NEUTRINO ASTRONOMY IN THE MEDITERRANEAN: FROM ANTARES TO KM3NET

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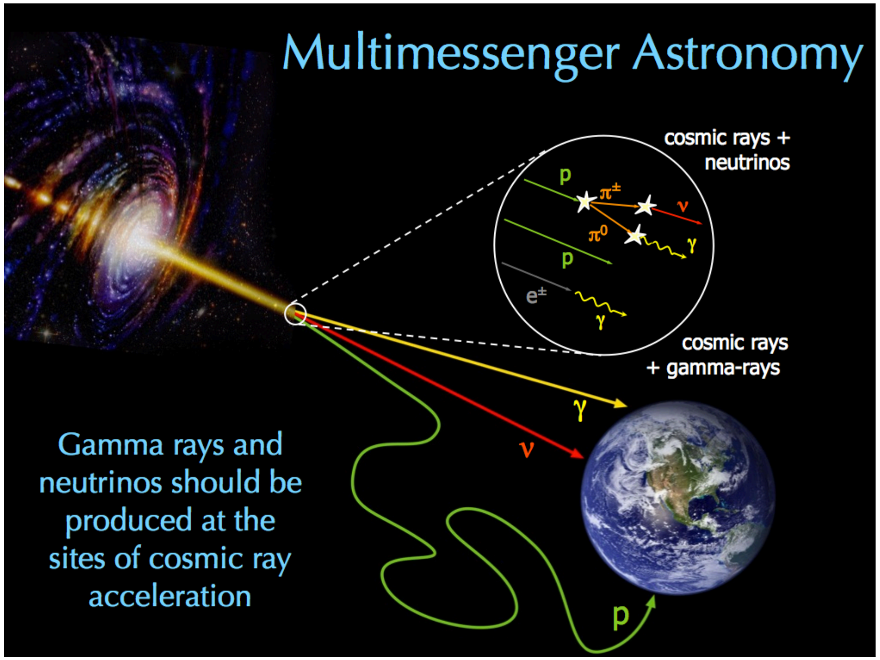
Outline

- Introduction
  - Principles of high-energy neutrino detection
- ANTARES
  - Some selected recent science results
- KM3NeT
  - Design, architecture, prototyping and status
  - Some selected sensitivity results
- Summary and conclusions

Physics with high-energy neutrinos



Neutrinos can provide unperturbed information on the sources

Charged Cosmic Rays

☺ copiously produced

☹ directions scrambled by magnetic fields

UltraHigh Energy Cosmic Rays

☺ not strongly deflected by magnetic field

☹ limited by GZK cut-off

High Energy Gamma Rays

☺ copiously produced both by hadronic and leptonic mechanisms

☹ absorbed on dust and radiation

Neutrinos

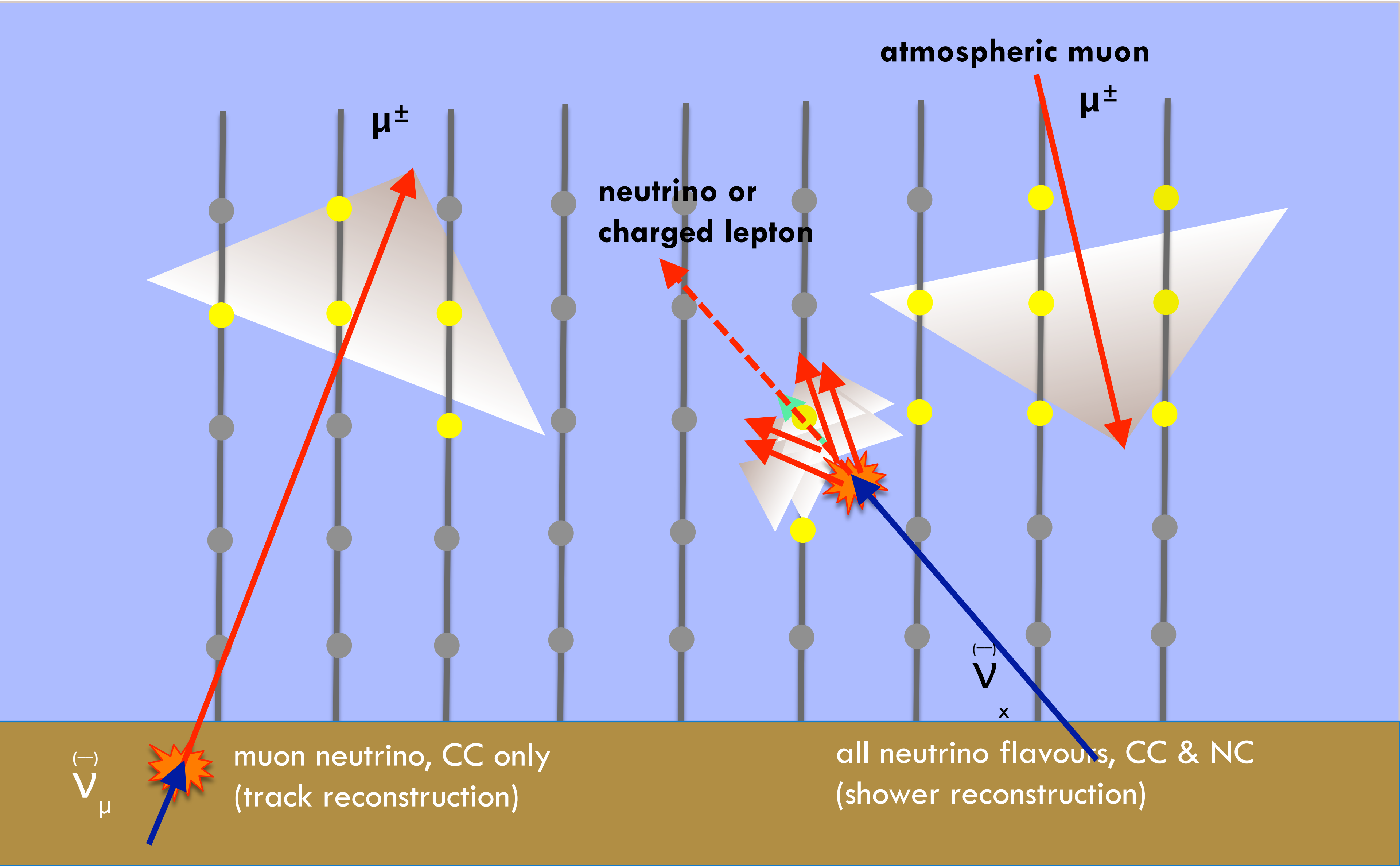
☺ produced only by hadronic mechanisms

☺ not affected by magnetic fields and radiation

☹ very low $\sigma_{interaction}$

… and Gravitational Waves too

Principles of high energy neutrino detection



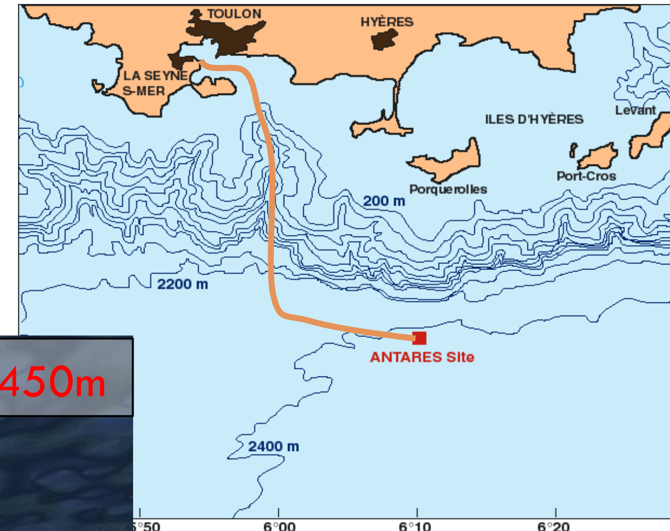
ANTARES

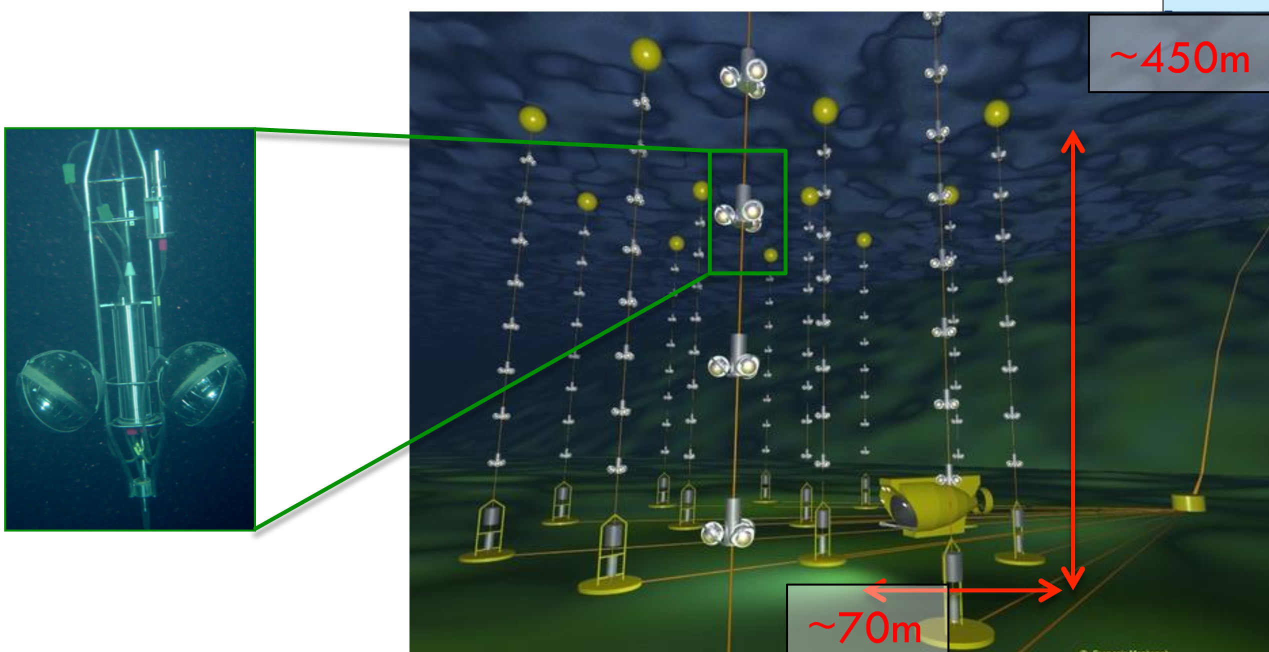
ANTARES birthday: February 14 2006 with installation of line 1

Detector installation completed in 2008

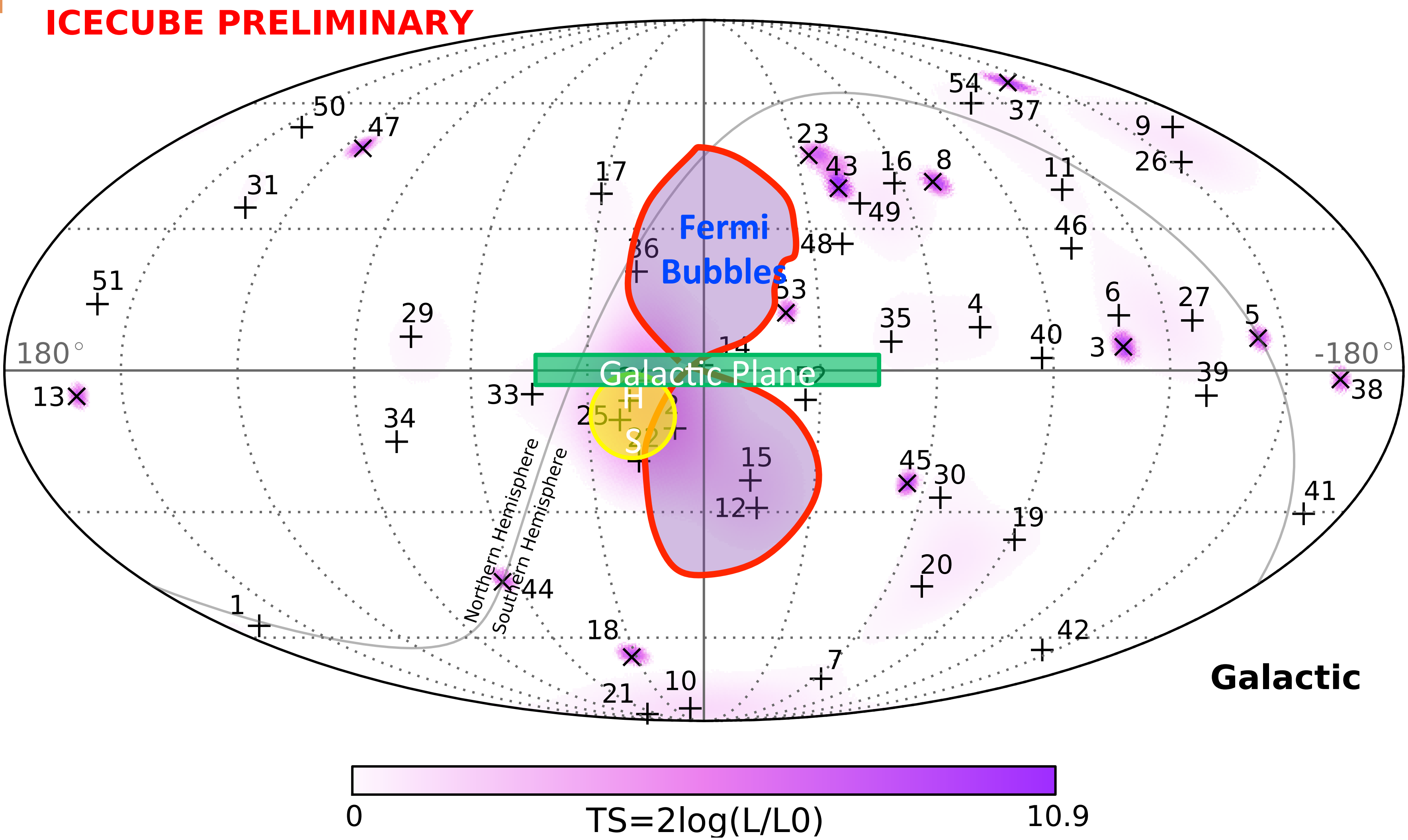
The ANTARES neutrino telescope

- 12 lines, ~70m spacing
- 25 storeys per line
- 3 x 10-inch PMTs per storey



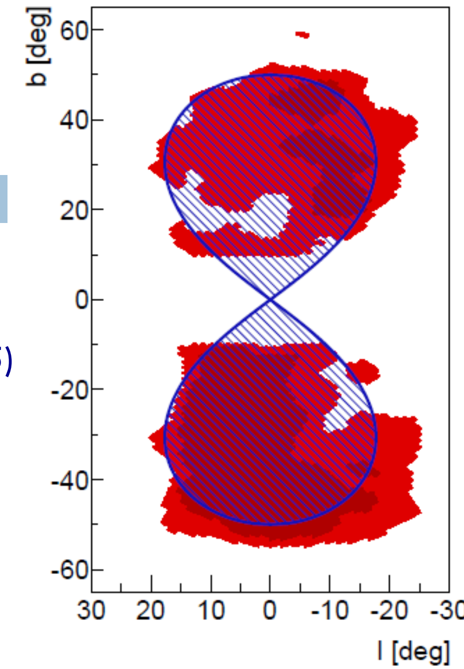


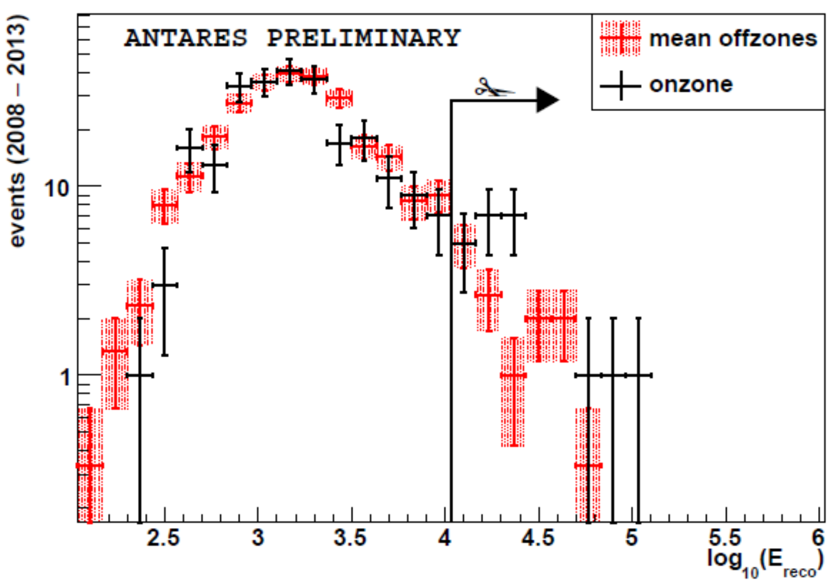
ANTARES and the IceCube signal

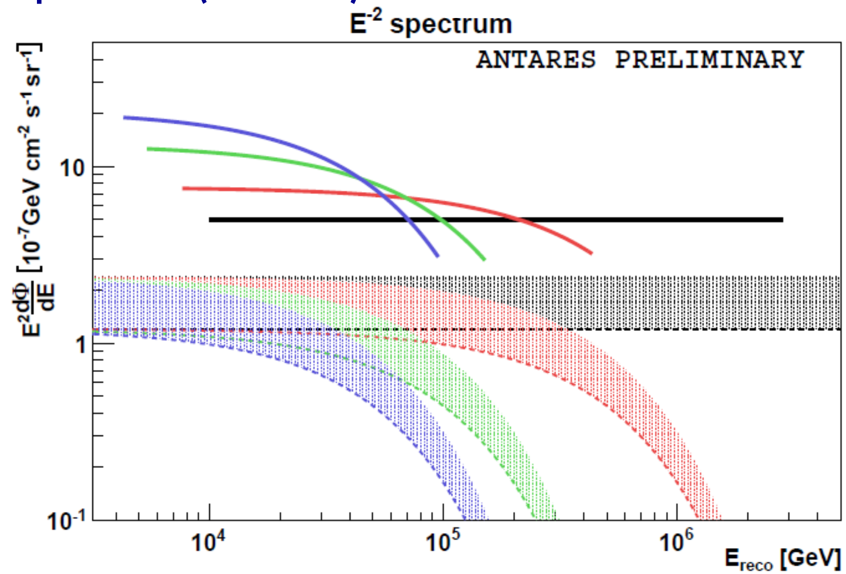


Fermi Bubbles

- Hadronic origin for the bubbles?
- E^{-2}, $E^{-2.18}$ spectra and different cutoff [Lunardini et al. PRD92 (2015) 2,021301]
- comparison on-zones/off-zones (3) of $\Delta\Omega$=0.66 sr
- 2008-2013 data analyzed (806+366 days).
- 22 events observed /13 background expected (1.9 σ)

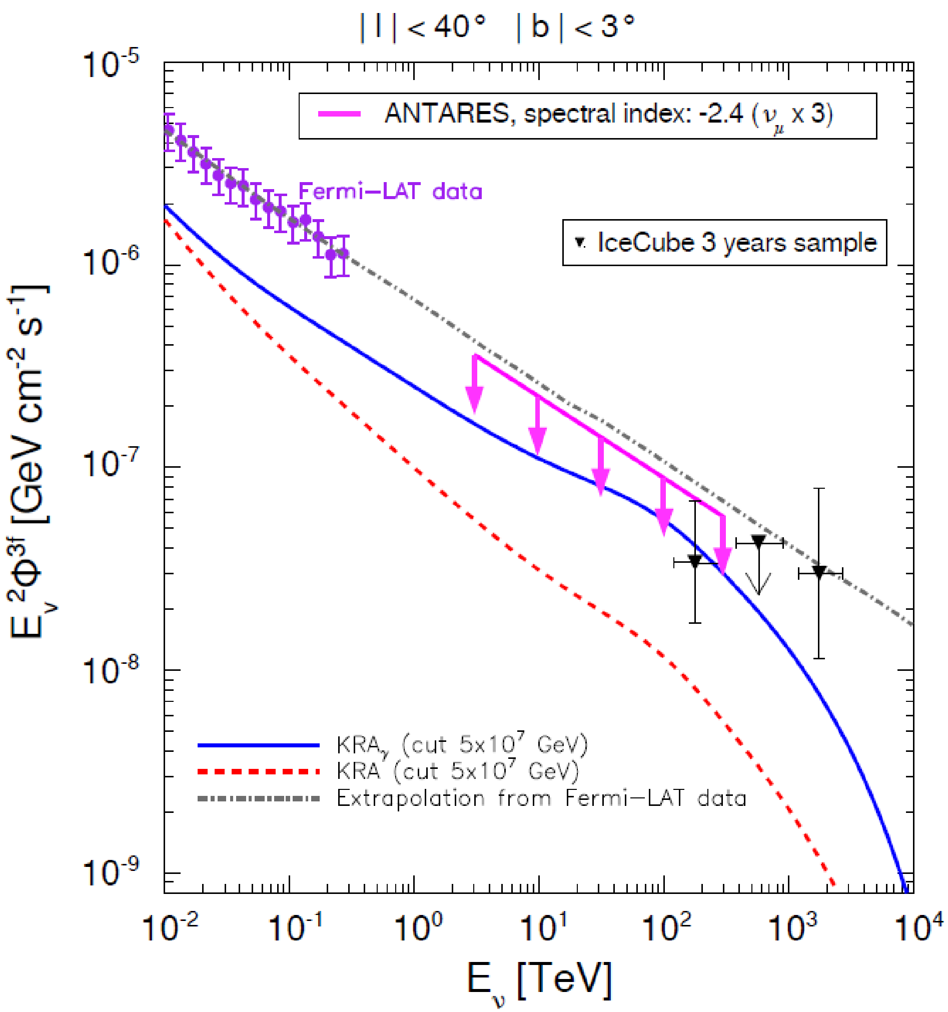






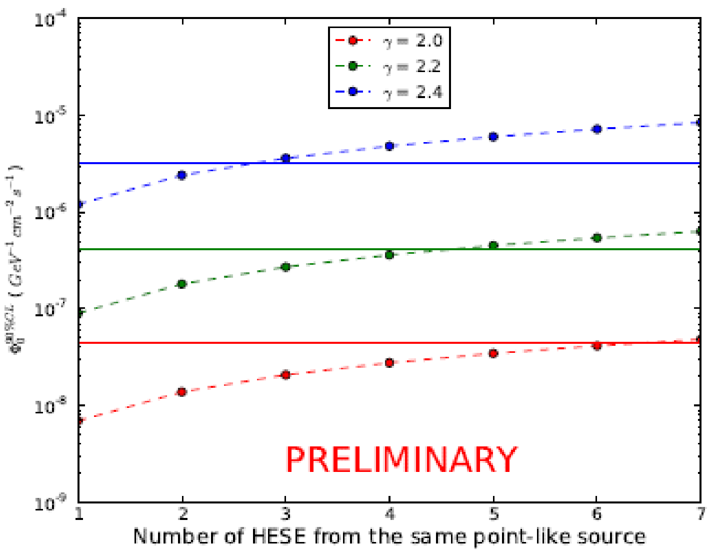
ANTARES: Galactic ridge

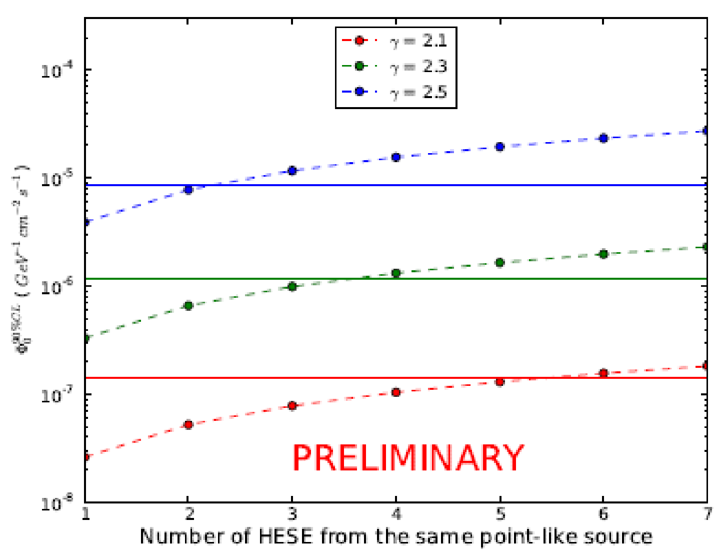
- arXiv:1602.03036
- Search for ν_μ from the Galactic ridge with 2008-2013 data
- Tracks (ν_μ) only
- No excess of events
- The extrapolation of the Fermi-LAT γ-rays to the IC neutrino ruled out
- Still consistent with more refined models
- Enough additional statistics (and ν_e) to test these models



IceCube Hot Spot: a single point-like source?

- Limits on a single point-like source in the Galactic center able to produce a given number of HESE
- Example: no source with $E^{-2.3}$ produces more than 3 HESE





Solid lines: 90%c.l. upper limits for source spectra
Dashed lines: flux required to produce a given expected number of HESE

Joint ANTARES IceCube search

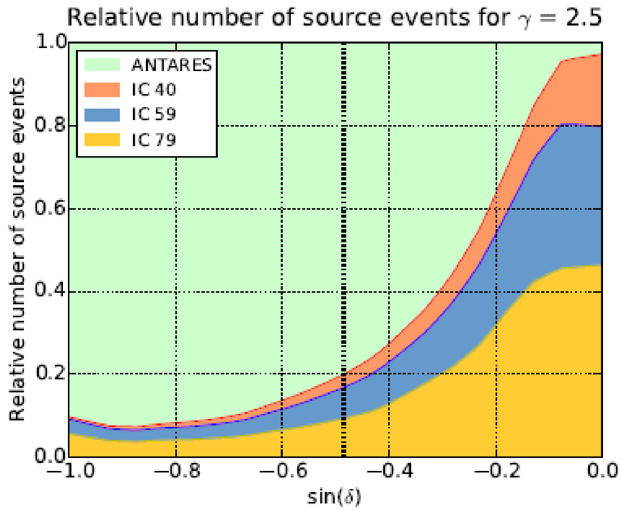
ANTARES data sample + IceCube (IC-40, IC-59, IC-79) data samples

1) Search for an excess over a background in the Southern Sky, for E^{-2} spectrum (unbinned)

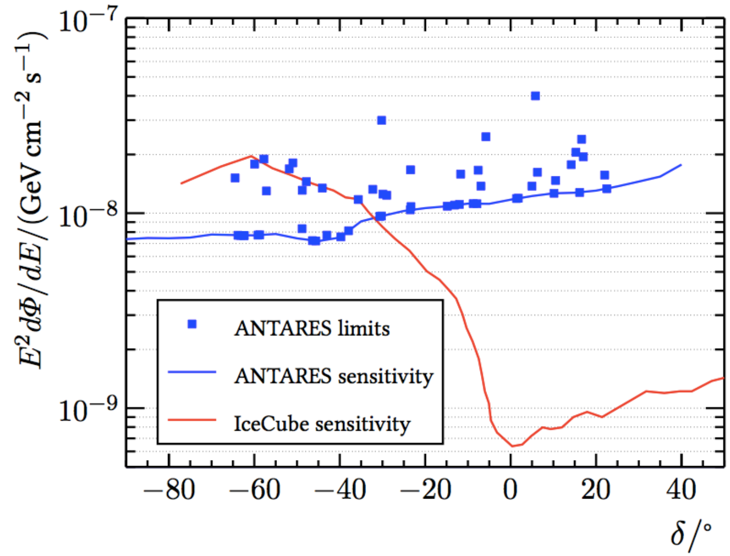
2) Search over a pre-selected list of candidate sources with : $\gamma = 2, 2.5$;
   energy cutoffs at 1 PeV, 300 TeV, 100 TeV

- ANTARES has better angular resolution (less scattering in seawater)
- IceCube has more events with better energy resolution (it's bigger!)
- Different declination dependencies – complementary regions

In print on ApJ

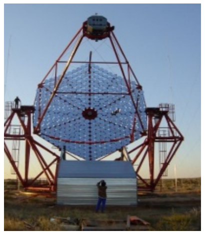


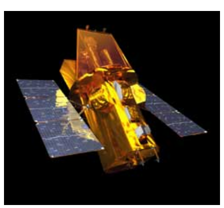
Relative fraction of signal events of each sample as a function of the source declination



90% CL limits for selected sources and sensitivities

Multimessenger searches





GeV-TeV γ -rays
Fermi / HESS…

📖 JCAP 03(2013) 006
📖 A&A 559 (2013) A9
📖 JCAP 05 (2014) 001

UHECR
Auger

📖 APJ 774 (2013) 19

HE neutrinos

Optic / X-ray
TAROT, ROTSE /
Swift, ZADKO

📖 APP 36 (2012) 204
📖 A&A 559 (2013) A9

Gravitational
Waves
Virgo / Ligo

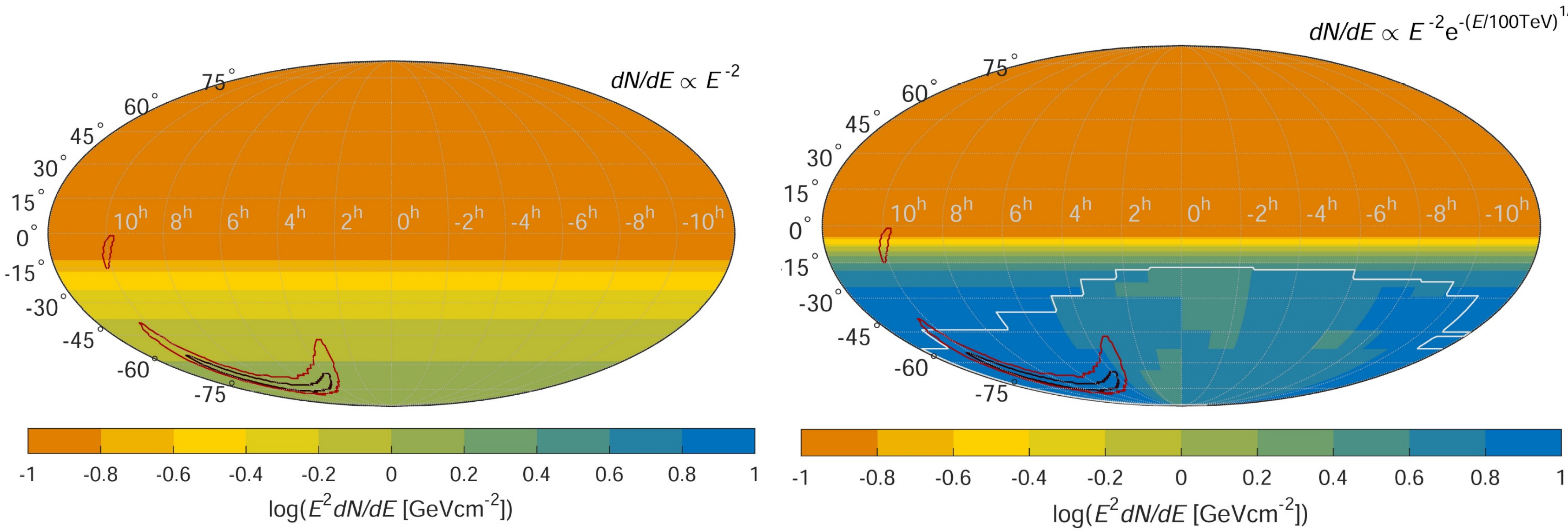
📖 JCAP 06 (2013) 008
📖 PRD 93 (2016)

Common sources for different messengers
Limits searches in time and space, low backgrounds
Uncorrelated backgrounds and systematics
Increased chances of detection

PHYSICAL REVIEW D **93**, 000000 (XXXX)

High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube

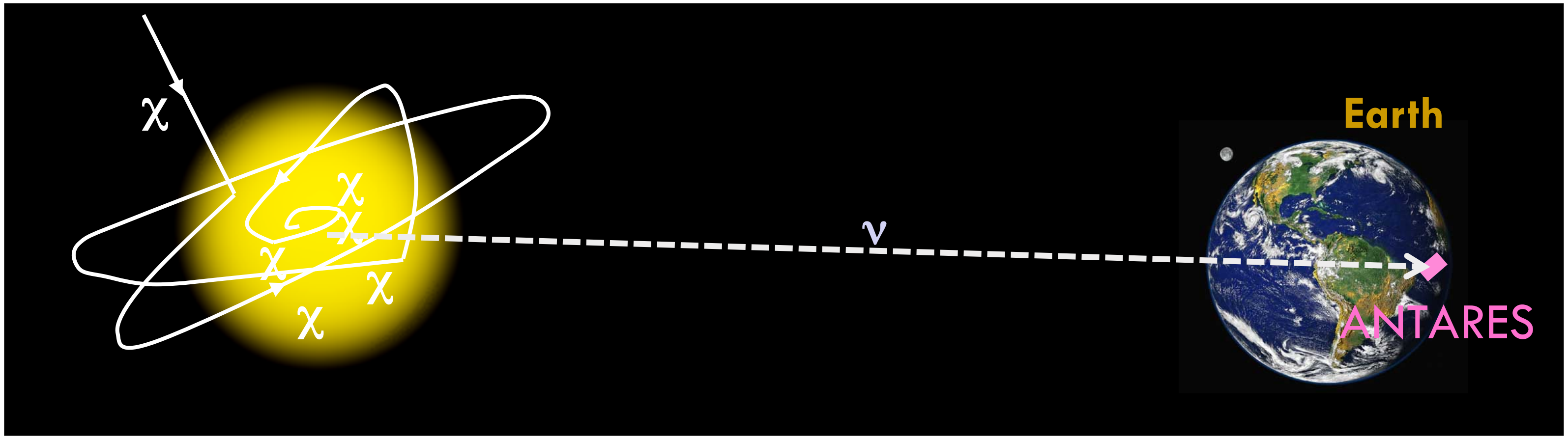
S. Adrián-Martínez *et al.*[*]
(The antares Collaboration, The IceCube Collaboration, LIGO Scientific Collaboration, and Virgo Collaboration)
(Received 21 February 2016)



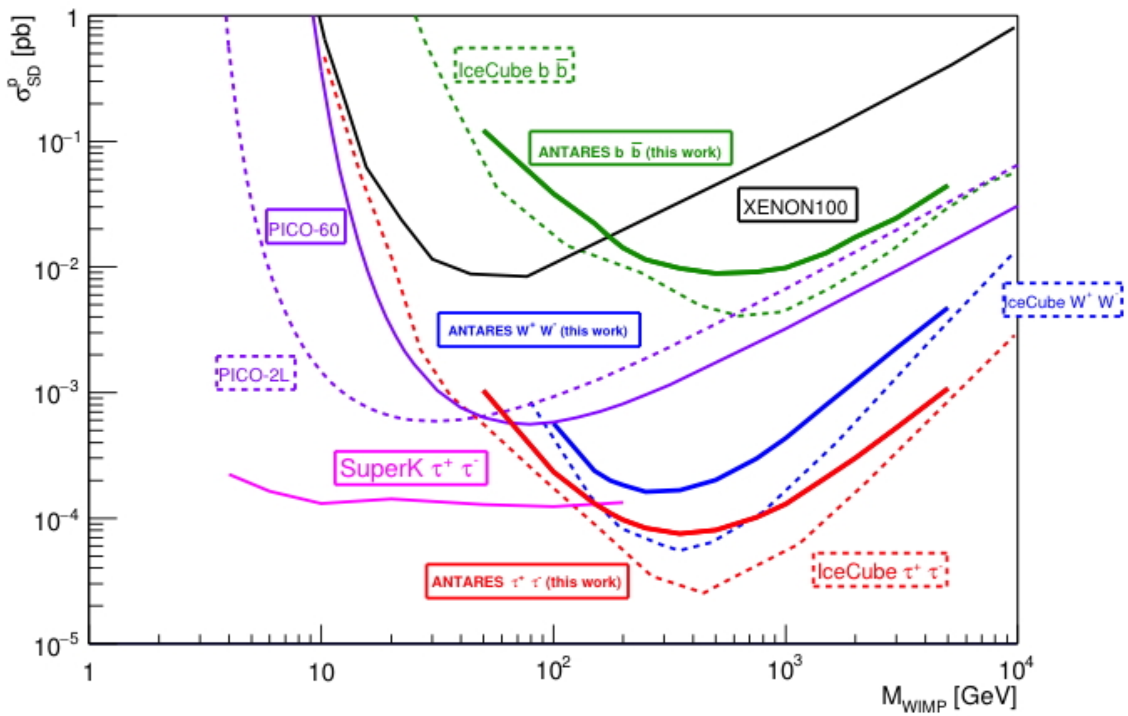
- Limits from ANTARES dominates below O(100 TeV) (white line)
- Size of GW150914: 590 deg^2 ANTARES resolution: <0.5 deg^2
- GW resolution much improved with LSC+Virgo; better localization for further follow-up
- Limits on total energy radiated in neutrinos: <10% GW
- In print on PRD
- Future: Receive / send alerts in real time

Indirect Dark Matter searches

Relic WIMPs gravitationally trapped via elastic collisions
(Sun, Earth, Galactic Center)

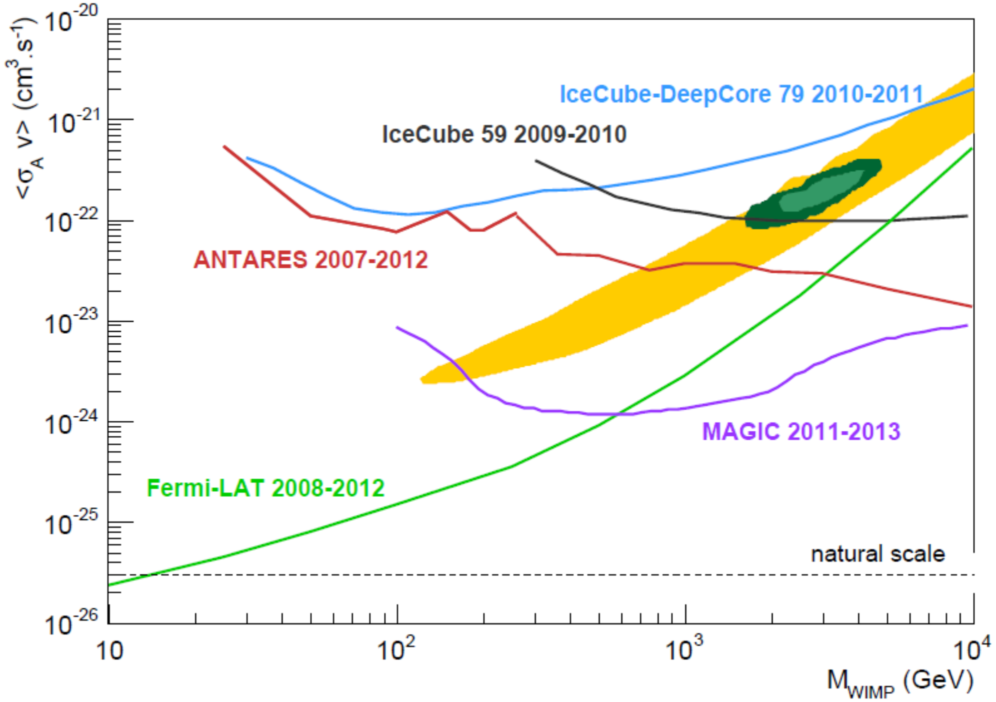


Dark Matter from The Sun



- Equilibrium between capture and annihilation rates inside the Sun assumed
- Much better sensitivity of ν-telescopes on SD cross-section w.r.t. direct detection (due to capture on H in the Sun).
- First ANTARES results in JCAP11 (2013) 032

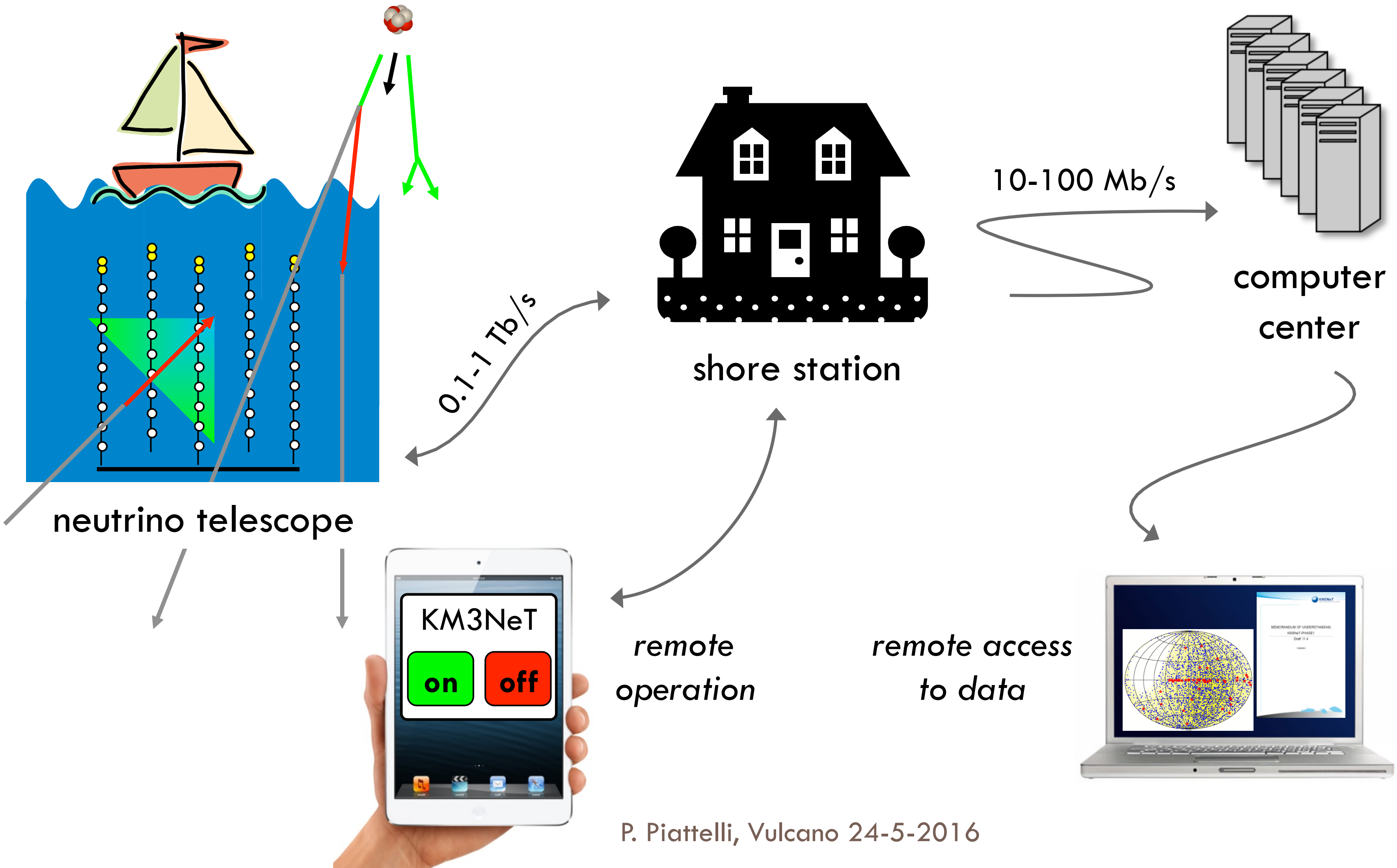
Dark Matter from Galactic Center



- HE νs from the direction of the Galactic Centre using 2007-2012 data
- Selection criteria chosen to maximize the sensitivity to possible self-annihilation of WIMPs accumulated in the GC
- Observed νs compatible with background.

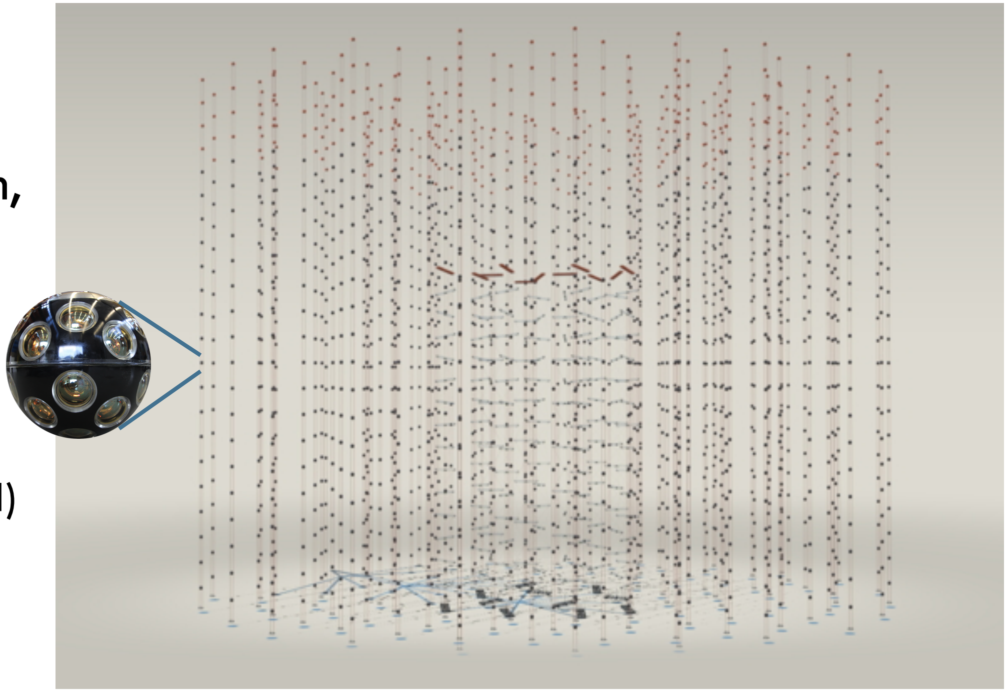
KM3NeT

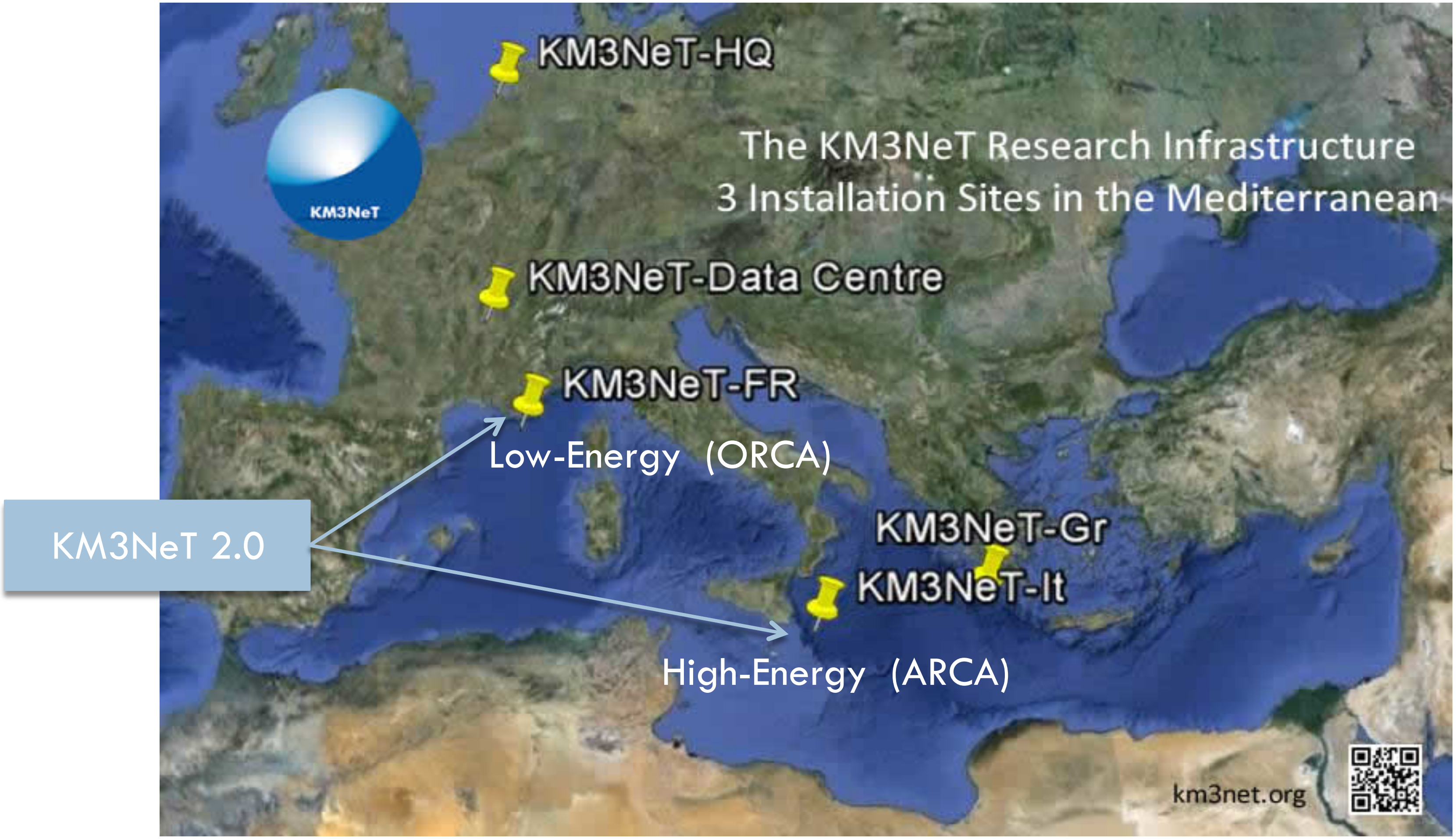
The KM3NeT architecture



The KM3NeT design

- Detection Unit (DU) – vertical slender string with multi-PMT Digital Optical Modules (DOMs)
- Power and data distributed by a single backbone cable with breakouts at DOMs
- Building blocks of 115 DUs each, allow for a distributed detector
- Multi-site infrastructure
  - High-energy neutrino astronomy at the KM3NeT-It site
  - Low-energy neutrino physics (NMH) at the KM3NeT-Fr site
- KM3NeT 2.0 selected by ESFRI for the next roadmap



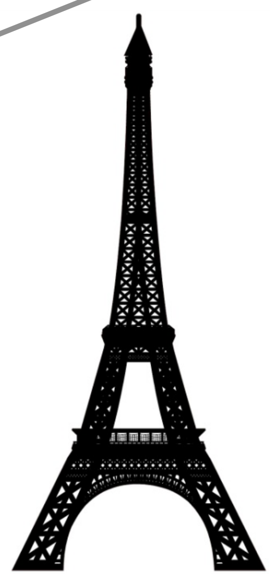

KM3NeT-HQ
KM3NeT
The KM3NeT Research Infrastructure
3 Installation Sites in the Mediterranean
KM3NeT-Data Centre
KM3NeT-FR
Low-Energy (ORCA)
KM3NeT 2.0
KM3NeT-Gr
KM3NeT-It
High-Energy (ARCA)
km3net.org

The Detection Unit

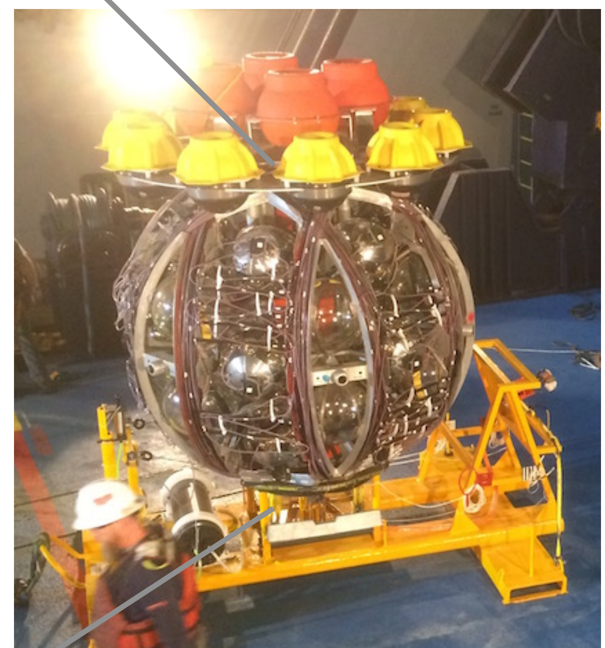
Optical module

17”

31 x 3” PMTs
PMT HV
LED & piezo inside
FPGA readout
White Rabbit
DWDM



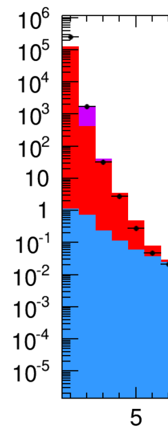
Launcher vehicle



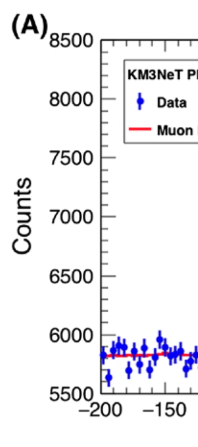
rapid deployment
autonomous unfurling
recoverable

Prototyping

Prototype DOM deployed at Antares



Prototype string (three DOMs) deploy



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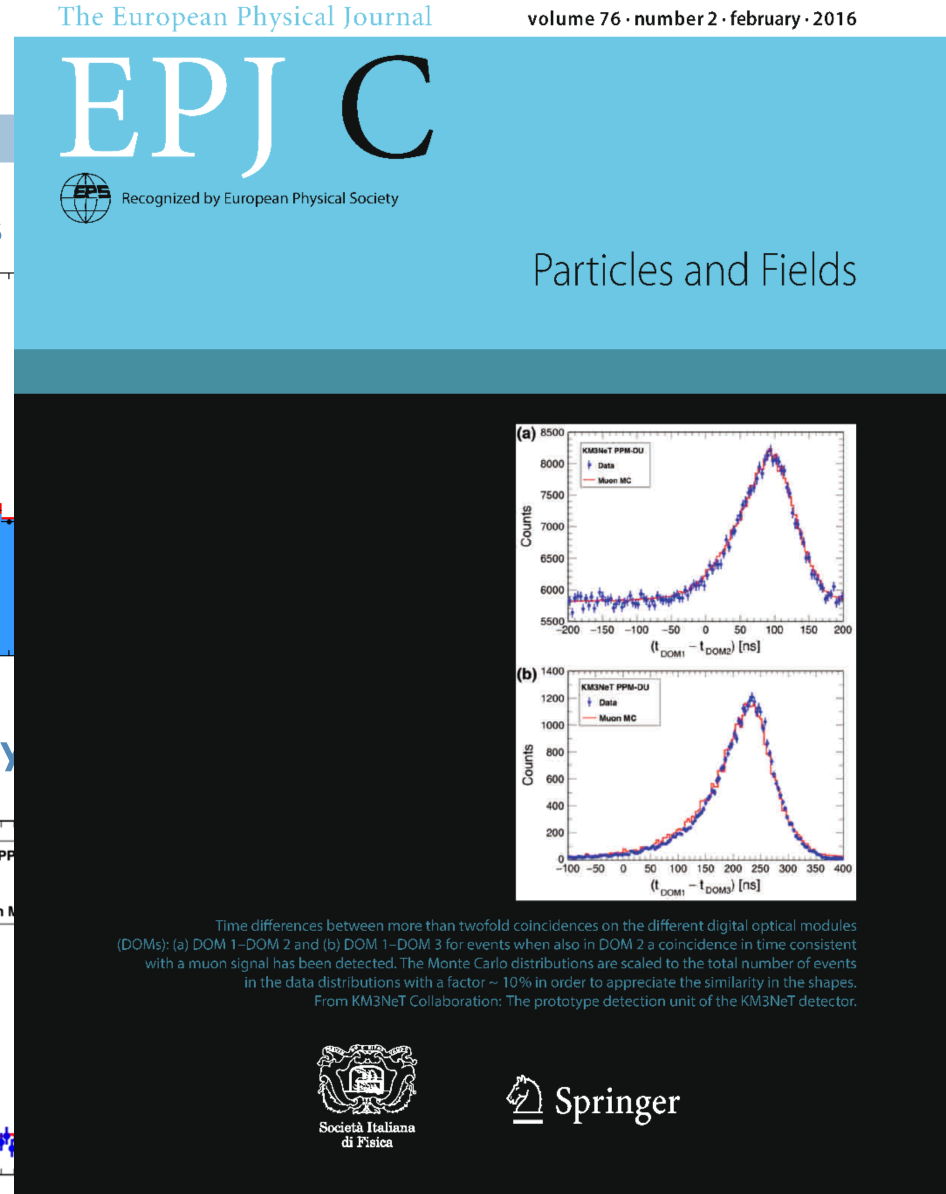


The KM3NeT/ARCA detector

ARCA: Astronomy Research with Cosmics in the Abyss

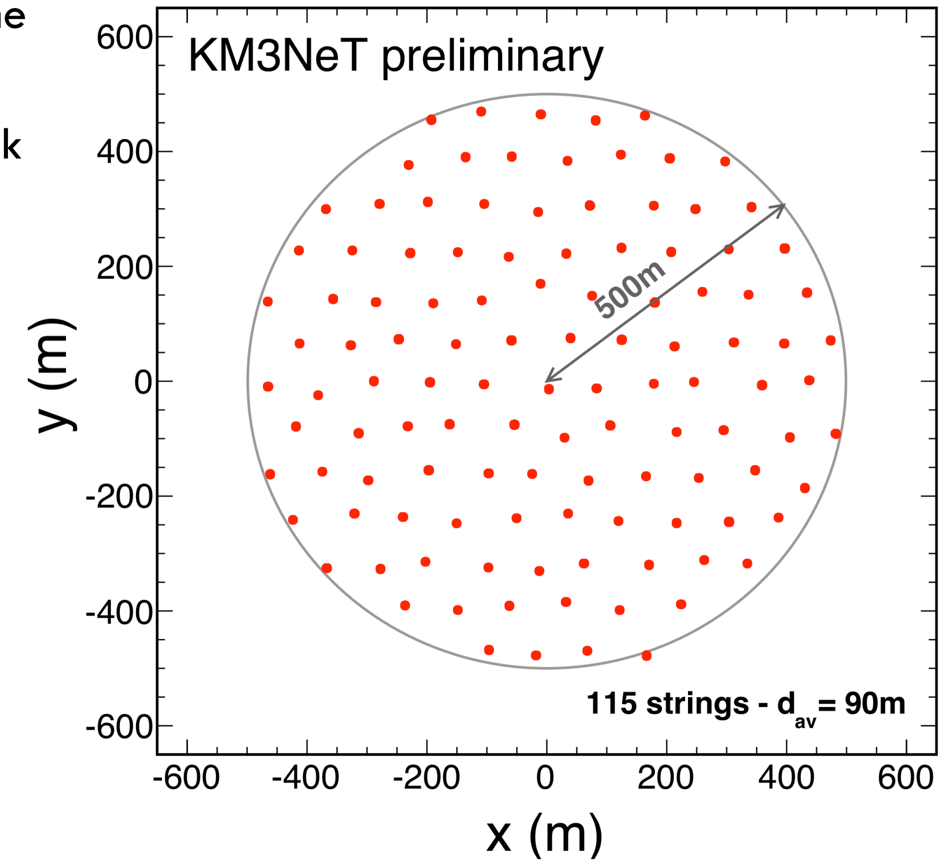
To be installed in the Italian site of the KM3NeT infrastructure

115 detection units per building block

18 DOM per DU

Vertical DOM spacing 36 m

Inter-DU spacing 90 m



The KM3NeT/ARCA detector

ARCA: Astronomy Research with Cosmics in the Abyss

To be installed in the Italian site of the KM3NeT infrastructure

115 detection units per building block

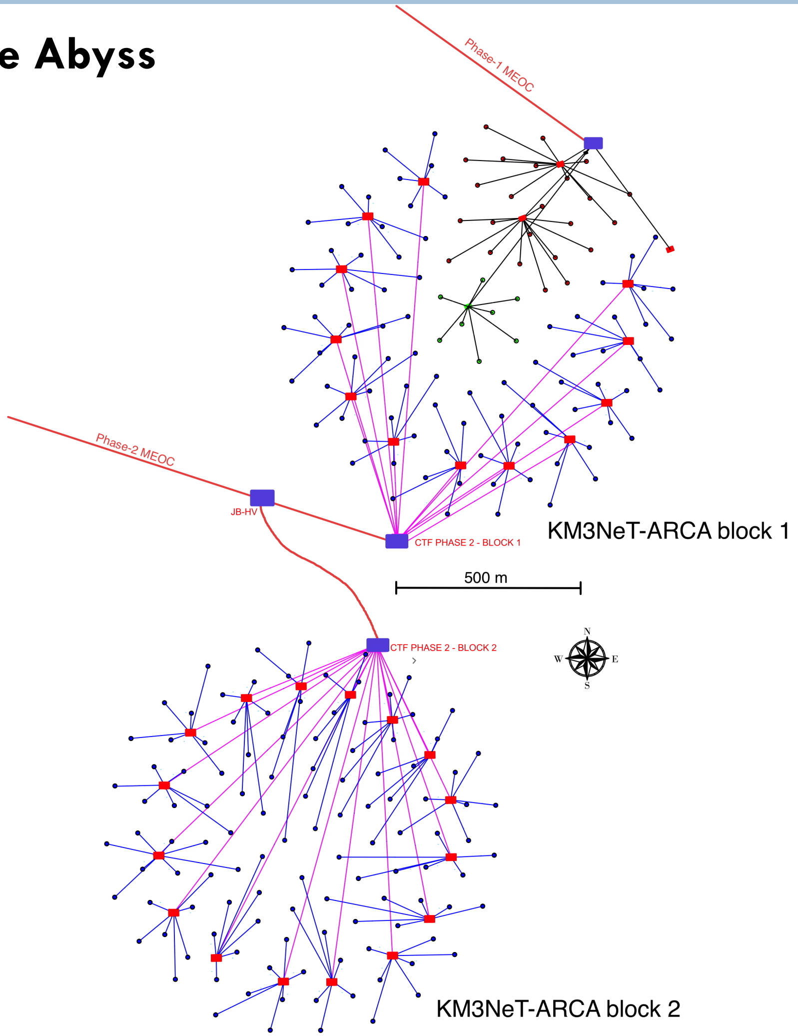
18 DOM per DU

Vertical DOM spacing 36 m

Inter-DU spacing 90 m

2 building blocks

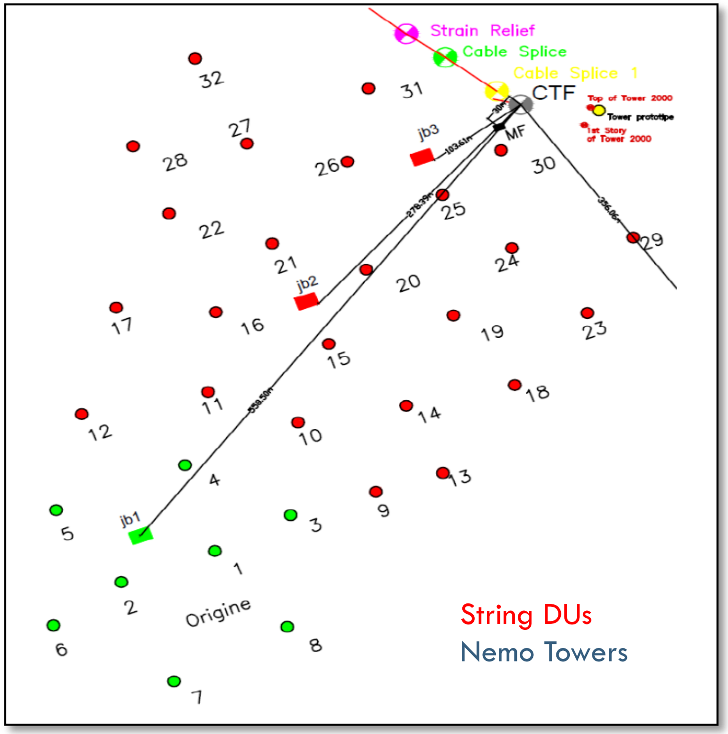
Total volume ≈1 km^3



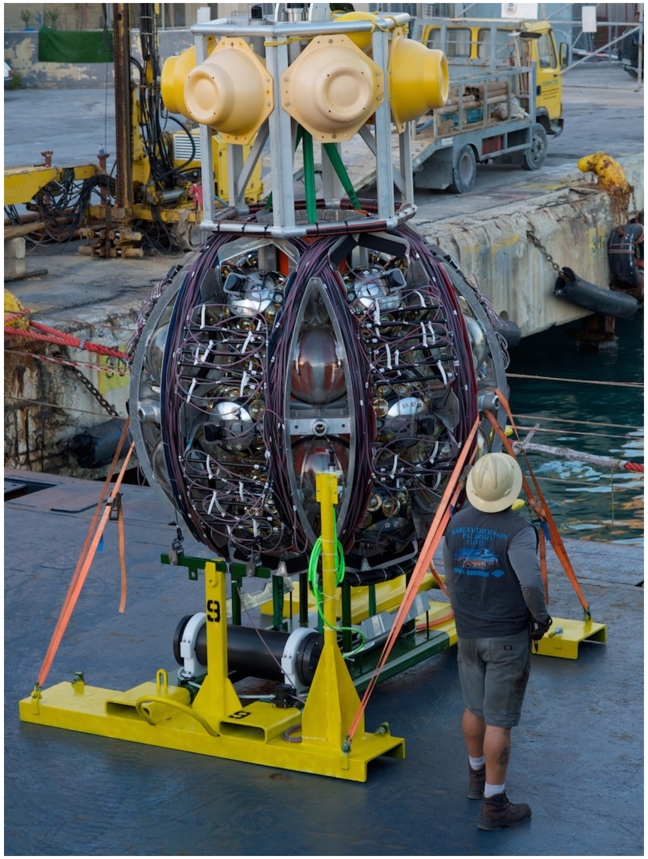
KM3NeT phase-1

Proof of feasibility of network of neutrino detectors:

- Started in January 2014
- Funded with 31 million Euro
- 31 detection units will be deployed in 2015-2017
- Sites:
  - ➢ KM3NeT-It off shore Capo Passero with 24 DUs,
  - ➢ KM3NeT-Fr off shore Toulon with 7 Dus
- 3 times improvement in sensitivity w.r.t. Antares



First "full" DU

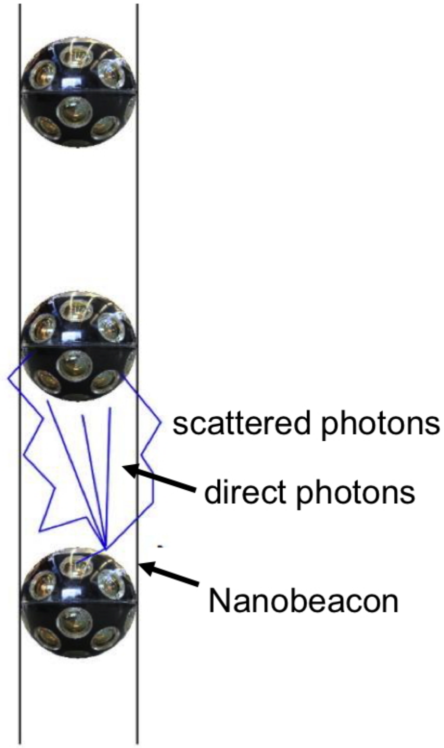


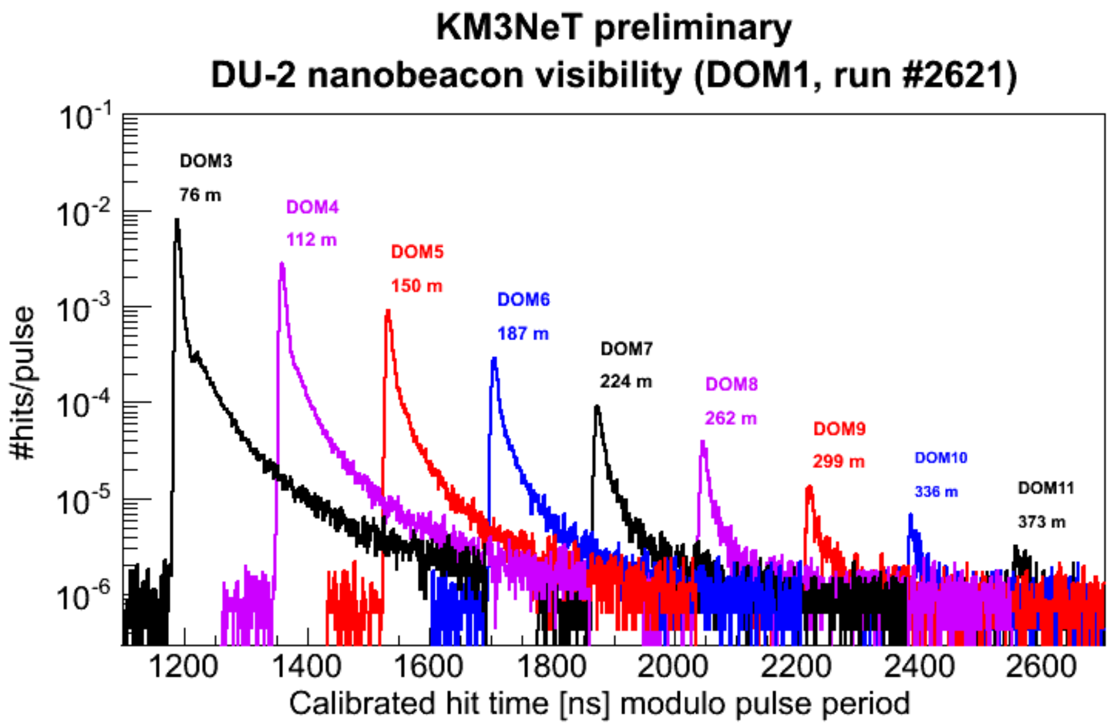
First full DU installed in Capo Passero in December 2015

Functional and operating since then

First DU preliminary results

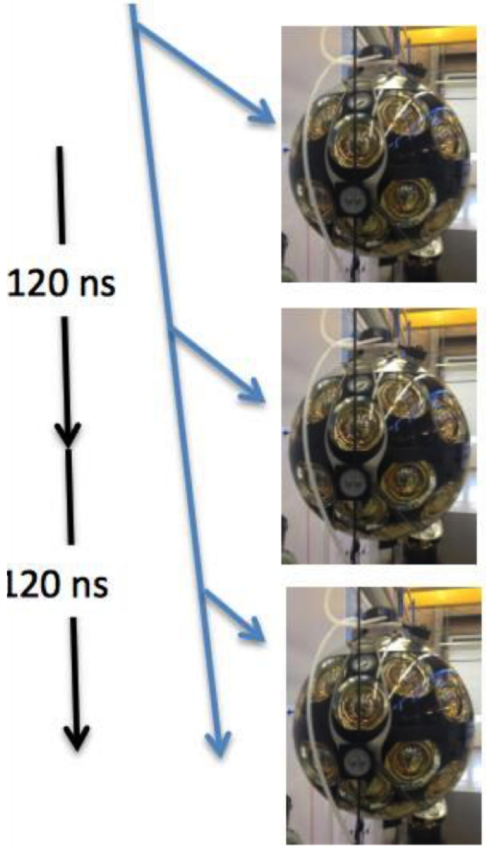
Inter-DOM time calibration with LED nanobeacons

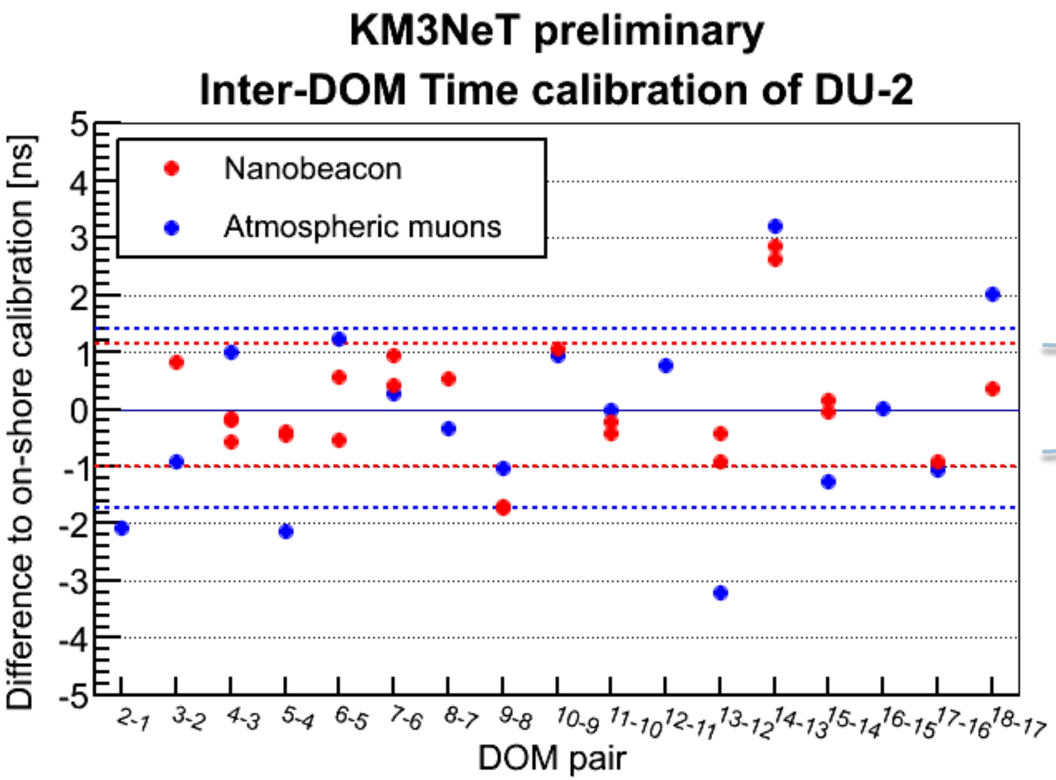




First DU preliminary results

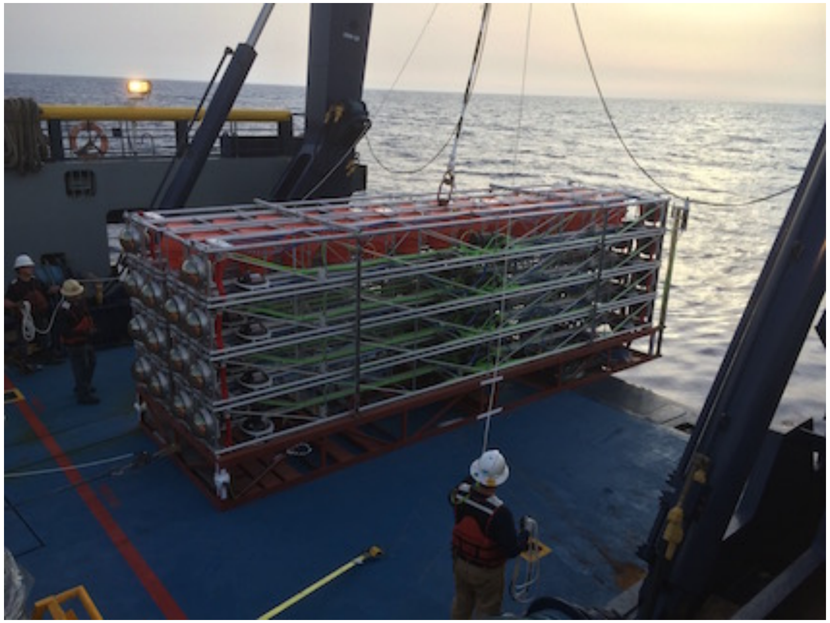
Comparison of calibration with LED nanobeacons and atmospheric muons to the on-shore laser calibration





In situ nanobeacon calibration and on.shore laser calibration agree to ≈1 ns

Growing up



- 2 more DUs installed in May 2016
- One tower installed in the same operation

The KM3NeT 2.0 Letter of Intent

arXiv.org > astro-ph > arXiv:1601.07459

Search or Article-id (Help | Advanced search) All papers Go!

Astrophysics > Instrumentation and Methods for Astrophysics

Letter of Intent for KM3NeT2.0

S. Adrián-Martínez, M. Ageron, F. Aharonian, S. Aiello, A. Albert, F. Ameli, E. Anassontzis, M. Andre, G. Androulakis, M. Anghinolfi, G. Anton, M. Ardid, T. Avgitas, G. Barbarino, E. Barbarito, B. Baret, J. Barrios-Martí, B. Belhorma, A. Belias, E. Berbee, A. van den Berg, V. Bertin, S. Beurthey, V. van Beveren, N. Beverini, S. Biagi, A. Biagioni, M. Billault, R. Bormuth, B. Bouhadef, G. Bourlis, S. Bourret, C. Boutonnet, M. Bouwhuis, C. Bozza, R. Bruijn, J. Brunner, E. Buis, J. Busto, G. Cacopardo, L. Caillat, M. Calamai, D. Calvo, A. Capone, L. Caramete, S. Cecchini, S. Celli, C. Champion, R. Cherkaoui El Moursli, S. Cherubini, T. Chiarusi, M. Circella, L. Classen, R. Cocimano, J. A. B. Coelho, A. Coleiro, S. Colonges, R. Coniglione, M. Cordelli, A. Cosquer, P. Coyle, A. Creusot, et al. (182 additional authors not shown)

(Submitted on 27 Jan 2016)

The main objectives of the KM3NeT Collaboration are i) the discovery and subsequent observation of high-energy neutrino sources in the Universe and ii) the determination of the mass hierarchy of neutrinos. These objectives are strongly motivated by two recent important discoveries, namely: 1) The high-energy astrophysical neutrino signal reported by IceCube and 2) the sizable contribution of electron neutrinos to the third neutrino mass eigenstate as reported by Daya Bay, Reno and others. To meet these objectives, the KM3NeT Collaboration plans to build a new Research Infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community. Three suitable deep-sea sites are identified, namely off-shore Toulon (France), Capo Passero (Italy) and Pylos (Greece). The infrastructure will consist of three so-called building blocks. A building block comprises 115 strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes. Each building block thus constitutes a 3-dimensional array of photo sensors that can be used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. Two building blocks will be configured to fully explore the IceCube signal with different methodology, improved resolution and complementary field of view, including the Galactic plane. One building block will be configured to precisely measure atmospheric neutrino oscillations.

Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; High Energy Astrophysical Phenomena (astro-ph.HE); High Energy Physics - Experiment (hep-ex); Instrumentation and Detectors (physics.ins-det)

Cite as: arXiv:1601.07459 [astro-ph.IM]
(or arXiv:1601.07459v1 [astro-ph.IM] for this version)

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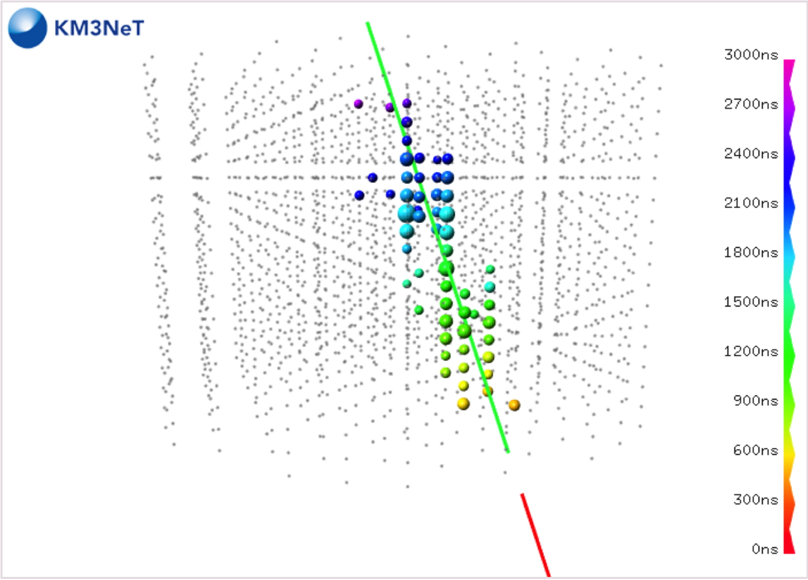
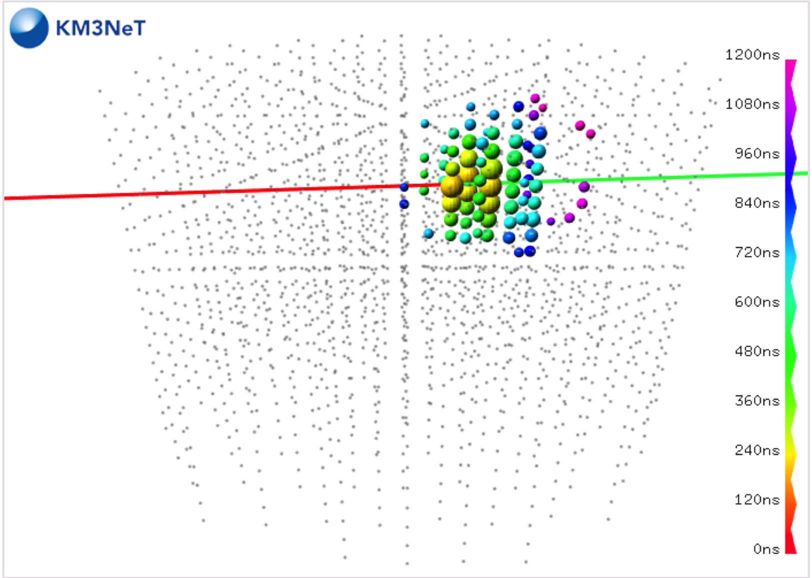
Accepted for publication on Journal of Phys. G

ARCA: event topologies



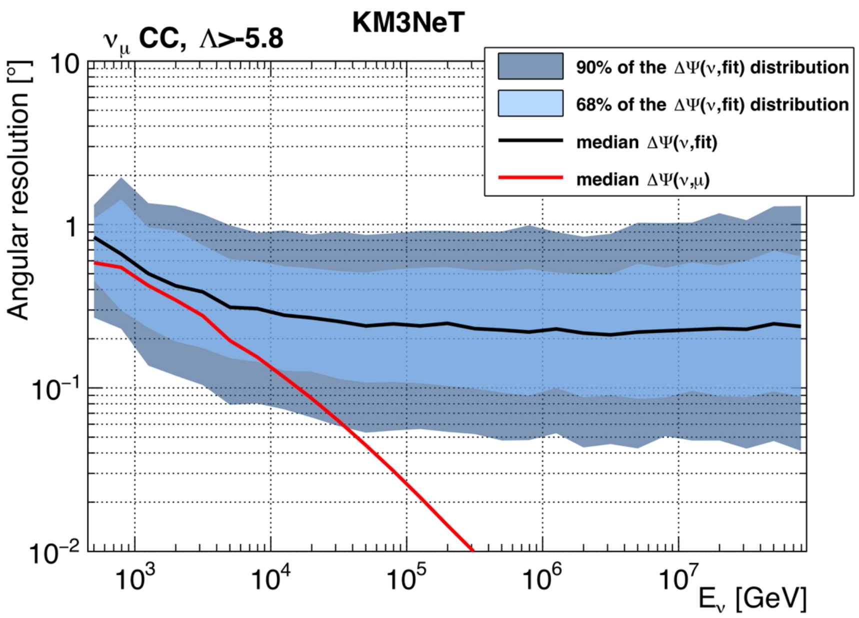
Upgoing ν_μ CC event – “track like”

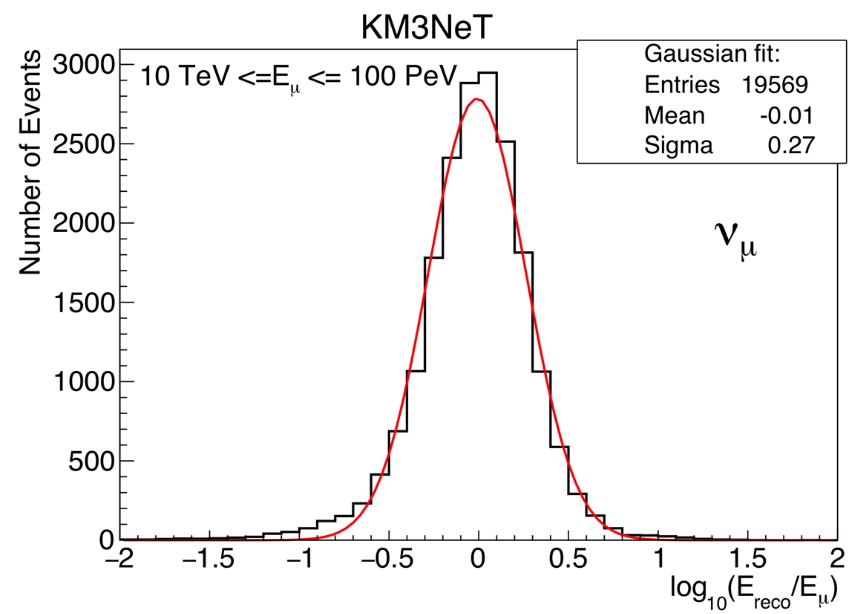


Contained ν_μ NC event – “shower”

ARCA: resolution for track reconstruction

After cuts optimized for track reconstruction



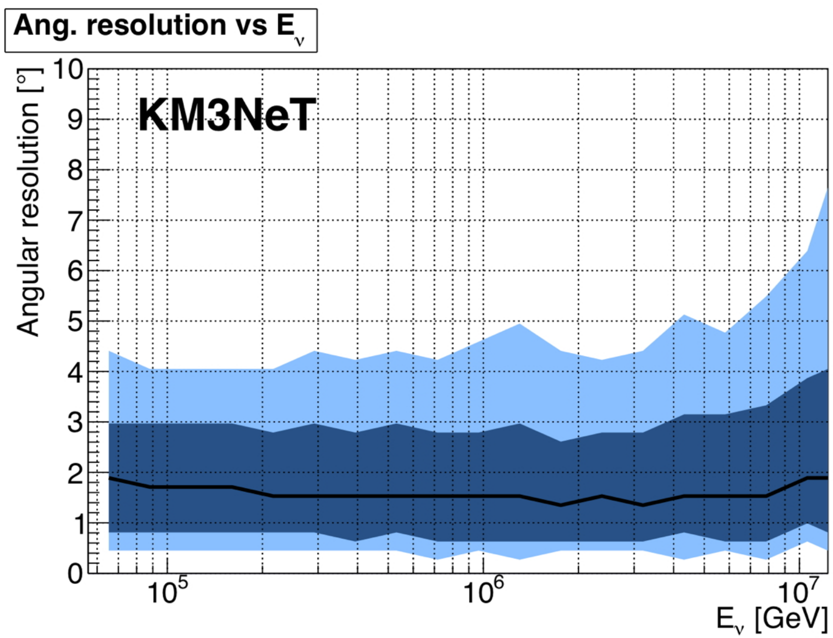


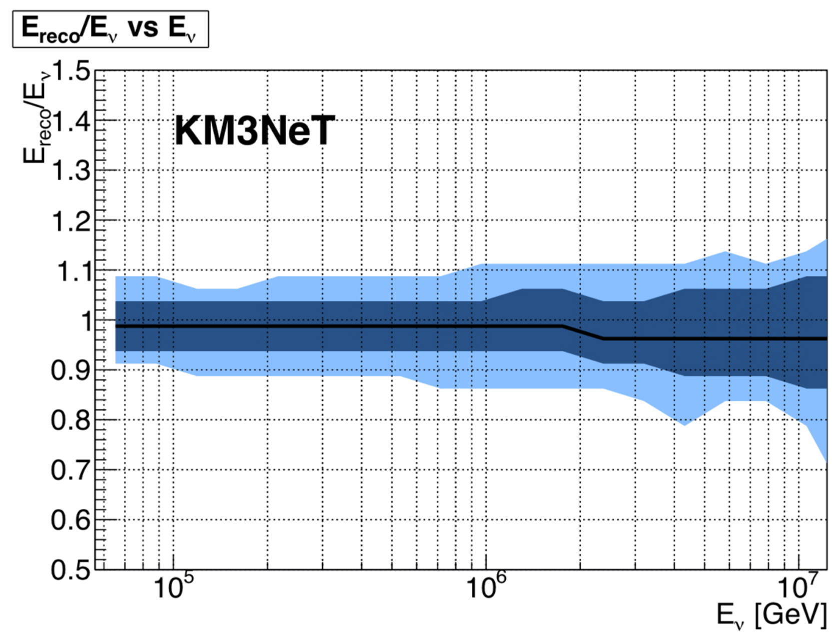
Angular resolution
about 0.2° (E_ν>10 TeV)

Energy resolution
0.27 in $\log E_\mu$
(1 TeV < E_ν < 100 PeV)

ARCA: resolution for cascade events

Angular and energy resolution for the event sample after the final cuts of the diffuse cascade analysis





Angular resolution about 2°

Energy resolution < 10%

ARCA: main physics goals

- Diffuse high-energy neutrino fluxes
  - Benchmark: the IceCube flux (assumed isotropic, flavour symmetric)

$$\Phi(E) = 1.2 \cdot 10^{-8} \left(E/1\ \mathrm{GeV}\right)^{-2} \exp\left(-E/3\ \mathrm{PeV}\right)\ \ \mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

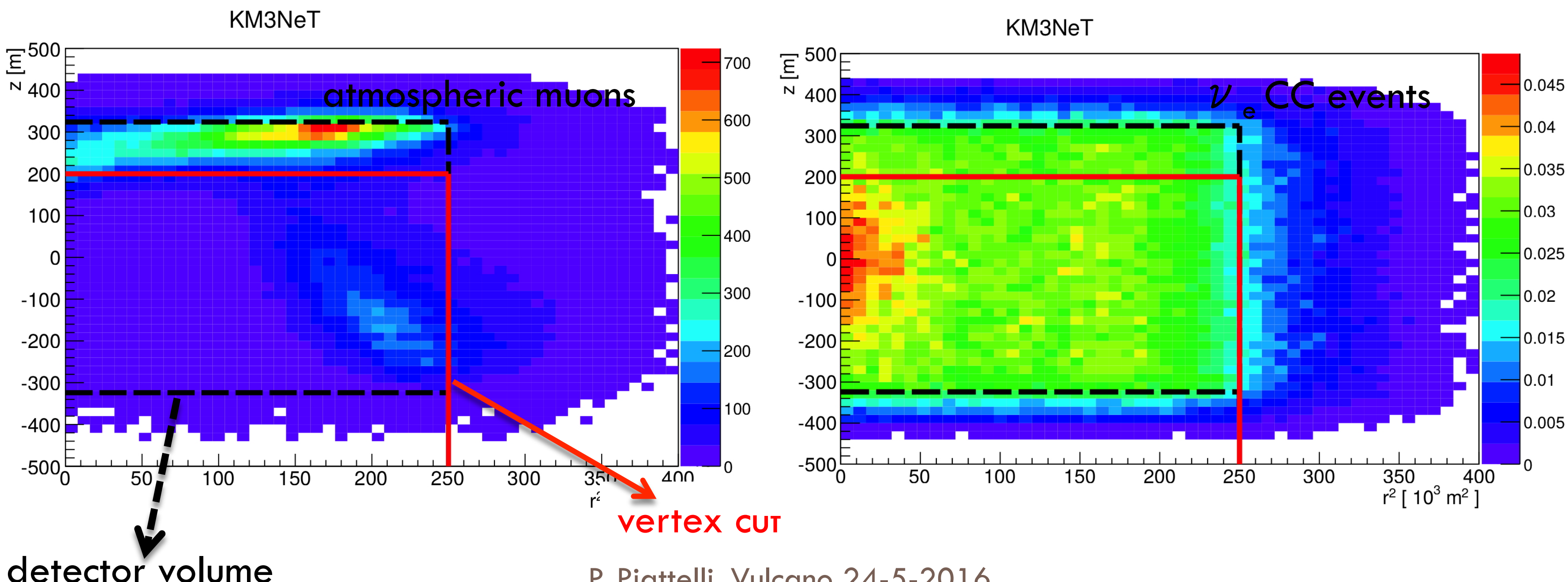
M.G. Aartsen et al., Science 342 (2013) 1242856

- Neutrino point-like sources
  - Benchmark: intense galactic TeV gamma sources

Diffuse flux: cascade event selection

All neutrino flavour MC simulation and 3 years of live time for high energy atmospheric muons

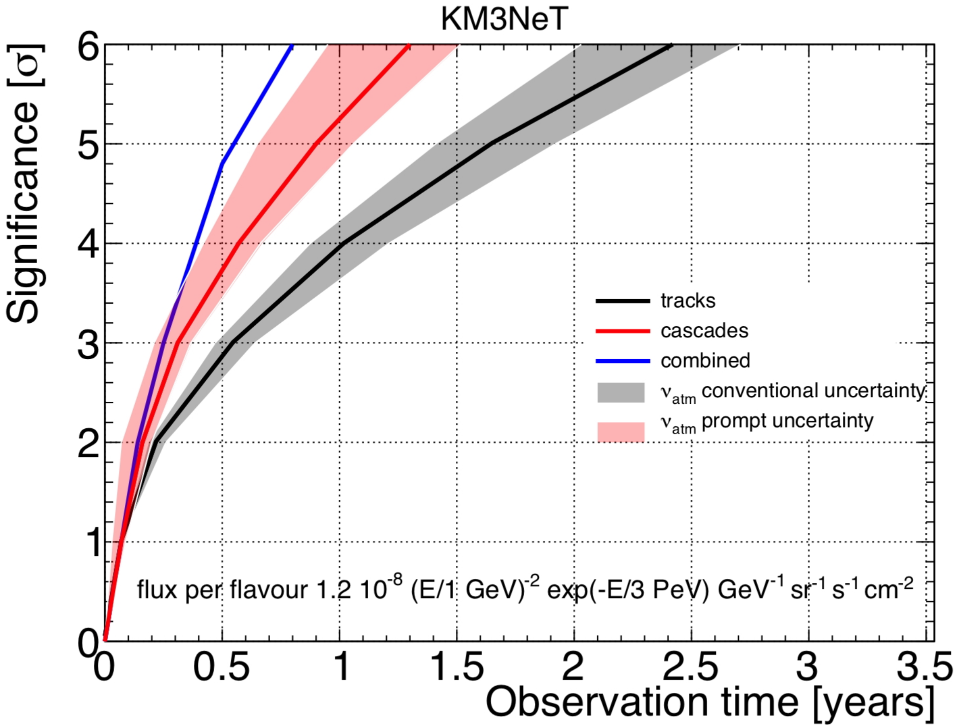
- Event pre-selection: reject most of the atmospheric muons on the reconstructed cascade vertex
  - **Online triggering:** ≥ 5 coincidences between PMTs in the same OM in Δt=10ns
  - **Vertex cut:** cut on the position of the reconstructed vertex to get rid of atmospheric muons (z<200m AND r<500m)
  - **Energy cut:** cut on the total ToT of the event (ToT>12 μs)
- Full sky analysis based on BDT and Max. likelihood.



ARCA sensitivity to neutrino diffuse flux

Analysis for the track events:

- **Track channel:** analysis for up-going events based on Max. likelihood
  Pre-Cuts on θ_{zen} >80°, Λ (reconstruction quality parameter), N_{hit} (number of hits -> parameter related to the muon energy)

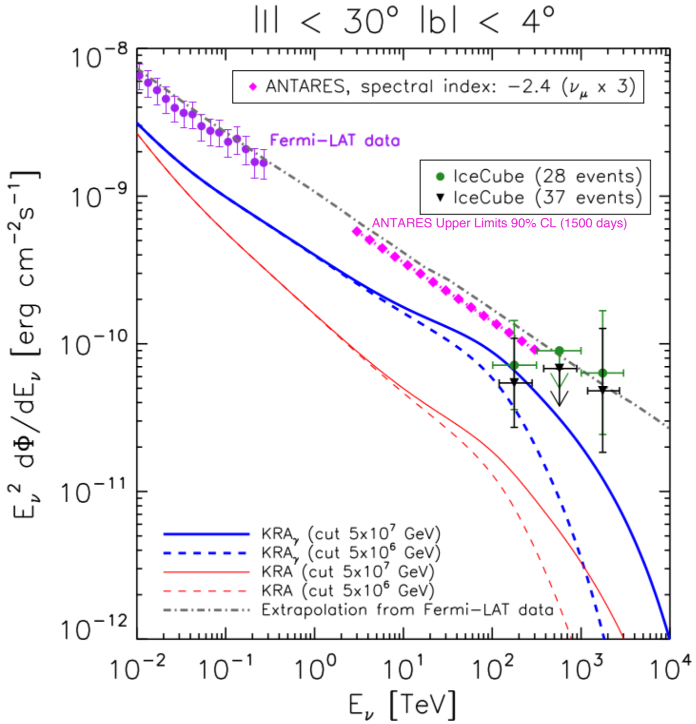


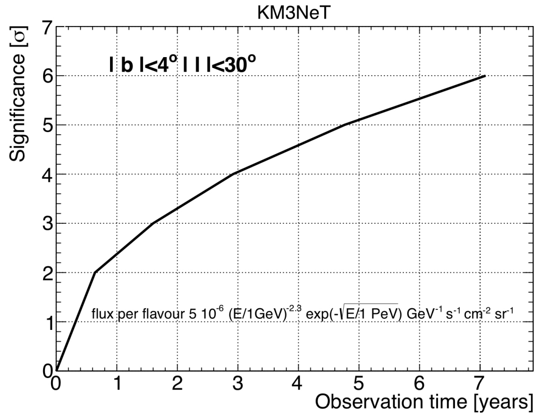
Discovery at 5σ significance (50% probability) in less than one year

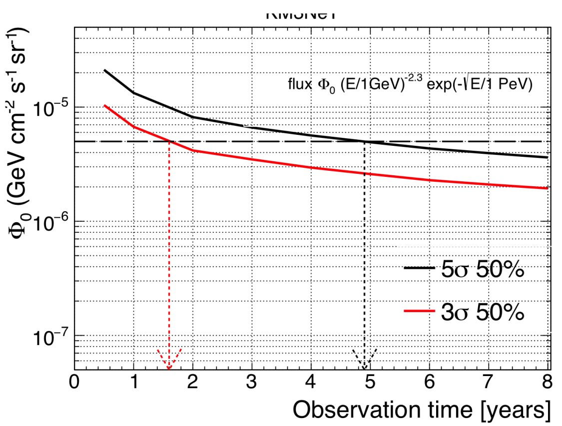
Diffuse flux from the galactic plane

ARCA performance to a flux from a region of the Galactic Plane near the Galactic Center
Evaluation of the neutrino flux based on a radially-dependent cosmic-ray transport properties

D. Gaggero et al., proceedings ICRC2015







Discovery at 5σ significance (50% probability) in about 5 years

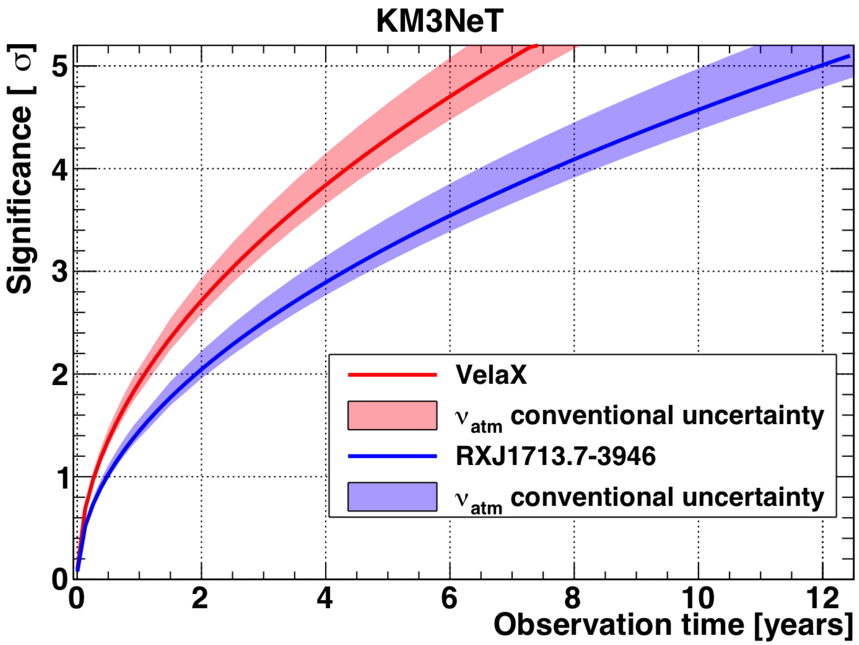
Galactic sources with ARCA

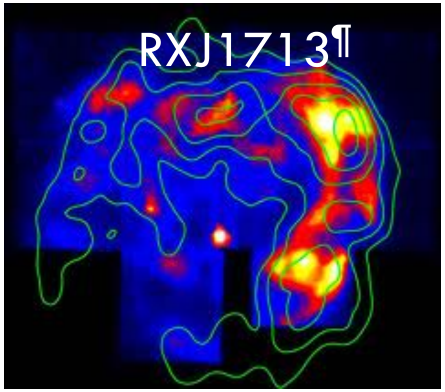
HE gamma emission observed by HESS in SNRs
Neutrino spectra predicted using gamma spectra

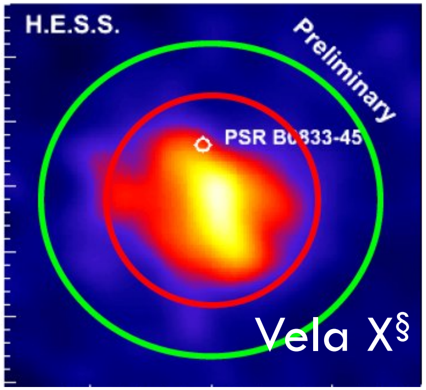
¶ S.R. Kelner, *et al.*, PRD 74 (2006) 034018

§ F.L. Villante and F. Vissani, PRD 78 (2008) 103007

Hypotheses: 100% hadronic emission and transparent source



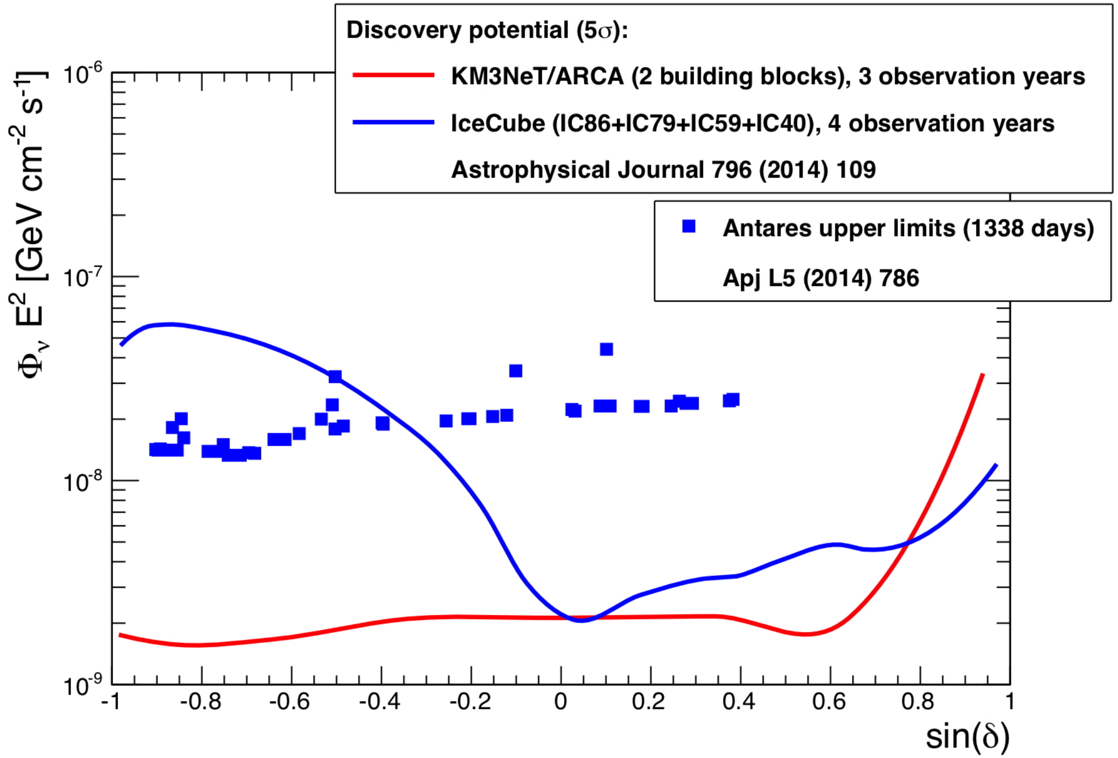




Vela X: 3σ in about 2 years
RXJ1713: 3σ in about 4 years

E^{-2} sources spectra

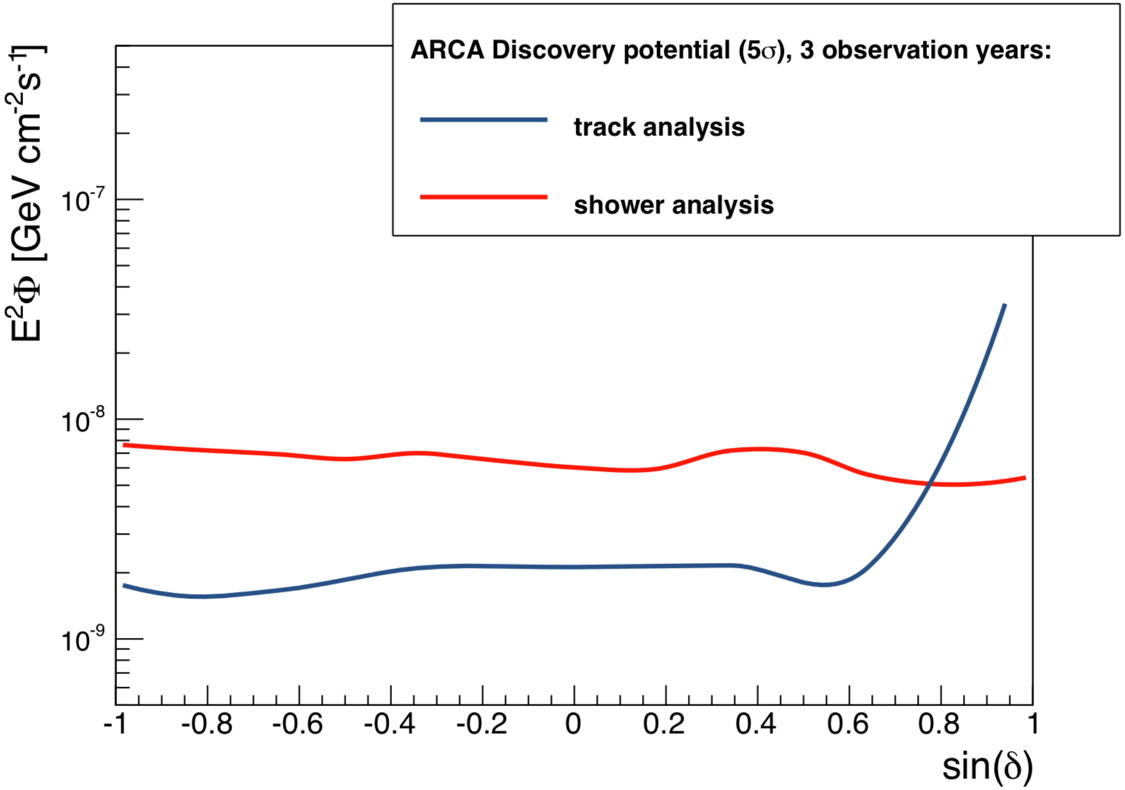
ARCA discovery potential for E^{-2} sources



Better sensitivity (for equivalent exposure) and better sky coverage than IceCube

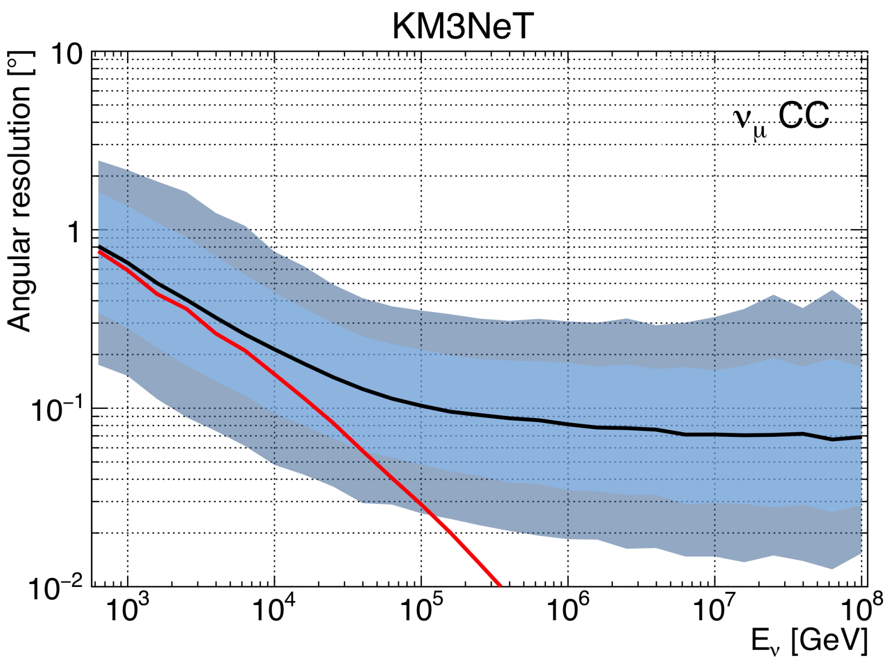
Shower and track analyses

ARCA discovery potential for E^{-2} sources for shower and track analyses



Improvements

Expectd improvements in point-like source analysis



New reconstruction algorithm developed

Not yet included in the analyses shown

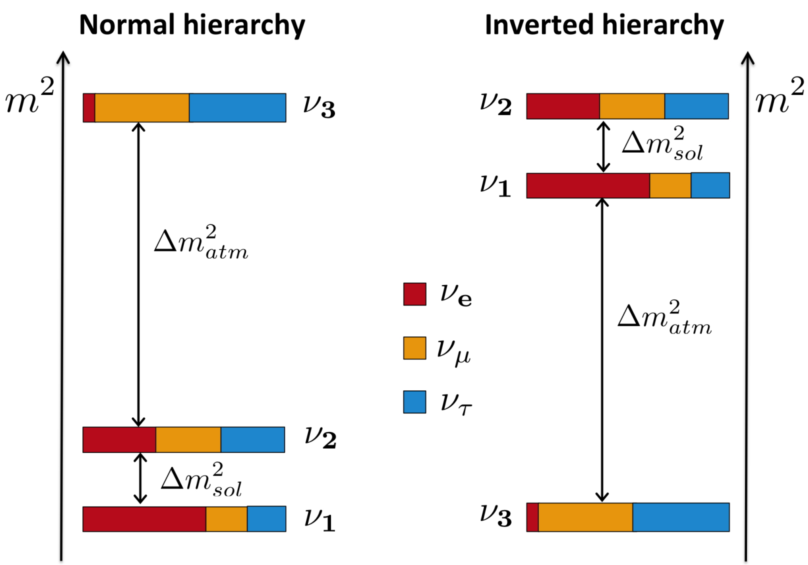
Angular resolution
better than 0.1° (E_ν>100 TeV)

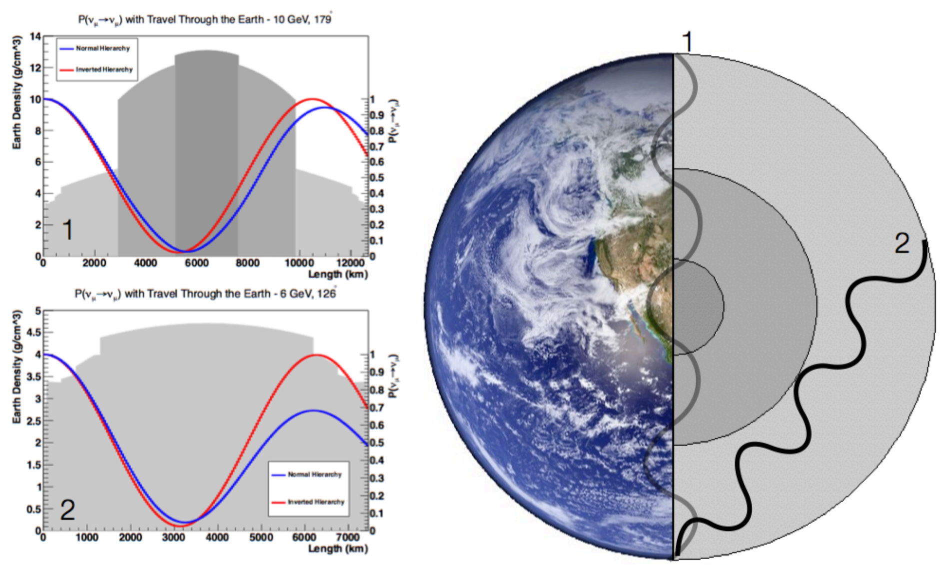
Measuring NMH with atmospheric neutrinos in the deep sea

Measurement of the Mass Hierarchy with atmospheric neutrinos passing through Earth in a deep sea Cherenkov detector at GeV energy

Oscillation signal enhanced at resonance energy in matter

Very challenging experiment…





The ORCA detector

ORCA: Oscillation Research with Cosmics in the Abyss

To be installed in the French site of the KM3NeT infrastructure

One building block with 115 detection units

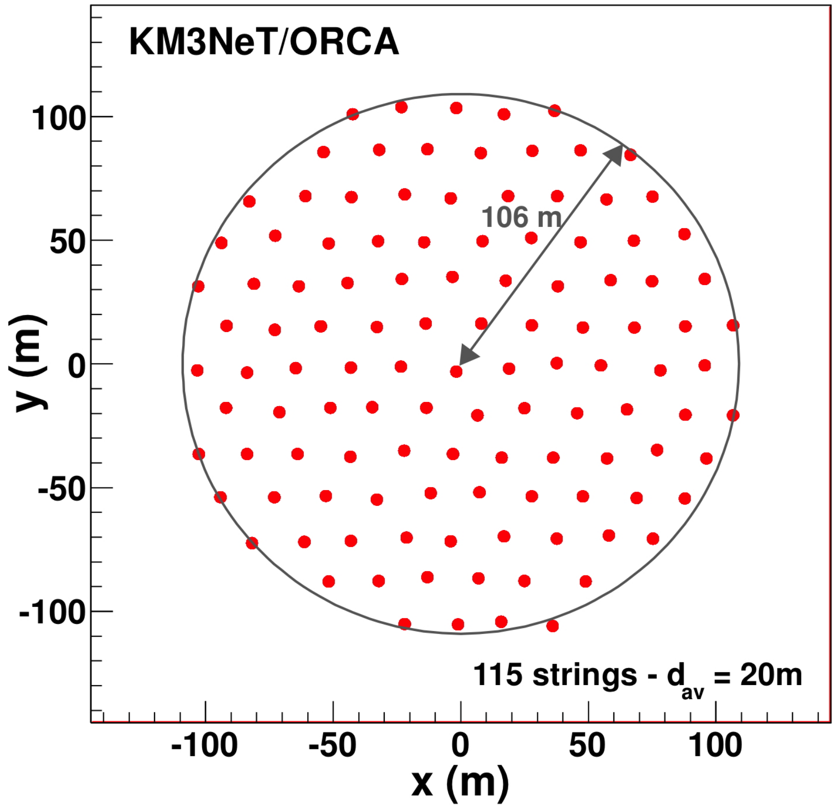
18 DOM per DU

Vertical DOM spacing 9 m

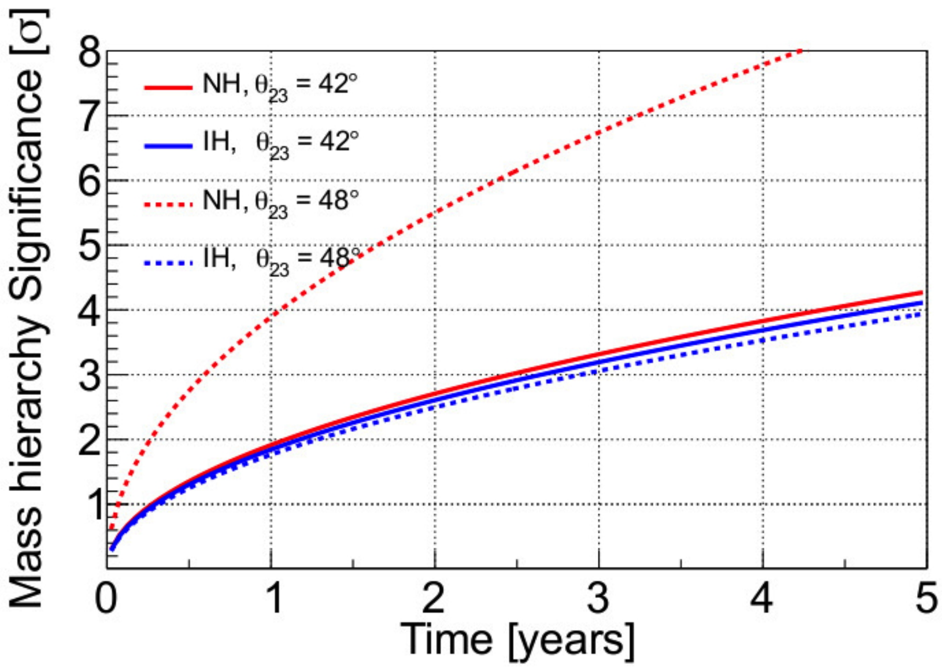
Inter-DU spacing 20 m

Volume ≈6 Mton

First ORCA string to be deployed in June 2016



ORCA: NMH sensitivity



Median significance for the determination of NMH

Full MC production
Trigger simulation, track and shower reconstruction included
Particle identification and muon background taken into account
Major systematics investigated
Vertical distance optimized (9m)

Still to be done
Exploit inelasticity
Improve reconstruction

KM3NeT development

Phase	Blocks / DUs	Primary deliverables / site(s)	Funding Construction
1	0.2 / 31	Proof of feasibility and first science results KM3NeT-It + KM3NeT-Fr	Fully funded 2015-17
2.0	2 /230 1 / 115	Measurement of neutrino signal reported by IceCube All-flavor neutrino astronomy KM3NeT-It Neutrino Mass Hierarchy KM3NeT-Fr	Applications pending 2017-2020
3	6 / 690	Neutrino astronomy including galactic sources Multiple sites	t.b.d.

Conclusions and outlook

- ANTARES just celebrated its 10° birthday
- 10 years of very exciting physics
- KM3NeT will soon take over as the biggest detector in the Northern Hemisphere (KM3NeT phase-1)
- Next phase (KM3NeT 2.0) to follow
  - ARCA (≈ 1 km^3) will be installed at the Italian node of the KM3NeT distributed infrastructure
  - ORCA will be installed at the French node
- Exciting physics prospects
  - Investigate the neutrino sky with unprecedented resolution and sky coverage with ARCA
  - Address the Neutrino Mass Hierarchy with ORCA