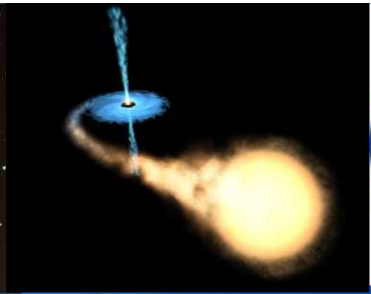
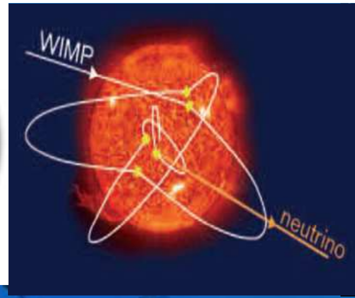
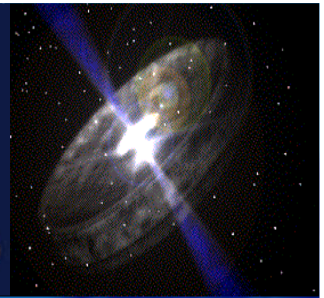


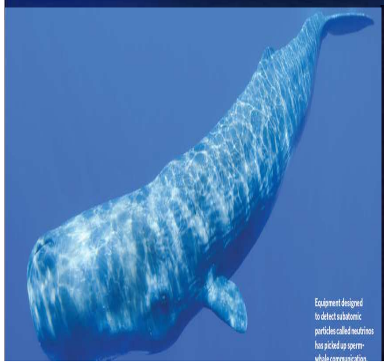


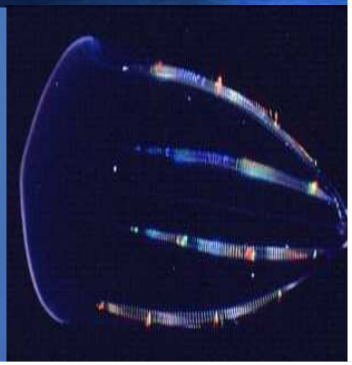


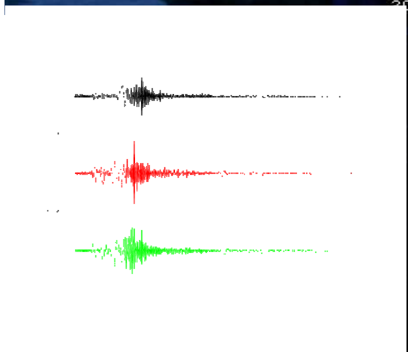
ANTARES/KM3NeT:
neutrinos out of the blue

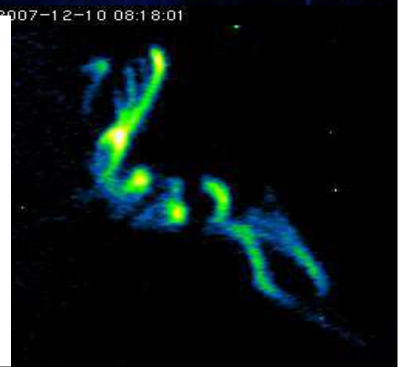
5th Air Shower Detection at High Altitude Workshop ,
27 May 2014

Paschal Coyle
Centre de Physique
des Particules de Marseille

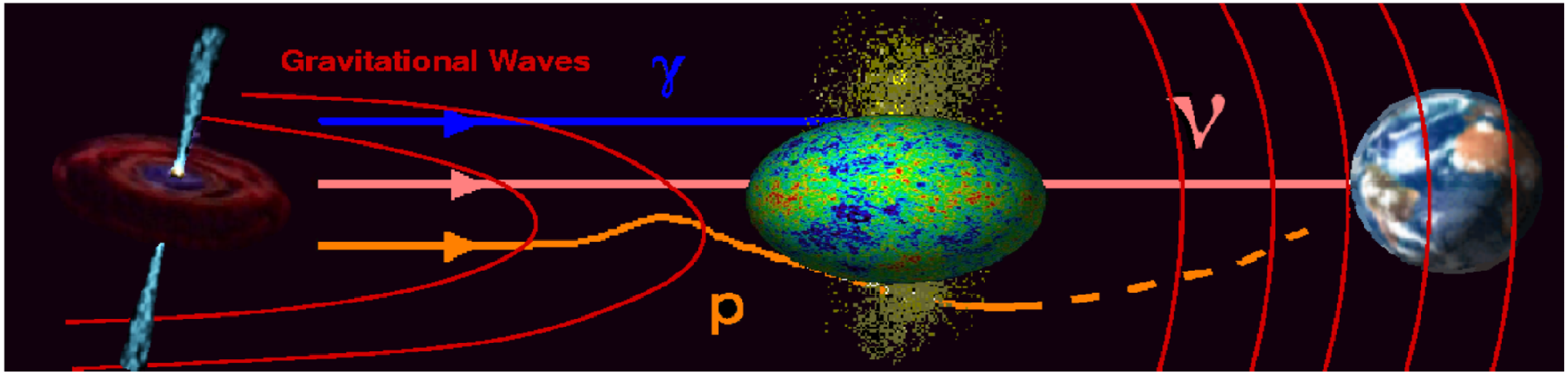








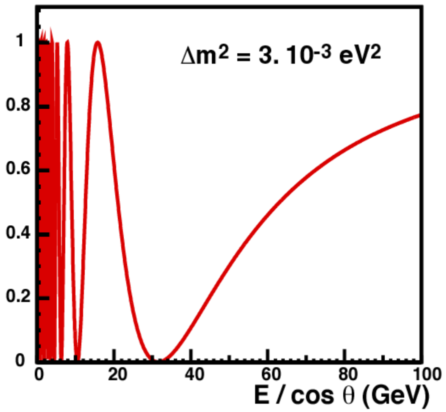
Multi-Messenger Astronomy

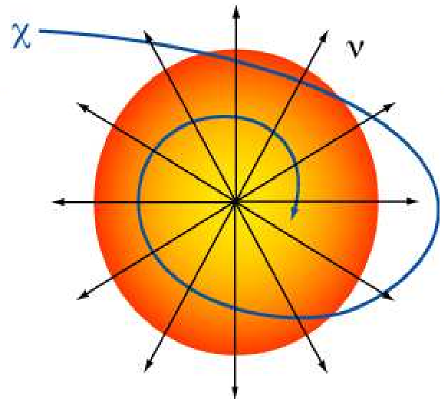


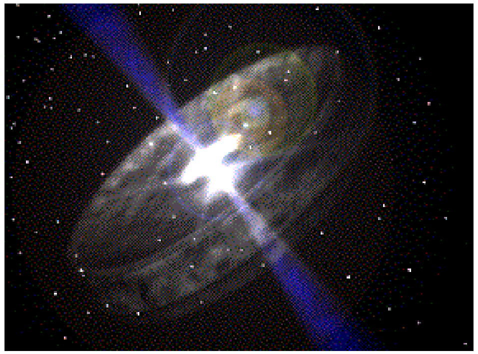
Neutrino

- ✓ Unambiguous signature of hadronic acceleration
  → sites of CR production
- ✓ Time/space correlate with electromagnetic/GW signals
- ✓ Undeviated by magnetic fields→ astronomy at all energies
- ✓ Not absorbed by CMB/EBL→ access to cosmological distances
- ✓ Not absorbed by matter→ access to dense regions
- ✓ Unexplored→ surprises can be expected

Neutrino telescopes: science scope







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

ν oscillations

Dark matter search

ν from extra-terrestrial sources

Origin and production mechanism of HE CR

↓

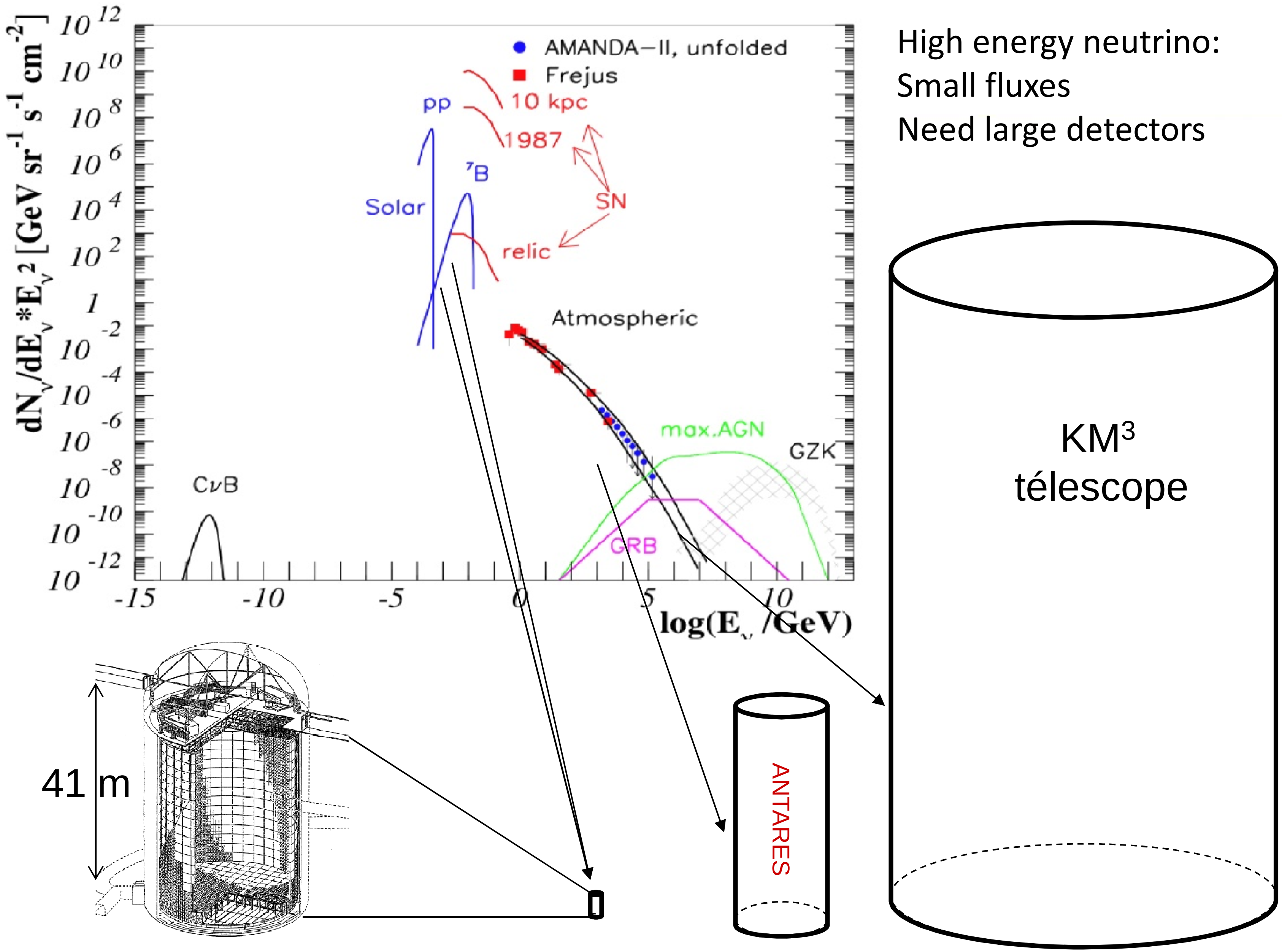
Primary goal

Exotic particle physics
Monopoles, nuclearites,…

Marine sciences: oceanography, biology, geology…

From MeV ν to PeV ν

High energy neutrino:
Small fluxes
Need large detectors



Water Versus Ice

- Complementarity to IceCube South Pole

  Excellent view of Galaxy

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

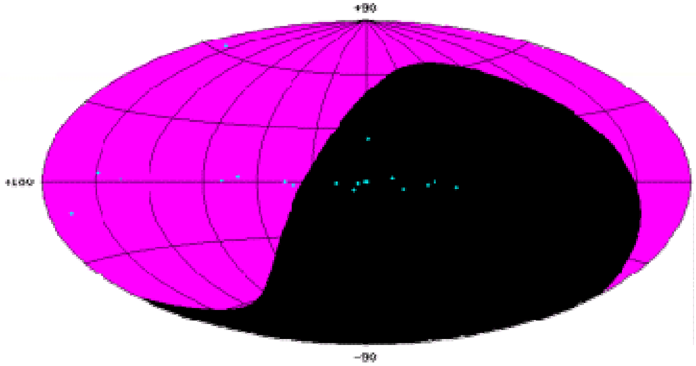
- Logistically attractive

  Close to shore (deployment / repair)

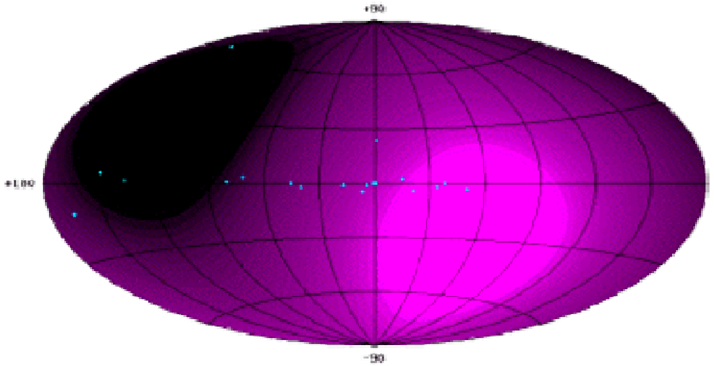
- K40 optical background

  Useful for calibration, but requires causality filters

South Pole visible sky



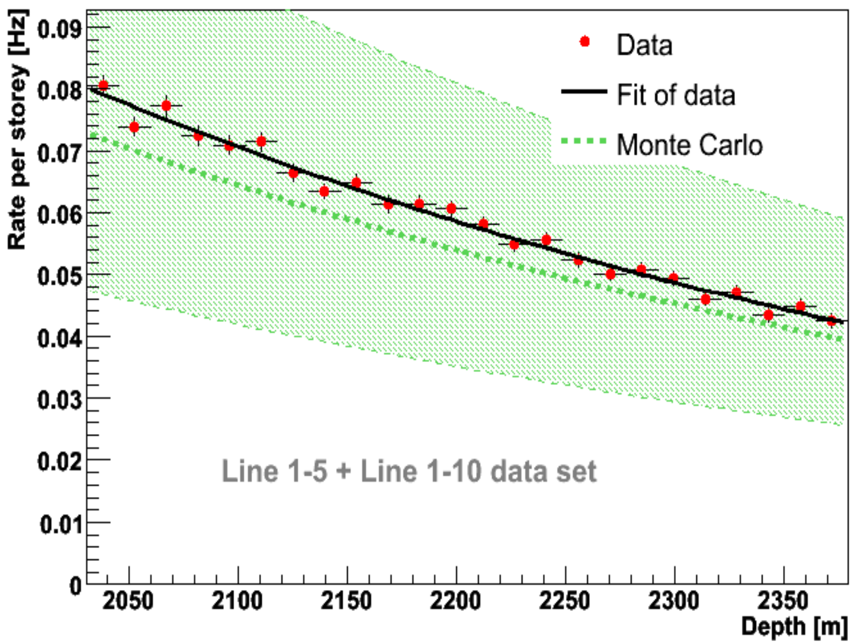
Mediterranean visible sky



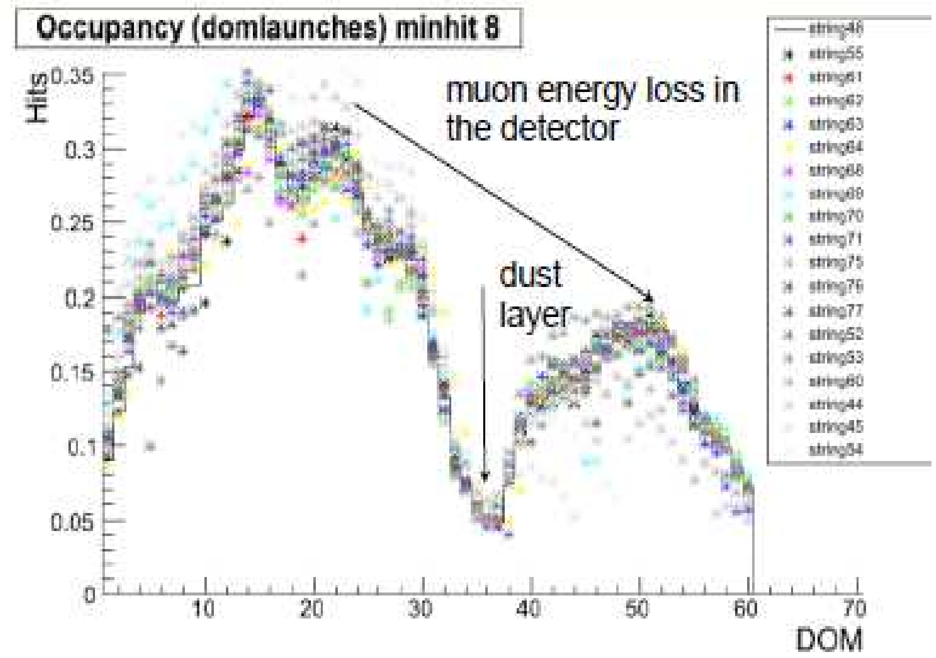
Most of the HESS TeV
Sources visible by Northern NT

The Sea: a Uniform Medium

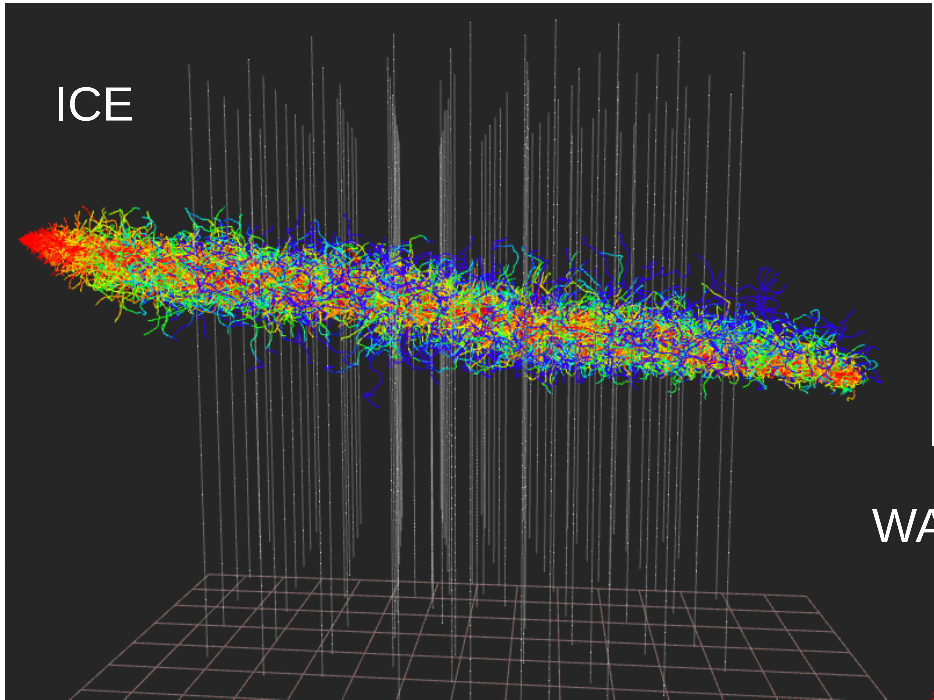
ANTARES



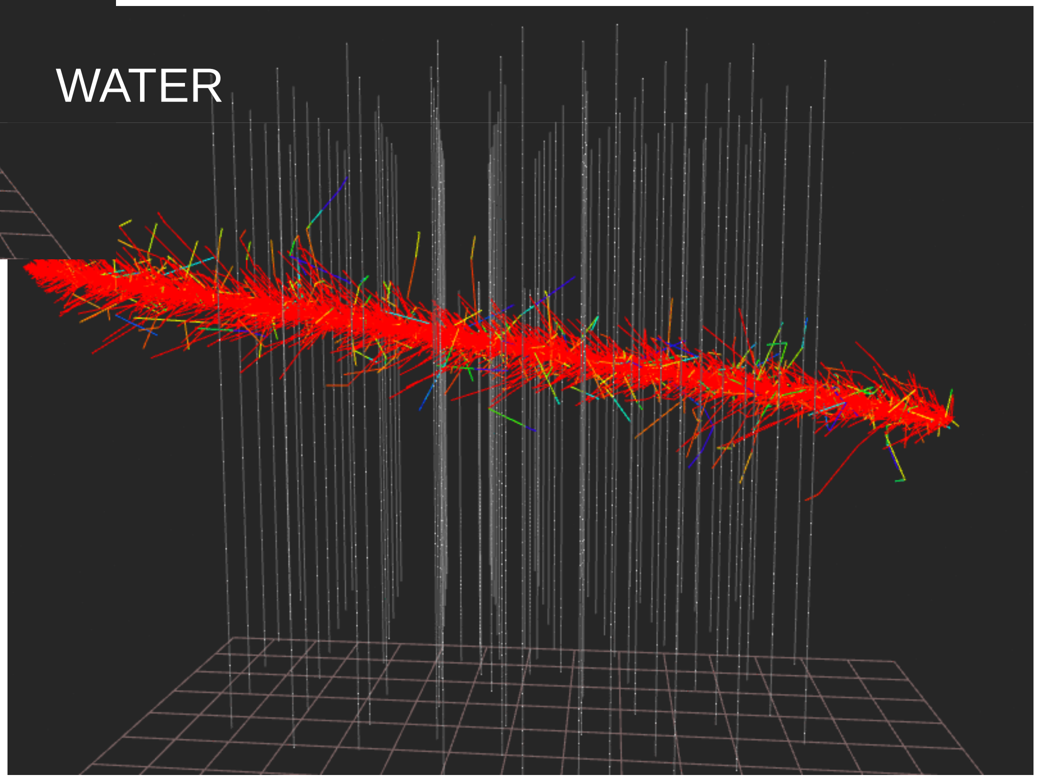
ICECUBE



10 TeV muon neutrino



IceCube resolution ~ 0.6°



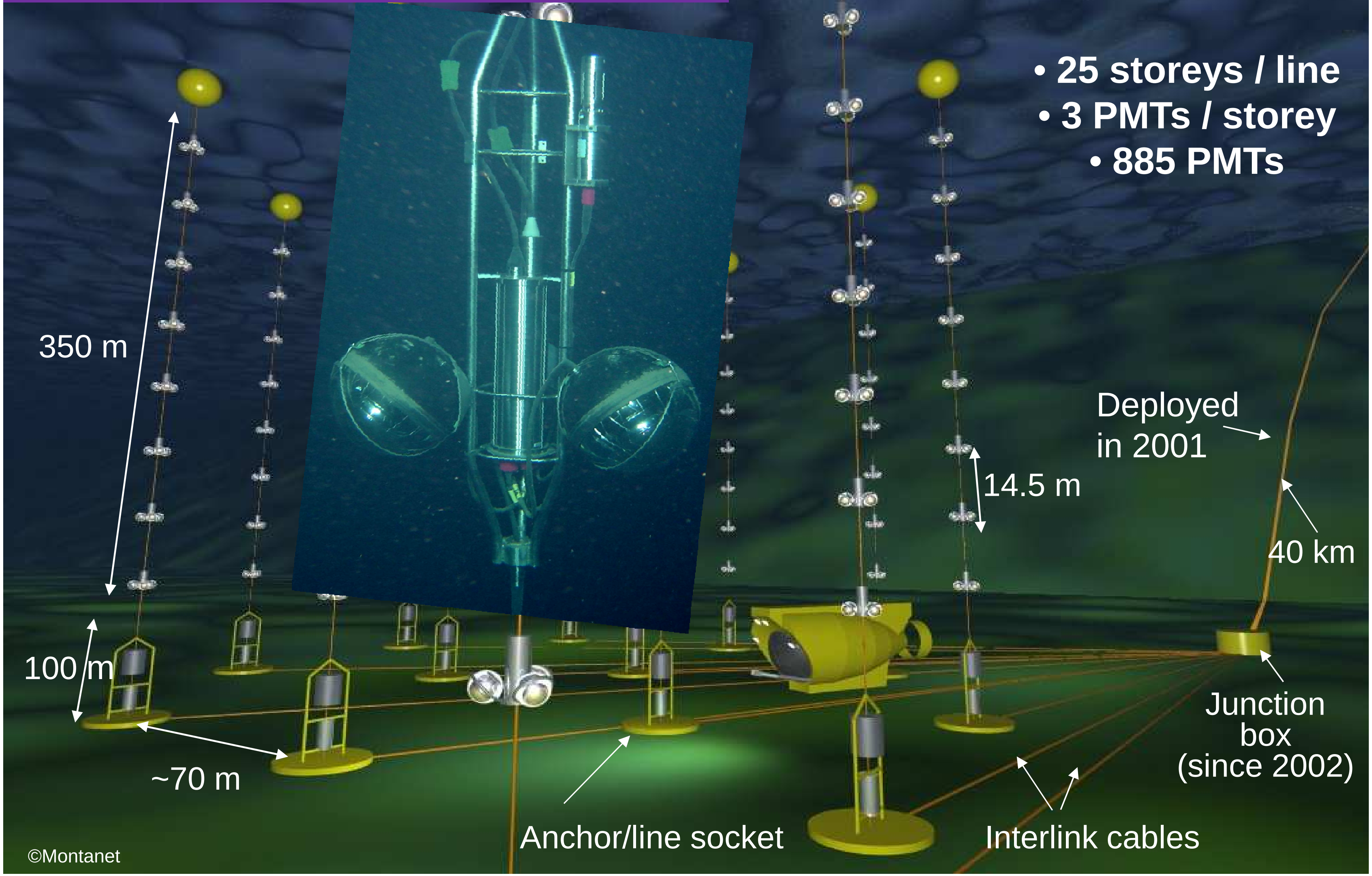
ANTARES/KM3NeT resolution ~ 0.3° / 0.1°


Toulon
M.Pacha
Antares
Electro-optical
Cable of
40 km
42 50'N, 6 10'E
Google
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA

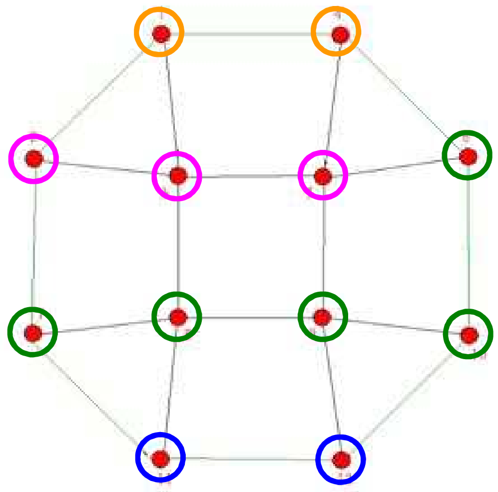
The ANTARES neutrino telescope

Detector completed in May 2008

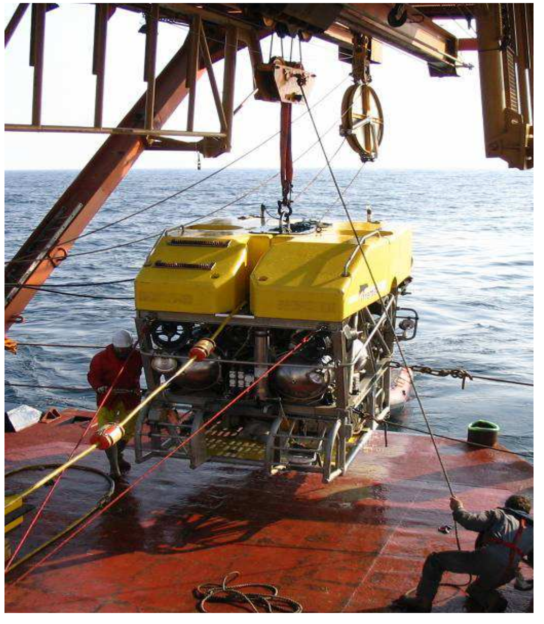
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

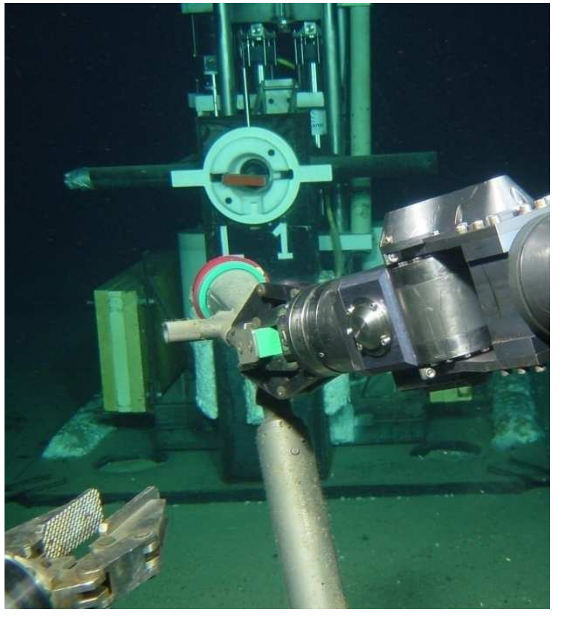


2006 – 2008: Construction Phase of the Detector



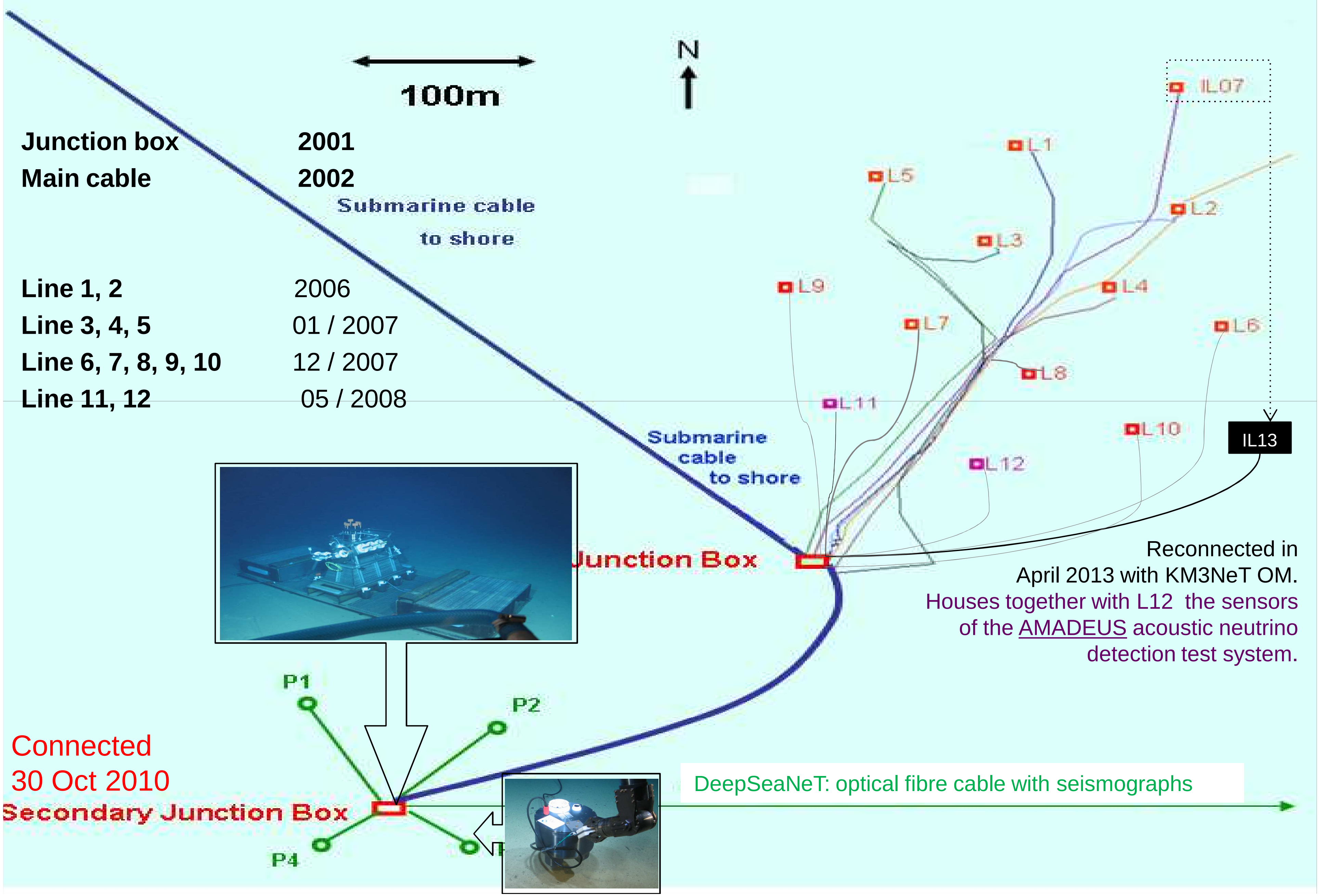
Junction box	2001
Main cable	2002
Line 1, 2	2006
Line 3, 4, 5	01/2007
Line 6, 7, 8, 9, 10	12/2007
Line 11, 12	05/2008
MOU until	2016





The ANTARES Infrastructure

Junction box	**2001**
Main cable	**2002**
Line 1, 2	2006
Line 3, 4, 5	01 / 2007
Line 6, 7, 8, 9, 10	12 / 2007
Line 11, 12	05 / 2008



Reconnected in
April 2013 with KM3NeT OM.
Houses together with L12 the sensors
of the AMADEUS acoustic neutrino
detection test system.

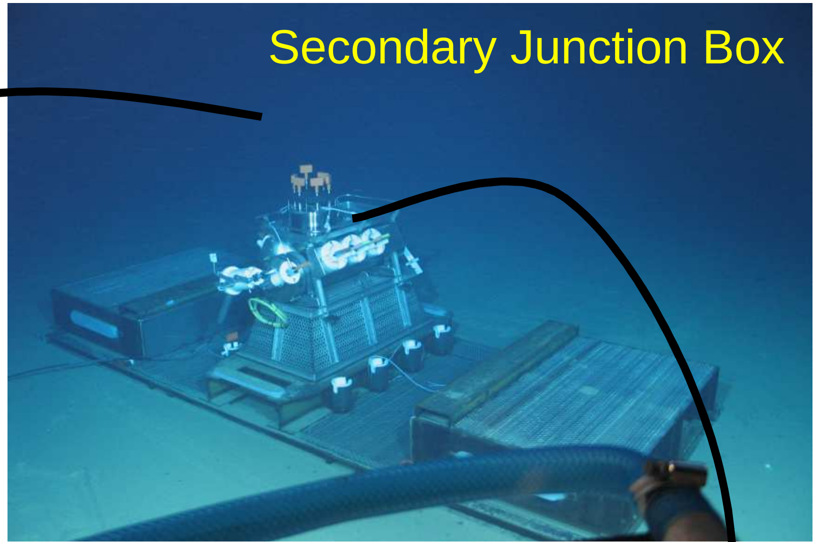
Connected
30 Oct 2010

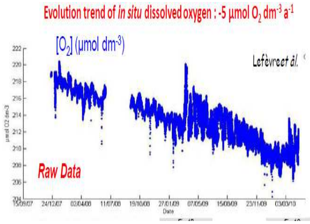
DeepSeaNeT: optical fibre cable with seismographs

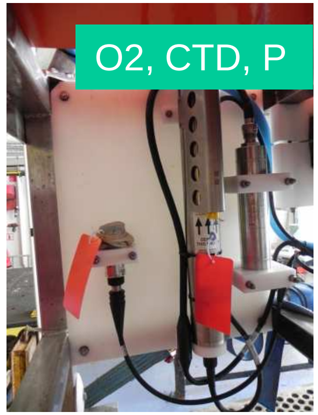
Earth and Sea Sciences

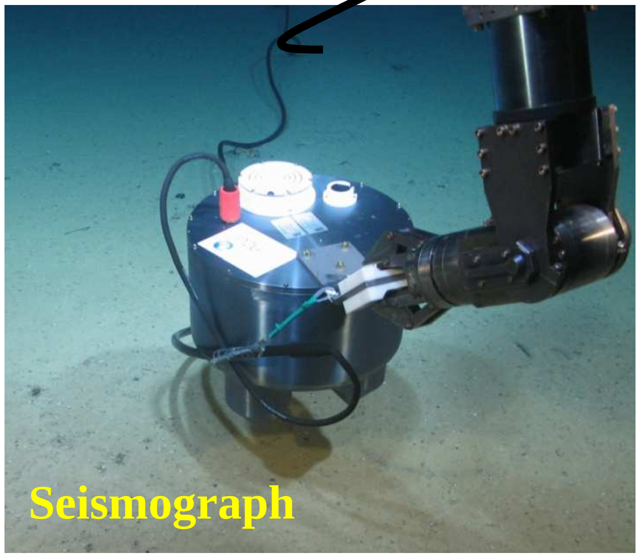
Deep Ocean Cabled Observatories Workshop-
https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=165389

Connected
30 Oct 2010

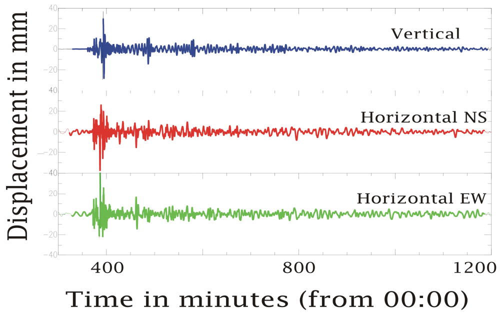


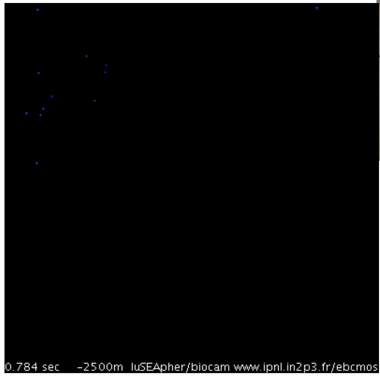


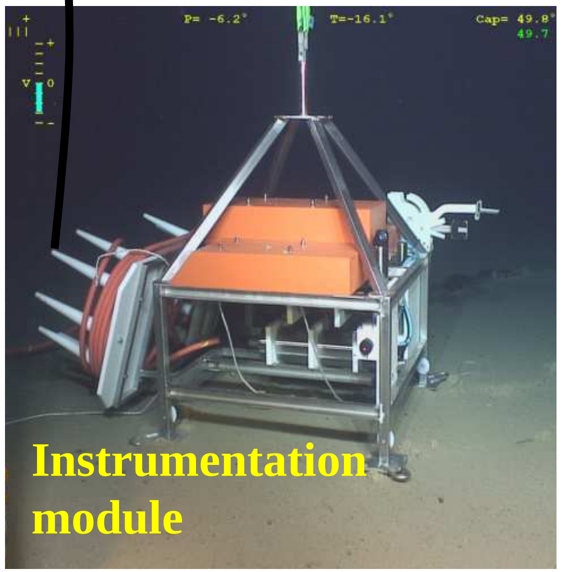




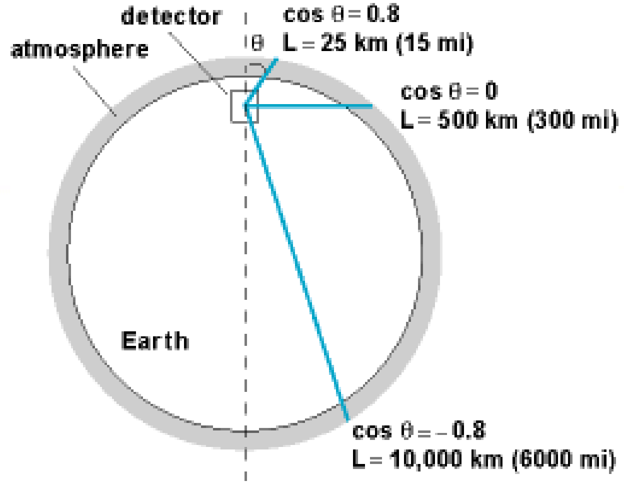
Japan earthquake 2011 March 11
at Antares site







Neutrino Oscillations



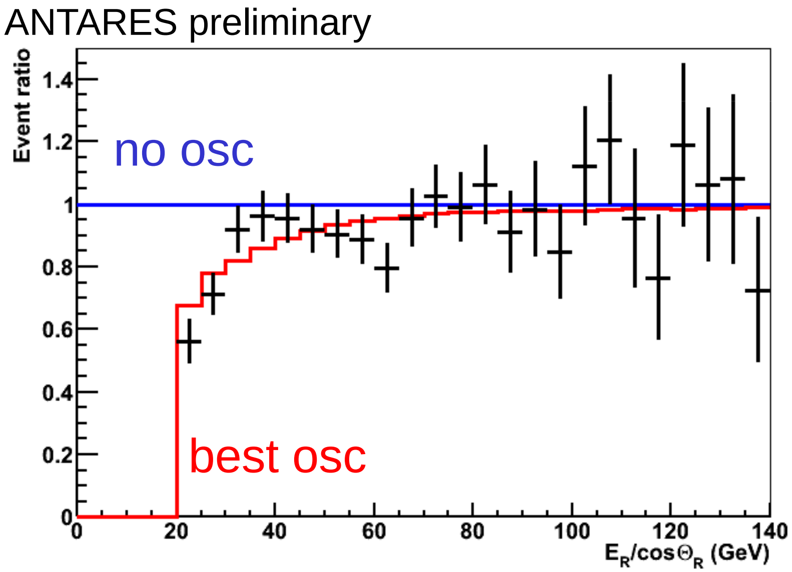
2008-2010 data (863 days):

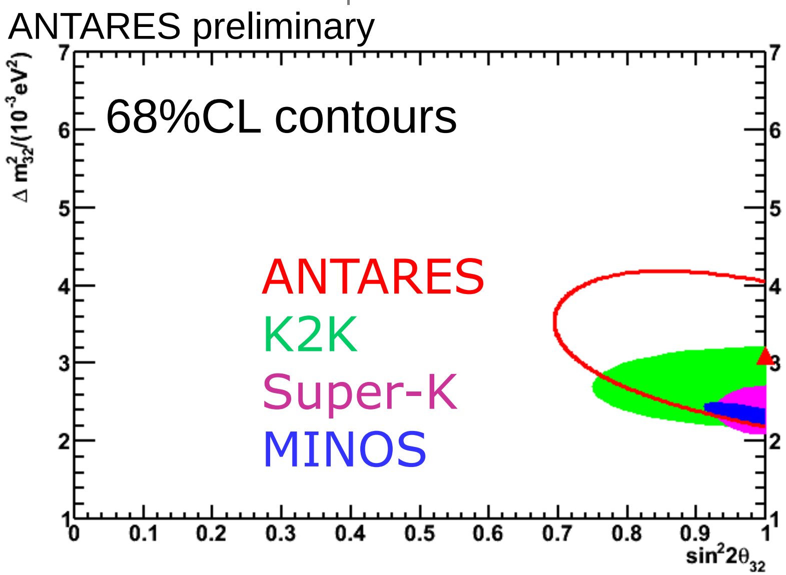
No oscillation: χ^2/NDF = 40/24 (2.1%)

Best fit: χ^2/NDF = 17.1/21

$\Delta m^2 = 3.1\ 10^{-3}\ eV^2$

$\sin^2 2\theta = 1.00$

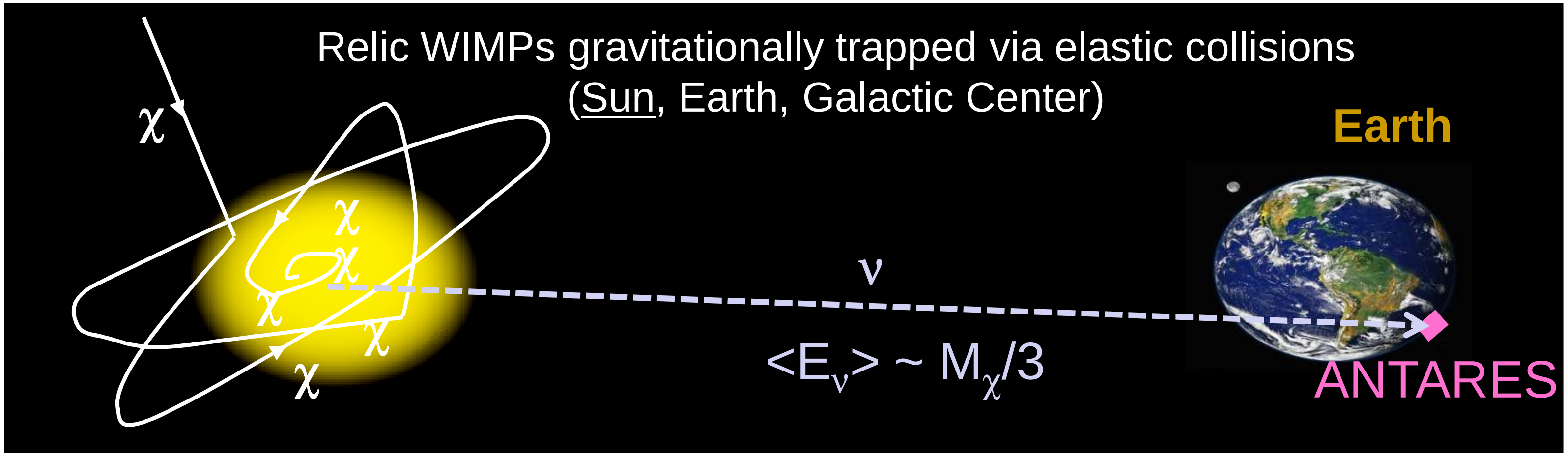




Assuming maximal mixing: $\Delta m^2=(3.1\pm0.9)\ 10^{-3}\ eV^2$

PLB: arXiv:1206.0645

Indirect search for Dark Matter



- HE neutrinos from the Sun → Clean DM signature

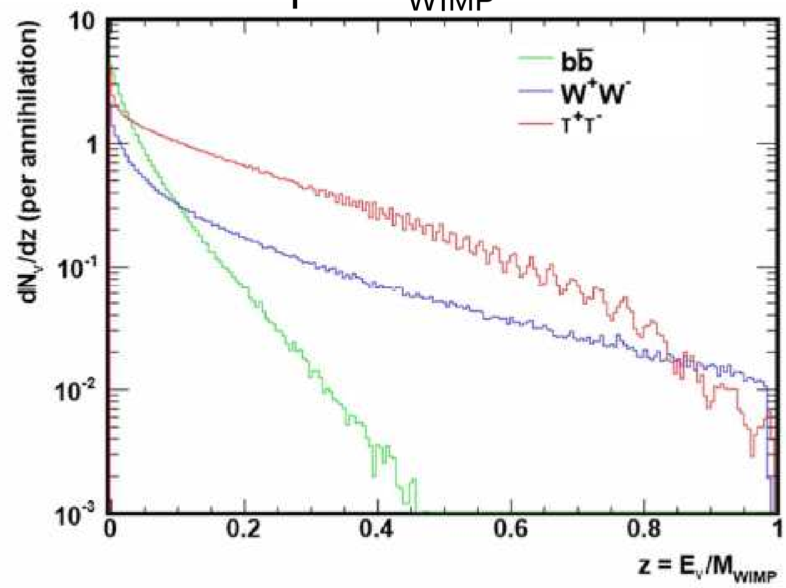
- Models where Lightest SUSY Particle (LSP) is stable (R-parity conservation) are considered
- Self-annihilation in c,b,t quarks, τ leptons or W, Z,H bosons induce HE neutrino flux
  - → b quarks (soft spectrum)
  - → τ leptons
  - → W bosons (hard spectrum)

  } benchmarks

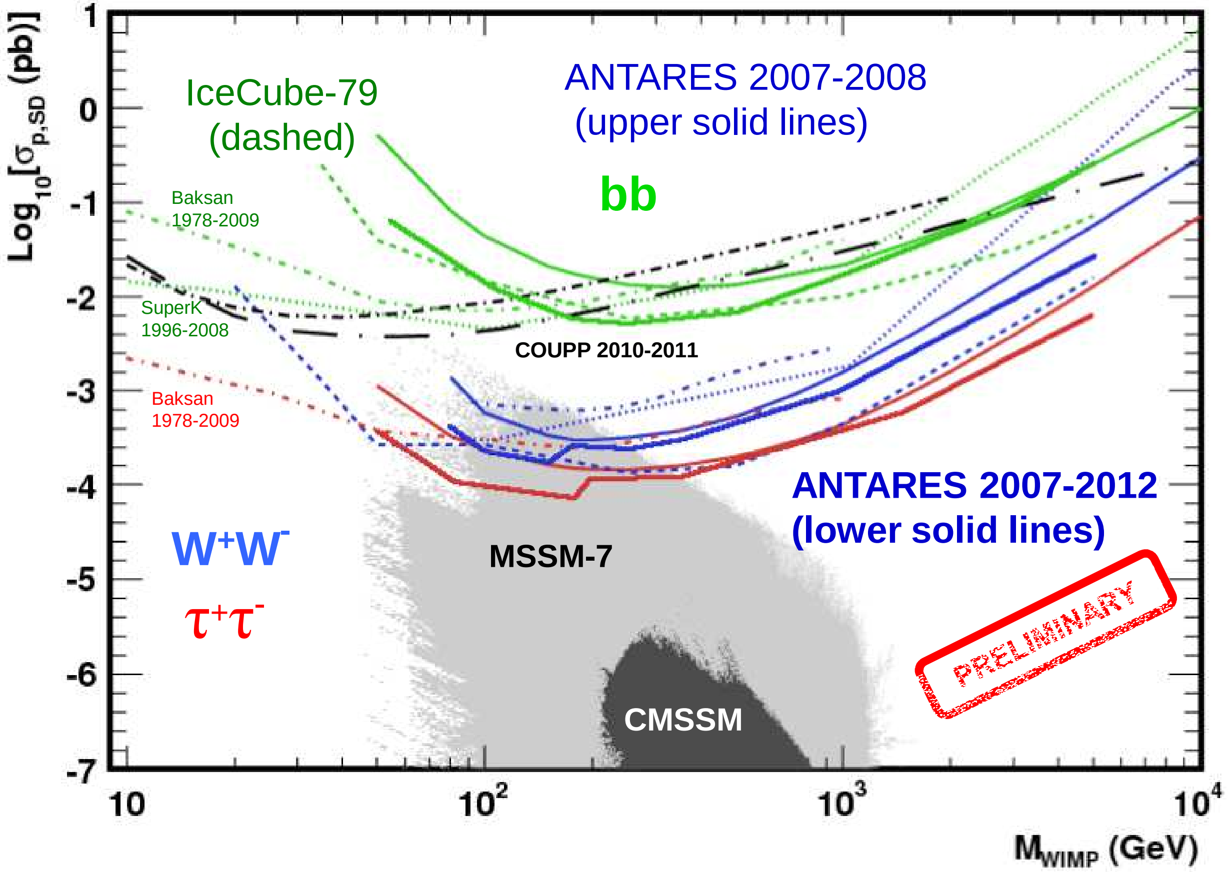
- Model-independent simulation using WIMPSIM

- Interactions in the Sun, flavor oscillations, and regeneration of ν_τ in the Sun taken into account

Example M_{WIMP}= 350 GeV



Sun – Limits on spin-dependent cross-sections



Conversion to limits on WIMP-proton SD-x sections assumes equilibrium between capture and annihilation rates inside the Sun

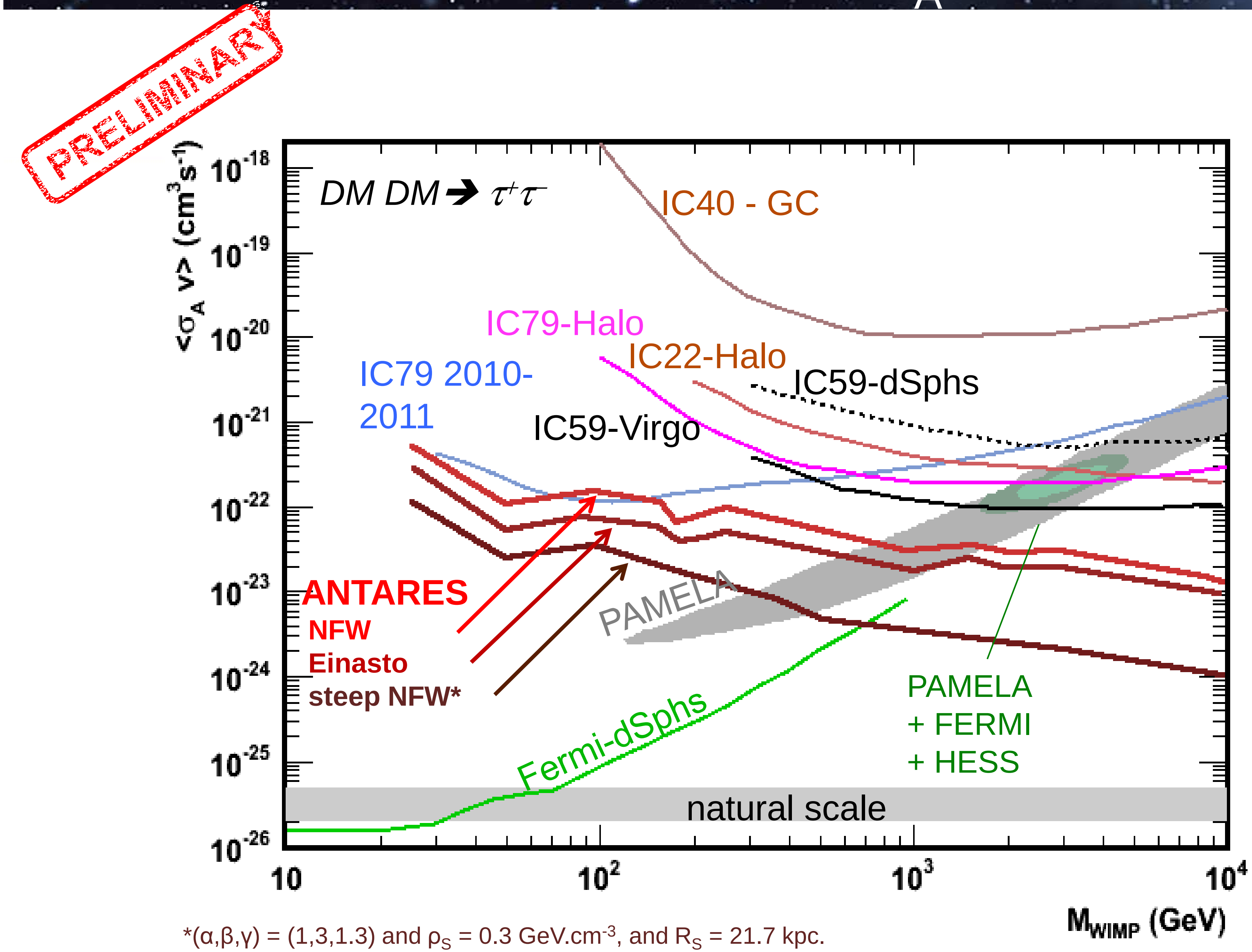
Much better sensitivity of ν-telescopes on SD cross-section w.r.t. direct detection (due to capture on H in the Sun).

First ANTARES results published in JCAP11 (2013) 032

MSSM-7 and CMSSM predictions take into account recent experimental constraints (Higgs mass,etc…).

There is still room for improvement in ANTARES: better reconstruction at low energies, binned method, more data "on tape", …

Galactic Centre – Limits on <σ$_A$v>



*(α,β,γ) = (1,3,1.3) and ρ_S = 0.3 GeV.cm^{-3}, and R_S = 21.7 kpc.

IceCube Signal for Diffuse Flux

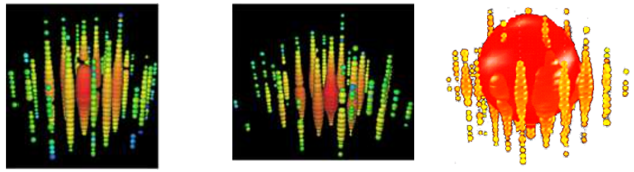
2 yr data (Science pub)
28 (21 cascade+7 track) events
'Ernie' and 'Bert'
Expected bkgd: 11 events
4 sigma

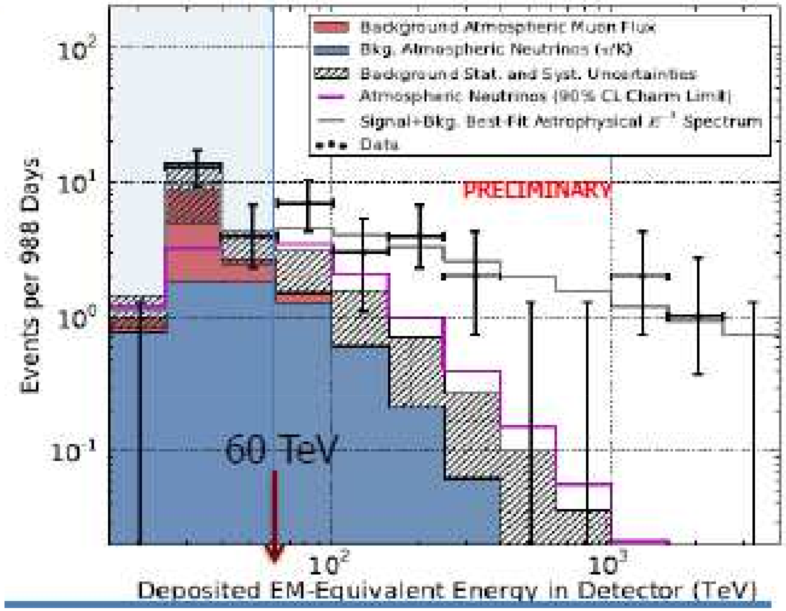
3 yr data: 988 days
+9 events
(big bird at 2 PeV)
5.7 sigma

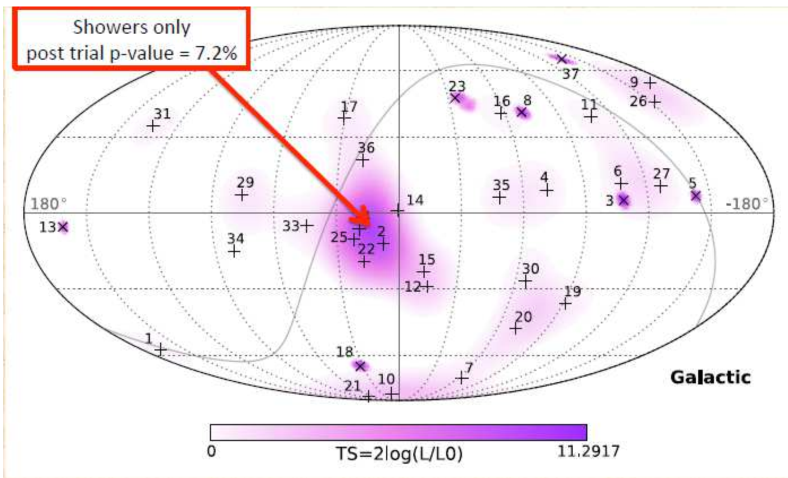
Best fit flux (single flavour)
~ $(0.95\pm0.3)\times10^{-8}$ E^{-2} GeV/cm^2/s/sr
(maybe cutoff around 2.3 PeV?)

Mainly shower events with poor angular resolution (~15°)

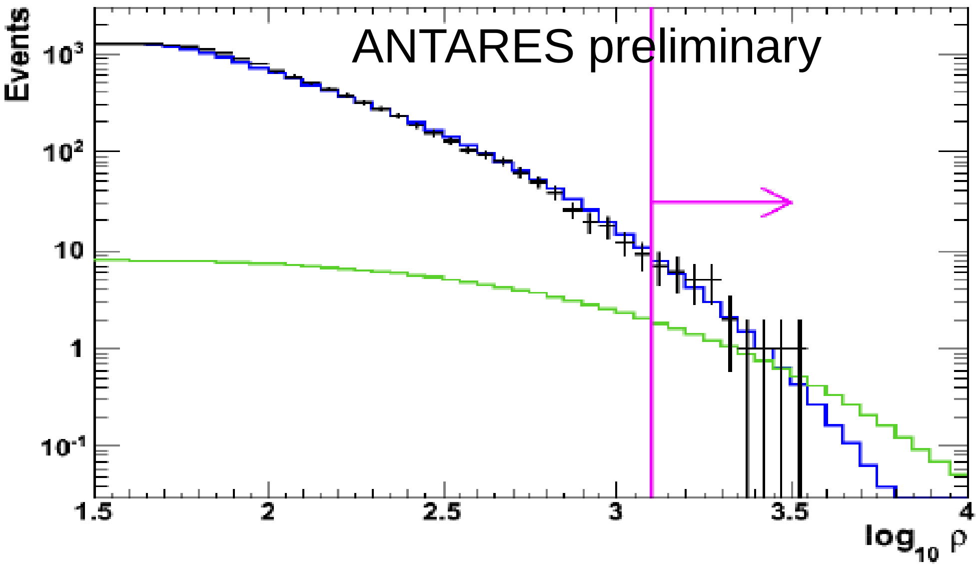
Clustering near Galactic Centre (7% prob)?





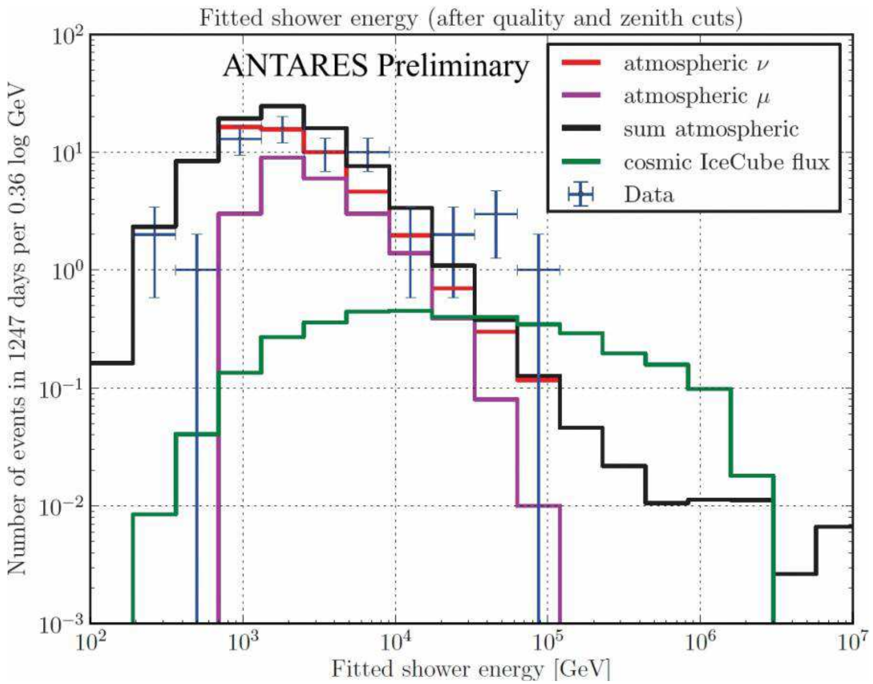


ANTARES Diffuse Neutrino Searches



Muons (2008-2011) 855 days
sensitivity & flux limit (90%CL):
5.1×10^{-8} GeV/cm^2/s/sr

Update expected for the summer



Cascades (2008-2012) 1247 days
sensitivity: 2.5×10^{-8} GeV/cm^2/s/sr

8 events observed, 4.9 expected
1.5 σ excess
signal: 1.32×10^{-8} GeV/cm^2/s/sr

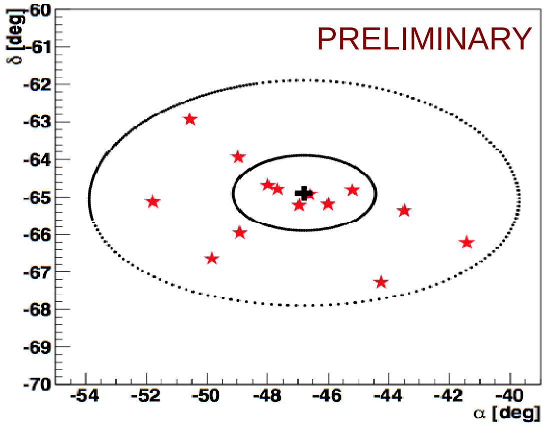
Flux limit (90%CL)
4.92×10^{-8} GeV/cm^2/s/sr

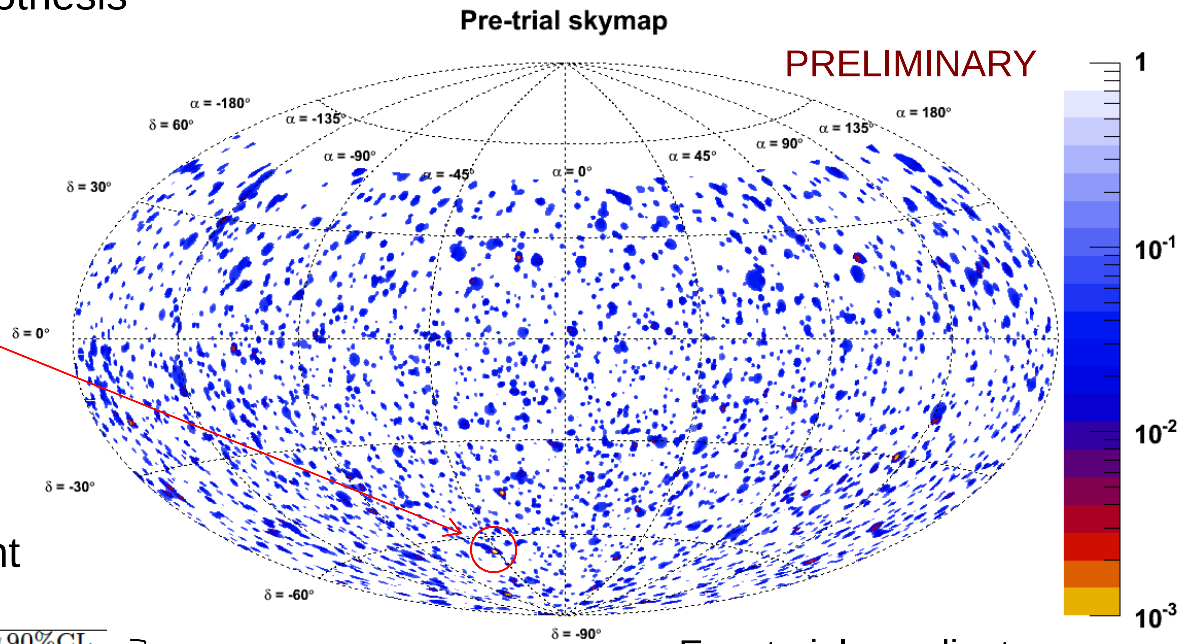
Angular resolution ~6-7°

Search for neutrino point sources

❖ updated muon search 2007-2012 (1340 days)

- 5516 neutrino candidates (90 % of which being better reconstructed than 1º)
- No significant excess
- Same most significant cluster with 6 additional events: p-value = 2.1% (2.3 σ)
  Compatible with background hypothesis





Equatorial coordinates

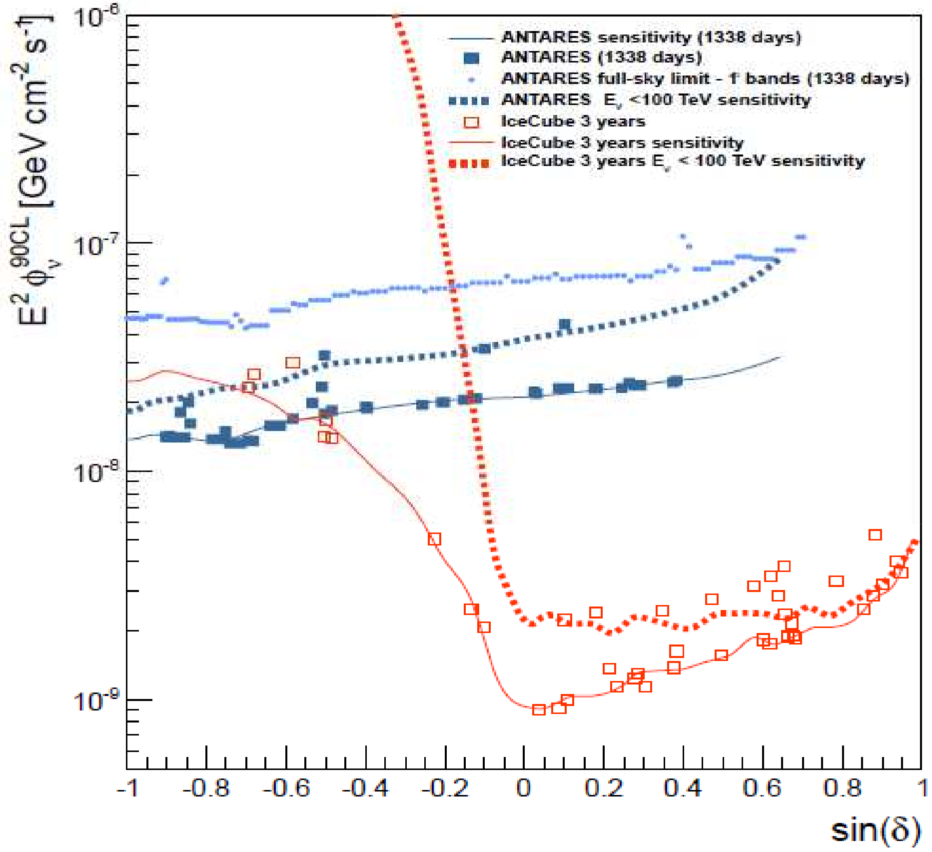
- Fixed search top 5 most significant

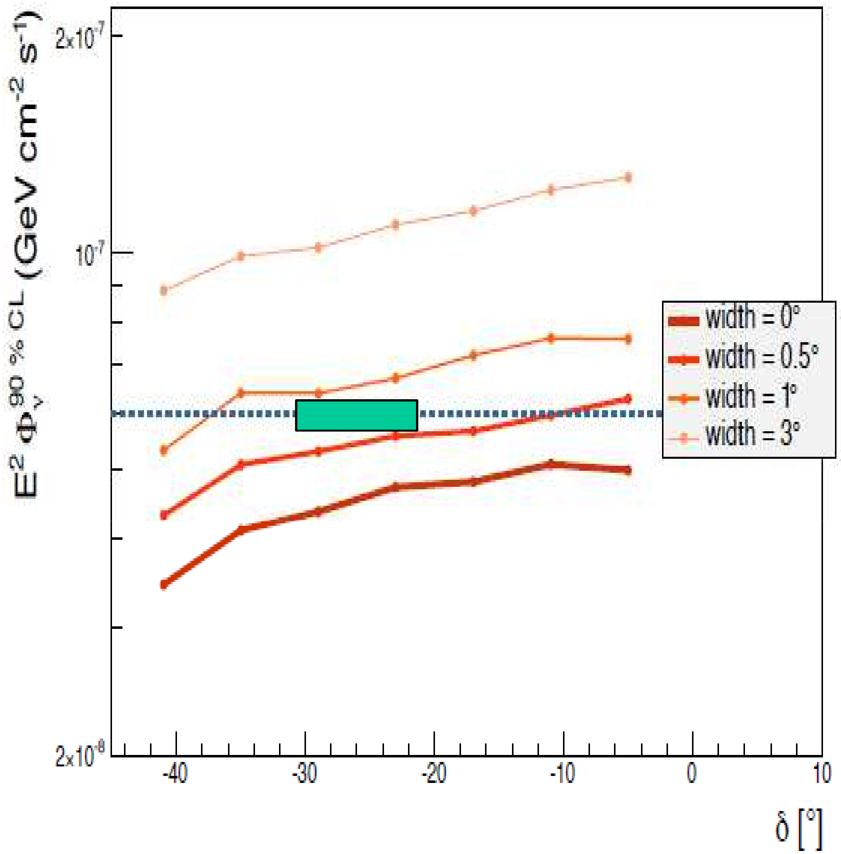
source	$\alpha_s [°]$	$\delta_s [°]$	p	$\phi^{90\%CL}$
HESSJ0632+057	98.24	5.81	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.14	3.23
3C279	194.05	-5.79	0.39	3.45
HESSJ1023-575	155.83	-57.76	0.82	2.01
ESO139-G12	264.41	-59.94	0.95	1.82

Limits on normalization factor
$(E/GeV)^{-2}\ 10^{-8}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

Significance post-trial 6.1% (1.9 σ)

Search for neutrino point sources





Most sensitive for 'galactic sources' (<100 TeV)

Exclude IceCube 'cluster' due to a point source up to 1° extension

"Searches for Point-like and extended neutrino sources close to the Galactic Centre using the ANTARES neutrino Telescope",

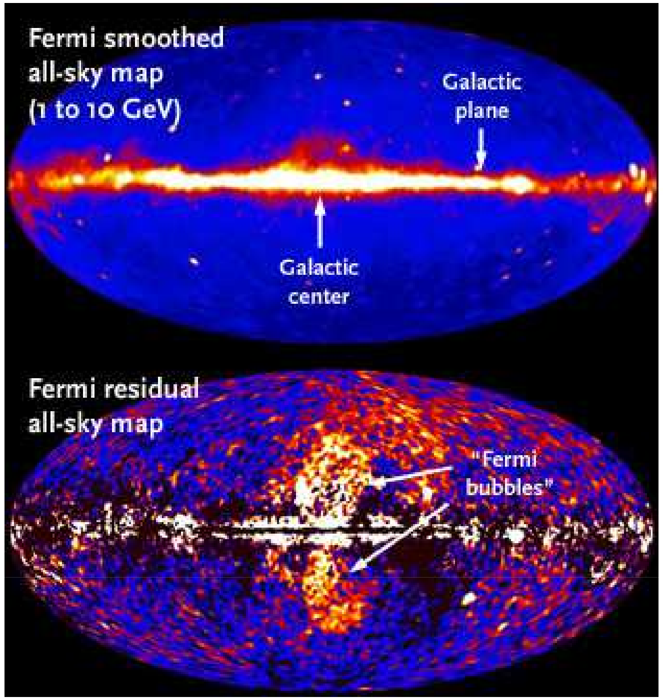
Adrián-Martínez et al., *accepted for publication in ApJL*, http://arxiv.org/abs/1402.6182

Fermi Bubbles

- Excess of γ- (and X-)rays in extended “bubbles” above and below the Galactic Centre.

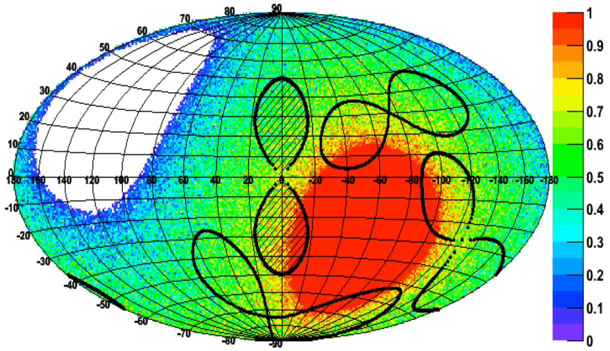
- Homogenous intensity, hard spectrum (E^{-2}) probably with cutoff.

  📖M. Su et al., ApJ. 724 (2010), G. Dobler et al., ApJ. 717, 825 (2010), M. Su & D.P. Finkbeiner ApJ 753, 61 (2012), R. Yang et al., astro-ph 1402.0403.



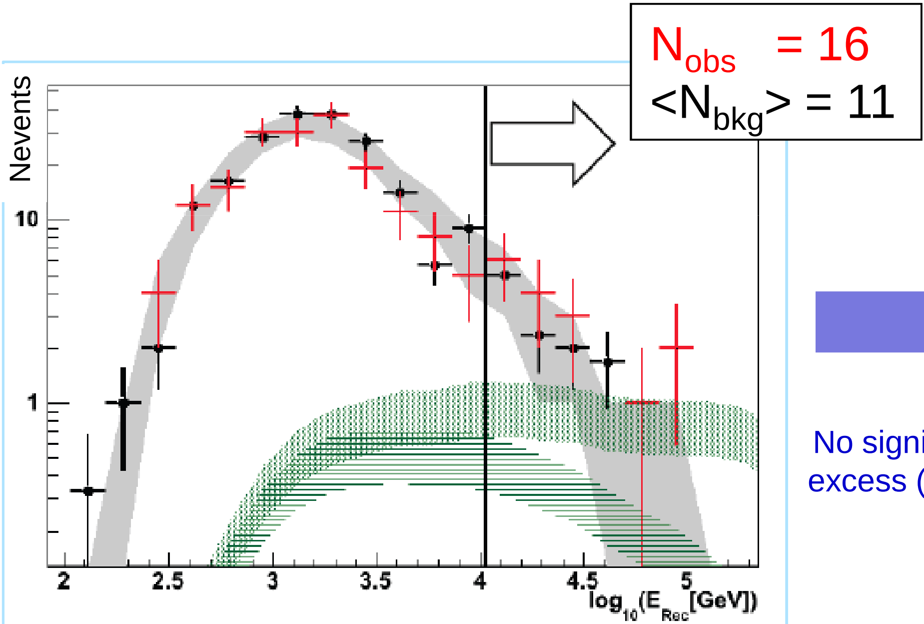
- Origin still unclear
  Some Galactic wind model involves hadronic processes (📖 Crocker & Aharonian, PRL 2011): accelerated cosmic rays interacting with ISM → π → γ,ν $\Phi_\nu \approx 0.4 \times \Phi_\gamma$. Leptonic + hadronic acceleration?

- In the field of view of ANTARES
  background estimated from average of
  3 non-overlapping “off-zone” data regions
  (same size, shape and average detector efficiency)

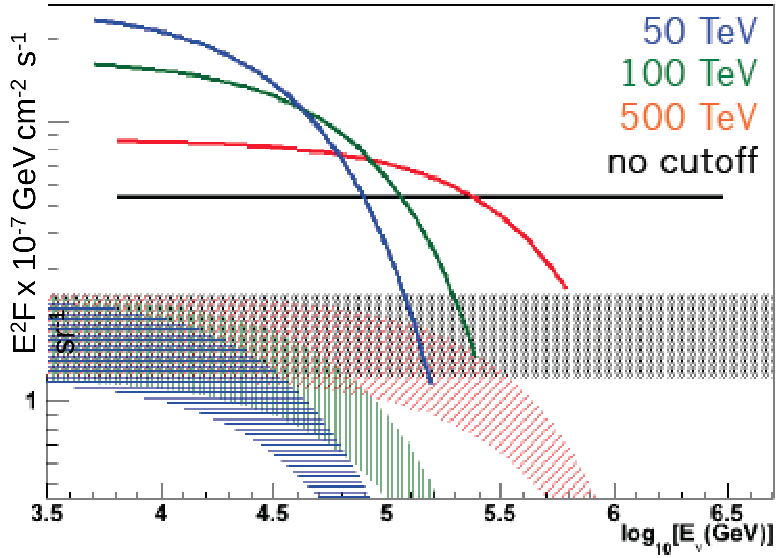


Fermi Bubbles

- 12-line data sample: May 2008 - Dec 2011 (806 days livetime). Only muon neutrinos.
- E_μ estimation based on Artificial Neural Networks.
- Optimization tuned on off-zone background events (MRF).



No significant excess (1.2 σ)

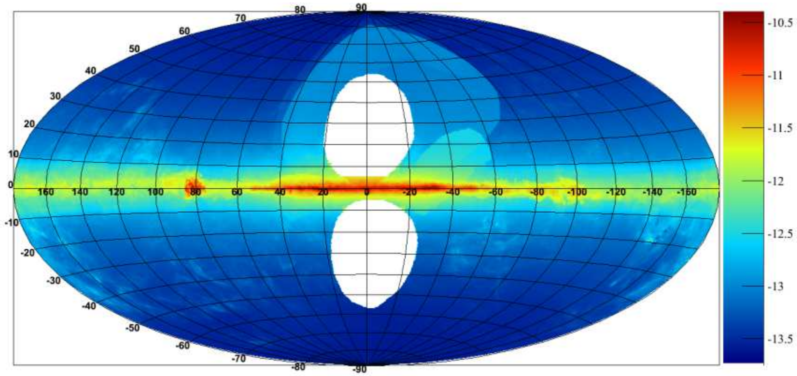


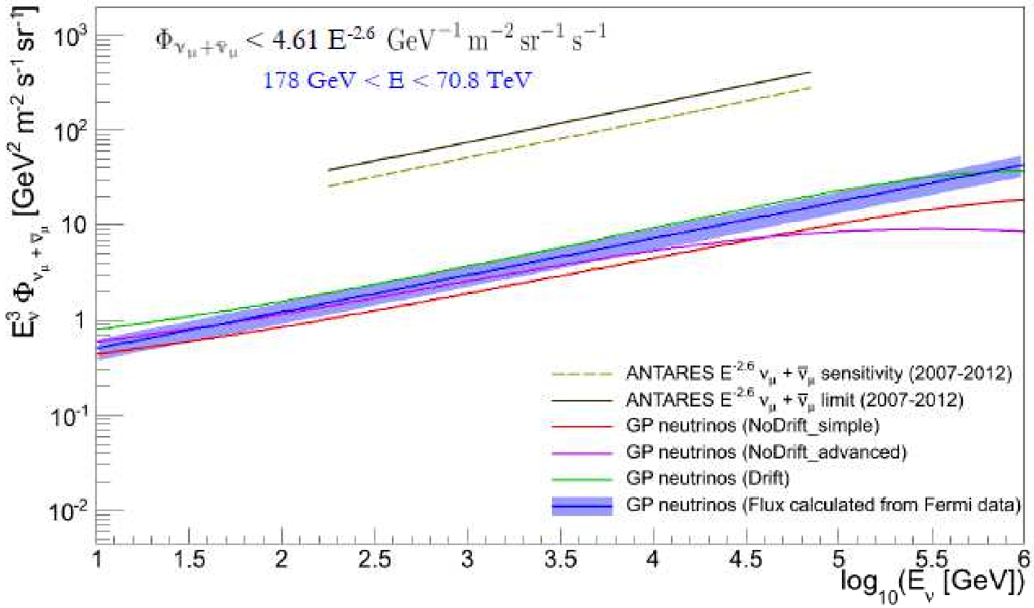
on-zone
off-zone average
expected signal (≠ cutoff, 50TeV cutoff)

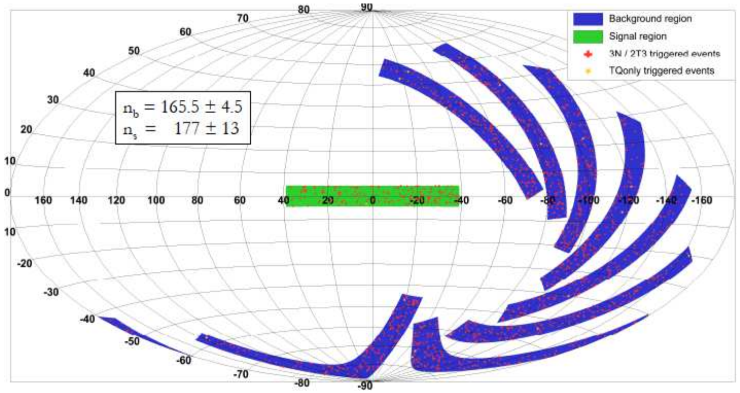
Upper limits with respect to different models

65% improvement expected with 2012-2016 data

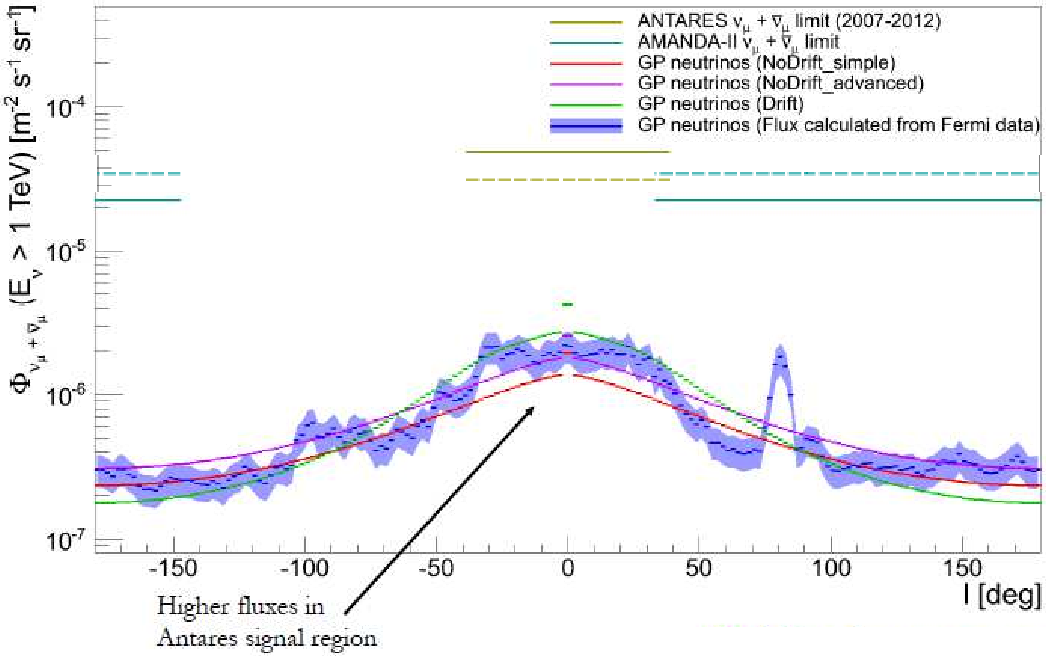
Galactic Plane



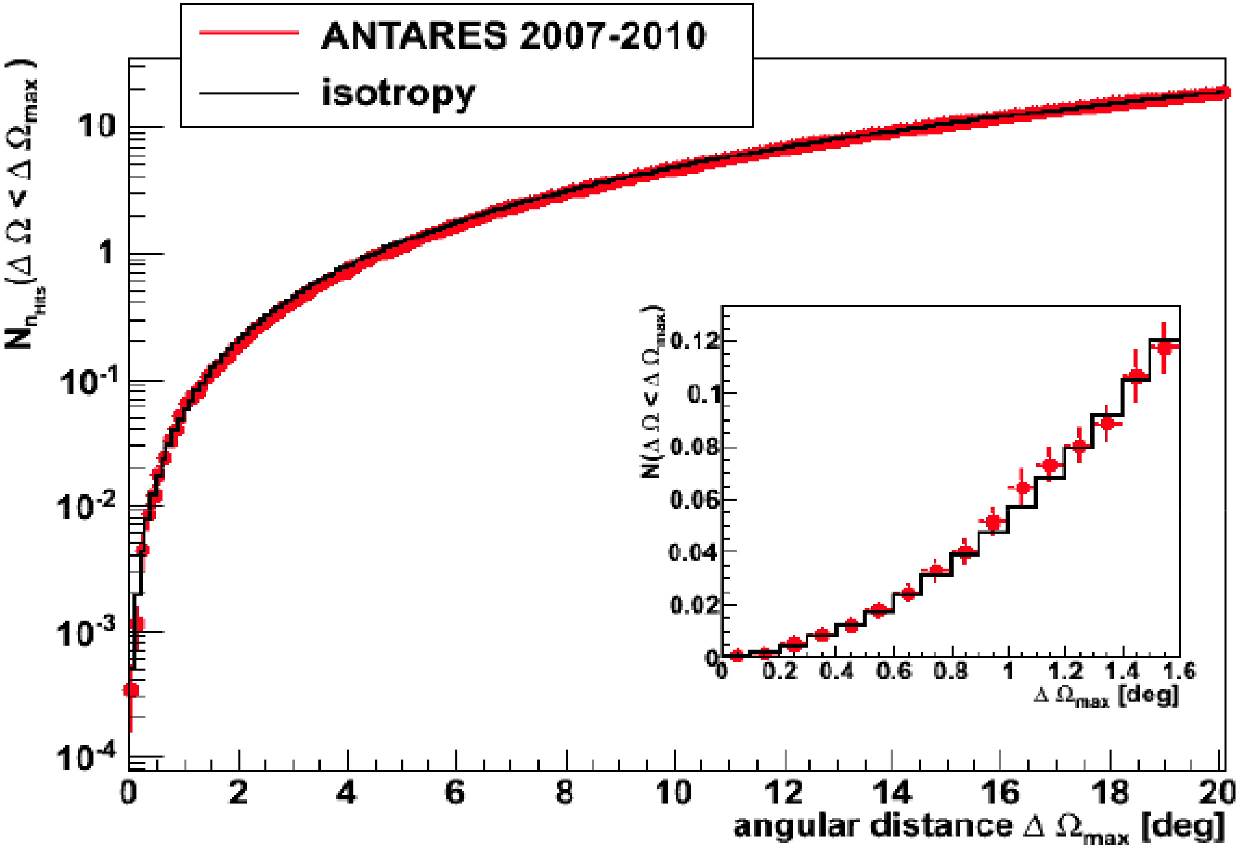




• 0.832 sigma → compatible with background



2-pt correlation function



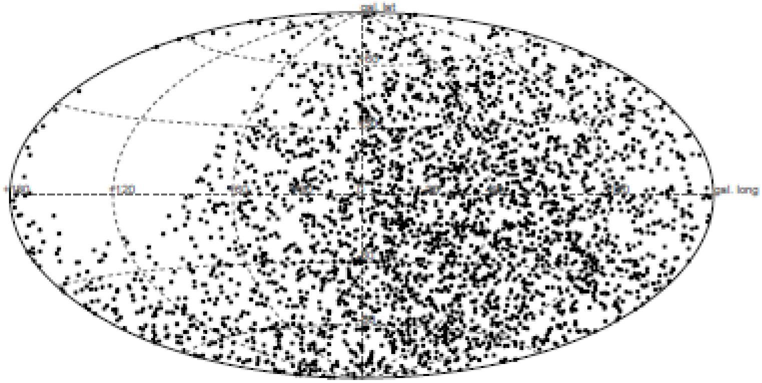
excess due to ANTARES hot spot

$$\mathcal{N}_p(\Delta\Omega) = \sum_{i=1}^{N} \sum_{j=i+1}^{N} w_{ij} \times H(\Delta\Omega_{ij} - \Delta\Omega),$$

Uses energy proxy (nhits) as weight.

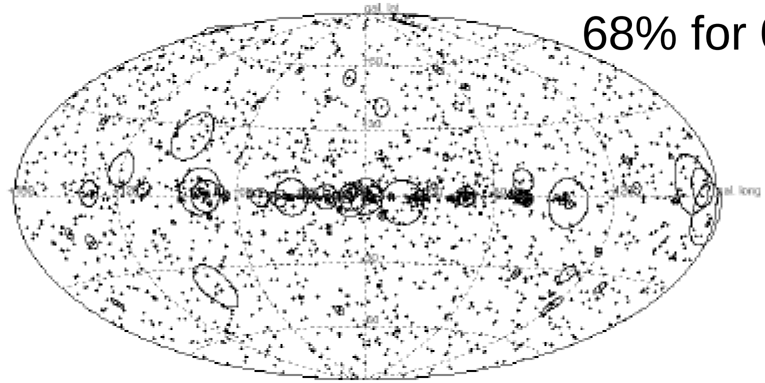
Post-trial p-value 9.6% for angles <1.1°

2-pt correlation function



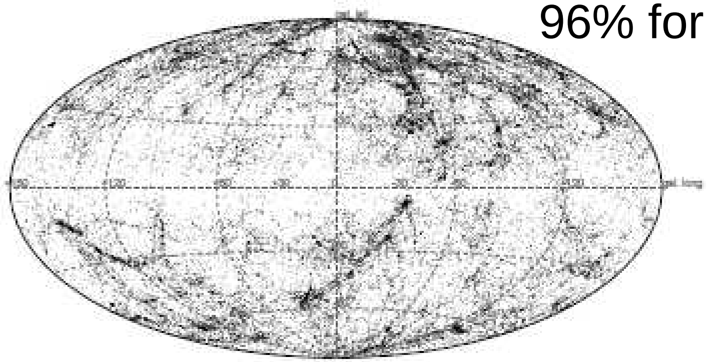
ANTARES neutrinos

68% for 0.6°



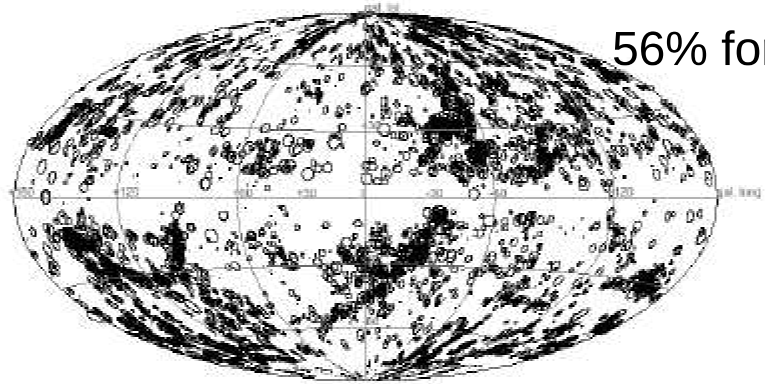
FERMI-LAT gammas

96% for 0.3°



Galaxies within 100Mpc

56% for 8.6°

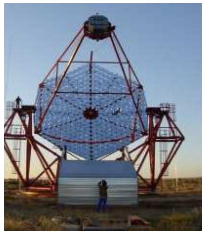


Massive black holes

No significant correlations

Accepted for publication in JCAP   http://arxiv.org/abs/1402.2809

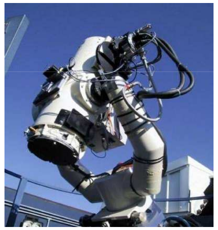
The Multi-messenger Program

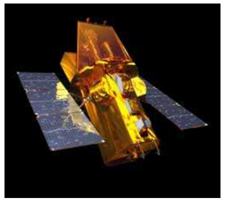


GeV-TeVγ-rays
Fermi / HESS…

UHECR
Auger

HE neutrinos





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

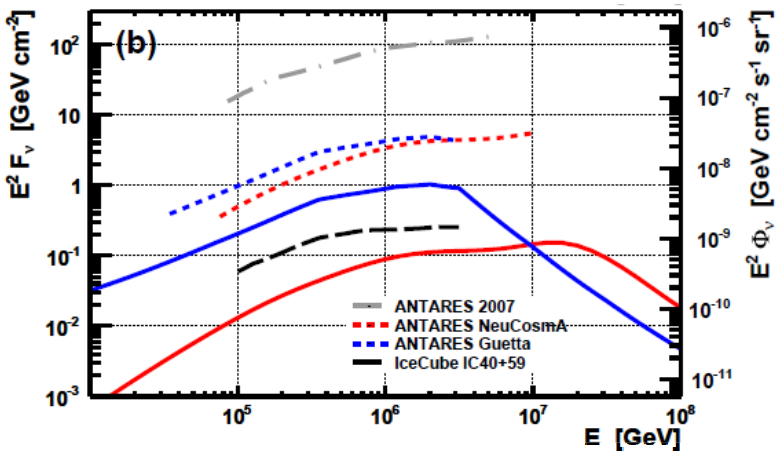
Gravitational Waves
Virgo / Ligo

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

Two examples of MM searches

- o Analysis of GRBs from late 2007 – 2011:
  296 long GRBs, Total prompt emission: 6.6 hours. Information from FERMI/SWIFT/GCN
- o GRB simulations of expected neutrino fluence:

  NeuCosmA [📖Hümmer et al. (2010)]
  Guetta [📖Guetta et al. (2004)]
- o No events found within 10° window from GRB
  Expected: 0.48 (Guetta), 0.061(NeuCosmA)
- o Dedicated analysis for GRB130427



Search with 40 blazars

- 2008-2011 data (750 days)
- 86 flaring periods 2FGL+Fermi Flare Advocates
- Allow a lag of ± 5 days for the flares
- 4 energy spectra considered

(E^{-1}, E^{-2}, E^{-1} and cutoff 1TeV, E^{-1} and cutoff 10 TeV).

- MDP optimization on Lambda quality cut only.
- Improved likelihood with energy proxy (Nhits)

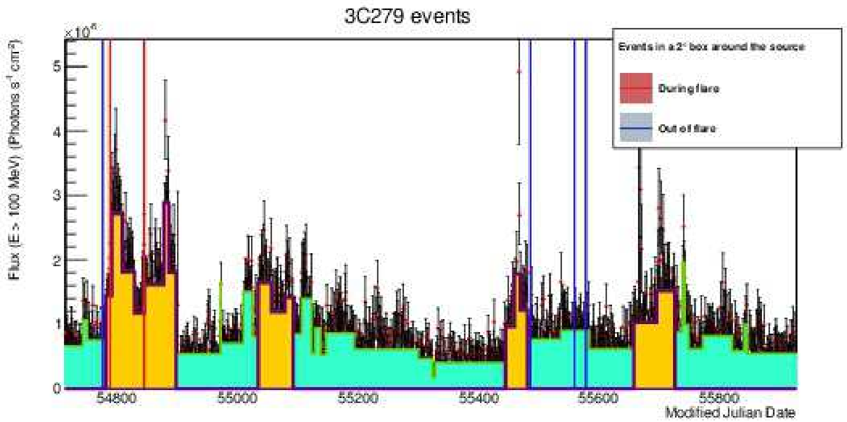
Separate optimization for 6 most significant flares

3C 279 (279 flaring days)

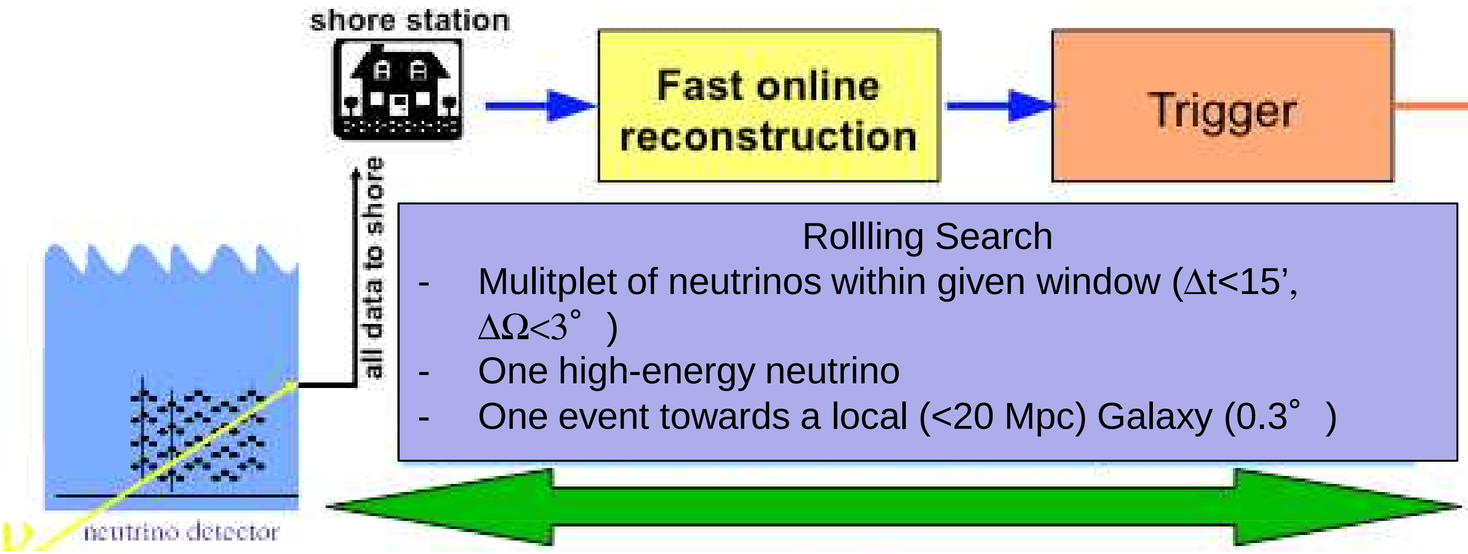
2 events compatible

in time and direction

- Lowest p-value (10%) for 3C279



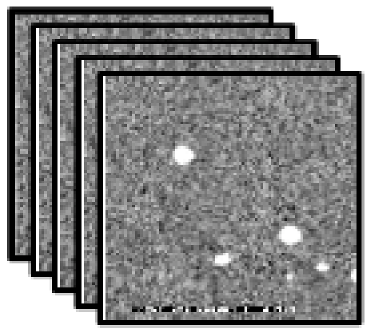
Alerts and Follow-up Program: TAToO



Total latency: alert sending (<1s) + repositioning (<10s)

optical telescopes (TAROT/ROTSE/ZADKO/Skymapper)

- Large sky coverage, high duty cycle
- No hypothesis on the nature of the source
- Sensitivity improved: 1 doublet is 3σ discovery, 1 triplet is 5σ !
- System active since 2009 with optical telescopes, now extended to SWIFT/XRT



T_0, T_0 +1, 3, 9 and 27 days

Astropart. Phys. 35 (2012) 530

Optical and X-ray follow-up: TAToO

- Since 2009, 107 alerts sent to TAROT and ROTSE robotic telescopes
  [84 with a good follow-up]

- Development and test of a dedicated and optimized optical image analysis pipeline

- Since mid 2013, alert sending operational with the SWIFT/XRT X-ray telescope;
  5 alerts sent and successfully followed

- Discussions ongoing to extend the network to others robotic telescopes
  and to TeV Cherenkov telescopes [HESS, VERITAS]

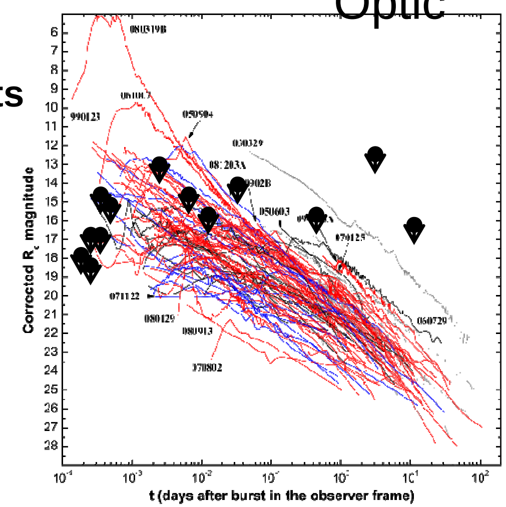
<u>Main results</u>:

“prompt” observations from 2010-2013 alerts

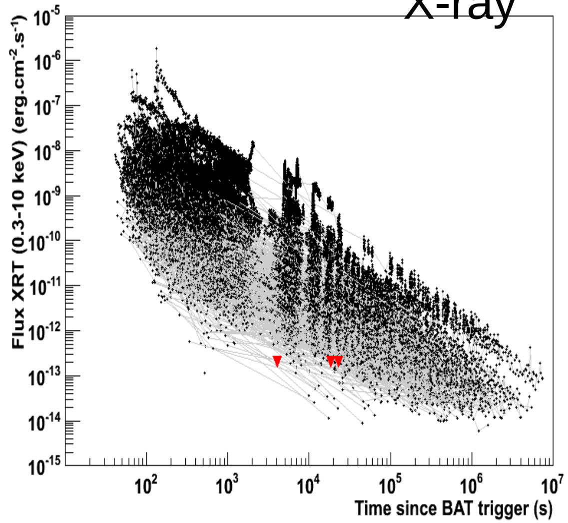
- No coincidence with fast transient [model independent]
- Upper-limits on the obs. magnitude
- Interpretation in the case of GRB

=> Paper for summer 2014

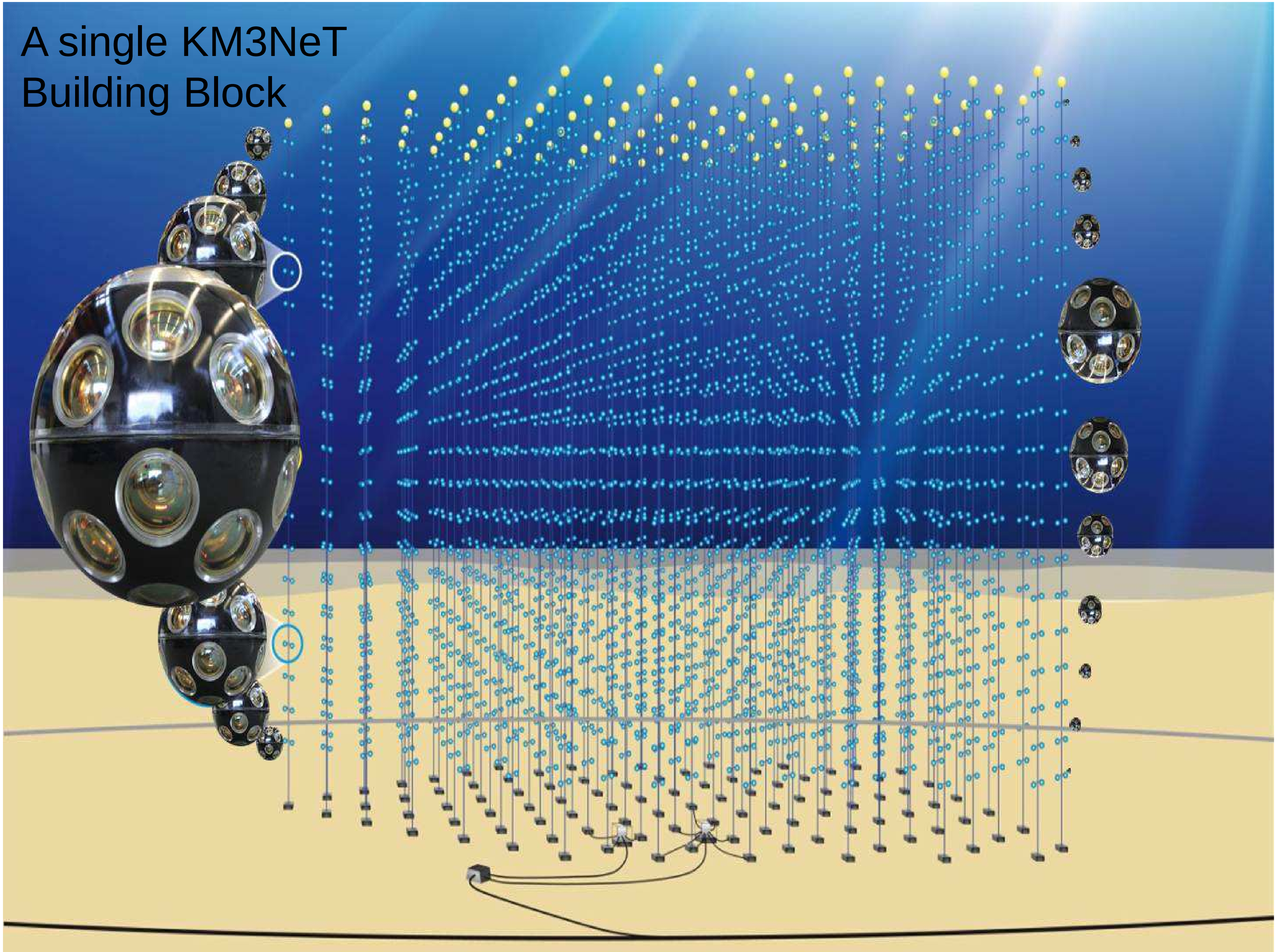
Optic



X-ray



Analysis of the long-term follow-up ongoing [supernovae search…]
results end of 2014


A single KM3NeT
Building Block

KM3NeT

- Multi-km^3 deep sea neutrino telescope in the Mediterranean Sea, substantially exceeding ANTARES/IceCube in sensitivity

- Two sites: Toulon, France, and Capo Passero, Sicily

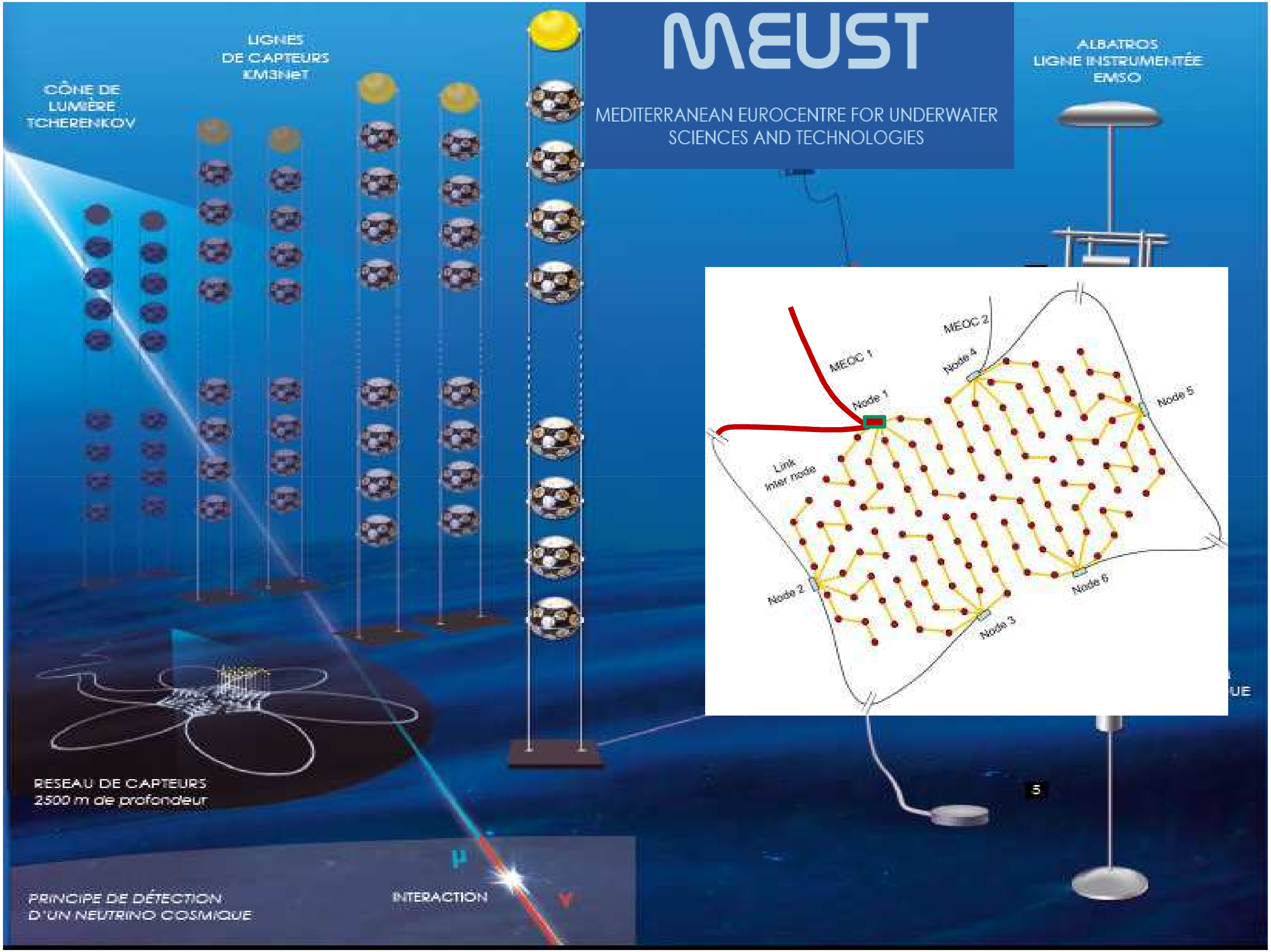
- Staged implementation:

Phase-1 in progress (31 M€)		31 strings (2 sites)	(local funding)
Phase-1.5	(LoI in prep.)	230 strings (2 sites, 2 building blocks)	
Phase-2		600 strings (6 building blocks)	

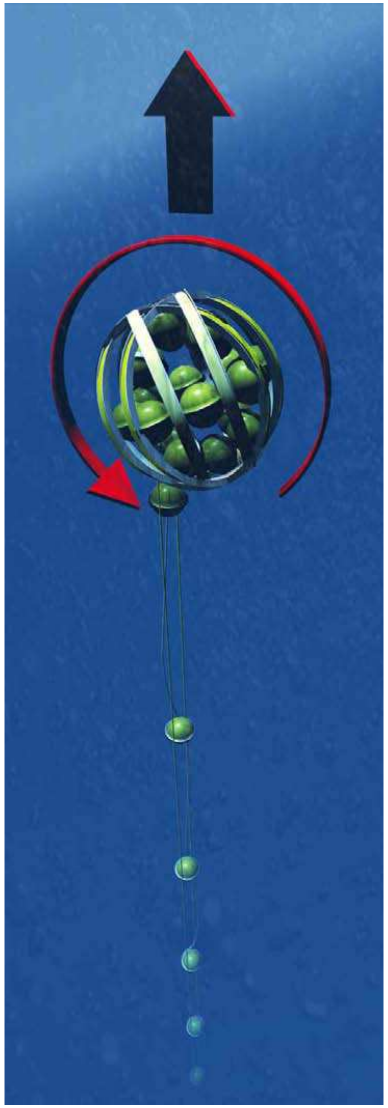
- Central physics goals:
  - Investigation of IceCube signal (Phase 1.5)
  - Neutrino Astronomy (neutrino “point” sources) (Phase 2)

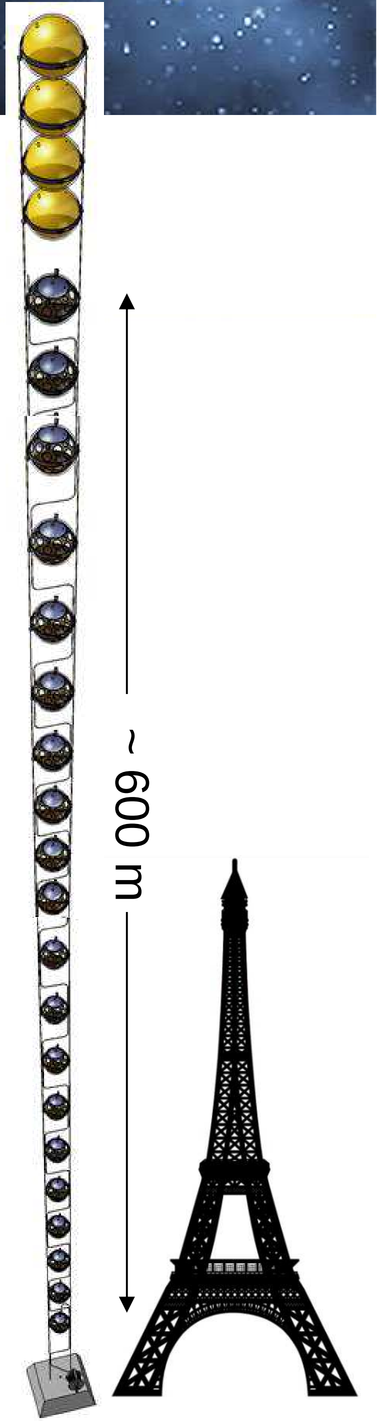
- Nodes for deep-sea research in marine sciences (EMSO)

- Possibility of a site optimised for low energy (neutrino mass hierarchy) under study→ORCA


MEUST
MEDITERRANEAN EUROCENTRE FOR UNDERWATER SCIENCES AND TECHNOLOGIES
CÔNE DE LUMIÈRE TCHERENKOV
LIGNES DE CAPTEURS KM3NeT
ALBATROS LIGNE INSTRUMENTÉE EMSO
MEOC 1
MEOC 2
Node 1
Node 2
Node 3
Node 4
Node 5
Node 6
Link inter node
RESEAU DE CAPTEURS
2500 m de profondeur
PRINCIPE DE DÉTECTION D'UN NEUTRINO COSMIQUE
INTERACTION
μ
ν

String Deployment





- Fast mounting of optical modules
- Rapid deployment
- Autonomous unfurling
- Recovery of launcher vehicle

Multiple deployments with a single cruise

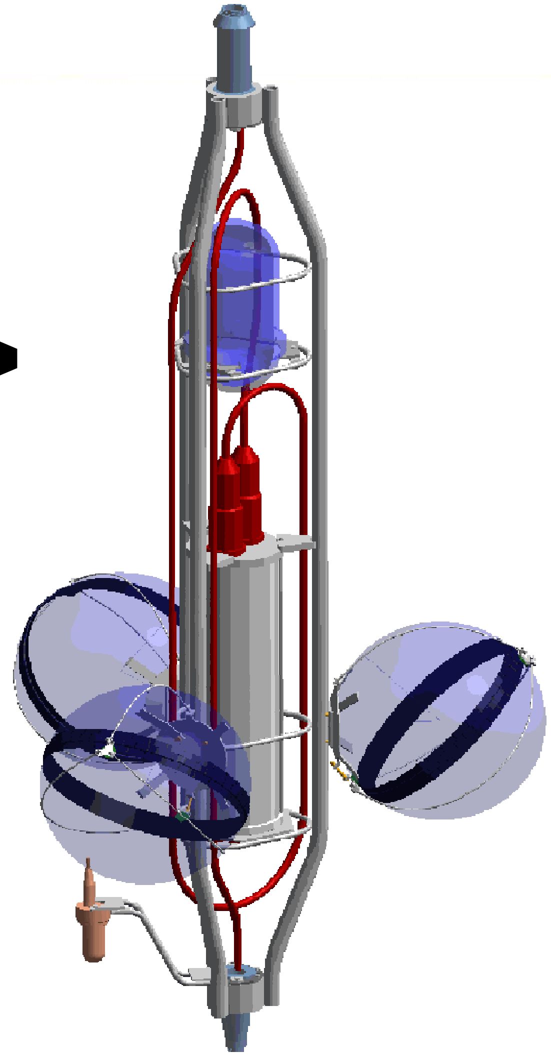
The Multi-PMT Digital Optical Module

17 inch

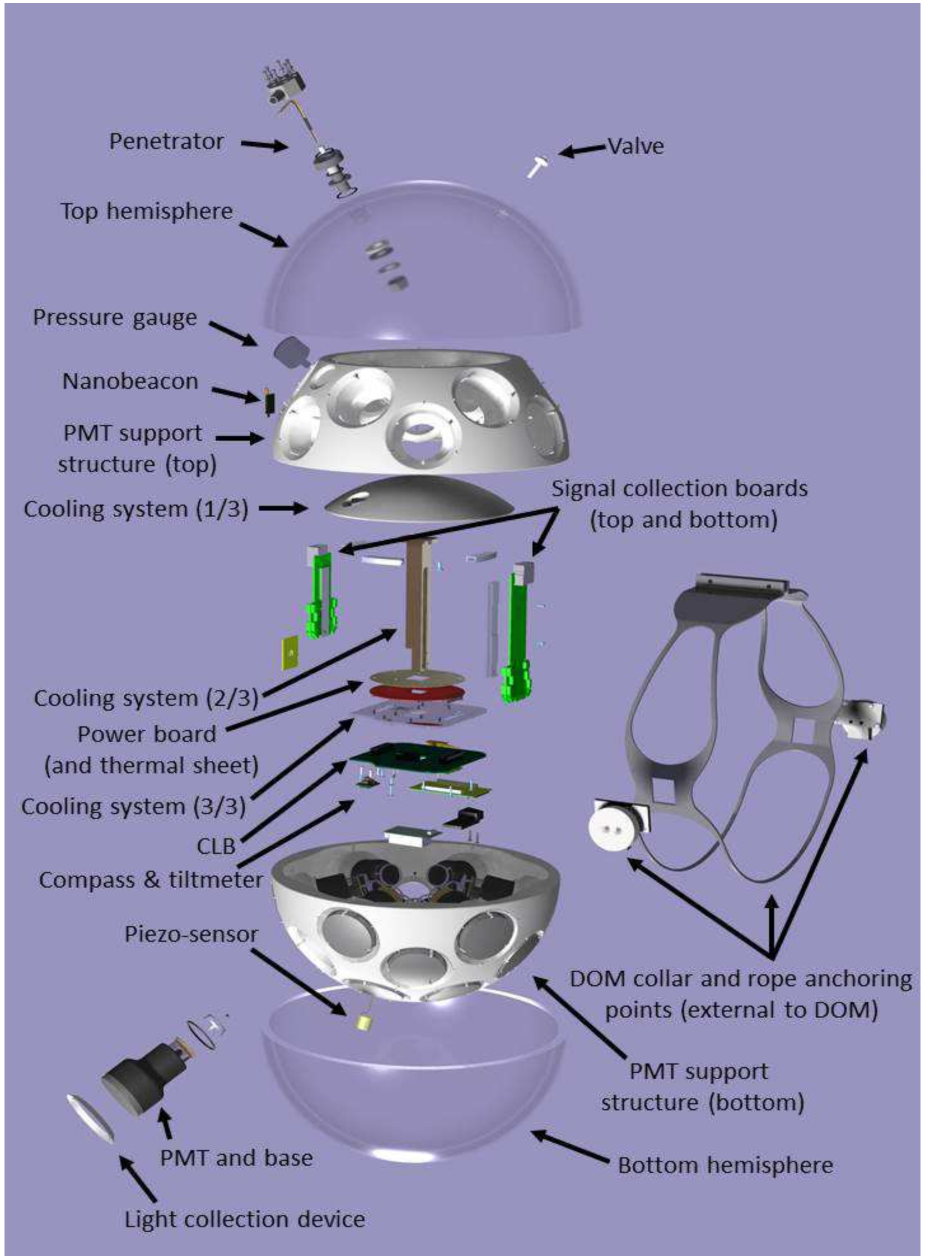
- Digital photon counting
- Directional information
- Wide angle of view
- Single pressure transition
- Cost reduction cf ANTARES

>

ANTARES Storey



The Multi-PMT Digital Optical Module II

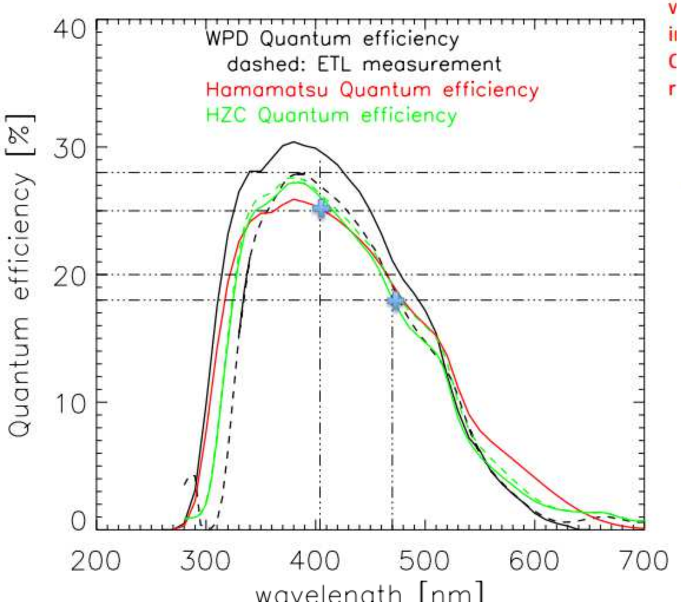


- 31 x 3" PMTs
  - Hamamatsu, ETL, HZC
- Light collection ring
  - 20–40% gain in PC for free
- Low power
  - 7 W / DOM
- FPGA readout
  - sub-ns time stamping
  - time over threshold
  - all data to shore
- Calibration
  - White rabbit time synchronisation
  - LED & acoustic piezo
- Optical fibre data transmission
  - DWDM with 80 wavelengths
  - Gb/s readout

PhotoMultiplier Development

Specifications

- QE: 20(18)%@470nm / 28(25)%@404nm
- TTS: 4.5(5.0)ns FWHM
- Gain 3 10^6 for 900V<HV<1300 V
- Prepulses <1%
- Delayed pulses <3.5%
- Afterpulses late<10%; early<2%
- Dark rate <1500 Hz

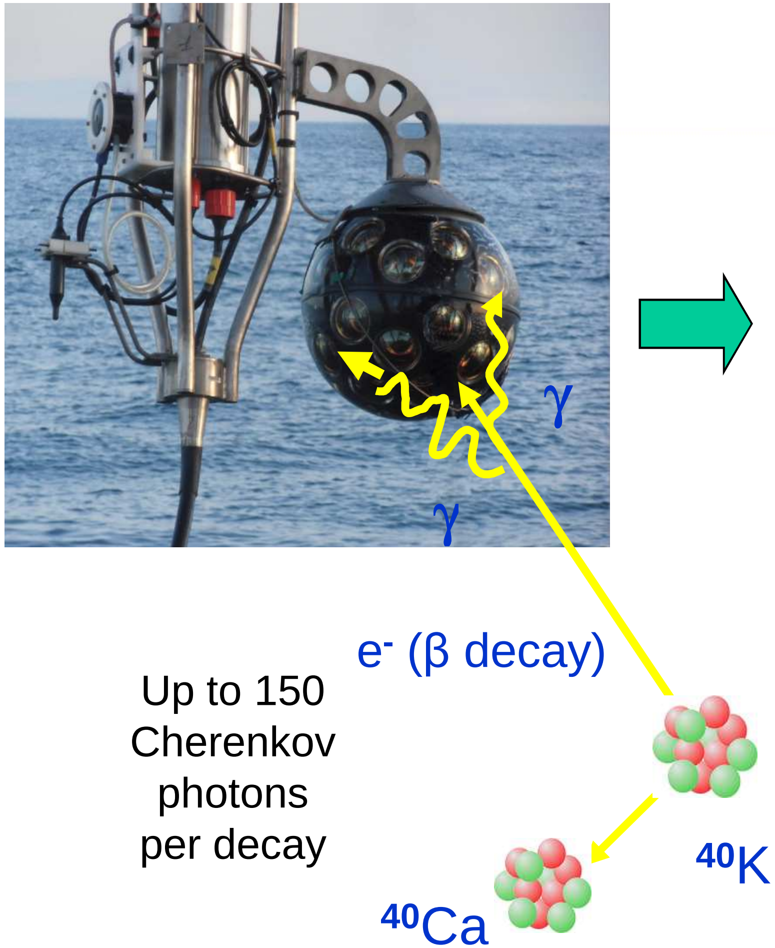


ETL
ETL D792KFL
9cm diameter

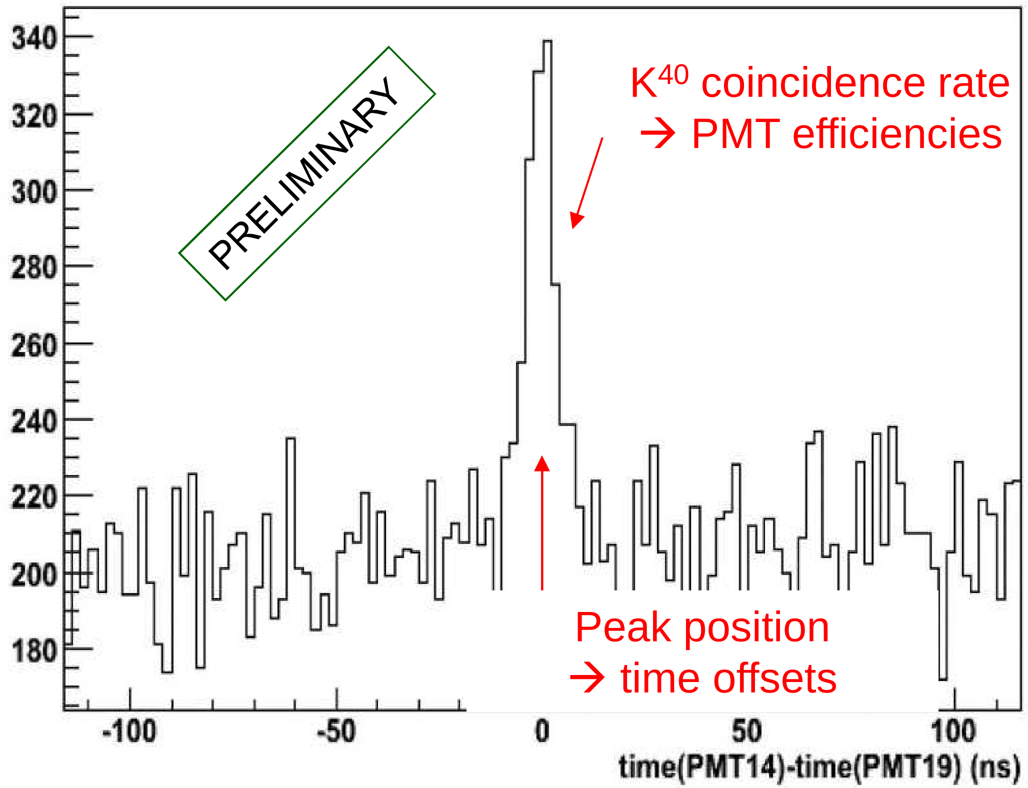
Hamamatsu
R12199-02
8cm diameter

Cost/PC area cheaper than 10 inch

PPM-DOM: K40 Coincidences

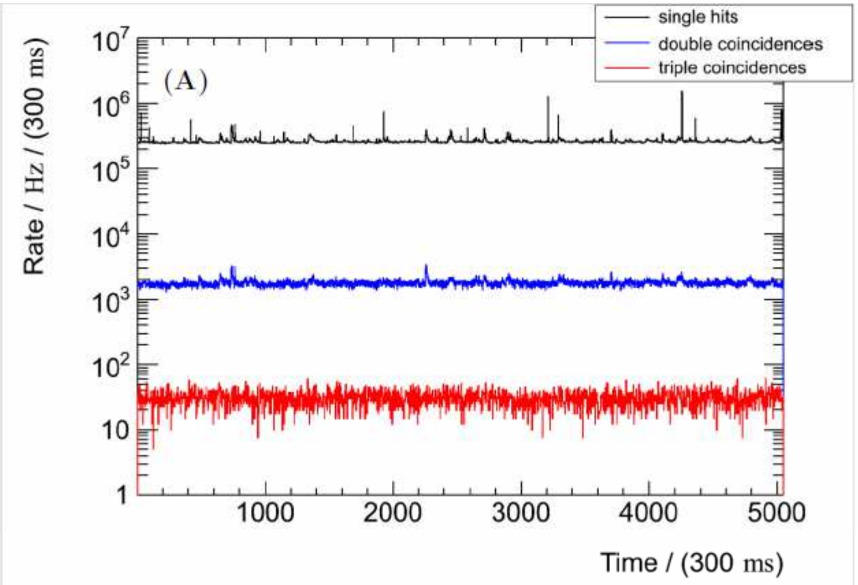


Coincidence rate on 2 adjacent PMTs

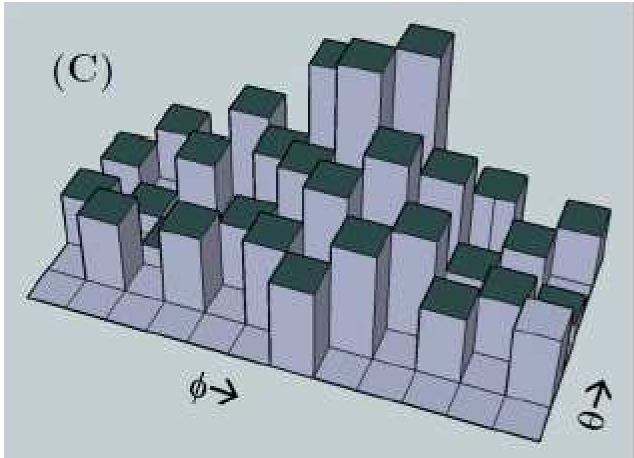


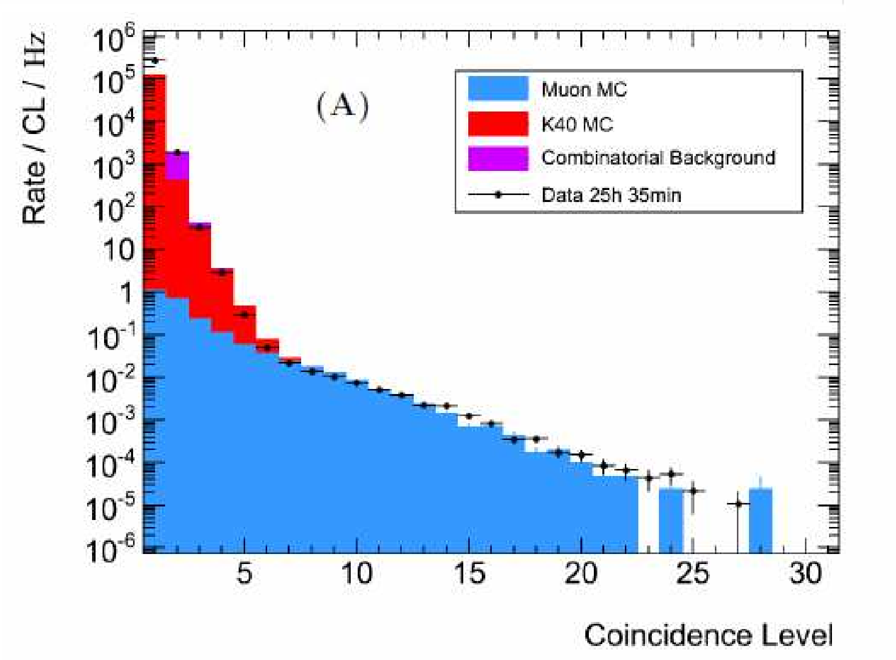
Concentration of ^{40}K is stable
(coincidence rate ~5 Hz on adjacent PMTs)

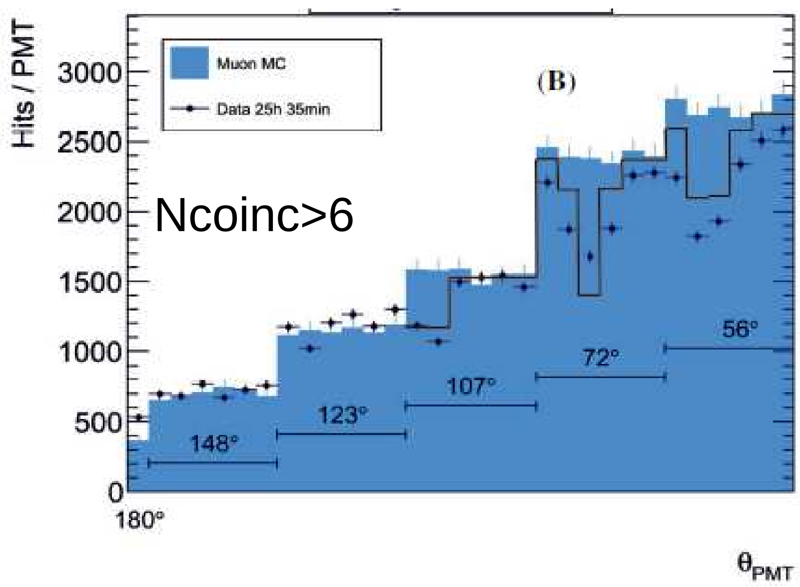
KM3NeT DOM: works beautifully



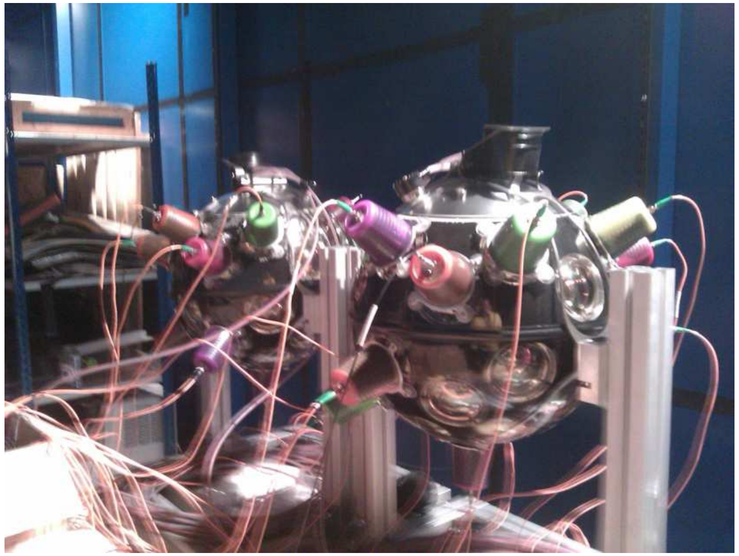
Most hits from the support structure





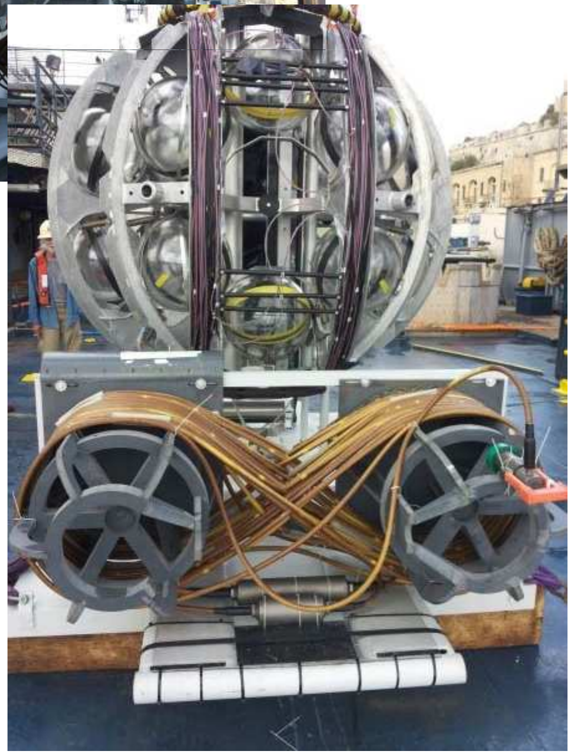


KM3NeT 'Mini-line' Deployed at Capo Passero (May 7, 2014)

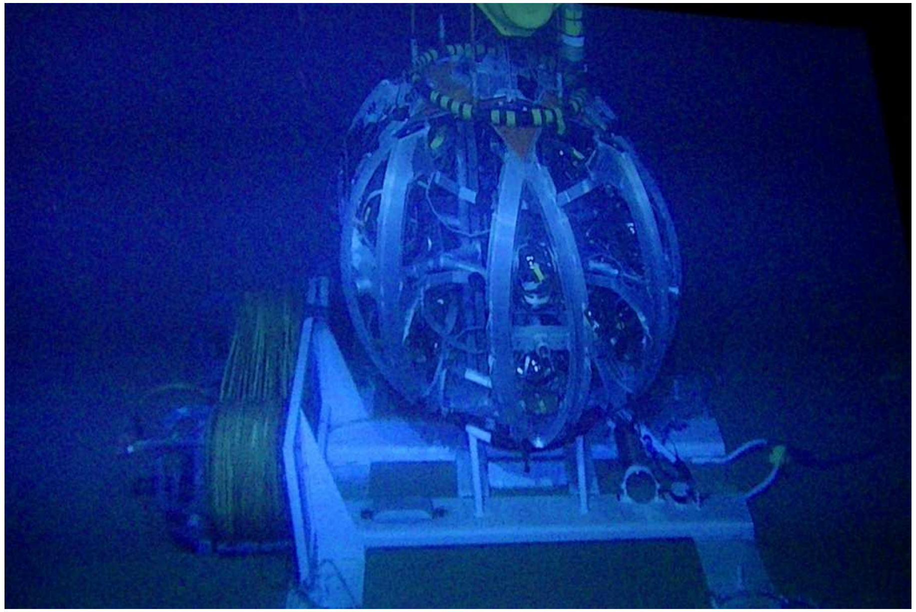


Integration
Nikhef +
CPPM

Deployment
Sicily



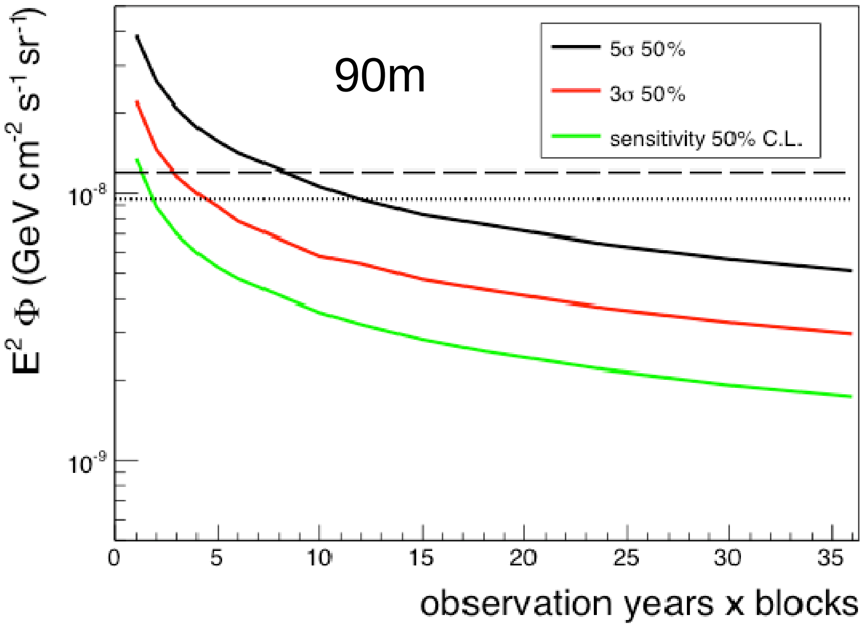
KM3NeT ‘Mini-line’ Deployed at Capo Passero (May 7, 2014)



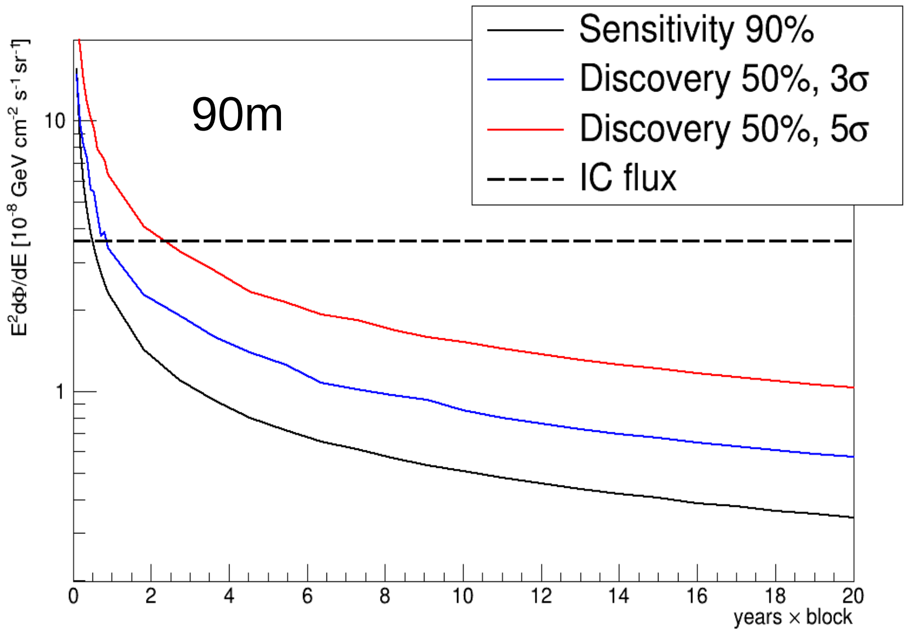
Diffuse Flux sensitivity

$\Phi_{cosm} = 1.2\ 10^{-8}\ E^{-2}\ e^{-E/3PeV}\ GeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}$ per flavour;

Muons



Cascade



5 sigma after 9 years*blocks

5 sigma after 3 years*blocks

30% improvement if use 120m spacing, but less good for galactic sources

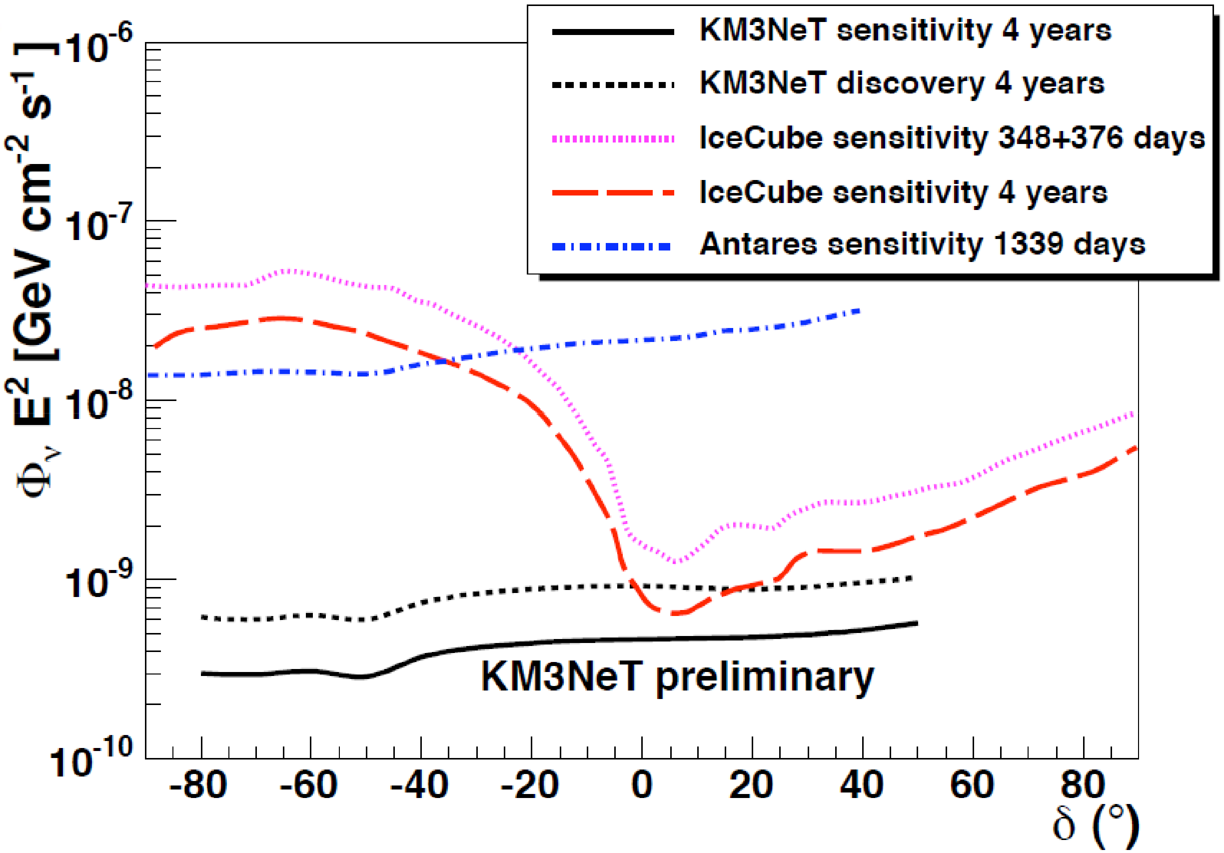
Point Source (muons)

Phase 2:
6 blocks
90m spacing

E-2 flux

~50*ANTARES

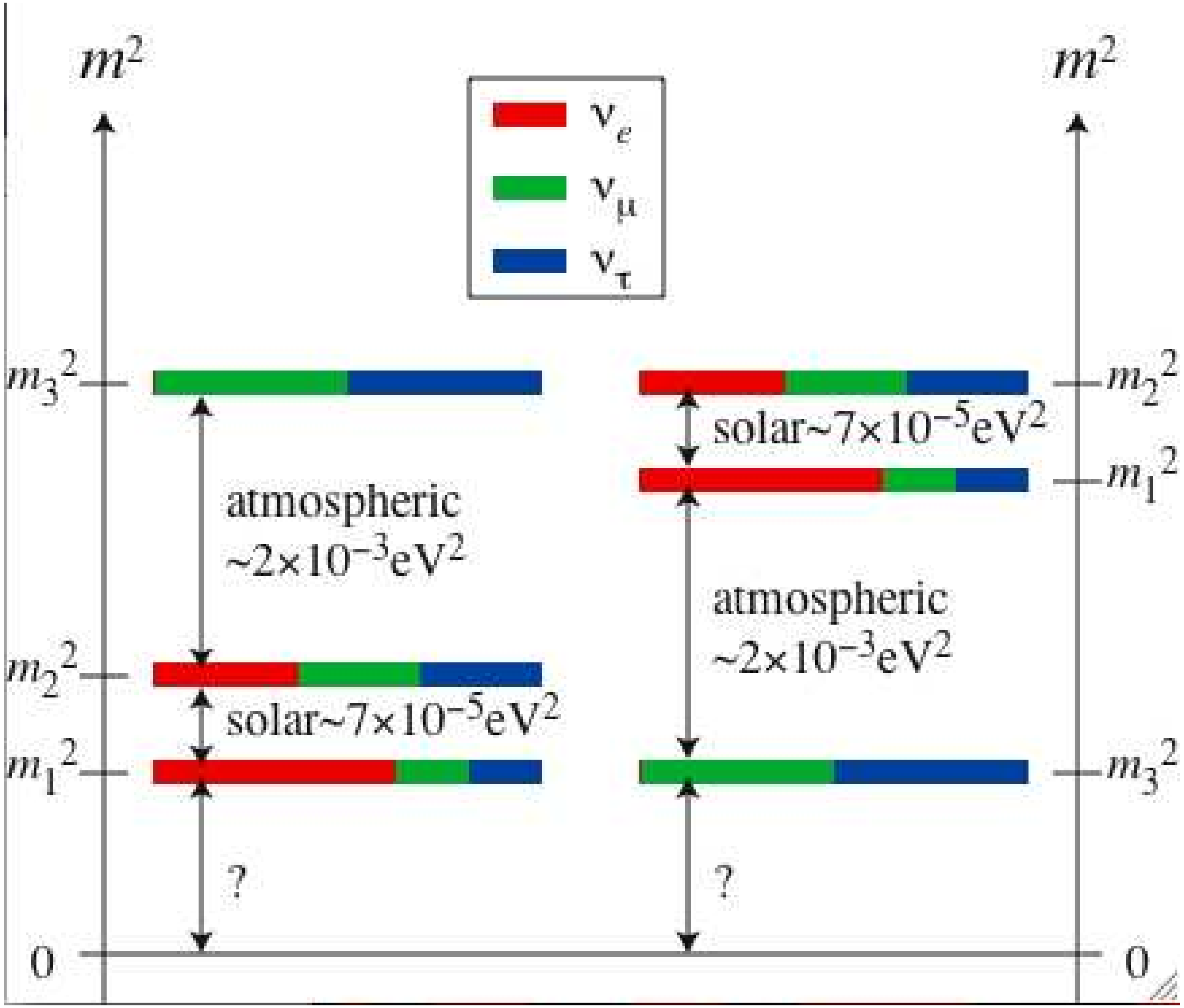
Angular resolution
<0.1° above 100 TeV



Muons alone: RXJ1713: 5 years @ 5 sigma
Vela X: 3 years @ 5 sigma
Fermi Bubbles: 1 year @ 1 sigma

(Assuming 100% hadronic)

The neutrino mass hierarchy



Normal **Inverted**

Mass Hierarchy Measurement with Atmospheric Neutrinos

- Free ‘beam’ of neutrinos
- Broad range of baselines (50-1250km)
- Broad range of energies (~GeV-PeV)
- Composite of beam well understood: flux (nu)~1.3 flux (anti-nu)

- mass effects lead to event rates at particular angles and energies

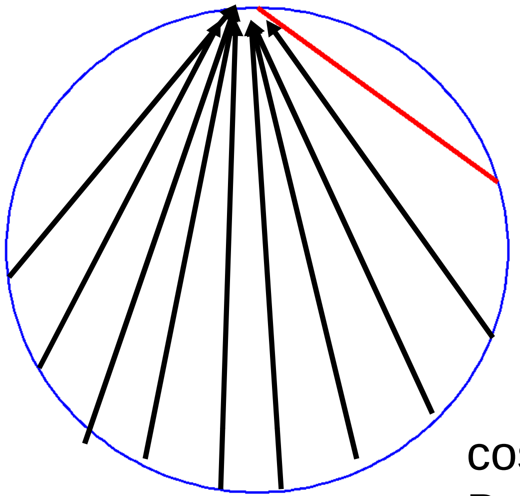
  which depend on the mass hierarchy and is opposite for neutrino/anti-neutrino

- At these energies $\sigma(\nu) \approx 2\sigma(\overline{\nu})$ so observe net effect

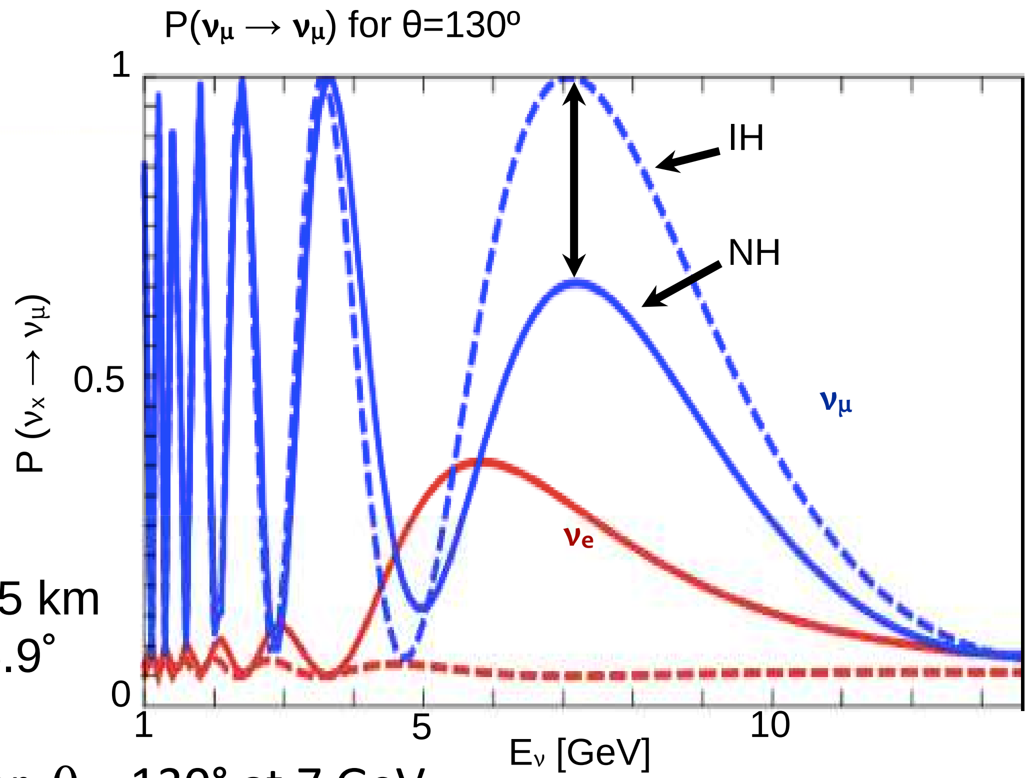
- See for example….Phys. Rev. D 78, 093003
- Revisited with improved knowledge of θ_{13}

  arxiv:1205.7071v4 ,Akhmedov, Razzaque, Smirnov

Mass Hierarchy Measurement with Atmospheric Neutrinos



cosθ = 0.6
Baseline = 7645 km
Inclination = 36.9°

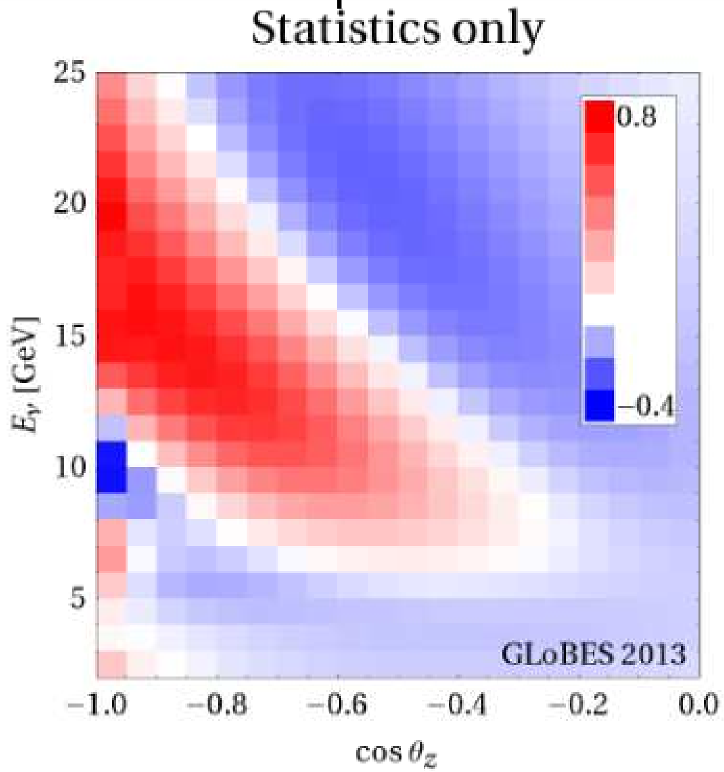


- Maximum difference NH ↔ IH for θ = 130° at 7 GeV
- For anti-ν, NH and IH are approximately swapped → effect cancels if detector cannot distinguish μ^+ and μ^-
- However: flux of atm.ν ~ 1.3 × flux of atm. anti -ν and σ(ν) ~ 2 × σ(anti-ν) at low energies
- **→ Count $N_\mu(\theta, E)$ from ν_μ + N →μ + X and compare with NH/IH predictions**

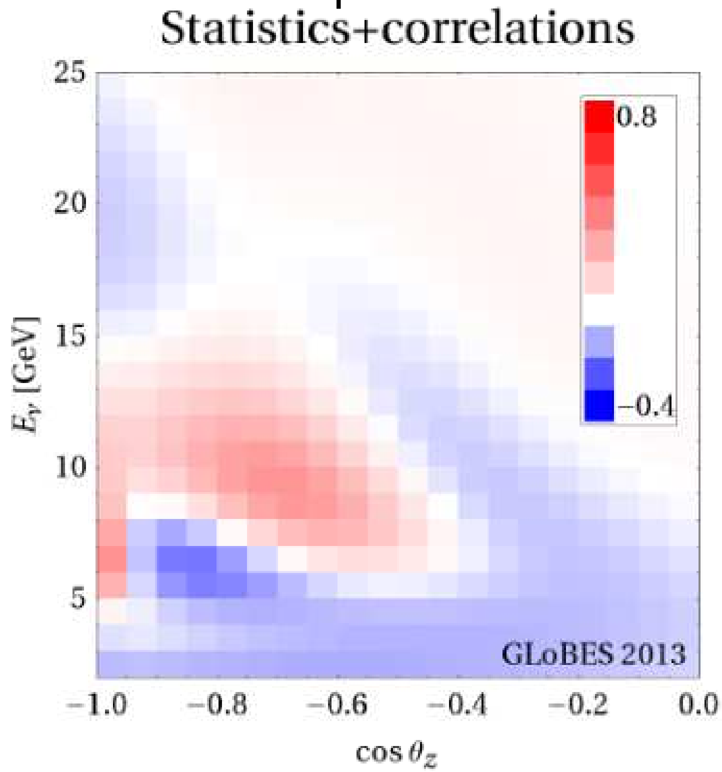
Sensitivity Calculation – atmospheric ν_μ

- Fit of event count in Energy-Zenith space
- Color code : bin-by-bin significance of hierarchy difference

Oscillation parameter fixed



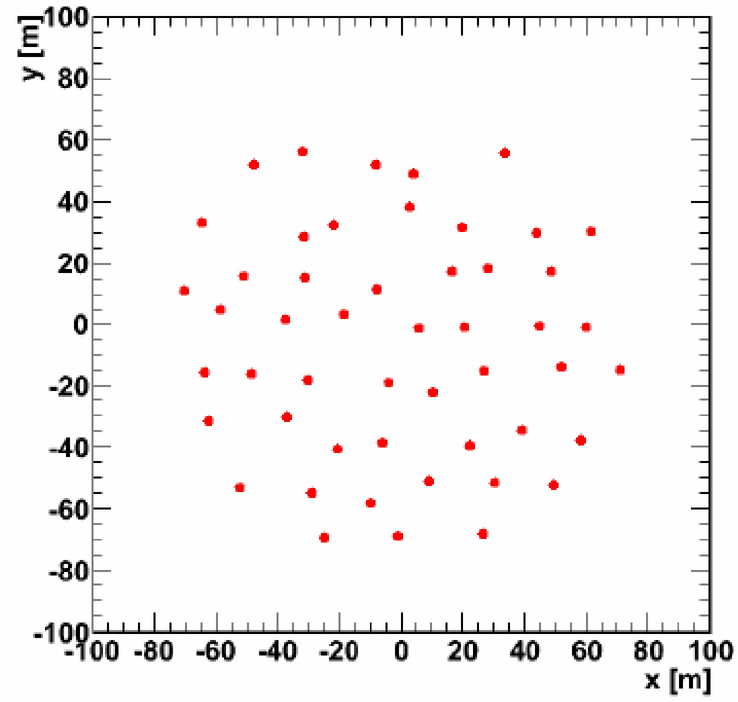
Oscillation parameter fitted



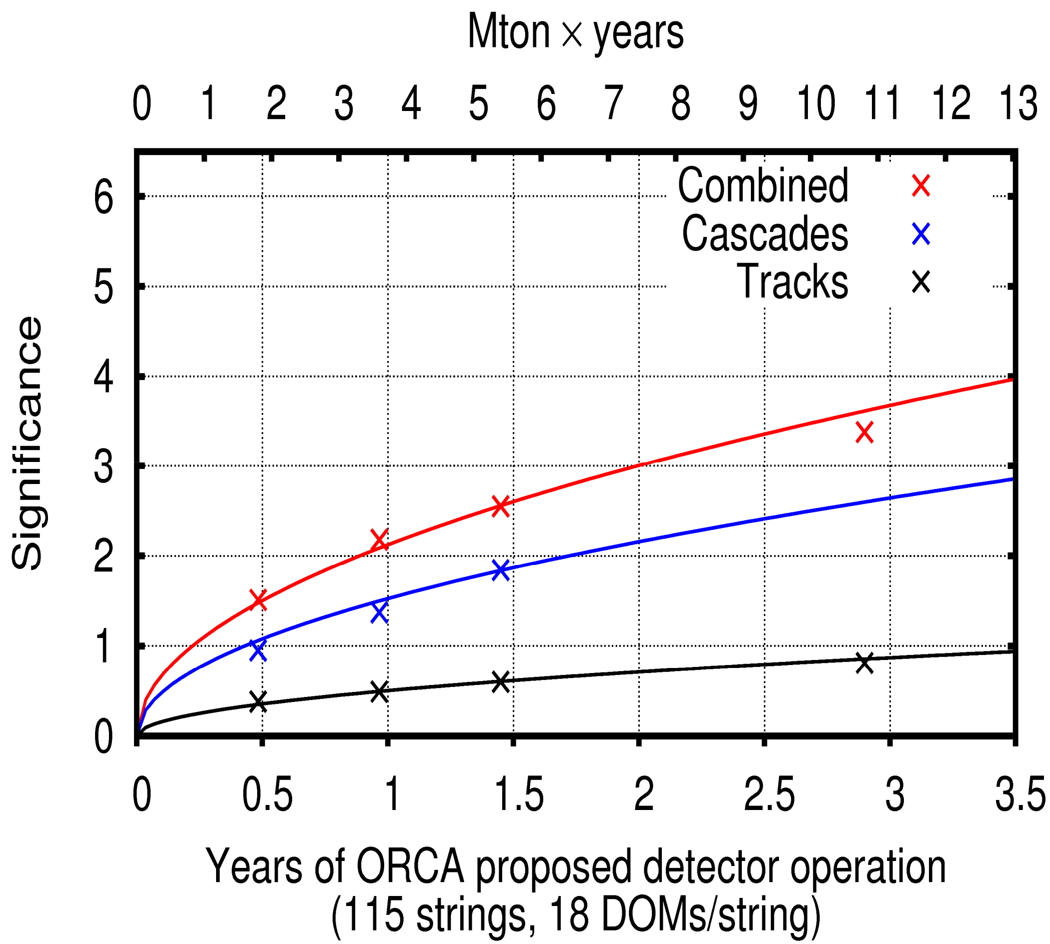
W. Winter : arXiv:1305.5539

Oscillation Research with Cosmics in the Abyss

Dense Mton detector with KM3NeT technology (e.g. 50 lines, 6m/20m)



ORCA sensitivity (PRELIMINARY)



Geometry not yet optimised
Bjorken y discrimination not yet used

+ Factor ~4 improvement on value of θ_{23}
+ Measurement of octant

Summary

- ANTARES in its seventh year of operation
- Thanks to it excellent angular resolution and view of Southern sky, ANTARES has competitive sensitivities despite its modest size
- KM3NeT Consortium -> Collaboration
- Site choice made (Toulon, Capo Passero)
- Technology chosen and prototypes under test
- Phased approach:
  - Phase 1.5: investigate IceCube diffuse flux
  - Phase 2: neutrino astronomy
  - ORCA looks very promising