



<http://antares.in2p3.fr>

<http://www.km3net.org>

Neutrino Studies in the Mediterranean Sea: from ANTARES to KM3NeT

Antoine Kouchner

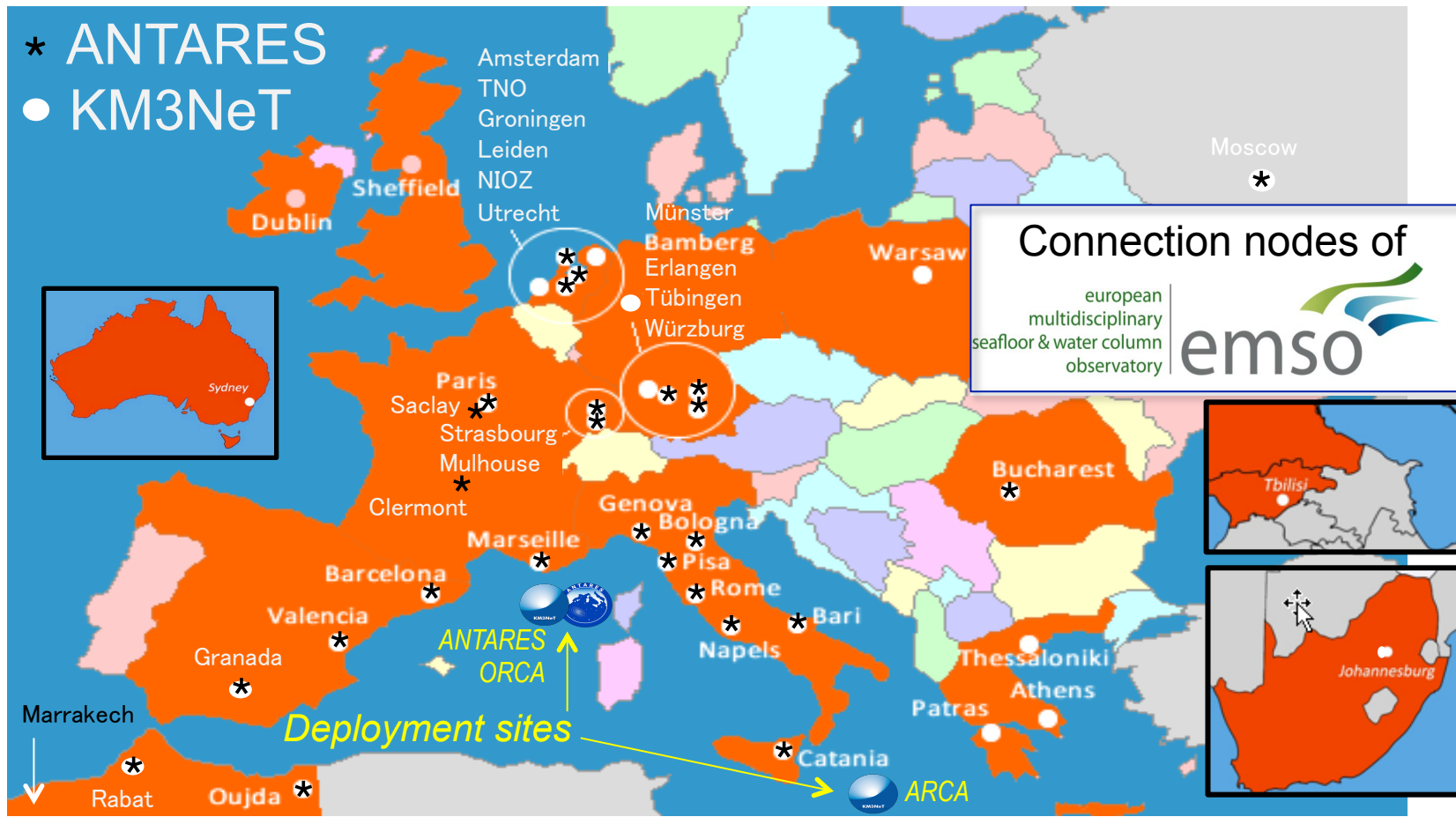




ANTARES & KM3NeT collaborations



* ANTARES
 ● KM3NeT



Connection nodes of

emso

emso logo: european multidisciplinary seafloor & water column observatory



📖 PLoS ONE 8 (7) 2013

Deep-sea bioluminescence blooms after dense water formation at the ocean surface

📖 *Journal of Geophysical Research: Oceans*, Vol 122, 3, 2017

Deep sediment resuspension and thick nepheloid layer generation by open-ocean convection

📖 *Deep-Sea Research I* 58 (2011) 875–884

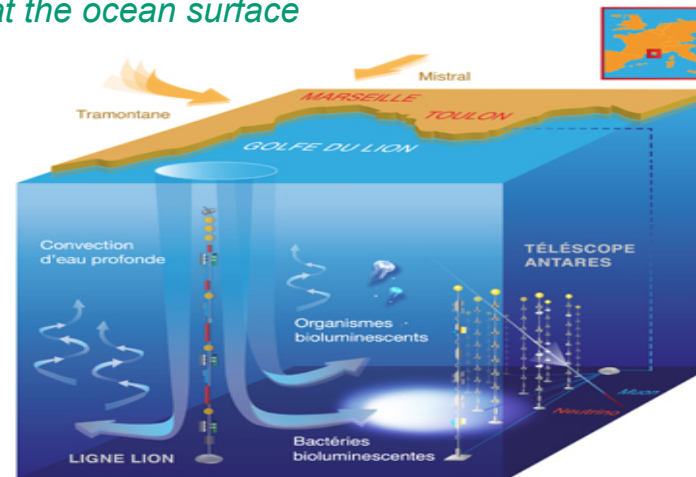
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

📖 *Sci. Rep.* 7 (2017) 45517

Sperm whale diel behaviour revealed by ANTARES, a deep-sea neutrino telescope

📖 *Ocean Dynamics*, April 2014, 64, 4, 507-517

High-frequency internal wave motions at the ANTARES site in the deep Western Mediterranean

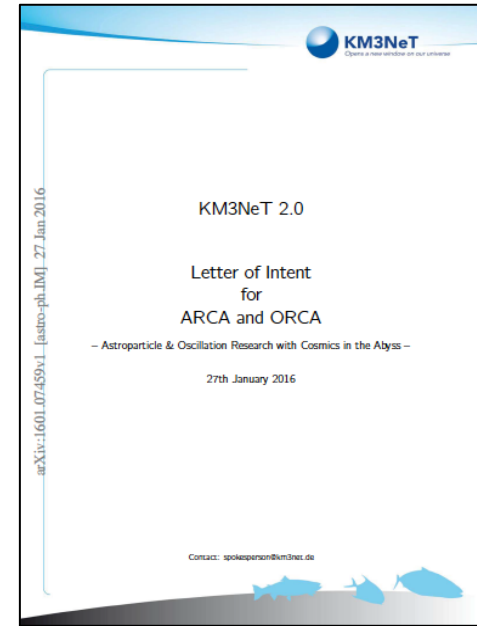


KM3NeT selected for the 2016 ESFRI Roadmap



10 March 2016 – Today, at its [launch event](#) at the Royal Netherlands Academy of Arts and Sciences in Amsterdam, the European Strategy Forum for Research Infrastructures (ESFRI) announced that KM3NeT 2.0 is selected for the 2016 ESFRI Roadmap for Research Infrastructures. The ESFRI Roadmap identifies new Research Infrastructures of pan-European interest corresponding to the long-term needs of the European research communities. Its mission is to ensure that scientists in

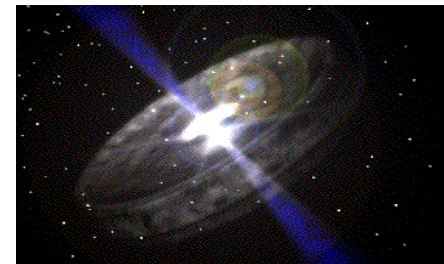
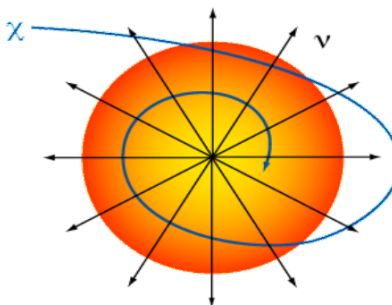
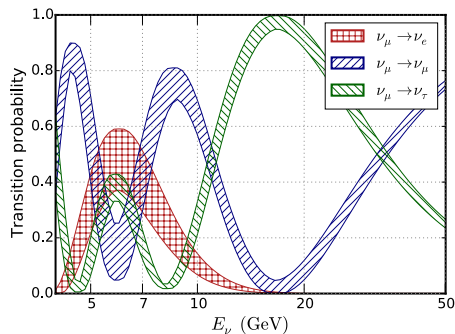
- Lol: *J. Phys. G*, **43** (2016) 084001
- H2020: funds to prepare the governance
- Since 2016 **KM3NeT** is back in the ESFRI roadmap
- Since 2018 **KM3NeT** is in the APPEC roadmap
- **Neutrino** research infrastructure in the deep Mediterranean Sea
 - discover and observe high neutrino sources in the Universe
 - ARCA** (off shore Capo Passero, It @ 3500 m depth)
 - determine neutrino mass hierarchy
 - ORCA** (off shore Toulon, Fr @2500 m depth)



Astroparticle
Research
with **C**osmics
In the **A**byss

Oscillation
Research
with **C**osmics
In the **A**byss





Low Energy
 $3 \text{ GeV} < E_\nu < 50 \text{ GeV}$

ν Oscillations
 ν Mass Hierarchy

Medium Energy
 $10 \text{ GeV} < E_\nu < 1 \text{ TeV}$

Dark Matter search
 + Exotic searches
 JHEP 07 (2017) 54

High Energy
 $E_\nu > 1 \text{ TeV}$

ν from extra-terrestrial sources
 Origin and production mechanism of HE CR





(TeV) Neutrino telescopes



<http://www.globalneutrino.org>



Antares
KM3NeT



Baikal
GVD

IceCube

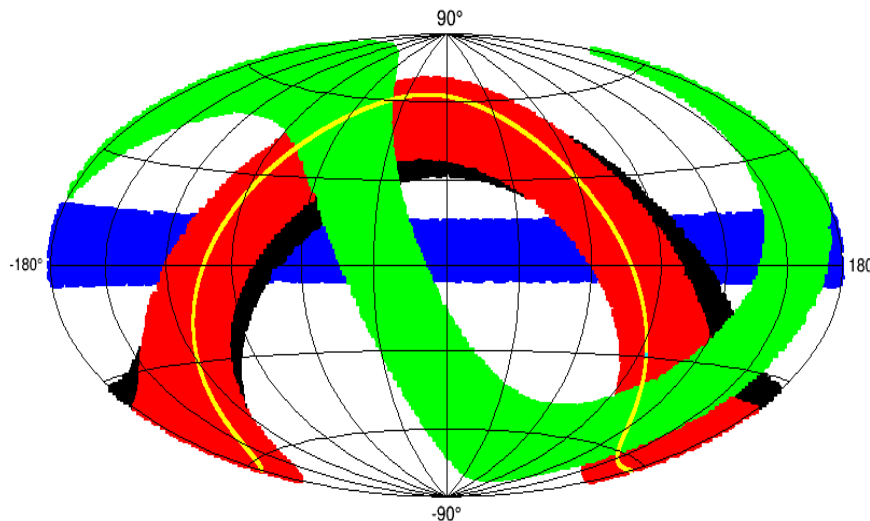
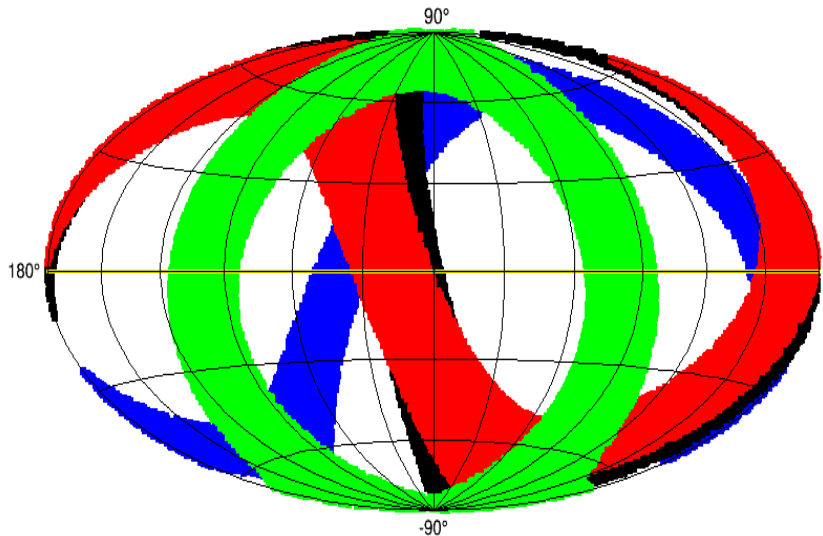




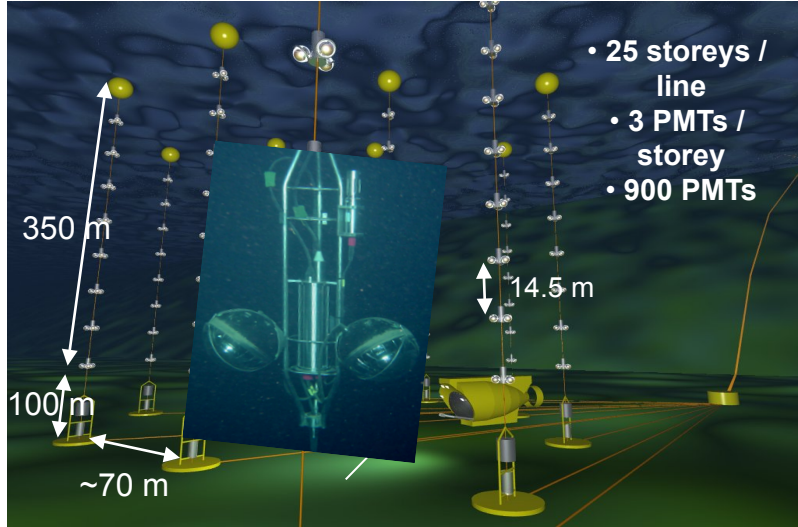
(TeV) Neutrino telescopes



An extra site in China (green) would offer nice complementarity at VHE (+/- 15° above) horizon wrt ARCA (red), ORCA (black) and IceCube (blue)



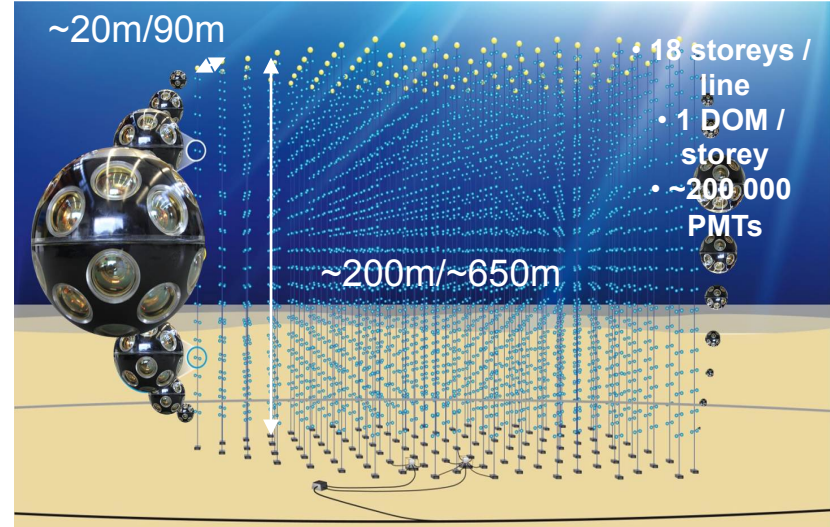
ANTARES Complete since 2008



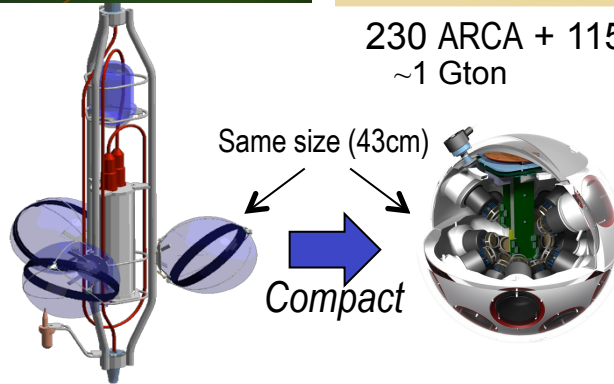
~10 Mton

12 lines
First Generation
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines **New Generation**
~1 Gton ~8 Mton



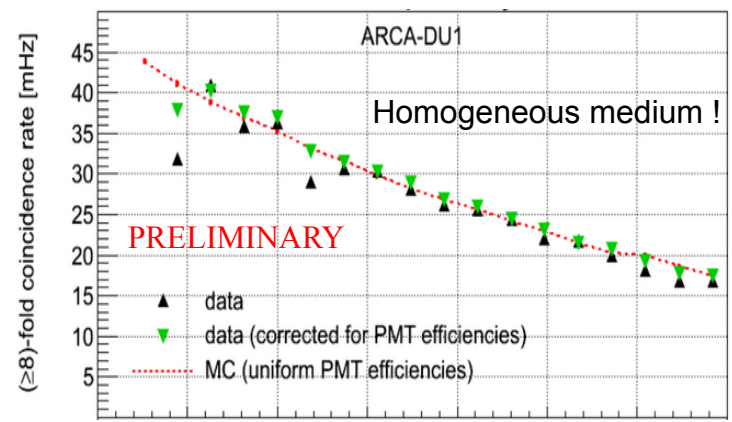
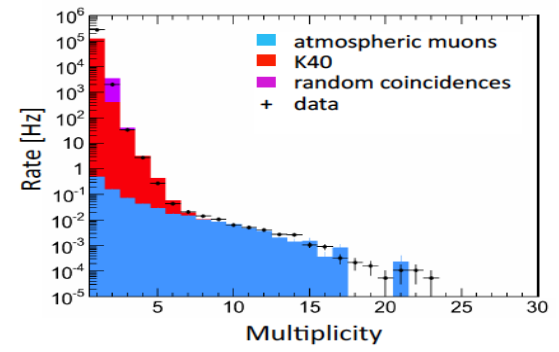
- **DOM: 31 3" PMTs**
- Digital photon counting
- Directional information
- Wide angle of view
- **Cost reduction wrt ANTARES**



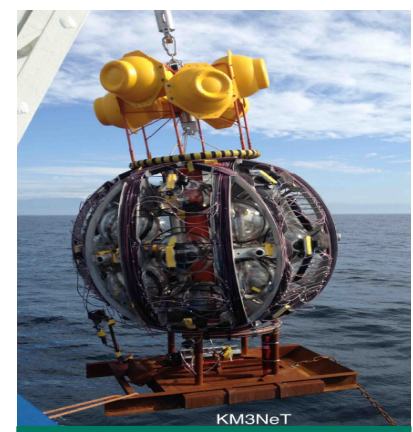
KM3NeT first Detection Units



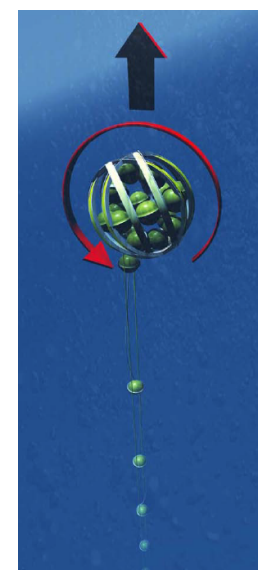
- ✓ Optical Module at Antares site, April 2013 (2500 m)
Muons from a single DOM ! Eur. Phys. J. C (2014) 74:3056
- ✓ Mini string (3 DOMs) at ARCA site, May 2014 (3500 m)
Track reconstruction Eur. Phys. J. C (2016) 76:54 -- Cover
- ✓ First full Detection Unit at ARCA site, Dec 2015



- ✓ One more line in operation in May 2016
→ 2 strings operated for 1 year: verify performances

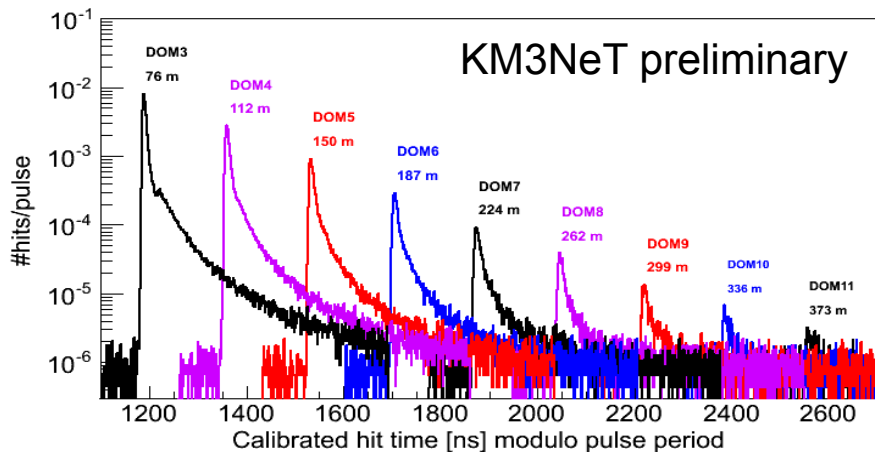
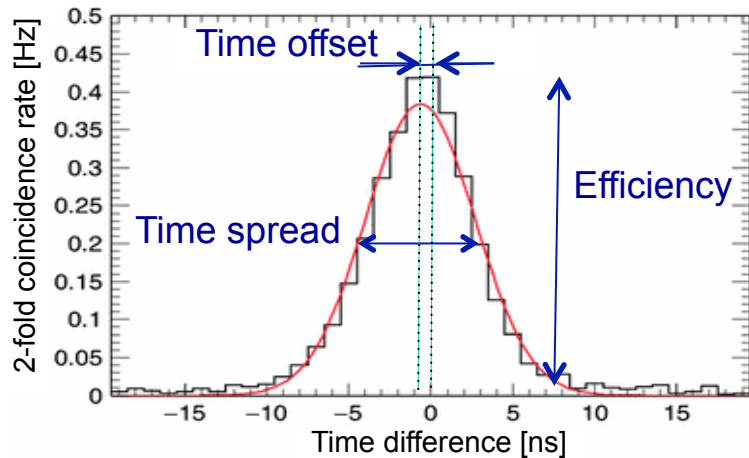
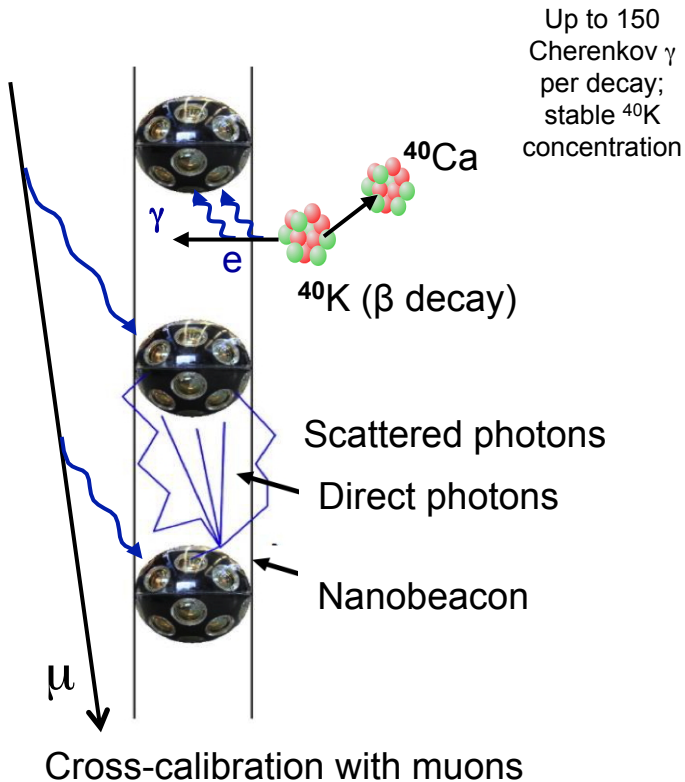


rapid deployment
autonomous unfurling
recoverable

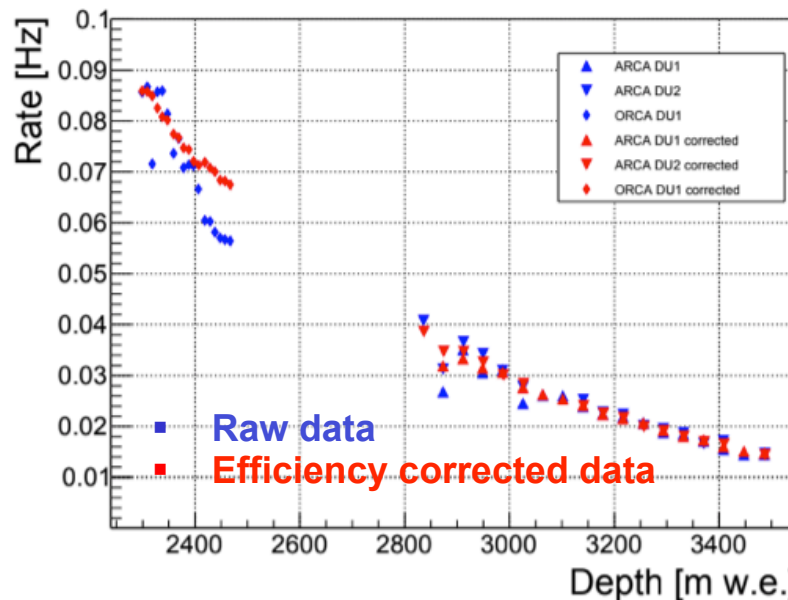


Watch <https://www.youtube.com/watch?v=tR8jwgG6uzk>

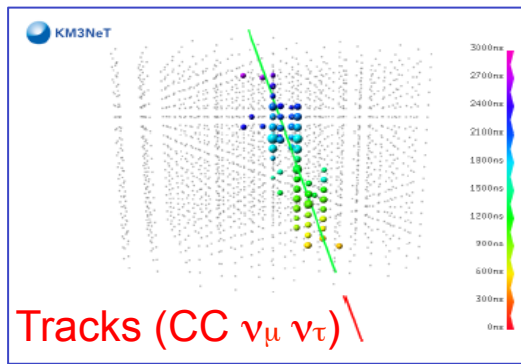
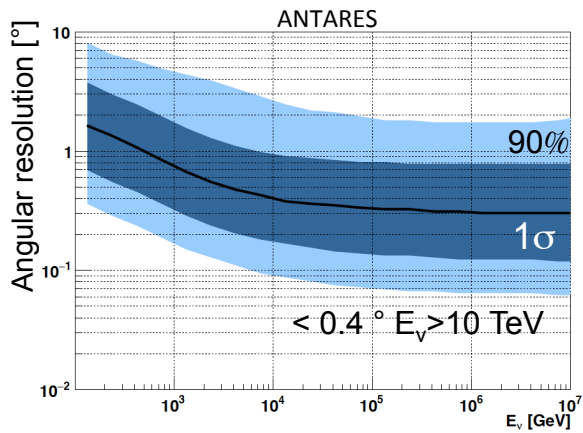




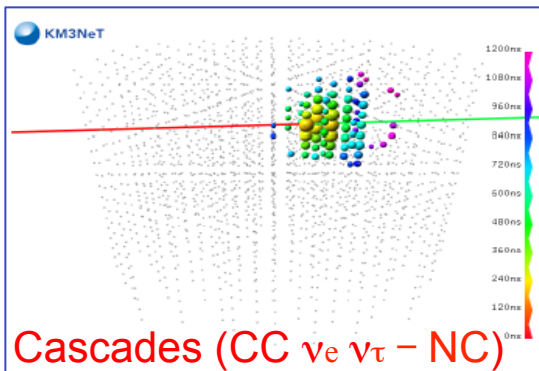
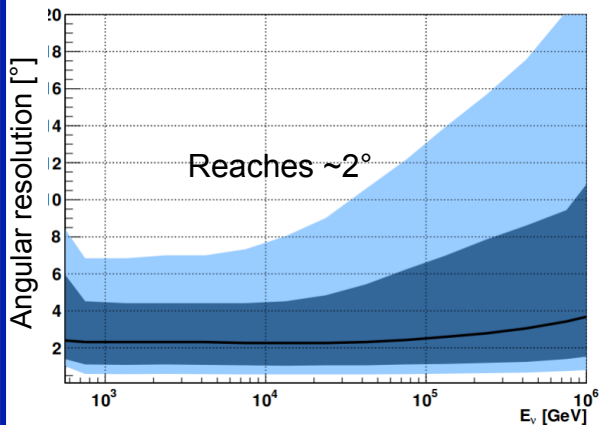
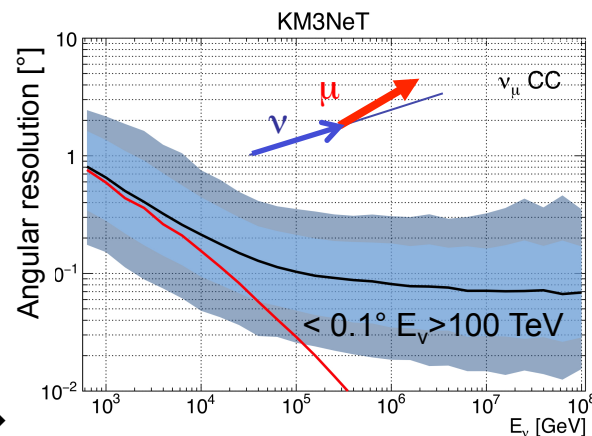
- Joint analysis shows the muon flux attenuation over > 1 km length



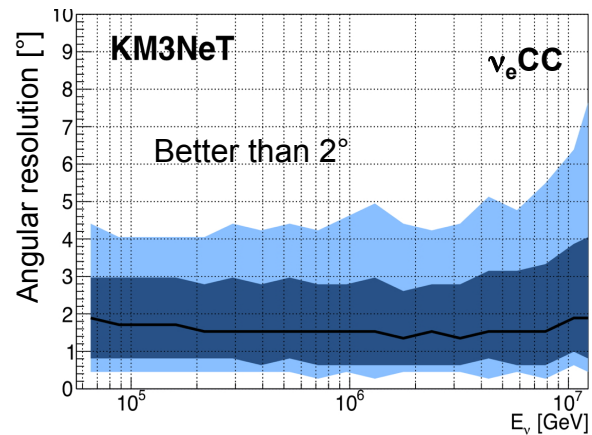
- Currently two strings in operation : one on each KM3NeT site
- 4 more ORCA strings to be deployed in the coming days.

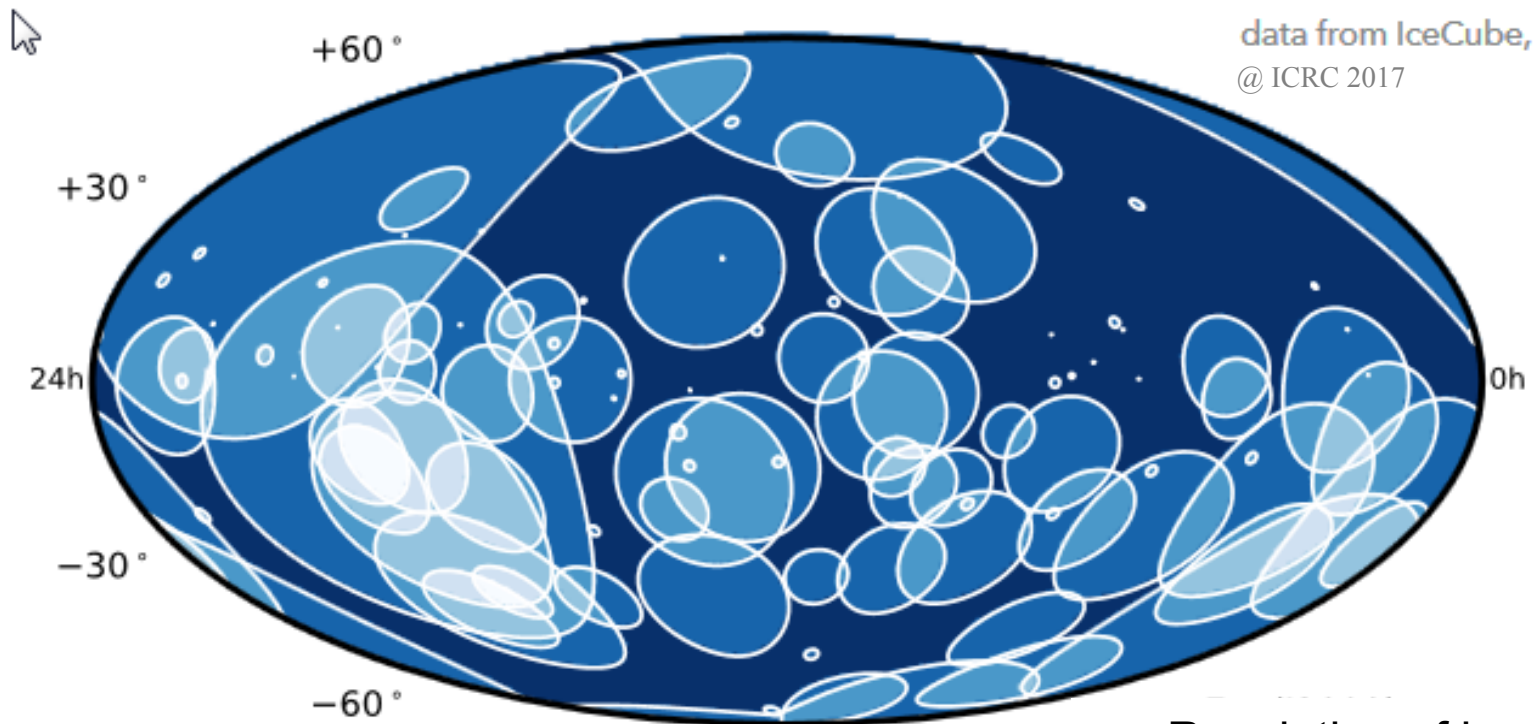


$\leftarrow 0.35 \text{ Log}(E_{\mu}) \text{ Resolution } 0.27 \rightarrow$



$\leftarrow \text{Energy Resolution } \sim 5\% \rightarrow$





credit E. Resconi

Resolution for ν_e
ANTARES ○
KM3NeT ◦

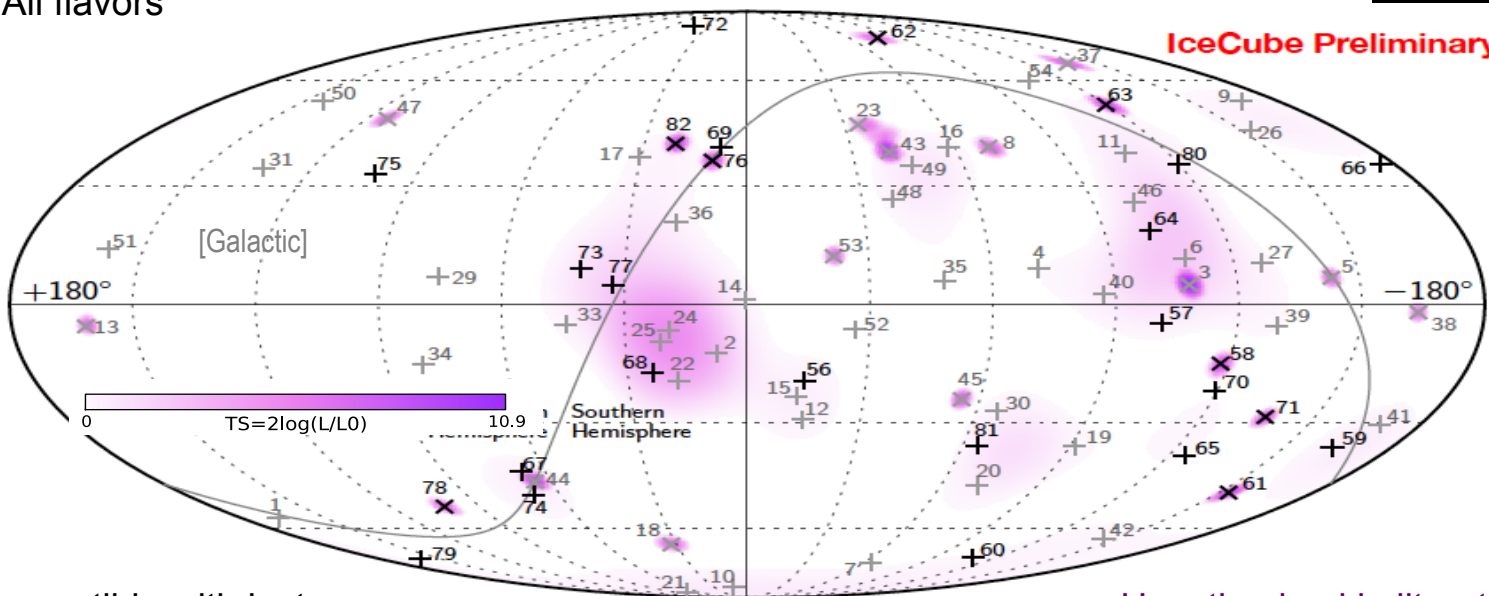
Resolution of key
importance
for catalogue searchers



First HE neutrinos seen by IceCube

HE Starting Events - 6 year - Kopper [ICRC17]
All flavors

Sources not clearly identified



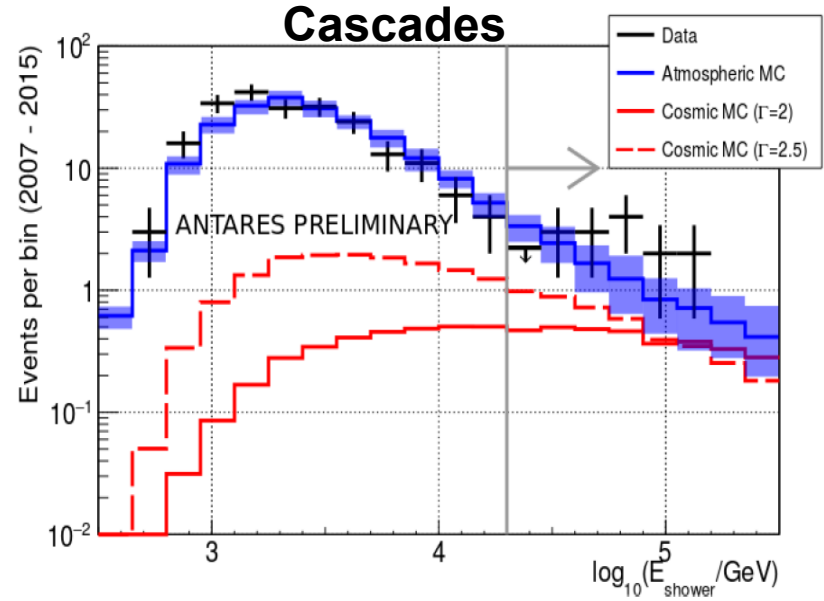
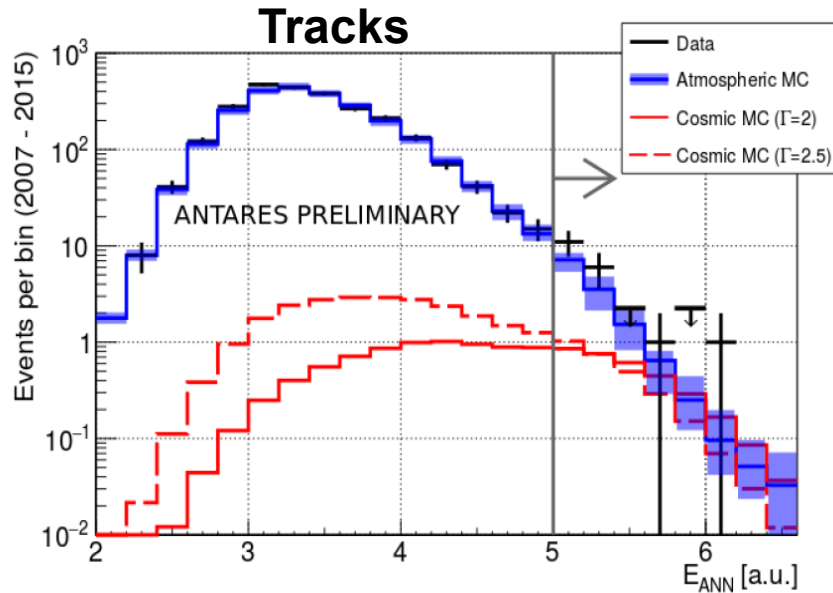
Compatible with isotropy
Moderate excess from Southern Hemisphere
Tension on spectrum from different analyses $E^{-\Gamma} \in [2, 2.9]$
Galactic component ? \rightarrow Northern Hemisphere telescopes

Hypothesized in literature:
Fermi Bubbles
Galactic Ridge
Galactic (point-like) source

Uncertainties reinforce the need of additional km³ NT in the Northern Hemisphere



- Search for excess at high energy -- Optimization based on MRF – Data 2007 – 2015 : 2451 days
 - Rely on Monte Carlo
- Variables used in analysis checked with burn sample ('0' ending runs)



- Neural network energy estimator for tracks, fitted E for cascades
- 33 observed, 24 +/- 7 expected from background, ~8 expected from IceCube flux
- P-value = 0.15, based on counting. **Not really constraining... but fully compatible with IceCube**

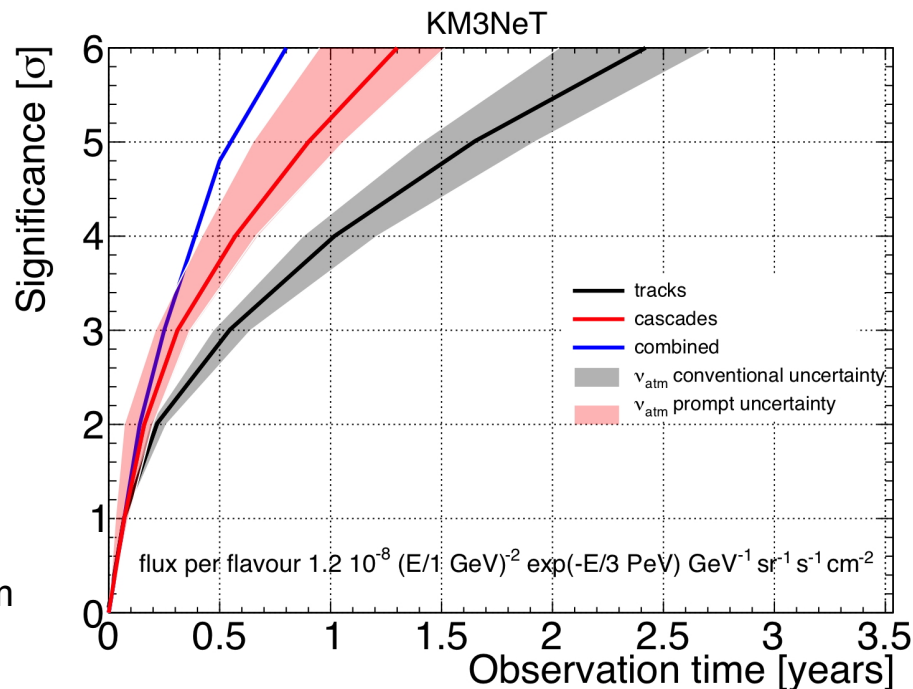
IC flux observable with high significance ~ 1 year with KM3NeT

- **Track channel**

Analysis for up-going events based on maximum likelihood
Pre-cuts on $\theta_{\text{zen}} > 80^\circ$, reconstruction quality parameter and N_{hit} (proxy for muon energy)

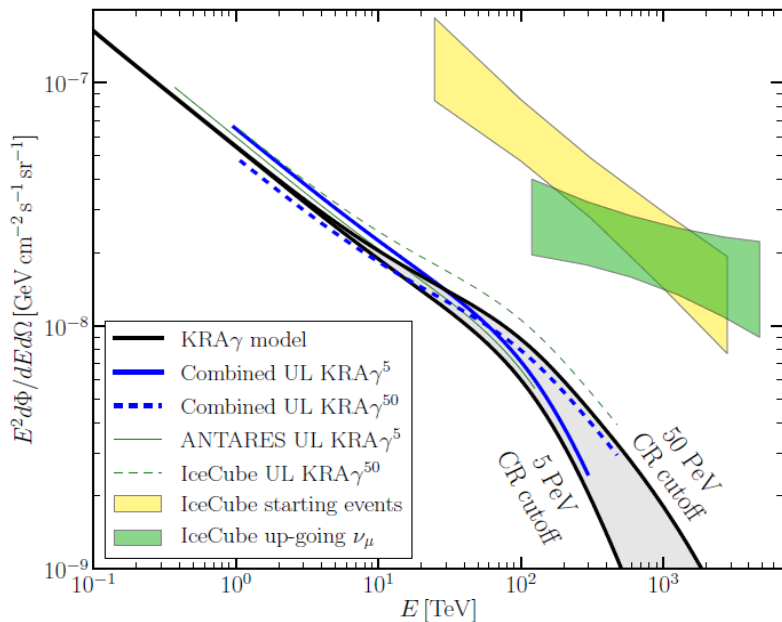
- **Cascade channel**

Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)
All sky analysis based on BDT and maximum likelihood.



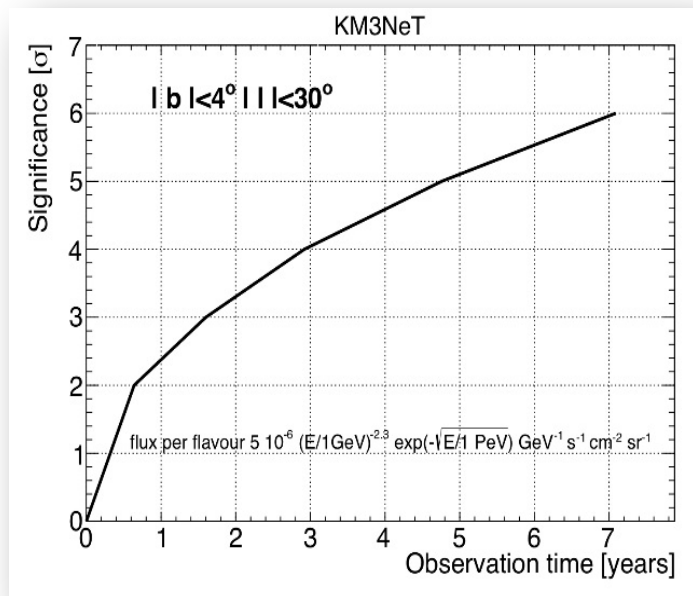
High resolution follow-up and e.g. flavour composition

Combined U.L. at 90% CL (blue line) on the 3-flavor neutrino flux of the $KRA\gamma$ model (5-50 PeV cutoff)



Result: total flux contribution of diffuse Galactic neutrino emission $< 8.5\%$ of the total diffuse IC astrophysical signal ($E_\nu > 30$ TeV) [ApJ 809:98(2015)].

ARCA sensitivity

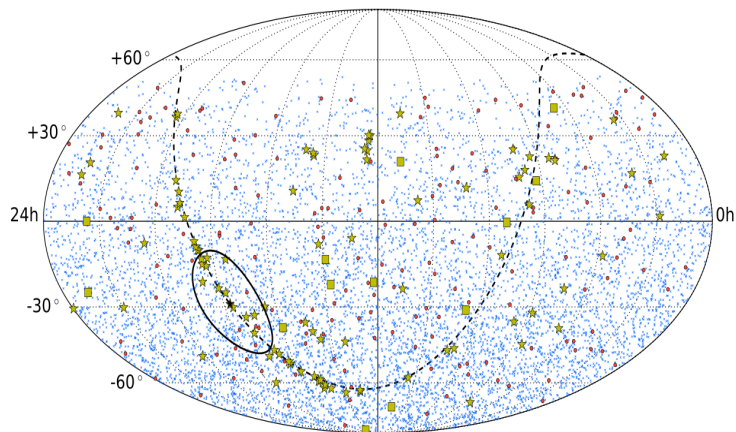


Discovery at 5σ significance in about 5 years



- ANTARES 2007-2015 (2424 days)

Arxiv:1706.01857, submitted to PRD



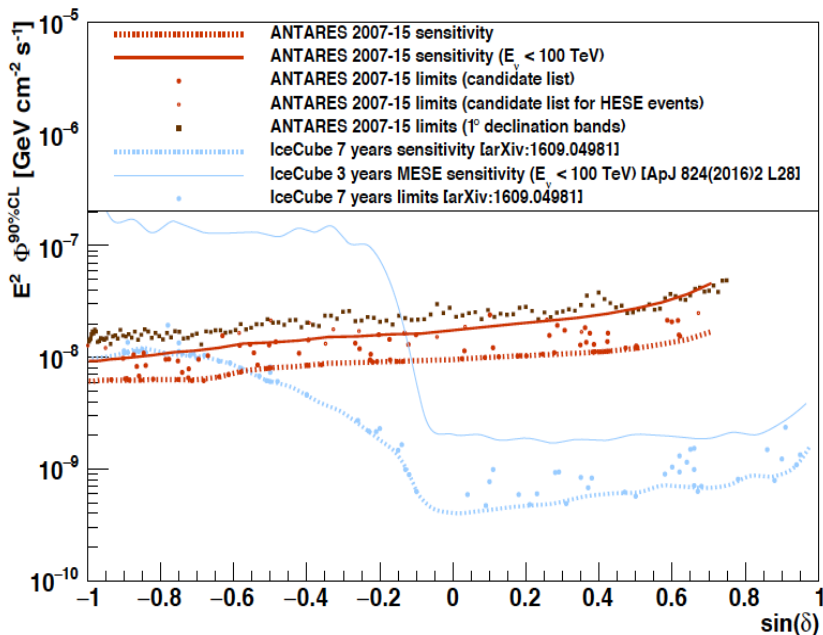
7629 tracks

180 cascades

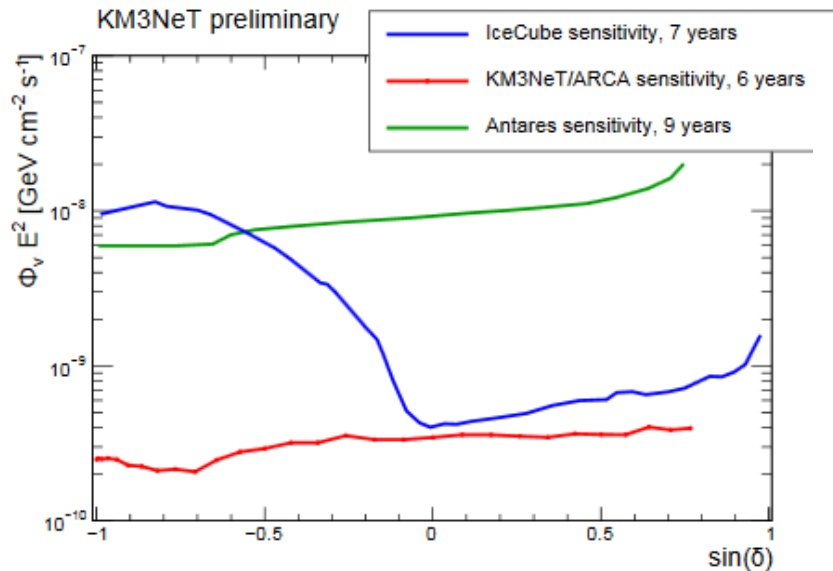
All-Sky + 106 candidate sources including
HAWC sources + 13 IC μ -HESE

Most significant cluster
in full sky
 $p = 6\%$ (1.9 sigma)
 $(\alpha, \delta) = (343.8^\circ, 23.5^\circ)$

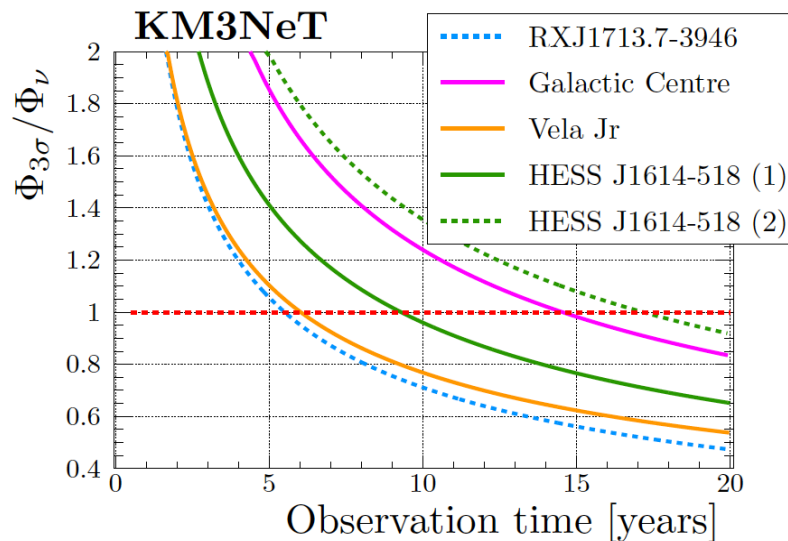
Most significant candidate
HESSJ0632+057
 $p = 13\%$
 $(\alpha, \delta) = (98.24^\circ, 5.81^\circ)$



World best limit on the Southern sky
below hundreds of TeV.
Combination with IceCube on-going



Sensitivity for Galactic Sources



Muon neutrinos still dominant in analysis

More than order of magnitude improvement in Southern Hemisphere

Directly constrain (or discover) hadronic scenario in galactic TeV gamma sources



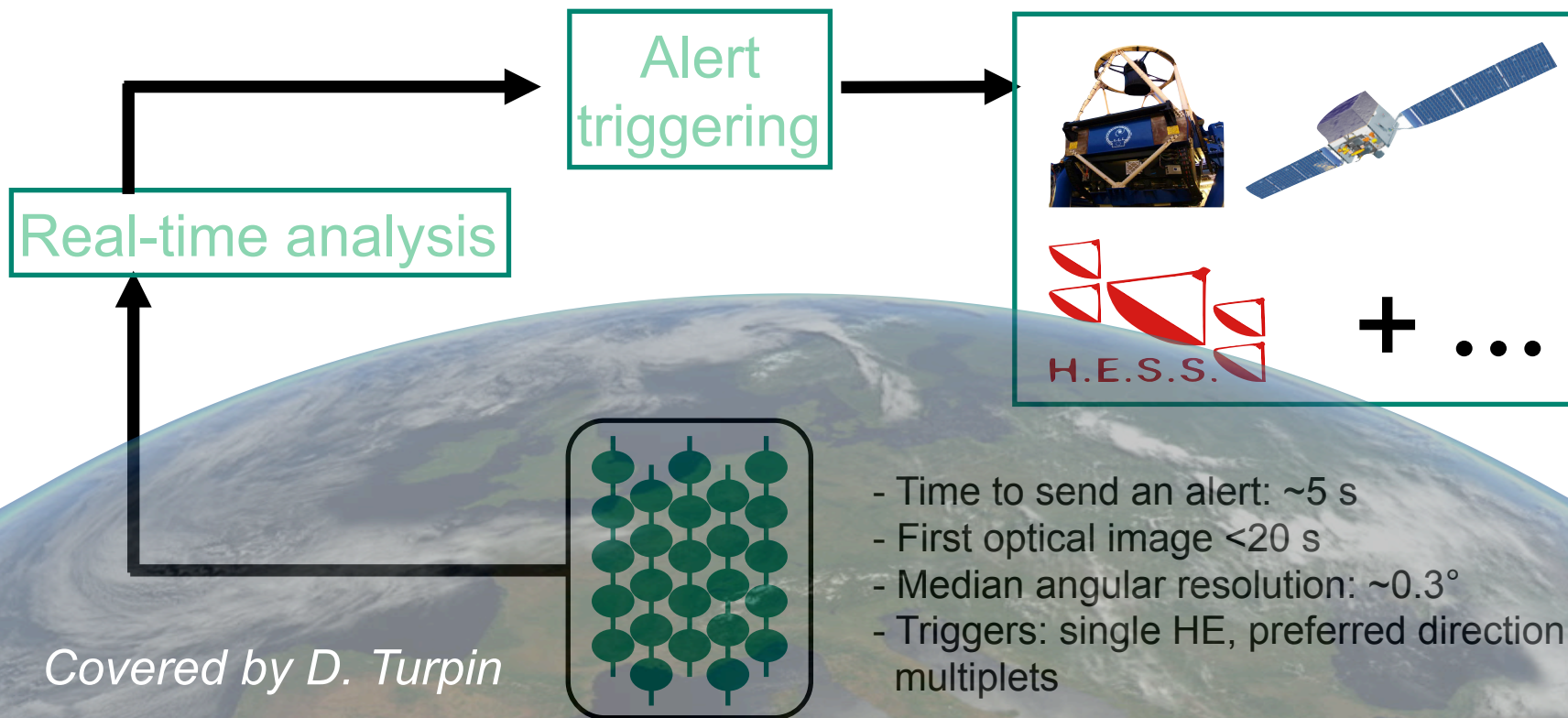
The multi-messenger program: TATOO



20

Telescope-Antares Target of Opportunity

1ST APPROACH:



Covered by D. Turpin

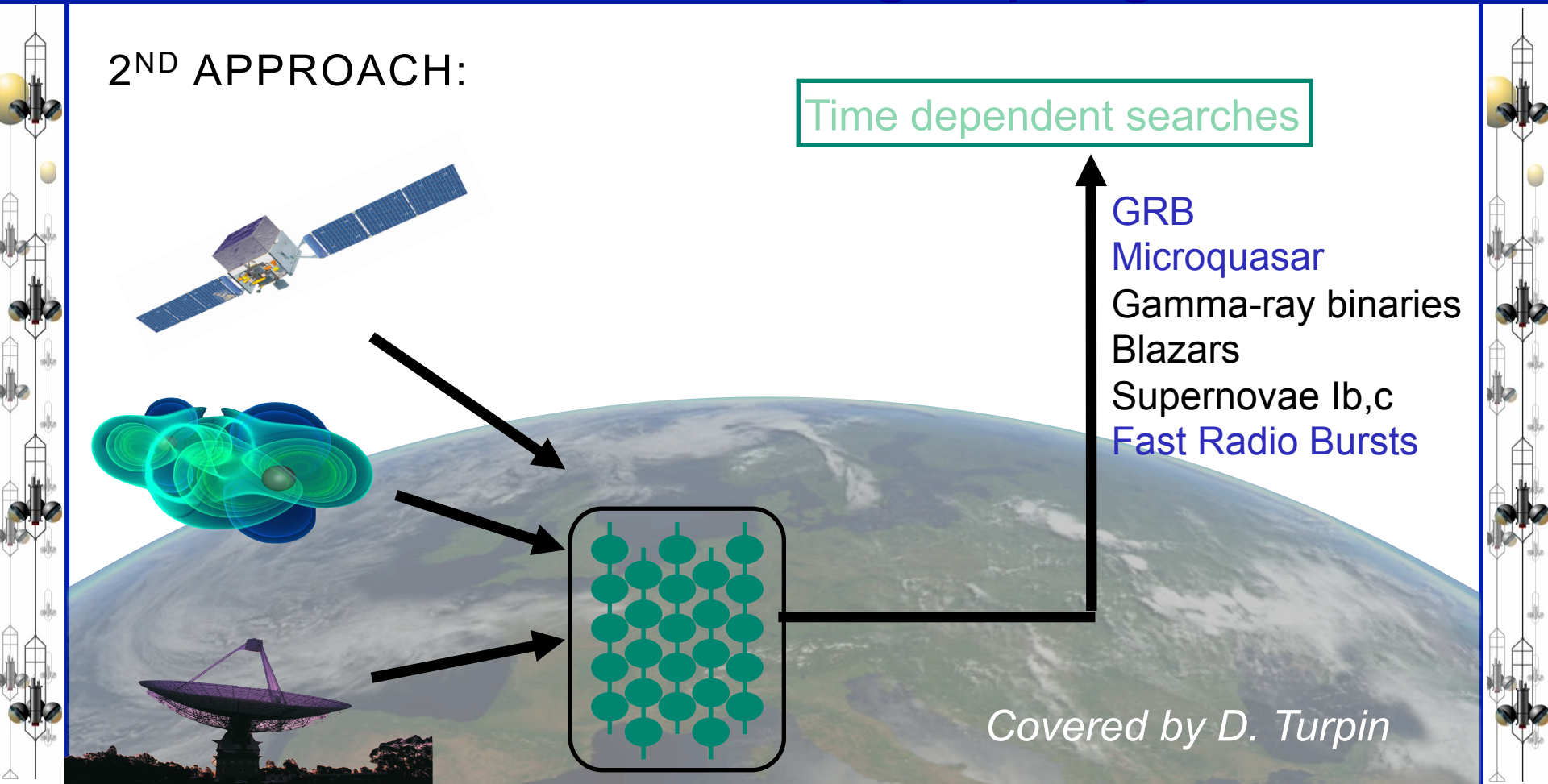
The multi-messenger program

2ND APPROACH:

Time dependent searches

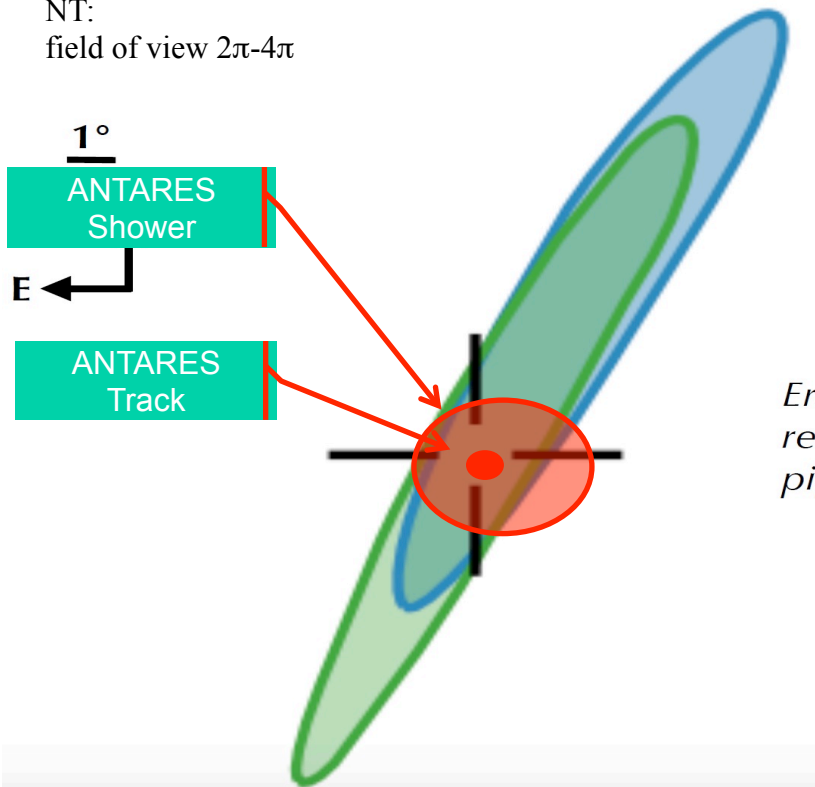
GRB
Microquasar
Gamma-ray binaries
Blazars
Supernovae Ib,c
Fast Radio Bursts

Covered by D. Turpin

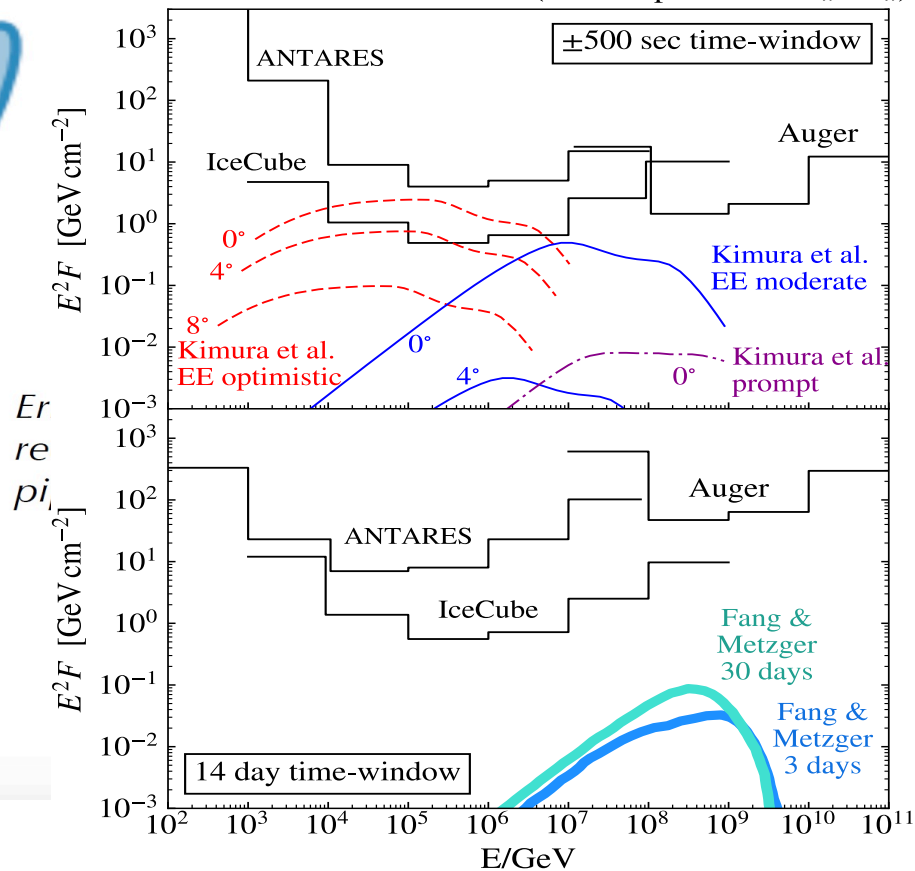


GW170817 follow-up

NT:
field of view $2\pi-4\pi$

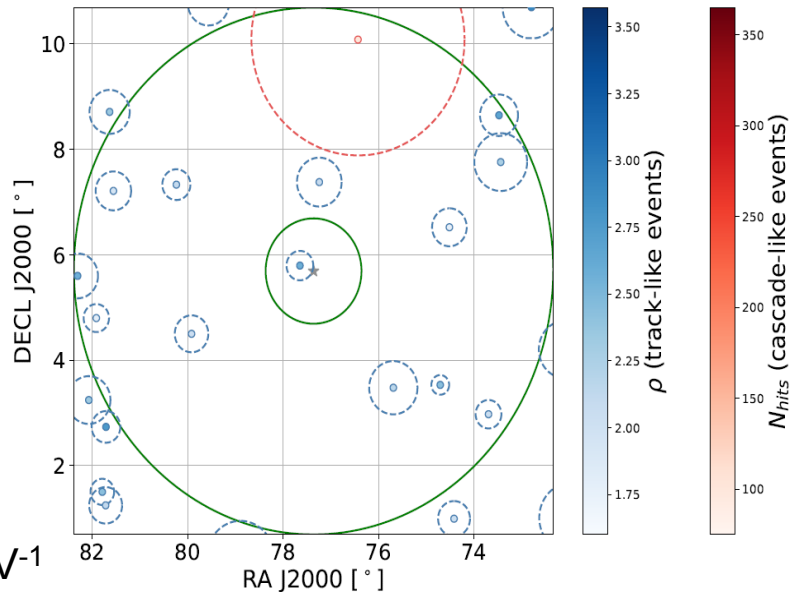


GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)



Time integrated archival search

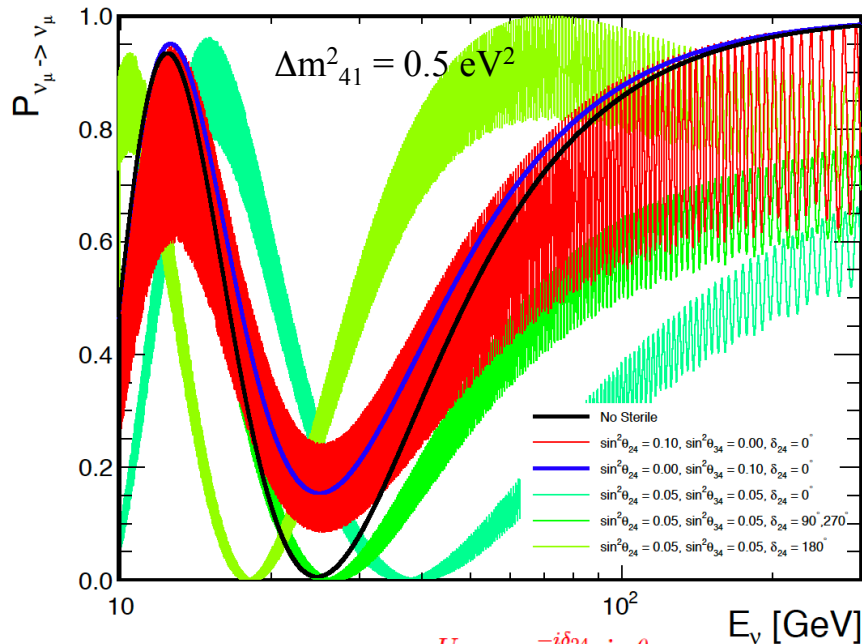
- Same method as PS searches, +2016/17
- Expected background (3136 days) :
 - 0.23/deg² for track-like
 - 0.005/deg² for shower-like events
- # of signal events fitted : $\mu_{\text{sig}} = 1.03$
- **Pre-trial p-value of 3.4%** (post-trial 87%)
- 1 track (12/12/2013) 0.3° from the source
- Flux U.L. (@100 TeV) for E⁻²: 1.6x10⁻¹⁸ GeV⁻¹ cm⁻² s⁻¹ in the range [2 TeV-4 PeV]
- In the list of 107 pre-selected sources, only two have a smaller p-value
- No event found during IC identified flare



Distribution of the 13 tracks +1 shower events in the (RA, δ) coordinates around (radius=1° and 5°) the position of TXS 0506+056.

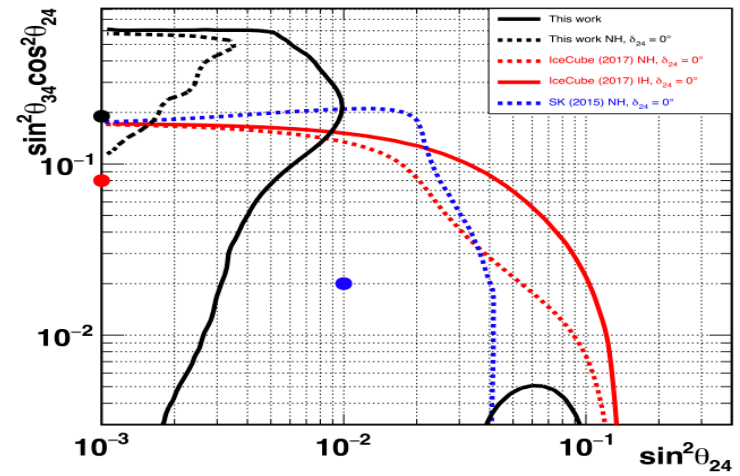
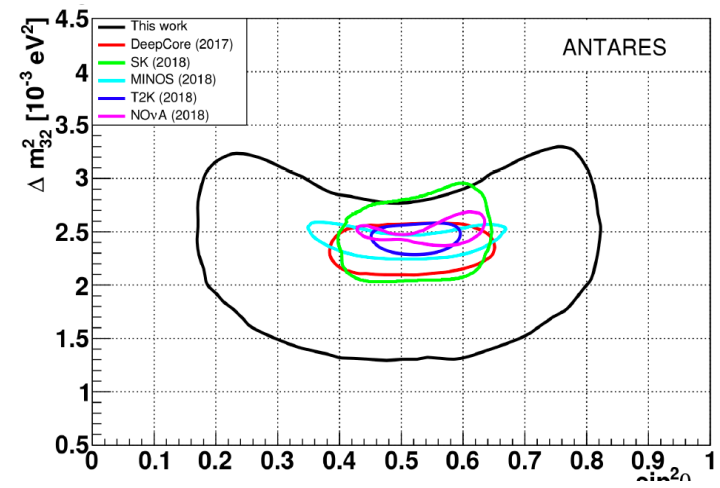
- 10 years of data 2007-2016
- Improves Sterile limits from IC & SuperK

$$\Delta m_{41}^2; \theta_{34}; \theta_{24}; \delta_{24}; (\theta_{14} = 0)$$



$$U_{\mu 4} = e^{-i\delta_{24}} \sin \theta_{24},$$

$$U_{\tau 4} = \sin \theta_{34} \cos \theta_{24}.$$

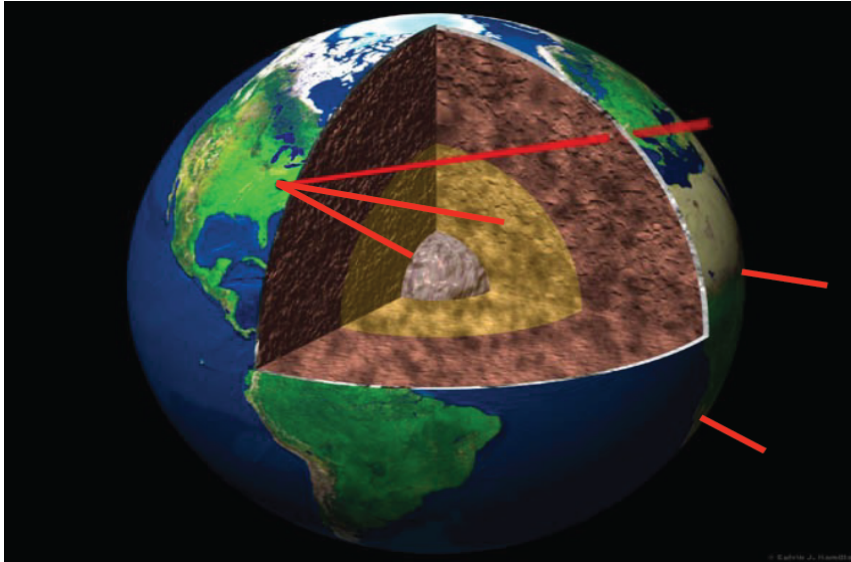


Sensitivity to Mass Ordering

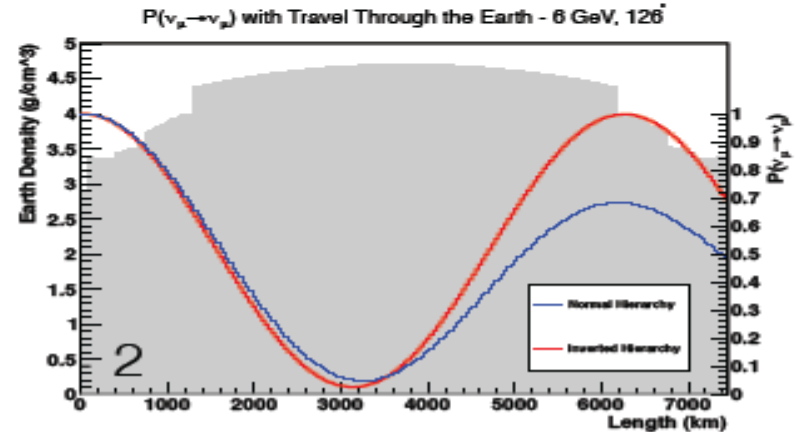
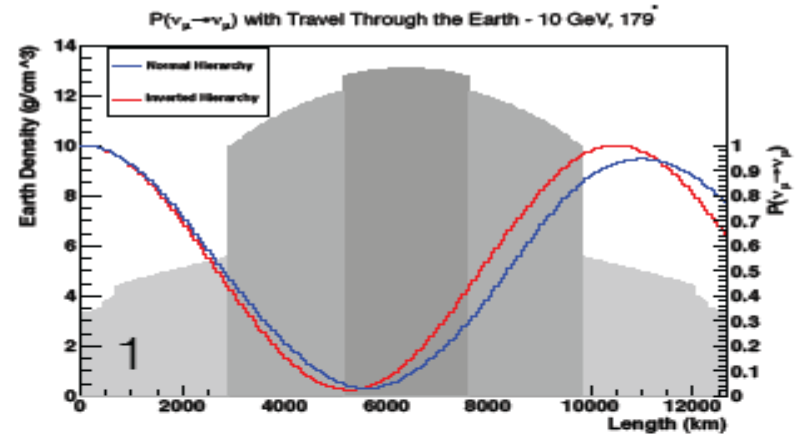
Earth density 4-13 g/cm³

→ Relevant E range 3 – 10 GeV

A "free beam" of known composition (ν_e, ν_μ)

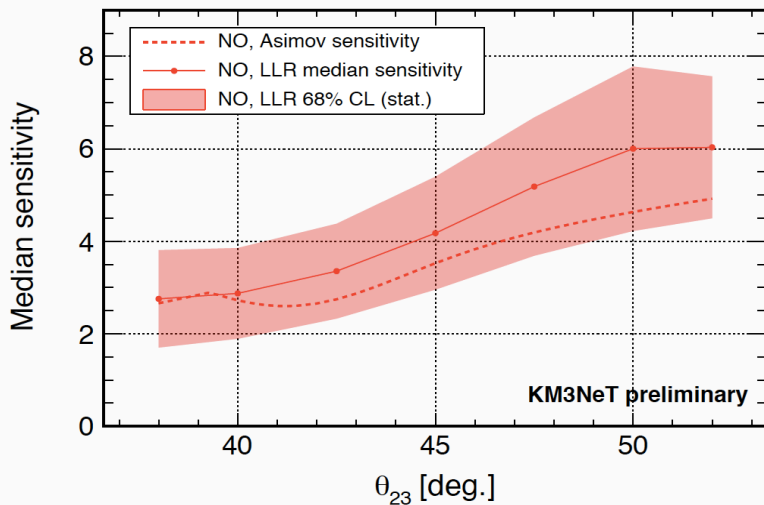


Method complementary to reactor ν 's
Synergies can be exploited in global fit

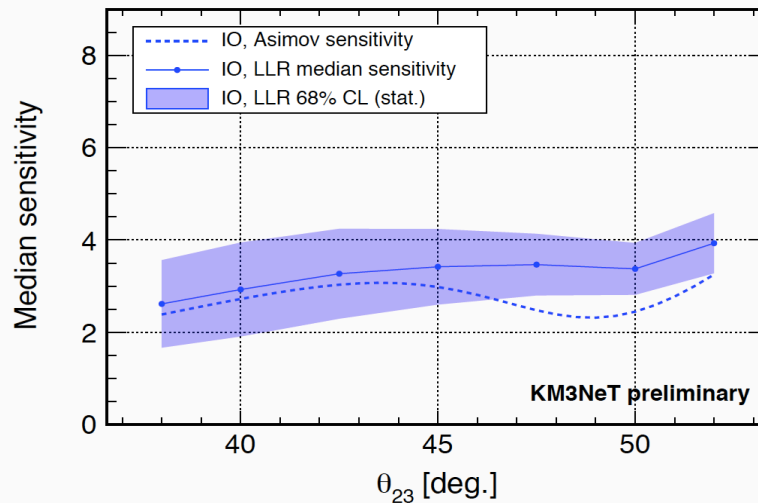


Assessing the Mass Ordering with ORCA

Asimov and LLR sensitivities after 3 years, true $\delta_{CP} = 0$



Asimov and LLR sensitivities after 3 years, true $\delta_{CP} = 0$



Fit in 2 'flavour' bins (track/shower)

Improvements expected with

- using inelasticity binning
- using more flavour bins

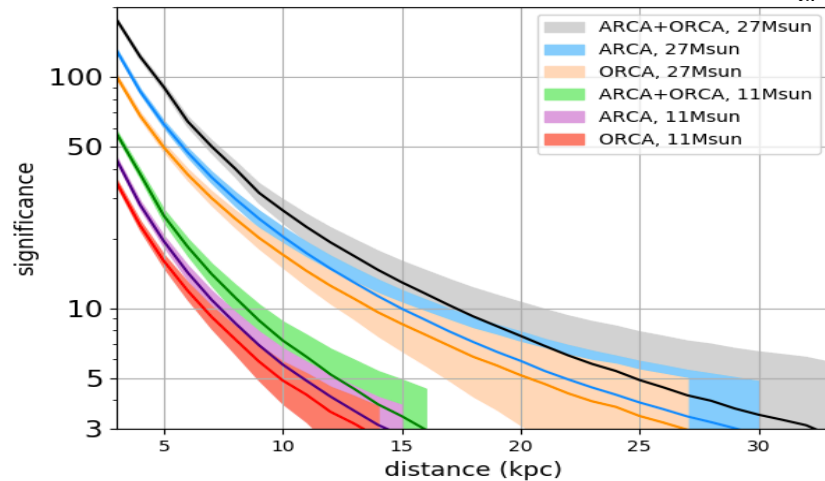
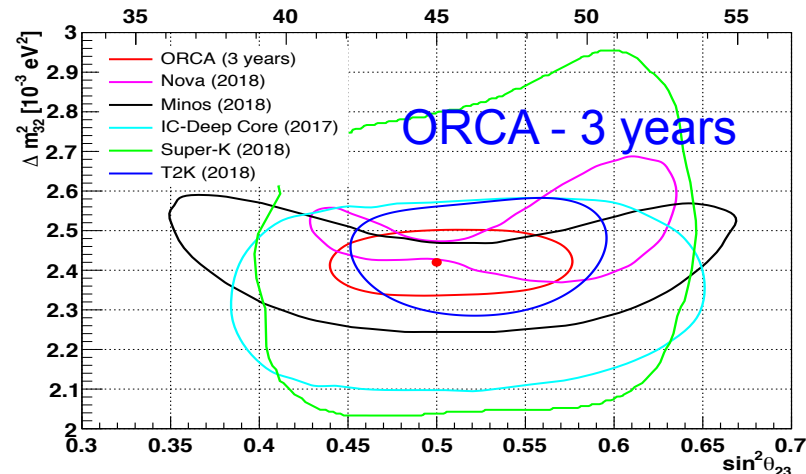
| <i>parameter</i> | <i>treatment</i> | <i>true value</i> | <i>prior</i> |
|--------------------------------------|------------------|----------------------|--------------|
| $ \Delta M^2 $ (eV ²) | fitted | $2.48 \cdot 10^{-3}$ | free |
| Δm^2_{21} (eV ²) | fix | $7.53 \cdot 10^{-5}$ | — |
| θ_{13} (°) | fitted | 8.42 | 0.26 |
| θ_{12} (°) | fix | 33.4 | — |
| θ_{23} (°) | fitted | 38 – 52 | free |
| δ_{CP} | fitted | 0 – 2π | free |
| Flux spectral tilt | fitted | 0 | free |
| $\nu/\bar{\nu}$ skew | fitted | 0 | 0.03 |
| Tracks normalisation | fitted | 1 | free |
| Cascades normalisation | fitted | 1 | free |
| NC events normalisation | fitted | 1 | 0.10 |



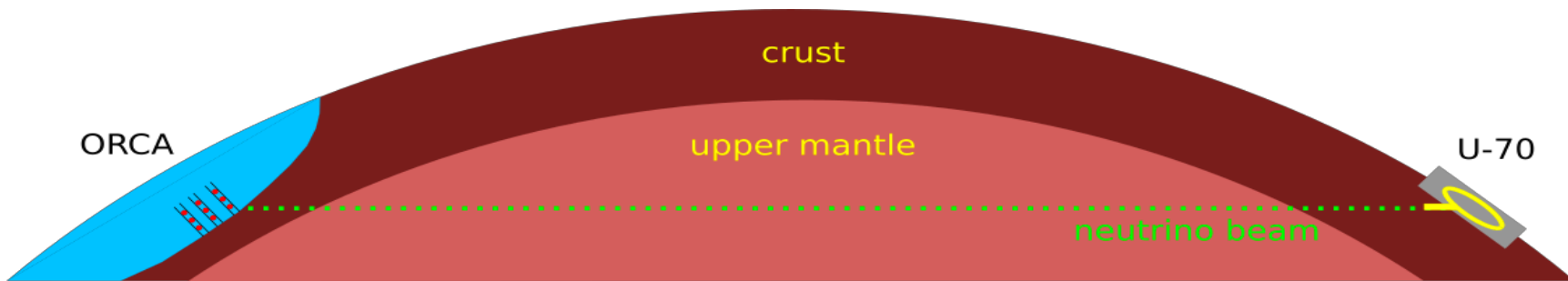
Additional ORCA Physics Topics



- Measurement of Δm^2_{32} & θ_{23}
- Unitarity of PMNS matrix (tau sector)
- Exotic physics
 - sterile neutrinos
 - non-standard interactions
- Dark Matter
- Earth tomography
- Low energy neutrino astronomy
 - Transient phenomena
- Supernovae monitoring
- Earth and Sea Science
- Neutrino beam from Protvino

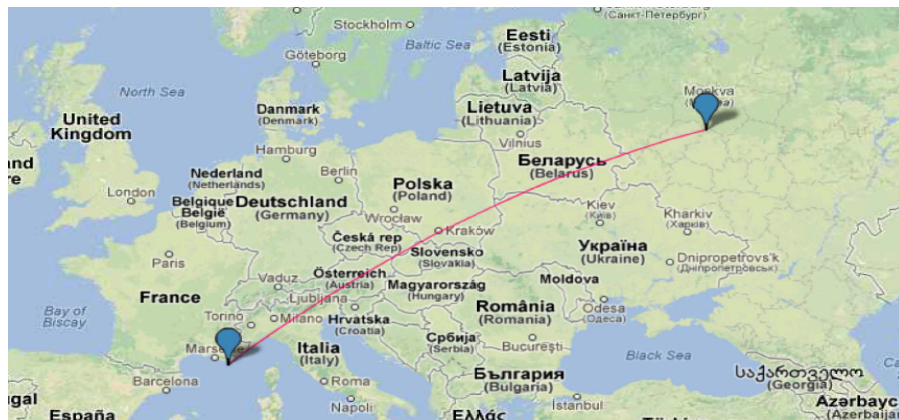


Protvino to ORCA (P20)



Baseline 2588 km

- Beam inclination : 11.7° ($\cos \theta = 0.2$)
- Deepest point : 134 km (3.4 g/cm^3)
- First oscillation maximum 5.1 GeV



→ Sensitivity to mass hierarchy and CP violation

- **ANTARES: first undersea NT, 10 years of continuous data taking**
 - Excellent angular resolution, view of Southern sky, competitive sensitivities
 - Constraints on the origin of the IceCube signal
 - Cascades routinely used in analyses with $\sim 3^\circ$ resolution
 - Weak excess at high energy, of magnitude expected from cosmic flux
 - Rich multi-messenger program – Data taking will cover LIGO-Virgo Run 03
 - Earth and Sea Science observatory
- **KM3NeT: under construction – funding in progress**
 - ESFRI Roadmap in 2016, Letter of Intent published: JPhys.G, 43 (8), 084001, 2016
 - Prototypes performed well, two strings in operation – 4 more next week on ORCA ?
 - **ARCA will confirm and study the observed cosmic flux (tracks & showers)**
 - **ORCA will measure the Neutrino Mass Ordering**

We welcome new contributors





Thank you !



Friends visiting during an operation
on the ANTARES/ KM3NeT site

