Recent results and status of the KM3NeT neutrino telescope

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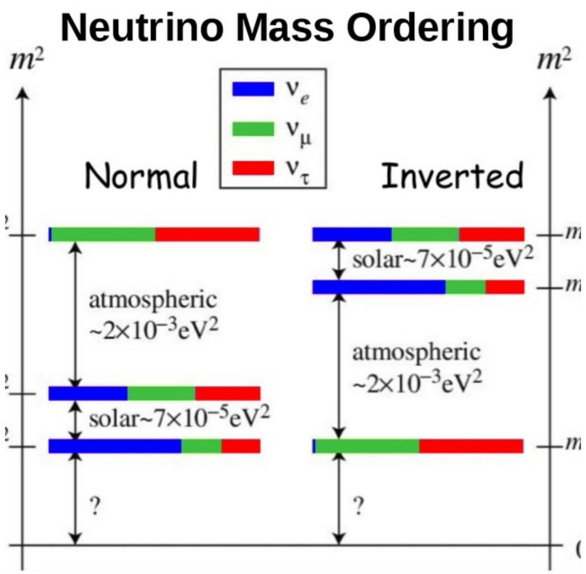
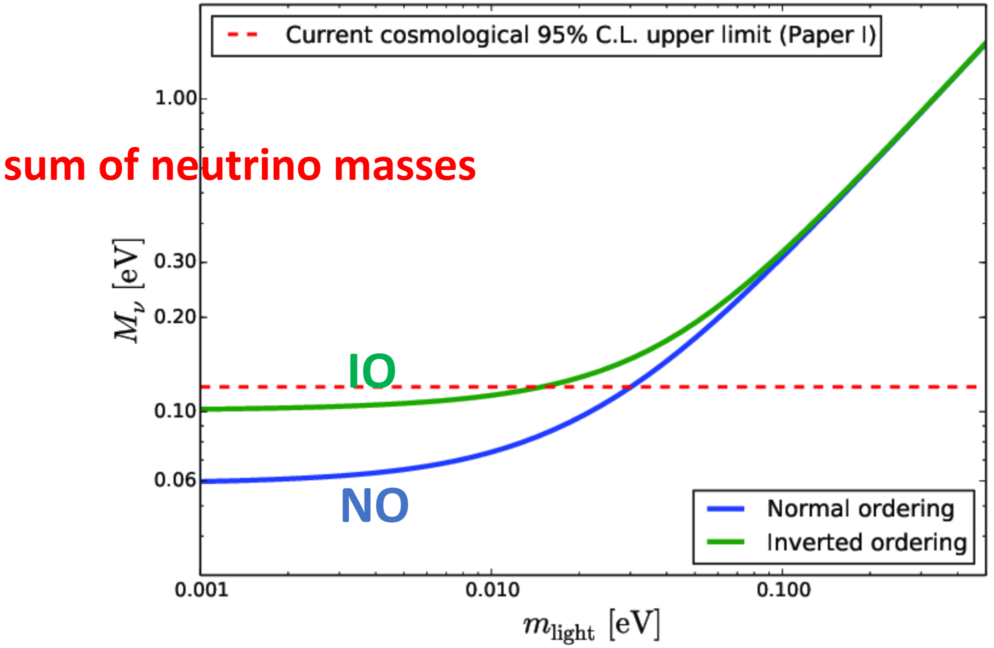
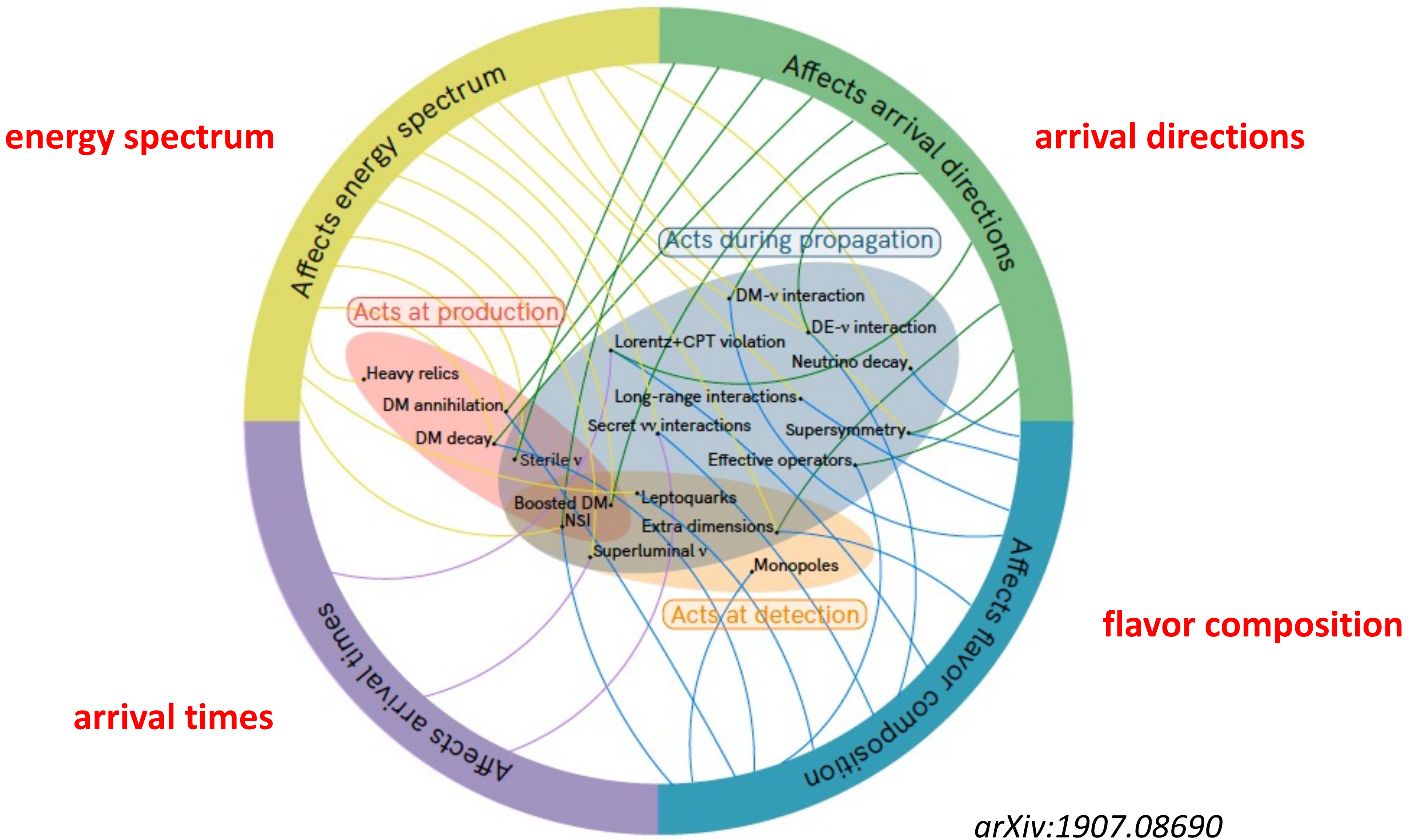
Open questions on neutrinos and relation with cosmology

- ν have tiny, but non-zero mass. New physics?
- ν states mix. How? Relation with quark mixing?
- What is the ν mass ordering?
- CP-violation in ν sector? Leptogenesis?
- Non-standard interactions?
- Sterile neutrinos? Dark matter?
- Dirac vs Majorana character?



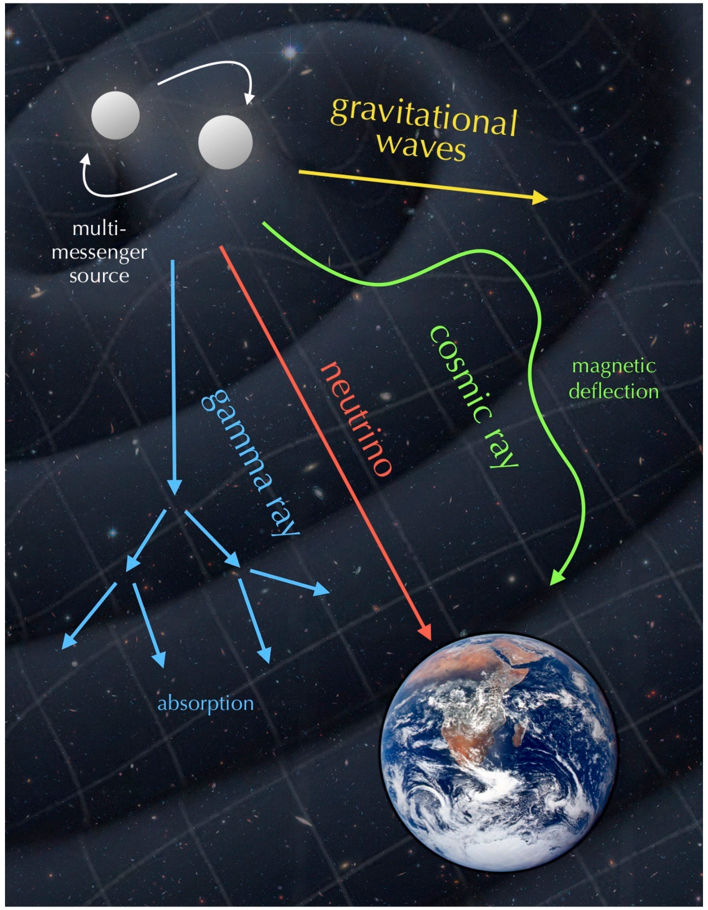


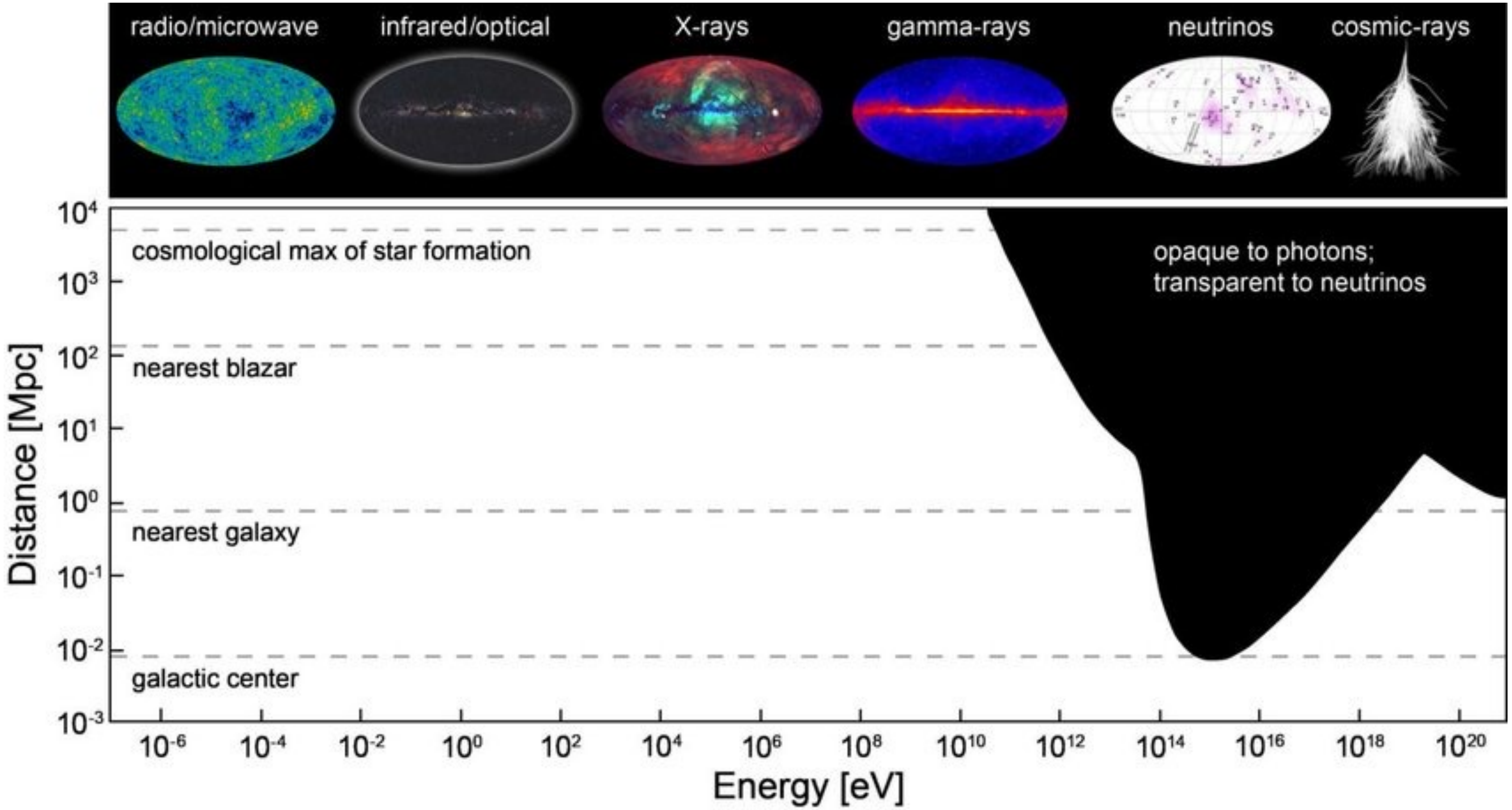
Beyond-the-Standard-Model physics with neutrinos



arXiv:1907.08690

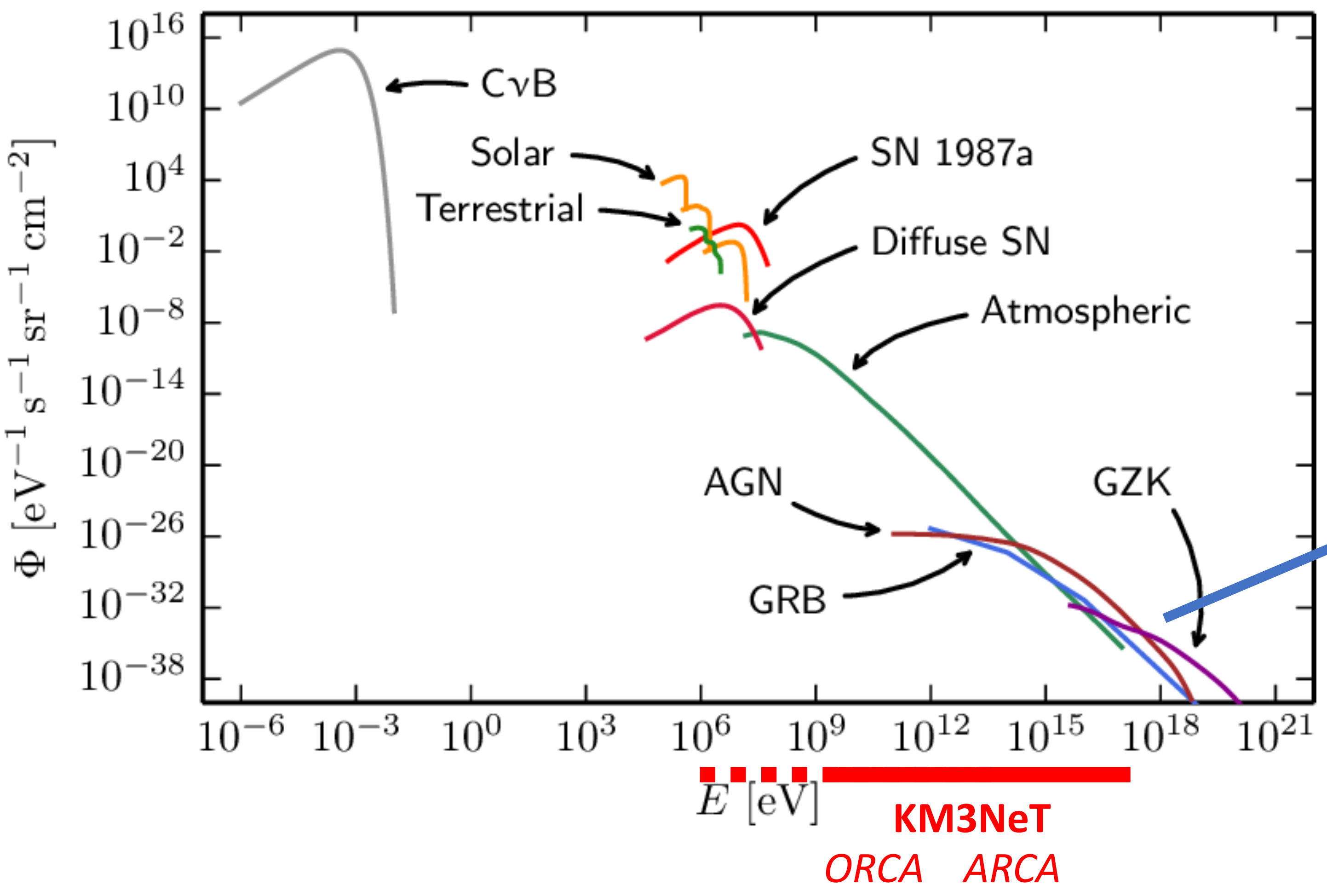
Neutrinos as a tool to study the cosmos

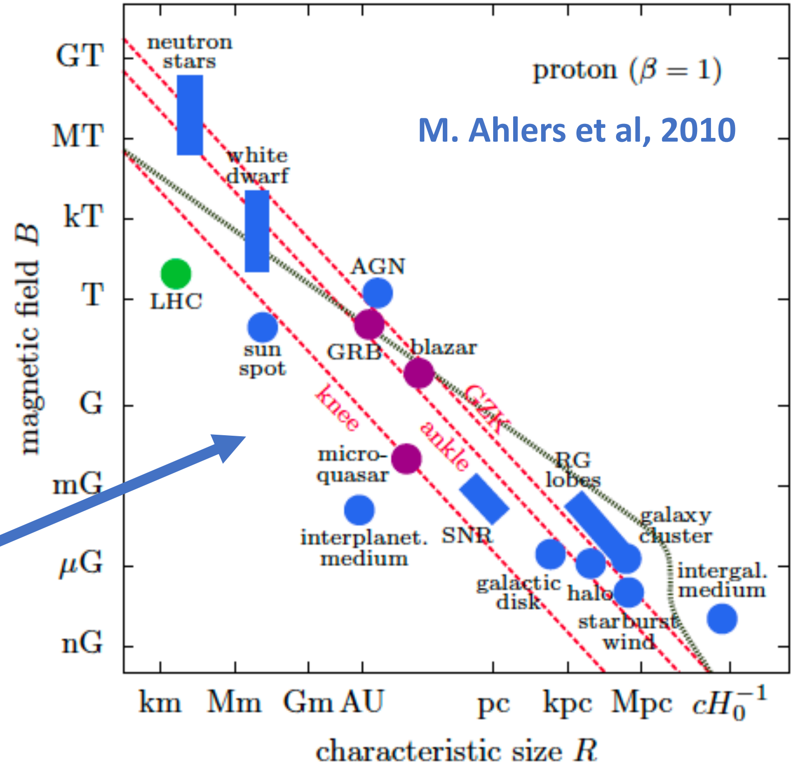




Neutrinos: straight trajectories, practically no absorption.
Sources: powerful cosmic hadronic accelerators.
Multimessenger astronomy: combine ν, γ-rays, other EM waves, gravitational waves, charged cosmic rays

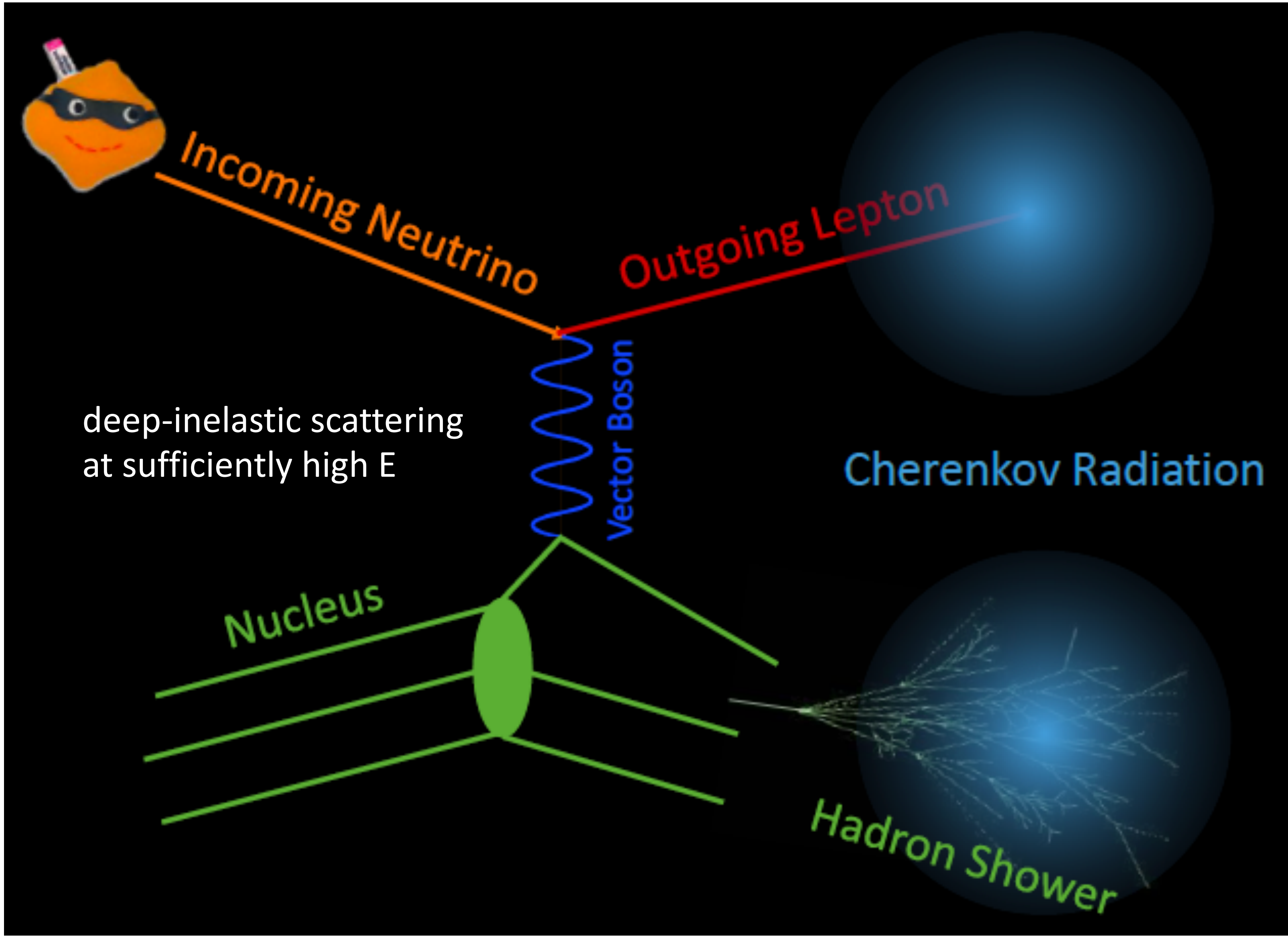
Neutrino spectrum





"Hillas plot"

Neutrino telescopes



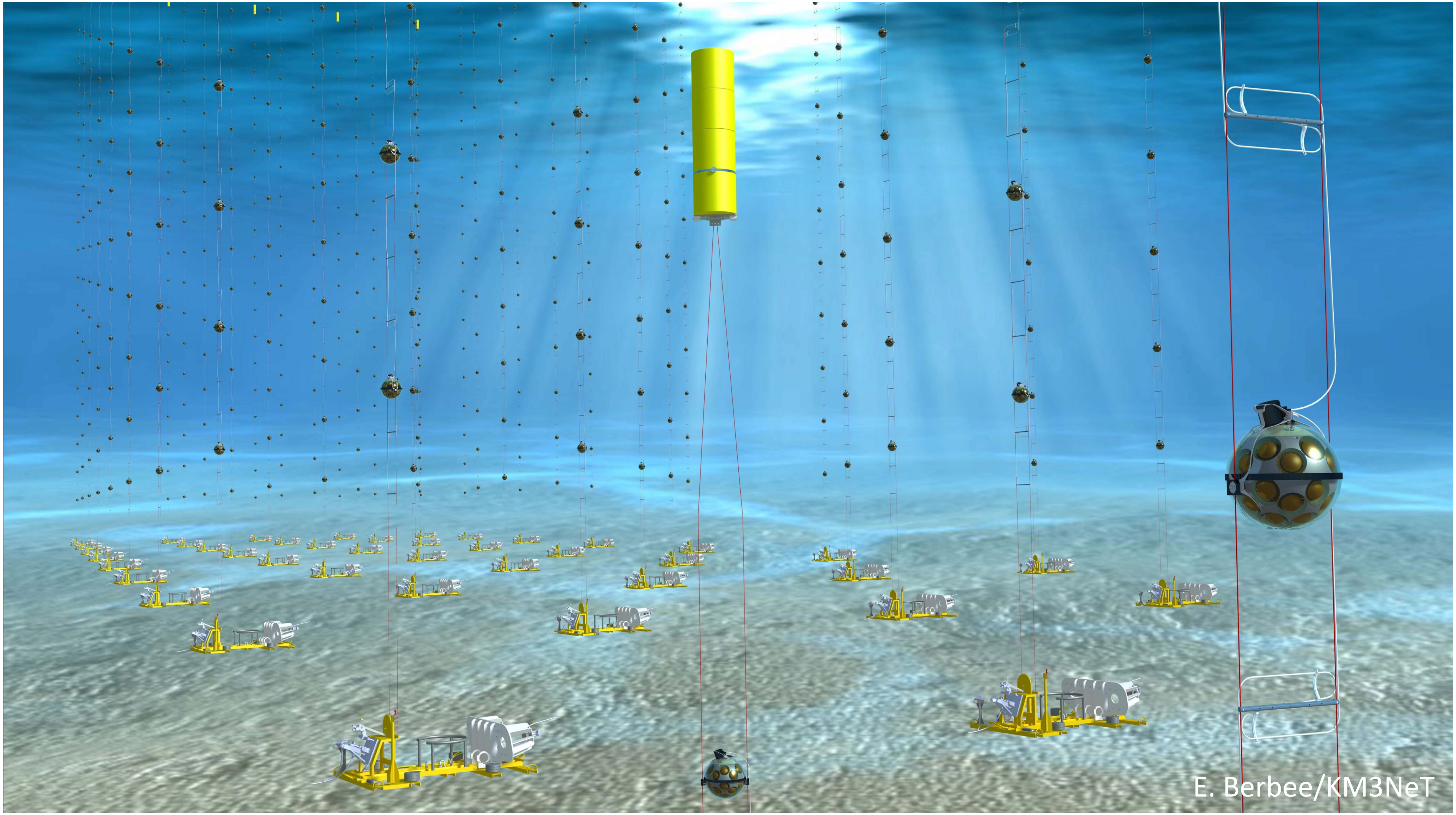
Detector properties:

- Transparent Medium
- Deep underground to shield backgrounds
- HUGE Volume

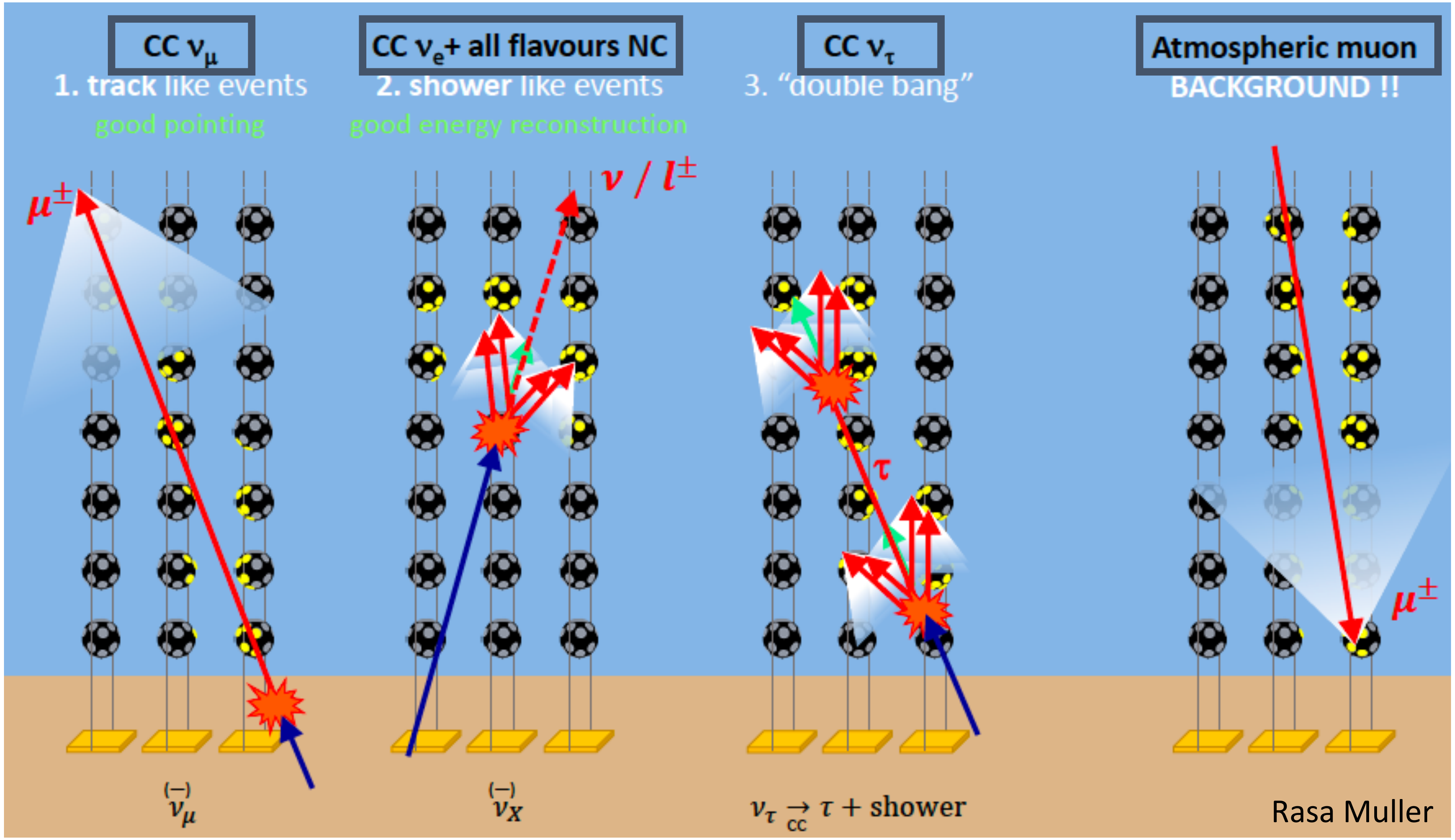
→ Deep Water / Ice

Philipp Eller

Neutrino telescopes



Neutrino telescopes



"tracks"

"showers"

background

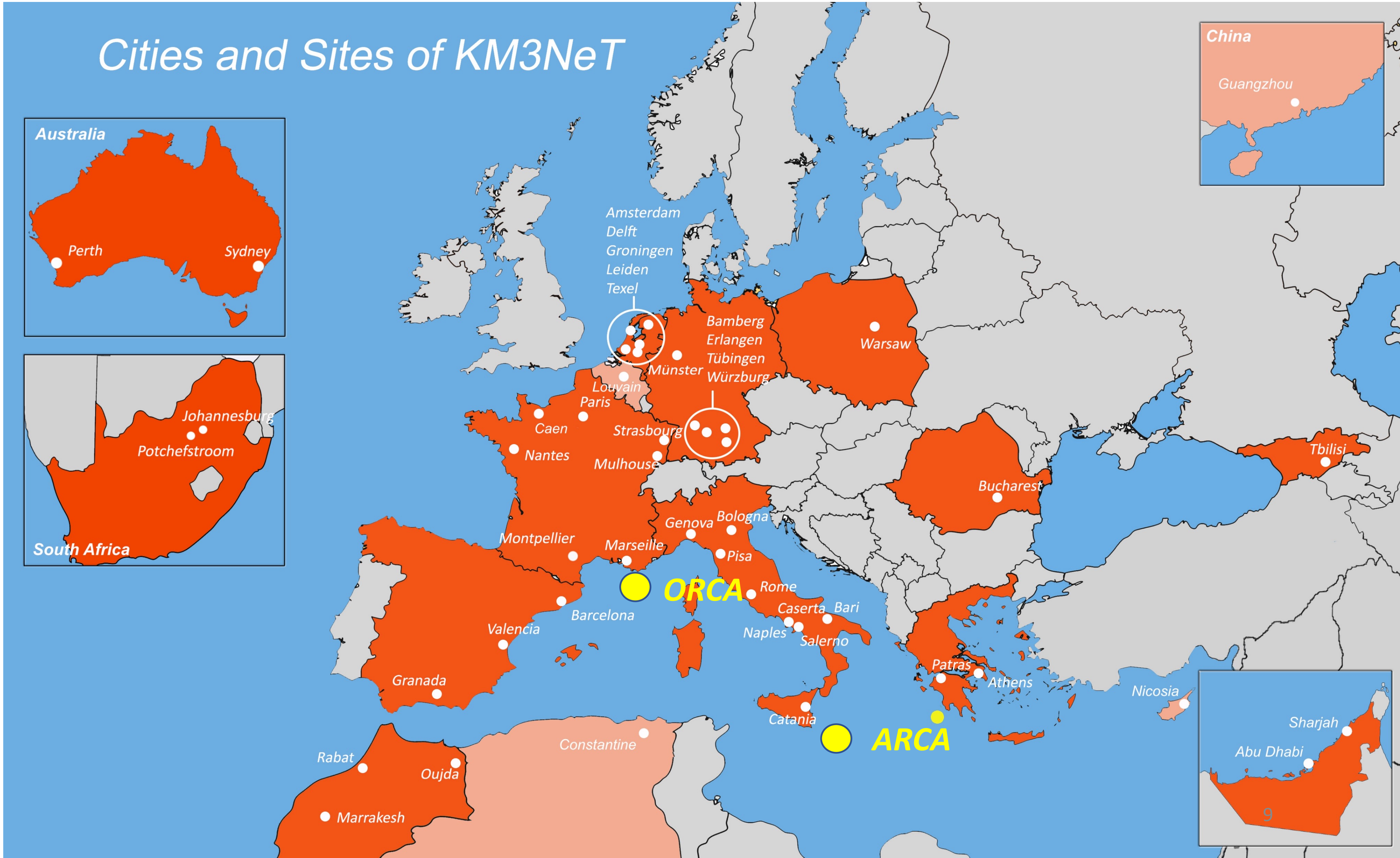
KM3NeT collaboration

KM3NeT

Numbers:

- ❖ 55 groups
- ❖ 16 countries
- ❖ 4 continents
- ❖ 2 detectors

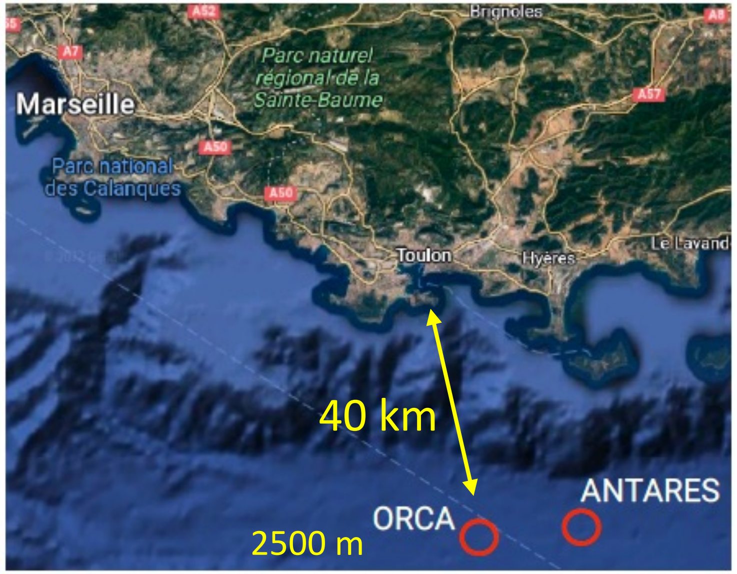
ORCA/ARCA



Legend:

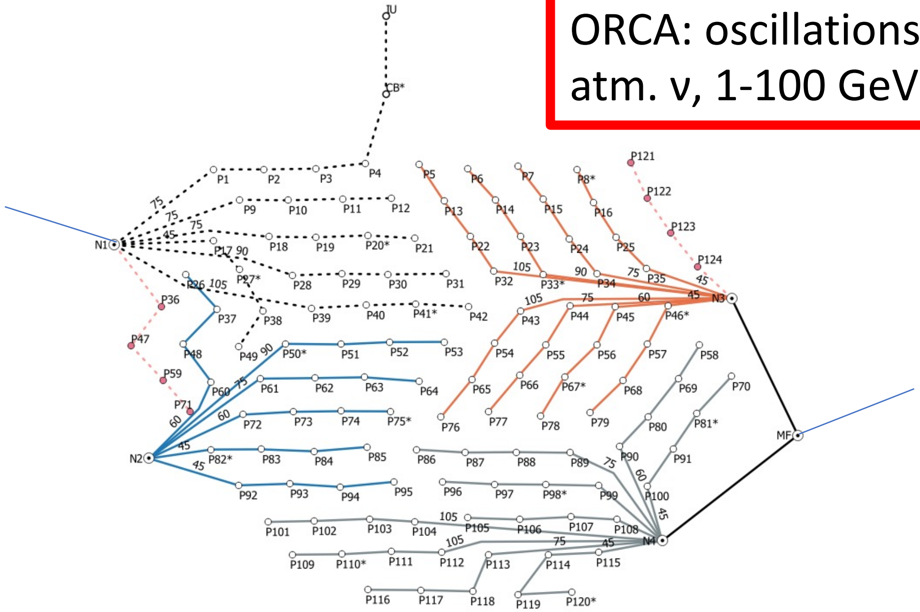
- group
- observer
- member

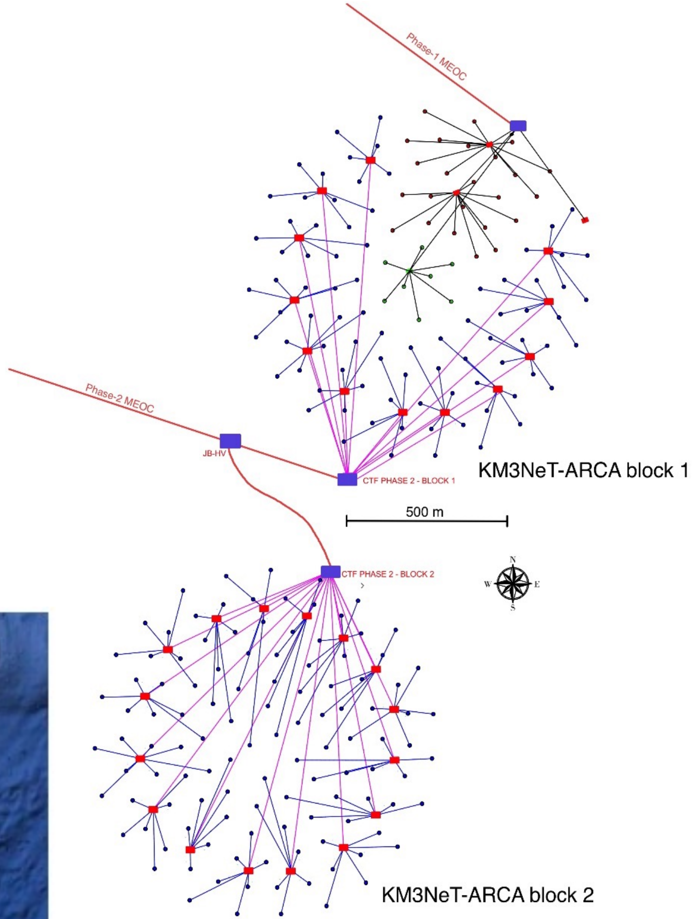
KM3NeT general layout



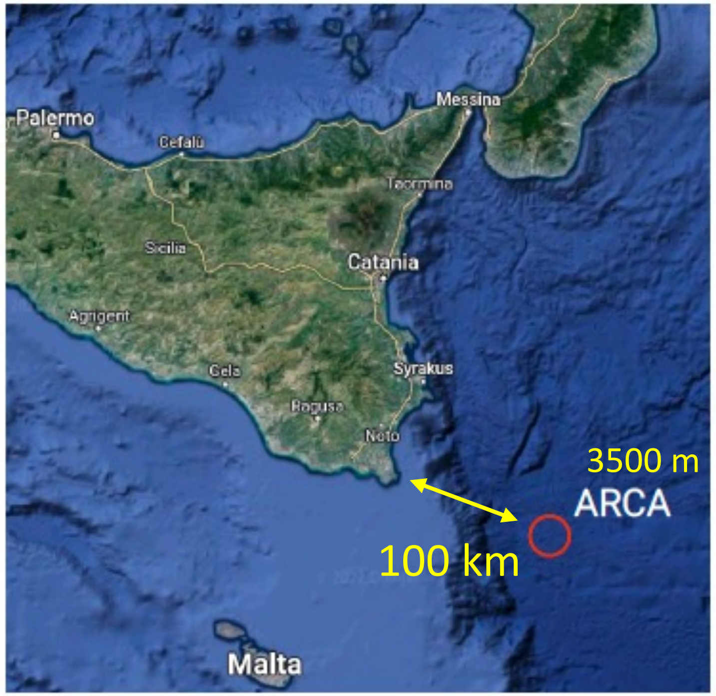
	ORCA	ARCA
String spacing	20 m	90 m
OM spacing	9 m	36 m
Instrumented mass	7 Mton	500*2 Mton

J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



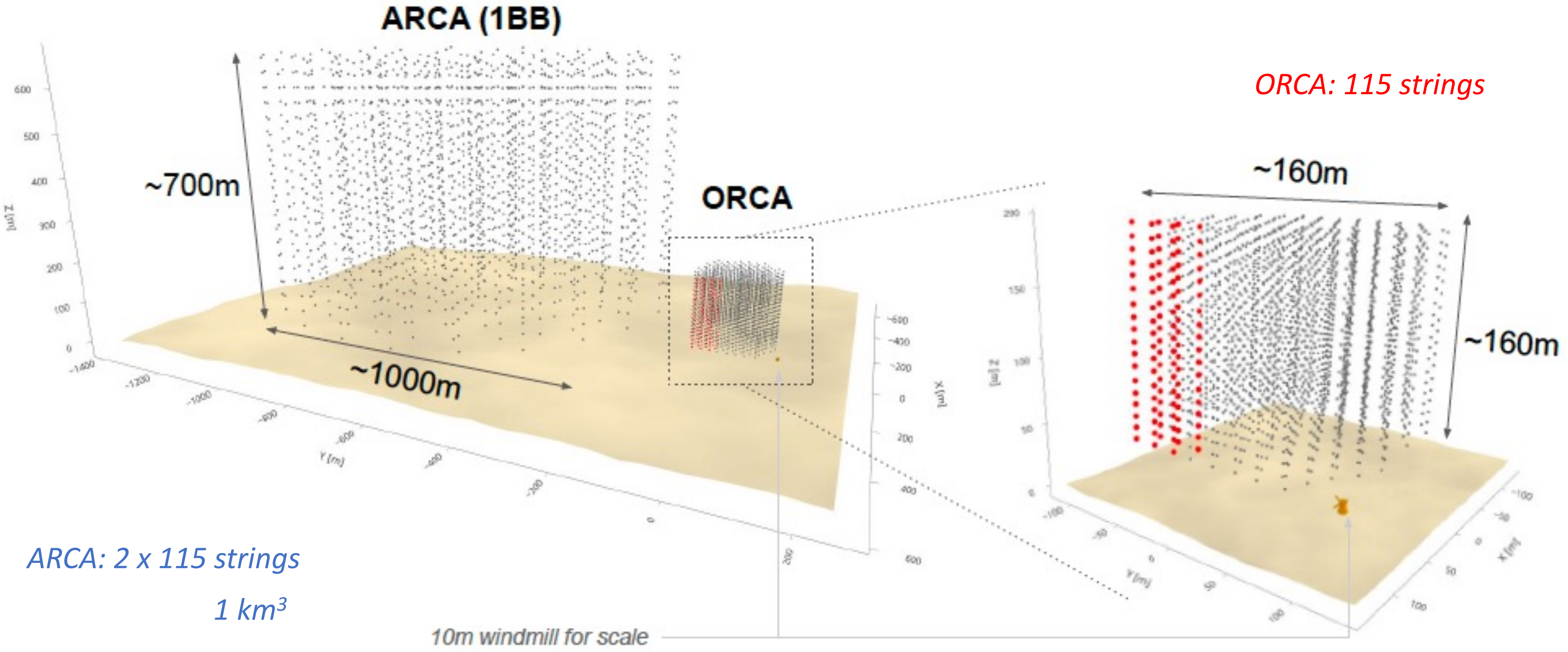


ORCA: oscillations atm. ν, 1-100 GeV



ARCA: cosmic neutrinos E > 100 GeV

KM3NeT general layout

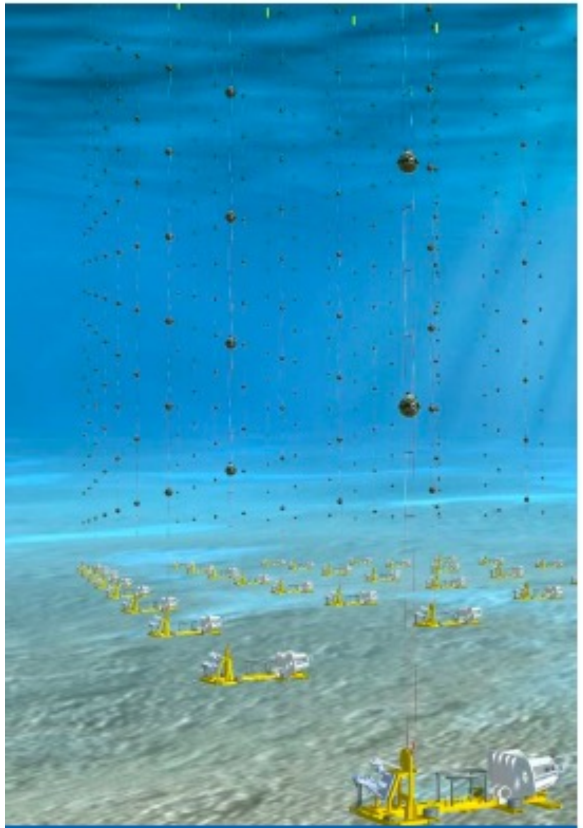


ORCA: 115 strings

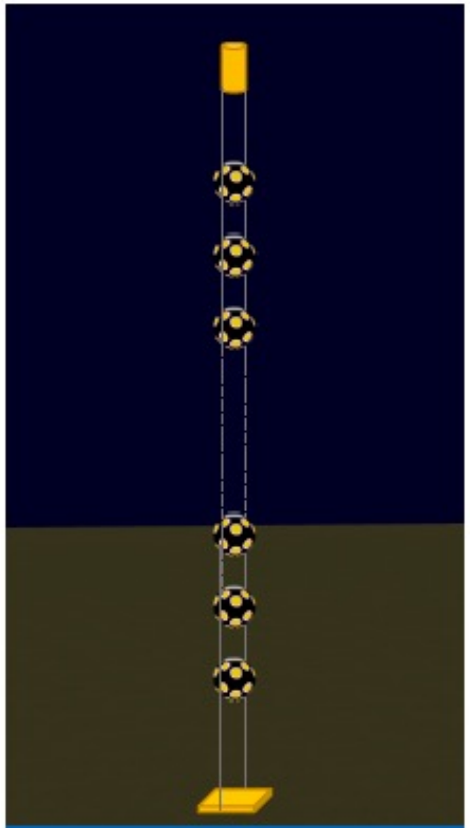
ARCA: 2 x 115 strings

1 km^3

KM3NeT components



1 building block =
115 lines



1 line =
18 optical modules

“detection unit (DU)”

1 optical module =
31 photomultiplier tubes

“digital optical module (DOM)”
31 3’’ photomultiplier tubes

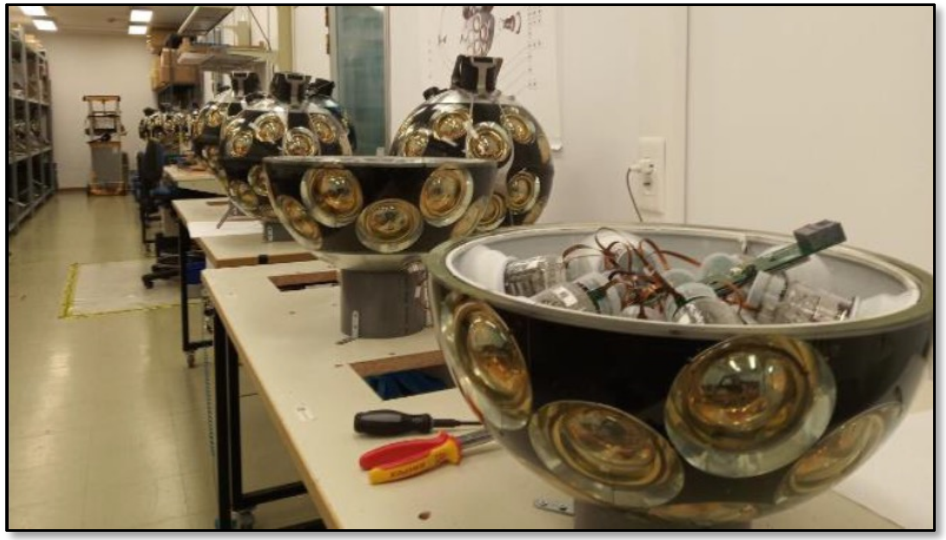
71 unique components
(in solid or liquid phase)

Rasa Muller

JINST 17 (2022) 07, P07038

identical for ORCA and ARCA

DOM and DU production

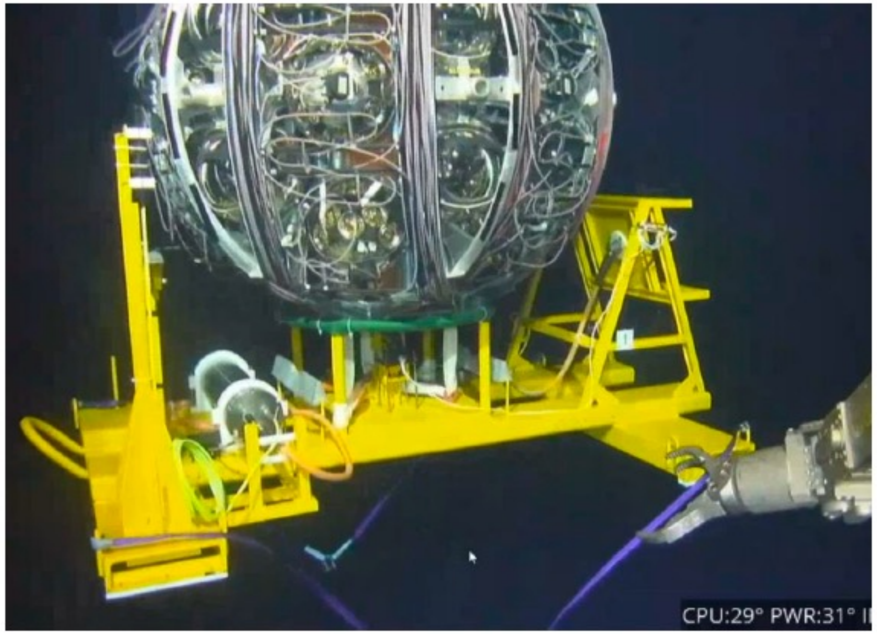


DOM: 8 sites
DU: 5 sites

+ sites for
base containers,
electronics,
testing

Deployments and status

JINST 15 (2020) P11027



Deployments: launcher module (LOM) with anchor, lower to sea floor, connect, test, unfurl, retrieve LOM

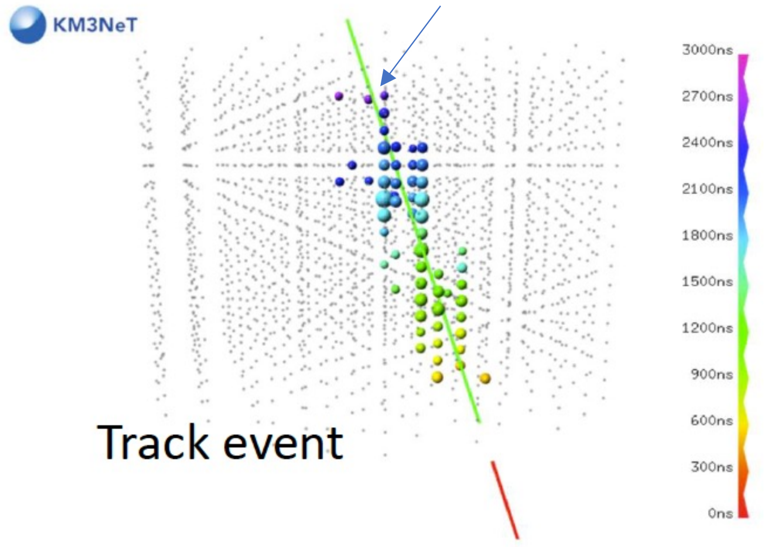
ORCA: 6 lines February 2020 – November 2021; currently taking data with 10 lines

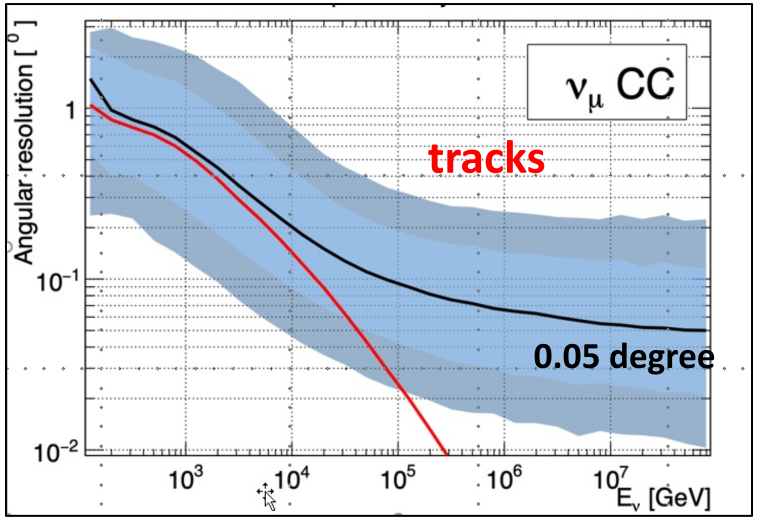
ARCA: 6 lines April – November 2021; 8 lines Nov 2021– June 2022, since June 2022 taking data with 19 lines

Further growth in coming months.

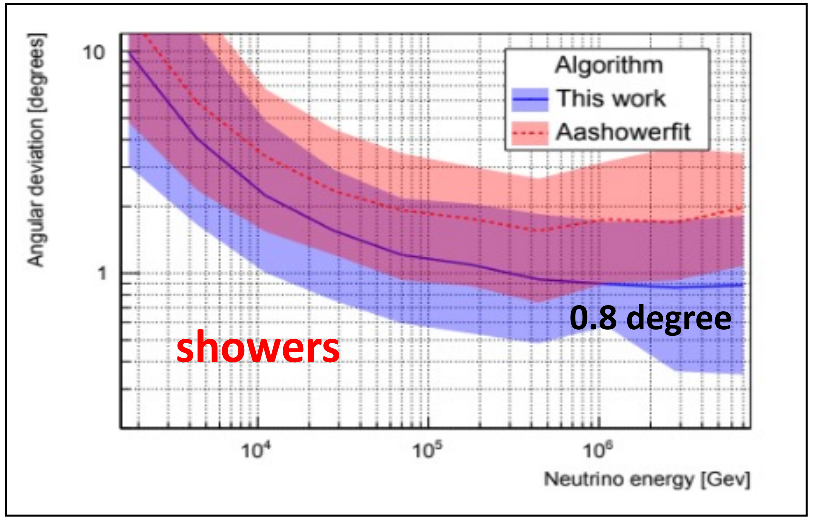
Event reconstruction

Each PMT: location, direction, time of hit, pulseheight (ToT): fit Cherenkov cone





KM3NeT preliminary



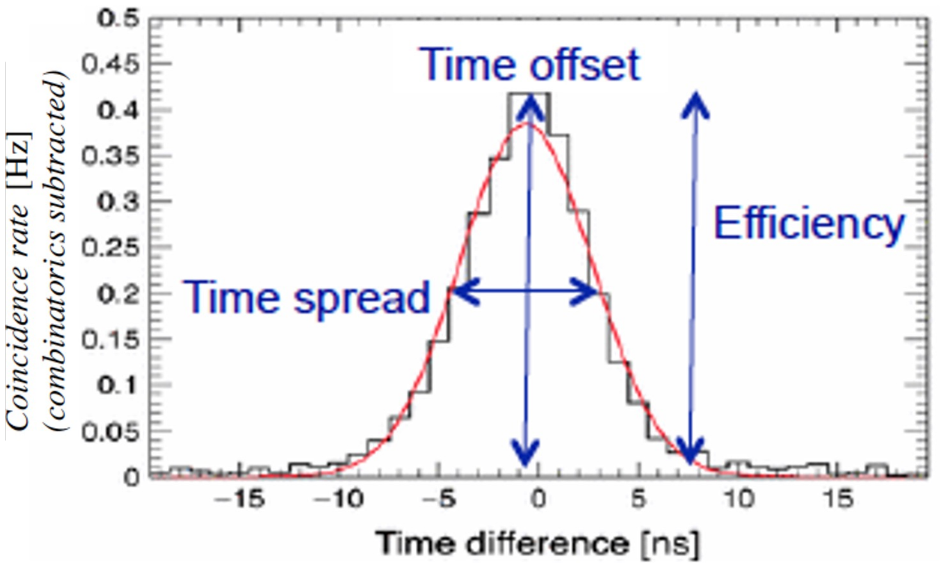
angular resolution: <4 arcmin @ PeV energies (tracks), 50 arcmin (showers)

KM3NeT vs IceCube:

Con: ^{40}K background, bioluminescence, need for position calibration, deep sea operations
Pro: ^{40}K calibration, better view of galactic center, no bubbles/dust → better angular resolution

Calibration: timing

information from PMT coincidences



Also: lab calibration of timing differences, LED flasher, timing from reconstructed tracks. Timing resolution better than 1 ns.

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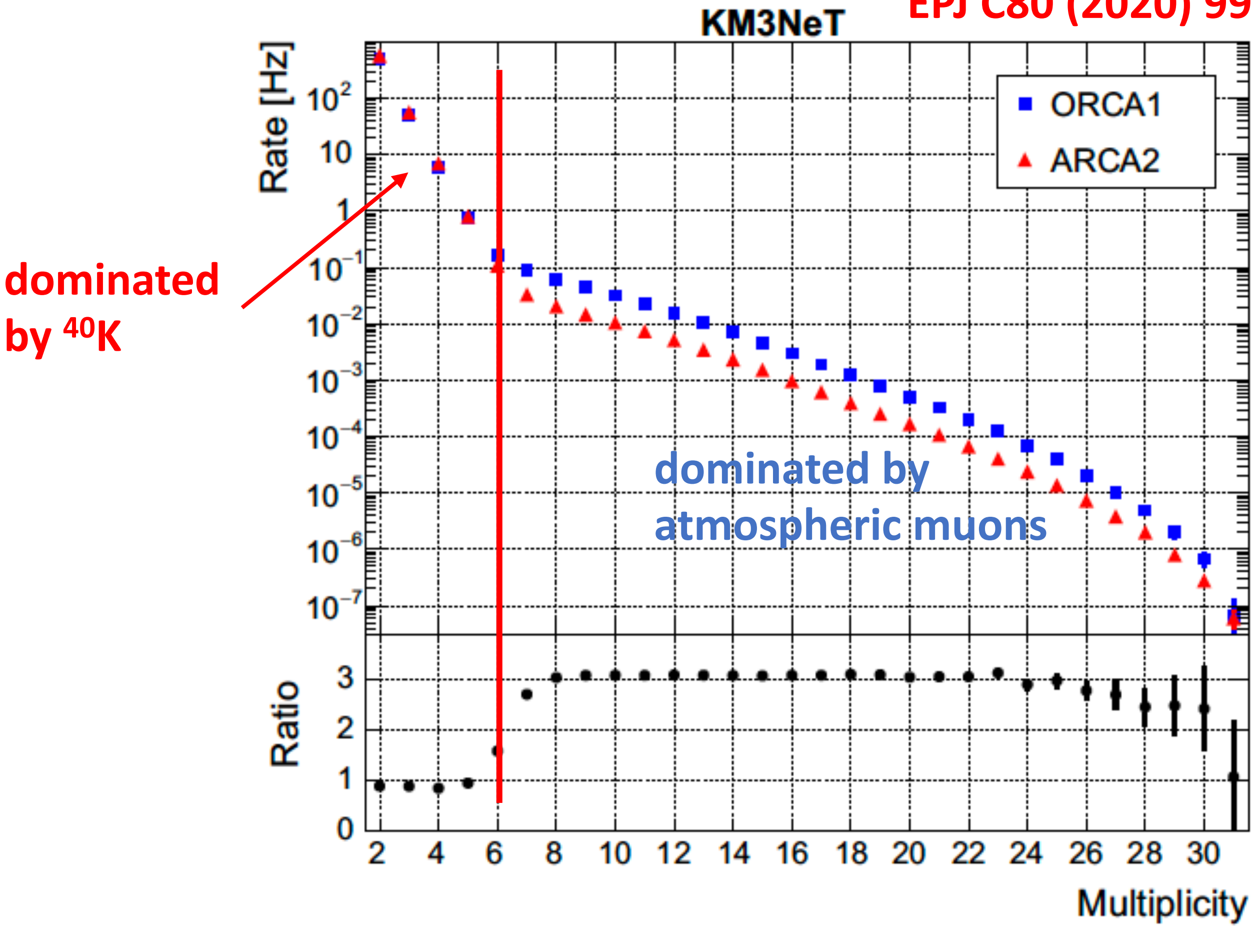
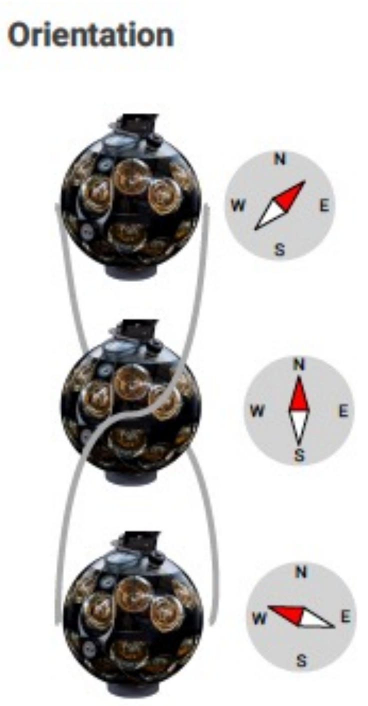


Coincidence rate between PMTs on a DOM for one ORCA and one ARCA line, as a function of PMT multiplicity

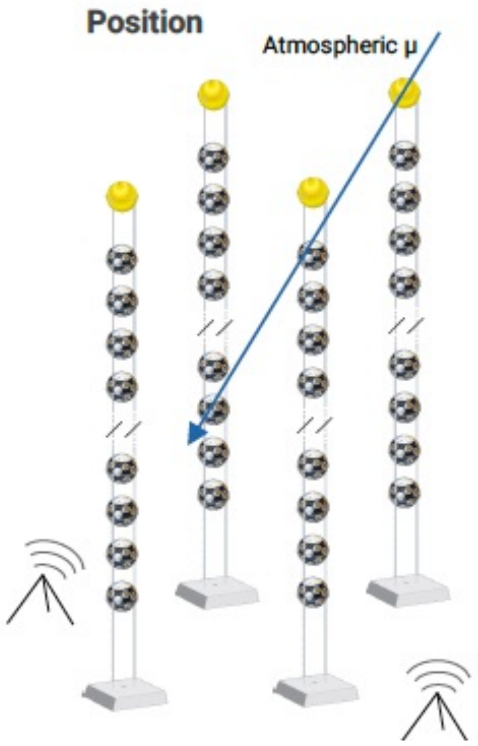
Calibration: positioning

Lines move with the sea current. Needs dynamic position calibration.

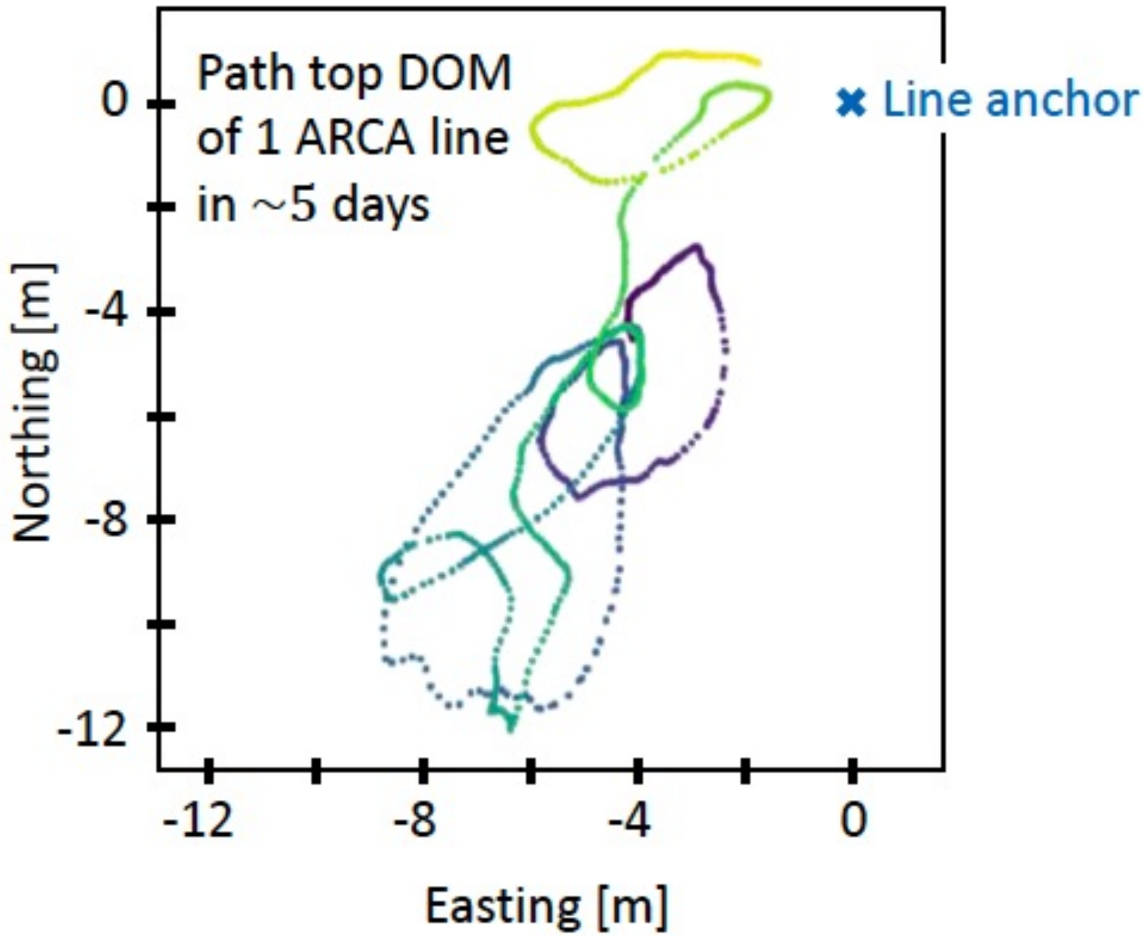
JINST 16 (2021) 09, C09023



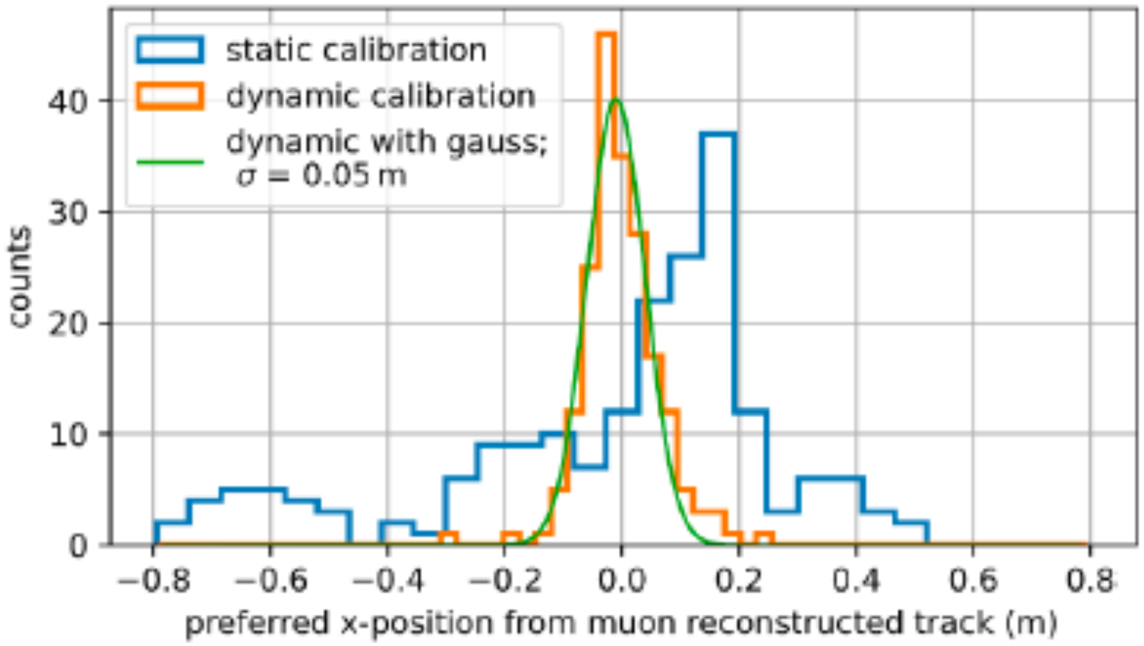
compass in DOMs



acoustic emitters, hydrophones, piezo sensors

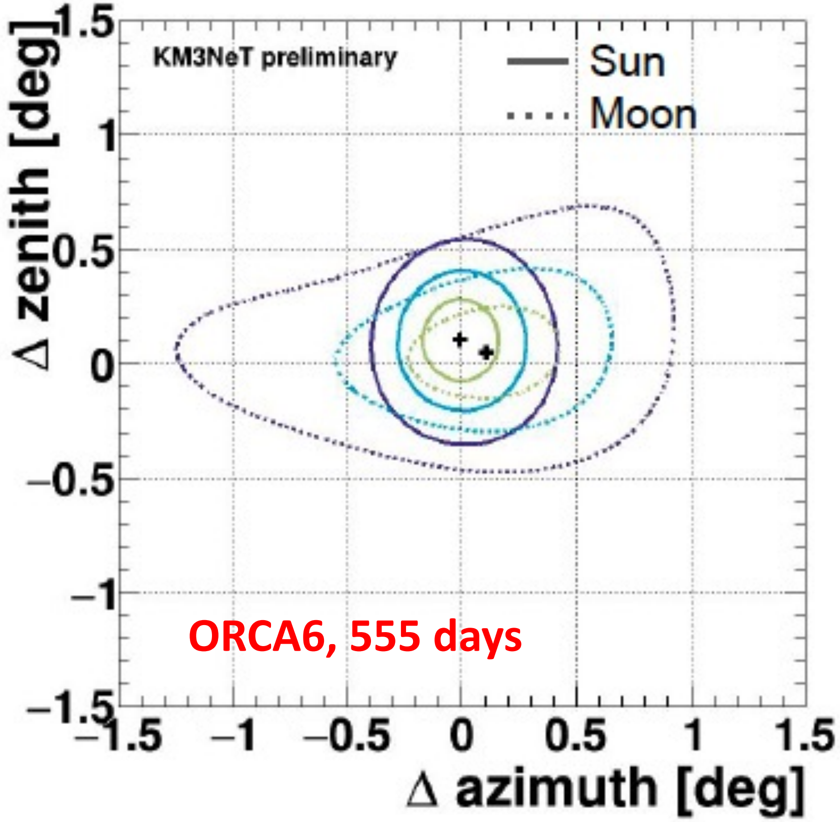


Calibration: positioning



Track residuals before (blue) and after (orange) dynamic position calibration.
After: 5 cm resolution.

Independent validation: cosmic ray shadow of sun and moon.
Observe a ~10% dip in event rates from sun and moon directions, with 4σ (moon) c.q. 6σ (sun) significance.



KM3NeT, ICHEP 2022

Data taking (ORCA)

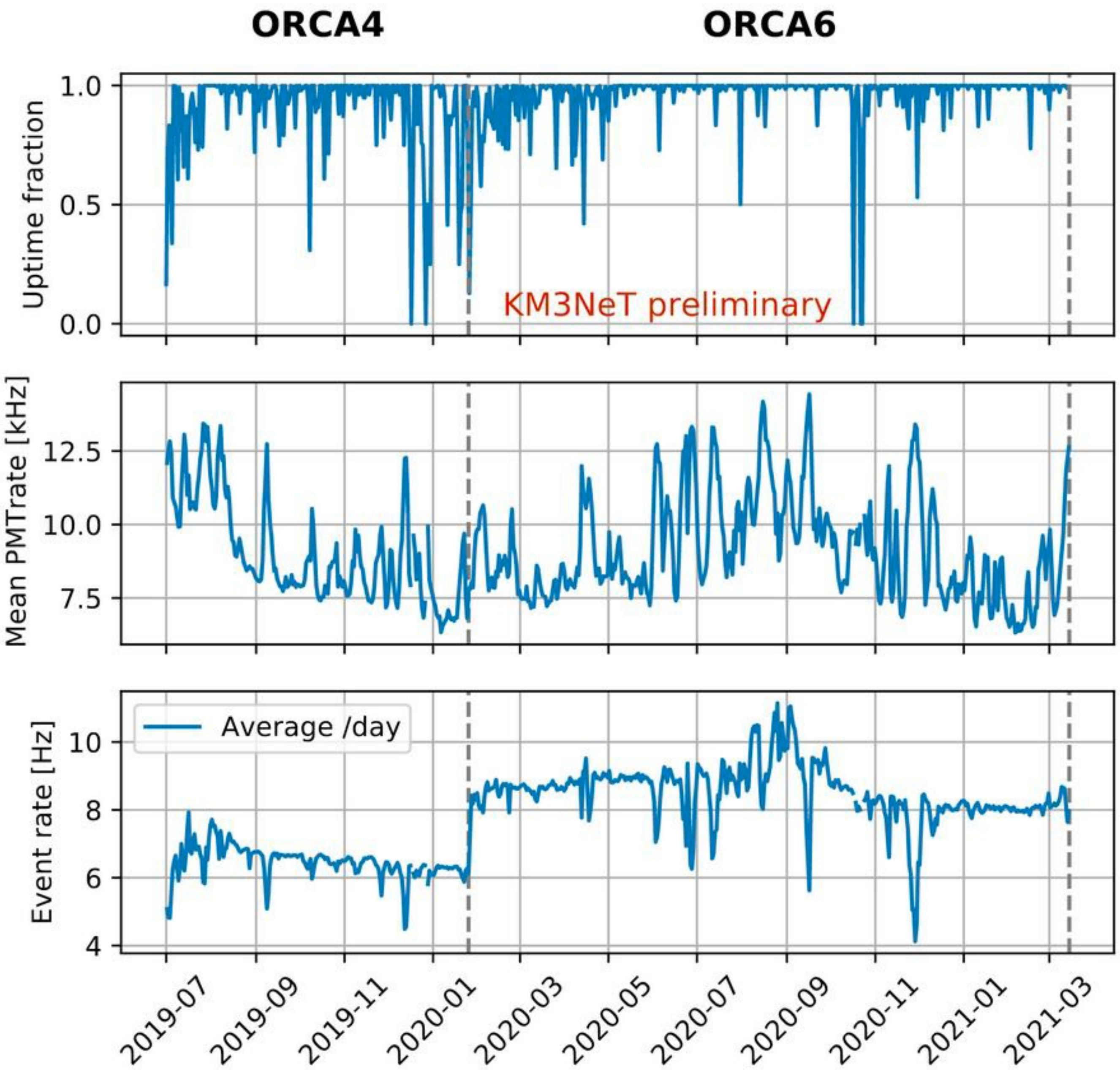
ORCA: 4 lines 2019, 6 lines 2020—2021

Data taking efficiency 91 → 99%

Stable trigger using coincidences;
efficient for E_ν > 3 GeV

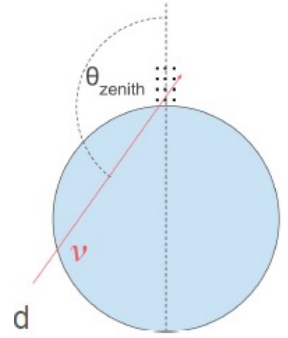
First oscillation analysis with ORCA6:
96% uptime
92% of runs pass quality selection

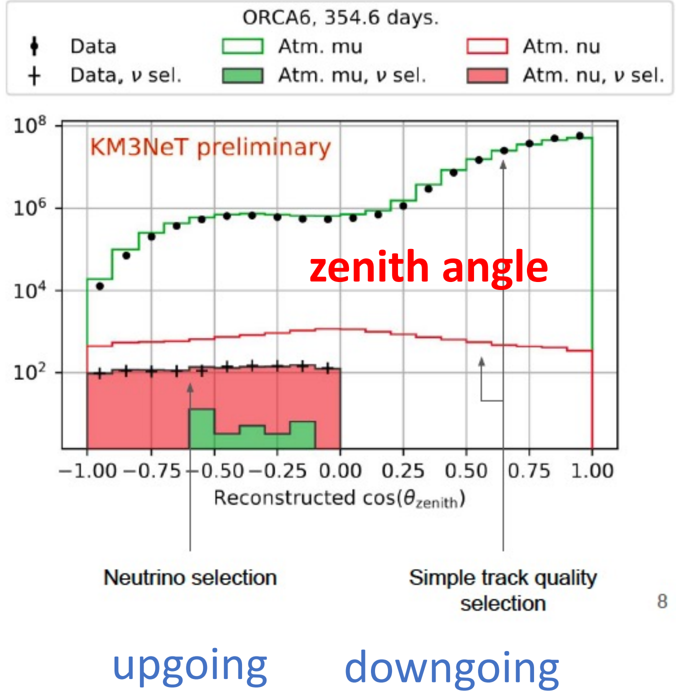
354.6 days exposure after selection

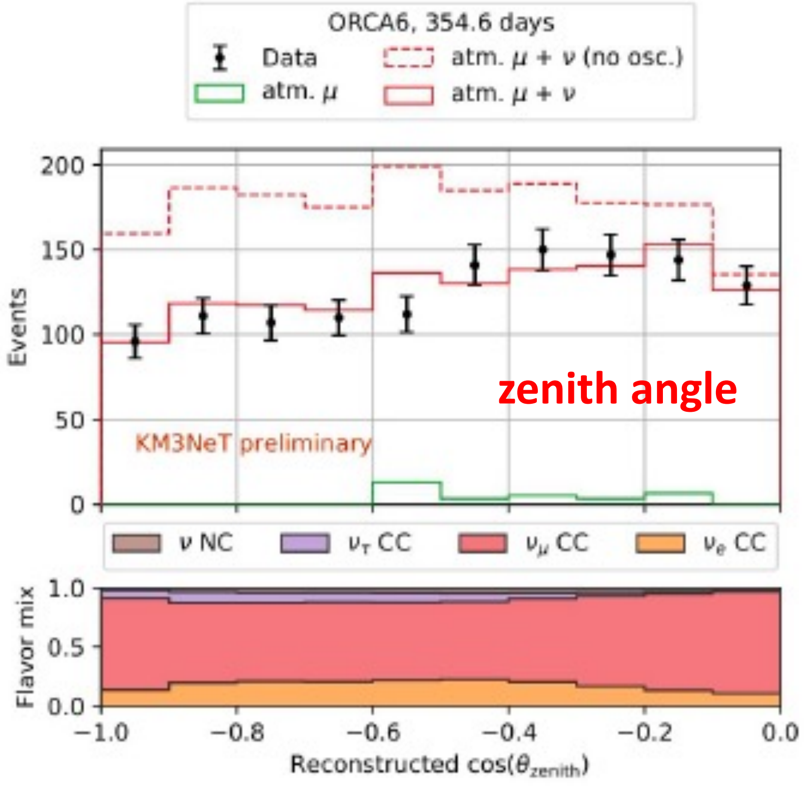


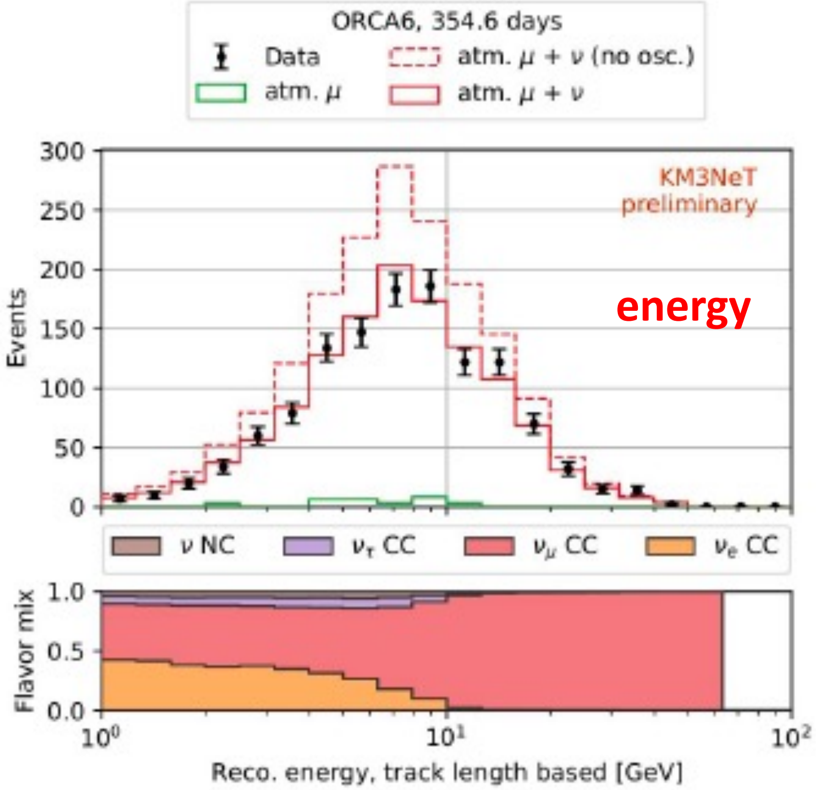
ORCA neutrino selection

ORCA6, 355 days *PoS* NuFact2021 (2022) 064





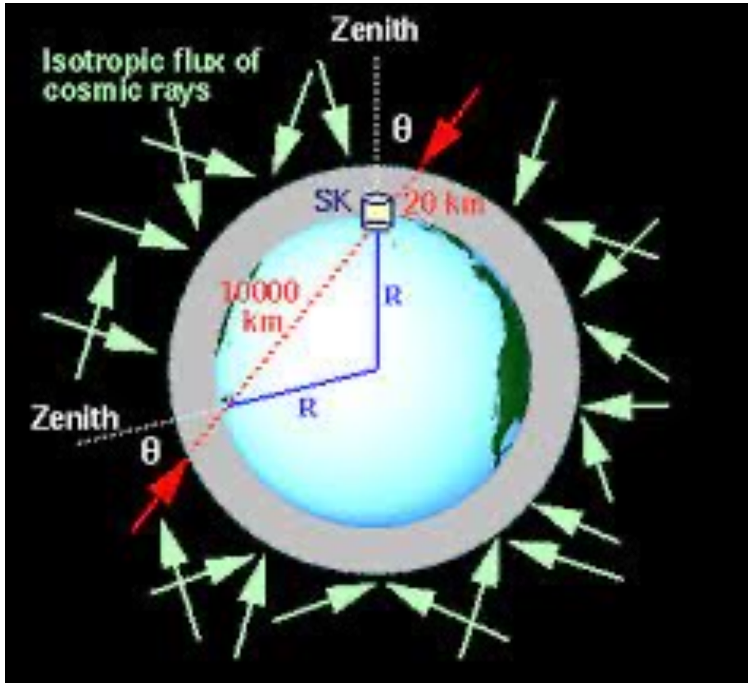




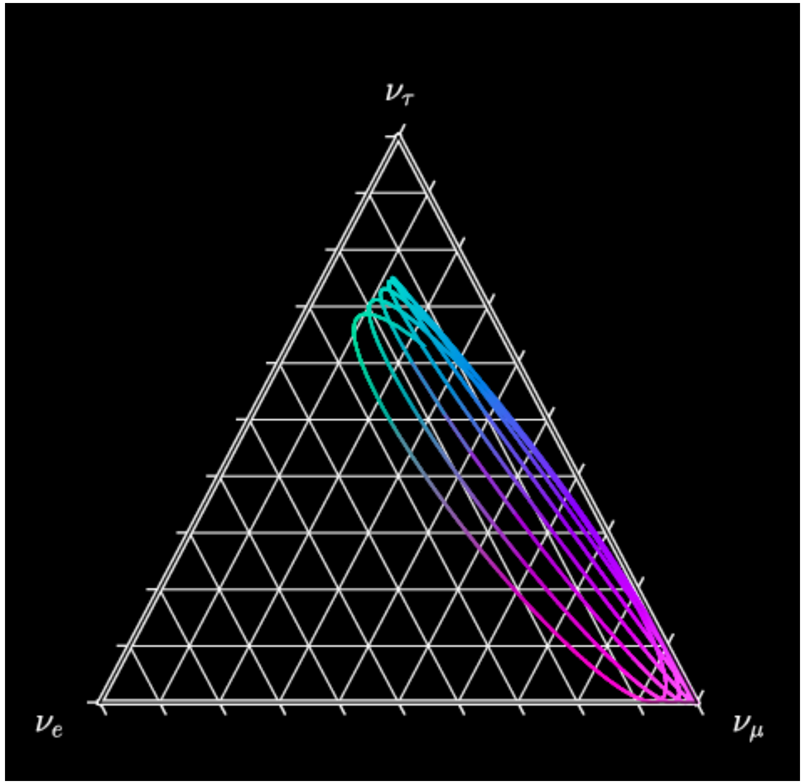
Selection based on track signature: mostly ν_μ
Background: atmospheric muons
Selection: vertex position, track fit quality, upgoing tracks

1237 ν candidates in 355 days, S/B~40

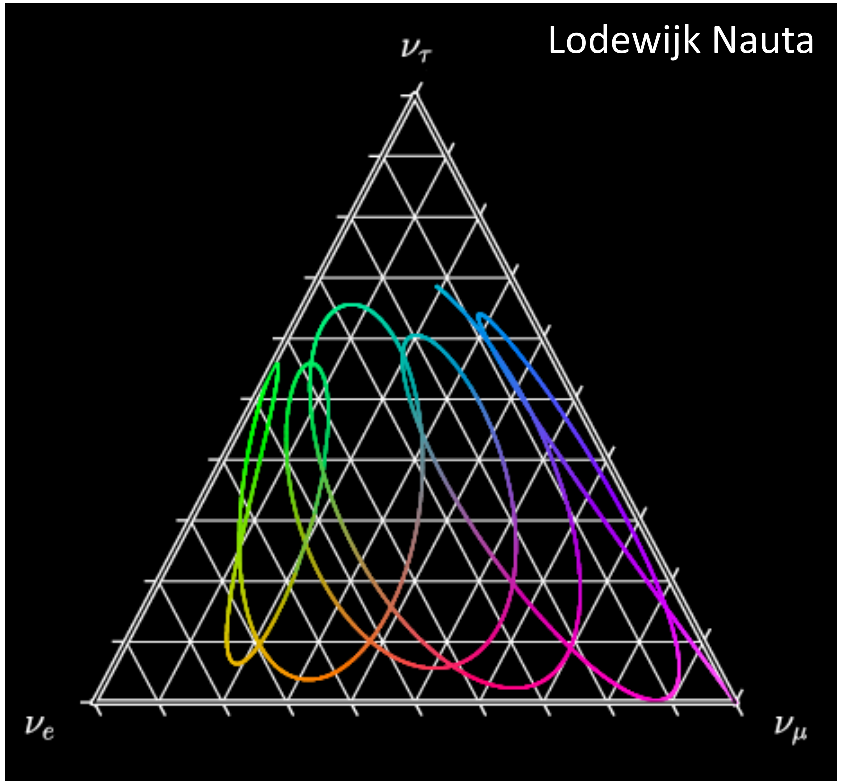
Neutrino Oscillations in Earth



Atmospheric neutrinos:
Zenith angle of events is a proxy for oscillation length.



Evolution of a pure ν_μ in vacuum

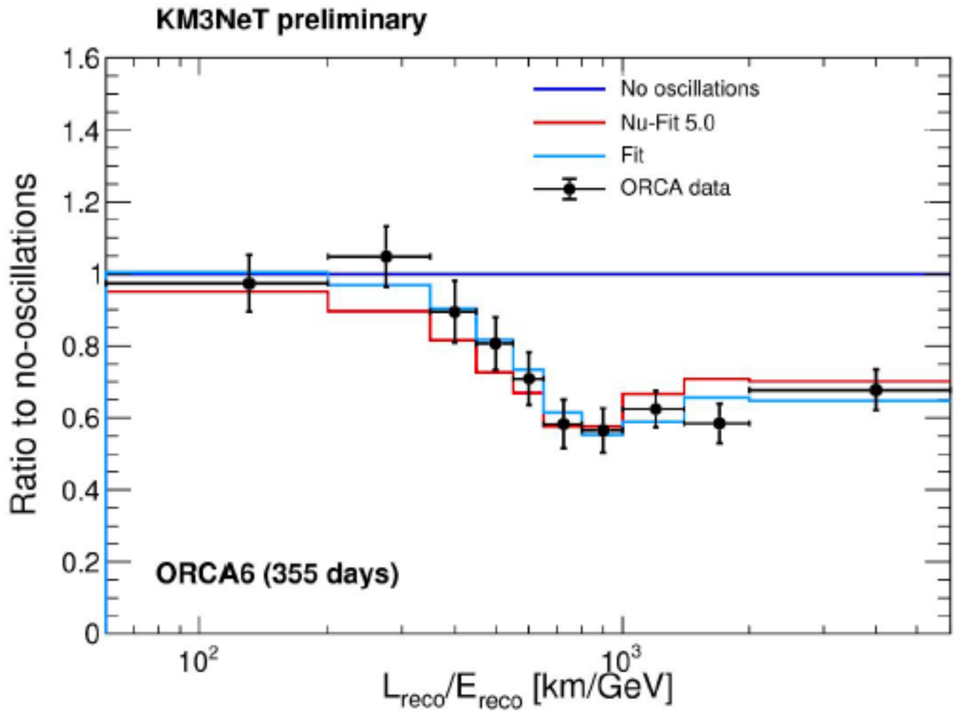


Evolution of a pure ν_μ in earth

Matter effect influences oscillations. Allows for determination of mass ordering and CP-violation because of different behaviour of neutrinos/antineutrinos.
KM3NeT: no event-by-event $\nu/\bar{\nu}$ separation, but differences in flux/kinematics/cross-section

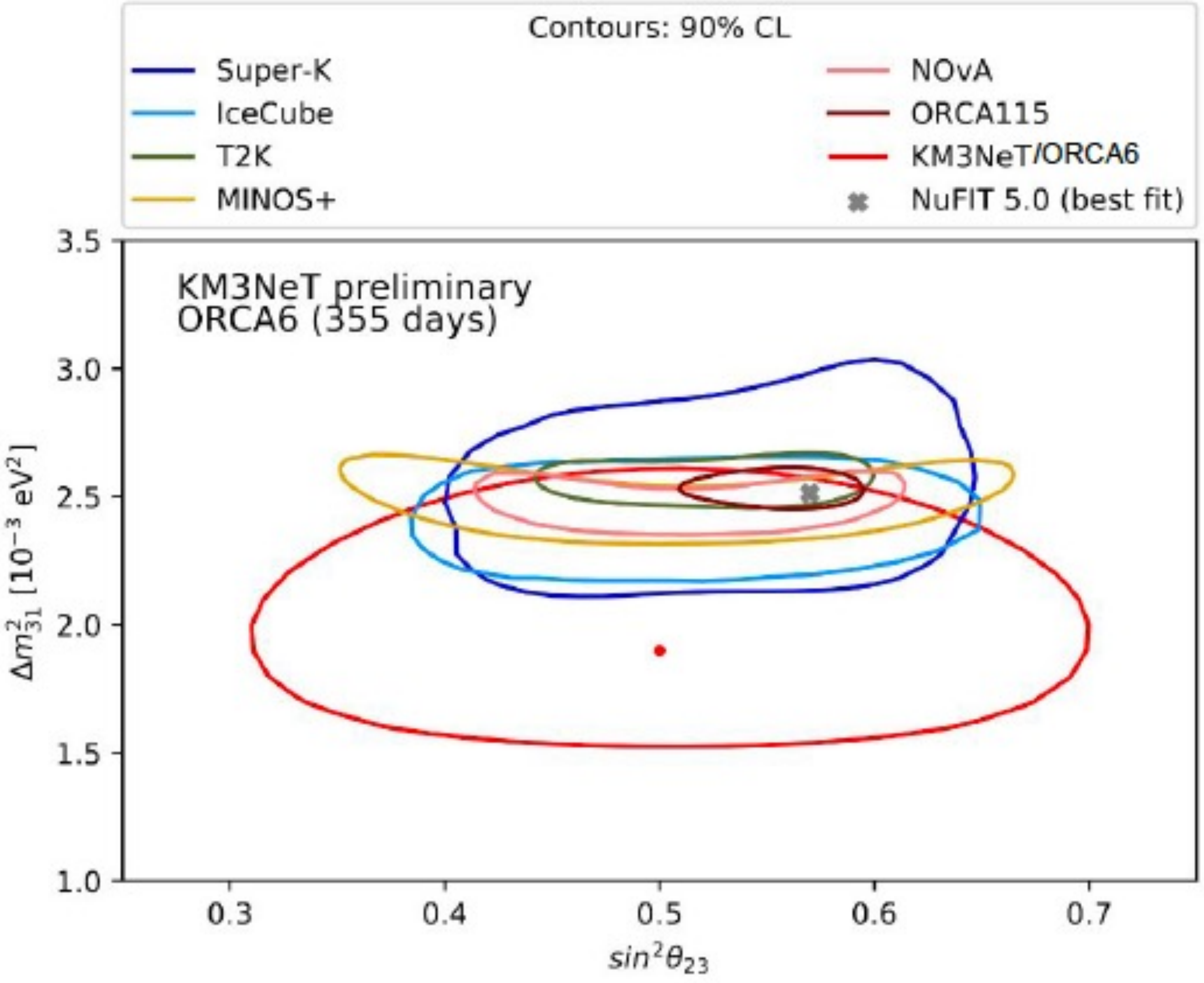
KM3NeT/ORCA Neutrino Oscillation Results

***PoS* NuFact2021 (2022) 064**



- Oscillation fit, binned in E_{reco}, θ_{zenith}
- Normalization left free, various systematics on flux, energy scale, tau- and NC normalization

Parameter	Treatment	Fit value
Δm^2_{31} [10^{-3} eV^2]	Free	$1.95^{+0.24}_{-0.21}$
θ_{23} [deg]	Free	$45.4^{+5.6}_{-5.7}$



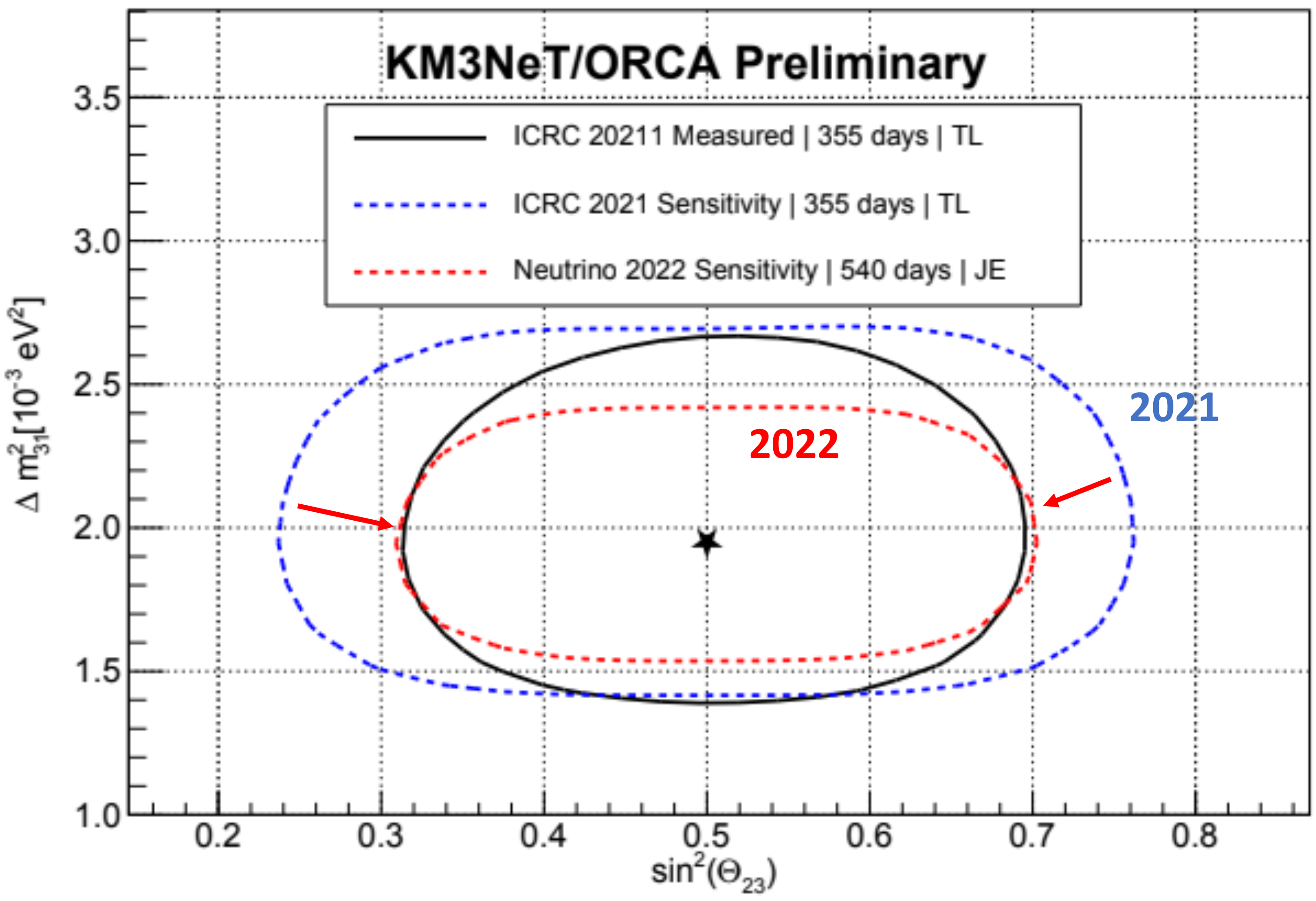
Oscillations sensitivity improvement

KM3NeT, Neutrino 2022

Definitive ORCA6 analysis on-going:

- Larger dataset (+50%)
- Introduction of shower reconstruction
- Shower/Track PID
- Improved fitting methodology

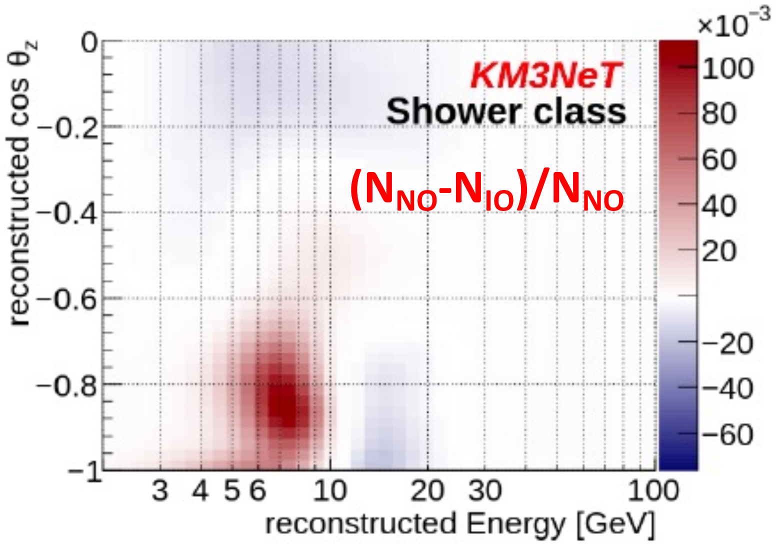
Major sensitivity improvement

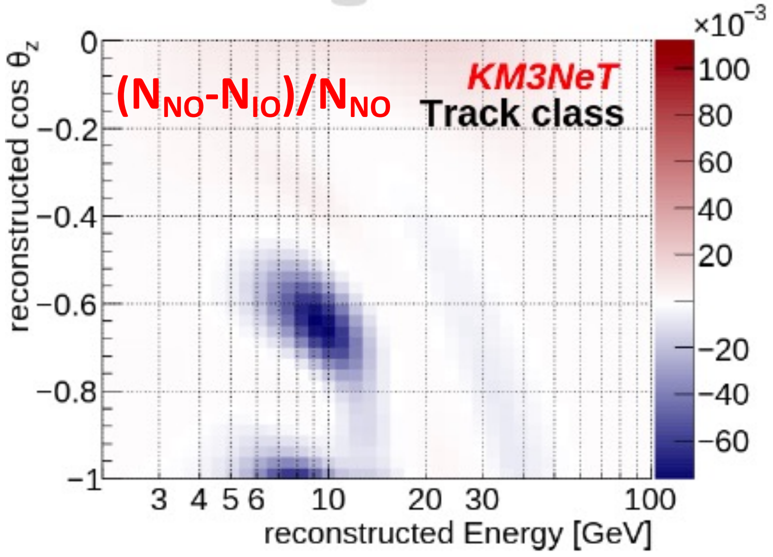


Neutrino mass ordering

Subtle (few percent) difference between tracks and showers distributions between NO and IO hypotheses.

Needs more data!





Expected sensitivity full KM3NeT/ORCA:

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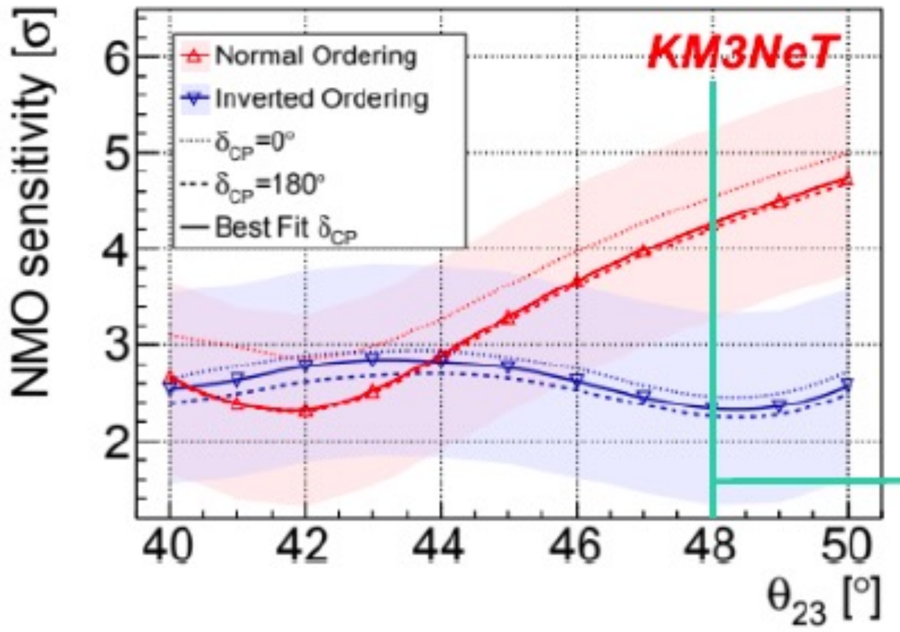
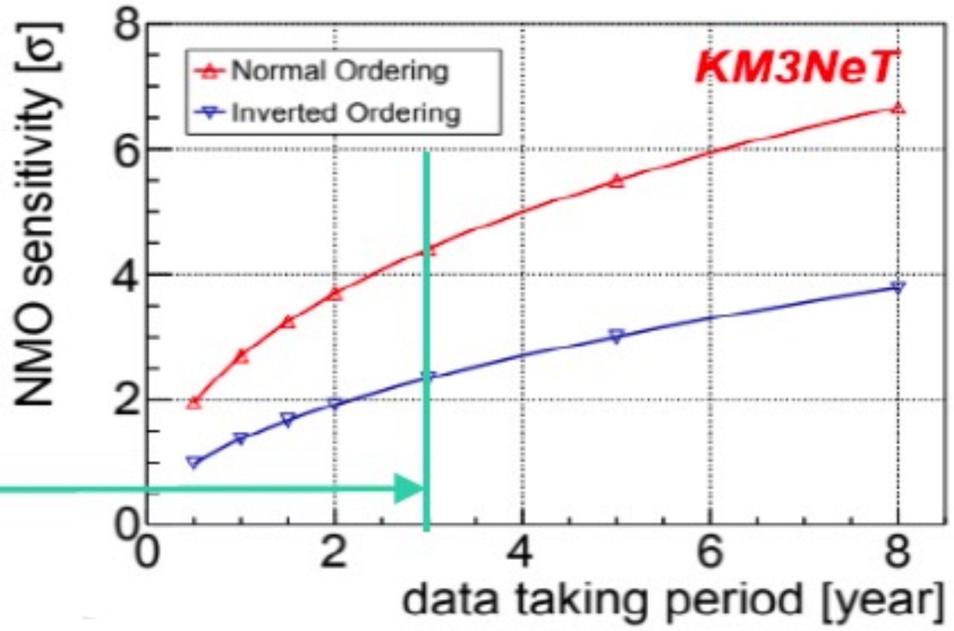
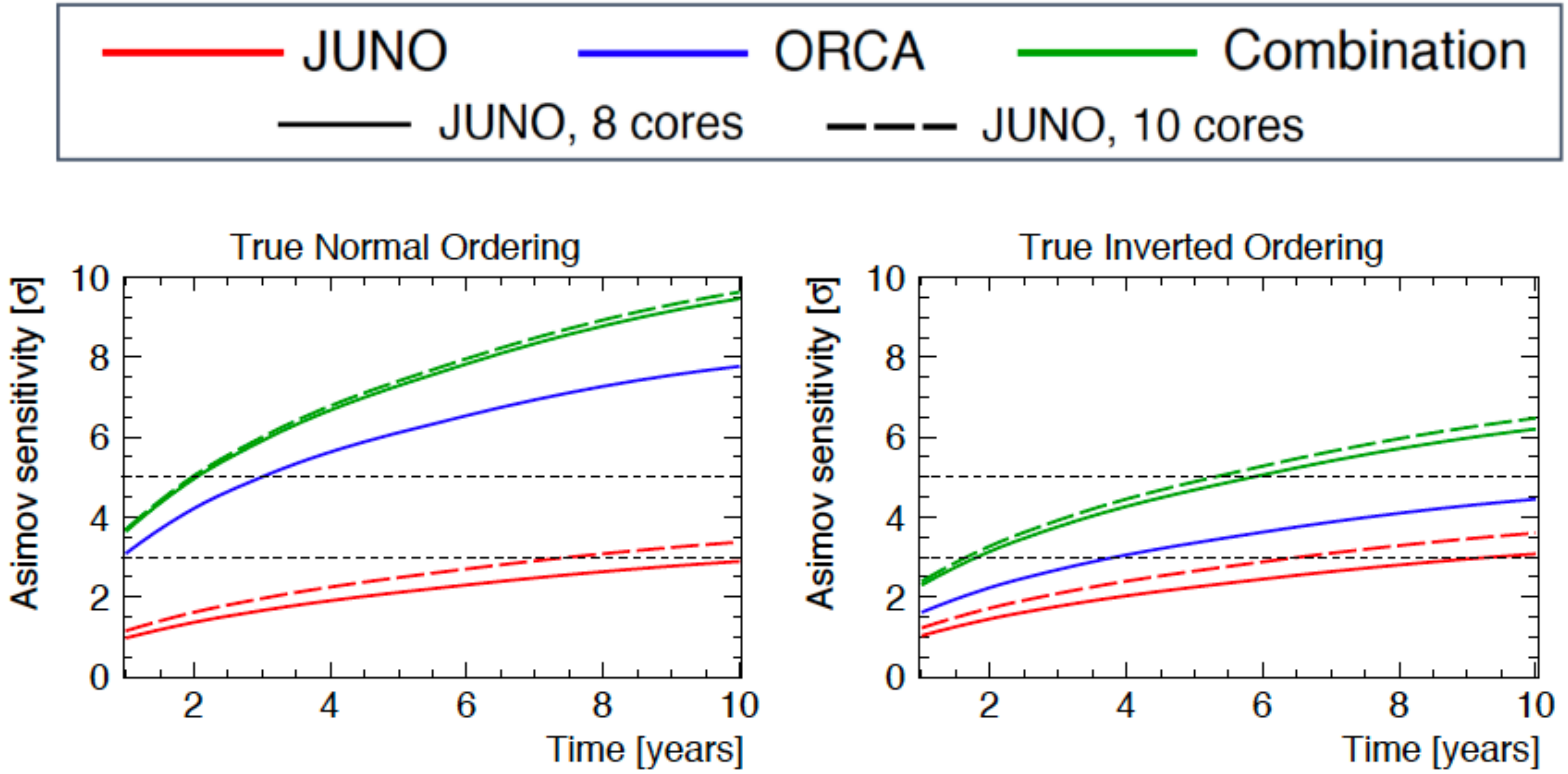




Neutrino mass ordering combining KM3NeT + JUNO

A combined analysis between KM3NeT and JUNO would speed up NMO determination.
Under the wrong NMO assumption, there will be tension in the determination of $|\Delta m_{31}^2|$
(PRD 71 (2005) 113009, PRD 72 (2005) 013009, JHEP 09 (2013) 089, PRD 101 (2020) 032006)



JHEP 03 (2022) 055

Non-standard interactions (NSI)

NSI parametrize effect on ν interactions at EW scale from new physics at much higher energy scale.

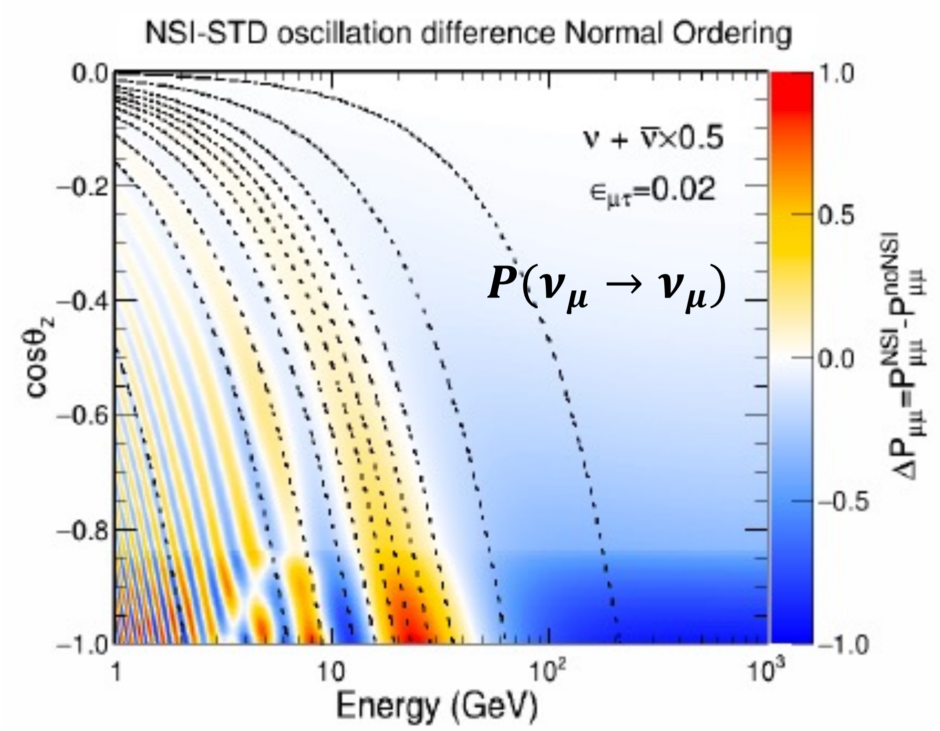
$$H = \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \sqrt{2} G_F n_e \begin{pmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{\mu e} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{\tau e} & \epsilon^*_{\tau\mu} & \epsilon_{\tau\tau} \end{pmatrix}$$

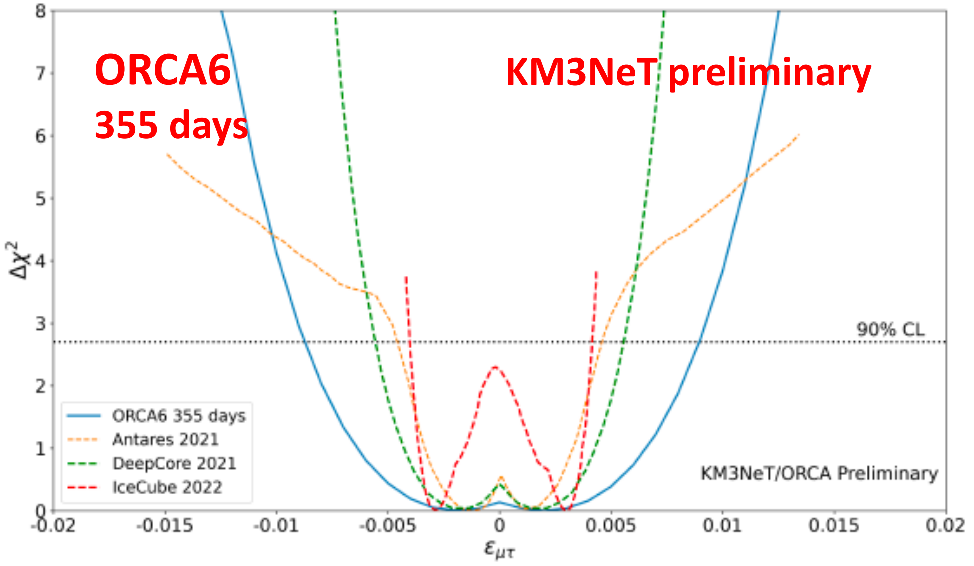
$$\epsilon_{\alpha\beta} = \cancel{\epsilon^{eC}_{\alpha\beta}} + \cancel{\frac{n_u}{n_e}\epsilon^{uC}_{\alpha\beta}} + \frac{n_d}{n_e}\epsilon^{dC}_{\alpha\beta}$$

← assumption

JINST 16 (2021) 09, C09016

KM3NeT, ICHEP 2022





KM3NeT/ORCA6 limit: $-8.7 \times 10^{-3} < \epsilon_{\mu\tau} < 9.0 \times 10^{-3}$

KM3NeT/ORCA115 3-year sensitivity: $-1.7 \times 10^{-3} < \epsilon_{\mu\tau} < 1.7 \times 10^{-3}$ (TBU)

Neutrino invisible decay

Still open as a subdominant contribution to neutrino deficits. Here assumed to affect ν_3 only.

$$H_T = \frac{1}{2E}\left[H_{vacuum} + H_{decay} + H_{matter}\right] = \frac{1}{2E}H$$

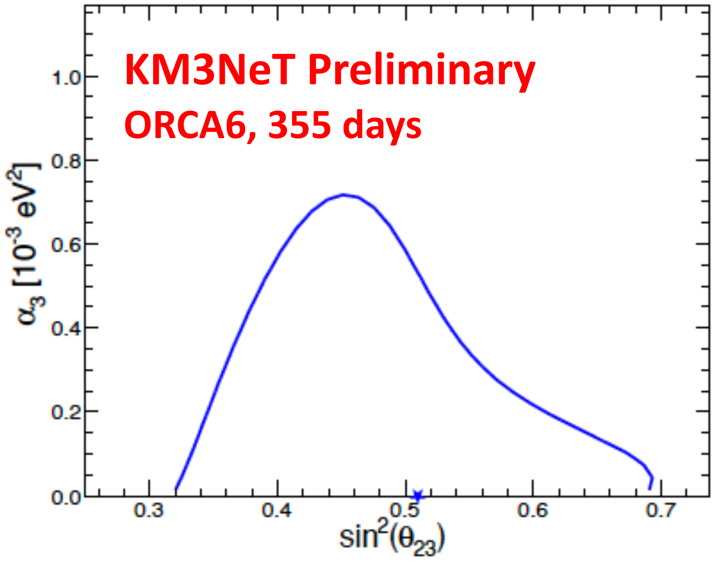
(ν_i decay to light invisible ν_4,
SN1987A and solar limits on ν_1, ν_2)

$$H = U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}U^\dagger + U\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{pmatrix}U^\dagger + \begin{pmatrix} V & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\alpha_3 = \frac{m_3}{\tau_3}$$

$$\Delta m^2_{31} \rightarrow \Delta m^2_{31} - i\alpha_3 \qquad V = \pm 2En_e\sqrt{2}G_F$$

Breaks PMNS unitarity, affects oscillations.



Experiment	L.L.(90%CL) (ps/eV)
ORCA6	2.4
ORCA115 (10y)	180
T2K, NOvA	2.3
T2K, MINOS	2.8
K2K, MINOS, SK I+II	290

$$\frac{1}{\alpha_3} = \frac{\tau_3}{m_3}$$

→ 2-flavour, no matter effects

KM3NeT, ICHEP 2022

Quantum decoherence: sensitivity study

Quantum gravity: possible presence of short-lived horizons at the Planck scale.

Could this generate non-unitary quantum evolution?

Unitary — Non-Unitary

$$\partial_t \rho = -i[H, \rho] + \not{\delta} H(\rho)$$

Dimensional Analysis

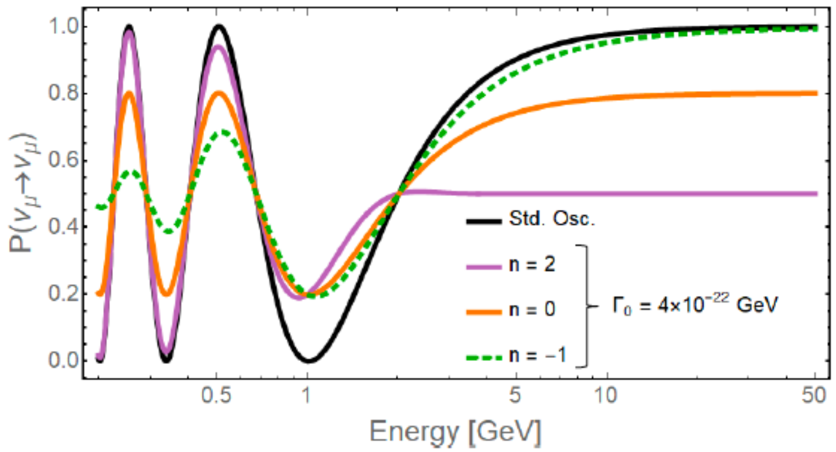
$$\not{\delta} H \sim \mu^2 / M_P$$

$\mu \sim E?$ $\mu \sim \Delta E?$

Neutrino oscillations: $P_{\alpha\beta} = \frac{1}{2} \sin^2 2\theta [1 - e^{-\Gamma t} \cos \Delta t]$

Little is known about how Γ depends on energy

- Take a phenomenological approach: $\Gamma(E) = \Gamma_0 (E/E_0)^n$

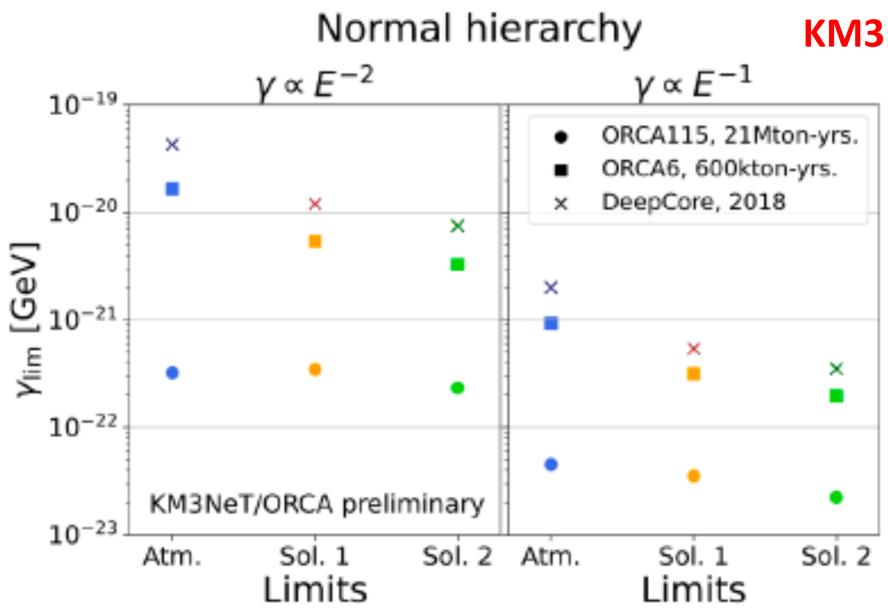


Three-flavour oscillations:
3 parameters Γ_{21}, Γ_{31} and Γ_{32}

Strong constraints on Γ_{21} from solar ν osc.

Interest KM3NeT: long baseline, strong matter effects

KM3NeT, ICHEP 2022



$\Gamma_{21} = 0 \rightarrow$ Atm. Limit
$\Gamma_{32} = 0 \rightarrow$ Solar Limit 1
$\Gamma_{31} = 0 \rightarrow$ Solar Limit 2

ORCA best for n = -1 or n = -2

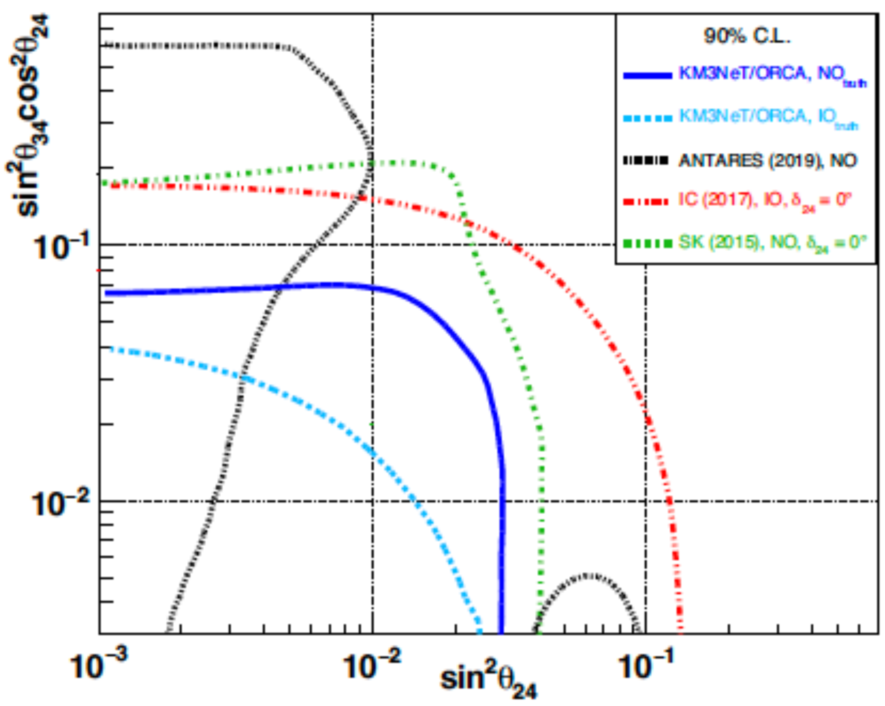
ARCA best for n = 1 or n = 2

→ competitive limits

Sterile neutrinos sensitivity study

Sensitivity study, assuming 4th, sterile neutrino: 3 new mixing angles, 2 phases, 1 mass.
Oscillation analysis, assuming 3 years data taking, full ORCA.
Systematic uncertainties same as in oscillation sensitivity study.

Expected exclusion for θ_{24}, θ_{34} assuming $\Delta m^2_{41} = 1$ eV²



Expected exclusion for $\Delta m^2_{41}, \theta_{24}$

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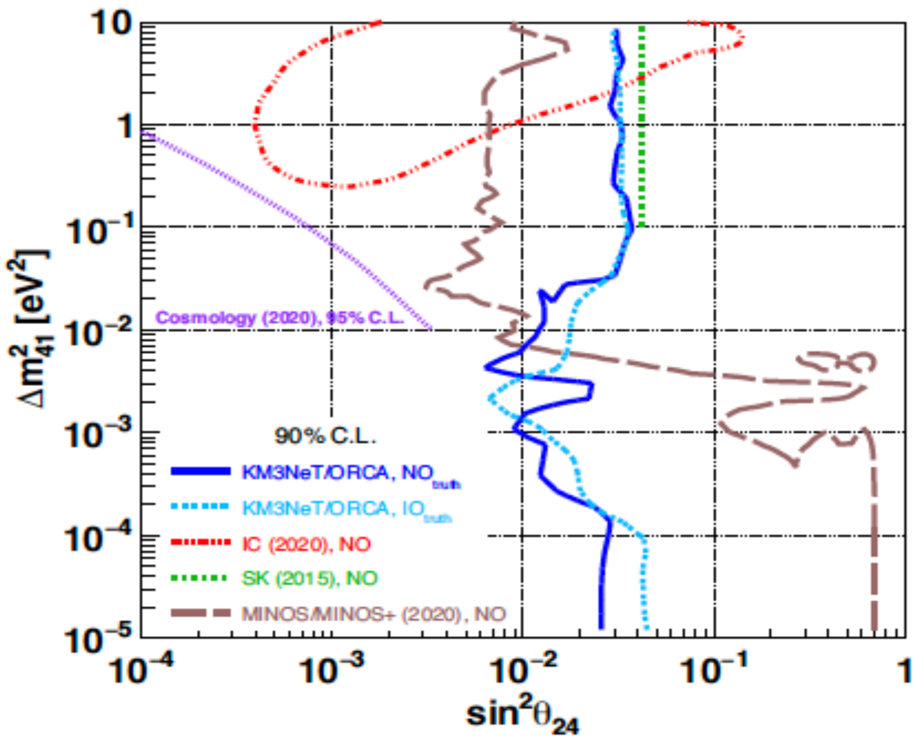

Neutrino selection in ARCA

First ARCA data: analysis in progress.

First data with ARCA6 shows presence of atmospheric ν, to the level expected.

Background of atmospheric μ is interesting for cosmic ray physics

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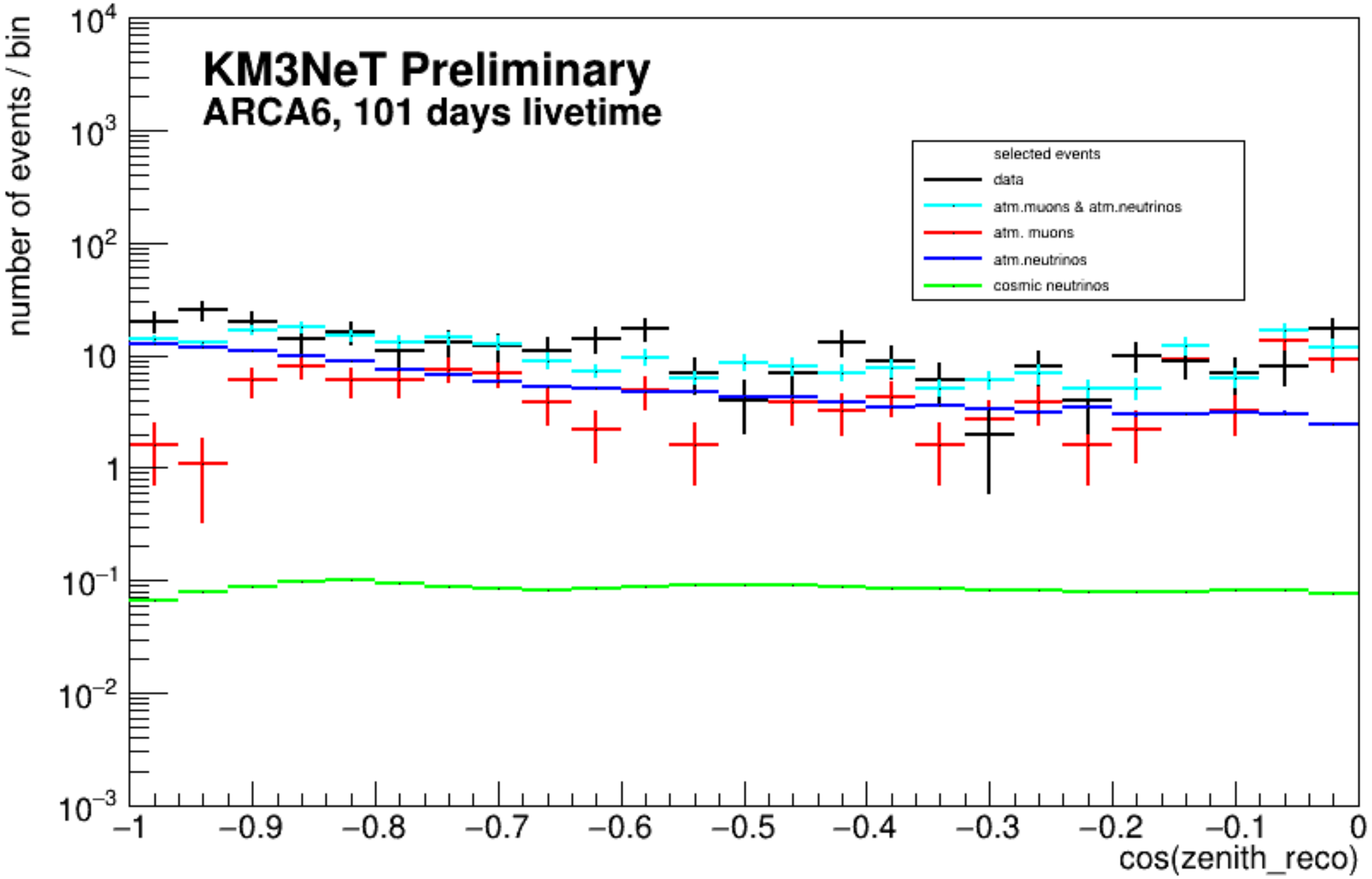
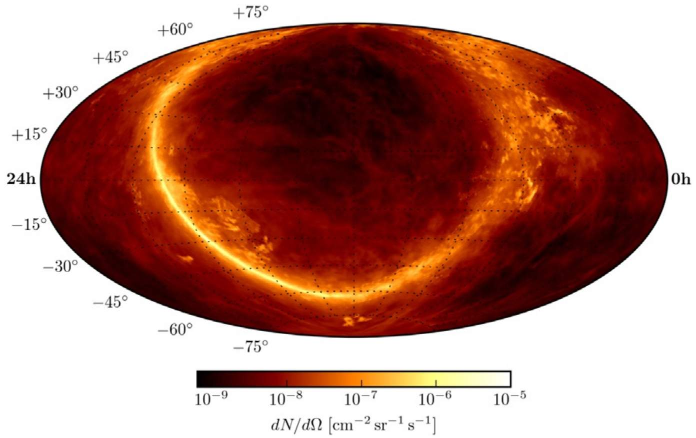


upgoing horizontal

Galactic ridge with ARCA

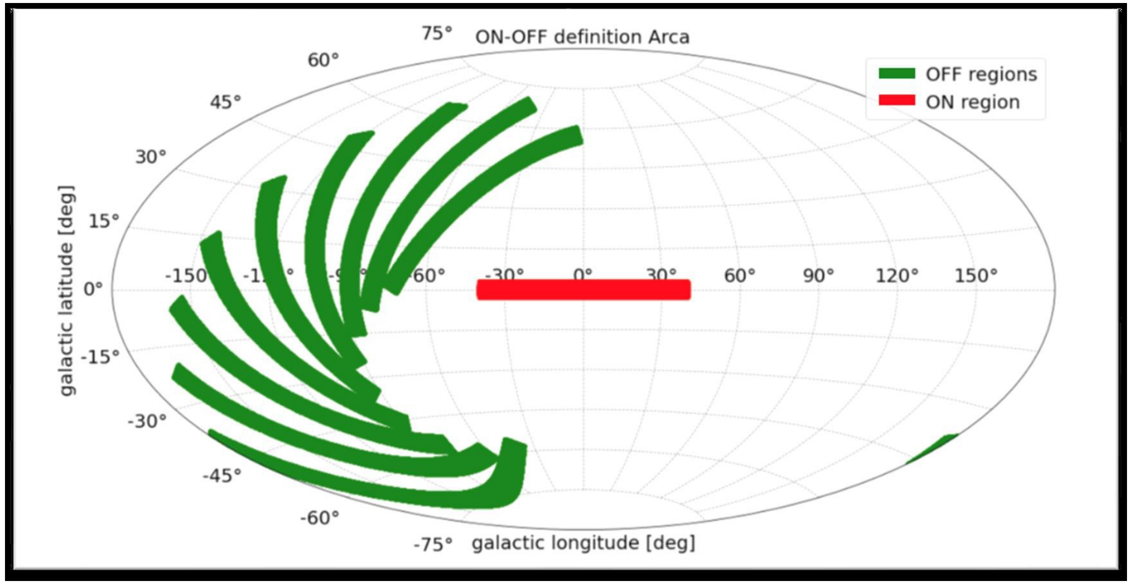
There are sources of HE Cosmic Rays in the galactic center; CR + interstellar medium → ν's!



ApJL 868 (2018) L20

method: ON/OFF technique

- ON region: galactic ridge ($|L_{gal}| < 40°$, $|B_{gal}| < 3°$)
- 9 OFF regions: obtained by time-shifting the ON region (avoiding the Fermi Bubbles)



Simulated signal flux 1.2 x 10^{-8} (E/1GeV)$^{-2.4}$ [GeV $^{-1}$ cm^{-2} s^{-1} sr $^{-1}$]	
MC simulated signal in ON region	1.81 x 10^{-4}
Background events: mean over 9 OFF regions (sum)	4.3 (39)
ON region events:	8

detector: ARCA6
livetime: 100 days
assumed spectrum: $\phi = \phi_0 \cdot E^{-2.4}$
selection:
reco quality pre-cuts + upgoing track-like events
+ additional bad reco rejection using a Neural Network

Excess, but not significant (yet)
[as expected]

Flux upper limit:
$6.2 \cdot 10^{-4}$ [GeV^{-1} $\cdot$ cm^{-2} $\cdot$ s^{-1} $\cdot$ sr^{-1}]

Cosmic neutrinos

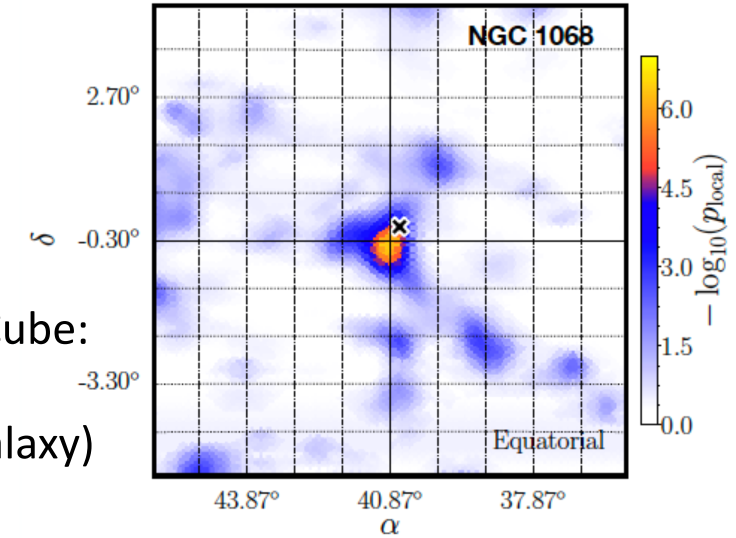
Flux of cosmic neutrinos well established by IceCube. Also hints from ANTARES and GVD (Lake Baikal).
Some discussion on single power law vs. two components (hard/soft) in flux.
Full ARCA will see this flux with 5σ within one year.

But what are the sources of cosmic neutrinos?

Blazars?

- IC170922A – TXS0506+056 (2017, 3.5σ)
- IC211208A – blazar PKS 0735+17 ?
- IC190730A (300 TeV ν_μ) -- blazar PKS 1502+106 ?

IceCube



3σ hotspot in IceCube:
NGC 1068
(=M77, Seyfert galaxy)

Tidal Disruption Events? IceCube

IC191001A -- AT2019dsg? IC200530A -- AT2019fdr?

Radio Galaxies?

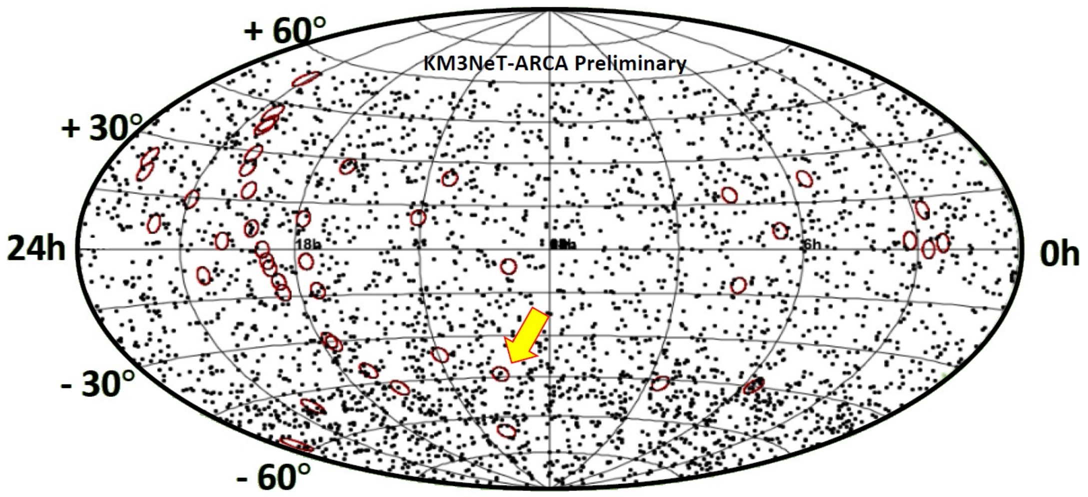
ANTARES:

Catalog	Equal Weighting			
	λ	p	P	$\Phi^{UL}_{90\%}$
Fermi 3LAC All Blazars	6.1	0.19	0.83	4.3
Fermi 3LAC FSRQs	0.83	0.57	0.97	2.2
Fermi 3LAC BL Lacs	8.3	0.088	0.64	4.8
Radio Galaxies	3.4	4.8×10^{-3}	0.10	4.2
Star-forming Galaxies	0.030	0.37	0.93	2.0
Dust-obscured AGNs	1.0×10^{-3}	0.73	0.98	1.5
IceCube High-energy Tracks	0.77	0.05	0.49	5.2

+ flaring radio blazar J0242+1101 (PKS0239+108)

Very active and dynamic field!

Point source searches with ARCA



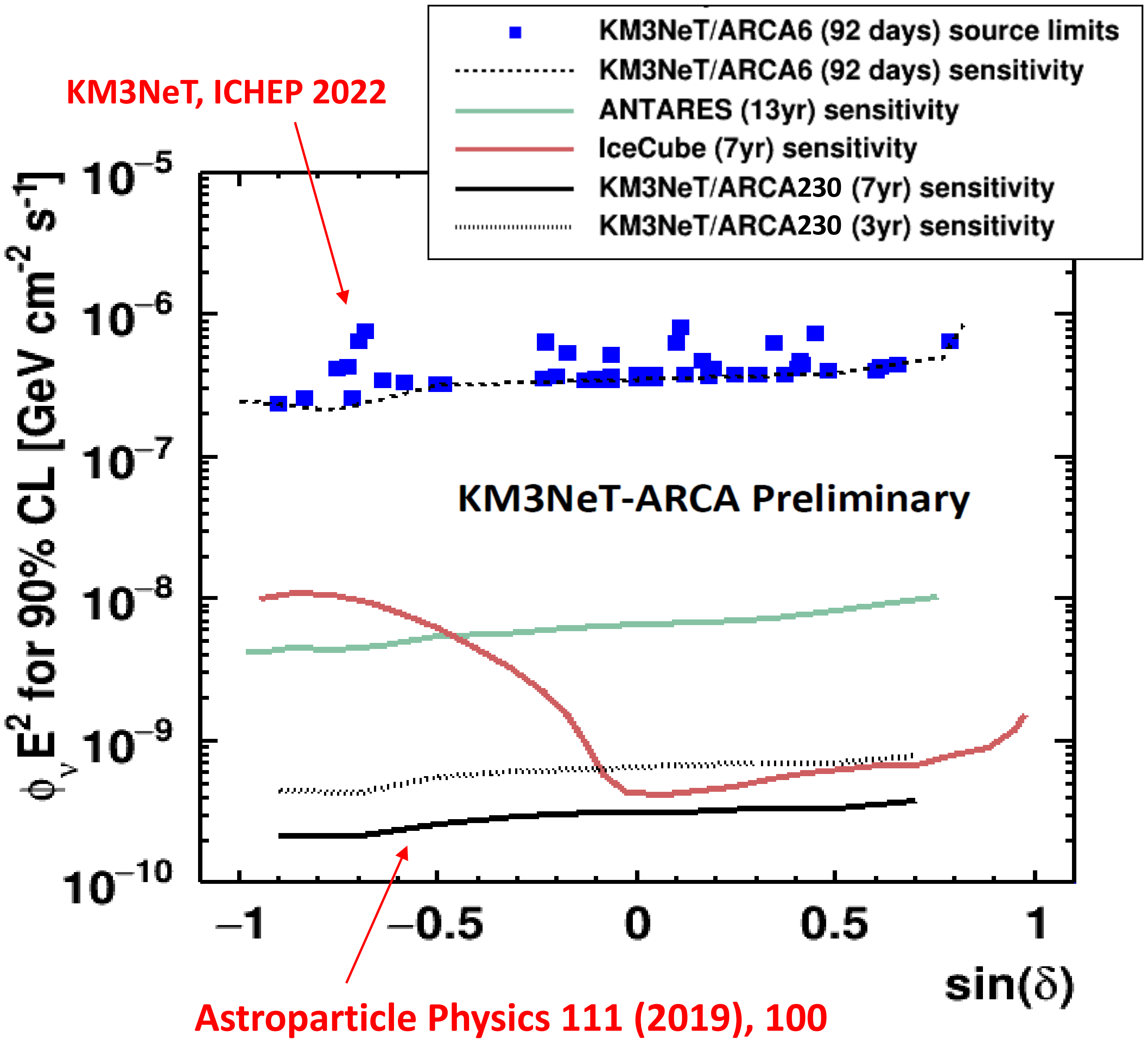
Some details:

- $time$-integrated Point Source search
- 46 candidate sources [red circles]
- Detector: ARCA6
- Livetime: 92 days (May-Sep 2021)
- $\Delta\psi \sim 1.3°$ (for E^{-2})

Result:

- No significant excess [as expected]
- Limits not (yet) competitive [as expected]
- Best source: Centaurus A ($p = 0.02$)

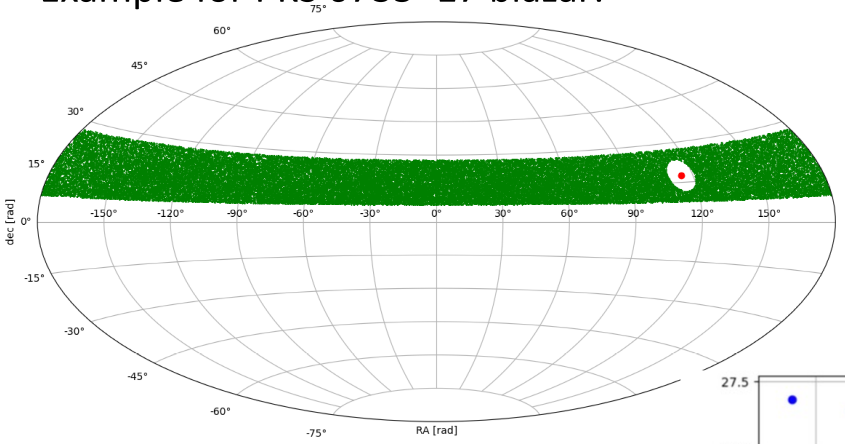
(radio galaxy; yellow arrow)



Followup on recent IceCube alerts (possible blazar associations)

Method: ON/OFF technique

- ON region: cone centered on the source position
- OFF region: declination band centered at the source's position (but with ON region subtracted). The solid angle is rescaled to be able to compare with the ON region.
- Example for PKS 0735+17 blazar:



detector: ARCA6

assumed spectrum:

$\phi = \phi_0 \cdot E^{-2}$ (all alerts)

selection:

upgoing track-like events

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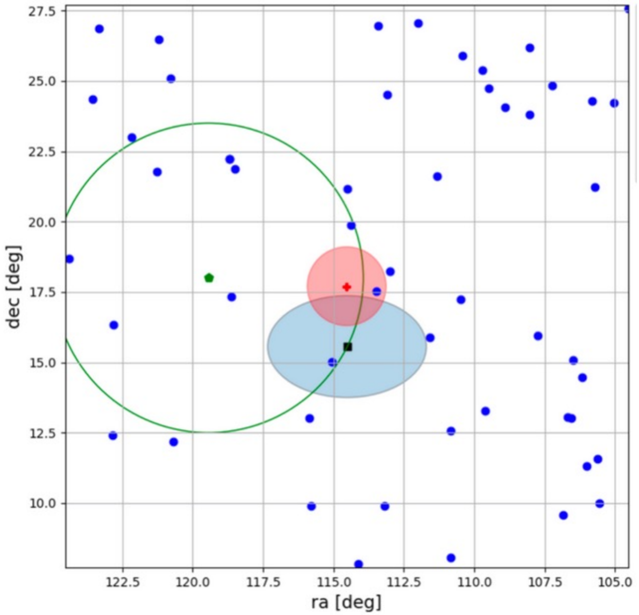
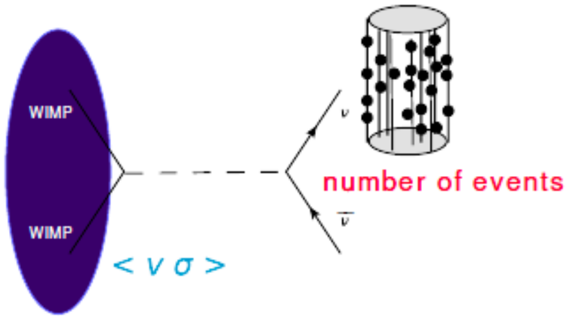


Alert	IC211208A		IC220205B
Associated blazar	PKS 0735+17		PKS 1741-03
Time window	± 1 day	1 month	± 1 day
Radius of Interest	1.4°	1.4°	1.9°
Expected signal	$8.9 \cdot 10^{-3}$	$1.2 \cdot 10^{-1}$	$9.7 \cdot 10^{-3}$
Expected bgd (MC)	$4.9 \cdot 10^{-2}$	$6.7 \cdot 10^{-1}$	$5.2 \cdot 10^{-2}$
Expected bgd (data)	$(4.7 \pm 0.7) \cdot 10^{-2}$	$(6.6 \pm 0.3) \cdot 10^{-1}$	$(4.9 \pm 0.9) \cdot 10^{-2}$
Events in ON region for 3σ	**2**	**5**	**2**
Measured events in ON region	**0**	**1**	**0**

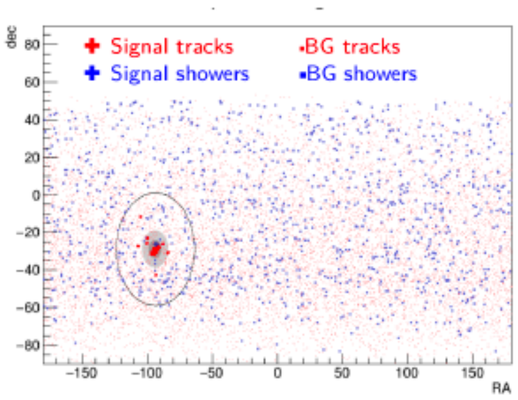
No significant discovery (yet?), only 1 ν_μ candidate with $E \sim 18$ TeV ($p = 0.14$) [as expected]

Dark matter

Search for excess flux of neutrinos from Sun or Galactic Center, from DM decay, or DM-DM annihilation.

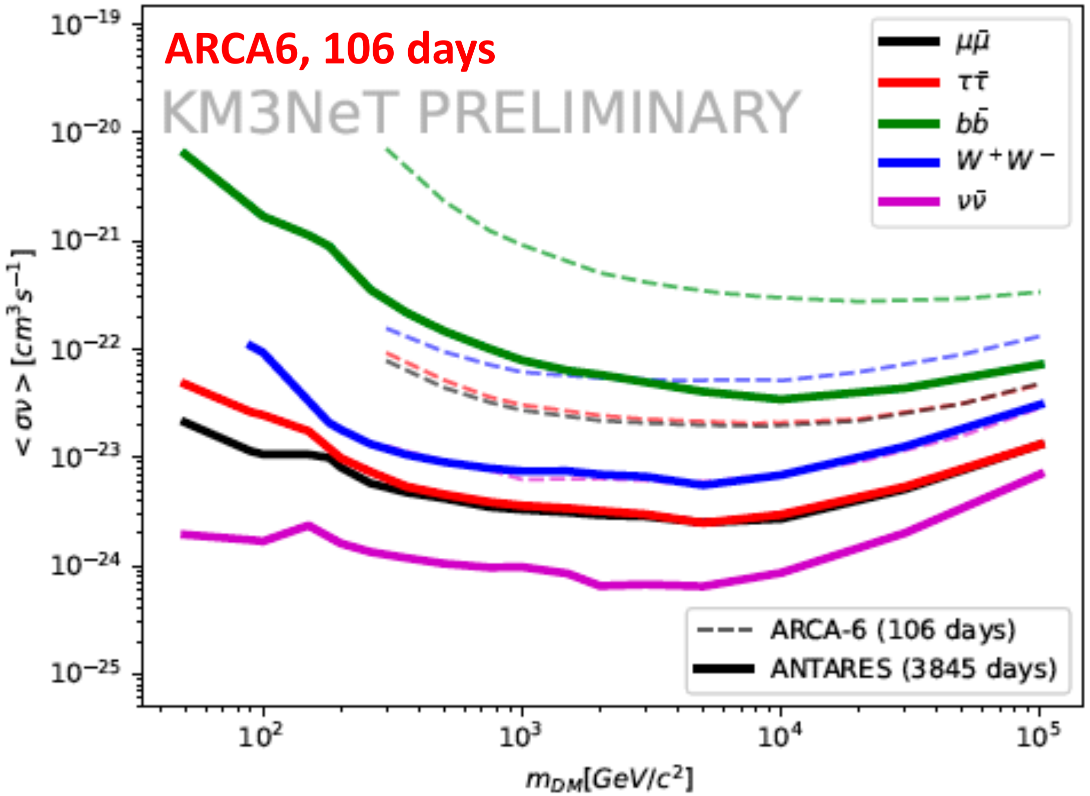


$$n = \frac{1}{2}\langle\sigma v\rangle \int_0^{M_{\rm DM}} \frac{dN}{dE} dE \, \frac{1}{4\pi} \, J \frac{1}{M_{\rm DM}^2} \, \mathcal{A}(M_{\rm DM}) \, t$$



Unbinned likelihood

KM3NeT, ICHEP 2022



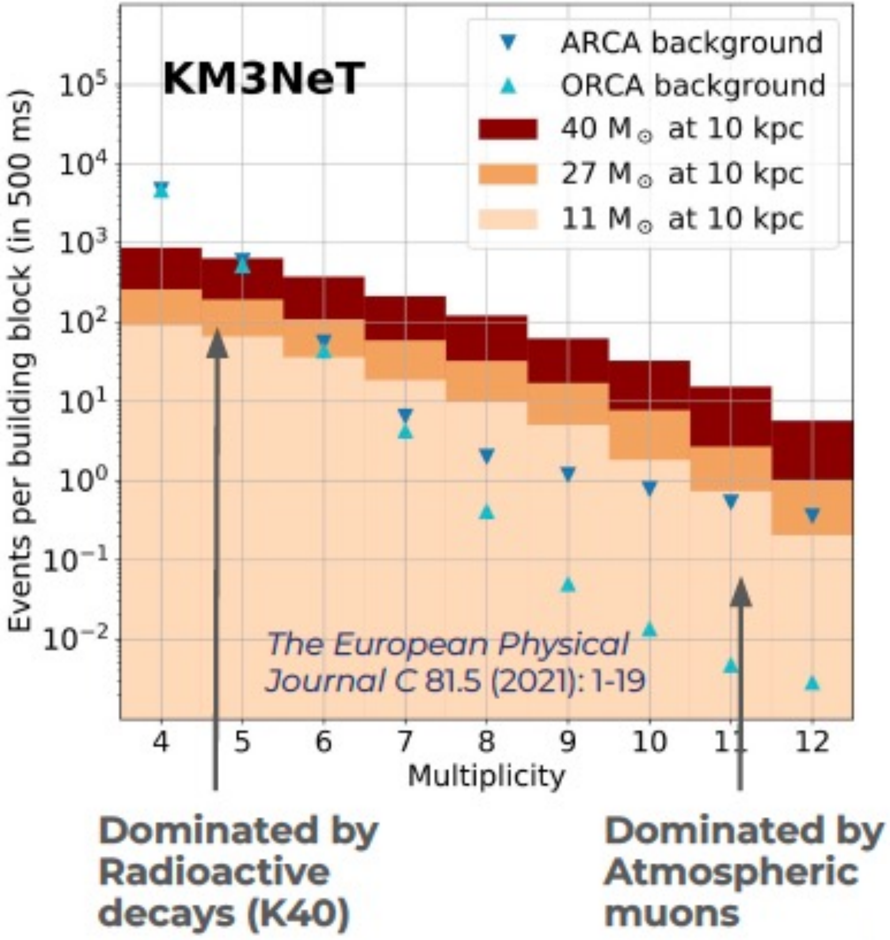
First results with ARCA6, no excess observed.
Limit on flux translated to limit on $< \sigma v >$

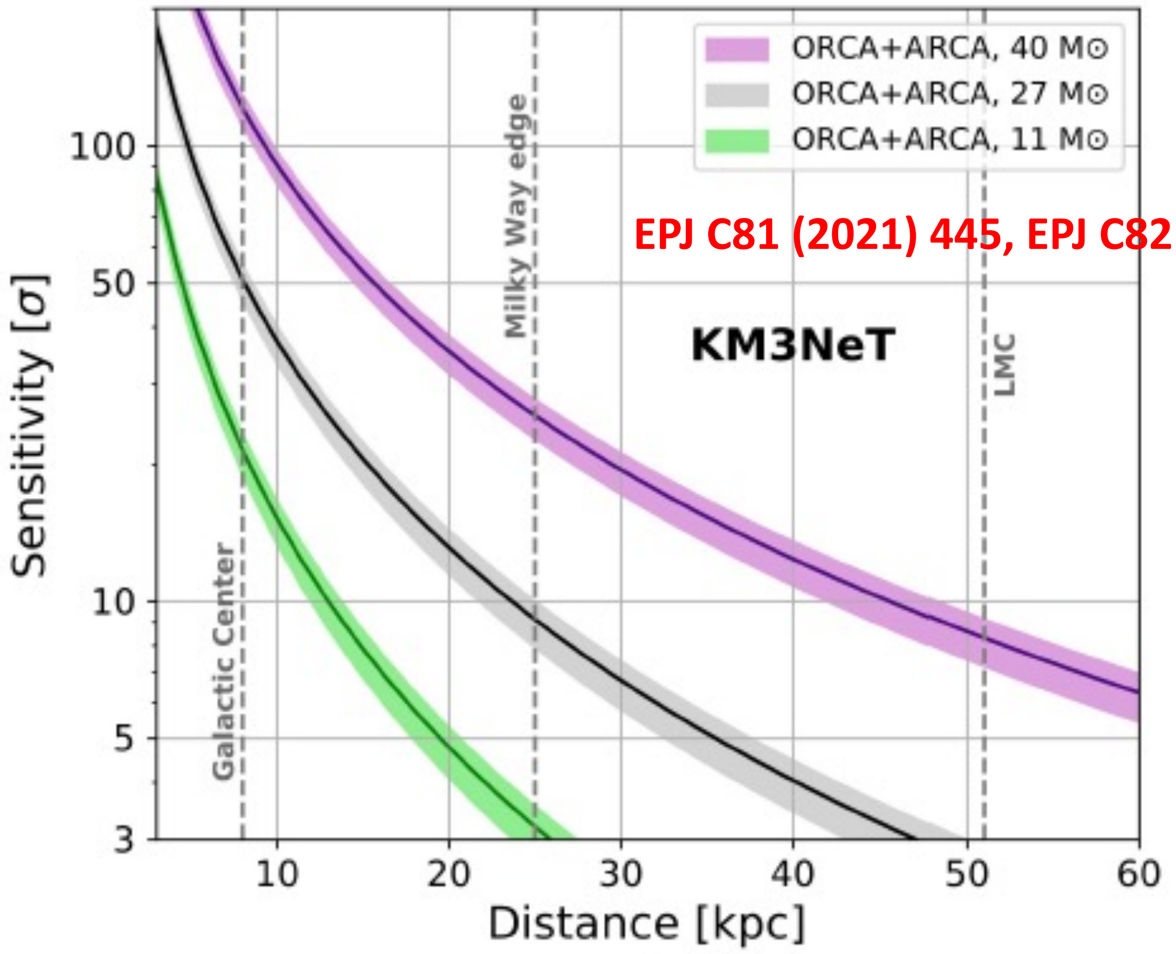
Limited exposure, needs more data.

Other results: secluded dark matter; analysis of power spectrum (i.e. anisotropies)

Supernova neutrinos

MeV neutrinos: no track or shower. But large multiplicity: PMTs see light of neutrino interactions (inverse beta decay) within 10-20 meter of DOMs.   Real-time alert trigger in place.





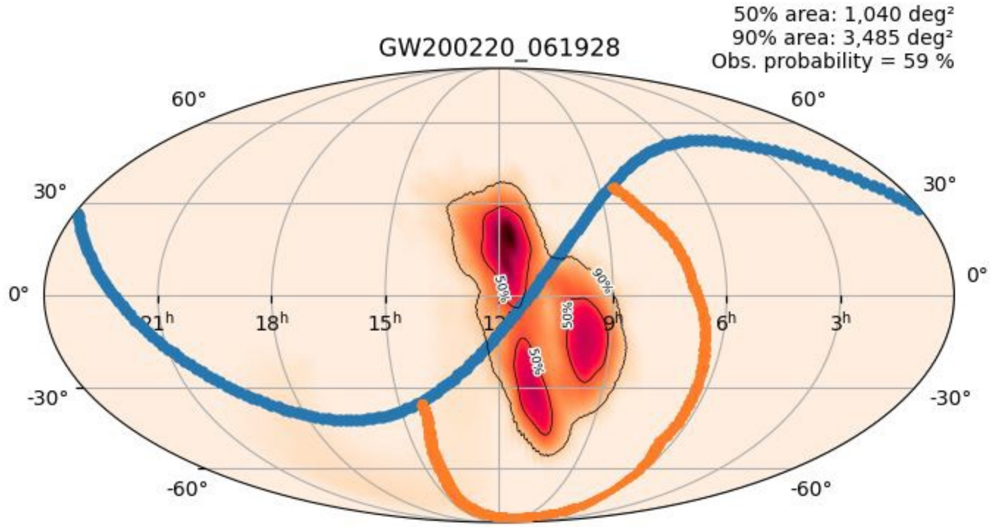
EPJ C81 (2021) 445, EPJ C82 (2022) 317

Multimessenger astronomy

- Static sources: searches based on catalogs (GW, γ-ray sources, radio galaxies, star-burst galaxies, etc etc)
- Transients: KM3NeT generates and acts on alerts. (GCN, SNEWS)

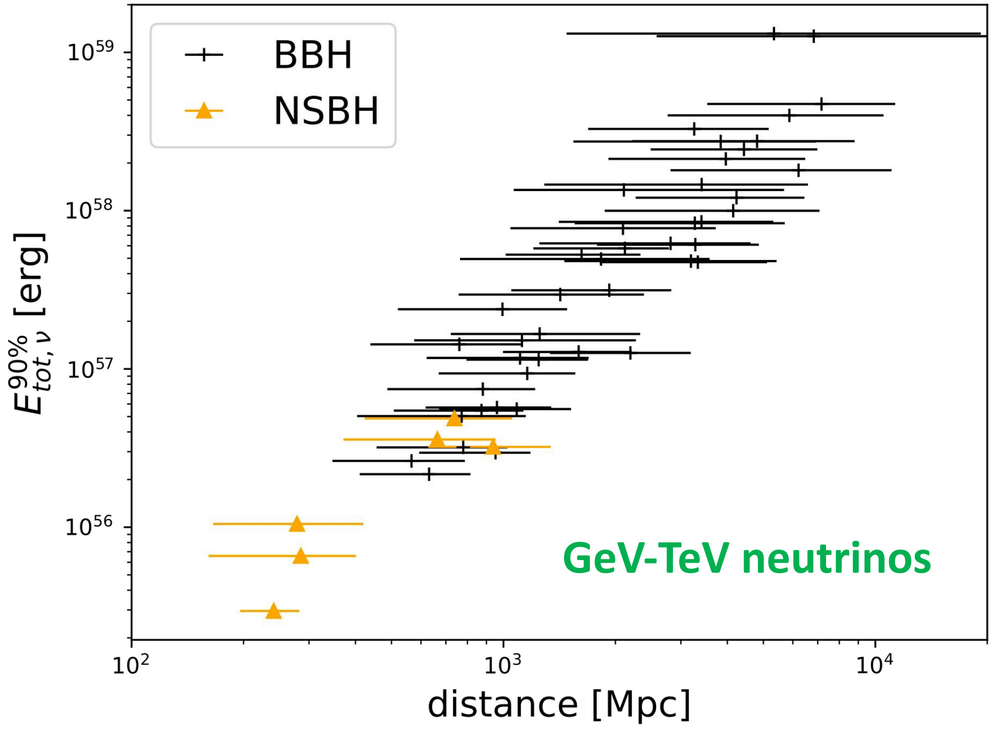
KM3NeT, Neutrino 2022

Example: Follow-up of Gravitational Wave events (LIGO/VIRGO 03) with ORCA



Search for 1000s in 30 degree area around the GW confidence region.

Limits on neutrino flux of 55 GW events in MeV and GeV-TeV ranges.



Summary and Outlook

KM3NeT is operational!
Detector performance is at least as good as expected.
First physics results with ORCA and ARCA obtained.
KM3NeT generates and acts on multimessenger alerts.

ORCA currently taking data with 10 lines.
~7 more lines ready for deployment later in 2022.
Funding assured, and procurement and construction in progress, for ~50 lines.

ARCA currently taking data with 19 lines.
Funding assured, and procurement and construction in progress, for ~150 lines.