High-energy astrophysical neutrinos

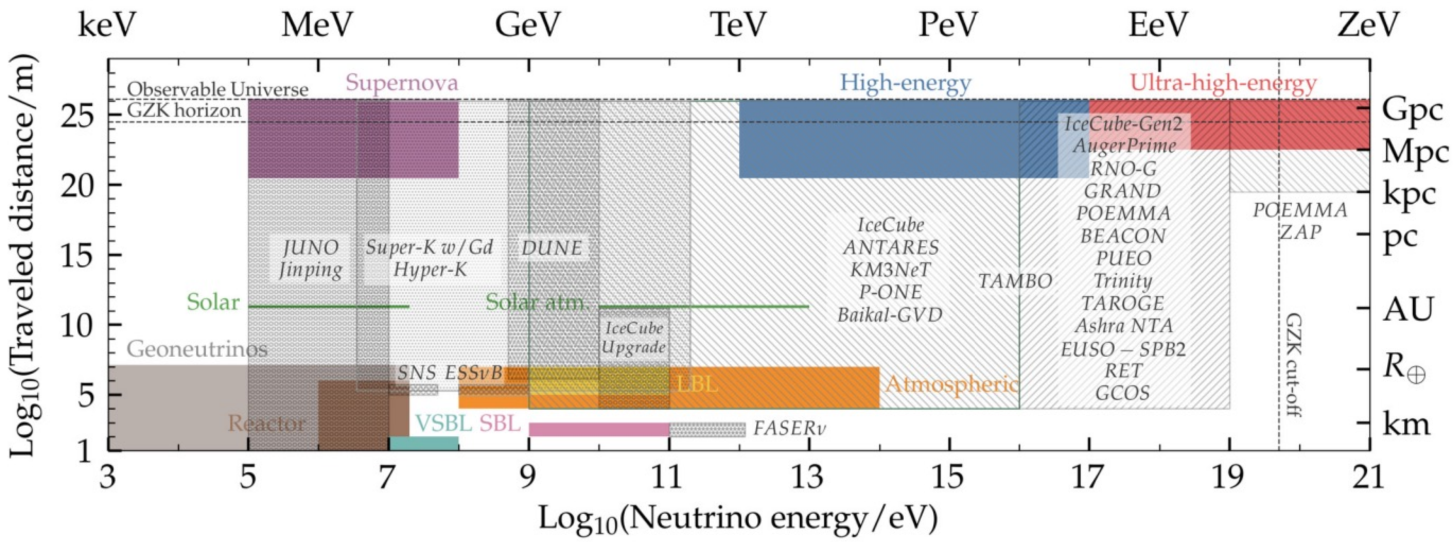
Figure credit: IceCube/NASA

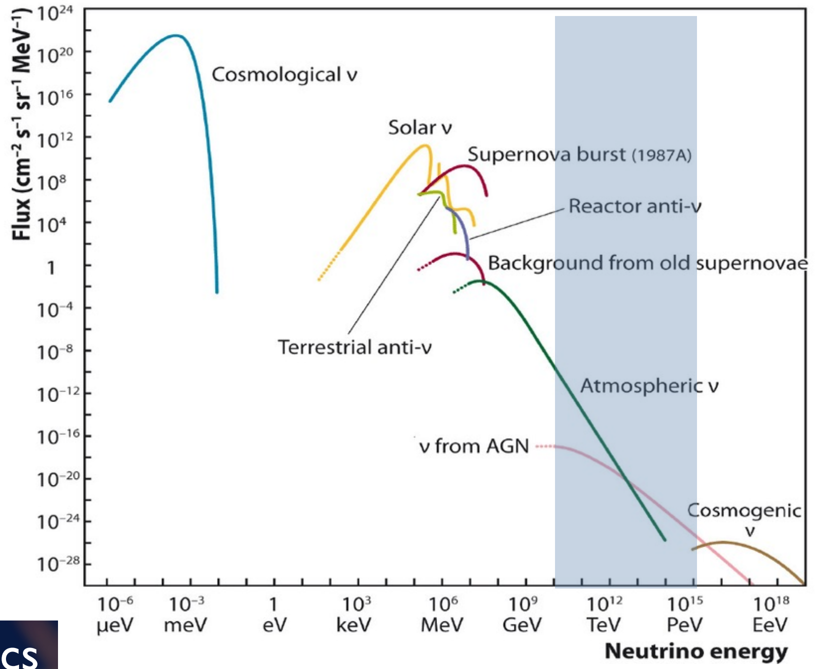
Giulia Illuminati

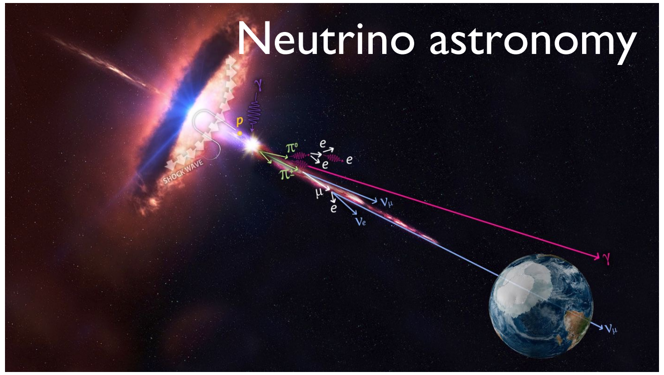
NNN23, Procida, 11-13 October 2023

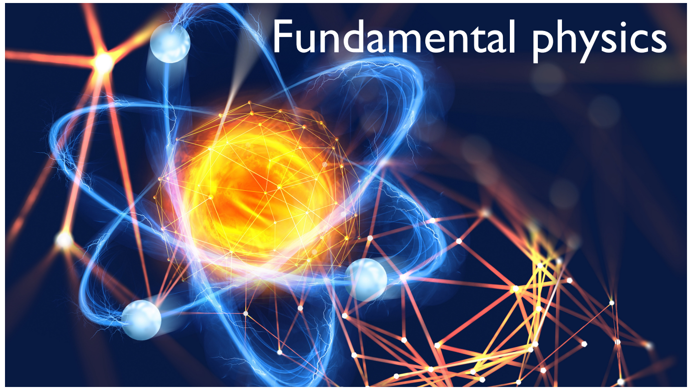
High energy astrophysical neutrinos

➡️ *JHEAp* 36 (2022) 55-110

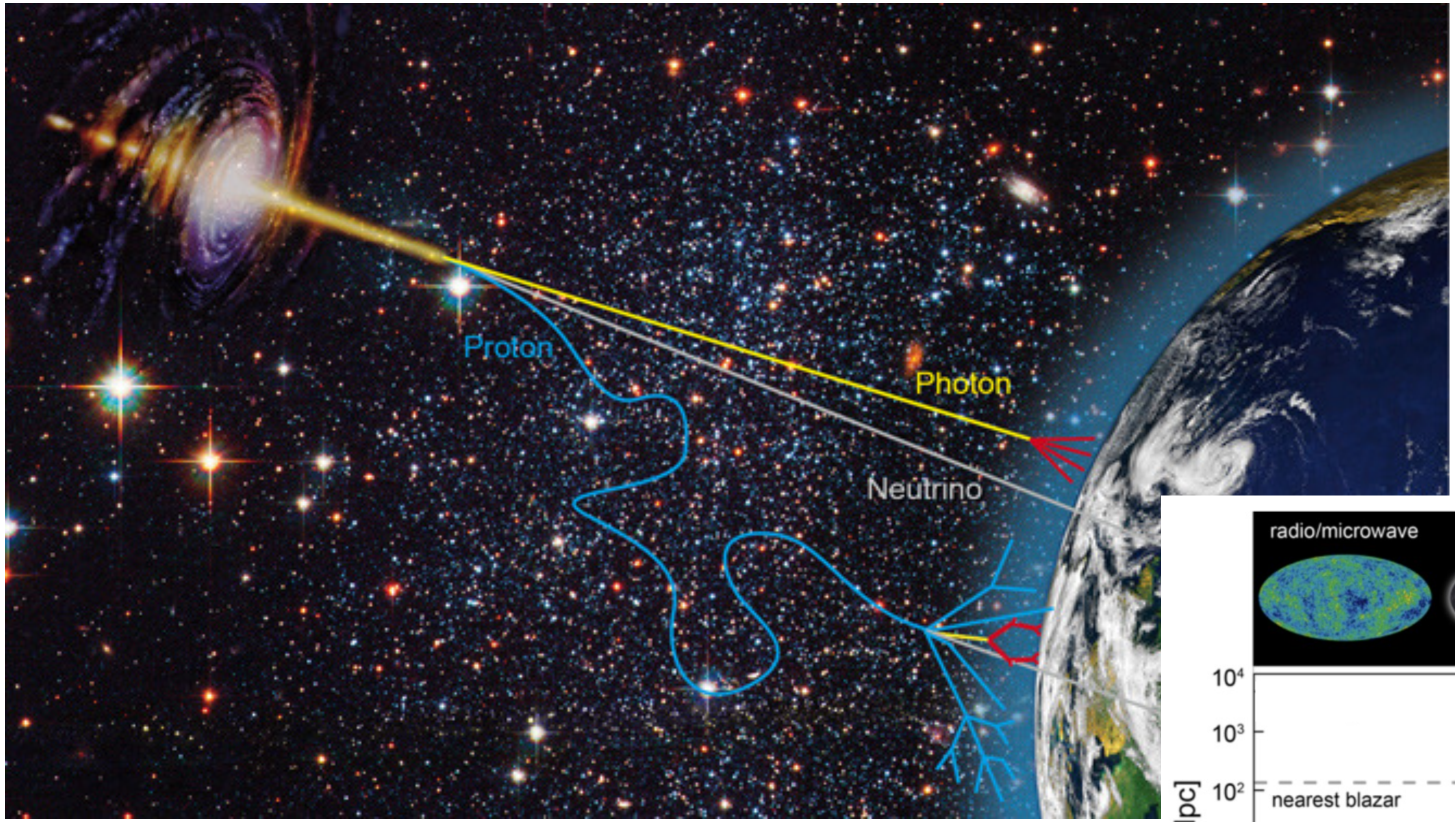






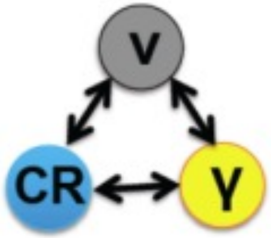


Neutrino astronomy: why?



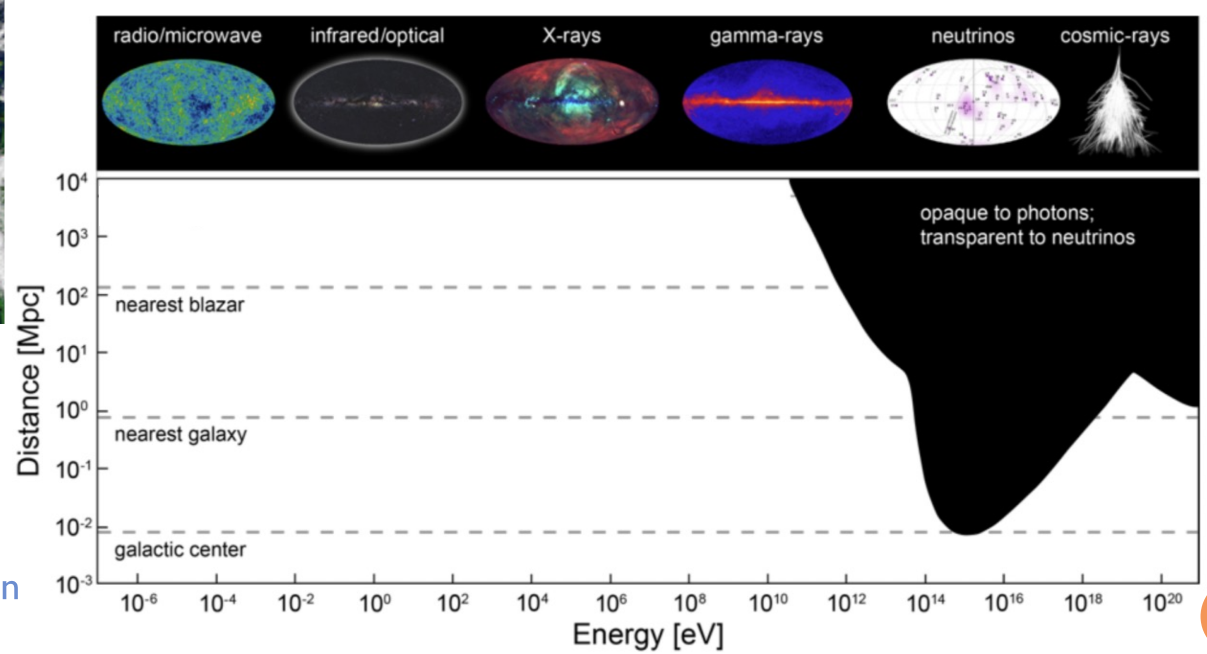
Neutrinos:

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

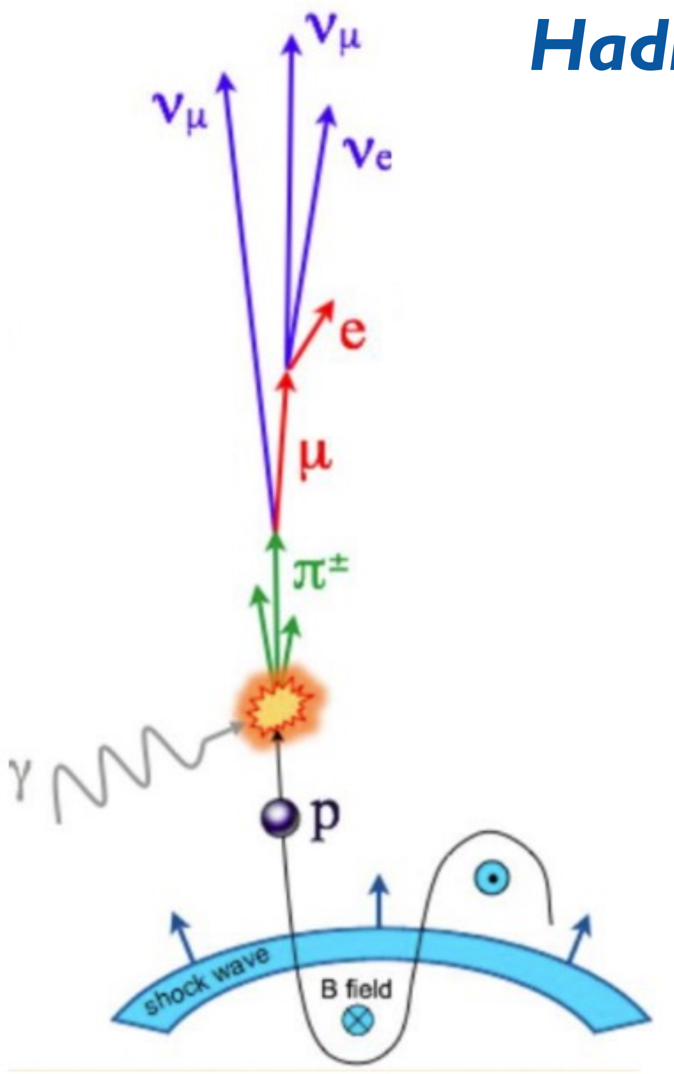


Offer unique chance to

- **access the highest energy universe**
- **unveil the origin of the cosmic rays,** discovered ~100 years ago, still unknown origin



Neutrino astronomy: why?



Hadronic scenario

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:

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

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

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

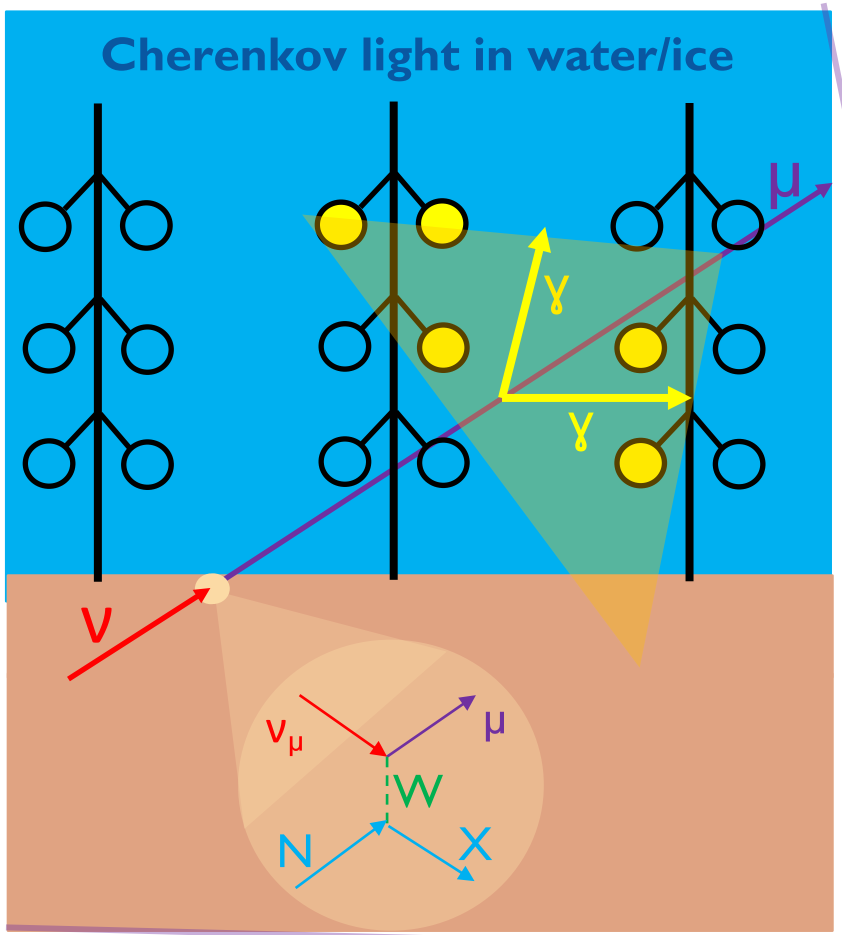
$\nu_e : \nu_\mu : \nu_\tau = 1:2:0$ at the source

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

Neutrinos:

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

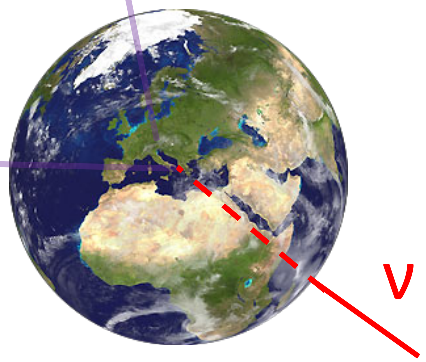
HE neutrino detection



Either **CC** or **NC** **interaction** with a nucleon N

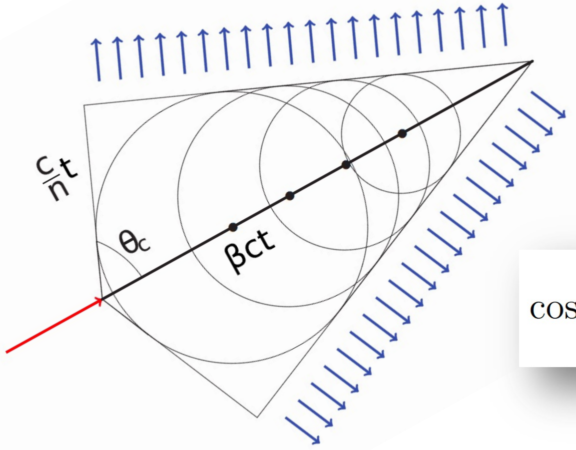
CC: $\nu_\ell + N \rightarrow \ell + X$

NC: $\nu_\ell + N \rightarrow \nu_\ell + X$



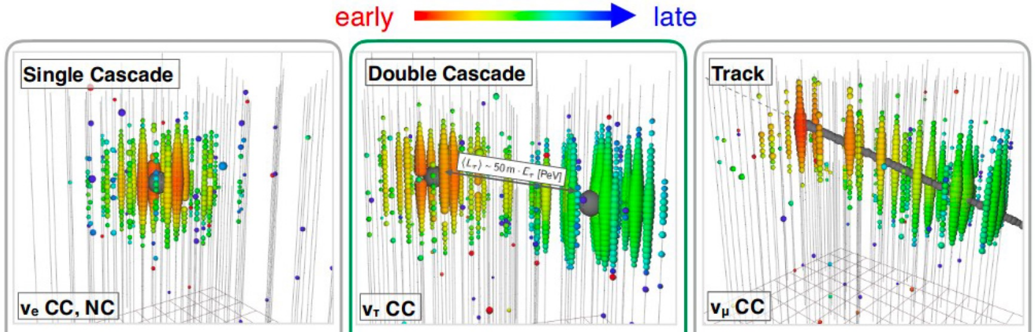
Cherenkov radiation detected by **arrays of PMTs**

Position, time and charge used to reconstruct **direction** and **energy**



$$\cos\theta_C = \frac{1}{\beta n}$$

Three event topologies

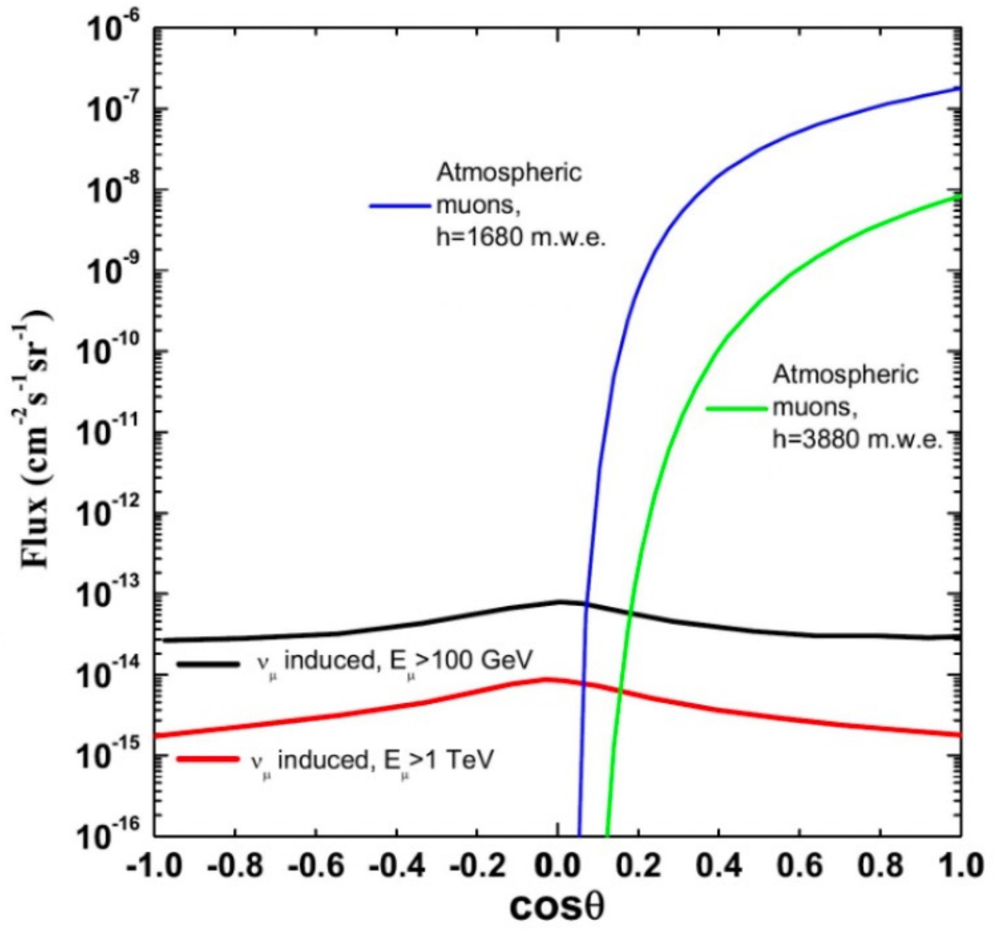


Single Cascade	Double Cascade	Track
All NC interactions ν_e CC interactions	ν_τ CC interactions with hadronic / electronic tau decay	ν_μ CC interactions Atmospheric μ ν_τ CC interactions with muonic tau decay
Good energy resolution Bad angular resolution	Good energy resolution Angular resolution gets better with larger lengths	Bad energy resolution Good angular resolution

Simulated event displays in the IceCube detector

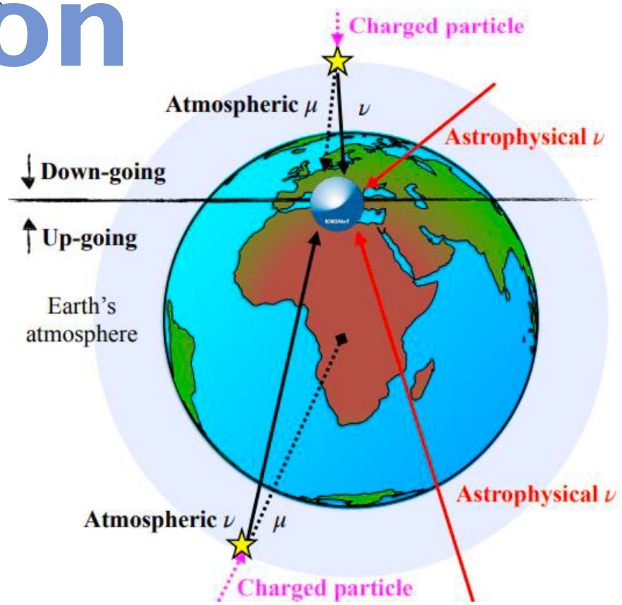
HE neutrino detection

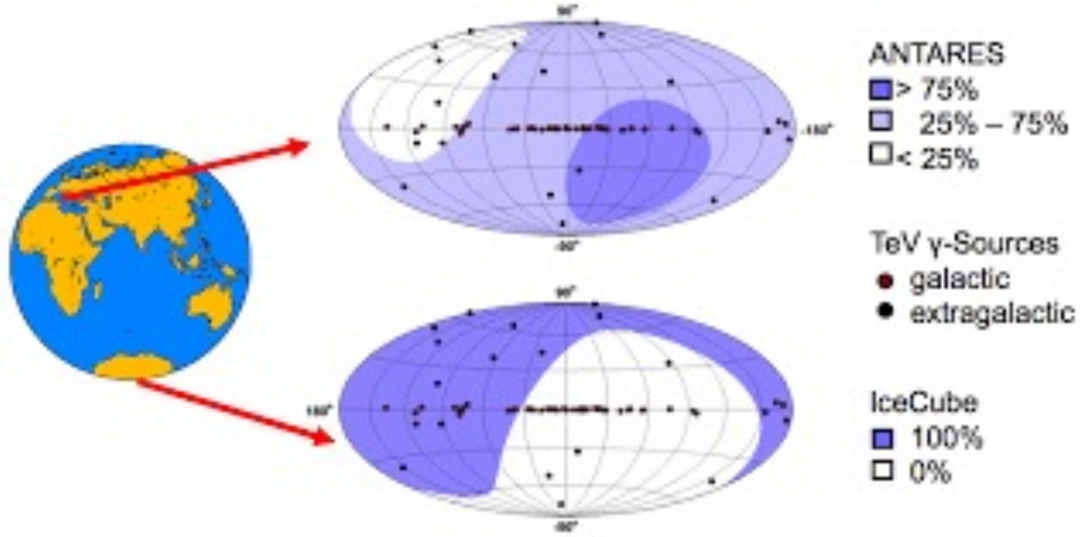
Main background:
Atmospheric muons and neutrinos



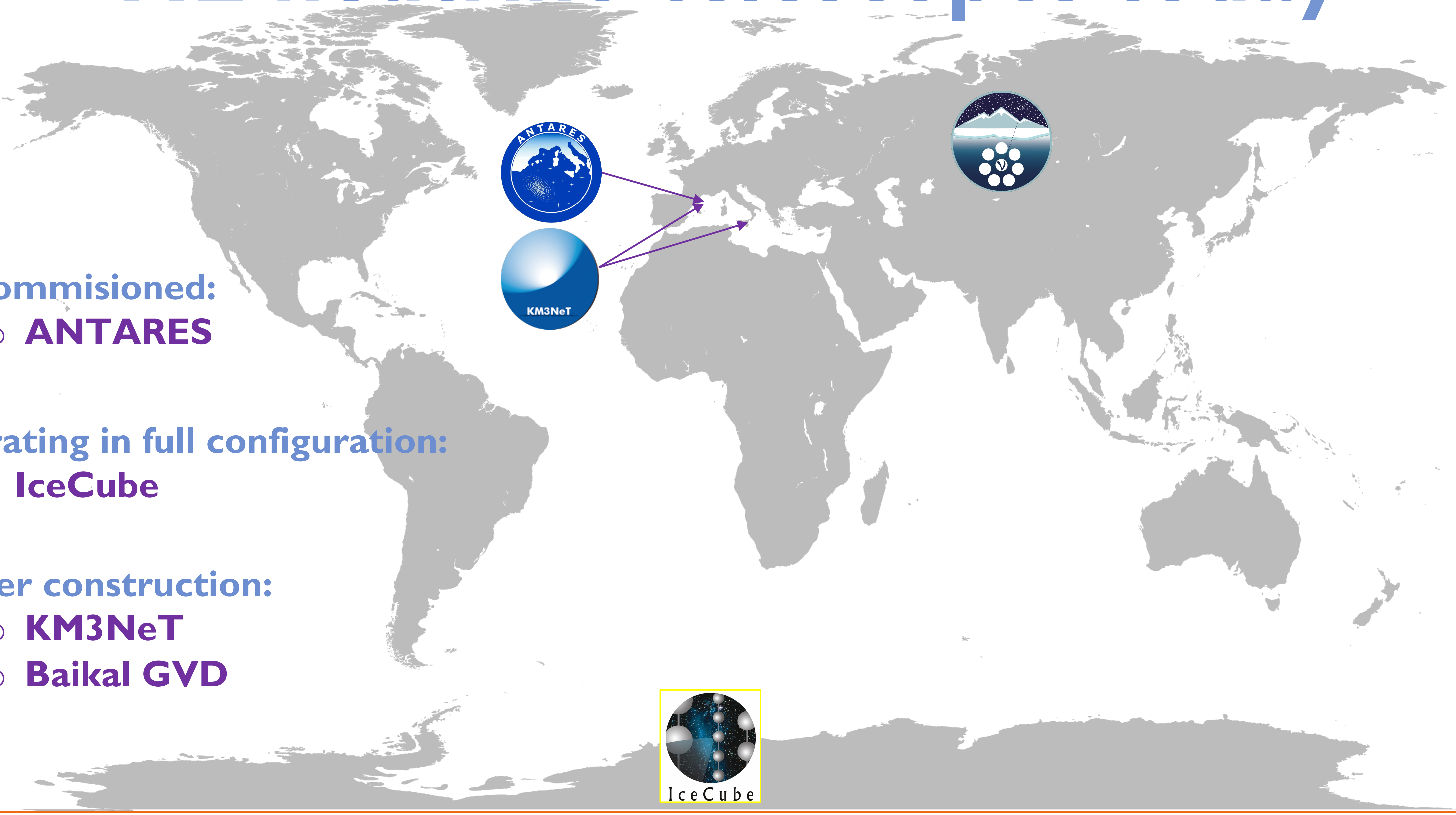
By selecting **up-going events,** neutrino telescopes can use **the Earth as a shield against atmospheric muons**

→ Different sky visibility depending on detector location





HE neutrino telescopes today

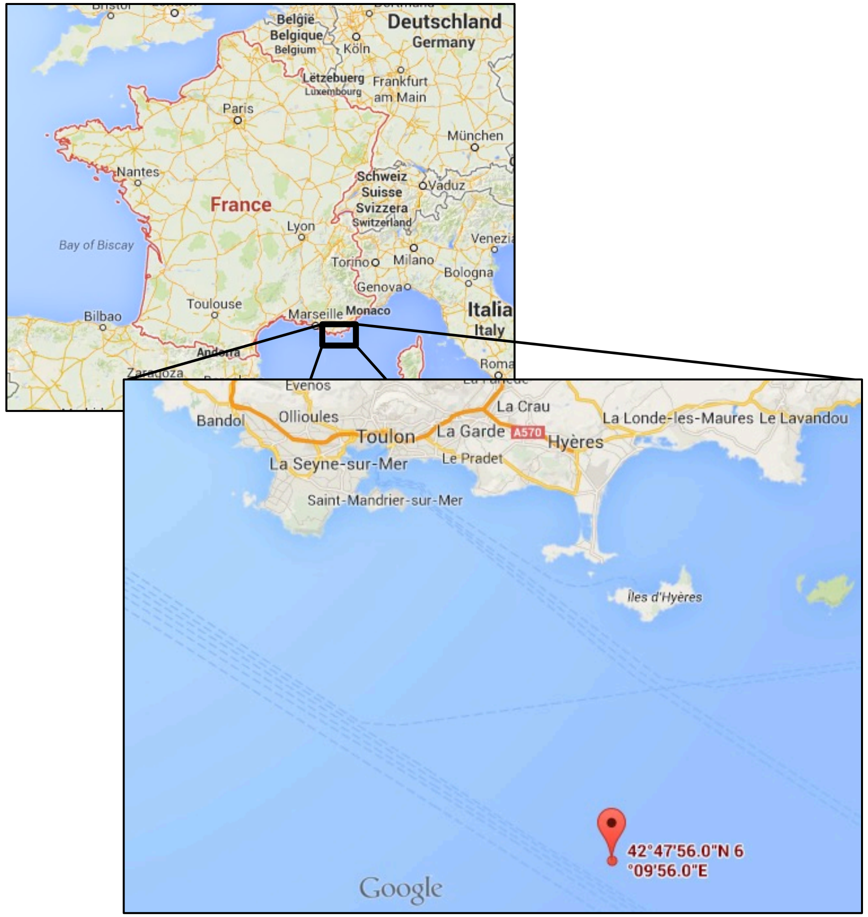


Decommisioned:
- **ANTARES**

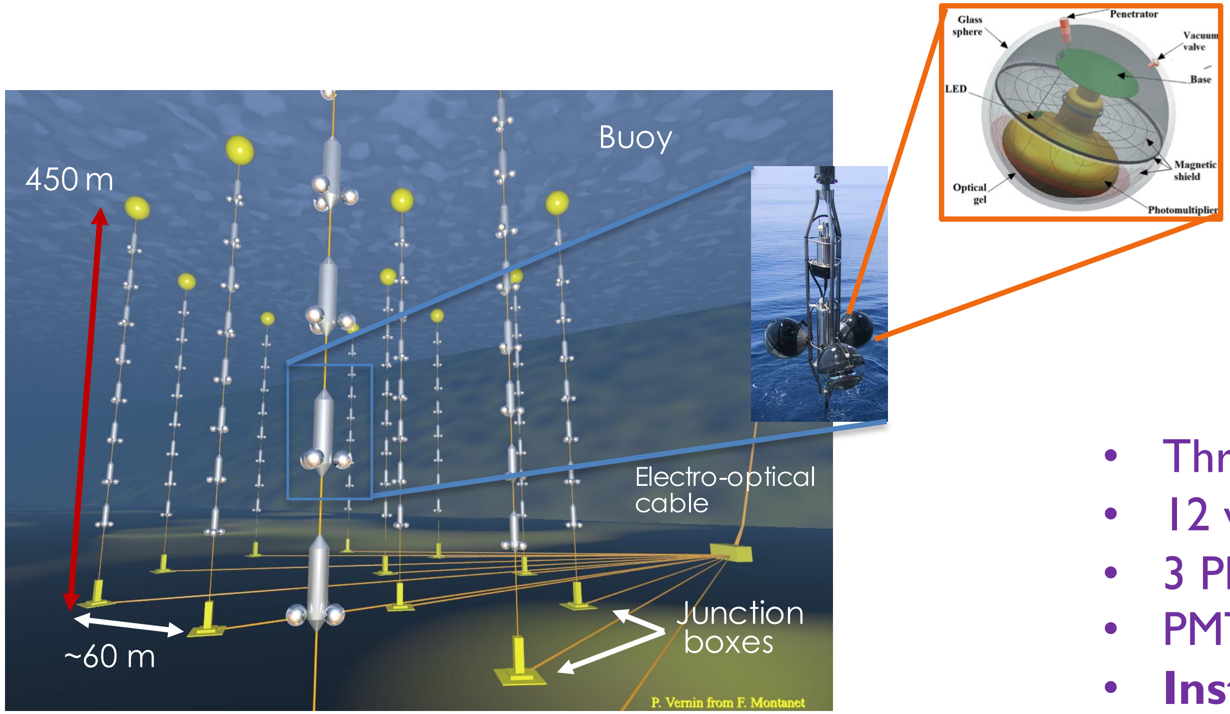
Operating in full configuration:
- **IceCube**

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

ANTARES

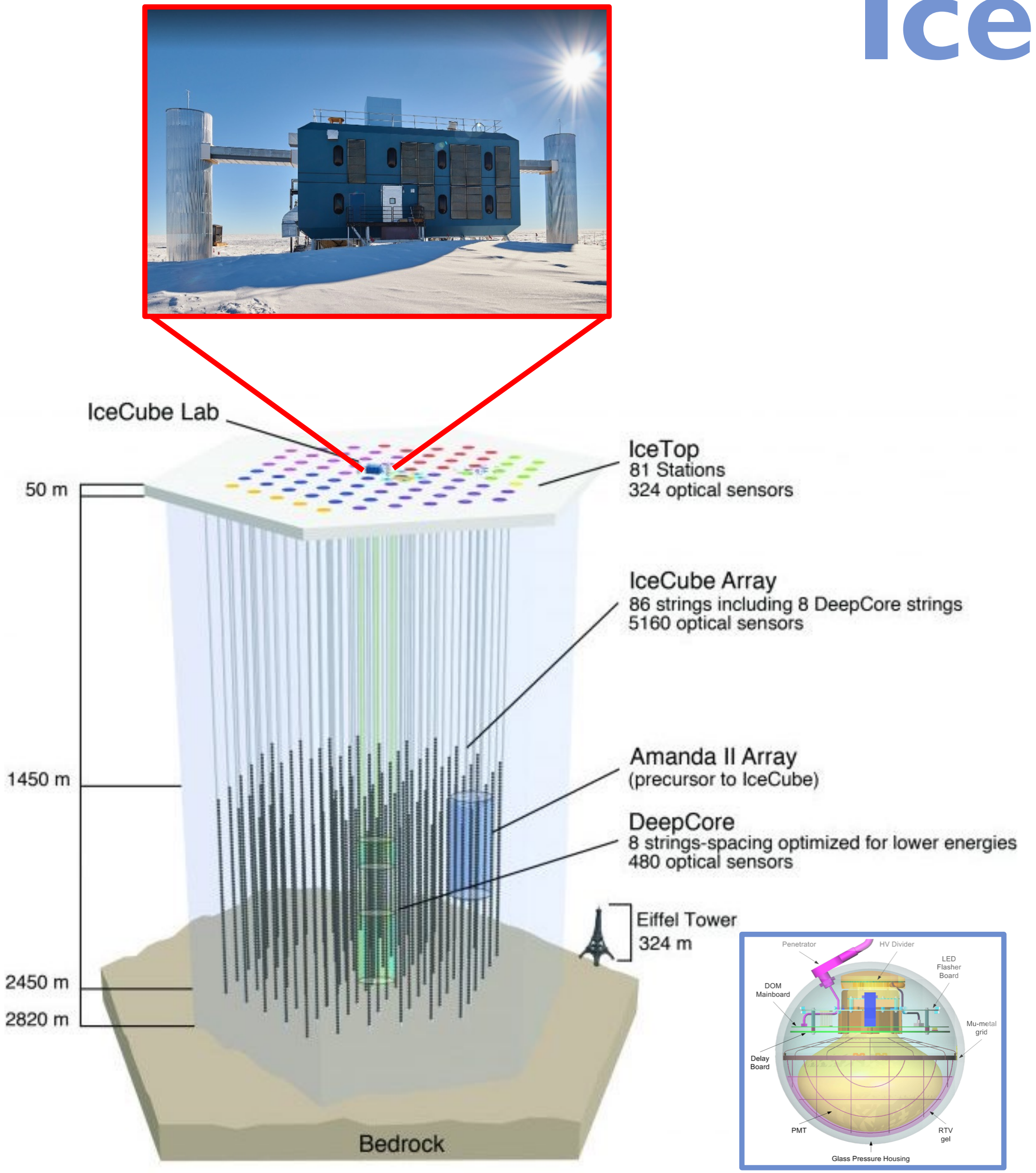


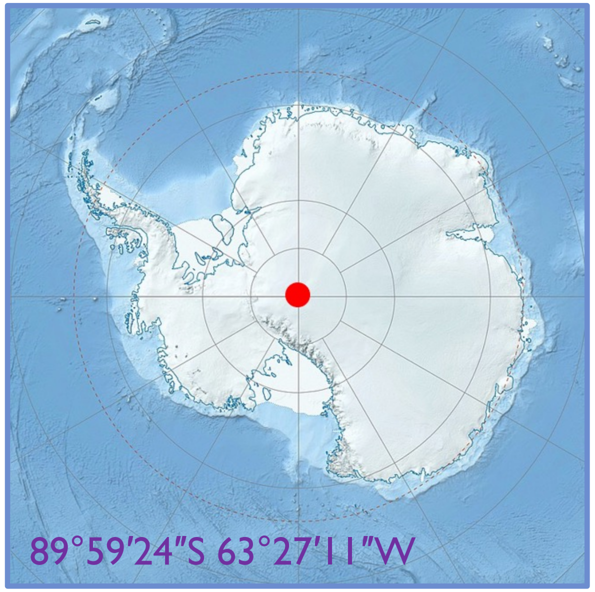
- Designed to detect ν **with E > few GeV**
- First detection line installed in early 2006
- **Completed in 2008, decommissioned in 2022**
- **2475 m depth** in the Mediterranean Sea
- 40 km offshore from Toulon



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

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 km^3 instrumented volume**
- **Largest neutrino telescope in the world**

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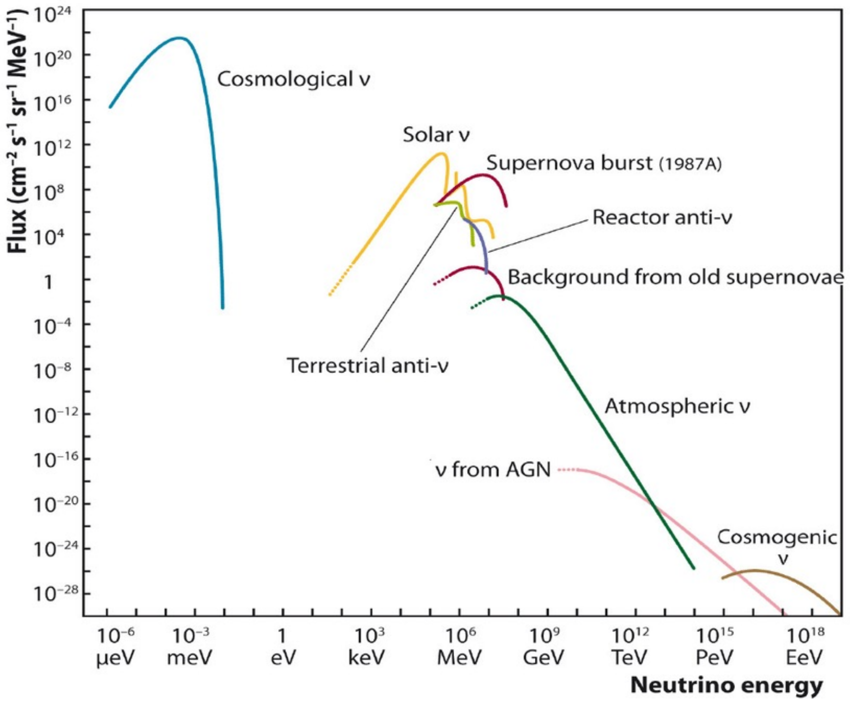
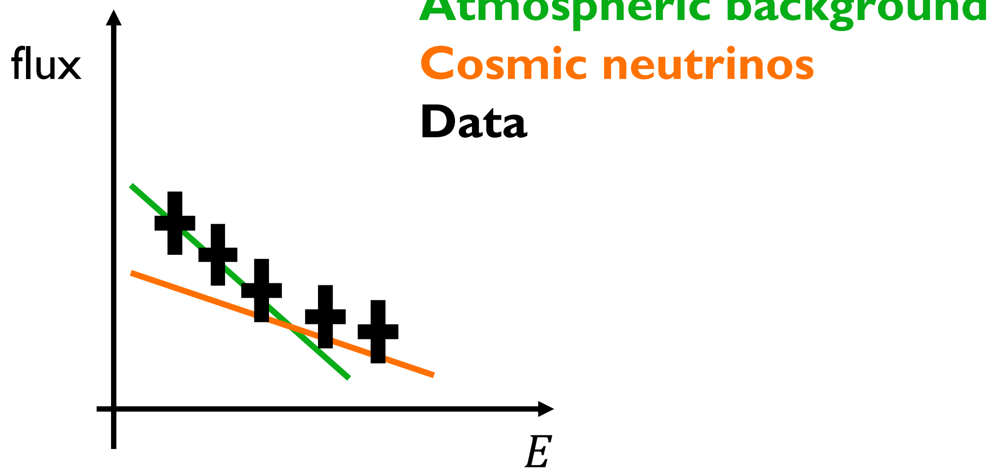
Diffuse astrophysical neutrino flux

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

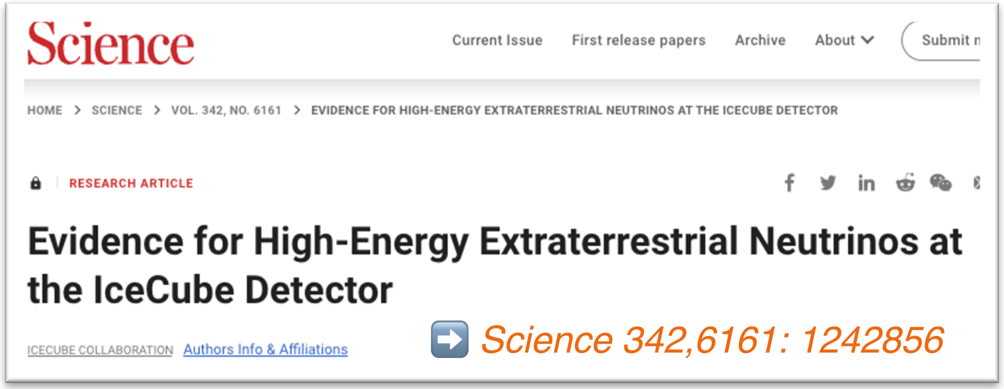
How to detect it: look for an excess of high-energy data





Diffuse astrophysical neutrino flux

The discovery (2013): HESE sample 2 years, 4.0σ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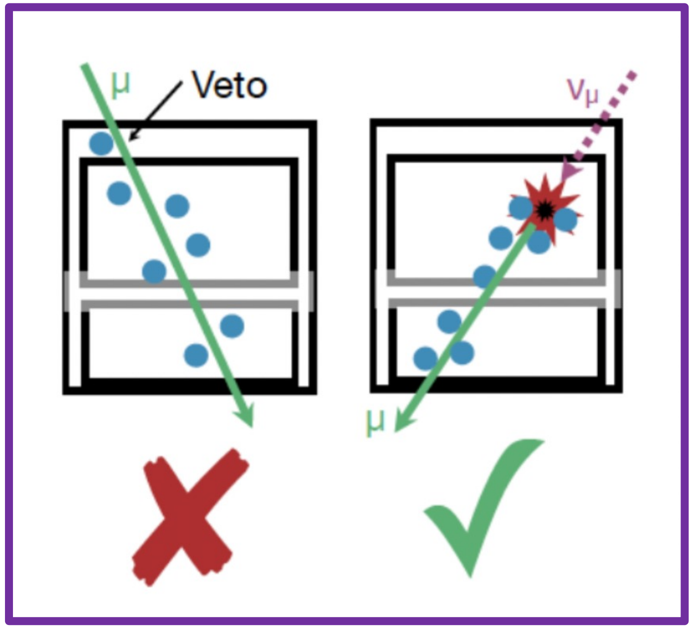
RESEARCH ARTICLE
Evidence for High-Energy Extraterrestrial Neutrinos at the IceCube Detector
ICECUBE COLLABORATION Authors Info & Affiliations

➡ *Science 342,6161: 1242856*

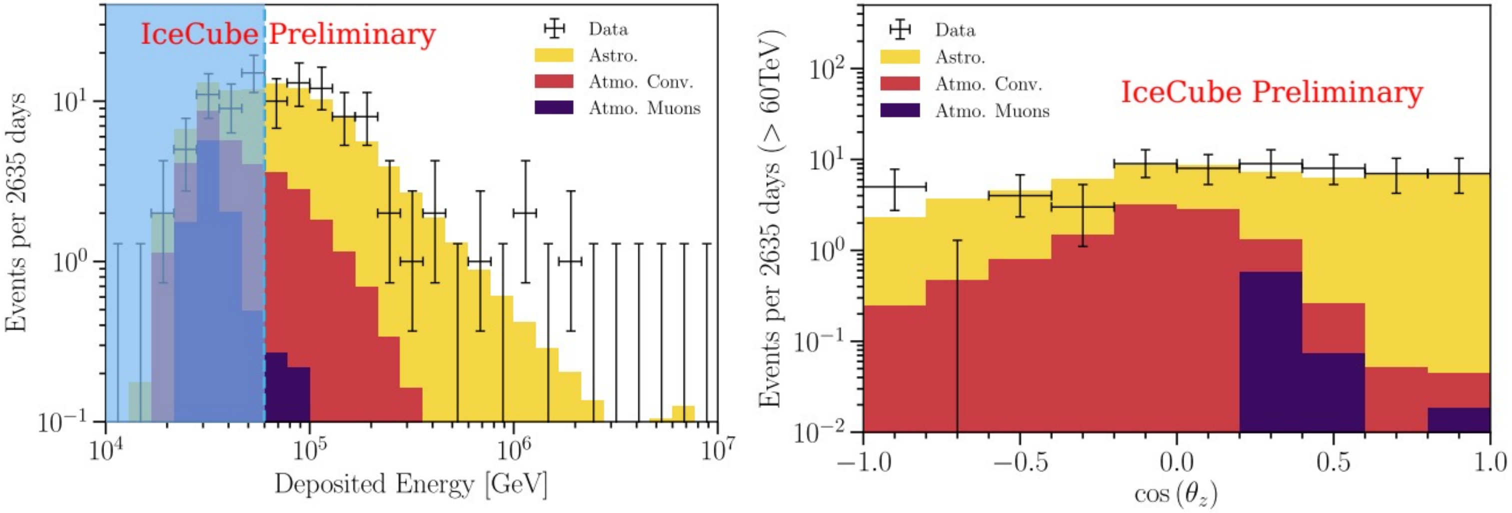
Events producing **first light in the veto** region discarded



→ Mainly **shower-like** events from **all-sky** with energy above **30-50 TeV**

Latest: HESE sample 7.5 years

➡ *PoS(ICRC2019)1004*



$\Phi^{1f}(100\ \text{TeV}) = (2.15^{+0.5}_{-0.15})\ 10^{-18}\ (\text{GeV cm}^2\ \text{s sr})^{-1}$

$\Gamma = 2.9 \pm 0.2$

Diffuse astrophysical neutrino flux

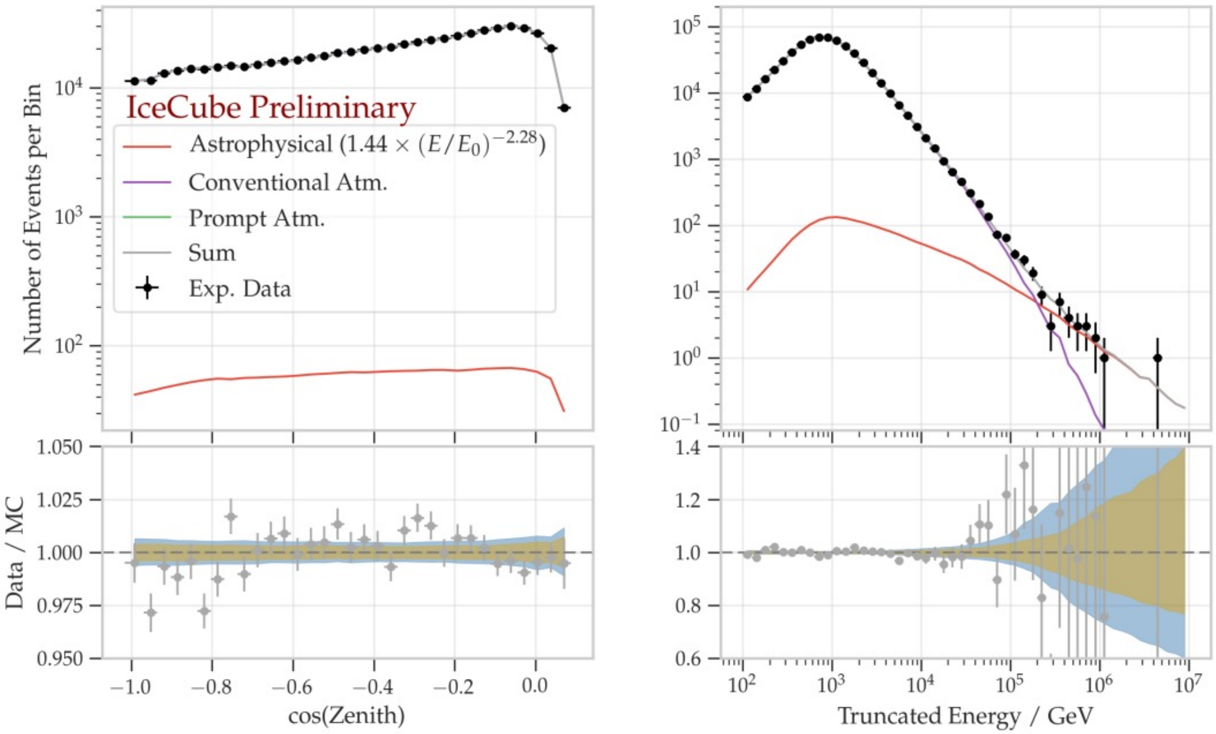
Upgoing track sample

Earth used as a **shield** against atmospheric muons

→ **Track-like** events from the **Northern Sky** with energy above **100-200 TeV**

Latest: 9.5 years

➡️ *PoS(ICRC2019)1017*

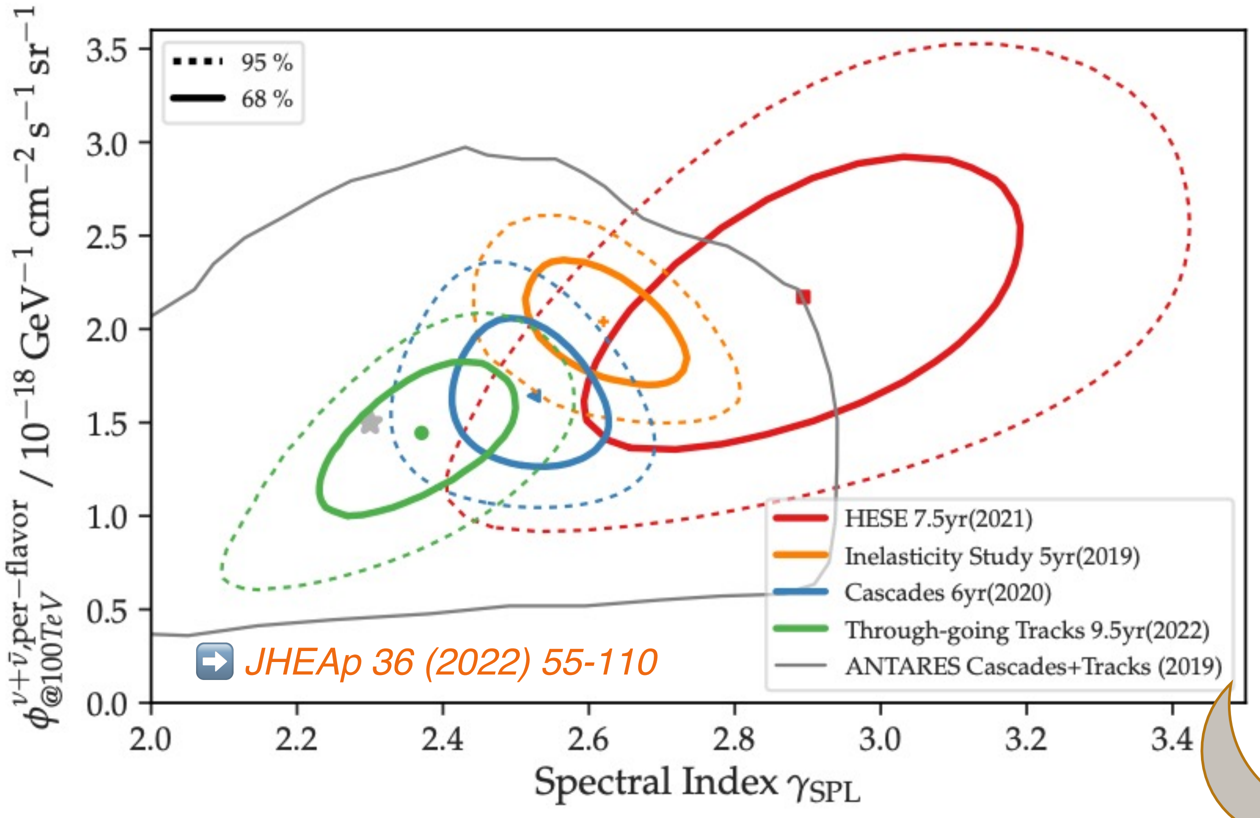


Φ^{1f}(100 TeV) = (1.44±0.25) 10^{-18} (GeV cm^2 s sr)$^{-1}$

Γ = 2.28±0.09

Diffuse astrophysical neutrino flux

Spectral constraints derived from IceCube and ANTARES analysis

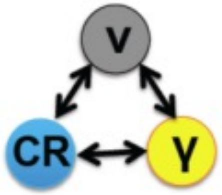


Slight **tension** between different measurements could be **due to** differences in

- **flavor composition,**
- **energy range,**
- **sky coverage,**
- **atmospheric background contamination**

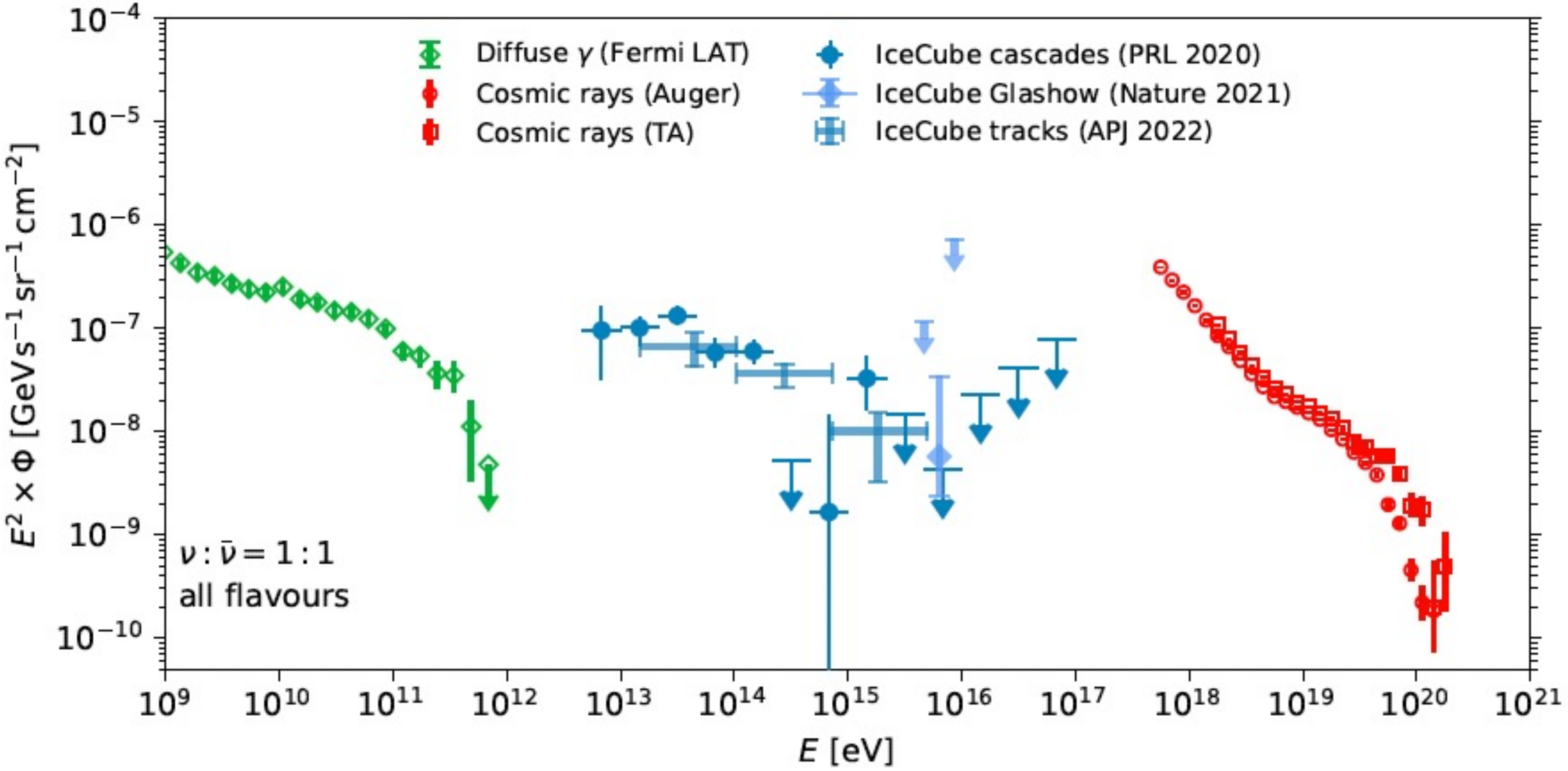
ANTARES results: mild excess (**1.8σ**)
Compatible with IceCube signal
➡️ **see talk by M. Spurio**

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

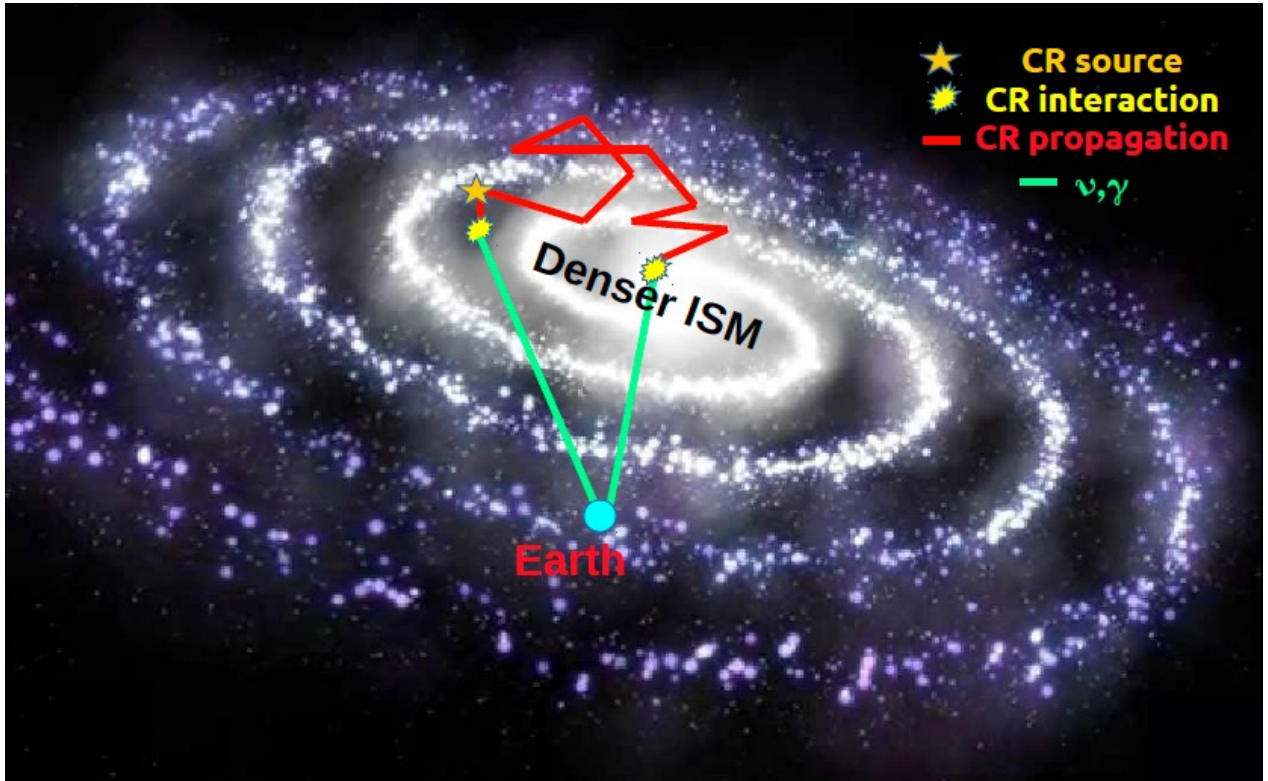
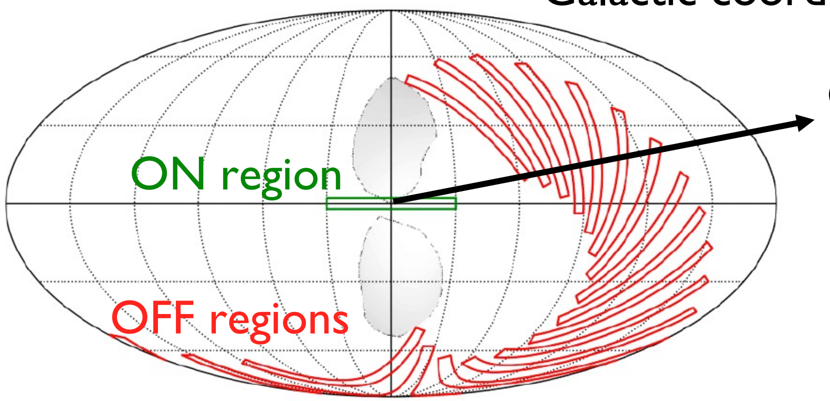


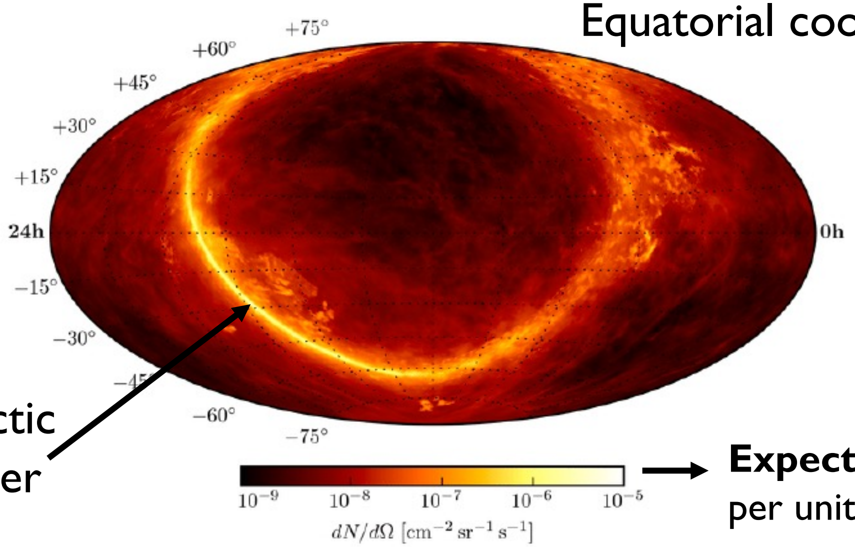
Figure credit: L. Fusco

• Galaxy filled by **CRs and ISM**
→ CR collisions will produce **γs** and **νs**
→ **Guaranteed neutrino component** in the Southern Sky because of the presence of the **Galactic Plane**

Neutrinos from the Galactic Plane

Two search methods:





1. ON/OFF search

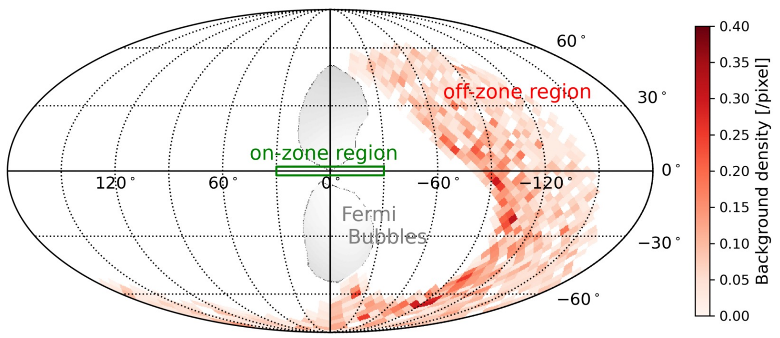
- Limited dependency on models
- Only possible for **mid-latatitude detectors**

2. Template search

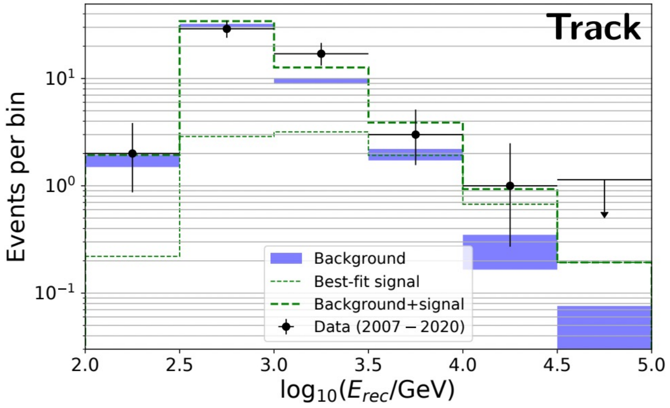
- expected neutrino sky-map from **models of Galactic diffuse neutrino emission**
- model-dependent results
- whole sky is relevant

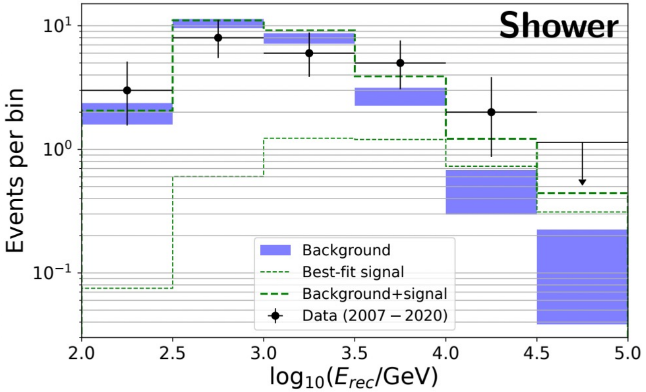
Neutrinos from the Galactic Plane

Recent hint (2.2σ) for a TeV neutrino emission from the Galactic Ridge reported by **ANTARES**



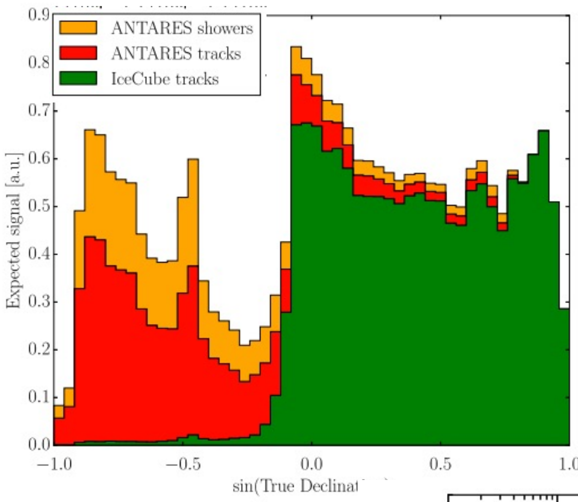
➡️ **see talk by M. Spurio**

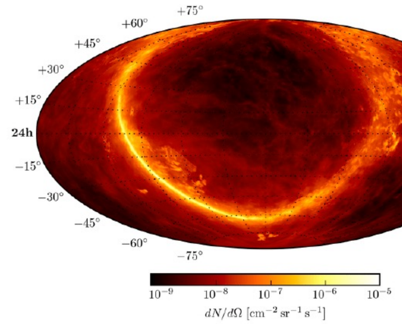




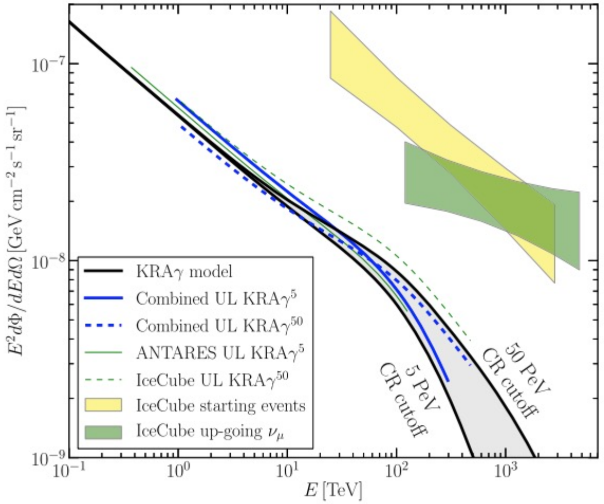
➡️ *Physics Letters B, Volume 841, 2023, 137951*

Joint effort from ANTARES+IceCube





Start to constraint the models



➡️ *Astrophys.J. 868 (2018) no.2, L20*

Neutrinos from the Galactic Plane

IceCube announced the detection of neutrinos from the Galactic Plane at 4.5σ (June 2023)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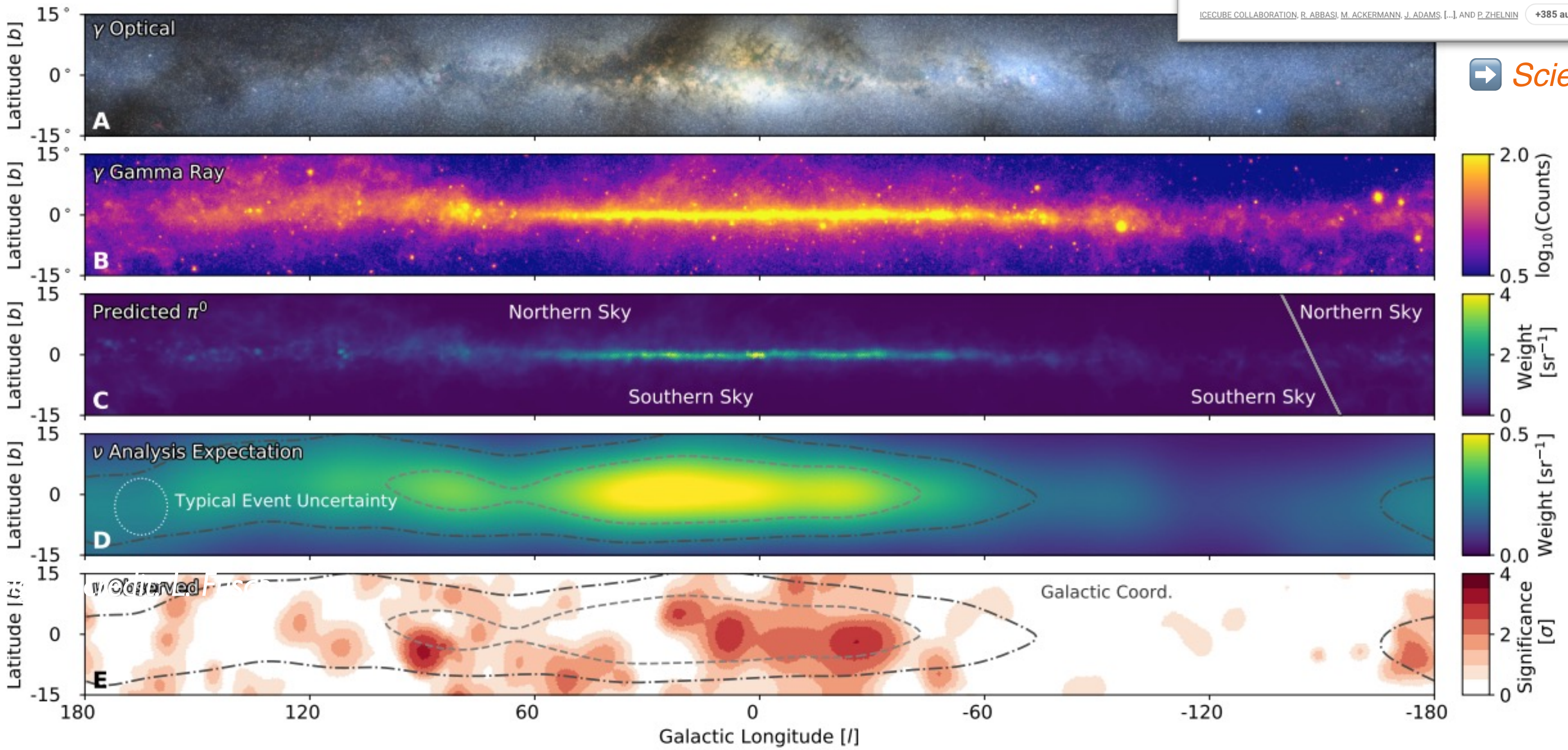
Observation of high-energy neutrinos from the Galactic plane
ICECUBE COLLABORATION, R. ABBASI, M. ACKERMANN, J. ADAMS, [...], AND P. ZHELNIN +385 authors Authors Info & Affiliations

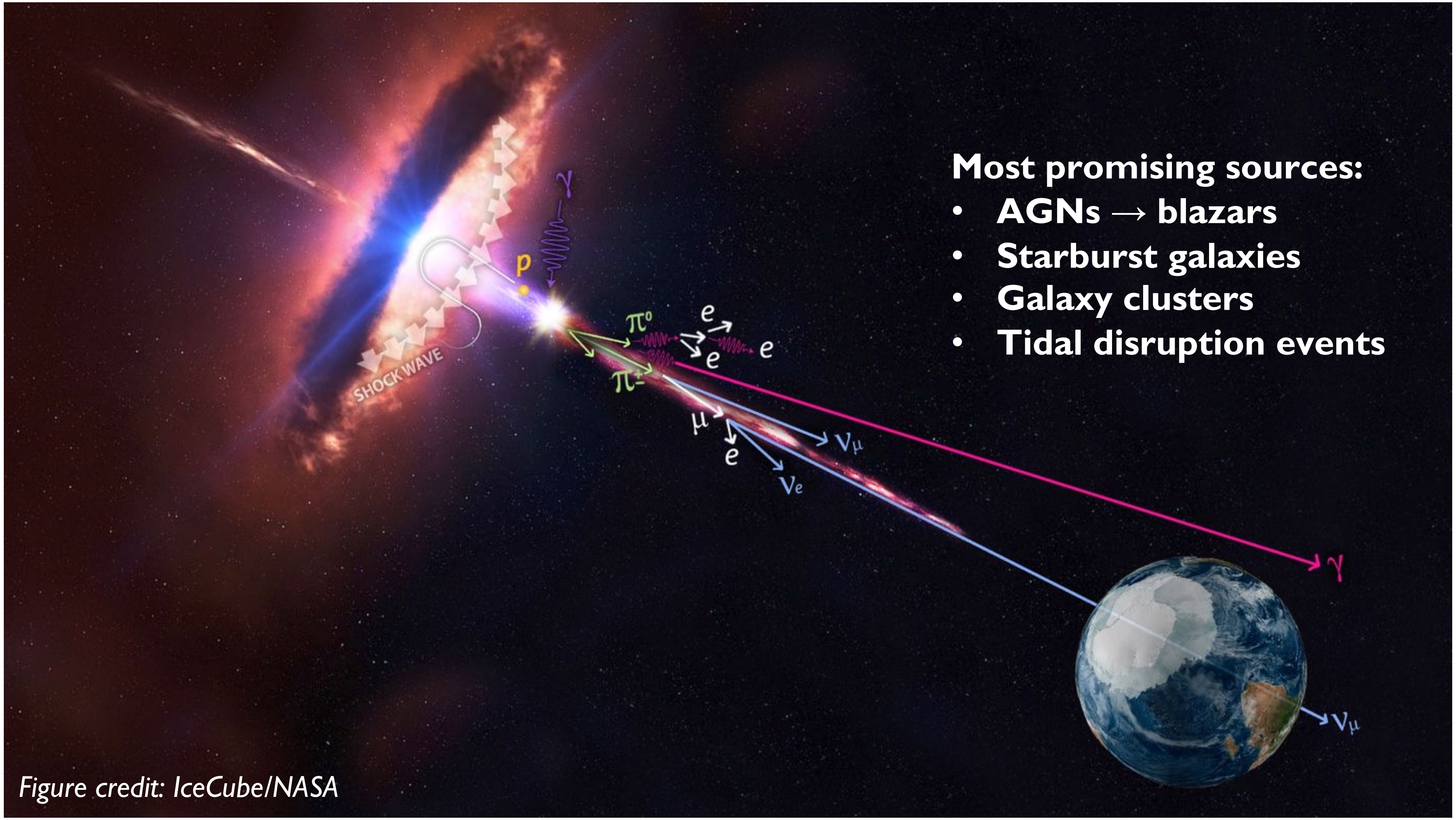
➡ *Science 380, 6652, 1338-1343 (2023)*



Sample: cascade events since

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

Individual sources of neutrinos



Most promising sources:

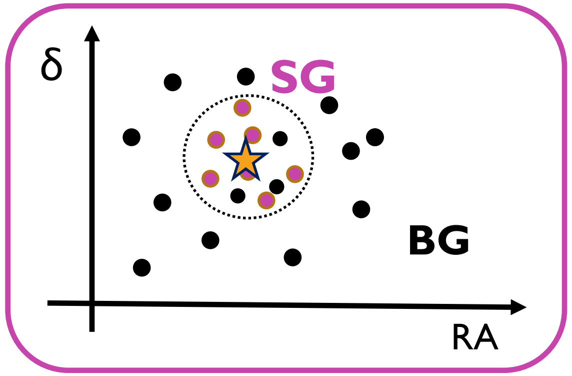
- **AGNs → blazars**
- **Starburst galaxies**
- **Galaxy clusters**
- **Tidal disruption events**

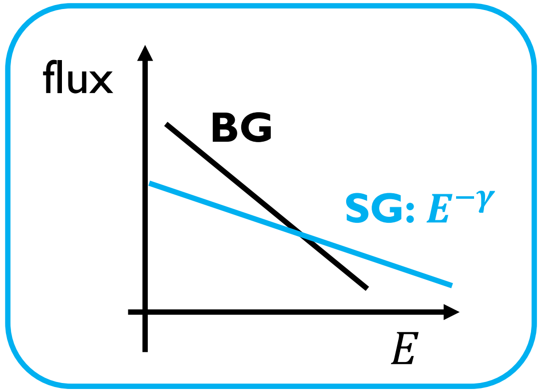
Figure credit: IceCube/NASA

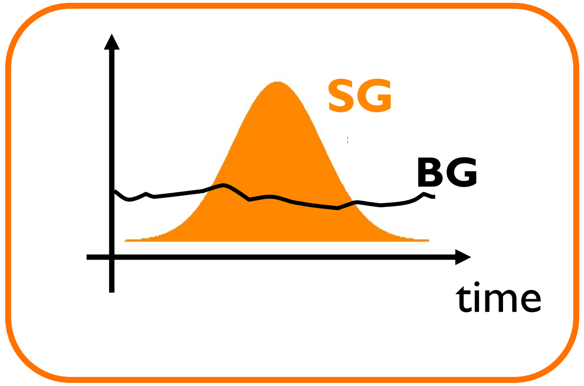
Individual sources of neutrinos

Two ways to detect them:

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

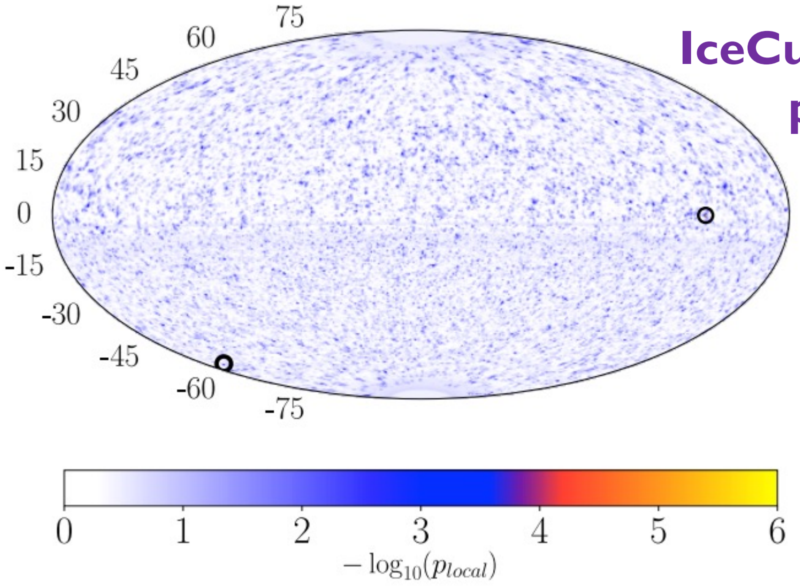




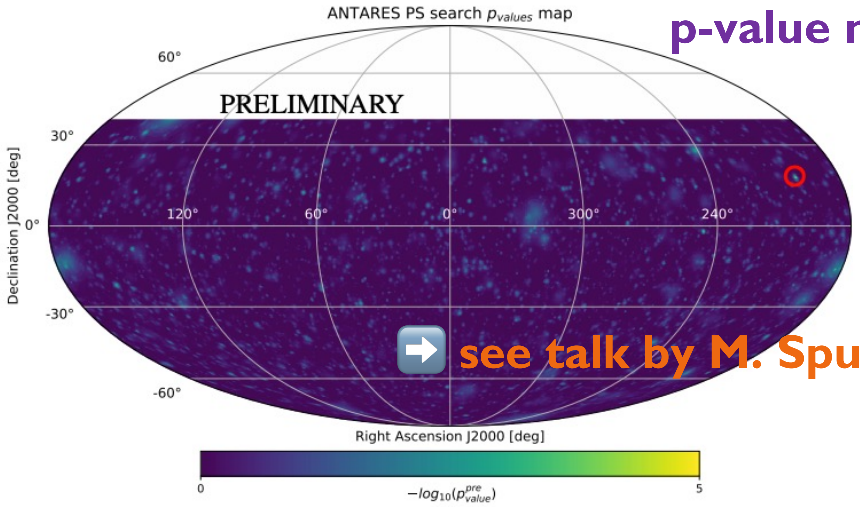


- Look for a **signal-like cluster** of events in **each direction** of the visible sky OR in the direction of **promising neutrino sources**
- **Weak points:**
  - need for a very high flux to **stand out from the BG**
  - **Significance killed** by trial factors

IceCube 10 years p-value map



ANTARES 15 years p-value map

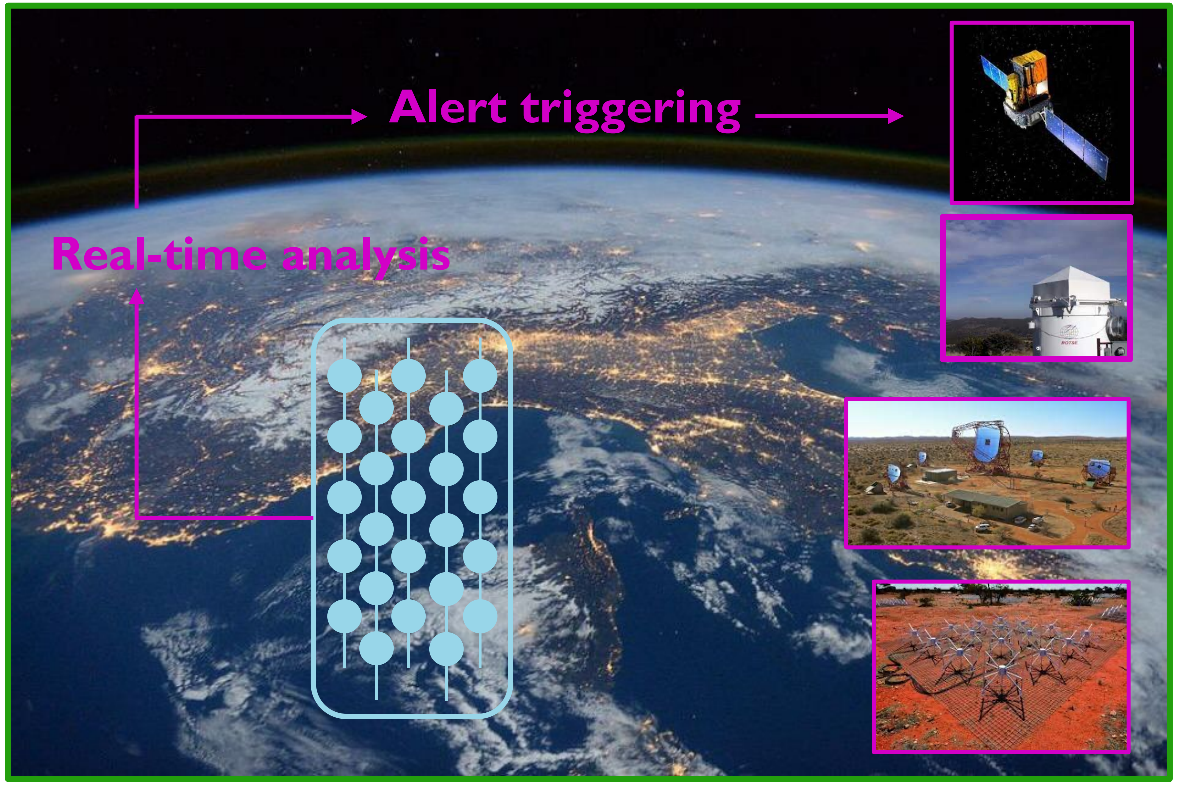


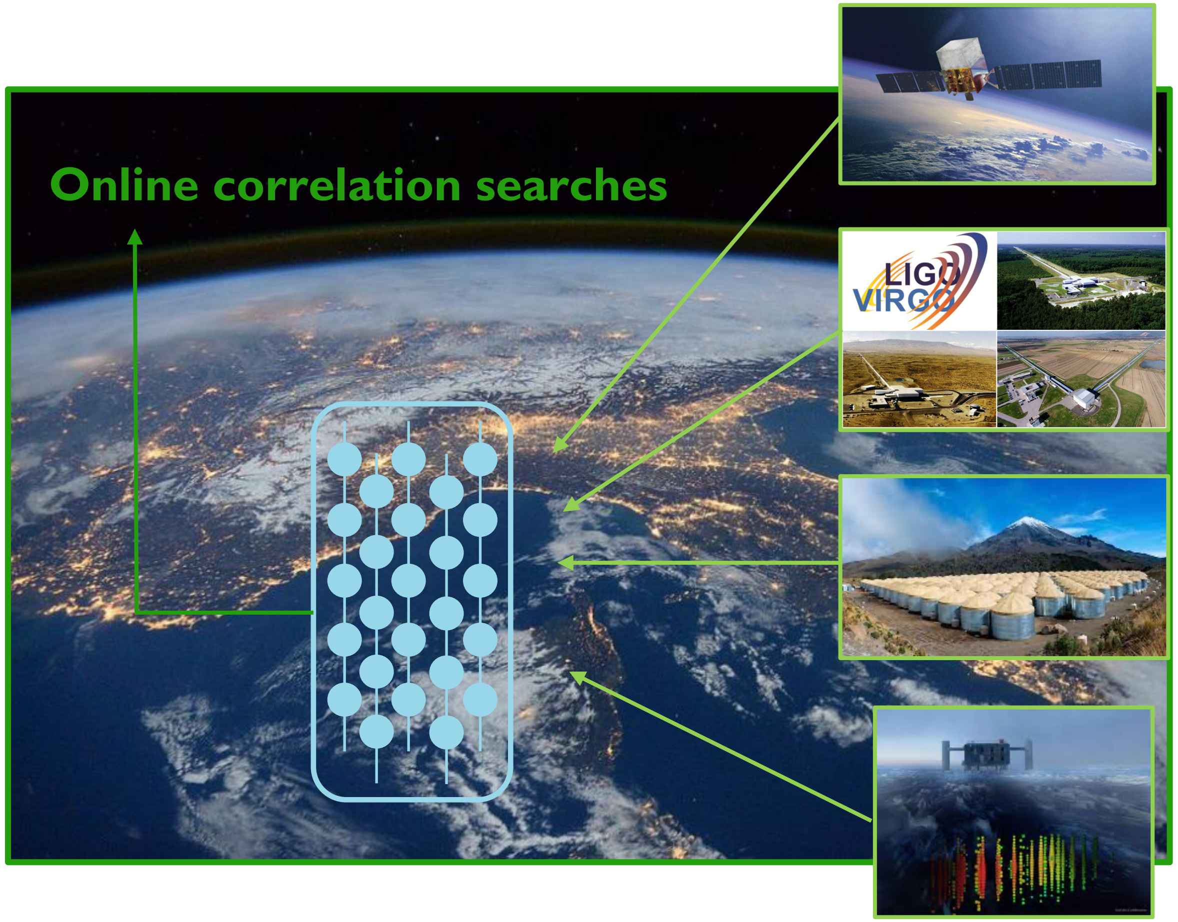
➡️ see talk by M. Spurio

Individual sources of neutrinos

Two ways to detect them:

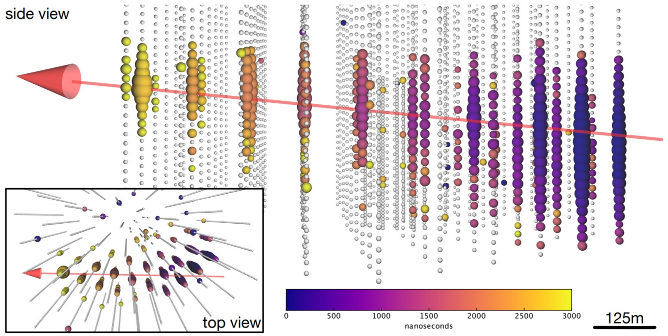
2) Exploit **real-time multi-messenger** approach

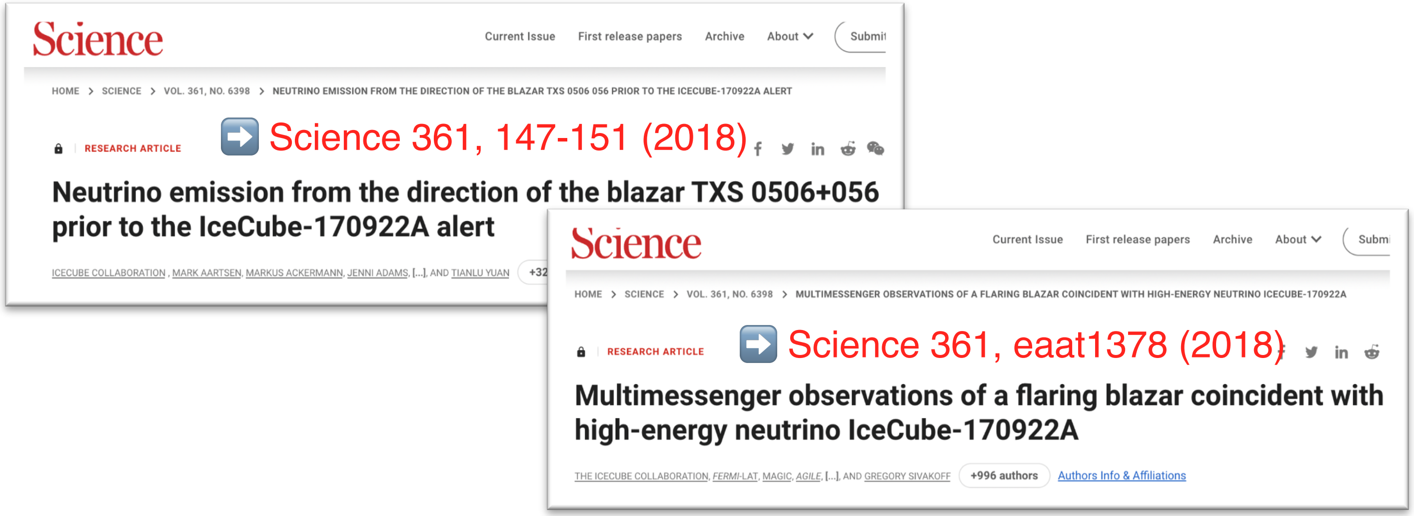




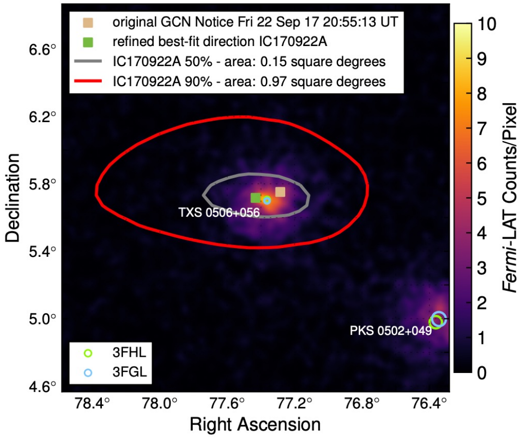
Individual sources of neutrinos

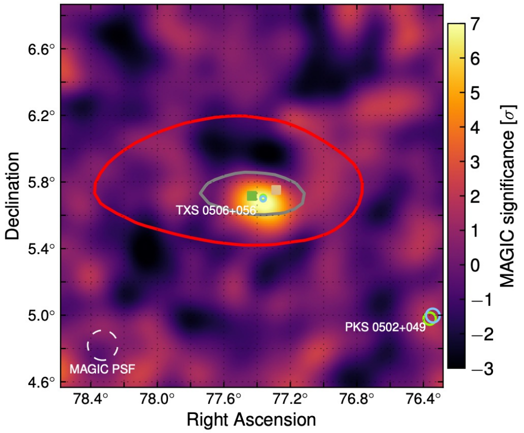
Blazar TXS 0506+056



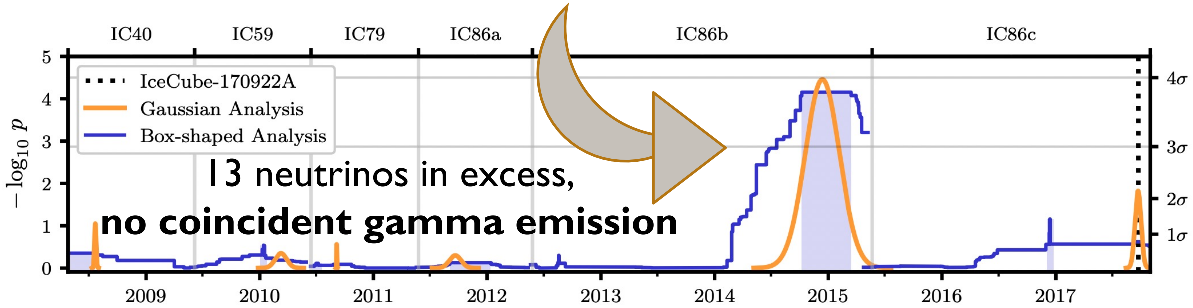


270 TeV muon detected by IceCube on 22 September 2017
in coincidence with flaring blazar
TXS 0506+056 observed by Fermi-LAT and MAGIC (**3σ**)





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



Lack of concordance picture of the multi-messenger data

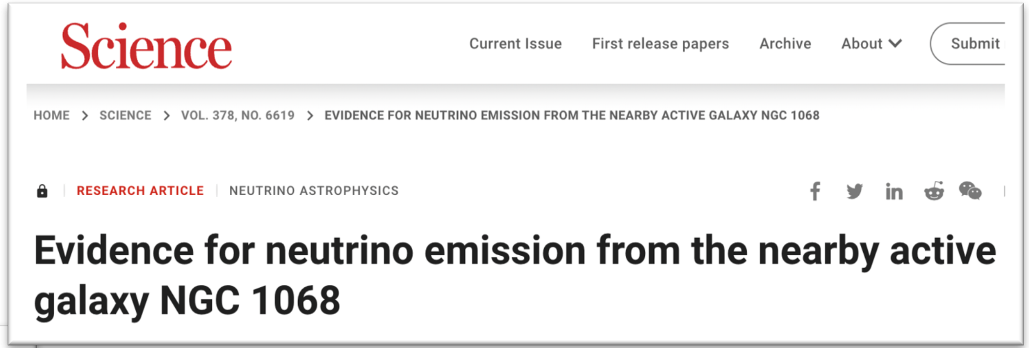
Other neutrinos-blazar correlation

Plavin et al *ApJ 894 (2020) 101, ApJ 908 (2021) 157, MNRAS 523 (2023) 1799*
Buson et al *2022 ApJL 933 L43, arXiv:2305.11263*
ANTARES *arXiv:2309.06874v1* ➡ **see talk by M. Spurio**

Individual sources of neutrinos

Active galaxy NGC 1068

➡️ Science 378, 6619, 538-543 (2022)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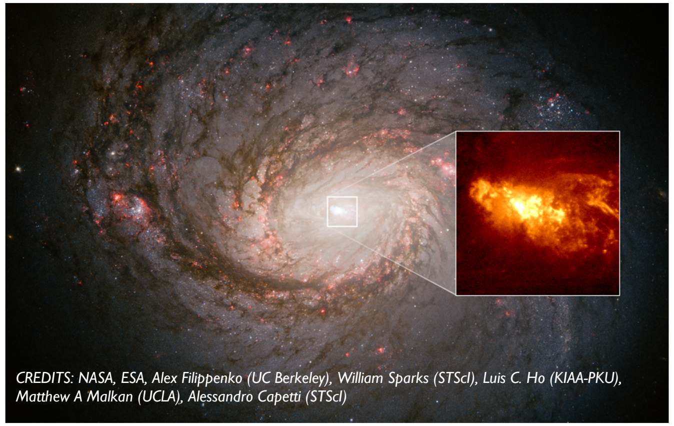
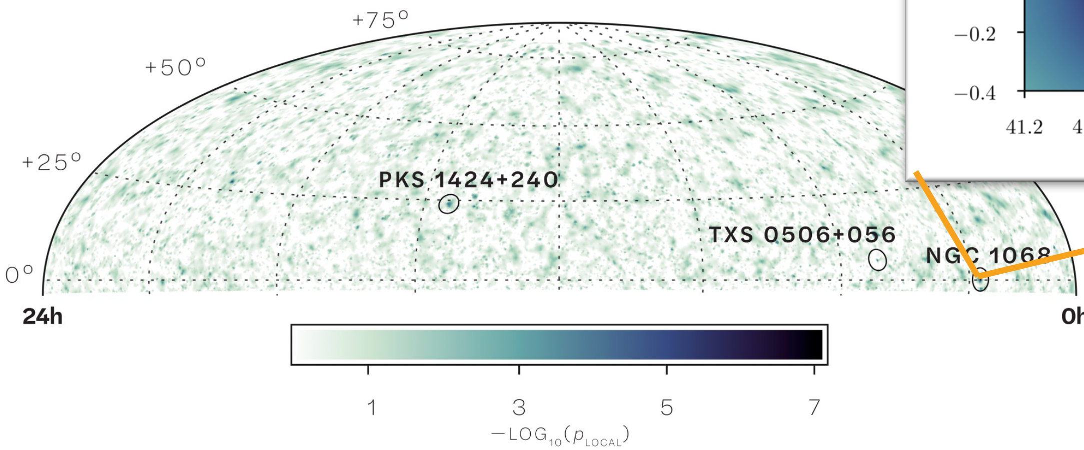
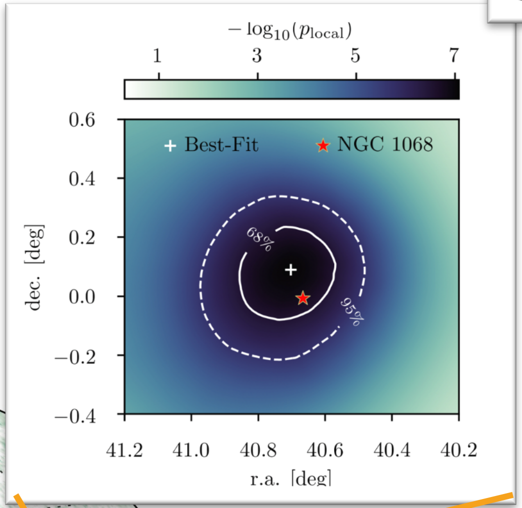
HOME > SCIENCE > VOL. 378, NO. 6619 > EVIDENCE FOR NEUTRINO EMISSION FROM THE NEARBY ACTIVE GALAXY NGC 1068
RESEARCH ARTICLE | NEUTRINO ASTROPHYSICS
Evidence for neutrino emission from the nearby active galaxy NGC 1068



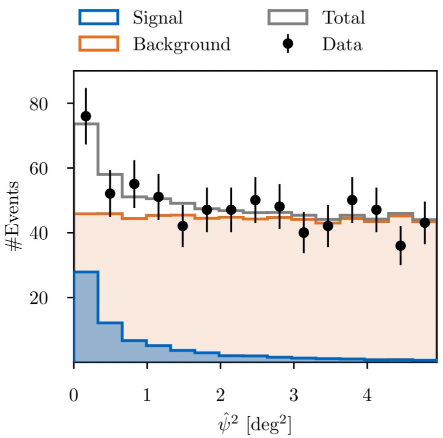
Brightest and one of the closest type 2 **Seyfert galaxies**

4.2σ post-trial (catalog search)

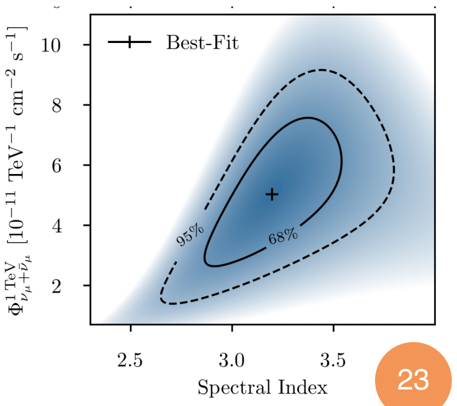




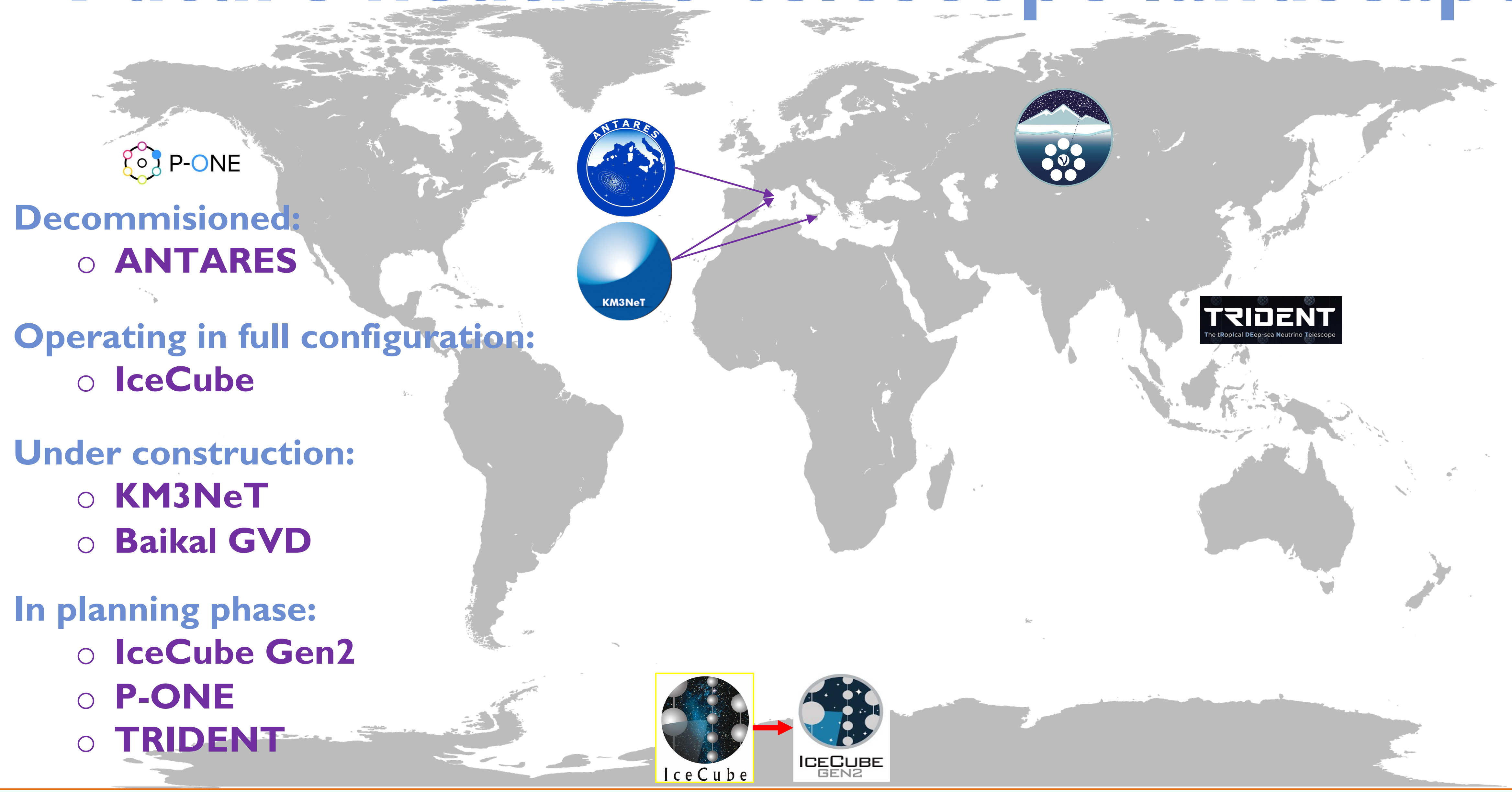
~80 detected neutrino events



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



Future neutrino telescope landscape



Decommisioned:
- ANTARES

Operating in full configuration:
- IceCube

Under construction:
- KM3NeT
- Baikal GVD

In planning phase:
- IceCube Gen2
- P-ONE
- TRIDENT

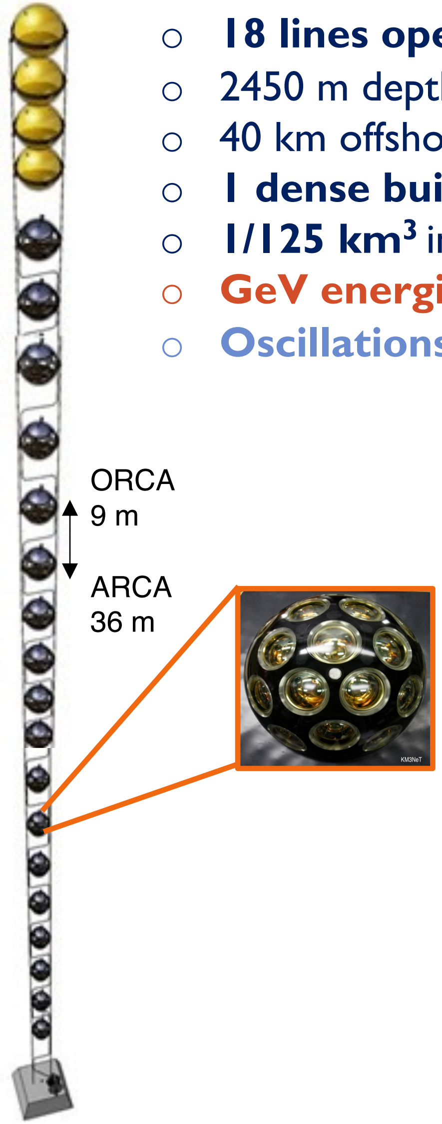
➡️ see talk by M. Spurio

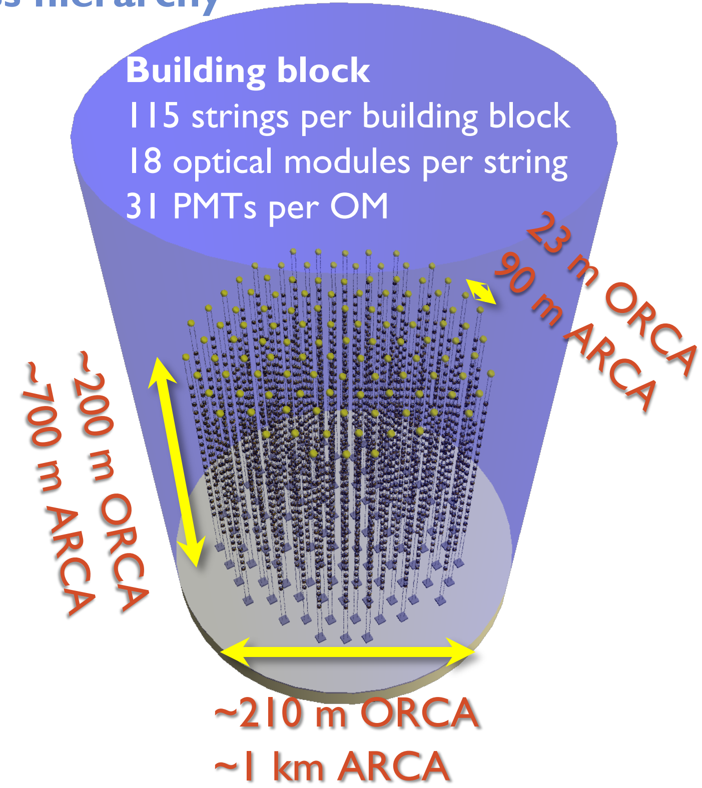
➡️ Journal of Physics G: Nuclear and Particle Physics, 43 (8), 084001, 2016

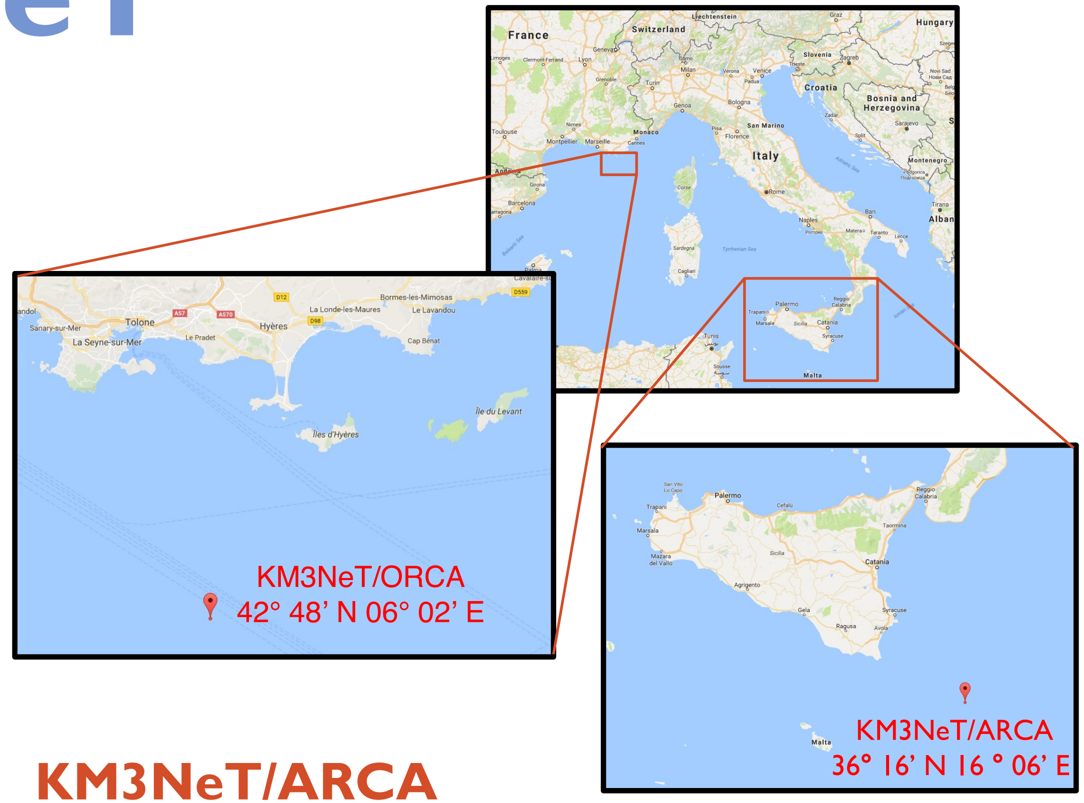
KM3NeT

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**







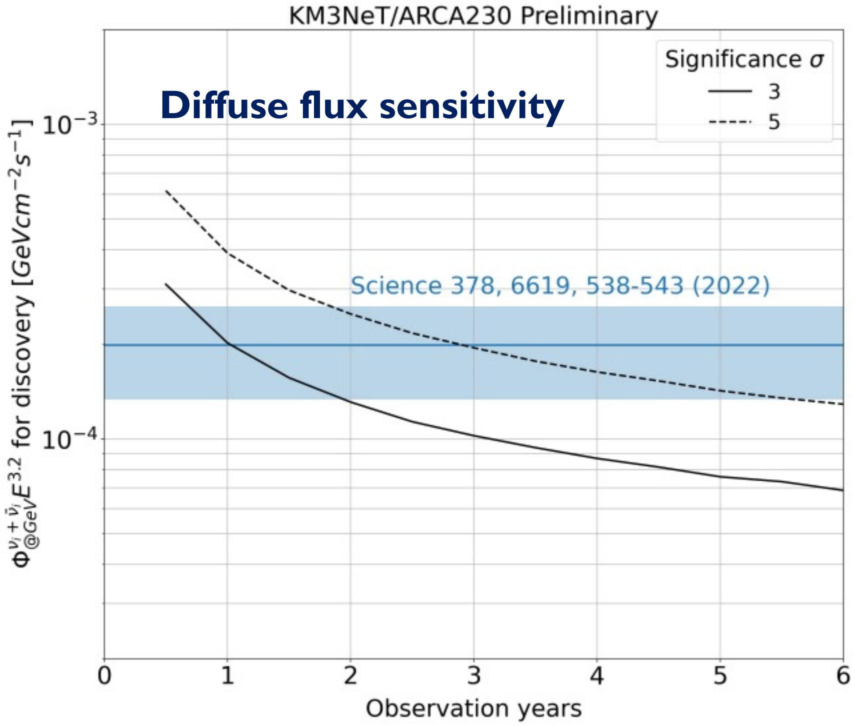
KM3NeT/ARCA

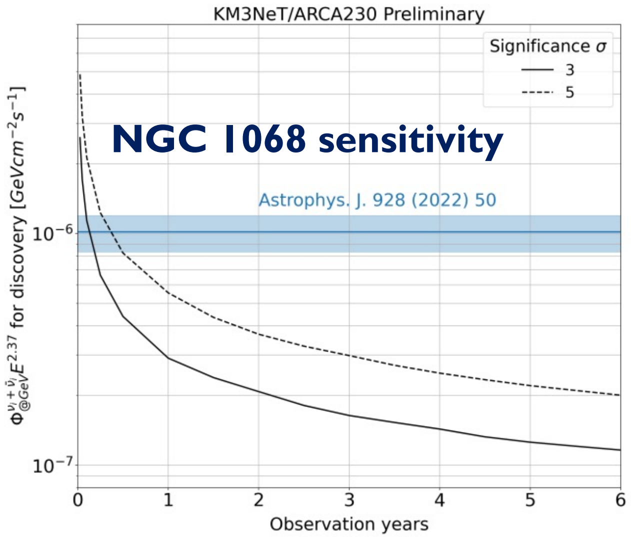
- **28 lines operating**, 230 lines foreseen
- 3500 m depth in the Mediterranean Sea
- 100 km offshore from Sicily
- **2 sparse building blocks**
- **1 km^3** instrumented volume
- **1-10 TeV energy threshold**
- **High-energy neutrino astronomy**

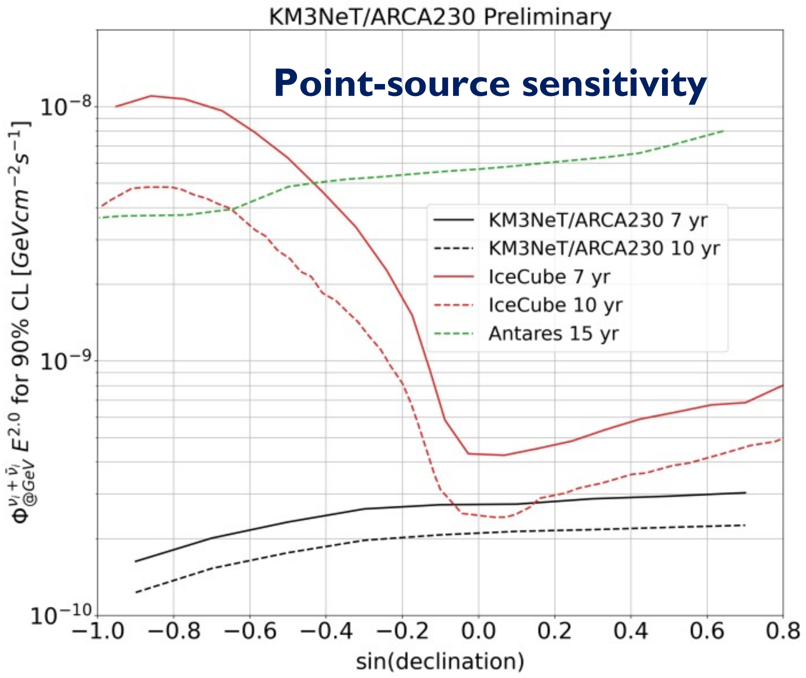
➡️ PoS(ICRC2023)1075

KM3NeT

- **ARCA angular resolution:**
  - **< 0.2° (E >10 TeV) for tracks**
  - **~ 2° (E >10 TeV) for showers**
- **ARCA energy resolution:**
  - **27% for tracks**
  - **<5% for showers**







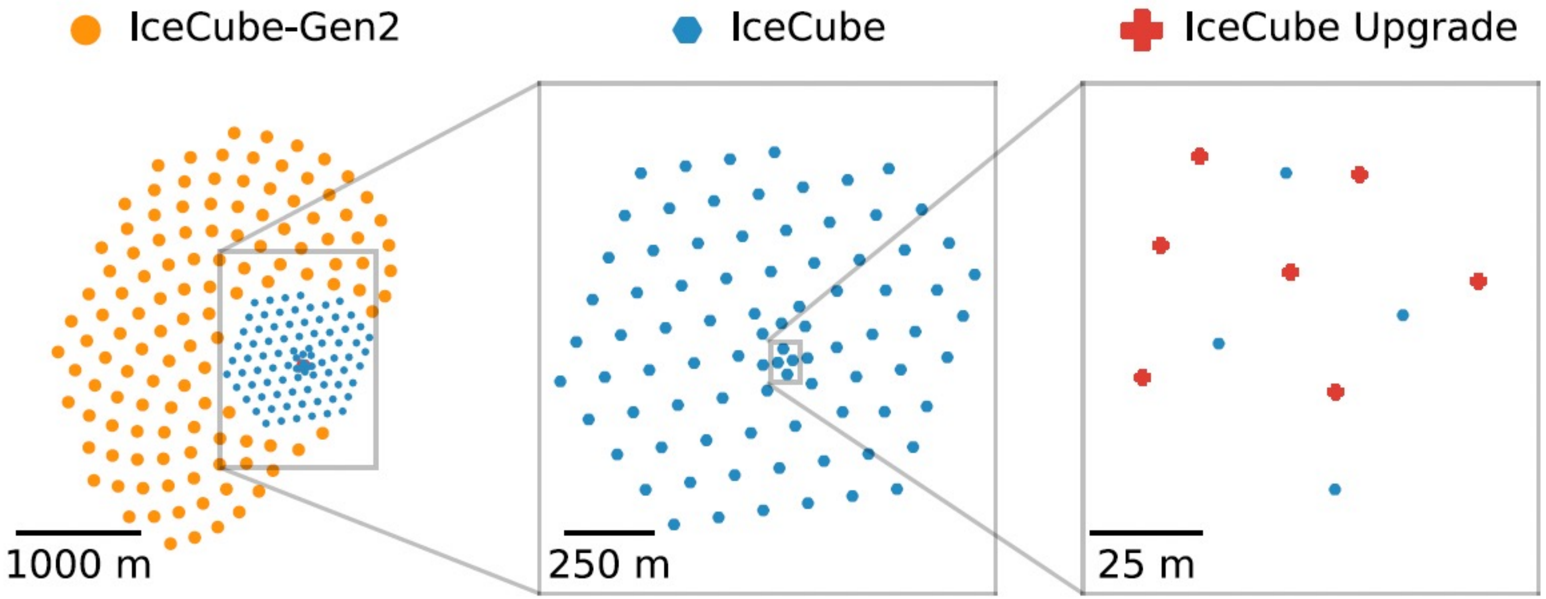
ARCA will be able to:

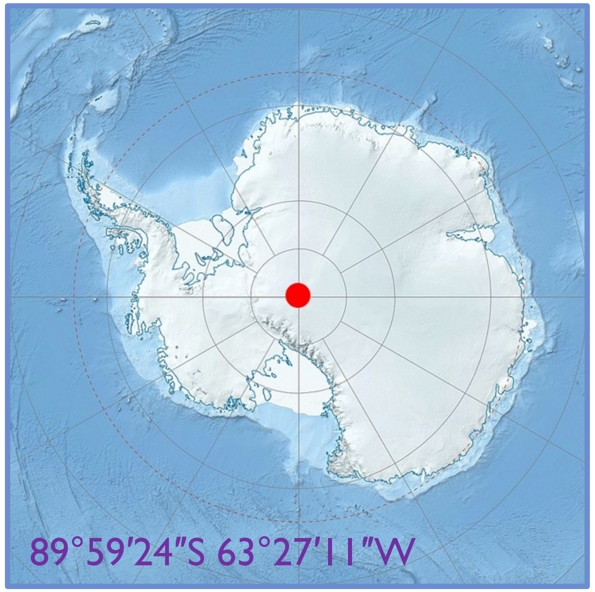
- **Confirm** IceCube's observation of **diffuse** and **Galactic Plane flux**
- Characterize the **neutrino spectrum and flavor composition**

- Look for **point-sources** of neutrinos with **unprecedented angular resolution**
- **Probe** the predicted fluxes for several **Galactic sources** in a few years of operation
- **Enhance** the power of **multi-messenger follow-up** studies

J.Phys.G 48 (2021) 6, 060501

IceCube-Gen2





IceCube-Gen2
8 km³
120 strings
240 m apart

IceCube
1 km³
86 strings
125 m apart

IceCube Upgrade
7 extra strings

HE vs (TeV-PeV)

LE studies, better understanding of ice optical properties

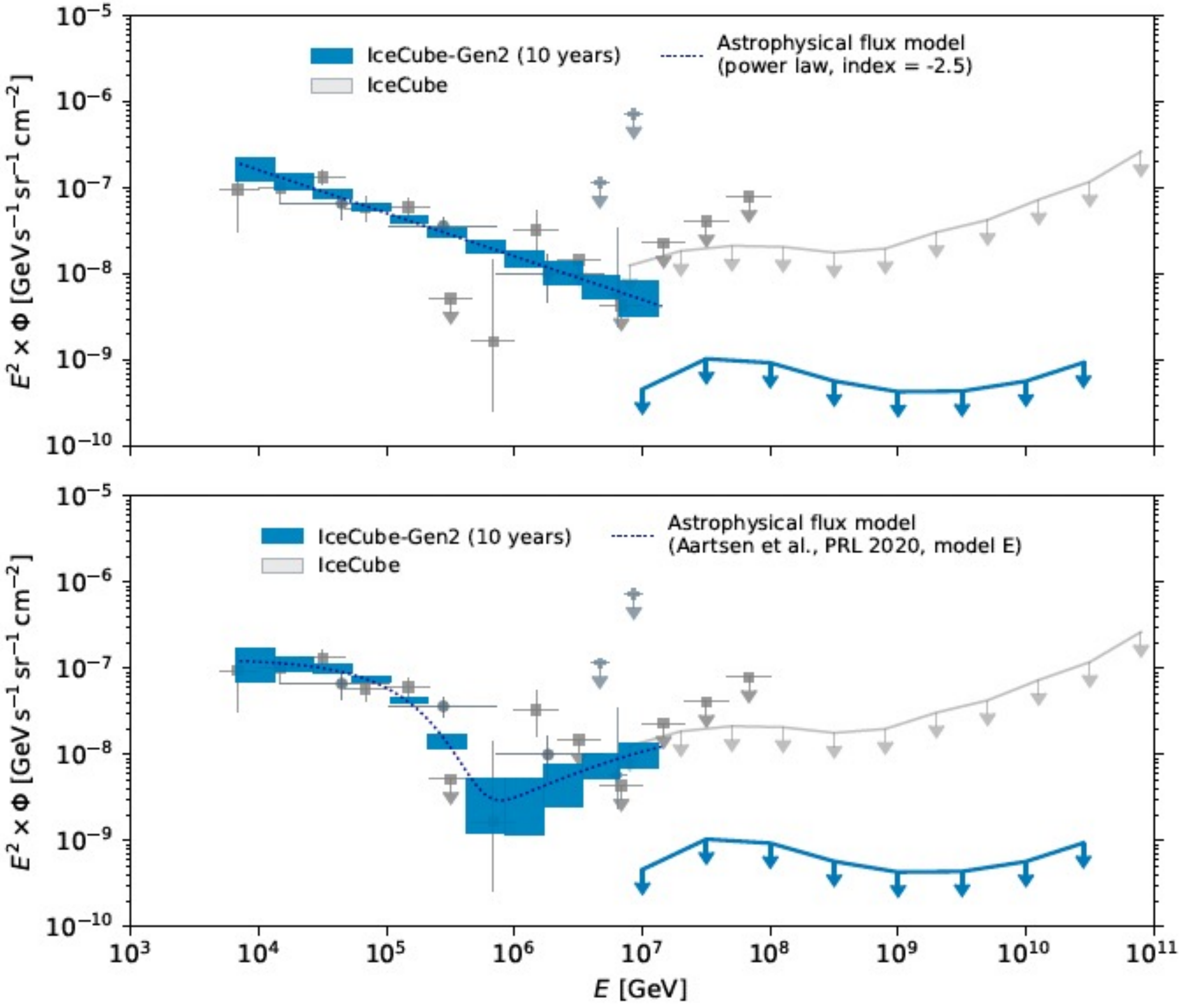
With respect to IceCube:

- **annual rate** of observed cosmic neutrinos increased by **a factor of ten**
- **enlarged energy range**
- improved angular resolution: **0.2° at 1 PeV**

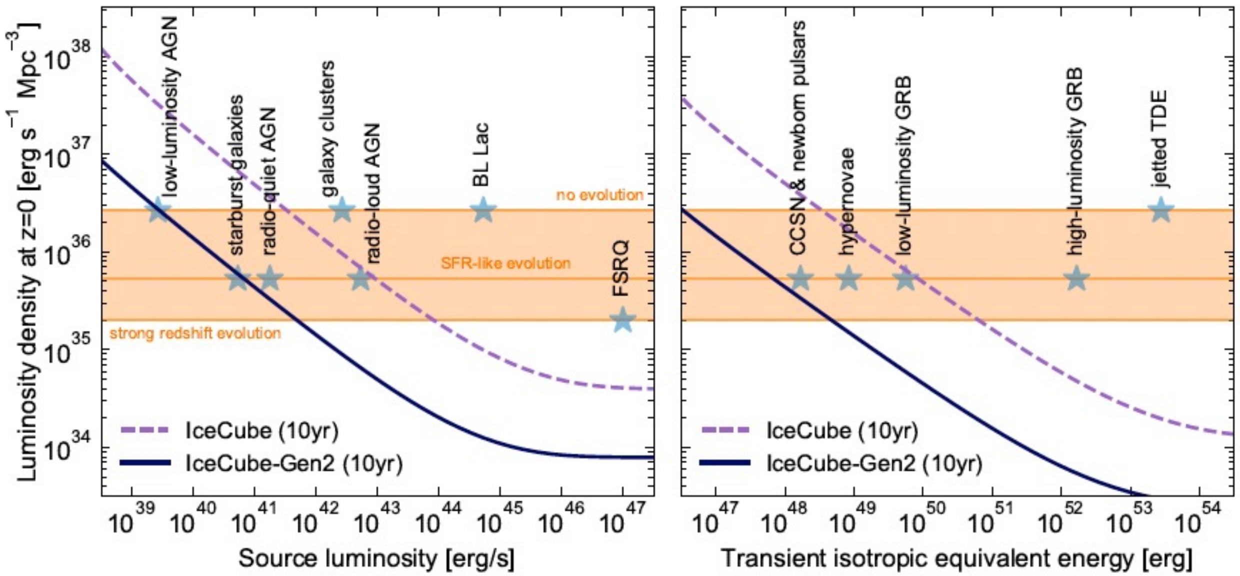
IceCube-Gen2

JHEAp 36 (2022) 55-110

Diffuse flux



Steady and transient point-like sources



IceCube-Gen2 will yield about 5 times more alerts with improved angular resolution compared to IceCube

Future neutrino telescope landscape

P-ONE
> 1 km^3 instrumented volume

ANTARES
KM3NeT
1 km^3 instrumented volume

1 km^3 instrumented volume

TRIDENT
The tRopIcal DEep-sea Neutrino Telescope
7.5 km^3 instrumented volume

Entering the high statistics era → high precision studies

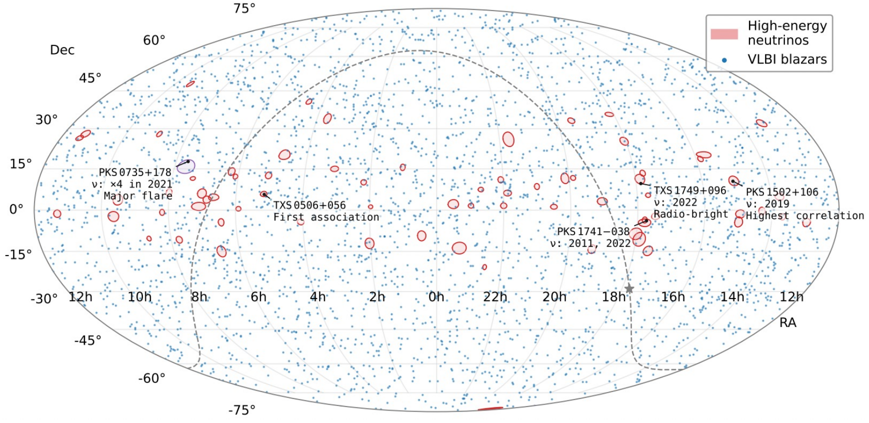
- Detailed studies of **diffuse flux: energy spectrum, flavour composition**
- Firmly **establish neutrino sources** and their properties
- Detection and characterization of **Galactic plane emission with km^3-sized Northern telescopes**
- Joint spectral measurements combining all operating neutrino might solve the apparent tension
- Improved **quality and quantity of neutrino alerts** → **more multi-messenger events** at higher significance

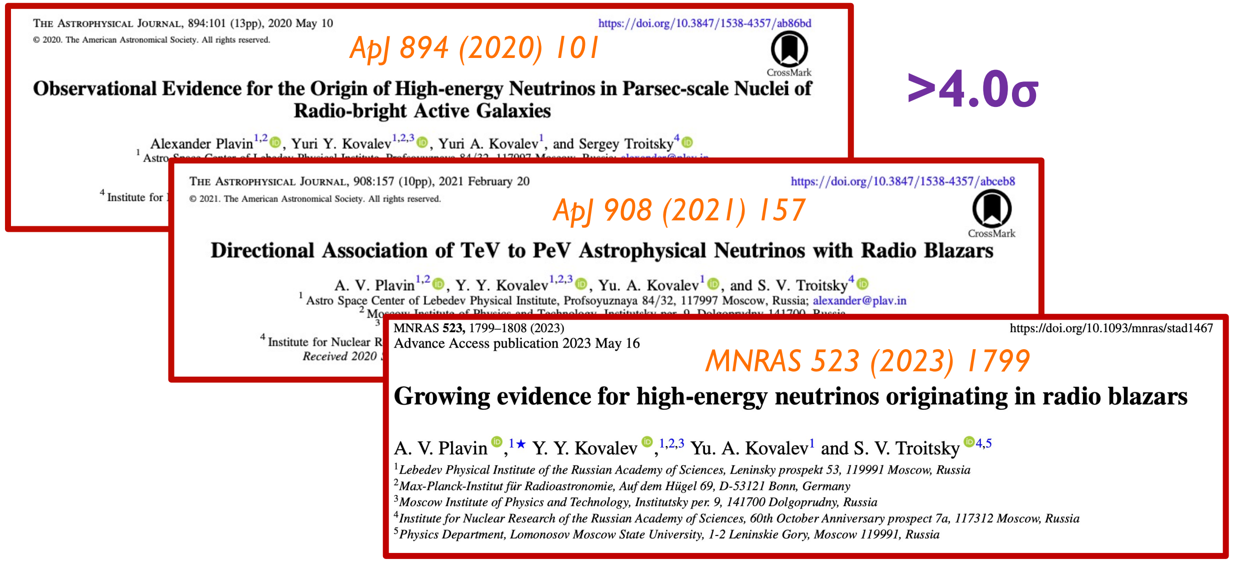
IceCube → IceCube Gen2
8 km^3 instrumented volume

Backup

Neutrinos and blazars

Radio-bright blazars





The Astrophysical Journal, 894:101 (13pp), 2020 May 10 https://doi.org/10.3847/1538-4357/ab86bd

ApJ 894 (2020) 101

Observational Evidence for the Origin of High-energy Neutrinos in Parsec-scale Nuclei of Radio-bright Active Galaxies

Alexander Plavin[1,2], Yuri Y. Kovalev[1,2,3], Yuri A. Kovalev[1], and Sergey Troitsky[4]

The Astrophysical Journal, 908:157 (10pp), 2021 February 20 https://doi.org/10.3847/1538-4357/abceb8

ApJ 908 (2021) 157

Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars

A. V. Plavin[1,2], Y. Y. Kovalev[1,2,3], Yu. A. Kovalev[1], and S. V. Troitsky[4]
[1] Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117997 Moscow, Russia; alexander@plav.in

MNRAS 523, 1799–1808 (2023) https://doi.org/10.1093/mnras/stad1467
Advance Access publication 2023 May 16

MNRAS 523 (2023) 1799

Growing evidence for high-energy neutrinos originating in radio blazars

A. V. Plavin[1★], Y. Y. Kovalev[1,2,3] Yu. A. Kovalev[1] and S. V. Troitsky[4,5]
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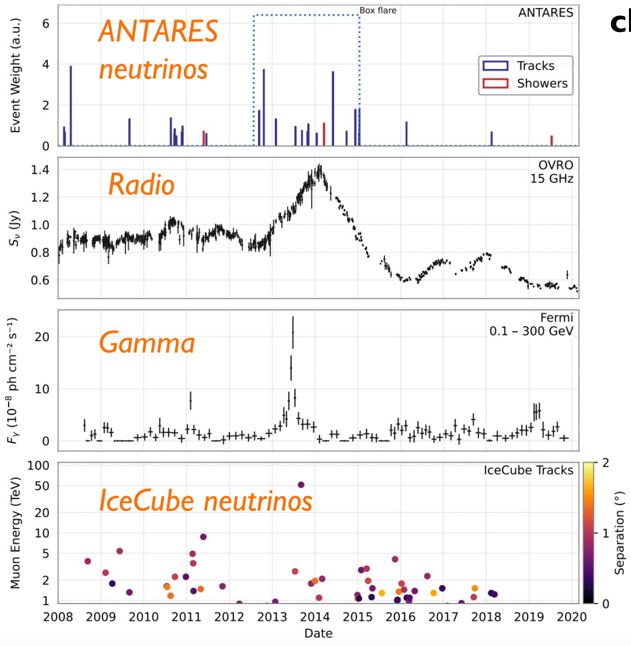
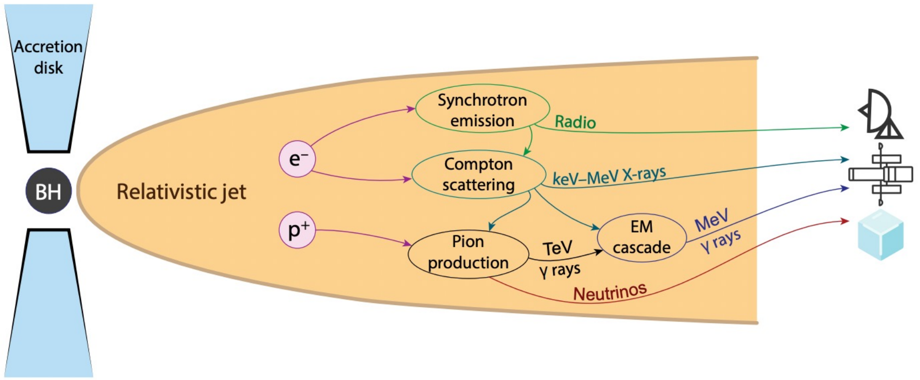
[4] Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary prospect 7a, 117312 Moscow, Russia
[5] Physics Department, Lomonosov Moscow State University, 1-2 Leninskie Gory, Moscow 119991, Russia

>4.0σ

Blazar J0242+1101 multi-messenger flare, 2.9σ chance probability

ANTARES arXiv:2309.06874v1





No correlation with radio-bright blazars **found in recent IceCube search** (*2023 ApJ 954 75*) mitigates these findings

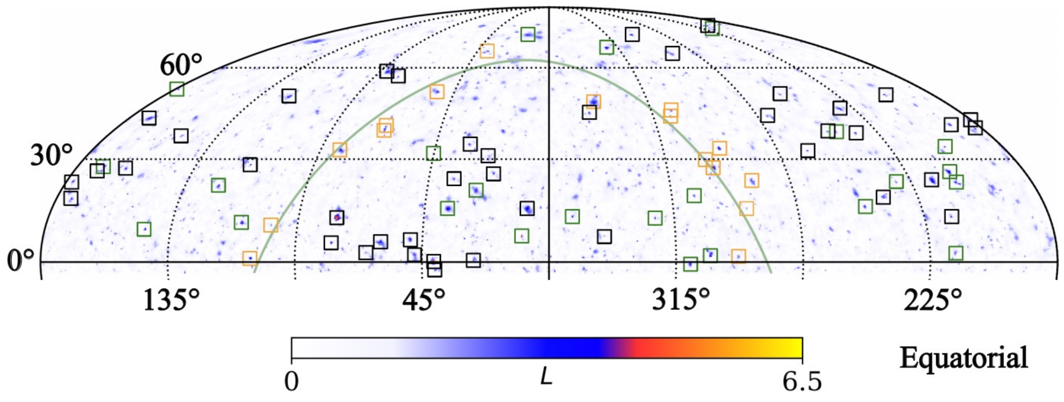
➡️ see talk by M. Spurio

Neutrinos and blazars

Roma-BZCat catalog

- 3561 objects
- **confirmed** or highly likely **blazars**
- **no preferred** selection toward a particular **wavelength** or survey strategy
- offers a **homogeneous sample** of the blazar population

Only northern sky *2022 ApJL 933 L43*



Combined sensitivity >5.0σ

Full-sky *arXiv:2305.11263*

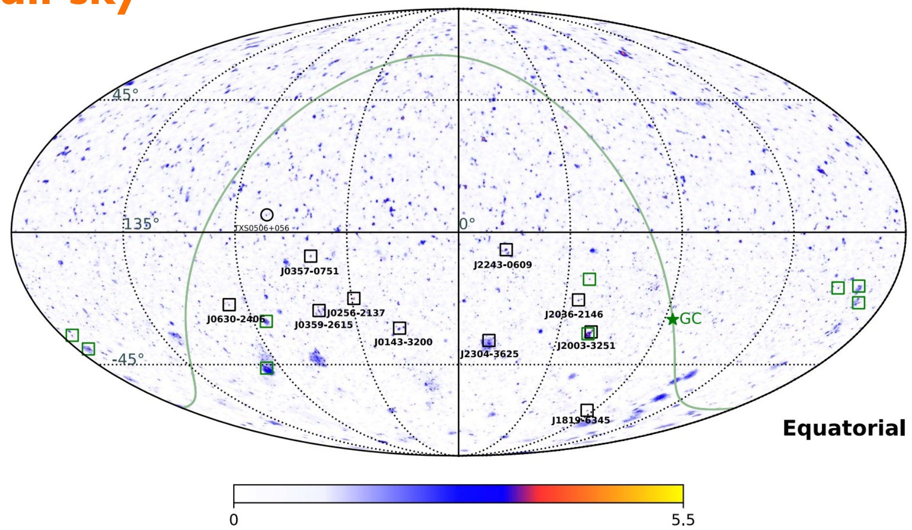


Figure 2. All-sky map in equatorial coordinates (J2000) of the IceCube neutrino local *p*-value logarithms denoted as *L*. Locations of PeVatron blazars associated with neutrino hotspots are pointed out by black squares. For visualization clarity, the label of 5BZCat objects is limited to reporting the unique numerical coordinate part. Unassociated hotspots are highlighted by green squares. The location of TXS 0506+056 is shown for reference (green circle). Squares are not to scale and serve the only purpose of highlighting the blazars' locations. The Galactic plane and Galactic center are shown for reference as a green line and star, respectively.

Tau neutrinos

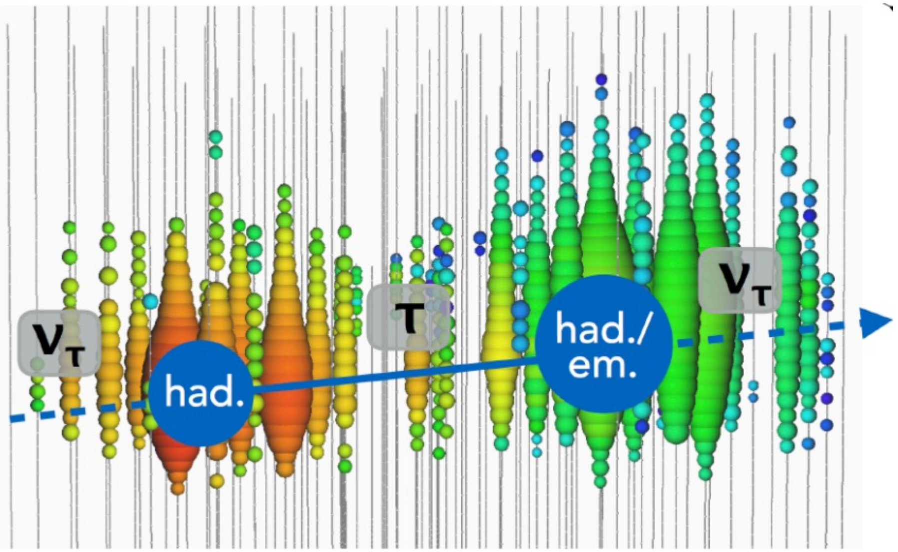
➡️ Eur.Phys.J.C 82 (2022) 11, 1031
➡️ PoS(ICRC2023)1122

Tau neutrinos

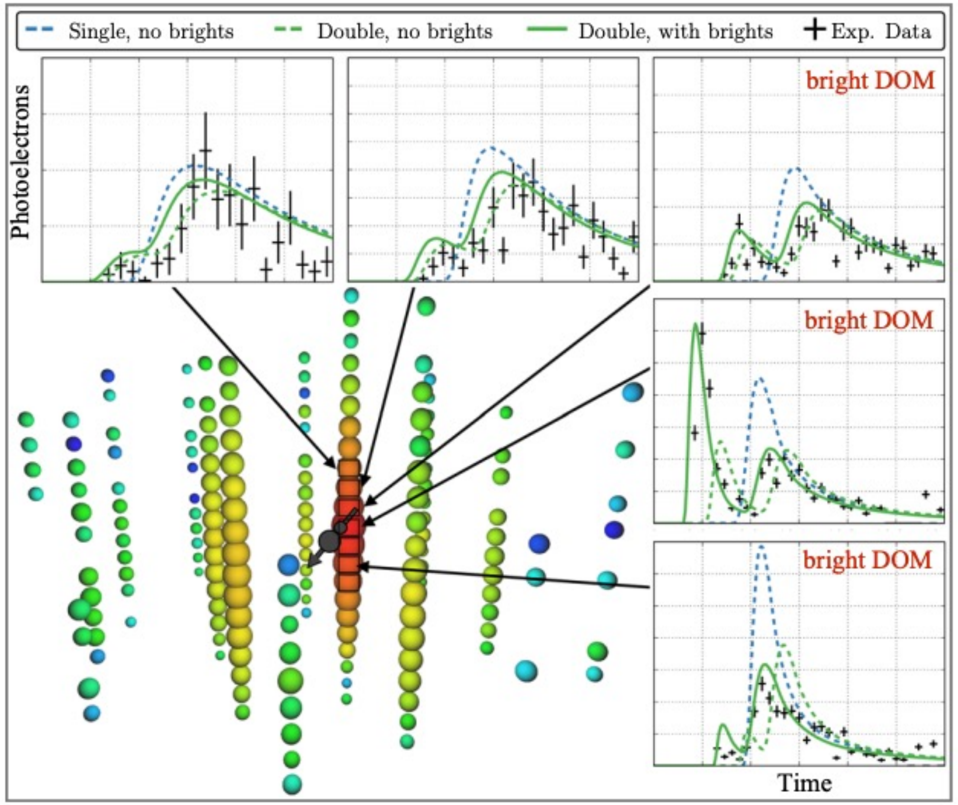
No atmospheric tau neutrinos at TeV-PeV energies

Detection of astrophysical tau neutrino candidates in IceCube

Regular Article – Experimental Physics | Open Access | Published: 15 November 2022
82, Article number: 1031 (2022)



tau decay length: 50m per PeV

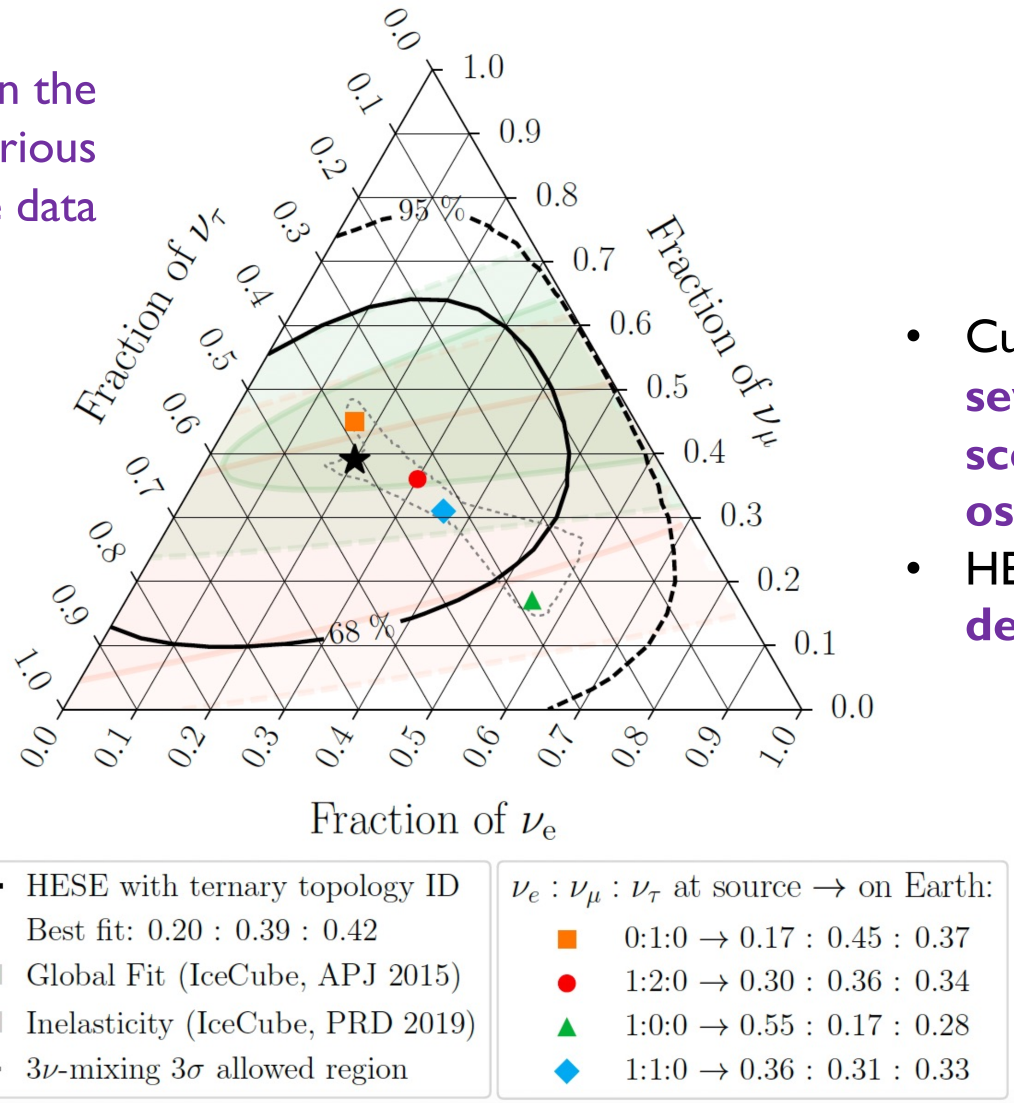


- **7 candidate events** found in 10 years of IceCube data
- **Consistent with 1:1:1 flavor ratio** of astrophysical neutrinos

➡️ JHEAp 36 (2022) 55-110

Flavour composition

Flavor constraints on the cosmic neutrino flux from various analyses of IceCube data



→ muon-damped case

→ pion decay

→ neutron beta-decay

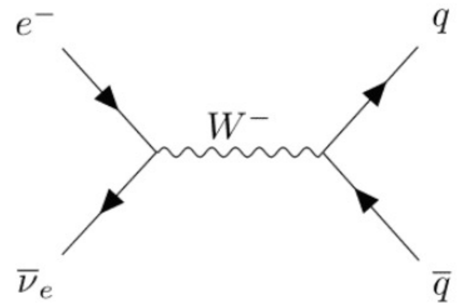
→ semileptonic decays of charm quarks

- Current constraints **compatible with several astrophysical production scenarios** and **standard neutrino oscillations**
- HE neutrino production from the **beta-decay of neutrons strongly disfavoured**

Glashow resonance

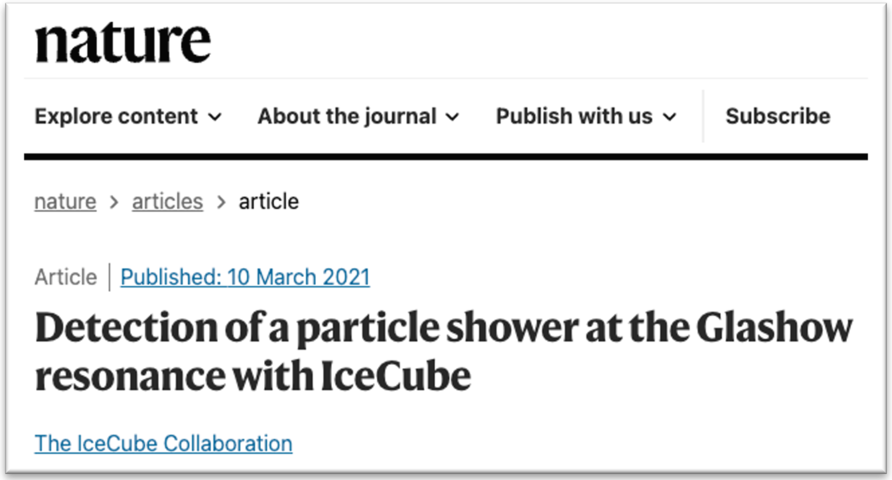
➡️ Nature 591, 220-224 (2021)

First observation of Glashow Resonance



Resonant production of an intermediate boson by an **antielectron neutrino** interacting with an atomic **electron**

Resonance energy: $\mathbf{E_\nu = 6.3}$ **PeV**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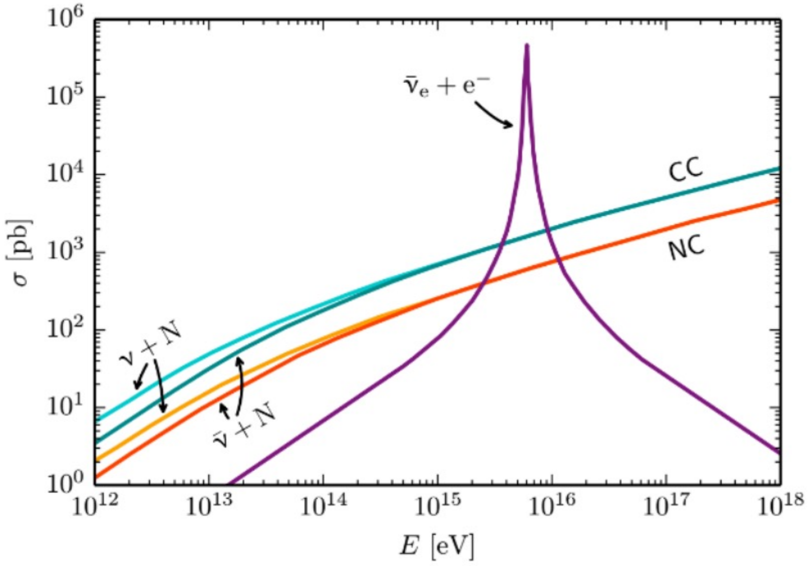
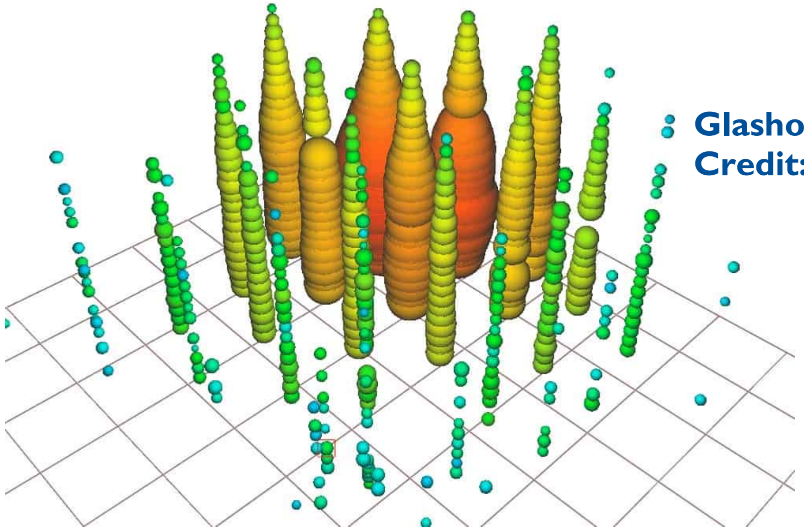
Article | Published: 10 March 2021

Detection of a particle shower at the Glashow resonance with IceCube

The IceCube Collaboration





Glashow event visualization
Credit: IceCube Collaboration

Cross section

➡️ Nature 551 (2017) 596-600
➡️ Phys. Rev. Lett. 122, 041101 (2019)
➡️ Phys. Rev. D 104, 022001 (2021)

First measurement of HE neutrino-nucleon cross section