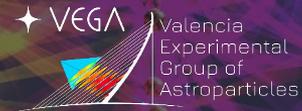


# Neutrino Telescopes

Latest news from the Mediterranean Sea



Agustín Sánchez Losa  
IFIC (CSIC-UV) | VEGA

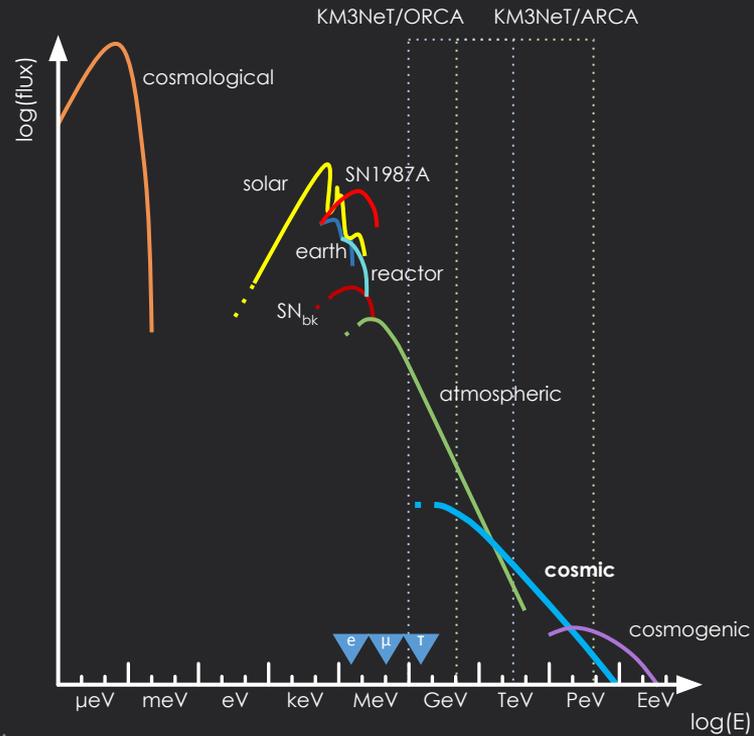
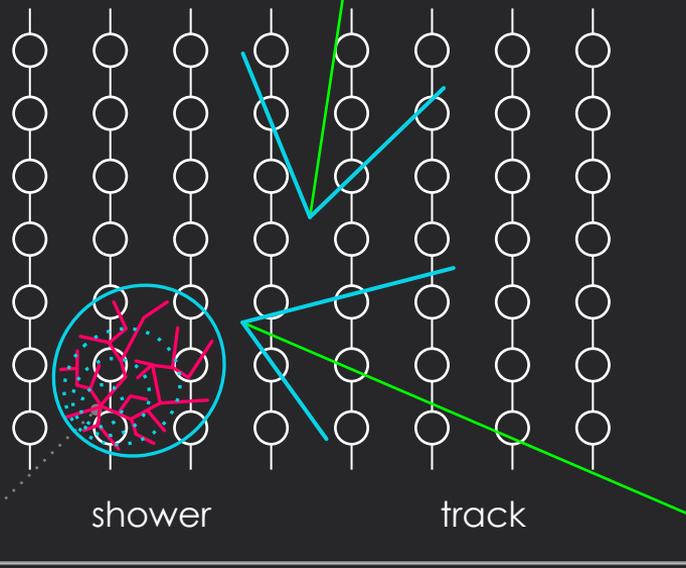


1st Meeting Aragón - Comunidad Valenciana  
Complementary Plans of Astrophysics and High Energy Physics

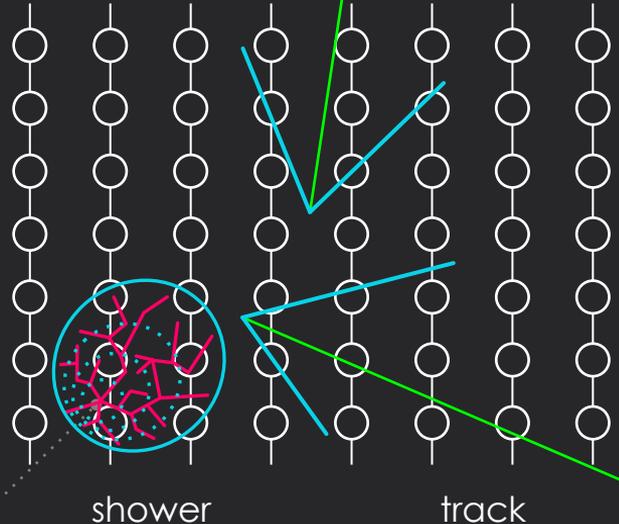
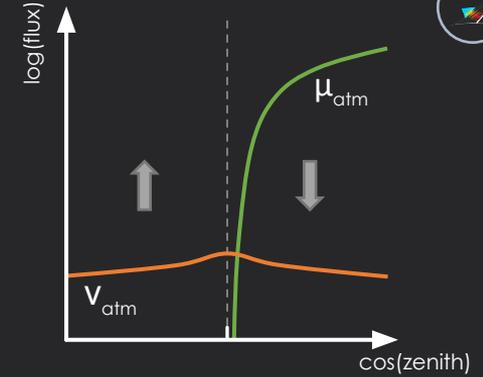
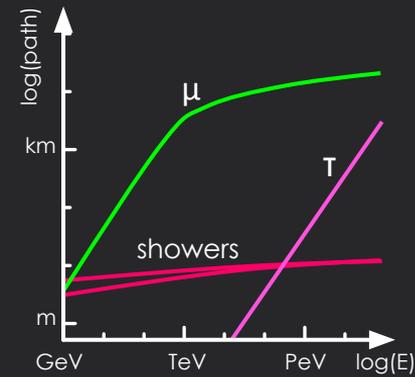


# A Neutrino Telescope

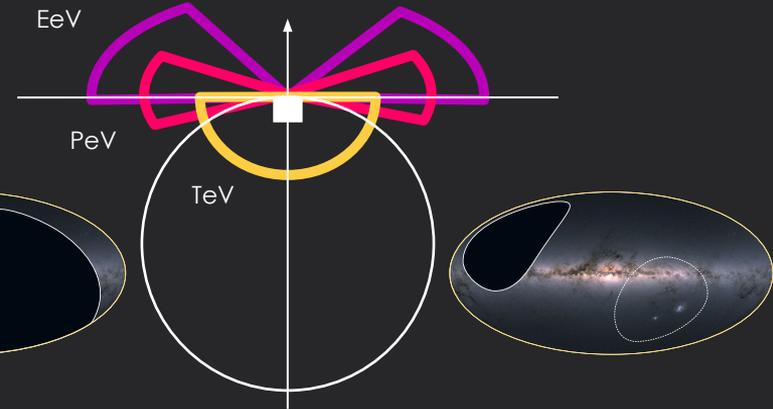
“We propose setting up apparatus in an underground lake or deep in the ocean in order to separate charged particle directions by Cherenkov radiation”, **Markov 1960**



# A Neutrino Telescope



$1 \text{ km}^3$   
 $\mu_{\text{atm}} \sim 2000 / \text{s}^{(1)}$   
 $\nu_{\text{atm}} \sim 400 / \text{day}^{(2)}$   
 $\nu_{\text{cos}} \sim 200 / \text{year}^{(2)}$   
 (1): depth dependent  
 (2): analysis dependent





### Pathfinders

- DUMAND (Hawaii)
- + Baikal
- + Amanda (Ant.)
- NESTOP (Med.)
- NEMO (Med.)
- + ANTARES (Med.)

### Taking data

- IceCube (Ant.)
- KM3NeT (Med.)
- GVD (Baikal)

### Planned

- IceCube Gen2
- P-ONE (Pac.)
- TRIDENT (China)
- HUNT (China)



### Operating in full configuration:

- **ANTARES** (\*) 0.01 km<sup>3</sup>
- IceCube 1 km<sup>3</sup>

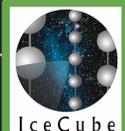
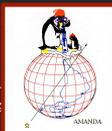
### Under construction, taking data:

- **KM3NeT** 1 + 0.006 km<sup>3</sup>
- Baikal GVD ~1 km<sup>3</sup>

### In planning phase:

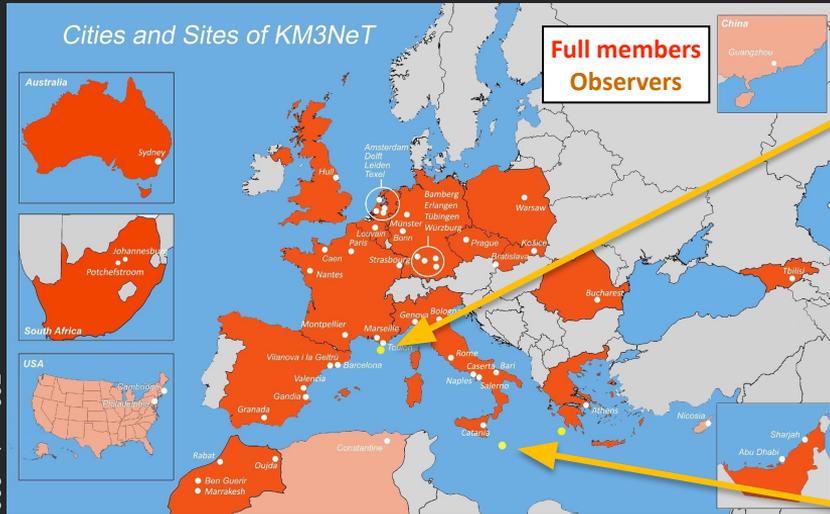
- IceCube-Gen2 ~8 km<sup>3</sup>
- P-ONE >1 km<sup>3</sup>
- TRIDENT ~7.5 km<sup>3</sup>
- HUNT ~30 km<sup>3</sup>
- NEON ~1 km<sup>3</sup>

(\*) Shut down Feb'22



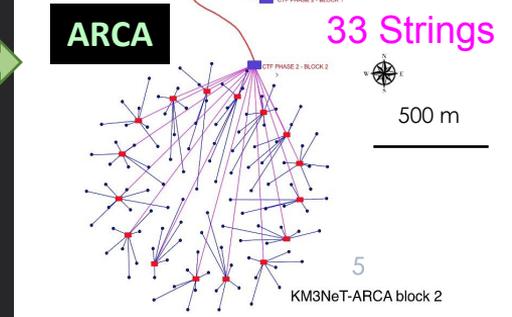
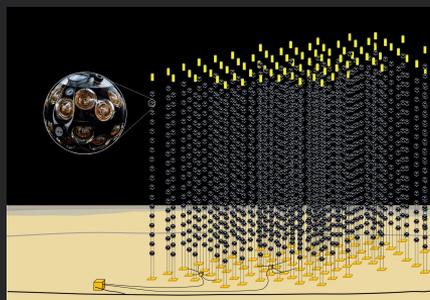
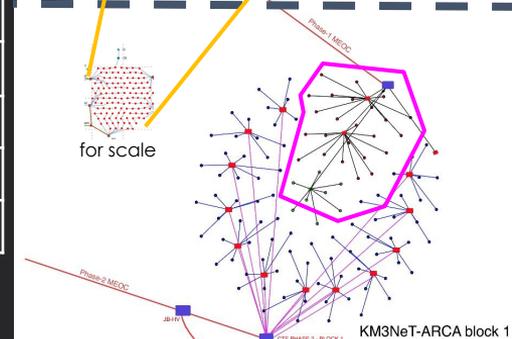
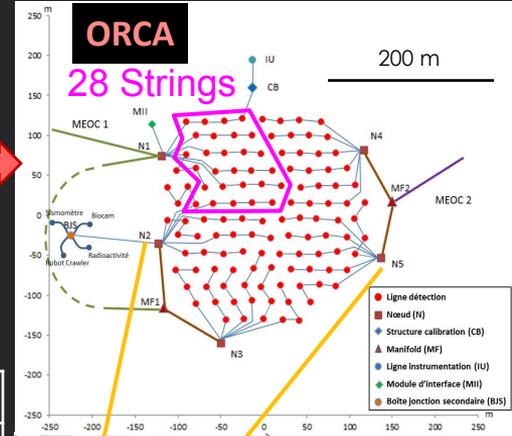
[www.globalneutrino.org](http://www.globalneutrino.org)  
Frame for enhanced cooperation

# The KM3NeT Detector



Oscillation Research with  
Cosmics in the Abyss

	ORCA	ARCA
Strings	115	115 × 2
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Instrumented mass	7 Mton	500 × 2 Mton
Energy range	GeV	TeV – PeV



27/05/2025

+ VEGA

Agustín Sánchez Losa | 1st Meeting

Astroparticle Research with  
Cosmics in the Abyss

# Broad Physics Scope

KM3NeT - ARCA

KM3NeT - ARCA

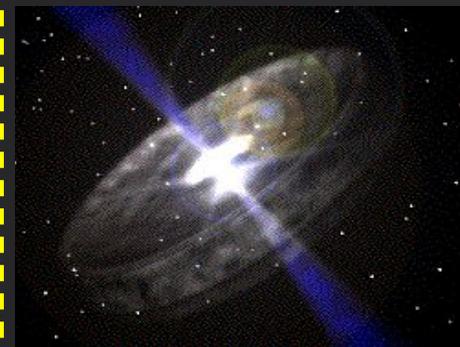
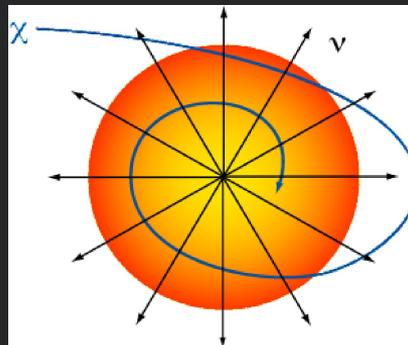
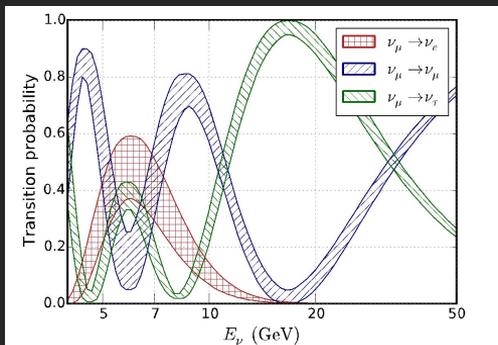
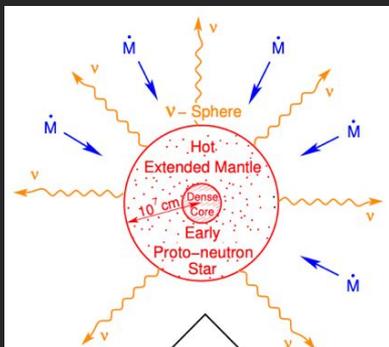
KM3NeT - ORCA

Low Energy  
~ MeV

Low Energy  
> 10 GeV

Medium Energy  
 $10 \text{ GeV} < E_\nu < 10 \text{ TeV}$

High Energy  
 $E_\nu > 1 \text{ TeV}$



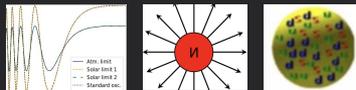
CCSN detection

$\nu$  oscillations

dark matter search

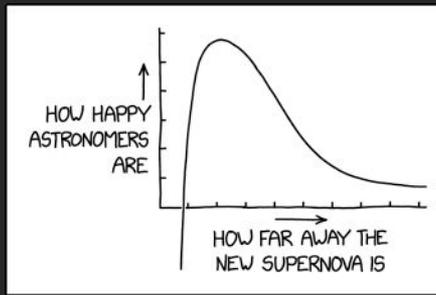
$\nu$  from extra-terrestrial sources,  
origin and production  
mechanism of HE CR

...and exotic searches

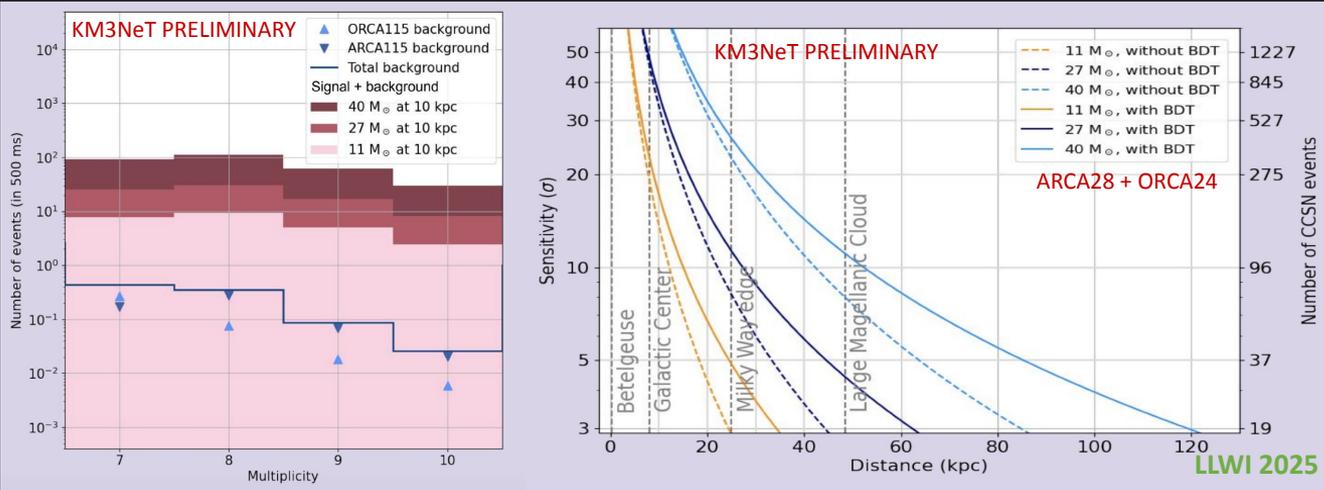


**NEUTRINO ASTRONOMY**

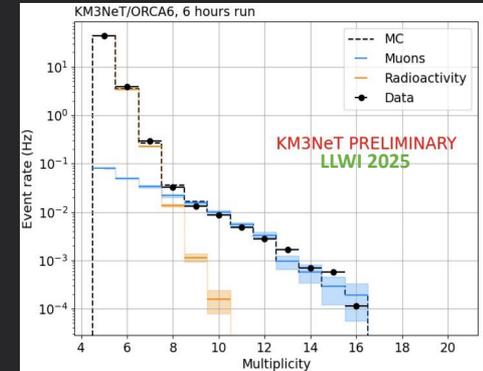
# CCSN searches



Each single DOM can act as a detector

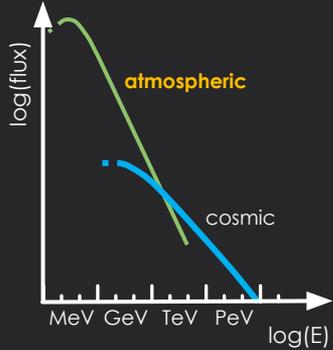


- Increase of DOM rates due to many MeV neutrinos from the collapse
- Alert system already operational and integrated in SNEWS network
- **5σ detection by ARCA+ORCA for 27 M<sub>⊙</sub> CCSN at <50 kpc distance**

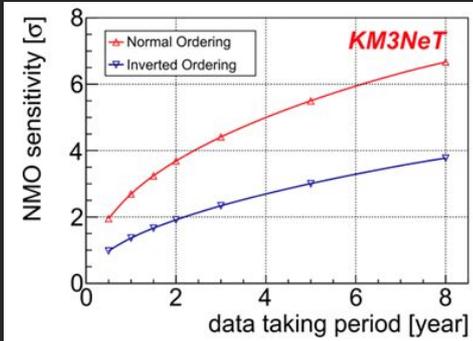


# Neutrino properties & exotics

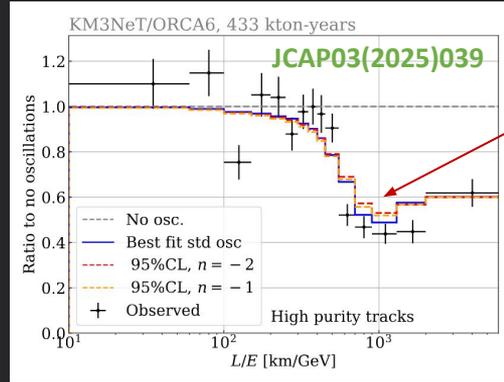
More exotics: sterile neutrinos/neutral heavy leptons, neutrino decay, long live particles, monopoles, nuclearites, etc.



## Neutrino Mass Ordering



Eur. Phys. J. C 82, 26 (2022)

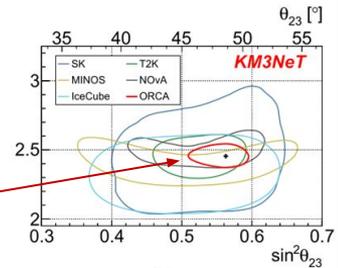
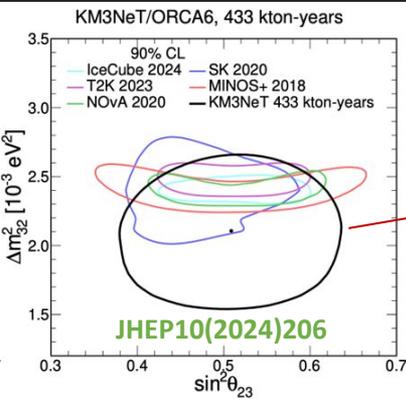
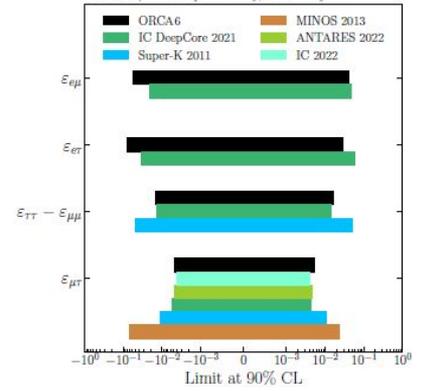


Quantum decoherence

Non-standard neutrino interactions

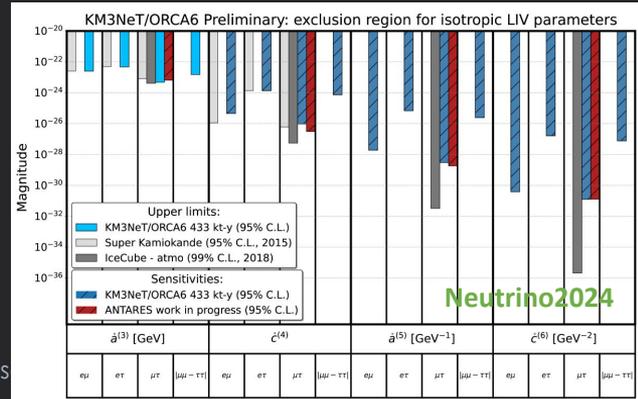
arXiv:2411.19078 [hep-ex]

KM3NeT/ORCA6 preliminary, 433 kton-yr



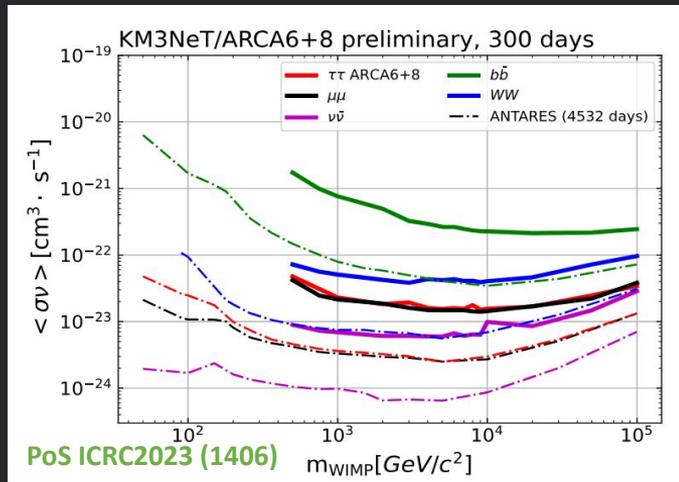
In 3 years of full ORCA115 (N.O.)

## Lorentz Invariance Violation

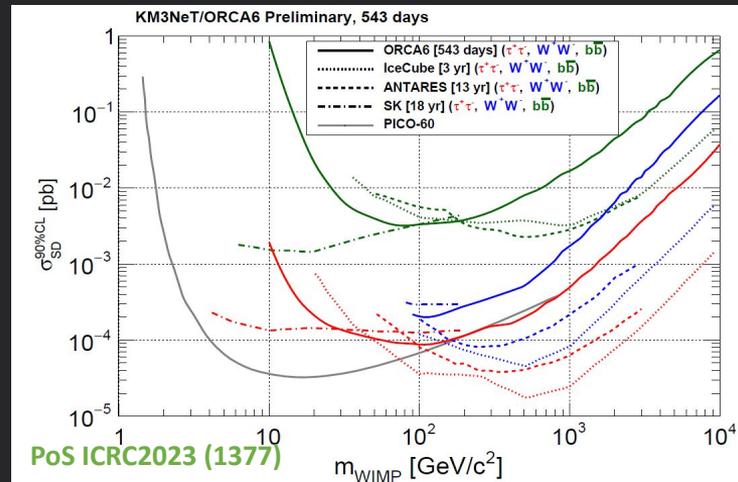
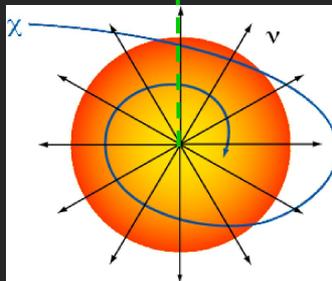
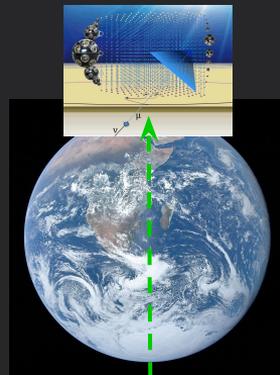


Neutrino2024

# Dark Matter searches

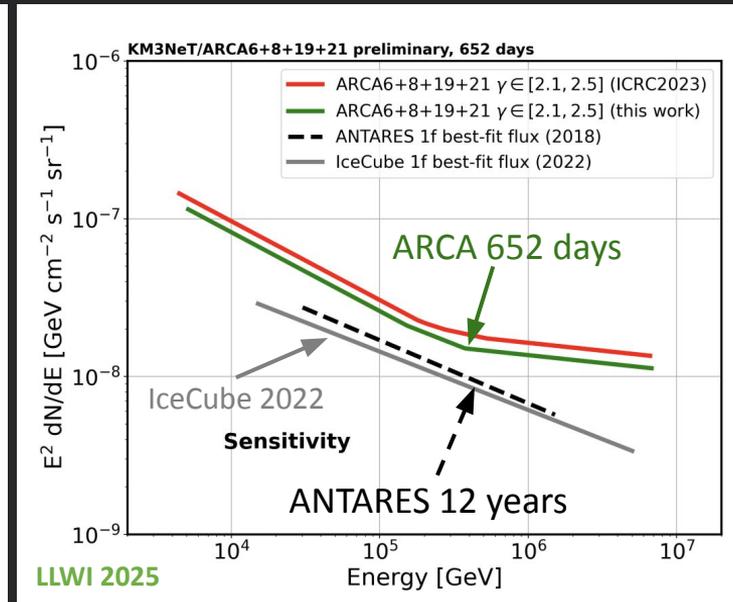
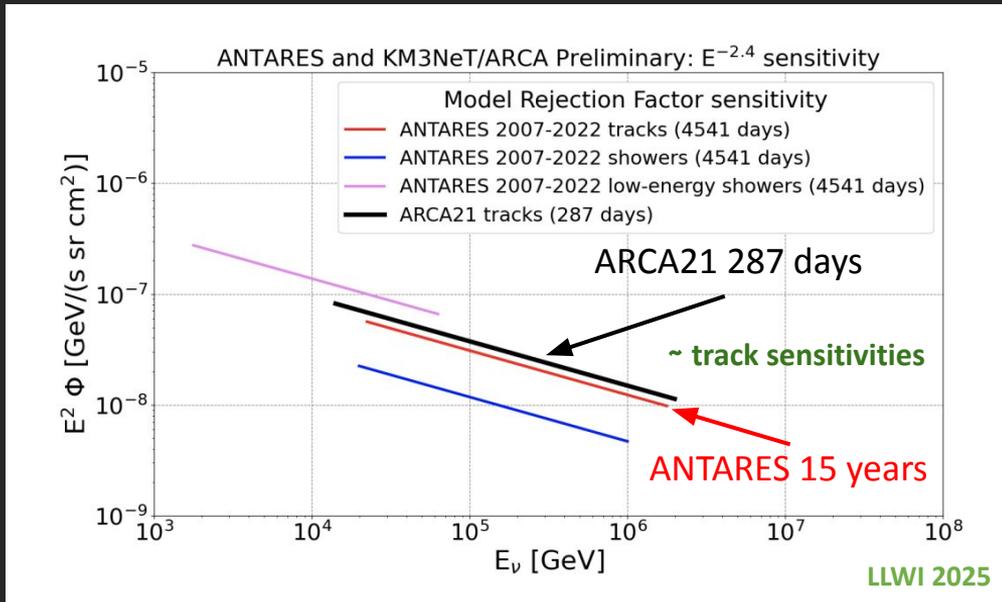


Dark matter from the  
Galactic Center



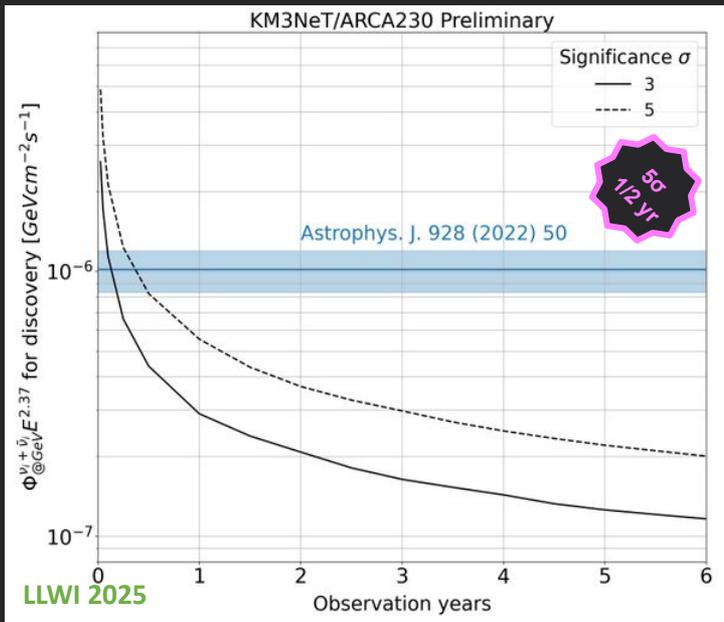
Dark matter from the  
Sun

# Diffuse searches

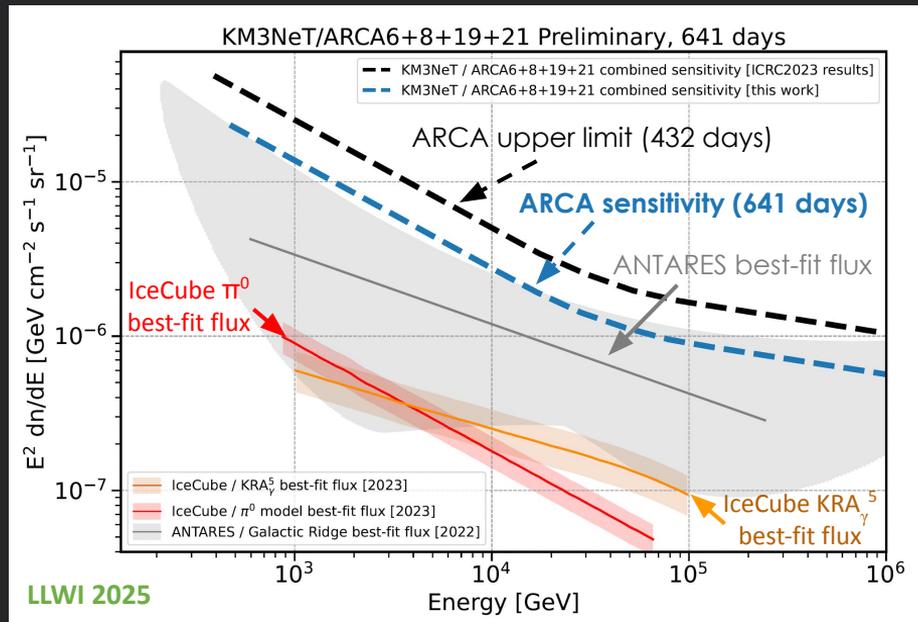


KM3NeT/ARCA rapidly approaching ANTARES/IceCube sensitivities

# Diffuse searches

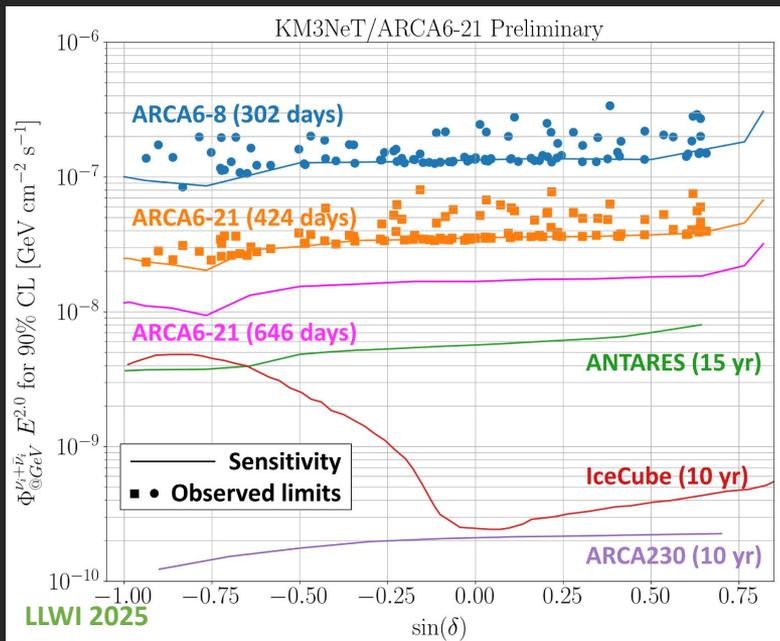


Full KM3NeT/ARCA  
diffuse flux discovery

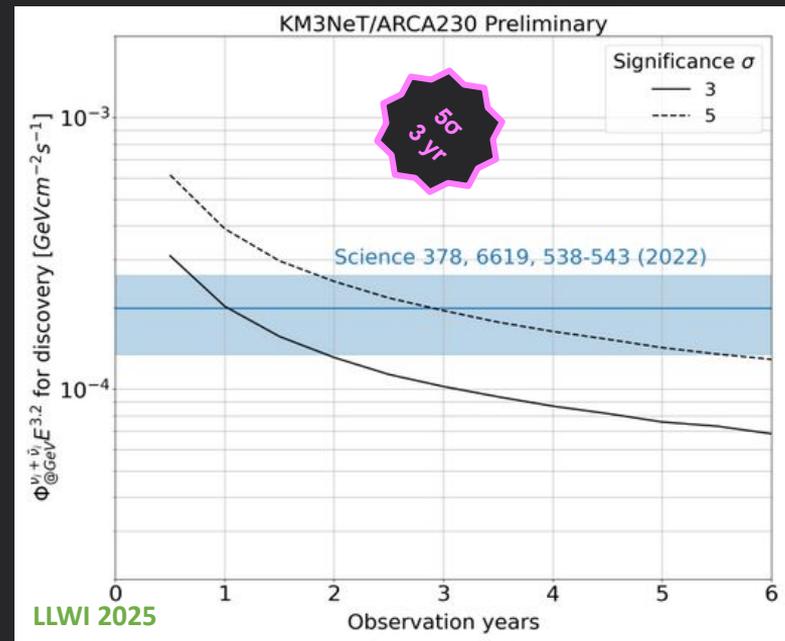


KM3NeT/ARCA Galactic Plane  
|l| < 31° |b| < 4°-5°

# Point source searches



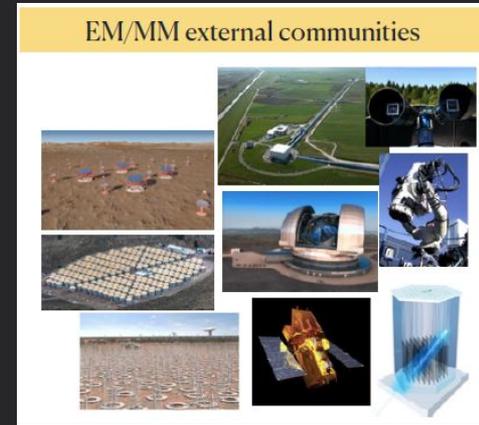
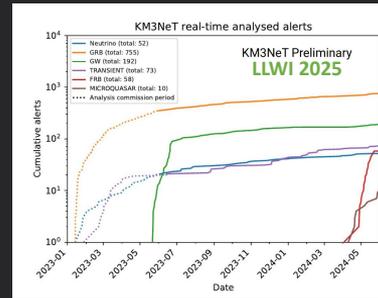
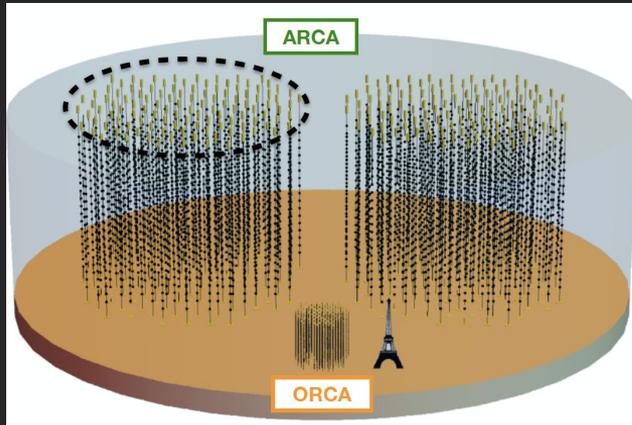
KM3NeT/ARCA partial configurations  
PS sensitivities & upper limits



Full KM3NeT/ARCA  
discovery for NGC 1068

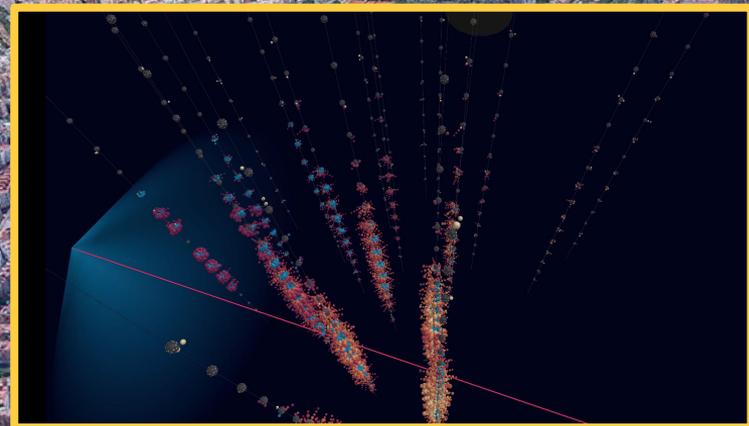
# Real Time Multi-Messenger Program

Dedicated software+hardware at shore stations for Real-Time Analysis (RTA)



Receiving alert system: **OPERATIVE**, since November 2022, on-line analysis and follow-up  
Sending alert system: **INCOMING**, HE neutrino alerts will be sent in real-time (commissioning in private with some partners starting this year)

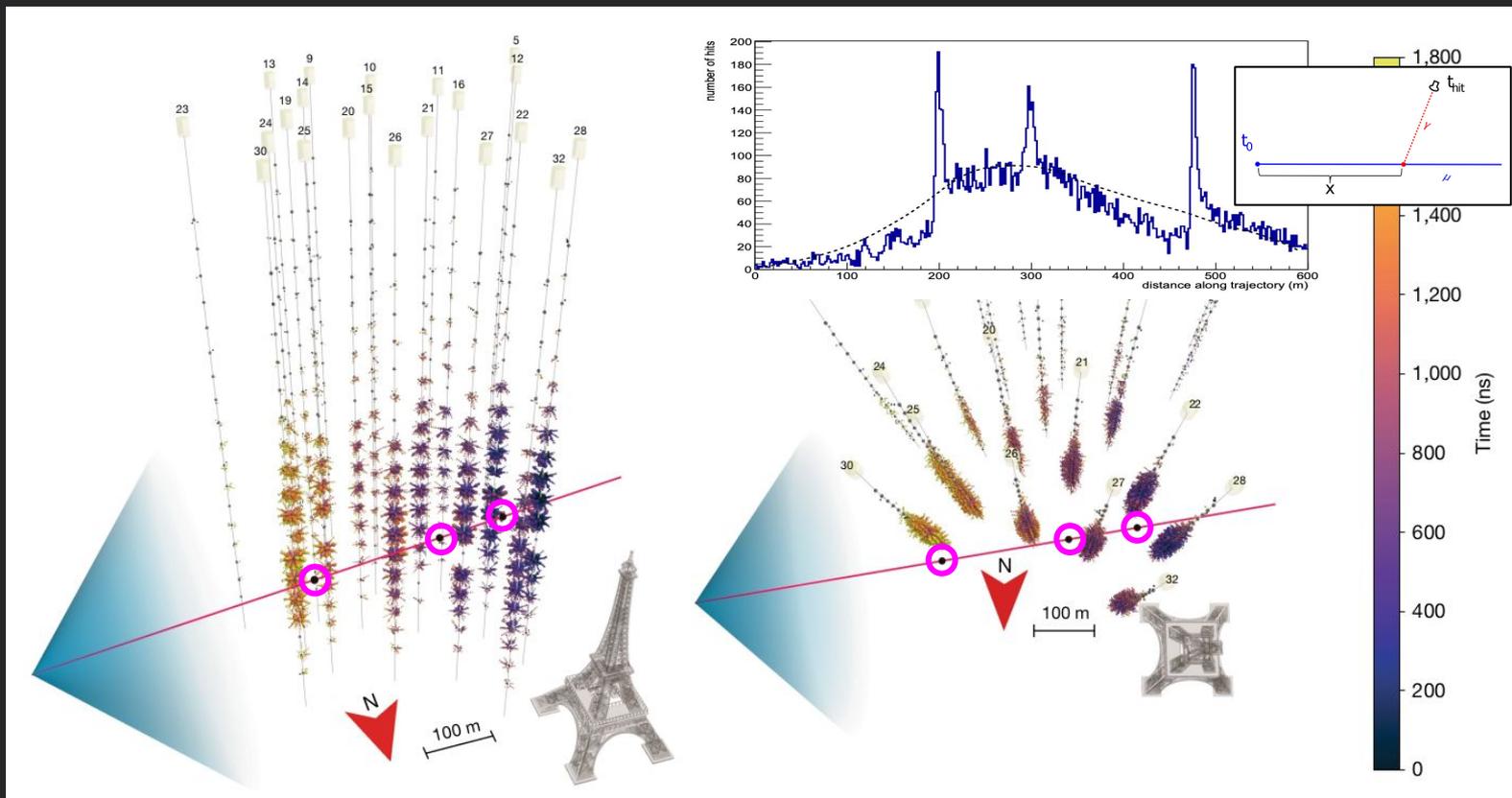
...and the unexpected



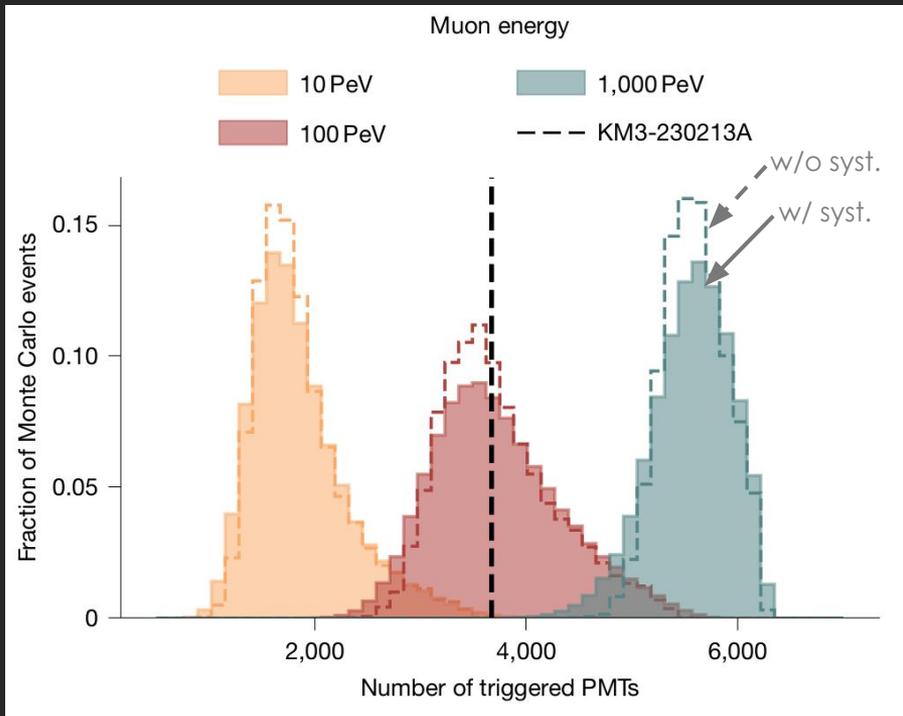
KM3-230213A: muon track compatible with a 220 PeV neutrino rendered in Valencia

# KM3-230213A event

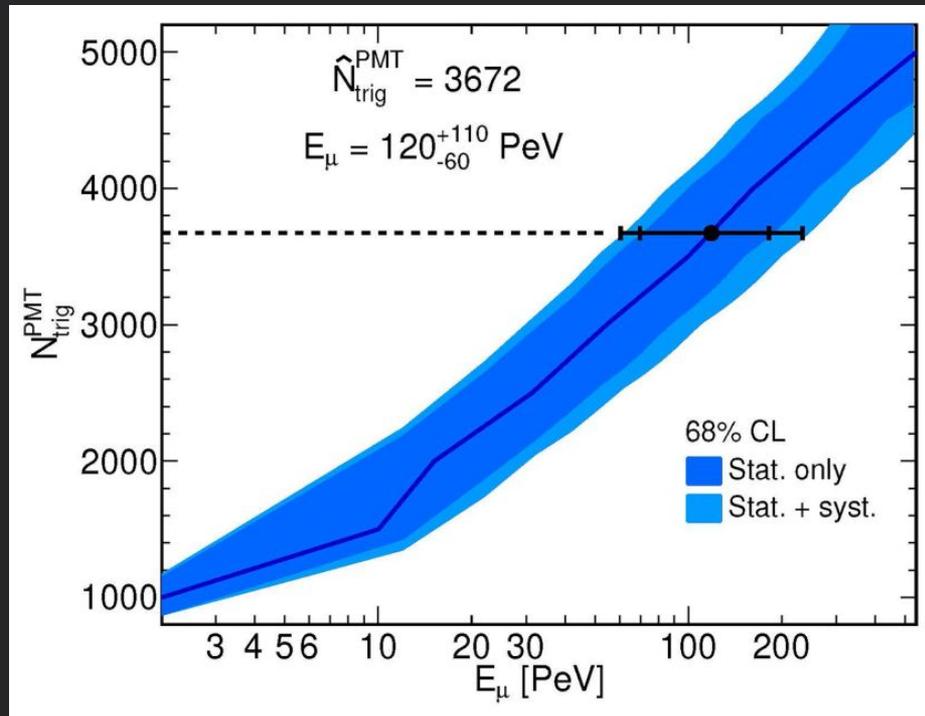
Event well reconstructed as a track, showing 3 large energy depositions through the detector



# KM3-230213A energy



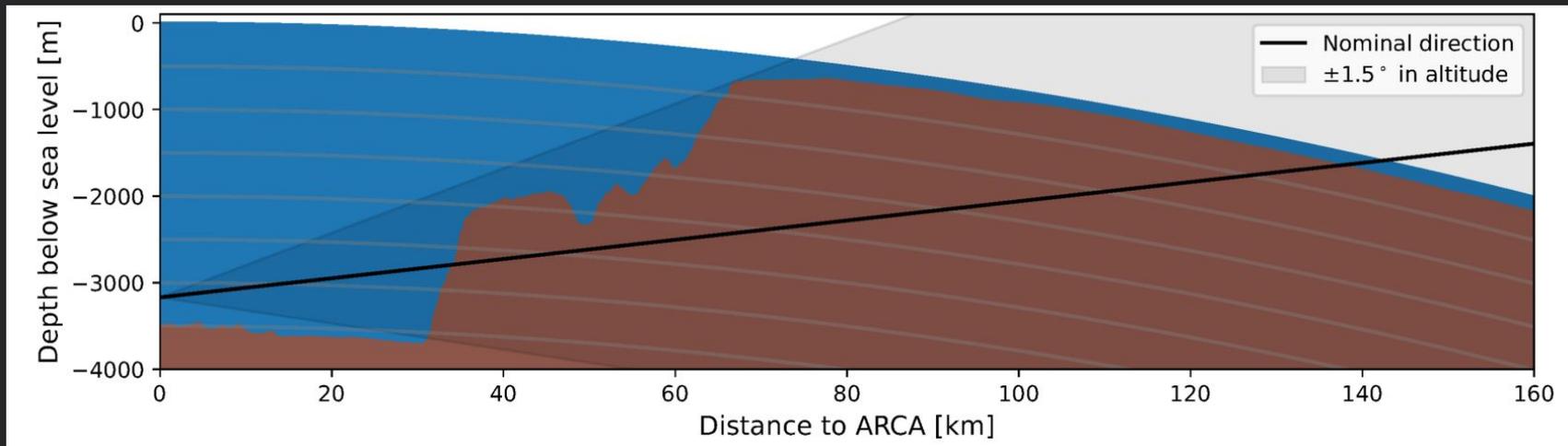
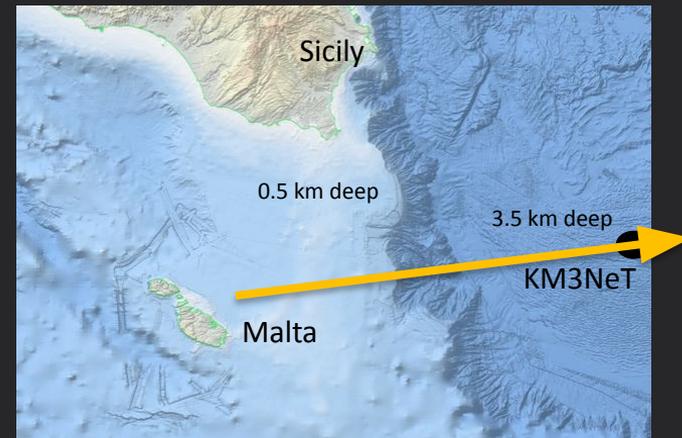
Number of triggered PMTs as a proxy of the energy  
KM3-230213A triggered 3,672 PMTs (35%)



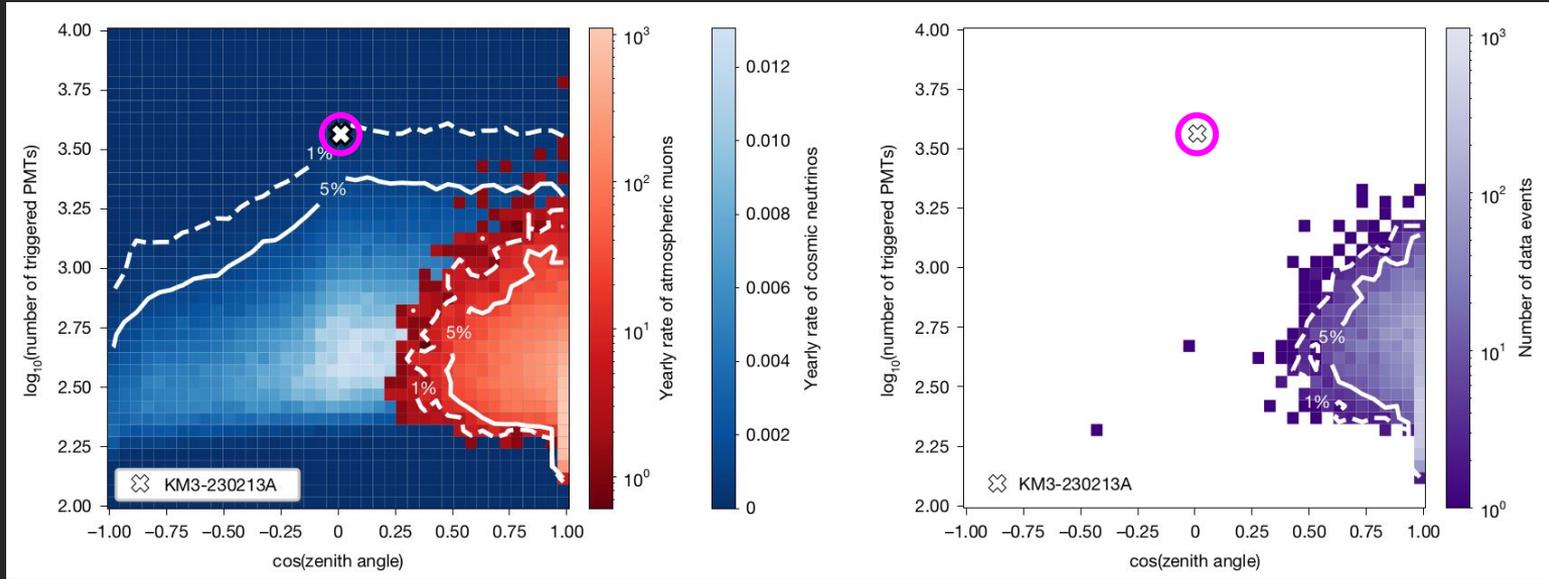
Muon energy estimation results in  $120^{+110}_{-60} \text{ PeV}$  ( $1\sigma$ )

# KM3-230213A direction

- ( az. , el. ) = ( 259.8° , 0.6° )
- Event coming from west, slightly downgoing
- Angular uncertainty  $\sim 1.5^\circ$ , dominated by absolute pointing
- EeV muons range  $< 60$  km (  $< 30$  km for a 10 PeV detection )
- Track 140 km from the surface ( 300 km w.e. )
- Even with zenith  $+2^\circ$  (  $\sim 90\%$  containment ) are  $\sim 60$  km w.e.



# KM3-230213A Earth origin

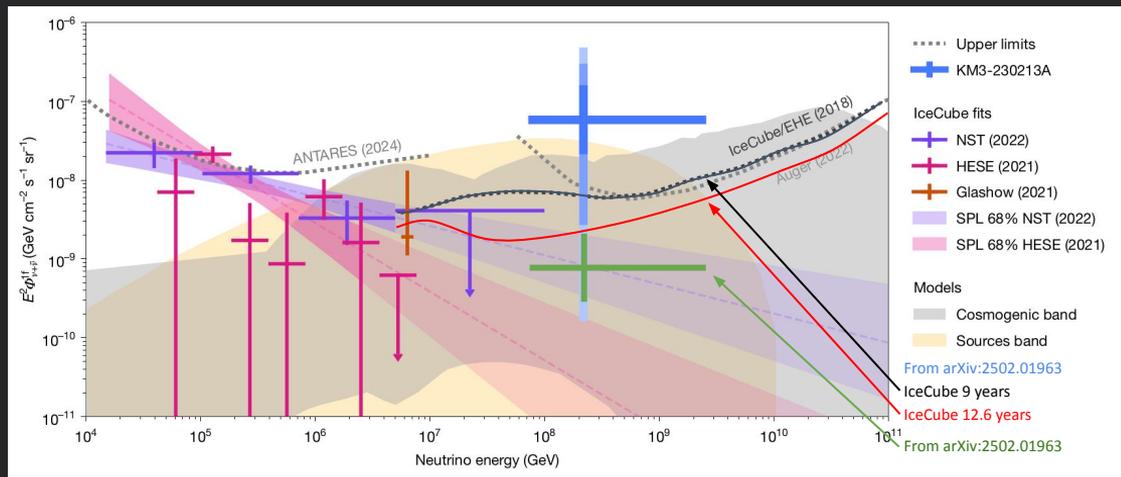
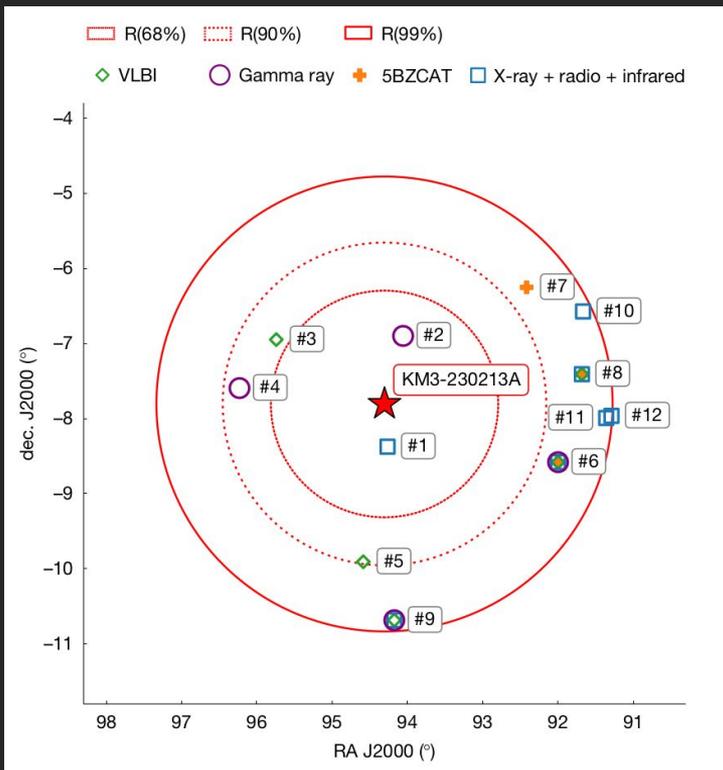


Unlikely atmospheric origin:

$P(\nu_{\text{atm}})$  beyond  $4\sigma$  (less than  $10^{-5}$  ev/year for  $>100$  PeV)

$P(\mu_{\text{atm}})$  beyond  $6\sigma$  (less than  $10^{-9}$  ev/year for 10 PeV)

# KM3-230213A celestial origin



- ( R.A. , dec. ) = ( 94.3° , -7.8° )
- Neutrino energy estimation:  $220^{+570}_{-110}$  PeV ( $1\sigma$ )
- No clear counterpart identified
- Corresponding  $E^{-2}$  flux:  $5.8^{+10.1}_{-3.7} \times 10^{-8}$  GeV cm<sup>-2</sup> s<sup>-1</sup> sr<sup>-1</sup> (90%)
- Tension of  $2.2\sigma$ , around once in 70 years in ARCA21

# Conclusions

- Over 15% of the KM3NeT detector already operational.
- Completion expected within the decade.
- Performances are fastly catching up the state of the art.
- Excellent angular resolution and an unprecedented survey of the Southern sky.
- Exceptional event detected with unknown origin.
- **...exciting times ahead for neutrino astronomy!**

*"ARCA WWRS DU splash in the Mediterranean sea at the sunrise"  
winner of the KM2NeT 2024 picture contest  
Andrea Simonelli*

Thanks for  
your attention

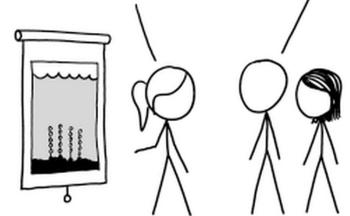


## KM3NET

THE KM3NET DEEP-WATER TELESCOPE  
DETECTS THE FLASHES OF CHERENKOV  
LIGHT FROM NEUTRINO INTERACTIONS.

HOW DO YOU KNOW YOU  
AREN'T JUST SEEING  
BIOLUMINESCENT FISH?

CHERENKOV RADIATION IS  
ONLY EMITTED WHEN THINGS  
EXCEED THE LOCAL SPEED  
OF LIGHT, SO IT CAN'T BE  
PRODUCED BY UNDER-C LIFE.



UNFORTUNATELY, KM3NET LED TO  
THE DISCOVERY OF THE PAULI  
ANGLERFISH, WHICH EMITS  
CHERENKOV RADIATION TO PREY ON  
NEUTRINO RESEARCHERS.



Neutrino Astronomy | Atmospheric neutrino oscillations | Dark matter & exotic searches

# KM3-230213A numbers summary

## Energy estimation summary

	←90%	←1σ	<b>E (PeV)</b>	1σ→	90%→
$E_{\mu}$	35	60	<b>120</b>	230	380
$E_{\nu}$	72	110	<b>220</b>	790	2600

## Background probability summary

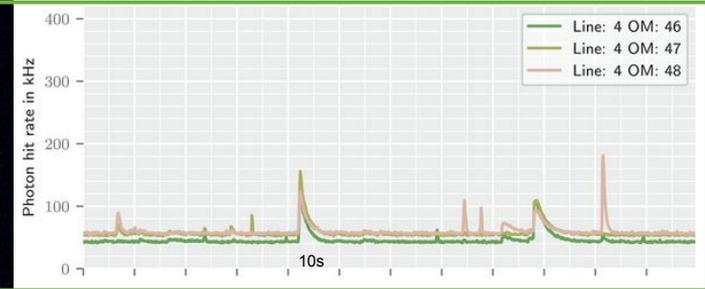
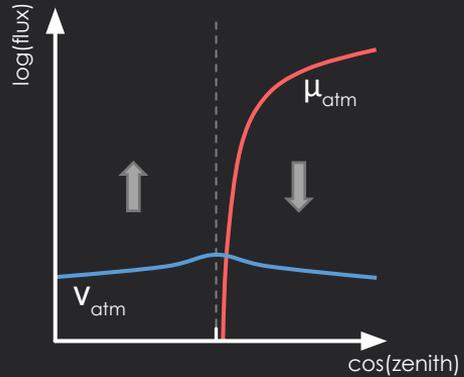
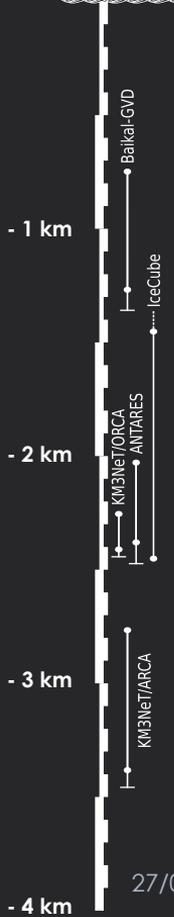
$P(\mu_{atm})$	<b>&gt;6σ</b>	10 <sup>-10</sup> ev/year for 100 PeV
		10 <sup>-9</sup> ev/year for 10 PeV
$P(\nu_{atm})$	<b>&gt;4σ</b>	1–5 x 10 <sup>-5</sup> ev/year for >100 PeV

## Angular estimation summary

( RA , dec )		( 94.3° , -7.8° )		
( az , el )		( 259.8° , 0.6° )		
ang. error	50%	<b>1σ</b>	90%	99%
	1.2°	<b>1.5°</b>	2.2°	3°
<u>From absolute pointing:</u>				
Moon shadow		0.24°		
Absolute orientation		<b>1°</b>		
<u>From track reconstruction:</u>		50%	90%	
100 PeV		0.12°	0.28°	
500 PeV		0.17°	0.38°	

# Backgrounds

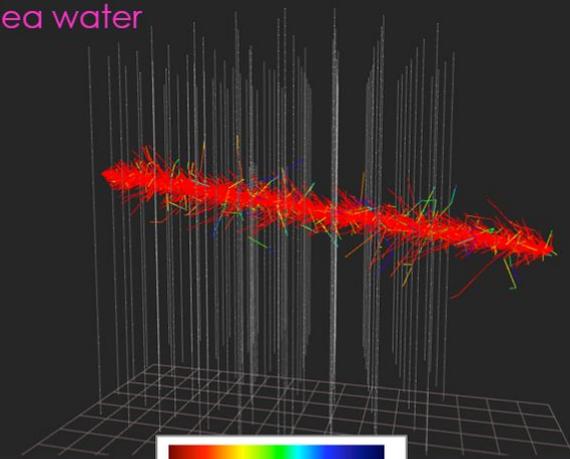
- **Atmospheric Muons:** downgoing muon tracks, from CR, depth dependent.
- **Atmospheric Neutrinos:** isotropic, soft energy spectrum neutrinos, from CR.
- **Light backgrounds in water:**
  - **$^{40}\text{K}$ :**  $\beta$  decay ( $\sim 1.3$  MeV vs water  $\check{C}_{th} \sim 0.8$  MeV) of  $^{40}\text{K}$  (120 ppm K) from **KCl**, 2,5% in seawater salt.
  - **Bioluminescence:** long light events (seconds), seasonal component.



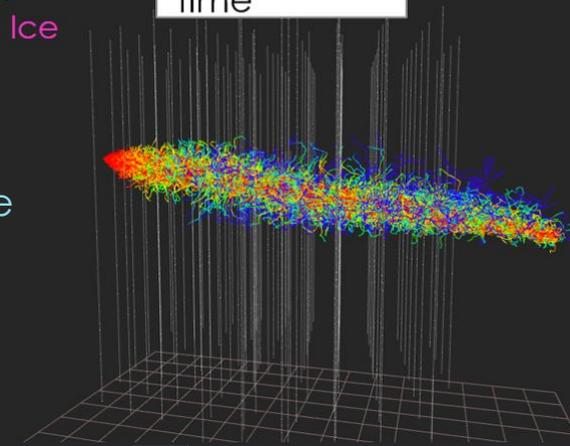
# Event reconstruction

- Event topology fits over all detected photons (hits)
- Impact from optical properties:
  - **Absorption** length:
    - **water**, blue(UV): 60(26) m (ANTARES)
    - **ice**, top[dust](bottom): 40[20]300 m (IceCube)
  - **Scattering** length:
    - **water**, blue(UV): 265(122) m (ANTARES)
    - **ice**: 5-50 m, depth dep., anisotropies,... complex → ice model (IceCube)
- **water** → optimal pointing accuracy | **ice** → better calorimeter
- Light speed events: positioning + time relative calibrations critical
  - Time: ~1 ns; beacons, muons, electronics (e.g. WhiteRabbit)
  - Positioning: ~10 cm; real time for **water** (acoustic), fixed for ice
- Energy resolution: energy scale calibration
- ML revolution: improving reconstruction, direction and energy
- Challenging!

Sea water



Ice



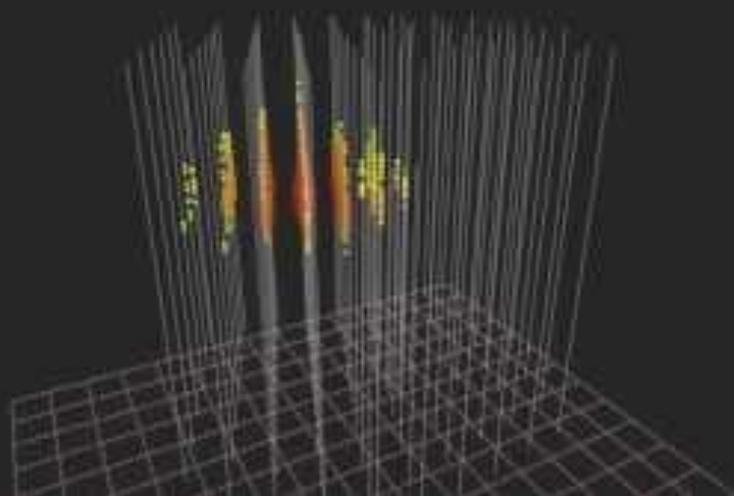


**TRACK**  
 $\nu_{\mu/\tau \rightarrow \mu} \text{-CC}$

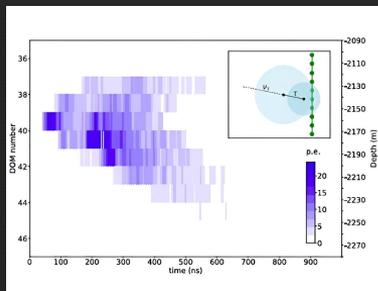


<https://www.youtube.com/shorts/B7cbc7OHCbM>

**SHOWER**  
 $\nu_{e/\mu/\tau} \text{-NC} +$   
 $\nu_{e/\tau \rightarrow e} \text{-CC}$



<https://www.youtube.com/watch?v=v6cmY-ibgys>



**DOUBLE BANG**  
 $\nu_{\tau} \text{-CC}$

IceCube tau neutrino candidates



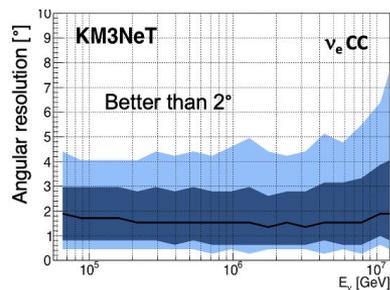
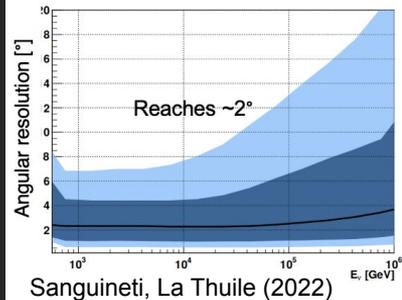
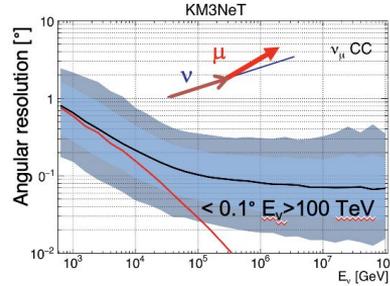
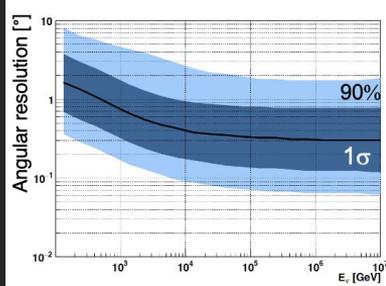
# Angular resolution

- Depends strongly on energy (and data quality selection)
- Much better for tracks than for showers... also better in water than in ice
- Typically subdegree median ang. res. on tracks above TeV; not in showers, which can worsen with energy
- GNN techniques under developing

ANTARES

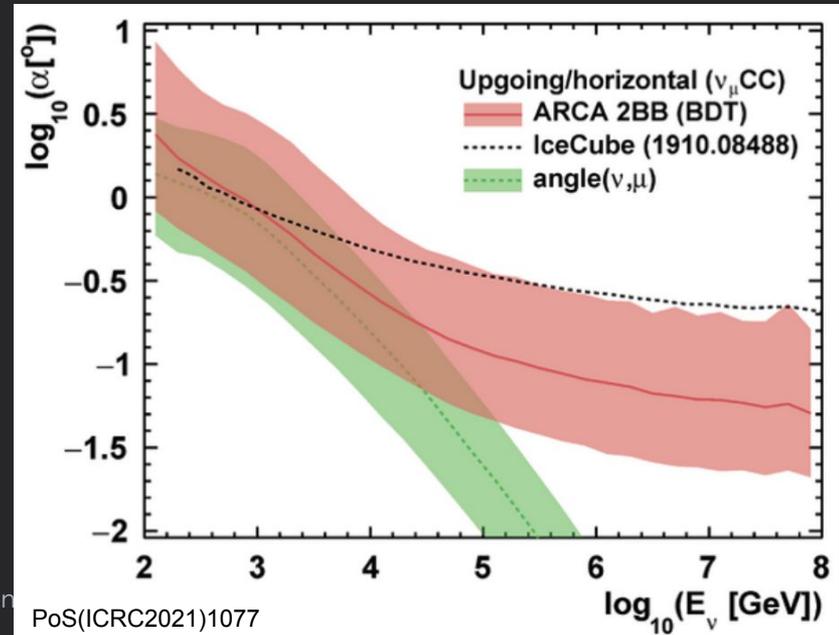
KM3NeT/ARCA

KM3NeT/ARCA vs IceCube



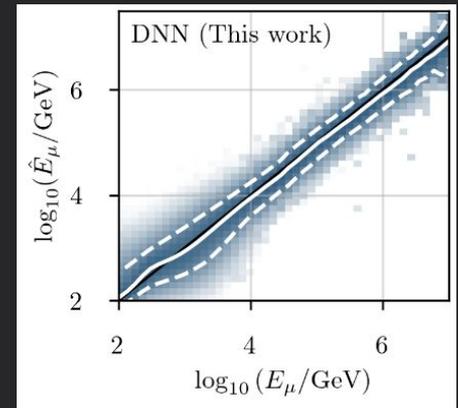
Energy resolution  $\sim 30\%$

Energy resolution  $< 5\%$

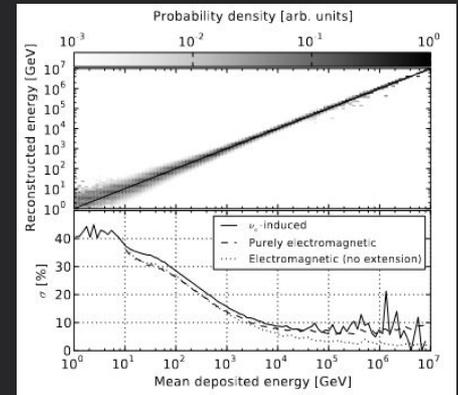


# Energy resolution

- Lower limits on **tracks**:
  - Which energy? Muon energy? Neutrino energy? Deposited energy?
  - Tracks only partially contained in the detector  $x$
- Better for **showers**:
  - Deposited energy
  - Energy dependent:
    - lowest energies vs detector density
    - highest energies vs detector size
- $\sim 30\% / \sim 5\%$  tracks/showers, sometimes better
- Analyses rely on energy estimators

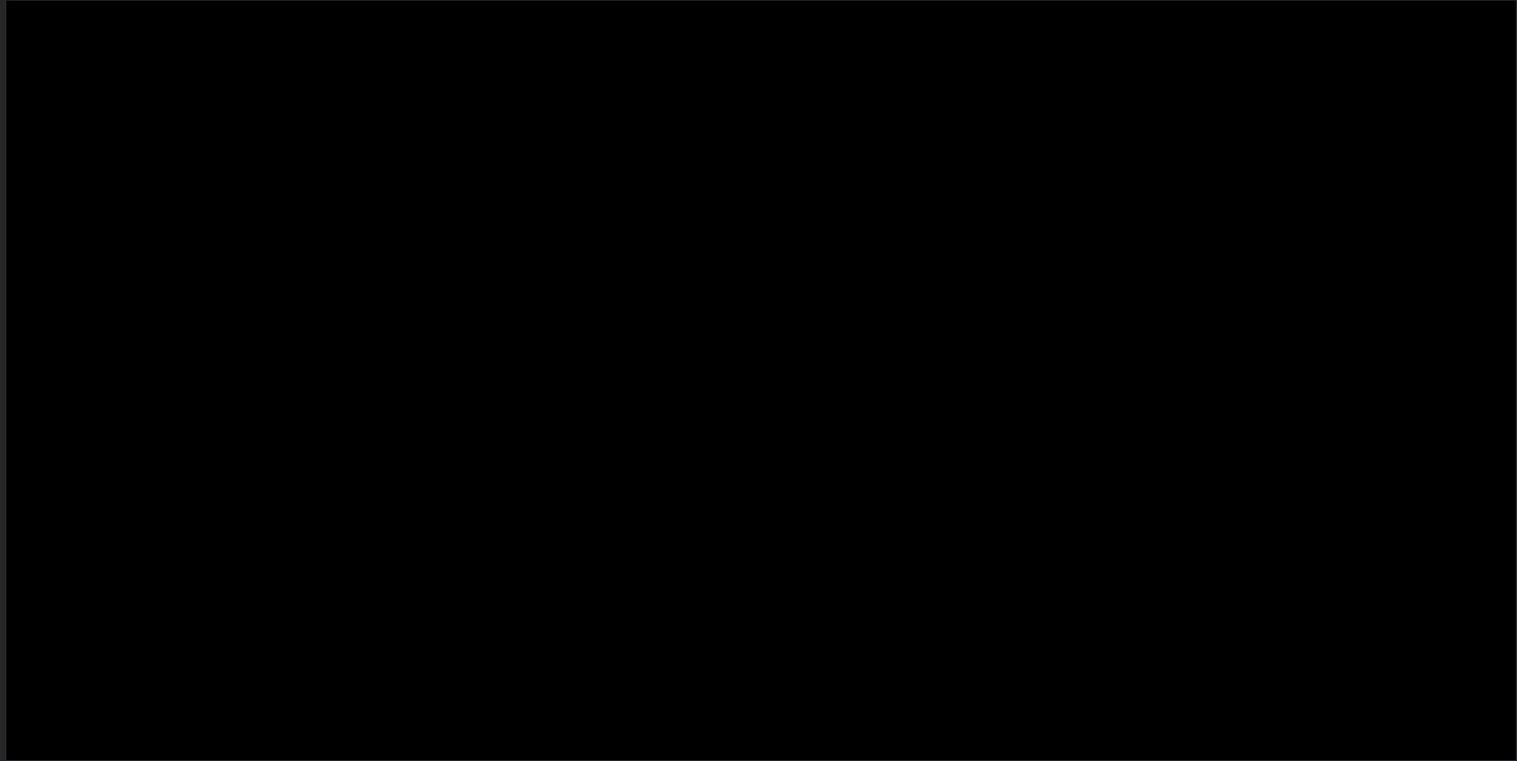


Muon energy entering IceCube  
Science 378 (2022) 6619 [sup. mat.]



Cascade deposited energy in  
IceCube, true vs reconstructed  
JINST 9 (2014), P03009

# Skymaps of selected events



<https://antares.in2p3.fr/data/>  
<https://icecube.wisc.edu/science/data-releases/>