From astroparticle to time-domain astronomy

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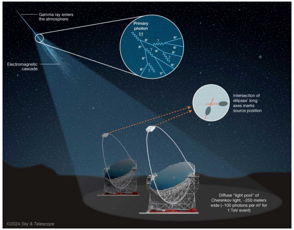
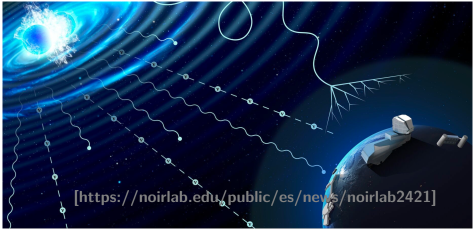
XVII Jornadas CPAN

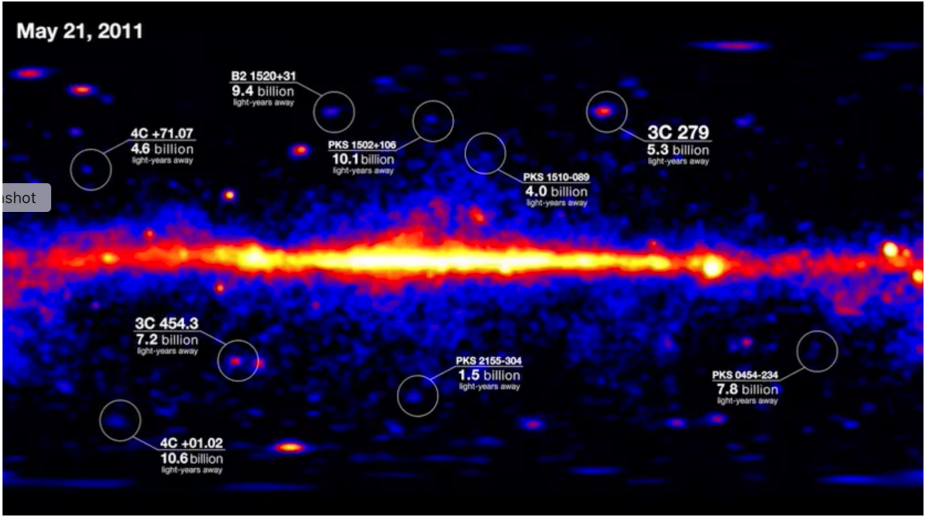
November 20, 2025

1. Particle physics is *by right* incorporated into ~~astronomy~~ $\to$ astroparticle
2. From static (picture) to time domain (flares, glares, explosions, turbulence) astronomy
3. Multi-wavelength $\to$ multi-messenger.





Flares

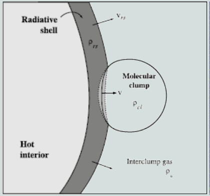

May 21, 2011
B2 1520+31
9.4 billion
light-years away
4C +71.07
4.6 billion
light-years away
PKS 1502+106
10.1 billion
light-years away
3C 279
5.3 billion
light-years away
PKS 1510-089
4.0 billion
light-years away
3C 454.3
7.2 billion
light-years away
PKS 2155-304
1.5 billion
light-years away
PKS 0454-234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

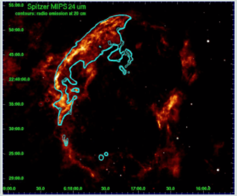
The neutrino-gamma-cosmic ray connection: hadron acceleration

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

1. $pN \rightarrow \pi^0, \pi^\pm, \eta^0 + X$ 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**

Hadron acceleration and prompt multimessenger: framed?

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)

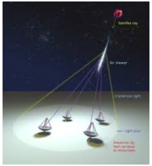
Prompt alerting system associated with rapid online analysis and pointing directions for telescopes.

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

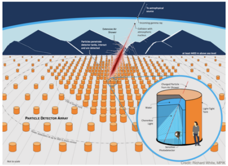
So catch $\nu \Rightarrow$ catch γ: find hadron. Double implication $\Leftarrow$? No: source could be obscured (NGC 1068); ν without electromagnetic counterpart. First ν association to steady source.

γ-ray instruments: performance

- $\sim$20 MeV $\rightarrow$ 300 GeV
- 100% duty cicle
- $>$2 sr FoV
- Modest angular resolution 0.15-3.5°
- Excellent energy resolution $\sim$ 10%
- γ collection area is limited



- $\sim$30 GeV $\rightarrow$ 100 TeV
- duty cicle (10-15%)
- 3.5-5° FoV
- Excellent angular resolution 0.1°
- Excellent sensitivity 1% Crab flux
- Source booking



- $\sim$100 GeV $\rightarrow$ 1 PeV
- $\sim$90% duty cicle
- 1 sr FoV
- Good angular resolution 0.2-0.8°
- Modest energy resolution $\sim$ 50%
- Good sensitivity 5%-10% Crab flux

Very-large volume ν detectors: performance

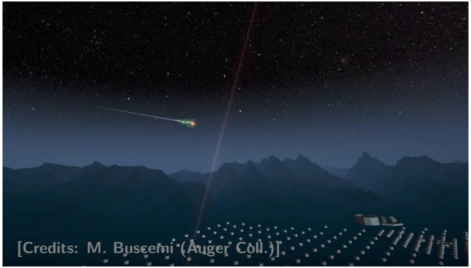
1. Faint signal rates, default 2π field of view, sub-degree angular resolution
2. Remotely operated, almost 100% duty cycle, one unique data set (no pointing)

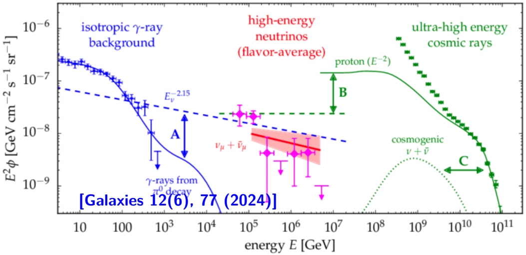
ANTARES

KM3NeT

IceCube

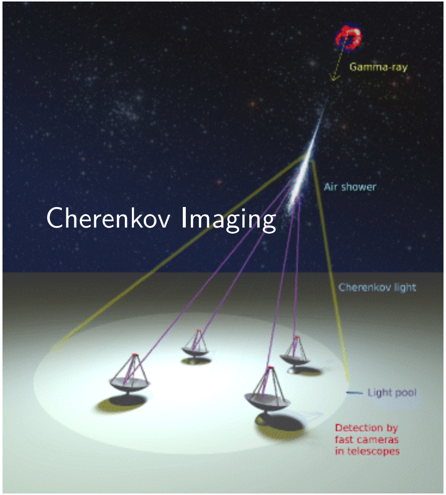
Cosmic Ray Observatories

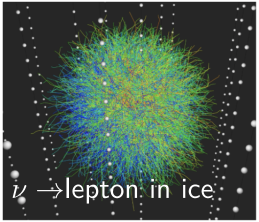


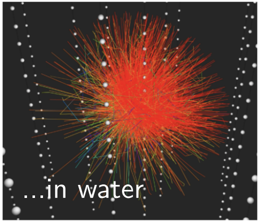


- Sub-degree resolution for hybrid events (ground array+fluorescence for lateral profile)
- $\sim 60^\circ$ opening $= \pi$ field of view if not considering very inclined events

Particle Astronomy: lenses





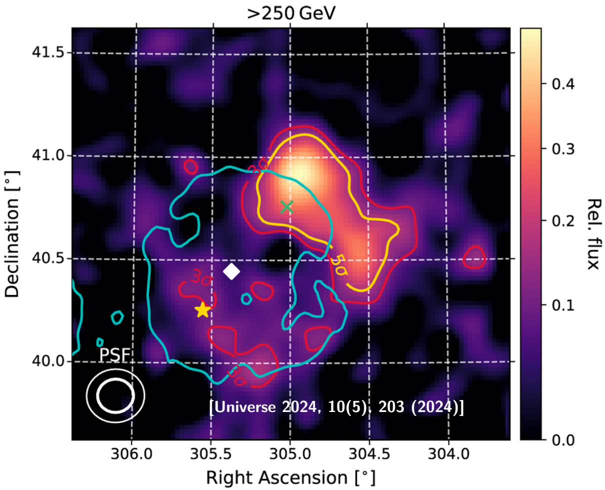


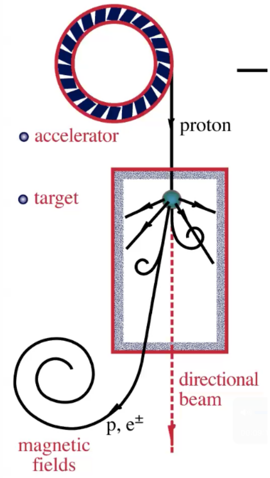
Only EM radiation (and not even all of that) interacts with detectors.

$$\gamma\gamma_{\mathrm{ambient}} \rightarrow e^{+}e^{-}$$

$$\nu N \rightarrow l X$$

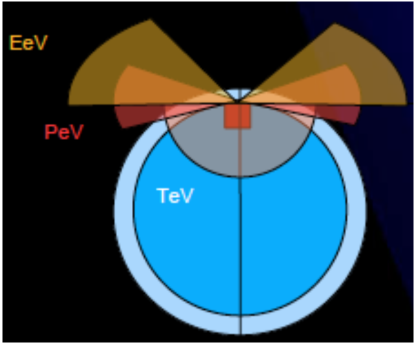
Neutrino astronomy is particle physics to all respects!

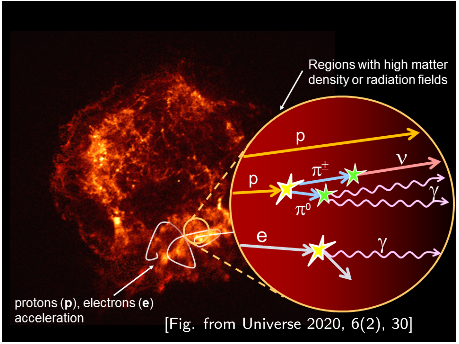




Neutrino astronomy *in the making*

Low fluxes, rare or sporadic events: an experimental challenge of suppressing background. Earth works as a good filter up to $\sim$ 500 TeV. Astrophysical ν: atmospheric ν: atmospheric μ $= 1{:}10^4 : 10^{10}$.

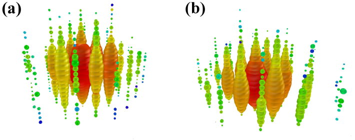


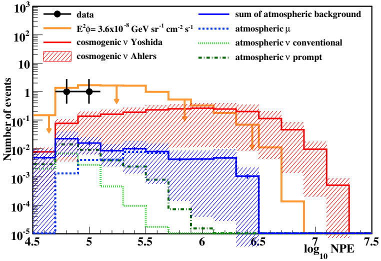


[Fig. from Universe 2020, 6(2), 30]

High energy neutrino sky crowds up

"whispers"

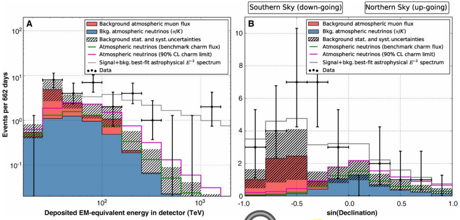




2012

First detection!

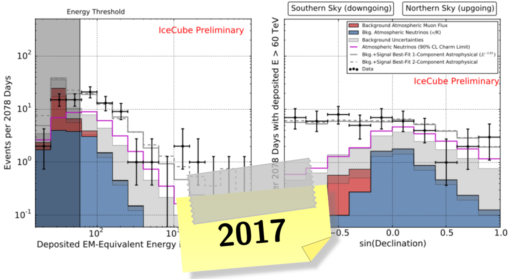
Extraterrestrial flux measured

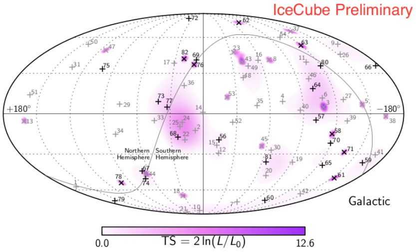


2013

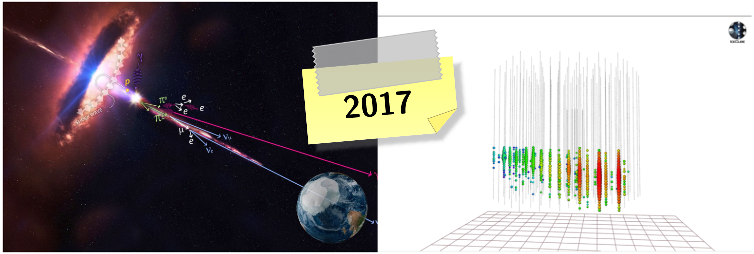
High energy neutrino sky crowds up... but still no sources

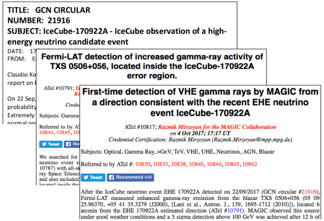
Data Set	Lifetime	Events	Significance	Reference
2-year HESE	662 days	28	4.1 σ	Science 342, 2013
3-year HESE	988 days	37	5.7 σ	PRL 113, 2014
4-year HESE	1347 days	54	4.3 σ	ICRC 2015
6-year HESE	2078 days	82	$> 7\sigma$	ICRC 2017





High energy neutrino sky crowds up... source!





TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

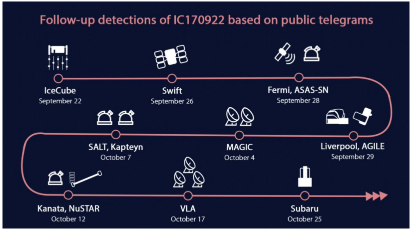
ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration* on *4 Oct 2017; 17:17 UT*

Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

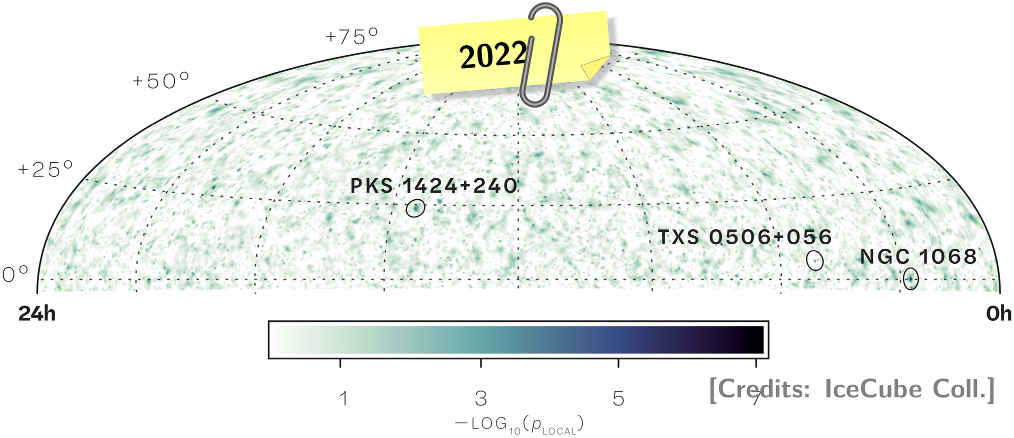
Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of

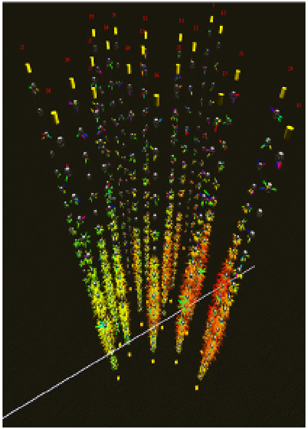


High energy neutrino sky crowds up

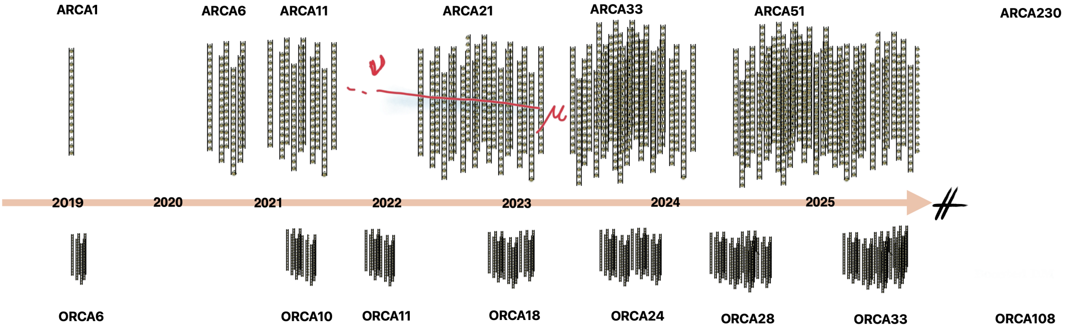


[Credits: IceCube Coll.]

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

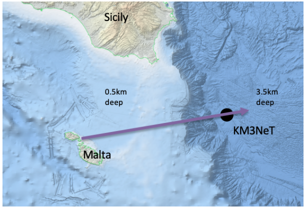


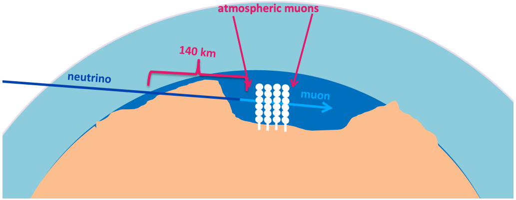
Observation of an ultra-high-energy cosmic ν with KM3NeT

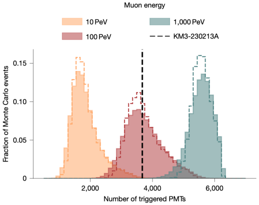


Observation of an ultra-high-energy cosmic ν with KM3NeT

- 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



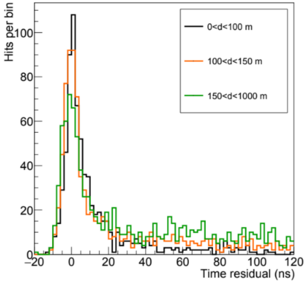


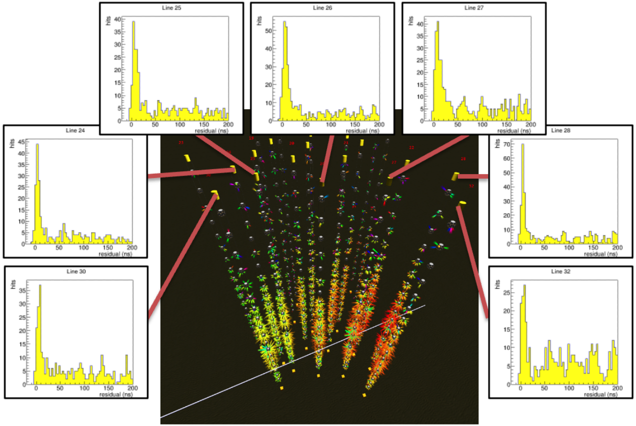


Actual water equivalent distance even larger due to continental shelf $\rightarrow$ not an atmospheric μ. Muon energy: 120^{+110}_{-60} PeV, neutrino energy: 220^{+570}_{-100} PeV, 110–790 PeV (68%), 72 PeV–2.6 EeV (90%), under the assumption of a E^{-2} spectrum.

Reconstruction of the muon track

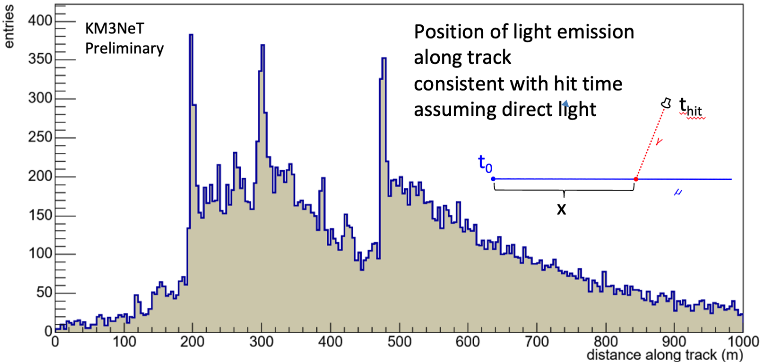
Arrival time residuals of photons at photomultipliers well understood.





Rich detail of the muon track

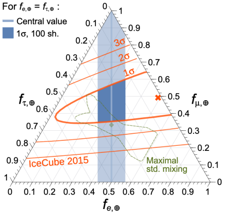
Light profile consistent with at least 3 large energy depositions along the muon track: characteristic of stochastic losses of very high energy muons.

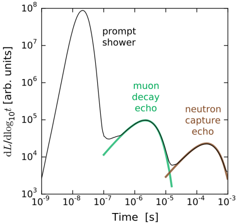


...an opportunity for neutrino echoes?

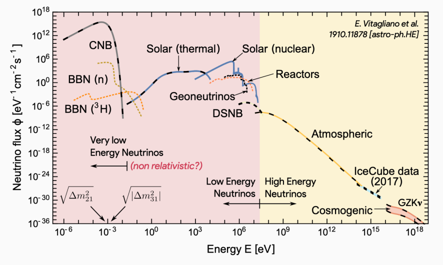
Technique to break the hadronic/electromagnetic shower degeneracy and measure $\nu_\tau : \nu_e$ flavour ratio, based on J. Beacom et al. **[PRL 122(2019)]**. Richt detail observed in light deposition could help see the μ-decay and neutron-capture echoes (late emission).

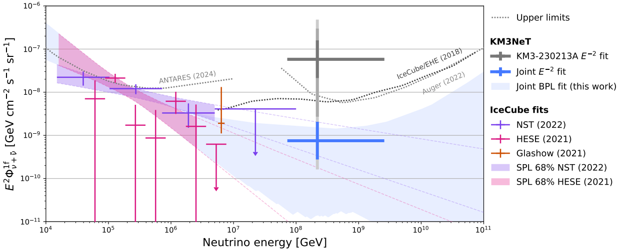
Case previously accosted in IceCube **[PoS(ICRC2017)1008]**), interesting for KM3NeT for good optical properties of water and multi-PMT structure.





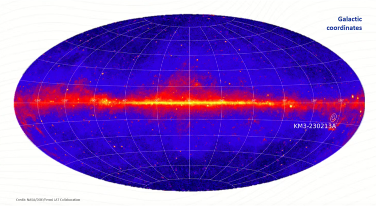
Null observations above tens of PeV from the IceCube and Pierre Auger observatories. Light tension with the standard cosmogenic neutrino predictions. Observation can be reconciled with limits by Pierre Auger and Telescope Array by extending up to a redshift of $z \simeq 6$ and assuming a subdominant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



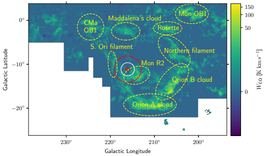


[Phys. Rev. X 15 (2025)]

KM3-230213A: origin?

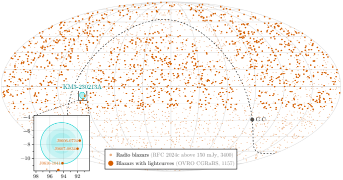


Celestial coordinates: $RA = 94.3°$, $\delta = -7.8°$



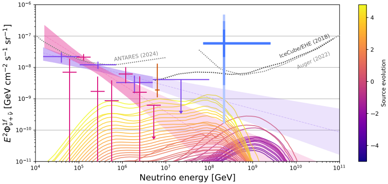
E_ν 220^{+570}_{-100} PeV. Unlikely galactic.

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



Unconclusive correlation with blazars

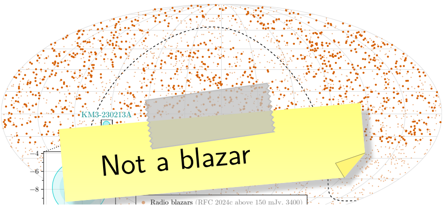
[https://arxiv.org/abs/2502.08484]

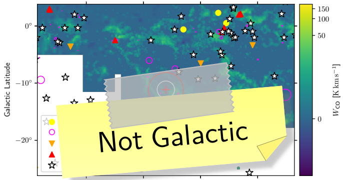


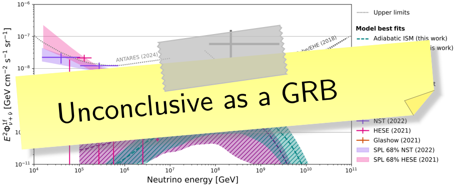
Cosmogenic origin?

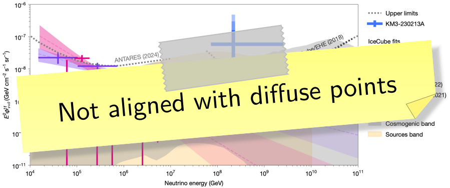
[ApJL 984 L41]

KM3-230213A: origin?



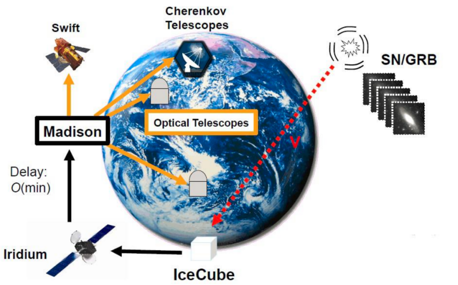


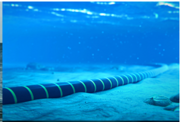


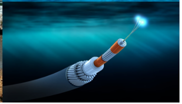


Or any other traceless transient? Heavy dark matter decay? Hawking radiation from primordial black hole evaporation? ...?

Multi-messenger networking

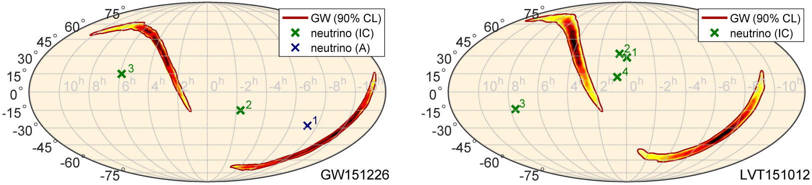






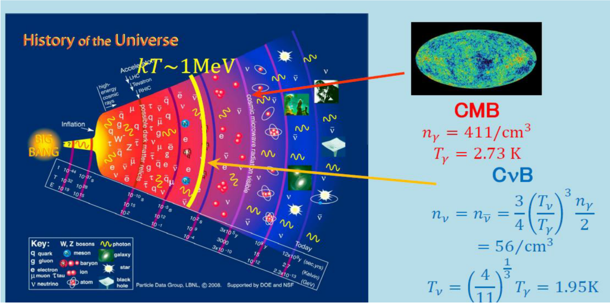
At the forefront: gravitational waves

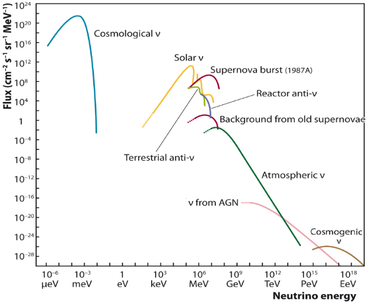
Multi-messenger alert network for flares, transients and other sources with time variability (GRBs, gravitational waves, supernovae)



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.

ν decouple 1 second after the Big Bang at T~1.95 K (for comparison: CMB after 300.000 y)

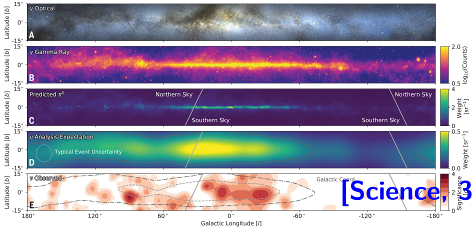


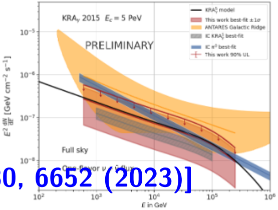


PTOLEMY: project for a first CNB detector based on ν capture on tritium (monoatomic tritium source deposited on a graphene substrate)

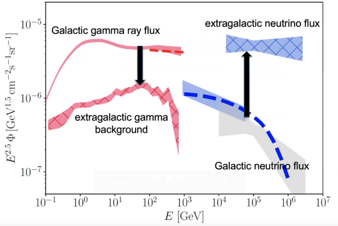
Galactic diffuse emission

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)]



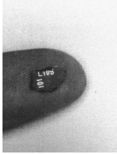
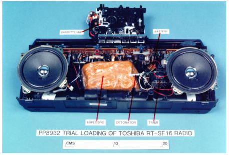
Perhaps powerful accelerators operate in other galaxies that do not exist in our own.

Other types of cosmic ν source: dark matter

High energy is owed to large mass of progenitor rather than cosmic accelerator. Indirect searches: Standard Model *debris* from DM collision/decay.

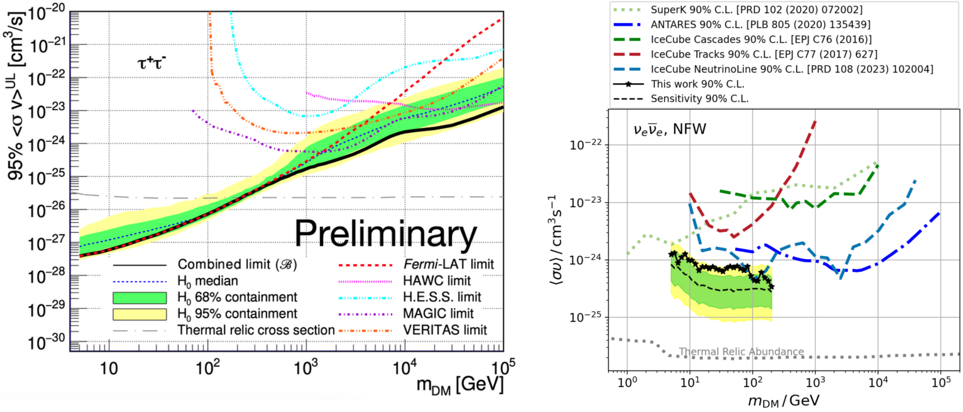
The extra trouble with indirect searches: external input. Unavoidably affected by **large uncertainties**, these searches alone can hardly make a univocal claim for detection.



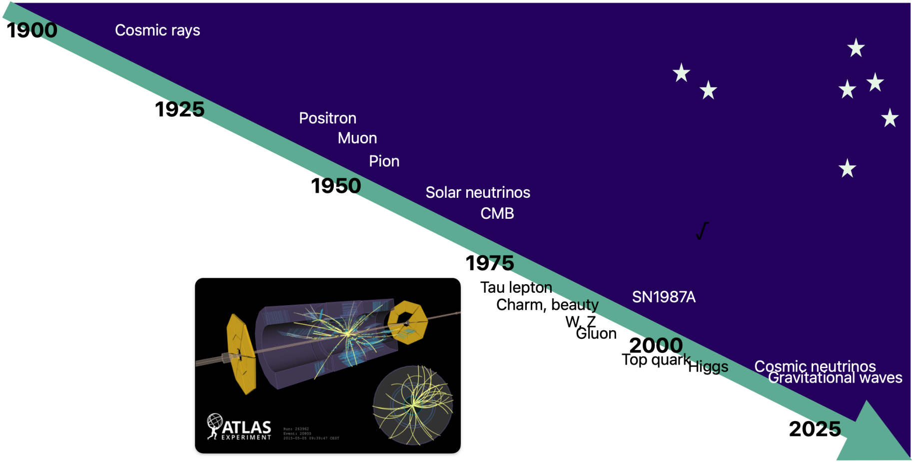
Not knowing the dark matter manufacturer, identification strongly relies on theory.

Indirect dark matter searches with γ and ν

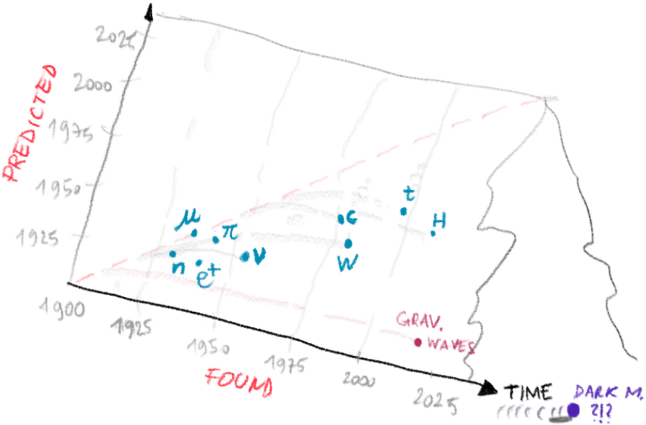


[PoS(ICRC2025)1424]

Wrapping up: cosmic environment is a particle physics lab



Warpping up: slip chart



Conclusions: a bright future ahead

Astroparticle has moved steps ahead. Sources start to populate sky atlas in these decades!

- Extraterrestrial neutrinos (2012-2013)
- Gravitational waves (2015)
- Neutrino source through multimessenger (2017)
- Static neutrino source with AGN association (2022)
- Still orphan (suggestively cosmogenic?) neutrino (2025)

Plenty of open dilemmas: dark matter, origin of cosmic rays. Proliferation era of ν telescopes.

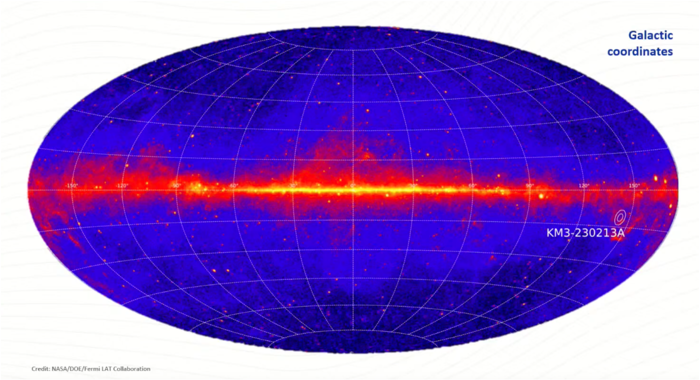
> The most exciting phrase to hear in science, the one that heralds new discoveries, is not '*Eureka!*' but 'That's odd...' [Isaac Asimov]

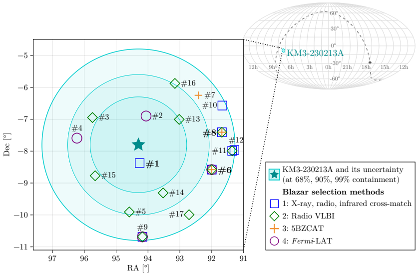
Conclusions

Backup to follow

KM3-230213A: search for blazar counterparts

Celestial coordinates: $RA = 94.3°$, $dec = -7.8°$. Candidate blazars selected: (1) radio flare on ν 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.

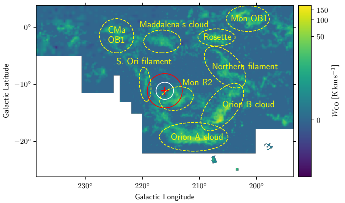




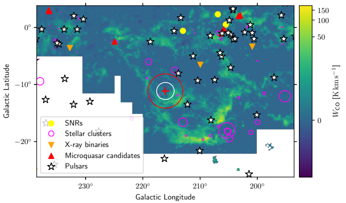
[https://arxiv.org/abs/2502.08484]

KM3-230213A: Search for Galactic counterparts

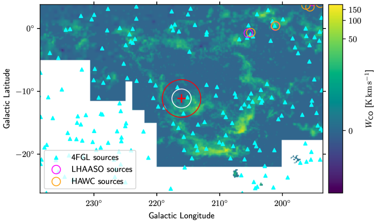
Lack of a nearby potential Galactic particle accelerator in the direction of the event. Low fluxes of the Galactic diffuse emission at event's energies. **Unlikely of Galactic origin**.



Map of CO clouds



Known potential CR accelerators

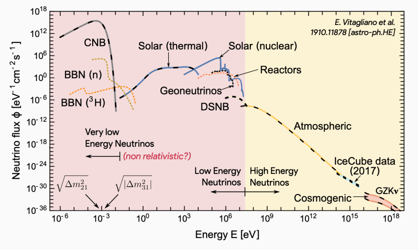


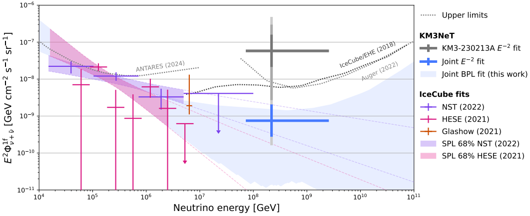
γ-ray sources from 4FGL-DR4 3HWC, LHAASO.

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

Search for multimessenger counterparts... or cosmogenic?

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.

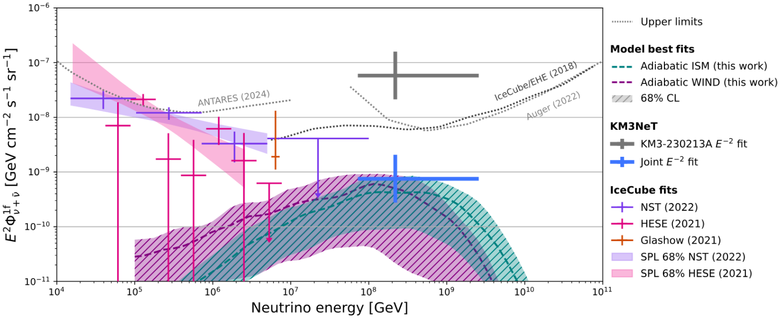




[https://arxiv.org/pdf/2502.08173] [https://arxiv.org/abs/2502.08508]

KM3-230213A to constrain gamma-ray burst parameters

In blast wave model, constrain baryon loading and density of surrounding environment by benchmarking to KM3-230213A



[https://arxiv.org/pdf/2509.14895]