Underwater neutrino telescopes: status and future

Paschal Coyle, 15/7/21

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

ONLINE ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE
Berlin | Germany
37th International Cosmic Ray Conference
12–23 July 2021

ANTARES

KM3NeT

P-ONE

Dedicated to the memory of Giorgos Androulakis

ANTARES/KM3NeT@ICRC21

Poster
Talk

Atmospheric neutrinos/muons – Oscillations

534 ANTARES: Solar atmospheric neutrinos, D. Lopez-Coto
1244 ANTARES/KM3NeT: NSI sensitivity, J. Manczak

1245 KM3NeT: neutrino mass ordering, M. Perrin-Terrin
536 KM3NeT: oscillation measurement, L. Nauta
1292 KM3NeT: neutrino tomography, L. Maderer
1260 KM3NeT: ORCA-JUNO NMO sensitivity, J. P. Athayde Andre
210 KM3NeT: Muon flux data/simulations, P. Kalaczyński
1445 KM3NeT: MUPAGE simulation, B. Ó Fearraigh
1172 KM3NeT: low energy astro neutrinos, M. Bendahman
566 KM3NeT: muon bundles id with Graph NN, S. Reck
586 KM3NeT: atmos. neutrinos with ORCA, D. Stavropoulos
701 KM3NeT: Atmos nu with ARCA, A. Sinopoulou

Cosmic neutrino sources/Multi-Messenger

1240 ANTARES: radio loud blazar search, J. Aublin
612 ANTARES: diffuse flux, L. Fusco
1137 ANTARES: untriggered flaring analysis, G. Illuminati
1142 ANTARES: point sources, G. Illuminati
967 ANTARES: HAWC template analysis, G. Ferrara, L. Fusco
529 ANTARES: GVD neutrino alerts, S. Alves
989 ANTARES: GRB searches, A. Zegarelli

1256 KM3NeT: starburst galaxies search, W. Idrissi Ibnsalih
928 KM3NeT: sensitivities diffuse, pt-like, R. Muller
1167 KM3NeT: tau neutrino reconstruction, T. van Eeden
1304 KM3NeT: Supernova analysis, V. Kulikovskiy
1159 KM3NeT: transient sources, J. Palacios Gonzalez

Dark Matter/Exotics

613 ANTARES: Dark Matter from Sun, C. Poire et al.
635 ANTARES: Monopole search, J. Boumaaza et al.
775 ANTARES: Nuclearite search, M. Boula
1207 ANTARES/KM3NeT: Dark Matter from GC, R. Gozzini et al.

1040 KM3NeT: Nuclearite search, A. Paun

Performance

556 ANTARES: Cosmic ray Sun shadow, M. Sanguineti
616 KM3NeT: DU line fit, C. Poire
1254 KM3NeT: The Calibration Unit, R. Le Breton
1435 KM3NeT: KM3NeT electronics, D. Real
1279 KM3NeT: real time analysis framework, F. Huang
1374 KM3NeT: Draw me a neutrino, M. Circella

GVD/P-ONE@ICRC21

Baikal-GVD

706. Laser optical calibration system for the Baikal-GVD, K Kopański
1057. Positioning system for Baikal-GVD , A. Avrorin
1212. Data Quality Monitoring system of the Baikal-GVD experiment, M Sorokovikov
747 Experimental string with fiber optic data acquisition for Baikal-GVD, V. Aynutdinov
748. Time synchronization of Baikal-GVD clusters, V. Aynutdinov
720. An efficient hit finding algorithm for Baikal-GVD muon reconstruction, Bair Shaybonov
487. Automatic data processing for Baikal-GVD neutrino observatory, Bair Shaybonov
1011. Performance of the muon track reconstruction with the Baikal-GVD neutrino telescope, Grigory Safronov
1250. Double Cascade Reconstruction Techniques in the Baikal-GVD Neutrino Telescope, Eliška Eckerová

405. Multi-messenger and real-time astrophysics with the Baikal-GVD telescope, O. Suvorova
400. The Baikal-GVD neutrino telescope as an instrument for studying Baikal water luminescence, R. Dvornicky
900. The Baikal-GVD neutrino telescope: search for high-energy cascades, Z. Dzhilkibaev
529. ANTARES - Baikal GVD Alerts Analysis, S. Garre
1449. Observations of track-like neutrino events with Baikal-GVD, D. Zaborov

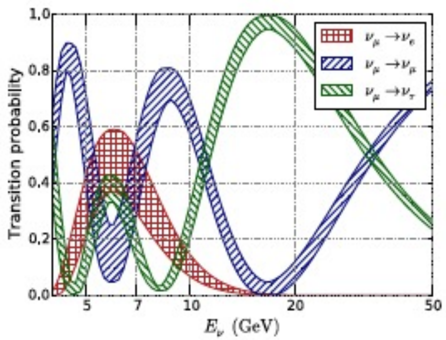
P-ONE

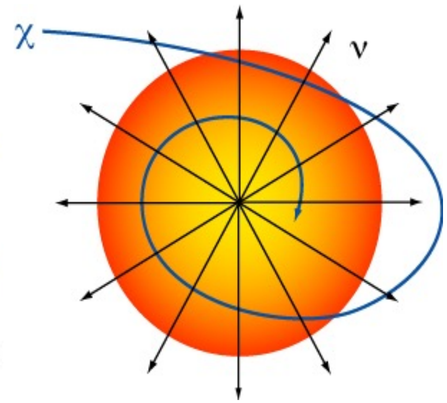
1138. Optical analysis of the P-ONE site using data from the first pathfinder mooring, C. Fruck
1183. P-ONE second pathfinder mission: STRAW-b, I. Carmen Rea
1270. Pacific Ocean Neutrino Experiment (P-ONE): prototype line development, C. Spannfellner

594. PLEnuM: A global and distributed monitoring system of high-energy neutrinos, L. Schumacher

Neutrino telescopes: science

MeV to PeV energies





Supernova
Solar flares

Atmos neutrinos
ν oscillations
ν mass ordering
Sterile, NSI, …

Dark matter
Monopoles,
Nuclearites,…

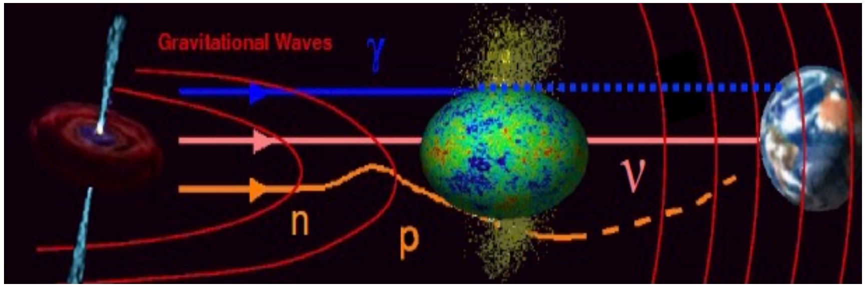
Cosmic neutrinos

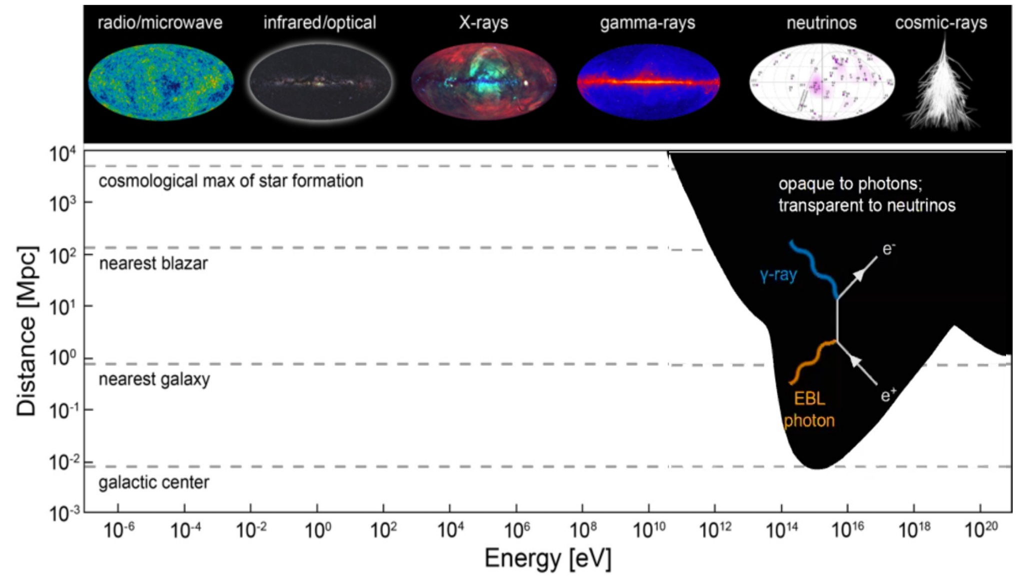
Cosmic rays

Origin and production mechanism of HE CR

+ oceanography, biology, bioacoustics, seismology,…

Neutrinos and multi-messenger astronomy





Neutrinos: neutral, stable, weakly interacting

- not absorbed by background light/CMB ➔ access to cosmological distances
- not absorbed by matter ➔ access to dense environments
- not deviated by magnetic fields ➔ astronomy over full energy range
- three flavours ➔ additional information on source

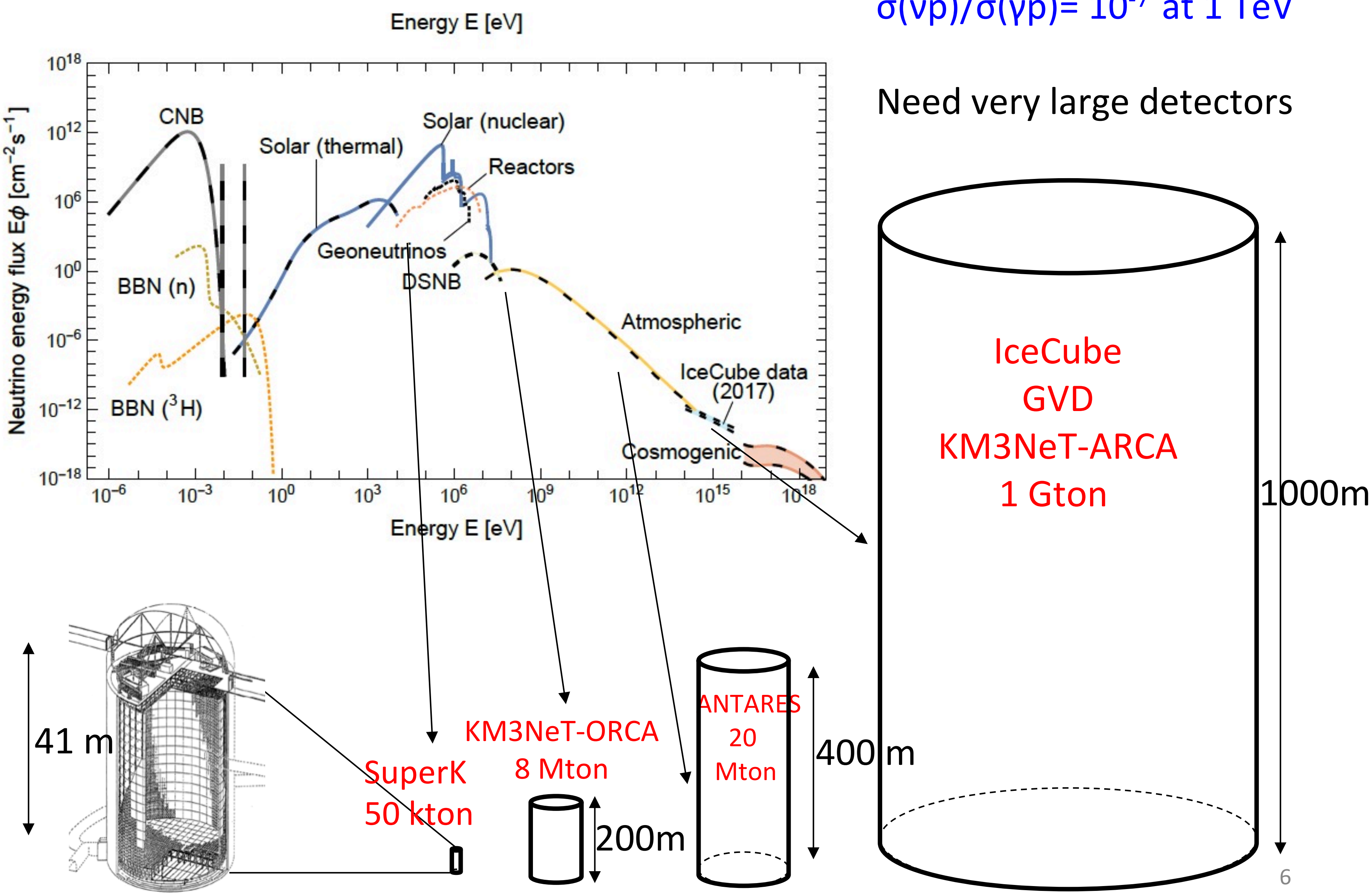
'Smoking gun' signature for hadronic processes

Correlated in time/direction with electromagnetic and gravitational waves

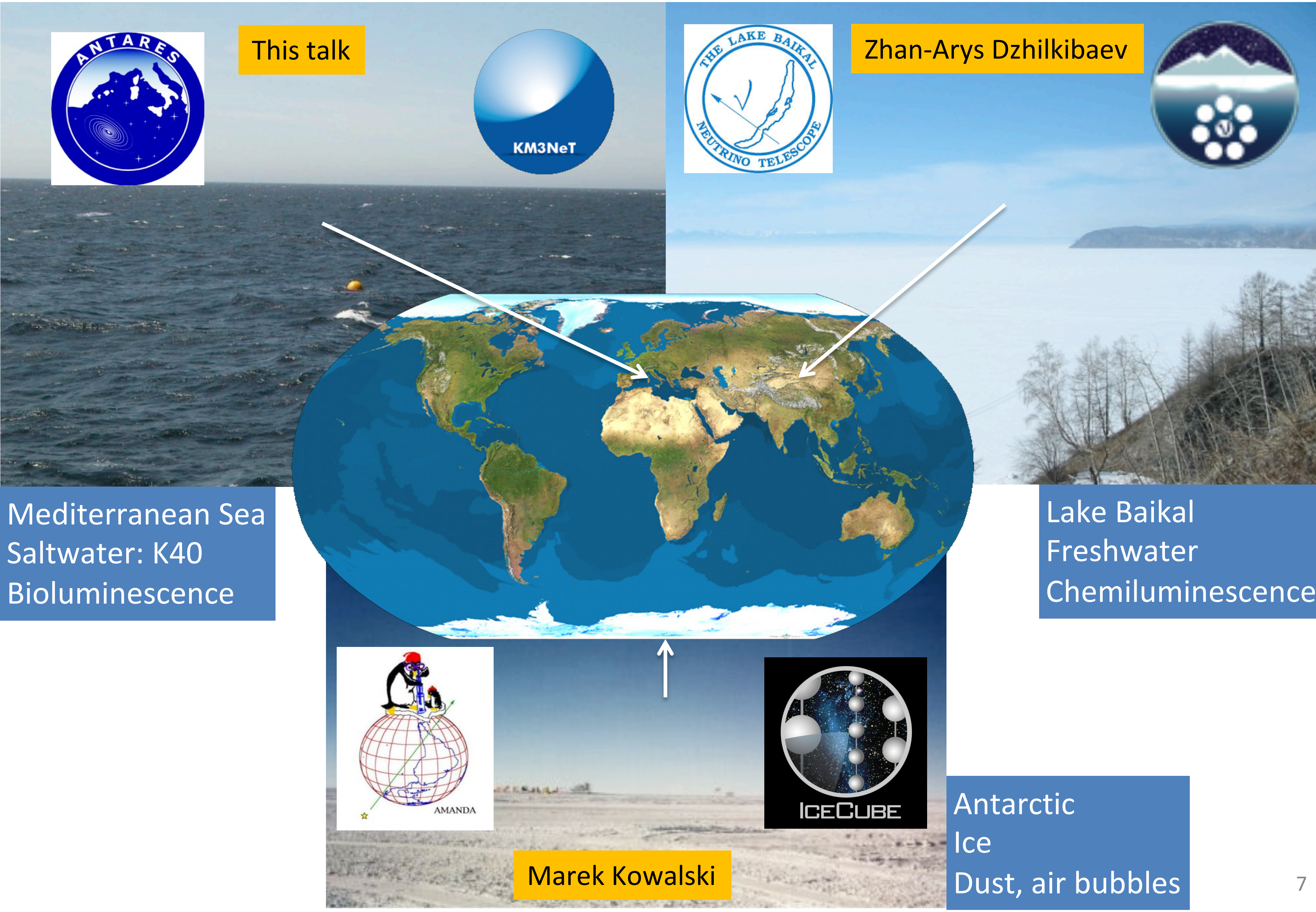
Neutrinos fluxes from MeV to PeV

$\sigma(\nu p)/\sigma(\gamma p) = 10^{-7}$ at 1 TeV

Need very large detectors

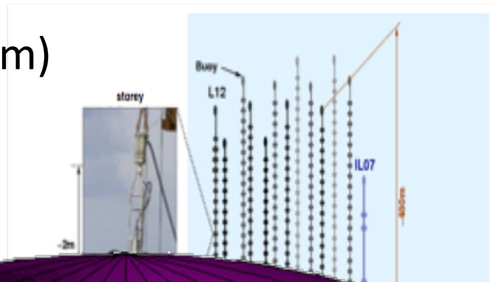


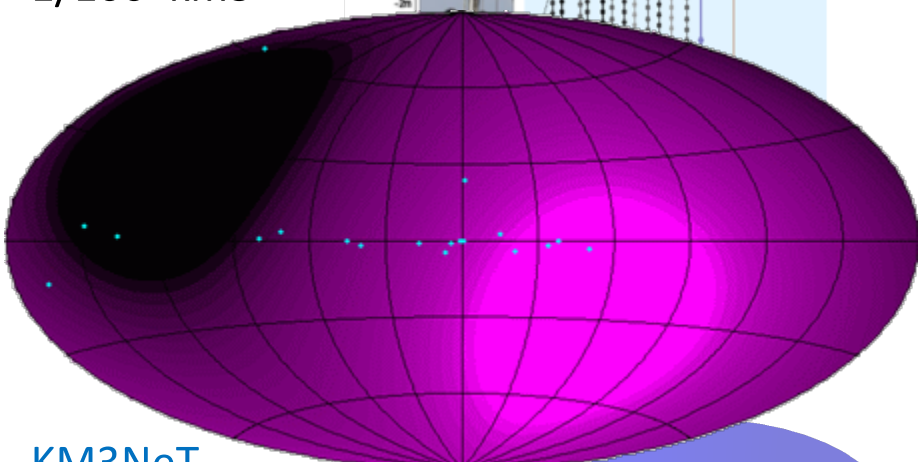
Very large volume neutrino telescopes



Current H20 (liquid+solid) neutrino telescopes

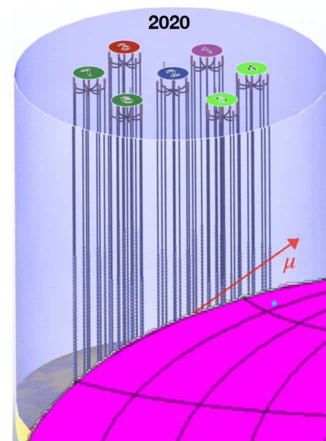
Antares
Med. Sea (-2.4km)
12 strings
885 PMTs (10“)
1/100 km3

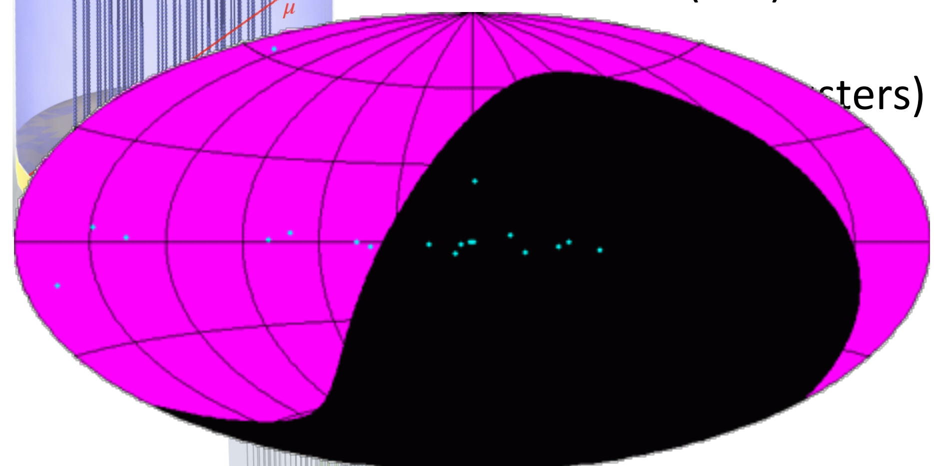




Baikal-GVD
Lake Baikal (-1.3km)
1 cluster =8 strings
0.4 km3 (8 clusters)
2304 PMTs (10”)

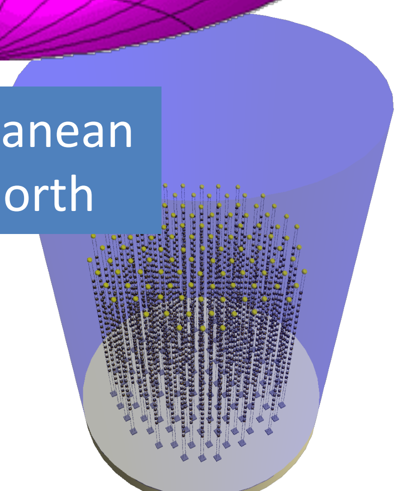
ters)





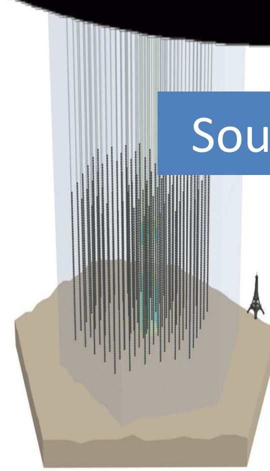
KM3NeT
Med. Sea (-2
6 strings

3BB (345 strings)
6000*31 PMTs (3“)
1.1 km3



Mediterranean
~ 43° North

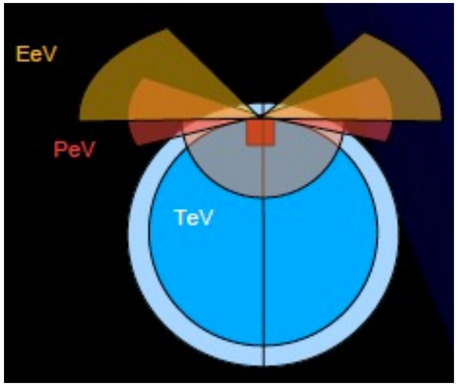
th Pole (-2.4km)
86 strings
5160 PMTs (10”)
1 km3



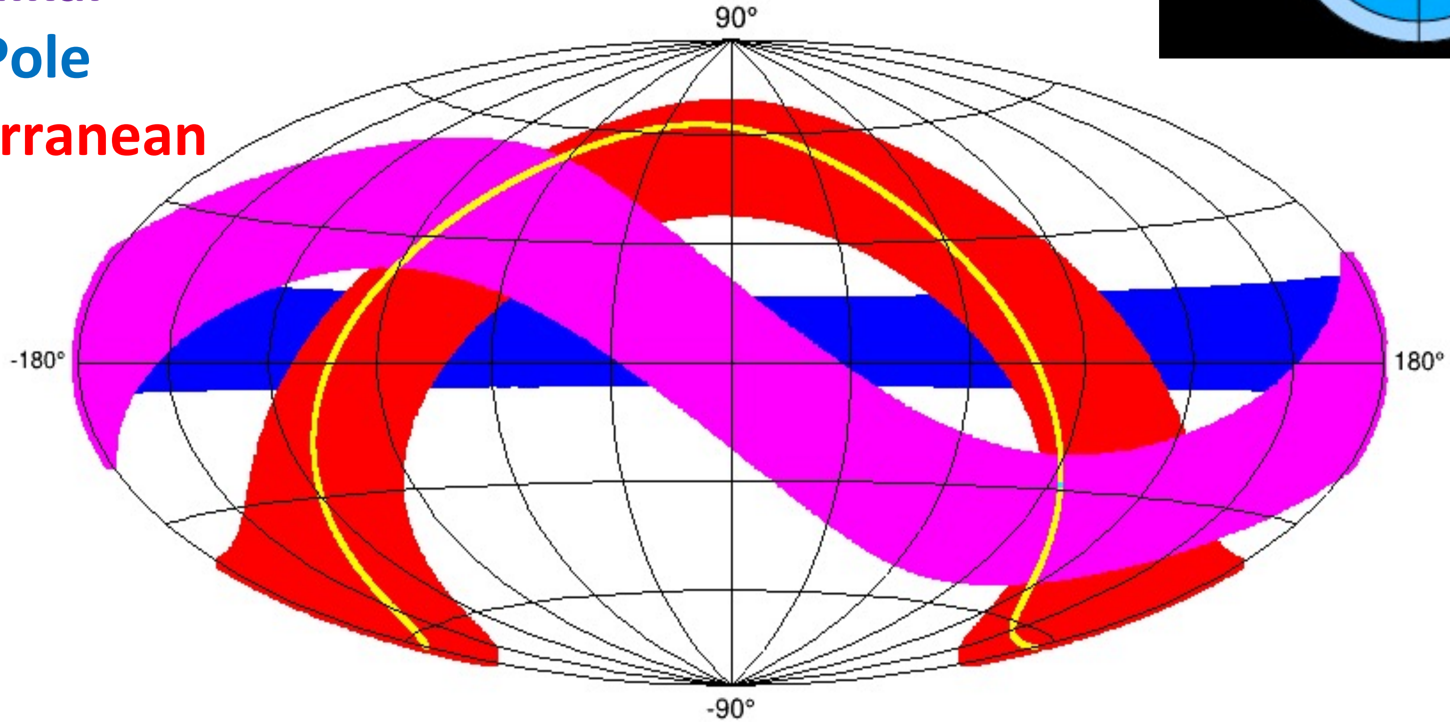
South Pole

Instantaneous PeV fields of view

At highest energies, neutrinos don't make it through the Earth: horizontal tracks are golden channel

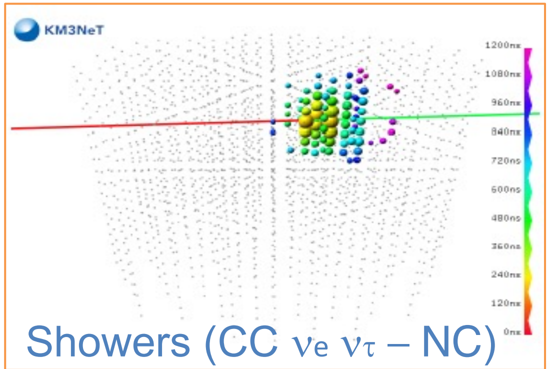


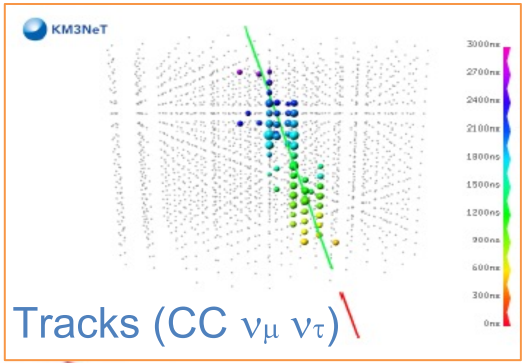
Lake Baikal
South Pole
Mediterranean

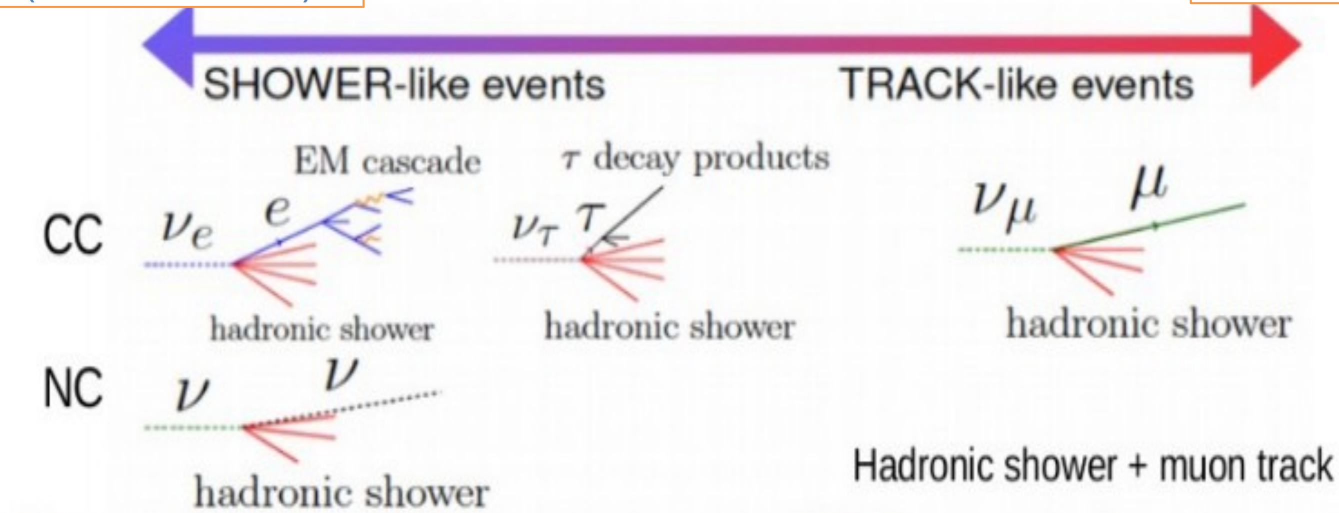


Instantaneous field of view with horizontal tracks

Resolutions







Angular resolution 10°/1° at 100 TeV for Ice/water

Energy resolution ~ 5%

Angular resolution 0.5°/0.1° at 100 TeV for Ice/water

Energy resolution ~ 200-300% (if contained: 25%)

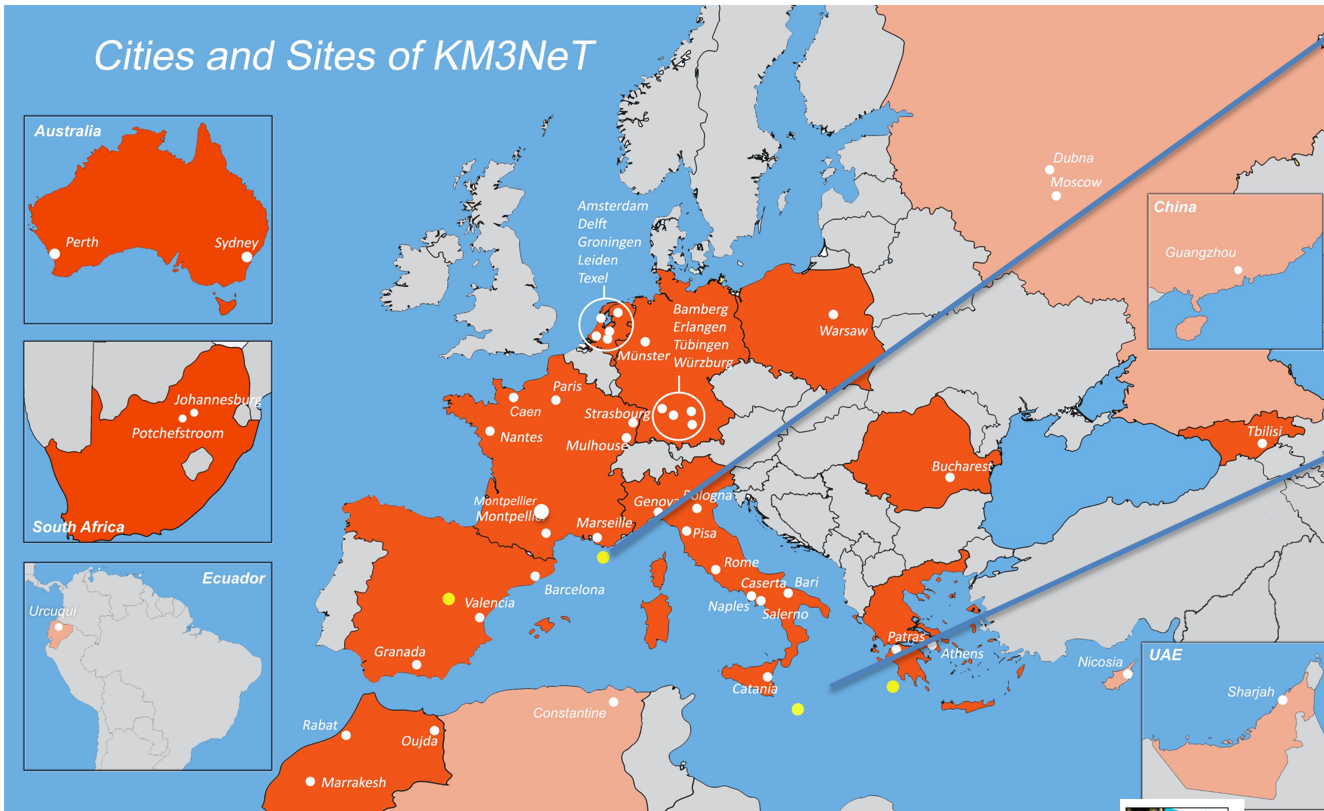
Precision multi-flavour astronomy with water based telescopes

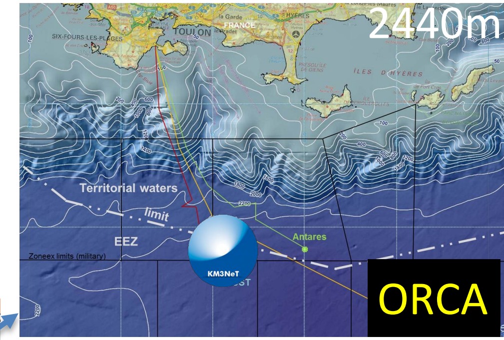
KM3NeT

Multi-site, deep-sea infrastructure

Selected for ESFRI roadmap

Single collaboration, Single technology





Oscillation Research with Cosmics In the Abyss

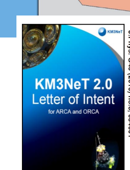
Astroparticle Research with Cosmics In the Abyss

Connection nodes of
european multidisciplinary seafloor & water column observatory
emso

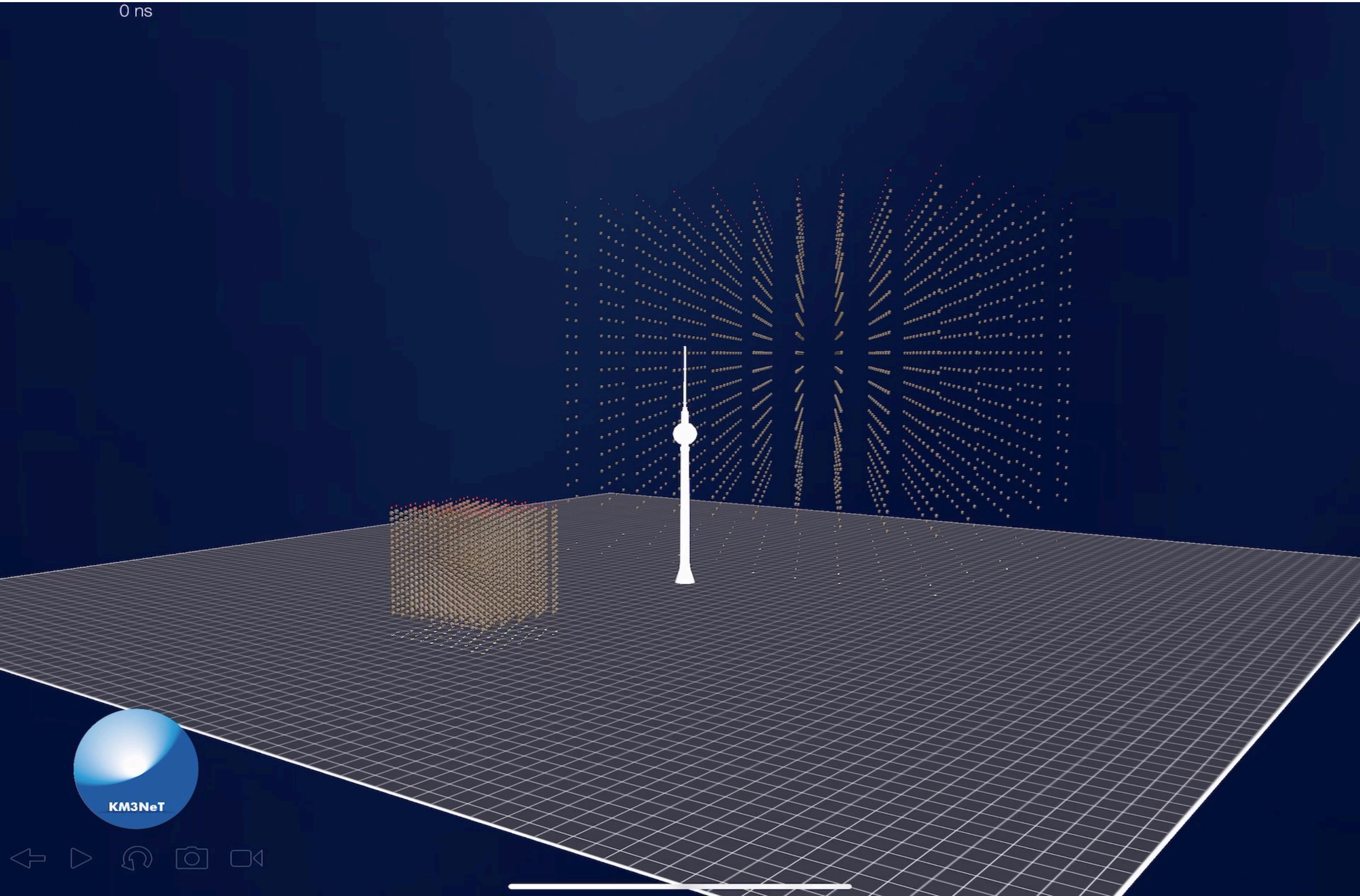
KM3NeT 2.0: Letter of Intent

http://dx.doi.org/10.1088/0954-3899/43/8/084001

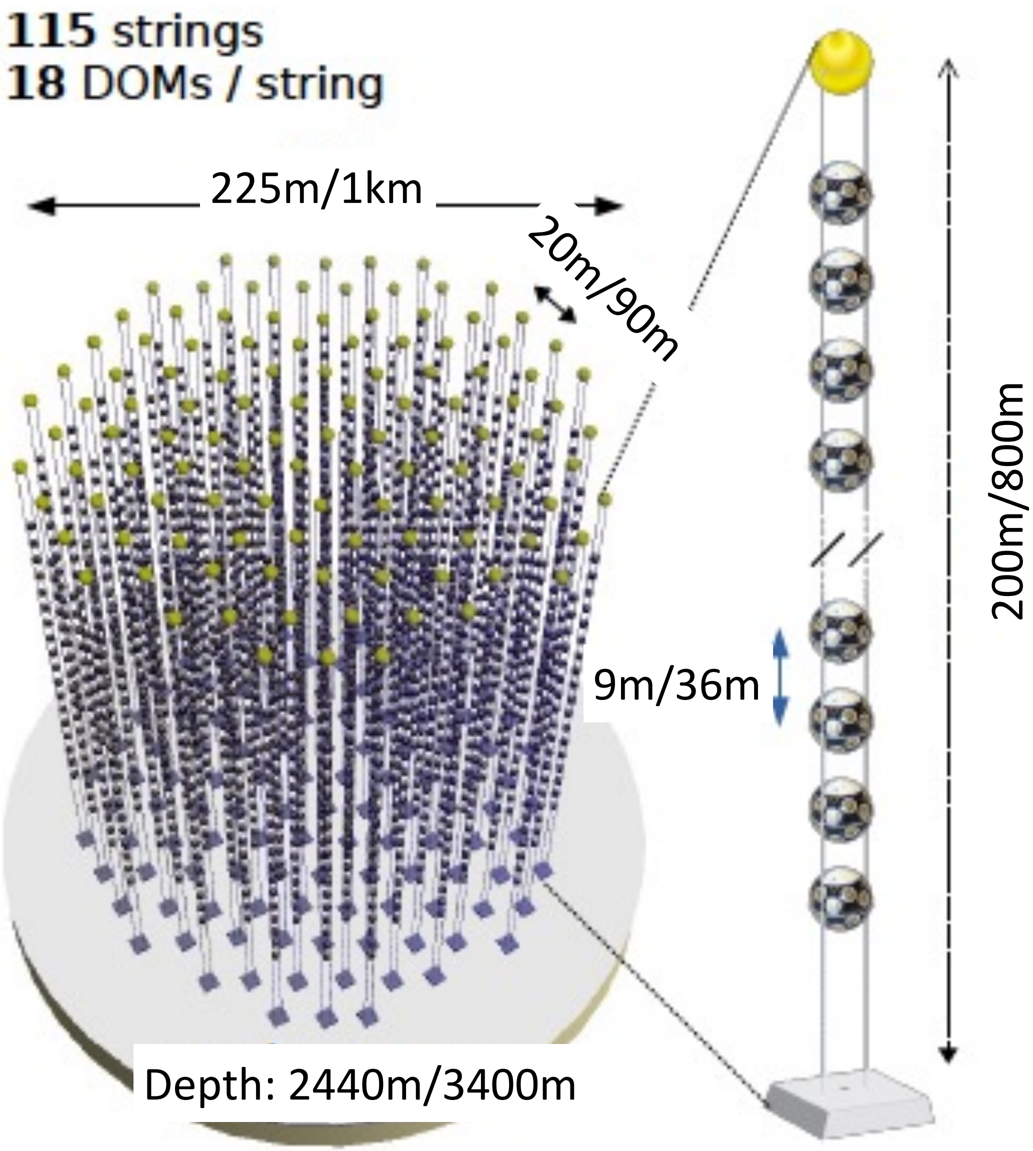
J. Phys. G: Nucl. Part. Phys. 43 (2016) 084001



KM3NeT: ARCA and ORCA



KM3NeT building block



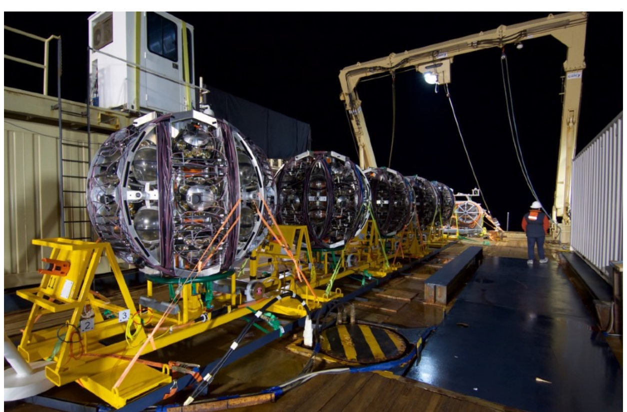
- 31 x 3” PMTs
- All data to shore: Gbit/s optical fibre
- White Rabbit time synchronisation
- LED flasher & acoustic piezo
- Tiltmeter/compass
- Low drag

Instrumented mass	**7 Mton**	**500*2 Mton**

Seafloor infrastructures

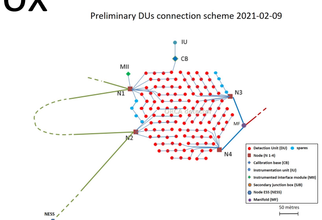
ORCA
2nd junction box
Oct 2020

ARCA
2nd Cable
Nov 2020



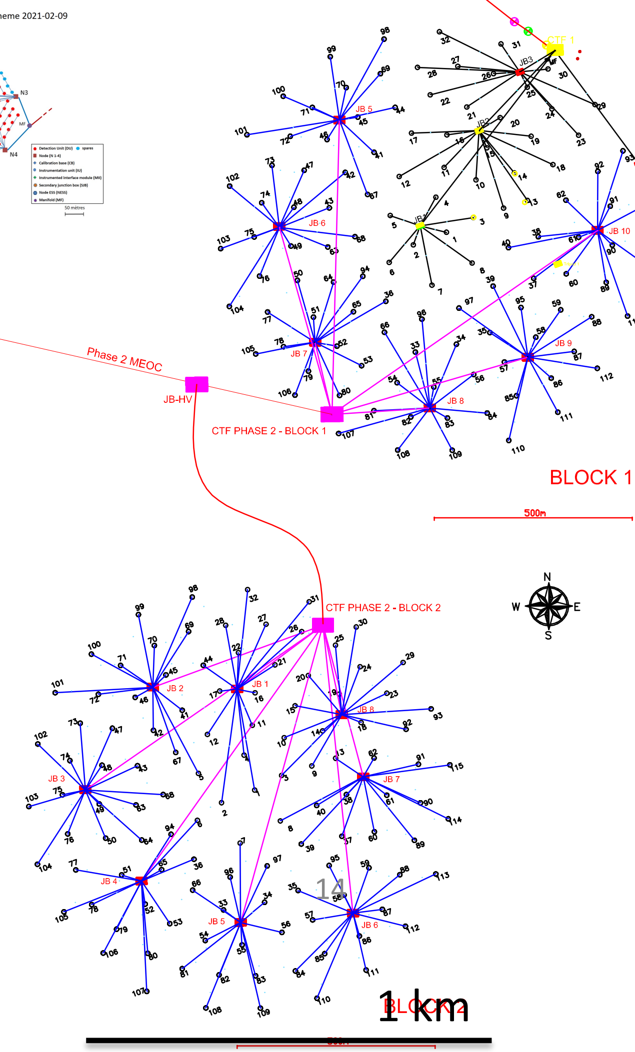
ARCA
junction box
+5 detection units
April 2021

ORCA
(France)



200 m

ARCA
(Italy)



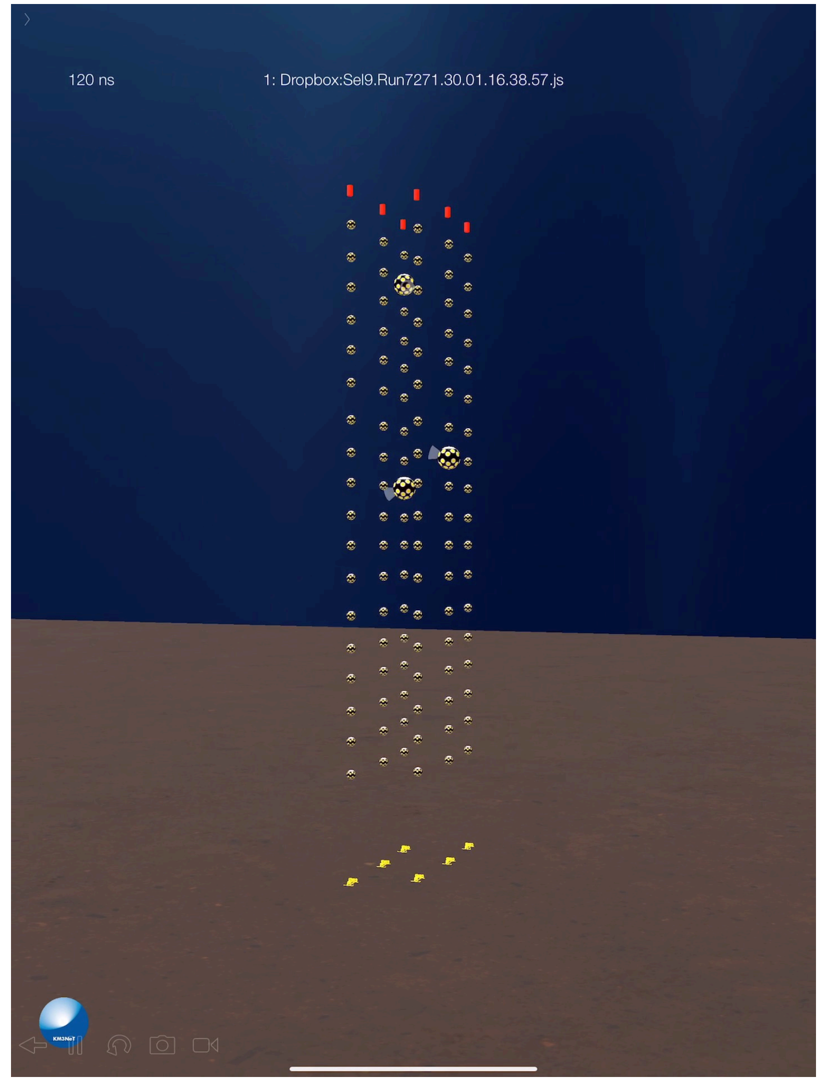
1 km

KM3NeT DU deployment

12 KM3NeT detection units now operational

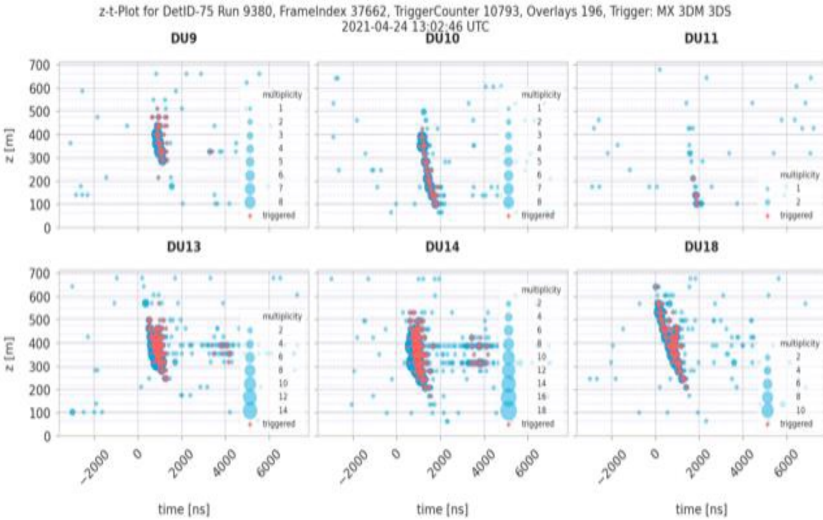
Downgoing muons from cosmic ray showers in ARCA6

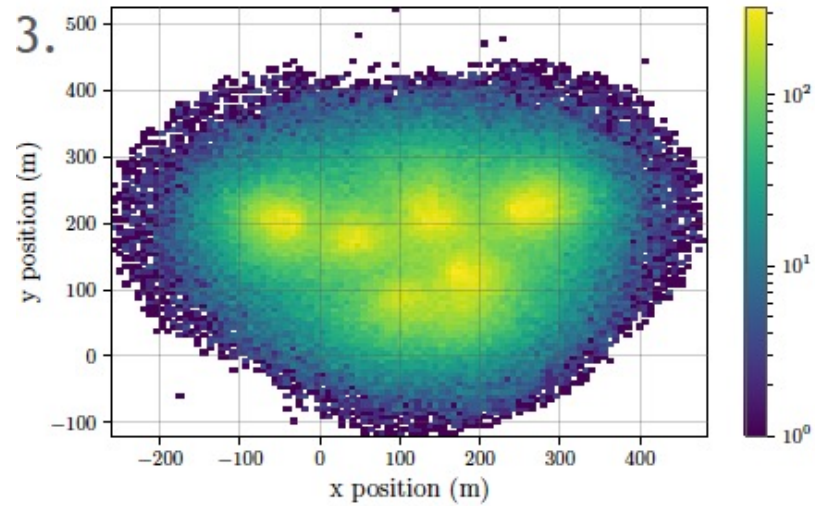
Upgoing muons from atmospheric neutrinos in ORCA6



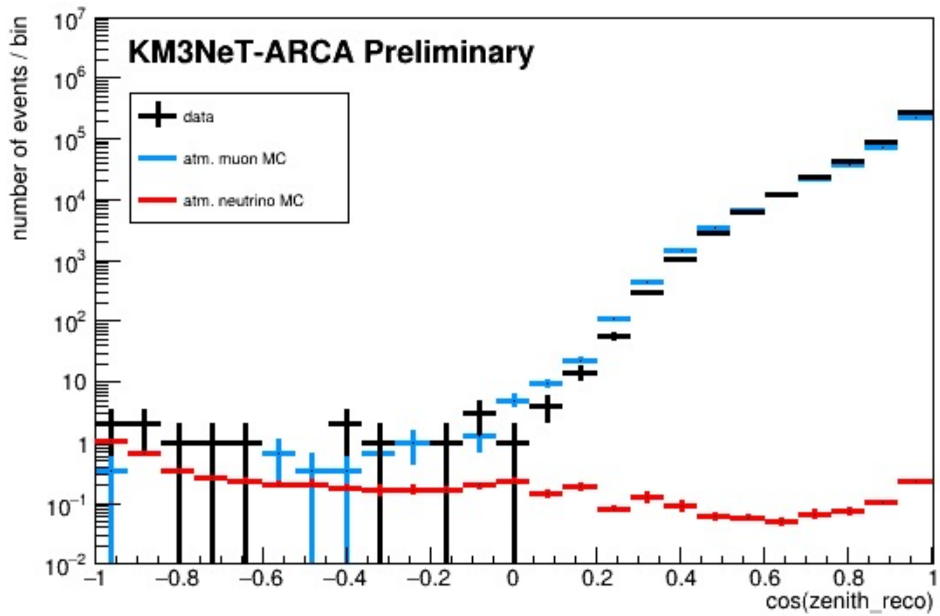
ARCA6 data

701 A. Sinopoulou

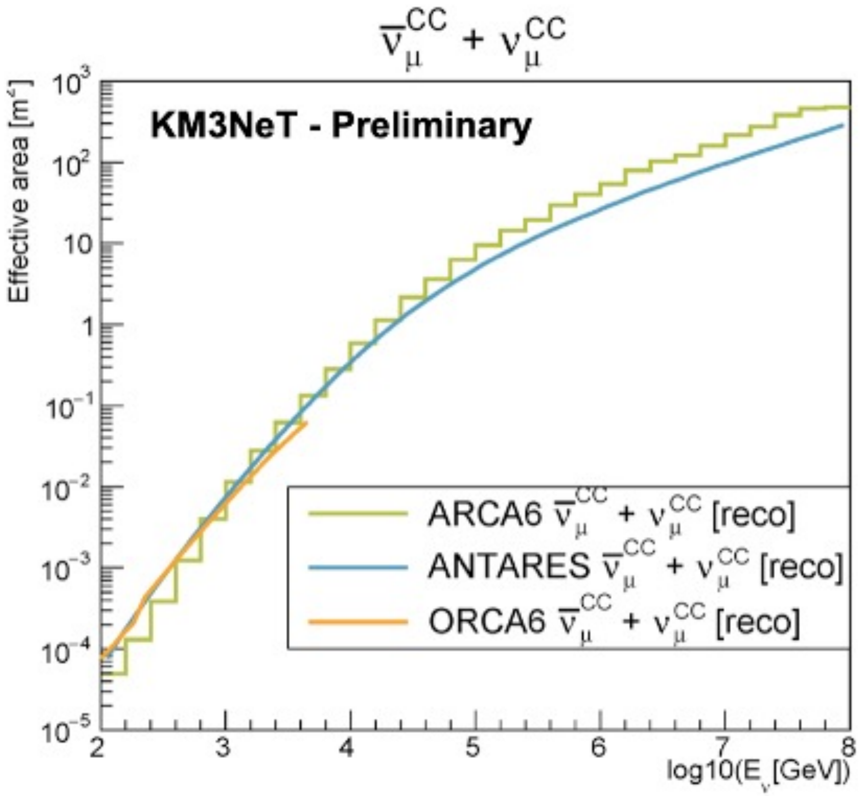


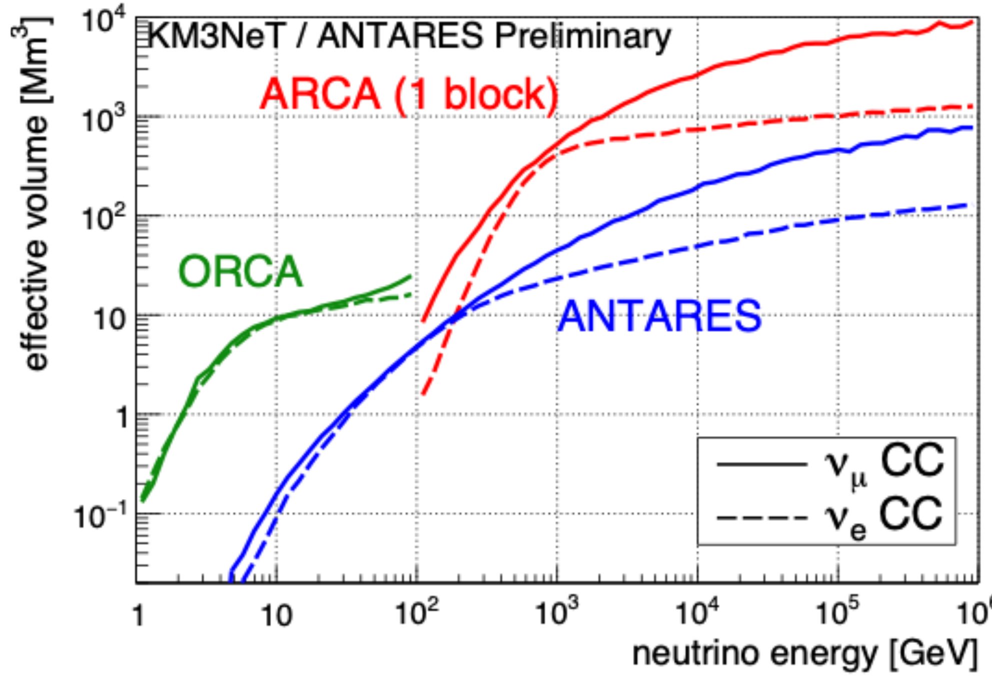


19 days



Effective areas: KM3NeT vs ANTARES



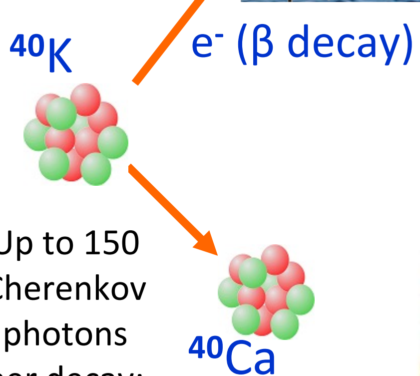


ARCA6+ORCA6 bit better than ANTARES

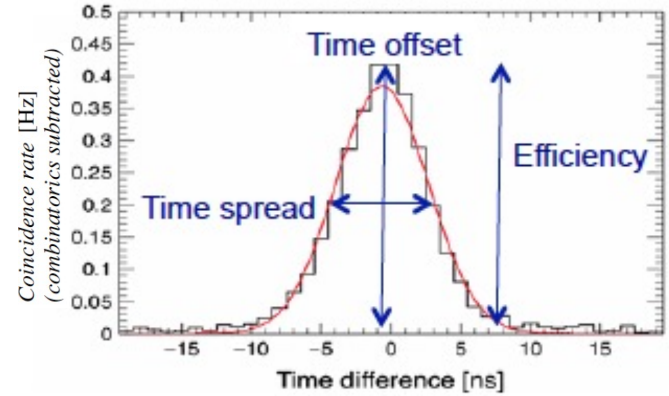
Doubling of detector in Sept 2021 (ARCA11 + ORCA13)

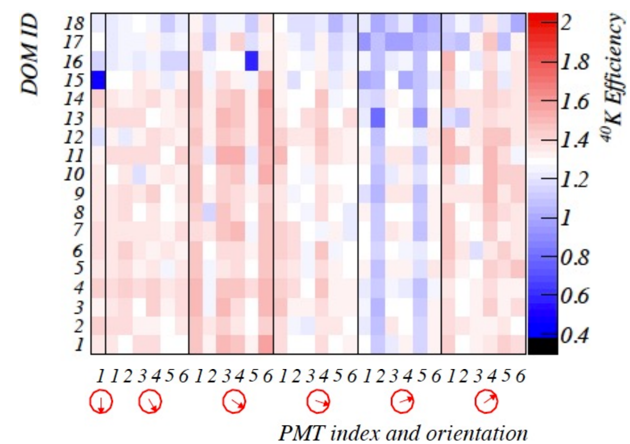
Completion of ORCA115 array in 2025 and ARCA230 in 2027

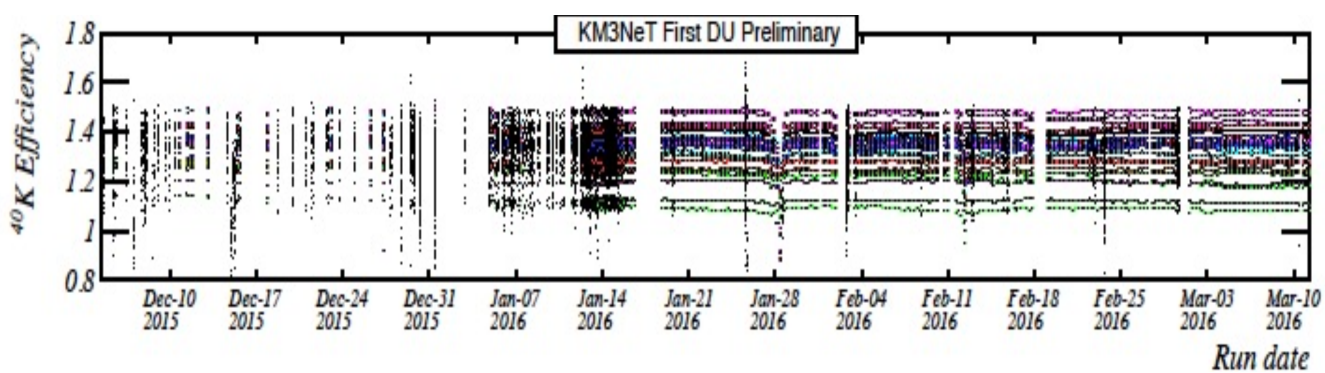
PMT efficiencies: ^{40}K



Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

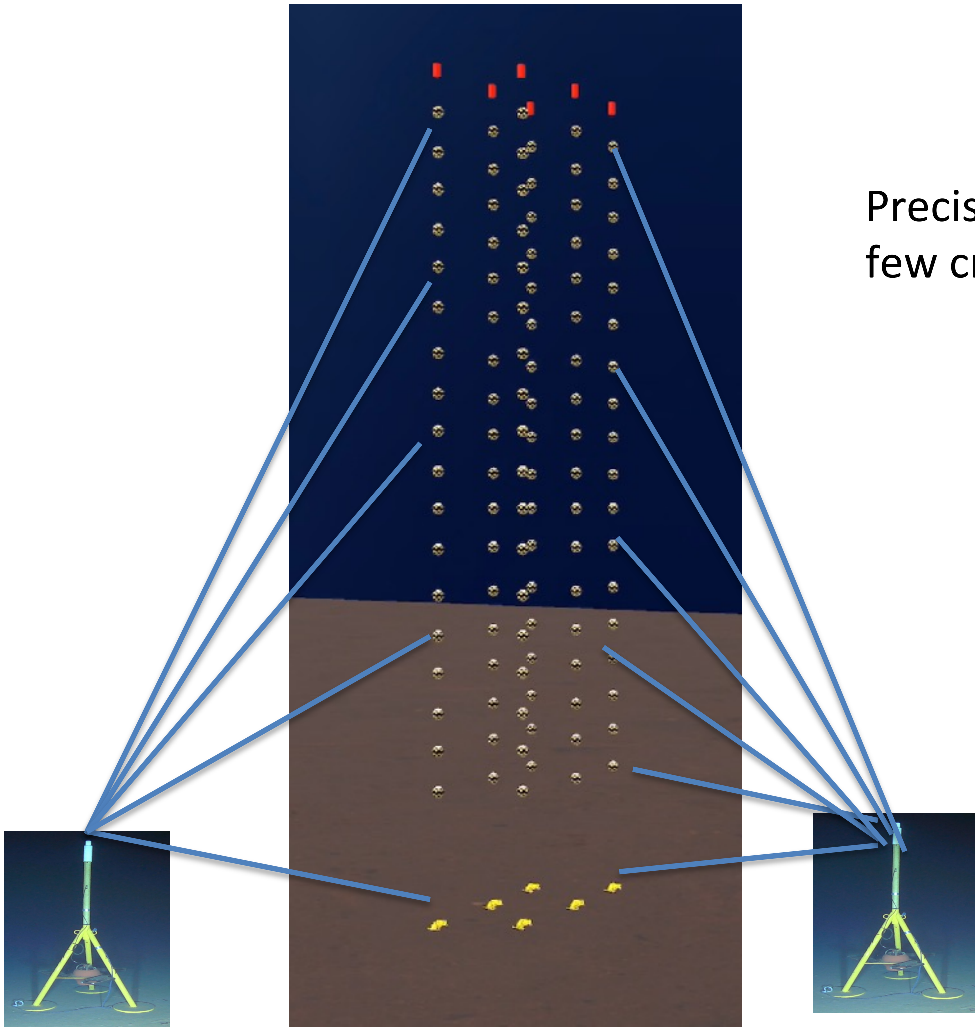






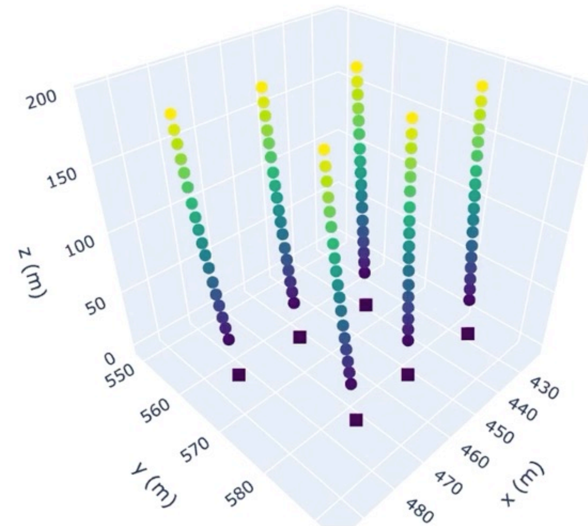
Acoustic position calibration in KM3NeT

1254 R. Le Breton
616 C. Poire

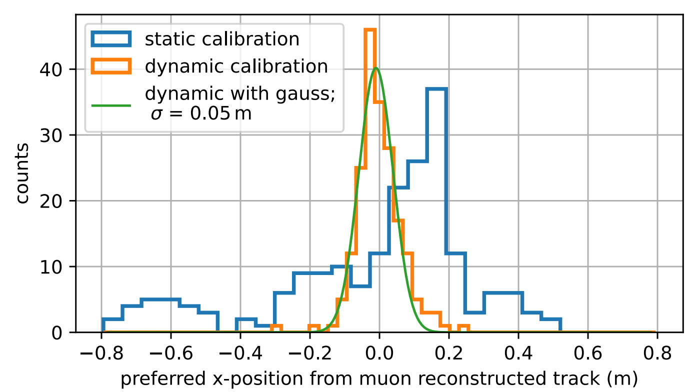


Precision
few cm

Animation of DU movement



Use of dynamic positions,
verified by muon calibration

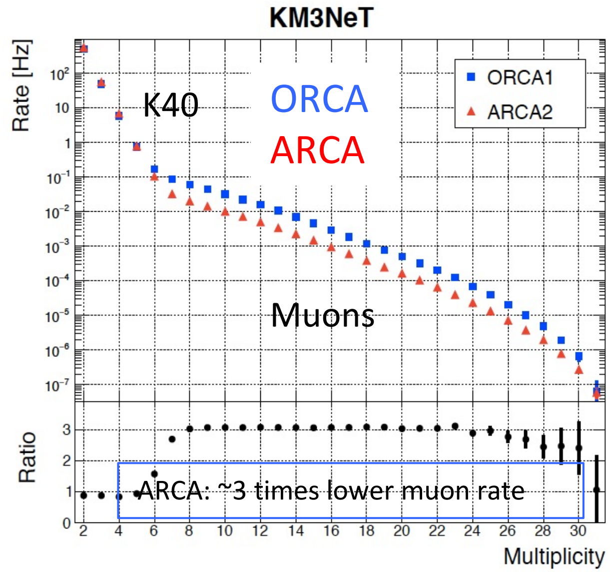


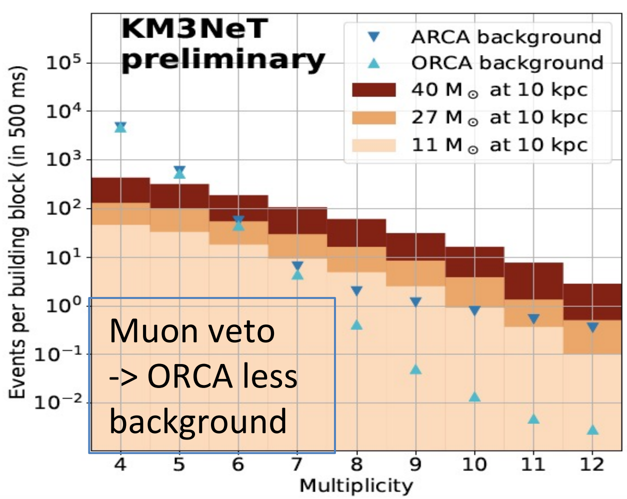
Supernova monitoring in KM3NeT

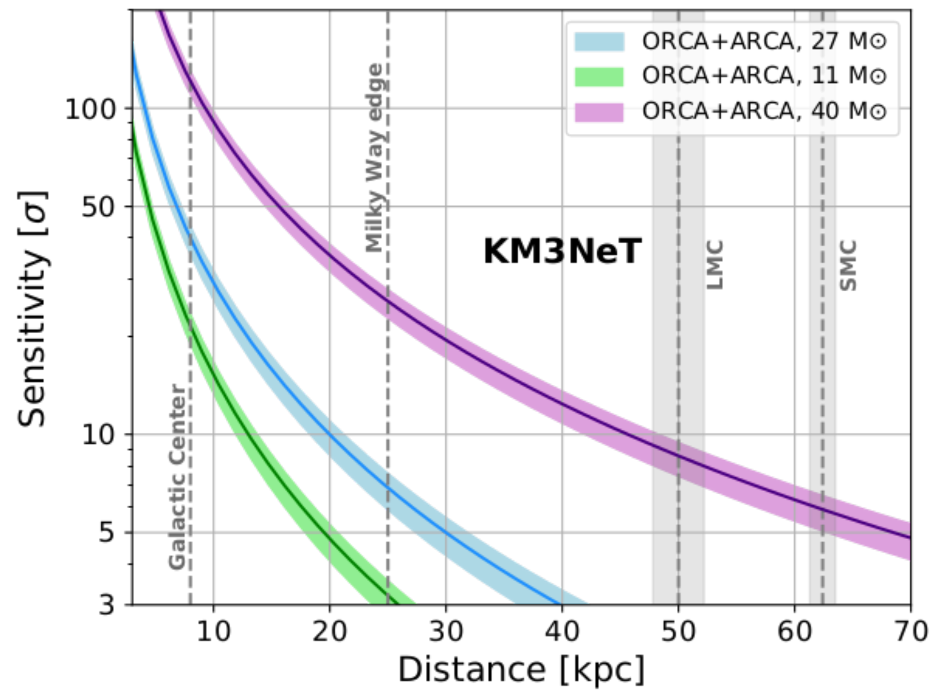
1304 V. Kulikovskiy

SN MeV neutrinos => collective excess of multi-fold coincidences on all DOMs

Eur. Phys. J. C81 (2021) 445





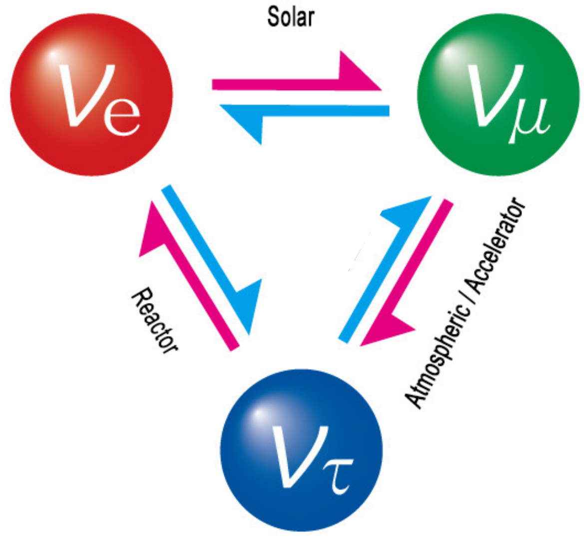


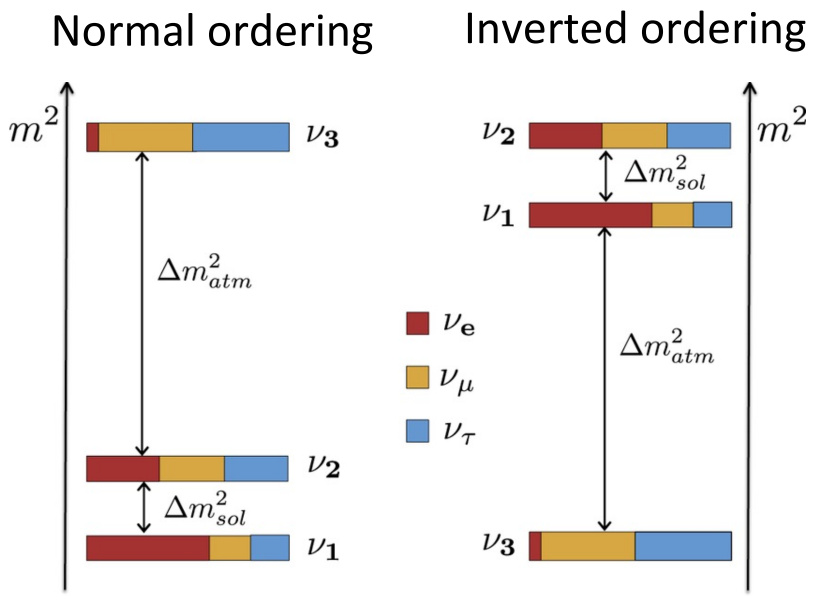
Discovery potential for 95% of Galactic CCSNe

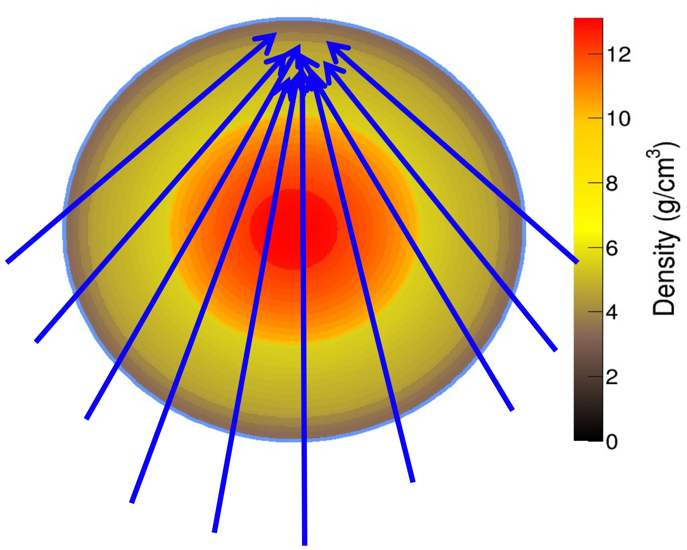
ARCA6+ORCA6 already sensitive to 60% of Galactic CCSNe (<11 kpc)

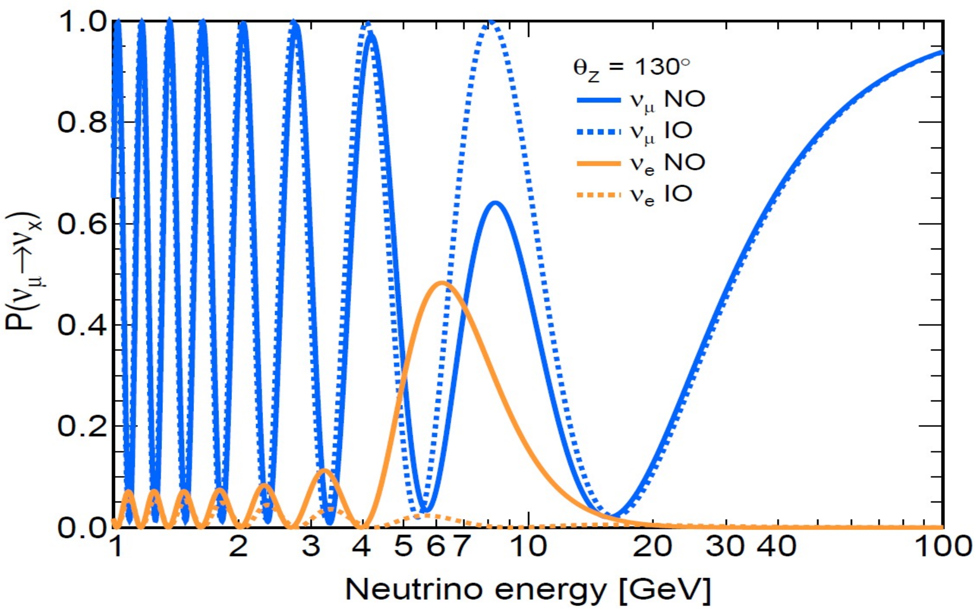
Joint real time trigger operational for SNEWS since early 2019

neutrino oscillations with atmospheric neutrinos



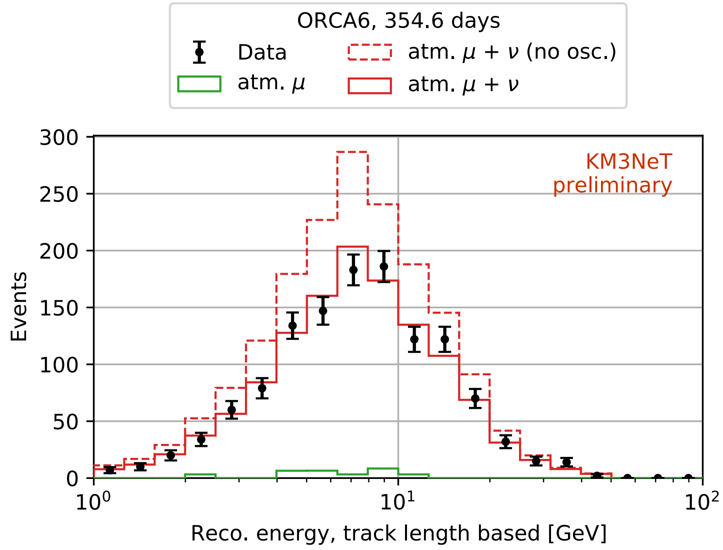


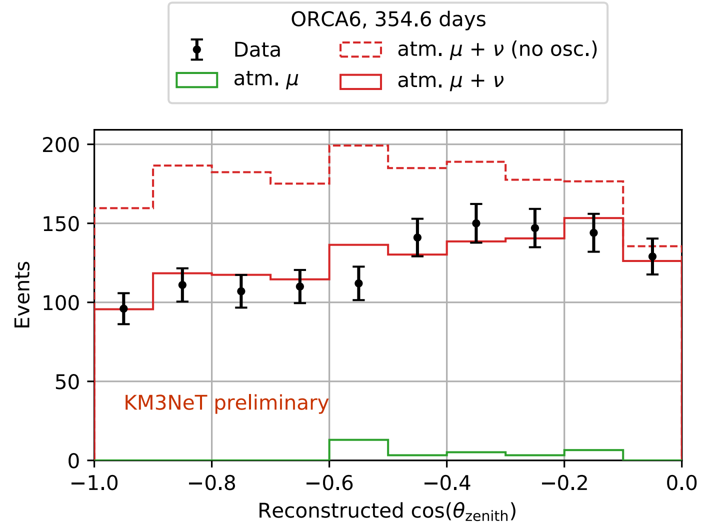


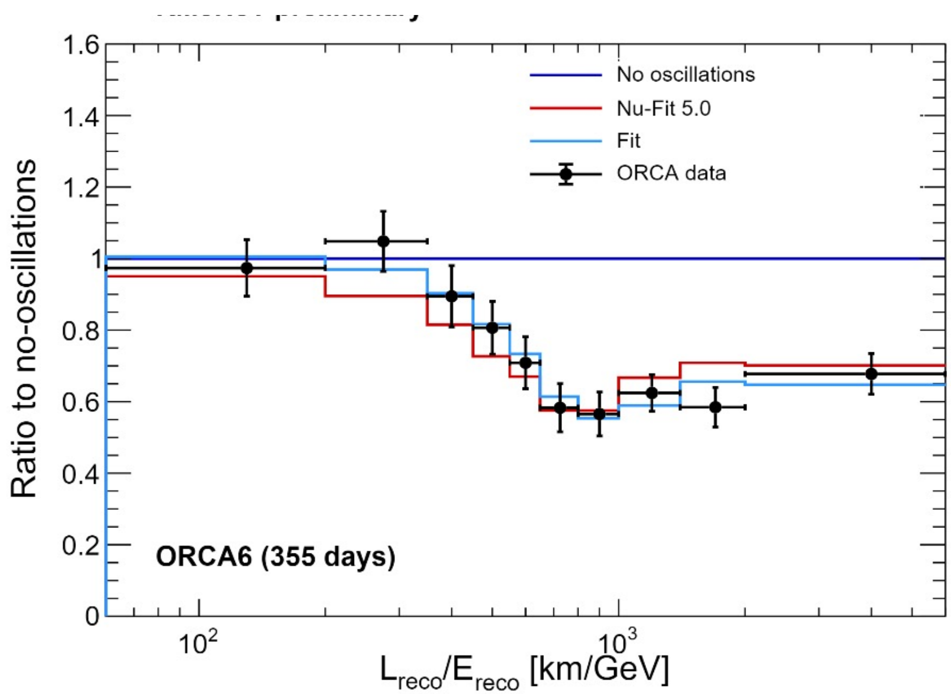


ORCA6 neutrino oscillations (tracks)

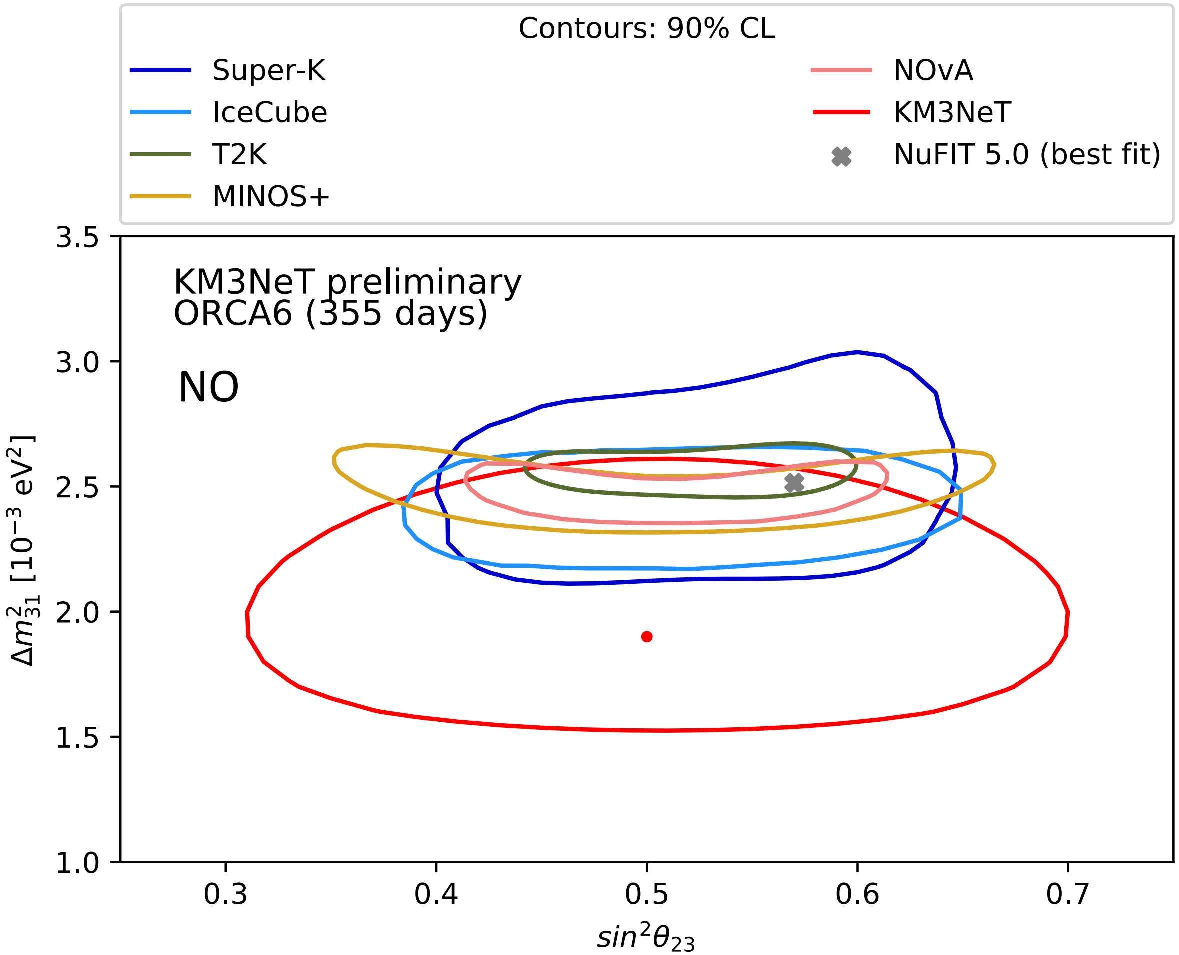
536 L. Nauta

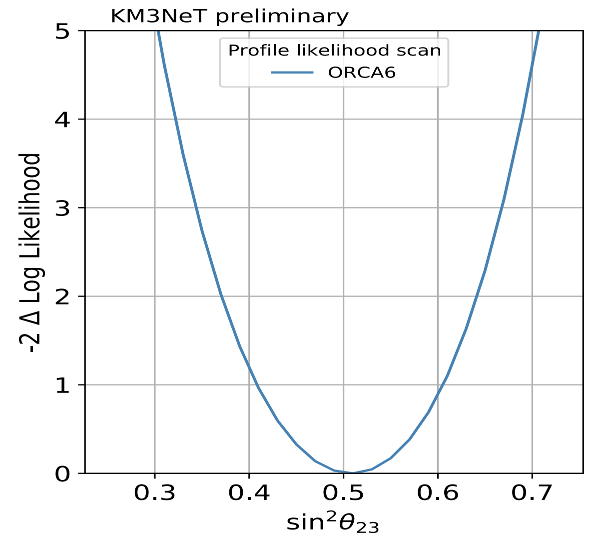




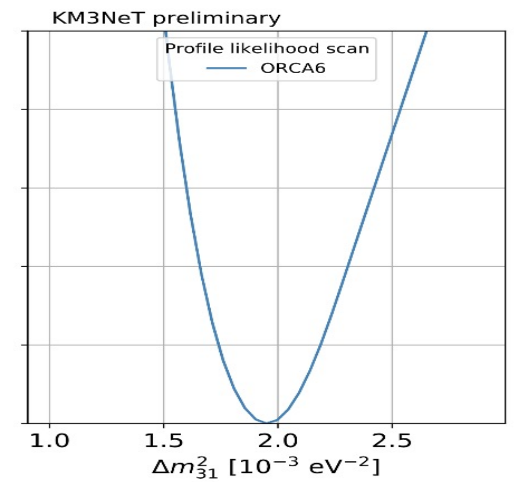


ORCA6: measurement of oscillation parameters



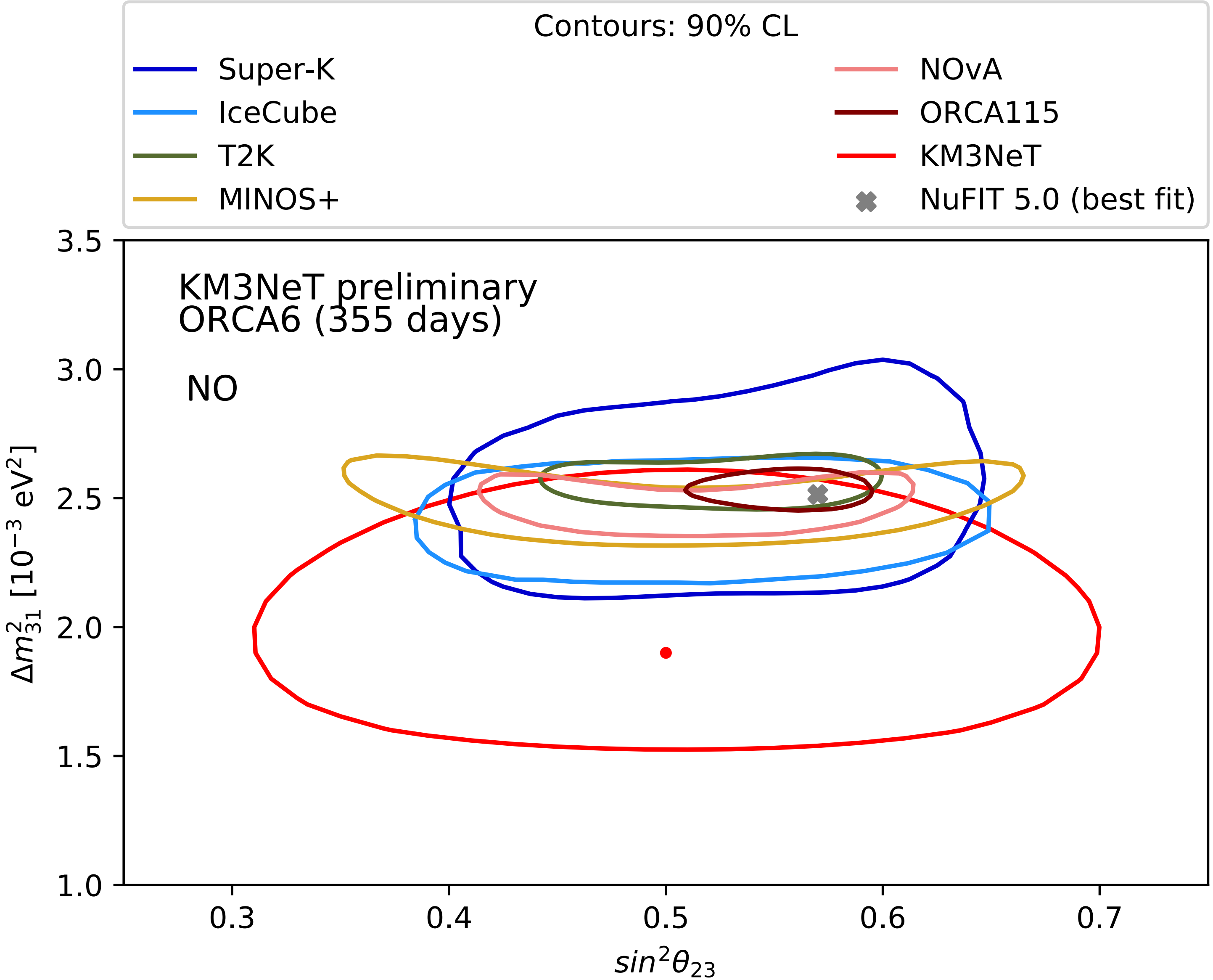


$\sin^2\theta_{23} = 0.50^{+0.097}_{-0.099}$ (stat+syst)



$\Delta m^2_{31} = 1.95^{+0.235}_{-0.212}$ (stat+syst) [10^{-3} eV^{-2}]

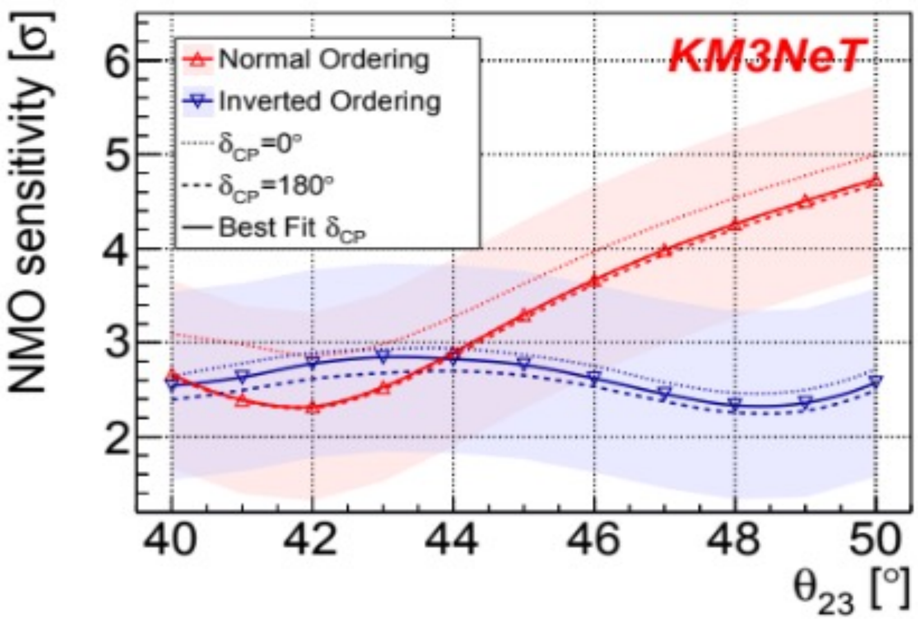
ORCA115: neutrino oscillations sensitivity (3 years)



ORCA115: neutrino mass ordering

3 years

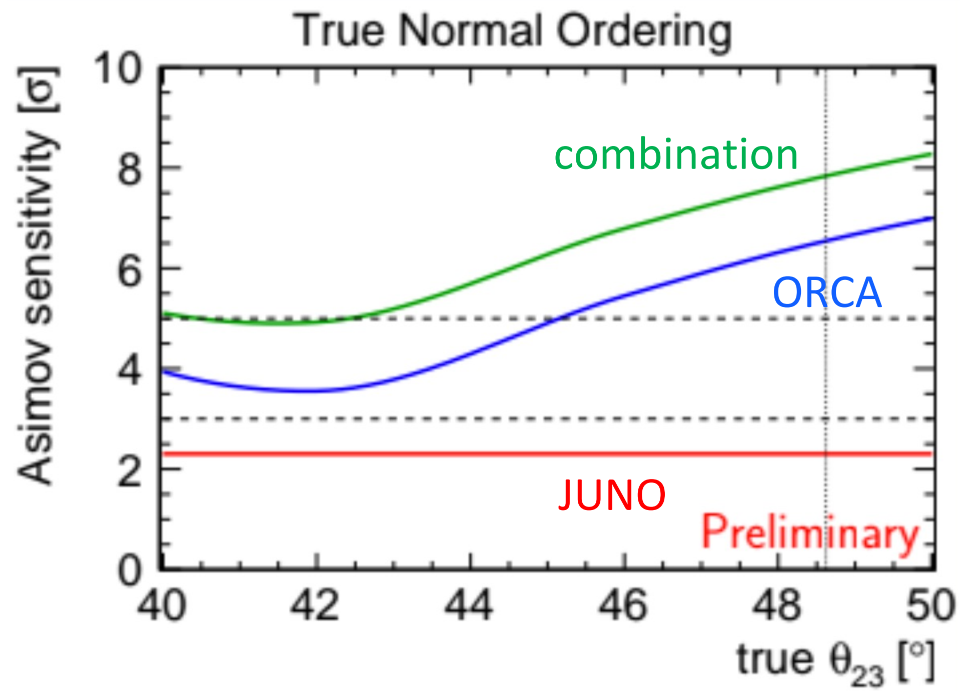
1245 M. Perrin-Terrin



2.5-5σ determination of Neutrino Mass Ordering possible in 3 years

6 yrs & combination with JUNO

1260 J. P. Athayde Andre



Combination power relies on tension between best-fit of Δm^2_{31} in “wrong ordering” between JUNO and ORCA

Atmospheric neutrino flux

612 L. Fusco

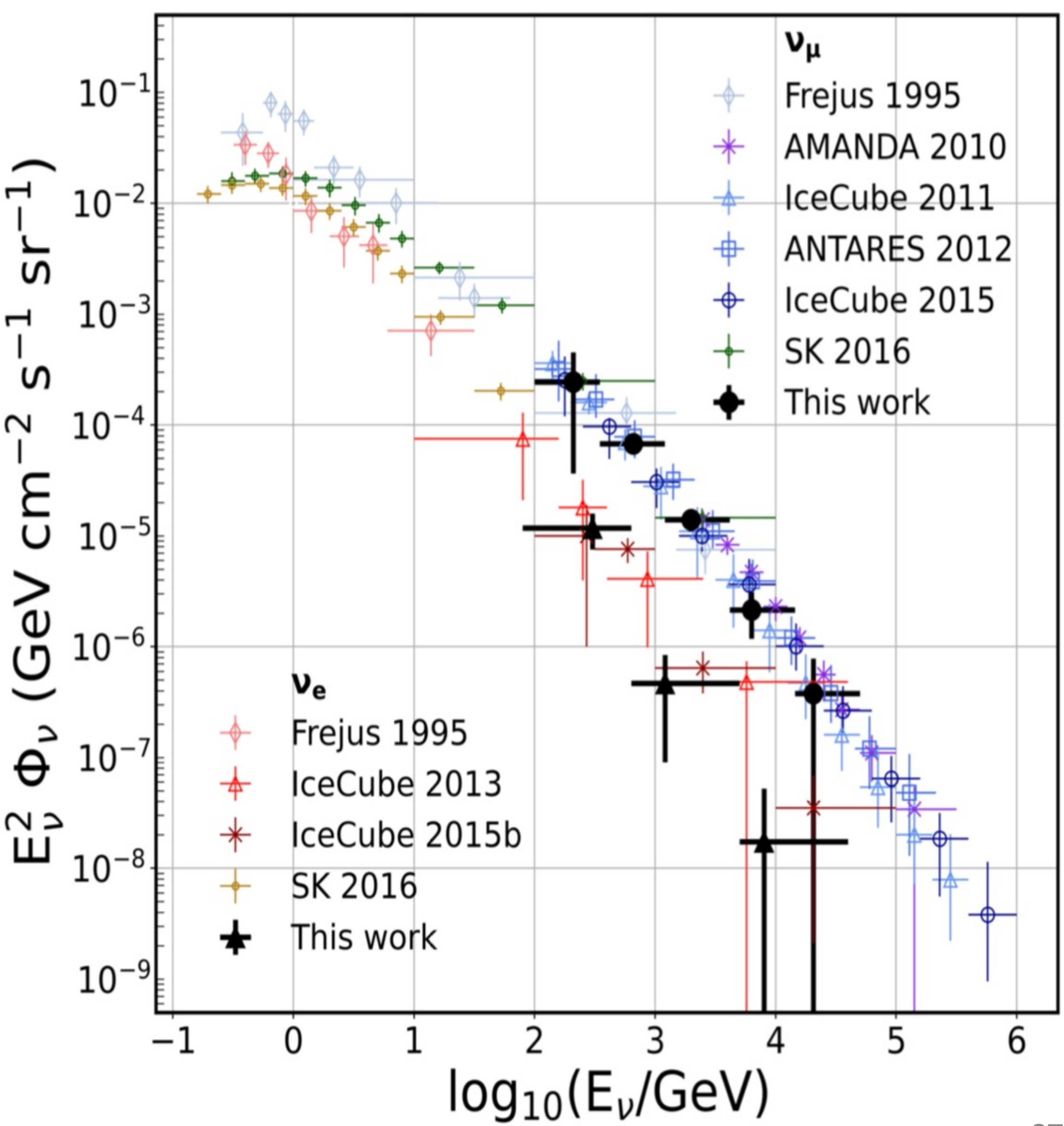
arXiv:2101.12170

ANTARES data 2007-2017

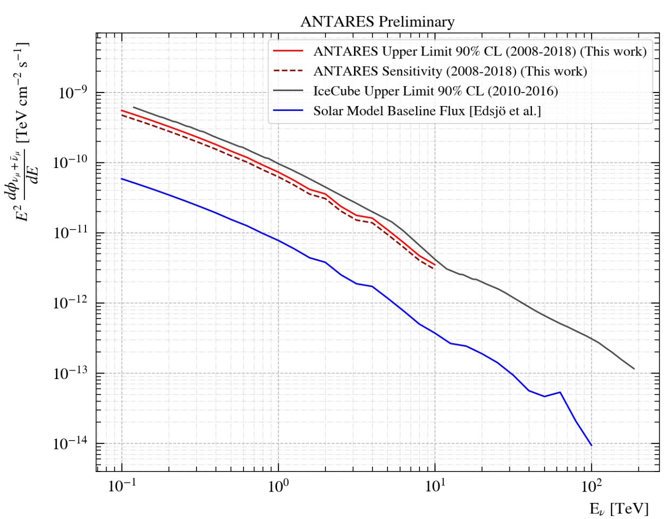
Boosted Decision Tree (BDT)
-> low-energy showers
-> atmospheric ν_e CC

Unfolding of energy spectrum

Compatible with existing measurements



Also Solar atmospheric flux!

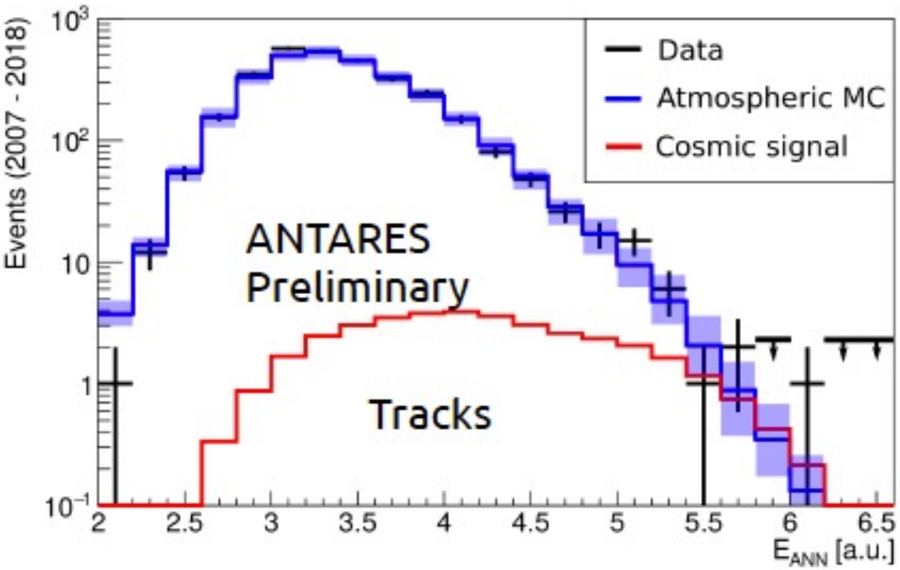


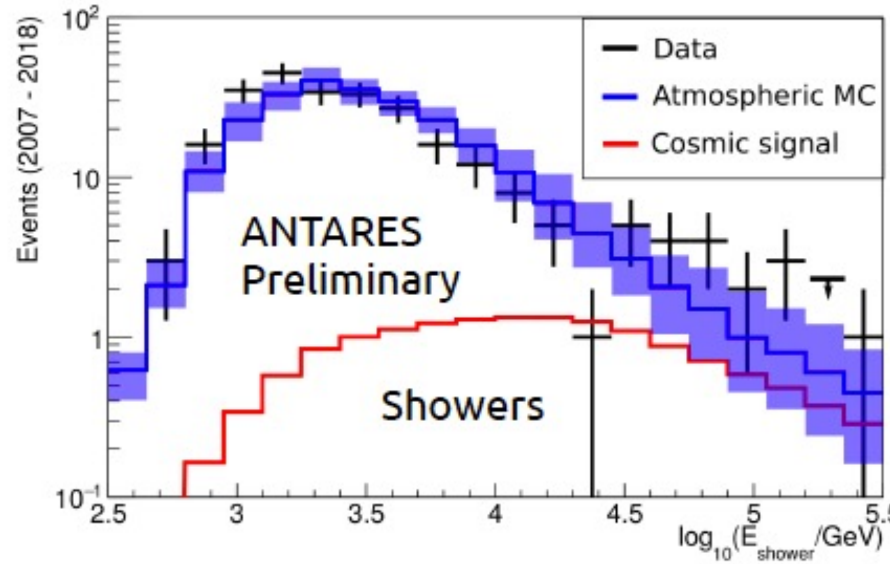
534 D. Lopes-Coto

Diffuse cosmic flux I

612 L. Fusco

ANTARES 2007-2018 (3330 days)





Data: 50 events (27 tracks + 23 showers)

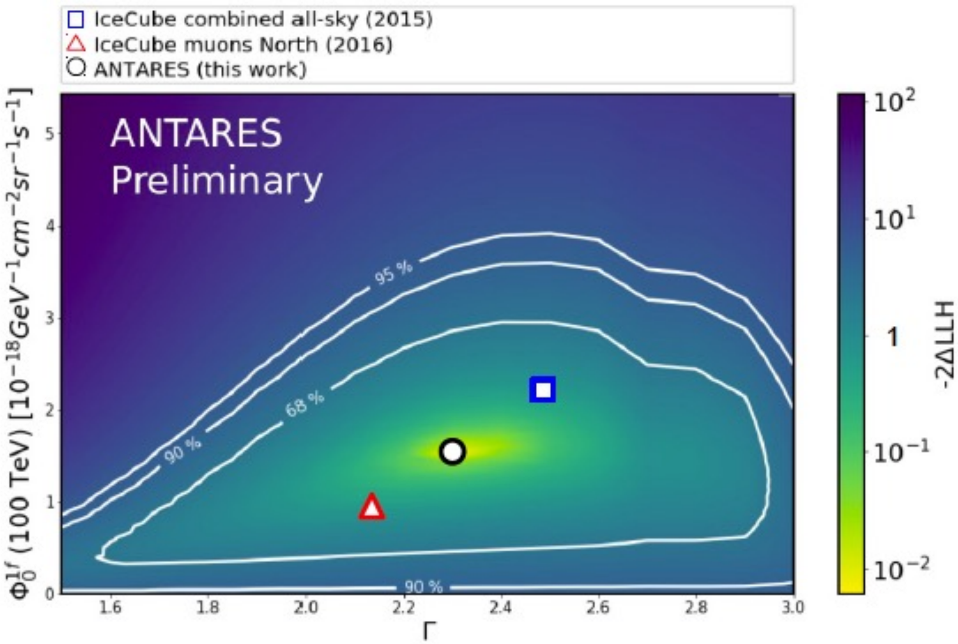
Background expectation (atm. flux, HONDA + Enberg, scaled x ~1.25) : 36.1 ± 8.7 (19.9 tracks and 16.2 showers) – stat. + syst.

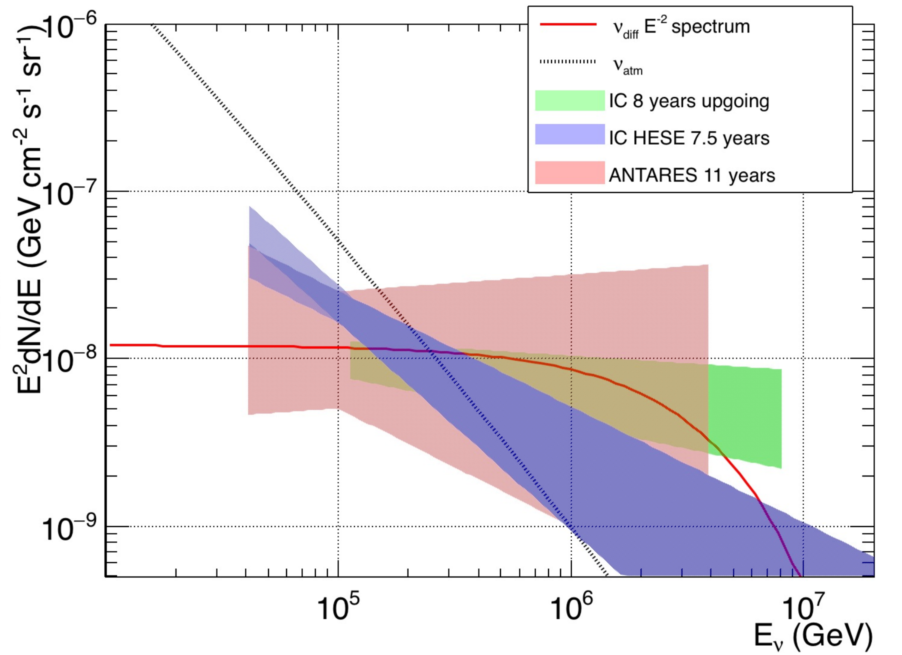
Results not really constraining… but fully compatible with IceCube

Updated and improved analysis coming soon

Diffuse cosmic flux II

Combined tracks & showers likelihood fitting:





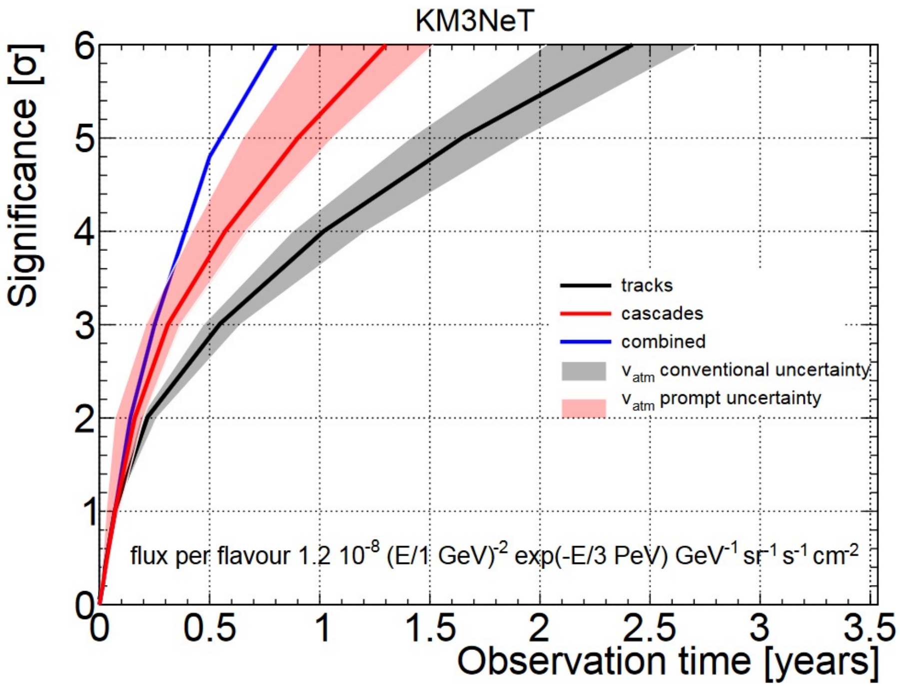
Cosmic flux:

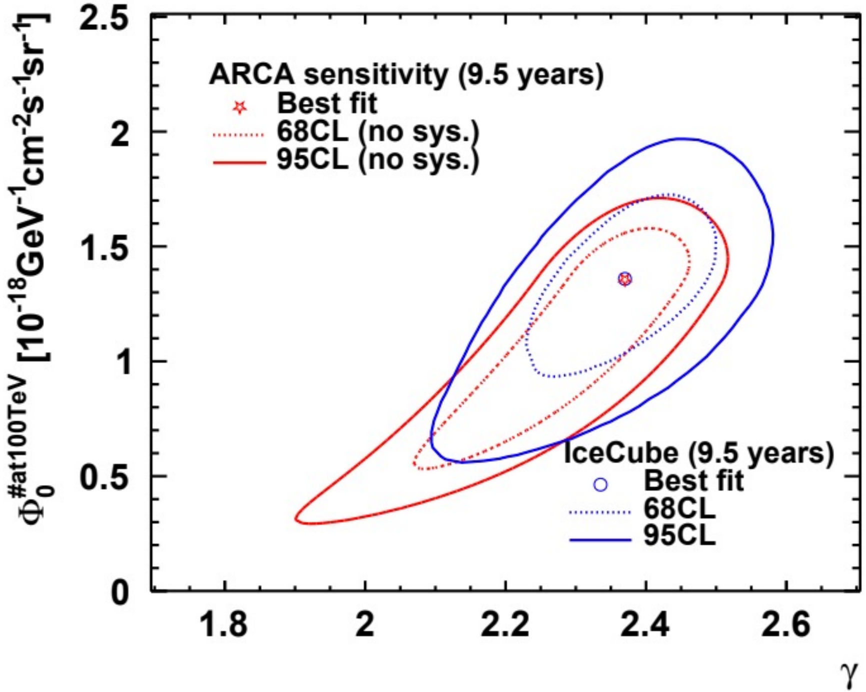
$$\Phi_{100\ \mathrm{TeV}} = (1.5 \pm 1.0) \times 10^{-18}\ \mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$$

$$\Gamma = 2.3 \pm 0.4$$

KM3NeT diffuse cosmic flux

928 R. Muller

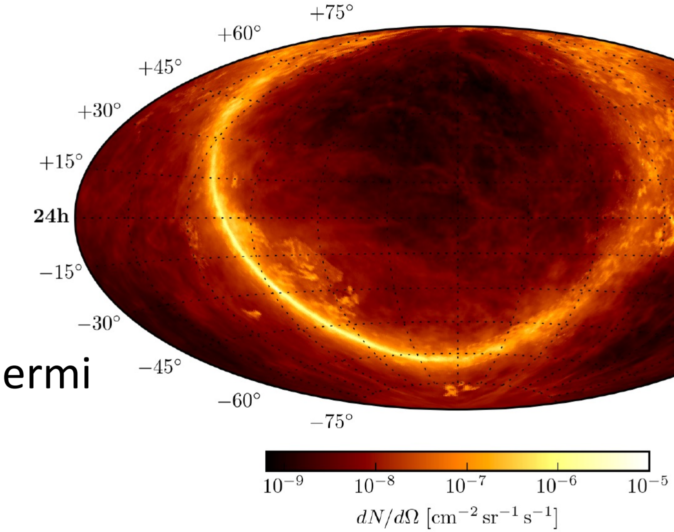




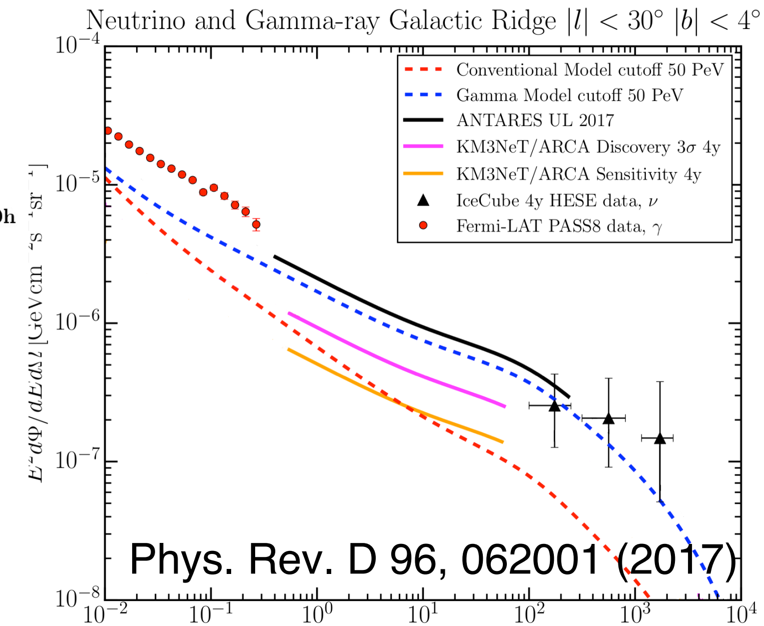
5σ in ~ 0.5 year for the full detector (230 DUs)

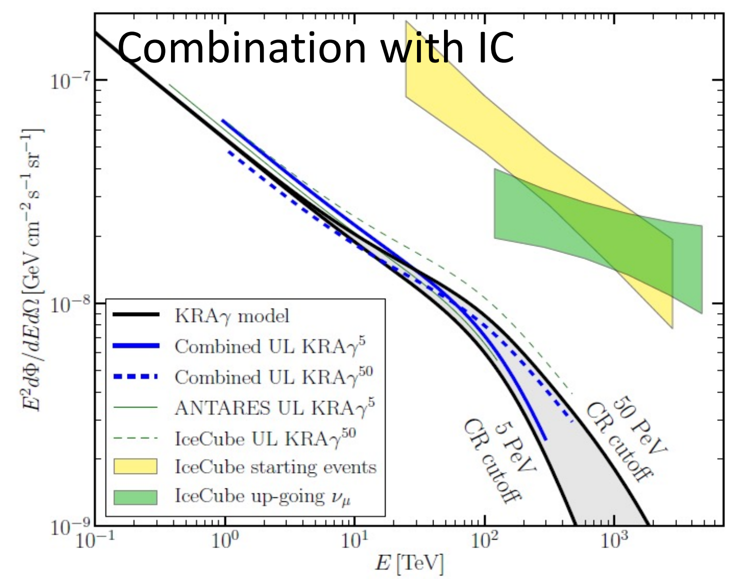
5σ ~ 1 year for one block detector (115 DUs)

Galactic plane



Fermi





ApJL 868, L20 (2018)

Guaranteed galactic neutrinos from CR interactions with matter

Analysis uses full model morphology & spectrum – tracks and cascades

ANTARES Limit is a factor 1.2 above the ‘KRAγ’ model.

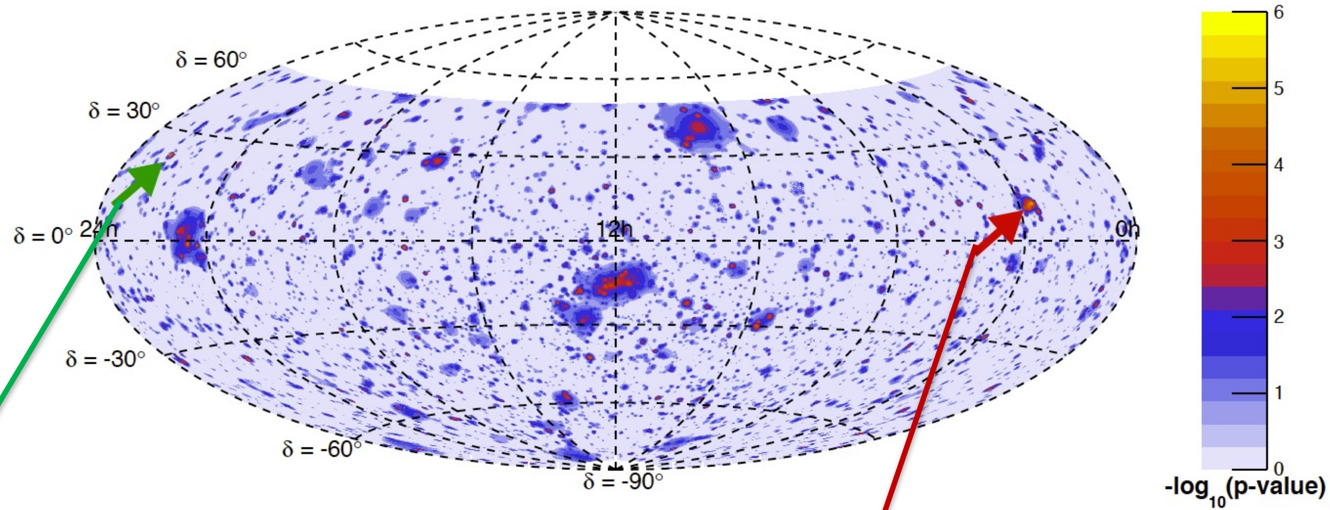
ANTARES updated analysis soon

KM3NeT sensitivity very promising

Point source searches

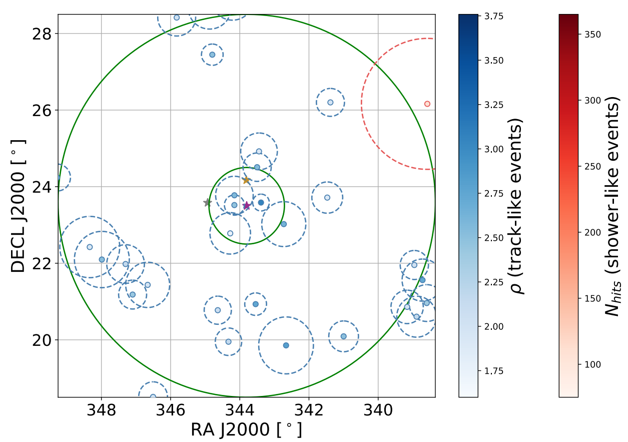
1142 G. Illuminati

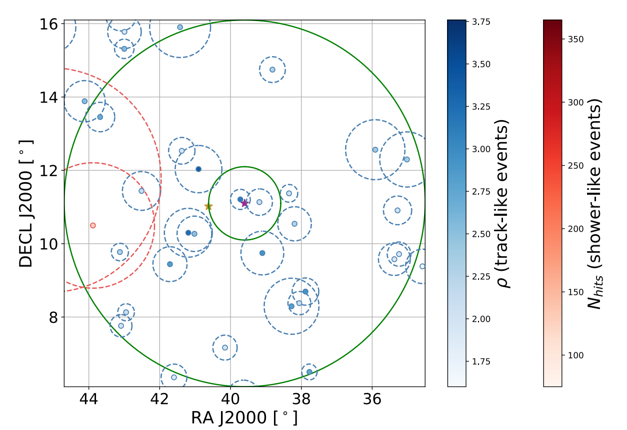
Updated: ANTARES 13 years (3845 days of live time): 10162 tracks and 225 showers



2nd most significant cluster:
RA=343.8° δ=+23.5°
pre trial: 4.2 σ
Close to blazar MG3 J225517+2409 (orange star)

The most significant cluster:
RA=39.6° δ=+11.1°
pre trial: 4.3 σ (48% post)
Within 1 degree of J0242+1101 (orange star)

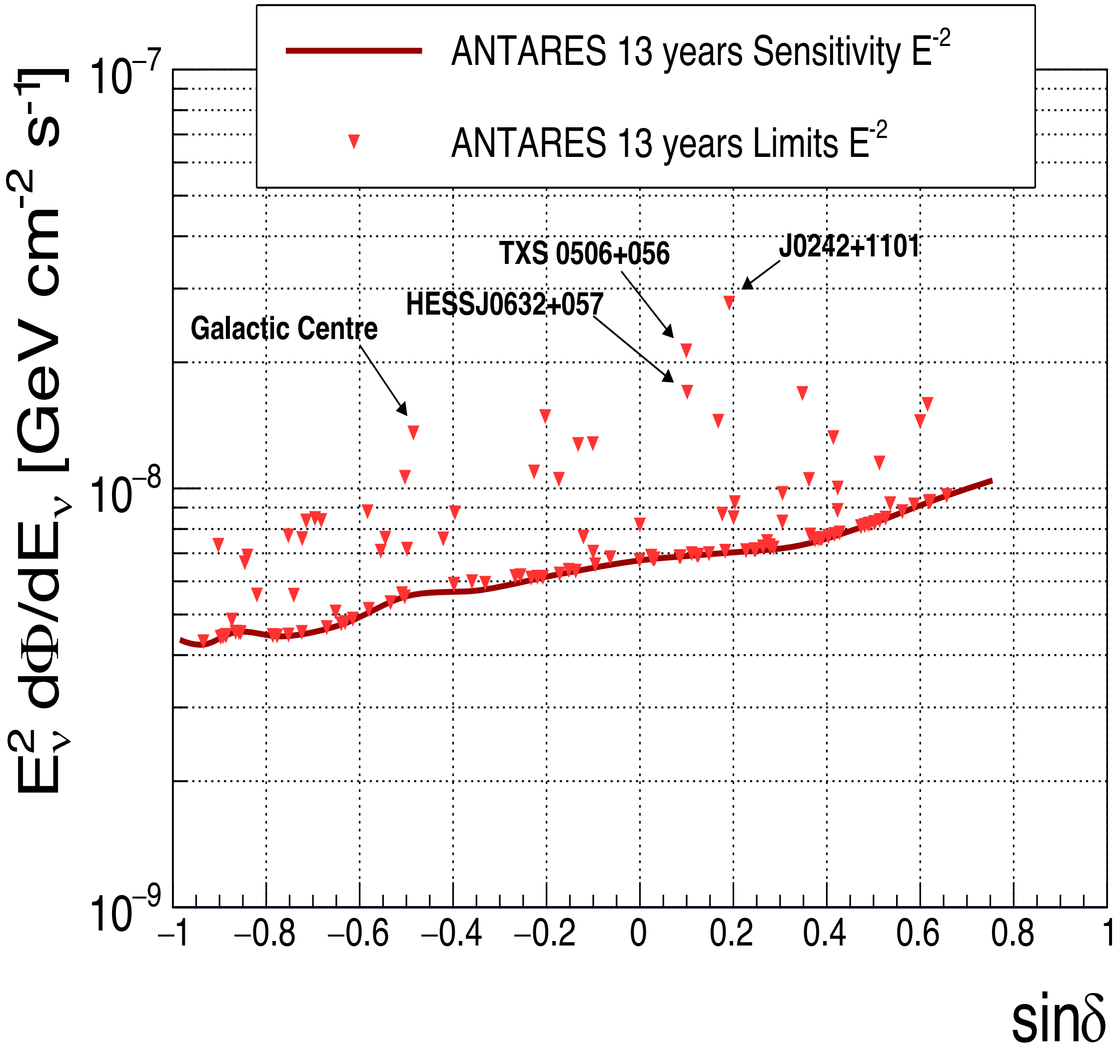




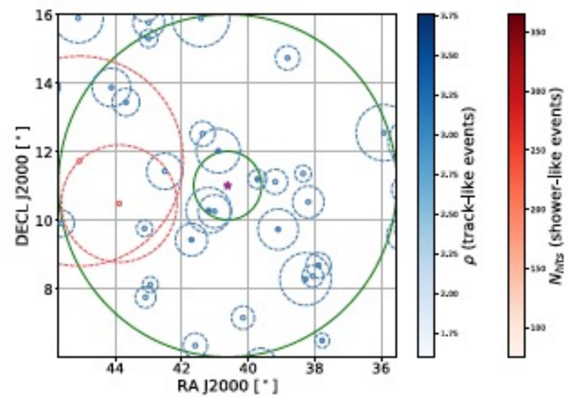
Candidate list

1142 G. Illuminati

121 sources investigated

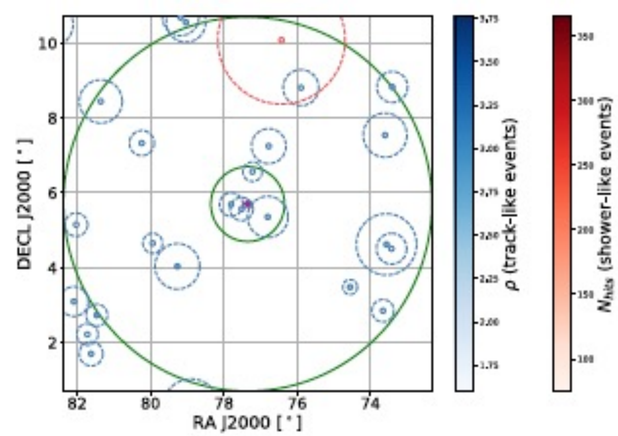


1st: J0242+1101



Pre (post) trial: 3.8σ (2.4σ)

2nd: TXS 0506+056



Pre (post) trial: 3.1σ (2.6σ)

4 muon events within 1°

Catalog-based stacking analyses

Catalog		p Pre-trial	P Post-trial	$\Phi^{UL}_{90\%}$ 10^{-9} $GeV^{-1}cm^{-2}s^{-1}sr^{-1}$	
Fermi 3LAC All Blazars		0.19	0.83	3.1	
Fermi 3LAC FSRQ		0.57	0.97	2.1	
Fermi 3LAC BL Lacs		0.09	0.64	4.6	MG3 J225517+2409
Radio Galaxies		$4.8\ 10^{-3}$	0.10	3.3	3C403 (2.5σ)
Star Forming Galaxies		0.37	0.93	1.9	
Obscured AGN		0.73	0.98	1.4	
IC High Energy Tracks		0.05	0.49	0.96	

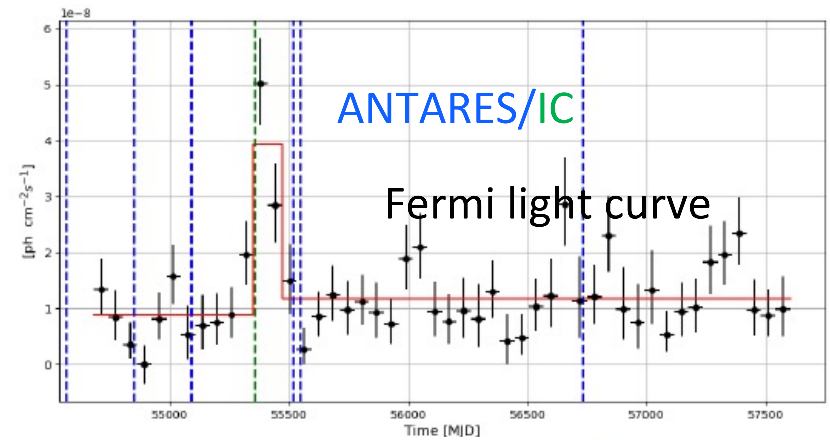
Blazar MG3 J225517+2409
Same optical and SED class as TXS 0506+056

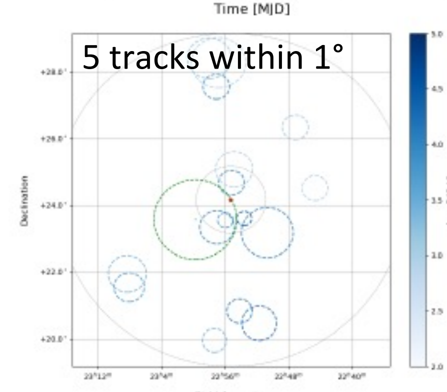
Coincident with second all-sky hotspot!

Source flare (~5 months) in Fermi 3FGL γ-ray light curve

One IC high-energy through-going track (ID#3) during the flare (July 2010)

5 ANTARES tracks + blazar : 2.3σ
IC track+blazar : 1.9σ
ANTARES+IC : 2.6σ





https://arxiv.org/abs/2012.15082

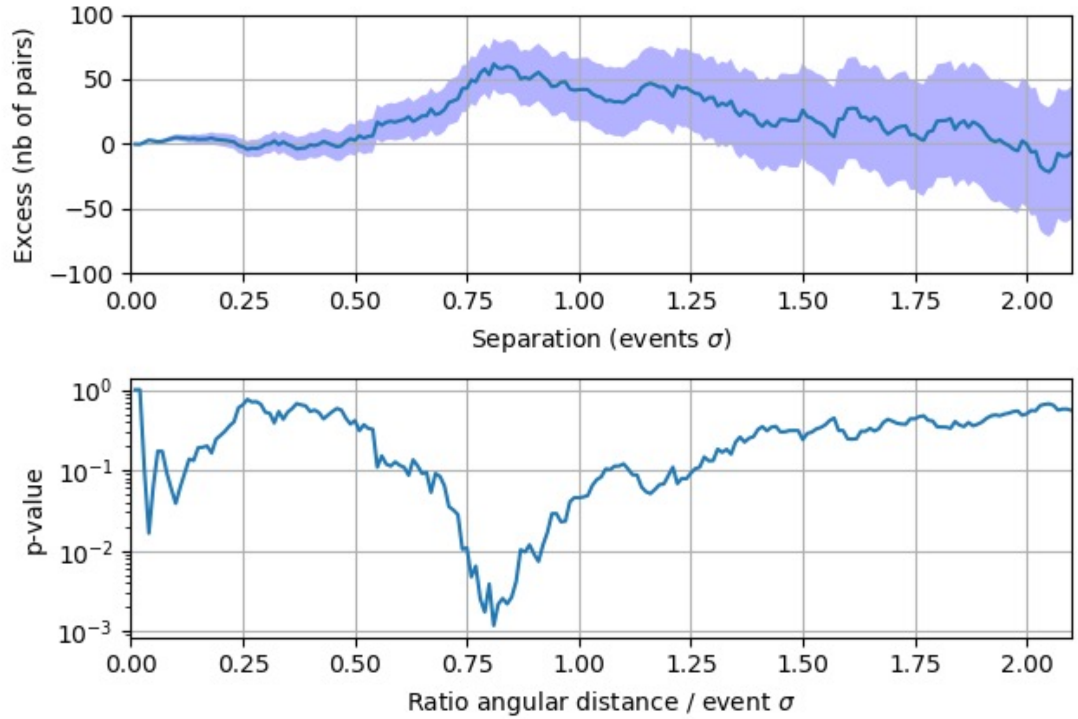
Radio loud blazars I

1240 J. Aublin

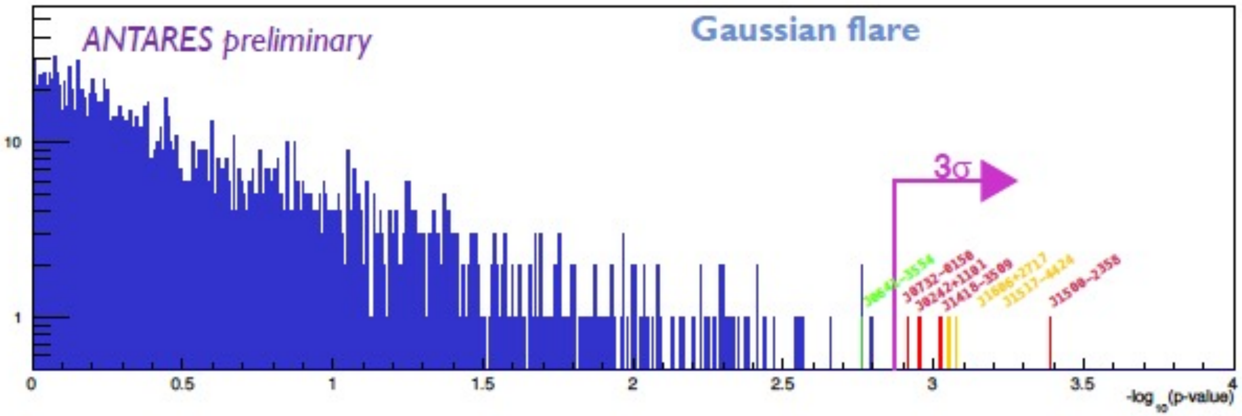
Inspired by A. V. Plavin et al, 2021 ApJ 908 157, search for correlation between IC neutrino candidates and radio blazars in VLBI data (2774 objects)

Use the ANTARES PS sample 2007-2020 (10162 tracks) with same stacking method yields a post-trial p-value of 2.2 10^{-2} (about 2.3 σ)

Simple pair counting shows indication of a collective excess of neutrino-blazar pairs at sub-degree angular scale (about 62 pairs in excess)

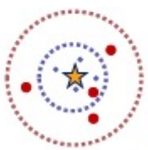


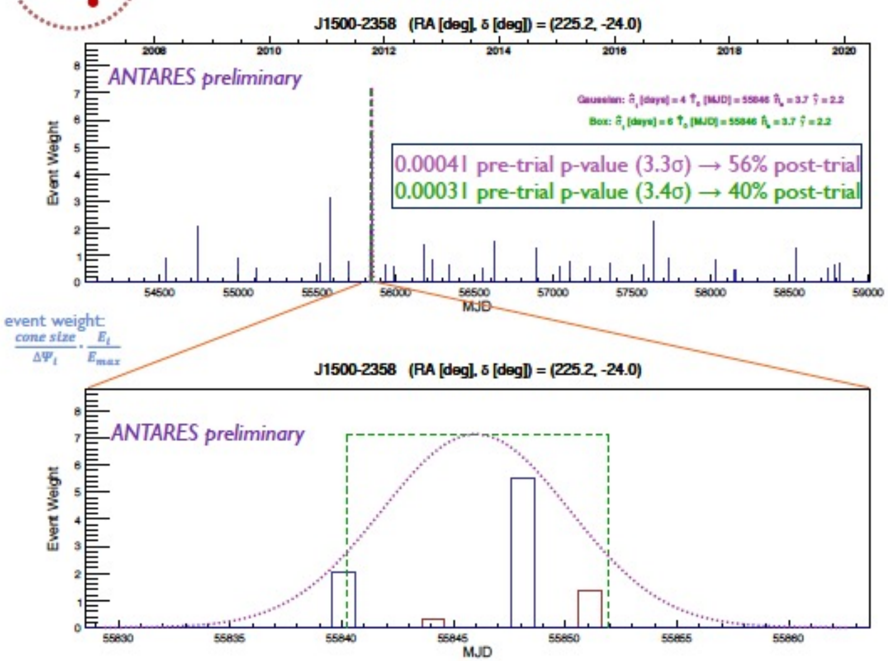
Radio loud blazars II

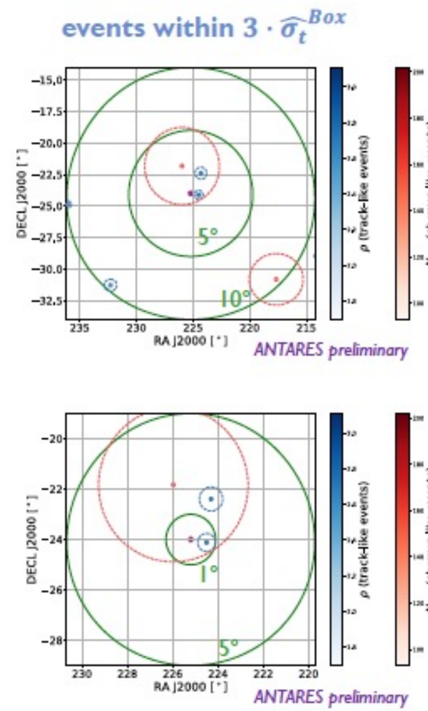


>3σ pre-trial
J1500-2358
J1517-4424
J1606+2717
J1418-3509
J0242+1101
J0732-0150
J0641-3554

J1500-2358





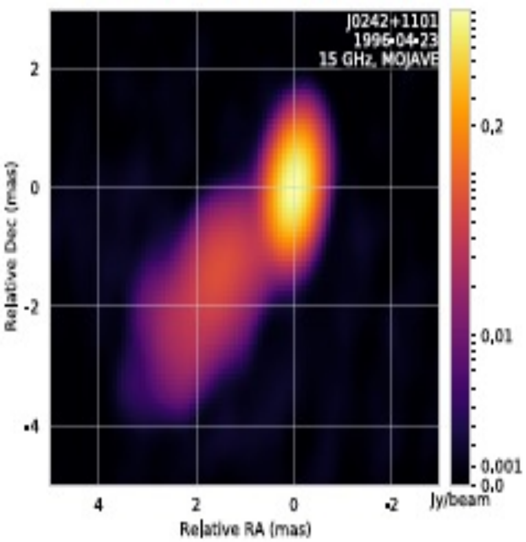


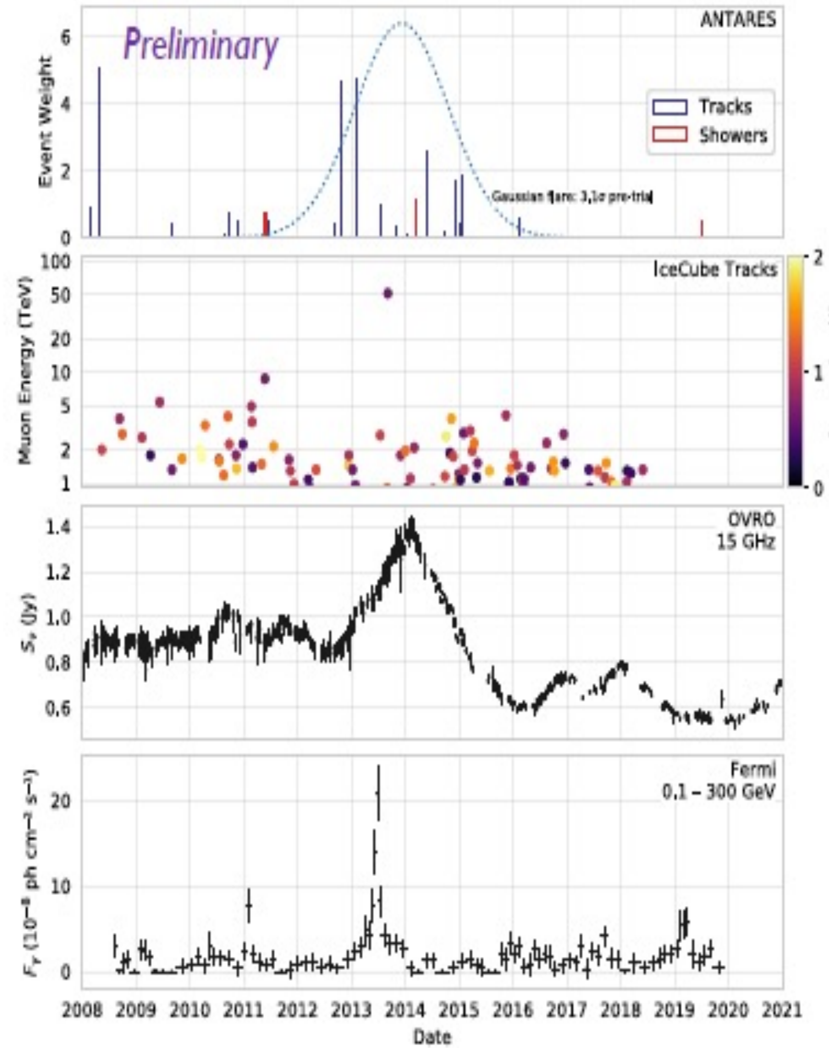
2 tracks
2 showers

J0242+1101: potential radio-γ-ν association

1137 G. Illuminati

VLBI image at 15 GHz





ANTARES best-fit flare for this source

IceCube tracks from 10-years point-source sample
- **Tracks within 90% angular error from source**
- **angular error < $10 deg^2$**

OVRO radio light-curve

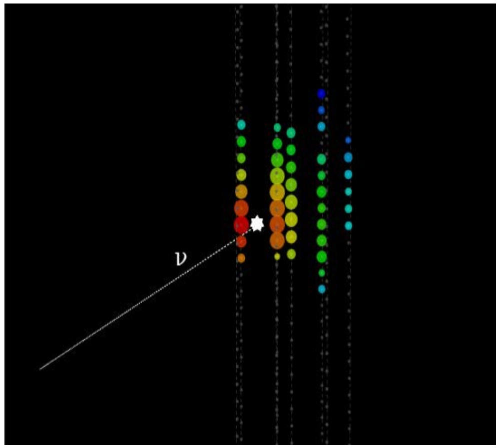
Adaptive binned gamma-ray light-curve obtained from Fermi LAT data

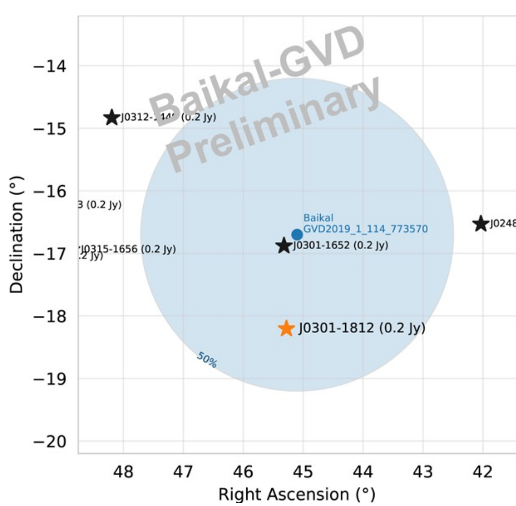
Chance probability of the multi-messenger association under study

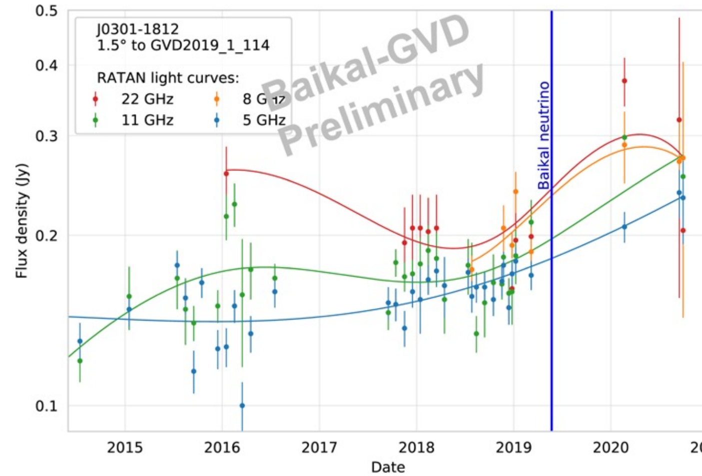
Baikal-GVD Cascade events

GVD2019_1_114_N

Radio blazar J0301-1812

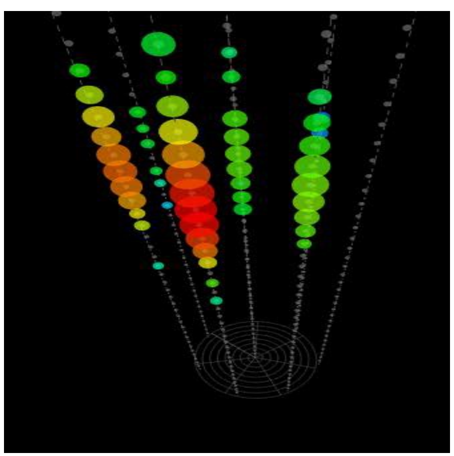


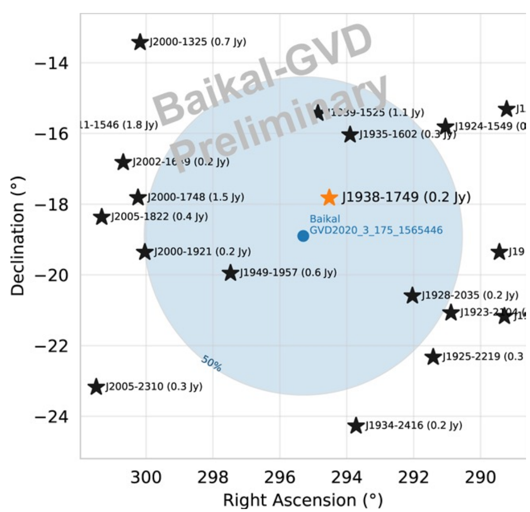


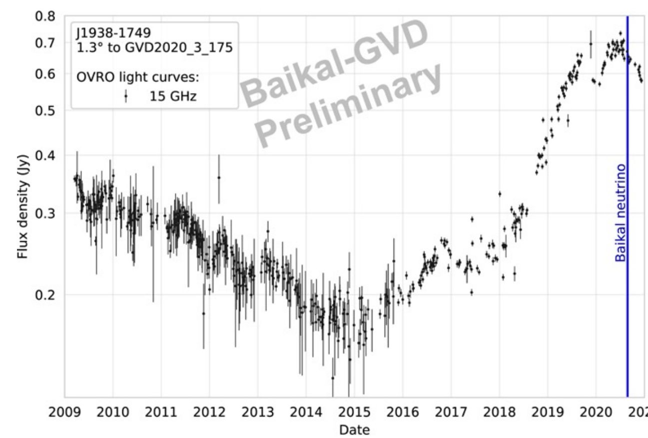


GVD2020_3_175_N

Radio blazar J1938-1749







GVD follow-up of ANTARES alerts

529 S. Alves

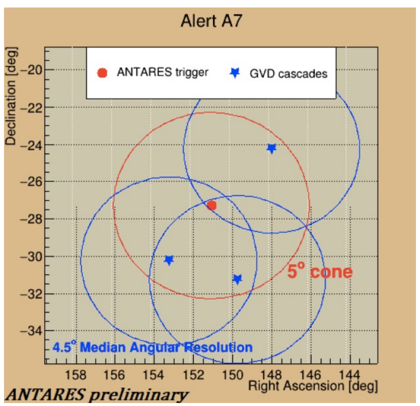
31 ANTARES alerts sent to GVD Baikal (5 clusters), 28 followed up:

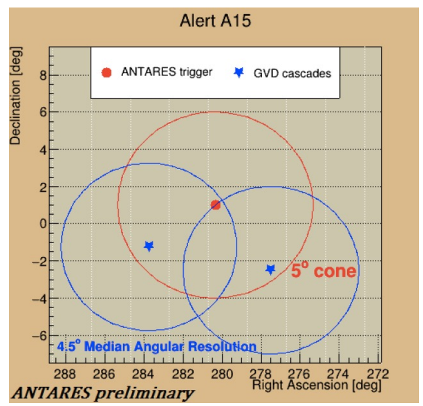
Search within ±500s, ±1hour, ±1 day within 5 degree

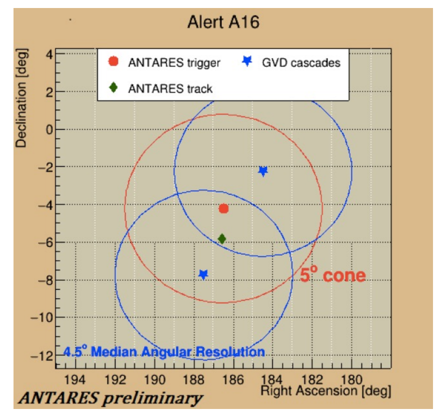
(cascade median resolution 4.5 degrees)

=> For 3 alerts multiplets of GVD cascades reconstructed within ±1 day

For 1 alert additional ANTARES track found within ±day







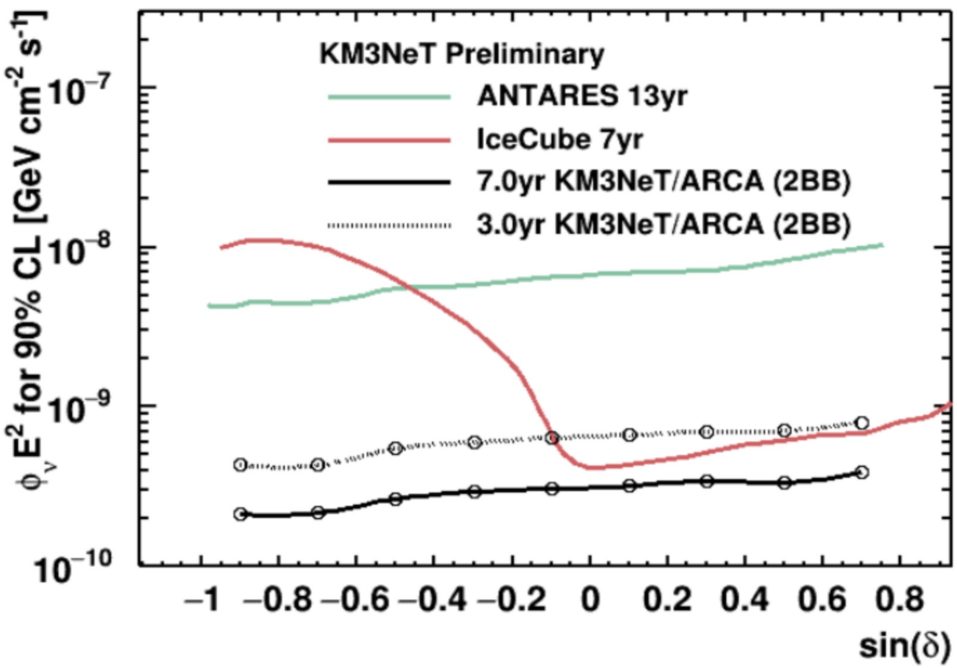
Expected background events/cluster/day ranging from 0.02-0.05

- No obvious source candidate close by

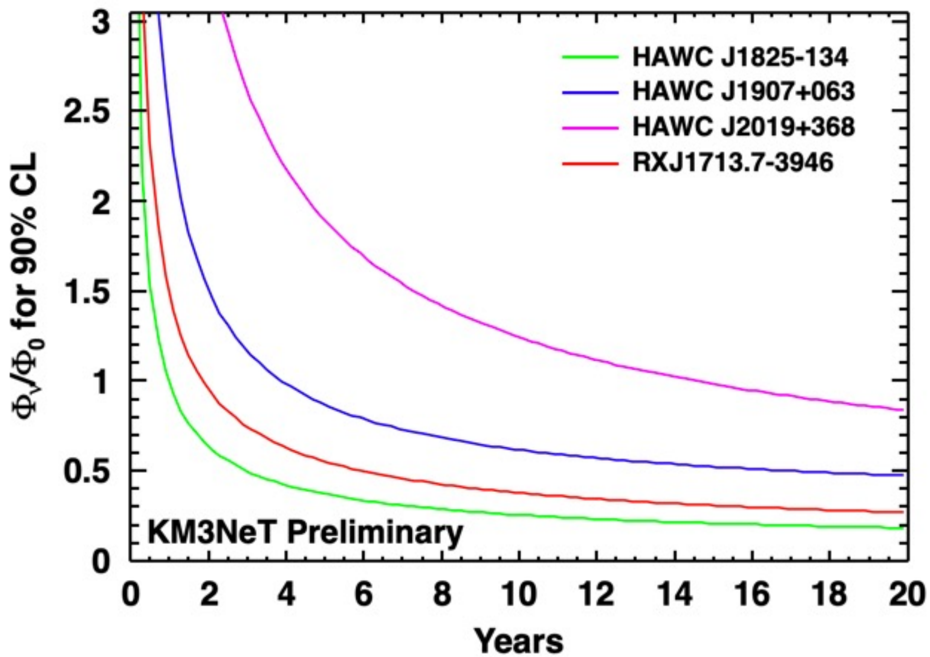
KM3NeT: sources

928 R. Muller

Point sources



Extended sources

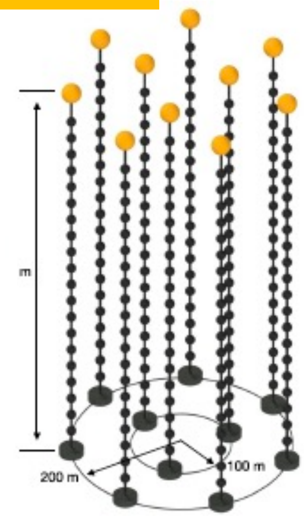


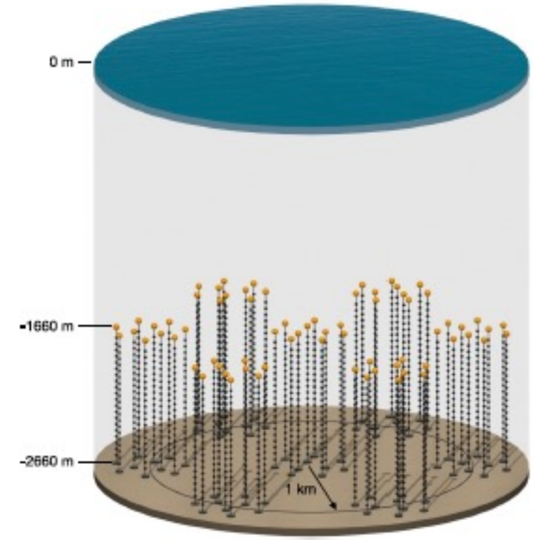
	Source	Decl, RA [°]	Ext [°]
— (red)	RXJ 713.7-3946	-39.77, 258.8	0.6 (disk)
— (green)	HAWC J1825-134	-13.37, 276.4	0.53 (Gauss)
— (magenta)	HAWC J2019+368	36.76, 304.92	0.356 (Gauss)
— (blue)	HAWC J1907+063	6.32, 286.91	0.67 (Gauss)

New initiative: Pacific Ocean Neutrino Explorer

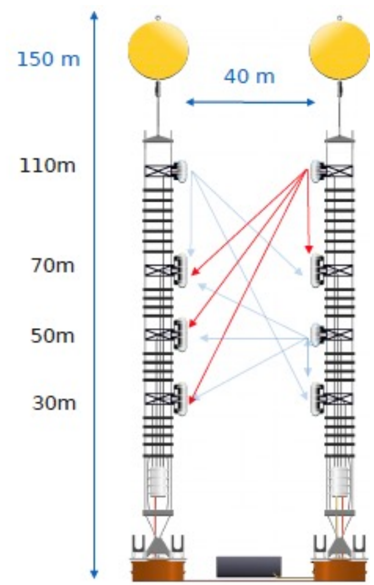
1272 E. Resconi
1138 C. Fruck, 1183 I. Carmen Rea, 1270 C. Spannfellner

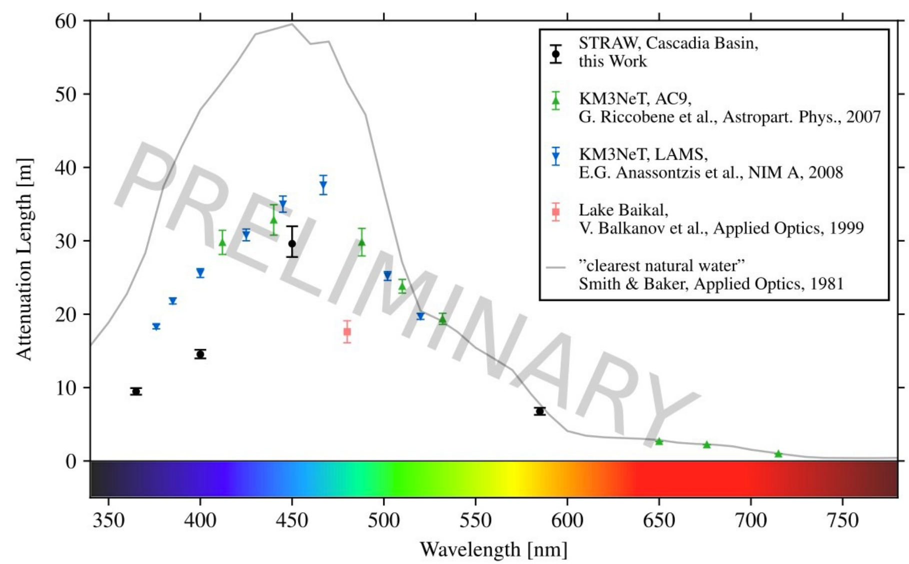
Images: Ocean Networks Canada





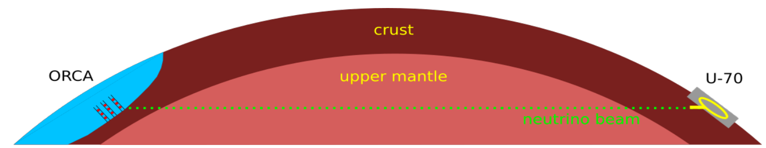
STRAW
STRAW-b
pathfinders



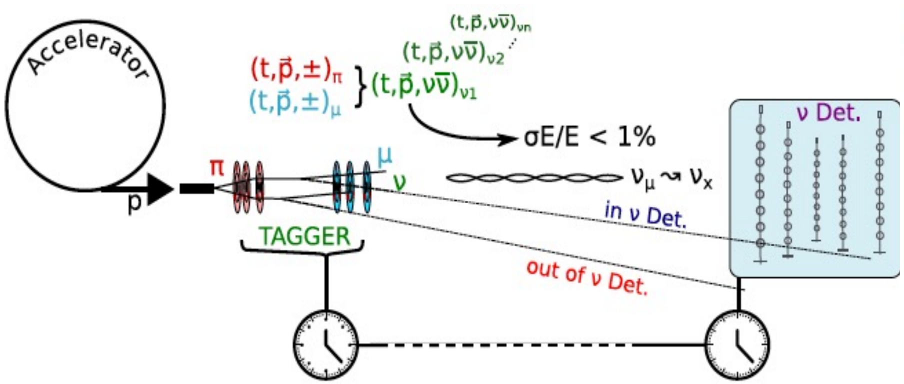


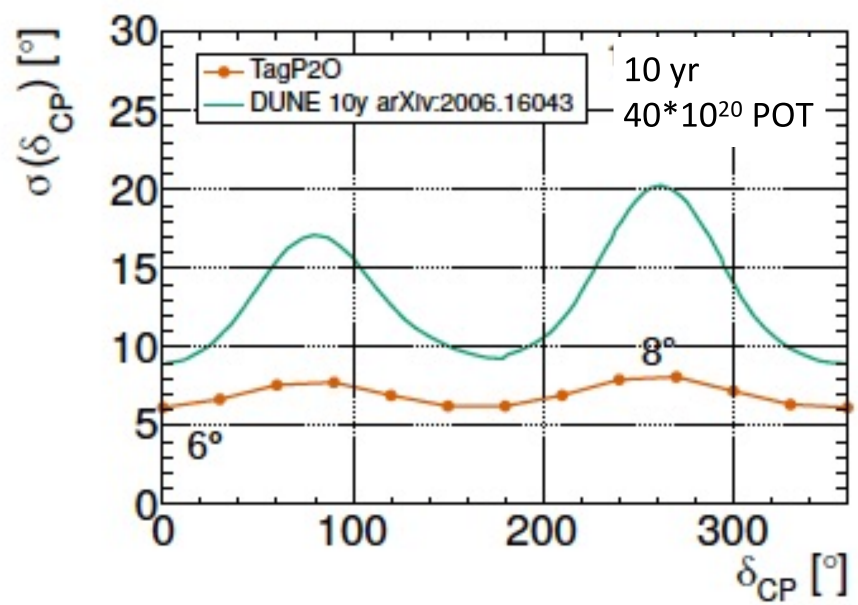
New idea: Tagged Protvino to ORCA

A. V. Akindinov et al.,
“Letter of Interest for a Neutrino Beam from Protvino to KM3NeT/ORCA"
https://arxiv.org/abs/1902.06083

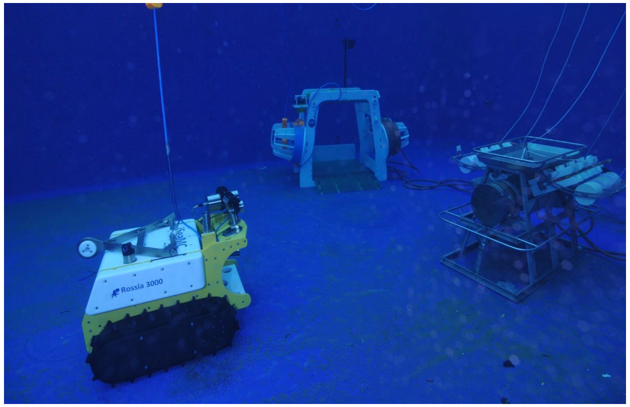


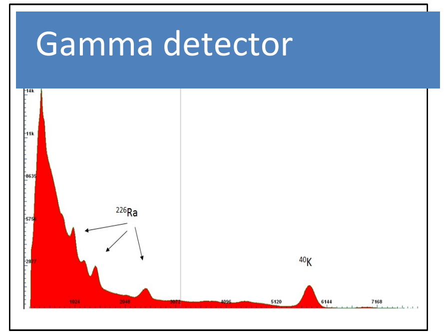
- Neutrino Beam from Protvino to ORCA
- Baseline 2590 km
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CPV
- LoI published: arXiv:1902.06083
- Huge detector -> relax beam power
- New idea - ν tagging at source:

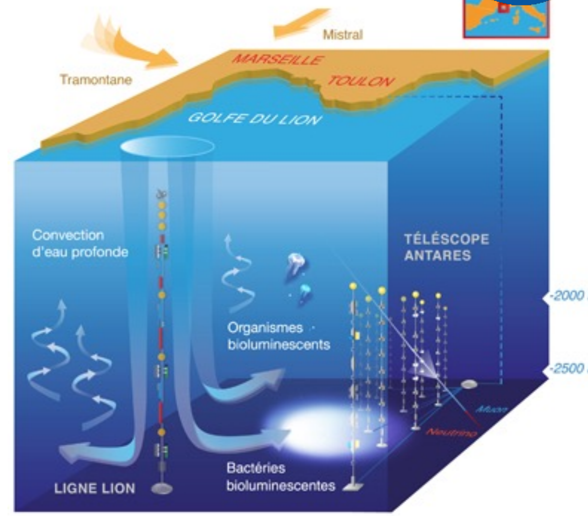


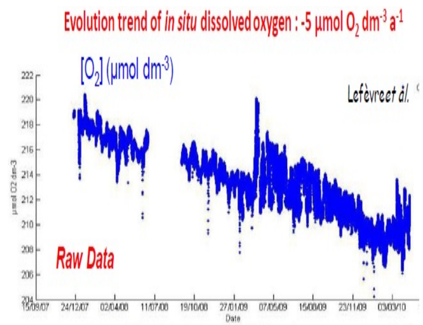


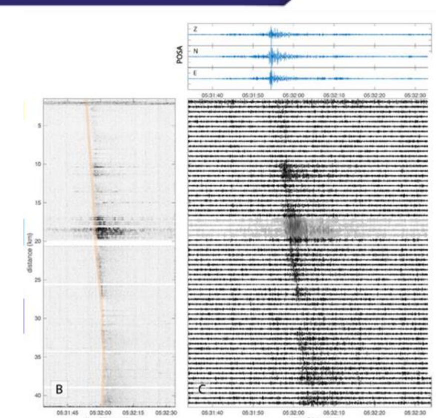
Earth and sea sciences

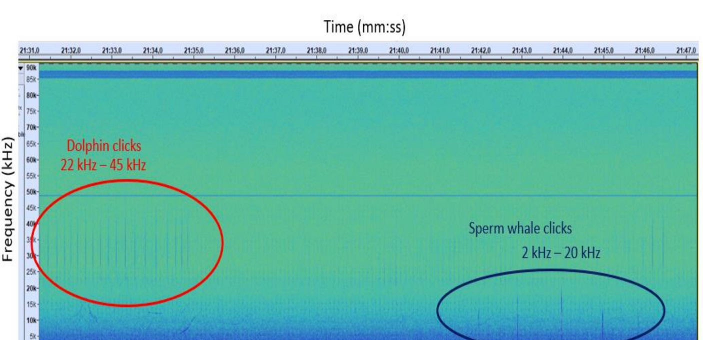


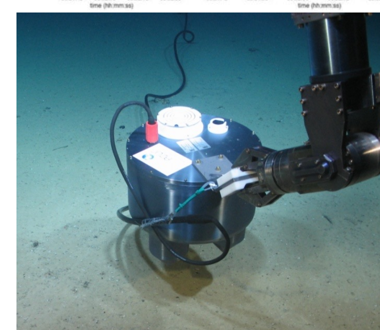












Conclusions and outlook

Water based detectors: angular resolution, multi-flavour astronomy, galactic sources

Intriguing indications of cosmic neutrino sources from ANTARES associated with radio loud and/or gamma blazar flares and IceCube HE energy events

- J0242+1101
- MG3 J225517+2409
- TXS 0506+056

Baikal-GVD and KM3NeT taking data and growing rapidly

GVD cascade events and radio-blazars

First measurement of neutrino oscillation parameters by ORCA6

New ideas in gestation

- P2O
- P-ONE

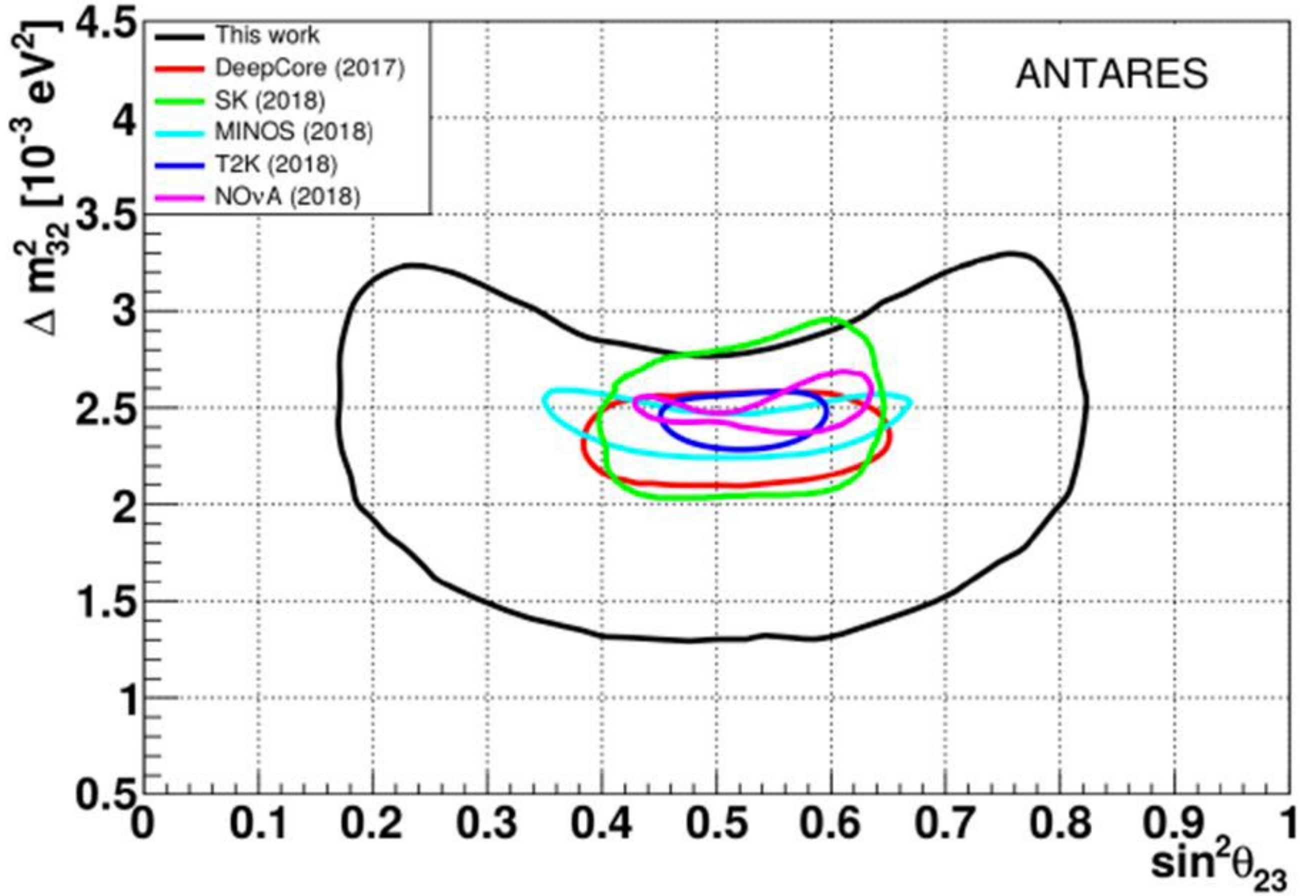
Looking forward to interesting results at the next ICRC!

BACKUP

ANTARES: neutrino oscillations

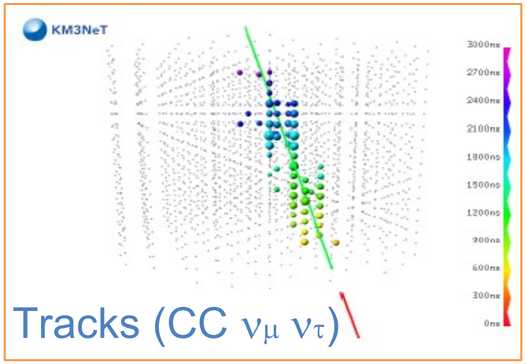
First oscillation measurement with a very large neutrino telescope

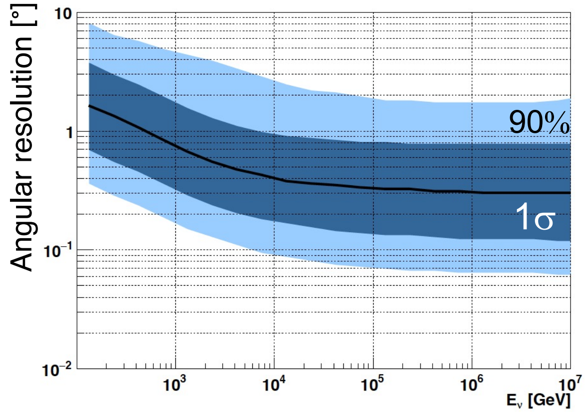
J. High Energ. Phys. (2019) 2019:113

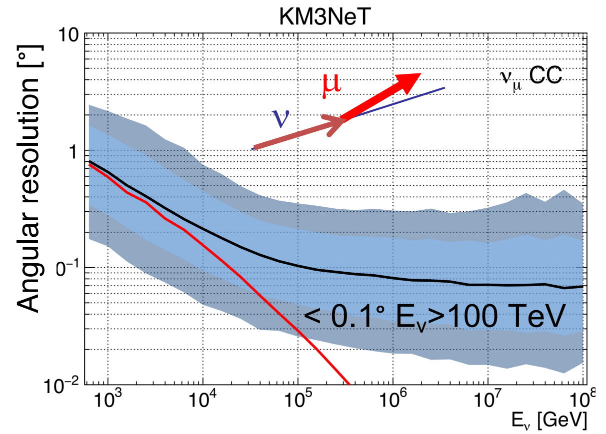


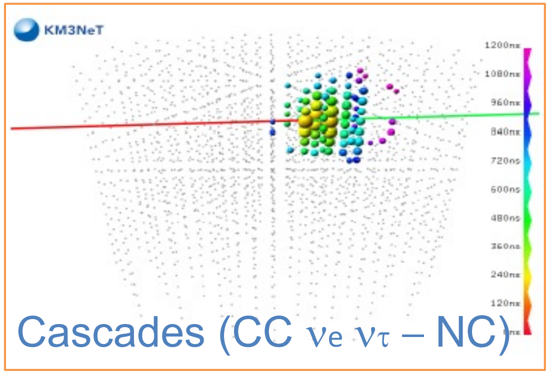
Angular resolutions I

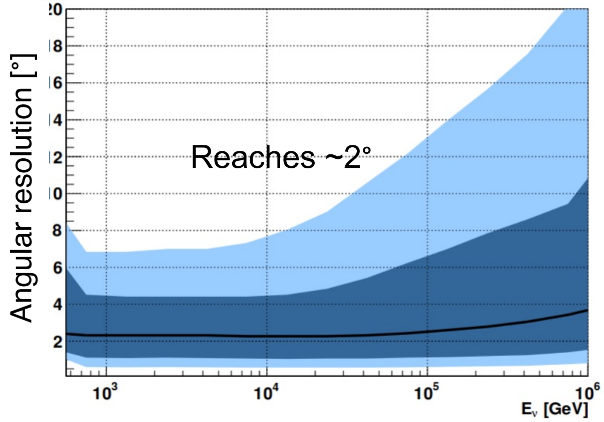
ANTARES | KM3NeT

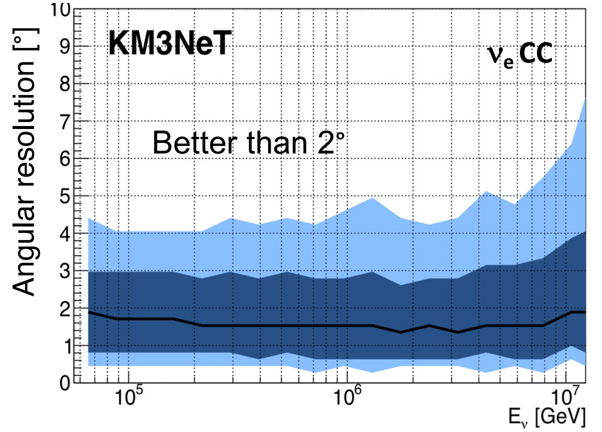




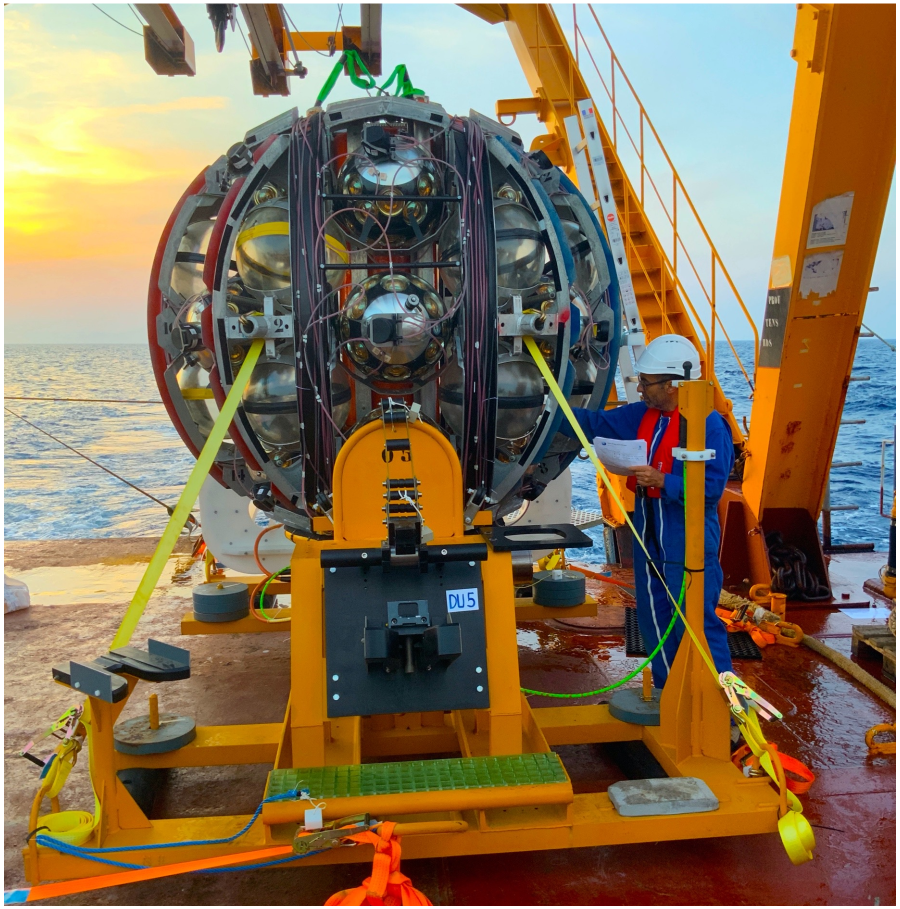


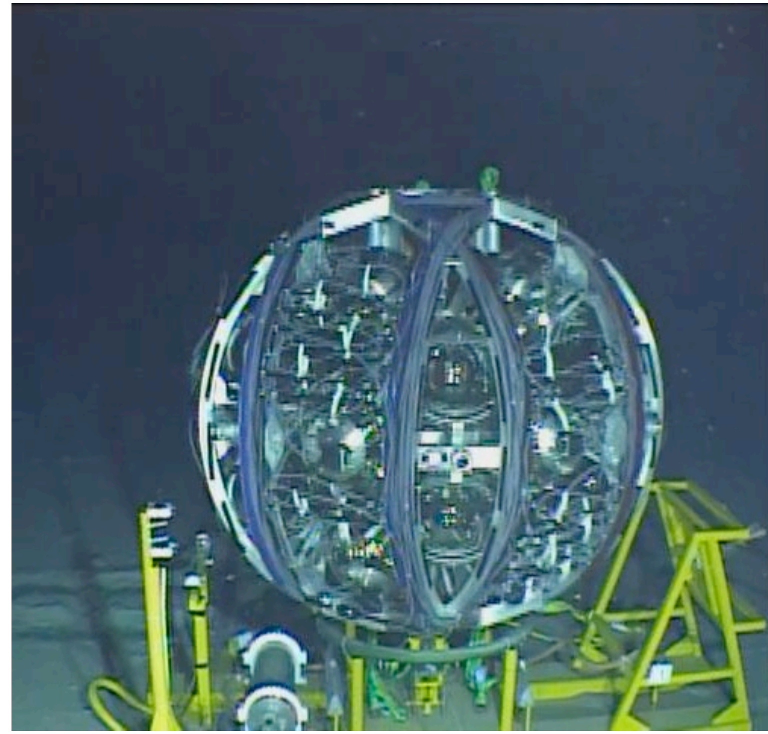


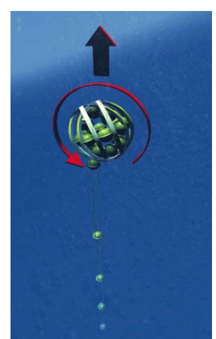




KM3NeT deployment



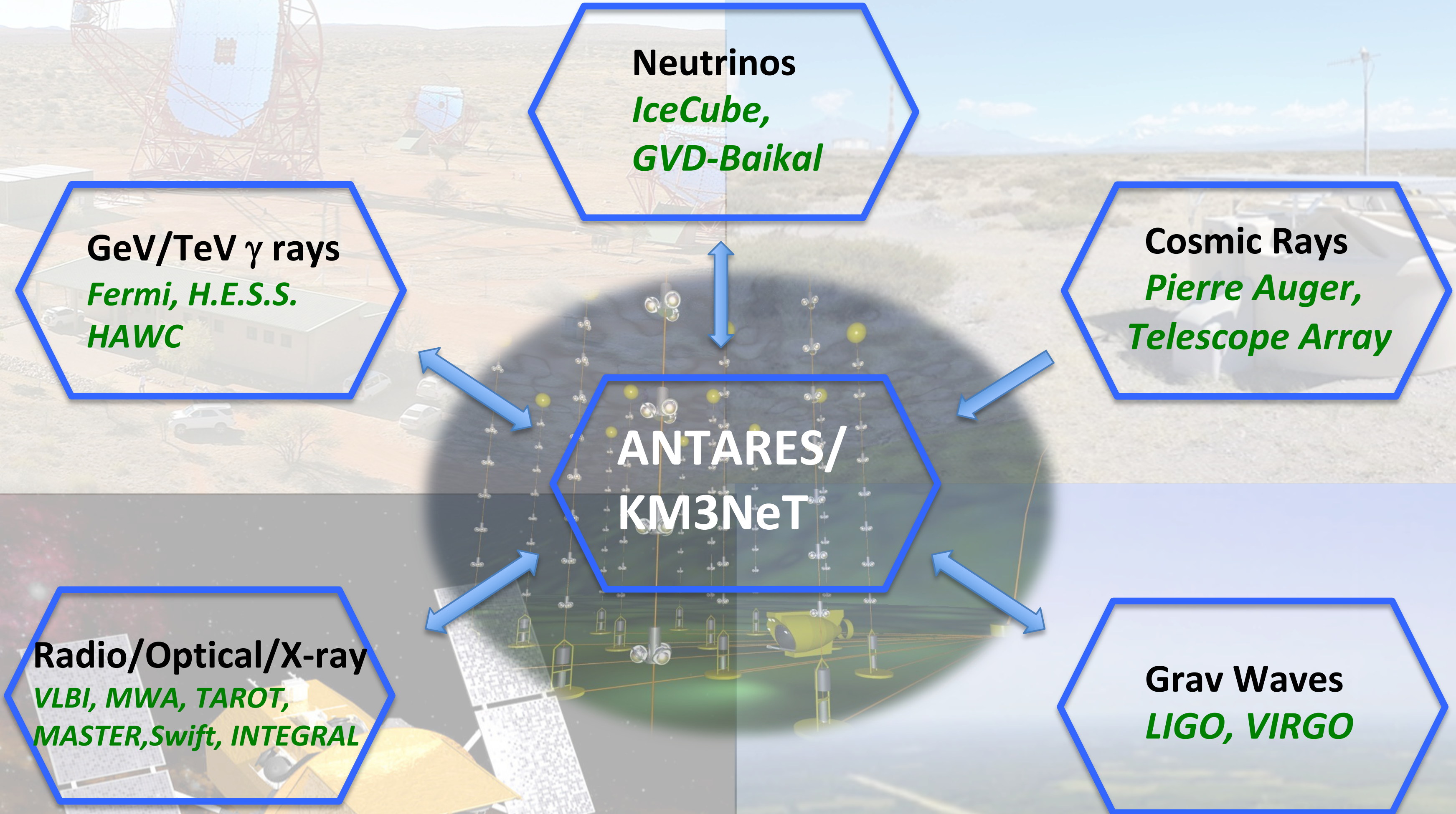




- Rapid deployment
- Multiple strings/sea campaign
- Autonomous/ROV unfurling
- Reuseable

Multi-messenger network

1279 F. Huang

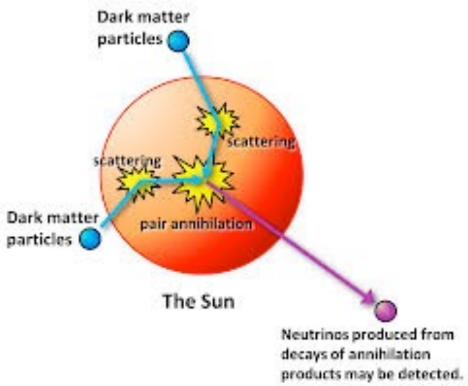


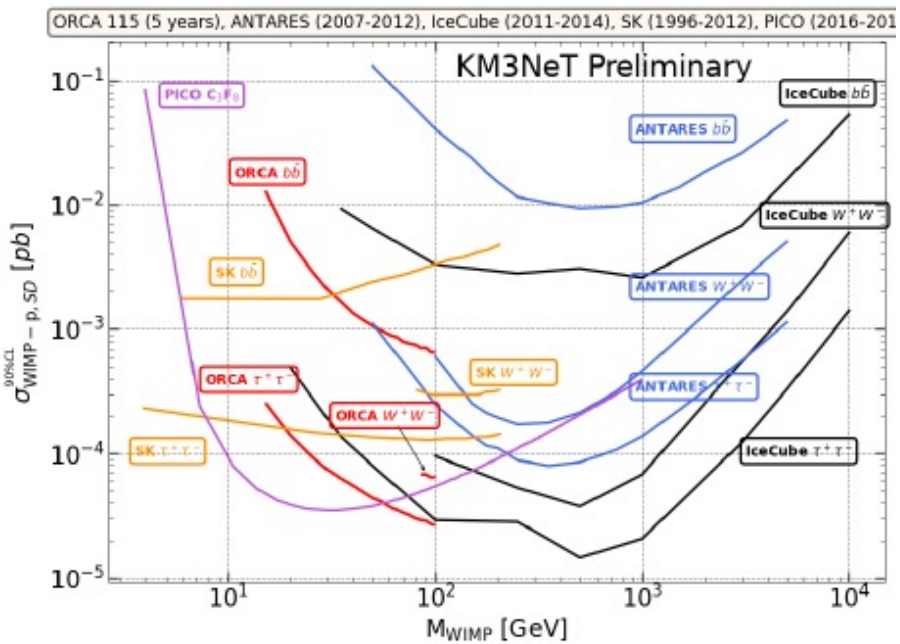
ANTARES real-time alerts

- Time to send alert 5s, median resolution 0.5deg
- A few 10 alerts per year sent

Dark matter-indirect detection

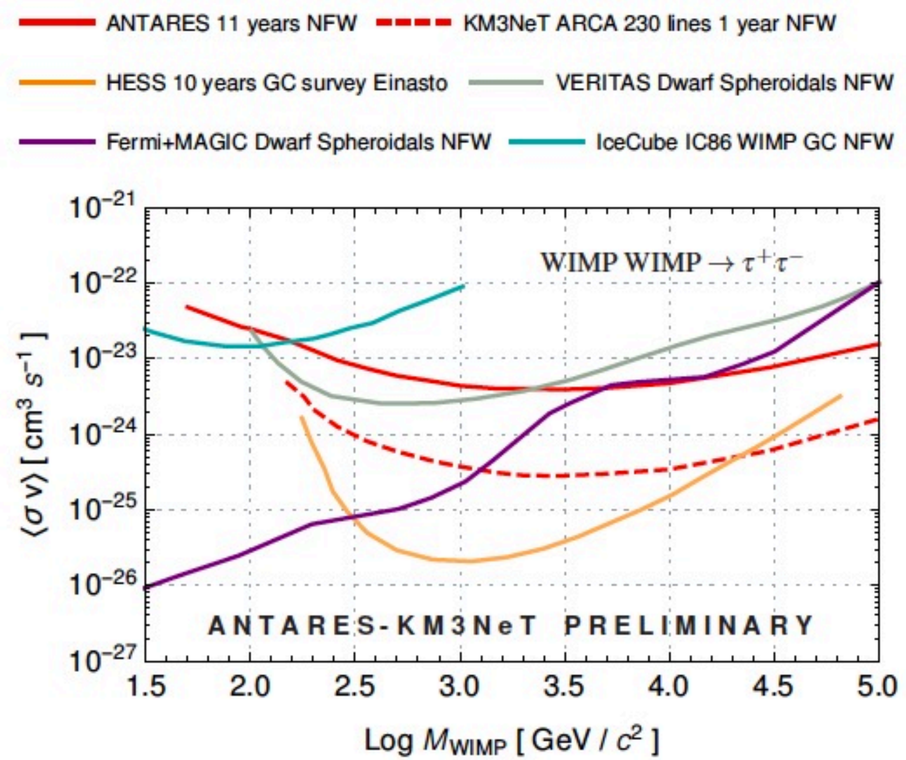
Sun
613 C. Poire





Phys.Lett. B759 2016

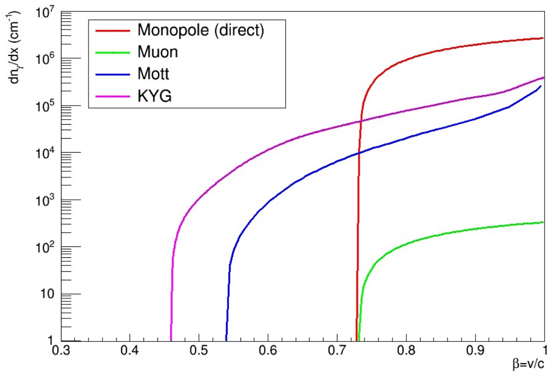
Galactic Centre
1207 R. Gozzini

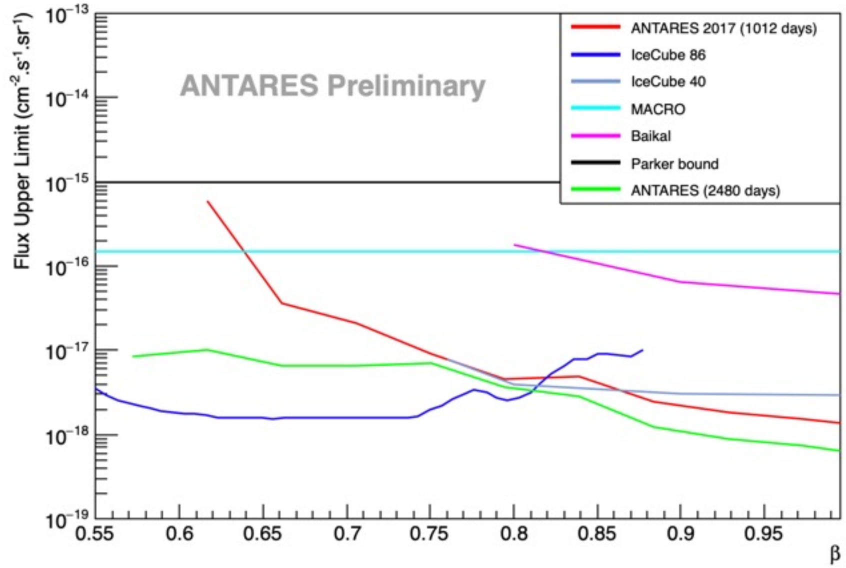


Phys. Lett. B 805 135439 (2020)

Magnetic monopoles/Nuclearites

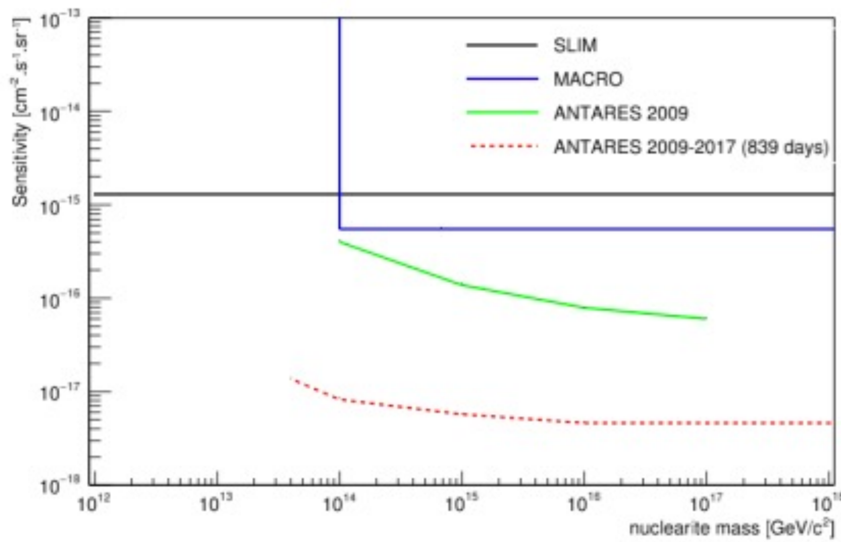
Magnetic monopoles **635 J. Boumaaza**





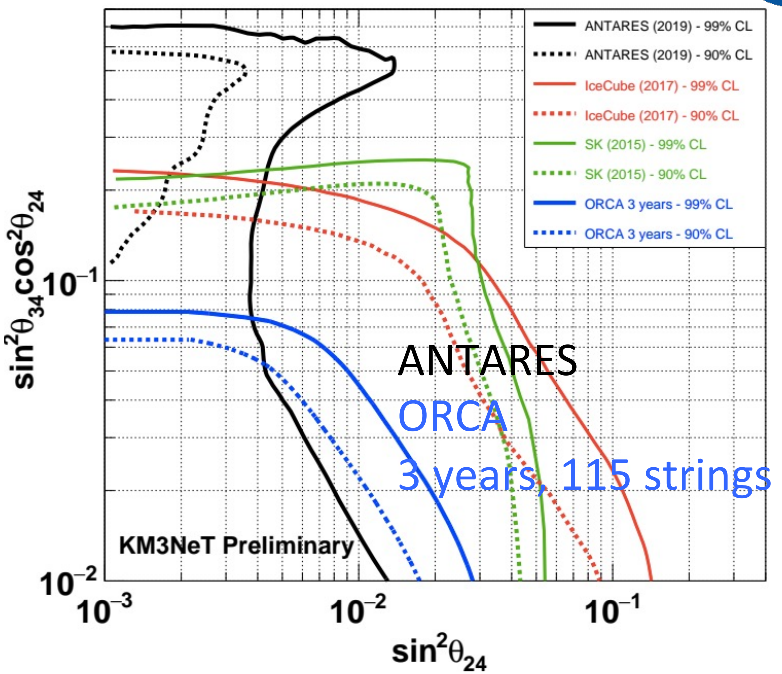
Nuclearites **775 M. Boula**
1040 A. Paun

massive nuggets of strange quark matter

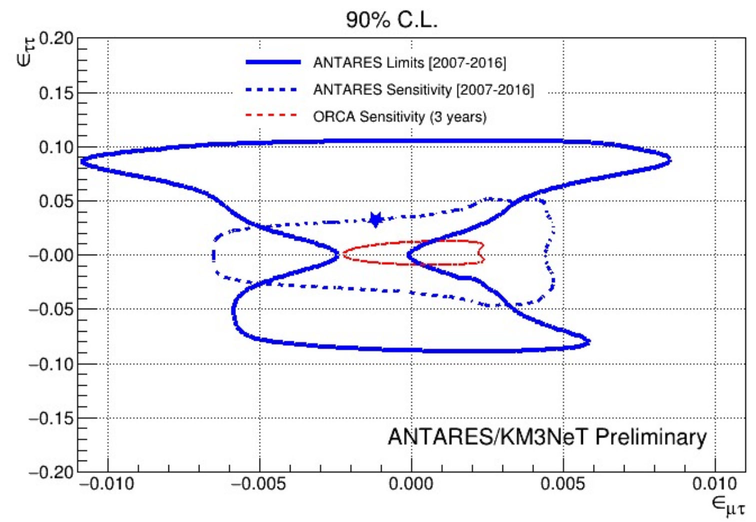


Sterile neutrinos and non-standard interactions

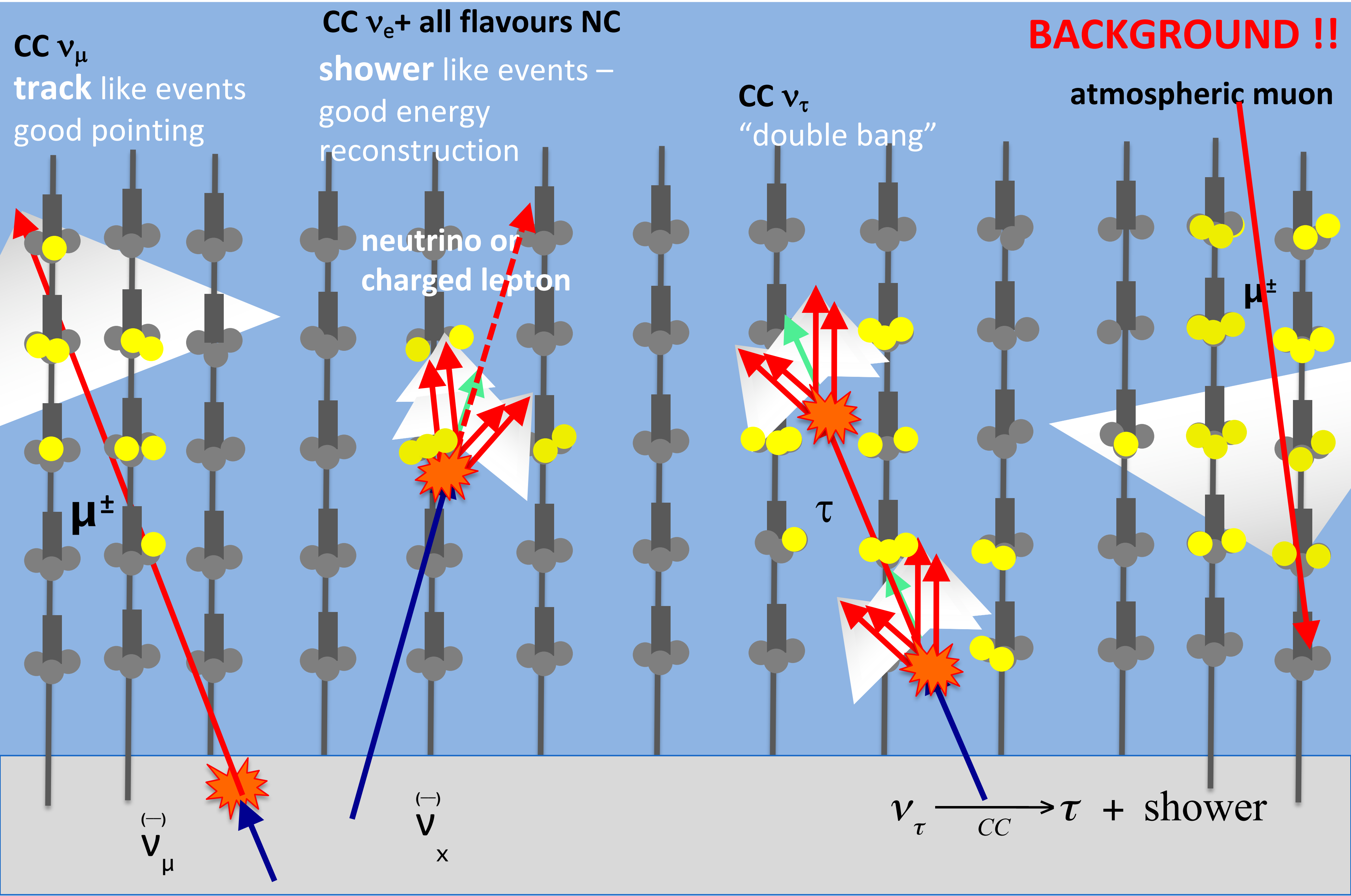
- (3+1) sterile neutrino models Δm_{41} ~$[10^{-4}–1]$ eV^2
- For $\Delta m_{41} < 0.1$ eV tight complementary information to eV-scale sterile neutrino searches



- Similarly non-standard interactions signature in neutrino oscillation pattern detectable
- Best fit $\varepsilon_{\tau\tau} > 0$
  -> similar as in sterile neutrino analysis
  with best fiit at $\theta_{34} > 0$



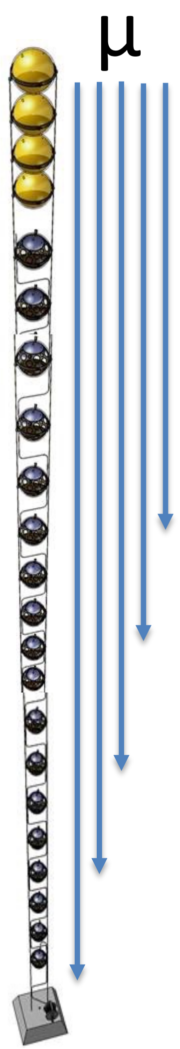
Event topologies

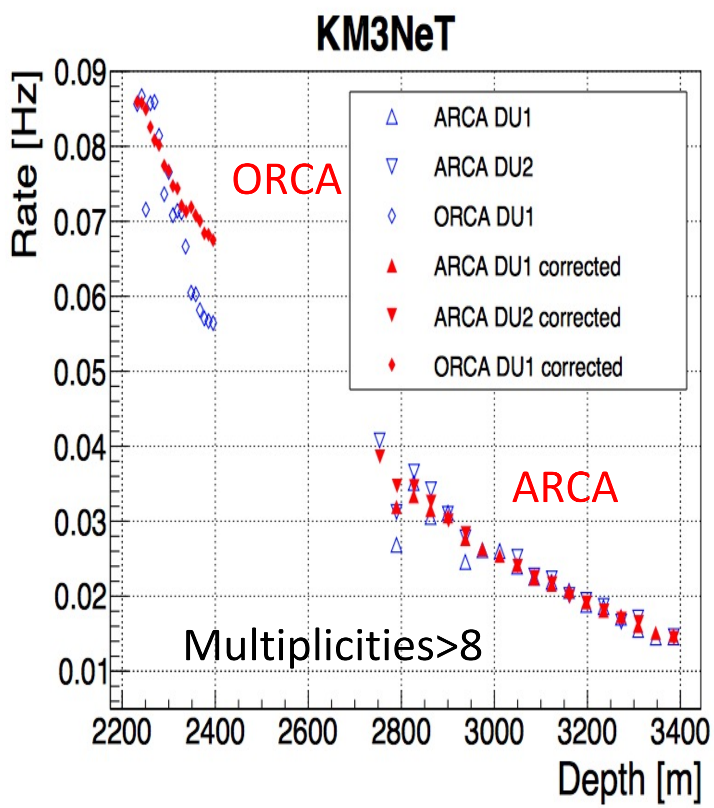


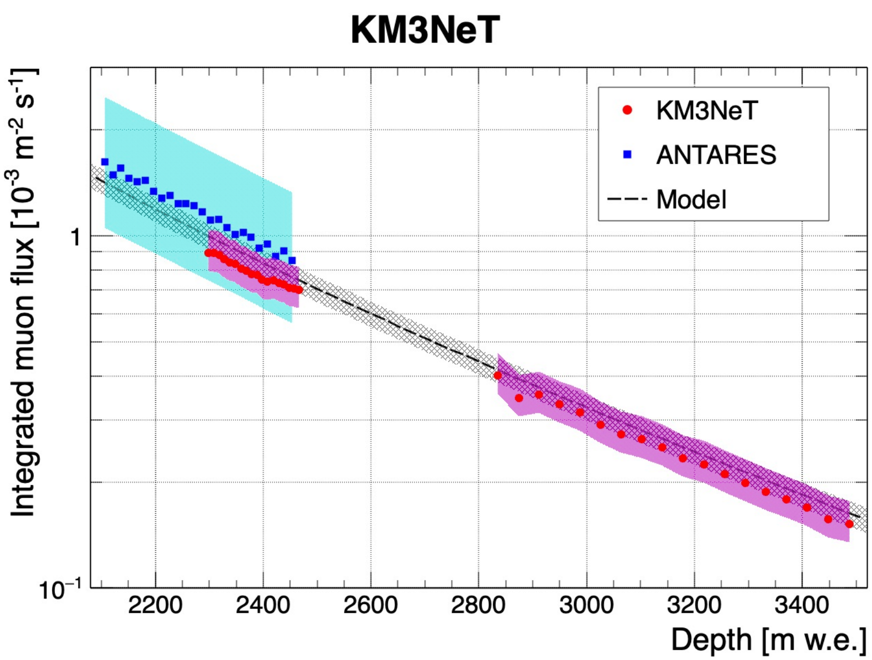
Muon depth dependence

2 DUs of ARCA (23/12/2016-2/3/2017) &
1 DU of ORCA (9/11/2017-13/12/2017)

Muon flux as function of depth compared to Bugaev model (Bugaev et al, Phys. Rev. D 58 1998 054001)





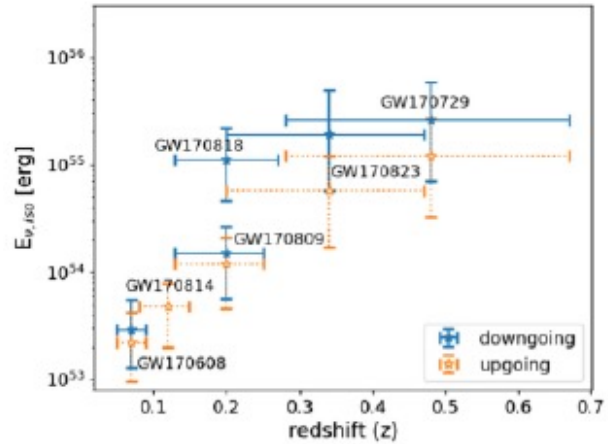


https://arxiv.org/pdf/1906.02704.pdf

PMT detection efficiency calibration verified

Some other searches

Gravitational waves



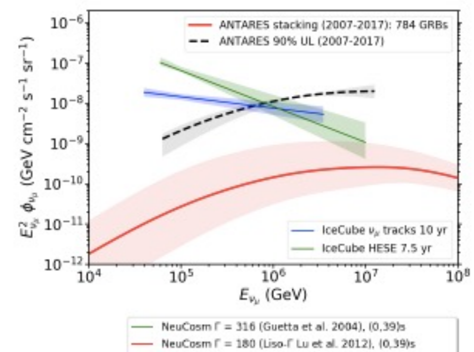
Gamma ray bursts

Stacking analysis of 784 GRBs
ANTARES data 2007-2017

- No coincidences found
- GRBs contribute <10% of astrophysical flux <100TeV

Flash Talk A. Zegarelli

MNRAS, 500, 5614–5628 (2021)



Tidal disruption events

Source		Results						
Name	γ	$\hat{\mu}_{sig}$	p-value	$\Phi_0^{90\%C.L.}$ sensitivity	$\Phi_0^{90\%C.L.}$ limit	$\mathcal{F}^{90\%C.L.}$ sensitivity	$\mathcal{F}^{90\%C.L.}$ limit	$\log(\frac{E_{min}}{GeV})$ - $\log(\frac{E_{max}}{GeV})$
AT2019dsg	2.0	< 0.1	12%	7.3×10^{-8}	1.0×10^{-7}	14	19	3.6 - 6.6
	2.5	0.2	10%	1.5×10^{-5}	2.2×10^{-5}	29	43	2.8 - 5.5
	3.0	0.7	8.9%	1.2×10^{-3}	2.0×10^{-3}	230	380	2.1 - 4.7
AT2019fdr	2.0	0.5	6.7%	8.5×10^{-8}	1.3×10^{-7}	15	23	3.6 - 6.6
	2.5	0.5	7.9%	2.1×10^{-5}	3.0×10^{-5}	39	55	2.8 - 5.5
	3.0	0.6	9.1%	2.0×10^{-3}	3.0×10^{-3}	360	540	2.1 - 4.7

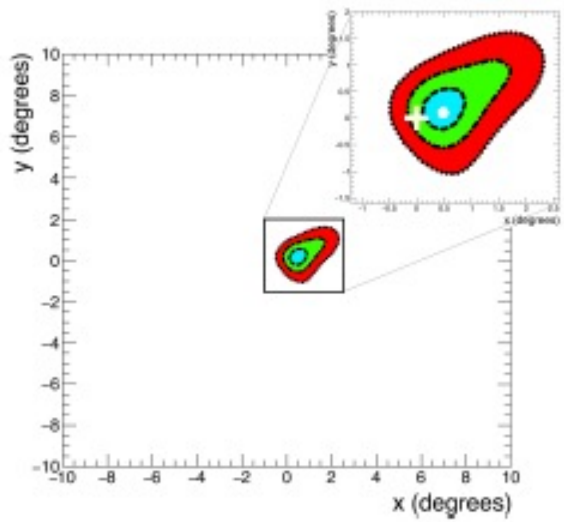
ORCA6: neutrino fit systematics uncertainties

Parameter	Treatment	Fit value
Δm^2_{31} $[10^{-3}\ \text{eV}^2]$	Free	$1.95^{+0.24}_{-0.21}$
θ_{23} [deg]	Free	$45.4^{+5.6}_{-5.7}$
Norm	Free	$0.88^{+0.03}_{-0.11}$
Flux: spectral index	$\mathcal{N}(0, 0.3)$	$0.052^{+0.053}_{-0.010}$
Flux: zenith angle bias	$\mathcal{N}(0, 0.07)$	$0.035^{+0.059}_{-0.060}$
Skew $\mu \overline{\mu}$	$\mathcal{N}(0, 0.1)$	$0.00^{+0.10}_{-0.10}$
Skew $e/\overline{e}$	$\mathcal{N}(0, 0.1)$	$0.00^{+0.10}_{-0.10}$
Skew μe	$\mathcal{N}(0, 0.03)$	$0.00^{+0.03}_{-0.03}$
NC normalization	$\mathcal{N}(1, 0.1)$	$0.99^{+0.10}_{-0.10}$
τ normalization	$\mathcal{N}(1, 0.2)$	$0.97^{+0.20}_{-0.20}$
Energy scale	$\mathcal{N}(0, 0.1)$	$0.00^{+0.03}_{-0.01}$

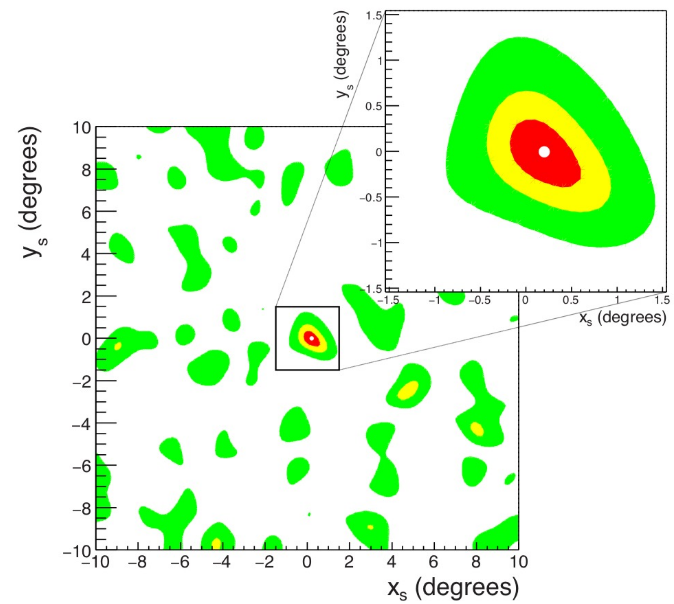
Absolute Pointing

The Sun shadow is also observed with a statistical significance of 3.7σ, and an angular resolution of 0.59° ± 0.10° for downward-going muons.

2007-2017 data



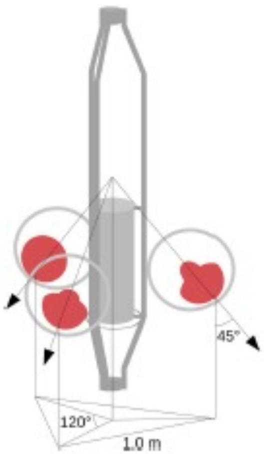
Eur.Phys. J. C78 (2018) no.12, 1006

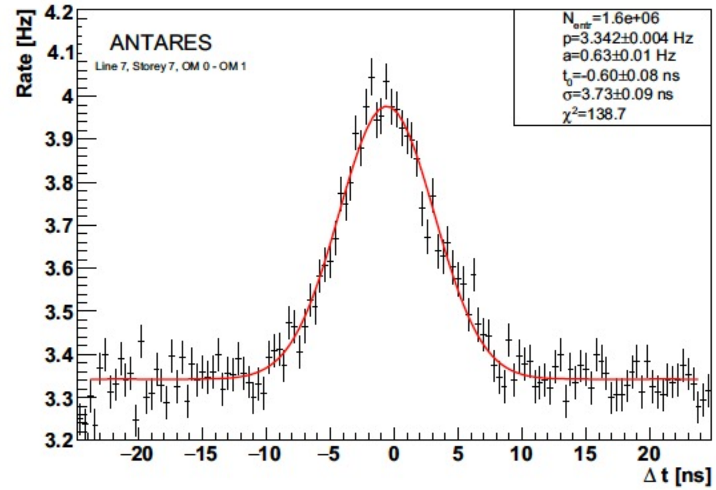


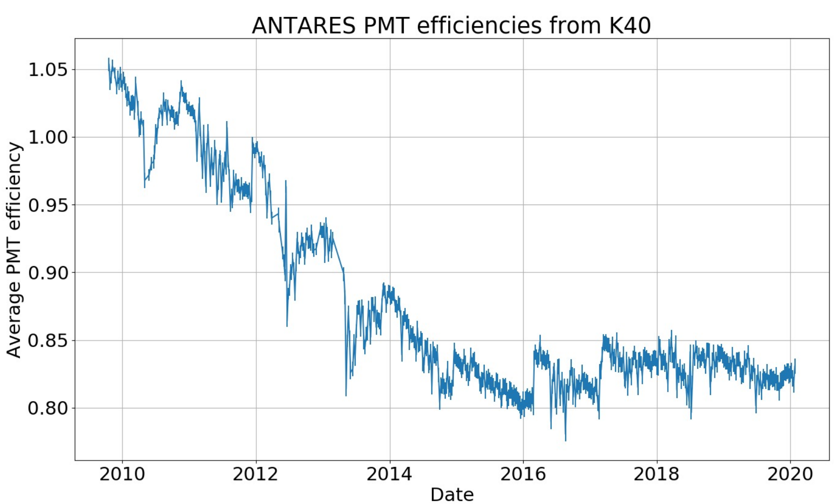
Phys. Rev. D 102, 122007 (2020)

^{40}K: Inter-PMT Calibration

40K powerful calibration tool



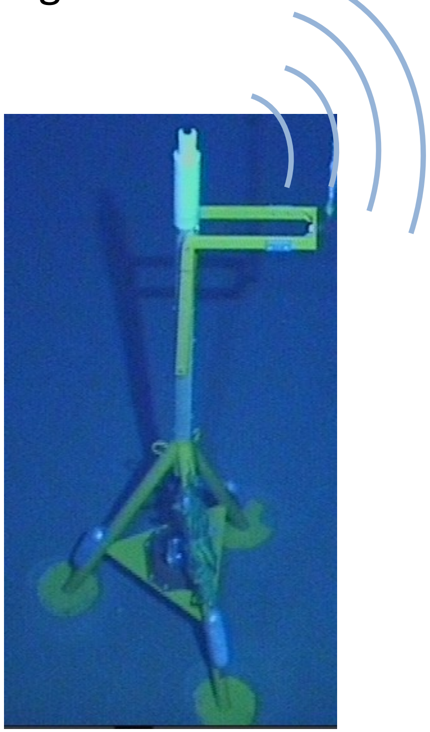


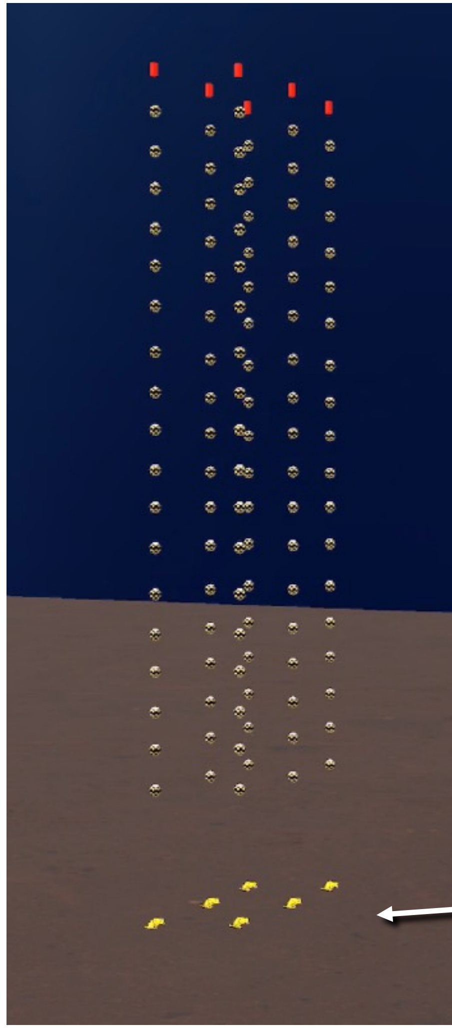


Regular tunings
Only ~20% efficiency loss after 5 years then stabilised

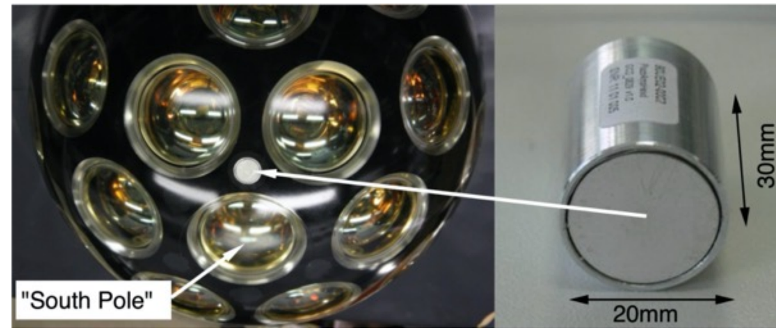
Acoustic position calibration in KM3NeT

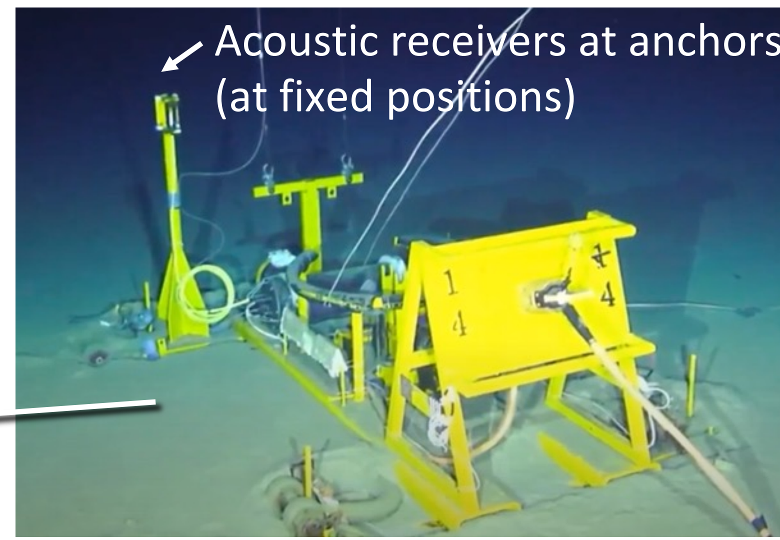
Several acoustic beacons located at fixed positions around detector emit pulse sequences at regular intervals





Acoustic receivers in DOMs (swaying in sea currents)

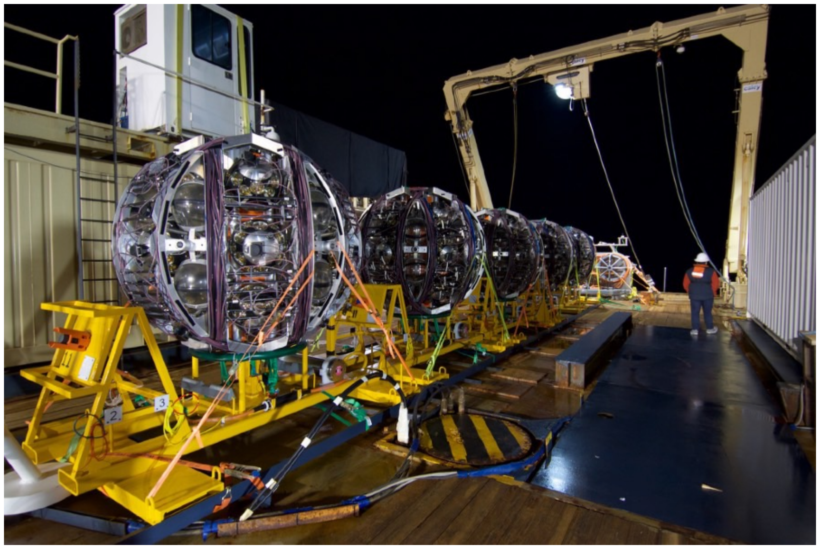


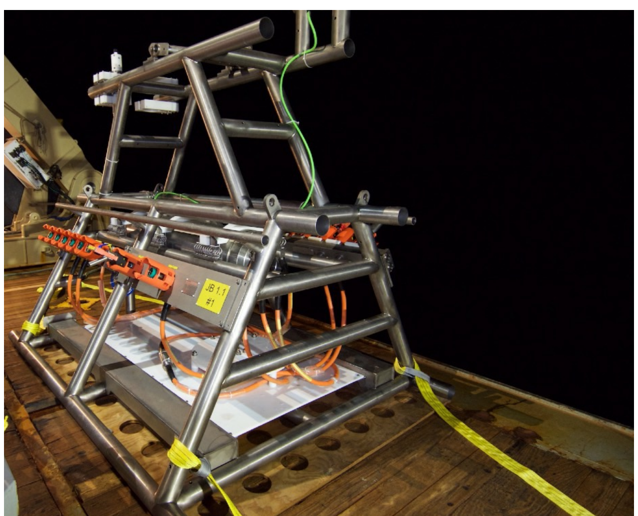


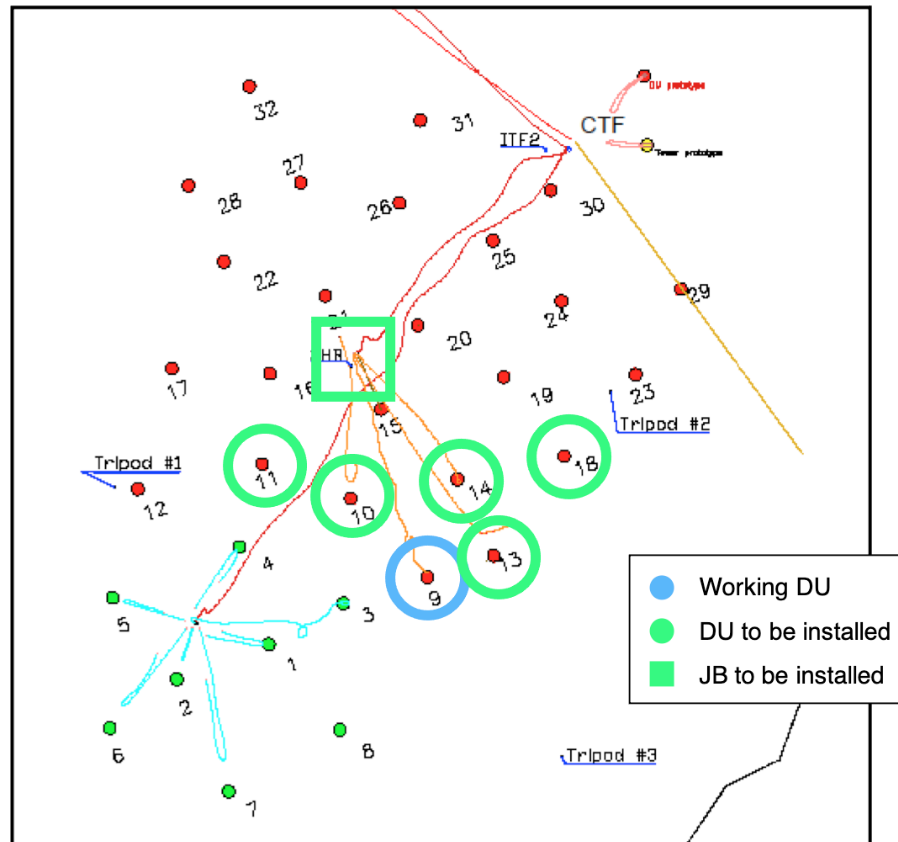
Positions of DOMs obtained dynamically from simultaneous fit of arrival times in all DOMs of signals from acoustic beacons at known positions to mechanical model of the DU

ARCA: Connection JB and 5 DUs

8-17 April 2021: Deployment of 1st Junction Box
Connection of +5 new DUs



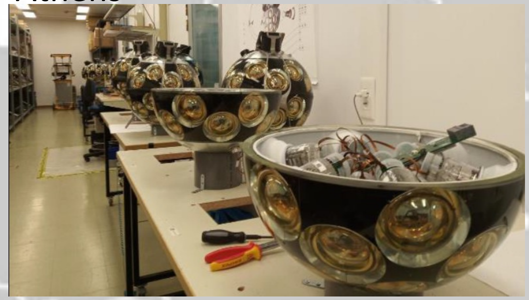




Production ongoing around europe

Amsterdam

Athens

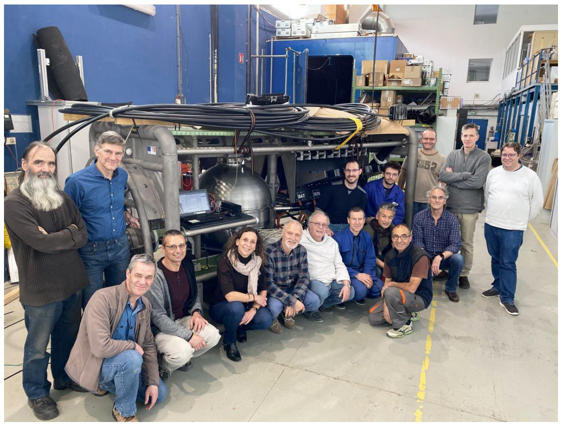


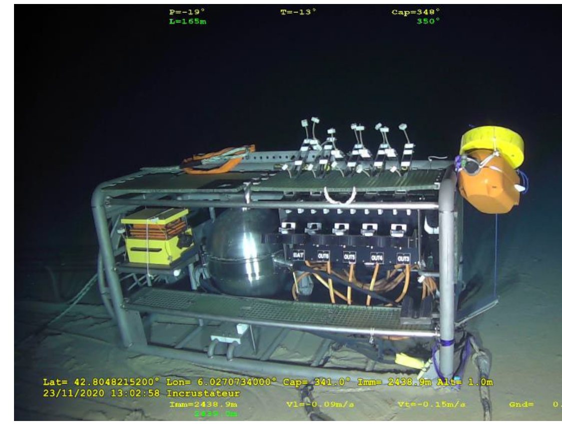
Bologna

Naples

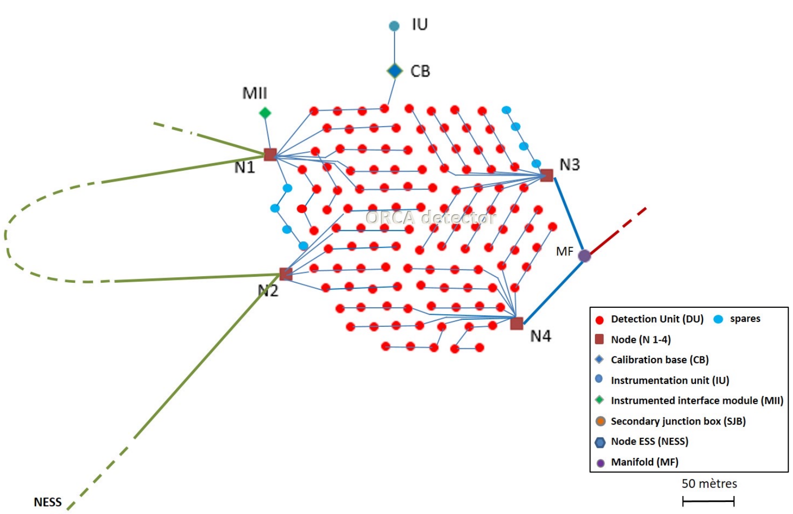
ORCA: Connection second junction box

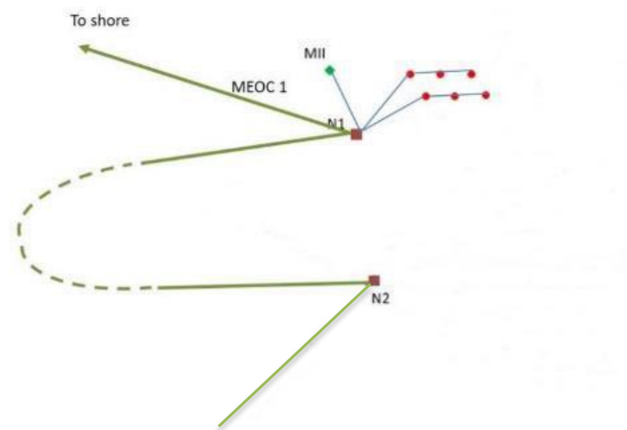
16-24 Oct 2020: Successful connection of Junction Box 2 to ORCA
https://www.km3net.org/sea-operation-in-times-of-corona/





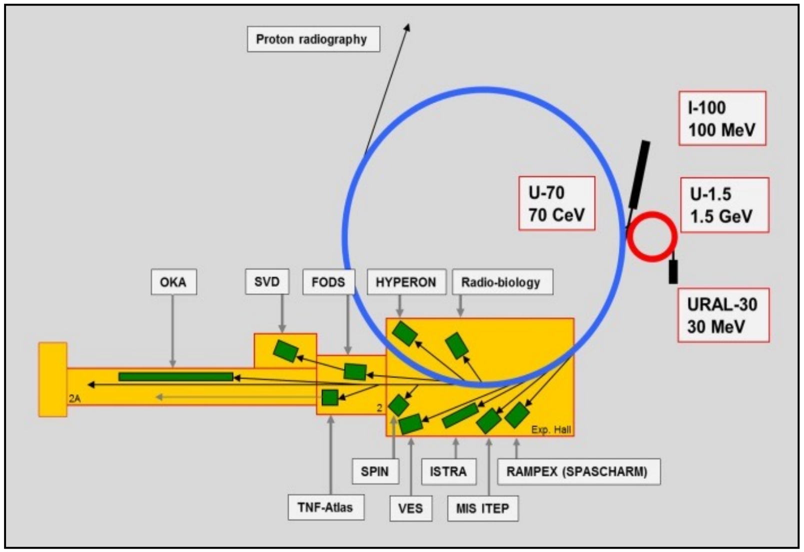
Preliminary DUs connection scheme 2021-02-09

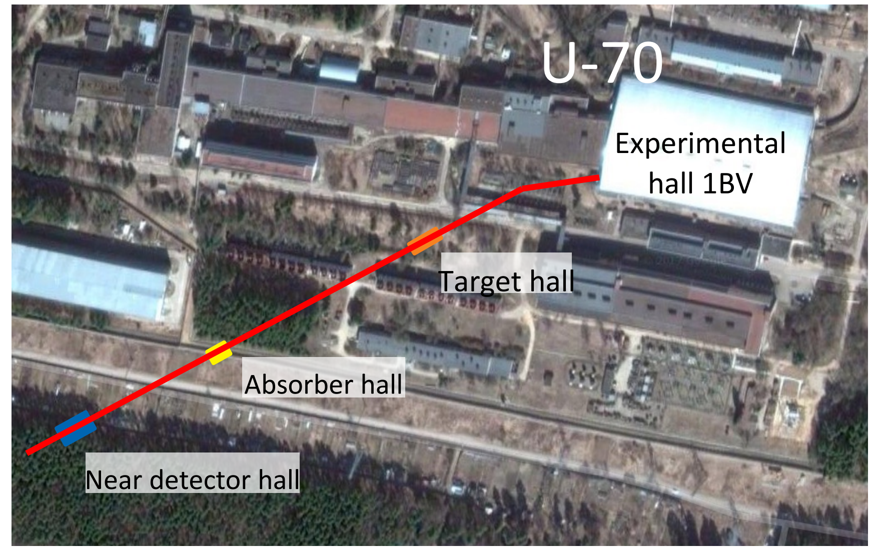


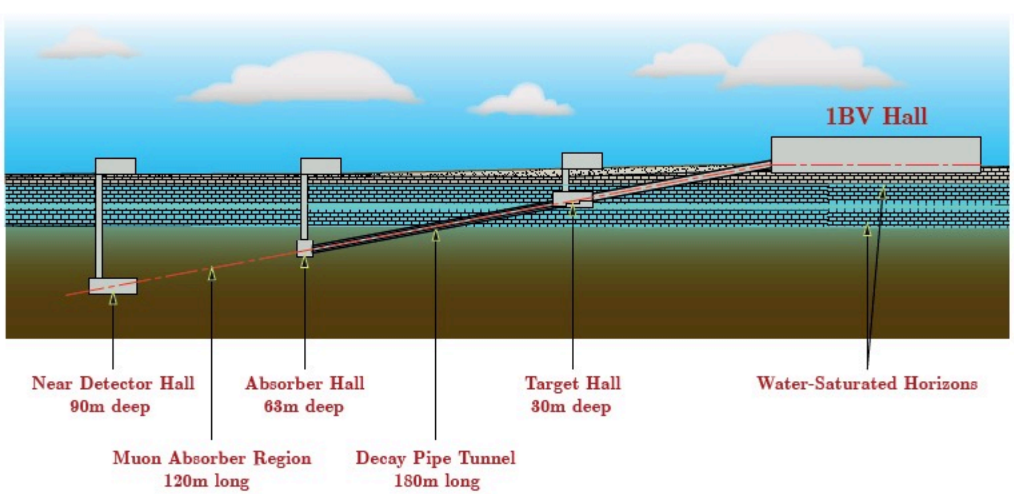


Can now connect upto 52 DUs

Proposed Protvino beamline







A. Zaitsev, VLVnT 2018
Anatoly Sokolov