Fleeting messengers: neutrinos in KM3NeT

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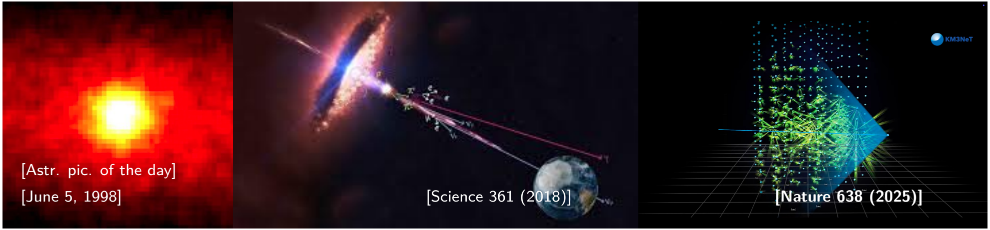
Foreword

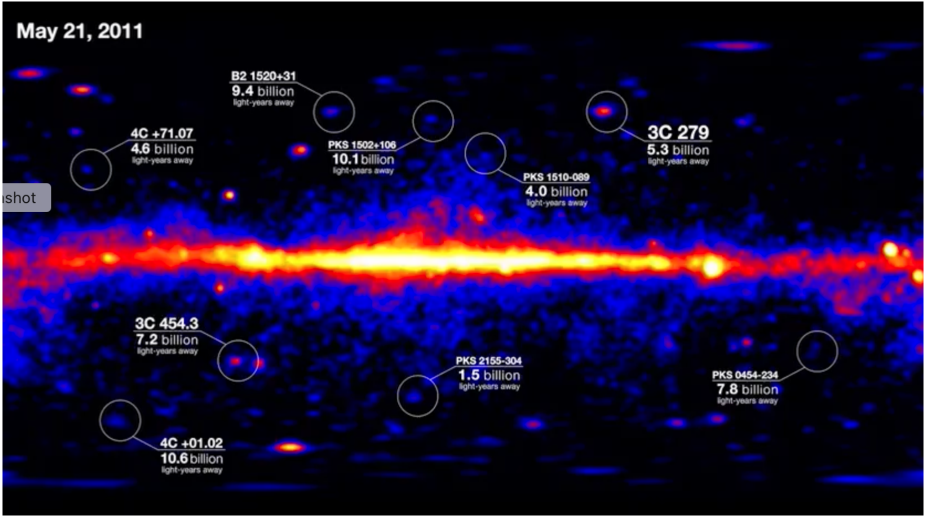
1987: A failed nuclear experiment accidentally gave birth to neutrino astronomy



A science in the making. Astrophysical neutrinos: atmospheric neutrinos: atmospheric muons $= 1{:}10^4 : 10^{10}$. If not for this, neutrinos are ideal for source backtracking.

Not only: ν oscillations were first observed with atmospheric and solar neutrinos at Cherenkov detectors.

Flares



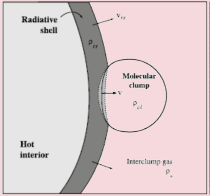
May 21, 2011
B2 1520+31
9.4 billion
light-years away
4C +71.07
4.6 billion
light-years away
PKS 1502+106
10.1 billion
light-years away
3C 279
5.3 billion
light-years away
PKS 1510-089
4.0 billion
light-years away
3C 454.3
7.2 billion
light-years away
PKS 2155-304
1.5 billion
light-years away
PKS 0454-234
7.8 billion
light-years away
4C +01.02
10.6 billion
light-years away

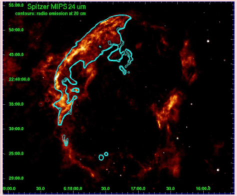
The neutrino-gamma-cosmic ray connection: hadron acceleration

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

1. $pN \to \pi^0, \pi^\pm, \eta^0 + X$ like in SNR with molecular clouds
2. $p\gamma \to \Delta^+ \to n + \pi^+$ 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**





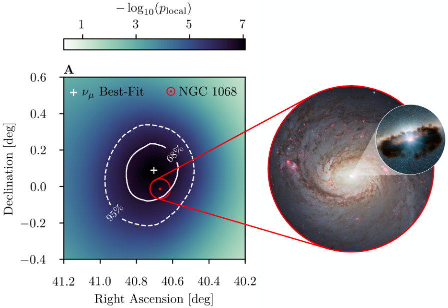
In extragalactic sources surrounded by high photon density, exhibiting flares:
$p - \gamma$ **of protons on AGN jets**

Flares, transients and other sources with ***time variability*** match suggestive scenario of hadronic emission on top of quiescent state (size of blob $\propto$ high state duration)

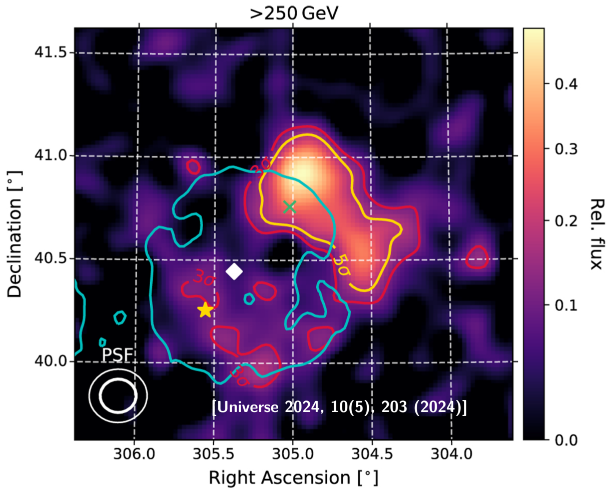
Prompt alerting system triggered by high significance perform rapid online analysis, reconstruct and pass pointing directions to telescopes.

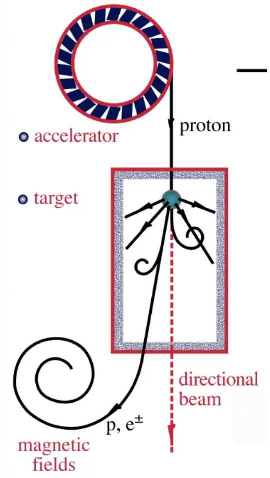
1. Leptonic acceleration-radiation: ν-less emission
2. Hadronic acceleration-radiation: $\gamma + \nu$

So catch $\nu \Rightarrow$ catch γ: find hadron. Double implication $\Leftarrow$? No: source could be obscured (NGC 1068); ν without electromagnetic counterpart. First ν association to steady source.



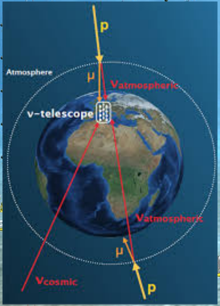
Neutrino astronomy is particle physics to all respects!

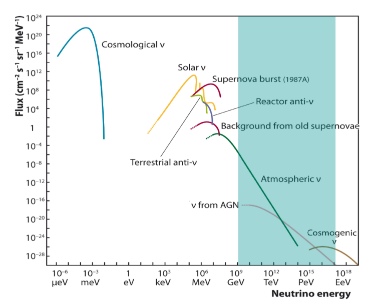




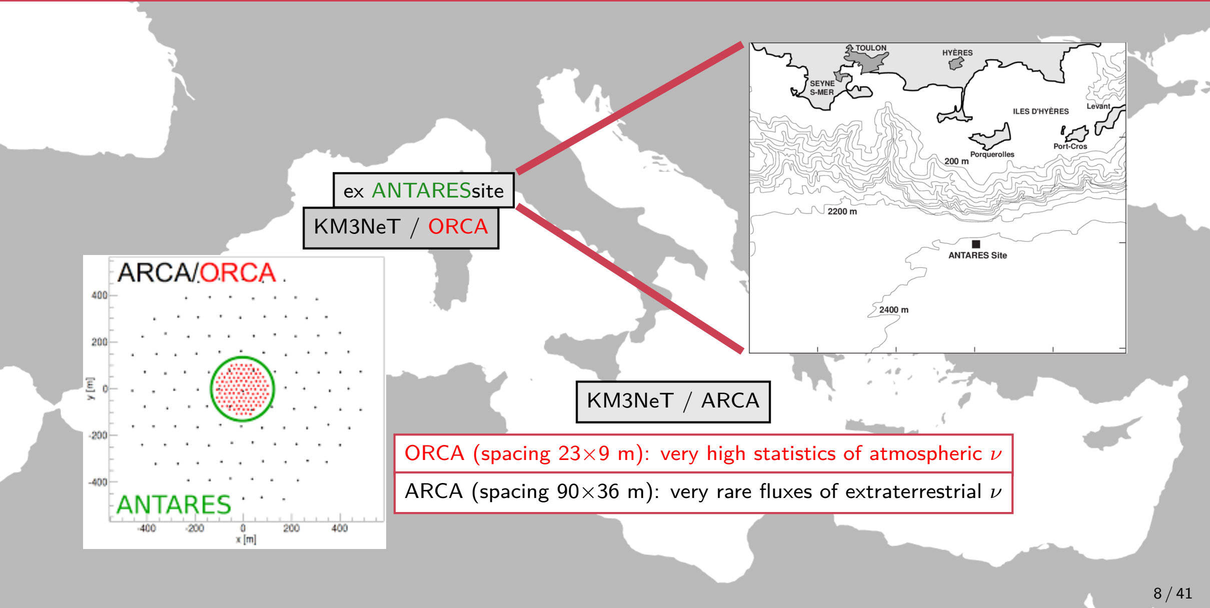
Very-large volume ν Cherenkov detectors

1. Faint signal rates, default 2π field of view, sub-degree angular resolution
2. Remotely operated, almost 100% duty cycle, one unique data set (no pointing)





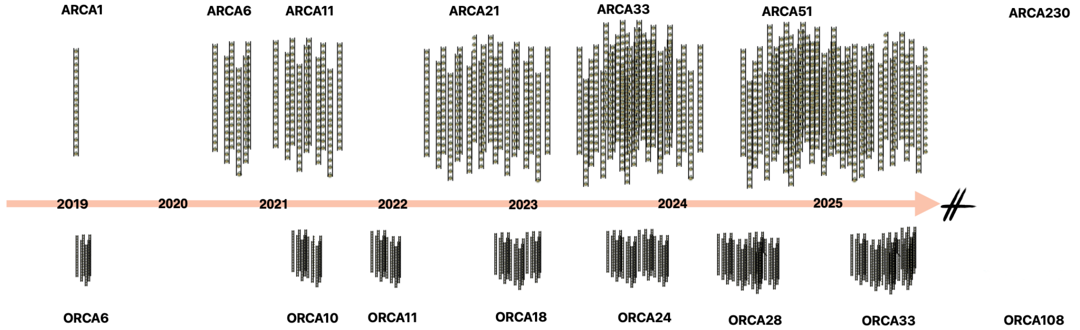
Neutrino detectors in the Mediterranean Sea



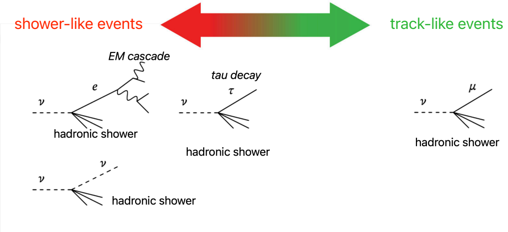
ORCA (spacing 23×9 m): very high statistics of atmospheric ν

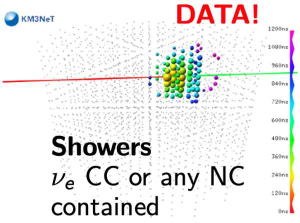
ARCA (spacing 90×36 m): very rare fluxes of extraterrestrial ν

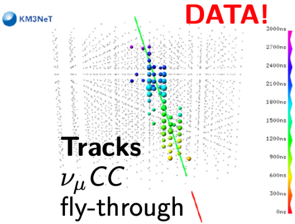
Construction timeline



Events in a ν Cherenkov detectors

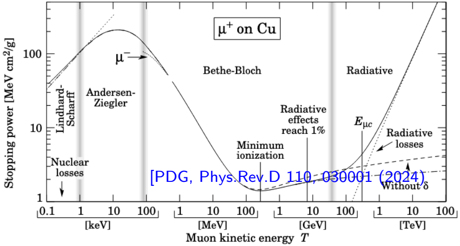




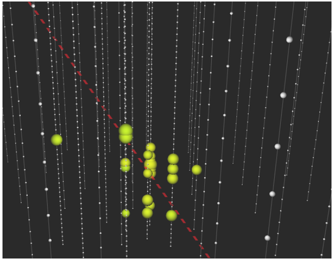


Performance: pointing, energy resolution, particle identification

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

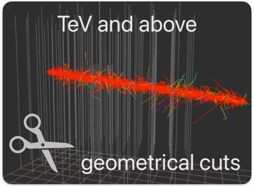


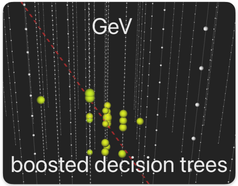
[PDG, Phys.Rev.D 110, 030001 (2024)]



Larger scattering length: direct photons → better pointing and particle identification.

Performance: pointing, energy resolution, particle identification



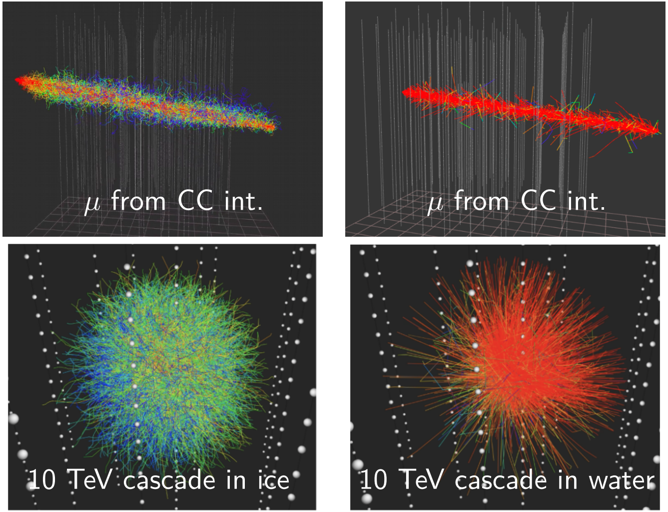


ANTARES

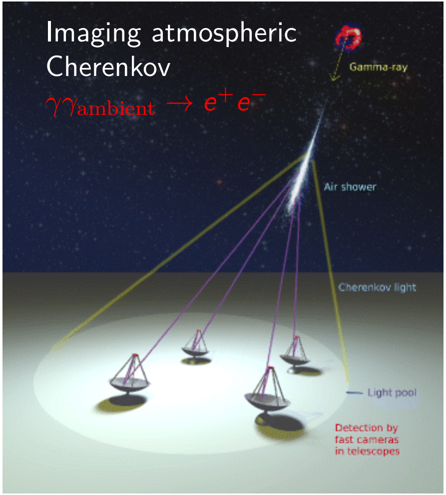
KM3NeT

IceCube

Neutrino astronomy: lenses

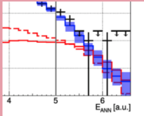


Particle astronomy: lenses (a more general problem)



Cosmic neutrinos: search types

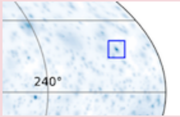
Diffuse excess at high energies without directional information



Multimessenger prompt coincidence upon alert from other experiments

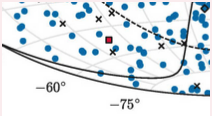
Sources (autocorrelation)

Space (-time) clusters of events, all-sky

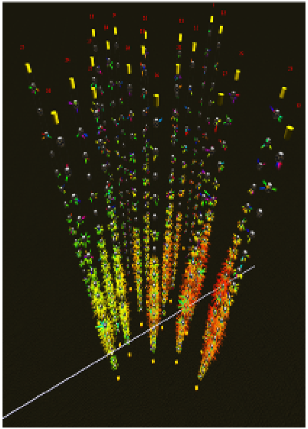


Sources (correlation with catalogue)

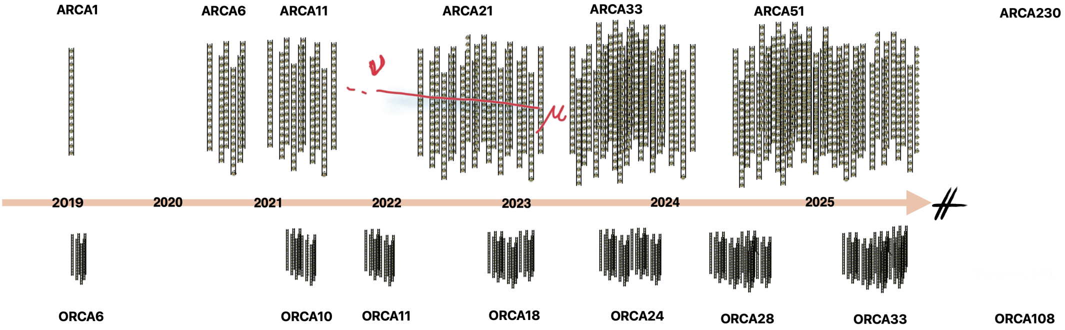
Coincidence with preselected objects



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

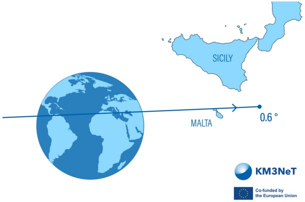


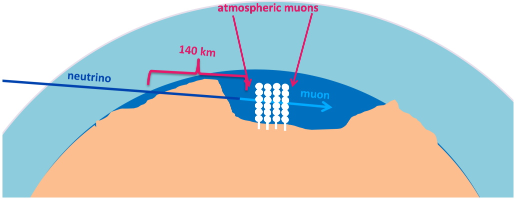
Observation of an ultra-high-energy cosmic ν with KM3NeT



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

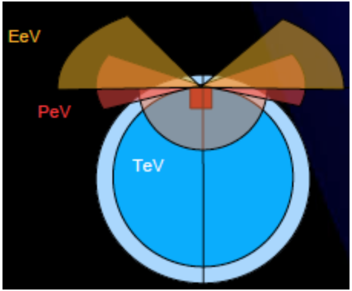


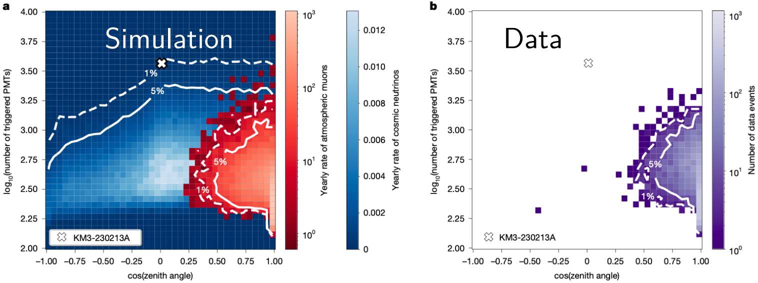


Actual water equivalent distance even larger due to continental shelf $\rightarrow$ not an atmospheric μ.

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

This event was spotted as a sensational outlier (1 in 110 million data events in corresponding data set of ∼287 days), extremely bright and from small patch of allowed sky.

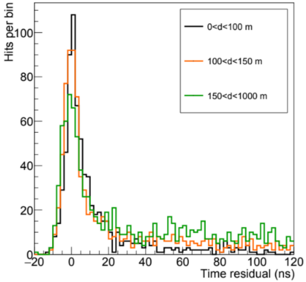


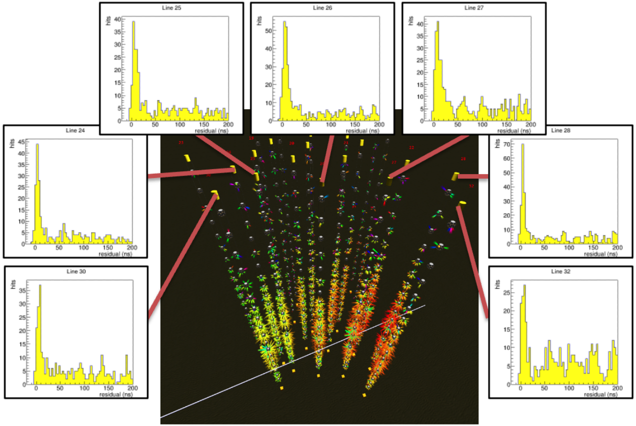


crossing Earth above sky

Reconstruction of the muon track

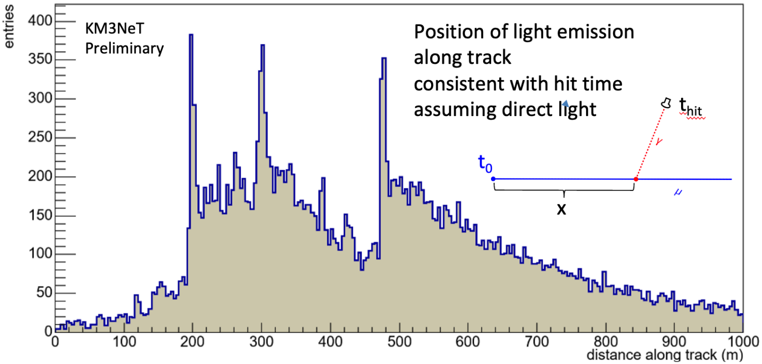
Arrival time residuals of photons at photomultipliers well understood.





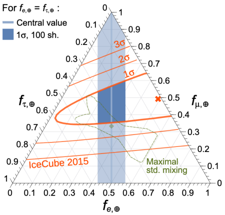
Rich detail of the muon track

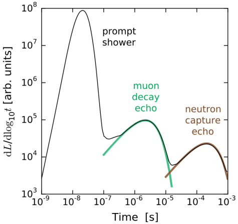
Light profile consistent with at least 3 large energy depositions along the muon track: characteristic of stochastic losses of very high energy muons.



Technique to break the hadronic/electromagnetic shower degeneracy and measure $\nu_\tau : \nu_e$ flavour ratio, based on J. Beacom et al. **[PRL 122(2019)]**. Richt detail observed in light deposition could help see the μ-decay and neutron-capture echoes (late emission).

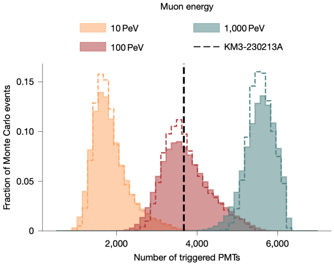
Case previously accosted in IceCube **[PoS(ICRC2017)1008]**), interesting for KM3NeT for good optical properties of water and multi-PMT structure.

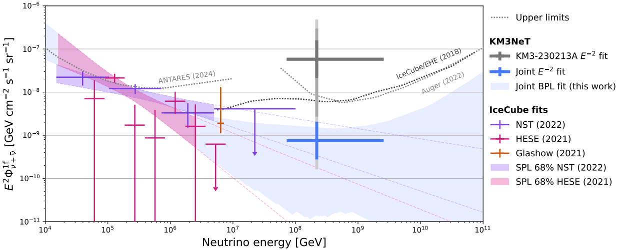




Reconstruction of energy

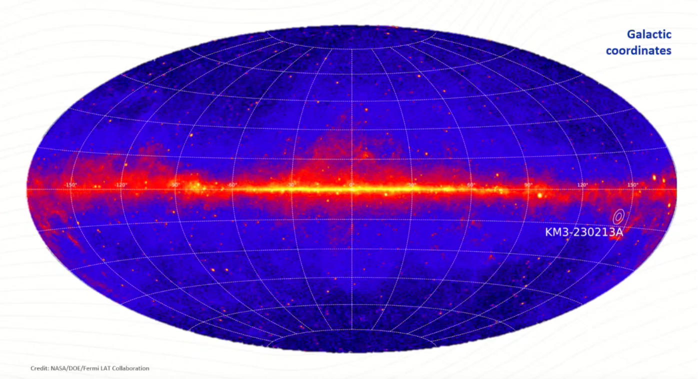
Muon energy: 120^{+110}_{-60} PeV, neutrino energy: 220^{+570}_{-100} PeV, 110–790 PeV (68%), 72 PeV–2.6 EeV (90%), under the assumption of a E^{-2} spectrum. Null observations above tens of PeV from the IceCube and Pierre Auger observatories.





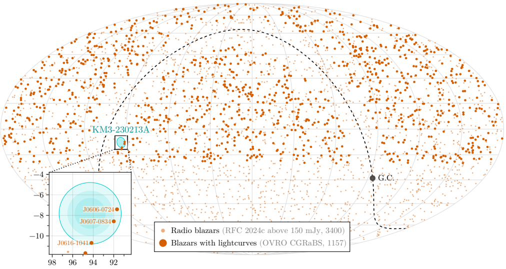
Ultra-high-energy cosmic ν with KM3NeT: arrival direction

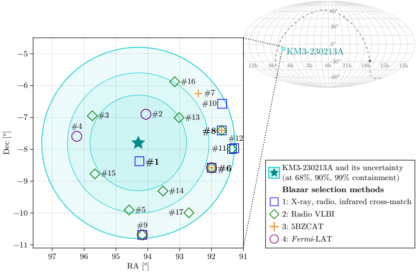
Celestial coordinates: $RA = 94.3°$, $dec = -7.8°$, with $1.5°$ uncertainty. Region-of-interest (cut/count) based searches will improve significance with more restrictive uncertainty radius.



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.

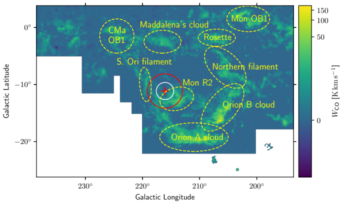




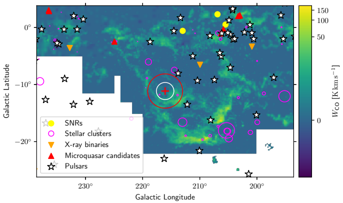
[https://arxiv.org/abs/2502.08484]

KM3-230213A: Search for Galactic counterparts

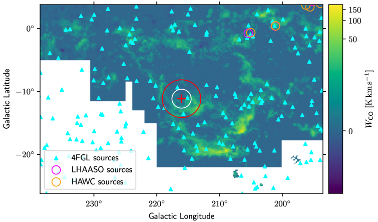
Lack of a nearby potential Galactic particle accelerator in the direction of the event. Low fluxes of the Galactic diffuse emission at event's energies. **Unlikely of Galactic origin**.



Map of CO clouds



Known potential CR accelerators

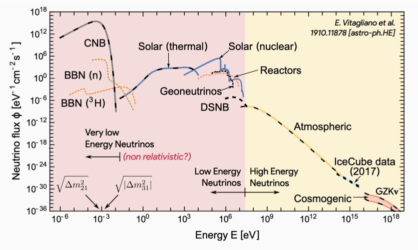


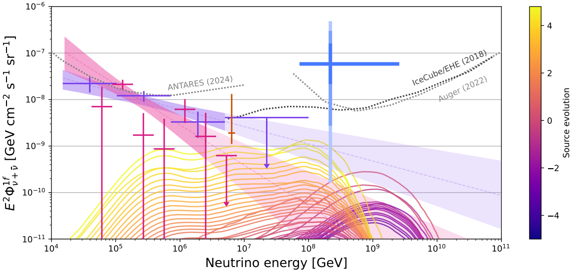
γ-ray sources from 4FGL-DR4 3HWC, LHAASO.

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

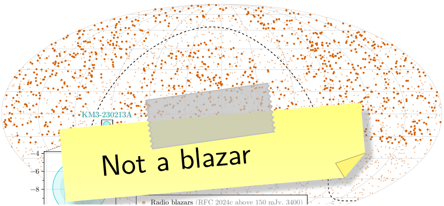
Ultra-high-energy cosmic ν with KM3NeT: search for counterparts

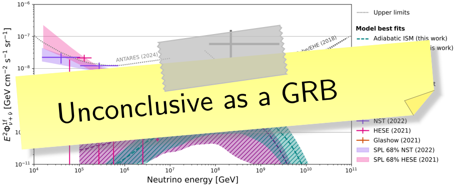
Light tension with the standard cosmogenic neutrino predictions. Observation can be reconciled with limits by Pierre Auger and Telescope Array by extending up to a redshift of $z \simeq 6$ and assuming a subdominant fraction of protons in UHE cosmic-ray flux.

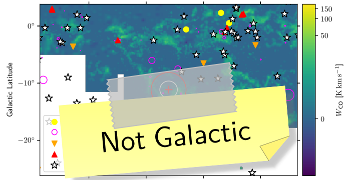


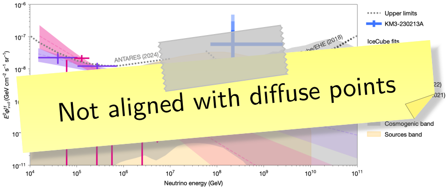


[Phys. Rev. X 15 (2025)] [https://arxiv.org/abs/2502.08508]





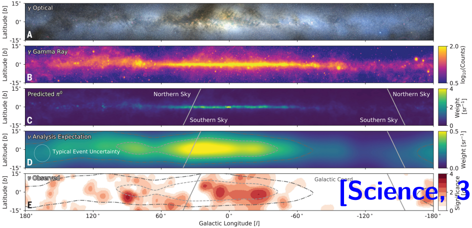




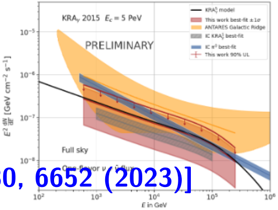
Or any other traceless transient? Heavy dark matter decay? Hawking radiation from primordial black hole evaporation? ...?

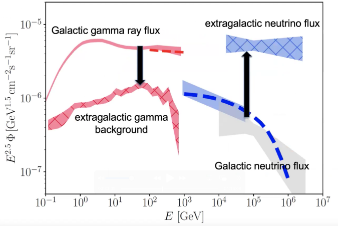
Galactic diffuse emission

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)



[Science, 380, 6652 (2023)]

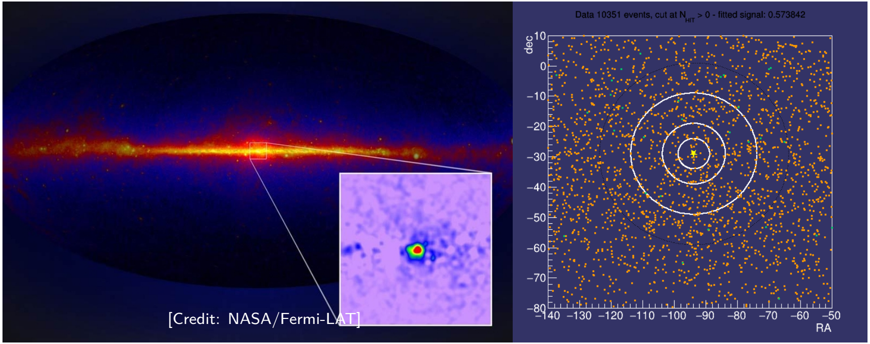




Perhaps powerful accelerators operate in other galaxies that do not exist in our own.

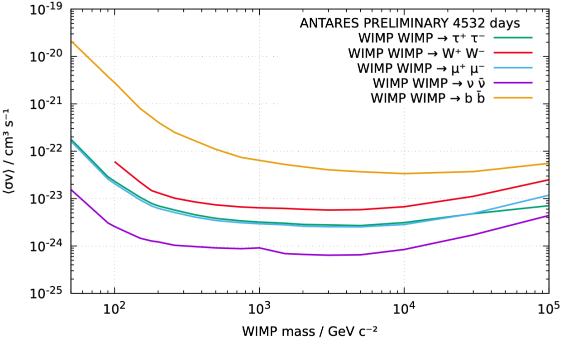
Other types of cosmic ν source: dark matter

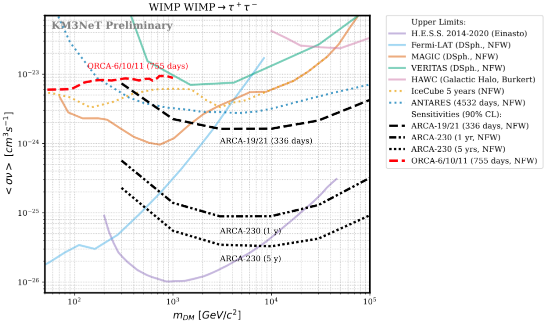
High energy is owed to large mass of progenitor rather than cosmic accelerator. Galactic Centre: high dark matter content but source confusion (recent excess in gamma rays that ν can start to probe). Major uncertainties from J-factor. Detector sits inside the source.



Indirect dark matter searches with ANTARES and KM3NeT

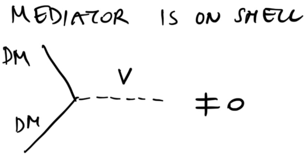
Galactic Centre uptime: about 70% . Data from ANTARES (2007 to 2022) and partial configuration of KM3NeT/ARCA is found consistent with background for all combinations of WIMP parameters **[Phys. Lett. B 805 (2020)] [JCAP03(2025)058]**

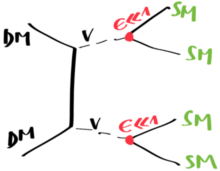


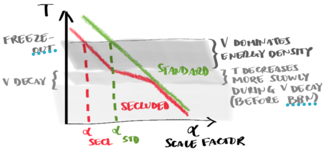


Non-WIMP scenarios

Above 10-100 TeV, in line with recent interest for BSM physics in heavy sectors at colliders.







Modified cosmological evolution: universe at freeze-out is smaller $\Rightarrow$ the same amount of DM is later more diluted $\Rightarrow$ σv(DM DM $\to$ VV) smaller $\Rightarrow$ DM can be **heavier**

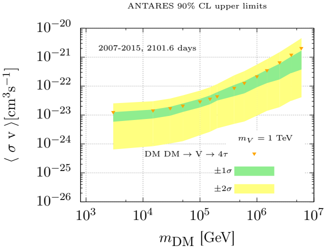
(I) Unitarity bound on the dark matter mass naturally evaded with a modified cosmology.
(II) $\mathrm{DM\,DM} \to 4\mathrm{SM}$ leaving the Galactic Centre as neutrinos. Spectra of relevance for experiments are computed from *boosted* PPPC4DMID **[JCAP02(2019)014]**.

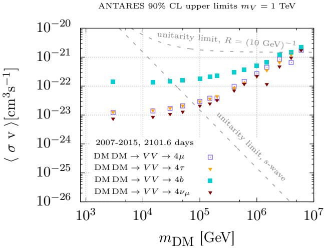
Non-WIMP scenarios

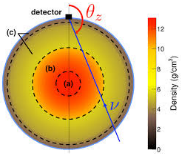
…*boosted* PPPC4DMID?

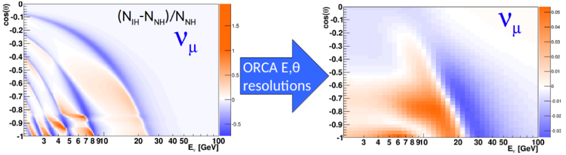
The relevant energy scale is not the heavy DM mass (that would demand a resummation of EW radiation for $m_{\rm DM} > 10$ TeV), but rather the sub-TeV mediator mass, where the first order treatment of EW corrections included in PPPC4DMID is under control.

Search explores parameter space regions up to 6 PeV **[JCAP06(2022)028]**.





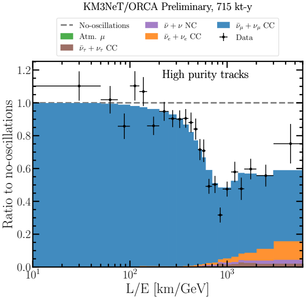


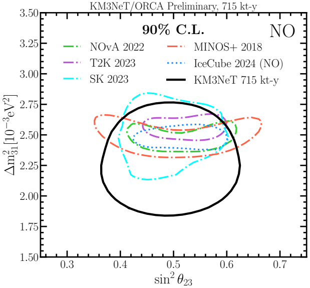


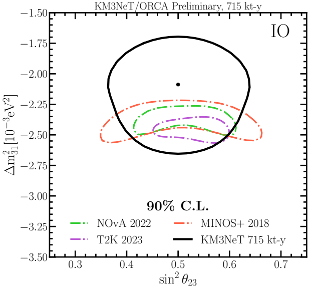
- Oscillations are seen in KM3NeT/ORCA through ν_μ **disappearance**.
- Matter effects in propagation through the Earth and different interaction cross section $\sigma_\nu/\sigma_{\bar{\nu}} \rightarrow$ differences in neutrino rates for **normal and inverted ordering**.
- Flavour-related observables require particle identification from signatures in detector, non trivial at GeV and just above.

Measurement of atmospheric oscillation parameters with KM3NeT

- Significance > 6 standard deviations in L/E distributions.
- 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.







Neutrino mass ordering

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

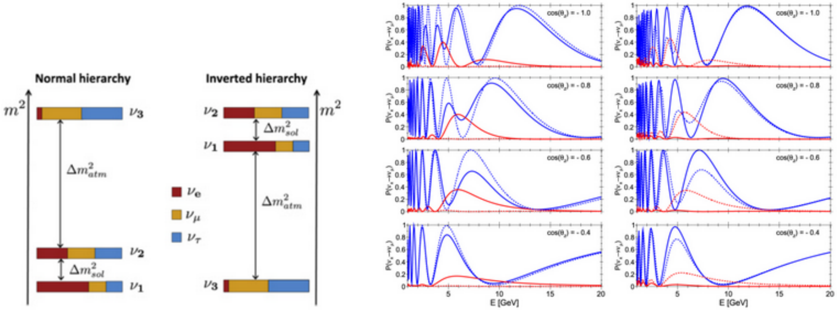
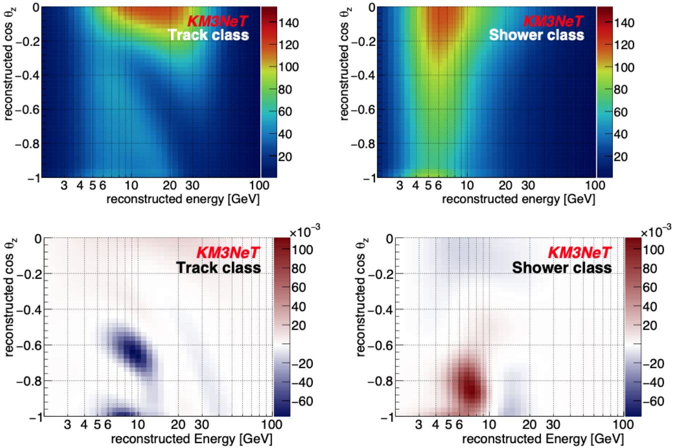


Figure: Right: oscillation probabilities $\nu_\mu \to \nu_\mu$ and $\nu_e \to \nu_\mu$ for different energies and baselines. The solid (dashed) lines are for NO (IO), ν (left) and $\bar{\nu}$ (right).

Neutrino mass ordering with KM3NeT

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.



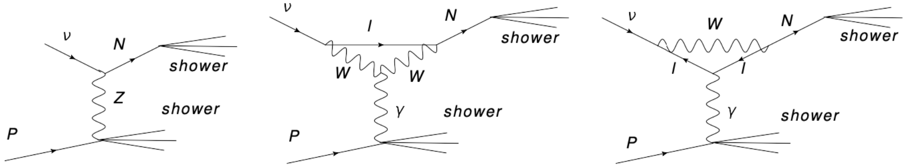
Expected sensitivity: number of expected events with normal/inverted hierarchy $(N_{IH} - N_{NH})/N_{NH}$

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

Search for heavy neutral lepton signatures

Signature: double cascade events at low energy. Active ν is atmospheric, after oscillations. **[JHEP05 030(2009)]**, **[PRL 119(2017)]**

1. HNL production via neutral current + mixing in final state. $|U_{\tau 4}|^2$ is the least constrained. Separation between vertices (decay length) depends on MN and on $|U_{\tau 4}|^2$.
2. HNL production via a transition magnetic moment: NC + W loop + mixing in final state

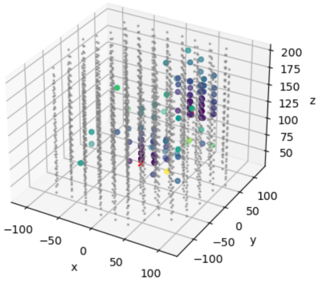


1) NC scattering with mixing

2) transition magnetic moment: W-loop and mixing in final state

Generation and identification in KM3NeT

Dedicated simulation of HNLs with the lepton injector of SIREN **[arXiv:2406.01745]**.
Machine learning regression (`dynedge`) to discriminate and reconstruct distance and energy.



Background?

1. Random coincidences of two uncorrelated muons: about $3{\cdot}10^{-9}$: negligible
2. Stochastic electromagnetic showers along the track: only relevant for μ, not for e
3. ν_τ: completely negligible. At GeV energies the two cascades are μm apart: completely overlayed.

The signature with two cascades separated by a long distance is characteristic fingerprint of something **new** outside the Standard Model

Wrap up

Bright future ahead for neutrino telescopes

- *Strike of luck* observation of highest-energy elementary particle ever measured. Still orphan of source (suggestively cosmogenic?)
- Atmospheric oscillations measured at more than 6 standard deviations
- Aiming at determination of neutrino mass ordering
- Active multimessenger networking ready
- Galactic diffuse emission and Galactic sources to appear soon.
- Broad field of action for indirect new physics searches: with effects on oscillation probabilities or novel signatures.

> The most exciting phrase to hear in science, the one that heralds new discoveries, is not '*Eureka!*' but 'That's odd...' [Isaac Asimov]

Wrap up

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