinos

Supernova types

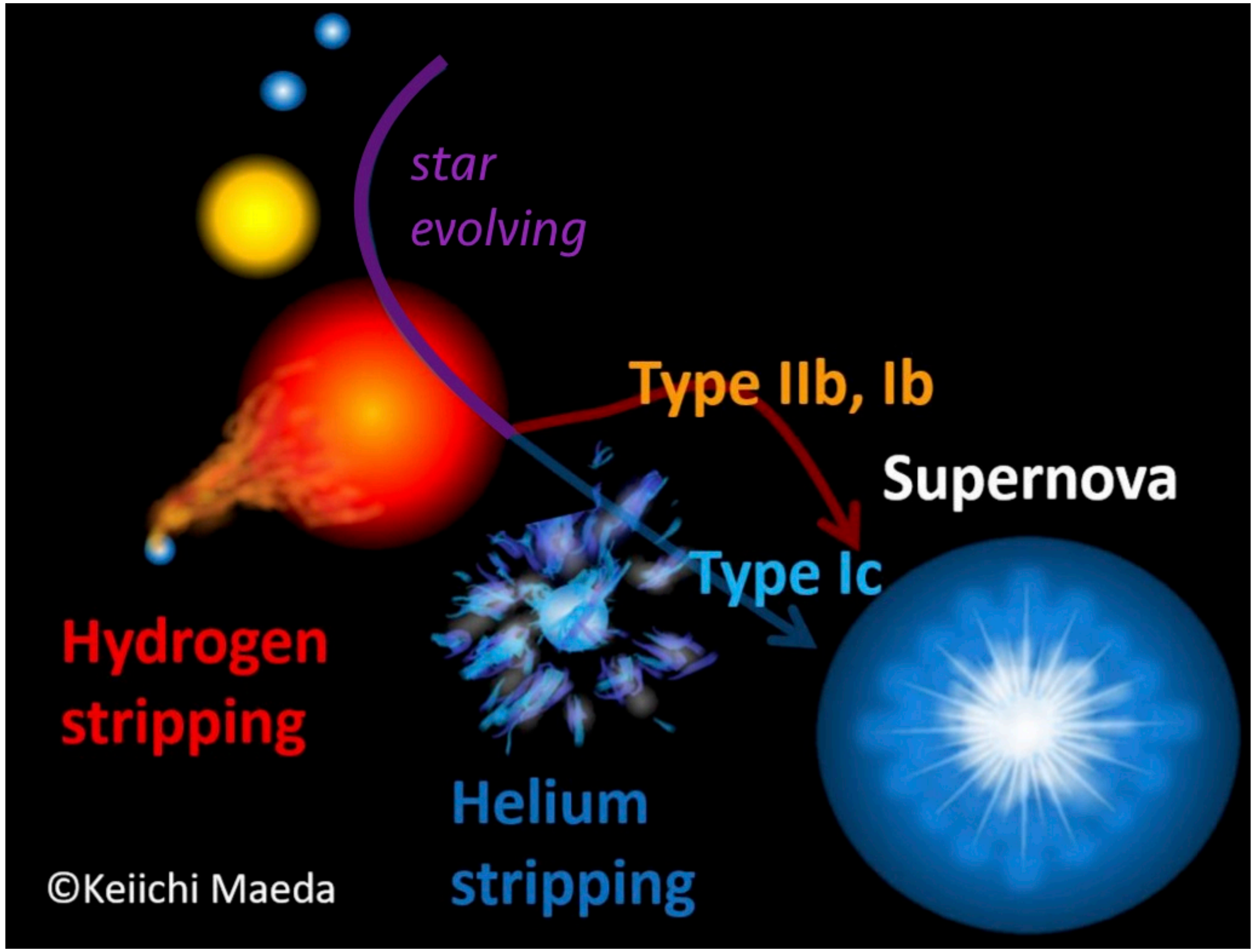
- SN divided into different types: spectroscopic characteristics near maximum luminosity and by the properties of the light curve, which depend on the composition of the SN progenitor star
- The two wide categories called type I and type II are characterized by the absence or presence of hydrogen lines.
- However, the most important physical characteristic is the **mechanism that generates the supernova,** which distinguishes SNe of type Ia from SNe of type Ib, Ic and II.



Supernova Ia



Supernova Ib, Ic, II



Supernovae

- When a massive star has exhausted hydrogen, it evolves by producing energy through the fusion of heavier elements up to the iron.
- Neutrinos produced during such reactions escape from the stellar material and more and more intense nuclear burning is needed to replace the huge amount of energy carried away.
- Once the inner region of a star becomes primarily iron, further compression of the core does not ignite nuclear fusion anymore; the star collapses to form a compact object such as a neutron star or a black hole.
- A prominent prediction from theoretical models of the core-collapse of a massive star is that 99% of the gravitational binding energy of the resulting remnant is converted to neutrinos with energies of a few tens of MeV over a timescale of 10 s.
- Neutrinos were observed from the celebrated 1987A supernova (SN1987A) in the Large Magellanic Cloud, 50 kpc away from the Earth,

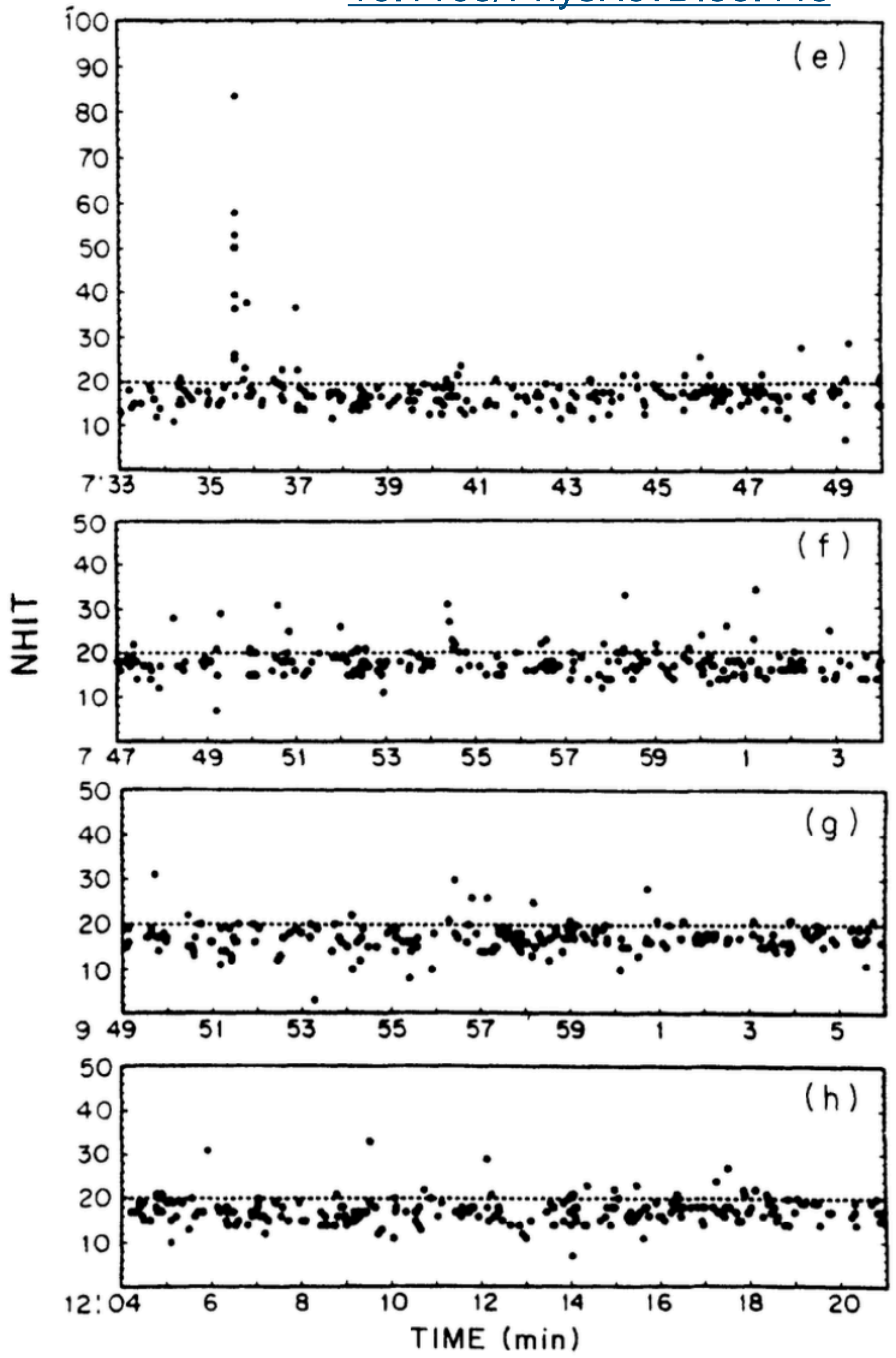
Supernova neutrinos

- From the point of view of neutrino physics, type Ib, Ic, and II SNe are much more interesting than type Ia SNe, simply because they produce a huge flux of neutrinos of all types.
- The astrophysics is complicated, the associated uncertainties are large and the theorists involved in the study of this type of events are still unsure whether their computer simulations include all the relevant physics.
- 30 years ago we had a successful observation of the neutrinos from one supernova, called SN 1987A, that has been recognized by the 2002 Nobel prize in physics to Koshiba, the leader of the Kamiokande experiment.

Kamiokande observation of SN 1987 A

10.1103/PhysRevD.38.448

- Observation of a single neutrino burst on 27 February 1987 at 7:35:35 UT.
- “The nature of the single, observed neutrino burst coincides remarkably well with the elements of the current model of type-II supernovae and neutron-star formation. This is the first direct observation in neutrino astronomy”.



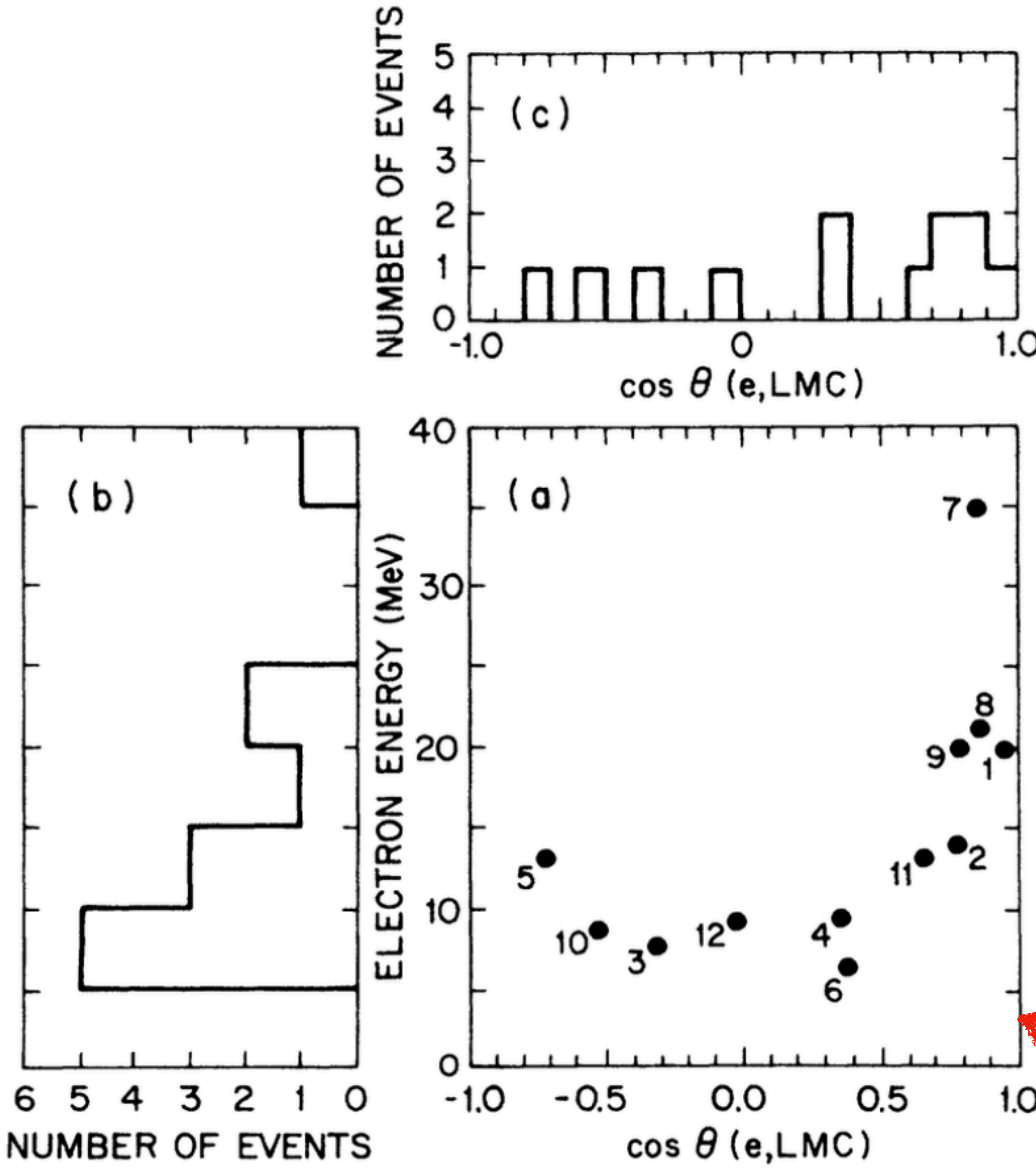
Kamiokande observation of SN 1987 A

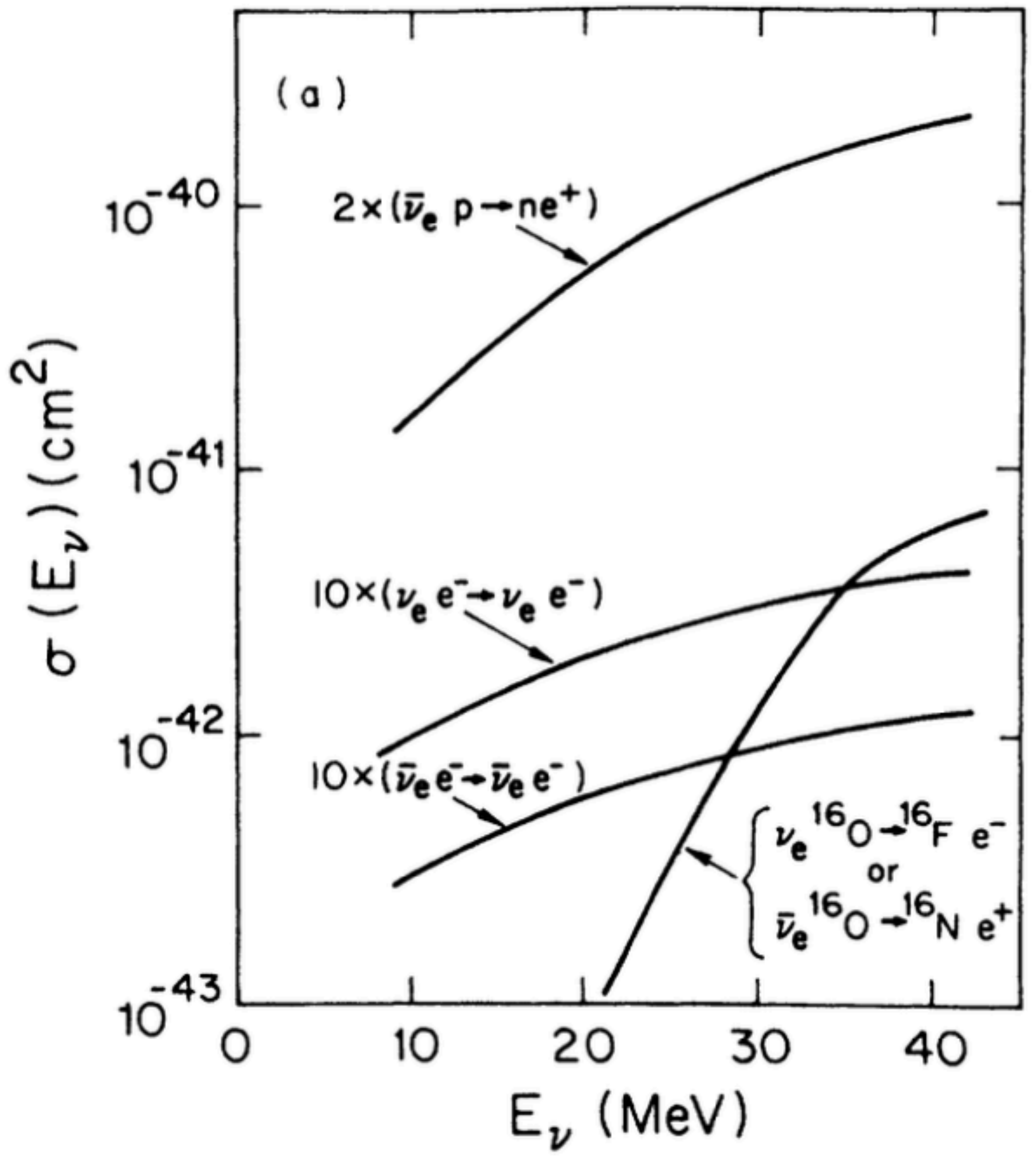
- The angular distribution was consistent with an isotropic distribution of the electrons relative to the Large Magellanic Cloud (LMC).

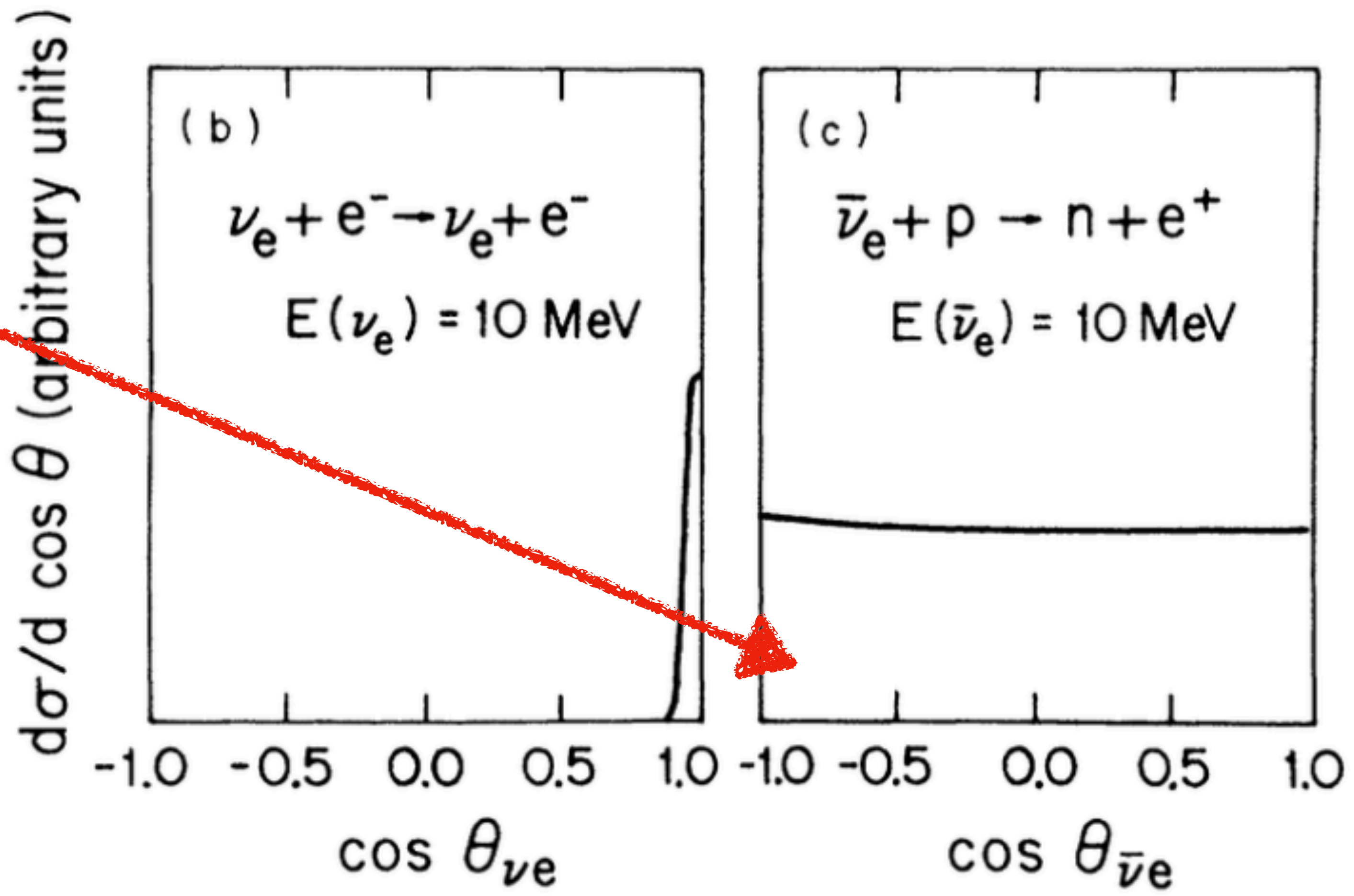
- This was consistent with the energy dependence of the neutrino cross sections: the dominant cross section is

$$\sigma(\bar{\nu}_e p_{\text{free}} \rightarrow e^+ n)$$

- with isotropic angular distribution.







10.1103/PhysRevD.38.448

10.1103/PhysRevLett.58.1490

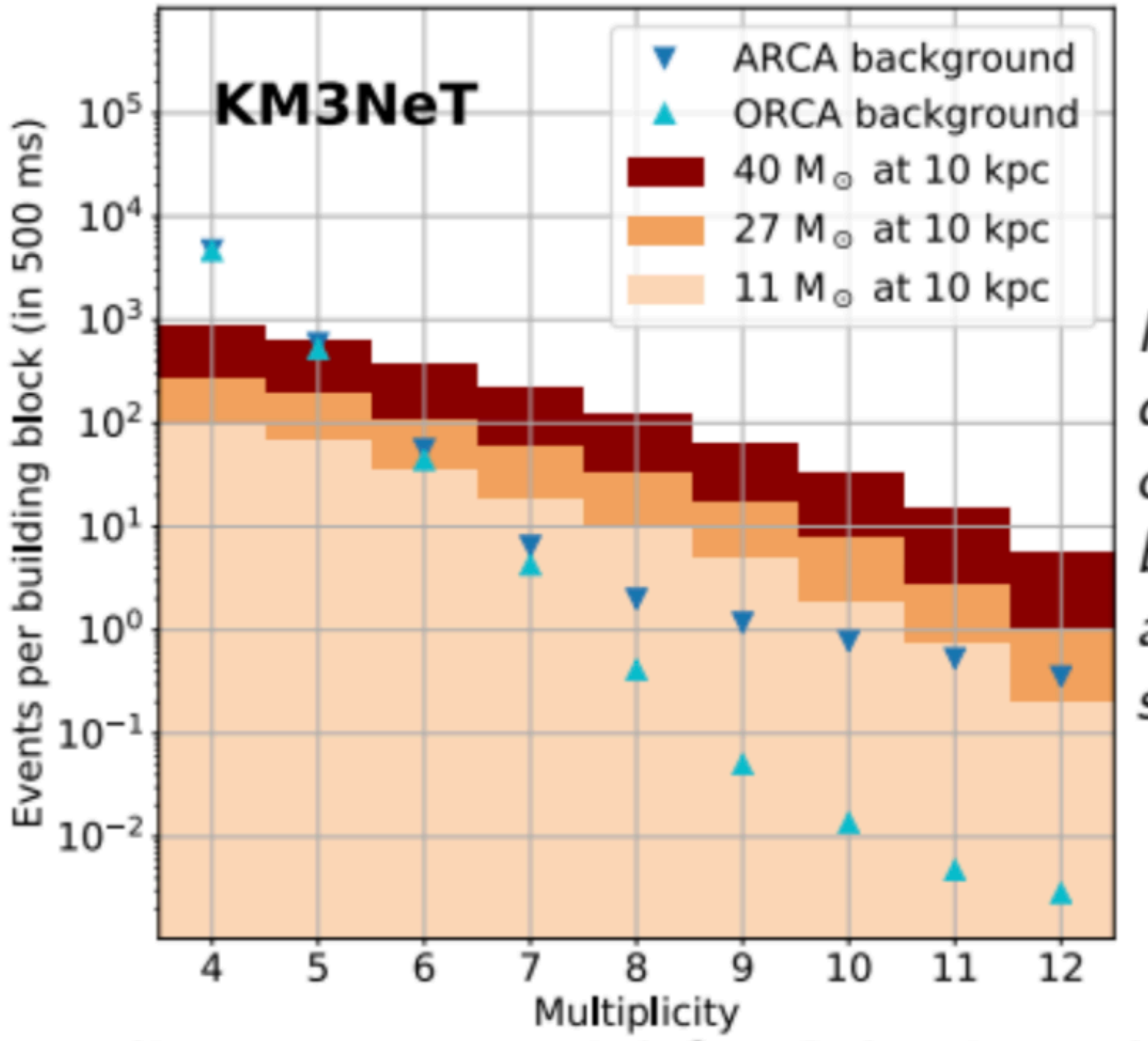
What else?

- Core-collapse supernovae with multi-PMT DOMs.

KM3NeT is sensitive to positrons induced by electron anti-neutrinos.

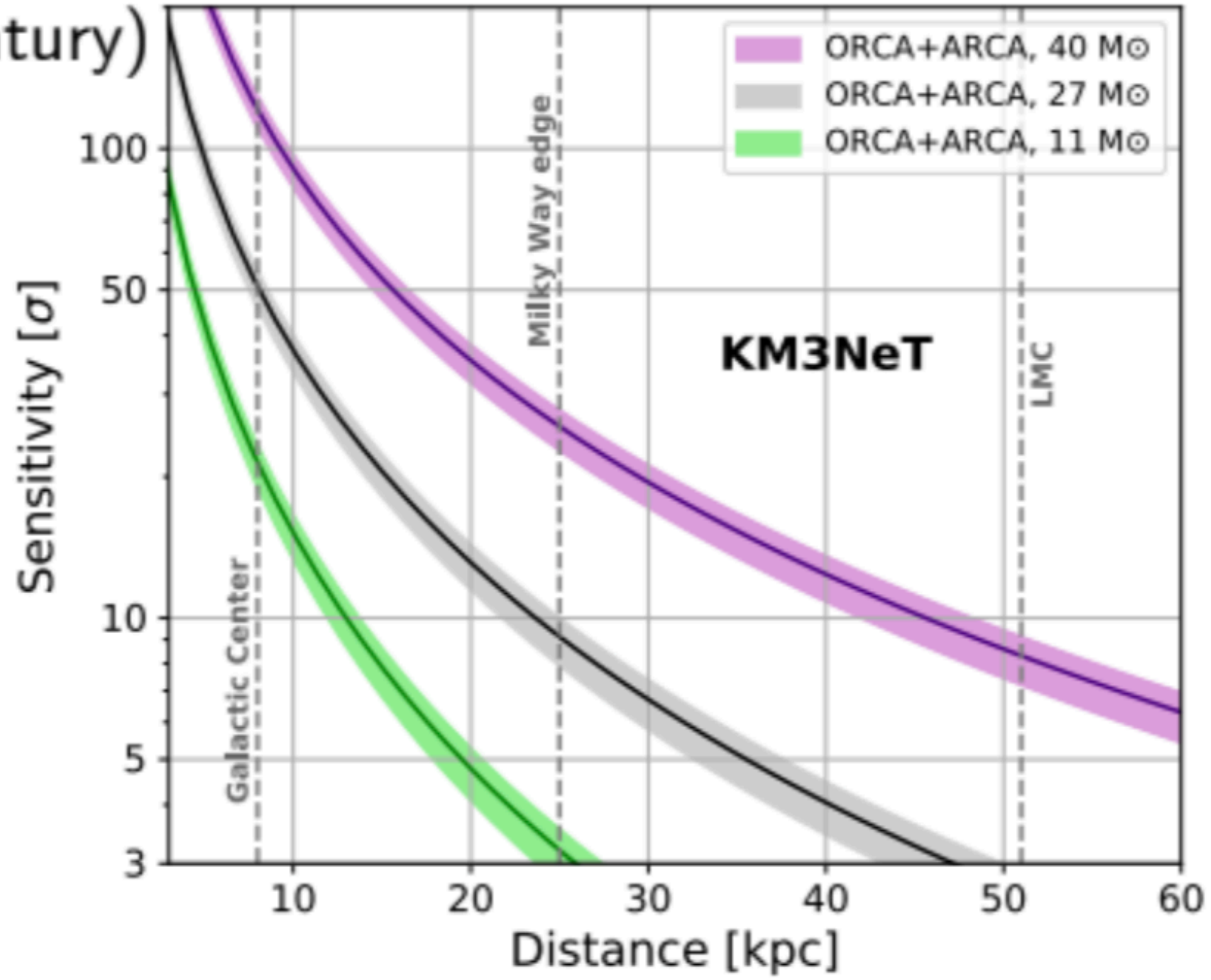
As they cannot be reconstructed individually, we search for an excess of hit coincidences between PMTs in single optical modules above the optical background.

A new method, described in [PNU1-33] improves the sensitivity by 23%.



Multiplicity distribution of optical background and CCSN signal

5σ discovery potential for Galactic and near Galactic events (expected rate of 1.5 per century)



Detection sensitivity as a function of distance

Alerts transmitted to the Supernova Early Warning System (SNEWS)

Summary & Conclusions

- The elusive nature of neutrino makes them ideal sources for astronomy and fundamental physics searches.
- Neutrino astronomy has proven to be very powerful in improving our understanding of the Universe.
- Astrophysics with neutrino telescope is still a young, growing discipline in its discovery phase.
- Plans for increasing current detectors in order to observe even higher energy events (IceCube-Gen2) and for building new and bigger detectors.
- Neutrino radio-detection also possible.

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  - C. Arguelles et al, *From the Dawn of Neutrino Astronomy to A New View of the Extreme Universe*, arXiv:2405.17623v1 (2024).
  - N. Kurahashi et al, *High-Energy Extragalactic Neutrino Astrophysics*, https://doi.org/10.1146/annurev-nucl-011122- 061547 (2022).