The ANTARES and KM3NeT neutrino telescopes: status and perspectives for neutrino physics and astrophysics

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ANTARES and KM3NeT Collaborations

ANTARES Collaboration

Paris
Orsay
Gif-sur-Yvette
Marseille
Strasbourg
Mulhouse
Clermont-Ferrand
Nice
Toulon
Sophia Antipolis
Oujda
Rabat
Marrakech
Valence
Grenade
Gandie
Vilanova i la Geltrú
Amsterdam
Texel
Leyde
Rome
Gênes
Bologne
Catane
Bari
Pise
Naples
Salerne
Erlangen
Wurtzbourg
Bamberg
Bucarest
Bentley

KM3NeT Collaboration

Paris
Marseille
Strasbourg
Mulhouse
Colmar
Caen
Nantes
Montpellier
Toulon
Oujda
Rabat
Ben Guerir
Marrakech
Valence
Vilanova i la Geltrú
Gandie
Grenade
Amsterdam
Leyde
Texel
Delft
Rome
Gênes
Bologne
Catane
Bari
Naples
Caserta
Salerne
Erlangen
Wurtzbourg
Bamberg
Münster
Tubingue
Bucarest
Sydney
Louvain-la-Neuve

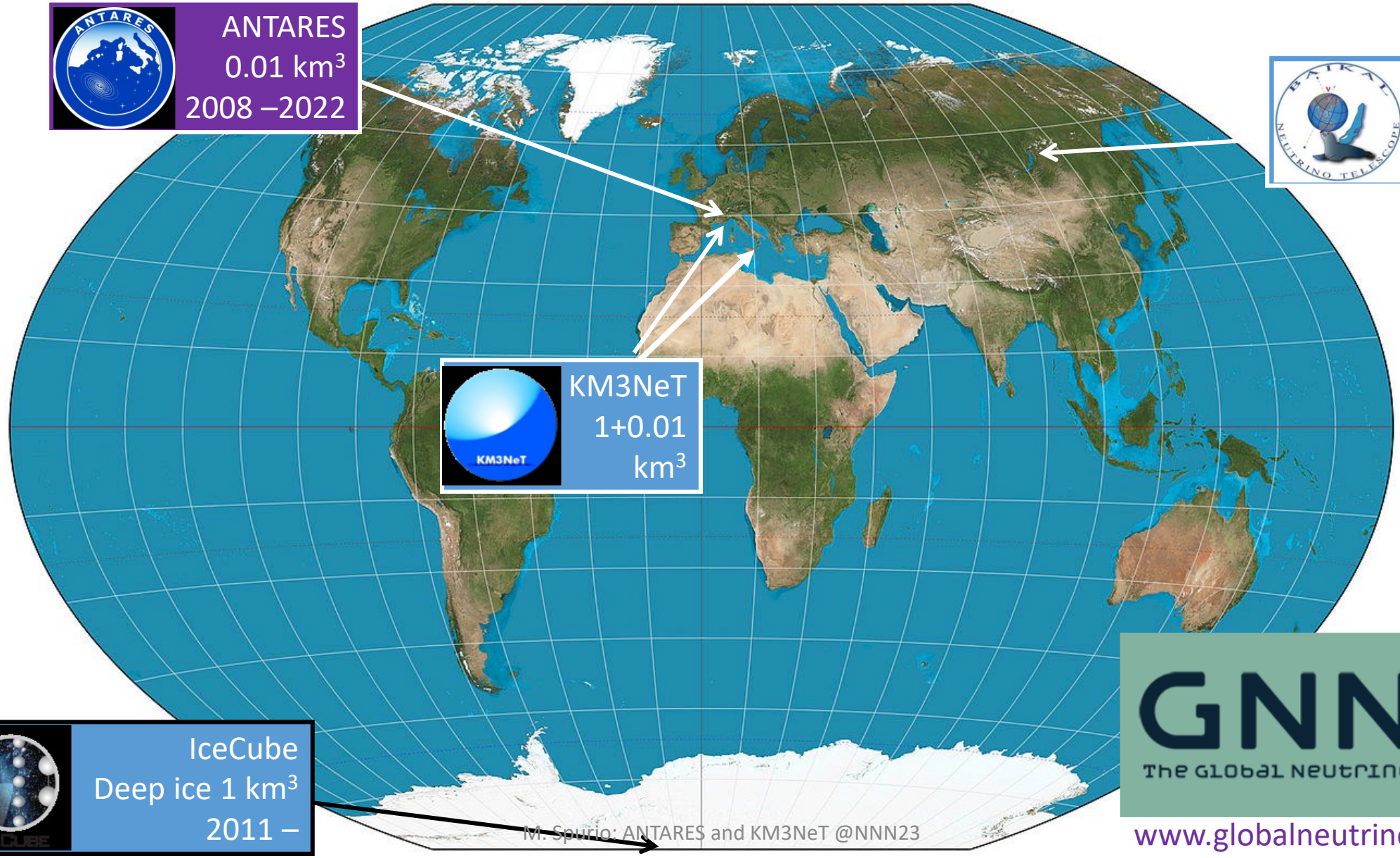
Hull
Prague
Bratislava
Varsovie
Athènes
Nicosie
Tbilissi
Abou Dabi
Charjah
Constantine
Ari'el
Johannesburg
Potchefstroom
Guangzhou

KM3NeT sites

ORCA
ARCA
KM3NeT-Gr

ANTARES site

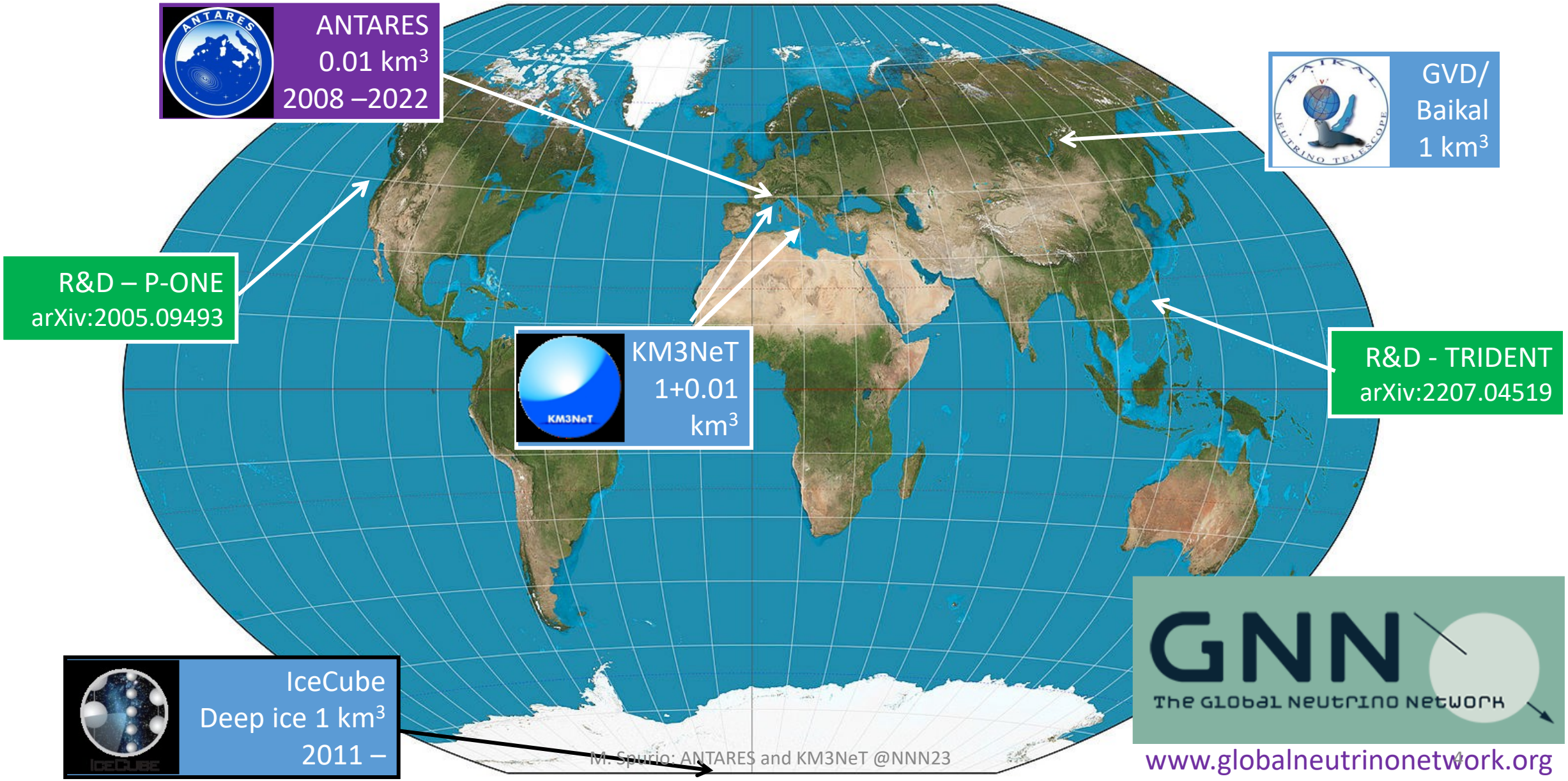
The neutrino telescope world map 202*



GNN
The Global Neutrino Network

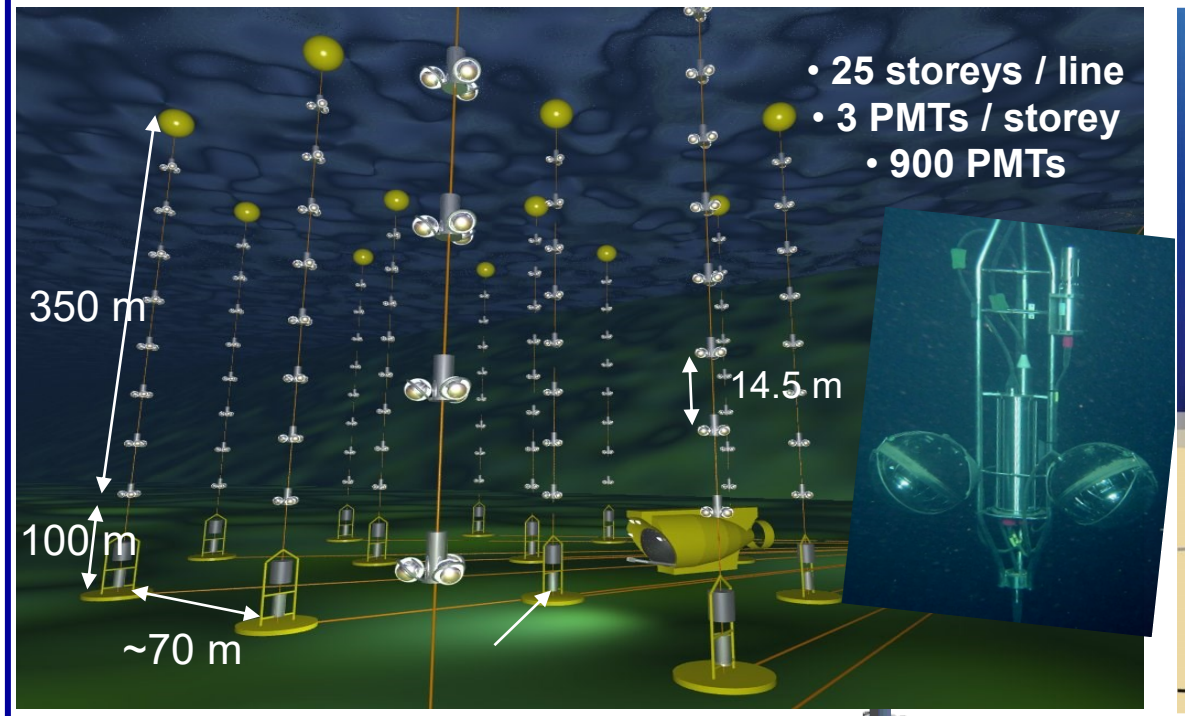
www.globalneutrinonetwork.org

The neutrino telescope world map 202*

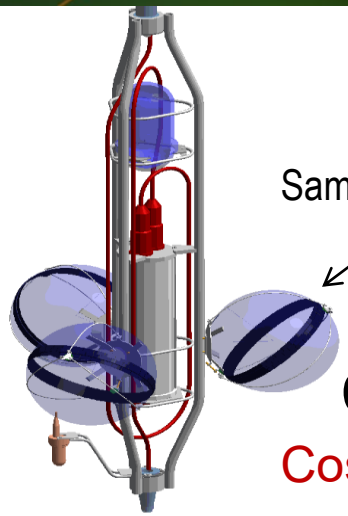


Mediterranean Detectors

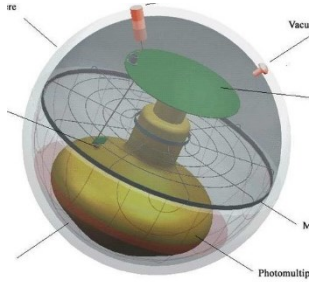
ANTARES complete 2008 - 2022



12 lines



First Generation



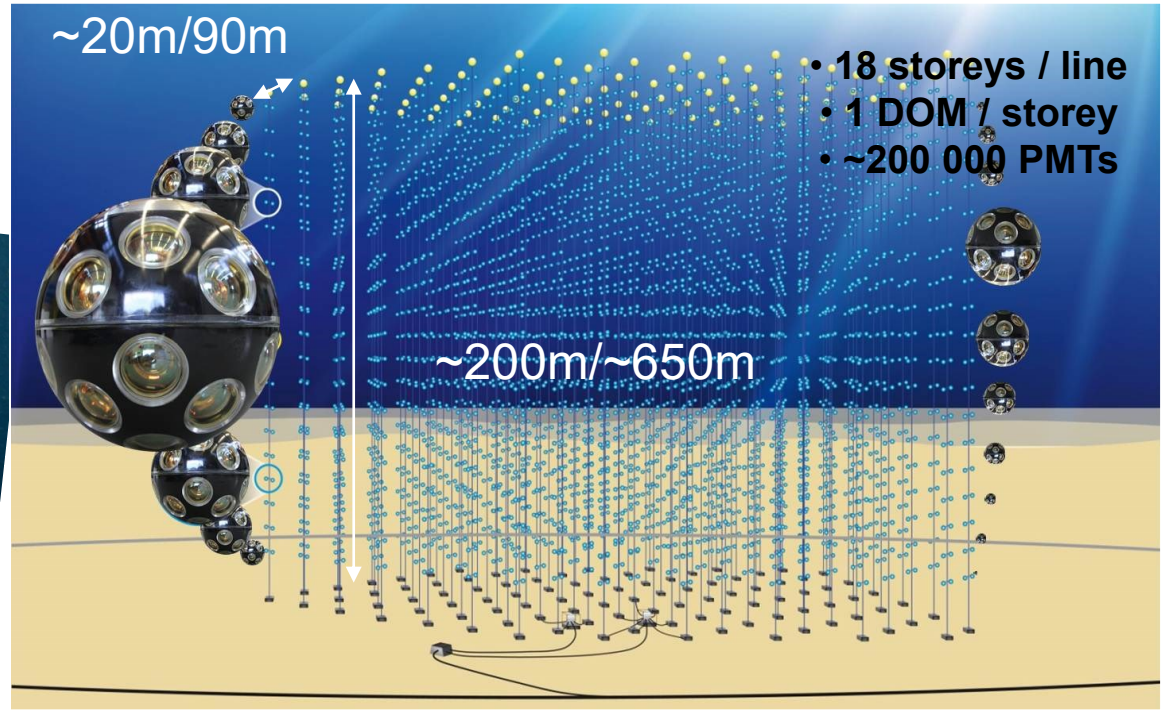
📖 NIM A 656 (2011)

Same size (43cm)

Compact

Cost reduction

KM3NeT Under Construction



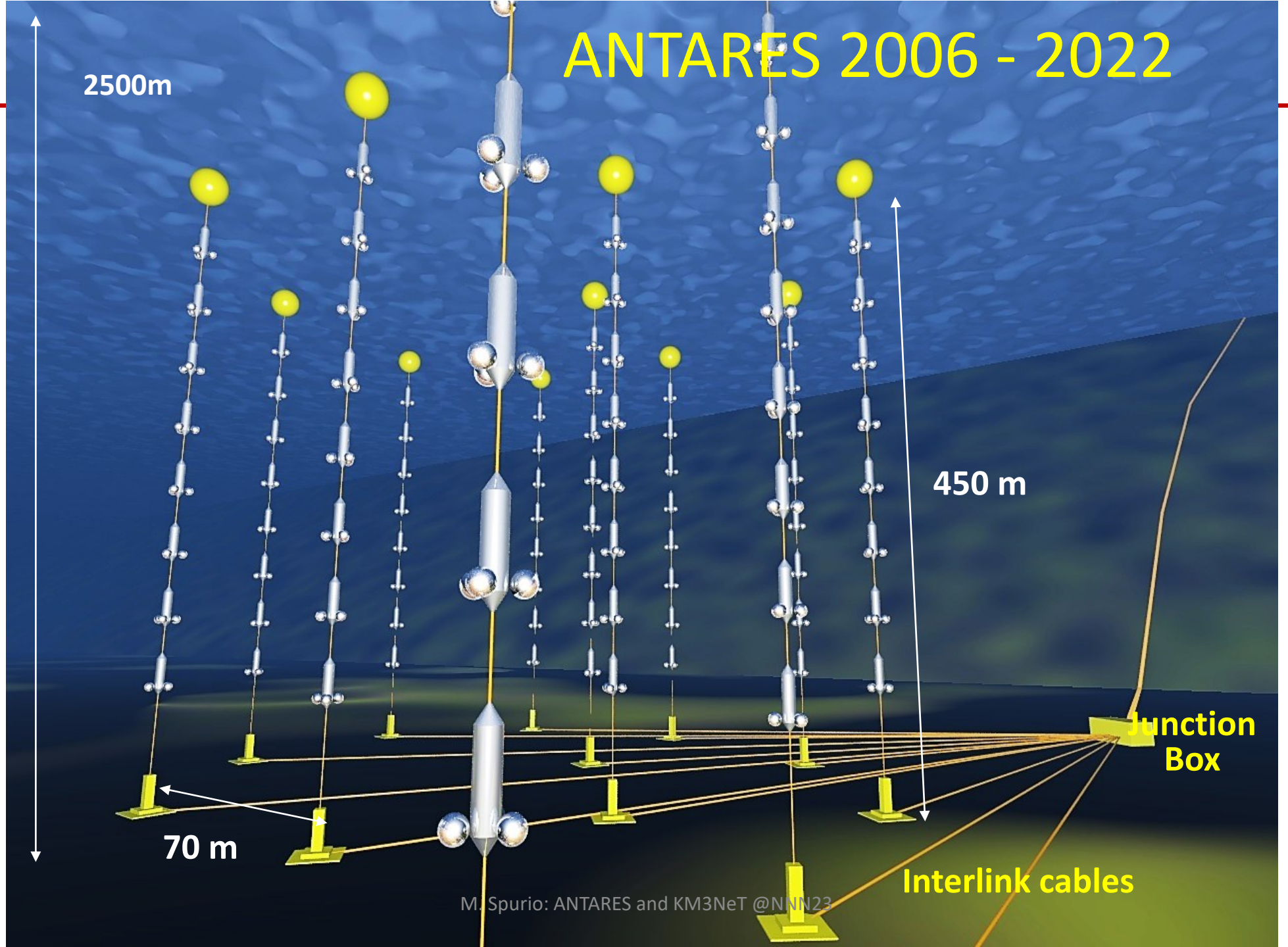
230 ARCA (Italy) + 115 ORCA (France) lines

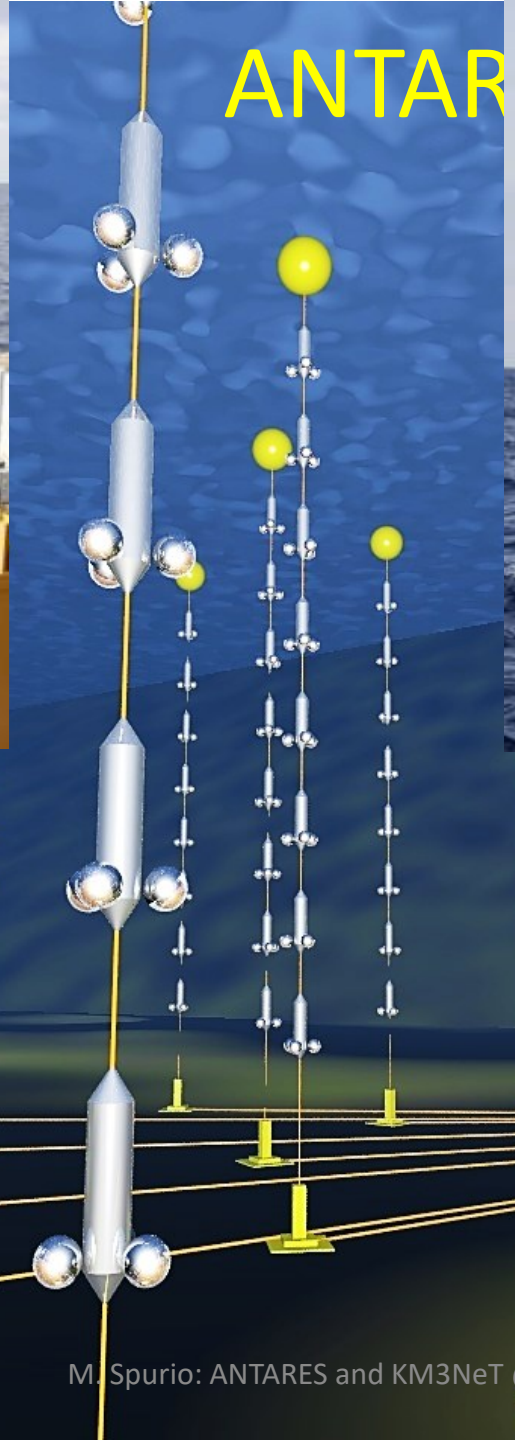
~1 Gton ~7 Mton

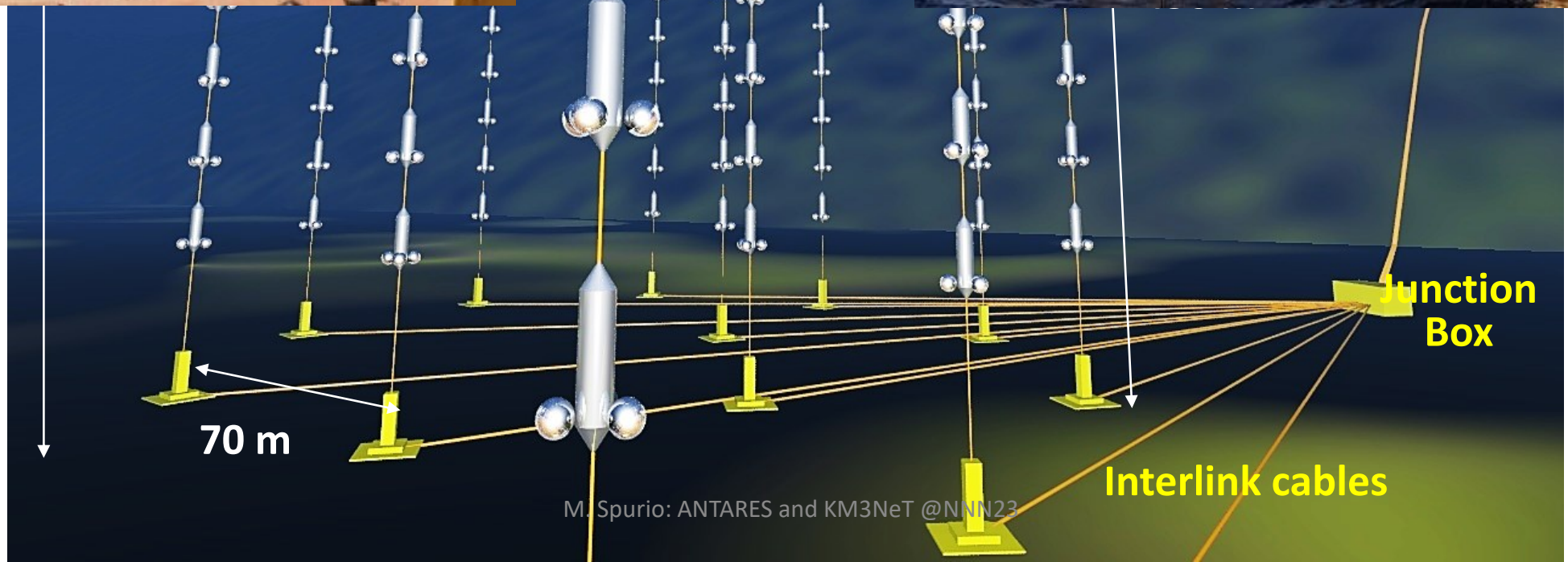
New Generation

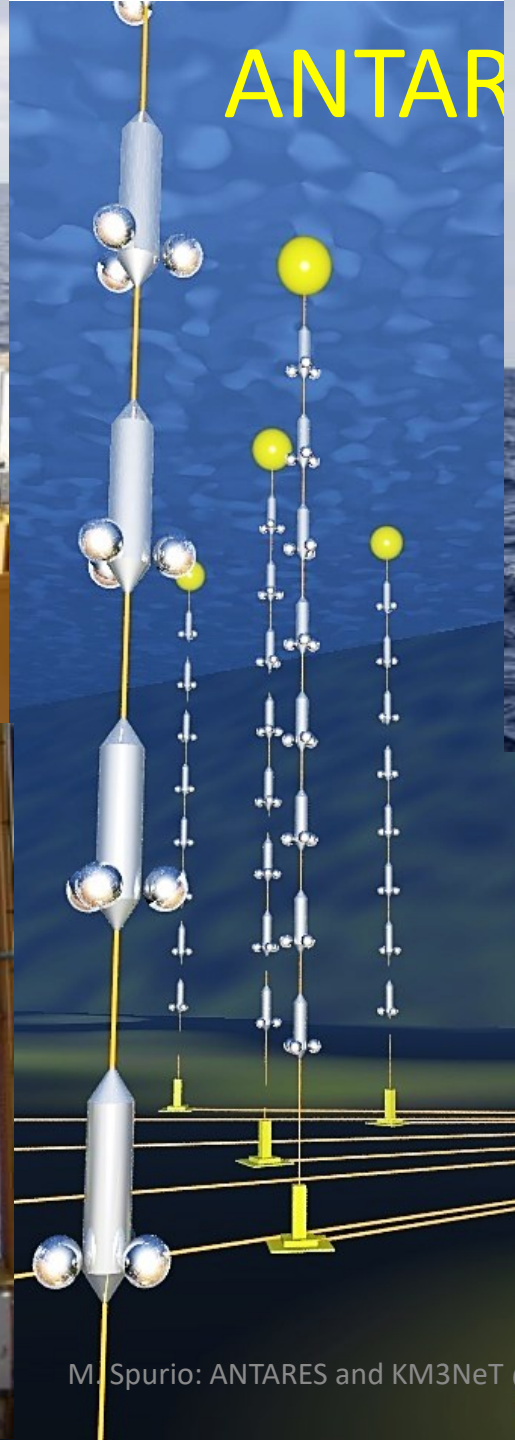
- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view

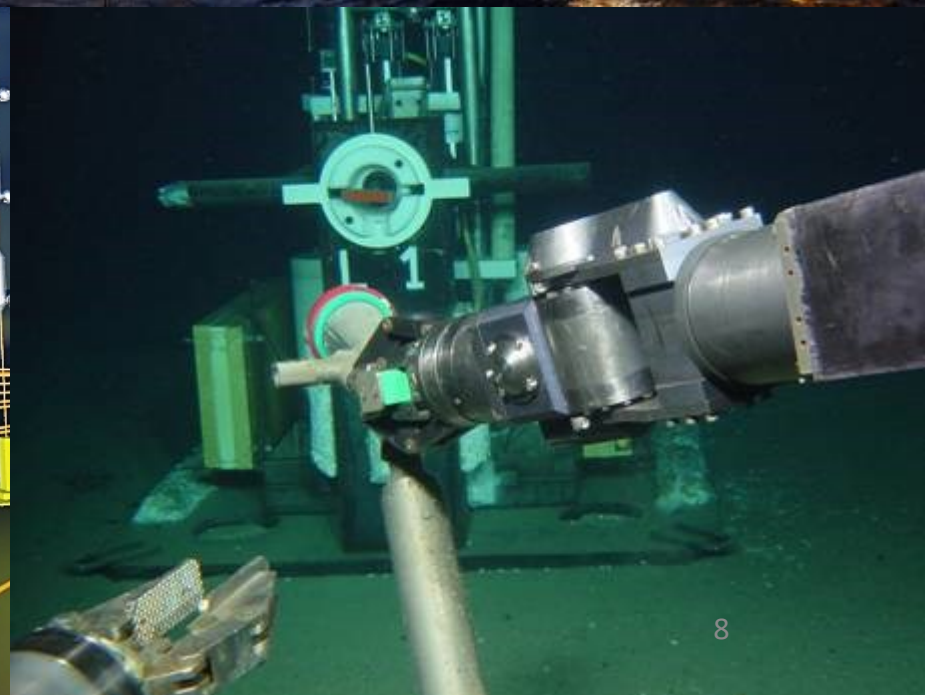
ANTARES 2006 - 2022




ANTAR

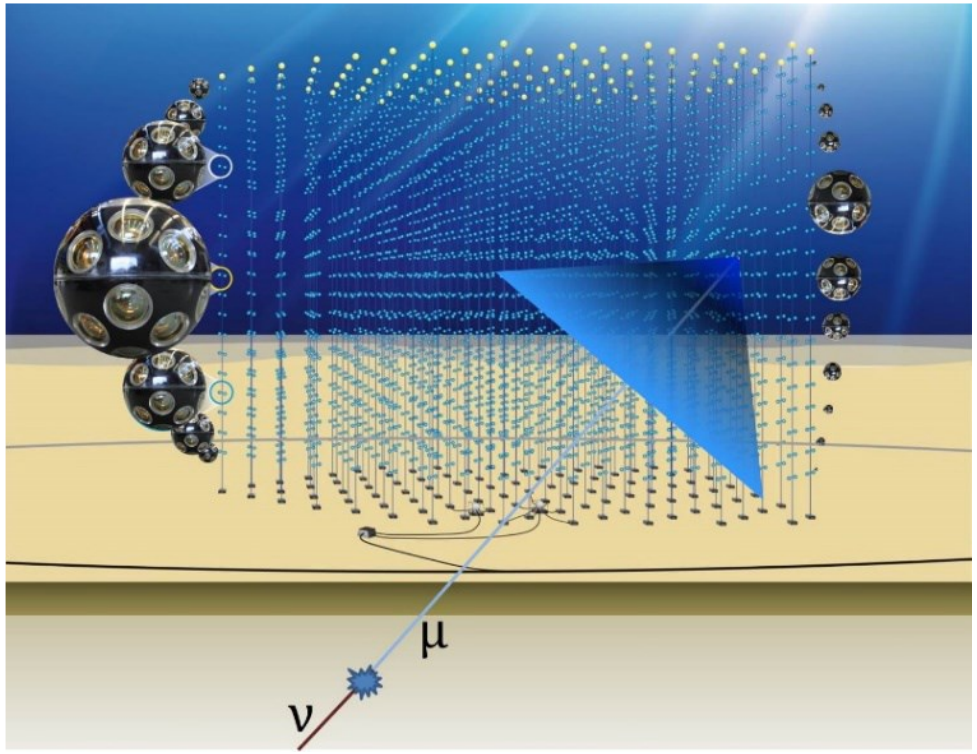

70 m
Junction Box
Interlink cables


ANTAR



KM3NeT detectors: ARCA and ORCA

Same technology for the two detectors



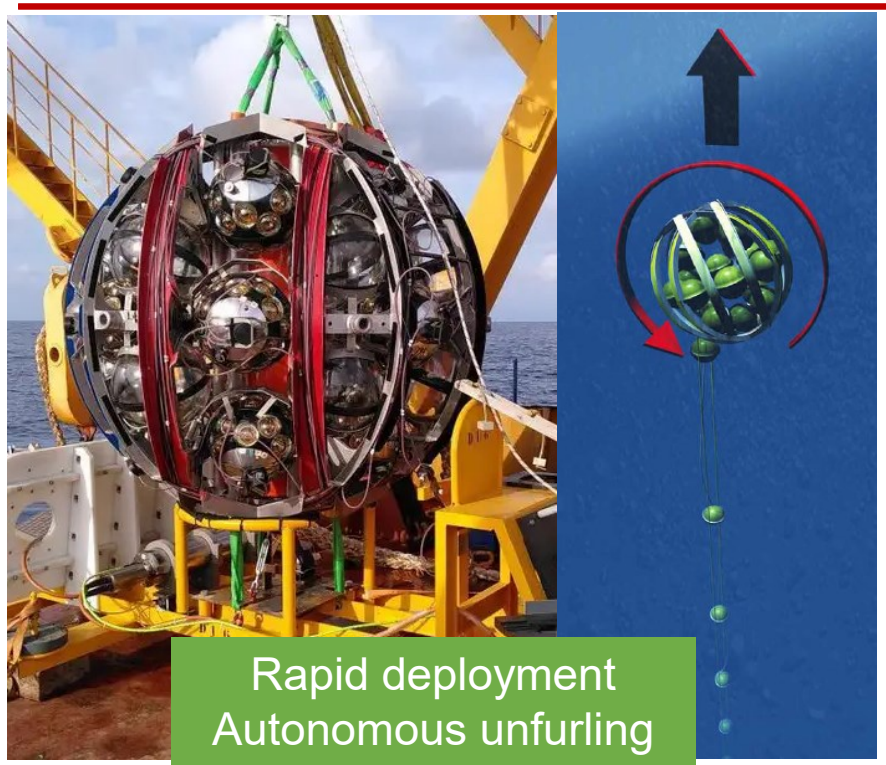
ORCA

- Depth ~2500 m
- One block of 115 Detection Units
- Average distanc between Detection Units ~20 m
- Average vertical distance between DOMs ~9 m

ARCA

- Depth ~3500 m
- Two blocks of 115 Detection Units each
- Average distance between Detection Units ~90 m
- Vertical distance between DOMs ~36 m

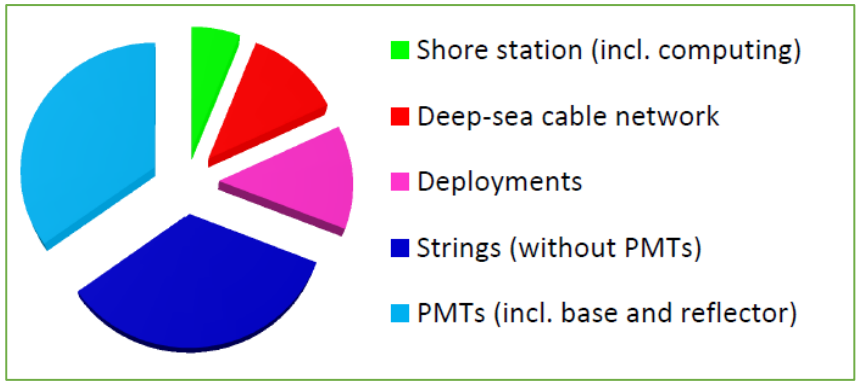
KM3NeT Construction



Rapid deployment
Autonomous unfurling
Recoverable

https://www.youtube.com/watch?v=tR8jwgG6uzk

- TODAY: 28 Detector Units (DUs) deployed in ARCA
- TODAY: 18 DUs deployed in in KM3NeT/ORCA
- ANTARES online acceptance overcome (> ×3)
- **Total KM3NeT cost: 320 M€ (>2/3 secured)**



APPEC

Flagship Experiment

Physics Studies

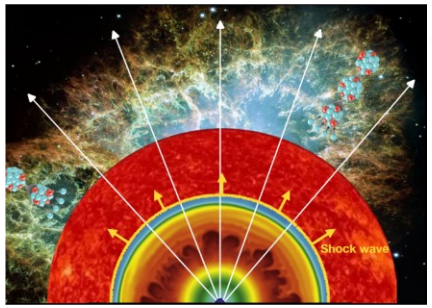
Supernovae Explosion

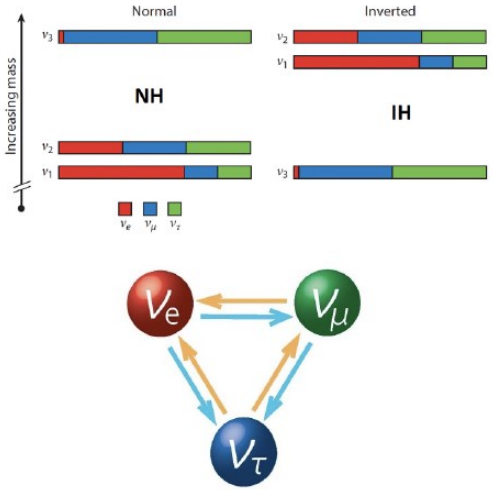
Neutrino Physics

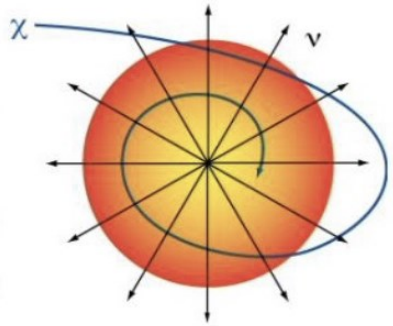
Dark Matter & Exotic searches

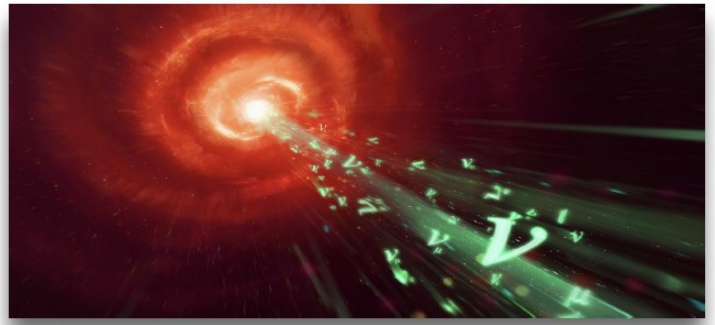
Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV









KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

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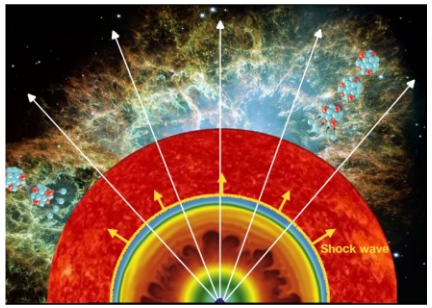
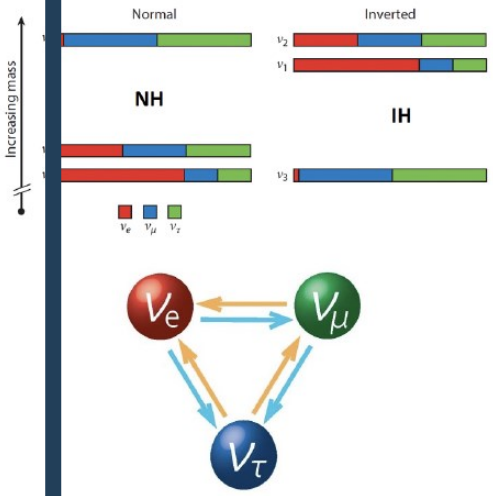
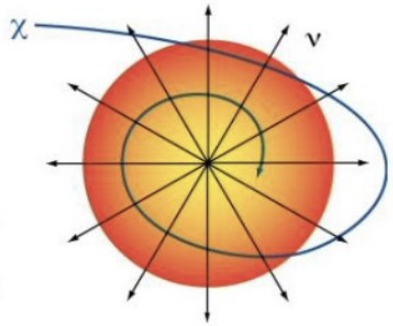
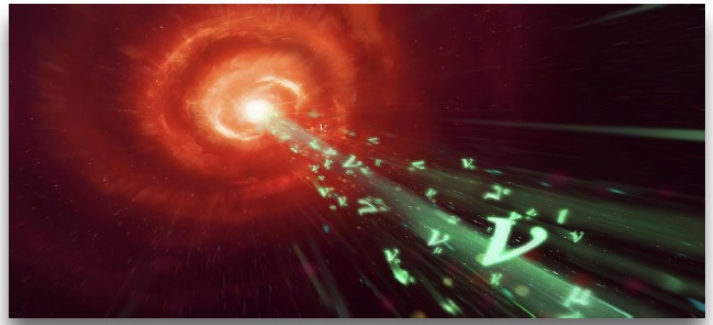
Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV



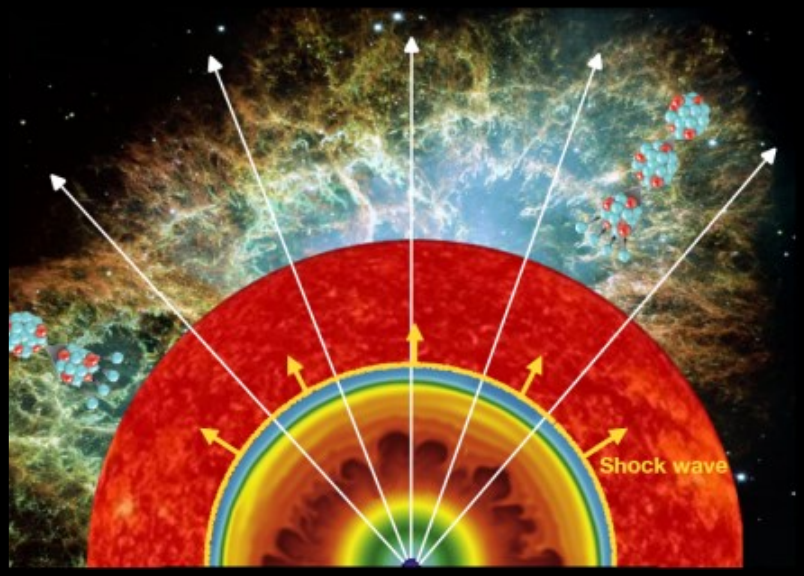


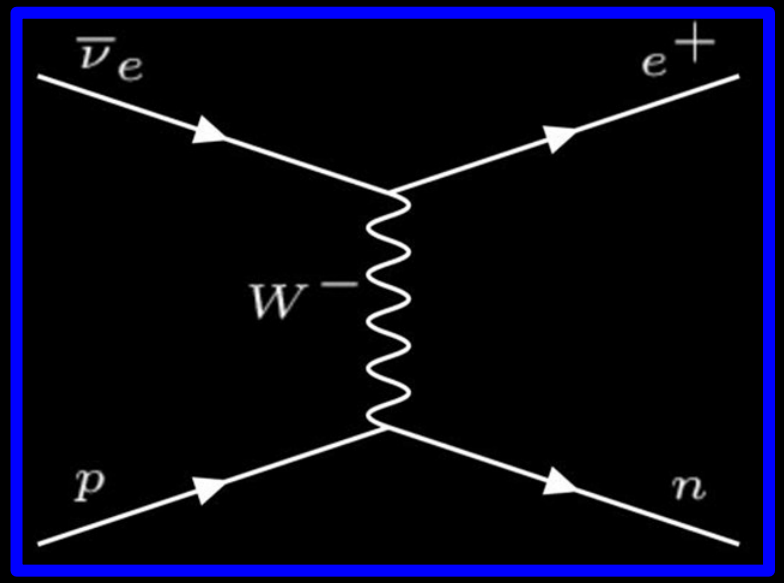


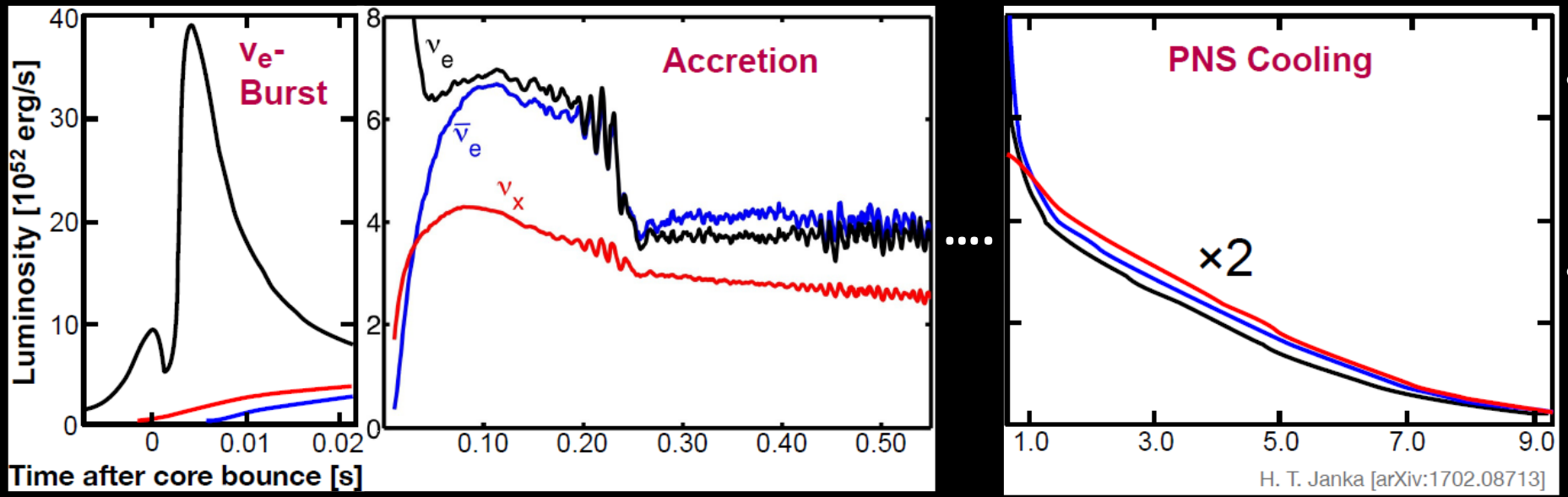


KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

ν from core-collapse supernovae





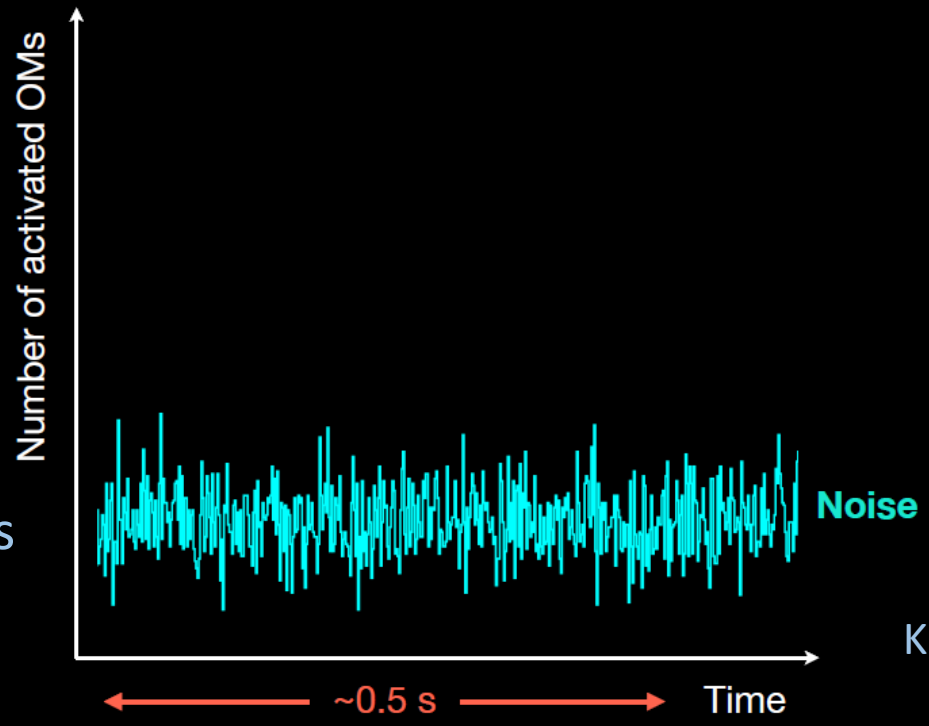


- **Signal Model:** Neutrino Emission from Supernovae. H.-Th. Janka. arXiv:1702.08713
- Accretion phase: 0.5 s
- **Signal in the detector**: 90% due to CC $\overline{\nu}_e$ interaction
- 10 MeV electron release its energy in about 5 cm of water
- Coherent increase of the "light" in the detector.

ν from core-collapse supernovae: signal and bck

- 2070 DOMs in one detector building block
- Each DOM is a detector
- 31 small PMTs in each DOM

MeV radioactivity: 1-2 PMTs in 20 ns



KM3NeT: EPJ. C (2021) 81:445

ν from core-collapse supernovae: signal and bck

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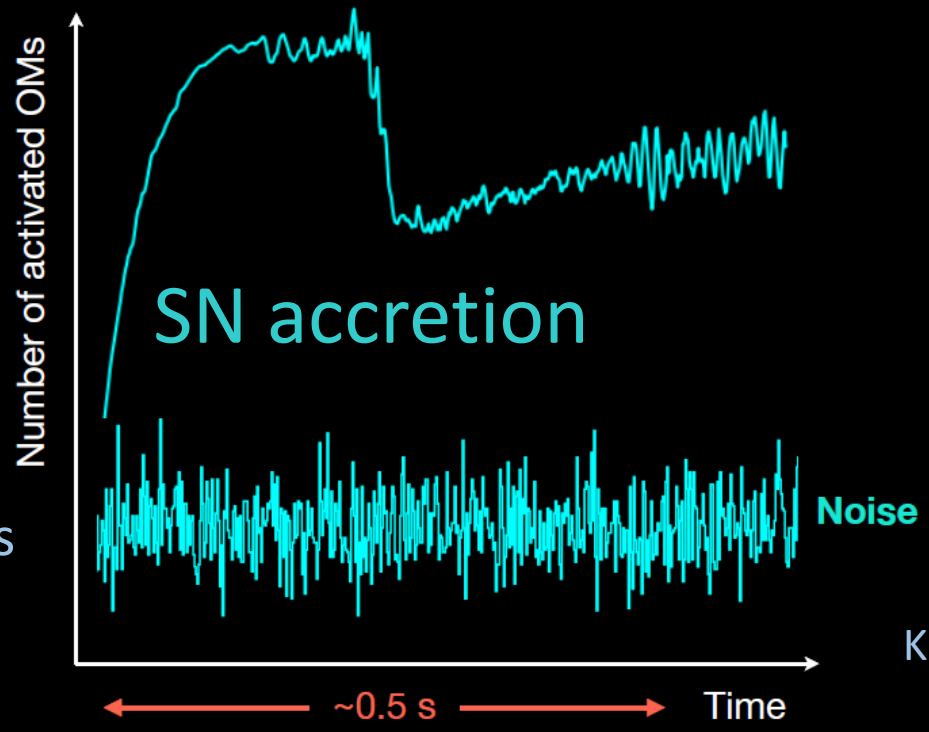
MeV radioactivity: 1-2 PMTs in 20 ns

10 MeV electron: > 4 PMTs in 20 ns



KM3NeT: EPJ. C (2021) 81:445

ν from core-collapse supernovae: signal and bck

- 2070 DOMs in one detector building block
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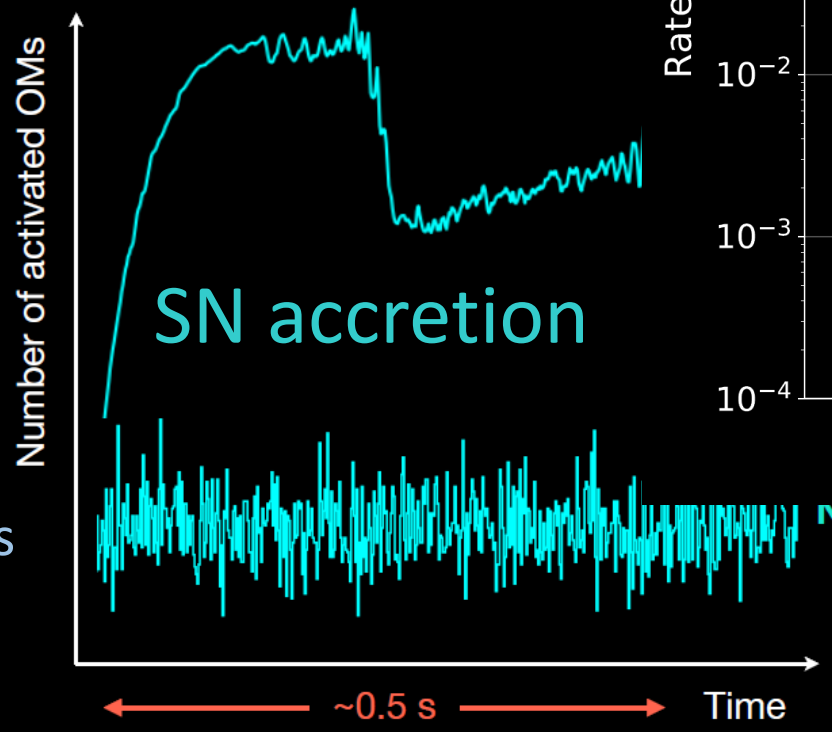
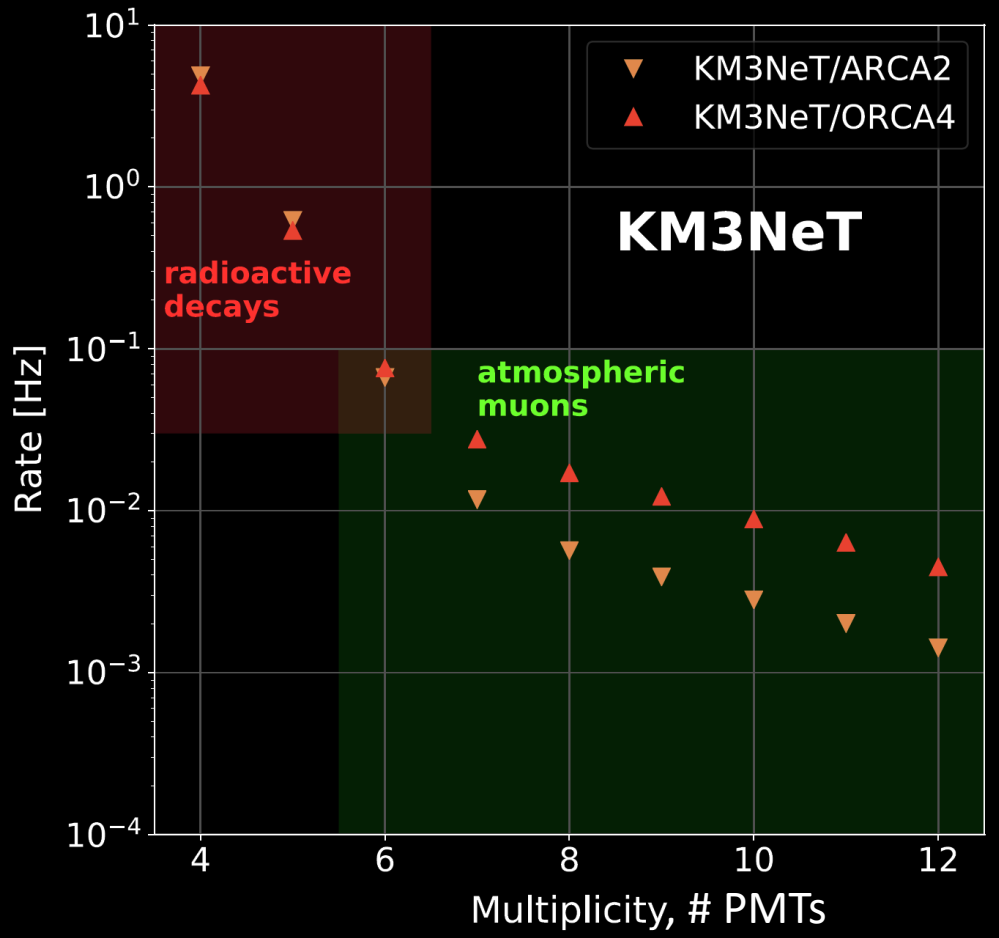
MeV radioactivity: 1-2 PMTs in 20 ns

10 MeV electron: > 4 PMTs in 20 ns

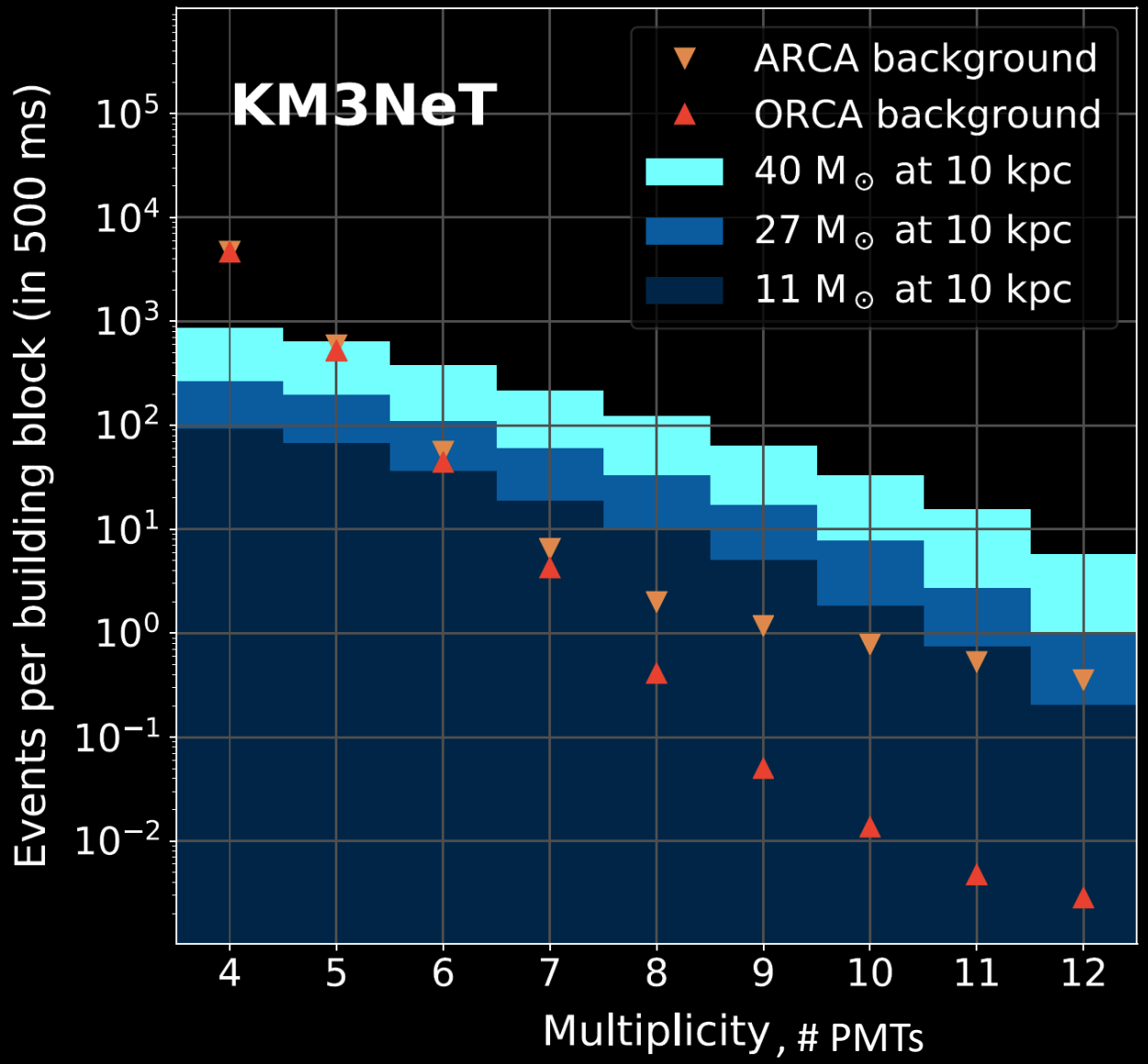
Muons: > 4 PMTs in many DOMSs but within few μs





KM3NeT: EPJ. C (2021) 81:445

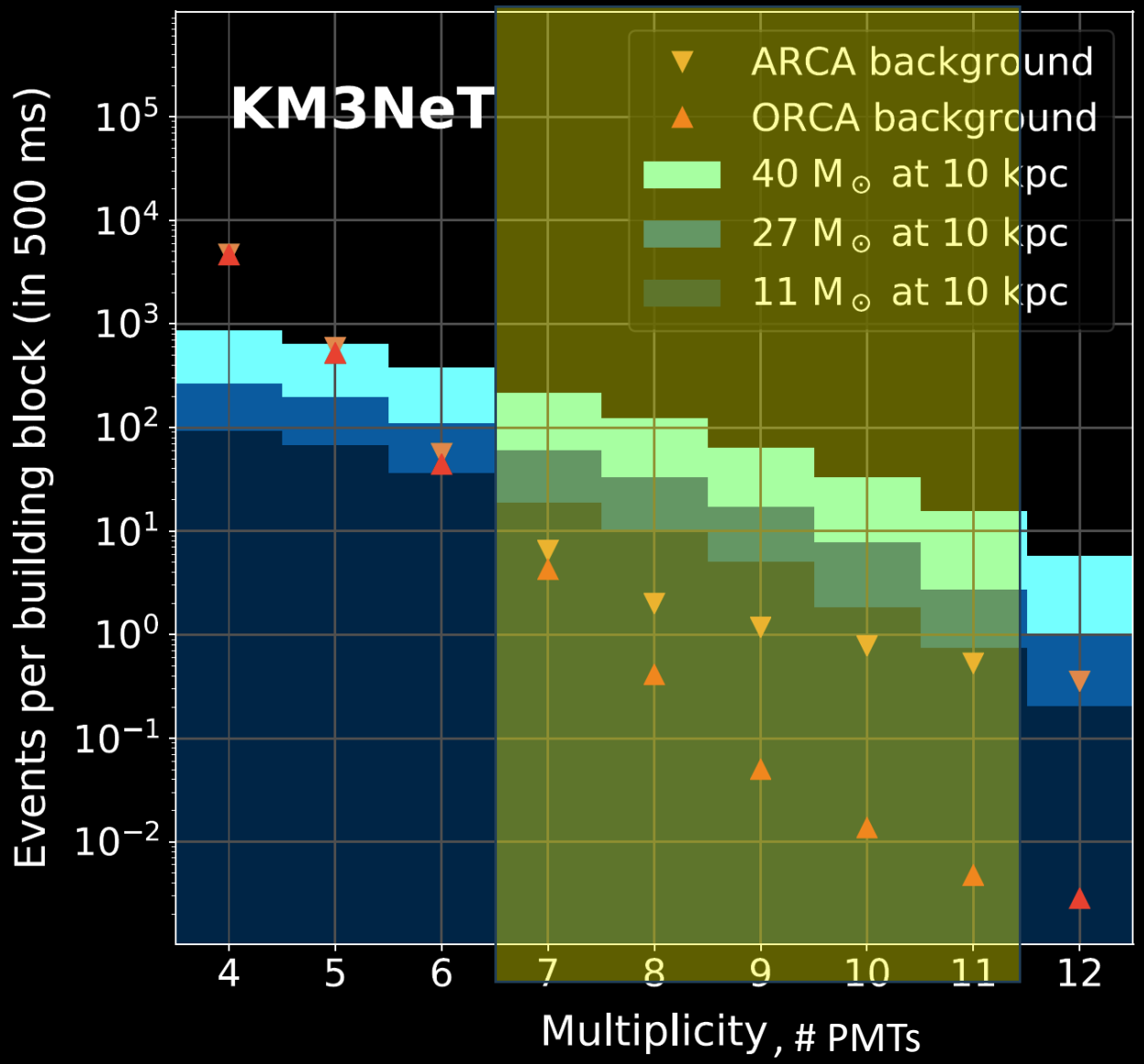
ν from core-collapse supernovae: events



- SNe @ 10 kpc (11,27, 40 M_{sun})
- Number of «events» in a time window of **0.5 s** in **2070 DUs** due to **signal** and **background**
- Significant excess for #PMTs>6
- Multiplicity distribution can be used as proxy of the SN neutrino energy spectrum.

KM3NeT: EPJ. C (2021) 81:445

ν from core-collapse supernovae: events



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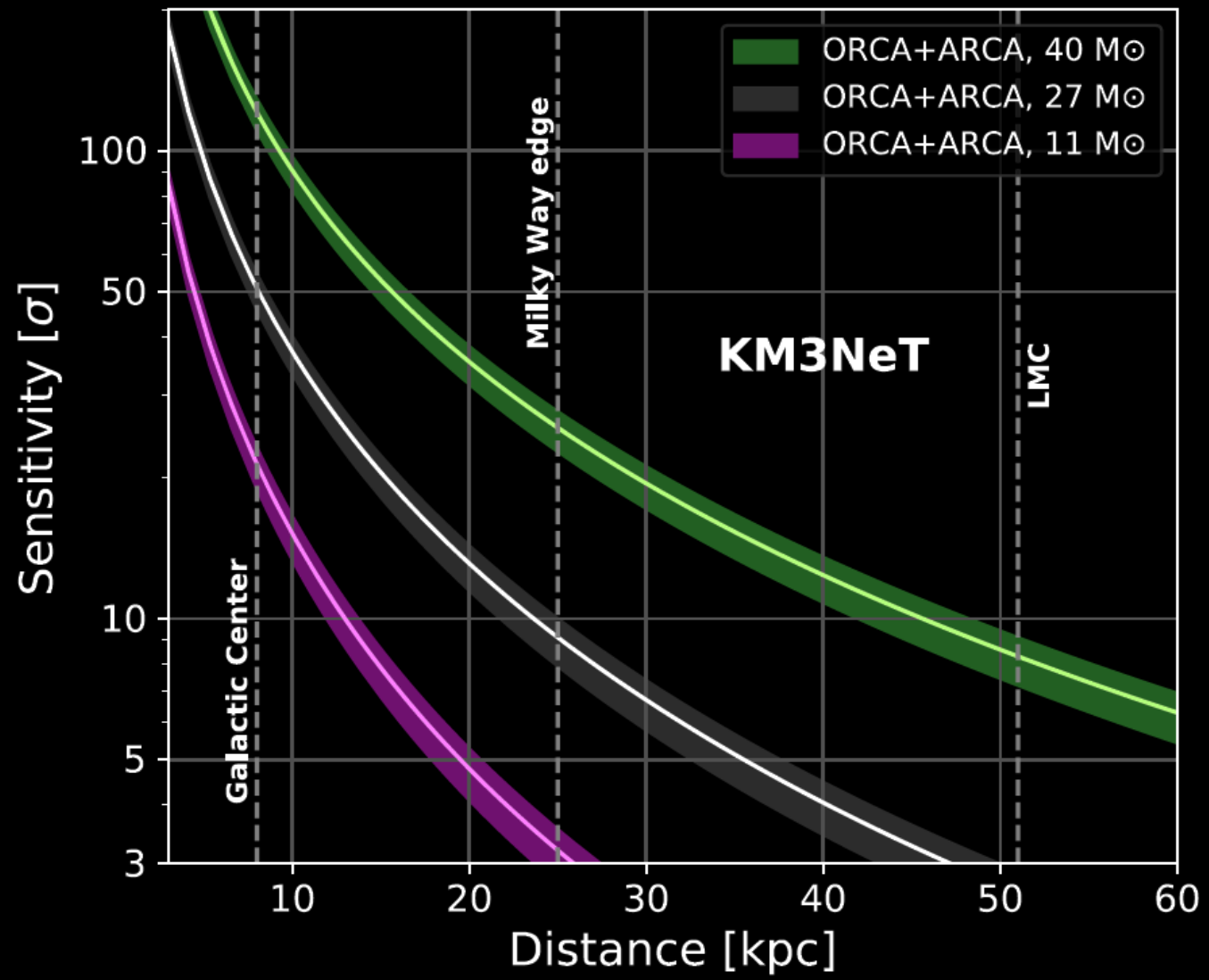
- Significant excess for #PMTs>6
- Multiplicity distribution can be used as proxy of the SN neutrino energy spectrum.

KM3NeT: EPJ. C (2021) 81:445

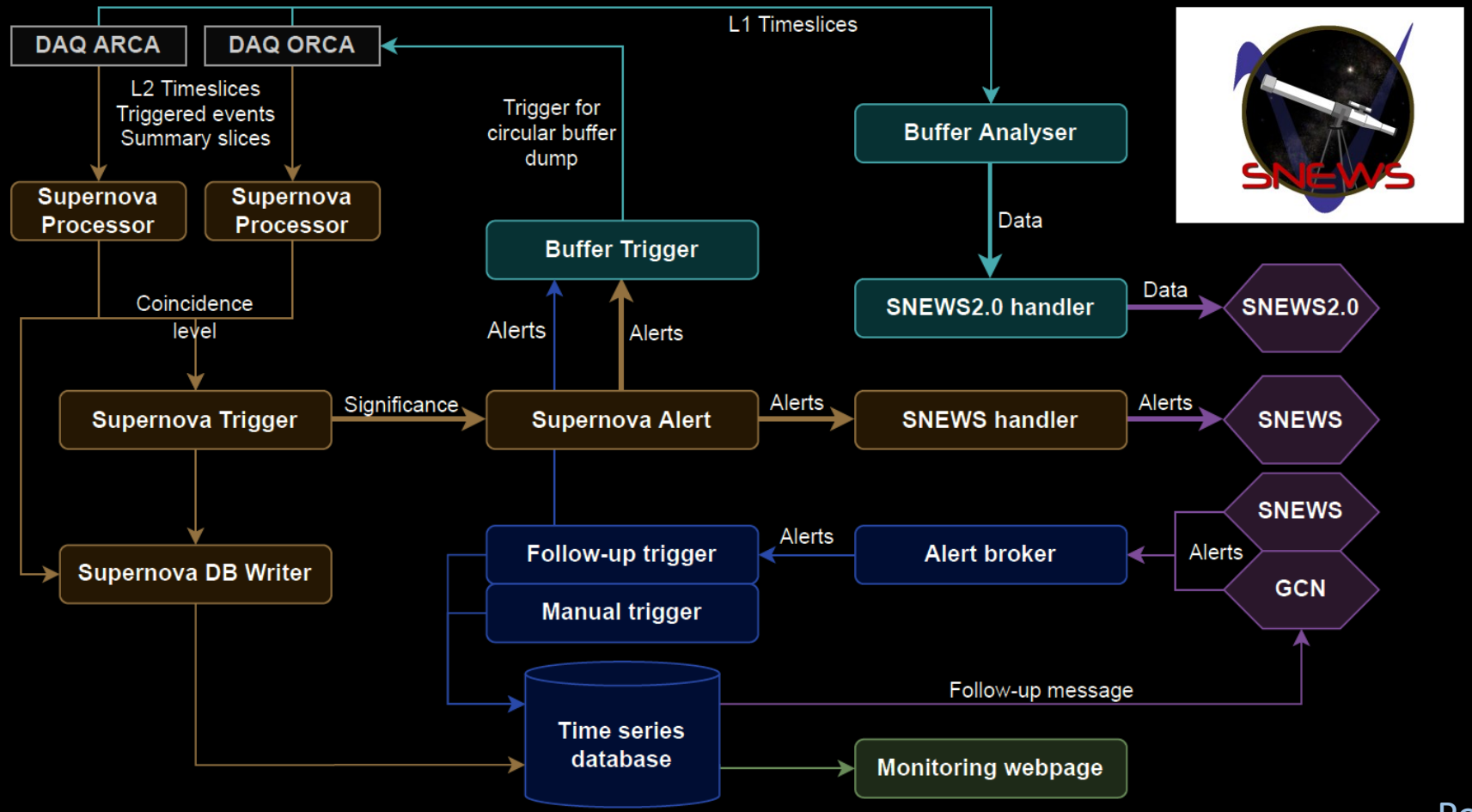
ν from core-collapse supernovae: sensitivity



- KM3NeT detection sensitivity as a function of the distance to the CCSN for the three progenitors considered.
- The error bars include the systematic uncertainties

KM3NeT: EPJ. C (2021) 81:445

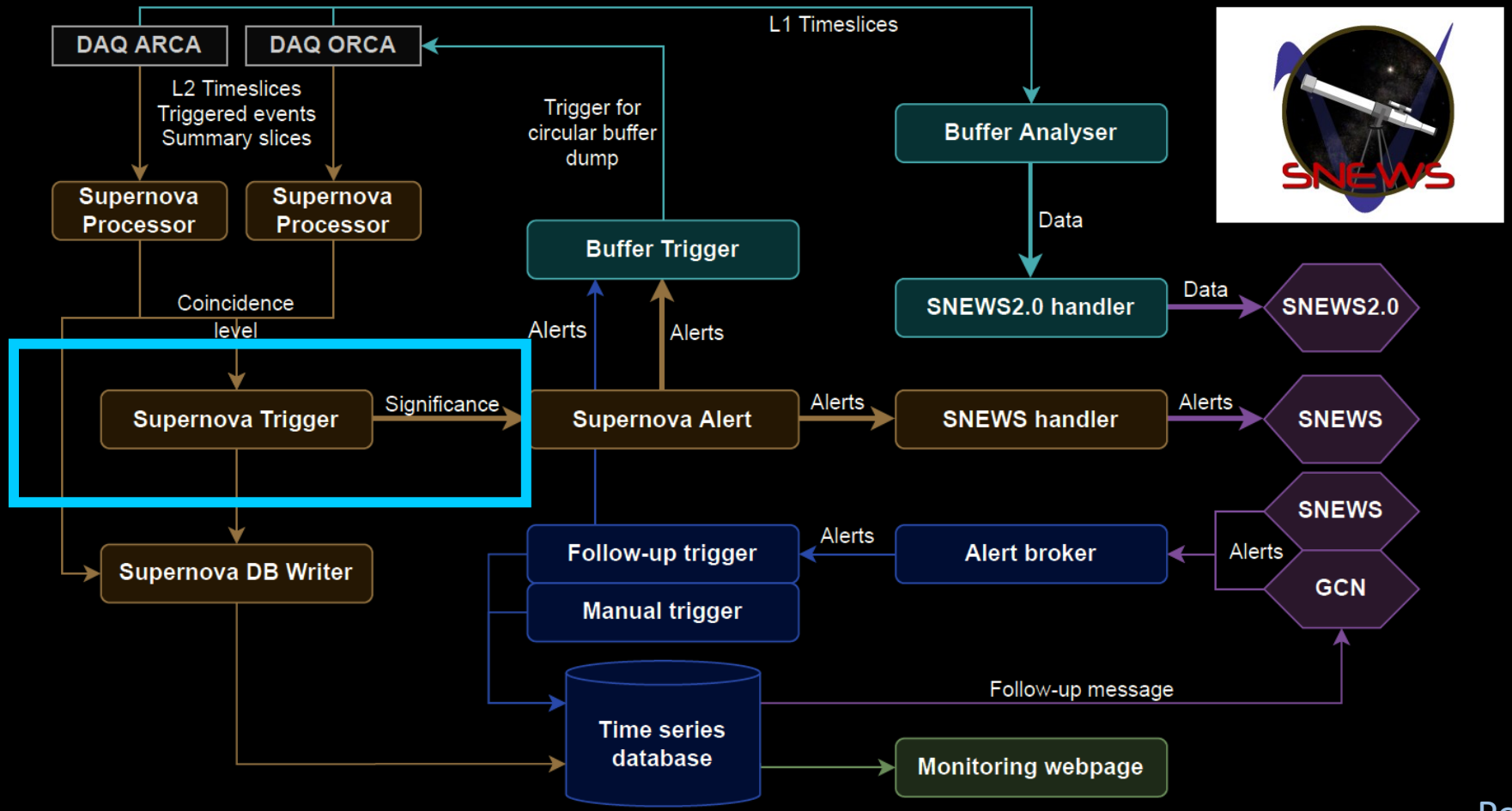
KM3NeT supernovae alert (online pipeline)



- Alert system: 20 s latency time
- Trigger threshold: adapt to background level 1 fake event/week

PoS(ICRC2023)1223

KM3NeT supernovae alert (online pipeline)



- Alert system: 20 s latency time
- Trigger threshold: adapt to background level 1 fake event/week
- Buffer 10 min of data
- Timing of the SN detection for triangulation with other experiments.

PoS(ICRC2023)1223

Physics Studies

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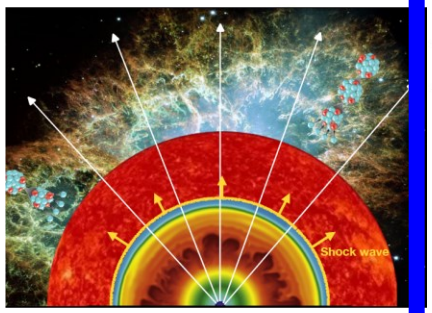
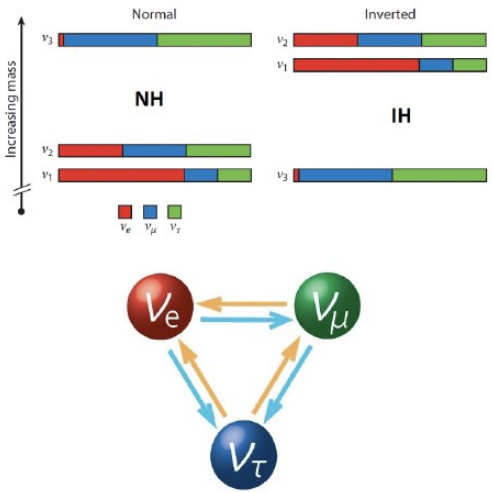
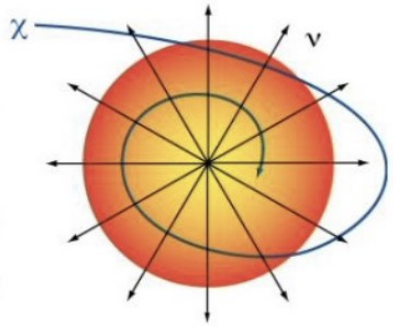
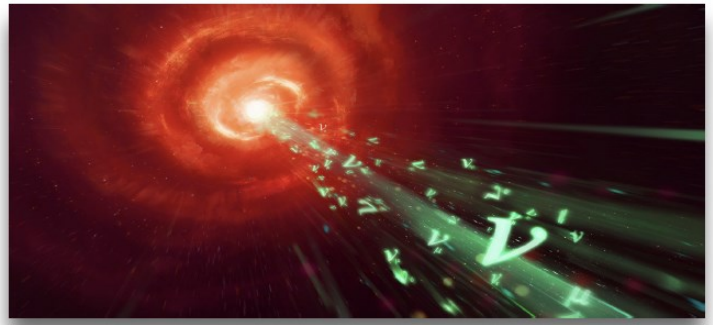
Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV









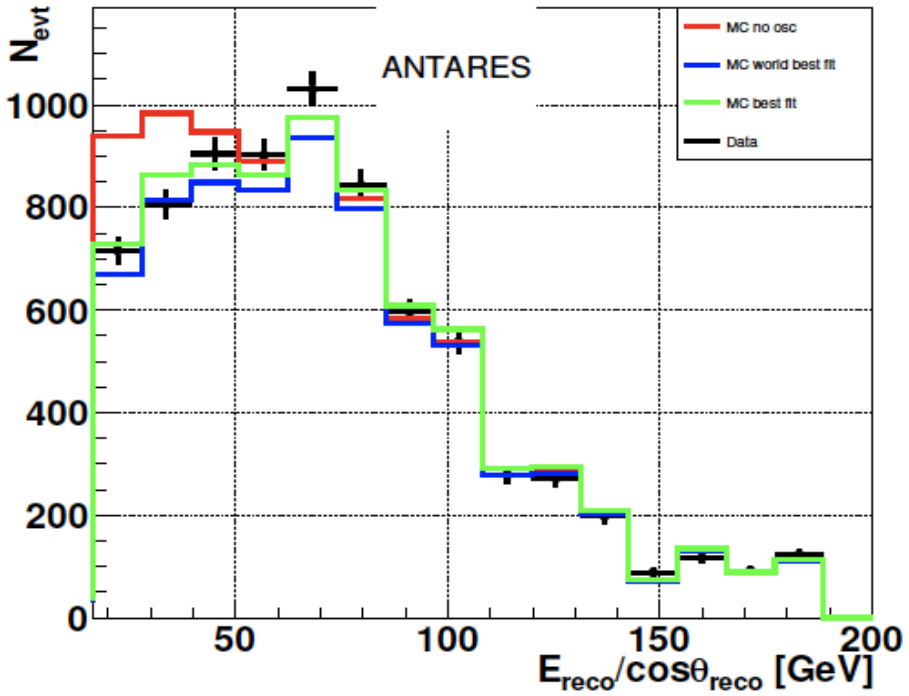
KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

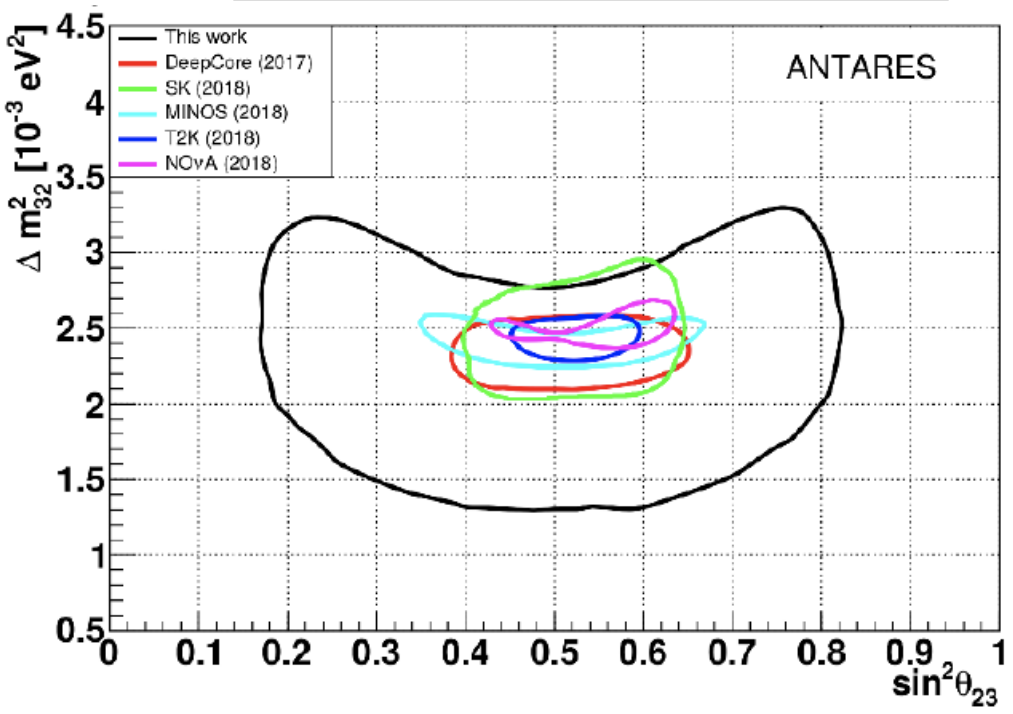
ν-oscillation (ν_μ- disappearance)

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

- A binned likelihood fit in 2D ($\log_{10}(E_{reco})$, $\cos\theta_{reco}$)
- Priors and fitted values obtained by minimization for all parameters of 3 flavor oscillations.
- No-oscillation hypothesis excluded at 4.6σ
- Data sample available on the ANTARES site

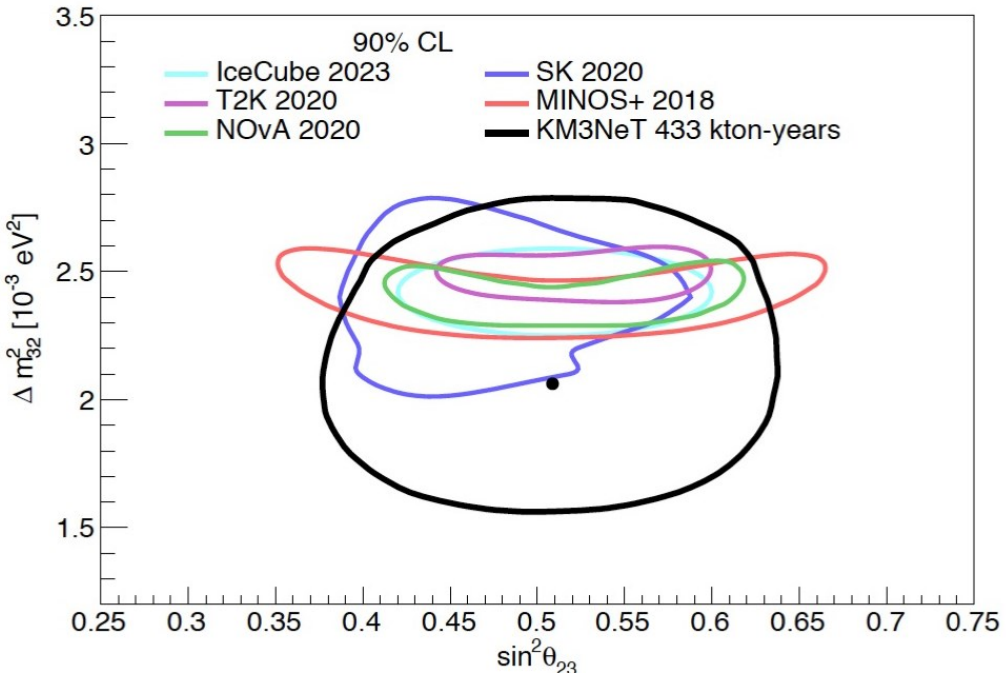
Parameter	Prior	Fit result
Δm^2_{32} $[10^{-3}\,\mathrm{eV}^2]$	none	$2.0^{+0.4}_{-0.3}$
θ_{23} [°]	none	45^{+12}_{-11}
n_ν	none	$0.81^{+0.10}_{-0.09}$
$\nu/\overline{\nu}$ [σ]	0.0 ± 1.0	$1.10^{+0.64}_{-0.56}$
$\Delta\gamma$	0.00 ± 0.05	-0.003 ± 0.036
N_μ	740 ± 120	414^{+48}_{-24}
θ_{13} [°]	8.41 ± 0.28	8.41 ± 0.28
M_A [σ]	0.0 ± 1.0	0.0 ± 1.0



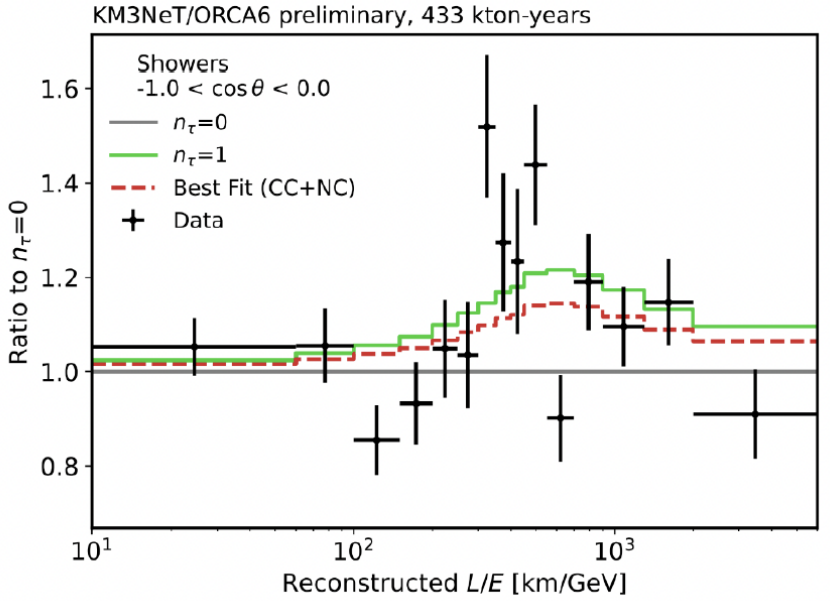


Oscillation Studies KM3NeT/ORCA

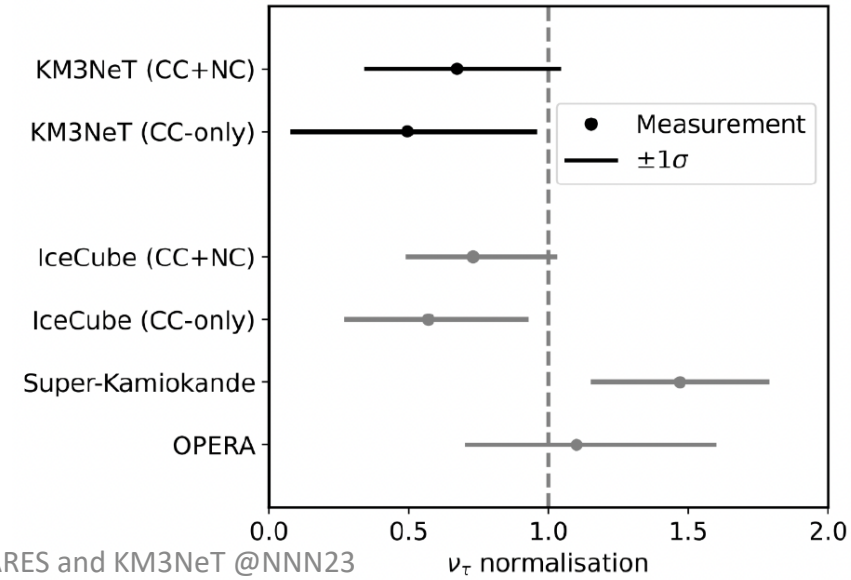
- Huge improvement with ORCA6 (510 days)



PoS(ICRC2023)996



Excess of showers consistent with ν_τ appearance



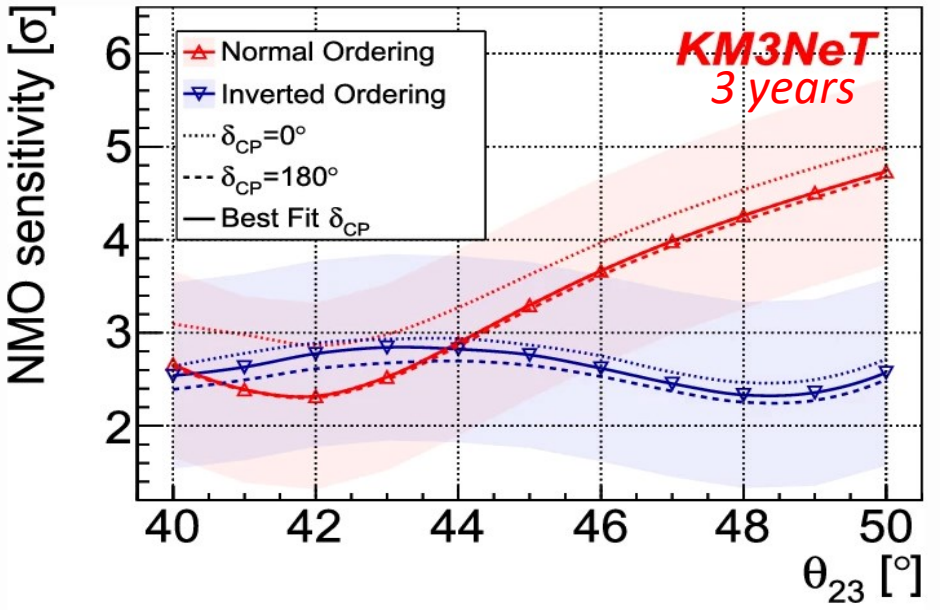
PoS(ICRC2023)1107

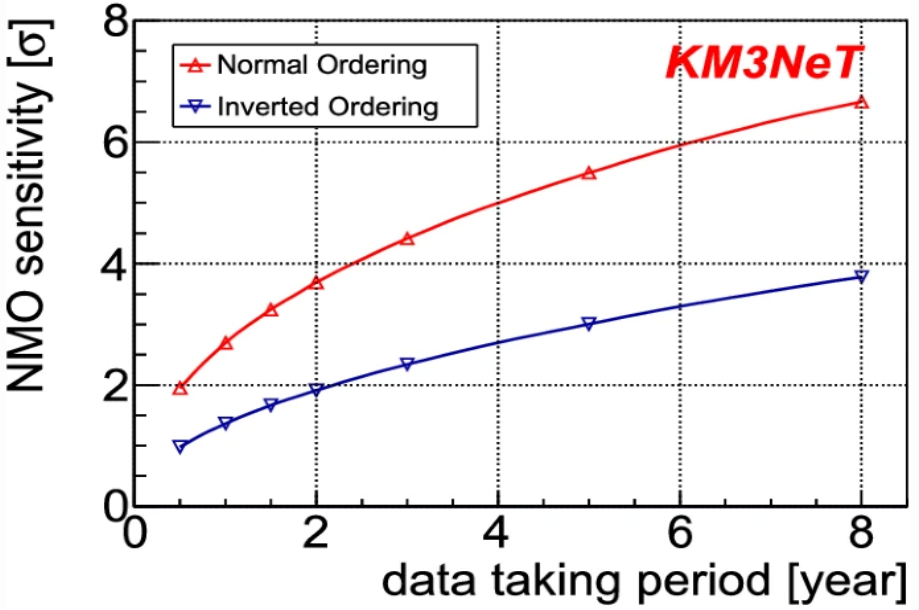
For results on constraints on:

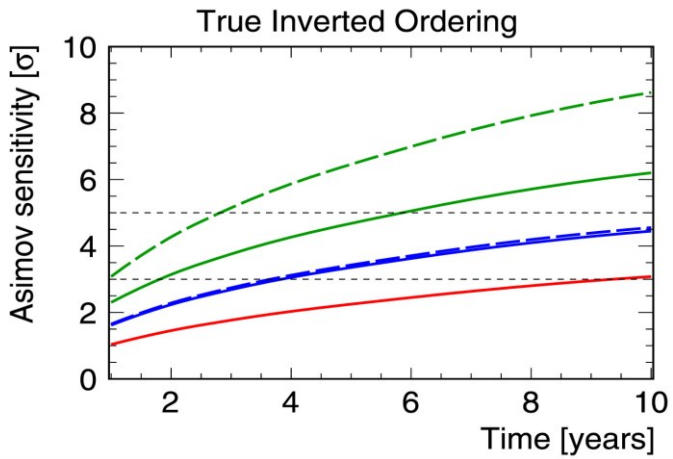
- ν NSI — PoS(ICRC2023)998
- ν decoherence — PoS(ICRC2023)1025
- ν decay — PoS(ICRC2023)997

Neutrino Mass Ordering: KM3NeT/ORCA goal

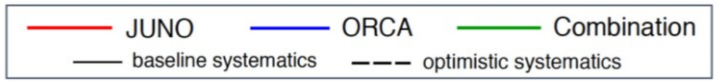
- Earth matter affects the oscillation pattern depending on NMO 📖 EPJ. C 82, 26 (2022)







- Exploiting synergies with reactor experiments can boost the measurement 📖 JHEP, 55 (2022)



Physics Studies

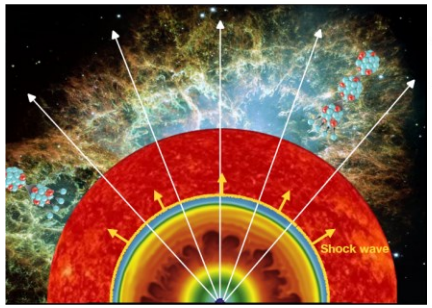
Supernovae Explosion

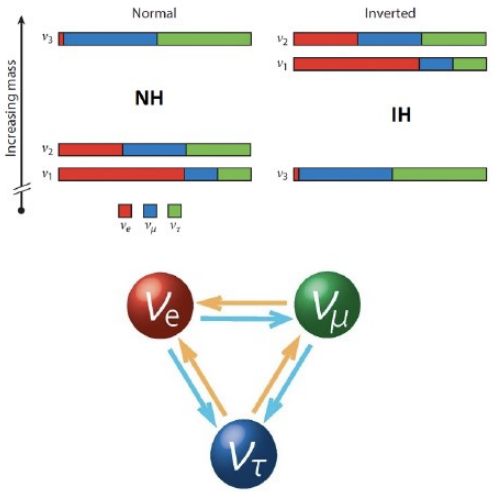
Neutrino Physics

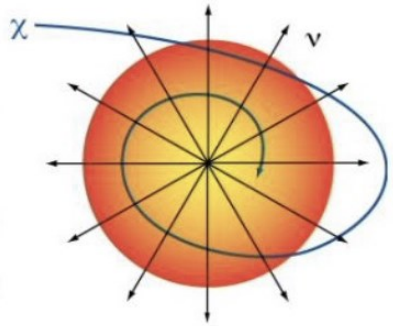
Dark Matter & Exotic searches

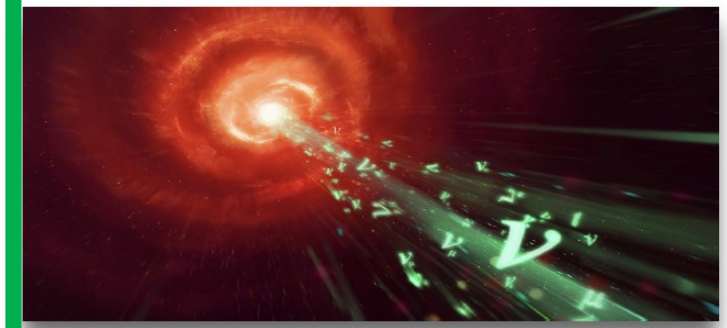
Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV









KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

Dark Matter

DM Earth

Physics of the Dark Universe, 16 (2017) 41–48

DM Sun

PoS(ICRC2023)1406

Phys.Lett. B759 2016
JCAP 05 (2016) 016
JCAP11 (2013) 032

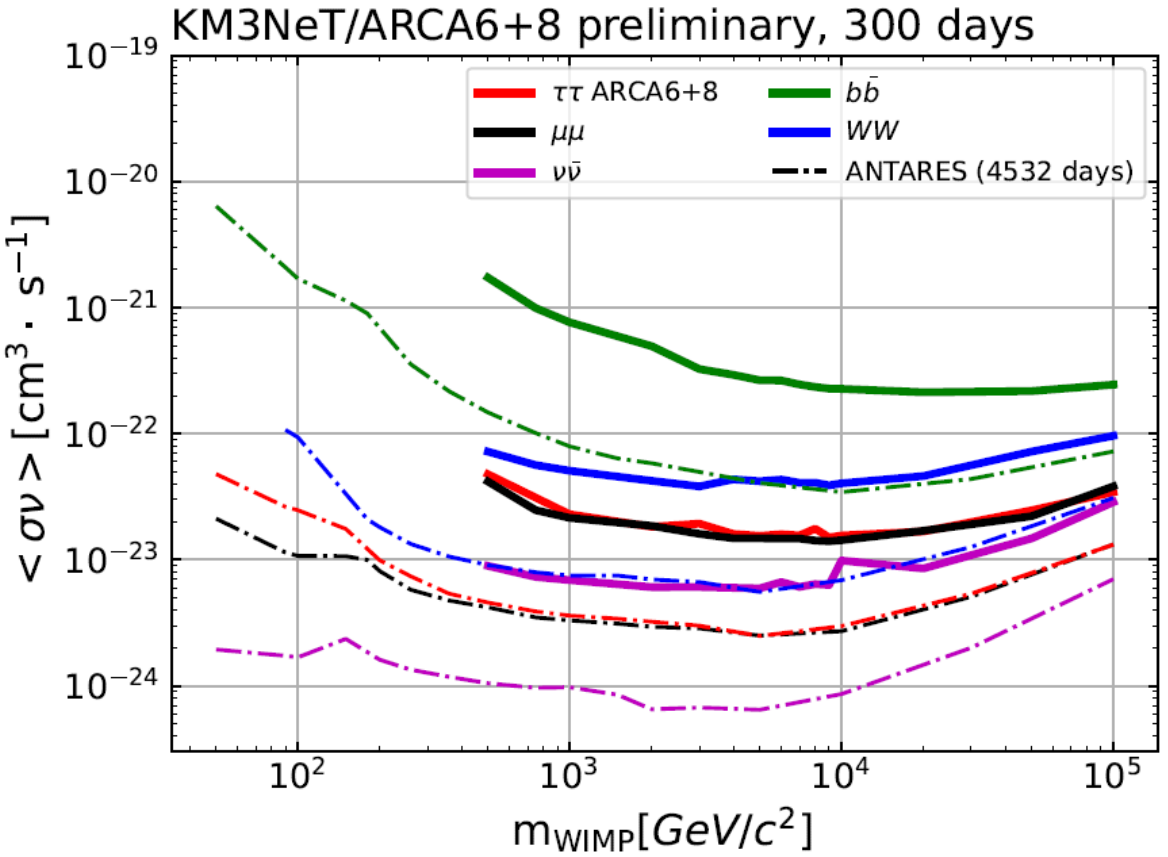
DM Galactic Center

JCAP 06 (2022) 06, 028 (secluded DM)
Phys. Lett. B 805 135439 (2020). *PoS(ICRC2023)1375*
Phys. Rev. D 102, 082002 (2020) *PoS(ICRC2023)1377*
Phys. Let. B 769 (2017) 249 *PoS(ICRC2023)1443*
JCAP 10 (2015) 068

Exotic

Magnetic monopoles: JHEAp, 34, 2022, 1-8 ;
Nuclearites (SQM): JCAP01(2023)012

Full ANTARES (4532.16 days) & ARCA6+8 (300 days)



The 90% CL upper limits on the thermally-averaged WIMP annihilation cross section vs. WIMP mass for each of the five annihilation channels using the GC direction

Physics Studies

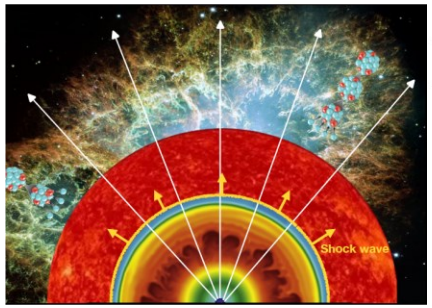
Supernovae Explosion

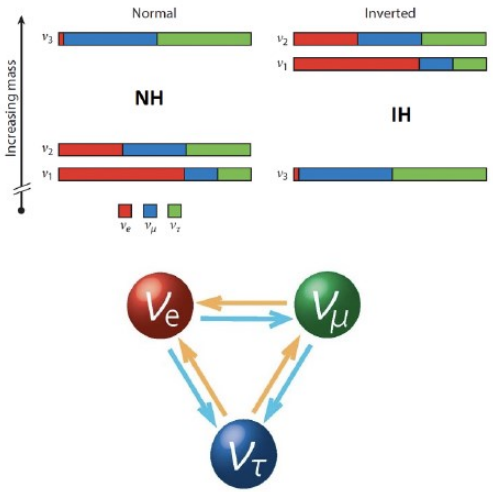
Neutrino Physics

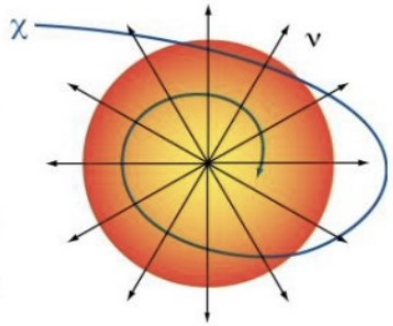
Dark Matter & Exotic searches

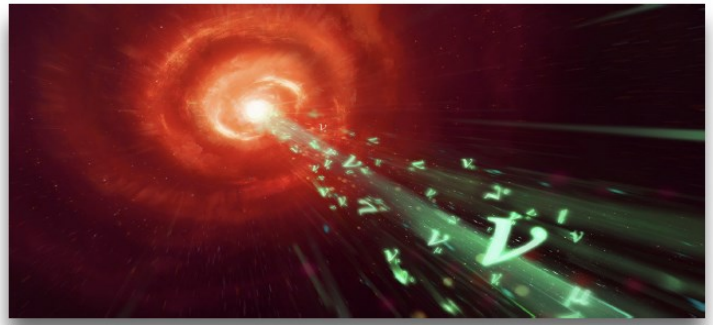
Cosmic neutrinos Multi-messenger program

MeV GeV TeV PeV







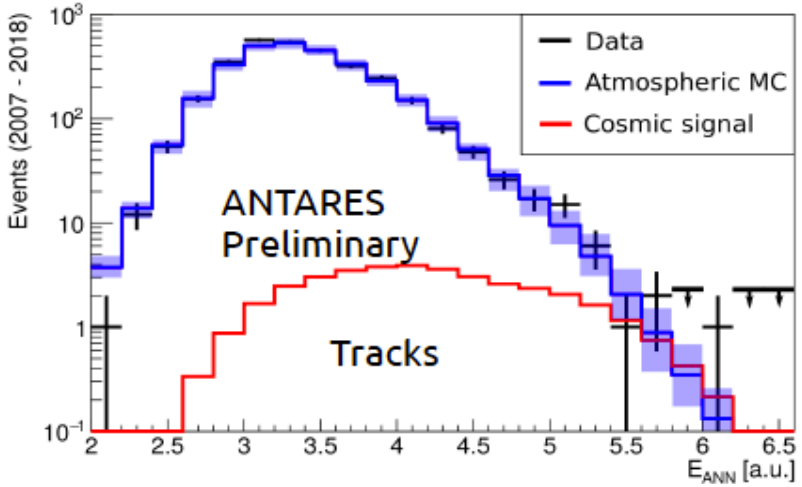


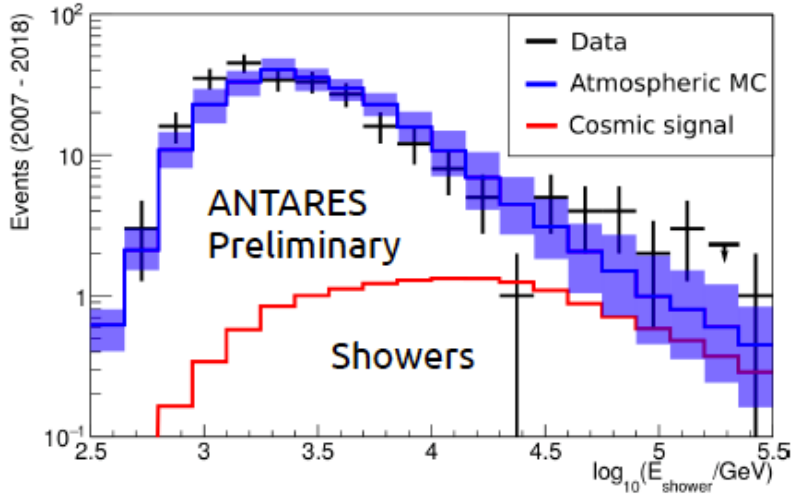
KM3NeT(-ORCA) ANTARES KM3NeT(-ARCA)

Diffuse ν flux searches

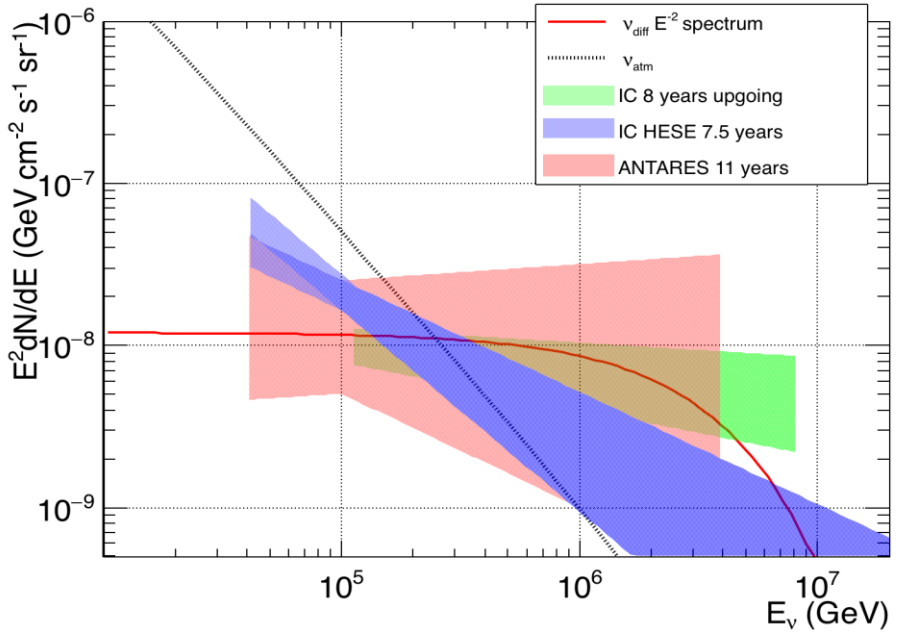
Data sample 2007-2018 (3330 days) All-sky / All-flavor neutrino search

- Selection cuts optimized with Model Rejection Factor procedure (spectral index Γ = 2.5)
- Look for excess above a given energy threshold





Data: **50 events** (27 tracks + 23 showers)
Background expectation (atm. flux, incl. prompt) :
36.1 ± 8.7 (19.9 tracks & 16.2 showers)

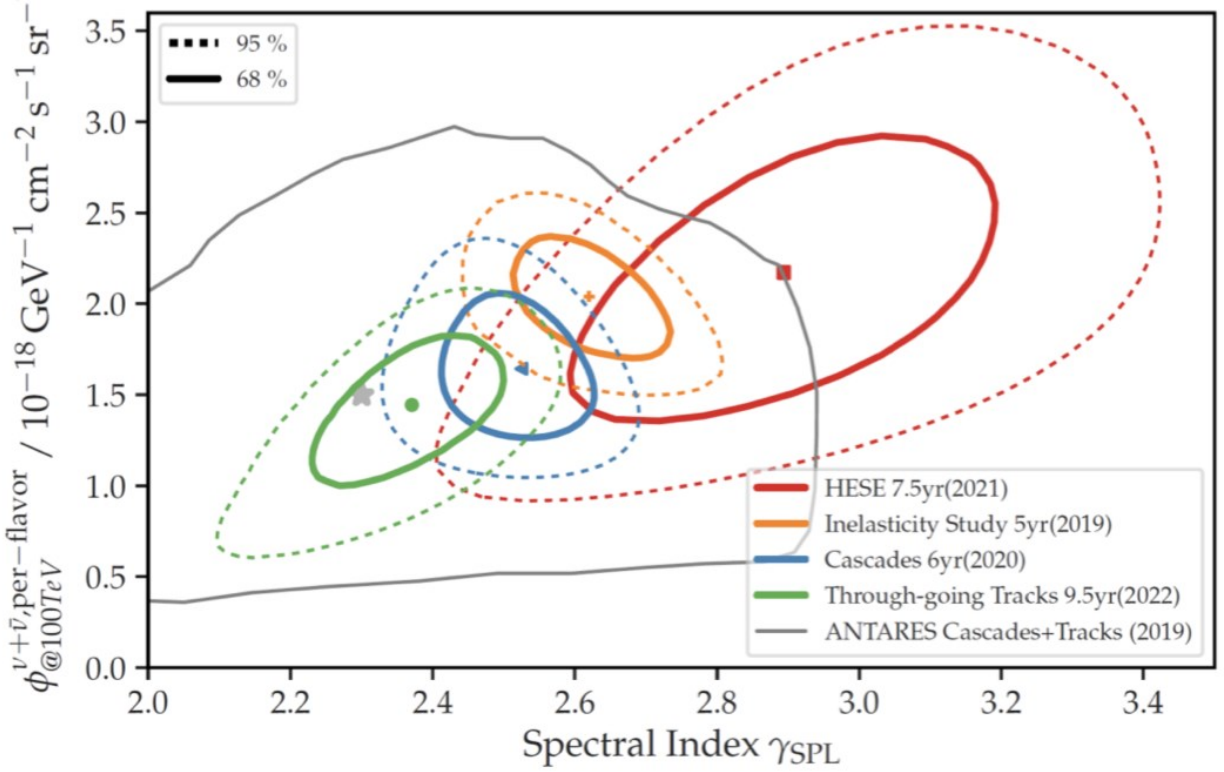


$\Phi_{100TeV} = (1.5 \pm 1.0) \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}
$\Gamma = 2.3 \pm 0.4$

Ap.J.Lett. 853 (2018) 1, L7

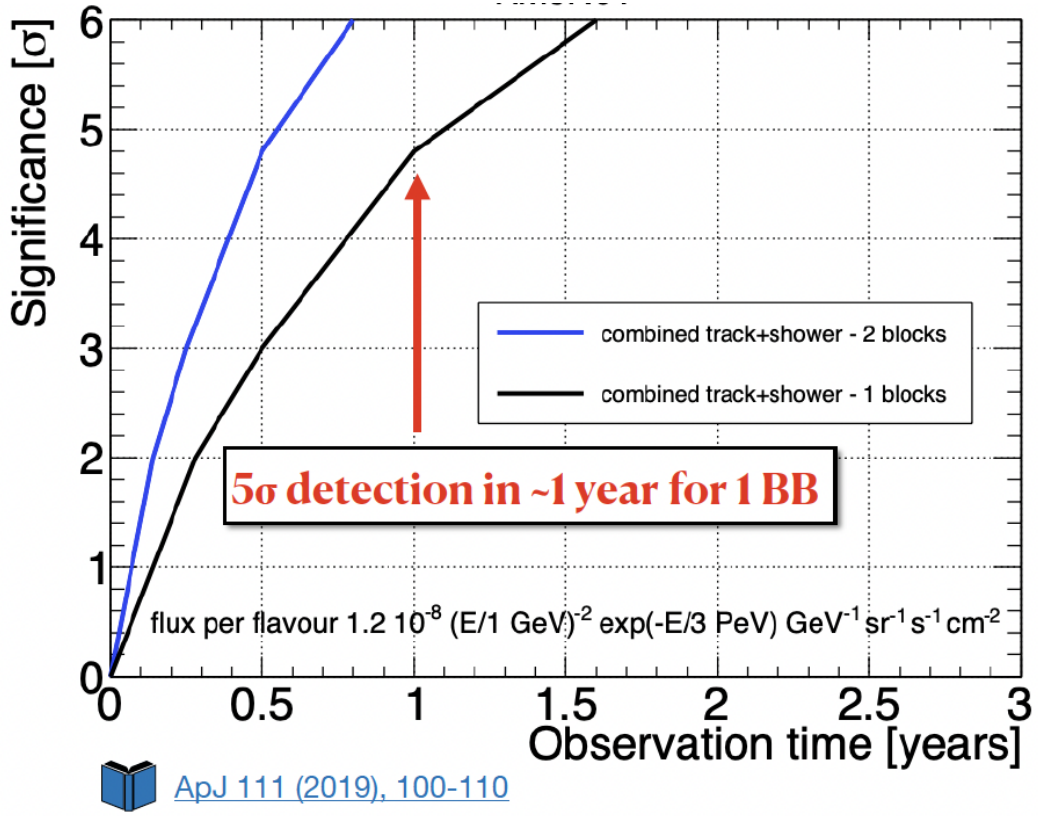
Diffuse flux – Towards a confirmation of IC

- Final ANTARES sensitivity ~ IceCube flux



Snowmass 2021: 🕮 arXiv:2203.08096

- Independent confirmation with KM3NeT

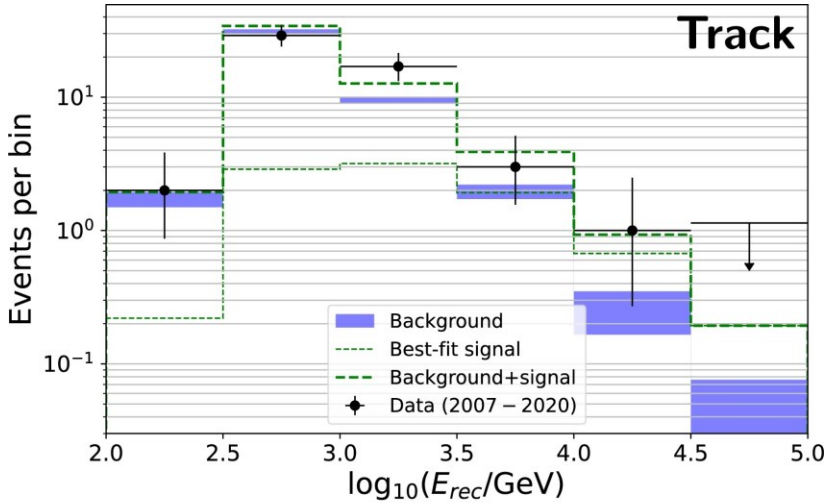


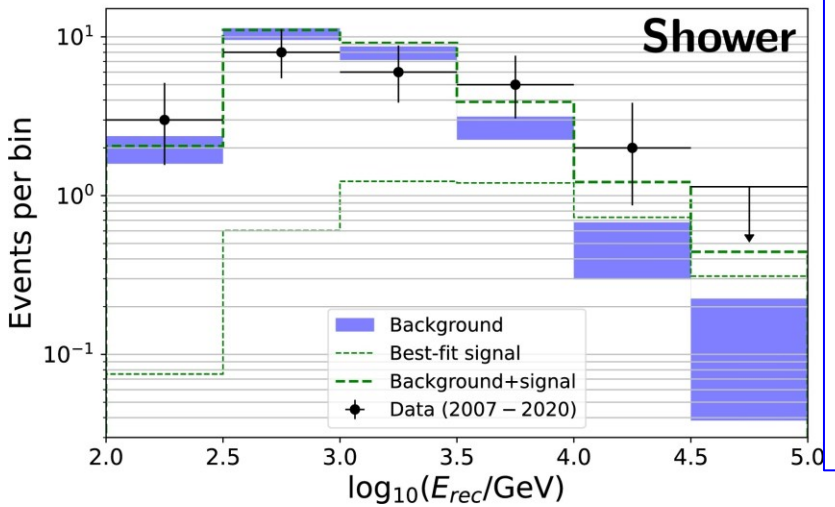
🕮 ApJ 111 (2019), 100-110

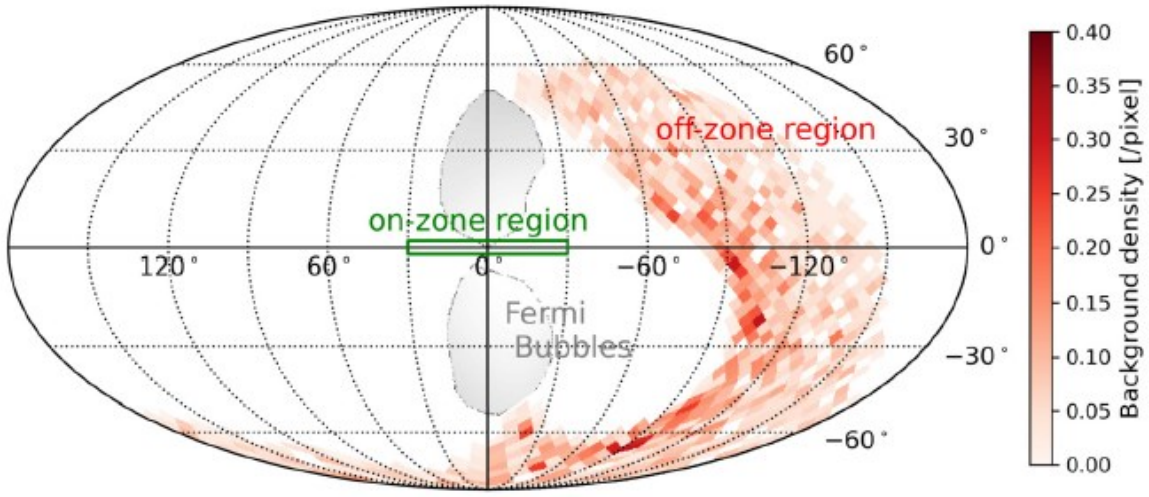
Preliminary KM3NeT results: 🕮 PoS(ICRC2023)1195

Search for Diffuse Galactic Emission

- More robust analyses: background measured from OFF regions of same local acceptance

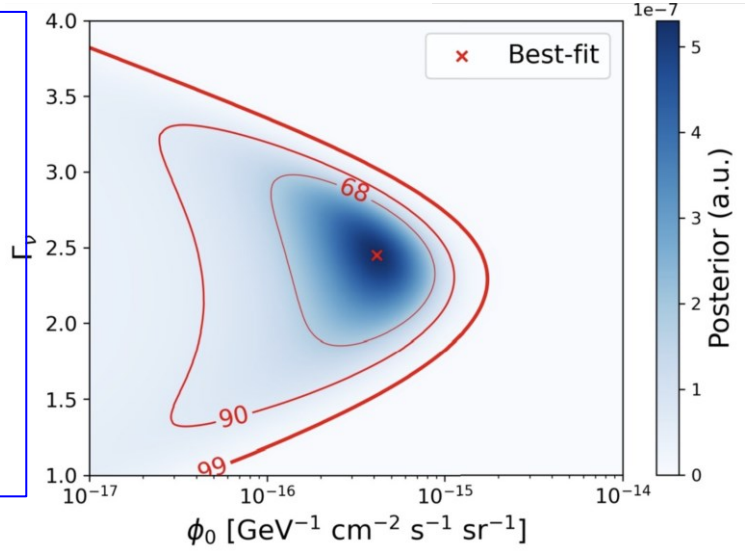




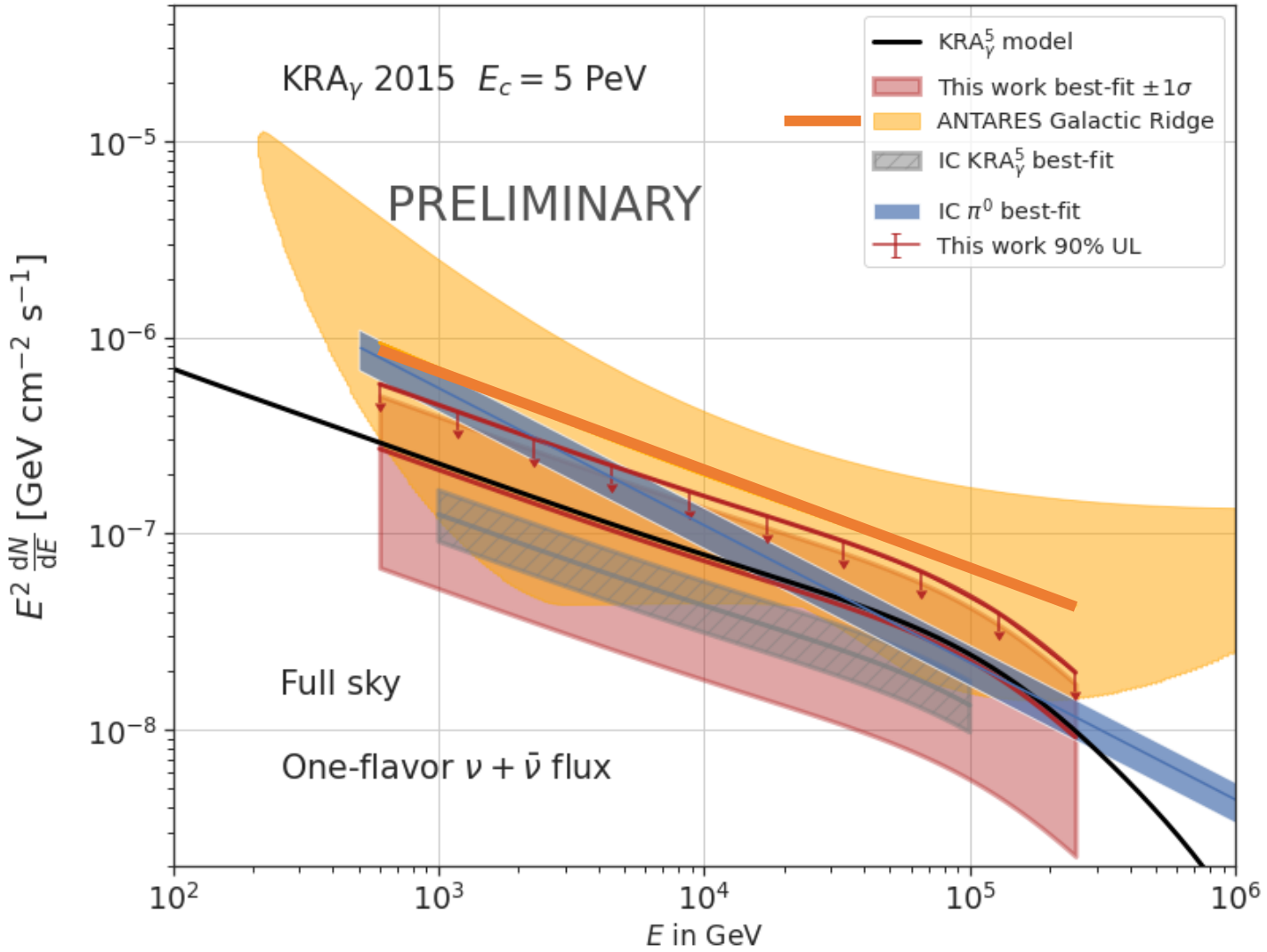


Above 1 TeV:

- Signal region: **21 (13)** tracks (showers)
- Background, **11.7 ±0.6 (11.2 ±0.9)**
- Background rejection significance of 98%, i.e. 2.2 σ one-tailed excess.
- Compatible with IceCube signal



Comparison with IceCube «template» results

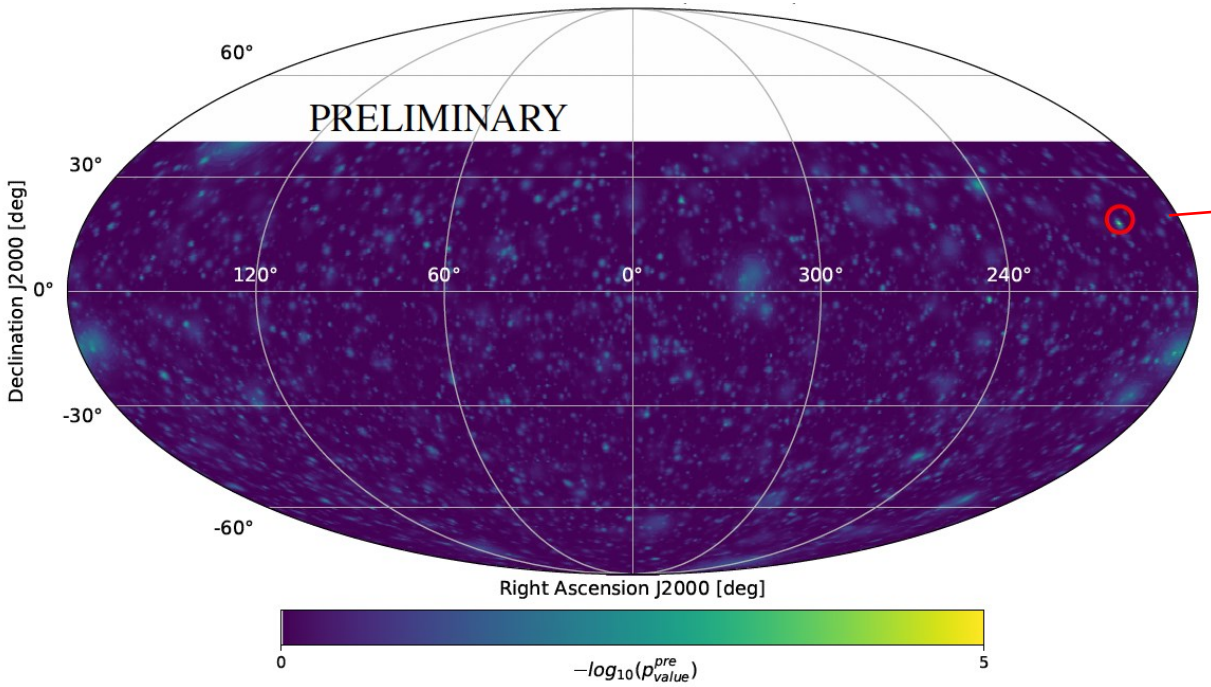


- ANTARES best fit from above the CR propagation models, even though its uncertainties are rather large
- ANTARES above the IceCube best fit
- IceCube results are a factor ~2 below the CR models for KRA-models, while above the π^0 model

This has triggered investigations

- V. Vecchiotti et al., arXiv.2306.16305
- A. Ambrosone et al. arXiv.2306.17285
- A. Neronov et al., arXiv.2307.07978
- LHAASO Coll., PoS(ICRC2023) 1091
- G. Schwefer et al. PoS(ICRC2023)1502
- G. Giacinti et al, *PoS* ICRC2023) 813
- ….

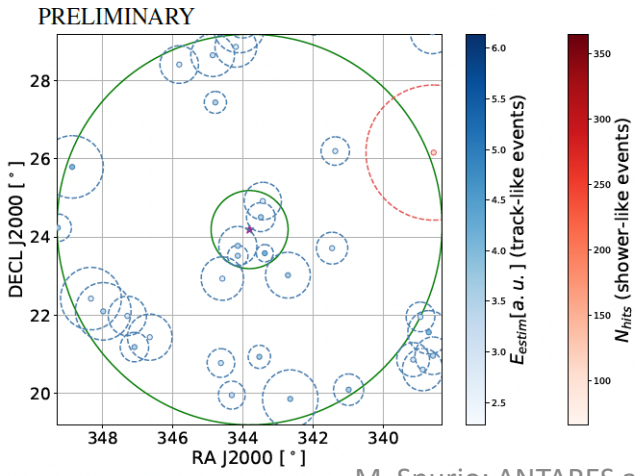
Search for Point Sources



ANTARES 2007-2022 final sample:
11029 tracks and 239 showers

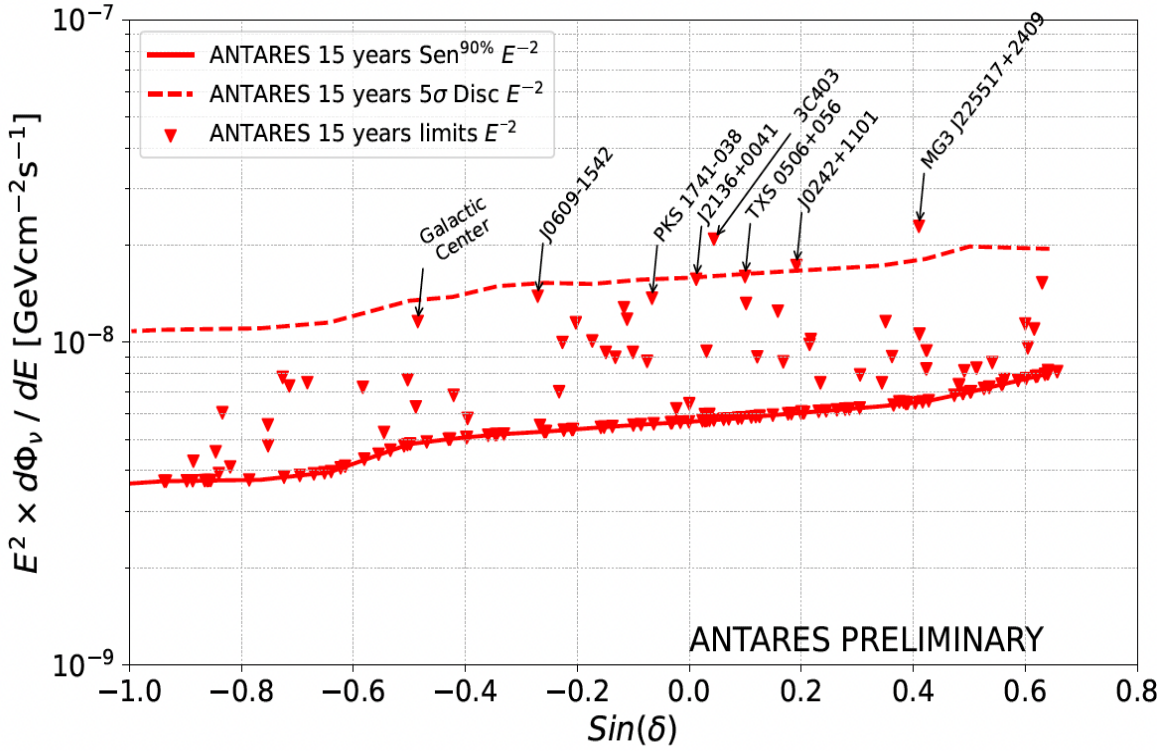
Hottest spot (δ, RA) = (17.74, 200.46)
Pre(post)-trial significance 4.0σ (1.2σ)

📖 PoS(ICRC2023)1128



Candidate-list search

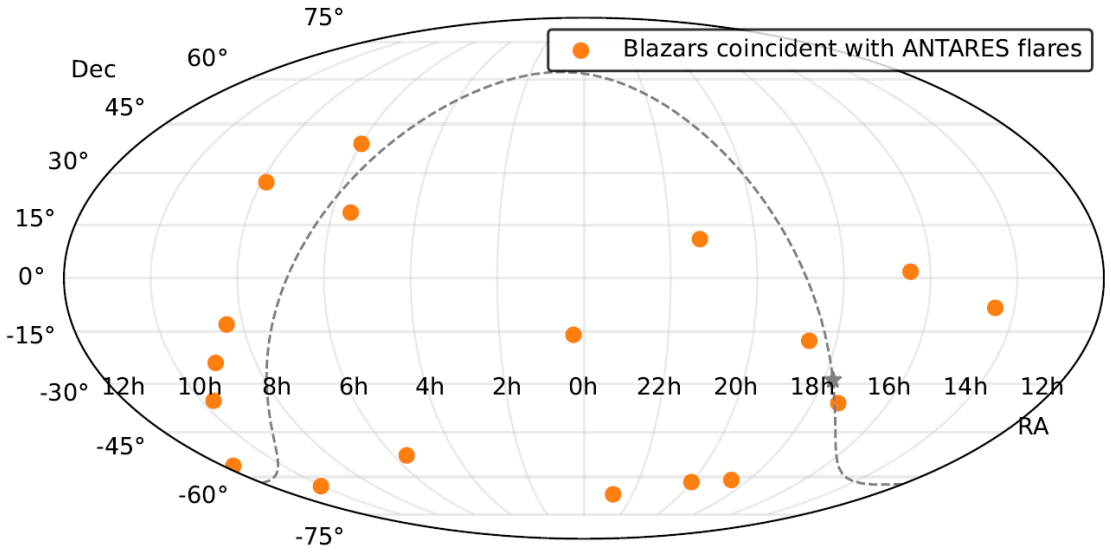
Most significant:
MG3 J225517+2409
Pre(post)-trial 3.4σ (1.7σ)



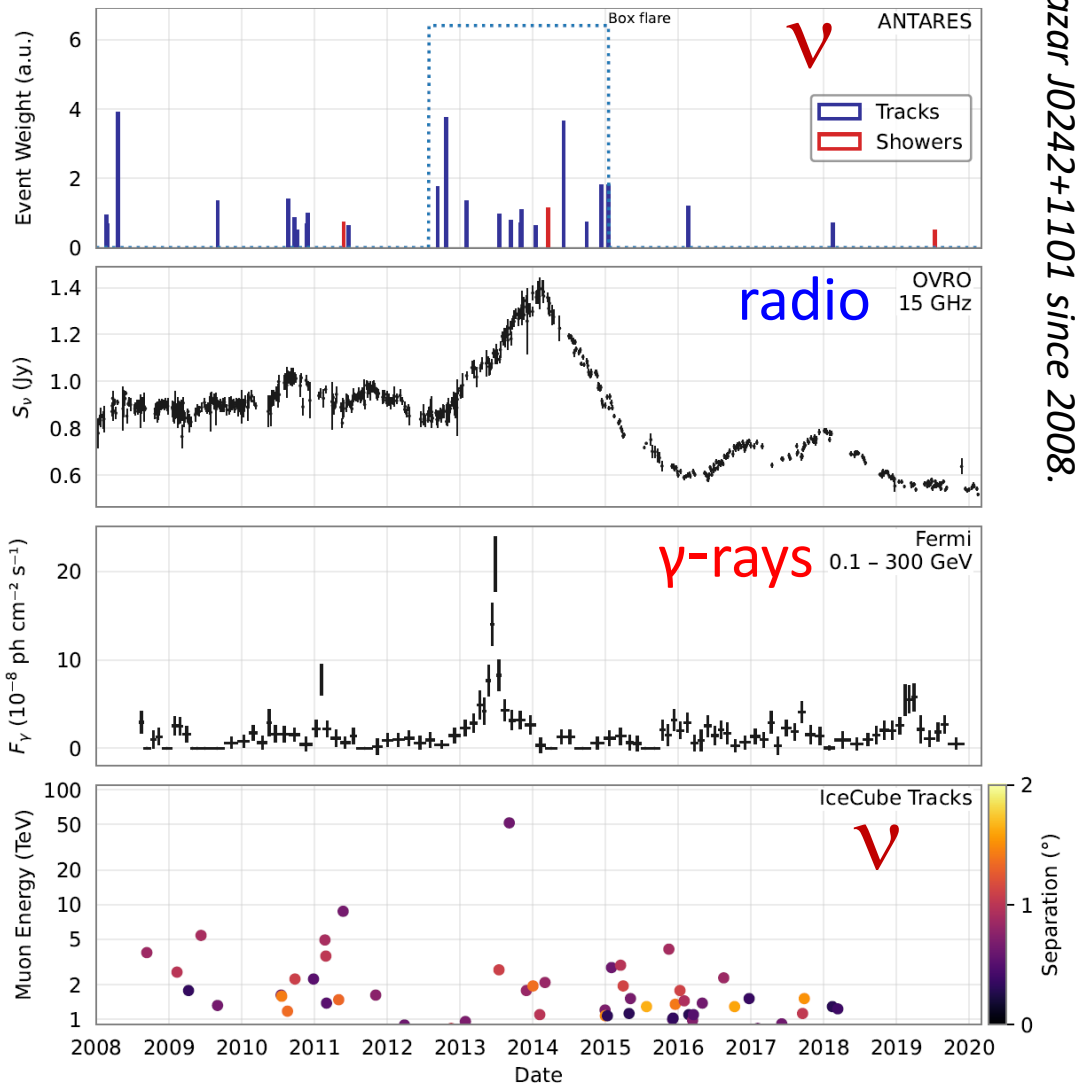
ν in the direction of radio-bright blazars

📖 arXiv:2309.06874

- ν-blazar directional correlation tested by a likelihood approach.
- The resulting post-trial p-value is 3.0% (2.2σ in the two-sided)
- A time-dependent analysis searching for temporal clustering of ν's yields **18 sources** with a pre-trial significance above 3σ indicates a p = 1.4% (2.5σ two-sided).
- An a posteriori investigation reveals a temporal coincidence of neutrino, radio, and γ-ray flares of **J0242+1101 blazar** at a p = 0.5% (2.9 σ two-sided) level.



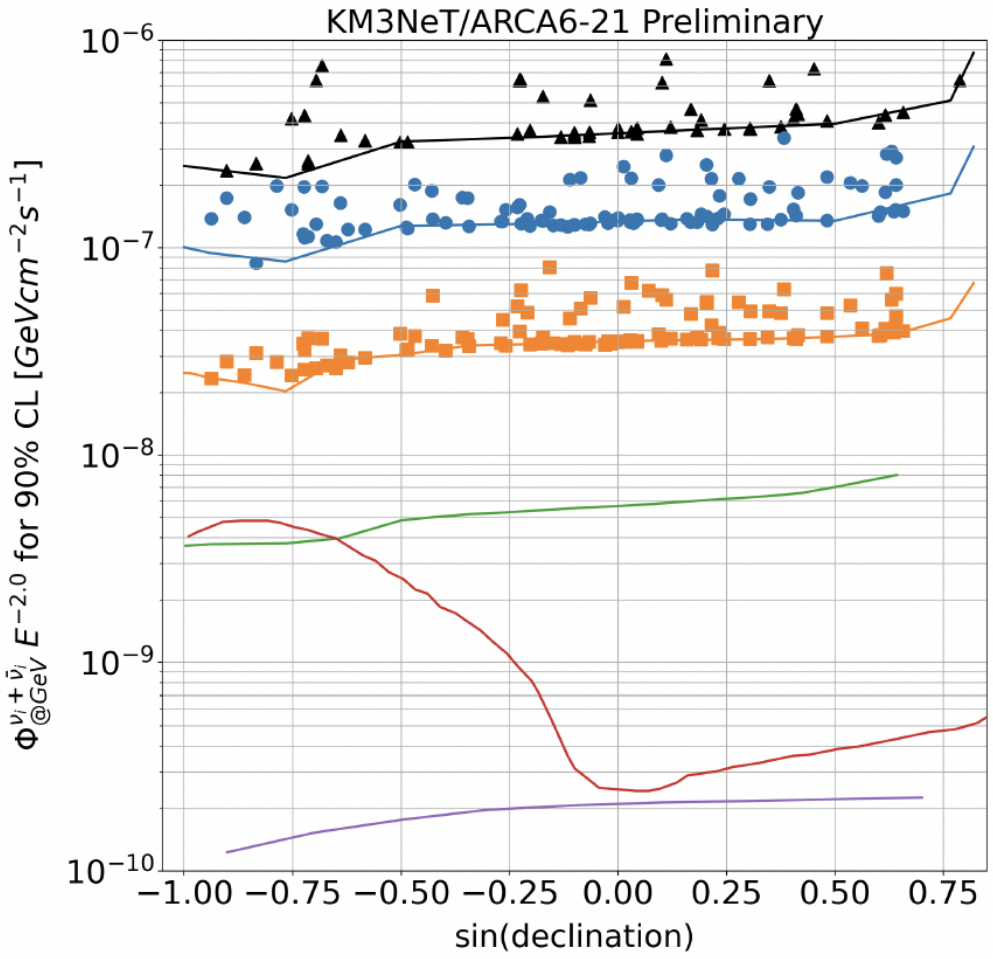
J0242+1101

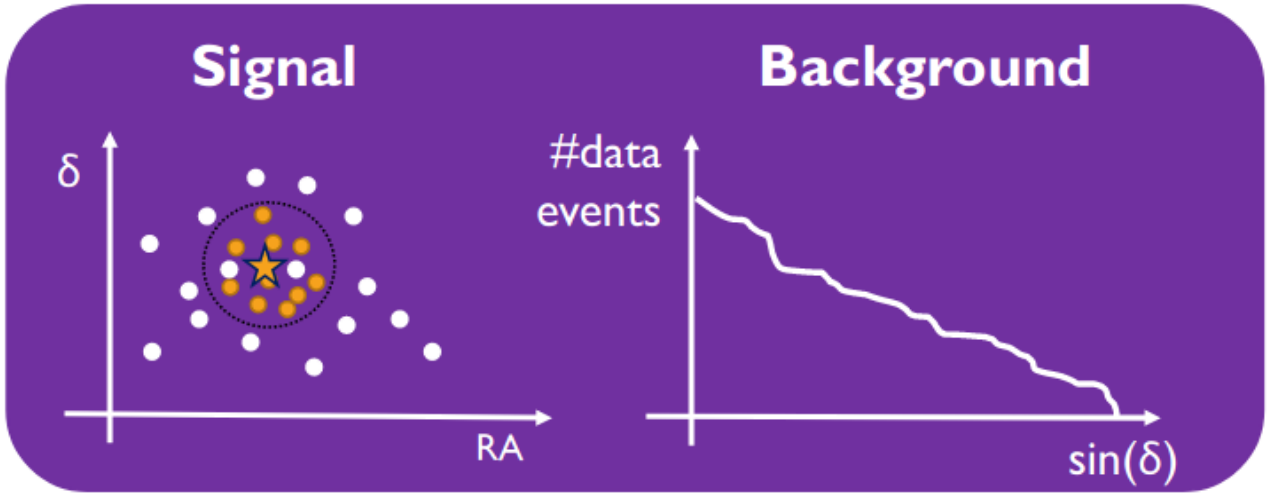


Multi-messenger light curves from the direction of the blazar J0242+1101 since 2008.

Search for point sources: perspectives

📖 PoS(ICRC2023)1018 & 1075



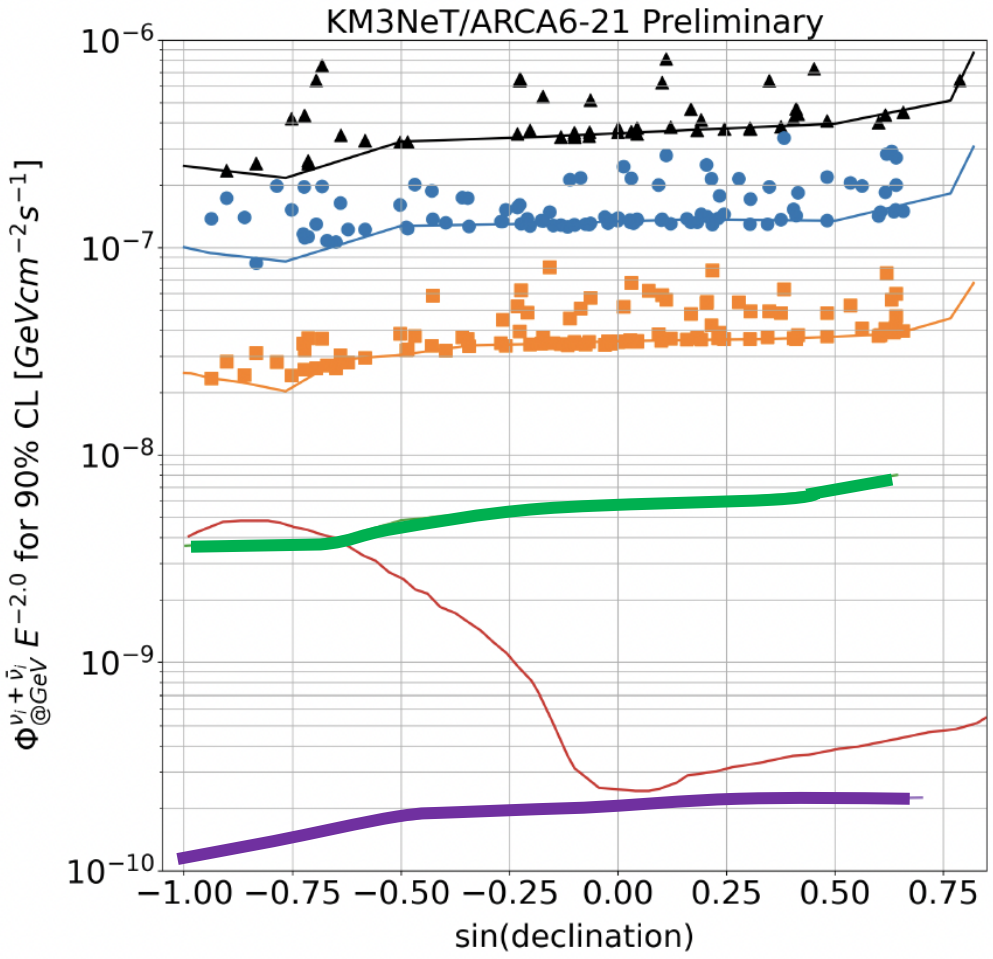


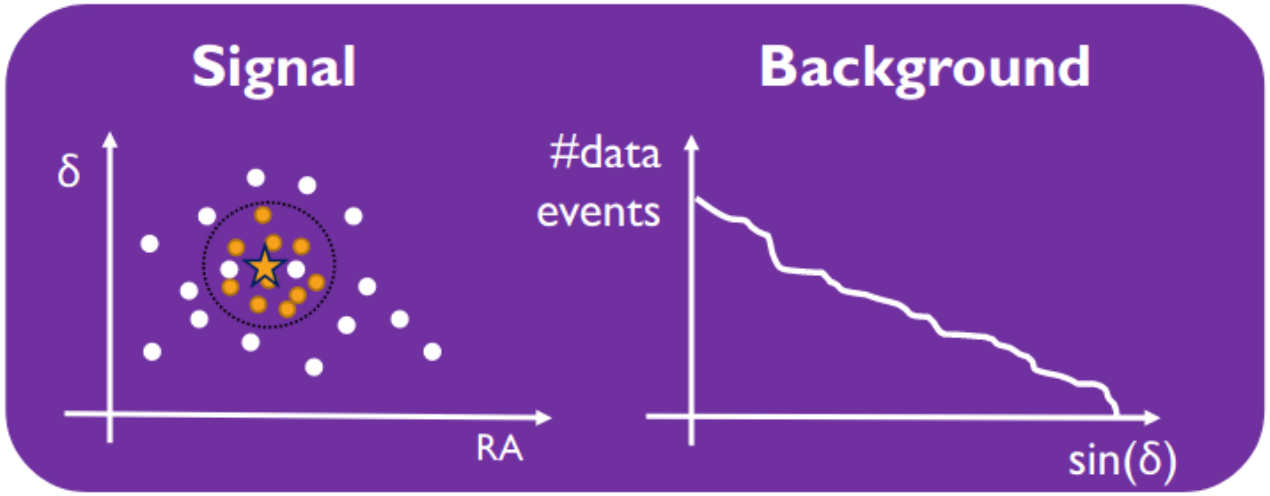
Sensitivity
- ARCA6 (92 days)
- ARCA6-8 (302 days)
- ARCA6-21 (424 days)
- ANTARES (15 yr)
- IceCube (10 yr)
- ARCA230 (10 yr)

Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

Search for point sources: perspectives

📖 PoS(ICRC2023)1018 & 1075





Sensitivity
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- ARCA6-8 (302 days)
- ARCA6-21 (424 days)
- ANTARES (15 yr)
- IceCube (10 yr)
- ARCA230 (10 yr)

ANTARES 15 y

KM3NeT/ARCA 10y

Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

The multi-messenger program

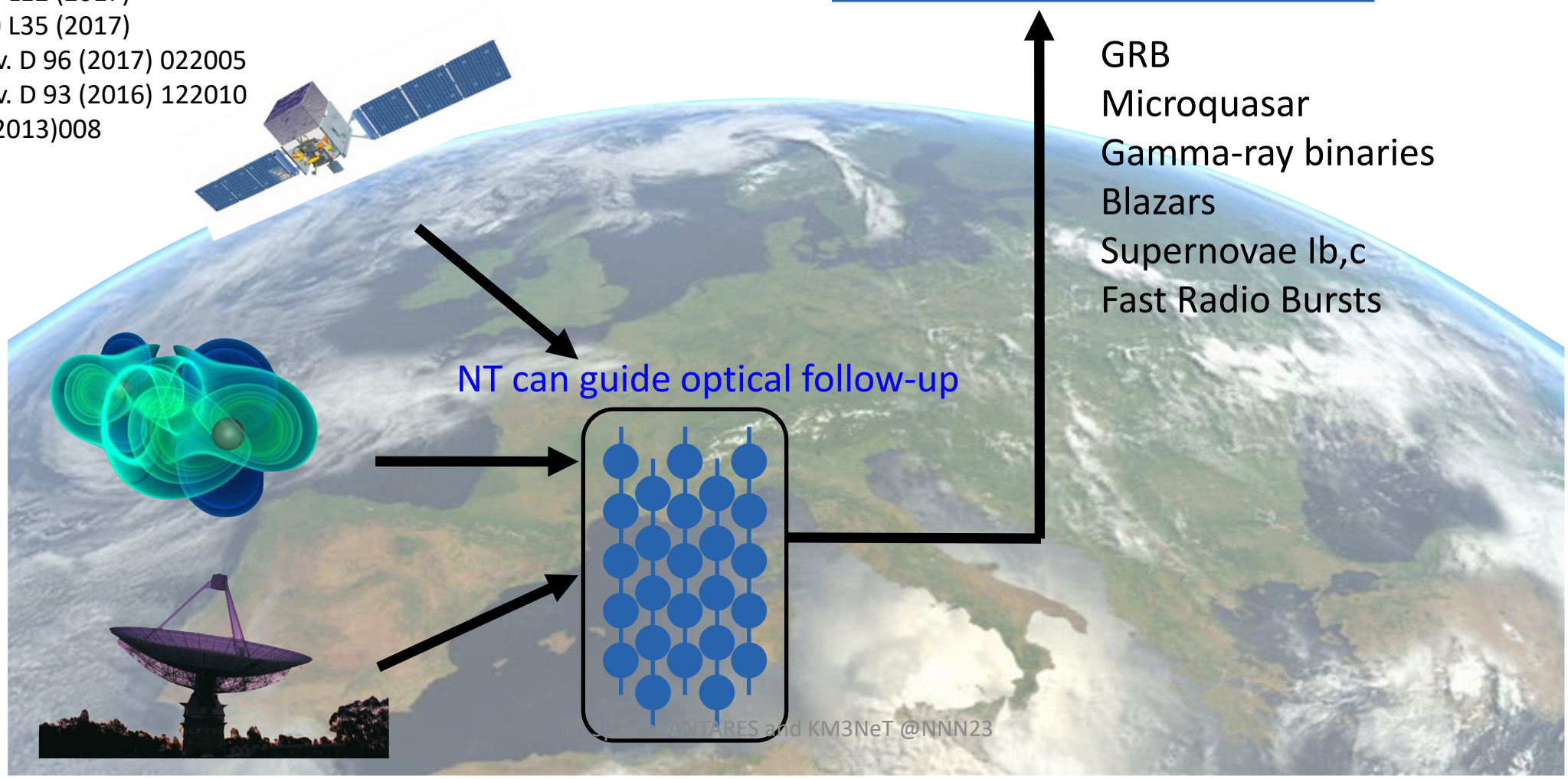
📖 Legacy paper arXiv:2211.07551

📖 Eur. Phys. J. C 80, 487 (2020)
📖 ApJ 870 (2019) 2
📖 ApJL 848 L12 (2017)
📖 ApJL 850 L35 (2017)
📖 Phys. Rev. D 96 (2017) 022005
📖 Phys. Rev. D 93 (2016) 122010
📖 JCAP06(2013)008

1ST APPROACH:

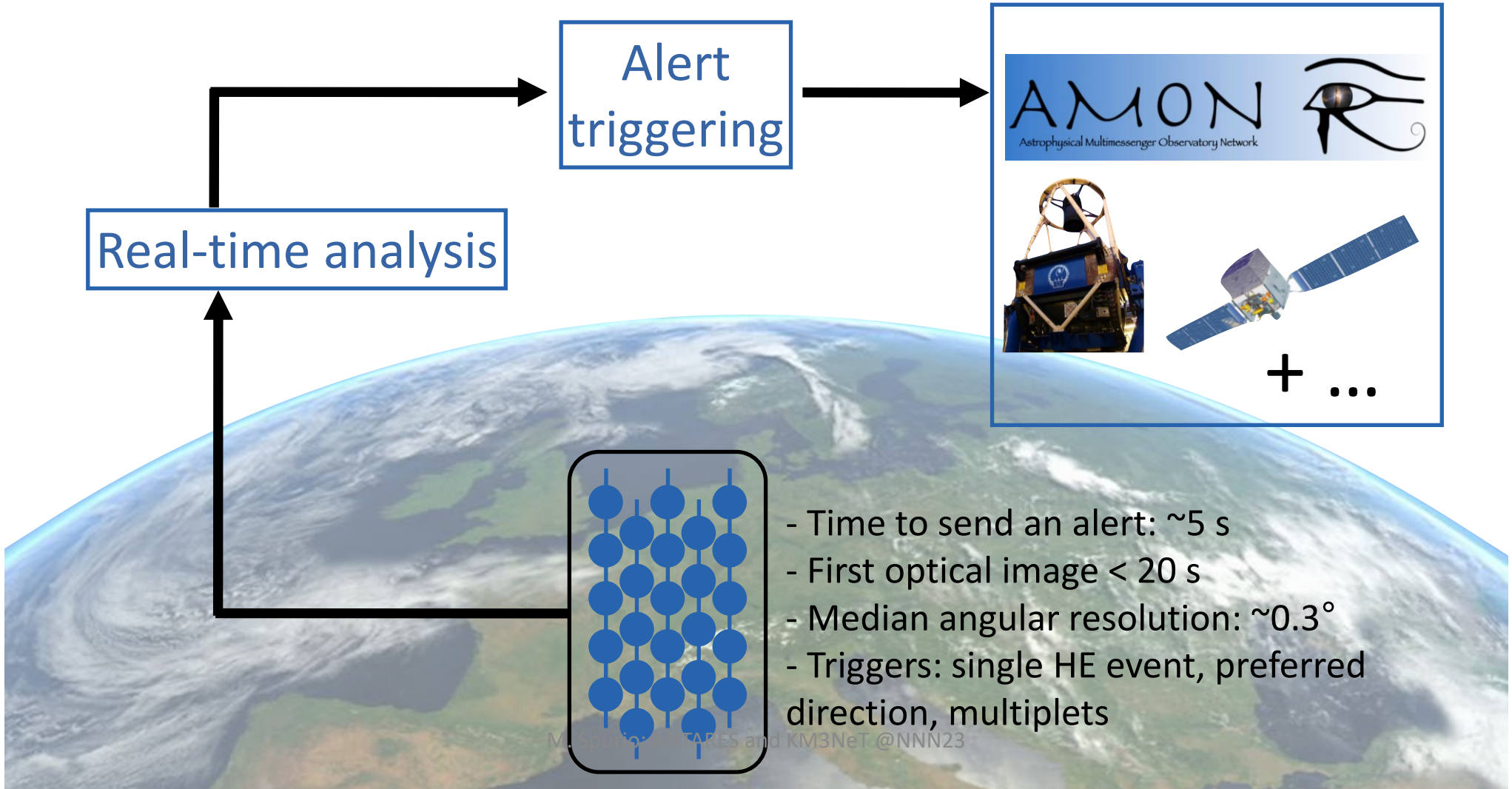
Time dependent searches

GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts

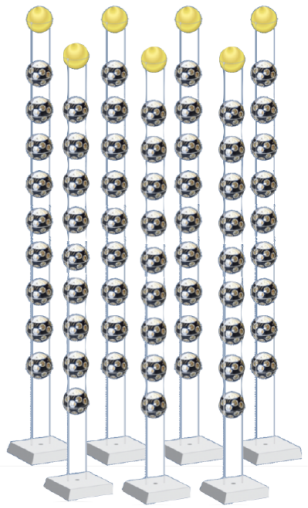


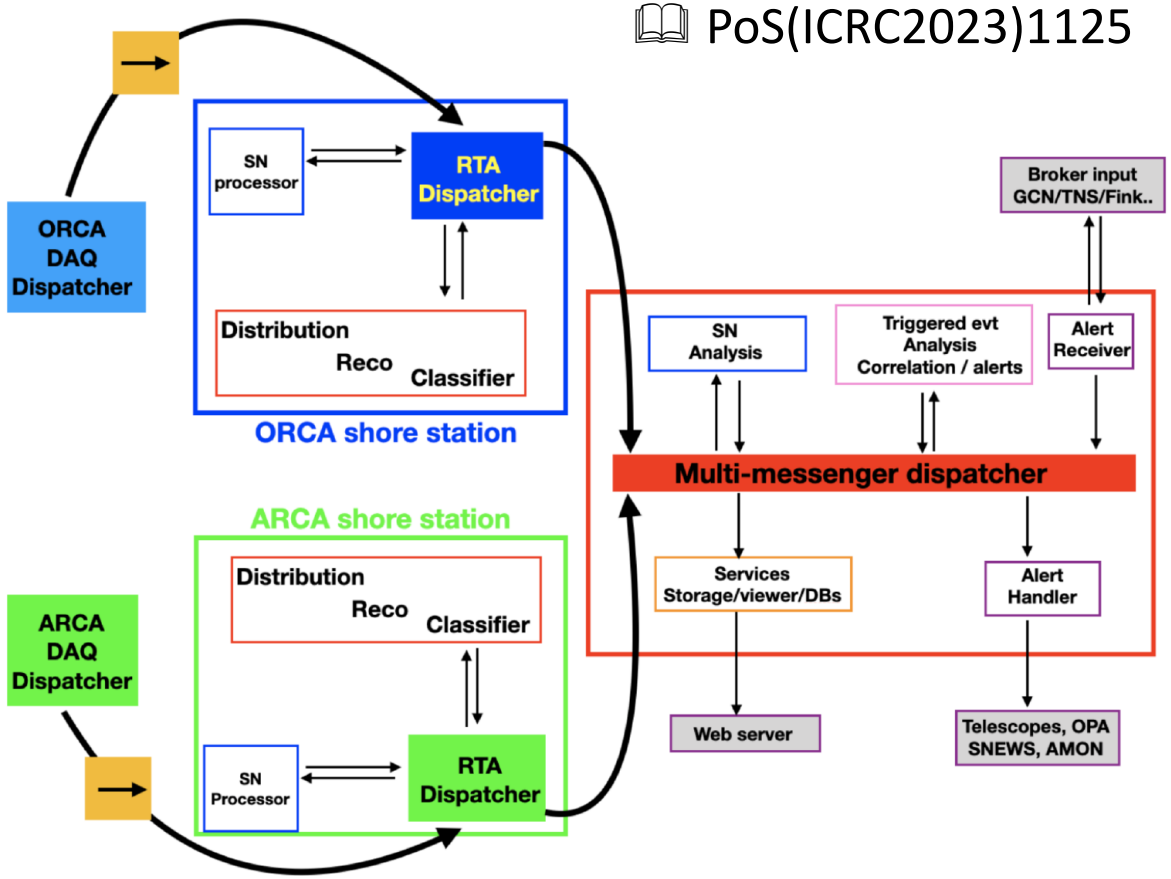
The multi-messenger program

2ND APPROACH:



KM3NeT taking up the torch online





📖 PoS(ICRC2023)1125

KM3NeT real-time platform active from November 2022

- On average ~4 s to reconstruct and classify ARCA events
- ~6 seconds to reconstruct and classify ORCA events

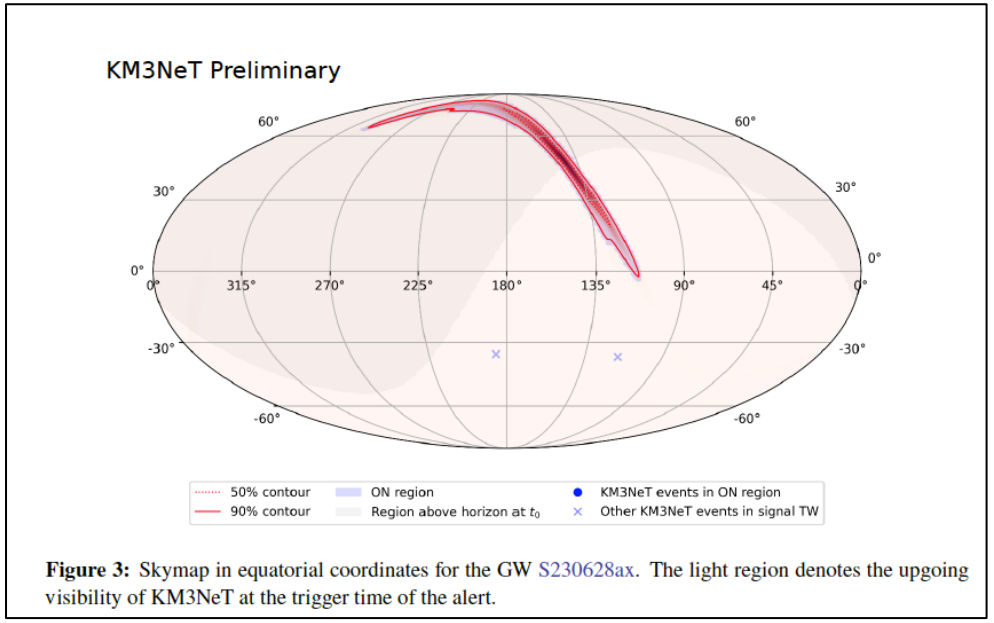


Figure 3: Skymap in equatorial coordinates for the GW S230628ax. The light region denotes the upgoing visibility of KM3NeT at the trigger time of the alert.

→ Follow-up of O3 events & on-going follow-up of O4 events 📖 PoS(ICRC2023)1506

Sea and Earth Science

During operation on the ANTARES/ KM3NeT site, last summer

📖 **Deep-Sea Research I 58 (2011) 875–884**
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

📖 **PLoS ONE 8 (7) 2013**
Deep-sea bioluminescence blooms after dense water formation at the ocean surface

📖 Ocean Dynamics, April 2014, 64, 4, 507-517
High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

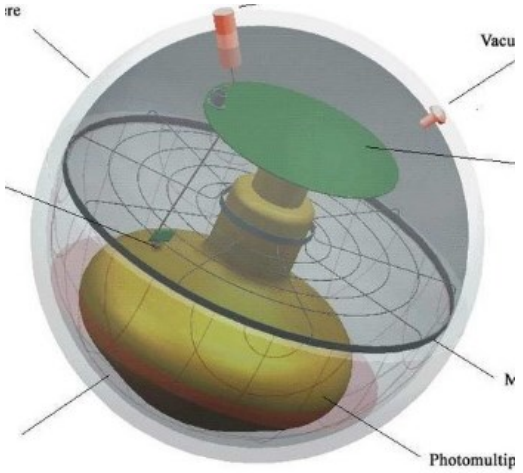
📖 **J of Geophysical Research: Oceans, 122, 3, 2017**
Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

📖 **Sci. Rep. 7 (2017) 45517**
Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 **https://arxiv.org/abs/2107.08063**
Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope

Conclusions

- **ANTARES**: first undersea Cherenkov detector
  - **Demonstration of the great potential of deep-sea Neutrino Telescopes**
  - Excellent angular resolution, view of Southern sky, competitive sensitivities
  - Constraints on the origin of the IceCube signal
  - Hint of a Galactic neutrino diffuse emission
  - Last results and legacy program to be pursued in the coming year

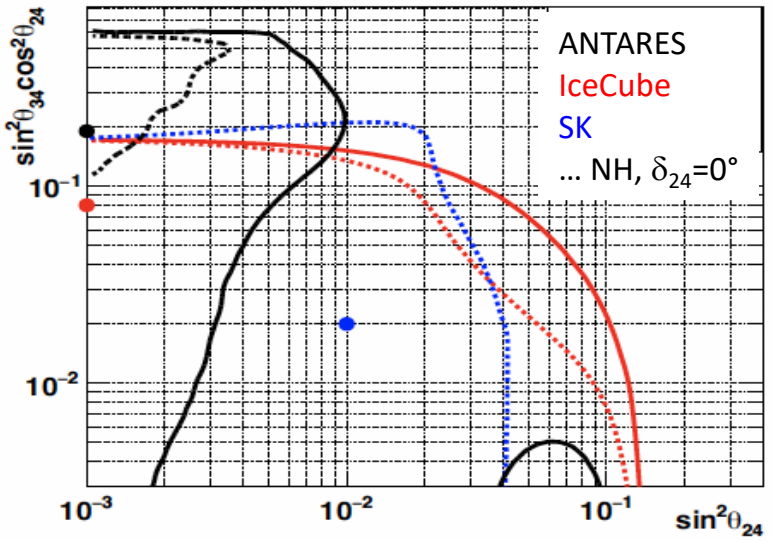


- **KM3NeT**: phased approach to next-generation neutrino telescope by 2028
  - Deployment of detection units at a good pace.
  - Now: KM3NeT/ARCA **28 strings** KM3NeT/ORCA **18 strings**
  - **KM3NeT/ORCA and ARCA combine a rich neutrino physics and astrophysics scientific scope, from MeV to PeV energies**
  - **Unique infrastructure for multidisciplinary program.**

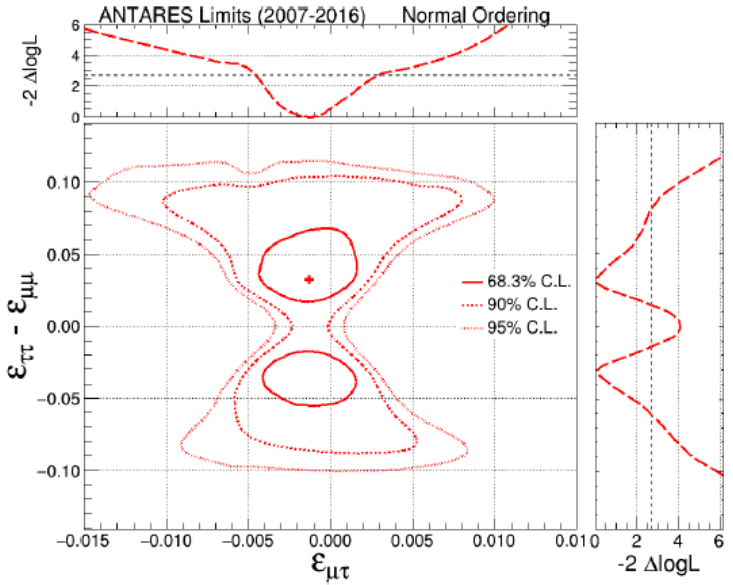
ν-oscillation studies: Sterile & NSI

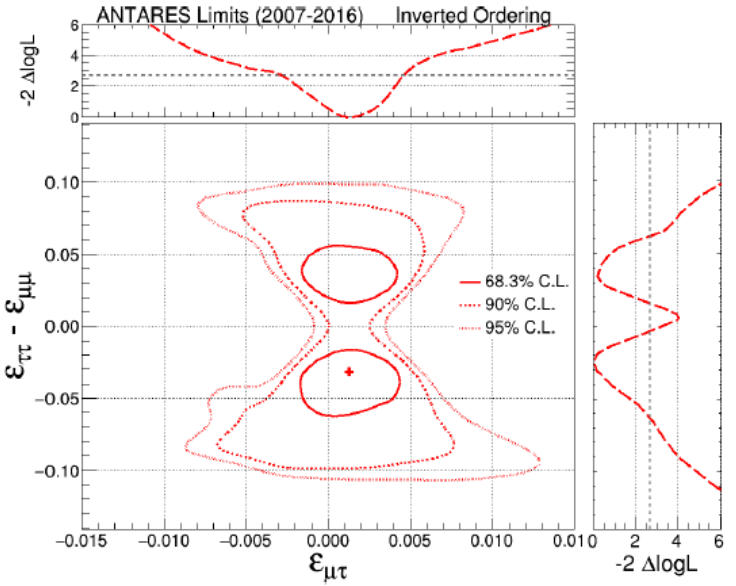
📖 JHEP (2019) 113
📖 JHEP (2022) 48

- (3+1) sterile neutrino models $\Delta m^2_{41} > 0.5\ eV^2$
- Our results (90% CL) exclude regions of the parameter space not yet excluded by other experiments.



- Non-standard interactions signature in ν oscillation patterns are detectable
- A log-likelihood ratio test of the dimensionless coefficients $\varepsilon_{\mu\tau}$ and $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ does not provide clear evidence of deviations from standard interactions.
- The non-NSI hypothesis is disfavored with a significance of 1.7σ (1.6σ) for the normal (inverted) mass ordering scenario.





Multidisciplinary Observatories

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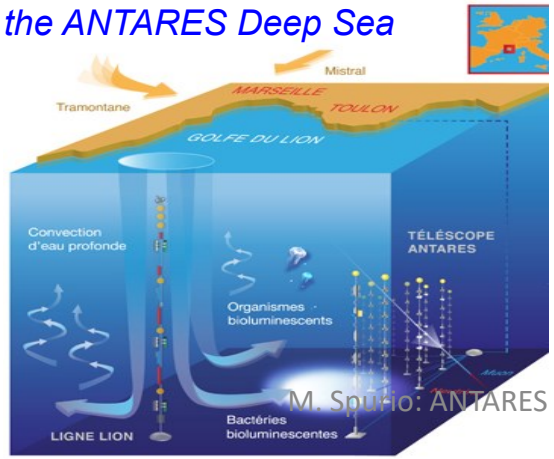
📖 https://arxiv.org/abs/2107.08063
Studying Bioluminescence Flashes with the ANTARES Deep Sea Neutrino Telescope

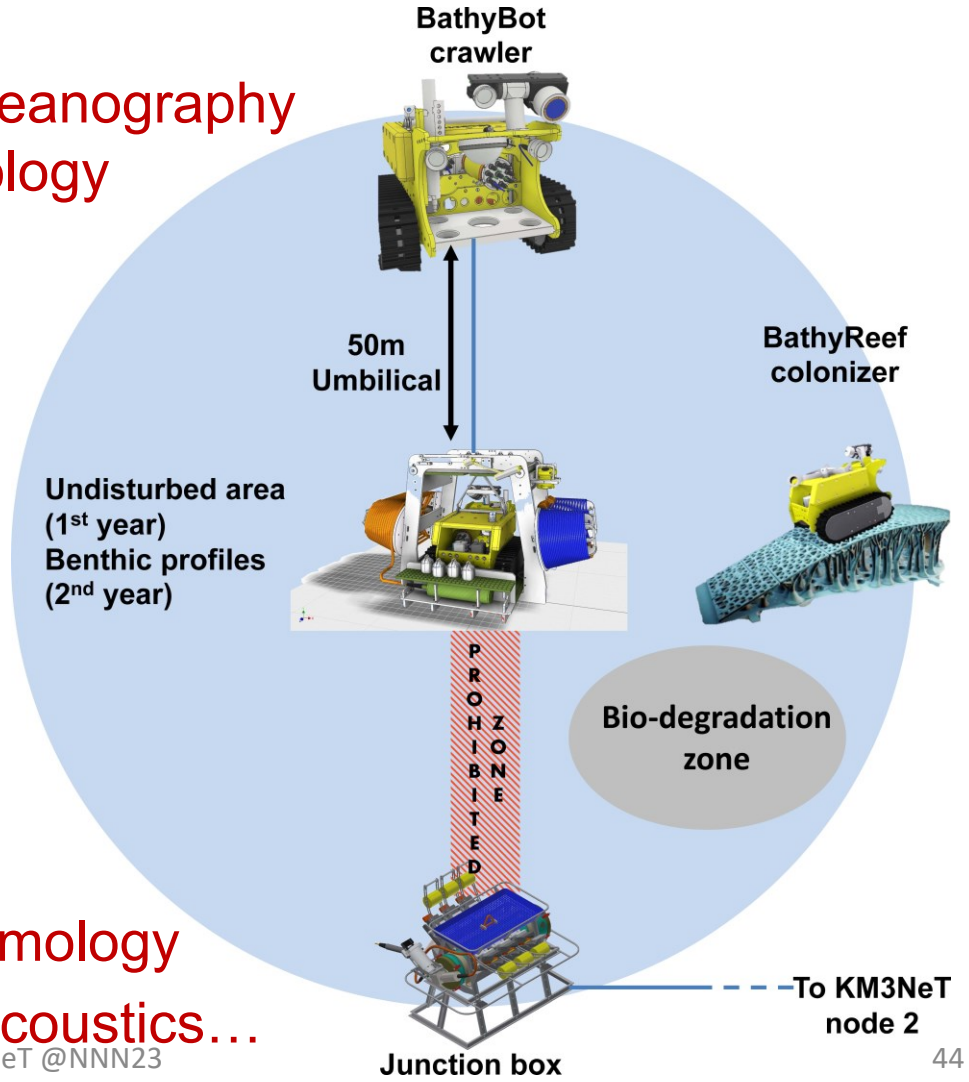
+ Citizen science

REINFORCE
REsearch INfrastructures FOR Citizens in Europe



A dedicated program on French KM3NeT Site

Oceanography
Biology



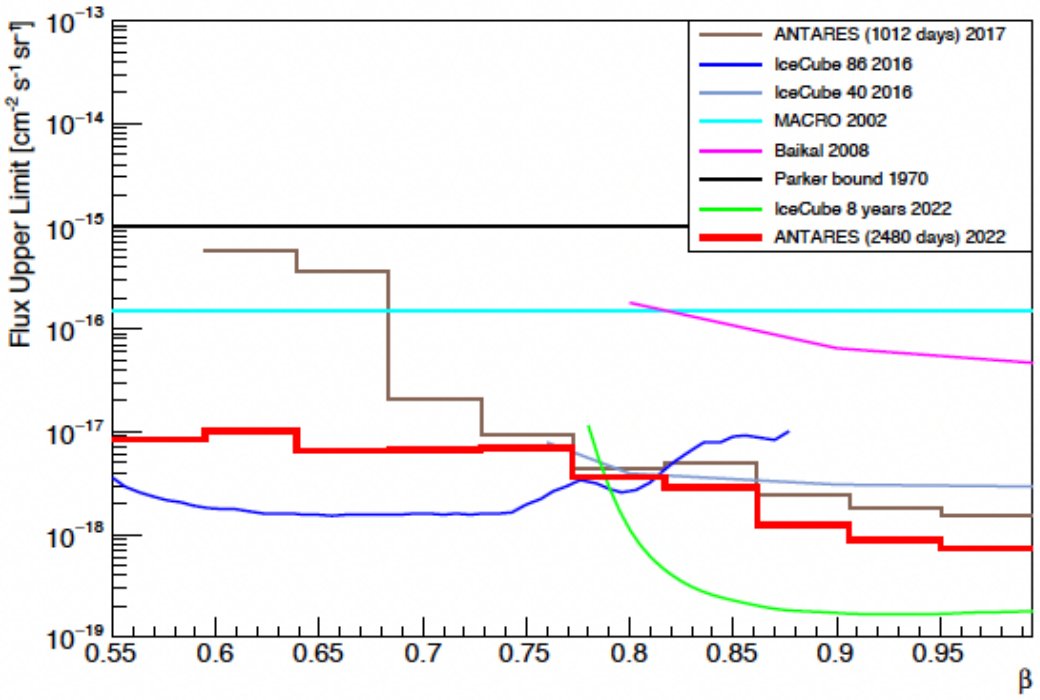
Seismology
Bioacoustics…

Search for Exotic Physics

Magnetic monopoles

Kasama, Yang and Goldhaber model

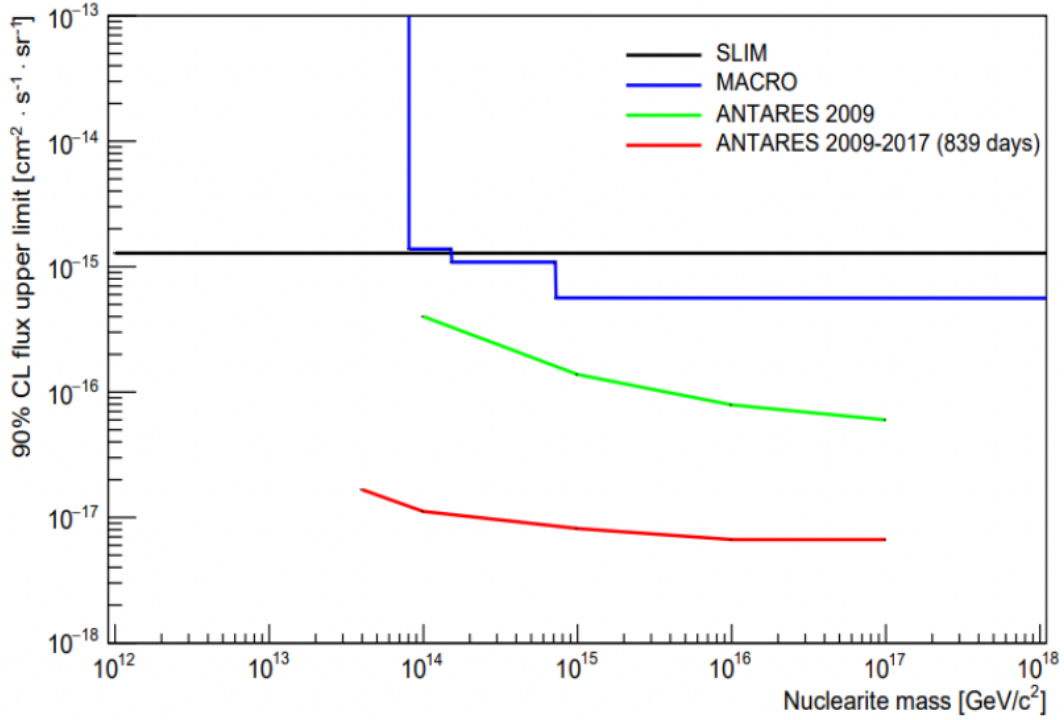
Adapted reconstruction for slow moving particles



📖 JHEAp (2022) 34

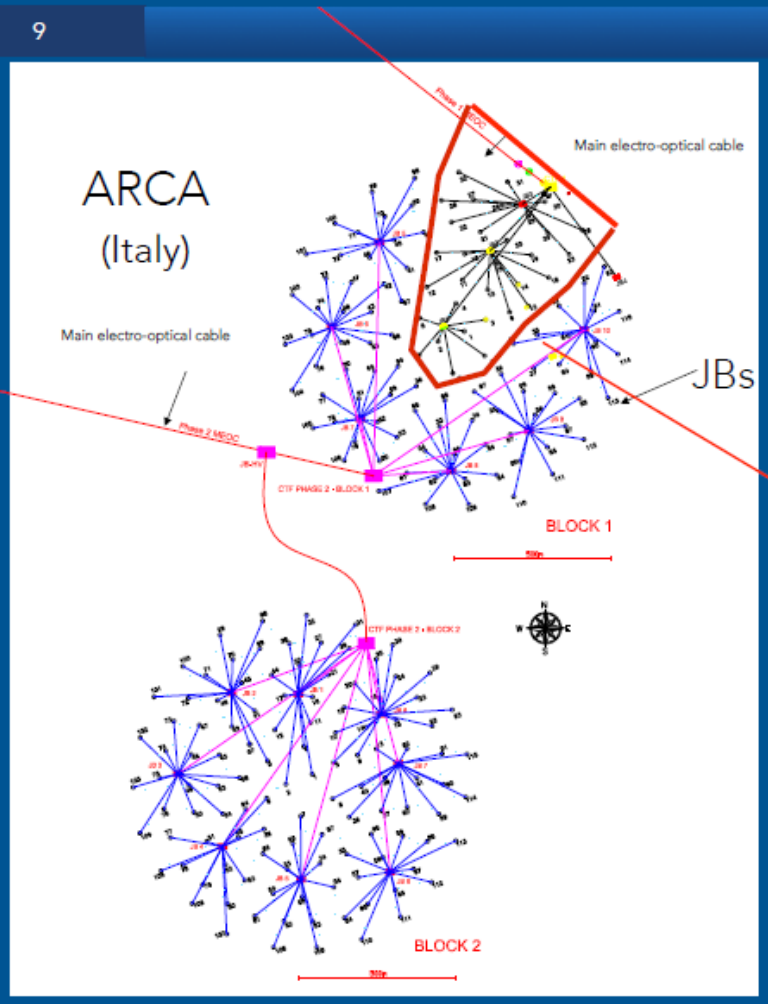
Nuclearites of strange quark matter

Down going flux with Galactic velocities according to De Rújula & Glashow model

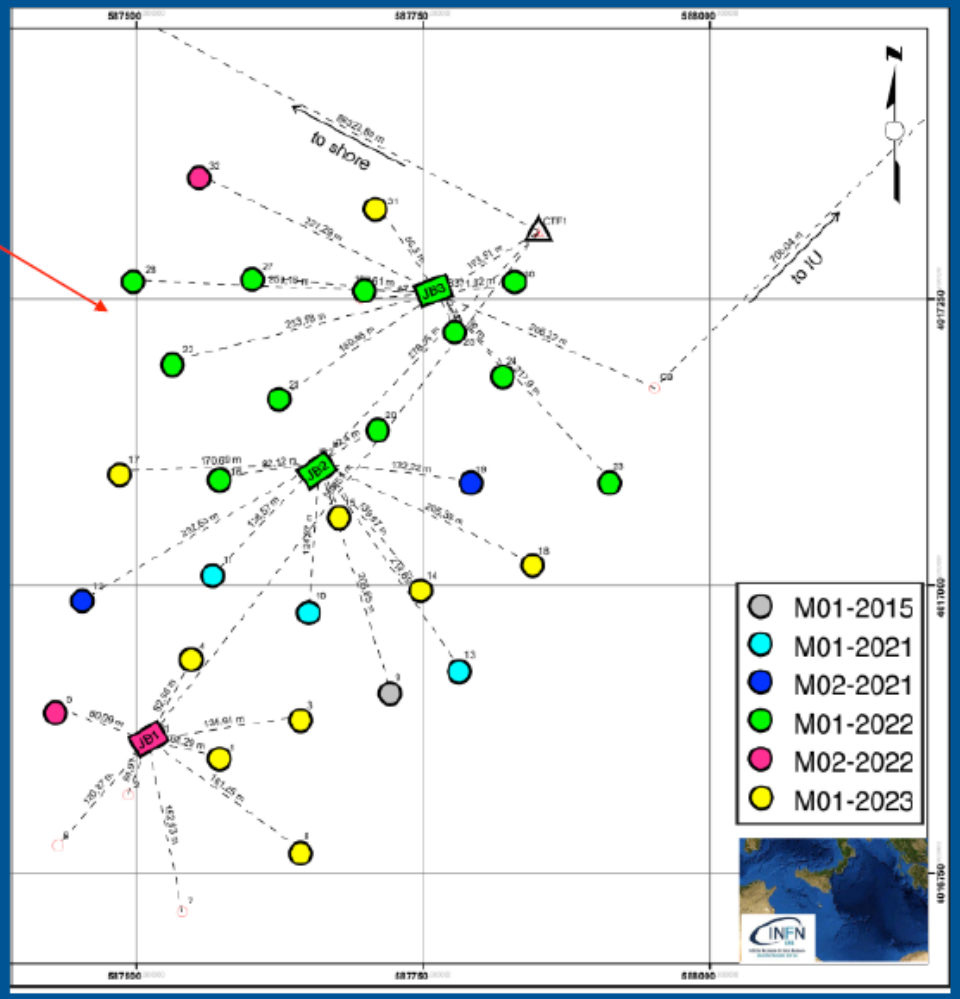


📖 JCAP01(2023)012

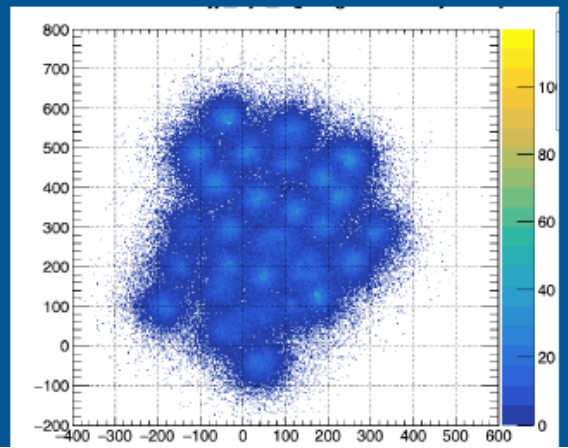
THE KM3NET/ARCA STATUS



Current status 28 DUs deployed
+ 3 JB

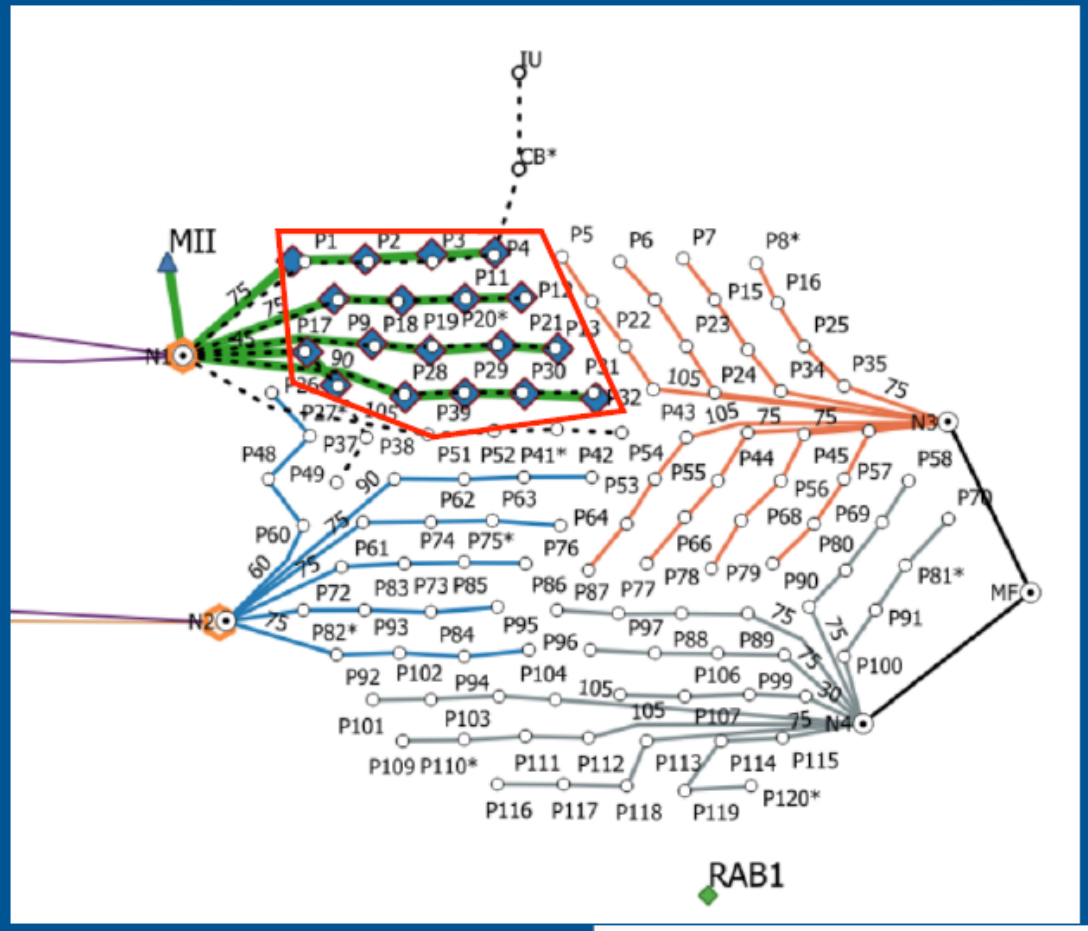


1-2 sea campaigns per year.
The last one in
September 2023 👉 recovered 2 DUs
not working and deployed 9 DUs
Detector commissioning on-going



THE KM3NET/ORCA STATUS

Current status 18 DUs deployed
16 DUs taking data



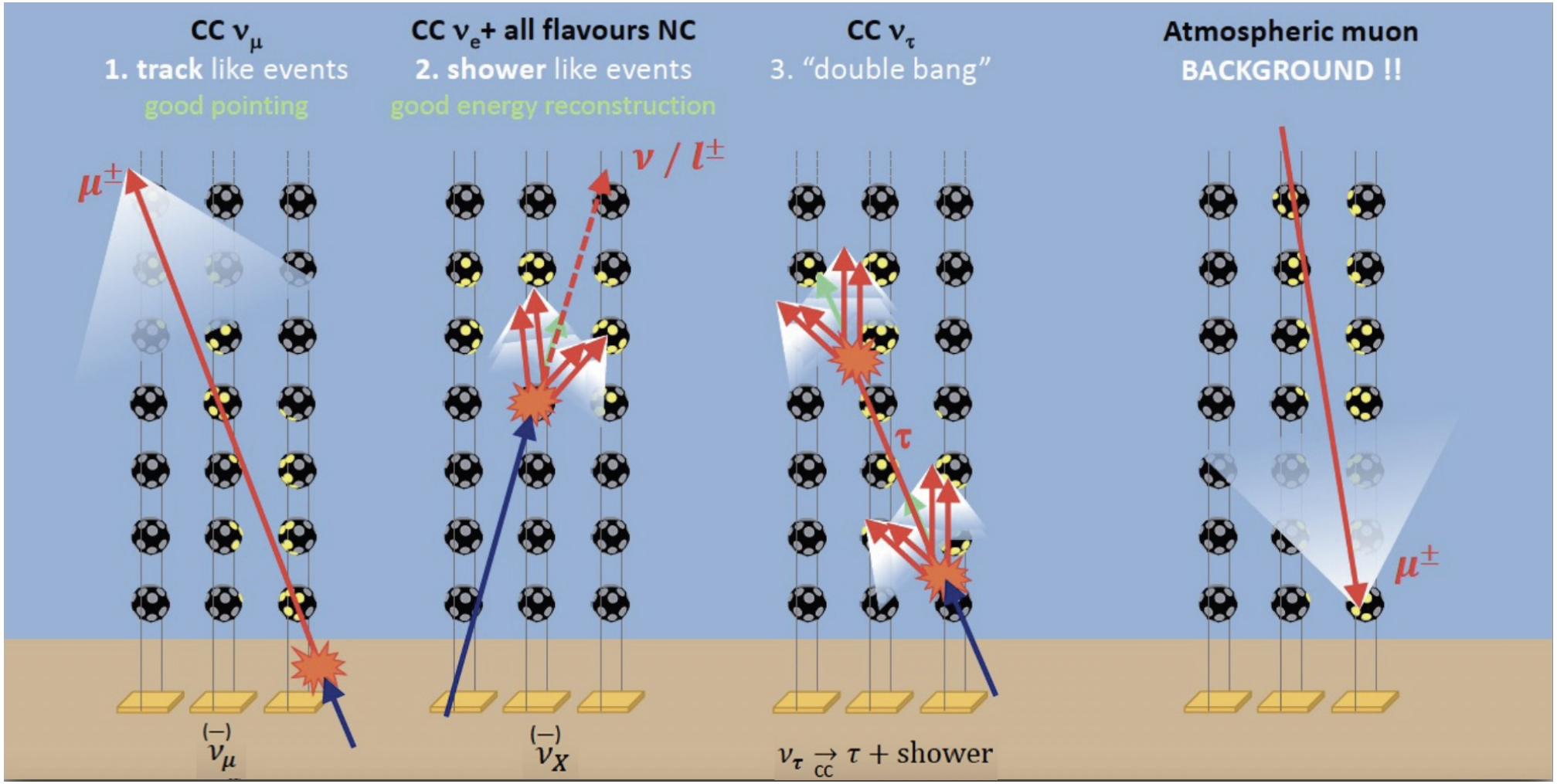
Many sea campaigns/year

Next campaigns

- November 2023 sea campaign 👉 Replace the two not working DUs and add 4 DUs 👉 22 DUs
- December 2023 sea campaign 👉 + 2 DUs 👉 24 DUs

For the end of 2023 completion of node 1 👉 24 DUs

Detection Principle in a nutshell



- Tracks: median ang. res. can drop below 0.1° above 100 TeV, factor 2 energy estimate
- Showers : median angular resolution can reach 1° at 100 TeV, 10% energy resolution