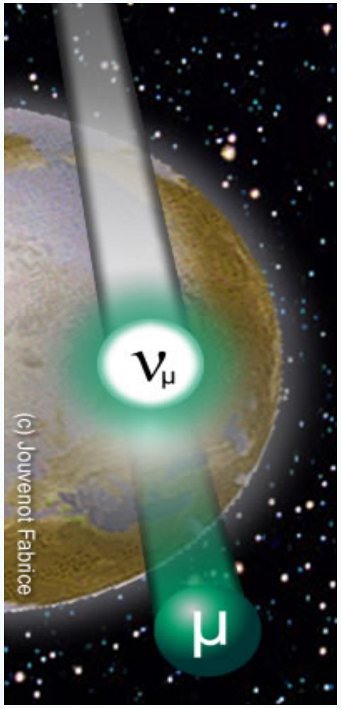
Underwater Cherenkov Detectors



Introduction

Science Scope-Detection Principles

Results from ANTARES

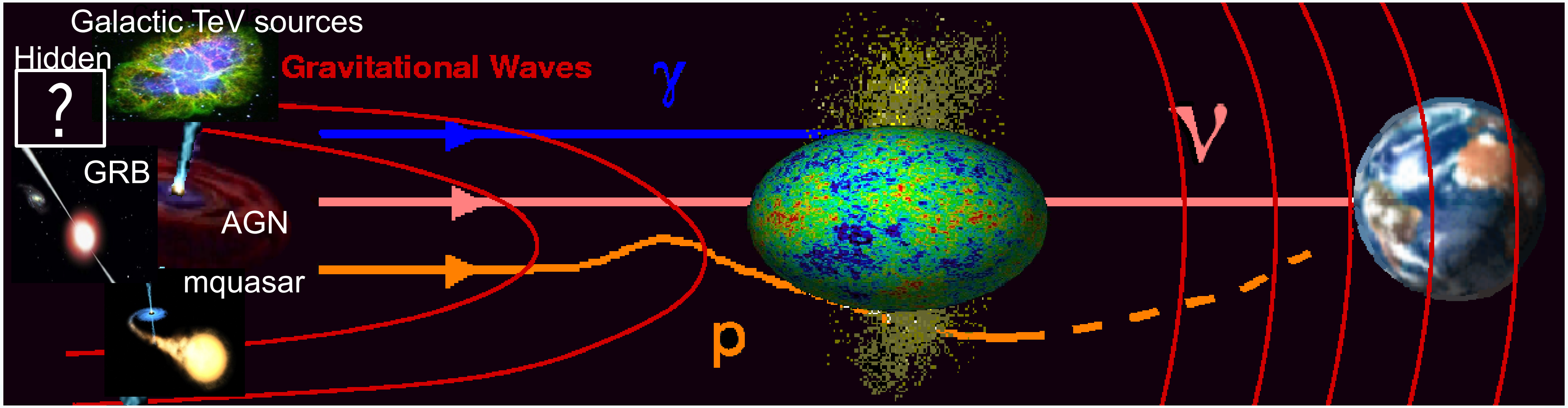
News and prospects about KM3NeT

Antoine Kouchner

University Paris 7 Diderot- AstroParticle and Cosmology

For the ANTARES and KM3NeT collaborations

Multi-messenger astronomy

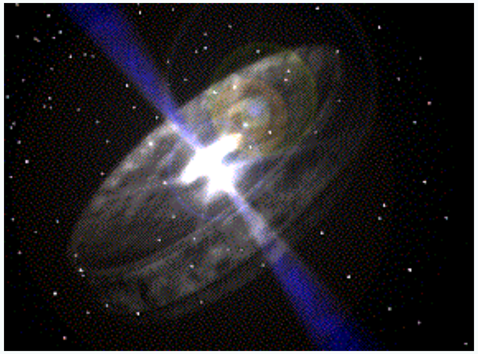


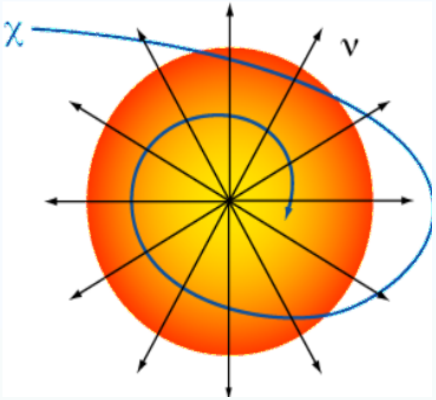
- Production by cosmic ray interactions: p+A/γ → mesons → ν, γ
  → trace hadronic processes
- No absorption, Weakly interacting → cosmological distances & dense objects
- No deflection by B → pointing accuracy

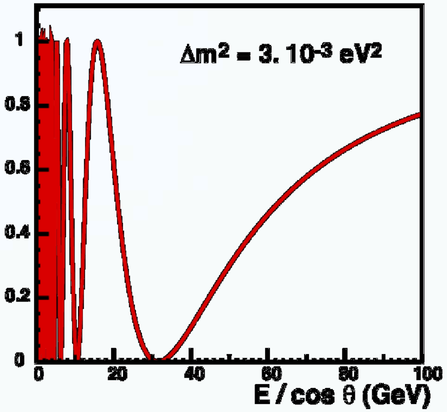
Neutrinos would open a new non-EM window on the Universe

Mutli-wavelength/messenger analysis → Modeling of the source

Neutrino telescopes: science scope







High Energy $E_\nu > 1$ TeV	Medium Energy 10 GeV $< E_\nu <$ 1 TeV	Low Energy 10 GeV $< E_\nu <$ 100 GeV

ν from extra-terrestrial sources

Dark matter search

ν oscillations

Origin and production mechanism of HE CR

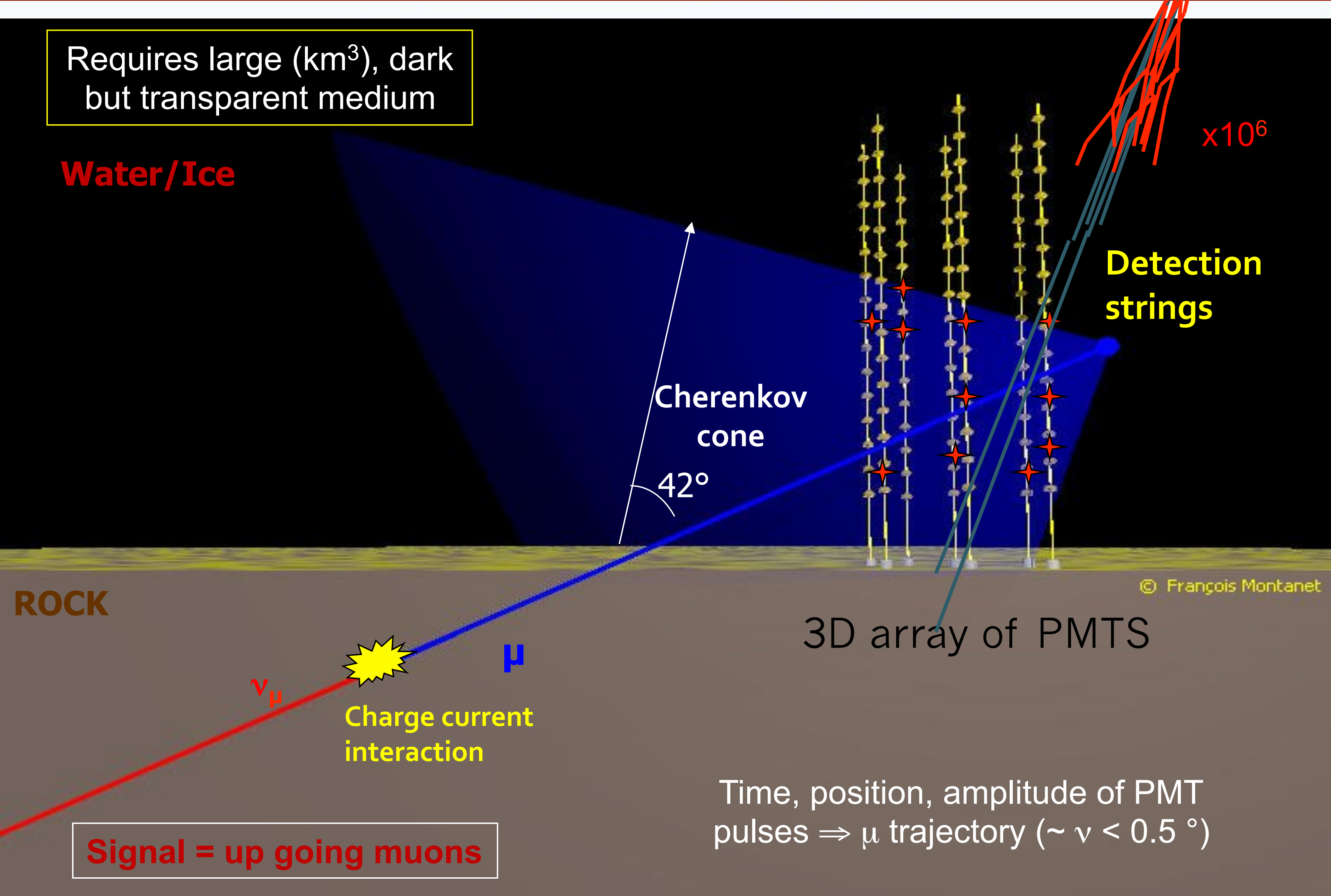
↓

Primary goal

Exotic particle physics
Monopoles, nuclearites,...

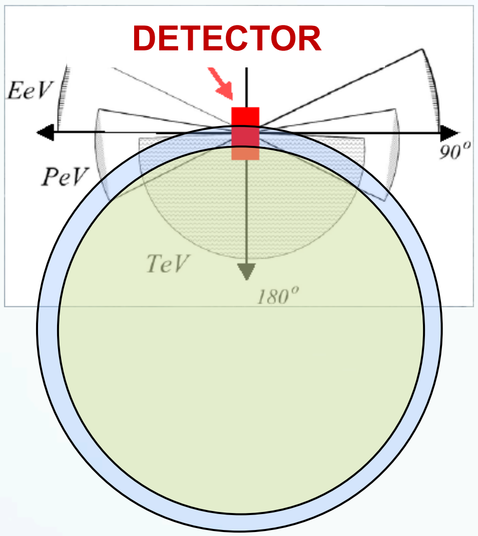
Marine sciences: oceanography, biology, geology...

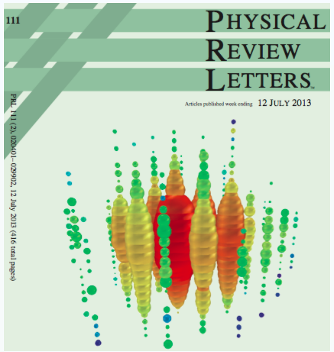
Reconstruction of the muon trajectory

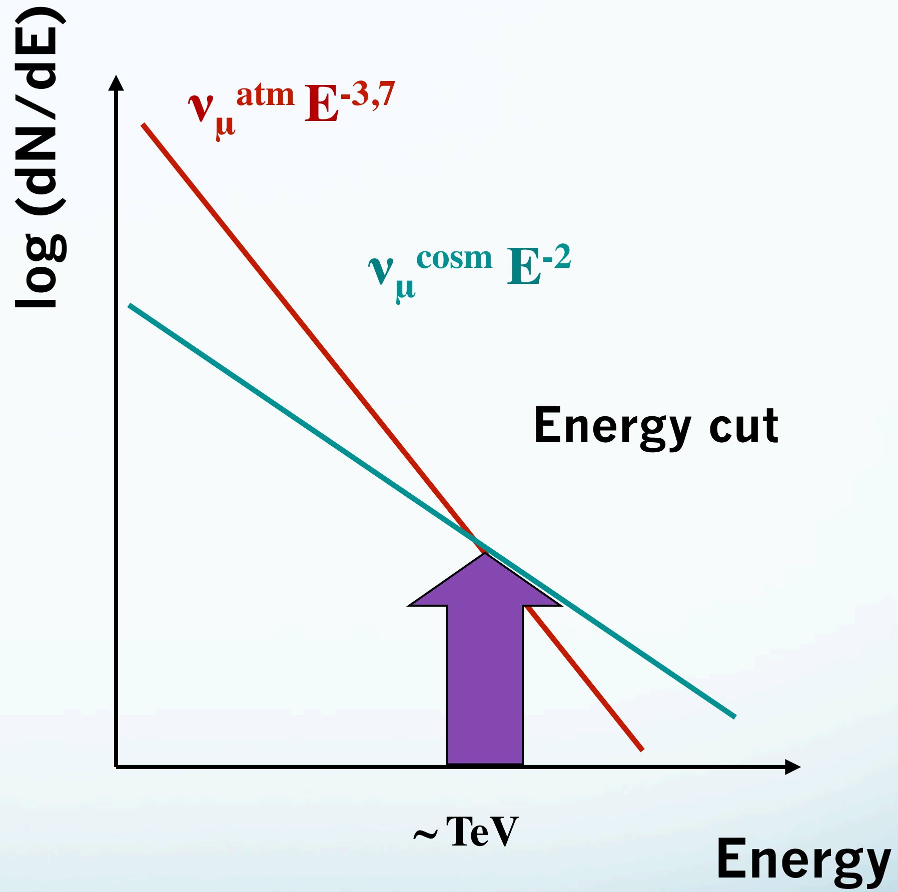


Atmospheric versus cosmic signals?

- High energy excess *[IceCube evidence]*
  - ☞ Good energy estimate







- Search for anisotropies
  - ☞ Good angular resolution

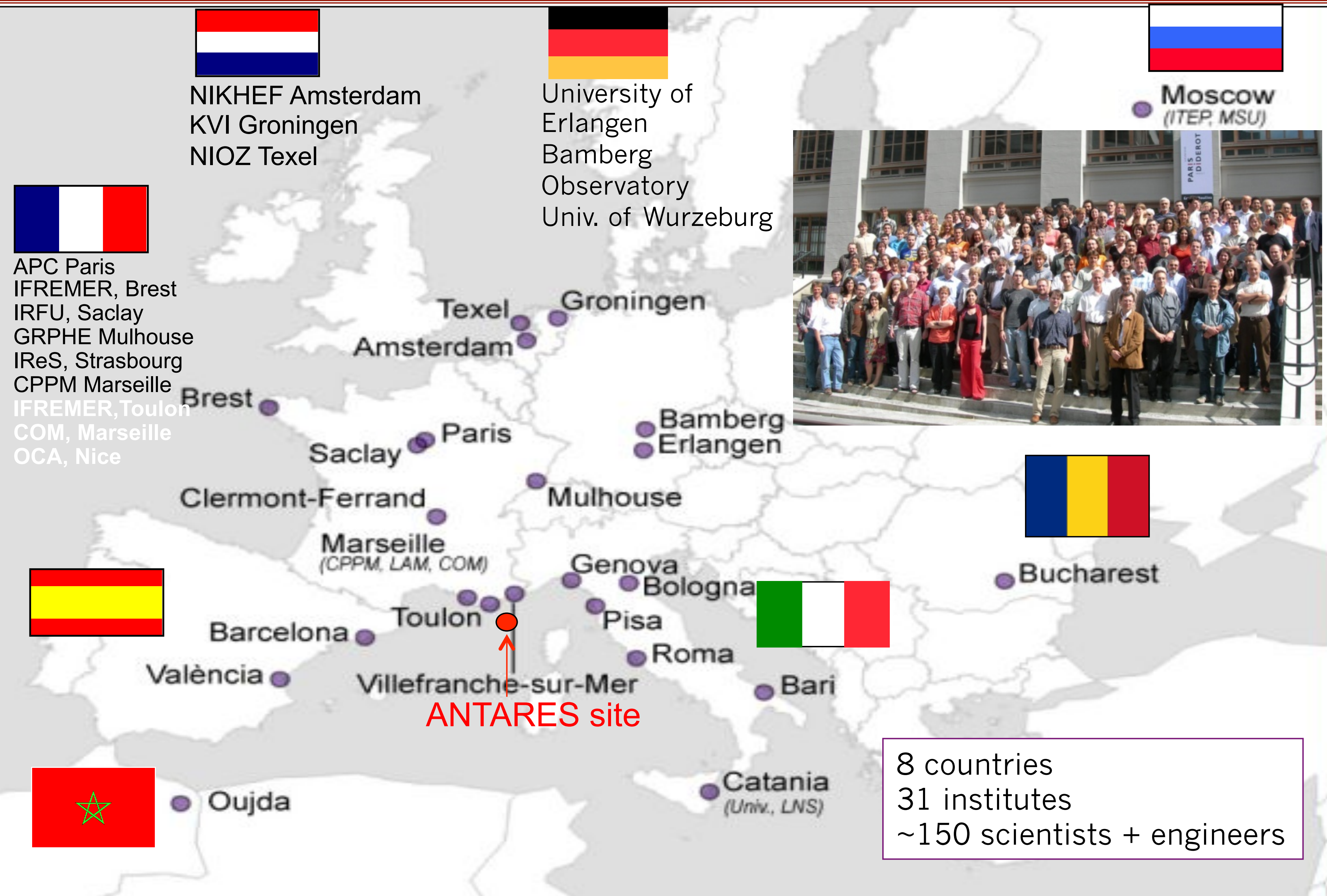
- Multi-messenger approach
  - ☞ Requires consistency with other probes (reduced, uncorrelated backgrounds) : GRB alerts, optical follow up, flaring sources, GW

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

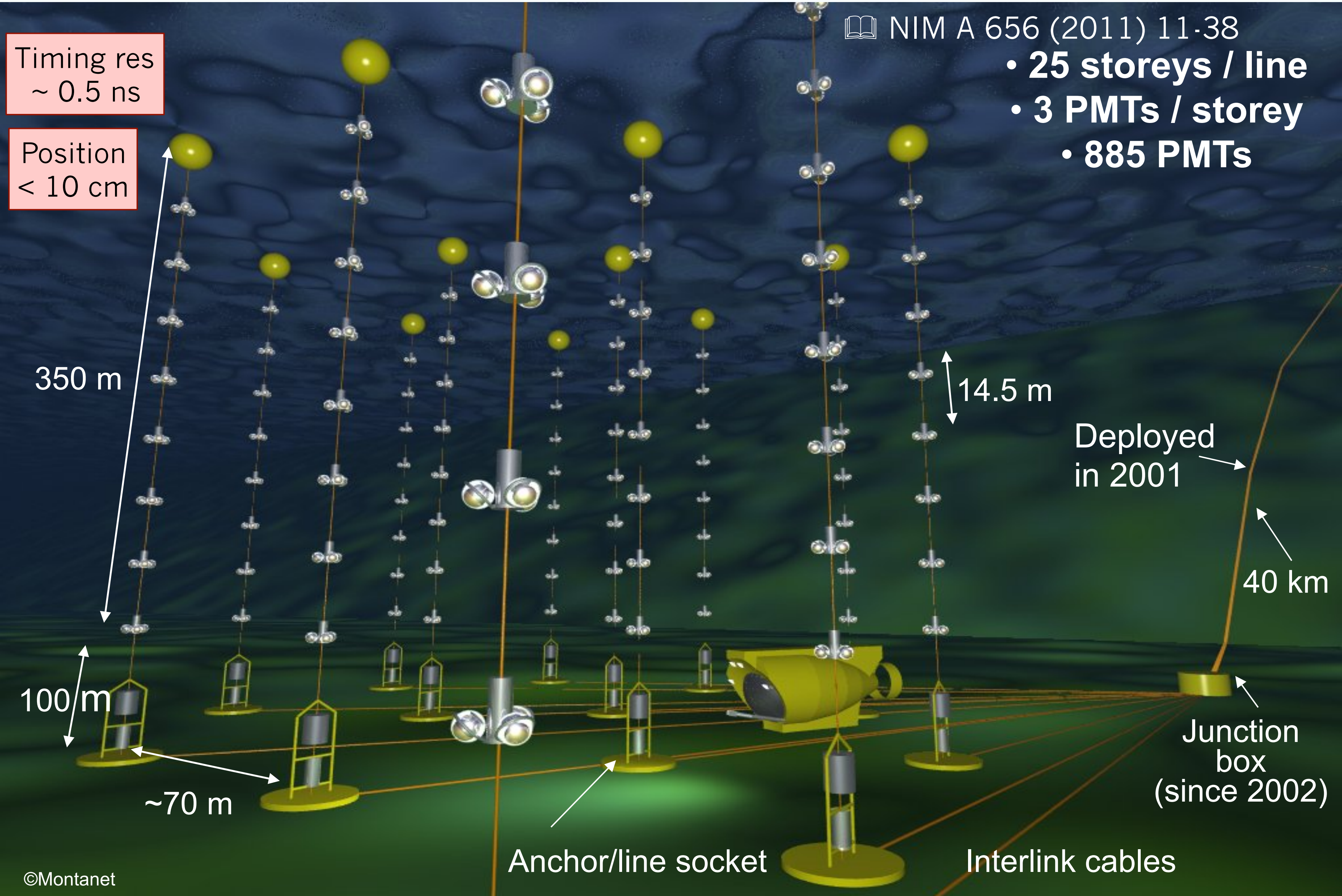


8 countries
31 institutes
~150 scientists + engineers

The ANTARES Site

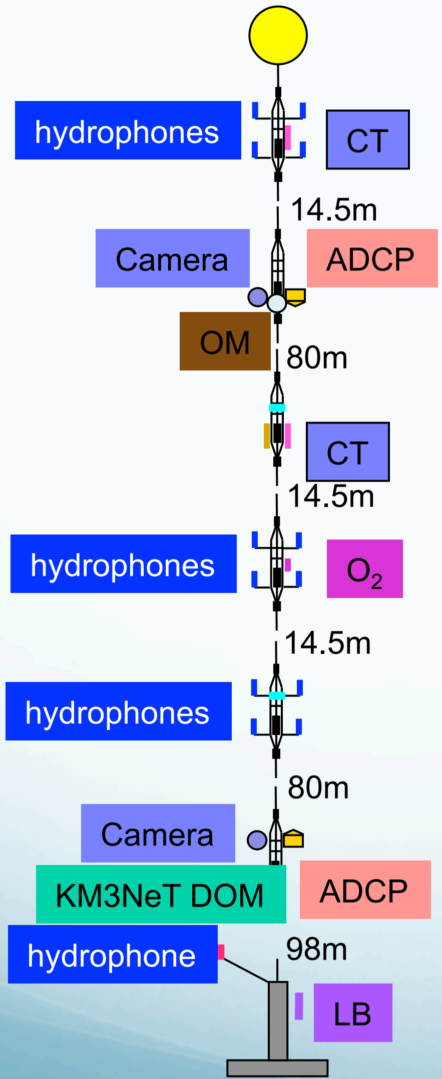
- Astropart. Phys 13 (2000) (Background light)
- Astropart. Phys 19 (2003) (Bio-fouling)
- Astropart. Phys 23 (2005) (Light transmission)
- Astropart. Phys 35 (2012) (Light velocity)

The ANTARES Neutrino Telescope

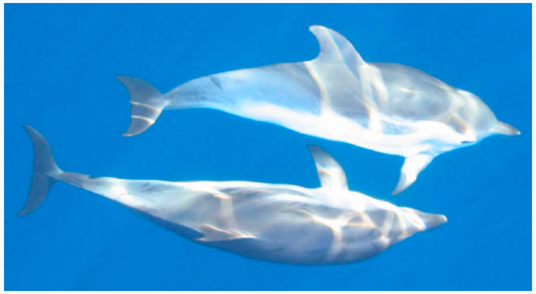


Earth and Sea Science

Instrumentation Line

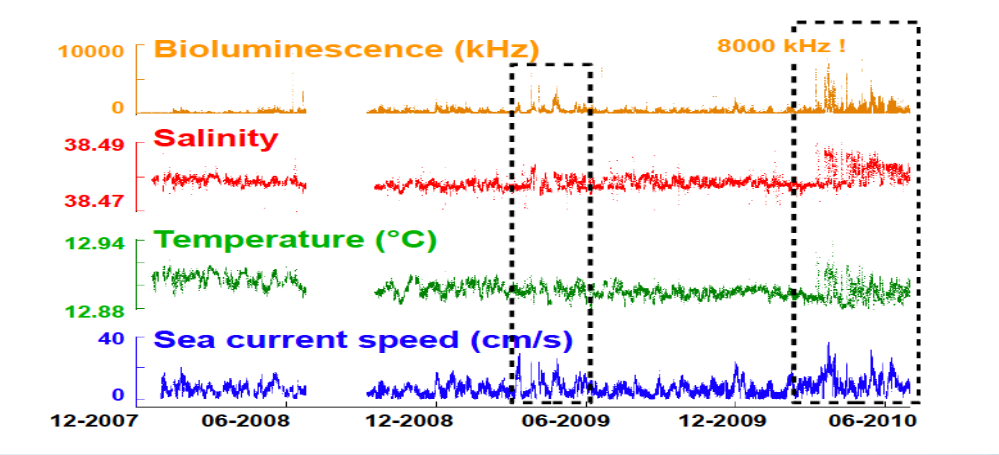


Video-monitoring
The deepest webcam
in the world?



Acoustic noises

ANTARES = multi-disciplinary observatory



IL13: houses together with L12 the sensors of the AMADEUS acoustic neutrino detection test system

📖 NIM A 626-627 (2011)

Reconnected in April 2013 with KM3NeT OM.

📖 C. Tamburini et al., to appear in PLOS one

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

Search for a diffuse cosmic ν_μ spectrum I

- Optimized on MC sample qualified on burn sample (10% data) for best limit

❖ First search with 2008-2009 data

Physics Letters B 696 (2011) 16

- 334 days of equivalent livetime
- Energy estimator : mean number of pulses seen by same PMT

Analysis sensitivity:

$E^2\Phi = 7.0 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Unblinded result: $n_{obs}=9$ $n_{bkg}=10.7$

$E^2\Phi_{90\%} = 5.3 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

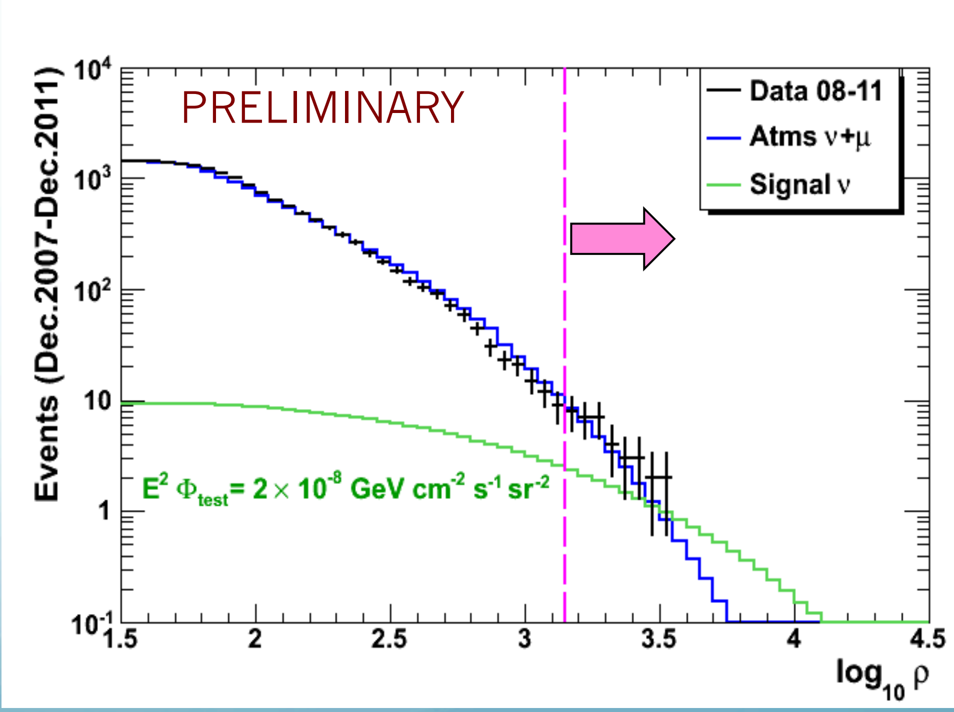
❖ Updated search 2008-2011 data

- 855 days of equivalent livetime
- Improved energy estimate based on dE/dX
- Muon contamination negligible (<0.4%)

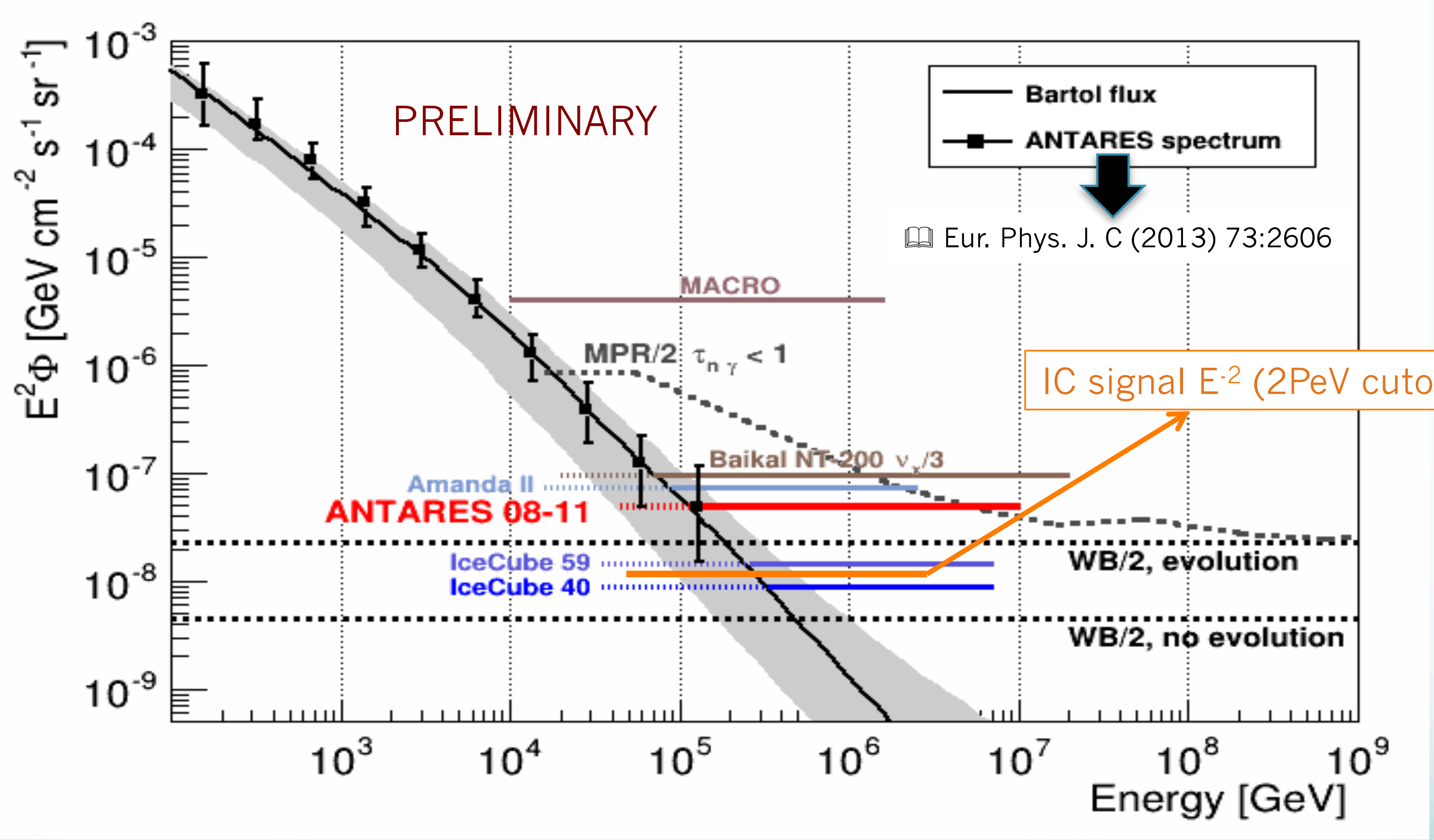
Better analysis sensitivity:

$E^2\Phi = 4.7 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

Unblinded result: $n_{obs}=8$ $n_{bkg}=8.4$ $n_{sig}=2.3$



Search for a diffuse cosmic ν_μ spectrum II



No significant improvement for upper limit:

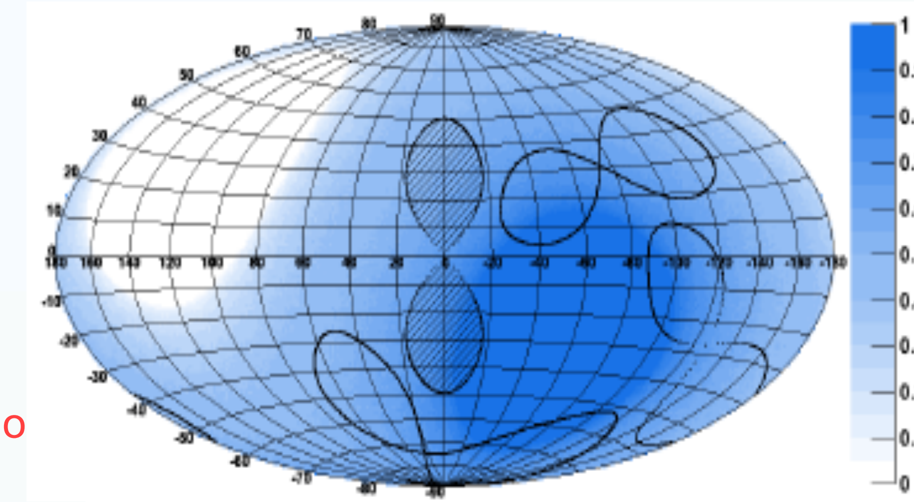
$E^2\Phi_{90\%} = 4.8 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}

45 TeV< E < 10 PeV

Search for a Diffuse Emission from the Fermi Bubbles

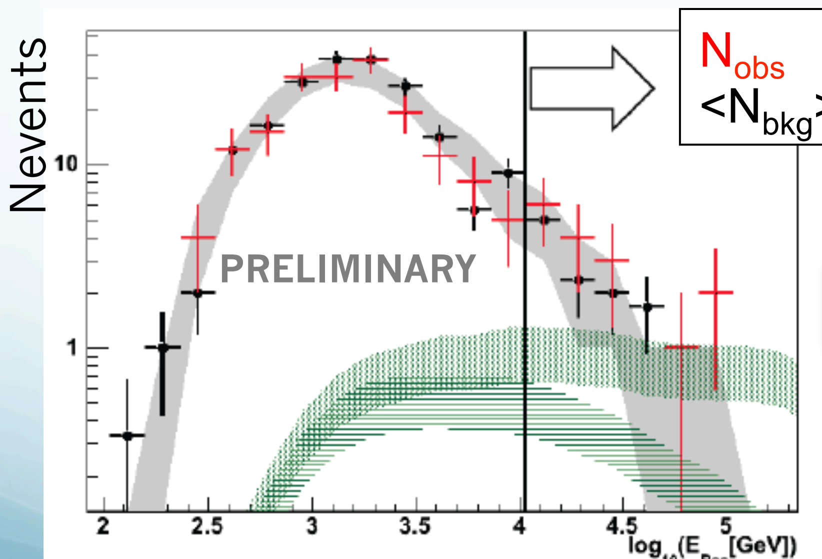
➢ Excess of γ- (and X-)rays in extended "bubbles" above and below the GC

Galactic wind model involves hadronic processes
📖 Crocker & Aharonian, PRL 2011
$\Phi_\nu \approx 0.4 \times \Phi_\gamma$ 📖 M. Su et al., Ap. J. 724 (2010)

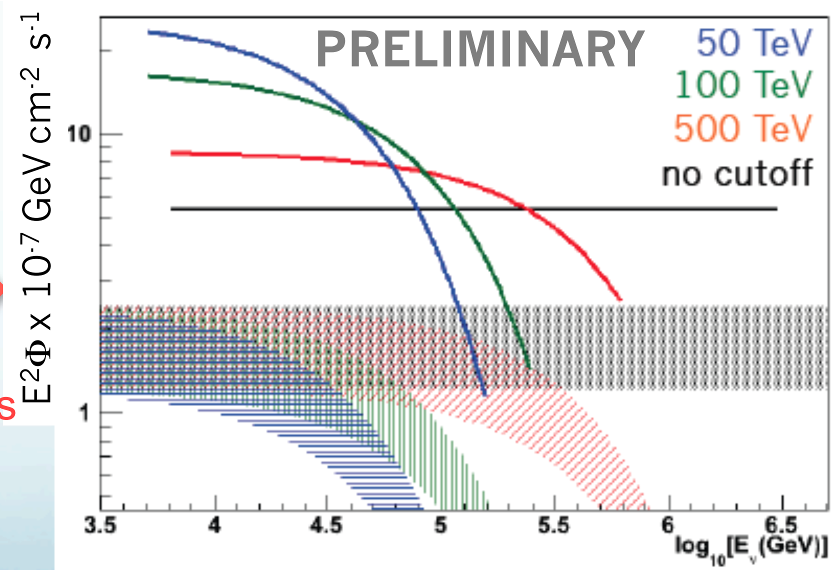


➢ In the field of view of ANTARES

background estimated from average of
3 non-overlapping "off-zone" data regions
2008 - 2011 (806 days livetime). Only muon neutrino



Small excess (1.2 σ)



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

KM3NeT (100 TeV cutoff) 📖 Astrop. Physics 42 (2013) 7
- 5σ (50%) [3σ (50%)] in 1.5 years [a few months]

Search for neutrino point sources I

❖ First search 2007-2010 (813 days)

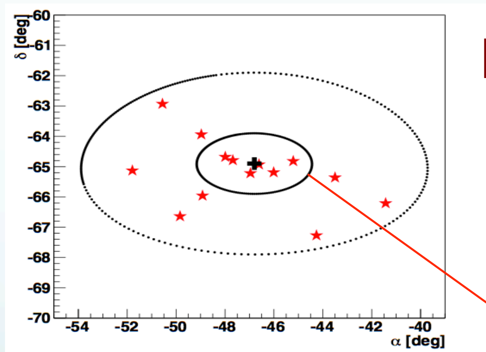
- 3058 neutrino candidates (85% purity)
- No statistically significant excess

📖 ApJ. 760:53 (2012)

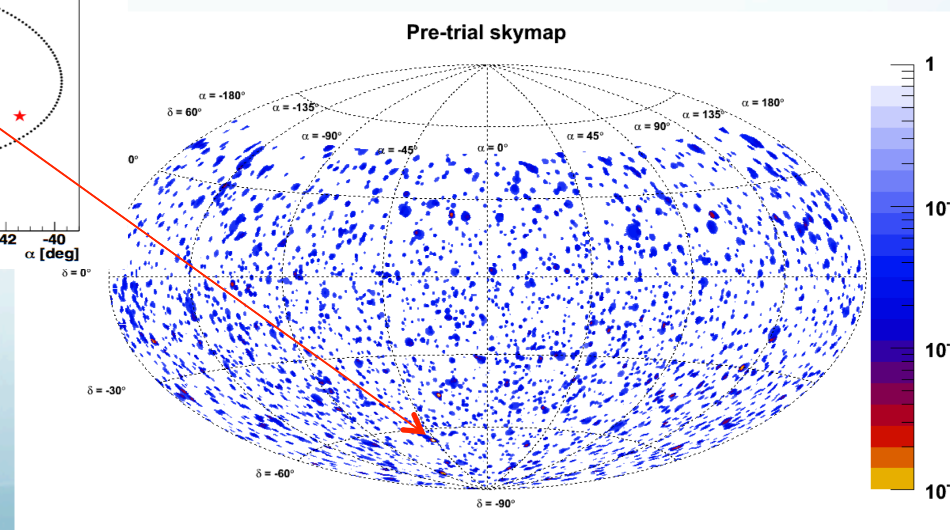
- Best cluster at (-46.5^{o}, -65.0^{o}), post-trial p=0.026
  No counterpart found in multi-wavelength study (Gallex/ROSAT/Fermi-LAT/HESS)

❖ New updated search 2007-2012 (1340 days)

- 5516 neutrino candidates (90 % of which being better reconstructed than 1^{o})
- Same most significant cluster with 6 additional events: p-value = 2.1% (2.3 σ)
  Compatible with background hypothesis



PRELIMINARY

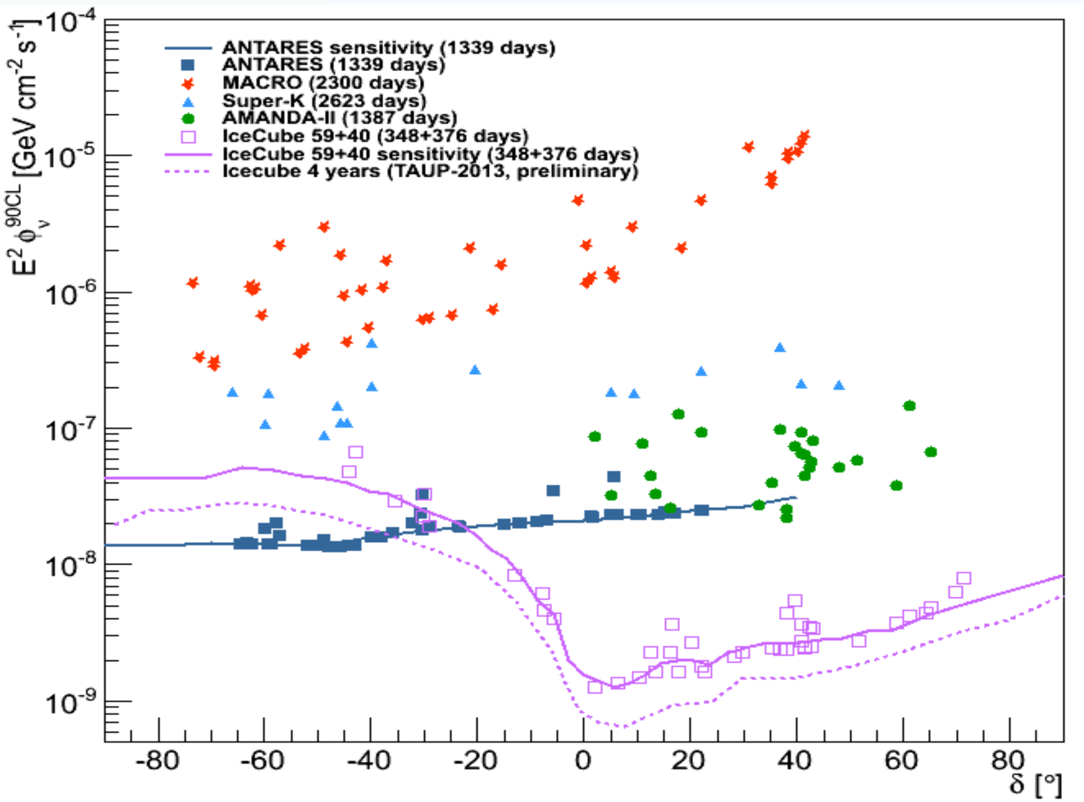


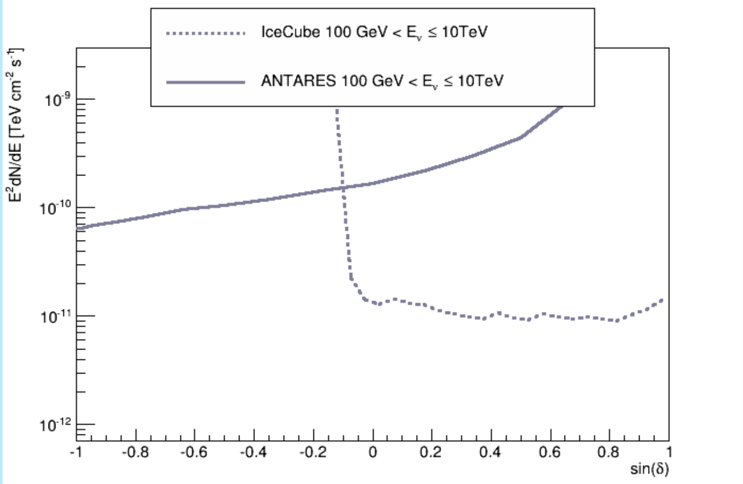
Limits on normalization factor
$(E/GeV)^{-2}\ 10^{-8}\ GeV^{-1}\ cm^{-2}\ s^{-1}$

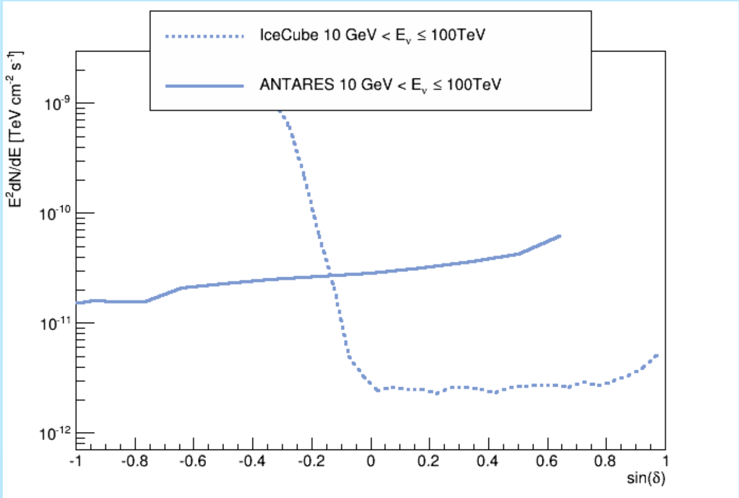
source	$\alpha_s [°]$	$\delta_s [°]$	p	$\phi^{90\%CL}$
HESSJ0632+057	98.24	5.81	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.14	3.23
3C279	194.05	-5.79	0.39	3.45
HESSJ1023-575	155.83	-57.76	0.82	2.01
ESO139-G12	264.41	-59.94	0.95	1.82

Search for neutrino point sources II

Most stringent limits for a large part of the Southern Sky in TeV region







Dedicated studies for extended sources (RXJ1713, Vela X) → limits

Expect further improvement including showers

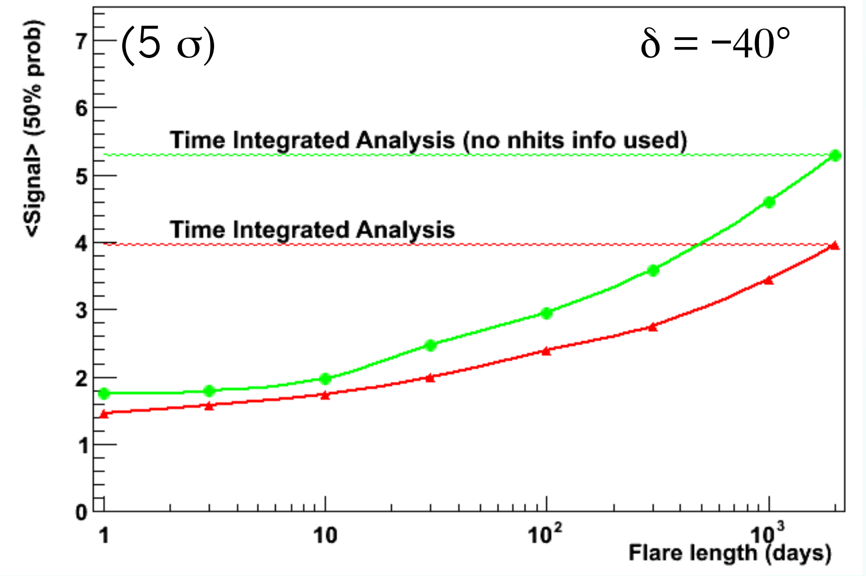
📖 IC79, arXiv:1307.6669

Search for neutrinos from flaring sources

❖ Search with 6 microquasars

- 2007-2010 data set (813 days)
- Microquasars with (x/γ)-ray outbursts
- Likelihood ratio method (no energy proxy)
- No events detected in coincidence
- Flux limit above predictions

📖 Levinson, Waxman (2001) & DiStefano et al. (2002)

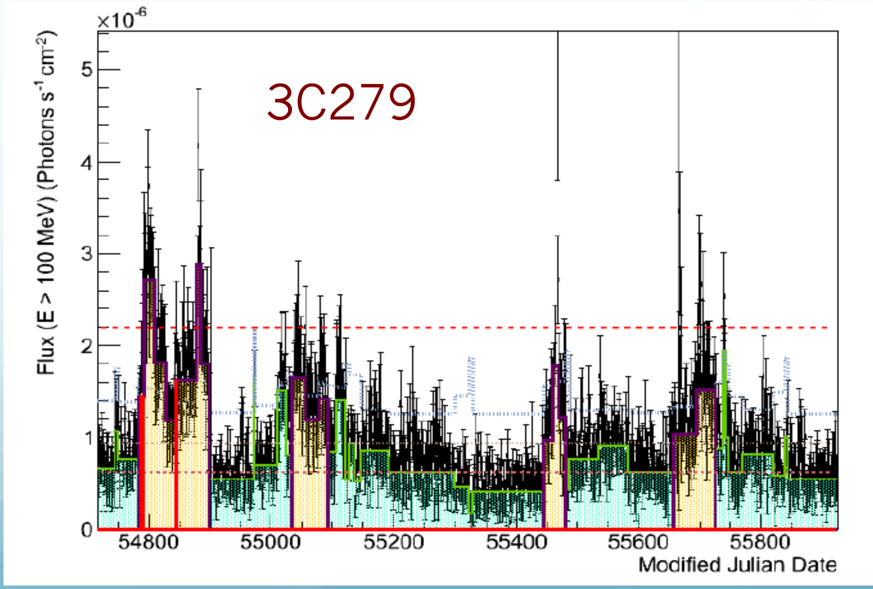


❖ Recent search with 41 blazars

- 2008-2011 data (750 days livetime)
- 86 flaring periods 2FGL+Fermi Flare Advocates
- Improved likelihood with energy proxy (Nhits)

PRELIMINARY

- Lowest p-value (12%) 3C279 (2 events)
  Compatible with background fluctuation



📖 Astropart. Phys. 36 (2012) 204

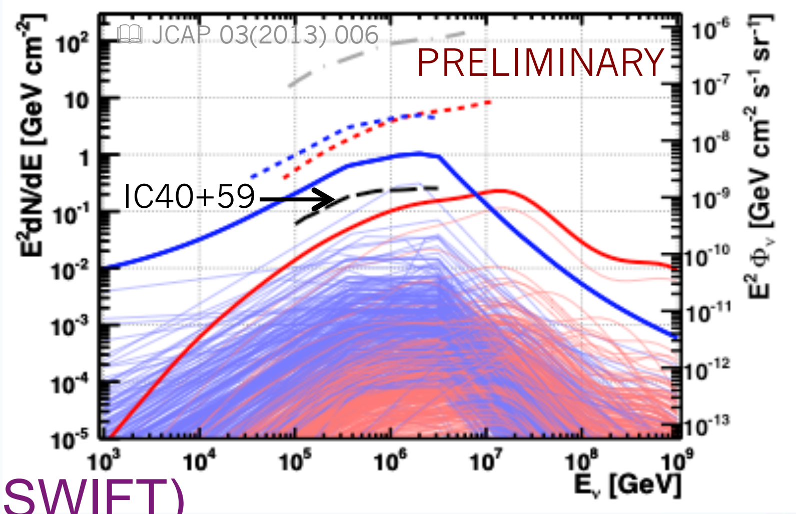
Triggered searches

- Search for neutrino events in coincidence with observed GRB
  - Time and direction known ☞ background reduction ☞ improved sensitivity

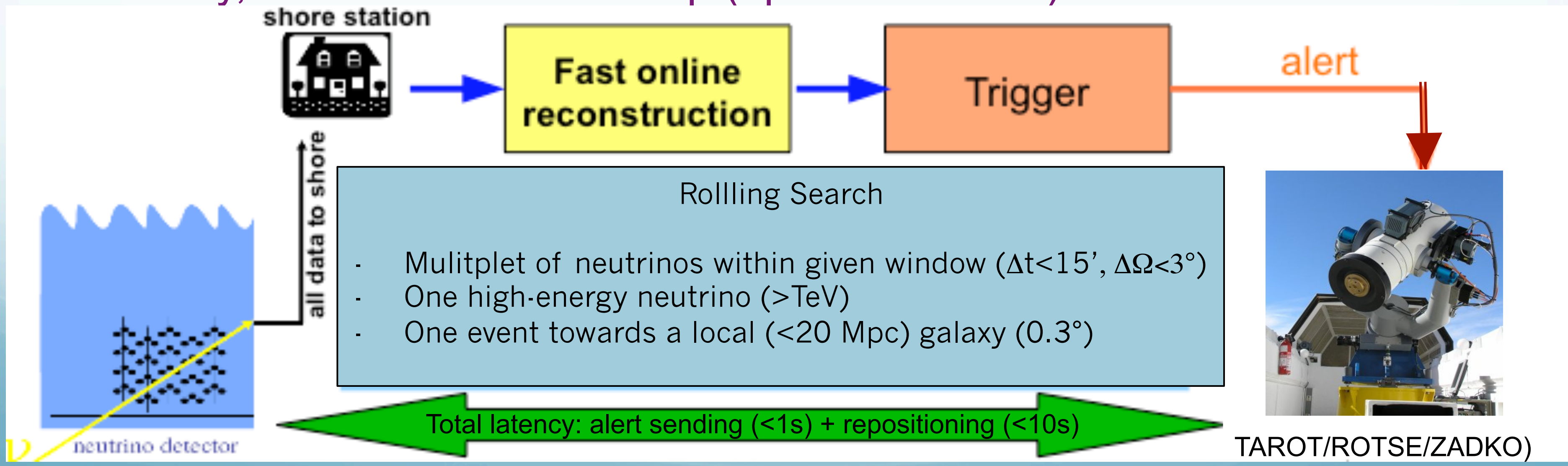
➢ Analysis of GRBs from late 2007 – 2011:
296 long GRBs, total prompt emission: 6.6 hours
Information from FERMI/SWIFT/GCN

➢ GRB simulations of expected neutrino fluence:
- NeuCosmA [📖Hümmer et al. (2010)]
- Guetta [📖Guetta et al. (2004)]

📖 Astronomy & Astrophysics 559, A9 (2013)



- Reversely, send alert for follow-up (optical+ SWIFT)



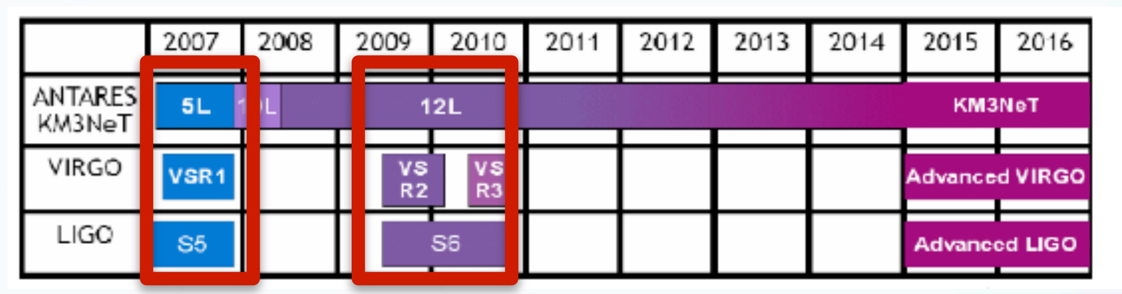
📖 Astropart. Phys. 35 (2012) 530

1 doublet is 3σ evidence, 1 triplet is 5σ !

Search for Coincidences with Gravitational Waves

Main motivations : plausible common sources (GRB, SGR)
discovery potential for hidden sources (e.g. failed GRB)
📖 Rev. Mod. Phys. 85 (2013)

Effective collaboration (MoU) between
LSC and ANTARES
since Sept 2009



- Search methodology:
  HEN selected events trigger the search for GW in time/space coincidence

- First analysis completed with 2007 concomitant dataset
  No coincidence found ☞ exclusion distances on common GW/HEN emitters

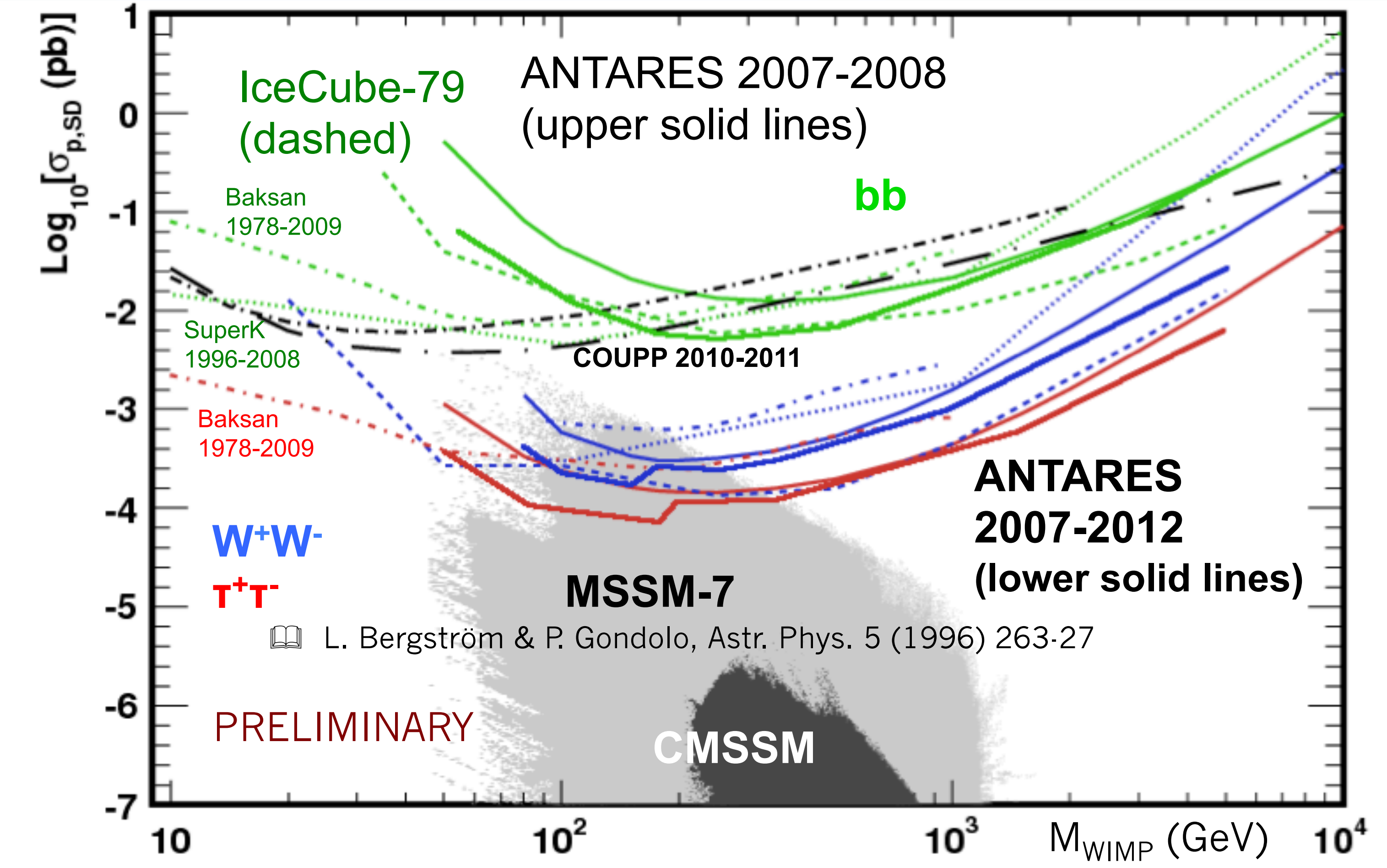
  📖 JCAP06(2013)008

- Improved Analysis of 2009-2010 dataset ongoing

Indirect search for Dark Matter

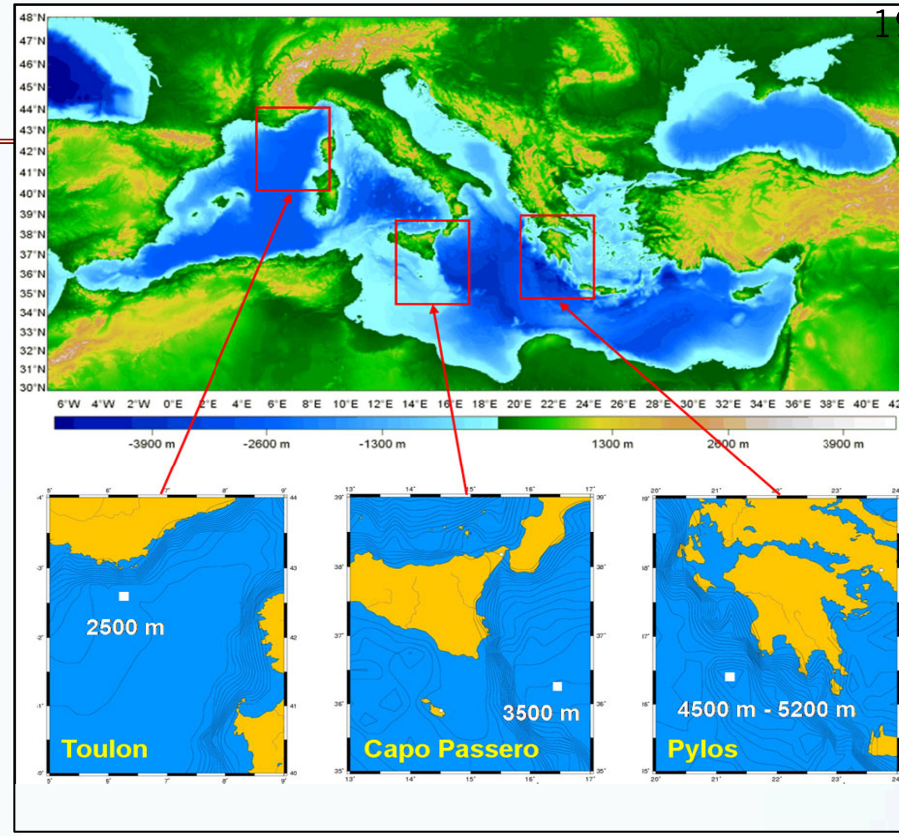
❖ New analysis: 2007-2012 (1321 days livetime)

- Background measurement by scrambled data in the Sun direction
- Optimization for best sensitivity for each M_{WIMP} (track fit quality, cone size Ψ)
- Two independent reconstruction algorithms tested
- Include single-line events → only zenith, but greatly improves at low Energy



The KM3NeT sites

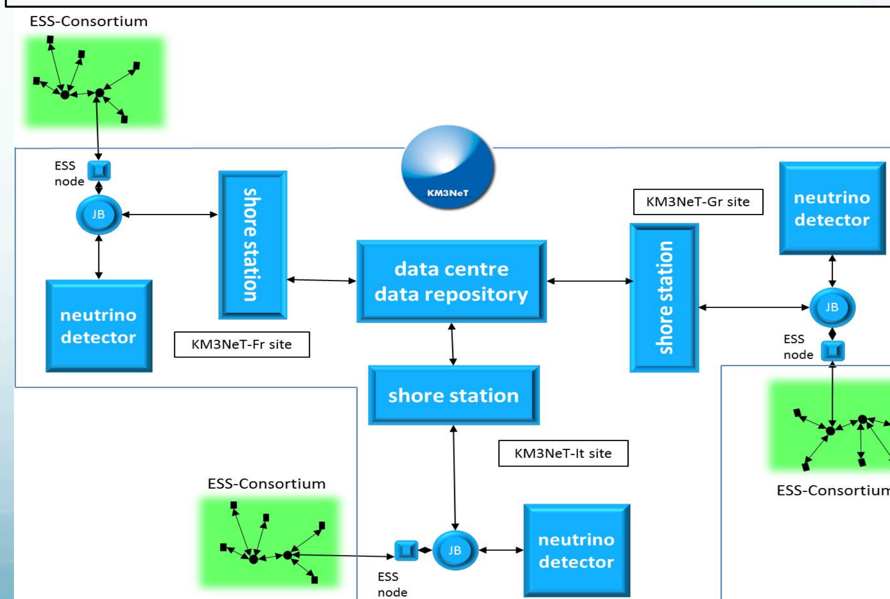
- The Mediterranean Sea
  - Large field of view, complementary to IceCube
- Long-term site characterisation performed
- Clean and homogeneous medium
  - Very good angular resolution
- Large volume (~3 km^3)
  - Exceed the northern hemisphere telescope by a factor ~50 in sensitivity
  - Exceed IceCube sensitivity by substantial factor
- Important node for Earth and Sea sciences



A distributed Infrastructure

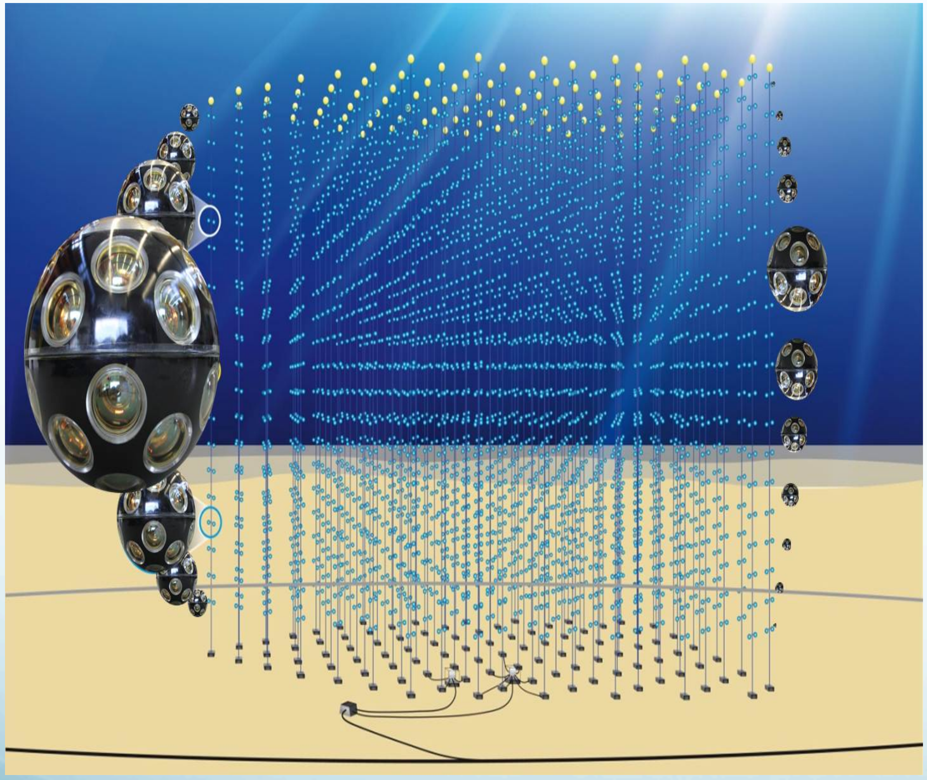
- KM3NeT-France: Toulon (~2500m)
  KM3NeT-Italy: Capo Passero (~3400m)
  KM3NeT-Greece: Pylos (~4500m)

- Centrally managed
- Common hardware
- Common software, data handling and operation control
- Consistent with funding structure (regional sources)



The KM3NeT detector

Building block concept: the detector is made of several blocks of Detection Units.



- 6 blocks of 115 DUs 90 m distant.
- Full volume ~ 3 km^3
- DU vertical string equipped with 18 Optical Modules
- Optical modules made of 31 3” PMTs
- Mooring line:
  - Buoy (probably syntactic foam)
  - 2 Dyneema© ropes (4 mm diameter)
  - 18 storeys (one OM each), 36m distance 100m anchor-first storey
- Electro-optical backbone (VEOC):
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - Fibres and copper wires
  - At each storey: connection to 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition

📖 KM3NeT TDR, 2010, ISBN 978-90-6488-033-9

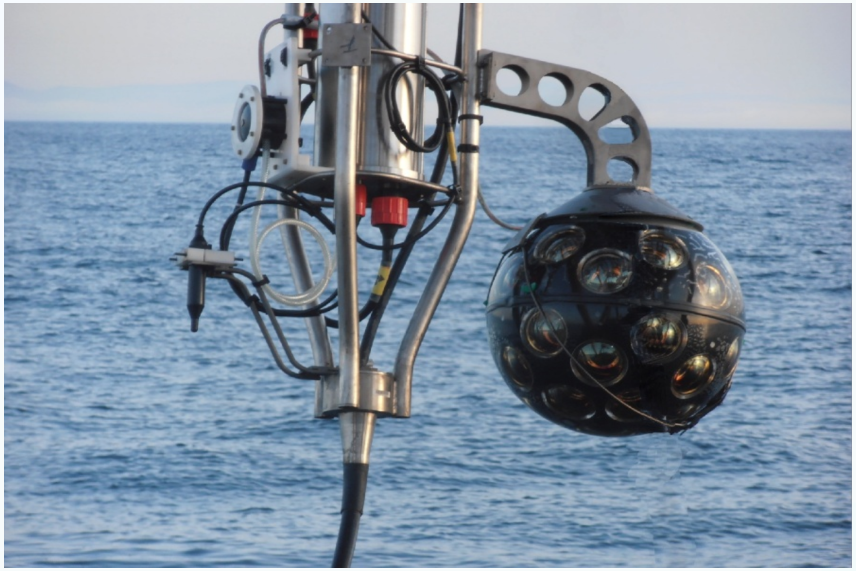
The Digital Optical Module

- 31 3-inch PMTs (cathode area ~ 3x10" PMTs) suspended by plastic structure with a light collection ring (20–40% gain in effective photocathode area)
- 31 PMT bases (total ~140 mW)
- Front-end electronics (FPGA readout for each individual PMT with sub-ns time stamping and time over threshold)
- Al cooling shield and stem
- Single penetrator
- 2mm optical gel

- 1-vs.-2 photo-electron separation
  - Better sensitivity to coincidences / background suppression
  - Information at online data filter level
- Directionality
  - Additional input to reconstruction and veto algorithms
  - Identification of down-going events (PMTs are also looking upwards)
  - Reduction of random background (K40, bioluminescence)

Tests of the Digital Optical Module

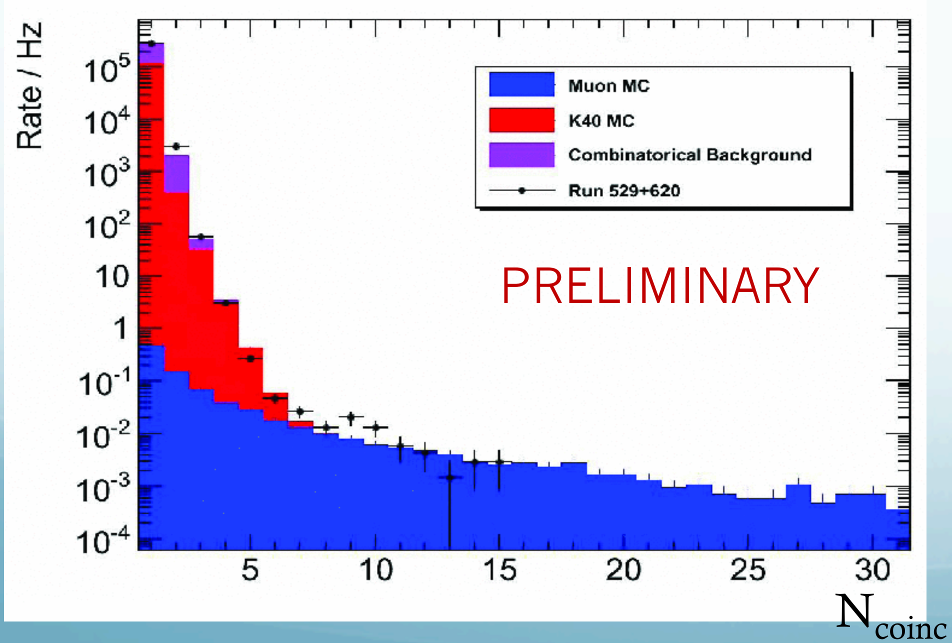
KM3NeT already taking data from an ANTARES line since April 2013



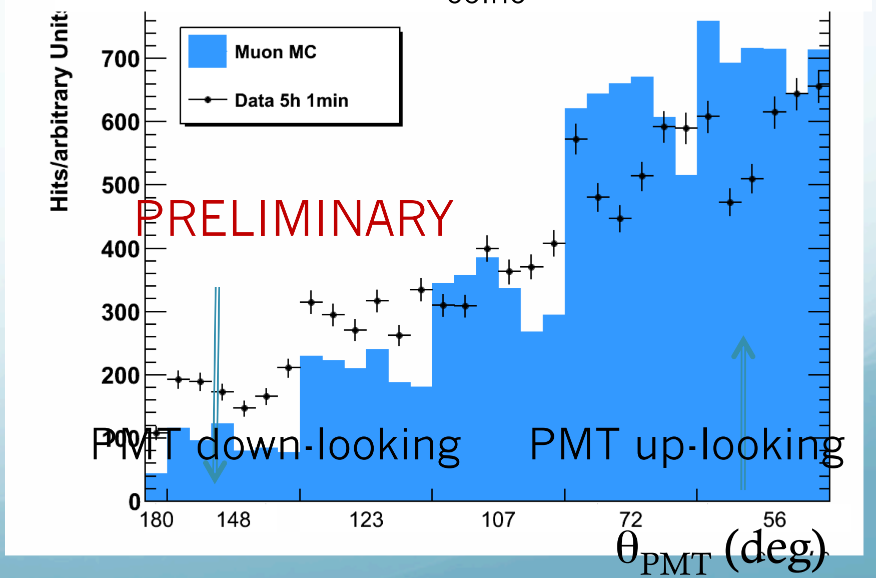
Coincidence in a DOM

↓

hits in different PMTs in a time window of 20ns



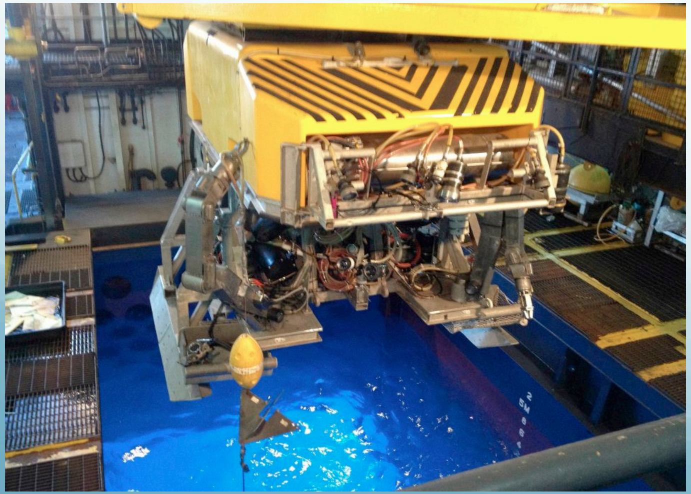
Events with N_{coinc}>6 selected

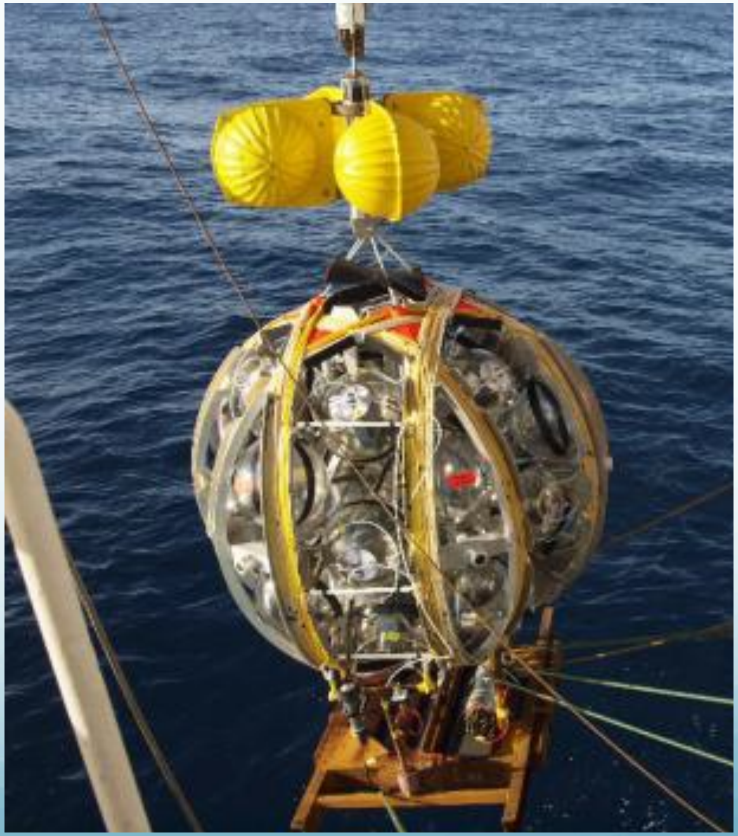


The string deployment

- Compact package – deployment – self-unfurling
  - Eases logistics (in particular in case of several assembly lines)
  - Speeds up and eases deployment; several units can be deployed in one operation
  - Self-unfurling concept being thoroughly tested and verified
  - Recovery of launcher vehicle
- Connection to seabed network by ROV

- In situ qualification campaigns
  - Dec 2009 and Feb 2011
  - April 2013 @ Motril (Spain) 10 days and five deployments

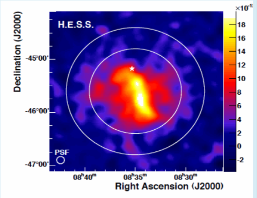




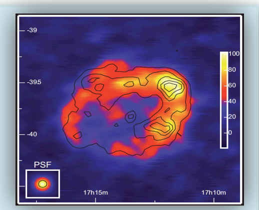
Physics Performances - Galactic sources

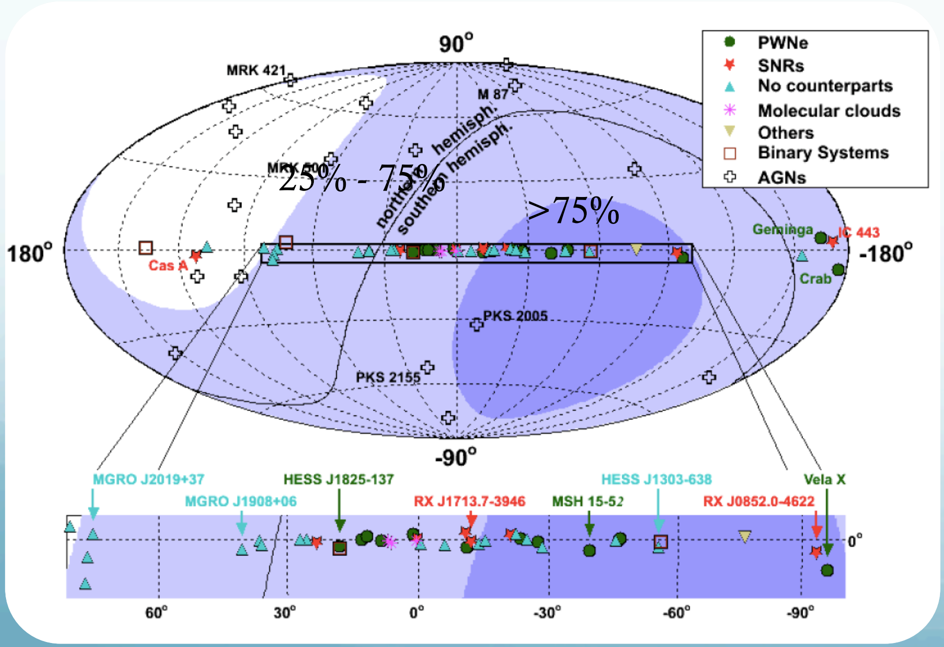
- The discovery of neutrinos from galactic sources is the primary physics objective for KM3NeT.
  - Detector optimization focused on discovery of Galactic sources
- Neutrino spectrum based on HE gamma observation (purely hadronic)

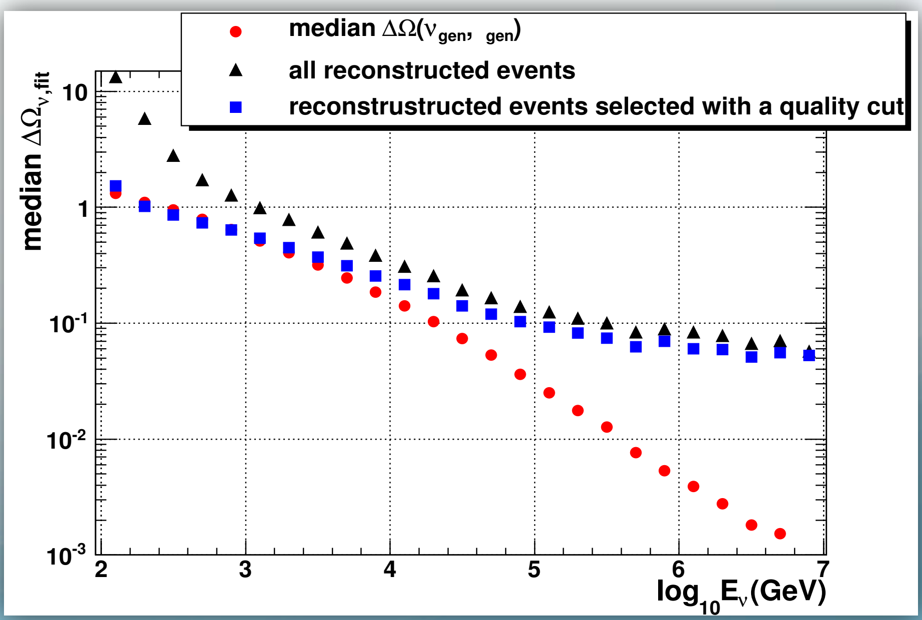
PWN VelaX:
- Discovery (5σ 50%) in ~ 3 years
- Evidence (3σ 50%) in ~ 1.2 years



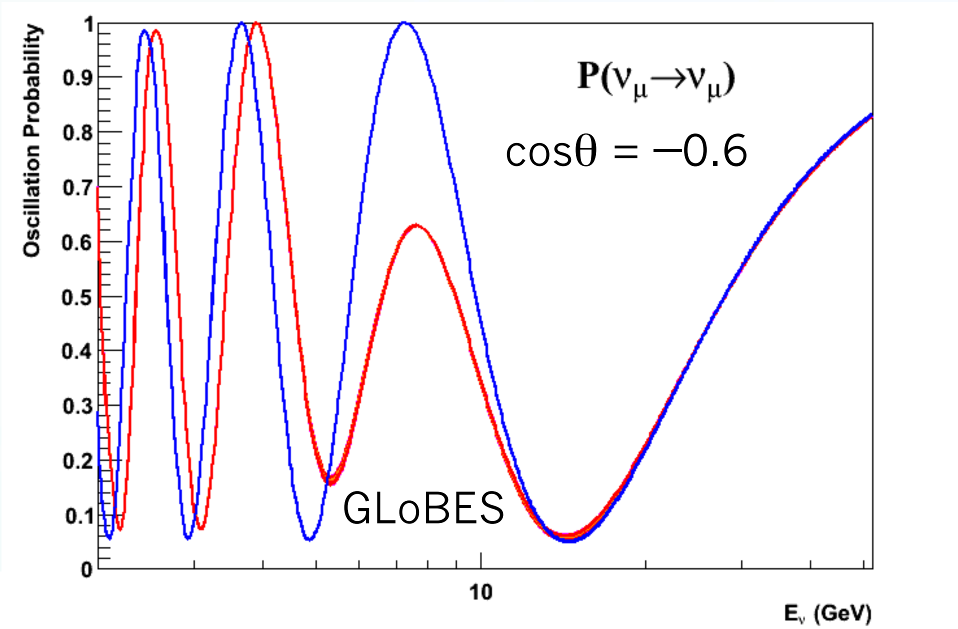
SNR RXJ1713:
- Discovery (5σ 50%) in ~ 5 years
- Evidence (3σ 50%) in ~ 2 years







Low energy oscillation studies



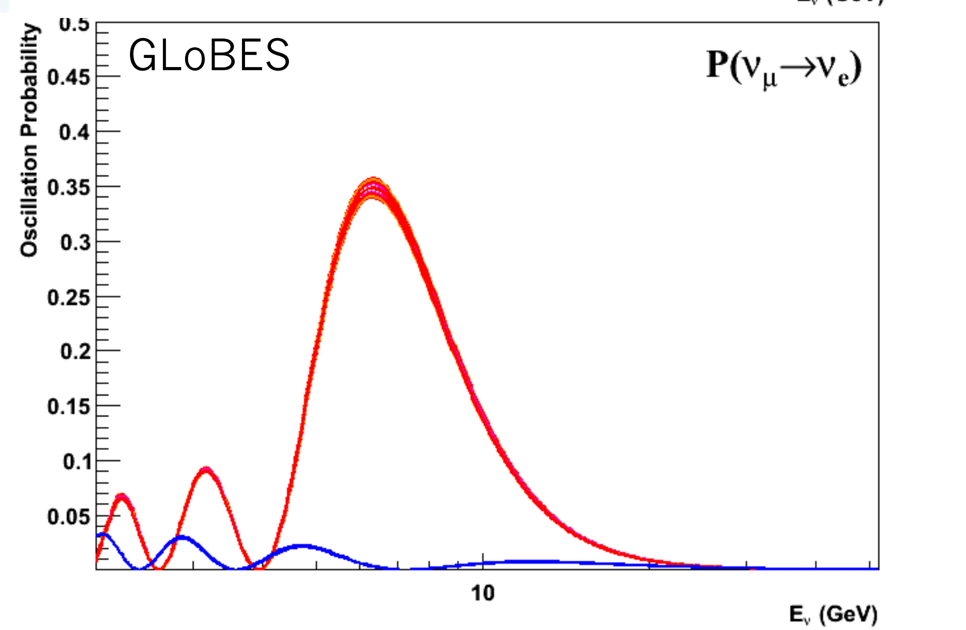
Inverted Hierachy

Normal Hierachy

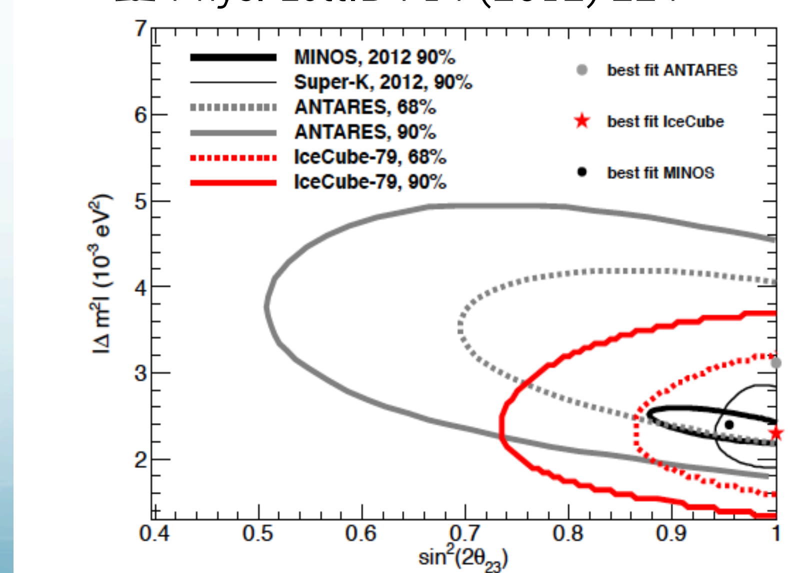
In each case, CP-phase is varied in steps of 30 degrees

- Hierarchy differences disappear at around 15 GeV
- $P(\nu_\mu \rightarrow \nu_e) < 2\%$ at 20 GeV

→First measurement by Neutrino Telescope

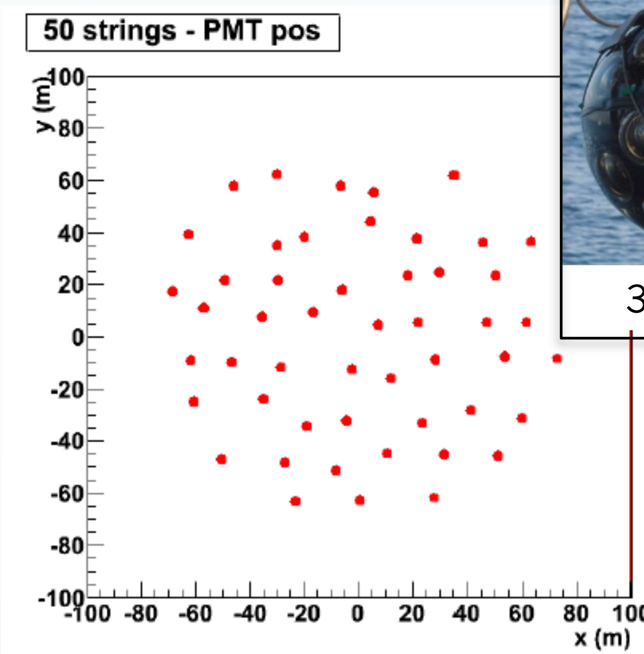


Phys. Lett.B 714 (2012) 224



ORCA: a possible low energy KM3NeT layout

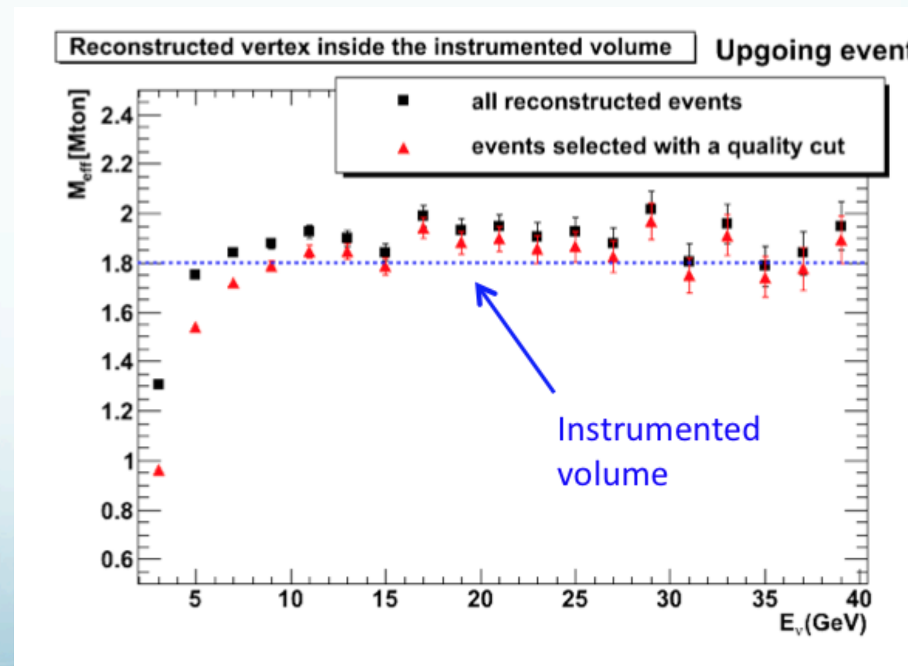
ORCA



31 3” PMTs

50 lines, 20m spaced,
20 OM/line 6m spaced
Instrumented volume ~2 Mt

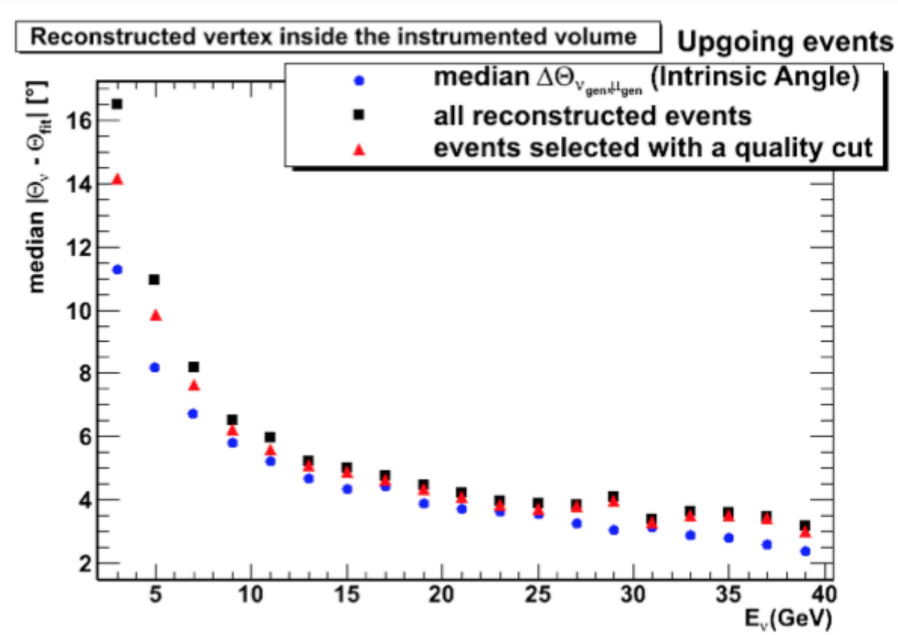
Could be deployed in <5 years

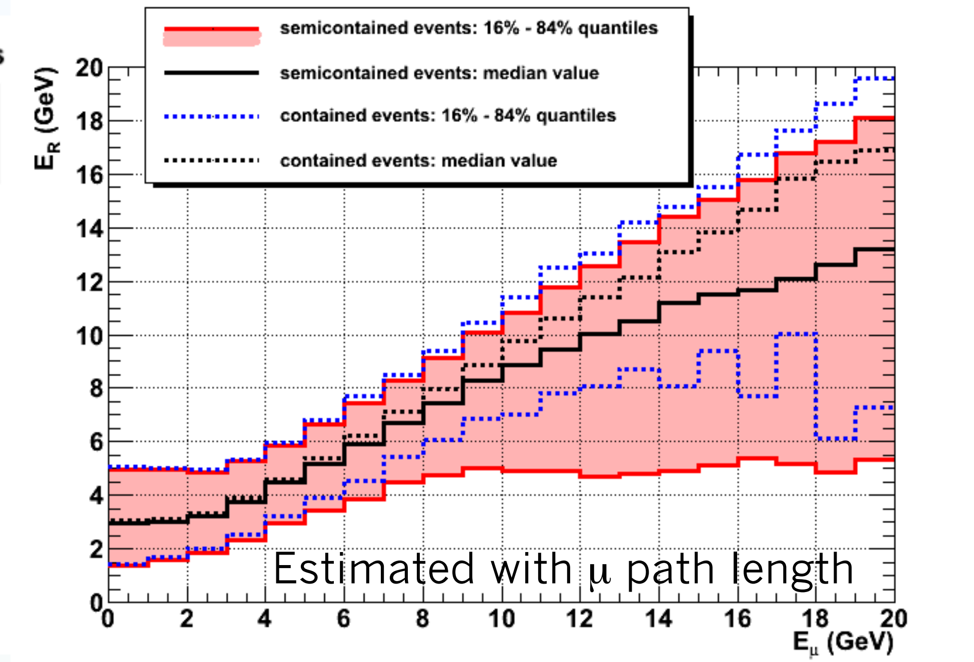


Optimized layouts still under study

P. Koojman et al, ICRC proc. 0164

Preliminary performances





A good angular resolution

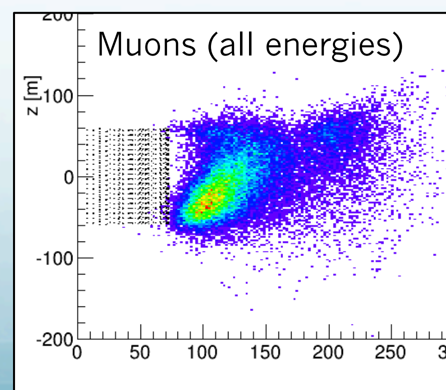
The energy resolution can be improved using the hits from the hadronic shower

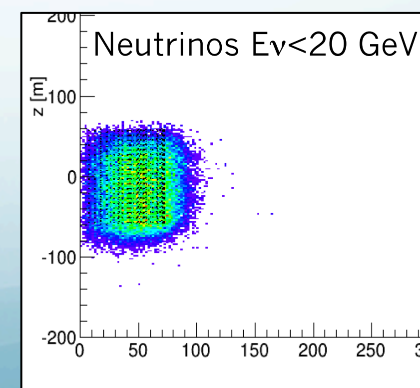
- Other ongoing studies

Muon background rejection: no veto needed

Try to separate track-like (ν)
from shower-like events ($\overline{\nu}$)

Study response to ν_e





ORCA sensitivity

all results are preliminary

To optimally distinguish between IH and NH: likelihood ratio test with nuisance parameters
→ *deal with degeneracies by fitting!*

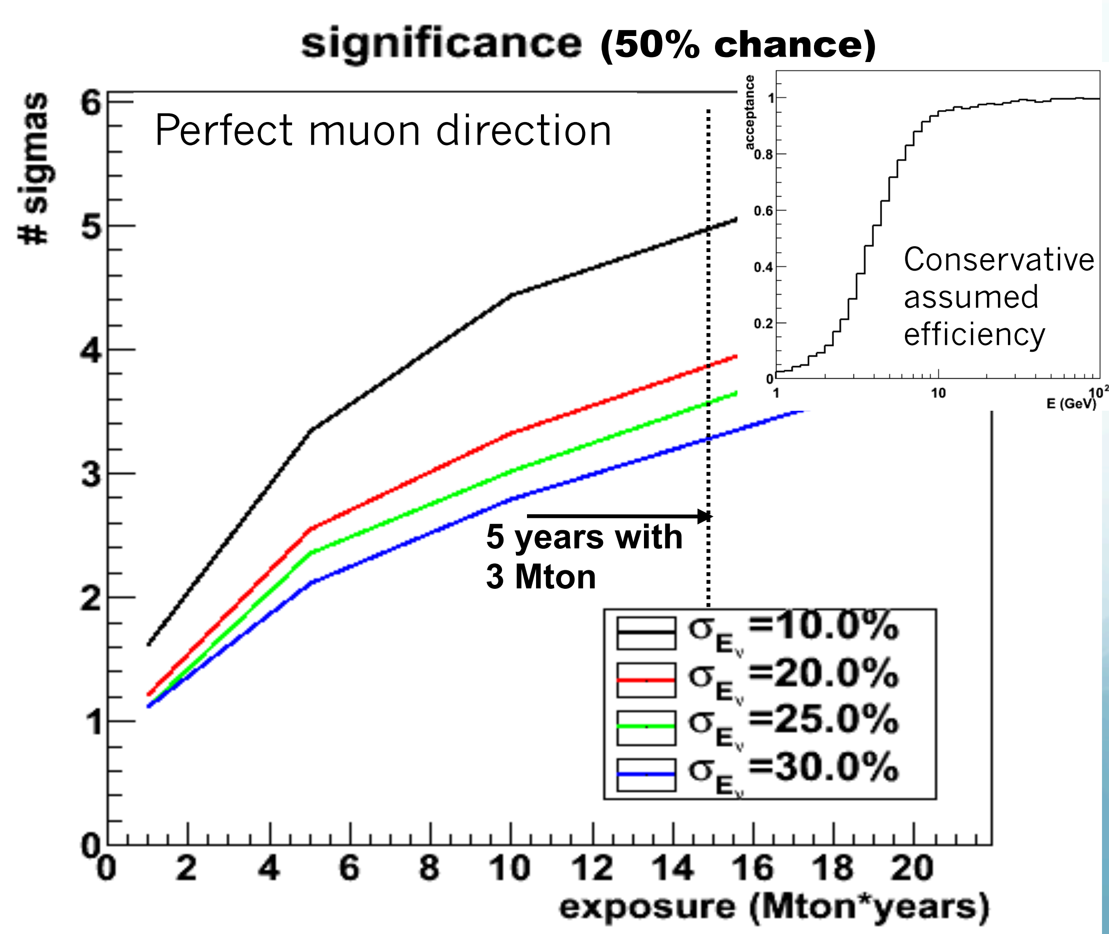
$$\Delta \log(L^{\max}) = \sum_{\text{bins}} \log P(\text{data}|\hat{\theta}^{\text{NH}}, \text{NH}) - \log P(\text{data}|\hat{\theta}^{\text{IH}}, \text{IH})$$

$\hat{\theta}^{\text{H}} =$ maximum-likelihood estimates for the Δm^2's and angles using both data and constraints from global fit.
nb: constraints are different for H=IH and H=NH

Uncertainty on the mixing parameters as a function of the exposure

Eres = 25%, 1-100 GeV

Mton x yr	$\sigma(\Delta m^2_{large})$ (eV^2)	$\sigma(\theta_{23})$ (°)	$\sigma(\theta_{13})$ (°)
0(now)	8.0e-5	1.3	0.45
1	4.3e-05	0.61	0.42
5	2.3e-05	0.32	0.44
10	1.8e-05	0.22	0.39
20	1.4e-05	0.16	0.39
30	1.2e-05	0.13	0.37



Studies of systematics

📖 D. Franco et al, JHEP 04 (2013) 008

Method: extended unbinned log-likelihood ratio

Earth Model → Almost negligible impact

Atmospheric neutrinos flux
- Shape → Moderate impact
- Normalization → Large impact but normalization from data

PMNS uncertainties

Solar sector → Negligible impact varying combinations of $\{\theta_{12}, \Delta m^2_{21}\}$ ($\pm 1\sigma$)

Atmospheric sector → Large impact varying combinations of $\{\theta_{13}, \theta_{23}, \Delta m^2_{31}\}$ ($\pm 1\sigma$)

δ_{cp} dependence → Small impact varying CP phase

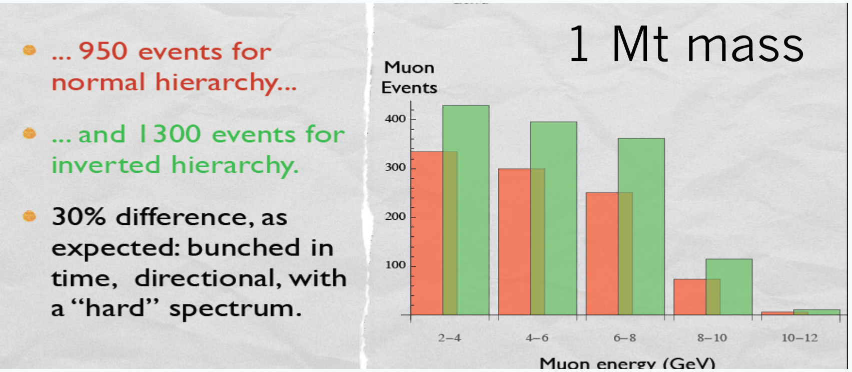
Several other studies point to the same conclusions...

A Neutrino beam to ORCA?

- Muon counting experiment - Optimum 6-8 GeV 6000-8000 km but beam inclination !

📖 Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439 ; Tang & Winter, JHEP 1202 (2012) 028

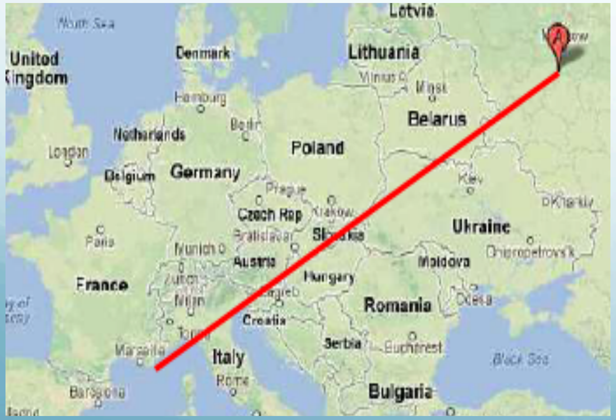
	Fermilab	CERN	J-Parc
South-Pole	11600 km	11800 km	11400 km
Sicily	7800 km	1200 km	9100 km
Baikal Lake	8700 km	6300 km	3300 km

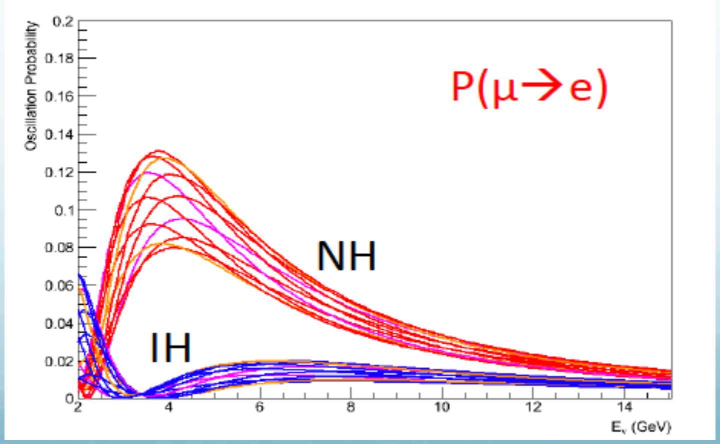


→ 9 σ separation on purely statistical ground in one year

- Electron counting experiment - Protvino-ORCA L=2588 km, beam inclined by 11.7°

📖 J. Brunner, arXiv:1304.6230





10^{21} pot -- 3 years
7 σ stat. separation
3 σ with 3-4% sys

No need for energy reconstruction

Strengthens the case for ORCA

Summary

- Neutrino astronomy has made tremendous progresses.
- Evidence for HE extraterrestrial neutrinos from IceCube.
  - What are the sources?
- ANTARES is the larger NT in the Northern Hemisphere...
  - **A multi disciplinary observatory (associated sciences).**
  - **Competitive physics results with extensive multi-messenger program.**
  - **Proves the feasibility of a deep sea Neutrino Telescope.**

→ **KM3NeT** will complement IceCube with a greater sensitivity

- 40 M€ available (out of ~220 M€ estimated for full KM3NeT), mostly from regional funds
- First construction phase will start 2014 and stop end 2016 (KM3NeT phase 1: ~3xANTARES).
- Path towards full implementation to be defined during phase-1.

- Interesting physics cases being investigated with low energy extensions: ORCA
  - May be faster and cheaper than other alternative for measuring the neutrino MH
- Global Neutrino Network (GNN) : signed Oct 15th
  - Networking agreement between ANTARES, Baikal, IceCube, KM3NeT
  - First step towards a Global Neutrino Observatory.