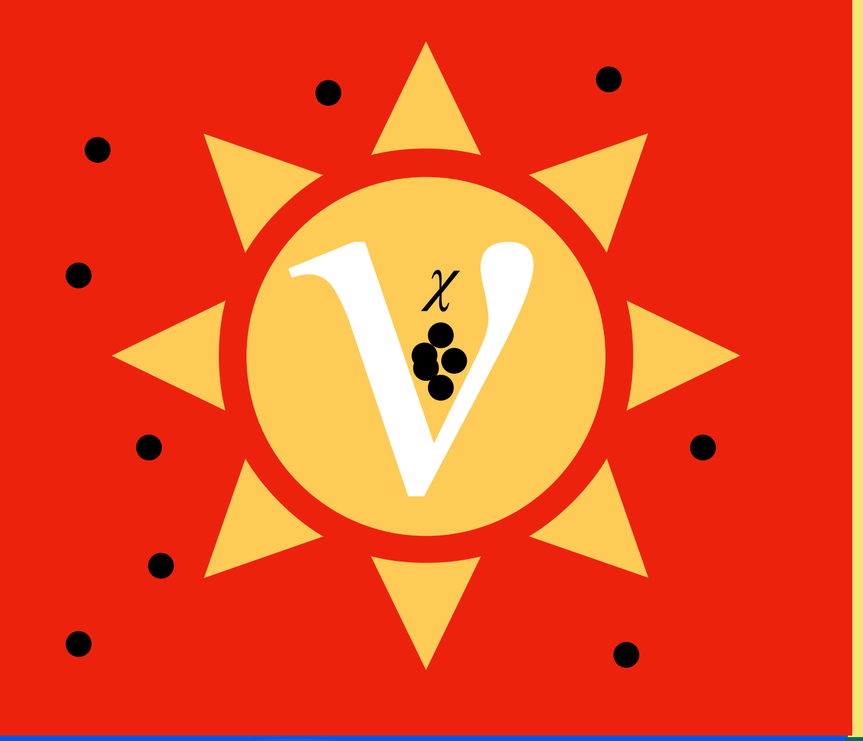
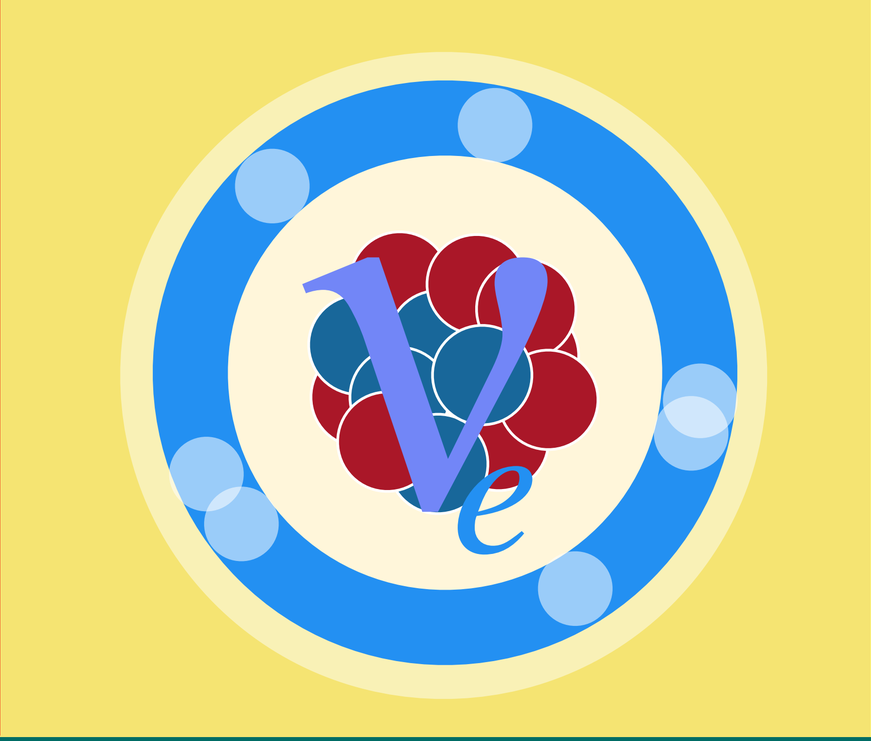
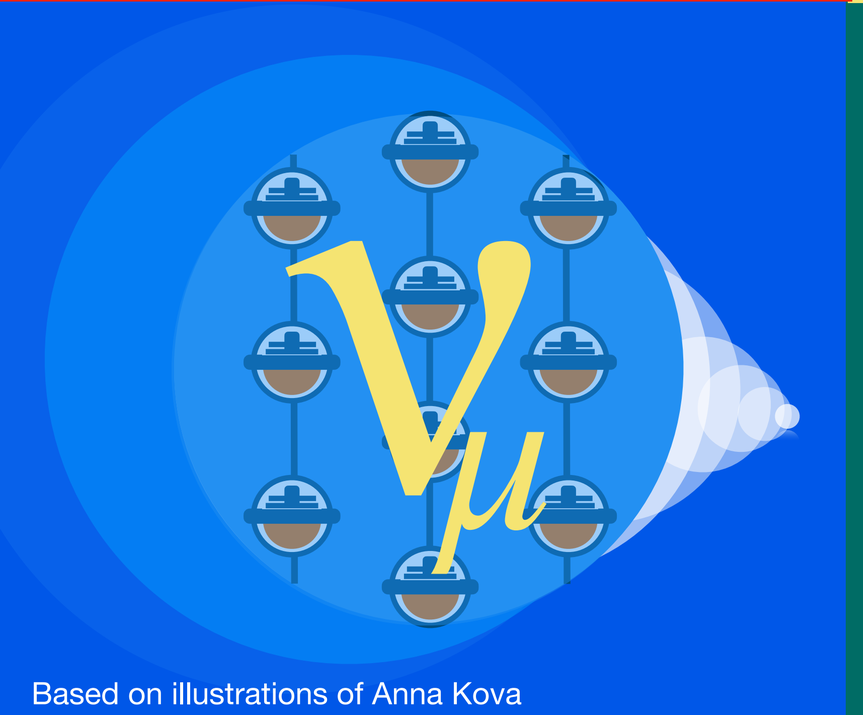








# Neutrino Physics & Astrophysics in Belgium

J. A. Aguilar, RECFA 2025

Based on illustrations of Anna Kova

# RECFA in 2017

## ASTROPARTICLE PHYSICS IN BELGIUM


## NEUTRINO PHYSICS IN BELGIUM


# RECFA in 2025

## ASTROPARTICLE PHYSICS IN BELGIUM

RNO-G

Radio Neutrino Observatory Greenland

IceCube

RADAR ECHO TELESCOPE

PIERRE AUGER OBSERVATORY

LOFAR

SKAO

PEPS

KM3NeT

## NEUTRINO PHYSICS IN BELGIUM

JUNO

SoLid

PROJECT 8

# RECFA in 2025

## ASTROPARTICLE PHYSICS IN BELGIUM


## NEUTRINO PHYSICS IN BELGIUM

JUNO

PROJECT 8

KM3NeT

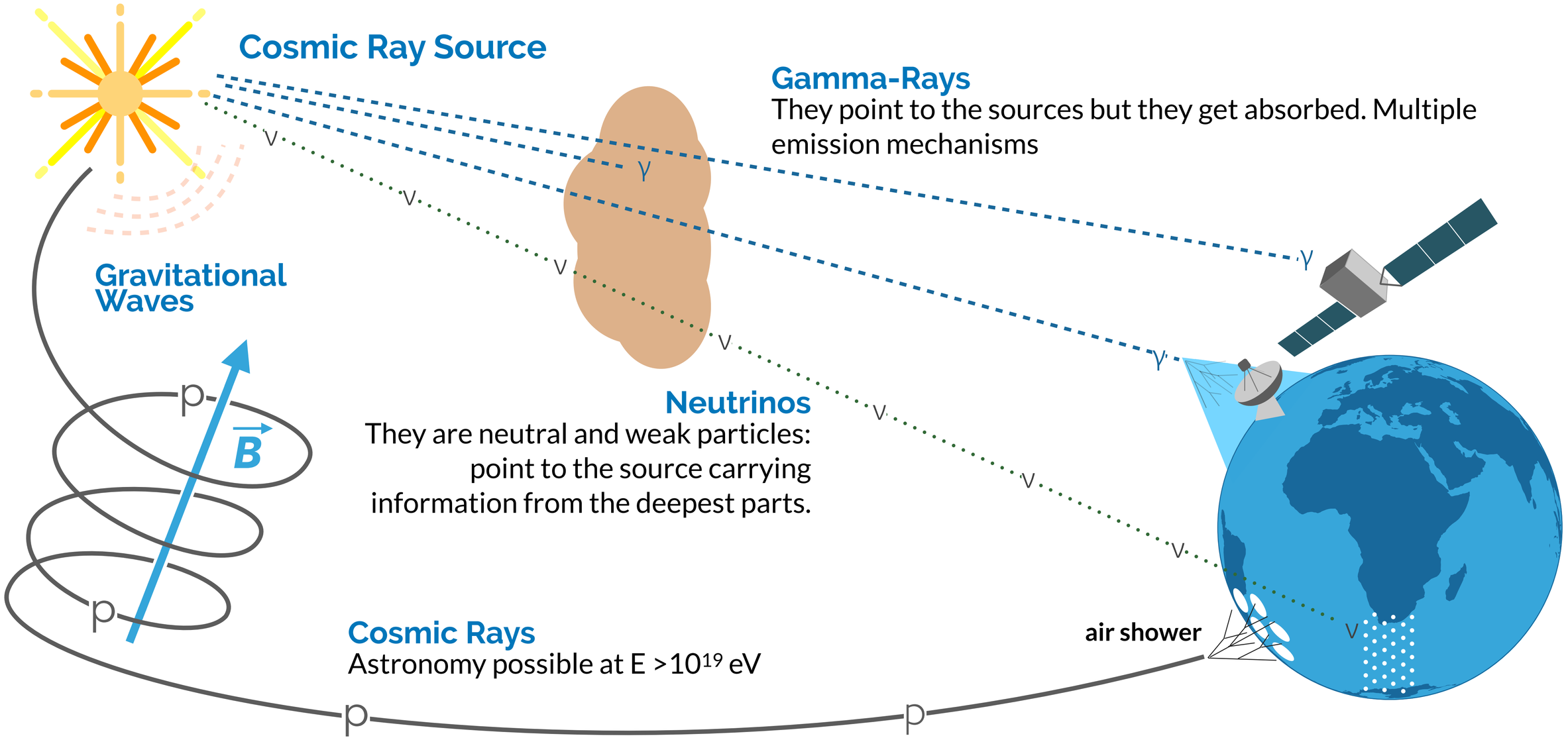
As Cosmic Messengers

As Fundamental Probes

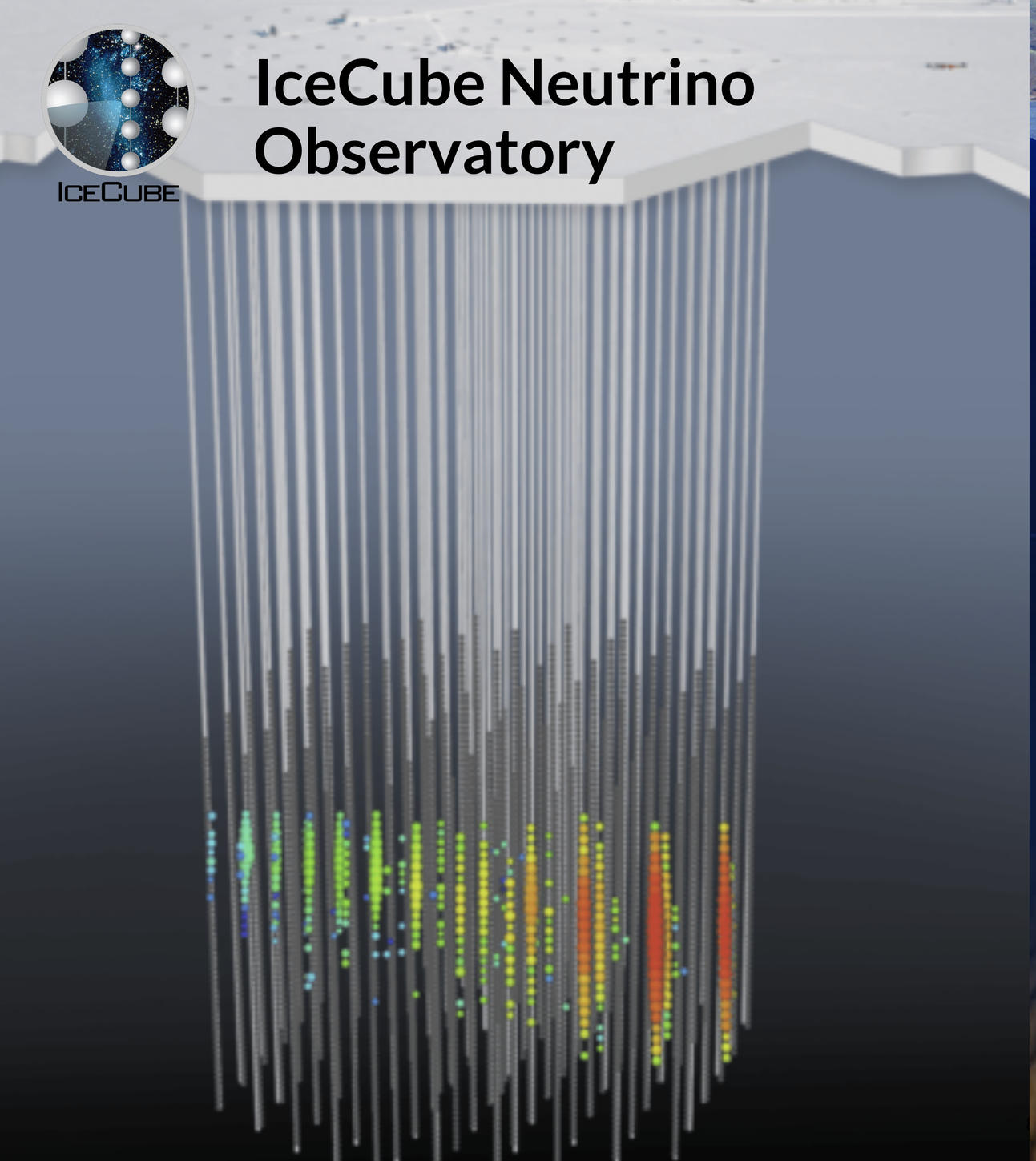
# As Cosmic Messengers

# As Fundamental Probes

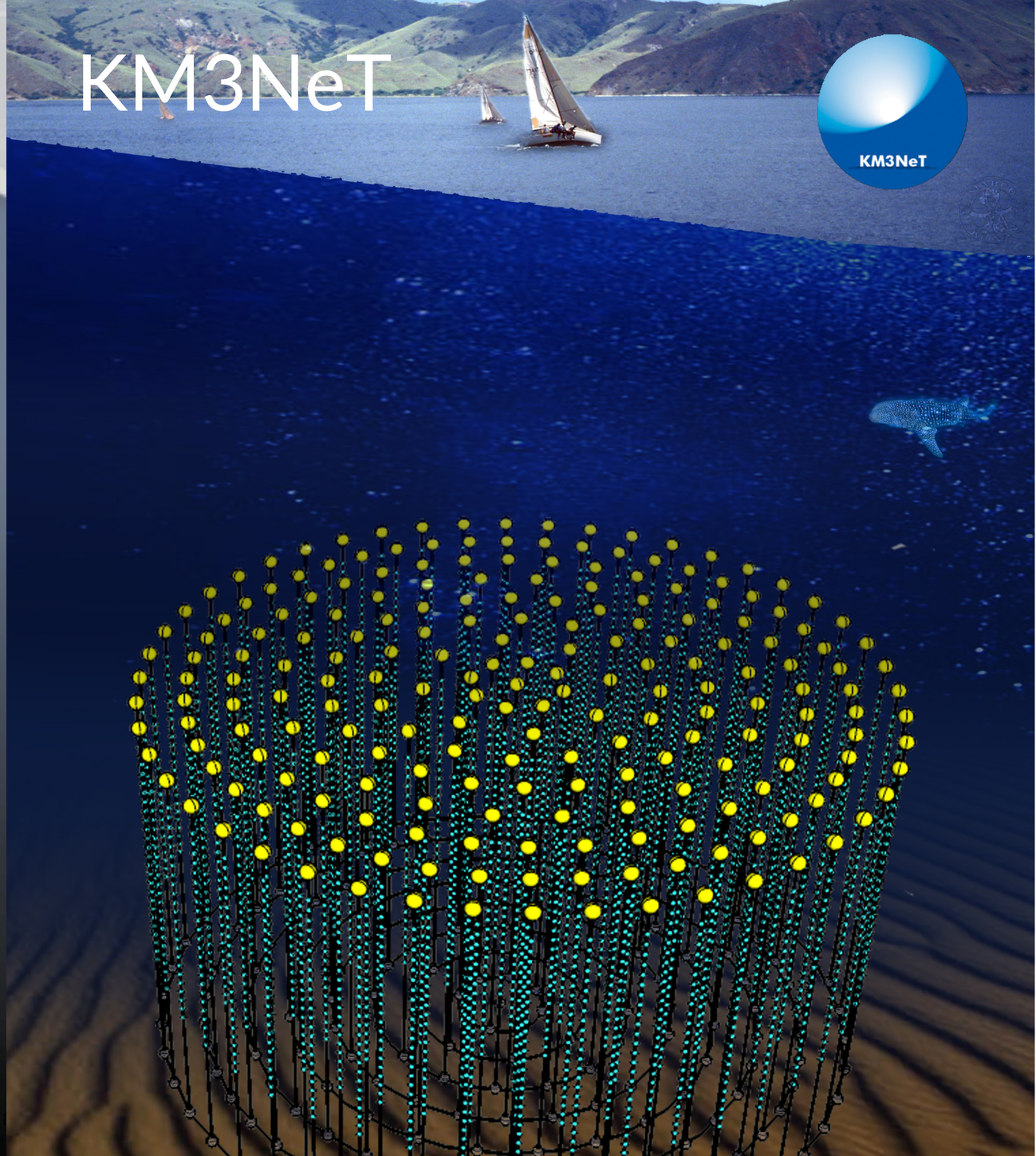
# Cosmic Messengers



# IceCube Neutrino Observatory

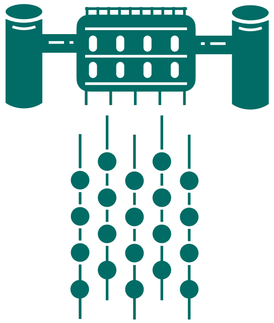


# KM3NeT

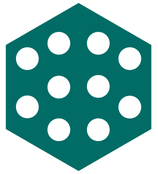


# IceCube Neutrino Observatory

**5,160** Digital Optical Modules (DOMs)



**86 strings** with 60 DOMs
**DeepCore**: 6 denser strings
**93 strings** in 2026 (Upgrade)



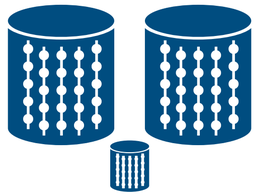
**IceTop:** 1 km$^2$ surface array with 324 DOMs

**Completed in December 2010**

# KM3NeT

**6,310** multi-PMTs Optical Modules with **192,510** PMTs

**ARCA** off shore Italy
**ORCA** off shore France



**ARCA** 2 block, 230 lines
**ORCA** 1 block, 115 lines

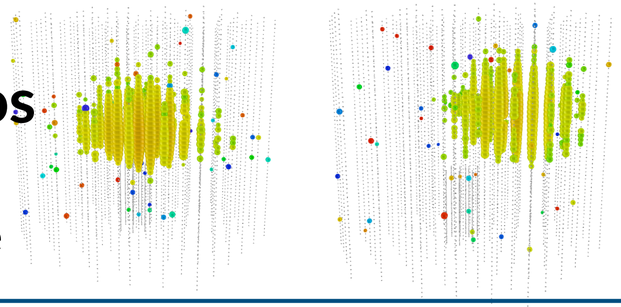
**ARCA** 51 lines deployed
**ORCA** 28 lines deployed

# Neutrino Astronomy Timeline

## A Decade of Discoveries

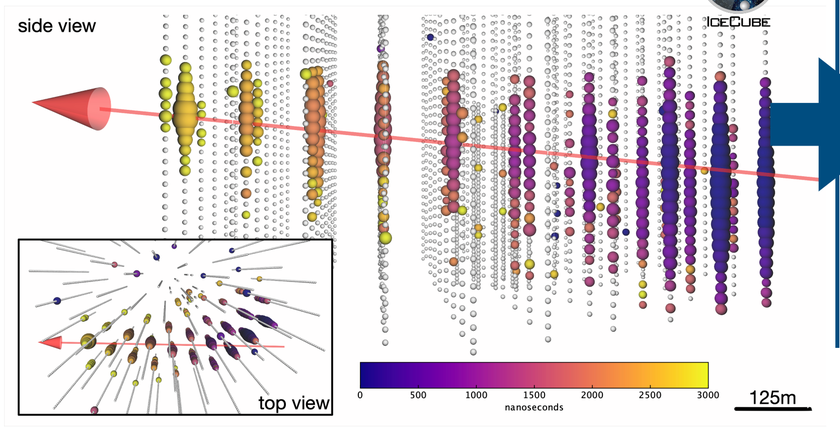
## 2013
## Astrophysical Neutrinos

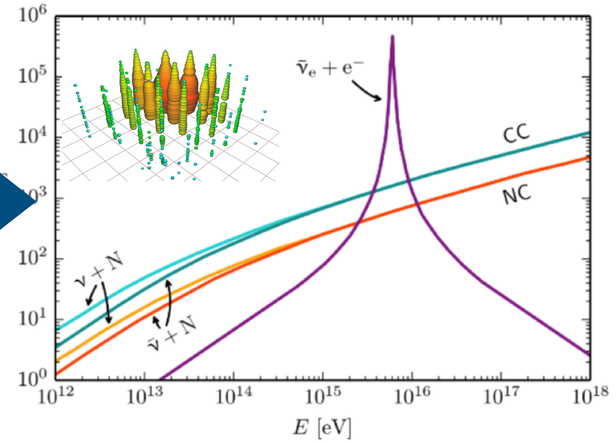
Detection of the first flux of astrophysical neutrinos by IceCube



## 2017
## TXS 0506+056

Coincidence of an IceCube neutrino event with a flare of gamma-rays from a Blazar



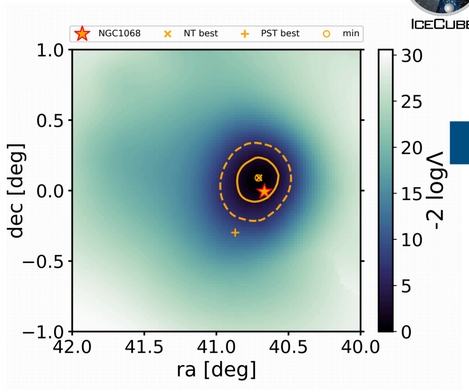




## 2021
## Glashow Resonance Event

IceCube observation of neutrino event at the Glashow energies (first $\overline{\nu}_e$)

## 2022
## NGC1068

First evidence of a neutrino source by IceCube

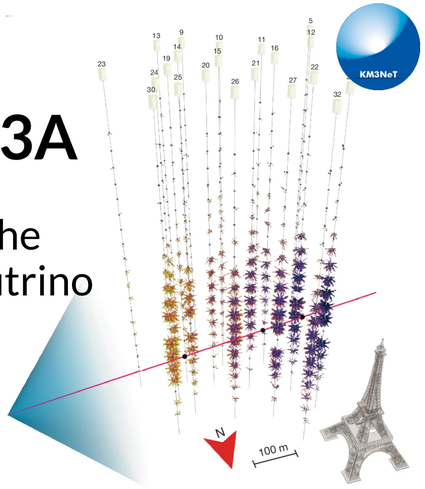



## 2023
## Our Galaxy

IceCube observation of the galactic diffuse neutrino emission

## 2024
## KM3-230213A

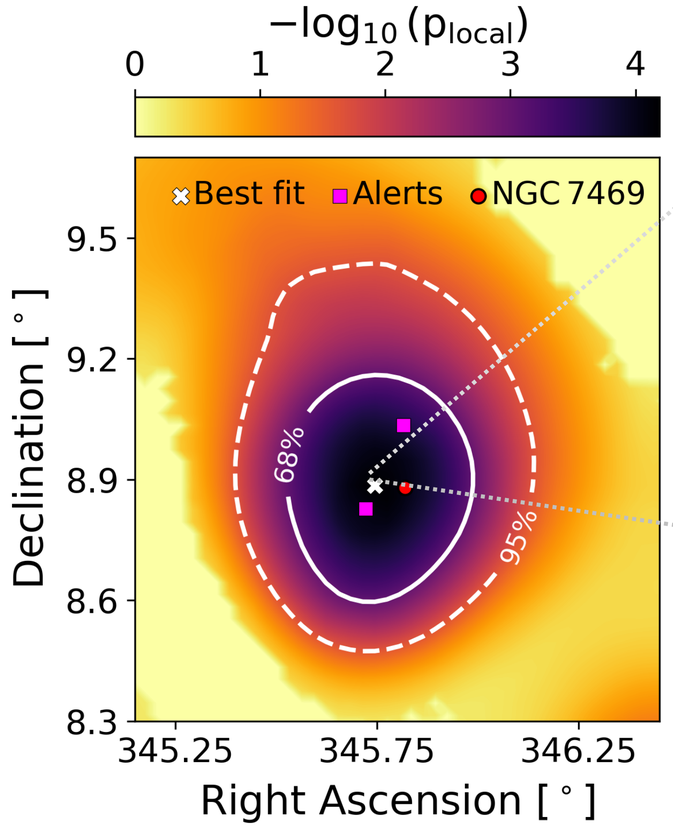
KM3NeT detects the highest energy neutrino ever observed



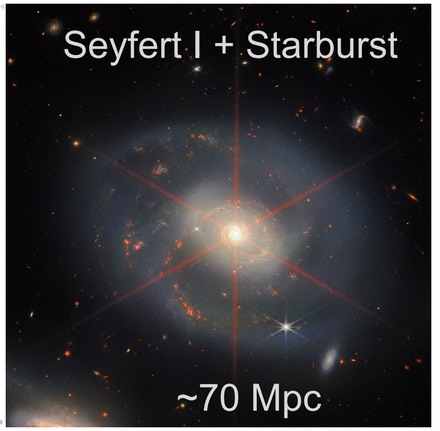
# Neutrino Astronomy

## Search for Steady Sources

- Search for neutrinos from **U**ltra **L**uminous **I**nfrared **G**alaxies
  - Dataset: Northern Hemisphere (13 yr)
- Catalog:
  - **113** northern U/LIRGs
  - Starburst (SB), Active Galactic Nuclei (AGNs) and hybrid (AGN+SB)
- Key Results
  - Most significant excess: **NGC 7469** (AGN+SB)
  - Excess only in **hybrid sources:** NGC 1068 & NGC 7469




**NGC7469**



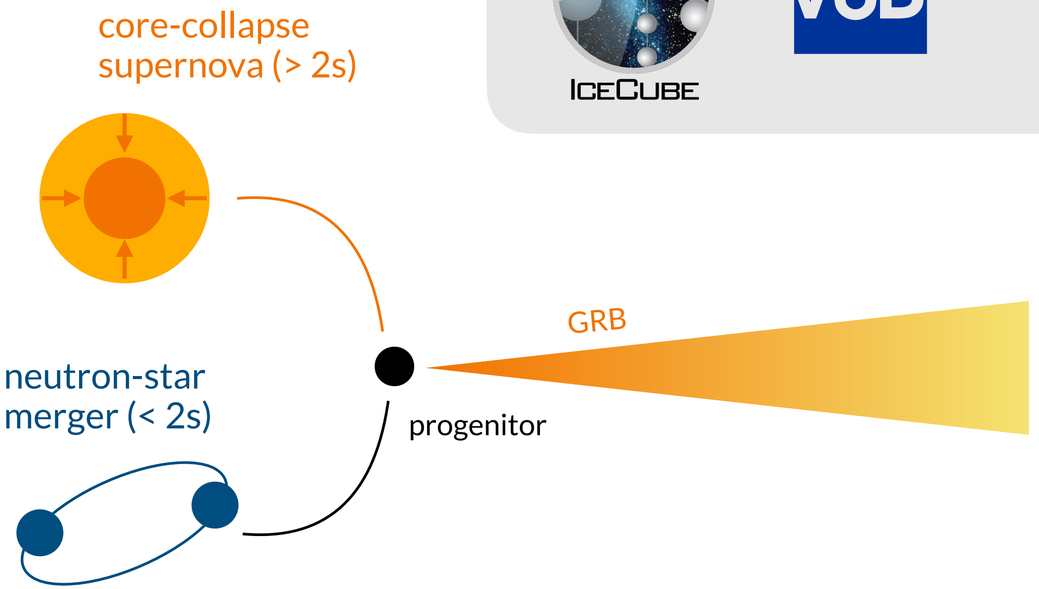

**2.3$\sigma$ excess** after trial correction

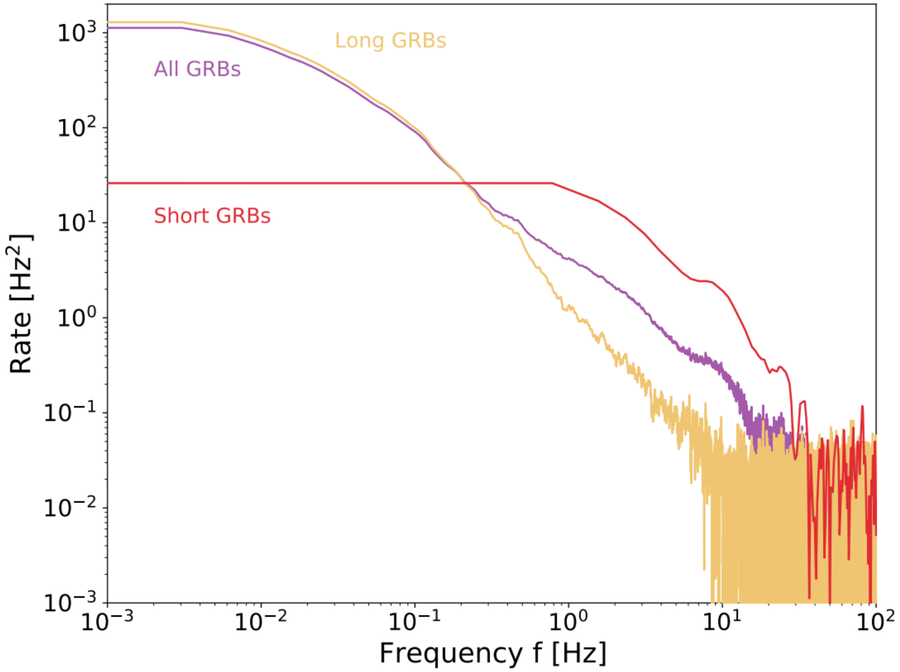
**Significance driven by two ~100 TeV IceCube alerts**

# Neutrino Astronomy

## Search for Transients Sources

- **G**amma-**R**ay-**B**urts (GRBs):
  - Very short pulses of gamma-rays
  - Still one of the main candidates for neutrinos
- Canonical classification:
  - Long GRBs (> 2s) → Collapse of a massive star
  - Short GRBs (< 2s) → Merger of compact objects
- New classification:
  - Look for traces of emission mechanisms in the time variability of the GRB light curves
  - Use a catalog for neutrino correlation studies

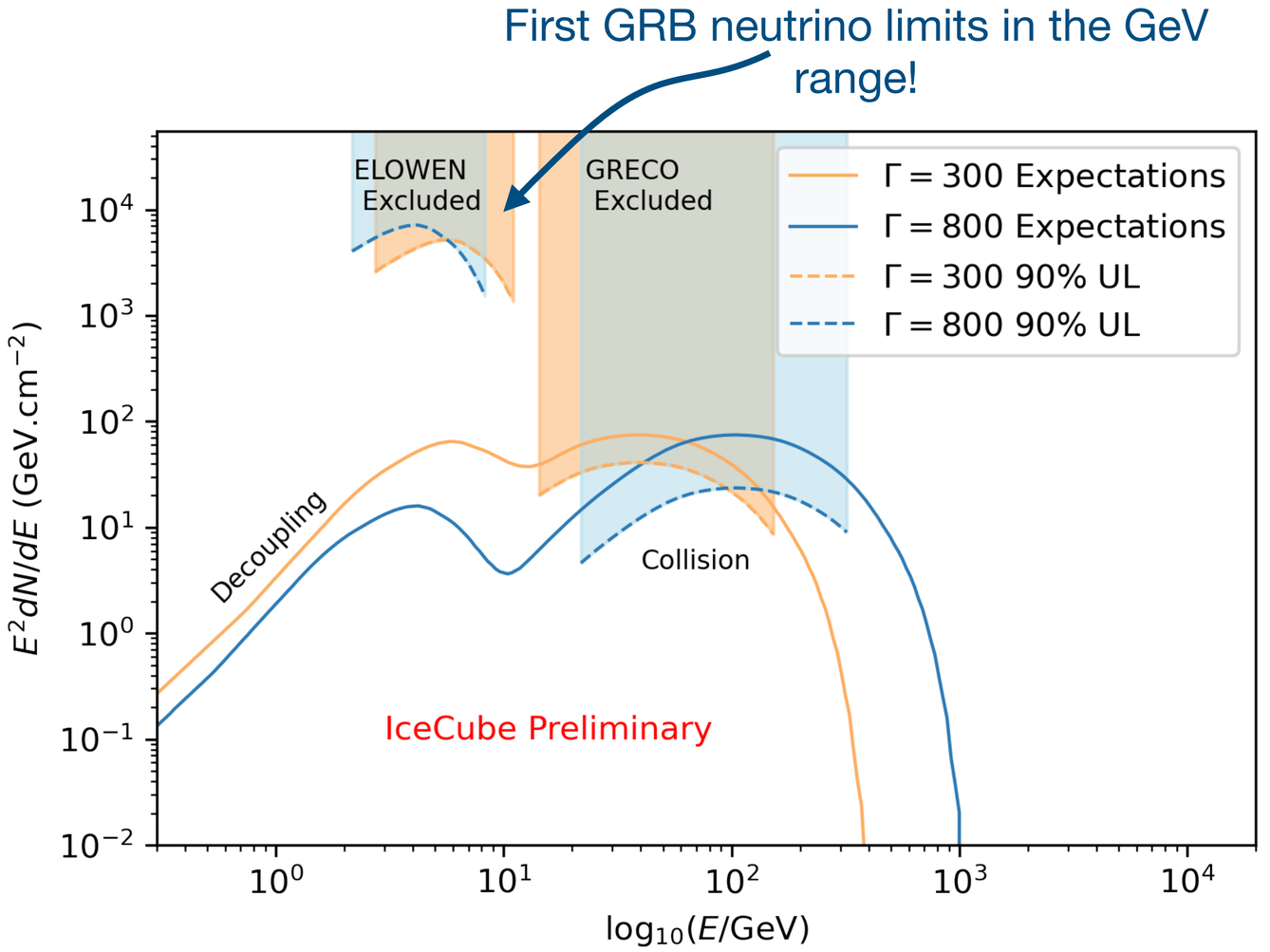


# Neutrino Astronomy

## Search for Transients Sources

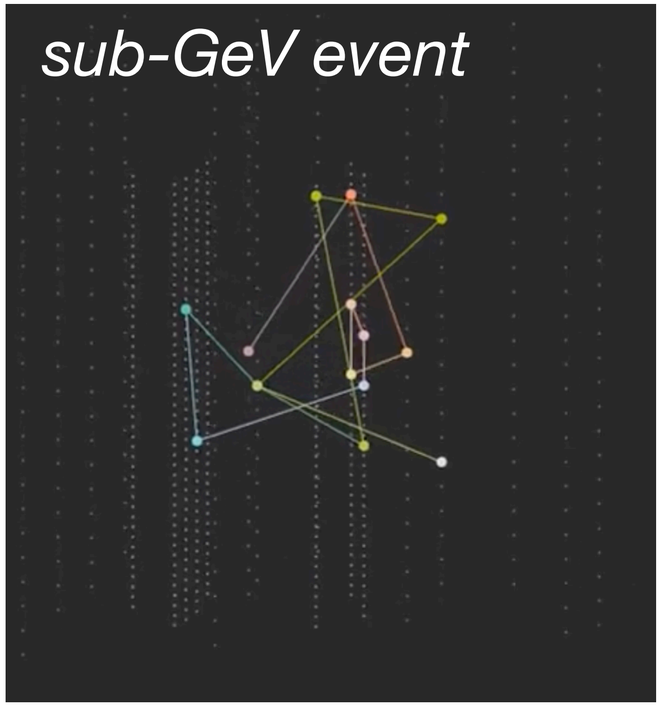
- **GRB 221009A**, the brightest GRB
  - Brightest Of All Time “BOAT”
- EM emission spanning 15 orders of magnitude
  - 18 TeV photons recorded!
- **ELOWEN:** lowest $\nu$-energy sample
  - All flavors, $E_\nu$ = 0.5-5 GeV.
- Search for neutrinos in the GRB time window $\Delta t = 1000$ s, $\Delta t = 2200$ s
- Publication:
  - **2024 ApJL 970 L43**

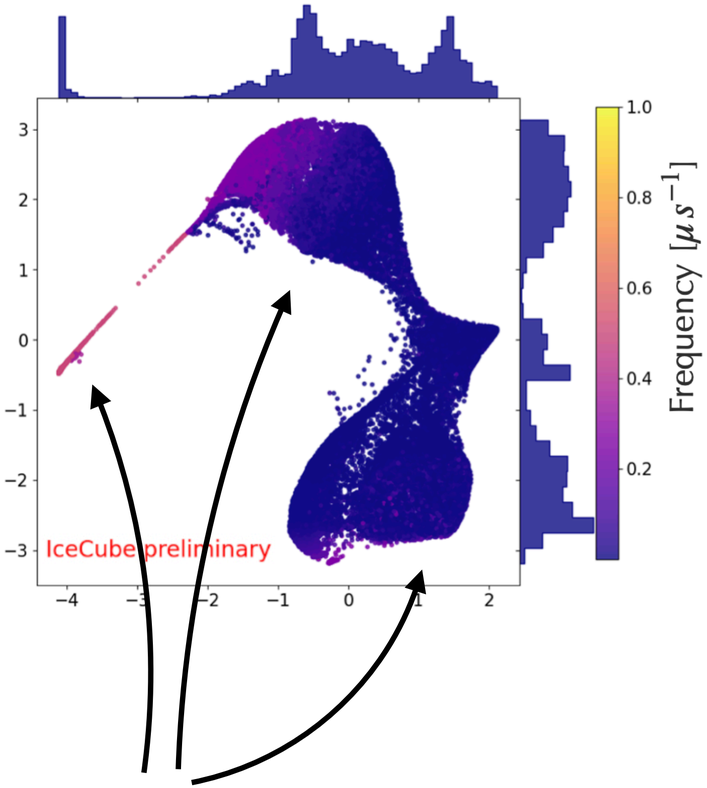


# Neutrino Astronomy

## (sub)GeV-astronomy

- Most astrophysical process follow a power-law spectrum:
  - Lower energy neutrinos are more abundant!
- Opening the window to GeV and sub-GeV astronomy
- Sub-GeV neutrinos in IceCube are buried in a large backgrounds:
  - Use dedicated DAQ: HitSpooling
  - Using unsupervised machine learning to search for *hit burst*



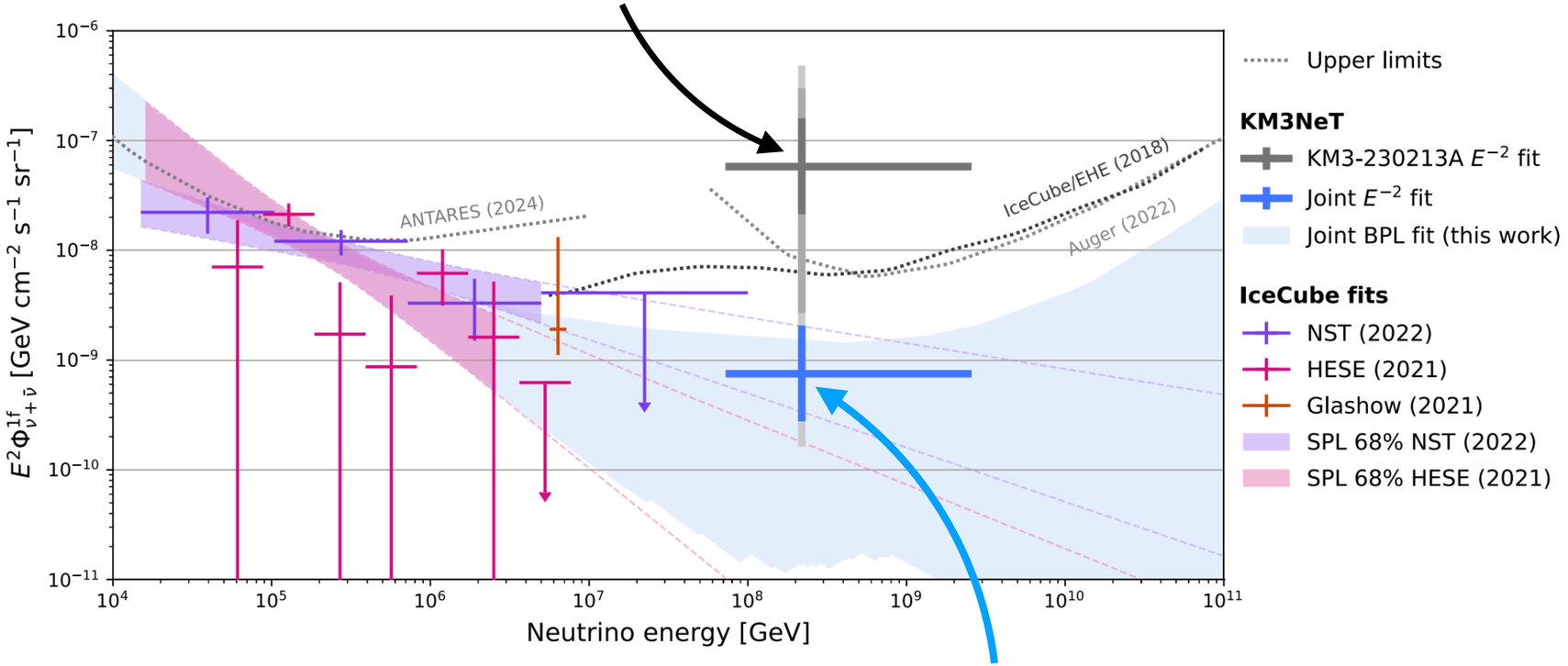

Different classes of *hit burts*

# Extremely High Energies

## KM3-23021A: A muon neutrino with record energy

- KM3NeT/ARCA: 21 Lines
- Estimated neutrino energy:
  - $E_\nu = 220^{+570}_{-110}$ PeV
- Is it consistent with IceCube and Auger limits?
  - Yes, at the level of $2.5\sigma$
- More details:
  - **PRX 15, 031016, 2025**

KM3-23021A




KM3-23021A + null observations

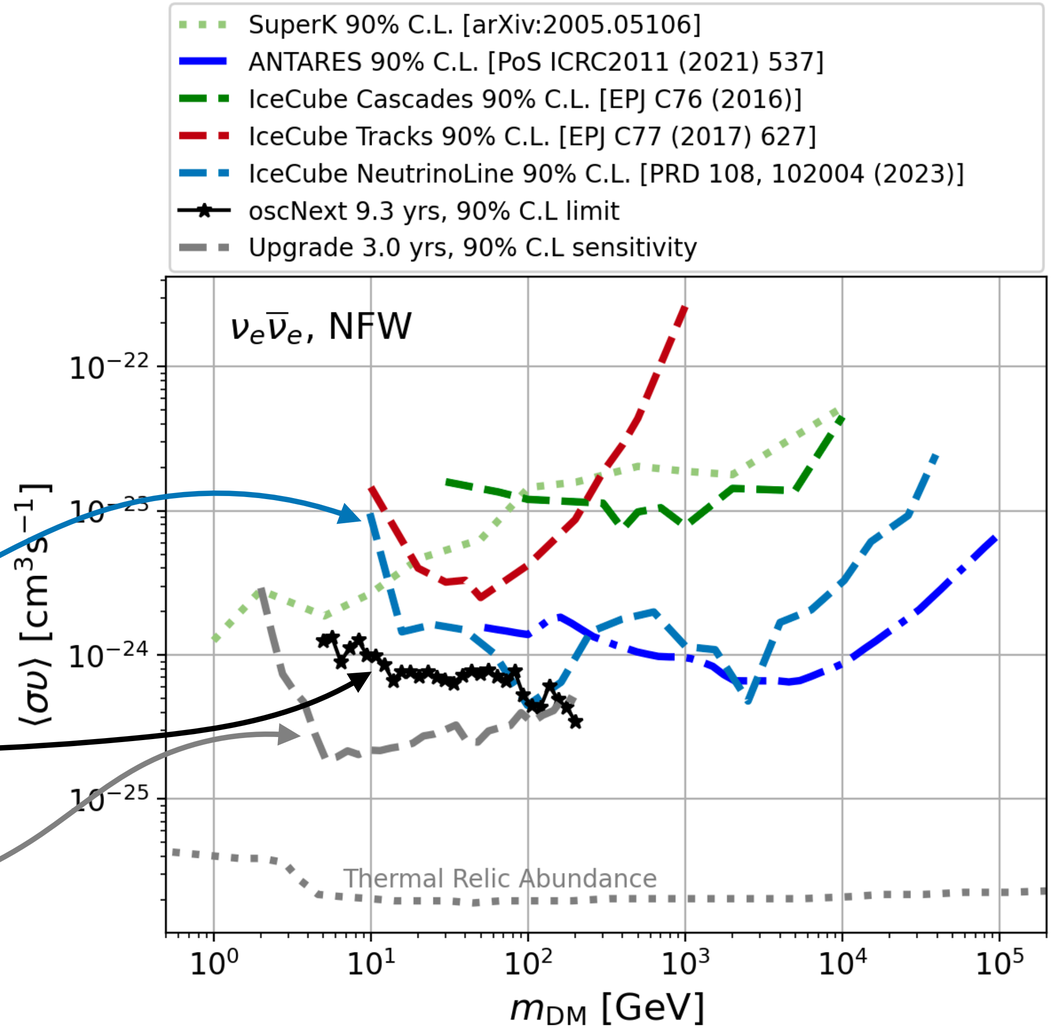
As Cosmic Messengers

As Fundamental Probes

# Dark Matter

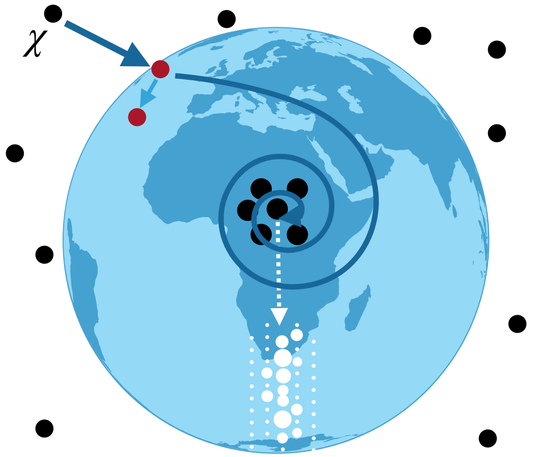
## Searches from the Galactic Center

- Looking for a dark matter annihilation and decay from the center of the Galaxy
- Limits on a wide mass range
  - 30 GeV - 100 TeV
- Publications:
  - **Physical Review D 108 (2023) 10, 102004**
  - **DeepCore (pubcom working review)**
  - **Projected sensitivity IC-Upgrade (planned)**

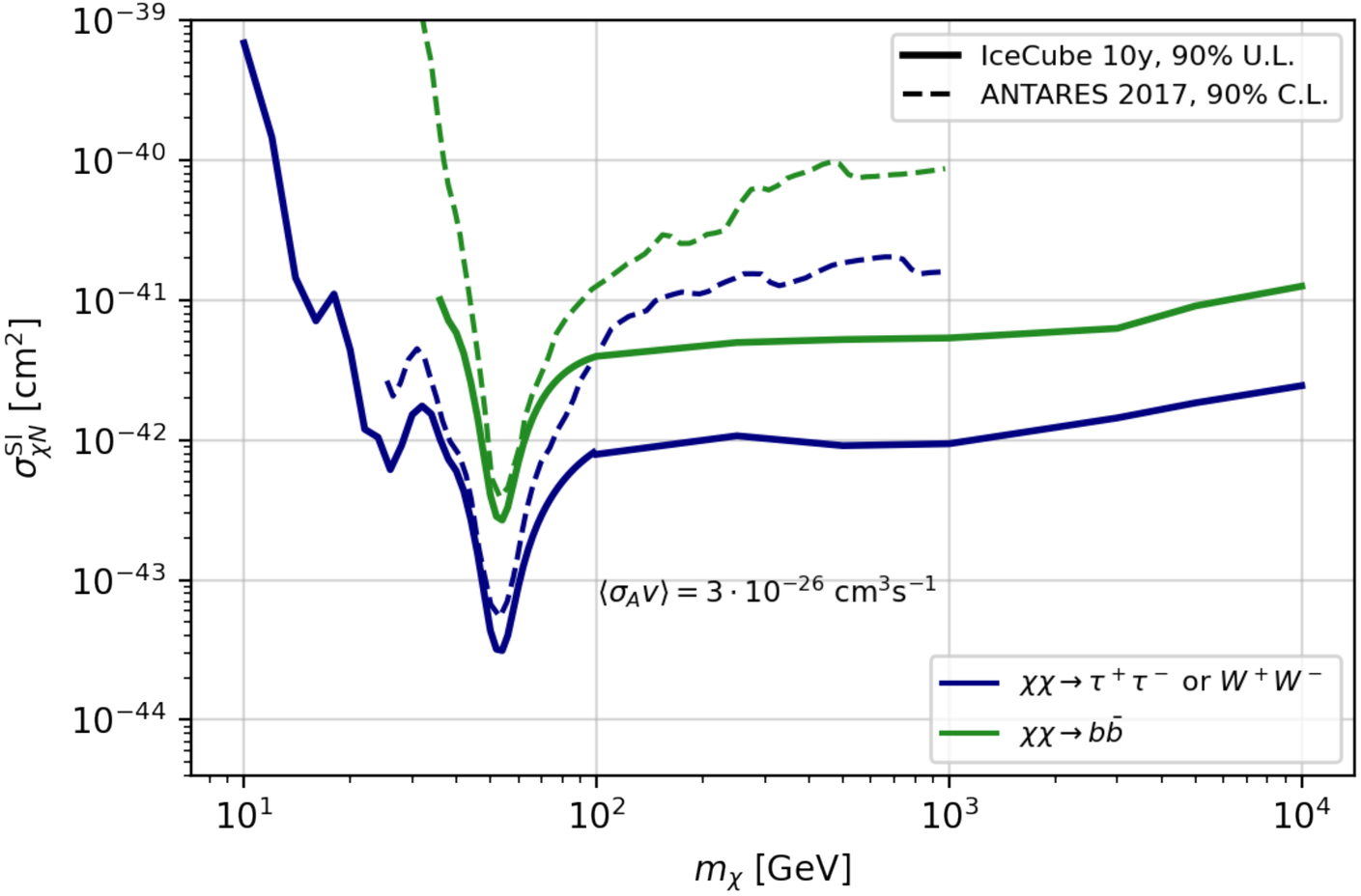


# Dark Matter

## Celestial Bodies

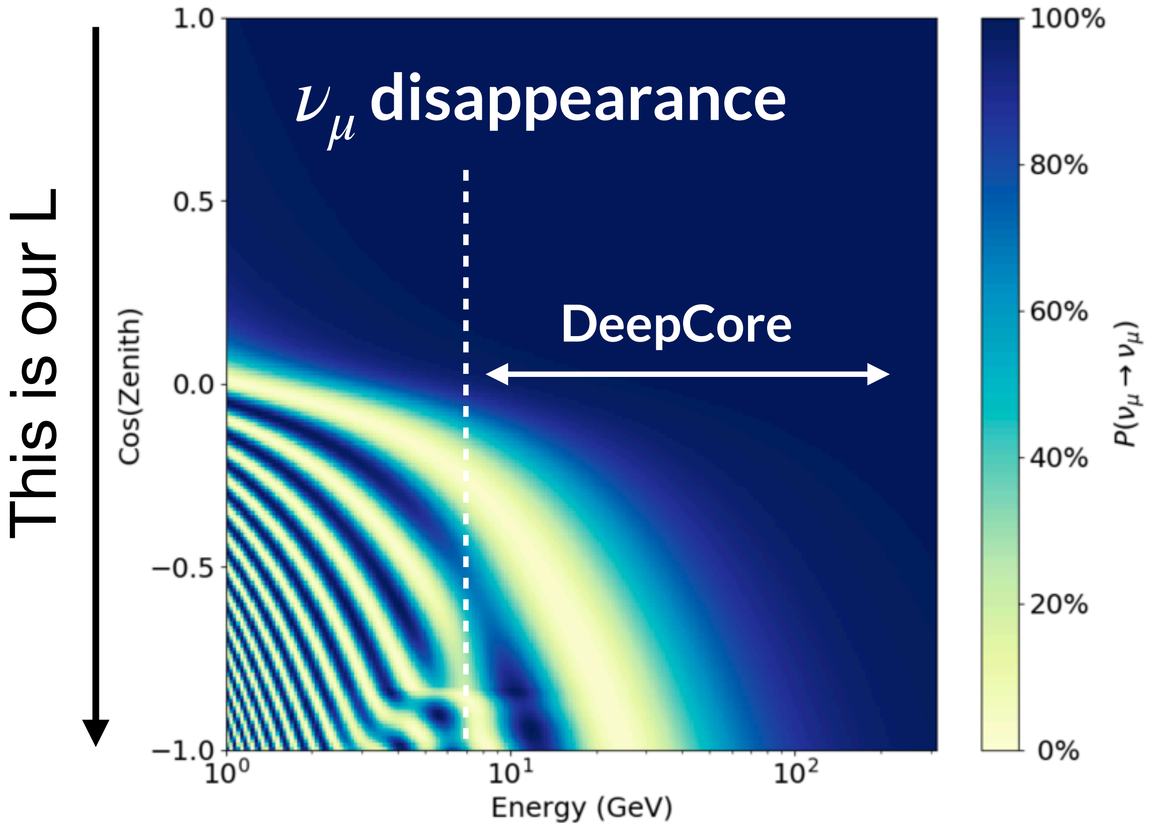



- Search for DM annihilation from the center of the Earth
- Challenging analysis:
  - Signal is in local coordinates
- Best published limits above 100 GeV
  - **EPJ C85 (2025) 490**



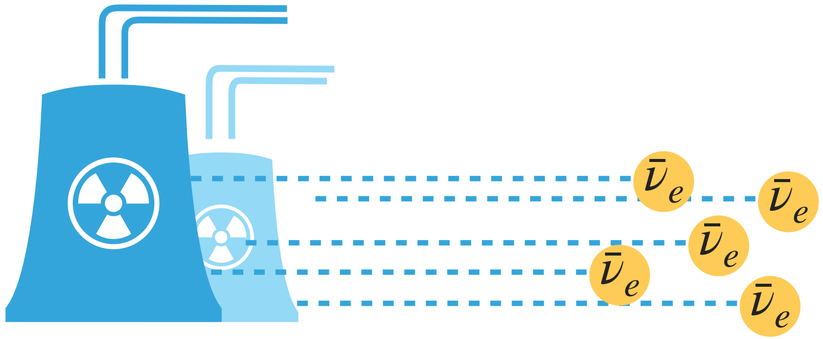
# Neutrino Oscillations

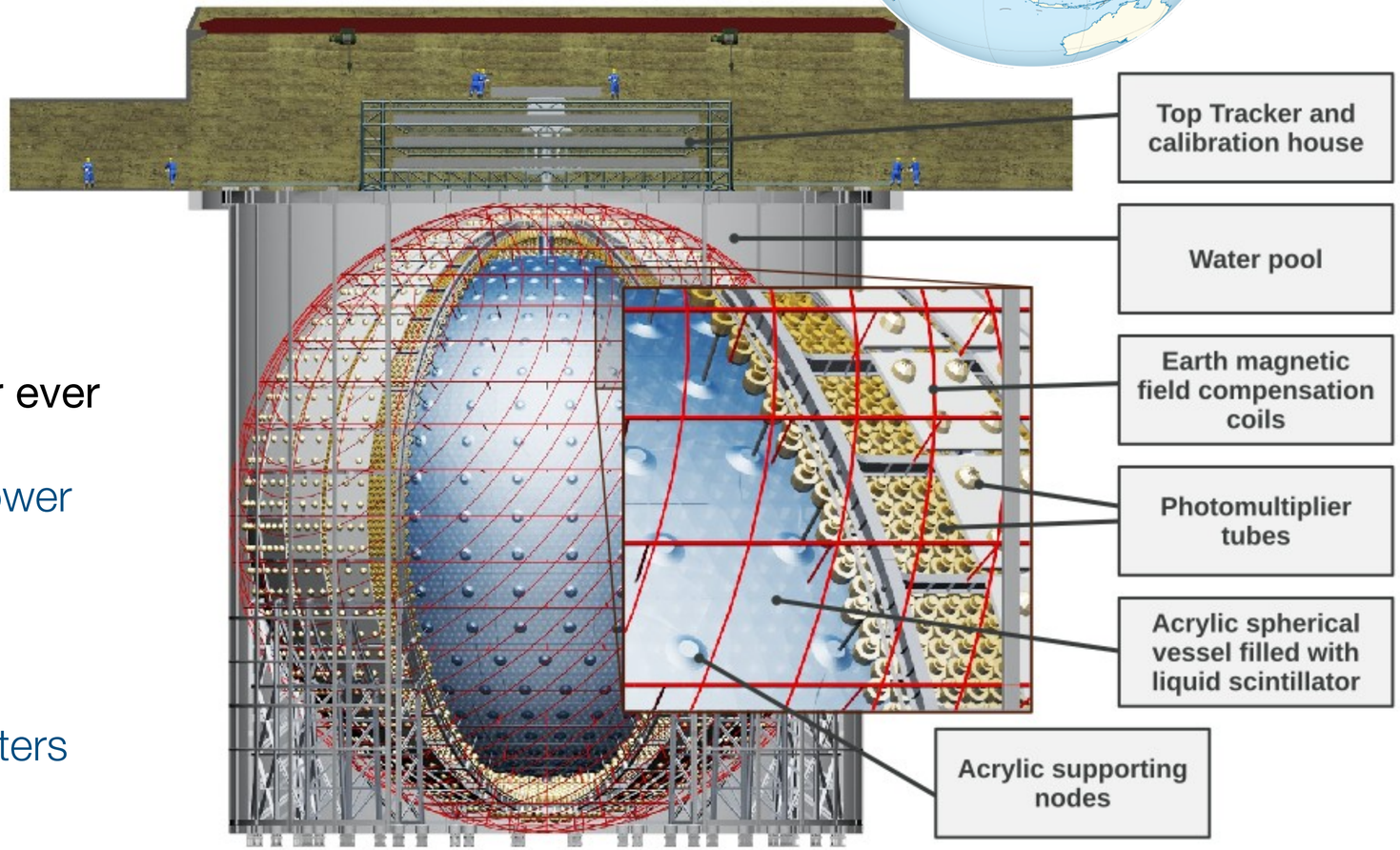
- Neutrino telescopes:
  - Oscillation ‘dip’ give sensitivity to *23* sector
- Precision measurement using pure and large statistics atmospheric neutrinos:
  - **IceCube:** DeepCore - Upgrade
  - **KM3NeT:** ORCA
- Oscillations are also a gateway to BSM:
  - Sterile neutrinos
  - Non-standard interactions
  - Flavor violation



# Reactor Neutrinos

## Jiangmen Underground Neutrino Observatory




- The first **multi-kton liquid scintillator** detector ever built
  - 53 km from Taishan and Yangjiang nuclear power plant (China)
- Physics goal:
  - Neutrino Mass Ordering
  - Precision Measurement of Oscillation Parameters
- Civil construction ended in Dec. 2021

# JUNO Status

## Taking data!

PHYS.ORG Topics Week's top Latest news

Nanotechnology Physics Earth Astronomy & Space Chemistry Biology Other Sciences Medicine

Home / Physics / General Physics

AUGUST 26, 2025 The GIST

### JUNO completes liquid filling and begins taking data to investigate ordering of neutrino masses

by Chinese Academy of Sciences

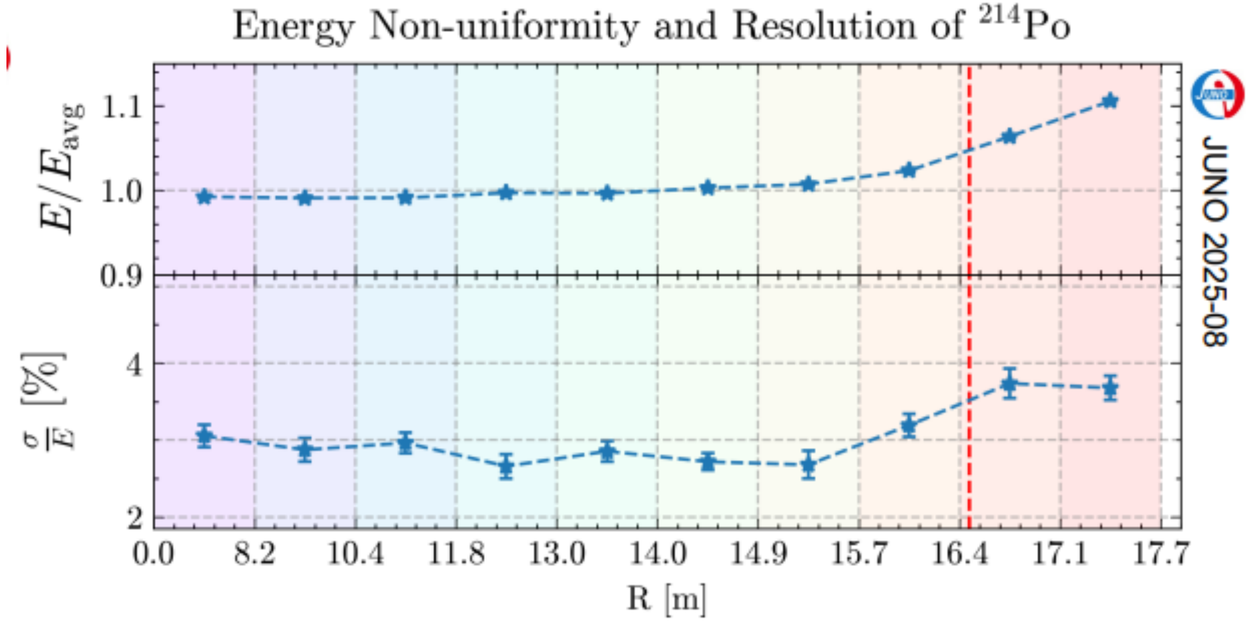
edited by Sadie Harley, reviewed by Robert Egan Editors' notes

The central acrylic sphere and PMTs. Credit: JUNO Collaboration

The Jiangmen Underground Neutrino Observatory (JUNO) has successfully completed filling its 20,000-tons liquid scintillator detector and began taking data on Aug. 26.

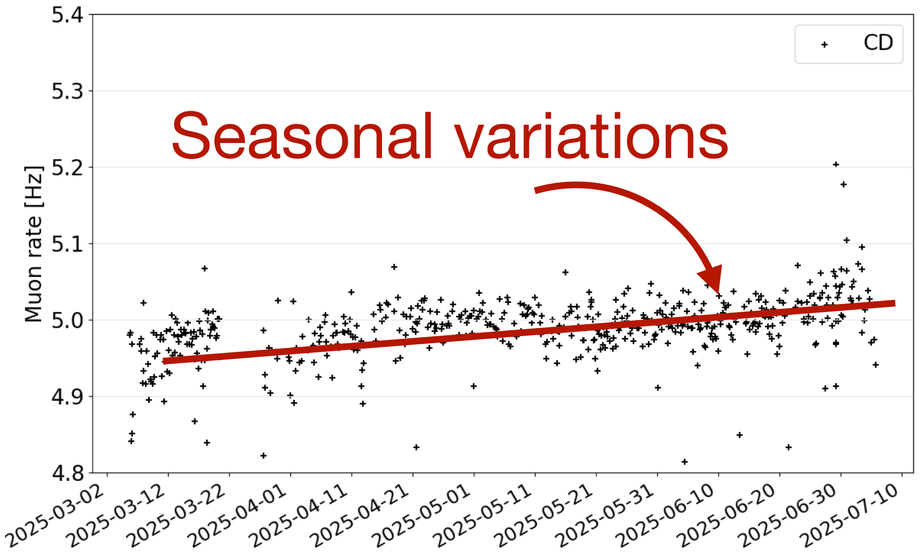
After more than a decade of preparation and construction, JUNO is the first of a new generation of very large neutrino experiments to reach this stage. Initial trial operations and data taking show that key performance indicators met or exceeded design expectations, enabling JUNO to tackle one of this decade's major open questions in particle physics: the ordering of neutrino masses—whether the third mass state ($\nu_3$) is heavier than the second ($\nu_2$).

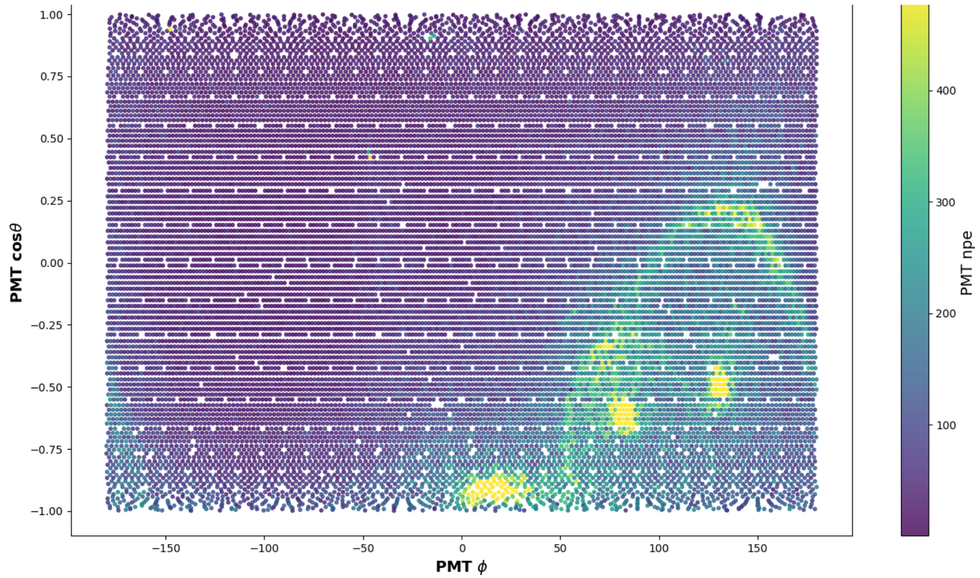
- 10 years of construction
  - Taking data since 26/08/2025!
- Liquid Scintillator cleanliness close to other solar neutrino experiments
- Energy resolution 3%



# Commissioning Data

- Muon tagging and monitoring:
  - Stability over ~5 months of commissioning data
  - Hint at seasonal variations
- First atmospheric neutrino candidates:
  - Multi-ring DIS interaction
- Other activities:
  - Hardware: 180 Back-End Cards
  - Supernova neutrino monitoring
  - Calibration: energy non-uniformity

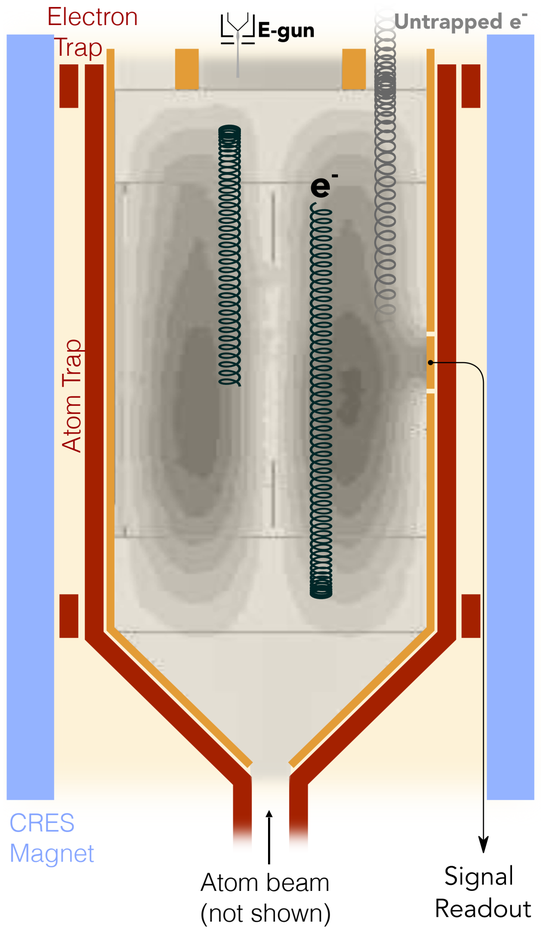


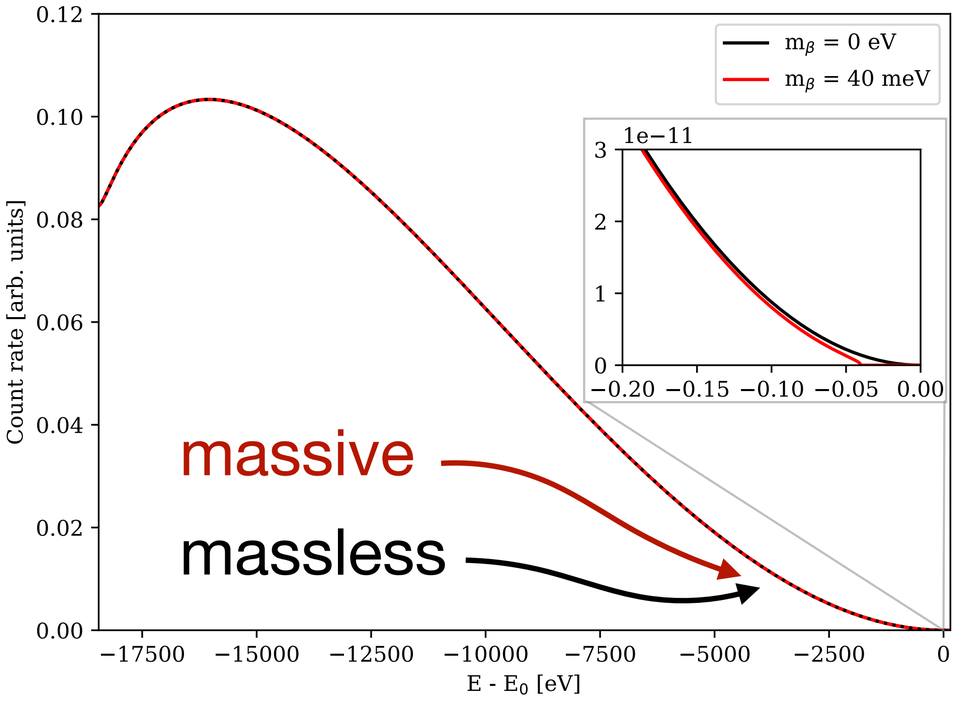



# Searching for the Neutrino Mass

## Project 8

- **Goal:** Measure the mass of the neutrino
- Tritium as a beta-decay source
  - Measurement of the electron spectrum
- Cyclotron motion:
  - Use cyclotron radiation to measure the electron's kinetic energy.
- Sensitive to electron-weighted neutrino mass:
  - $m_\beta^2 = \sum |U_{ei}|^2 m_i^2$
- New funding ERC staring-Grant



# And many other activities…

## Activities:

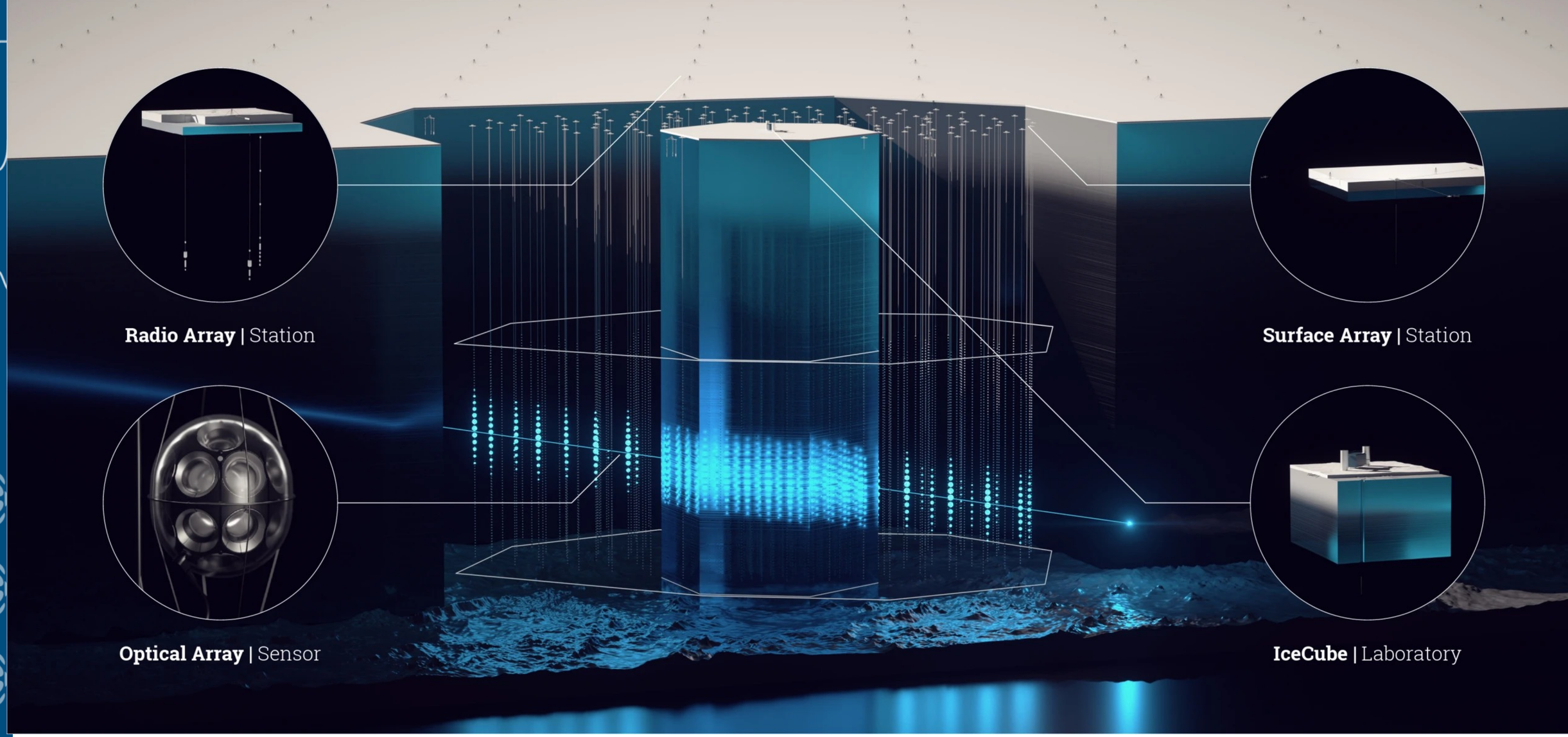
- Search for milli-Charge Particles / IceCube ULB
- Search for D-muons / KM3NeT ULB
- Search for neutrino-lines in KM3NeT / KM3NeT ULB
- EHE neutrino discrimination / IceCube ULB
- Follow-up of Gravitational Events / IceCube UCLouvain
- Marine Biology / KM3NeT UCLouvain
- Direct detection of Boosted DM / IceCube UCLouvain
- TeV search of messenger / IceCube UCLouvain
- Tau neutrino identification / IceCube UGent

- ***R&D for future Neutrino Telescopes (next slide)***

## Key roles:

- **Y. Yang (ULB)** - Convenor of the electronics data link group JUNO
- **M. Colomer (ULB) -** Convenor of the $\nu$-atm group of JUNO and ECR
- **B. Clerbaux (ULB) -** Member of the JUNO Publication Committee.
- **J. A. Aguilar (ULB) -** Member of Executive Committee IceCube / Publication Committee Chair IceCube / Analysis Coordinator IceCube (22-24)
- **G. W. Dewasseige (UCLouvain) -** Convenor Supernova group IceCube.
- **S. Toscano (ULB) -** L3 manager Radio-Detection Production for IceCube-Gen2
- **M. Lamoureux (UCLouvain) -** Astro convener KM3NeT
- **UCLouvain:** ACME center of expertise and WP7 leader
- **K. Kruiskwijk (UCLouvain) -** SN Technical lead IceCube
- **J. Lazar (UCLouvain) -** BSM Technical lead IceCube

And more in the backup!




IceCube GEN2

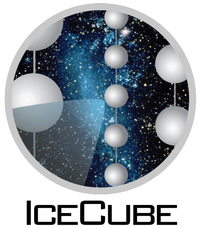
https://icecube-gen2.wisc.edu/

White paper: https://arxiv.org/abs/2008.04323

# Conclusions

- Belgium has a broad and extensive neutrino research program.
- IceCube has pioneered neutrino astronomy, delivering groundbreaking results.
- Neutrino telescopes (IceCube, KM3NeT) are powerful tools for both neutrino physics and BSM studies.
- Upcoming experiments, such as JUNO, already taking data, and Project 8, will deepen our understanding of neutrinos.
- Future large-scale observatories, including IceCube-Gen2, will provide new insights into the high-energy Universe.

# Many Thanks




**ULB:** J. A. Aguilar (IL), S. Toscano, I. Mariş / Postdocs: N. Chau, F. Schlütter, A. Parenti
**VUB:** N. Van Eijndhoven (IL), K. De Vries
**UCLouvain:** G. W. Dewasseige (IL) / Postdocs:  K. Jansson, J. Lazar
**UGent:** J. Stachurska (IL)

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**UCLouvain:** G. W. Dewasseige (IL), V. Lemaitre / Postdocs: M. Lamoureux, R. Clark.
**ULB** (Observer Institution): J. A. Aguilar

---


**ULB:** B. Clerbaux (IL), Y. Yang / Postdocs:  A. Khatun, F. Gao, M. Colomer

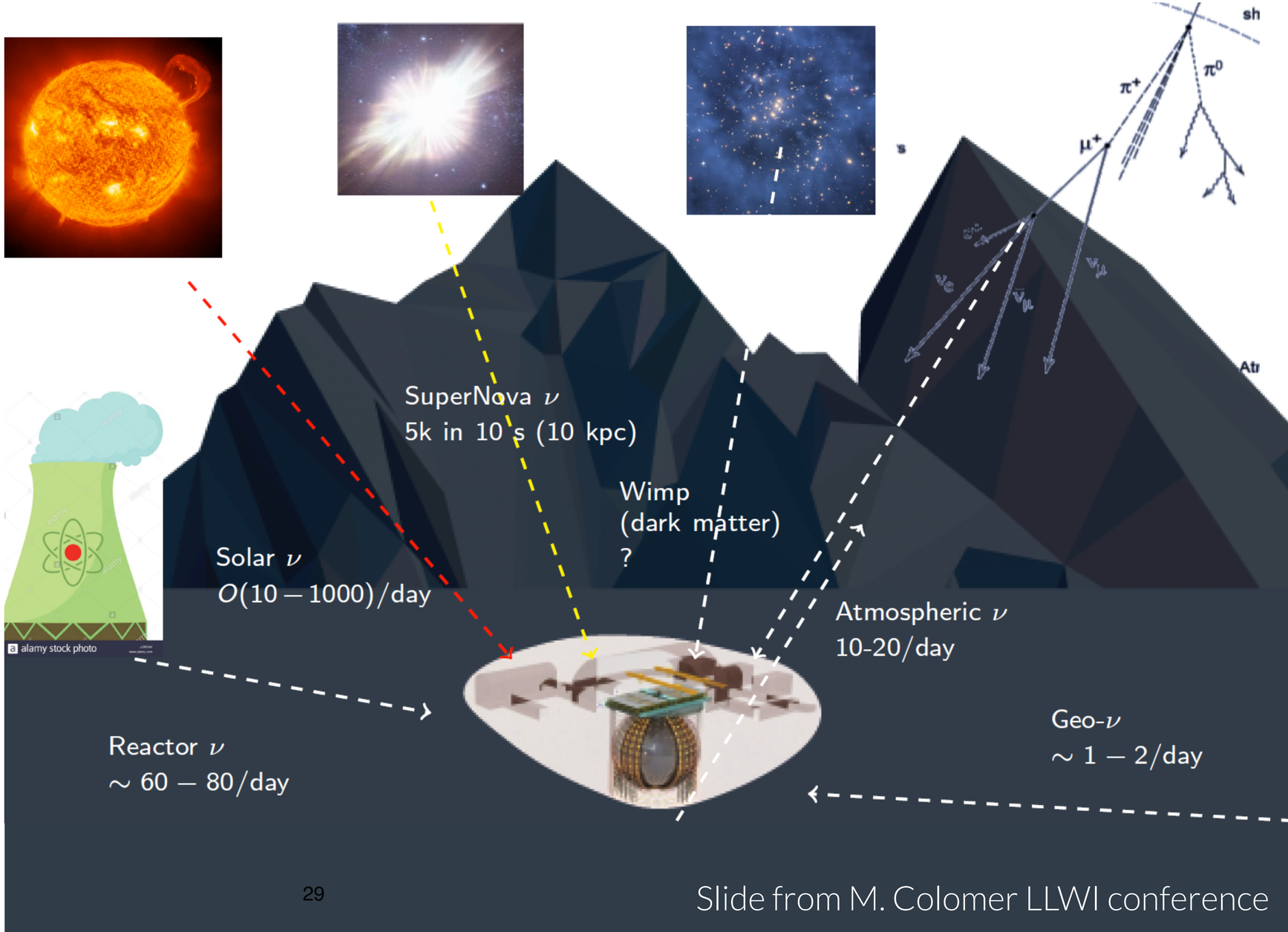
---


**UGent:** J. Stachurska (IL)

# Backup

# JUNO physics program

- **Main Goals:**
  - Neutrino mass ordering
  - Precision Measurement of Oscillation Parameters
- But also…
  - Supernova neutrinos
  - Dark Matter…

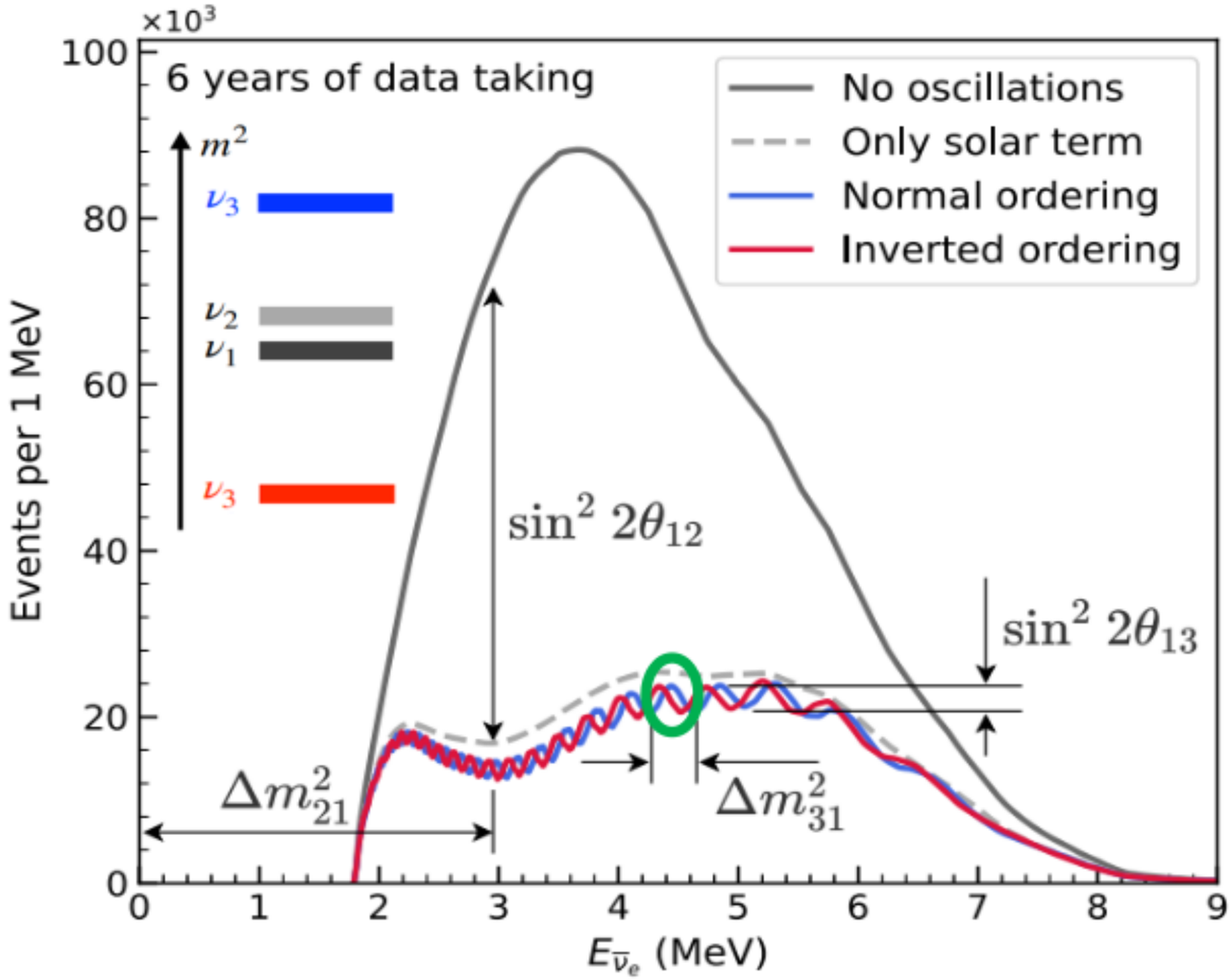





Slide from M. Colomer LLWI conference

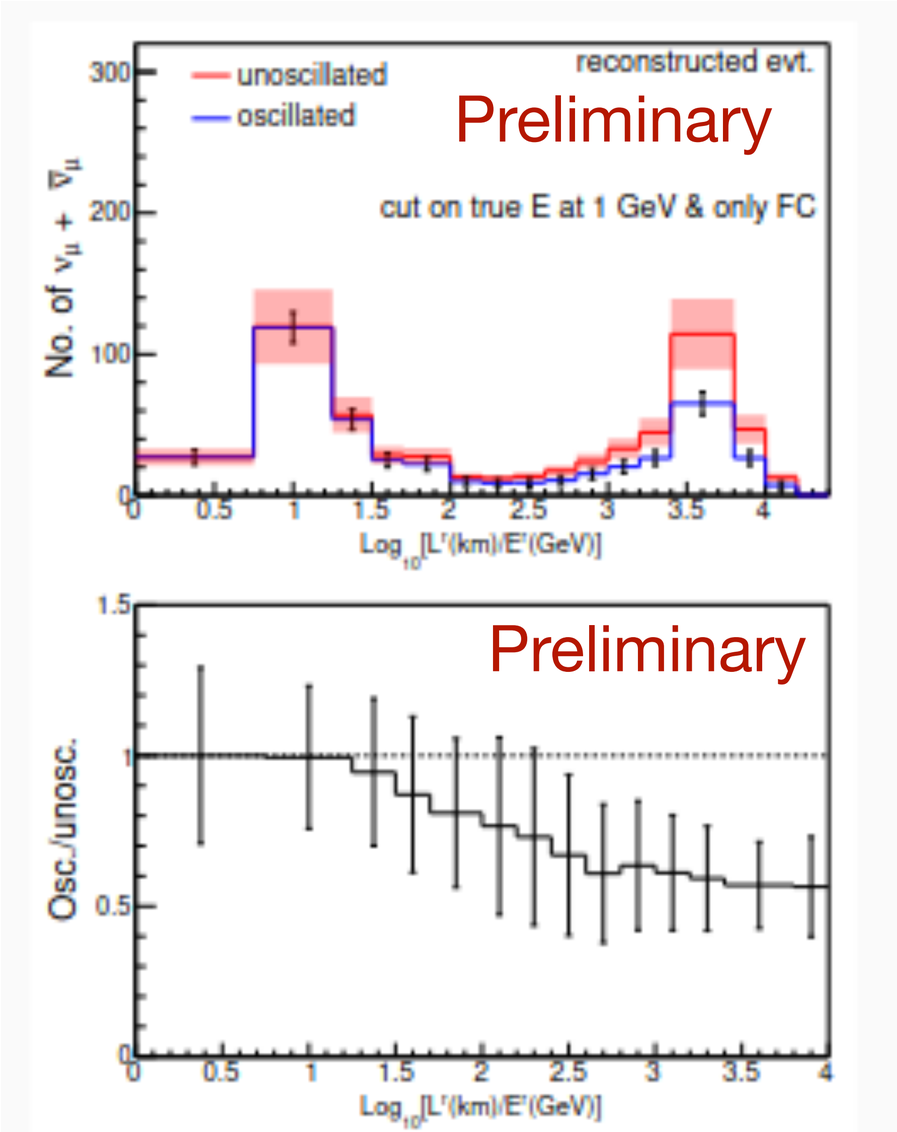
# JUNO Physics Goal

- Main Goals:
  - Neutrino mass ordering
  - Precision Measurement of Oscillation Parameters
- But also astrophysics
  - Supernova neutrinos



# Physics Sensitivities

- Neutrino oscillations with atmospheric neutrinos:
  - Observation of the GeV dip with 1 year of data
- Confirm the oscillation of GeV neutrino with **LS detector for the first time**
- Atmospheric neutrino will also help in the neutrino mas hierarchy by combining with reactor neutrinos.



# Astrophysical Neutrinos

## Flavor Ratio


**pion production**

$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$
$$\downarrow$$
$$e^{\pm} + \overset{(-)}{\nu}_{e} + \overset{(-)}{\nu}_{\mu}$$

**(1:2:0)**

**neutron decay**

$$n \rightarrow p + e^{-} + \overline{\nu_e}$$

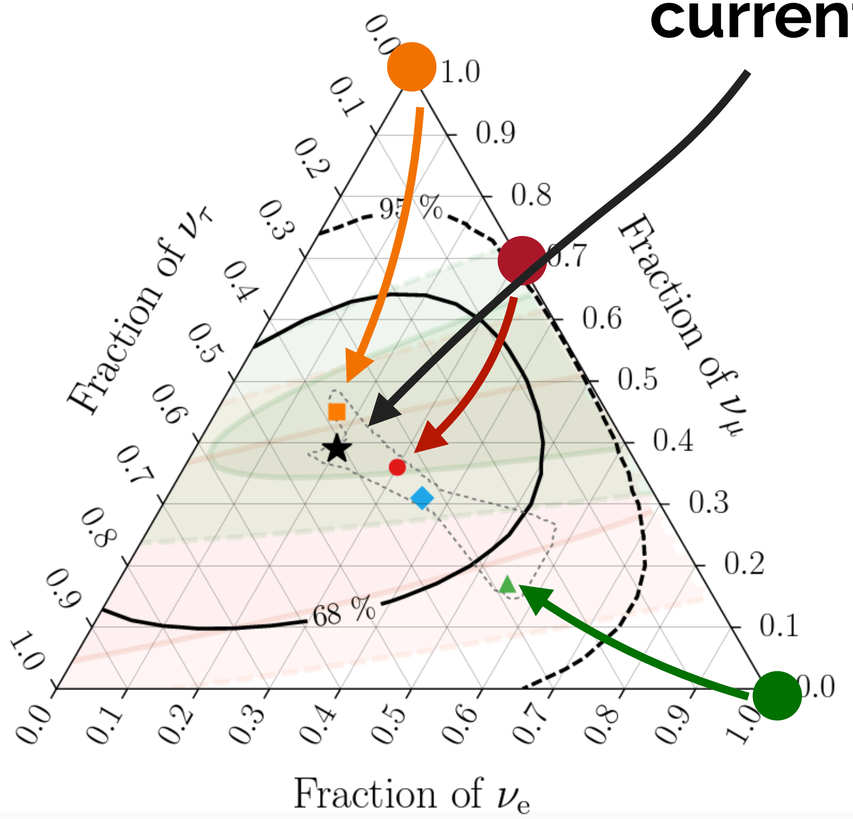
**(1:0:0)**

**muon dumped**

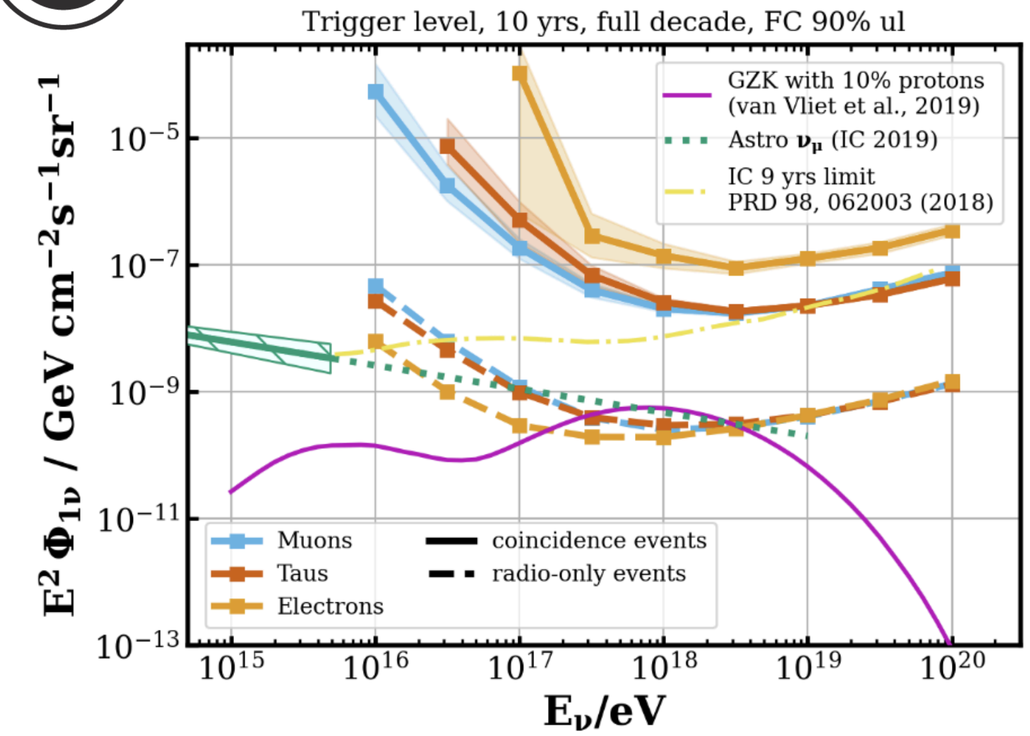
$$\pi^{\pm} \rightarrow \mu^{\pm} + \overset{(-)}{\nu}_{\mu}$$

**(0:1:0)**

**current results**



# R&D for Gen2




- Study of hybrid (optical/radio) events in Gen2
- Rate estimated too low for current layout
  - 0.2 events in 10 year
- Results in **PoS(ICRC2023)1022.**

# Plans for IceCube Gen2

- Scale of funding for full IceCube-Gen2 is **~$500M** from *National Science Foundation (NSF)*, **~$74M** (in kind) from international partners.
- This scale of funding from NSF must go through the ***MREFC*** (Major Research Equipment and Facilities Construction) funding line and be approved by the National Science Board.
- Meanwhile, IceCube as been encouraged by NSF to submit a proposal for MSRI-I Design and Development (capped at $20M over 5 years)

IceCube GEN2

# IceCube-Gen2

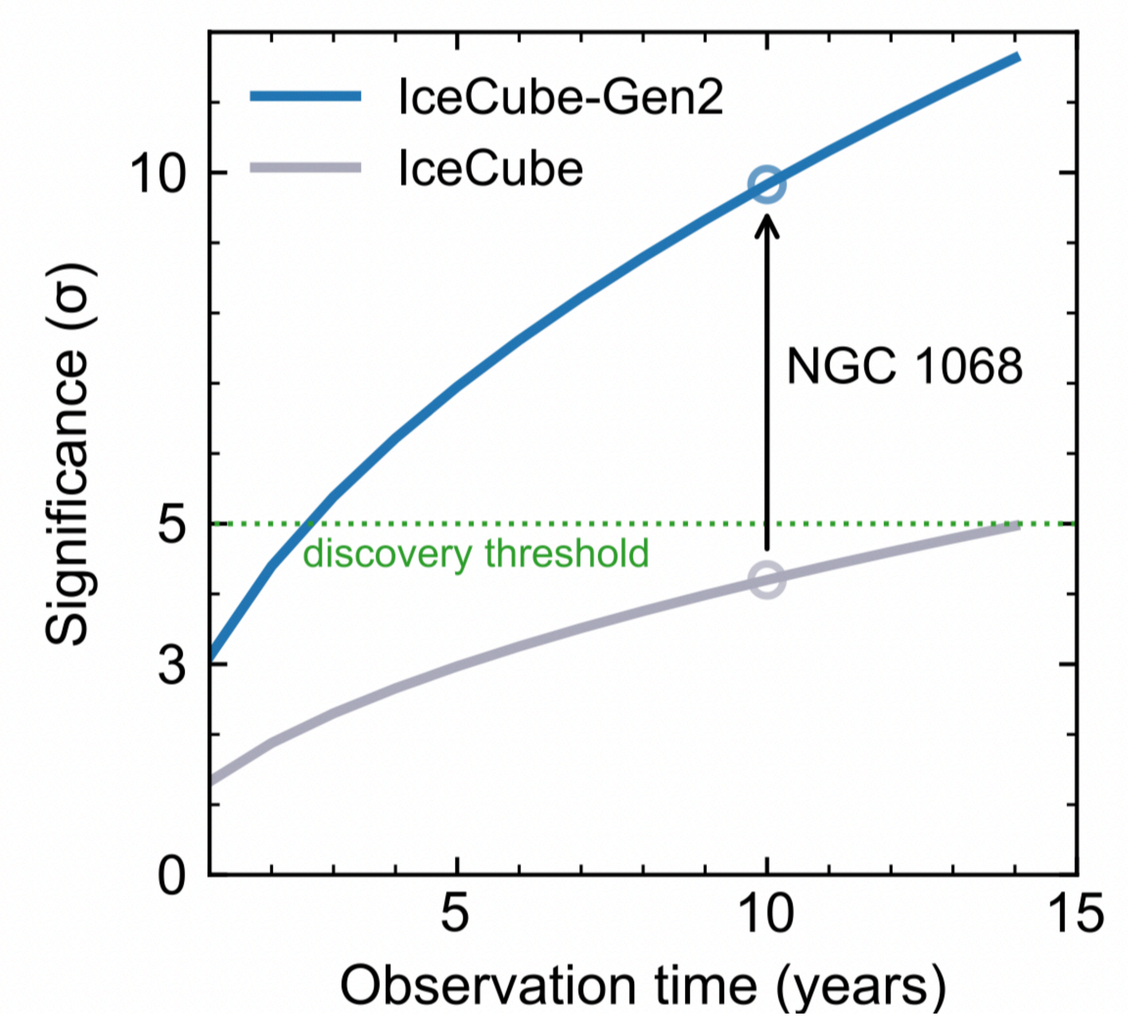
## Point Sources

- $5\times$ improvement in effective area
- $2\times$ improvement in angular resolution

- **IceCube-Gen2** will allow to firmly discover the brightest AGNs on the neutrino sky

- NGC1068: 10 $\sigma$ after 10 years
  - Precise measurement of the spectral shape of the neutrino emission

https://icecube-gen2.wisc.edu/science/publications/tdr/

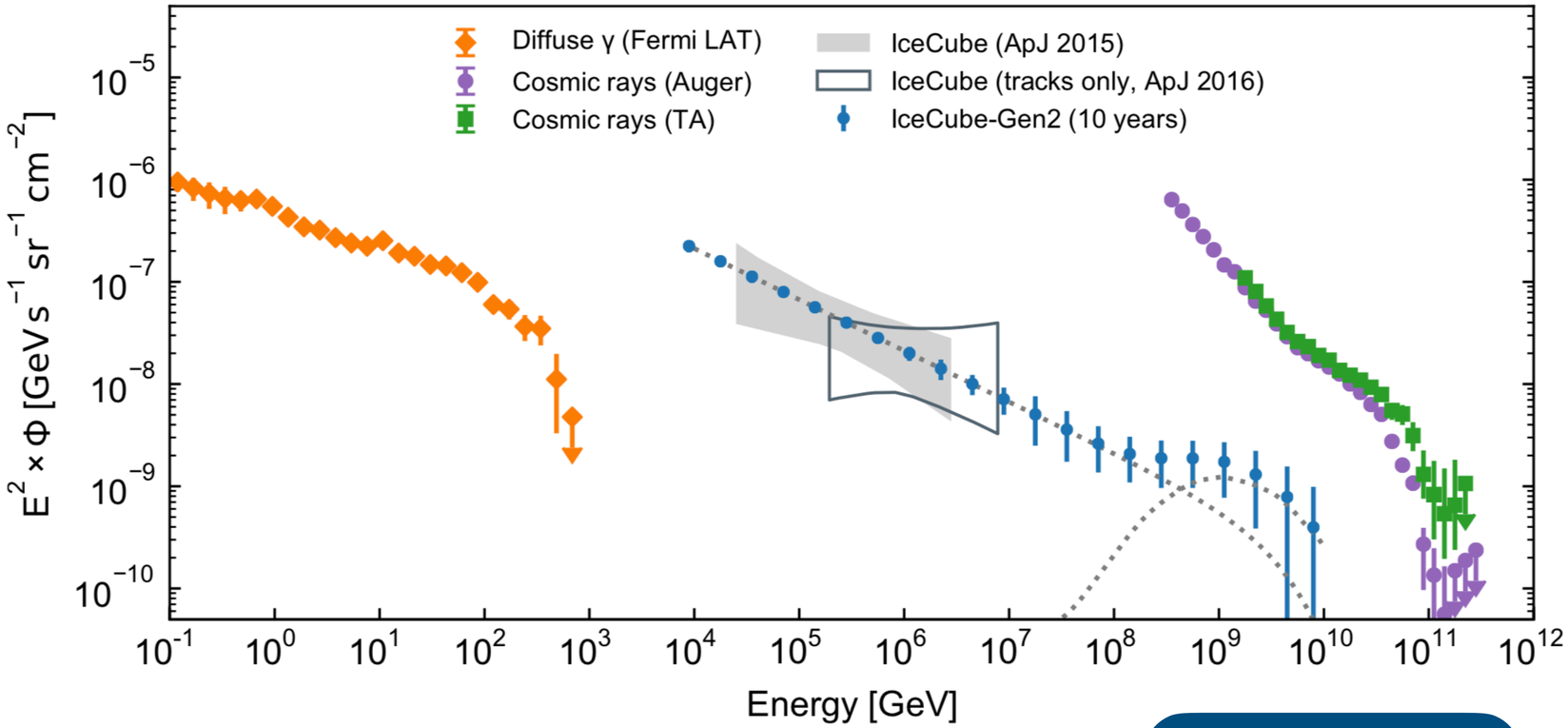


# IceCube-Gen2

## Multimessenger spectroscopy

- 5x improvement in effective area
- 2x improvement in angular resolution

- *Is there a change in the spectrum?*
- *Is there a cut-off?*
- *Are there cosmogenic neutrinos there?*

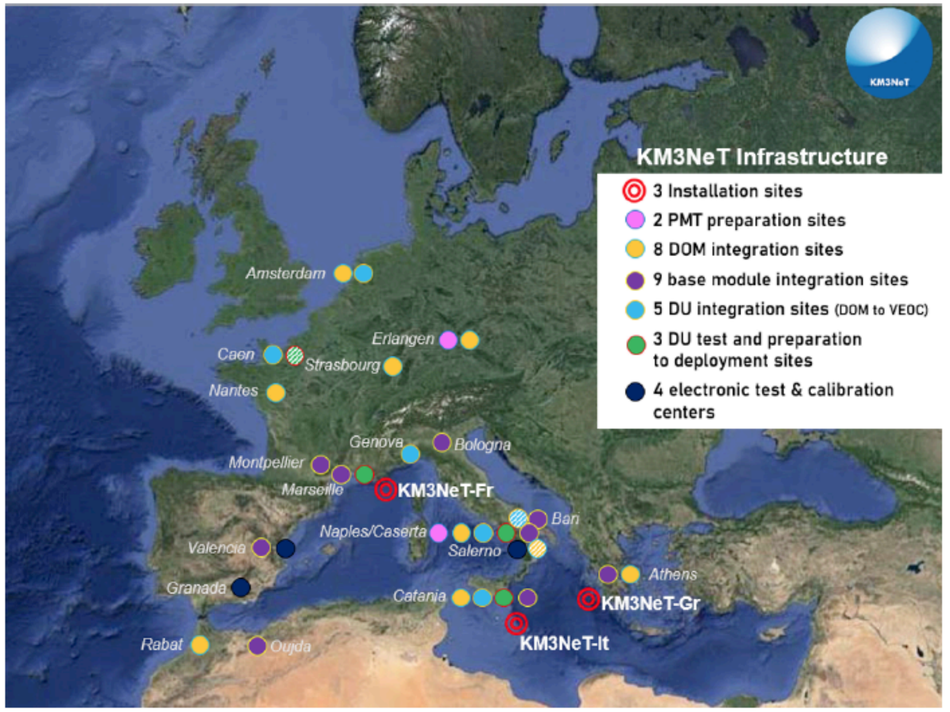



TDR, in preparation

IceCube GEN2

# Status of the construction

- **Parallel construction of ORCA and ARCA**
- Multiple integration sites across the world
- **~2000 optical modules built**
- **~100 detection units integrated**
- **End of the construction 2030 for both detectors**




| | ARCA | | ORCA | |
|---|---|---|---|---|
| | quantity | % completed out of total | quantity | % completed out of total |
| **Optical Modules** | 1116 | 28% | 828 | 40% |
| **Base Modules** | 59 | 26% | 44 | 38% |
| **Detection Units** | 58 | 26% | 33 | 29% |

D. Real (Pos PO-2) I. Del Rosso (Pos PO-2) C. Bozza (Pos PO-1) S. Viola (Pos PO-2)

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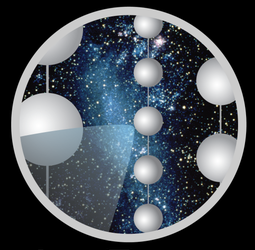
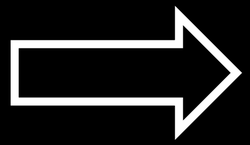
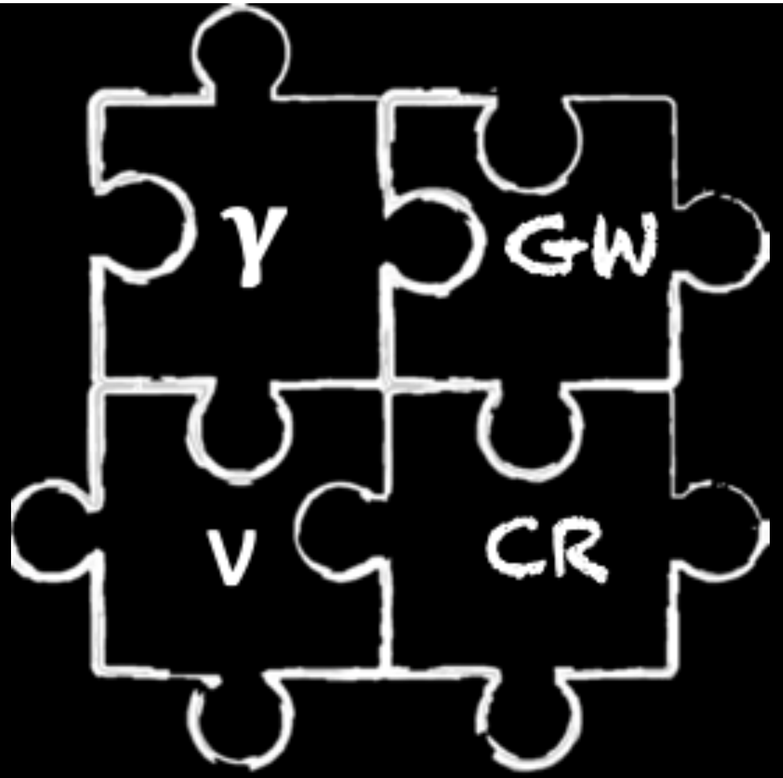
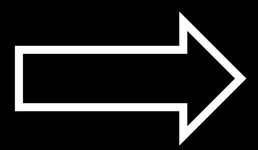
# Multi-energy, multi-detector, and multi-messenger searches

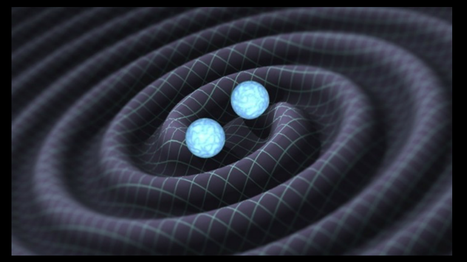


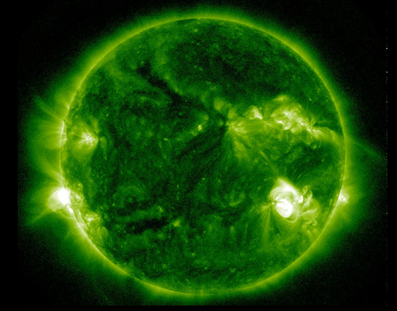
IceCube



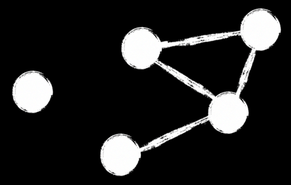



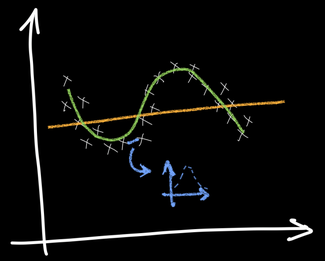




- Enhanced reconstruction tools
- Home-made:
  - event selections
  - source selections
  - Bayesian framework
- Innovative data analyses
- Alert systems
- Science communication

Data science tools





Astrophysical transients

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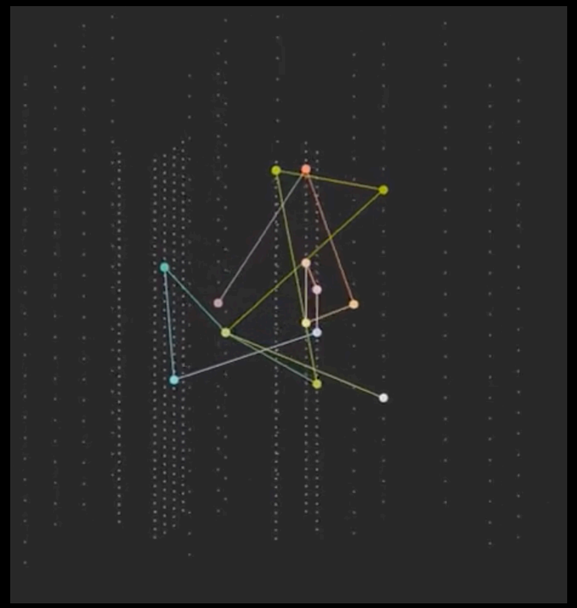
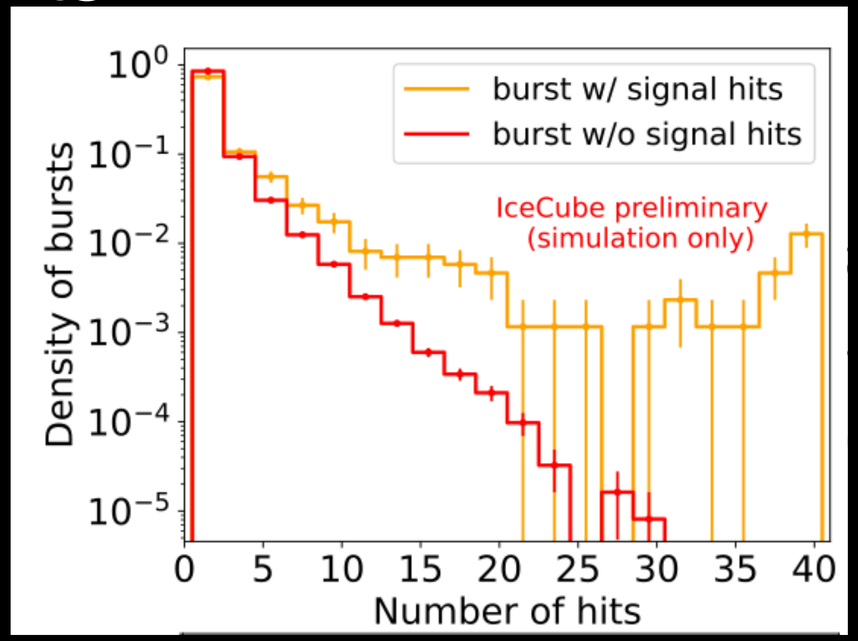
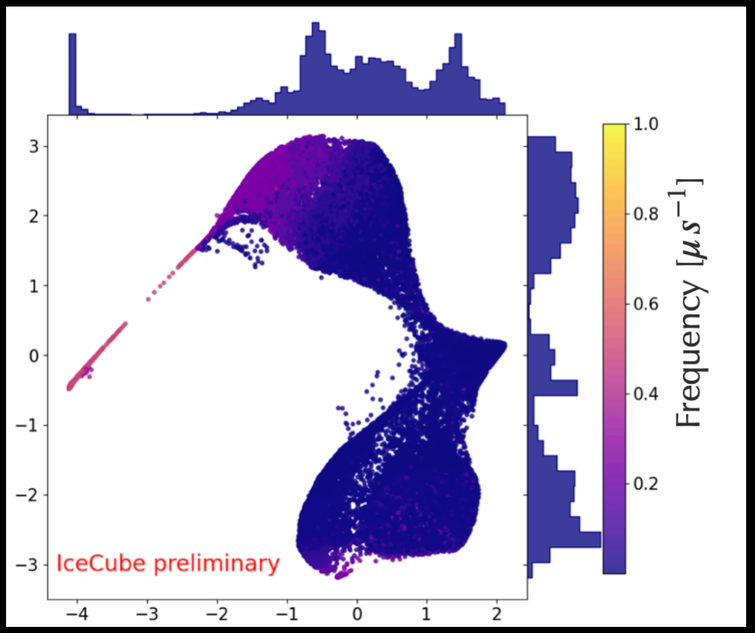
# Sub-threshold events



## Burst search

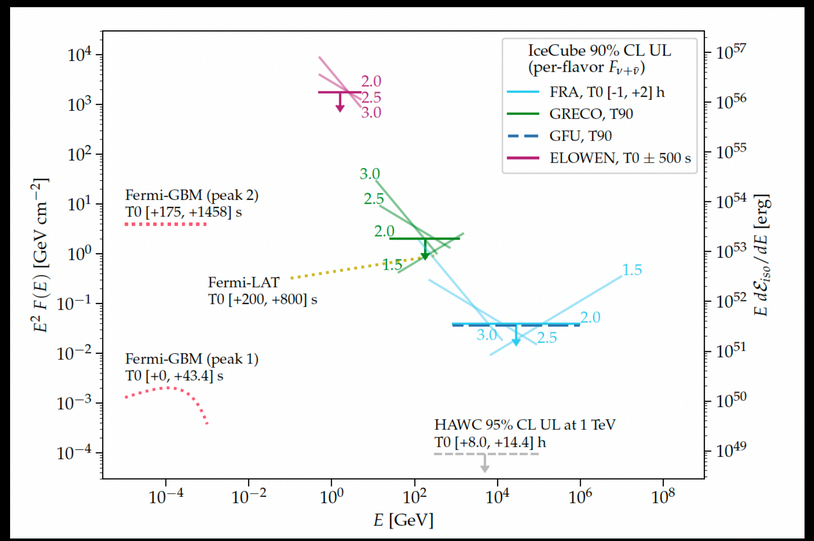



## Sub-population identification

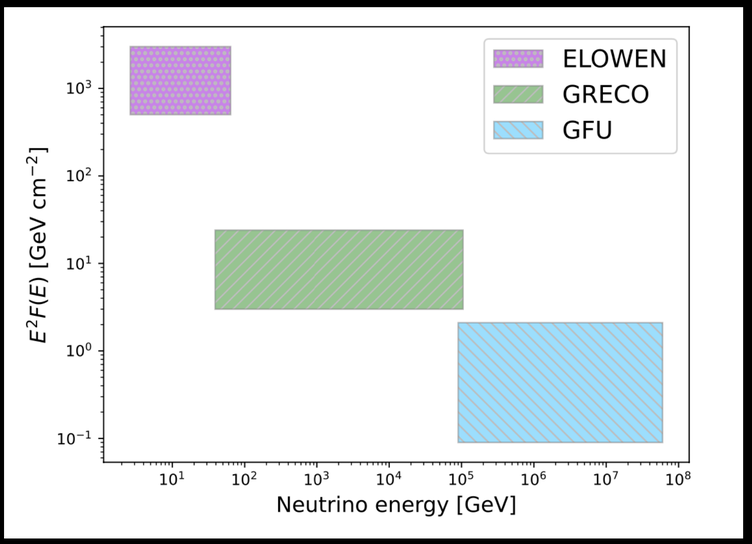



# GeV neutrino

## GRB221009A - the BOAT




## GW follow-ups O1-O4



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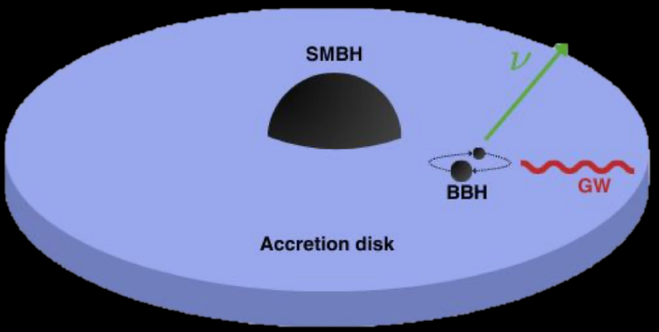
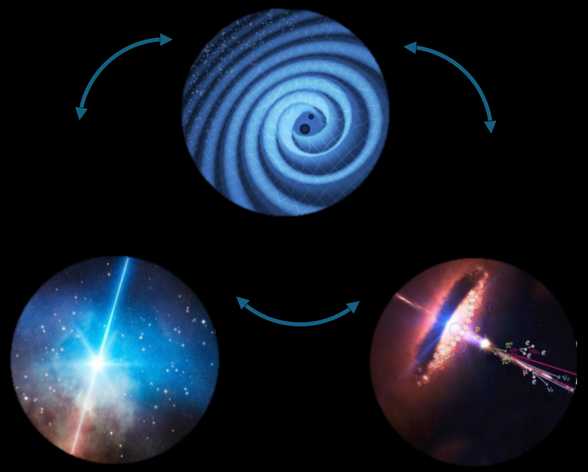
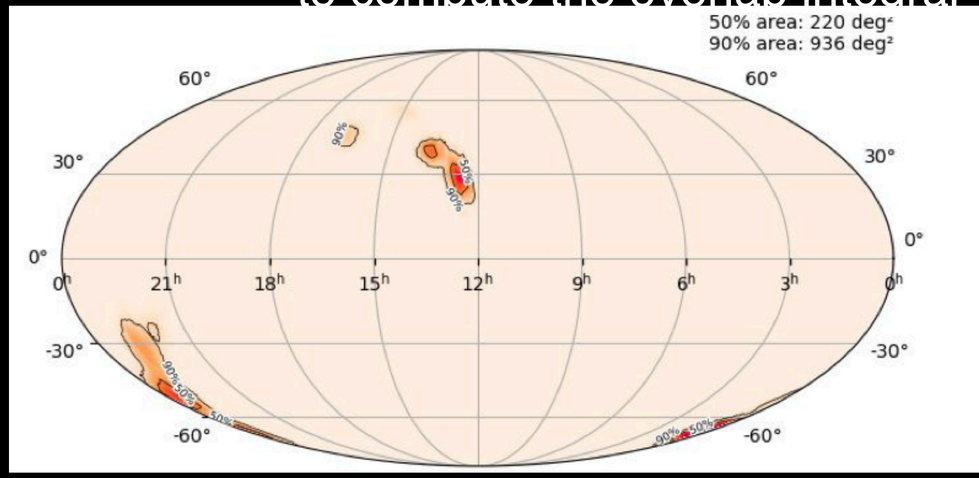
# TeV neutrino



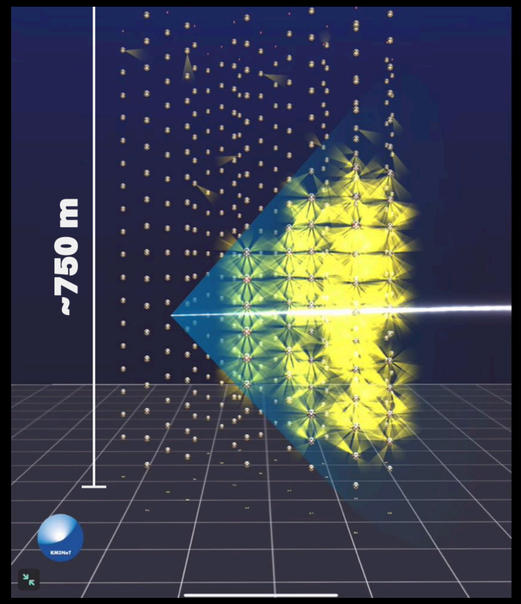

First 3-messenger search

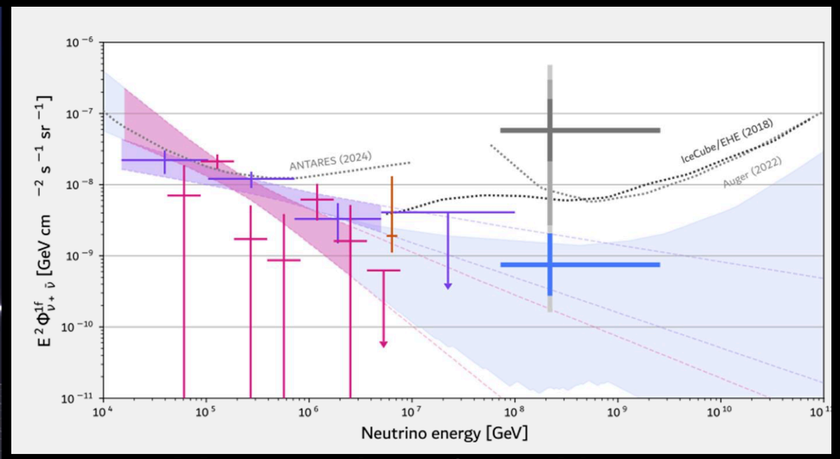


Combination of neutrino posterior with GW posterior and AGN positions to compute the overlap integral

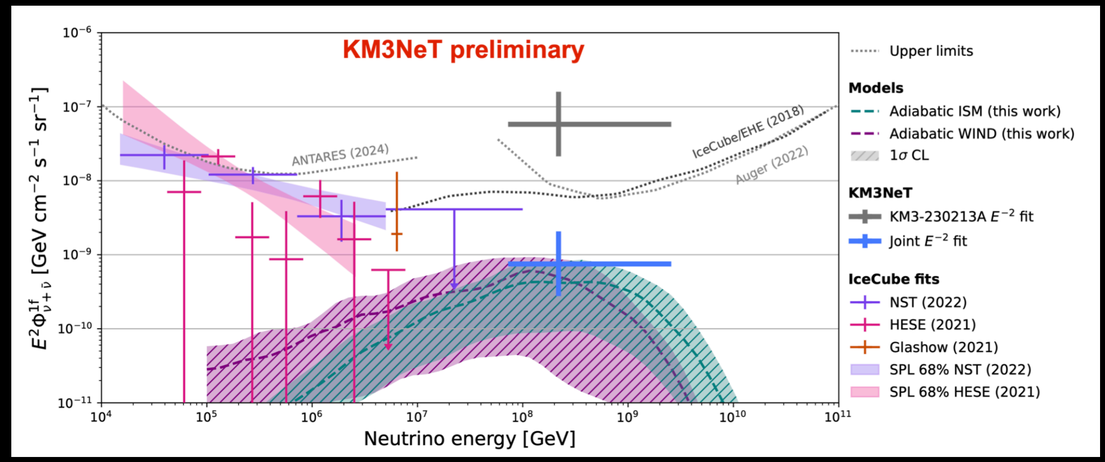



# PeV neutrino




Money plot of the Nature paper
+ model-agnostic
multi-detector flux constraints




GRB interpretation

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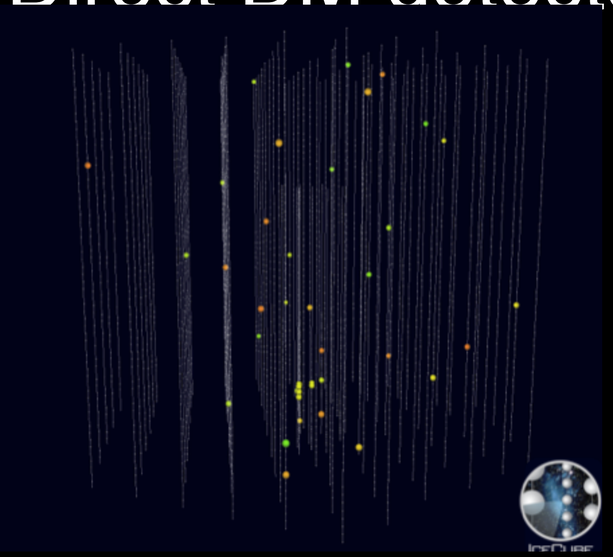
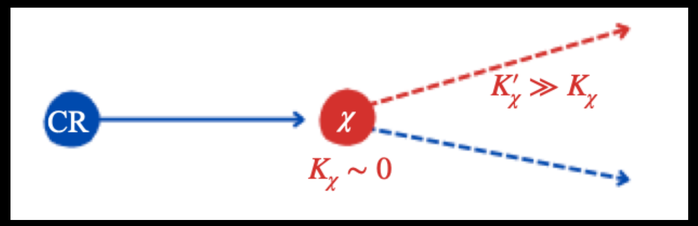
# Direct DM detector

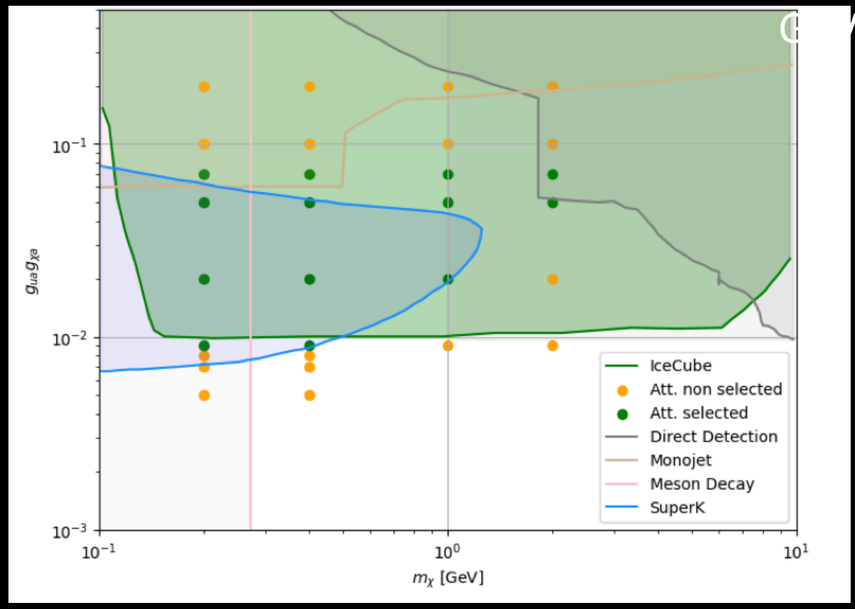


DM up-scattered by cosmic rays lead to sub-GeV like signal in IceCube

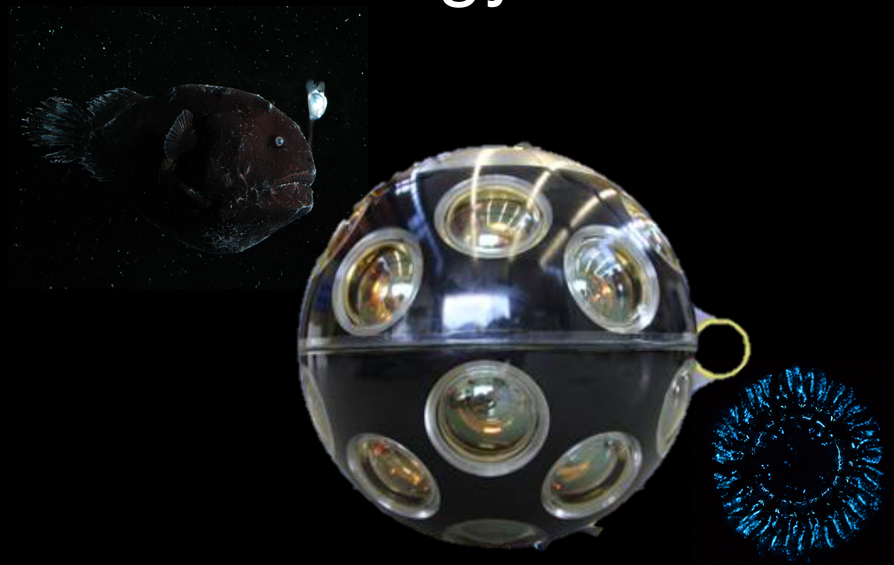


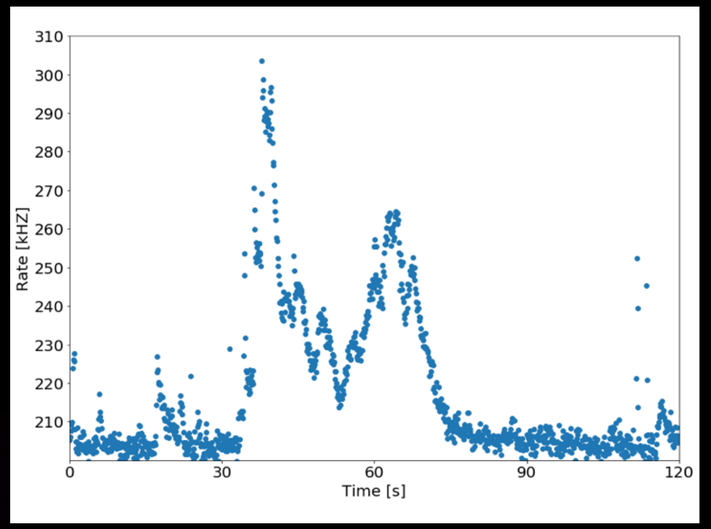

Limits lying in regions allowed by existing constraints from colliders/direct detection

Pseudoscalar mediator with WIMP mass of 1 G

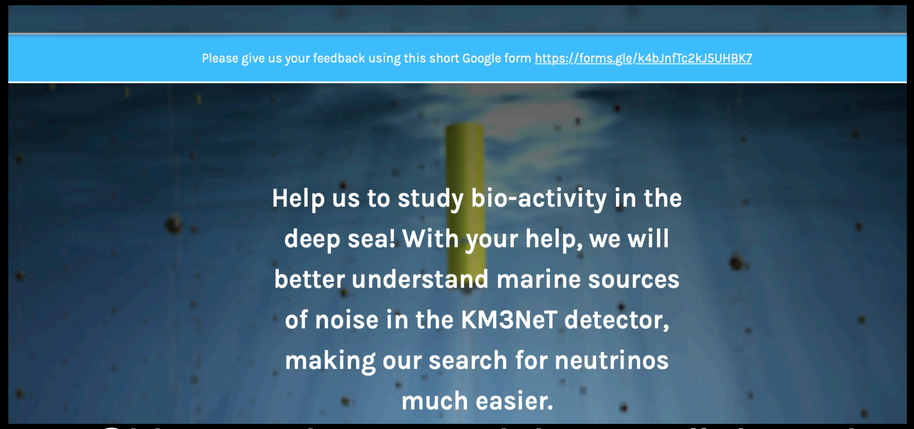



# Marine biology






Minute-long lightcurve vs ns-long signal for neutrinos




Citizen-science activity + collaboration with biologists

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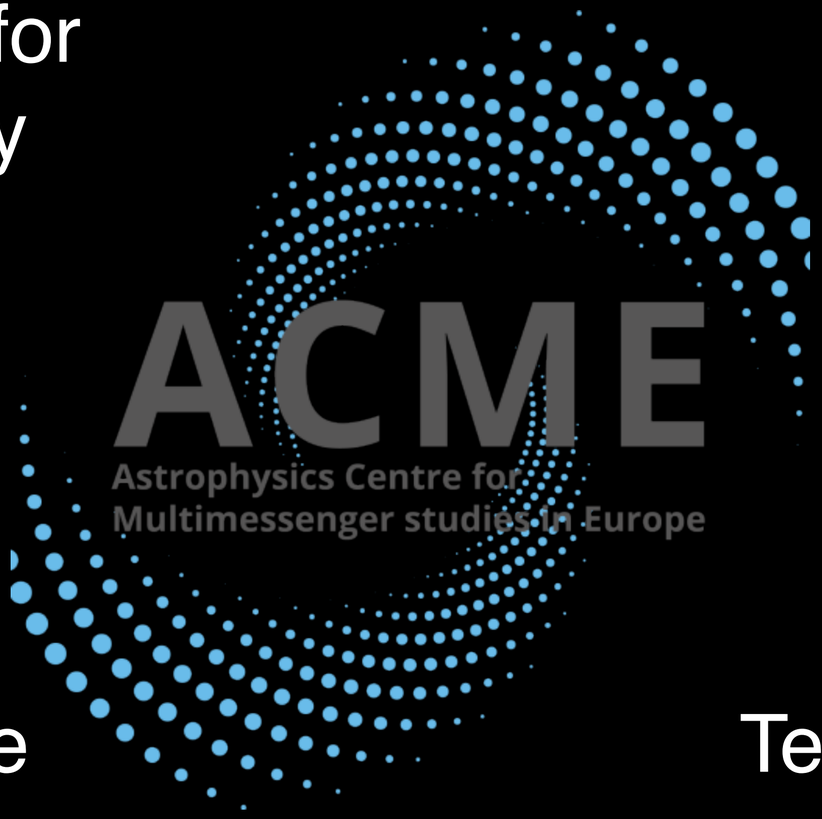
Team led by Gwenhaël Wilberts Dewasseige

Center of expertise for neutrino astronomy

WP leader: Intedisciplinary science




Steering committee + Writing team member

Technical coordination of the project

HORIZON-INFRA-2023-SERV-01-02 - Research infrastructure services advancing frontier knowledge

https://cordis.europa.eu/project/id/101131928

https://www.acme-astro.eu