



**KM3NeT**

*Opens a new window on our universe*



# Deep Sea Neutrino Telescopes: Latest Results from ANTARES and Perspectives for KM3NeT

Daan van Eijk

on behalf of the ANTARES and  
KM3NeT Collaborations

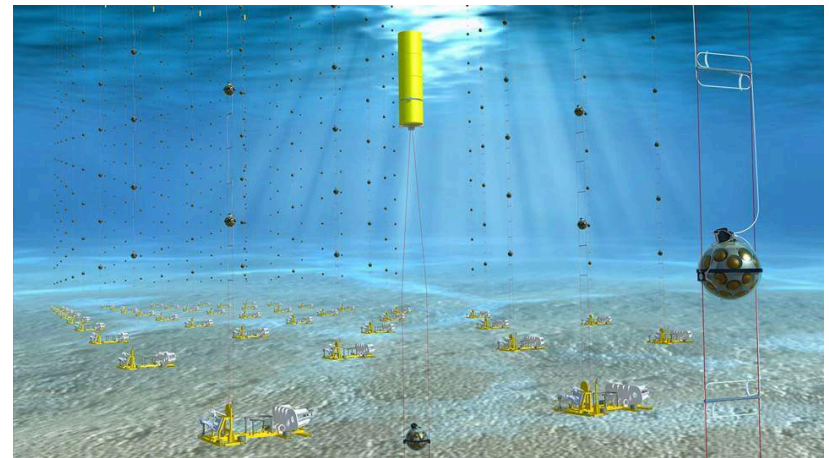
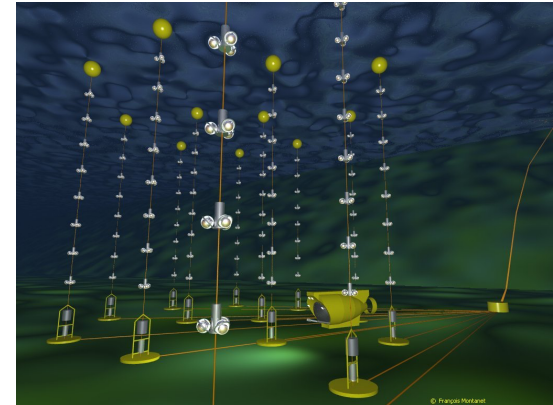
August 11  
TeVPA 2017  
Columbus, Ohio

# Disclaimer

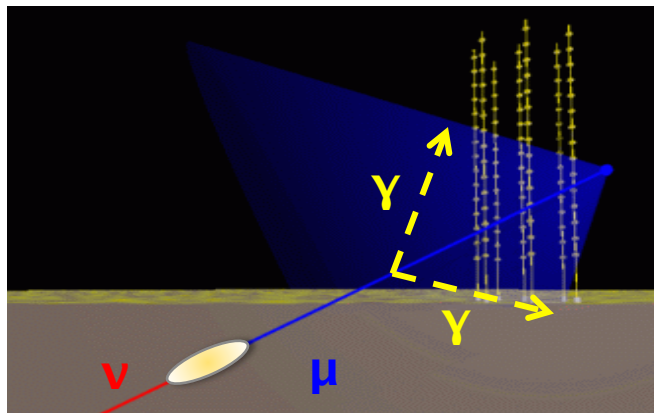


# Outline

- Deep Sea Neutrino Telescopes
  - Detection Principle
- ANTARES
  - Detector Overview
  - Results: Diffuse Searches, Point Sources, Multi-Messenger
- KM3NeT
  - Detector Overview
  - ARCA and ORCA Physics Potential
  - Timeline
  - Commissioning and Calibration of the first DU's

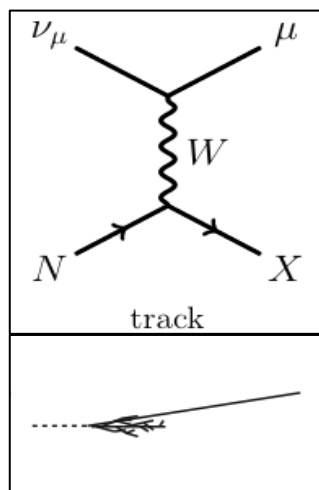


# Water-Cherenkov Neutrino Detection



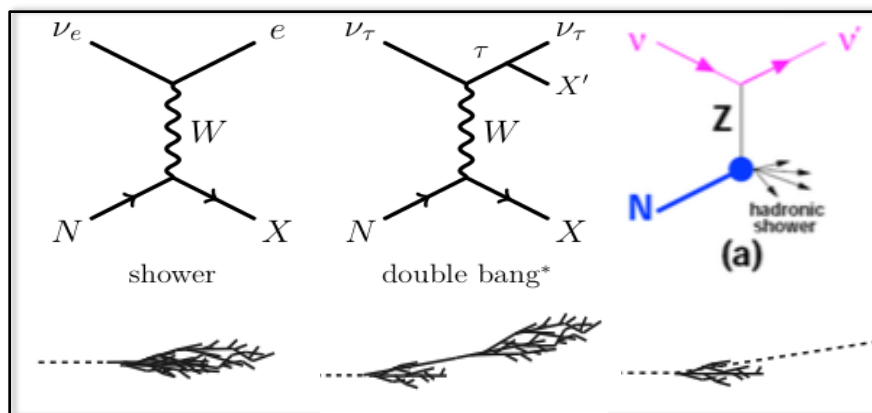
## Tracks:

- Charged Current (CC) interaction:
  - Muon neutrino
- Good angular resolution
- Poor energy resolution



## Cascades:

- Charged Current (CC) interaction
  - Electron and tau neutrino
- Neutral Current (NC) interaction:
  - All neutrino types
- Good energy resolution
- Poor angular resolution



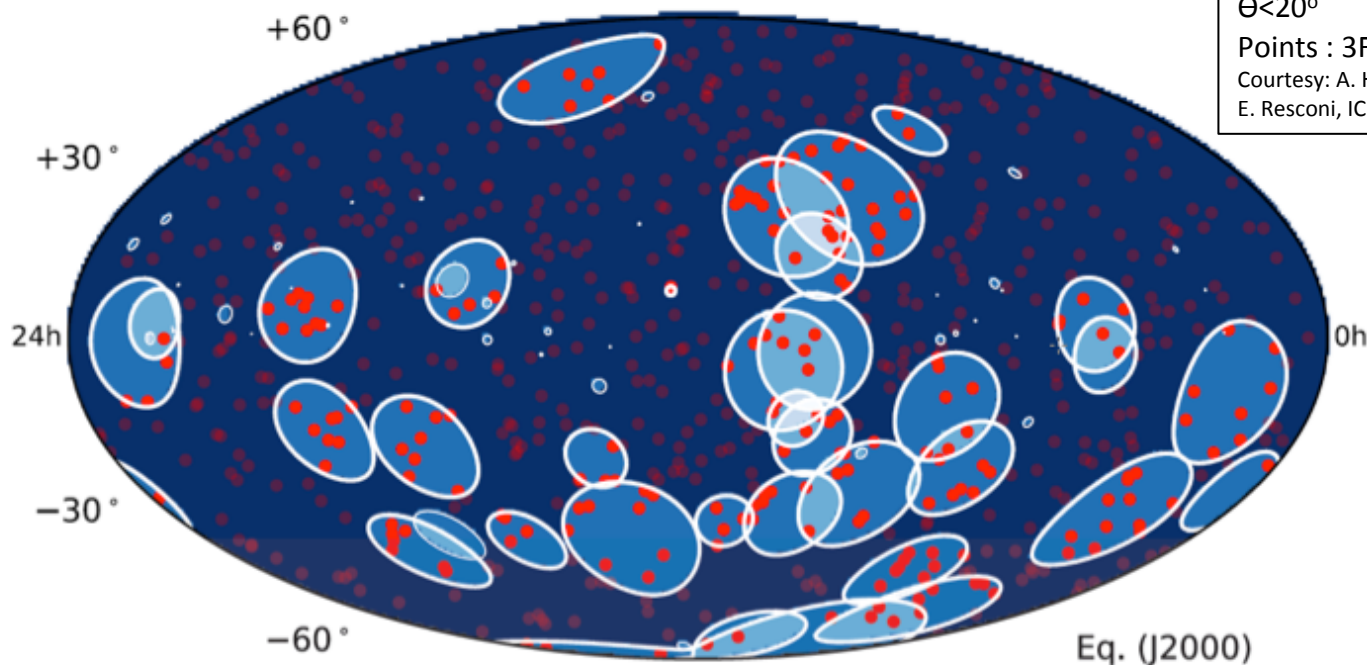


# Water as Detection Medium

Photon propagation in water (relative to ice):

- Long(er) scattering length
  - **Good angular resolution**
- Short(er) absorption length

6 year HESE data  
 $E > 60 \text{ TeV}$   
 $\Theta < 20^\circ$   
 Points : 3FHL, HBL  
 Courtesy: A. Heijboer and  
 E. Resconi, ICRC 2017



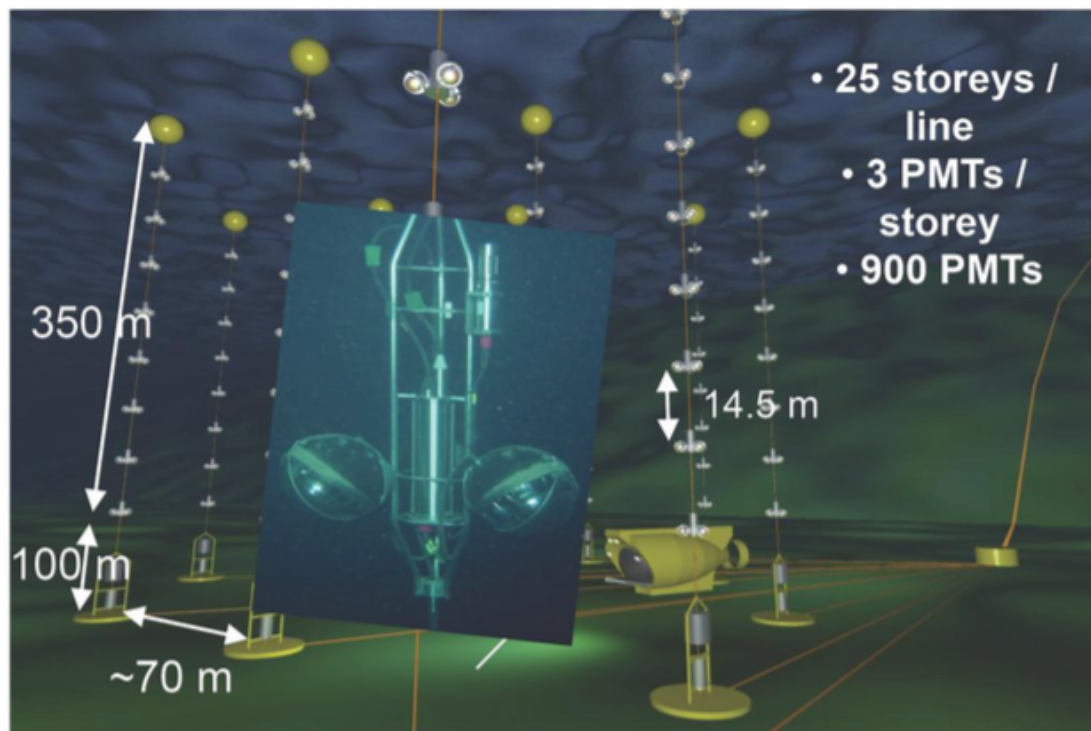
Resolution for  $\nu_e$   
 ANTARES ○  
 KM3NeT ◦

Resolution for  $\nu_\mu$   
 ANTARES ·  
 KM3NeT ·

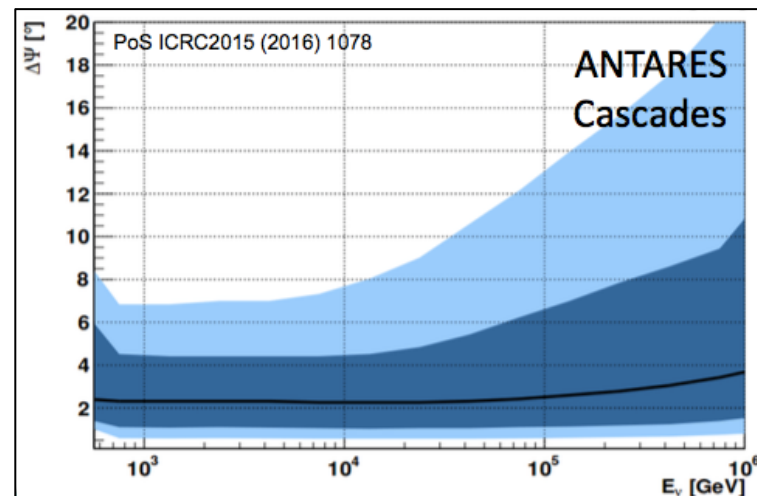
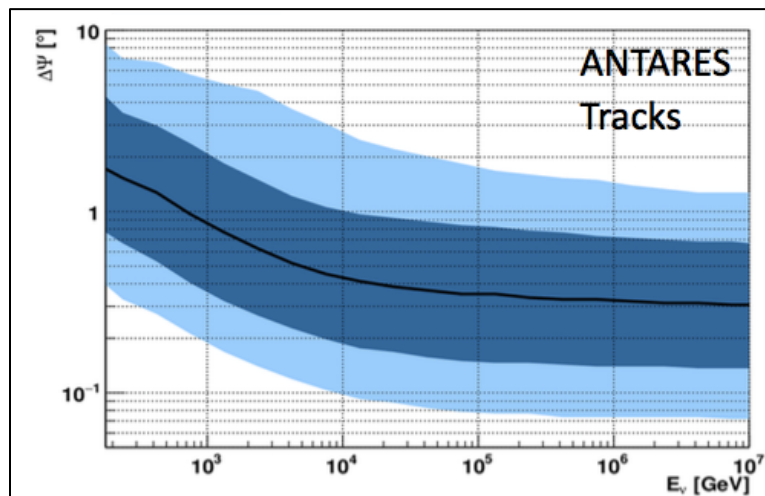
# ANTARES Detector Overview



- Complete since 2008
- 12 detection lines
- 40 km off French coast
- 2.5 km depth
- 10 Mton,  $0.01 \text{ km}^3$
- Studies  $E_\nu$  in range 10 GeV - 100 TeV
- Single downward-looking PMT
  - At 45 degree angle w.r.t. vertical



# ANTARES Resolutions



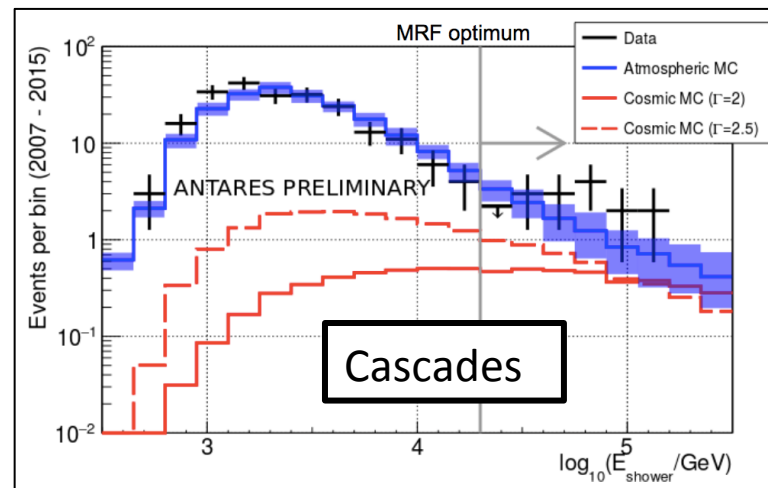
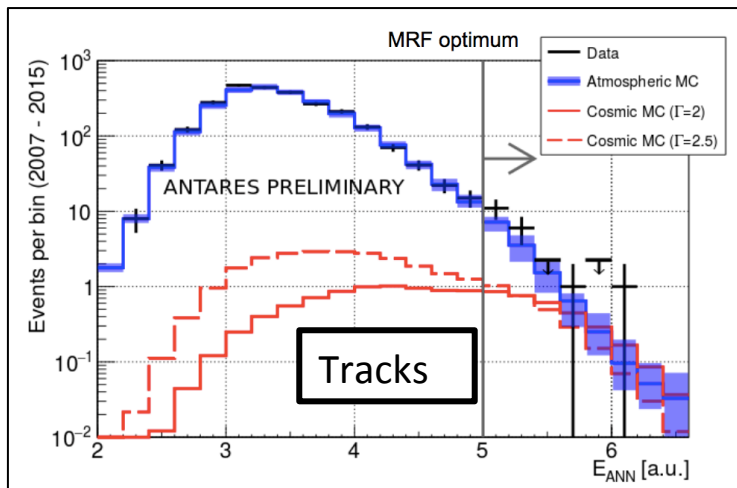
Upgoing tracks ( $\nu_\mu$  CC):

- Angular resolution  $< 0.4^\circ$  for  $E_\nu > 10$  TeV
- Energy resolution:  $\sim 0.35$  in  $\log_{10}(E_{\text{reco}}/E_\nu)$

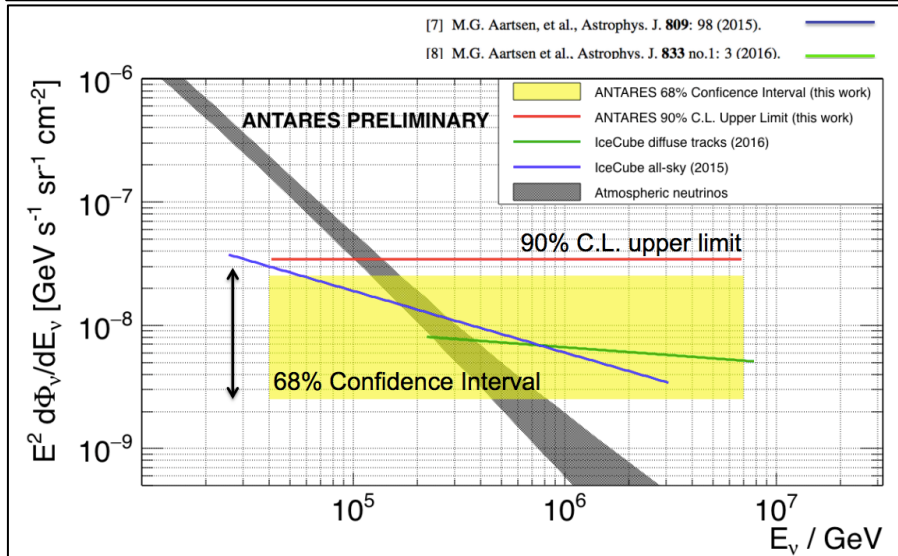
Cascades (NC,  $\nu_{e,\tau}$  CC):

- Angular resolution  $< 3^\circ$
- Energy resolution for  $\nu_e$ : 5%

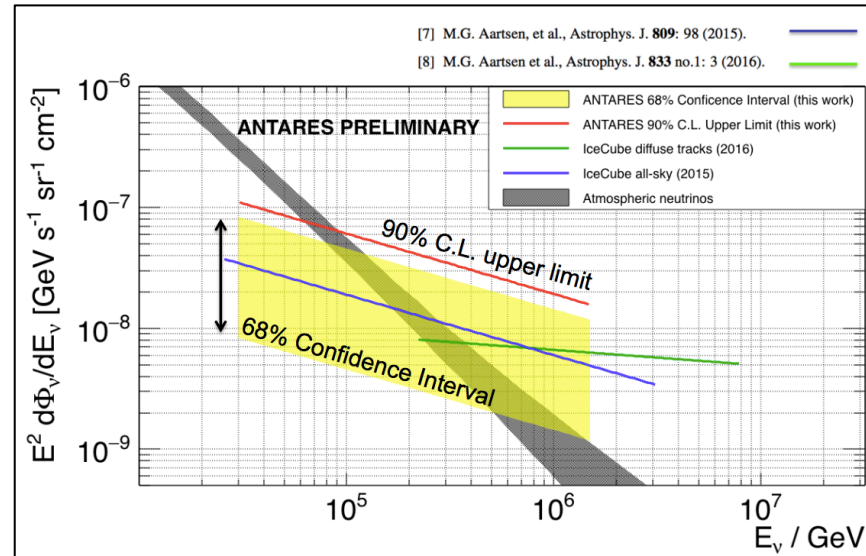
# ANTARES Diffuse Flux Search



Assume  $E^{-2}$ , including systematics



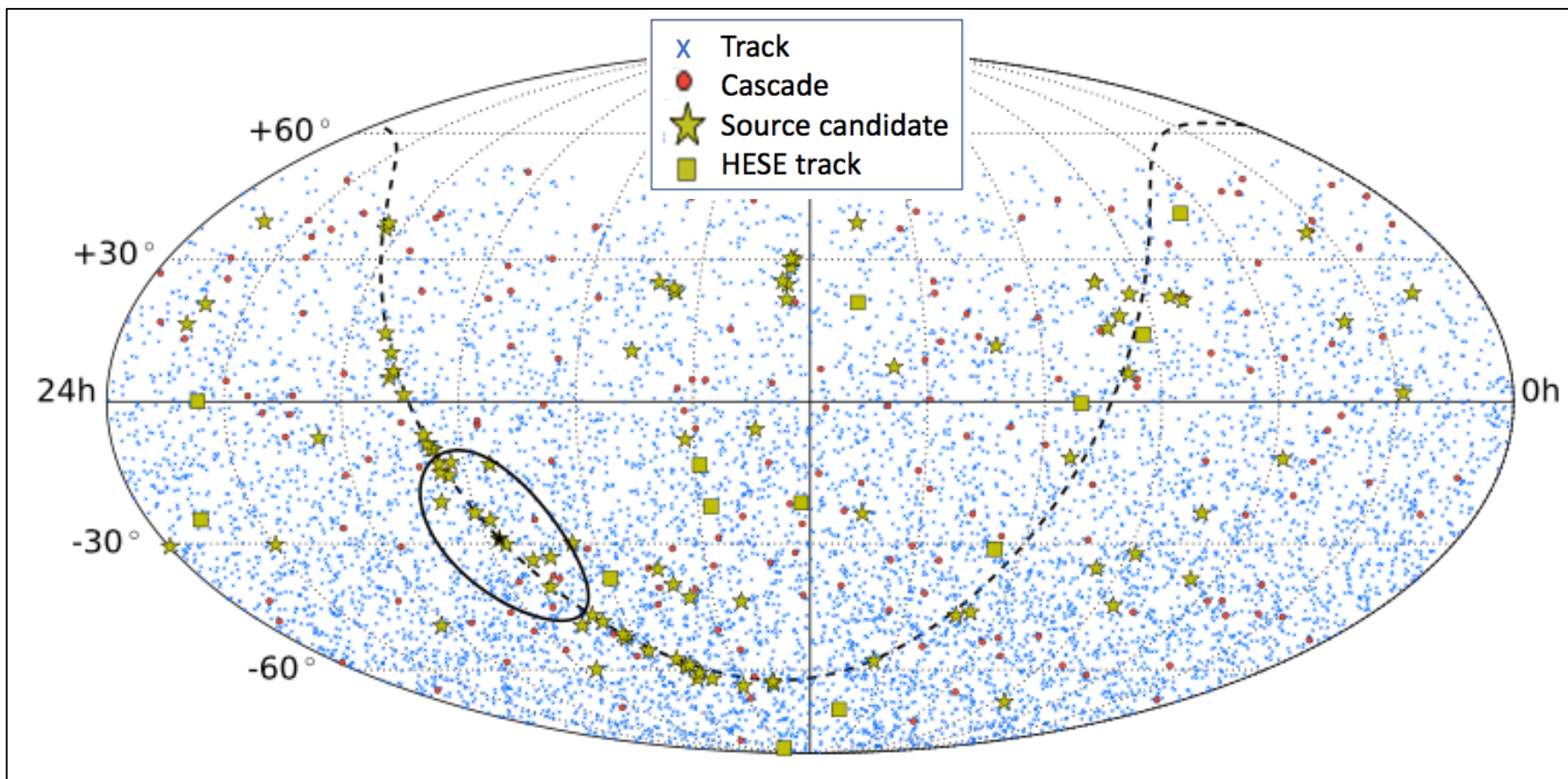
Assume  $E^{-2.5}$ , including systematics



- ANTARES compatible with IC signal + background
- But: no significant observation of the IC signal yet

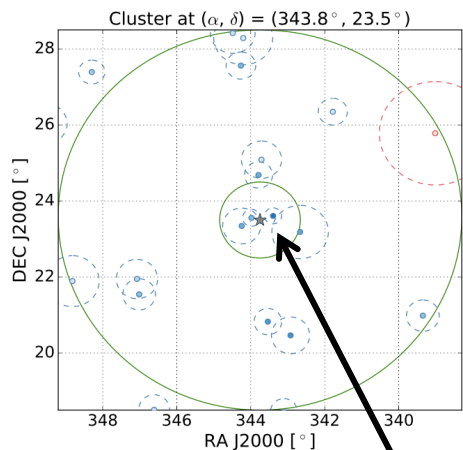


# ANTARES All-Flavor Point Source Search



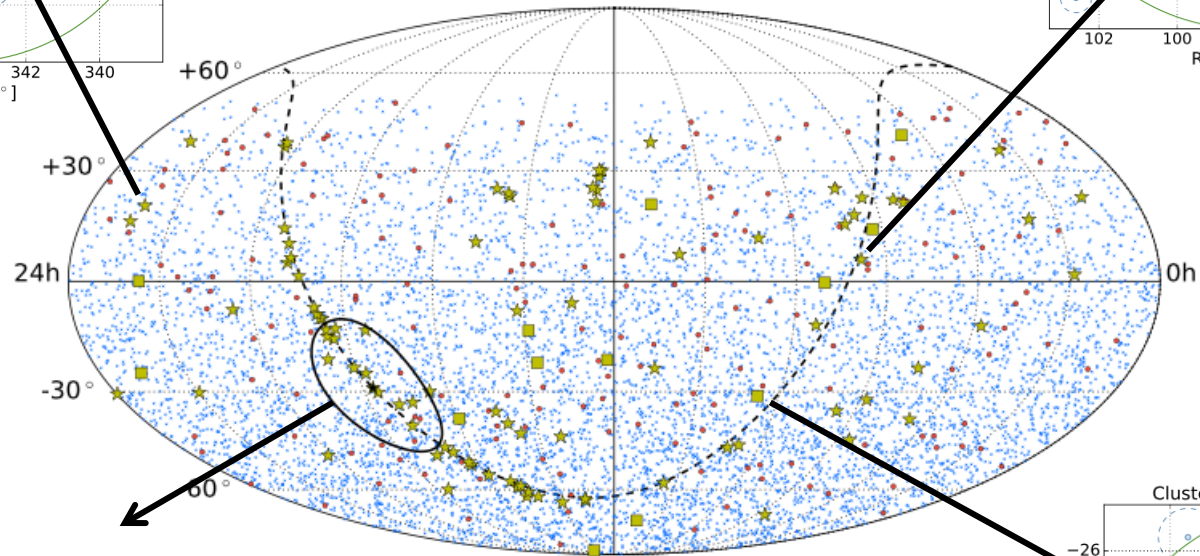
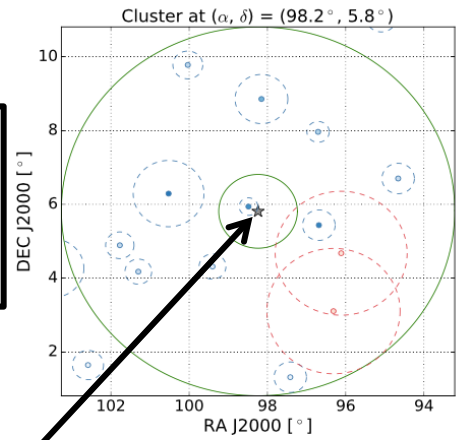
- 2424 days of live-time
- 7629 tracks, 180 cascades
- Extract limits for 103 (catalogue) source candidates and 13 IC HESE tracks

# ANTARES Point Source Results

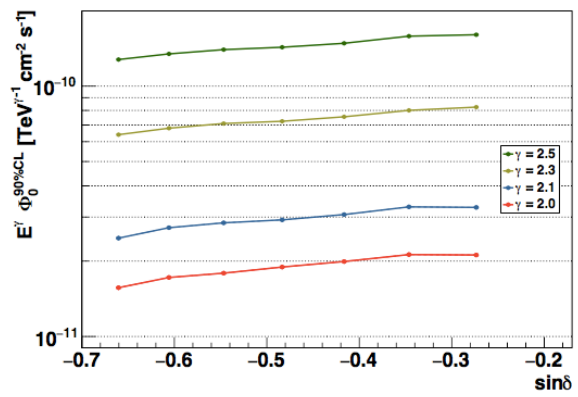


Most significant cluster in full sky:  
 $p=6\%$  ( $1.9\sigma$ )

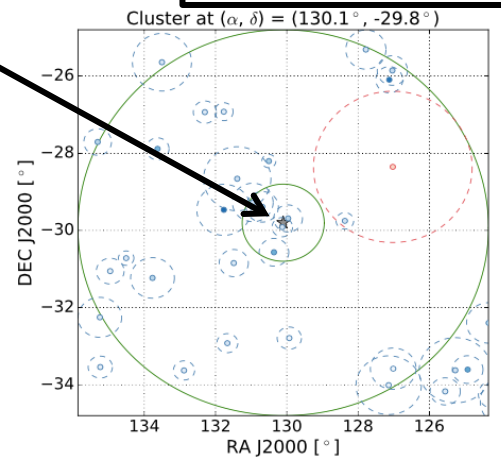
Most significant candidate source:  
 HESSJ0632+057  
 $p=13\%$



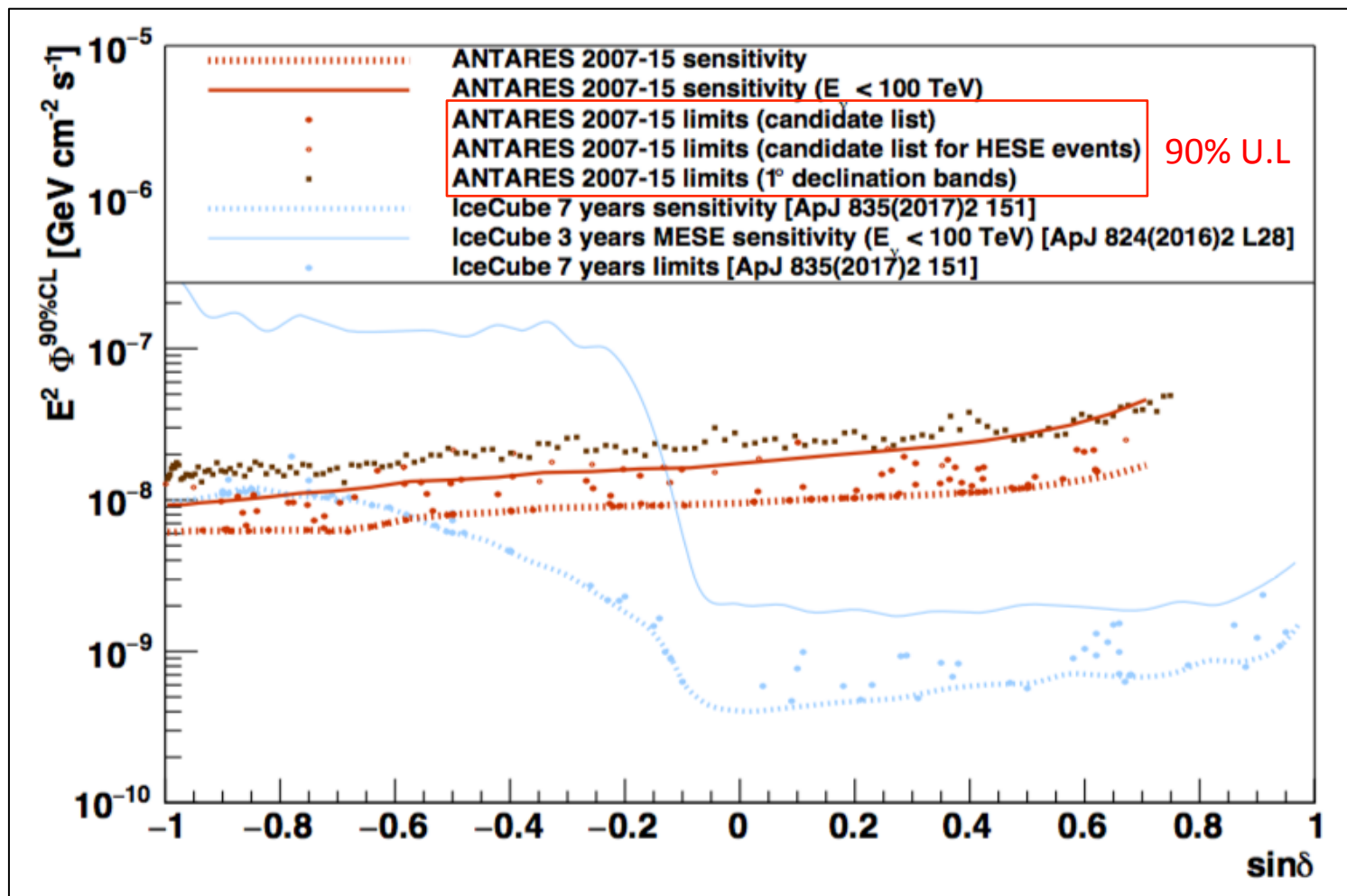
Most significant HESSE track:  
 $p=20\%$



Depending on assumed spectrum, flux needed for significant detection near galactic center



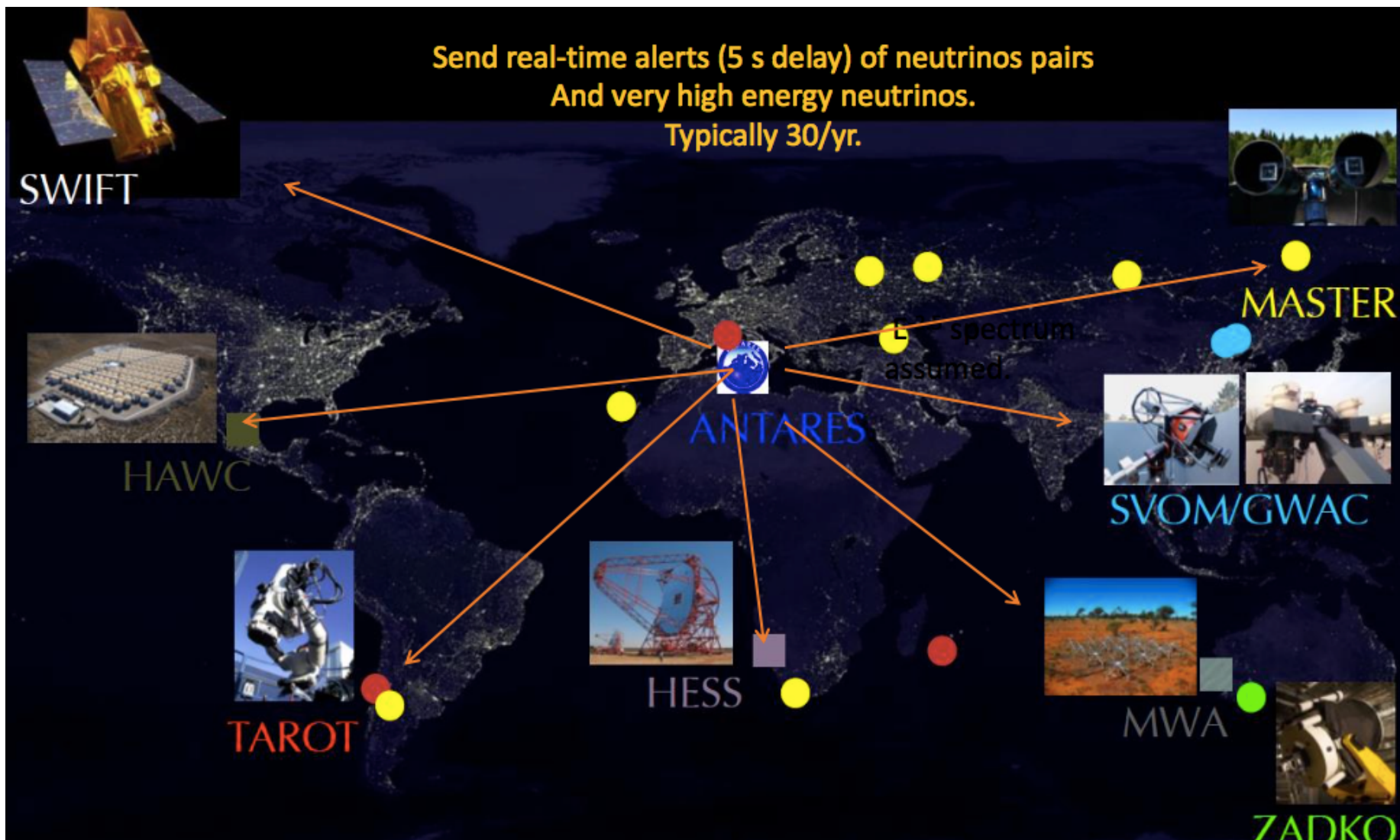
# ANTARES Point Source Results (cont'd)



- No significant excess observed
- ANTARES yields best limits for part of the Southern Hemisphere at  $E_\nu < 100 \text{ TeV}$  (relevant energy range for neutrinos from Galactic Sources)

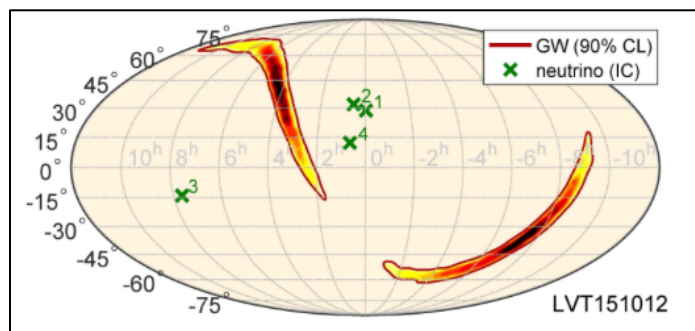
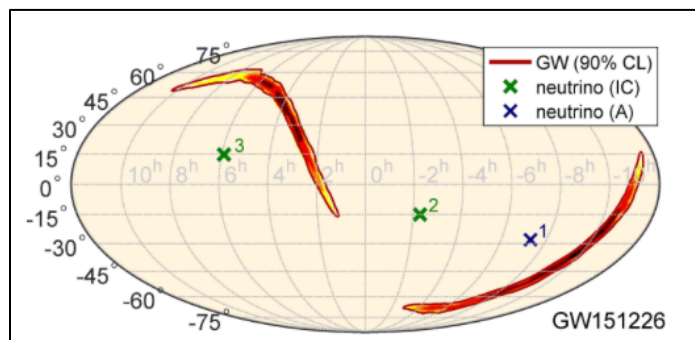
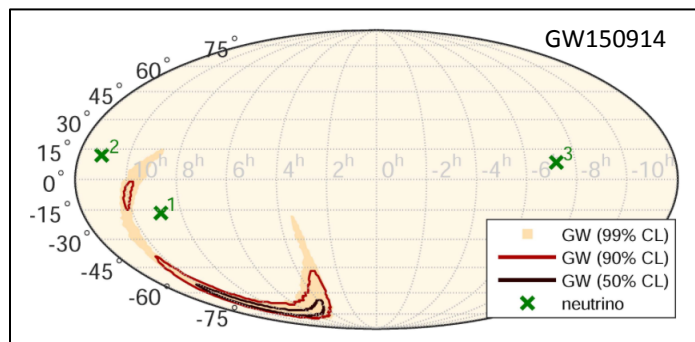


# ANTARES Multi-Messenger Program





# The Other Way Around: GW Follow-Up



## Motivation:

- Binary black hole merger might emit neutrinos
- Coincident neutrino signal would allow pinpointing at  $<1 \times 1$  degree
  - Compared to  $> 100 \times 100$  degrees for the GW observation

## Result:

- No neutrino counterpart observed
- This sets a limit on the total energy radiated as neutrinos:  $\sim 10\%$
- ANTARES limit dominates for  $E_\nu < 100$  TeV
- Real-time follow-up in upcoming LIGO/VIRGO science runs

Phys. Rev. D 93, 122010 and Phys. Rev. D 96, 022005

# ANTARES, Not Covered Here...

- 'Extended' sources: galactic plane, Fermi bubbles
- Dark matter searches (Sun, Galactic Plane, Earth)
- Oscillations
- Sterile neutrino searches
- Magnetic monopole searches
- Searches for neutrinos in correlation with GRBs, blazars, FRBs, X-ray binaries, Auger events

# KM3NeT Detector Overview

- Currently under construction
- Two separate geographical sites



## KM3NeT ORCA

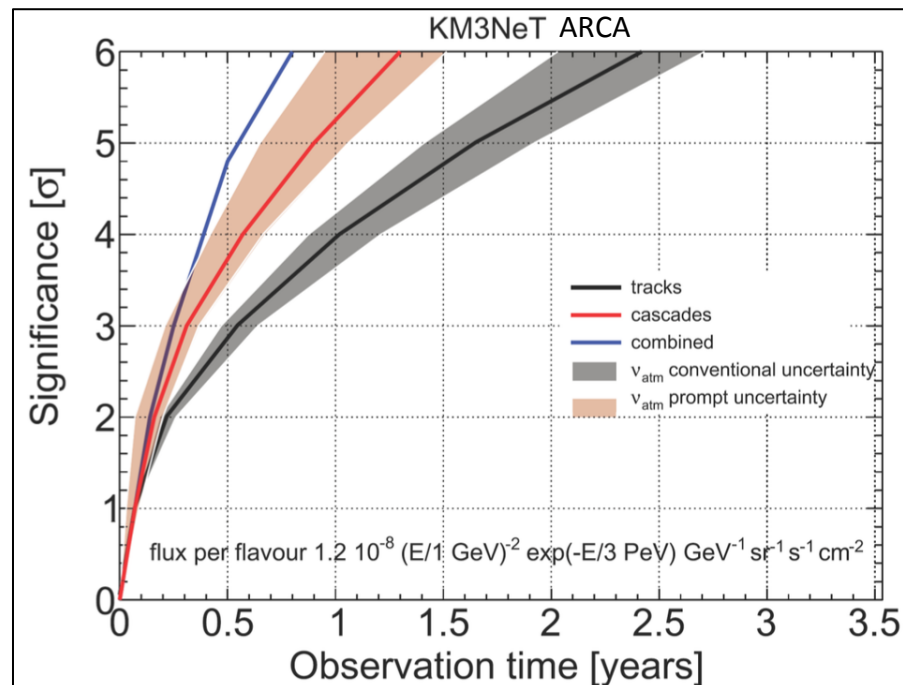
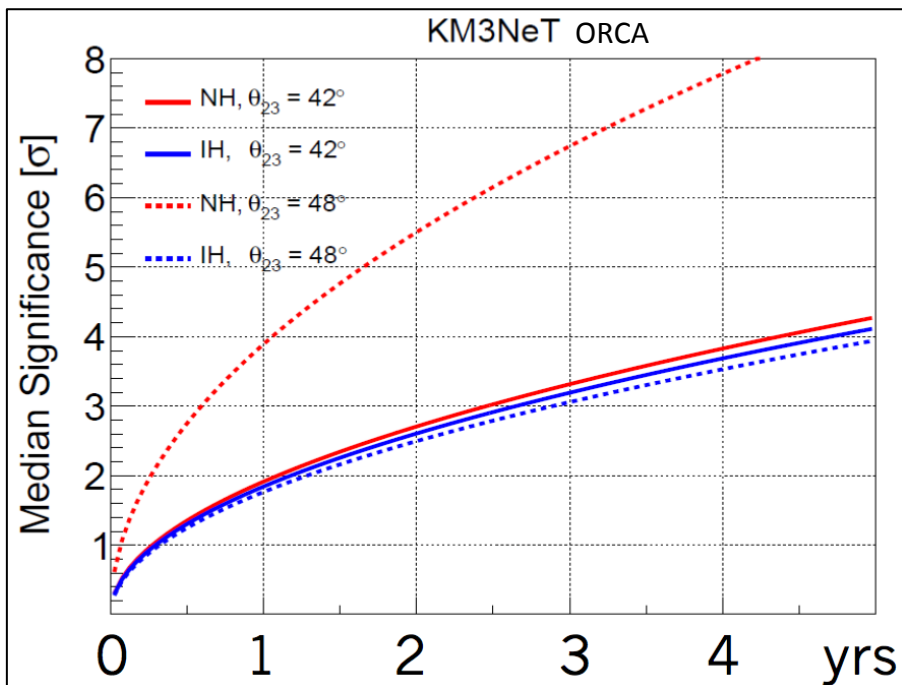
- Neutrino oscillation research
- 40 km off French coast
- 2.5 km depth
- Dense DOM configuration:
  - 9 m vertical
  - ~20 m horizontal
- GeV atmospheric neutrinos
- 8 Mton detector



## KM3NeT ARCA

- Neutrino astrophysics research
- 100 km off Italian coast
- 3.5 km depth
- Sparse DOM configuration:
  - 36 m vertical
  - ~100 m horizontal
- TeV-PeV neutrinos
- ~1 km<sup>3</sup>/Gton instrumented volume

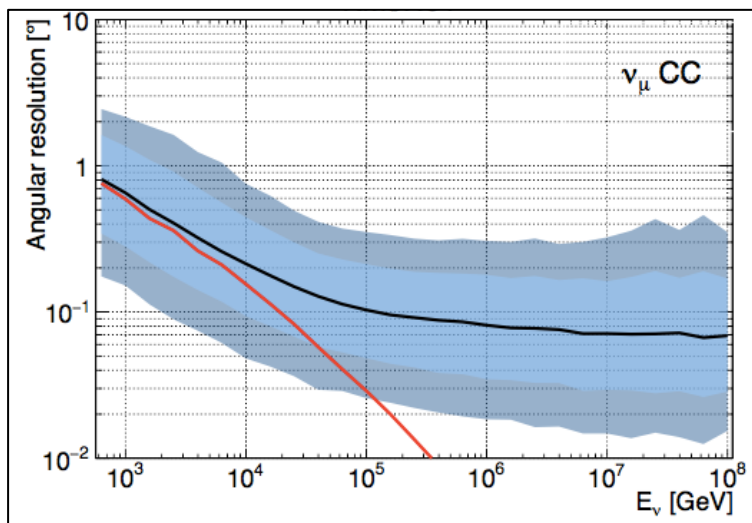
# KM3NeT Physics Goals



- Determine mass hierarchy
- Precision measurement of  $\theta_{23}$  and  $\Delta m_{32}^2$
- Resolve  $\theta_{23}$  octant
- $\nu_\tau$ -appearance: unitarity check
- NSI and sterile neutrino searches

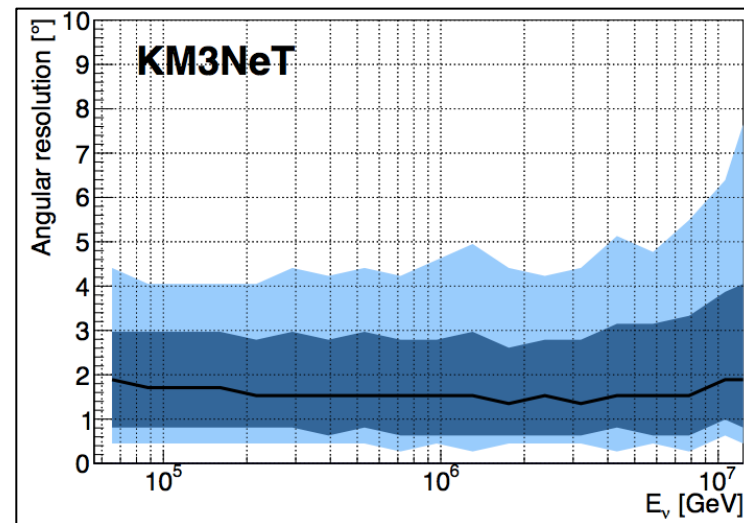
- Confirm astrophysical IceCube flux at 5 sigma within one year
- Having unprecedented angular resolution, resolve and identify point sources
- At least order of magnitude better point source sensitivity

# KM3NeT Resolutions



Upgoing tracks ( $\nu_\mu$  CC):

- Angular resolution  $< 0.2^\circ$  for  $E_\nu > 10$  TeV
- Energy resolution  $< 0.3$  in  $\log_{10}(E_{\text{reco}}/E_\nu)$



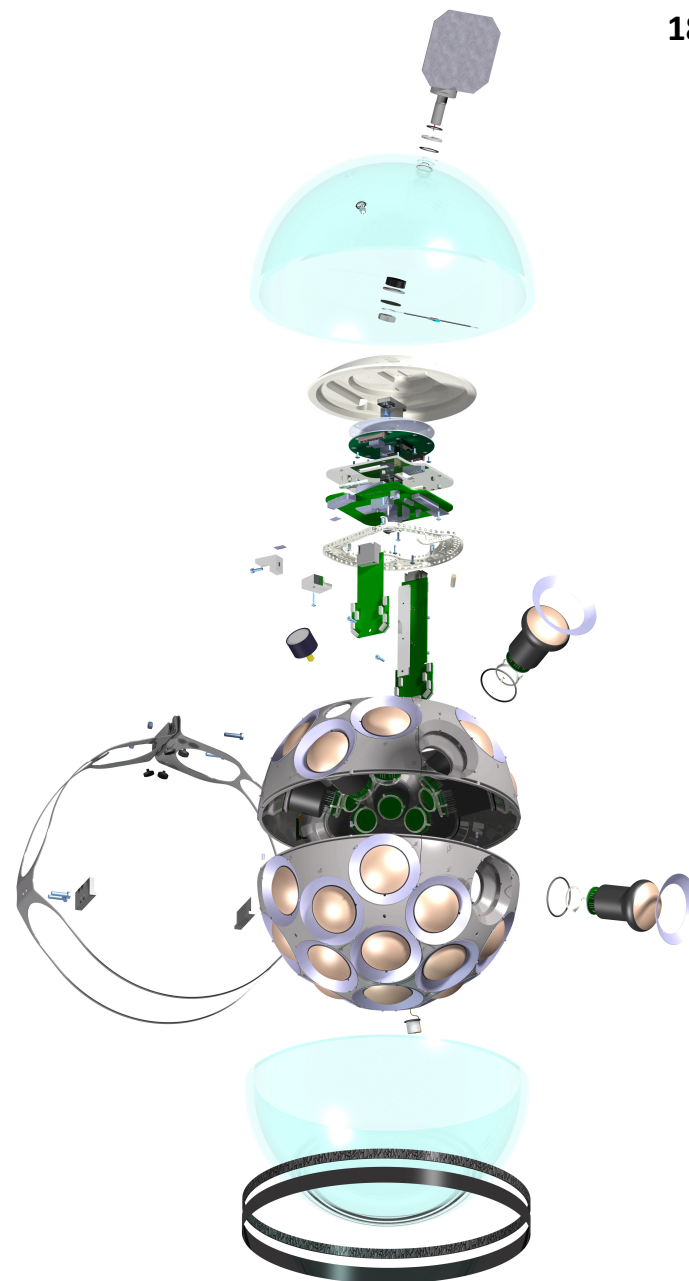
Cascades (NC,  $\nu_{e,\tau}$  CC):

- Angular resolution  $< 1.5^\circ$
- Energy resolution for  $\nu_e$ :  $\sim 5\%$

# KM3NeT DOM

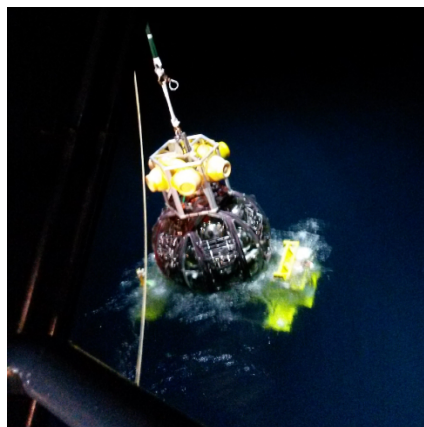
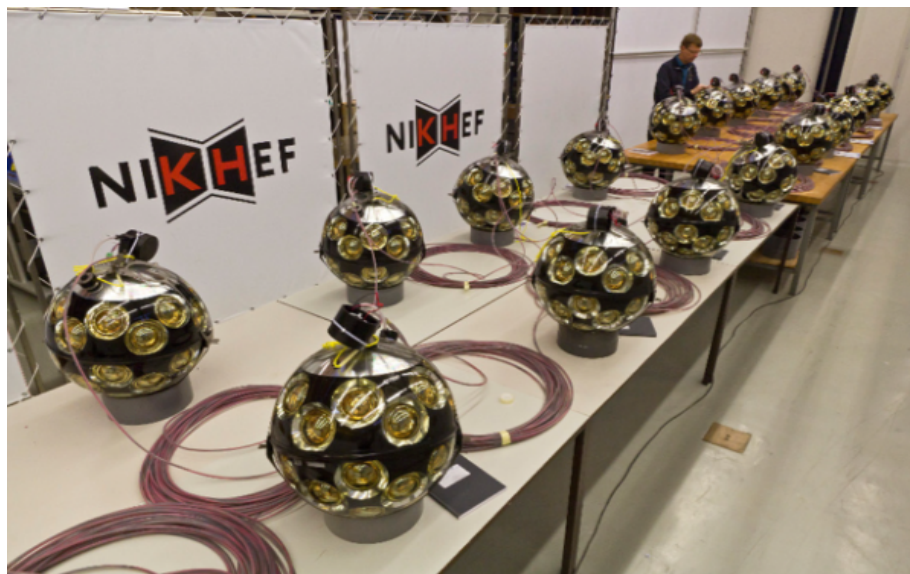


- 31 3" PMTs (total cathode area  $\sim 3 \times 10''$ )
  - Directional sensitivity
  - $< 2$  ns (RMS) timing
  - $\geq 25$ -30% QE
  - $\geq 90\%$  collection efficiency
  - Lower price/area compared to 10" PMT
- LED flasher for timing calibration
- Piezo sensor for position calibration
- Compass and tiltmeter for PMT orientation



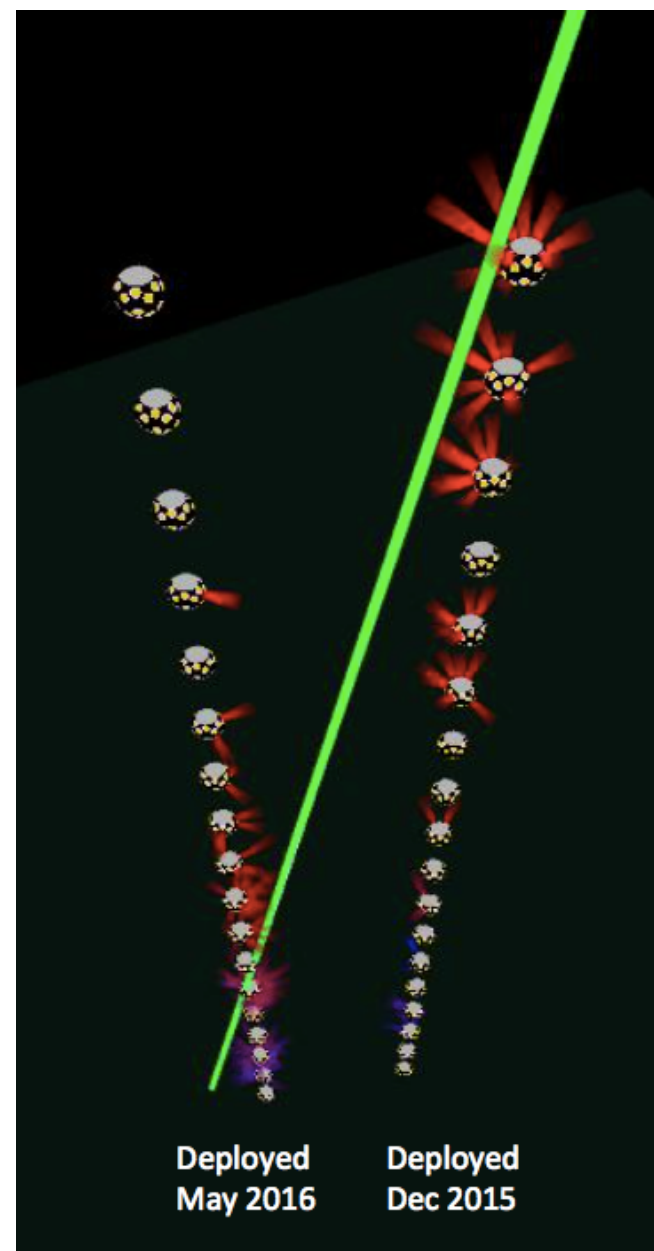


# KM3NeT DU and Deployment



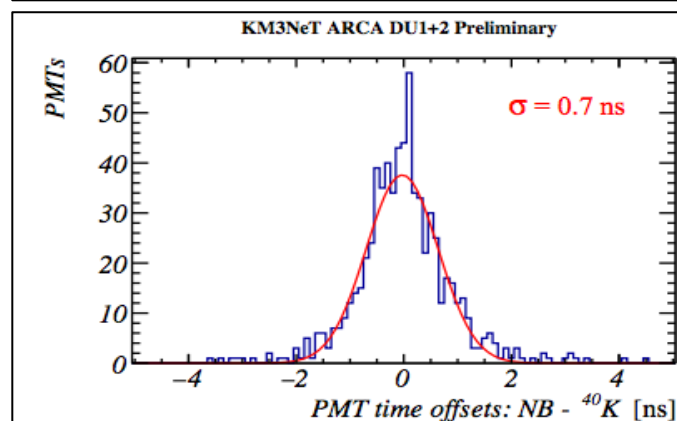
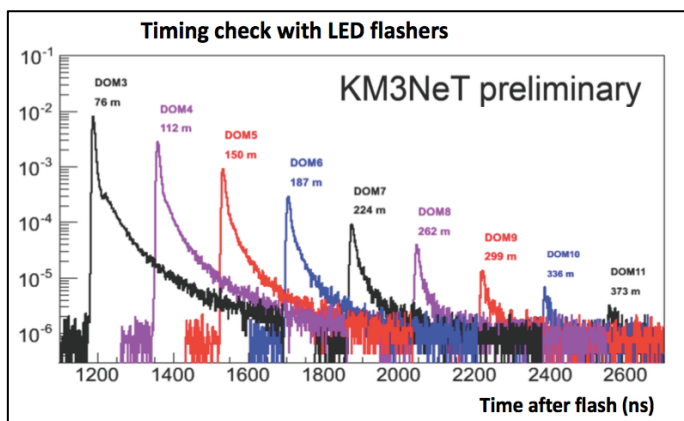
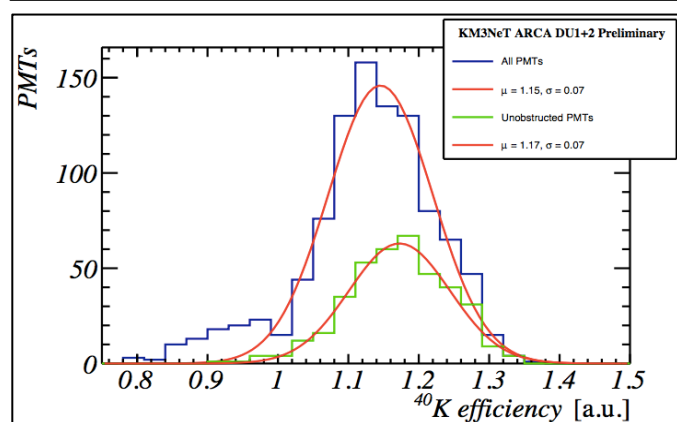
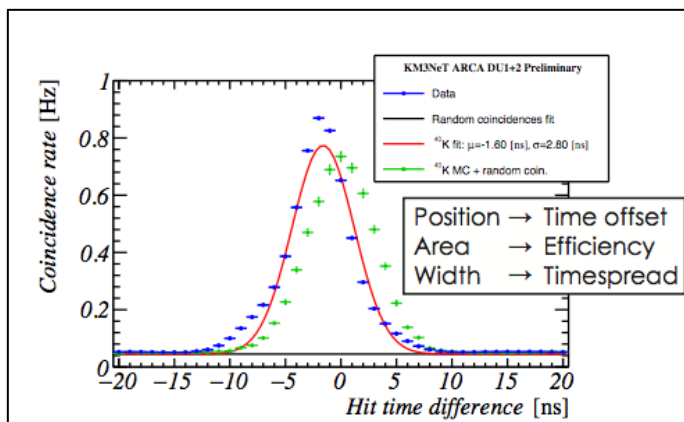
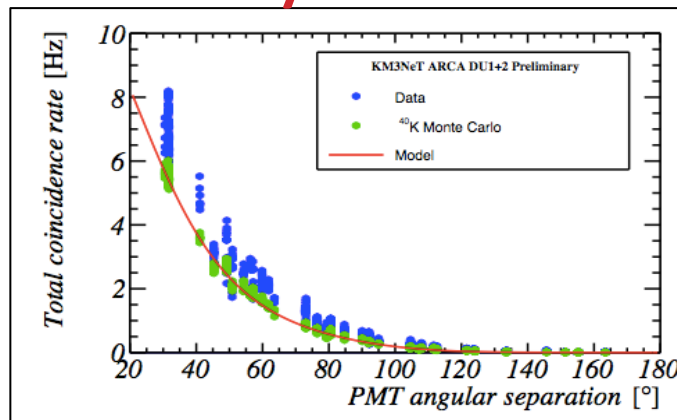
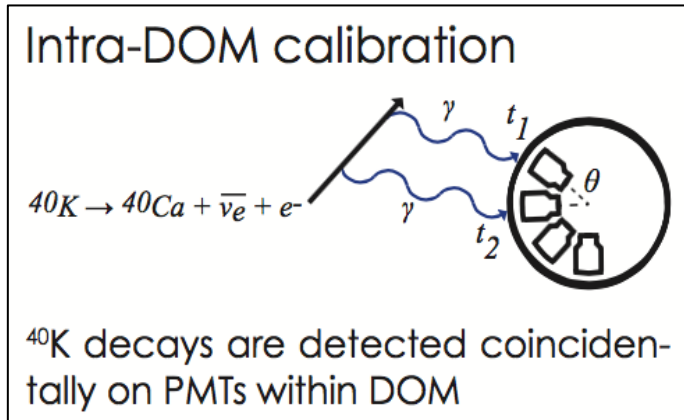
# KM3NeT Status and Outlook

- KM3NeT Phase-1:
  - Fully funded and under construction
  - 24 ARCA DU's (2 already deployed)
  - 6 ORCA DU's (2 to be deployed by end of Summer)
- KM3NeT 2.0:
  - ORCA: 115 DU's by end 2020 (first funds available)
  - ARCA: 2 x 115 DU's by end 2022 (first funds available)
  - On 2016 ESFRI roadmap (European Strategy Forum on Research Infrastructures)

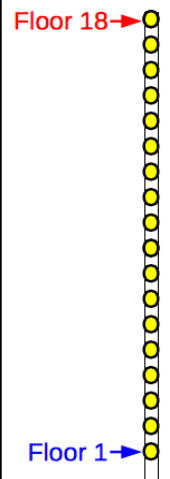
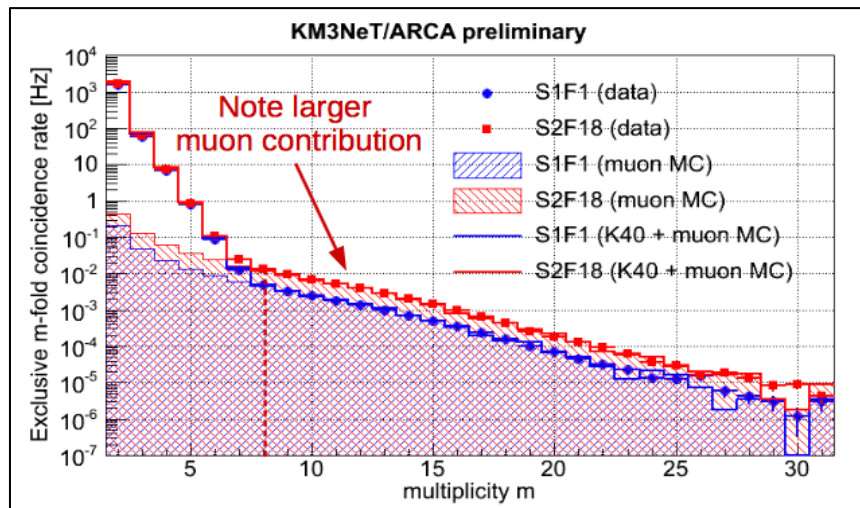




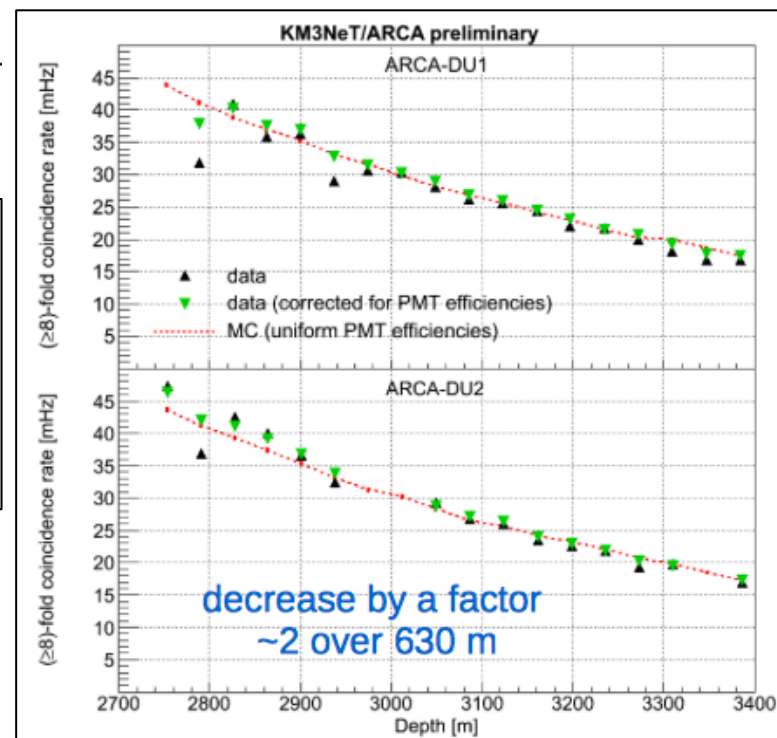
# Calibration: Per-PMT Efficiency



# Calibration: Muon Rate Depth Dependence



- Depth dependence of high-multiplicity rates measured with ARCA-DU1 and ARCA-DU2
- Excellent data/MC agreement
- In-situ measured PMT efficiencies improve data/MC agreement

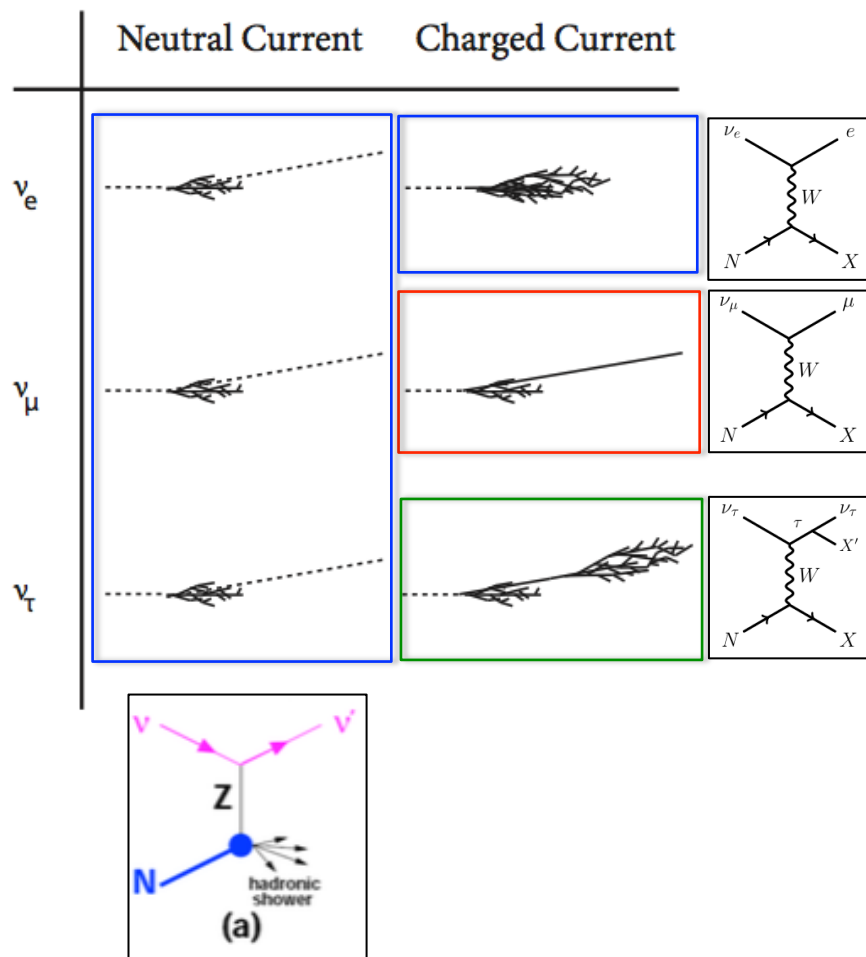


# Summary

- **ANTARES**
  - 10 years of data-taking
  - Point source results set strongest limits for Galactic Sources in the Southern Hemisphere, for neutrino energies below 100 TeV
  - At higher energies, only a very weak excess of events, magnitude in agreement with IceCube astrophysical flux
  - Many multi-messenger studies (X-ray, TeV- $\gamma$ , GW)
  - Oscillation research, exotics...
- **KM3NeT**
  - Currently under construction
  - First two ARCA DU's in operation for 1 year, commissioning and calibration ongoing, first two ORCA DU's to be deployed this summer
  - Good angular resolutions in both track and cascade reconstruction
  - **ORCA:** measure neutrino mass hierarchy (3 sigma in three years)
  - **ARCA:** independent confirmation of IceCube astrophysical neutrino flux (5 sigma in one year), resolve and identify astrophysical neutrino sources

BACKUP

# Event topologies



Three event topologies:

- Shower-like
- Track-like
- Tau double-bang

# ANTARES Diffuse

- 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.

## Results after energy cut

- Event expectations from Monte-Carlo simulation:

for background: **24 +/- 7 events**, i.e.  
13.5 track-like + 10.5 shower-like

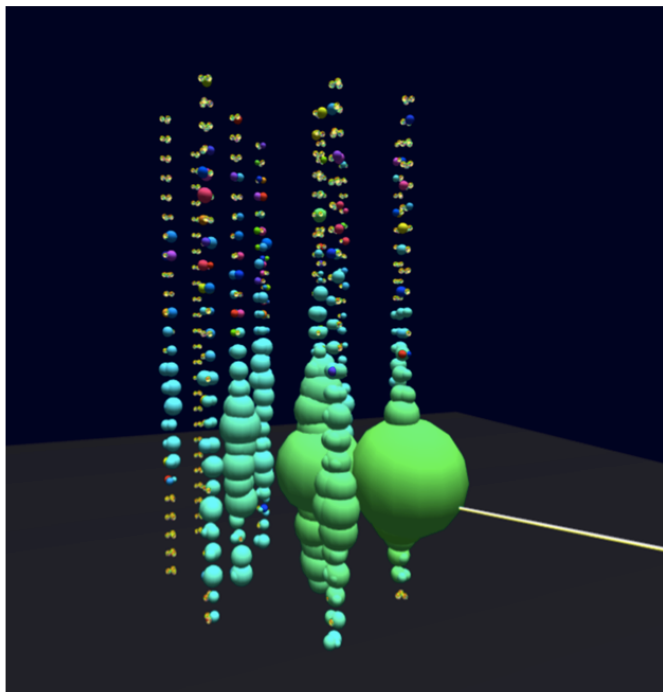
for cosmic signal: **7 events**, i.e.  
3 - 3.5 track-like + 4 shower-like

- Systematic uncertainties considered:
  - atmospheric neutrino and muon flux normalisation
  - water properties
  - optical module efficiencies

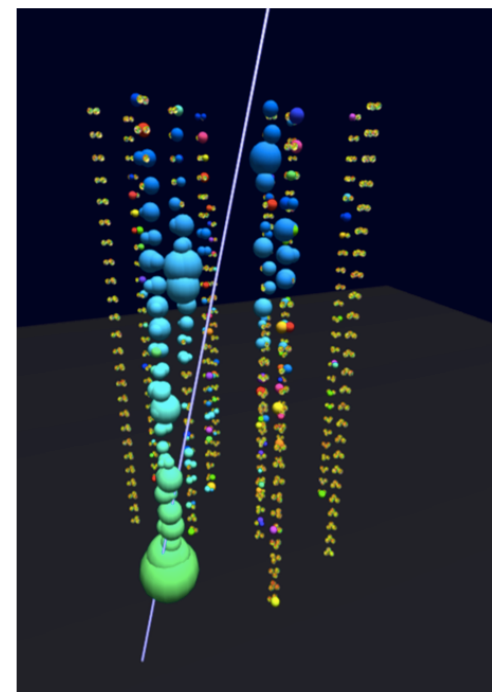
- **Observation: 33 events** (p=0.15)

19 track-like + 14 shower-like

Shower-like event

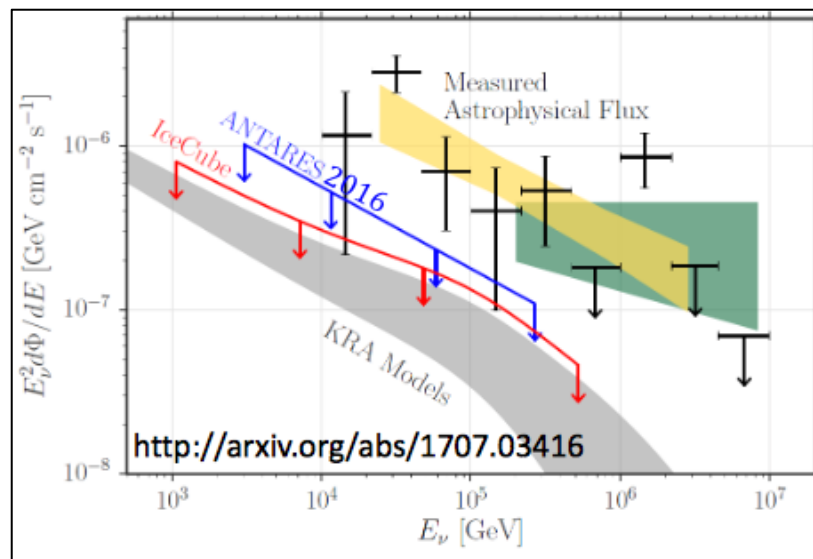
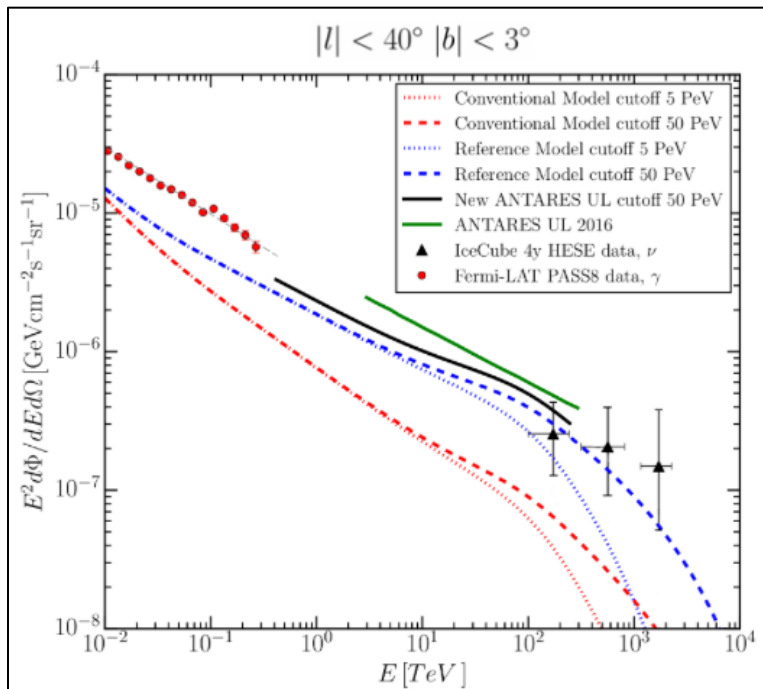


Track-like event



# ANTARES Galactic Search

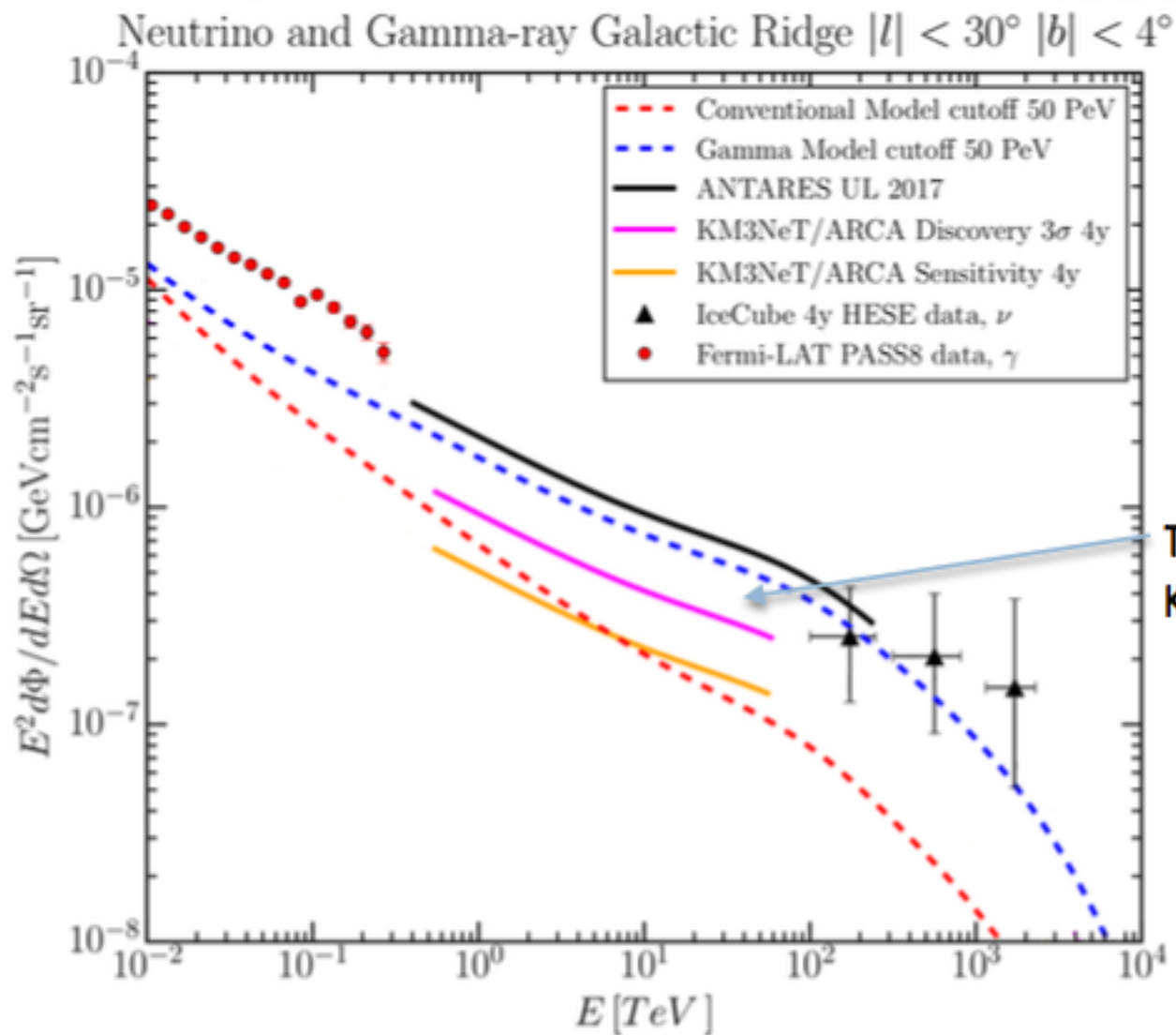
**Question:** can the diffuse astrophysical flux be (fully) explained by neutrinos from our own Milky Way?



**Answer:** No

- ANTARES limit: less than 1.3 x KRA (50PeV cutoff)
- IceCube: not more than 14% of the diffuse flux @  $\gamma = 2.5$  from the Galactic plane

# KM3NeT Galactic Flux



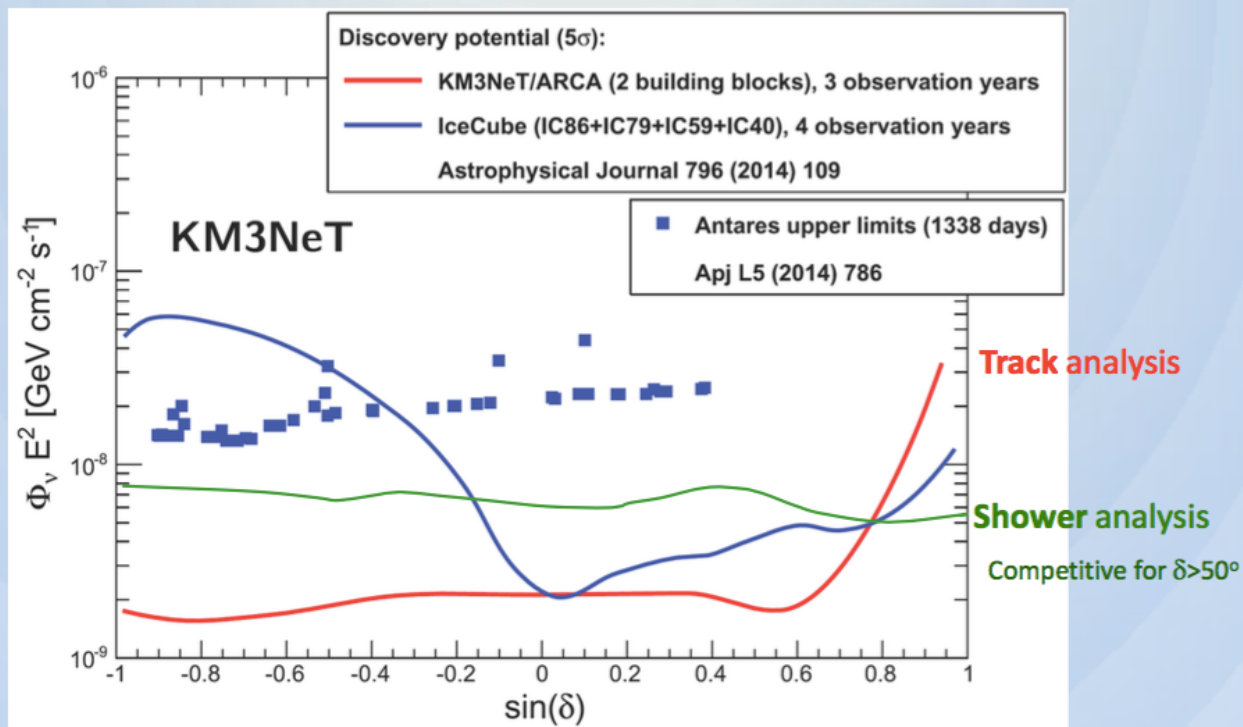
Track analysis

KM3NeT **discovery  $3\sigma$  4y**  
**sensitivity 4y**



# KM3NeT Point Sources

- $5\sigma$  Discovery potential for 3 yrs of observation with ARCA (2 building blocks)
- Broad coverage.  $E^{-2}$  spectrum assumed.



# PMT Coincidence Rates

