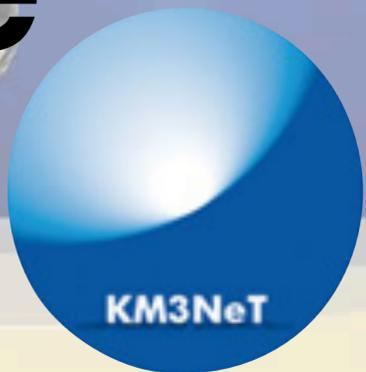


KM3NeT — Astrophysics Case

Conseil Scientifique de l'IN2P3

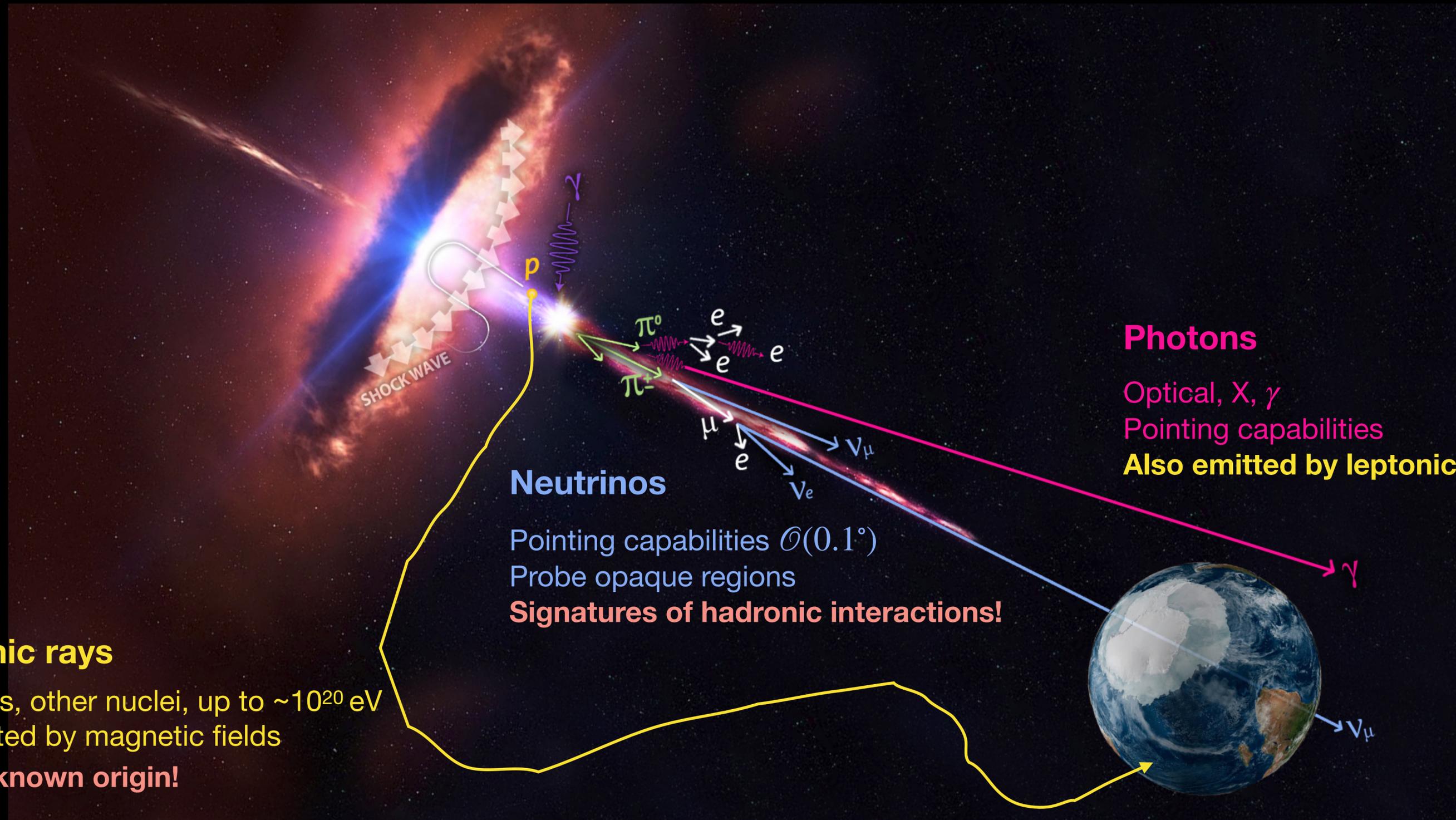
Sonia El Hedri — 02/03/2026



Neutrinos and the origin of cosmic rays

Cosmic rays

Protons, other nuclei, up to $\sim 10^{20}$ eV
Deflected by magnetic fields
→ **Unknown origin!**

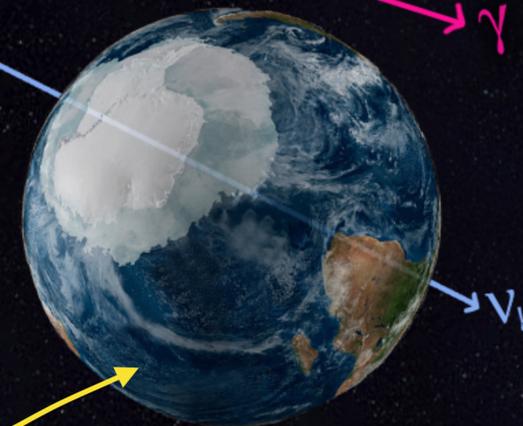


Neutrinos

Pointing capabilities $\mathcal{O}(0.1^\circ)$
Probe opaque regions
Signatures of hadronic interactions!

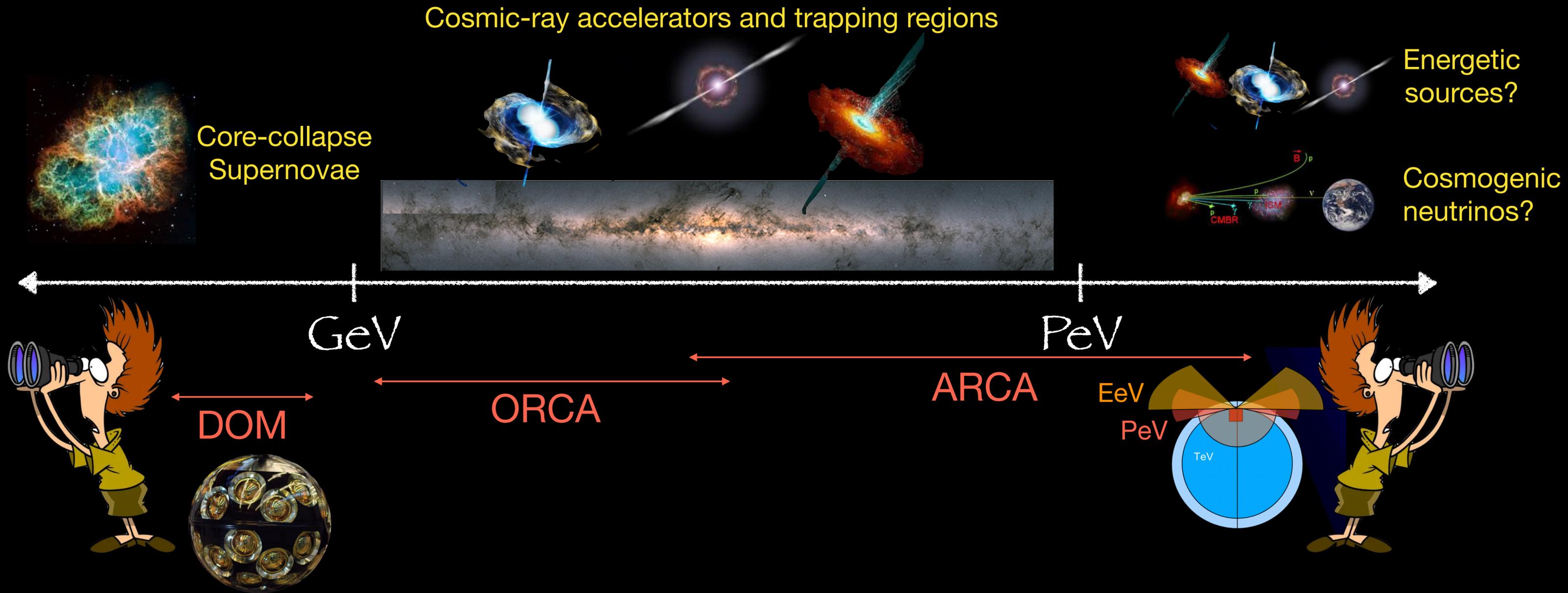
Photons

Optical, X, γ
Pointing capabilities
Also emitted by leptonic interactions



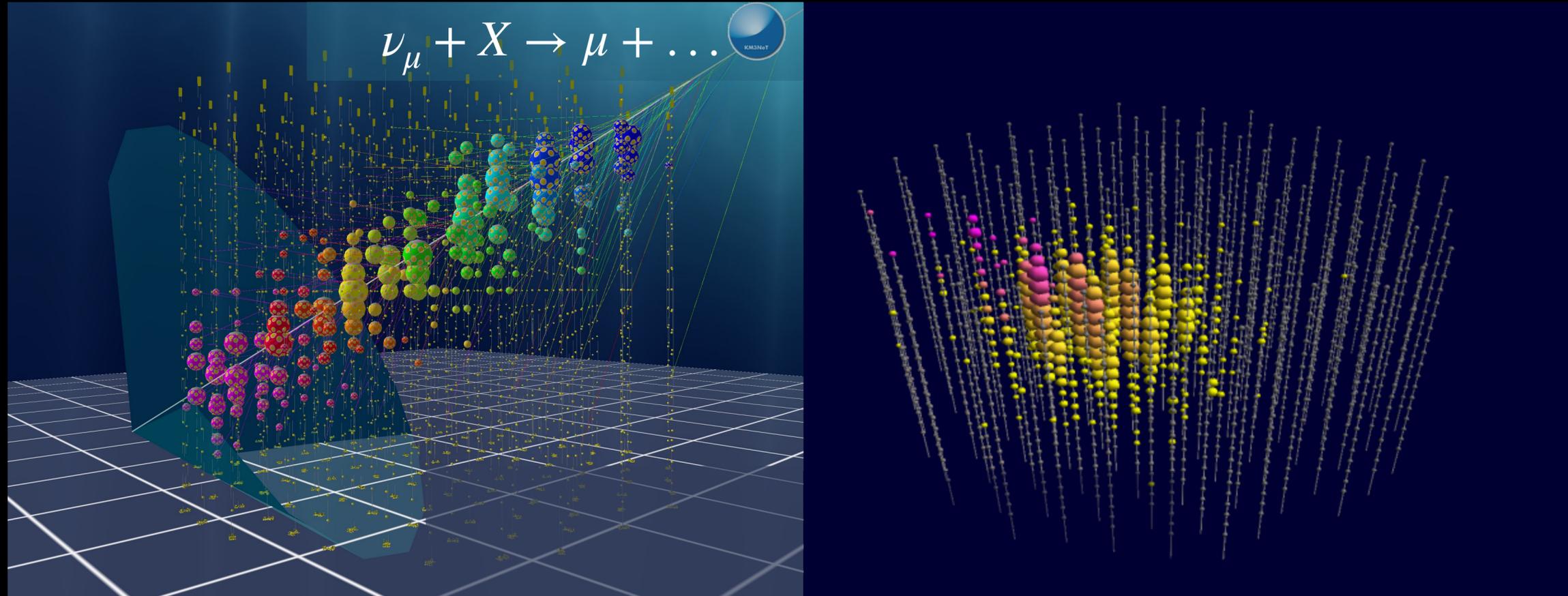
KM3NeT's astrophysics potential

Exploring the MeV to PeV range



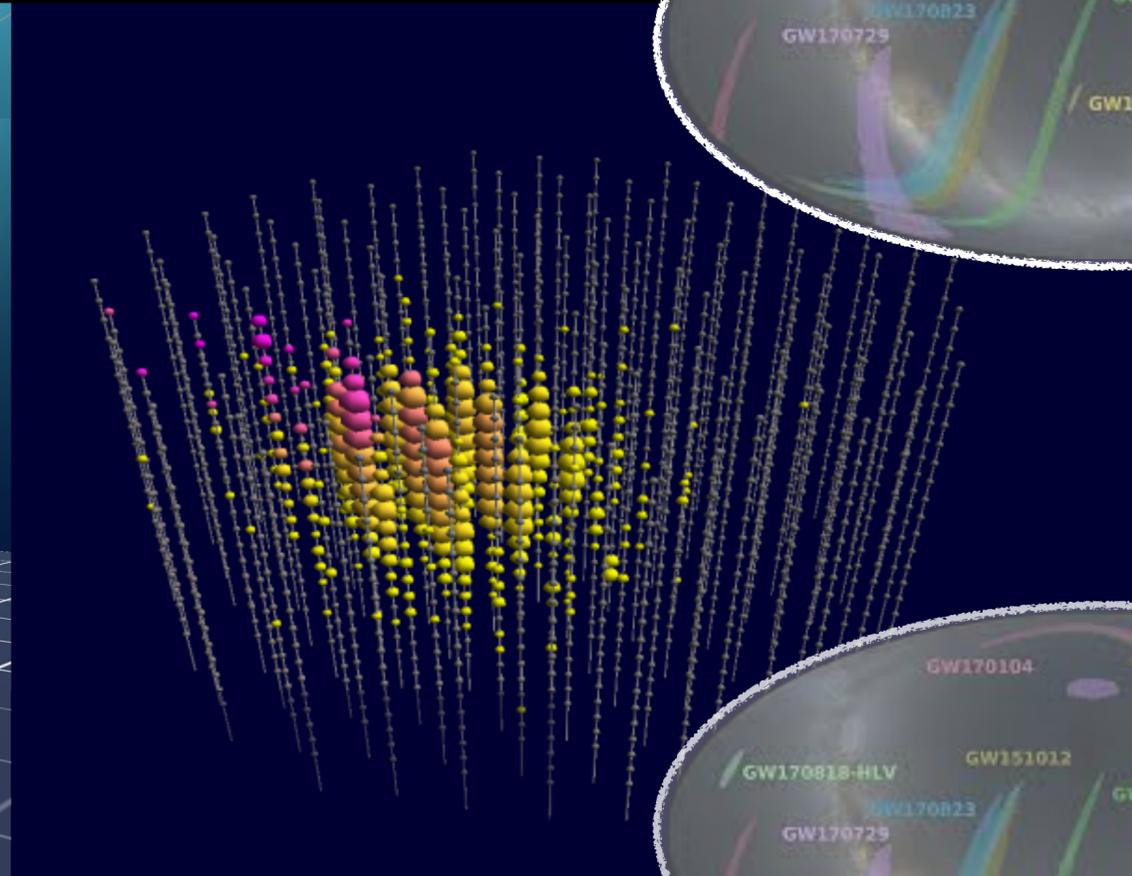
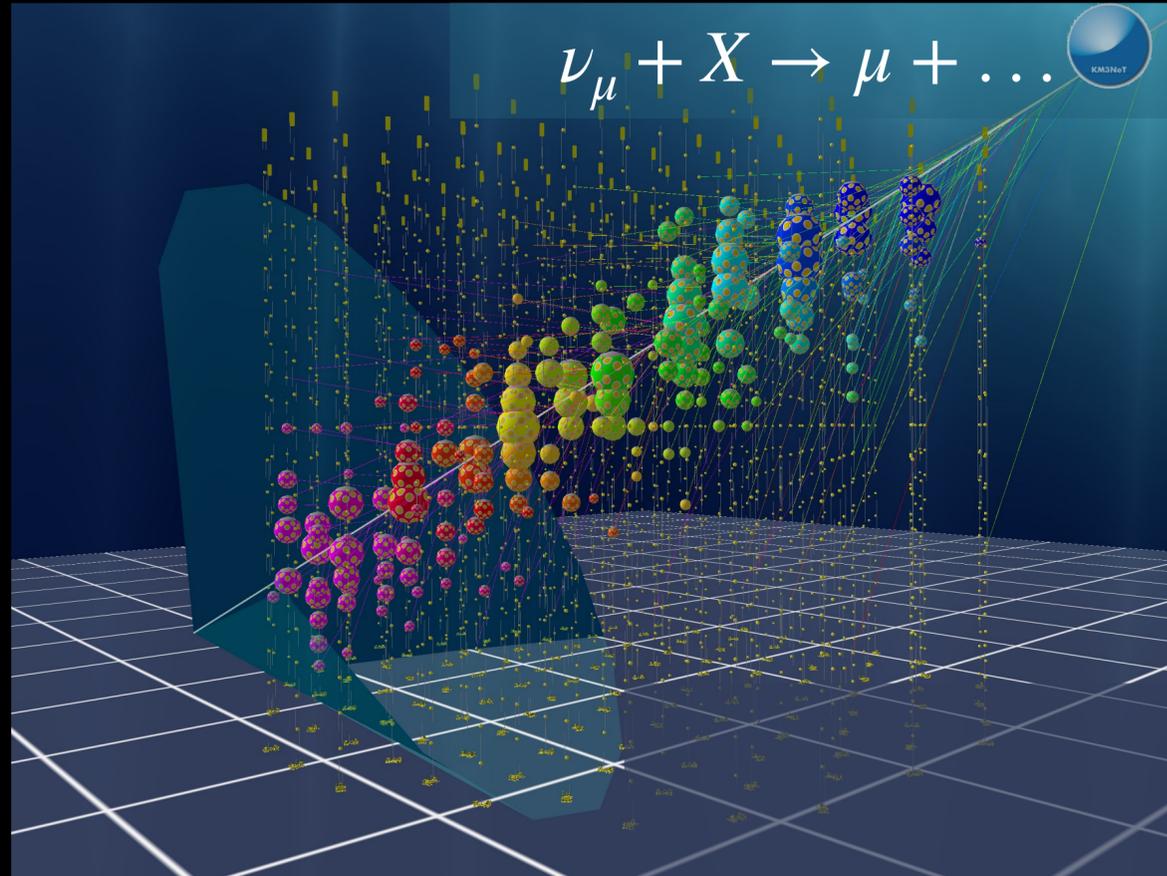
Neutrino events and backgrounds

Tracks and showers



Neutrino events and backgrounds

Tracks and showers



Upgoing showers

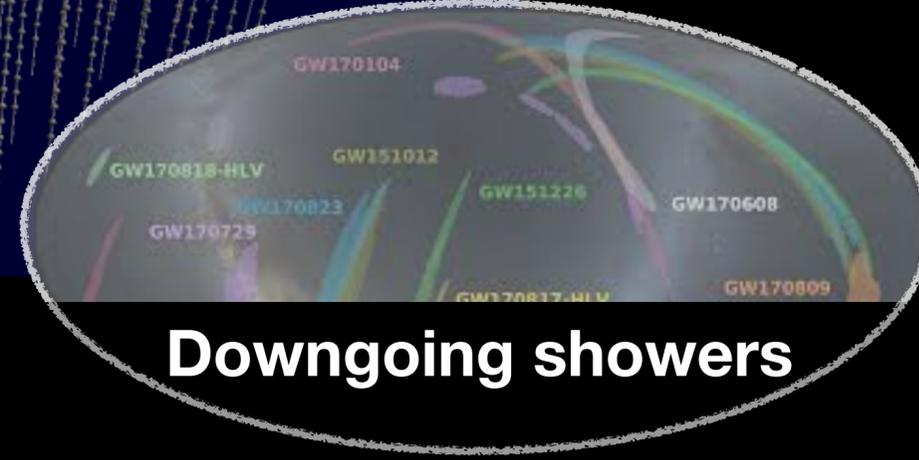
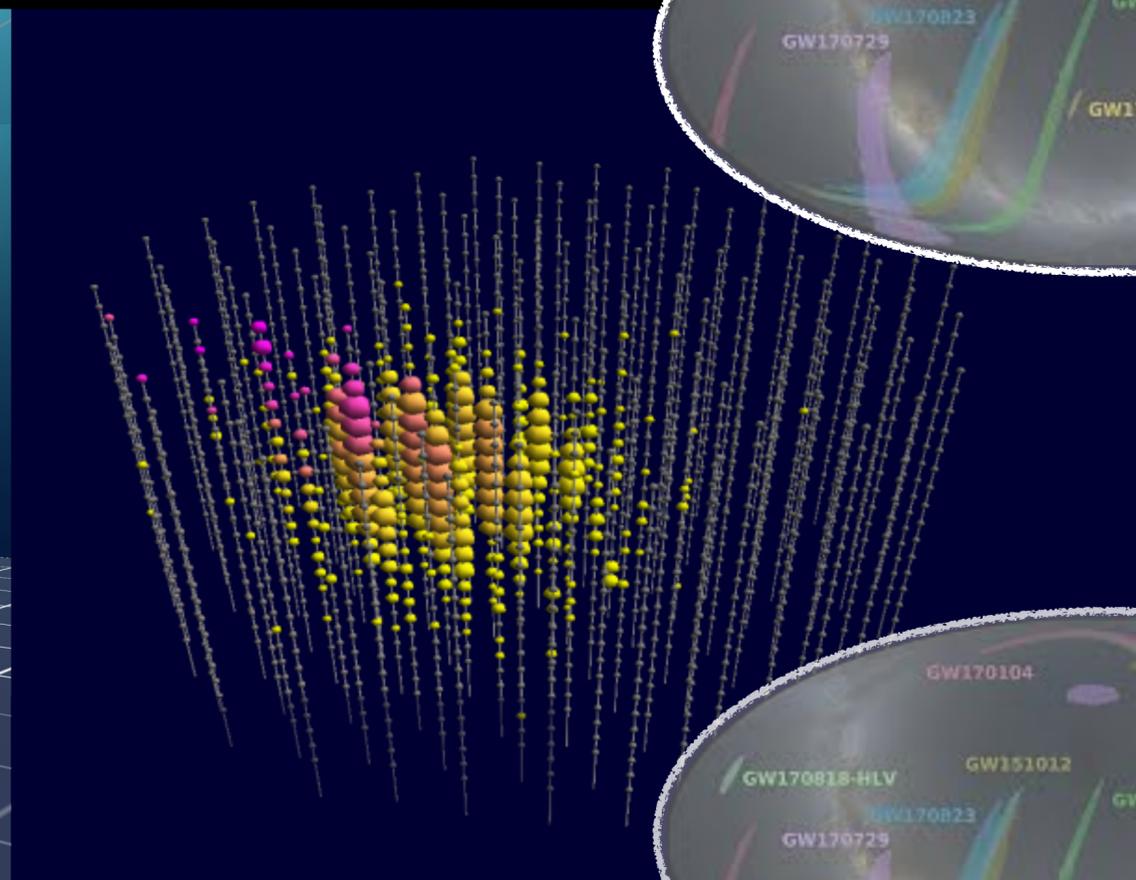
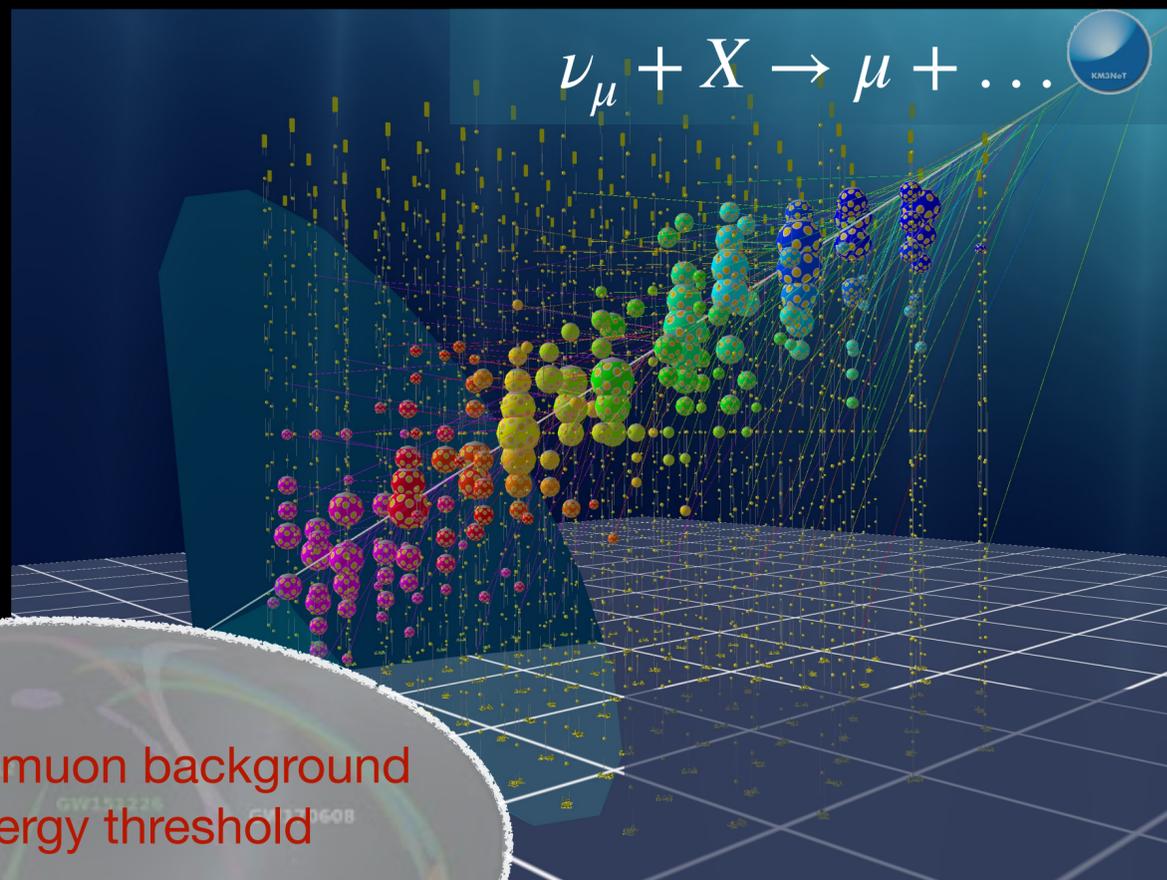


Downgoing showers



Neutrino events and backgrounds

Tracks and showers

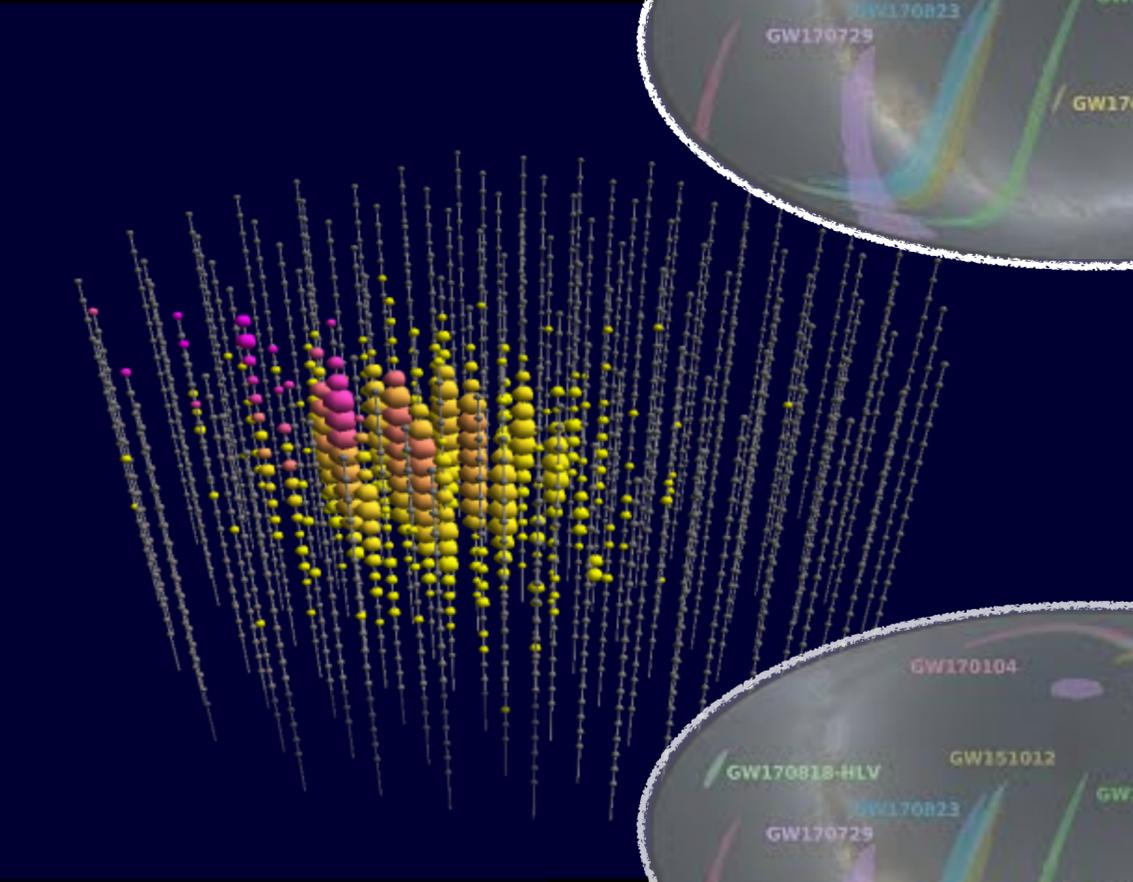
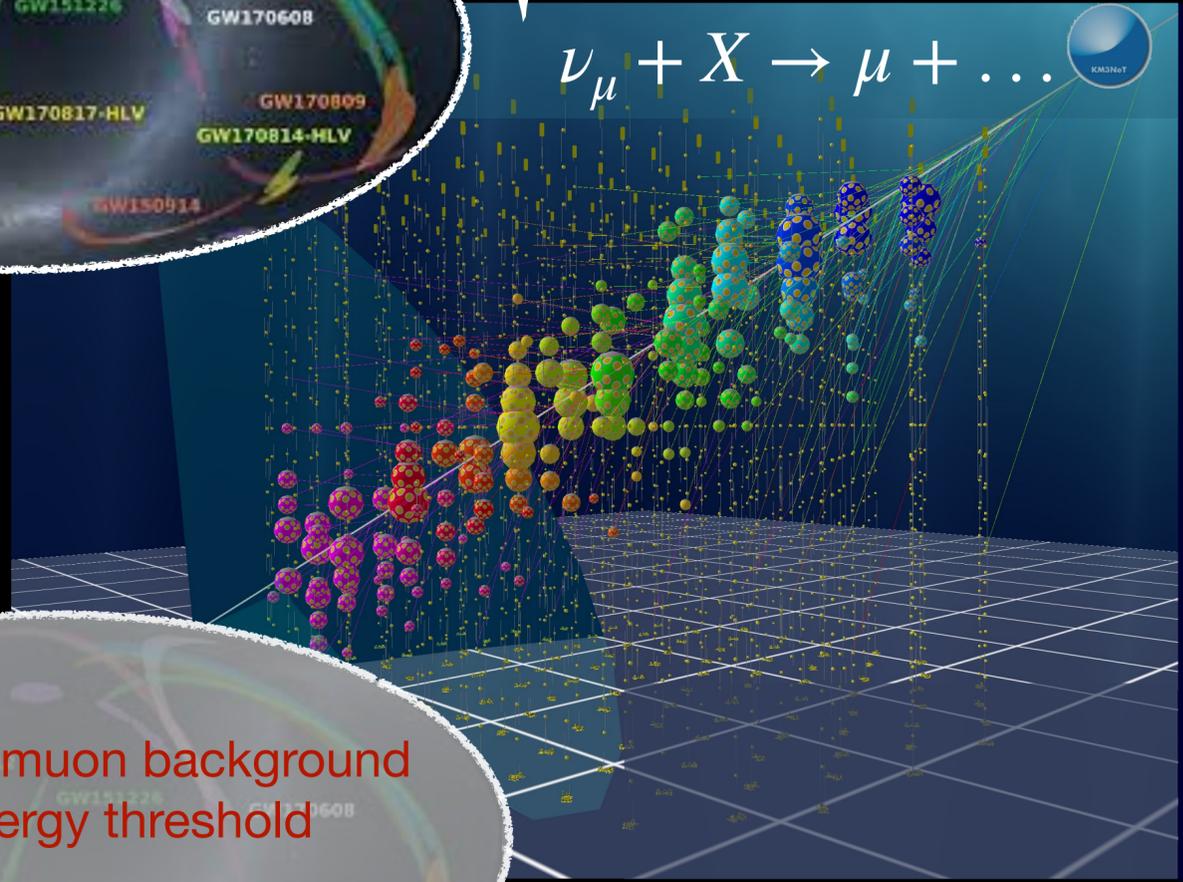
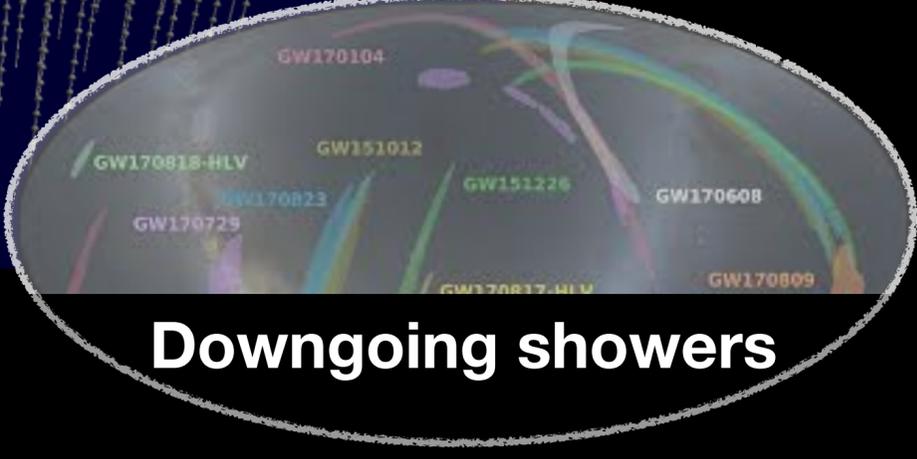
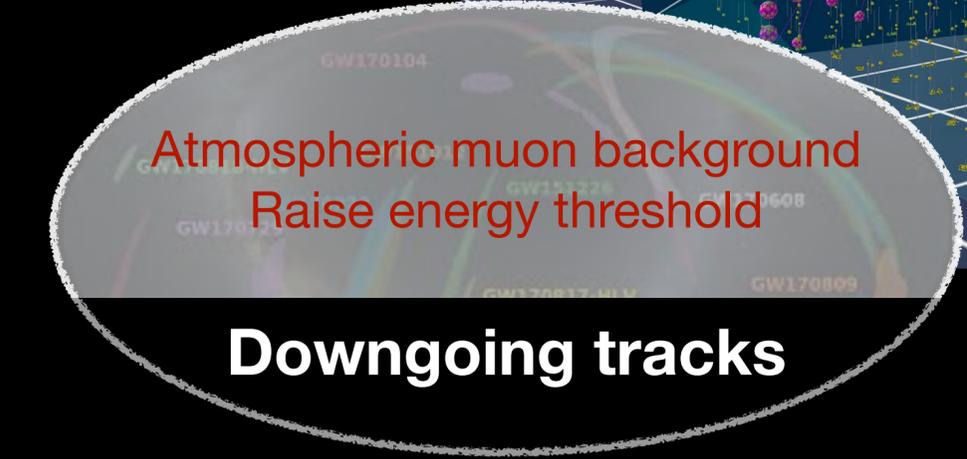


Neutrino events and backgrounds

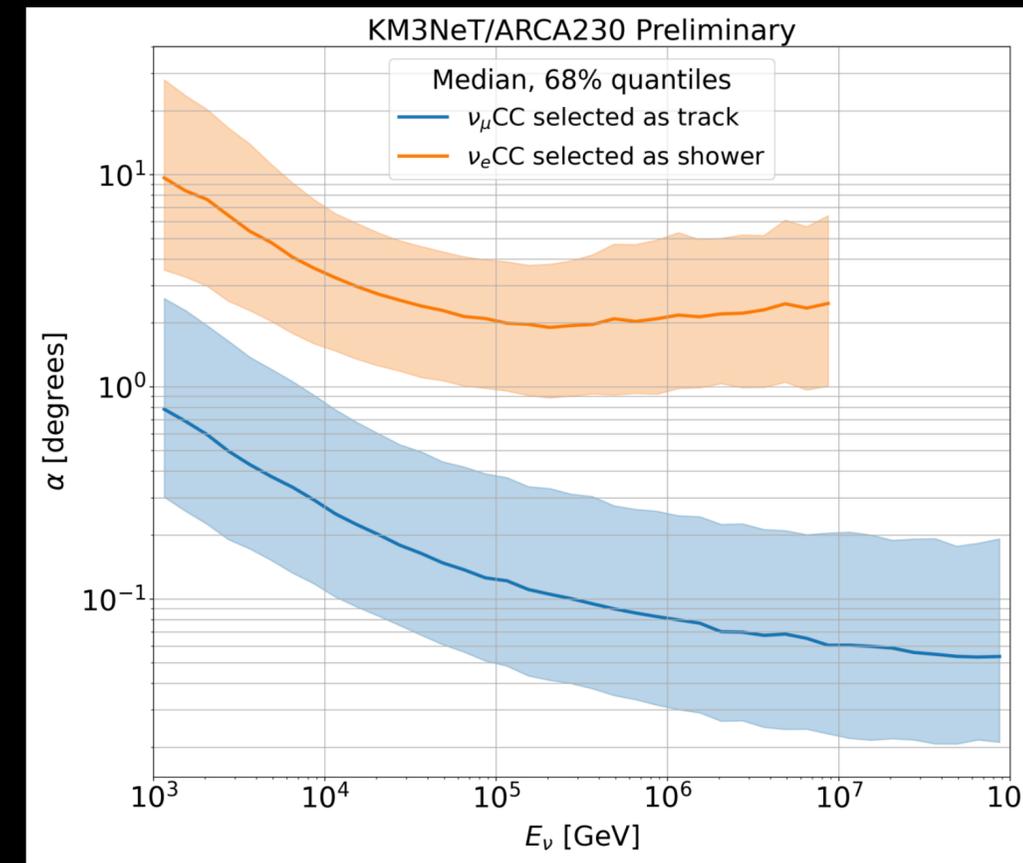
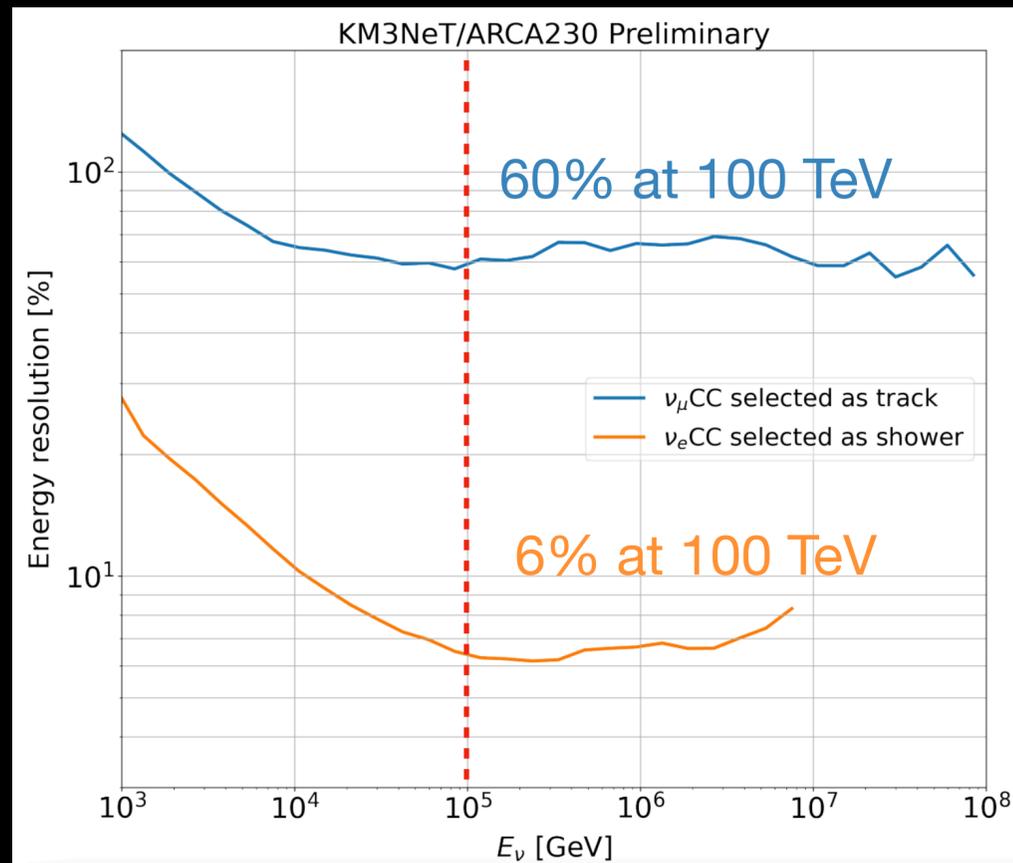
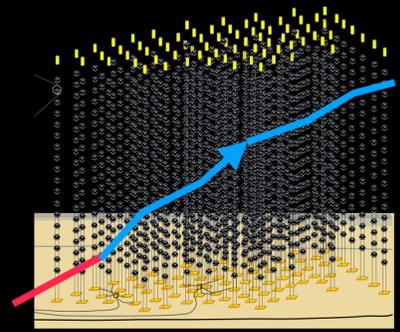
Tracks and showers

✦ *Clean!* ✦

$$\nu_{\mu} + X \rightarrow \mu + \dots$$

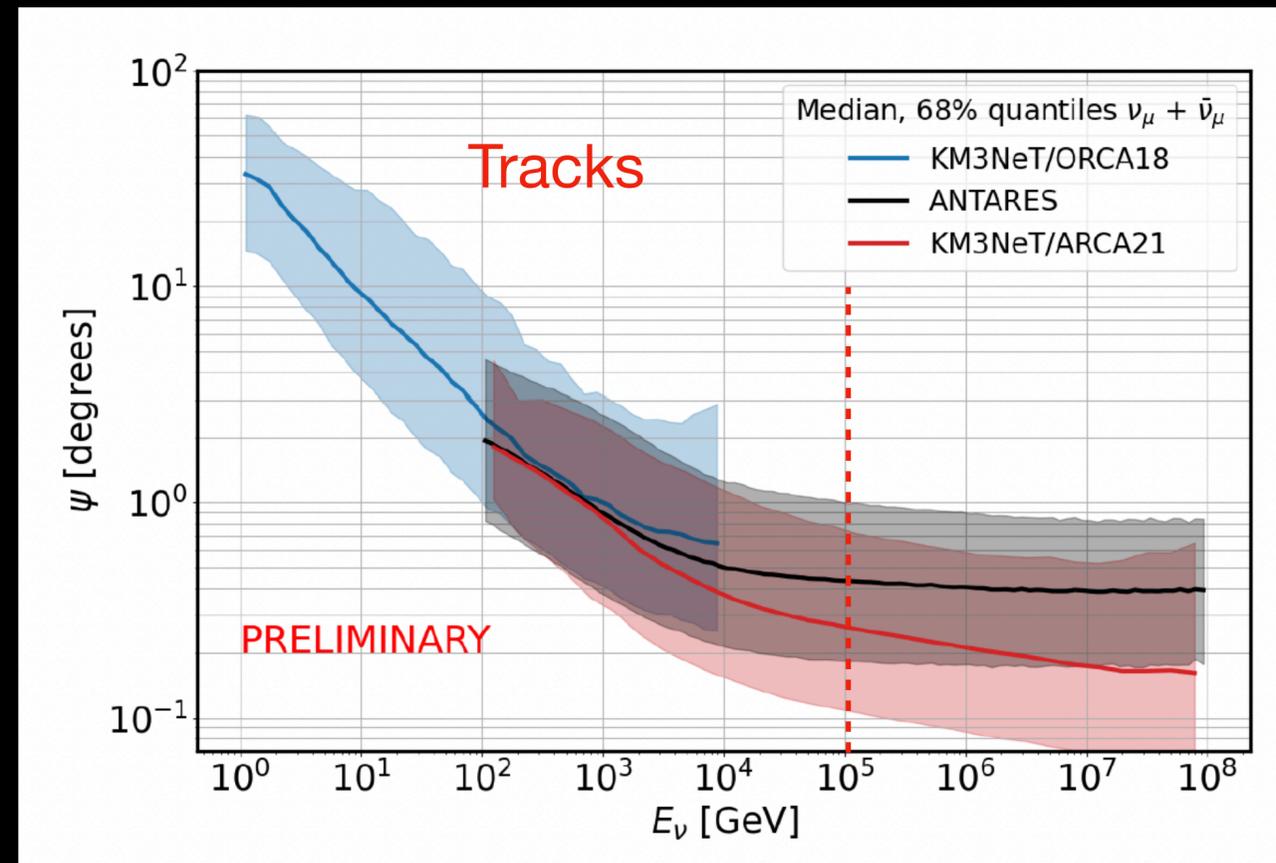
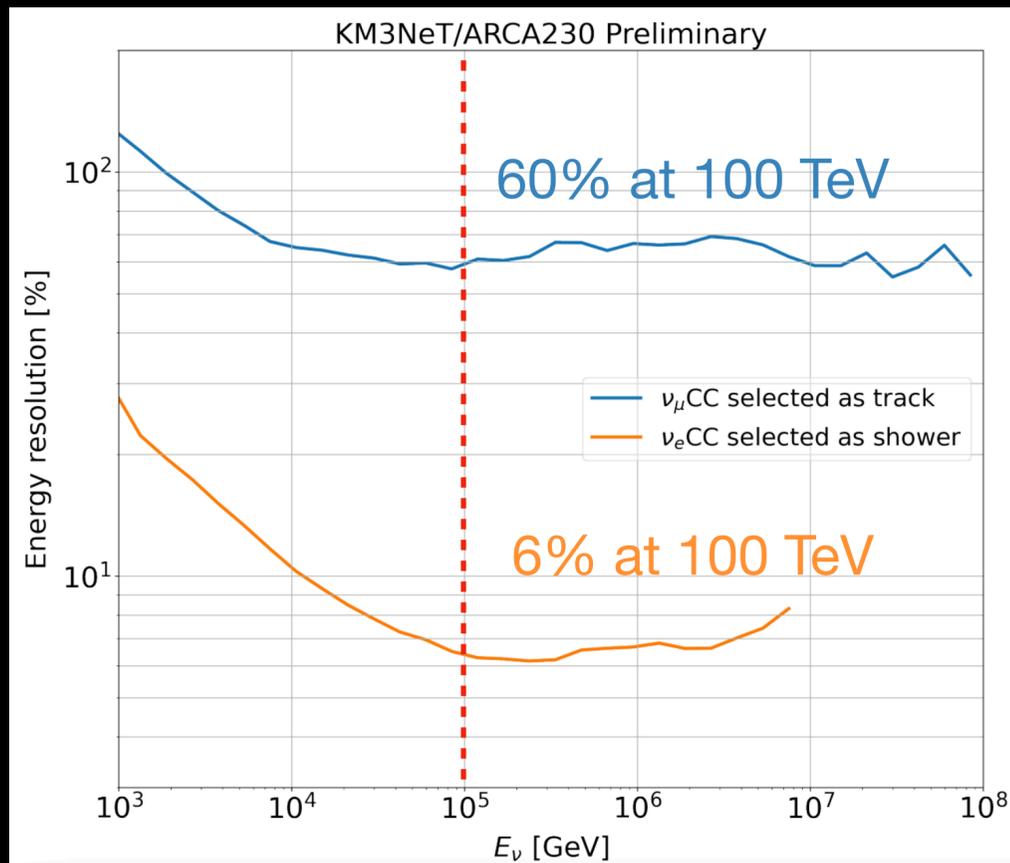
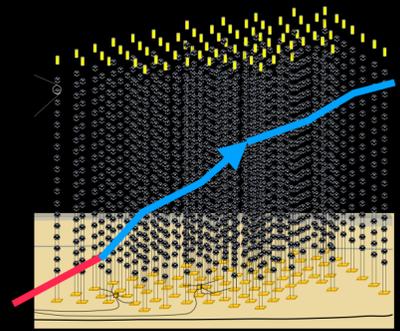


KM3NeT energy and pointing resolution



Shower direction resolution: 2° at ARCA at 100 TeV, evaluation ongoing at ORCA

KM3NeT energy and pointing resolution

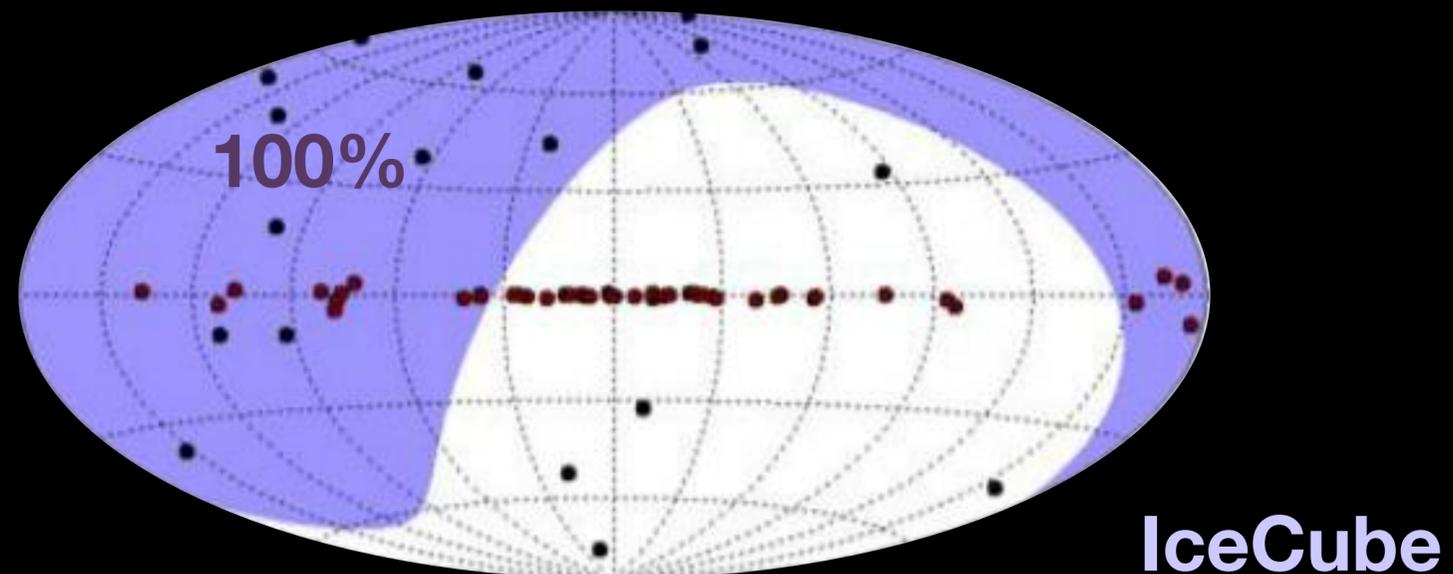
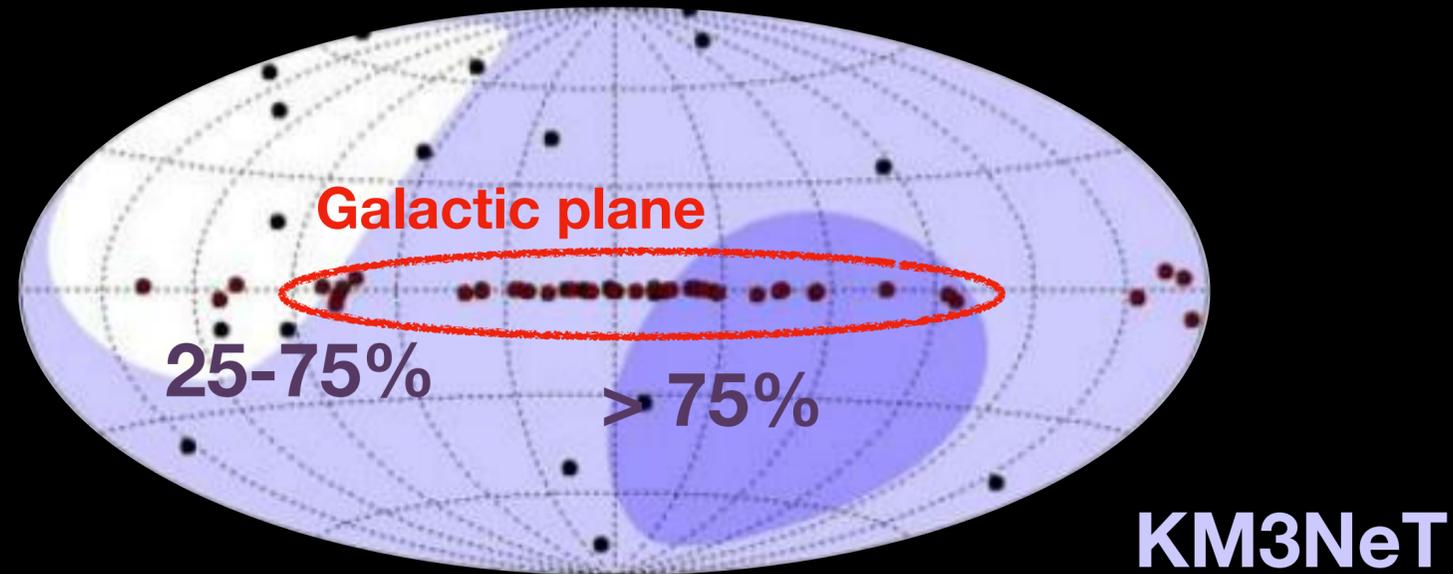
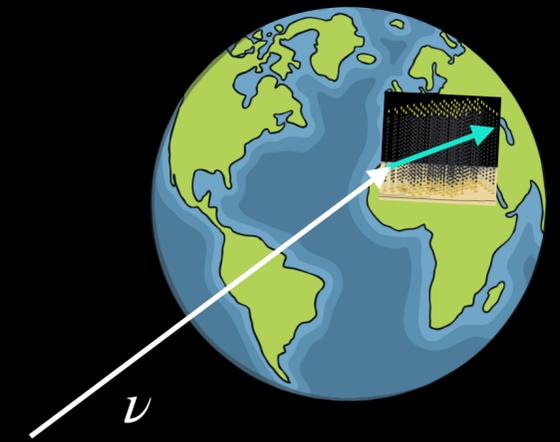


~0.2° at 100 TeV

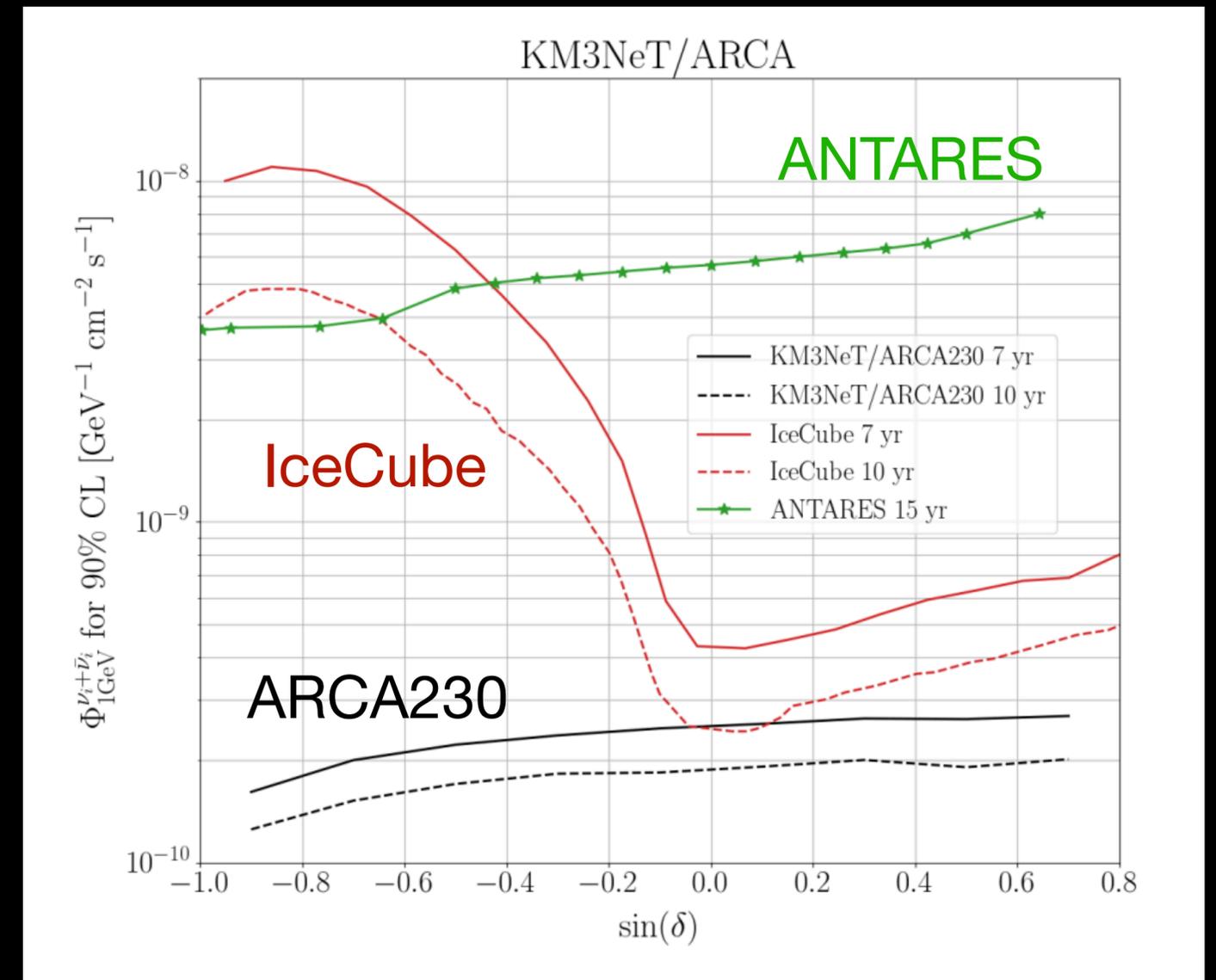
Shower direction resolution: 2° at ARCA at 100 TeV, evaluation ongoing at ORCA

KM3NeT sky coverage for tracks

Complementarity with IceCube



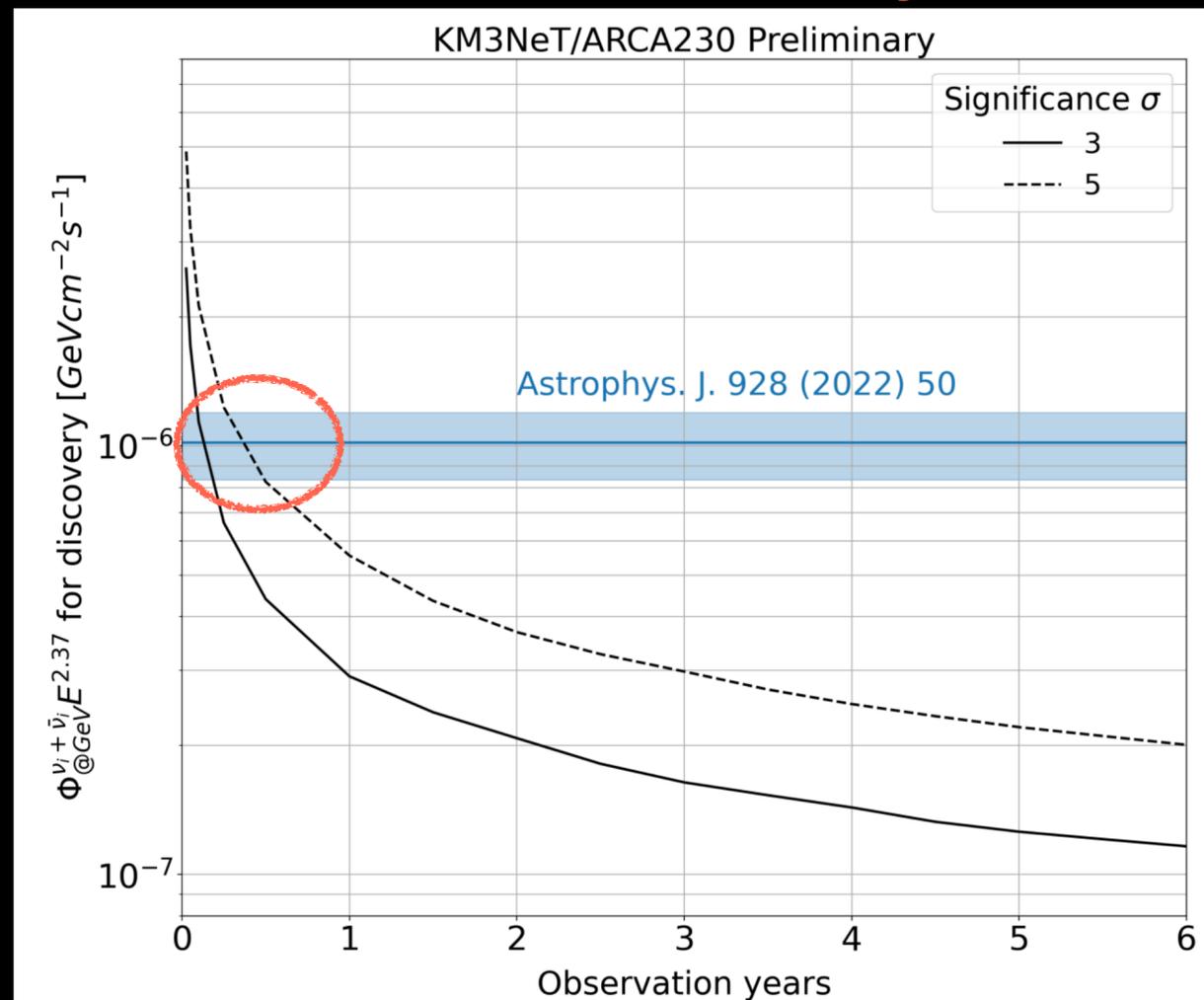
Sensitivity to resolved sources



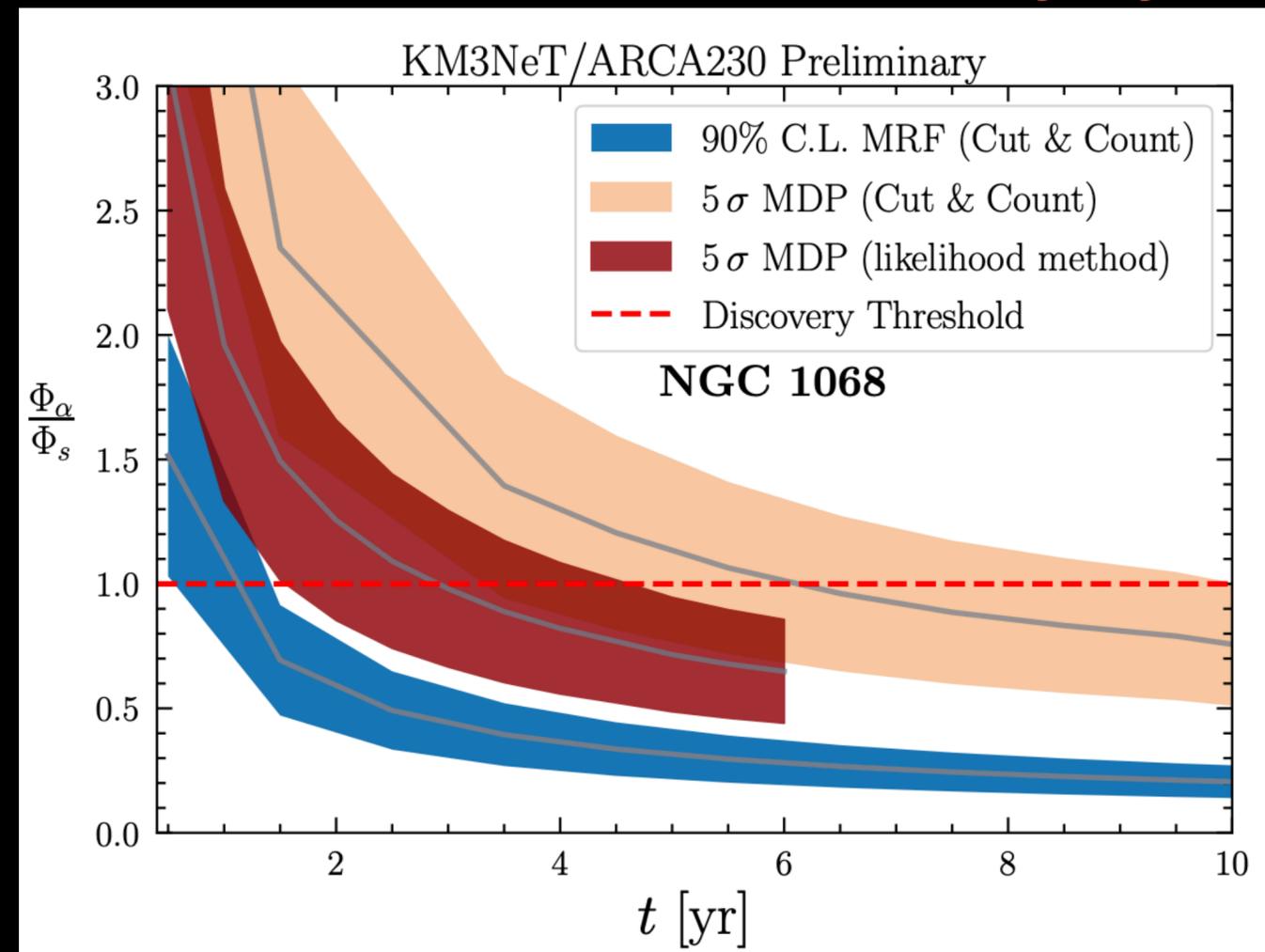
KM3NeT's astrophysics potential

ARCA230: diffuse neutrino flux & NGC1068

Diffuse ν flux rediscovery: 6 months



NGC1068 ν flux rediscovery: 3 years



Current astrophysical analyses: ARCA6-21 (640 days) & ORCA6-18 (1200 days)

Outline

- Searches for point-like neutrino sources
 - An ultra-high-energy cosmic neutrino
 - Searching for resolved neutrino sources
 - Multi-detector studies
- Extended sources and diffuse fluxes
 - All-sky diffuse astrophysical neutrino flux
 - Galactic neutrino emission
- Core-Collapse Supernova neutrinos: outside KM3NeT's main energy range

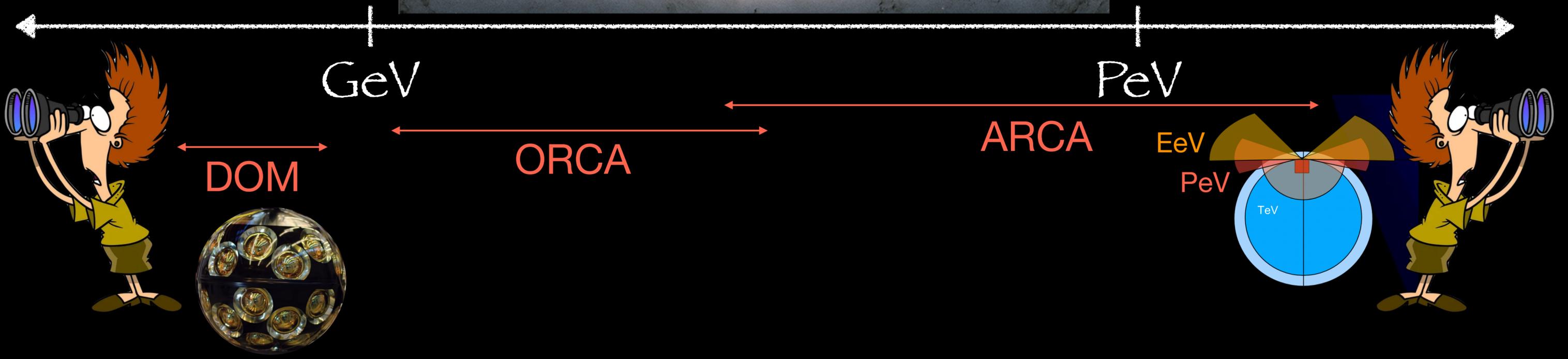
Outline

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The Ultra-High-Energy regime

Beyond the PeV

Cosmic-ray accelerators and trapping regions



The Ultra-High-Energy regime

Beyond the PeV

Cosmic-ray accelerators and trapping regions



Energetic sources?

Cosmogenic neutrinos?

GeV

PeV

DOM

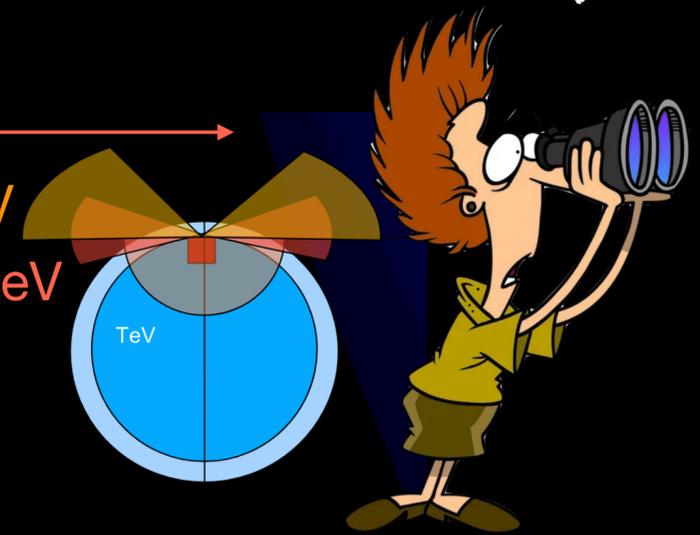
ORCA

ARCA

EeV

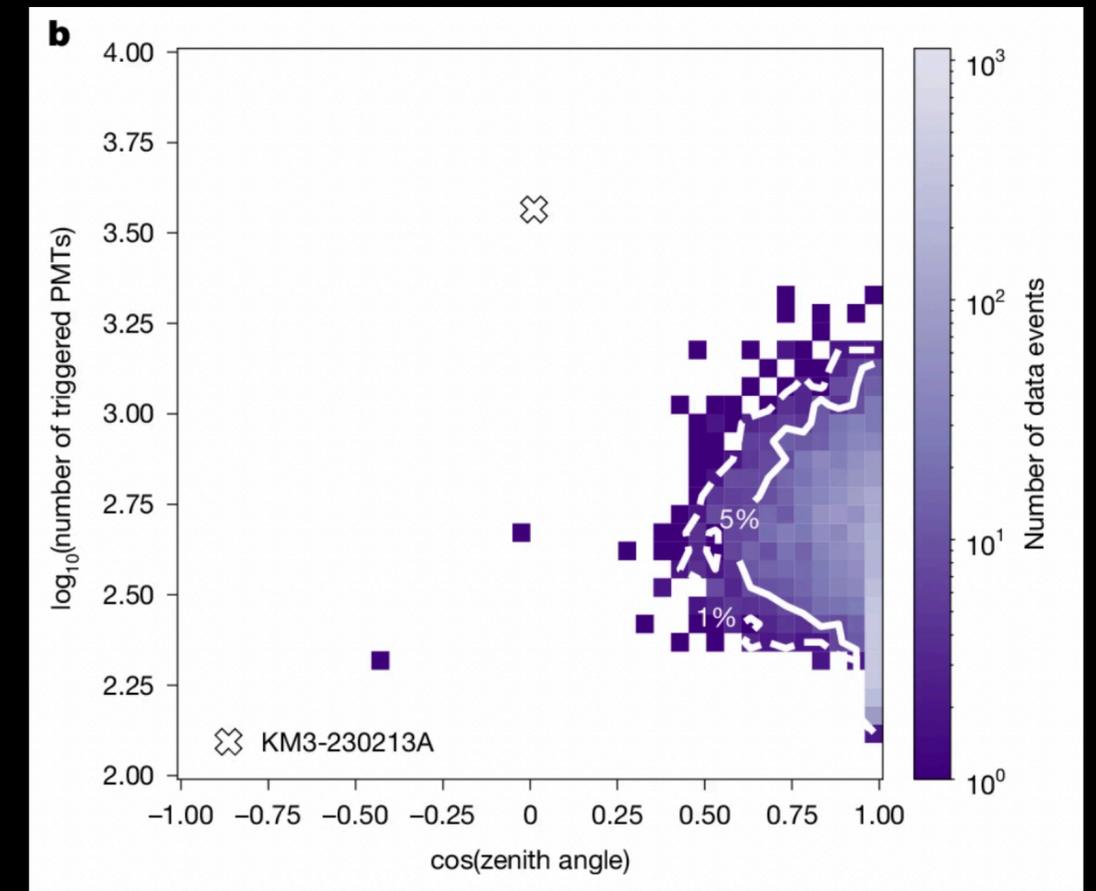
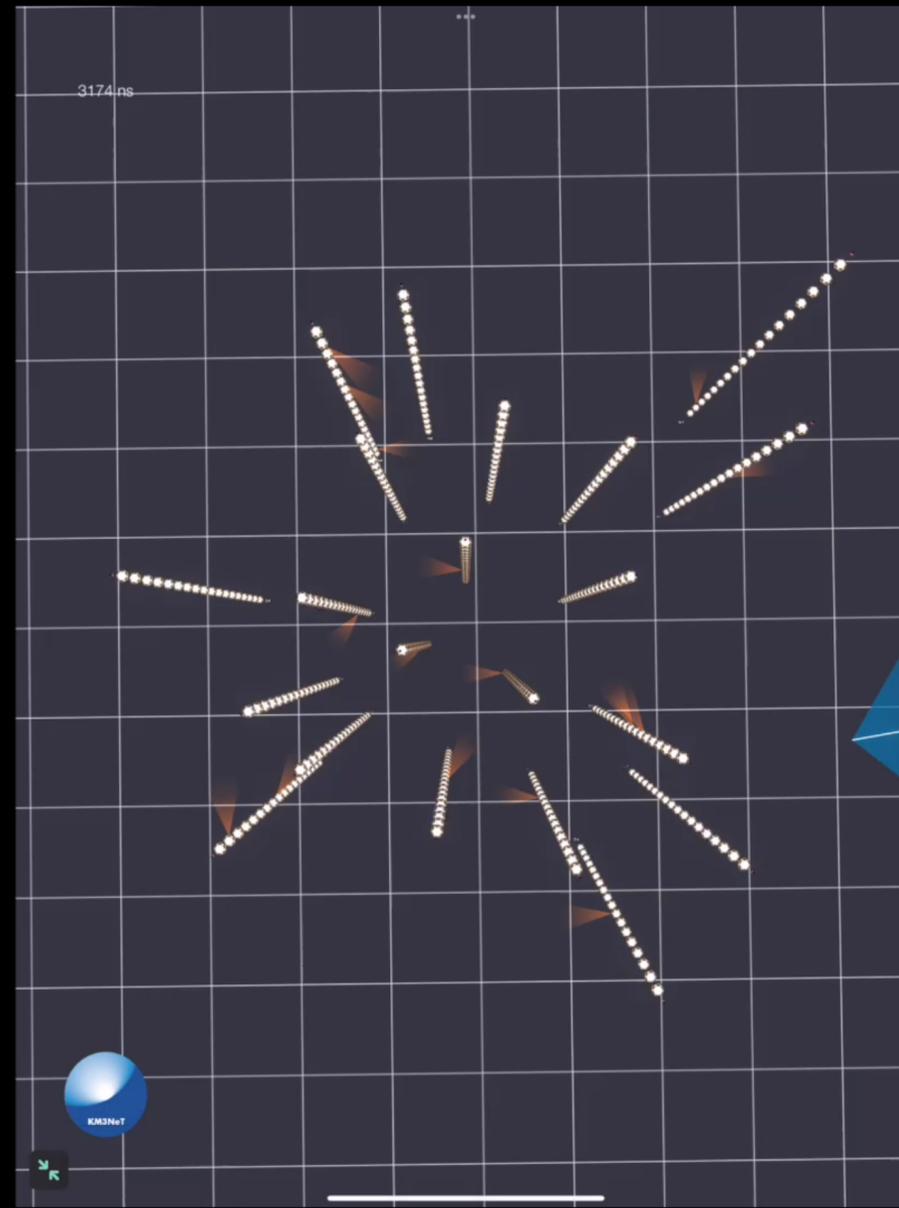
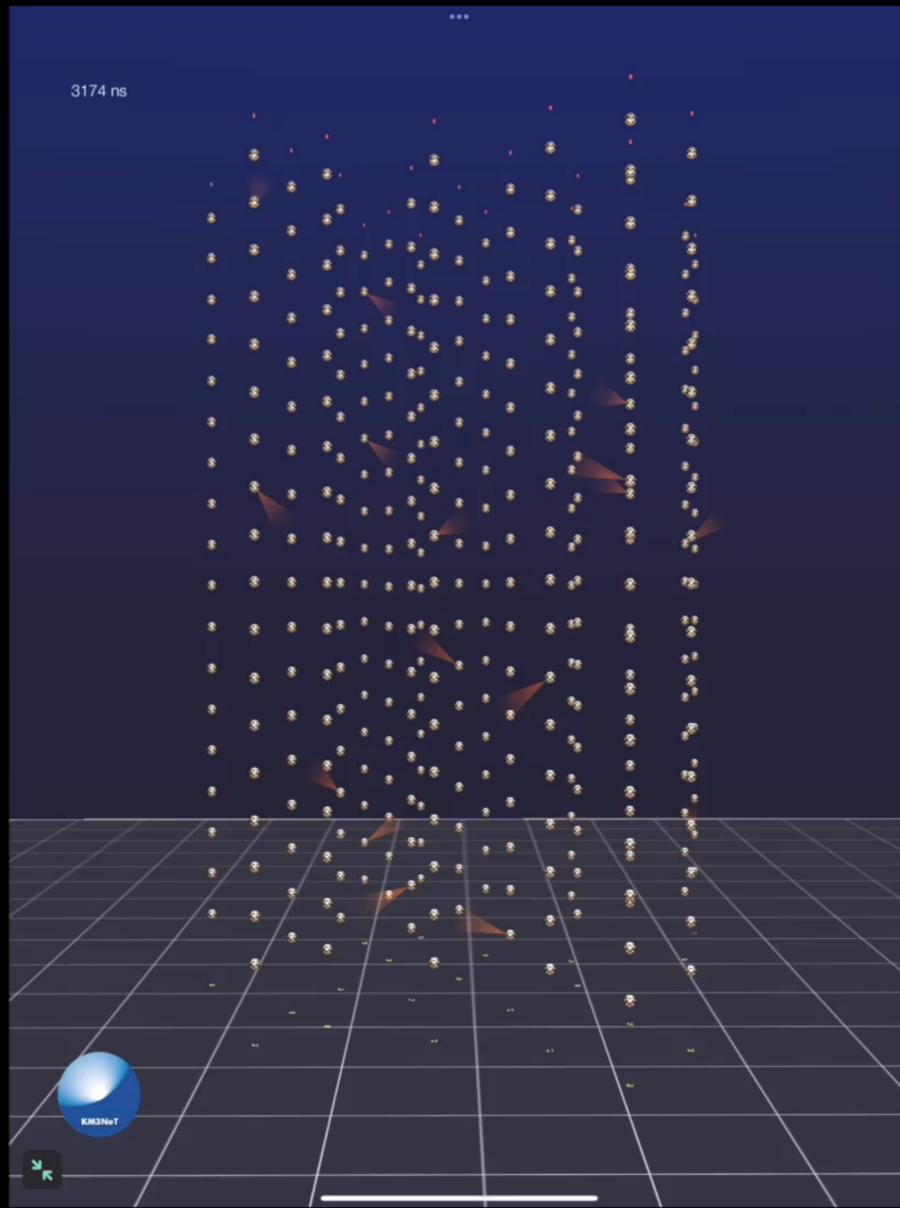
PeV

TeV



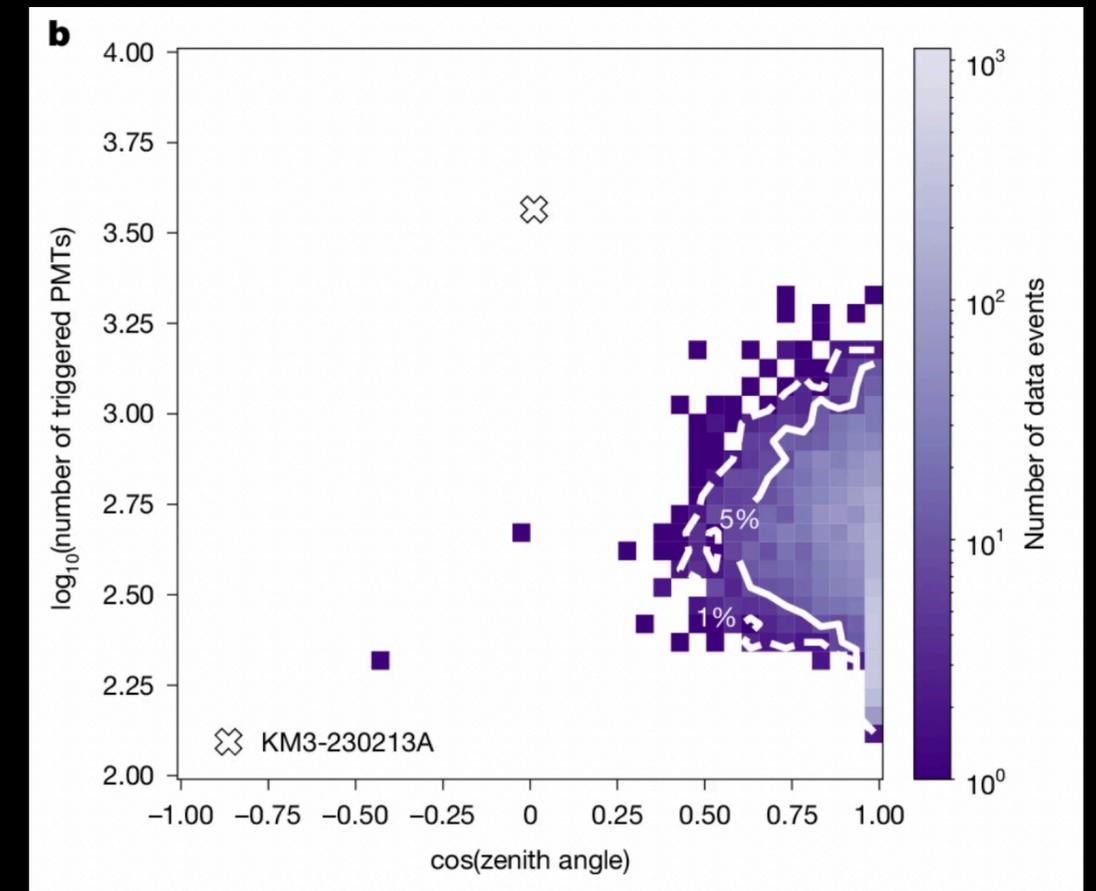
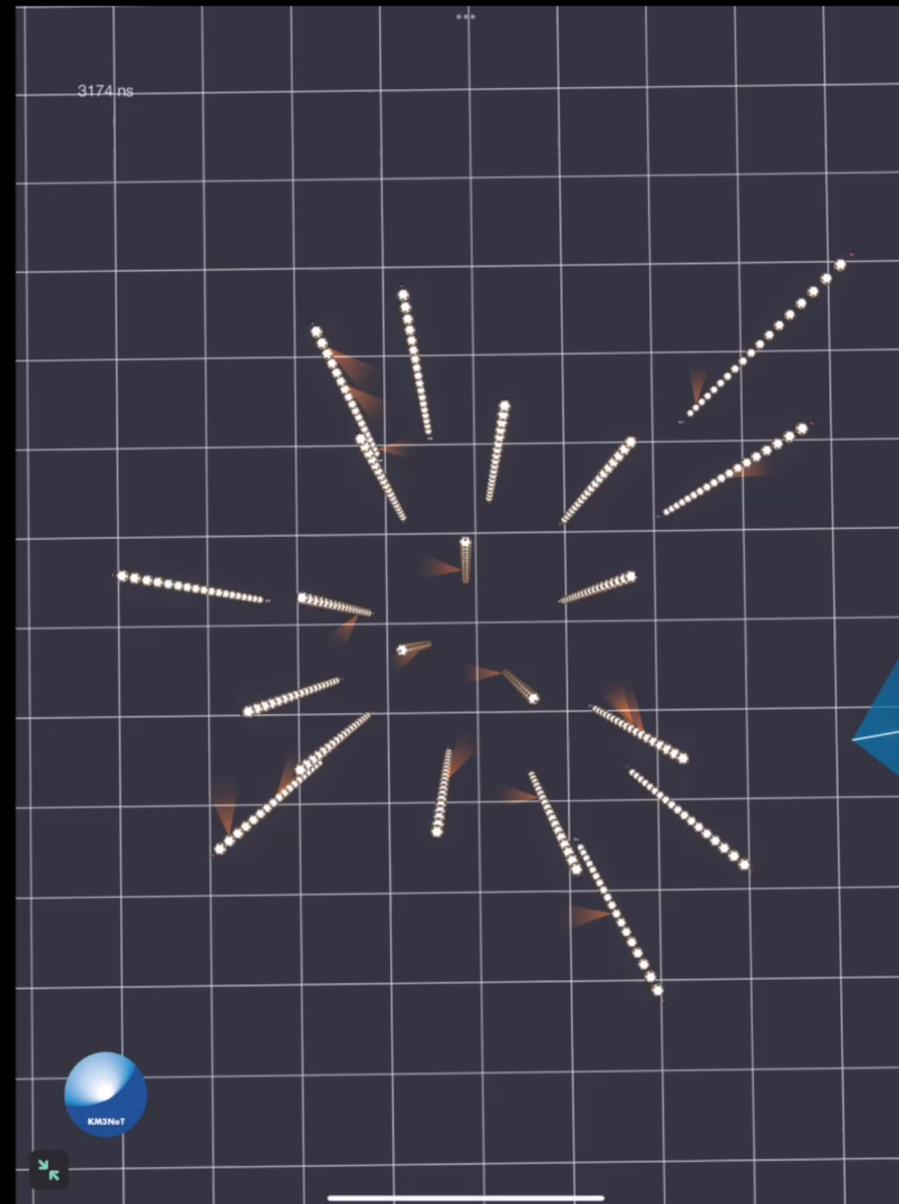
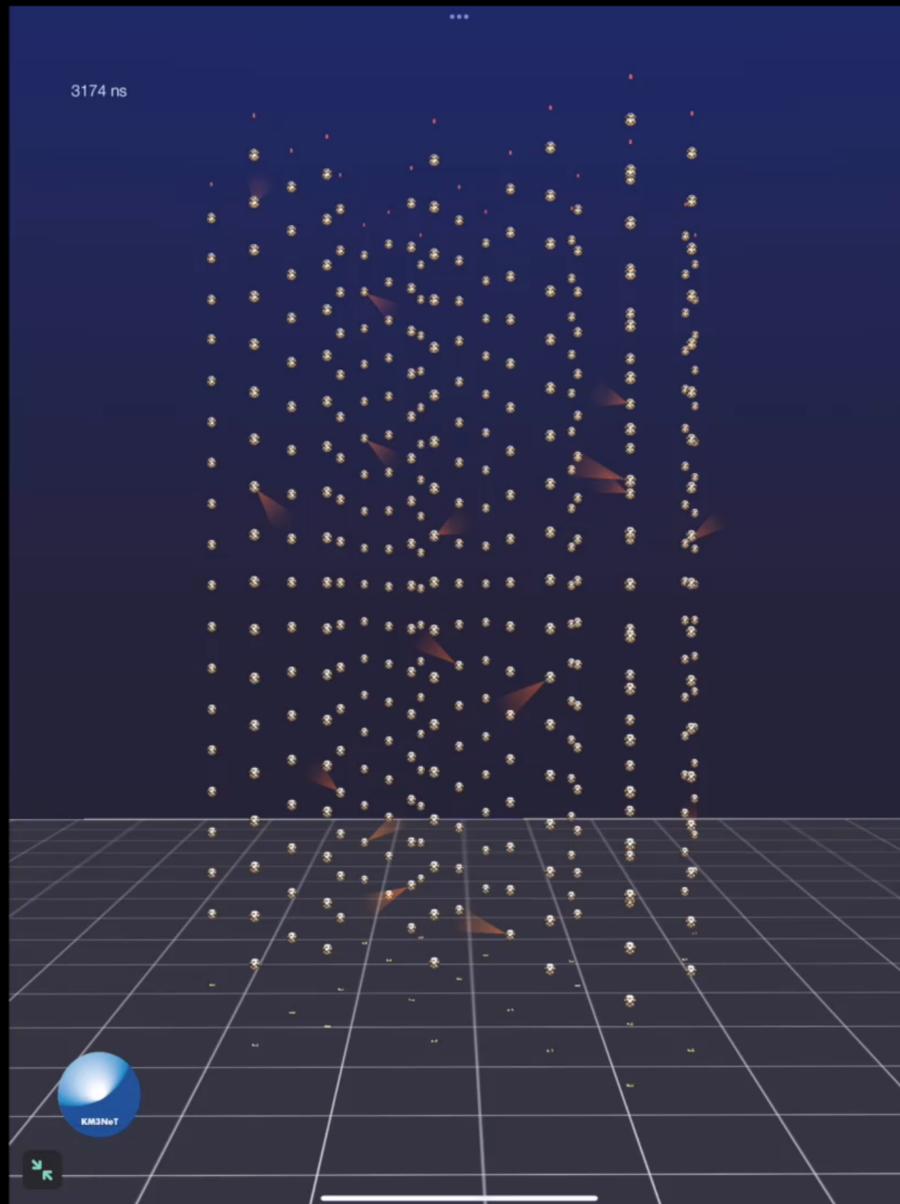
A very-high-energy event — Feb 13th, 2023

01:16:47 UTC



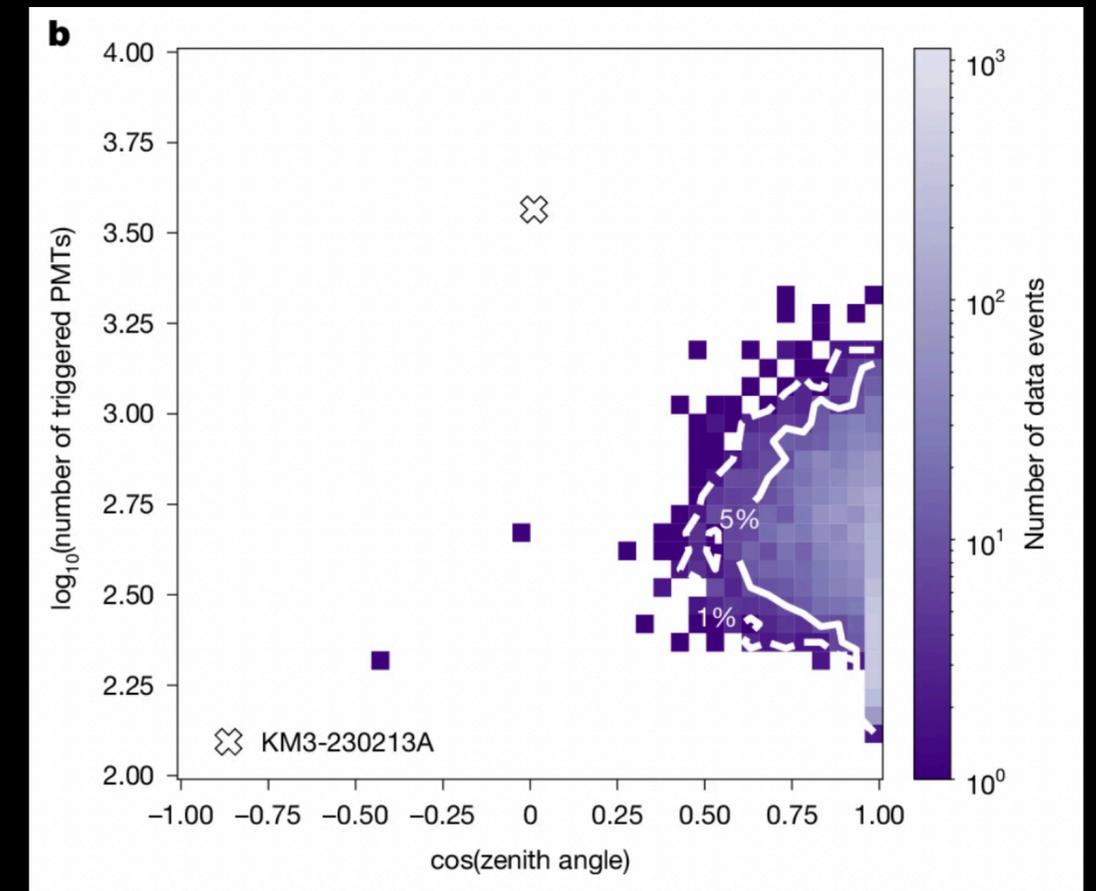
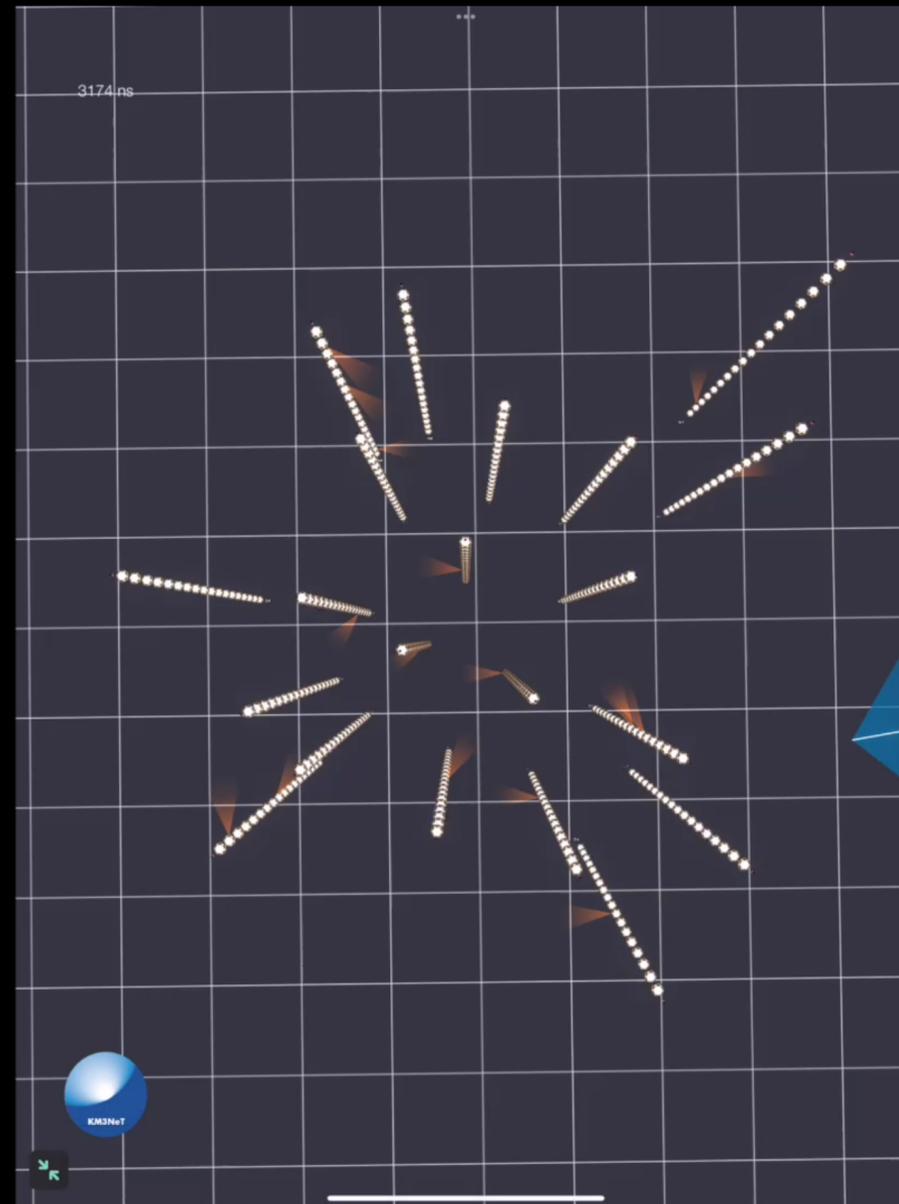
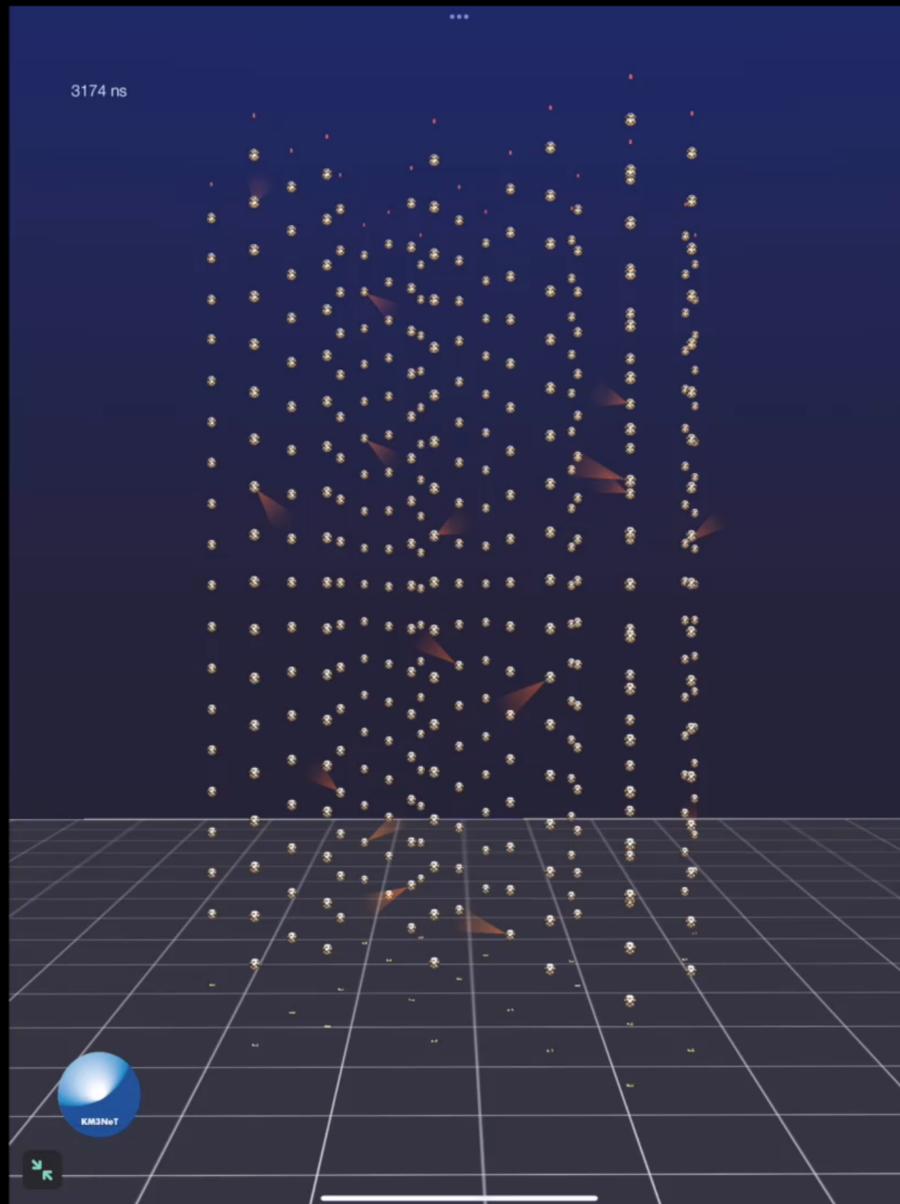
A very-high-energy event — Feb 13th, 2023

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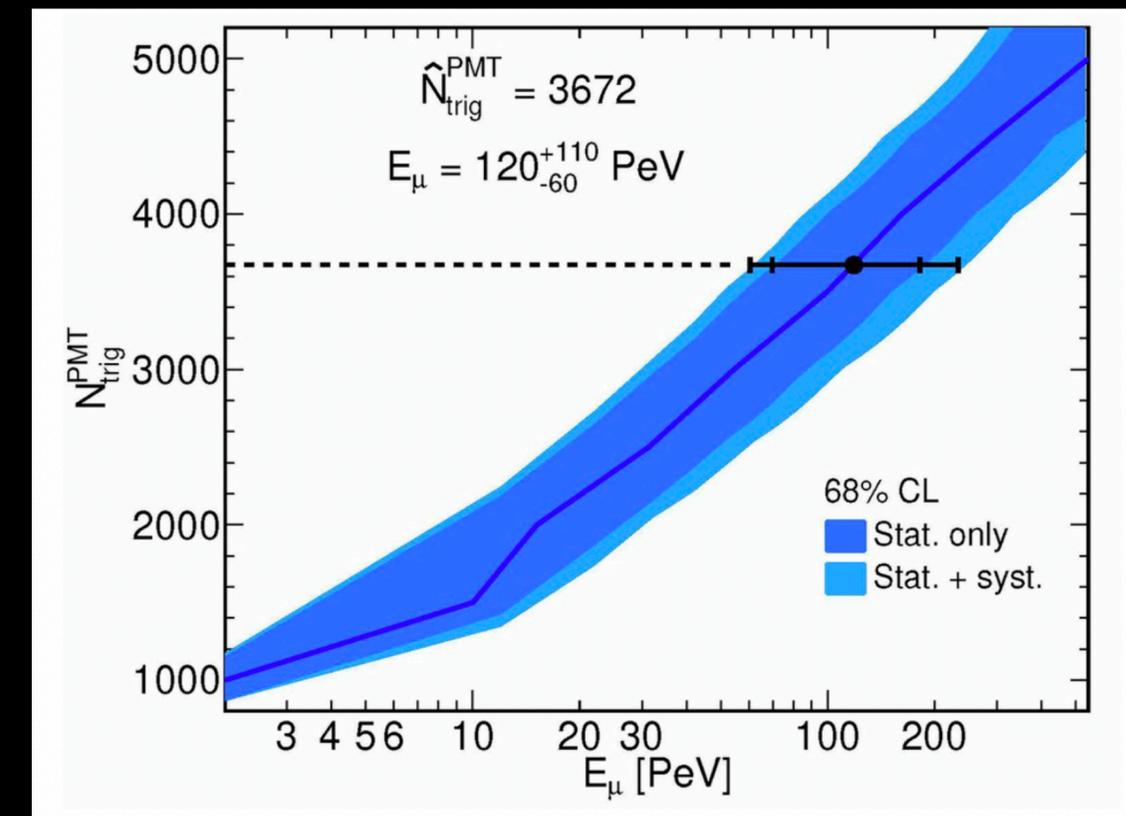
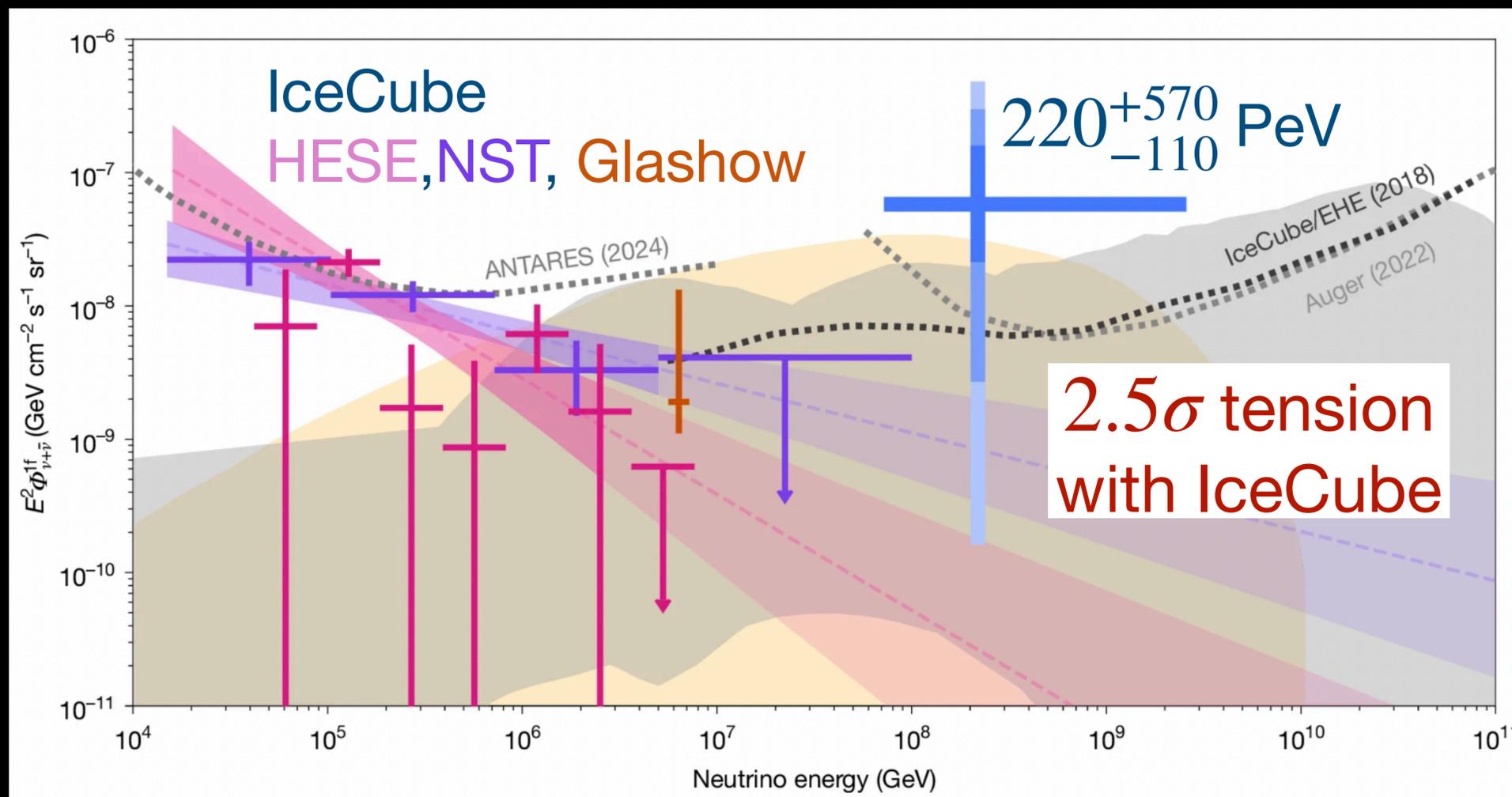
01:16:47 UTC



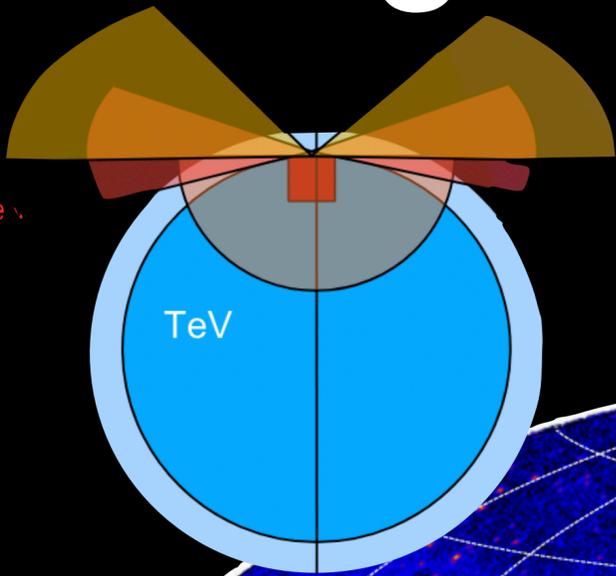
The astrophysical neutrino landscape

From TeV scale to 100s of PeVs

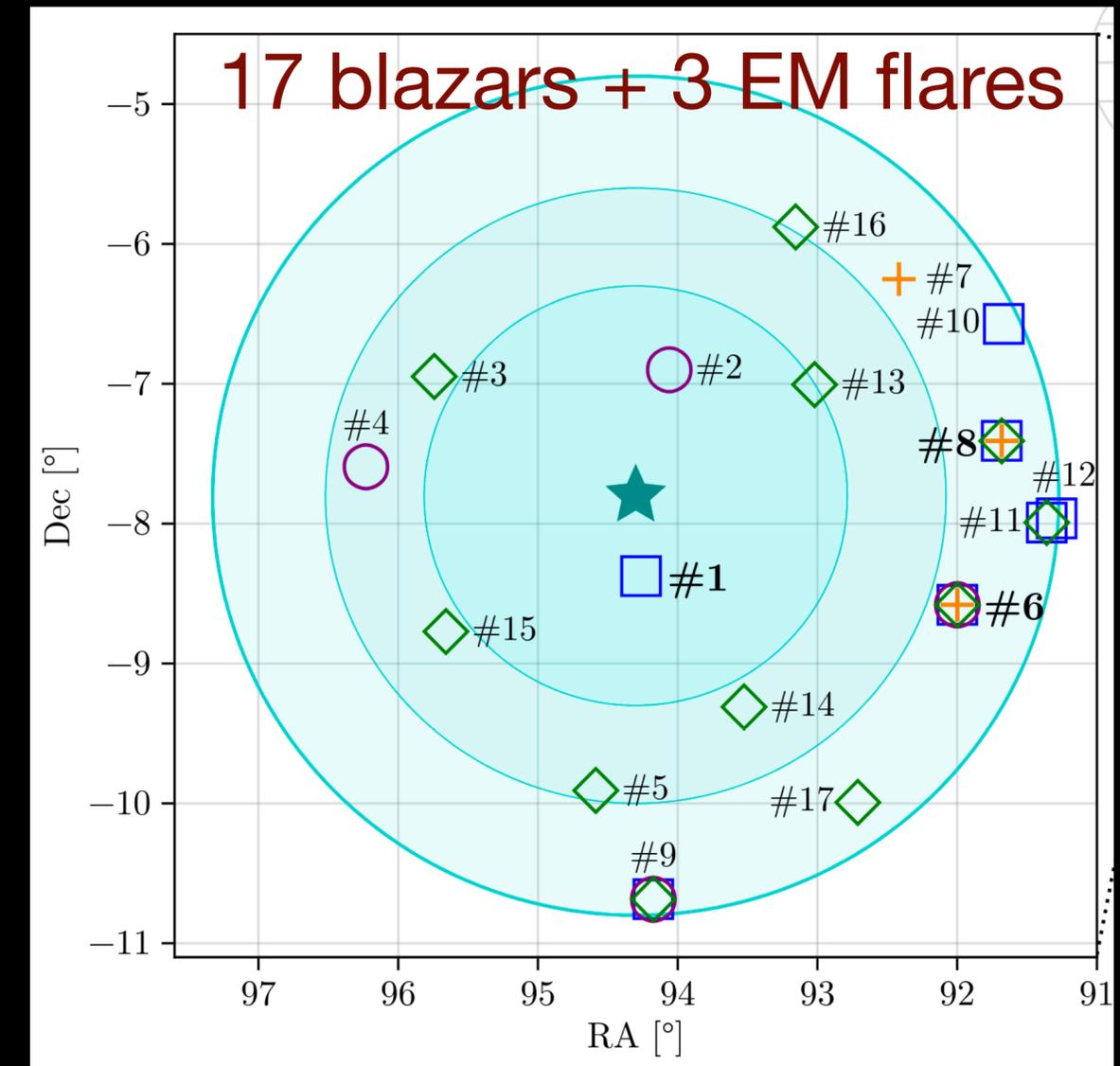
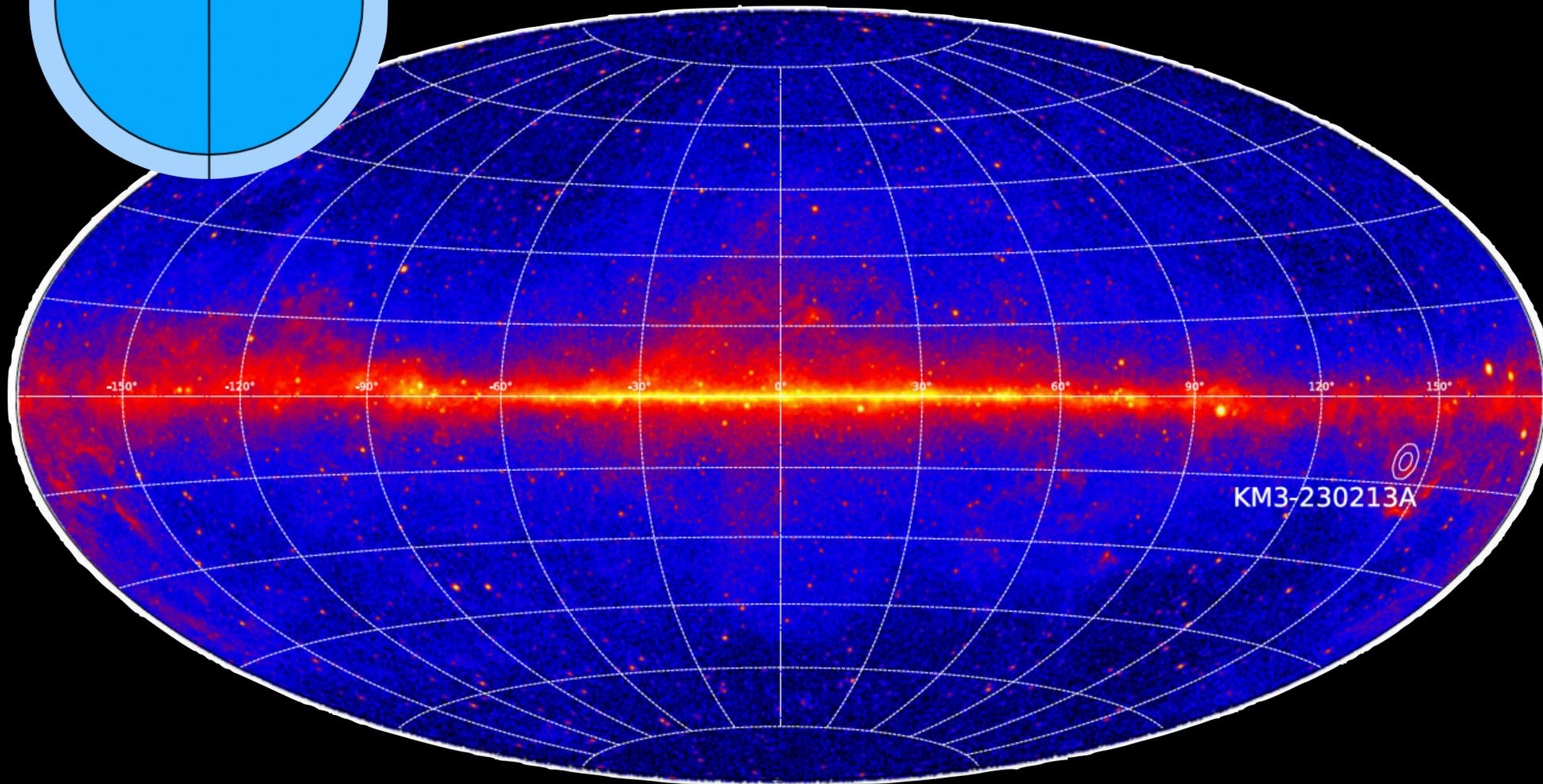
Simulations: Infer muon energy from number of PMT hits



Origin unidentified yet



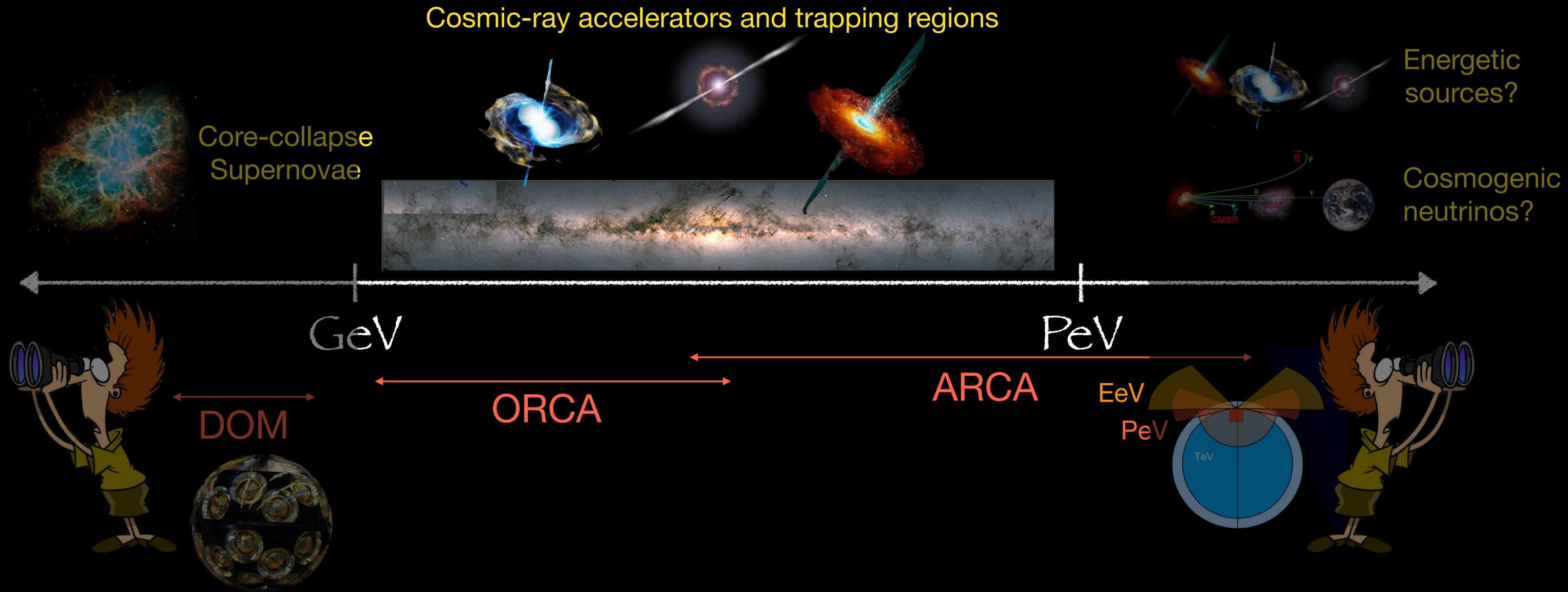
RA=94.3° dec=-7.8°
with 1.5° error circle (to be improved!!)



- No Galactic candidate
- No lower-energy neutrinos
- Compatible with predictions for blazar & GRB populations

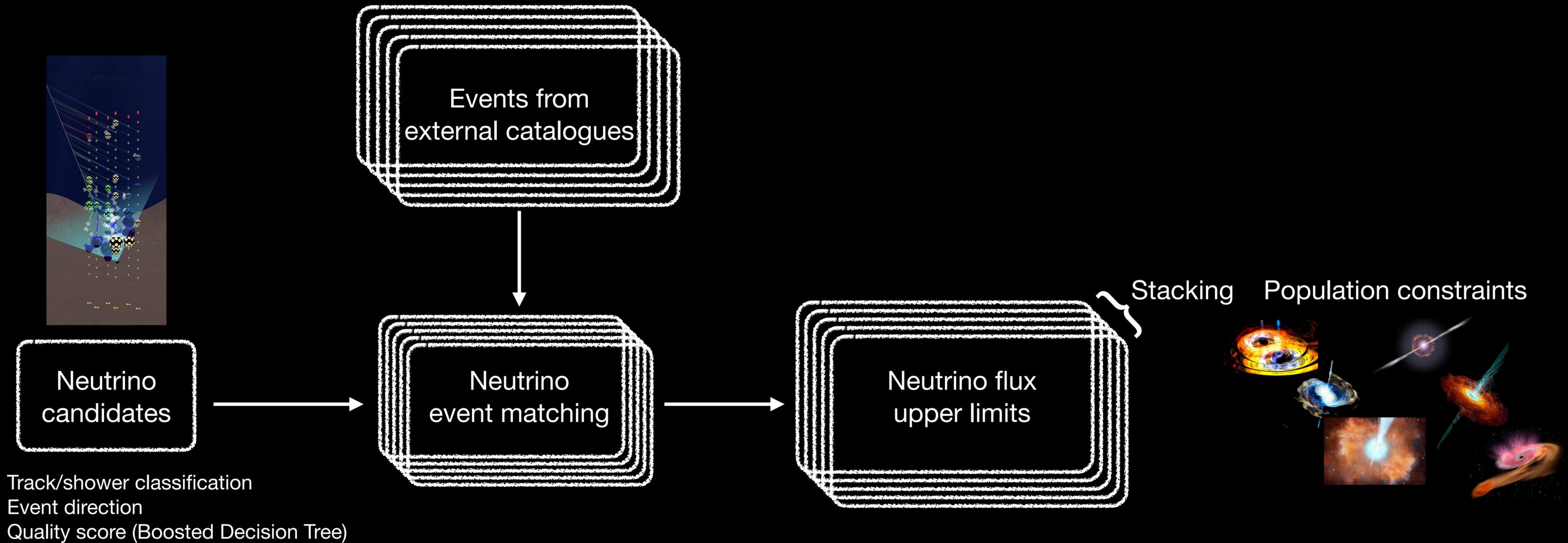
KM3NeT's astrophysics potential

Exploring the MeV to PeV range



Searching for resolved neutrino sources

Analysis strategy



Matching and upper limits

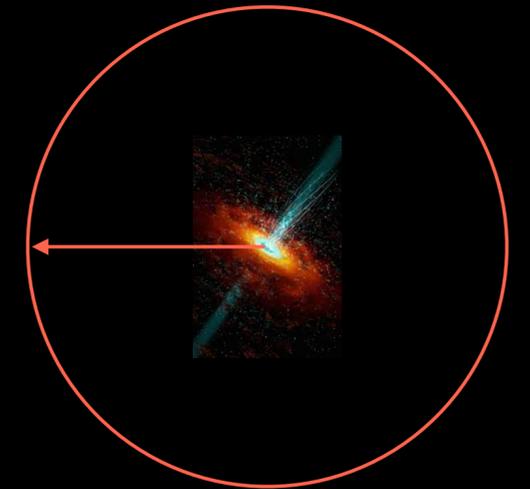
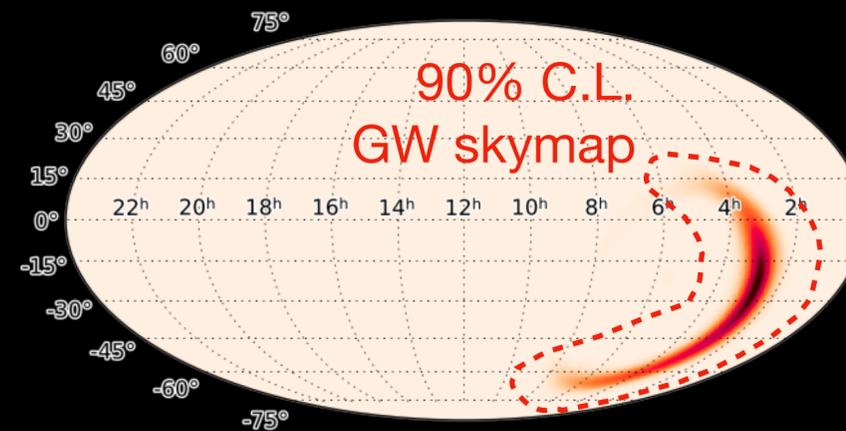
Time coincidence (for transients)

GWs : $\pm 500\text{s}$, $[-500\text{s}, +6\text{h}]$

ν alerts : $\pm 1\text{h}$, $\pm 24\text{h}$

GRBs, transients: $\pm 500\text{s}$, $\pm 1\text{h}$, $\pm 24\text{h}$

Spatial coincidence



Adjustable margin: optimize significance
Fixed margin: likelihood analysis

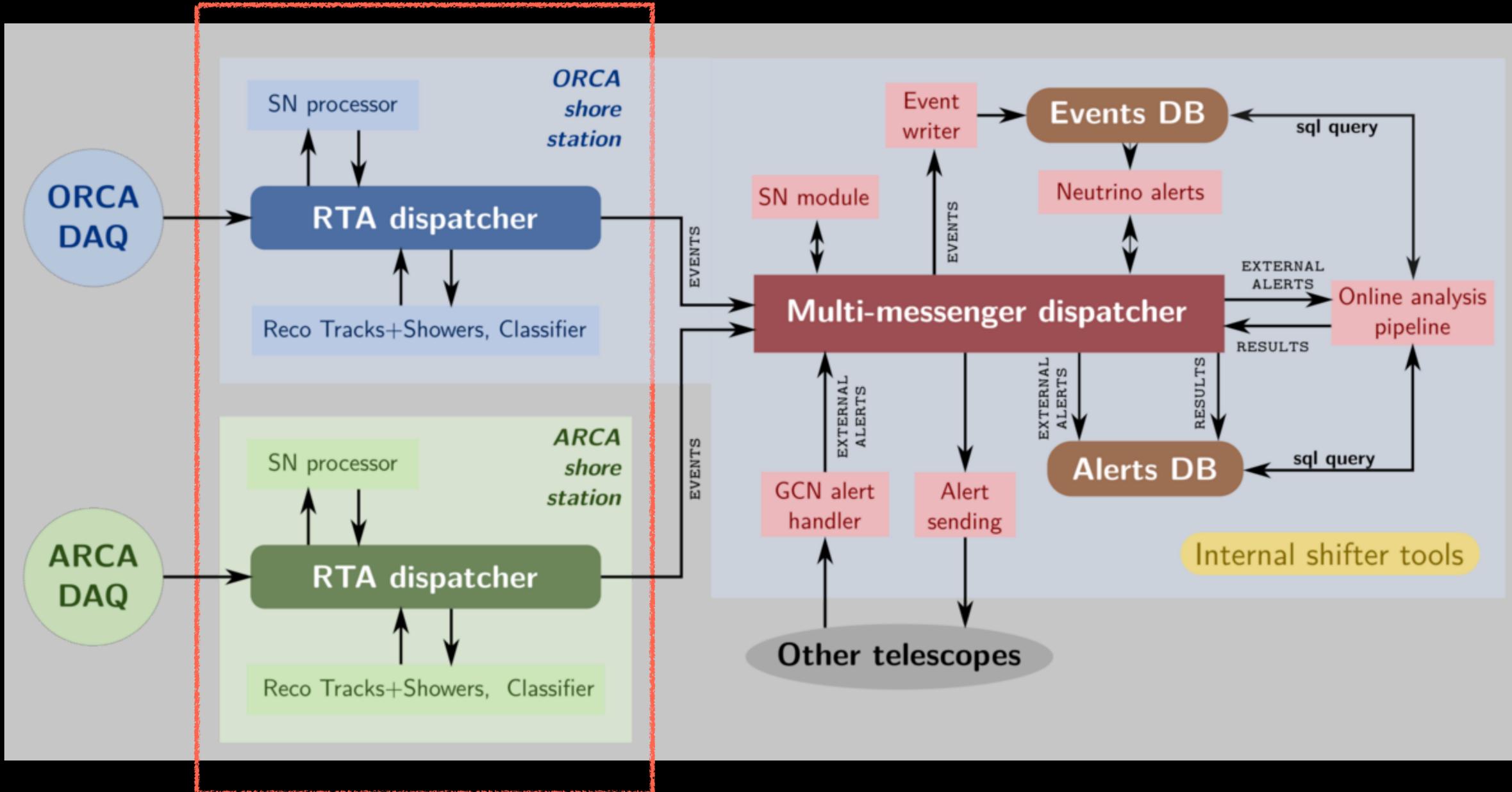
Likelihood analysis — Isotropic emission:

$$\phi(E_\nu) = \phi_0 E_\nu^{-\gamma} \longrightarrow \mathcal{L}(N_{\text{obs}}, B, \phi_0, \gamma)$$

...or a cut-and-count search (e.g. realtime analyses)

Realtime analysis system – External triggers

Currently $< 1^\circ$ precision
above 10 TeV

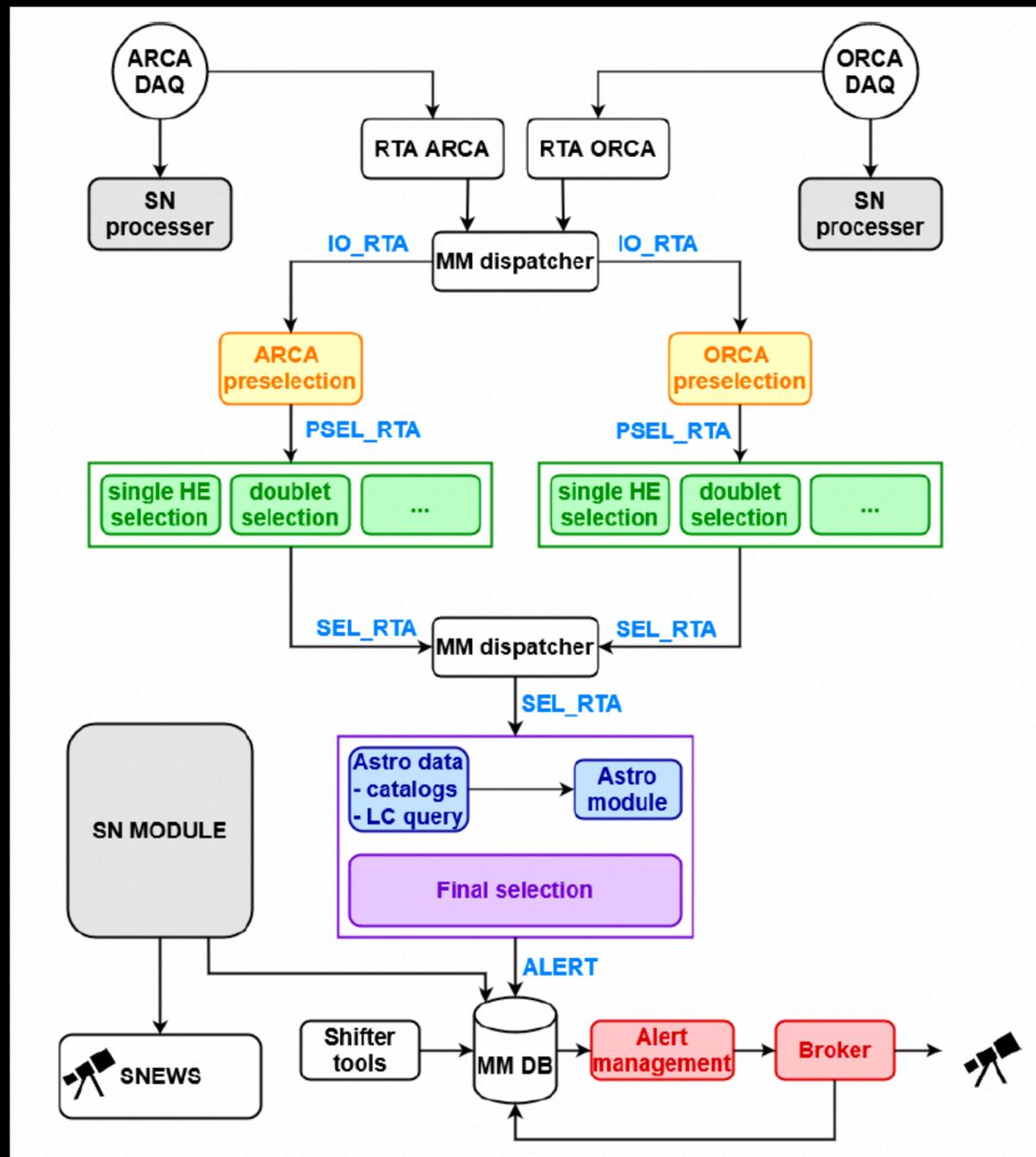


\approx 1400 alerts processed
up to now

Upgoing AND downgoing tracks
7s latency

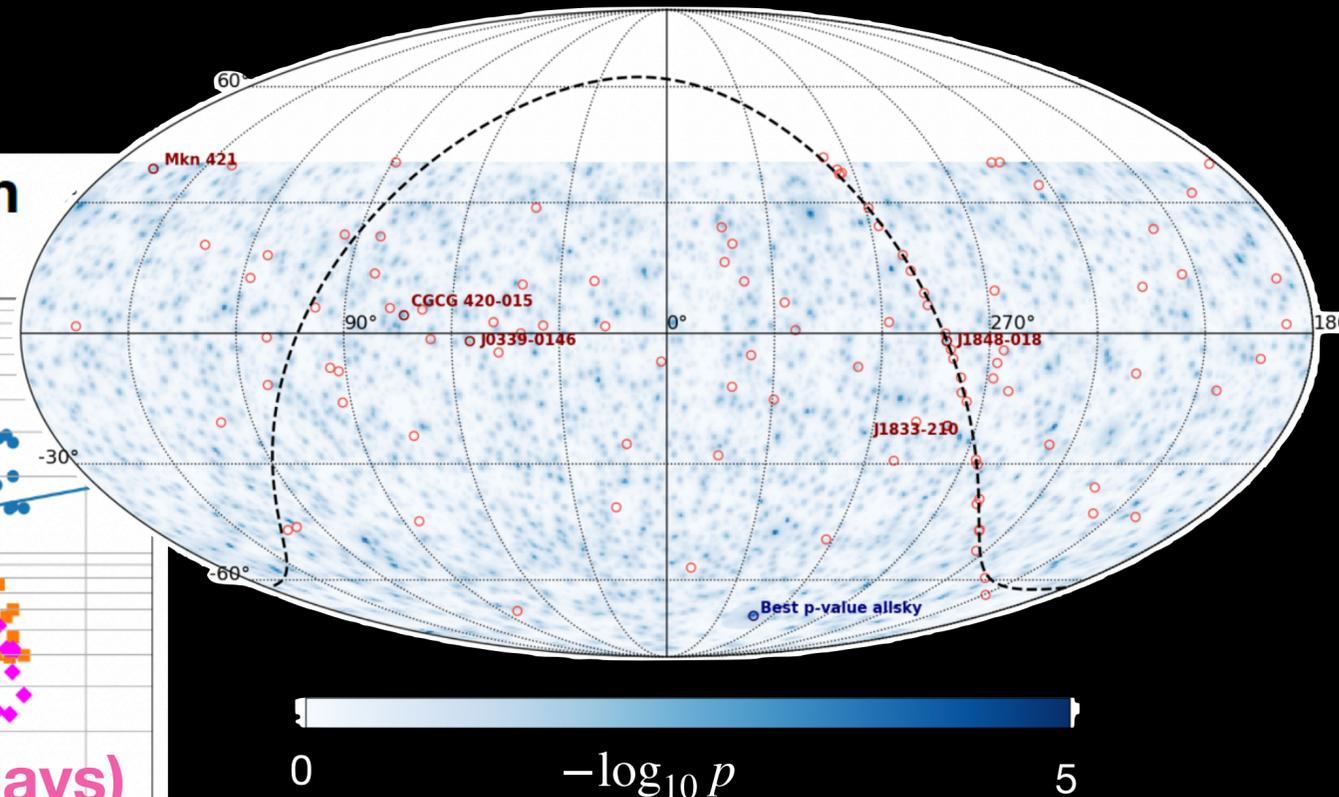
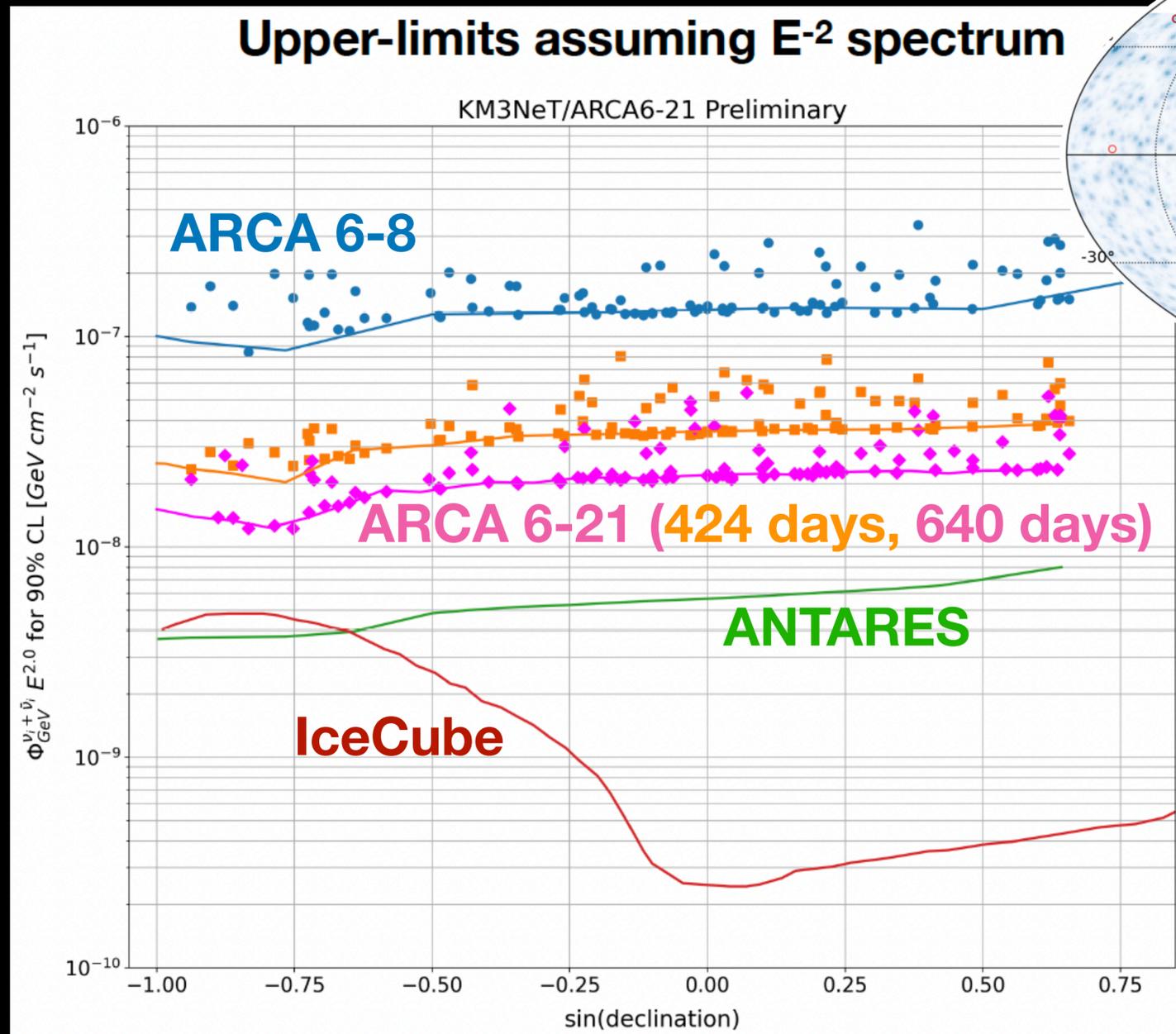
KM3NeT real-time analysis system

Alert sending



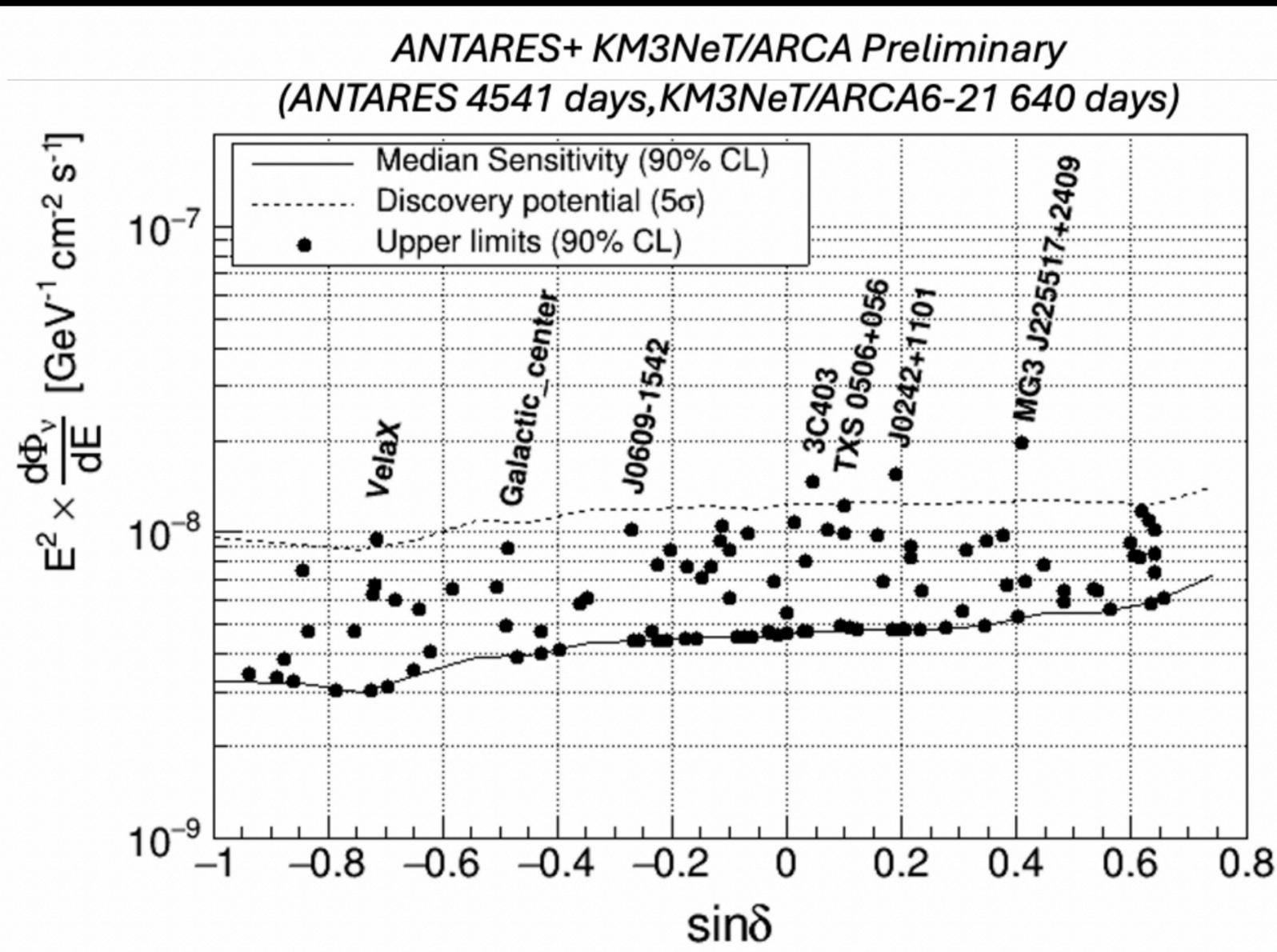
- Search for correlations with a selection of known astrophysical objects (considering e.g. X-ray, γ -ray, radio brightness)
- If coincidence, check object activity
- Neutrino-only alerts could be issued for exceptional events
- Deployment date: End of 2026

Offline search for point-like sources



- Binned likelihood analysis: all-sky search + search with catalogue of 106 EM sources
- Upgoing + nearly-horizontal tracks
- Low-energy extension @ ORCA6-18
Not unblinded — x5 discovery potential improvement @ TeV scale!

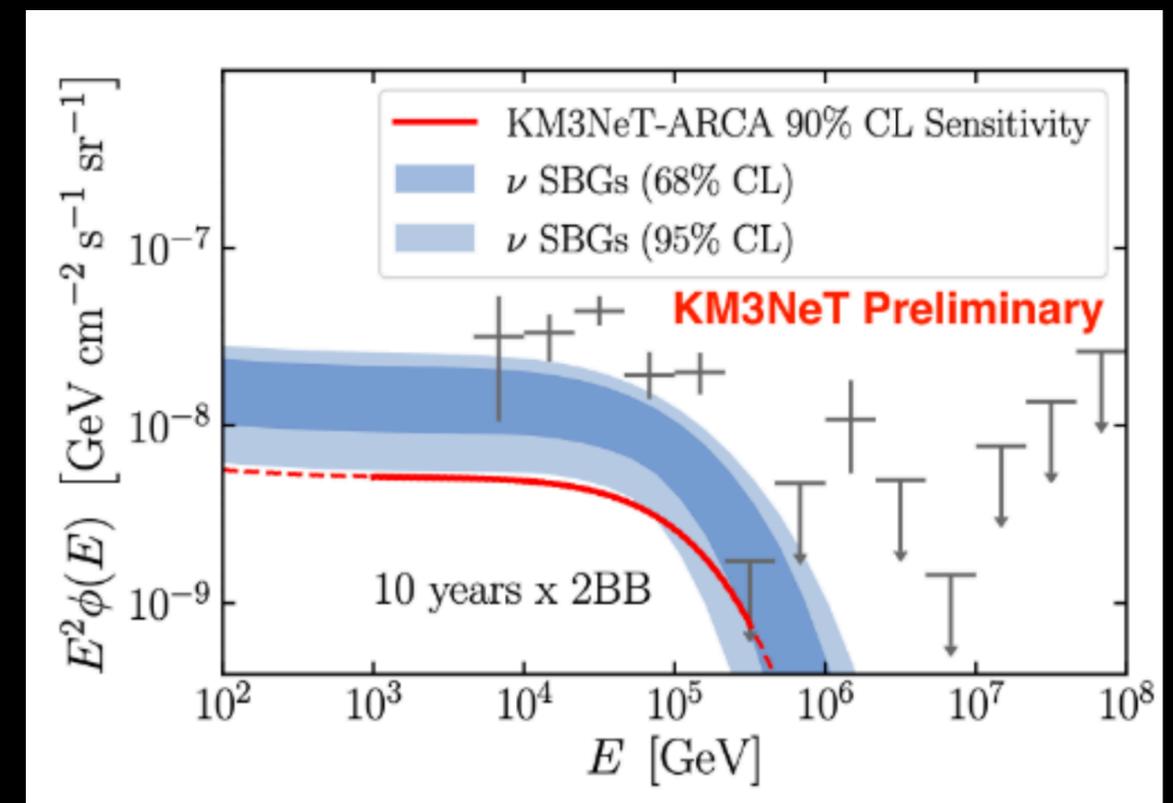
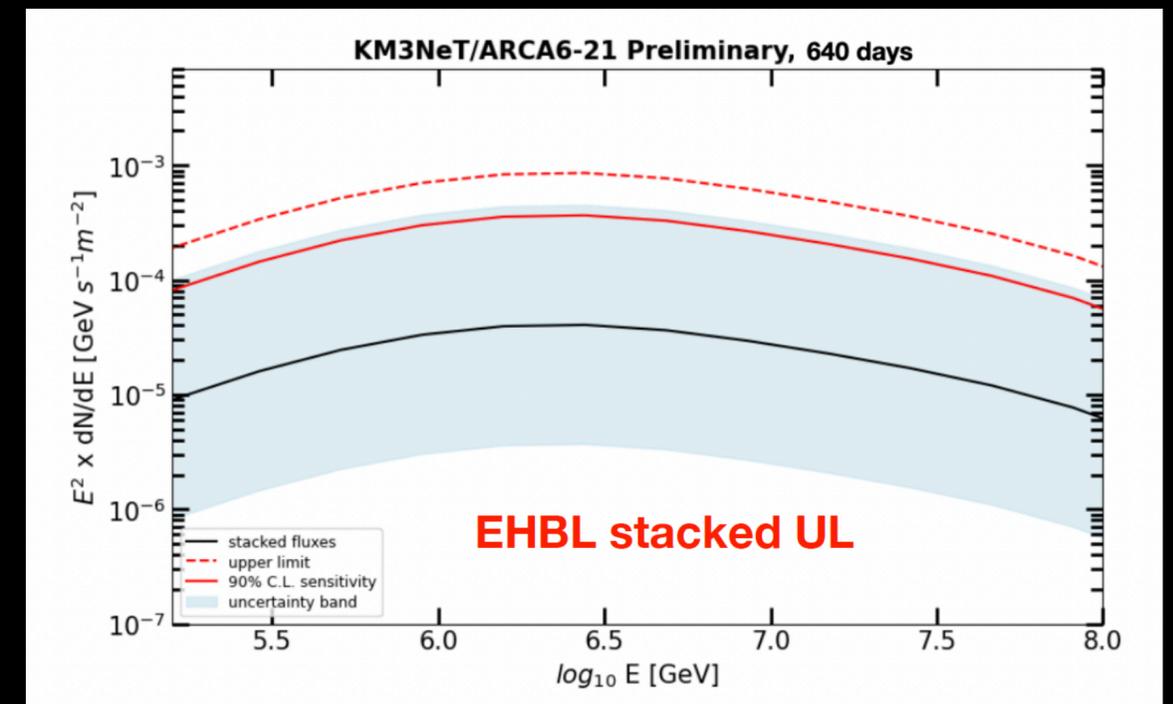
Search for point-like sources — ANTARES+ARCA



- 4541 days ANTARES + 640 days ARCA
- 20% sensitivity improvement compared to ANTARES
- 3.9-sigma **pre-trial** p-value for MG3 J22517+2409 blazar

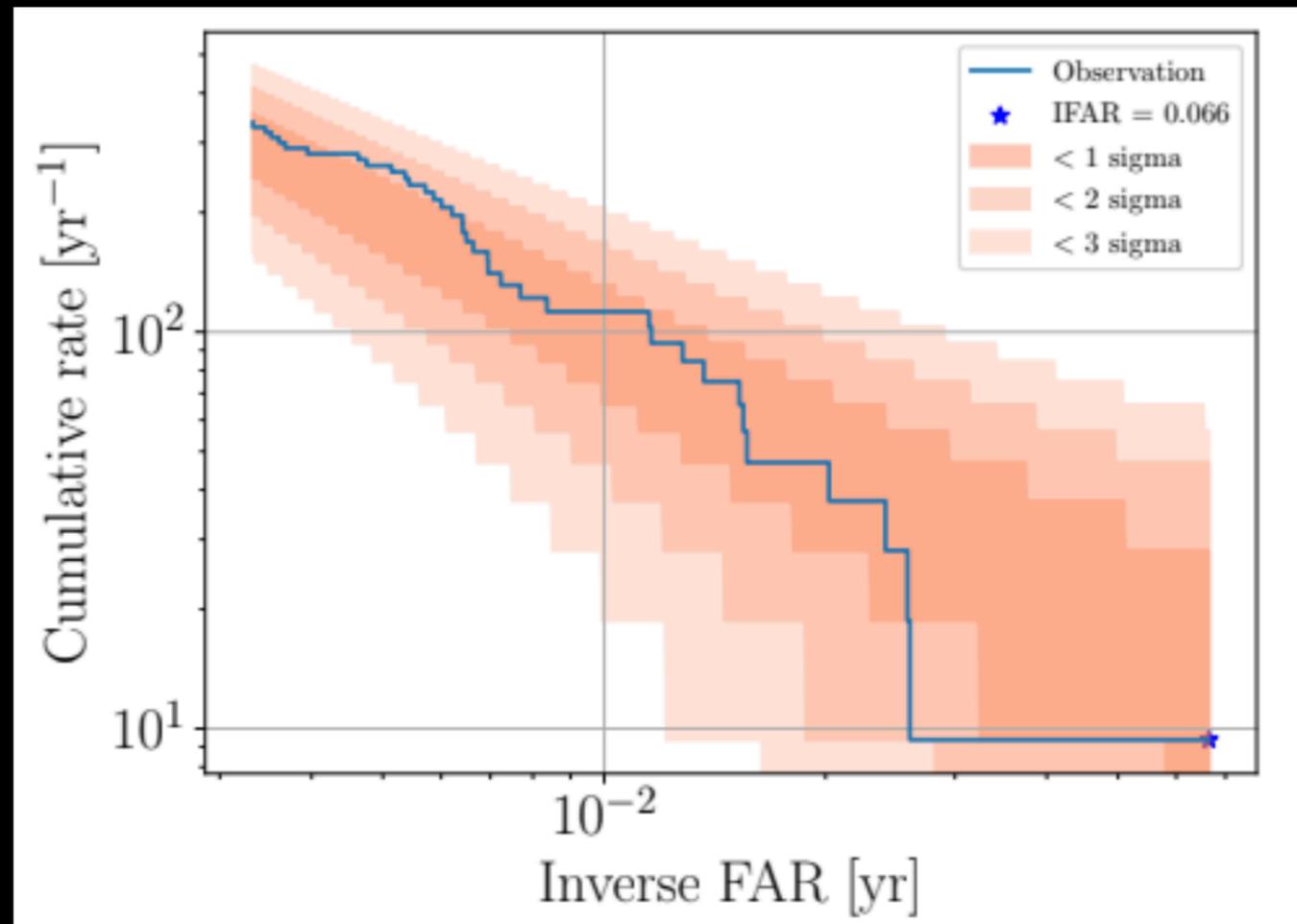
Population studies

- High-Frequency Peaked BL Lacs
232 blazars + LeHa-Paris model
Extreme blazars: 88 objects + LeHAMoC model
- Seyfert Galaxies/Star-forming galaxies
ARCA21: 32 Seyfert galaxies (BASS catalogue)
ARCA230: populations of star-forming galaxies
- Ultra-Luminous Infrared Galaxies
- Transient sources (GRBs, FRBs, microquasars)



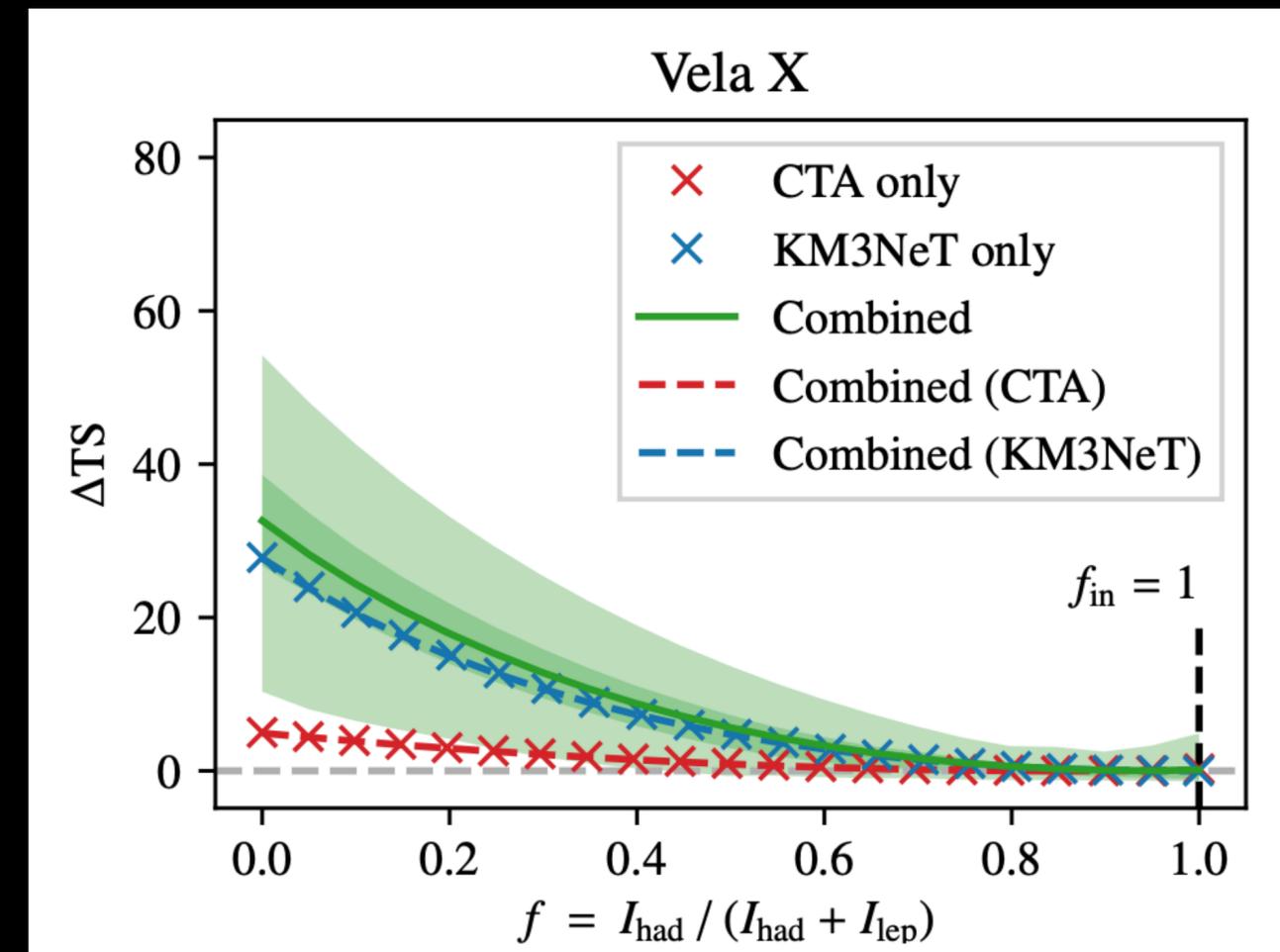
Multi-detector searches

Neutrinos + Gravitational Waves



In progress: ANTARES+ORCA6 search
Coincident sub-threshold GW & neutrino signals
→ Population constraints (CCSNe, CBCs, etc...)

Neutrinos + Gamma Rays



Combined likelihood analyses using Gammapy
→ Galactic sources, ARCA230: constrain fraction of γ -ray emission from hadronic processes

Outline

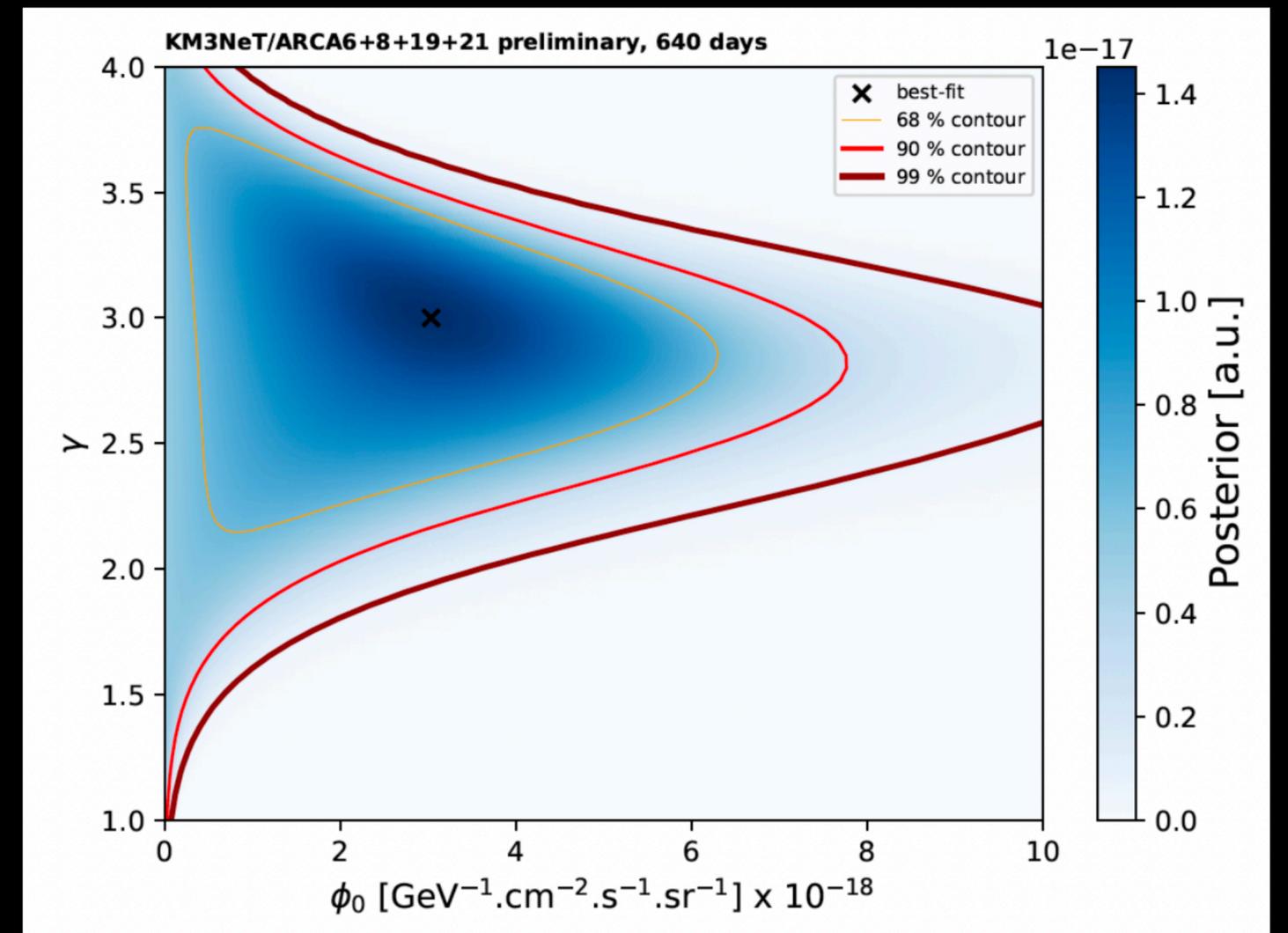
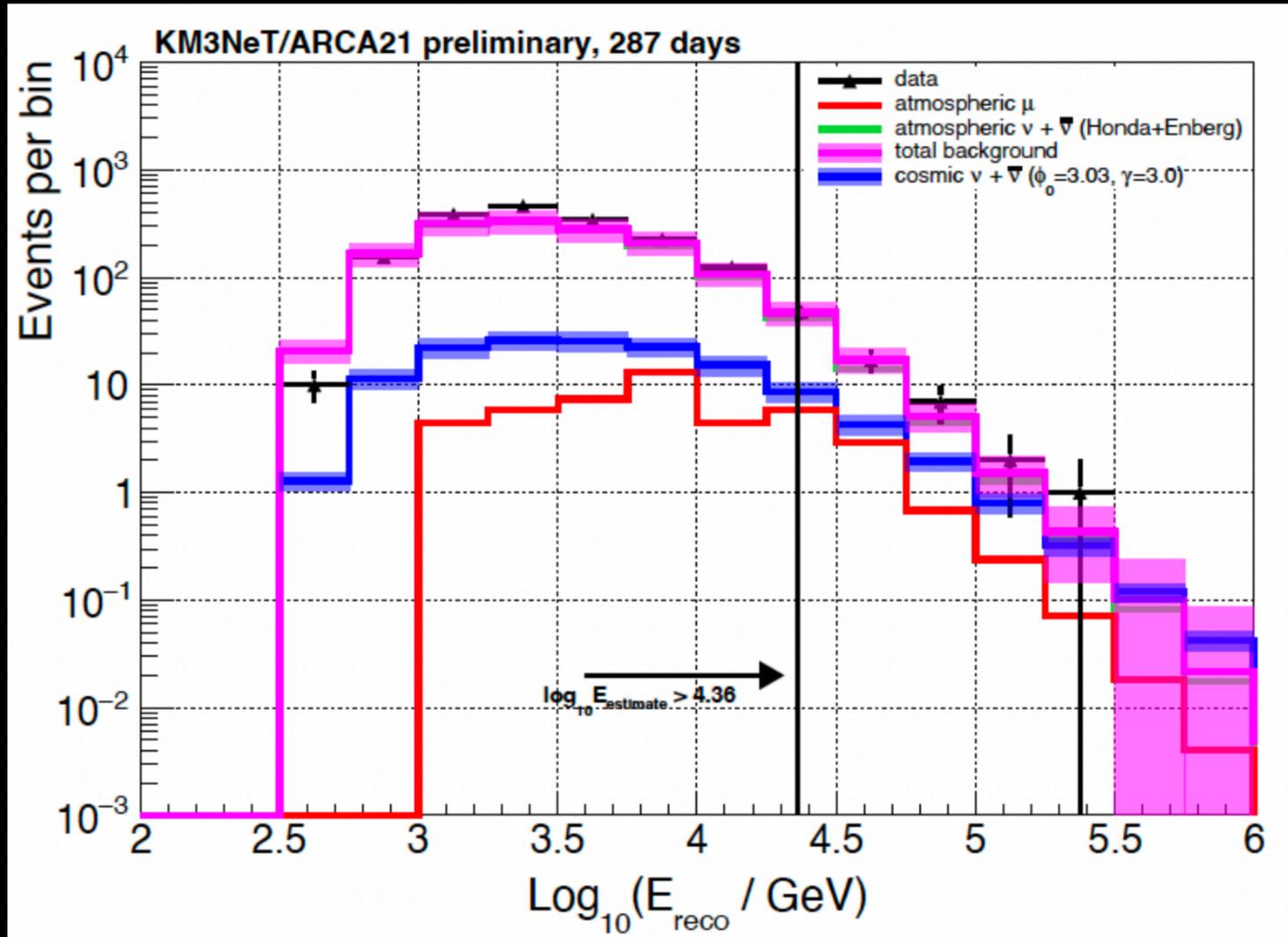
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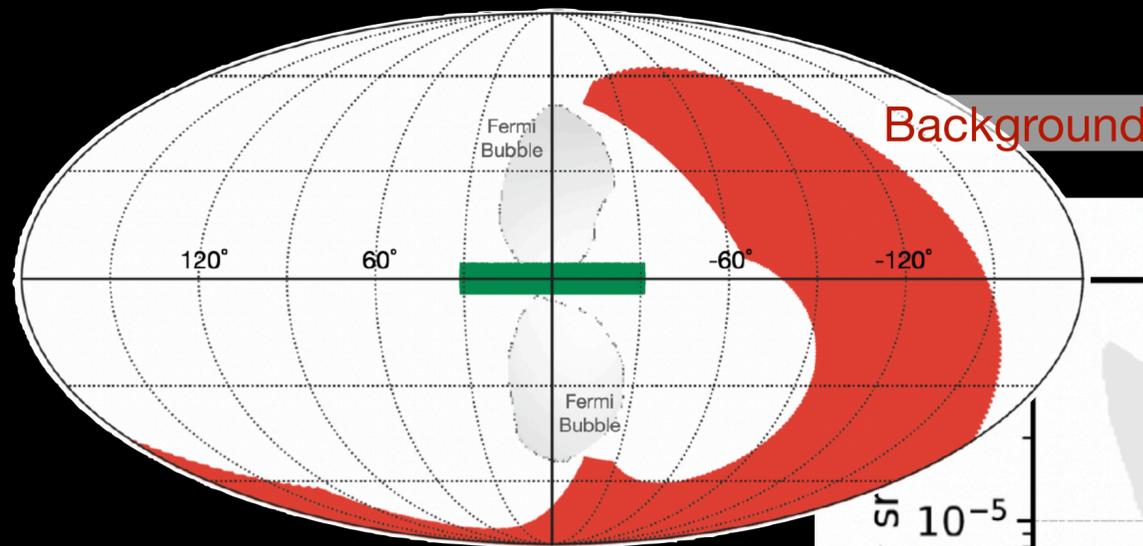
All-sky diffuse neutrino flux

ARCA6-21, 640 days, upgoing tracks



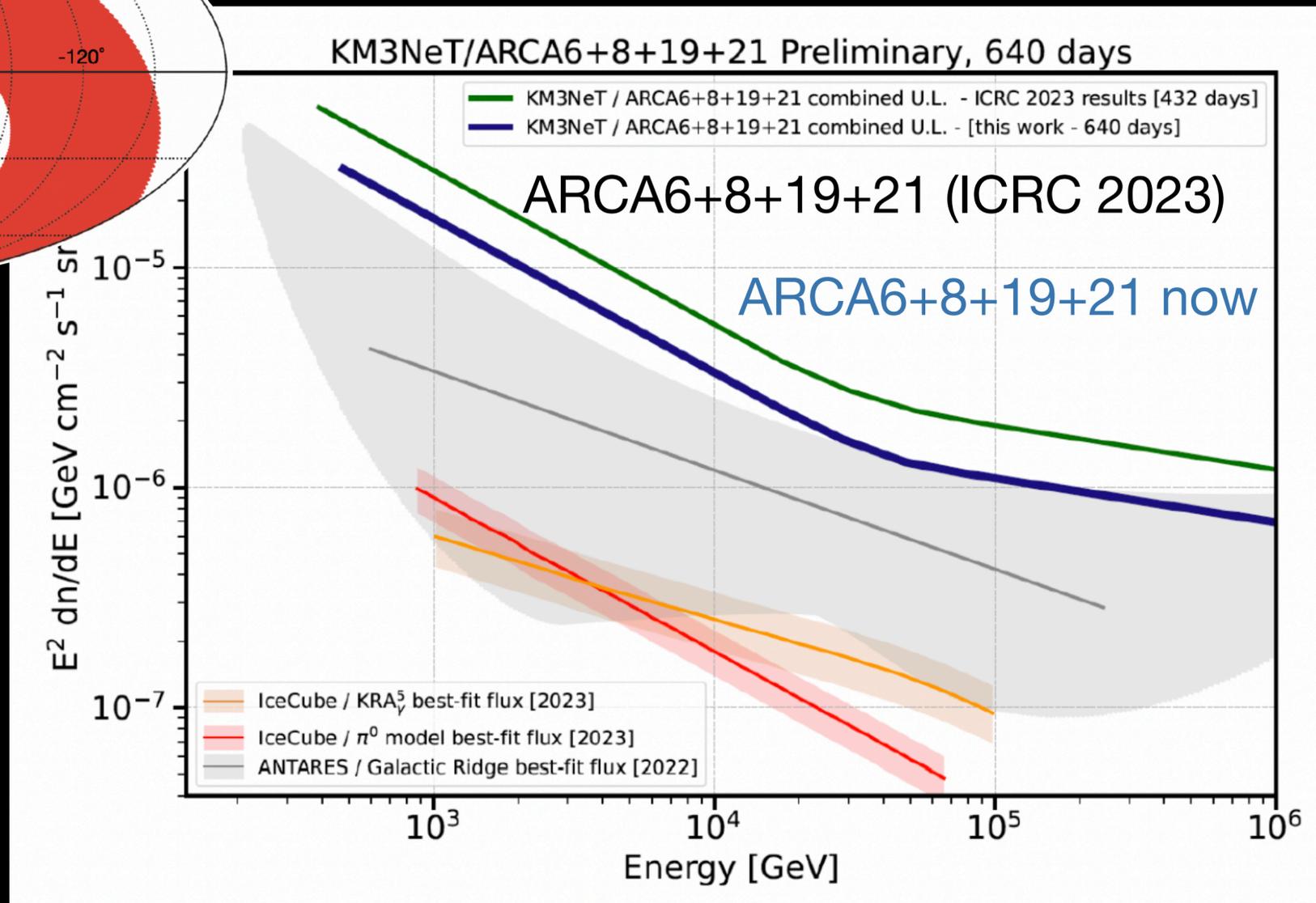
No excess — Spectral fit (Bayesian interpretation) compatible with IceCube

Exploring the Galactic Ridge



ON-OFF analysis

ARCA6-21, 640 days, upgoing tracks

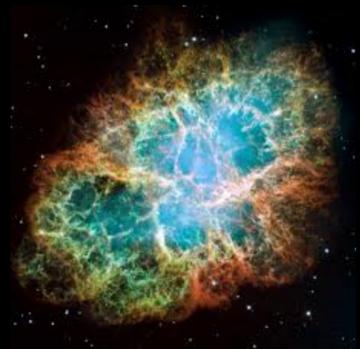


Current sensitivity limited by exposure

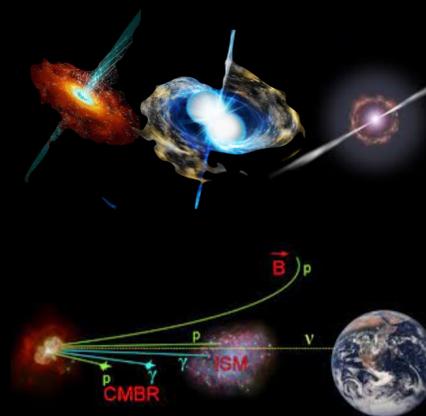
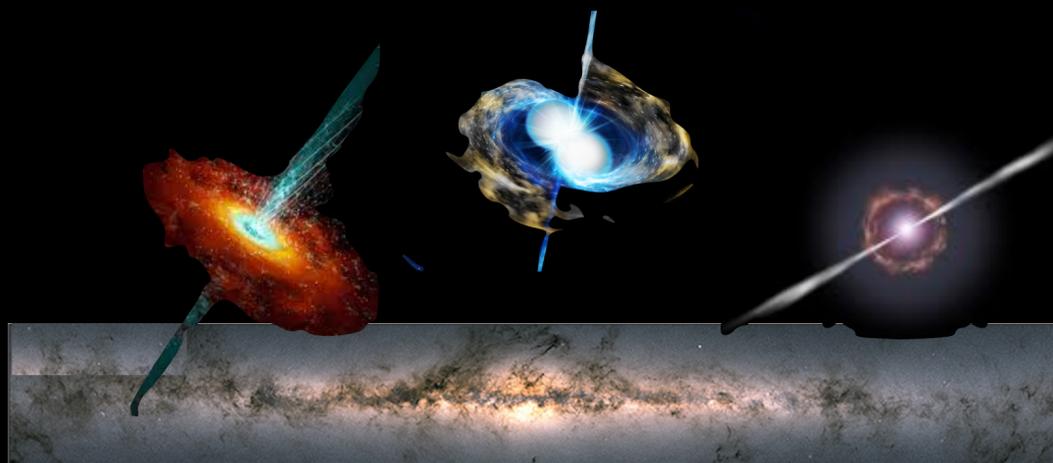
2σ excess at ANTARES Bayesian analysis

The two ends of the neutrino energy spectrum

Hunting rare astrophysical events

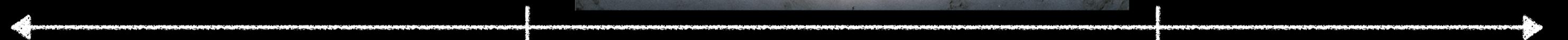


Core-collapse
Supernovae



Energetic
sources?

Cosmogenic
neutrinos?

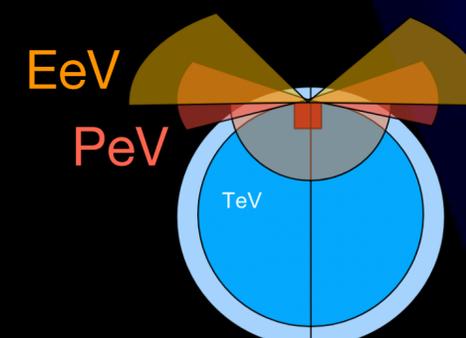


TeV

PeV



- Low detection efficiency
 - Limited reconstruction
 - High background rates
- ⇒ Need a short and intense neutrino burst

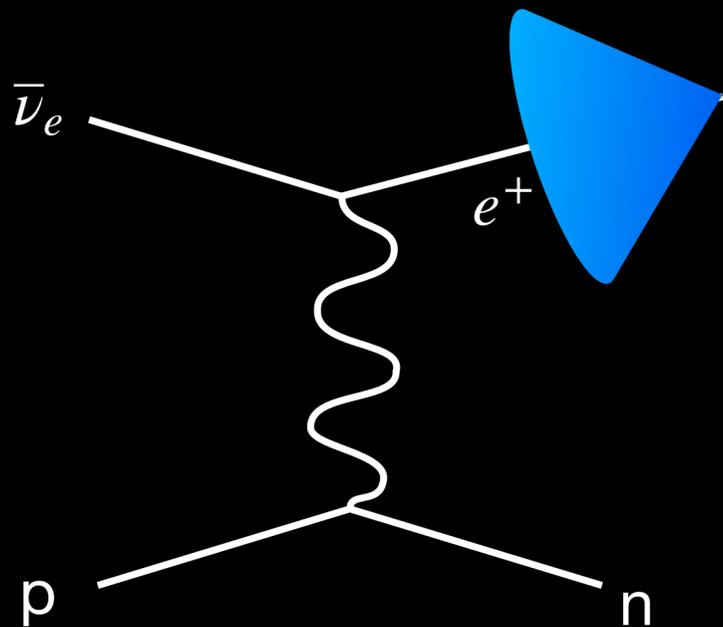


Counting supernova neutrinos

Monitoring supernovae without event reconstruction



Single module activation
No reconstruction

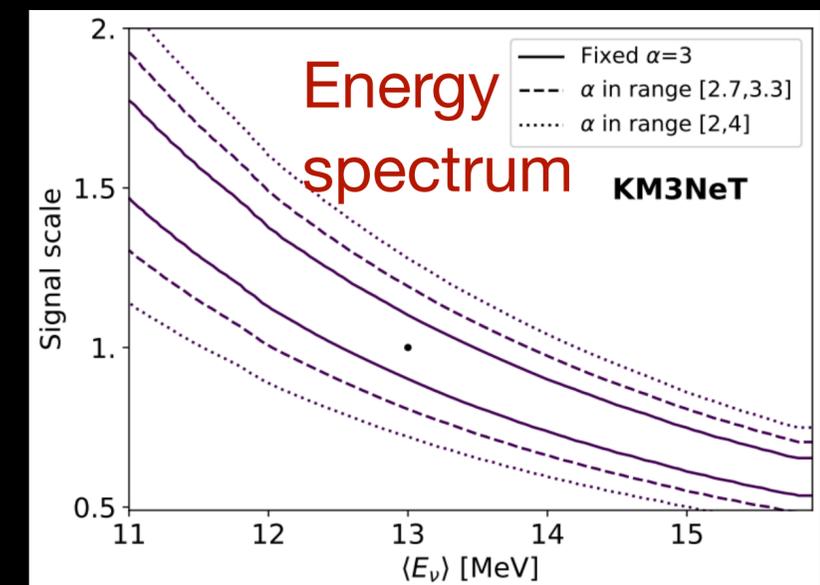
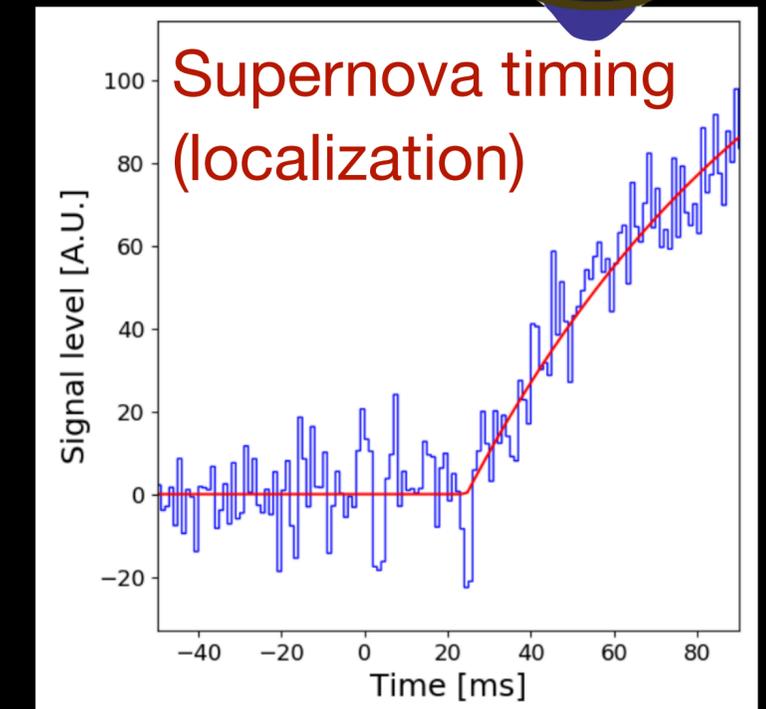
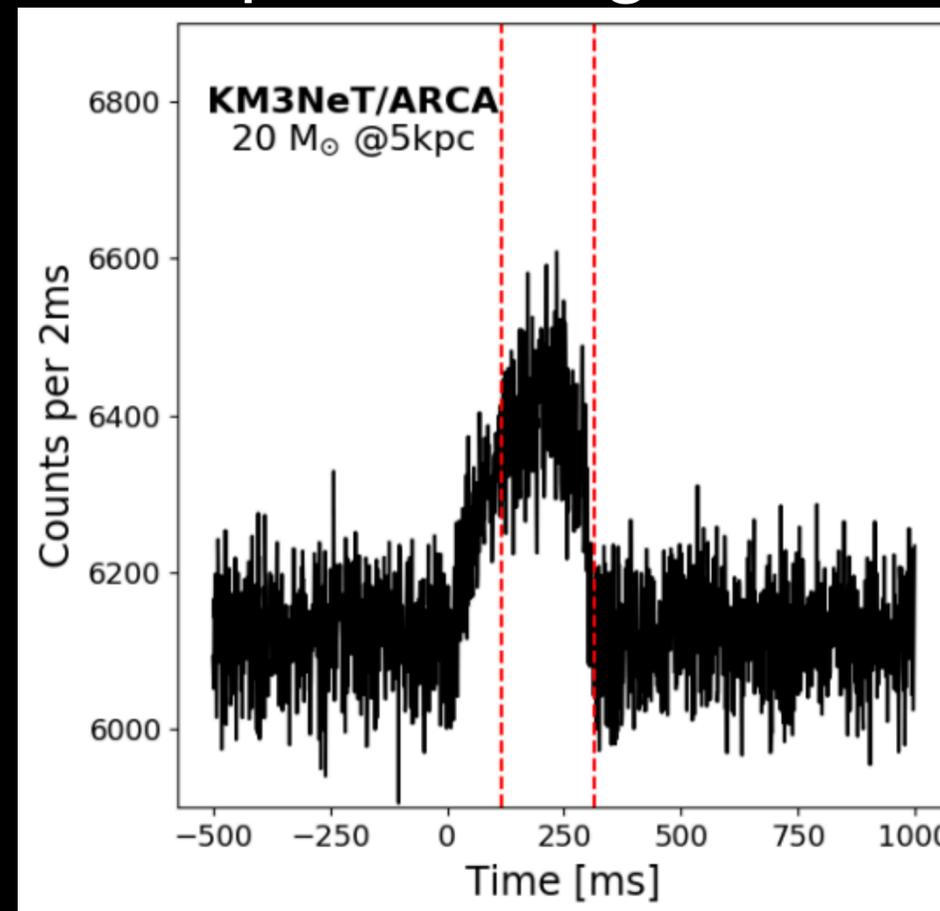


Inverse Beta Decay

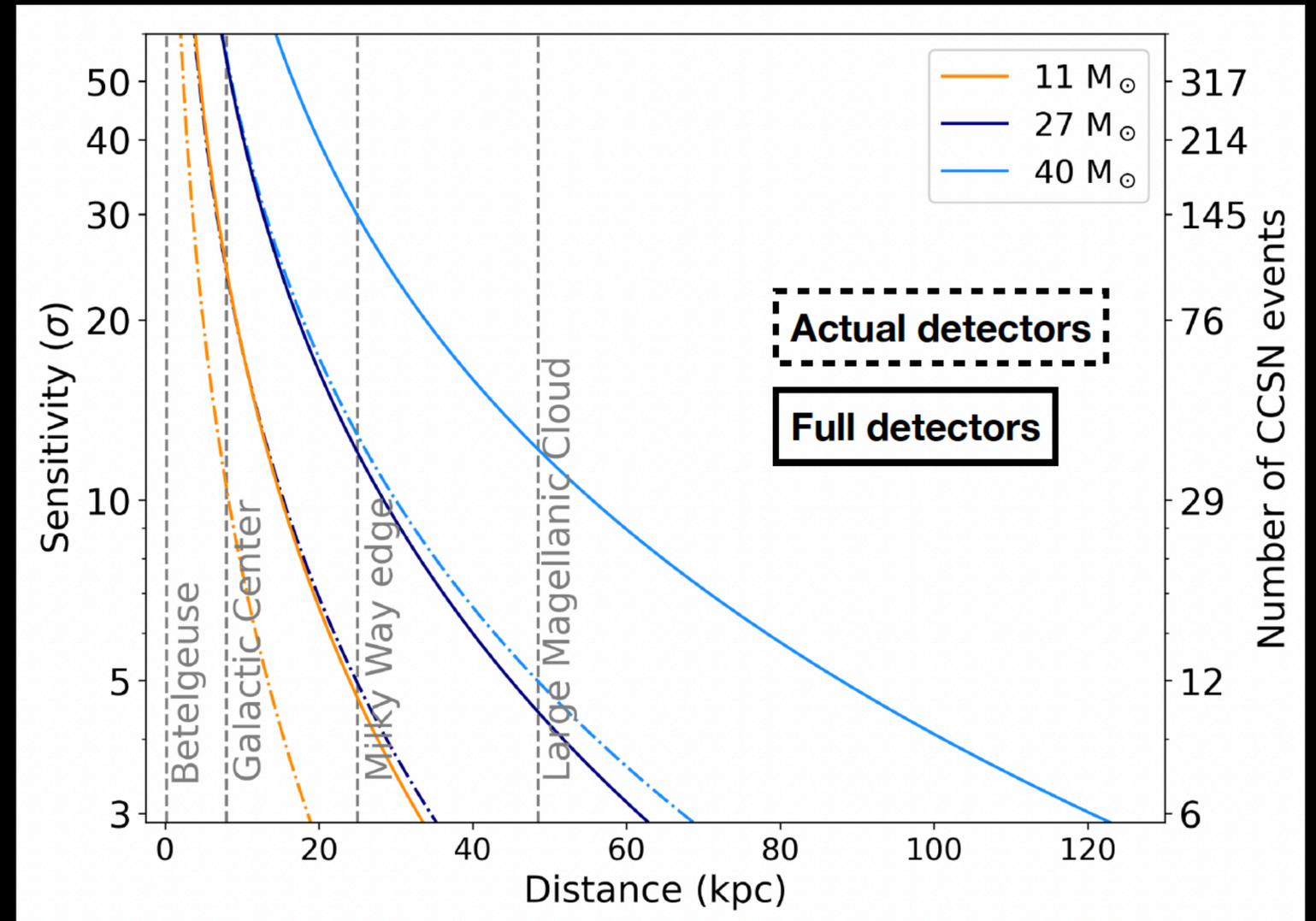
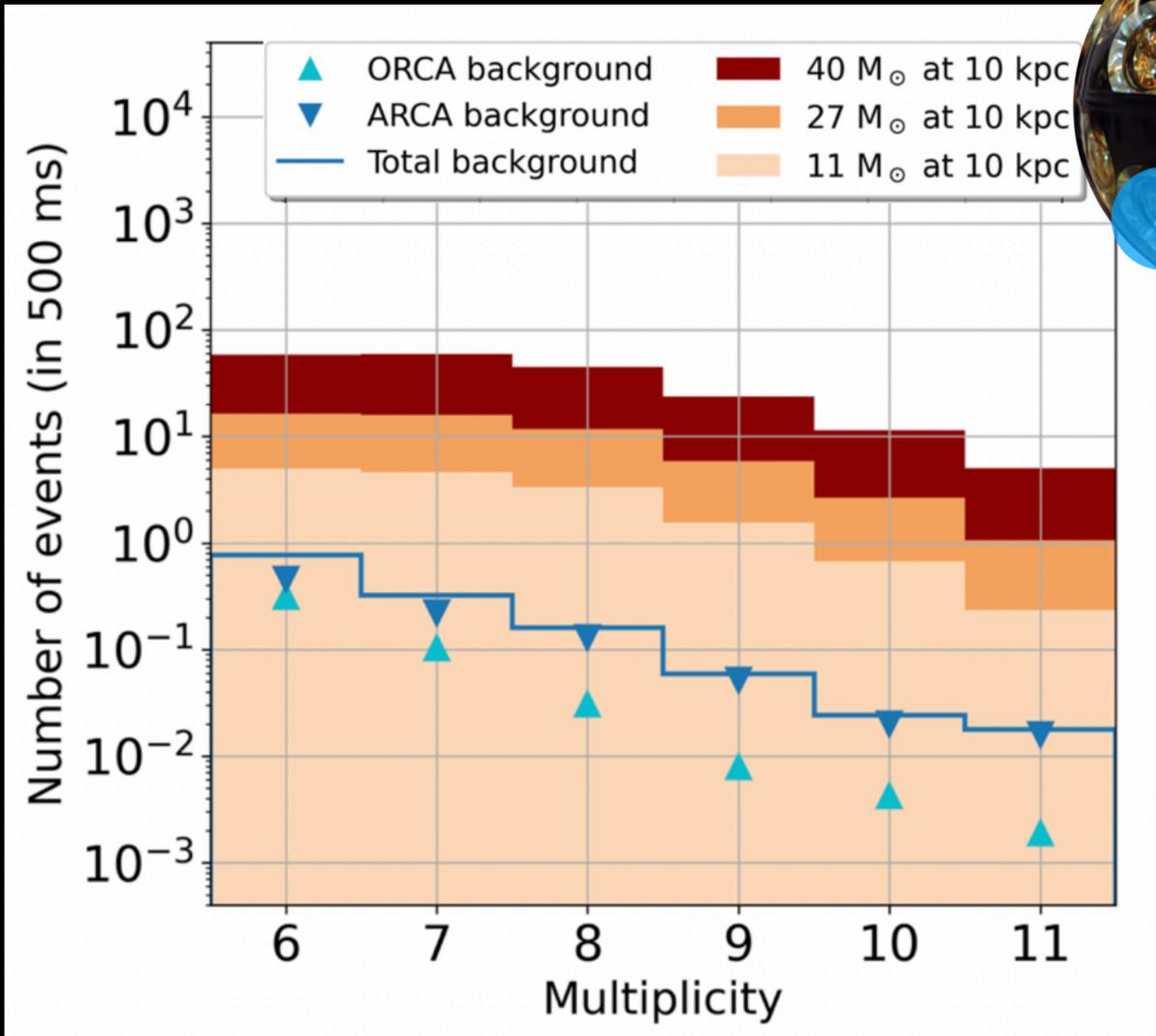
@(10 MeV) electron antineutrinos

→ **Detection at both ARCA and ORCA!**

Supernova light curve

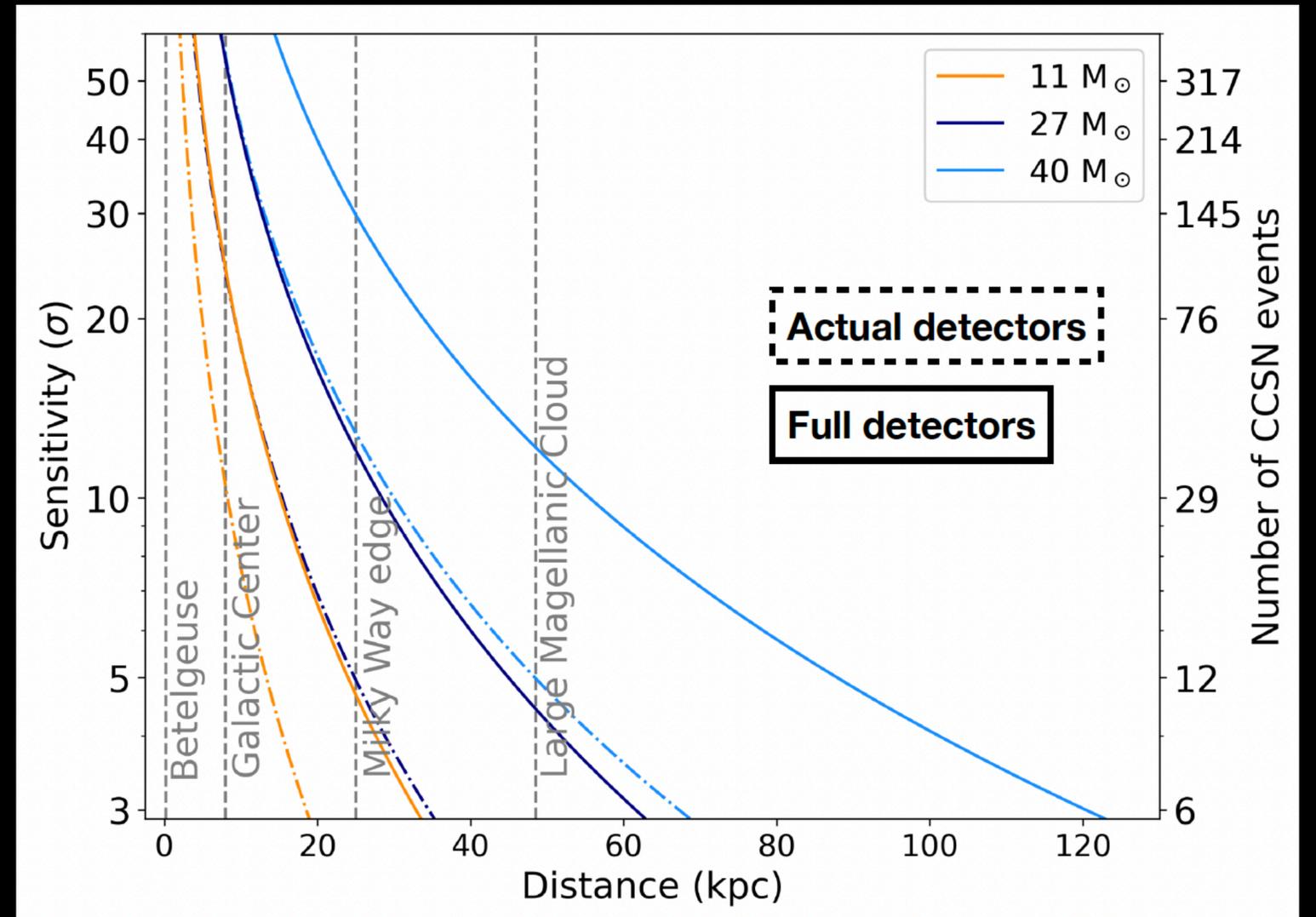
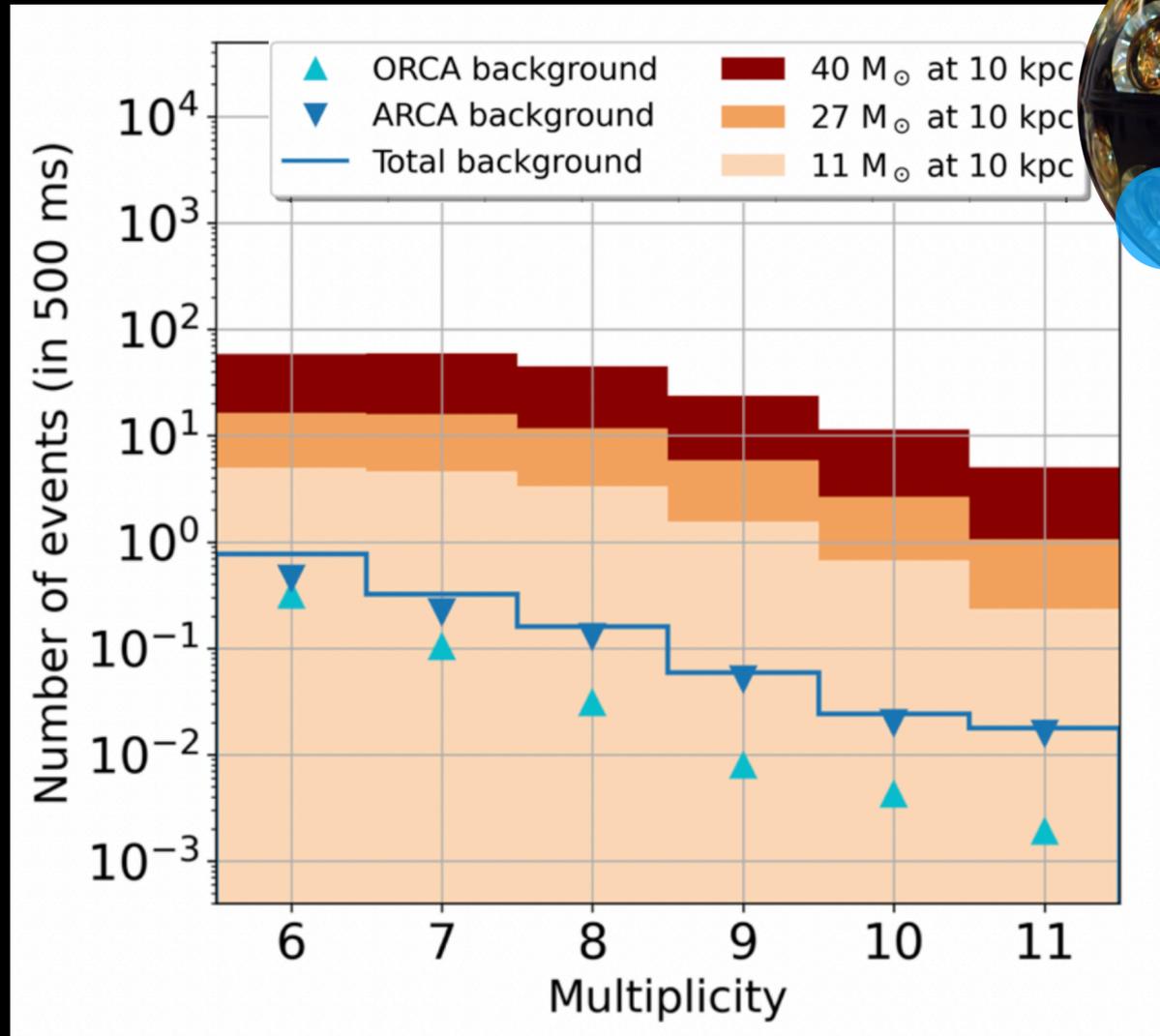


Improved CCSN analysis at KM3NeT



Improved selection → 30% reach increase

Improved CCSN analysis at KM3NeT



Improved selection \rightarrow 30% reach increase

Full galactic sensitivity with the completed detector

Conclusion

- Wide range of astrophysical analyses with available ARCA and ORCA data
- Multi-detector analyses in progress (gamma-ray & GW experiments)
- Motions of Understanding signed with 12 collaborations
- Collaborations with theorists for emission models (Galactic Plane, blazars)
- Real-time analysis system currently being finalized

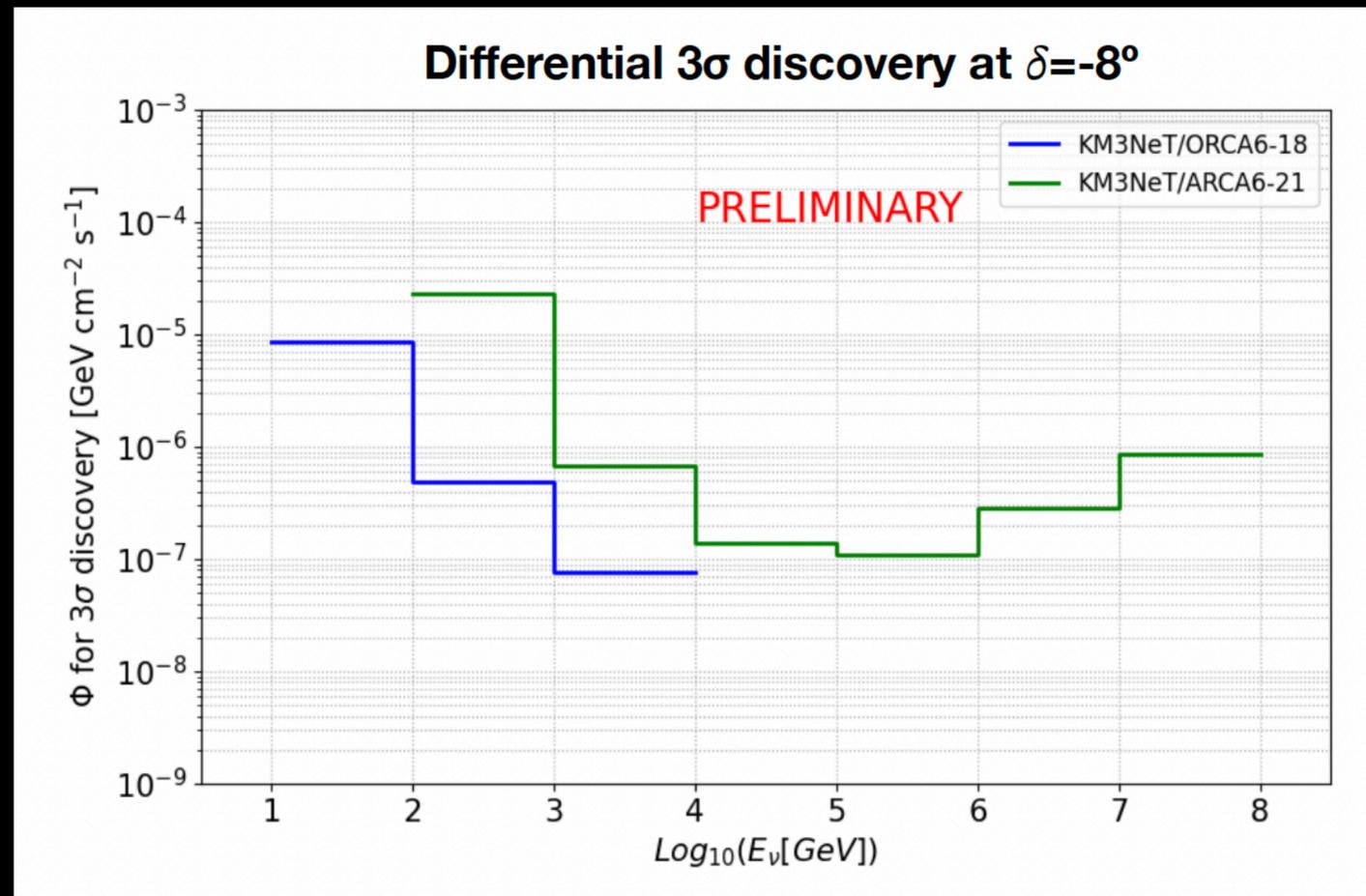
Plans

- Estimate timeline to observe the neutrino sources discovered by IceCube
- Search for origin of UHE event using improved localization
(New system deployed in Summer 2026 — Goal: $\mathcal{O}(0.1^\circ)$ resolution)
- Deploy the KM3NeT alert system
- Harmonize event selection procedures across analyses, investigate upgrades based on machine learning techniques (e.g. Graph Neural Networks)
- Build a common analysis framework & reinforce links with Gammapy developers
- Expand the scope of multi-detector analyses
(e.g. joint analyses with IceCube, GW+neutrino analyses with O4 data, etc...)



Thank you for your attention

ORCA astrophysics potential

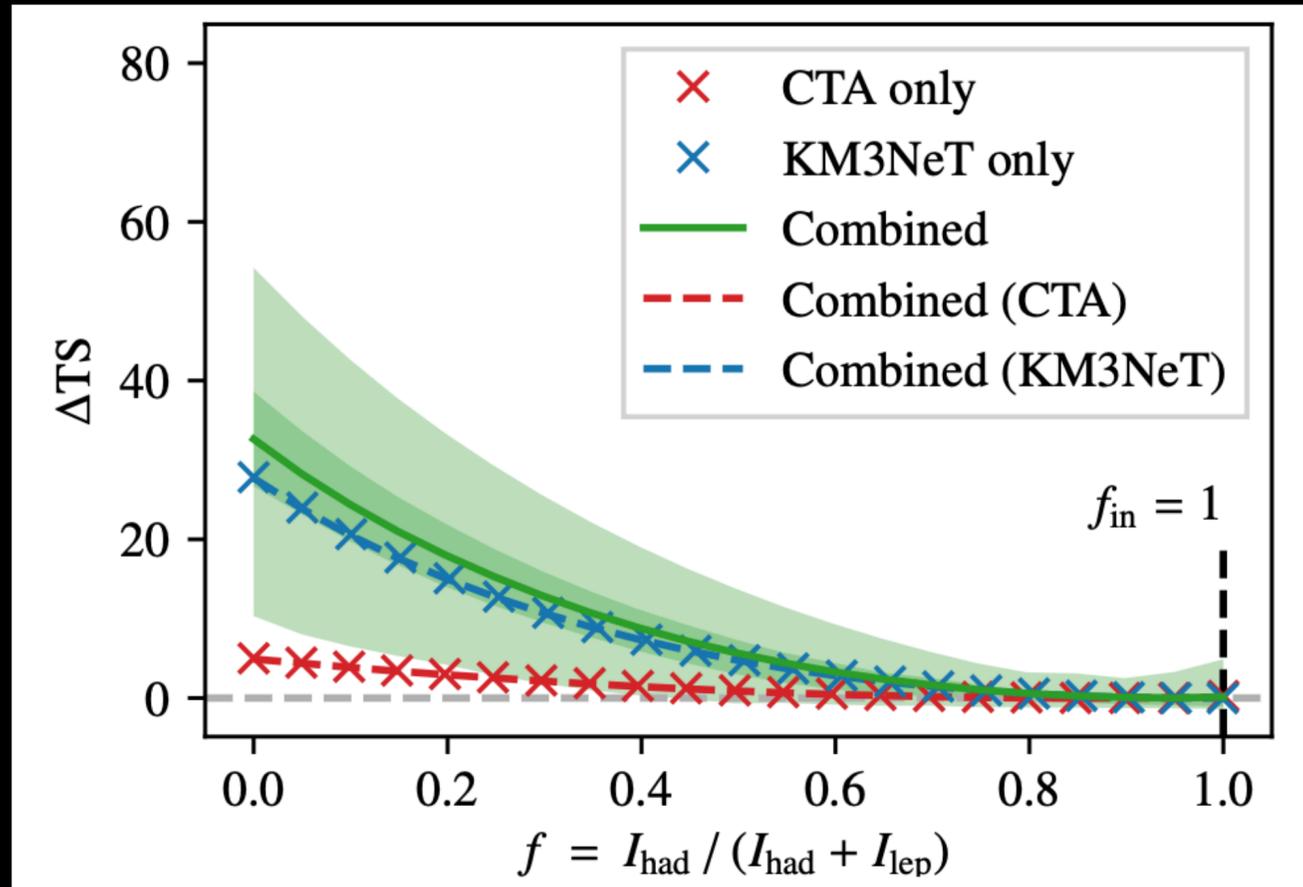


⇒ Both ORCA & ARCA used
in realtime analysis system

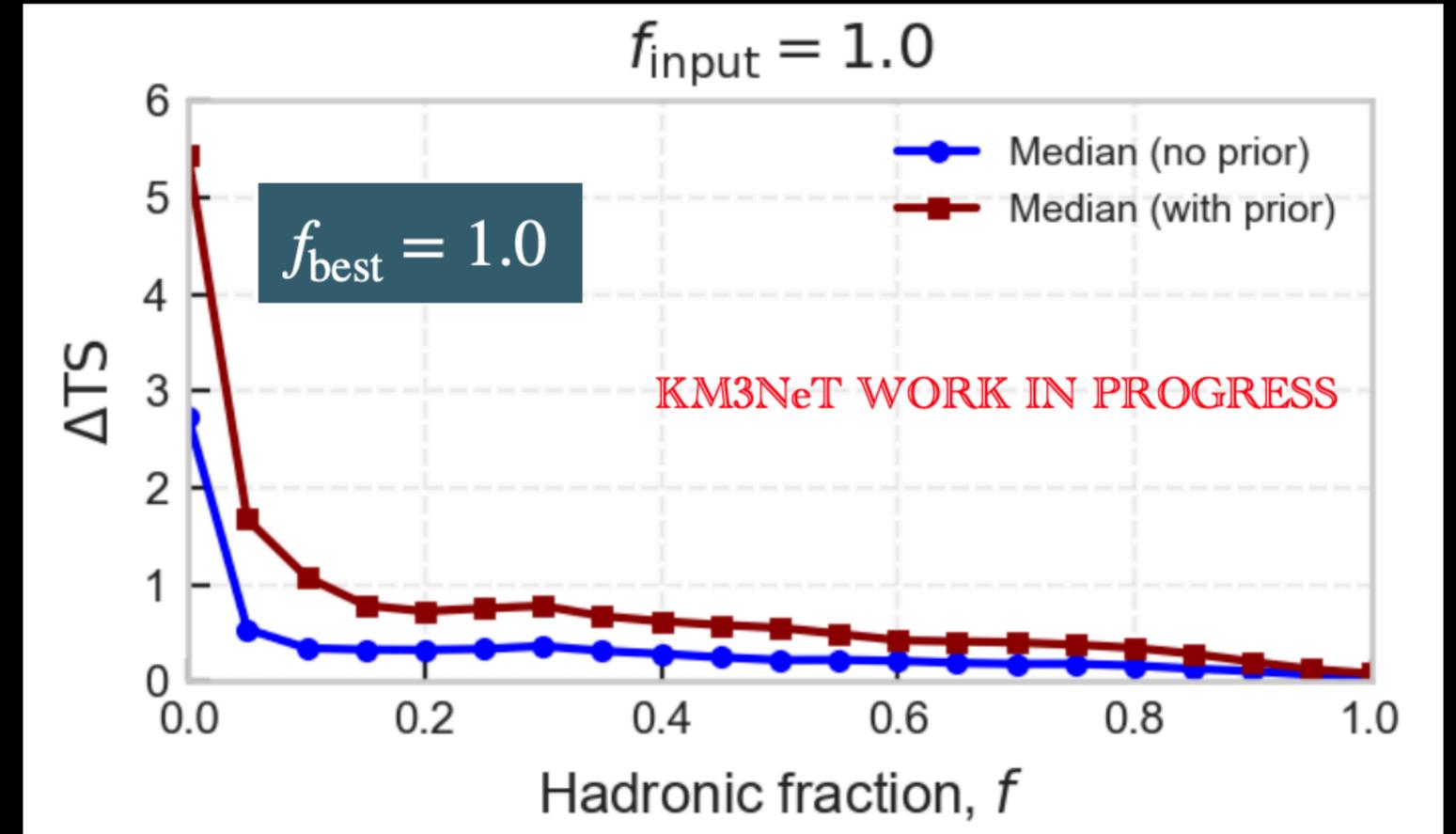
- GeV - TeV range → large atmospheric backgrounds
- **Diffuse neutrino flux:** limited capabilities
- **Stationary sources:** improved discovery potential below 10 TeV
- **Transient high-energy sources:** strong complementarity to ARCA (energy spectrum)
- **Core-collapse supernovae:** sensitivity similar to ARCA
ORCA+ARCA → SN localization

Combined neutrino and gamma-ray searches

Vela X @ ARCA230 (+ CTA)

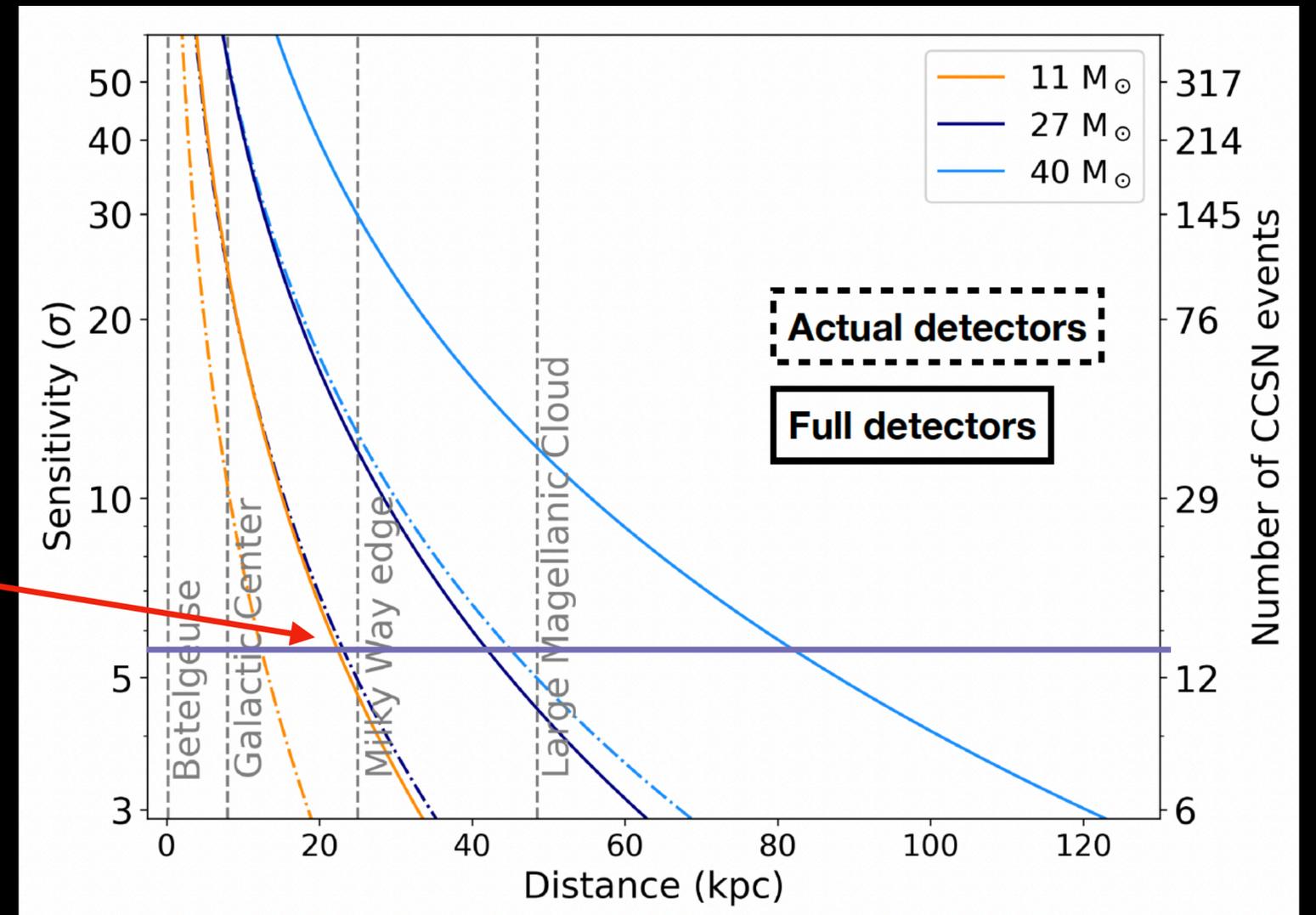
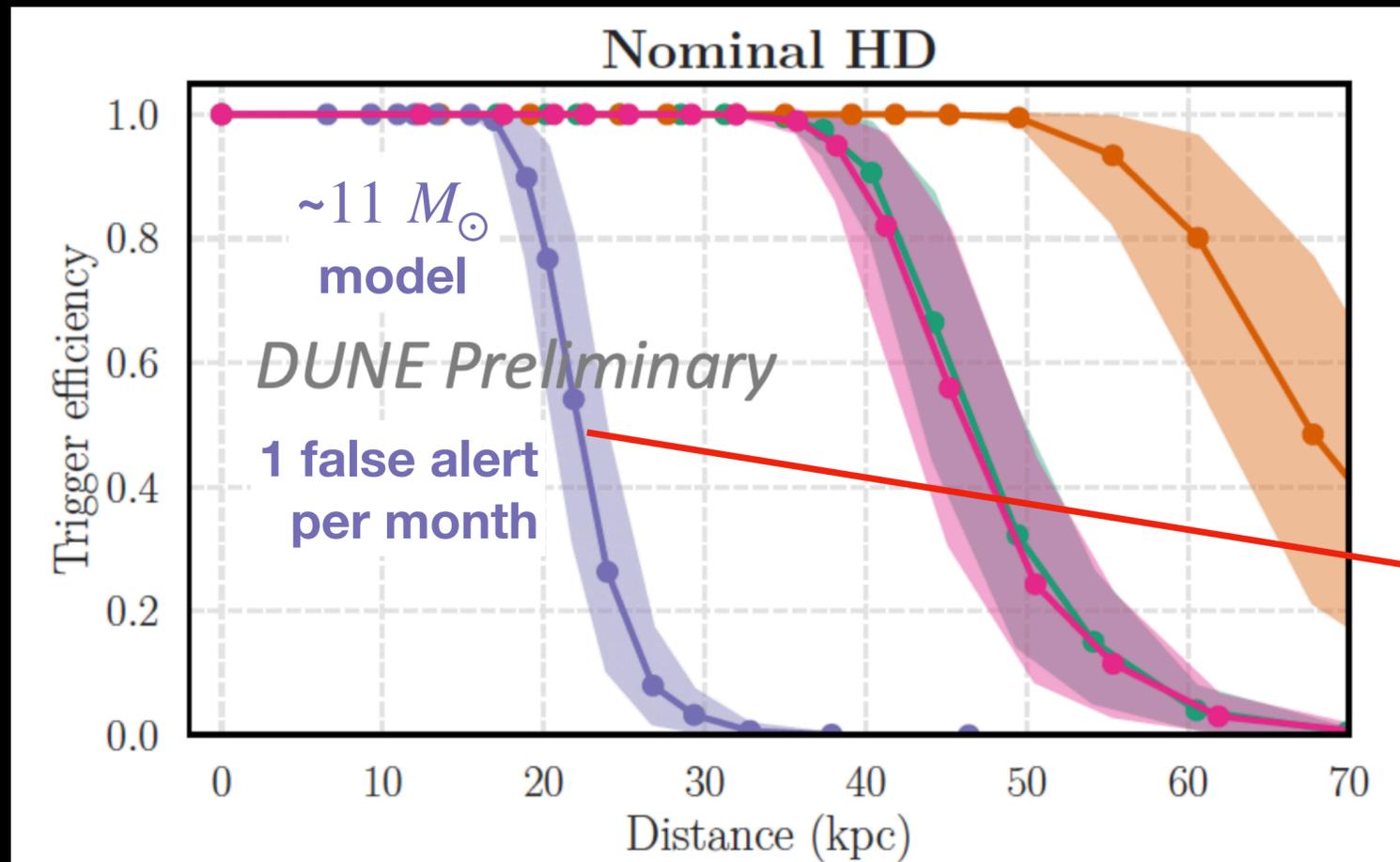


Galactic center @ ARCA230 (+ HAWC)

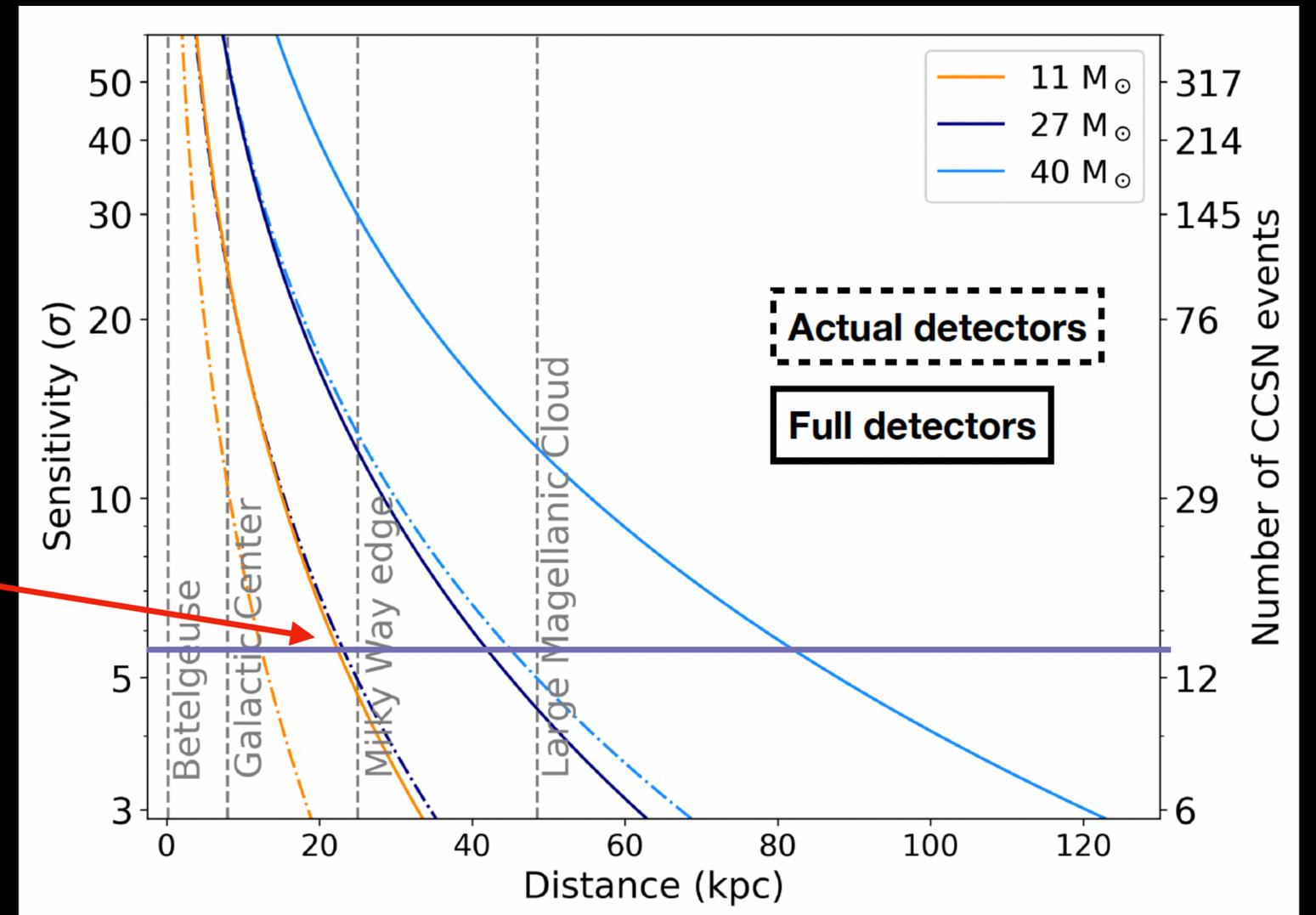
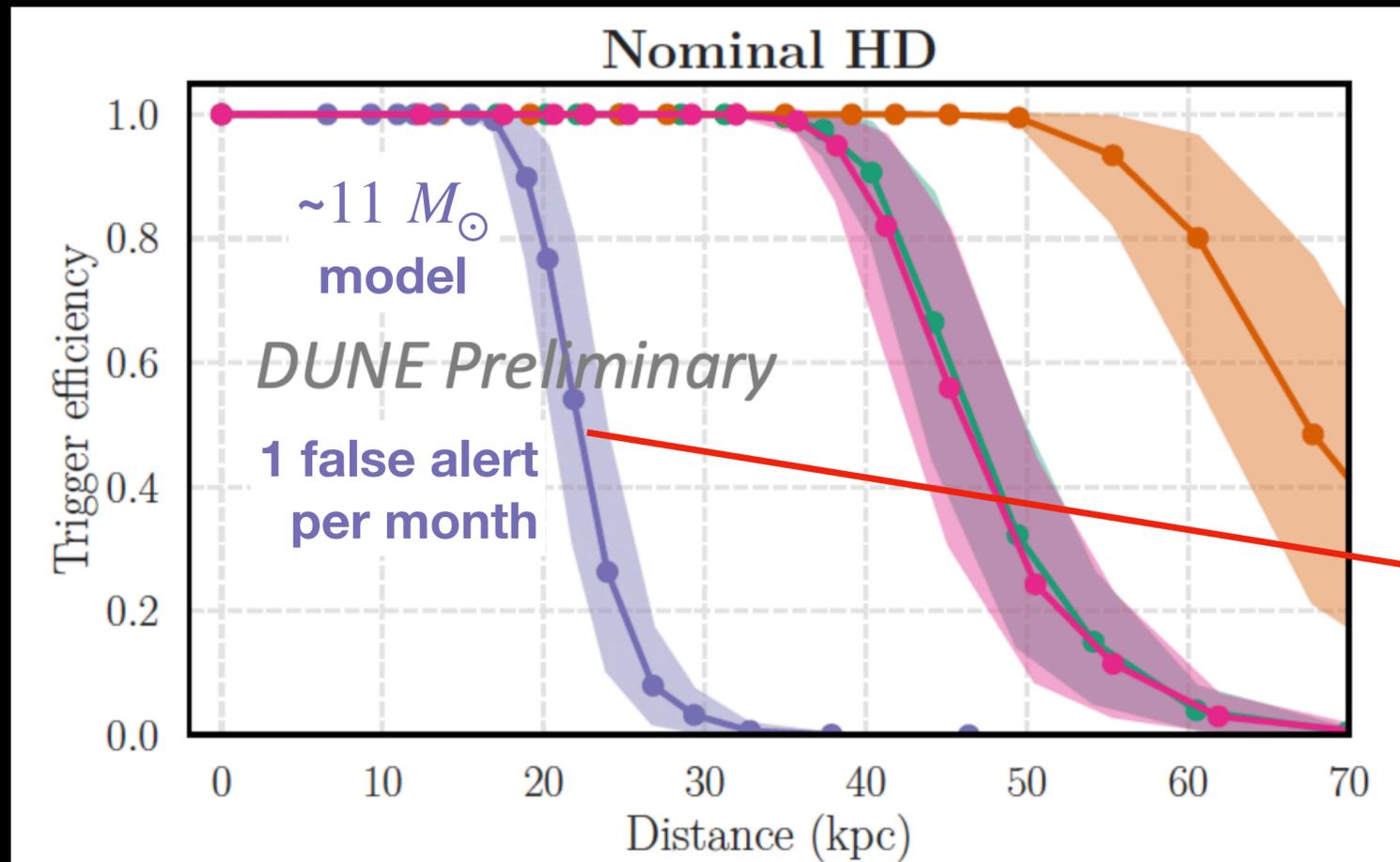


Added value of the combination depends on the source and the experiment

KM3NeT CCSN sensitivity – Comparison

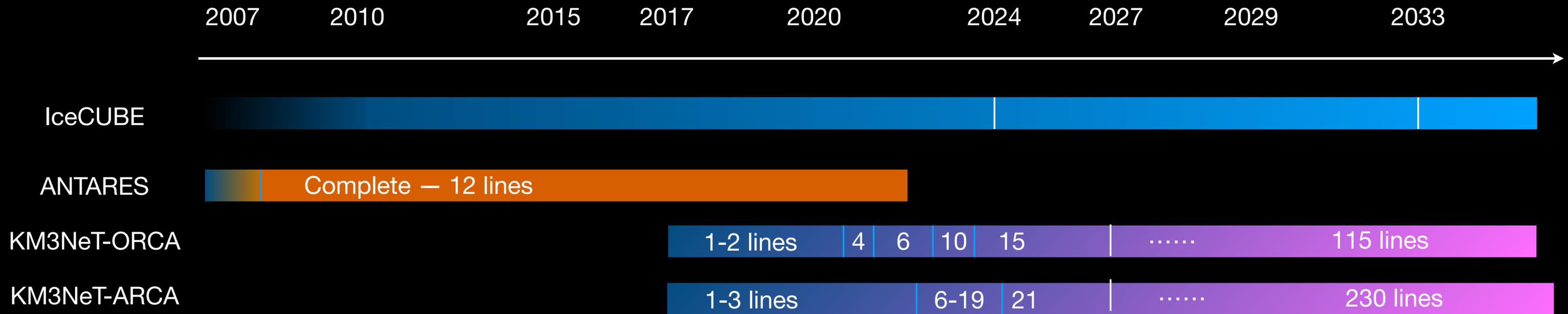


KM3NeT CCSN sensitivity – Comparison



- **Trigger:** sensitivity comparable to DUNE (40 kT), lower than Hyper-/Super-Kamiokande
- **Light curve:** $\mathcal{O}(10^4)$ events @ 5 kpc at complete detector but 4.5 MHz background
- **Pointing:** very limited capabilities alone but will contribute to triangulation within SNEWS

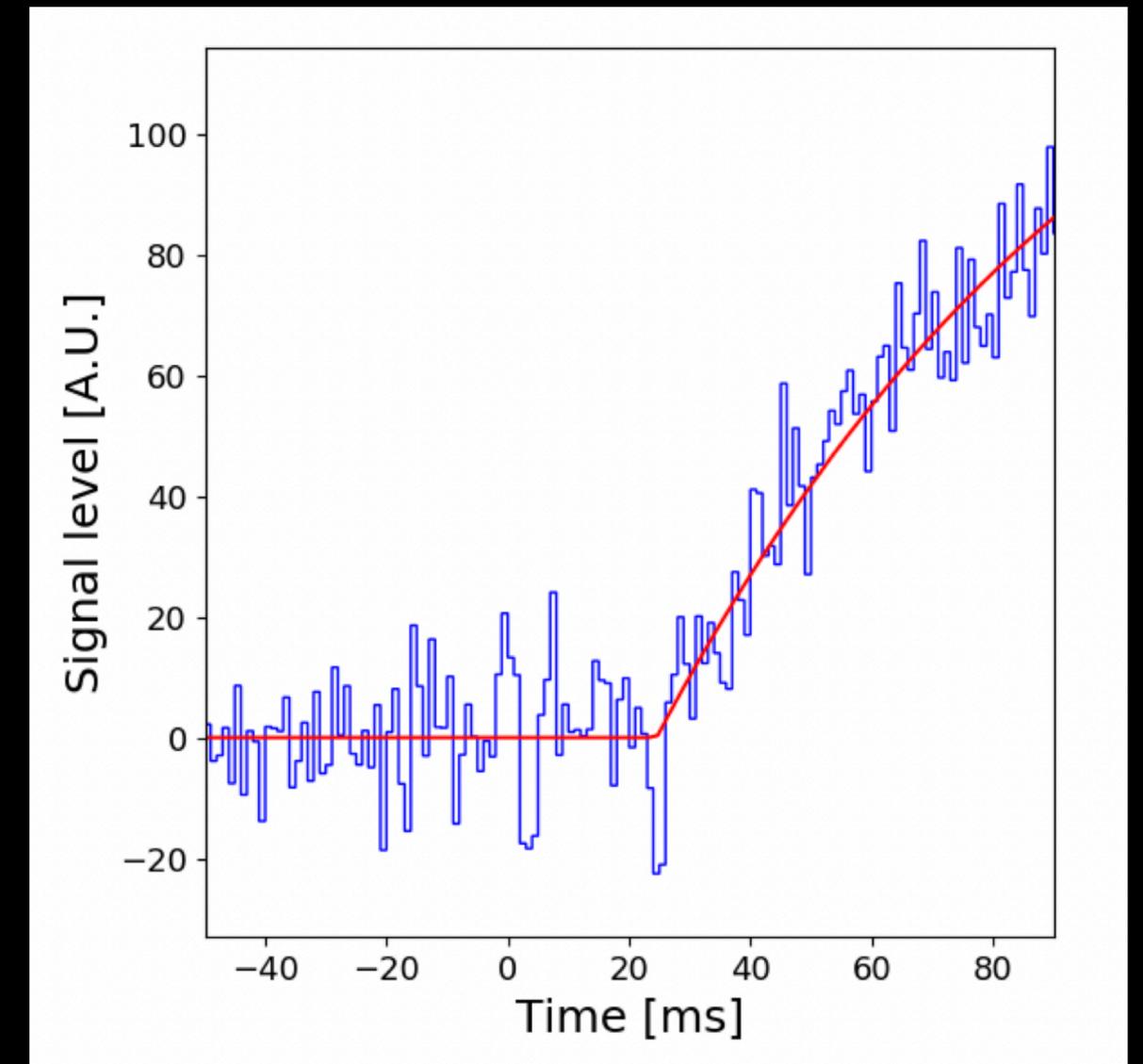
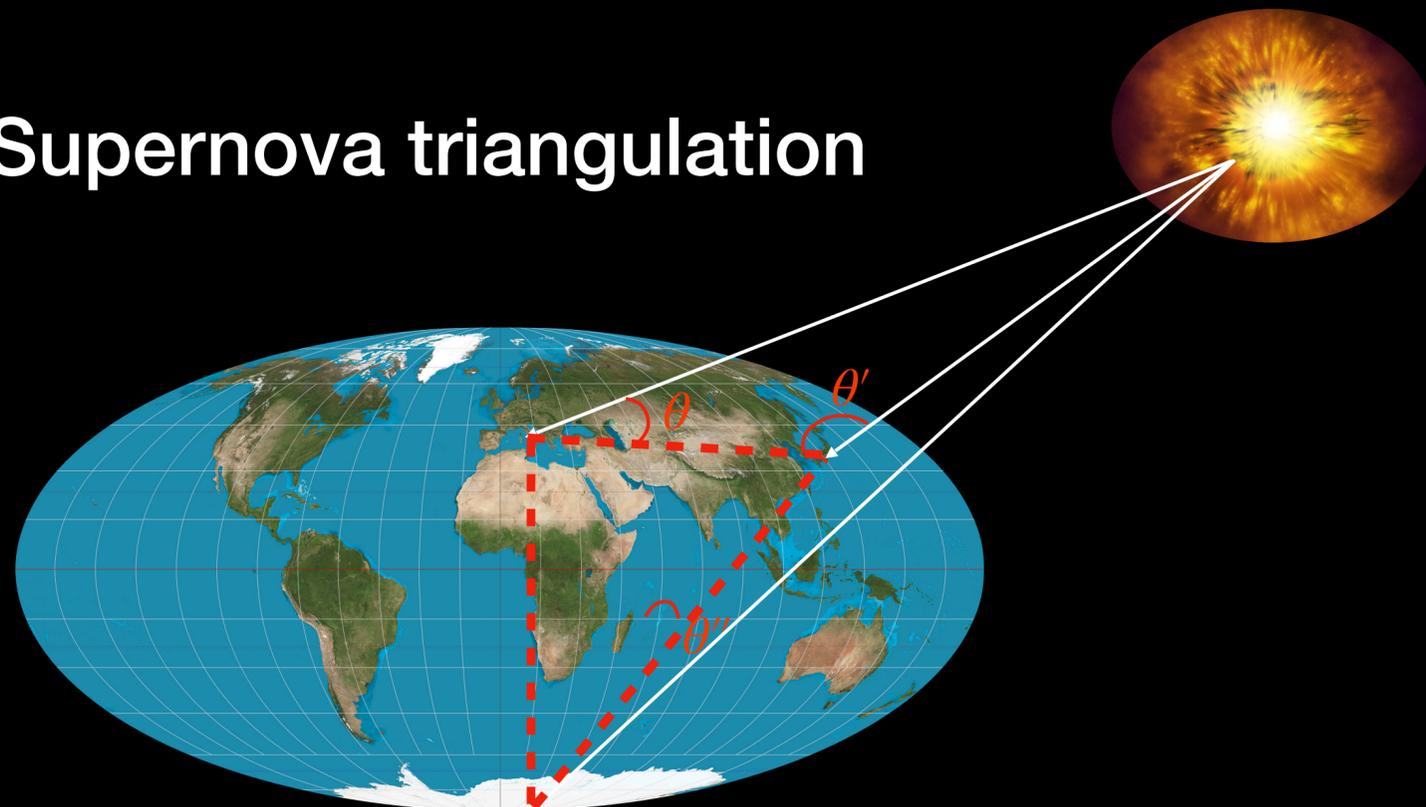
Status, funding, plans



Locating supernovae using CCSN detection times

- Fit the initial neutrino rate rise by an exponential
- Full ARCA: 8ms uncertainty at 8 kpc
- Detectors with energy thresholds < 10 MeV
→ 1 ms resolution on CCSN detection time

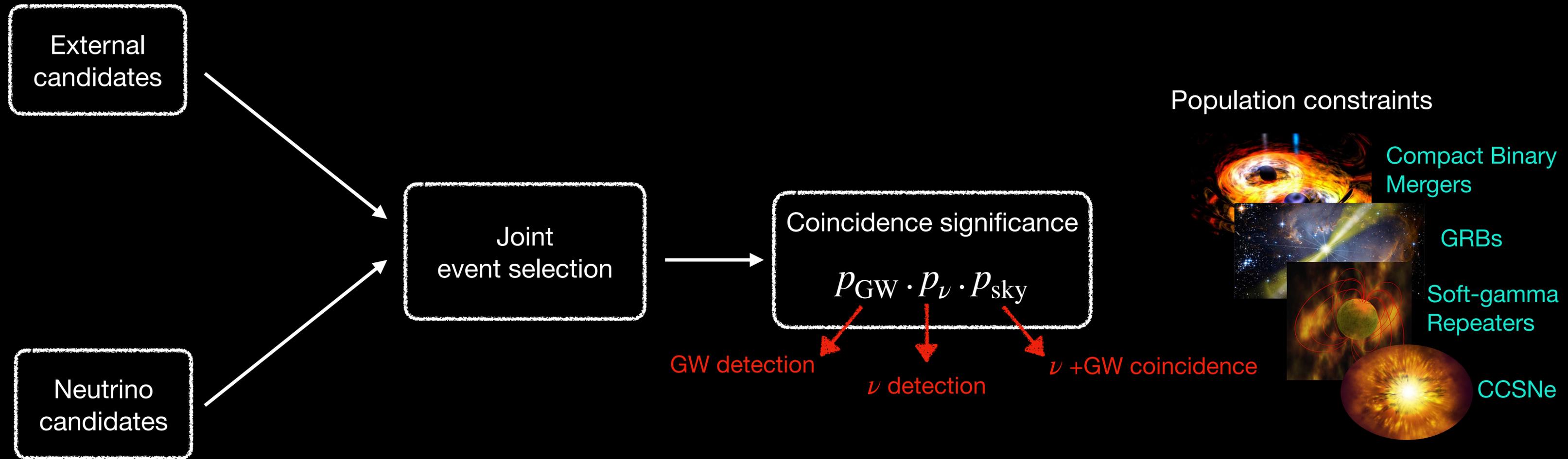
Supernova triangulation



KM3NeT collaboration, *Eur. Phys. J. C* 81 (2021)

Beyond follow-ups: sub-threshold events

Neutrino coincidences with untriggered LIGO-VIRGO events

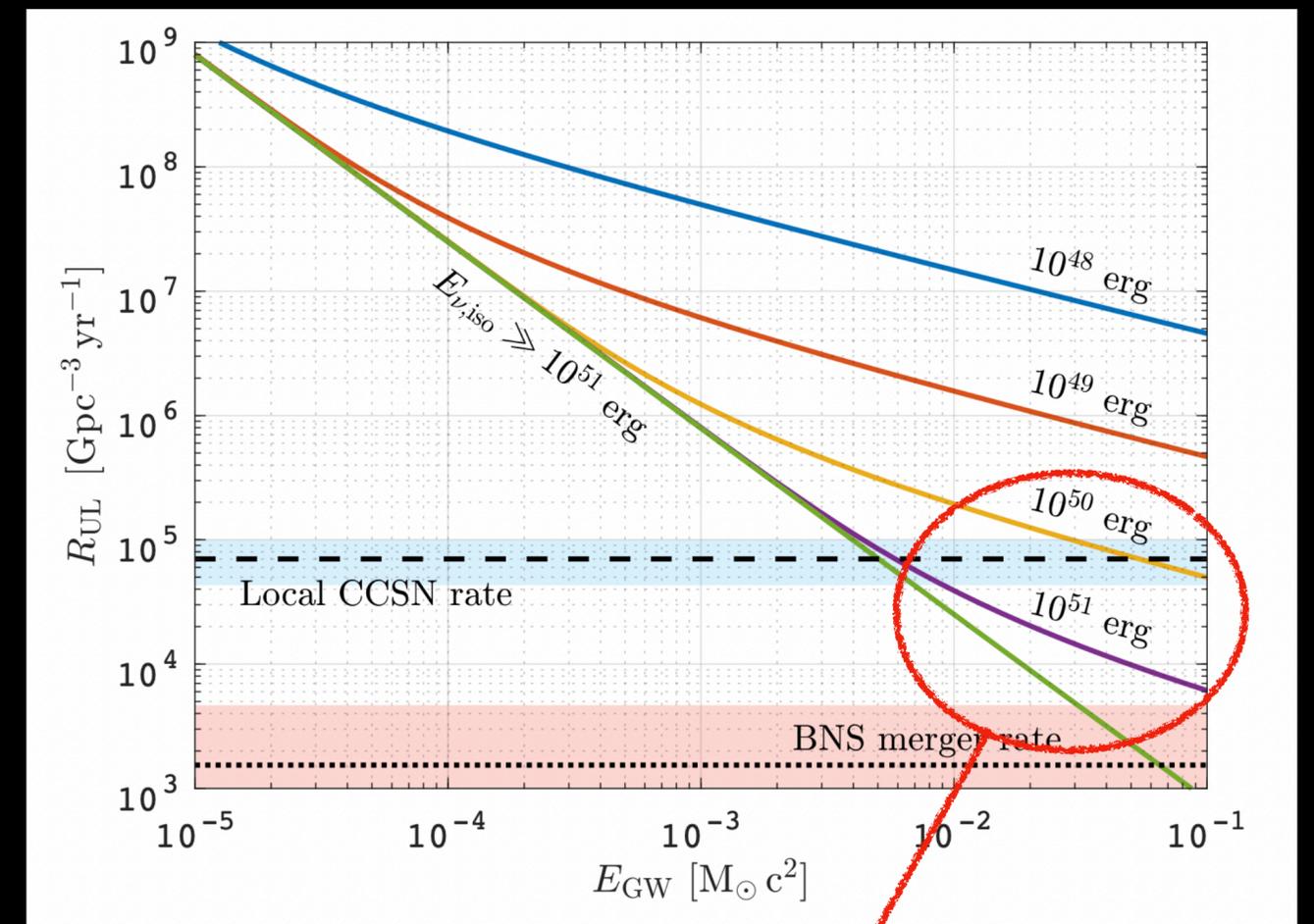


Sub-threshold analysis: O1 follow-up

Advanced LIGO – ANTARES – IceCube

- **GW candidates:** 1 false alarm per day
46 GW candidates considered
- **Neutrino selection:** track events
upgoing for ANTARES, full-sky for IceCube
- First constraints on physical rate densities
- **KM3NeT will probe CCSNe & short GRBs**
⇒ complementary to GW event searches

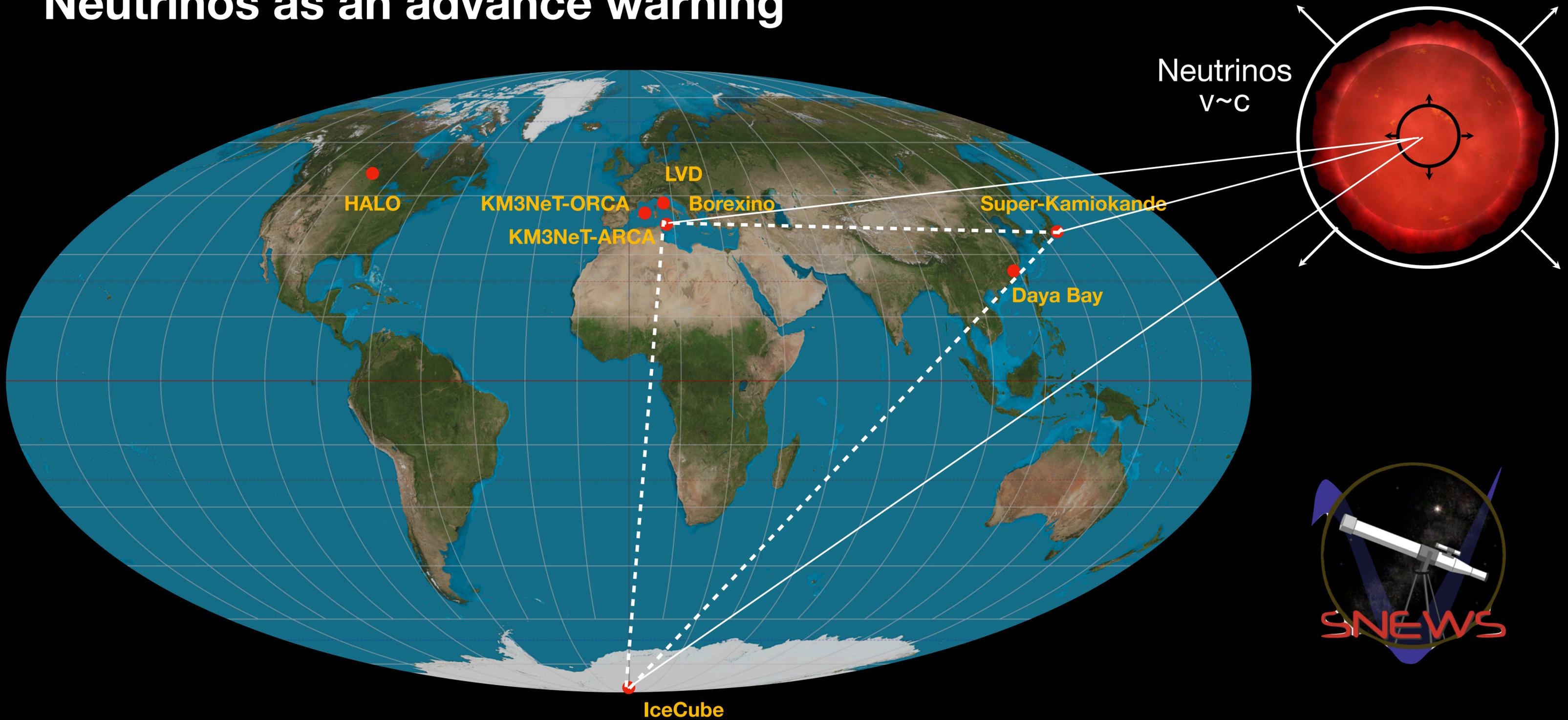
ANTARES, IceCube, LIGO/VIRGO , *Astrophys. J.* 870 (2019)



Physical region

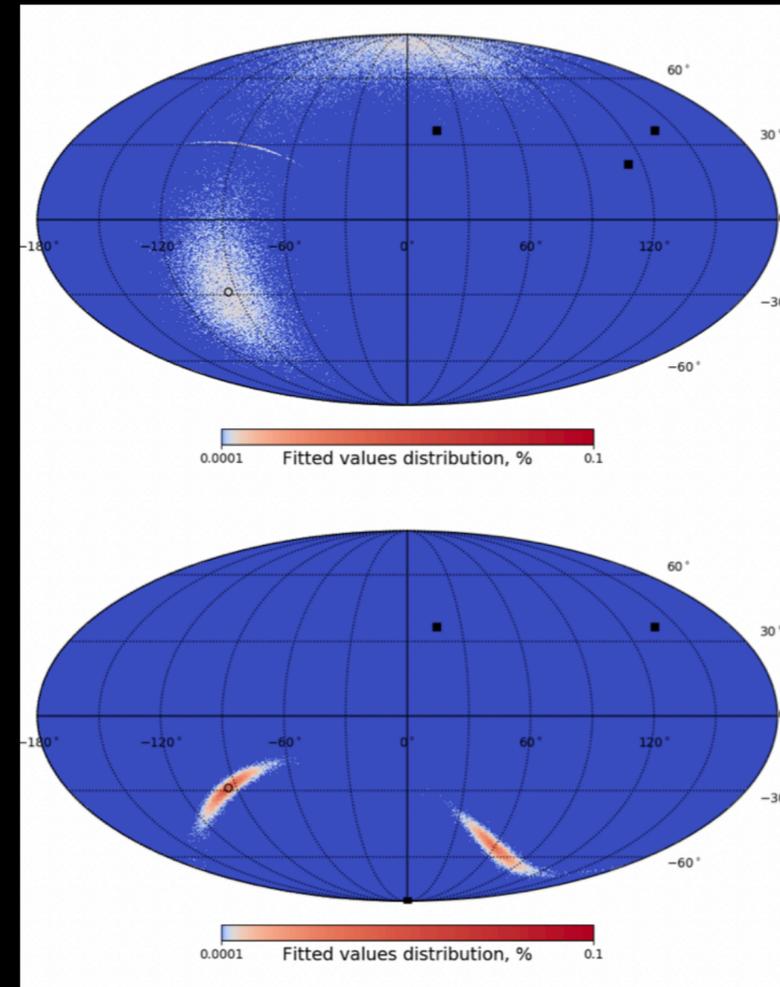
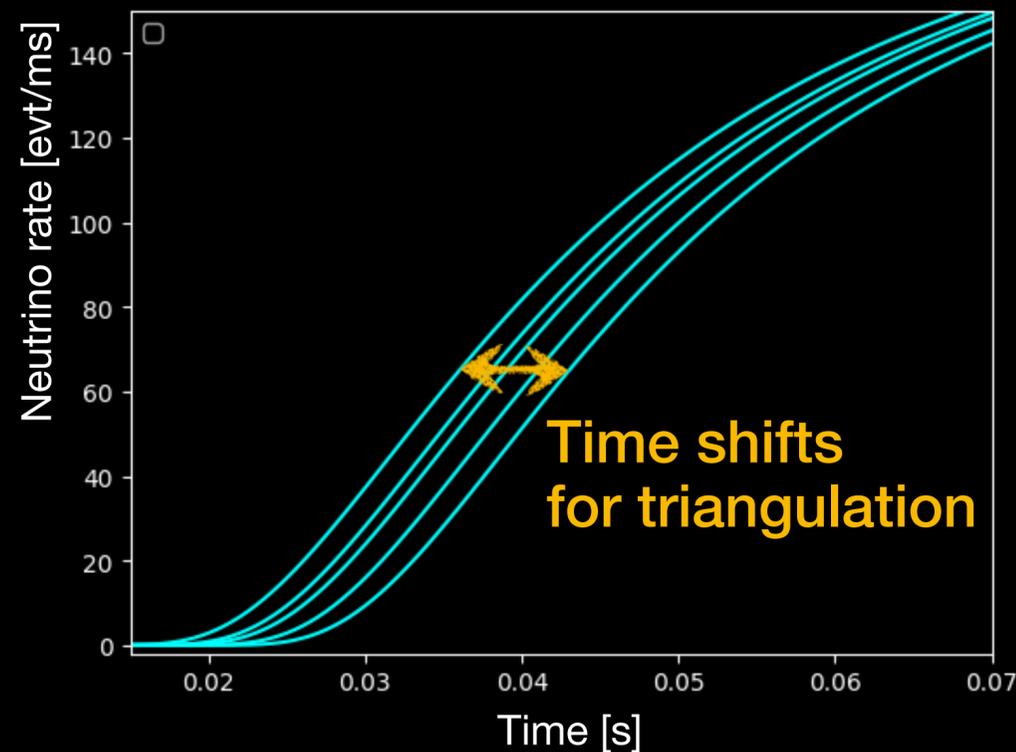
Locating a supernova

Neutrinos as an advance warning



Supernova localization accuracy

Match supernova rate increases for multiple detectors



IceCube
KM3NeT-ARCA
JUNO

Hyper-Kamiokande
KM3NeT-ARCA
JUNO

A. Coleiro *et al*, Eur. Phys. J. C 80 (2020)

Constraint down to a **140 squared degree** region within minutes after detection
Wolf-Rayet stars: light can arrive 40 seconds after the neutrinos