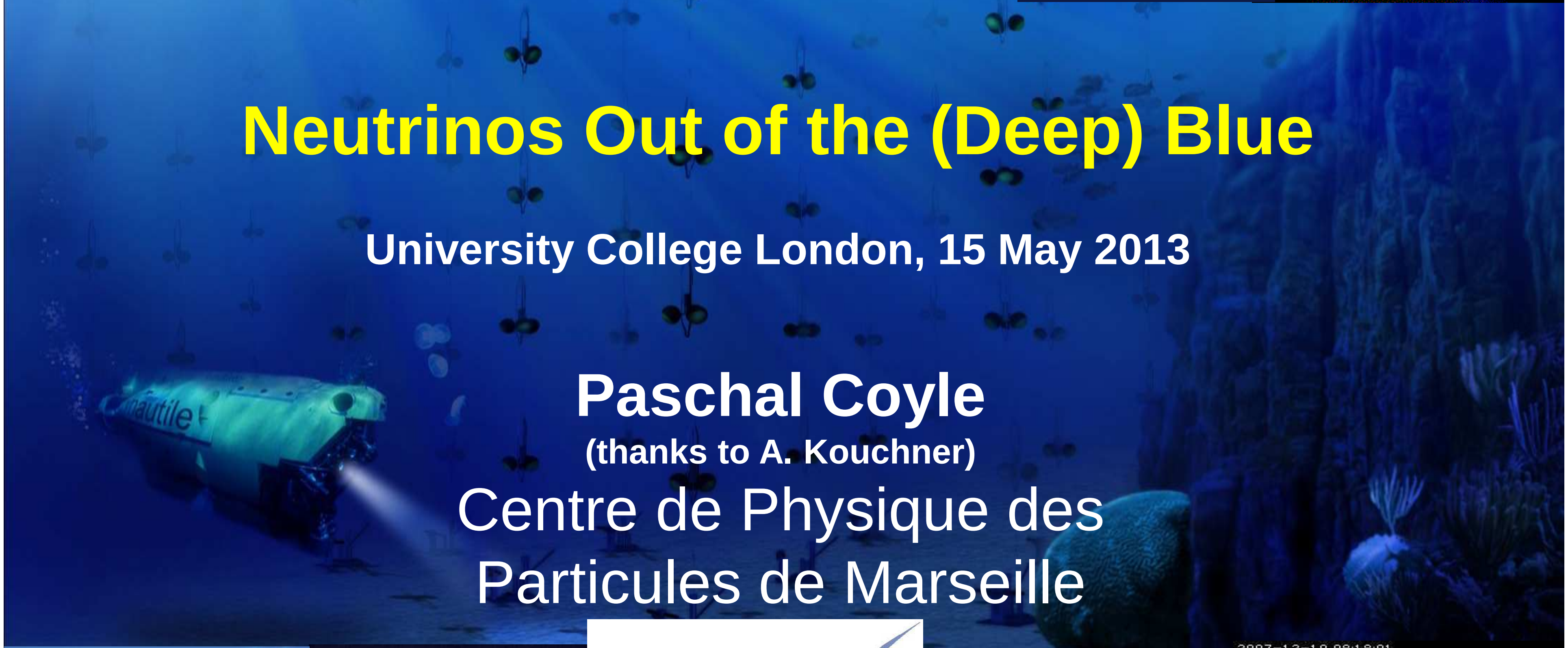


Neutrinos Out of the (Deep) Blue

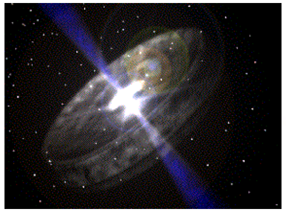
University College London, 15 May 2013

Paschal Coyle

(thanks to A. Kouchner)

Centre de Physique des
Particules de Marseille

Outline

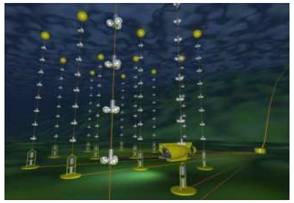


Neutrino astronomy

Historical aspects

Scientific motivations

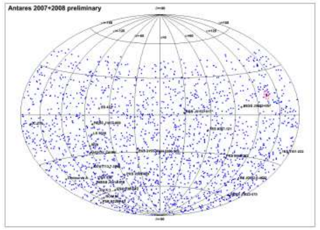
Cosmic neutrino sources



Neutrino telescope

Detection principles

Current telescopes



Selected results

Diffuse Flux

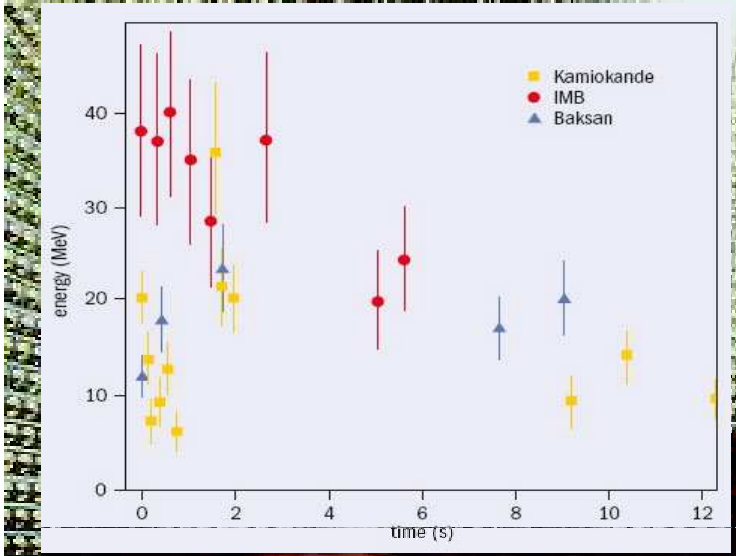
Search for point sources

Dark matter searches

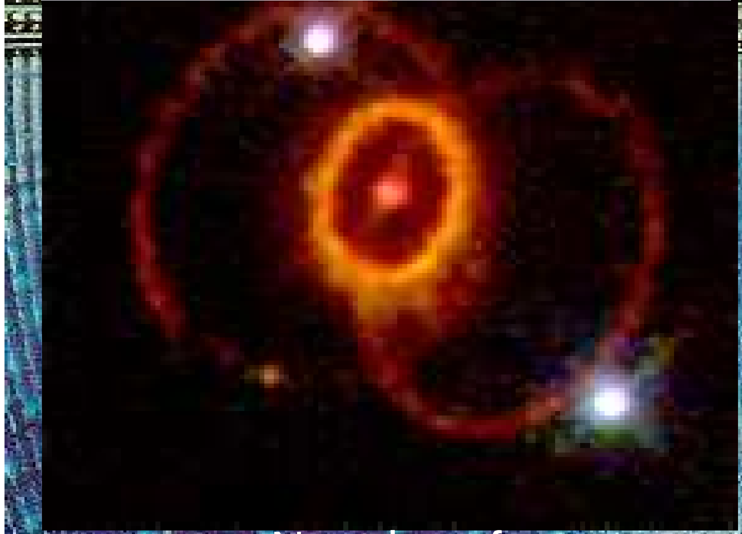
KM3NeT

ORCA/PINGU

First extraterrestrial neutrinos

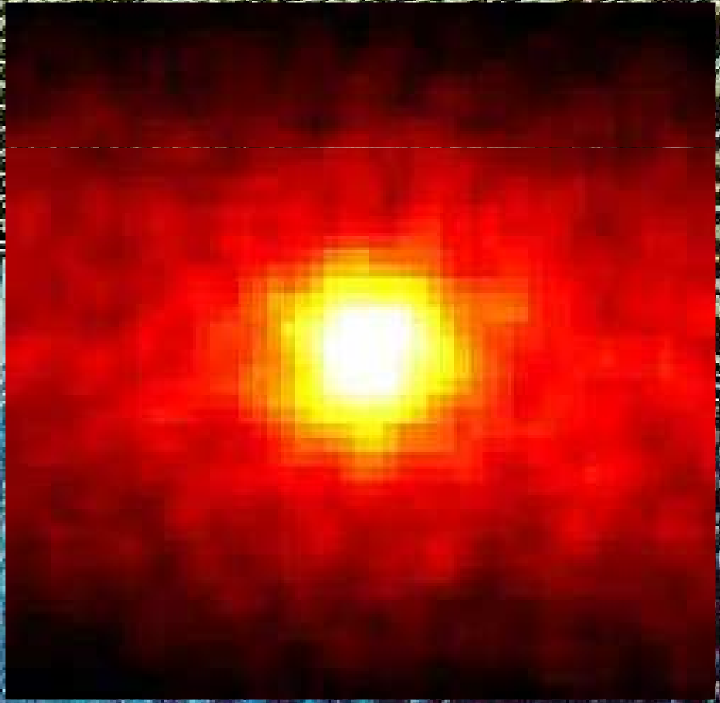


Kamiokande then SuperKamiokande



Neutrinos from
SN1987A
25 events in 12 s

~MeV



The Sun seen by
SuperKamiokande

Neutrinos from space: the long quest

The Nobel Prize in Physics 2002

"for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos"

"for pioneering contributions to astrophysics, which have led to the discovery of cosmic X-ray sources"

Raymond Davis Jr.	Masatoshi Koshiba	Riccardo Giacconi
◔ 1/4 of the prize	◔ 1/4 of the prize	◑ 1/2 of the prize
USA	Japan	USA
University of Pennsylvania Philadelphia, PA, USA	University of Tokyo Tokyo, Japan	Associated Universities Inc Washington, DC, USA
b. 1914	b. 1926	b. 1931 (in Genoa, Italy)

Solar neutrinos

(MeV energies)

Davis et al. 1955 – 1978

Koshiba et al., 1987 – 1988

« These neutrino observations are so exciting and significant that I think we're about to see the birth of an entirely new branch of astronomy: neutrino astronomy.»

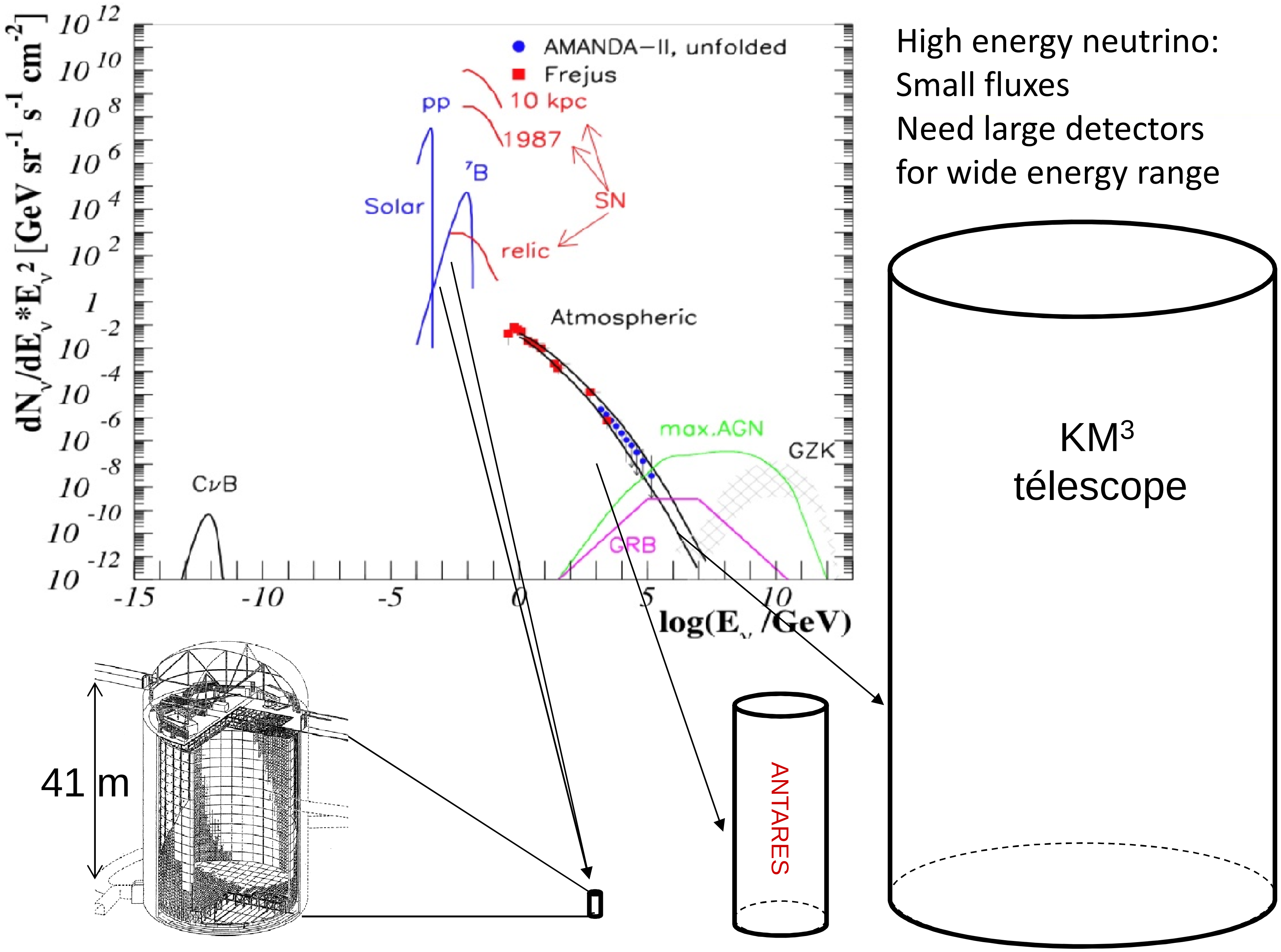
J.Bahcall
New York Times (3 Apr 1987)

Presence of cosmic neutrinos E > GeV?

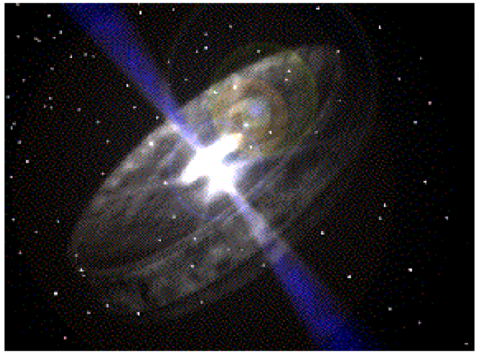
Galactic
Extragalactic

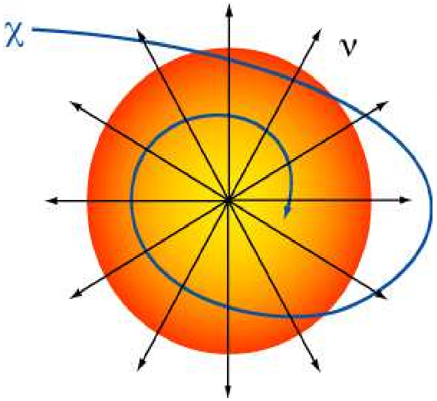
From MeV ν to PeV ν

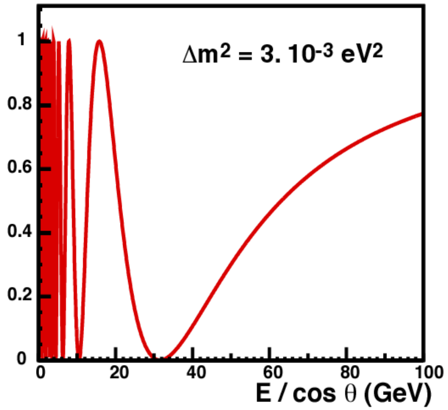
High energy neutrino:
Small fluxes
Need large detectors
for wide energy range



Neutrino telescopes: science scope







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

ν from extra-terrestrial sources

Dark matter search

ν oscillations

Origin and production mechanism of HE CR

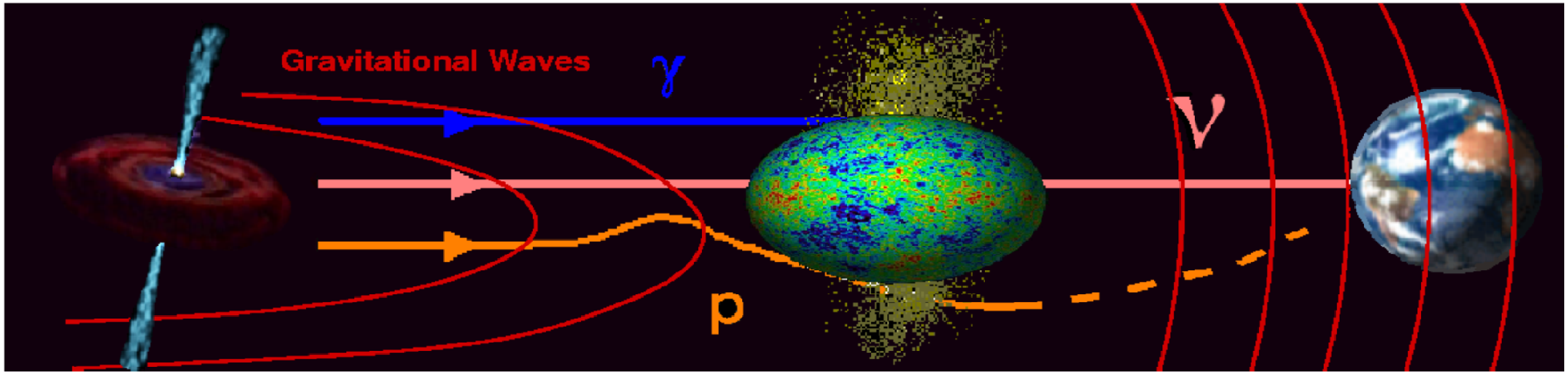
↓

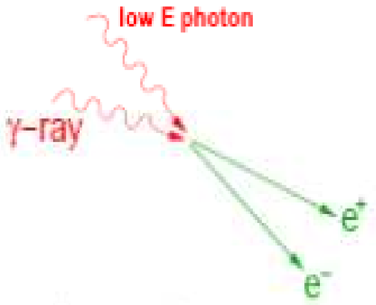
Primary goal

Exotic particle physics
Monopoles, nuclearites,…

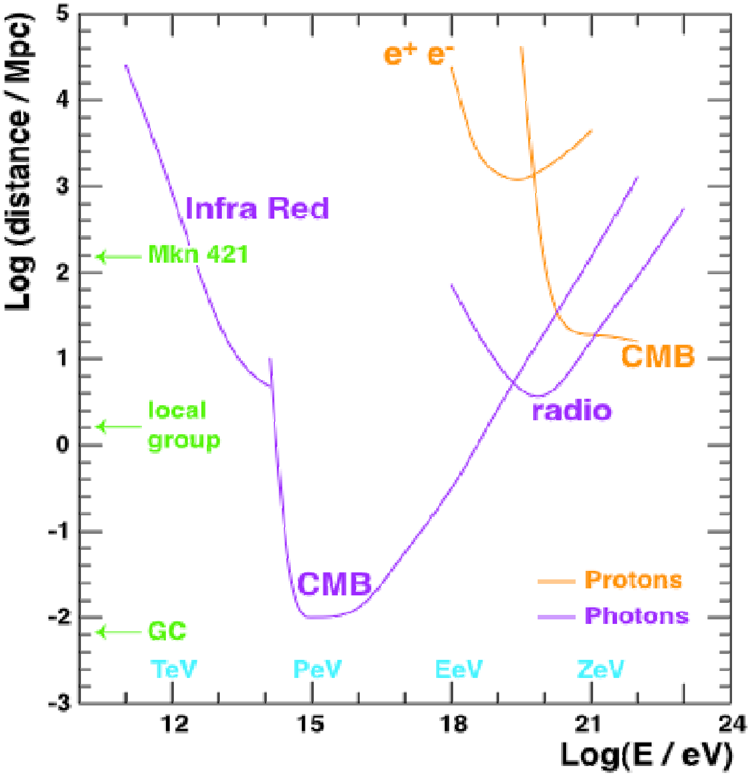
Marine sciences: oceanography, biology, geology…

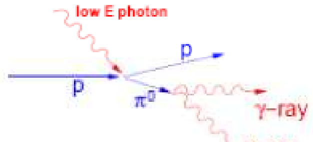
Multi-messenger astronomy



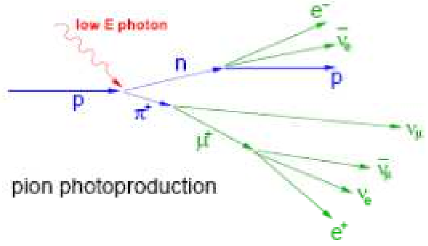


photon–photon pair production

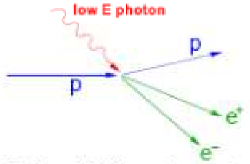




pion photoproduction



pion photoproduction



Bethe–Heitler pair production

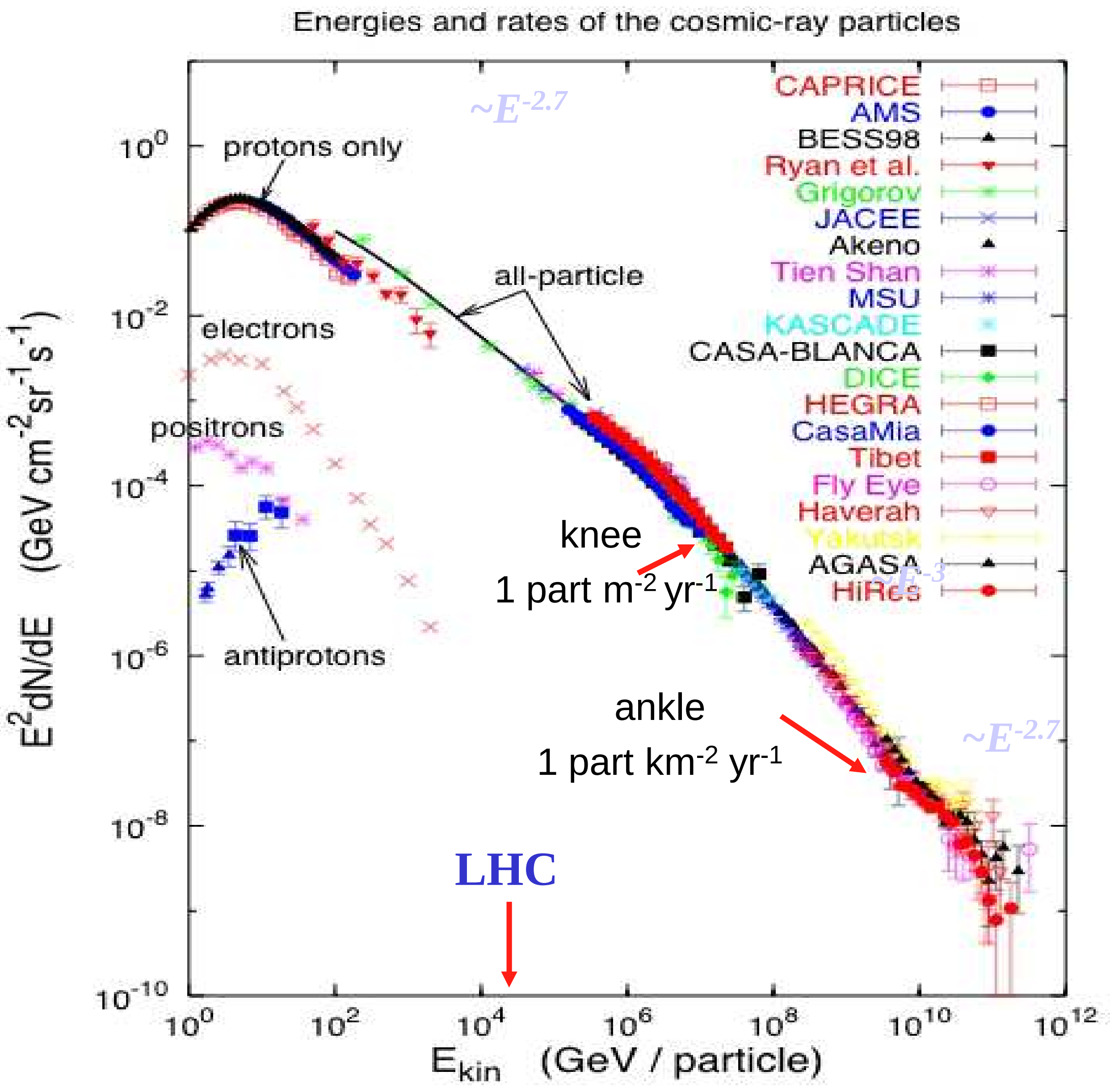
UHE cosmic rays

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

Cutoff probably confirmed
But…

where?

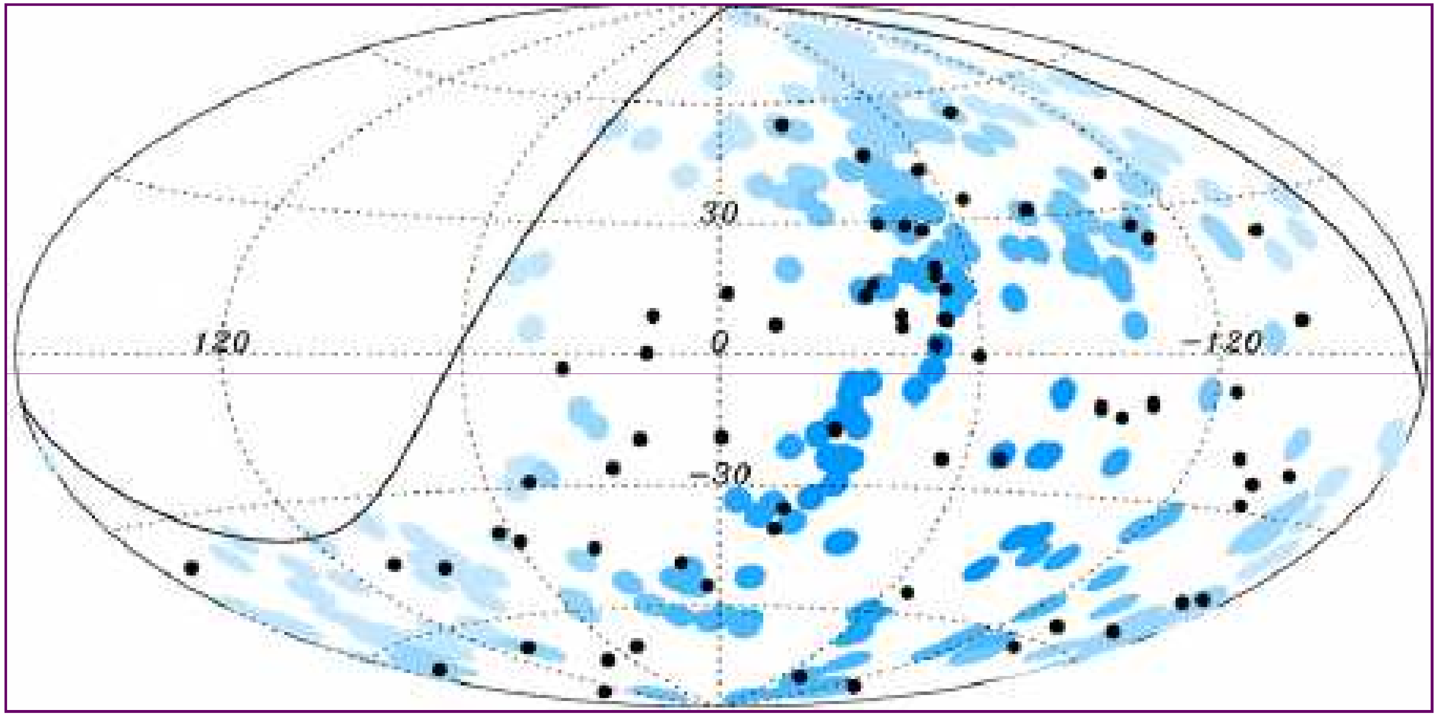
how?



Only (controversial) indications

📖 Astropart. Phys. 34 (2010)

AUGER 69 evts E>55 EeV
VCV catalogue



The correlation rate dropped
From 68% (2007) to 38% (2010)
More data are needed…

Due to
magnetic deflection
small window
for astronomy
~ 10^{20} eV

Even harder if composition
changes to heavier nuclei

Cosmic Ray Connection

- Hadronic cascades (as for atmospheric showers)

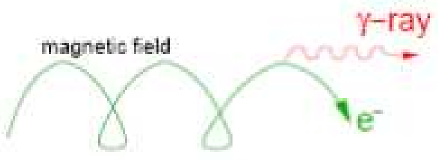
$$\begin{array}{llll} p/A + p/\gamma \rightarrow \pi^0 & +\pi^+ & +\pi^- & +N+\ldots \\ \qquad\quad\ \downarrow & \ \downarrow & \ \downarrow & \\ \qquad\quad \gamma+\gamma & \mu^+ + \nu_\mu & \mu^- + \bar{\nu}_\mu & \\ & \ \downarrow & \ \downarrow & \\ & e^+ + \nu_e + \bar{\nu}_\mu & e^- + \bar{\nu}_e + \nu_\mu & \end{array}$$

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

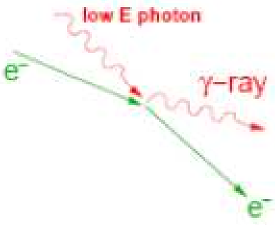
- Primary acceleration («Bottom-Up»)
  - Stochastics shocks (Fermi mechanism)
  - Explosion /Accretion / Core collapse

- But HE γ also from electromagnetic processes

Synchrotron Inverse Compton

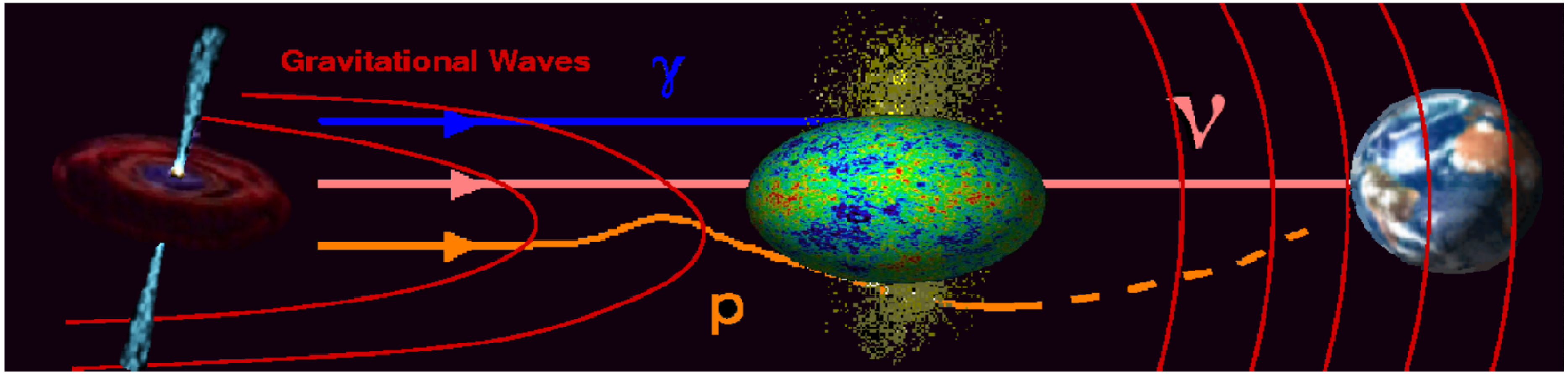


synchrotron radiation



inverse Compton scattering

Multi-messenger astronomy



Neutrino

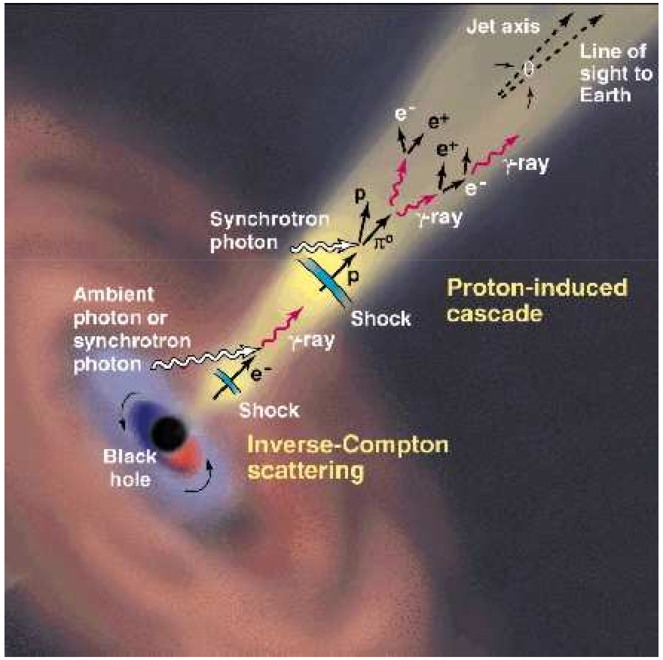
- ⇒ Correlate with optical/GW signals
- ⇒ Cosmological distances
- ⇒ Core of astrophysical bodies
- ⇒ Point sources

Potential extragalactic sources

Active Galactic Nuclei (AGN)

Steady (though flaring) sources

Observed luminosities $10^{9} - 10^{15}\ L_{\odot}$



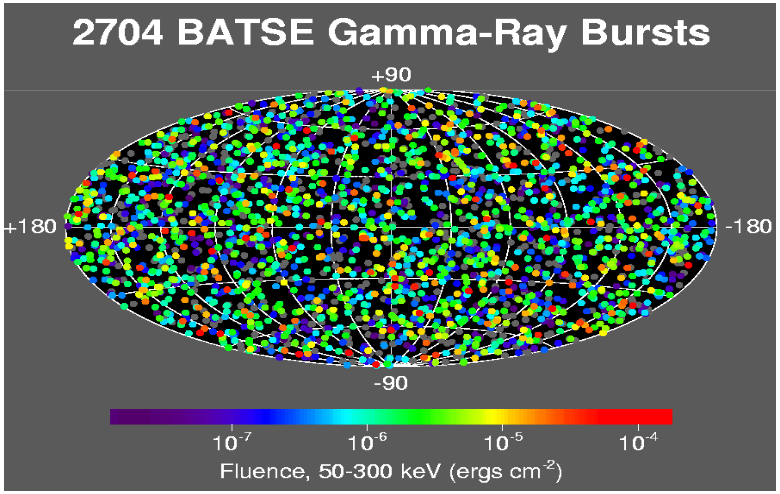
Gamma Ray Bursters (GRB)

Short emissions (~1s)

Very bright ~ $10^{18} \times L_{\odot}$

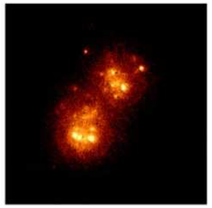
Counterparts : z up to 8.3

BATSE : 1 burst/day

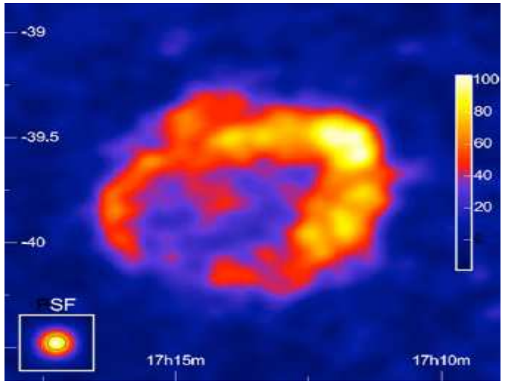


Starburst Galaxies

supernovae -> cosmic rays + dense gas -> pions



Potential Galactic Sources



Microquasars X-ray binaries with compact object (neutron star or black hole) accreting matter and re-emitting it in relativistic jets (intense radio & IR) flares.

SNRs Supernova Remnants
Acceleration at shock fronts,
interaction with molecular clouds.

Galactic Center
seen with TeV photons

- *Soft gamma repeaters*

pulsars, neutron stars

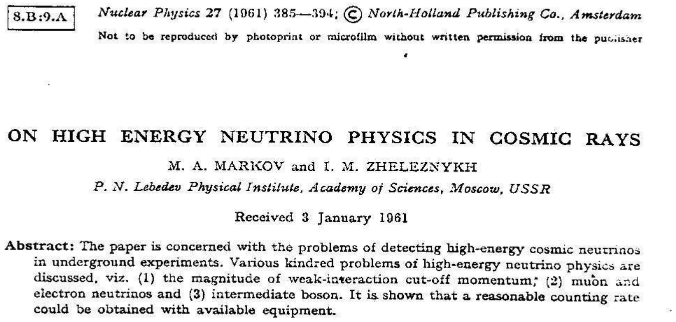
- *Dense regions*

Sun , Galactic Centre,
Interstellar medium

→ Mosty seen by Northern Hemisphere neutrino telescopes

→ Energy cutoffs expected at the source

Markov idea: muon neutrino



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Nuclear Physics 27 (1961) 385—394; © *North-Holland Publishing Co., Amsterdam*

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ON HIGH ENERGY NEUTRINO PHYSICS IN COSMIC RAYS

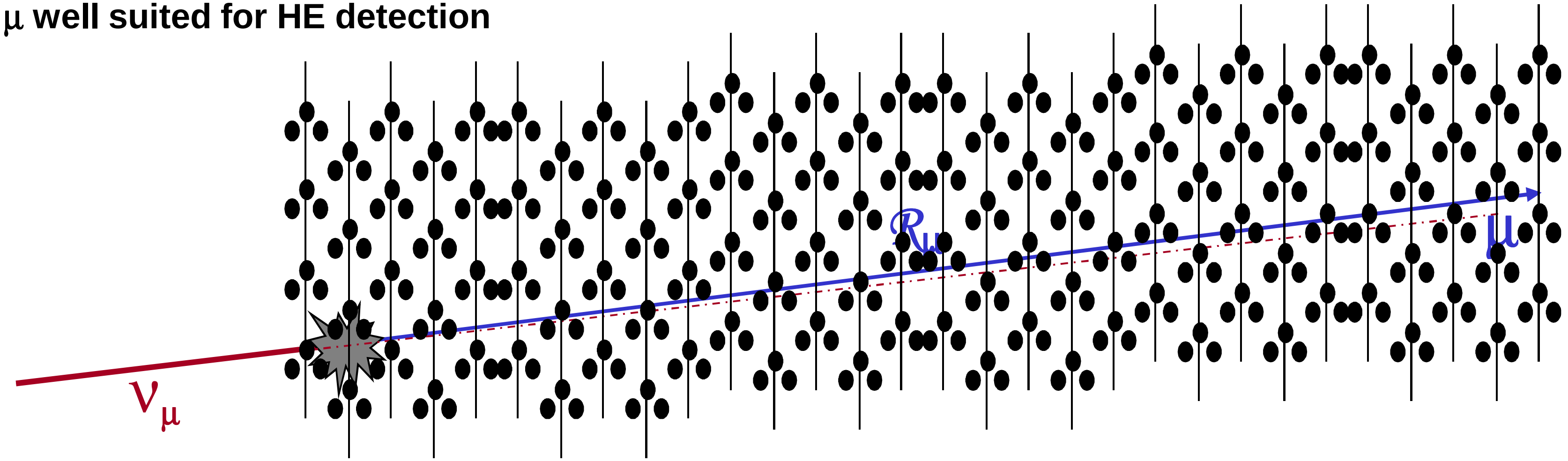
M. A. MARKOV and I. M. ZHELEZNYKH

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.

μ well suited for HE detection



In Water

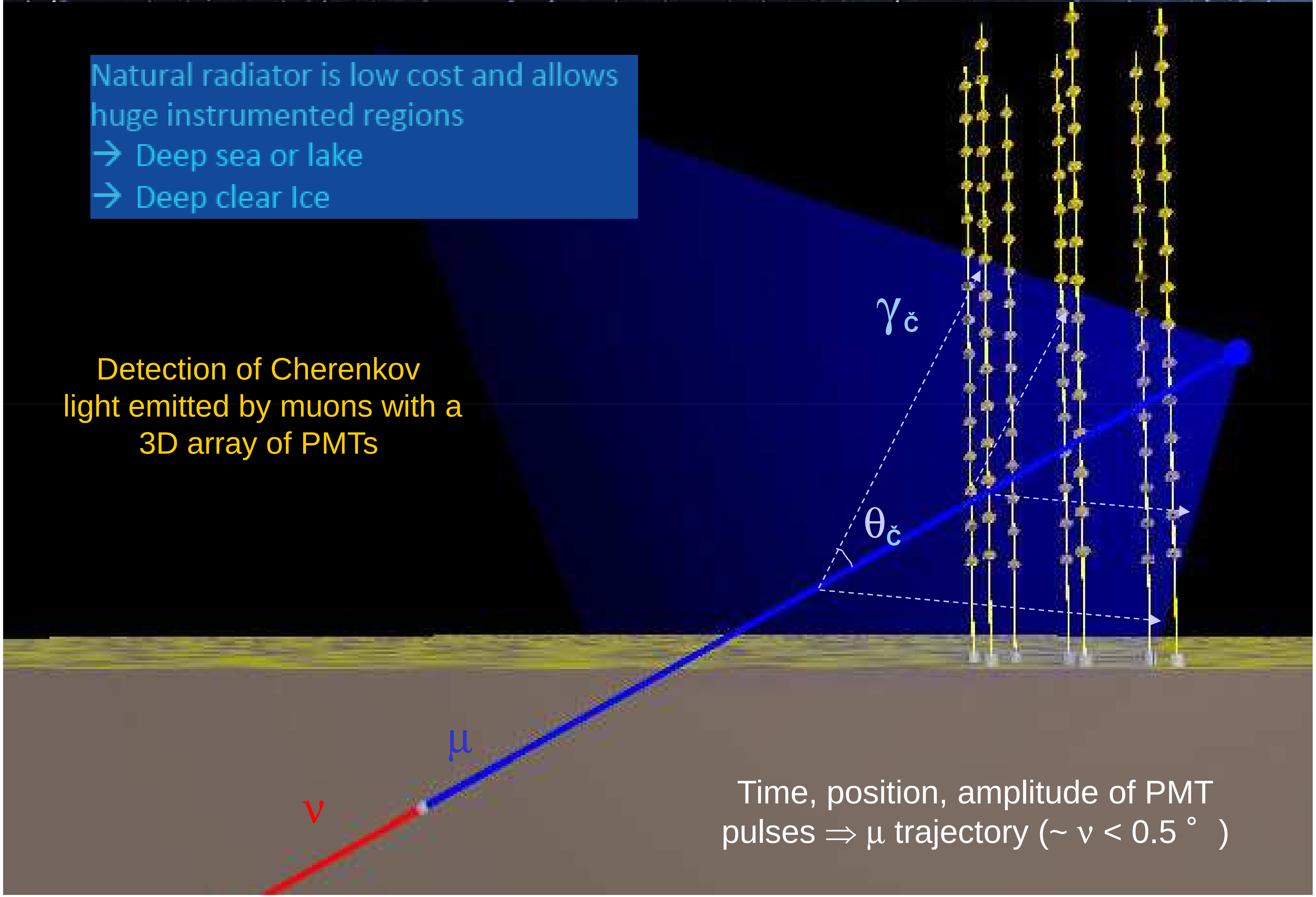
R_μ(1 TeV) = 3 km

R_μ(1 PeV) > 10 km

- Detection effective volume increases with E_ν
- Angle between ν and μ decreases with E_ν
- Interaction cross section increases with E_ν

Detection of HE muon neutrinos is favoured

Reconstruction of muon trajectory



Natural radiator is low cost and allows huge instrumented regions

→ Deep sea or lake

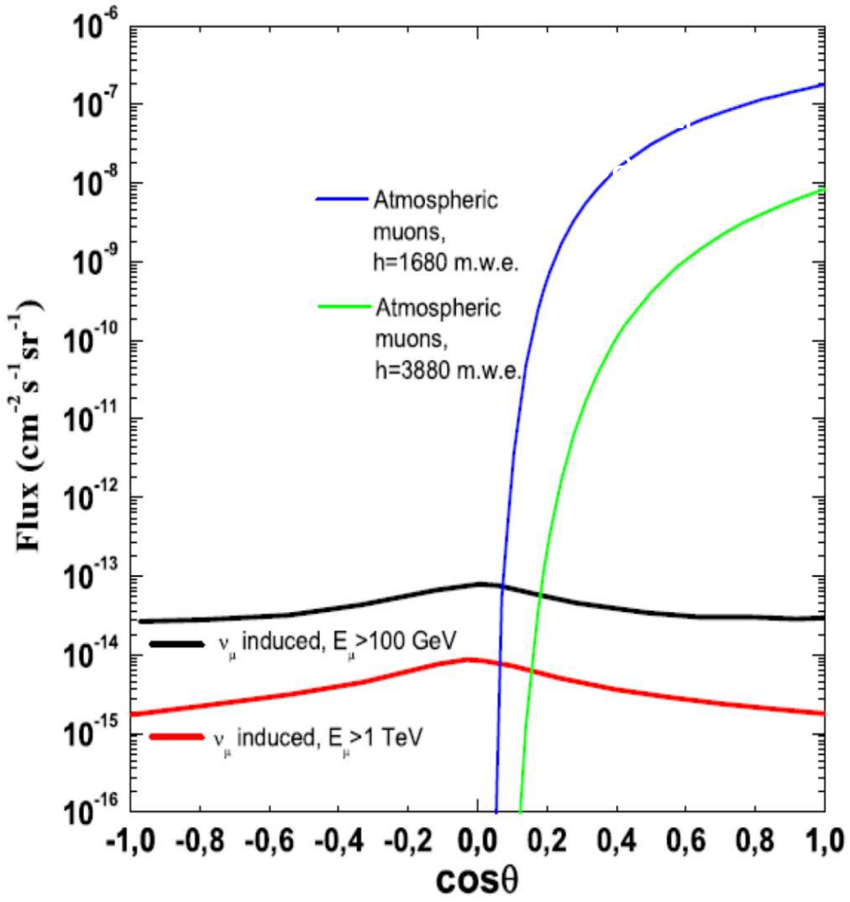
→ Deep clear Ice

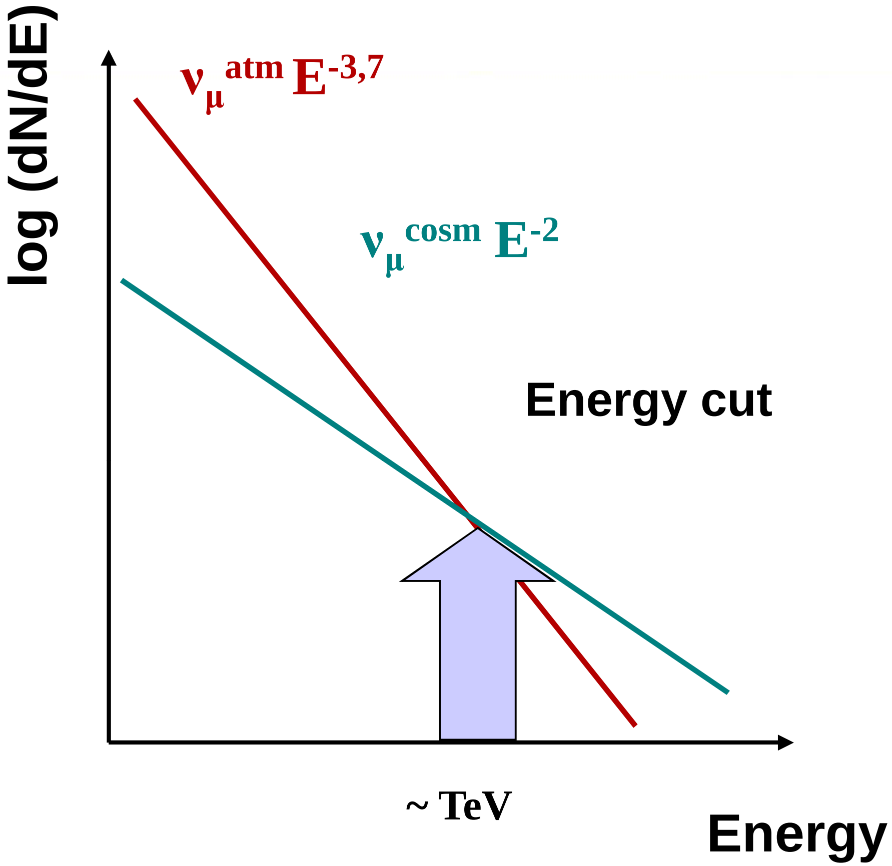
Detection of Cherenkov light emitted by muons with a 3D array of PMTs

Time, position, amplitude of PMT pulses ⇒ μ trajectory (~ ν < 0.5 °)

Atmospheric background vs cosmic ν's

Atmospheric muons ⇒ shield detector & define signal as upward muons



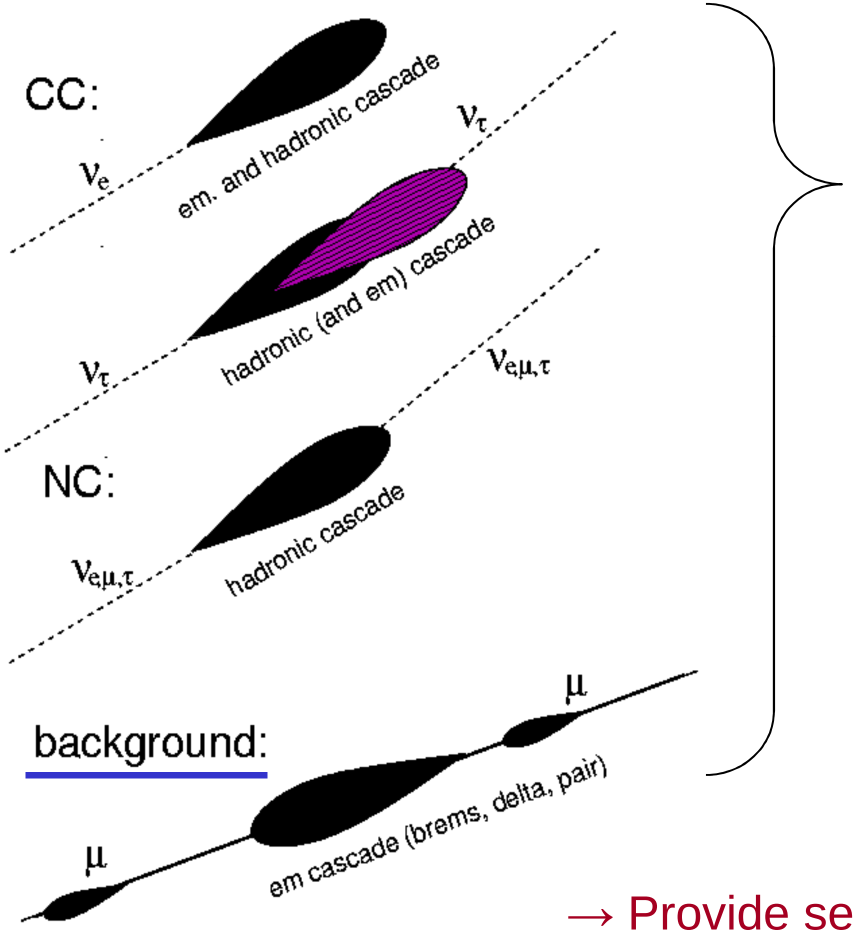


Atmospheric neutrinos ⇒ search for

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

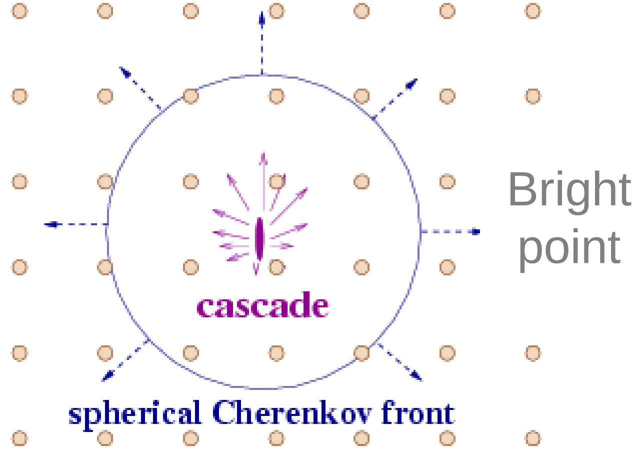
Other neutrino interaction topologies

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



So-called "cascade" events

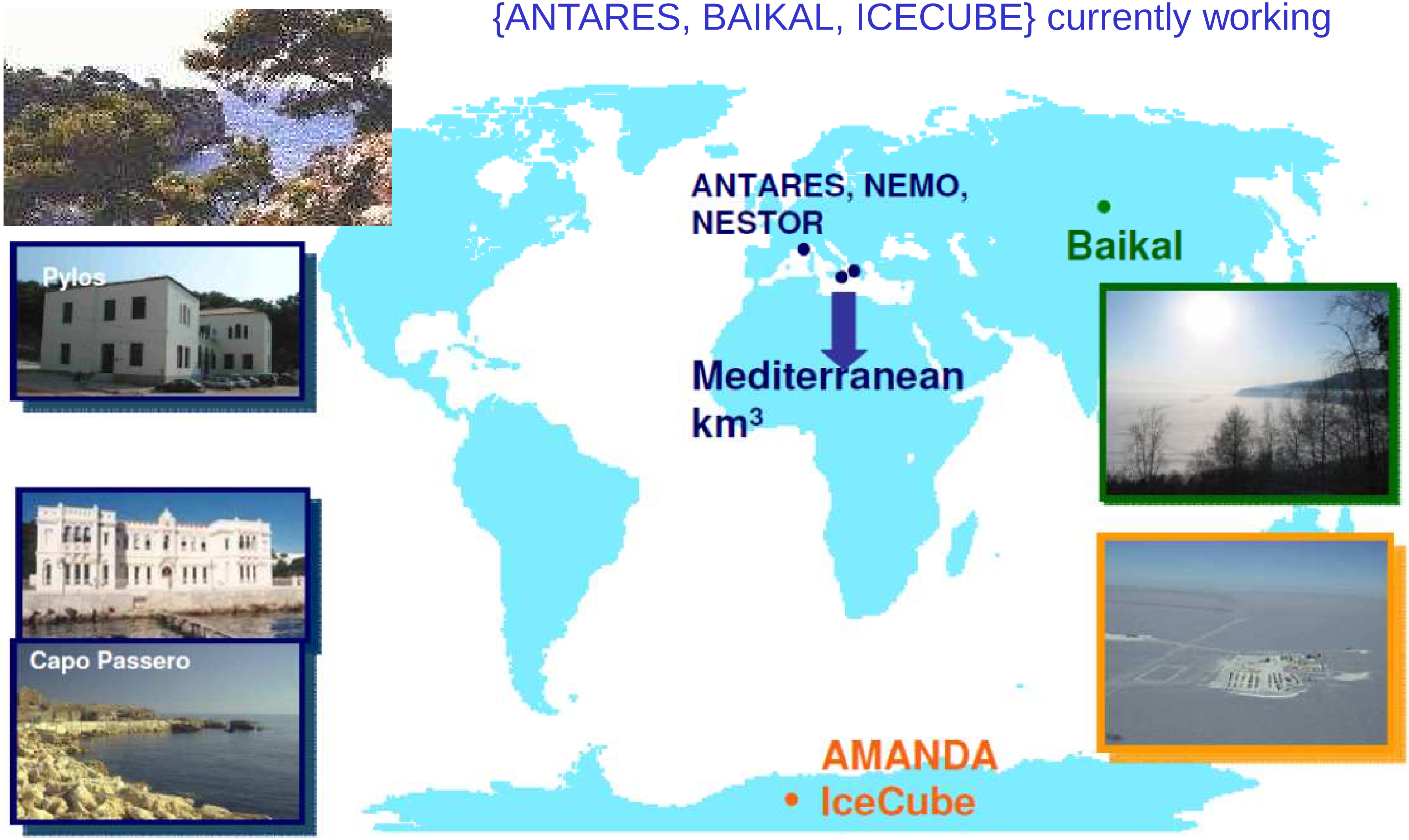
Generic reconstruction:



→ Provide sensitivity to all neutrino flavours

Neutrino telescopes (TeV)

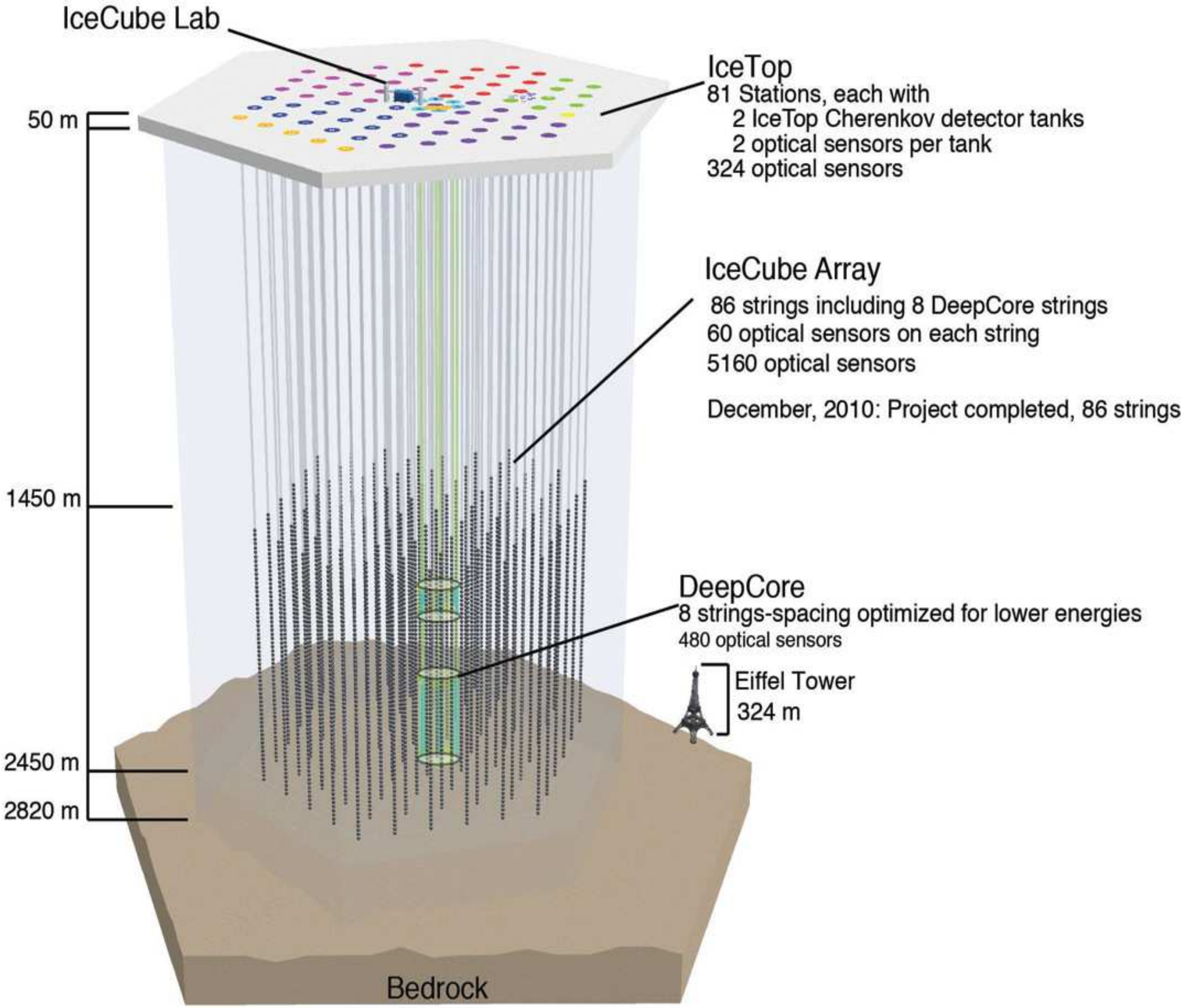
{ANTARES, BAIKAL, ICECUBE} currently working



{ANTARES, NEMO, NESTOR} ∈ KM3NeT Collaboration

IceCube : the biggest NT in the world

Completed since December 2010.



IceCube Lab

50 m

1450 m

2450 m

2820 m

Bedrock

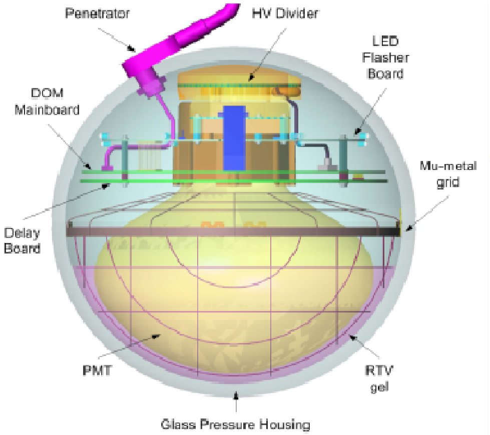
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

Eiffel Tower
324 m



Why the Mediterranean Sea?

- Complementarity to IceCube South Pole

  Excellent view of Galaxy

- Long (homogeneous) scattering length

  Good pointing accuracy

- Deep sites: 2500→5000m

  Shielding from downgoing muons

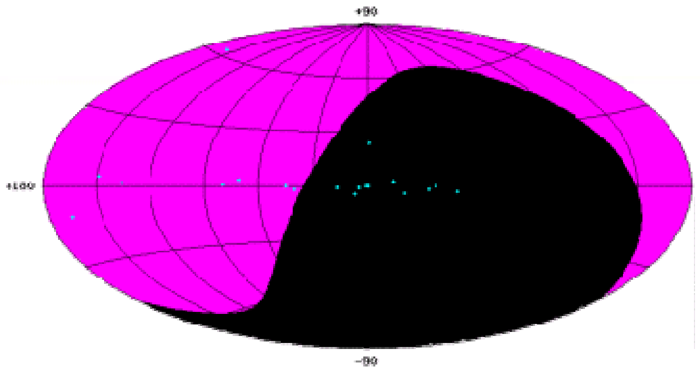
- Logistically attractive

  Close to shore (deployment / repair)

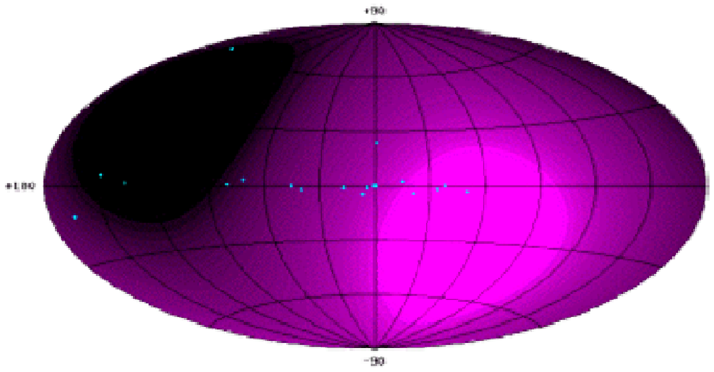
- K40 optical background

  Useful for calibration, but requires causality filters

South Pole visible sky



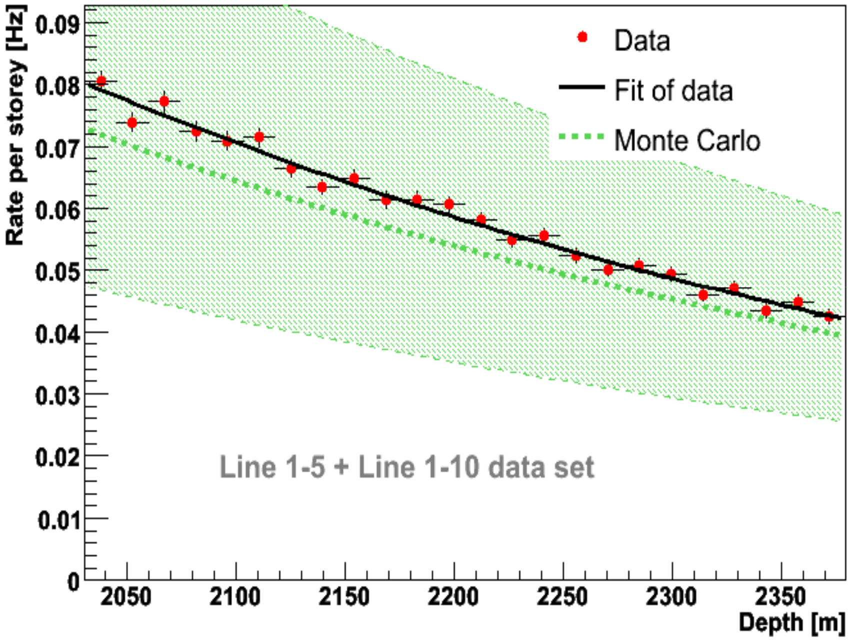
Mediterranean visible sky



Most of the HESS TeV
Sources visible by Northern NT

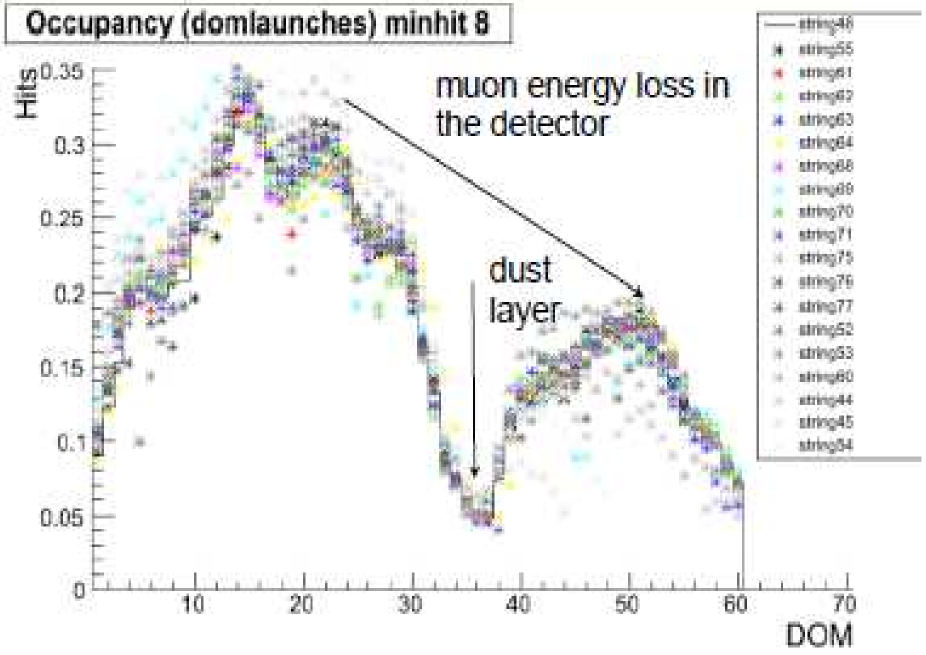
The Sea: a Uniform Medium

ANTARES



Resolution ~ 0.3°

ICECUBE



Resolution ~ 0.6°

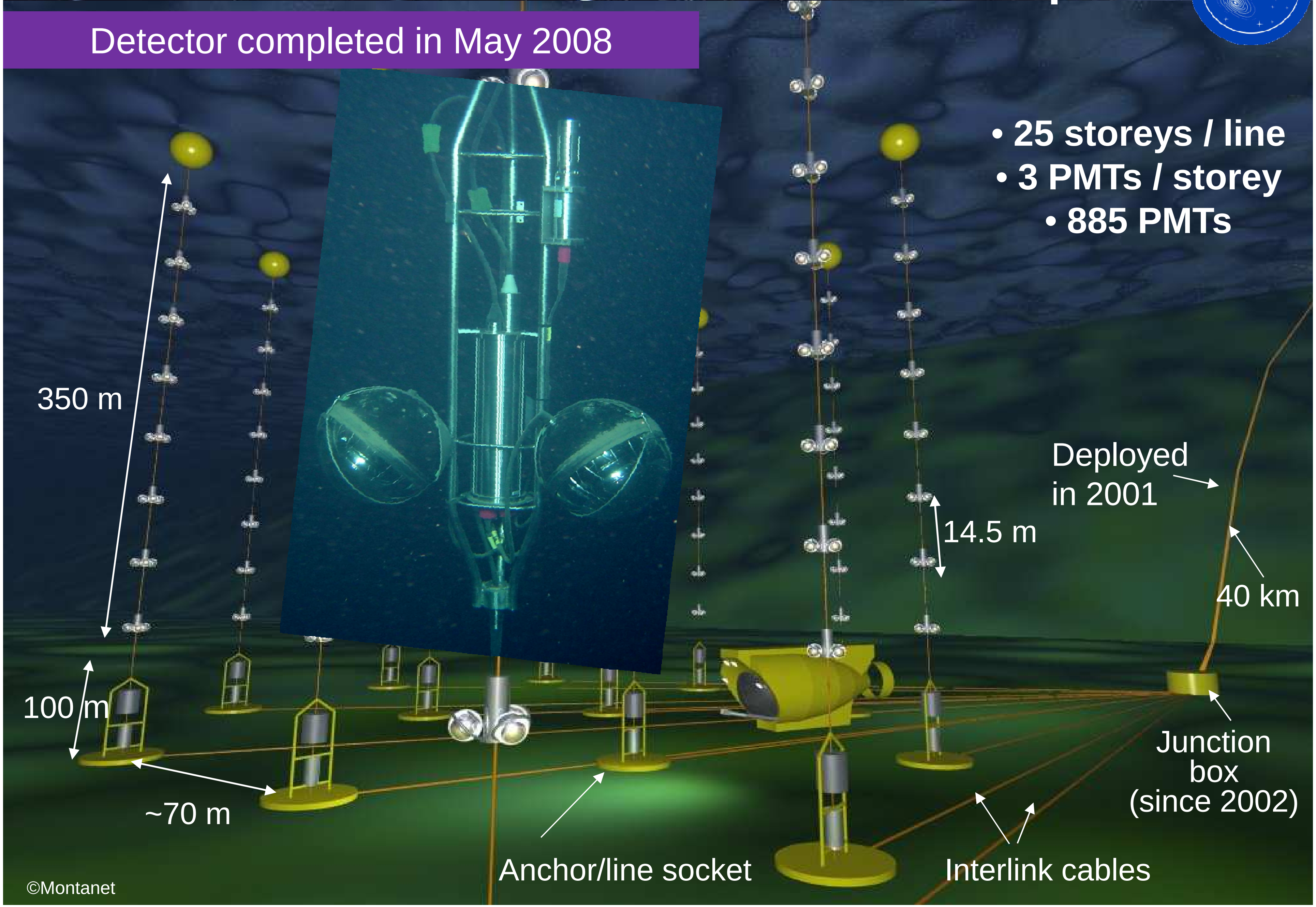
Electro-optical
Cable of
40 km

42 50'N, 6 10'E

The ANTARES neutrino telescope

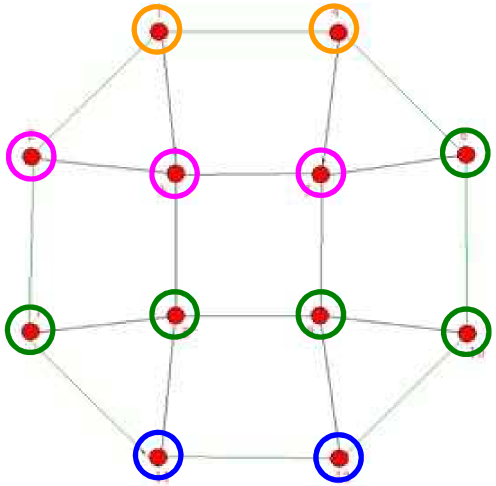
Detector completed in May 2008

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

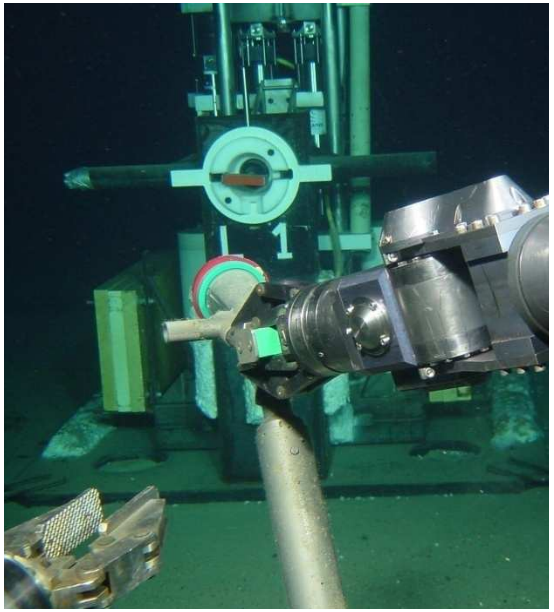


©Montanet

2006 – 2008: Construction Phase of the Detector

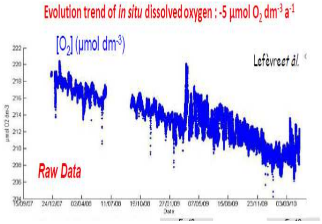


Junction box	2001
Main cable	2002
Line 1, 2	2006
Line 3, 4, 5	01 / 2007
Line 6, 7, 8, 9, 10	12 / 2007
Line 11, 12	05 / 2008

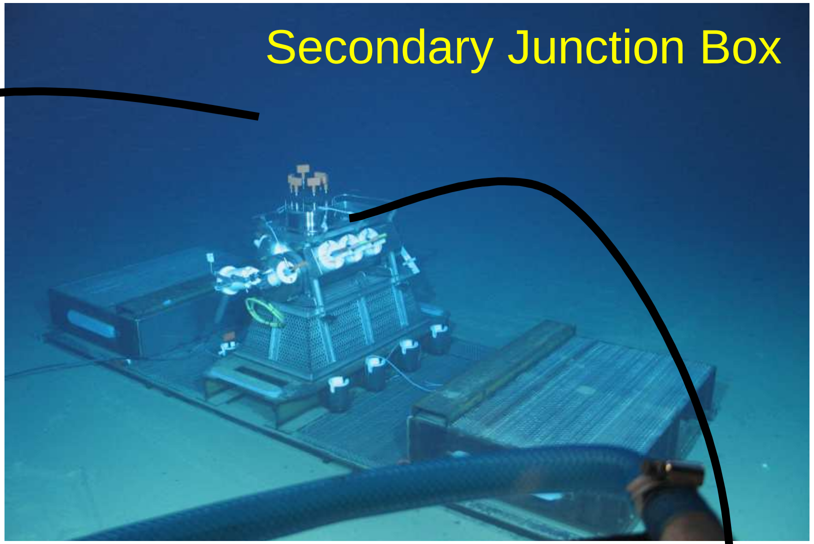


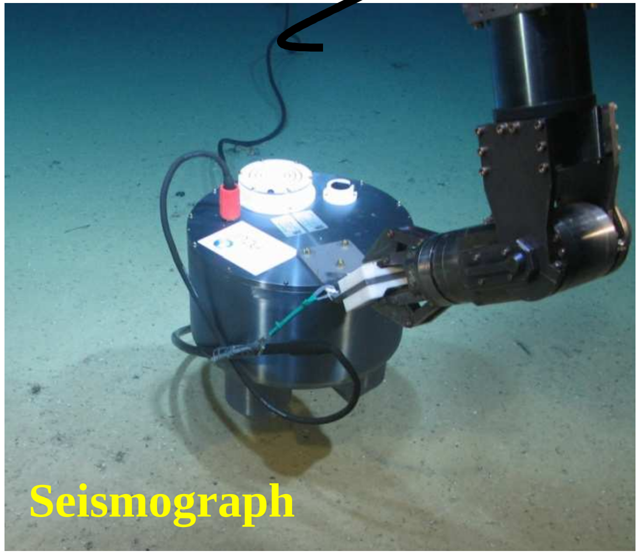
Earth and Sea Sciences

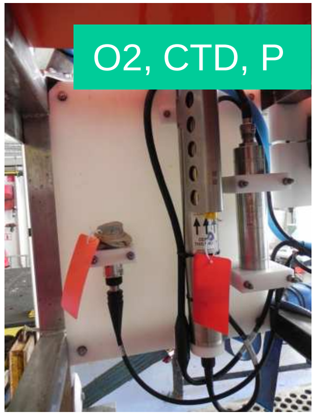
Deep Ocean Cabled Observatories Workshop-
https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=165389

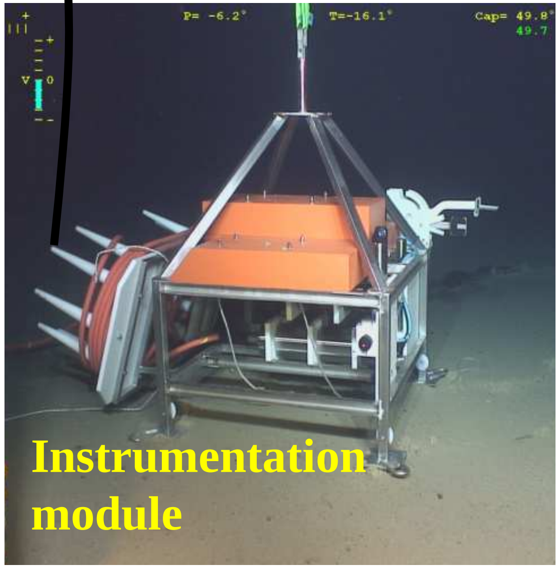


Connected
30 Oct 2010

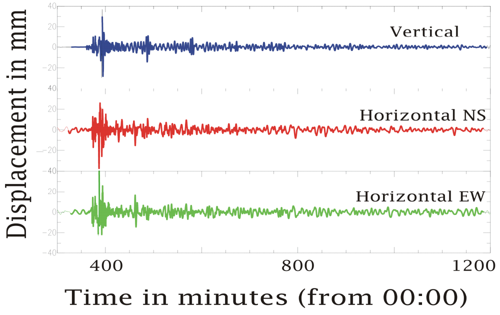




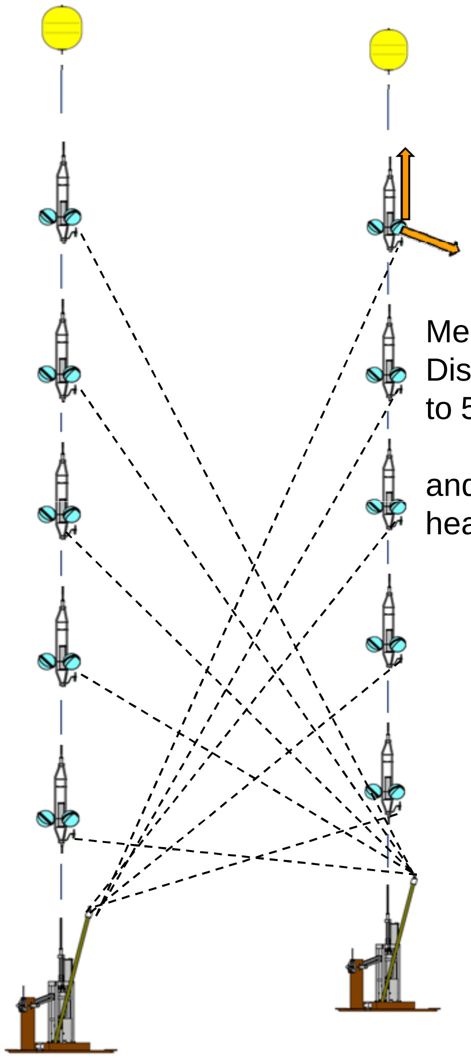




Japan earthquake 2011 March 11
at Antares site

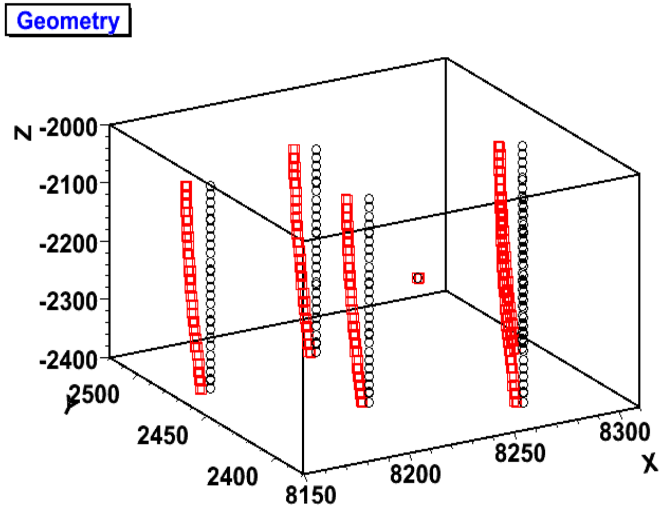


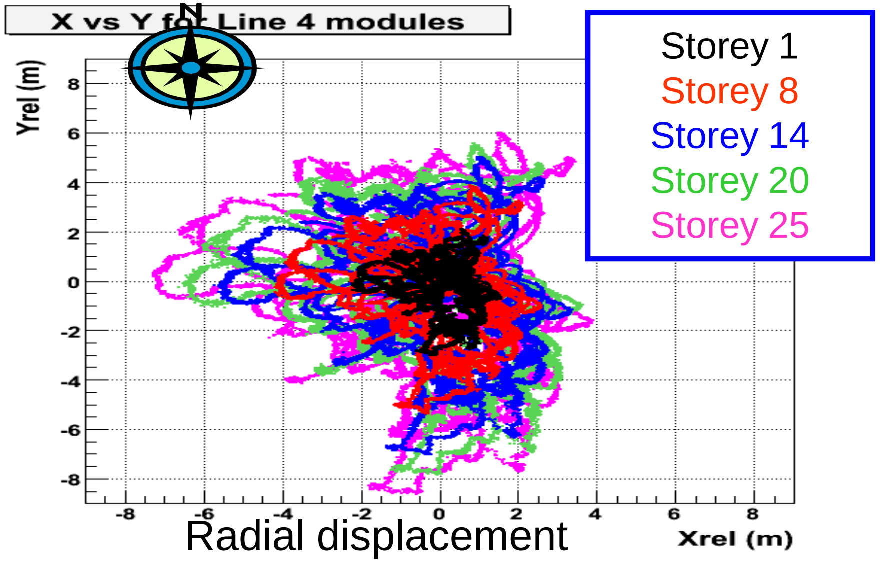
Acoustic Positioning



Measure every 2 min:
Distance line bases
to 5 storeys/line

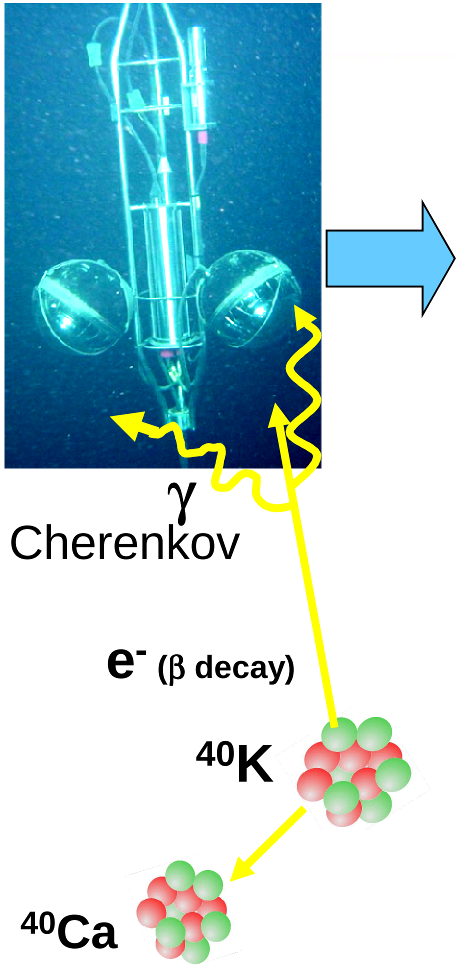
and also storey
headings and tilts

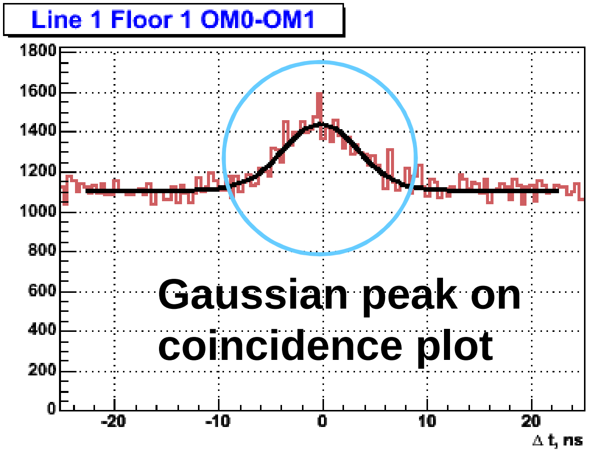




Radial displacement

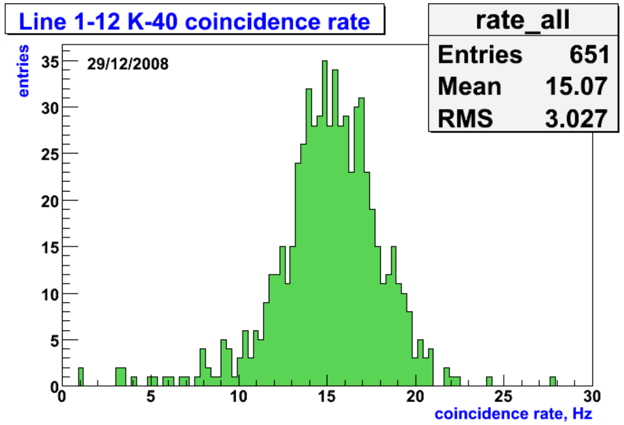
ANTARES Calibration : use of K40 hits





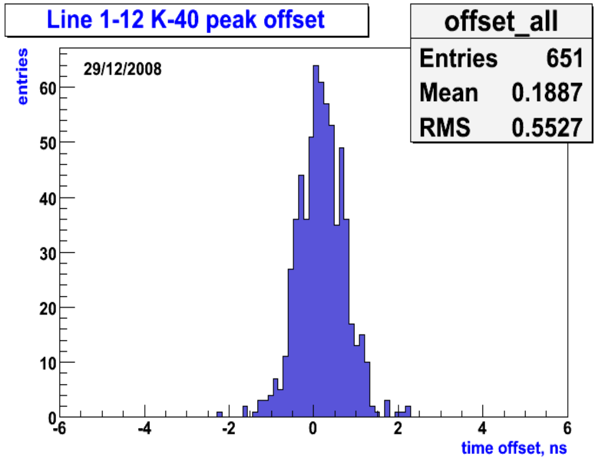
Gaussian peak on coincidence plot

Integral under peak



Precision (~5%) monitoring of OM efficiencies

Peak offset



Cross check of time calibration from optical beacons

Diffuse Flux Neutrino Searches

- Look for high-energy neutrino events above the rapidly falling atmospheric neutrino spectrum
    - Upward muon neutrinos
    - Cascade events (CC ν_e and ν_τ , NC all flavours)

- ν_μ diffuse search
    - IC40 published 📖 PRD 84, 082001 (2011)
    - Results from IC59

- Cascade search
    - Analysis with IC40 not yet published
    - IC79+IC86 [2011] search for cosmogenic neutrinos
        ➔ 2 events near threshold…

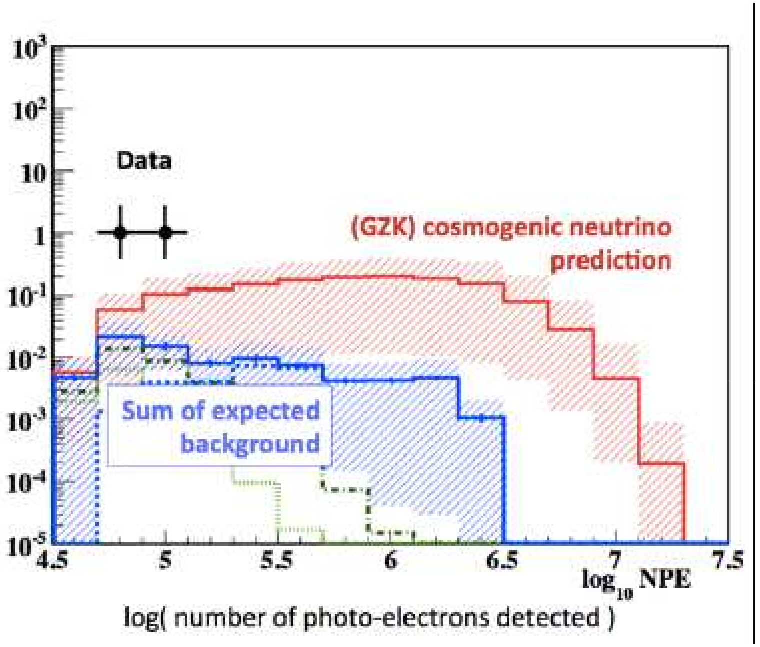
IC79+IC86 ν UHE Search

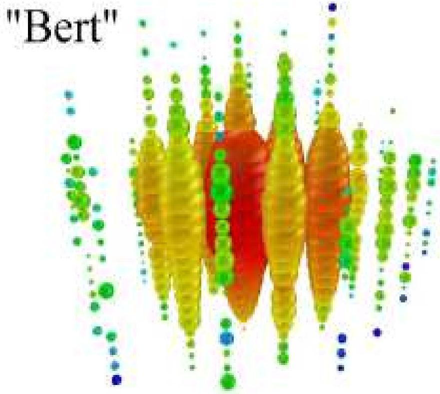
Nb of events per bin (615.9 days)

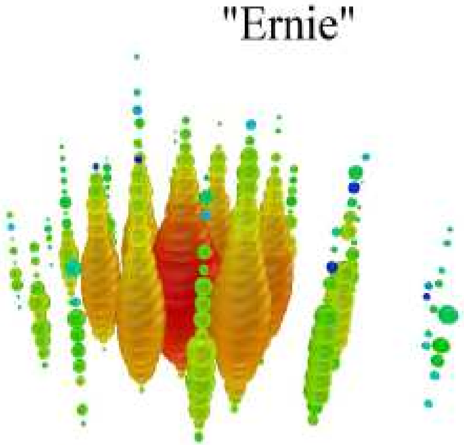
Analysis targeting ultra high energy GZK neutrinos

Expected background 0.08+-0.05 events
Observed in data: 2 events
Significance 2.8 sigma

Too low in energy for GZK
Too high in energy for atmospheric







Physical Review Letters 111 (2013) 021103: arXiv:1304.5356

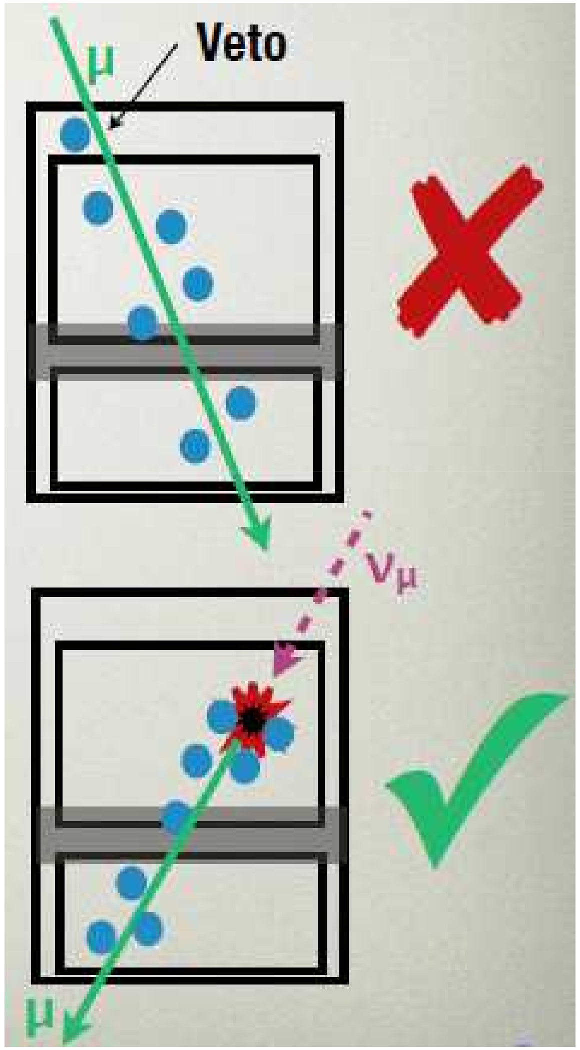
Starting Track Analysis: IceCube Signal for diffuse flux

Restrict to starting tracks:
veto events with hits in outer layers

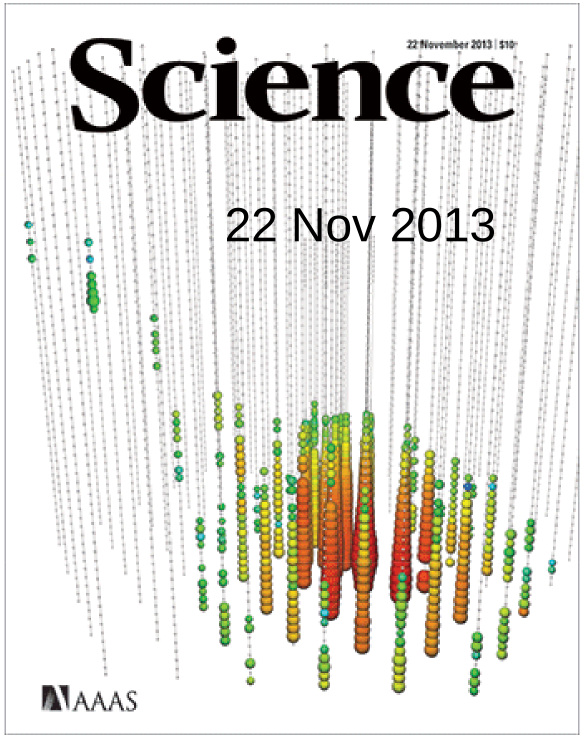
Removes atms muon background
Removes atms neutrino background

4pi acceptance
All flavours

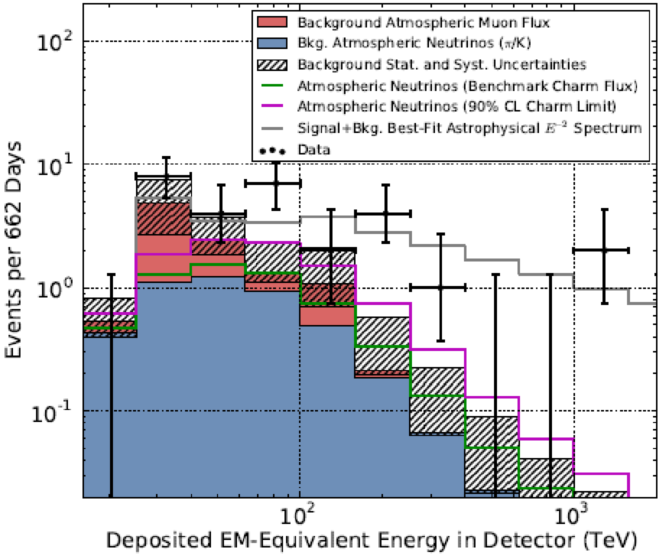
Reduces effective volume
Cascade events poor resolution

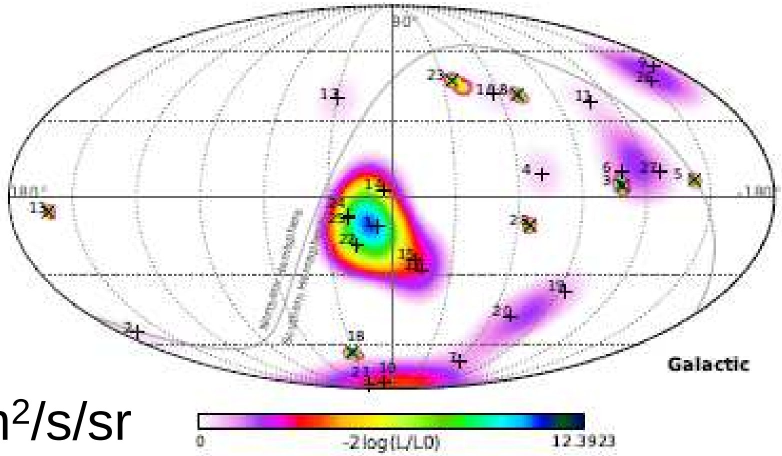


Veto Analysis: IceCube Signal for diffuse flux



22 Nov 2013

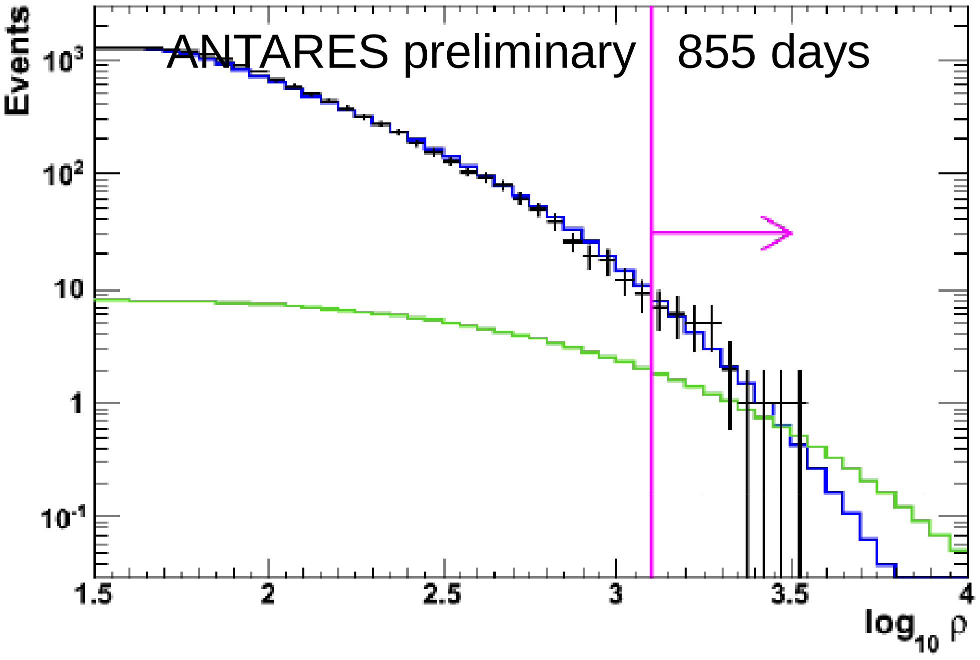




28 events (7 track, 21 cascade)
4.3 sigma effect (incl Erin and Bert)
Cascade angular resolution ~10-15°

Flux (single flavour)~ 1.2×10^{-8} GeV/cm^2/s/sr
Galactic?

Diffuse Muon Neutrino Searches

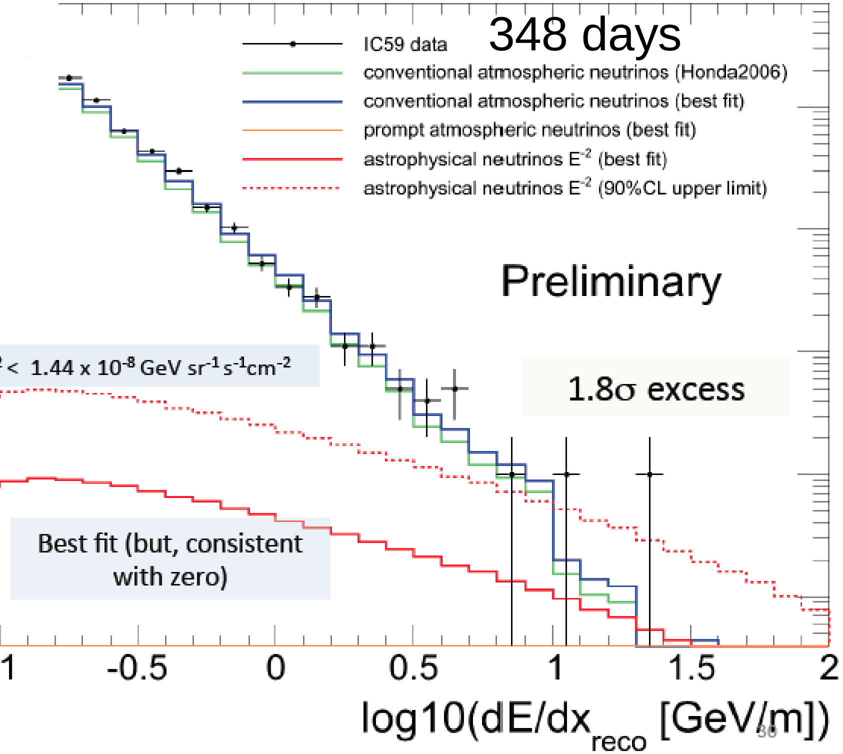


ANTARES flux limit:
$4.7*10^{-8}$ GeV/cm^2/s/sr

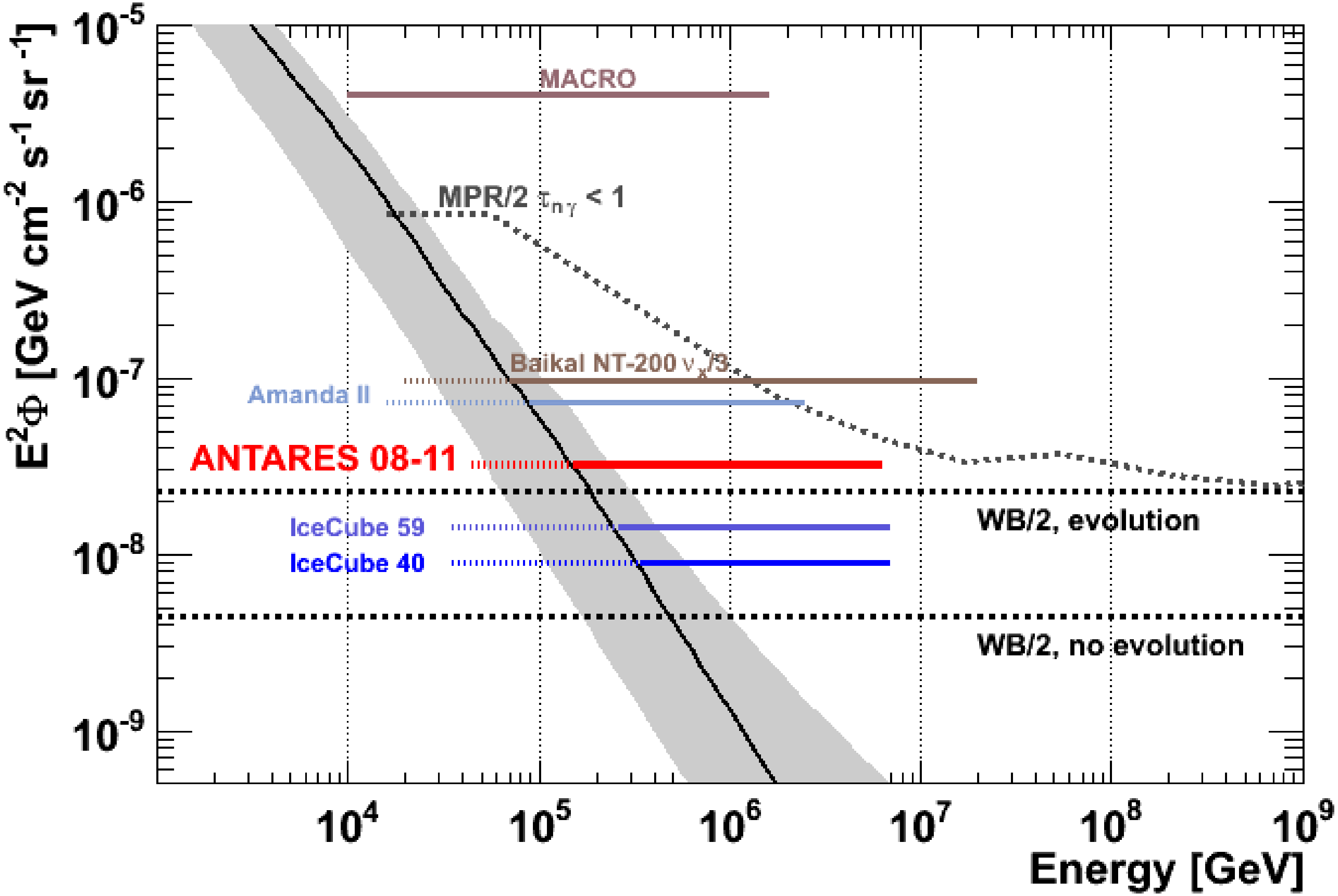
IC59

Good angular resolution

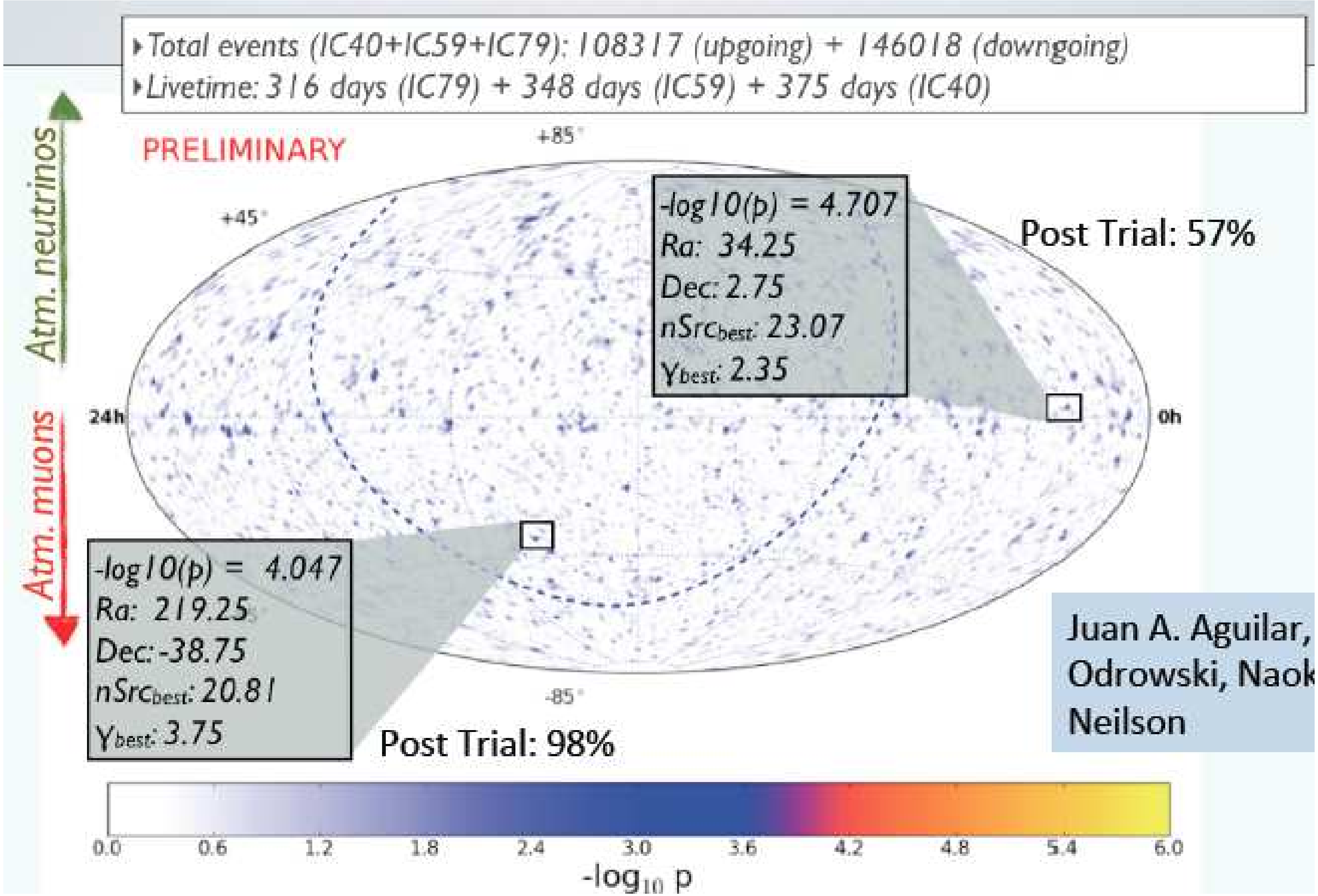
Eagerly awaiting results from IC89



muon neutrino diffuse limits



Sky map: IceCube



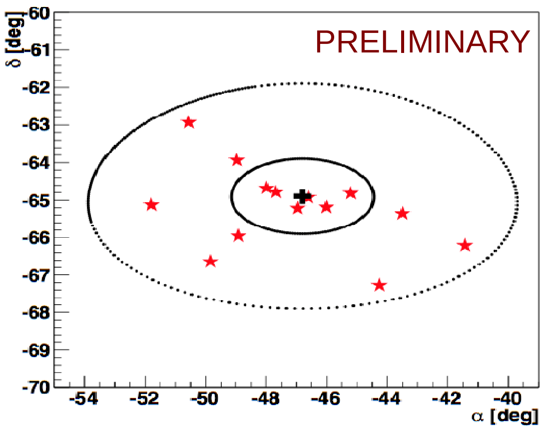
- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*

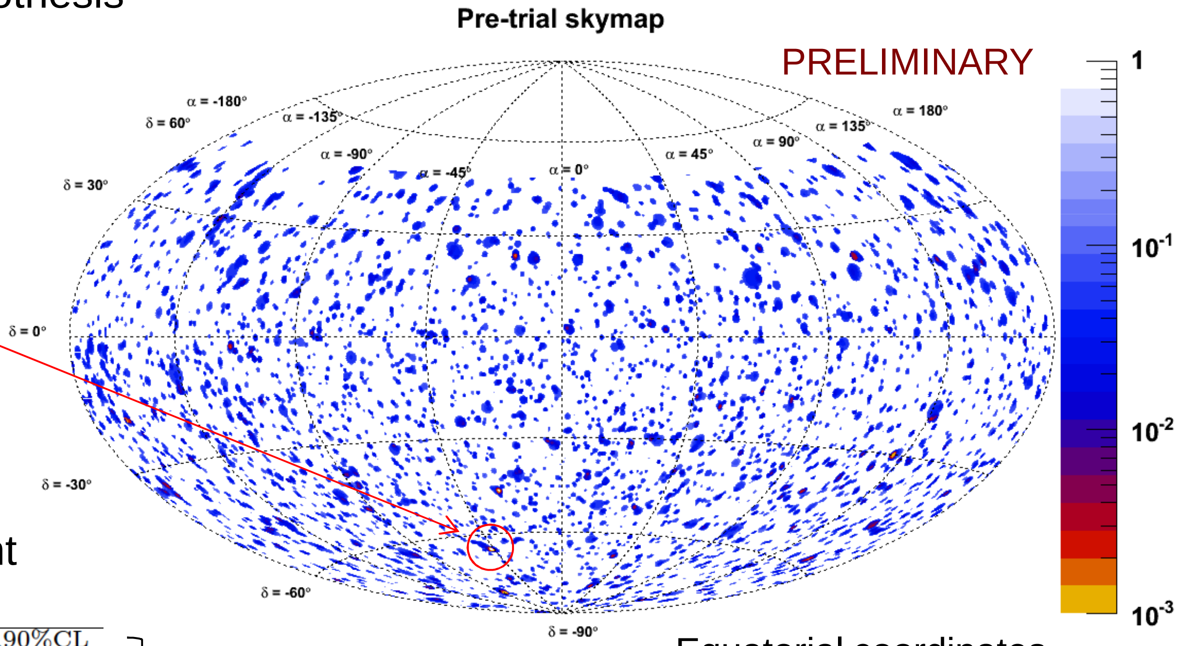
Juan A. Aguilar,
Odrowski, Naok
Neilson

SkyMap: ANTARES

❖ New updated 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

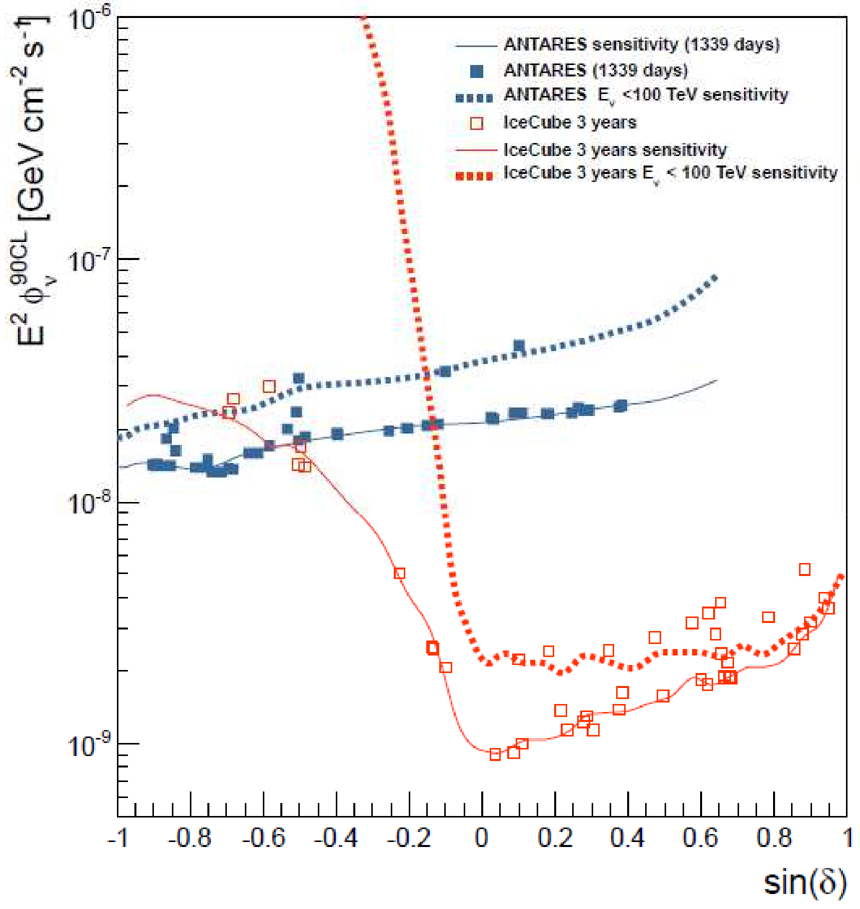
- Fixed search top 5 most significant

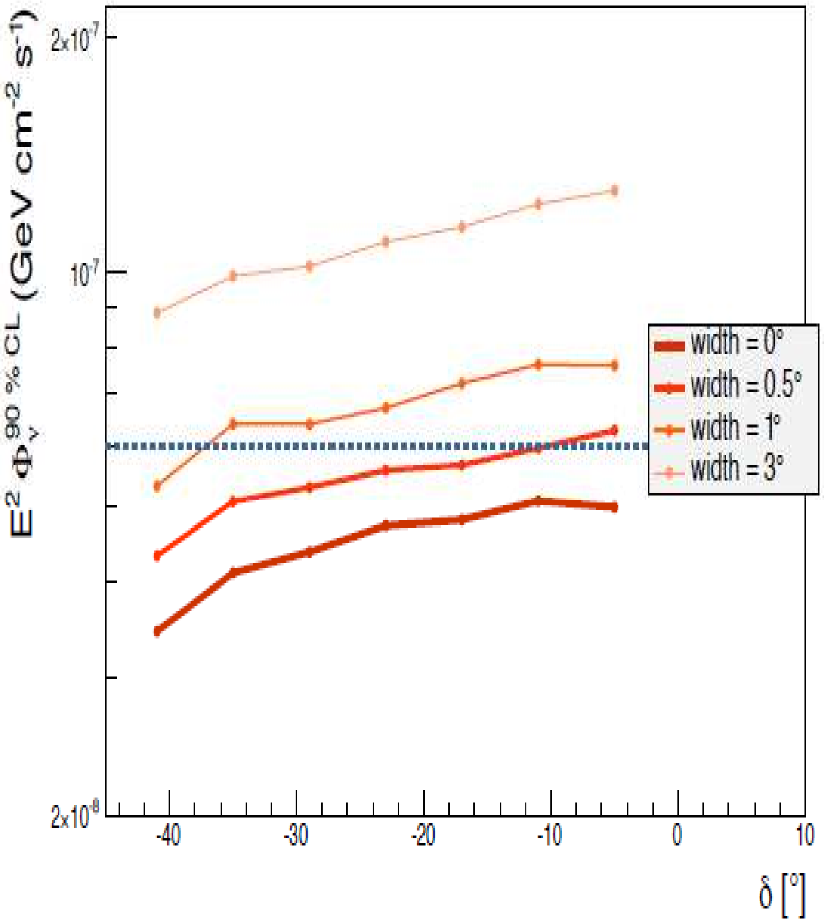
source	$\alpha_s[^\circ]$	$\delta_s[^\circ]$	p	$\phi^{90\%\mathrm{CL}}$
HESSJ0632+057	98.24	5.81	0.07	4.40
HESSJ1741-302	265.25	-30.20	0.14	3.23
3C279	194.05	-5.79	0.39	3.45
HESSJ1023-575	155.83	-57.76	0.82	2.01
ESO139-G12	264.41	-59.94	0.95	1.82

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





Factor 2 improvement
cf 2 years ago

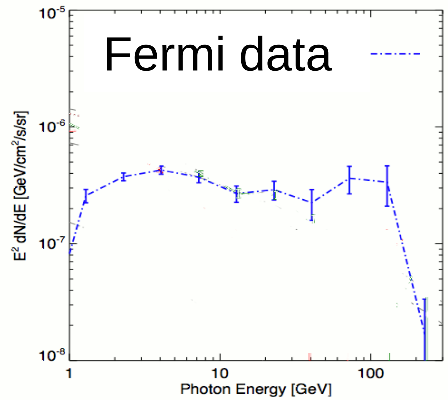
Exclude IceCube 'cluster' is due to a point source up to an extension of 1°

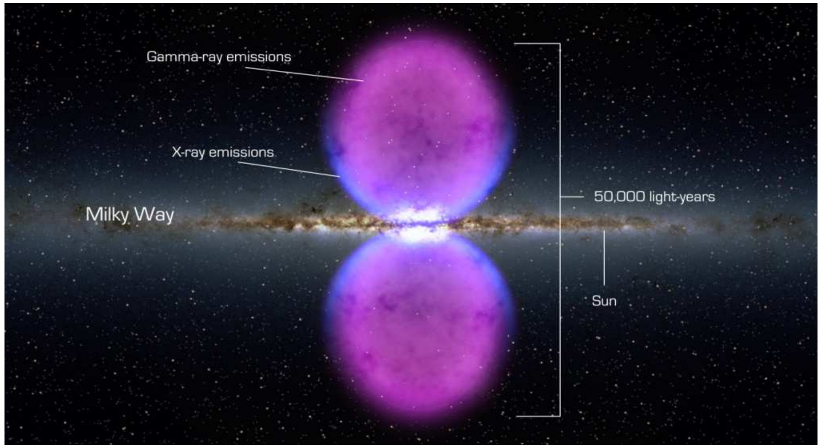
Search for a Diffuse Emission from the Fermi Bubbles I

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

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

🕮 M. Su et al., Ap. J. 724 (2010)





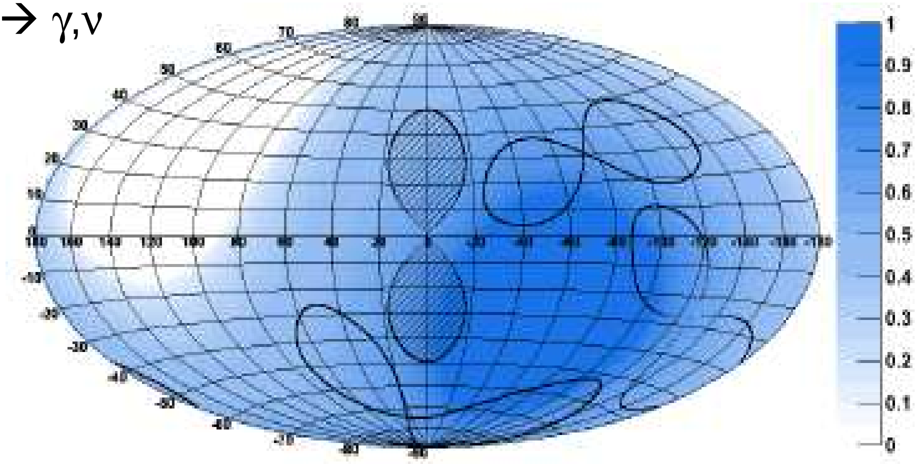
- Origin still debated;

promising Galactic wind model involves hadronic processes (🕮 Crocker & Aharonian, PRL 2011): accelerated cosmic rays interacting with ISM → π → γ,ν

$\Phi_\nu \approx 0.4 \times \Phi_\gamma$

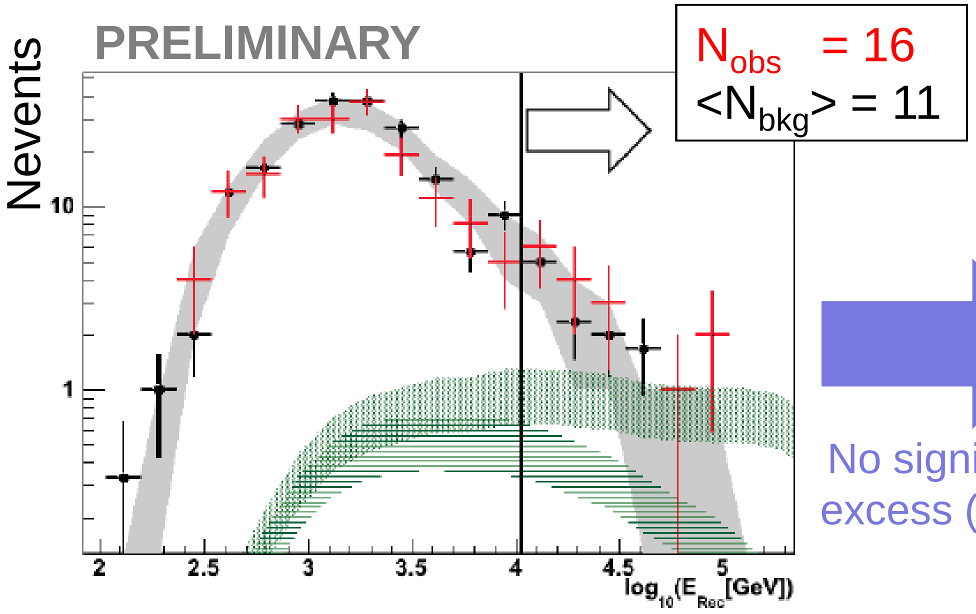
- In the field of view of ANTARES

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



Search for a Diffuse Emission from the Fermi Bubbles II

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



N_{obs} = 16

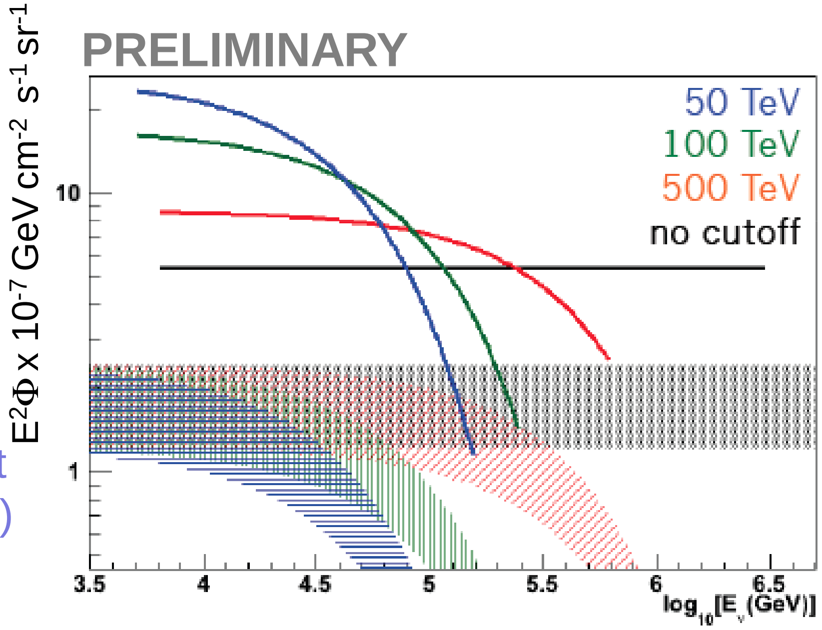
$<N_{bkg}>$ = 11

on-zone

off-zone average

expected signal (≠ cutoff, 50TeV cutoff)

No significant excess (1.2 σ)

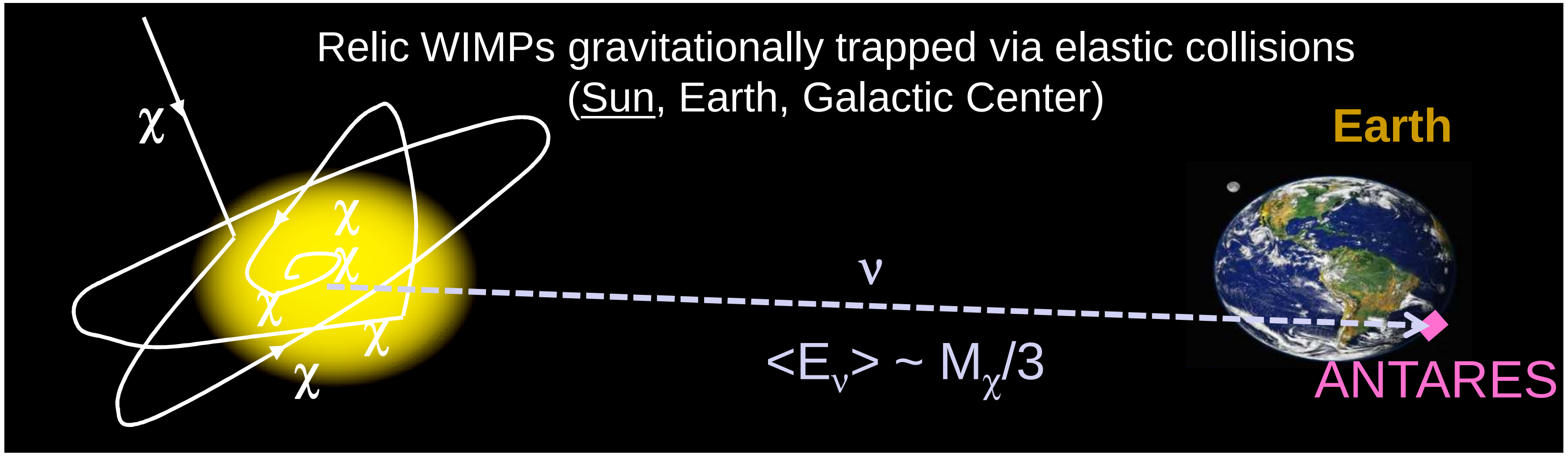


Upper limits with respect to different models

65% improvement expected with 2012-2016 data

S. Adrián-Martínez et al., accepted for publication in European Physics Journal C.

Indirect search for Dark Matter



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

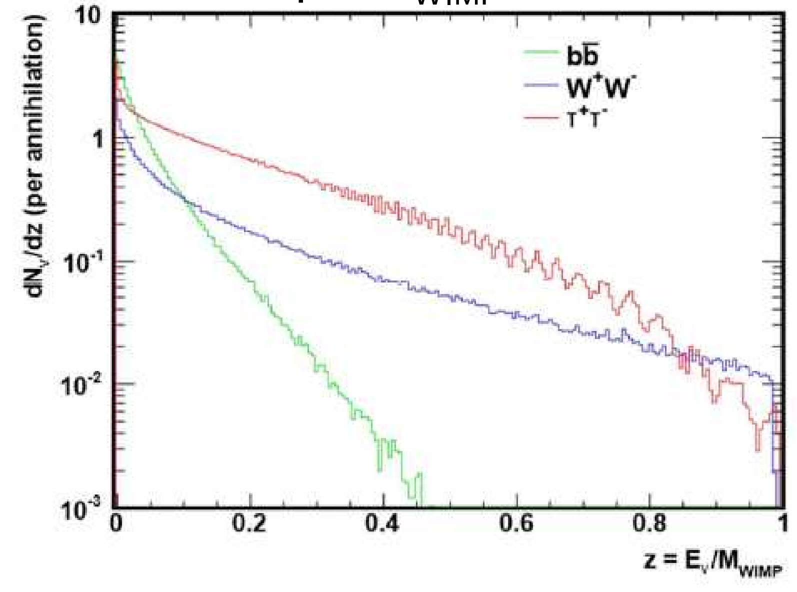
- HE neutrinos from the Sun → Clean DM signature

- 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 📖JCAP01(2008)021
- Interactions in the Sun, flavor oscillations, and regeneration of ν_τ in the Sun accounted

Example M_{WIMP}= 350 GeV



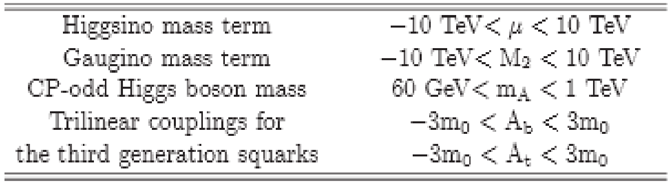
Indirect search for Dark Matter: Sun

➡ Limits on WIMP-proton SD/SI cross sections (equilib. capture/annihilation)

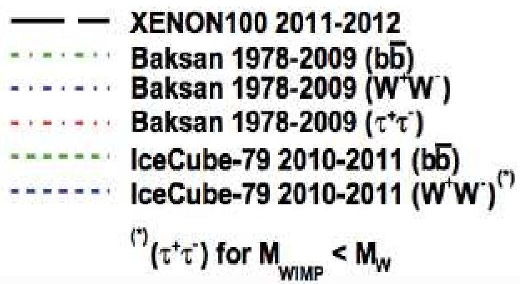
→ Much better sensitivity on SD cross sections w.r.t direct detection

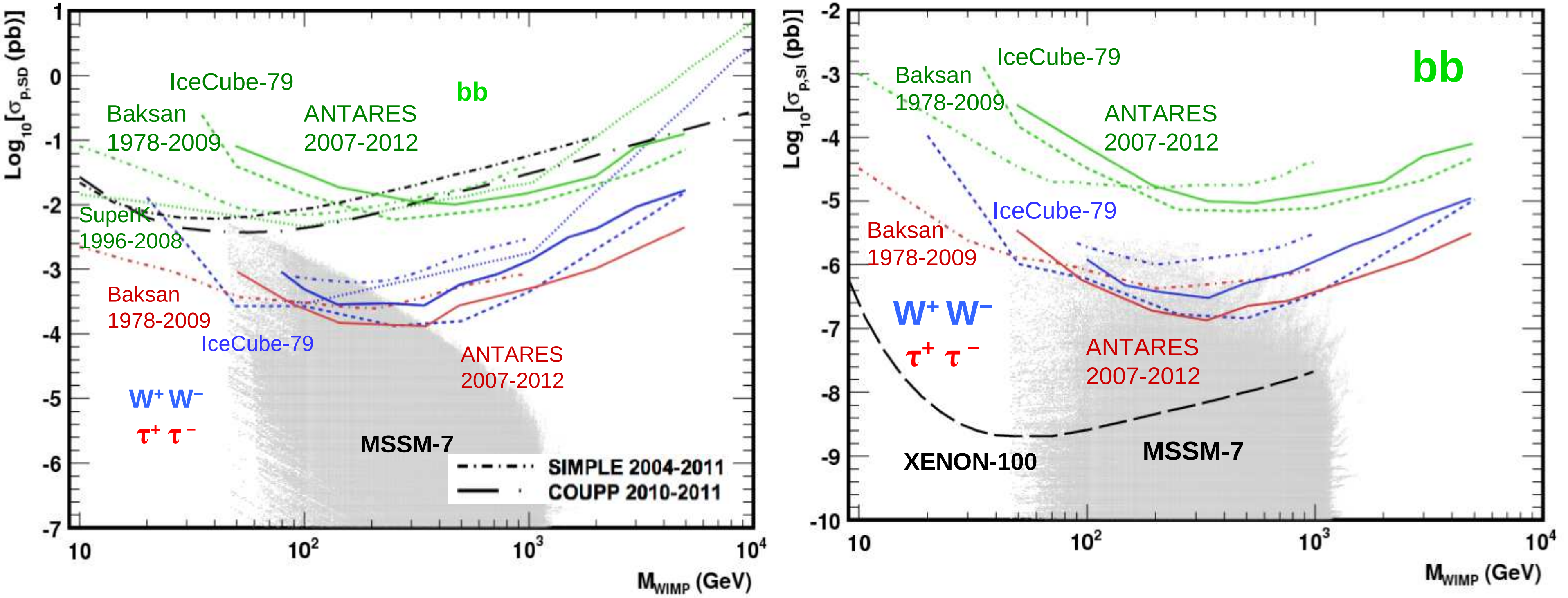
Comparison to predictions of MSSM-7 phenomenological model

📖 L. Bergström & P. Gondolo, Astropart. Phys. 5 (1996) 263-27



Higgsino mass term	$-10\ \text{TeV} < \mu < 10\ \text{TeV}$
Gaugino mass term	$-10\ \text{TeV} < M_2 < 10\ \text{TeV}$
CP-odd Higgs boson mass	$60\ \text{GeV} < m_A < 1\ \text{TeV}$
Trilinear couplings for	$-3m_0 < A_b < 3m_0$
the third generation squarks	$-3m_0 < A_t < 3m_0$

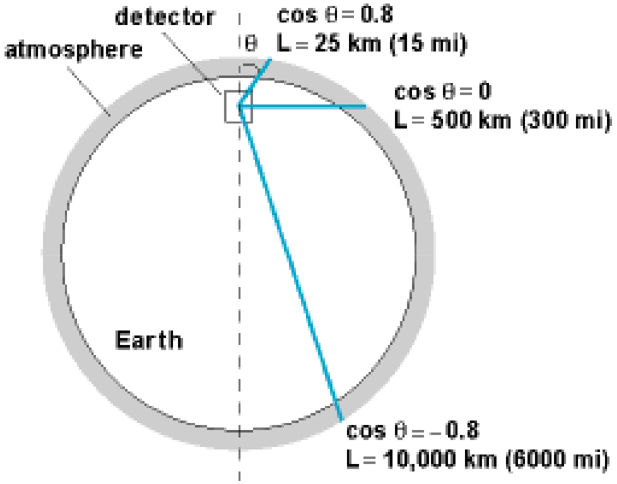


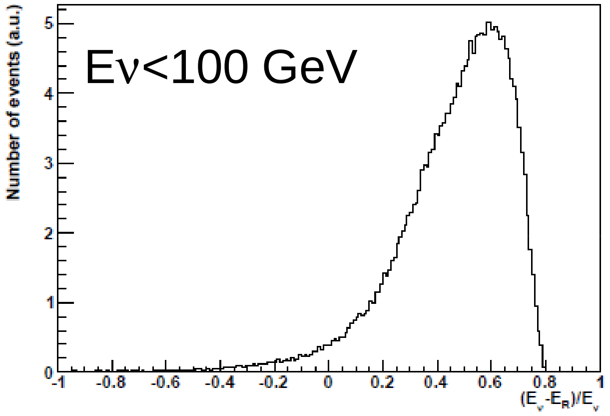


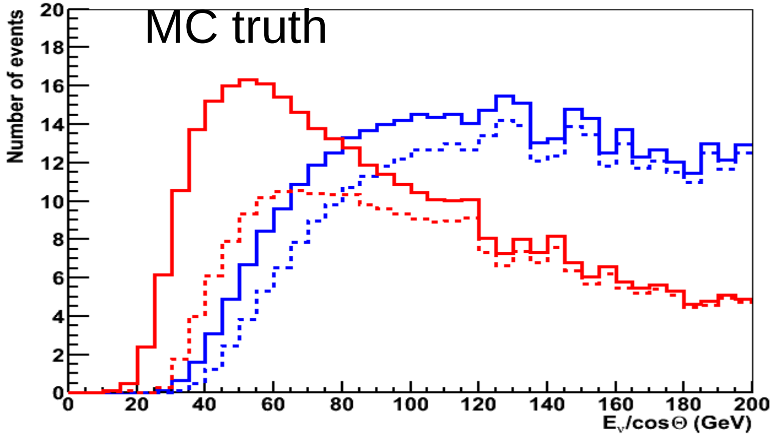
Oscillations with Atmospheric Neutrinos

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{1.27\Delta m^2_{32} L}{E_\nu}\right) = 1 - \sin^2 2\theta_{32} \sin^2\left(\frac{16200\ \Delta m^2_{32} \cos\Theta}{E_\nu}\right)$$

$L=2\ R_{Earth}\ \cos\theta$, from track fit







Oscillations maximal at 24 GeV for vertical neutrinos (muon range~120m)

Larger effect on single-line (low energy) than multi-line (higher energy) events

Neutrino Oscillations: Result

2008-2010 data (863 days):

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

Best fit: χ^2/NDF = 17.1/21

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

$\sin^2 2\theta = 1.00$

Systematics:

(Absolute normalisation free)

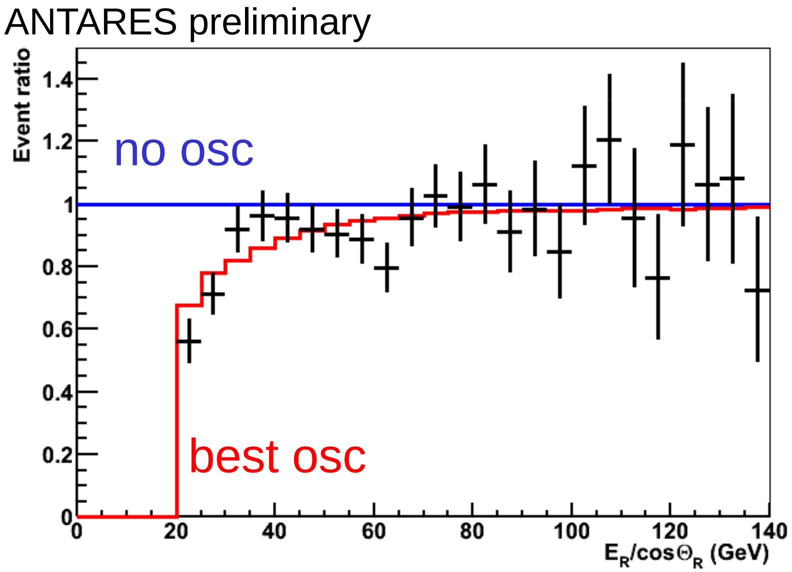
Absorption length: ±10%

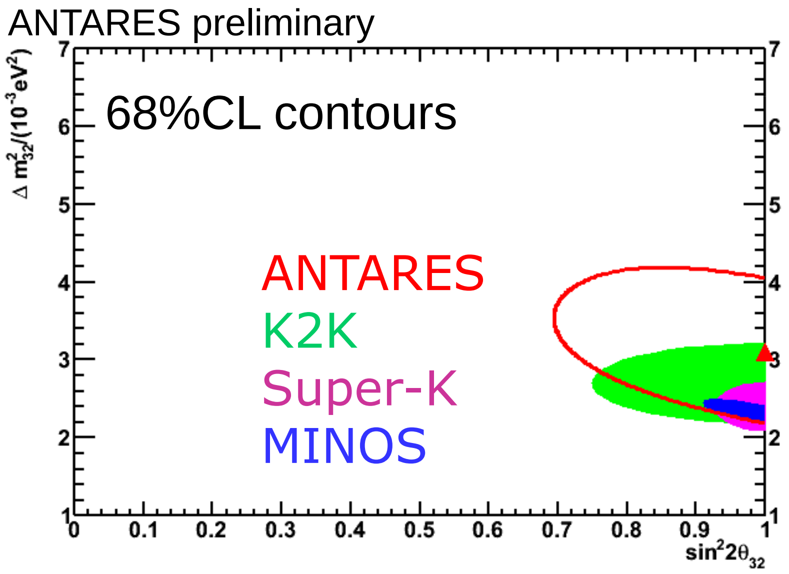
Detector efficiency: ±10%

Spectral index of ν flux: ±0.03

OM angular acceptance

5% error on slope vs $E_R/\cos\vartheta_R$





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

PLB: arXiv:1206.0645

The KM3NeT Infrastructure

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

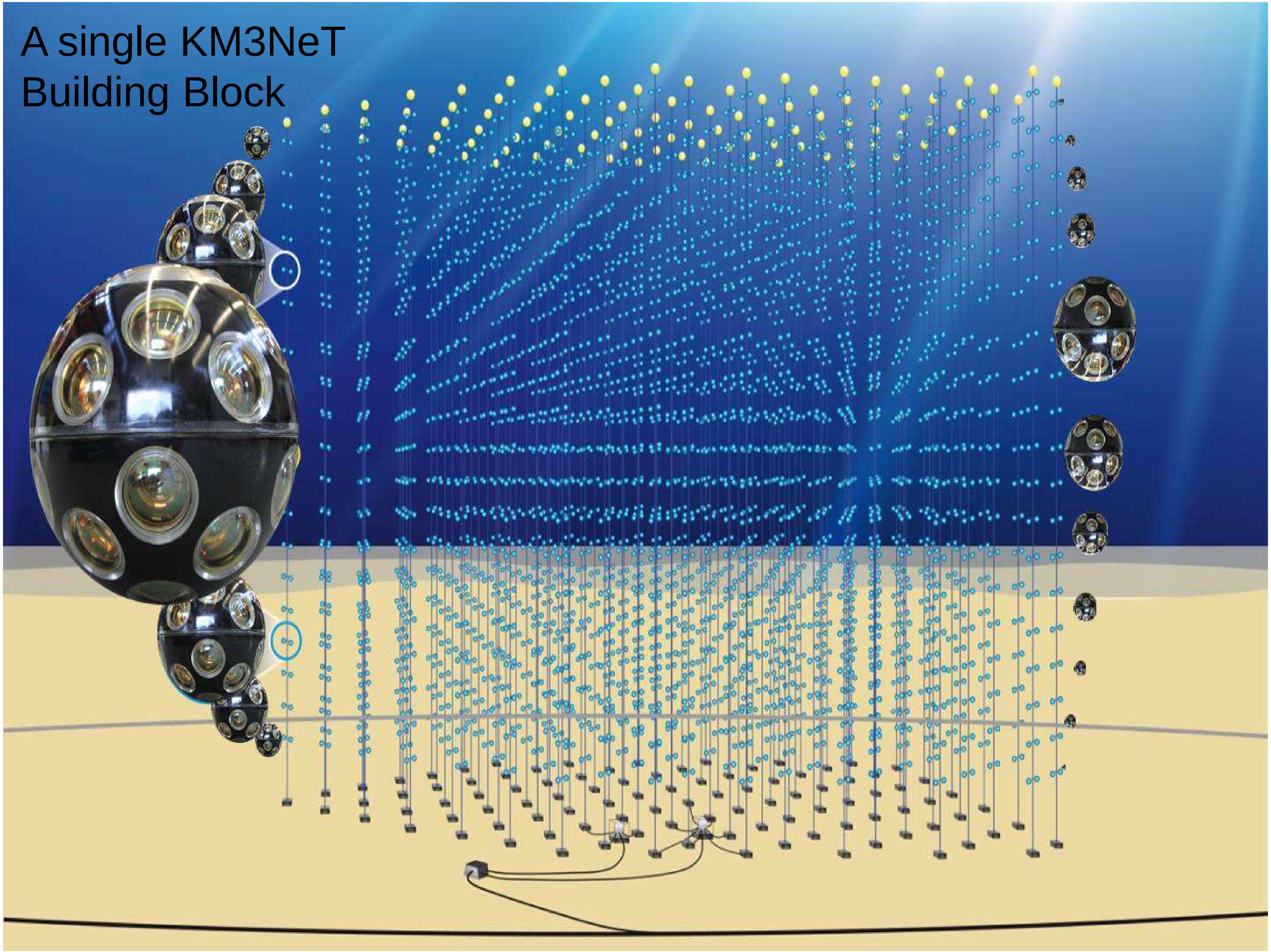
- Staged implementation:

Phase-1 in progress (31 M€)	31 strings (2 building blocks)
Phase-1.5 LoI	220 strings (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)

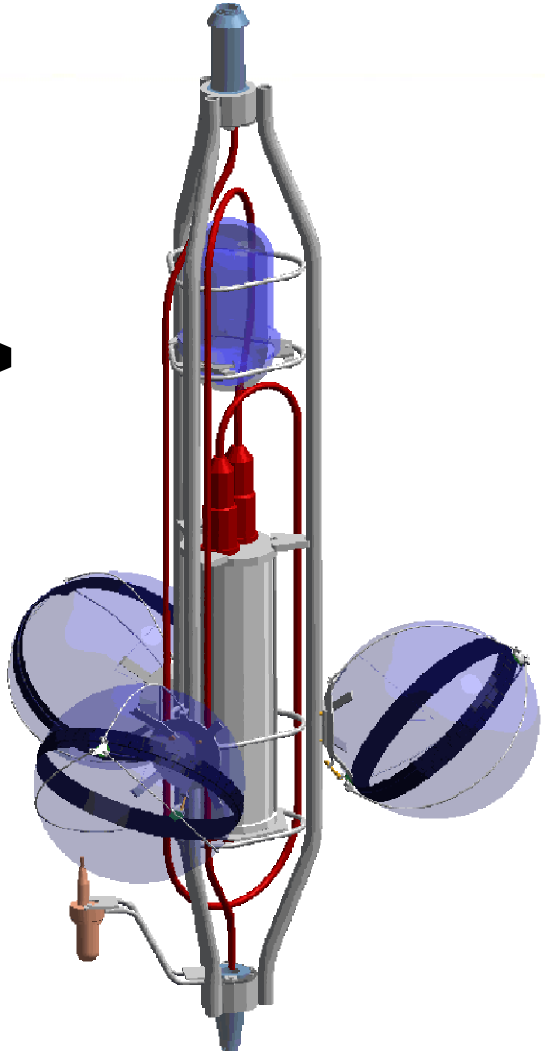
- Nodes for deep-sea research in marine sciences (EMSO)

A single KM3NeT Building Block



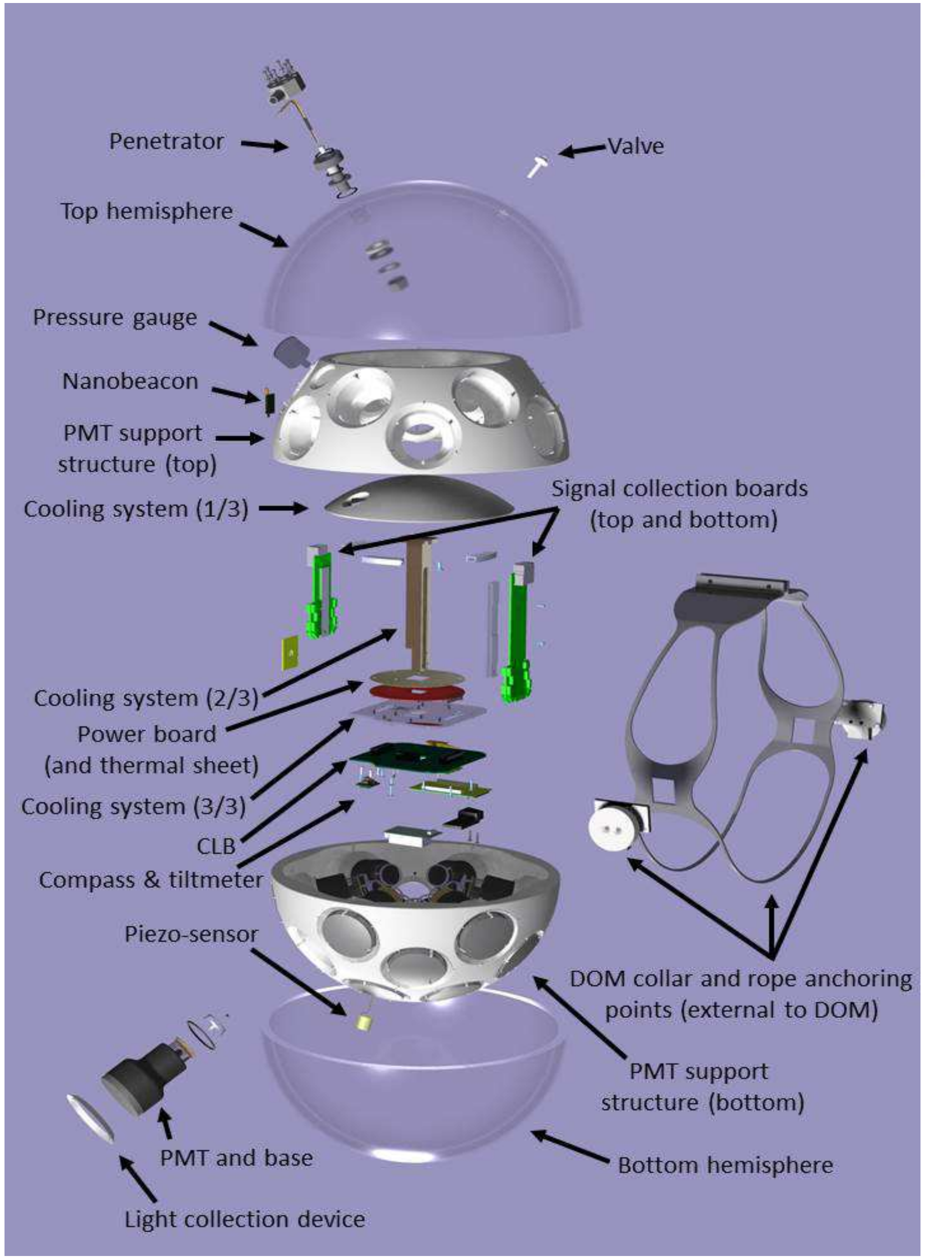
The Multi-PMT Digital Optical Module I

ANTARES Storey



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

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
  - <10 W / DOM

- FPGA readout
  - sub-ns time stamping
  - time over threshold
  - all data to shore

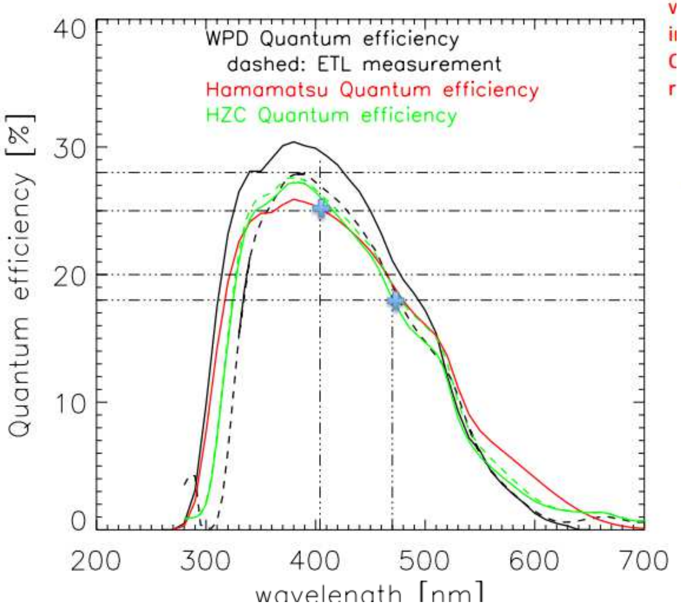
- Calibration
  - LED & acoustic piezo

- 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



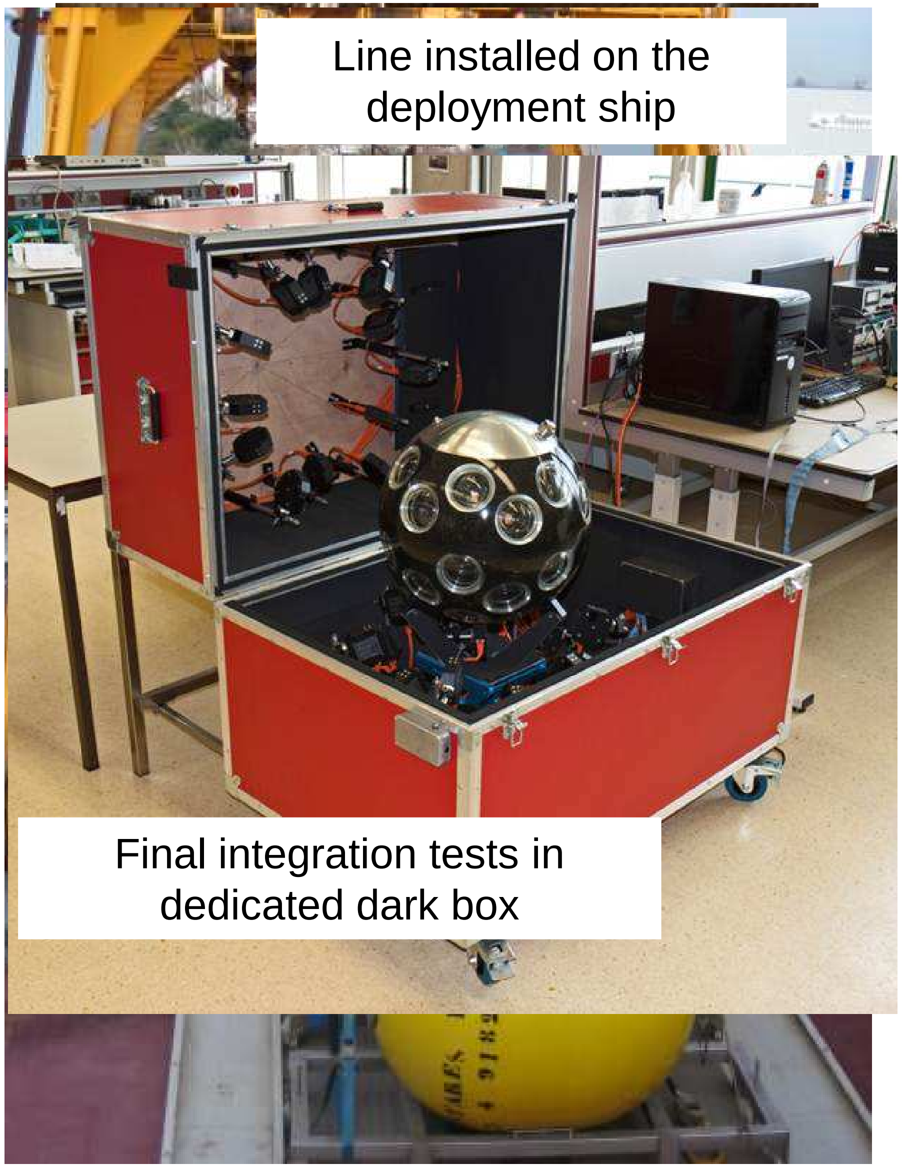
ETL
ETL D792KFL
9cm diameter

Hamamatsu
R12199-02
8cm diameter

Cost/PC area
cheaper than
10 inch

The Pre-Production Optical Module (PPM-DOM)

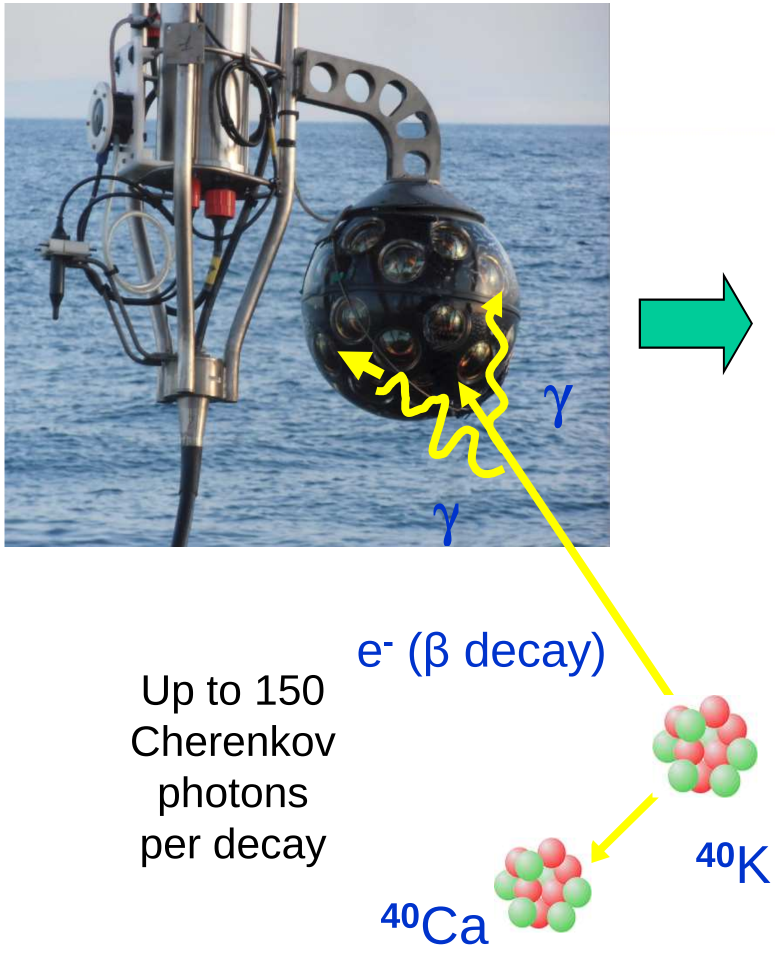
- Fully equipped DOM (31 PMTs + acoustic positioning sensors + time calibration LED beacon)
- Mounted on the Instrumentation Line of ANTARES (2475m deep)
- deployed and connected with ROV on 16 April 2013
- PPM-DOM fully operational and working well



Line installed on the deployment ship

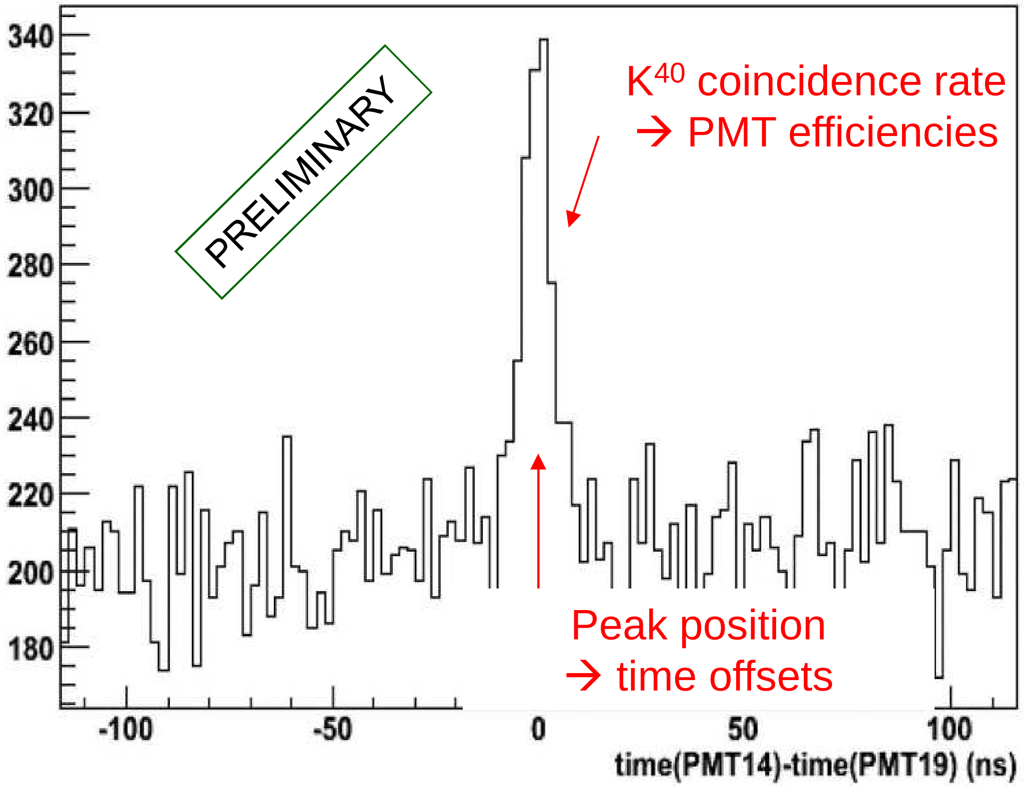
Final integration tests in dedicated dark box

PPM-DOM: K40 Coincidences



Up to 150
Cherenkov
photons
per decay

Coincidence rate on 2 adjacent PMTs

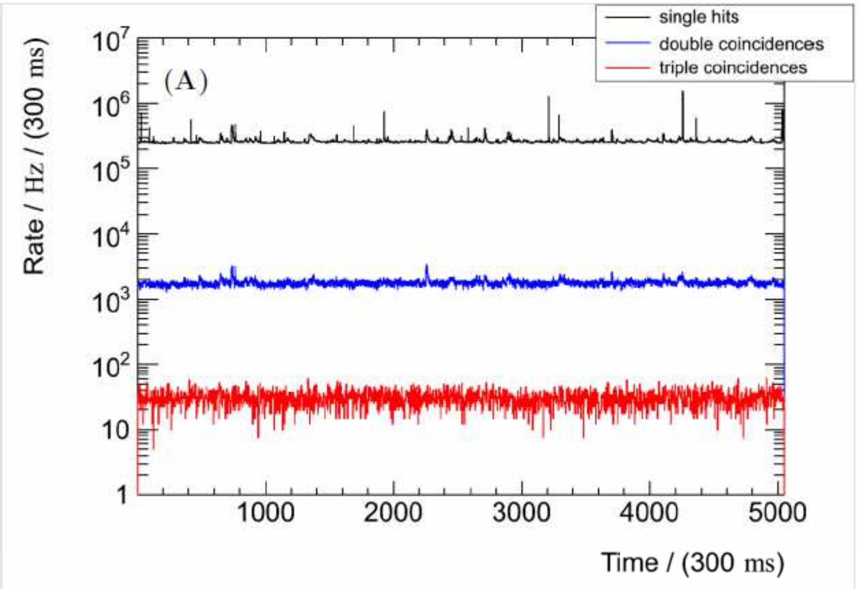


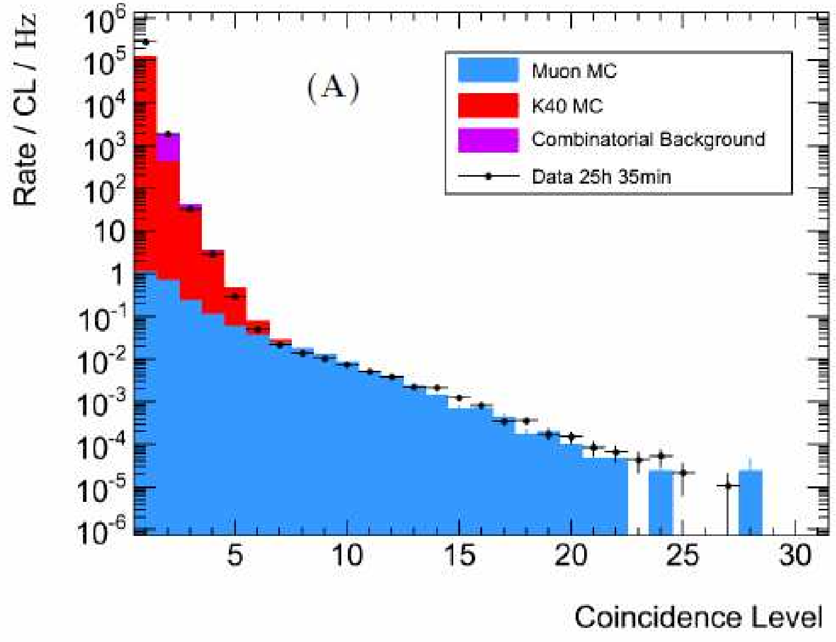
K^{40} coincidence rate
→ PMT efficiencies

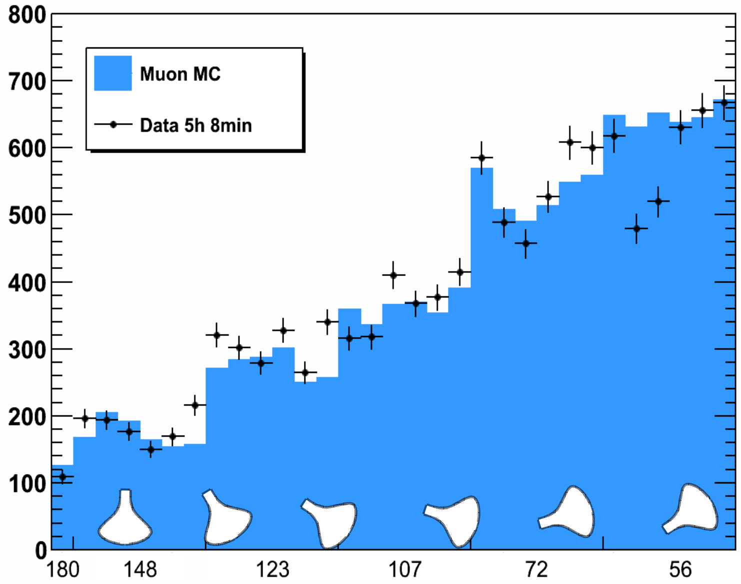
Peak position
→ time offsets

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

KM3NeT DOM: works beautifully



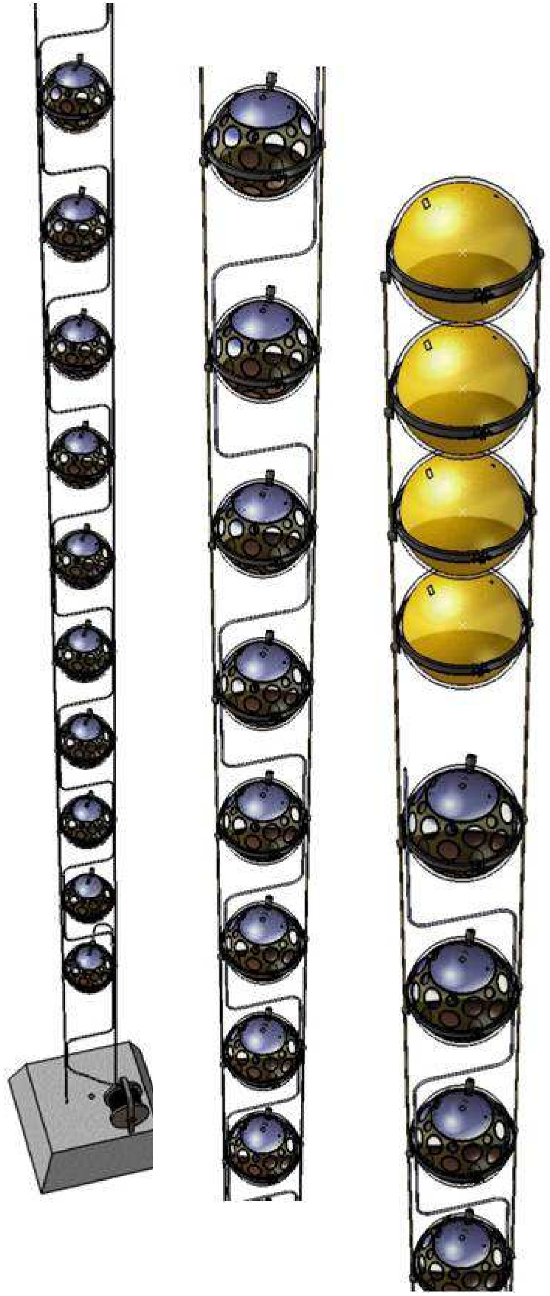




Strings

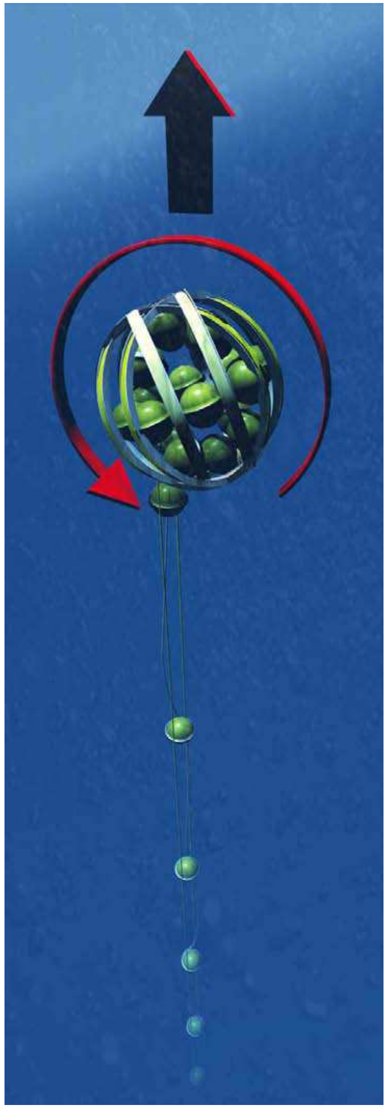
- Mooring line:
  - Buoy
  - 2 Dyneema ropes (4 mm diameter, prestreched)
  - 18 storeys (one DOM each),
    36m spacing, 100m anchor-first storey

- Electro-optical backbone:
  - Oil filled flexible hose ~6mm diameter
  - 12 fibres and 2 copper wires
  - At each storey: 1 fibre+2 wires
  - Break out box with fuses at each storey:
    single pressure transition



String Deployment

Slender string rolled up for self-unfurling:

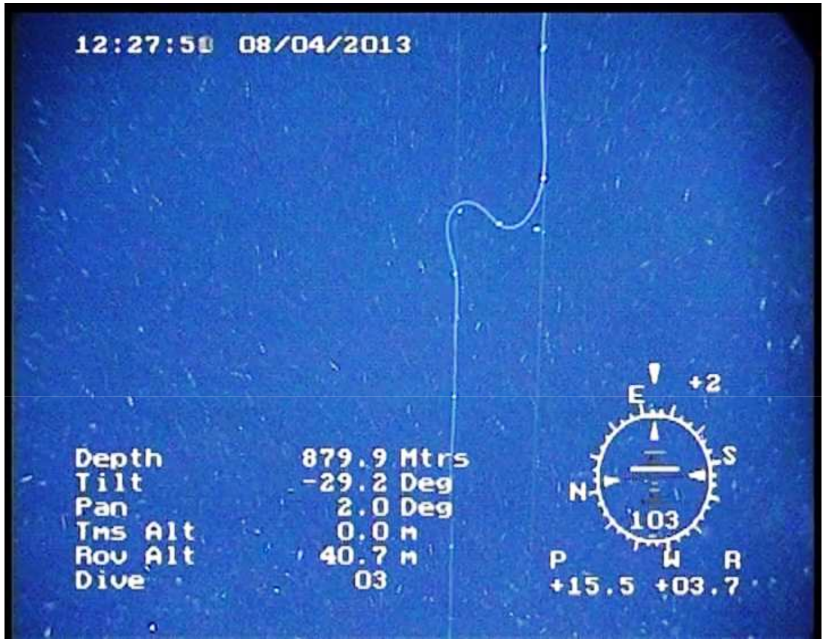


- Fast mounting of optical modules
- Rapid deployment
- Autonomous unfurling
- Recovery of launcher vehicle

Multiple deployments with a single cruise

String Mechanical Deployment Tests

5 deployments 2-12 April at a depth of 1000m (NIOZ boat)
20 miles off the coast of Motril, Spain



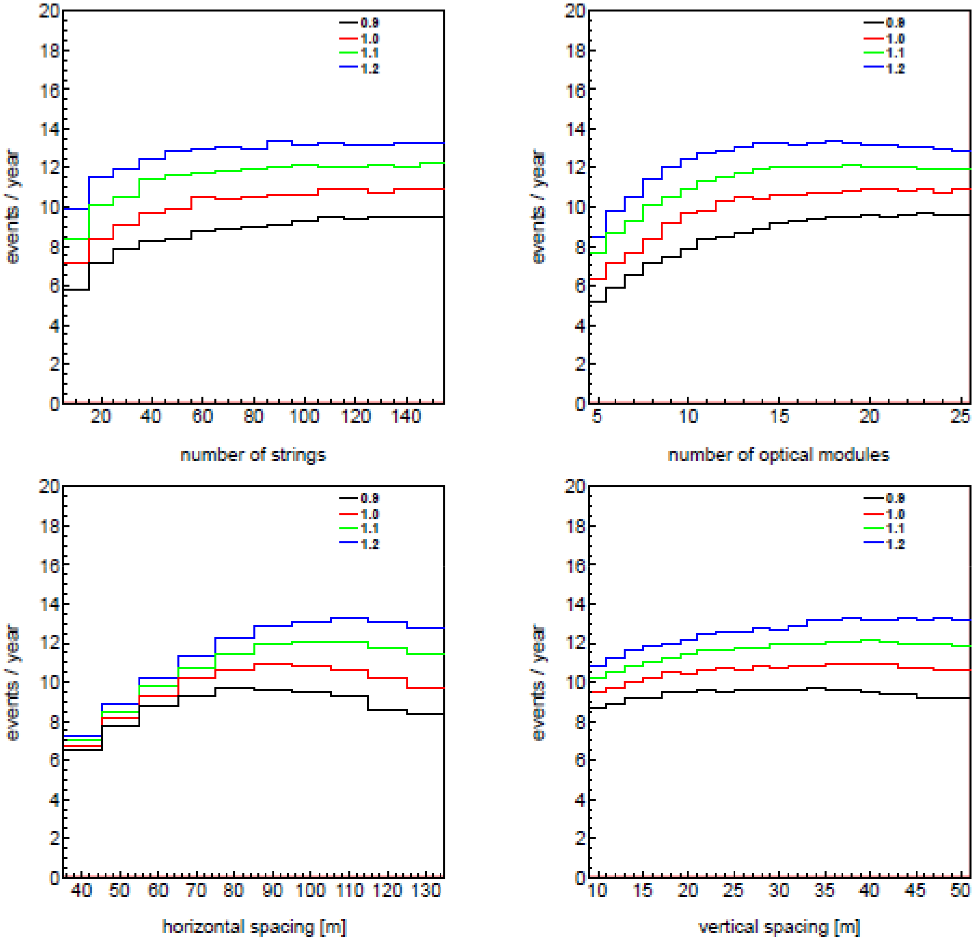
- Successful demonstration of deployment concept
- DOMs are horizontal
- VEOC cable -> no leaks
- Some issues with penetrators (understood)
- Second test in June

Detector Optimisation

Optimised for muon neutrinos
from Galactic sources-

Test case: estimated neutrino flux
from HESS gamma measurement of
SNR RXJ1713
→ spectra with high energy cutoff

optimal⇒
Inter-string spacing: ~90m
Inter-DOM spacing: ~36m
DOMs/string: 18
Building block: ~115 strings
No of building blocks: 6



Technical preference for smaller blocks
-> no sensitivity loss for blocks of ~1/2 IceCube size or larger
-> Eases multi-site implementation

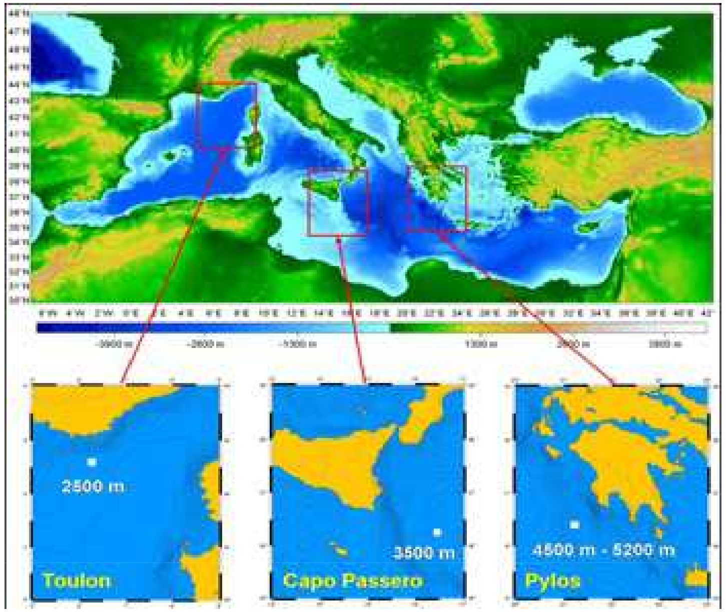
Seabed Infrastructure

- Decision taken for distributed infrastructure:

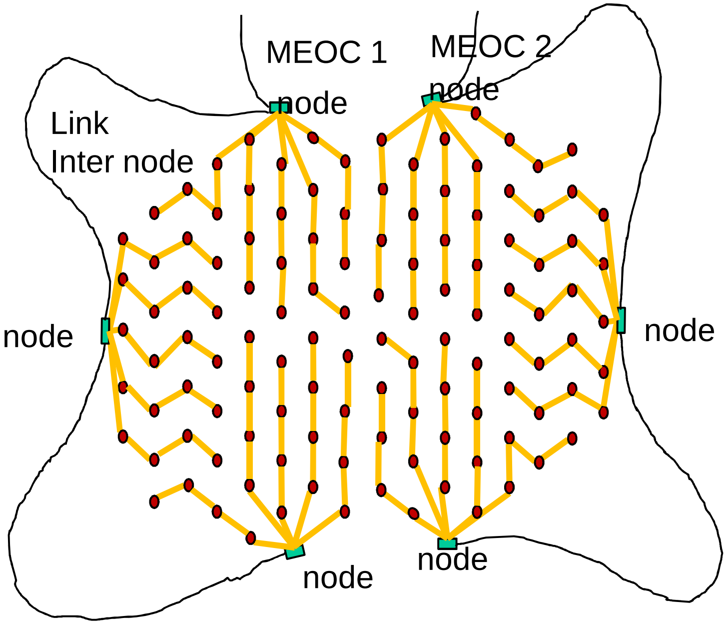
  - KM3NeT-France (Toulon) ~2500m

  - KM3NeT-Italy (Capo Passero) ~3400m

  - KMNeT-Greece (Pylos) Phase2 ~4500m



- Shore distances; 15km-100km
- Power via main electro-optical cable
  - short distances (AC), Long distances (DC)
  - 24-36 Optical fibres
- e.g; KM3NeT-Fr
  - 3 nodes per MEOC
  - 20 strings per node
  - 4 strings in series

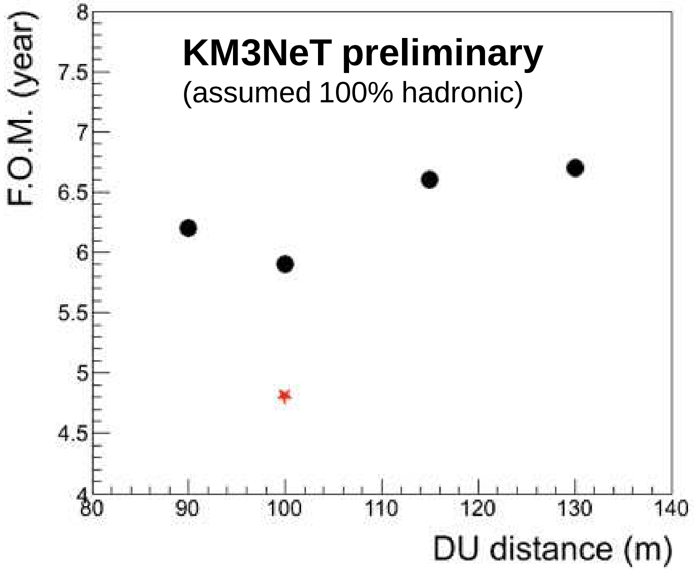


KM3NeT Science: Some Examples

SNR RXJ1713

5 years for observation at 5σ (50% probability)

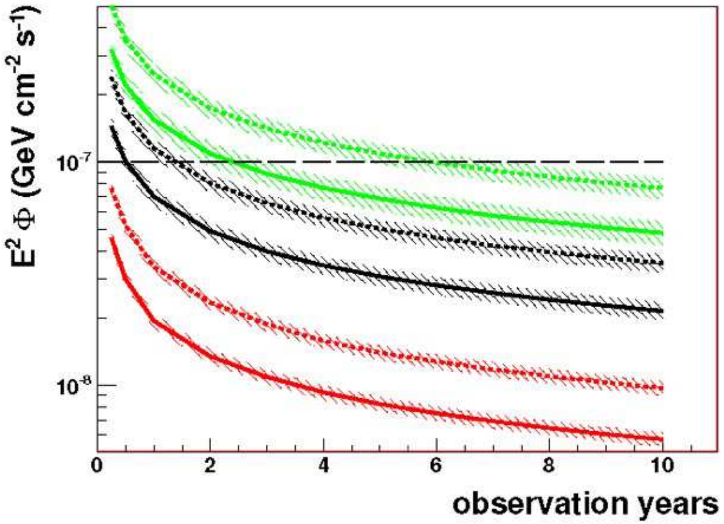
Further candidate sources with similar or better discovery chances (Vela X, Fermi Bubbles)



Fermi Bubbles

Easily detectable by KM3NeT
5 sigma in 1 year (100 TeV cutoff)

Martinez et al. Astrop. Phys. 42 (2013) 7



Diffuse Flux

Neutrino flux from multitude of unresolved sources

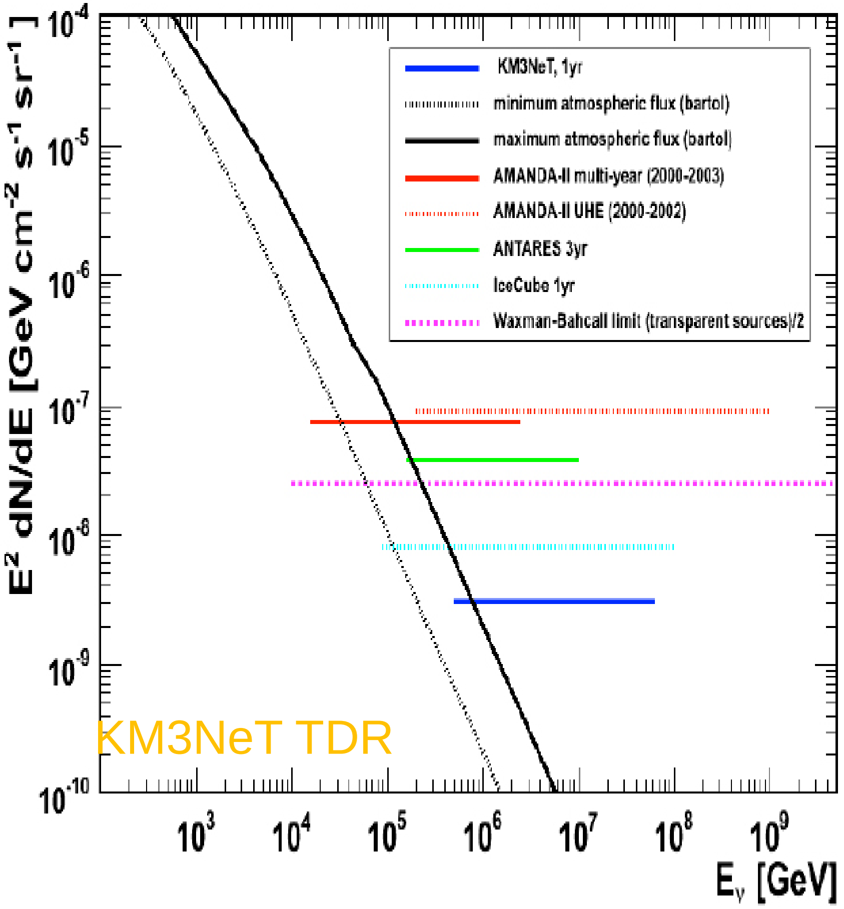
KM3NeT sensitivity:
~3.7 10^{-9} GeV/cm^2/s/sr (1 yr, Phase 2)
(5σ, 2yrs, Phase 1.5)

Current ANTARES sensitivity:
4.7 10^{-8} GeV/cm^2/s/sr (3 yrs)

IceCube ‘excess: muon nu flux
of ~1.2 10^{-8} GeV/cm^2/s/sr (2 yrs)

KM3NeT performance for cascade channels, muon veto under evaluation

Muon neutrino

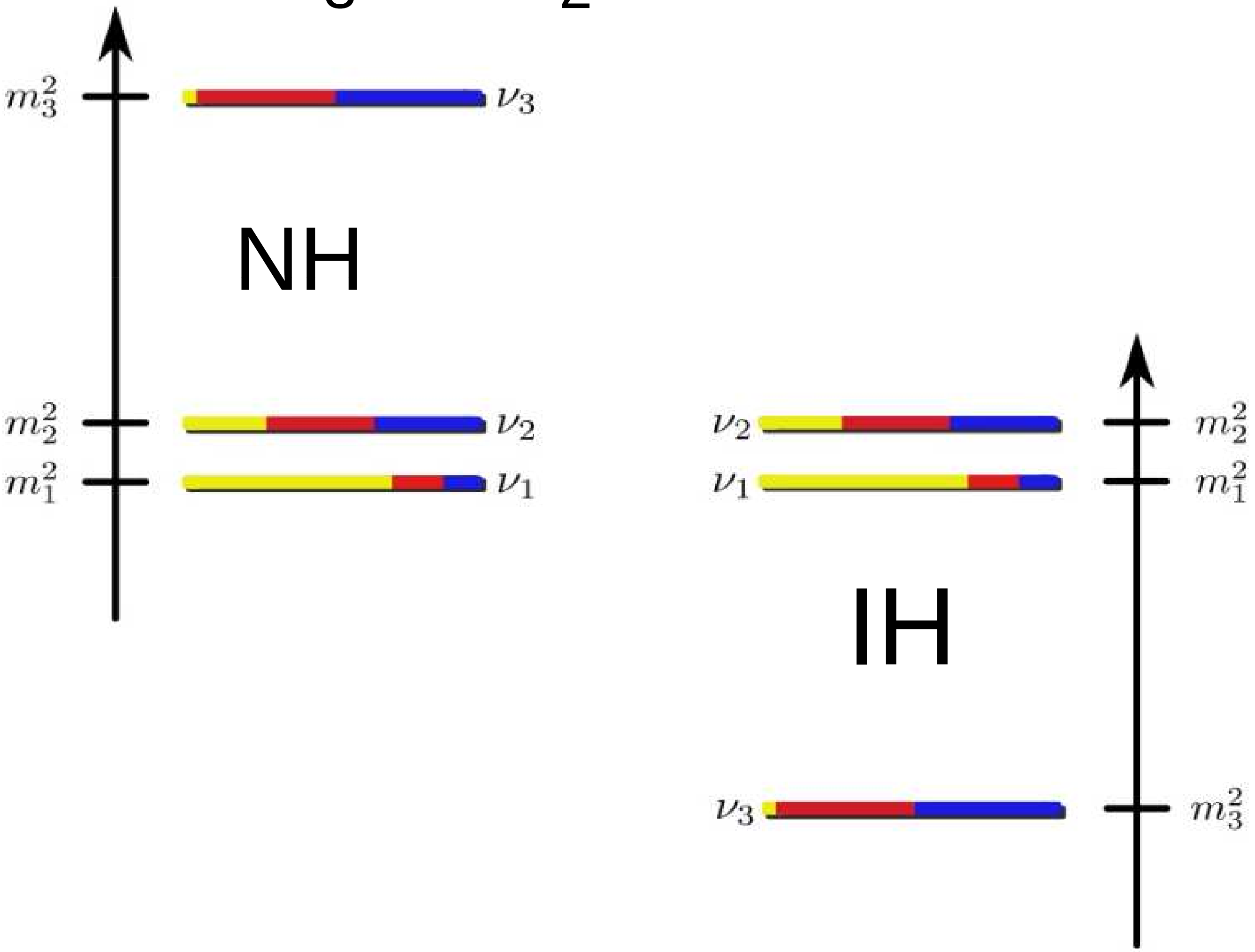


KM3NeT TDR

Neutrino Mass Hierarchy

$m_3^2 > m_2^2$ Normal hierarchy

$m_3^2 < m_2^2$ Inverted hierarchy



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

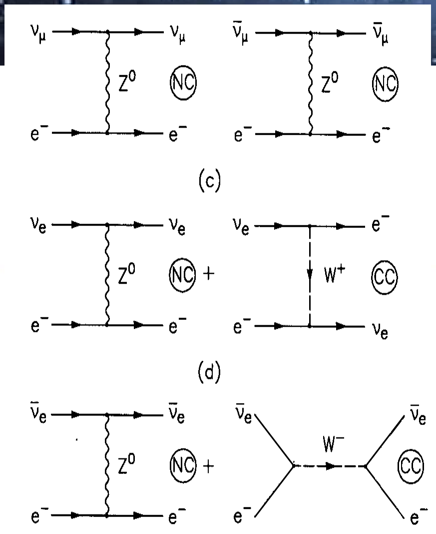
- At these energies $\sigma(\nu) \approx 2\sigma(\overline{\nu})$ so observe net effect

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

  arxiv:1205.7071v4 ,Akhmedov, Razzaque, Smirnov

Matter Effects

- Ordinary matter: electrons, but no μ, τ
- Coherent forward scattering on electrons in matter: Net effect on electron flavour component of neutrino mass eigenstates



Vacuum: $P_{\alpha\alpha} = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}$

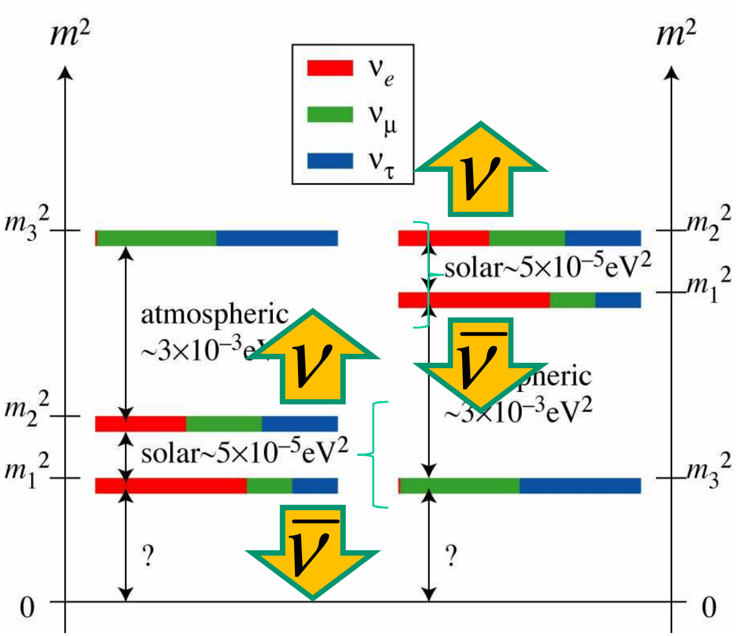
Matter: $P_{\alpha\alpha} = 1 - \sin^2 2\tilde{\theta} \sin^2 \frac{\Delta \tilde{m}^2 L}{4E}$

$$\boxed{\Delta\tilde{m}^2 = \xi\cdot\Delta m^2, \qquad \sin 2\tilde{\theta} = \frac{\sin 2\theta}{\xi},}$$

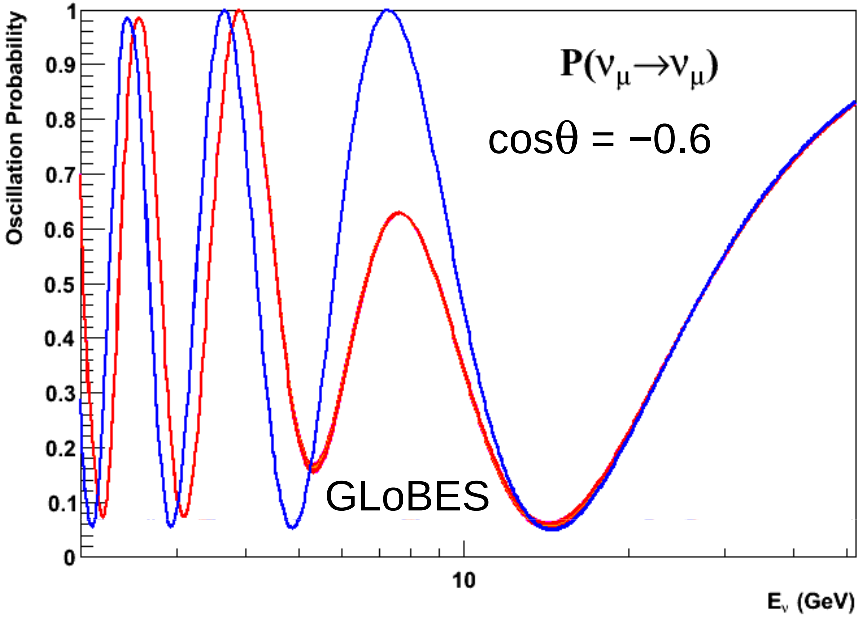
$$\xi \equiv \sqrt{\sin^2 2\theta + \left(\cos 2\theta - \hat{A}\right)^2},$$

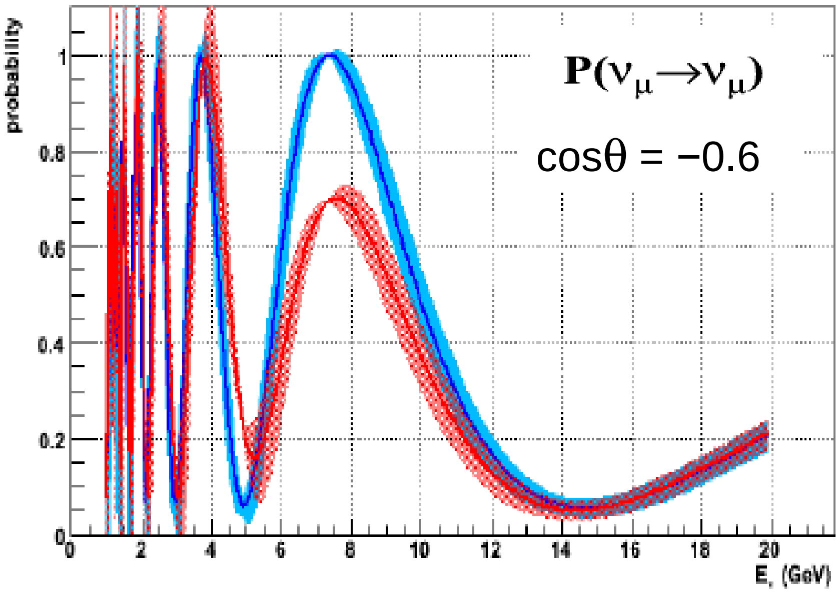
$$\hat{A} = \frac{2EV}{\Delta m^2} = \frac{\pm 2\sqrt{2} E\, G_F\, n_e}{\Delta m^2}$$

⇨ MH



Phenomenological Considerations





Inverted Hierachy

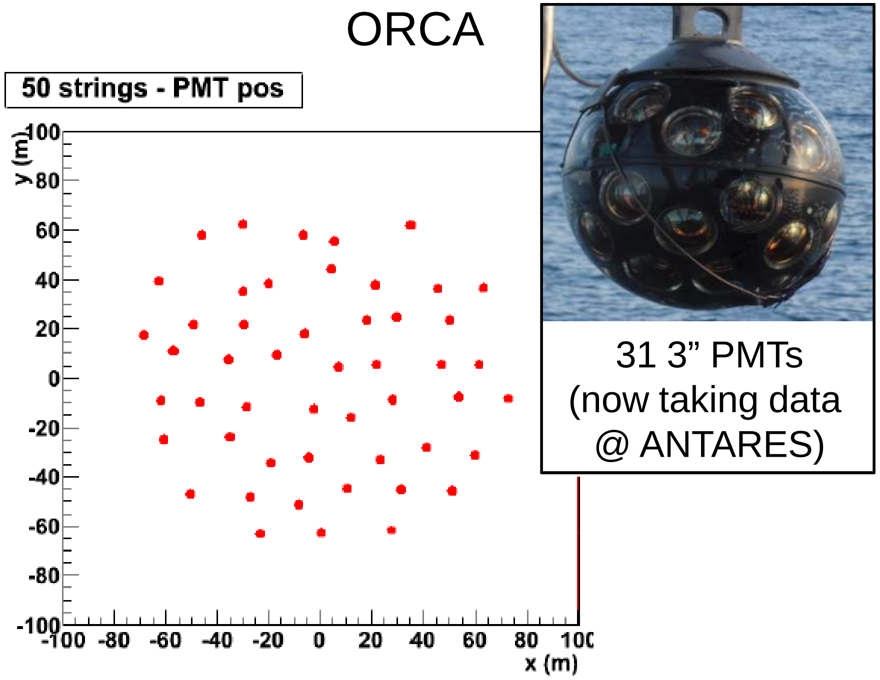
Normal Hierachy

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

Degeneracies due to parameter uncertainties must be carefully considered!

Proposed Low Energy Extensions

ORCA

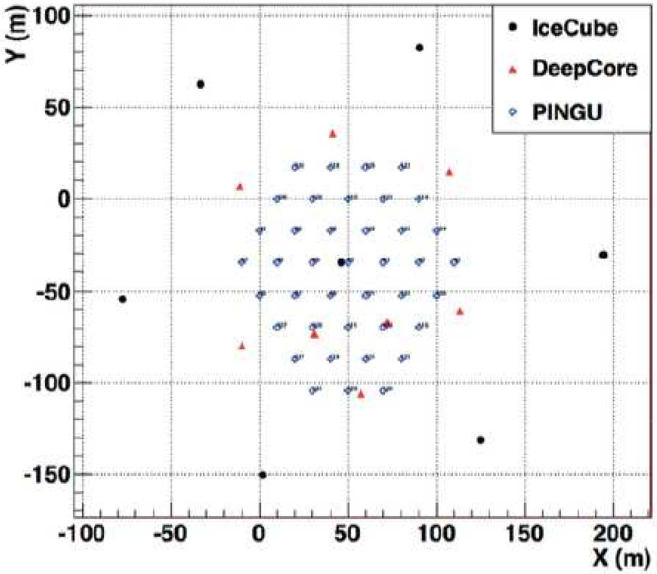


31 3” PMTs
(now taking data
@ ANTARES)

50 lines, 20m spaced,
20 OM/line 6m spaced
Instrumented volume ~2 Mt, 1000 OM

Could be deployed in <5 years
31 M€ available in KM3NeT Phase-1

PINGU



40 strings, 20-25m spaced,
60 OM/string 5m spaced
Instrumented volume ~ 6 Mt, 2400 OM

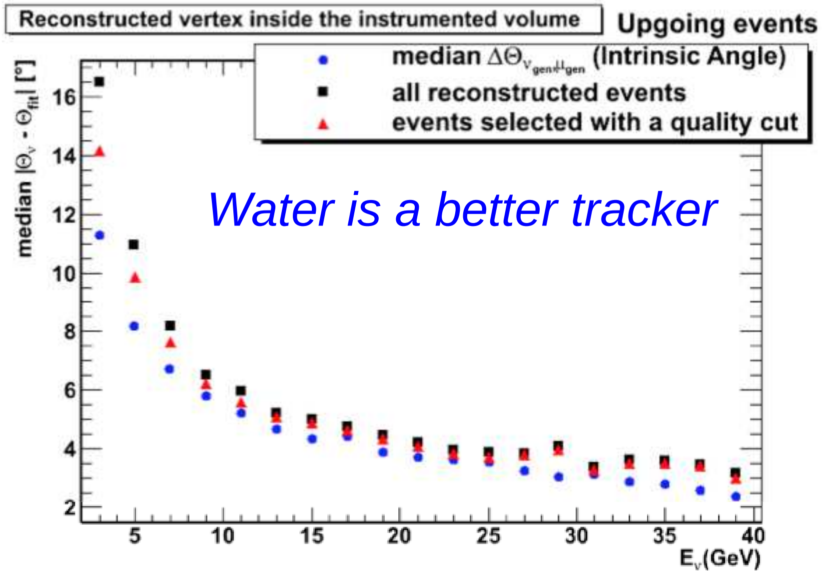
Could be deployed 2016-2020 if funded
(~60-80M$)

Optimized layouts still under study

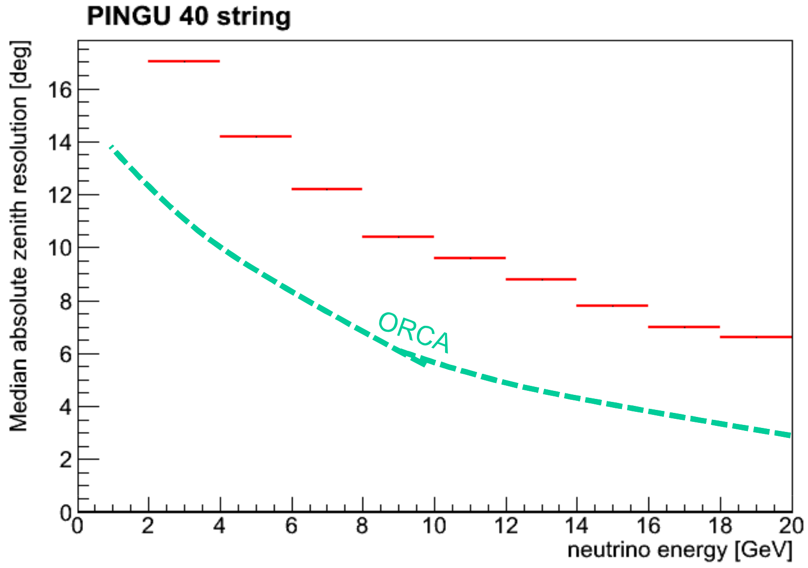
📖 P. Koojman et al, ICRC proc 0164

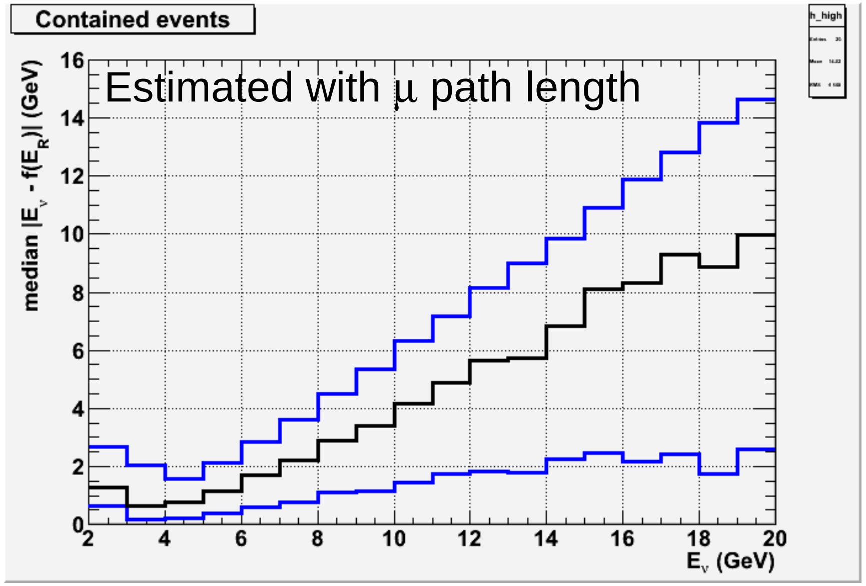
📖 http://arxiv.org/abs/1401.2046

Preliminary performances

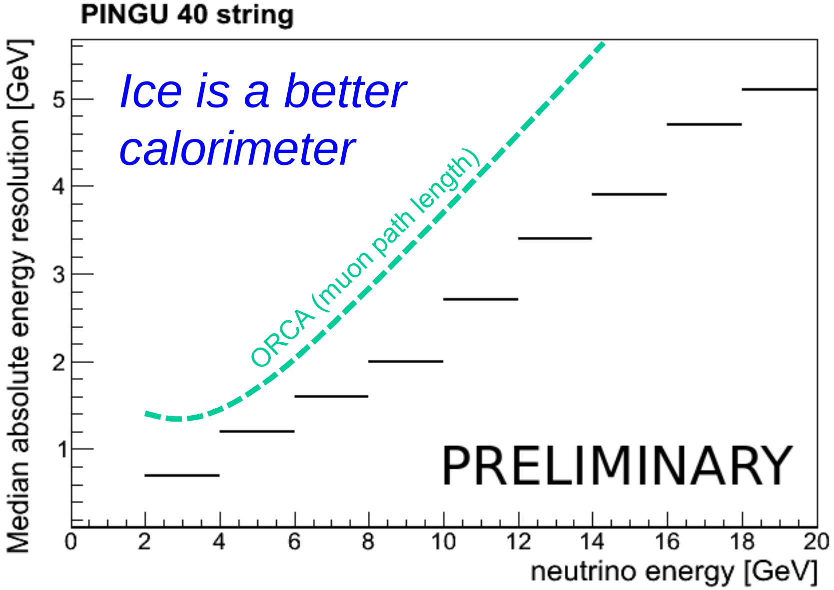


Water is a better tracker





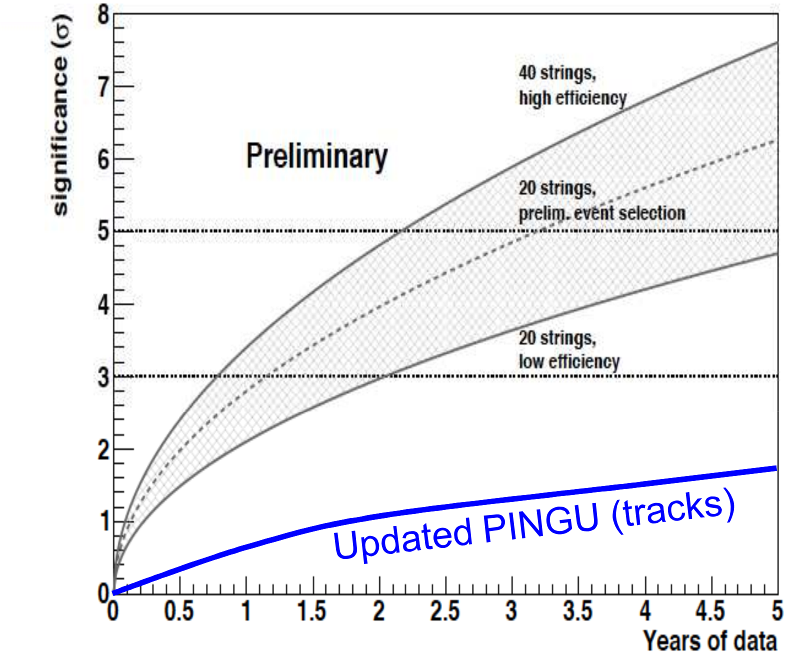
Estimated with μ path length



Ice is a better calorimeter

PINGU sensitivities

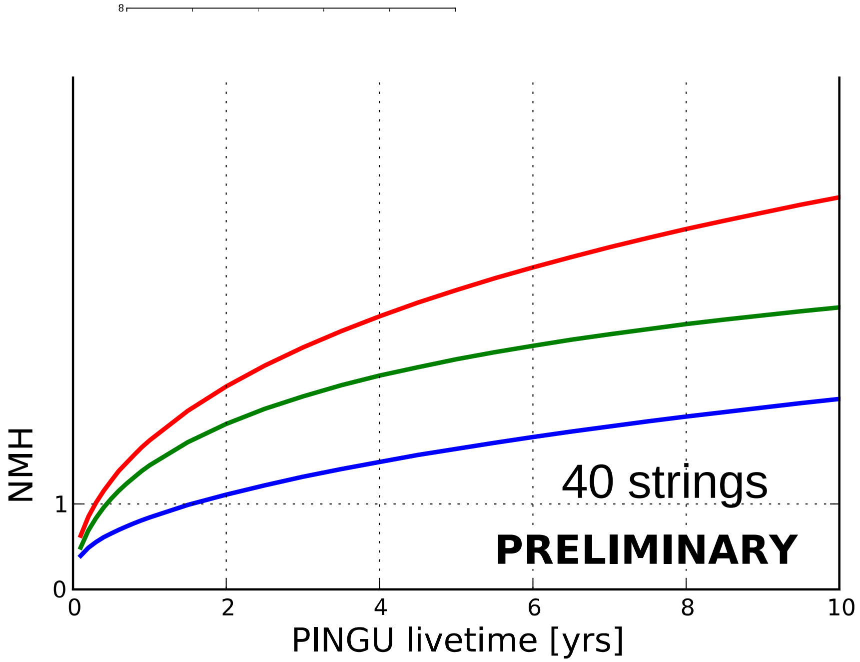
📖 PINGU collaboration, arXiv:1306.5846



Different studies performed.
Sys uncertainties include norm (30%), spectral index (±0.05), energy scale (10%), zenith bias (10%)
Realistic energy and direction resolutions

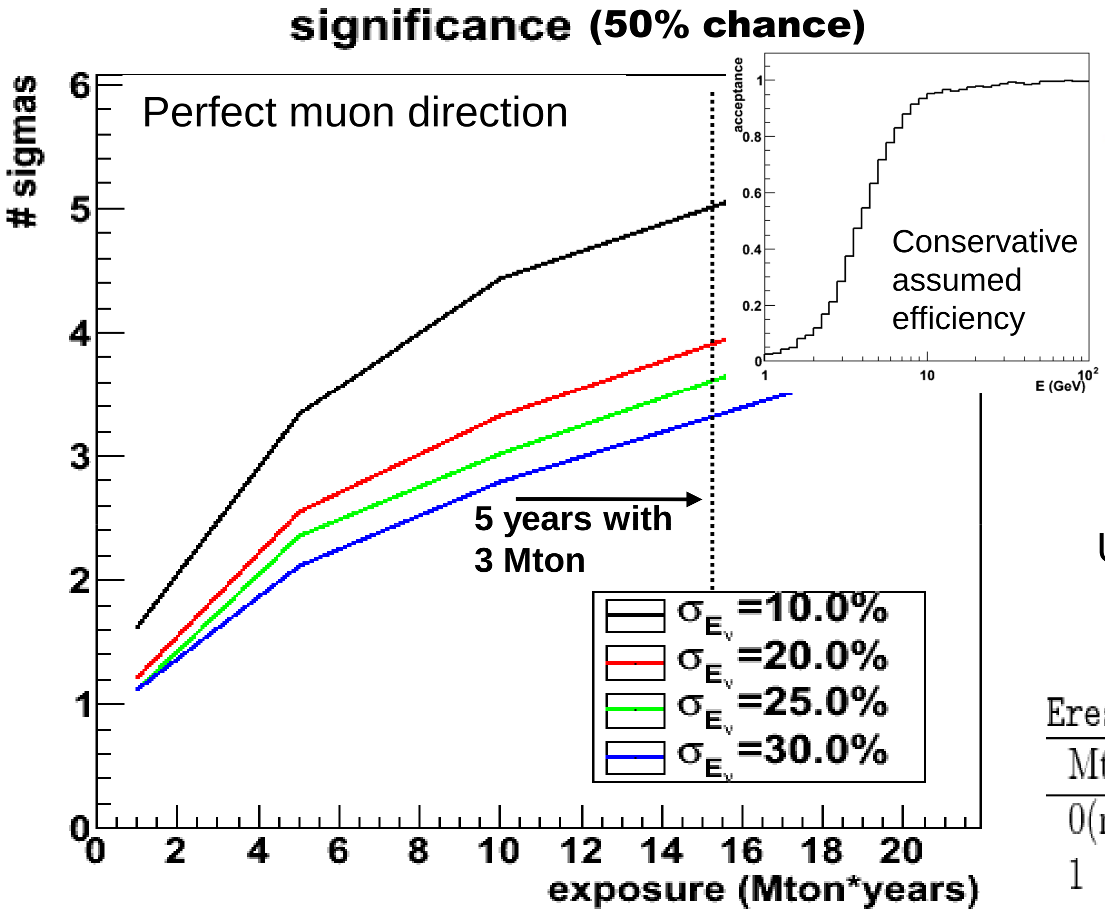
Some sensitivity recovered with "cascade" events
(same resolutions as tracks)

📖 Recent Update (includes cascades)



- Analysis fully updated since Snowmass
  - Factors lowering significance:
    - higher MC sampling to eliminate unanticipated systematic bias from fluctuations
    - more accurate resolution parametrizations
    - inclusion of NC events
    - kinematic suppression of ν_τ events
  - Factors raising significance:
    - improved event selection
    - improved event fitting
    - use of cascades, PID

ORCA sensitivity



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

all results are preliminary

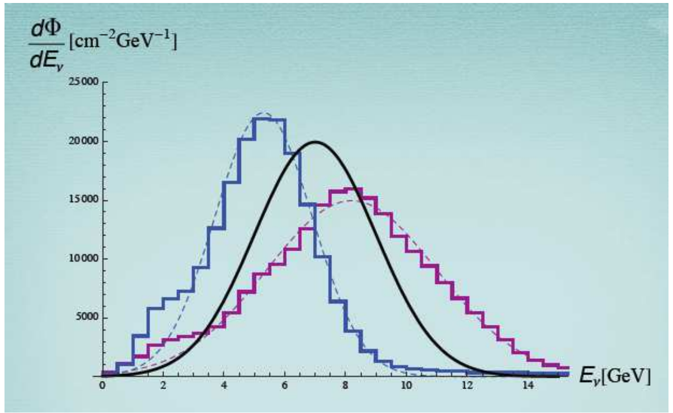
A Neutrino beam to ORCA? I

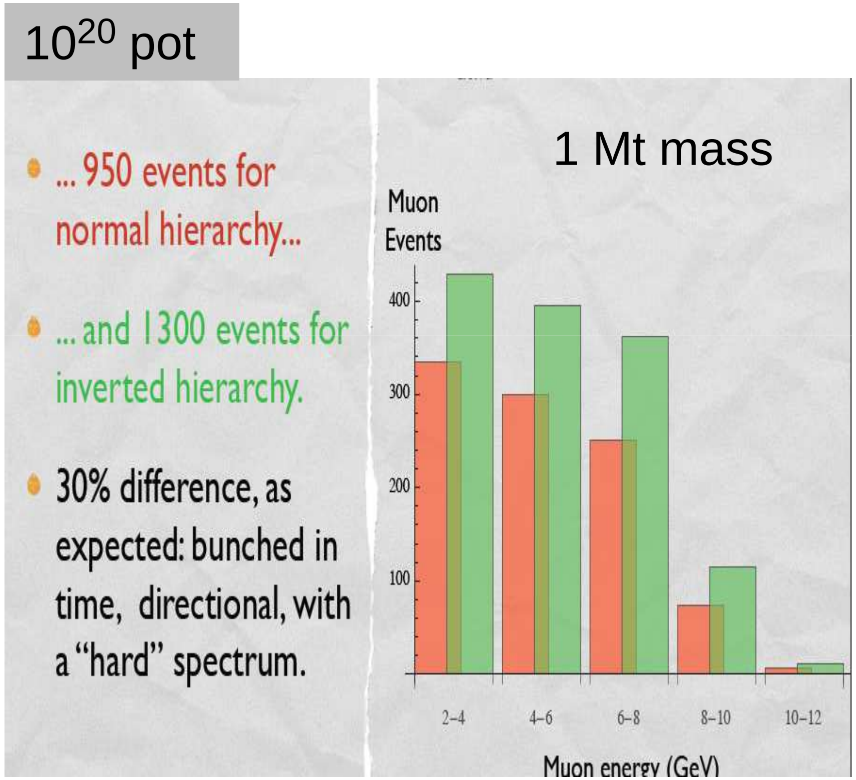
- Muon counting experiment - Optimum 6-8GeV, 6000-8000km but large beam inclination

📖 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

NUMI beam rescaled to 7800 km





- ... 950 events for normal hierarchy...
- ... and 1300 events for inverted hierarchy.
- 30% difference, as expected: bunched in time, directional, with a "hard" spectrum.

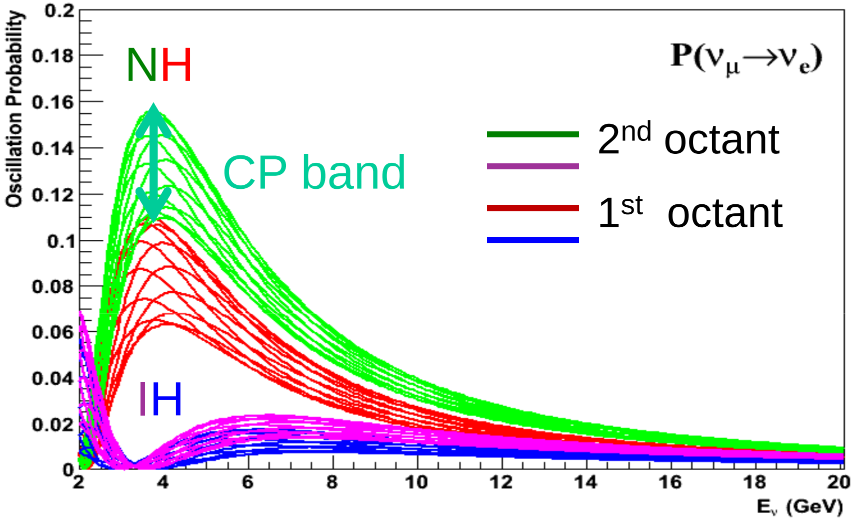
→ 9 σ separation on purely statistical ground in one year

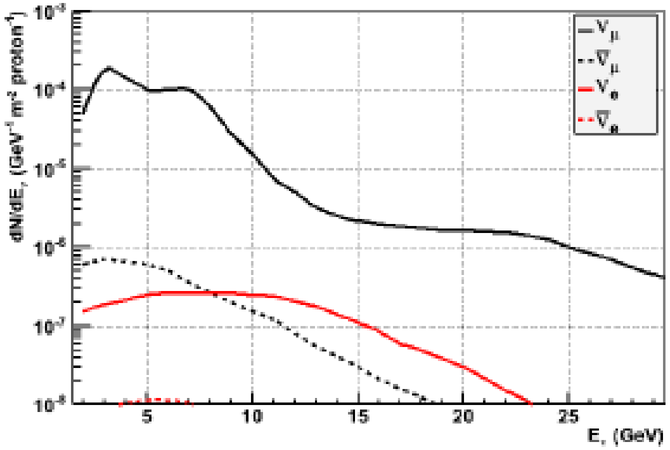
A Neutrino beam to ORCA? II

- Electron counting experiment - Protvino-ORCA L=2588 km, beam inclined by 11.7°
(3° off-axis from Fréjus Underground laboratory)

📖 J. Brunner, arXiv:1304.6230

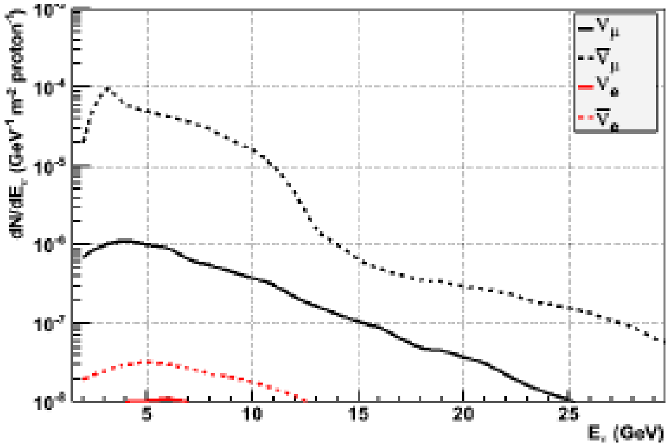
Oscillations with GLOBES





← Neutrino
Anti-neutrino →
Fluxes

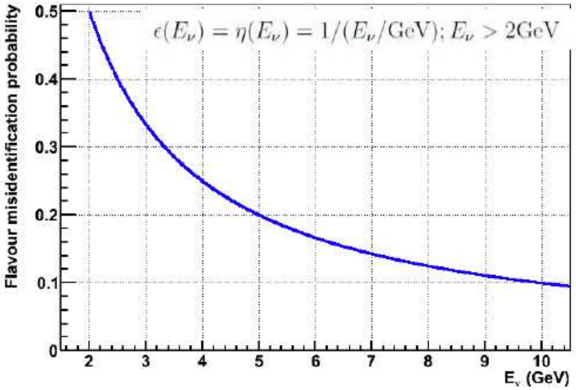
(SKAT exp. Needs update)

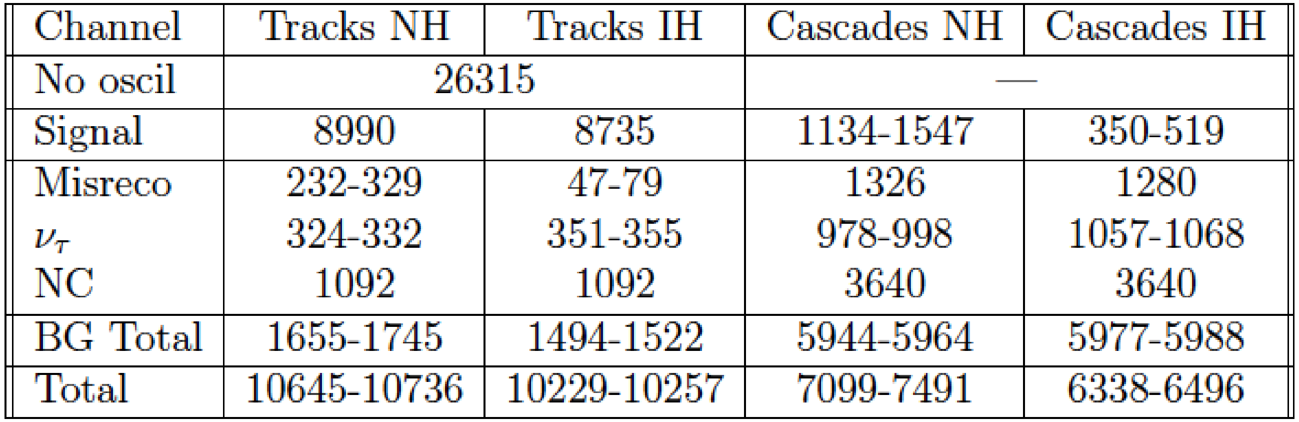


A Neutrino beam to ORCA? III

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

  - Vertex inside ORCA reference detector
  - Flavor misidentification probability based on C2GT project →
  - Event rates for 1.5x10^{21} pot (3 years)



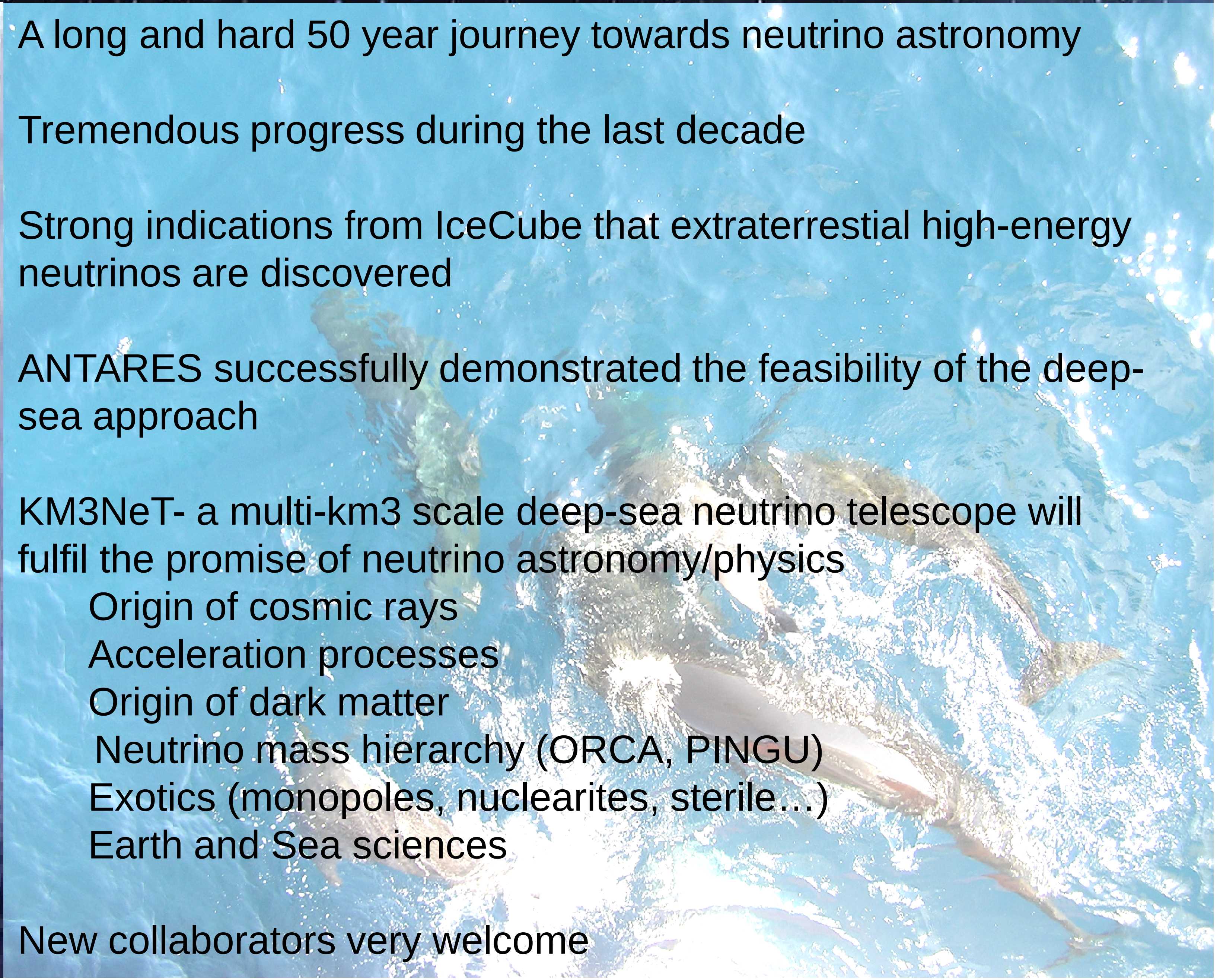


Channel	Tracks NH	Tracks IH	Cascades NH	Cascades IH
No oscil	26315		—	
Signal	8990	8735	1134-1547	350-519
Misreco	232-329	47-79	1326	1280
ν_τ	324-332	351-355	978-998	1057-1068
NC	1092	1092	3640	3640
BG Total	1655-1745	1494-1522	5944-5964	5977-5988
Total	10645-10736	10229-10257	7099-7491	6338-6496

7 σ stat. separation
3 σ with 3-4% sys

No assumption on energy reconstruction

Summary



A long and hard 50 year journey towards neutrino astronomy

Tremendous progress during the last decade

Strong indications from IceCube that extraterrestial high-energy neutrinos are discovered

ANTARES successfully demonstrated the feasibility of the deep-sea approach

KM3NeT- a multi-km3 scale deep-sea neutrino telescope will fulfil the promise of neutrino astronomy/physics
- Origin of cosmic rays
- Acceleration processes
- Origin of dark matter
- Neutrino mass hierarchy (ORCA, PINGU)
- Exotics (monopoles, nuclearites, sterile…)
- Earth and Sea sciences

New collaborators very welcome