KM3NeT: Status and Prospects for Neutrino Astronomy at Low and High Energies

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on behalf of the KM3NeT collaboration
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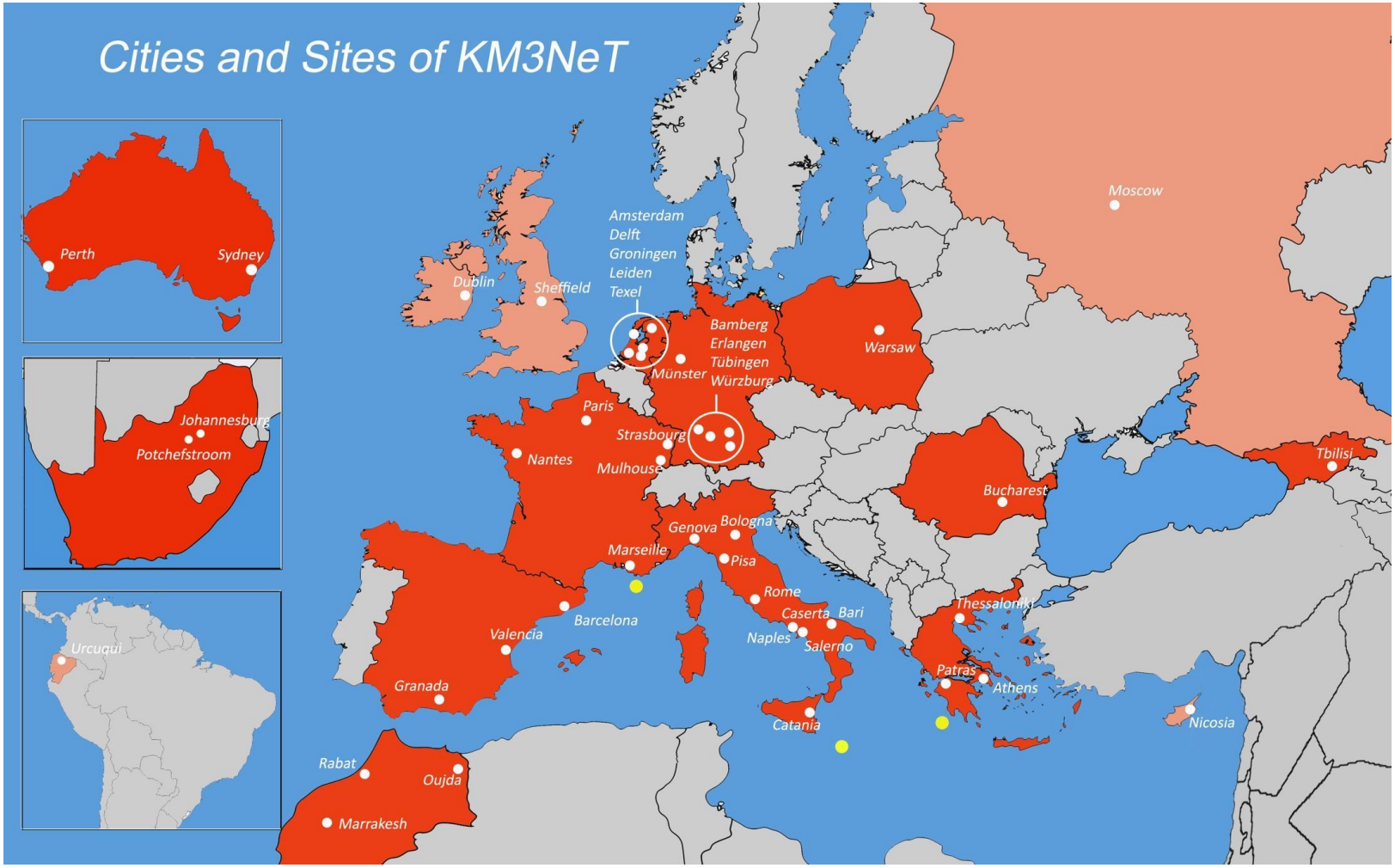
Outline

1. KM3NeT Introduction
2. Neutrino Astronomy at KM3NeT
   a. Diffuse Neutrino Flux
   b. Point-like Neutrino Sources
   c. Core-Collapse Supernova Neutrinos
   d. Multi-messenger Astronomy
3. Status & Outlook

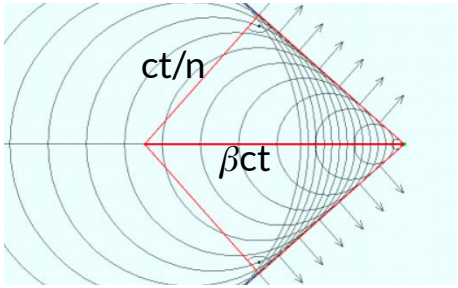
1. KM3NeT Introduction

The KM3NeT Collaboration

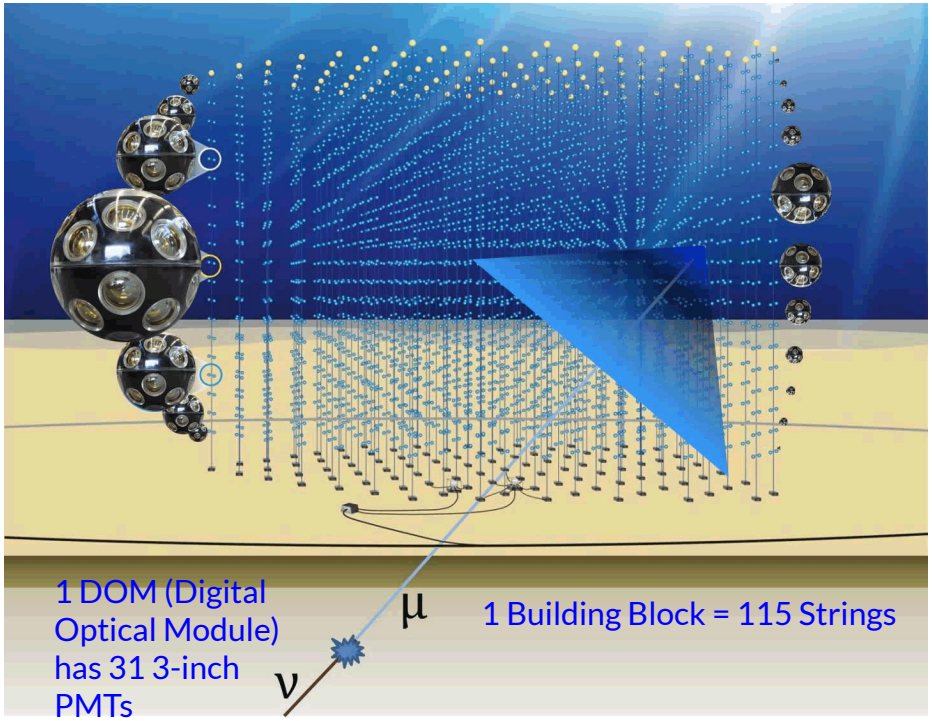


The KM3NeT Detector

Cherenkov Radiation:
Light emitted by a charged particle moving in a dielectric medium with speed greater than speed of light in the medium (c/n)

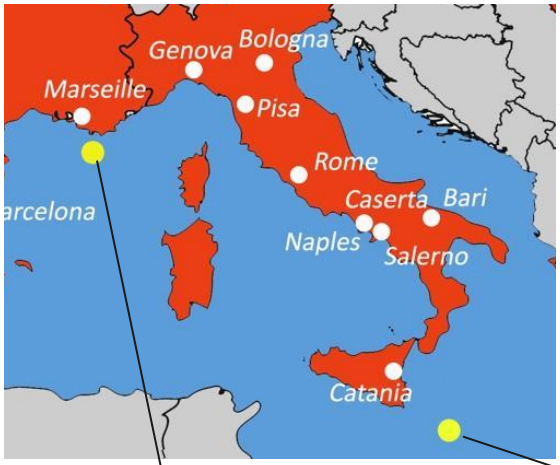


1 String = 18 DOMs



- Detection Technique:
  - DOMs detect Cherenkov light emitted by secondary particles of neutrino weak interactions in water
  - Reconstruct ν direction and energy given the arrival time and amplitude of the observed light
    - Positioning information down to a few cm level and timing resolution of 1 ns guarantees accurate and precise direction reconstruction
- All data to shore via optical fibers

KM3NeT Phased Construction



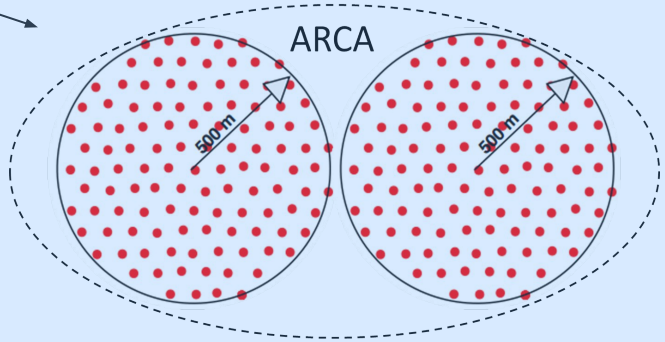
- **Phase 1** (Fully funded): 6 string ORCA + 24 string ARCA
  Proof of feasibility and first science results
  Current working: 6 ORCA (for 6 months) + 1 ARCA
- **Phase 2** (Letter of Intent, Partially funded): ORCA (1 block) + ARCA (2 blocks)
  Search for IceCube astrophysical neutrino signal
  Determine the neutrino mass hierarchy
  Neutrino Astronomy/Astrophysics, Dark Matter, ...

Phase 2

ORCA

Oscillation Research with Cosmics in the Abyss

Dense spacing:
Sensitive to neutrino in [GeV, TeV]
(horizontal 20 m and vertical 9 m)



Astroparticle Research with Cosmics in the Abyss

Sparse spacing: Sensitive to neutrino in [TeV, 10 PeV]
(horizontal 90 m, vertical: 36 m)

KM3NeT Science Goals

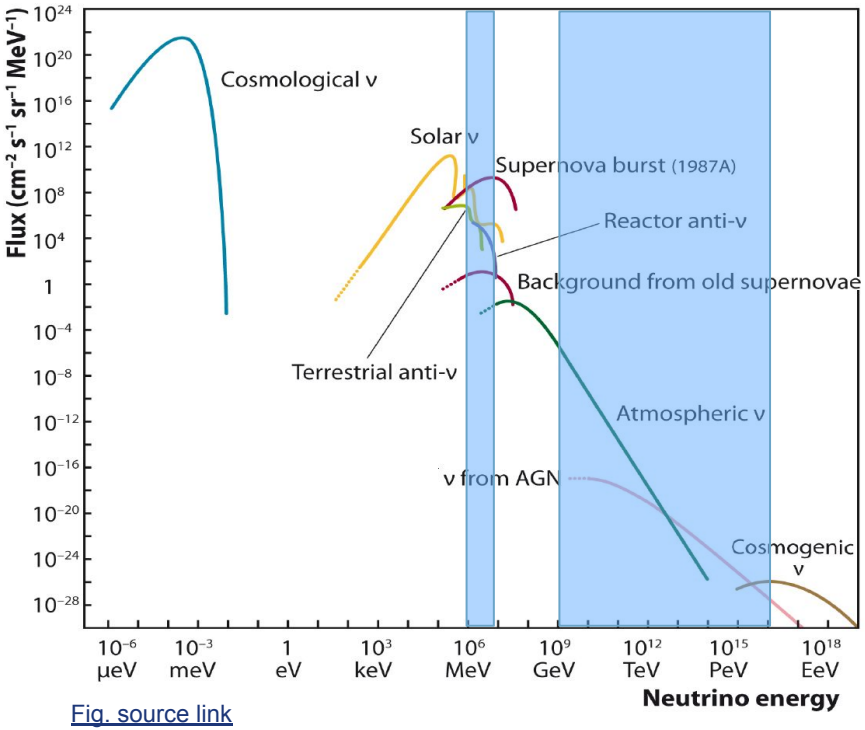
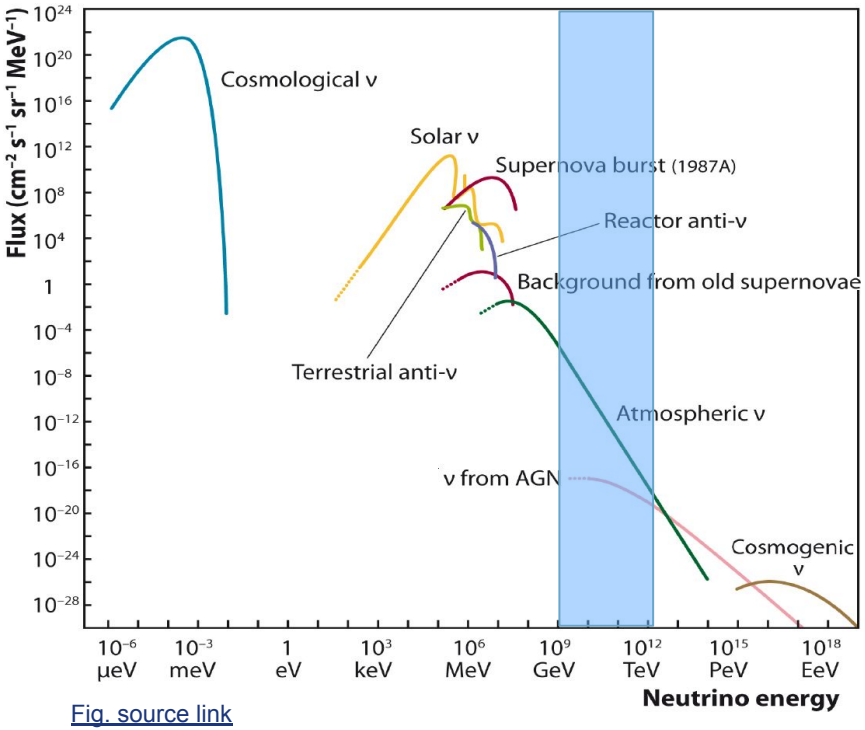


Fig. source link

KM3NeT Region of Interest

- ORCA: (GeV - TeV):
  - ν oscillations, NMH, ν_τ appearance, ...
  - Low energy astronomy for time/space clusters
    - winds of binaries, choked GRBs, hidden jets in core-collapse supernova (CCSN), ...
- ARCA: (TeV - 10 PeV):
  - Neutrinos in galactic point-like sources
    - RX J1713.7-3946, Vela Jr, Galactic center, ...
  - Diffuse neutrino flux
  - Multi-messenger Astronomy: send/receive alerts for transient sources
- Both: MeV scale CCSN neutrinos
  - 1 single DOM acts as a detector

KM3NeT Science Goals



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ORCA GeV - TeV

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  - ν oscillations, NMH, ν_τ appearance, ...
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KM3NeT Science Goals

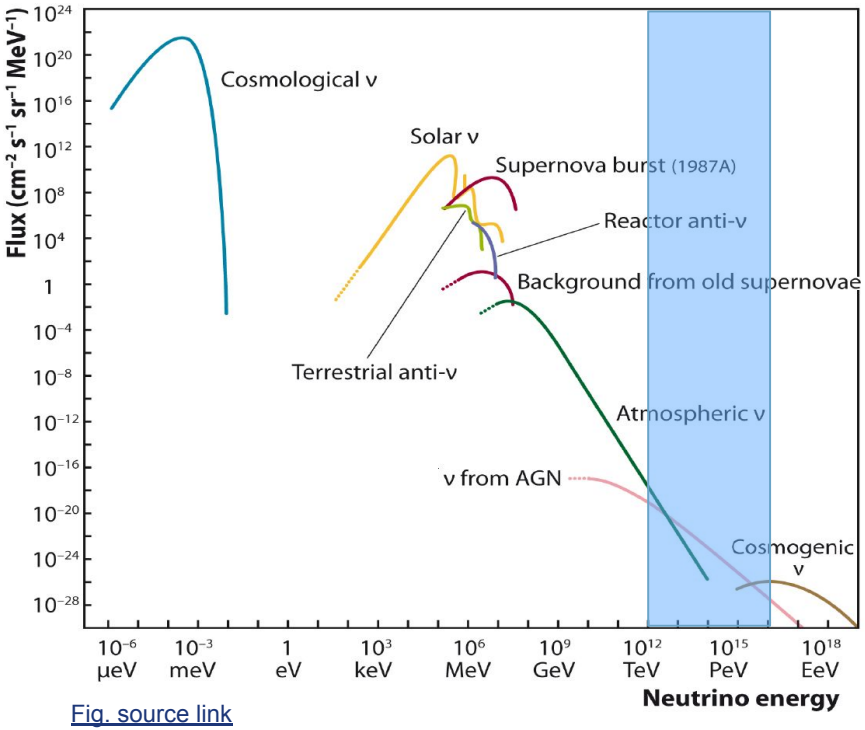

Fig. source link

ARCA TeV - 10 PeV

- ORCA: (GeV - TeV):
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  - Low energy astronomy for time/space clusters
    - winds of binaries, choked GRBs, hidden jets in core-collapse supernova (CCSN), ...
- ARCA: (TeV - 10 PeV):
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    - RX J1713.7-3946, Vela Jr, Galactic center, ...
  - Diffuse neutrino flux
  - Multi-messenger Astronomy: send/receive alerts for transient sources
- Both: MeV scale CCSN neutrinos
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KM3NeT Science Goals

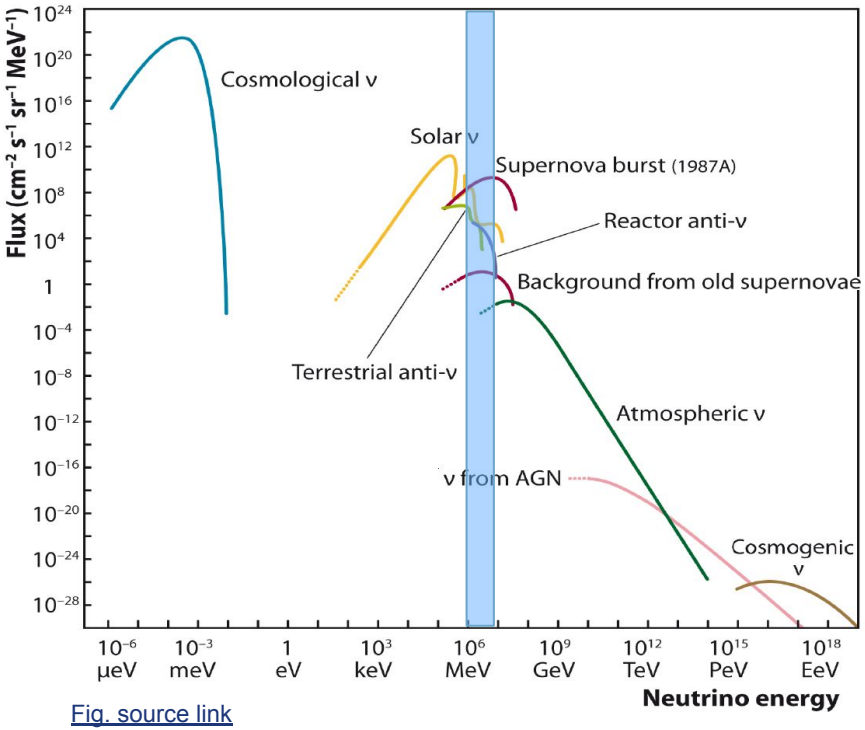


Fig. source link

Both ORCA & ARCA: MeV supernova burst neutrinos

- ORCA: (GeV - TeV):
  - ν oscillations, NMH, ν_τ appearance, ...
  - Low energy astronomy for time/space clusters
    - winds of binaries, choked GRBs, hidden jets in core-collapse supernova (CCSN), ...
- ARCA: (TeV - 10 PeV):
  - Neutrinos in galactic point-like sources
    - RX J1713.7-3946, Vela Jr, Galactic center, ...
  - Diffuse neutrino flux
  - Multi-messenger Astronomy: send/receive alerts for transient sources
- Both: MeV scale CCSN neutrinos
  - 1 single DOM acts as a detector

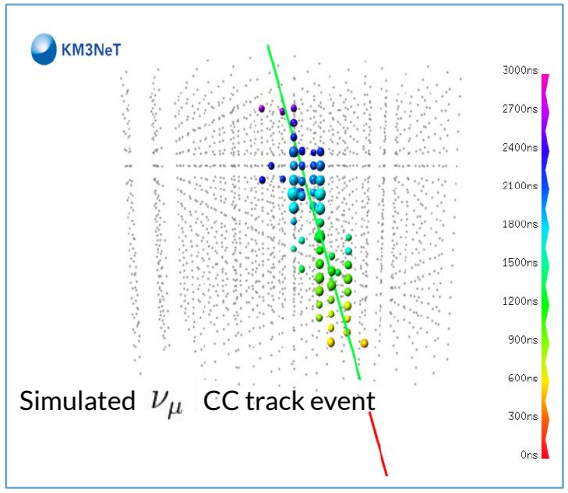
Neutrino Signatures

Track-like: events with visible muon track. Great pointing resolution for point-like neutrino source study

(median angular resolution < 0.1° at E>100 TeV for tracks)

$$\nu_\mu + N \rightarrow \mu^- + X$$
$$\nu_\tau + N \rightarrow \tau^- + X$$
$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$$

(N: nucleon
X : hadrons)

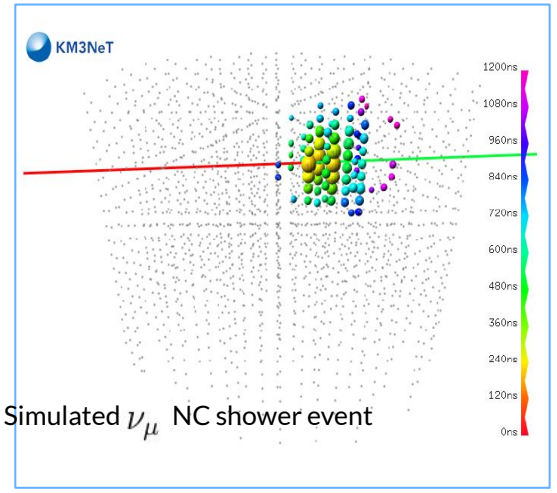


Simulated ν_μ CC track event

Shower-like: events with no visible muon track. Good energy resolution.

ARCA shower median angular resolution < 2°

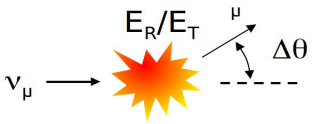
$$\nu_l + N \rightarrow \nu_l + X$$
$$\nu_e + N \rightarrow e^- + X$$
$$\nu_\tau + N \rightarrow \tau^- + X$$
$$\tau^- \rightarrow \pi^- + \pi^0 + \nu_\tau$$
$$\tau^- \rightarrow e^- + \bar{\nu}_e + \nu_\tau$$
...

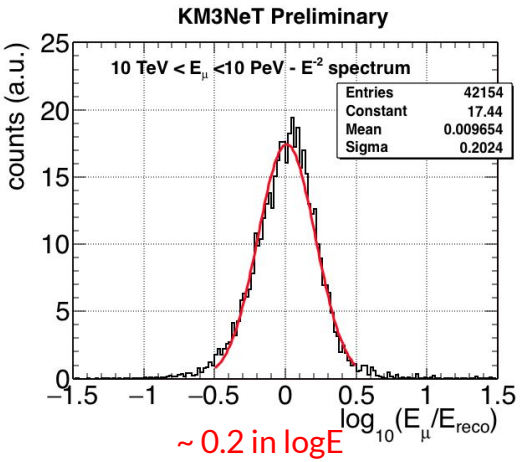


Simulated ν_μ NC shower event

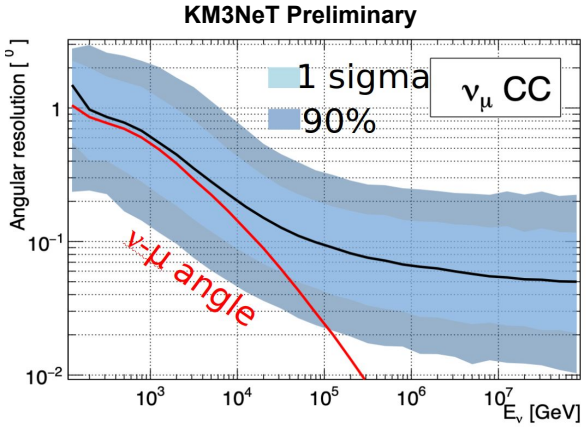
ARCA Reconstruction Resolutions

- Track:



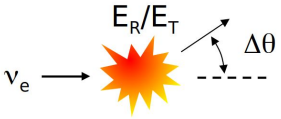


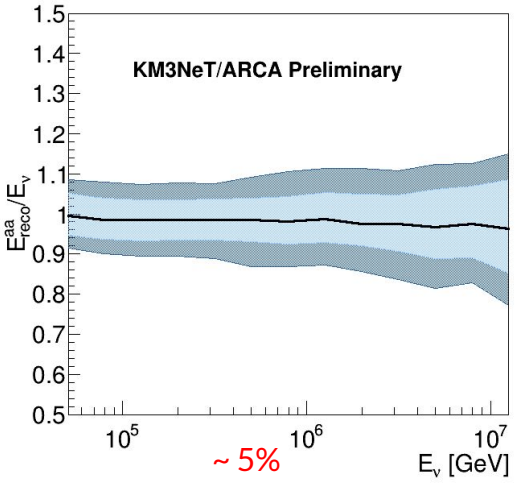
~ 0.2 in logE



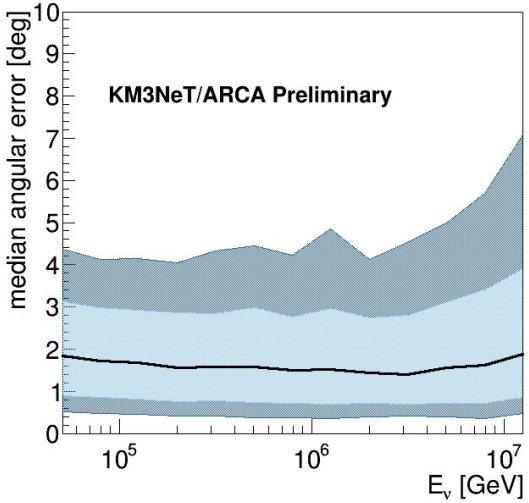
Track median angular resolution < 0.1° at E>100 TeV

- Shower:





~ 5%



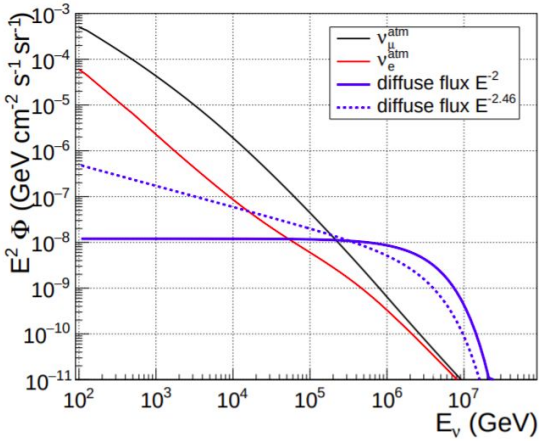
Shower median angular resolution < 2°

2. KM3NeT Neutrino Astronomy

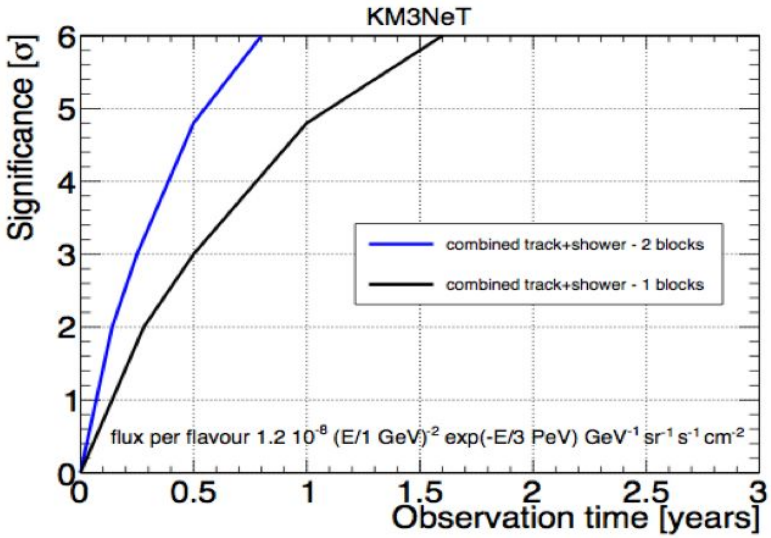
a. Diffuse Neutrino Flux
b. Point-like Neutrino Sources
c. Core Collapse Supernova Neutrinos
d. Multi-messenger Astronomy

Diffuse Neutrino Flux

- Goal: Detect astrophysical neutrino diffuse flux
  - Assuming the astrophysical signal by IC originates from isotropic, flavour-symmetric neutrino flux following a power law spectrum with a cut-off at a few PeV
  - Track + shower combined selection
- Sensitivity:
  - 5σ ~ 1 year with 1 block of ARCA (115 strings)
  - 5σ in ~ 0.5 year with 2 blocks of ARCA (2 x 115 strings)



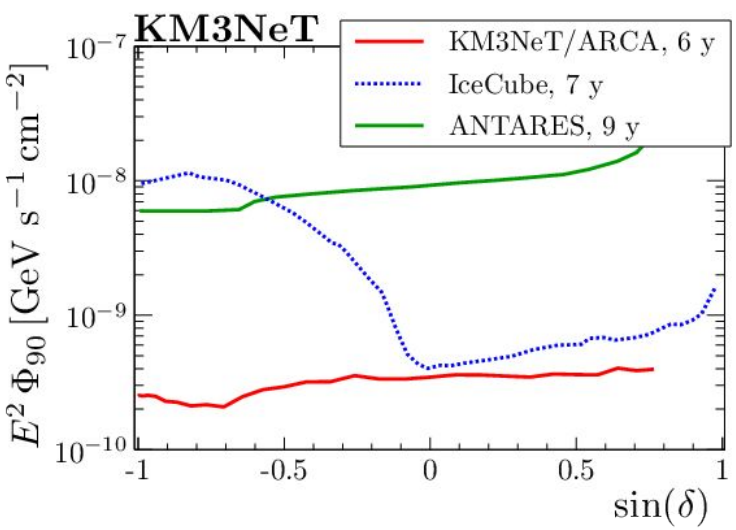
Two assumed astrophysical diffuse fluxes' comparison with conventional neutrino flux



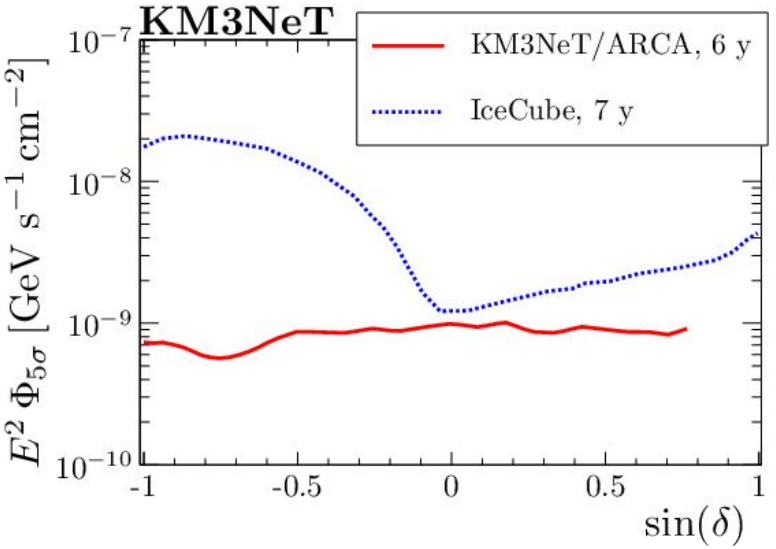
([Link to LOI])

Point-like Neutrino Sources

- Sensitivity and discovery flux at 5 σ for for **sources with a generic neutrino flux $\propto E^{-2}$**
  - Over 1 order of magnitude better than IceCube at the Southern Hemisphere



Sensitivity (the median upper limit at 90% C.L.) vs. source declination

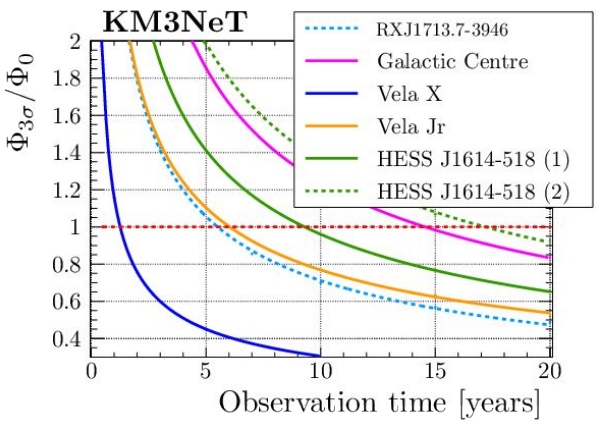


Discovery flux vs. source declination

Extended Galactic Sources

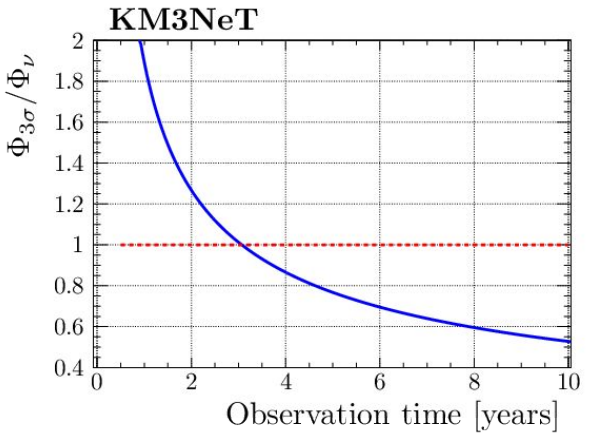
- Several Galactic sources with neutrino flux derived from their γ-ray flux, can be observed by KM3NeT in a few years (assuming γ-ray emission is 100% hadronic)
  - (see flux parameterization, sources' angular extension in backup, Link to Paper)

Vela Jr: 3σ in 6 yrs;
RX J1713.7-3946: 3σ in 5.5 yrs



Ratio of the discovery potential $\Phi_{3\sigma}$ to the expectation flux Φν vs. observation time for different sources

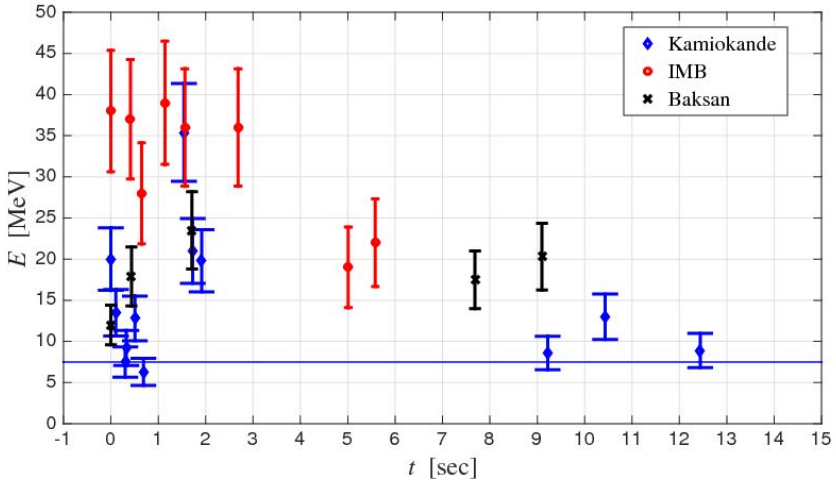
For the stacking analysis of the two:
3σ observation after 3 yrs



$\Phi_{3\sigma}$ / Φν for the stacking analysis including RX J1713.7-3946 and Vela Jr (Φν = sum of the 2 sources)

Core Collapse Supernova Neutrinos

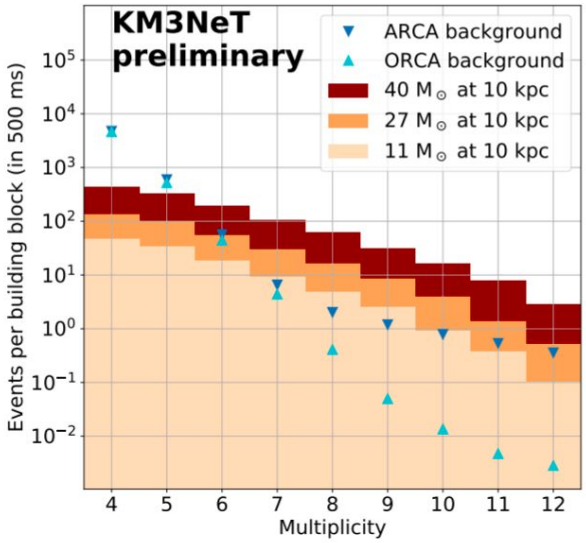
- Neutrinos produced when a star's core collapse at the end of its evolution
- Most prominent: 1987A, 25 neutrinos 2 to 3 hours before light arrival
- Future event could have thousands of neutrinos

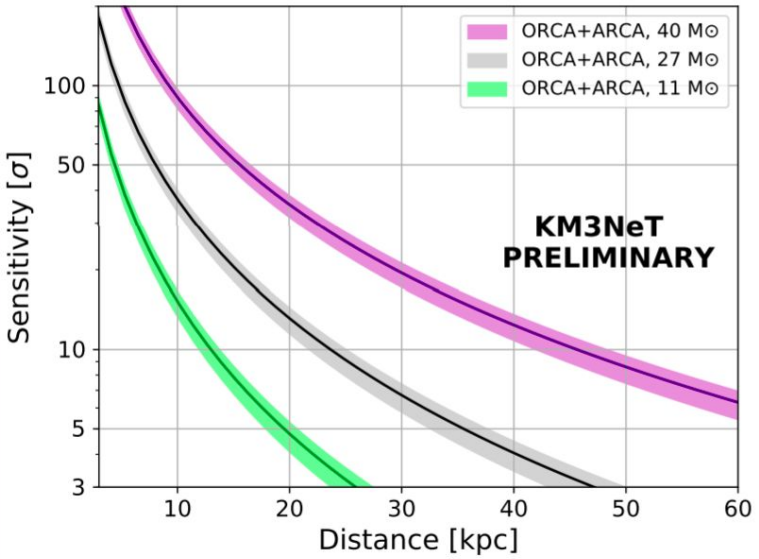


1987A neutrinos observed (2 to 3 hours before visual light arrival), lasting 13 seconds (DOI: 10.3847/0004-637X/828/1/31)

Core Collapse Supernova Neutrinos

- Expected significance based on 7-11 multiplicity coincidences after the filter, in a 500 ms time window (Link to Neutrino 2020 Poster #245)
  - Multiplicity: number of PMT hits within coincidence window in a DOM
- KM3NeT real-time CCSN search running, evaluated each 100 ms in a 500 ms sliding window; ARCA and ORCA in a single trigger.
- CCSN also important in multi-messenger community: KM3NeT already connected to SNEWS (SuperNova Early Warning System)





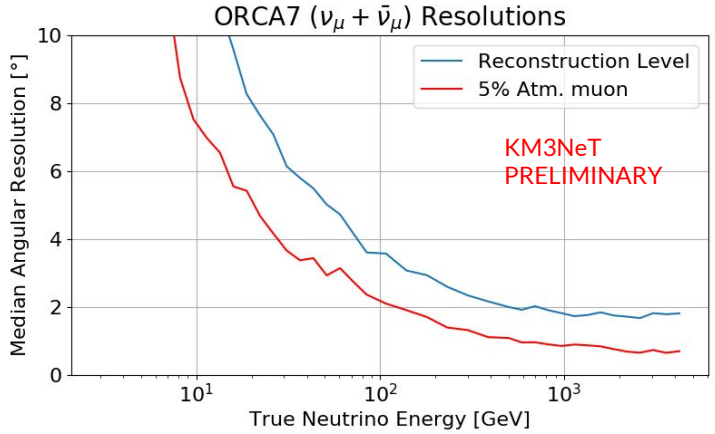
Rates as a function of the multiplicity compared for signal and background

Multi-messenger Astronomy

- 4 Messengers: EM radiation, Cosmic rays, Gravitational waves, Neutrinos
  - Successful multi-messenger detections:
    - SN1987A: supernova neutrinos + optical observations; 2017 Gravitational wave + EM observations; Blazar TXS 0506+056: neutrinos + gamma rays
- Multi-messenger real-time analysis with KM3NeT:
  - Goals:
    - Receive external EM/GW/ν alerts and perform online neutrino correlation search
    - Send online (all flavor, all-sky) neutrino alerts (e.g. multiplets, HE) to external observatories for follow-up
  - Requirement: Fast online reconstruction + fast selection of high-purity neutrino sample

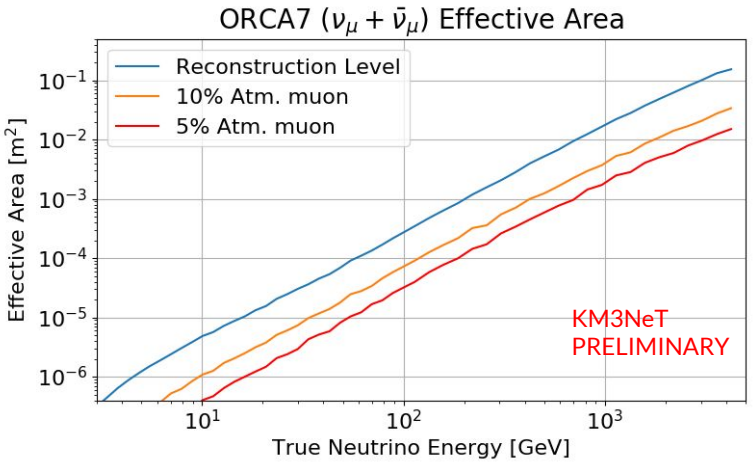
KM3NeT Real-time Framework

- Online reconstruction performance with current ORCA:
  - Reconstruction code same as offline
  - Standard track direction reconstruction: ~ 0.1 s /event
  - Shower reconstruction: ~ 1 s /event
- Angular resolution with 7-string ORCA: ~ 1° at 1 TeV



- Current time delay (online filtering + reco + selection): ~ 4s on average

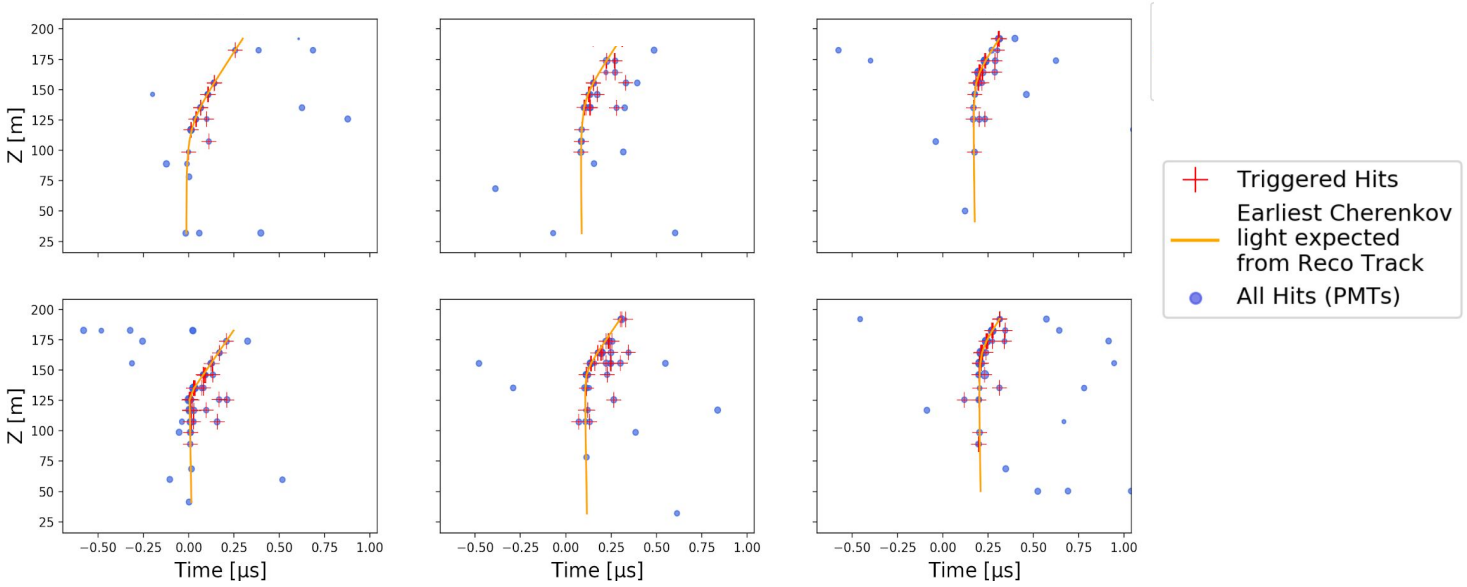
- Online event selection:
  - Gradient BDT for event classification
  - Time: ~ 0.1s /event
  - Preliminary selection: At 5% muon contamination rate, background muon reduced by 10^5 times while keeping over 30% of ν_μ CC
  - (Link to Neutrino 2020 Poster #340)
- Online Correlation: On-going development



3. Status & Outlook

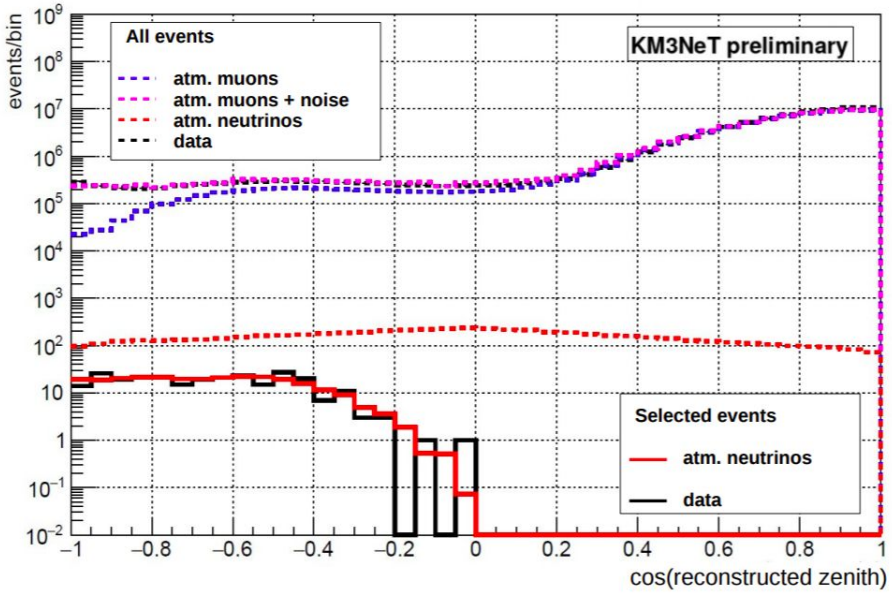
Status

- KM3NeT is being constructed, current setup:
  - ORCA 6 strings running since Jan 2020; ARCA 2 strings installed, temporarily shut down for a major intervention at the shore station
  - Goal: 115 string ORCA in 2024; 2x115 string ARCA in 2026
- Example neutrino candidate event view in 6 strings of ORCA: video link and its triggered hits' vertical position(z) vs. hit time
  - Yellow curve: earliest Cherenkov light expected from the reconstructed track

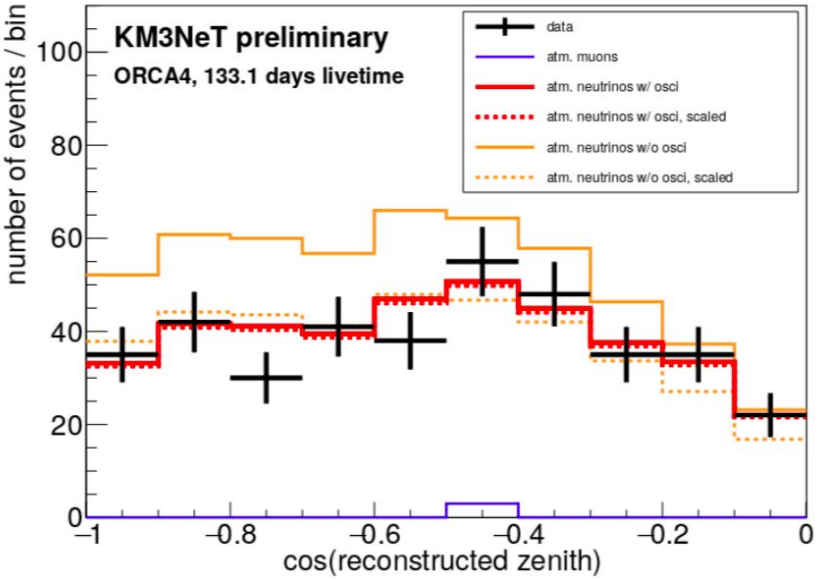


4-String ORCA data

- cos(zenith) distribution of 4-string ORCA data observed over 133.1 days of livetime (Neutrino2020 Poster #363)
  - Up-going track-like events are selected: 99% purity, 2-3 ν / day
  - Main background: Atmospheric muons
    - Before selection: Atmospheric μ / ν ~ 10^5
  - Oscillation favored at 2 σ



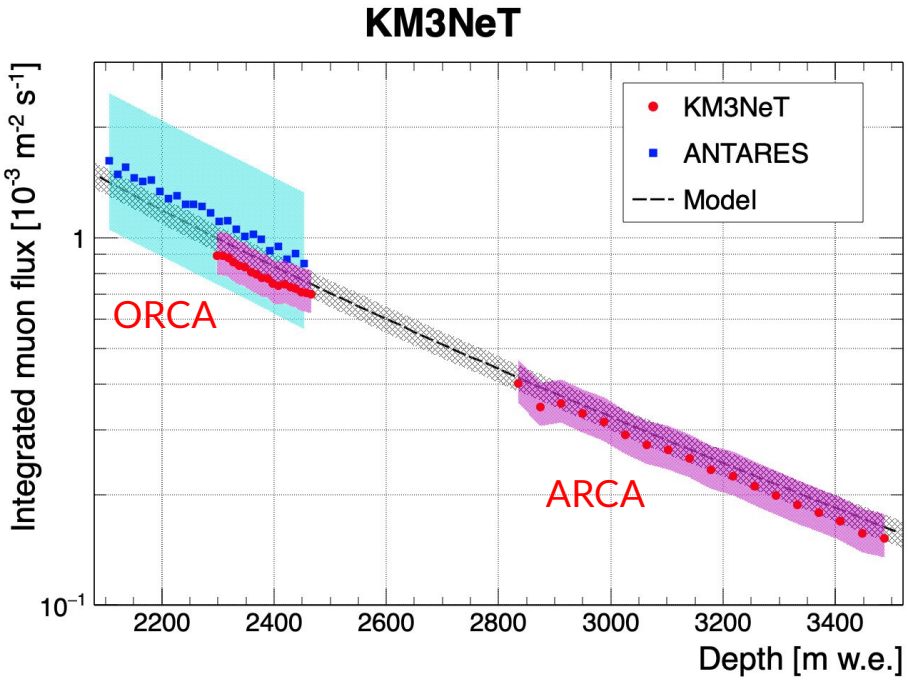
Up-going track-like ν event selection



Yellow: Null hypothesis, no oscillation

Atmospheric Muon Flux Measurement

- Measured atmospheric muon flux vs. sea water depth (link to paper)
- We have a good understanding of our detectors



Red Dots: Atm. Muon Flux Measurement with 1 string ORCA and 2 strings ARCA.
Red & Blue Shade: systematic errors; grey: Bugaev model error

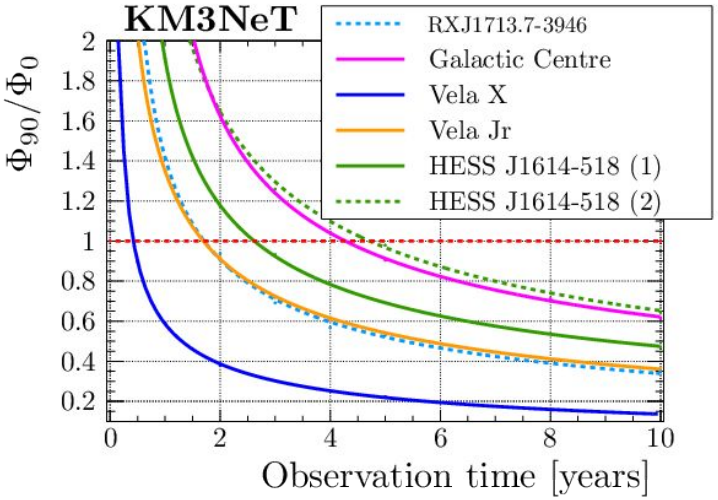
Summary & Outlook

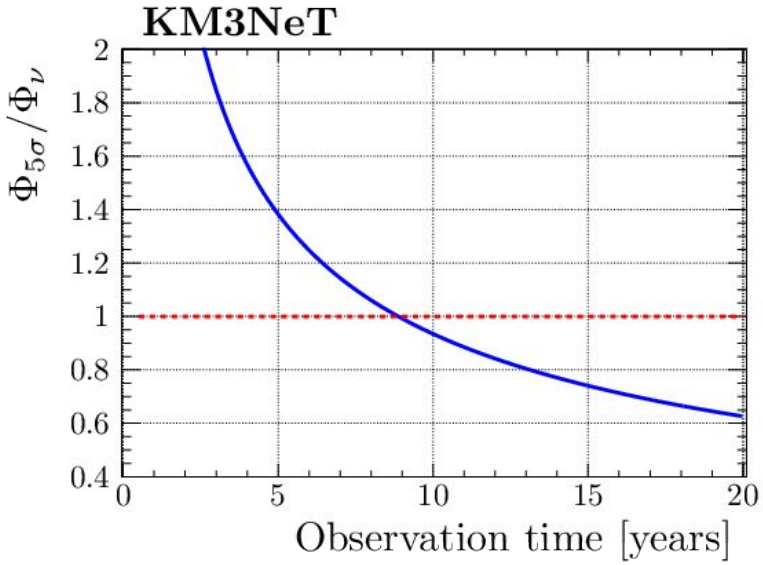
- Having a great angular resolution (< 0.1° above 100 TeV), and with the galactic center in view, KM3NeT will contribute enormously to the neutrino astronomy
- For physics with ORCA, please go to this KM3NeT/ORCA Talk on Friday 08:15
- Current deployed: 2 strings ARCA + Phase-1 ORCA (**6** strings running for **6** months, see our music celebrations: Route 66 song and Tango for 6 hands by 6 pianos)
- New deployment planned soon. Finishing construction of Phase-2 ORCA and ARCA in 2024/2026
- **Stay tuned!**

Thank you!

Backup

Point Source Neutrinos Backup





Extended Galactic Sources backup

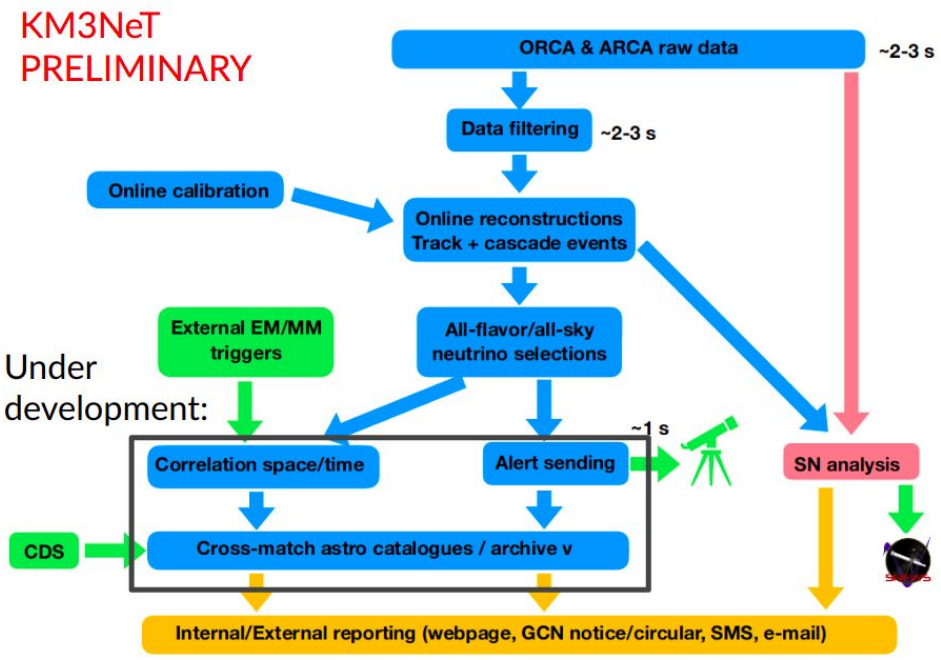
Flux parameterization:

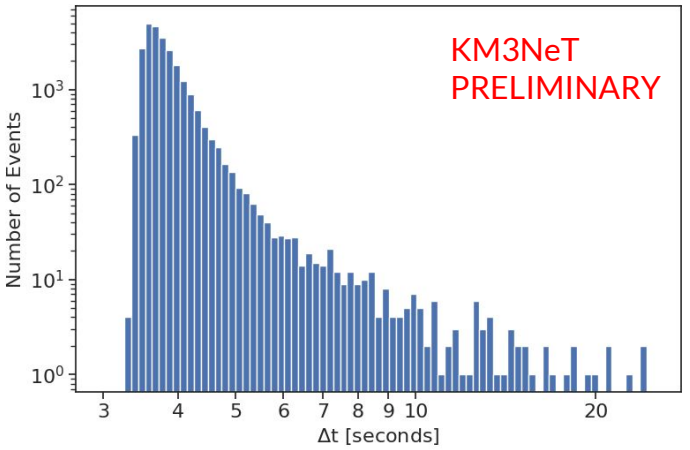
$$\Phi_\nu(E) = k_0 \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\Gamma} \exp\left[-\left(\frac{E}{E_{\mathrm{cut}}}\right)^{\beta}\right], \qquad (1)$$

Table 1: Parameters of the candidate sources investigated, references for the corresponding γ-ray measurements and source type. The neutrino flux is expressed according to Eq.(1), with the normalisation constant k_0 in units of $10^{-11}\,\mathrm{TeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ and E_{cut} in units of TeV. See the text for further details (note that $\xi_{\mathrm{had}} = 1$ is assumed).

Source	δ	radius	k_0	Γ	E_{cut}	β	γ-ray data	type
RX J1713.7-3946	-39.77°	0.6°	0.89	2.06	8.04	1	[11]	SNR
Vela X	-45.6°	0.8°	0.72	1.36	7	1	[23]	PWN
Vela Jr	-46.36°	1°	1.30	1.87	4.5	1	[12]	SNR
HESS J1614-518 (1)	-51.82°	0.42°	0.26	2.42	-	-	[24]	SNR
HESS J1614-518 (2)	-51.82°	0.42°	0.51	2	3.71	0.5	[24]	SNR
Galactic Centre	-28.87°	0.45°	0.25	2.3	85.53	0.5	[25]	UNID
MGRO J1908+06 (1)	6.27°	0.34°	0.18	2	17.7	0.5	see text	UNID
MGRO J1908+06 (2)	6.27°	0.34°	0.16	2	177	0.5	see text	UNID
MGRO J1908+06 (3)	6.27°	0.34°	0.16	2	472	0.5	see text	UNID

KM3NeT Online Framework





A Time Delay of average 4s with events in 6 string ORCA. (Δt = time for raw PMT hits to go through data filtering, track reconstruction and event classification)

External EM/MM triggers: CTA, HAWC/LHAASO, Fermi, Swift, LIGO/Virgo, ELT,...

CDS: Astronomical Data Center with catalogues of the astronomical objects outside the solar system

SNEWS: SuperNova Early Warning System