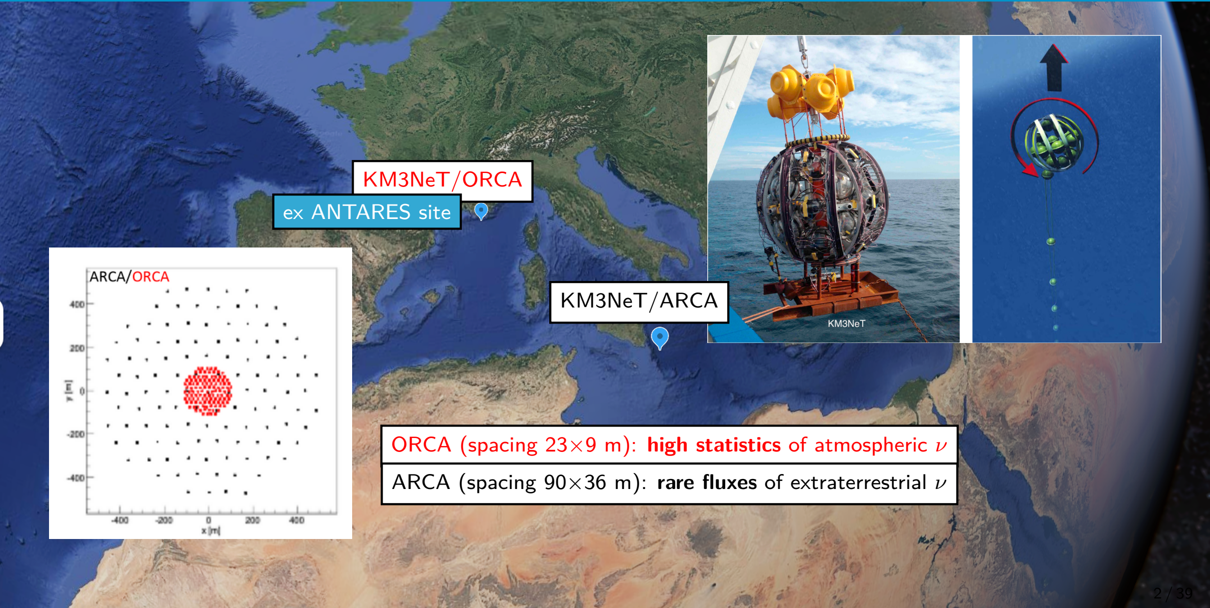
KM3NeT: results and future with cosmic neutrinos

Sara Rebecca Gozzini (IFIC, CSIC-UV) for the KM3NeT Collaboration

RENATA 2025

September 22, 2025

KM3NeT: layout [J.Phys.G:Nucl.Part.Phys.**43** 084001 (2016)]



ORCA (spacing 23×9 m): **high statistics** of atmospheric ν	
ARCA (spacing 90×36 m): **rare fluxes** of extraterrestrial ν	

France
- CNRS Nucléaire et Particules
- Astroparticle and Cosmology Laboratory, Université Paris Cité, CNRS
- Centre for Particle Physics of Marseille, Aix-Marseille Université, CNRS
- Laboratoire d'Astrophysique de Marseille
- Mediterranean Institute of Oceanography, CNRS Terre et Univers, Marseille
- Université de Toulon
- Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, CNRS
- Subatech, IMT Atlantique, Nantes Université
- Laboratoire Univers et Particules de Montpellier
- Laboratoire de Physique Corpusculaire de Caen, Université de Caen, CNRS

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- Université Libre de Bruxelles

The Netherlands
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- Universiteit van Amsterdam
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- NIOZ, Texel
- TNO, Technical Sciences, Delft

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- Max-Planck-Institut für Radioastronomie, Bonn
- Universität Würzburg
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- INFN Sezione di Firenze, Università di Firenze
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- INFN Sezione di Napoli, Università della Campania L. Vanvitelli, Università di Napoli Federico II
- INFN Sezione di Roma, Sapienza Università di Roma
- INFN Sezione di Bari, Politecnico di Bari
- INFN Sezione di Bologna, Università di Bologna
- INFN Sezione di Padova, Università di Padova
- Università di Salerno, INFN Gruppo Collegato di Salerno

Slovakia
- Univerzita Komenského v Bratislave
- Slovenská akadémia vied, Kosice

Czech Republic
- Czech Technical University in Prague, Institute of Experimental and Applied Physics

Poland
- AGH University of Krakow
- NCBJ - National Centre for Nuclear Research, Warsaw
- Nicolaus Copernicus Astronomical Center, Particle Astrophysics Science and Technology Centre, Warsaw

Romania
- Institute of Space Science - INFLPR Subsidiary, Magurele

Greece
- Institute of Nuclear and Particle Physics, NCSR Demokritos, Athens
- National and Kapodistrian University of Athens

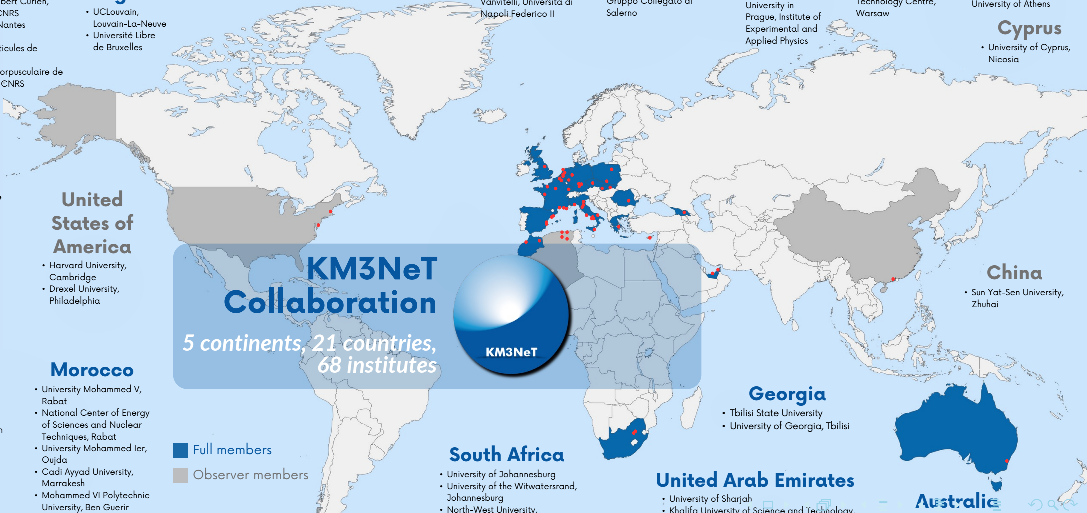
Cyprus
- University of Cyprus, Nicosia

Spain
- Consejo Superior de Investigaciones Científicas (CSIC)
- Instituto de Física Corpuscular, Universitat de València, CSIC
- Universitat Politècnica de València, IGIC, Gandia, València
- Universidad de Granada
- Centro Oceanográfico de Murcia (IEO-CSIC)
- Laboratori d'Aplicacions Bioacústiques, Universitat Politècnica de Catalunya, Vilanova i la Geltrú
- Instituto de Ciencias del Mar, CSIC, Barcelona

United States of America
- Harvard University, Cambridge
- Drexel University, Philadelphia

KM3NeT Collaboration

5 continents, 21 countries, 68 institutes



China
- Sun Yat-Sen University, Zhuhai

Algeria
- Center of Research in Astronomy, Astrophysics, and Geophysics, Bouzaréah
- Université Badji Mokhtar, Annaba
- University of Constantine
- Mohamed Boudiaf University, M'sila

Morocco
- University Mohammed V, Rabat
- National Center of Energy of Sciences and Nuclear Techniques, Rabat
- University Mohammed Ier, Oujda
- Cadi Ayyad University, Marrakesh
- Mohammed VI Polytechnic University, Ben Guerir

Georgia
- Tbilisi State University
- University of Georgia, Tbilisi

South Africa
- University of Johannesburg
- University of the Witwatersrand, Johannesburg
- North-West University, Potchefstroom

United Arab Emirates
- University of Sharjah
- Khalifa University of Science and Technology, Abu Dhabi

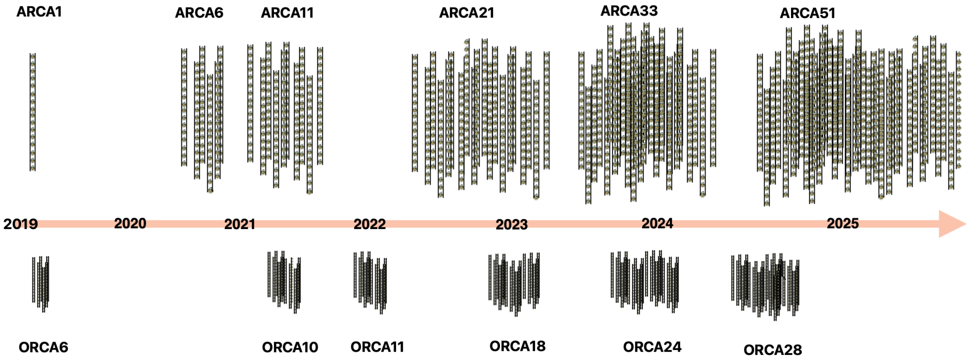
Australia
- Western Sydney University

KM3NeT AISBL (non-profit organisation)

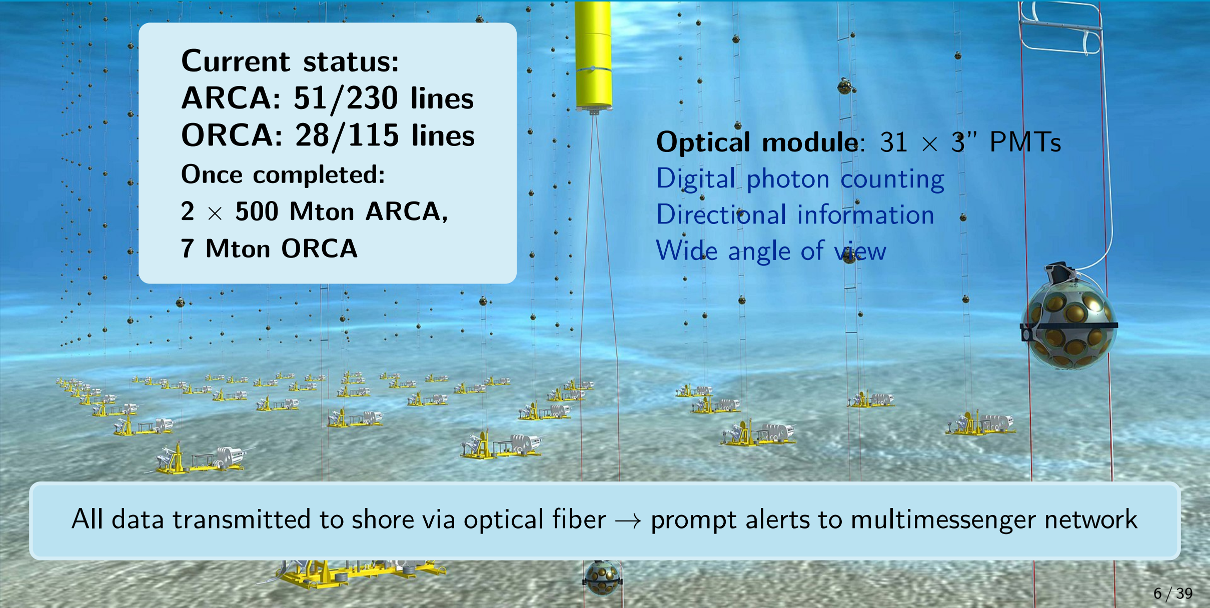
KM3NeT has recently become an Association Internationale Sans But Lucratif (AISBL), with University of Valencia as one of its five members. This will help for a more efficient organization for construction, installation, operation, maintenance, scientific exploitation, and decommissioning of the infrastructure. It is also a requirement to become an ESFRI landmark. The founding members are CNRS (France), INPP/NCSRD (Greece), University of Valencia (Spain), INFN (Italy) and NWO-I (the Netherlands). Other members expected to join soon.

https://www.km3net.org/km3net-aisbl-is-born/

KM3NeT: building roadmap



KM3NeT: layout

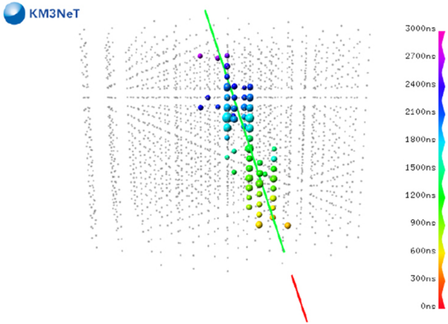


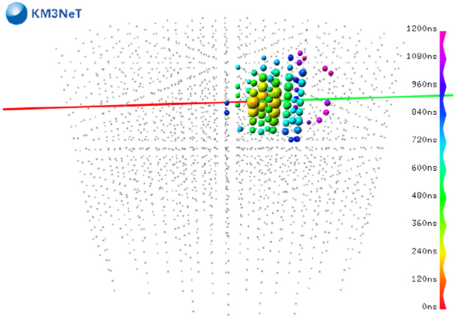
Current status:
ARCA: 51/230 lines
ORCA: 28/115 lines
Once completed:
2 × 500 Mton ARCA,
7 Mton ORCA

Optical module: 31 × 3" PMTs
Digital photon counting
Directional information
Wide angle of view

All data transmitted to shore via optical fiber → prompt alerts to multimessenger network

Performance: pointing





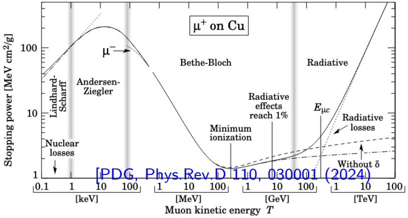
KM3NeT reconstructs two classes of events:

Tracks: predominantly $\nu_\mu CC$; angular resolution down to 0.1° at 1 PeV - fly-through

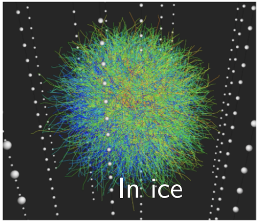
Showers: predominantly ν_e CC or any NC; angular resolution 1° at 1 PeV - contained

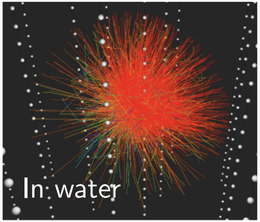
Performance: particle identification

Example: 1 GeV muon leaves a track of a few metres in water. ORCA granularity: 23×9 m



[PDG, Phys.Rev.D 110, 030001 (2024)]



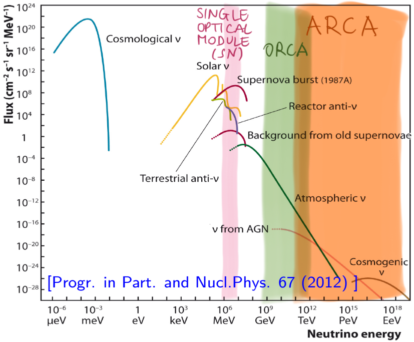


Simulation of light from a 10 TeV cascade in ice (left) and water (right).

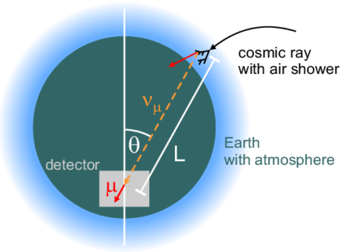
Larger scattering length: direct photons $\rightarrow$ better **pointing** and **particle identification**.

Neutrino astronomy *in the making*: experimental challenge

Preserve source information thanks to very weak interaction: large enough detector volume + a good filter (the Earth). Astrophysical ν: atmospheric ν: atmospheric μ = 1:10^4 :10^{10}.



[Progr. in Part. and Nucl.Phys. 67 (2012)]



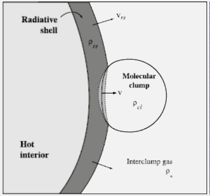
[Pic. credits: J Coelho]

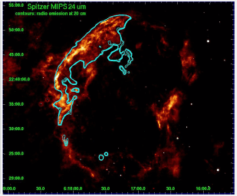
The neutrino-gamma connection: hadron acceleration

All sites where proton or nuclei are accelerated radiate γ and ν

1. $pN \rightarrow \pi^0, \pi^\pm, \eta^0 + X$ like in SNR with molecular clouds
2. $p\gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$ or $p + \pi^0 ... + X$ like in jets of active galactic nuclei

In Galactic sources surrounded by clouds, with steady emission: $p - N$ of protons on molecular gas

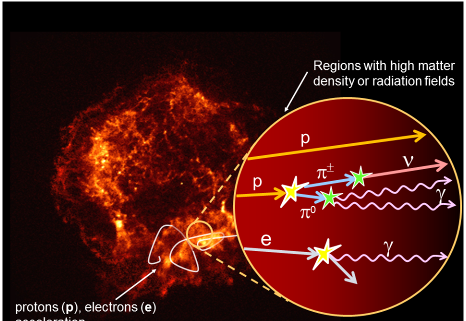




In extragalactic sources surrounded by high photon density, exhibiting flares: $p - \gamma$ of protons on AGN jets

Physics case 1: extraterrestrial neutrinos

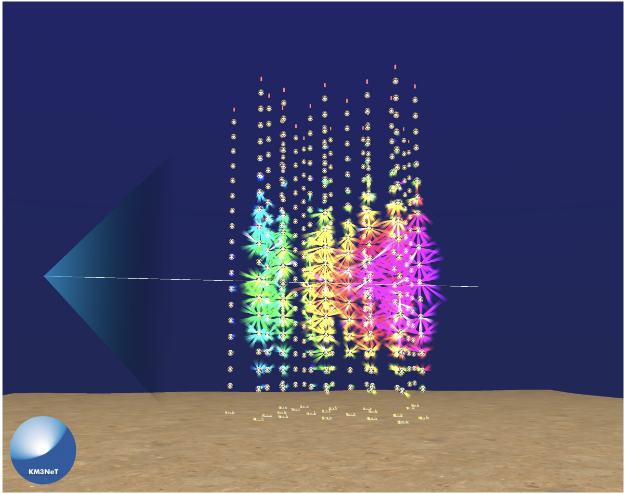
High-energy cosmic ν are expected from collisions yielding particles such as $\pi^{\pm}$ and $\mu^{\pm}$, through *pp* and $p\gamma$ scattering, taking place in different environments, steady or with flares



[Fig. from Universe 2020, 6(2), 30]

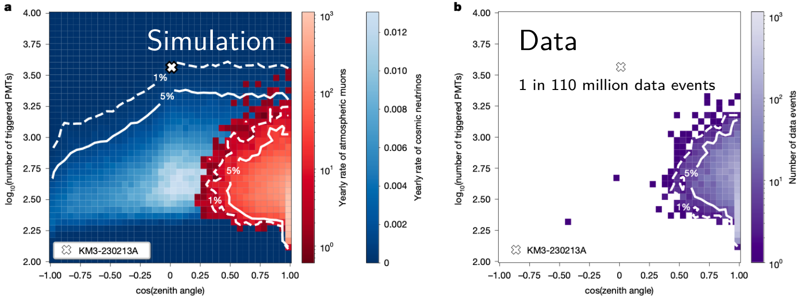
- Neutrino astronomy: backtracking sources
  1. As a **correlation** with underlying catalogue
     1. Jets of active galactic nuclei (AGNs)
     2. Starburst galaxies, star-forming galaxies
     3. Expanding front of supernova remnants
     4. Gamma-ray bursts
     5. IceCube HE events
  2. As **autocorrelation** or clusters in space (-time)
- Search for a diffuse excess and measurement of its energy spectrum. Accelerator properties.
- Search for prompt multimessenger coincidences

Observation of an ultra-high-energy cosmic ν with KM3NeT

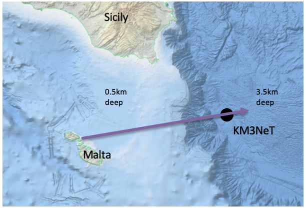


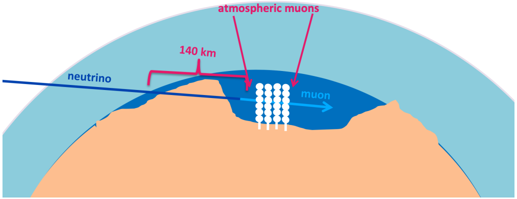
Observation of an ultra-high-energy cosmic ν with KM3NeT

- Observed with 21-line configuration of KM3NeT/ARCA **[Nature 638, 376–382 (2025)]**
- Horizontally crossing the detector traversing continental shelf: not an atmospheric muon
- 35% of the detector (3672 photomultipliers) triggered

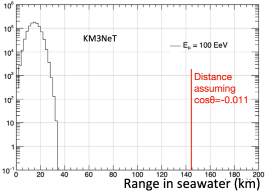


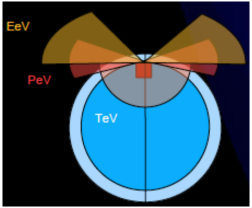
KM3-230213A: horizontal muon from ν_μ



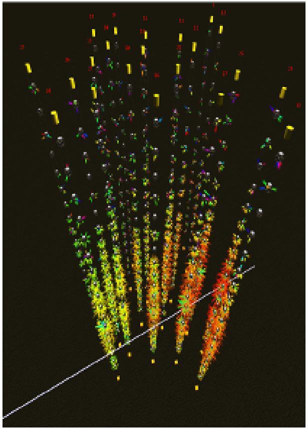


Actual water equivalent distance even larger due to continental shelf $\rightarrow$ not an atmospheric μ.



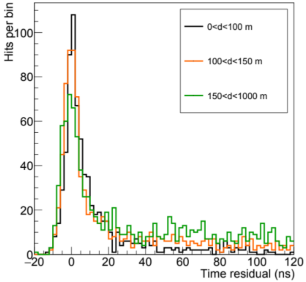


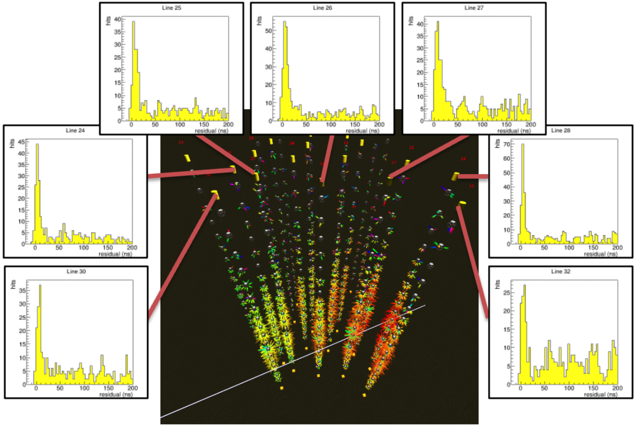
Observation of an ultra-high-energy cosmic ν with KM3NeT



Reconstruction of the muon track

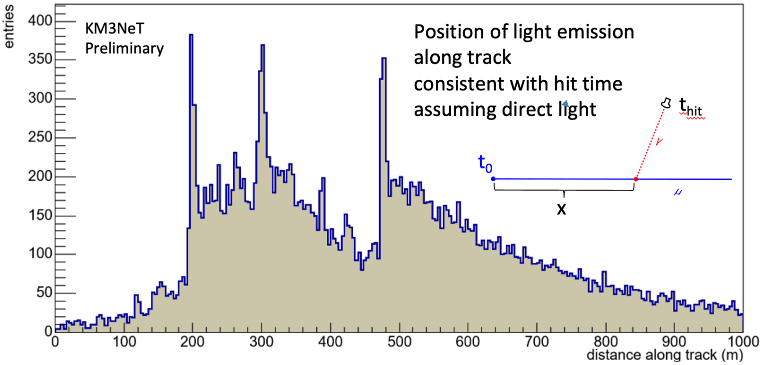
Arrival time residuals of photons at photomultipliers well understood.





Rich detail of the muon track

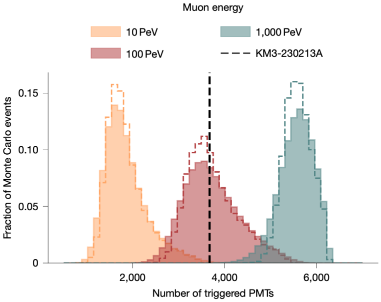
Light profile consistent with at least 3 large energy depositions along the muon track: characteristic of stochastic losses of very high energy muons.

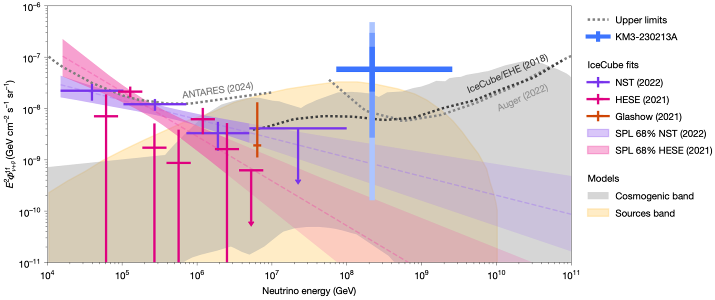


Ultra-high-energy cosmic ν with KM3NeT: energy

Muon energy: 120^{+110}_{-60} PeV, based on Monte Carlo simulation. The measured muon energy serves as a lower limit on the incoming neutrino energy.

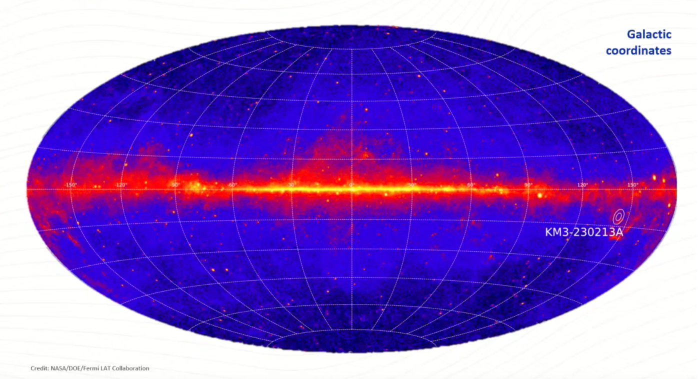
Neutrino energy: 220^{+570}_{-100} PeV, 110–790 PeV (68%), 72 PeV–2.6 EeV (90%), under the assumption of a E^{-2} spectrum.





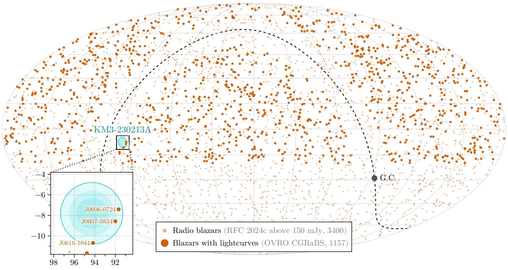
Ultra-high-energy cosmic ν with KM3NeT: arrival direction

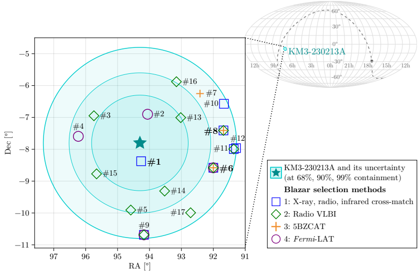
Celestial coordinates: $RA = 94.3°$, $dec = -7.8°$, with $1.5°$ uncertainty. Region-of-interest (cut/count) based searches will improve significance with more restrictive uncertainty radius.



KM3-230213A: search for blazar counterparts

Candidate blazars selected through multi-wavelength properties with dedicated proposals. (1) radio flare on neutrino arrival time (pre-trial $p = 0.26\%$); (2) rising trend in the X-ray flux in a one-year window around the event; (3) γ-ray flare. Correlation non conclusive.

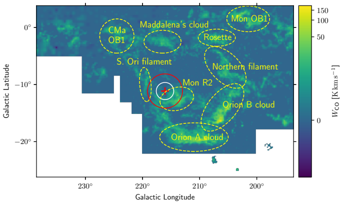




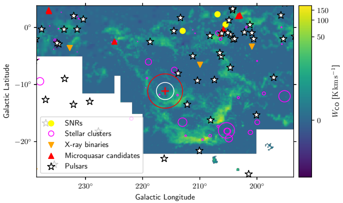
[https://arxiv.org/abs/2502.08484]

KM3-230213A: Search for Galactic counterparts

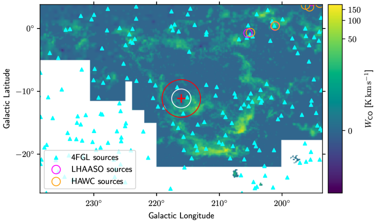
Lack of a nearby potential Galactic particle accelerator in the direction of the event. Low fluxes of the Galactic diffuse emission at event's energies. **Unlikely of Galactic origin**.



Map of CO clouds



Known potential CR accelerators

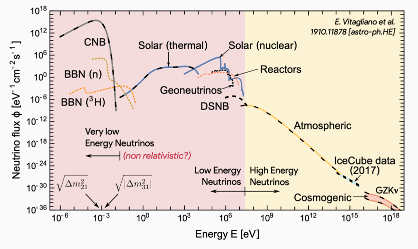


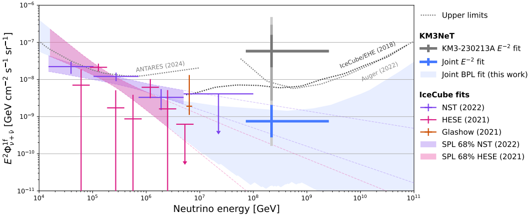
γ-ray sources from 4FGL-DR4 3HWC, LHAASO.

[https://arxiv.org/pdf/2502.08387]

Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

Null observations above tens of PeV from the IceCube and Pierre Auger observatories. Light tension with the standard cosmogenic neutrino predictions. Observation can be reconciled with limits by Pierre Auger and Telescope Array by extending up to a redshift of $z \simeq 6$ and assuming a subdominant fraction of protons in UHE cosmic-ray flux.



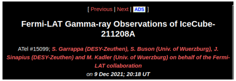


[https://arxiv.org/pdf/2502.08173] [https://arxiv.org/abs/2502.08508]

Flares, transients and other sources with time variability (GRBs, gravitational waves, SN)

Example: flares caused by hadronic emission on top of quiescent state → Prompt alerting system associated with rapid online analysis and pointing directions for telescopes

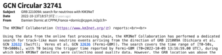
1. SNEWS pipeline active for real-time analysis
2. KM3NeT replaces ANTARES in follow-up of alerts (ATel, GCN via AMON)


[Previous | Next | ADS]

Fermi-LAT Gamma-ray Observations of IceCube-211208A

ATel #15099; *S. Garrappa (DESY-Zeuthen), S. Buson (Univ. of Wuerzburg), J. Sinapius (DESY-Zeuthen) and M. Kadler (Univ. of Wuerzburg) on behalf of the Fermi-LAT collaboration*

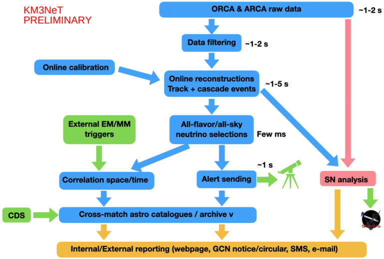
on 9 Dec 2021; 20:18 UT


GCN Circular 32741

Subject GRB 221009A: search for neutrinos with KM3NeT
Date 2022-10-13T18:57:37Z (2 years ago)
From Damien Dornic at CPPM,France <dornic@cppm.in2p3.fr>

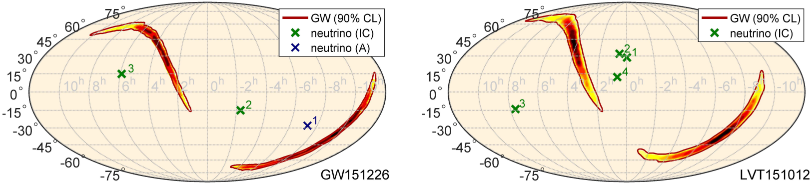
The KM3NeT Collaboration (https://www.km3net.org/) reports:

Using the data from the online fast processing chain, the KM3NeT Collaboration has performed a dedicated search for track-like muon neutrino events arriving from the direction of GRB 221009A (Dichiara et al. GCN 32632 (Swift); Veres et al. GCN 32636 (Fermi-GBM)). The search covers the time range of [T0-50s, T0+5000s], with T0 being the trigger time reported by Fermi-GBM (T0=2022-10-09 13:16:59.00 UTC), during which both KM3NeT detectors were collecting good quality data. However, the GRB location was above the



Neutrino coincidence with gravitational waves

Multi-messenger alert network for flares, transients and other sources with time variability (GRBs, gravitational waves, supernovae)



Offline analysis of event rate alerts in O3 run of VIRGO/LIGO - 190 of 900 alerts were inside the field of view of KM3NeT. Real-time follow-up of O4 alerts.

Produced in stellar core collapse at the end of stellar evolution like SN1987A. Real-time search for simoultaneous rate raise in DOMs [PoS(ICRC2023)1160]

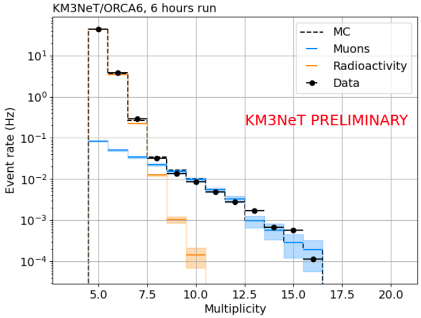
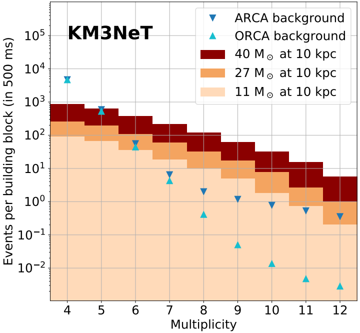


Figure: Left: image of a DOM with 4 out of the 31 PMTs highlighted. Right: Multiplicity distribution for a 6 hour period of ORCA6 (full black) compared to simulations.

Produced in stellar core collapse at the end of stellar evolution like SN1987A. Real-time search for simoultaneous rate raise in DOMs [PoS(ICRC2023)1160]



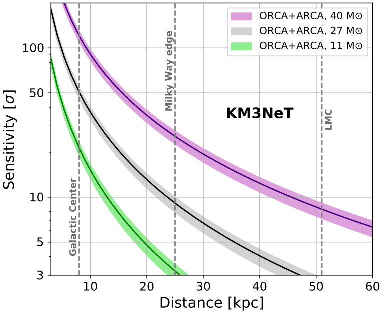
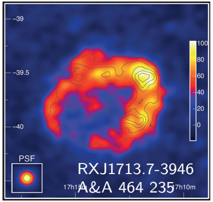


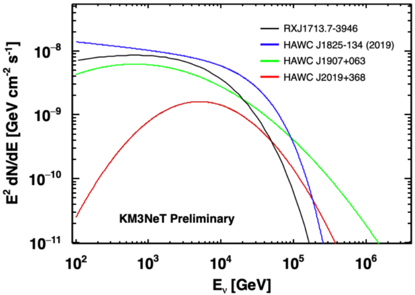
Figure: Left: SN events expected from 3 simulated progenitors at ORCA and ARCA as a function of different multiplicity values compared with BG rates. Right: Sensitivity as a function of distance.

Sensitivity to strongest Galactic sources

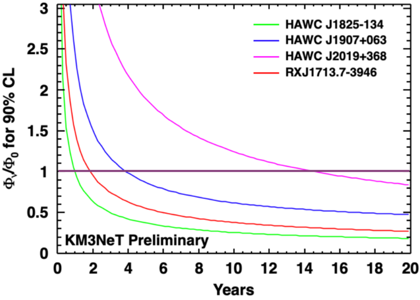
In hypothesis of hadronic emission, computing ν flux from γ-ray flux, several **extended Galactic sources** will be observable in a few years of operation.



Example of γ-ray emission as seen by H.E.S.S.



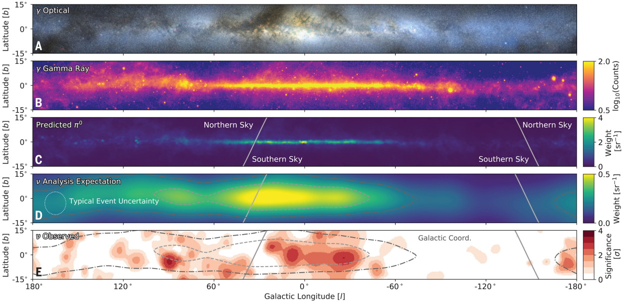
Expected ν fluxes (assumed 100% hadronic scenario)

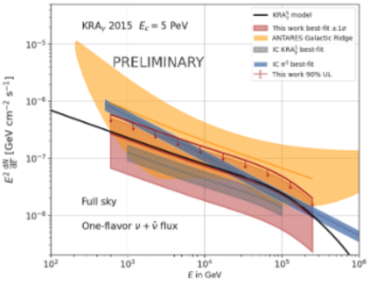


Sensitivity at 90% CL as a function of the observation time

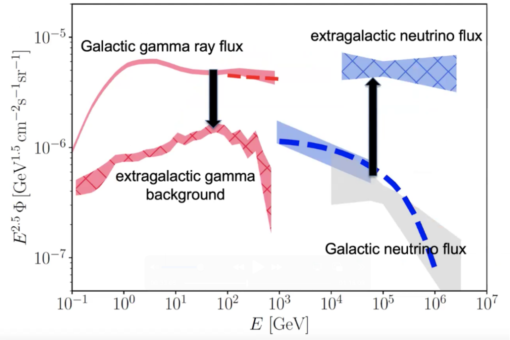
Galactic diffuse emission

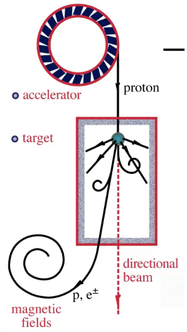
Characterize and identify sources with KM3NeT in model-independent way (ON/OFF method) or template fit (from γ rays, KRA, CRINGE). Small excess seen by ANTARES with $1.5 - 1.8\ \sigma$. IceCube: only template method (Pole does not rotate)





Galactic diffuse emission: message





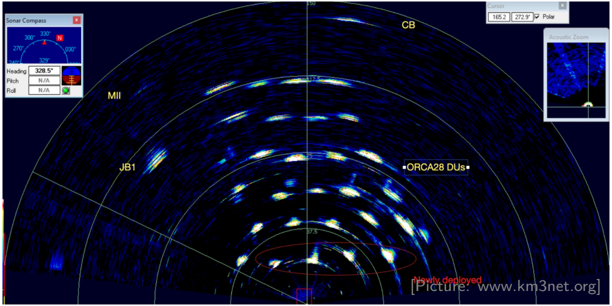
Neutrino astronomy is particle physics at all effects! Moreover

> *Powerful accelerators operate in other galaxies that do not exist in our own.*

Physics case 2: fundamental neutrino properties

Oscillations, mass ordering and related observables

Flavour-related observables require particle identification in detector (e, μ, τ lepton?). Ideal region for search is GeV and just above, at the first disappearance peak.

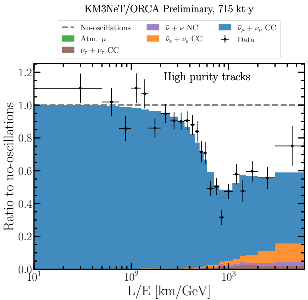


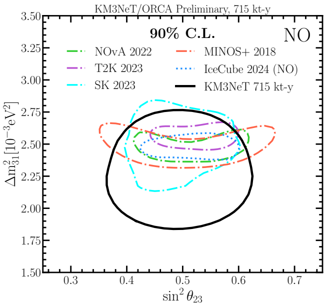
[Picture: www.km3net.org]

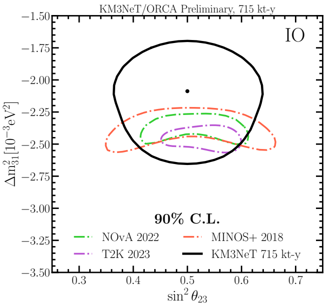
Measurement of atmospheric oscillation parameters with KM3NeT

Oscillations are seen in KM3NeT/ORCA through ν_μ **disappearance** with significance $> 6\sigma$

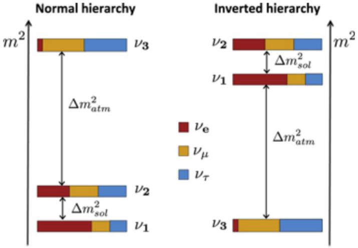
- Data set: 715 kton-years (6+10+11 detector lines). 1.6 Mton-y of data awaiting.
- Best fit: $\sin^2\theta_{23} = 0.50^{+0.07}_{-0.07}$ $\Delta m^2_{31} = -2.09^{+0.17}_{-0.21} \cdot 10^{-3}\text{eV}^2$.
- Data display a slight preference for inverted ordering.







Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO).



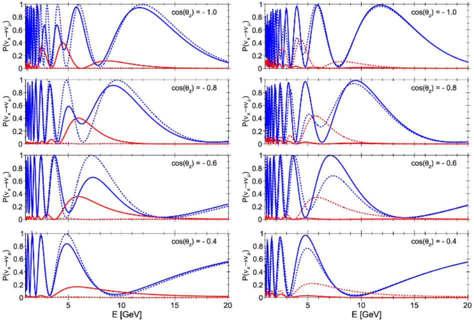
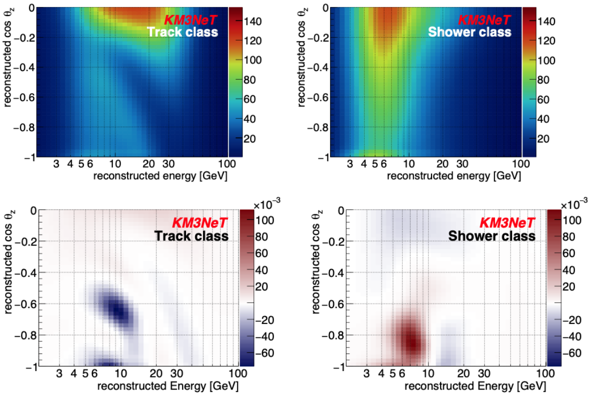


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

Neutrino mass ordering

Matter resonance at 5 GeV affects: ν if normal ordering (NO), $\bar{\nu}$ if inverted ordering (IO). Sensitivity due to ν-$\bar{\nu}$ asymmetry in flux and cross section. Both μ- and e-channels contribute.



Expected sensitivity: number of expected events with normal/inverted hierarchy $(N_{IH} - N_{NH})/N_{NH}$

and relative χ^2. Left: muons; right: electrons. Electron channel is more robust against detector resolution.

Indirect searches for *new physics* signatures

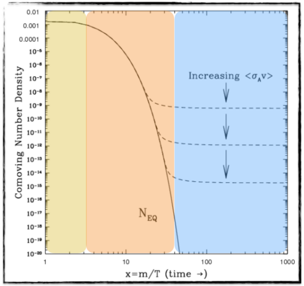
Neutrino telescopes are versatile instruments!

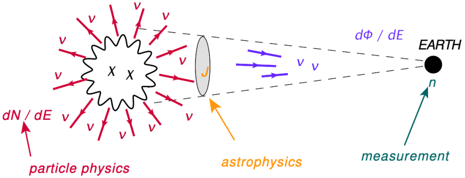
1. Indirect dark matter searches (rather unconstrained par. space, both ORCA and ARCA)
2. Effects that alter oscillations of **atmospheric neutrinos**, which are measured with **high statistics** (ORCA)
3. At TeV-PeV energies: limits from cosmic neutrinos: effects that **scale with energy** or **accumulate along large distances** (ARCA)

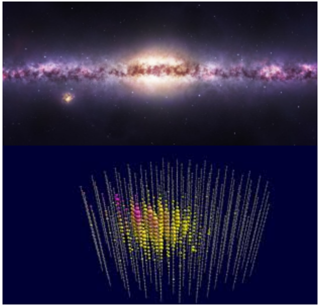
Searches for new physics signatures target both cosmic and atmospheric neutrinos

Dark matter as a thermal relic

Particularly symptomatic candidates (WIMPs: correct relic density in a freeze-out scenario) give rise to sizeable fluxes of high-energy ν. Overdensity regions of dark matter in Galactic haloes. Characterize energy distribution and source morphology.



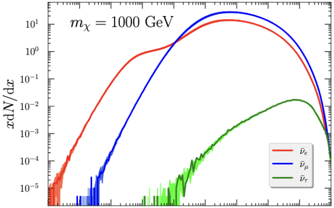


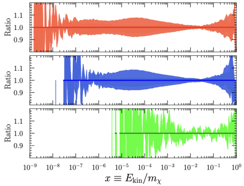


The extra trouble with indirect searches: external input

Indirect searches are unavoidably affected by **large uncertainties**. This also means that these searches alone can hardly make a univocal claim for detection.

(I) Energy feature

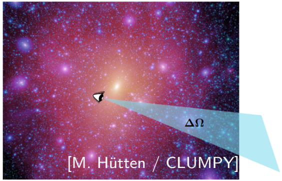




$x = E_{kin}/m_\chi$

Affected both by energy rec. of the detector (20% – 5%) and by theoretical uncertainties (10% – 30%) mostly on hadronization model [JCAP03(2024)035]

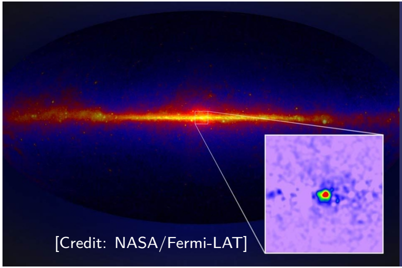
(II) Ambient

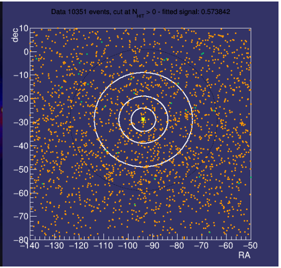


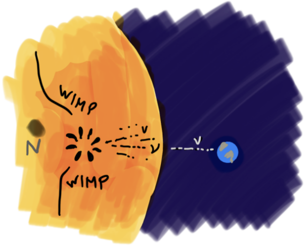
Dominated by astrophysical input for modelling haloes

Indirect dark matter searches with ANTARES and KM3NeT

Search for a signal of neutrinos from the annihilation of WIMP dark matter in the Galactic Centre and the Sun, using maximum likelihood algorithm.

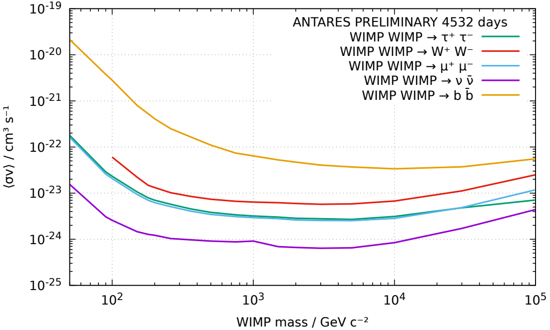


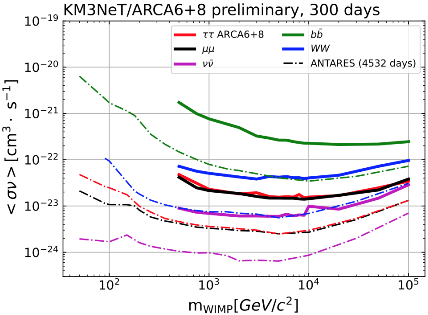




Indirect dark matter searches with ANTARES and KM3NeT

Galactic Centre visible for about 70% of the time in regular data taking mode, using the Earth as a filter. Data from ANTARES (2007 to 2022) and partial configuration of KM3NeT/ARCA is found consistent with background for all combinations of WIMP parameters **[Phys. Lett. B 805 (2020)] [JCAP03(2025)058]**





Conclusions

KM3NeT has recorded 715 kton-year (ORCA) and 332 days (ARCA) of **high-quality data**

- Rare UHE event observed with E = 220 PeV, likely extragalactic origin, however no conclusive evidence of candidate source associated
- Multi-messenger program ongoing: real-time monitoring of astrophysical transient, IceCube neutrinos, gravitational waves
- Flavour oscillations measured through ν_μ disappearance with more than 6σ
- Indirect tests of physics beyond the Standard Model expectations through effects on oscillation probabilities, indirect dark matter searches

The most exciting phrase to hear in science [...] is not '*Eureka!*' but 'That's funny...' [Isaac Asimov]