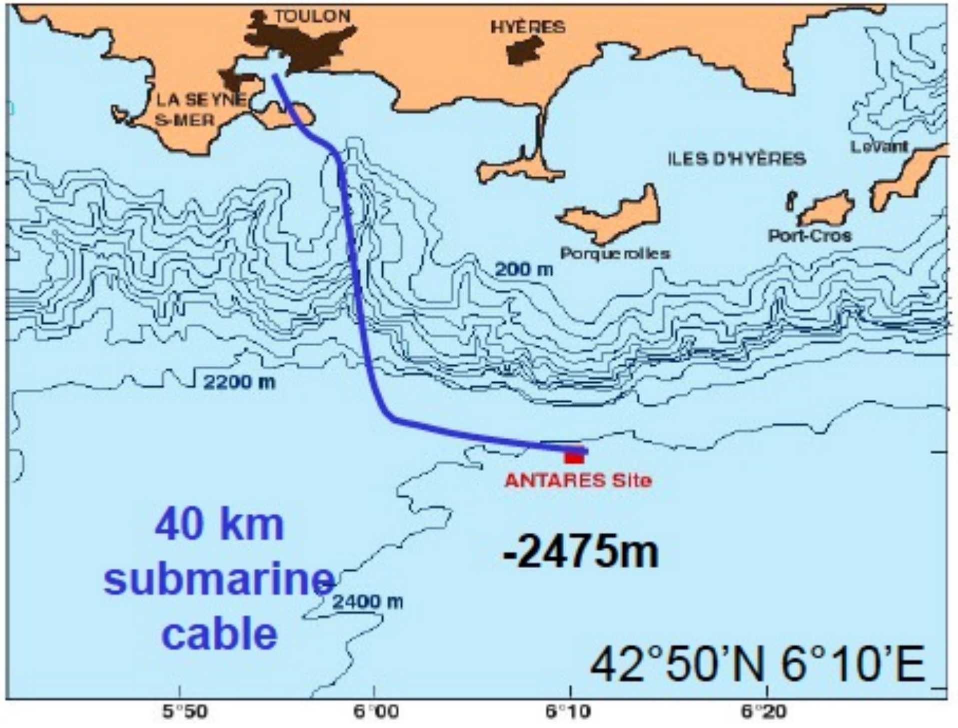
Legacy results of the ANTARES Neutrino Telescope

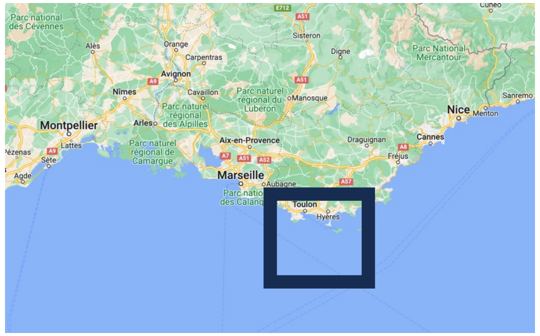
Paul de Jong (University of Amsterdam and Nikhef)

on behalf of the ANTARES Collaboration

HEP2023 HAMBURG

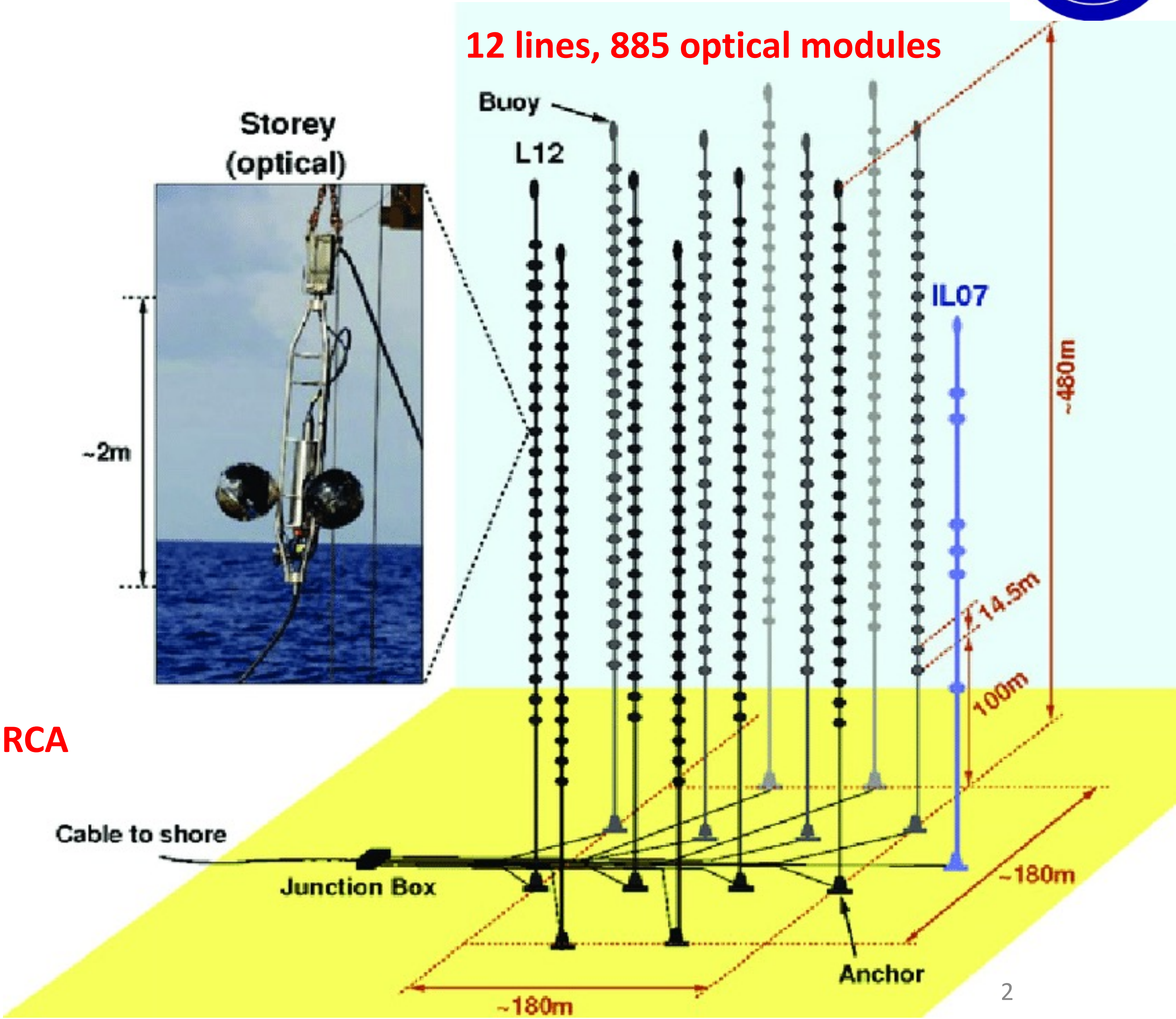
ANTARES location and layout





~ 10 km east of KM3NeT/ORCA

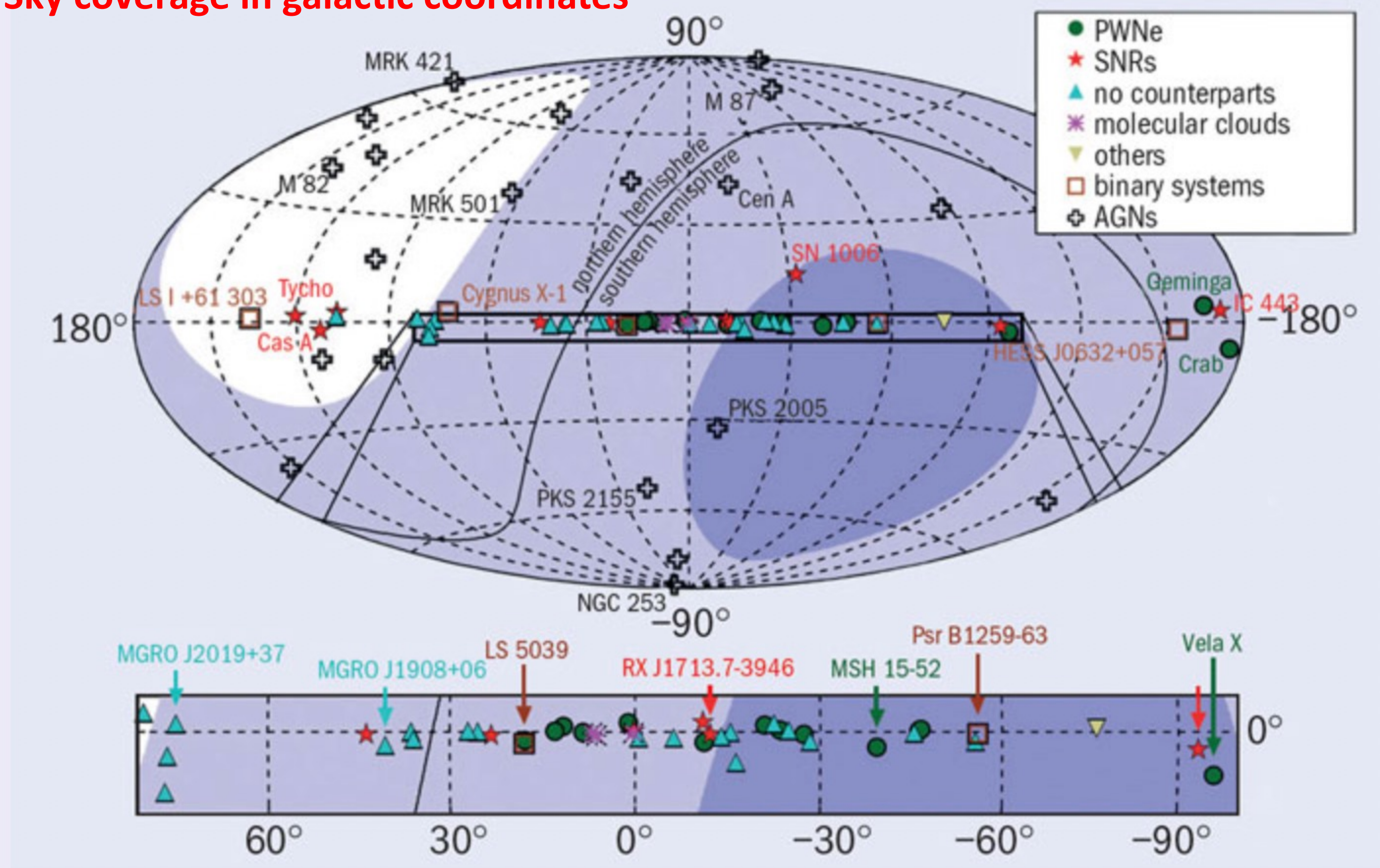
12 lines, 885 optical modules



Why the (Mediterranean) Sea?

- Long (homogeneous) scattering length
  → good pointing accuracy
- Deep: 2475 m → shielding from
  downgoing muons
- Logistically attractive, close to shore
- ^{40}K optical background
  → useful calibration
- Mid latitude → Excellent view of Galaxy, on/off studies, complementarity with IceCube

Sky coverage in galactic coordinates

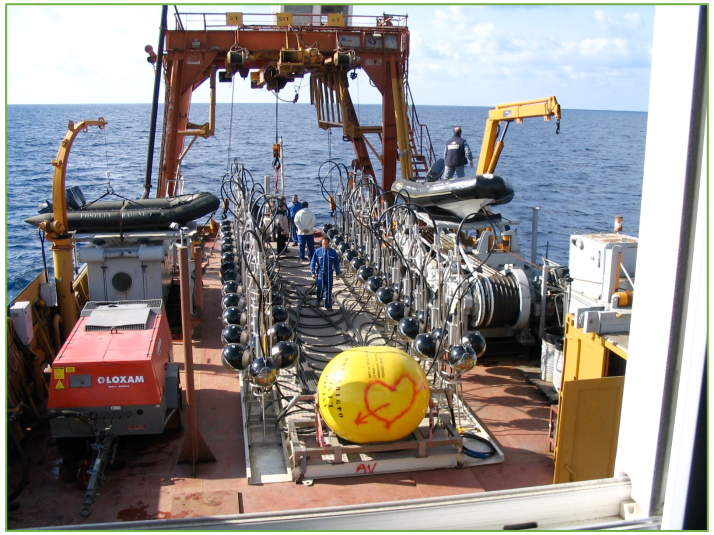


CERN Courier/Alexander Kappes

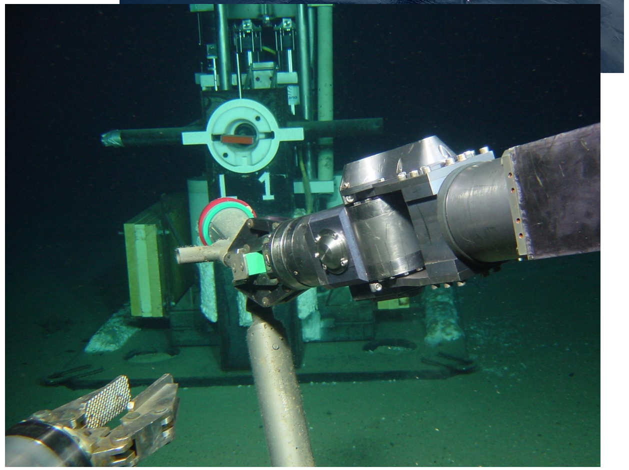
Dark blue: >75% visibility
Light blue: > 25% visibility

ANTARES 2006-2022

Cable to shore 2001
First line 2006
12 lines 2008



Data taking stopped and dismantling 2022

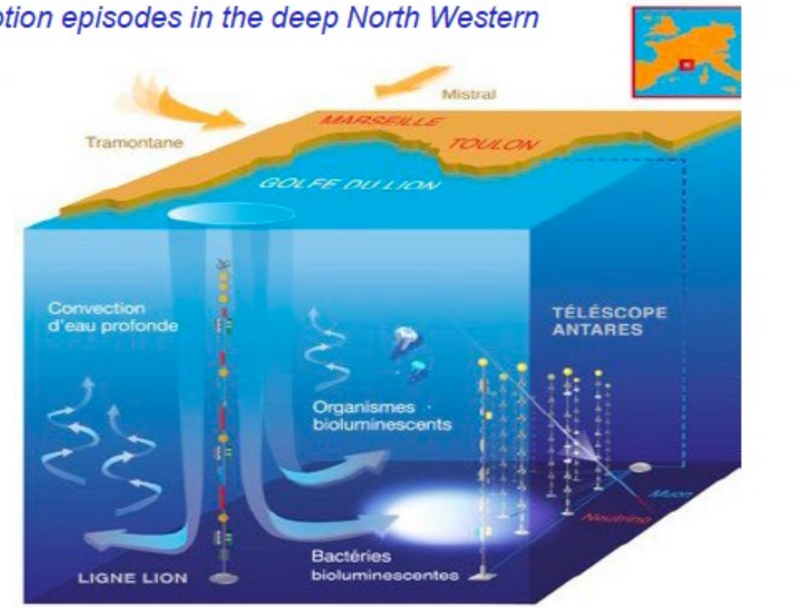


A Multidisciplinary Infrastructure!

Neutrino astronomy, neutrino properties, multimessenger astronomy

but also:

- 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

+ Citizen science

REINFORCE
REsearch INfrastructures FOR Citizens in Europe

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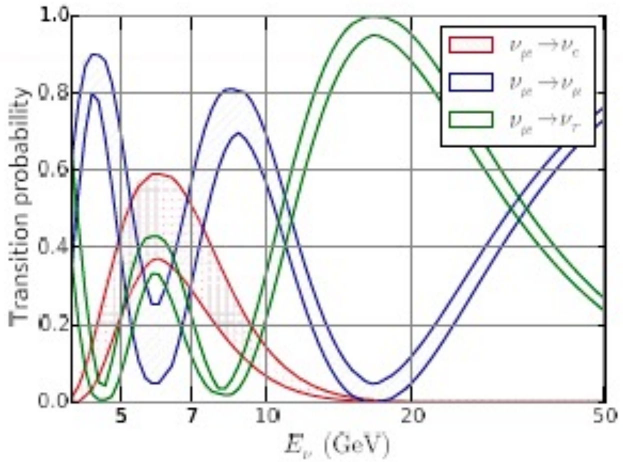
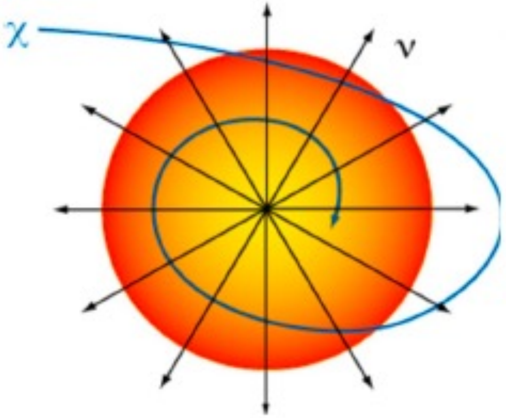
Neutrino science scope





Low Energy

10 GeV < E_ν < 100 GeV

Medium Energy

10 GeV < E_ν < 10 TeV

High Energy

E_ν > 1 TeV

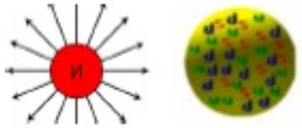
E

ν Oscillations

Dark matter search

ν from extra-terrestrial sources

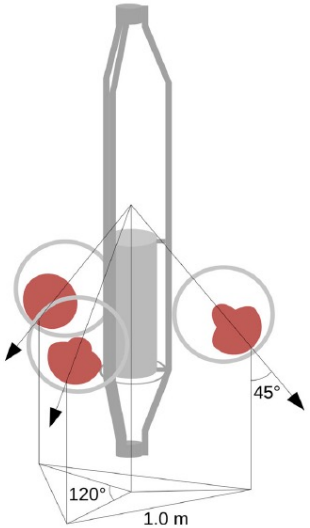
+ Exotic searches



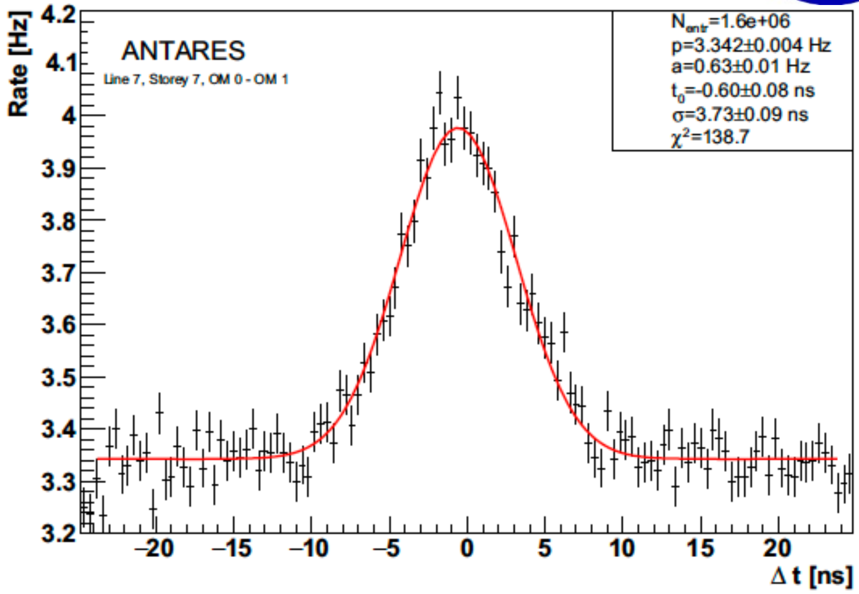
Origin and production mechanism of high-energy cosmic-rays

Optical Module Efficiency calibration

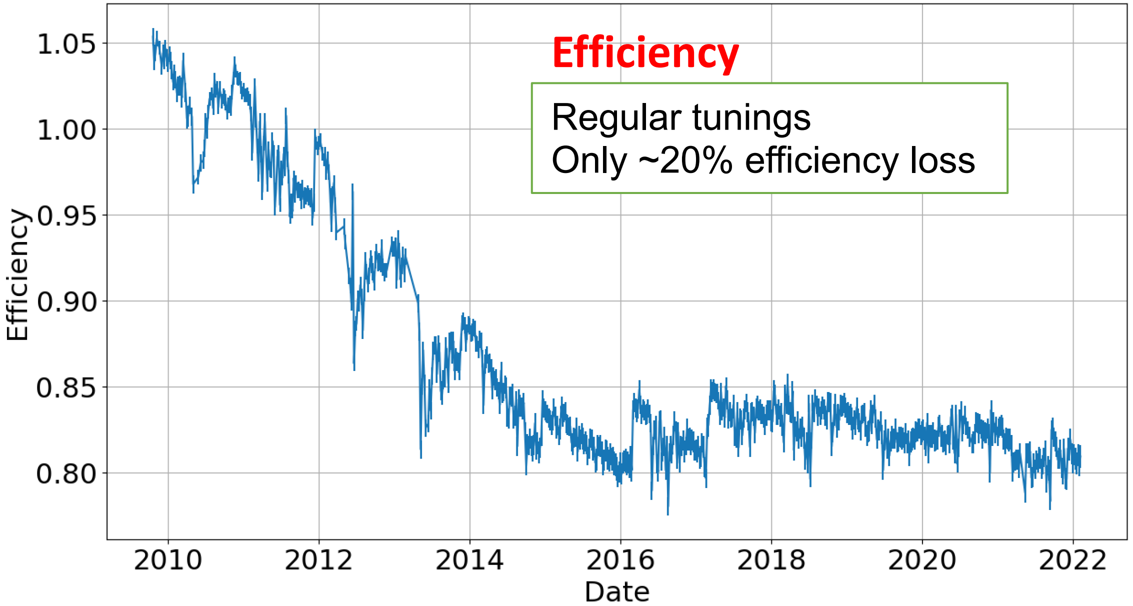
$$^{40}\mathrm{K} \rightarrow \; ^{40}\mathrm{Ca} + e^- + \overline{\nu}_e \qquad (89.3\%)$$
$$^{40}\mathrm{K} + e^- \rightarrow \; ^{40}\mathrm{Ar}^* + \nu_e \qquad (10.7\%)$$
$$\hookrightarrow \; ^{40}\mathrm{Ar} + \gamma$$



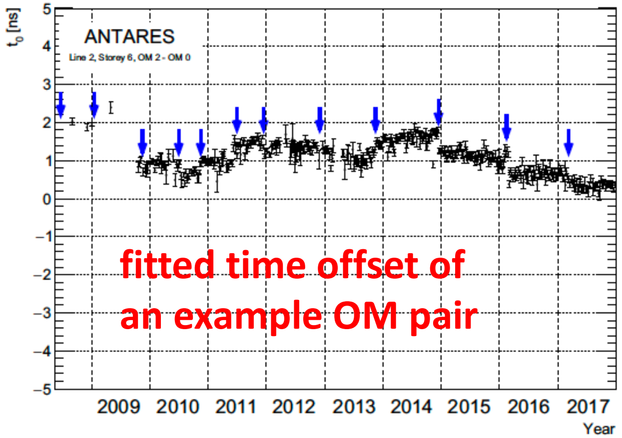
coincidences between 2 OMs

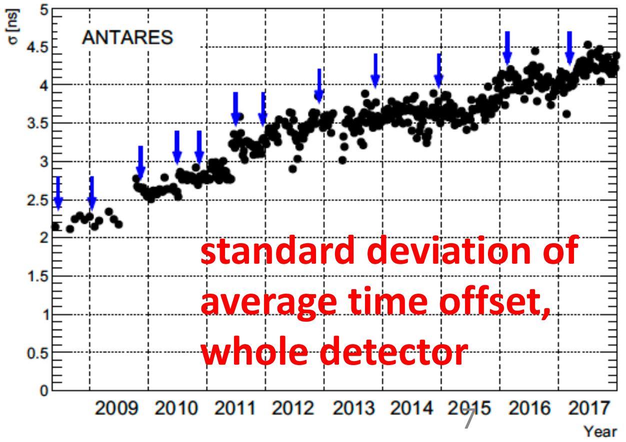


EPJ C78 (2018) 669



also provides timing calibration:



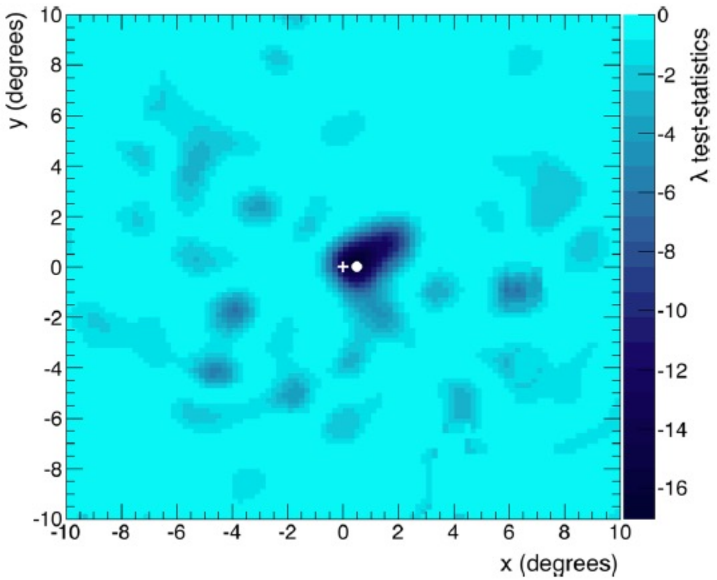


Pointing calibration and resolution

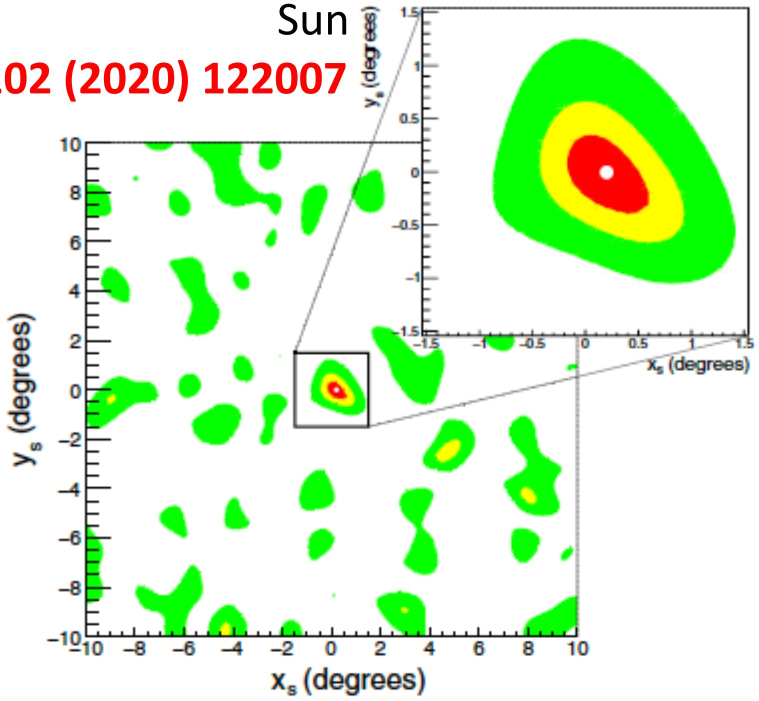
Lines move with the sea current.
Positioning through acoustic triangulation.

Test: find cosmic ray shadow of sun and moon and compare to nominal position:

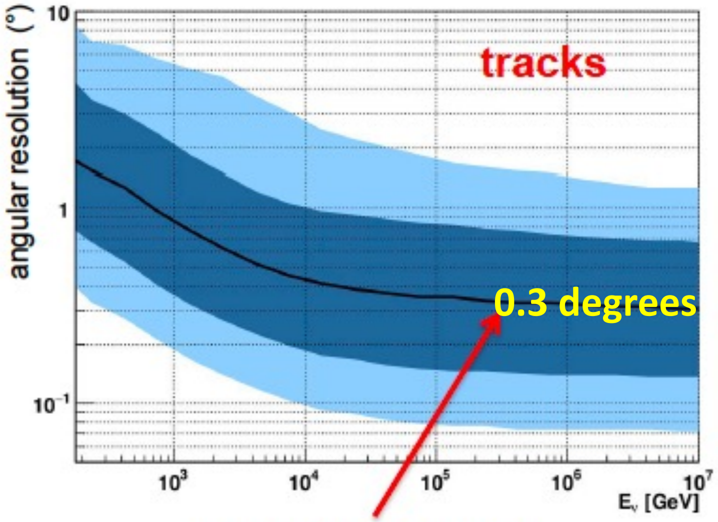
Moon **EPJ C78 (2018) 1006**

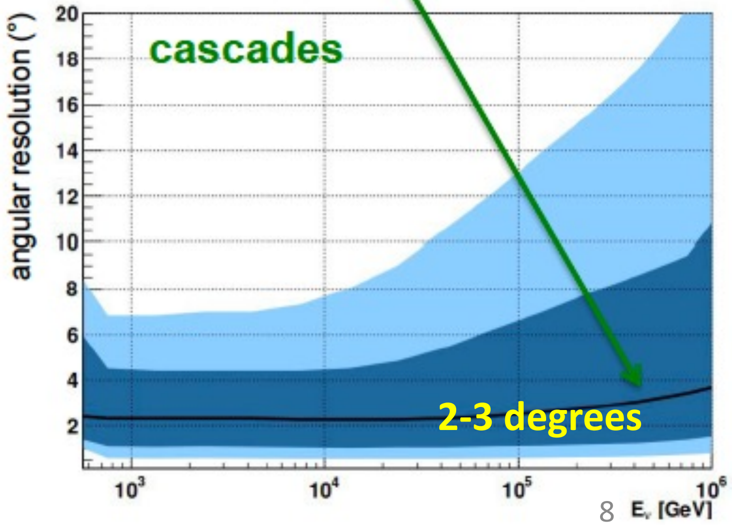


Sun **PRD 102 (2020) 122007**



Angular resolution for neutrino candidates (tracks and cascades)





Atmospheric Neutrino Spectrum

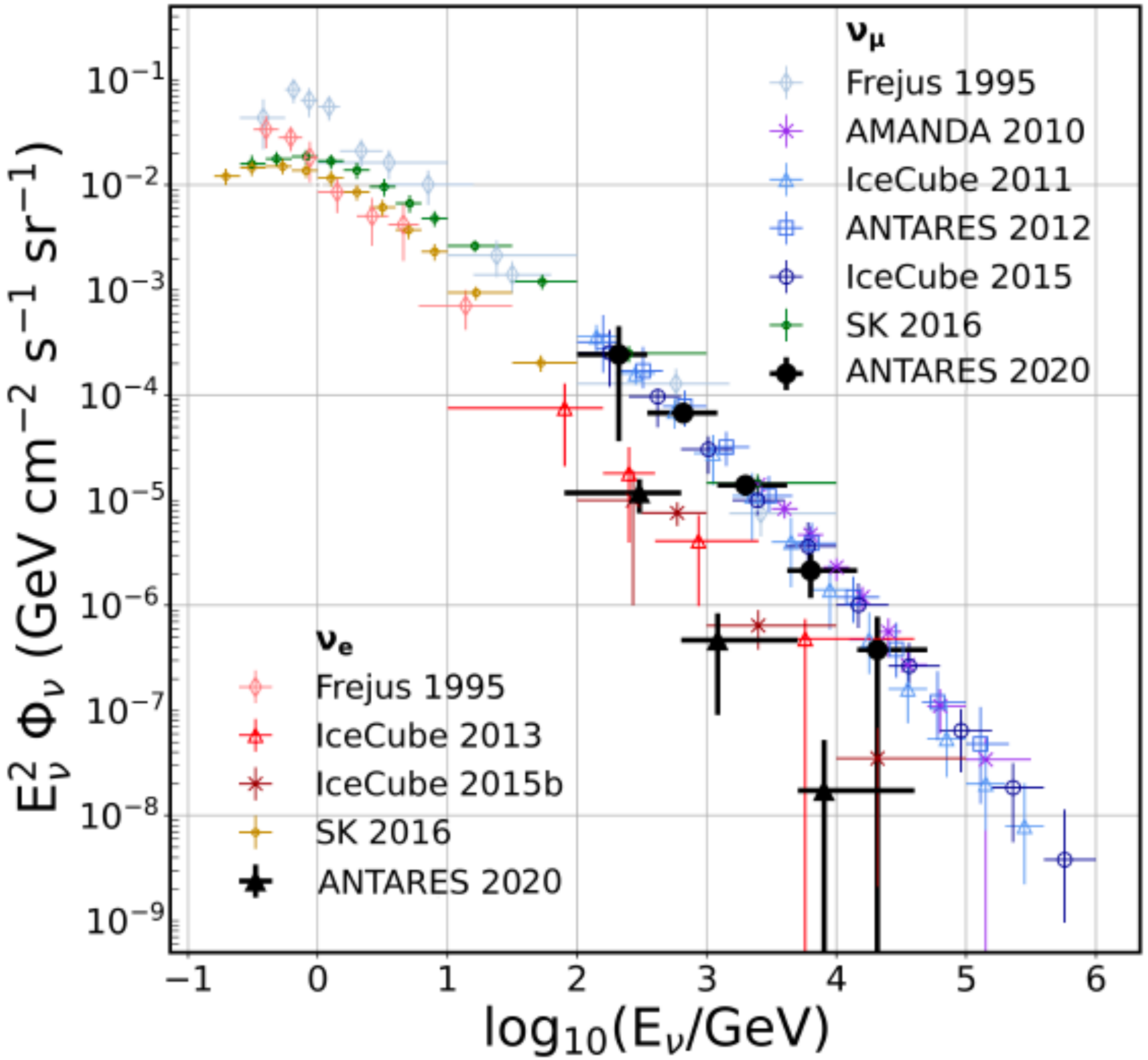
ANTARES 2007-2017, 3012 days

BDT selection, 1016 events

MC: 68% $(\nu_\mu + \bar{\nu}_\mu)$ CC
11% $(\nu_e + \bar{\nu}_e)$ CC
21% NC

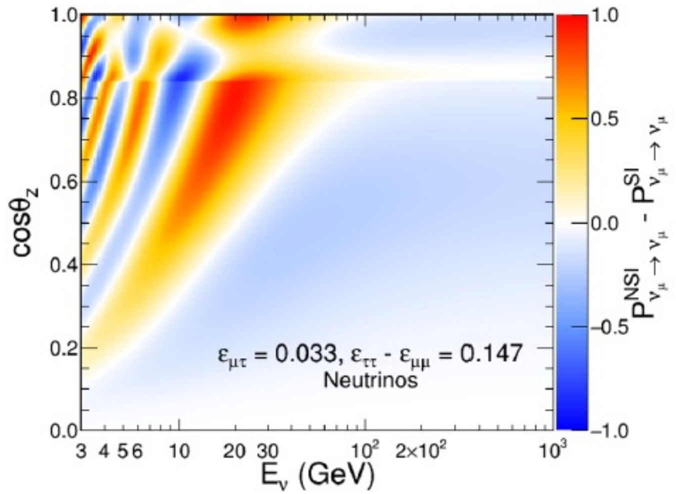
Unfolded energy spectrum

PLB 816 (2021) 136228

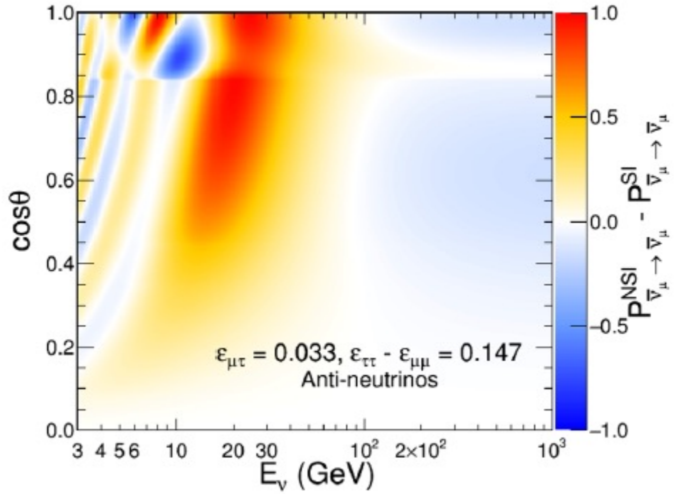


Atmospheric Neutrino Non-Standard Interactions

ν disappearance prob. change



$\bar{\nu}$ disappearance prob. change



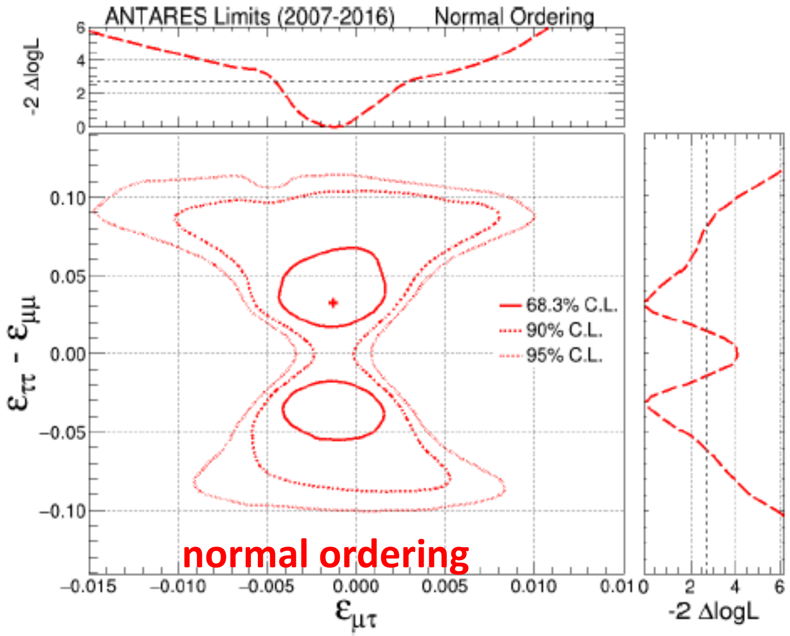
JHEP07 (2022) 048

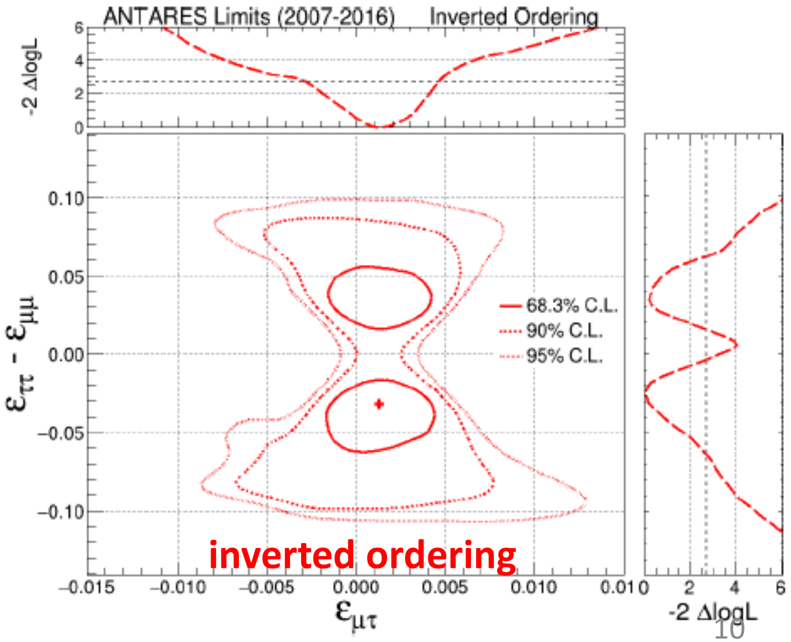
ANTARES 2007-2016, 2850 days, 7710 track events

NSI = modification of neutrino interactions, visible when propagating through Earth

$$\mathcal{H}_{\rm eff} = \frac{1}{2E}\mathcal{U}\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{bmatrix}\mathcal{U}^{+} + A(x)\begin{bmatrix} 1+\varepsilon_{ee} & \varepsilon_{e\mu} & \varepsilon_{e\tau} \\ \varepsilon^*_{e\mu} & \varepsilon_{\mu\mu} & \varepsilon_{\mu\tau} \\ \varepsilon^*_{e\tau} & \varepsilon^*_{\mu\tau} & \varepsilon_{\tau\tau} \end{bmatrix}$$

Resulting limits: (comparable to those of IC/SK)



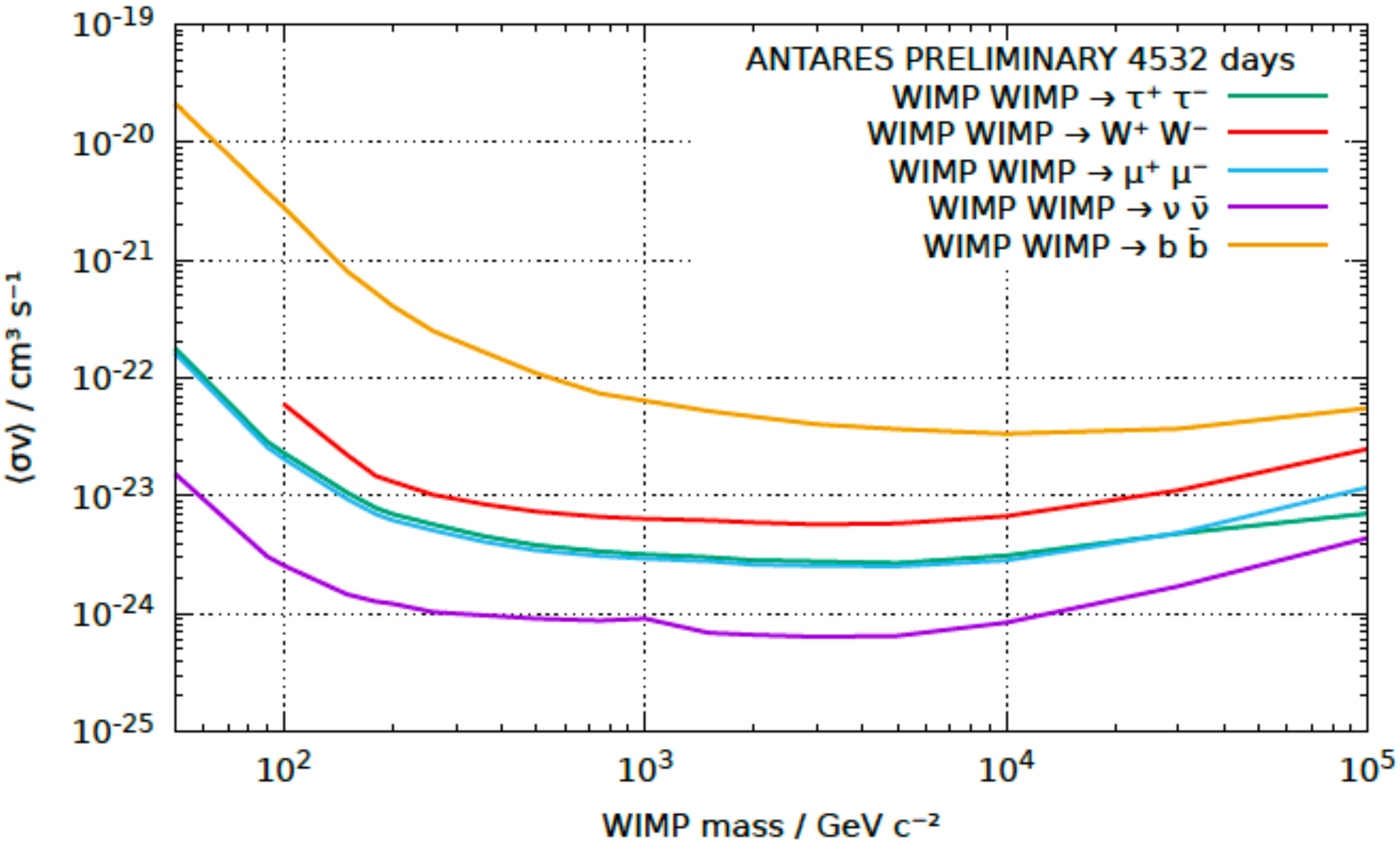


Dark matter

PoS (ICRC2023) 1375

ANTARES 2007-2022, 4532 days
11850 tracks, 235 showers

Limits on $< \sigma v >$ from WIMP annihilation in galactic center:
(assuming NFW profile and 100% Br)

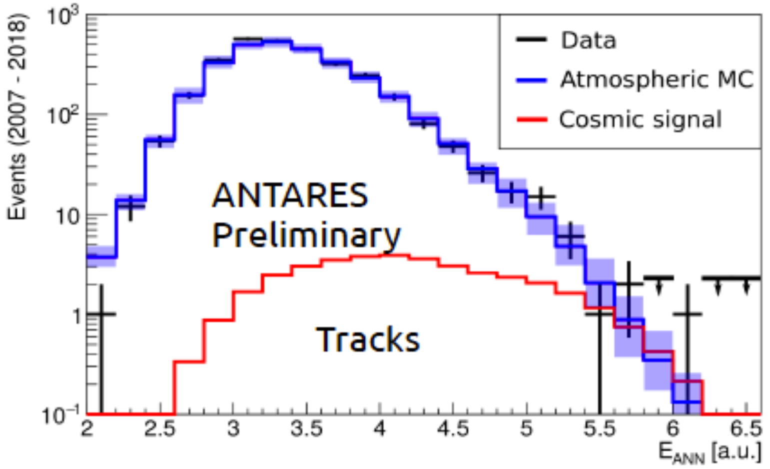


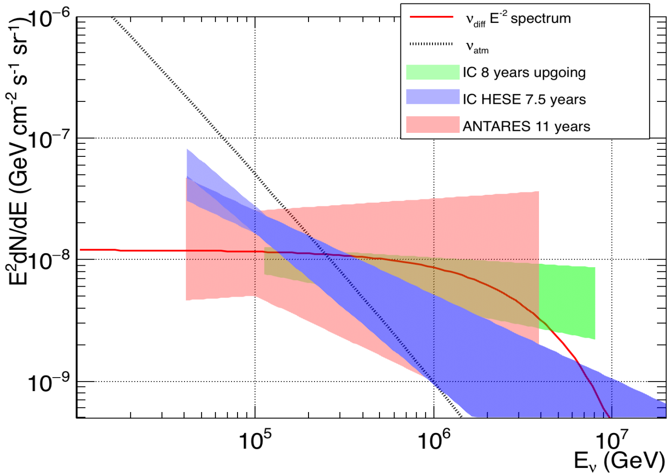
ANTARES has also set limits on WIMP annhilation in Earth and Sun, and secluded dark matter.
Still in progress: low-energy single-line reconstruction with machine learning.

Diffuse cosmic flux

ApJ Lett. 853 (2018) 1, L7
PoS (ICRC2021) 1126

ANTARES data 2007-2018, 3330 days. All-sky, all-flavour search. Look for excess above certain energy threshold.

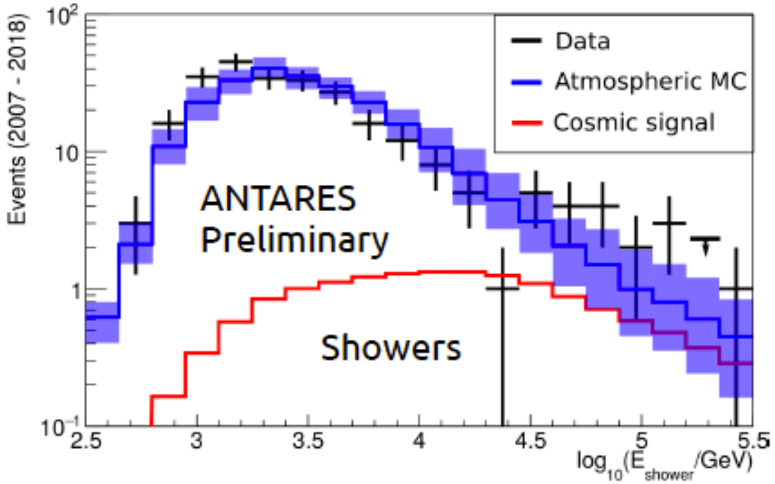




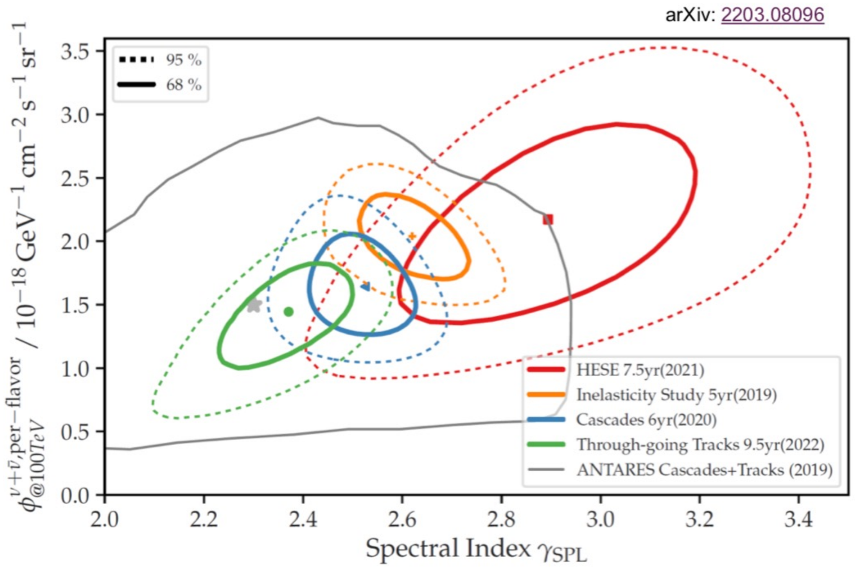
Data: 50 events (27 tracks + 23 showers)
Background expectation (atm. flux, incl. prompt) :
36.1 ± 8.7 (19.9 tracks & 16.2 showers) stat. + syst.

Excess corresponds to 1.8 σ

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

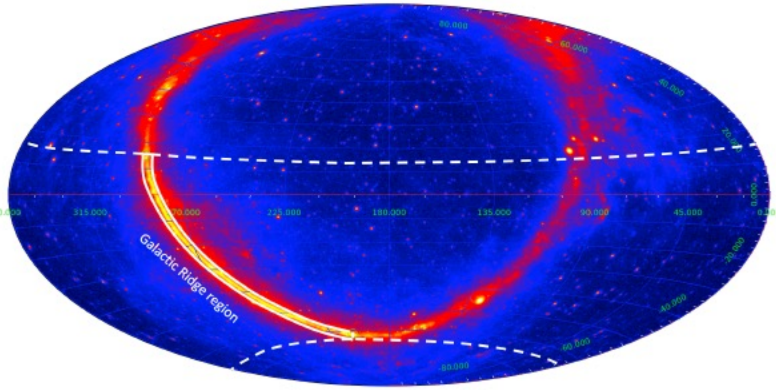


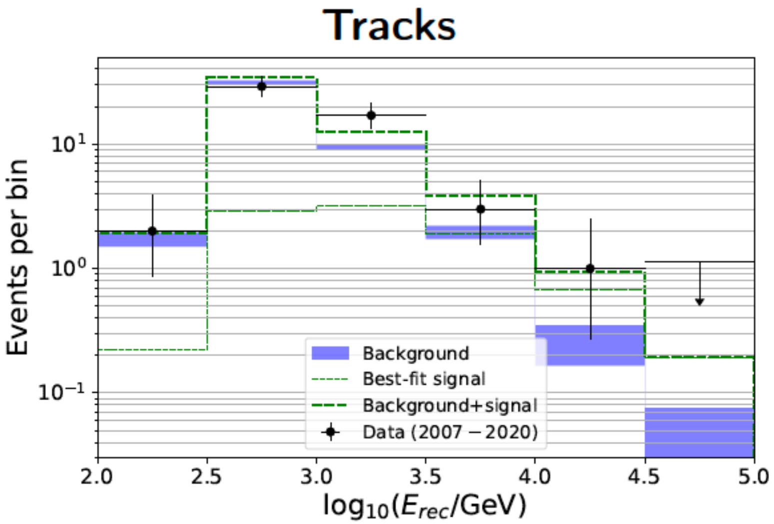
Comparison to IceCube diffuse flux

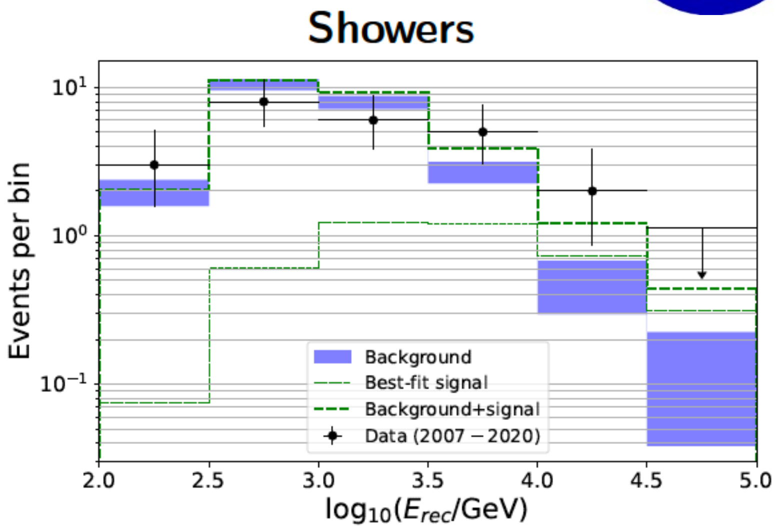


Neutrinos from the Galactic ridge

Galactic ridge (central part of galactic plane) is likely source of cosmic-ray-induced neutrinos.

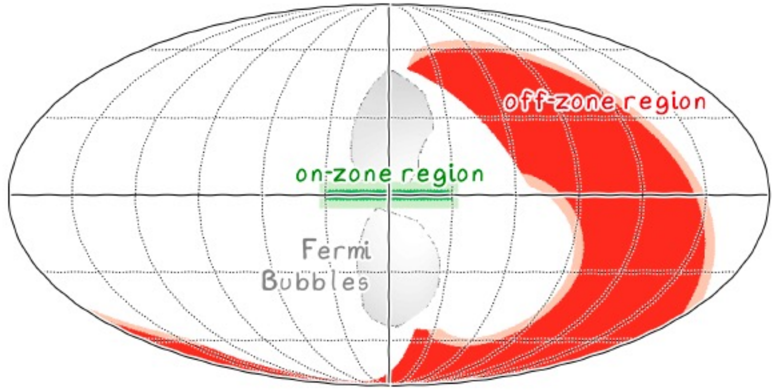






PLB 841 (2023) 137951

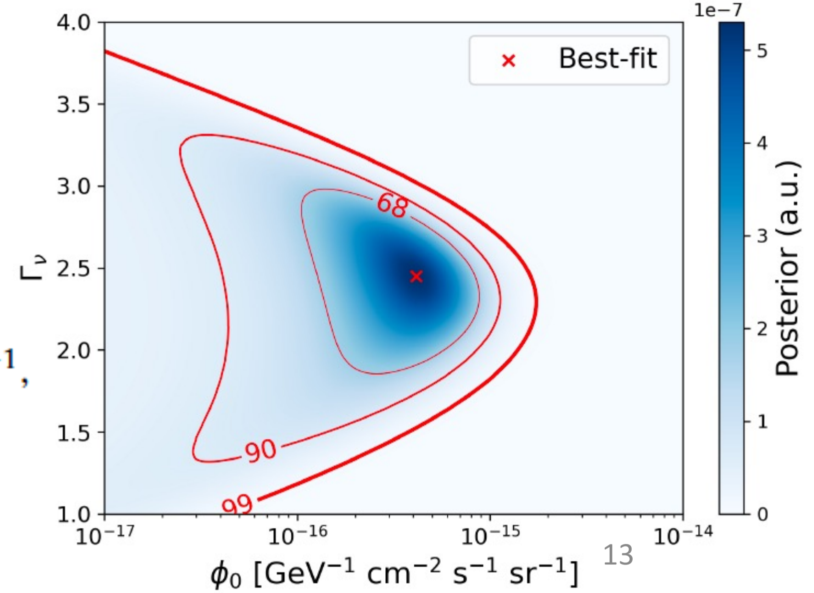
ANTARES data 2007-2020, bg from off-zone



Excess over bg
2.2 **σ** in tracks
0.2 **σ** in showers

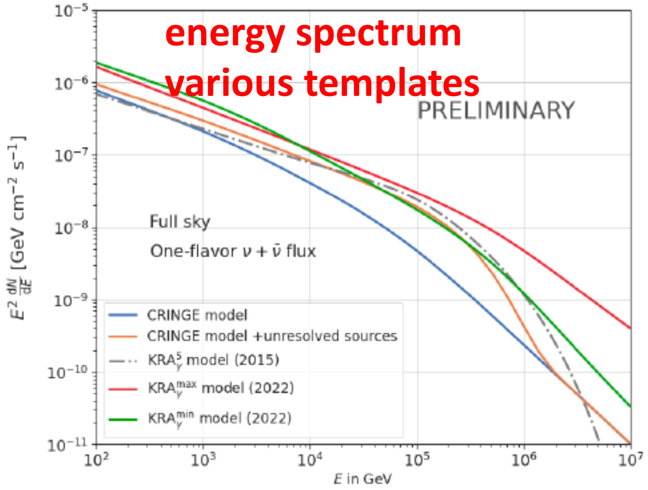
$$\Phi(40\,\mathrm{TeV}) = 4.0^{+2.7}_{-2.0} \times 10^{-16}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1},$$

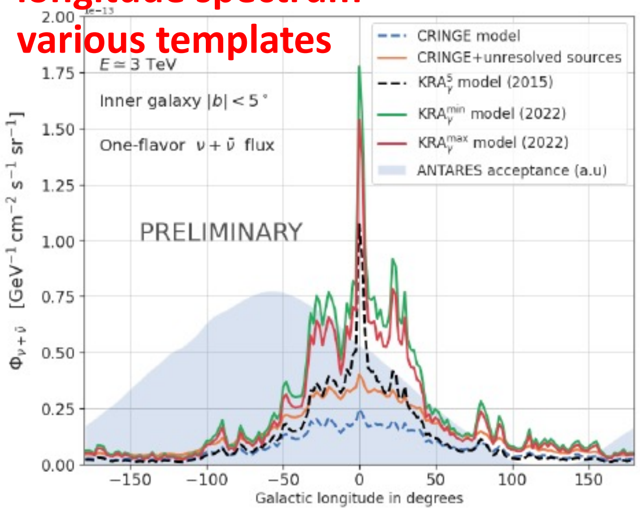
$$\Gamma_\nu = 2.45^{+0.22}_{-0.34}.$$



Diffuse Neutrino Emission from the Galactic plane

New: template fit to galactic plane: **PoS (ICRC2023) 1084**

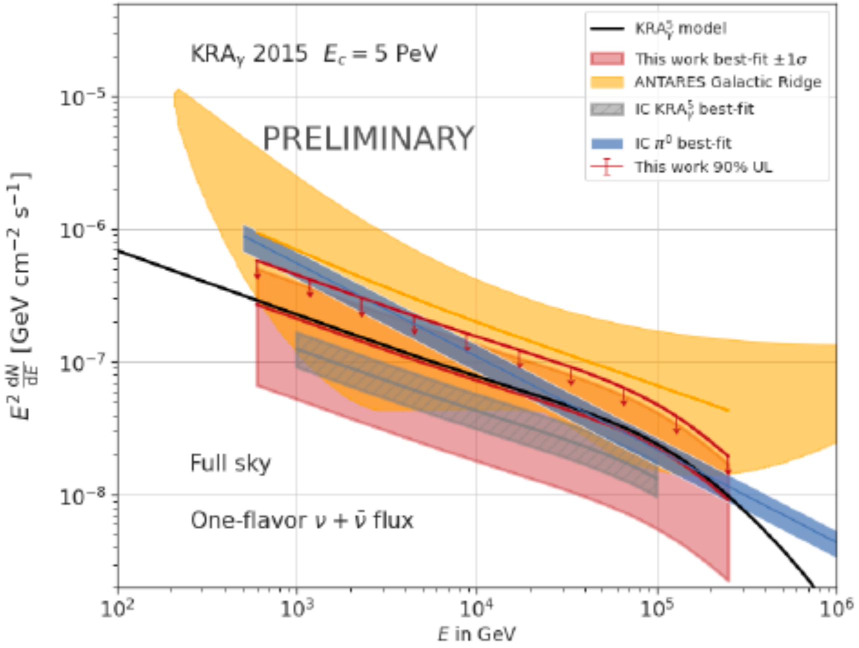


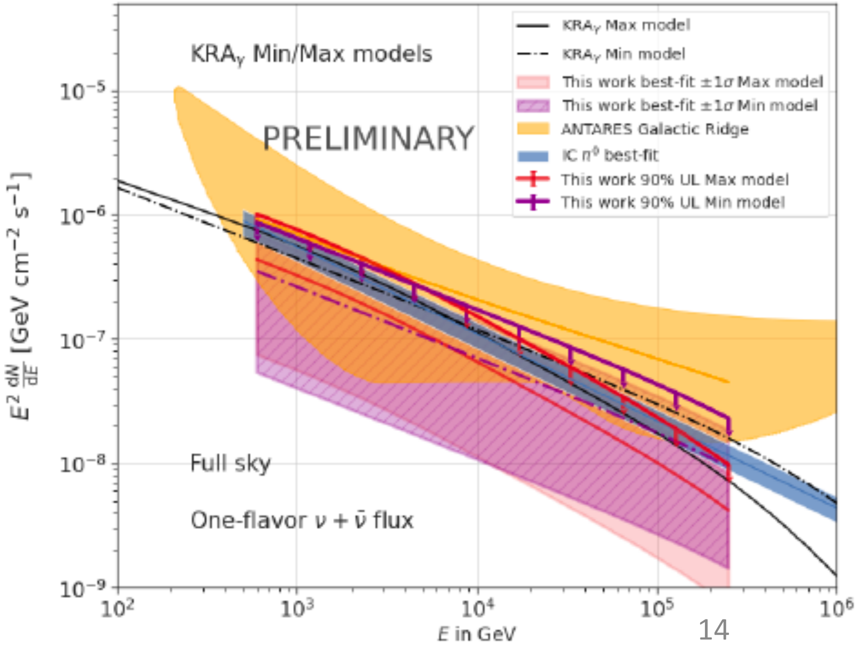


Templates derived from γ-ray emission of galactic plane.

ANTARES data 2007-2022, 4541 days, 7501 track-like events

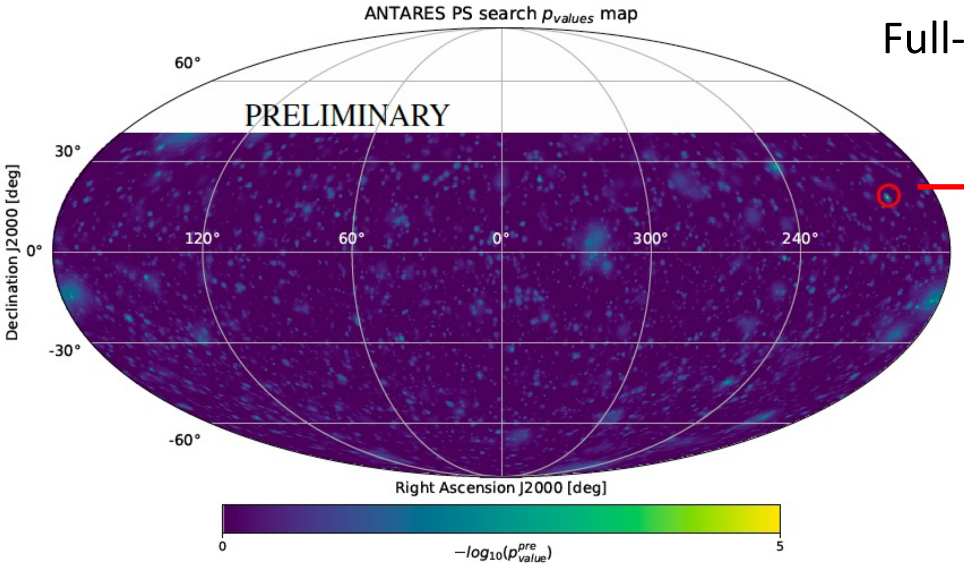
Best fit to KRA$_\gamma{}^5$ model, significance 1.7 $\boldsymbol{\sigma}$, flux ratio 0.93
Results are consistent with those of IceCube





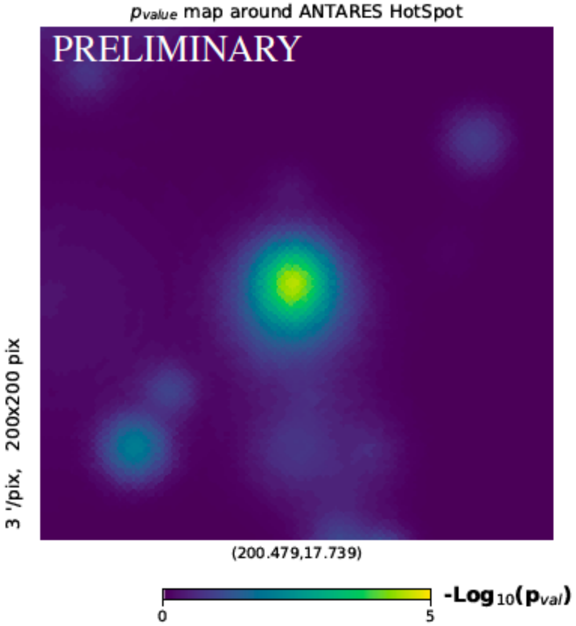
Point sources search

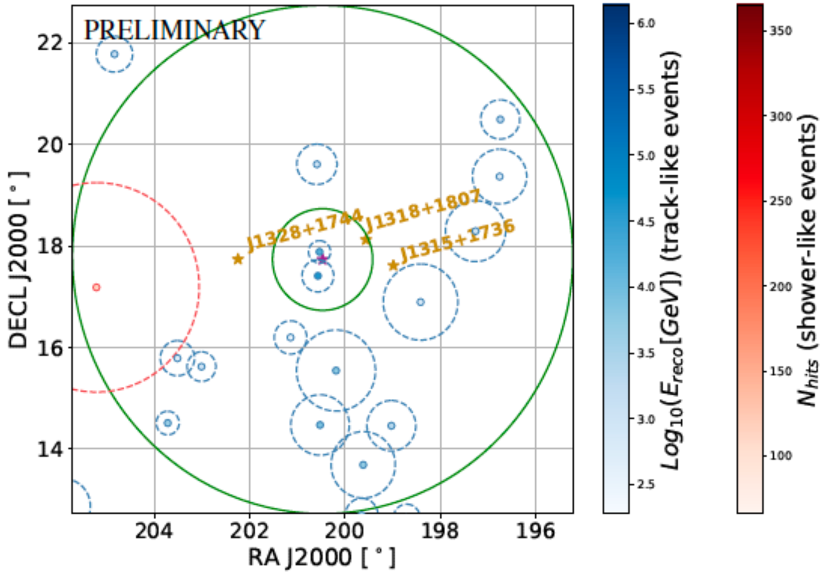
ANTARES 2007-2022, 4541 days: 11029 tracks and 239 showers **PoS (ICRC2023) 1128**



Full-sky spatial clustering search, colours show clustering significance

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





Sky map around hottest spot.
Three radio sources at distances of 1.0^o, 1.5^o, 1.7^o.

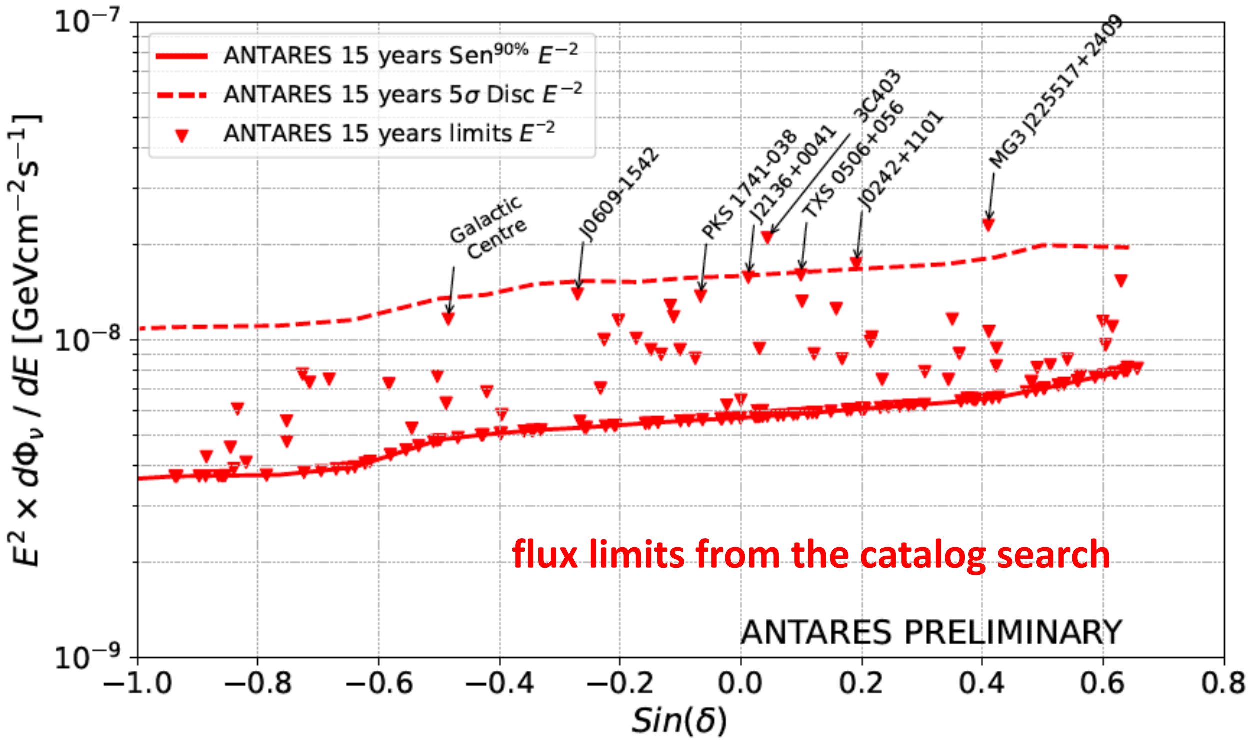
Catalog search

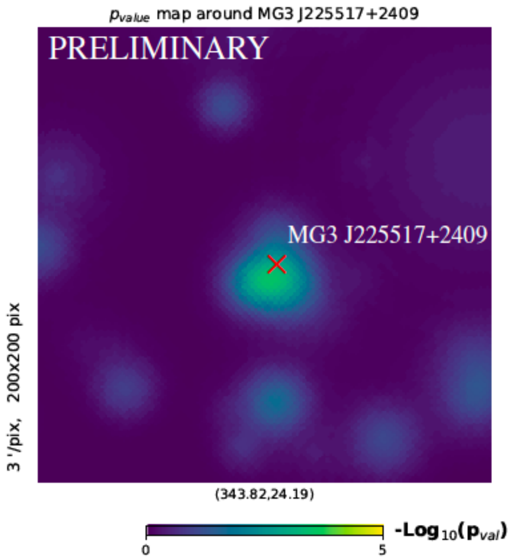
ANTARES 2007-2022, 4541 days: 11029 tracks, 239 showers

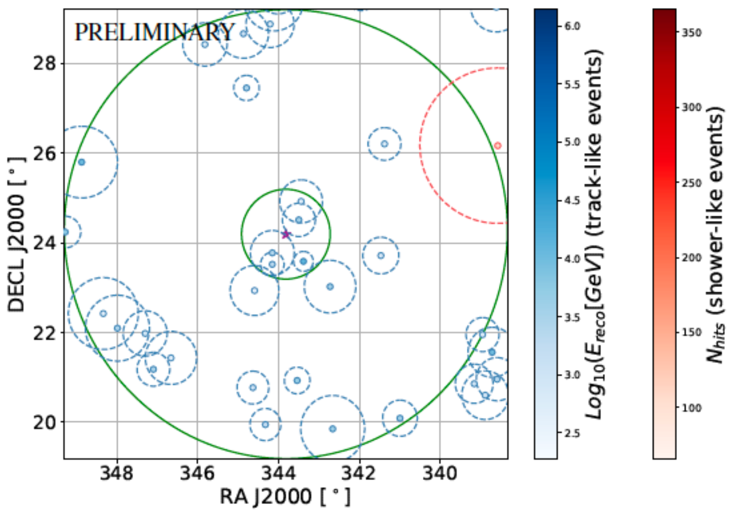
Search for ν from sources in a list of 168 candidates

PoS (ICRC2023) 1128

8 sources with pre-trial significance above 2 σ (including TXS 0506+056, galactic center)







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

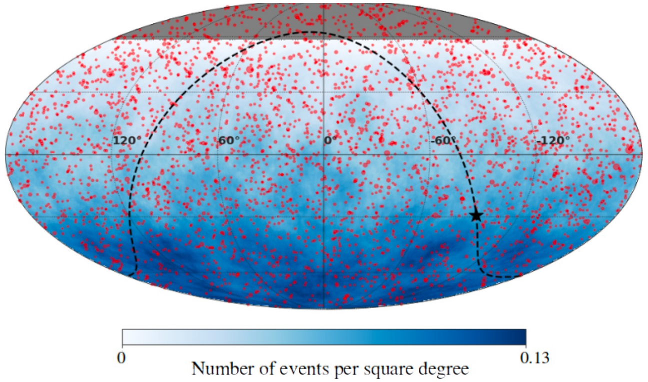
IC hotspot NGC1068:
p-value 0.19:
not significant, as expected

Other noteworthy possible sources

PoS (ICRC2023) 1567

ANTARES data 2007-2020, 3845 days, 10504 tracks, 227 showers

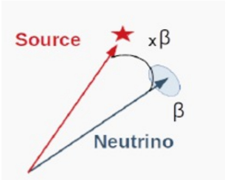
VLBI blazars (3411 red dots):



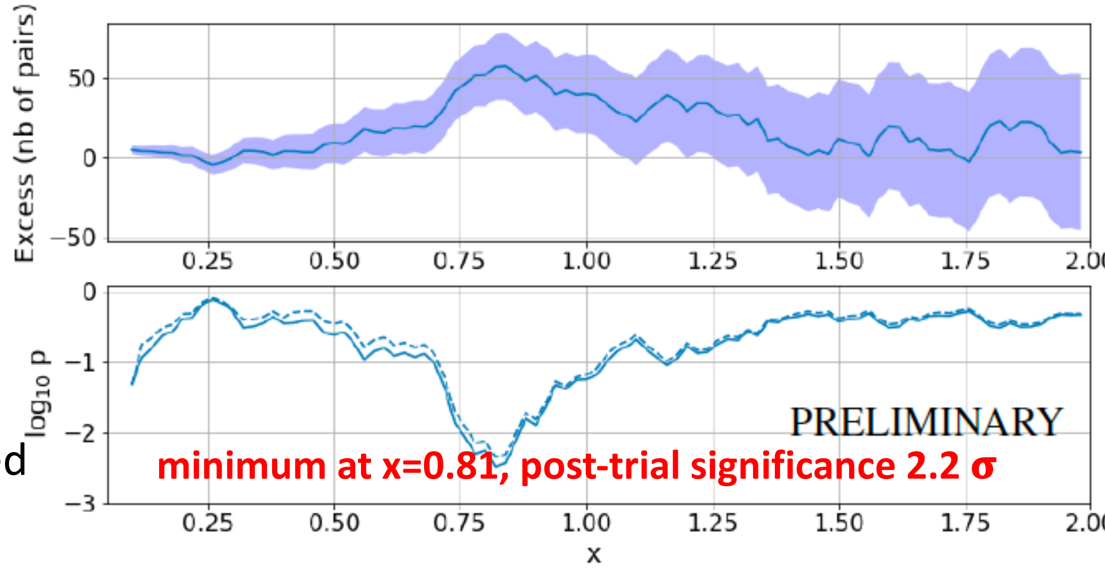
Plavin et al (ApJ 908 (2021) 157) claim correlation with IceCube, ANTARES

- Counting analysis

- Count n-blazar pairs at less than $x\beta$
- x accounts for possible systematics
- Scan over x to search for most significant excess



Confirmed with time-integrated likelihood analysis: 2.2 $\boldsymbol{\sigma}$



Analysis of flaring periods of VLBI blazars: 18 sources found with pre-trial significance > 3$\boldsymbol{\sigma}$
Chance probability: 1.4% (2.5 $\boldsymbol{\sigma}$)

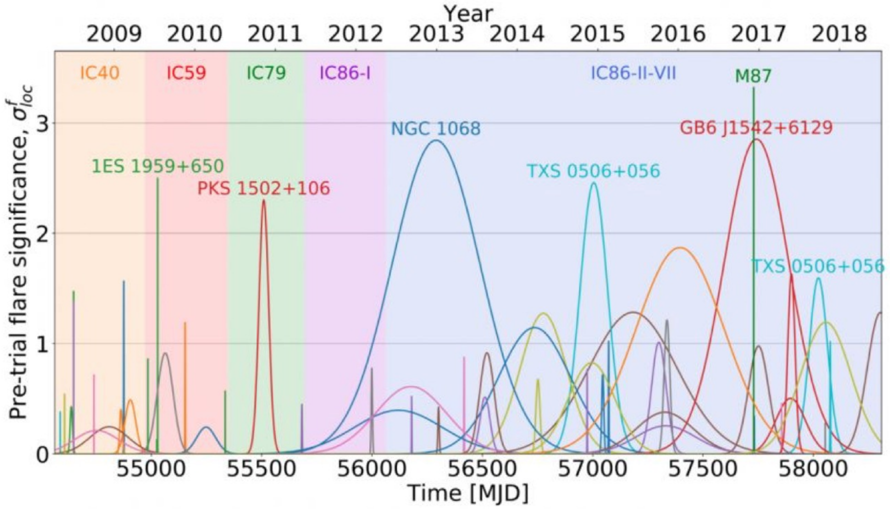
HAWC γ-rays + ANTARES: ApJ 944 (2023) 166: 3 coincidences in 4.4 years, consistent with background
Tidal Disruption Events AT2019dsg, AT2019fdr: ApJ 920 (2021) 50: no significant neutrino signal
UHECR + neutrinos: ApJ 934 (2022) 164: no significant correlation observed

Flaring periods

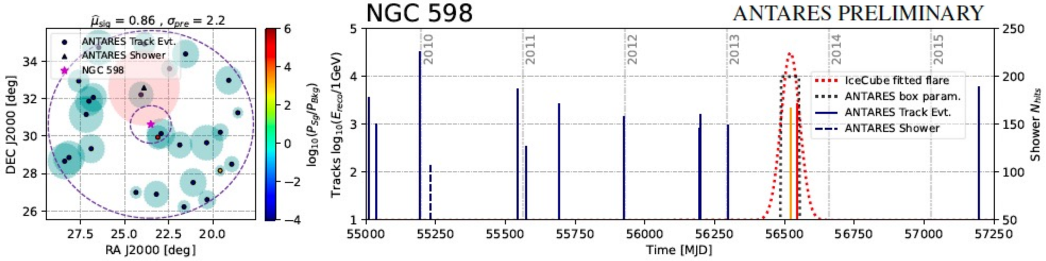
Search for $\boldsymbol{\nu}$ from flares **PoS (ICRC2023) 1567**

ANTARES data 2007-2020, 3901 days.

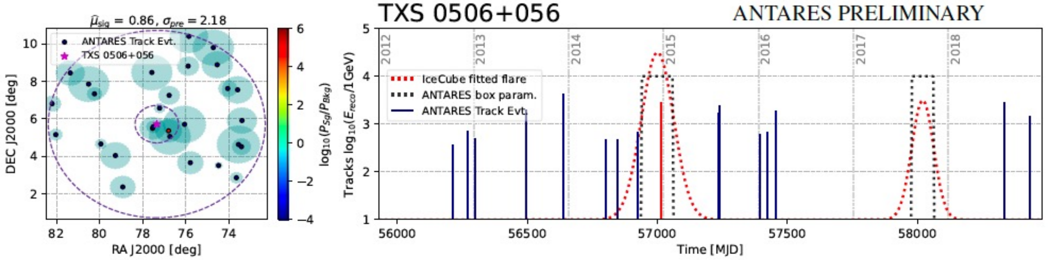
36 sources considered, selected from a list of 110 possible neutrino flares considered by IceCube (ApJ Lett. 920 (2021) L45), for ANTARES visibility and flare duration.



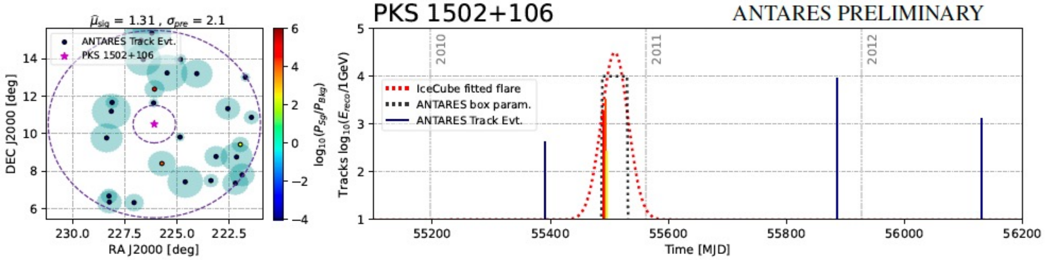
Overall no significant correlation found, but fit finds signal contribution in 4 sources:



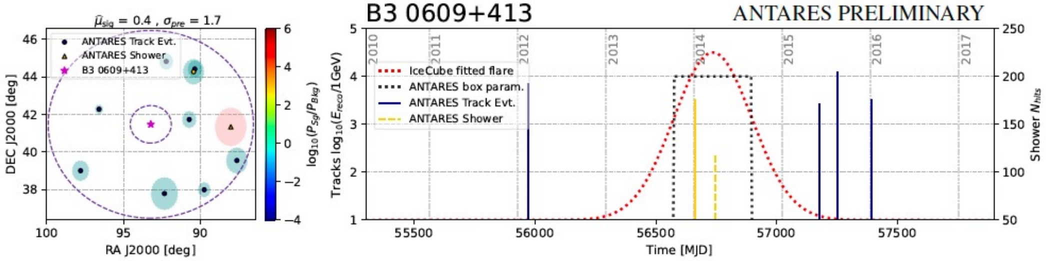
2.2 σ



2.1 σ



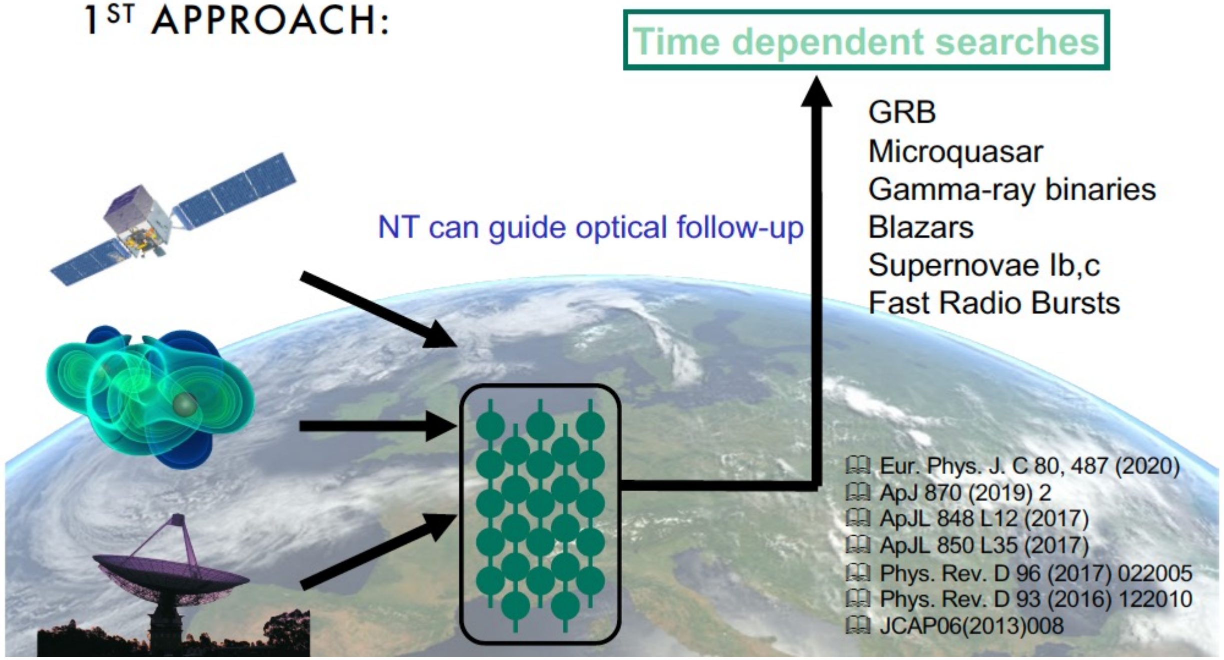
2.1 σ



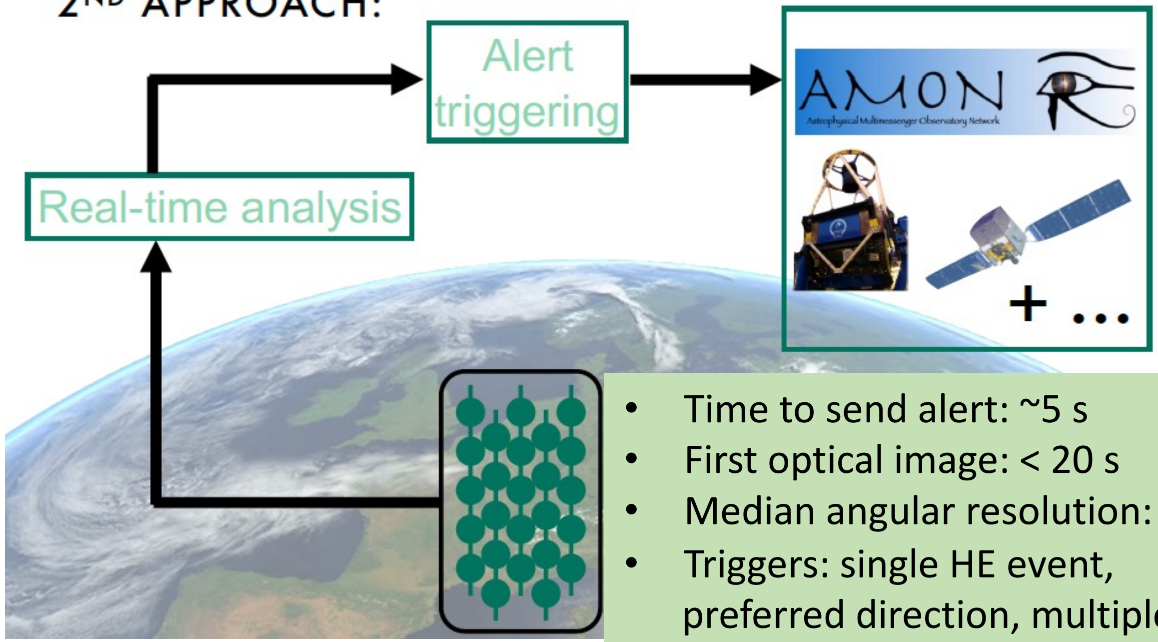
1.7 σ

Multimessenger Astronomy

1ST APPROACH:

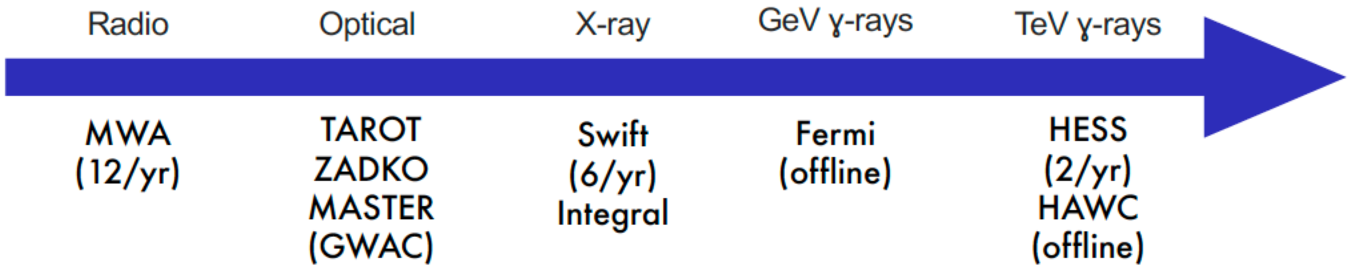


2ND APPROACH:



- Time to send alert: ~5 s
- First optical image: < 20 s
- Median angular resolution: ~0.3º
- Triggers: single HE event, preferred direction, multiplets

Overview: **arXiv:2211.07551** (accepted by JCAP)



Sent neutrino alerts (2009-2021)

322 to robotic telescopes
+26 to Swift
+15 to INTEGRAL
+20 to MWA
+2 to HESS

Follow-up efficiencies: ~70% (X-ray /optical) ; ~20% (radio)

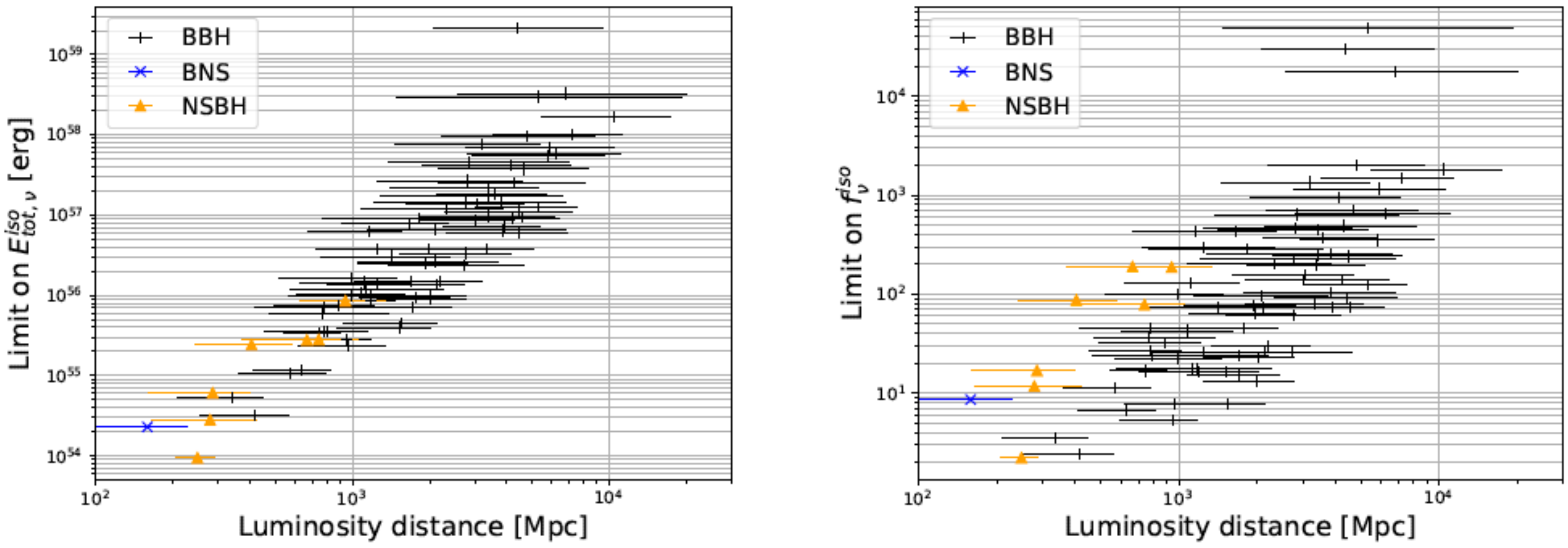
Search for neutrinos from GW O3 candidates

ANTARES data 2019, 2020. Upgoing and downgoing tracks and showers in separate categories.

Followup of 80 significant GW candidates reported by LIGO/VIRGO during O3. **JCAP 04 (2023) 004**

No significant excess observed in time windows of ±500 seconds around GW event.

Limits set on $E^{iso}_{tot,\nu}$ (left) and $f^{iso}_{\nu} = E^{iso}_{tot,\nu}/E_{tot,GW}$ (right)



Summary and Conclusions

ANTARES has proven the feasibility of a deep-sea neutrino telescope.
Reliable and efficient operation over 16 years.
Good pointing accuracy in seawater.

Northern hemisphere Neutrino Telescope is complementary to IC.

Physics results on neutrino properties: oscillations, limits on sterile neutrinos and Non-Standard-Interactions.

Limits set on neutrinos from dark matter annihilation and exotics.

Searches for cosmic neutrinos: a few 2 sigma hints in diffuse flux, neutrinos from galactic plane, neutrinos from VLBI blazars, and from a few other individual sources. Extensive multi-messenger program.

Torch is now passed to KM3NeT!