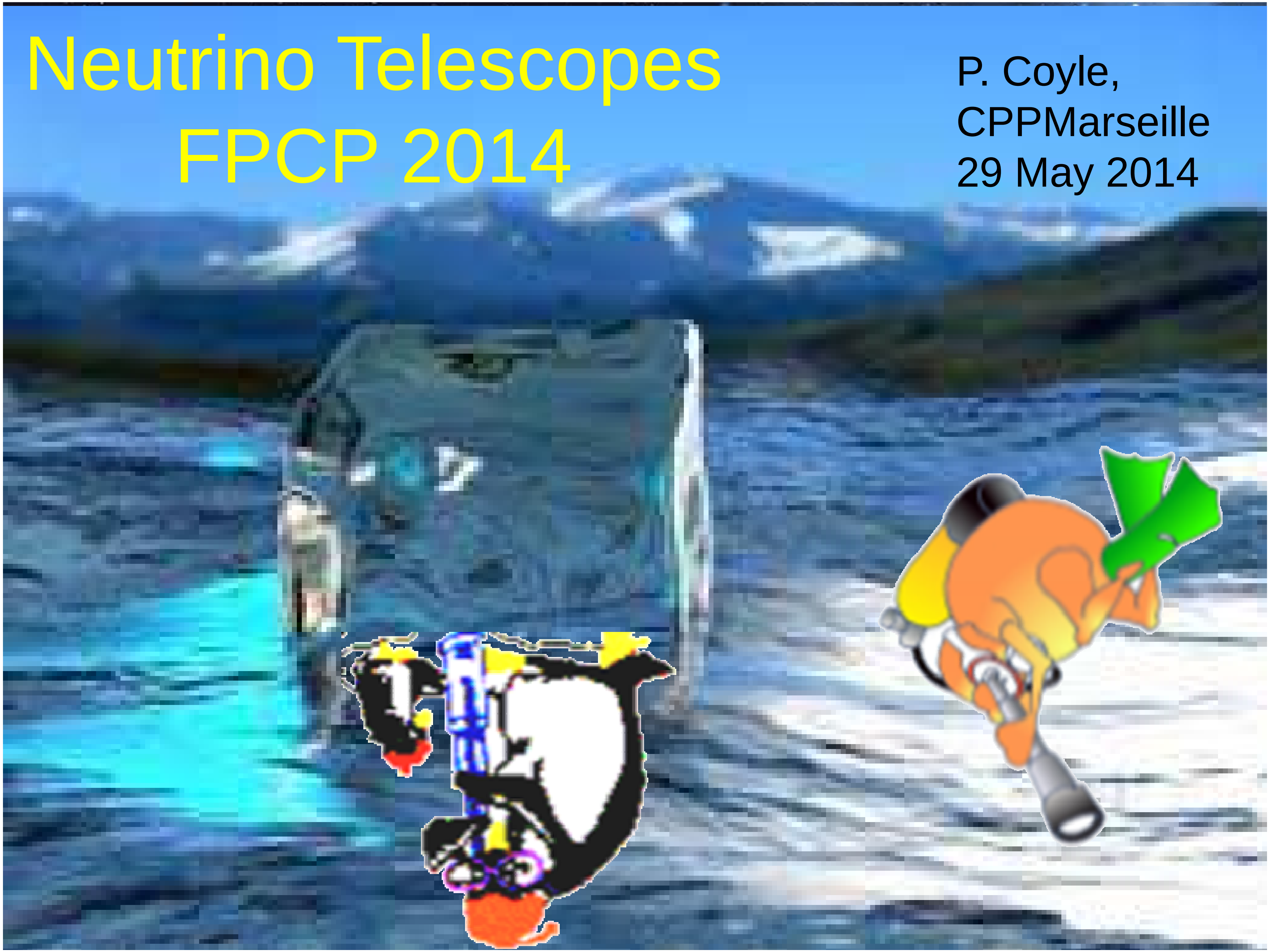
Neutrino Telescopes
FPCP 2014

P. Coyle,
CPPMarseille
29 May 2014

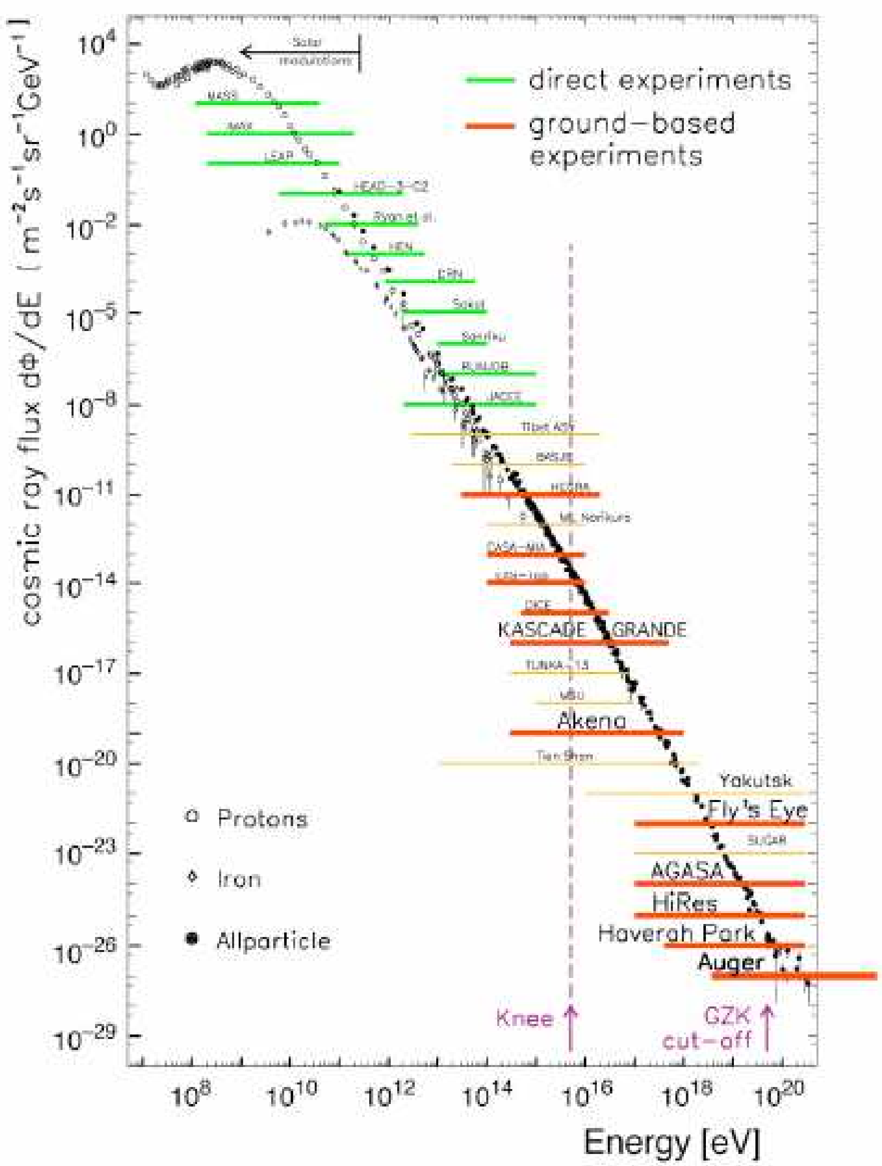


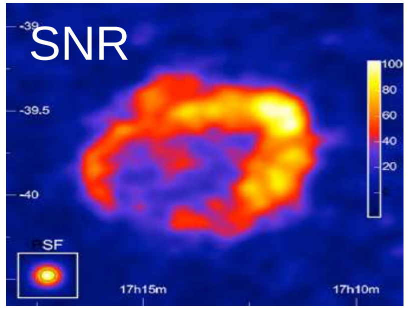
Ultra High Energy Cosmic Rays

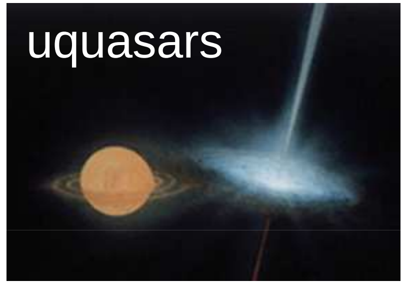
Nature undoubtably accelerates hadrons to energies10^{7} times that of LHC!

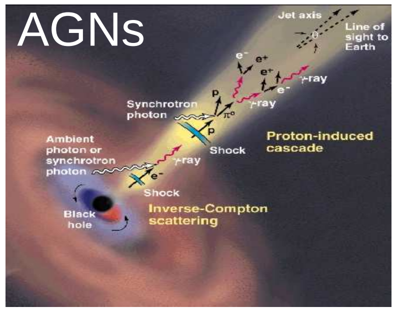
where?

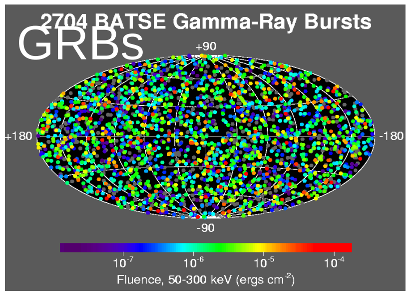
how?











Cosmic Ray-gamma-neutrino Connection

- Hadronic cascades (as for atmospheric showers)

$$p/A + p/\gamma \rightarrow \pi^0 + \pi^+ + \pi^- + N + \ldots$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

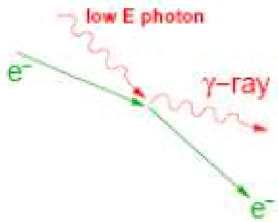
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu, \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$\nu_e:\nu_\mu:\nu_\tau = 1:2:0 \ \text{source} \xrightarrow{oscillations} \nu_e:\nu_\mu:\nu_\tau = 1:1:1 \ \text{Earth}$$

- Primary acceleration («Bottom-Up»)
  - Stochastics shocks (Fermi mechanism)
  - Explosion /Accretion / Core collapse

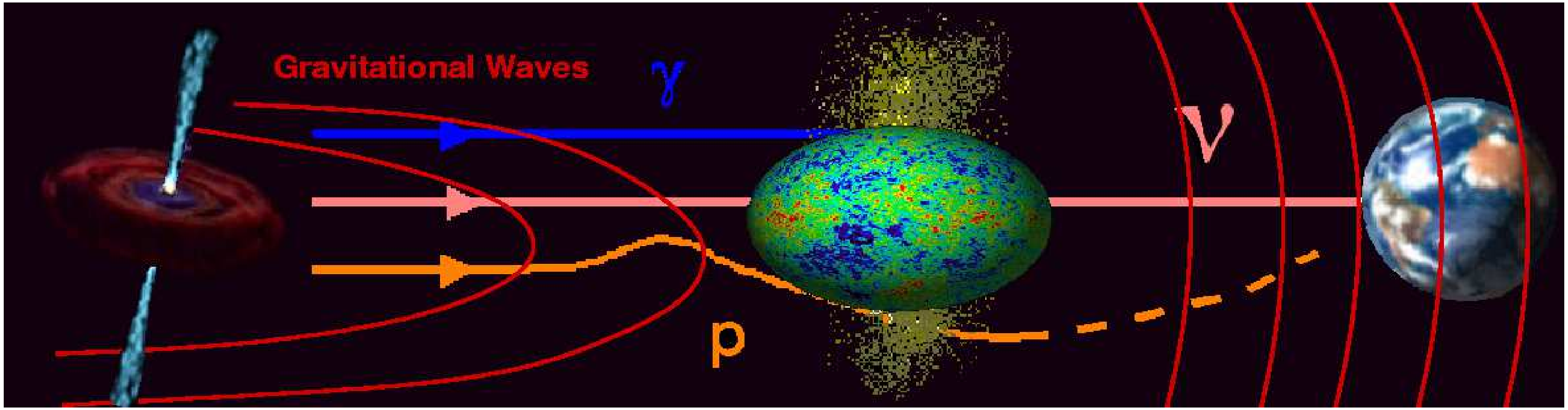
- But HE γ also from electromagnetic processes
  - Synchrotron Inverse Compton

synchrotron radiation



inverse Compton scattering

Neutrinos and Multi-Messenger Astronomy



Cosmic Rays
Subject to deflection by magnetic fields
Horizon limited by GZK cutoff
Large time delay w.r.t. optical signals

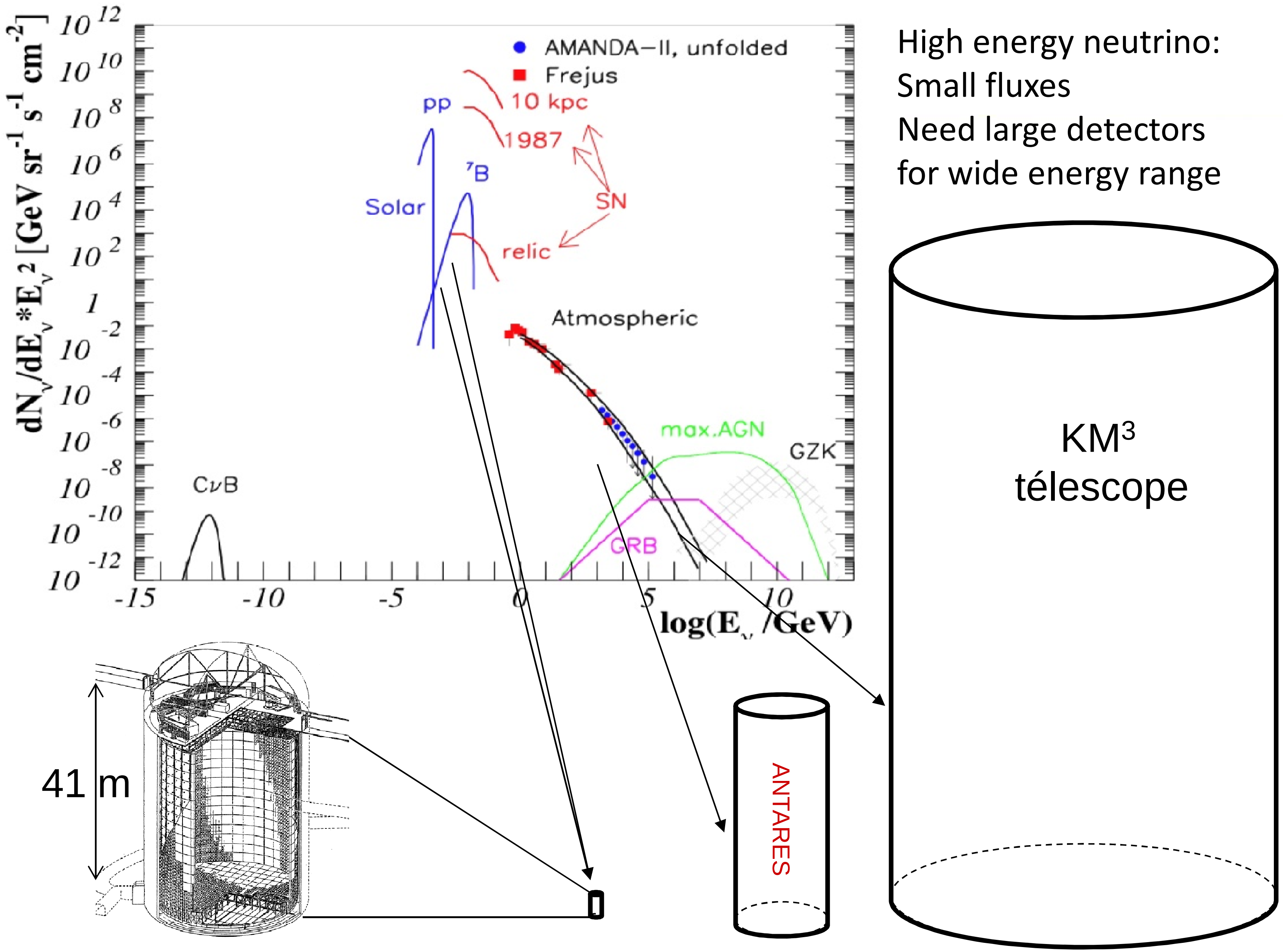
Photons
leptonic and hadronic processes-> confusion
Absorbed at high energies and large distances

Neutrinos
<u>Unambiguous</u> signature of hadronic acceleration
Not deflected by magnetic fields or absorbed by dust
Horizon not limited by interaction with CMB/IR
Escape from region of high matter density
Time correlated with optical signals

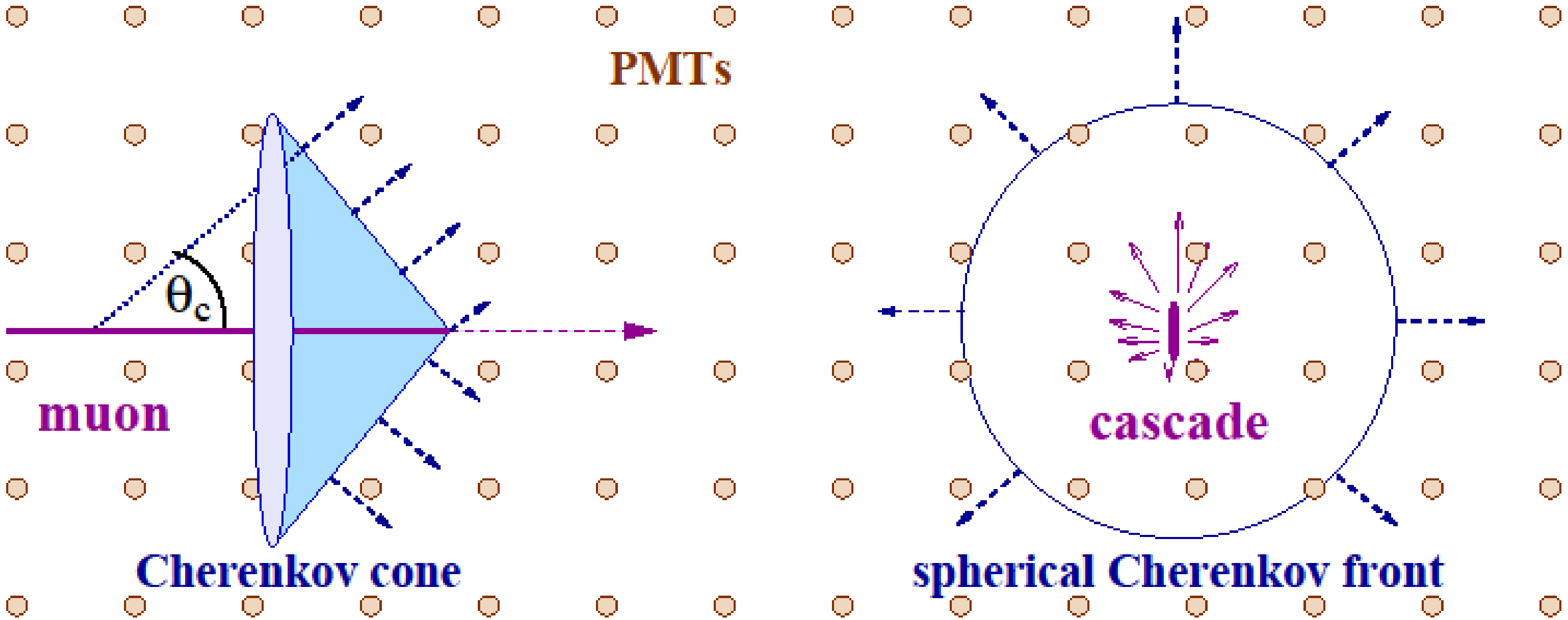
-> identify cosmic ray sources

From MeV ν to PeV ν

High energy neutrino:
Small fluxes
Need large detectors
for wide energy range



Detection Modes



Muon track from CC muon neutrinos

- Angular resolution 0.5° /0.1°

  for ice/water 1km³
- dE/dx resolution factor 2-3

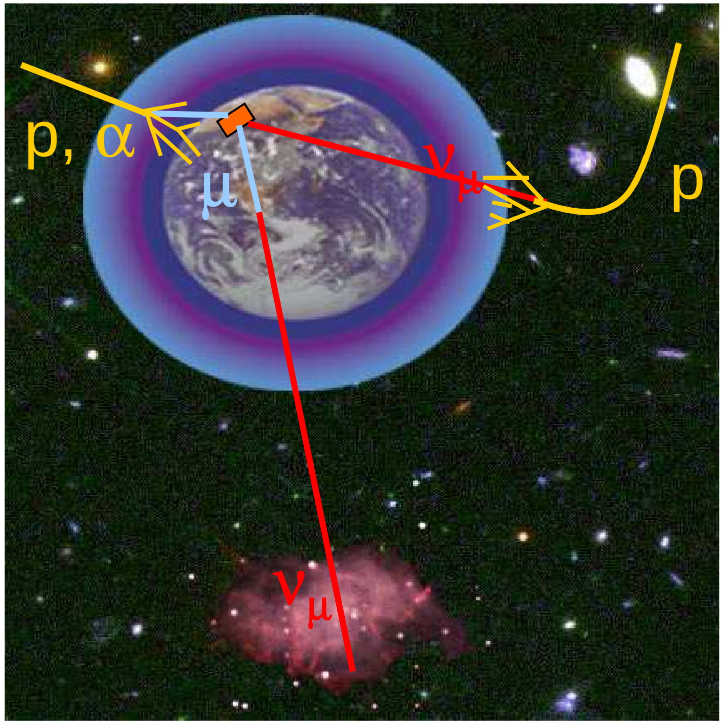
Cascade from CC electron/tau and NC all flavour interactions

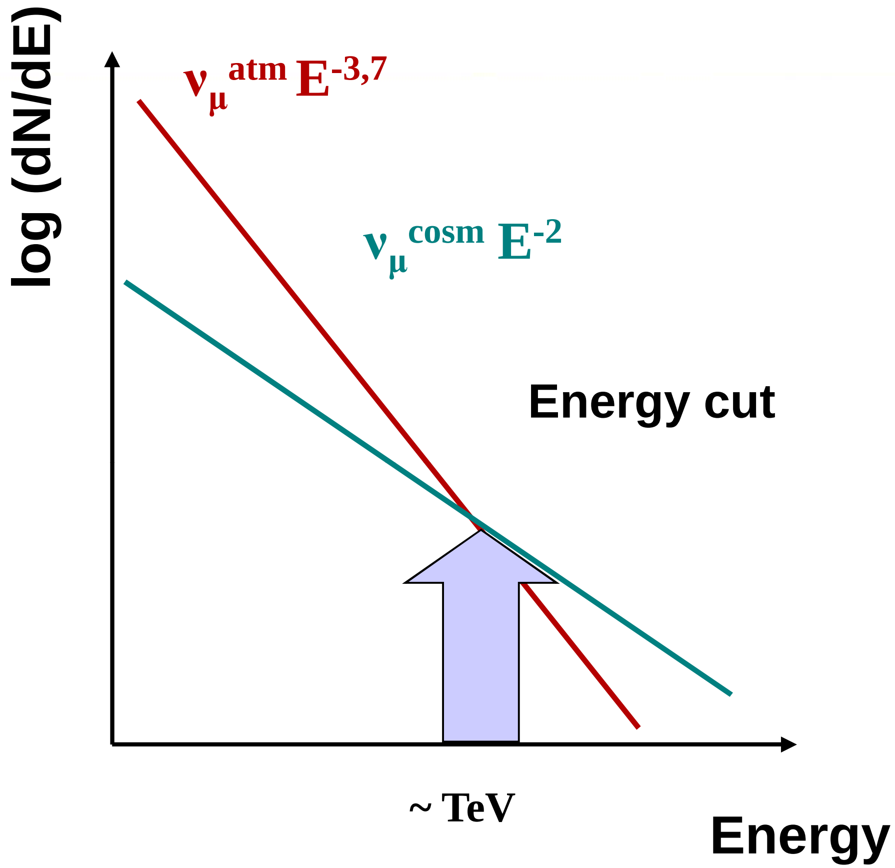
Angular resolution 10° /3°
at 100 TeV for ice/water

Energy resolution ~ 15%

Atmospheric background vs cosmic ν's

Atmospheric muons ⇒ shield detector, look down, apply veto

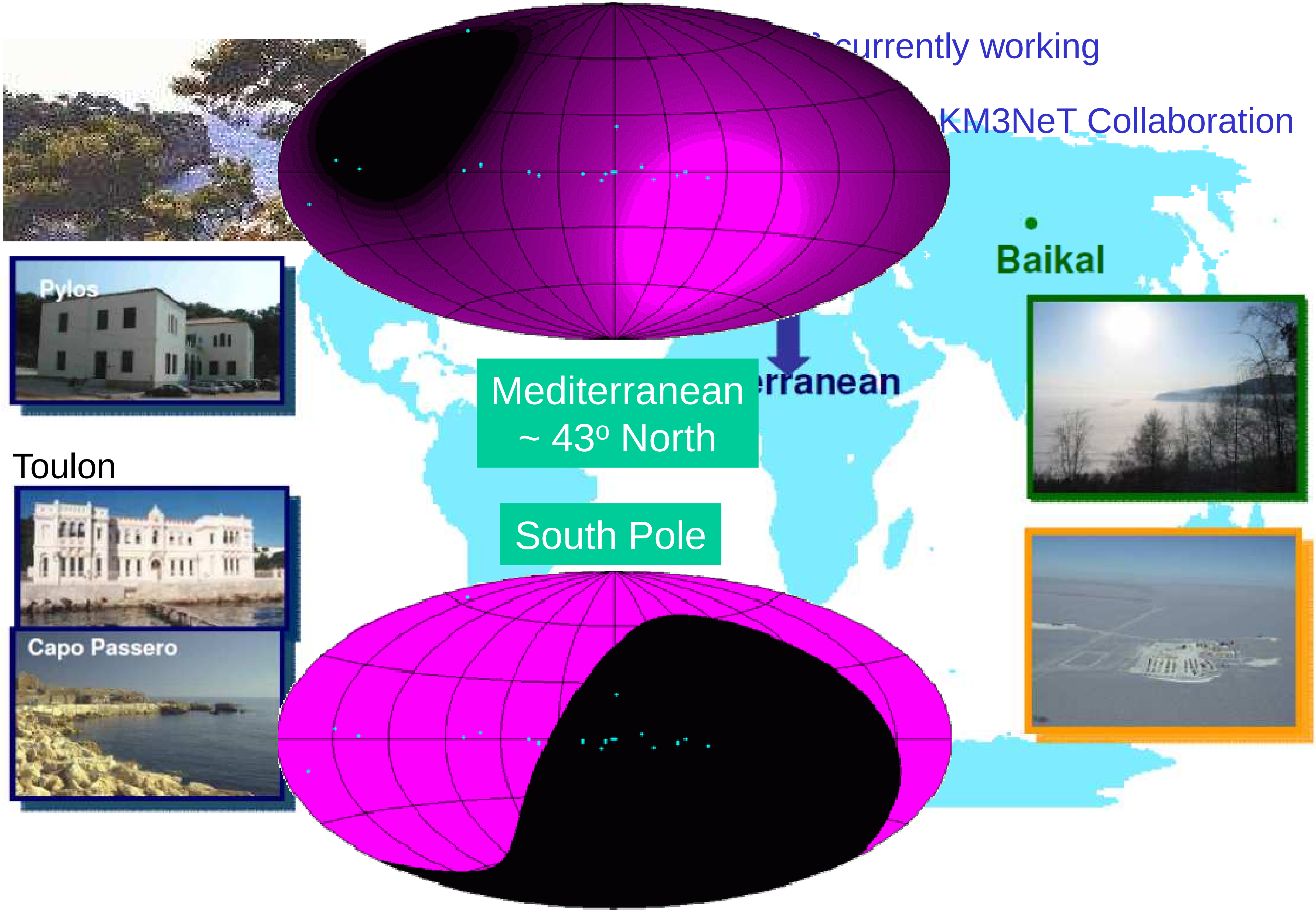




Atmospheric neutrinos ⇒ search for

- an excess at high energy
- spatial clustering
- time / space coincidence with other cosmic messengers

Neutrino telescopes (TeV)

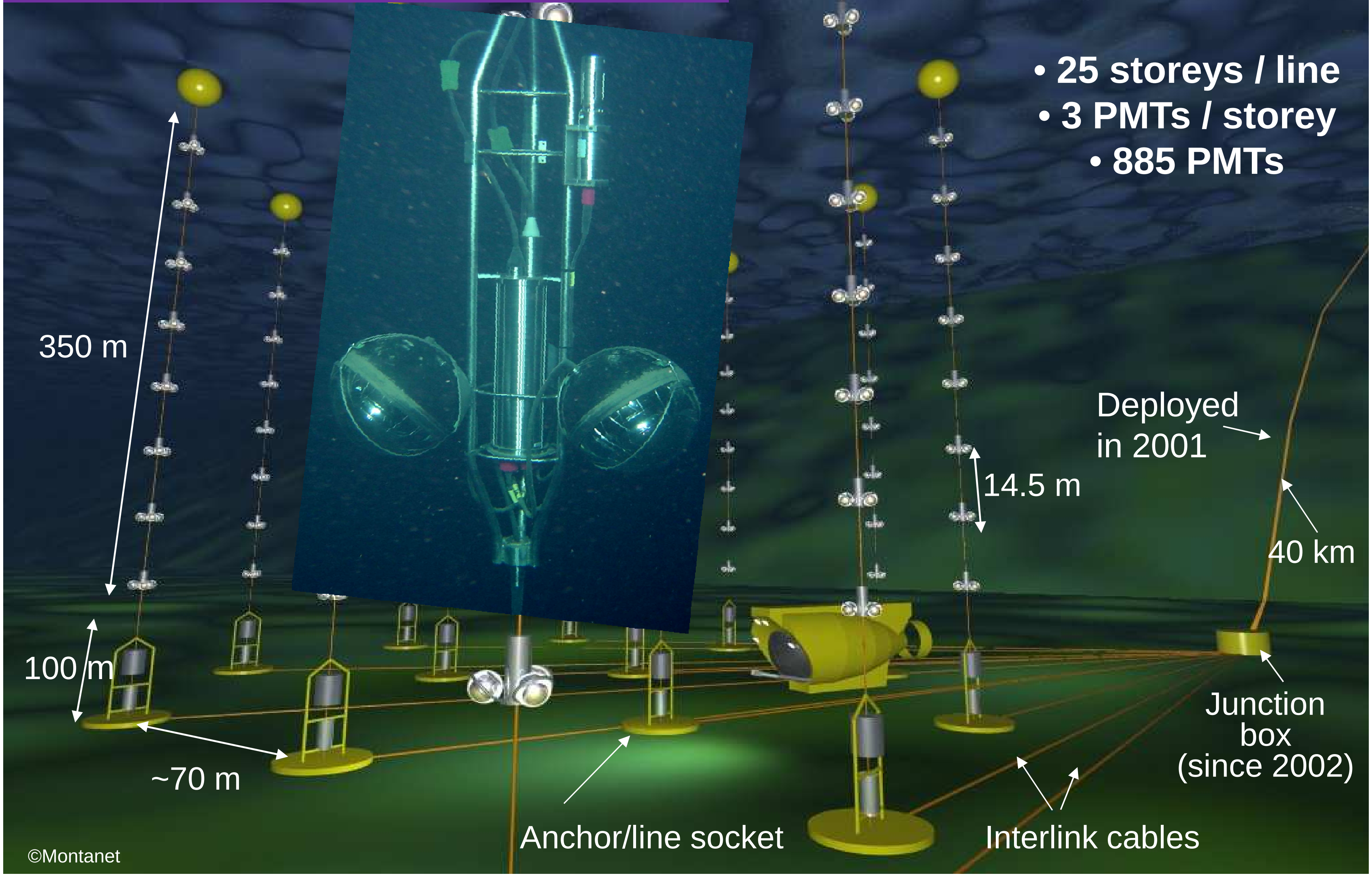



Toulon
M.Pacha
Antares
Electro-optical
Cable of
40 km
42 50'N, 6 10'E
Google
© 2008 Cnes/Spot Image
Image © 2008 DigitalGlobe
Image NASA

The ANTARES neutrino telescope

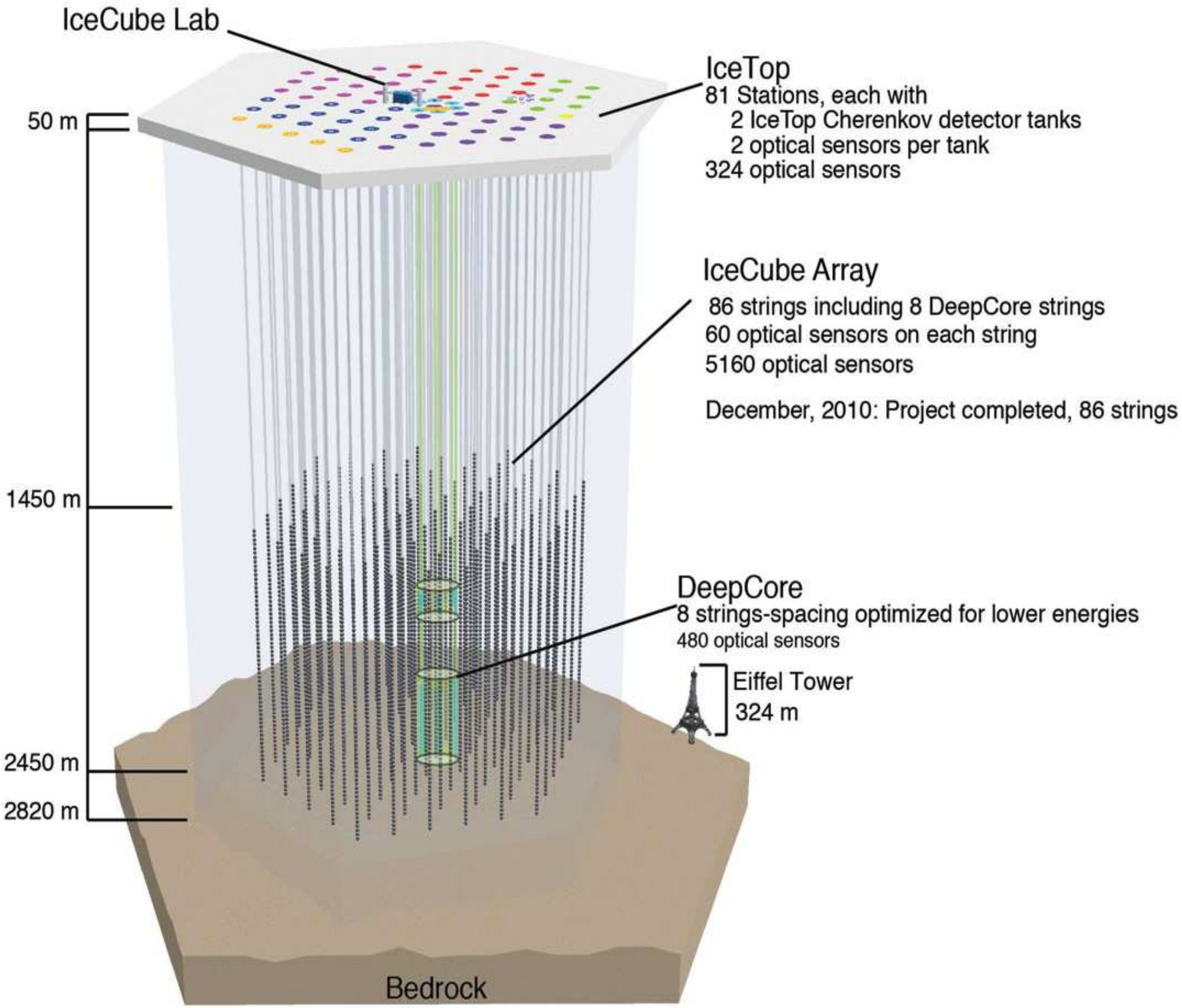
Detector completed in May 2008

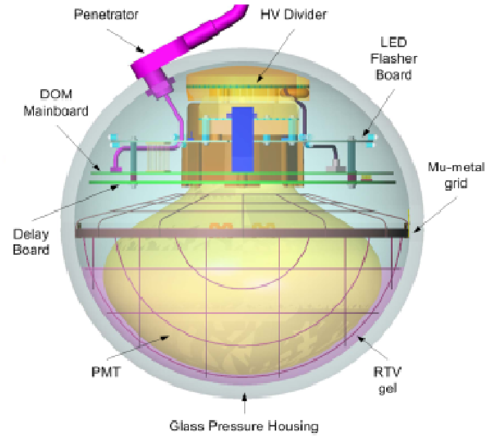
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs



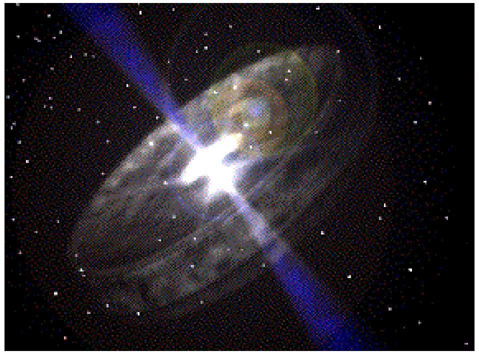
IceCube : the biggest NT in the world

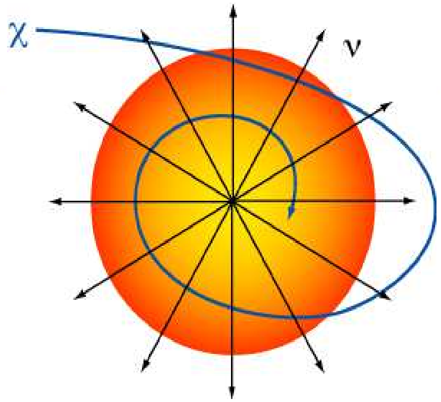
Completed since December 2010.

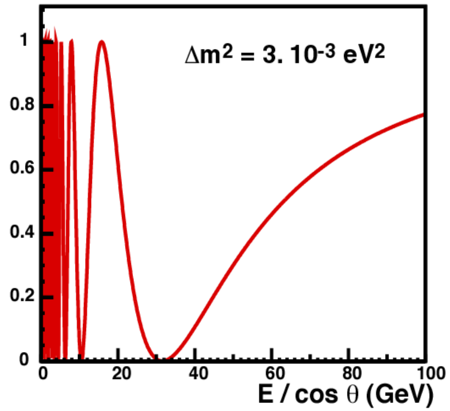




Neutrino telescopes: science scope







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

ν from extra-terrestrial sources

Dark matter search

ν oscillations

Origin and production mechanism of HE CR

↓

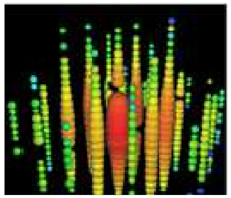
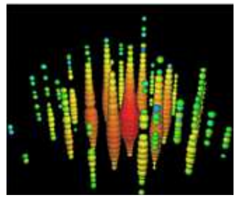
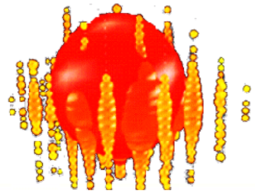
Primary goal

Exotic particle physics
Monopoles, nuclearites,…

Marine sciences: oceanography, biology, geology…

IceCube Signal for Diffuse Flux

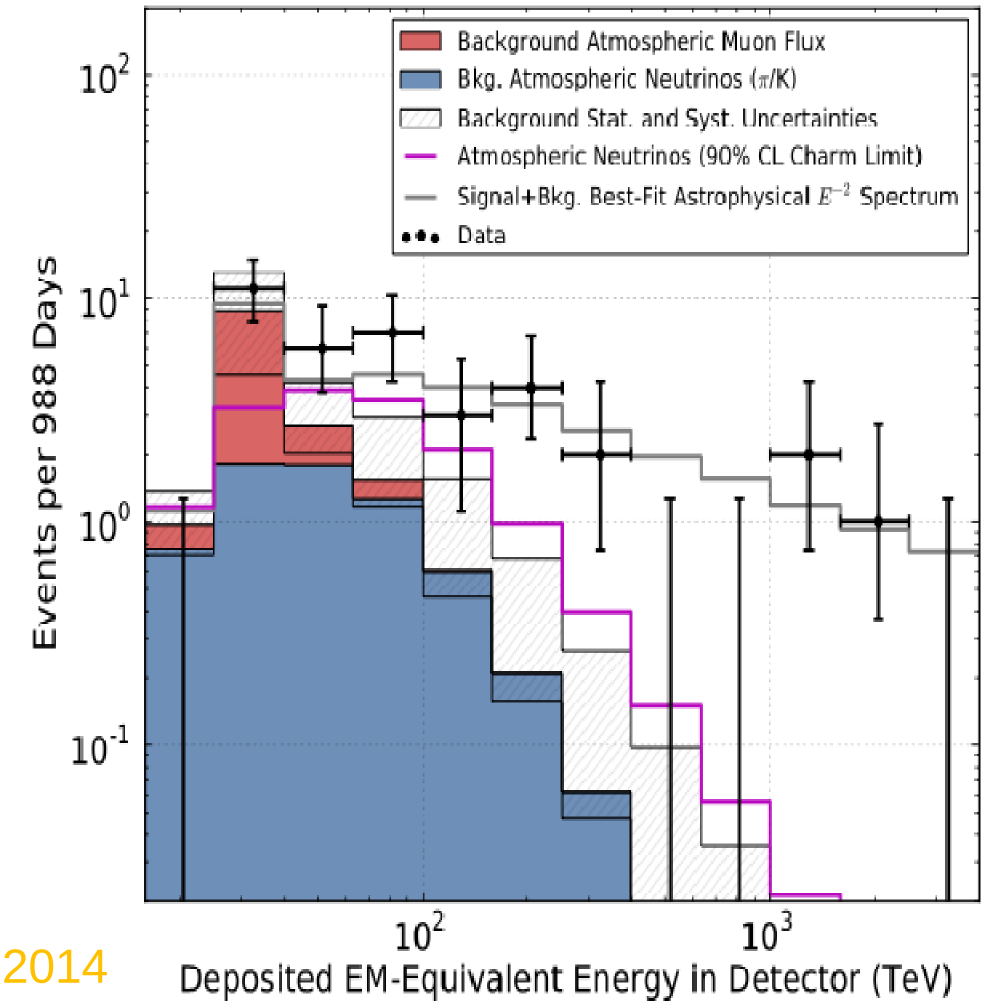
2 yr data (Science paper)
28 events (21 cascade+7 track)
'Ernie' and 'Bert'
Expected bkgd: 11 events
4 sigma

3 yr data: 988 days
37 events (29 cascade+8 track)
'big bird' at 2 PeV
Expected bkgd:

- $6.6^{+5.9}_{-1.6}$ atm. neutrinos
- 8.4 ± 4.2 atm. muons

5.7 sigma



Best fit flux (single flavour)
$(0.95+-0.3)*10^{-8}$ E^{-2} GeV/cm^2/s/sr

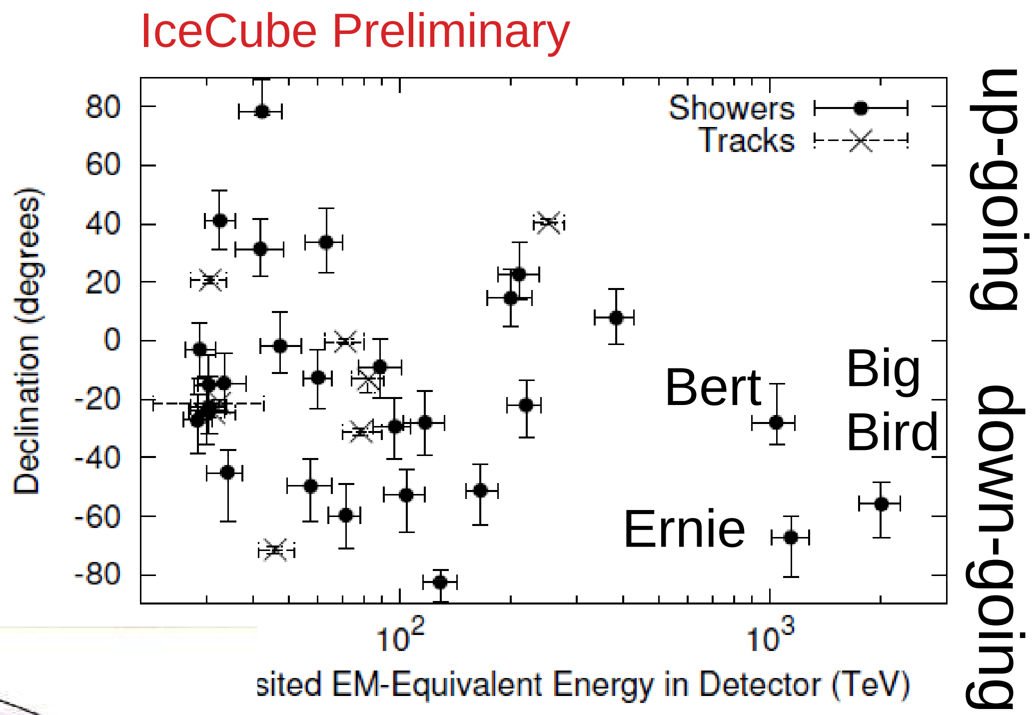
(maybe cutoff around 2.3 PeV?)

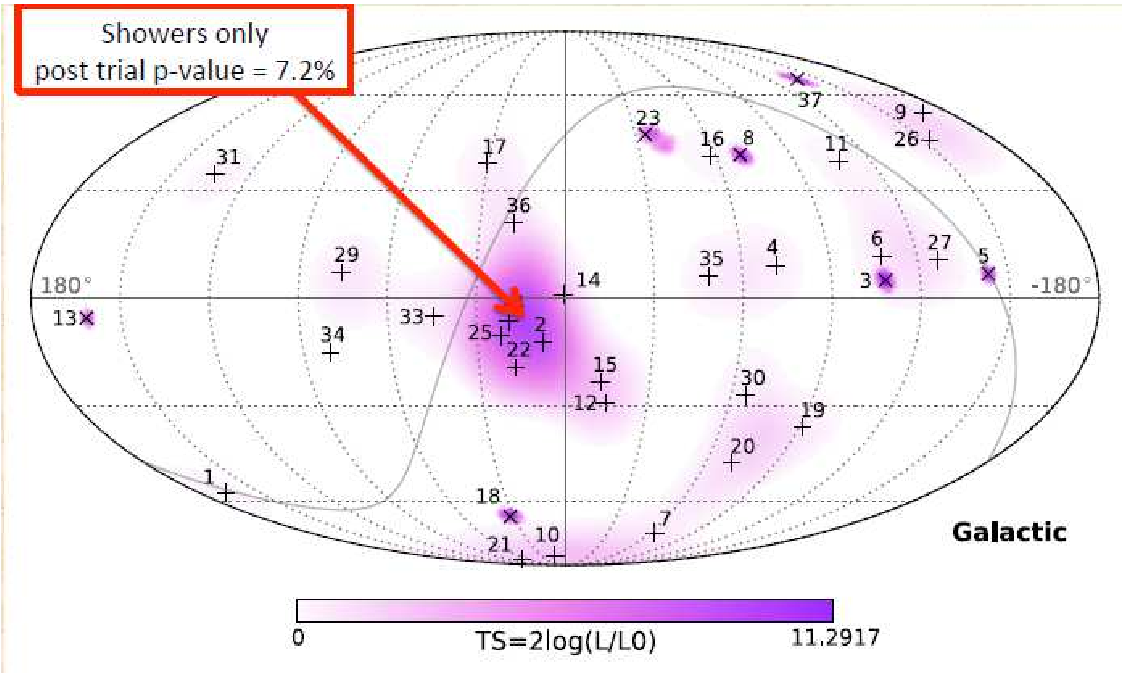
arXiv:1405.5303v1 [astro-ph.HE] 21 May 2014

IceCube Signal for Diffuse Flux

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

Shower events: clustering near Galactic Centre (7% prob)?

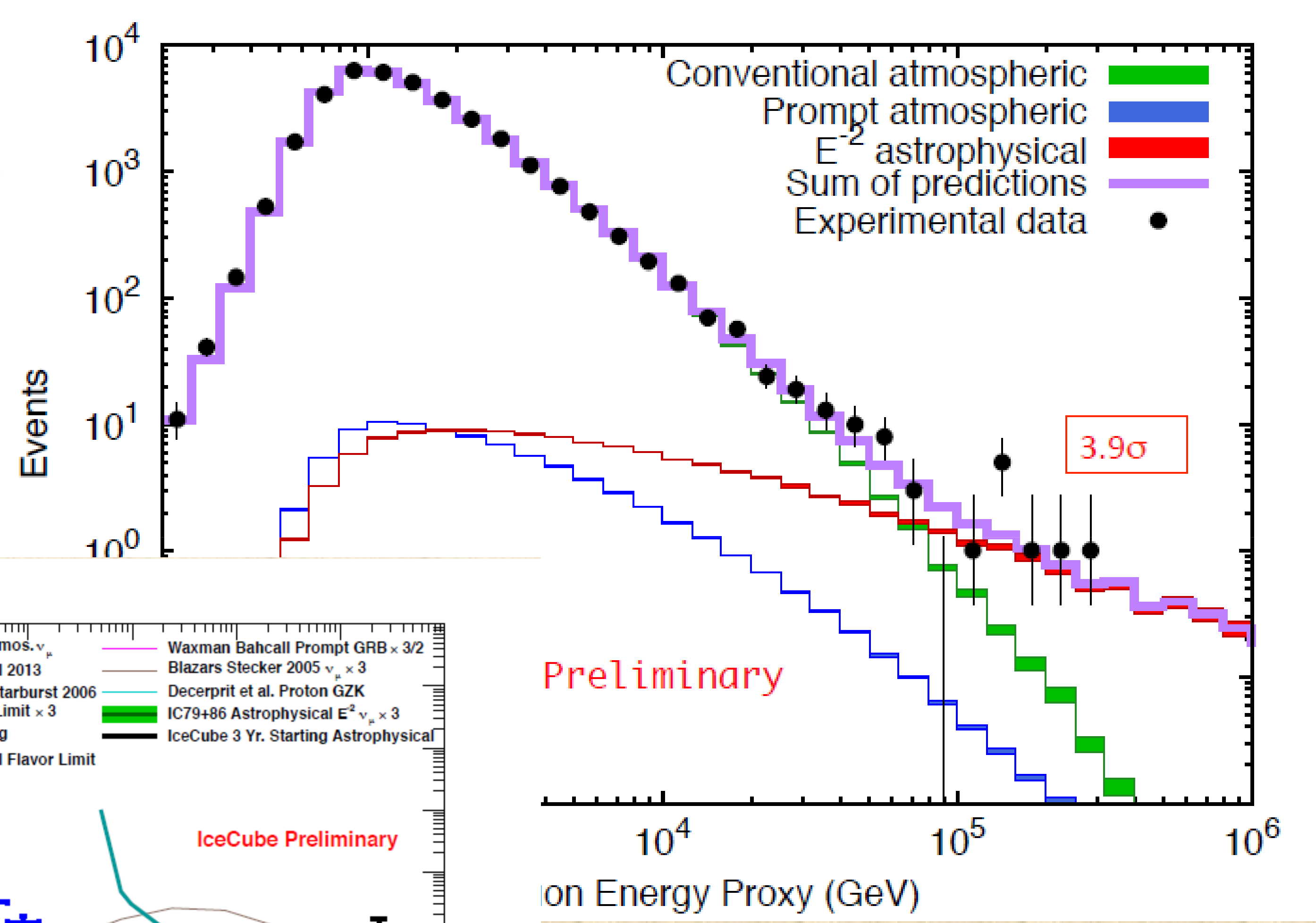


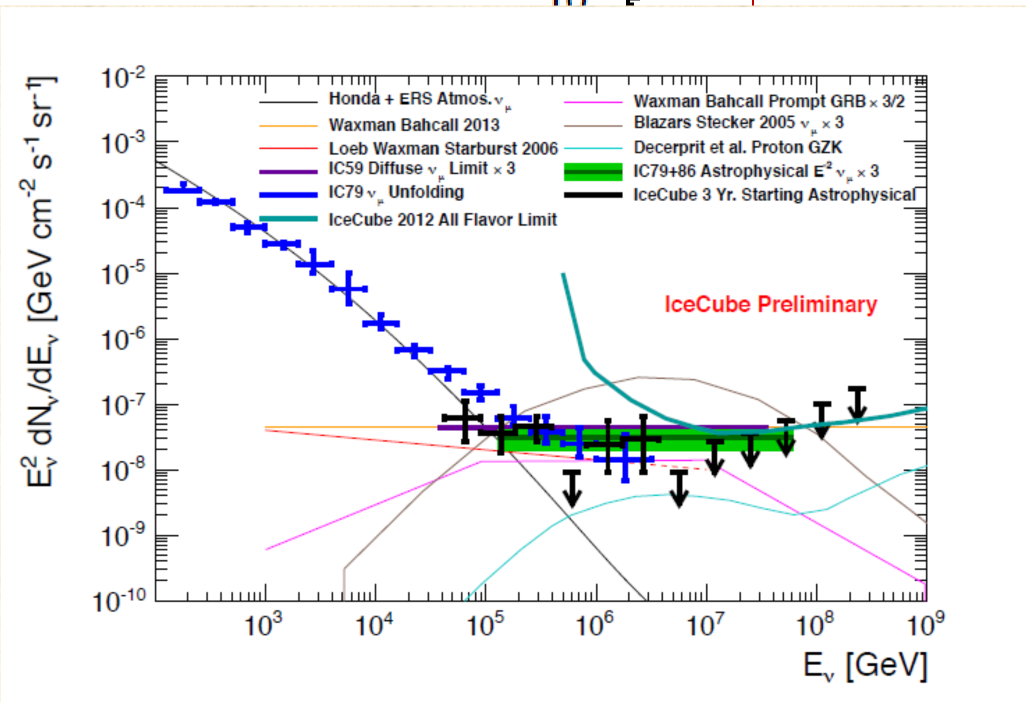


Diffuse Muon Neutrino Searches

IC79+IC86-1

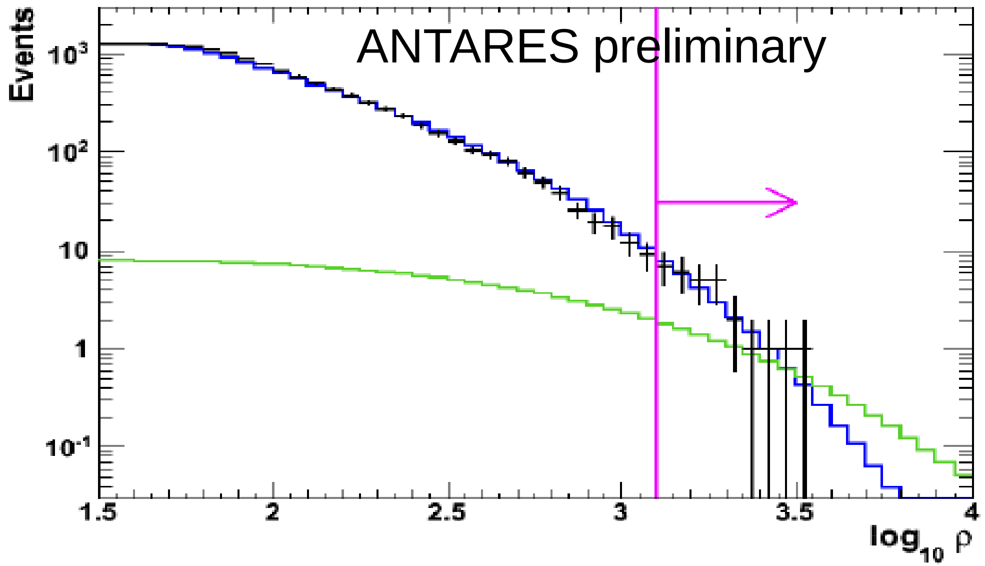
3.9 sigma





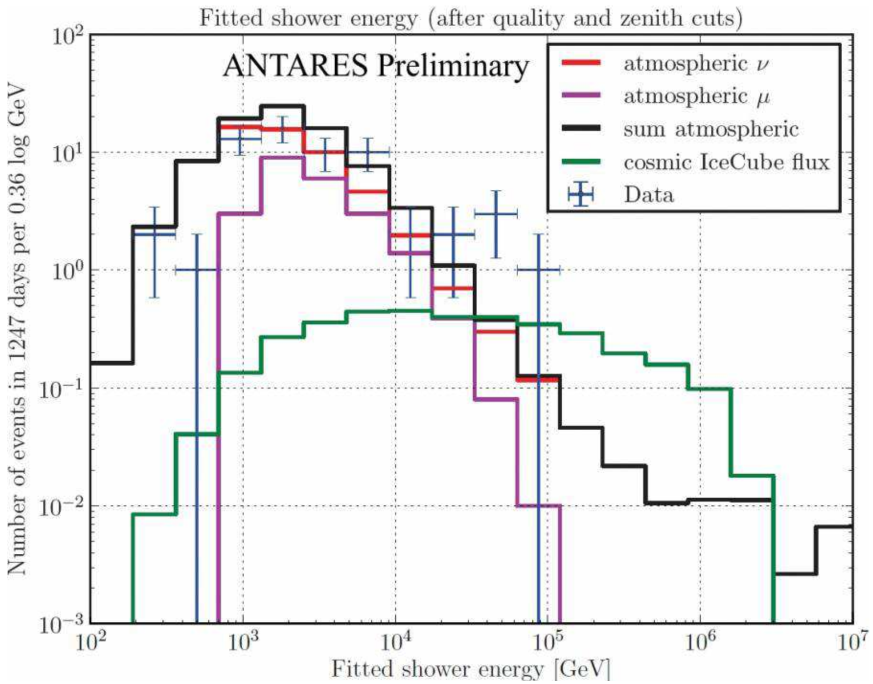
Consistency muons and cascades

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

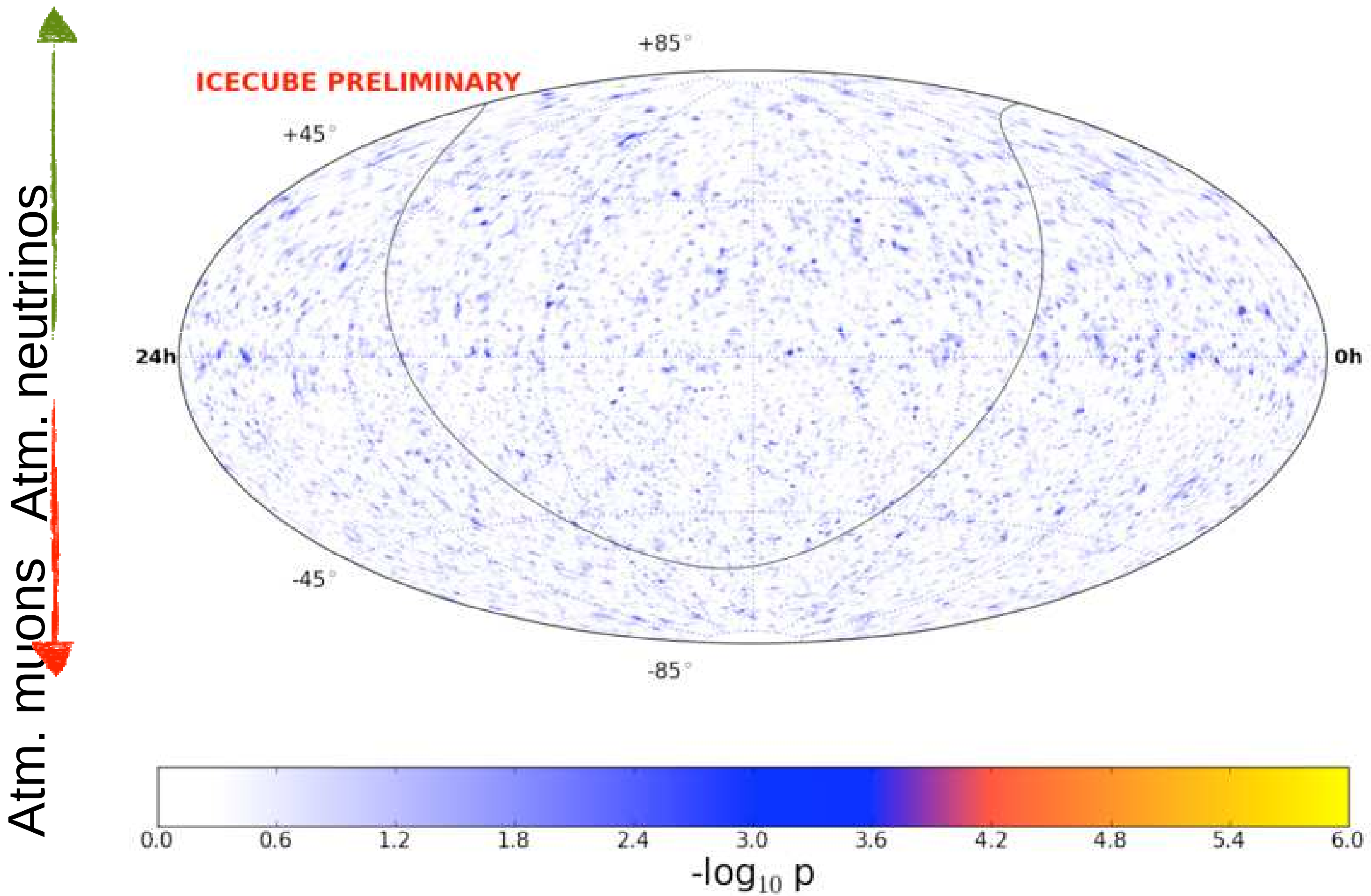
Flux limit (90%CL)
$4.92 * 10^{-8}$ GeV/cm^2/s/sr

Angular resolution ~6-7°

Point Source Search Skymap

- Total events: 394,000 (178k upgoing + 216k downgoing)
- Livetime: 1371 days

4 years



Point Source Search Skymap

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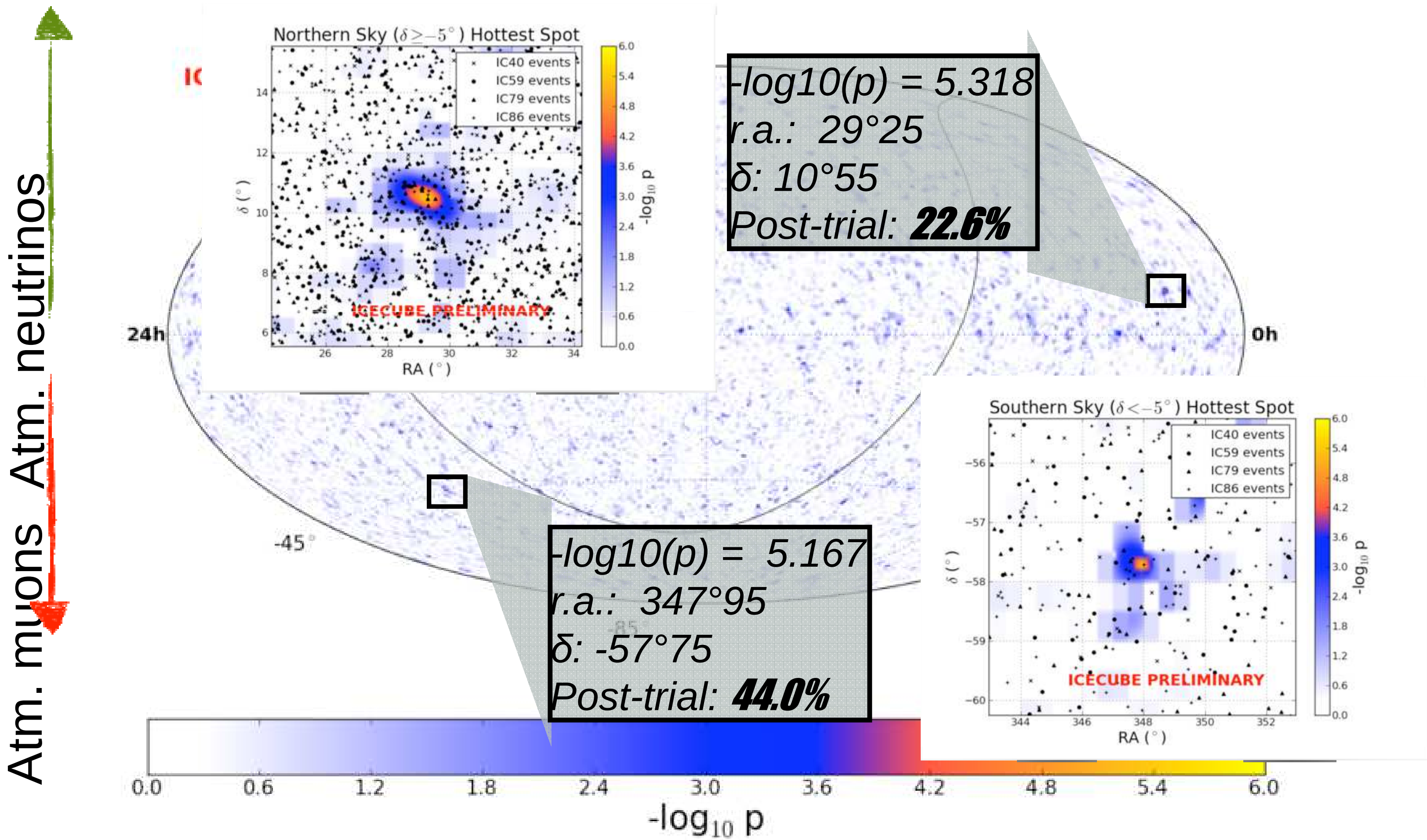
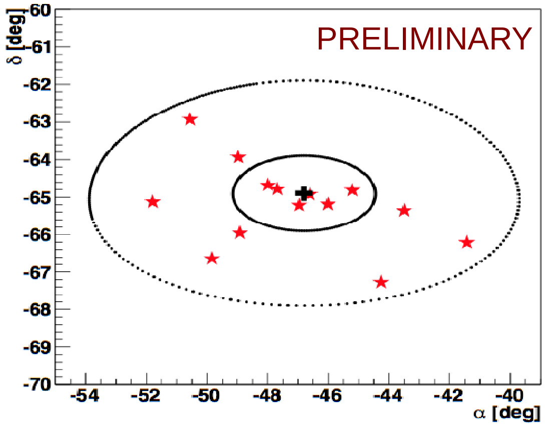
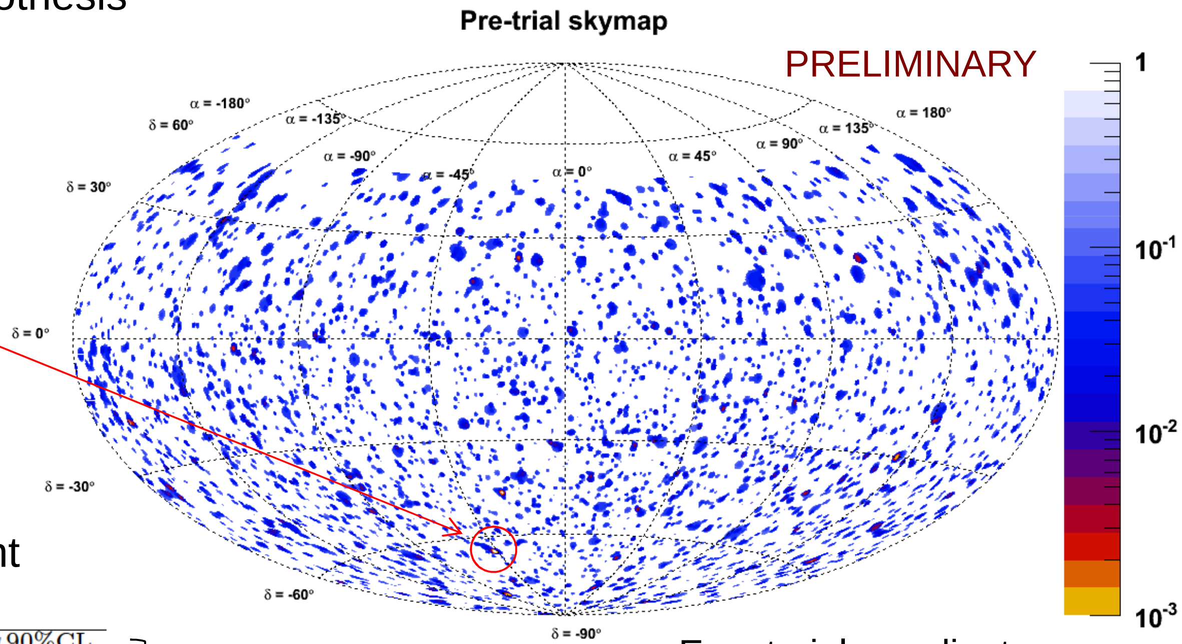


Search for neutrino point sources

❖ 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

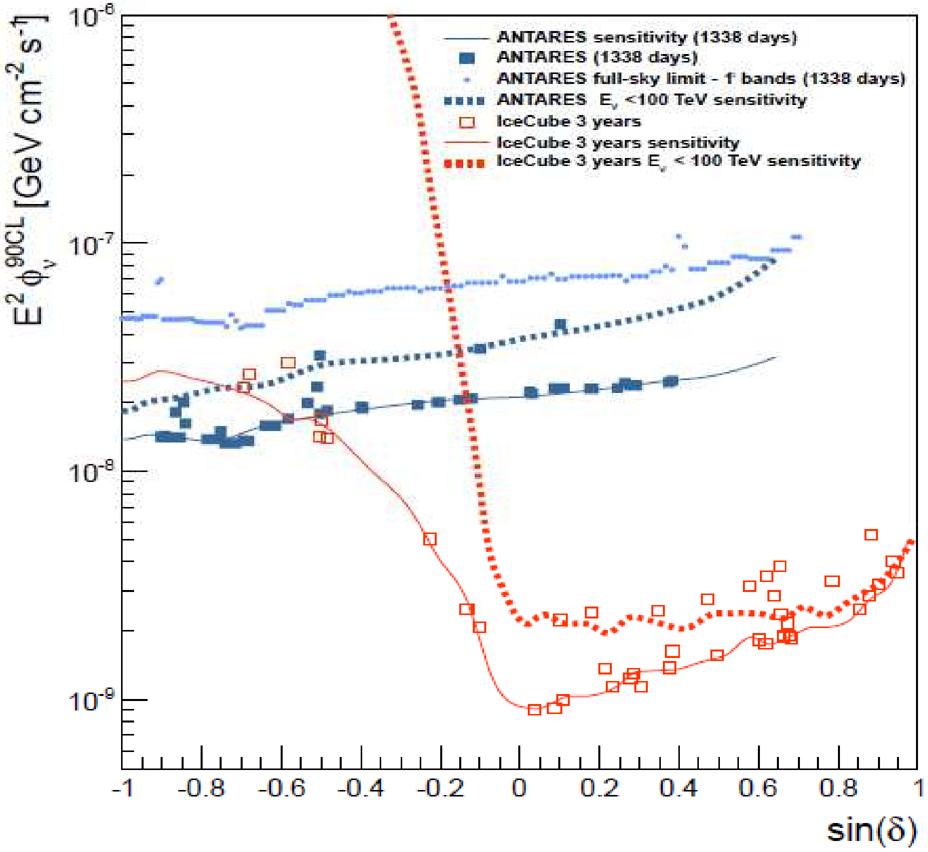
- Fixed search top 5 most significant

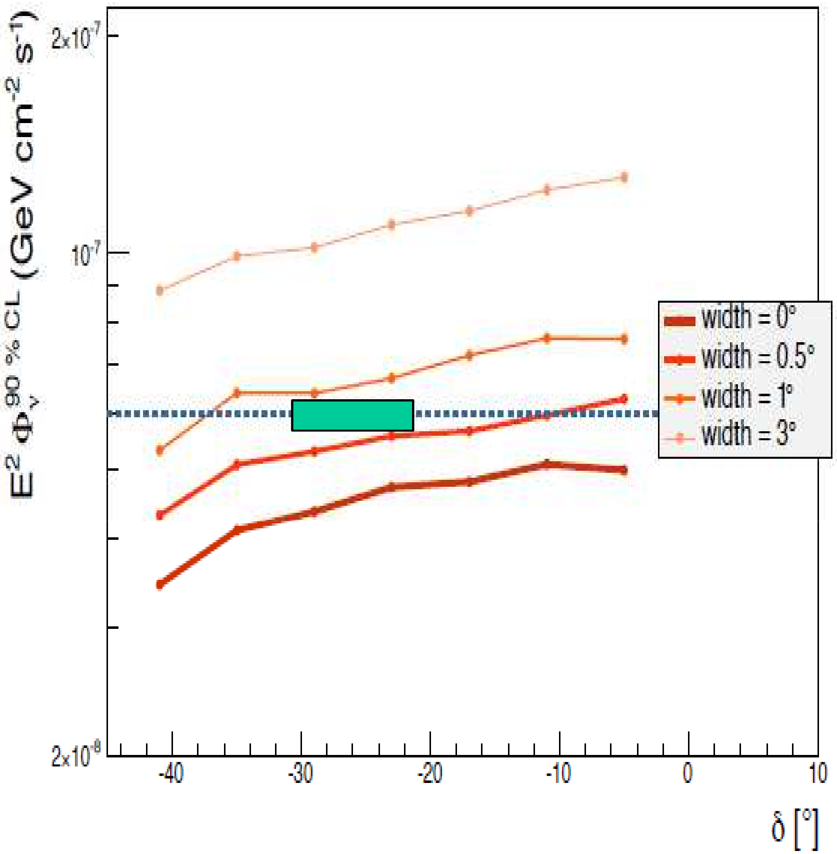
source	$\alpha_s[°]$	$\delta_s[°]$	p	$\phi^{90\%CL}$
HESSJ0632+057	98.24	5.81	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.14	3.23
3C279	194.05	-5.79	0.39	3.45
HESSJ1023-575	155.83	-57.76	0.82	2.01
ESO139-G12	264.41	-59.94	0.95	1.82

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





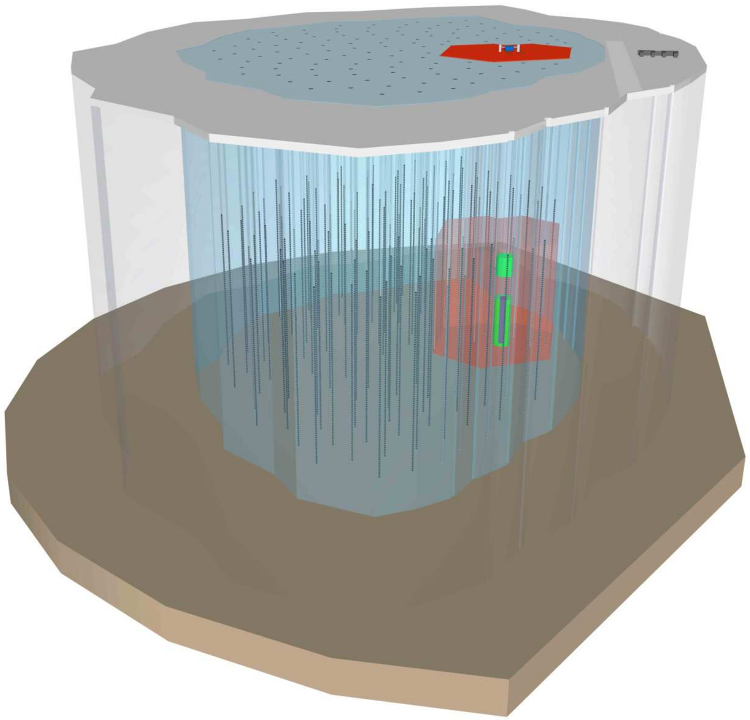
Most sensitive for 'galactic sources' (<100 TeV)

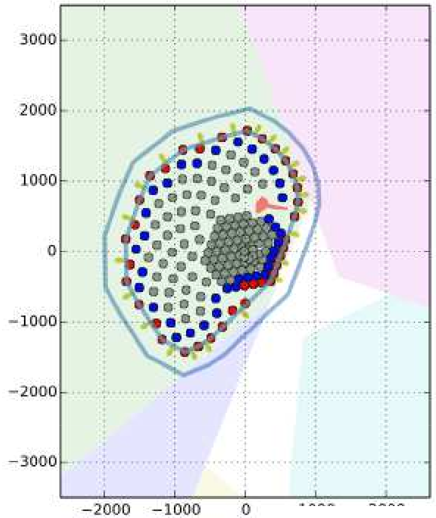
Exclude IceCube 'cluster' due to a point source up to 1° extension

"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

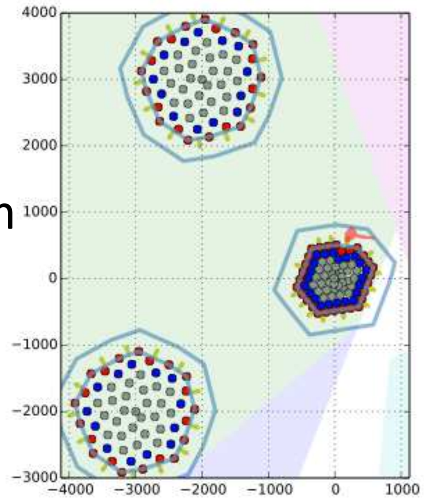
DecaCube





IceCube + 96 strings
Spacing 240 m

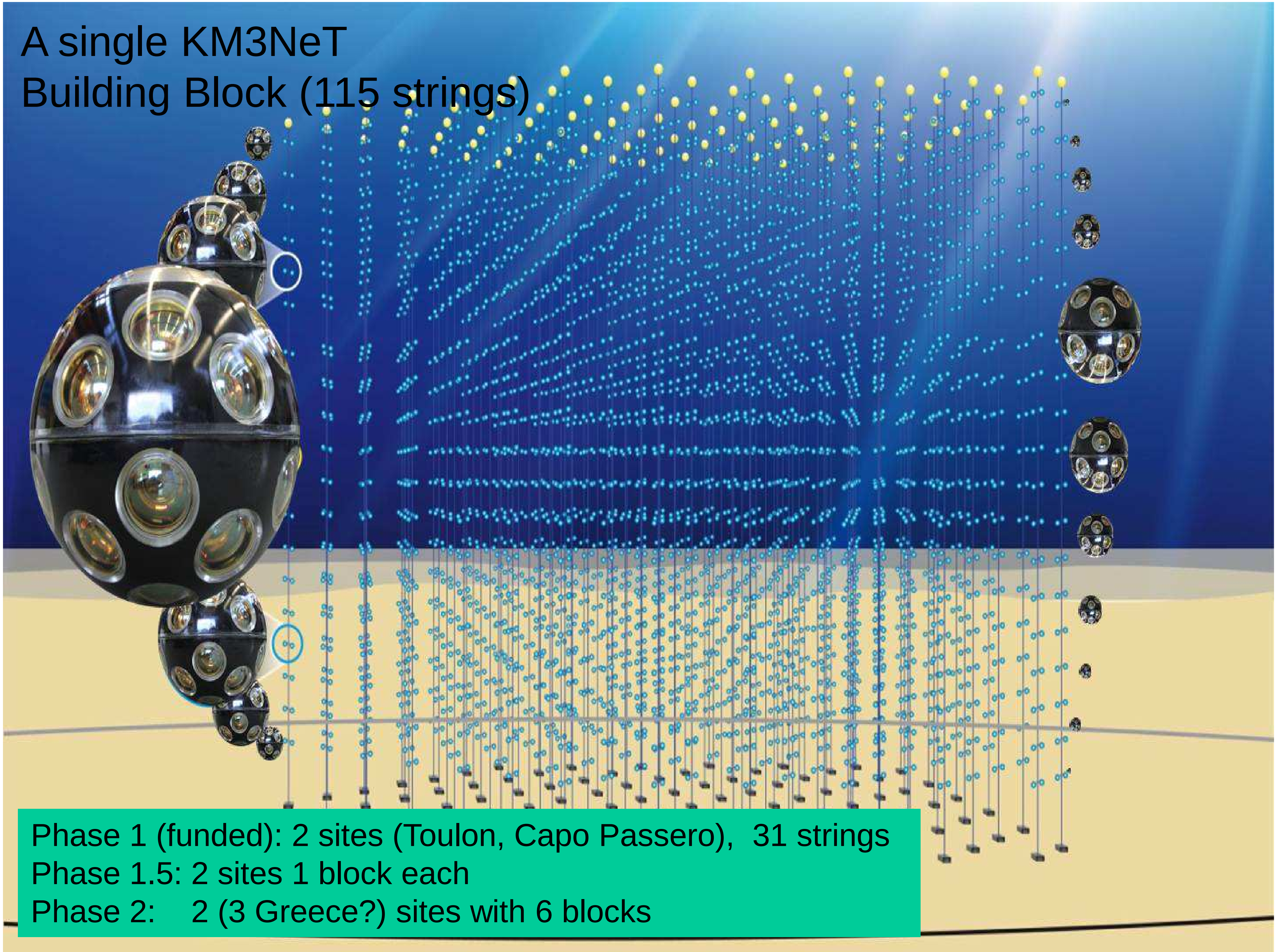
IceCube +
2 x 60 strings
spacing 240 m



- ~ 100 strings
- + surface veto detector
- + PINGU for oscillations (40 strings)
- Start 2018/19?

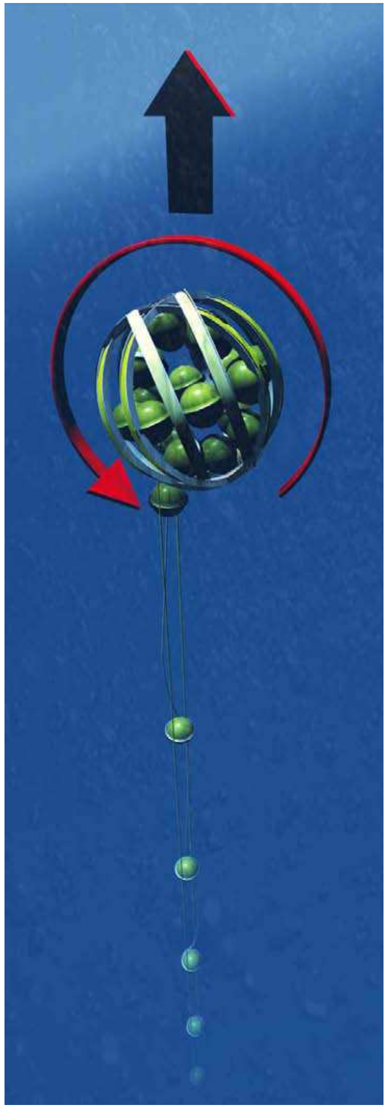
Albrecht Karle, Arlington Meeting April 24, 2014

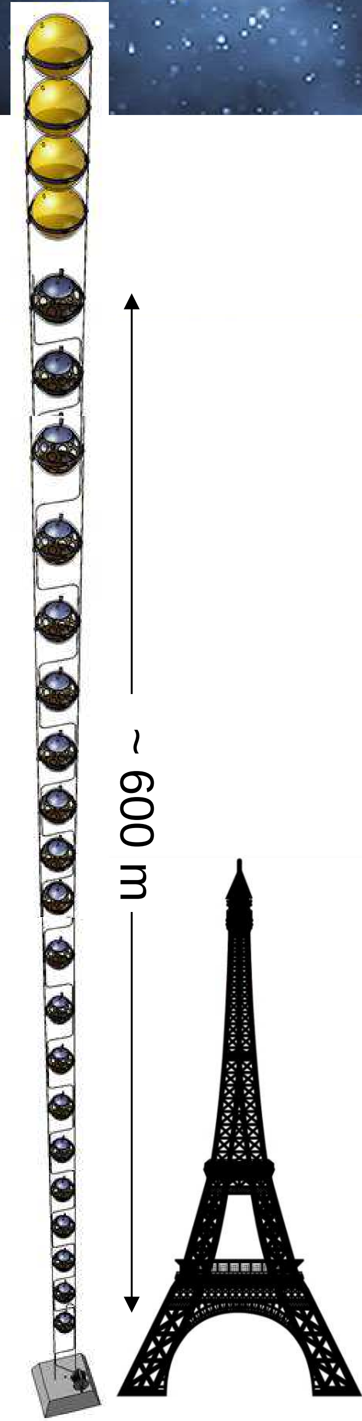
A single KM3NeT Building Block (115 strings)



Phase 1 (funded): 2 sites (Toulon, Capo Passero), 31 strings
Phase 1.5: 2 sites 1 block each
Phase 2:   2 (3 Greece?) sites with 6 blocks

String Deployment





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

Multiple deployments with a single cruise

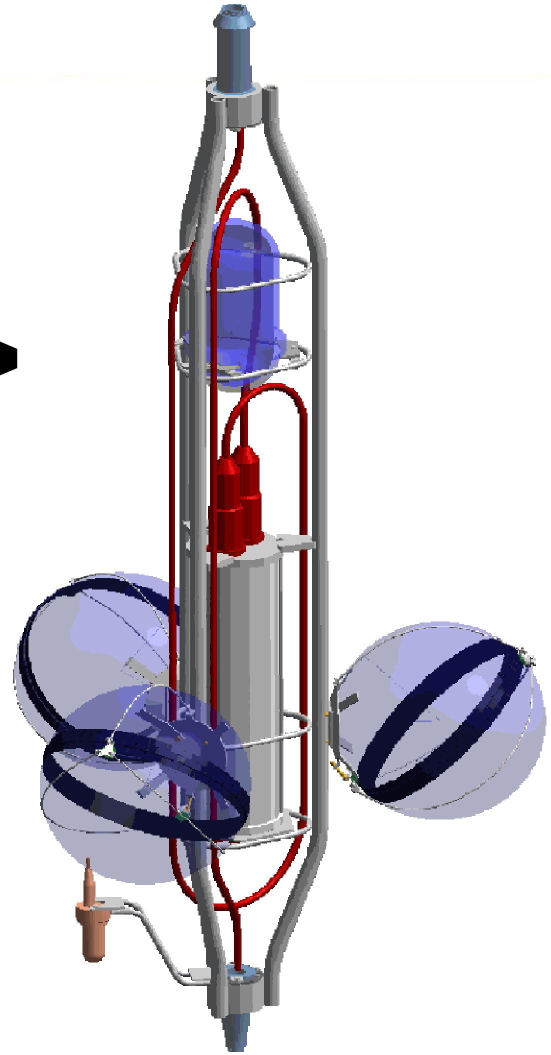
The Multi-PMT Digital Optical Module

17 inch

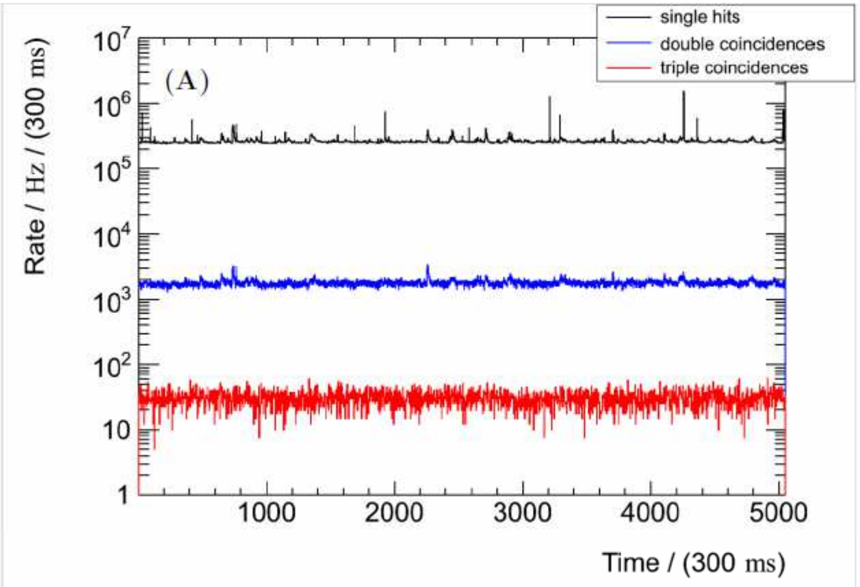
- Digital photon counting
- Directional information
- Wide angle of view
- Single pressure transition
- Cost reduction cf ANTARES

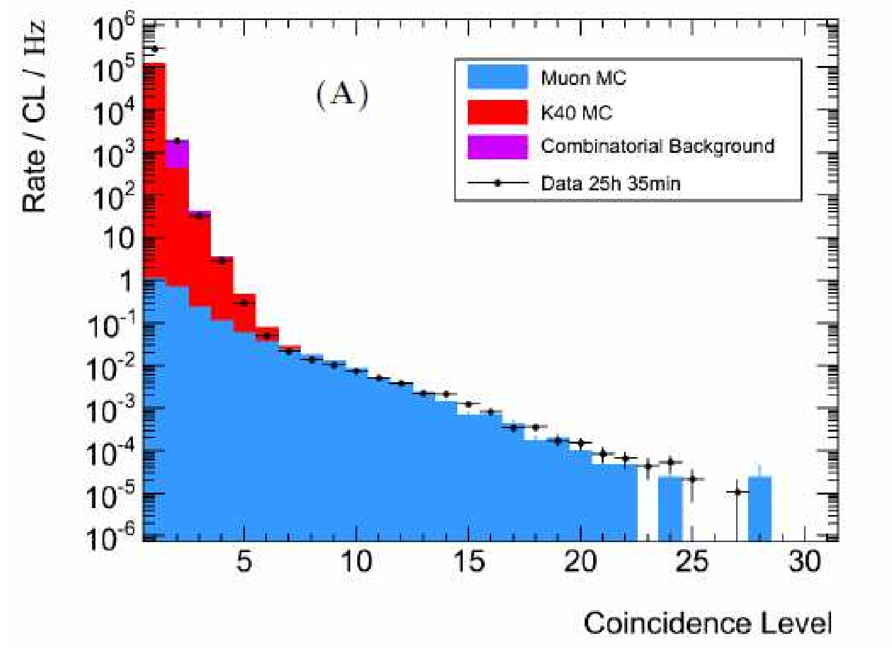
>

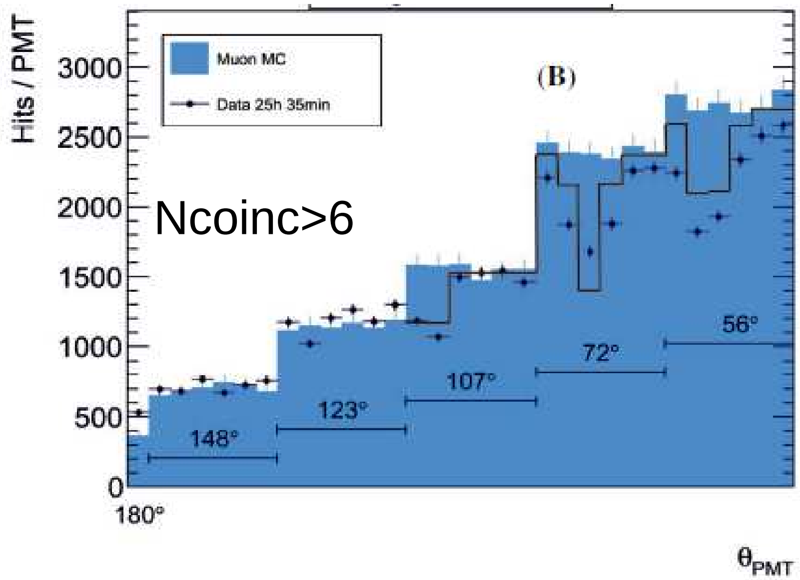
ANTARES Storey



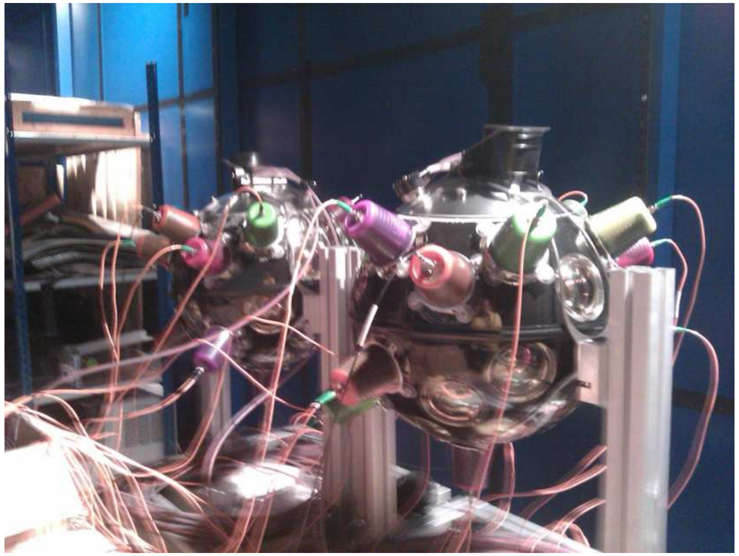
KM3NeT DOM: works beautifully





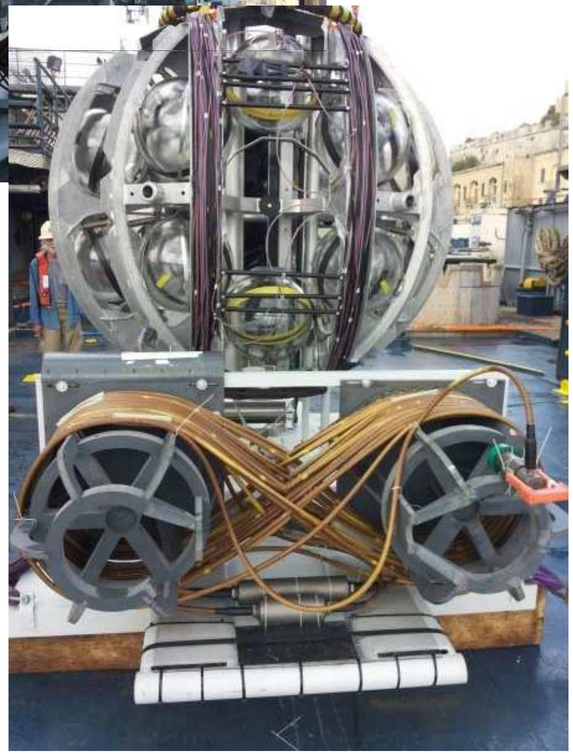


KM3NeT 'Mini-line' Deployed at Capo Passero (May 7, 2014)



Integration
Nikhef +
CPPM

Deployment
Sicily



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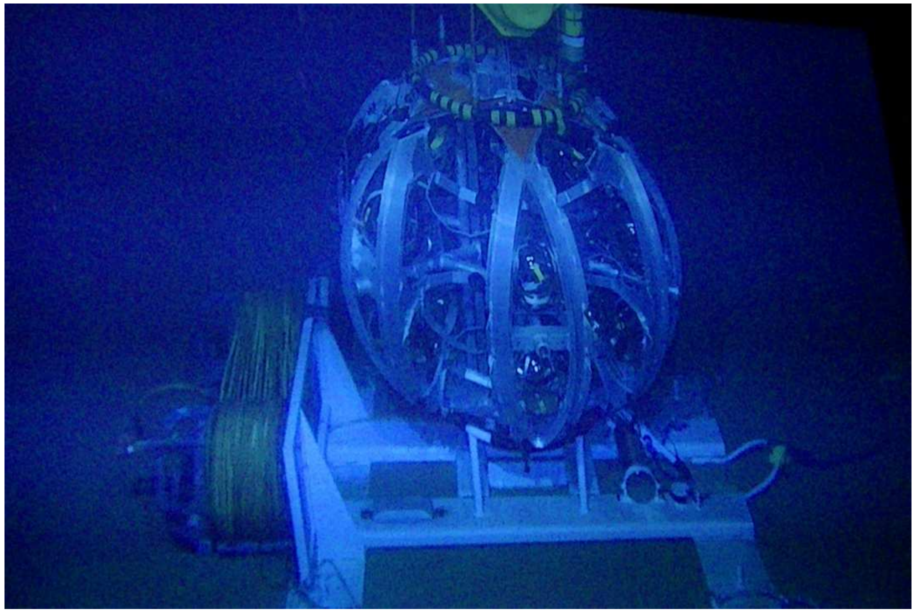
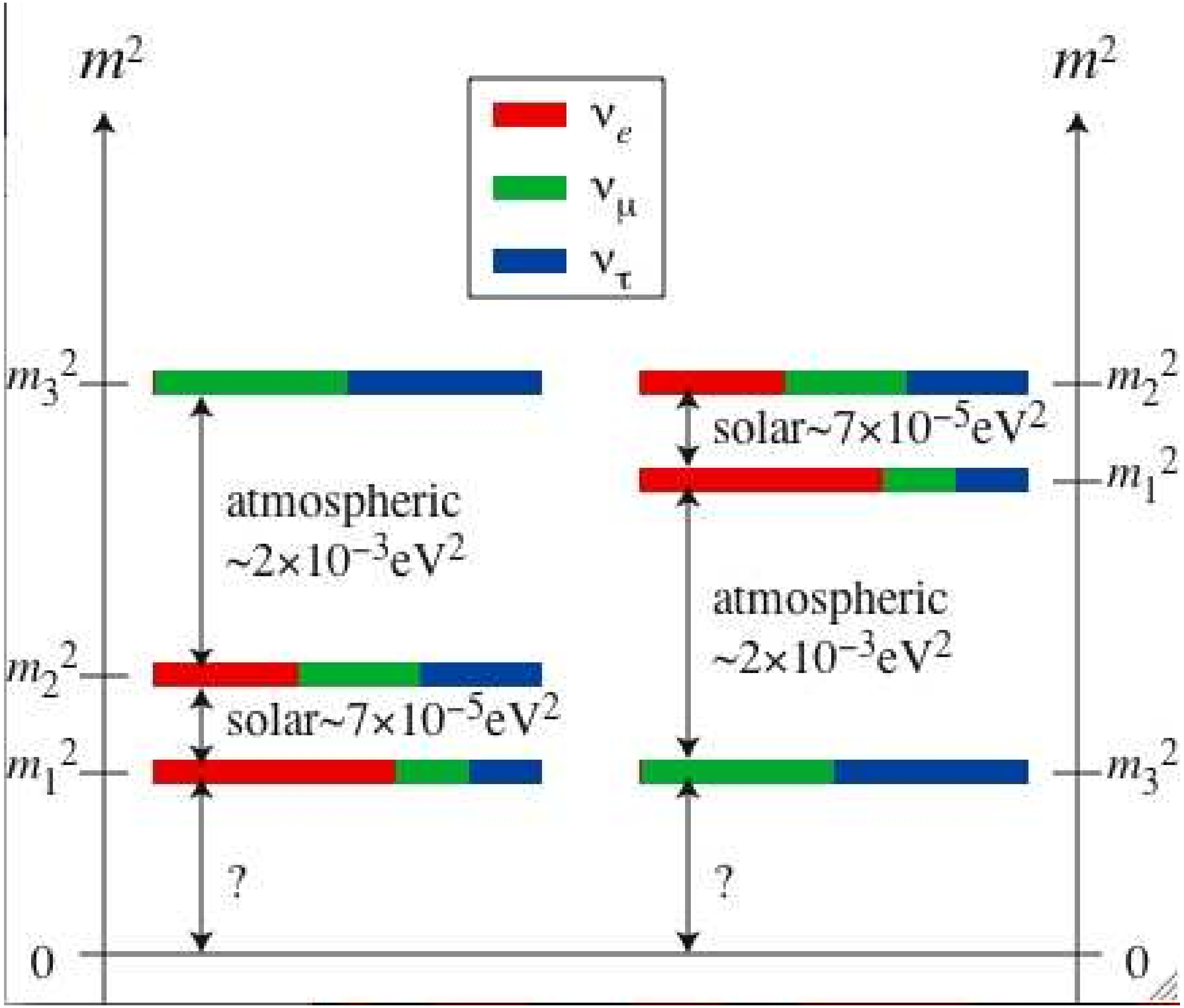


The neutrino mass hierarchy



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

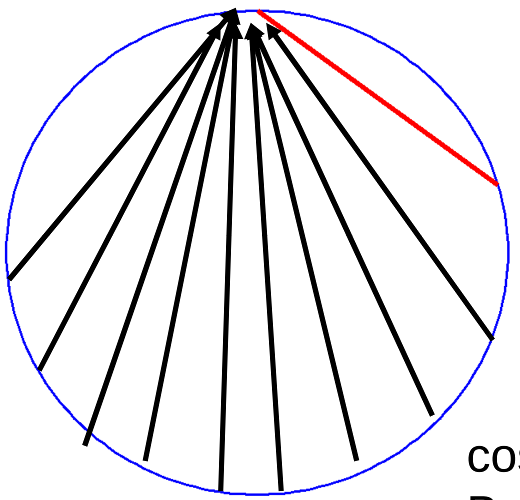
  which depend on the mass hierarchy and is opposite for neutrino/anti-neutrino

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

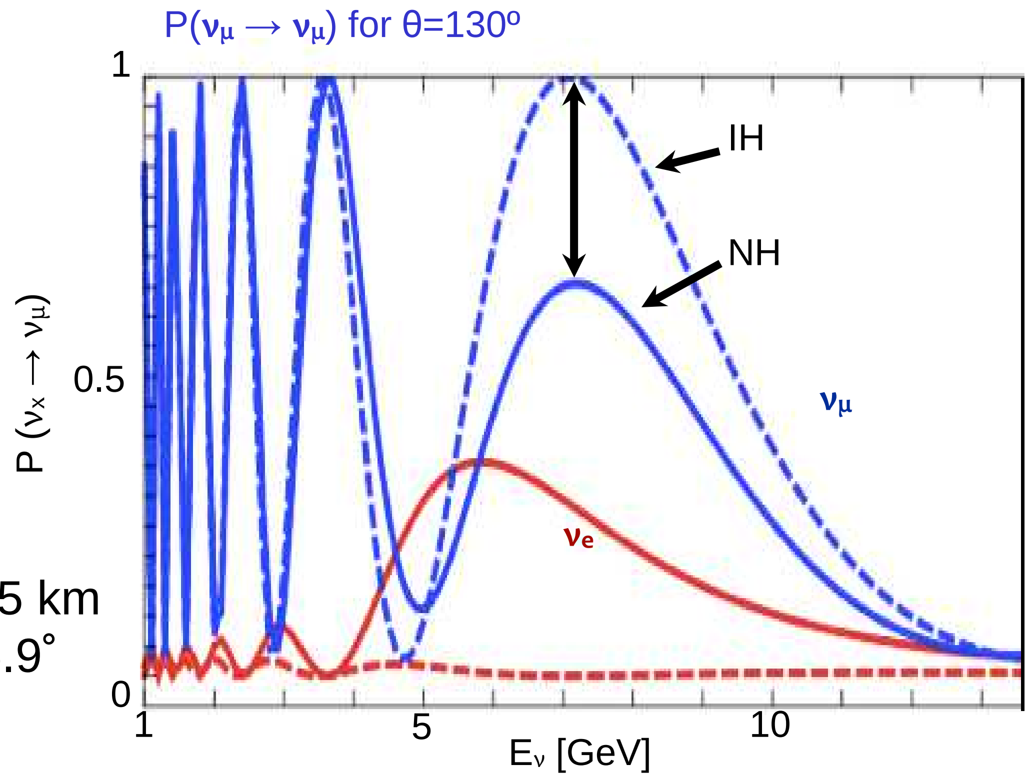
- See for example….Phys. Rev. D 78, 093003
- Revisited with improved knowledge of θ_{13}

  arxiv:1205.7071v4 ,Akhmedov, Razzaque, Smirnov

Mass Hierarchy Measurement with Atmospheric Neutrinos



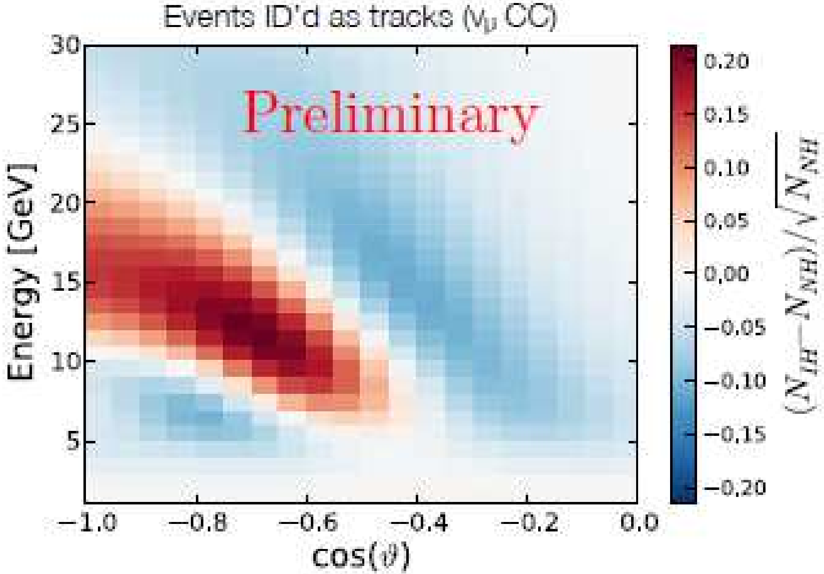
cosθ = 0.6
Baseline = 7645 km
Inclination = 36.9°



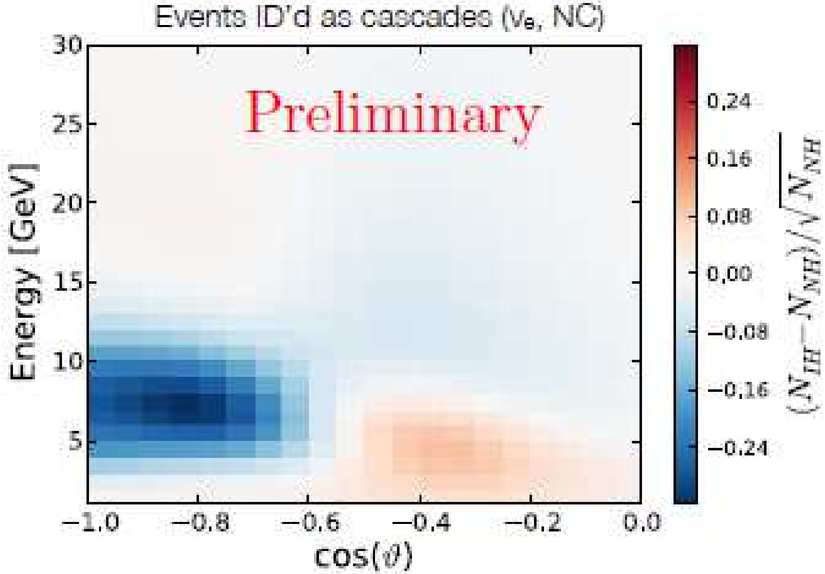
Sensitivity Calculation – atmospheric ν_μ

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

track



Cascade



Distinctive (and quite) different hierarchy dependent signatures are visible in both the track and cascade channels

Full MC detector efficiency, reconstruction and particle id included

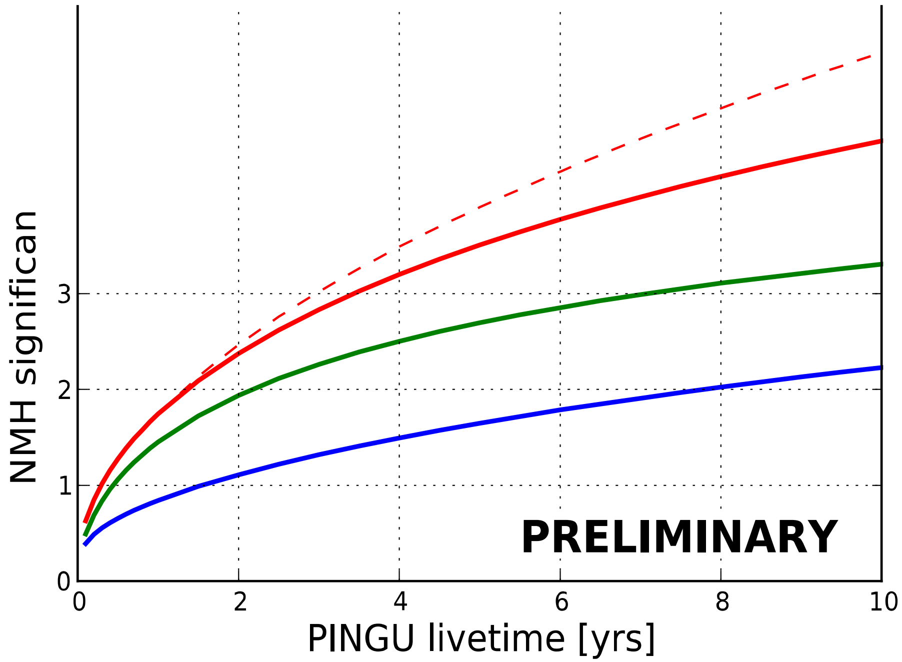
Mass Hierarchy Sensitivities

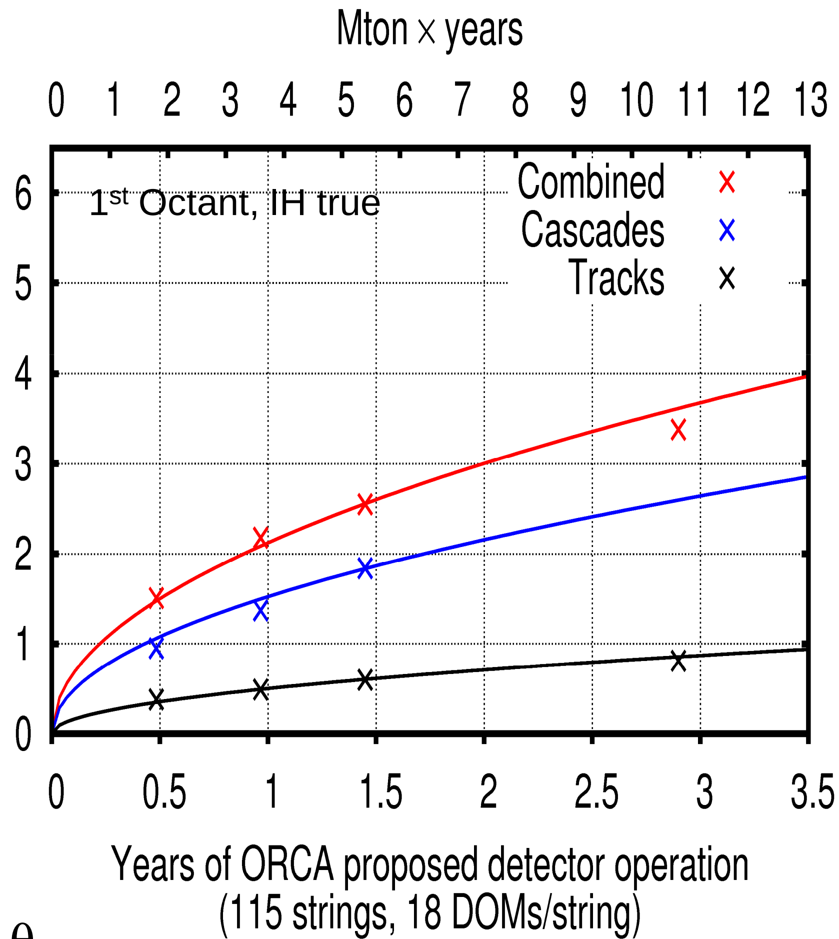
PRECISION ICECUBE NEXT GENERATION UPGRADE

KM3NeT Collaboration

PINGU sensitivity (40 strings, 60 OM/string, 5m/25m)

ORCA sensitivity (115 strings, 18 OM/string, 6m/20m)



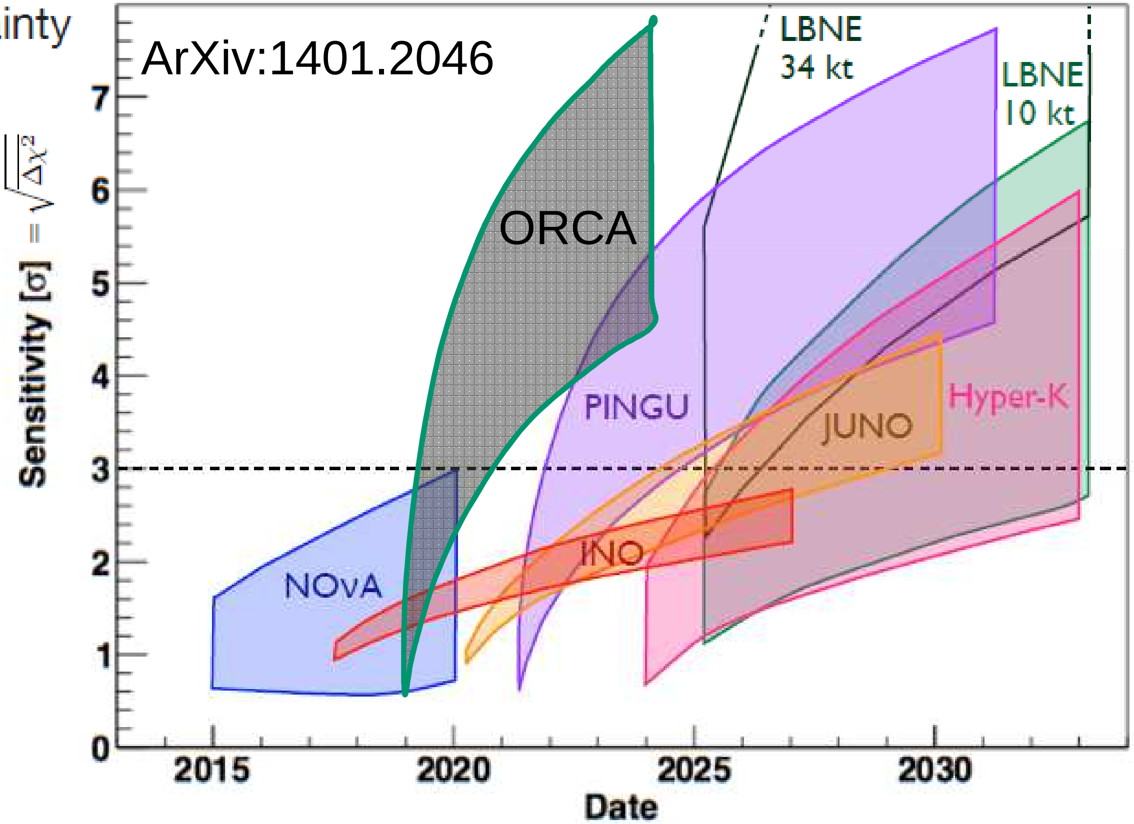


+ Factor ~4 improvement on value of θ_{23}
+ Measurement of octant

Sensitivity to mass hierarchy

- Several current or planned experiments will have sensitivity to the neutrino mass hierarchy in the next 10-15 years
  - NB: *median* outcomes shown – large fluctuations possible
- Widths indicate main uncertainty
  - LBNE/NOvA: δ_{CP}
  - JUNO: σ_E (3.0-3.5%)
  - PINGU/INO: θ_{23} (38.7°–51.3°, 40°–50°)
  - Other projections presented here assume worst-case parameters (1st octant)
- PINGU timeline based on aggressive but feasible schedule; LBNE from LBNE-doc-8087-v10, all others from Blennow

after Blennow et al., arXiv:1311.1822



Slide taken from Ty DeYoung, Arlington Meeting April 24, 2014

Summary

Exciting times for neutrino telescopes!...

IceCube and ANTARES searching hard for the ‘smoking gun’ site(s) of cosmic ray production

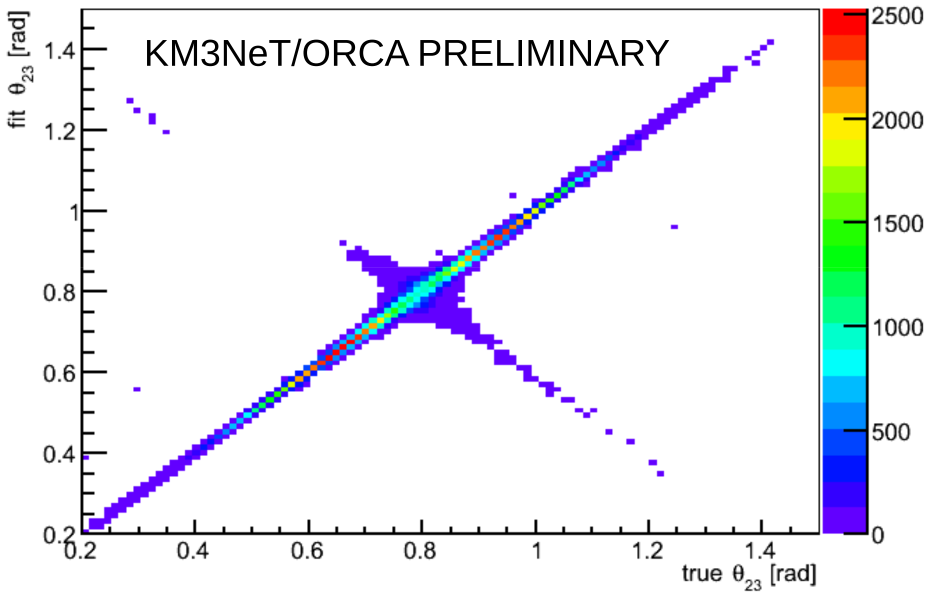
IceCube first measurement of (diffuse) flux of high energy cosmic neutrinos

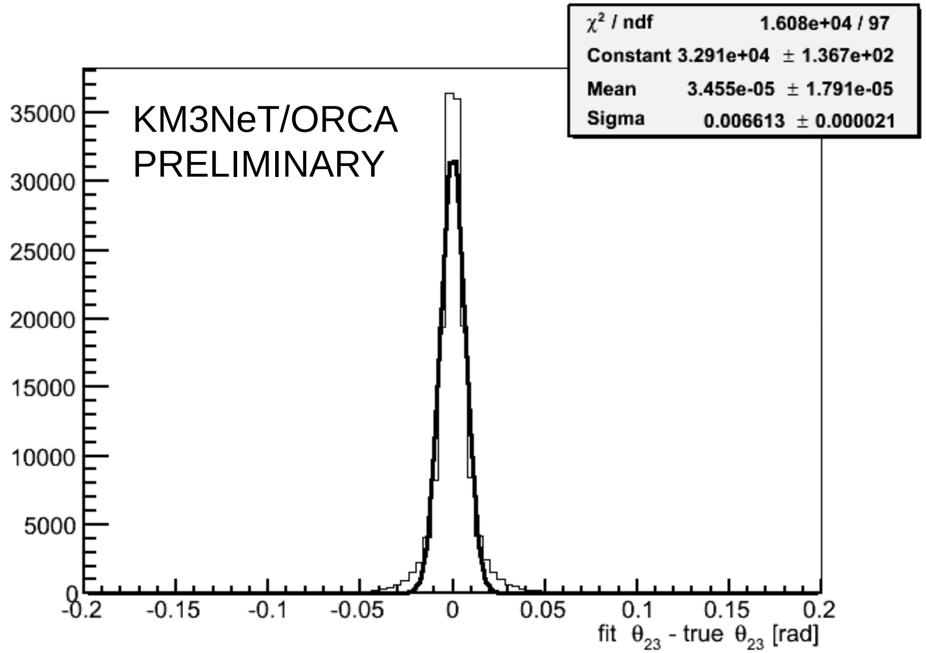
Good progress for proposed extension of infrastructures for high energies (KM3NeT, DecaCube)

Mass hierarchy measurement with dense arrays (PINGU, ORCA) very promising

BACKUP SLIDES

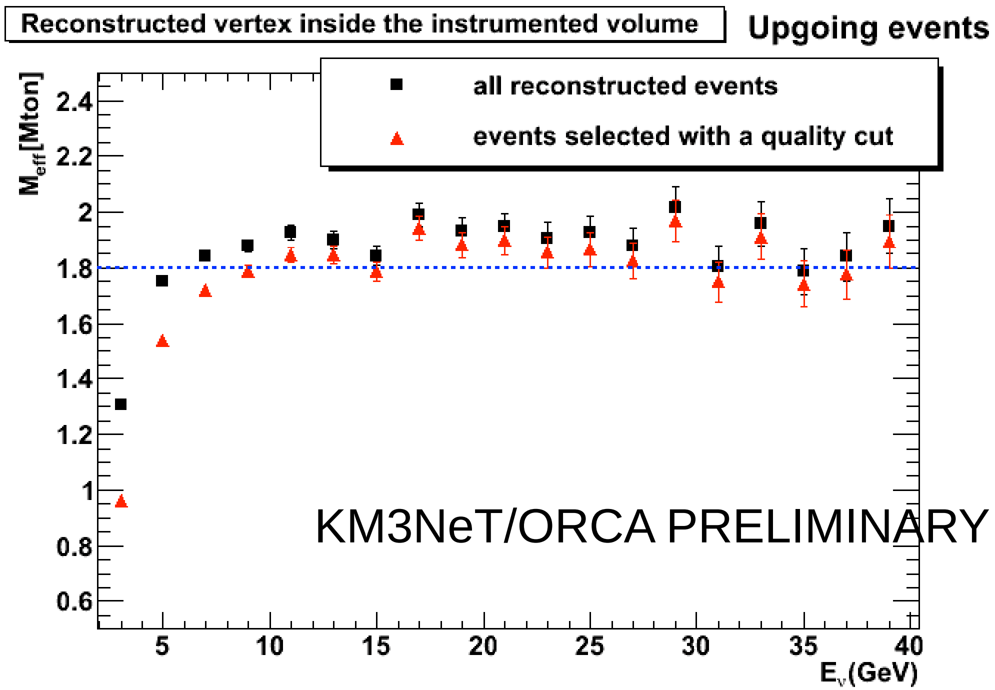
Sensitivity to θ_{23}





Expected error on θ_{23} after 3 years of running the proposed detector can be reduced to 6.6 mrad (currently around 28 mrad)

Performances in muon channel (I)

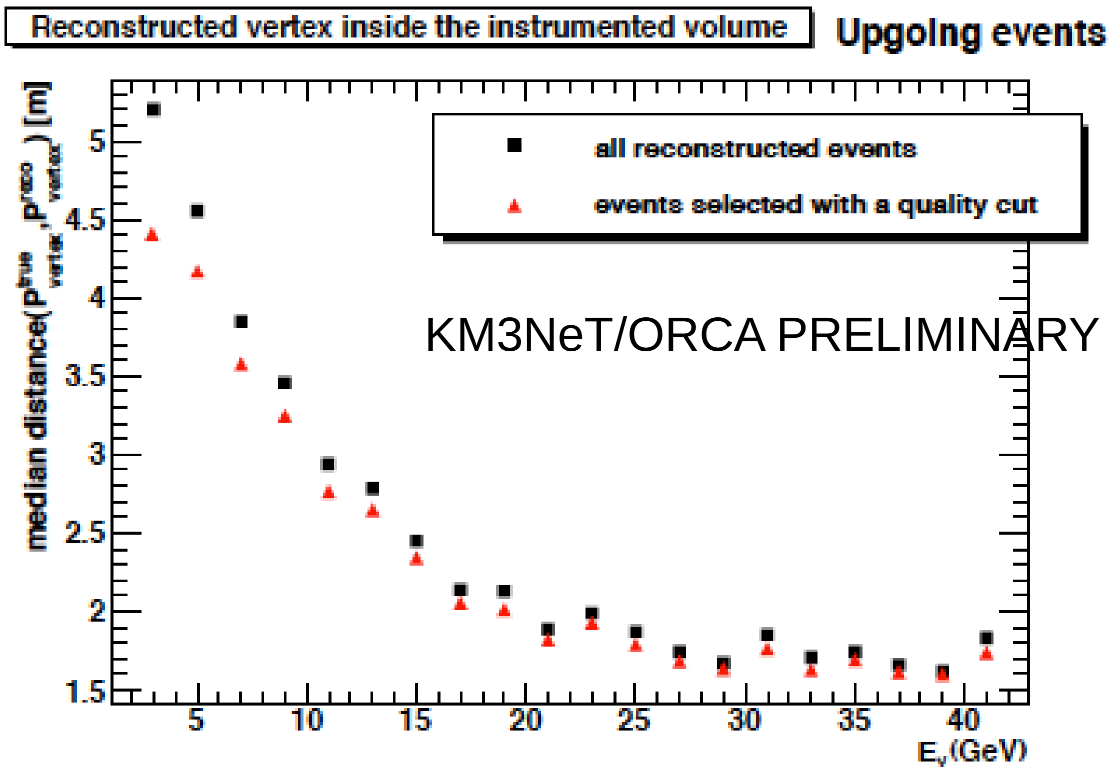


Events are asked to have a reconstructed vertex inside the detector

Results obtained with the “reference detector”

Performances in muon channel (II)

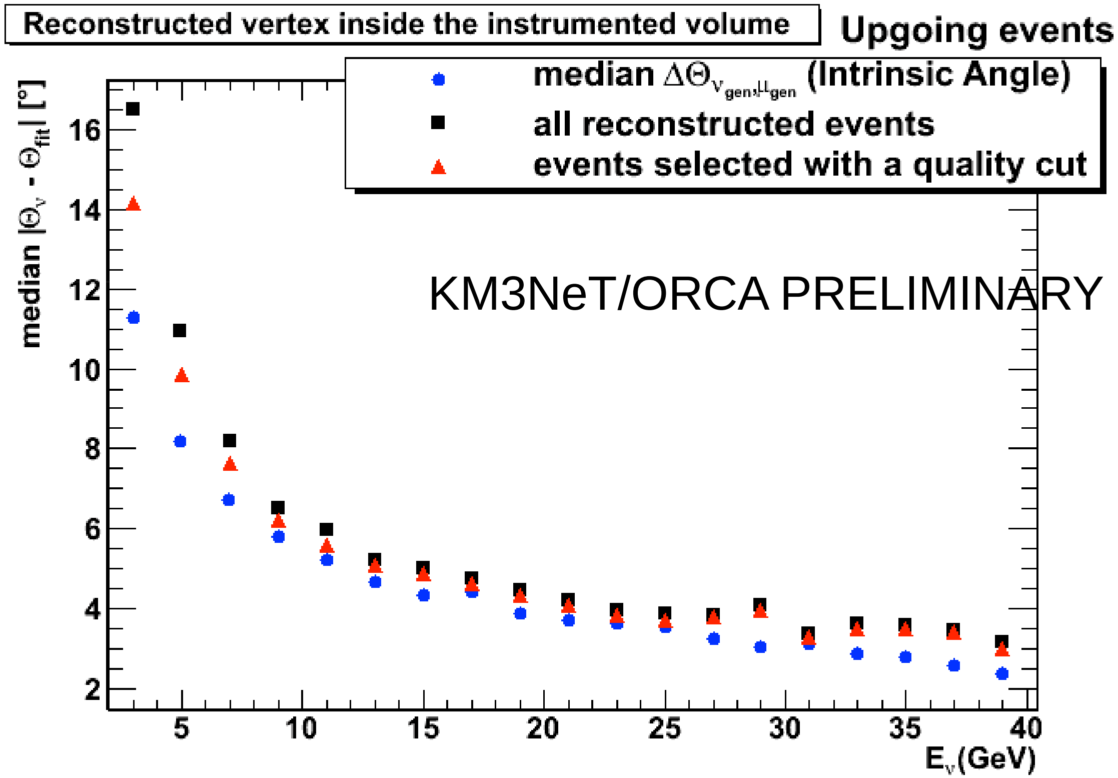
Position of reconstructed vertex



Results obtained with the “reference detector”

Performances in muon channel (III)

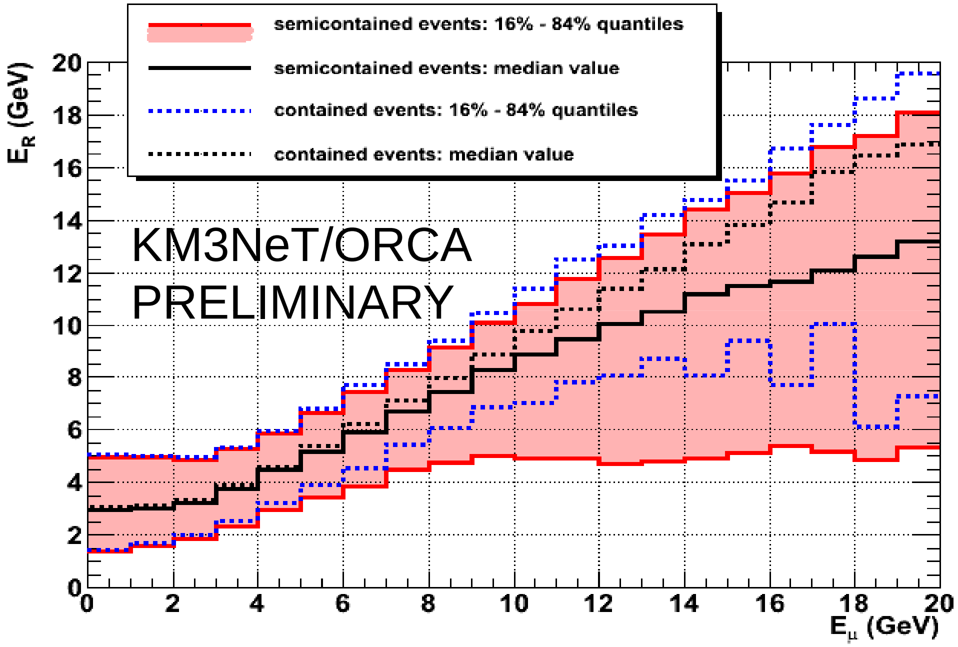
Zenith angle resolution

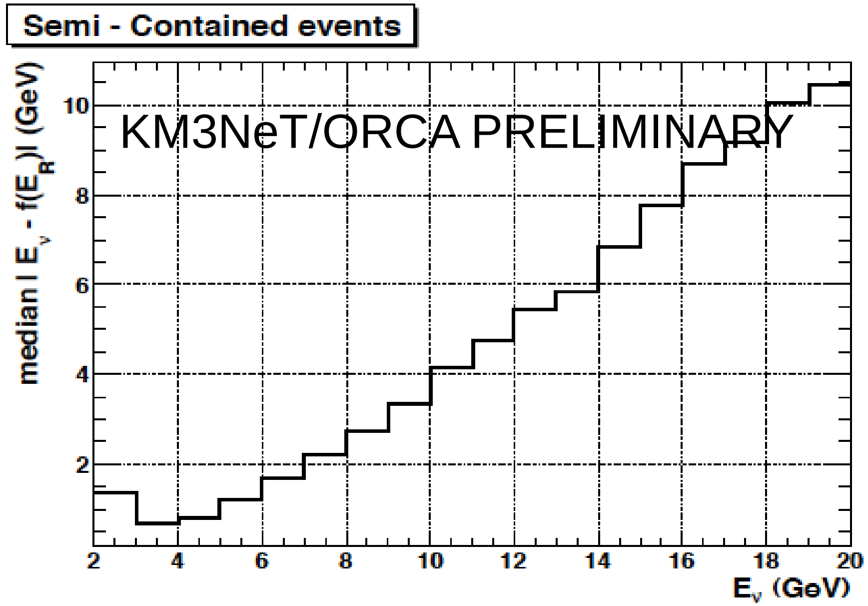


Results obtained with the “reference detector”

Performances in muon channel (IV)

Resolution in Energy

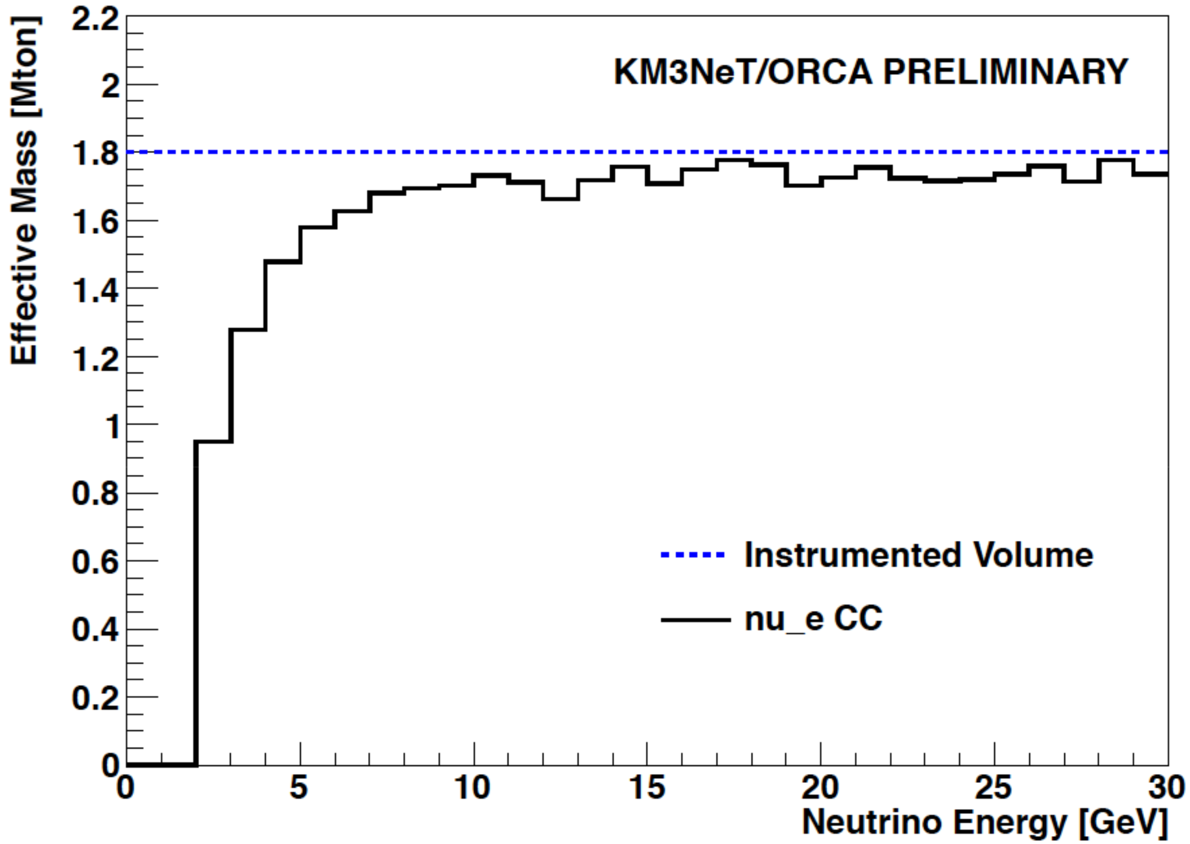




We expect to improve this in the future, using the information from the hits arising from the hadronic cascade. So far, only the muon path length is used for the energy estimate.

Results obtained with the "reference detector"

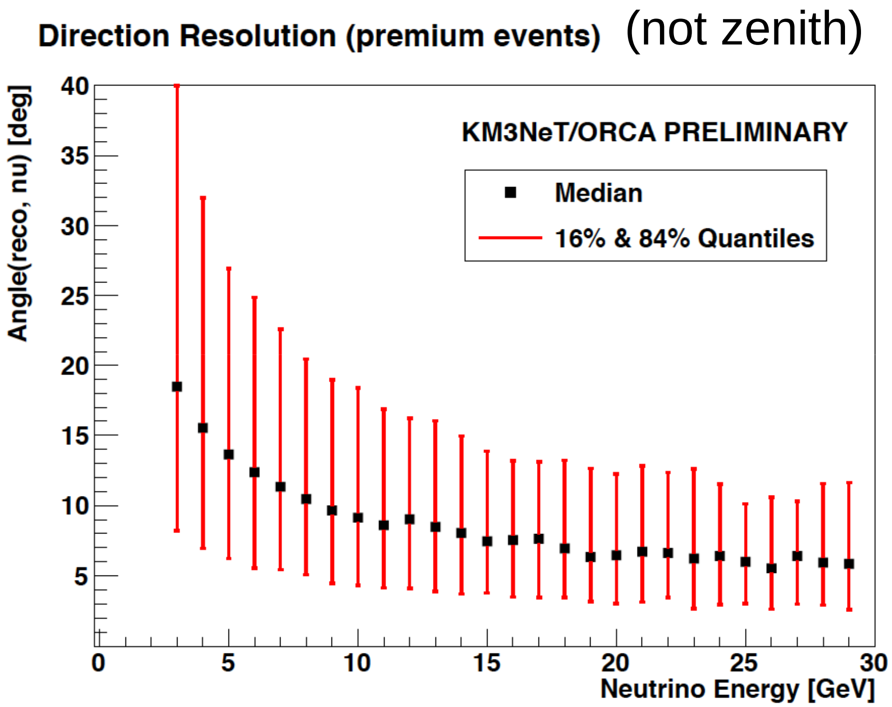
Performances in cascade channel (I)

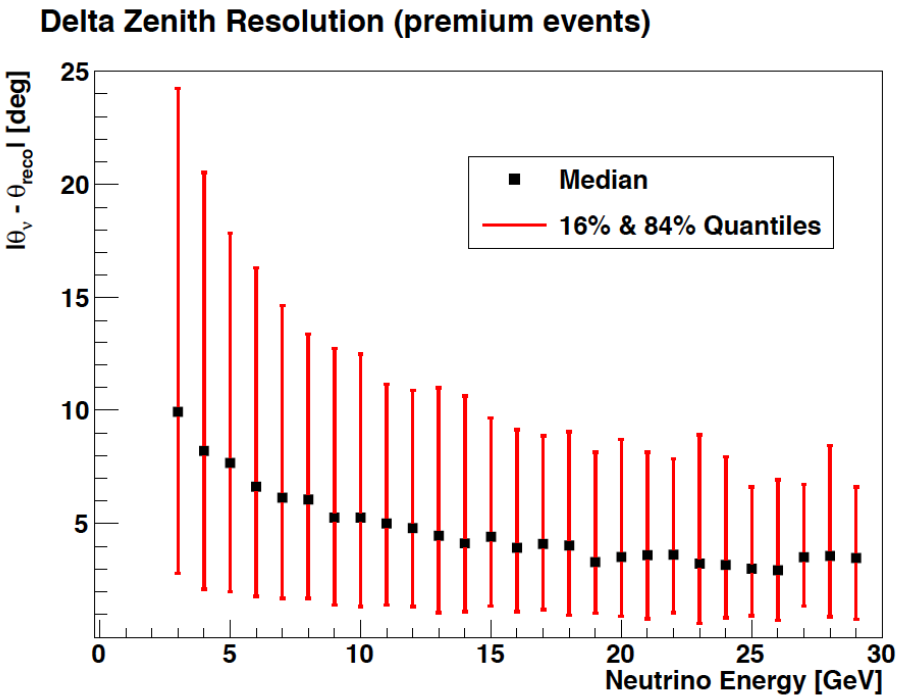


The effective volume is estimated from upgoing events with true vertex inside the instrumented volume and a 3L1 trigger requirement (L1: coincidence of >= 2PMT---hits within same OM, time window 14ns). The black line shows the effective volume and the blue dotted line shows the instrumented volume.

Results obtained with the “reference detector”

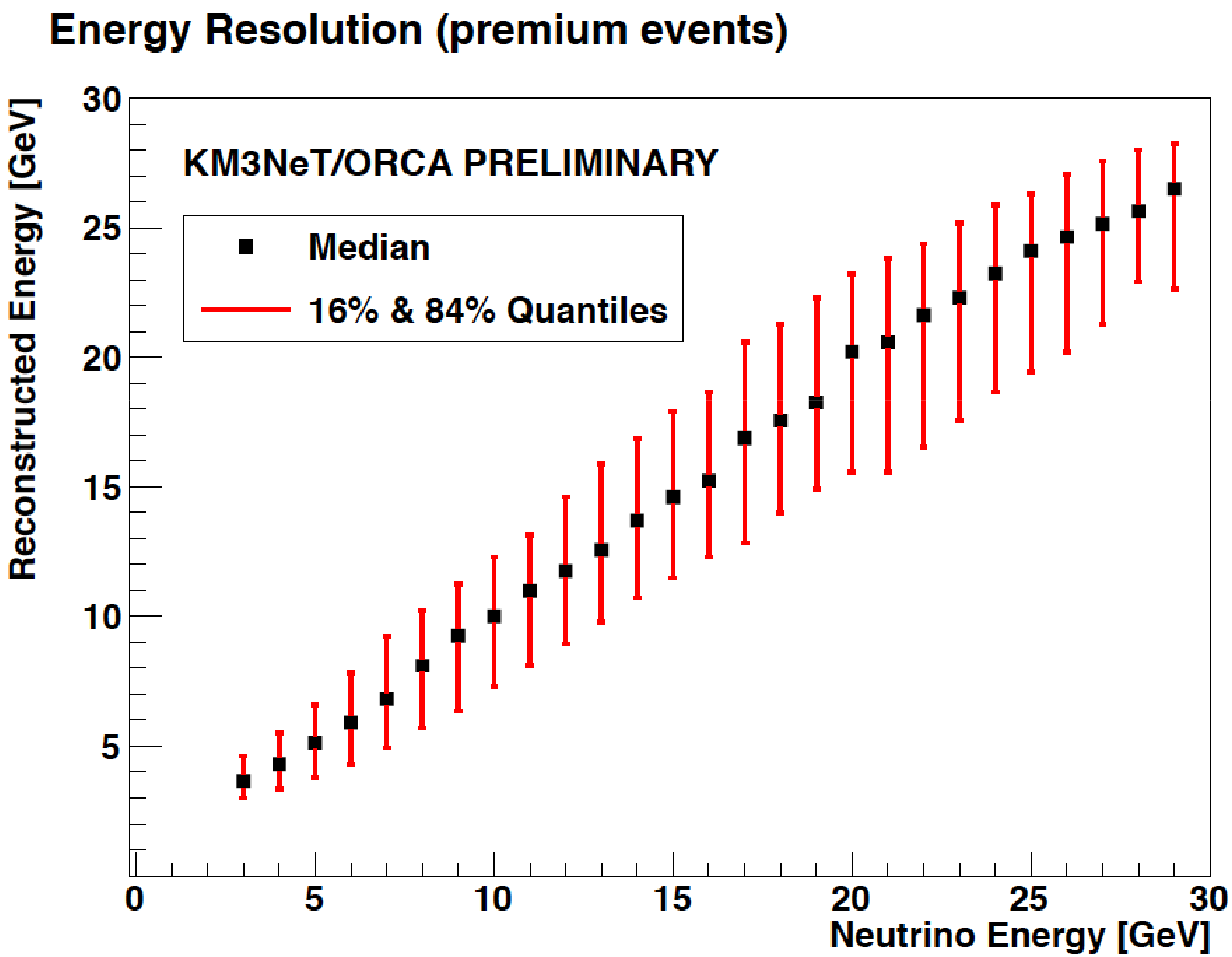
Performances in cascade channel (II)





Results obtained with the “reference detector”

Performances in cascade channel (III)

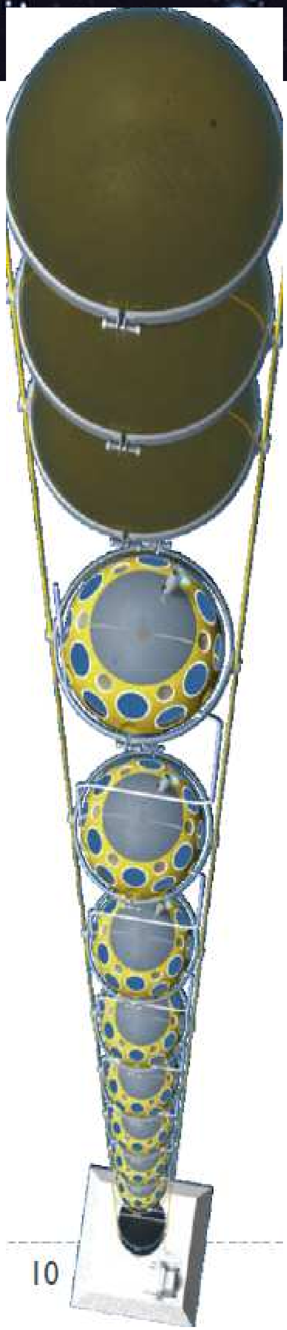


Results obtained with the “reference detector”

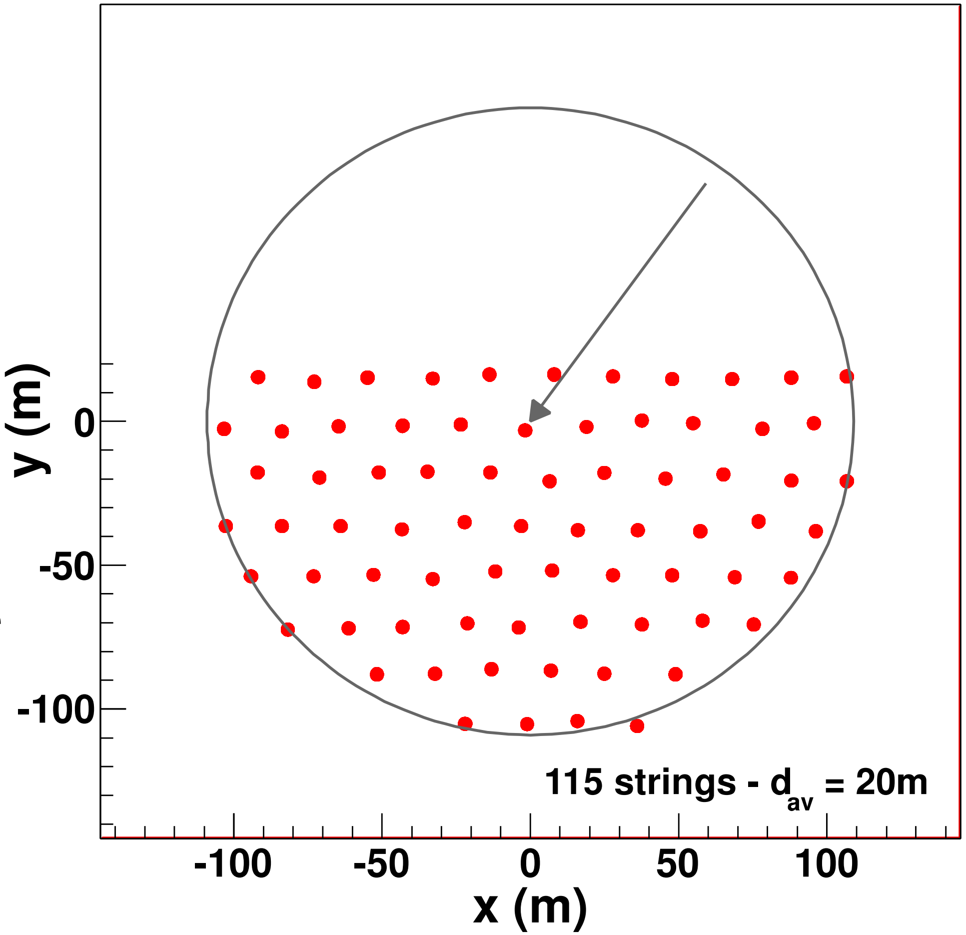
Sensitivity to the NMH

- ORCA's mass hierarchy significance is assessed by means of a likelihood ratio test. Pseudo-experiments are generated using random oscillation parameter values. They are then fitted assuming NH and assuming IH to obtain the log likelihood-ratio.
- First octant is assumed
- Includes fit of (δ, θ_{23}, Δm^2)
- The following plot is for rejection of NH (IH rejection is slightly higher)
- Includes some misidentification rate based on MC studies
- Does not include yet:
  - Overall flux uncertainty
  - NC events
  - Altered resolution for misidentified events

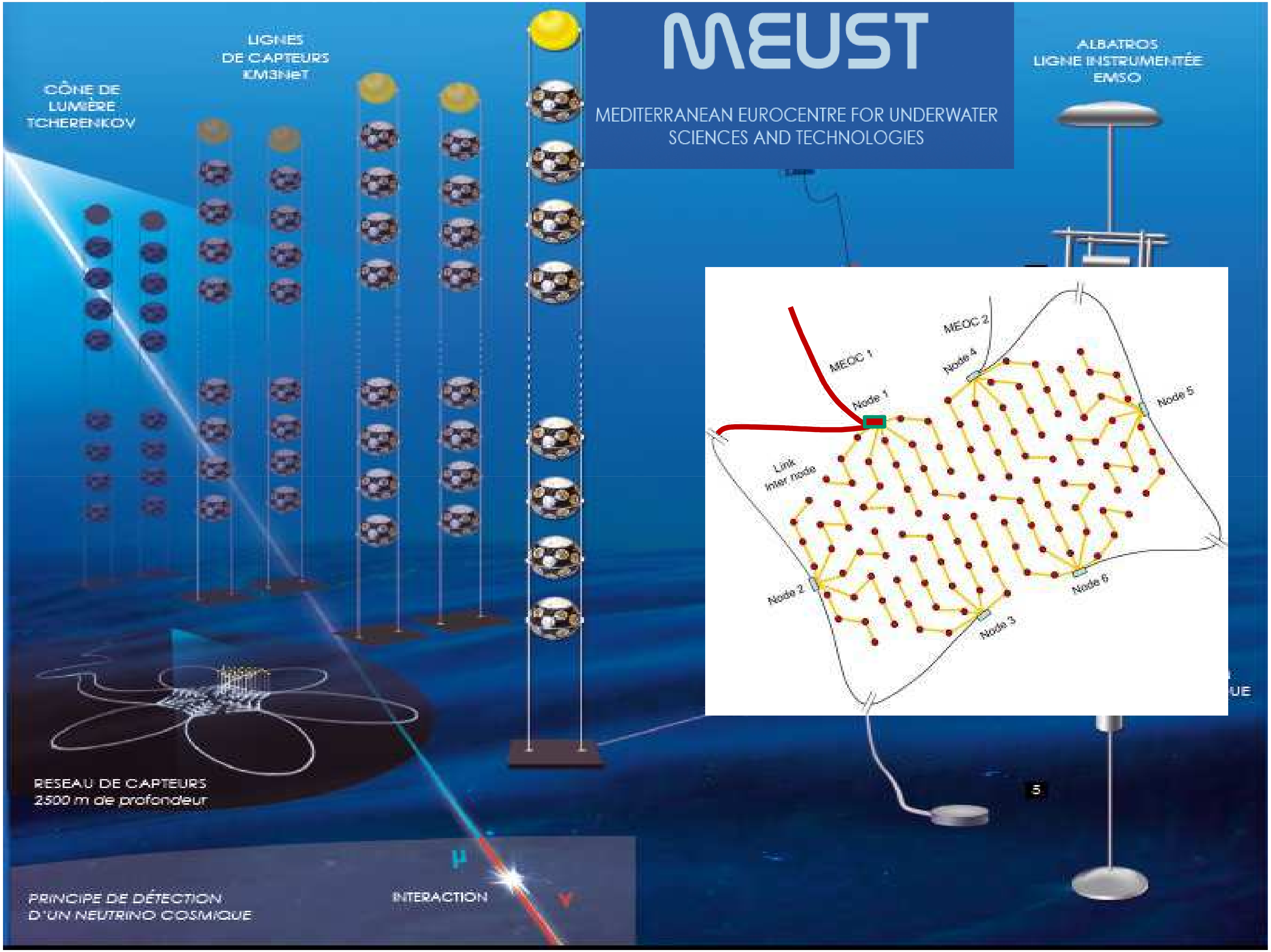
The ORCA proposed detector



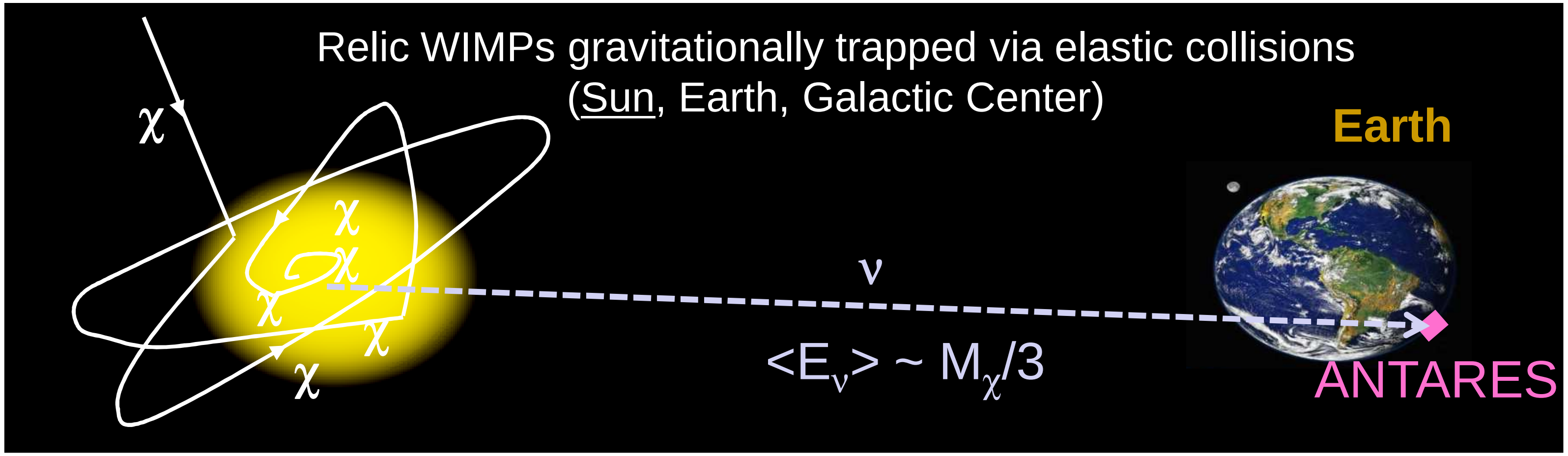
Multi-PMT DOM
31 small PMTs
Almost uniform coverage
Photon counting
Direction of photon
All electronics inside



115 strings (building block) of 18 DOMs each
Estimated cost 40M€


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
5

Indirect search for Dark Matter



- HE neutrinos from the Sun → Clean DM signature

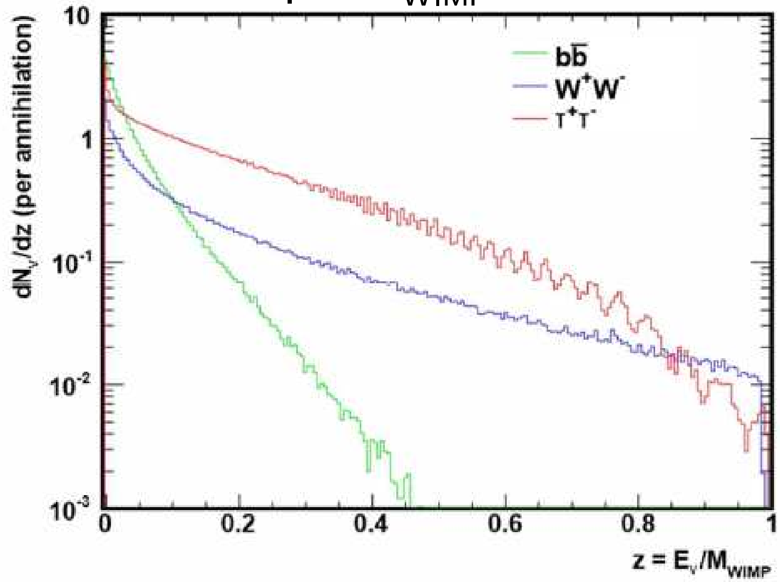
- Models where Lightest SUSY Particle (LSP) is stable (R-parity conservation) are considered
- Self-annihilation in c,b,t quarks, τ leptons or W, Z,H bosons induce HE neutrino flux
  - → b quarks (soft spectrum)
  - → τ leptons
  - → W bosons (hard spectrum)

  } benchmarks

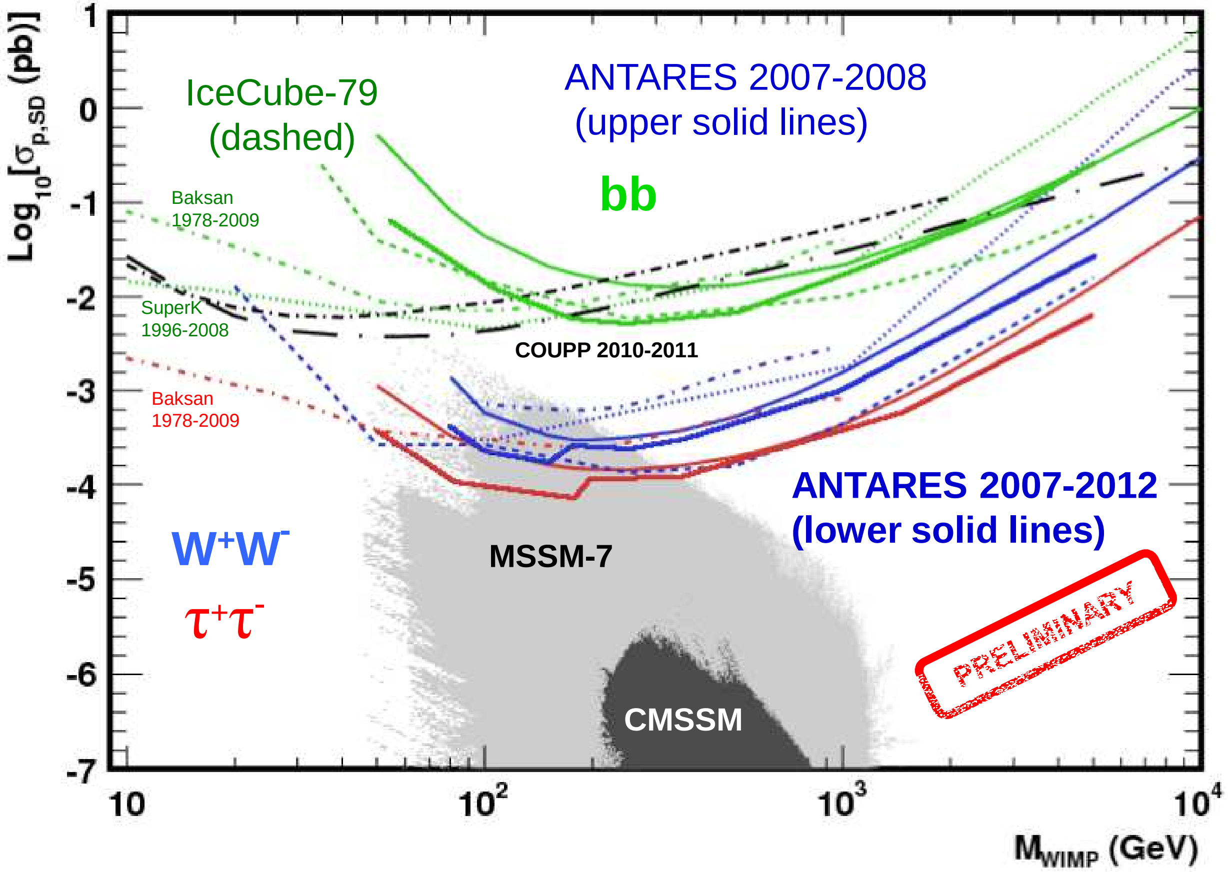
- Model-independent simulation using WIMPSIM

- 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

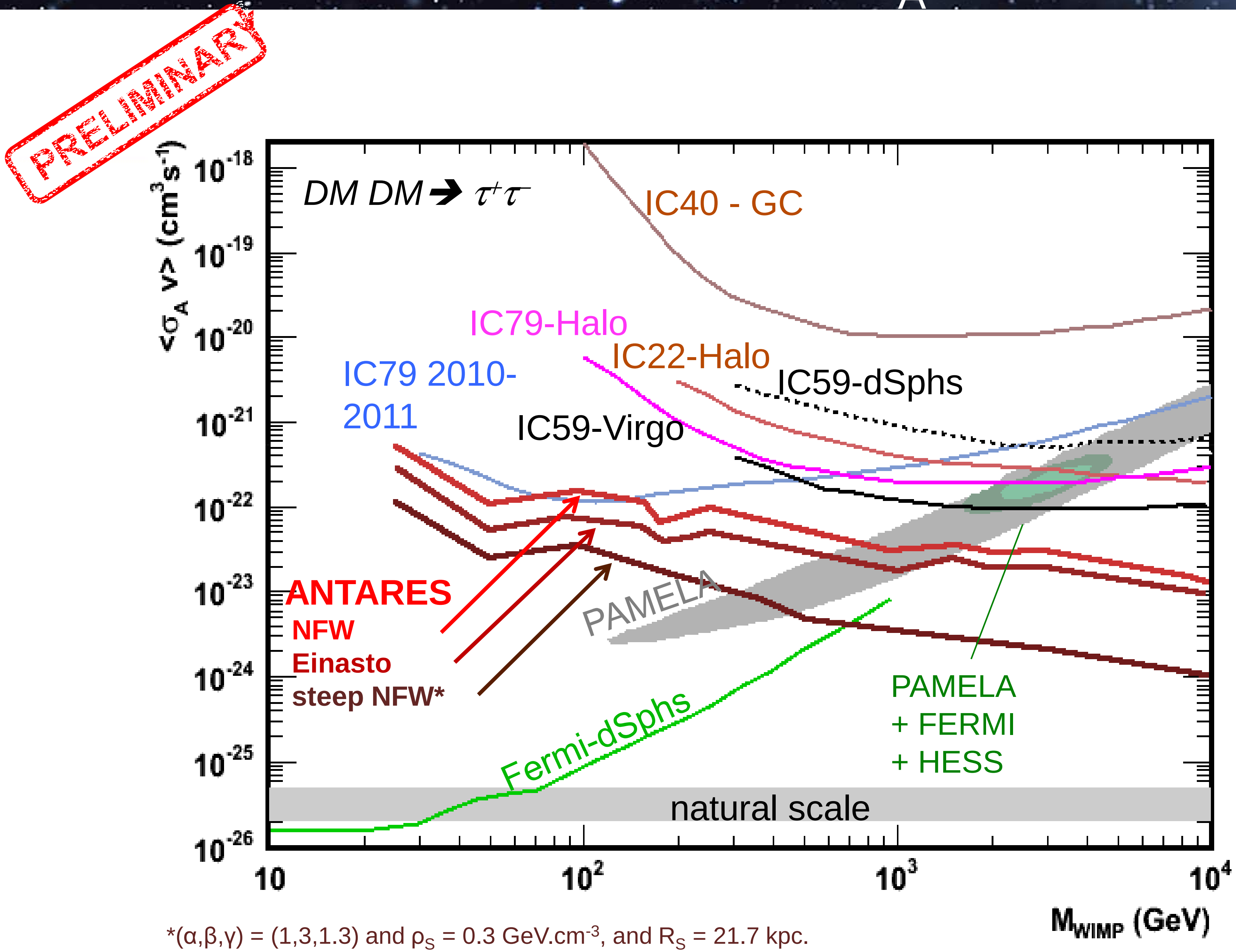
Much better sensitivity of ν-telescopes on SD cross-section w.r.t. direct detection (due to capture on H in the Sun).

First ANTARES results published in JCAP11 (2013) 032

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

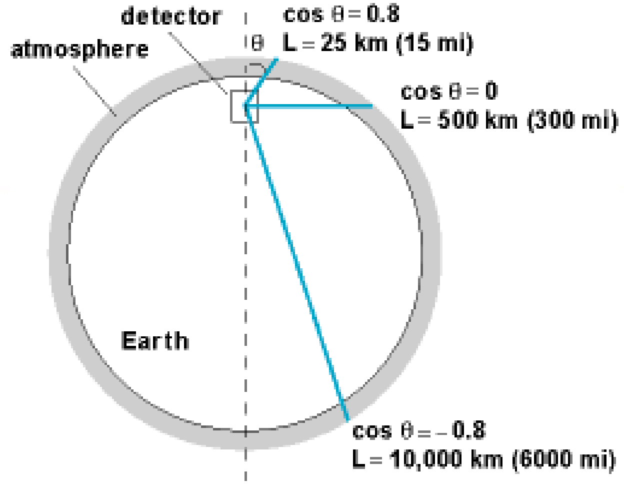
There is still room for improvement in ANTARES: better reconstruction at low energies, binned method, more data “on tape”, …

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.

Neutrino Oscillations



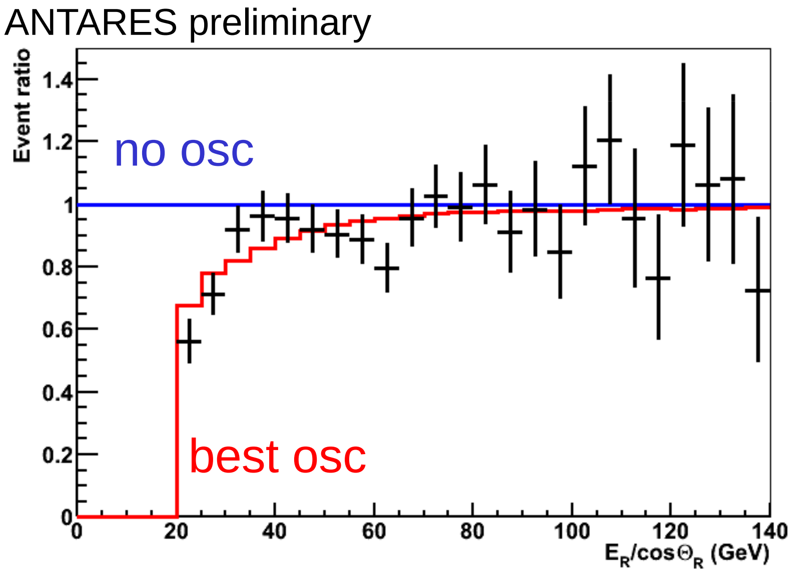
2008-2010 data (863 days):

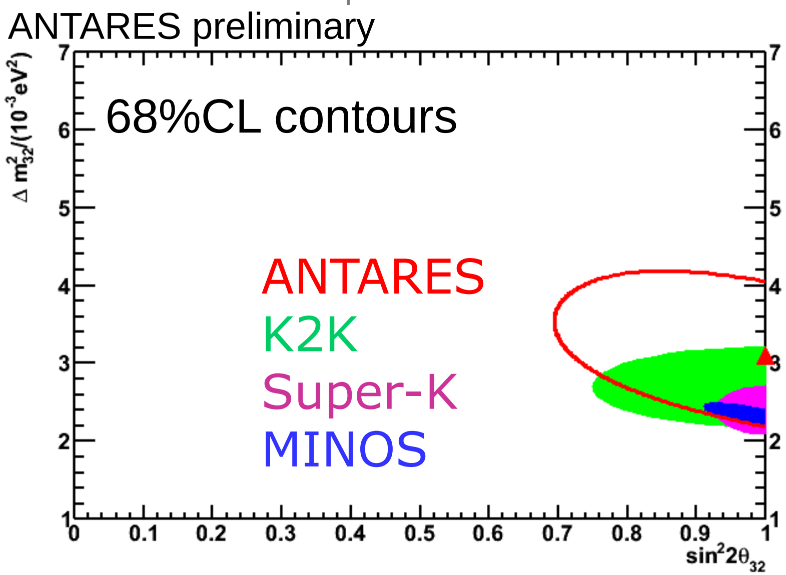
No oscillation: $\chi^2/NDF = 40/24$ (2.1%)

Best fit: $\chi^2/NDF = 17.1/21$

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

$\sin^2 2\theta = 1.00$





Assuming maximal mixing: $\Delta m^2 = (3.1 \pm 0.9)\ 10^{-3}\ eV^2$

PLB: arXiv:1206.0645

Atmospheric Oscillations – 2nd Generation

- Expected contours from current analysis are becoming competitive with world's leading measurements
  - Data to be "unblinded" before Neutrino 2014
  - Here: injecting maximal mixing to illustrate sensitivity
- 3rd generation of event selections and reconstructions in the pipeline – we will soon do even better!