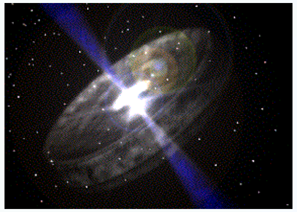
Mediterranean Neutrino Telescopes: ANTARES & KM3NeT

Astroparticle & Oscillations Research with Cosmics in the Abyss

LPSC Grenoble – March 10, 2016

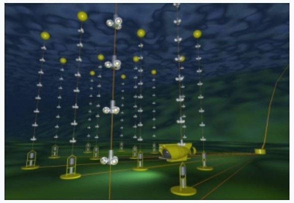
Outline



The High-Energy Physics Case – The cosmic endeavour

Historical aspects & Scientific motivations & Detection principles

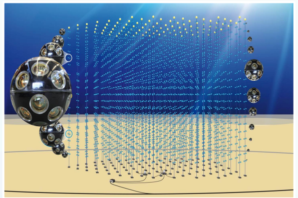
Today's context & IceCube discovery



Status of ANTARES and KM3NeT/ARCA

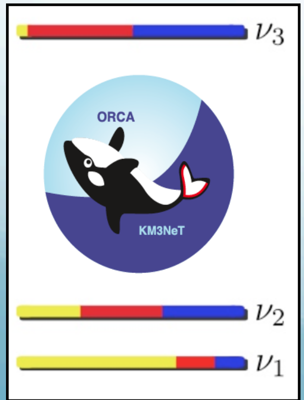
Selected results

Prospects



The Low-Energy Physics Case – A new endeavour

Phenomenological reminder



KM3NeT/ORCA

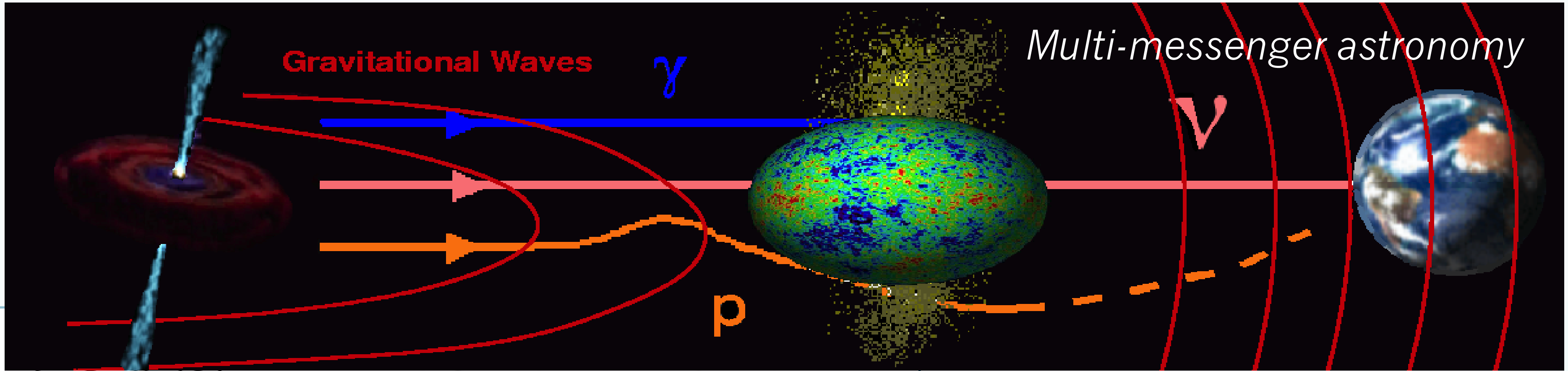
Proposed detector & performances

Sensitivity study

Planning

Conclusion

First ideas early 60's...science



Ann.Rev.Nucl.Sci
10 (1960) 1

By Frederick Reines[1]

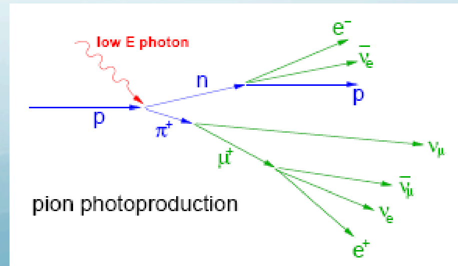
IV. COSMIC AND COSMIC RAY NEUTRINOS

As we have seen, interactions of high-energy particles with matter produce neutrinos (and antineutrinos). The question naturally arises whether the neutrinos produced extraterrestrially (cosmic) and in the earth's atmosphere (cosmic ray) can be detected and studied. Interest in these possibilities stems from the weak interaction of neutrinos with matter, which means that they propagate essentially unchanged in direction and energy from their point of origin (except for the gravitational interaction with bulk matter, as in the case of light passing by a star) and so carry information which may be unique in character. For example, cosmic neutrinos can reach us from other galaxies whereas the charged cosmic ray primaries reaching us may be largely constrained by the galactic magnetic field and so must perforce be from our own galaxy. Our more usual source of astronomical information, the photon, can be absorbed by cosmic matter such as dust. At present no acceptable theory of the origin and extraterrestrial diffusion of cosmic rays exists so that the cosmic neutrino flux can not be usefully predicted. An observation of these neutrinos would provide new information as to what may be one of the principal carriers of energy in intergalactic space.

The situation is somewhat simpler in the case of cosmic-ray neutrinos: they are both more predictable and of less intrinsic interest. Cosmic-ray

Greisen, 1960, Proc. Int. Conf on Instrum for HE physics

One may even anticipate eventual high-energy neutrino astronomy, since neutrino travel in straight lines, unlike the usual primary cosmic rays, and the neutrinos will convey a new type of astronomical information quite different from that carried by visible light and radio waves



First ideas early 60's...method

Ann.Rev.Nucl.Sci
10 (1960) 63

COSMIC RAY SHOWERS[1]

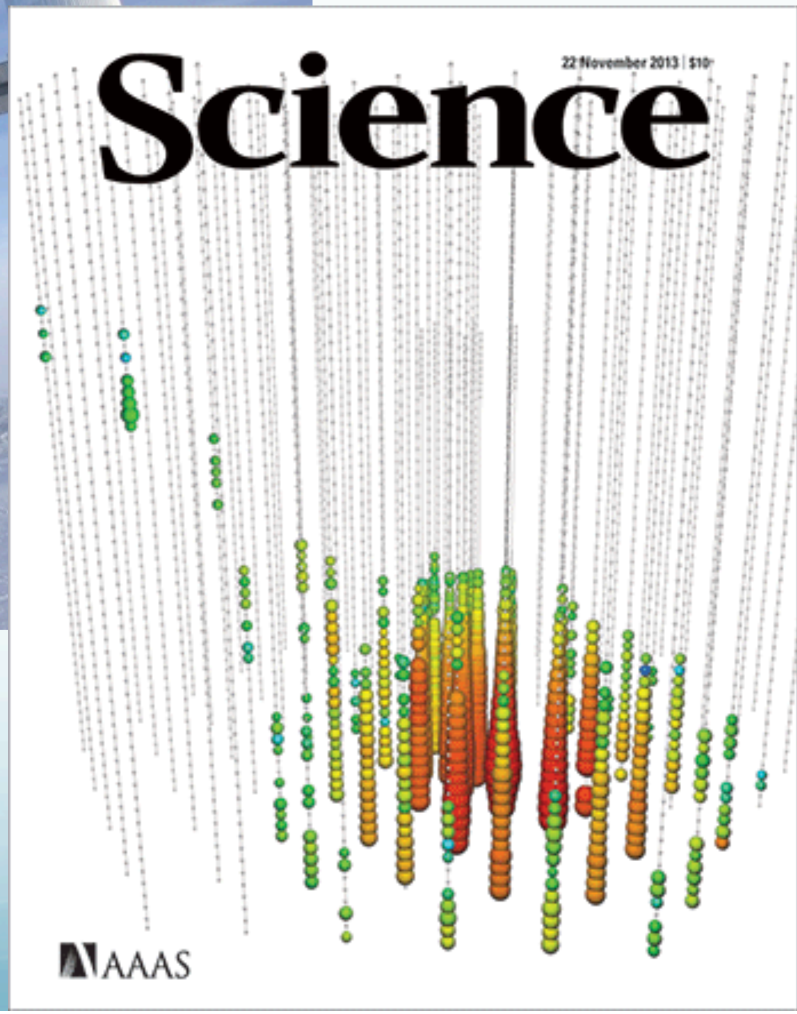
BY KENNETH GREISEN

Let us now consider the feasibility of detecting the neutrino flux. As a detector, we propose a large Cherenkov counter, about 15 m. in diameter, located in a mine far underground. The counter should be surrounded with photomultipliers to detect the events, and enclosed in a shell of scintillating material to distinguish neutrino events from those caused by μ mesons. Such a detector would be rather expensive, but not as much as modern accelerators and large radio telescopes. The mass of sensitive detector could be about 3000 tons of inexpensive liquid. According to a straightforward

For example, from the Crab nebula the neutrino energy emission is expected to be three times the rate of energy dissipation by the electrons, leading to a flux of $6 \cdot 10^{-4}$ Bev/cm.^{2}/sec. at the earth. In the detector described above, the counting rate would be one count every three years with the lower of the theoretical cross sections—rather marginal, though the background from other particles than neutrinos can be made just as small. The detector has the virtue of good angular resolution to assist in distinguishing rare events having unique directions.

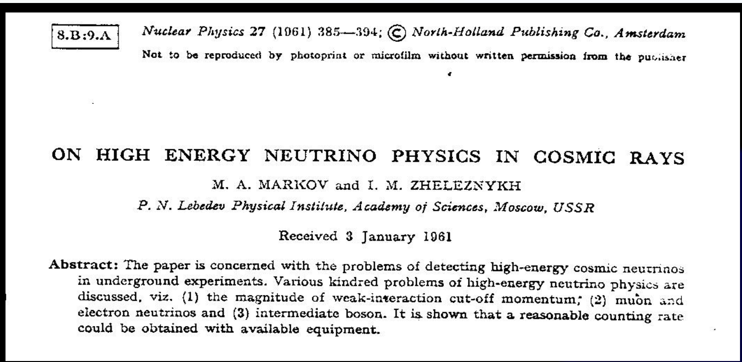
Fanciful though this proposal seems, we suspect that within the next decade, cosmic ray neutrino detection will become one of the tools of both physics and astronomy.

First HE detection … 2013!



The field is now truly open !

Markov idea: muon neutrino



8.B:9.A | *Nuclear Physics* 27 (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

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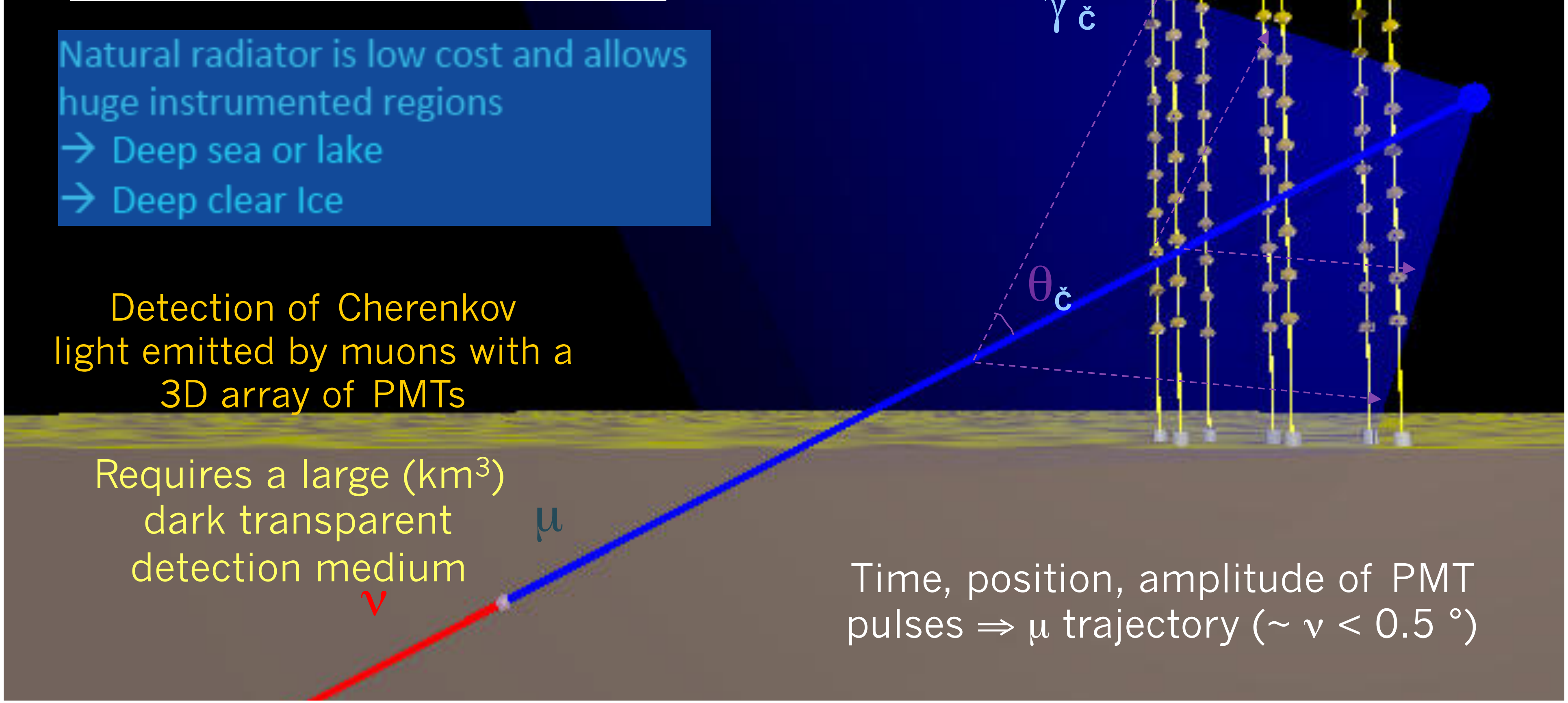
ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

M. A. MARKOV and I. M. ZHELEZNYKH

P. N. Lebedev Physical Institute, Academy of Sciences, Moscow, USSR

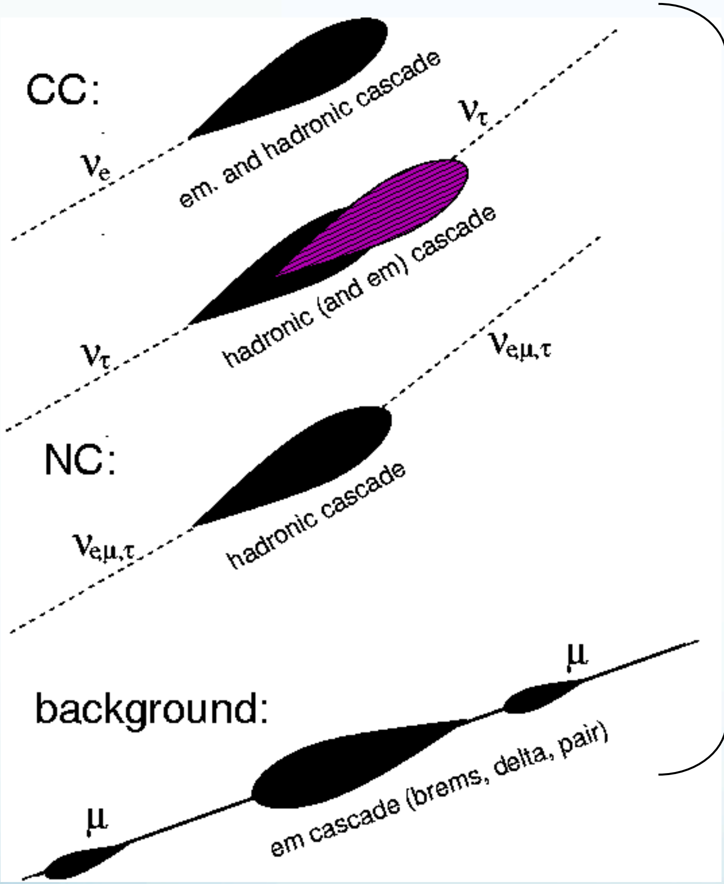
Received 3 January 1961

Abstract: The paper is concerned with the problems of detecting high-energy cosmic neutrinos in underground experiments. Various kindred problems of high-energy neutrino physics are discussed, viz. (1) the magnitude of weak-interaction cut-off momentum; (2) muon and electron neutrinos and (3) intermediate boson. It is shown that a reasonable counting rate could be obtained with available equipment.



Cascade topology

$\nu_e:\nu_\mu:\nu_\tau$ =1:2:0 at source —*oscillation*→ $\nu_e:\nu_\mu:\nu_\tau$ =1:1:1 at Earth !

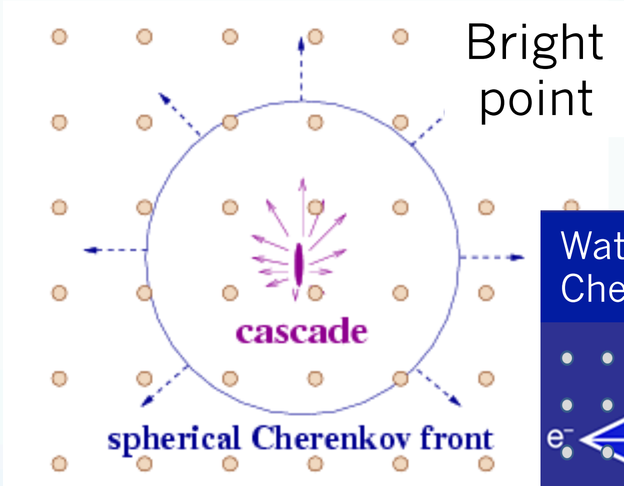


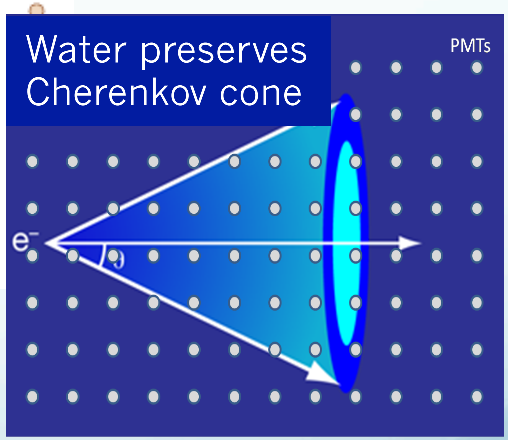
IceCube discovery channel

Use for astronomy in water

Generic reconstruction:

Bright point



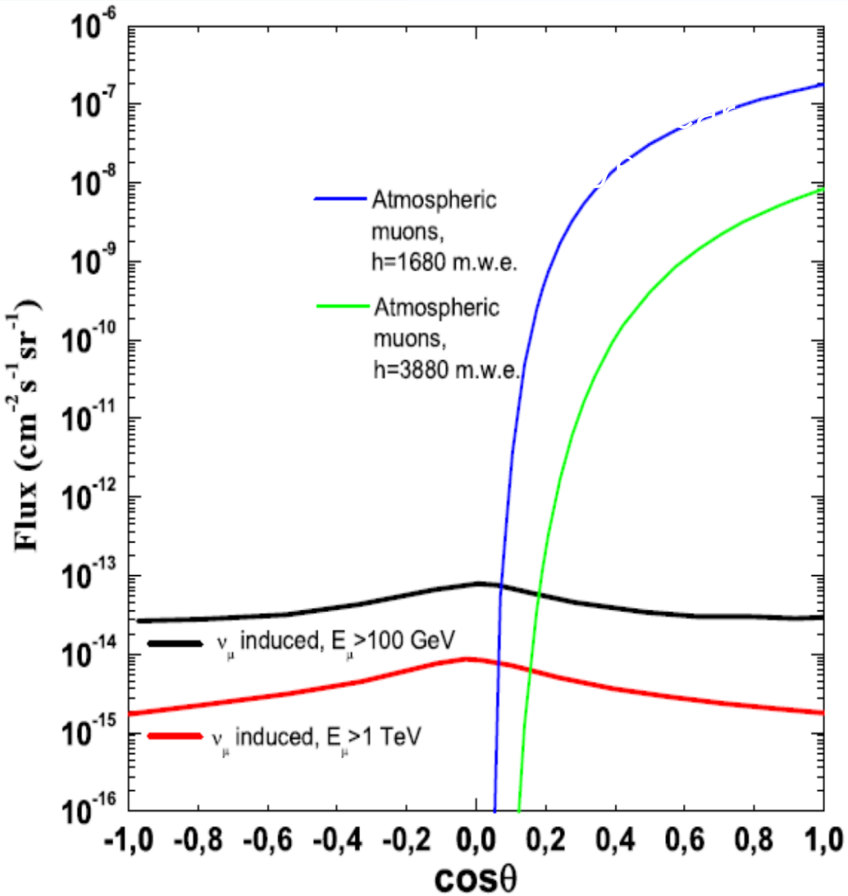


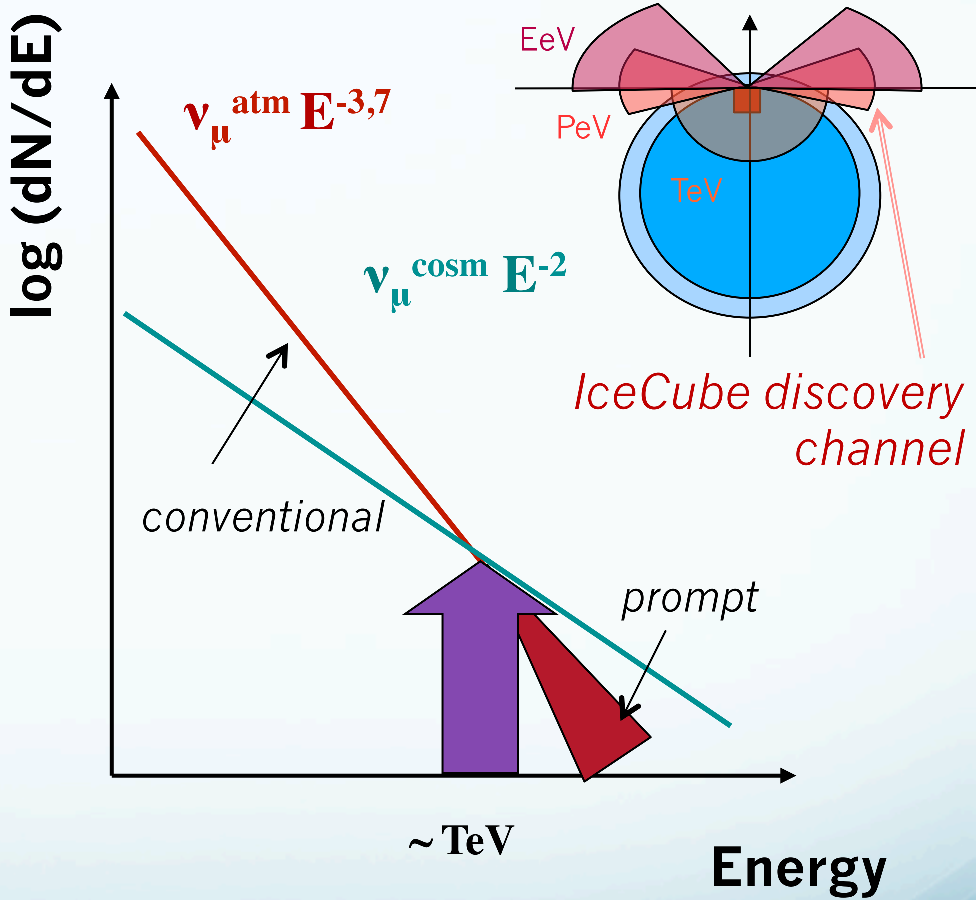
→ Provide sensitivity to all neutrino flavours – Increase overall detector sensitivity

- Angular resolution 10° - 30° / 1°- 5° at 100 TeV for ice / water
- Energy resolution ~ 15%

Atmospheric background vs cosmic ν's

Atmospheric muons: shield detector, look down, apply veto



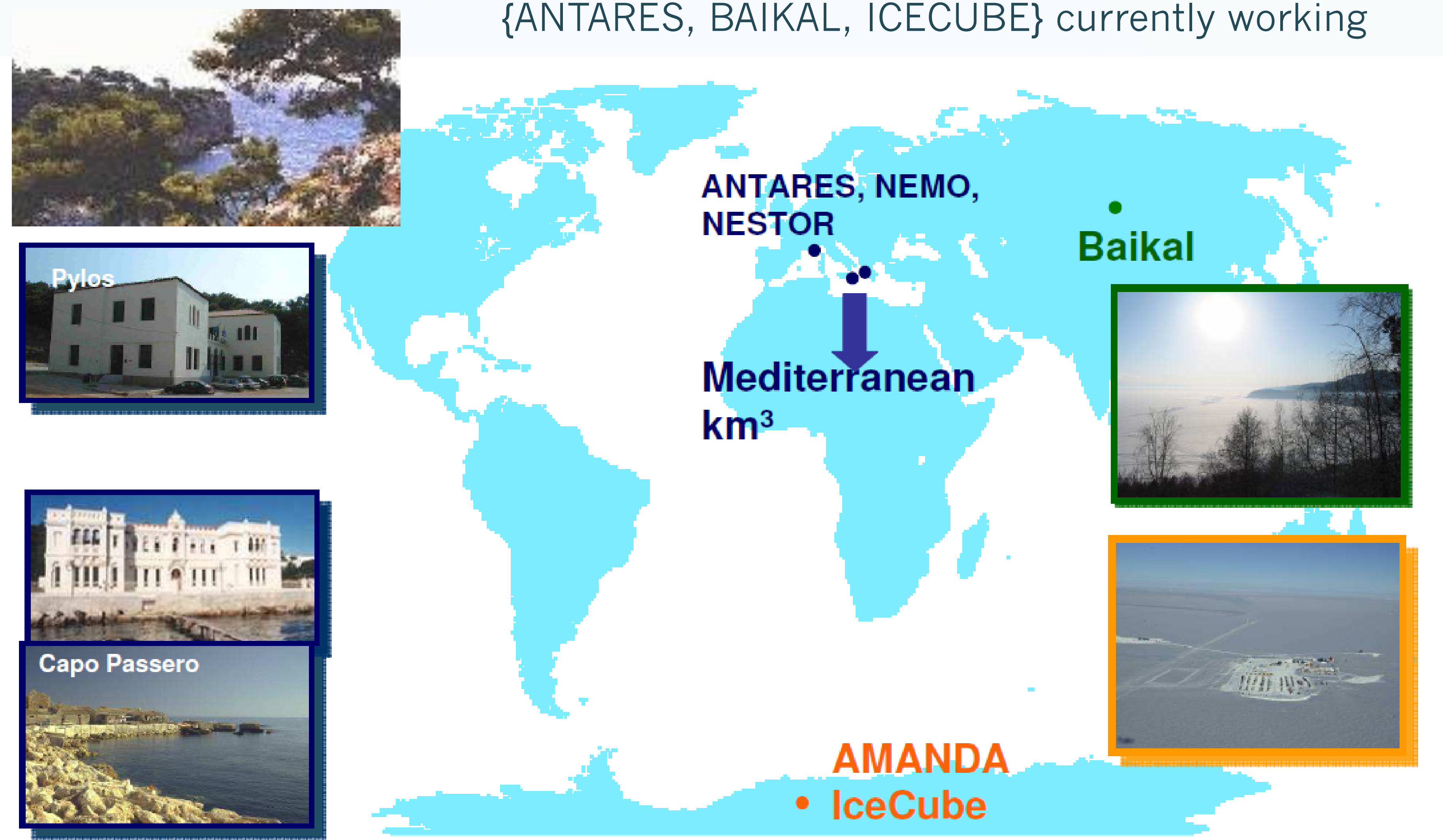


Atmospheric neutrinos: search for

- An excess at High Energy
- Anisotropies, spatial clustering
- Time / space coincidence with other cosmic probes

(TeV) Neutrino telescopes

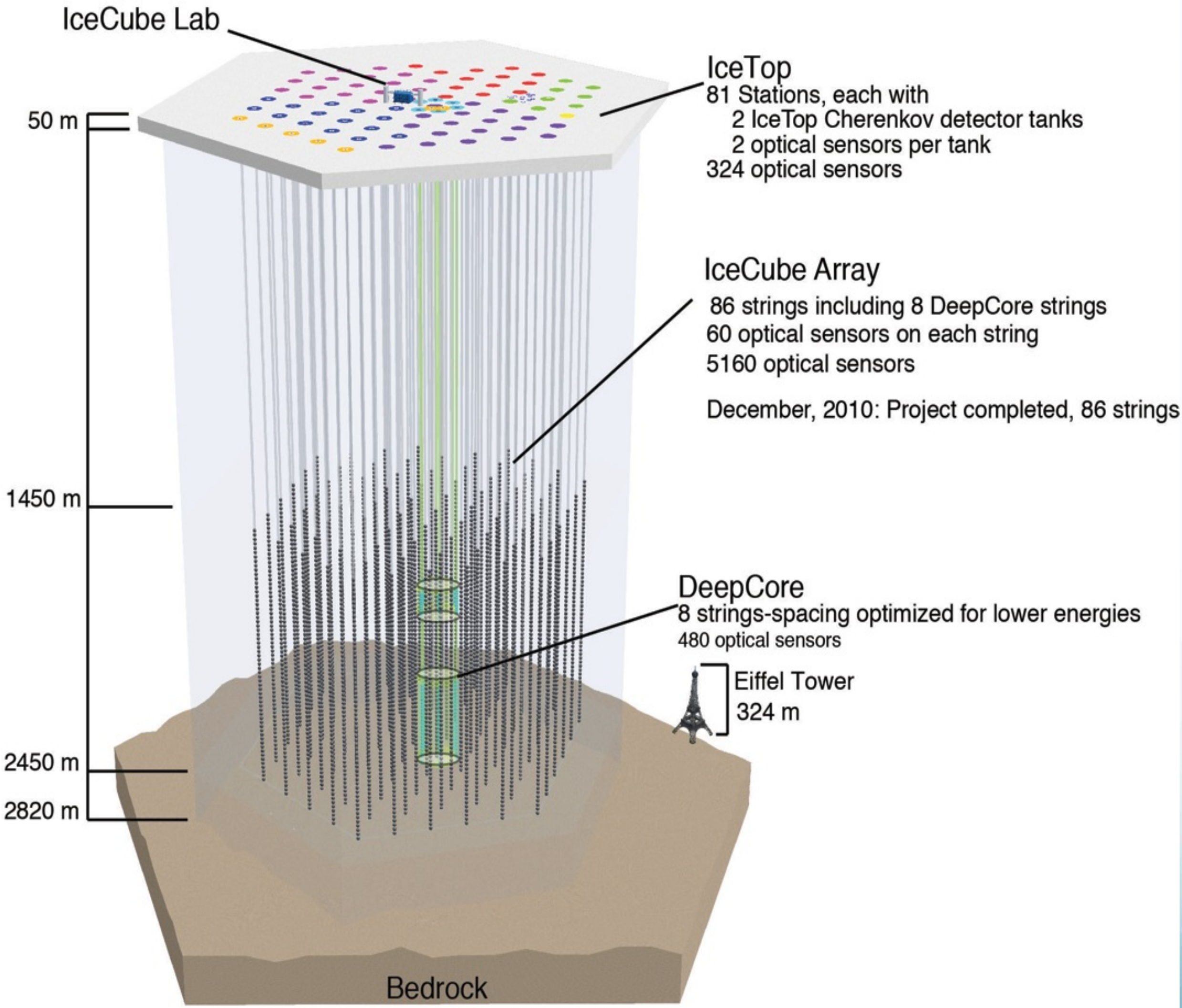
{ANTARES, BAIKAL, ICECUBE} currently working

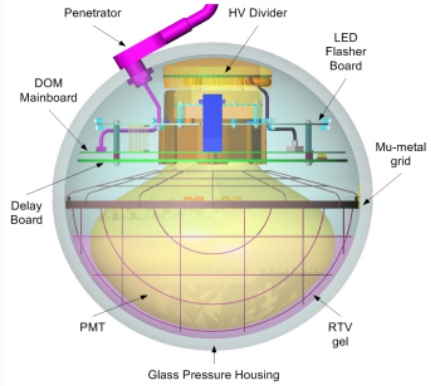


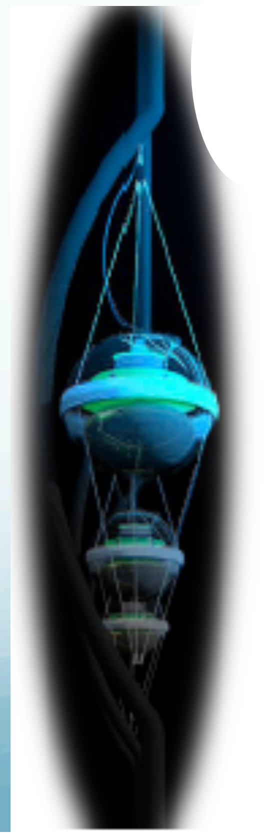
{ANTARES, NEMO, NESTOR} now in KM3NeT collaboration

IceCube: the biggest NT in the world

Completed since December 2010.





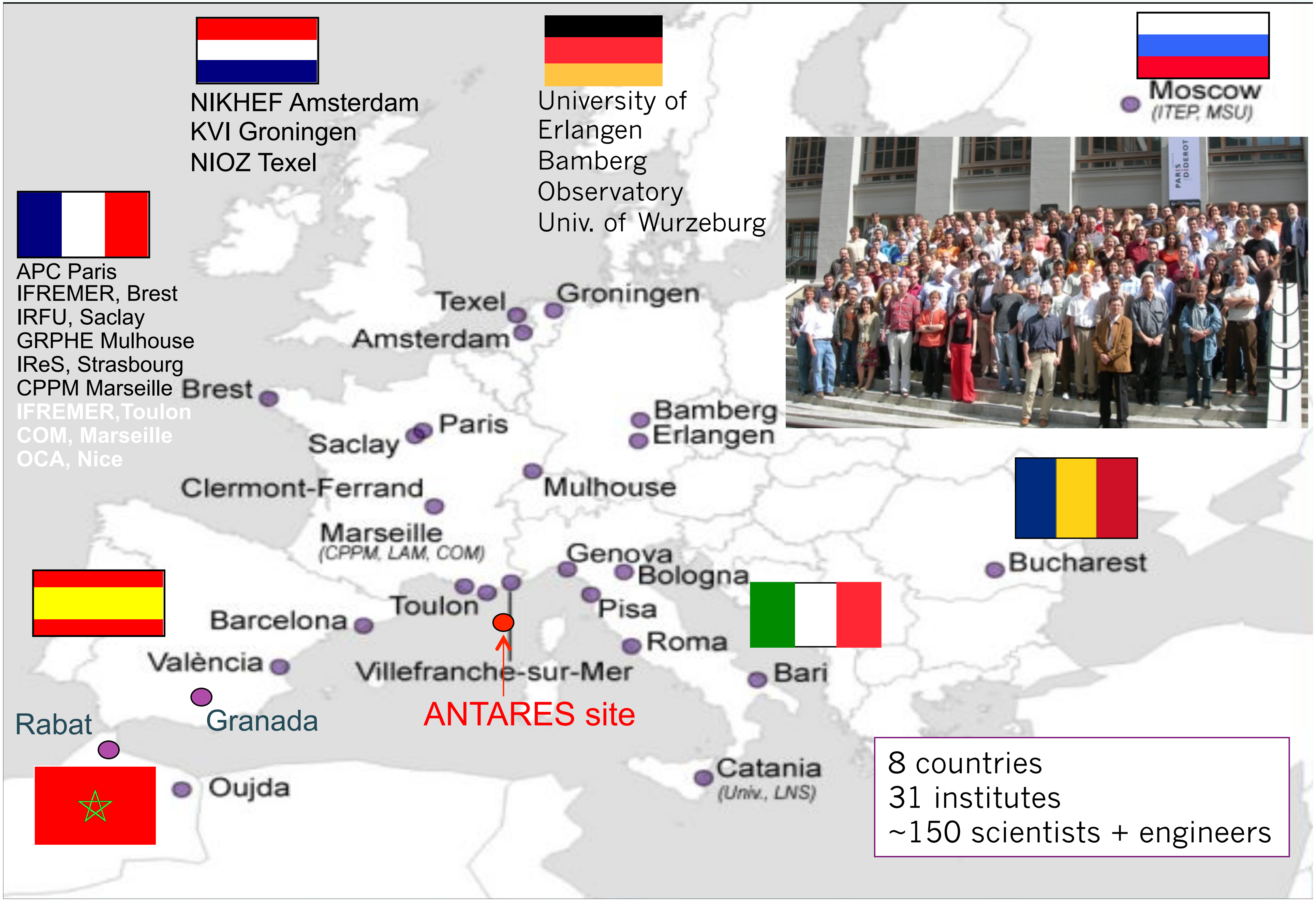


The ANTARES collaboration

NIKHEF Amsterdam
KVI Groningen
NIOZ Texel

University of Erlangen
Bamberg Observatory
Univ. of Wurzeburg

APC Paris
IFREMER, Brest
IRFU, Saclay
GRPHE Mulhouse
IReS, Strasbourg
CPPM Marseille
IFREMER,Toulon
COM, Marseille
OCA, Nice



8 countries
31 institutes
~150 scientists + engineers

The ANTARES neutrino telescope

Water versus Ice

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

- Logistically attractive

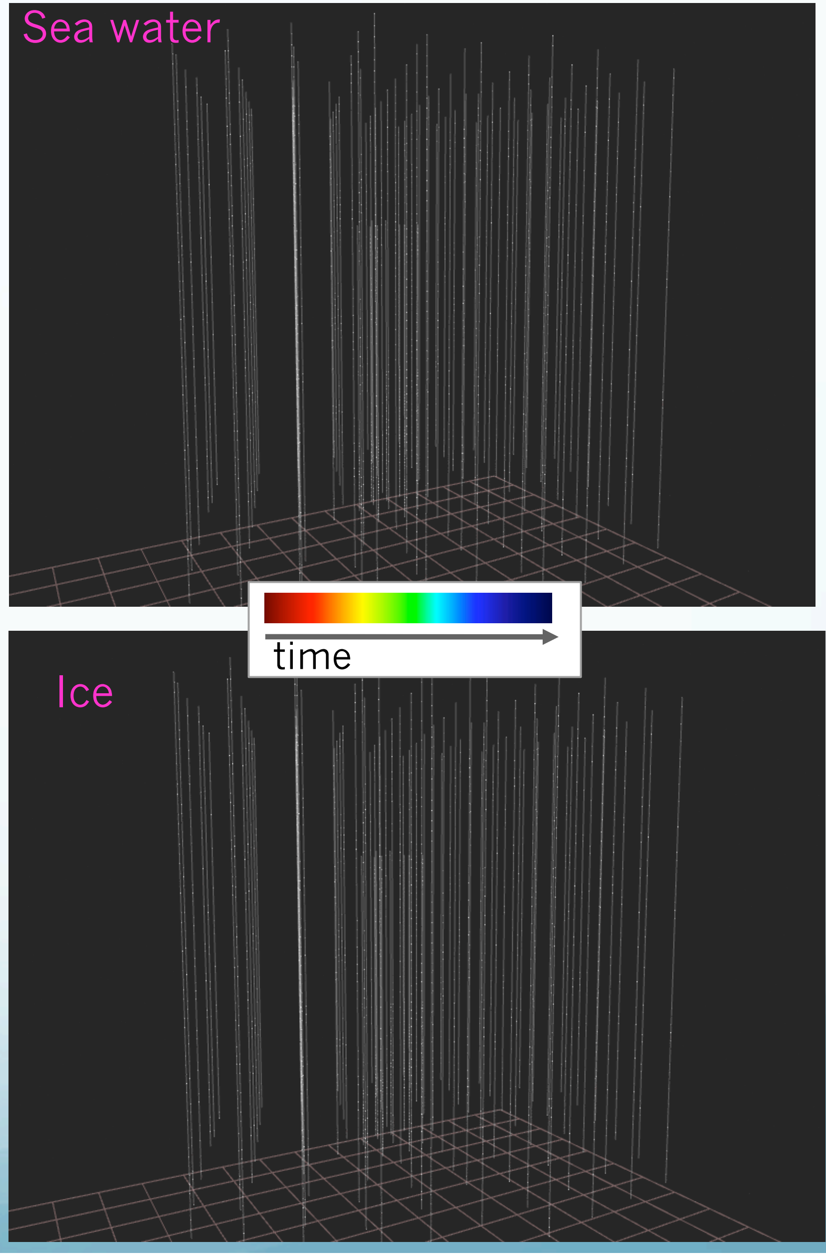
  Close to shore (deployment / repair)

- Complementarity to IceCube South Pole

  Excellent view of Galaxy

- K40 optical background

  Useful calibration, but requires causality filters

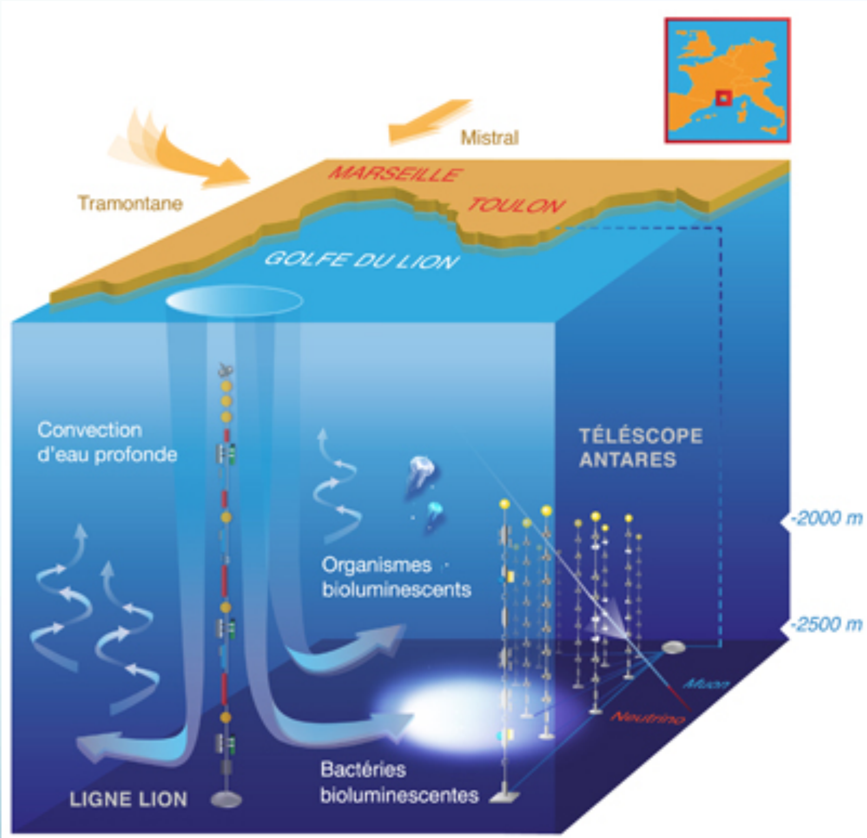


Interest for deep-sea science

ANTARES awarded "La Recherche Prize" category "Coup de Coeur"

📖 C. Tamburini, S. Escoffier et al., PLoS ONE 8(7) 2013

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

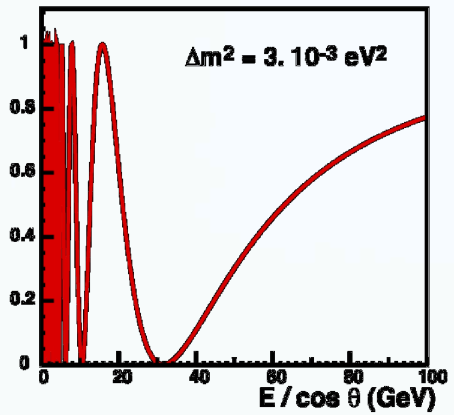


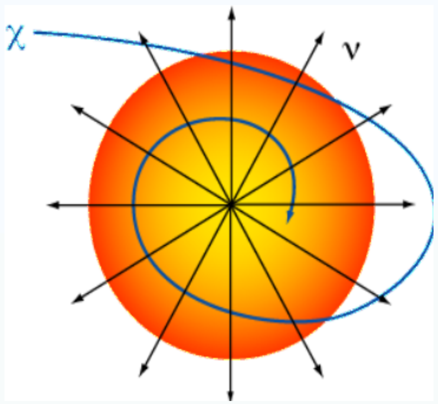
📖 H. van Haren et al., Ocean Dynamics, April 2014, Volume 64, Issue 4, pp 507-517

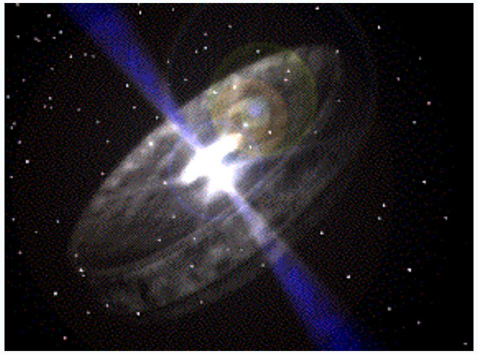
📖 H. van Harenz et al., Deep-Sea Research I 58 (2011) 875–884

📖 To come: Sperm whale diel behaviour

Physics scope







Low Energy	Medium Energy	High Energy
3 GeV < E_ν < 100 GeV	10 GeV < E_ν < 1 TeV	E_ν > 1 TeV

ν Oscillations
ν Mass hierarchy

Dark matter search

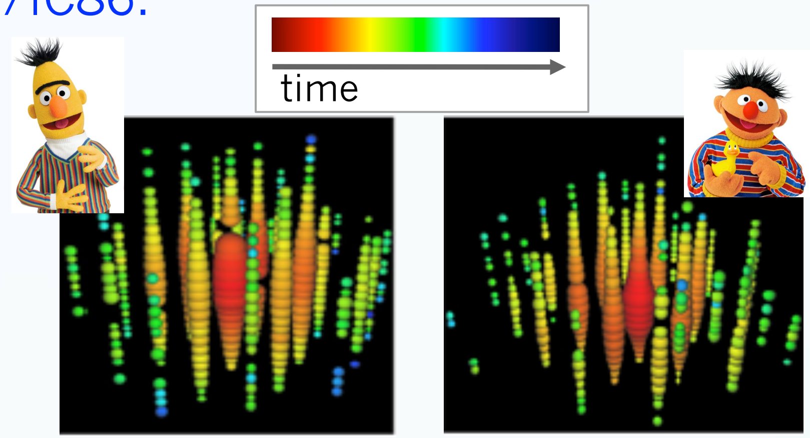
ν from extra-terrestrial sources

Origin and production mechanism of HE CR

Exotic particle physics
Monopoles, nuclearites,...

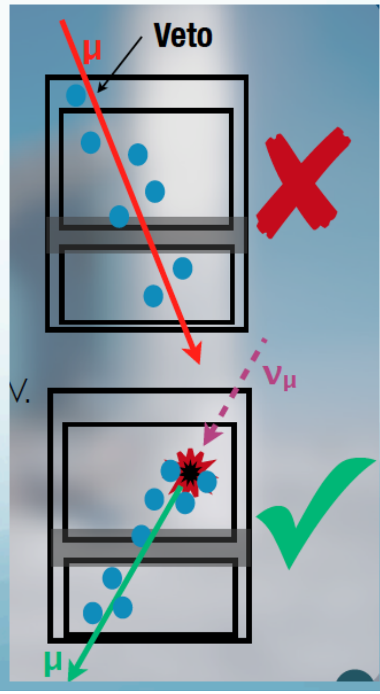
IceCube Discovery of HE neutrinos

- Two interesting cascade events found in IC79/IC86:
  - analysis targeting GZK neutrinos (~EeV)
  - significance 2.8σ (expected 0.08±0.05)
  - 🕮 Phys. Rev. Lett. 111, 021103 (2013)



1.0 +/- 0.2 PeV   1.1 +/- 0.2 PeV

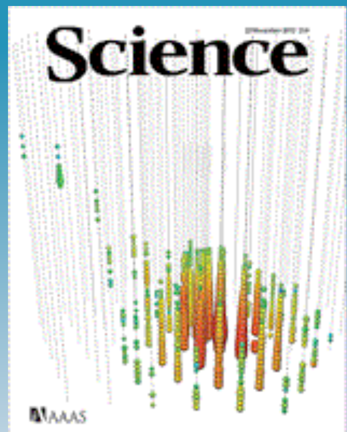
- Re-tuned on high-energy starting events:
  - total deposited charge > 6000 p.e.
  - track-like + shower-like events
  - outer layer used as veto against μ_{atm} & ν_{atm}



28 events selected (2-year data sample)
11 expected from μ_{atm} & ν_{atm} background:

first signal of high-energy
astrophysical neutrinos !
4.1σ stastistical significance

... and a Science cover



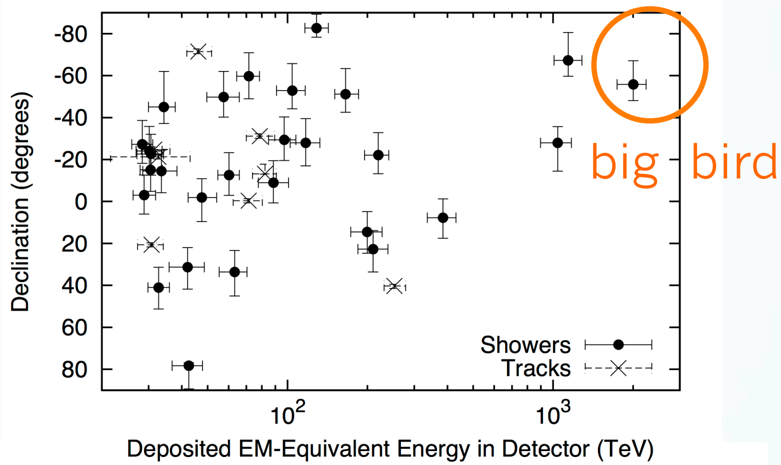
High Energy Starting Events (HESE)

Follow up analysis: the IceCube signal

2 year analysis:
28 events
4.1 σ
(📖Science 342, 2013)

→

3 year analysis:
37 events
5.7 σ
(📖PRL, 113, 101101, 2014)



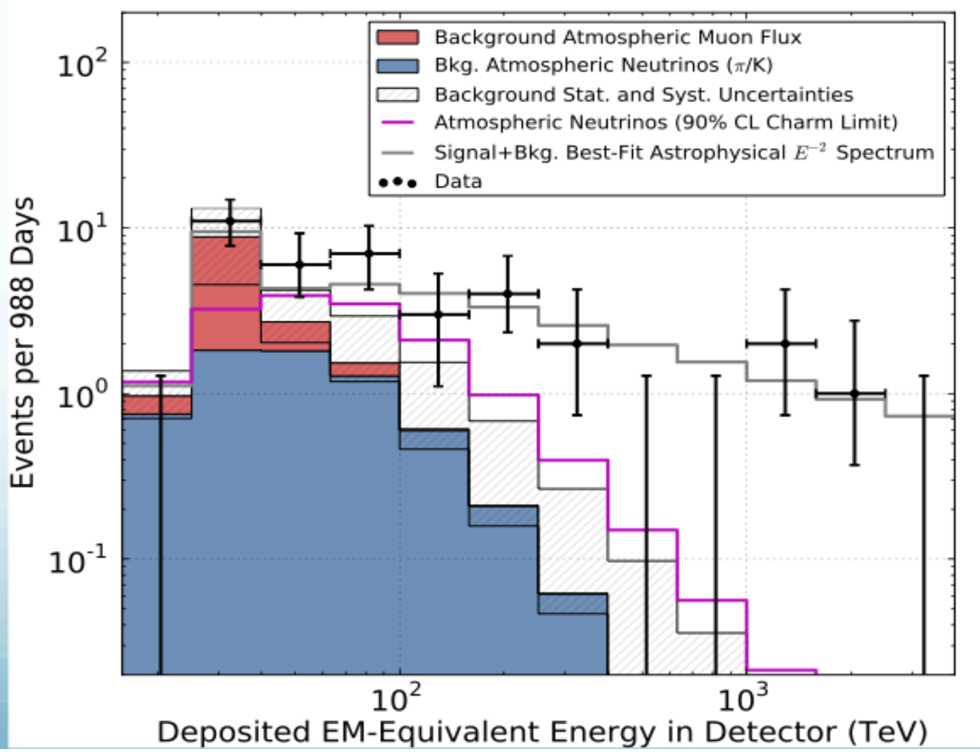
7 → 9 track-like events
1° angular resolution
muon takes some energy away
total expected background: 11 events

21 → 28 cascade-like events
10° - 45° angular resolution
15% visible energy reconstruction

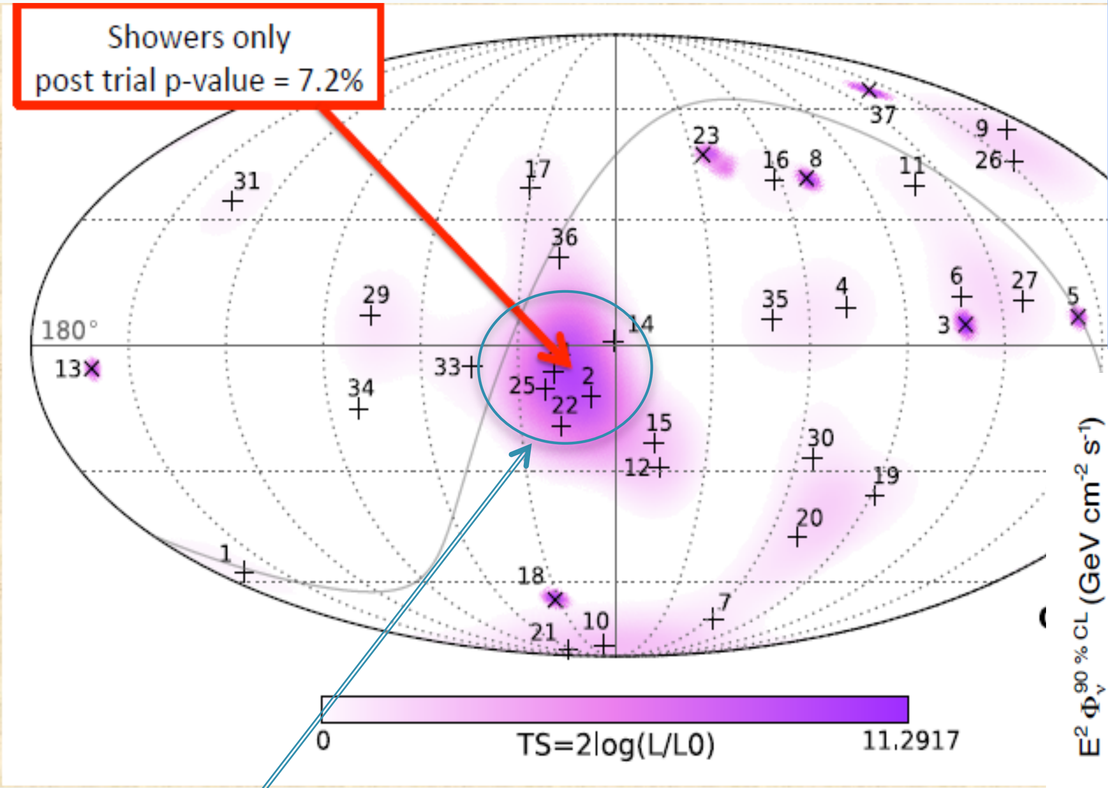
Best fit (per flavor):

$0.95 \pm 0.3 \times 10^{-8}\, E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

highest energy event @ 2 PeV
cutoff at ~2.3 PeV ?



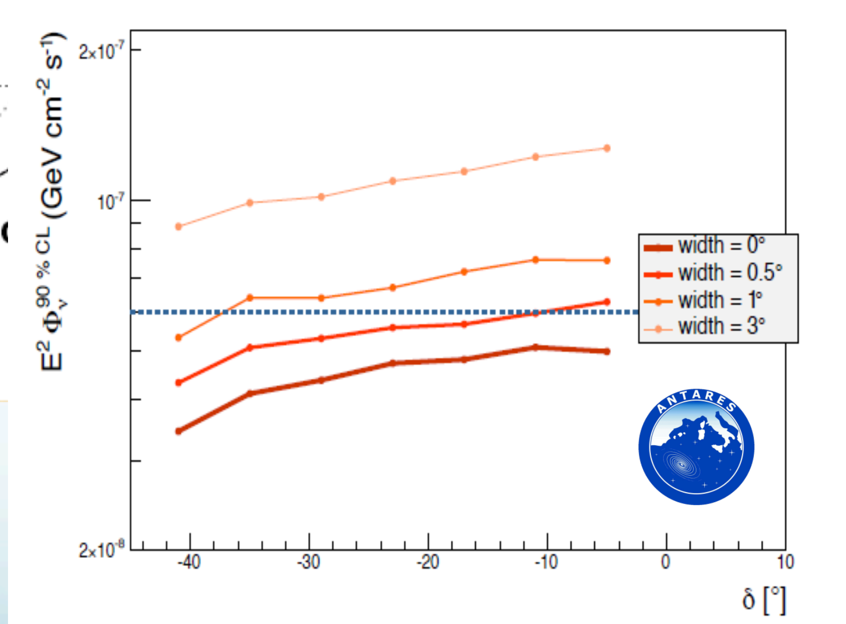
A source near the Galactic Center?



Hypothesized Galactic Source ?
📖 *Gonzalez-Garcia et al, APP 57 (2014)*

Point Source at $(\alpha, \delta) = (-79°, -23°)$:

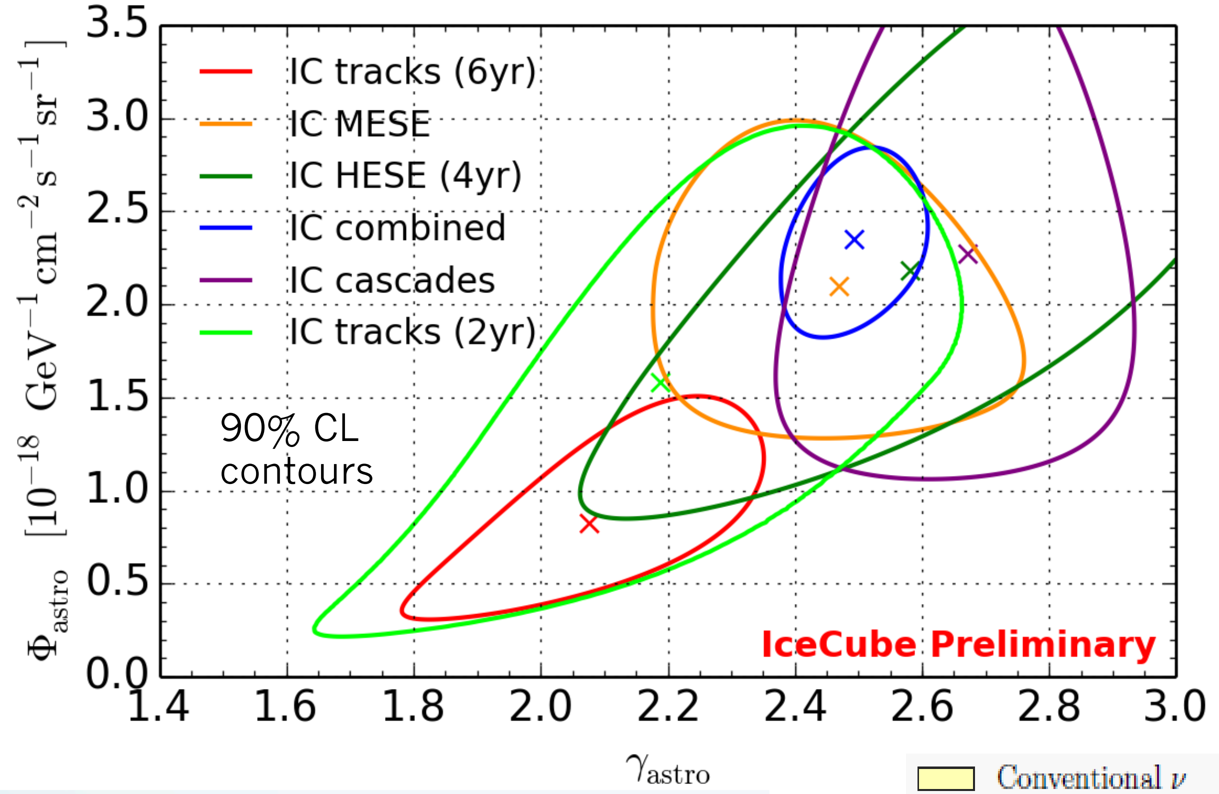
$\Phi = 6 \times 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}}$



ANTARES excludes single point source (E^{-2} spectrum) as origin of the cluster within 20° off GC
📖 Astrophys. J. Lett. 786:L5 (2014)

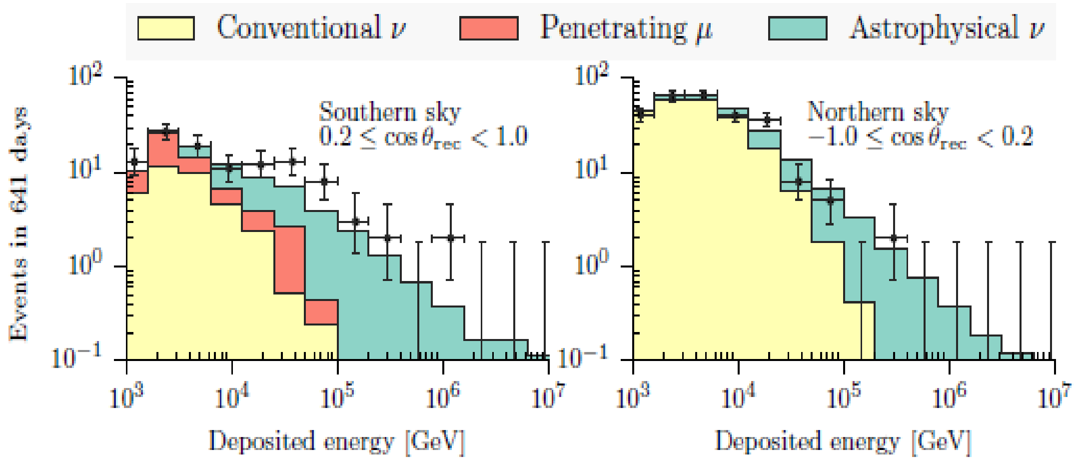
- A point source yielding n_p>2 excluded for Γ=2.3
- Clusters made of $n_p \geq 2$ is excluded for Γ> 2.3.

Summary of recent IC results



Results of IC tracks(6yr) and IC combined not compatible at > 3.6 σ level

Medium Energy Starting Events



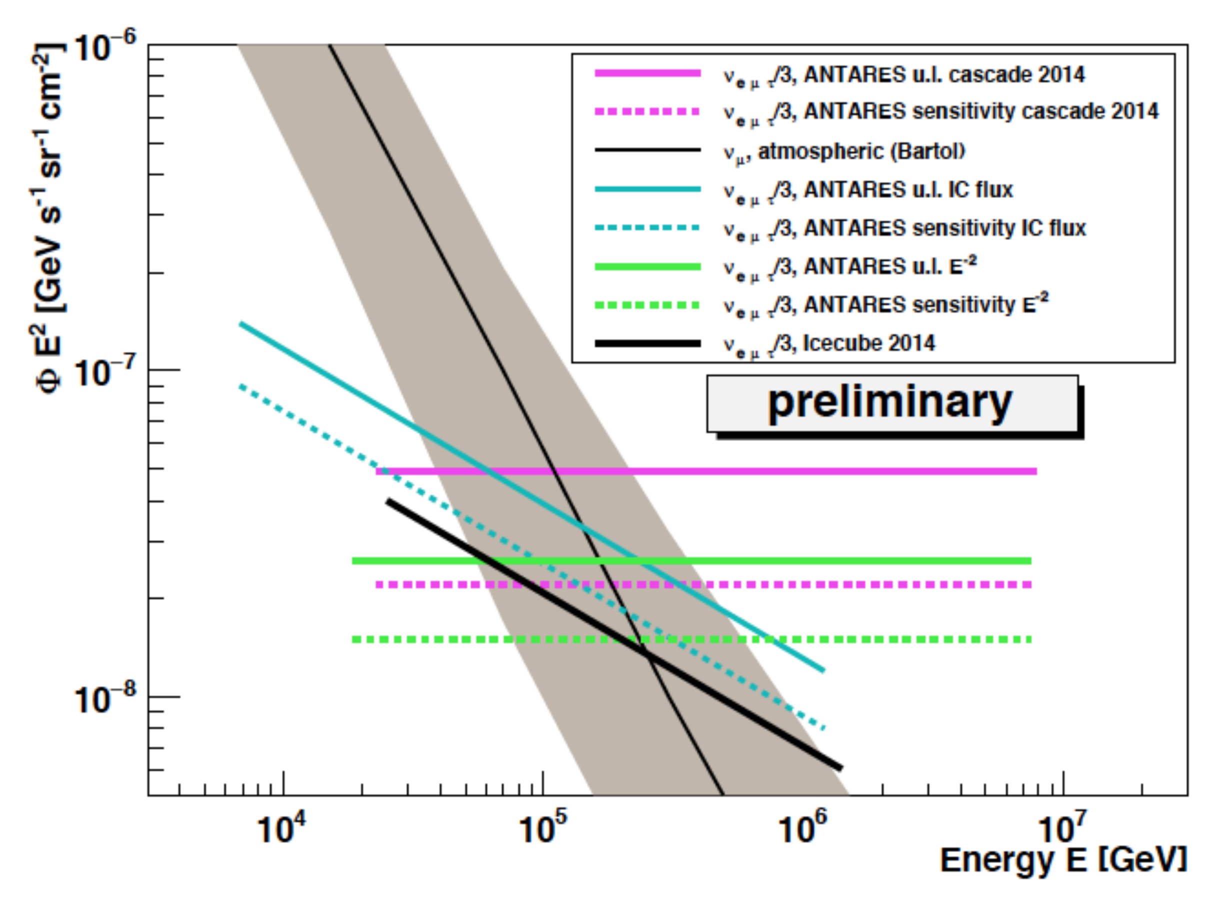
Indication of spectral break (different energy thresholds) ?

Indication of galactic and extra-galactic contributions (different hemispheres) ?

ANTARES Diffuse Neutrino Searches

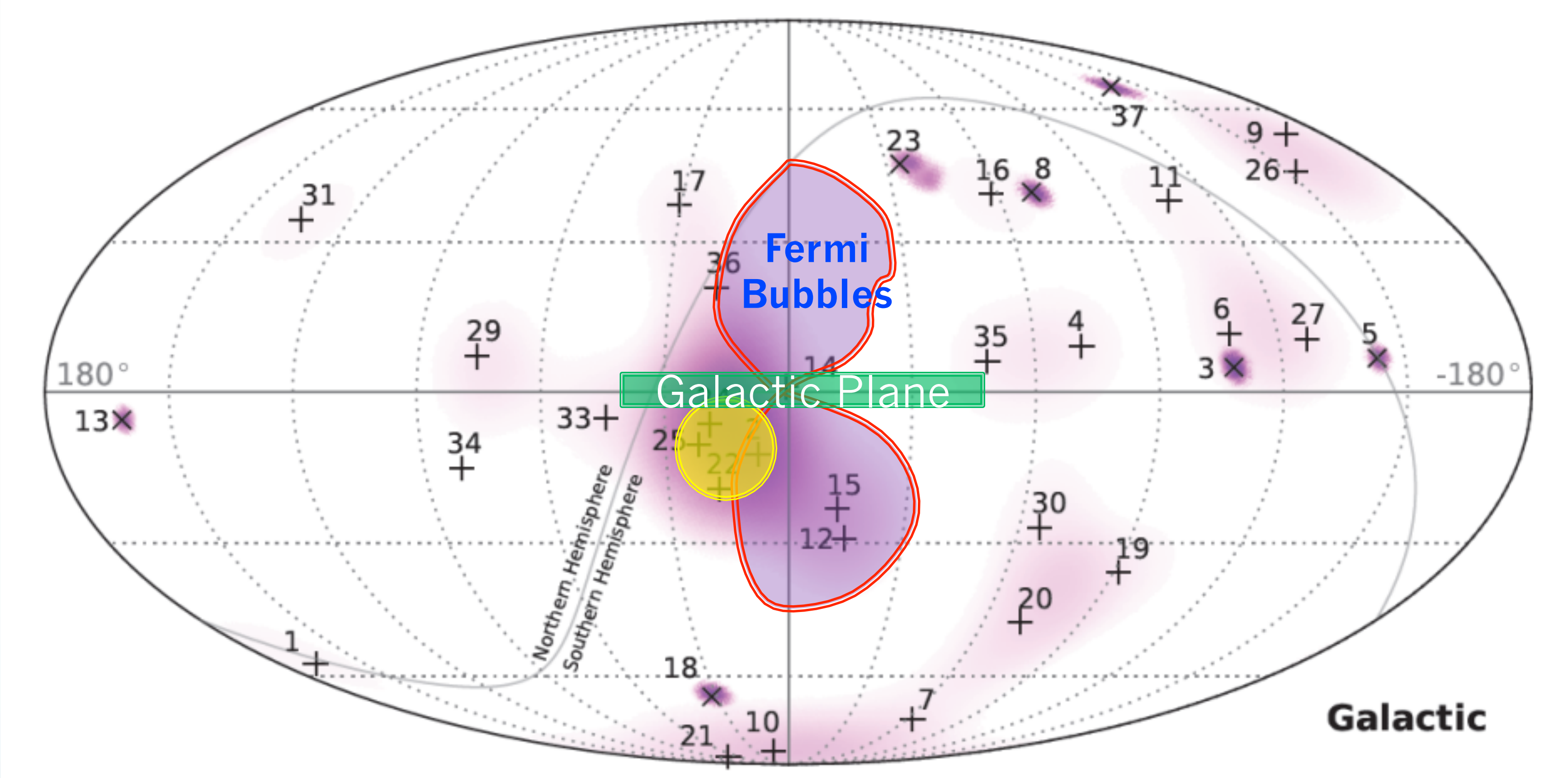
Data sample 2007 – 2013, strong quality cuts (data/MC agreement):
913 days effective lifetime (= about half available sample)

2-steps multivariate analysis: - removal of atmospheric muon background
- track/shower classification



- Expected:
  - 9.5 ± 2.5 bkgd
  - 5.0 ± 1.1 IC flux
- Observed:
  - 12 events
  - 1.75σ excess
- Results:
  - Consistent with bkgd
  - Consistent with IC

Reducing the search window

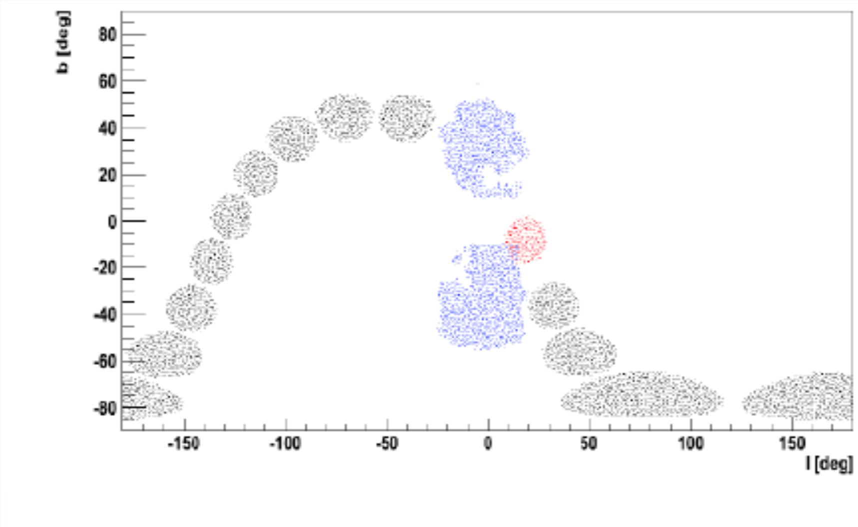


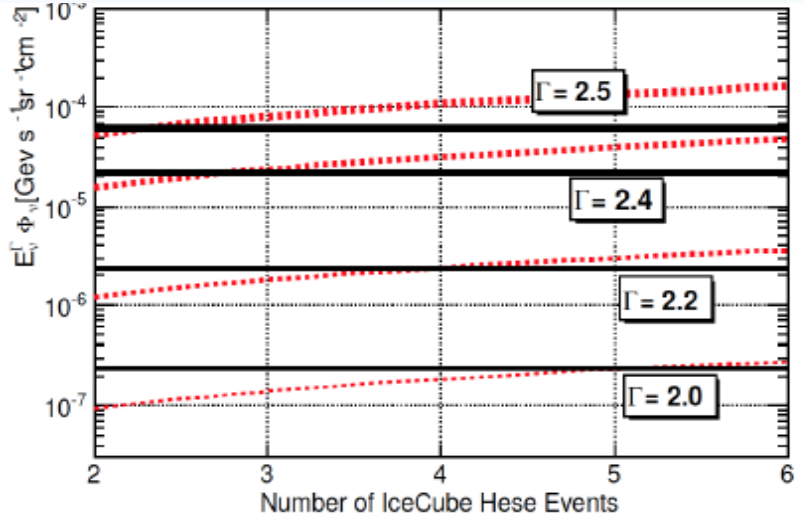
- **Fermi-Bubble region**.
- **Galactic Center region**.
- **IC hot spot.**

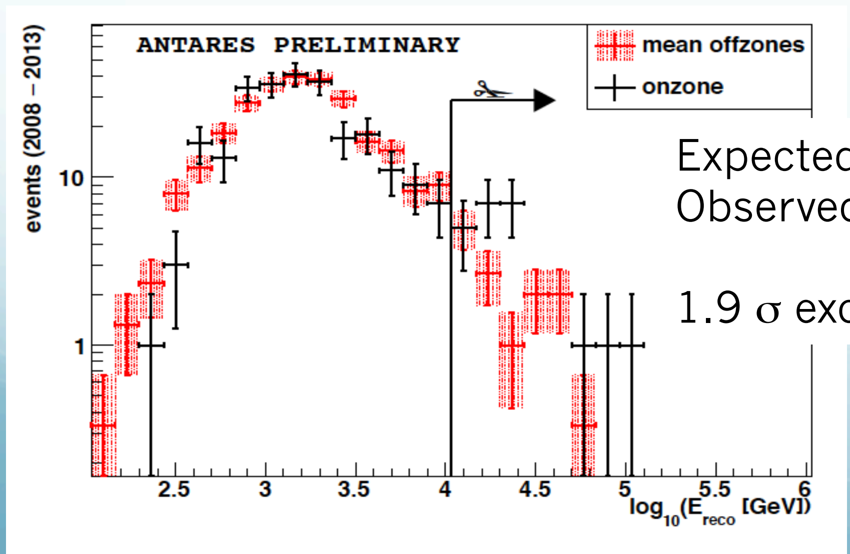
Muons only !

IC hotspot and FB

- May 2008- Dec 2013 (1172 days livetime); ν_μ only

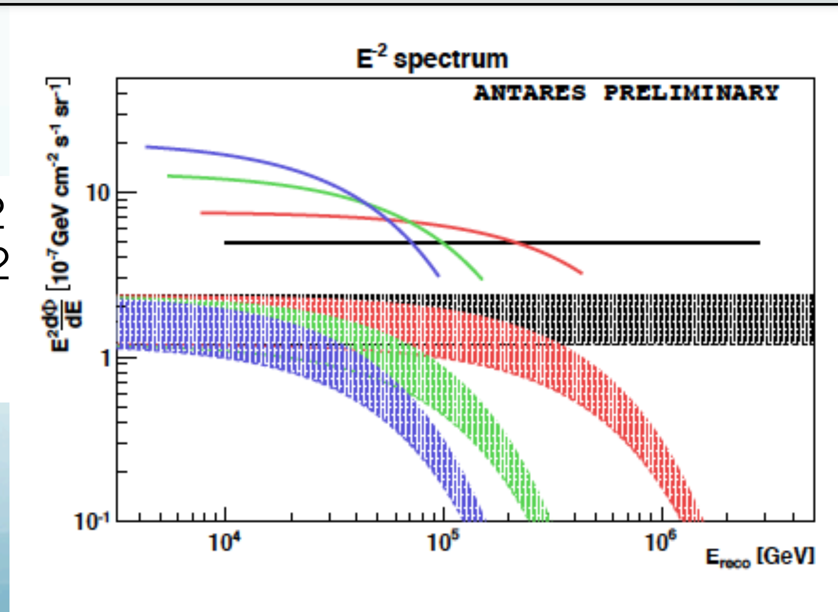




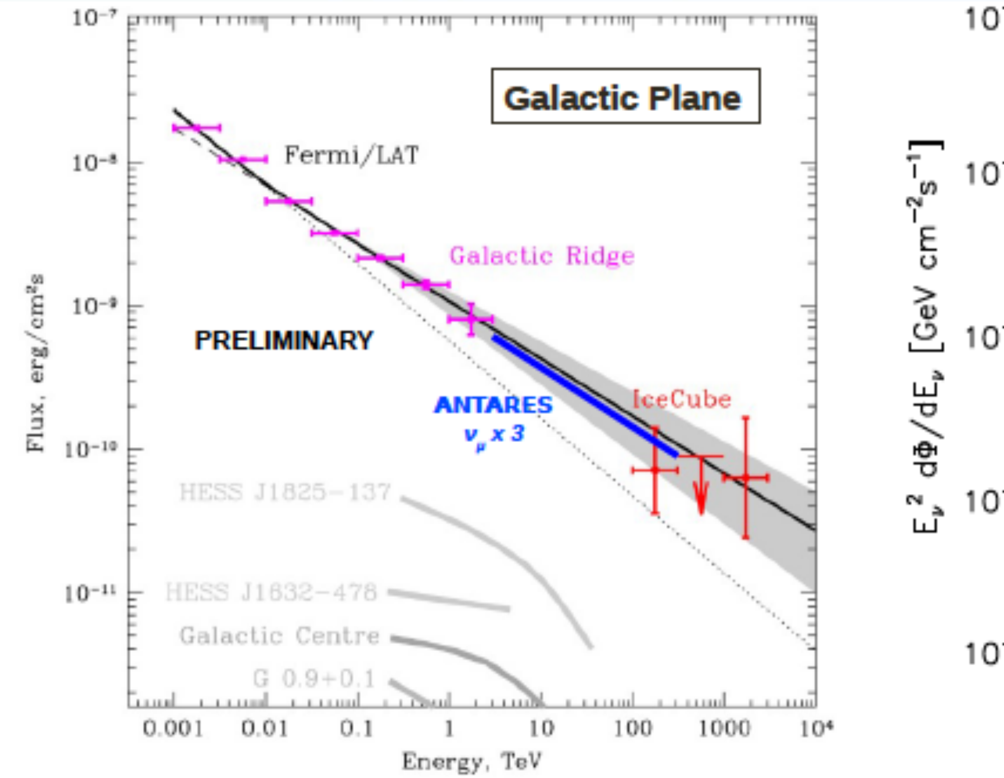


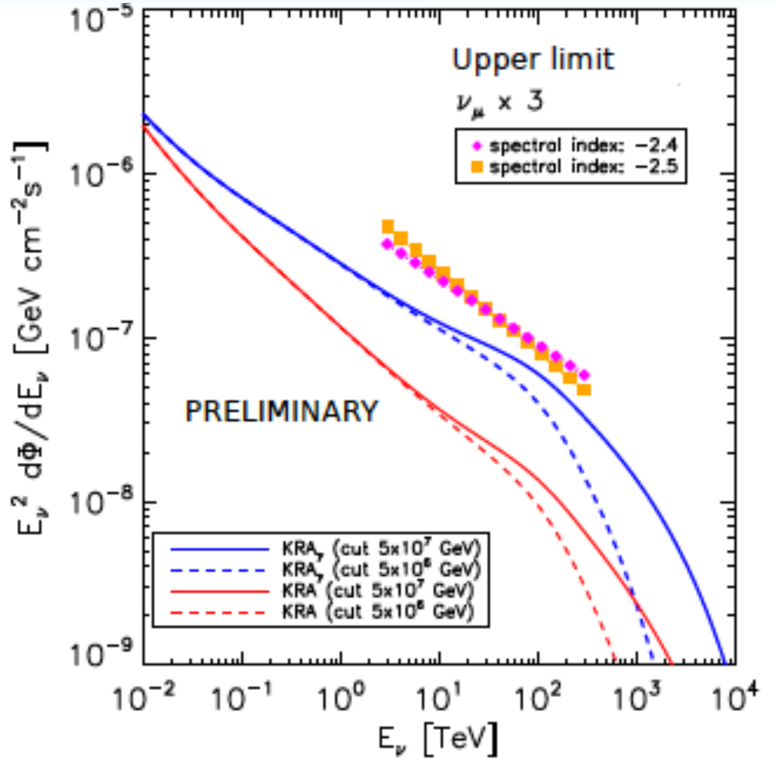
Expected: 12
Observed: 22

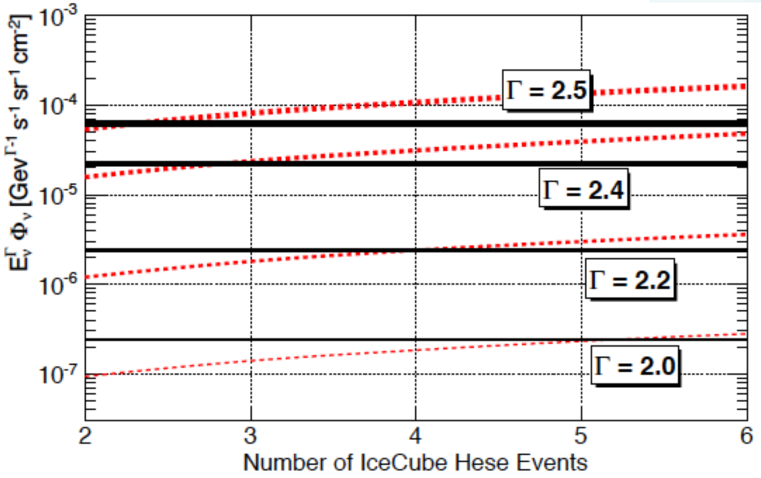
1.9 σ excess



New vision of Galactic Ridge?







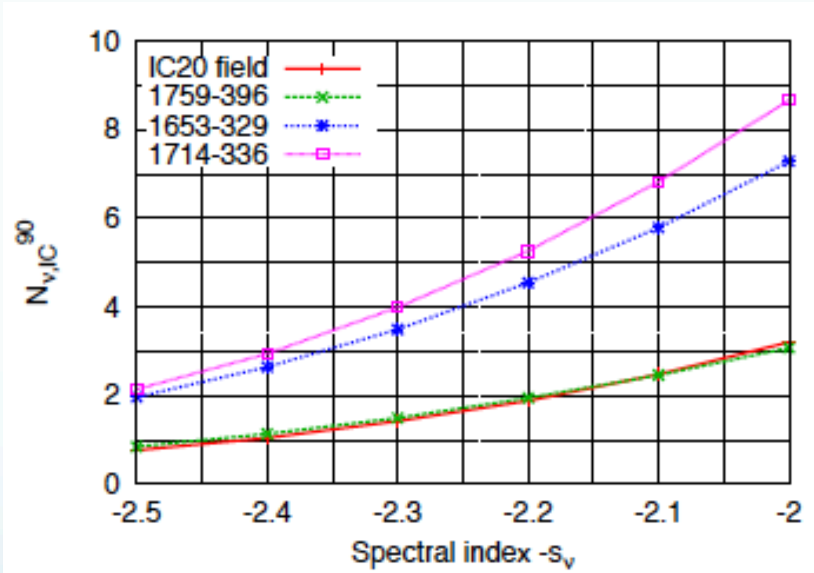
- 🕮 A. Neronov et al. Phys. Rev. D89, 103002 (2014)
- 🕮 D. Gaggero et al.,The Astrophysical Journal Letters, 815:L25 (2015)
- 🕮 ANTARES arXiv:1602.03036, submitted to PLB

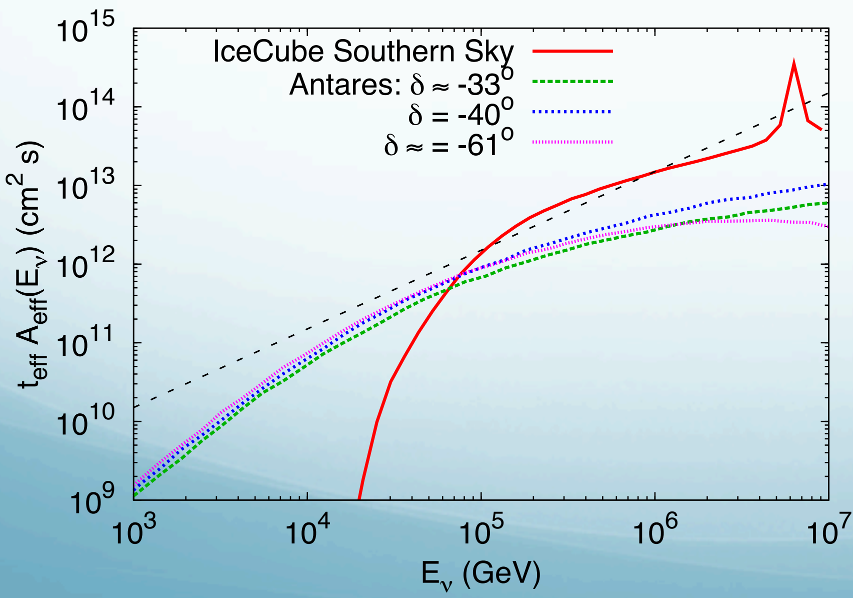
AGNs close to Ernie and Bert?

TANAMI collaboration reported observations of 6 bright blazars locally compatible with the 2 first PeV IceCube events IC14 and IC20.
📖 Krauß, F. et al. 2014, A&A, 566, L7

Source	N_{sig}	p	Limit 10^{-8} GeV^{-1} cm^{-2} s^{-1}
0235−618	0	1	1.3
0302−623	0	1	1.3
0308−611	0	1	1.3
1653−329	1.1	0.10	2.9
1714−336	0.9	0.04	3.5
1759−396	0	1	1.4

ANTARES inferred limits





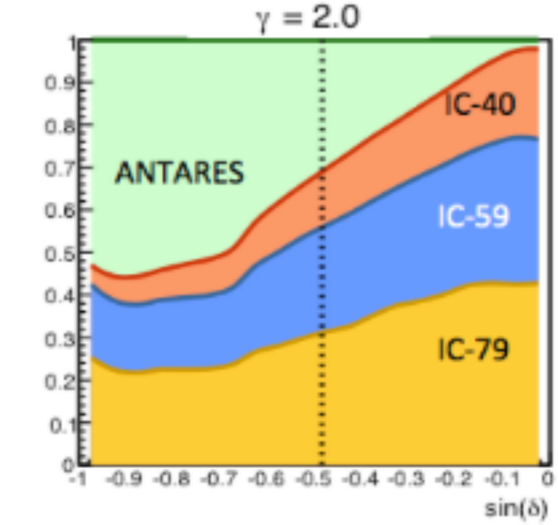
→ Relevant constraints on spectral index of potential source

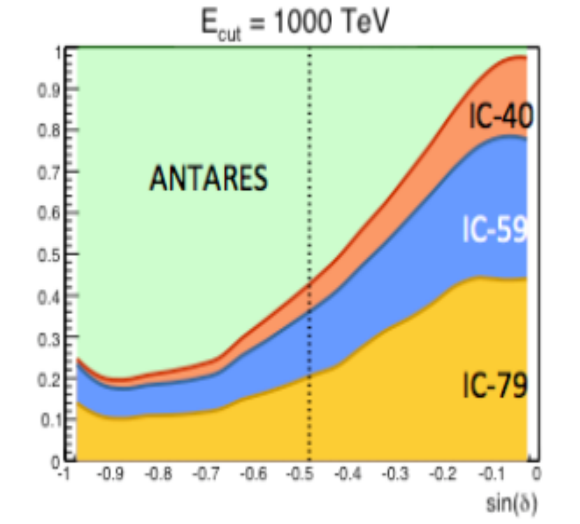
📖 Antares, A&A 576, L8 (2015)
Highlighted in the Nature vol 520, April 2015

Join ANTARES-IceCube search

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

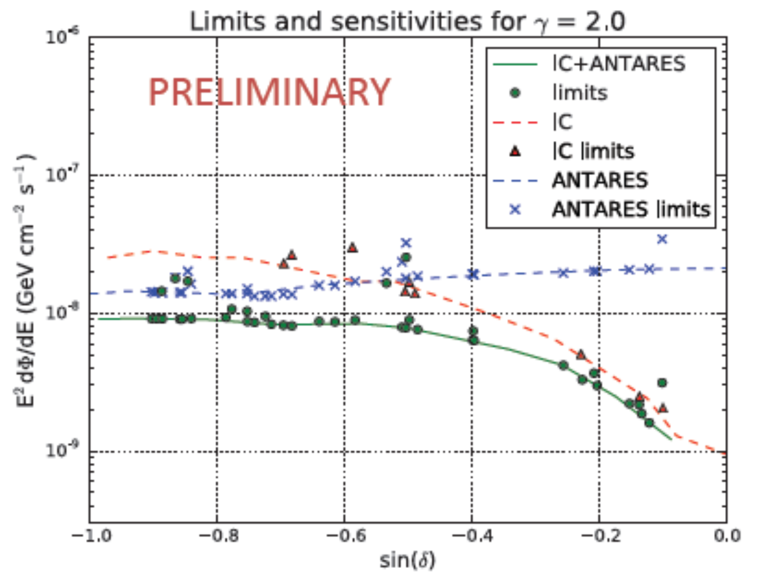
📖 *1511.02149v1 accepted in ApJ*

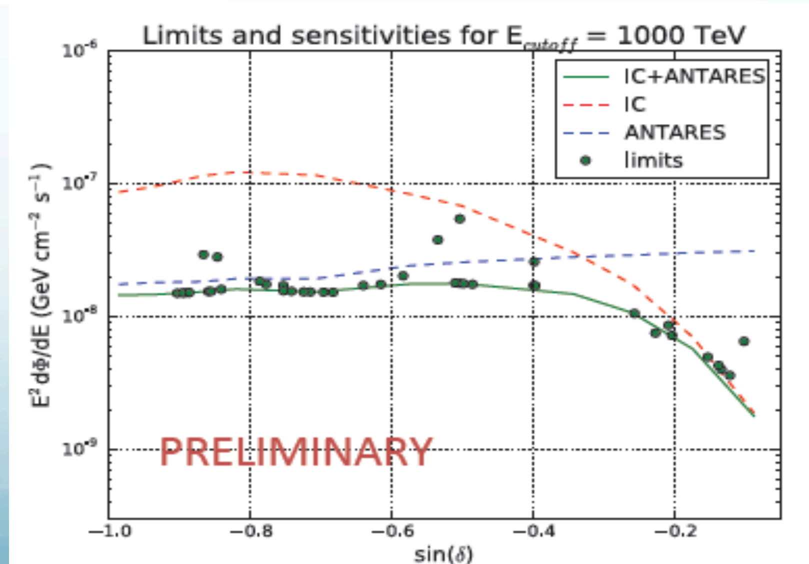




Fraction of signal events which would be detected by each sample ($E^{-\gamma}$):

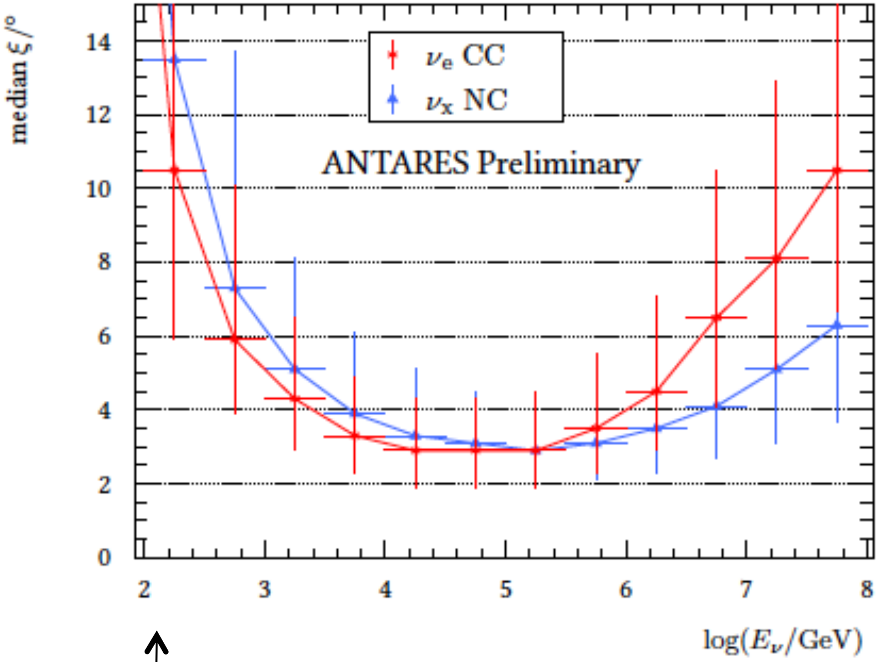
$$\frac{d\Phi}{dE} = \Phi_0 E^{-2} e^{-\sqrt{\frac{E}{E_{cutoff}}}}$$



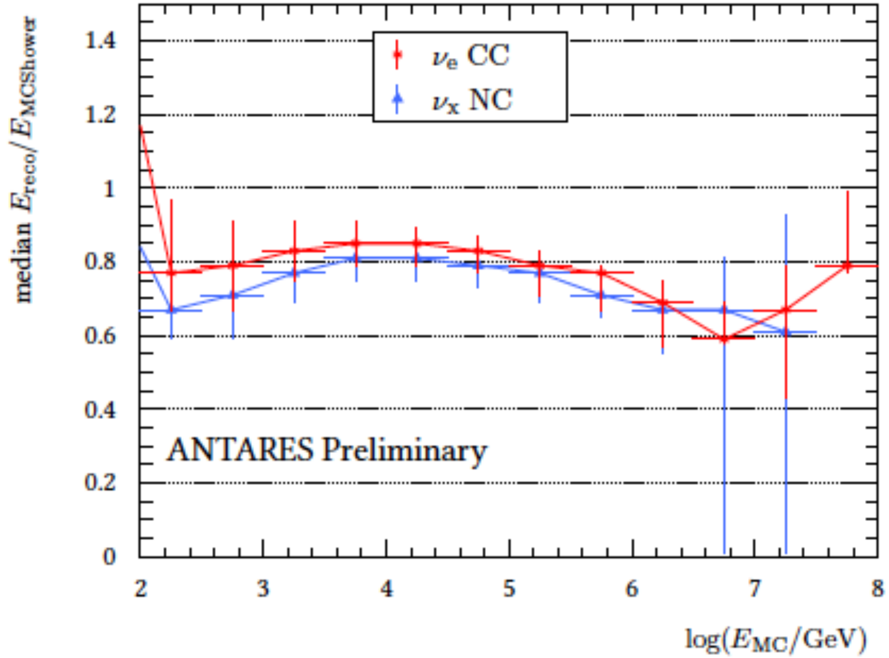


ANTARES can add the cascades

Median angular resolution
(shower vs. neutrino)



Median shower energy resolution



3° median resolution
10 TeV → 1 PeV

Too few photons,
too sparse detector

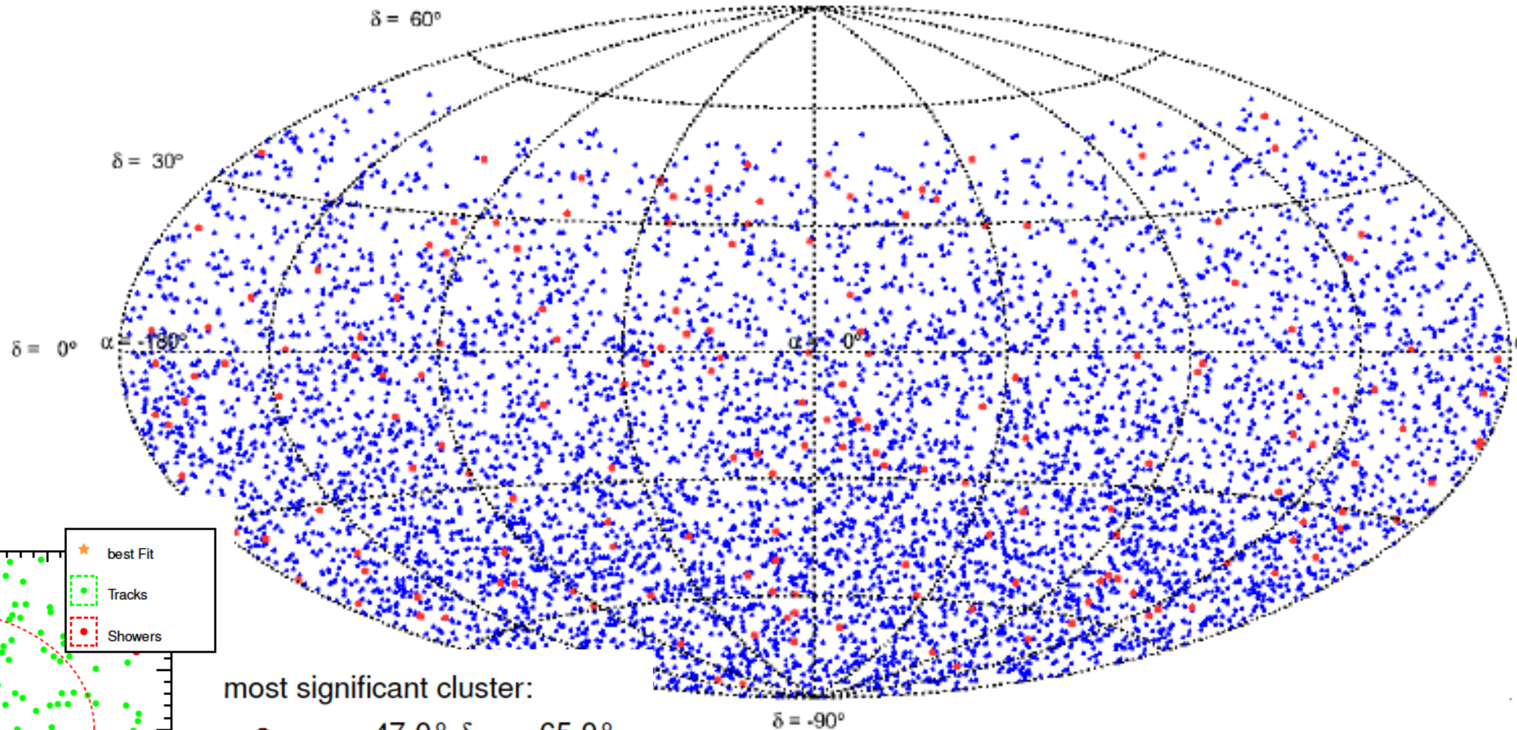
PMT saturation,
limited size of
detector

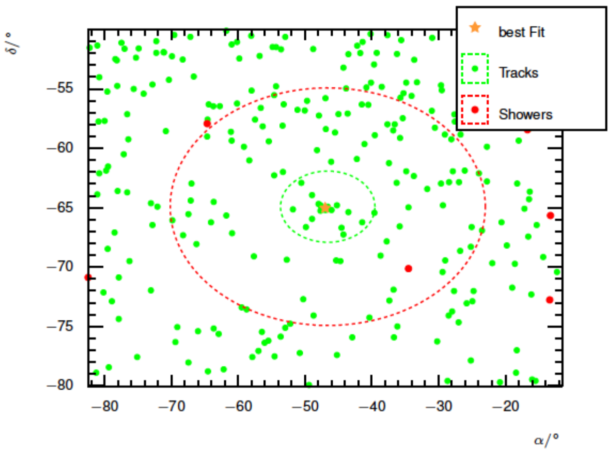
~5% resolution

~20% systematic underestimation
bias corrected a posteriori

Latest ANTARES skymap

- 1690 days from 2007 to the end of 2013 (including 5-line data also in shower channel)
- contains 6490 muon track candidates and 172 cascade events
- for E^{-2} flux with 1:1:1 flavour composition, shower channel increases signal event rate by 45 %



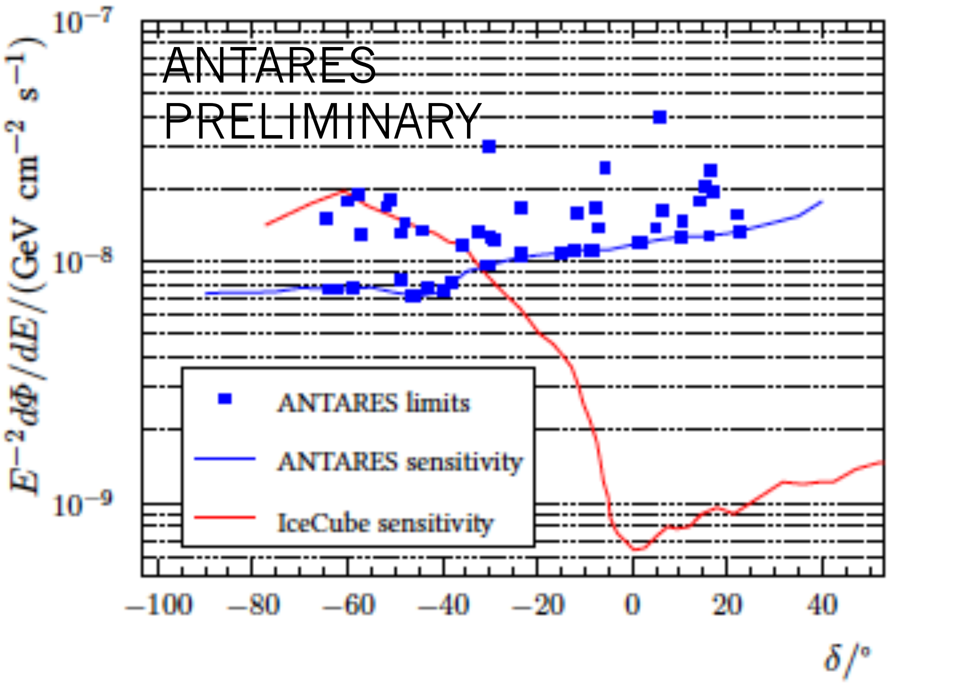


most significant cluster:

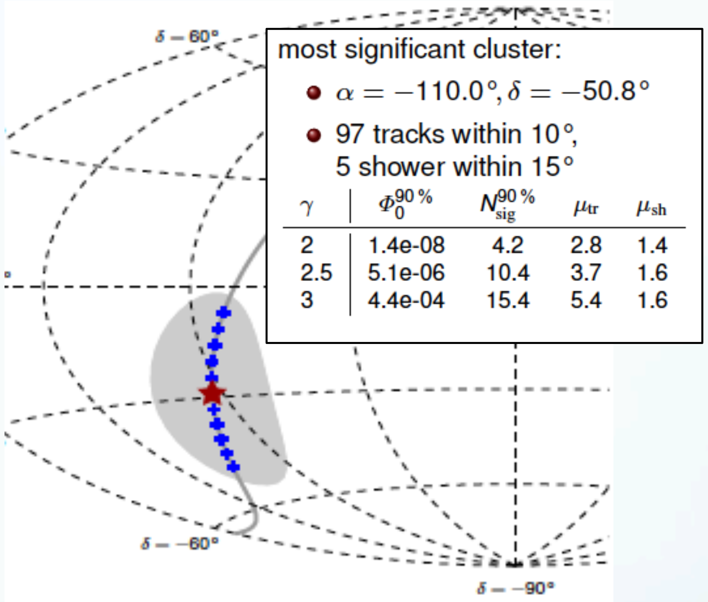
- $\alpha = -47.0°, \delta = -65.0°$
- 17 tracks within 3°, 1 shower within 10°
- NSig = 7.3 + 0.0 (Tracks + Showers)
- p-value: 0.0418, sigma: 2.04

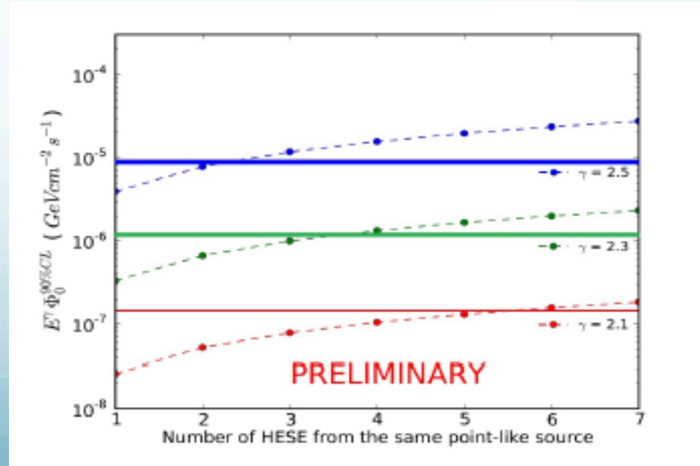
Latest ANTARES PS search

Fixed point source search sensitivity



Scan in Galactic centre region:

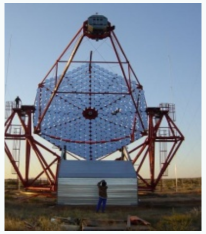


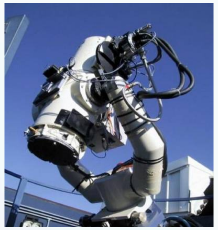


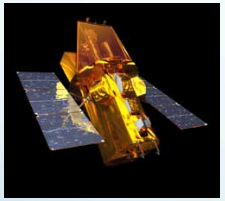
Best limits in Southern Sky in TeV-PeV

Rules out any single PS close to the GC with spectral index of -2.5 as having a flux corresponding to more than 2 HESE.

The Multi-messenger Program







GeV-TeV γ-rays
Fermi /
HESS...

UHECR
Auger

HE neutrinos

Optic / X-ray

Gravitational
Waves
Virgo / Ligo

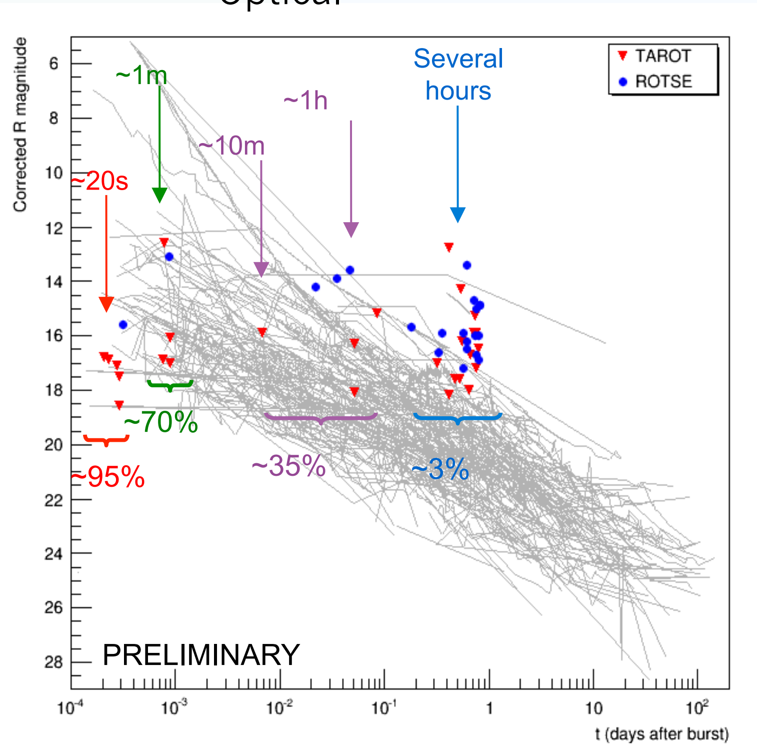
- A way to better understand the sources and the related physics mechanisms
- A way to increase the detector sensitivities (uncorrelated backgrounds)

TAToO: GRB search results

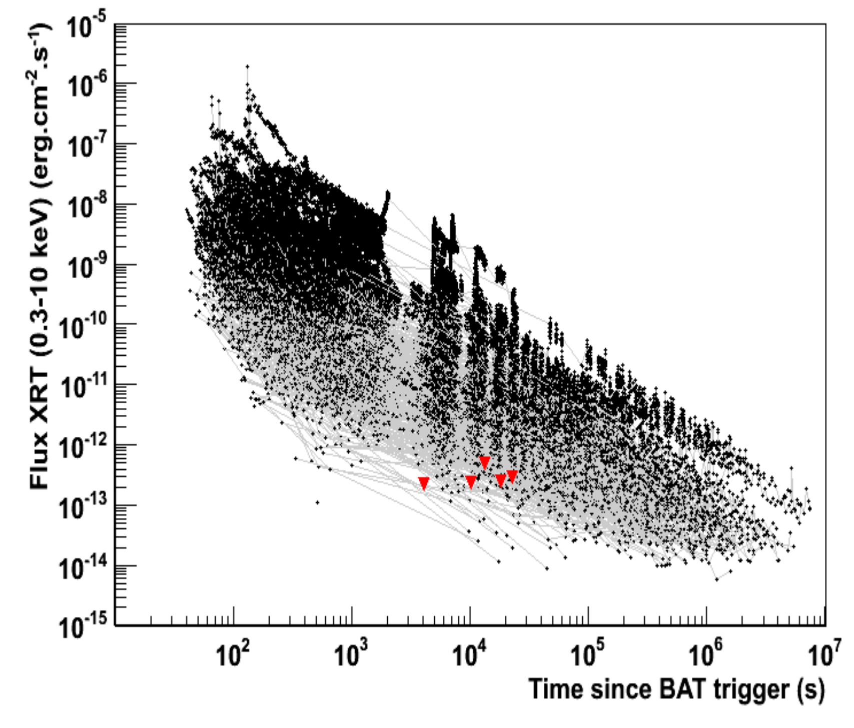
No counterpart observed → limits on Magnitude

📖 *TaToO paper accepted in JCAP*

Optical



X-ray



Grey: 158 optical afterglow lightcurves detected from 1997 to 2014 (Kann).

Grey: 503 X-ray afterglow lightcurves detected by Swift/XRT from 2008 to 2013

Now also Radio (Murchison Widefield Array)

📖 arXiv:1603.02271 accepted in ApJ Letters

GW150914 follow-up

LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech ar

About | Learn More | News | Gallery | Educational Resou

Detection Papers

Scientific paper describing the detection published in *PRL* 116, 061102 (2016).

Companion Papers

"Unmodeled Searches Used for First LIGO Gravitational Wave Detection"

"A Search for Gravitational Waves from Compact Binary Coalescences in 16 Days of Advanced LIGO Data associated with GW150914"

"GW150914: A Merging Binary Black Hole at Redshift ~0.1"

"Constraints on the Rate of Binary Black-hole Coalescences from 16 Days of Advanced LIGO Observations"

"Astrophyiscal Implications of the Binary Black-hole GW150914 Detected by LIGO"

"GW150914: A Black-hole Binary Coalescence as Predicted by General Relativity"

"The Stochastic Gravitational-wave Background from Black Hole Binaries: The implications of GW150914"

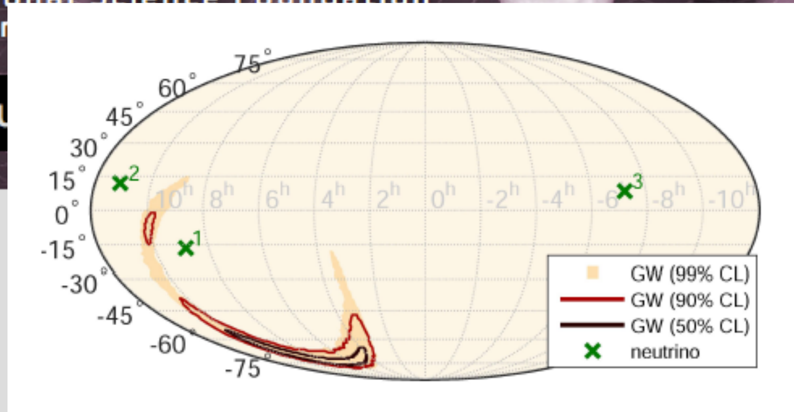
"Calibration Uncertainty of the Detectors in Early Advanced LIGO"

"Characterization of Transient Noise in the Advanced LIGO Interferometers Relevant to Gravitational Wave Signal GW150914"

"Localization and Broadband Follow-up of the Gravitational-wave Candidate G184098"

"High-energy Neutrino Follow-up Search of the First Advanced LIGO Gravitational Wave Event with IceCube and ANTARES" ←

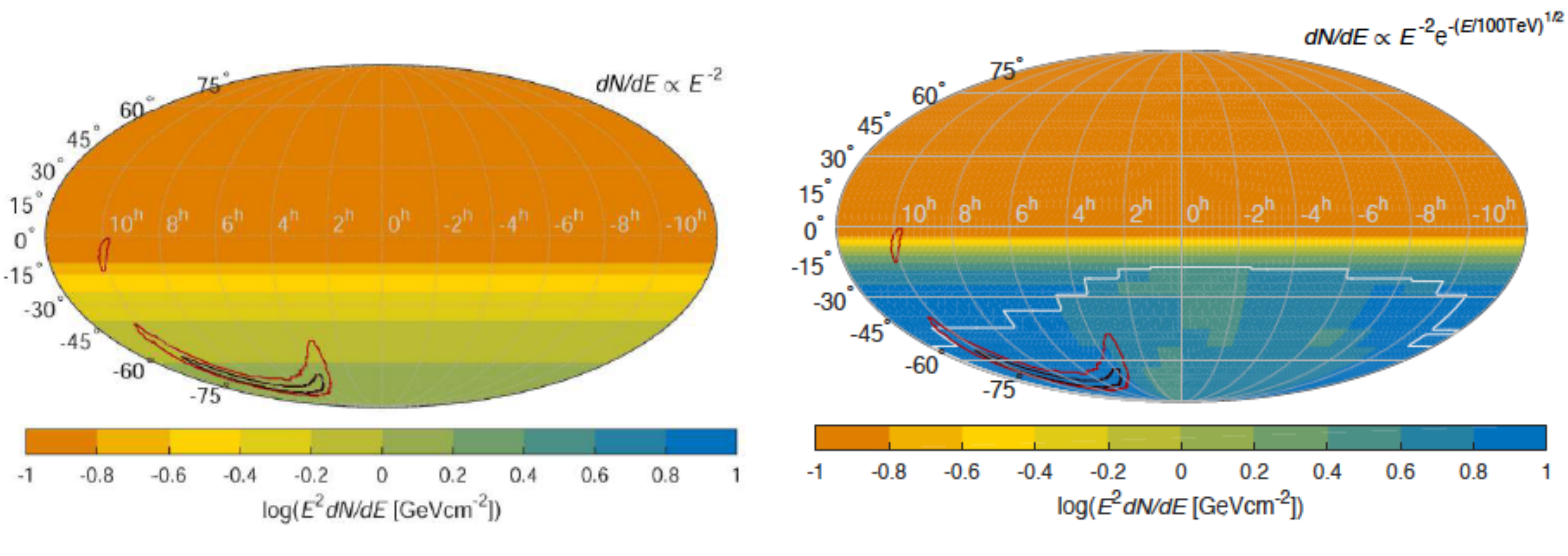
"The Advanced LIGO Detectors in the Era of First Discoveries"



arXiv:1602.05411 – submitted to PRD

GW150914 follow-up

=> (best)Limits on the neutrino spectral fluence (E^{-2} spectrum)



⇒ Limits from ANTARES dominates below O(100 TeV) (white line)

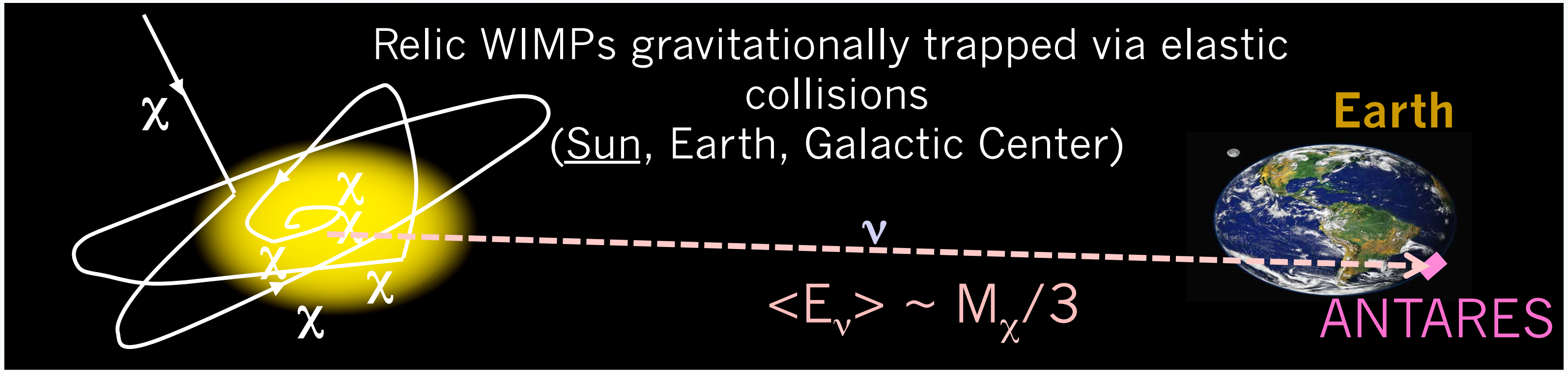
➜ Integrating emission between [100 GeV; 100 PeV] and [100 GeV; 100 TeV]:

$$E^{ul}_{\nu,tot} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{gw}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Size of GW160914 : 590 deg² ANTARES resolution: <0.5 deg²

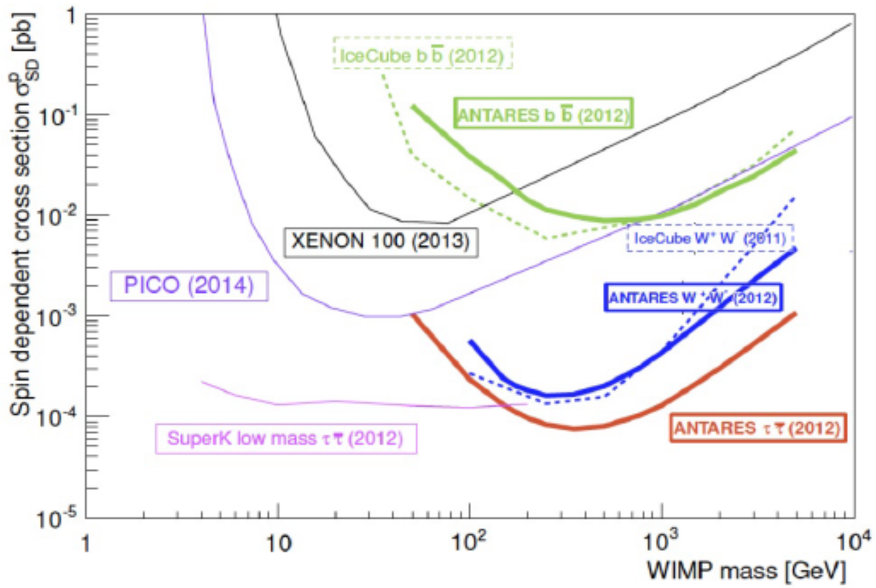
A rapid observation of counterpart would help a better localization for further follow-up

Dark matter indirect searches



Sun

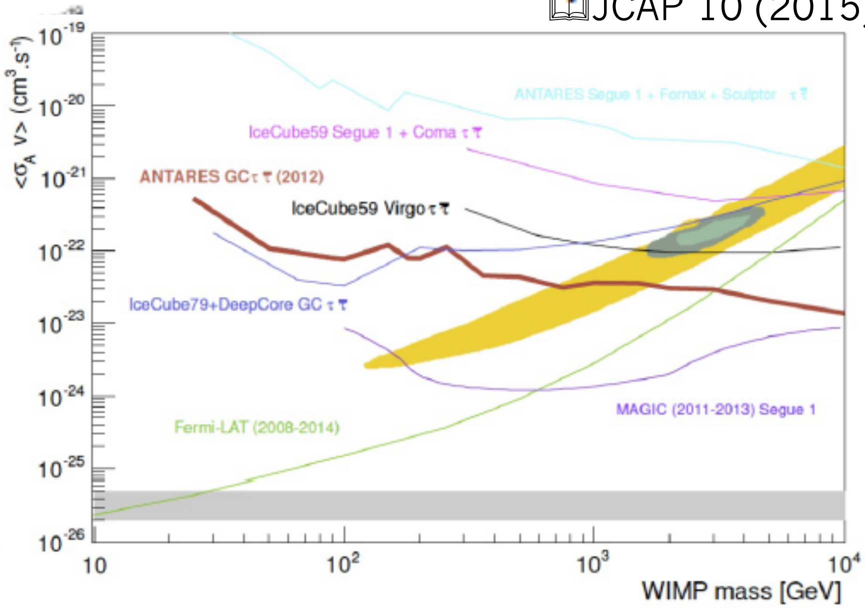
📖 arXiv:1603.02228



- Limits in the spin-dependent Wimp-nucleon cross section

Galaxy

📖JCAP 10 (2015) 068



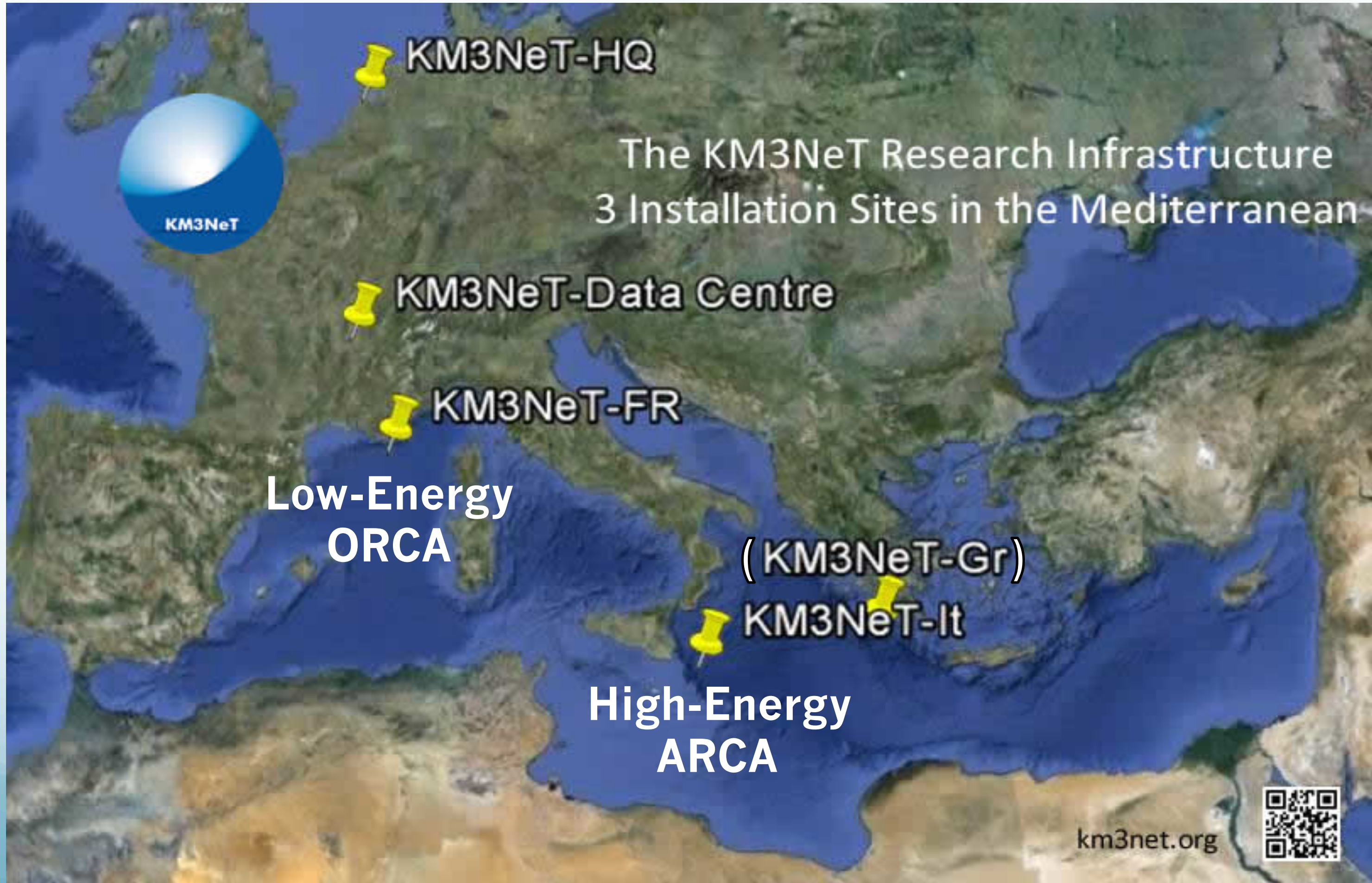
- Limits on the Wimp self annihilation cross section

KM3NeT: Next generation detectors

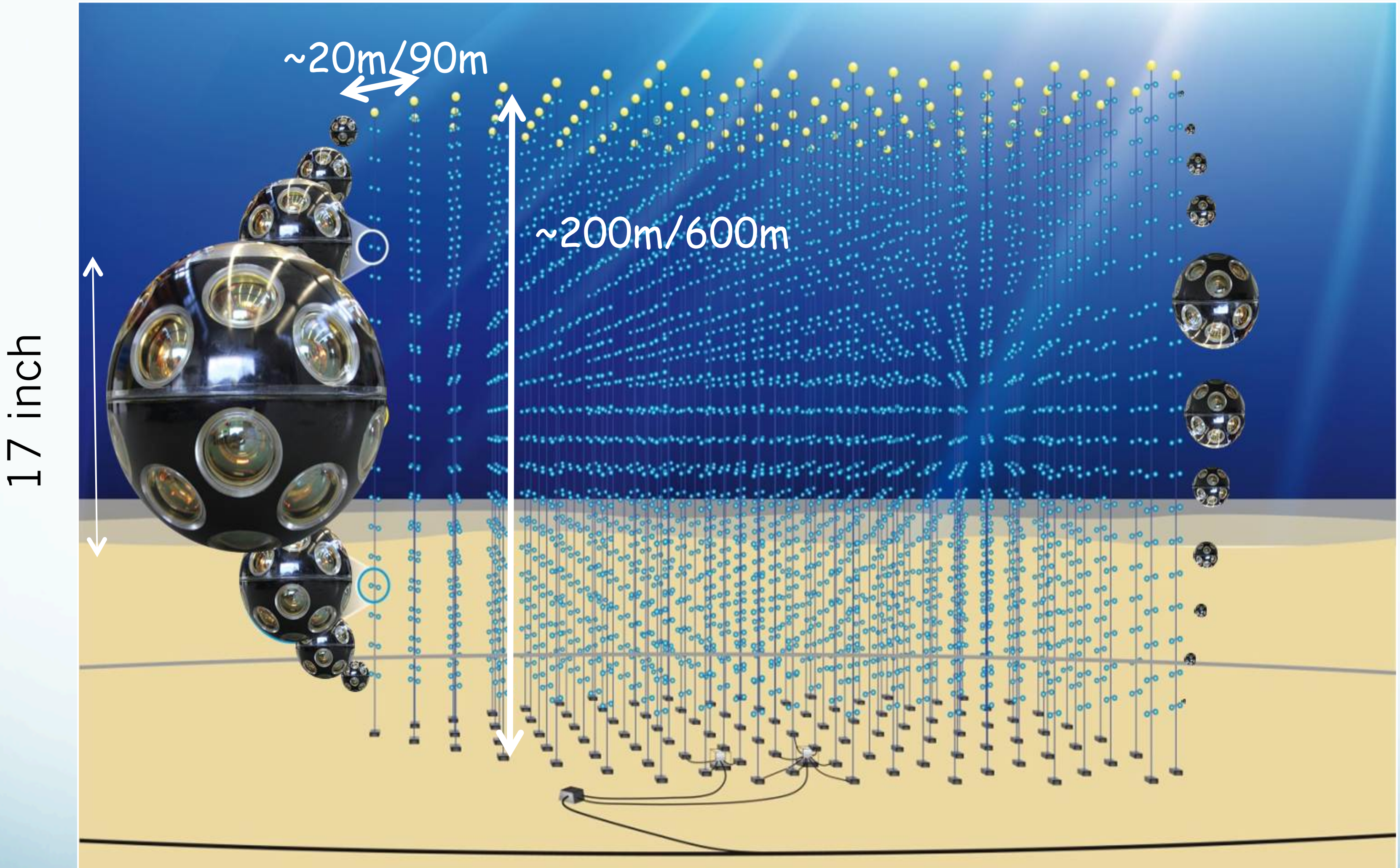
KM3NeT is a distributed research infrastructure with 2 main physics topics:

Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos

Single Collaboration -- Single Technology



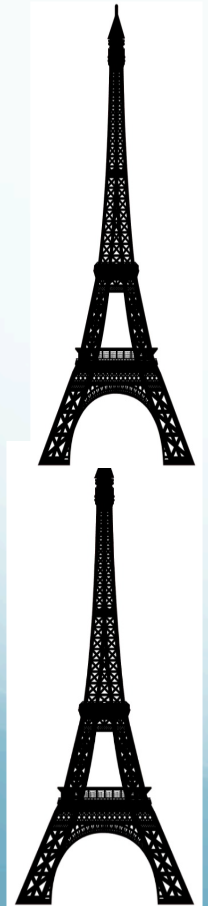
Detector technology

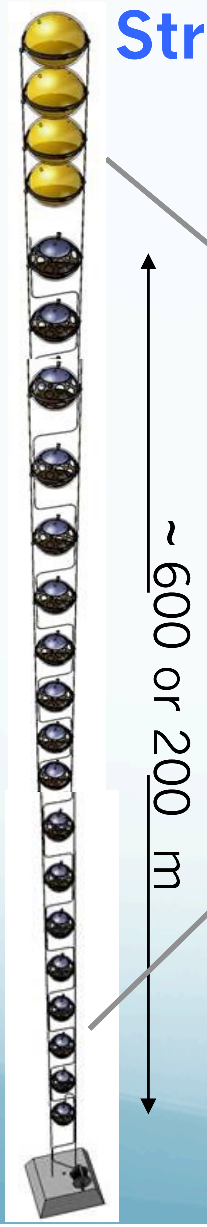


- 31 3” PMTs
- Digital photon counting
- Directional information
- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

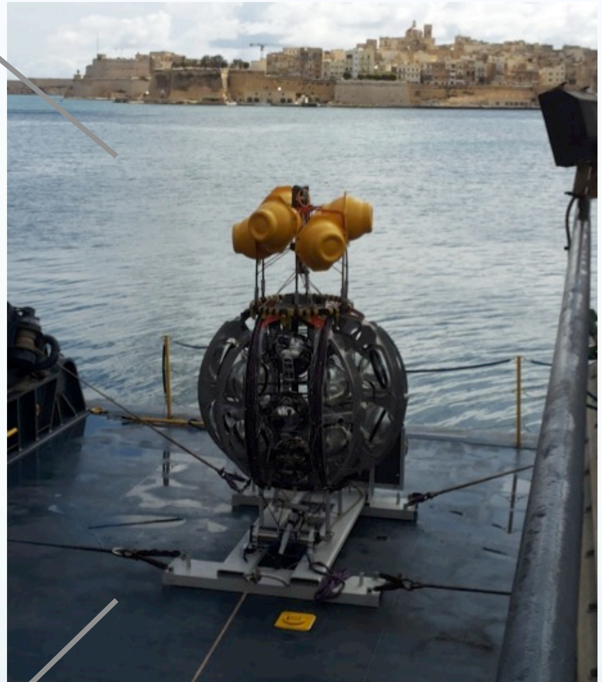
KM3NeT design

String





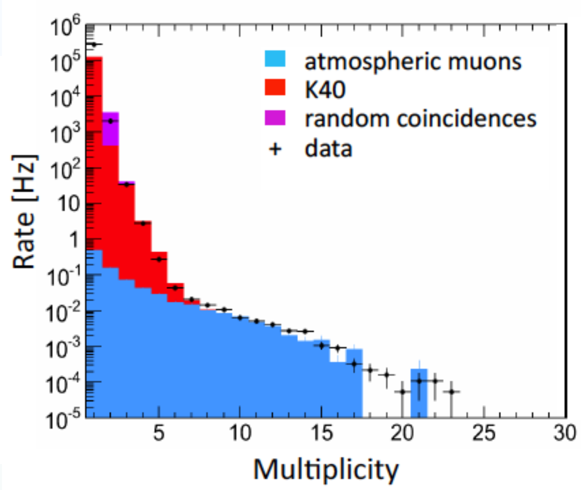
Launcher Vehicle



- *Rapid deployment*
- *Compact*
- *Autonomous unfurling*
- *Recoverable*

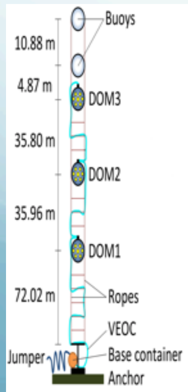
KM3NeT Prototypes

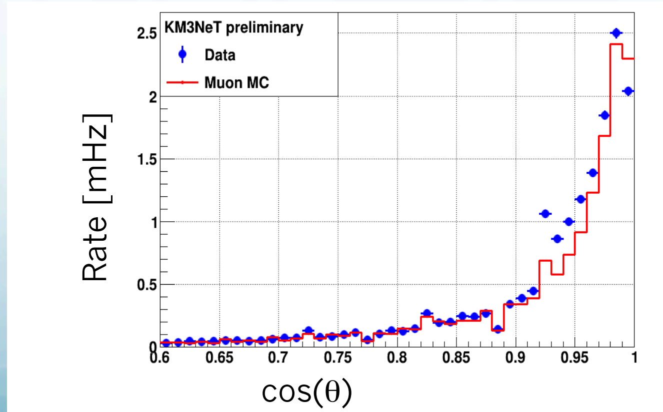
1) Optical Module deployed at Antares, April 2013 (2500 m)



📖 Eur. Phys. J. C (2014) 74:3056

2) Mini string deployed at Capo Passero, May 2014 (3500 m)





📖 arXiv:1510.01561 Accepted by Eur. Phys. J. C

A phased implementation

Parallel to ORCA (+40M€)

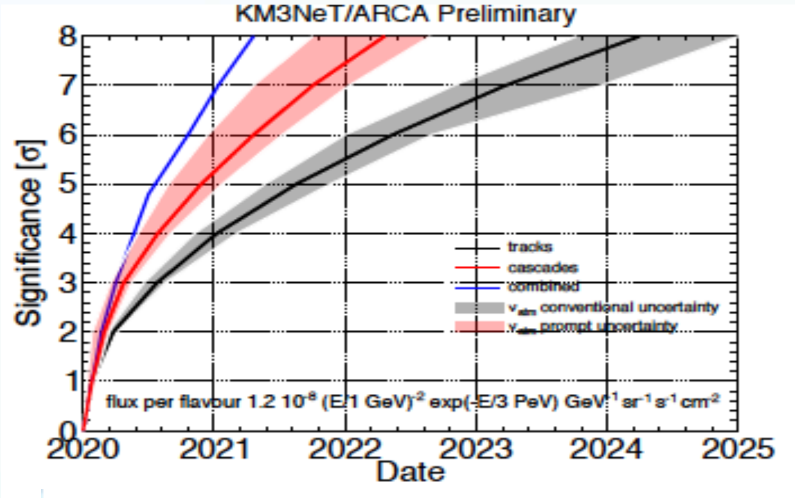
PHASE 1:

Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It

31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)

Proof of feasibility of network of distributed neutrino telescopes and more?

31 M€
FUNDED
ONGOING



2016 PHASE 2:ARCA

230 lines (2 building blocks)

Investigation of IceCube signal

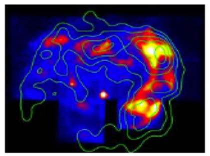
Letter of Intent
arXiv:
1601.07459

2020 KM3NeT NEXT:

6 building blocks

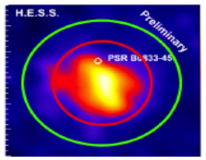
Neutrino astronomy

RXJ1713¶

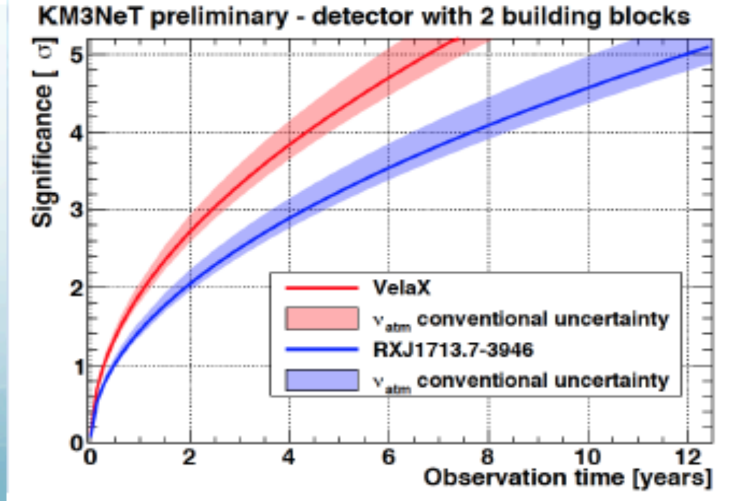


S.R. Kelner, *et al*

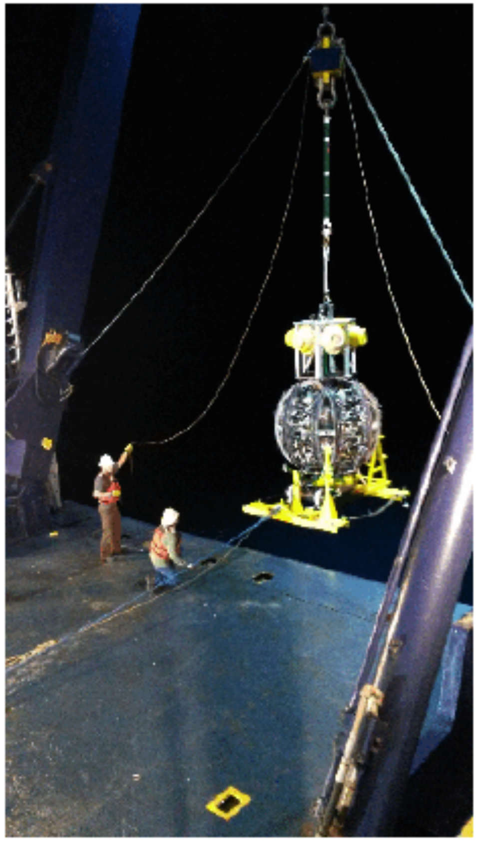
Vela X§



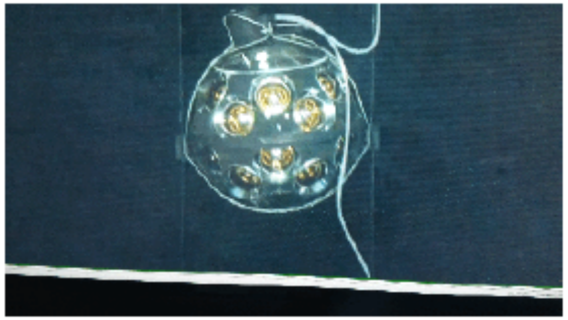
Villante & Vissani



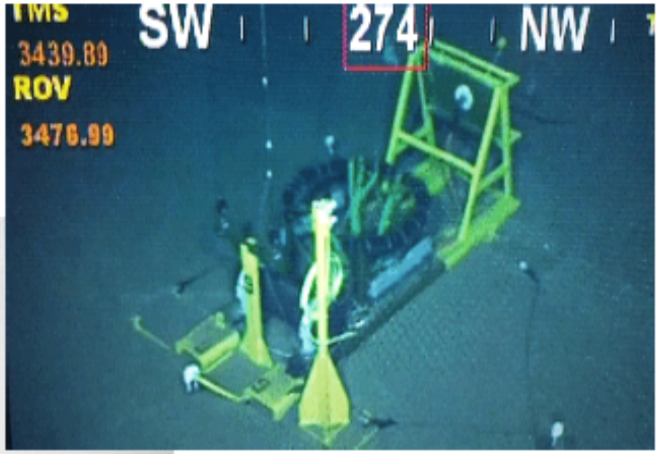
A first string working

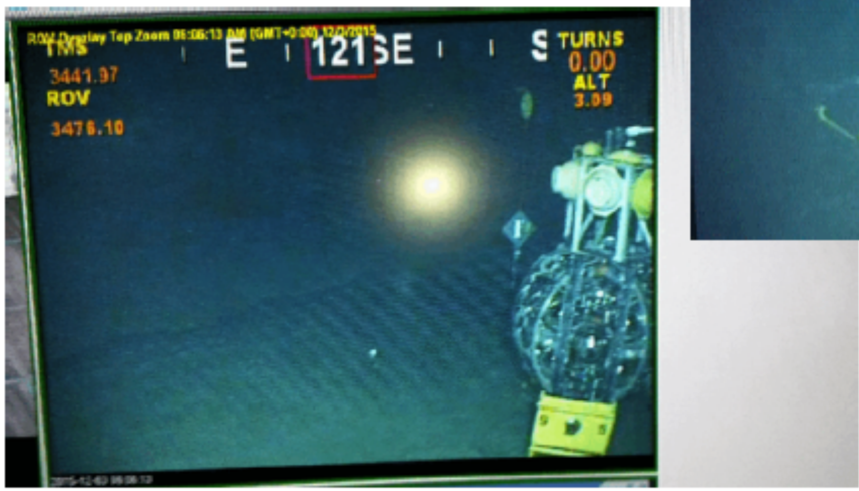


04/12/2015
Laid on seabed
Unfurled
Powered on
Taking data !



First reconstructed μ seen!

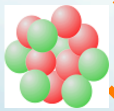




^{40}K-based Calibration

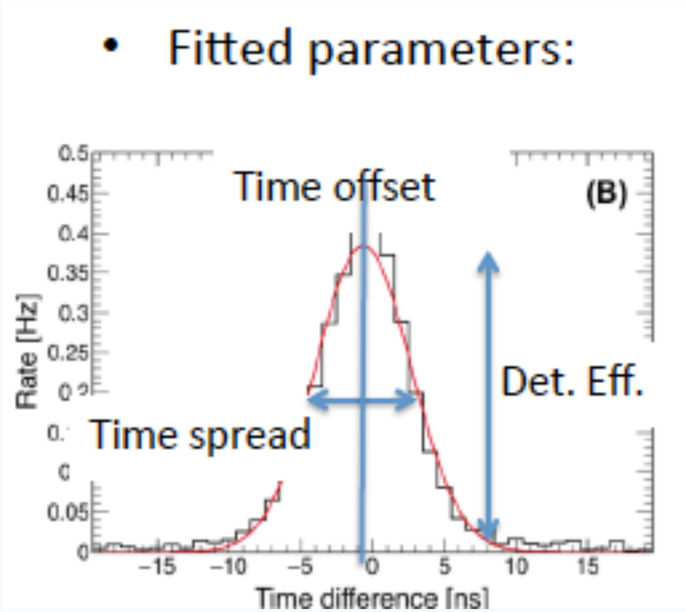
^{40}K

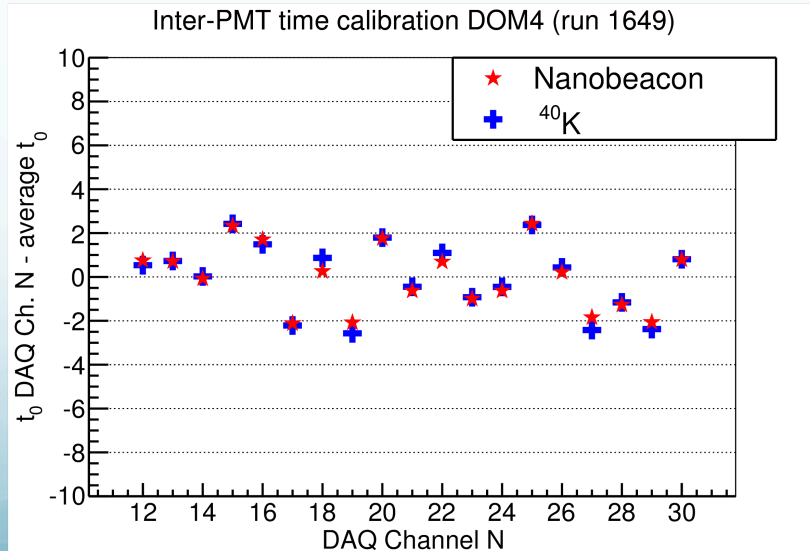
e$^-$ (β decay)



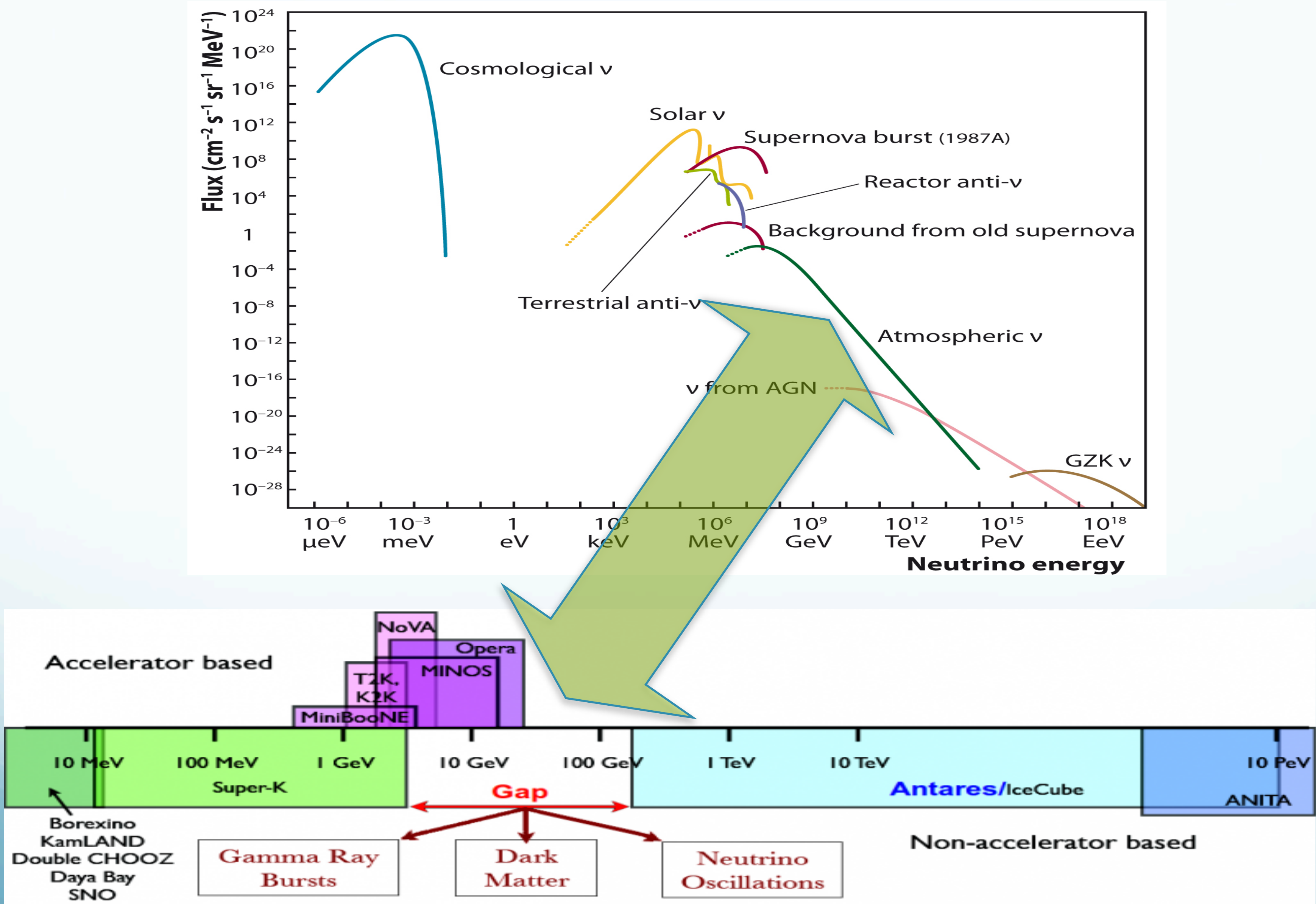
Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

^{40}Ca





LE neutrinos with deep-sea detectors



Oscillations of Massive Neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&c_{23}&s_{23}\\0&-s_{23}&c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13}&0&s_{13}e^{-i\delta_{CP}}\\0&1&0\\-s_{13}e^{i\delta_{CP}}&0&c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{21}&s_{12}&0\\-s_{12}&c_{12}&0\\0&0&1\end{pmatrix}\cdot\begin{pmatrix}e^{i\eta_1}&0&0\\0&e^{i\eta_2}&0\\0&0&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

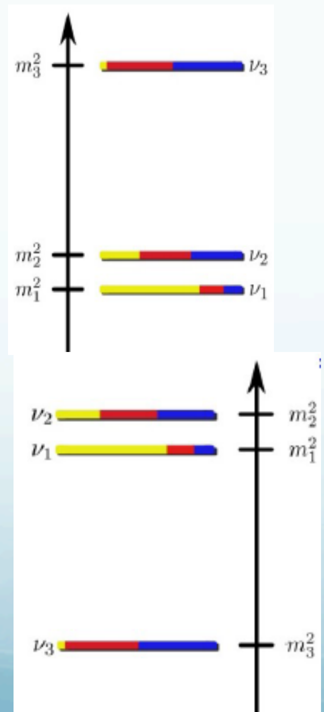
Atmospheric **θ_A~45°** | Reactor θ_{13}~9° | Solar $\theta_\odot$~30° | Majorana

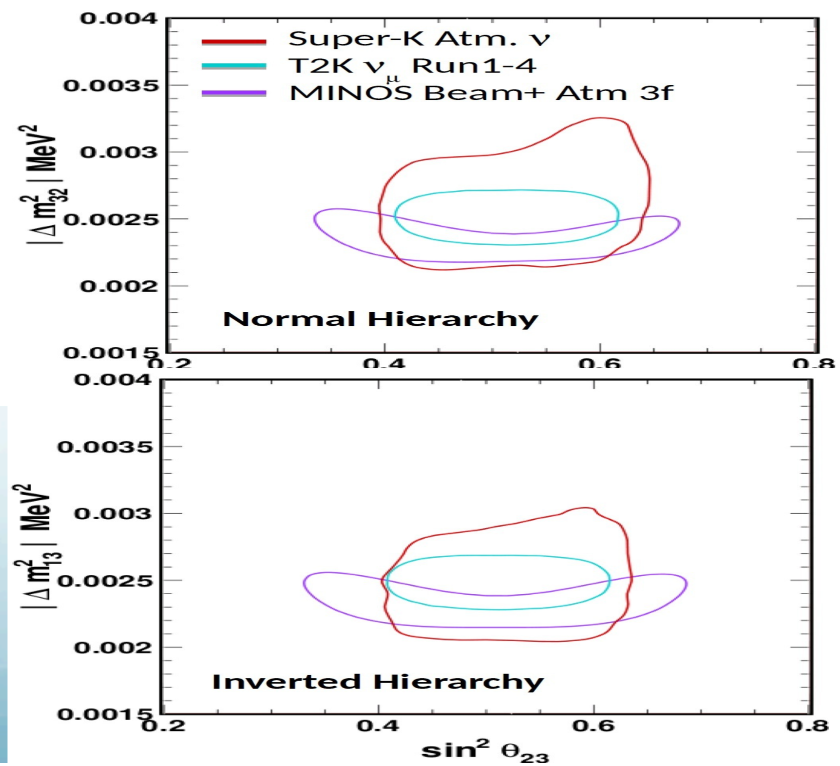
↓

CP violating phase δ_{CP}

$$m_1^2 < m_2^2$$
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

All parameters measured to fair precision except:
<u>mass hierarchy</u>
octant of θ_{23}
CP phase





Oscillations of Massive Neutrinos

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\cdot\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13}\end{pmatrix}\cdot\begin{pmatrix}c_{21} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\cdot\begin{pmatrix}e^{i\eta_1} & 0 & 0\\ 0 & e^{i\eta_2} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Atmospheric $\theta_A \sim 45°$ | Reactor $\theta_{13} \sim 9°$ | Solar $\theta_\odot \sim 30°$ | Majorana

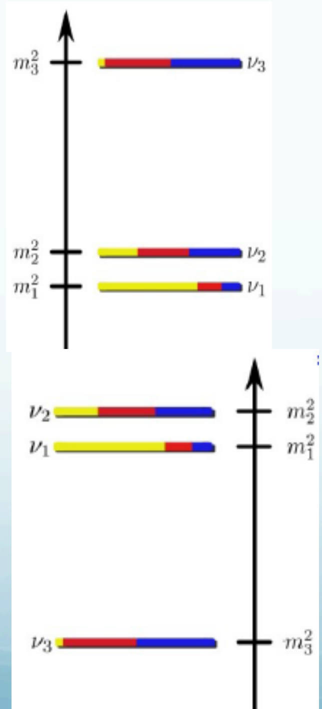
↓

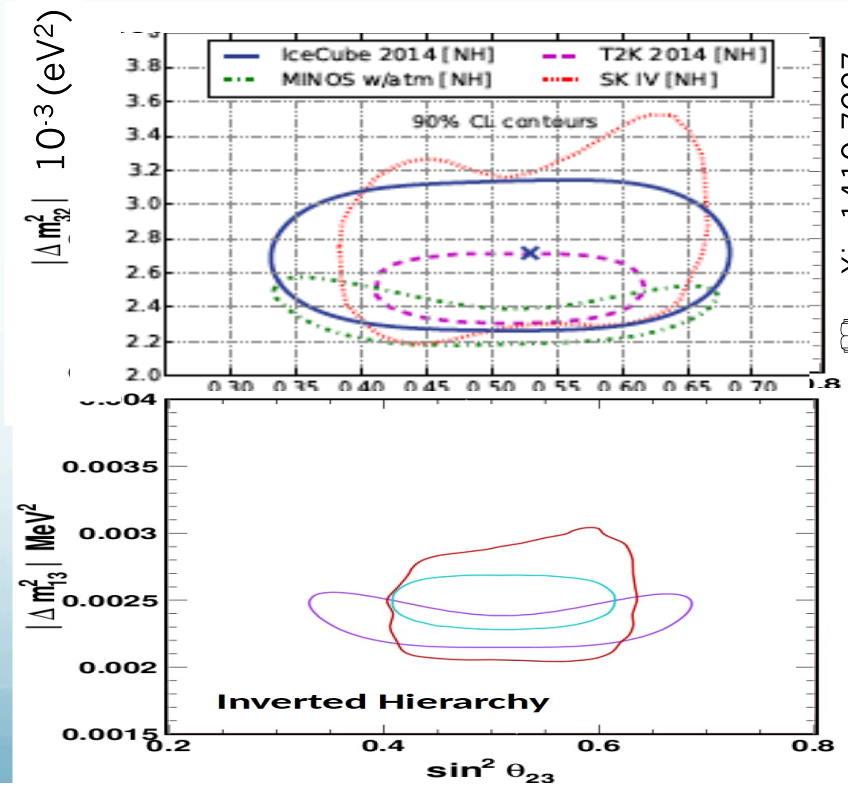
CP violating phase δ_{CP}

$$m_1^2 < m_2^2$$

$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

All parameters measured to fair precision except:
<u>mass ordering</u>
octant of θ_{23}
CP phase



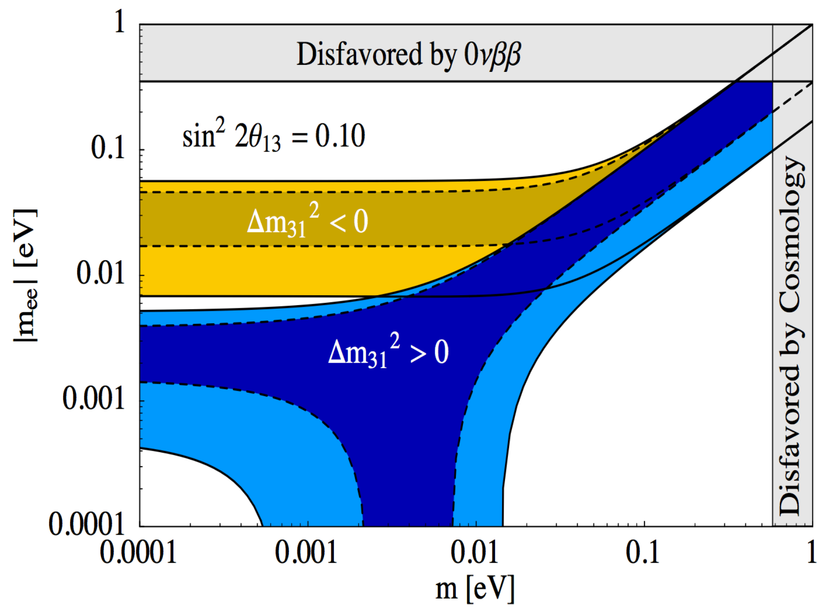


arXiv:1410.7227

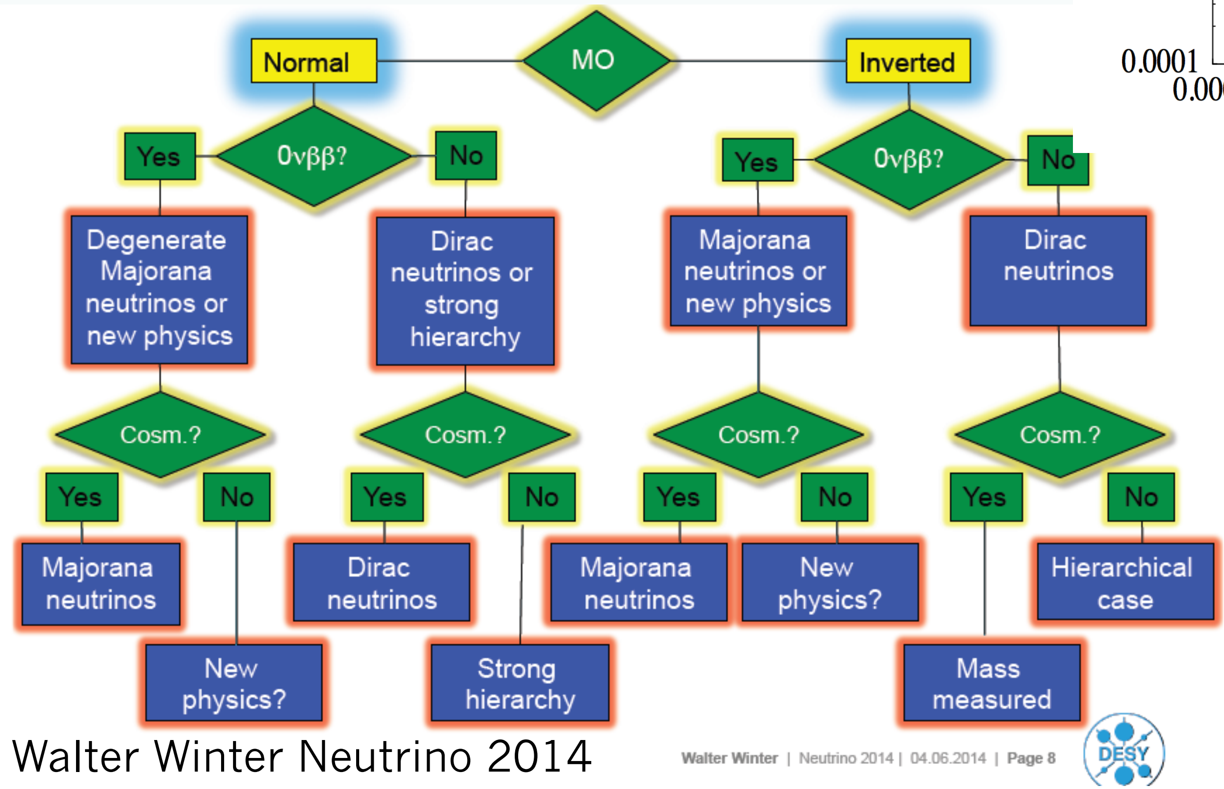
Why knowing the mass hierarchy?

- Prime discriminator for theory models

- Help measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Origin of neutrino mass and flavor
- Core-Collapse Supernovae Physics



Impact of direct mass ordering measurement



Walter Winter Neutrino 2014

MH with LBL experiments

- « Standard approach » :probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm^2_{31}

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\, P_{2\nu} = \sin^2\theta_{23}\,\sin^2 2\theta^{m}_{13}\,\sin^2\left(\frac{\Delta^{m} m^2_{31} L}{4E_\nu}\right)$$

[Neglecting solar (> a few GeV and >1000’s km) and CP violation effects]

- Insensitive to the sign of Δm^2_{13} at leading order.
- Matter effects (MSW) come to the rescue

$$P^{m}_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\,\sin^2 2\theta^{m}_{13}\,\sin^2\left(\frac{\Delta^{m} m^2_{31} L}{4E_\nu}\right)$$

$$\sin^2 2\theta^{m}_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^{m} m^2_{31}}\right)^2$$

$$\Delta^{m} m^2_{31} \equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - 2E_\nu A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

→ Additional potential A in the Hamiltonian

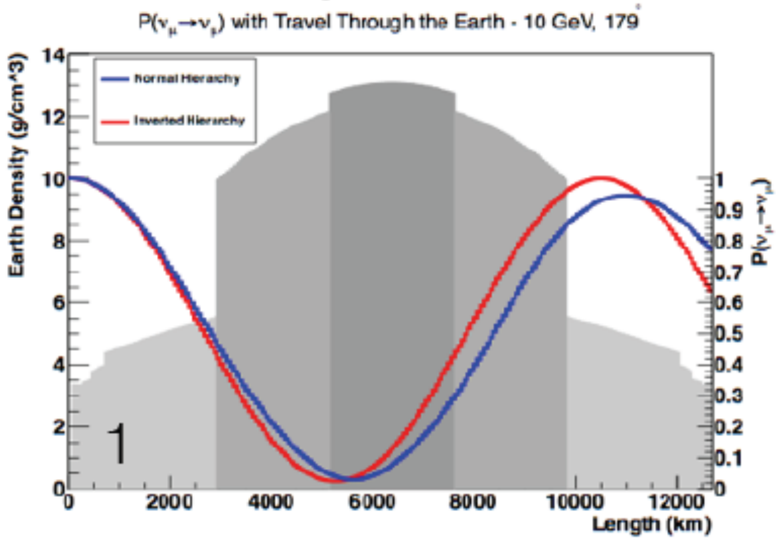
$A \equiv \pm\sqrt{2} G_F N_e$ (–)+ for (anti-)neutrinos

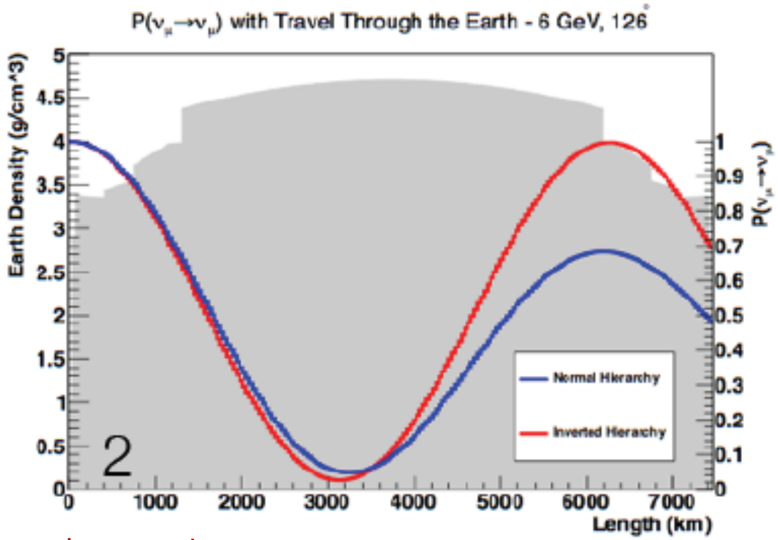
→ Modify the oscillation probability

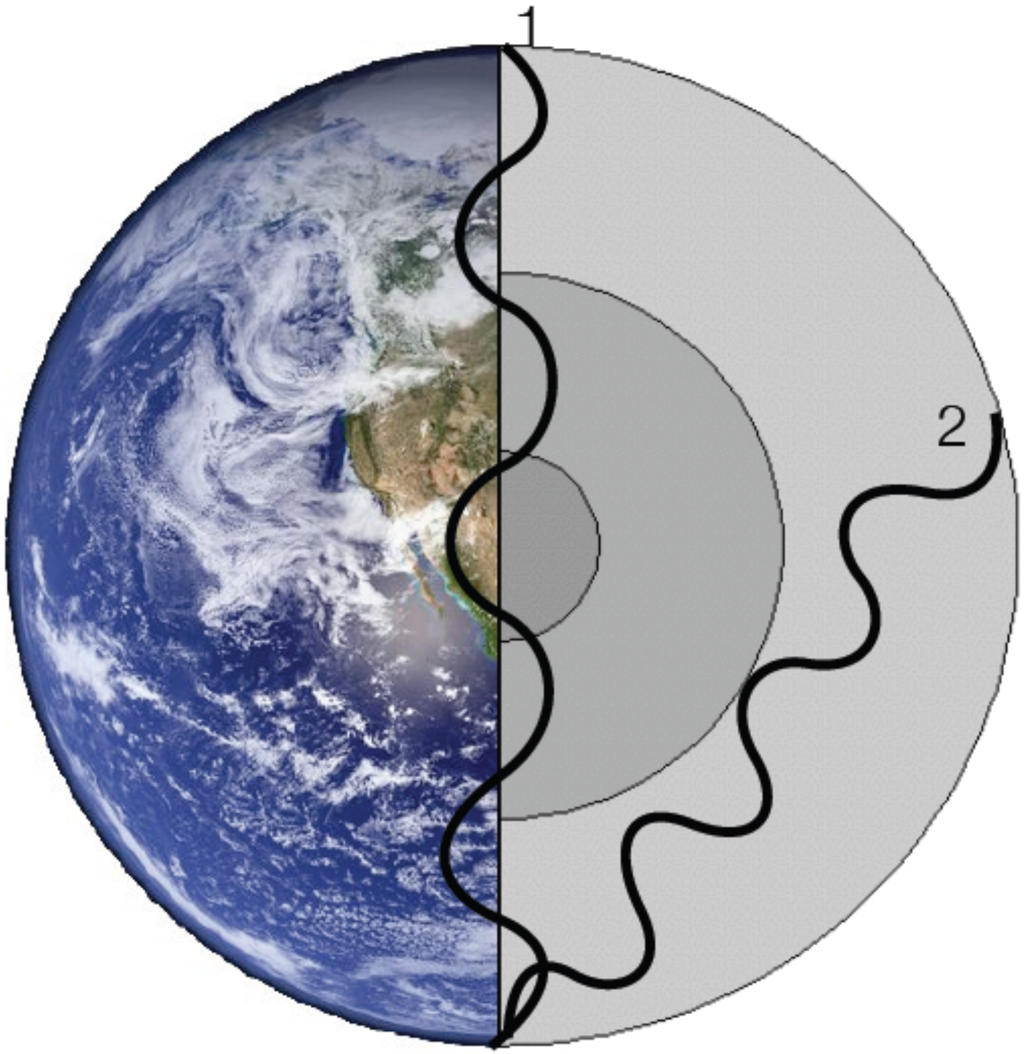
Resonance energy Earth:
- Mantle E_{res} ~ 7 GeV
- Core E_{res} ~ 3 GeV

- Earth density variations (e.g. mantle-core) also affect the oscillations (*parametric resonance*)

Matter effect in the Earth





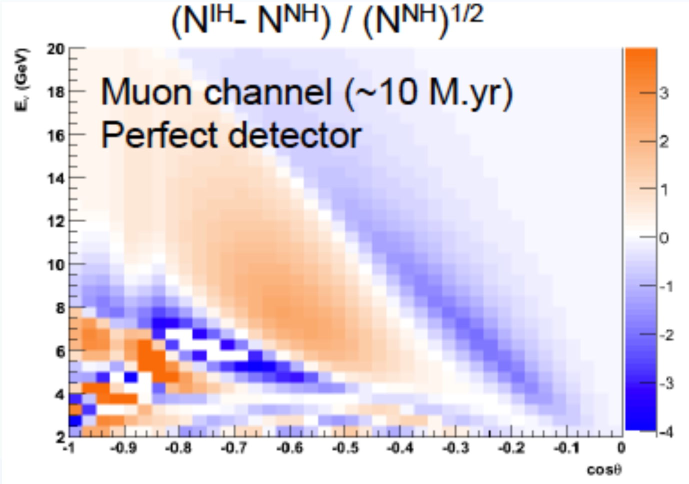


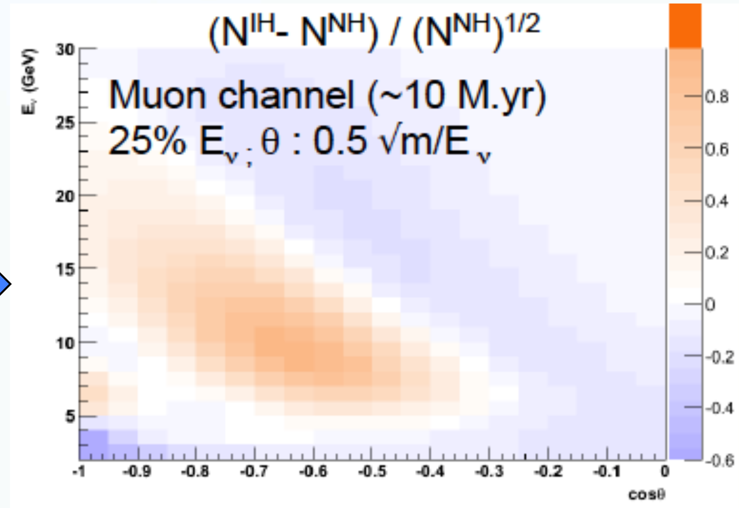
Requirements:

- $\Delta_{13} \sim A$ matter potential must be significant but not overwhelming
- L large enough – matter effects are absent near the origin
- Distinction between neutrinos and anti-neutrinos → different flux and cross-sections!

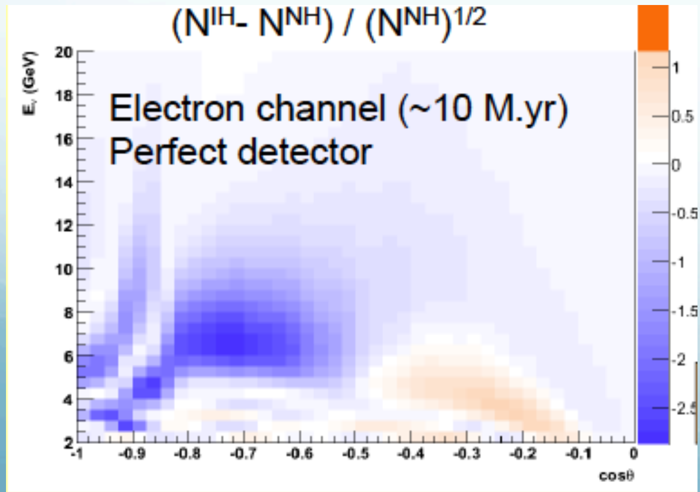
Muon versus Electron channels

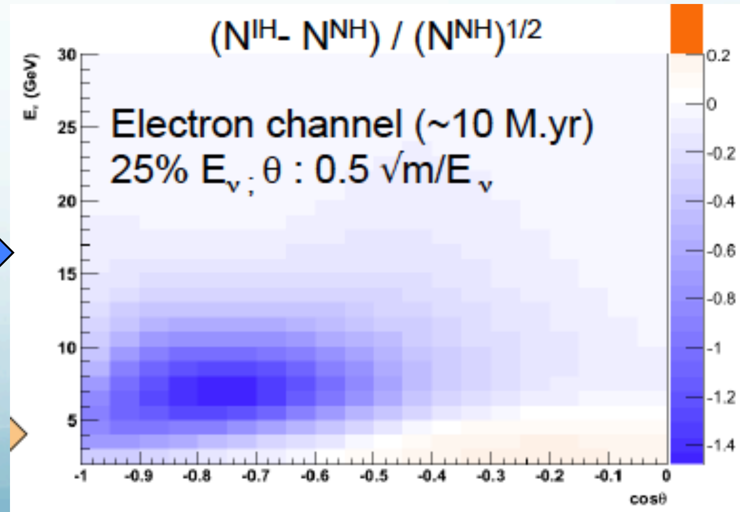
Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:
(Significances a la Akhmedov et al. 📖 JHEP 02 (2013) 082)





E, θ smearing
(kinematics
+ detector
resolution)

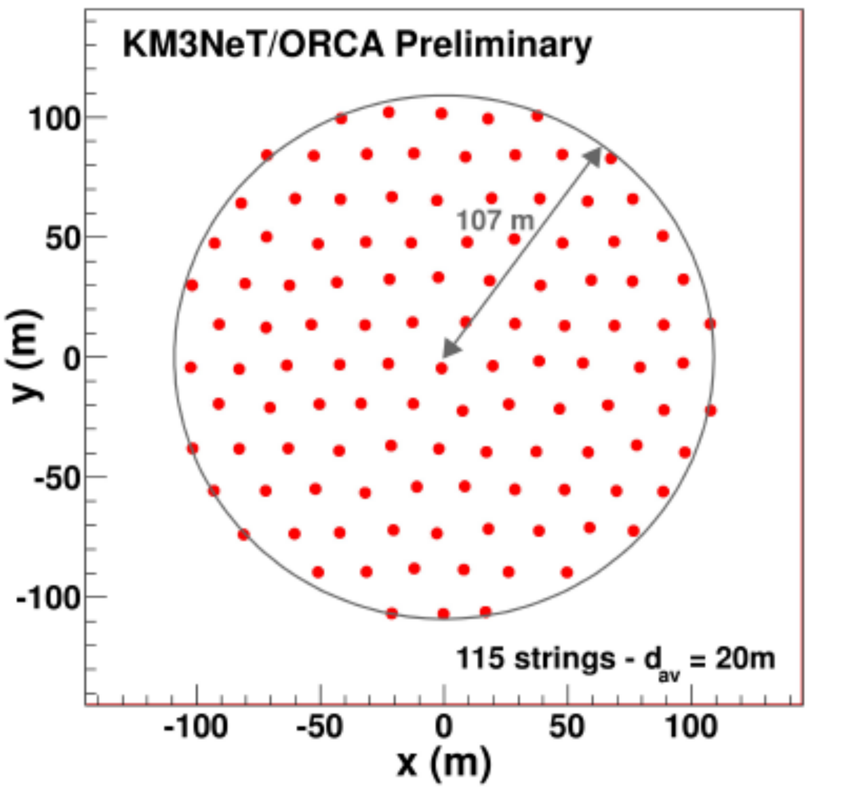


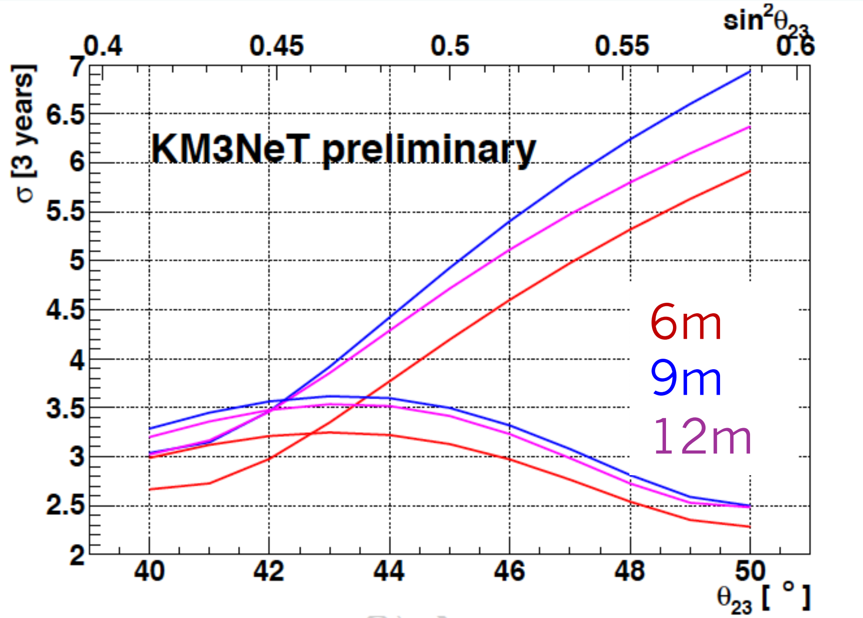


The ORCA detector

115 lines, 20m spaced,
18 DOMs/line 9m spaced

Instrumented volume ~6.5 Mt,
2070 OM
Optical background:
10kHz/PMT & 500Hz coincidence





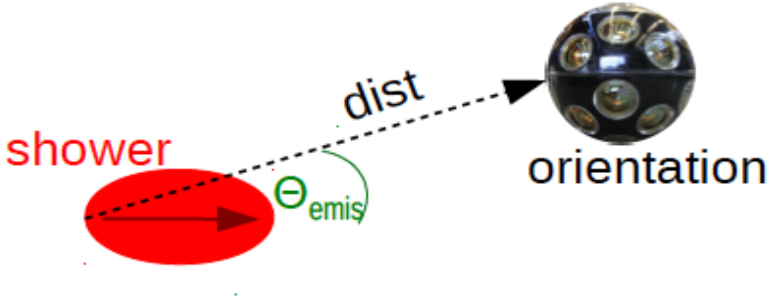
Vertical spacing optimized ~9m -- Horizontal spacing constrained by deployment

Shower reconstruction (ν_e)

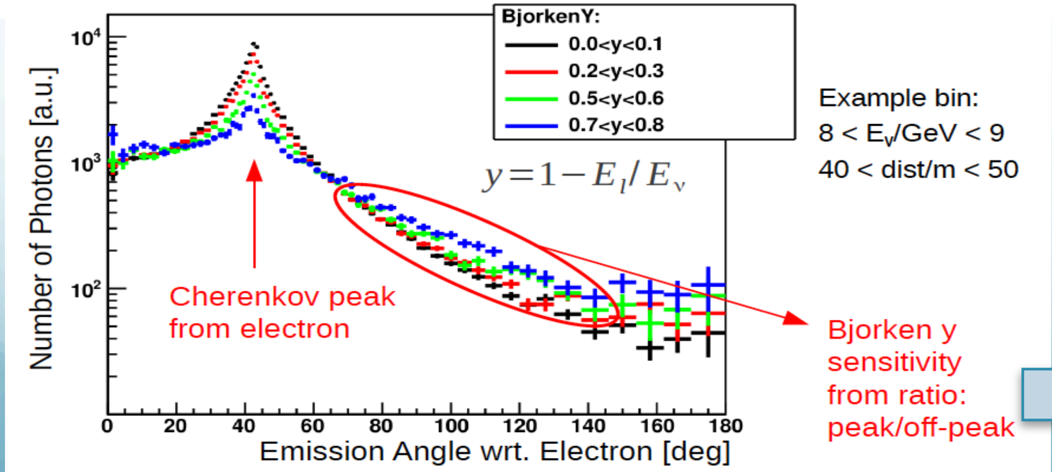
- 1. Vertex fit:
  - maximum likelihood method based on time residuals
  - two fits: first robust prefit then more precise fit

Res. (σ): 0.5-1 m

- 2. Energy + direction fit:
  - PDF for number of expected photons depending on: E_ν , Bjorken y, emission angle, OM orientation, distance(OM,vertex)



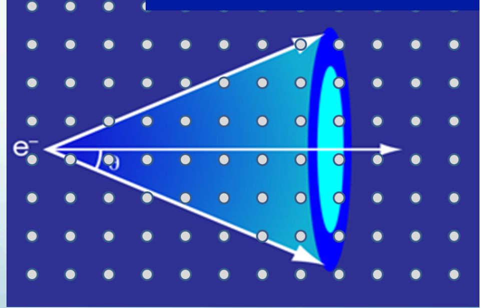
  - maximum likelihood method based probability that hits have been created by certain shower hypothesis (E_ν, Bjorken y, direction)



Example bin:
$8 < E_\nu/\mathrm{GeV} < 9$
$40 < \mathrm{dist/m} < 50$

Bjorken y sensitivity from ratio: peak/off-peak

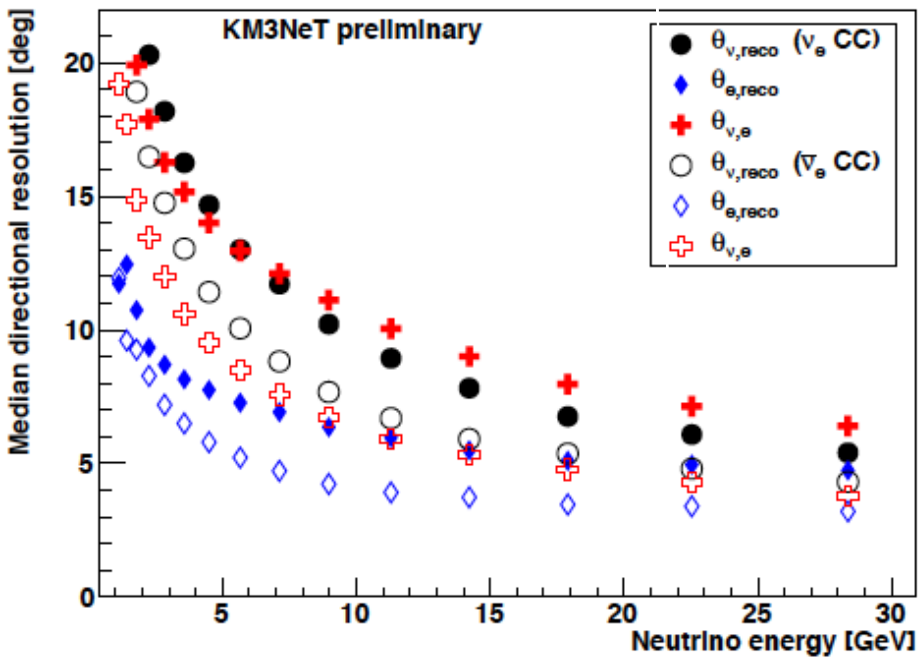
Water preserves Cherenkov cone



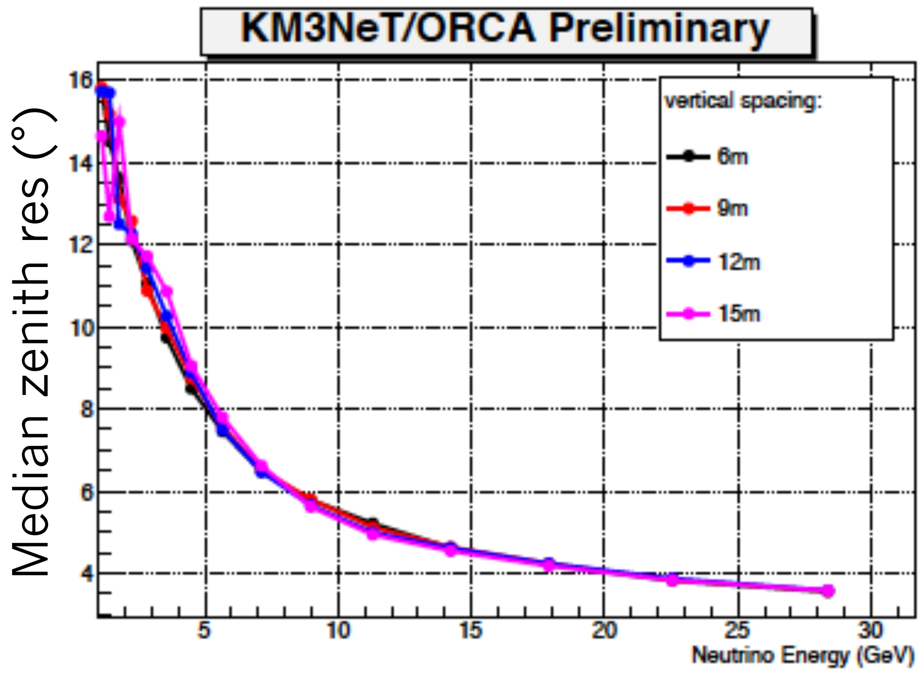
Much more challenging in Ice

Angular Resolutions

cascade



track

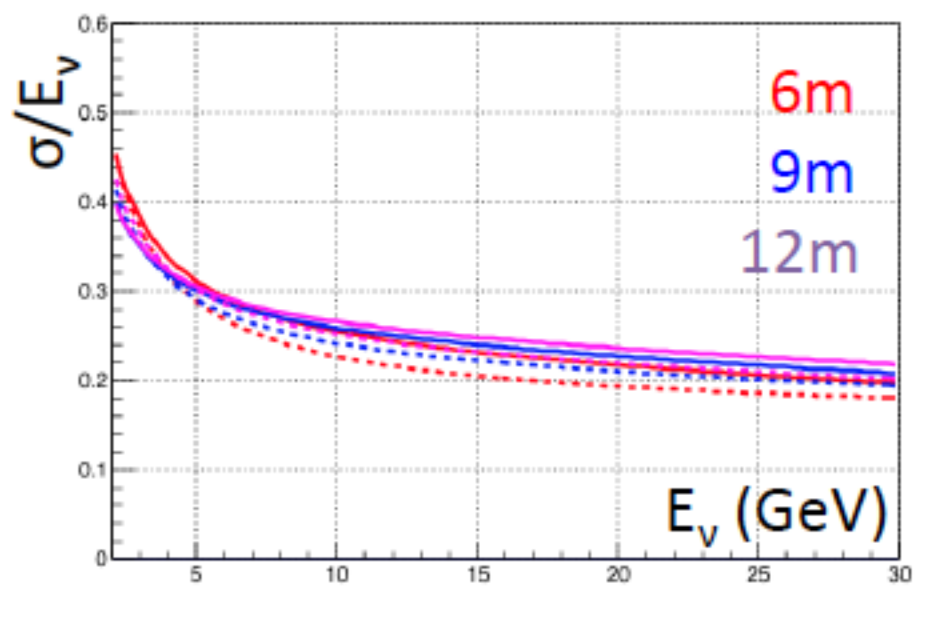


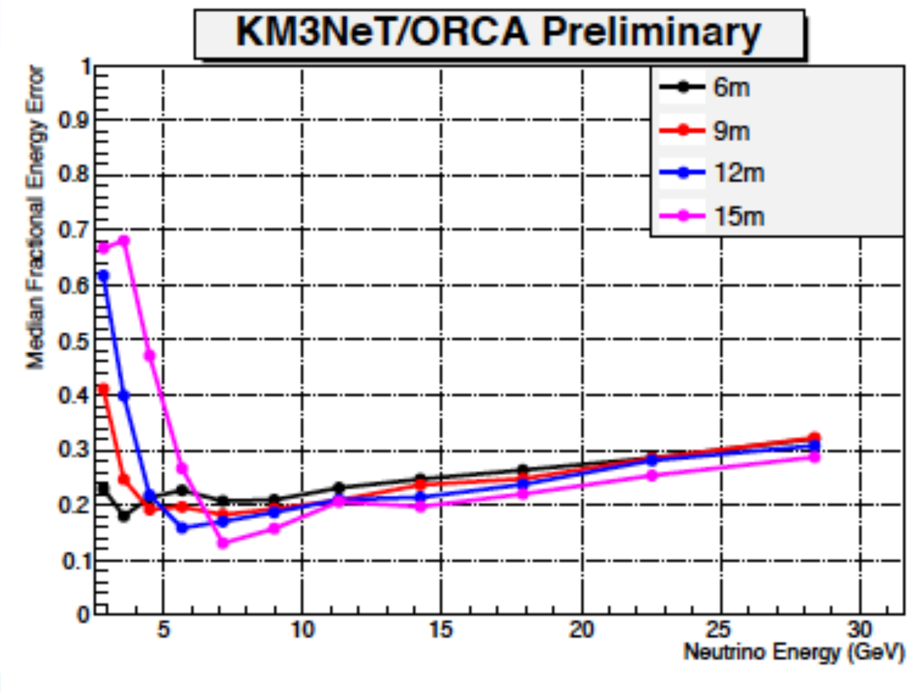
Excellent angular resolution
Dominated by kinematics
Largely independent of vertical spacing

Energy Resolutions

cascade

track



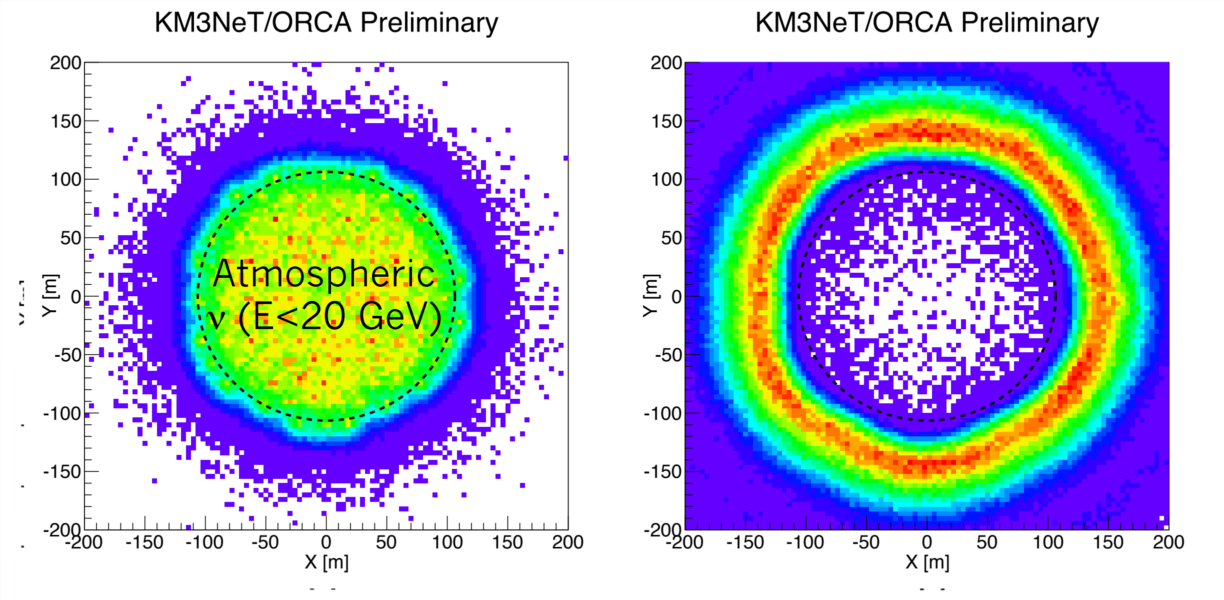


Energy resolution better than 25% in relevant range

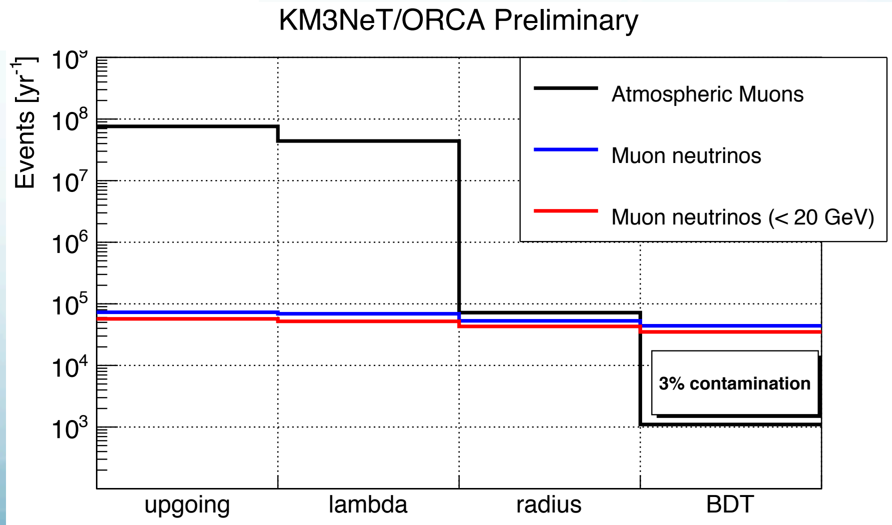
close to Gaussian

Atmospheric muon rejection

- Simulation based on MUPAGE (📖 Astropart. Phys. 25 (2006) 1) at depth 2475 m
- ν_μ reconstruction: cut on the reconstructed pseudo-vertex and quality parameters + BDT

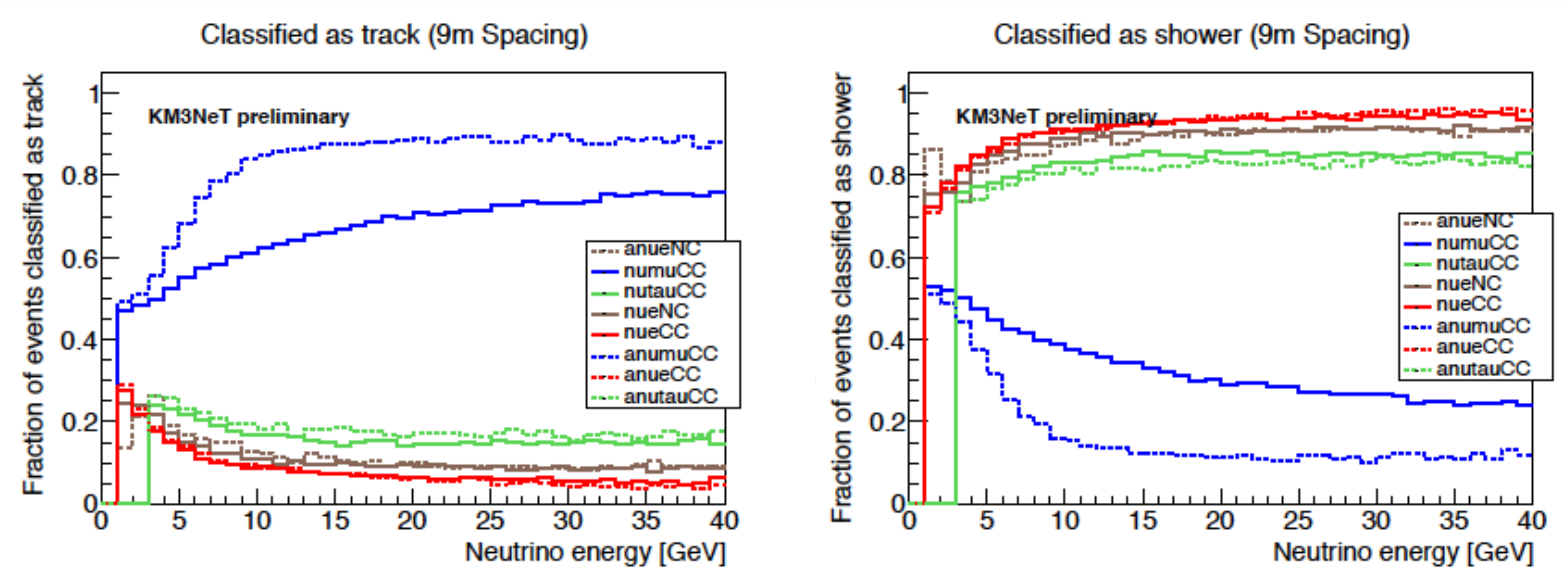


Instrumental veto not mandatory



Tunable few % contamination achievable without too strong signal loss

Flavour (mis)-identification



- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, ν_e^{CC}) events
- Classification uses "Random Decision Forest"
- Better than 80% above 10 GeV for all channels but ν_μ^{CC}

Sensitivity studies

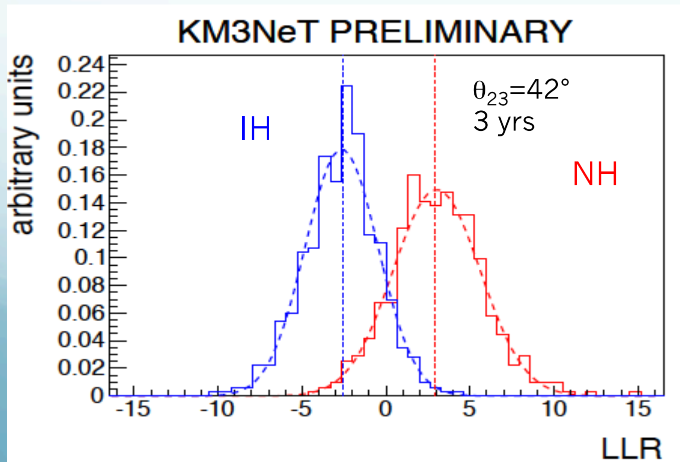
Global Fit Approach

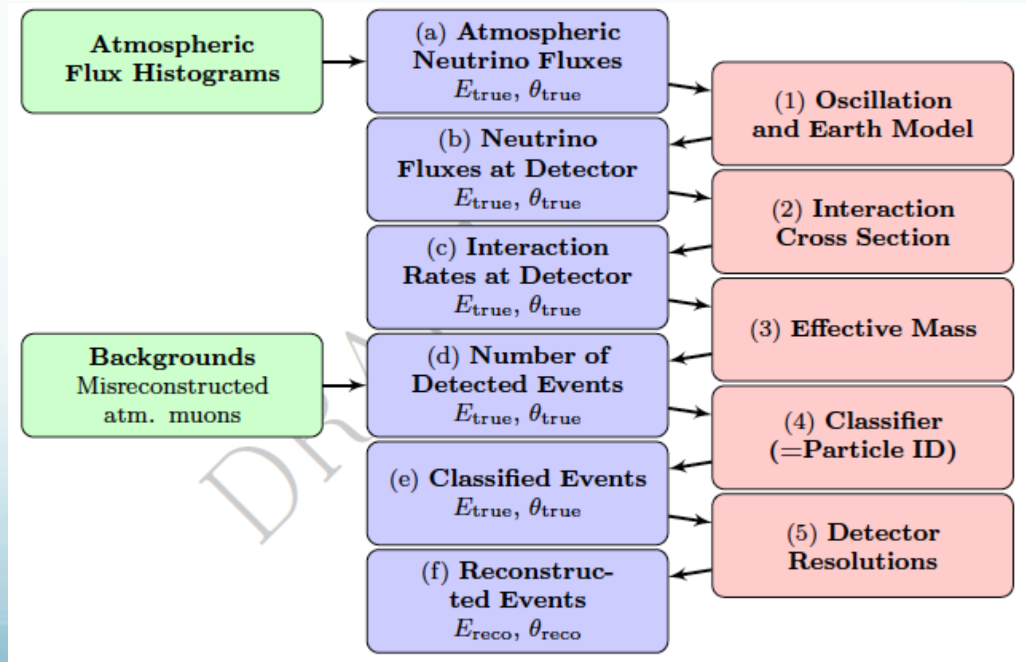
The performance of ORCA for the determination of the NMH is assessed by means of a likelihood ratio test:

$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ Maximum likelihood estimates for Δm^2's and angles.

1) fit mixing parameters assuming NH
2) fit mixing parameters assuming IH
3) compute ΔlogL = log(L(NH)/L(IH))





Sensitivity studies

Systematics

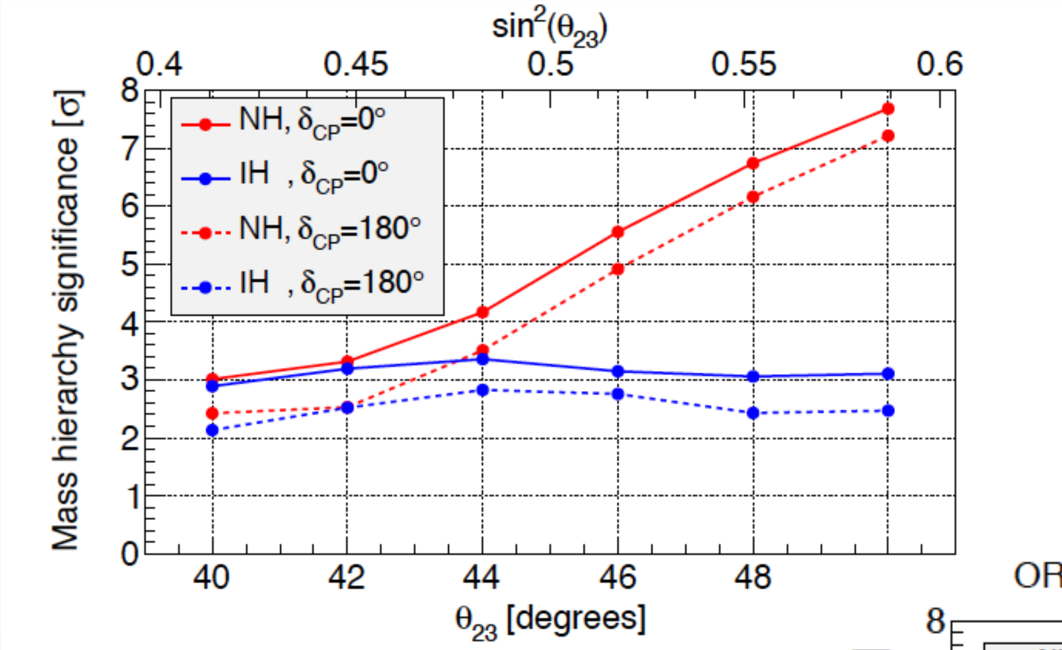
- Various systematic effects taking into account
  - Oscillation parameters
    - Δm^2, θ_{12} fixed; θ_{13} fitted within its error
    - ΔM^2, θ_{23}, δ_{CP} → fitted unconstrained
- Flux, cross section, detector related

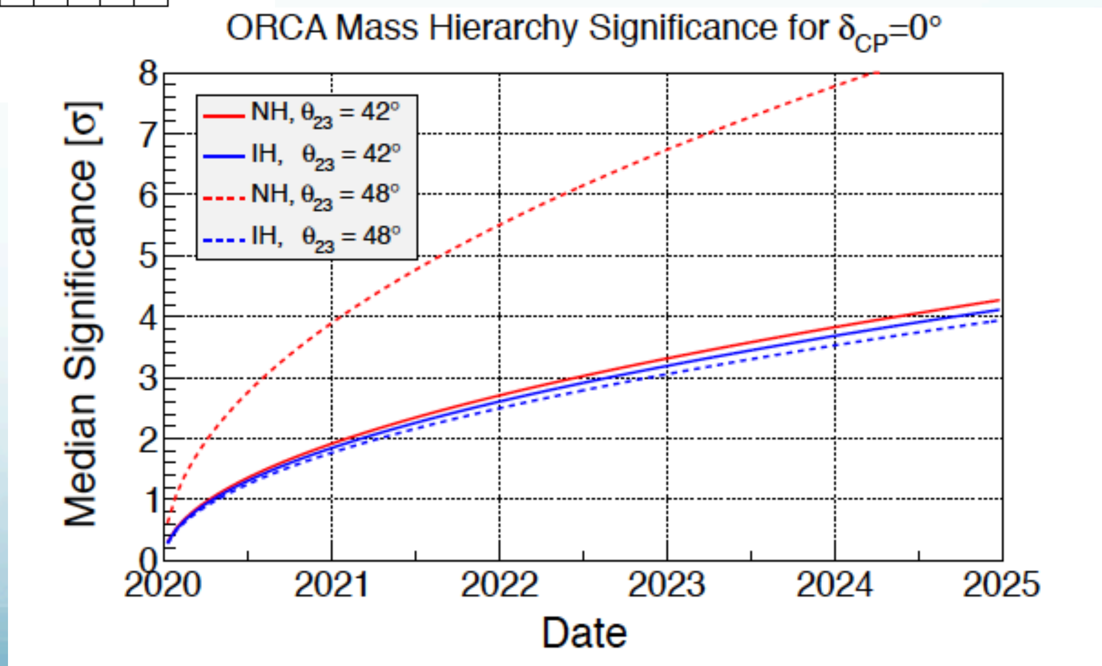
(average fluctuation w.r.t. nominal)

- Overall normalisation (2.0%)
- $\nu / \bar{\nu}$ ratio (4.0%)
- e/μ ratio (1.2%)
- NC scaling (11.0%)
- Energy slope (0.5%)
- →Fitted unconstrained

Impact consistent with what (now) reported by PINGU

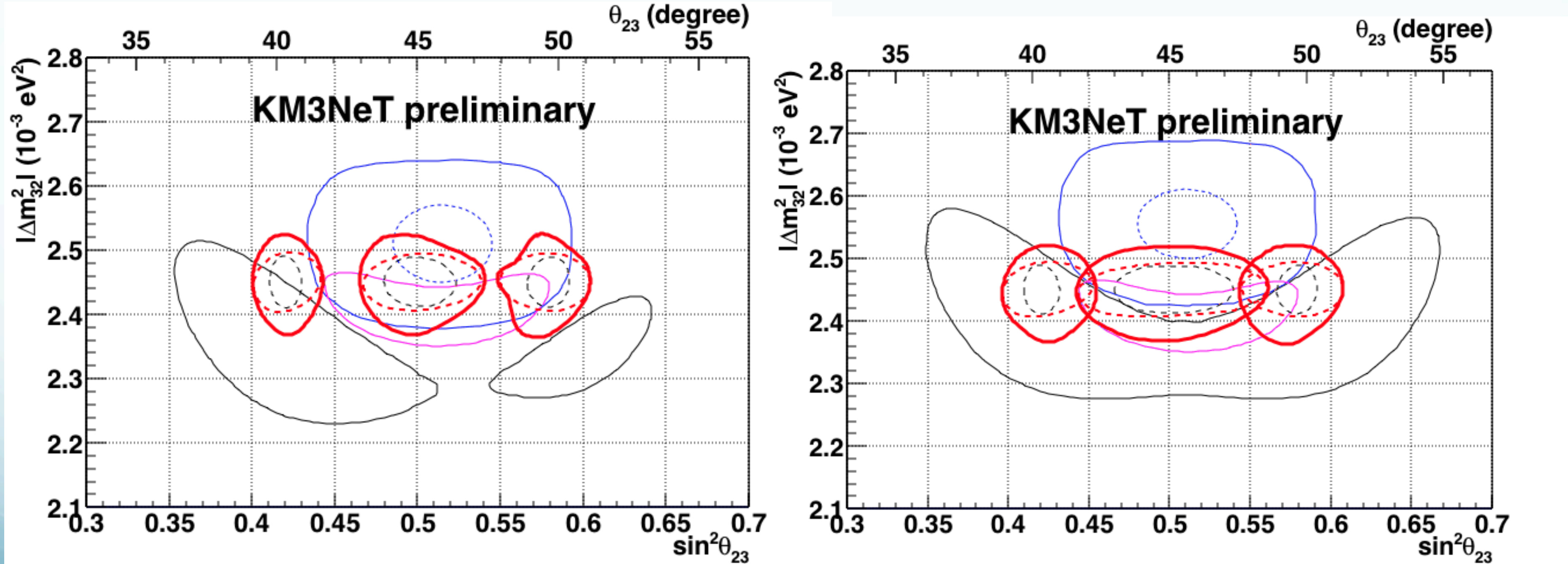
Sensitivity to Neutrino Mass Hierarchy





Sensitivity to PMNS parameters

3 year sensitivity to the atmospheric parameters
ORCA: red ellipses (solid/dashed=with/wo additional E scale)
1 σ contour: 3% in ΔM^2, 4-10% in $\sin^2\theta_{23}$



ORCA, MINOS, T2K, NovA 2020

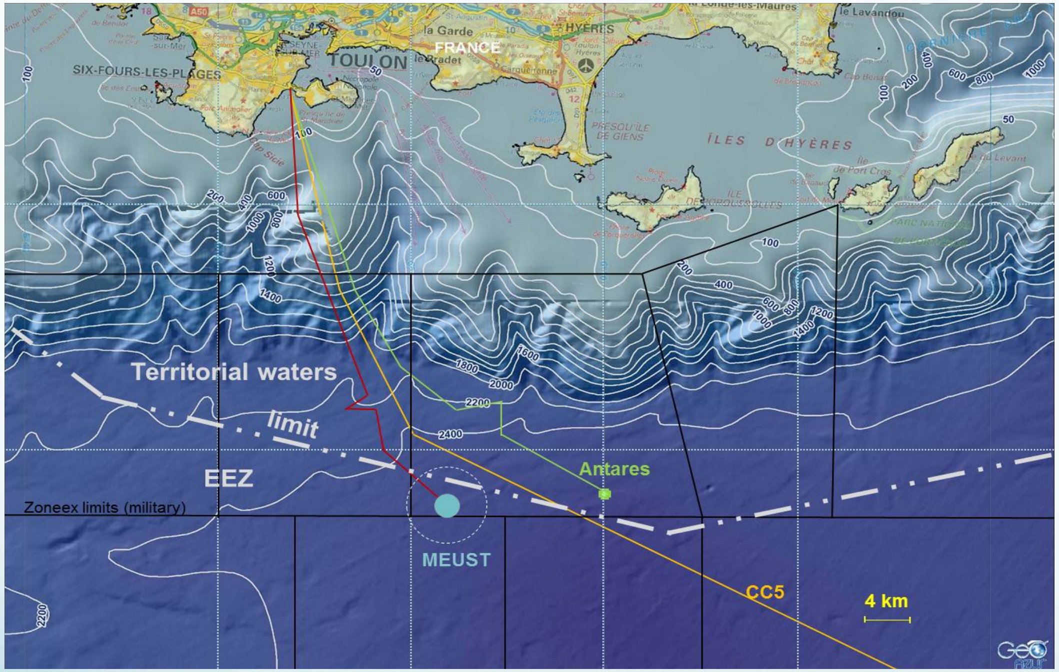
Additional ORCA physics topics

- Sterile neutrinos & tau appearance
- Indirect Search for Dark Matter
- Earth tomography and composition
  - Gonzales-Garcia et al.,Phys.Rev.Lett.100:061802,2008,
  - Agarwalla et al., arXiv:1212.2238v1
- Test NSI and other exotic physics
  - Ohlsson et al, Phys. Rev. D 88 (2013) 013001
  - Gonzales-Garcia et al., Phys.Rev. D71 (2005) 093010
- Sensitivity to CP phase (Threshold <1GeV, MH known)
  - Razzaque & Smirnov, arXiv:1406.1407
- Supernovae monitoring (takes advantage of new DOM features)
- Low Energy Neutrino Astrophysics
  - Gamma-ray bursts, Colliding Wind Binaries
    - J. Becker Tjus, arXiv:1405.0471 ...
- A Neutrino beam to ORCA (NMH and CP phase)
  - Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439
  - Tang & Winter, JHEP 1202 (2012) 028
  - J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.

ORCA timeline

Phase 1 (funded- 11M€) : deploy a 6 string array in the ORCA configuration to demonstrate detection method in the GeV range.

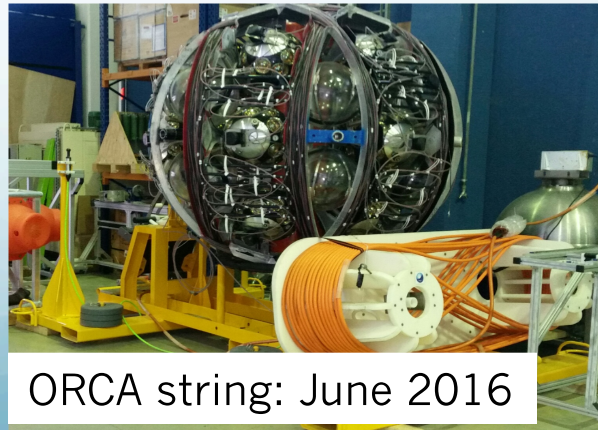
+ ANR DAEMONS [APC-CPPM-IPHC]



Phase 2 (+40 M€): deploy 1 building block 115 strings in French KM3NeT site
Completion in 2020
Funds: 9M€ (France)+5M€(Netherlands)+…

Main cable: Dec 2015

node: April 2016



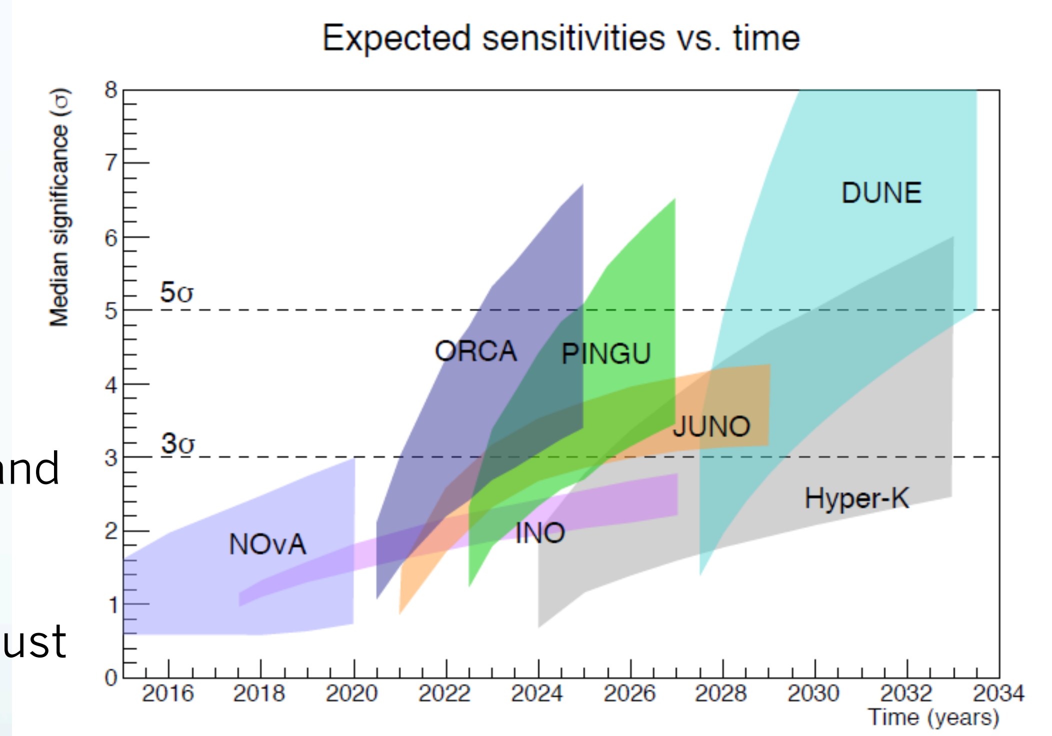
ORCA string: June 2016

Summary and perspectives (I)

- IceCube has just opened the field of neutrino astronomy suggesting a higher level of hadronic activity in the non-thermal universe than previously though.
  → Exciting times ahead !
- Sources remain to be identified.
- ANTARES: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky
  - Competitive sensitivities (especially for Galactic neutrino component, Dark matter searches)
  - Improvements still to come: include showers in all analyses
  - Taking data until superseded by KM3NeT in 2017
- KM3NeT: phased approach to next-generation neutrino telescope
  - Letter of Intent ready
  - Prototypes performing well
  - Deployment of the first detection unit (Phase 1).
  - **ARCA → HE neutrino astronomy (tracks & showers)**
  - **ORCA for the measurement of NMH**

Summary and perspectives (II)

- Atmospheric Neutrinos have still a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy and the search for exotic phenomena.
- Proposed detectors include Iron Calorimeter, Liquid Argon and Cherenkov detectors. None of these projects being firmly funded.
- Low energy (GeV) extensions of Neutrino Telescopes may be faster and cheaper than other alternatives...
- ...but challenging, as systematics must be carefully controlled.



- Preliminary ORCA sensitivities are quite promising.
- Combination with LBL/reactor experiments may provide the first high significance MH determination...