



Co-funded by the European Union

ANTARES & KM3NeT/ARCA:

Present and future of neutrino telescopes in the Mediterranean Sea

32nd Rencontres de Blois

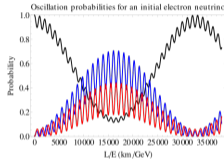
Mathieu Lamoureux 

(APC Univ-Paris, France & INFN Sezione di Padova, Italy)
for the ANTARES & KM3NeT collaborations

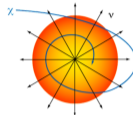
supernovae



oscillations

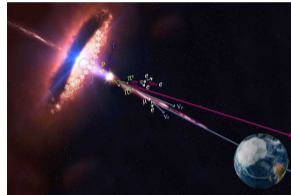


dark matter



and other
exotic searches

high-energy astronomy



+ Earth and Sea
sciences:
oceanography, biology,
geology...

MeV

GeV

TeV

PeV

EeV

E_ν

SPECIFICITIES OF THE MEDITERRANEAN SEA

Location (N.Hemisphere)

complementary to IceCube
coverage of Galactic Centre

Medium (sea water)

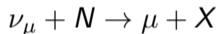
low light scattering → good ang. resolution
bioluminescence & ^{40}K backgrounds

The detectors

Detection principle

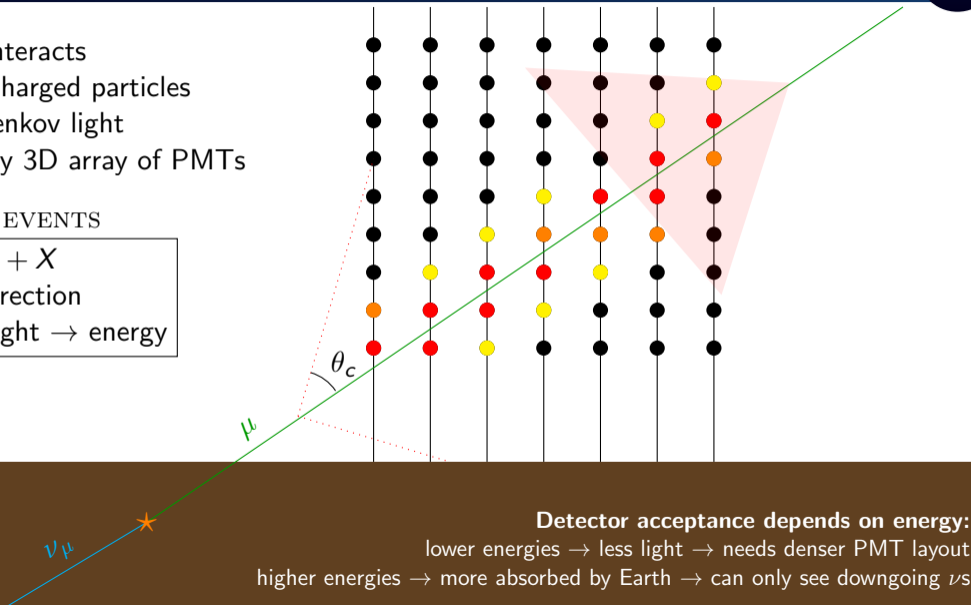
1. Neutrino interacts
2. Produces charged particles
3. Emit Cherenkov light
4. Detected by 3D array of PMTs

TRACK EVENTS



- fit line \rightarrow direction

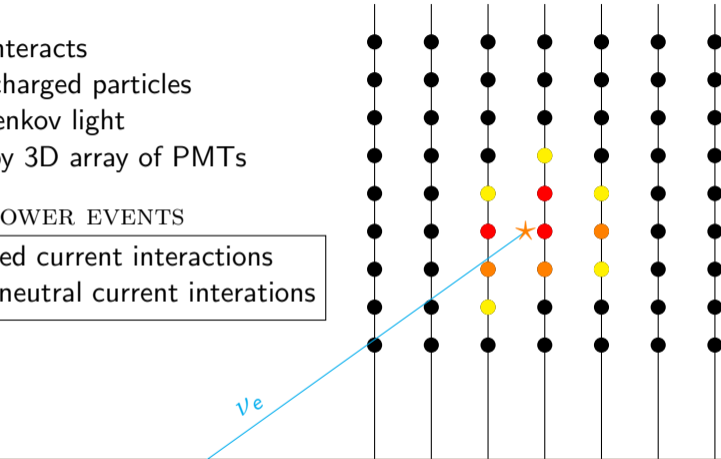
- amount of light \rightarrow energy



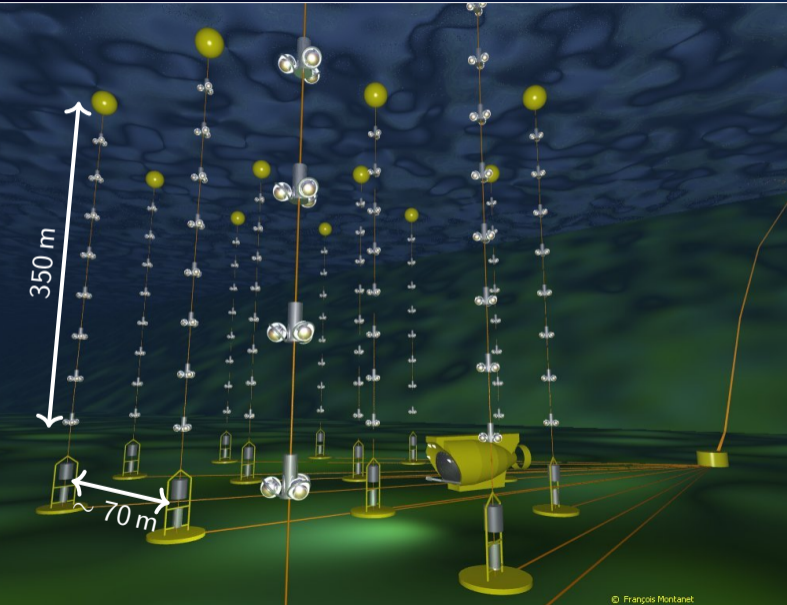
1. Neutrino interacts
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4. Detected by 3D array of PMTs

SHOWER EVENTS

$\nu_e + \nu_\tau$ charged current interactions
 $\nu_e + \nu_\mu + \nu_\tau$ neutral current interactions



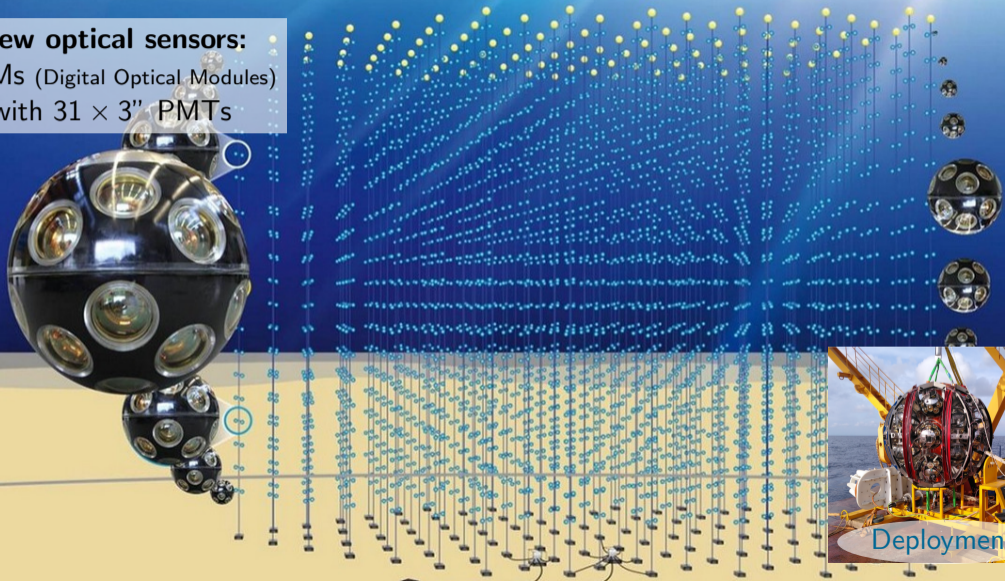
Detector acceptance depends on energy:
lower energies \rightarrow less light \rightarrow needs denser PMT layout
higher energies \rightarrow more absorbed by Earth \rightarrow can only see downgoing ν_s



- In operation since 2006 (completed in 2008)
- Off the coast of Toulon
- 12 lines
- 25 storeys/line
- 3 PMTs / storey

*Total instrumented
volume:
10 Mt*

New optical sensors:
DOMs (Digital Optical Modules)
with $31 \times 3''$ PMTs

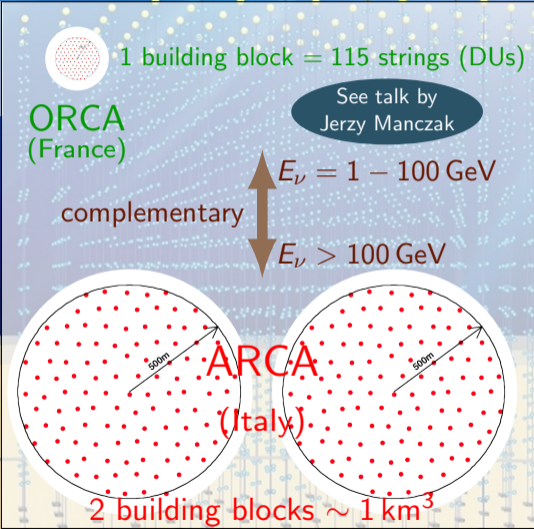


18 DOMs / string



Deployment

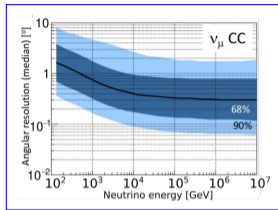
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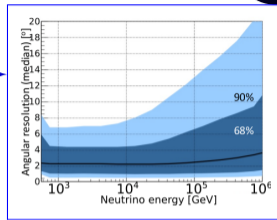
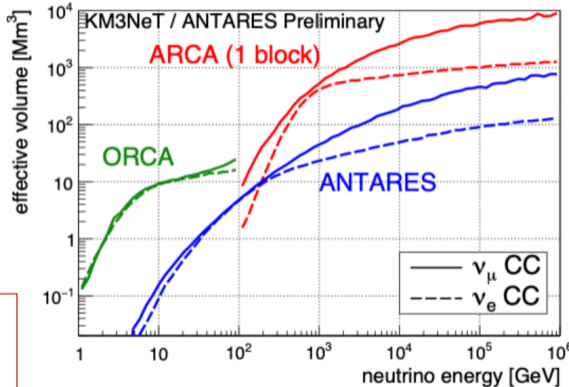
Deployment



$< 0.4^\circ @ E_\nu > 10 \text{ TeV}$

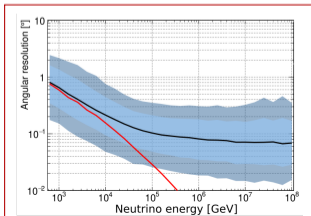
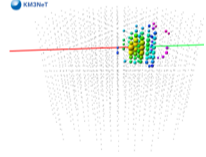
$< 3^\circ, \Delta E/E < 10\%$

ANTARES



KM3NeT

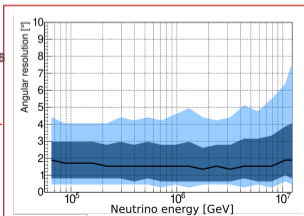
SHOWERS



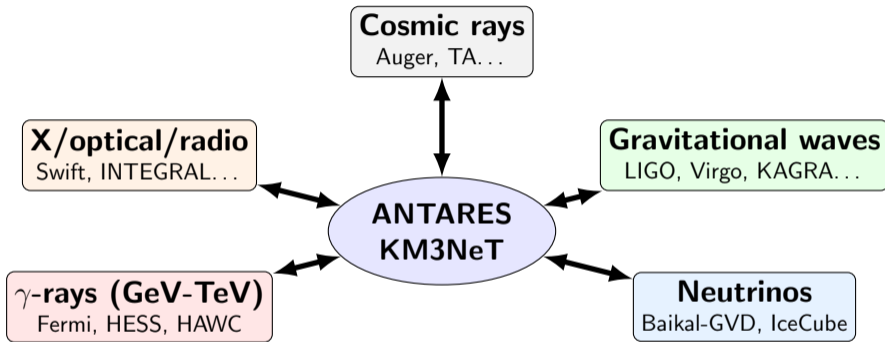
$< 0.2^\circ @ E_\nu > 10 \text{ TeV}$

$< 2^\circ, \Delta E/E < 5\%$

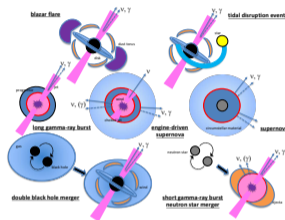
KM3NeT/ARCA



ANTARES results



Diversity of multi-messenger sources



ANTARES receives alerts:

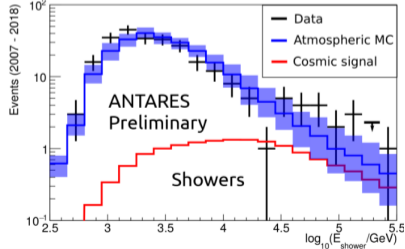
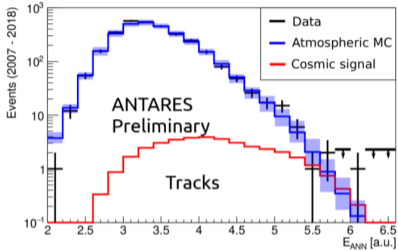
- transient events reported in GCN
- follow-ups issued in few days (IceCube, GW...)
- (+ offline analyses)

ANTARES sends alerts:

- alert ready in ~ 5 s
- median angular resolution: $\sim 0.3^\circ$
- triggers: single high-energy ν , multiplets
- alerts sent to AMON and partners

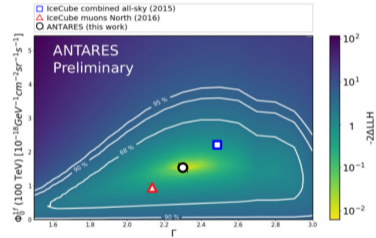
KM3NeT will

join the real-time efforts in 2022



- **Data sample: 2007-2018**
- **All-sky and all-flavours search**
- **1.8 σ excess**

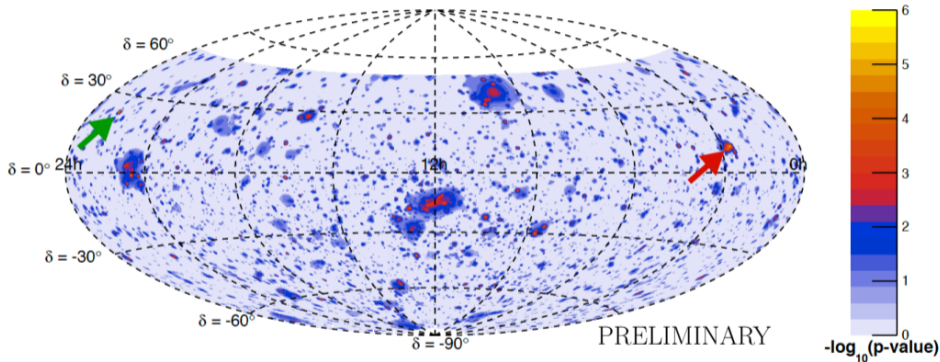
	Obs.	Exp.
Tracks	27	19.9
Showers	23	16.2
Total	50	36.1 \pm 8.7



Best fit

- $\Phi_0(100 \text{ TeV}) = (1.5 \pm 1.0) \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$
- spectral index $\Gamma = 2.3 \pm 0.4$

- **Data sample:** 2007-2017
- Looking for point sources in the full sky, with $1^\circ \times 1^\circ$ pixels



Most significant cluster

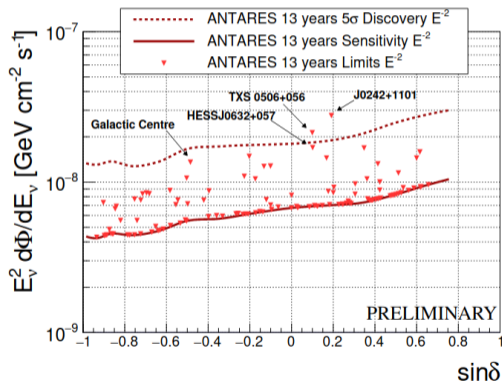
$RA = 39.6^\circ$, $\delta = 11.1^\circ$
 within 1° of J0242+1101
 pre-trial = 4.3σ (48% post-trial)

2nd most significant cluster

$RA = 343.8^\circ$, $\delta = 23.5^\circ$
 close to blazar MG3 J225517+2409
 pre-trial = 4.2σ

Candidate-list search

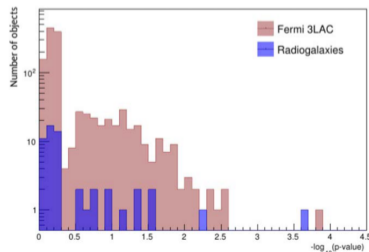
121 sources (potential neutrino emitters)

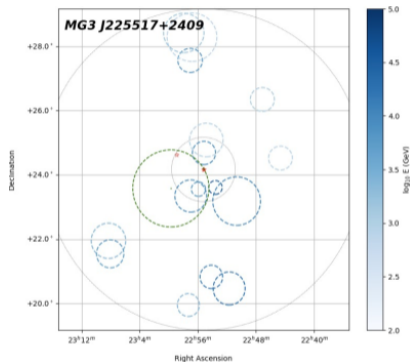


Mild excess for TXS 0506+056, J0242+1101...

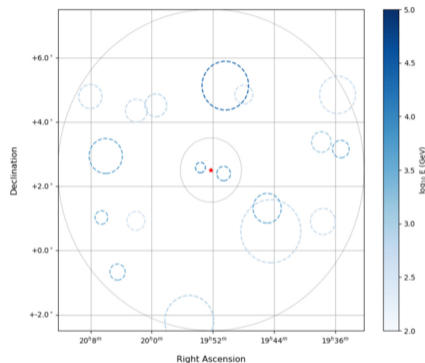
Catalog-based stacking

Catalog	p(pre)	p(post)	$\Phi_{90\%}$
Fermi 3LAC (All Blazars)	0.19	0.83	4.3
Fermi 3LAC (FSRQ)	0.57	0.97	2.2
Fermi 3LAC (BL Lacs)	0.09	0.64	4.8
Radio Galaxies	0.0048	0.10	4.2
Star-Forming Galaxies	0.37	0.93	2.0
Obscured AGN	0.73	0.98	1.5
IC High Energy Tracks	0.05	0.49	5.2

[*] Flux in $10^9 \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ 

Blazar MG3 J225517+2409

- Also second all-sky hotspot
- 5 ANTARES tracks + blazar $\rightarrow 2.3\sigma$
- 1 IC tracks + blazar $\rightarrow 1.9\sigma$

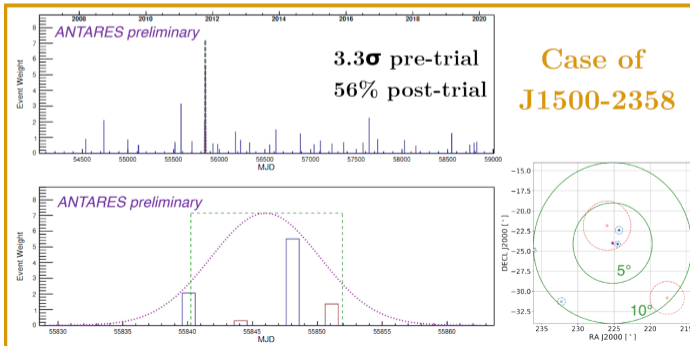
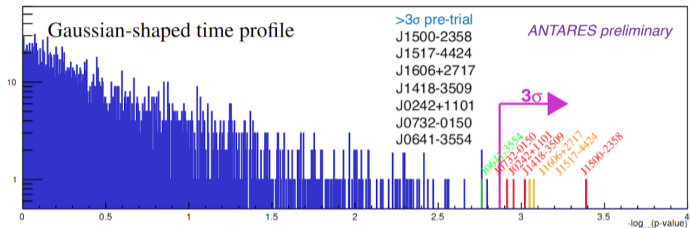
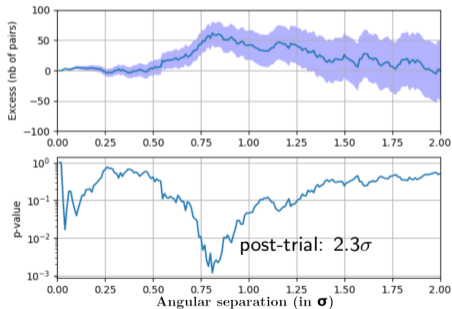
Radio galaxy 3C 403

- Pre-trial = 3.7σ
- Post-trial = 2.5σ

Radio-loud blazars

Inspired by [ApJ 908 \(2021\) 2, 157](#) (search for correlations between IceCube ν s and blazars)

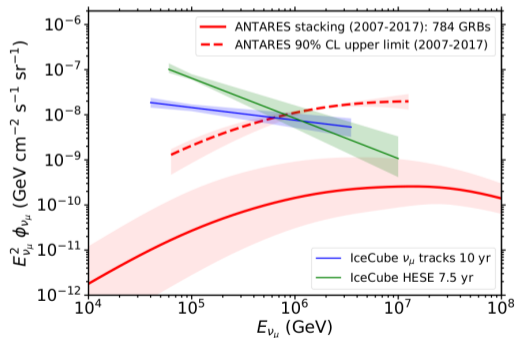
Counting neutrino-blazar pairs in cones of variable size.



Stay tuned for final results

Gamma-ray bursts

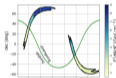
- ANTARES data sample: 2007-2017
- GRB catalog: 784 GRBs
- **No coincidence** → flux upper limits



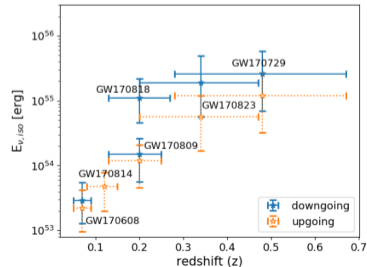
GRBs contribute < 10% of astro flux @ 100 TeV

Gravitational waves

- GW = Merger of compact objects (black holes / neutron stars)
- Search for ν in time (± 500 s) and spatial (compatible with GW localisation) coincidence
- Offline studies for O2 (2017) + online follow-up for O3 (2019-2020)
- **No coincidence** → upper limits



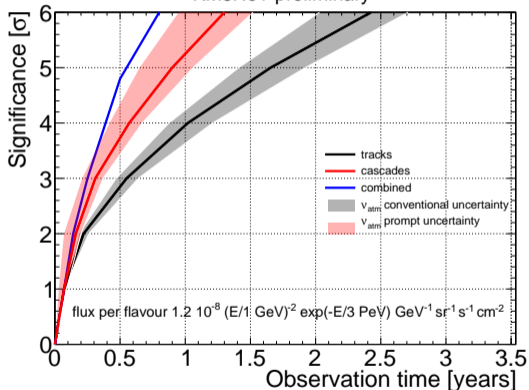
Ongoing analysis of O3 (GWTC-2 catalog). It will include stacking



Prospects with KM3NeT

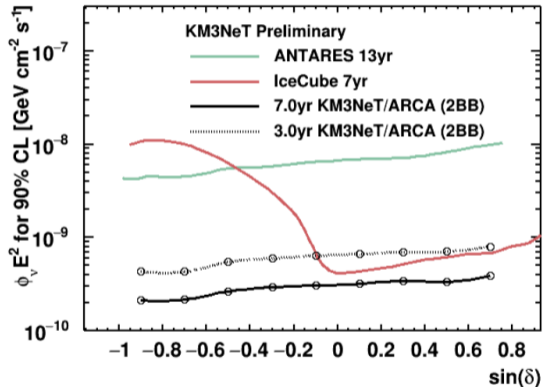
Diffuse flux

KM3NeT preliminary



Detect IceCube astro flux at 5σ in 6 months

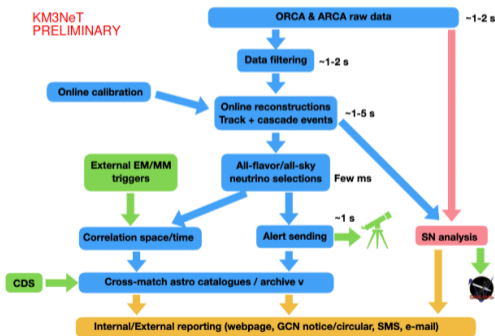
Point-source searches



Full-sky coverage with KM3NeT

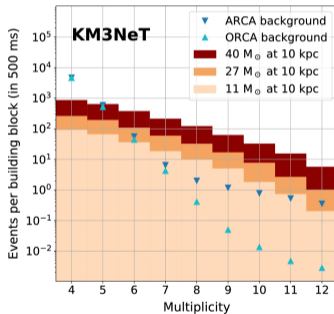
From ANTARES to KM3NeT:

- increased effective area: sensitivity to lower flux
- improved angular resolution: better pointing for subsequent follow-ups



Alerts expected to be sent starting in 2022

MeV Core-Collapse Supernova pipeline



Coincident hits in PMTs above the background

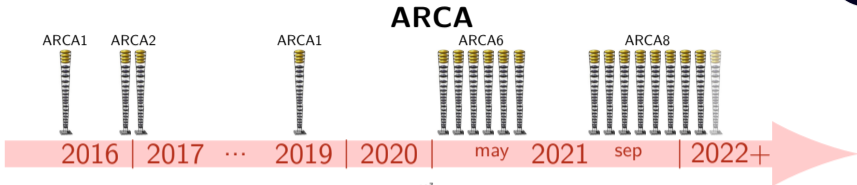
(radioactive decays / muons)

- 5σ for Milky Way (up to SMC @ 60 kpc for optimistic models)
- Time with $\mathcal{O}(\text{ms})$ precision @ $\lesssim 6$ kpc (for triangulation)
- SASI measurements @ $\lesssim 3 - 4$ kpc

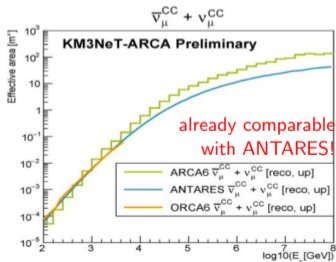
ORCA

6 strings currently taking data
New strings deployed this Autumn

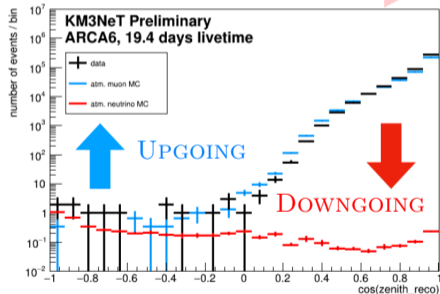
See talk by Jerzy Manczak



- Milestones this year:**
- 5 new strings deployed in Spring 2021
 - 3 strings deployed in September (one with connector issue)



ARCA



In ~ 19 days of ARCA6 data:

- observed = 15 upgoing events
- expected = 4 atmospheric ν + 7 atmospheric μ

Successful operation on 11-14th of September, 2021

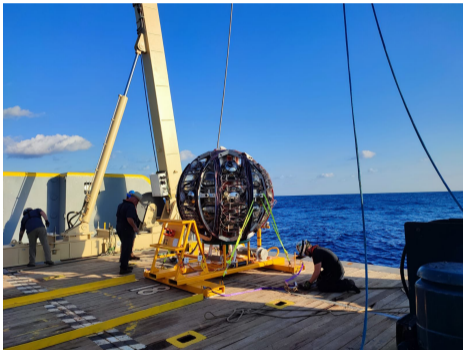


Figure: One string ready to be deployed

More details on [Twitter @km3net](#) and on [KM3NeT website](#)

Next operations

- **Scheduled for Spring and Autumn 2022:**
 - new strings
 - + one junction box
 - + calibration unit
- ... up to the 230 strings final configuration



Figure: Junction box

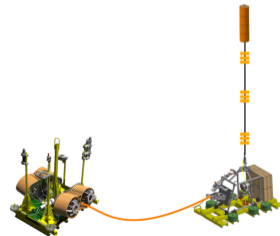
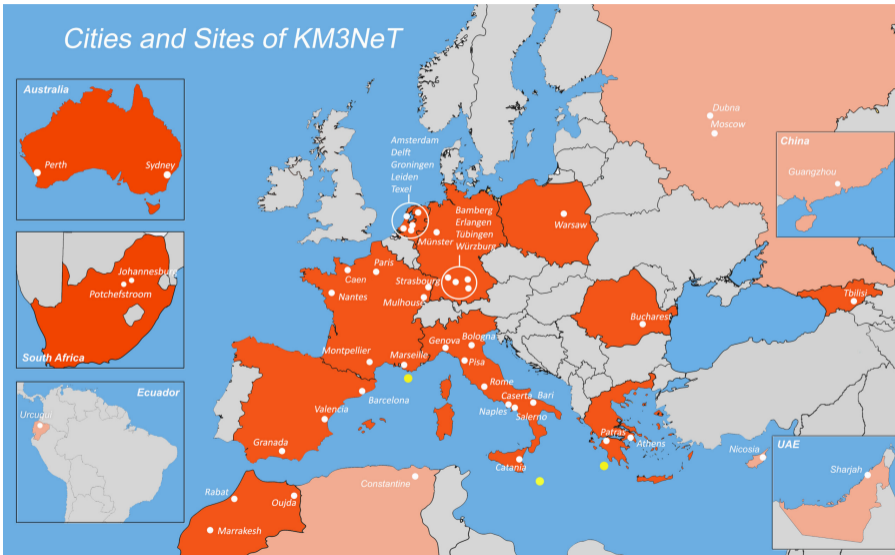


Figure: Calibration unit

- Several Cherenkov telescopes in the Mediterranean Sea:
 - ANTARES (since 2006), 12 lines, 10 Mt
 - KM3NeT/ORCA (under construction), 115 strings, 7 Mt, $E_\nu \sim \text{GeV-TeV}$ ← see Jerzy's talk
 - KM3NeT/ARCA (under construction), 2×115 strings, 1 Gt, focus on higher energies
- A plethora of results with ANTARES:
 - Mild excess for the diffuse astrophysical flux
 - Some interesting sources...
 - Broad multi-messenger program
- Bright future ahead with KM3NeT:
 - First strings are taking good-quality data and good data/MC agreement
 - New strings to be deployed in the coming years
 - Promising sensitivities over large energy spectrum (MeV \rightarrow EeV)

Backups

Cities and Sites of KM3NeT



56 institutes
17 countries
4 continents

One building block

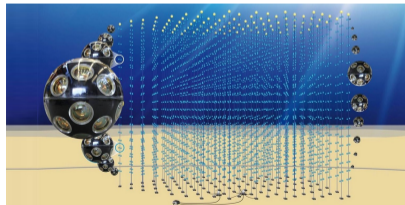
115 strings

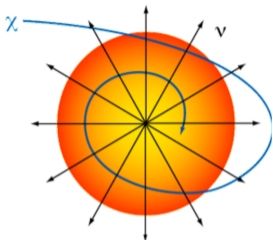
18 DOMs / string

31 PMTs / DOM

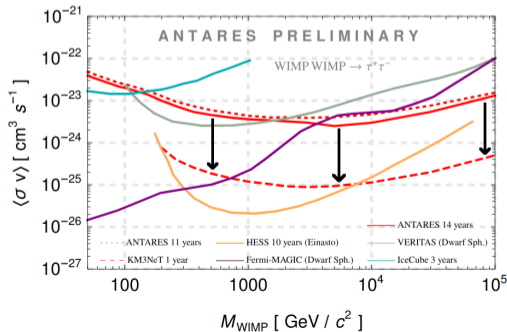
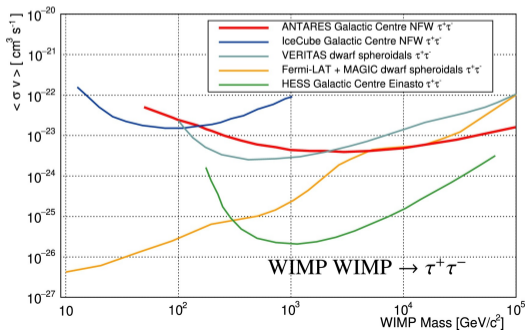
Total of $64k \times 3''$ PMTs

	ORCA	ARCA
	1 building block	2 building blocks
String spacing	20 m	90 m
DOM spacing	9 m	36 m
Depth	2470 m	3500 m
Instrumented mass	~ 7 Mt	$\sim 2 \times 0.5$ Gt



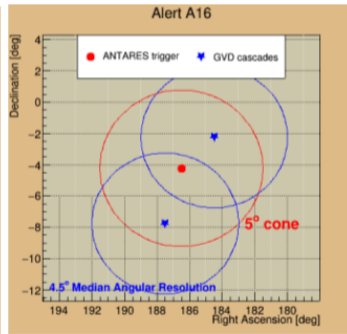
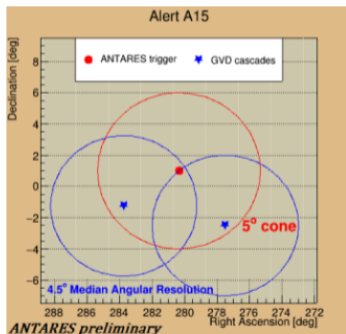
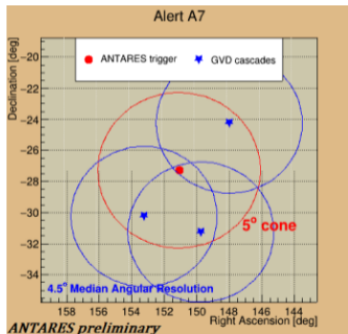


- Relic WIMPs gravitationally bound in the center of an astrophysical object (**Galactic Center, Sun core, Earth...**)
- Search for an excess of ν_μ due to WIMP annihilation ($\chi + \chi \rightarrow b\bar{b}, W^+W^-, \tau^+\tau^-, \mu^+\mu^-, \nu_\mu\bar{\nu}_\mu, \langle E_\nu \rangle \sim M_\chi/3$)

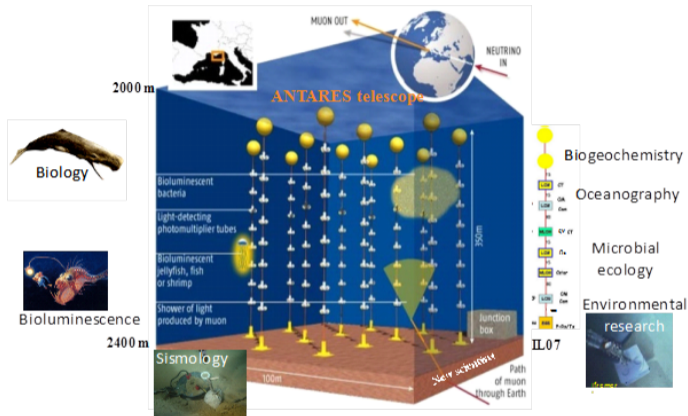


Baikal-GVD follow-up

- 38 alerts sent to Baikal-GVD
- 32 follow-ups
- 3 with GVD cascades in time (± 1 d) and spatial ($< 5^\circ$) coincidence



~ 0.1 background events per cluster per day



- Bioluminescence Flashes: [arXiv:2107.08063](https://arxiv.org/abs/2107.08063)
- Sperm whale long-range echolocation: [Sci. Rep. 7 \(2017\) 45517](https://doi.org/10.1038/s41598-017-04551-7)
- High-frequency internal wave motions: [Ocean Dynamics, April 2014, 64, 4, 507-517](https://doi.org/10.1007/s10841-014-9607-4)
- REINFORCE European project, “Deep Sea Hunters” program