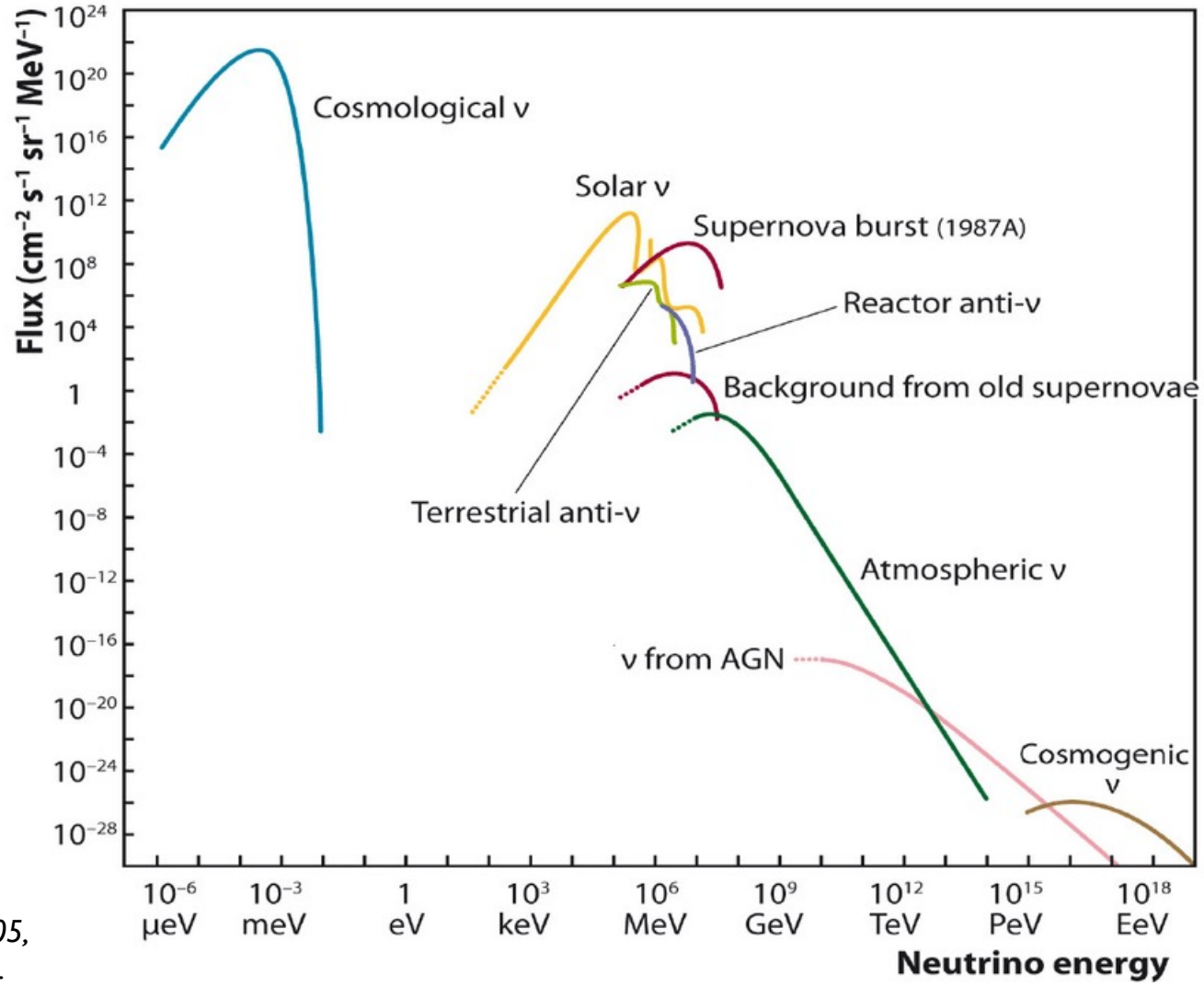
CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

# Neutrino telescopes and results

Big thanks to G. Illuminati for providing me a lot of materials

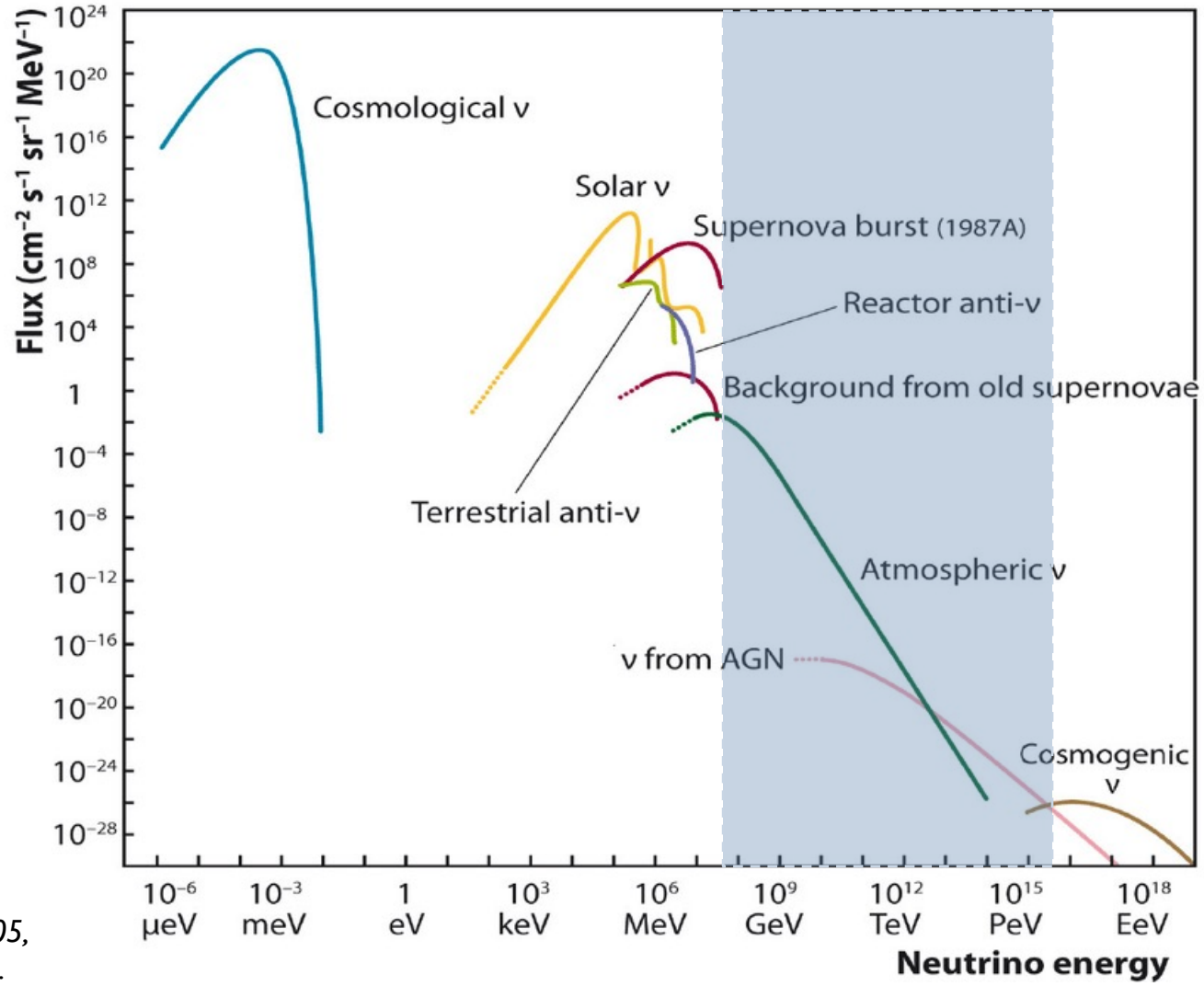
*Figure credit: IceCube/NASA*

# Astrophysical neutrinos



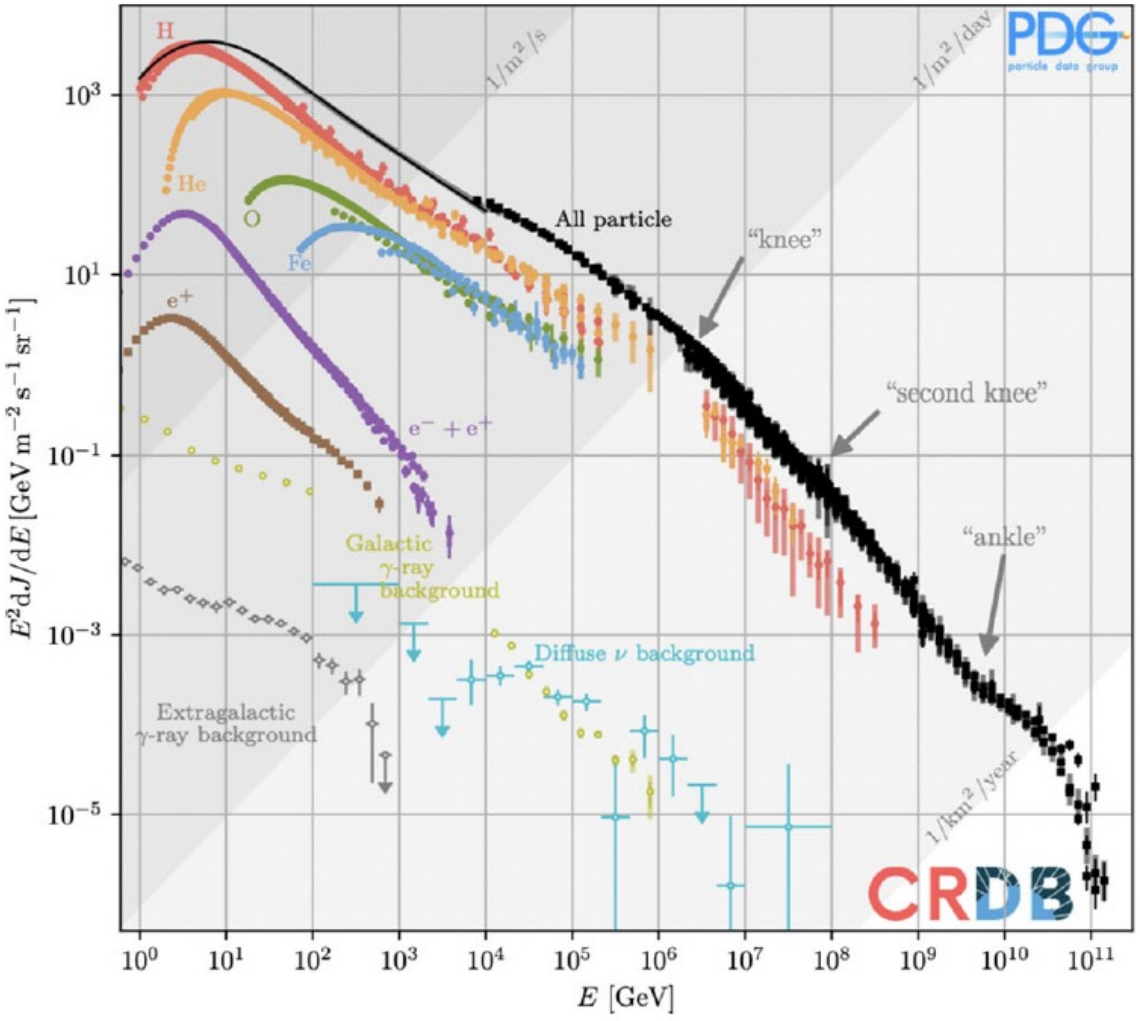

*C. Spiering, in Rev. Mod. Astron. pp. 375–405, ISBN 9783527622993, URL http://doi.wiley.com/10.1002/9783527622993.ch16.*

# Astrophysical neutrinos



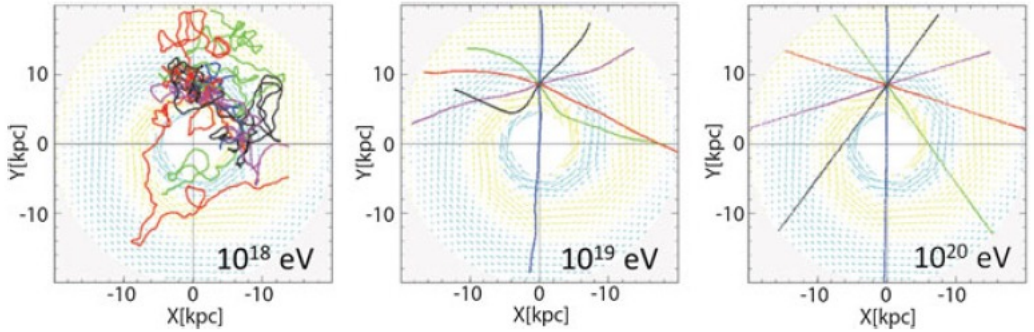

*C. Spiering, in Rev. Mod. Astron. pp. 375–405, ISBN 9783527622993, URL http://doi.wiley.com/10.1002/9783527622993.ch16.*

# High-energy astrophysical neutrinos

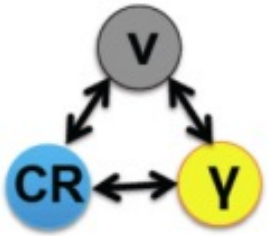



**Cosmic rays:**
discovered >100 years ago, still unknown origin

Simulated trajectory of charged particles in the galactic magnetic field

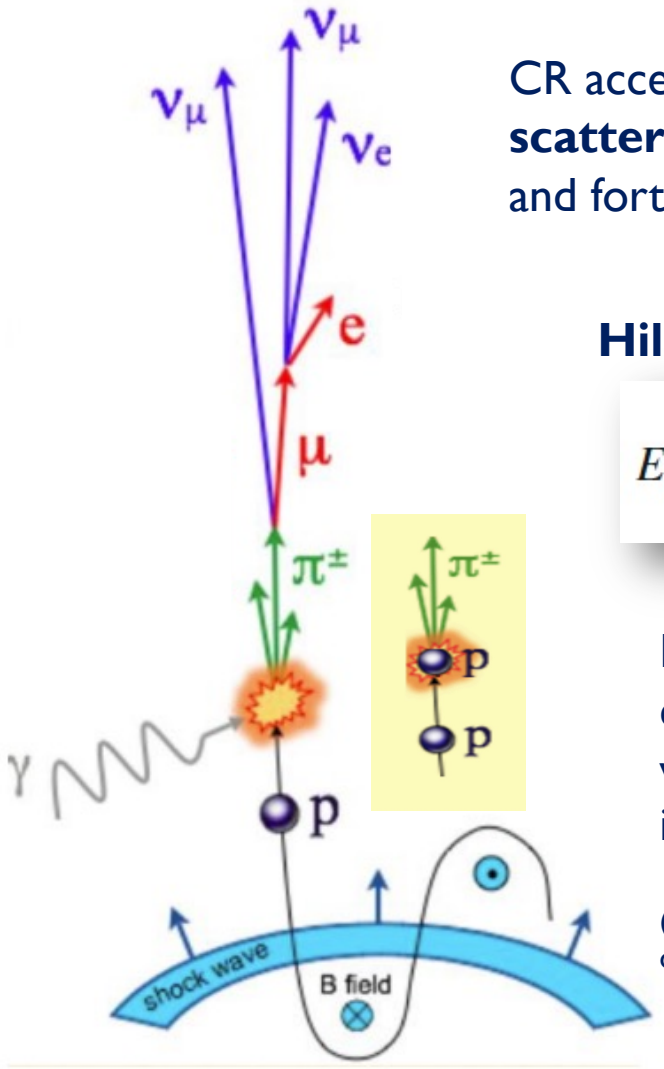



*Credit: prof.T. Ebisuzaki (http://www.asi.riken.jp/en/laboratories/chieflabs/astro/index.html)*




**CRs imply astrophysical neutrinos**
**Neutrinos can reveal the origin of CRs**

# High-energy astrophysical neutrinos



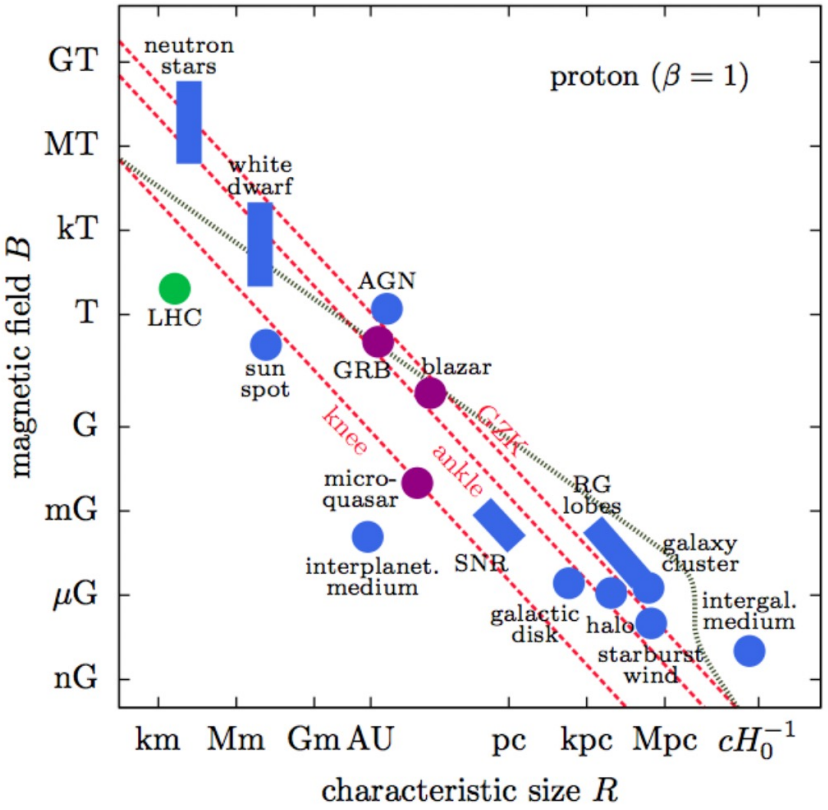

CR acceleration mechanism based on **repeated scattering on magnetic irregularities** back and forth across a shock front

**Hillas criterion:**

$$E^{\max} \simeq Z\beta \cdot \left(\frac{B}{\mu\mathrm{G}}\right) \cdot \left(\frac{L}{\mathrm{kpc}}\right) \quad [\mathrm{EeV}]$$

**Maximum energy** of a CR nucleus of charge Ze accelerated in a region where the **magnetic field B** changes in a **spatial region of size L**

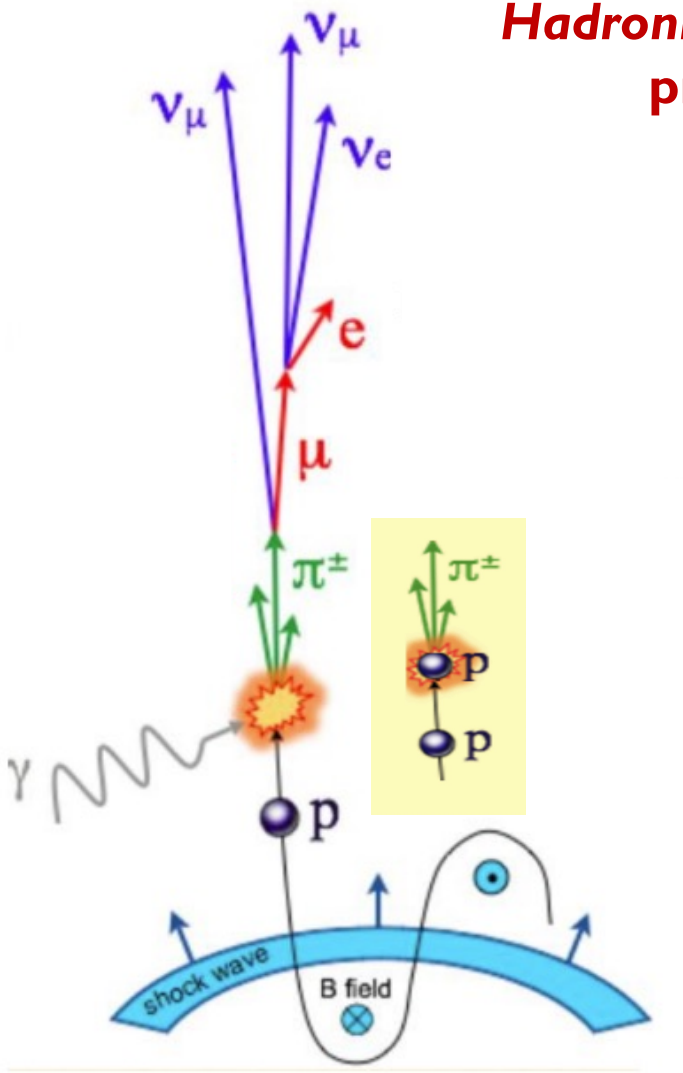
(β = U/c, where U is the characteristic velocity of magnetic scattering centers)



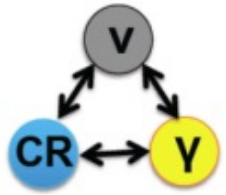

Modern adaption of the *Hillas plot*

*Advances in Space Research 62 (2018) 2902-2930*

# High-energy astrophysical neutrinos




## *Hadronic* scenario for $\gamma$ production




**proton-photon:**

$$p + \gamma \rightarrow \Delta^+ \rightarrow \pi^0 + p$$
$$\rightarrow \pi^+ + n$$

$\pi^0 \rightarrow \gamma + \gamma$

Also produced in the ***leptonic*** scenario via synchrotron emission + inverse Compton scattering

**proton-nucleon:**

$$p + p \rightarrow p + p + \pi^0$$
$$\rightarrow p + n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$$
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu$$

$$p + n \rightarrow p + n + \pi^0$$
$$\rightarrow p + p + \pi^-$$

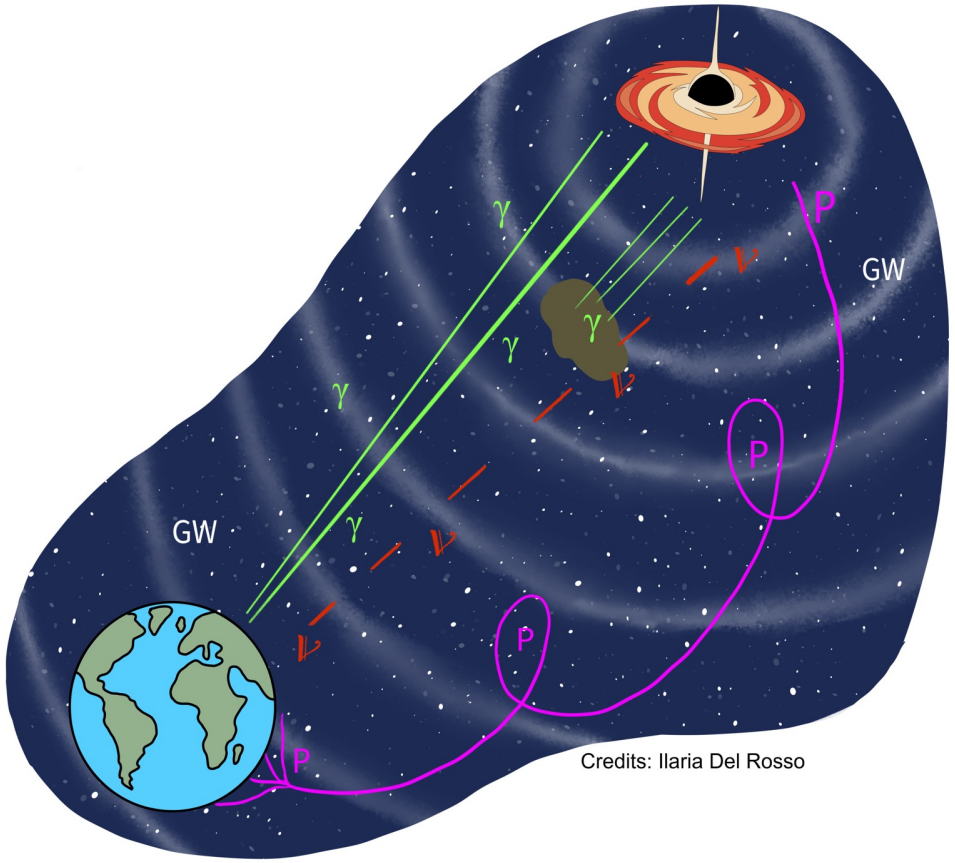
$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ at the source

$\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ at Earth

## Neutrinos:

- Provide a **strong indication of hadronic acceleration** in astrophysical sources
- Smocking gun of the **cosmic-ray sources**

# High-energy astrophysical neutrinos

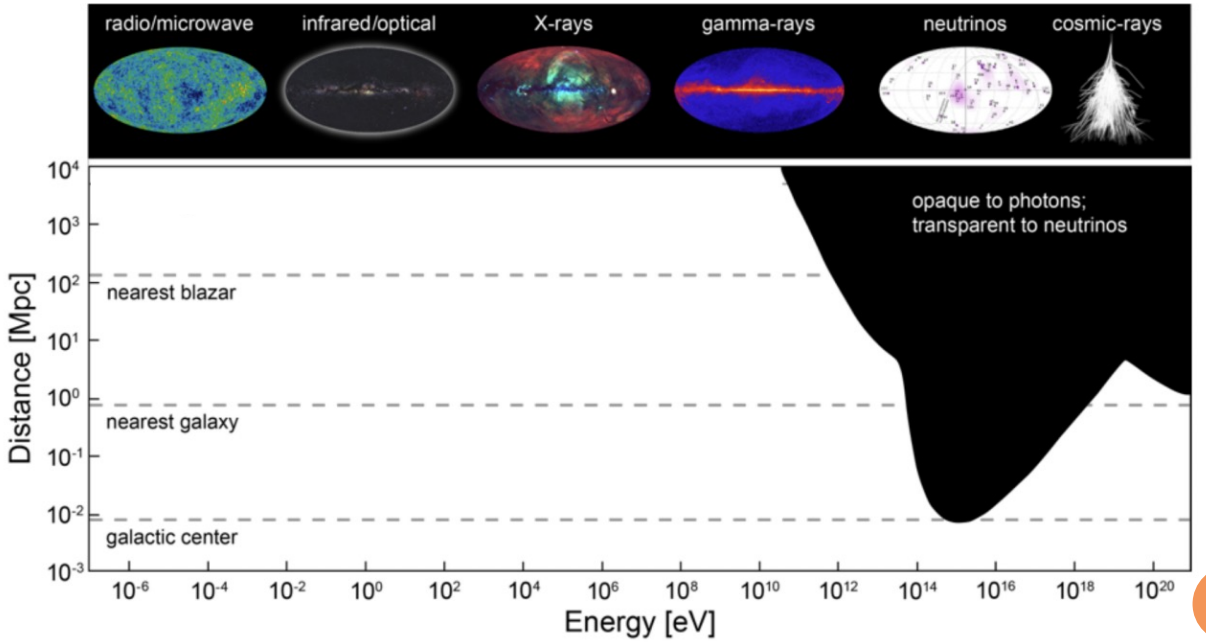



The Universe is opaque to EM radiation for ¼ of the spectrum, i.e. above 10-100 TeV

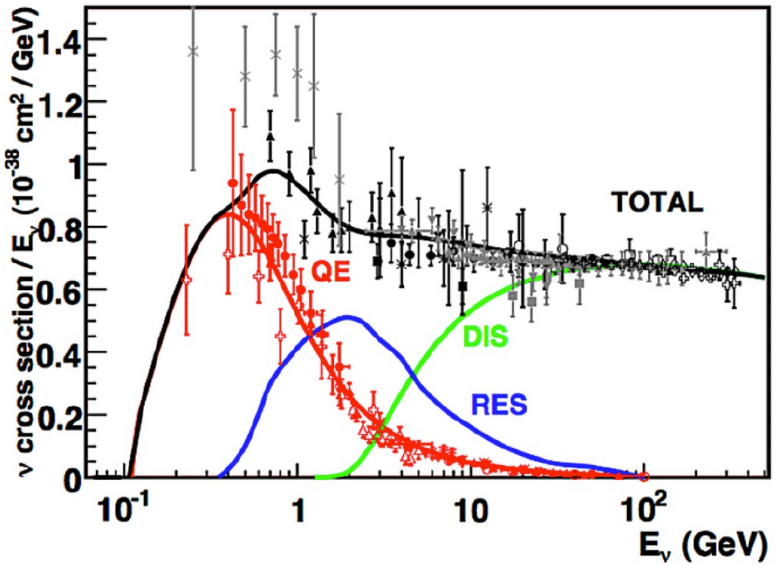
**→ neutrinos offer unique chance to access the highest energy universe**

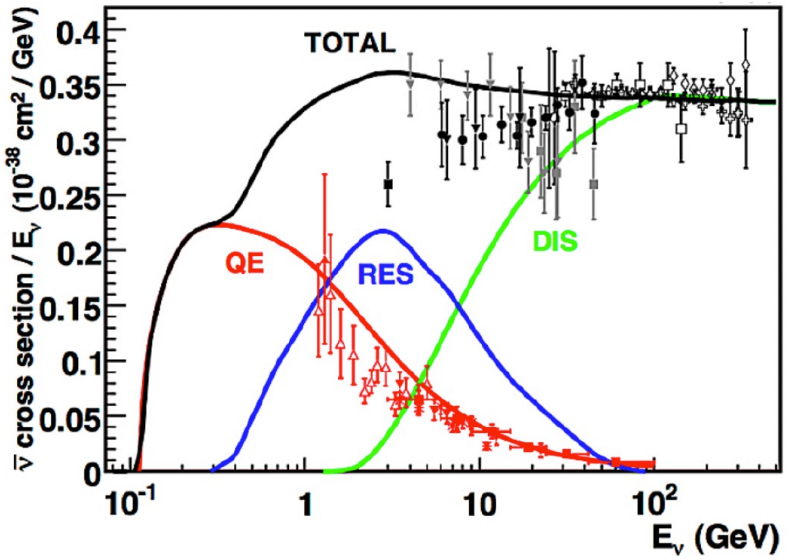
## Neutrinos:

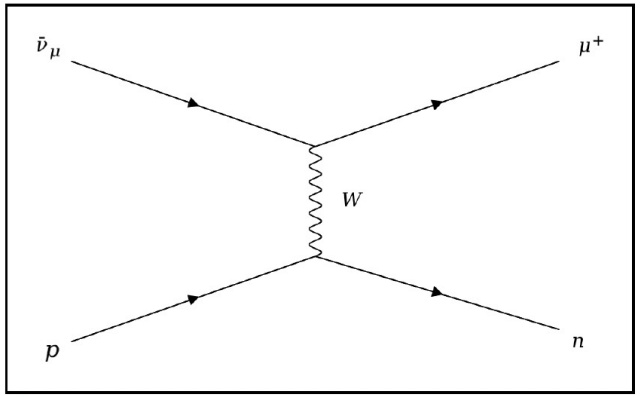
- neutral → trajectory not affected by magnetic fields, **point back to the source**
- weakly interacting → **penetrate regions opaque to photons**



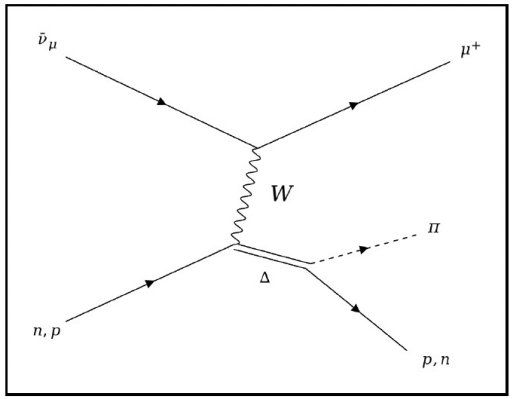
# Neutrino-nucleon interactions



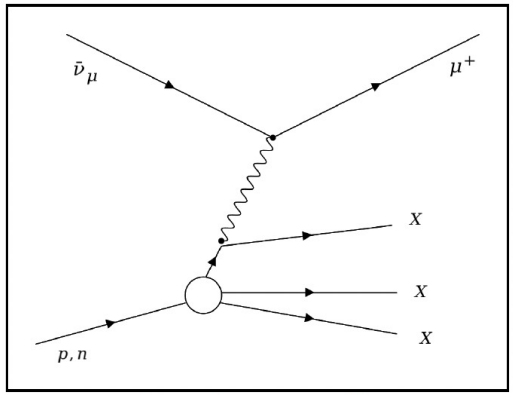




Quasi-elastic

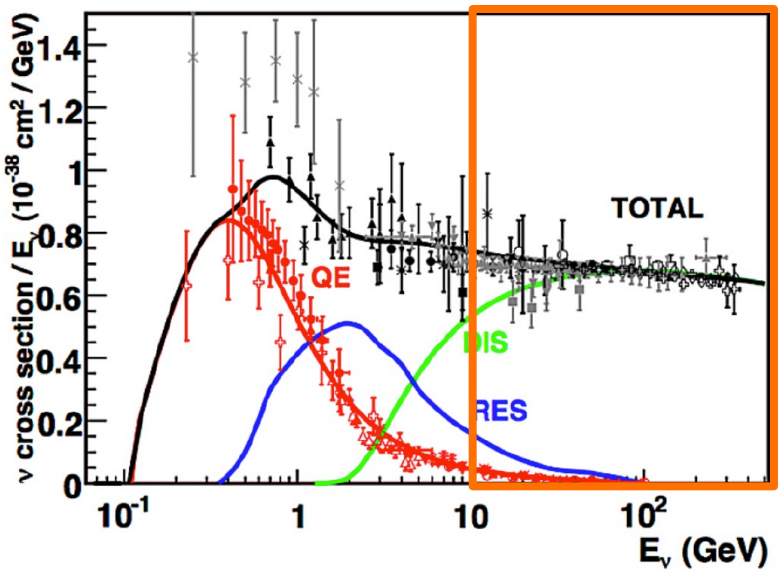


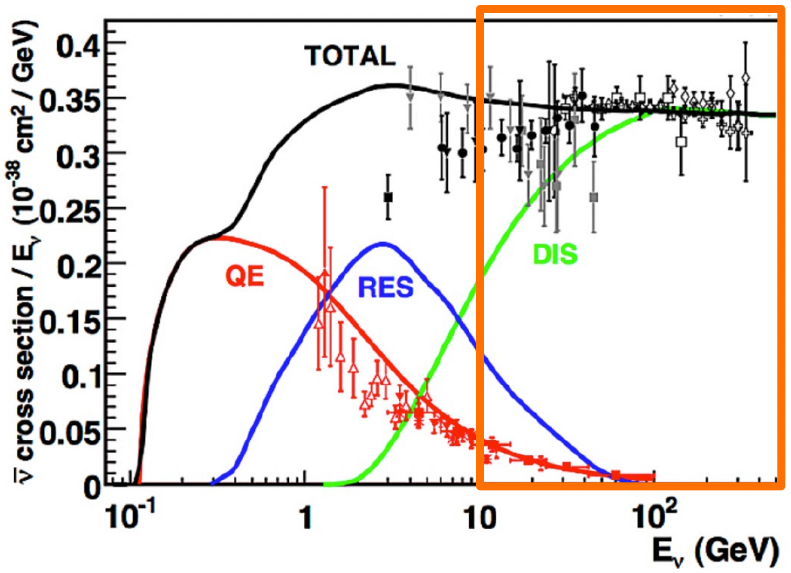

Δ Resonance



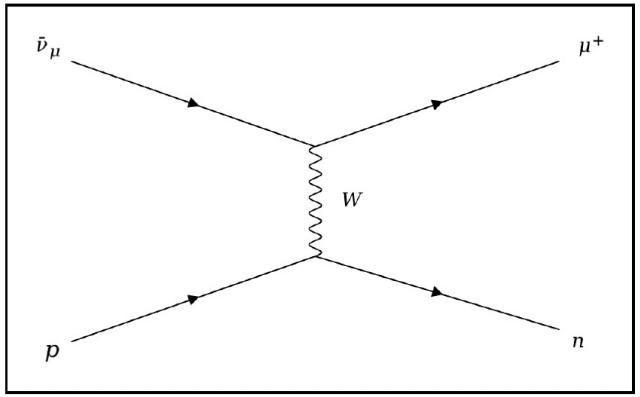

Deep Inelastic Scattering

# Neutrino-nucleon interactions

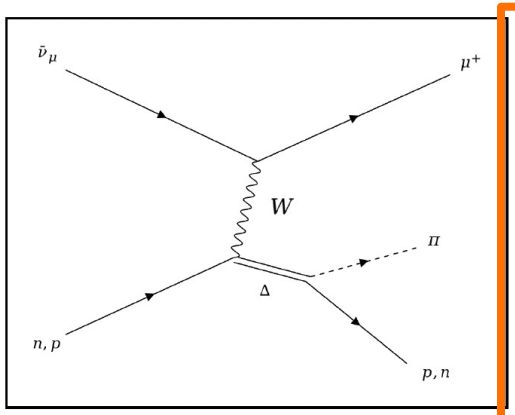


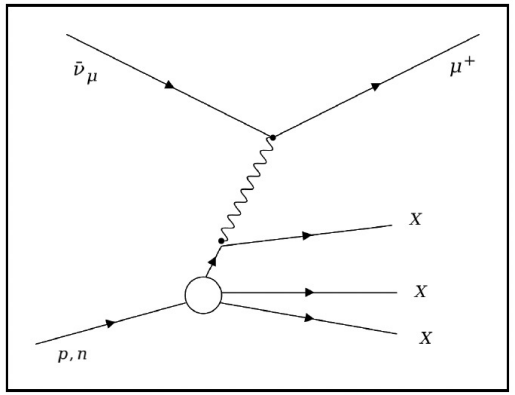

**Above 10 GeV only Deep Inelastic Scattering is relevant**




Quasi-elastic




Δ Resonance

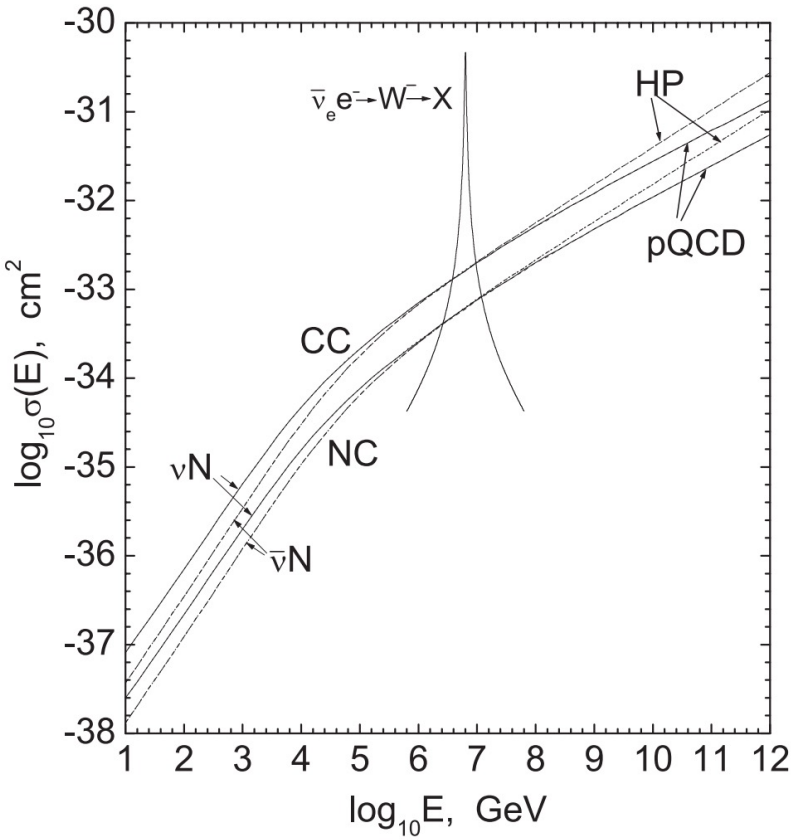



Deep Inelastic Scattering

# Neutrino-nucleon interactions

The DIS cross-section increases as $\sigma \sim E_\nu$ up to $10^4$ GeV

At higher energies, the linear rise starts flattening out




*Comput.Phys.Commun. 172 (2005) 203-213*

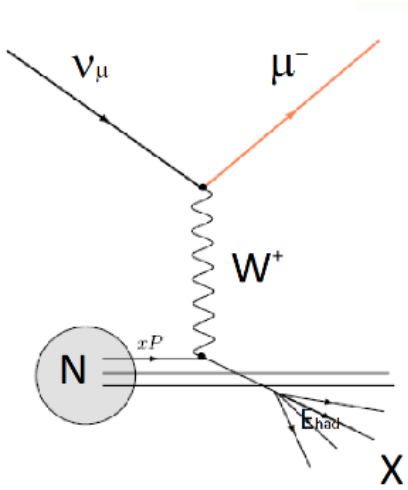
High energy ν interact with *partons* of the nucleons, via:

- charged current (CC) weak interactions ($l$ = e; μ; τ)

$$\nu_l + N \to l + X$$

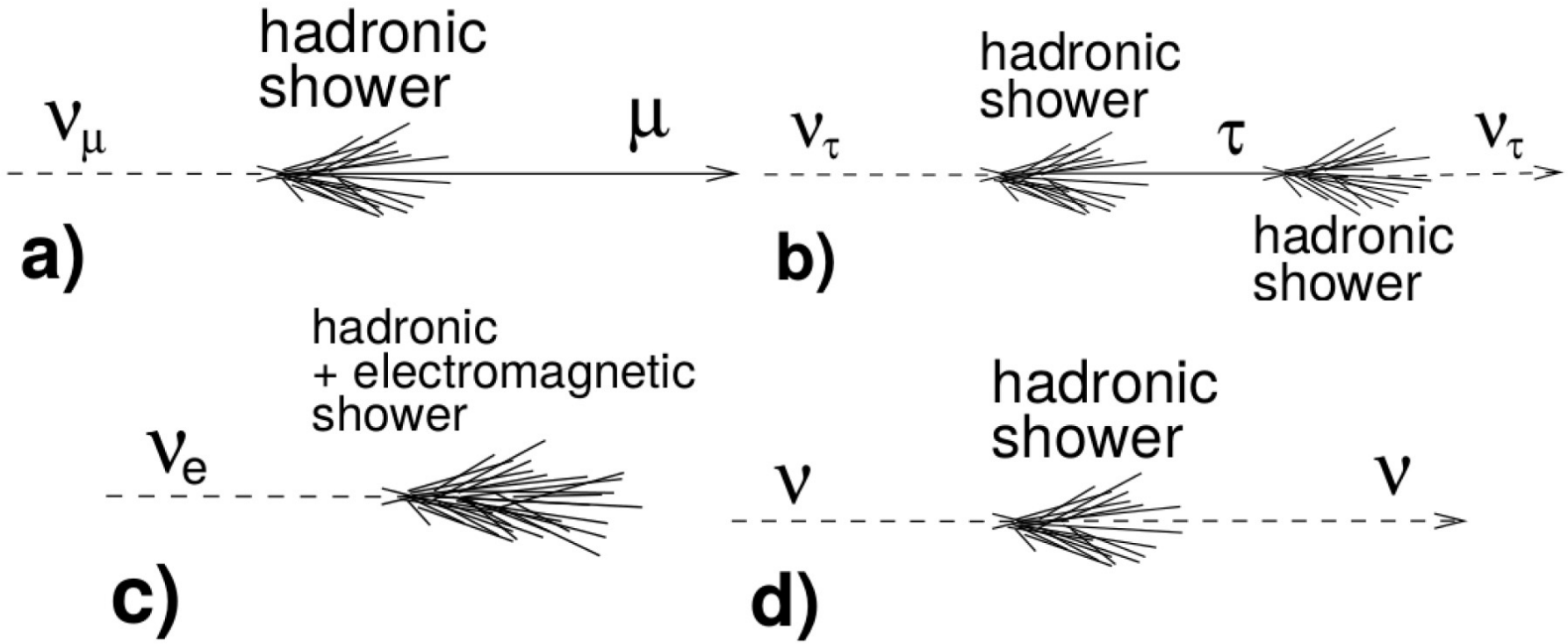
- or neutral current (NC)

$$\nu_l + N \to \nu_l + X$$




The hadronic system X carries away part of the incoming neutrino energy

# Neutrino-nucleon interactions



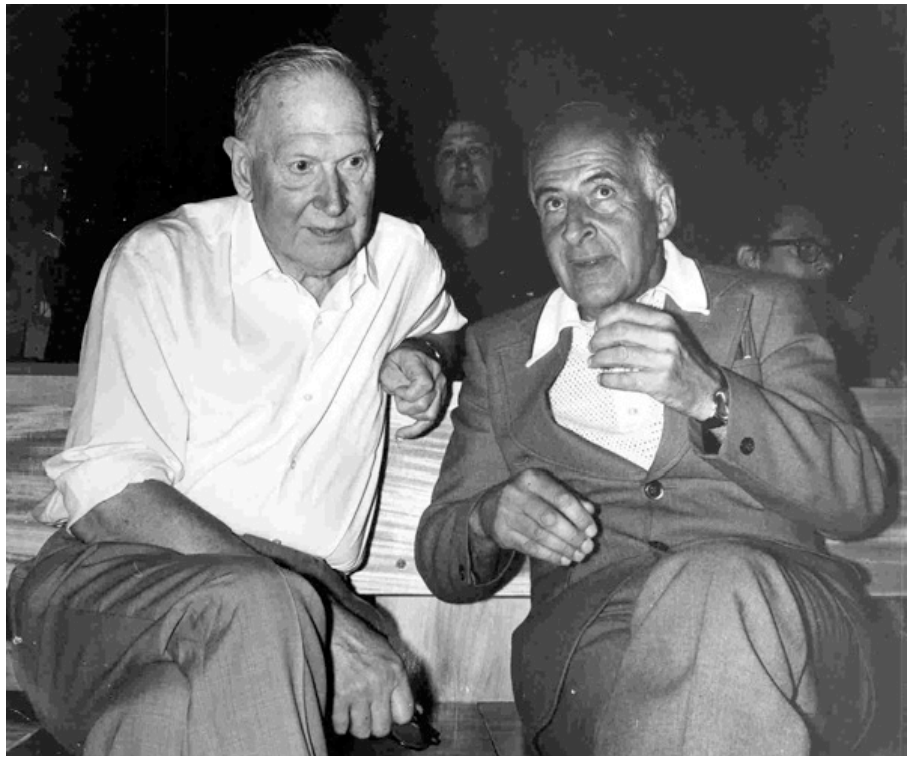
# HE neutrino detection principle

- Neutrinos cannot be seen directly
  → **we have to rely on the products of their interaction**
- Neutrino-nucleon cross sections are extremely low
  → **whatever is the interaction target, it has to be huge**

# HE neutrino detection principle

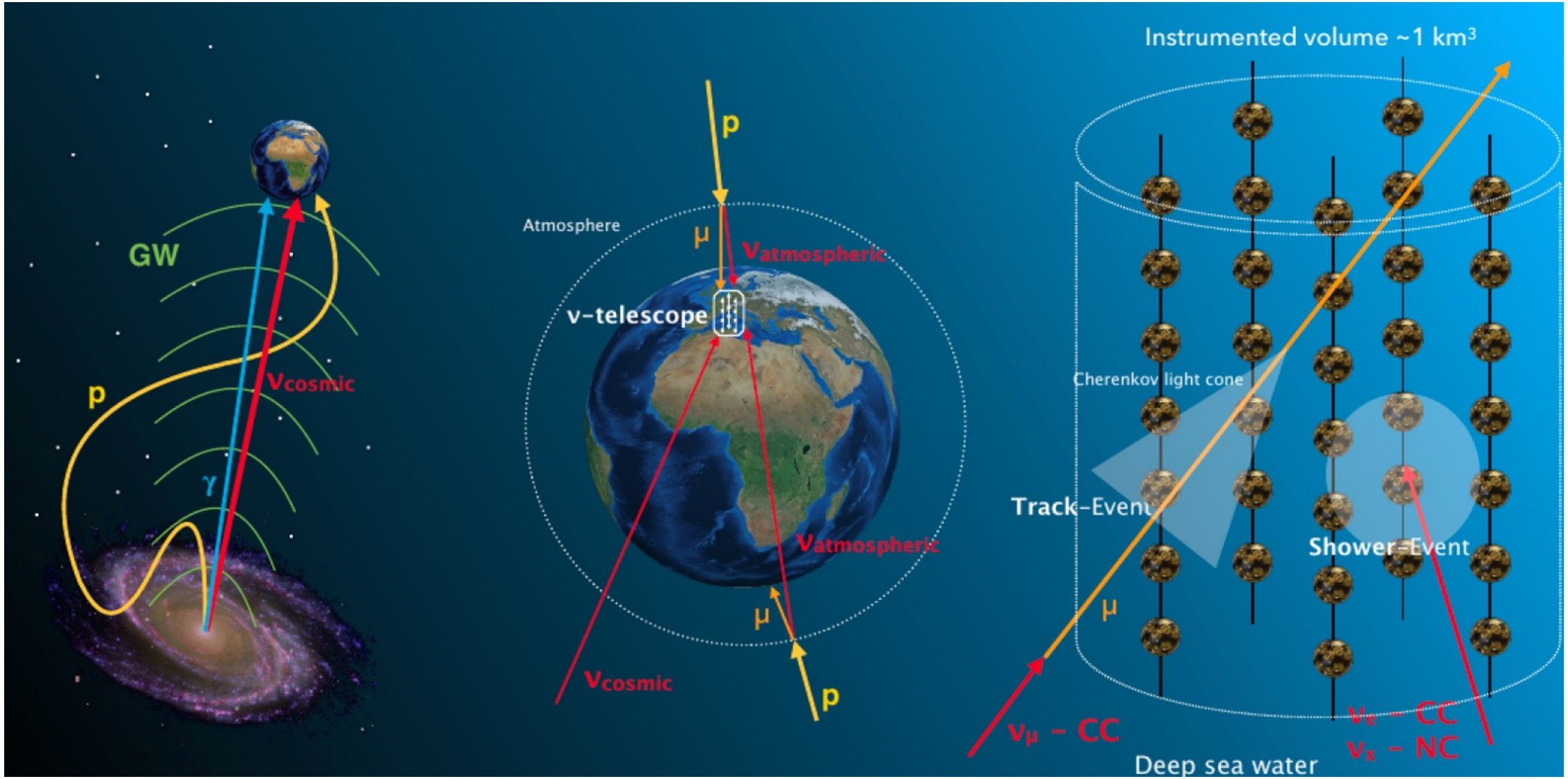
- Neutrinos cannot be seen directly
  → **we have to rely on the products of their interaction**
- Neutrino-nucleon cross sections are extremely low
  → **whatever is the interaction target, it has to be huge**

**M. Markov**: 1960, Rochester Conference
"*We propose to install detectors **deep** in a **lake or in the sea** and to determine the direction of the charged particles with the help of **Cherenkov radiation***"



M.A. Markov and B.M. Pontecorvo at the International conference on neutrino physics and astrophysics. Baksancanyon, Cheget, the Caucasus, 1977

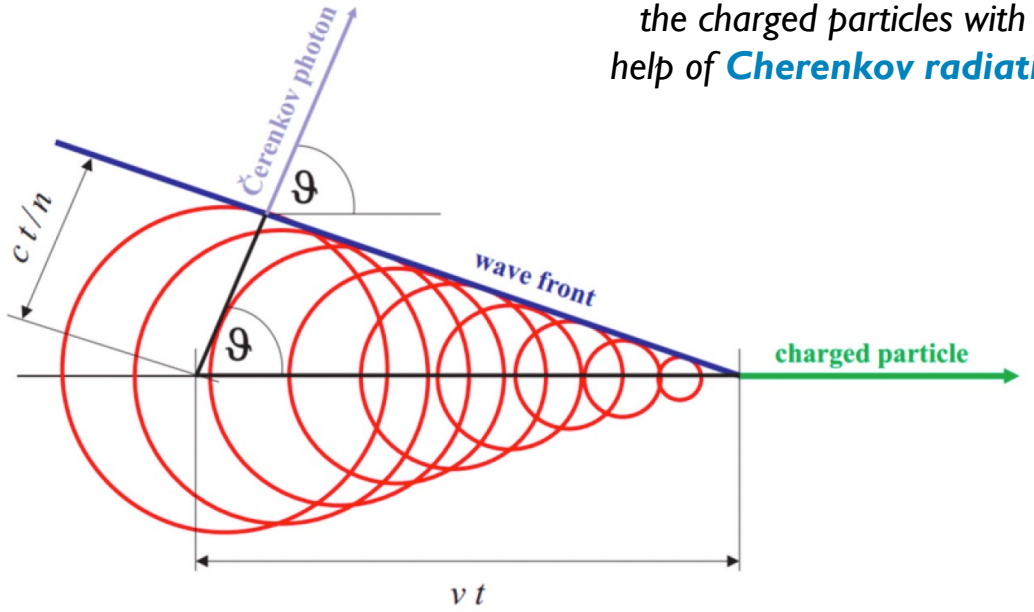
# Principle of detection



# Cherenkov radiation

*We propose to install detectors **deep** in a **lake or in the sea** and to determine the direction of the charged particles with the help of **Cherenkov radiation***

- Cherenkov radiation is induced by **charged particles** crossing a dielectric medium with **speed exceeding that of light** in the medium
- As charged particles travels through a medium, they **polarize and excites the surrounding molecules,** which then relax back to their ground state by emitting photons
- The coherent radiation is emitted along a cone with a characteristic angle $\theta$ such that $\boldsymbol{\theta = \frac{1}{\beta n}}$, where $n$ is the refracting index of the medium and $\beta$ is the particle speed in units of $c$

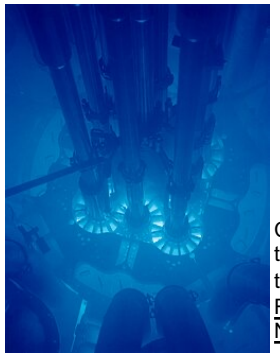



fine-structure constant
charge of the particle

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

**Number of Cherenkov photons**, per unit wavelength interval and unit distance travelled

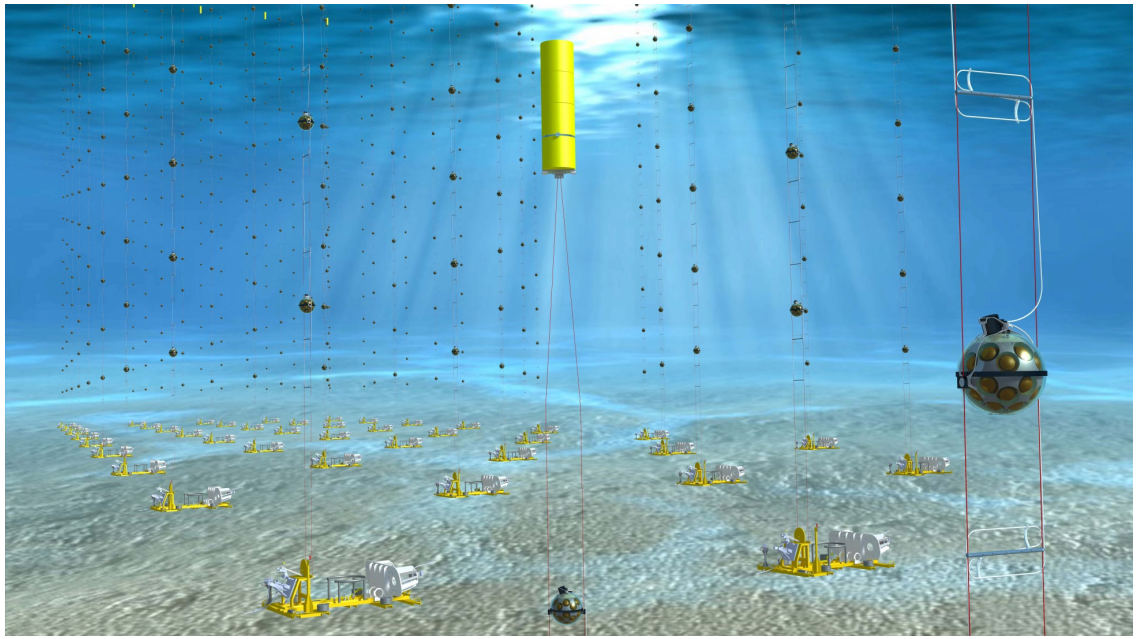
Shorter wavelengths contribute more significantly to the Cherenkov radiation → UV range and blue



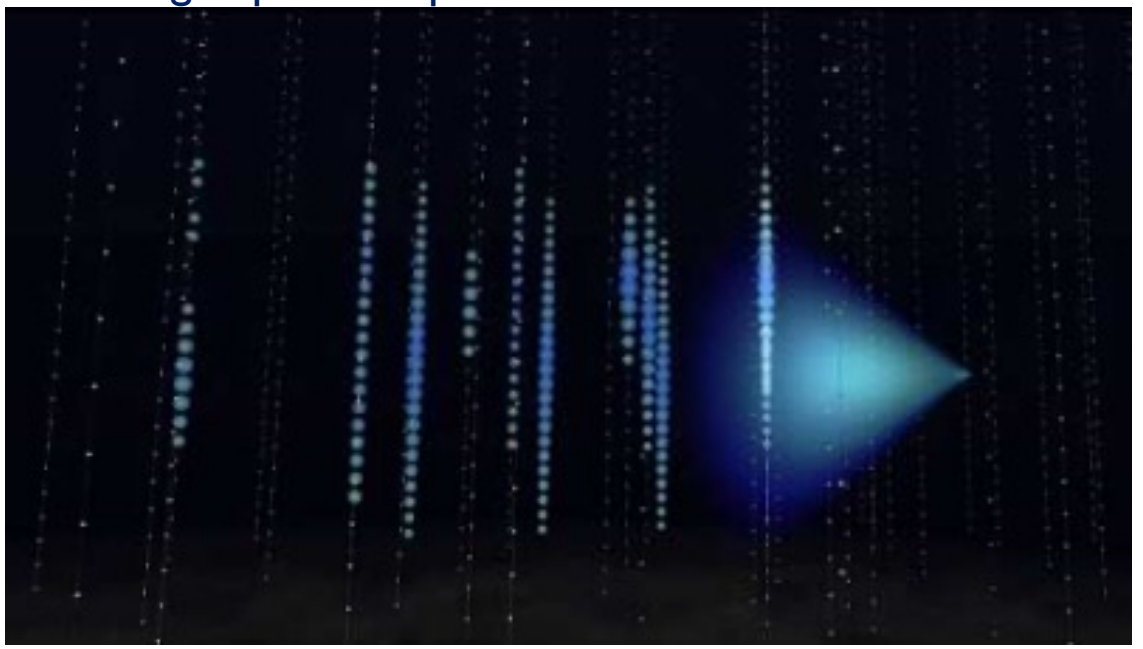
Cherenkov radiation in the core of the Advanced Test Reactor at Idaho National Laboratory

# HE neutrino detectors

3D matrix of **photomultiplier (PMT) tubes** under water/ice surface

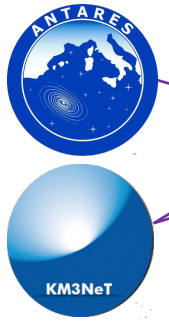


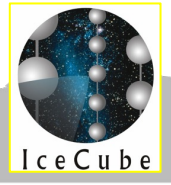
**PMTs detect the Cherenkov light** induced by the charged particles produced in neutrino interactions



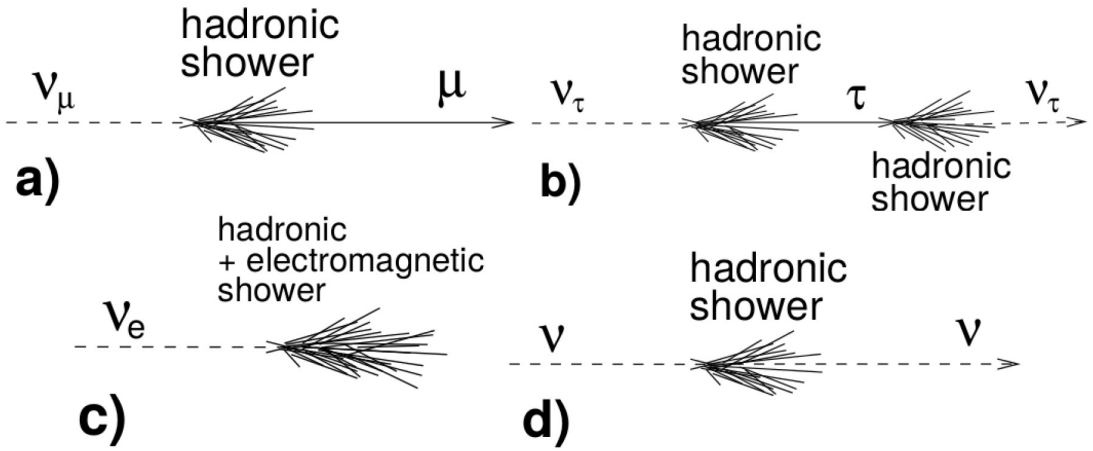
Extremely low neutrino-nucleon cross section
→ Lakes/seas/oceans/Antarctica provide **huge volumes of water/ice "for free"**

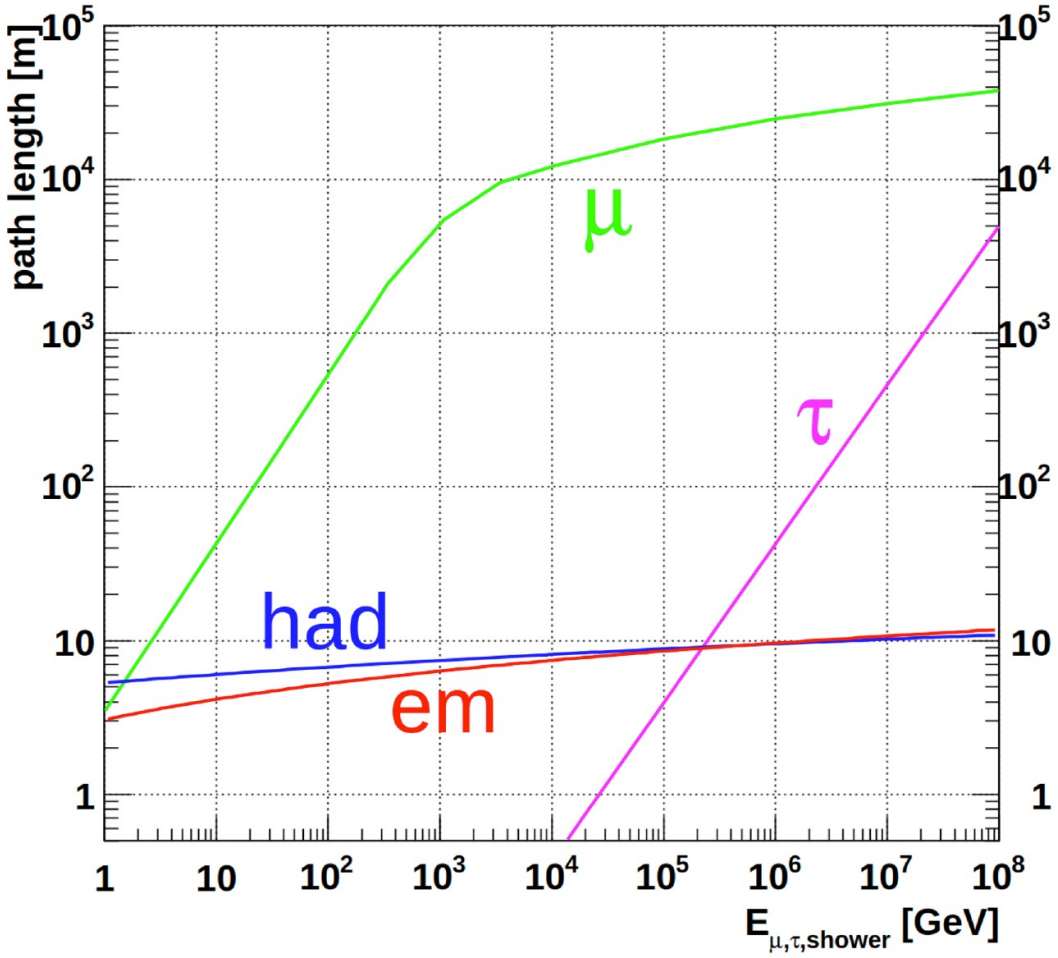
# First glance at experiment locations





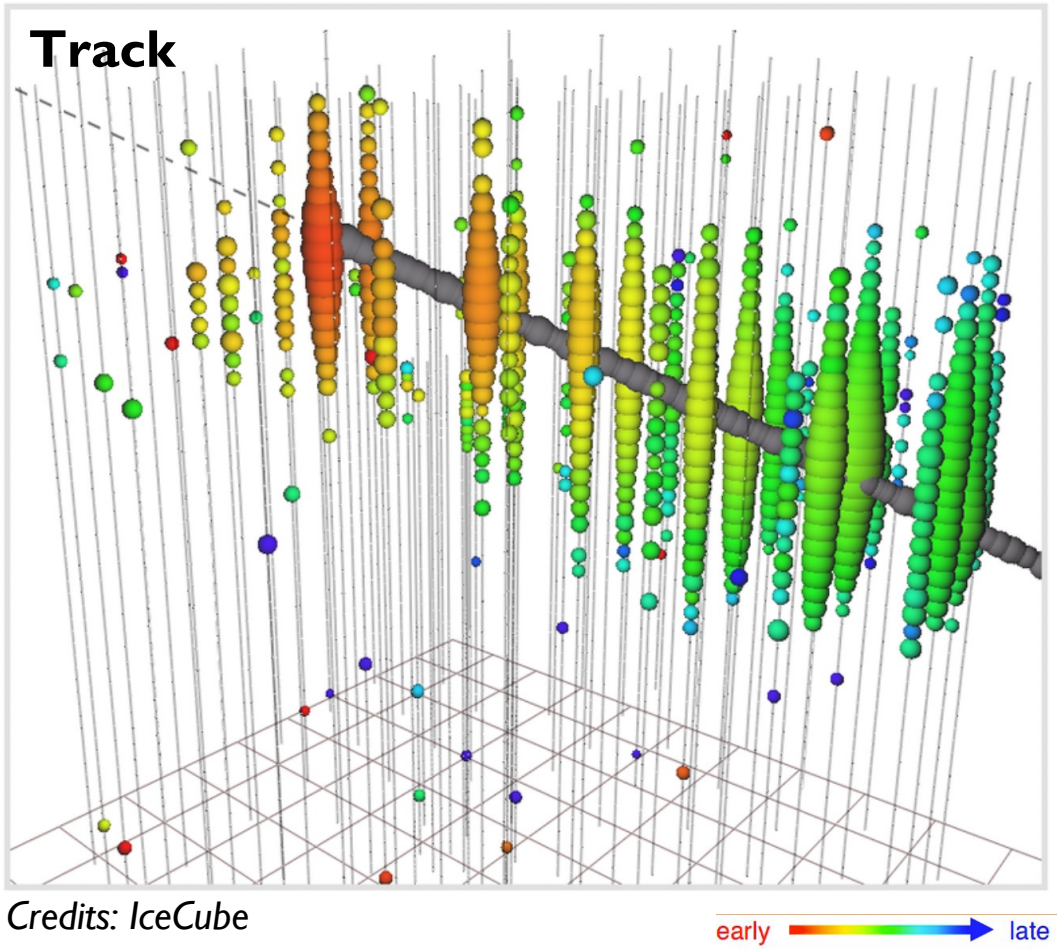
# Event signatures



$\nu_\mu CC$

# Event signatures




*Credits: IceCube*

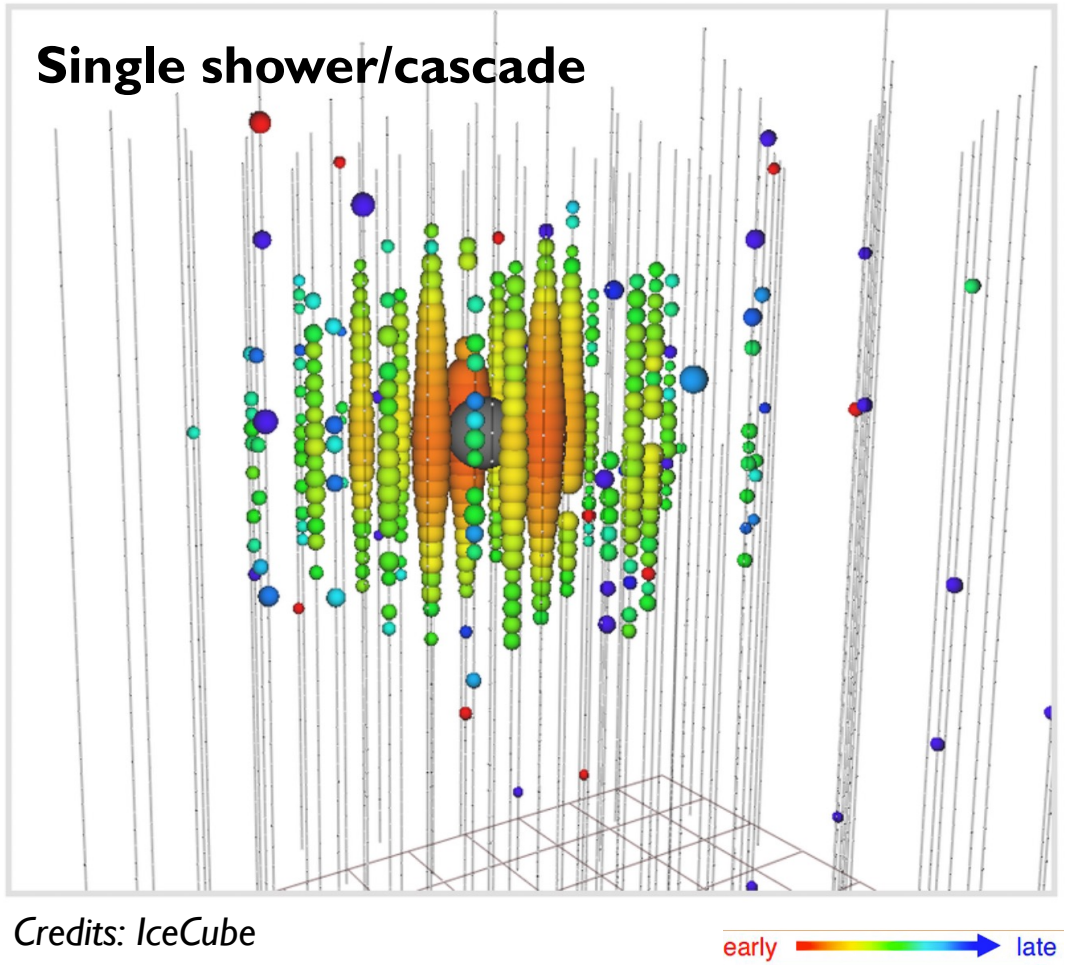
**$\nu_\mu$ undergoing CC interactions will produce a long-lived $\mu$**

- The muon travels on a straight line and induces Cherenkov radiation
- The muon is collinear with the incoming neutrino

$$\theta_{\nu\mu} \simeq \frac{0.6^\circ}{\sqrt{E_\nu(\mathrm{TeV})}}$$

$\nu_e CC, \nu_x NC$

# Event signatures

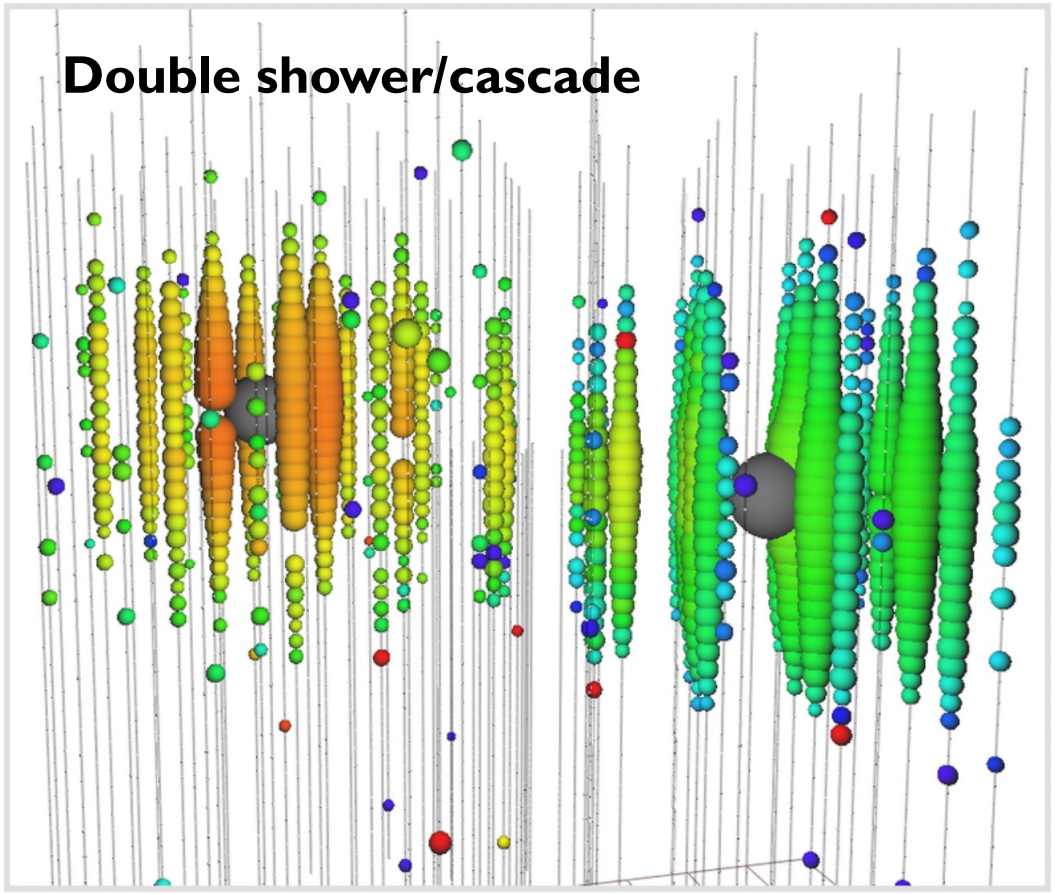



*Credits: IceCube*

- **All three flavours undergoing NC interactions** will hadronic showers
- **$\nu_e$ undergoing CC interactions** will produce both hadronic and electromagnetic showers

$\nu_\tau CC$

# Event signatures



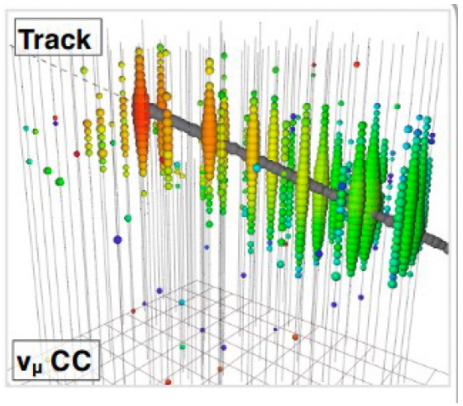

*Credits: IceCube*

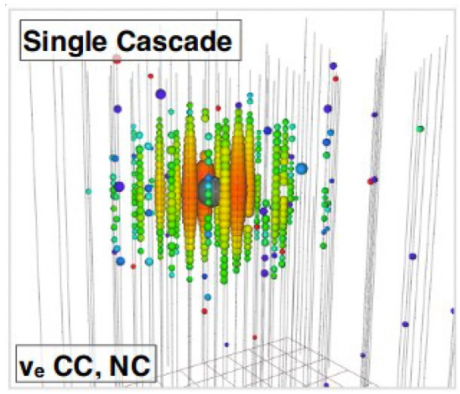
**$\nu_\tau$ undergoing CC interactions** will produce a $\tau$ + hadronic shower

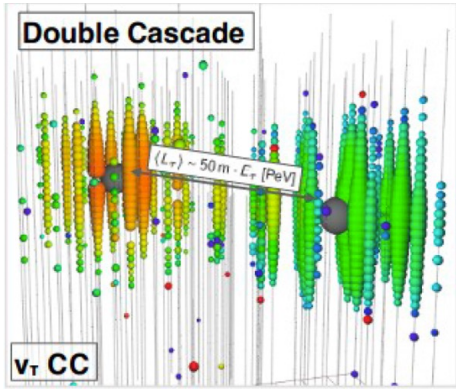
- $\tau$ is a short-lived lepton and decays producing a second shower (87% BR)
- At high energies, the two showers are separated enough to be distinguished

→ One shower event at the neutrino interaction vertex + One shower event at the $\tau$ decay point

# Event signatures



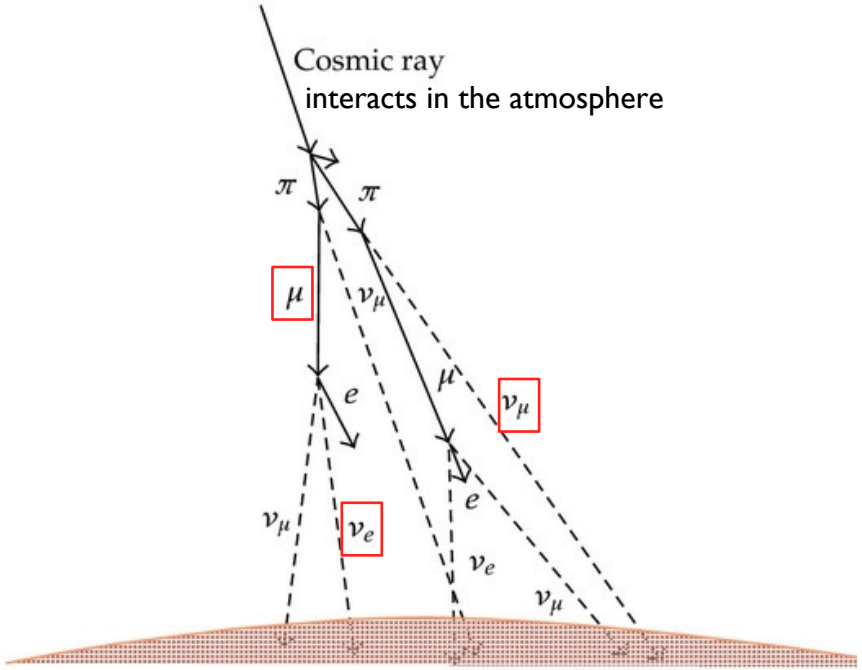



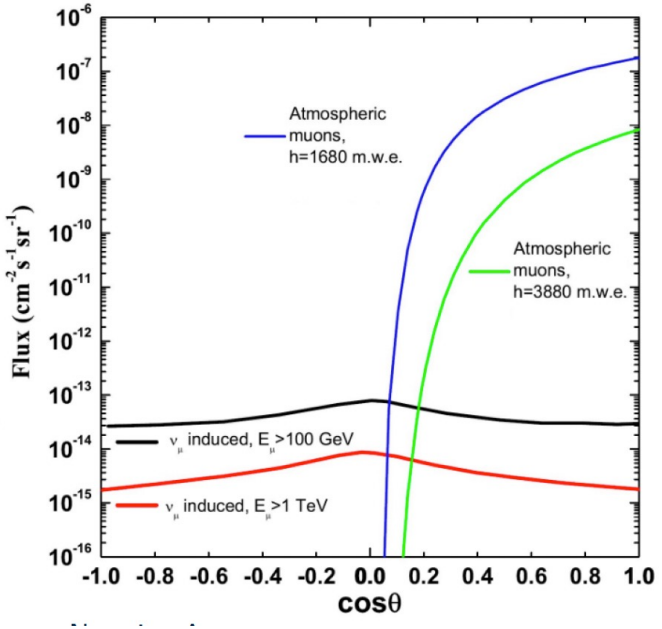

- Muons travel on a straight line and are collinear with the incoming neutrinos
  → **Good directional reconstruction**
- Muons can be detected even if the interaction happened many kilometers away
  → **Increase the detector efficiency**
  → **Energy reconstruction is uncertain**

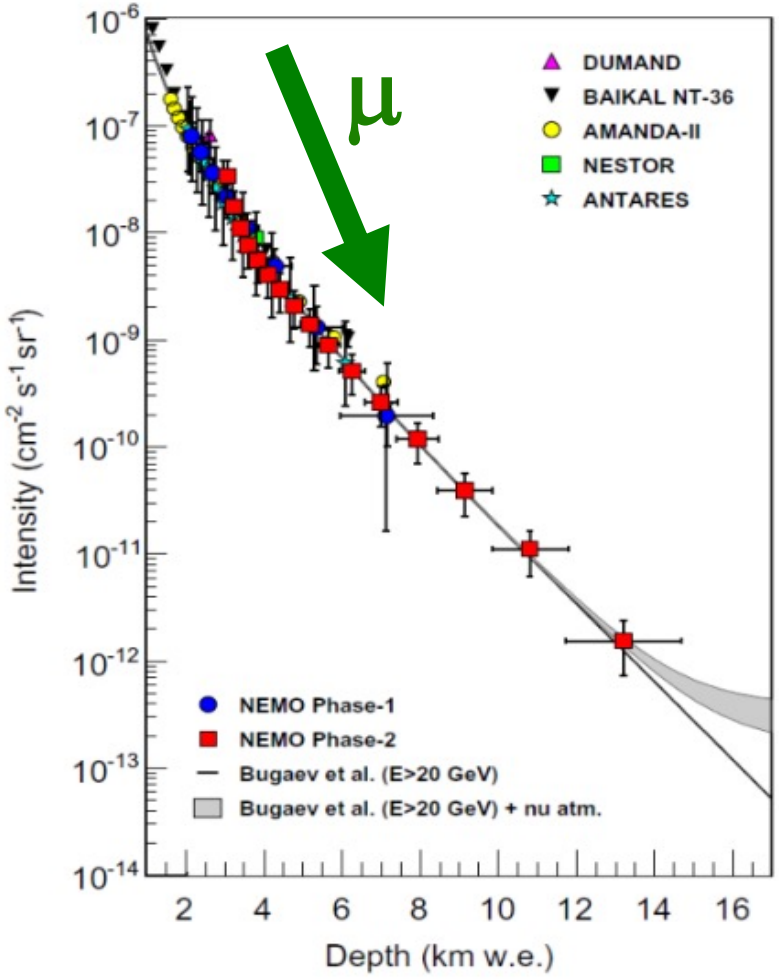
- The shower is limited in size (few meters)
  → **It can be measured only in the proximity of the detector**
  → **Directional reconstruction is difficult**
- Whole energy dissipated in the detector
  → **Allows calorimetric energy measurement**

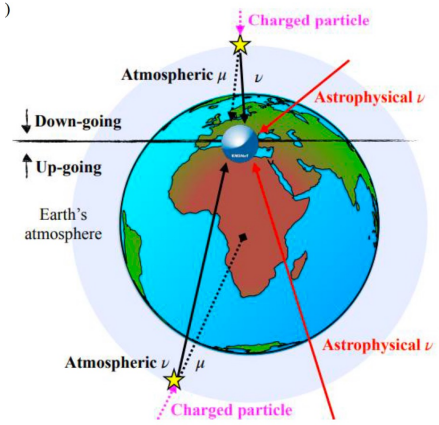
A double shower is **tricky to recognize** but worth the attempt:
**a $\nu_\tau$ can only be astrophysical!**

# Background




Atmospheric muons can be drastically reduced by:

- **going deep** (use above water/ice as a shield)
- selecting **upward-going events** (use Earth as a shield)

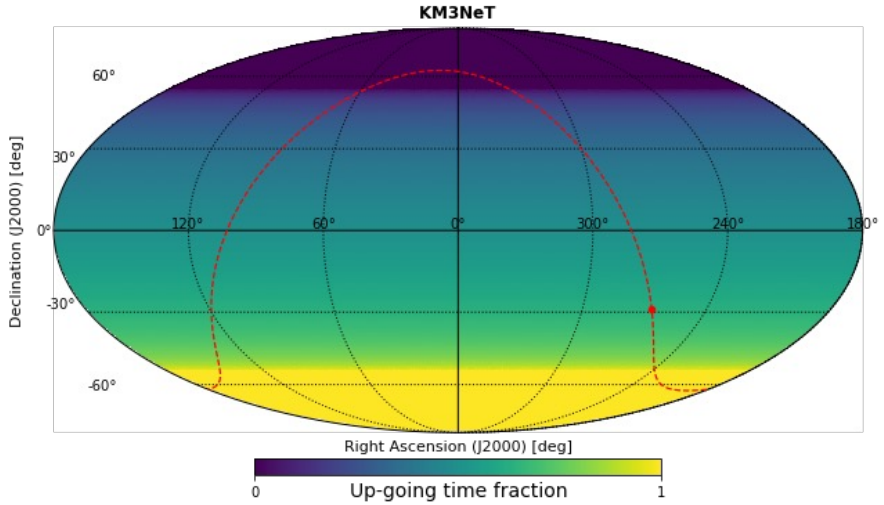
Different techniques are needed to get rid of atmospheric neutrinos depending on analysis

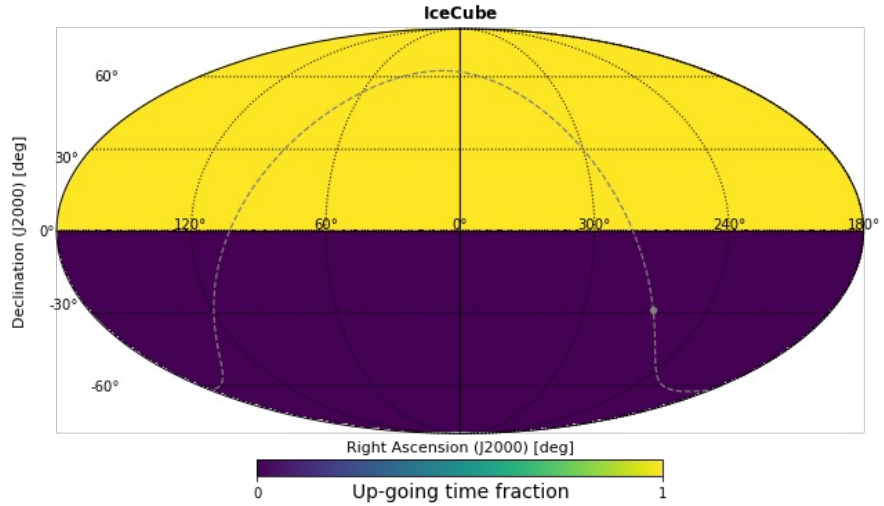
# Sky visibility

**Daily averaged** visibility, i.e. fraction of the day during which a certain sky region is visible using up-going events

**36°16' N**
16°06' E
(Mediterranean Sea)

**89°59'24"S**
63°27'11"W
(Antarctica)




Where to locate a telescope to have all the sky always monitored?

# Earth absorption

Interaction length:

$$\lambda = \frac{1}{n\sigma}\ [cm]$$

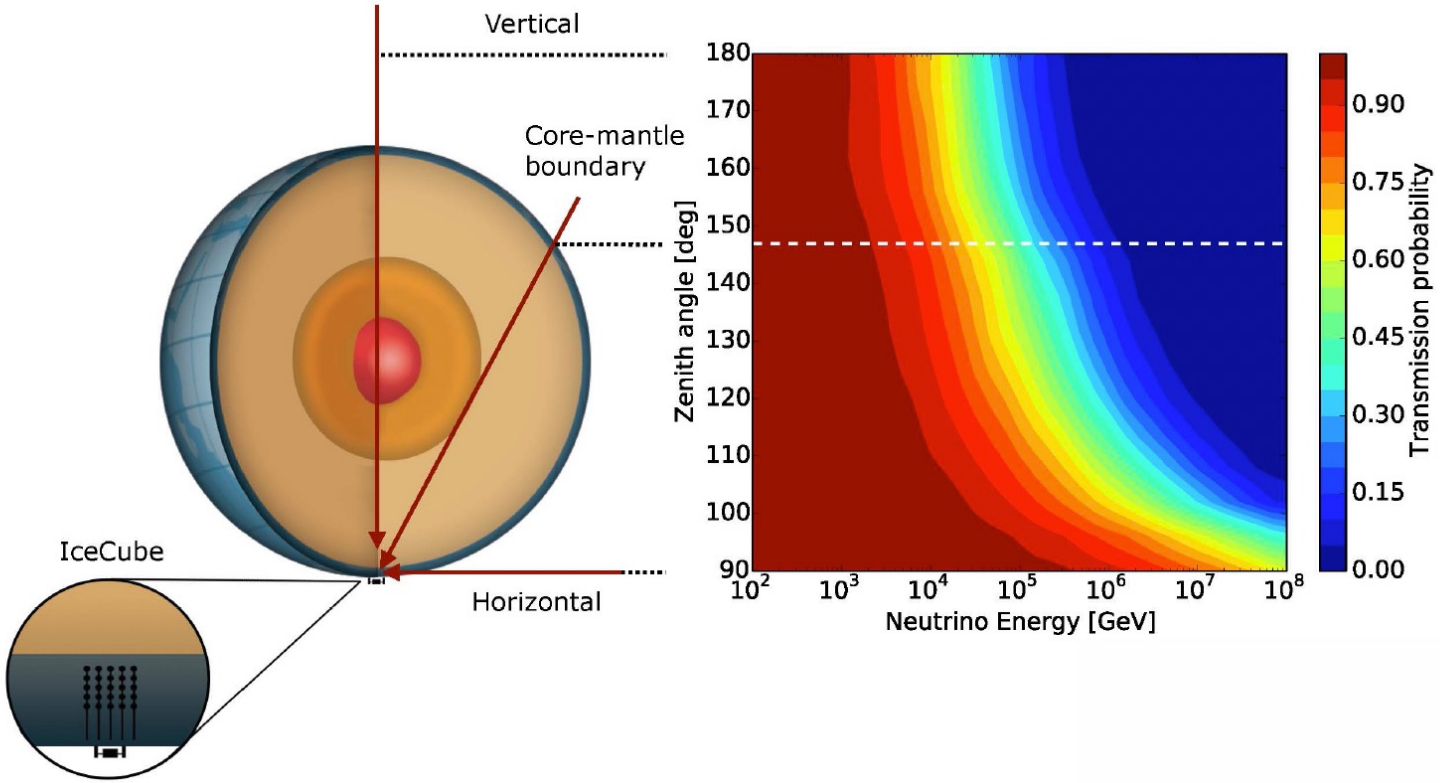
- $n$: number density of nucleons
- $\sigma$: neutrino-nucleon cross section

$$n = \frac{N_A}{M}\rho\ \ [cm^{-3}]$$

- $M$: mass, $\rho$: density of the material

→ Surviving fraction of particles:

$$N(x) = N_o e^{-x/\lambda}$$




**At 1 TeV:** Earth starts to be opaque to neutrinos
**Above 10 PeV:** neutrinos can only be detected if coming horizontally

# Antarctic ice versus Mediterranean sea

## How does the chosen medium affect light propagation?

- **Event Reconstruction** based on time-space correlations of fired PMTs (hits)
- The effects of the medium (water or ice) on propagation are:
  - **Absorption,** which reduces the amplitude of the Cherenkov wavefront
  - **Scattering,** which changes the direction of propagation of the Cherenkov photons

→ **Both affect the reconstruction capabilities of the telescope**

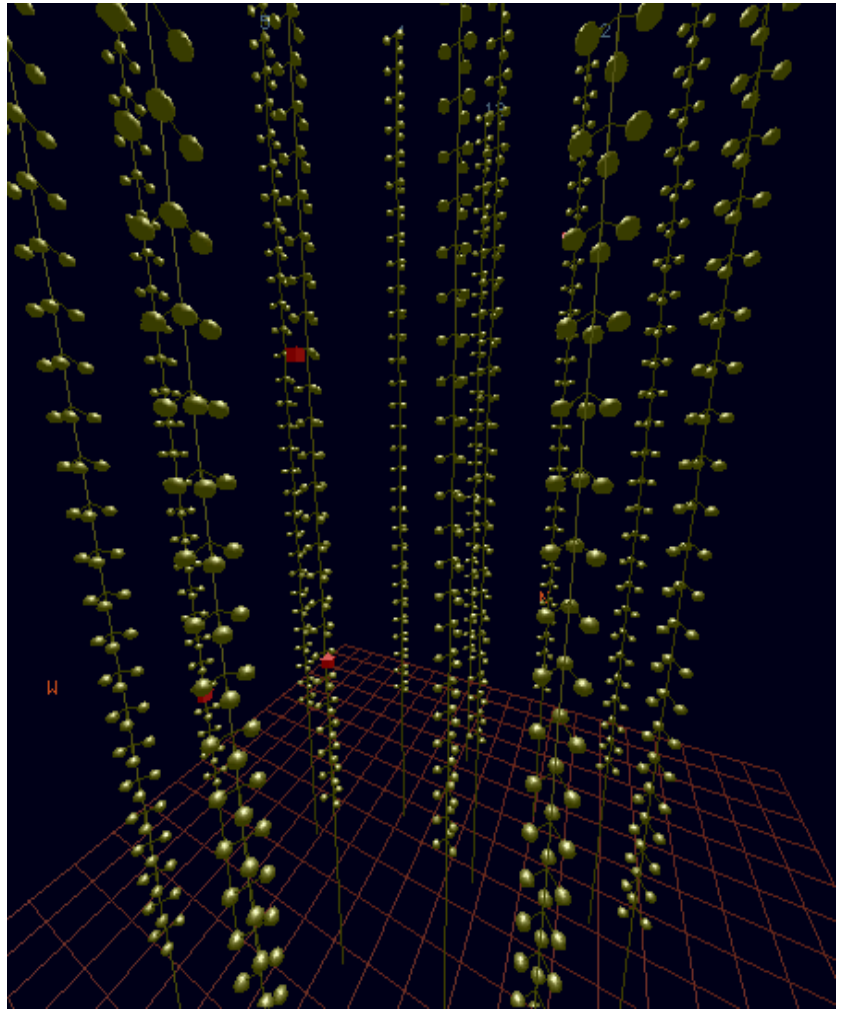
At a given wavelength λ
- Absorption coefficient: a(λ)
- Scattering coefficient: b(λ)
- Attenuation coefficient: c(λ)

$$c(\lambda) = a(\lambda) + b(\lambda)$$

The corresponding absorption, scattering and attenuation length:

$$L_i = i(\lambda)^{-1} \quad i = a, b, c$$

- $La$ : path after which the light intensity is reduced by a factor $1/e$ because of absorption
- $Lb$ : path after which the number of "direct" photons is reduced by a factor $1/e$ because of scattering



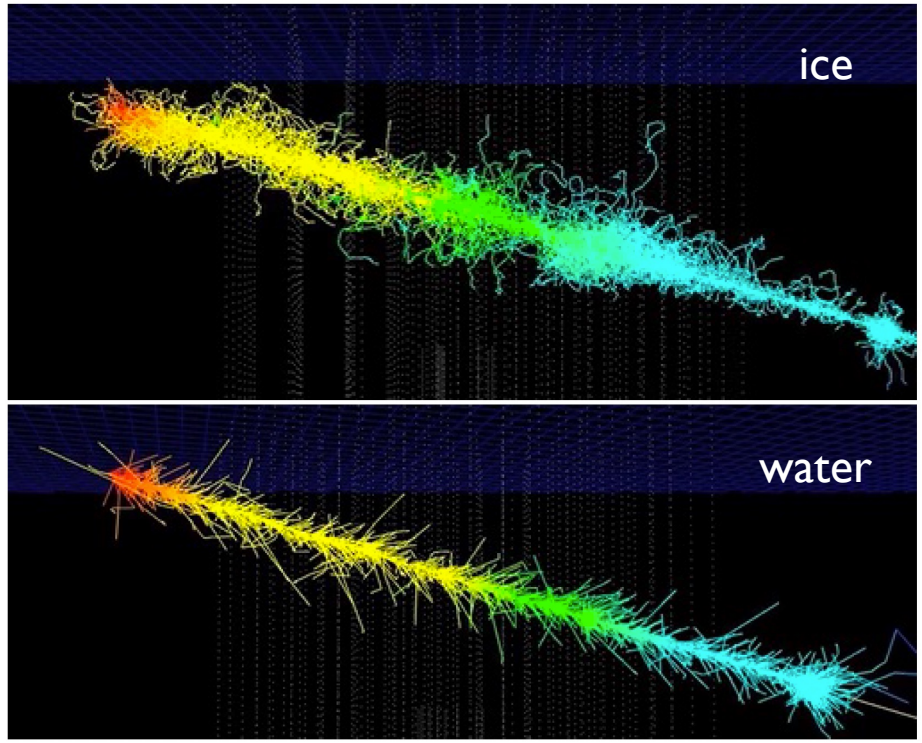
# Antarctic ice versus Mediterranean sea

Sea Water (Mediterranean Sea, KM3NeT site):
- **Absorption length ~ 60-70 m** for $\lambda \simeq 400$ nm
- **Scattering length $\gg$ 100 m**

Antarctic Ice (IceCube site):
- **Absorption length $\gg$ 100 m** for $\lambda \simeq 400$ nm
- **Scattering length ~ 10 m** (impurities due to ice formation)

→ **Larger effective volume in ice** given the same instrumented volume **w.r.t. seawater**
→ **Larger degradation of the angular resolution in ice w.r.t. seawater**

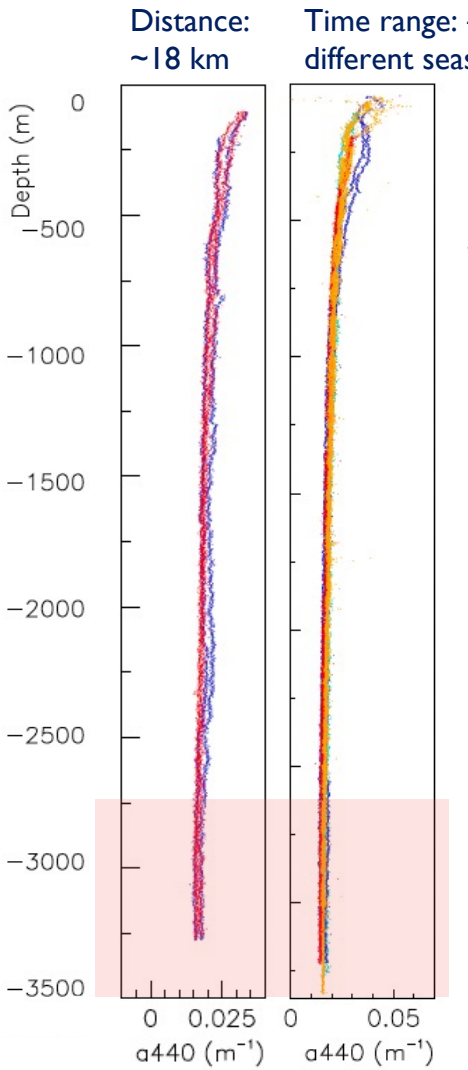
**Difference between light propagation in water and ice**




**Cherenkov photons induced by a muon traversing ice/water**

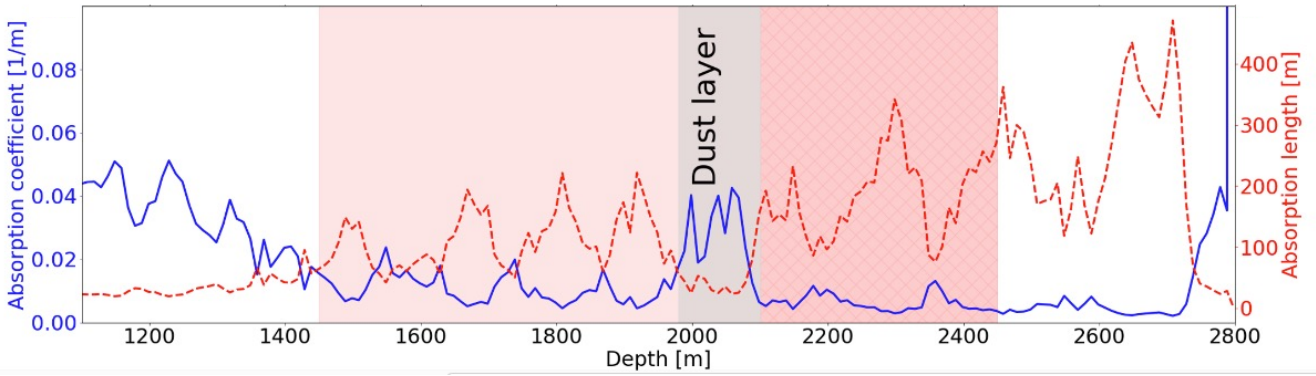
*Credits: C. Kopper (FAU Erlangen-Nürnberg, ECAP)*

# Antarctic ice versus Mediterranean sea




**Water properties are ~homogeneous in the Mediterranean site**

**South Pole Ice: sedimentation of the snow in the last $10^5$ y**
**Air bubbles and dust are trapped in the ice**
**→ Require a precise modeling of the ice layers**



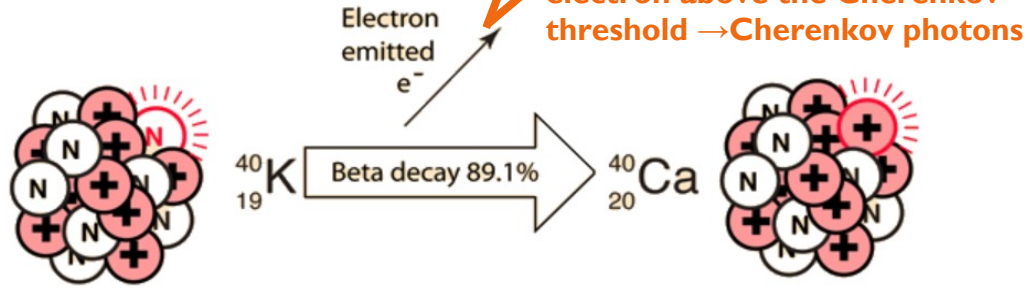

*https://icecube.wisc.edu/science/research/#glaciology*

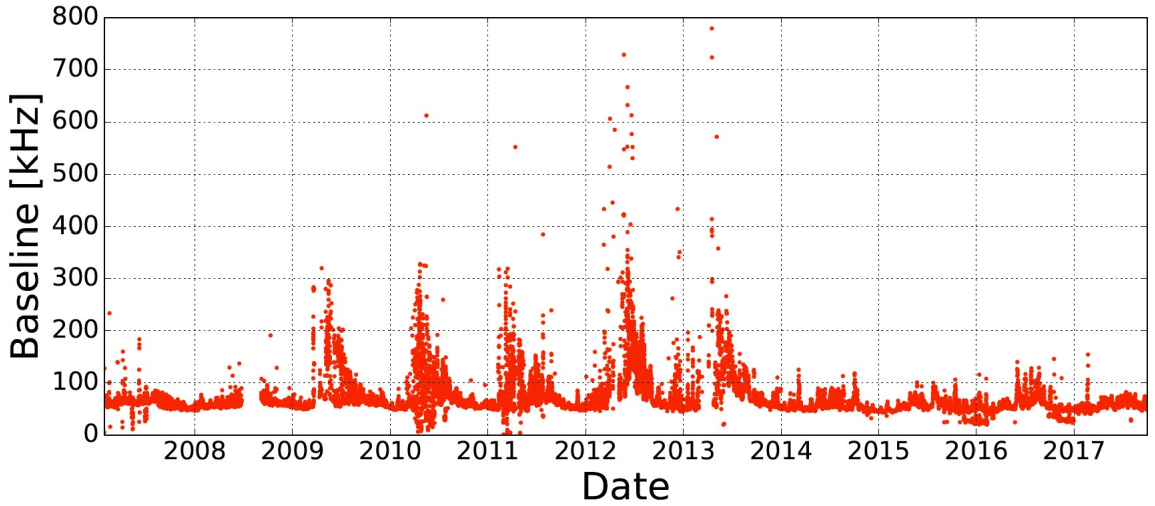
*Astropart.Phys. 27 (2007) 1-9*

# Antarctic ice versus Mediterranean sea

Water shows **natural optical backgrounds** from:

- decay of radioactive elements dissolved in water, mainly $^{40}$**K** (only in salt water)
- **bioluminescence**: luminescence produced by organisms

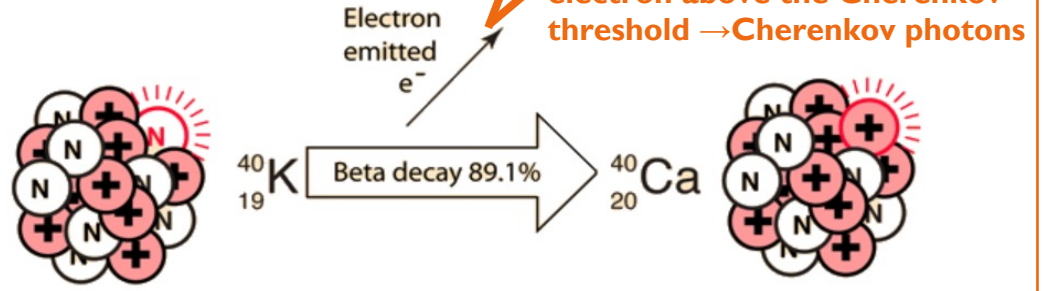


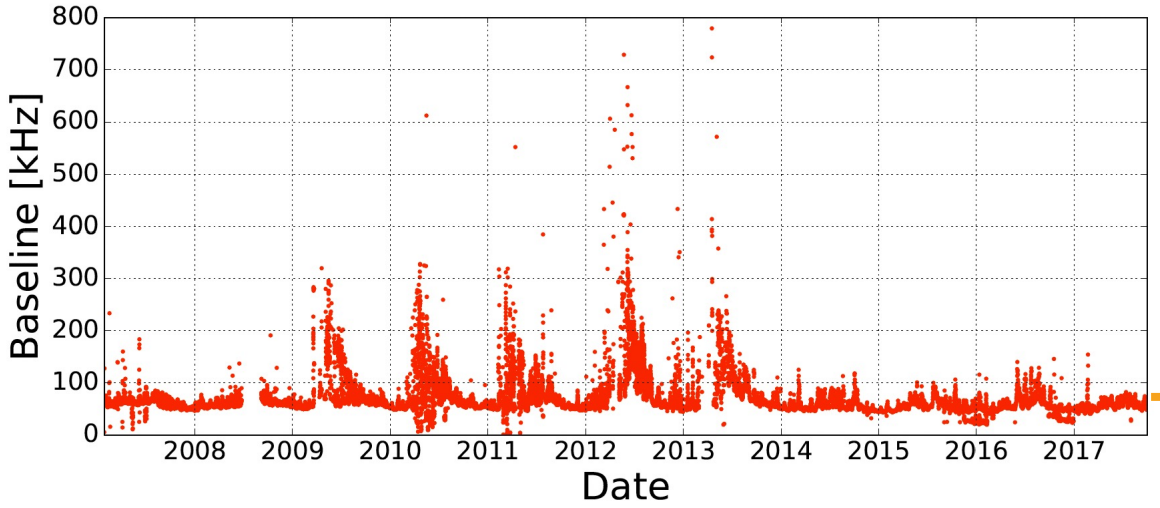



# Antarctic ice versus Mediterranean sea

Water shows **natural optical backgrounds** from:

- decay of radioactive elements dissolved in water, mainly **$^{40}$K** (only in salt water)
- **bioluminescence**: luminescence produced by organisms




**Baseline:**
$^{40}$K decays
~ 40–50 kHz in a 10-inch PMT
~ 6–7 kHz in a 3-inch PMT

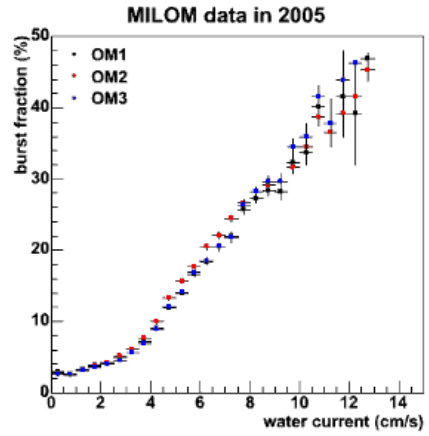
**Advantages of $^{40}$K:**

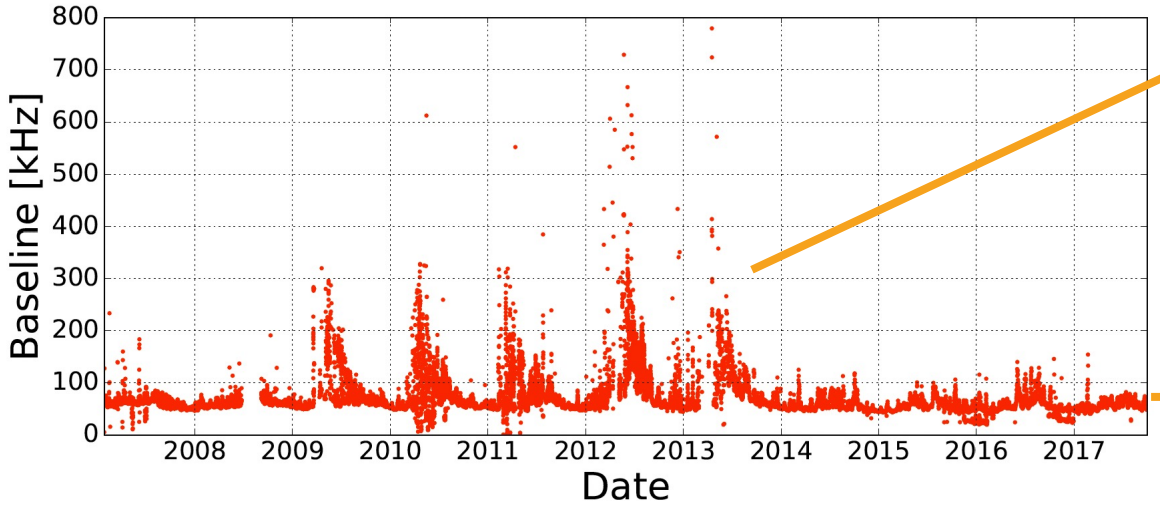
- Rate of $^{40}$K
  → **Measure the efficiency of the PMTs**
- $^{40}$K concentration is stable
  → **Time-dependent evolution of the rate allow to measure the loss of efficiency of PMTs**
- Coincidences from same $^{40}$K decay
  → **Time calibration of the PMTs**

# Antarctic ice versus Mediterranean sea

Water shows **natural optical backgrounds** from:

- decay of radioactive elements dissolved in water, mainly $^{40}$**K** (only in salt water)
- **bioluminescence**: luminescence produced by organisms




**Bioluminescence bursts:**

Animal species which emit light by flashes

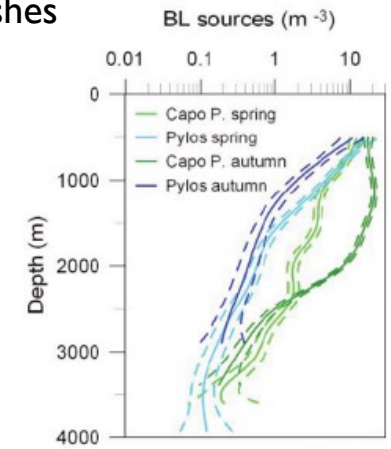
- Periodical
- Correlated with water speed

**Baseline:**

$^{40}$K decays

~ 40–50 kHz in a 10-inch PMT

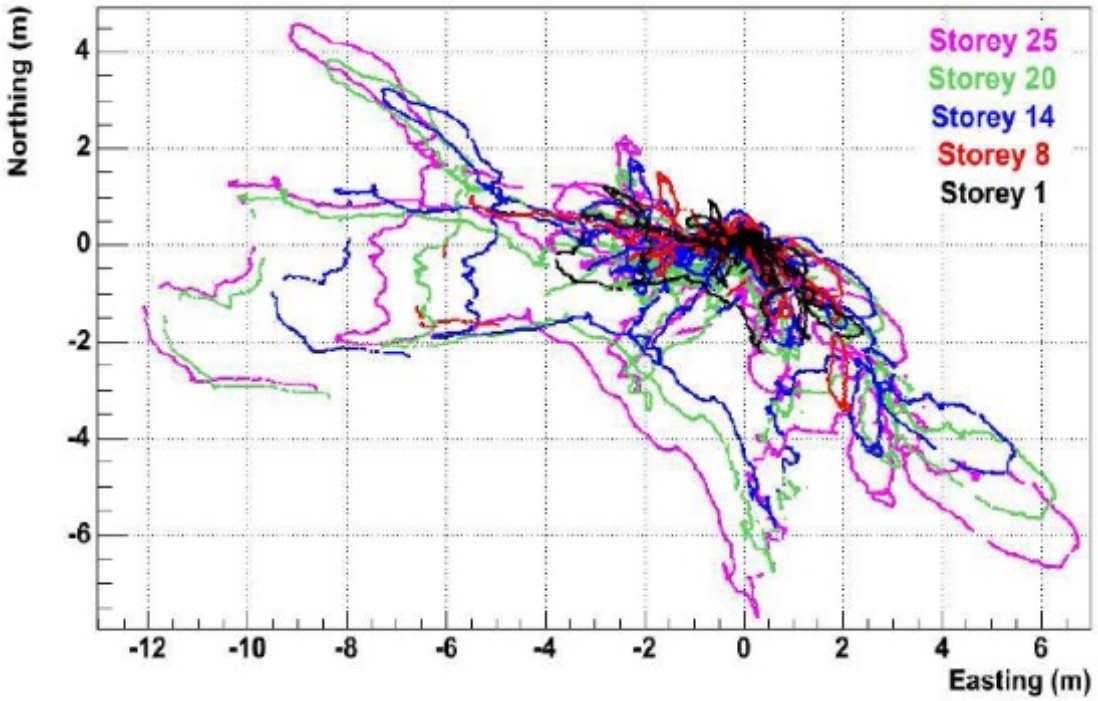
~ 6–7 kHz in a 3-inch PMT



# Antarctic ice versus Mediterranean sea

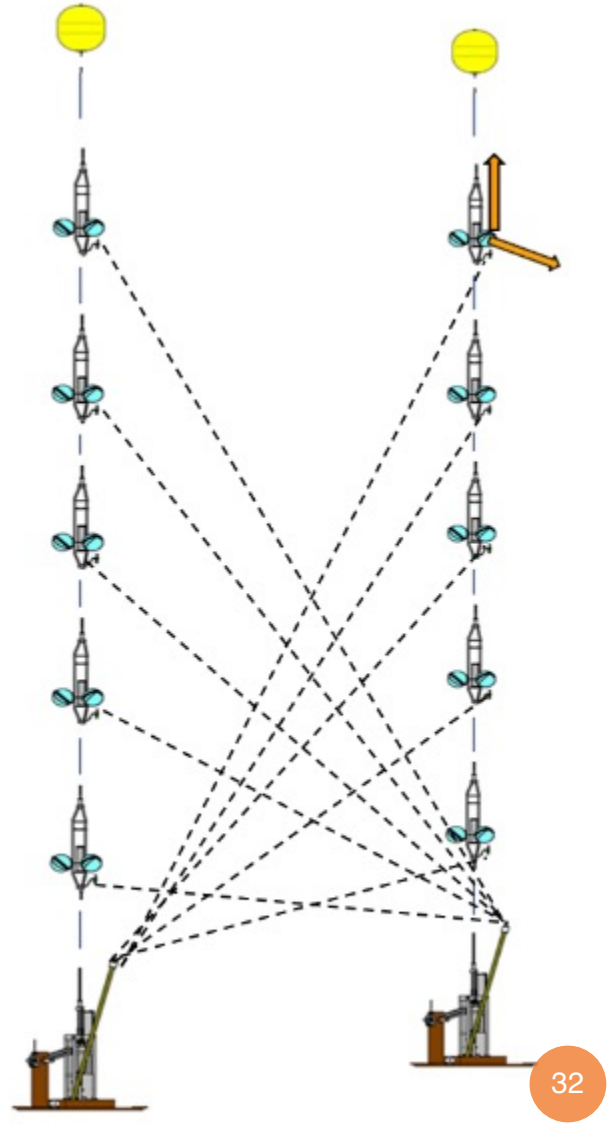
**Water moves** due to sea currents (5–20 cm/s)

→ the position of strings must be monitored constantly



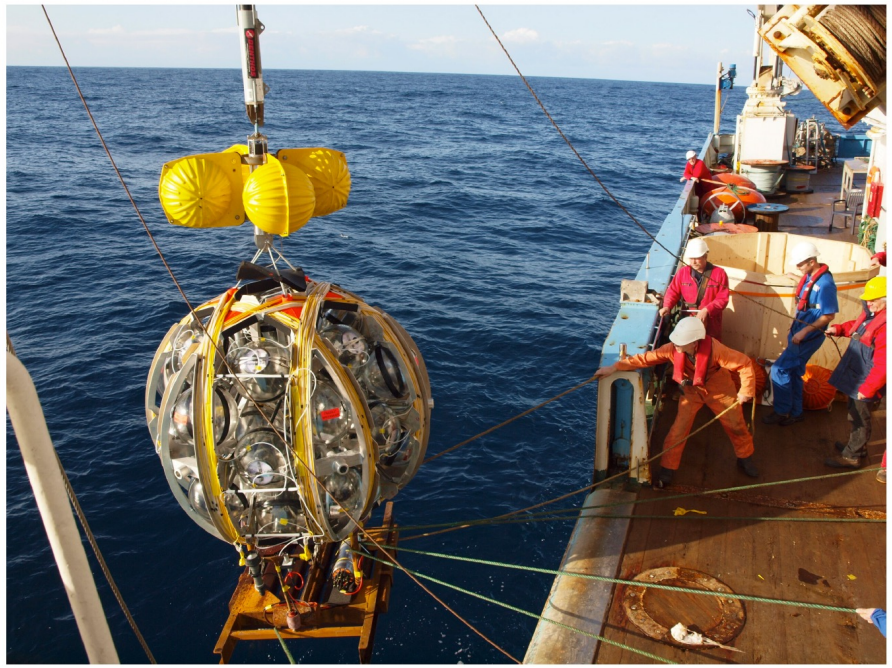

System of acoustic emitters/receivers and compasses to track movements and rotations

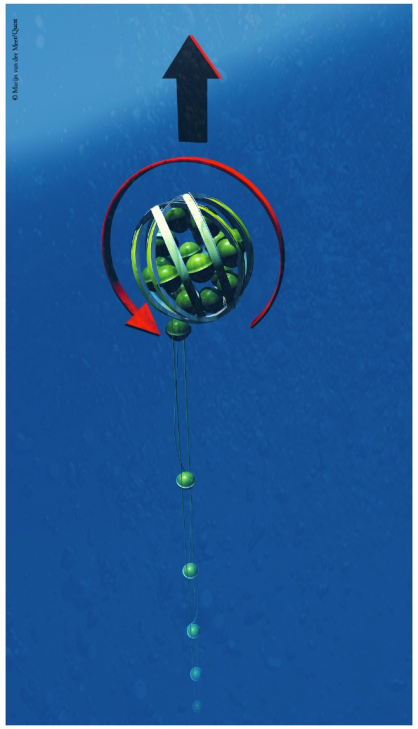
Goal: knowing the position of the detector elements **within 10 cm** (why?)



# Antarctic ice versus Mediterranean sea

## String deployment and recovery

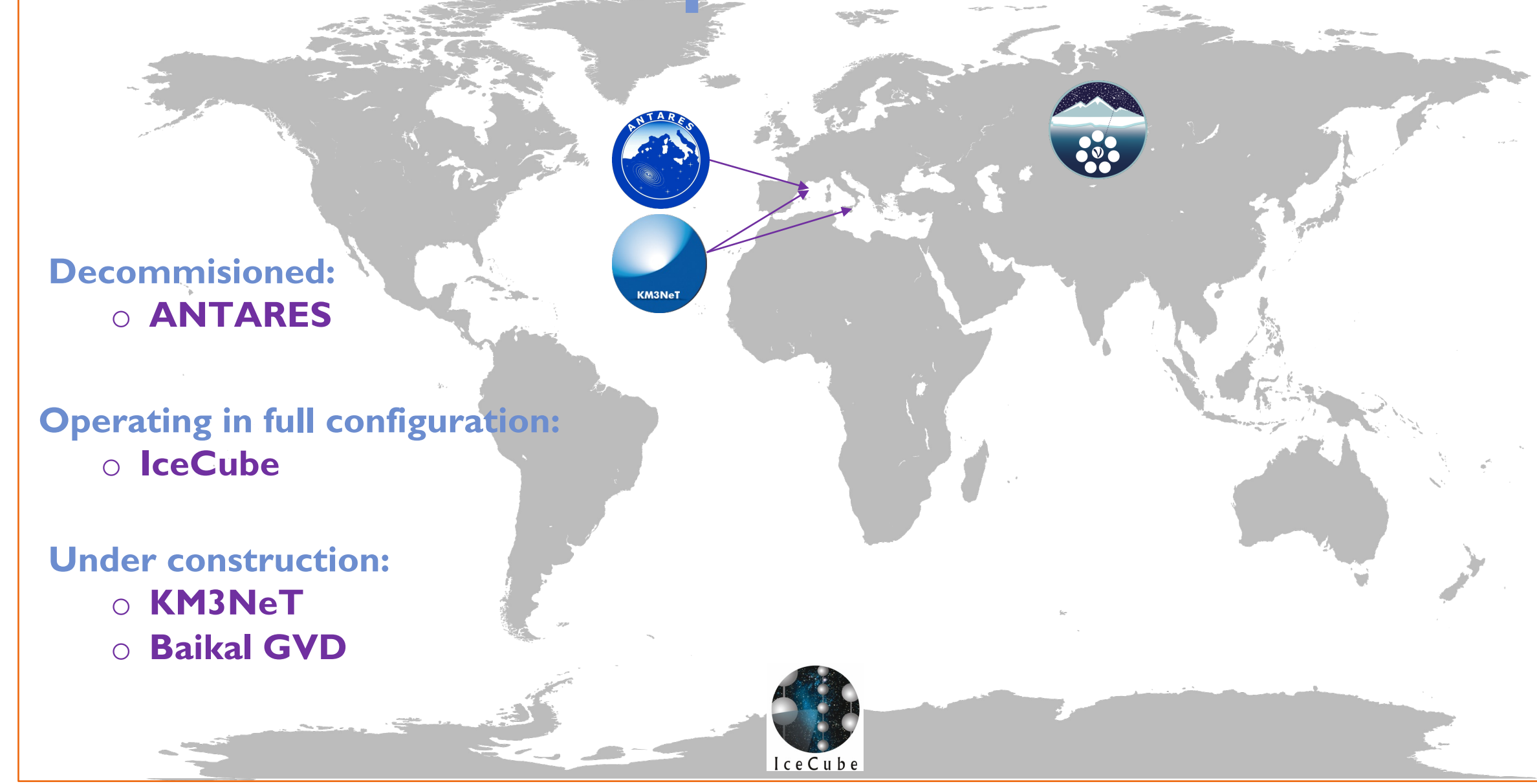




- Expensive, mainly due to boat rental
- Subject to weather conditions
- String recovery possible

- Expensive, mainly due to Antarctica being difficult to reach
- String recovery not possible

# HE nu telescopes of the last decade



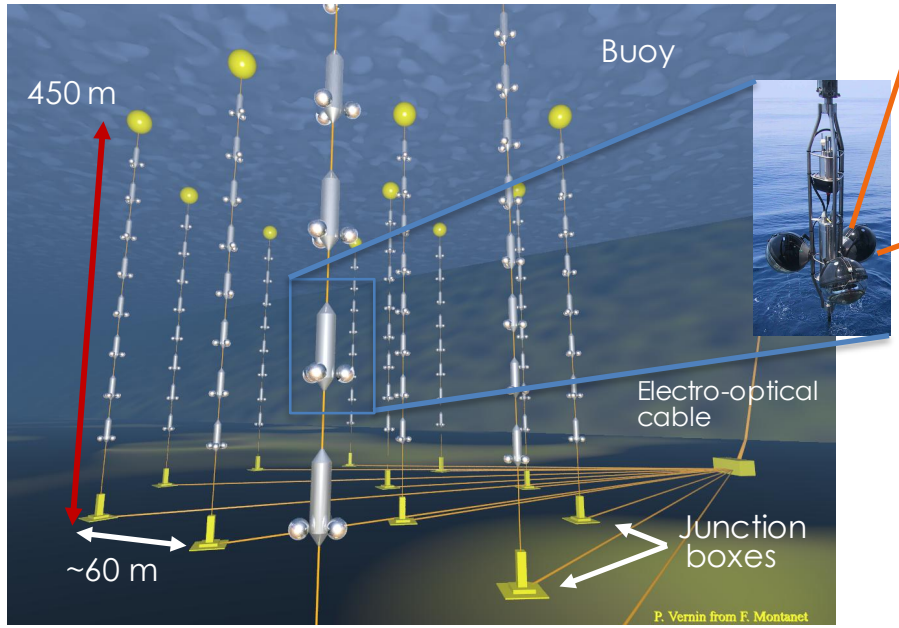

**Decommisioned:**
- **ANTARES**

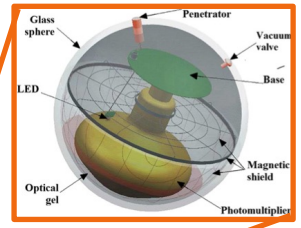
**Operating in full configuration:**
- **IceCube**

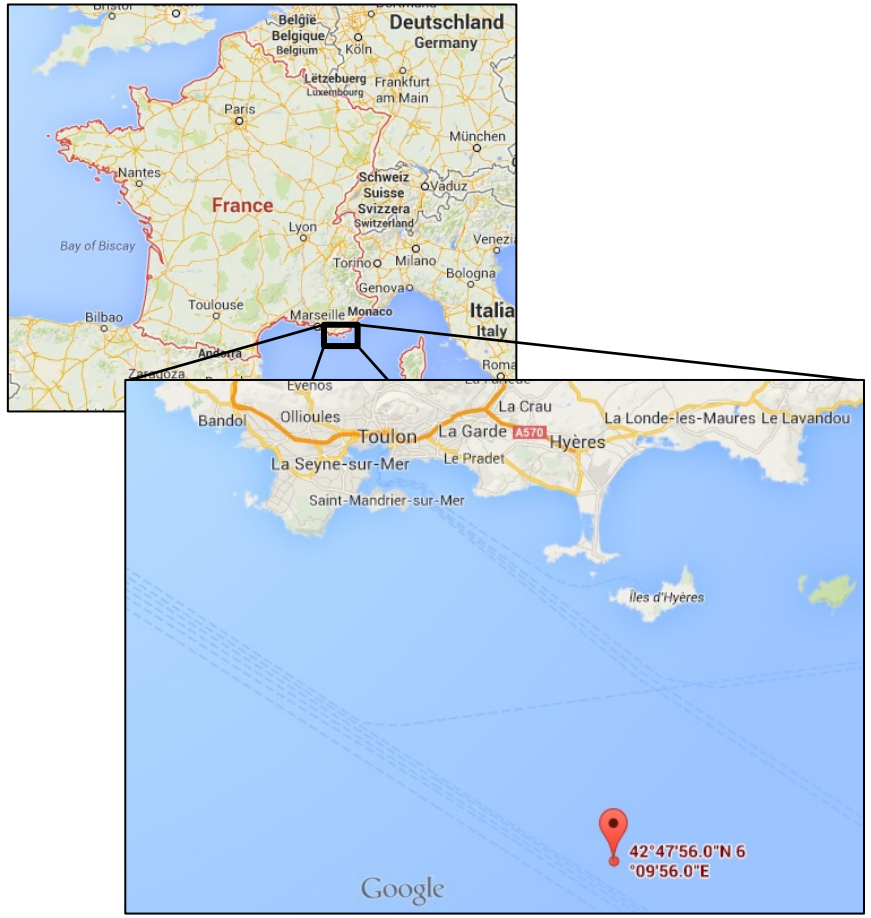
**Under construction:**
- **KM3NeT**
- **Baikal GVD**

# ANTARES

- Designed to detect **ν with E > few GeV**
- First detection line installed in early 2006
- **Completed in 2008, decommissioned in 2022**
- **2475 m depth** in the Mediterranean Sea
- 40 km offshore from Toulon

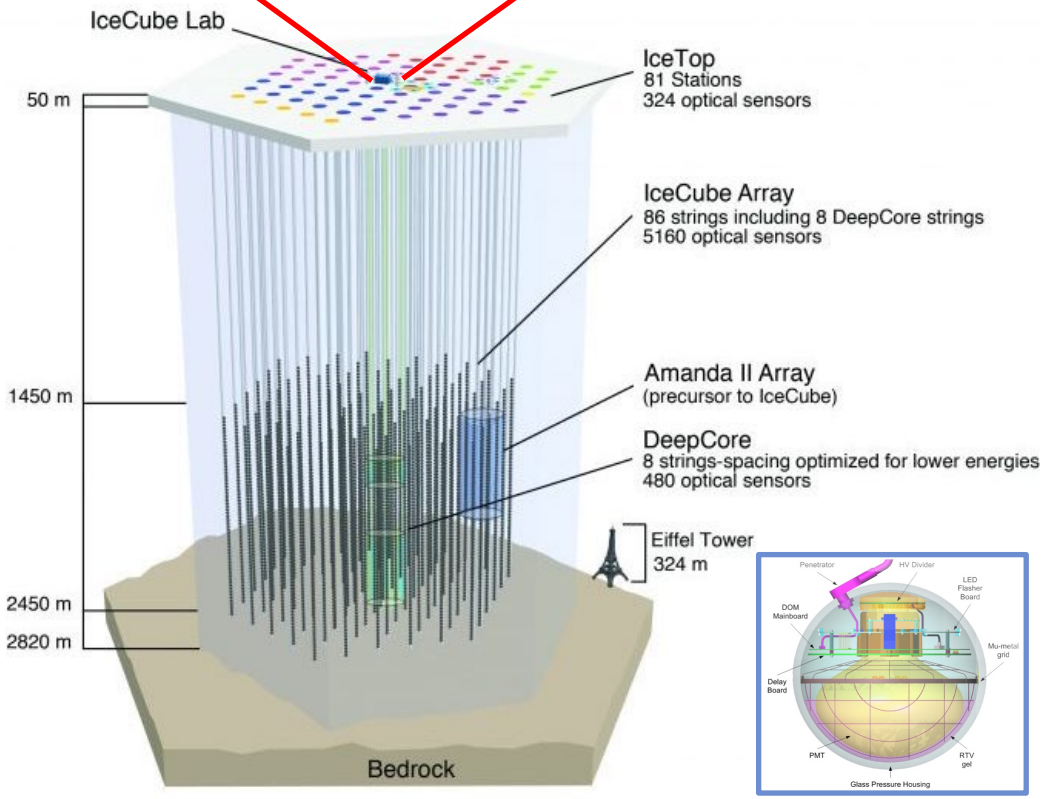


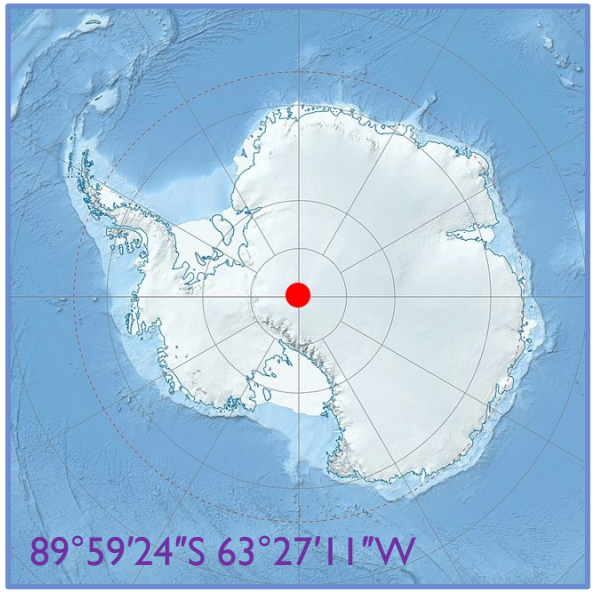

- Three-dimensional array of **885 PMTs**
- 12 vertical lines, 25 storeys
- 3 PMTs per storey
- PMT facing 45° downwards
- **Instrumented volume ~0.01 km³**

# IceCube



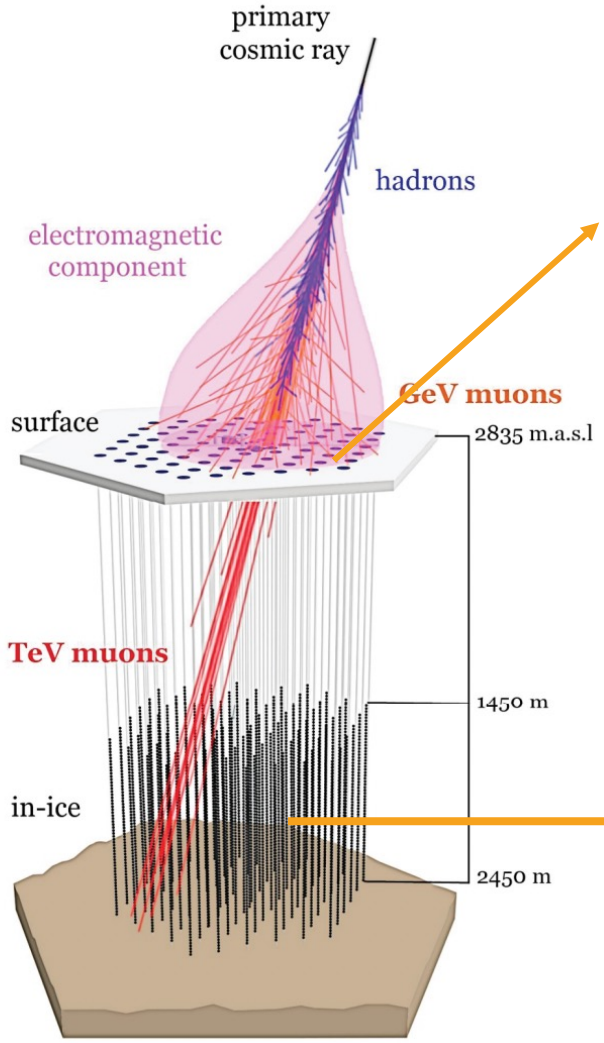







- Completed in 2010
- Taking data since 2005 with partial configuration
- Between 1450 and 2500 m deep
- **86, 1km high, vertical lines, 5160 PMTs**
- Horizontal separation between strings: 125 m
- Vertical separation between DOMs: 17 m
- **~1 km³ instrumented volume**
- **Largest neutrino telescope in the world**

# IceCube IceTop and DeepCore



**IceTop**

81 surface stations

Ice-filled tanks equipped with PMTs

Detect Cherenkov light produced by secondary particles from cosmic-ray air showers

Purpose:

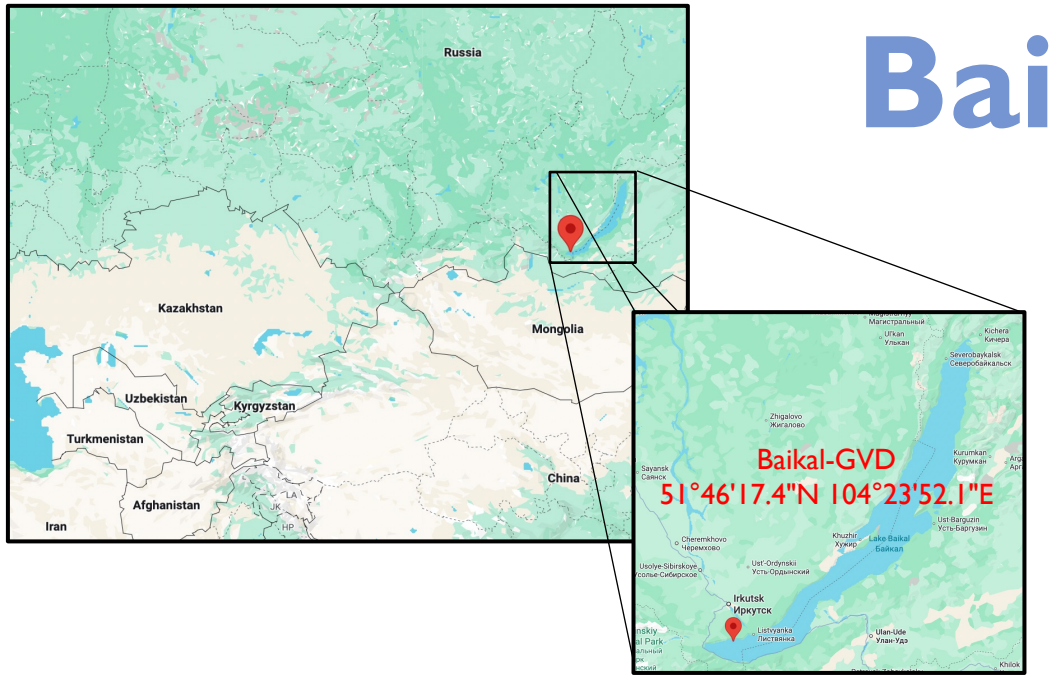
- **calibrate** IceCube by measuring **muons** that pass through both IceTop and the deep array
- provides data on the **energy spectrum** and **composition** of cosmic rays
- can help **veto atmospheric muons**, improving neutrino detection in the main IceCube array

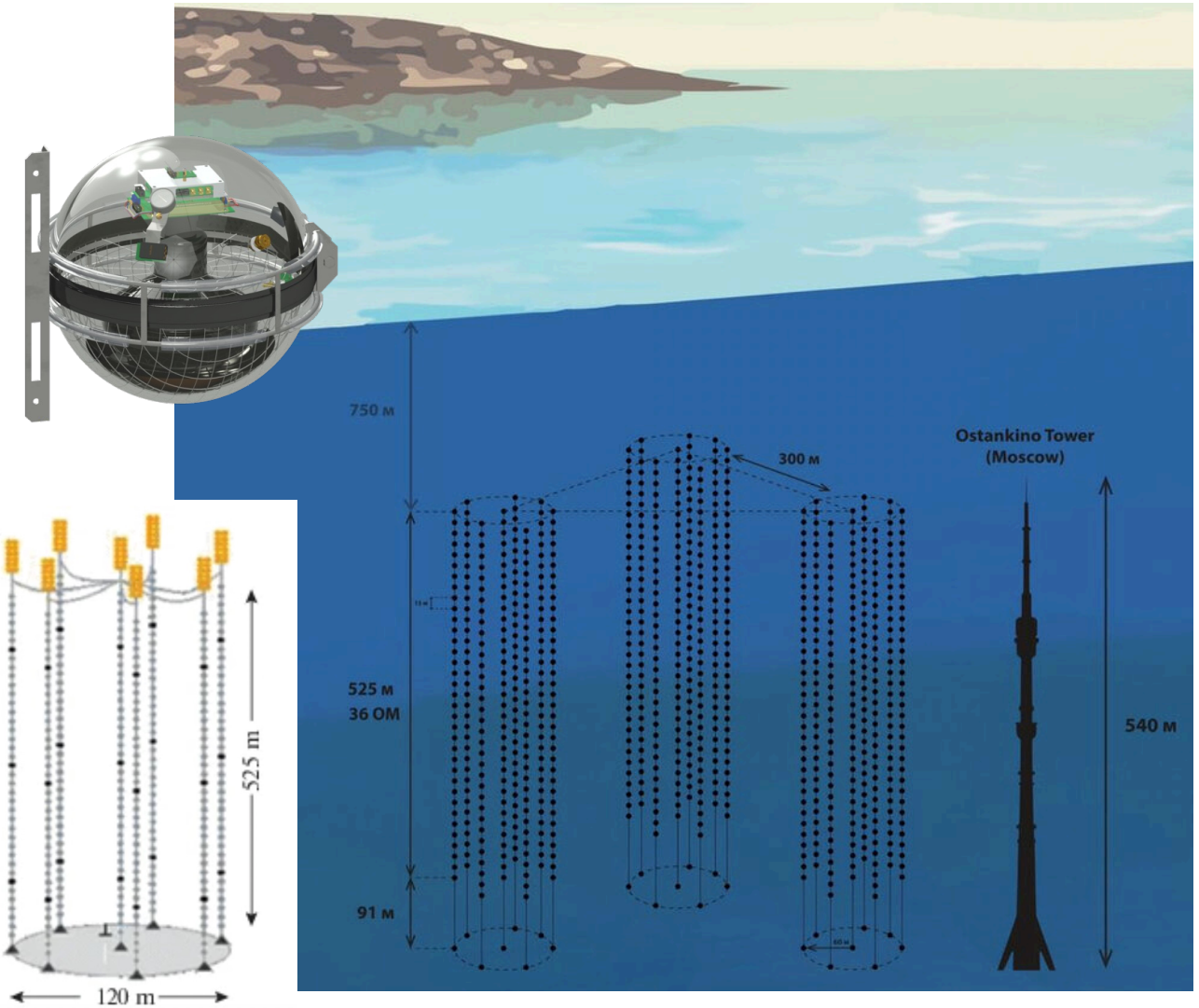
**DeepCore**

Denser array with 8 extra strings

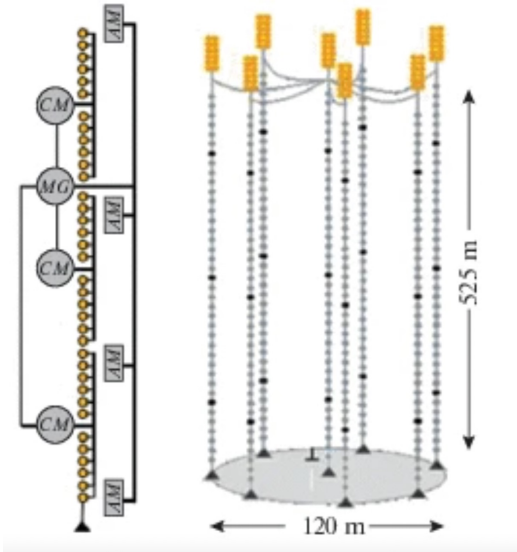
Optimized for lower energy studies (dark matter, oscillation…)

# Baikal-GVD




- Located 4 km offshore
- 1366 m depth in the Baikal lake
- Deployment started in 2017
- **Currently running with 14 clusters**
- Current instrumented volume: **0.7 km³**
- **> 1 km³ expected** when completed
- Horizontal separation between strings: 60 m
- Vertical separation between DOMs: 15 m



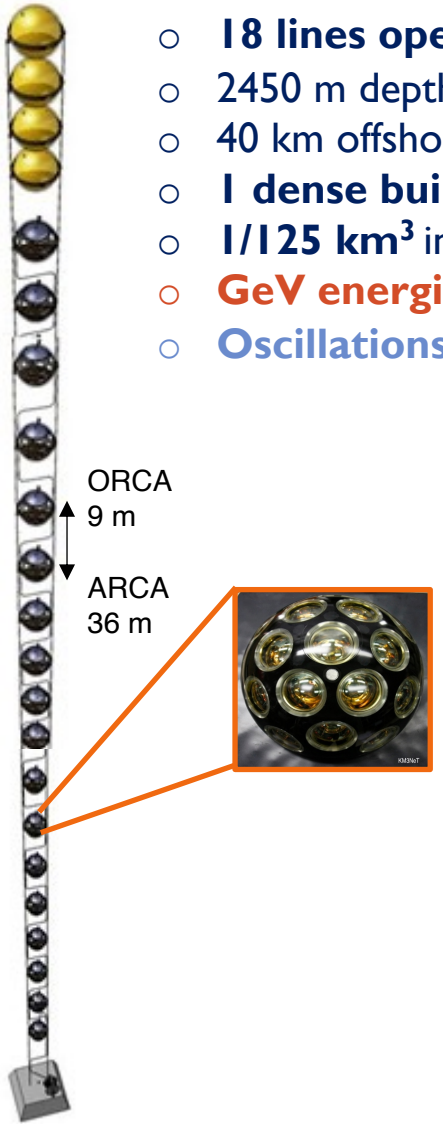

**Each cluster: 8 string x 36 OMs**

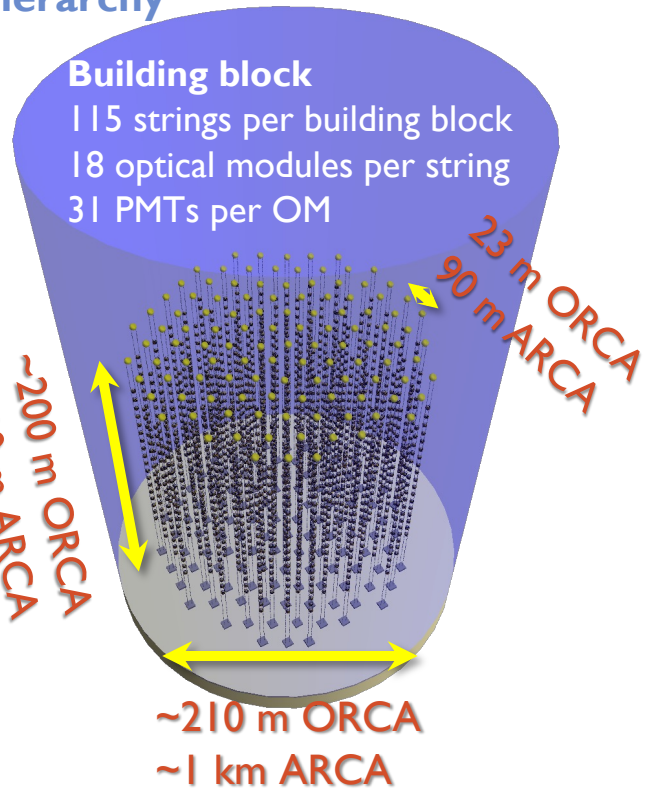
# KM3NeT

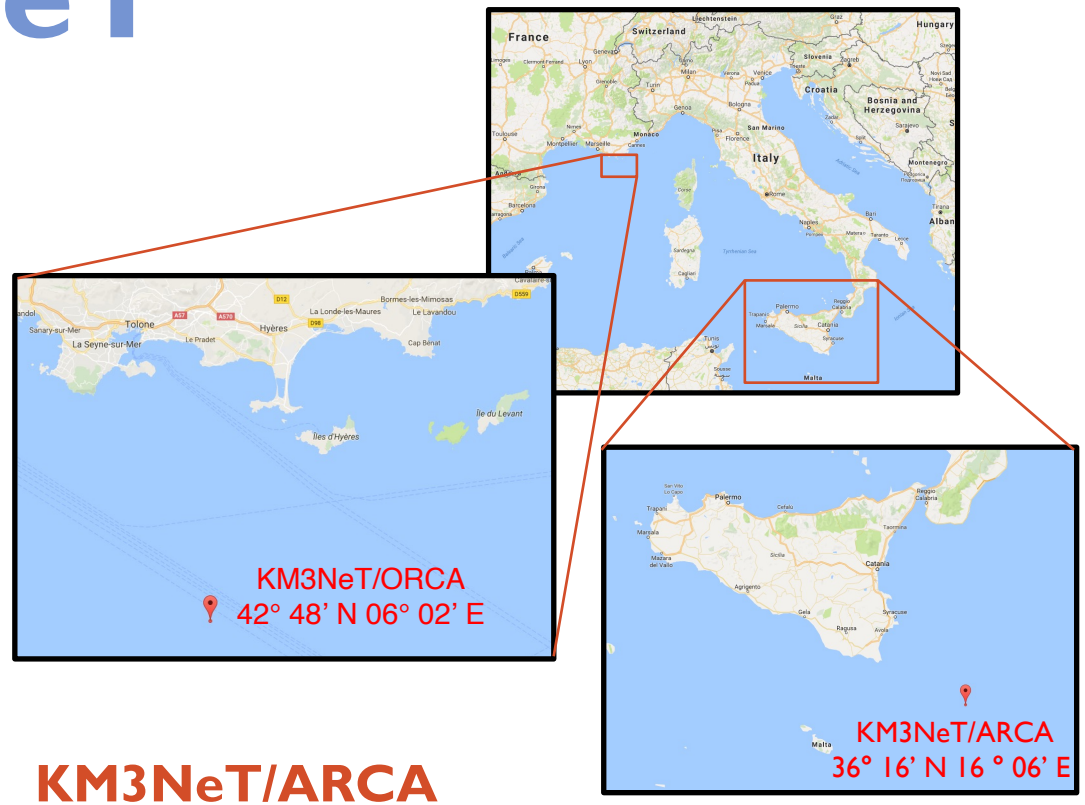
Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

## KM3NeT/ORCA

- **18 lines operating**, 115 lines foreseen
- 2450 m depth in the Mediterranean Sea
- 40 km offshore from Toulon
- **1 dense building block**
- **1/125 km$^3$** instrumented volume
- **GeV energies**
- **Oscillations, mass hierarchy**

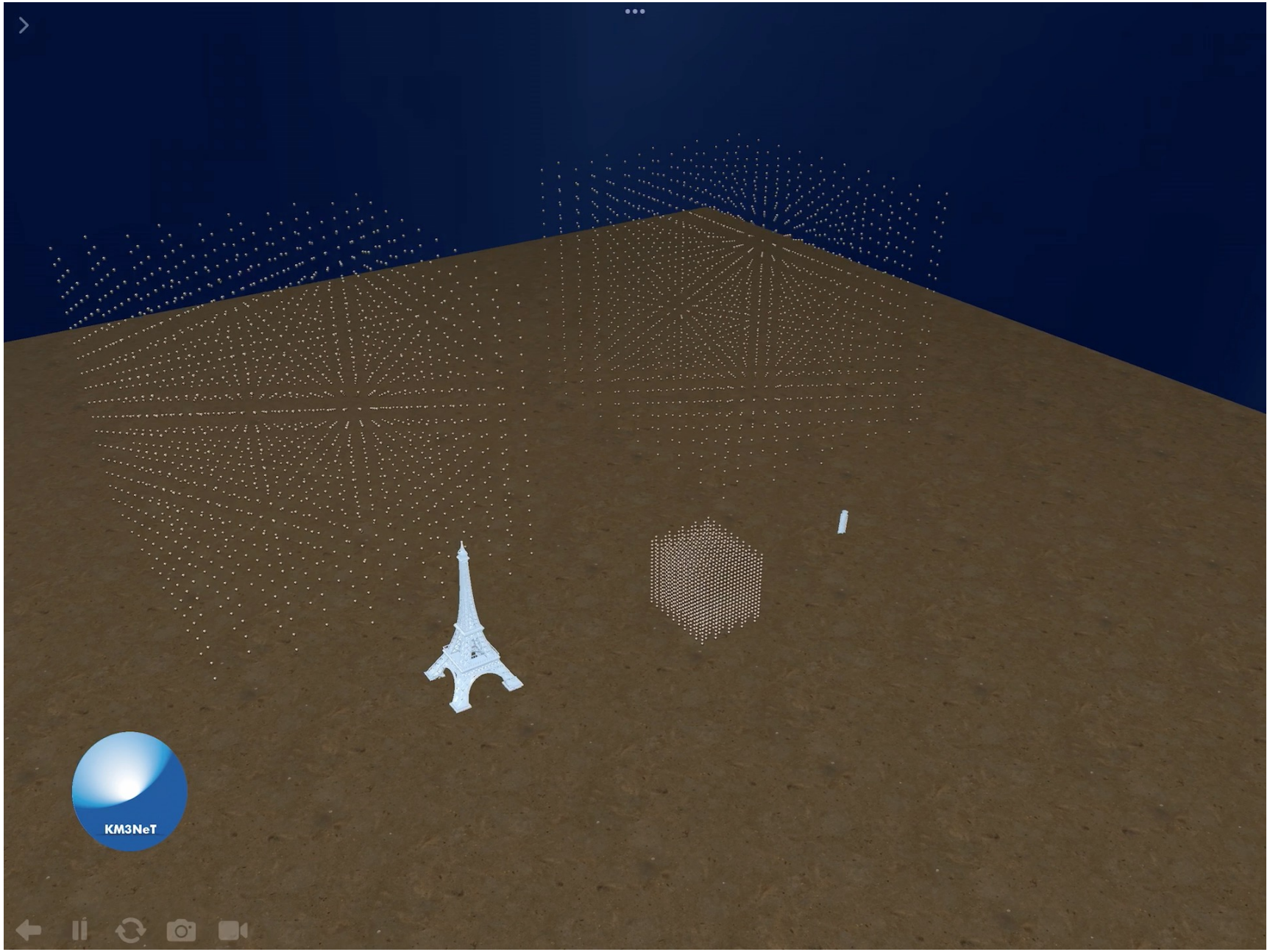



## KM3NeT/ARCA

- **28 lines operating**, 230 lines foreseen
- 3500 m depth in the Mediterranean Sea
- 100 km offshore from Sicily
- **2 sparse building blocks**
- **1 km$^3$** instrumented volume
- **1-10 TeV energy threshold**
- **High-energy neutrino astronomy**

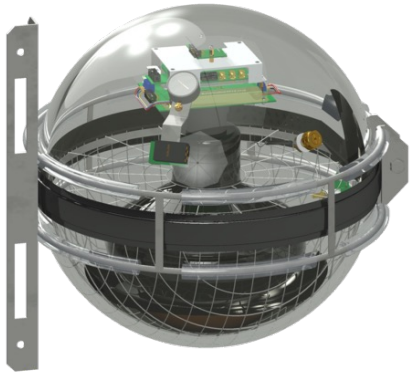

KM3NeT

# Detectors' eyes

**ANTARES**

**IceCube**

**Baikal-GVD**



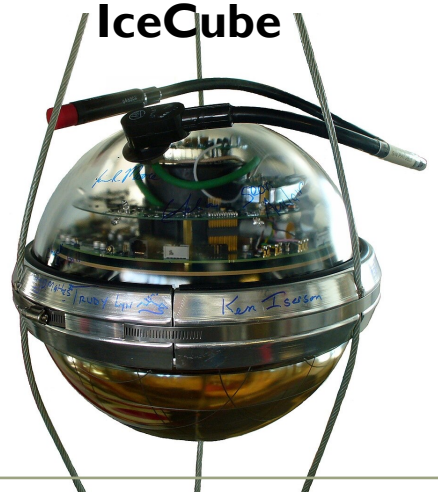
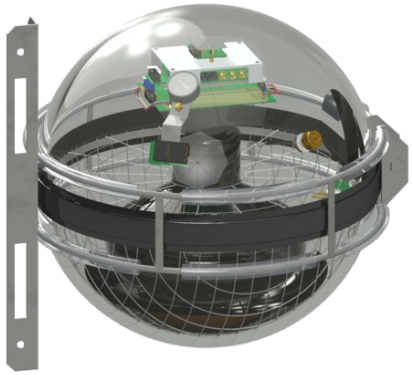
**KM3NeT**

**DOMs:** pressure-resistant glass sphere containing:

- PMT
- Electronics & Readout Systems
- Calibration Devices

**Do you spot any difference?**

# Detectors' eyes

| | ANTARES | IceCube | Baikal-GVD | KM3NeT |
|---|---|---|---|---|
| | |  |  | |
| **DOM Shape** | 17" sphere | 13" sphere | 17" sphere | 17" sphere |
| **PMTs per DOM** | 1 | 1 | 1 | 31 |
| **PMT Size** | 10" | 10" | 10" | 3" |
| **Angular coverage** | $\sim 2\pi$ sr | $\sim 2\pi$ sr | $\sim 2\pi$ sr | $\sim 4\pi$ sr |

Which do you think are the advantages of KM3NeT **multi-PMT** DOM design?

# Detectors' eyes

**KM3NeT**

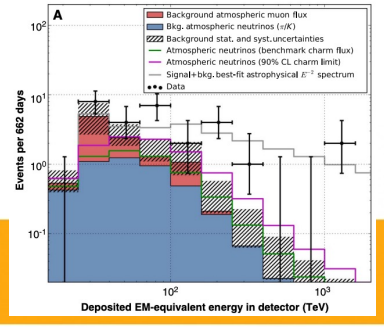
- **Larger effective photocathode area**: 3 times the equivalent photo-cathode area of a single 10-inch PMT in a 17-inch sphere
- **Directional information**: allows for reconstructing the direction of incoming photons, improving reconstruction performance and event topology analysis (distinguishing tracks vs showers)
- **Background suppression via coincidences**: identifying photon hits across multiple PMTs helps efficiently reject optical background (bioluminescence and radioactive decay)

→ **All projects for future neutrino telescope foresee this design**

# Neutrino astronomy: a young field

**2013**

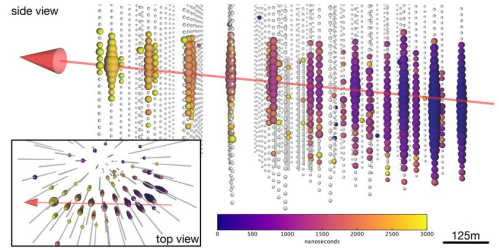
**4σ evidence for high-energy cosmic neutrinos by IceCube**




Later confirmed at >5σ with more statistics, different IceCube samples, and by Baikal-GVD (3σ)

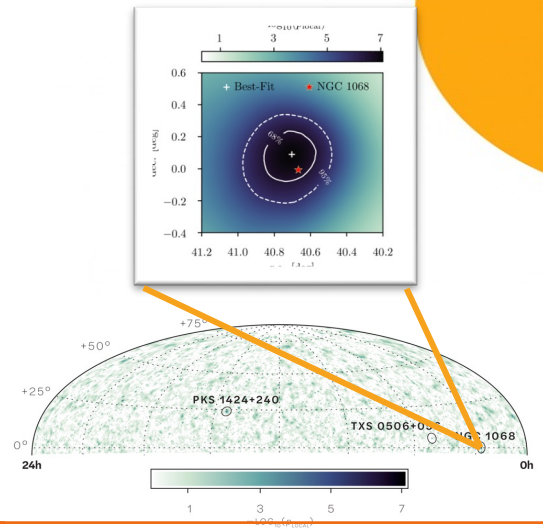
**2018**

**3σ association between IceCube alert and flaring blazar TXS 0506+056**



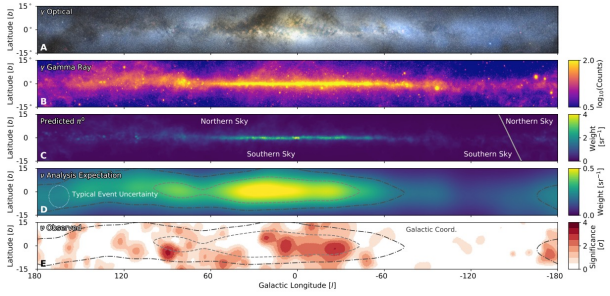

**2022**

**>4σ evidence for neutrino emission from active Galaxy NGC 1068 seen by IceCube**



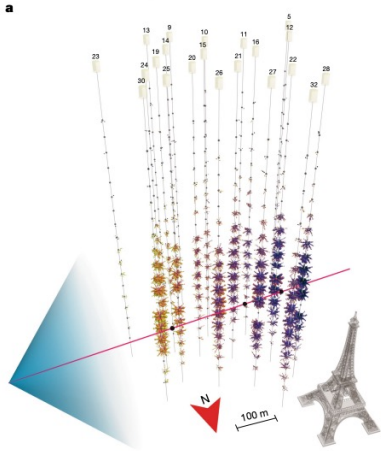

**2023**

**4.5σ observation of neutrinos from the Galactic plane by IceCube**



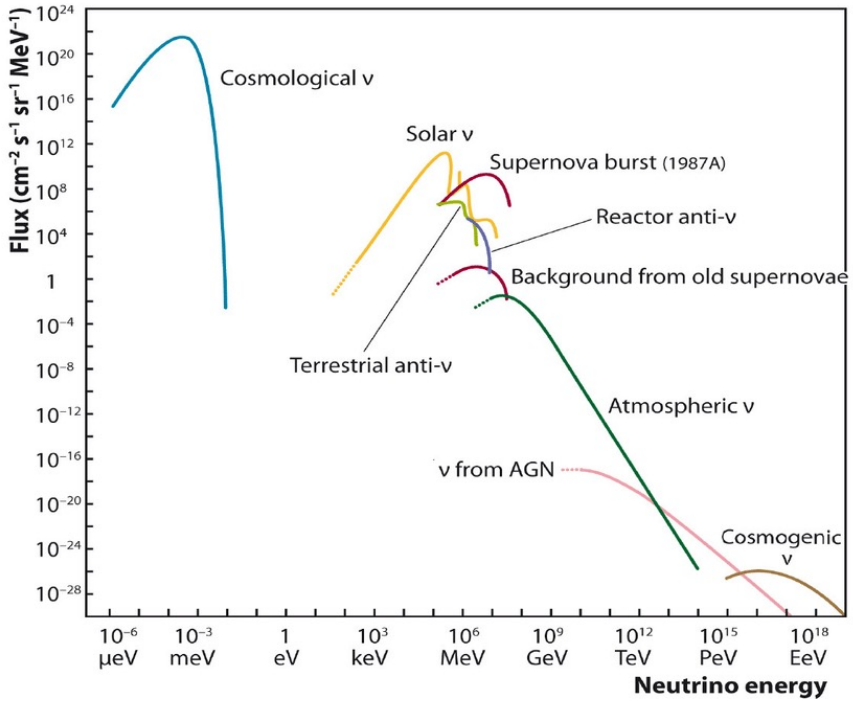

**2025**

**Observation of a 220 PeV neutrino by KM3NeT**



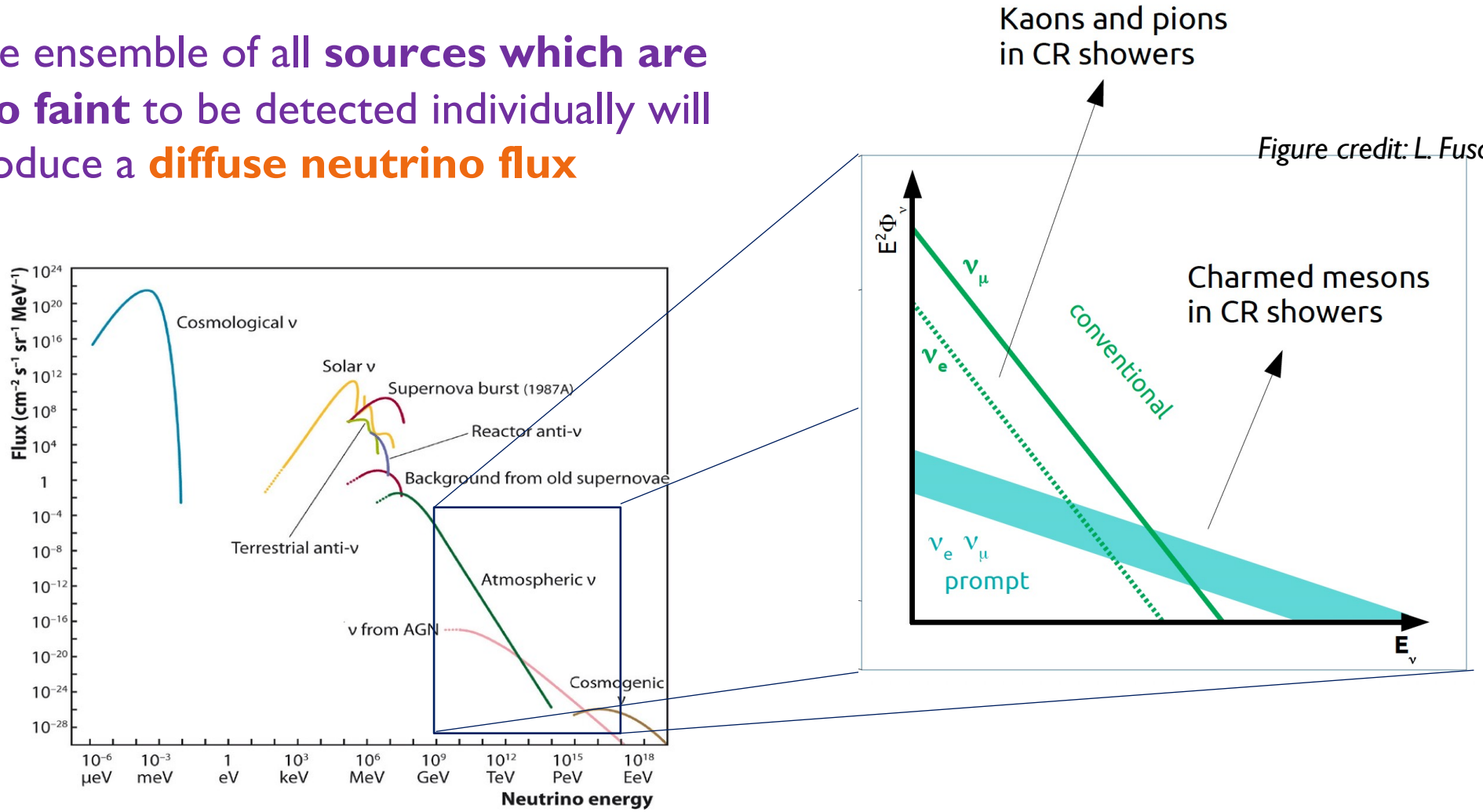
# Diffuse astrophysical neutrino flux

The ensemble of all **sources which are too faint** to be detected individually will produce a **diffuse neutrino flux**



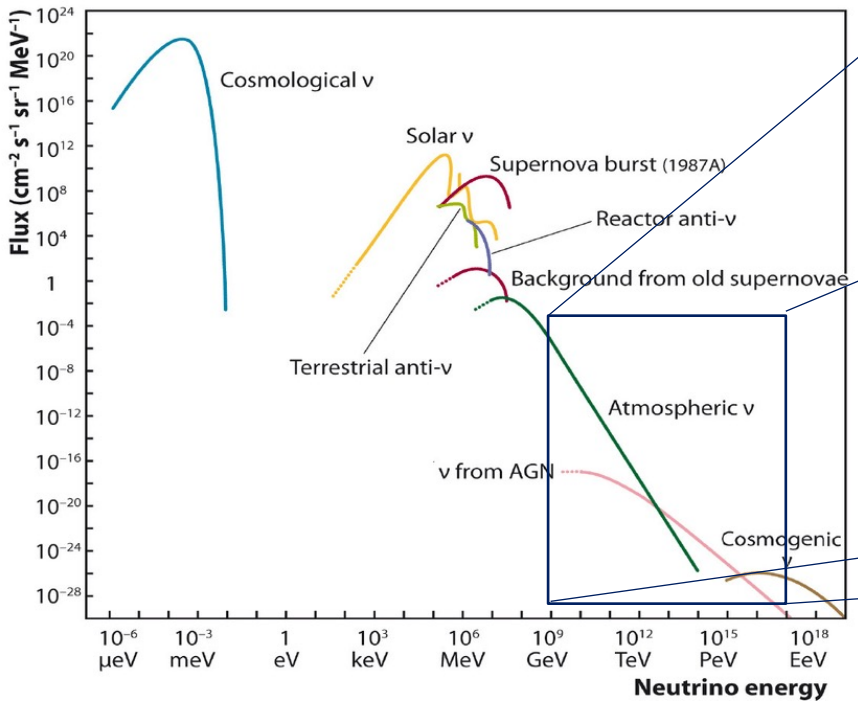
# Diffuse astrophysical neutrino flux

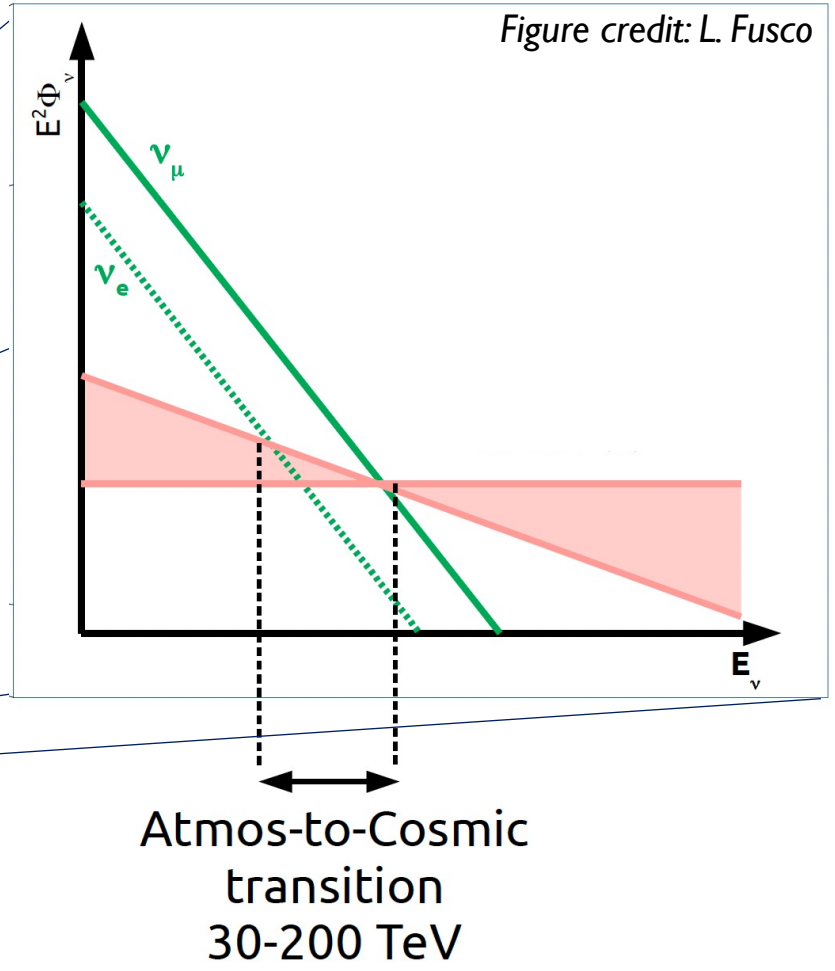
The ensemble of all **sources which are too faint** to be detected individually will produce a **diffuse neutrino flux**



# Diffuse astrophysical neutrino flux

The ensemble of all **sources which are too faint** to be detected individually will produce a **diffuse neutrino flux**

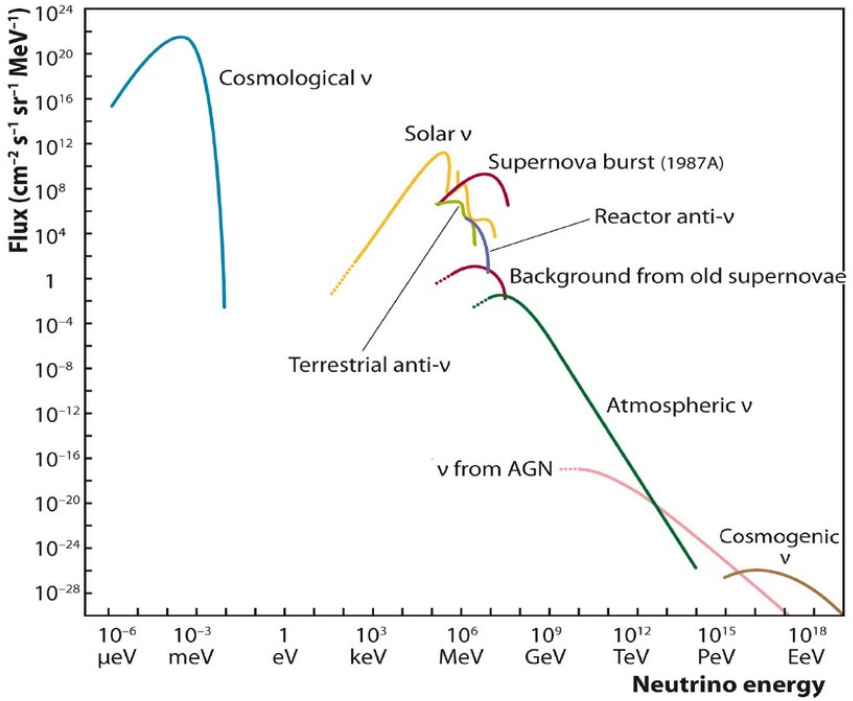


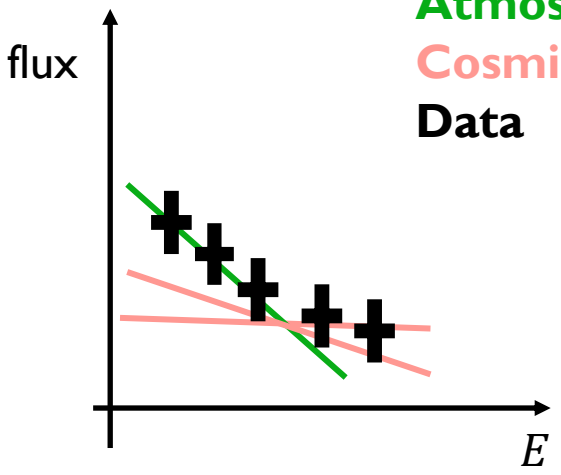



# Diffuse astrophysical neutrino flux

The ensemble of all **sources which are too faint** to be detected individually will produce a **diffuse neutrino flux**

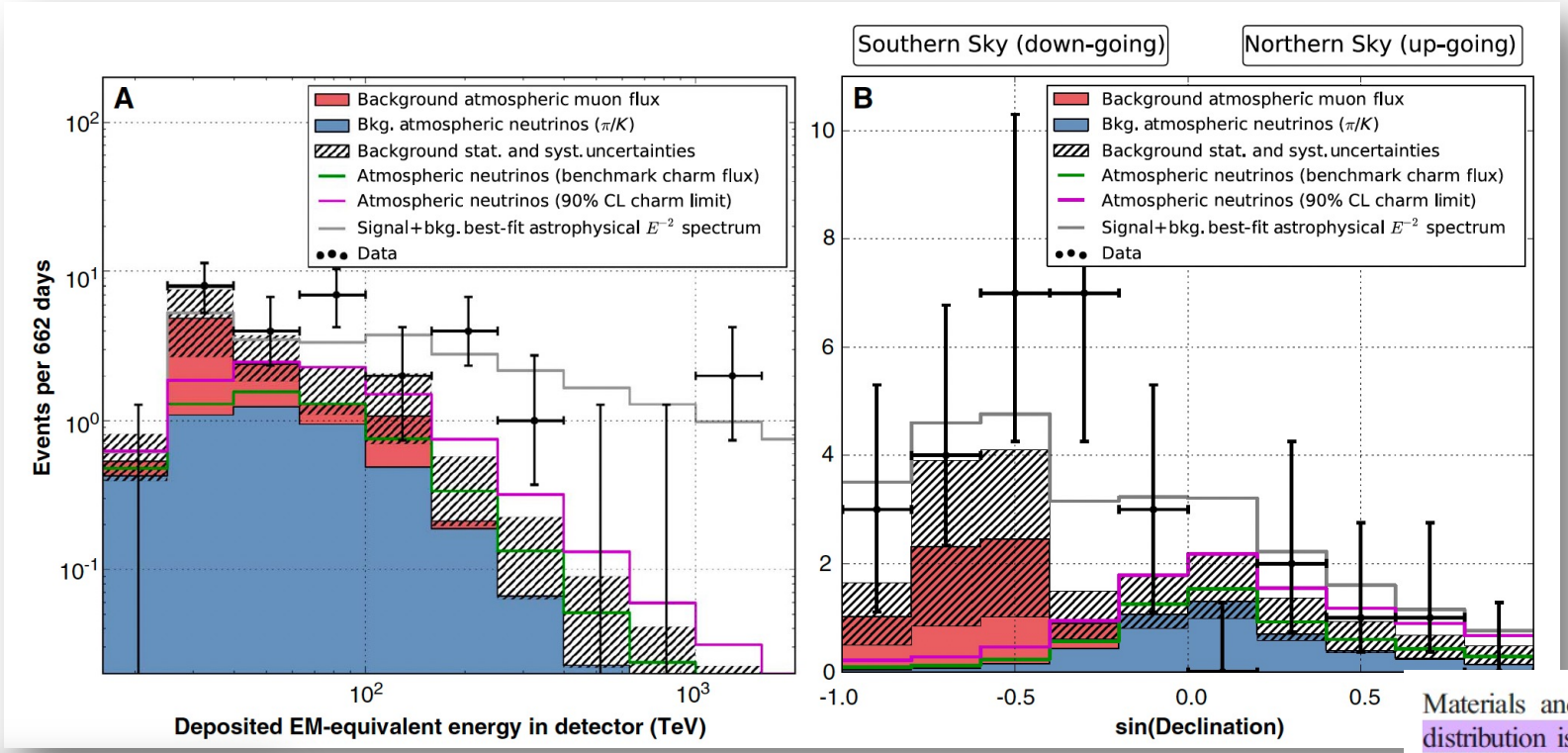
**How to detect it: look for an excess of high-energy data**




**Atmospheric background**
**Cosmic neutrinos**
**Data**

# Evidence for HE extraterrestrial neutrinos




were the previously reported PeV events (*3*). Seven events contained clearly identifiable muon tracks, whereas the remaining 21 were showerlik

By comparison, a neutrino flux produced in extraterrestrial sources would, like our data, be heavily biased toward showers because neutrino oscillations over astronomical baselines tend to equalize neutrino flavors (*12*, *13*). An equal-flavor $E^{-2}$ neutrino flux, for example, would be expected to produce only one-fifth of track events (see

Materials and Methods). The observed zenith distribution is also typical of such a flux: As a result of absorption in Earth above tens of TeV energy, most events (about 60%, depending on the energy spectrum) from even an isotropic high-energy extraterrestrial population would be expected to appear in the Southern Hemisphere. Although the zenith distribution is well explained (Fig. 4) by an isotropic flux, a slight southern excess remains, which could be explained either as a statistical fluctuation or by a source population that is either relatively small or unevenly distributed through the sky.

# Evidence for HE extraterrestrial neutrinos

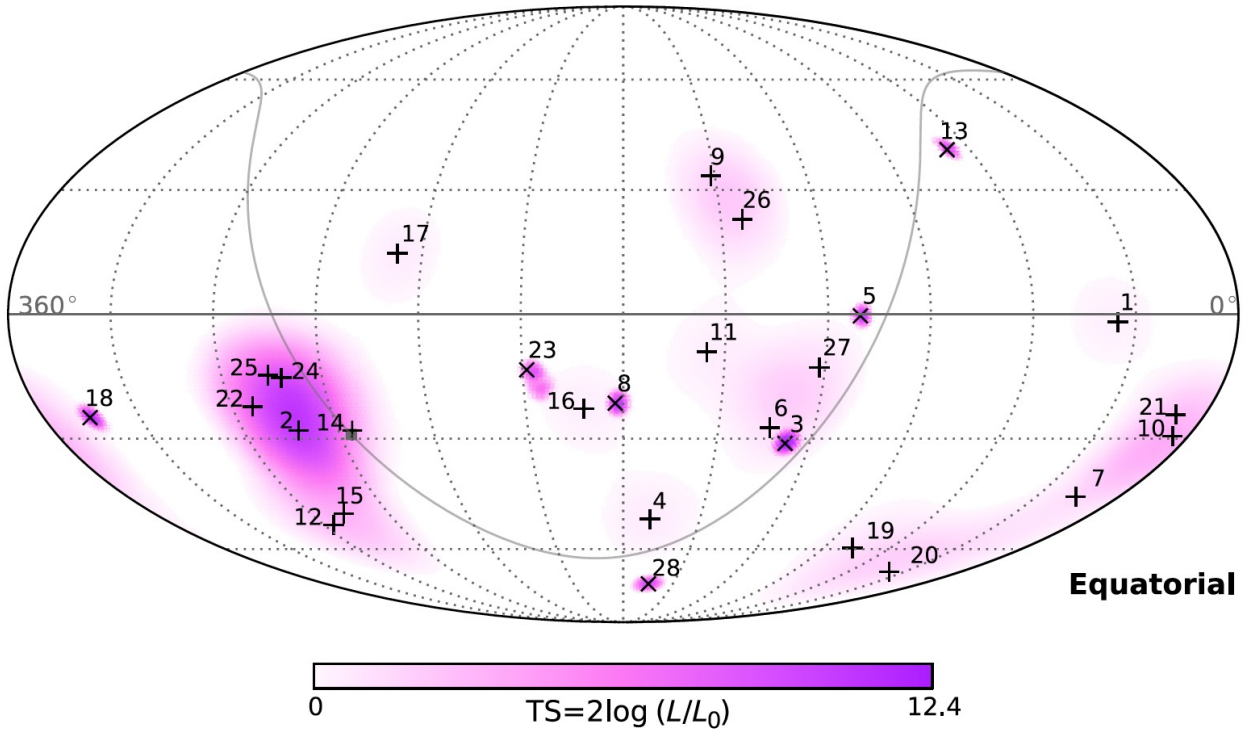



**Fig. 5. Sky map in equatorial coordinates of the TS value from the maximum likelihood point source analysis.** The most significant cluster consists of five events—all showers and including the second highest energy event in the sample—with a final significance of 8%. This is not sufficient to identify any neutrino sources from the clustering study. The galactic plane is shown as a curved gray line with the galactic center at the bottom left denoted by a filled gray square. Best-fit locations of individual events (listed in Table 1) are indicated with vertical crosses (+) for showers and angled crosses (×) for muon tracks.

***Search for Neutrino Sources***

To search for spatial clustering, indicating possible neutrino sources, we conducted a maximum likelihood point source analysis (*14*). At each point

When using all events, the likelihood map reveals no significant clustering compared to randomized maps. For the shower events, the coordinates with the highest TS are at right ascension = 281°, declination = −23° (galactic longitude $l$ = +12°, latitude $b$ = −9°). Five events, including the second highest energy event in the sample, contribute to the main part of the excess with two others nearby. The fraction of randomized data sets that yield a similar or higher TS at this exact spot is 0.2%. (At the exact location of the galactic center, the fraction is 5.4%.) The final significance, estimated as the fraction of randomized maps with a similar or higher TS anywhere in the sky, is 8%. This degree of clustering may be compatible with a source or sources in the galactic center region, but the poor angular resolution for showers and the wide distribution of the events do not allow the identification of any sources at this time.

# Diffuse flux with IC muon track sample

THE ASTROPHYSICAL JOURNAL

OPEN ACCESS

Improved Characterization of the Astrophysical Muon–neutrino Flux with 9.5 Years of IceCube Data

R. Abbasi, M. Ackermann, J. Adams, J. A. Aguilar, M. Ahlers, M. Ahrens, J. M. Alameddine, C. Alispach, A. A. Alves Jr., N. M. Amin ▾ Show full author list

Published 2022 March 25 • © 2022. The Author(s). Published by the American Astronomical Socie

The Astrophysical Journal, Volume 928, Number 1

**Citation** R. Abbasi *et al* 2022 *ApJ* **928** 50

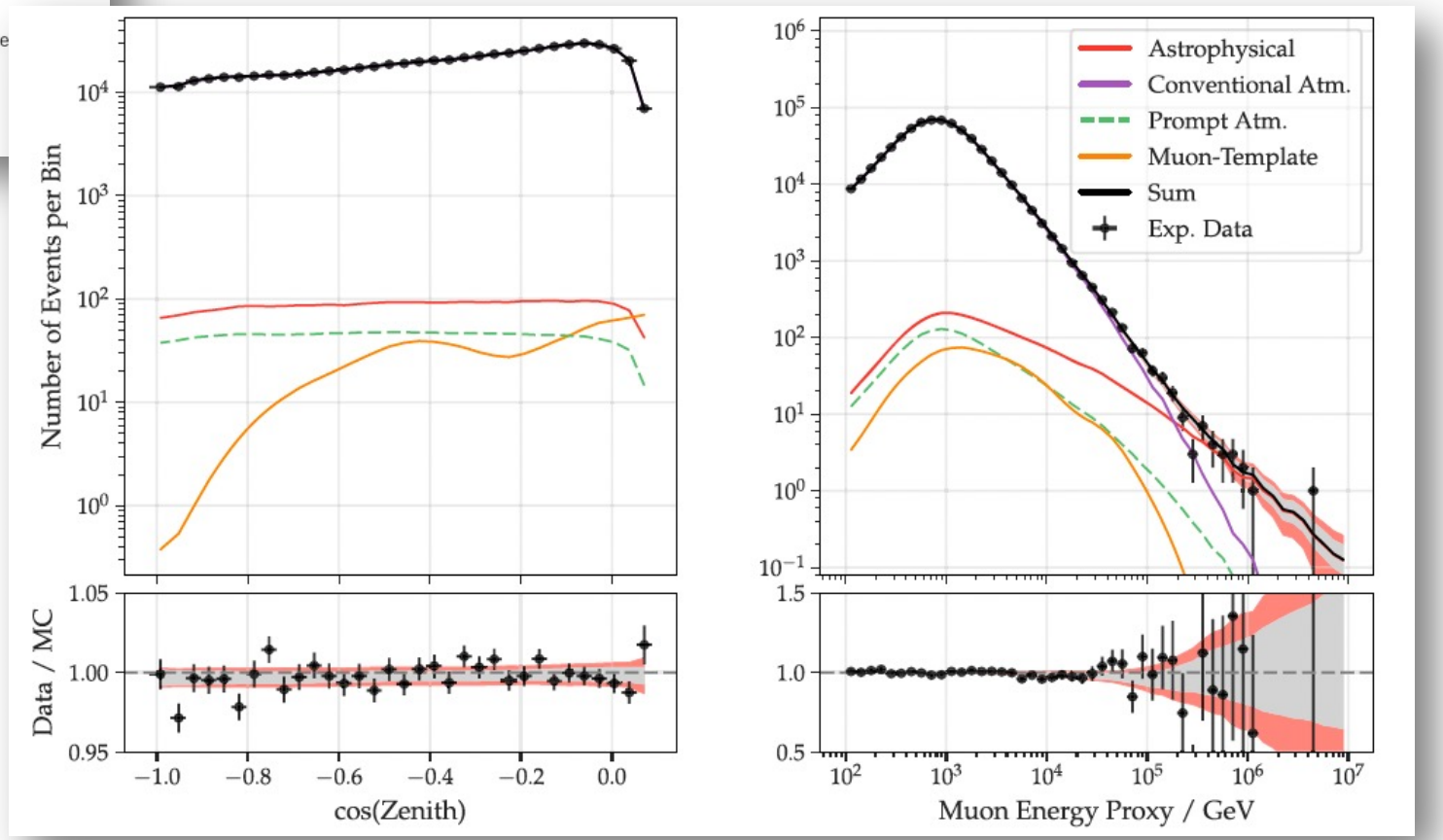
**DOI** 10.3847/1538-4357/ac4d29

Purely atmospheric hypothesis excluded at **5.6σ**

$$\Phi(E) = \Phi_0 E^{-\Gamma}$$

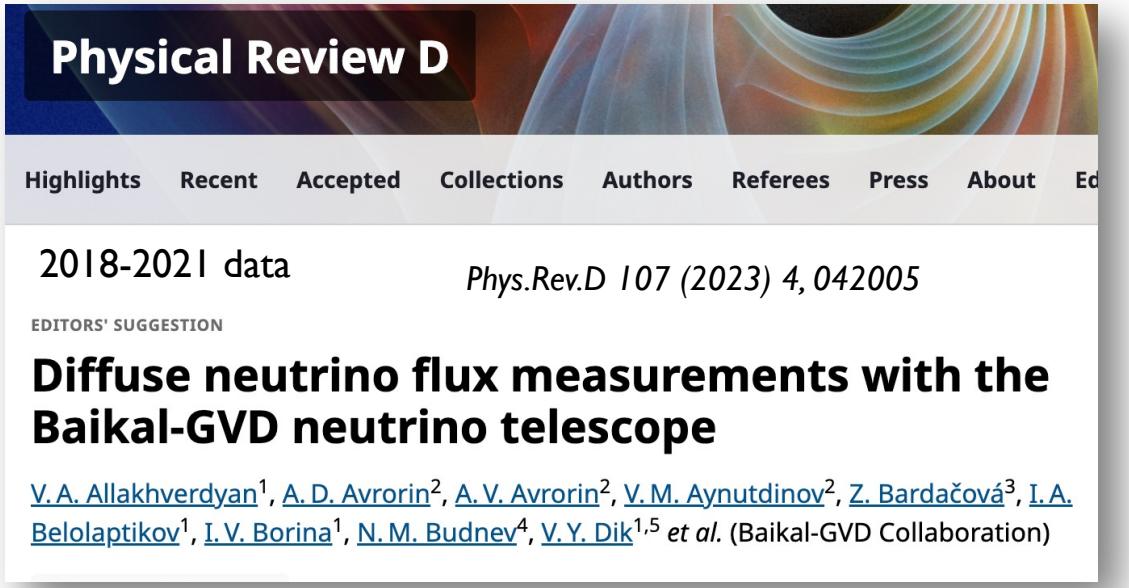
$$\Phi_0^{1f}(100\ \mathrm{TeV}) = 1.44^{+0.25}_{-0.26} \times 10^{-18} \left(\mathrm{GeV\ cm^{-2} sr^{-1}}\right)^{-1}$$

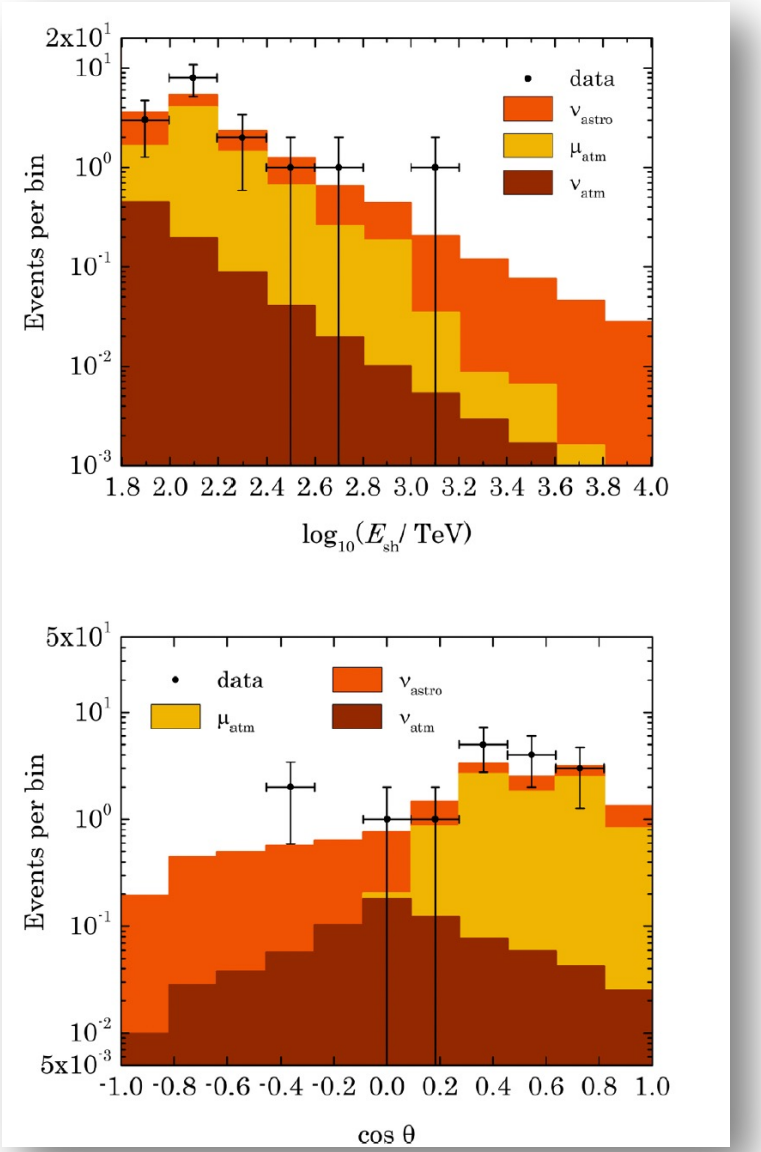
$$\boldsymbol{\gamma = 2.37^{+0.09}_{-0.09}}$$




**Track-like** events from the **Northern Sky** with energy above **100 TeV**

# Diffuse flux with Baikal-GVD



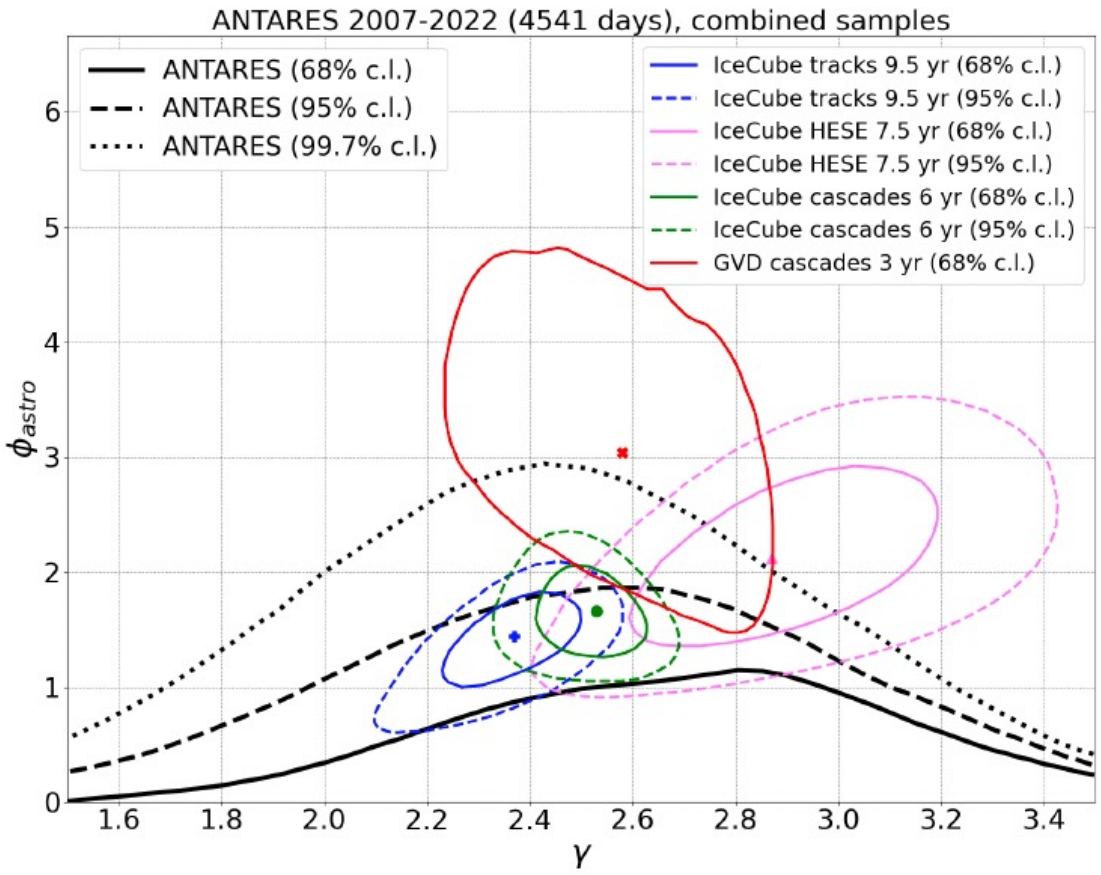

**Shower-like** events from all-sky directions and with energy above **70 TeV**

Purely atmospheric hypothesis excluded at **3.05σ**

$$\Phi(E) = \Phi_0 E^{-\Gamma}$$

$$\Phi_0^{1f}(100\ \text{TeV}) = 3.04^{+1.52}_{-1.21} \times 10^{-18} \left(\text{GeV cm}^{-2}\text{sr}^{-1}\right)^{-1}$$
$$\boldsymbol{\gamma = 2.58^{+0.27}_{-0.33}}$$

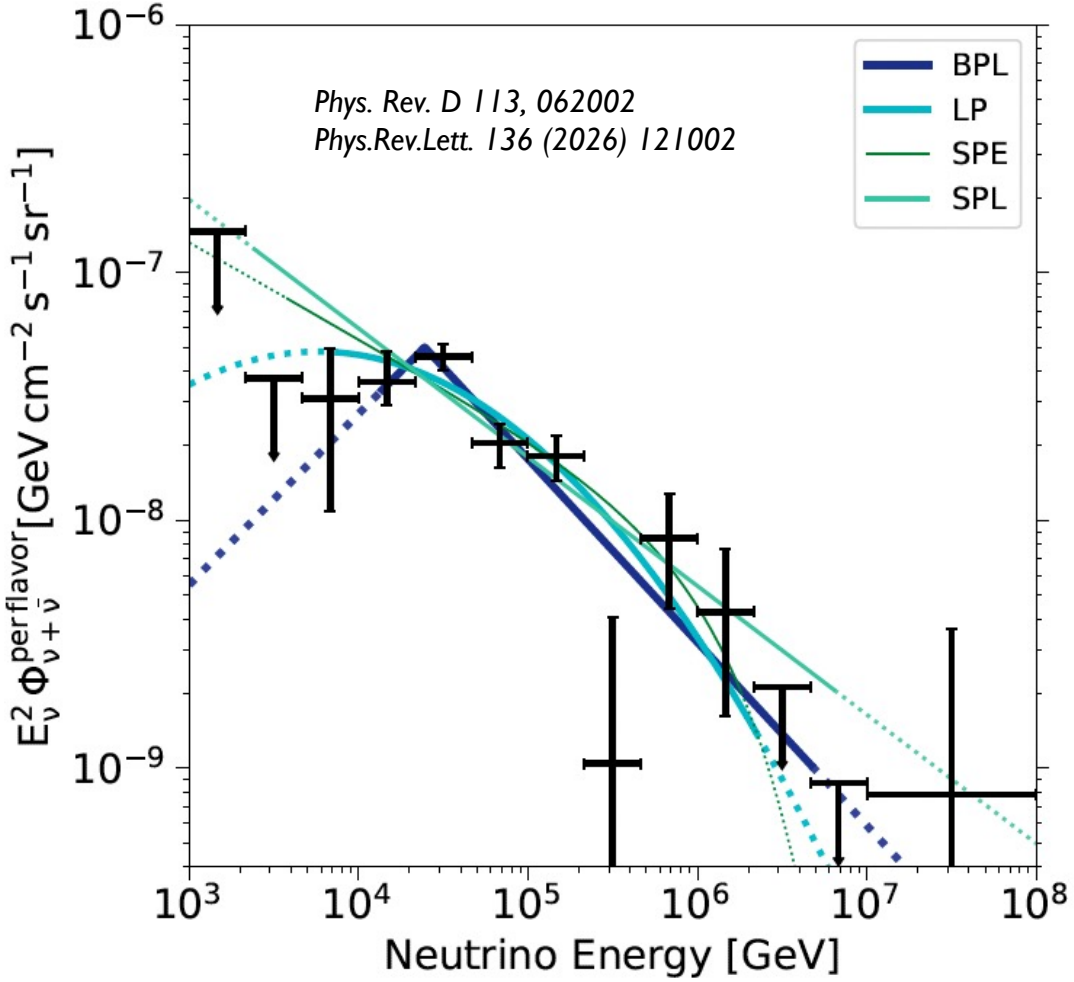
# Global picture




**Tension** between different measurements could be **due to** differences in

- **flavor composition,**
- **sky coverage,**
- **energy range**

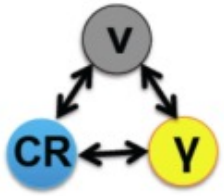
# IceCube combined track+cascade fit




**Single power-law** between 5 TeV and 10 PeV **disfavoured at > 4σ**

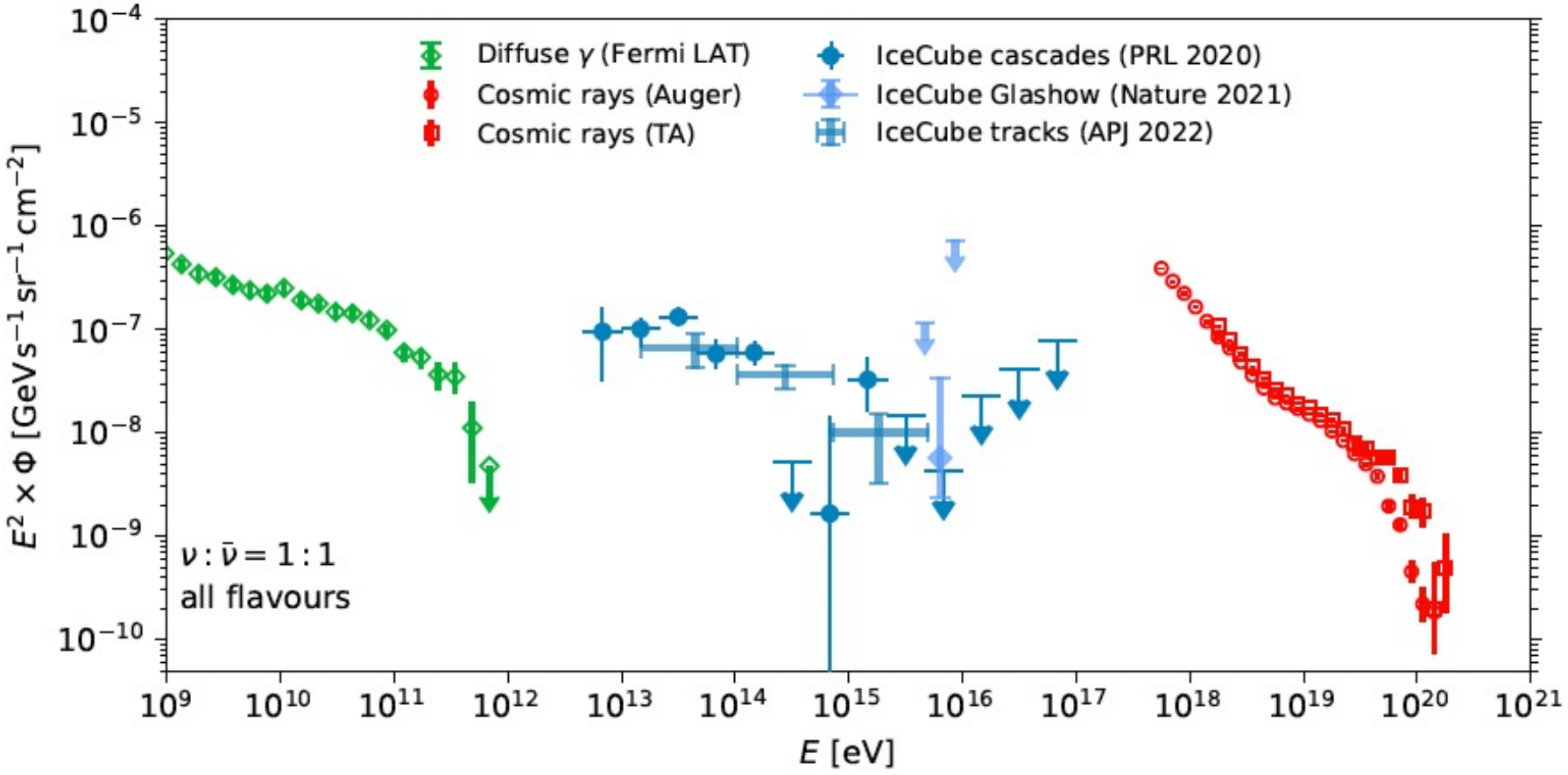
Favoured scenario:
$\gamma \lesssim 2$ below ~30 TeV
$\gamma \sim 2.8$ above ~30 TeV

# Diffuse astrophysical neutrino flux




**Diffuse neutrino flux in a multi-messenger context**

➡ *JHEAp* 36 (2022) 55-110




**Same energy density** for sub-TeV diffuse γ, HE neutrinos and UHE CRs → **strong multi-messenger connection**

# Neutrinos from the Galactic Plane

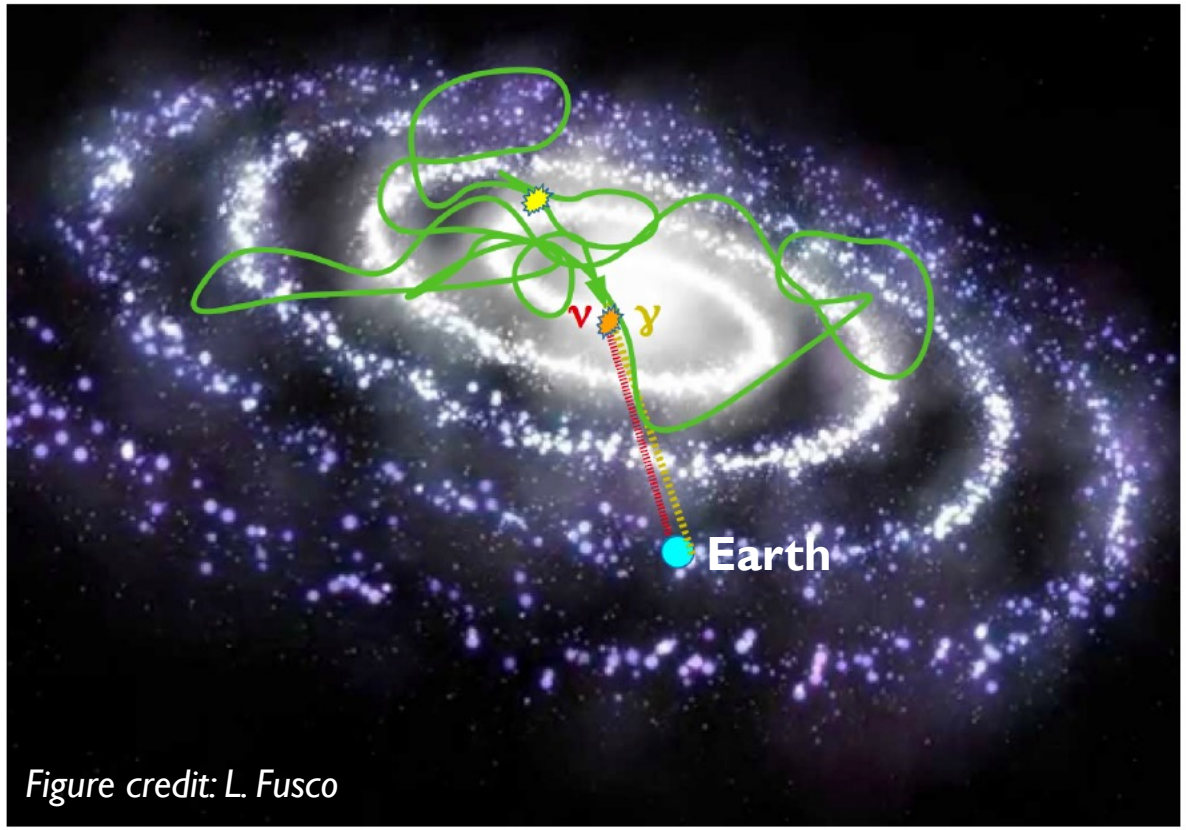
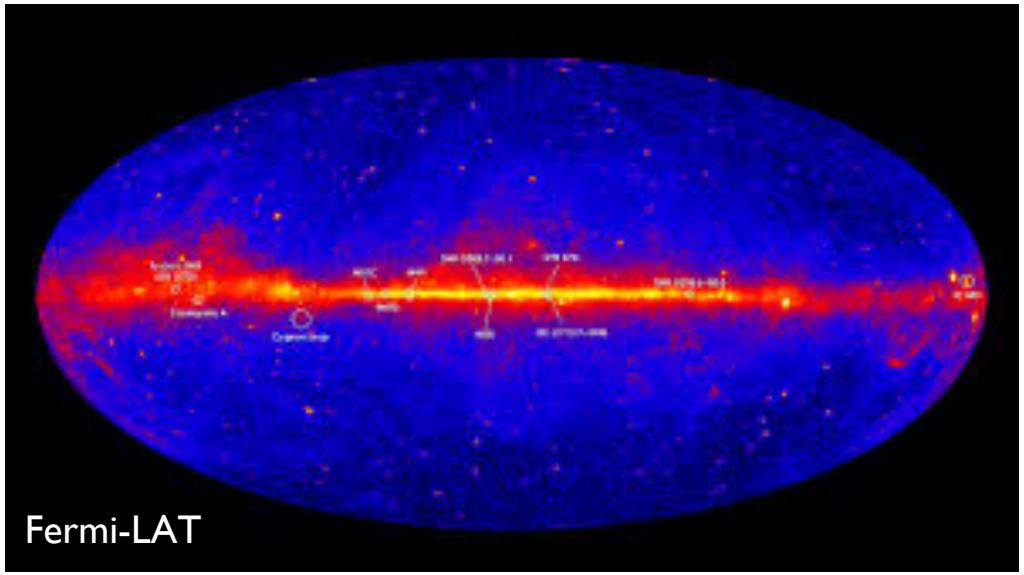


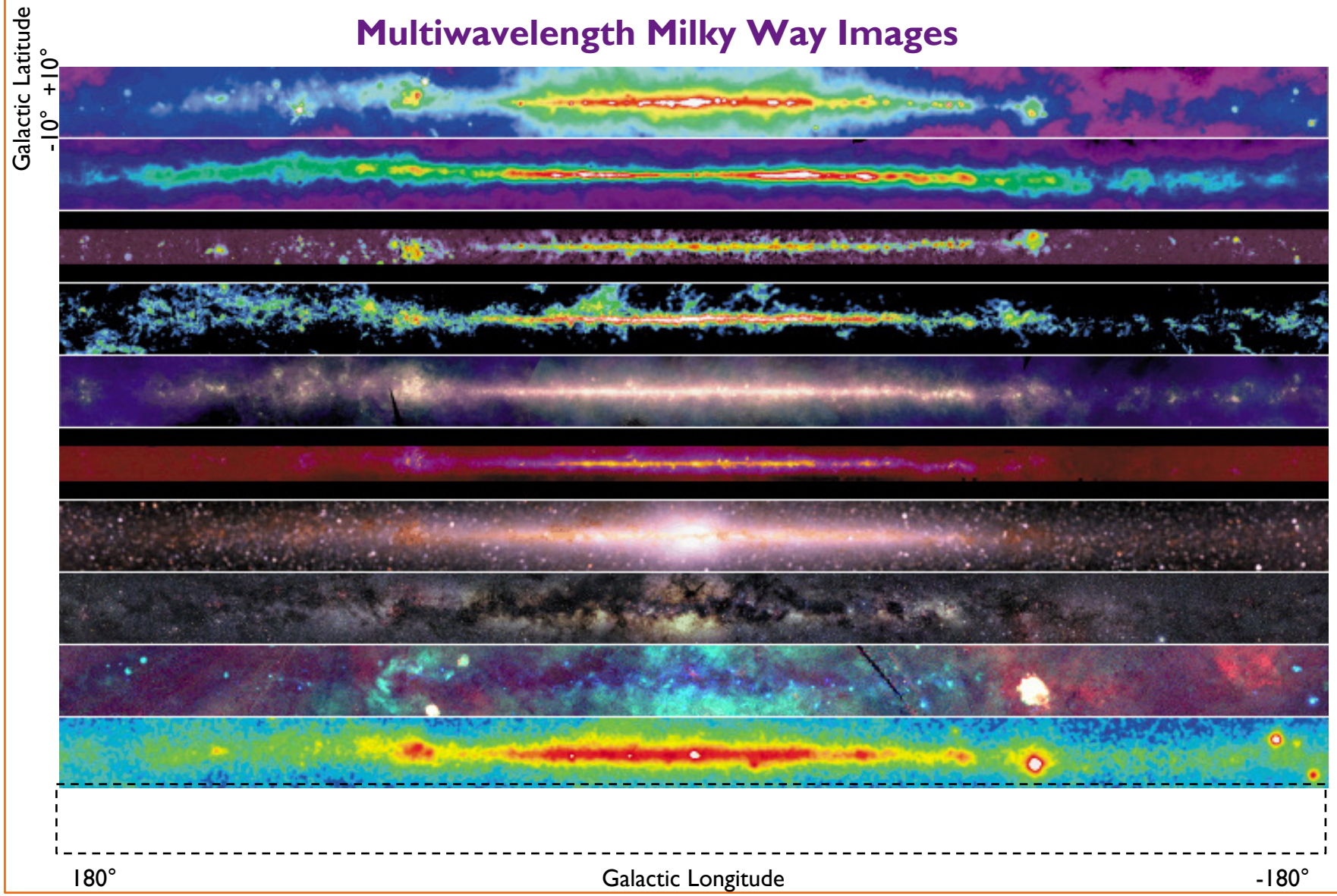
*Figure credit: L. Fusco*

Galaxy filled by **Cosmic Rays and Interstellar Medium**
→ CR collisions will produce **γs** and **νs**
→ **Guaranteed neutrino emission** from the **Galactic Plane**



# Neutrinos from the Galactic Plane

https://asd.gsfc.nasa.gov/archive/mwmw/mmw_images.html




Radio Continuum (408 MHz)

Atomic Hydrogen

Radio Continuum (2.4 - 2.7 GHz)

Molecular Hydrogen

Mid Infrared

Mid Infrared

Near Infrared

Optical

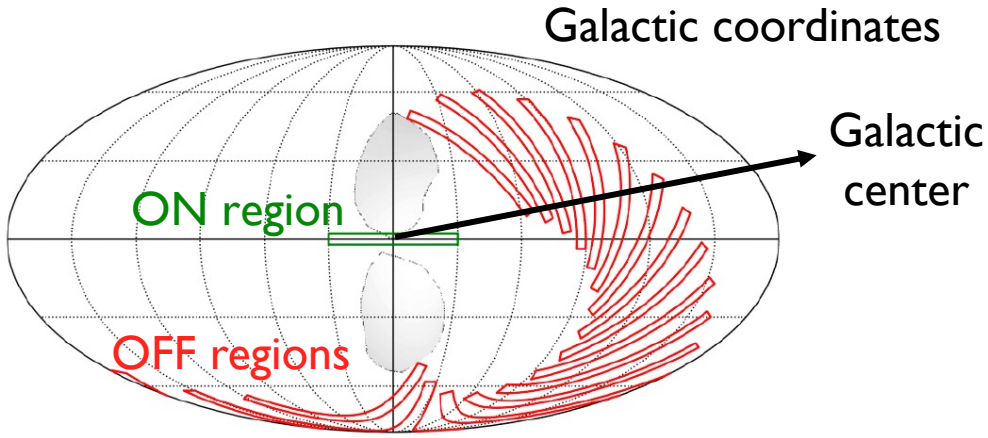
X-Ray

Gamma Ray

Neutrinos?

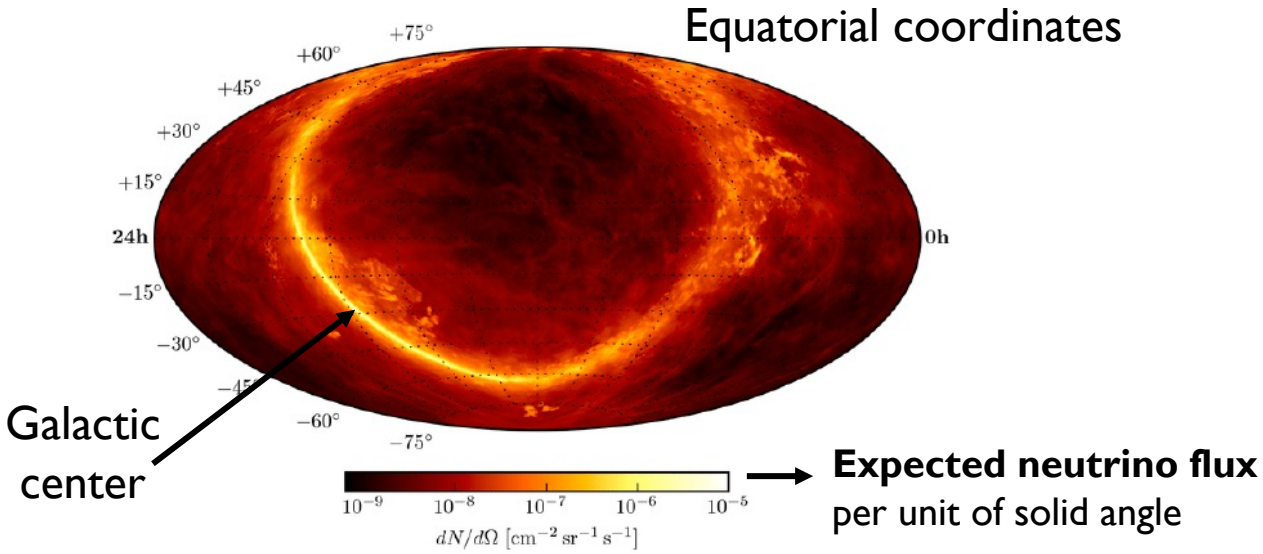
# Neutrinos from the Galactic Plane

**Two search methods:**




## 1. ON/OFF search

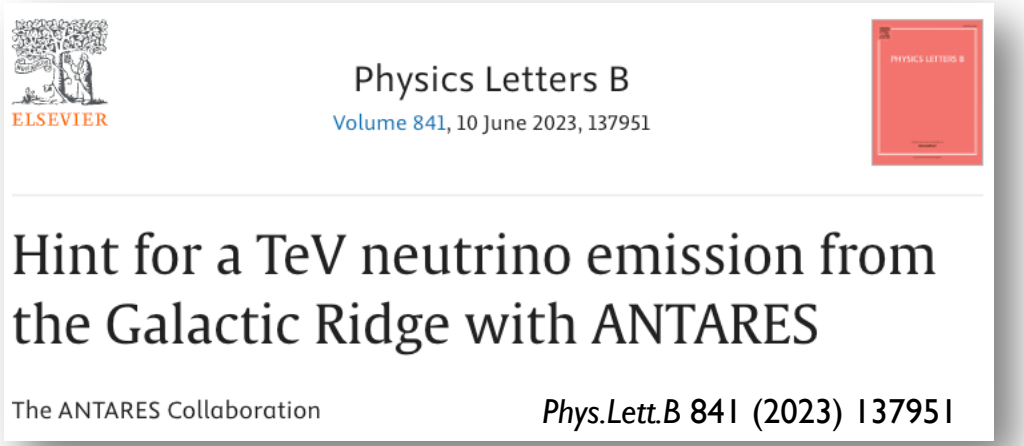
- Model-independent approach
- Rely on Earth rotation → only possible for **mid-latitude detectors**



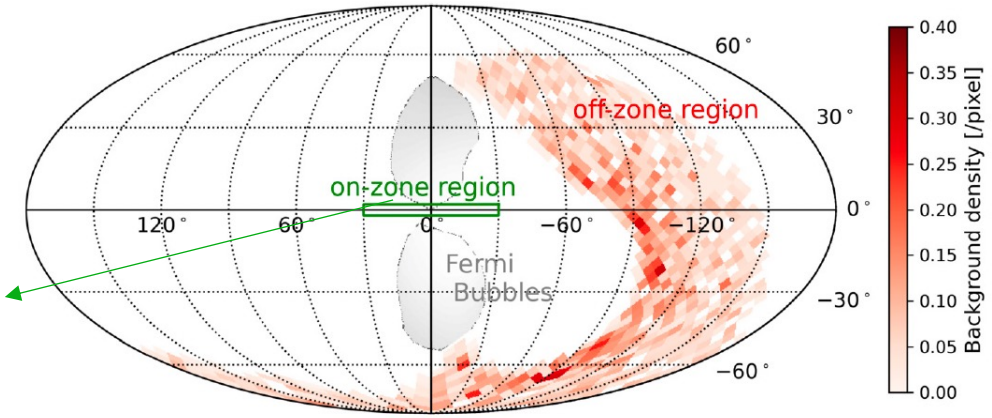

## 2. Template search

- Model-dependent approach
- Rely on expected neutrino sky-map from **models of Galactic diffuse neutrino emission**

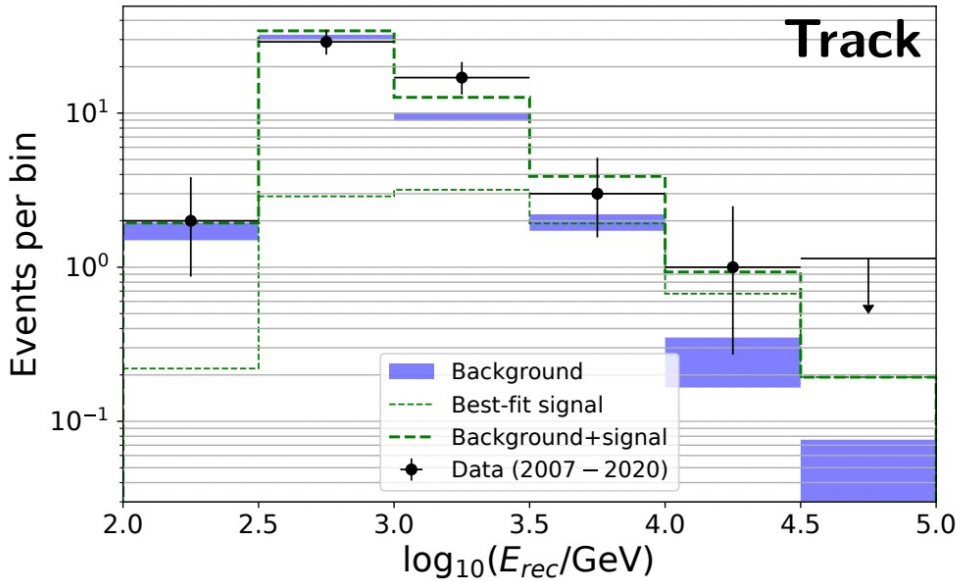
# Neutrinos from the Galactic Plane

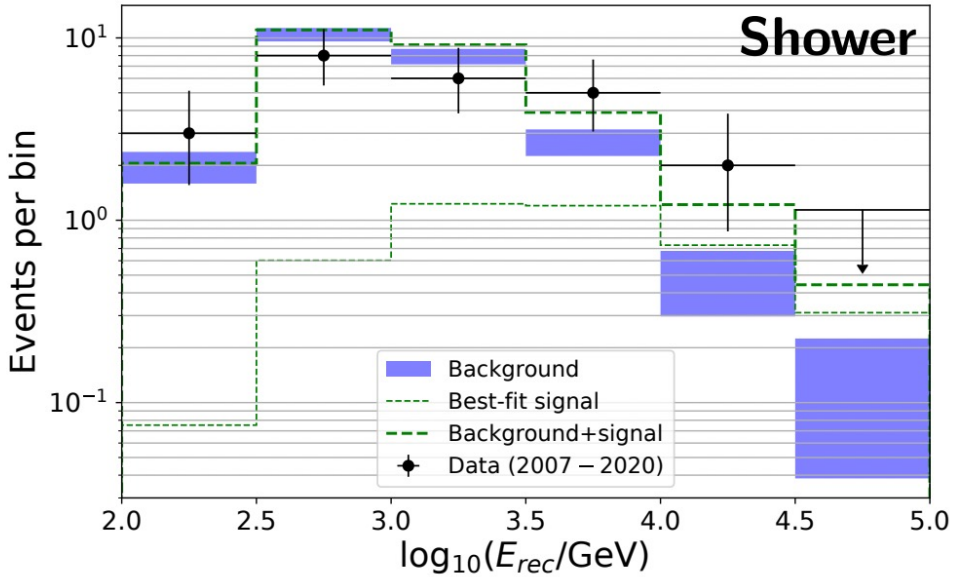



ON region
$|l| < 30^\circ$ $|b| < 2^\circ$
to allow direct comparisons with Fermi-LAT measurements of the ridge

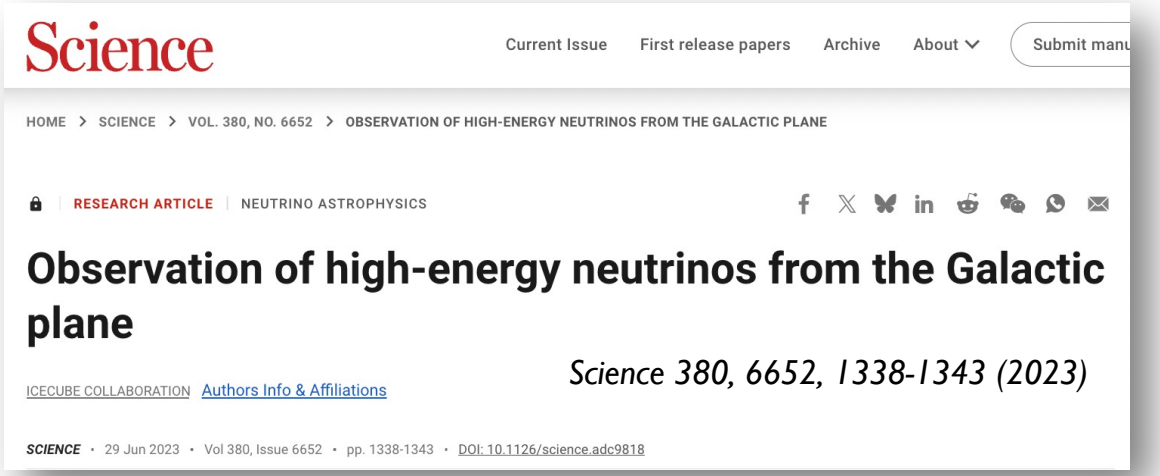



Energy distribution above 1 TeV not compatible with expected BG at **2.2σ**



# Neutrinos from the Galactic Plane


Science

Current Issue First release papers Archive About Submit manu

HOME > SCIENCE > VOL. 380, NO. 6652 > OBSERVATION OF HIGH-ENERGY NEUTRINOS FROM THE GALACTIC PLANE

RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS

**Observation of high-energy neutrinos from the Galactic plane**

ICECUBE COLLABORATION Authors Info & Affiliations

*Science 380, 6652, 1338-1343 (2023)*

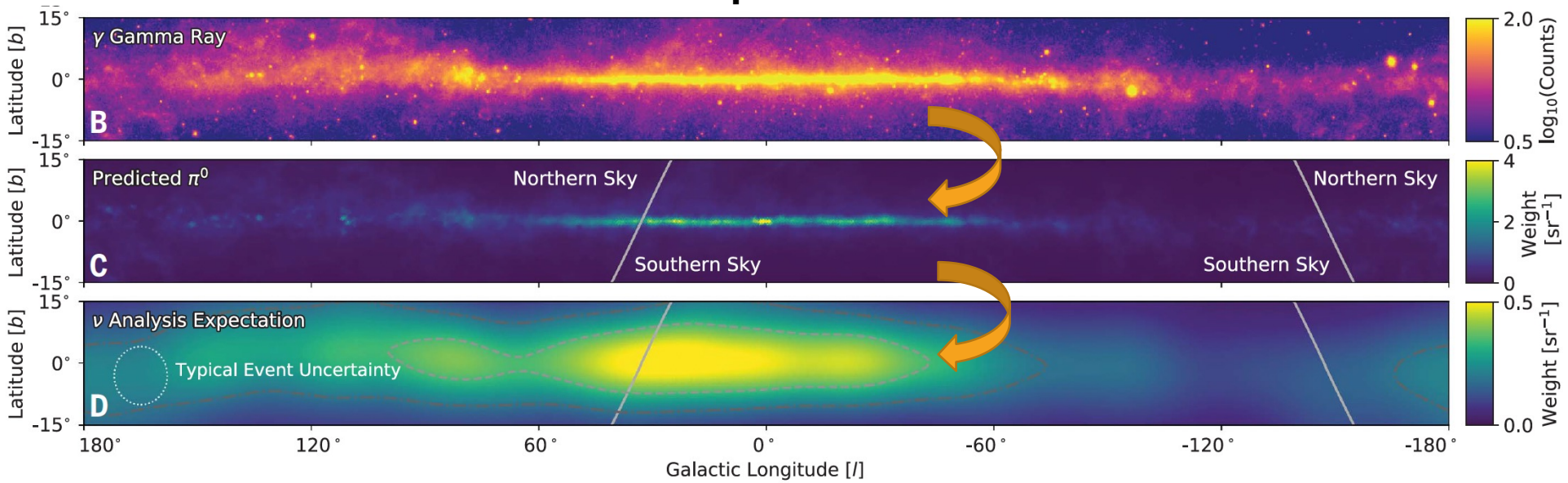
SCIENCE · 29 Jun 2023 · Vol 380, Issue 6652 · pp. 1338-1343 · DOI: 10.1126/science.adc9818

**IceCube announced the detection of neutrinos from the Galactic Plane at 4.5σ**

**Search based on shower events:**

- less atmospheric background in the down-going Sky
- lower energy threshold
- no need for best angular resolution

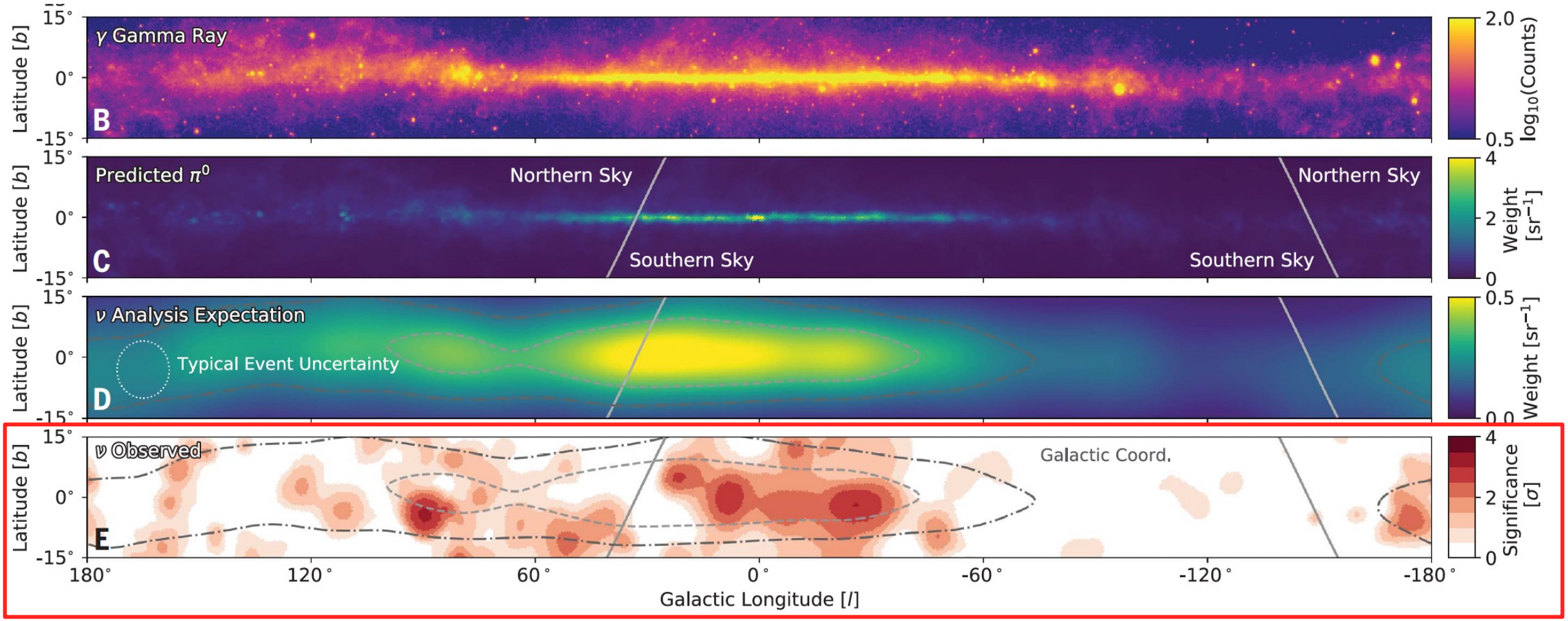
**Method: template search**




Expected ν emission depends on:

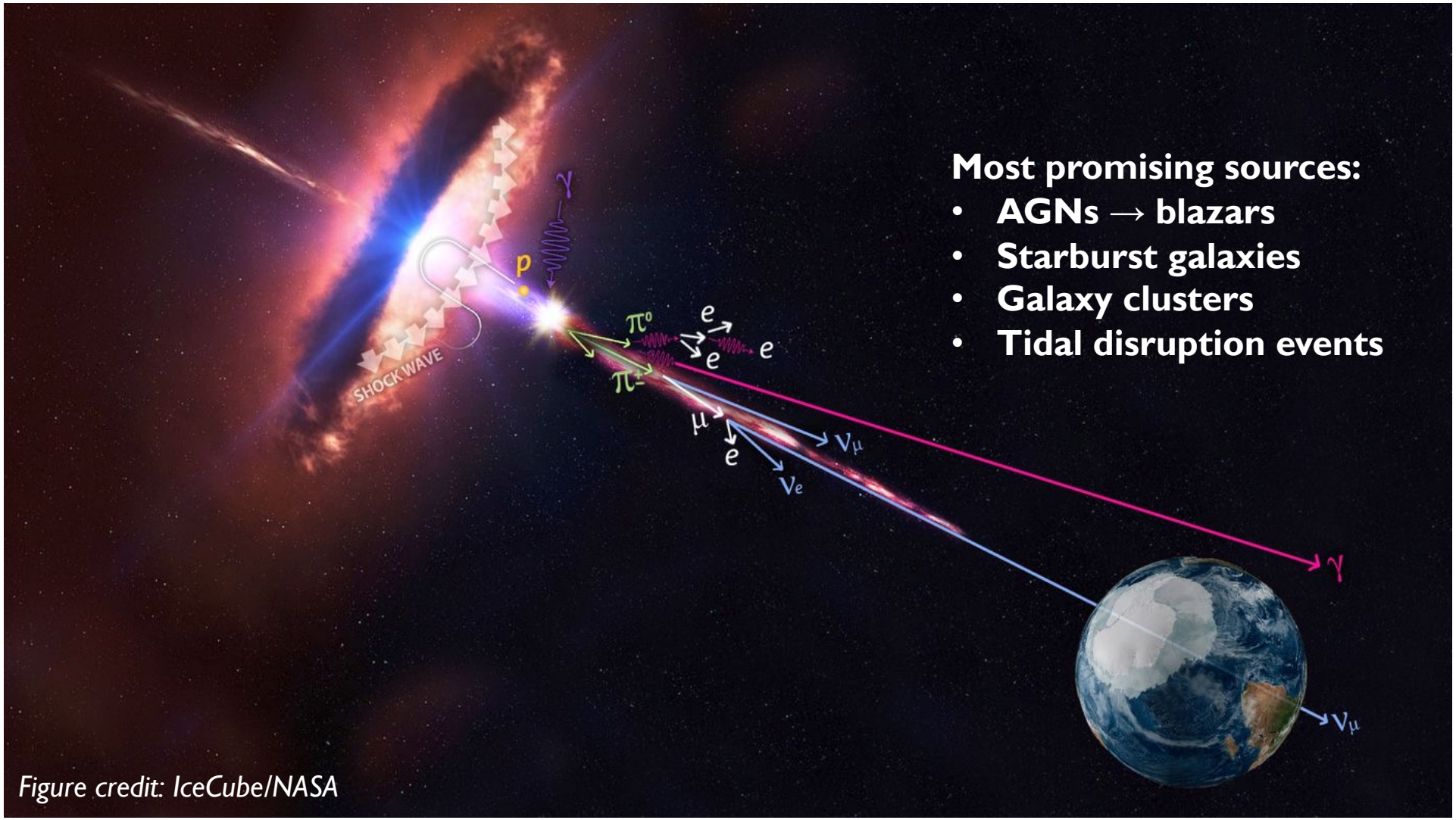
- distribution and emission spectrum of CR sources in the Galaxy
- properties of CR diffusion in the ISM
- spatial distribution of target gas

# Neutrinos from the Galactic Plane




**Results: data compatible with expectations from $\pi^0$ model at > 4σ**

# Individual sources of neutrinos




**Most promising sources:**

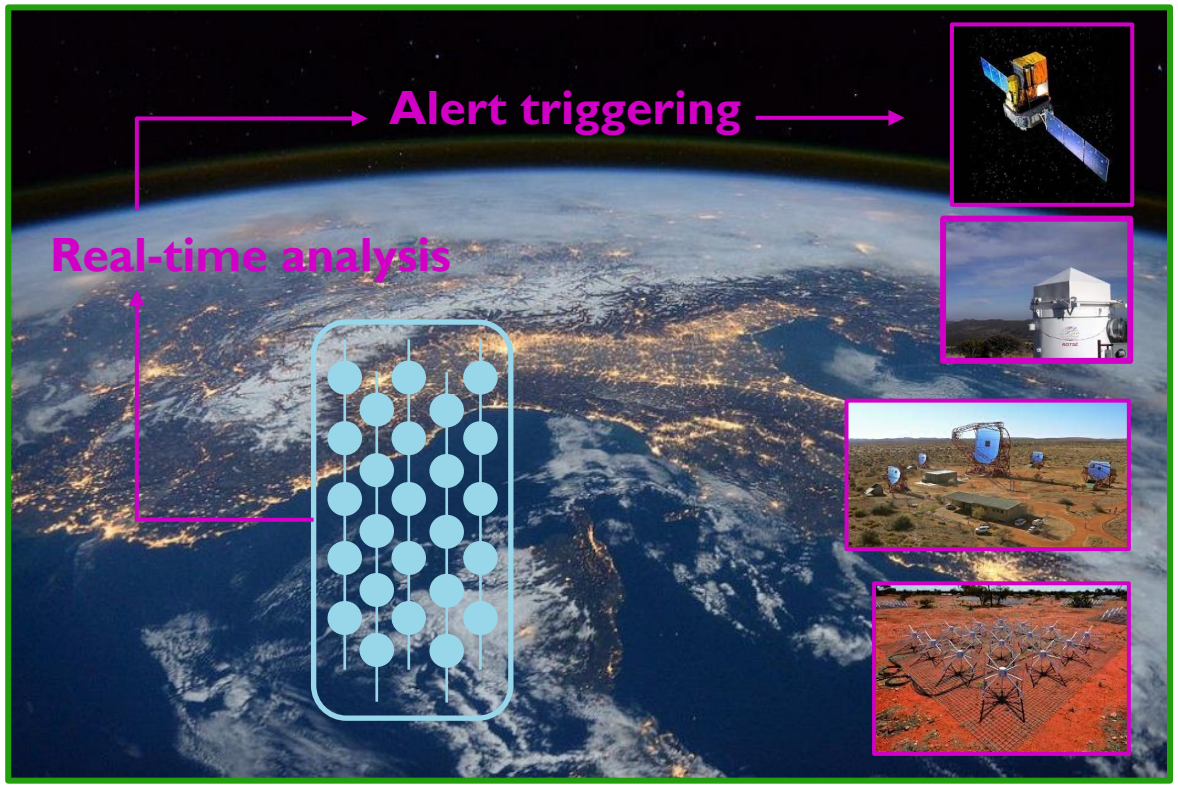
- **AGNs → blazars**
- **Starburst galaxies**
- **Galaxy clusters**
- **Tidal disruption events**

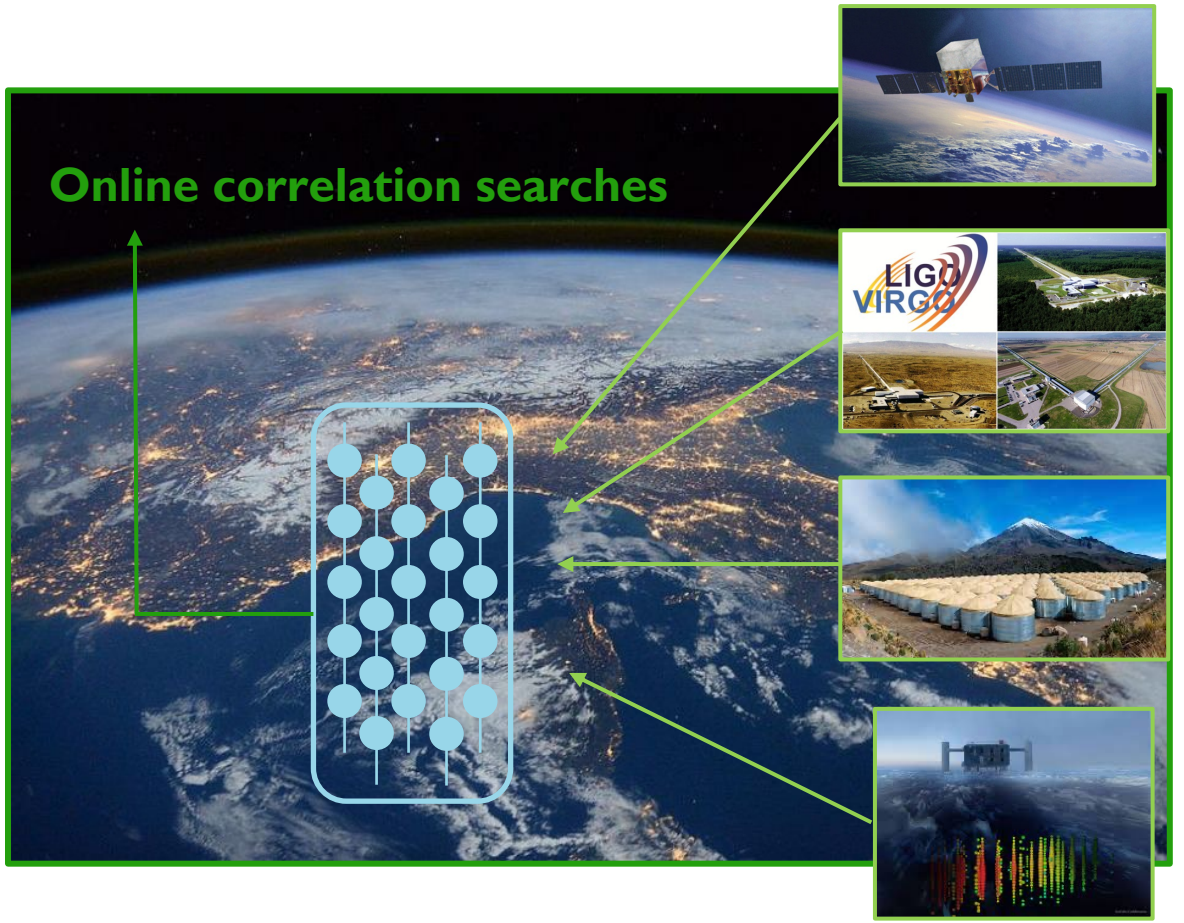
*Figure credit: IceCube/NASA*

# Individual sources of neutrinos

**Two ways to detect them:**

1) Exploit **real-time multi-messenger** approach



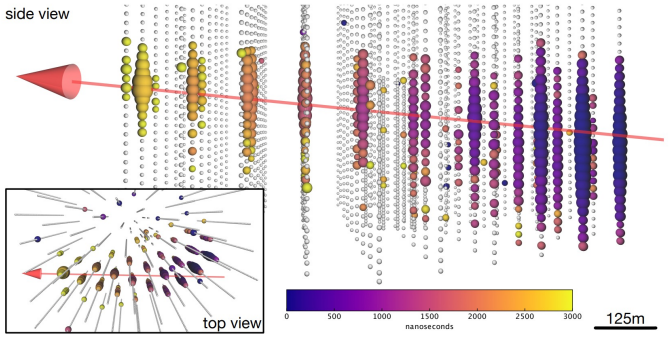



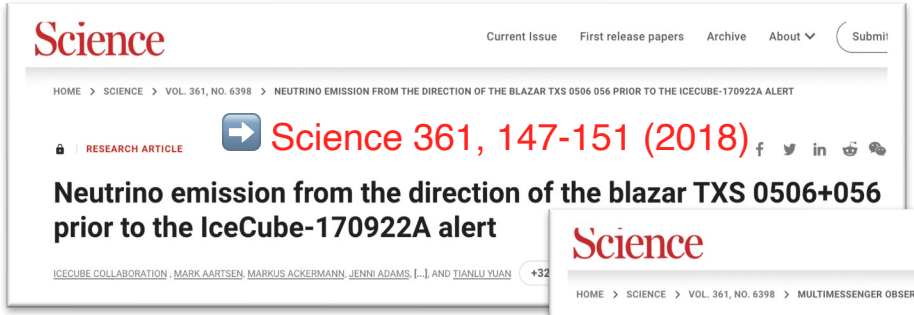

**Example of events worth an alert:**

- High-energy events
- Multiplets

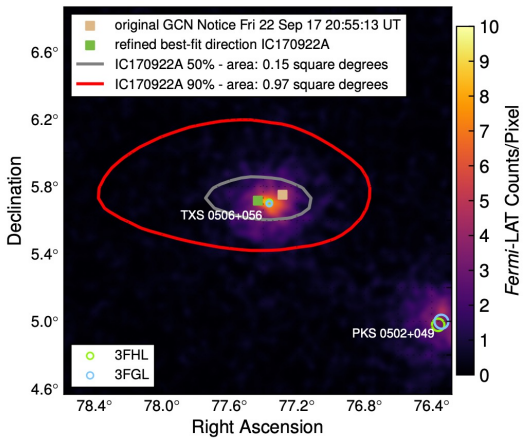
# Individual sources of neutrinos

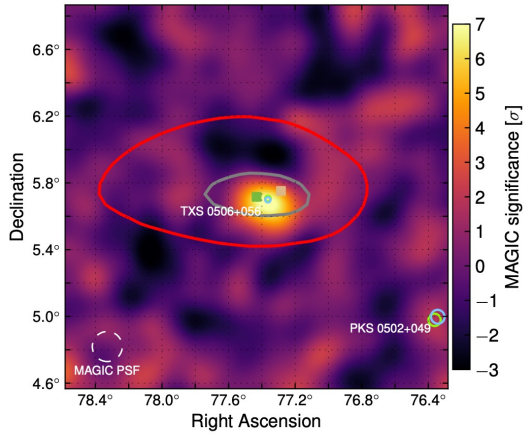
## Blazar TXS 0506+056



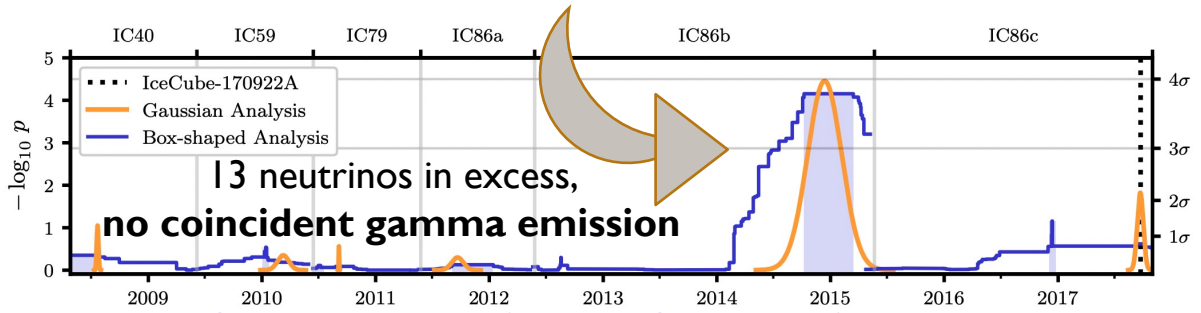



270 TeV muon detected by IceCube on 22 September 2017
in coincidence with flaring blazar
**TXS 0506+056** observed by Fermi-LAT and MAGIC (**3σ**)




**Neutrino flare** found in 2015 (**3.5σ**)

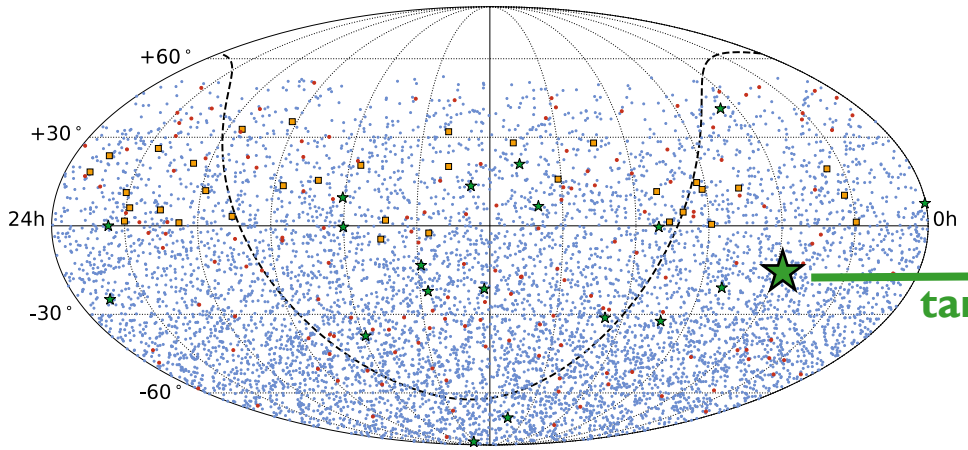


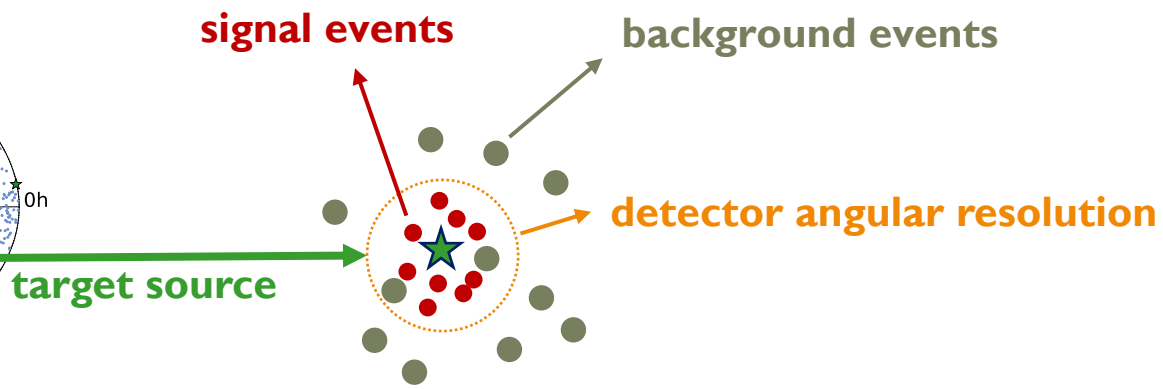

**Lack of concordance picture of the multi-messenger data**

# Individual sources of neutrinos

**Two ways to detect them:**

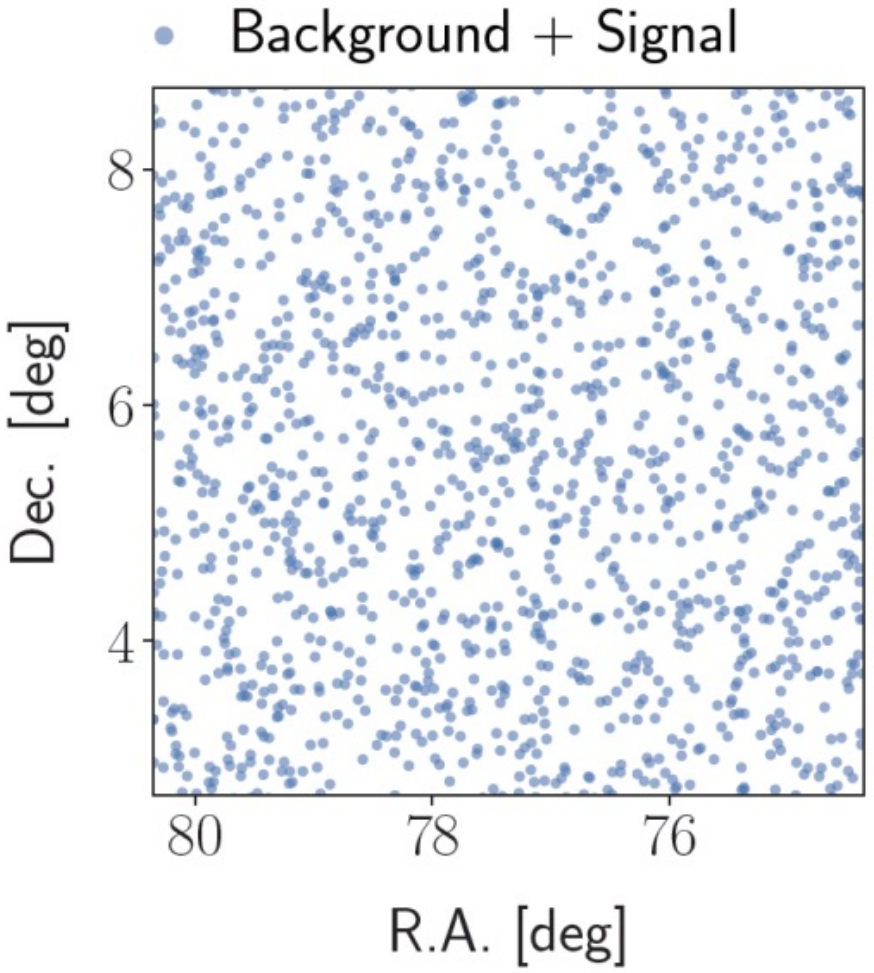
2) Exploit **different expected** spatial, energy (and time) **distribution** between signal and backgound:



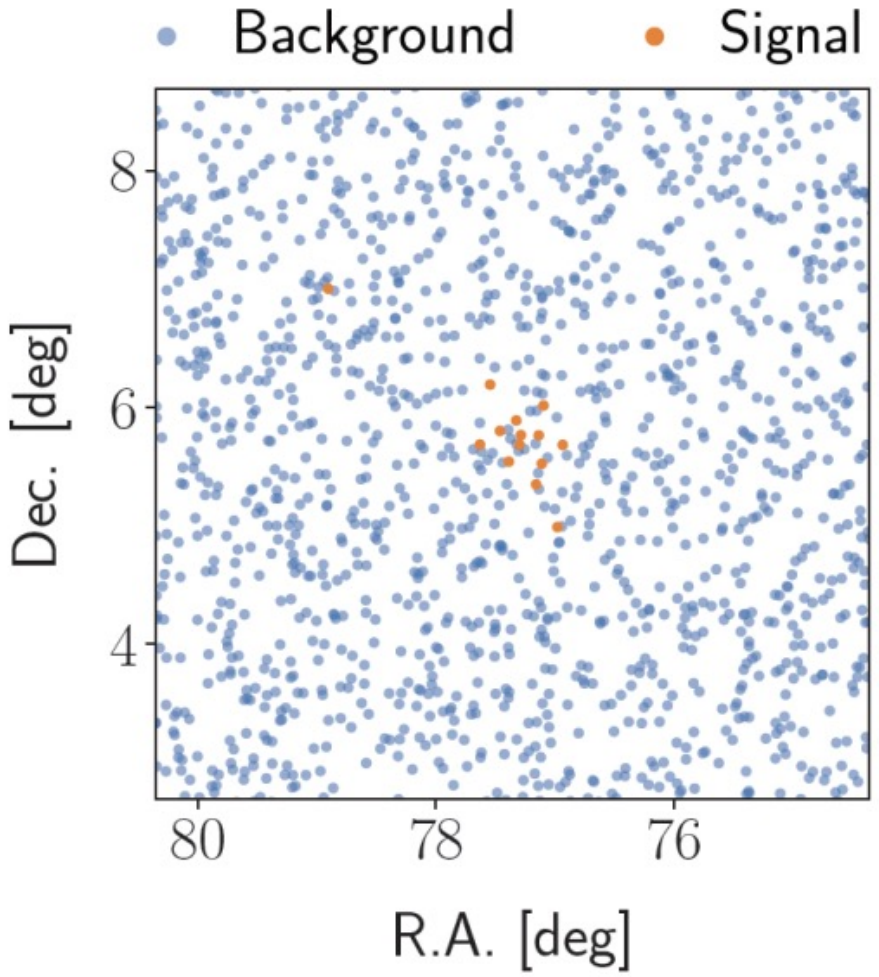

Is the **spatial+energy(+time) distibution** of the events in a given direction of the sky **compatible** with that expected from neutrinos from an **astrophysical source**?

# Individual sources of neutrinos




*Credits: Francis Halzen*

# Individual sources of neutrinos




*Credits: Francis Halzen*

# Individual sources of neutrinos

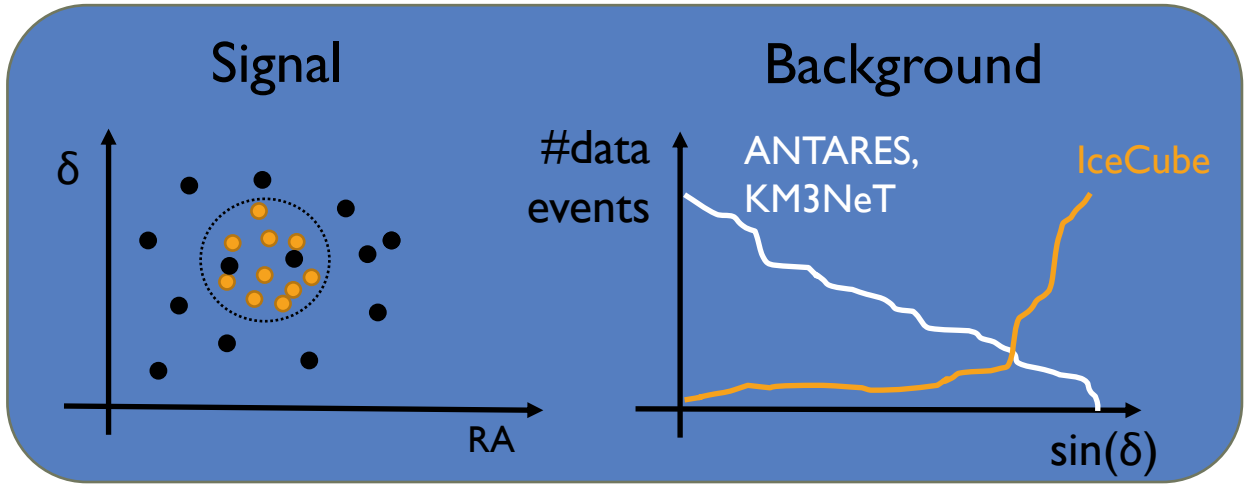
$$L(n_s, \Theta) = \prod_{j=1}^{N_{samples}} \prod_{i=1}^{N_{events}^{j}} \left[ \frac{n_s^j}{N_{events}^j} S_i^j(\Theta) + \left(1 - \frac{n_s^j}{N_{events}^j}\right) B_i^j \right]$$

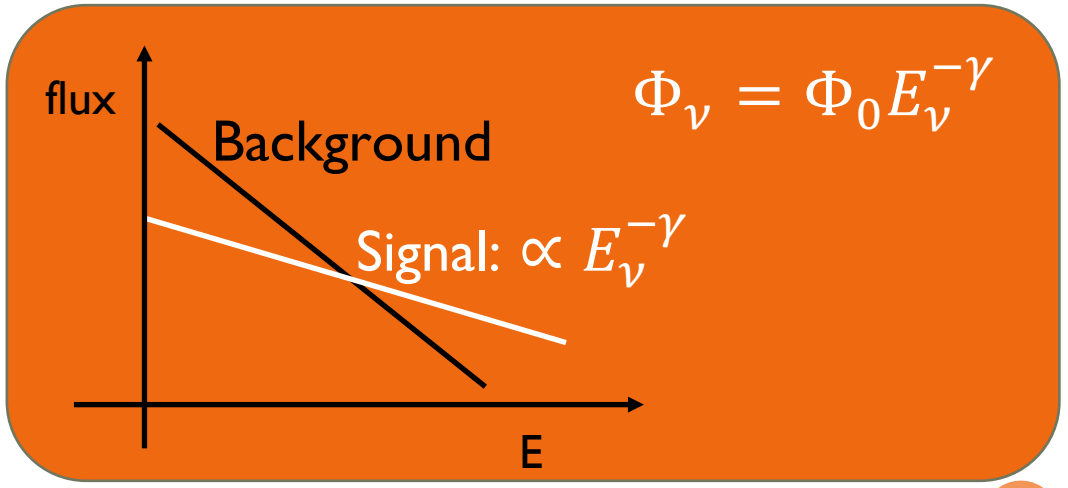
Signal PDFs

Background PDFs

$$S_i = S^{space} \cdot S^{energy}$$

$$B_i = B^{space} \cdot B^{energy}$$



# Individual sources of neutrinos

$$L(n_s, \Theta) = \prod_{j=1}^{N_{samples}} \prod_{i=1}^{N_{events}^{j}} \left[ \frac{n_s^j}{N_{events}^j} S_i^j(\Theta) + \left(1 - \frac{n_s^j}{N_{events}^j}\right) B_i^j \right]$$

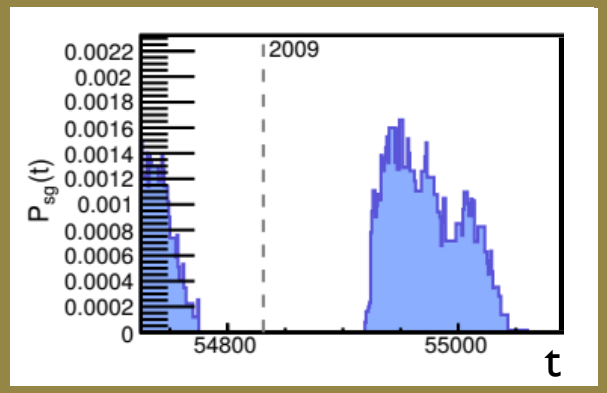
Signal PDFs

Background PDFs

$$S_i = S^{space} \cdot S^{energy} \cdot S^{time} \qquad B_i = B^{space} \cdot B^{energy} \cdot B^{time}$$

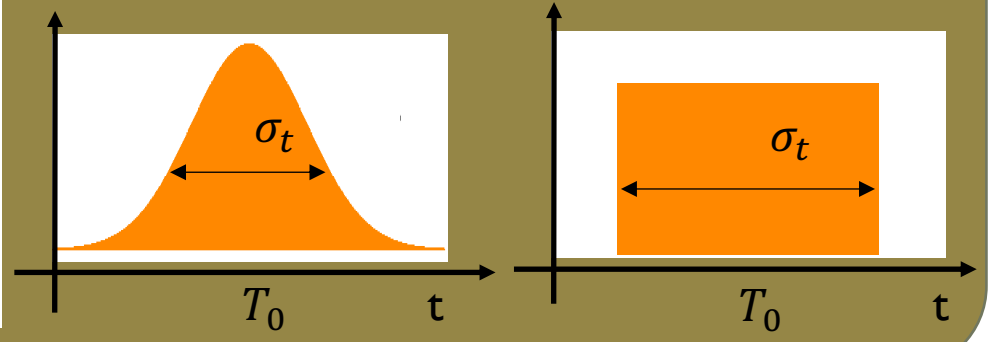
**Signal time profile** either taken from **EM lightcurves** or **generic shapes** (gaussian/box) **with free time parameters**

From EM lightcurve

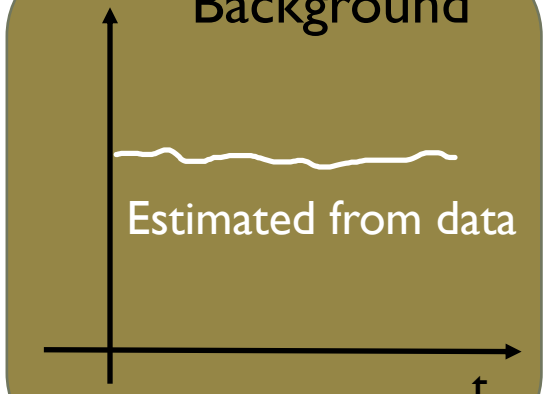



Signal

Generic time profiles




Background



# Individual sources of neutrinos

$$L(\underbrace{n_s, \Theta}) = \prod_{j=1}^{N_{samples}} \prod_{i=1}^{N_{events}^{j}} \left[ \frac{n_s^j}{N_{events}^j} S_i^j(\Theta) + \left(1 - \frac{n_s^j}{N_{events}^j}\right) B_i^j \right]$$

free parameters

$n_s$: number of detected signal events

$\Theta$: set of model parameters

Likelihood maximization → $\hat{n}_s, \hat{\Theta}$ best estimation of $n_s, \Theta$

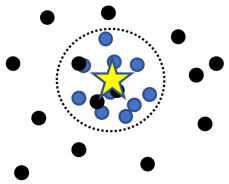
- $H_0$: the data consist solely of background
- $H_S$: the data contain also astrophysical neutrino events ($n_s$) coming from a source with some given features ($\Theta$)

signal spectral index, source extension, flaring duration…

test statistic

$$Q = \log \frac{L(\hat{n}_s, \hat{\Theta})}{L(n_s = 0)}$$

# Individual sources of neutrinos



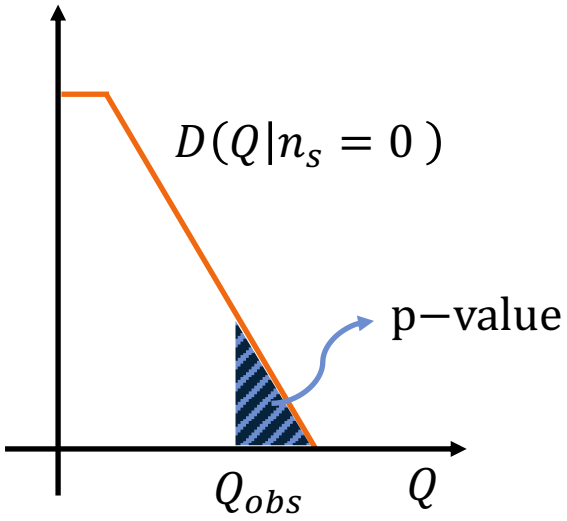
Likelihood maximization

test statistic

$$Q = \log \frac{L(\hat{n}_s, \hat{\Theta})}{L(n_s = 0)}$$

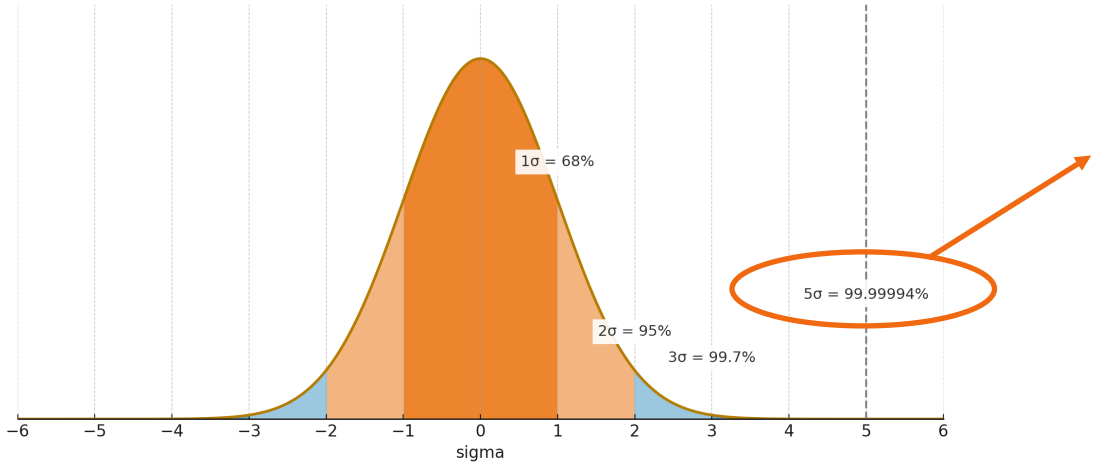
**significance (p−value and #σ)?**

Distributions of $Q$ obtained from pseudo-experiments (same analysis performed on fake datasets)




$$\text{p−value} = \int_{Q_{obs}}^{\infty} D(Q|n_s = 0)\, dQ$$

$$D(Q|n_s = 0)$$

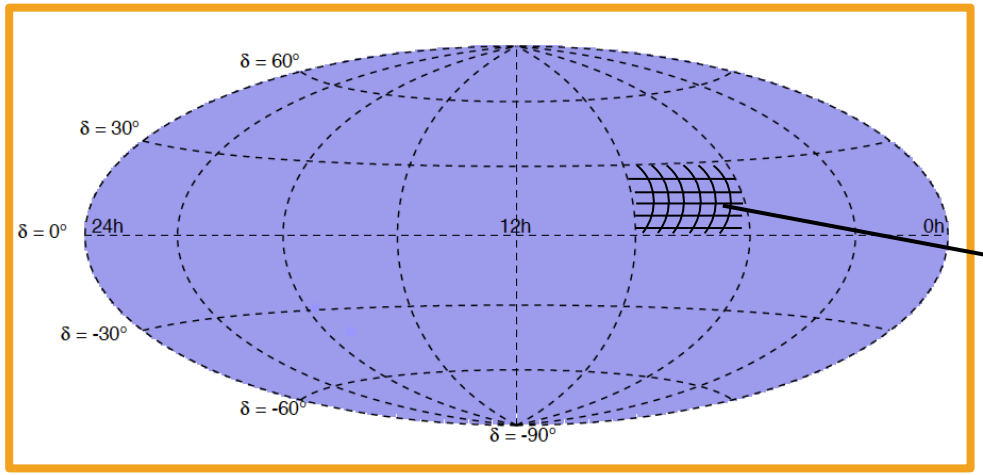



$$\text{p−value} = (5.73 \cdot 10^{-7})/2$$
$$\equiv 2.87 \cdot 10^{-7}$$
$$\equiv 5\sigma \text{ significance}$$

one-sided

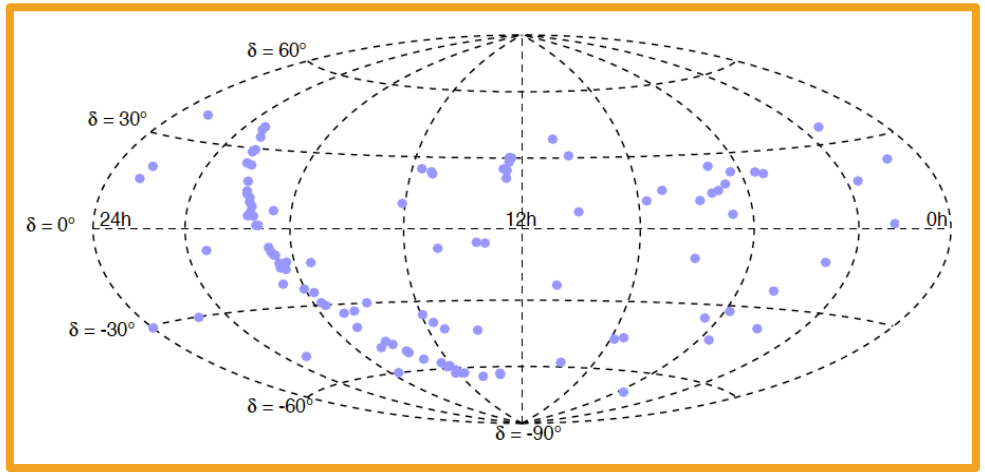
$$\#sigmas = \sqrt{2}\,\mathrm{erf}^{-1}(1 - 2 \cdot \text{p−value})$$

# Individual sources of neutrinos




## All-sky search

- **Sky divided into a grid** with a finer spacing than the typical event reconstruction uncertainty
- Likelihood evaluated in each bin of the grid → **one p-value per pixel**
- Cluster with smallest p-value → all-sky hotspot
- Advantage: **unbiased by EM observations** (no prior assumptions regarding source directions)
- Disadvantage: **large trial factor**




## Candidate List search over astrophysical objects

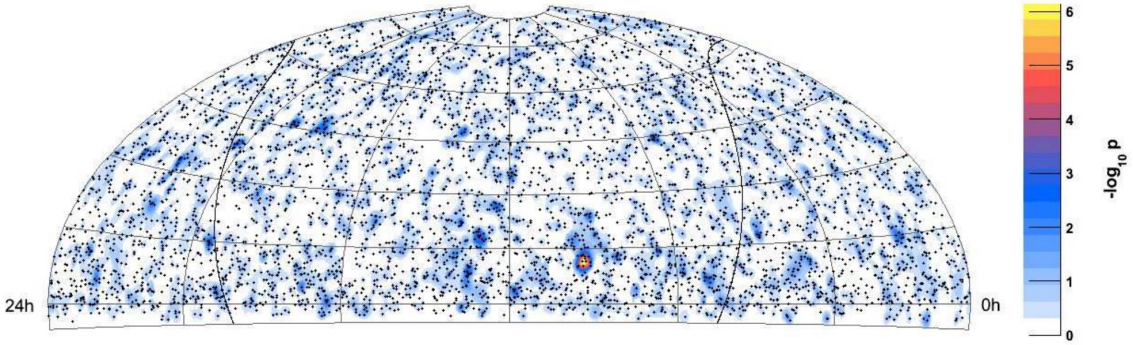
- Investigated directions: **pre-selected source candidates** from EM catalogs
- Likelihood evaluated at each source location→ **one p-value per source**
- Advantage: **reduced trial factor**
- Disadvantage: **biased** (the brightest ν sources may differ from the brightest EM sources)

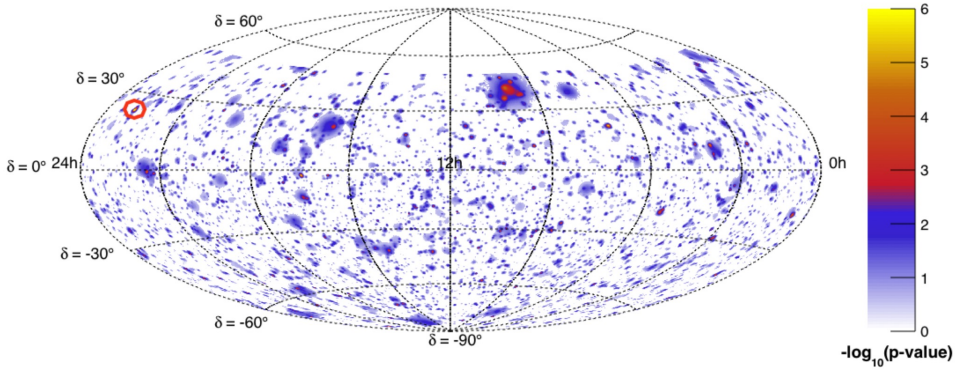
## Stacking search over source catalogs

- Investigated directions: **all sources in a pre-selected catalog**
- All sources in the catalog analysed together → **one p-value per catalog**
- Extra advantage: **sensitive to individually weak sources** that produce a significant cumulative signal

# Individual sources of neutrinos

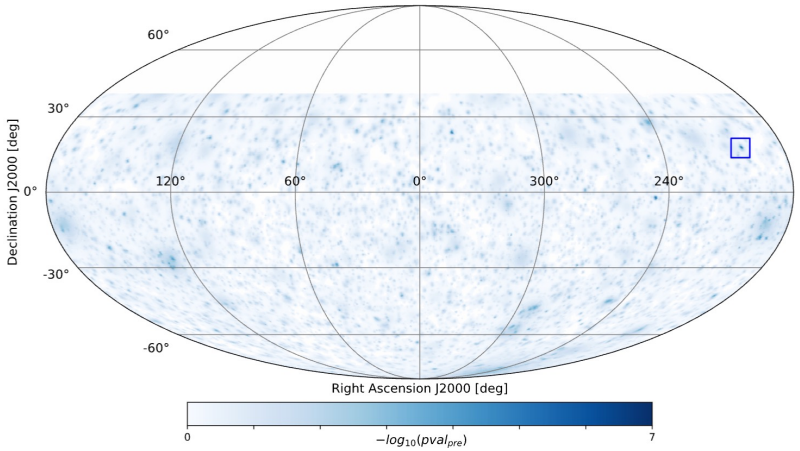
IceCube-22, p-value map, *Astrophys.J.701:L47-L51,2009*



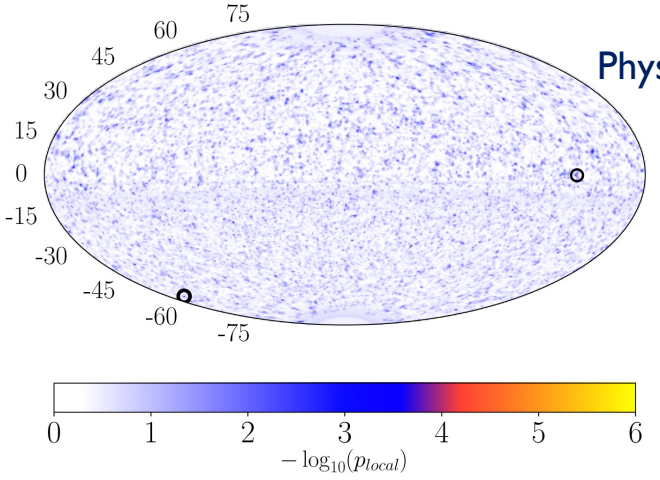




ANTARES+IceCube, combined p-value map, *Astrophys. J. 892 (2020) 92*

ANTARES, 15-y legacy p-value map, *arXiv:2511.07239 [astro-ph.HE]*

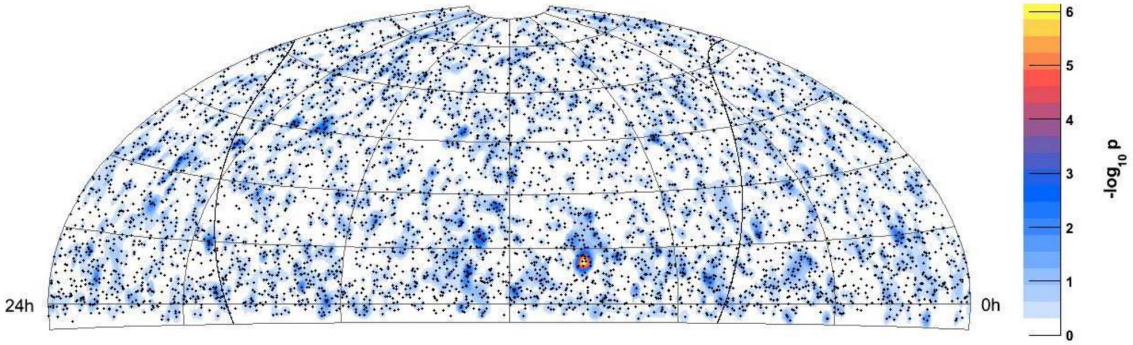


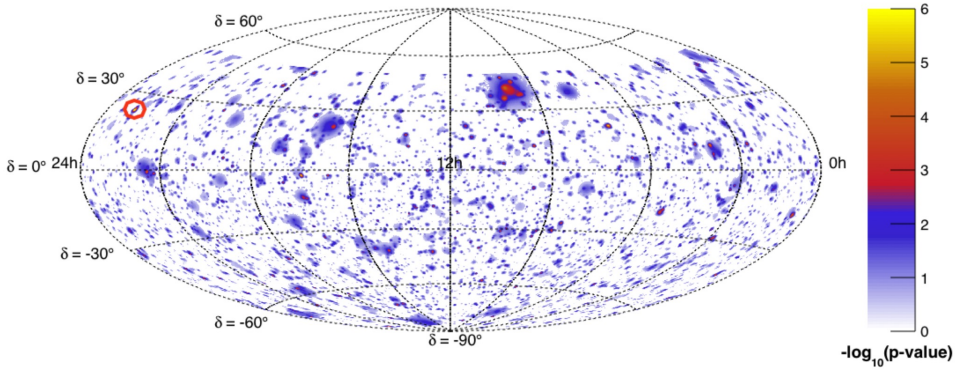

IceCube, 10-y p-value map, Phys. Rev. Lett. 124, 051103 (2020)



# Individual sources of neutrinos

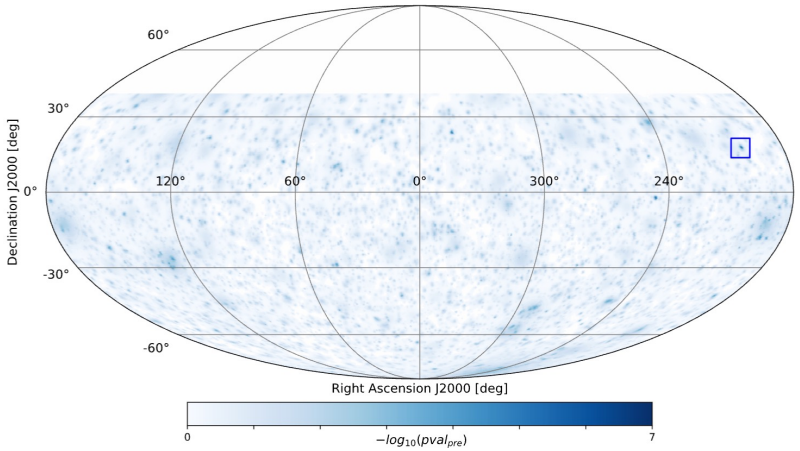
IceCube-22, p-value map, *Astrophys.J.701:L47-L51,2009*

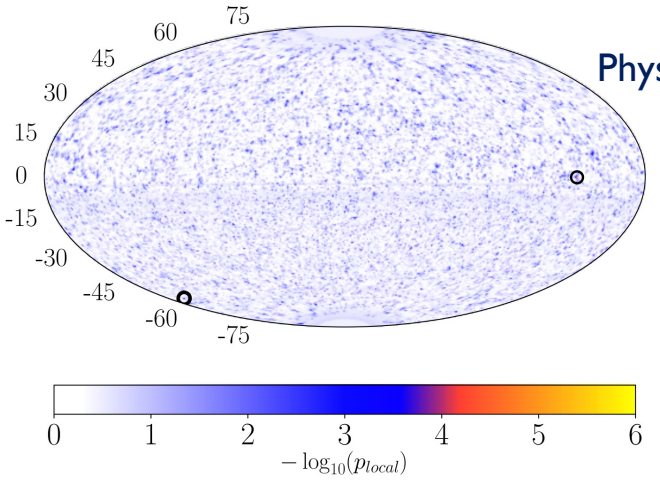



ANTARES+IceCube, combined p-value map,
*Astrophys. J. 892 (2020) 92*

ANTARES, 15-y legacy p-value map,
*arXiv:2511.07239 [astro-ph.HE]*

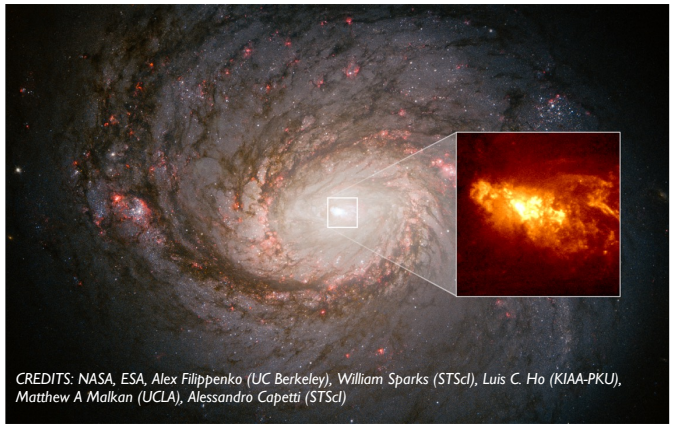



IceCube, 10-y p-value map,
Phys. Rev. Lett. 124, 051103 (2020)

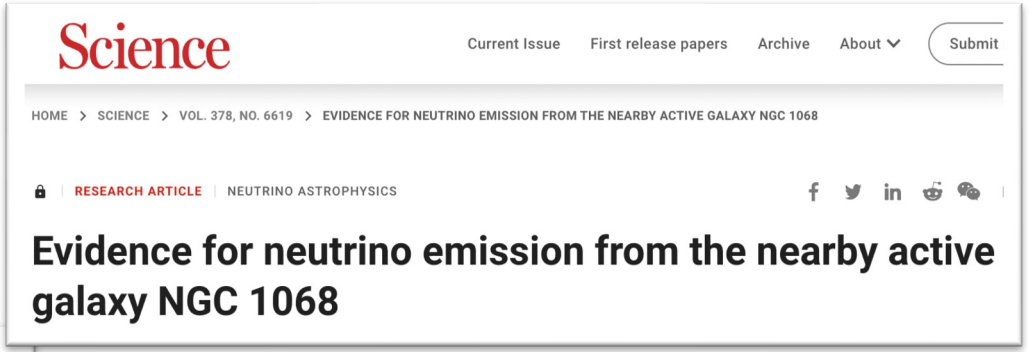
# Individual sources of neutrinos

## Active galaxy NGC 1068

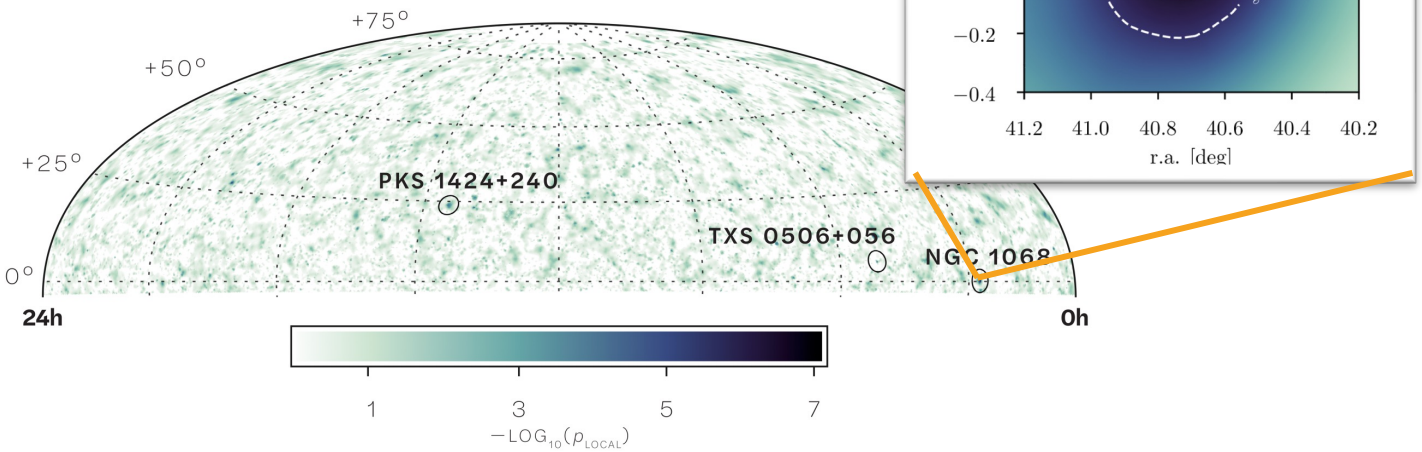


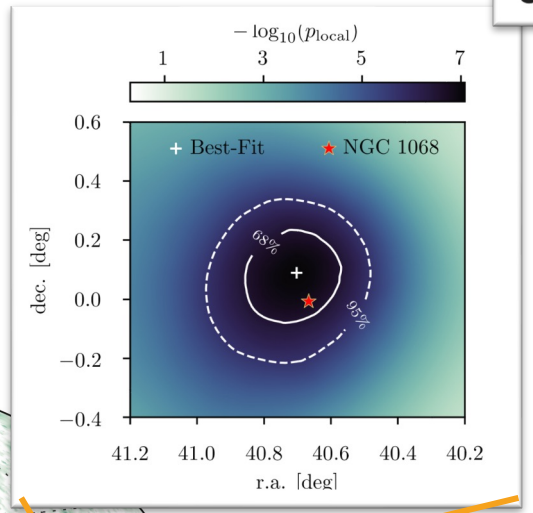

**Brightest** and one of the closest type 2 **Seyfert galaxies**

Science 378, 6619, 538-543 (2022)

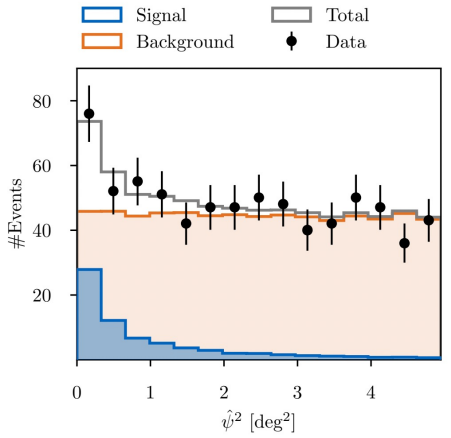



**4.2σ post-trial (catalog search)**

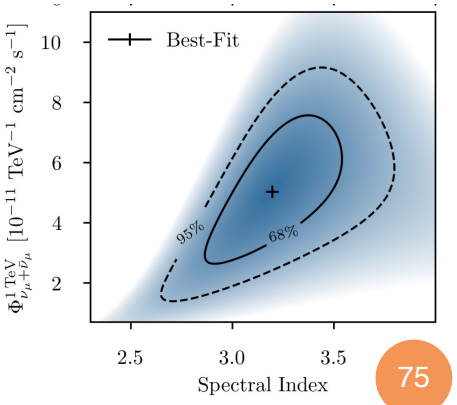



~80 detected neutrino events

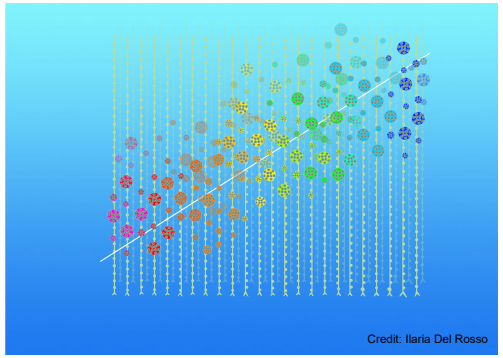


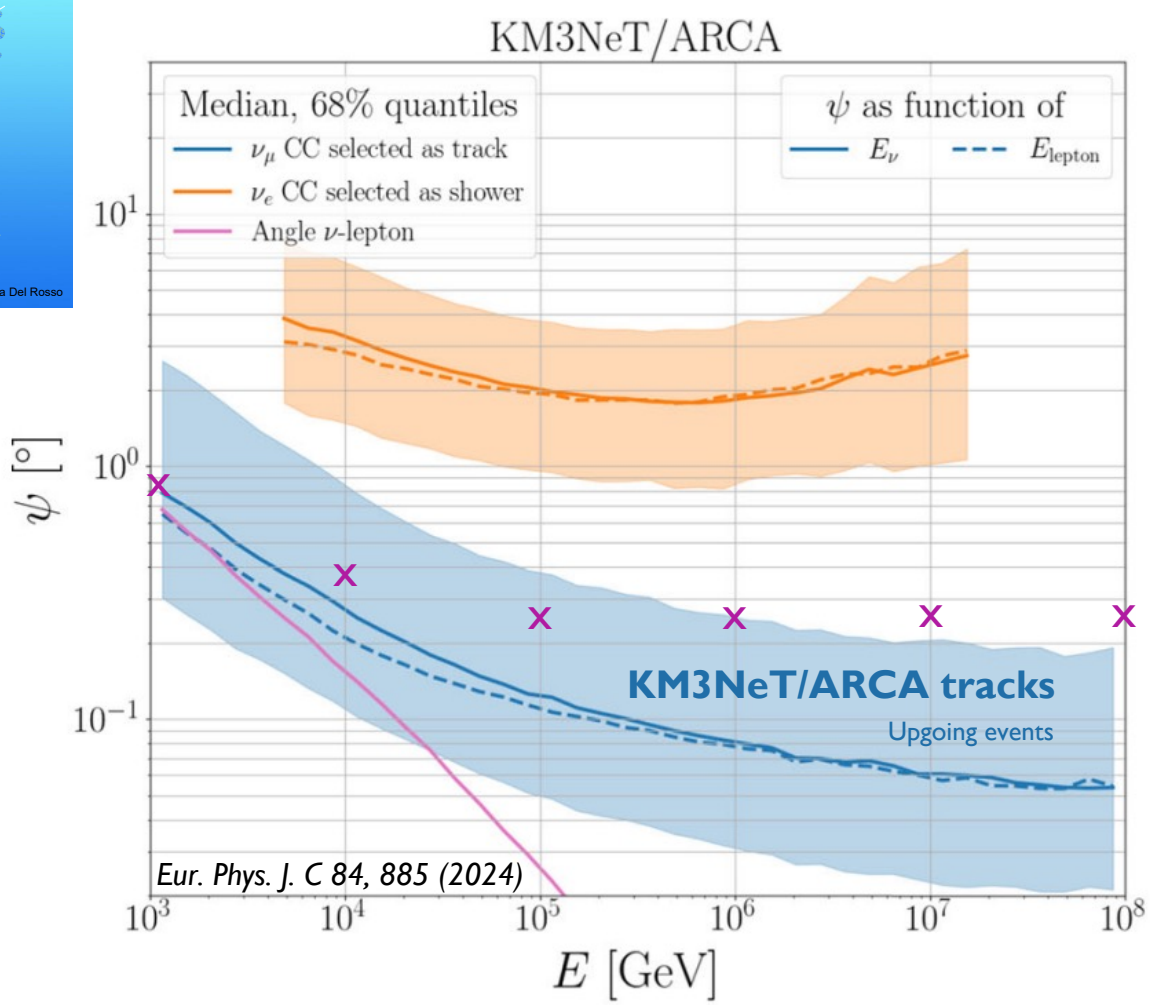

Soft best-fit spectrum of $E^{\gamma}, \gamma = 3.2 \pm 0.2$



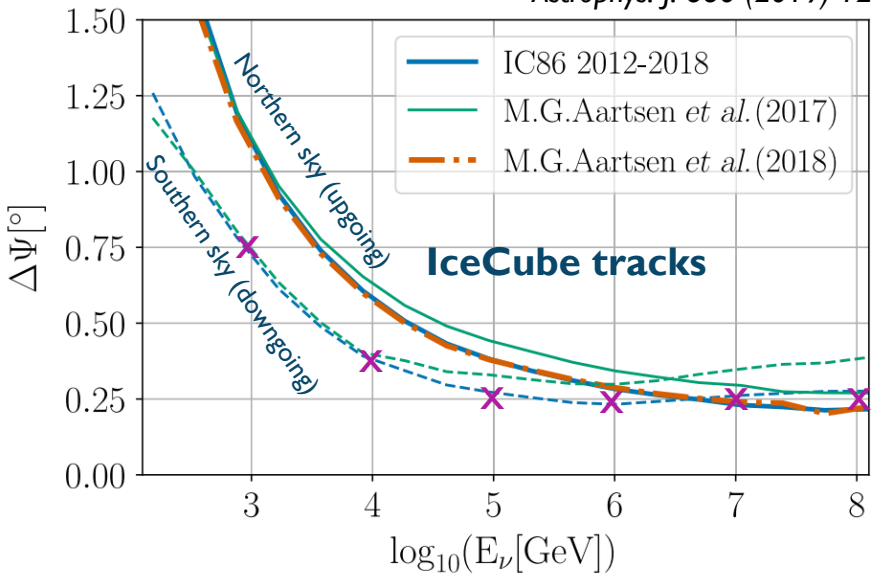
# Prospects for KM3NeT

## Track channel



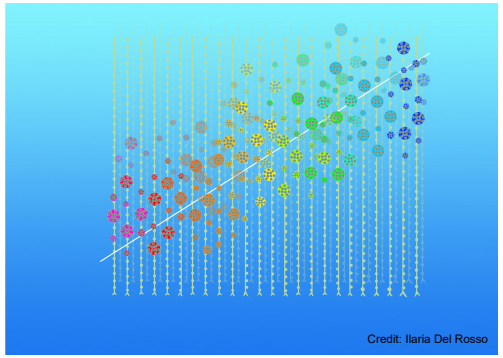



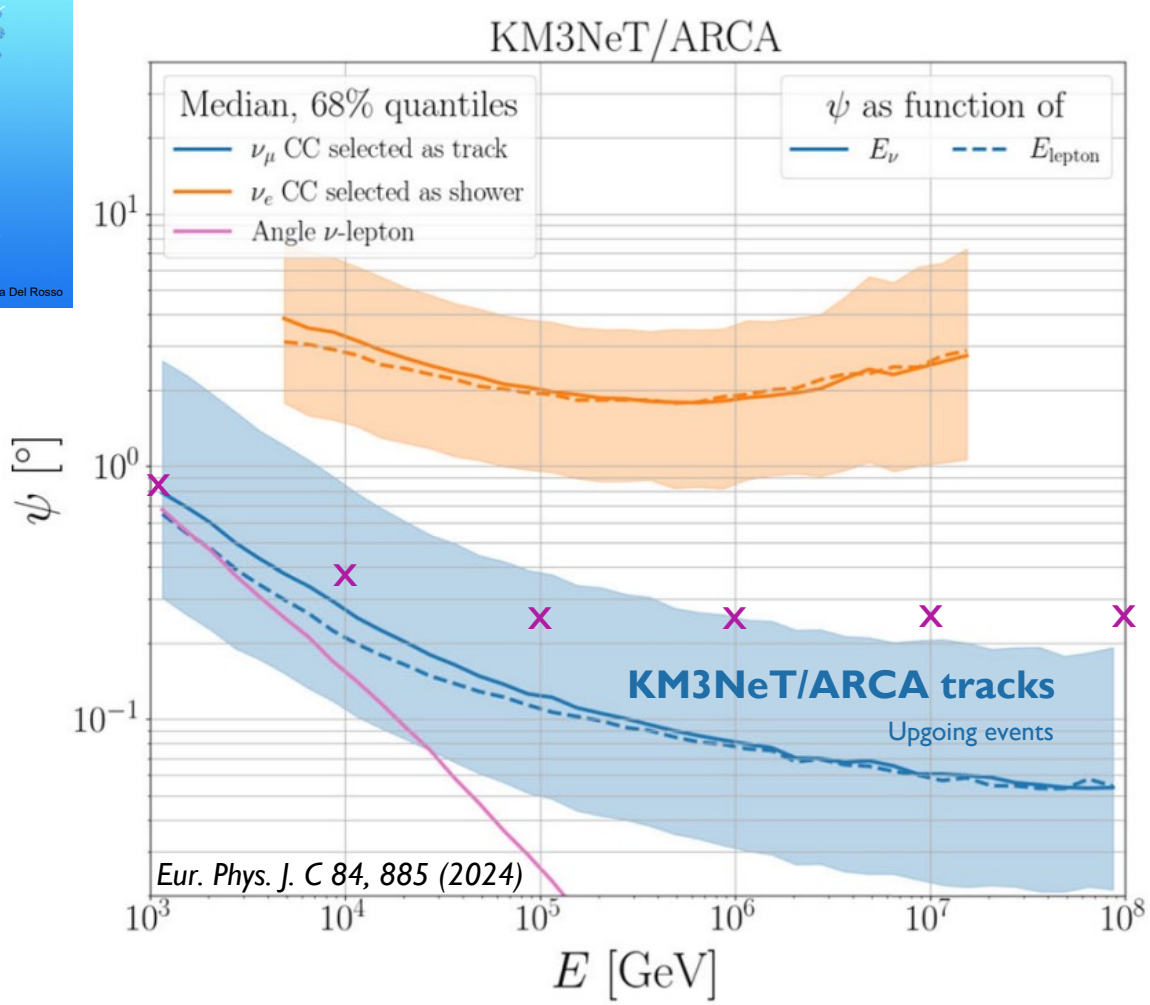

Astrophys. J. 886 (2019) 12

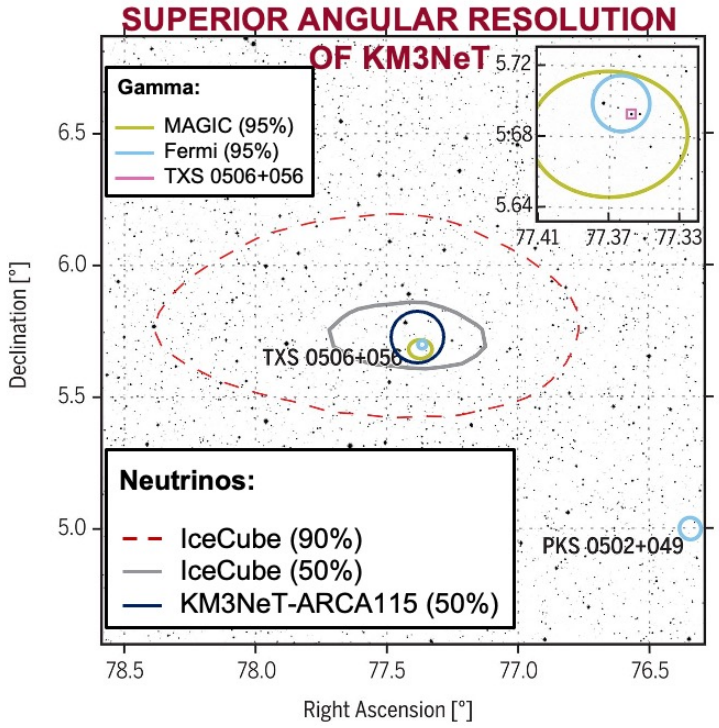


# Prospects for KM3NeT

## Track channel

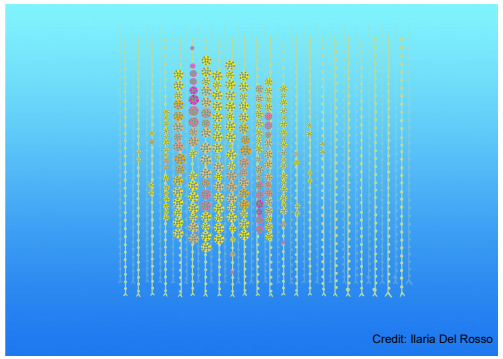


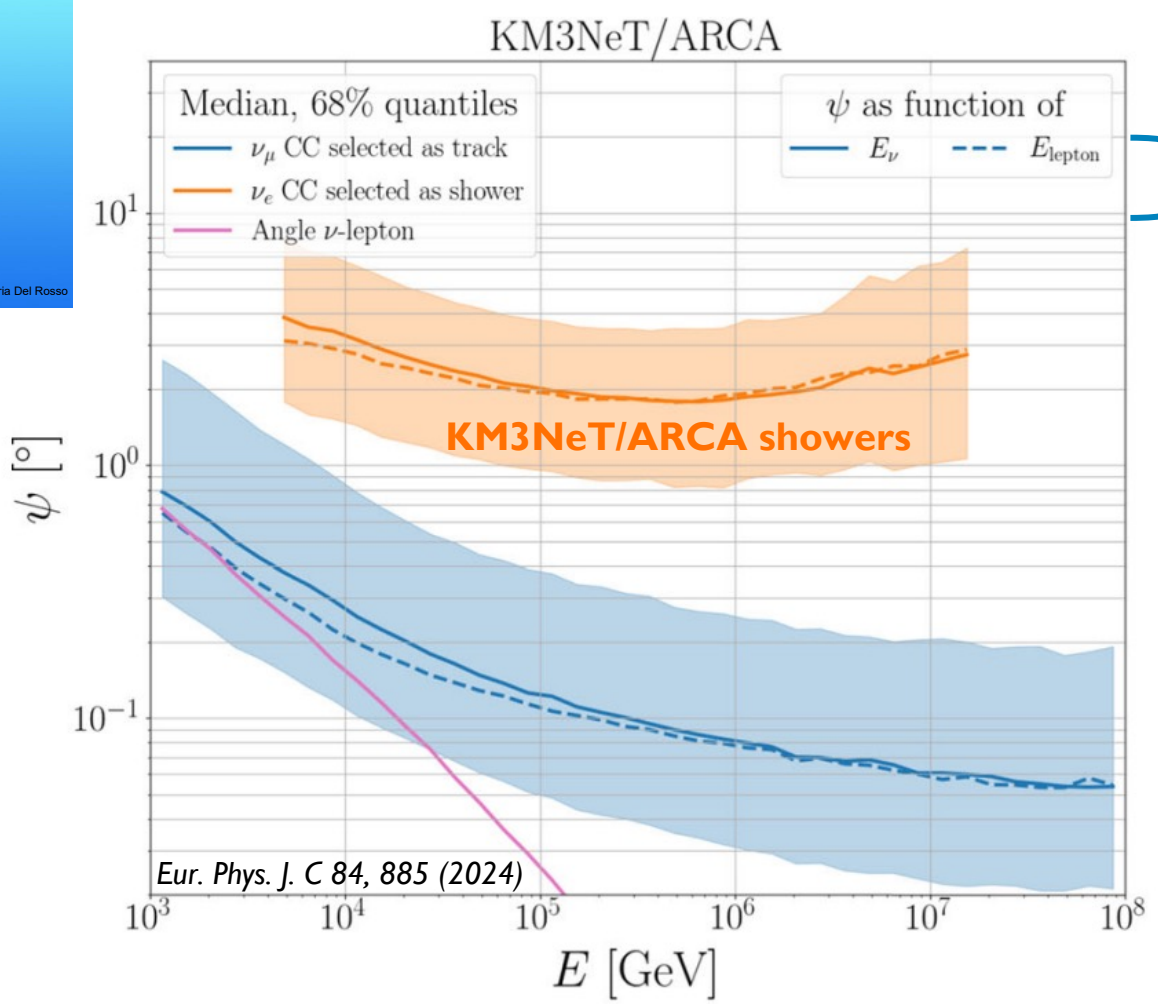



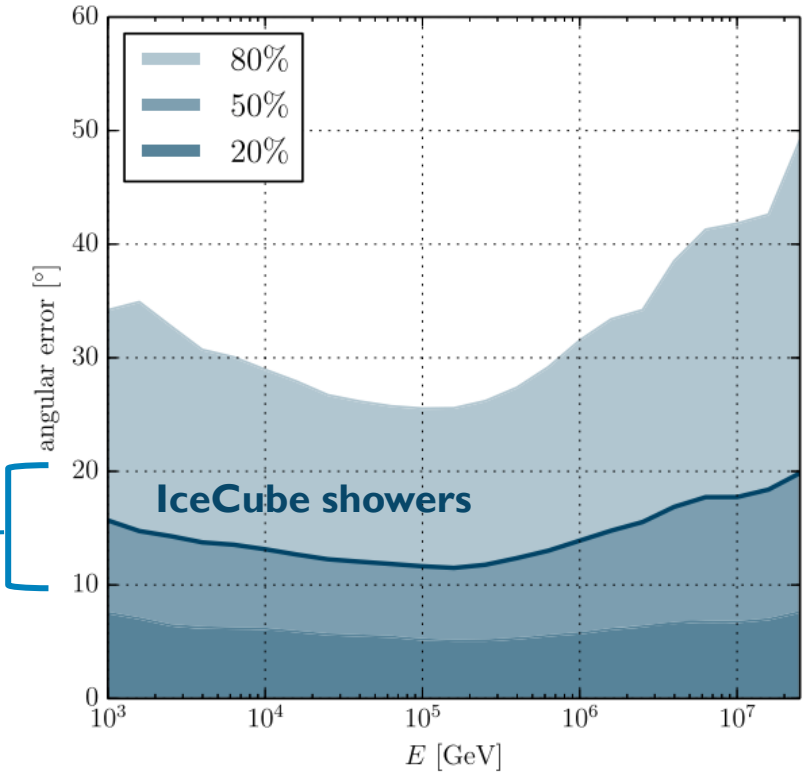



# Prospects for KM3NeT

**Shower channel**

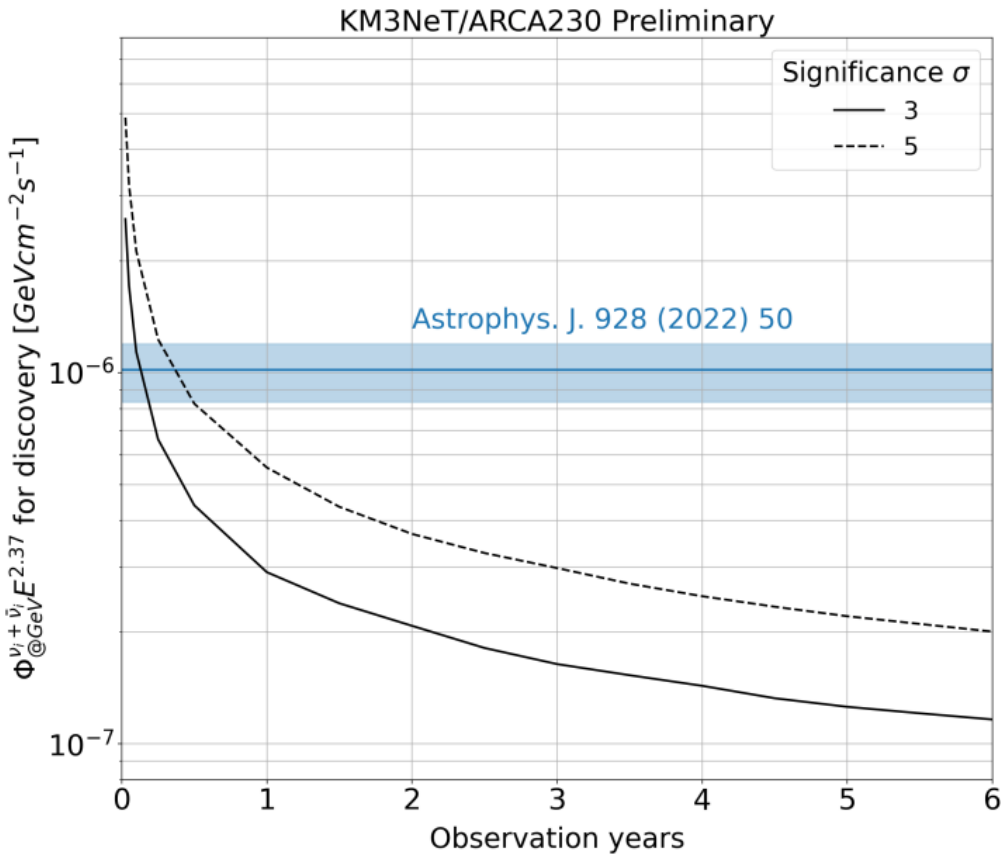


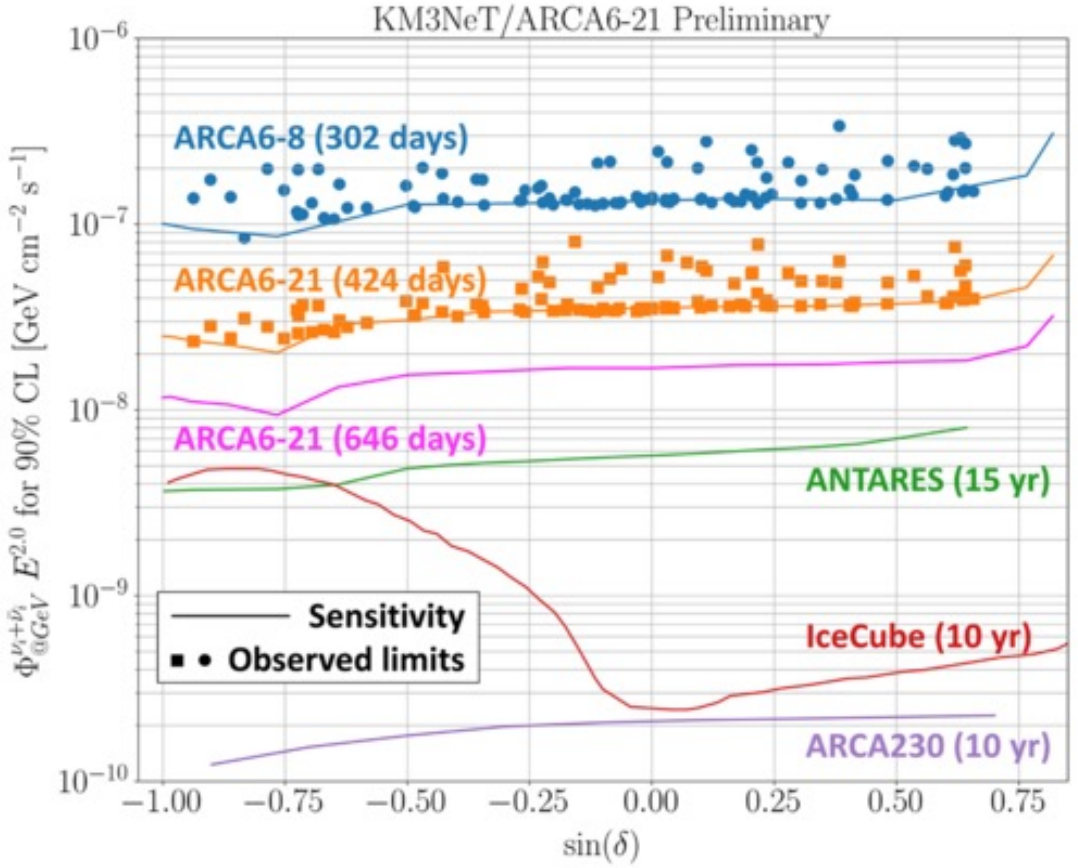



# Prospects for KM3NeT

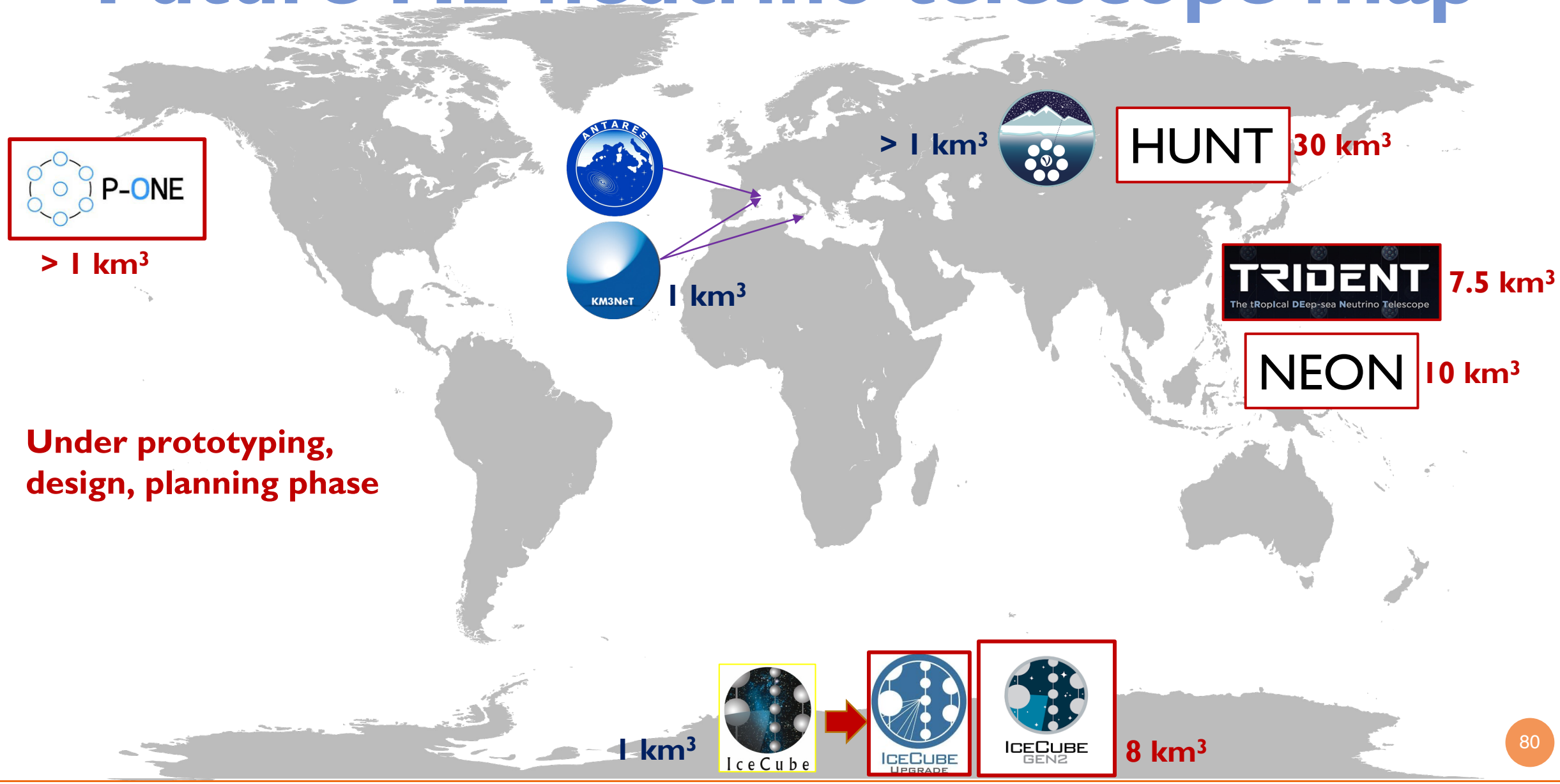
**Diffuse flux: IceCube observed flux will be confirmed within 1 year of operation with ARCA230**




**KM3NeT/ARCA is rapidly evolving approaching ANTARES and IceCube sensitivities**



# Future HE neutrino telescope map



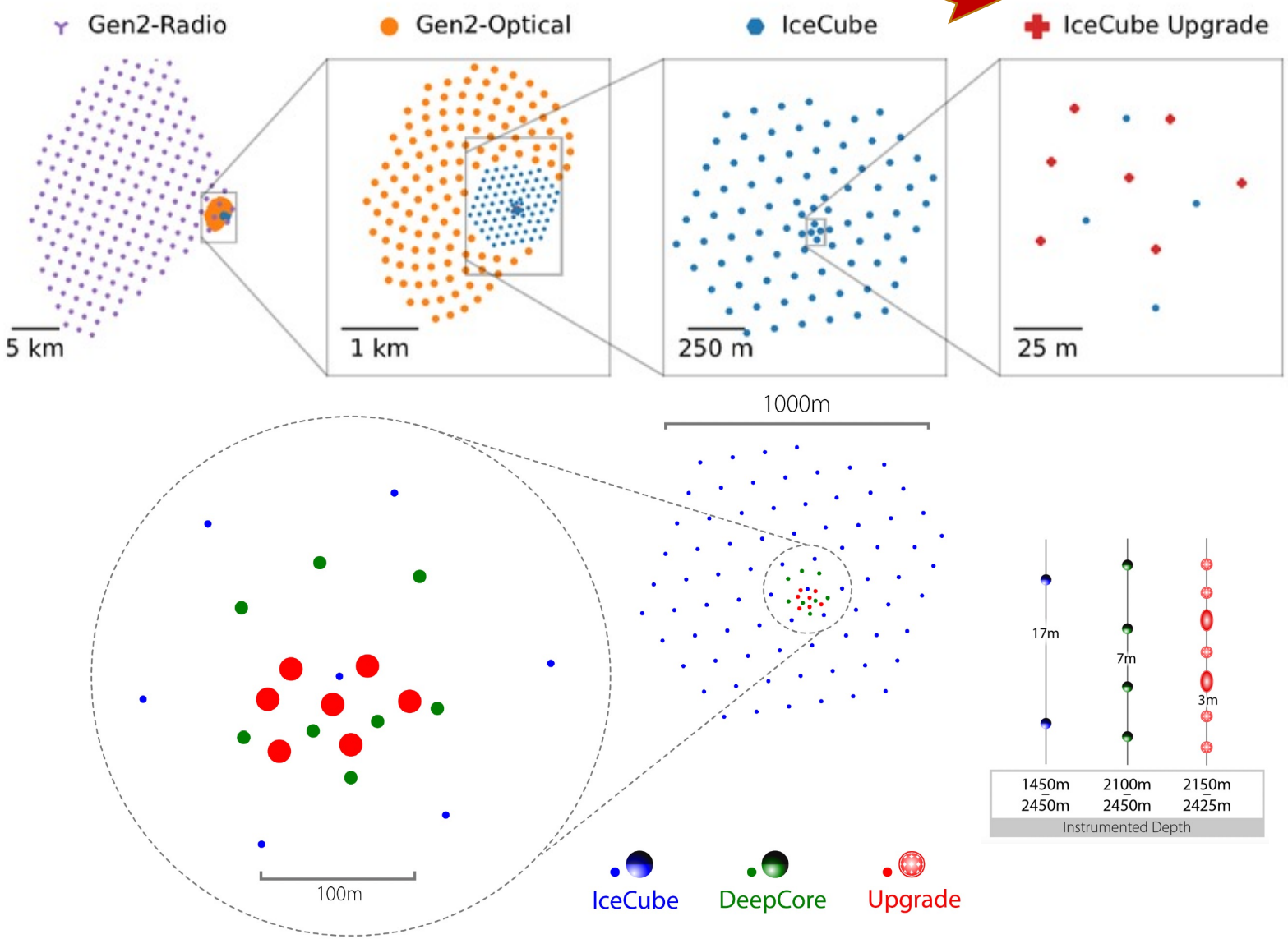
PoS(ICRC2019)1031

# IceCube-Upgrade

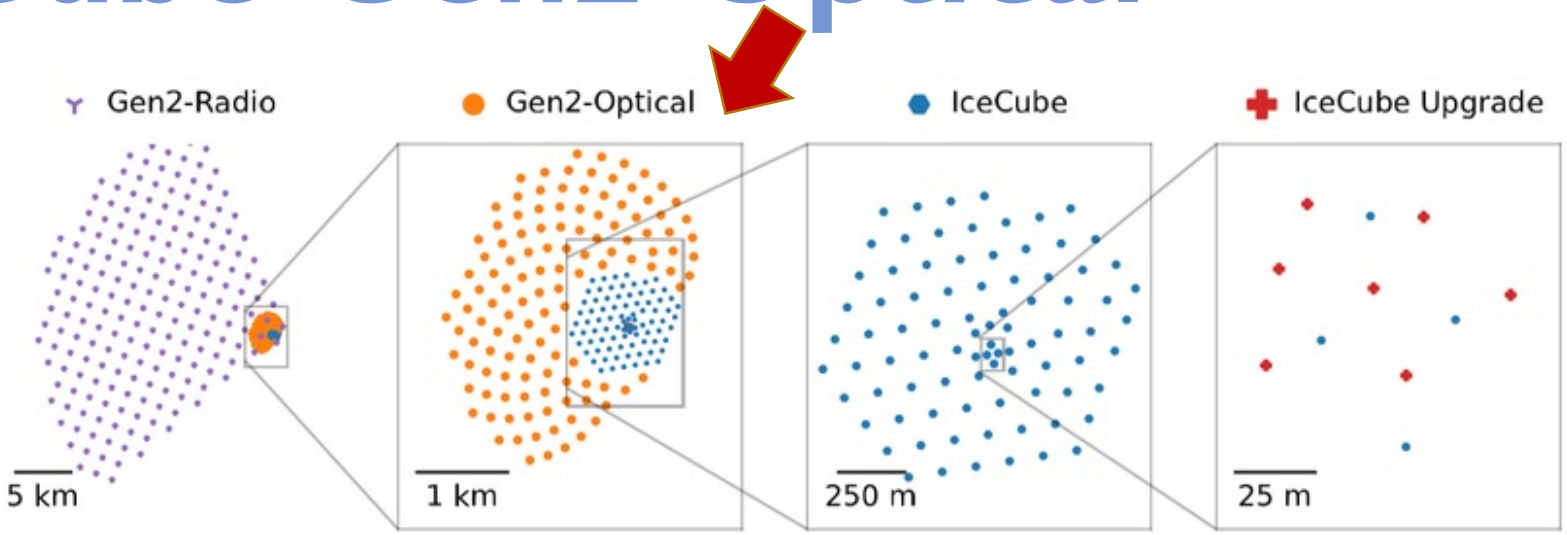
- 7 new strings with ~20 m spacing
- ~700 optical sensors
- New calibration devices
- Located inside of IceCube-DeepCore

Calibration devices will **improve knowledge of optical properties** of glacial ice and the detector response
→ recalibrate IC archival data

Science:
**Oscillations, dark matter, tau neutrinos, …**

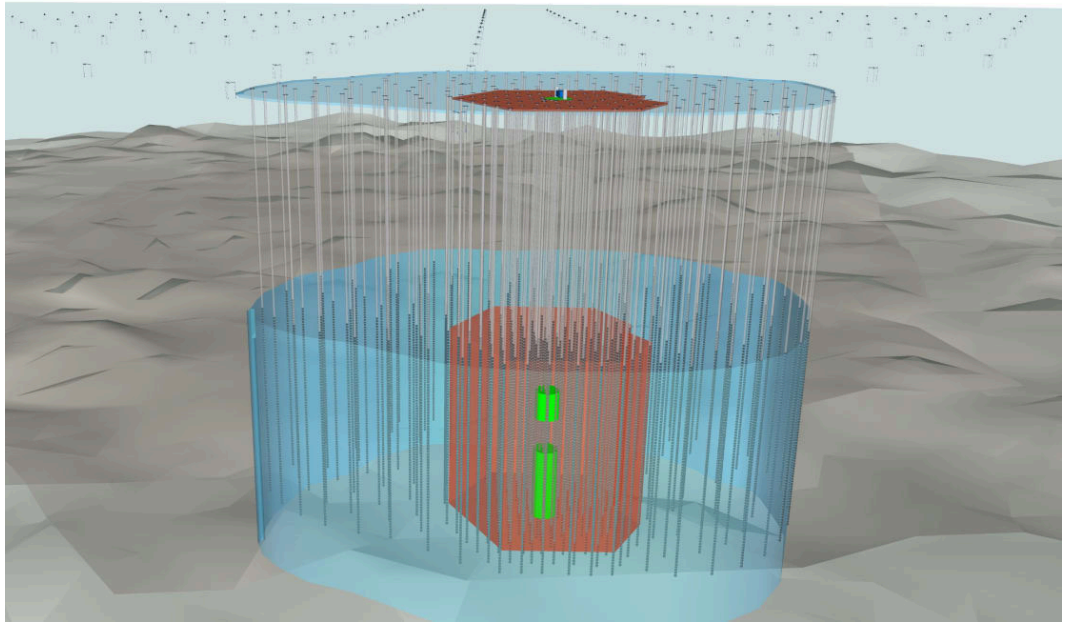


# IceCube-Gen2-Optical




**Sparse array of Cherenkov strings** around existing IceCube

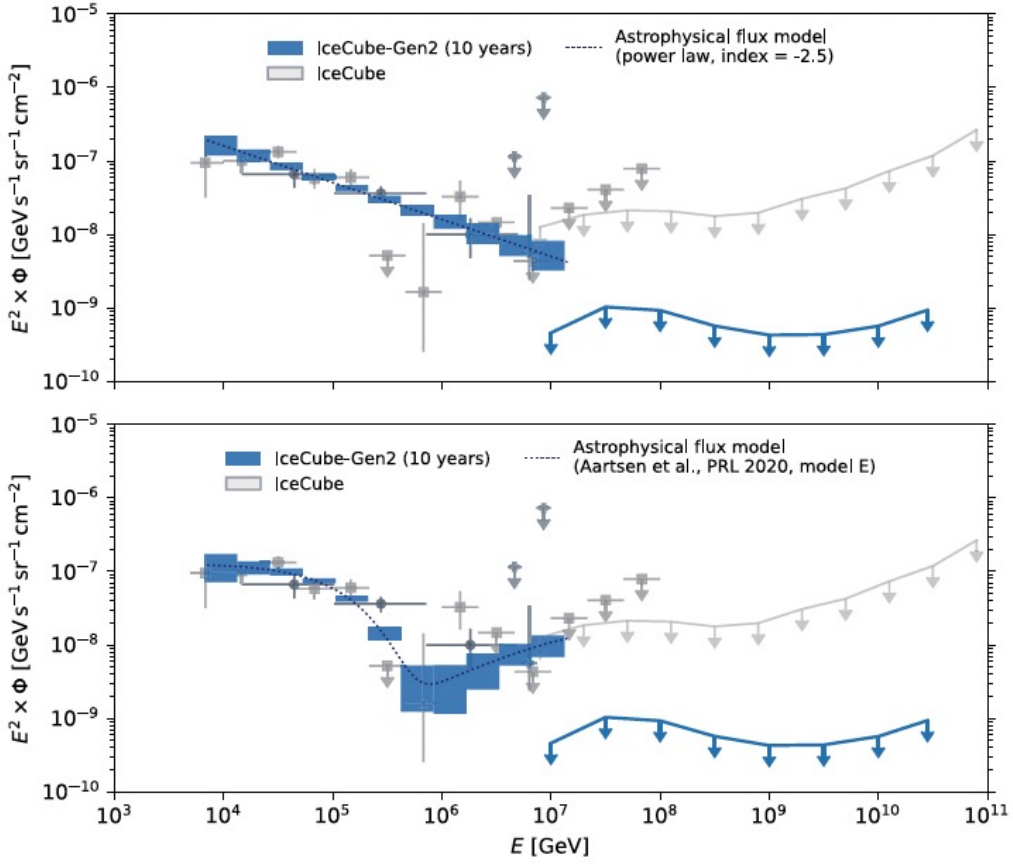
- ~8 km$^3$
- 120 (extra) strings
- 80 DOMs each
- String spacing: 240 m (125 m in IC)

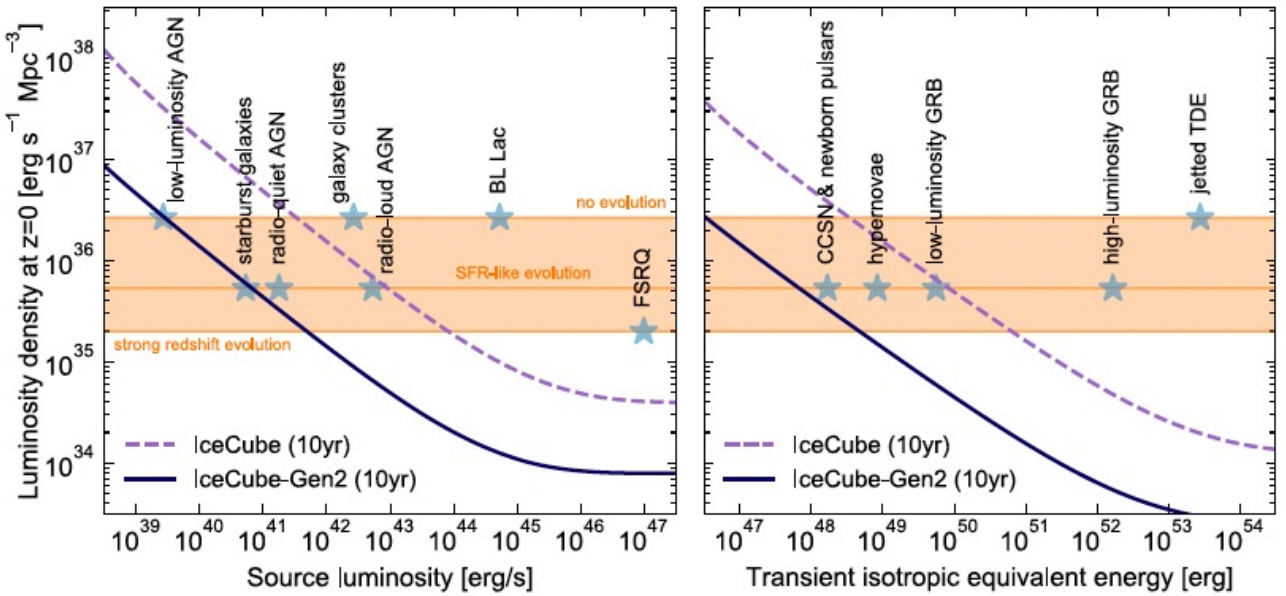


- **An order of magnitude more neutrino events** detected per year compared to IceCube
- **Five times better sensitivity** to point sources
- → **High statistics regime**

*JHEAp* 36 (2022) 55-110

# IceCube-Gen2-Optical

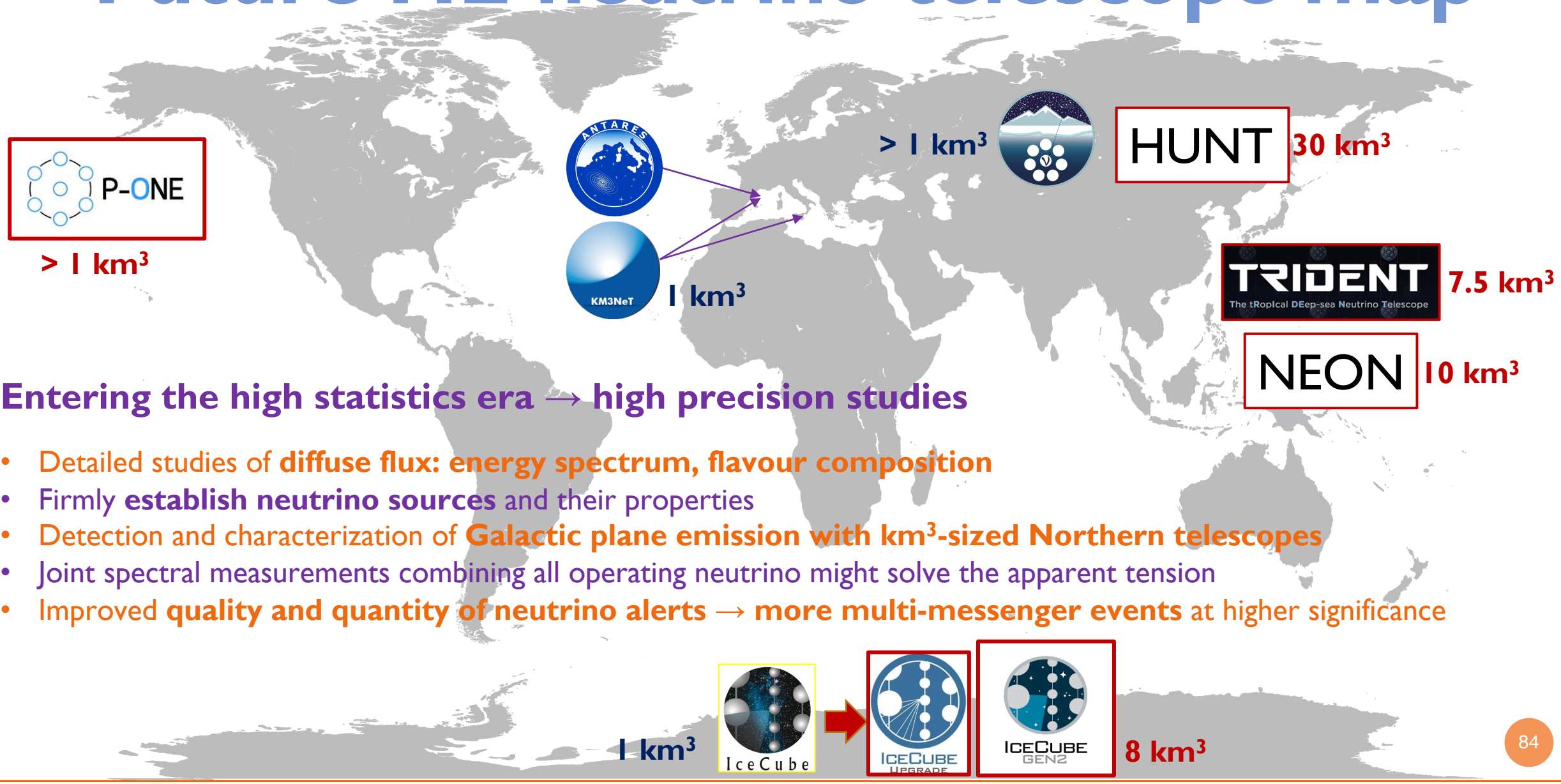



Key measurements to reveal

- **spectral features** in the astrophysical neutrino component
- the ***dominant* population** for the observed diffuse neutrino flux

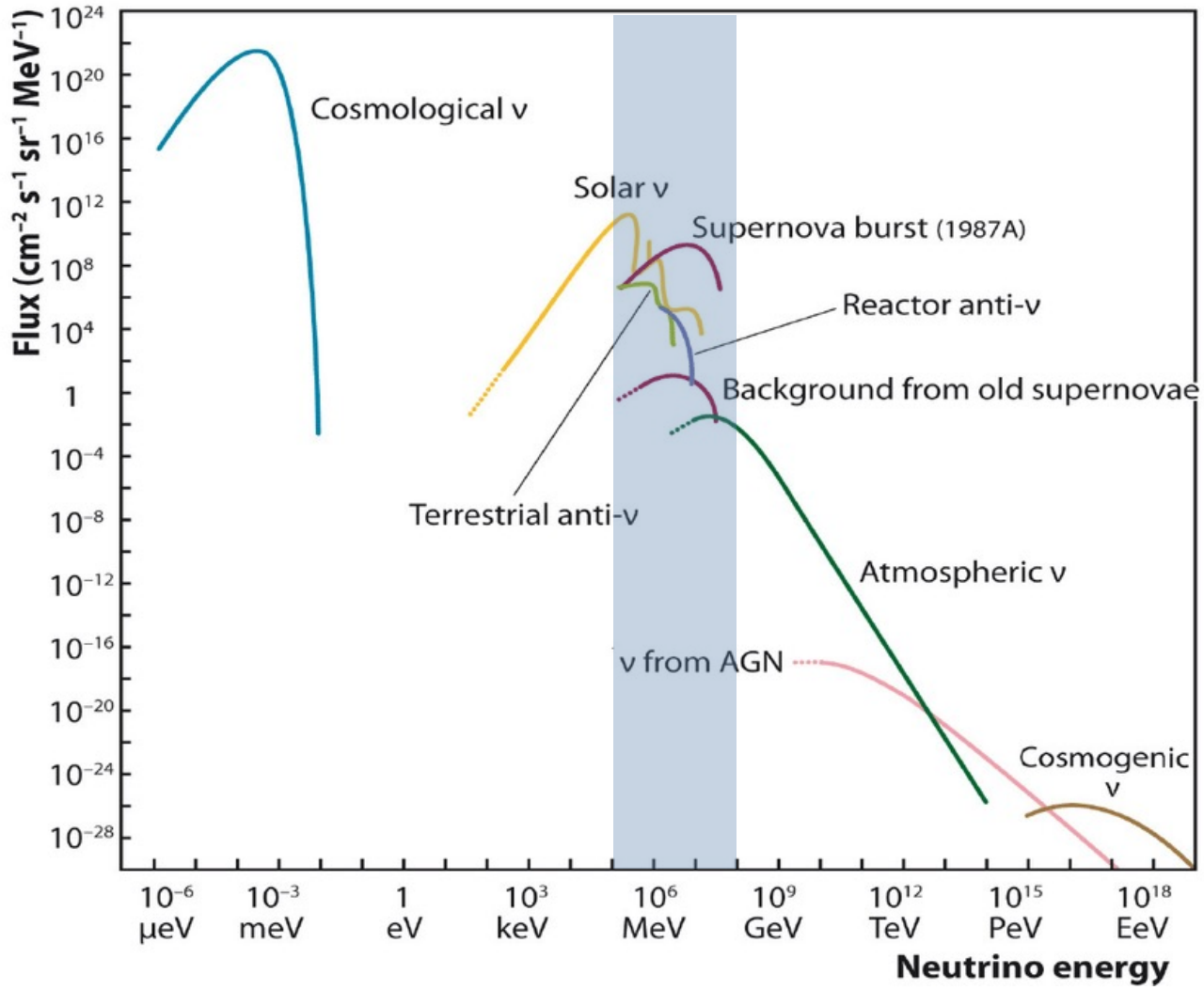
# Future HE neutrino telescope map



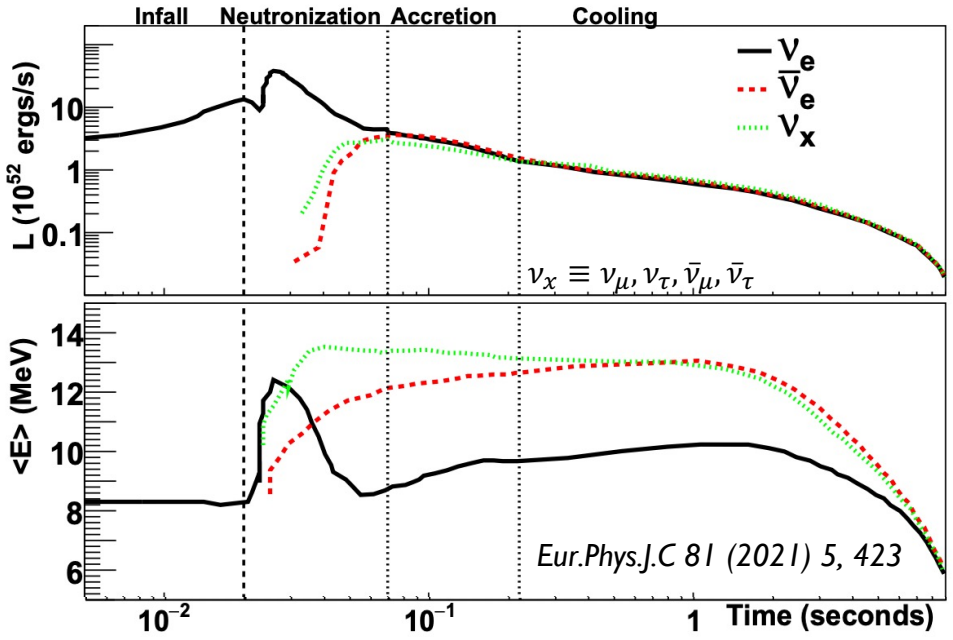

**Entering the high statistics era → high precision studies**

- Detailed studies of **diffuse flux: energy spectrum, flavour composition**
- Firmly **establish neutrino sources** and their properties
- Detection and characterization of **Galactic plane emission with km³-sized Northern telescopes**
- Joint spectral measurements combining all operating neutrino might solve the apparent tension
- Improved **quality and quantity of neutrino alerts → more multi-messenger events** at higher significance

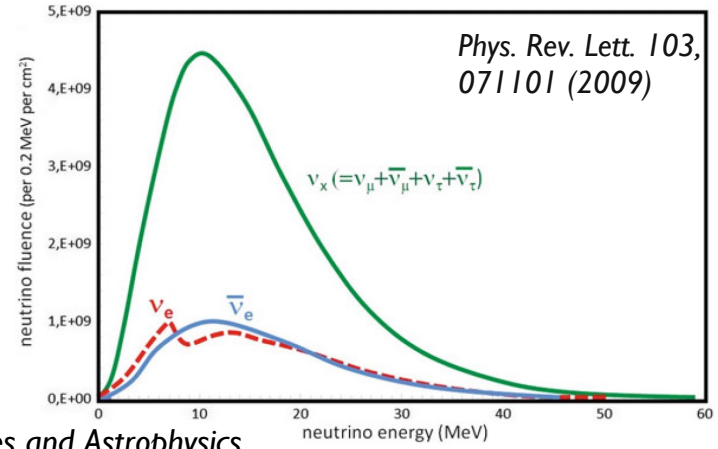
# MeV range: solar and CCSN neutrinos



# Neutrino signal from CCSN




Integrating in time




*Book: Particles and Astrophysics*

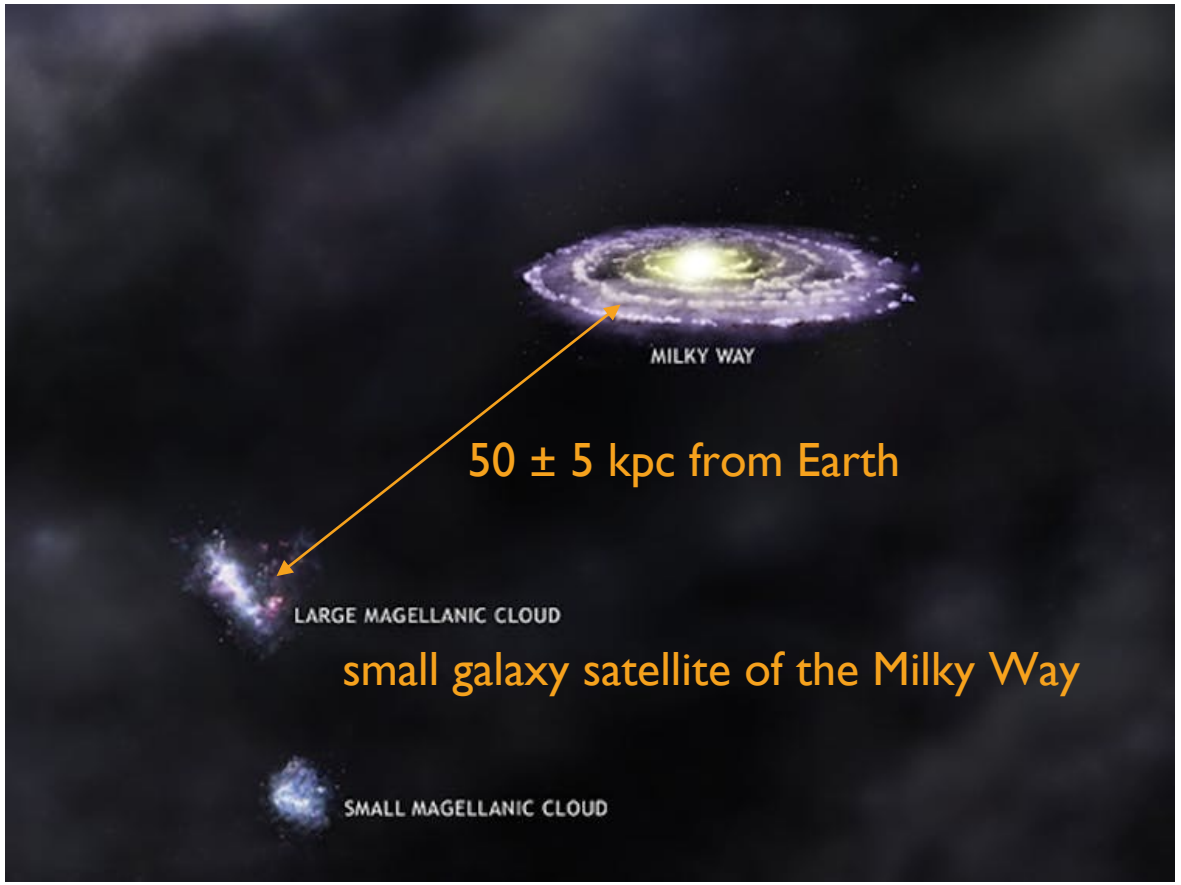
**Luminosity**: total energy carried away by neutrinos per unit time
**Mean neutrino energy:** typical energy of individual neutrinos

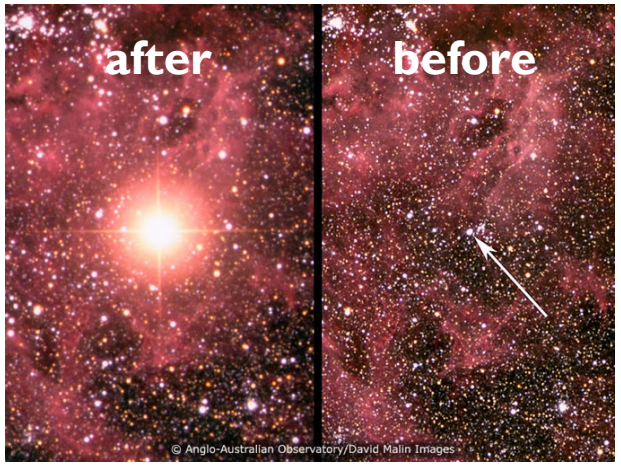
The time evolution of luminosity and mean energy for different neutrino flavors depends on several physical factors, including:

- **the production mechanism**, such as:
  - electron capture
  - positron capture
  - electron–positron pair production
- the **type of interaction with matter**, in particular:
  - charged-current interactions (for $\nu_e$ and $\bar{\nu}_e$)
  - neutral-current interactions (for all flavors, dominant for $\nu_x$)
- **Thermalization through repeated interactions**, which erases memory of the initial production energy
- The **radius of the neutrinosphere**, which differs for each flavor and determines the local temperature at decoupling

# SN1987A

## First and only CCSN seen in neutrinos




archival optical image

**February 23, 1987**

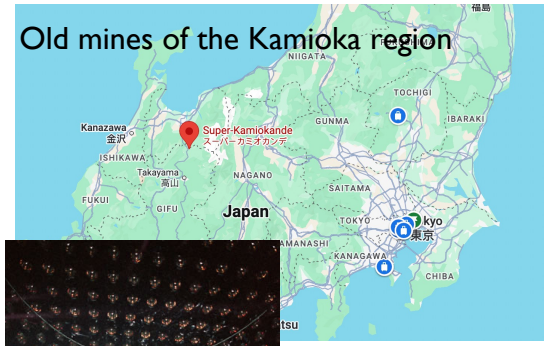
Progenitor: **Sanduleak-69202**

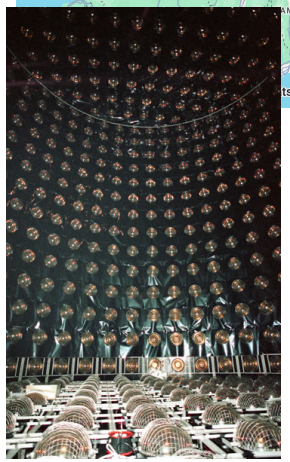
- **mass 16-22 $M_\odot$**
- **Located in LMC**

- Closest CCSN since 1604 (Kepler's supernova)
- As Kepler's SN, it was even visible with naked eye
- **First discovered optically at the Las Campanas Observatory in Chile**

# SN1987A

## First and only CCSN seen in neutrinos

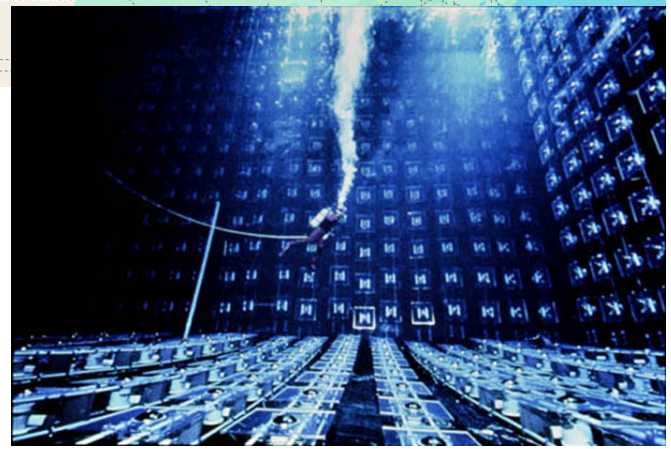


### Kamiokande

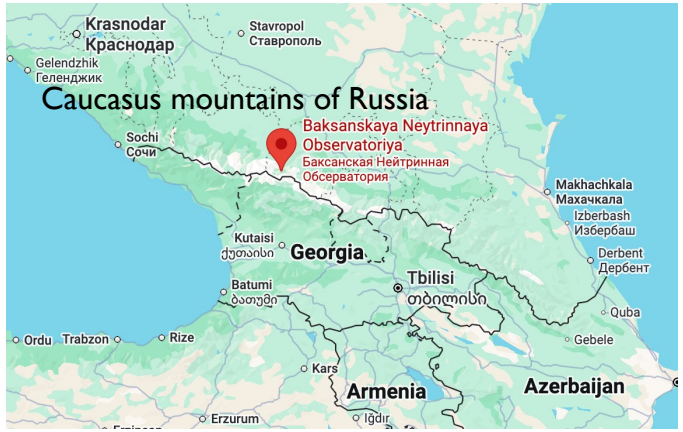
- Detects ~20 MeV neutrinos mainly through: $\bar{\nu}_e + p \rightarrow n + e^+$

### IMB
**Irvine Michigan Brookhaven experiment**

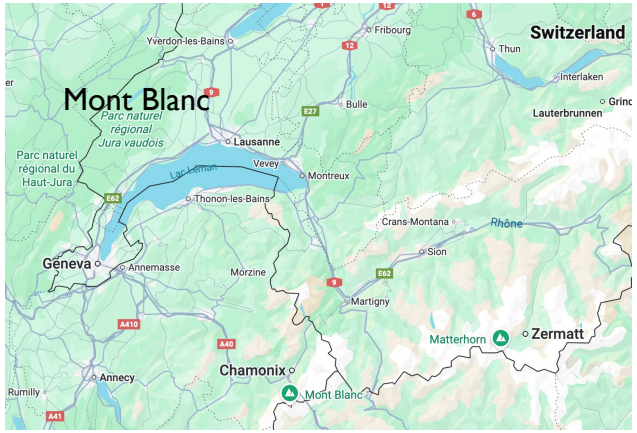


- **Water Cherenkov**
- 5 kt, 1570 mwe deep
- Smaller and sparser PMTs compared to Kamiokande
- **20 MeV energy threshold → not suitable for solar neutrinos**
- **Science goal: detecting proton decay** through $p \rightarrow e^+ + \pi^0$
- Could see neutrinos through: $\bar{\nu}_e + p \rightarrow n + e^+$

### Baksan




### LSD (Liquid Scintillation Detector)




### Scintillator detectors

Limited their sensitivity compared to Kamiokande and IMB due to smaller size and higher background

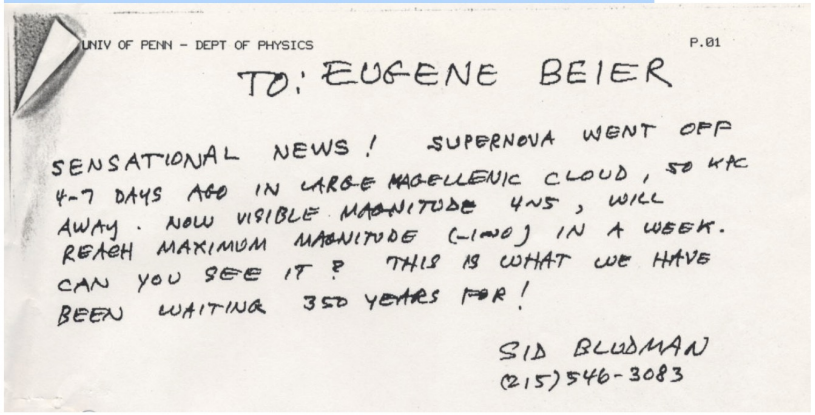
# SN1987A

https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/324

## First and only CCSN seen in neutrinos

### The day of detection of the supernova neutrinos

On February 25, 1987, two days after the observation of supernova SN1987A through naked eyes, a fax was sent from Pennsylvania University to the University of Tokyo to inform them about the supernova explosion. Soon after receiving the fax, Prof. Yoji Totsuka asked the researcher in Kamioka to send the magnetic tapes that recorded the Kamiokande data. (At that time, the information network was not developed, so the data was delivered physically.)



UNIV OF PENN - DEPT OF PHYSICS P.01

TO: EUGENE BEIER

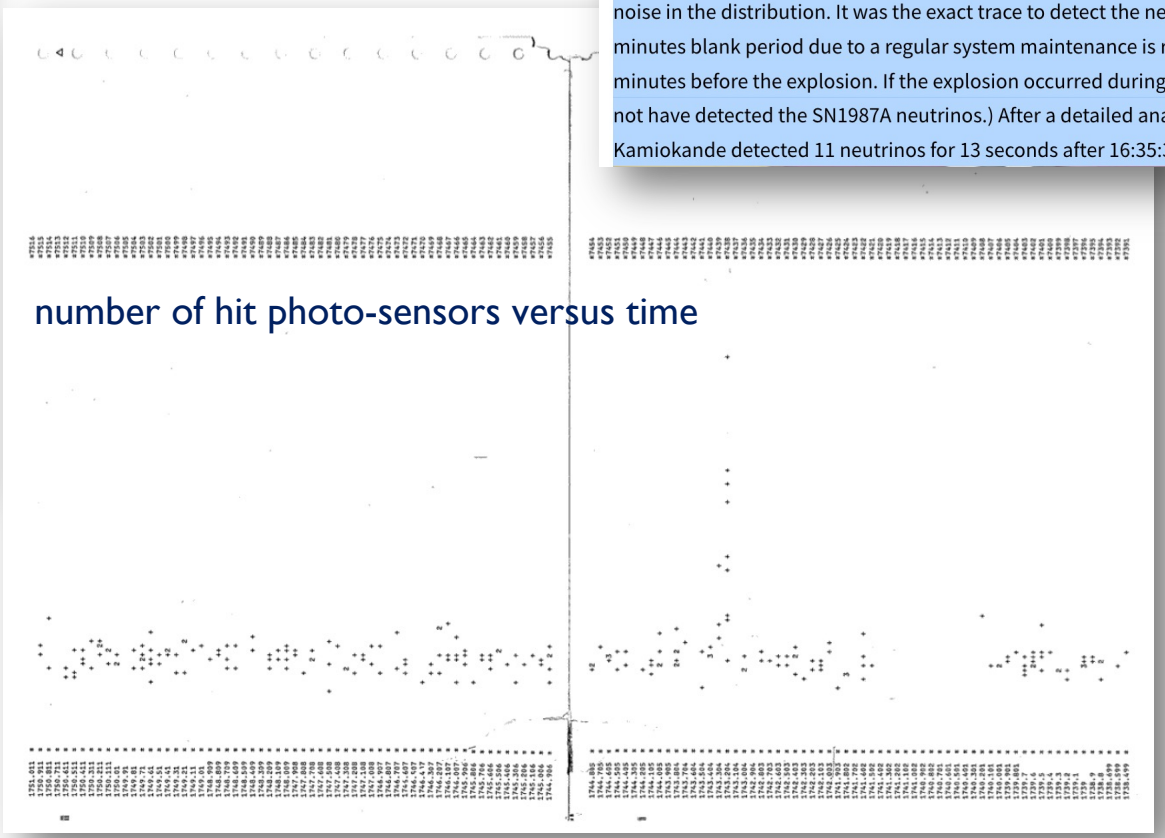
SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4M5, WILL REACH MAXIMUM MAGNITUDE (-1M0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

The fax sent from Pennsylvania University to inform about the supernova explosion.

The magnetic tape recorded SN1987A data

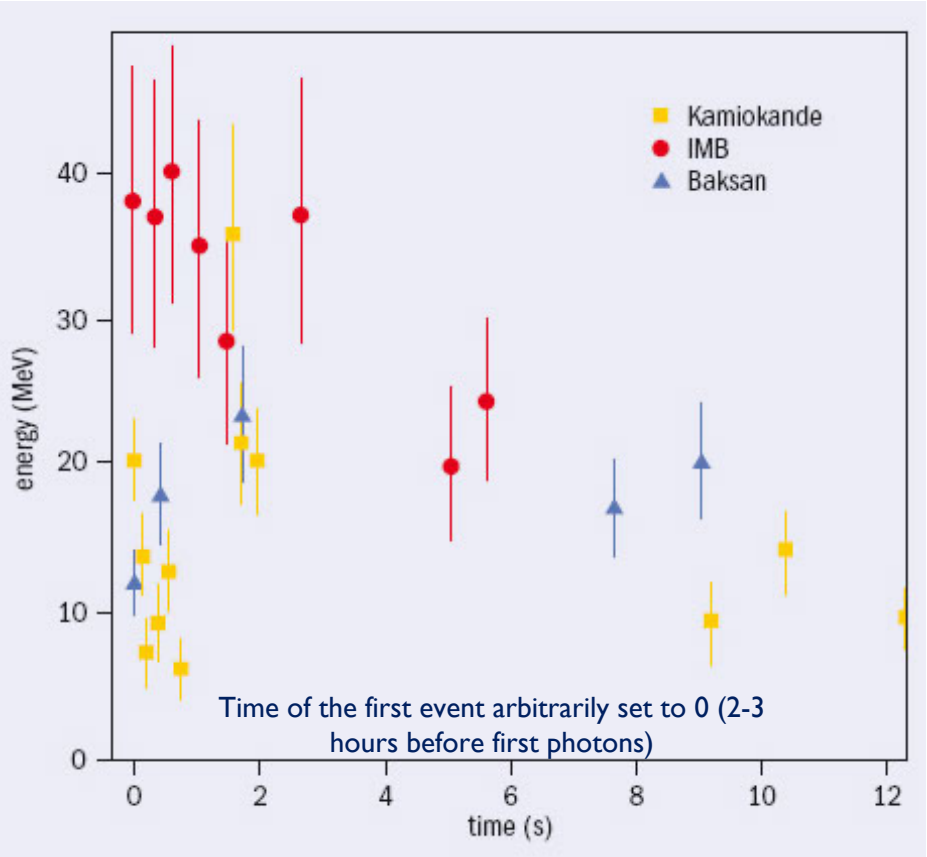
On February 27, when the magnetic tapes arrived at the laboratory in Tokyo, Prof. Masayuki Nakahata (currently the spokesperson of Super-Kamiokande experiment), who was then a PhD student immediately started the analysis. On the morning of February 28, while Prof. Nakahata printed out the analysis plot between the detection time and number of photo-sensors that detect the light, Ms. Keiko Hirata, a Master's student found a peak, obviously different from the noise in the distribution. It was the exact trace to detect the neutrinos from SN1987A. (A two minutes blank period due to a regular system maintenance is recorded in the plot, at a few minutes before the explosion. If the explosion occurred during this period, Kamiokande could not have detected the SN1987A neutrinos.) After a detailed analysis, it was clear that Kamiokande detected 11 neutrinos for 13 seconds after 16:35:35 on February 23, 1987.



# SN1987A

## First and only CCSN seen in neutrinos

- **Kamiokande, IMB → robust detection**
- **Baksan → weaker but compatible excess**
- **LSD** → signal ~5 hours earlier, not explainable by standard core-collapse models, **controversial**




Although few events were detected, **they were enough to confirm the baseline model of CCSN:**

- time distribution in agreement with predictions of a **~10 s burst**;
- energy distribution gives a **measure of the temperature (T~4.2 MeV) of the ν-sphere and confirms typical neutrino energies of ~10-20 MeV**;
- number of the observed events is in agreement with **~3 × $10^{53}$ erg luminosity** of a CCSN burst

**First astrophysical neutrino source observed outside the Sun and first multi-messenger astronomical event**

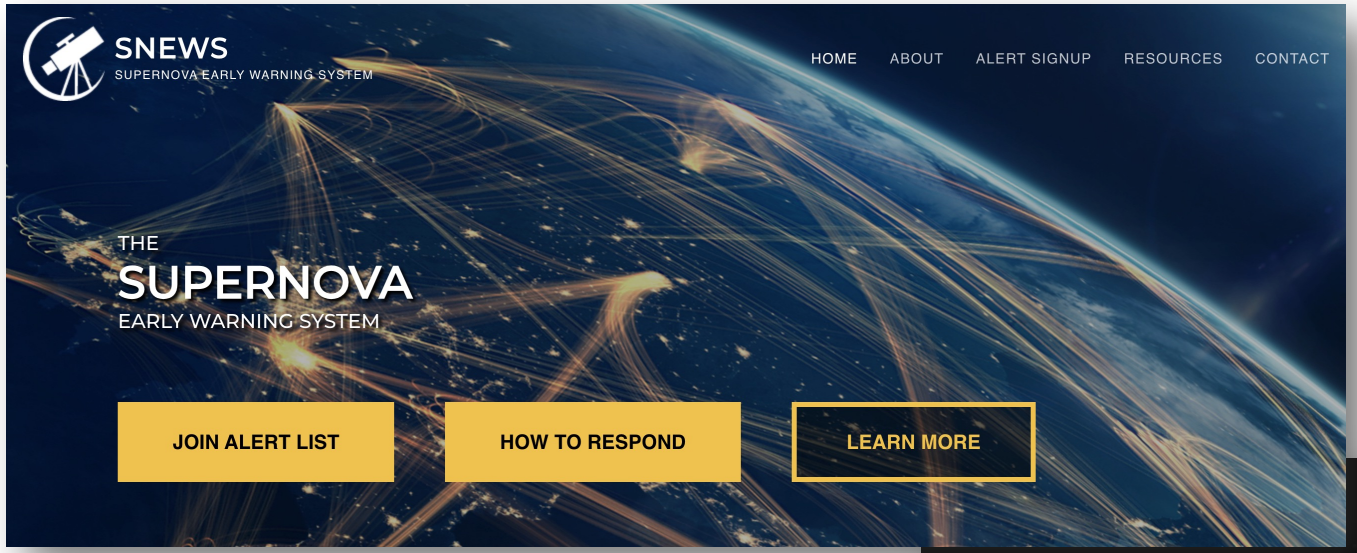
# Detecting the next CCSN

https://snews2.org/about/

| Experiment | Type | Mass [kt] | Location | 11.2 $M_\odot$ | 27.0 $M_\odot$ | 40.0 $M_\odot$ |
|---|---|---|---|---|---|---|
| Super-K | $H_2O/\bar{\nu}_e$ | 32 | Japan | 4100/4100 | 7800/7600 | 7600/4900 |
| Hyper-K | $H_2O/\bar{\nu}_e$ | 220 | Japan | 28K/28K | 54K/52K | 52K/34K |
| IceCube | String/$\bar{\nu}_e$ | 2500* | South Pole | 320K/340K | 670K/660K | 820K/630K |
| KM3NeT | String/$\bar{\nu}_e$ | 150* | Italy | 18K/19K | 39K/40K | 55K/46K |
| LVD | $C_nH_{2n}/\bar{\nu}_e$ | 1 | Italy | 190/190 | 360/350 | 340/230 |
| KamLAND | $C_nH_{2n}/\bar{\nu}_e$ | 1 | Japan | 190/190 | 360/350 | 340/230 |
| Borexino | $C_nH_{2n}/\bar{\nu}_e$ | 0.278 | Italy | 52/52 | 100/97 | 95/65 |
| JUNO | $C_nH_{2n}/\bar{\nu}_e$ | 20 | China | 3800/3800 | 7200/7000 | 6900/4700 |
| SNO+ | $C_nH_{2n}/\bar{\nu}_e$ | 0.78 | Canada | 150/150 | 280/270 | 270/180 |
| NO$\nu$A | $C_nH_{2n}/\bar{\nu}_e$ | 14 | USA | 1900/2000 | 3700/3600 | 3600/2400 |
| Baksan | $C_nH_{2n}/\bar{\nu}_e$ | 0.24 | Russia | 45/45 | 86/84 | 82/56 |
| HALO | Lead/$\nu_e$ | 0.079 | Canada | 4/3 | 9/8 | 9/9 |
| HALO-1kT | Lead/$\nu_e$ | 1 | Italy | 53/47 | 120/100 | 120/120 |
| DUNE | Ar/$\nu_e$ | 40 | USA | 2700/2500 | 5500/5200 | 5800/6000 |
| MicroBooNe | Ar/$\nu_e$ | 0.09 | USA | 6/5 | 12/11 | 13/13 |
| SBND | Ar/$\nu_e$ | 0.12 | USA | 8/7 | 16/15 | 17/18 |
| DarkSide-20k | Ar/any $\nu$ | 0.0386 | Italy | 120/120 | 200/200 | 110/110 |
| XENONnT | Xe/any $\nu$ | 0.006 | Italy | 39/39 | 69/69 | 44/44 |
| LZ | Xe/any $\nu$ | 0.007 | USA | 33/33 | 61/61 | 42/42 |
| PandaX-4T | Xe/any $\nu$ | 0.004 | China | 26/26 | 46/46 | 29/29 |

# Detecting the next CCSN

https://snews2.org/



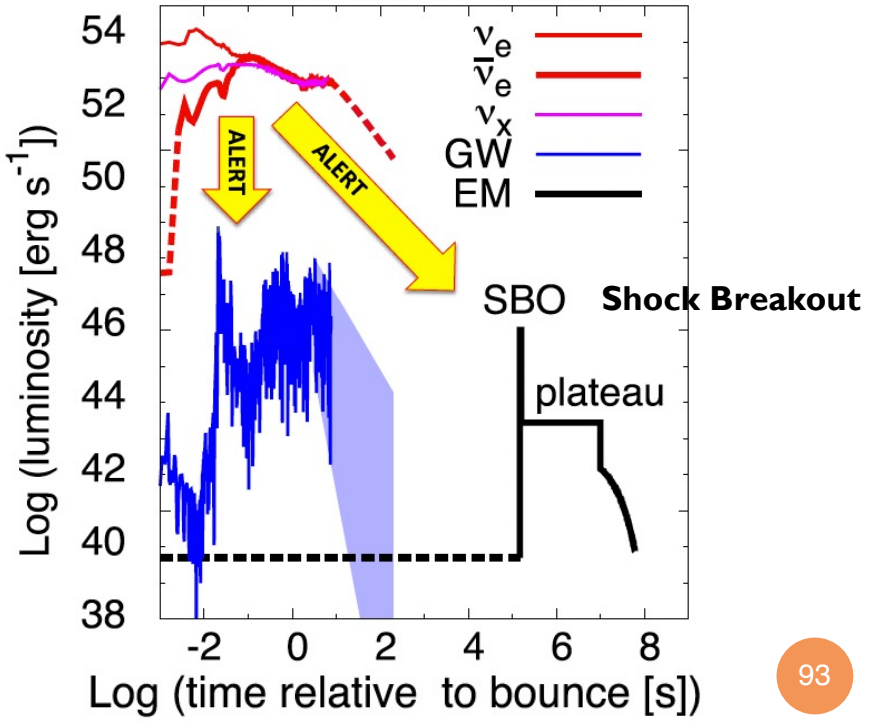
# Detecting the next CCSN

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

**CCSN are rare: ~1.6/century in the Milky Way→ crucial to be ready with all available instruments**
**Neutrinos, being the first observable messangers from CCSN, are crucial to ensure early warning**

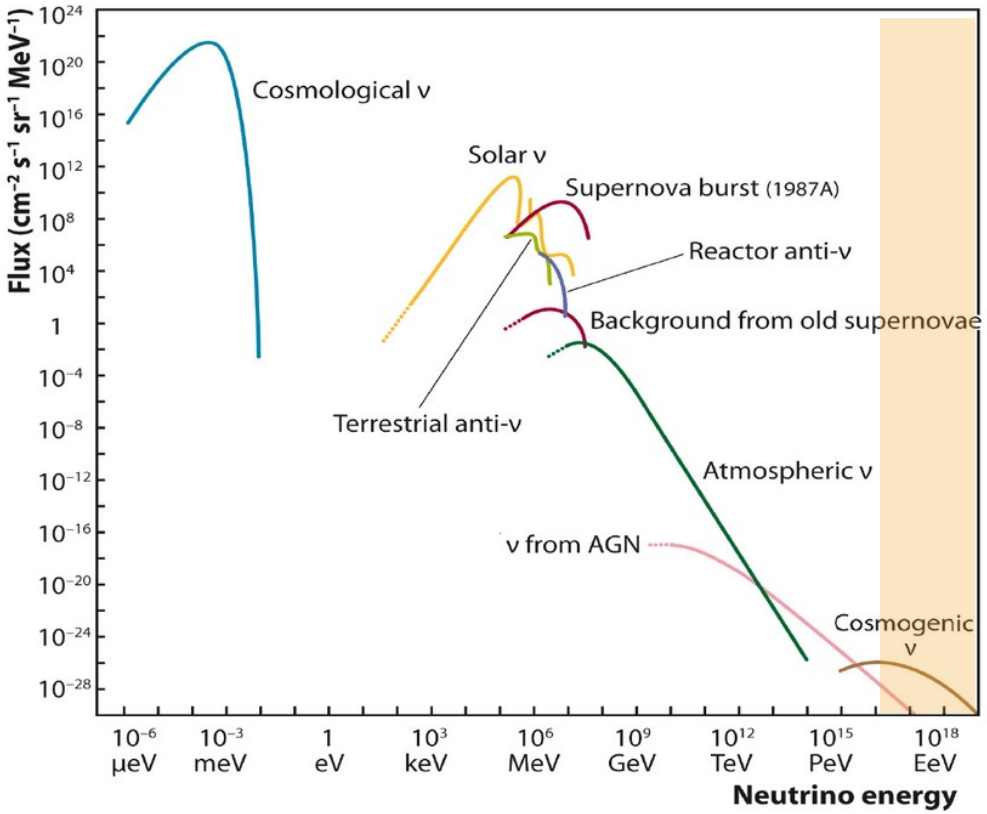
**Why combining detectors?**

- **reduce the threshold for generating alerts**
- **reduce alert latency**
- **provide CCSN direction though timing triangulation**
- **organize planned shutdowns to optimize monitoring uptime**

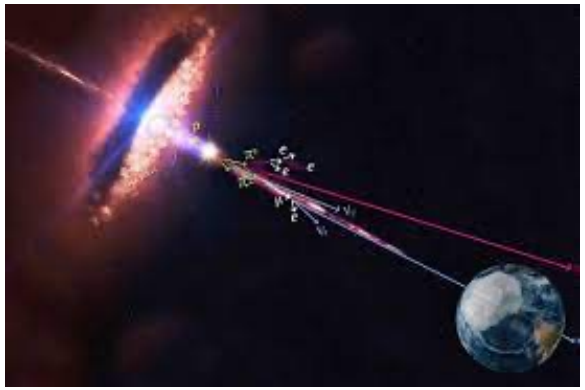



*New J. Phys. 23 031201 (2021)*

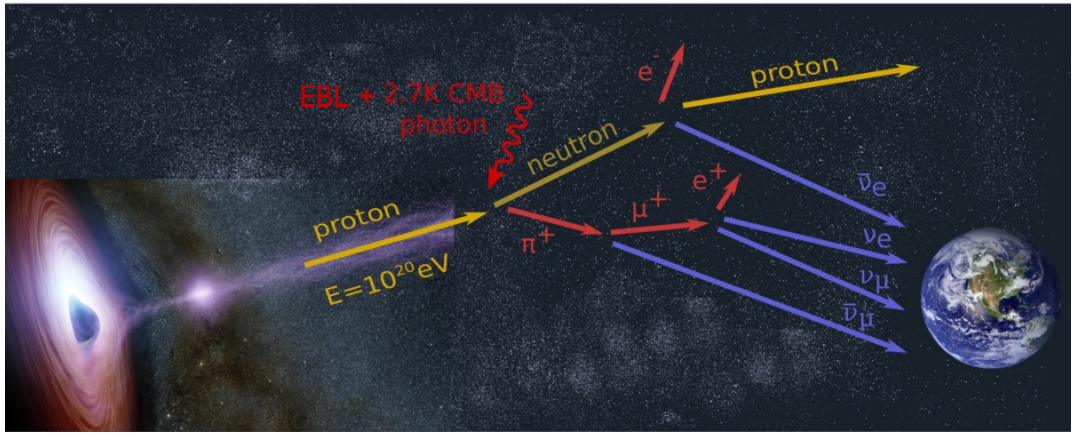
# UHE neutrinos



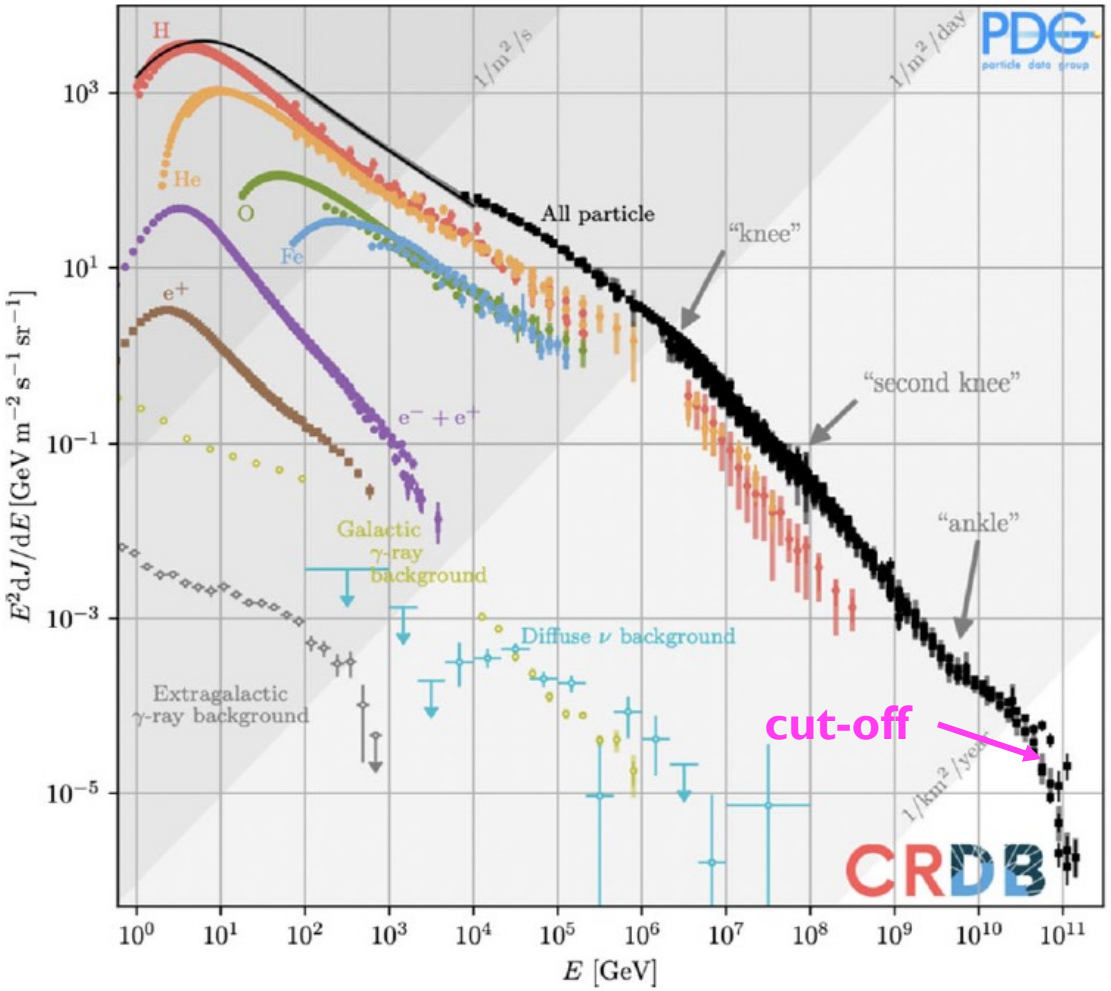

## UHE neutrinos from astrophysical sources



## Cosmogenic neutrinos
## result of UHECRs interacting with cosmic microwave background (CMB) photons and EBL



# UHE neutrinos




**UHECRs measured up to > $10^{20}$ eV (> $10^{11}$ GeV) by Pierre Auger Observatory and Telescope Array, with a cut-off at ~4-6 x$10^{19}$ eV**

**Possible reasons for the cut-off:**

Astrophysical sources are **unable to accelerate** CRs to higher energies

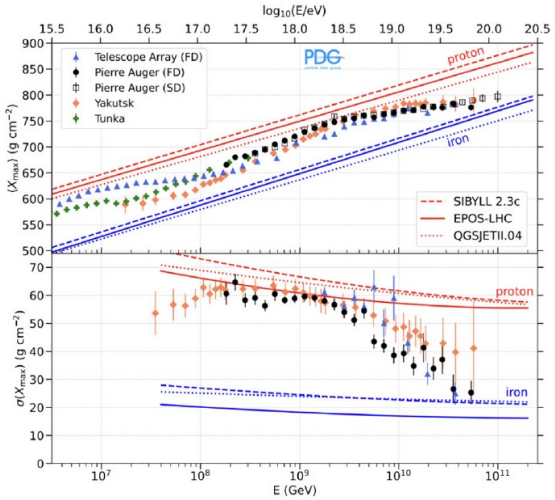
and

Greisen–Zatsepin–Kuzmin **(GZK) effect**: UHECR interactions with the CMB

$E_p \gtrsim 5\times10^{19}$ eV

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

**But are UHECRs protons?**




Nuclei interacting with CMB will primarily **photodisintegrate**

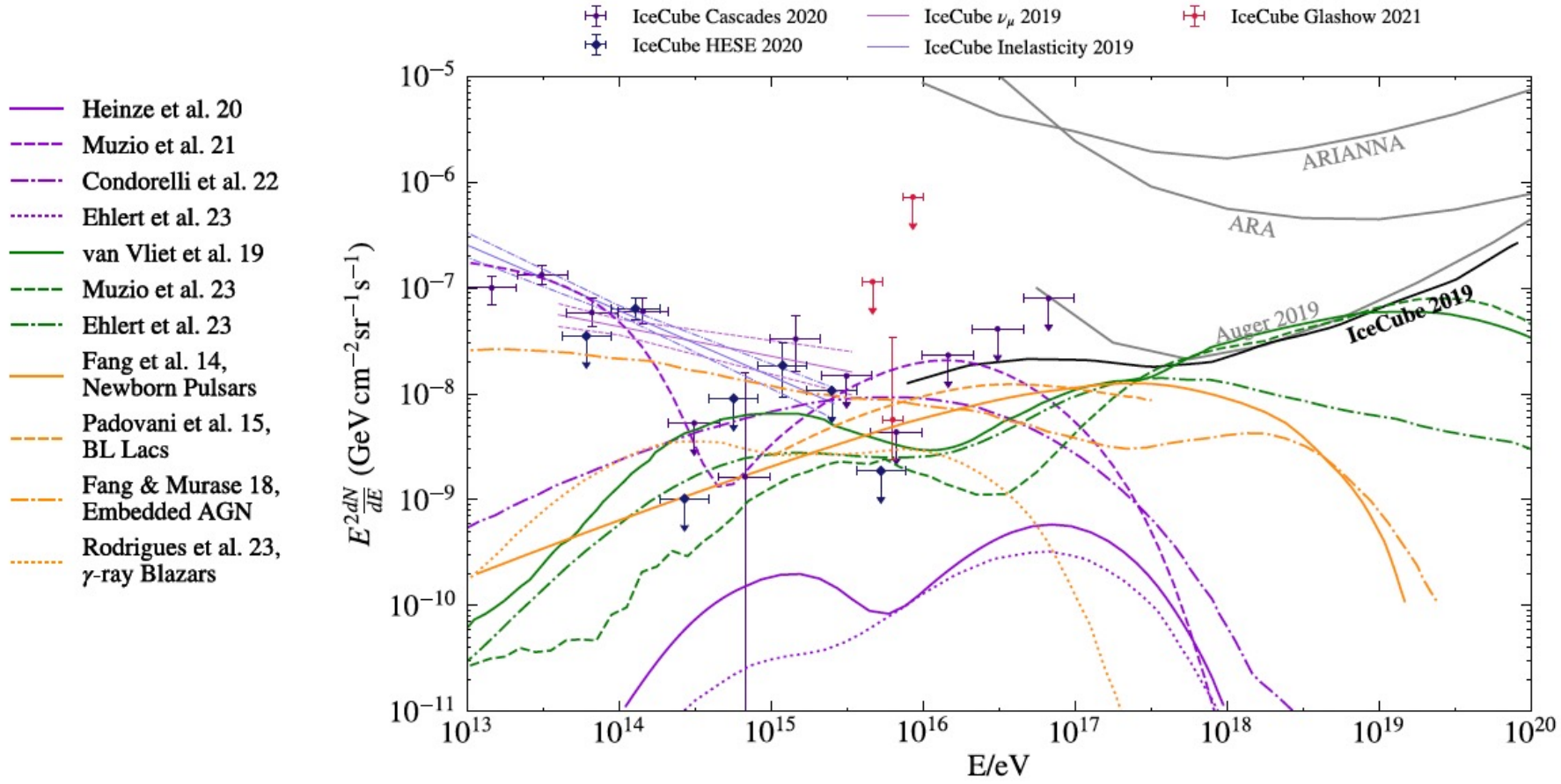
$A + \gamma_{CMB/EBL} \rightarrow (A-1) + N$

→ **UHE neutrinos with suppressed flux and shifted to lower energy** compared to that produced by protons

→ Uncertainties in UHECRs composition lead to **big uncertainties on expected neutrino fluxes**

# UHE neutrinos

## The zoo of the UHE neutrino flux models




**Different assumptions lead to different expected fluxes:**

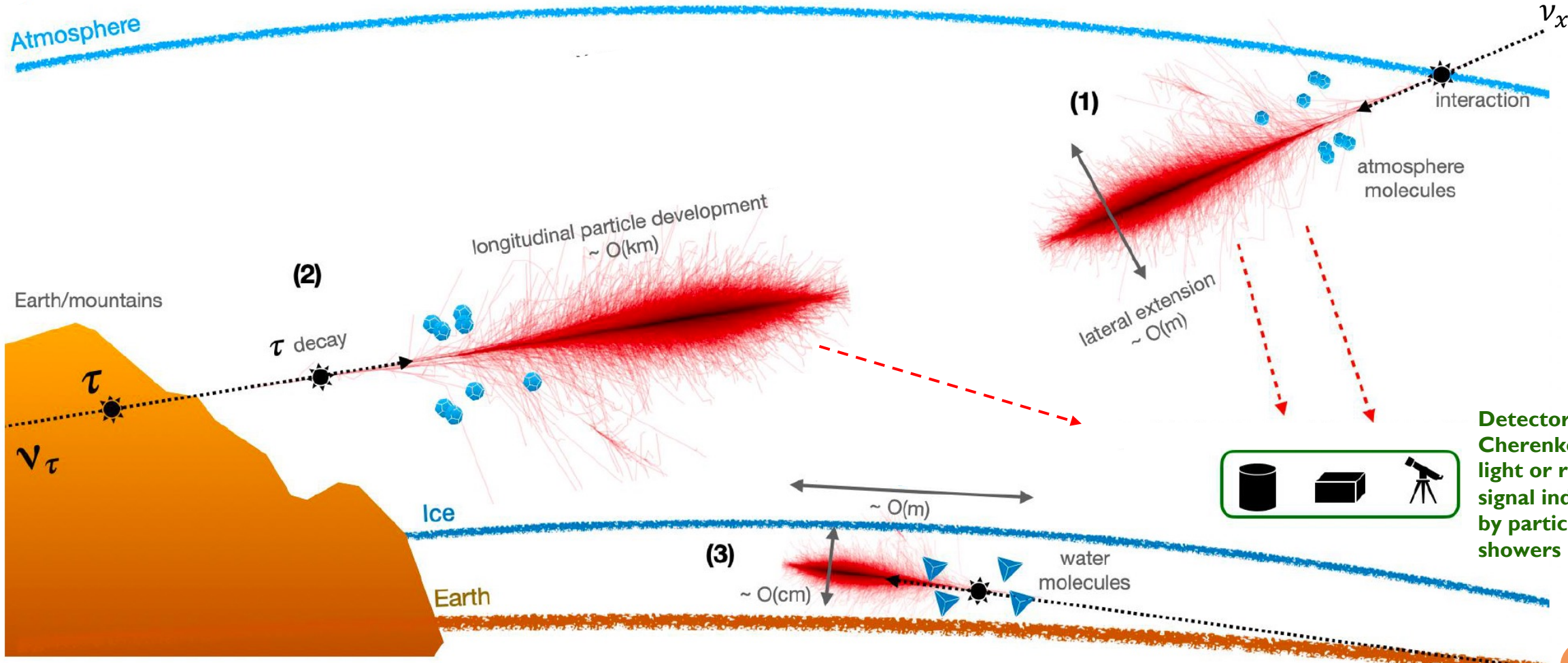
- UHECR composition (proton vs mixed vs heavy nuclei)
- Injection spectral index
- Source redshift evolution
- Maximum acceleration energy
- …

Assumptions must be **compatible with UHECR spectrum and composition** observations and the resulting **neutrino and gamma fluxes should be compatible with existing bounds and data**

*Eur. Phys. J. Spec. Top. (2025) 234:4939–4949*

# UHE neutrino detection

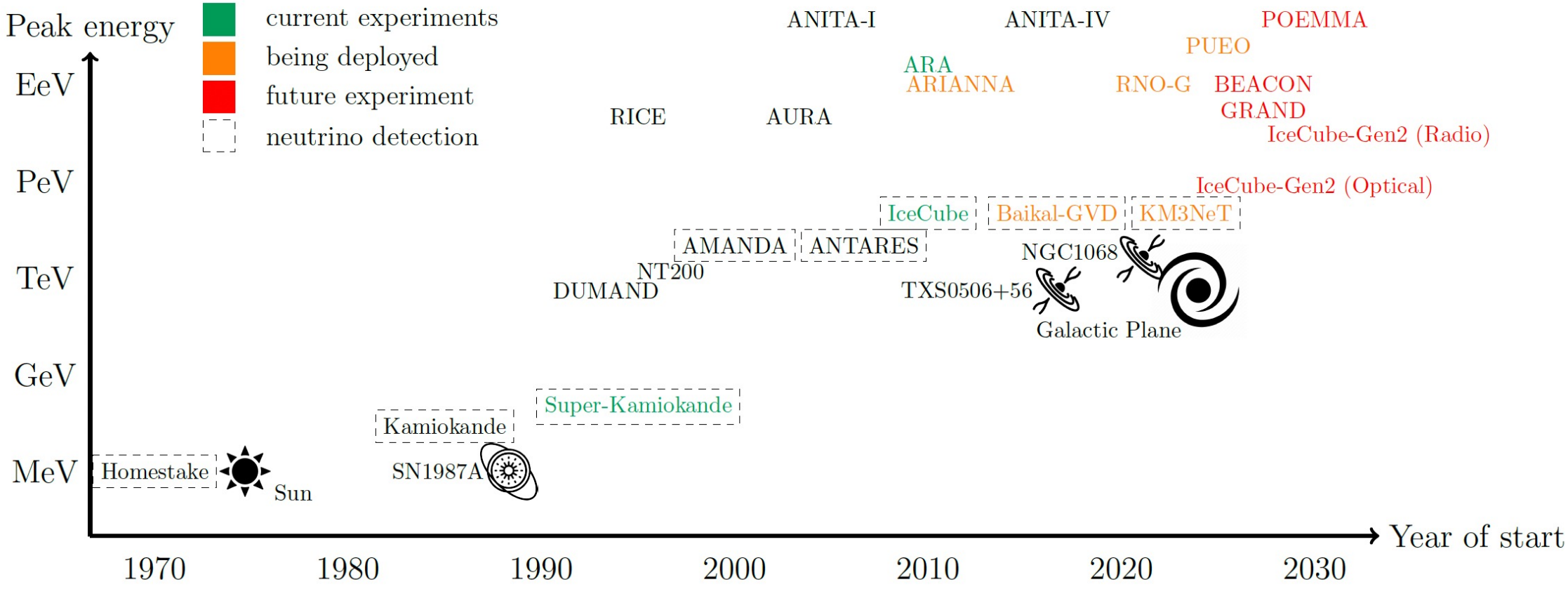
**Particle showers resulting from ν-interaction and/or induced by leptons produced in ν-interactions**




**Detectors of Cherenkov light or radio signal induced by particle showers**

*Modified from Chiche & Decoene, Moriond 2022*

# UHE vs: status




*PoS(ICRC2023)026*

# KM3-230213A: first ultra-high-energy ν

Article

## Observation of an ultra-high-energy cosmic neutrino with KM3NeT

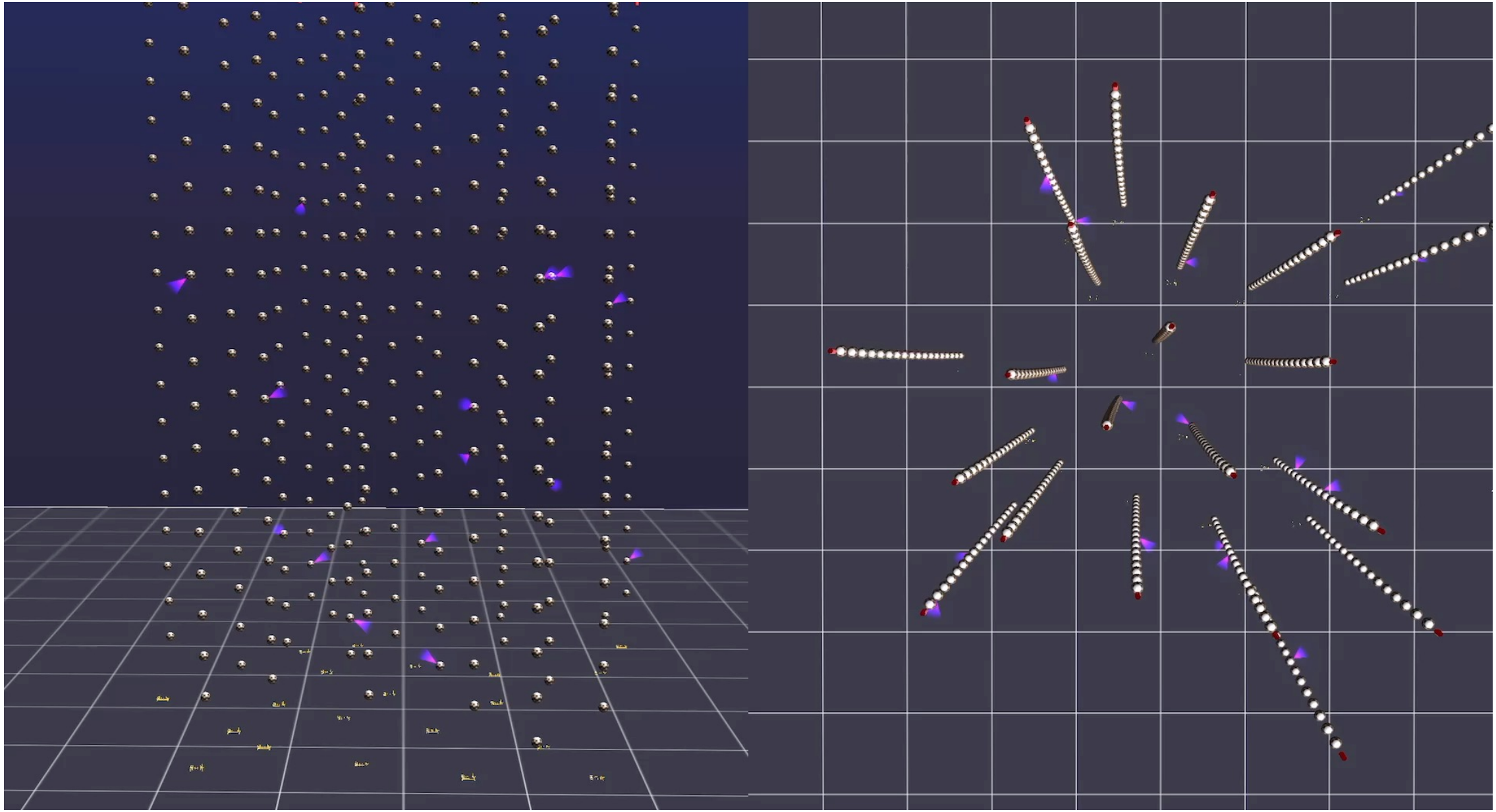
https://doi.org/10.1038/s41586-024-08543-1
Received: 19 August 2024
Accepted: 18 December 2024
Published online: 12 February 2025
Open access
Check for updates

The KM3NeT Collaboration*

The detection of cosmic neutrinos with energies above a teraelectronvolt (TeV) offers a unique exploration into astrophysical phenomena[1–3]. Electrically neutral and interacting only by means of the weak interaction, neutrinos are not deflected by magnetic fields and are rarely absorbed by interstellar matter: their direction indicates that their cosmic origin might be from the farthest reaches of the Universe. High-energy neutrinos can be produced when ultra-relativistic cosmic-ray protons or nuclei interact with other matter or photons, and their observation could be a signature of these processes. Here we report an exceptionally high-energy event observed by KM3NeT, the deep-sea neutrino telescope in the Mediterranean Sea[4], which we associate with a cosmic neutrino detection. We detect a muon with an estimated energy of $120^{+110}_{-60}$ petaelectronvolts (PeV). In light of its enormous energy and near-horizontal direction, the muon most probably originated from the interaction of a neutrino of even higher energy in the vicinity of the detector. The cosmic neutrino energy spectrum measured up to now[5–7] falls steeply with energy. However, the energy of this event is much larger than that of any neutrino detected so far. This suggests that the neutrino may have originated in a different cosmic accelerator than the lower-energy neutrinos, or this may be the first detection of a cosmogenic neutrino[8], resulting from the interactions of ultra-high-energy cosmic rays with background photons in the Universe.

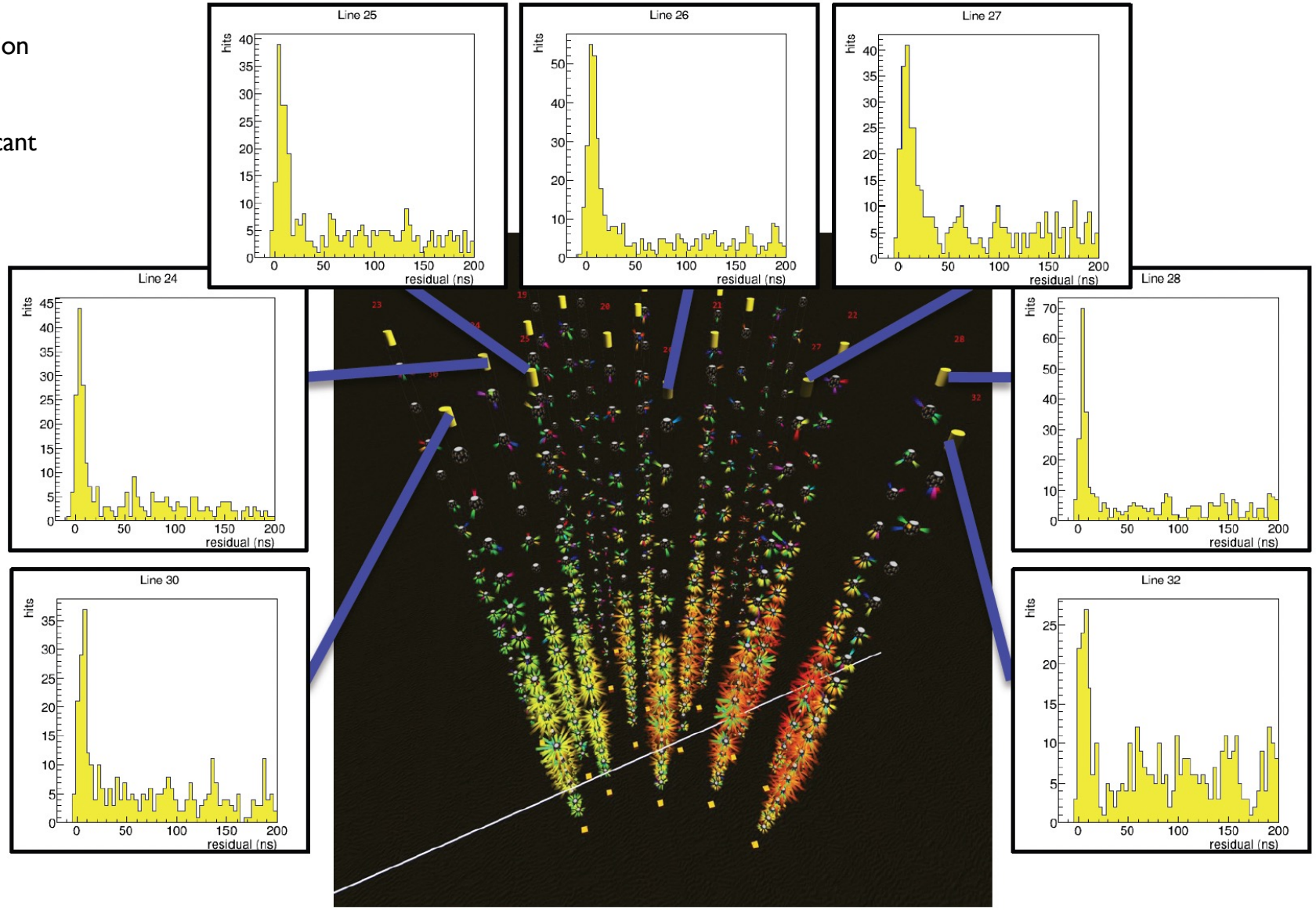
*Nature volume 638, pages 376–382 (2025)*

# KM3-230213A: 1st UHE neutrino



# KM3-230213A: 1st UHE neutrino

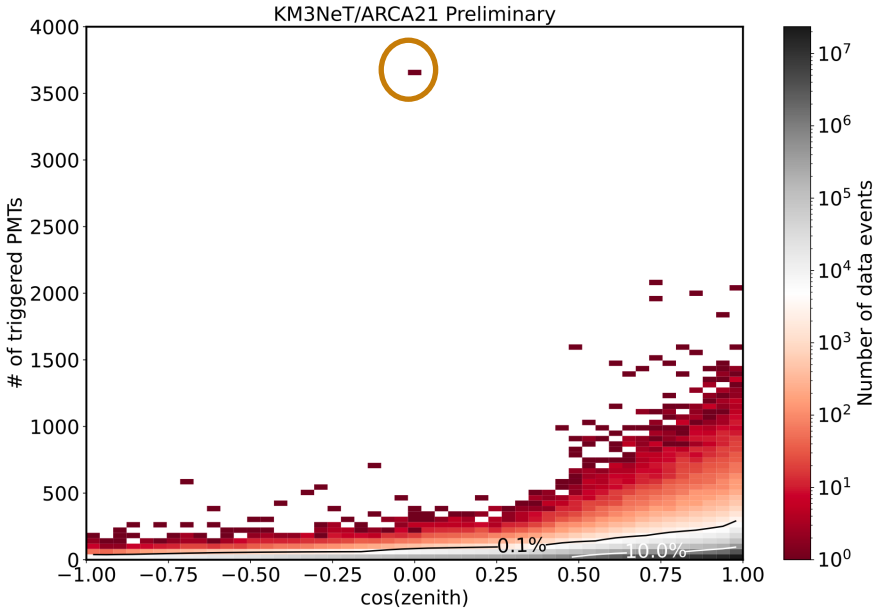
- Extremely high-quality track reconstruction
- Search for lower-energy neutrinos with ANTARES / KM3NeT / IC ⟹ No significant excess

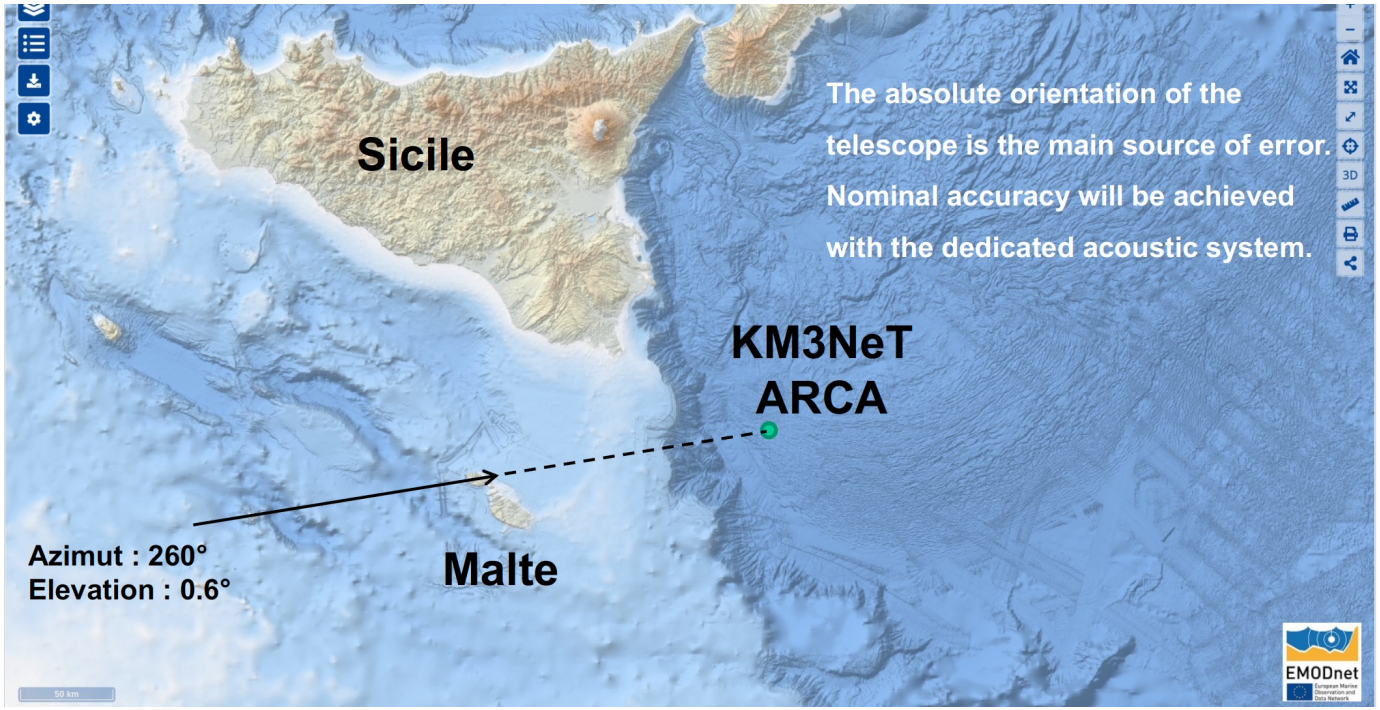


# KM3-20230213A: event

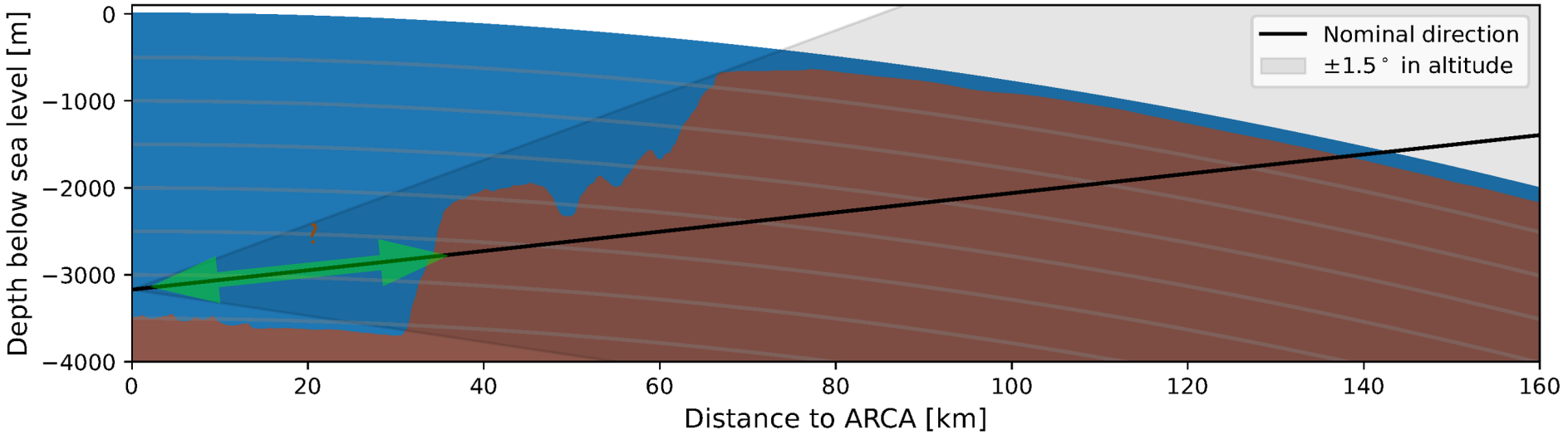
- Very horizontal, light deposition in 1/3 of the detector
- Brightest among $10^8$ events collected in the ARCA21 configuration

⟹ 3672 PMTs (35%) triggered during the event



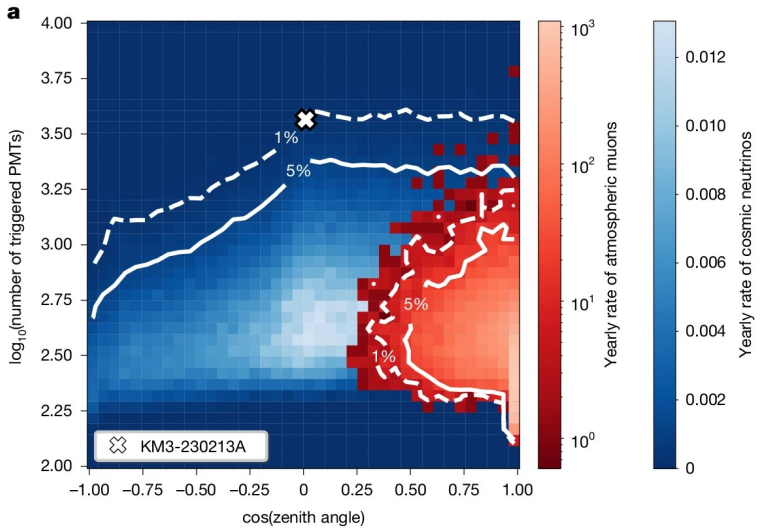



# KM3-230213A: event




Exceedingly unlikely for atmospheric muon to travel through that much
water/column depth ⟹ **It is a COSMIC NEUTRINO !**

- Atm. muon rate: << $10^{-10}$ /yr (< $10^{-5}$ in worse case scenario)
- Muon bundles also unlikely ($10^{-3}$ /yr)
- Atm. neutrinos with such energies ≤$10^{-5}$ /yr



# KM3-20230213A: energy

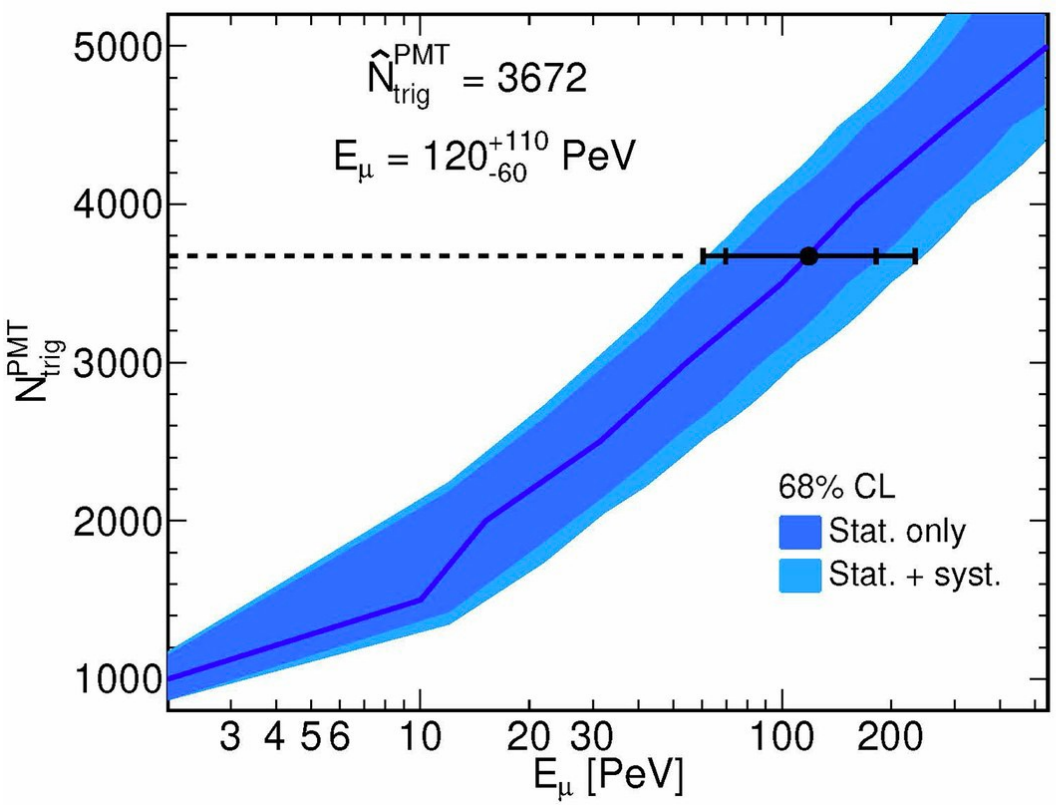
- Muon energy estimate with detailed MC simulation using the best knowledge of the detector performances and detailed muon propagation simulation in water
- Using number of triggered PMTs as proxy
- Estimation of the neutrino energy:

$$E_\mu = 120^{+110}_{-60}\ \text{PeV}$$

$$E_\nu = 220^{+570}_{-110}\ \text{PeV}$$

*(assuming an $E^{-2}$ source spectrum)*

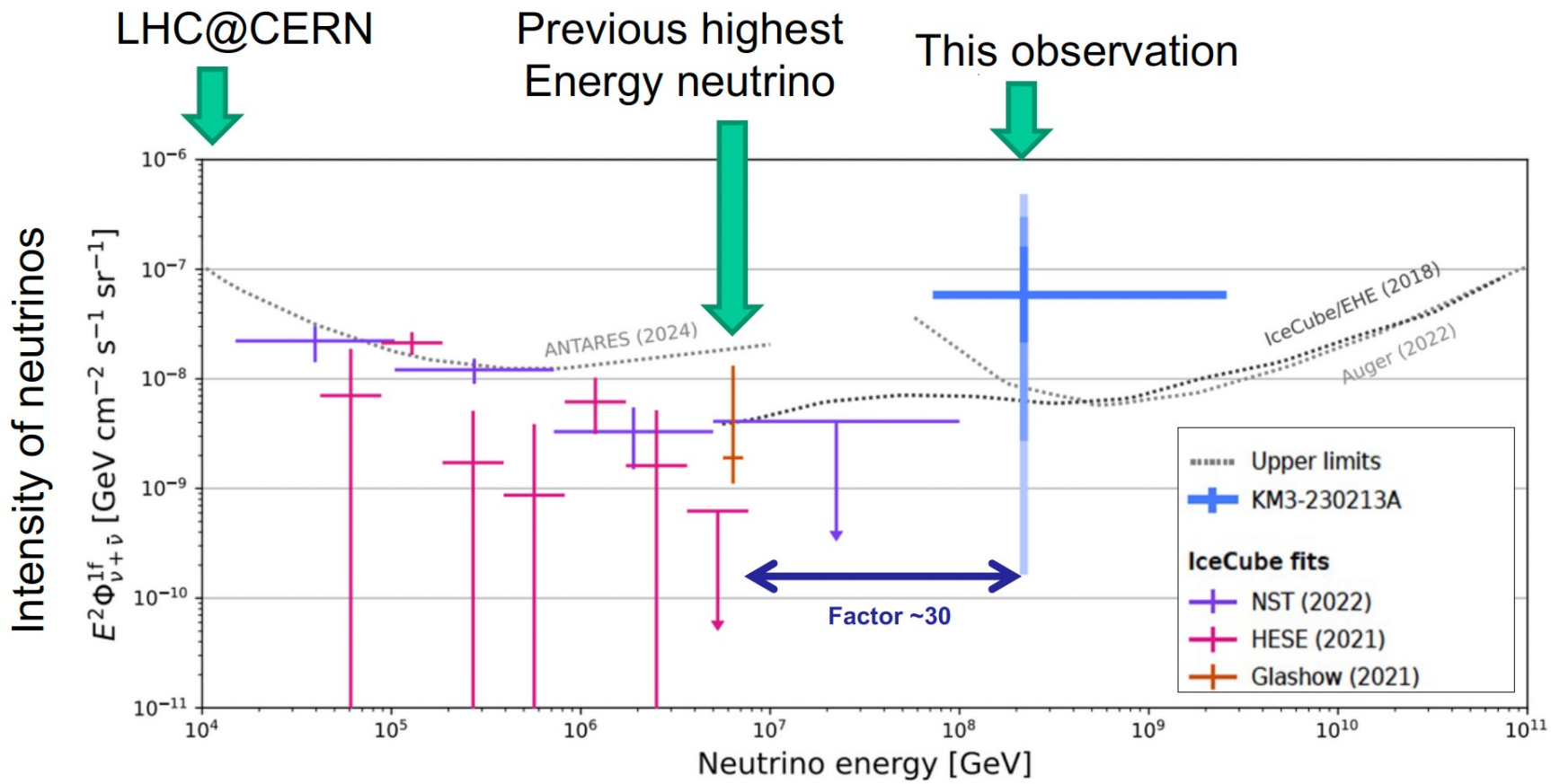
(If p, $E_p$>1.5 EeV)



# KM3-230213A: spectrum

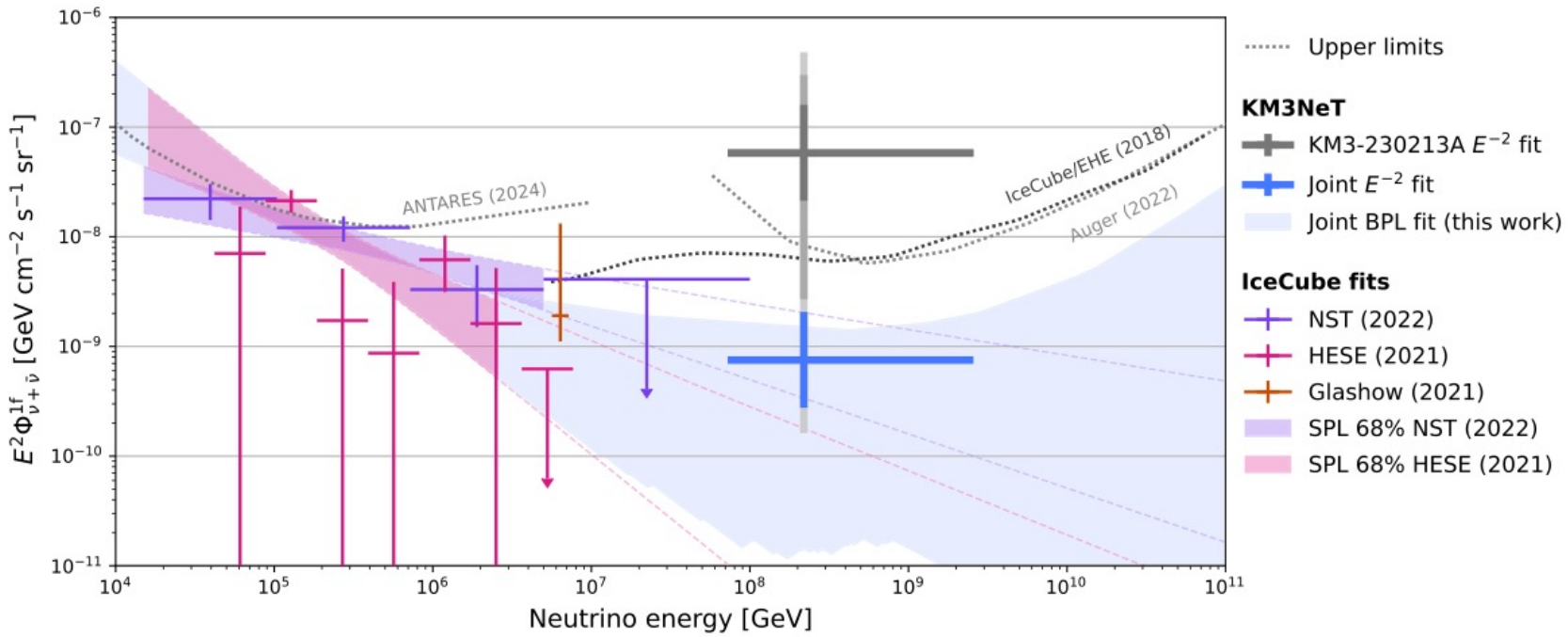
Assuming an $E_\nu^{-2}$ flux, we estimate:

$$E_\nu = 220^{+570}_{-110}\,\mathrm{PeV} \text{ and } E^2\Phi^{1f}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7}\times10^{-8}\,\mathrm{GeV cm^{-2} s^{-1} sr^{-1}}$$




Search for lower-energy neutrinos with ANTARES / KM3NeT ⟹ No significant excess

# KM3-230213A: comparison with others exp.




**KM3NeT-only**

$$E^2\Phi^{1f}_{\nu+\bar{\nu}} = 5.8^{+10.1}_{-3.7} \times 10^{-8}$$

**Joint fit**

$$E^2\Phi^{1f}_{\nu+\bar{\nu}} = 7.5^{+13.1}_{-4.7} \times 10^{-10}$$

- Using single power-law, moderate tension with non-observation by IceCube and Auger (~ 2.5-3σ)
- Joint-fit: no preference for additional component

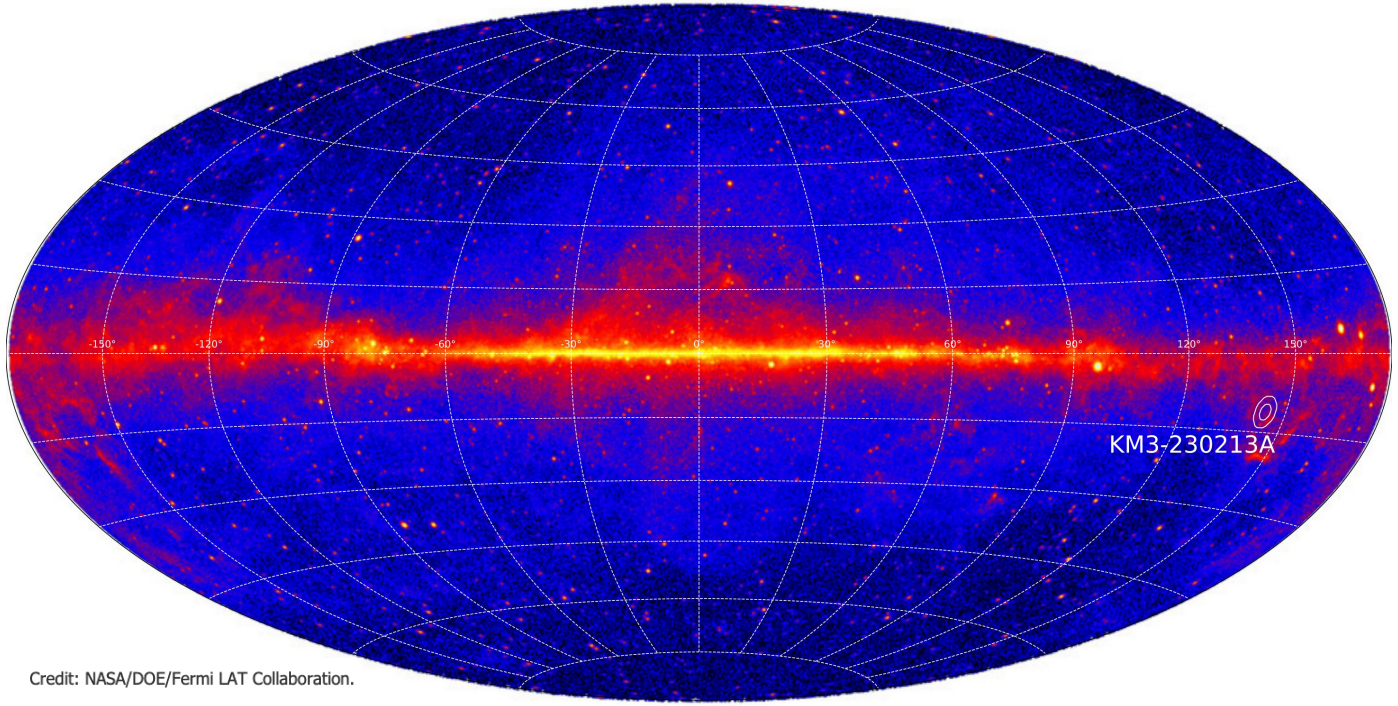
# KM3-230213A: scientific interest

--- astro. Counterparts
--- heavy dark matter
--- it's not a (normal) neutrino
--- constraints on exotic stuff (LIV)
--- evaporating black holes
--- cosmogenic/connection to CR/γ

# KM3-230213A: direction

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°
- NEWS: Ongoing campaigns to improve acoustic emitter position accuracy → recalibrate the data and improve pointing/energy estimations

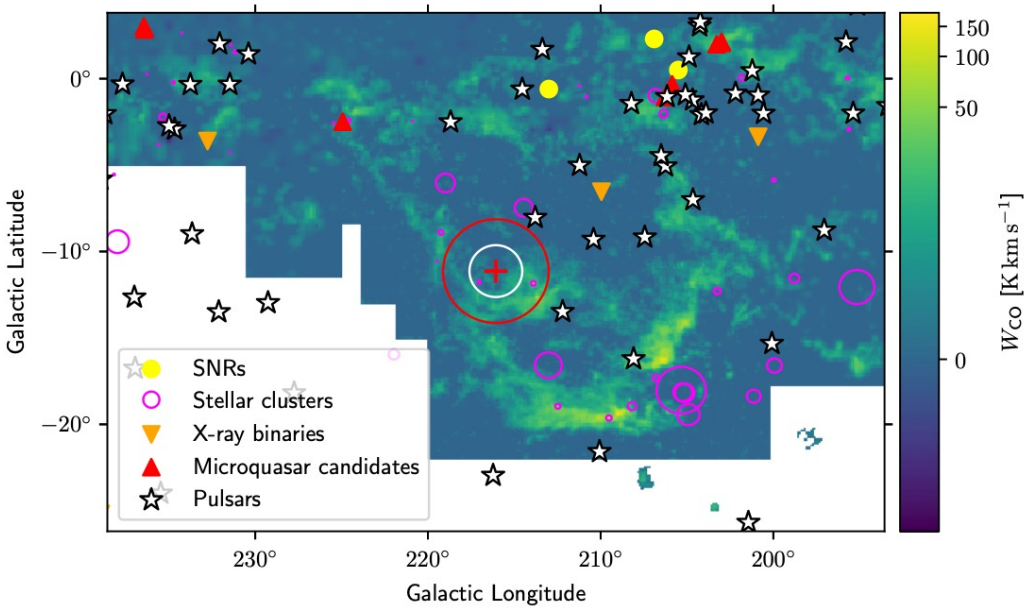


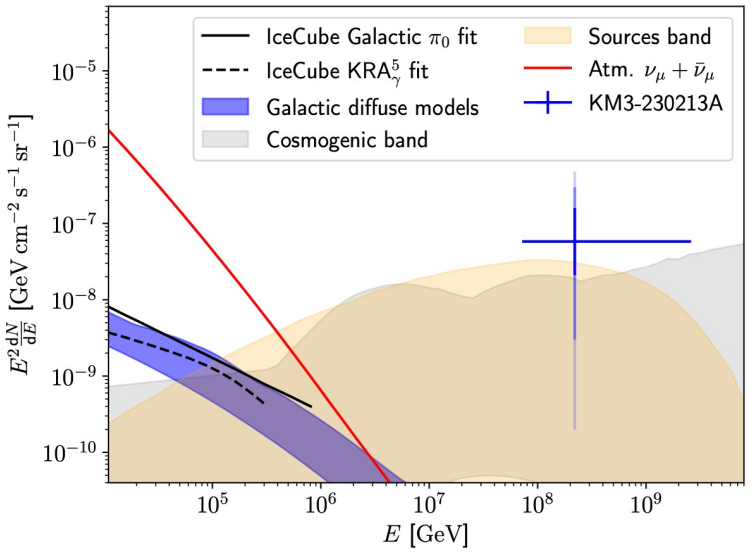

Credit: NASA/DOE/Fermi LAT Collaboration.

# KM3-230213A: origin ?

Search of counterpart performed within the Milky Way (Monoceros 2 cloud region)

- 11° below the Galactic Plane
- No Galactic sources in this direction



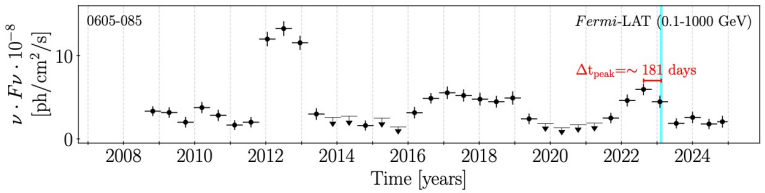



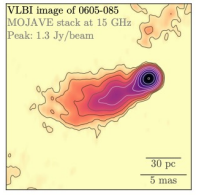

$\Longrightarrow$ highly unlikely to be galactic origin

# KM3-20230213A: origin ?

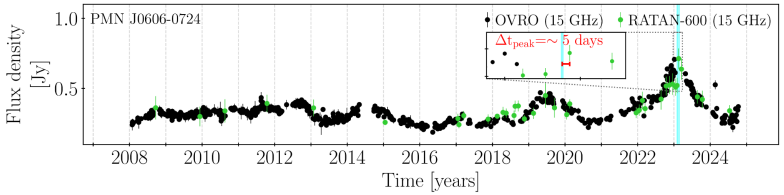
- Crossmatch with gamma/X/radio catalogs
  - 17 blazar candidates identified
  - 3 coincidence electromagnetic flares

## 0605-085 (id #6)

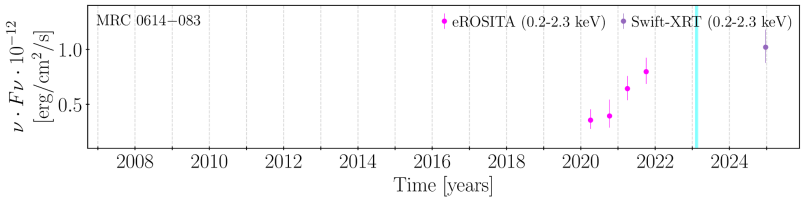


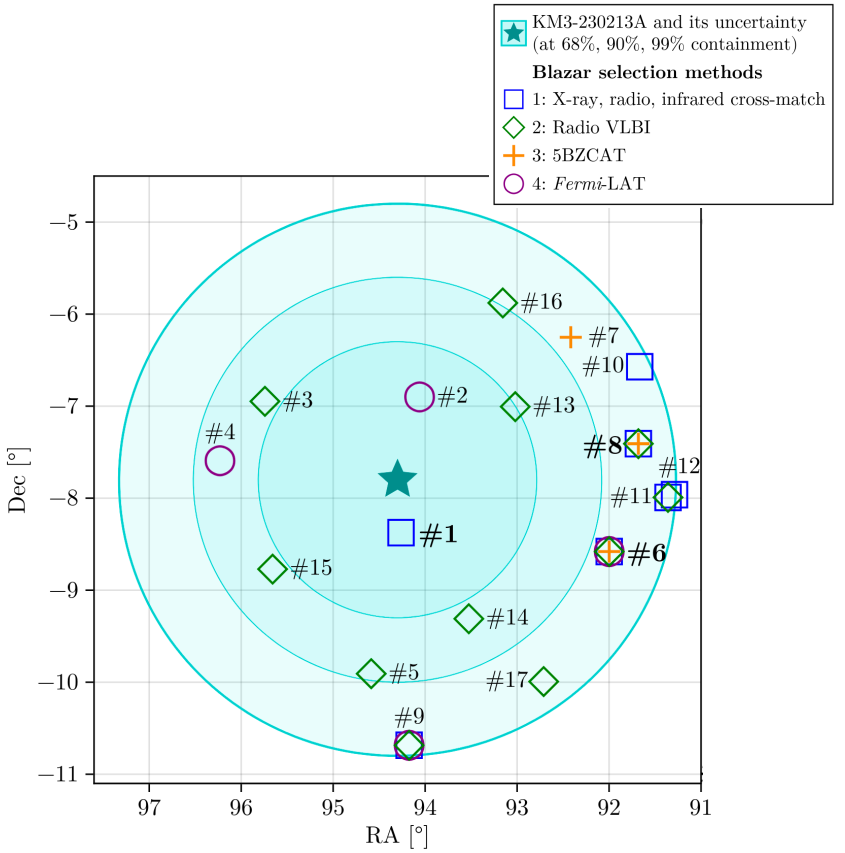




## PMN J0606-0724 (id #12)




## MRC 0614-083 (id #1)



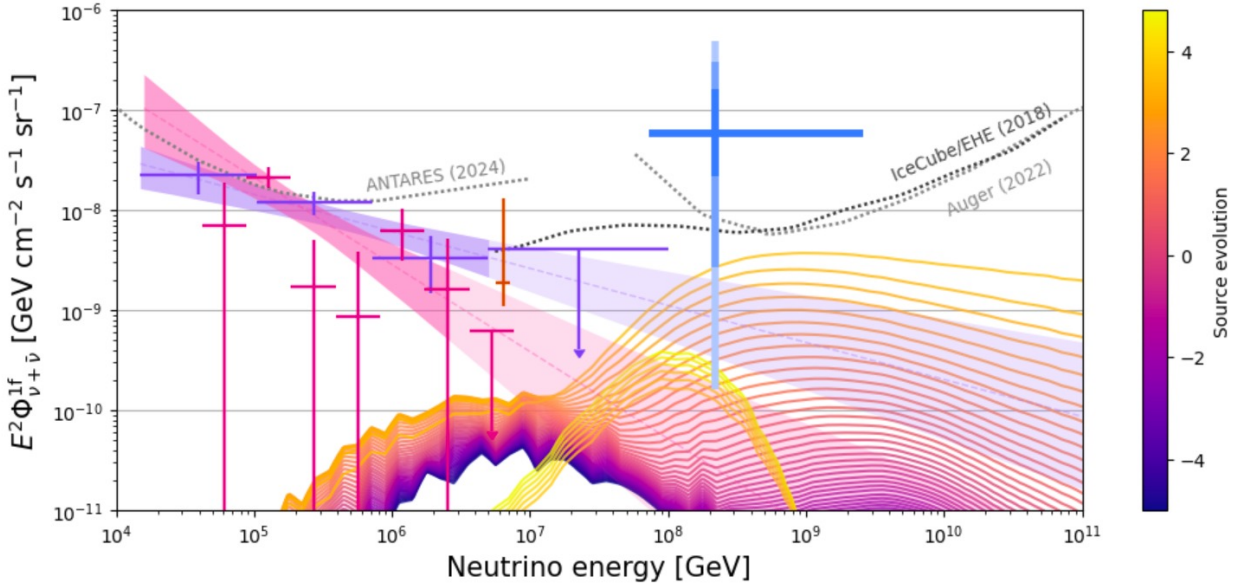




⟹ Others studies: consistent with blazar, GRB, LFBOT population studies

# KM3-20230213A: origin ?

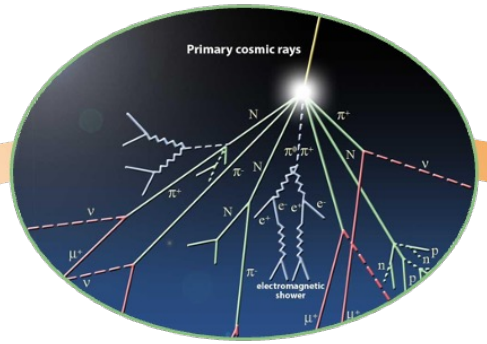
What do we know on the origin? still unknown

- Cosmogenic neutrino: p-CMB interaction during the CR propagation
  - Constrain with the Auger+TA UHECR spectrum/composition + EGB Fermi-LAT flux
  - Playing with source evolution and extending $z_{max}$ $\Longrightarrow$ compatibility [require strong source evolution and sub-dominant proton fraction]

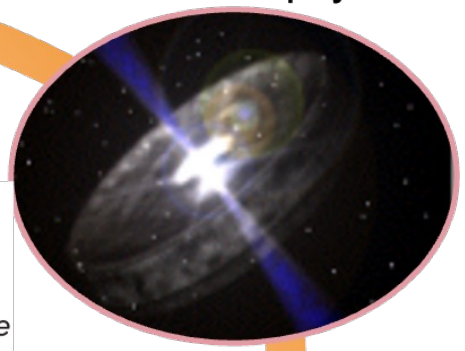


# Science cases with KM3NeT

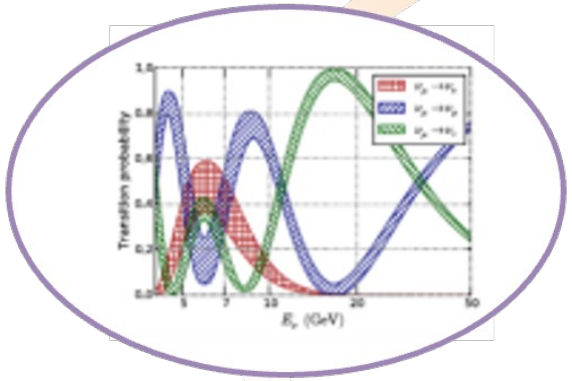
Cosmic Rays




Astrophysics



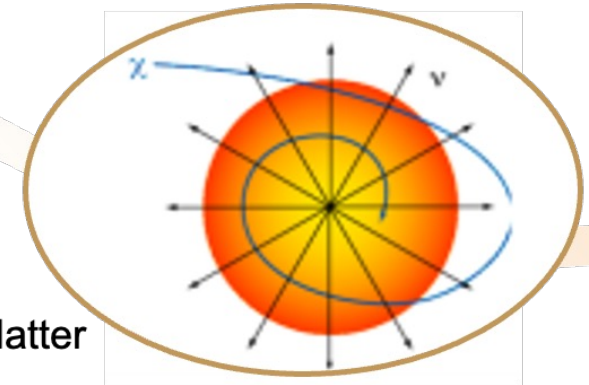
Neutrino Physics




KM3NeT

*Opens a new window on our universe*

Complementarity of ORCA and ARCA on all topics




Dark Matter

Earth and Sea