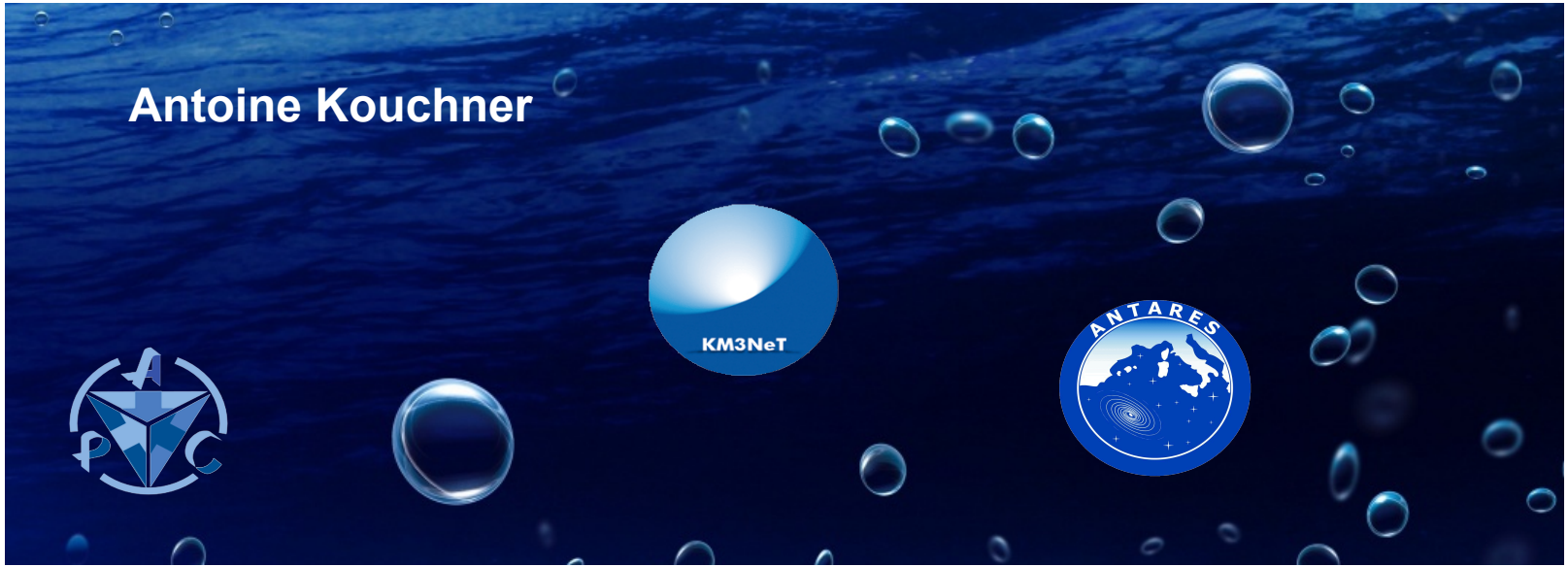
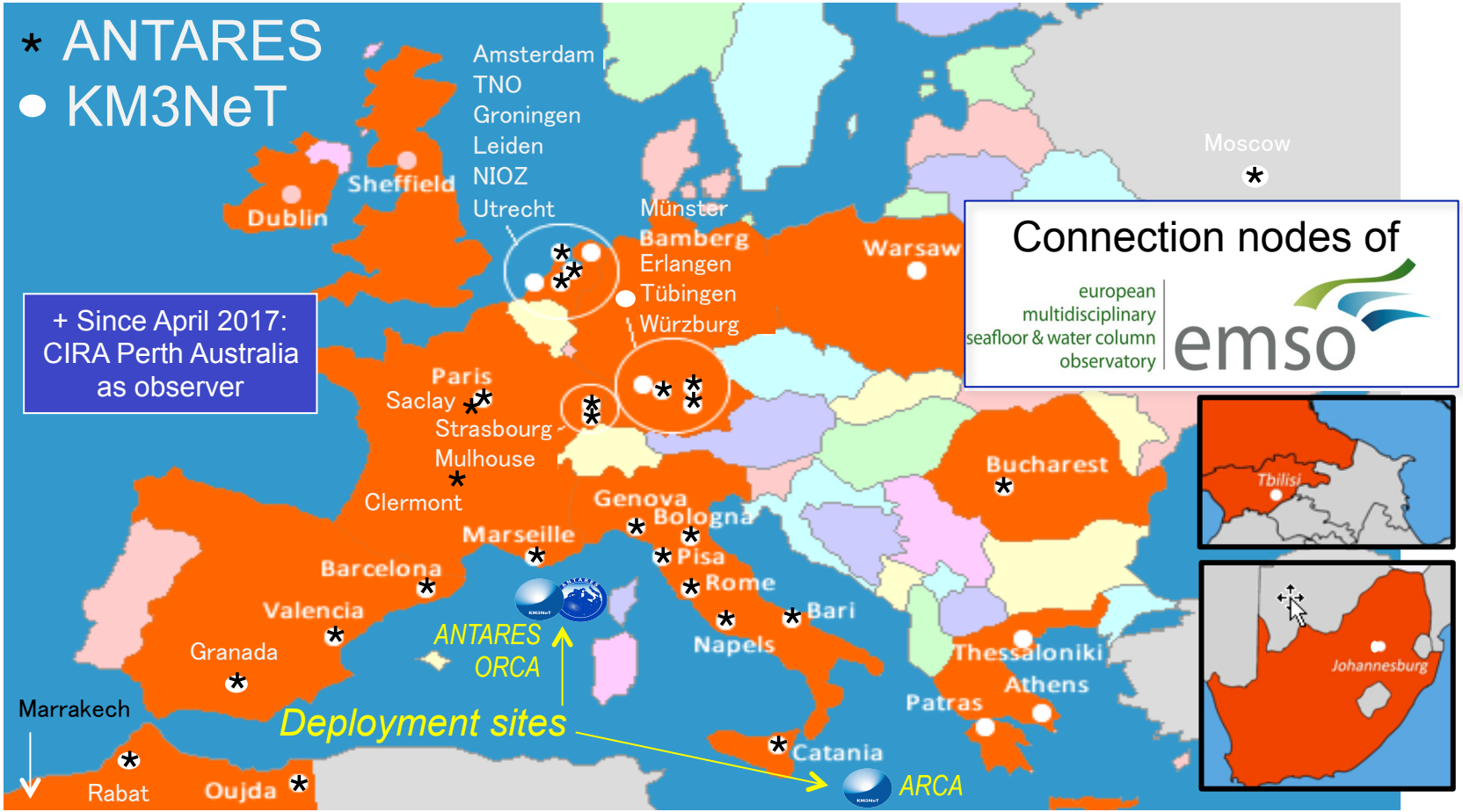
http://antares.in2p3.fr
http://www.km3net.org

High-Energy Neutrino Searches in the Mediterranean Sea: probing the Universe with ANTARES and KM3NeT/ARCA



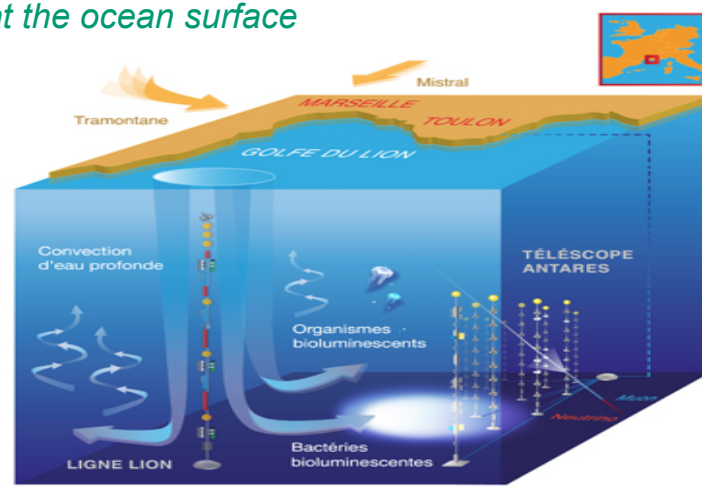
ANTARES & KM3NeT collaborations



Connections to Earth & Sea sciences

📖 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



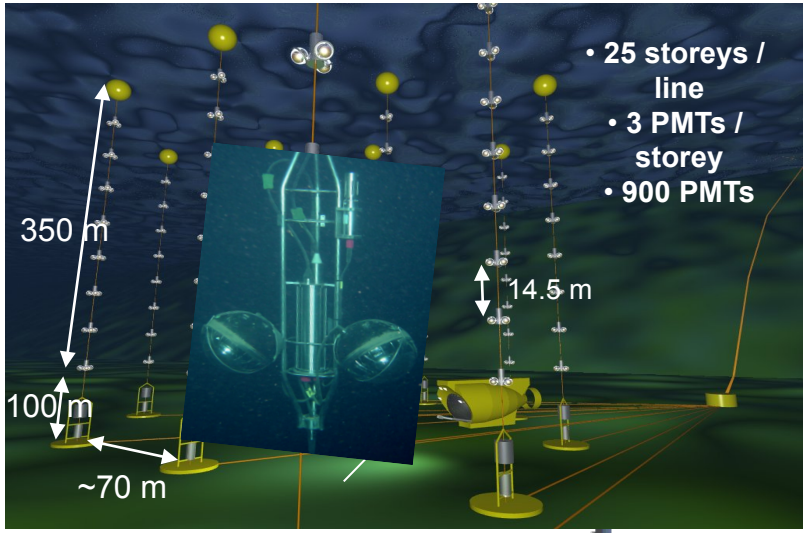
📖 Deep-Sea Research I 58 (2011) 875–884
Acoustic and optical variations during rapid downward motion episodes in the deep North Western Mediterranean

📖 *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

Mediterranean Detectors

ANTARES Complete since 2008



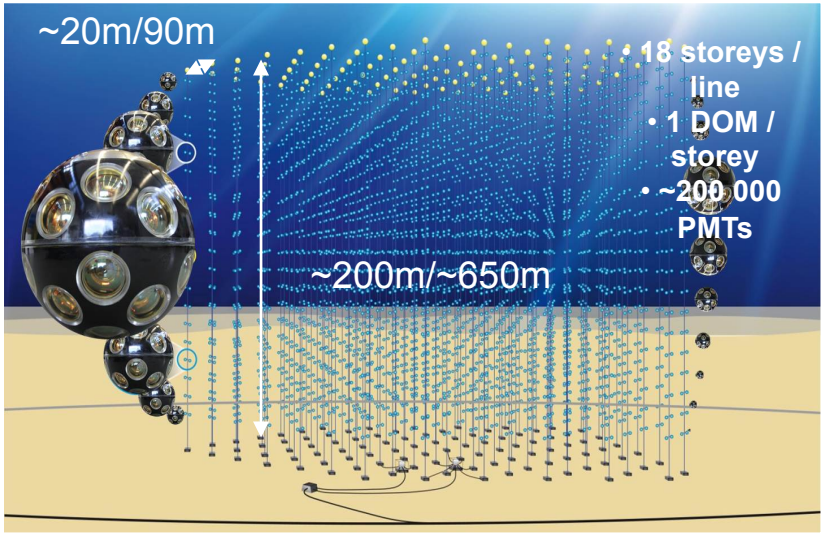
~10 Mton

12 lines

First Generation

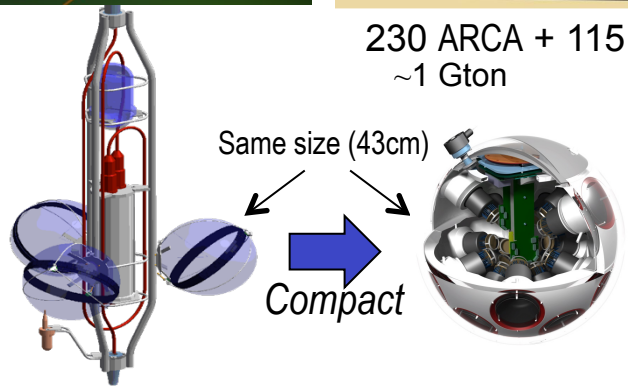
First line since 10 years

KM3NeT Under Construction



230 ARCA + 115 ORCA lines New Generation

~1 Gton ~8 Mton



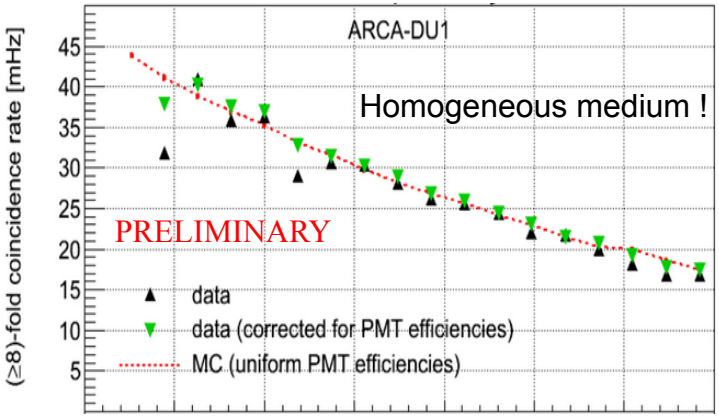
- DOM: 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- Cost reduction wrt ANTARES

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

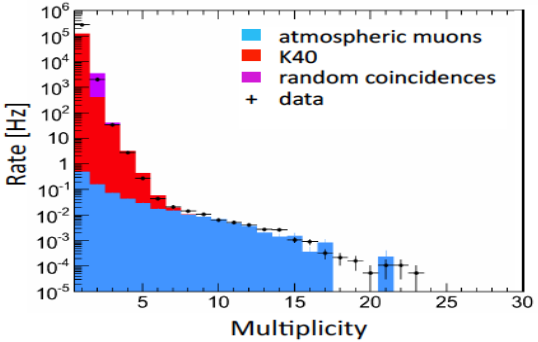
- ✓ Mini string (3 DOMs) at ARCA site, May 2014 (3500 m)
  Track reconstruction 🕮 Eur. Phys. J. C (2016) 76:54 -- Cover

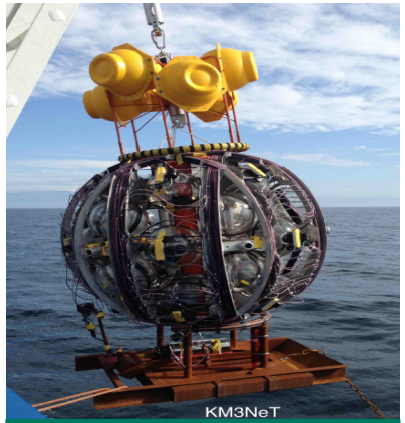
- ✓ First full Detection Unit at ARCA site, Dec 2015



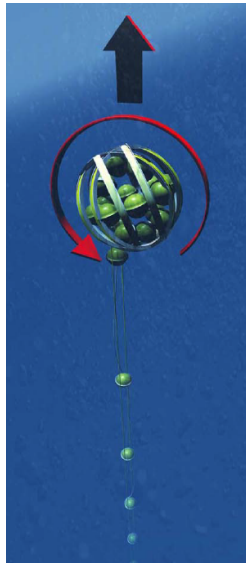
- ✓ One more line in operation in May 2016

→ 2 strings operated for 1 year: verify performances



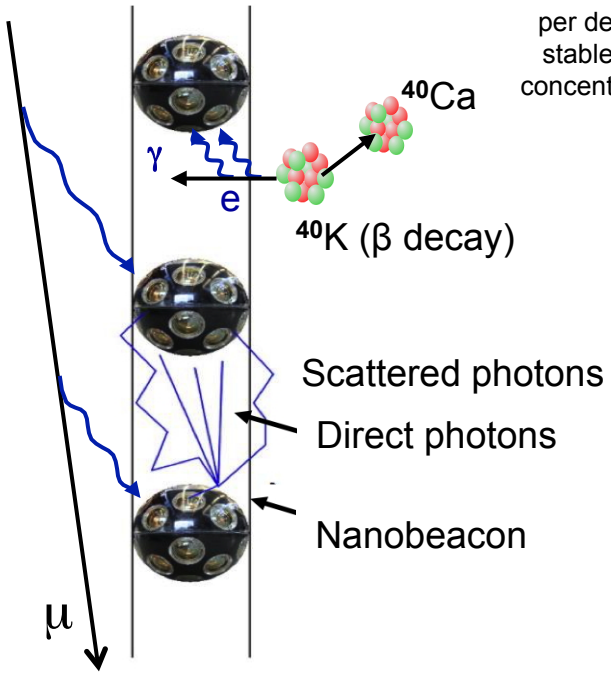


rapid deployment
autonomous unfurling
recoverable



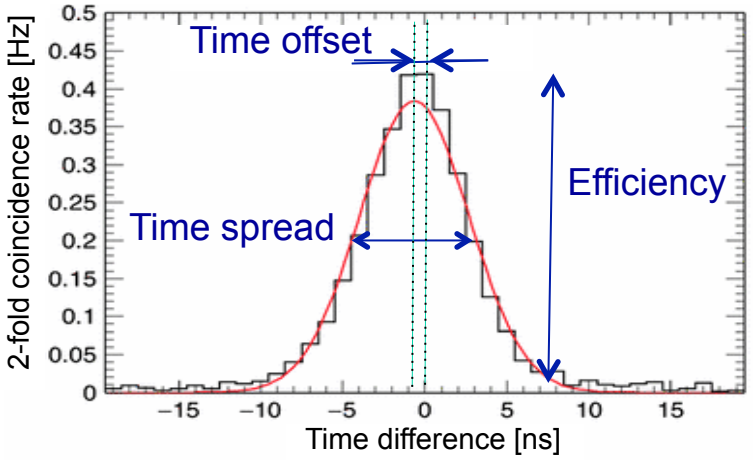
Watch https://www.youtube.com/watch?v=tR8jwgG6uzk

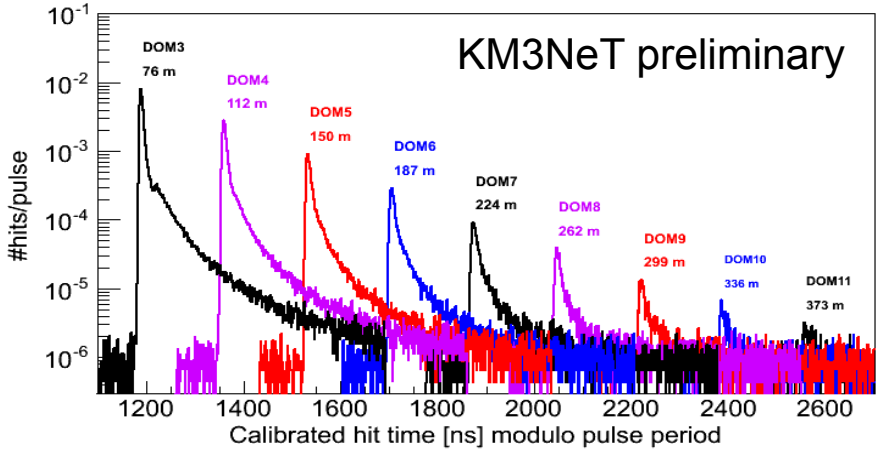
Fast calibration procedures



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

Cross-calibration with muons





Fast calibration procedures

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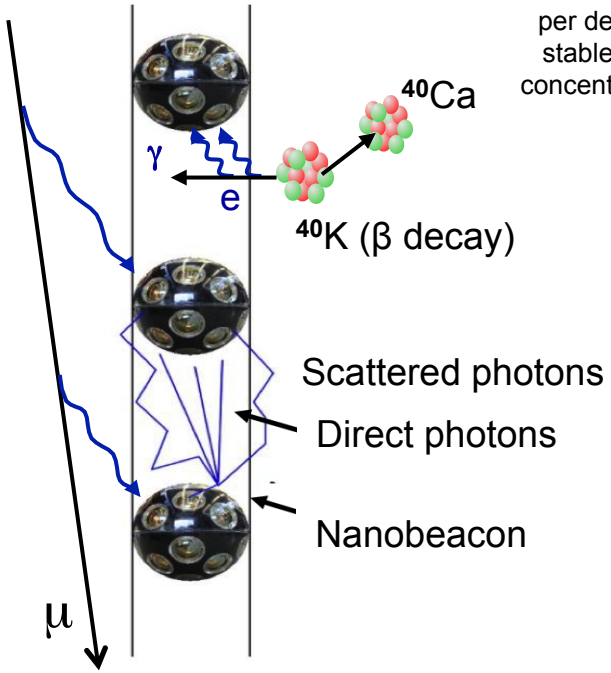
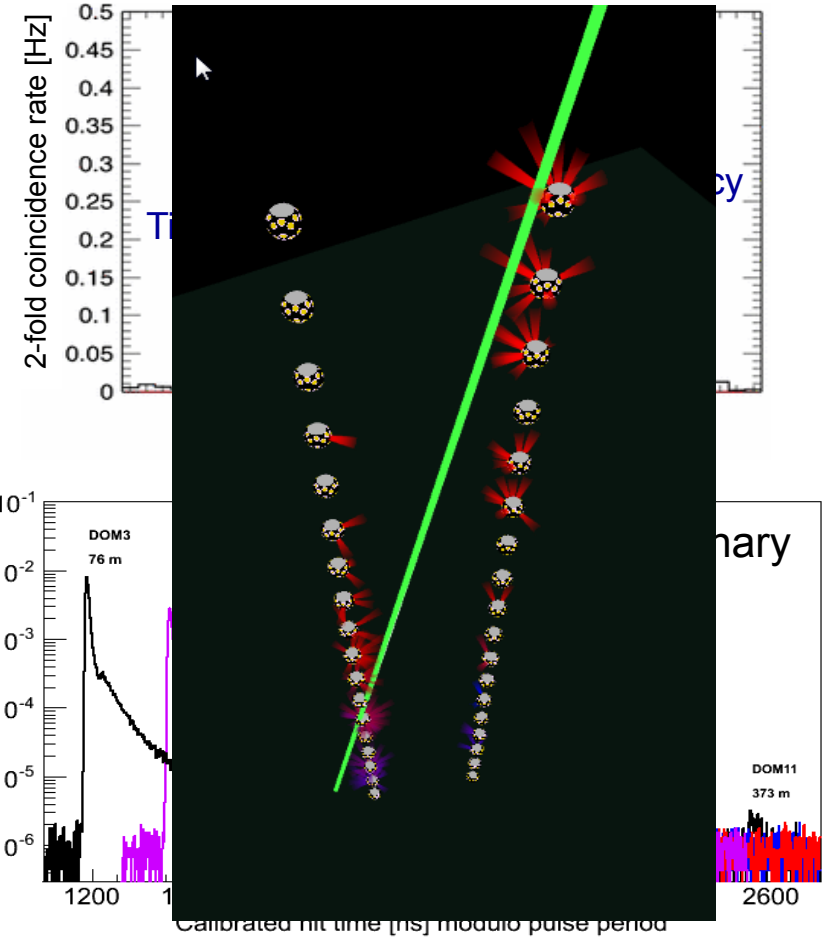
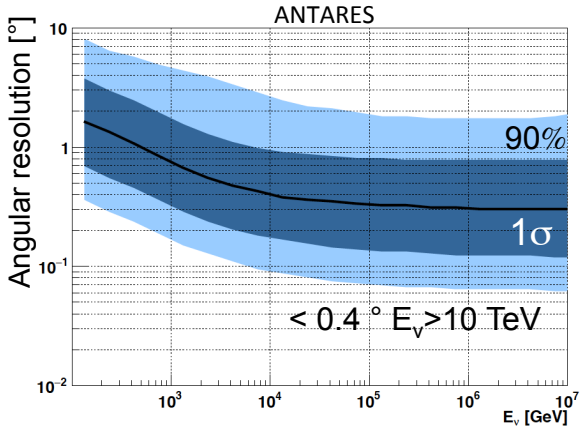
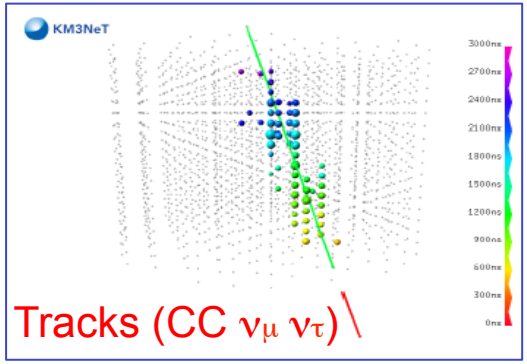


Cross-calibration with muons

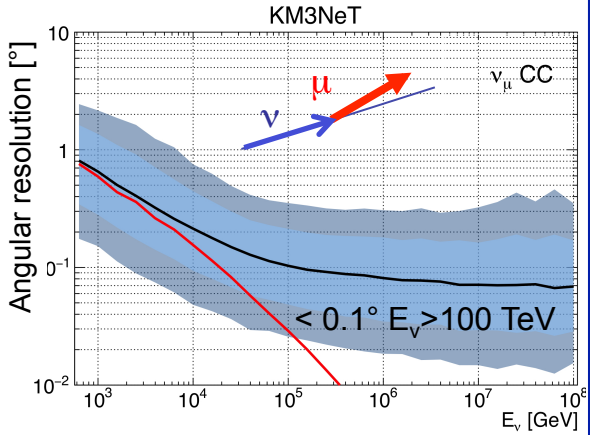


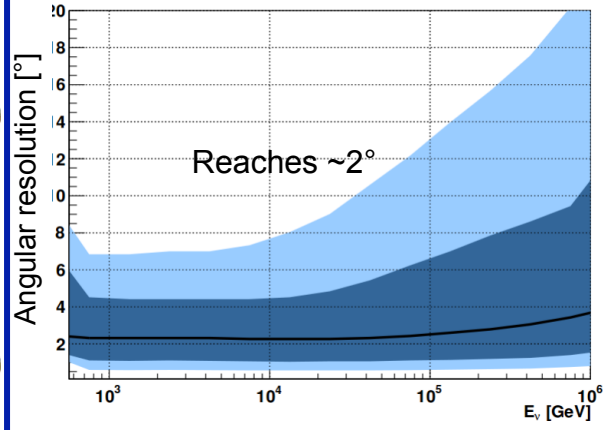
Reconstruction Performances

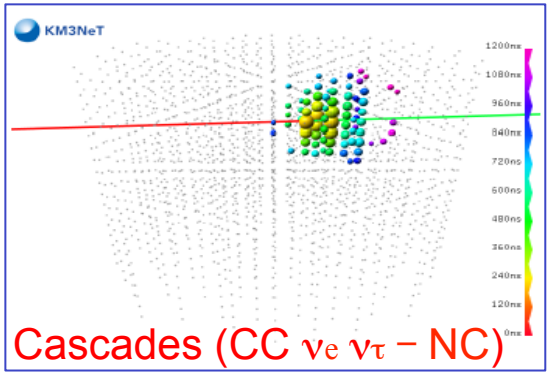




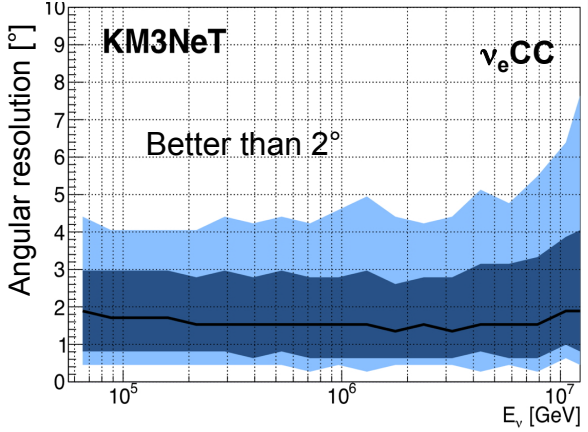
←0.35 Log(Eμ) Resolution 0.27→



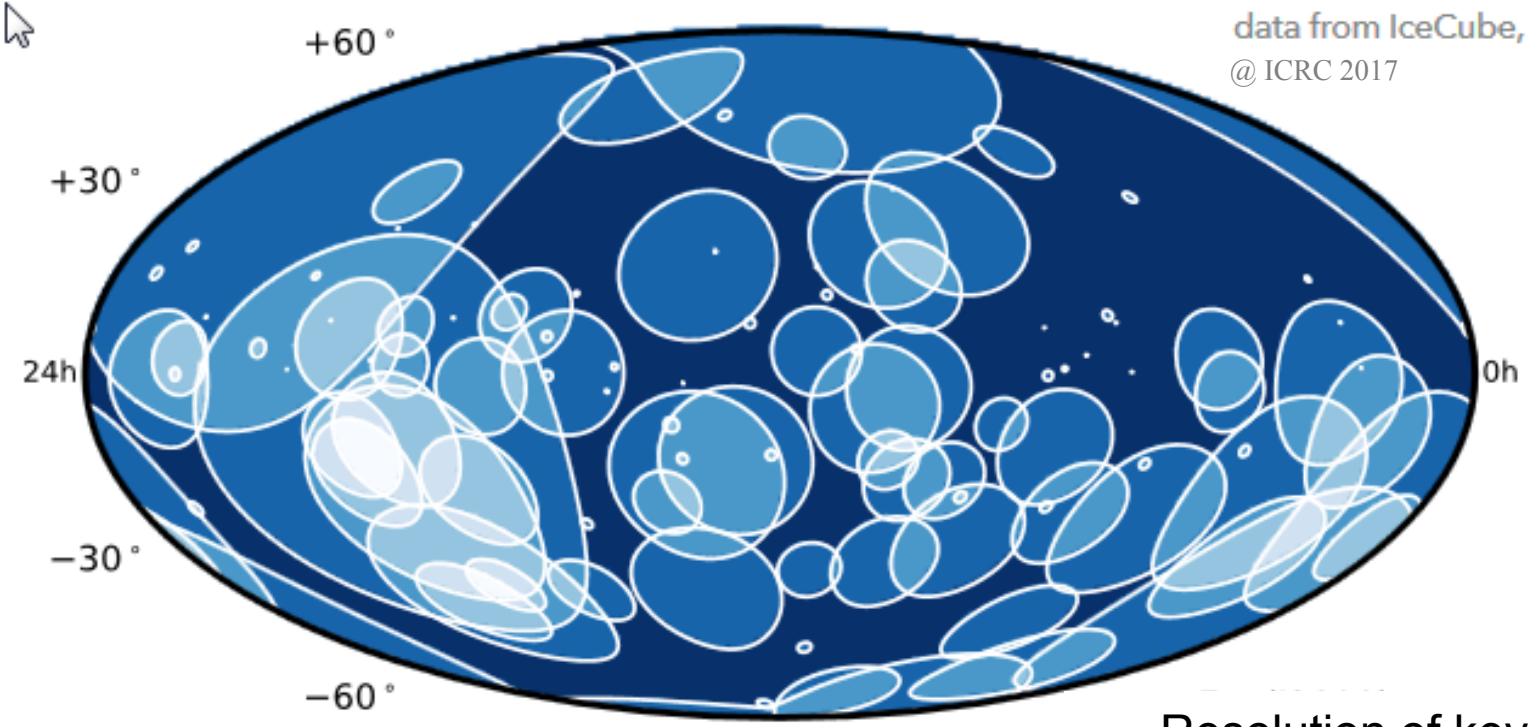




← Energy Resolution ~5% →



Sea Water as a detection medium

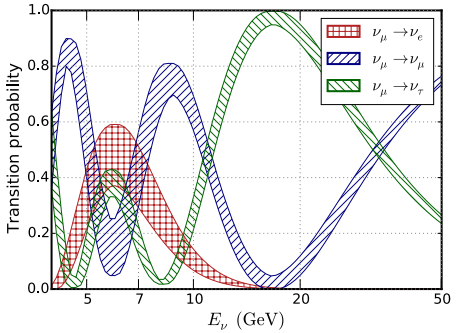


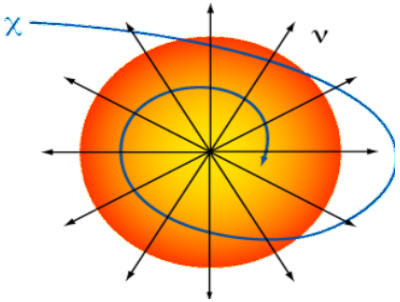
credit E. Resconi

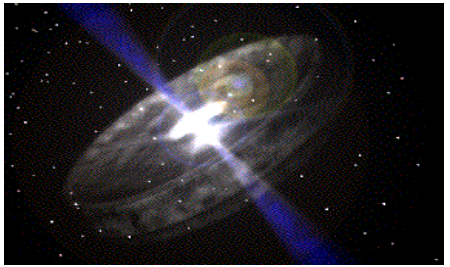
Resolution for ν_e
ANTARES ○
KM3NeT ○

Resolution of key importance for catalogue searchers

Physics Studies







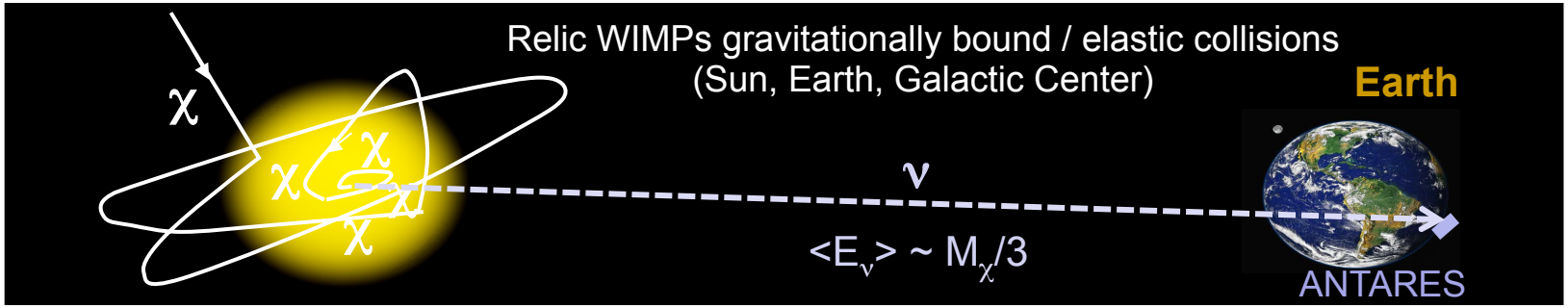
Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 50 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV
ν Oscillations ν Mass Hierarchy	Dark Matter search + Exotic searches 📖 JHEP 07 (2017) 54	ν from extra-terrestrial sources Origin and production mechanism of HE CR

KM3NeT-ORCA — ANTARES — KM3NeT-ARCA

See talk by J. Coelho

See talk by T. Gaisser

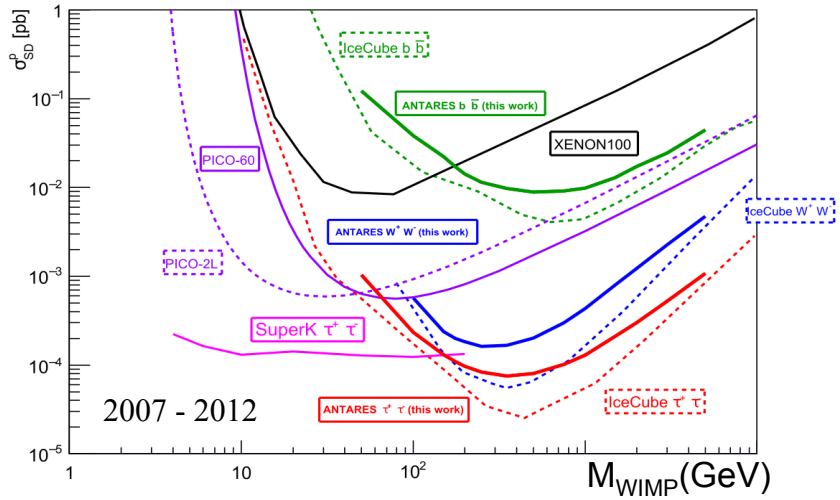
Indirect Search for Dark Matter

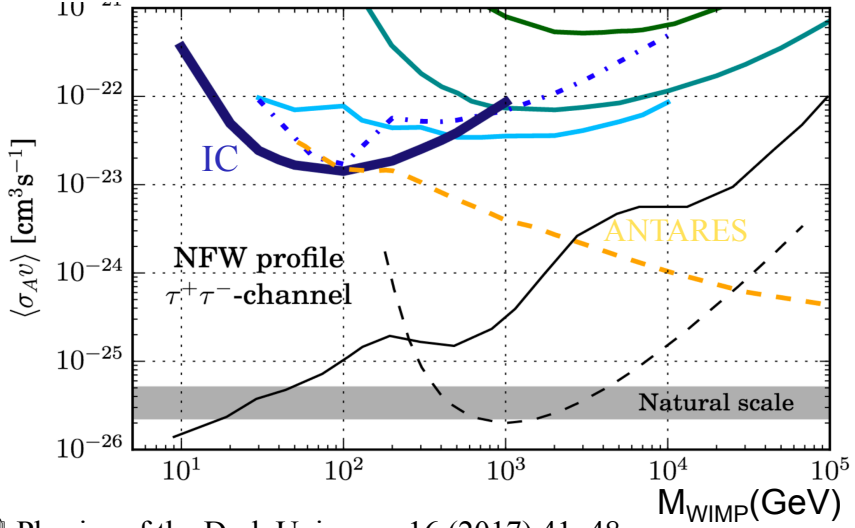


📖 Phys.Lett. B759 (2016) 69-74

Track channel only

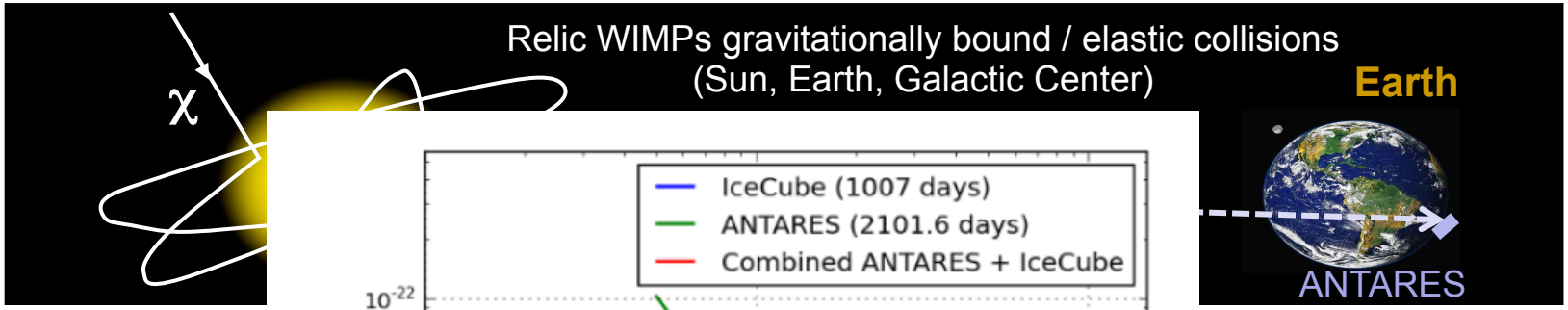
📖 Phys. Let. B 769 (2017) 249

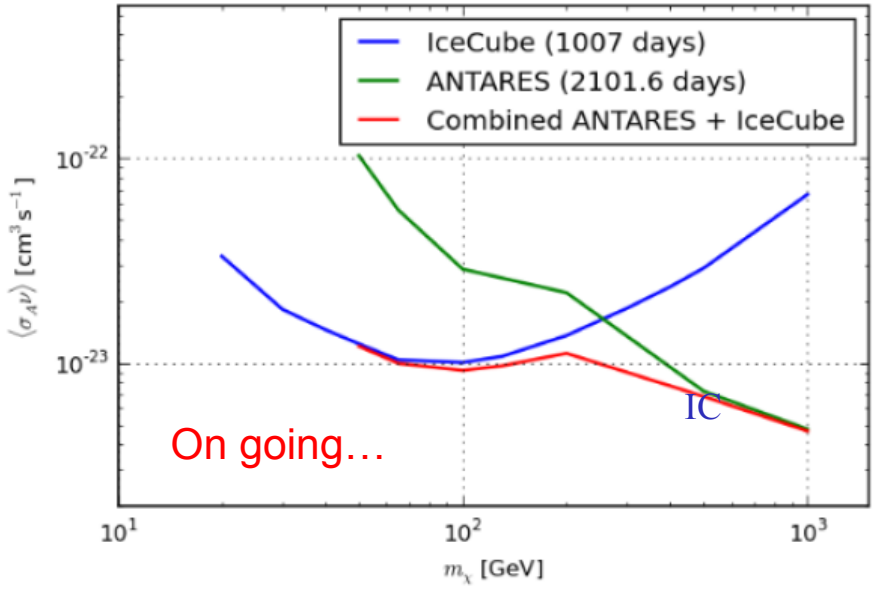




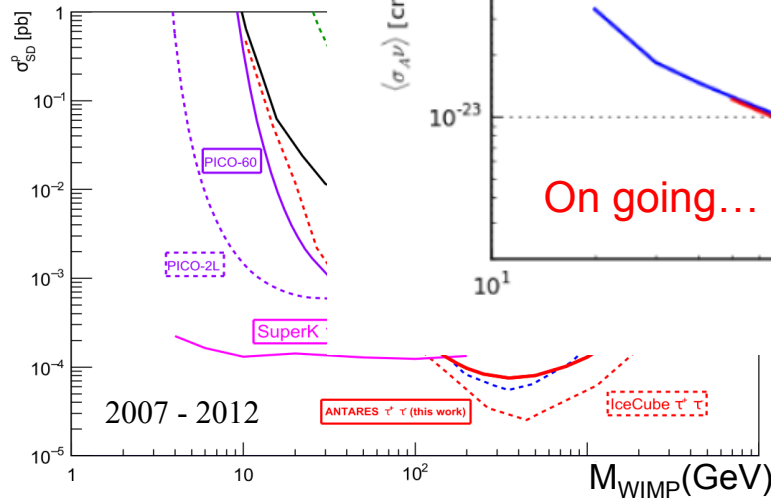
Also DM from the Center of the Earth : 📖 Physics of the Dark Universe, 16 (2017) 41–48

Indirect Search for Dark Matter

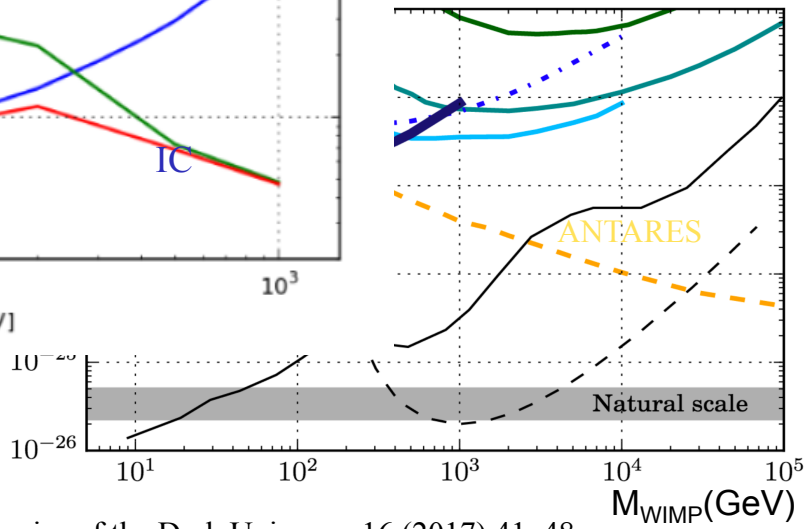




📖 Phys.Lett. B759 (2016



📖 Phys. Let. B 769 (2017) 249



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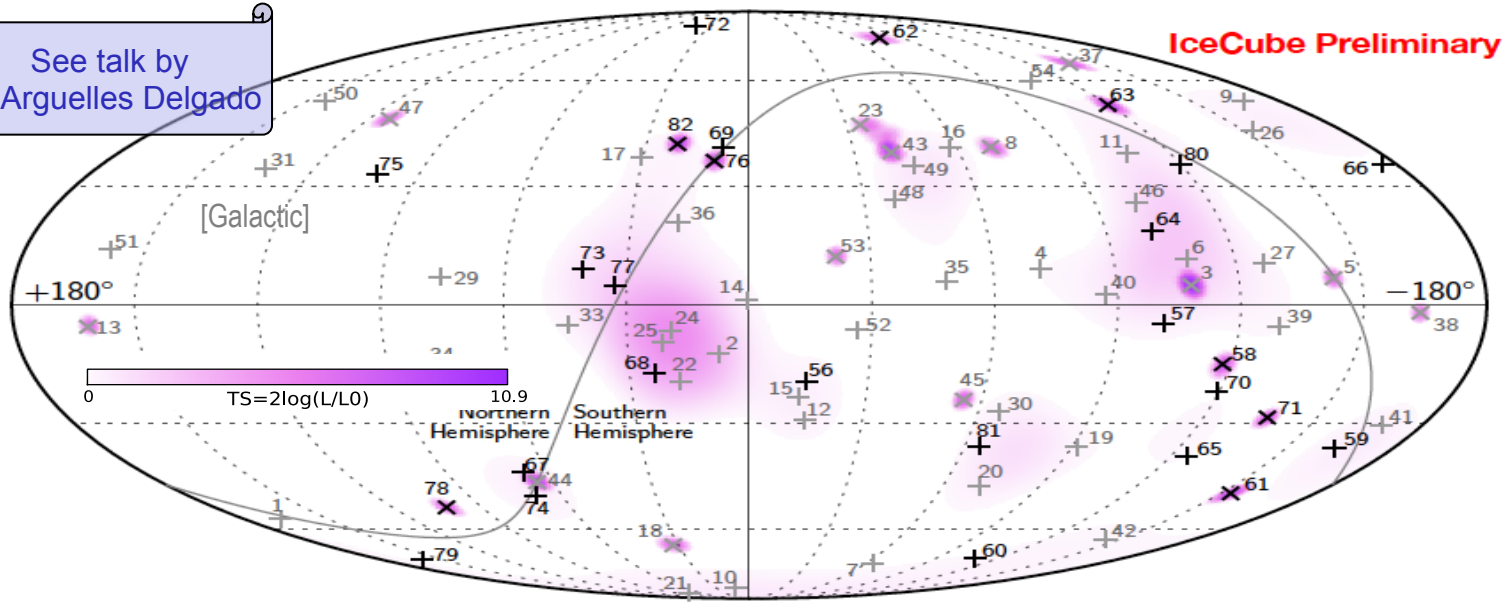
First HE neutrinos seen by IceCube

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

Sources not identified

See talk by
C. Arguelles Delgado



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

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

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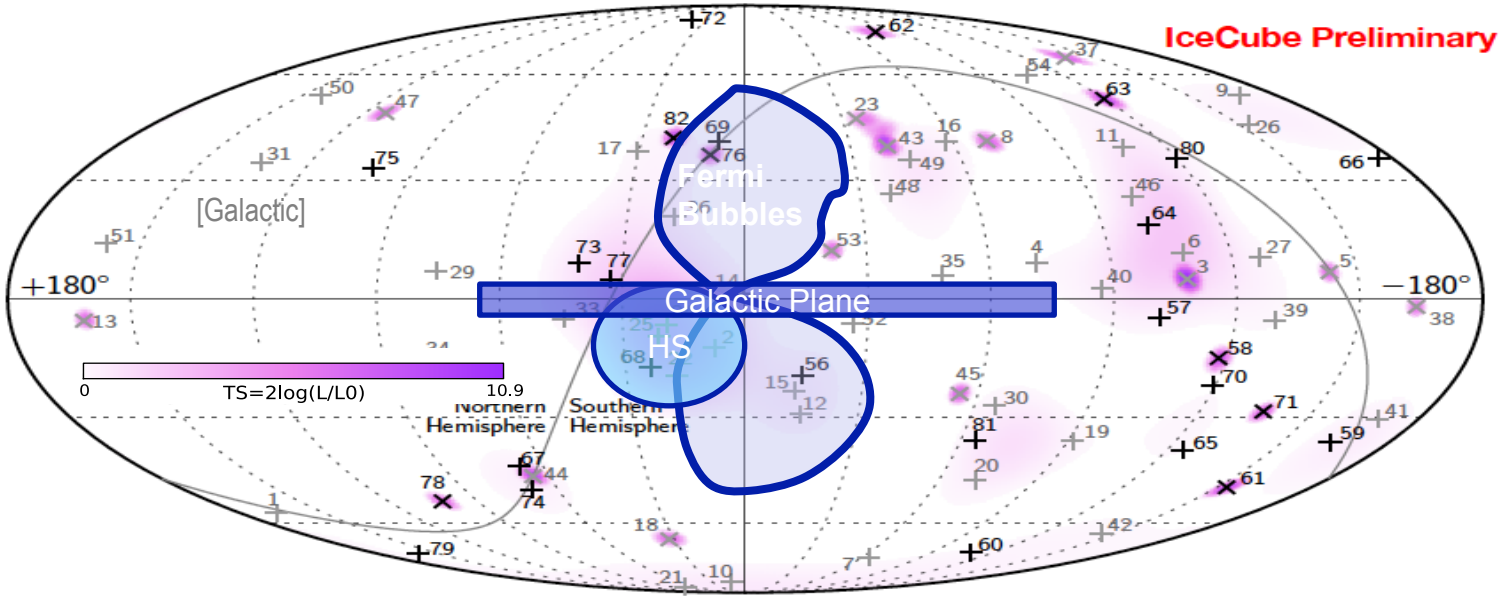

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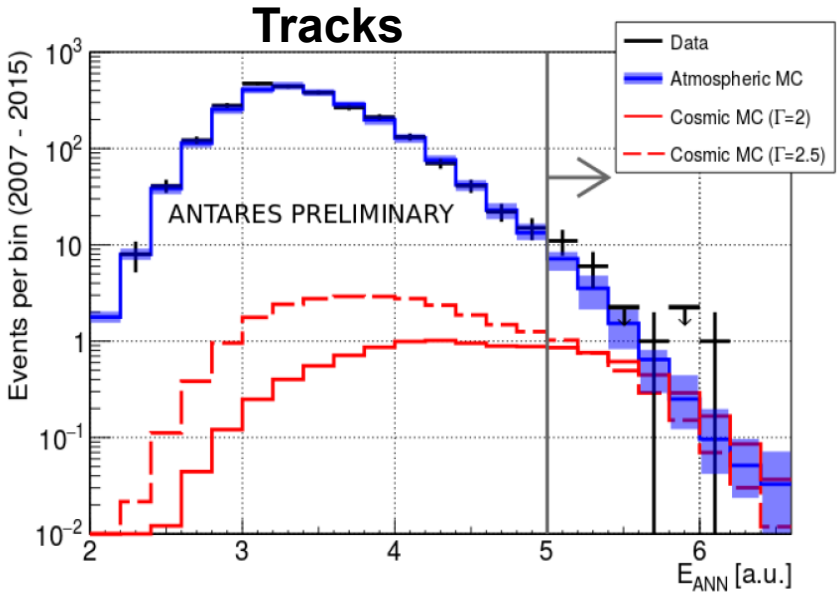
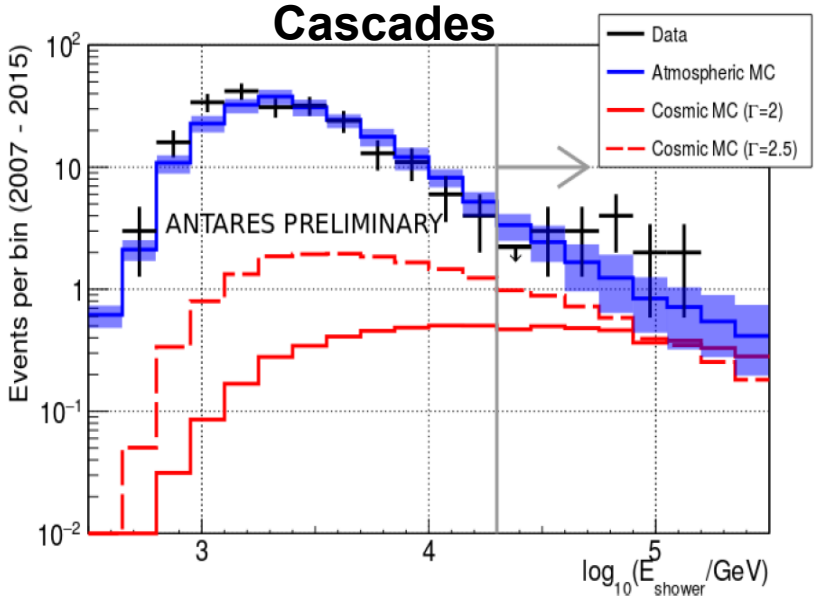
Diffuse Flux Searches

- 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.

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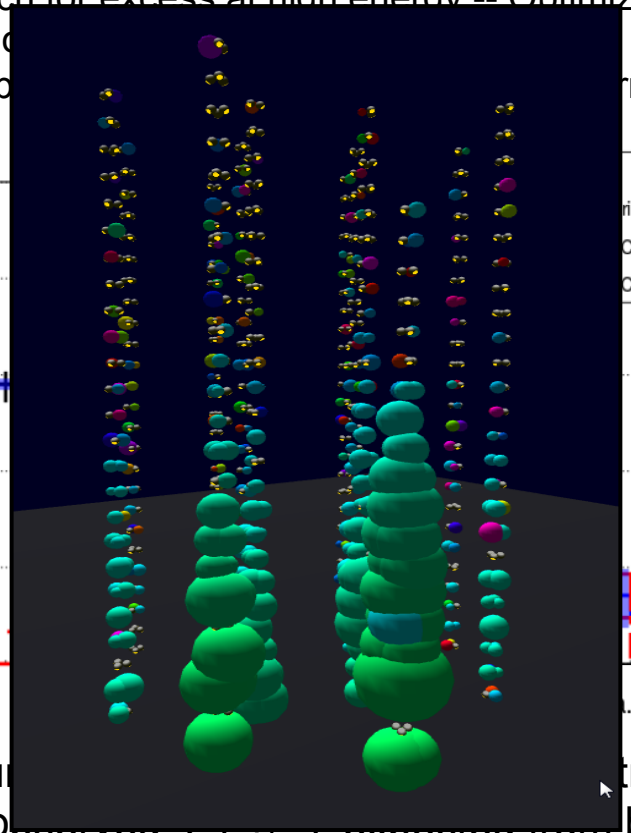

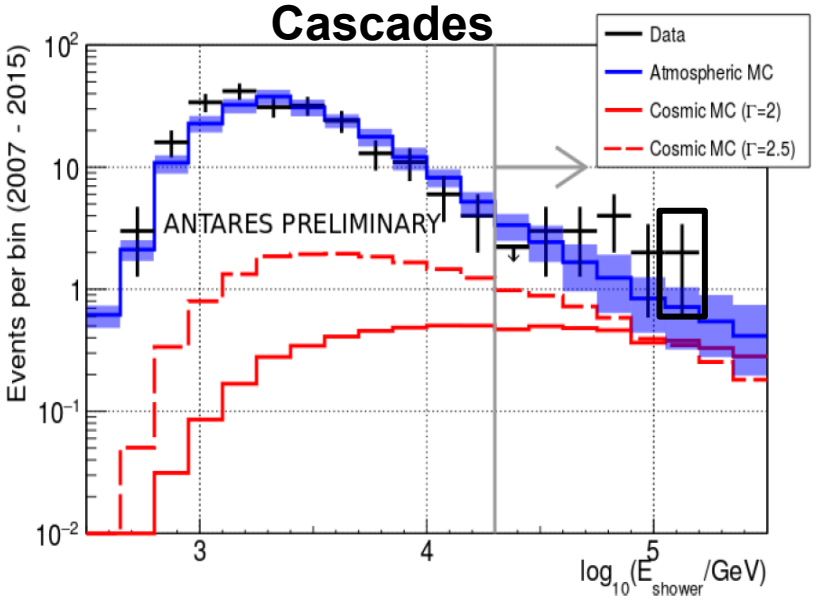

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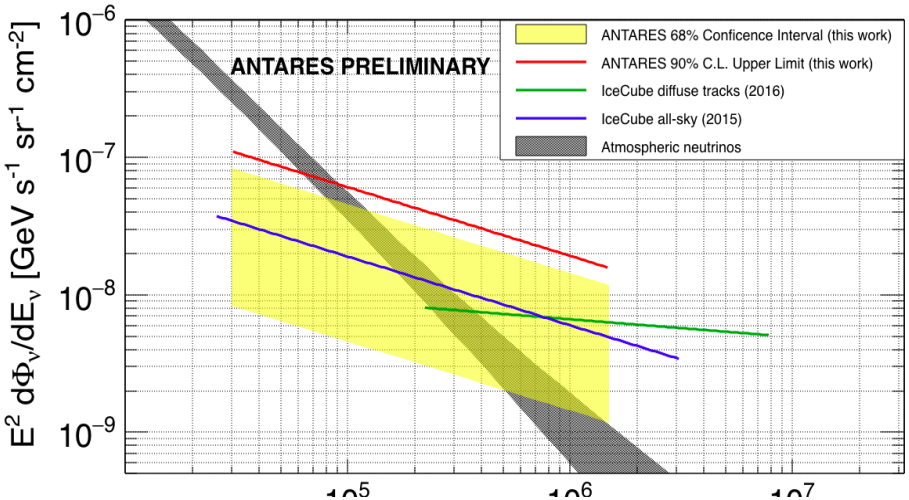
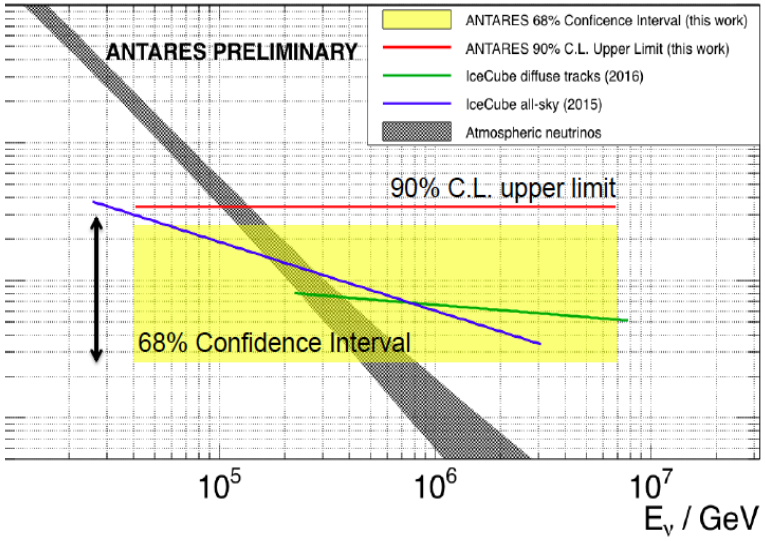




[7] M.G. Aartsen, et al., Astrophys. J. **809**: 98 (2015).

[8] M.G. Aartsen et al., Astrophys. J. **833** no.1: 3 (2016).

Results not really constraining… but fully compatible with IceCube

Diffuse Flux Searches

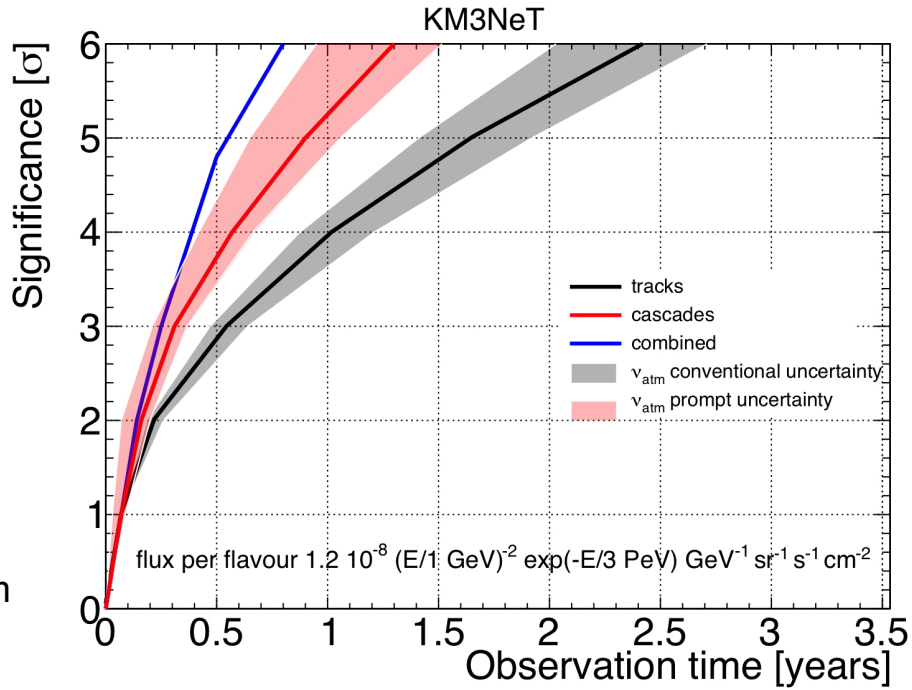
IC flux observable with high significance ~1 year with KM3NeT

- **Track channel**

Analysis for up-going events based on maximum likelihood
Pre-cuts on θ_{zen} >80°, reconstruction quality parameter and N_{hit} (proxy for muon energy)

- **Cascade channel**

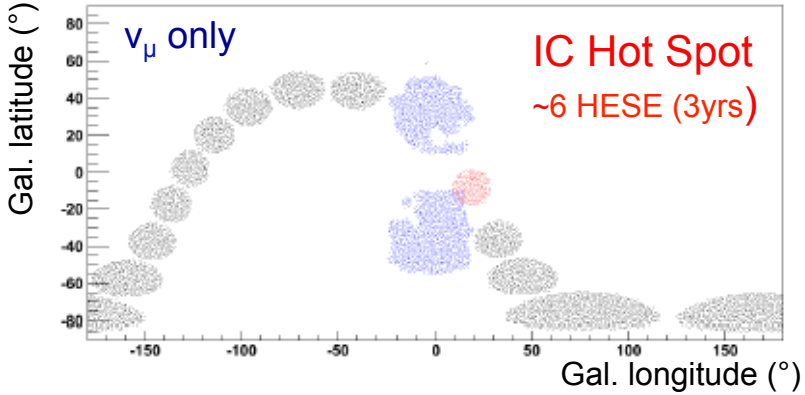
Containment cut on reconstructed vertex to remove atmospheric muons (excludes upper 100m layer)
All sky analysis based on BDT and maximum likelihood.

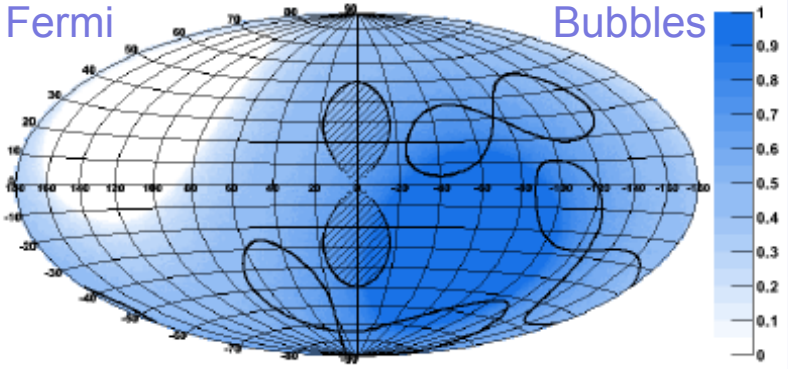


High resolution follow-up and e.g. flavour composition

Reduced search window

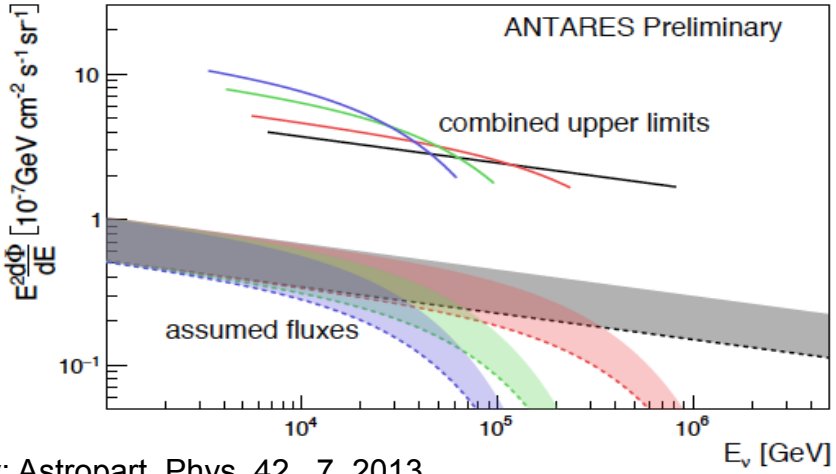
More robust analyses: background measured from OFF regions of same local acceptance





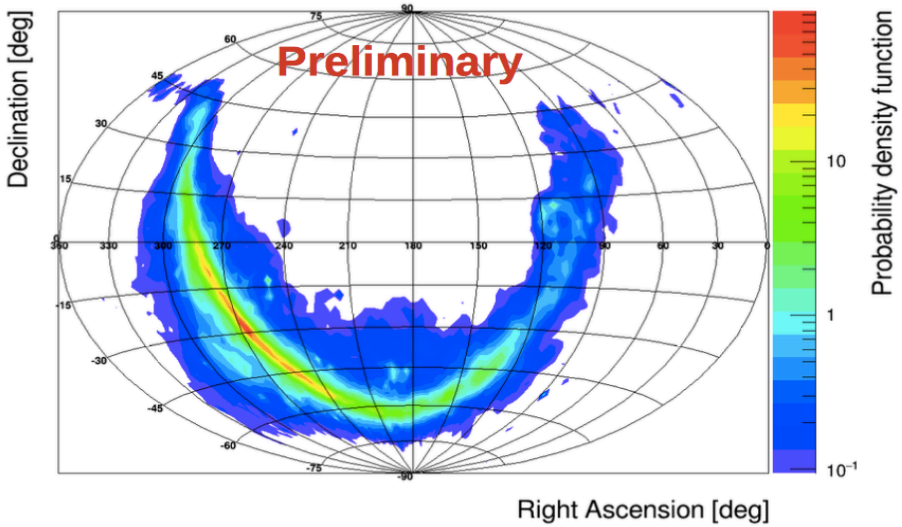
May 2008 - Dec 2015 (tracks & cascaddes)

- Fermi Bubbles : 3 OFF-zones regions
- Assumed spectrum accounts for HAWC contraints
- ON-region : 16 (28) showers (tracks), exp. 13.3 (19.7)
- Insignificant excess



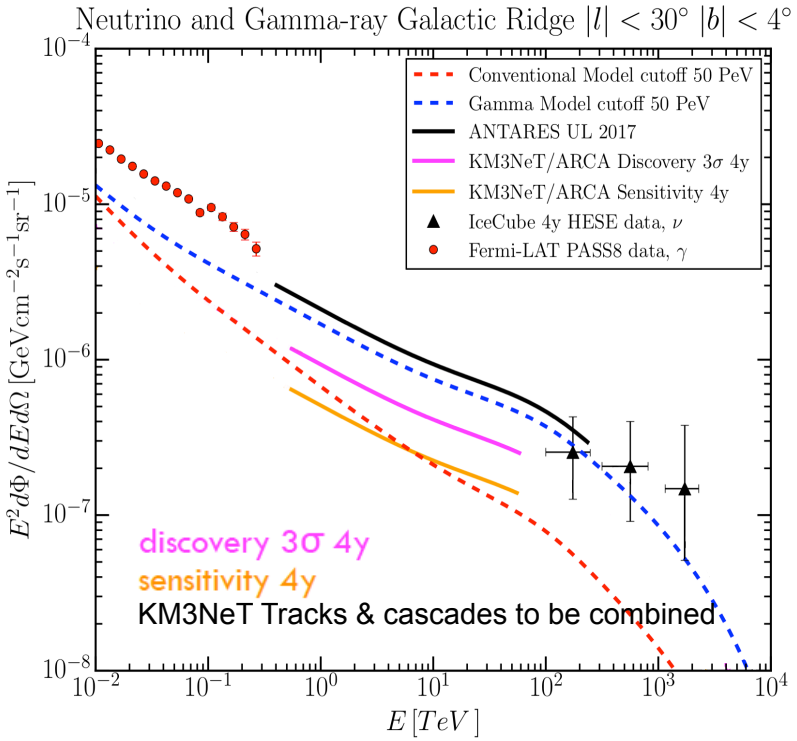
📖 KM3NeT sensitivity: Astropart. Phys. 42 , 7, 2013

Focus on the Galactic Plane



- Guaranteed galactic neutrinos from CR interactions with matter
- Does it contribute to IC flux ?
- Test ‘KRAγ’ model reproduce Fermi & Milagro data.
- Analysis uses full model morphology & spectrum – tracks and cascades

- ANTARES Limit is a factor 1.3 above the ‘KRAγ’ model.
- KMNeT sensitivity promising.

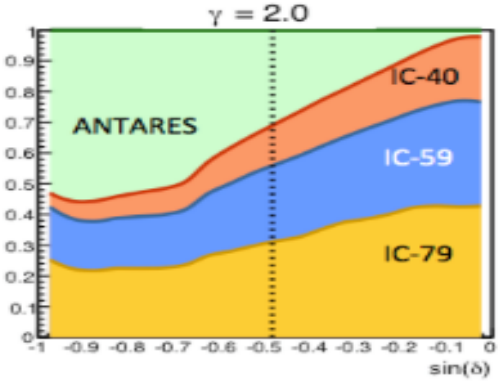


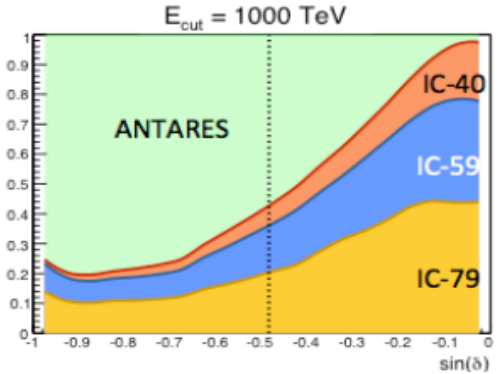
Joint ANTARES-IceCube PS search

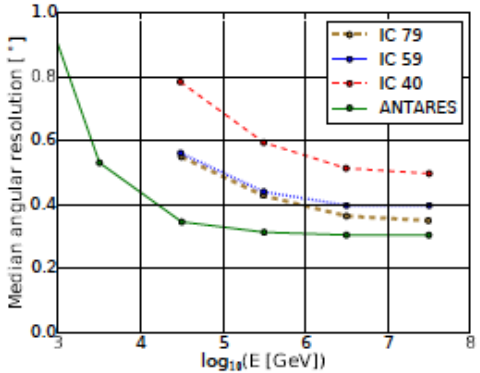
ANTARES 2007-2012 and the IC40, IC59, and IC79 samples for the Southern Hemisphere

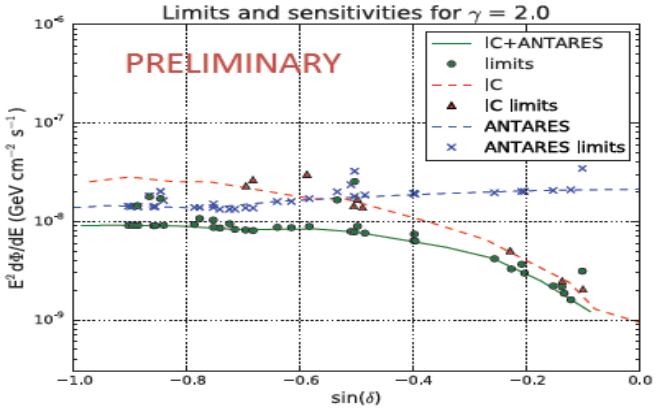
📖 Astrophys. J. Lett. 786:L5 (2014)

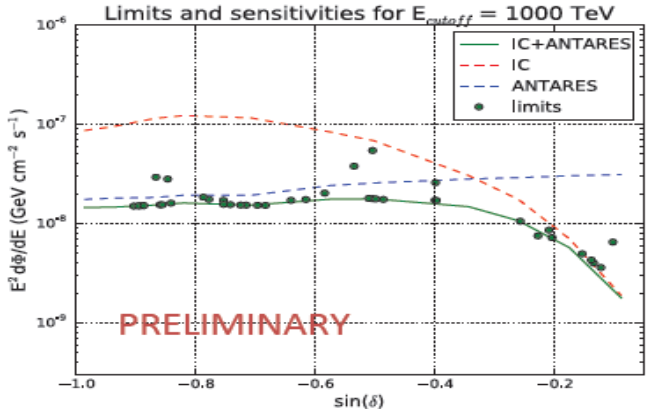
📖 ANTARES+IC, The Astrophysical Journal 823 (2016) 65





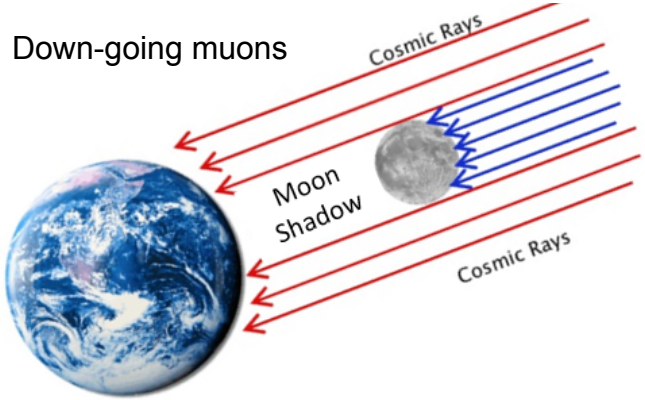




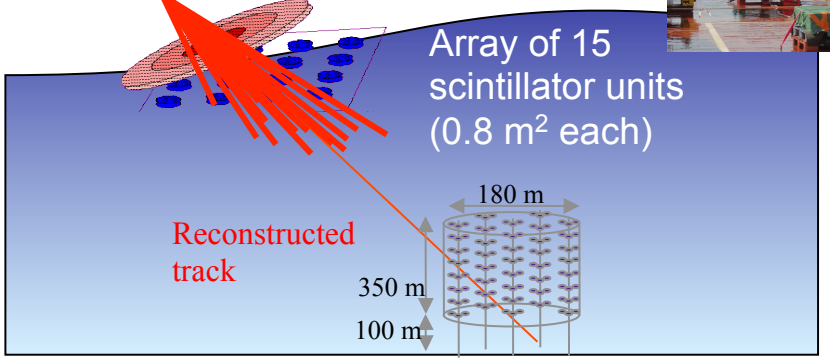


Absolute Pointing

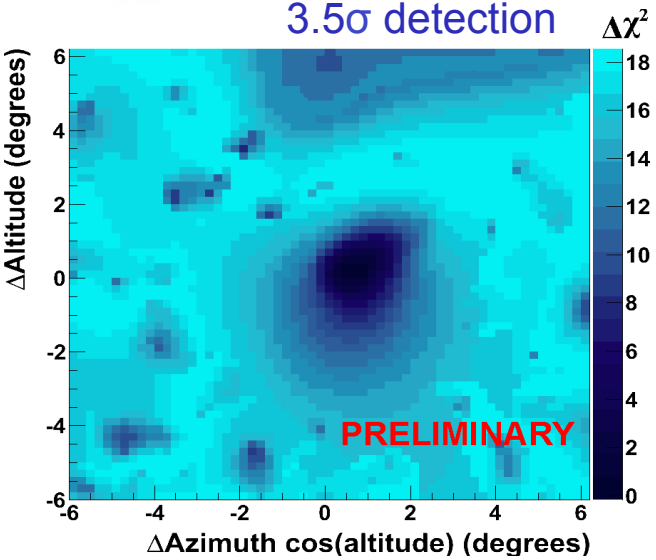
Down-going muons

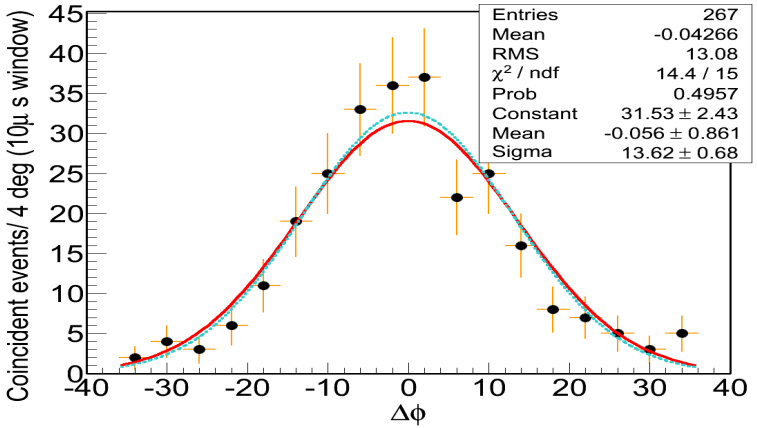


Atmospheric shower



3.5σ detection

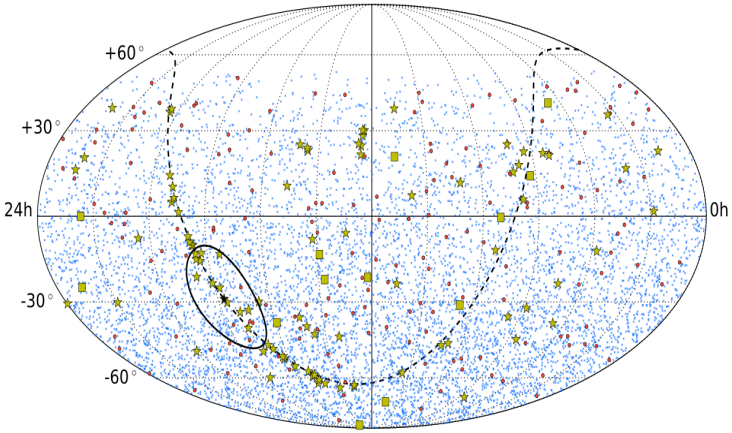




Consistent with results from 2 dedicated sea campaigns

First all flavor PS search

- ANTARES 2007-2015 (2424 days)



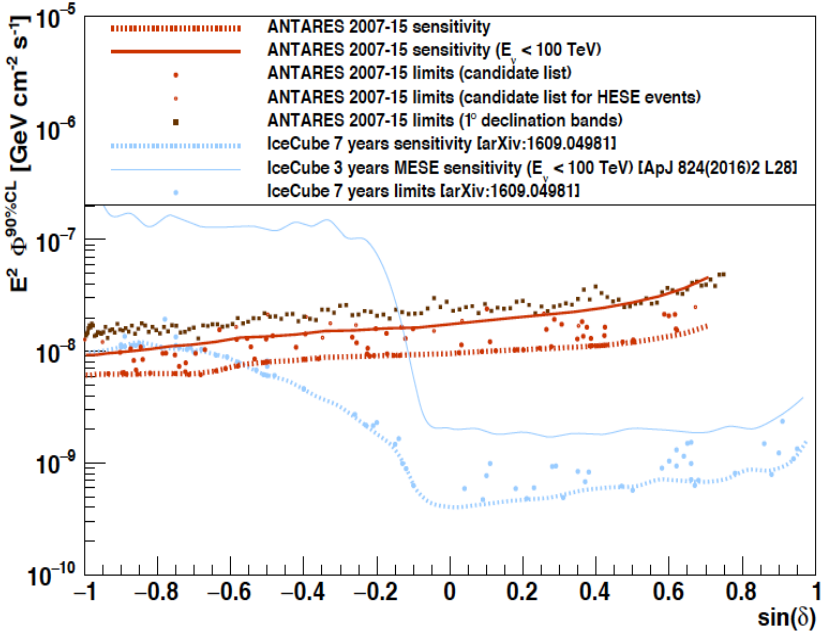
7629 tracks 180 cascades

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

Most significant cluster in full sky
p = 6% (1.9 sigma)
(α,δ) = (343.8°, 23.5°)

Most significant candidate HESSJ0632+057
p = 13%
(α,δ) = (98.24°, 5.81°)

Arxiv:1706.01857, submitted to PRD



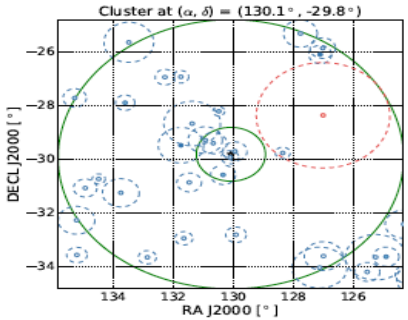
World best limit on the Southern sky below hundreds of TeV.

Special focuses

- IceCube HESE muon tracks Limits (10^{-8} GeV cm^{-2} s^{-1})

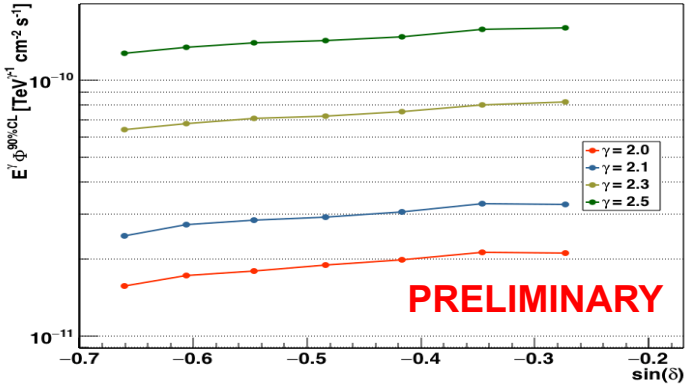
IceCube event ID	α[°]	δ[°]	β_{IC}[°]	$\Phi_0^{90\%}$
3	127.9	-31.2	1.4	2.1
5	110.6	-0.4	1.2	1.5
8	-177.6	-21.2	1.3	1.7
13	67.9	40.3	1.2	2.4
18	-14.4	-24.8	1.3	2.0
23	-151.3	-13.2	1.9	1.7
28	164.8	-71.5	1.3	1.2
37	167.3	20.7	1.2	1.7
38	93.2	14.0	1.2	2.1
43	-153.4	-22.0	1.3	1.3
44	-23.3	0.0	1.2	1.8
45	-141.0	-86.3	1.2	1.2
53	-121.0	-37.7	1.2	1.6

5.3 sig. events
1.3 σ

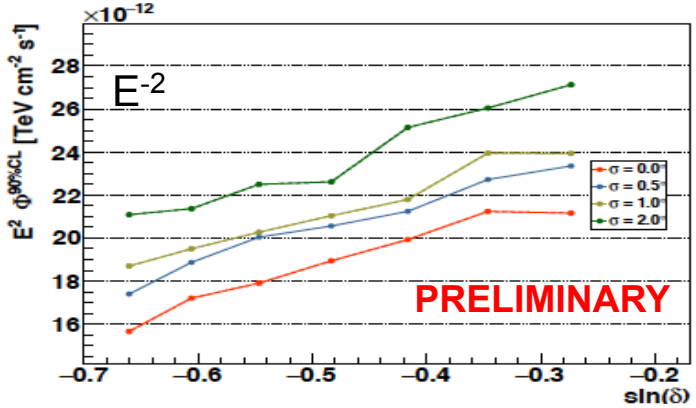


- Dedicated Search in GC region

no PS (Γ=-2.5;-2) yielding ≥ 2-6 HESE (3yrs)

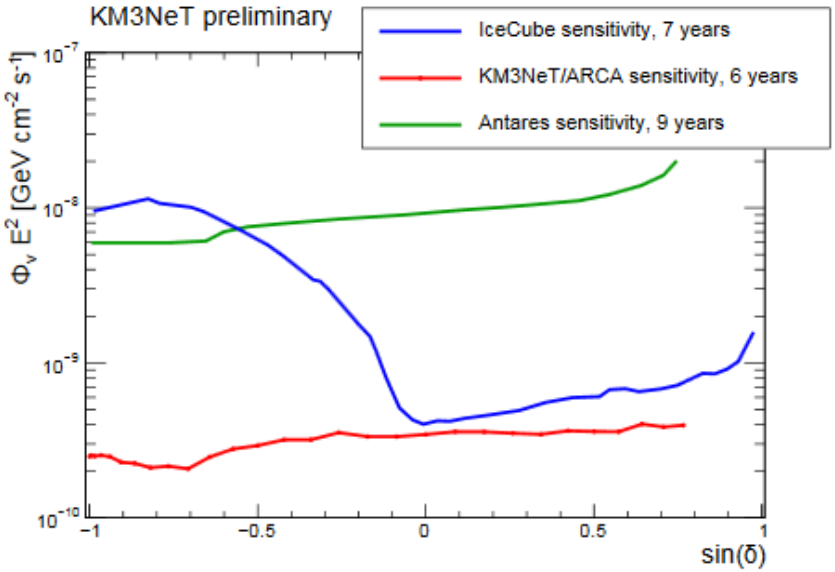


Spectral index

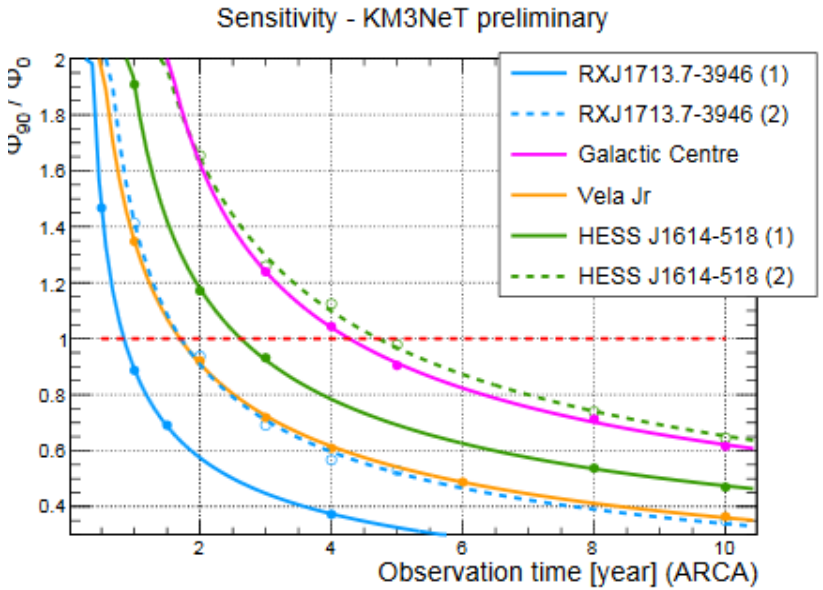


Extension

Prospects for KM3NeT



Sensitivity for Galactic Sources



Muon neutrinos still dominant in analysis

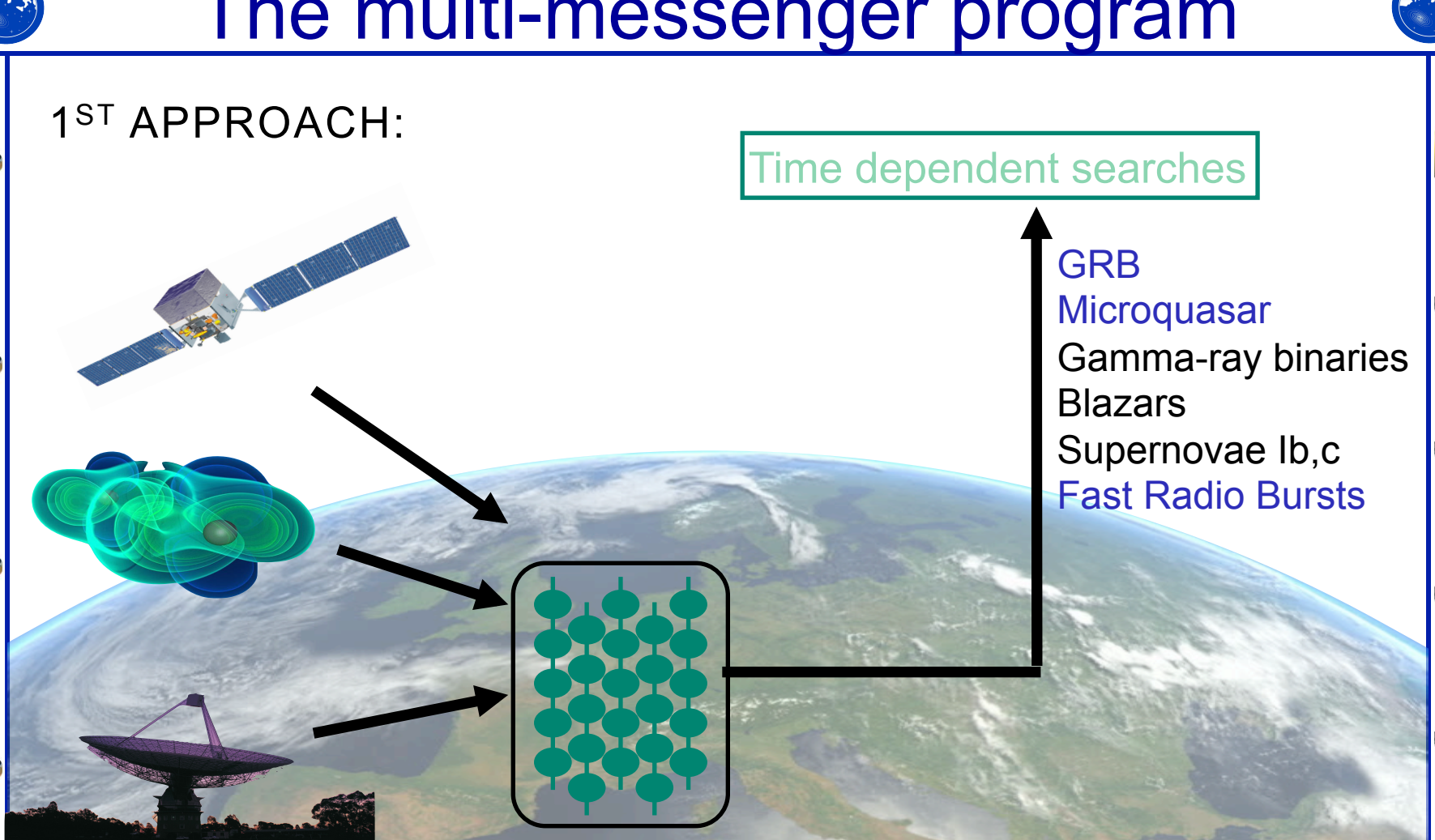
More than order of magnitude improvement in Southern Hemisphere

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

RXJ(1) : Kelner et al RXJ(2): Vissani a Villante ; HESS (1): no cut-off HESS(2) : cut-off

The multi-messenger program

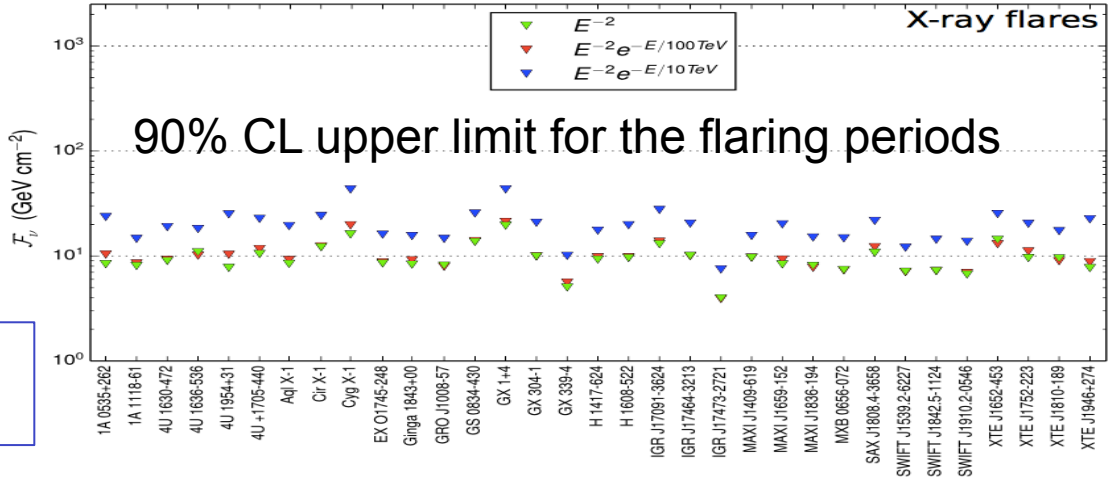
1ST APPROACH:

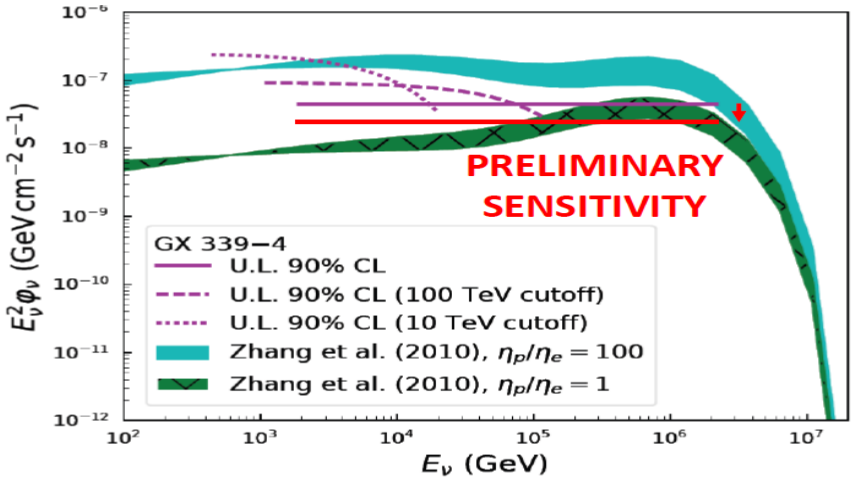


Constraints on neutrino emission by flaring X ray Binaries

Use light curves and assume neutrino emission coincident in time with electromagnetic outburst

Using track events 2008-2012
📖 JCAP 04 (2017) 019





Start constraining some hadronic microquasar emission models

High baryonic loading disfavored

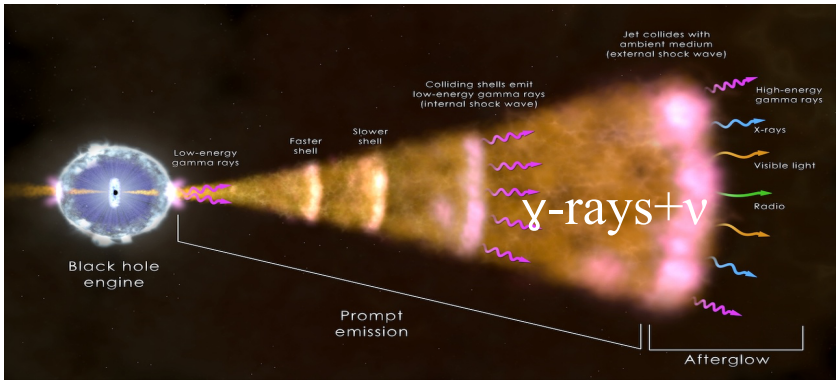
To be updated soon

Gamma-ray bursts

- Search for muon neutrinos for 4 bright GRB observed between 2008 and 2013
- Two scenarios are investigated:
  - internal shocks
  - photospheric models

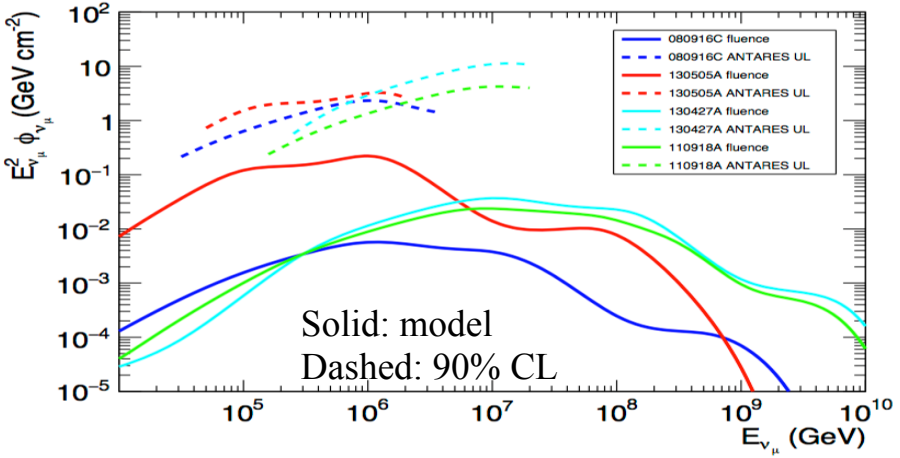
→ use of unfiltered data + special algorithm

📖 MNRAS(2017) 469 (1): 906-915

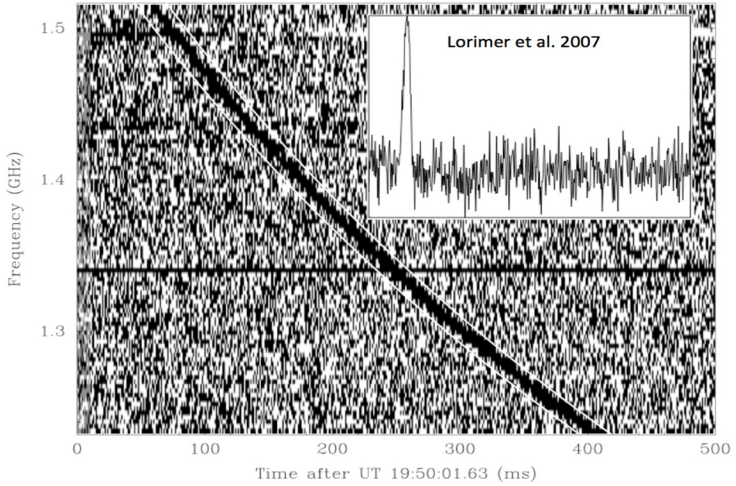


- Stacked search for time shifted neutrinos (during 5 years of ANTARES data): probes wider time windows up to 40 days: no significant detection

📖 Eur.Phys.J. C77 (2017)



Fast Radio Bursts

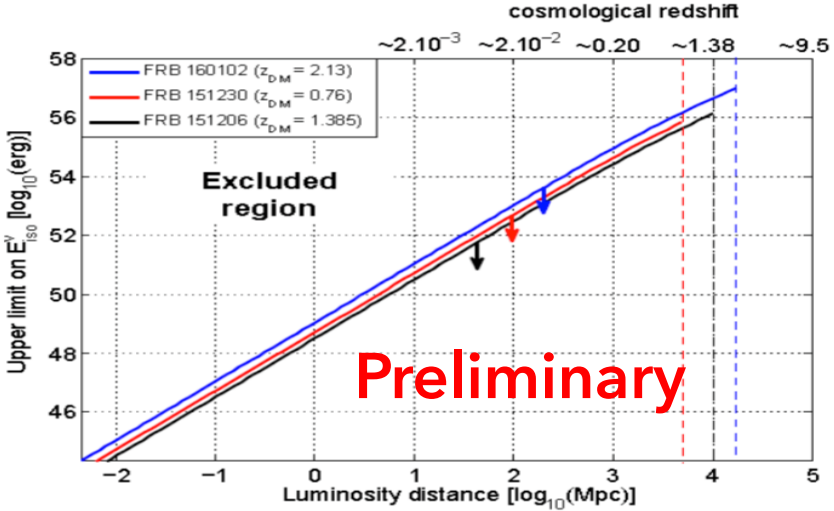


- MoU signed in 2015 between the SUPERB project (FRB discovery) at the Parkes
- SUPERB team → send the FRB trigger alerts to the ANTARES alert pipeline
- ANTARES coll.→ fast search for neutrino counterpart in the online neutrino data stream
- 7 FRBs analyses by ANTARES so far

No events within [T_{FRB}-250s;T_{FRB}+750s] in RoI=2°, Compatible with background

⇒ 90% C.L. upper limit on the total energy emitted in neutrinos for E^{-2} & E^{-1}
1.4×10^{55} erg (E^{-2})
3.1×10^{56} erg (E^{-1})

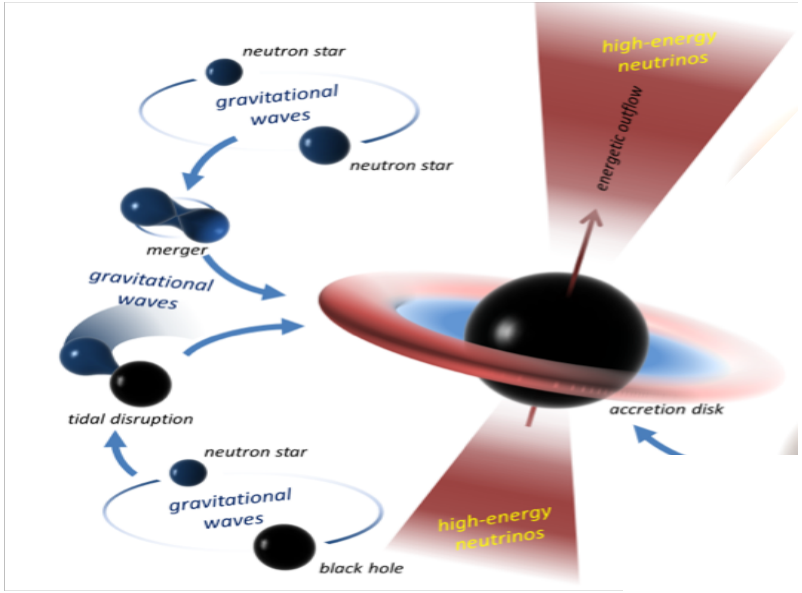
📖 MNRAS (2017) 469 (4): 4465-4482



Search for Coincidences with Gravitational Waves

Mostly for BH/NS or NS/NS systems :

Gravitational waves
+ electromagnetic
+ neutrino emission (if baryonic ejecta)

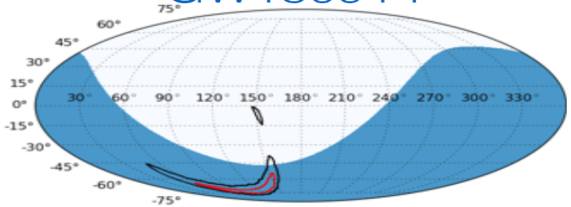


No counterpart observed so far

Limits from ANTARES dominate En < 100 TeV wrt IC

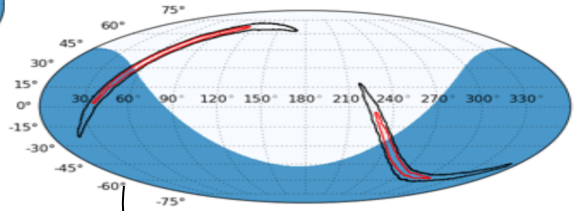
Limit on total energy radiated in neutrinos: <10% GW

GW150914

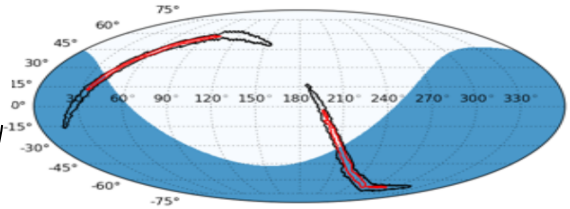


📖 PRD 93, 2016

LVT151012



GW151226



Now real time follow-up of ongoing science run

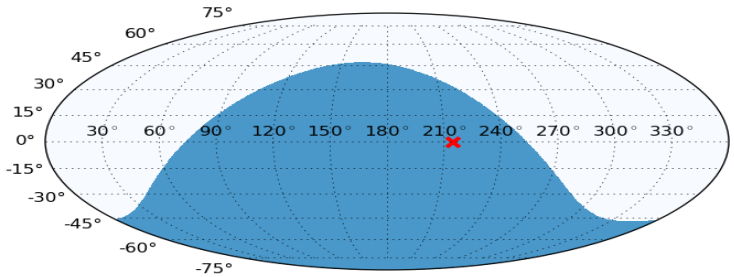
📖 PRD 96, 022005 (2017)

Search for counterpart to IceCube events

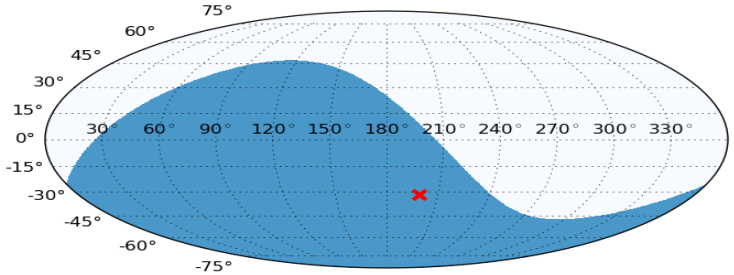
ICECUBE HE EVENTS

IceCube High Energy Starting Events and Extremely High Energy (>1 PeV) events.

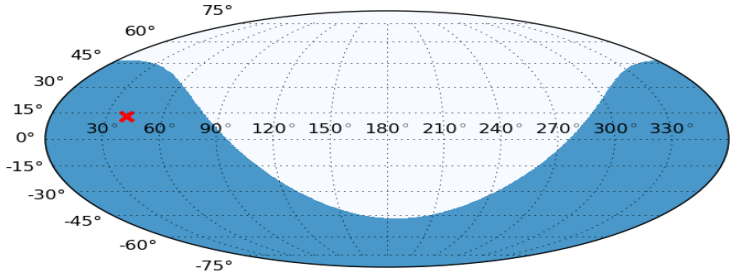
IC160731



IC160814



IC161103



No event found in coincidence (ROI=2°), ± 500 s ; ± 1h

→ Upper limit on the radiant neutrino fluence for E^{-2} and $E^{-2.5}$ spectra:

~15 GeV/cm^2 in [2.8 TeV, 3.3 PeV] for E^{-2}
~30 GeV/cm^2 in [0.4 TeV, 280 TeV] for $E^{-2.5}$

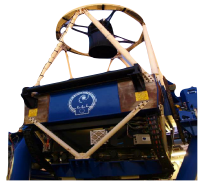
The multi-messenger program: TATOO

Telescope-Antares Target of Opportunity

2ND APPROACH:

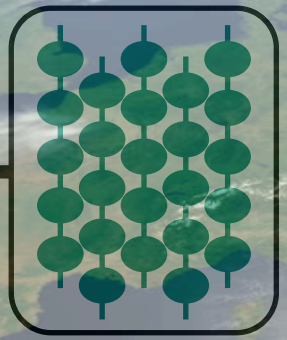
Alert triggering

Real-time analysis



H.E.S.S.

+ ...



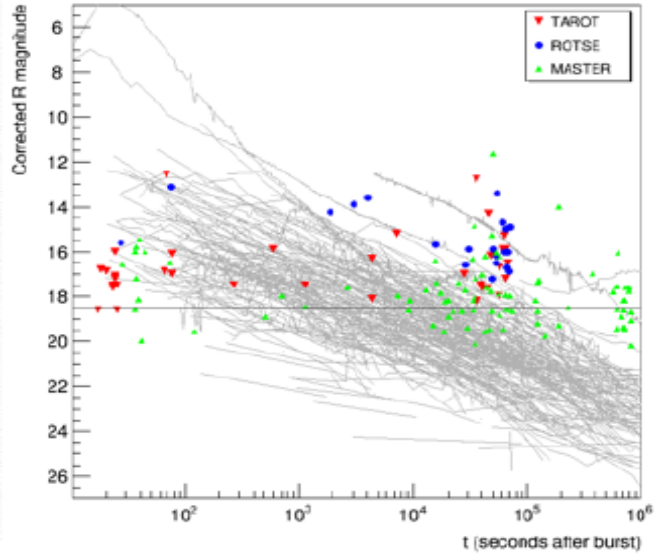
- Time to send an alert: ~5 s
- First optical image <20 s
- Median angular resolution: ~0.3°
- Triggers: single HE, preferred direction, multiplets

TATOO and the GRBs

Radio	Optical	X-ray	GeV γ-rays	TeV γ-rays
MWA (12/yr)	**TAROT ZADKO MASTER (GWAC) (30/yr)**	**Swift (6/yr)**	**Fermi (offline)**	**HESS (2/yr) HAWC (offline)**

- 256 alerts sent
- 24 follow-ups with delay < 1min (best 17s)
- 13 X-ray Swift follow-up (5-6hr delay)
- No transient candidate associated to neutrinos

GRB origin unlikely



JCAP 02:062, 2016

Summary

- 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 ~3° resolution
  - Weak excess at high energy, of magnitude expected from cosmic flux
  - Rich multi-messenger program
  - Earth and Sea Science observatory

- KM3NeT: under construction
  - ESFRI Roadmap in 2016, Letter of Intent published: JPhys.G, 43 (8), 084001, 2016
  - Prototypes performed well, first 2 strings operated for 1 year : check performances
  - **ARCA will confirm and study the observed cosmic flux (tracks & showers)**
  - **ORCA will measure the Neutrino Mass Ordering**

We welcome new contributors

Thank you !