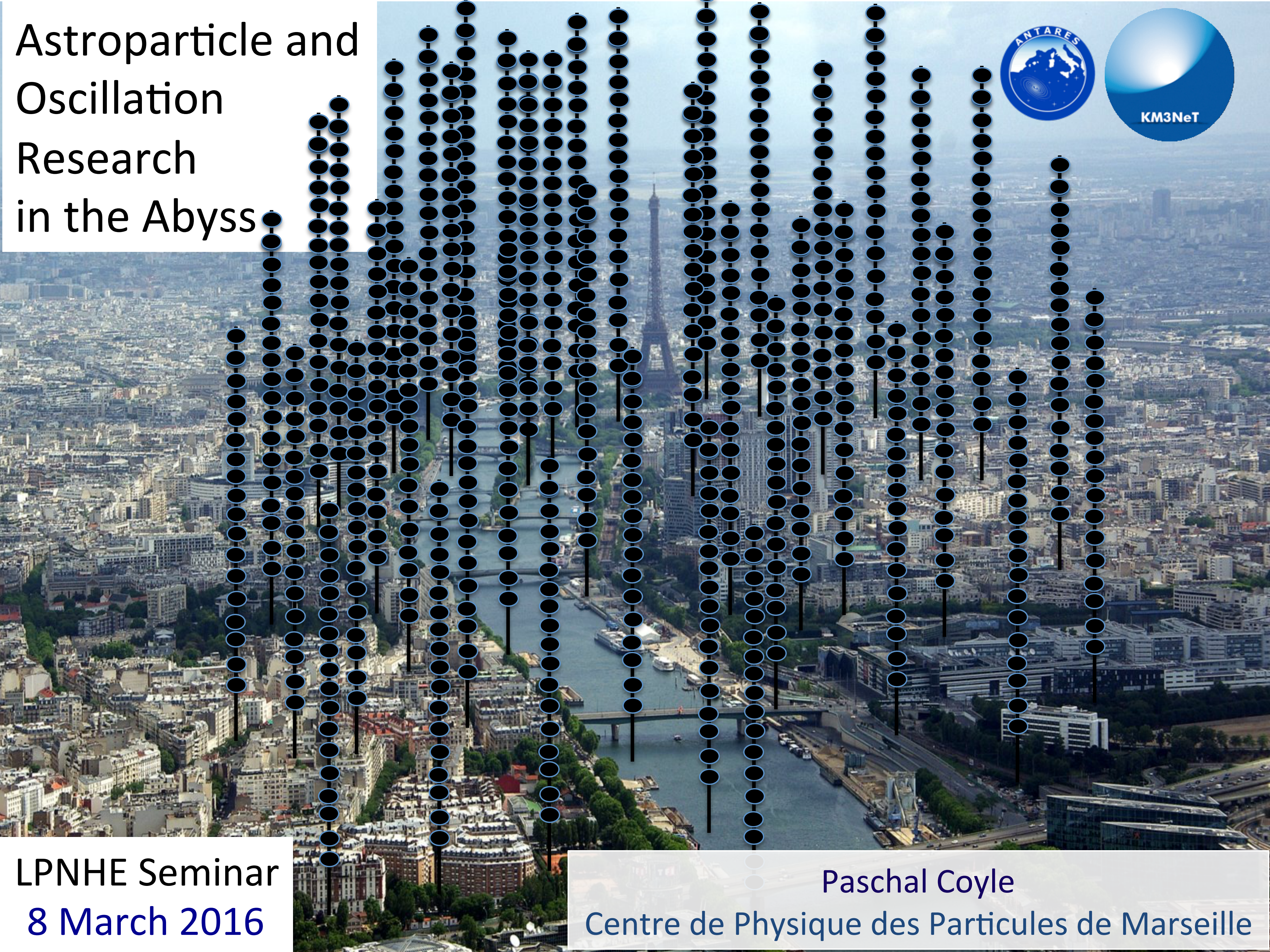
Astroparticle and Oscillation Research in the Abyss



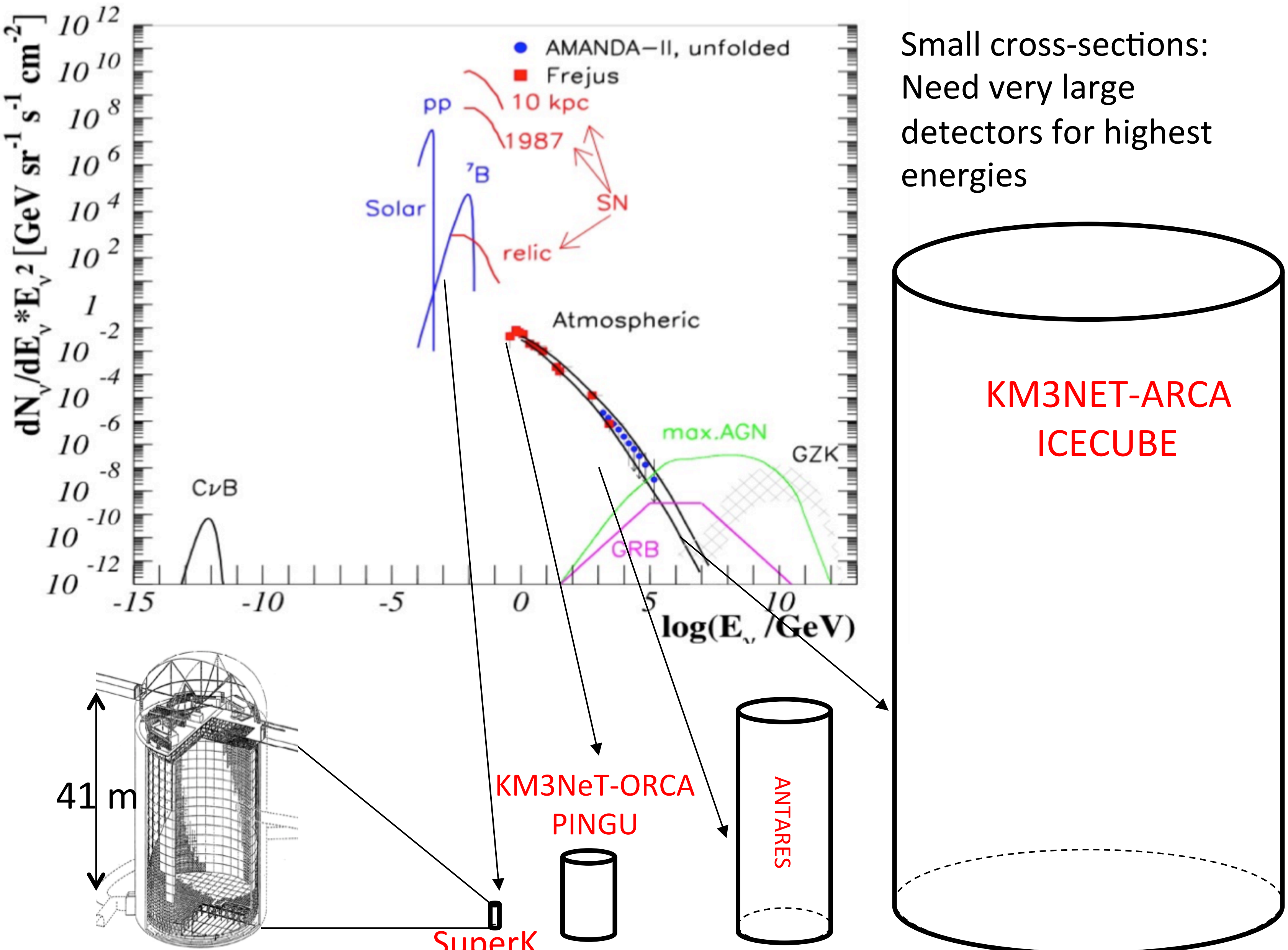
LPNHE Seminar

8 March 2016

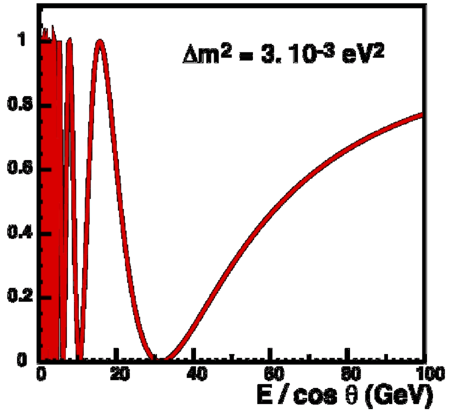
Paschal Coyle
Centre de Physique des Particules de Marseille

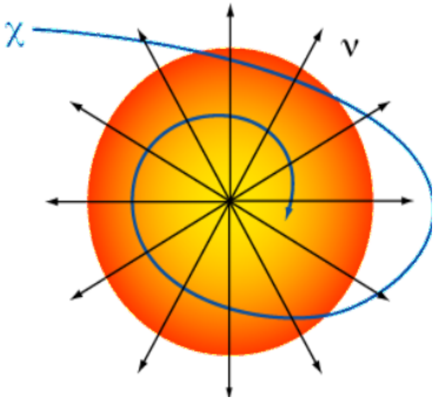
Neutrinos From MeV to PeV

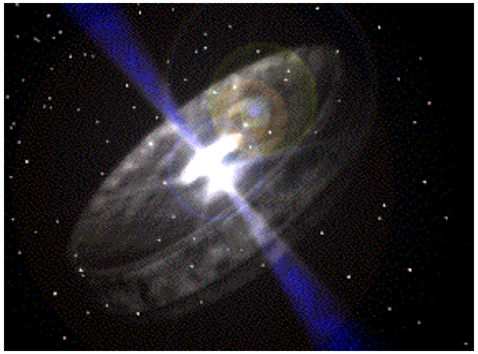
Small cross-sections: Need very large detectors for highest energies



Neutrino telescopes: science scope







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

ν Oscillations
ν Mass hierarchy

Dark matter search

ν from extra-terrestrial sources

Origin and production mechanism of HE CR

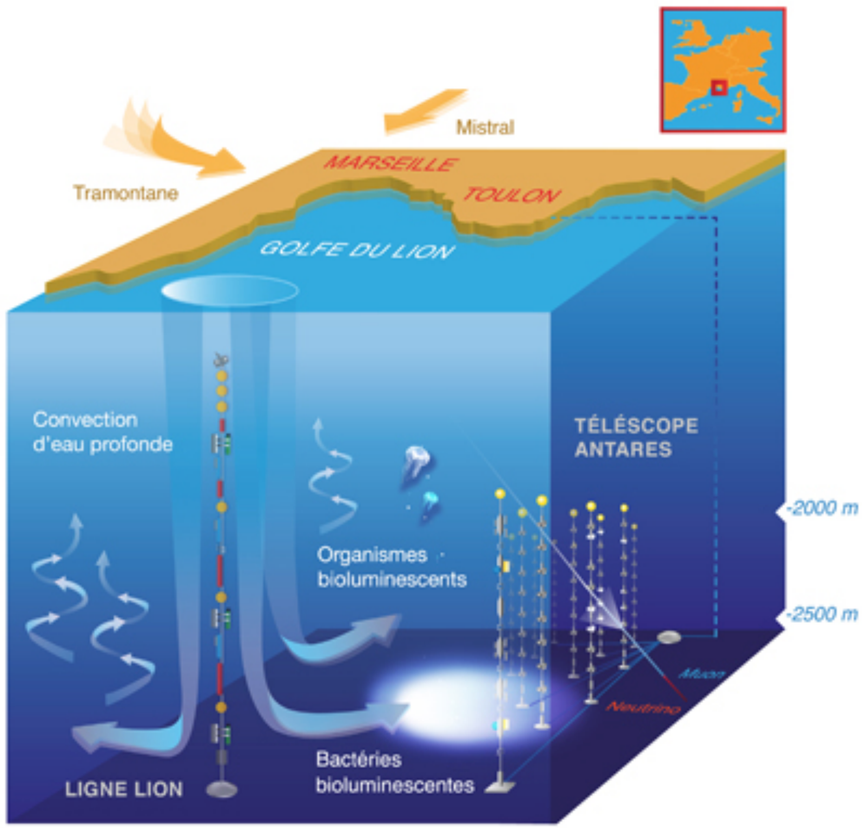
Exotic particle physics
Monopoles, nuclearites,…

oceanography, biology, seismology,…

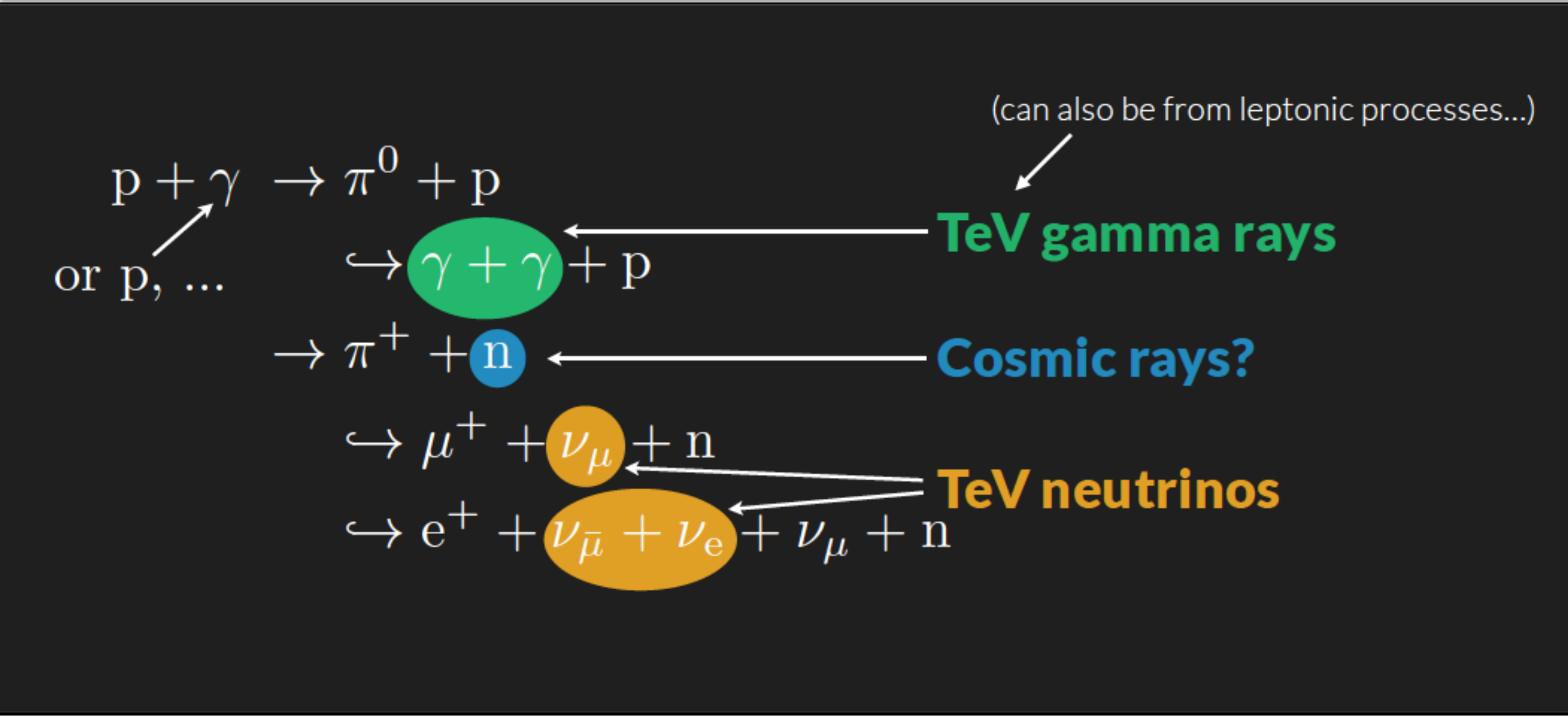
Synergies with deep-sea science

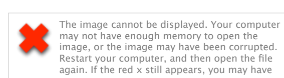
ANTARES awarded "La Recherche Prize" category "Coup de Coeur"

📖 C. Tamburini, S. Escoffier et al., PLoS ONE 8(7) 2013
Deep-sea bioluminescence blooms after dense water formation at the ocean surface



The CR-Gamma-Neutrino Connection

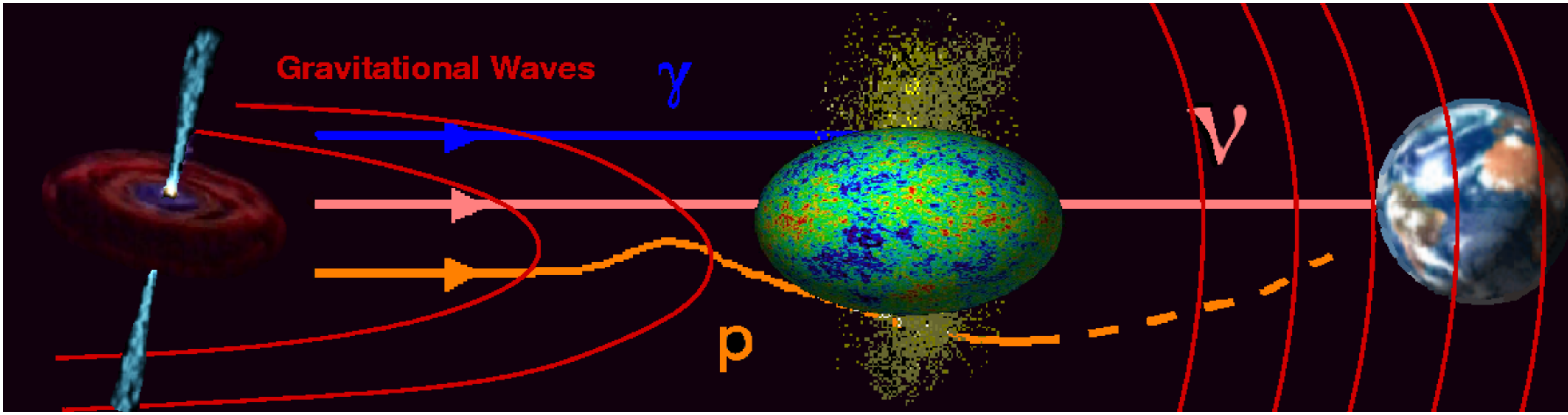


$\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ source 

$\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ Earth

$$E_\nu \approx \frac{1}{20} E_P \approx \frac{1}{2} E_\gamma$$

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

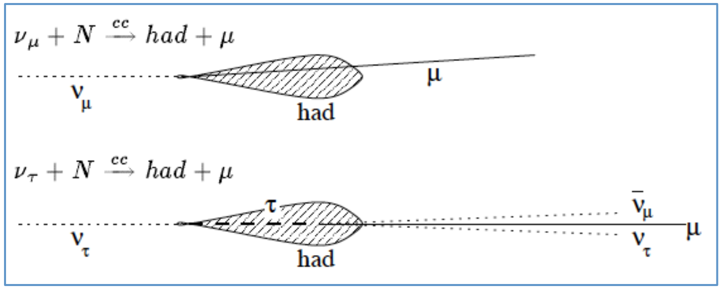
Neutrinos

Unambiguous 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 EM signals
Full sky
24/24, 7/7

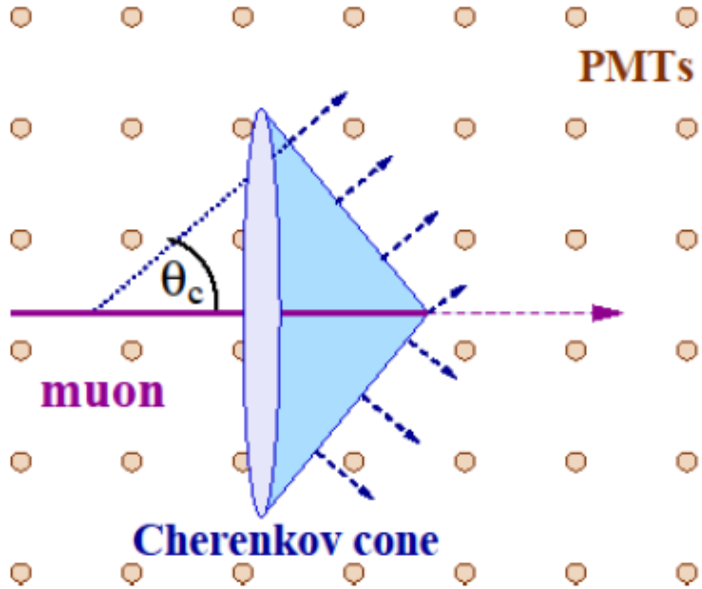
-> identify the cosmic ray sources

Event Topologies

Track-like



Track-like contains both a cascade and one track



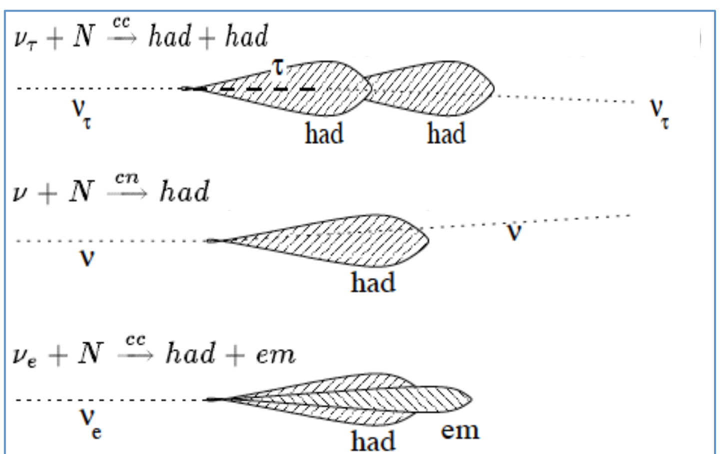
Muon track from CC muon neutrinos

Angular resolution 0.5°/0.1° for ice/water

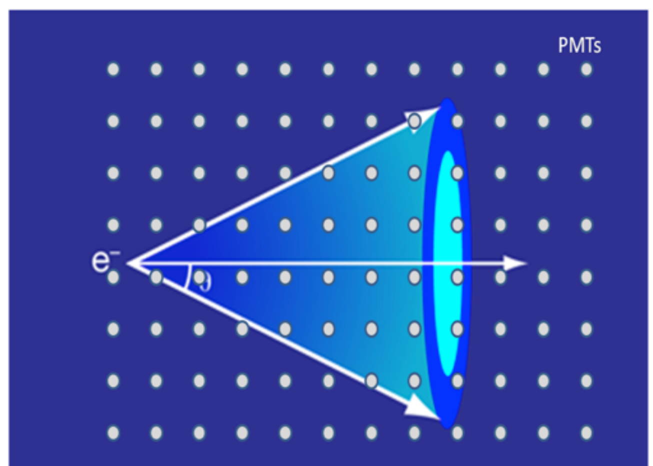
dE/dx resolution factor 2-3

Not to scale

Shower-like



No track is identified



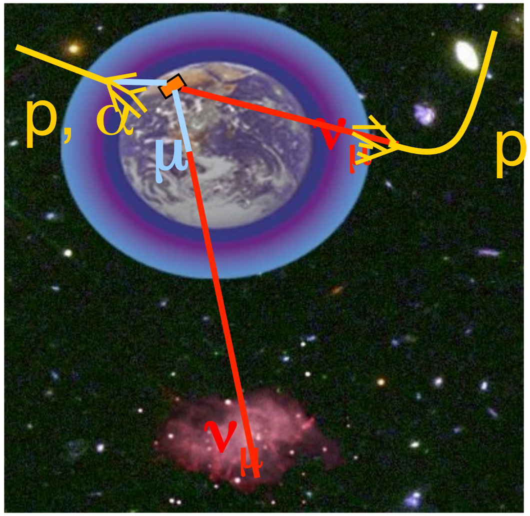
CC electron/tau and NC all flavour

80% of all nu interactions

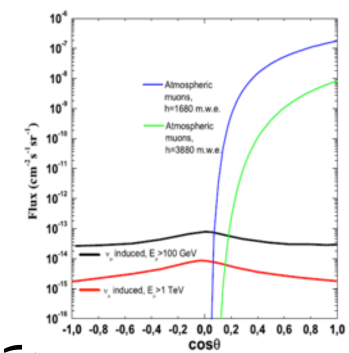
Angular resolution 10°/1° at 100 TeV for ice/water

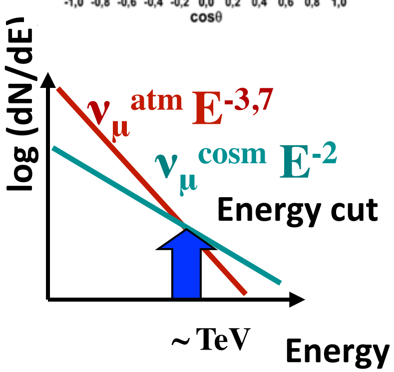
Energy resolution ~ 10%

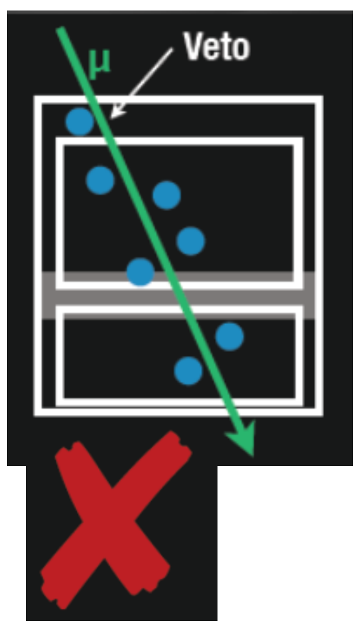
Reducing Atmos Muon and Atmos nu Backgrounds

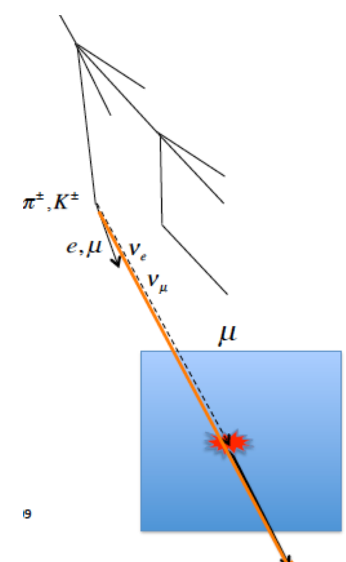


Atmospheric muons:	Atmospheric neutrinos:
Select upgoing	Select upgoing
Go deep	Go deep
Energy cut	Energy cuts
Spatial clustering	Spatial clustering
Time clustering	Time clustering
Coinc. with EM signals	Coinc. with EM signals
Veto outer layers	Veto assoc. muon (outer layers)
	Go shallow







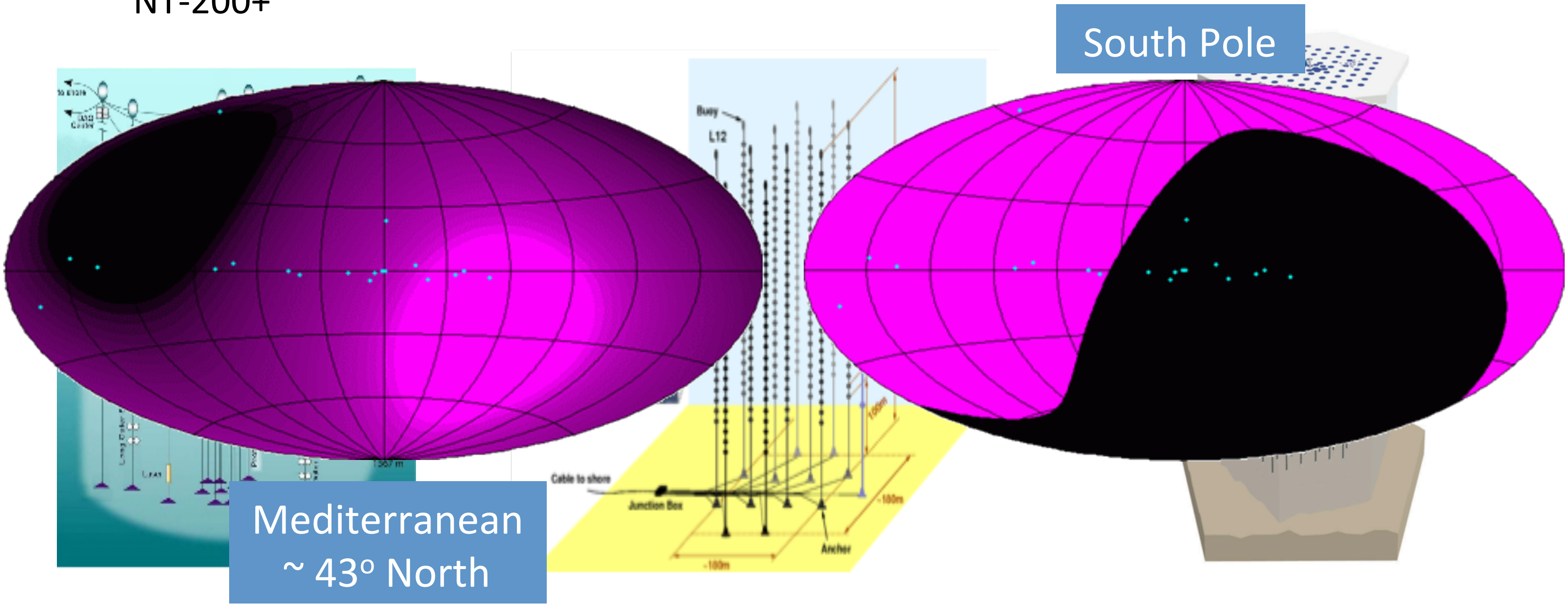


Current Neutrino Telescopes

NT-200+

Antares

IceCube



Lake Baikal
1/2000 km3
228 PMTs

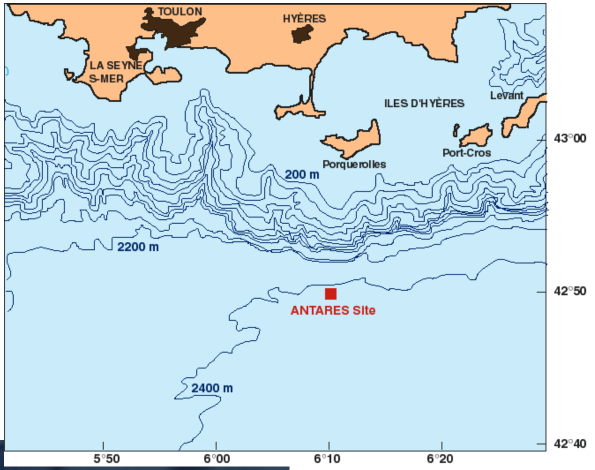
Mediterranean Sea
1/100 km3
885 PMTs

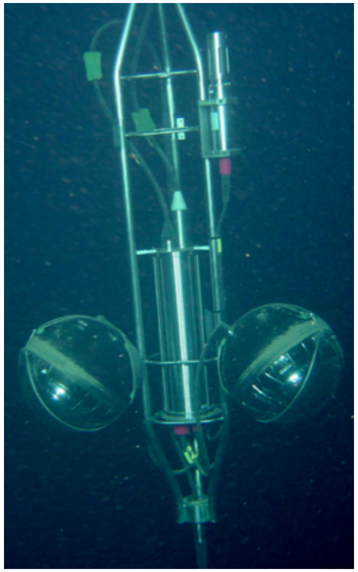
South Pole glacier
1 km3
5160 PMTs

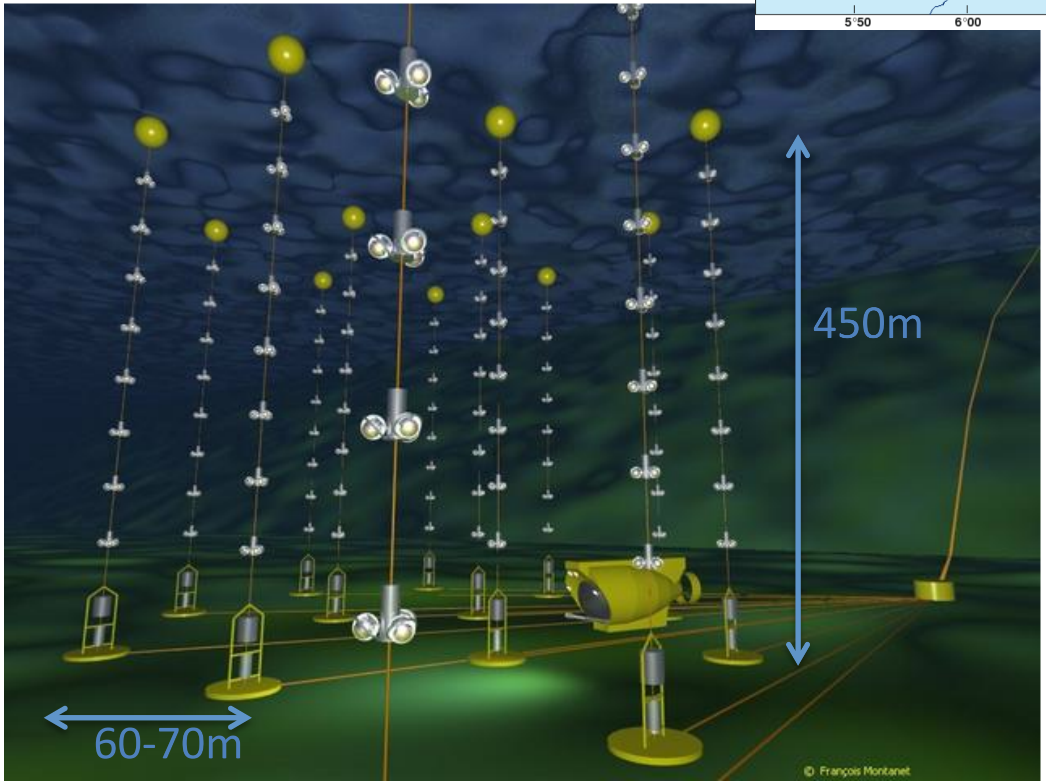
Larger, sparser

ANTARES

- Completed 2008
- Depth 2475m
- 12 lines, ~70m spacing
- 25 storeys per line
- 3x10-inch PMTs per storey
- Decomissioning 2017



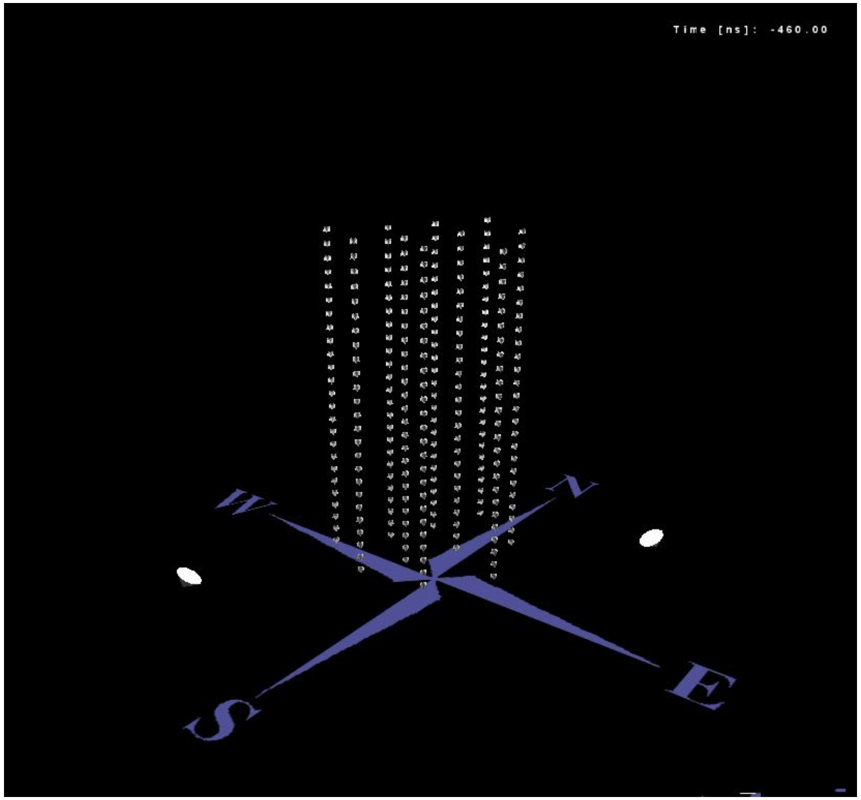




ANTARES

Atmospheric muon

neutrino



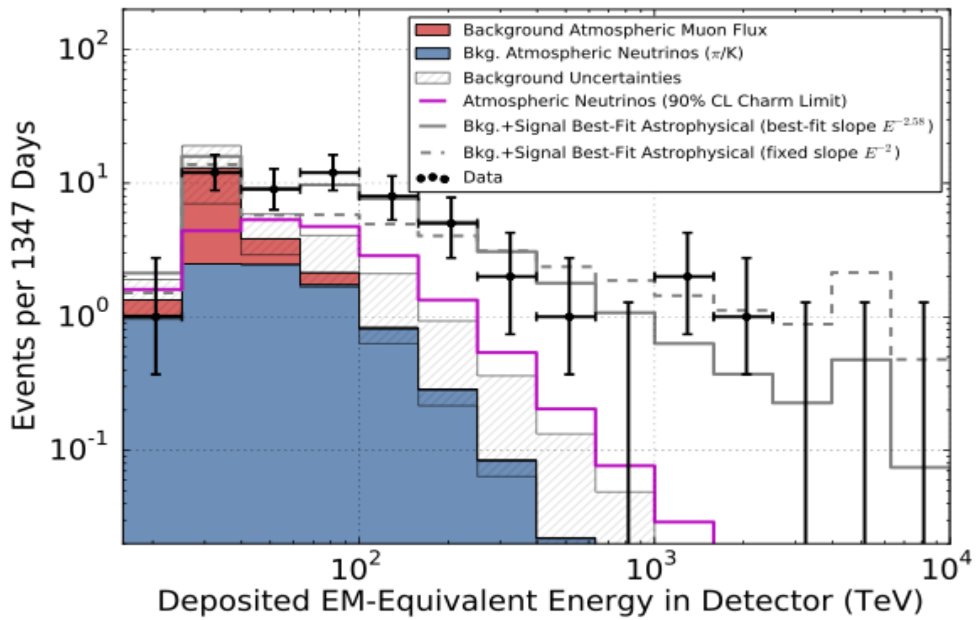
IceCube Diffuse Flux Signal

4 year HESE analysis
ICRC 2015

53 events

5.7 sigma
Ethreshold: 60 TeV

Best fit spectral index: -2.58

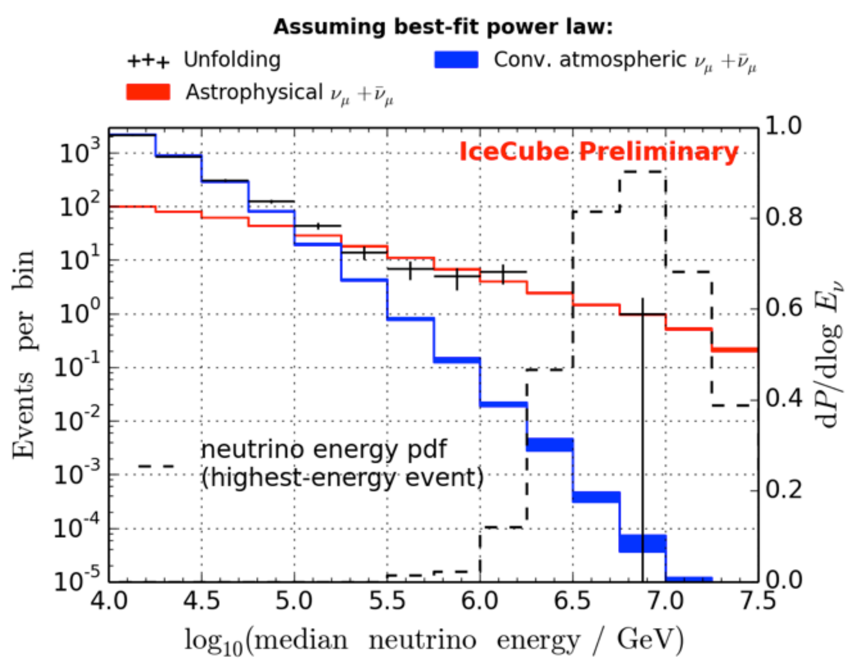


Unfolded upgoing muon spectrum
TEVPA 2015

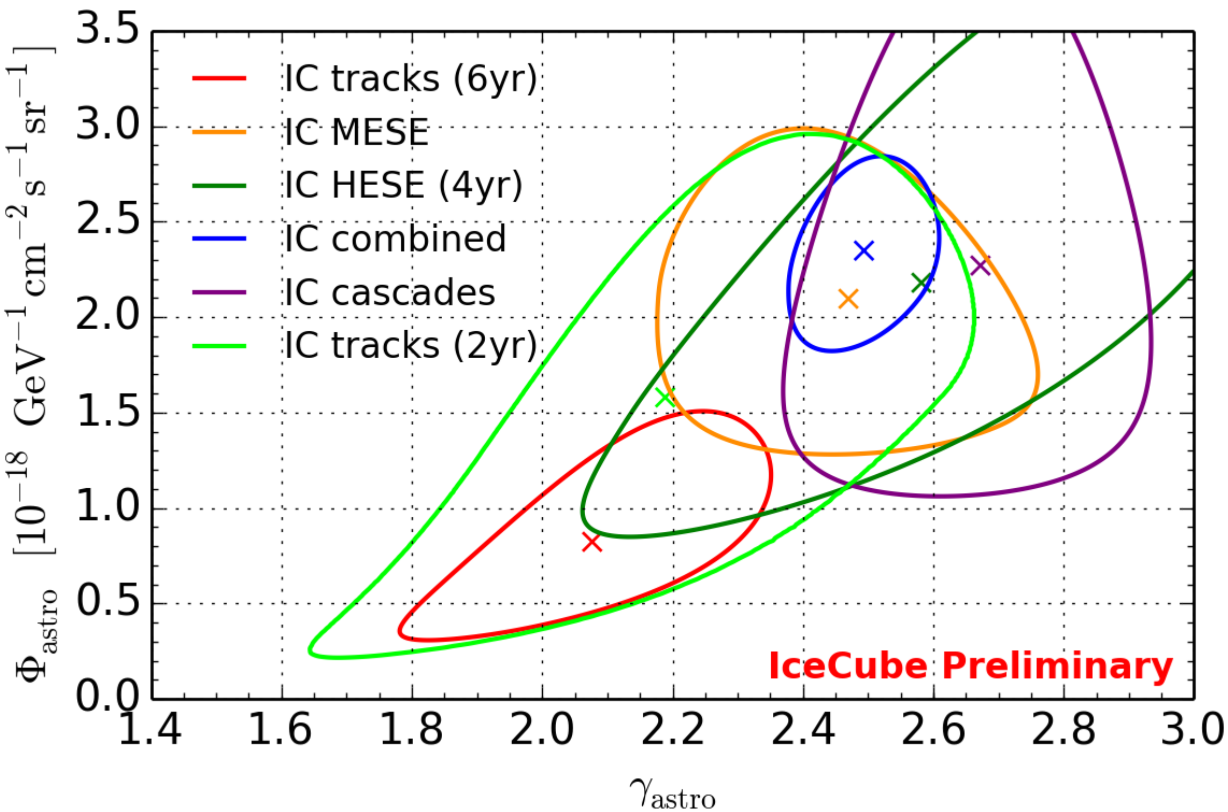
6 yr data

5.9 sigma
Ethreshold: 200 TeV

Best fit spectral index: -2.03+-0.13



Flux Characteristics



90% CL contours

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

Indication of spectral break (different energy thresholds) ??

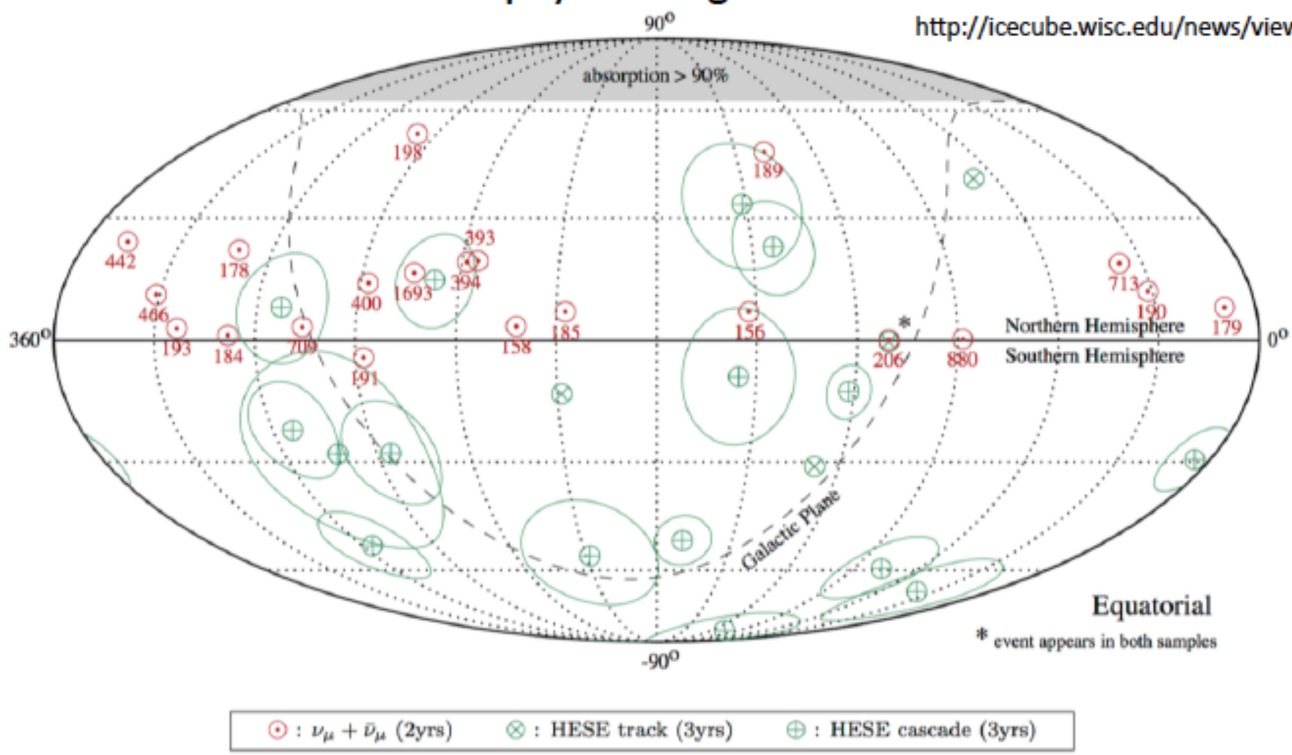
Indication of galactic and extra-galactic contributions (different hemispheres) ??

Origin of Astrophysical Neutrinos?

Only highest energy events are shown.

Most of these events are of astrophysical origin.

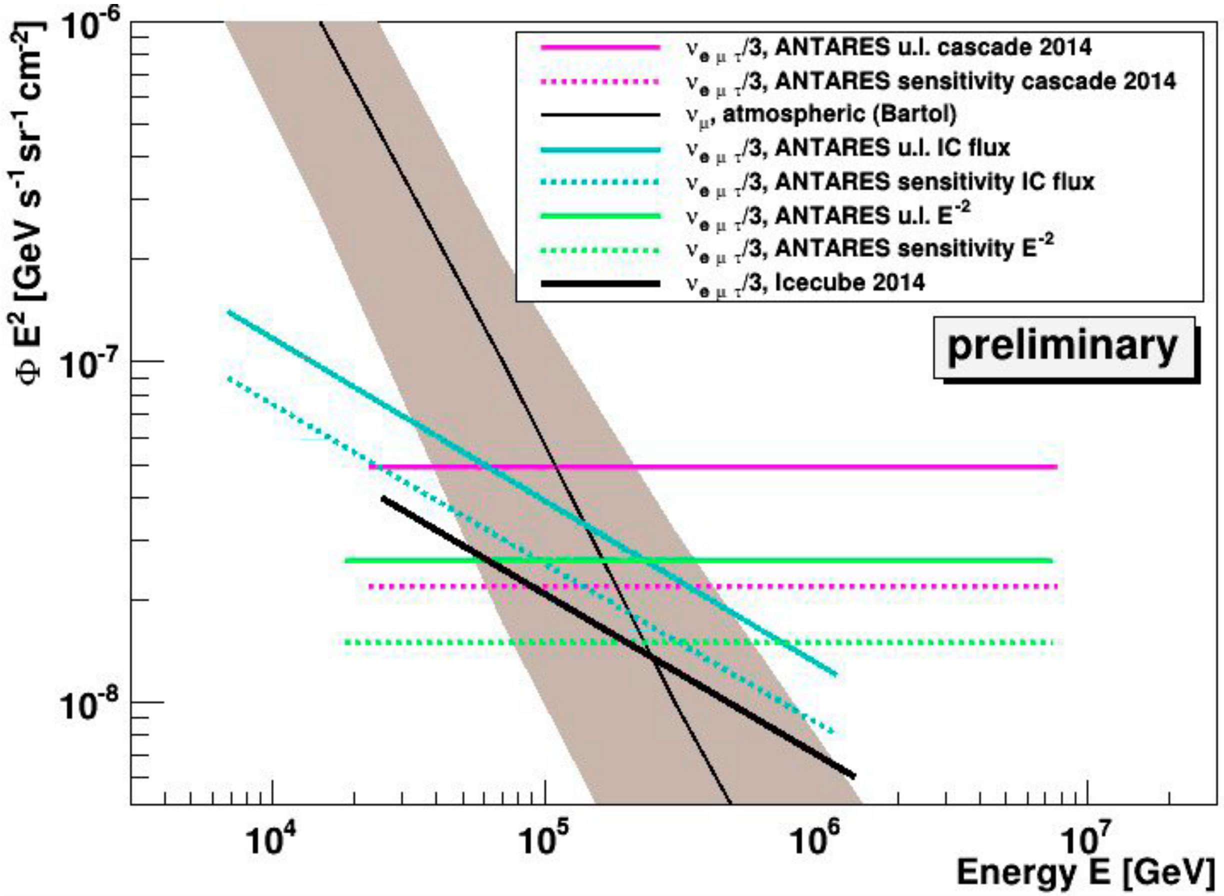
http://icecube.wisc.edu/news/view/348



Cascade resolution 10-15° - mainly Southern hemisphere
Muon resolution 0.5° - only Northern hemisphere

p=2.5% in gal. plane scan within ± 7.5° gal. latitude
Indications of Galactic and extra-galactic contributions ??

ANTARES Diffuse flux



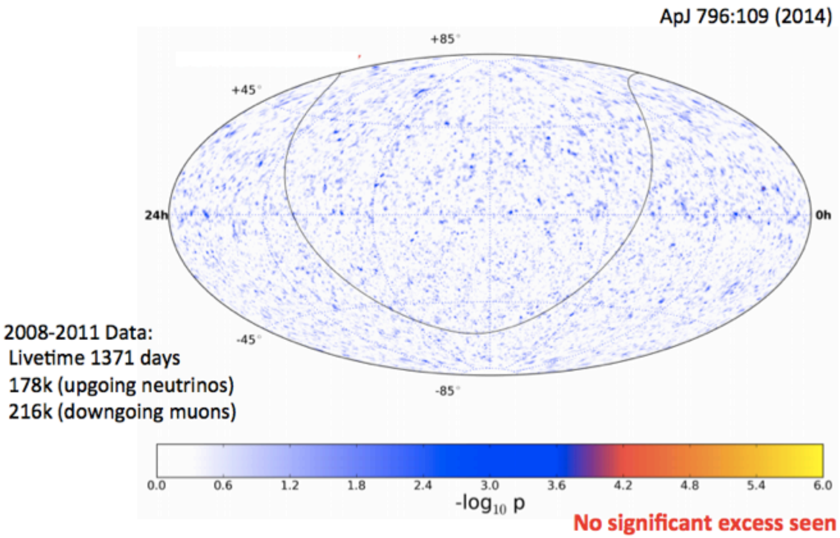
Expected:
9.5 ± 2.5 bkgd
5.0 ± 1.1 IC flux

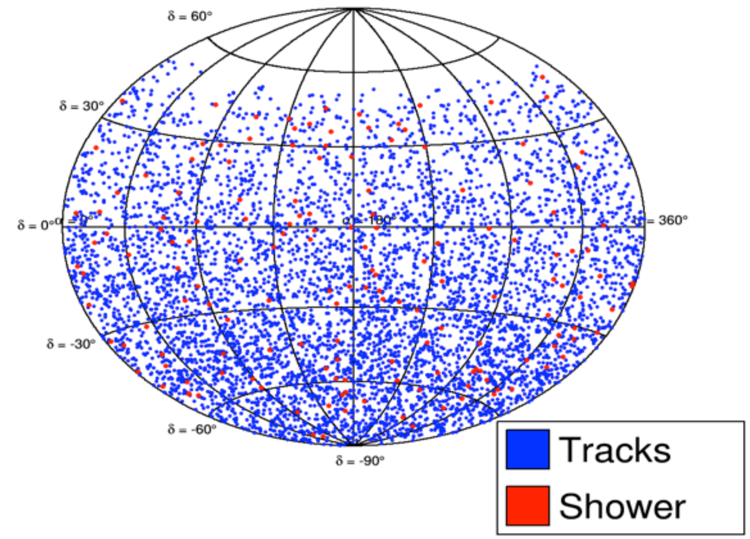
Observed:
12 events

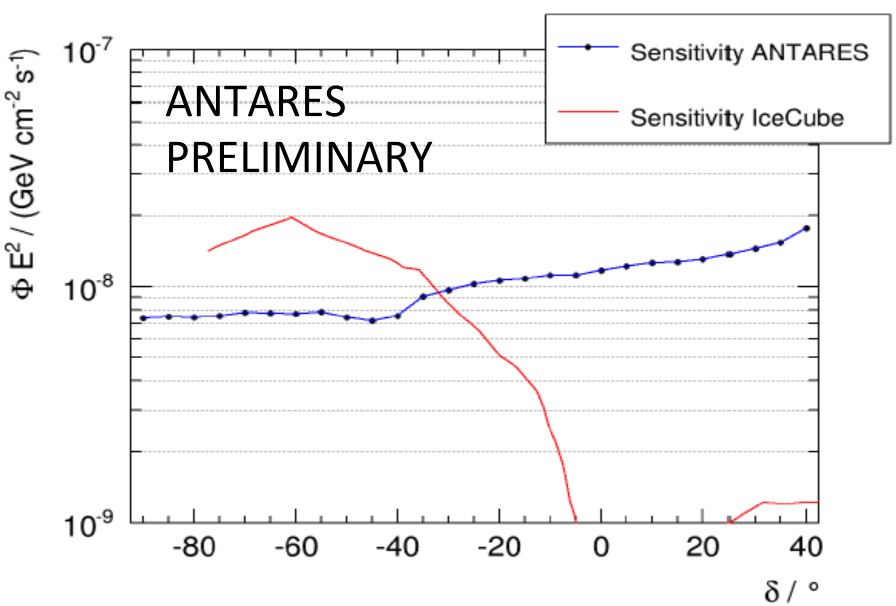
1.75σ excess

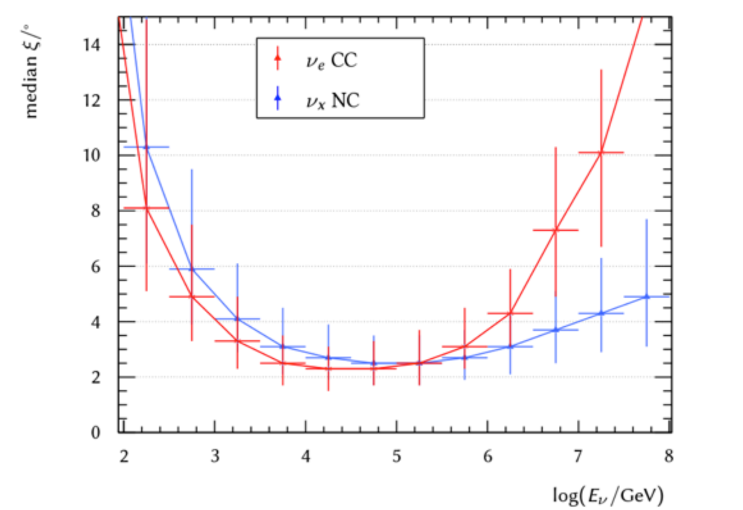
Consistent with bkgd
Consistent with IC

No Point Source Found (yet)







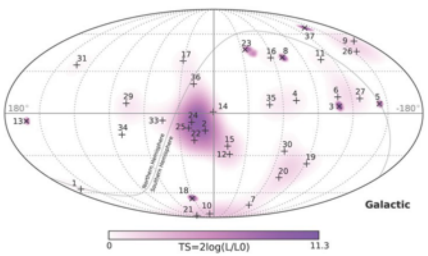


Cascade resolution <4°

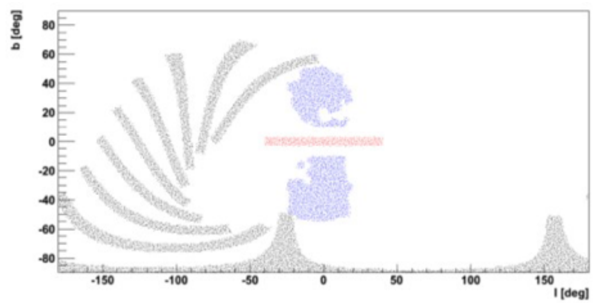
30% improvement adding cascades

ANTARES: Some Galactic Searches

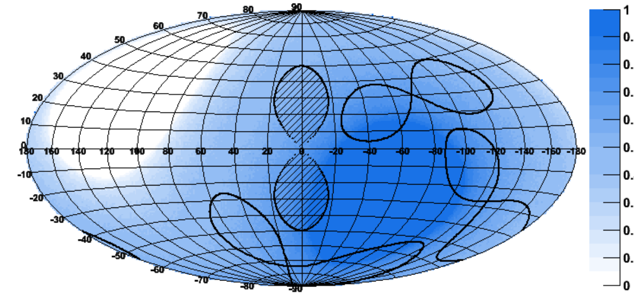
IC hot spot

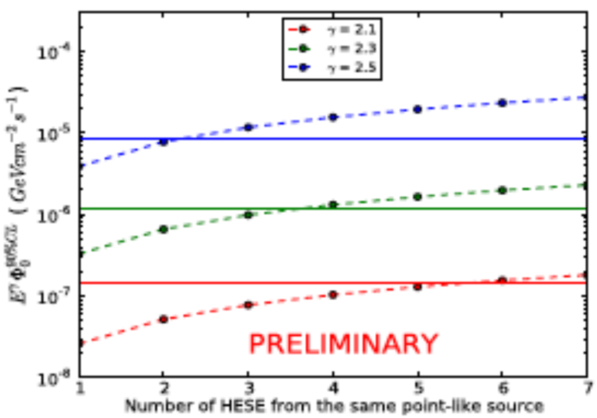


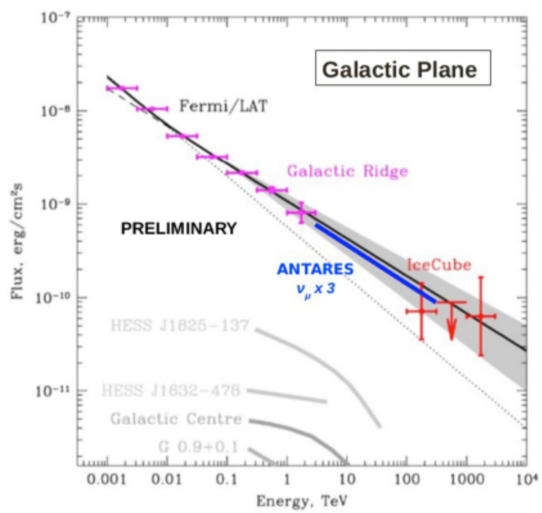
Galactic plane: molecular clouds

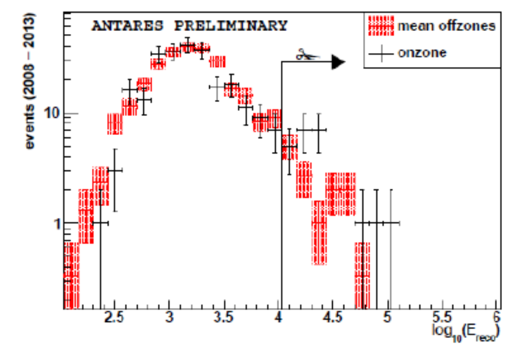


Fermi Bubbles









No signifcant cluster found within 20° of IC hotspot

Exclude more than 2 HESE events for index=2.5

Expected: 12
Observed: 22

1.9 σ excess

GW150914 follow-up -- I

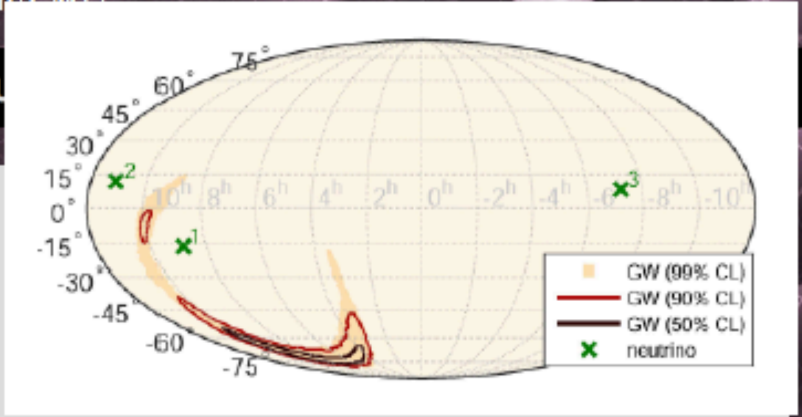
LIGO

Laser Interferometer Gravitational-Wave Observatory

Supported by the National Science Foundation

Operated by Caltech and MIT

About | Learn More | News | Gallery | Educational Resou



Detection Papers

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

Companion Papers

"Unmodeled Searches Used for First LIGO Gravitational Wave Detection"

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

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

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

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

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

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

"Calibration Uncertainty of the Detectors in Early Advanced LIGO"

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

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

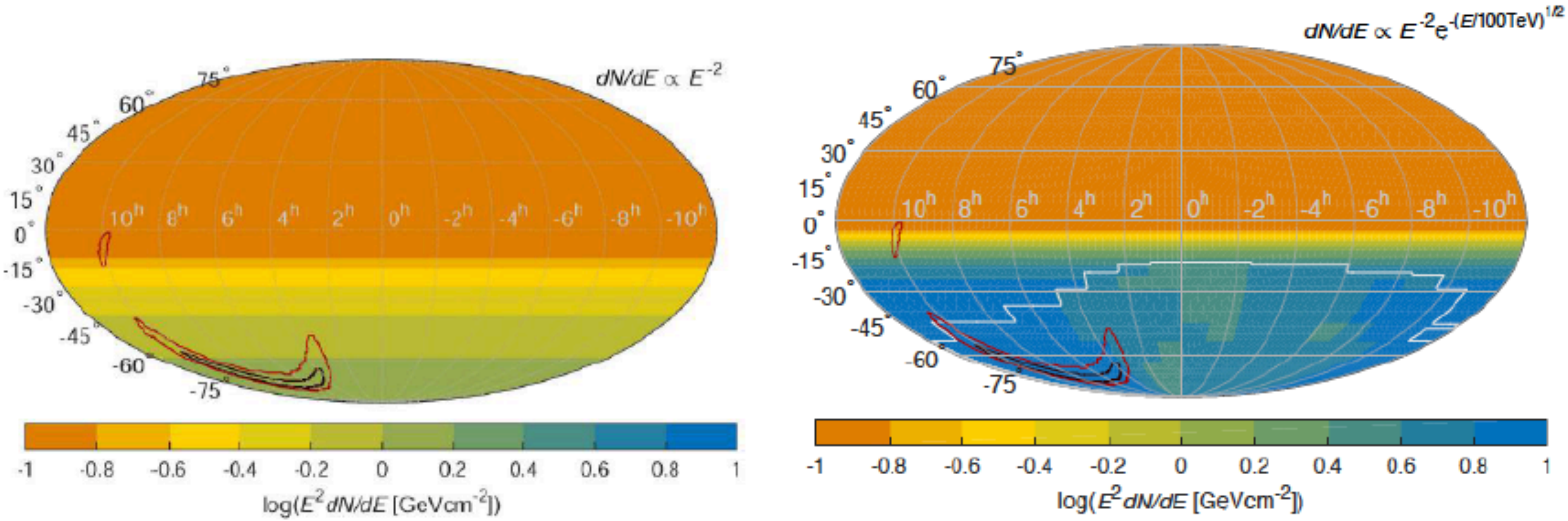
"High-energy Neutrino Follow-up Search of the First Advanced LIGO Gravitational Wave Event with IceCube and ANTARES" ←

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

arXiv:1602.05411 – submitted to PRD

GW150914 follow-up -- II

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



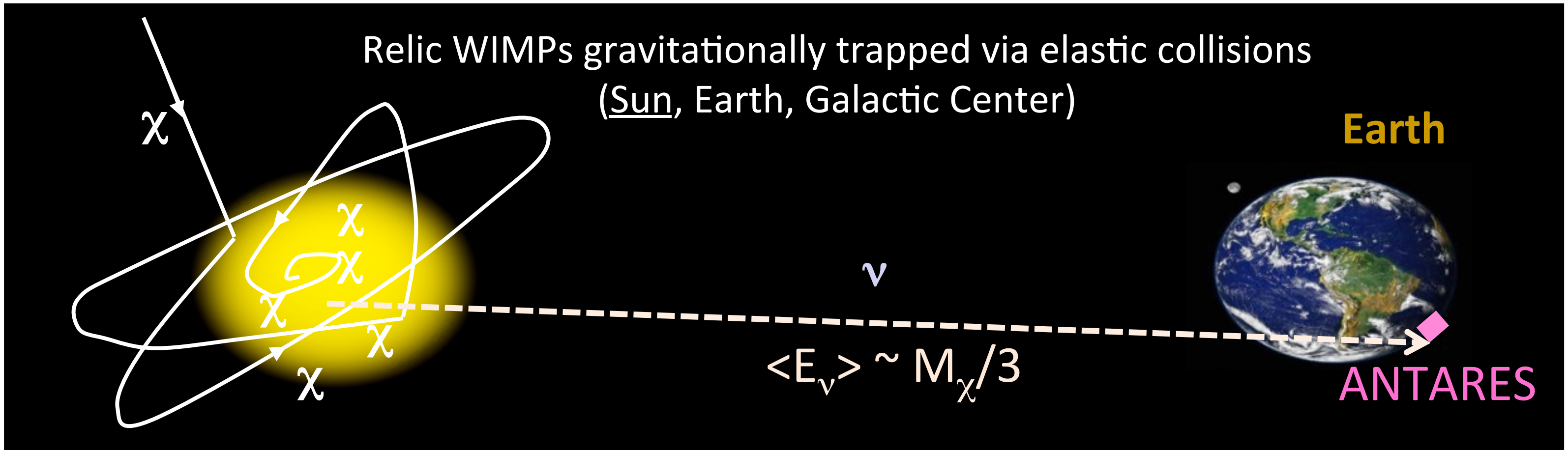
⇒ Limits from ANTARES dominates below O(100 TeV) (white line)

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

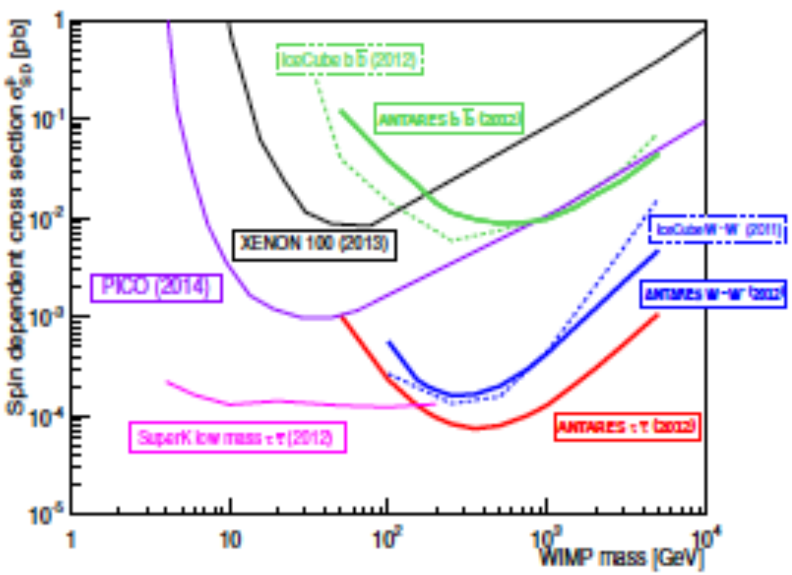
$$\mathrm{E}^{\mathrm{ul}}_{\nu,\mathrm{tot}} \sim 10^{52}\text{–}10^{54} \left(\frac{D_{\mathrm{gw}}}{410\,\mathrm{Mpc}}\right)^2 \mathrm{erg}$$

Size of GW160914 : 590 deg^2 ANTARES resolution: <0.5 deg^2
A rapid observation of counterpart would help a better locatization for further follow-up

Indirect Searches for Dark Matter

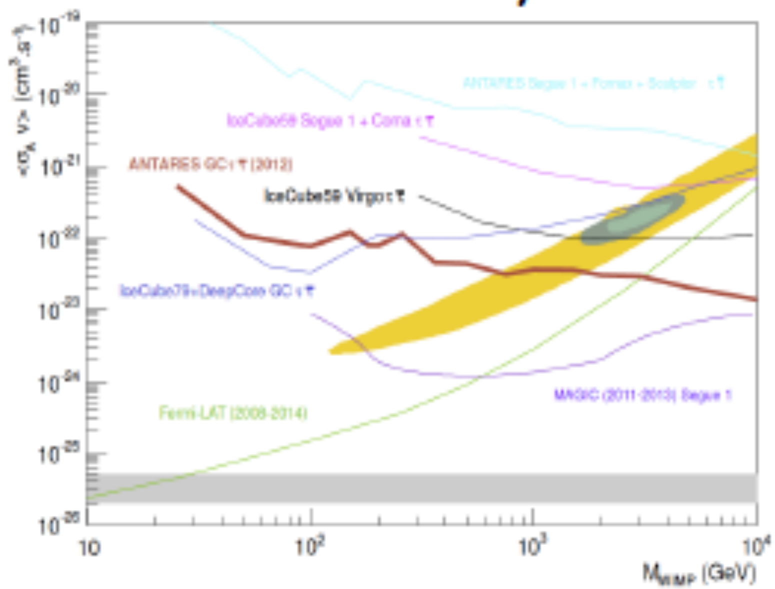


Sun



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

Galaxy



- Limits on the Wimp self annihilation cross section

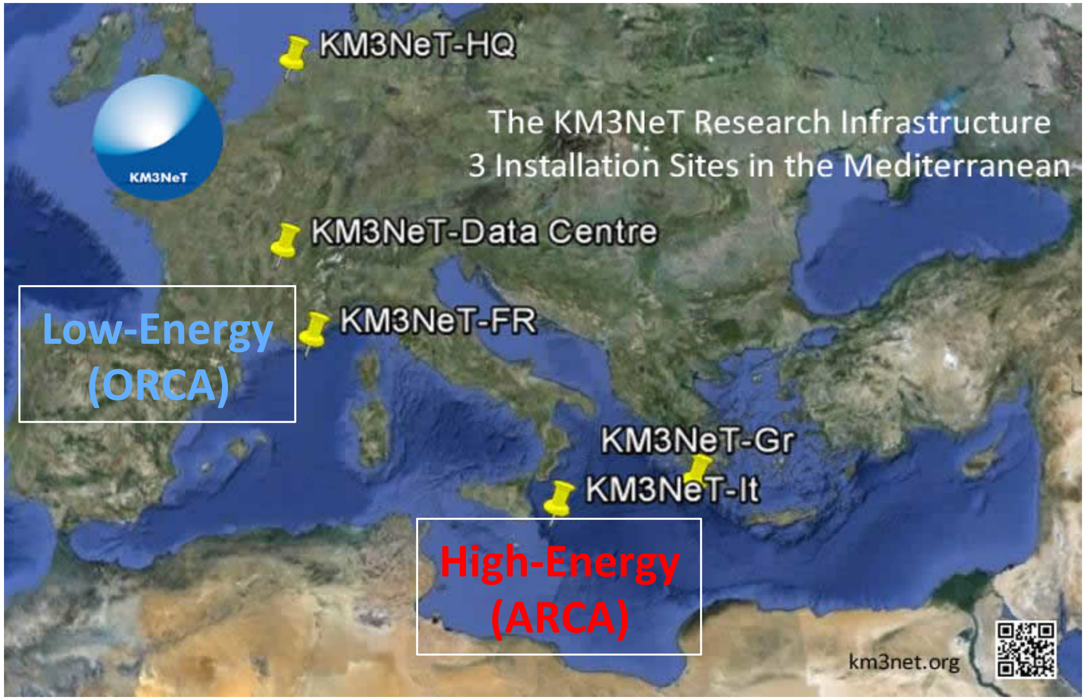
KM3NeT

KM3NeT is a distributed research infrastructure with 3 main science topics:

- The origin of cosmic neutrinos (high energy)
- Measurement of fundamental neutrino properties (low energy)
- Deep Sea Observatory - Oceanography, bioacoustics, bioluminescence, seismology

Single Collaboration

Single Technology



ARCA- Astroparticle Research with Cosmics in the Abyss

ORCA- Oscillation Research with Cosmics in the Abyss

KM3NeT Collaboration

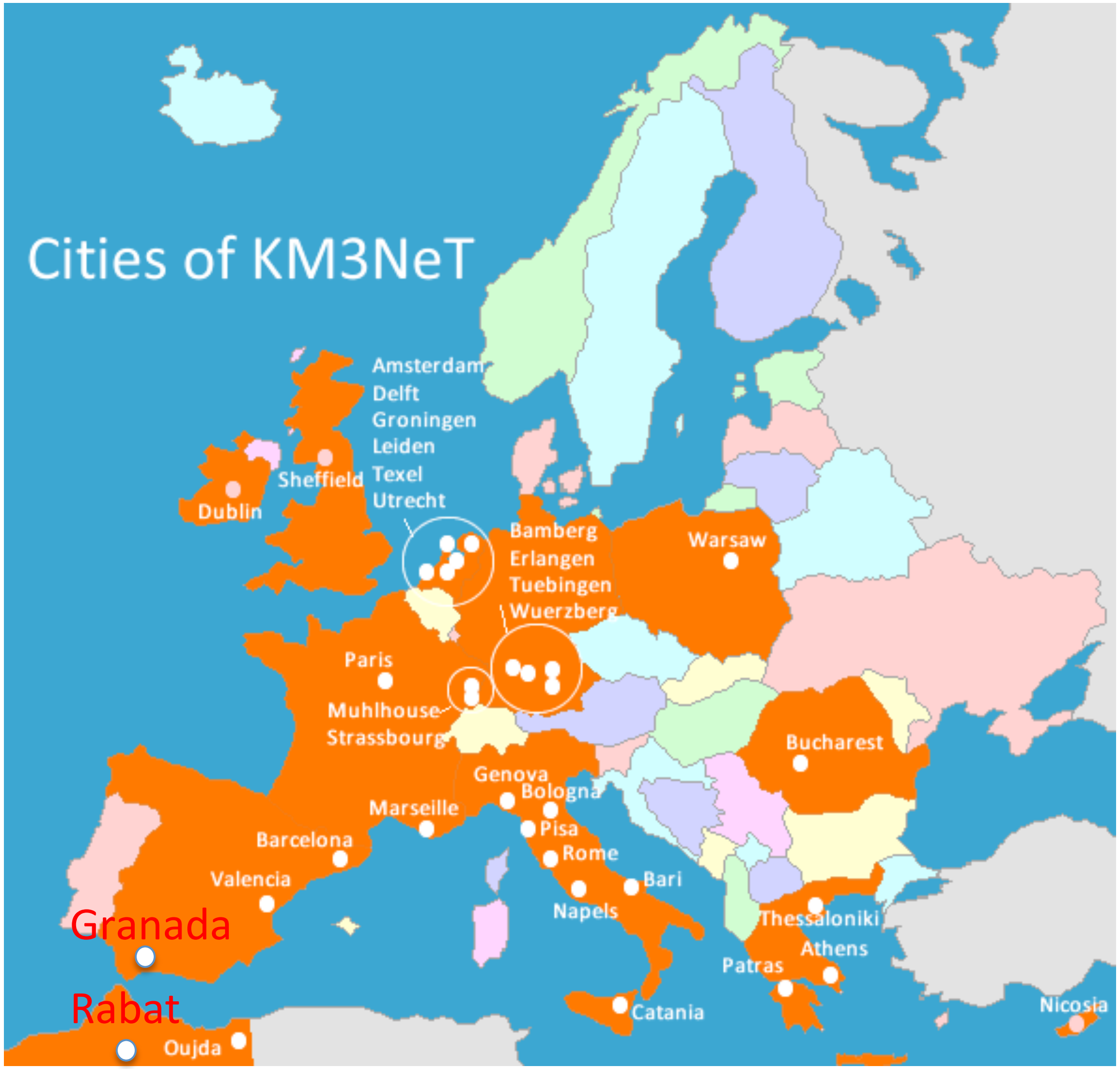
12 Countries
42 Institutes
225 Scientists

APC
Calibration Unit base
PMT studies

CPPM
seafloor infrastructure
base and anchor
string integration+deployment
shore station

IPHC+Mulhouse
DOM integration

Nantes, Clermont Ferrand, Grenoble, CEA, …
in discussion



KM3NeT Timeline

KM3NeT Technical Design Report¶

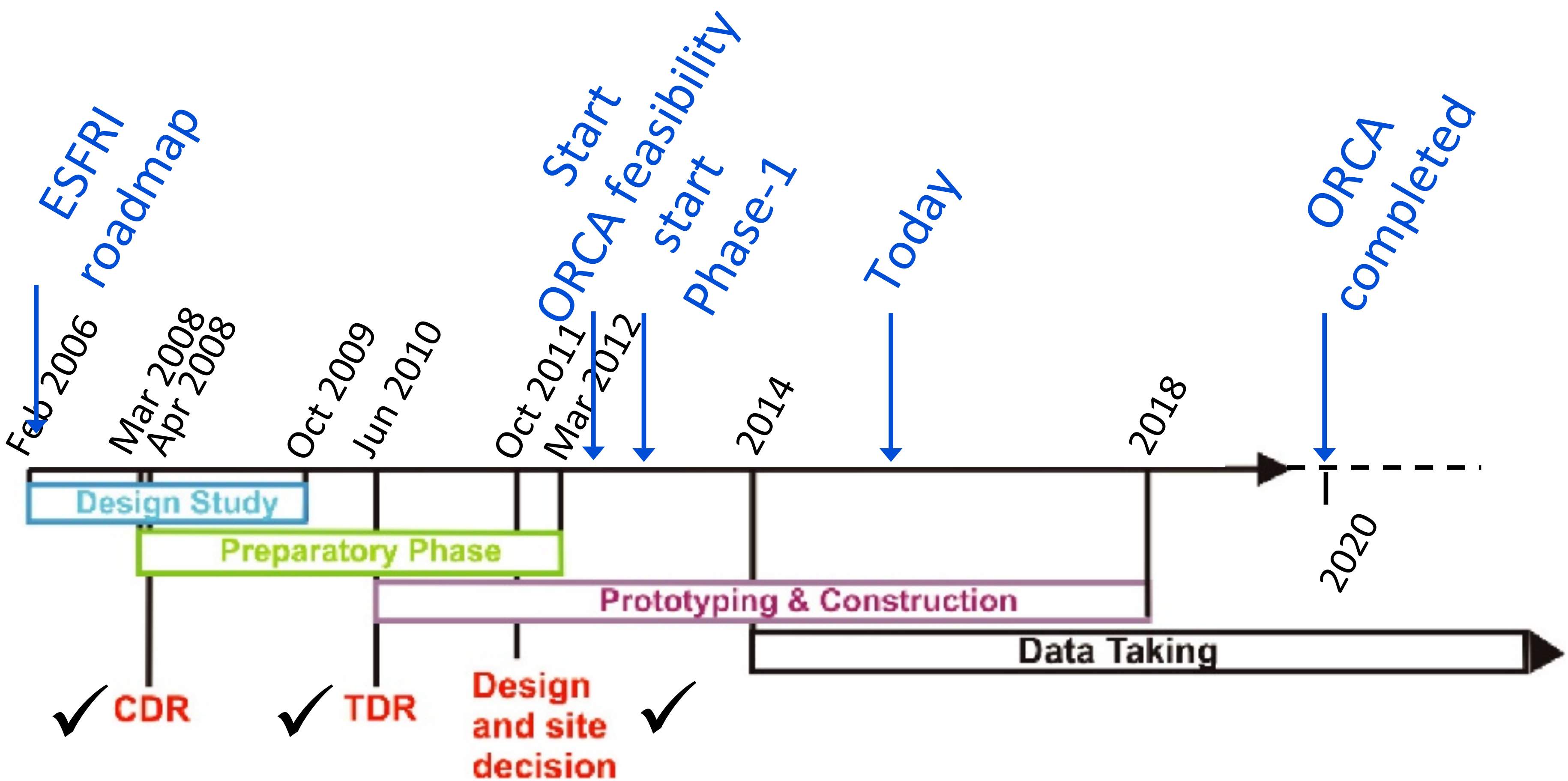
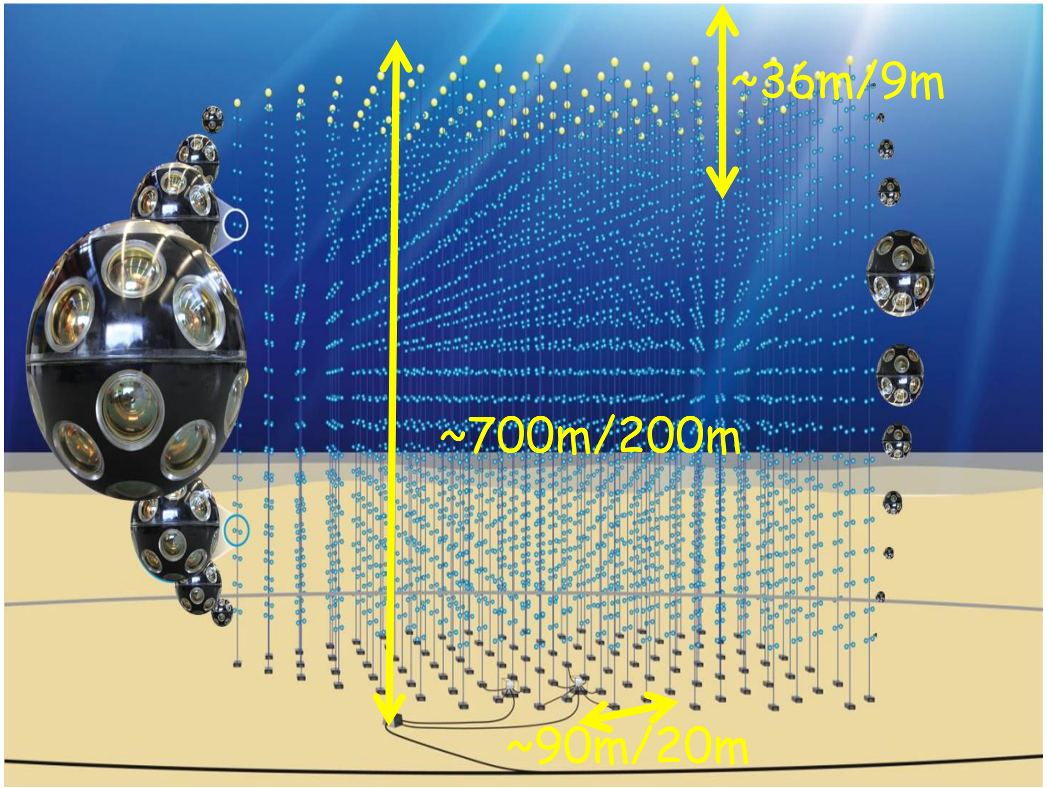
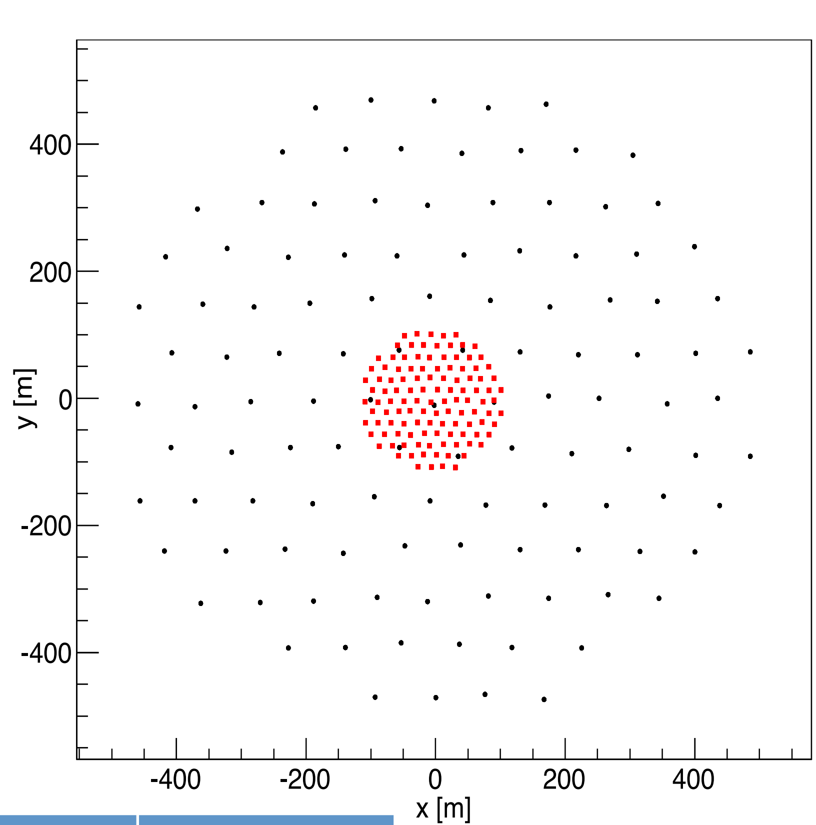


Figure 10-1: Overall time schedule of the KM3NeT project.

¶ Deliverable of EU-funded Design Study.

KM3NeT Building Block (115 strings)



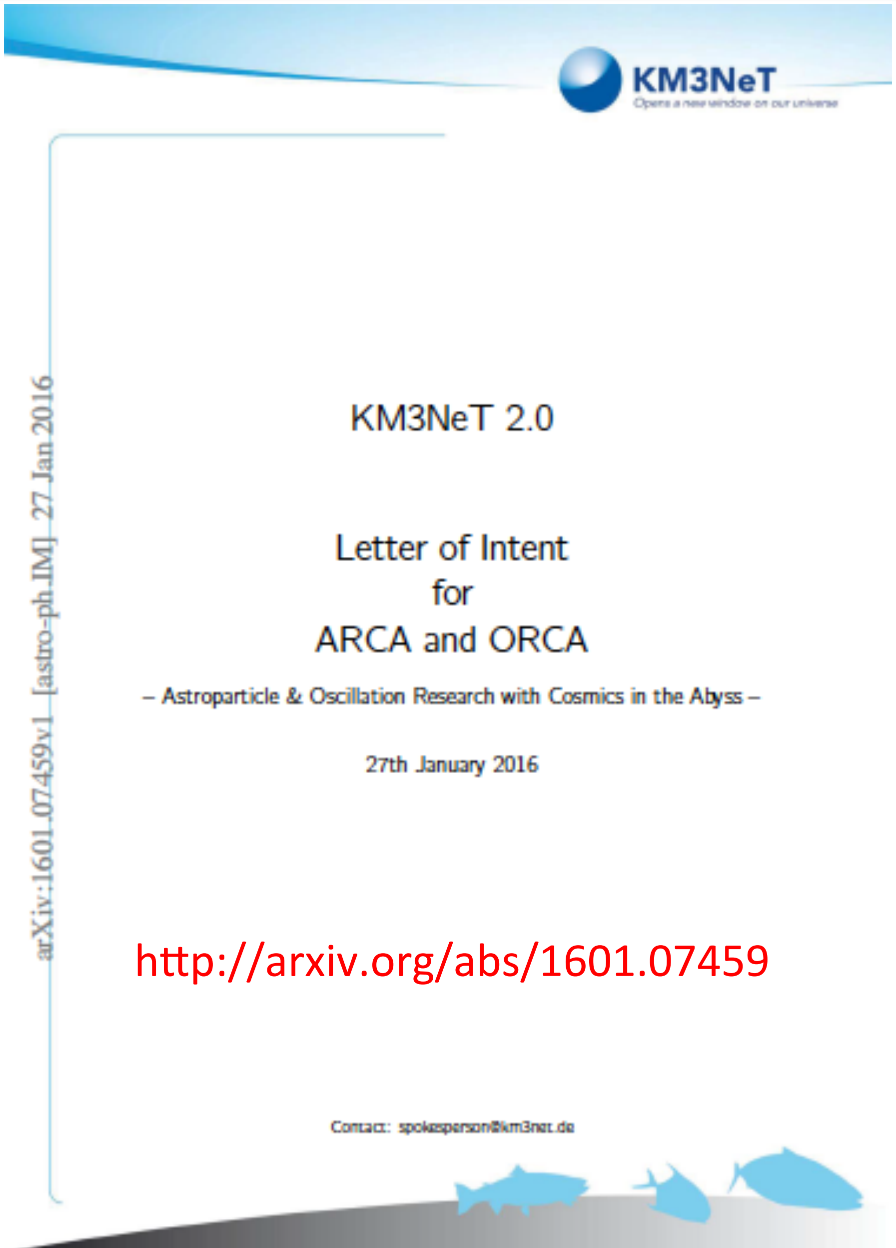


	ARCA	ORCA
Location	Italy	France
String distance (m)	90	20
DOM spacing (m)	36	9
Volume (MTon)	500*2	3.8

Phased Implementation

Phase	Blocks	Primary deliverables
1	0.2	Proof of feasibility and first science results (6 ORCA strings/ 24 ARCA strings)
2.0	2 *ARCA*	Study of neutrino signal reported by IceCube; All flavor neutrino astronomy
	1 *ORCA*	Neutrino mass hierarchy
3	1+6	Neutrino astronomy including Galactic sources

KM3NeT 2.0: Letter of Intent



KM3NeT

arXiv:1601.07459v1 [astro-ph.IM] 27 Jan 2016

KM3NeT 2.0

Letter of Intent
for
ARCA and ORCA

– Astroparticle & Oscillation Research with Cosmics in the Abyss –

27th January 2016

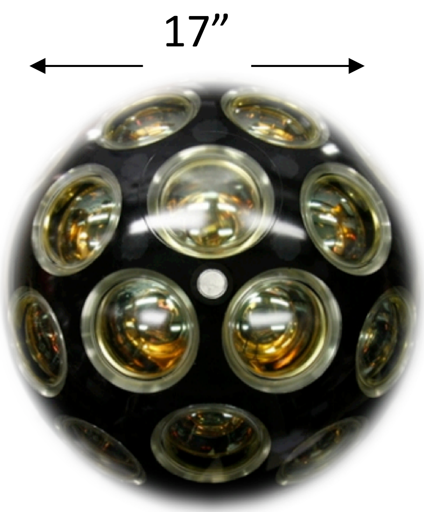
Contact: spokesperson@km3net.de

http://arxiv.org/abs/1601.07459

The main objectives of the KM3NeT Collaboration are i) the discovery and subsequent observation of high-energy neutrino sources in the Universe and ii) the determination of the mass hierarchy of neutrinos. These objectives are strongly motivated by two recent important discoveries, namely: 1) The high-energy astrophysical neutrino signal reported by IceCube and 2) the sizable contribution of electron neutrinos to the third neutrino mass eigenstate as reported by Daya Bay, Reno and others. To meet these objectives, the KM3NeT Collaboration plans to build a new Research Infrastructure consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. A phased and distributed implementation is pursued which maximises the access to regional funds, the availability of human resources and the synergetic opportunities for the earth and sea sciences community. Three suitable deep-sea sites are identified, namely off-shore Toulon (France), Capo Passero (Italy) and Pylos (Greece). The infrastructure will consist of three so-called building blocks. A building block comprises 115 strings, each string comprises 18 optical modules and each optical module comprises 31 photo-multiplier tubes. Each building block thus constitutes a 3-dimensional array of photo sensors that can be used to detect the Cherenkov light produced by relativistic particles emerging from neutrino interactions. Two building blocks will be configured to fully explore the IceCube signal with different methodology, improved resolution and complementary field of view, including the Galactic plane. One building block will be configured to precisely measure atmospheric neutrino oscillations.

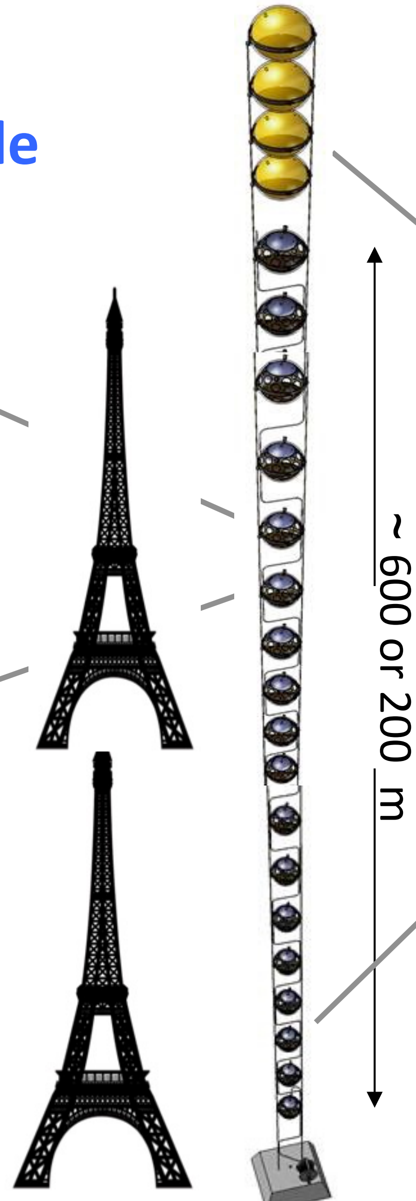
KM3NeT Design

Digital Optical Module

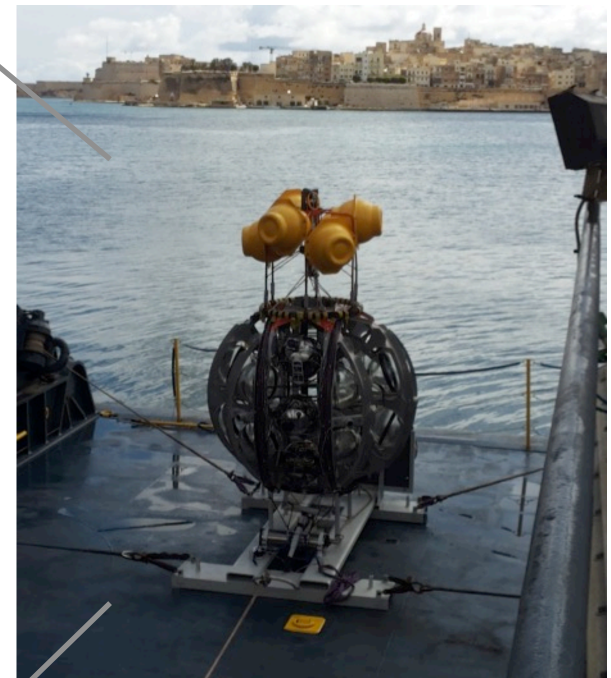


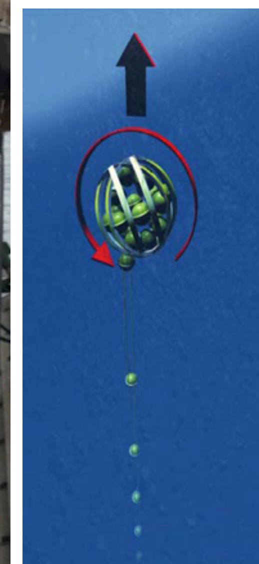
- *31 x 3” PMTs*
- *LED & acoustic piezo inside*
- *Uniform angular coverage*
- *Directional information*
- *Photon counting*
- *Background rejection*
- *Low ageing*
- *Low drag*

String



Launcher Vehicle

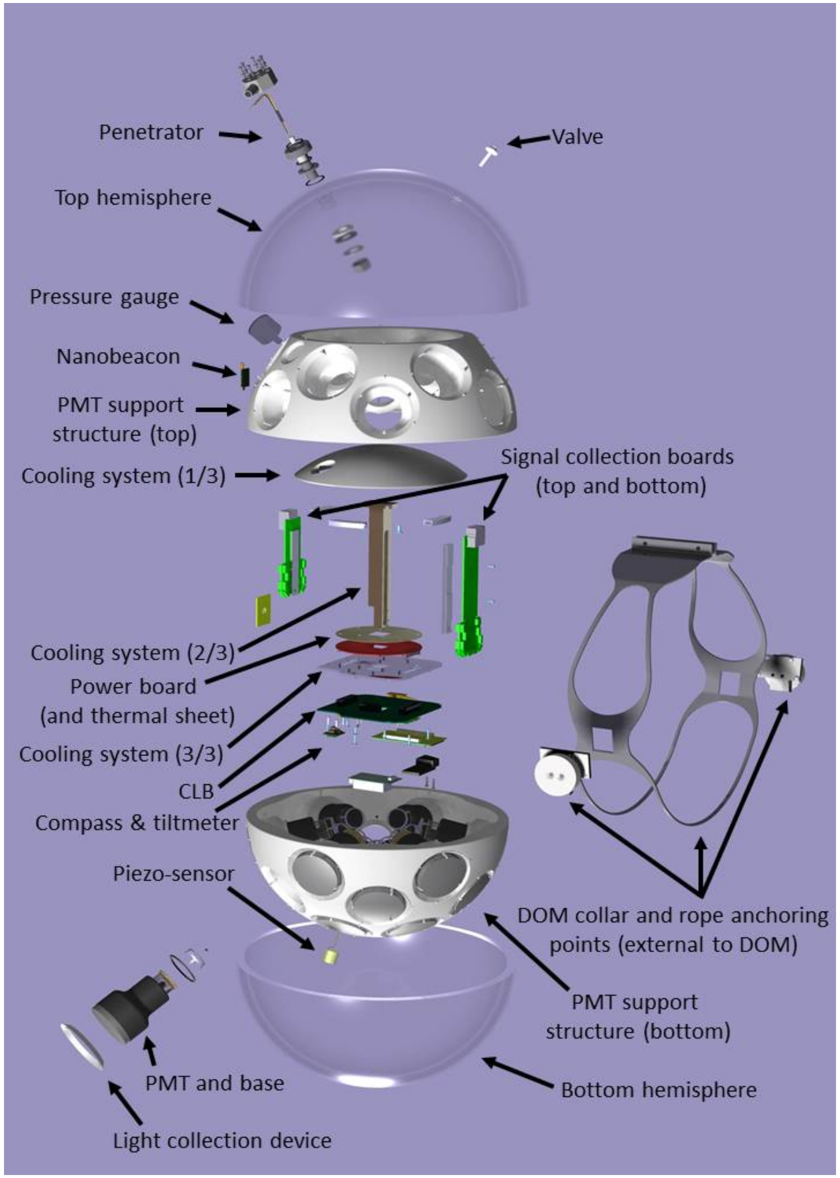




- *Rapid deployment*
- *Compact*
- *Autonomous unfurling*
- *Recoverable*

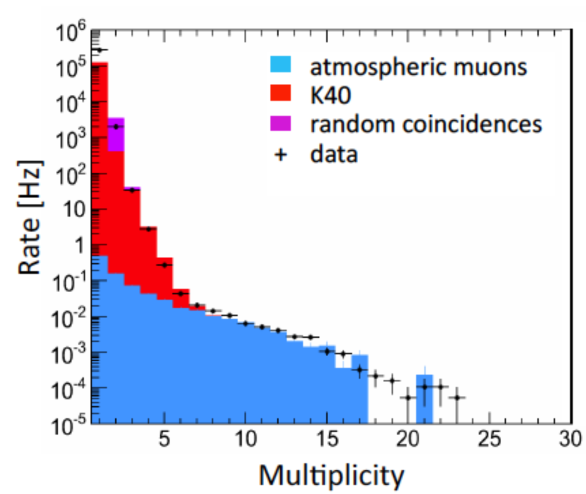
KM3NeT Digital Optical Module

- 31 x 3" PMTs
- Reflective rings around PMTs (+27% light detection, JINST 8 (2013) T03006)
- PMTs supported by plastic structure produced by 3D-printing
- Electronics components attached to cooling mushroom
- One single penetrator for connection to vertical cable
- Optical fibre data transmission
  - DWDM with 80 wavelengths
  - Gb/s readout
- FPGA readout
  - 1 ns time stamp
  - Time over threshold
- Modified White Rabbit time synchronisation
- Calibration: piezo-acoustic sensor, compass + tiltmeter, nano-LED beacon
- Low power (7W per DOM)



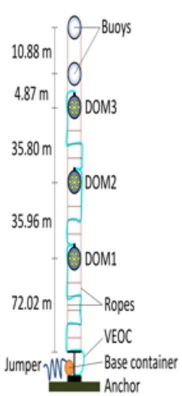
KM3NeT Prototypes

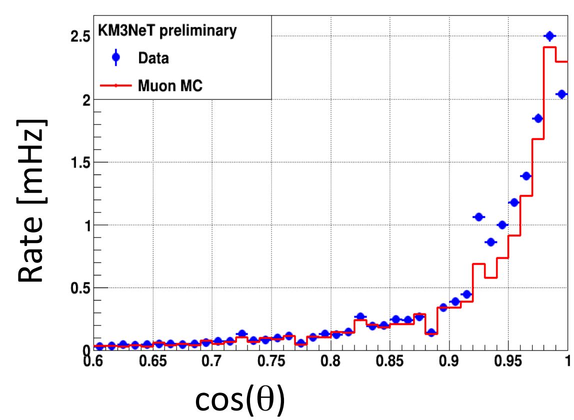
1) Optical Module deployed at Antares, April 2013 (2500 m)



Eur. Phys. J. C (2014) 74:3056

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

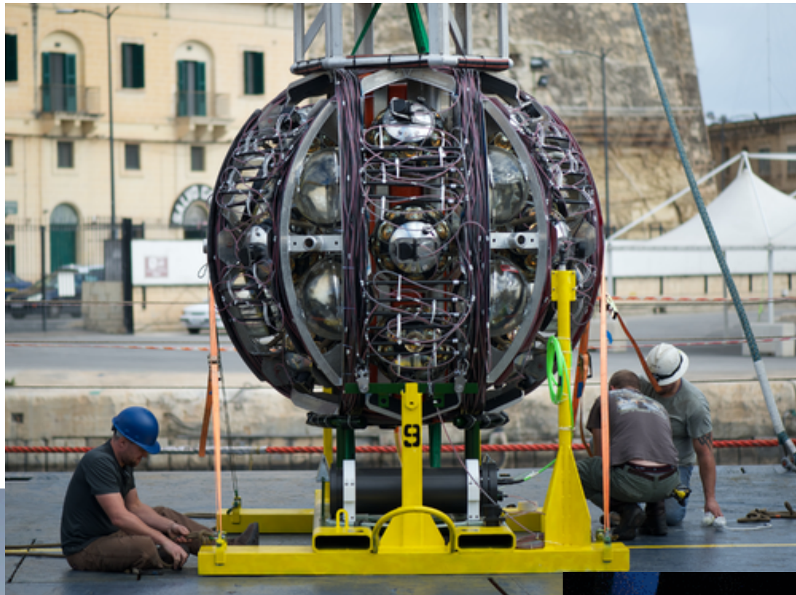


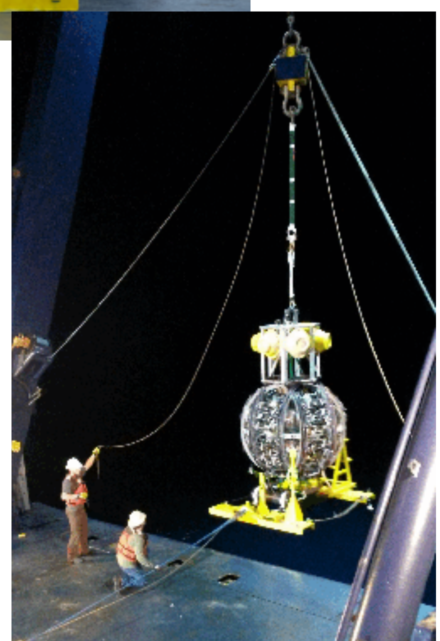


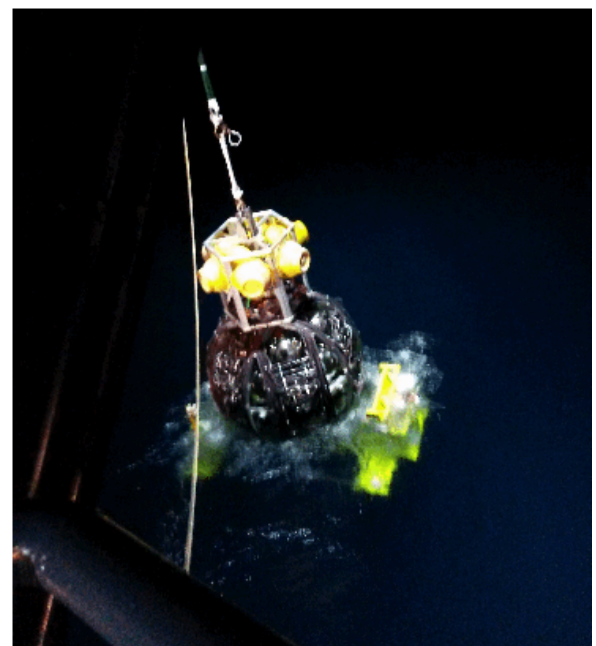
arXiv:1510.01561 Accepted by Eur. Phys. J. C

The first KM3NeT String: construction

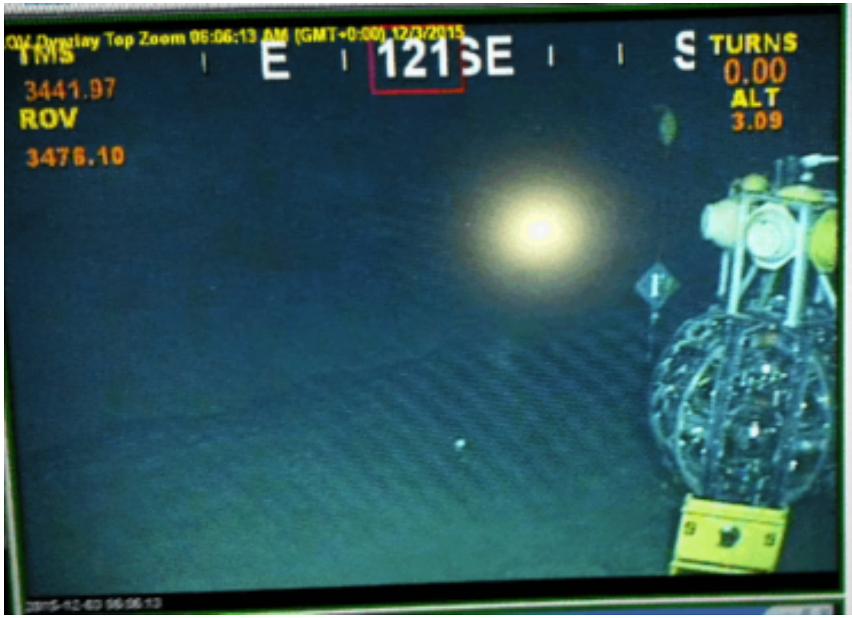
The first KM3NeT String: deployment

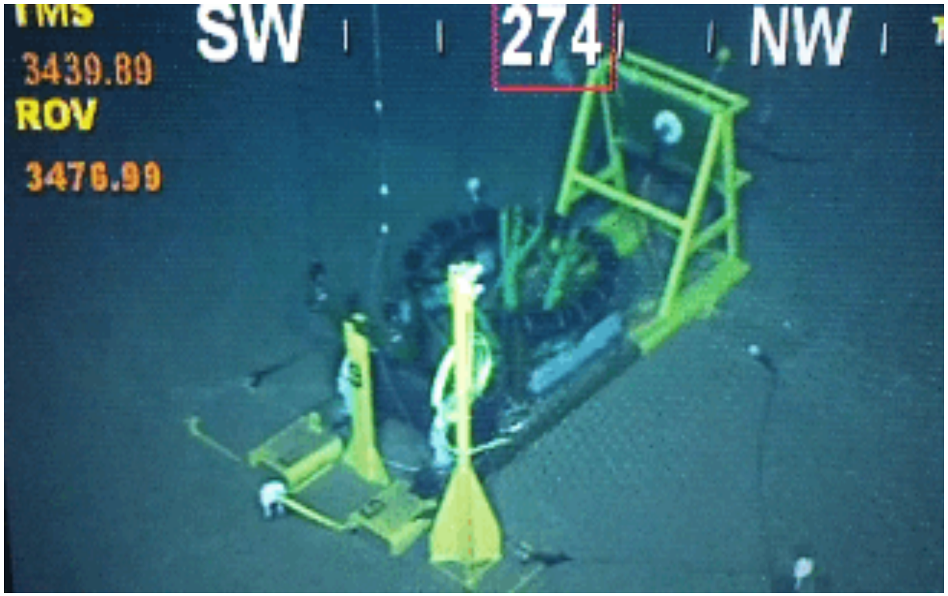


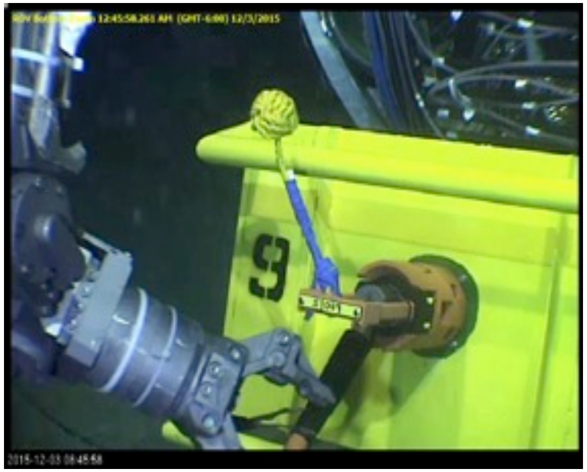




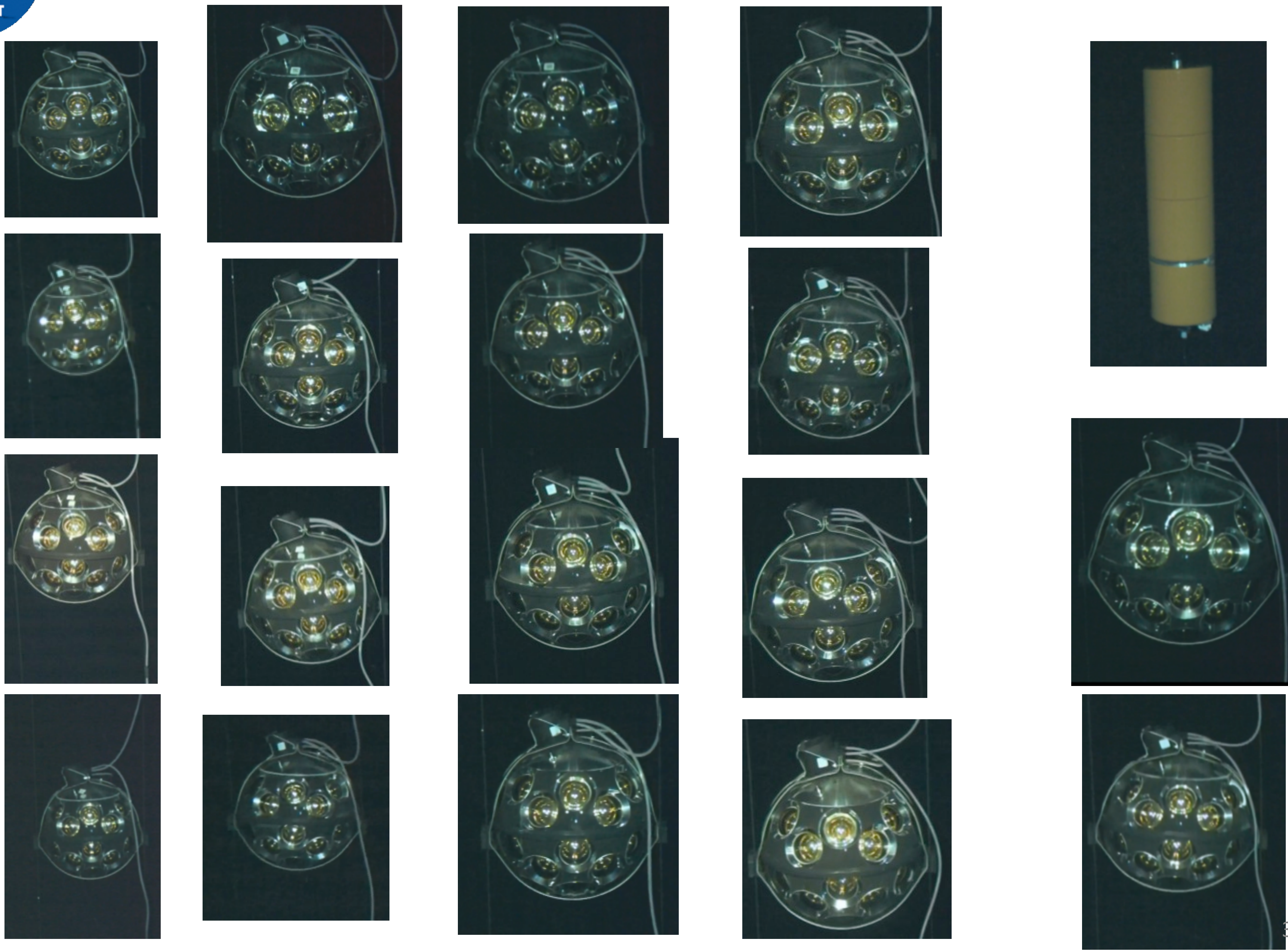
KM3NeT string connection (3rd Dec 2015)





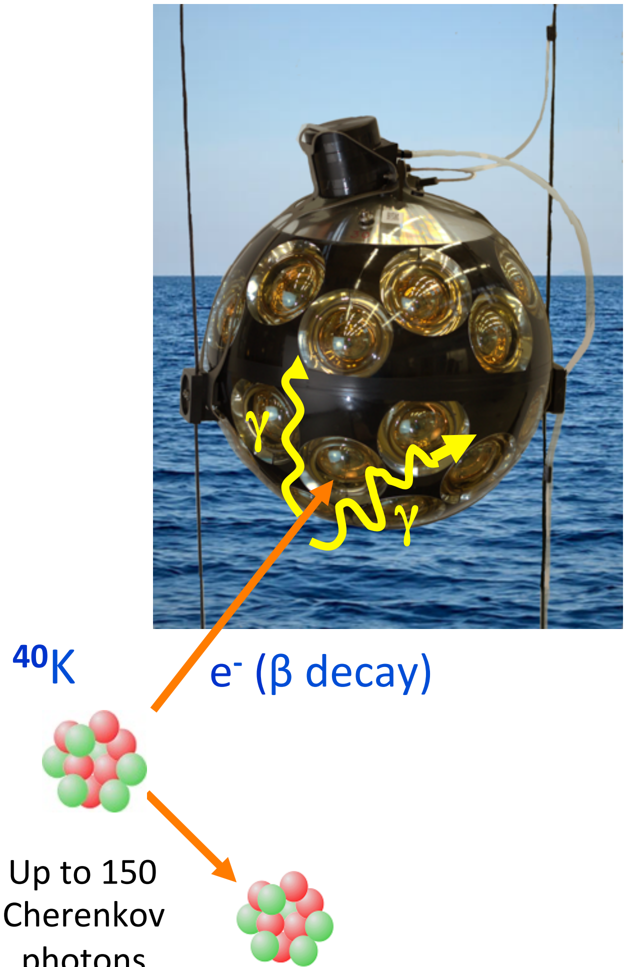


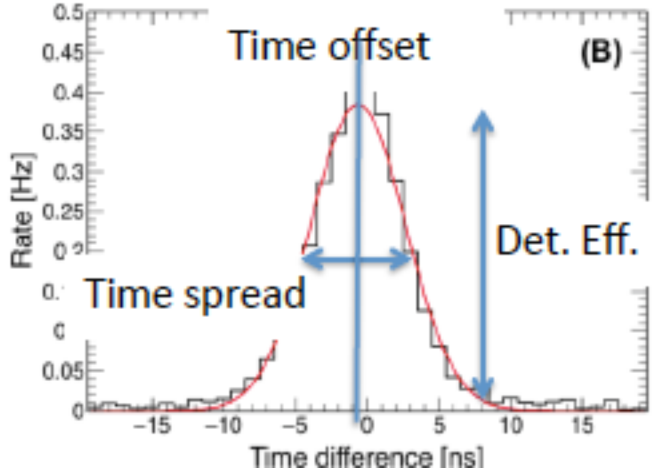
The first KM3NeT String

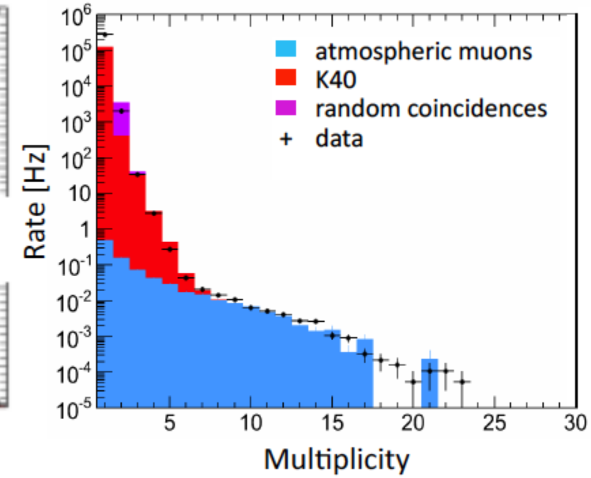


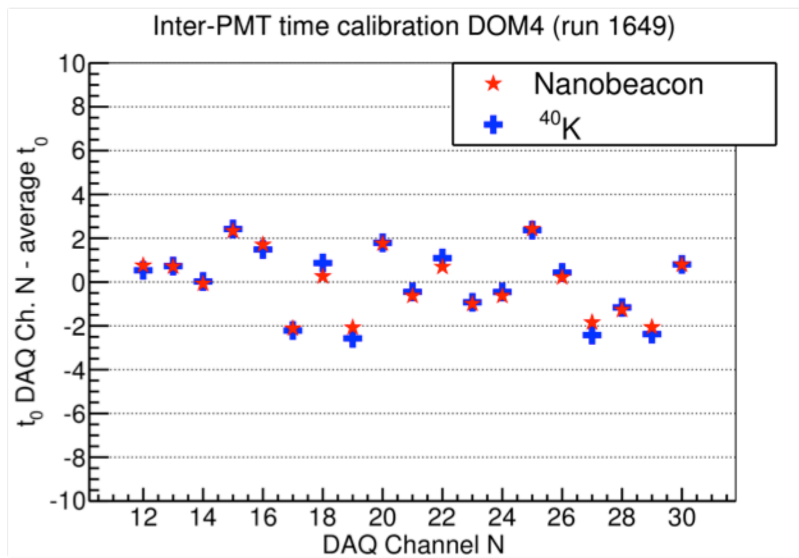
K40 Inter-PMT Calibration

- Fitted parameters:





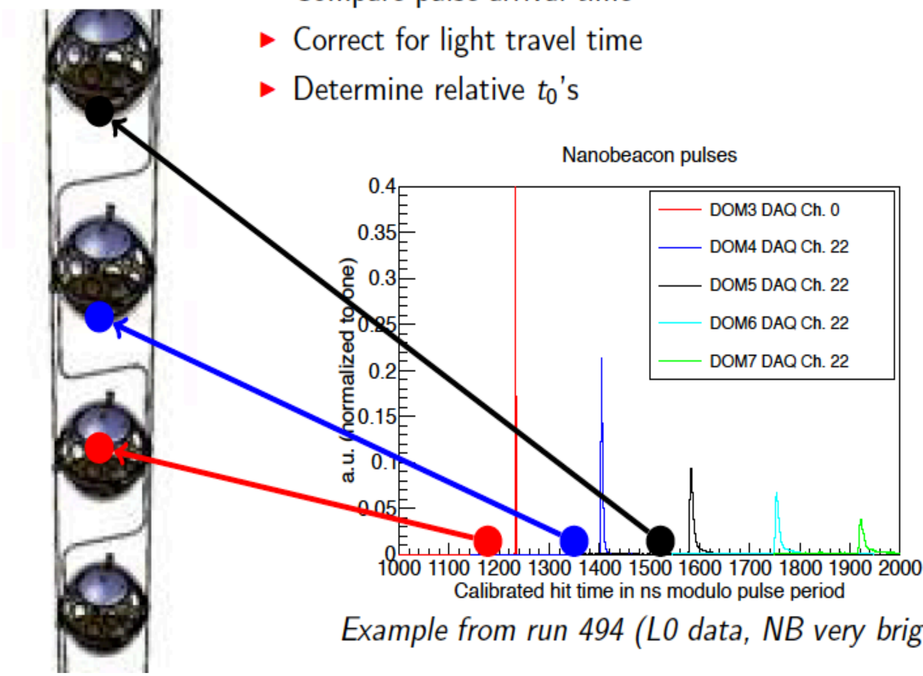




Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

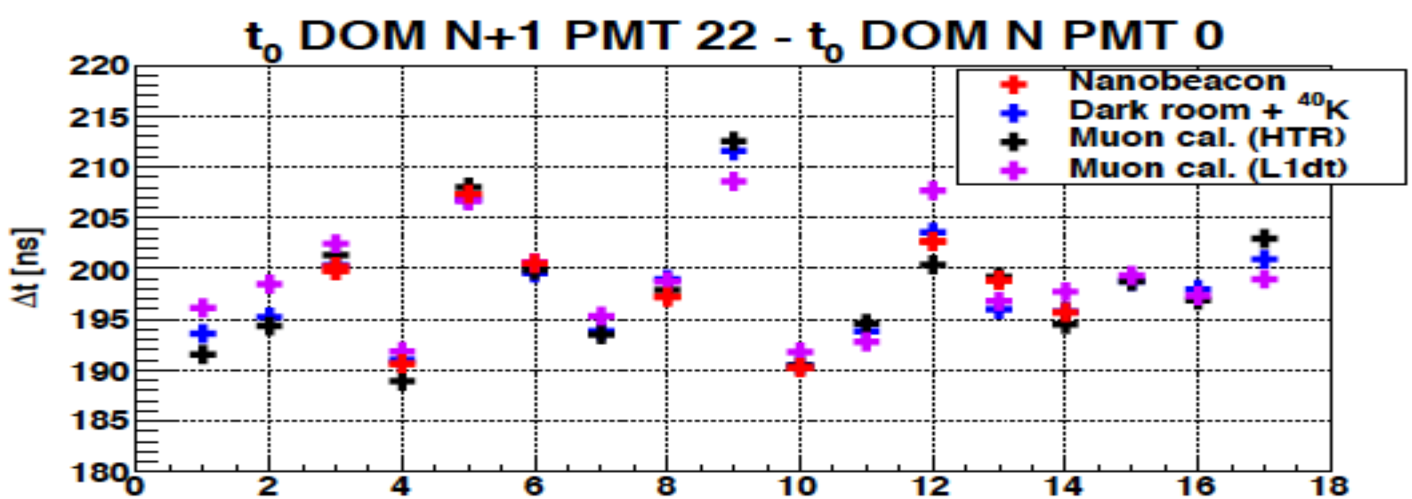
Inter-DOM calibration

- Compare pulse arrival time
- Correct for light travel time
- Determine relative t_0's

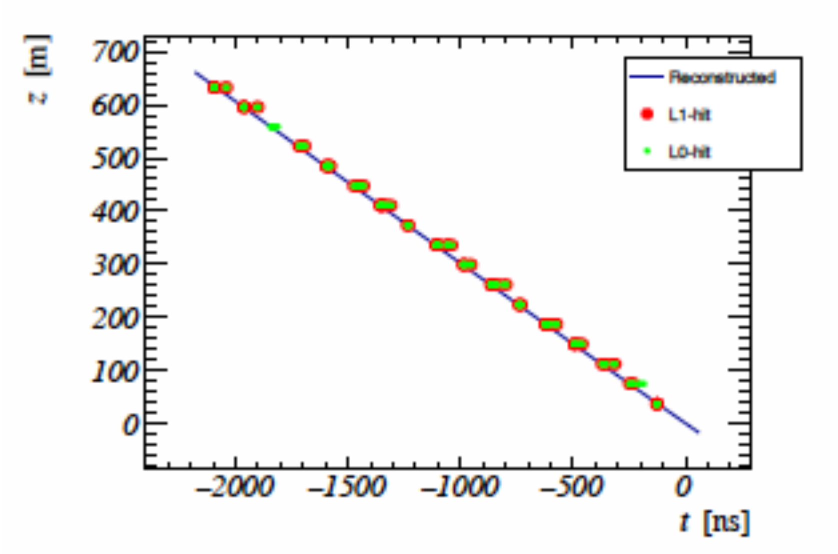


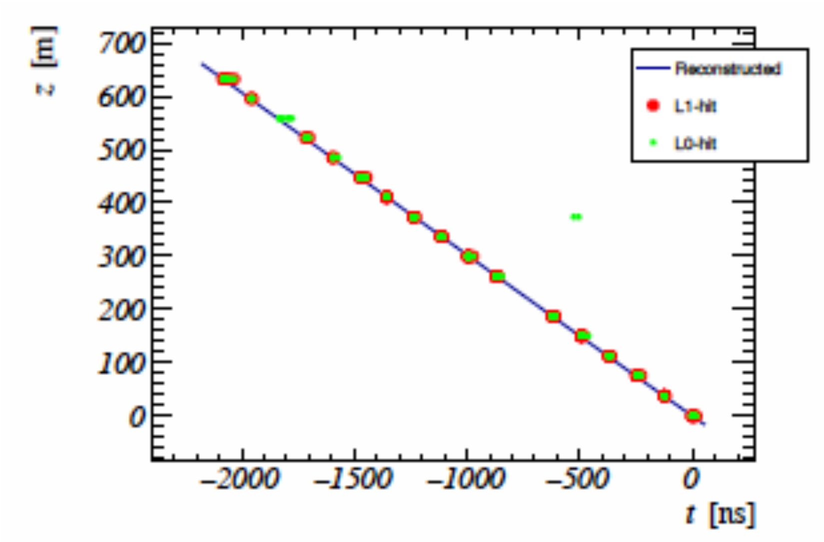
Example from run 494 (L0 data, NB very bright)

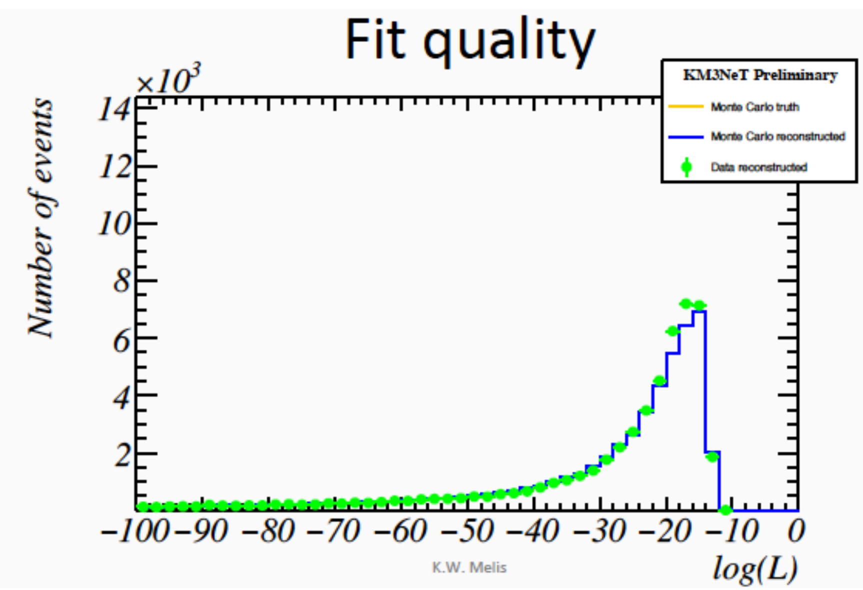
- Method 2:
- Hit time residual excluding one DOM
- Triggered events ≥ 6 DOMs hit

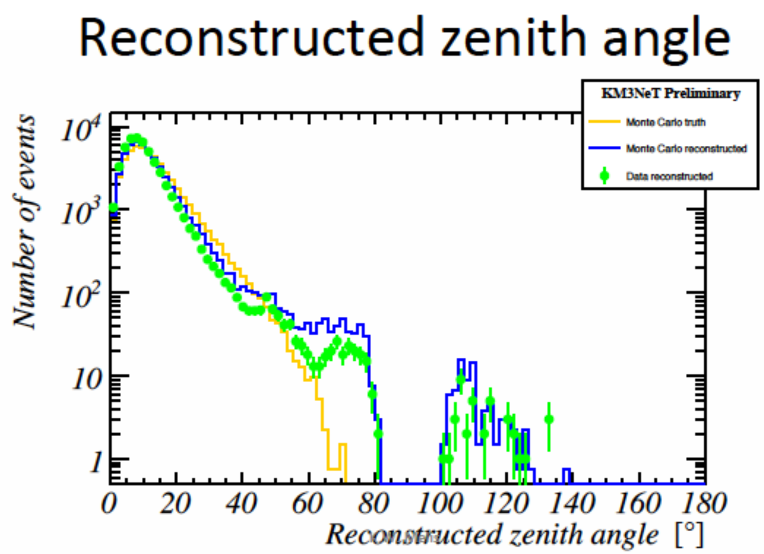


Atmos Muon Reconstruction



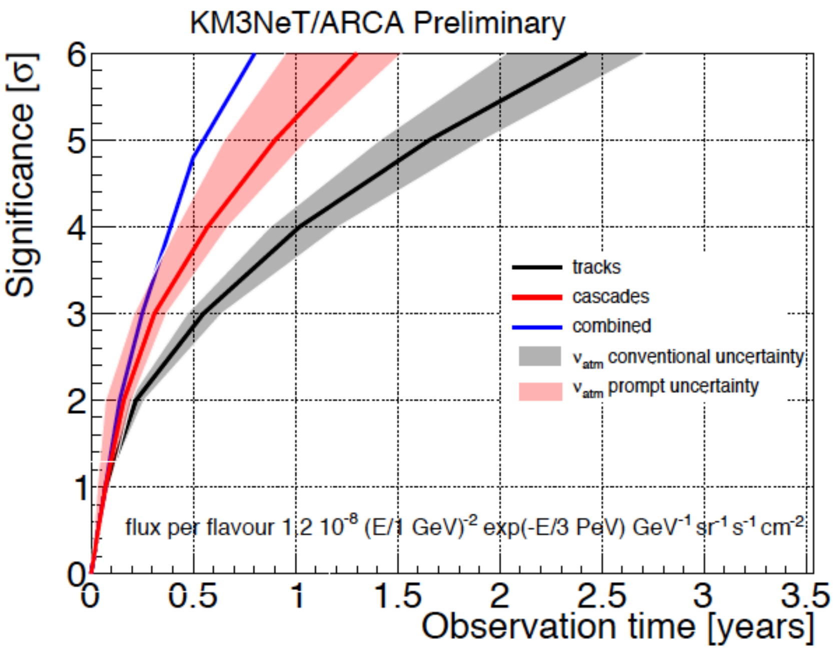






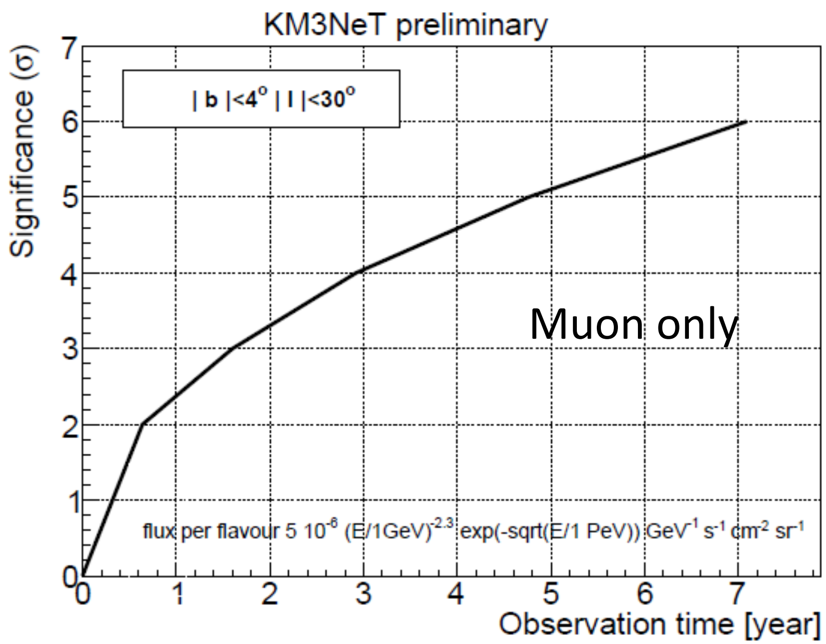
KM3NET: Diffuse Flux

IC Diffuse flux



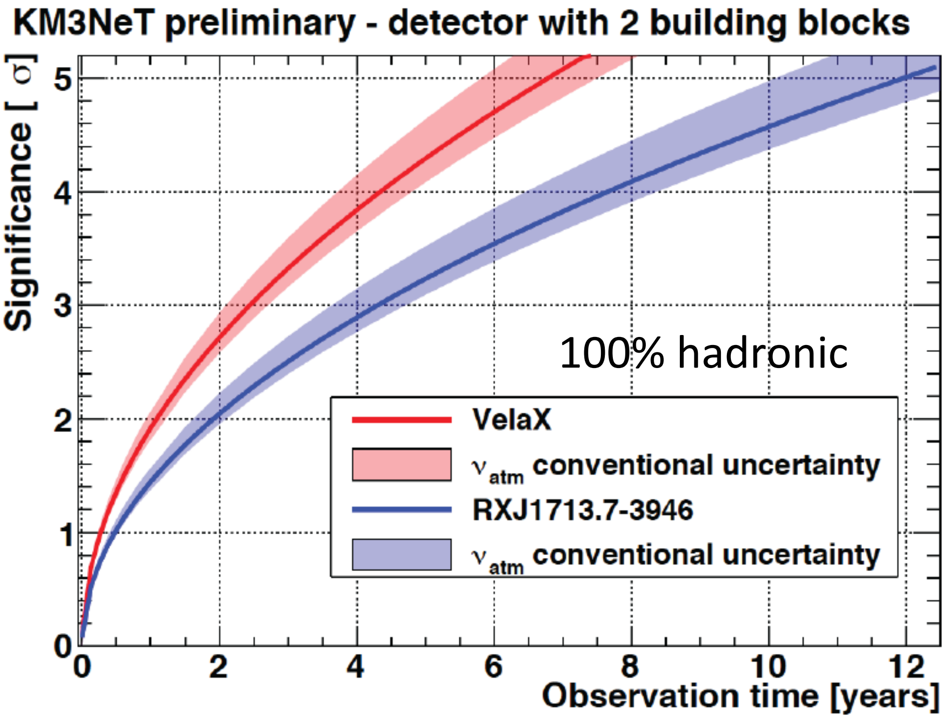
KRAγ Model

radially dependent diffusion coefficient for Galactic cosmic rays



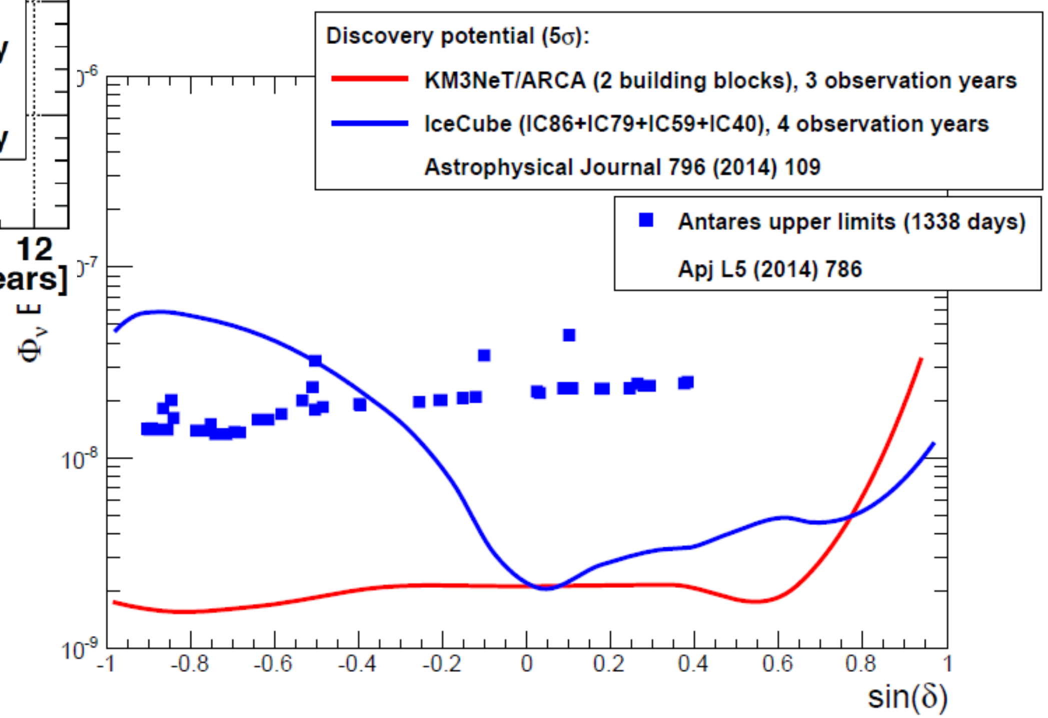
	muon	cascade
Angular resolution	0.1°	2°
Energy resolution	300%	5%

KM3NET: Point Sources



- Galactic sources in reach

- Significant discovery potential for extragalactic sources



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Oscillation of massive neutrinos

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

Atmospheric
θ_A~45°

Reactor
θ_{13}~9°
↓
CP violating phase δ_{CP}

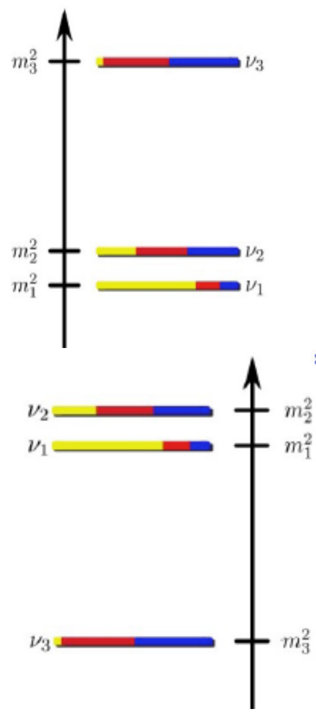
Solar
$\theta_\odot$~30°

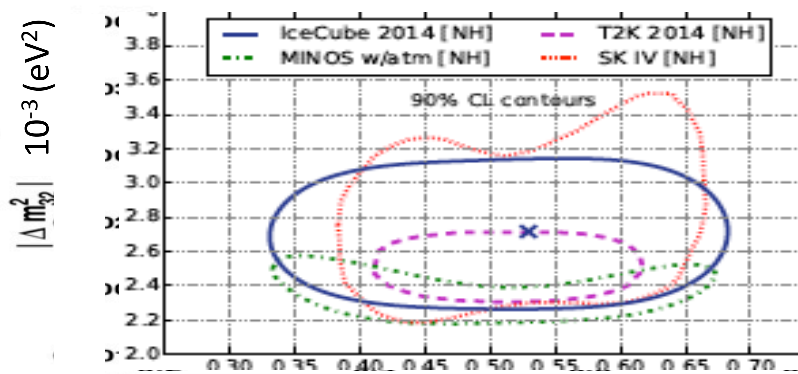
Majorana

$$m_1^2 < m_2^2$$

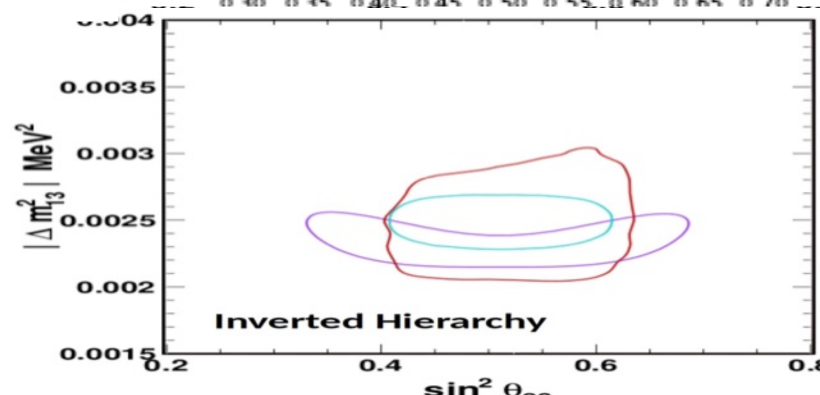
$$m_2^2 - m_1^2 \ll |m_3^2 - m_{1,2}^2|$$

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





arXiv:1410.7227



The neutrino mass hierarchy

- Prime discriminator for theory models
- Origin of neutrino mass and flavour
- Help measuring the CP phase
- Absolute mass scale
- Nature (Dirac vs Majorana)
- Core-Collapse Supernovae Physics

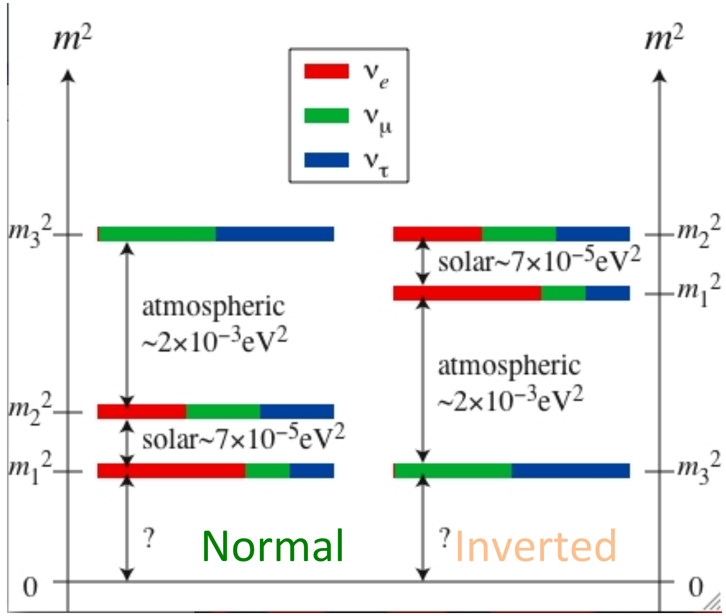
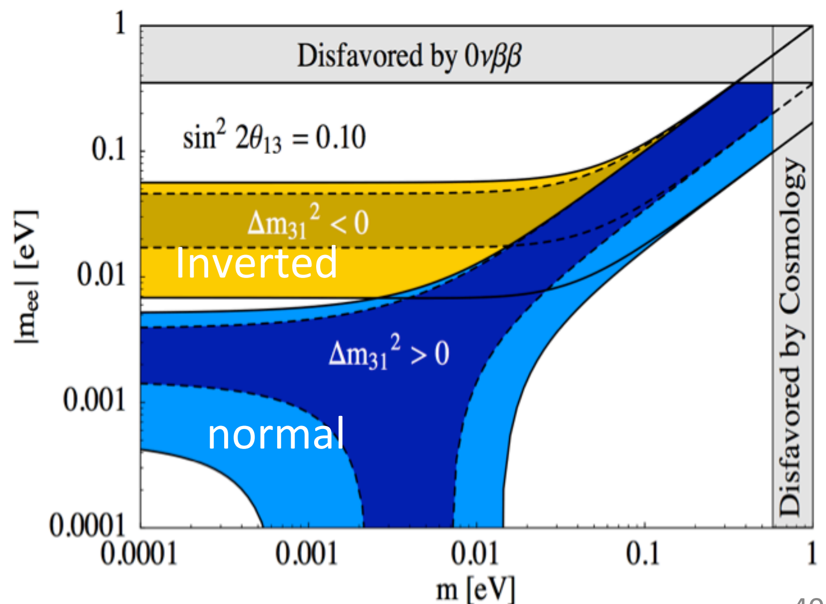


TABLE I: Mixing Angles for Models with Lepton Flavor Symmetry.

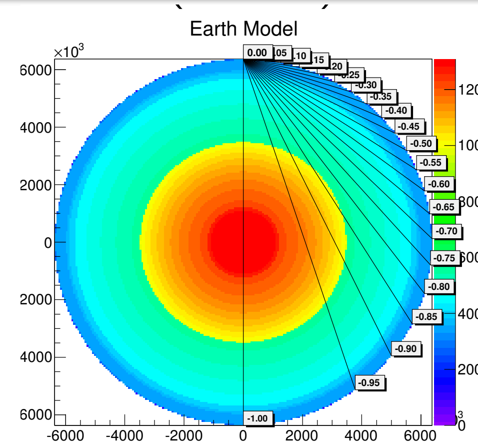
Reference		Hierarchy	$\sin^2 2\theta_{23}$	$\tan^2\theta_{12}$	$\sin^2\theta_{13}$
Anarchy Model:					
dGM	[18]	Either			≥ 0.011 @ 2σ
$\mathbf{L_e - L_\mu - L_\tau}$ **Models:**					
BM	[35]	Inverted			0.00029
BCM	[36]	Inverted			0.00063
GMN1	[37]	Inverted		≥ 0.52	≤ 0.01
GL	[38]	Inverted			0
PR	[39]	Inverted		≤ 0.58	≥ 0.007
$\mathbf{S_3}$ **and** $\mathbf{S_4}$ **Models:**					
CFM	[40]	Normal			0.00006 - 0.001
HLM	[41]	Normal	1.0	0.43	0.0044
		Normal	1.0	0.44	0.0034
KMM	[42]	Inverted	1.0		0.000012
MN	[43]	Normal			0.0024
MNY	[44]	Normal			0.000004 - 0.000036
MPR	[45]	Normal			0.006 - 0.01
RS	[46]	Inverted	$\theta_{23} \geq 45°$		≤ 0.02
		Normal	$\theta_{23} \leq 45°$		0
TY	[47]	Inverted	0.93	0.43	0.0025
T	[48]	Normal			0.0016 - 0.0036
$\mathbf{A_4}$ **Tetrahedral Models:**					
ABGMP	[49]	Normal	0.997 - 1.0	0.365 - 0.438	0.00069 - 0.0037
AKKL	[50]	Normal			0.006 - 0.04
Ma	[51]	Normal	1.0	0.45	0
SO(3) Models:					
M	[52]	Normal	0.87 - 1.0	0.46	0.00005
Texture Zero Models:					
CPP	[53]	Normal			0.007 - 0.008
		Inverted			≥ 0.00005
		Inverted			≥ 0.032
WY	[54]	Either			0.0006 - 0.003
		Either			0.002 - 0.02
		Either			0.02 - 0.15



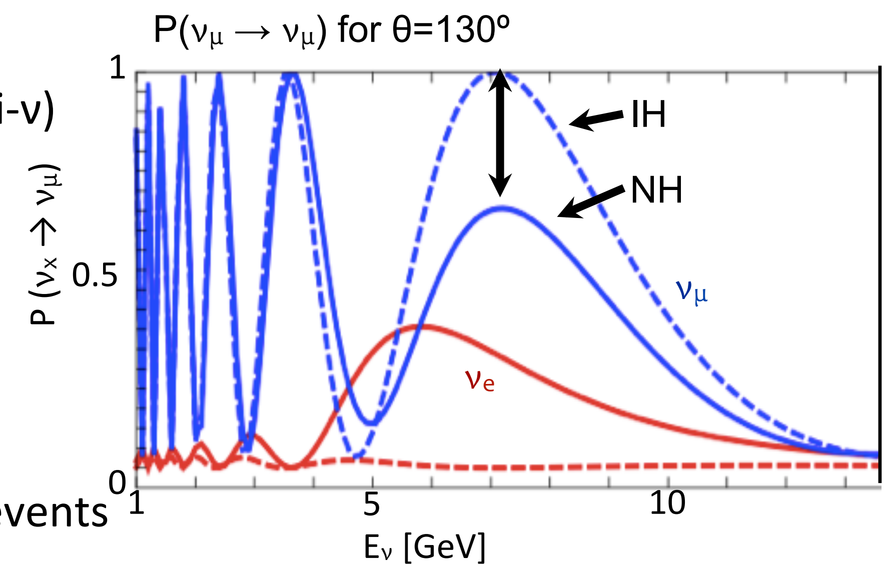
Measuring the neutrino mass hierarchy with atmospheric neutrinos

- a « free beam » of known composition (ν_e, ν_μ)
- wide range of baselines (50 → 12800 km) and energies (GeV → PeV)
- oscillation pattern distorted by Earth matter effects (hierarchy-dependent):

  maximum difference IH ↔ NH at
  θ=130° (7645 km) and E_ν = 7 GeV



- opposite effect on anti-neutrinos: IH(ν)≈NH(anti-ν)
  BUT differences in flux and cross-section:
  $\Phi_{atm}(\nu) \approx 1.3 \times \Phi_{atm}(\text{anti-}\nu)$
  $\sigma(\nu) \approx 2\sigma(\text{anti-}\nu)$ at low energies

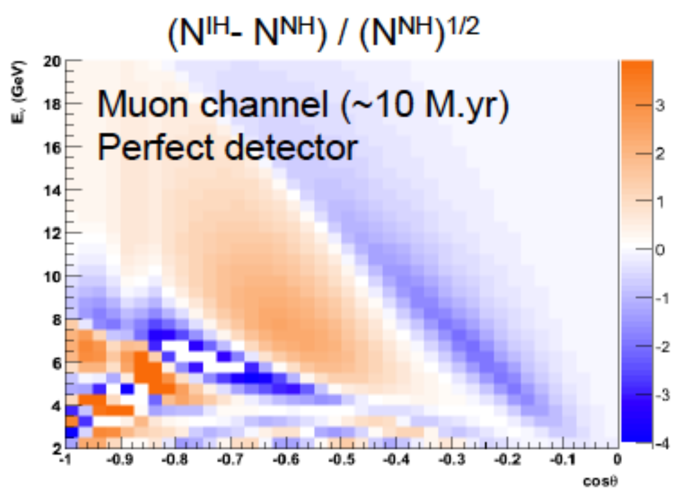


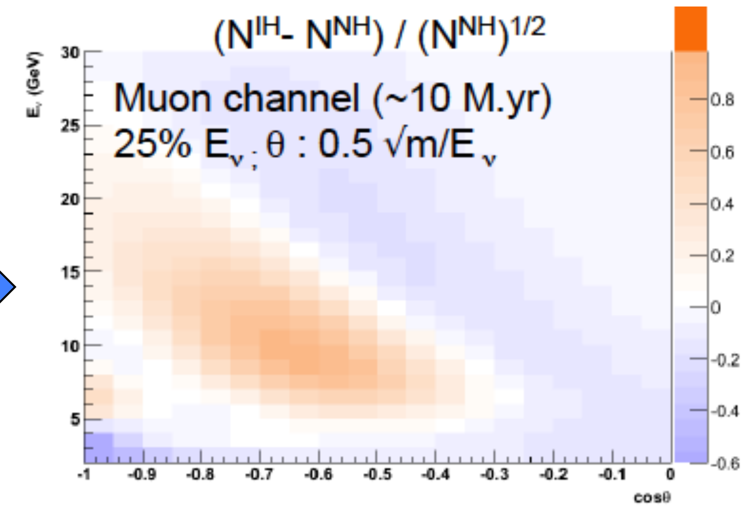
- measure zenith angle and energy of upgoing atmospheric GeV-scale neutrinos,
  identify and count muon and electron channel events
- feasible now that θ_{13} is measured to be large

Akmedov, Razzaque & Smirnov, JHEP 02 (2013) 082

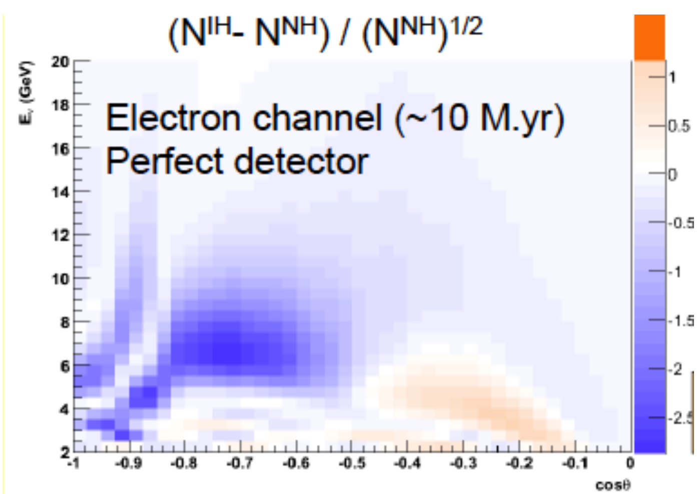
Experimental signature

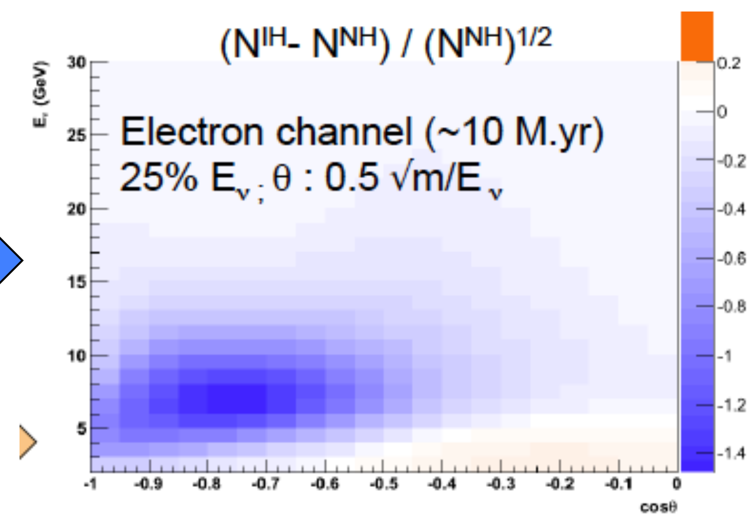
Both muon- and electron-channels contribute to net hierarchy asymmetry
electron channel more robust against detector resolution effects:





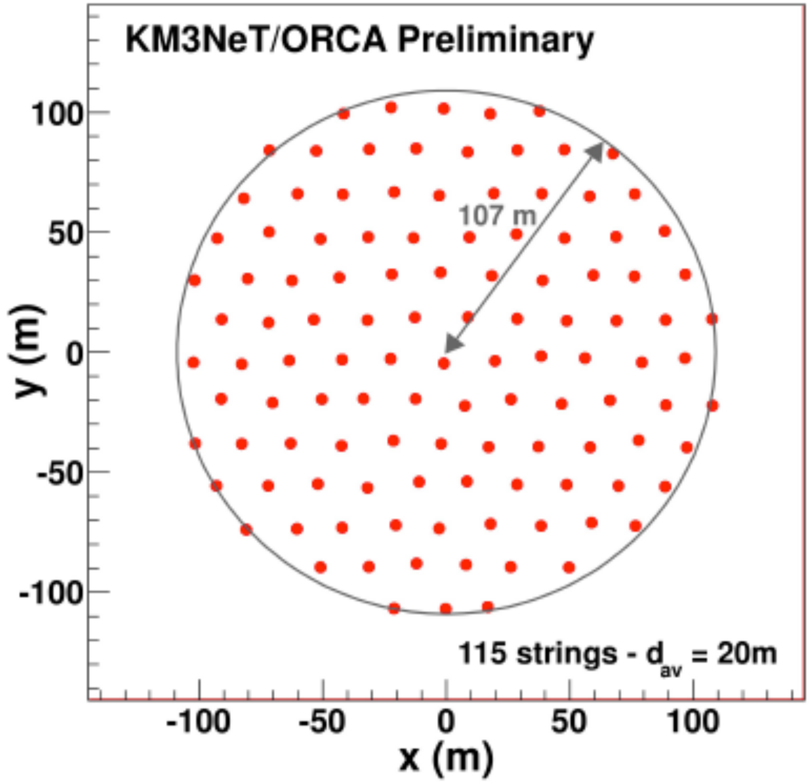
E, θ smearing (kinematics + detector resolution)



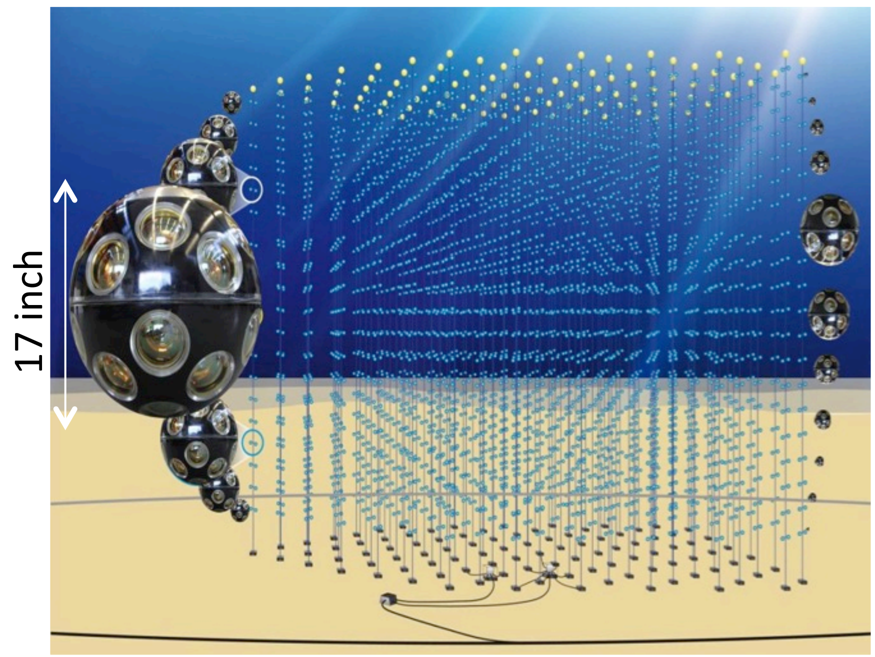


The ORCA benchmark design

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

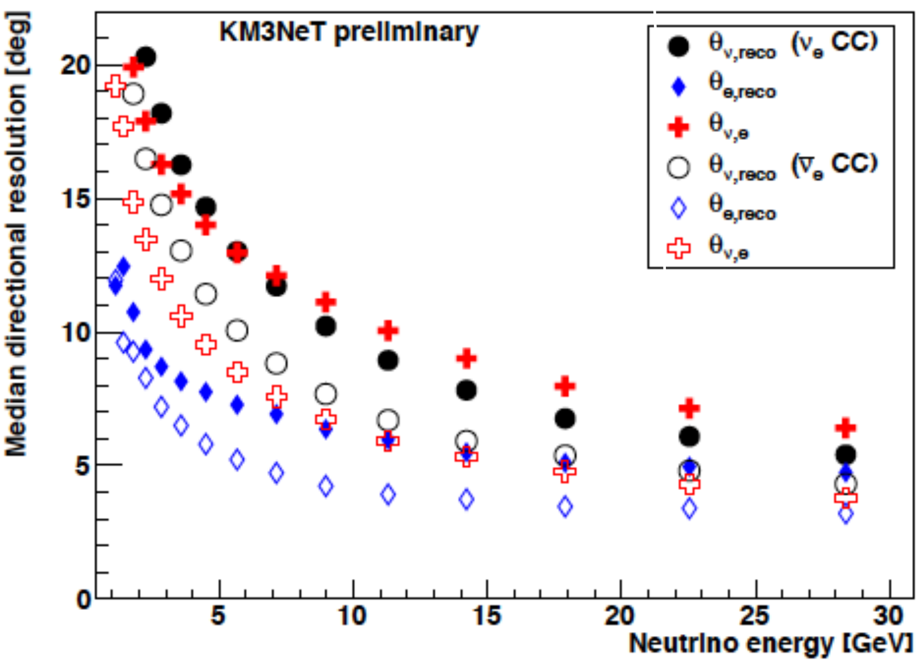


Instrumented volume ~6.5 Mt, 2070 OM
Optical background:
10kHz/PMT & 500Hz coincidence

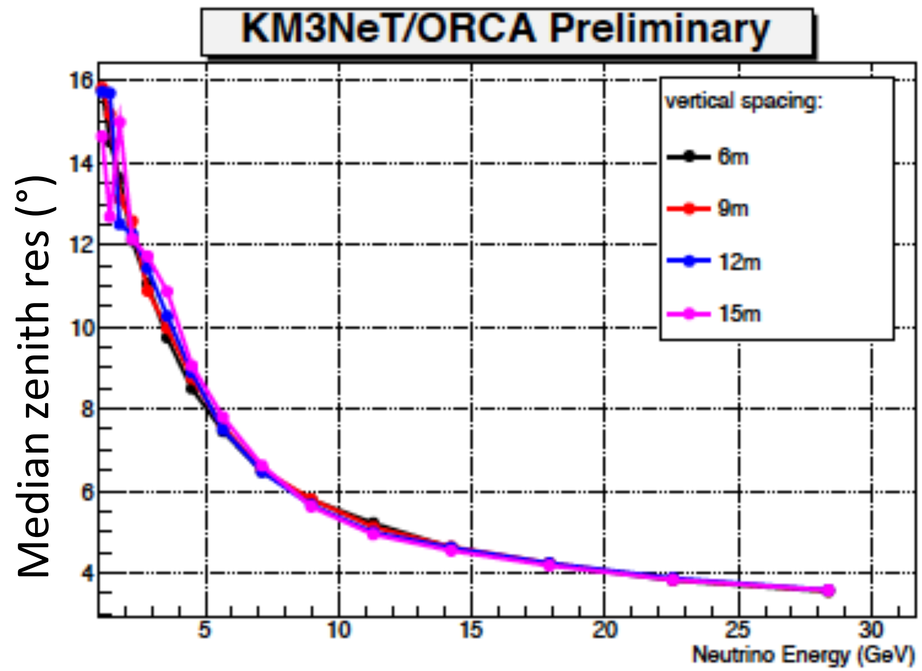


Angular Resolutions

cascade



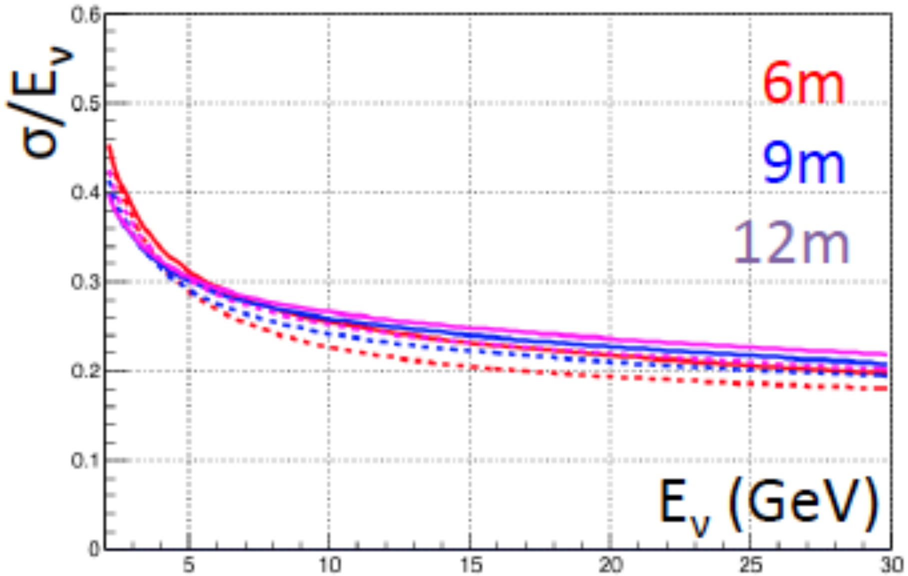
track



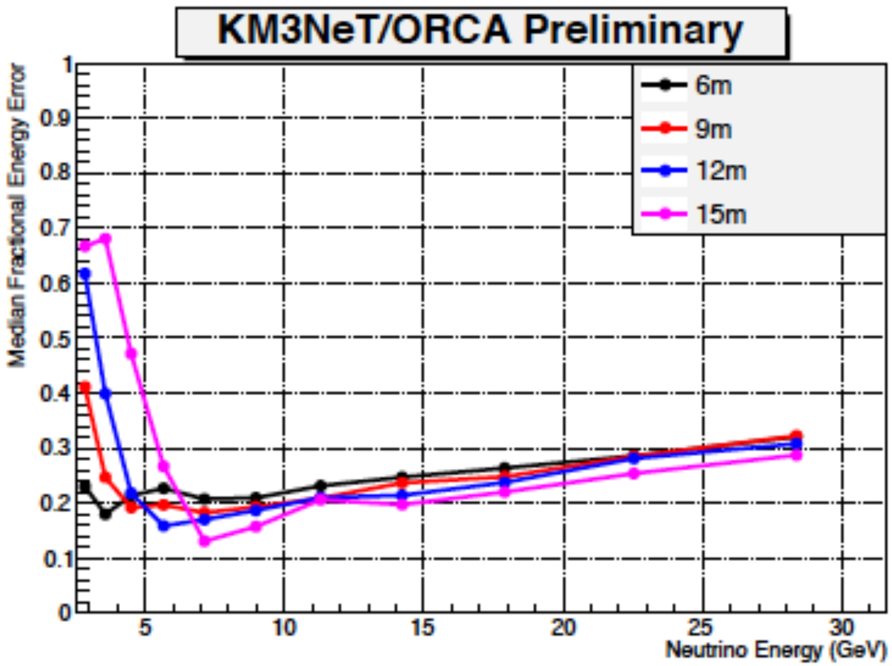
Excellent angular resolution
Dominated by kinematics
Largely independent of vertical spacing

Energy Resolutions

cascade

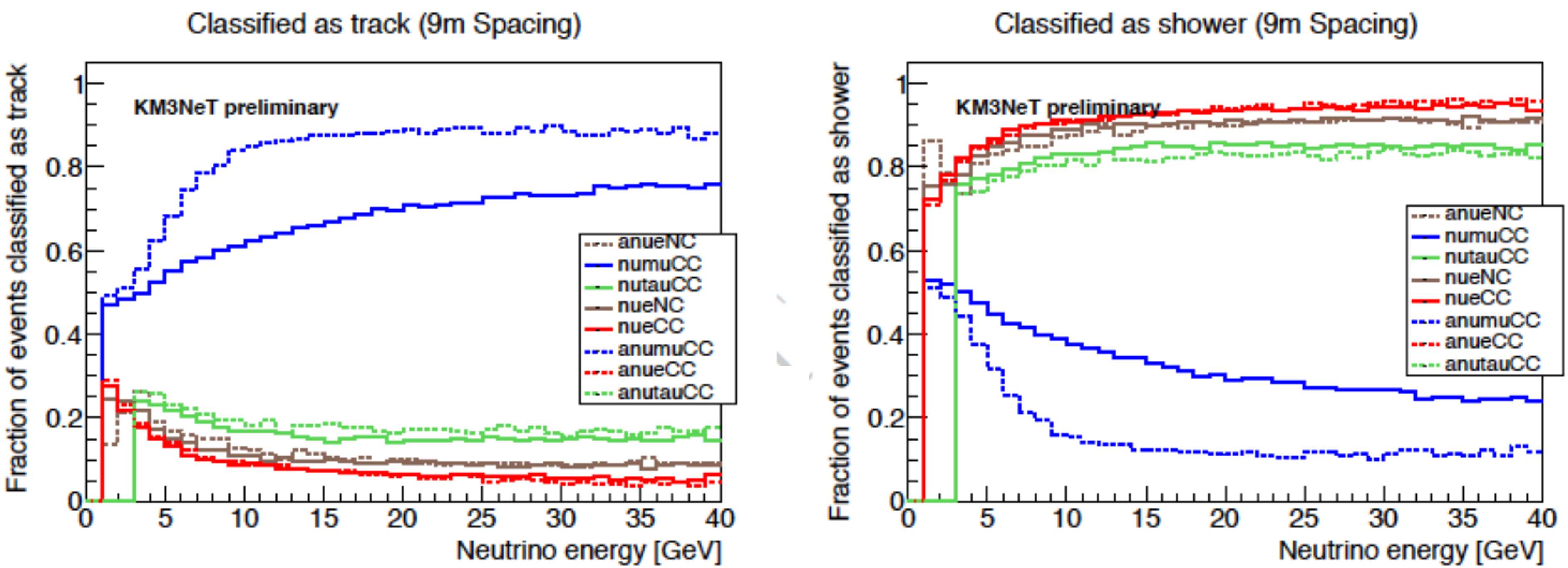


track



Energy resolution better than 25% in relevant range
– close to Gaussian

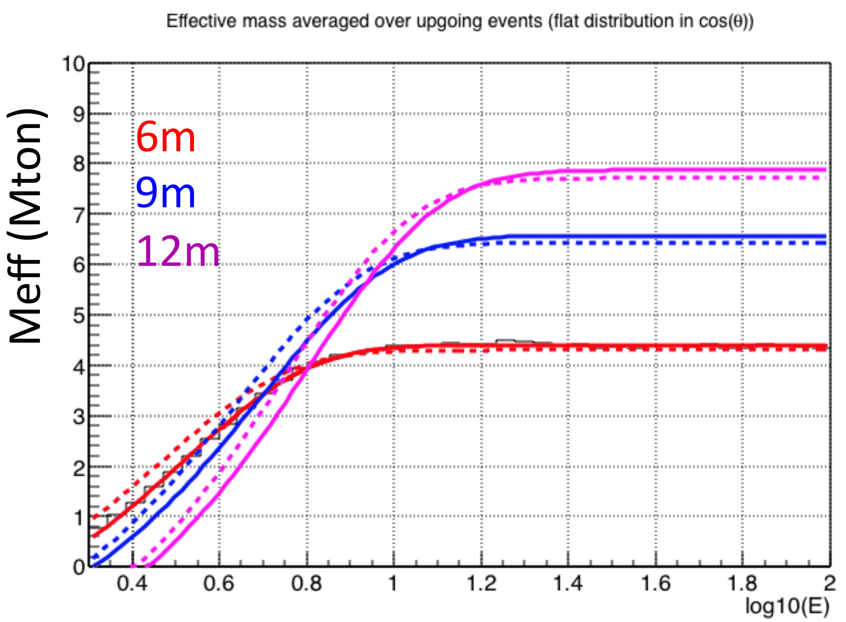
Cascade/track identification

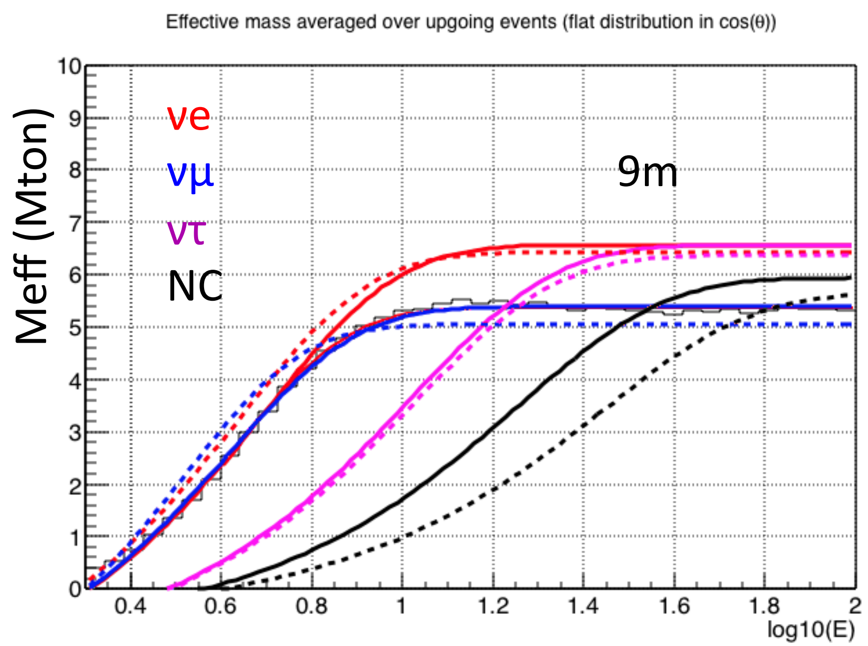


- Discrimination of track-like (ν_μ^{CC}) and cascade-like (ν^{NC}, ν_e^{CC}) events
- Classification uses "Random Decision Forest"
- At 10 GeV:
  - 90% correct identification of ν_e^{CC} and anti –mu
  - 70% correct identification of ν_μ^{CC}

Effective Mass

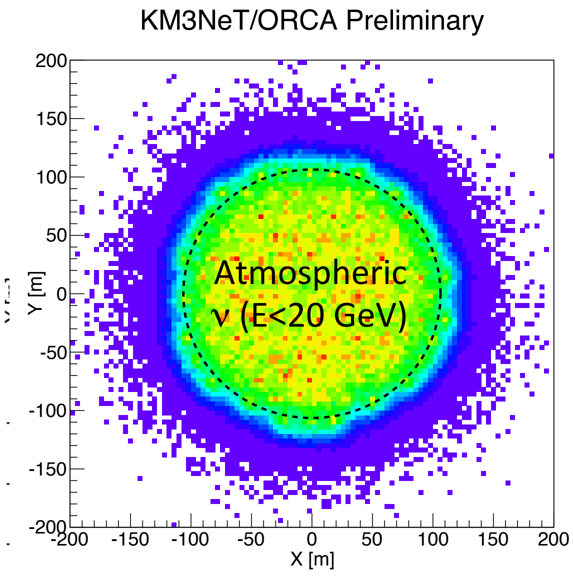
- Instrumented volume reached at ~30 GeV
- 50% Efficiency at 5-10 GeV depending on vertical spacing
- Solid : nu–Dashed: anti-nu

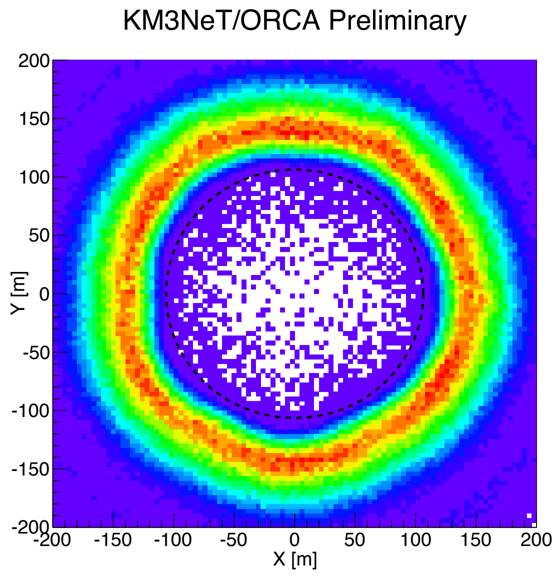




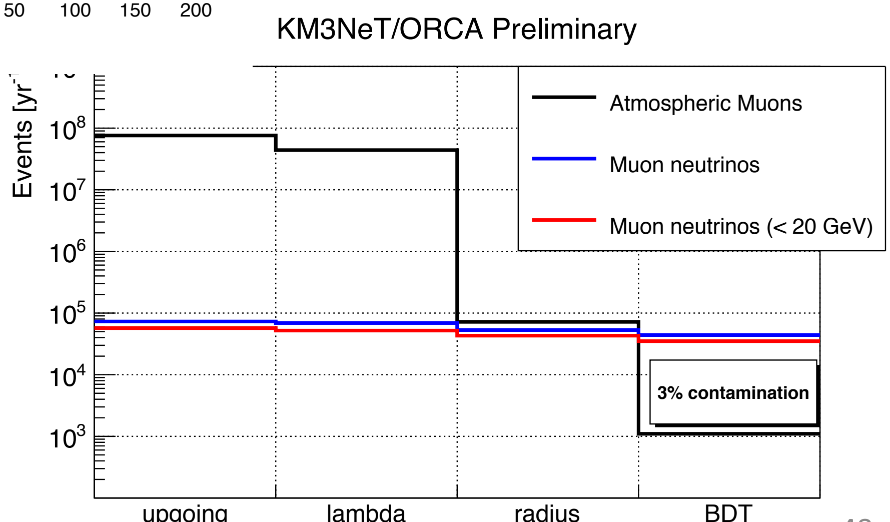
Atmospheric muon rejection

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





Instrumental veto not mandatory



Tunable few % contamination achievable without too strong signal loss

Sensitivity Studies

Various systematic effects taken into account:

- Oscillation parameters
  - Δm^2, θ_{12} fixed; θ_{13} fitted within its error
  - ΔM^2, θ_{23}, δ_{CP} → fitted unconstrained

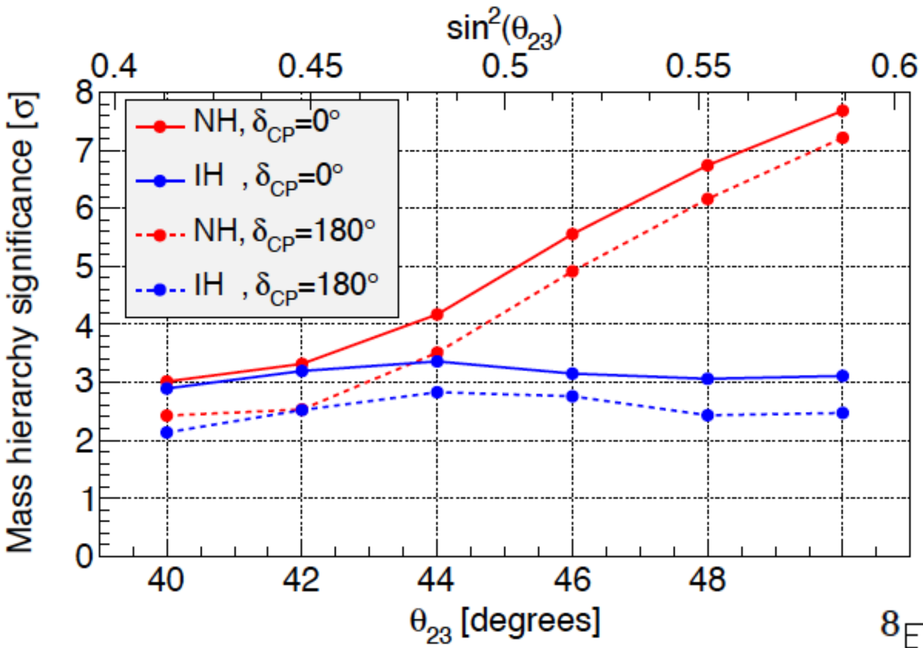
- Flux, cross section, detector related

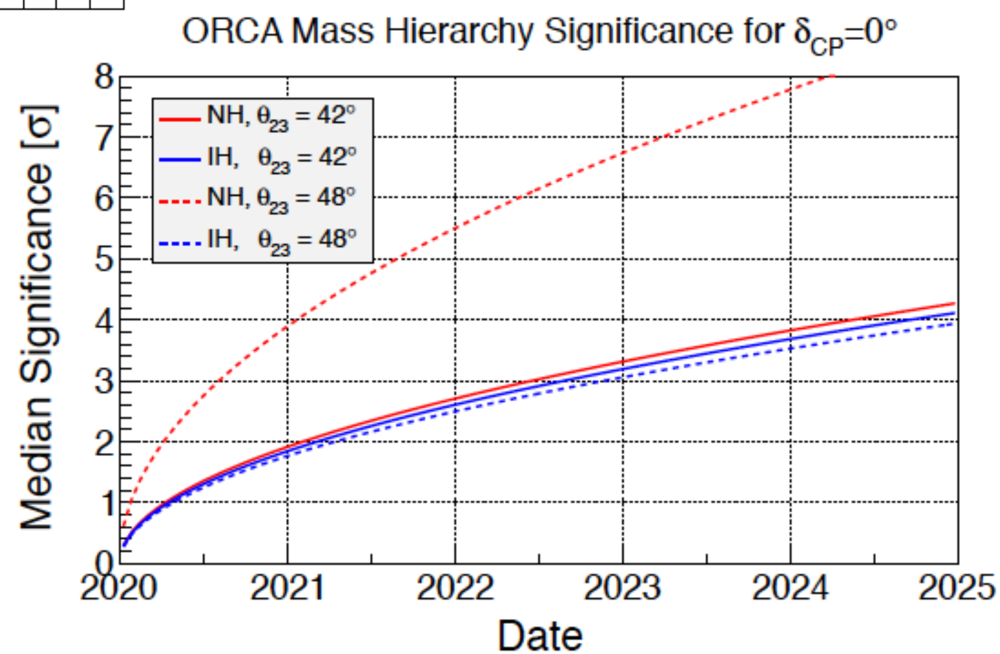
(average fluctuation w.r.t. nominal)

  - Overall normalisation (2.0%)
  - ν/ν ratio (4.0%)
  - e/μ ratio (1.2%)
  - NC scaling (11.0%)
  - Energy slope (0.5%)
  - Energy scale

→Fitted unconstrained

Sensitivity to mass hierarchy



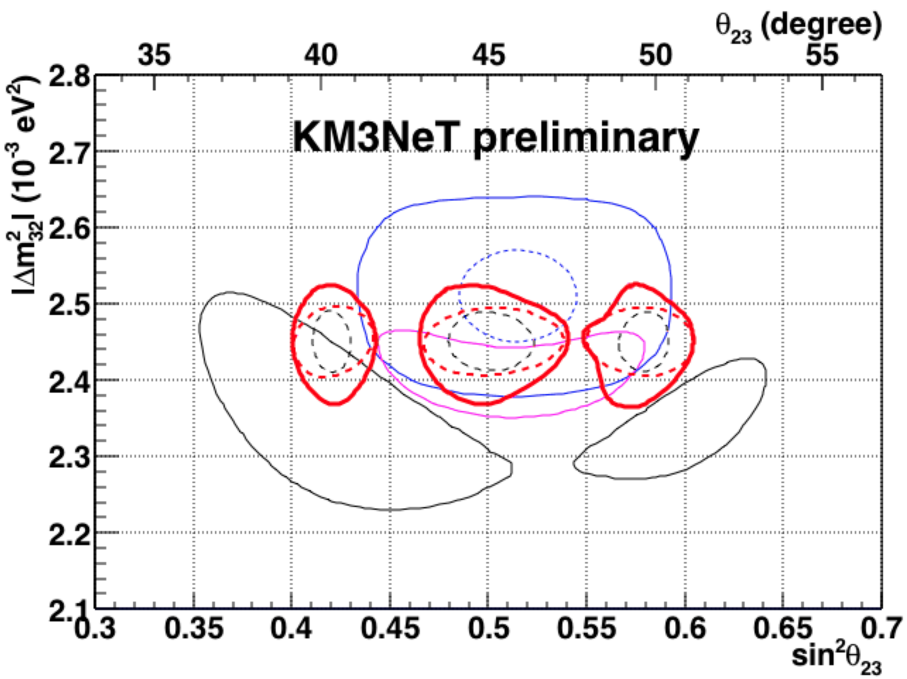


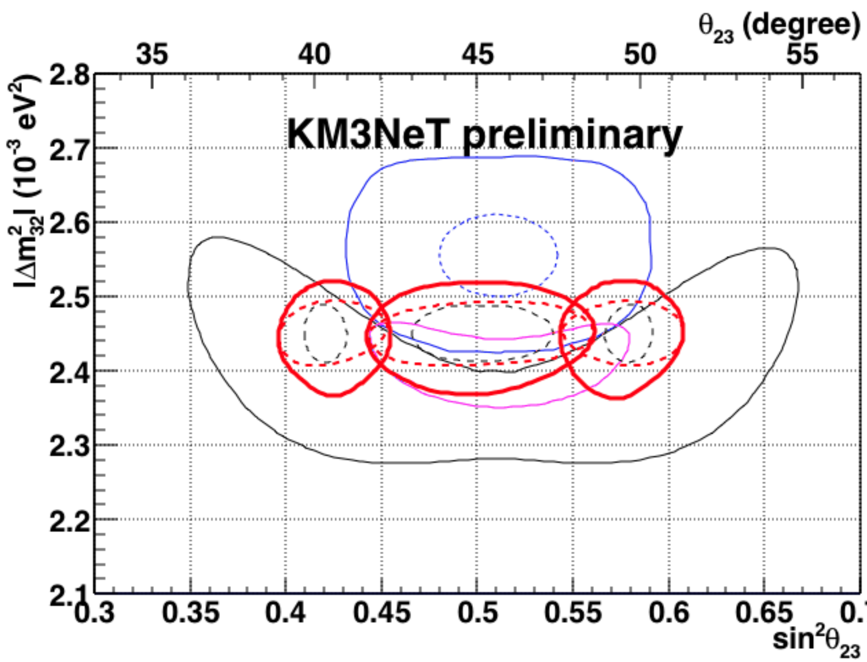
Sensitivity to PMNS parameters

3 year sensitivity to the atmospheric parameters

ORCA: red ellipses (solid/dashed=with/wo Eν scale)

1 σ contour: 3% in ΔM^2, 4-10% in $\sin^2\theta_{23}$

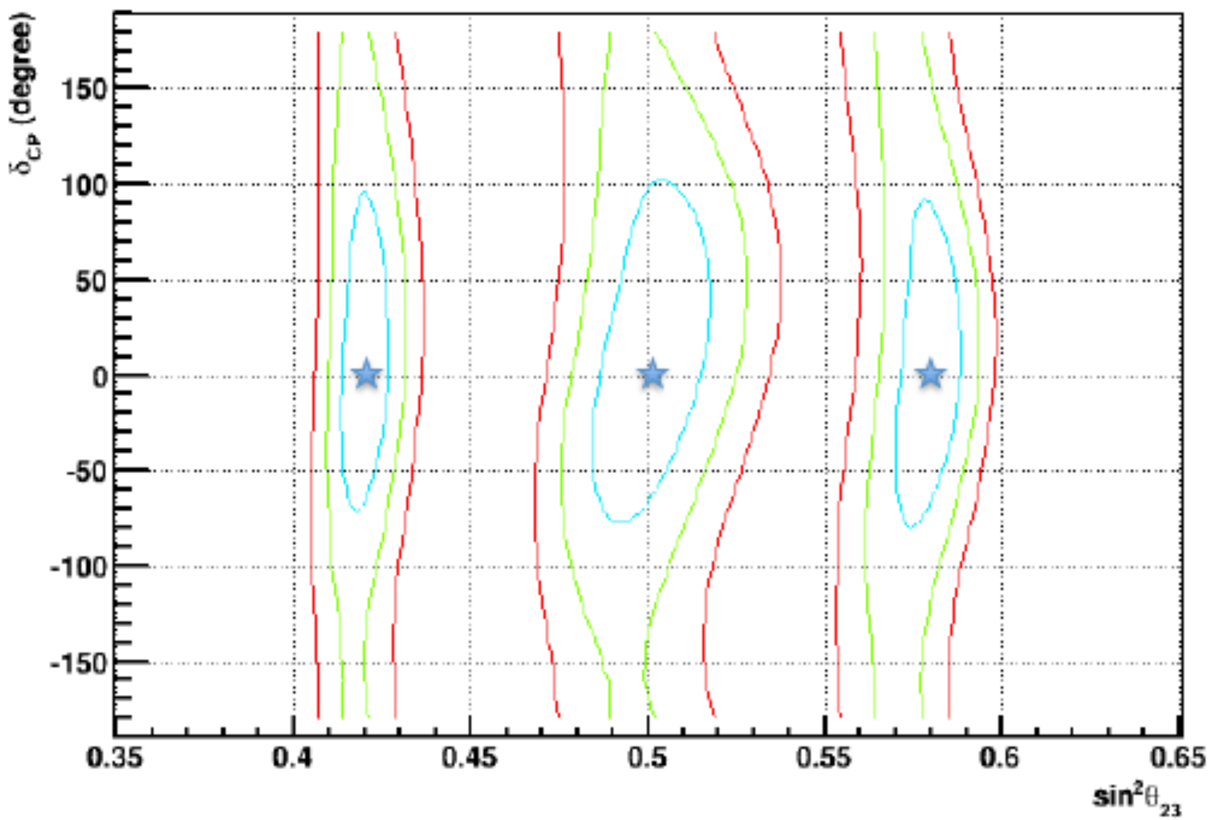




ORCA, MINOS, T2K, NovA 2020

Sensitivity to CP phase ?

6 years, no systematics
NH true, δCP=0, three test points, 1/2/3 sigma



Additional ORCA physics topics

- Indirect Search for Dark Matter

- Earth tomography and composition

    📖 Gonzales-Garcia et al.,Phys.Rev.Lett.100:061802,2008,
    📖 Agarwalla et al., arXiv:1212.2238v1

- Test NSI and other exotic physics

    📖 Ohlsson et al, Phys. Rev. D 88 (2013) 013001
    📖 Gonzales-Garcia et al., Phys.Rev. D71 (2005) 093010

- Supernovae monitoring (takes advantage of new DOM features)

- Low Energy Neutrino Astrophysics
    - Gamma-ray bursts, Colliding Wind Binaries

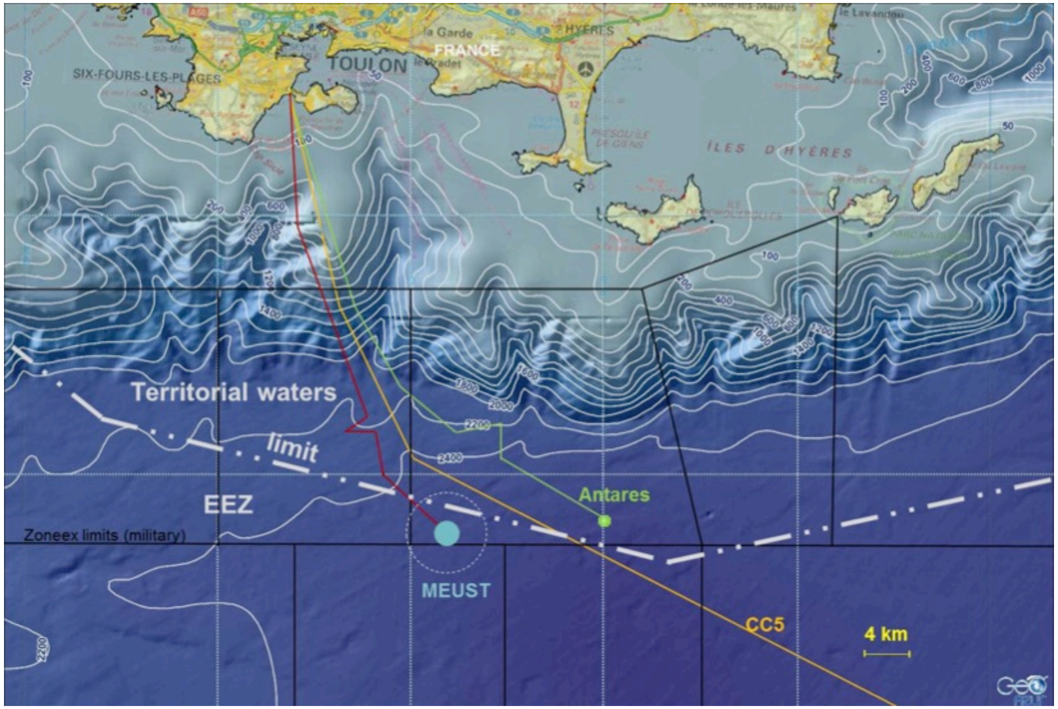
    📖 J. Becker Tjus, arXiv:1405.0471 ...

- A Neutrino beam from to ORCA (NMH and CP phase)

    📖 Lujan-Peschard et al, Eur. Phys. J. C (2013) 73:2439
    📖 Tang & Winter, JHEP 1202 (2012) 028
    📖 J. Brunner, AHEP, Volume 2013 (2013), Article ID 782538.

ORCA Construction

Phase 1 (funded- 11M€) : deploy a 6-7 string array In the ORCA configuration to demonstrate detection method in the GeV range.



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

Main cable: dec 2015

node: april 2016

ORCA string: june 2016

Summary and perspectives (I)

- Diffuse flux of cosmics neutrinos observed
- higher level of hadronic activity in the non-thermal universe than previously thought → Exciting times ahead !
- Sources remain to be identified

- ANTARES: first undersea Cherenkov detector
  - Excellent angular resolution, view of Southern sky
  - Competitive sensitivities (Galactic neutrino component, Dark matter searches)
  - Improvements still to come: include showers in all analyses
  - Taking data until superseded by KM3NeT circa end of 2016

- KM3NeT: phased approach to next-generation neutrino telescope
  - Capo Passero (KM3NeT-It) → **ARCA for HE neutrino astronomy (tracks & showers)**
  - Toulon (KM3NeT-Fr) → **ORCA for measurement of NMH**
  - First string performing well
  - Letter of Intent published
  - Selected for new ESFRI roadmap

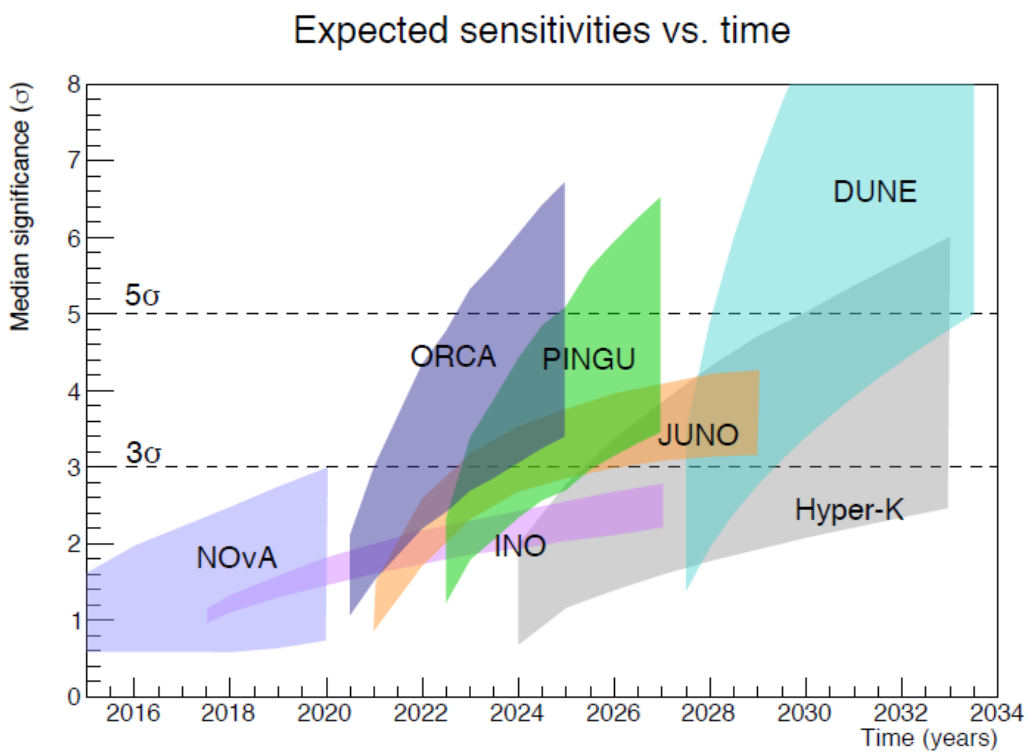
Summary and perspectives (II)

- Atmospheric Neutrinos still have a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy and the search for exotic phenomena

- Low energy (GeV) extensions of Neutrino Telescopes faster and cheaper than other alternatives…

- …but challenging, as systematics must be carefully controlled

- Preliminary ORCA sensitivities are very promising and expected to improve




KM3NeT
ANTARES

Sensitivity studies

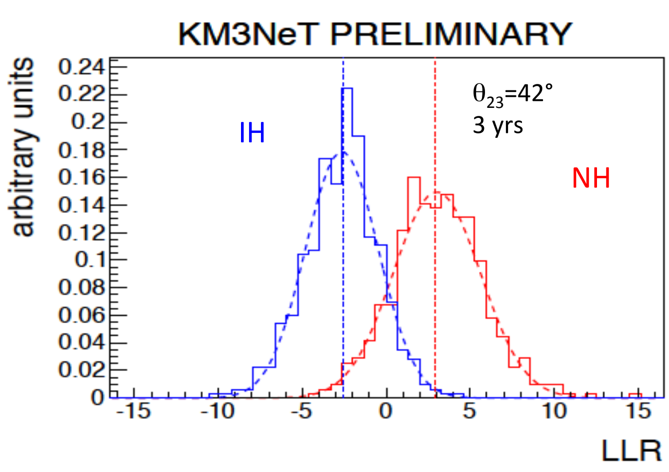
Global Fit Approach

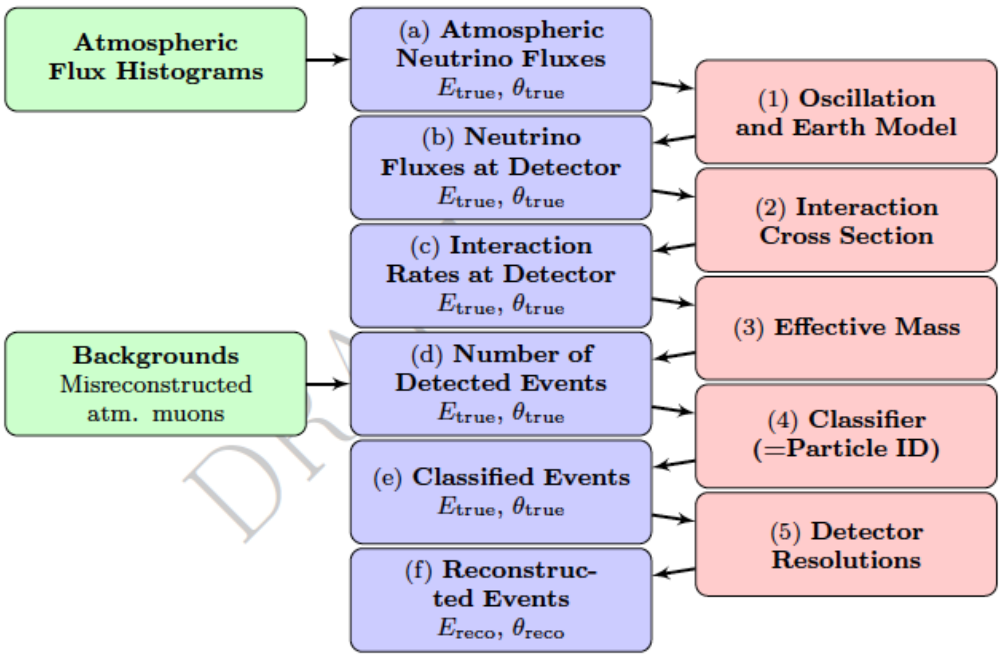
The performance of ORCA for the determination of the NMH is assessed by means of a likelihood ratio test:

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

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

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





ORCA/PINGU: Neutrino Mass Hierarchy Determination

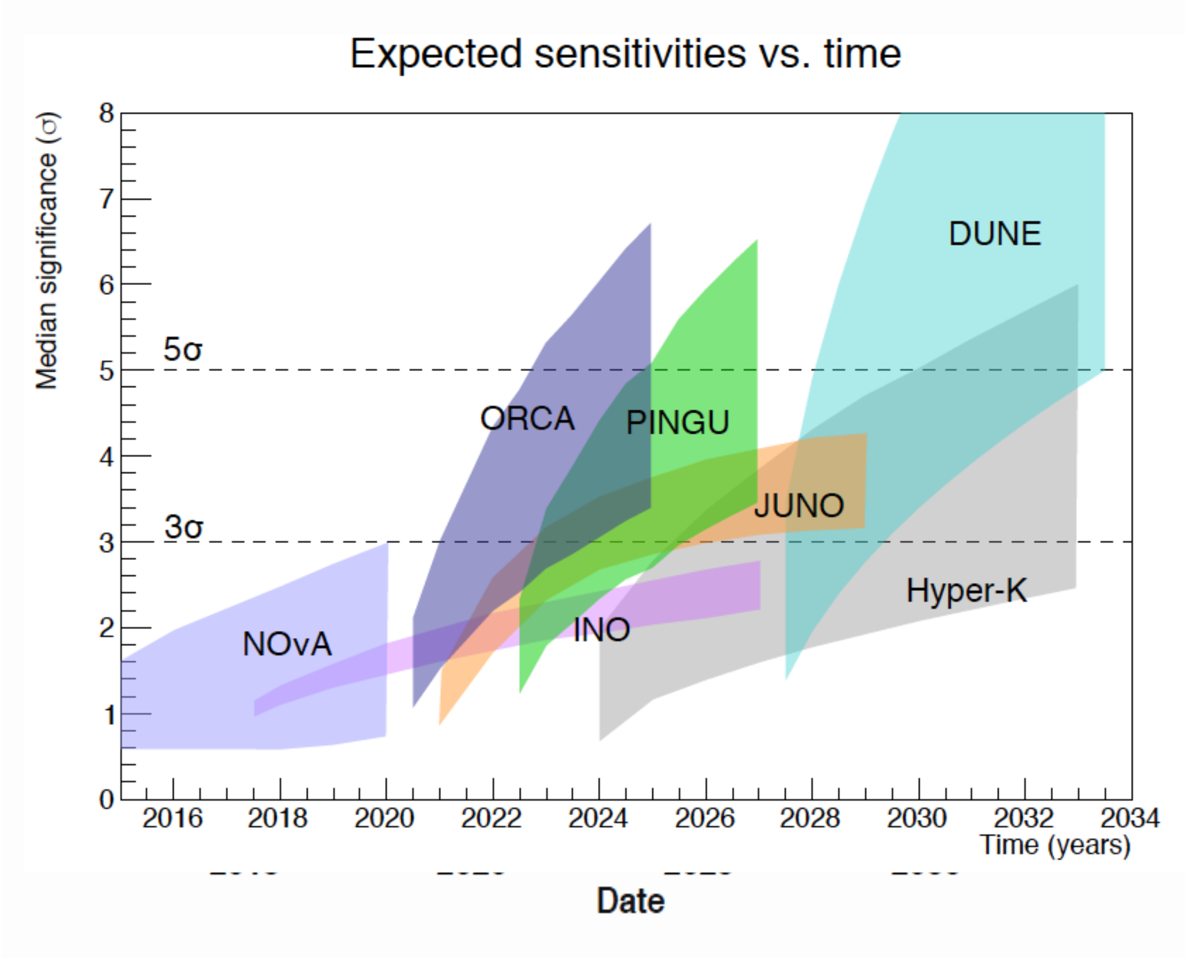
3 sigma determination of neutrino mass hierarchy in 3/4 years

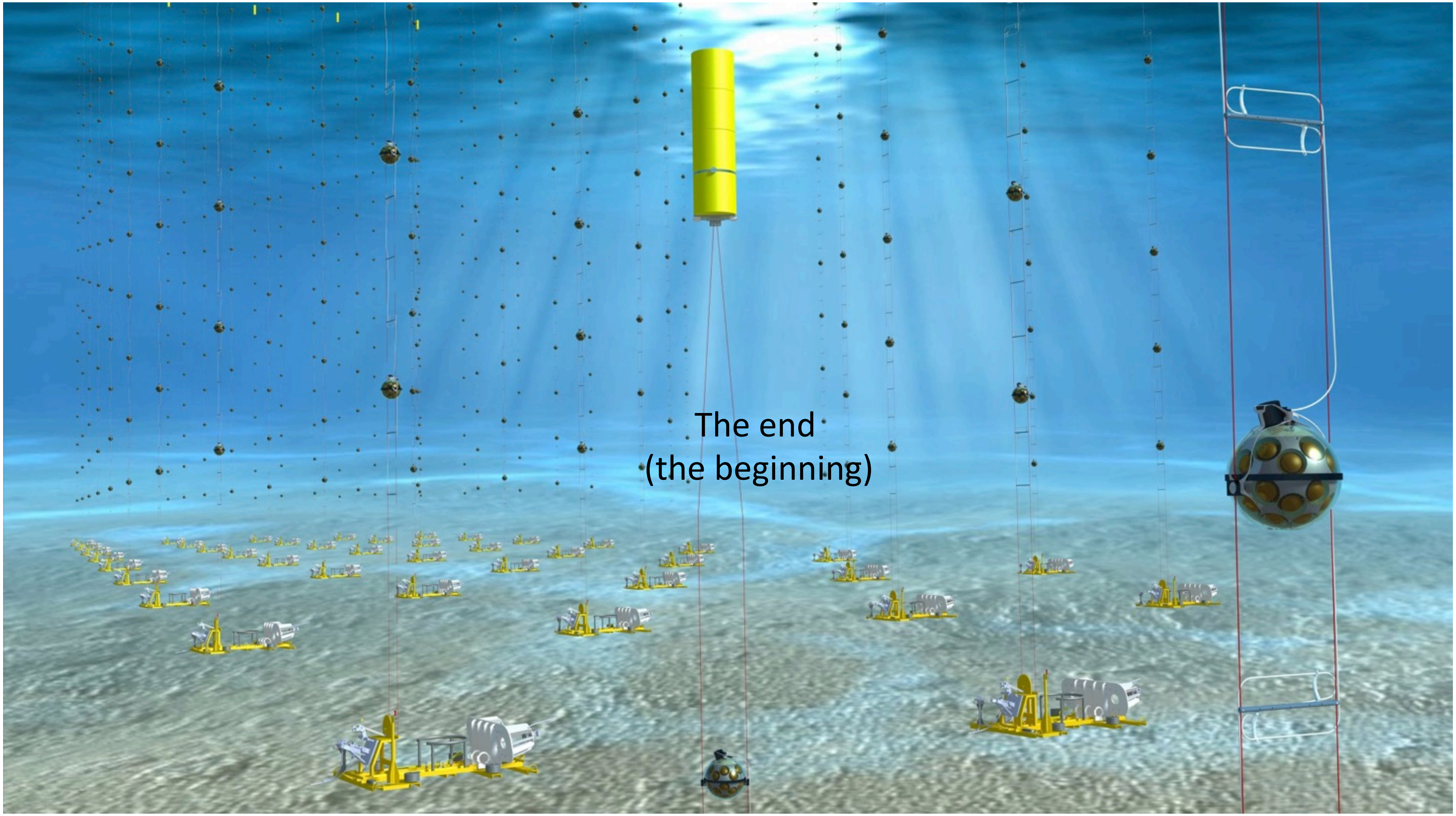
Widths indicate main uncertainty
- LBNE/NOVA: δcp
- JUNO: σE (3.0-3.5%)
- ORCA/PINGU/INO: θ_{23}

Other projections assume worst case parameters (1st oct)

ORCA timeline, assumes start construction 2017 for 3 years

LBNE from LBNE-doc-8087-V10
PINGU from MANTS 2015
Others Blennow

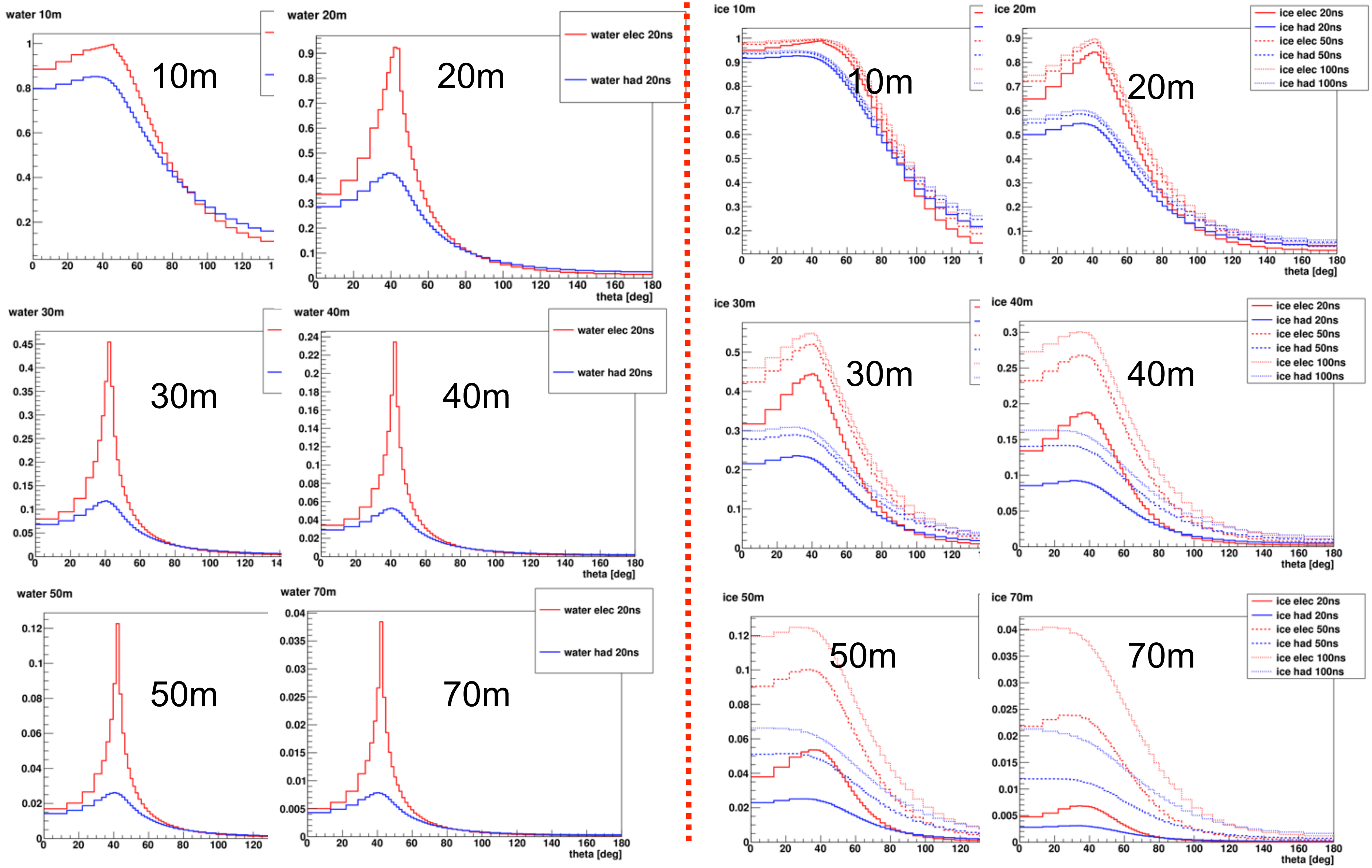




The end
(the beginning)

Water vs Ice: OM-hit probability

Probability to have at least one detected photon (KM3NeT OM)



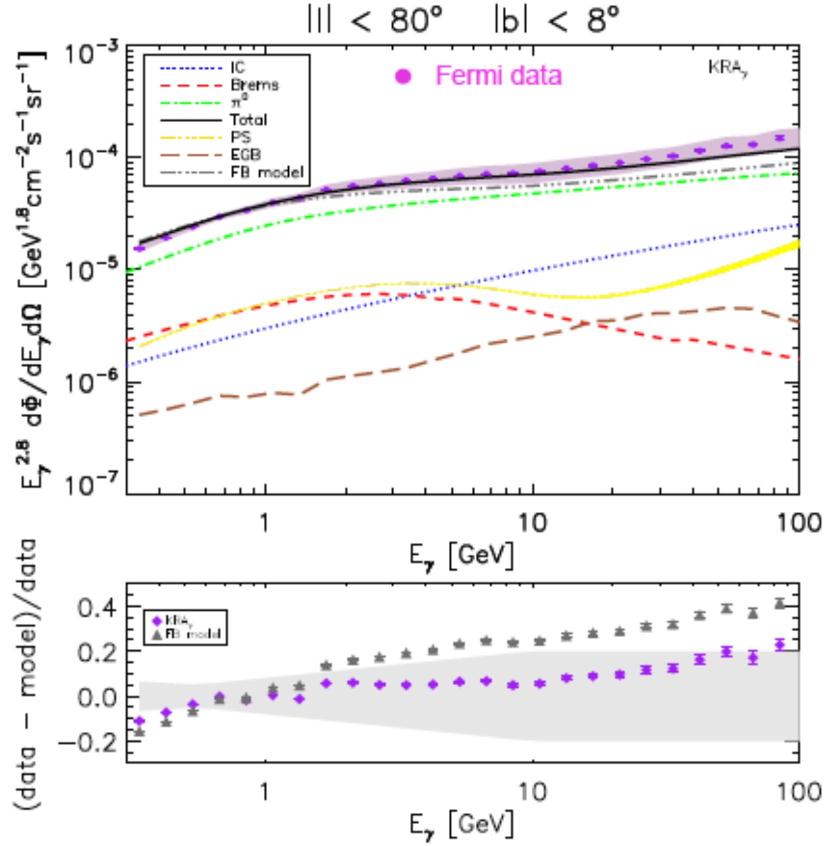
The KRAγ model: Radial dependency of CR transport

This is a phenomenological model built to reproduce over the entire sky the diffuse γ-ray emission spectrum of the Galaxy as measured by Fermi-LAT.

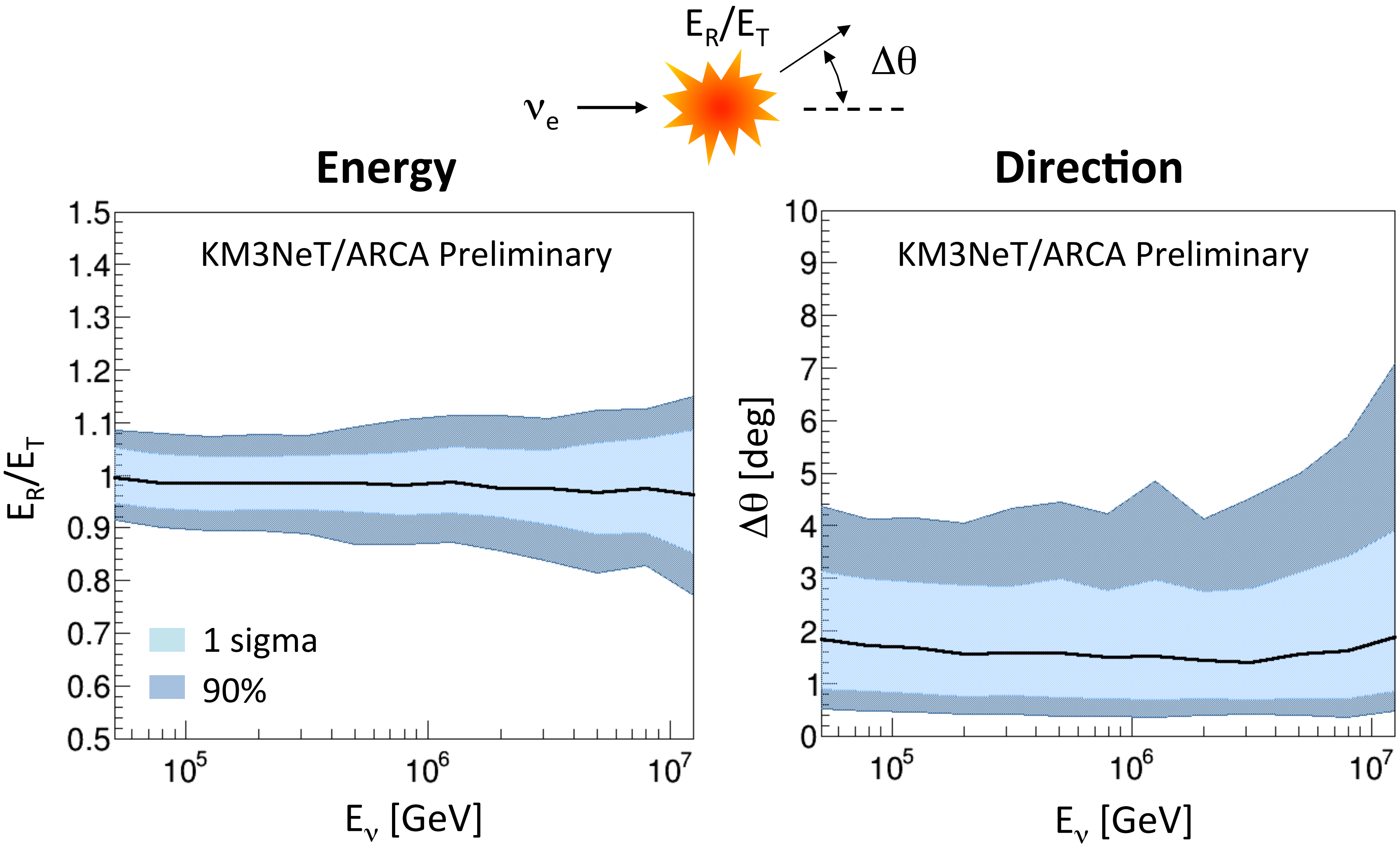
Differently from the Fermi benchmark model (FB) based on GALPROP under the hypothesis of uniform cosmic ray (CR) diffusion, <u>the KRAγ model adopts a radial dependent diffusion coefficient</u> ($\delta(R) = A * R + B$) which turns into a spectral hardening toward the GC region. This is implemented with the DRAGON code.

This allows to correct the discrepancy between high energy Fermi data and the FB model in the inner Galactic plane region without spoiling the local cosmic-ray quantities (spectra, B/C, antiprotons…)

Gaggero, Urbano, Valli, Ullio, Phys.Rev. D91 (2015) 8, 083012



ARCA: Cascade Resolutions

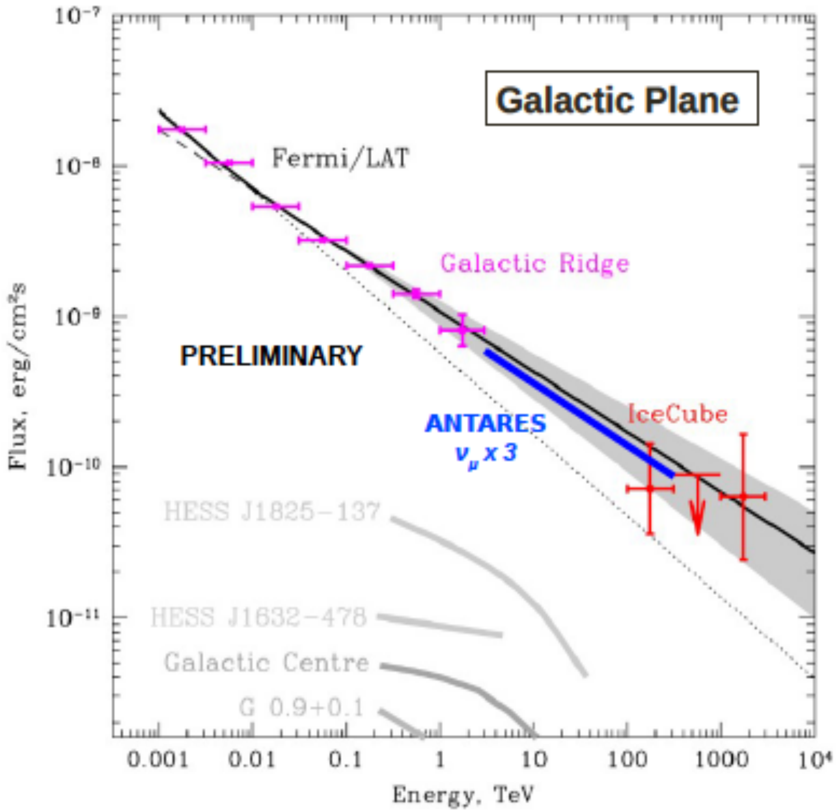


5%

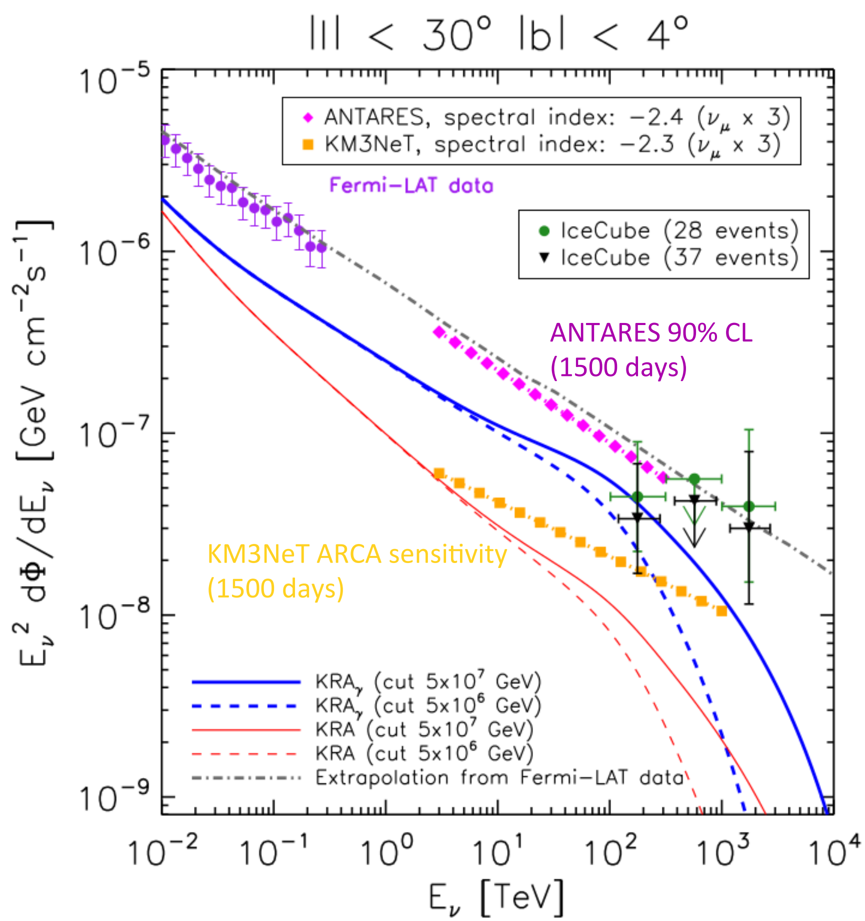
<2°

Neutrinos from CR interaction in the Galactic Ridge?

Neronov et al. arXiv:1412.1690, 4 Dec 2014



Gaggero et al. arXiv:1504.00227



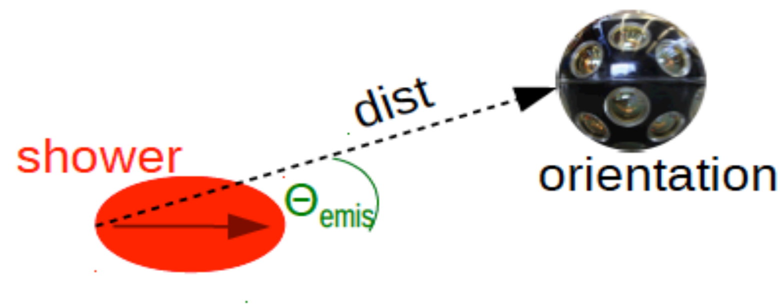
The KRAγ model adopts a radial dependent diffusion coefficient which turns into a spectral hardening toward the GC region.

Shower reconstruction (ν_e)

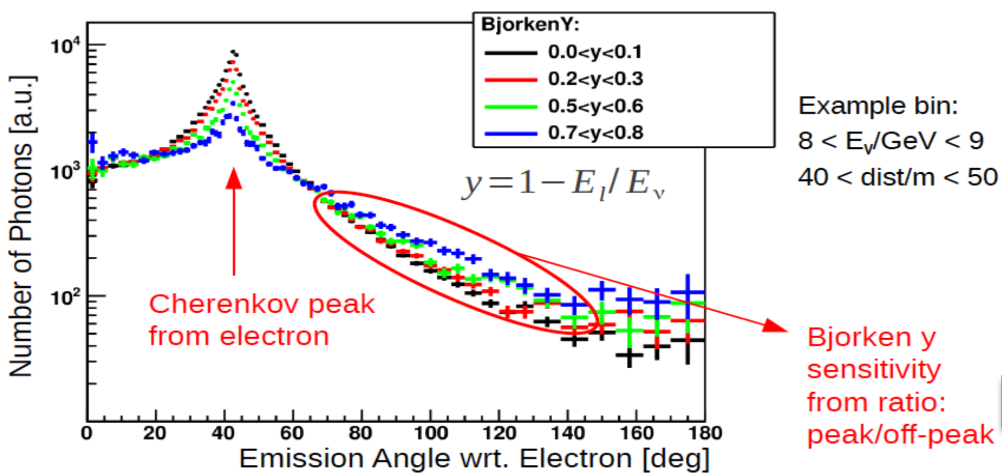
- 1. Vertex fit:
  - maximum likelihood method based on time residuals
  - two fits: first robust prefit then more precise fit

Res. (σ): 0.5-1 m

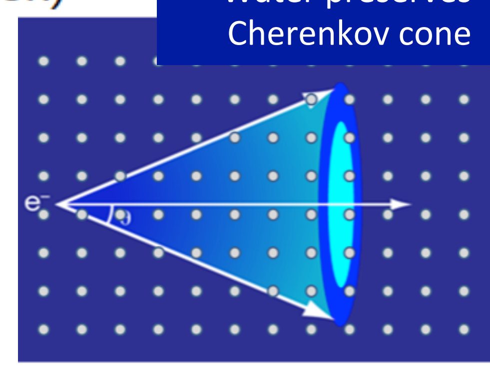
- 2. Energy + direction fit:
  - PDF for number of expected photons depending on: E_ν , Bjorken y, emission angle, OM orientation, distance(OM,vertex)



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



Water preserves Cherenkov cone

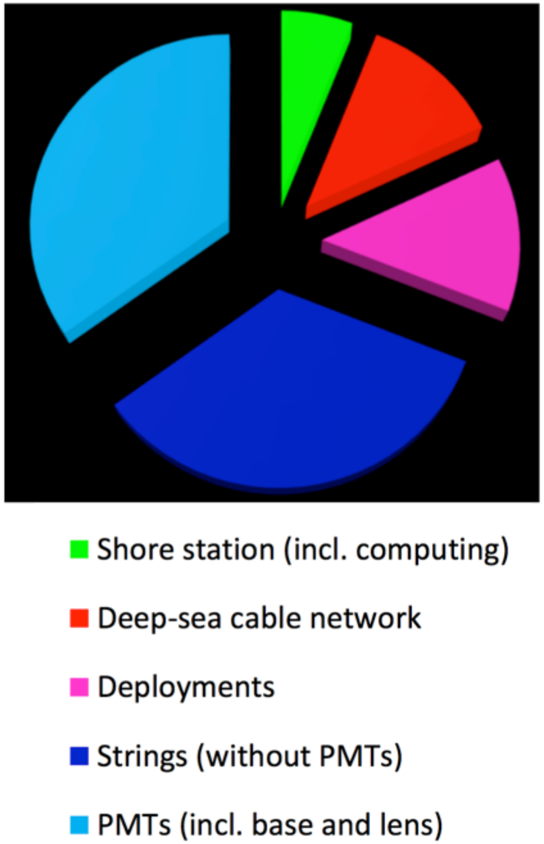


Much more challenging in Ice

Cost of ORCA (115 Strings)

Factor 4 cost reduction cf ANTARES

item	quantity	unit cost (k€)	total cost (k€)
MEOC	2	1800	3600
nodes +deployment	6	700	4200
string+IL+deployment	115	320	36800
readout			500
			45100
but with phase 1 we have 1 MEOC, 1 node, 6 strings		MEOC	-1800
reuse ANTARES MEOC cable (400k to relocate)		ant meoc	-1400
		1 node	-700
		6 strings	-1920
			39280

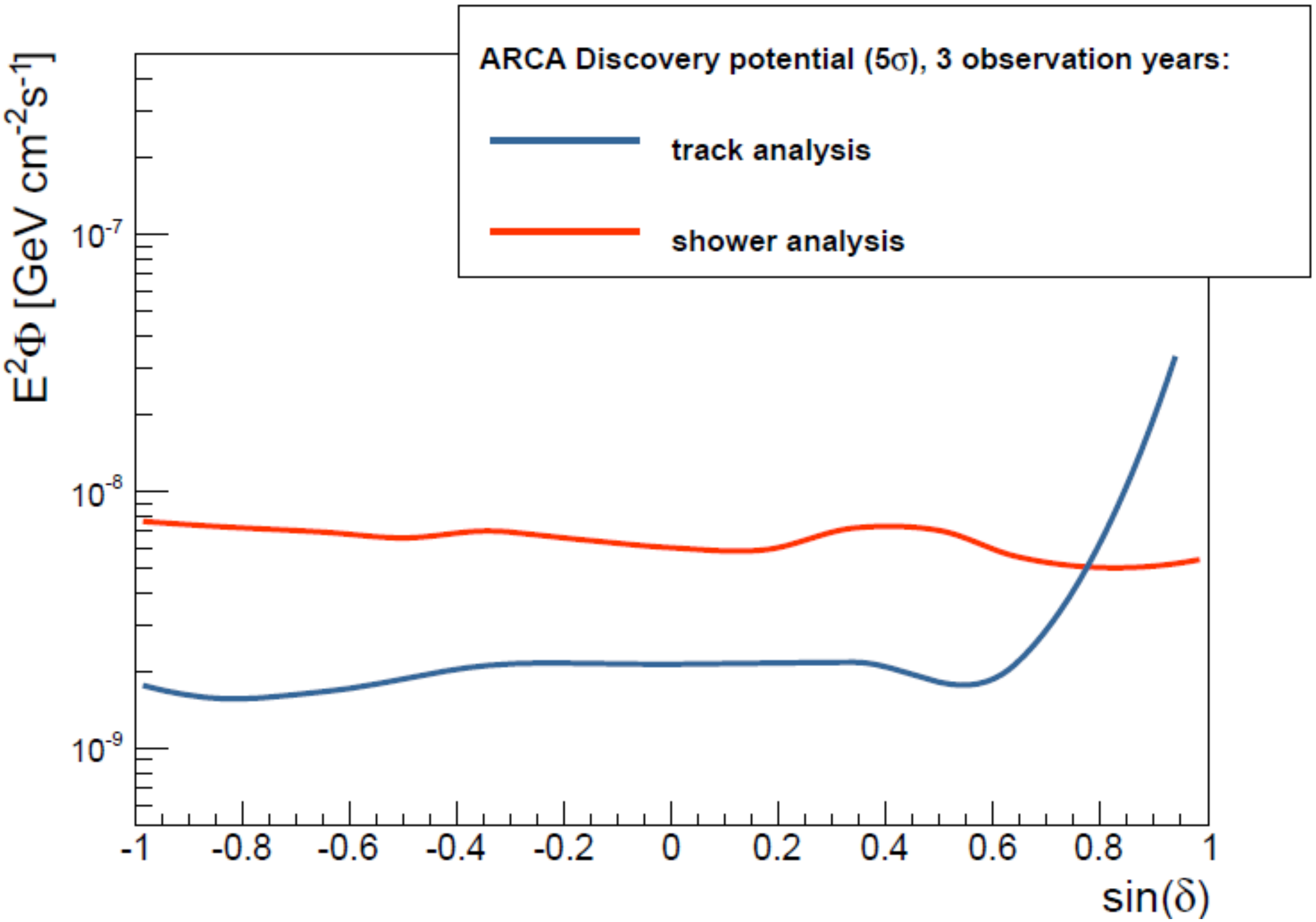


Based on actual Phase-1 costs
Anticipate 20% reduction in PMT costs and benefit from economy of scale

Many ideas for further cost reduction:

PowerSea connectors, 20 DOMs in string, 5 nodes, ….

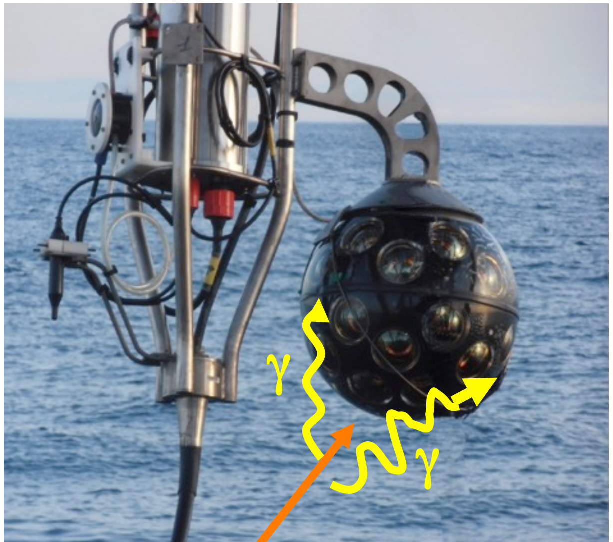
Point-source search with cascades



- Results are "rather preliminary"
- Important: Provides cascade event sample for source candidates
- Closes visibility gap

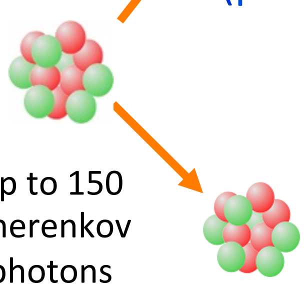
DOM Prototype on ANTARES

April 2013: First DOM installed on ANTARES instrumented line (KM3NeT-Fr)



^{40}K

e$^-$ (β decay)



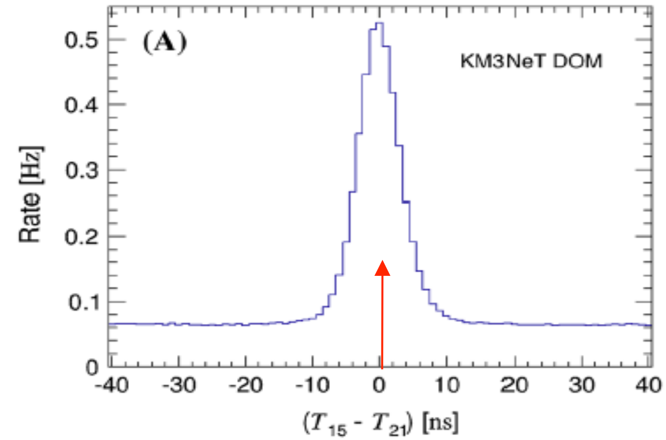
^{40}Ca

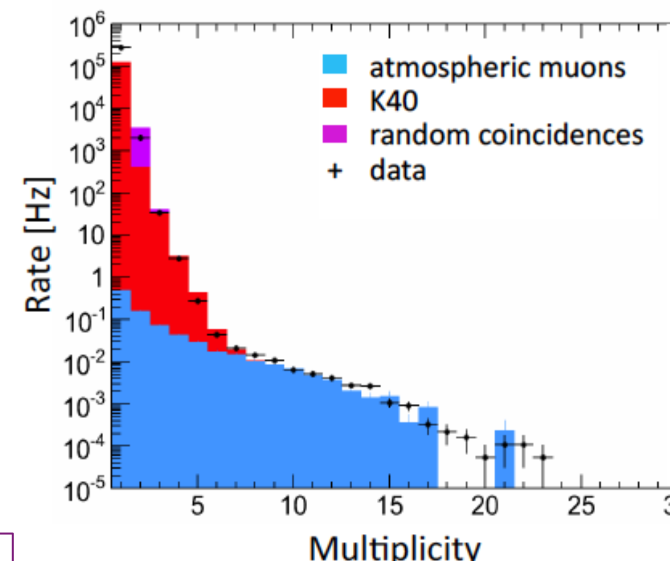
Up to 150 Cherenkov photons per decay; stable ^{40}K concentration

^{40}K decay provides:
- intra-DOM time calibration
- absolute PMT efficiencies

(coincidence rate ~5 Hz on neighbouring PMTs)

📖 Eur. Phys. J. C (2014) 74:3056

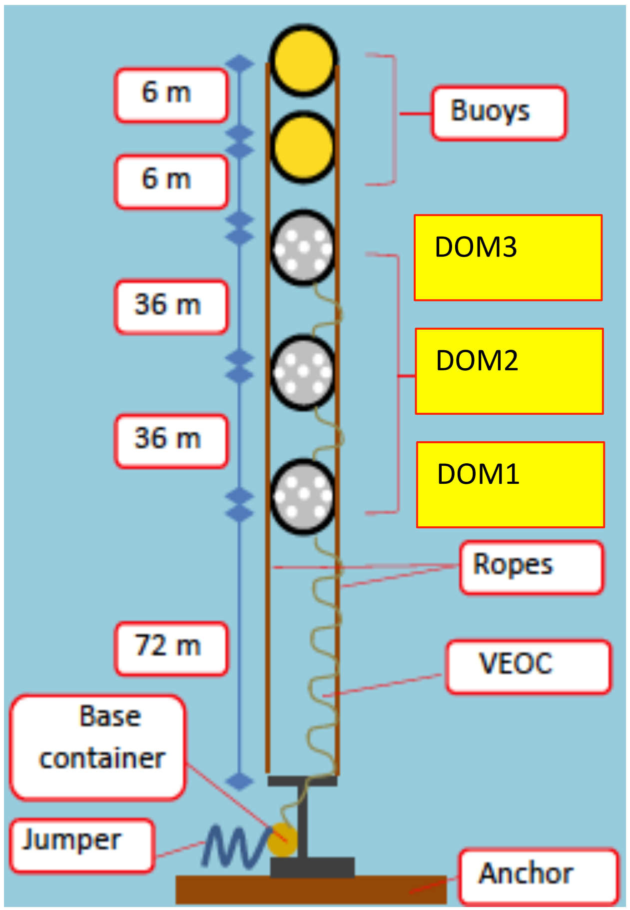


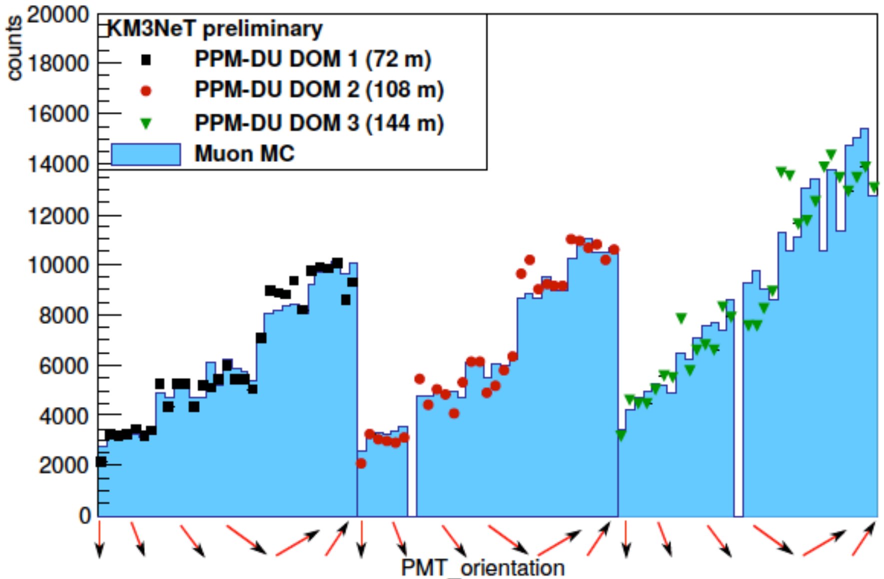


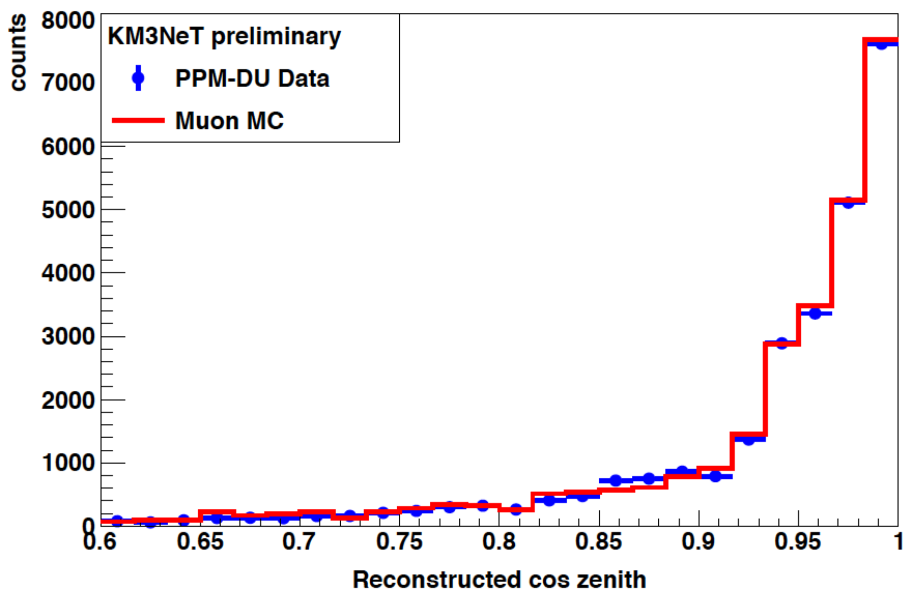
(Δt=20 ns)

KM3NeT mini-line @ Capo Passero

Smooth operation and data taking since May 2014







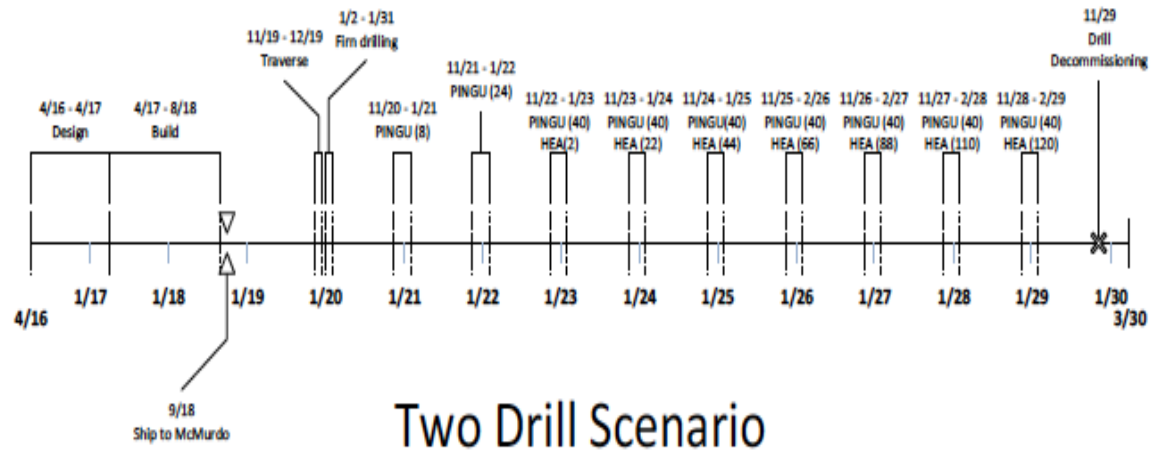
ICECUBE-GEN2 COLLABORATION Deployment Schedule

This schedule is premised on the drill being in the critical path. Instrumentation development is not explicity listed here but assumed available when holes are delivered.

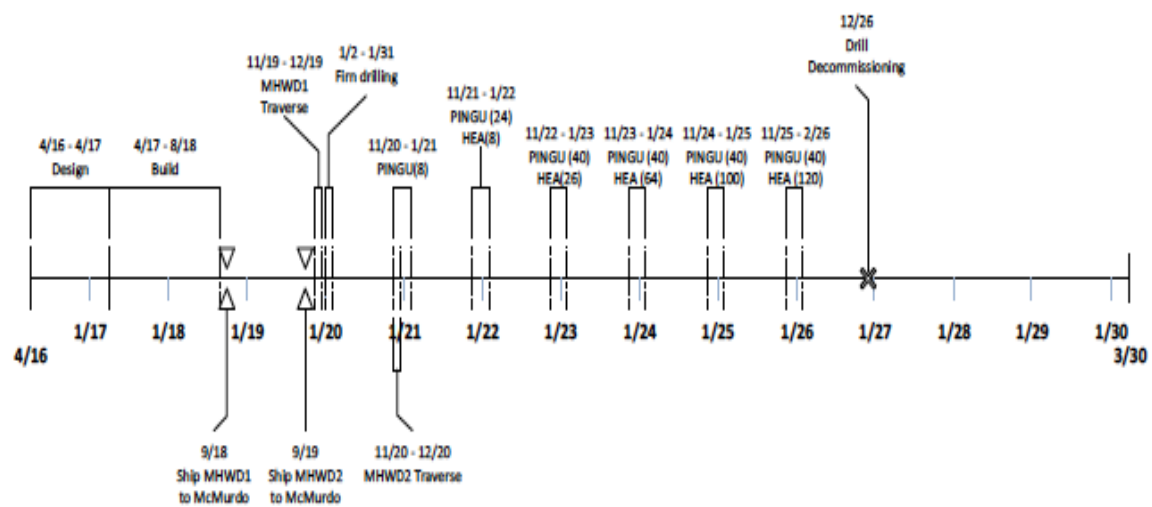
Note: this schedule is achievable but is optimistic.

Of course money (== flights) could be spent to accelerate the shipping delays.

One Drill Scenario



Two Drill Scenario

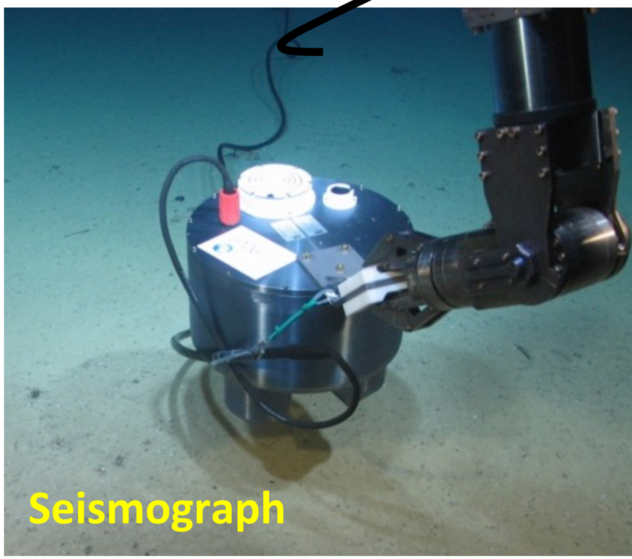


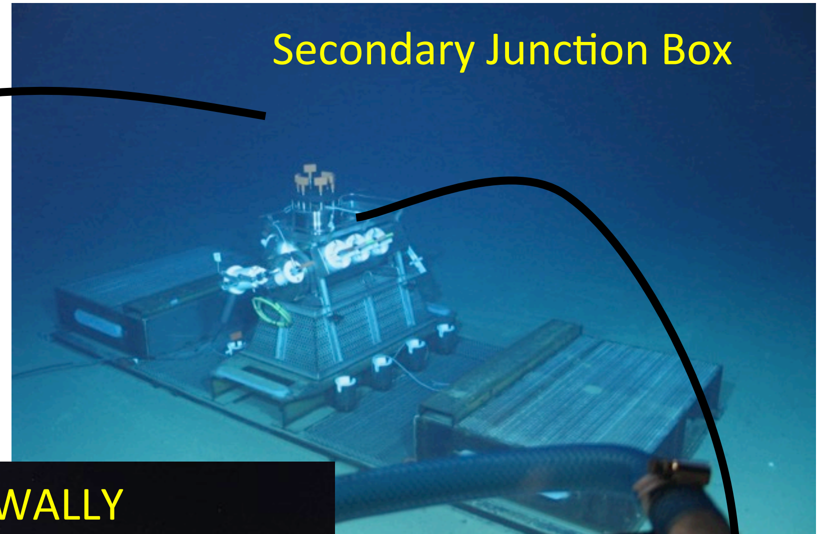
One unique example to note is the IceCube-Gen2/PINGU proposal (discussed in Box 2.4). Although the Committee acknowledges that this project has the potential to lead to exciting new scientific advances, we were cognizant of the fact that construction of the original IceCube facilities had major impacts on the USAP logistical system, and we had concerns that high demands on USAP logistical support likely required for the IceCube-Gen2 construction would be incompatible with our recommendations to expand logistical support for activities for West Antarctic research.

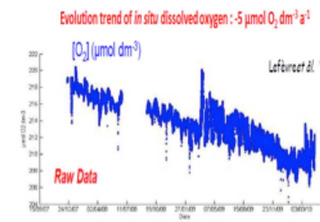
Earth and Sea Sciences

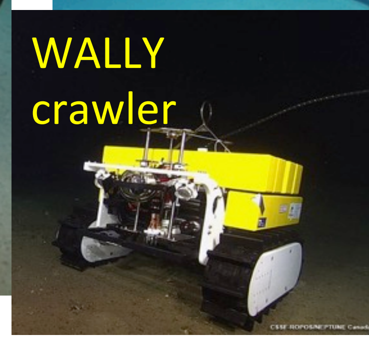
Deep Ocean Cabled Observatories Workshop-
https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=165389

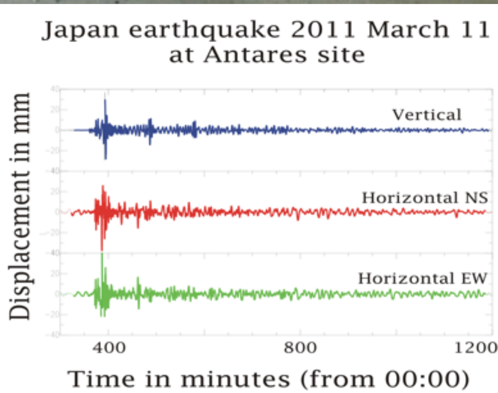
Connected
30 Oct 2010

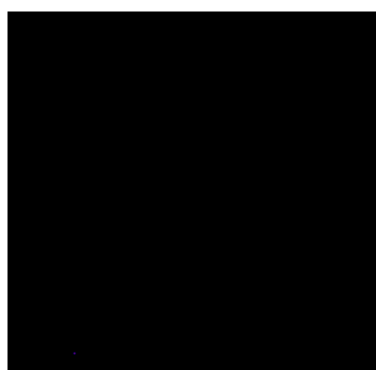


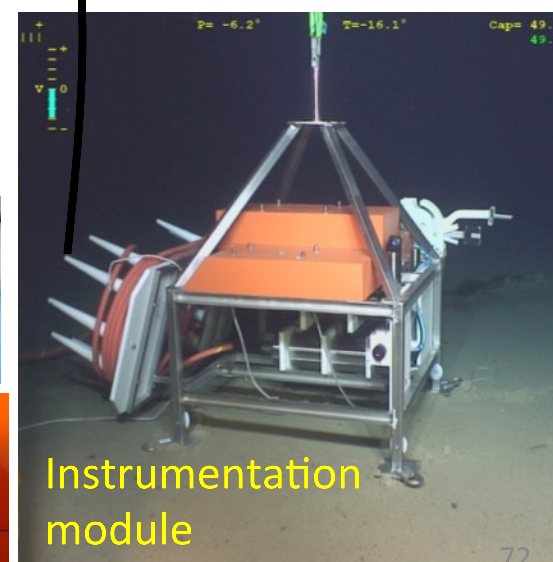






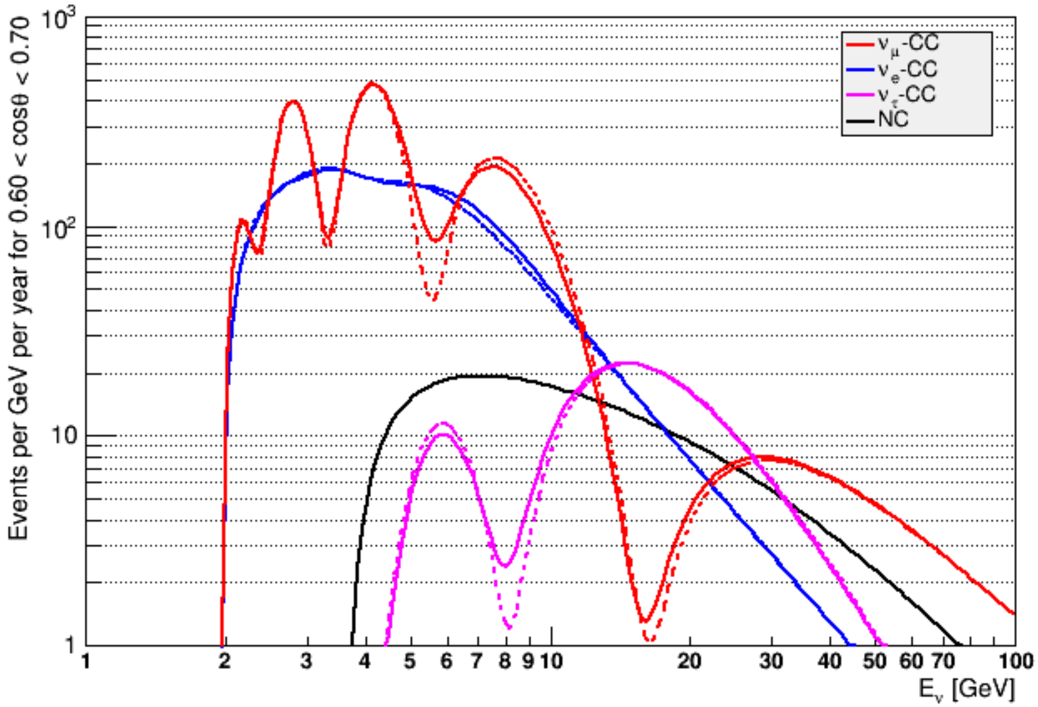






Event rate in ORCA (9m)

- Events per year per GeV
- No resolutions, no PID
- One example bin in cosθ (width 0.1 at 45°)



For all angles:

ν_μ CC 24,800

ν_e CC 17,300

ν_τ CC 3,100

NC 5,300

28

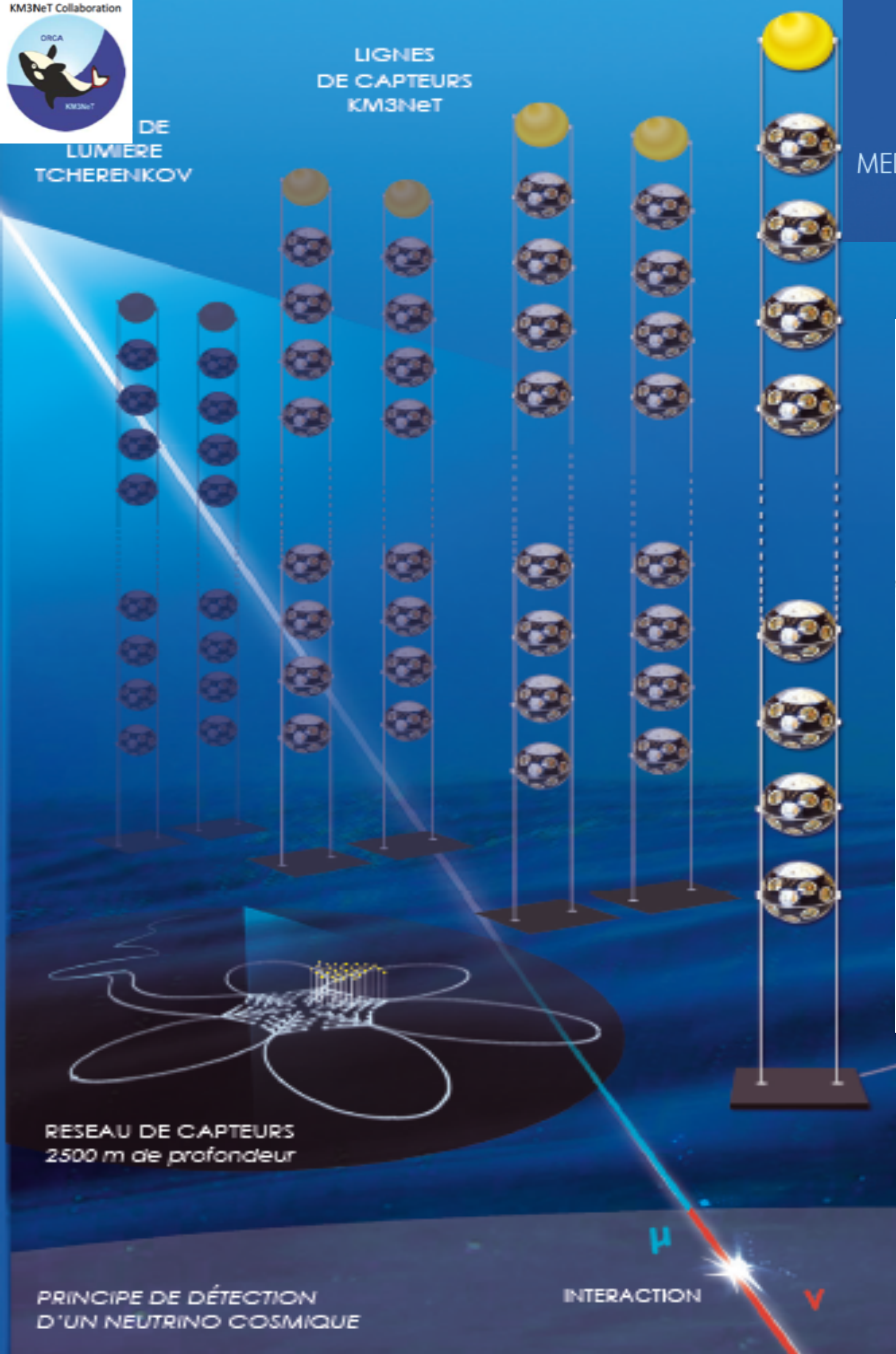
Comparison with other projects

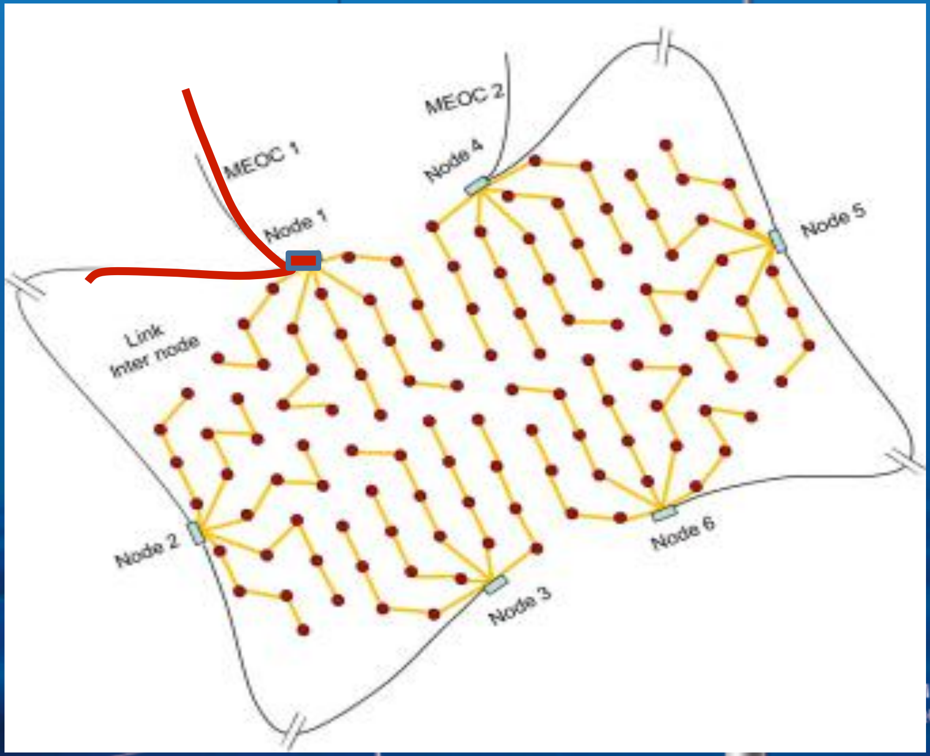
- ORCA
- Per year ν_μ CC : 24,800 & ν_e CC : 17,300

- NOVA (2x 1.8 10^{21} p.o.t.)
  - per year ~70 ν_μ and 15-25 ν_e (less with anti-nu)
  - 6 years running planned (shared nu/anti-nu)
- T2K (7.8 10^{21} p.o.t.)
  - Until 2020 : 1400 ν_μ and 240 ν_e
- DUNE (34kt)
  - Per year 150 ν_e

MEUST

MEDITERRANEAN EUROCENTRE FOR UNDERWATER SCIENCES AND TECHNOLOGIES





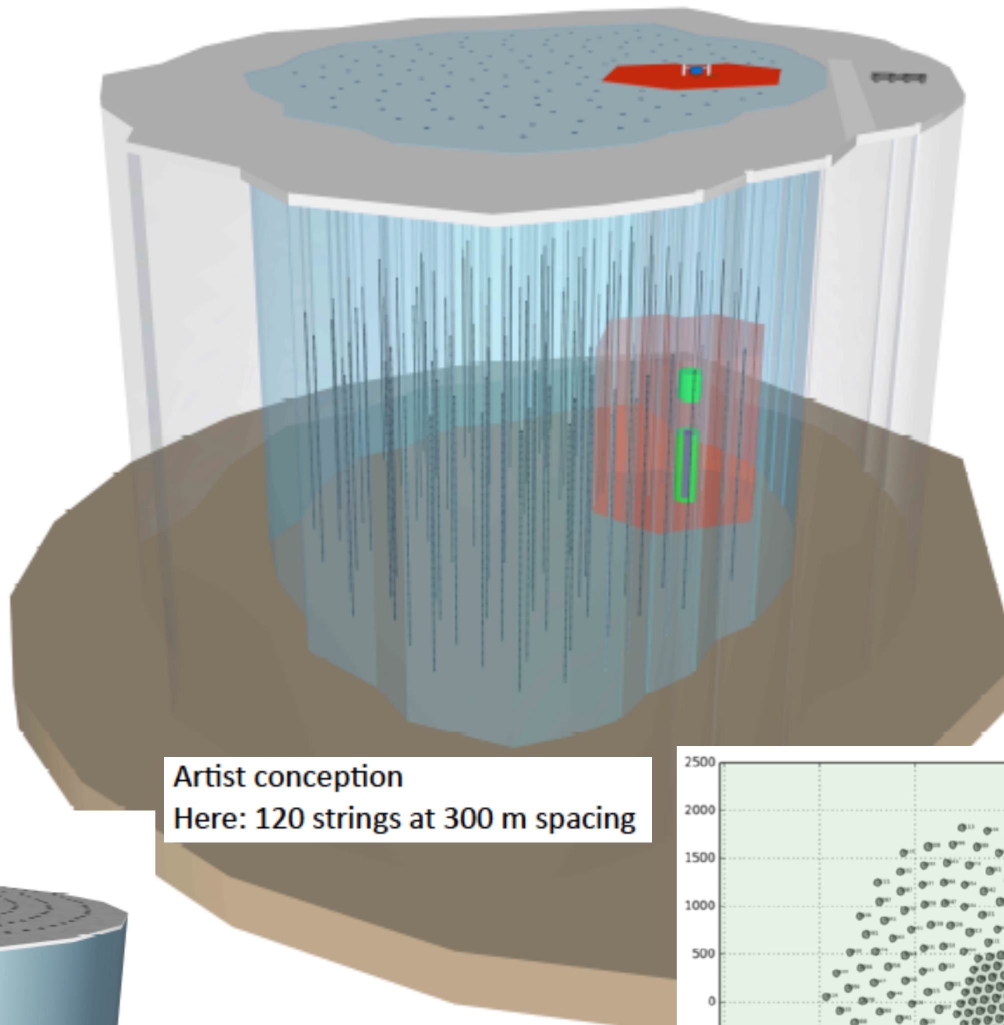
AC power transmission
Daisy chain of 4 strings

IceCube-Gen2

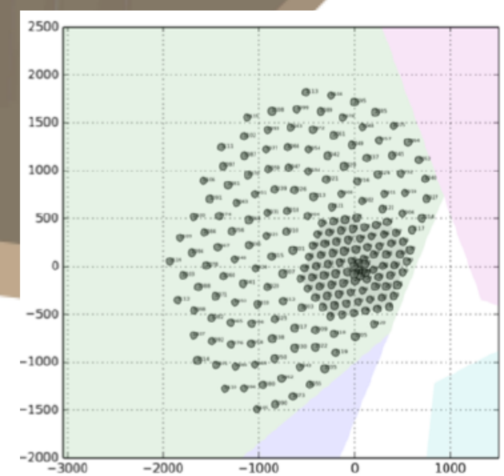
Vision for a
Next Generation IceCube:
Increase energy threshold
allows larger string spacing

Focus on high energies.

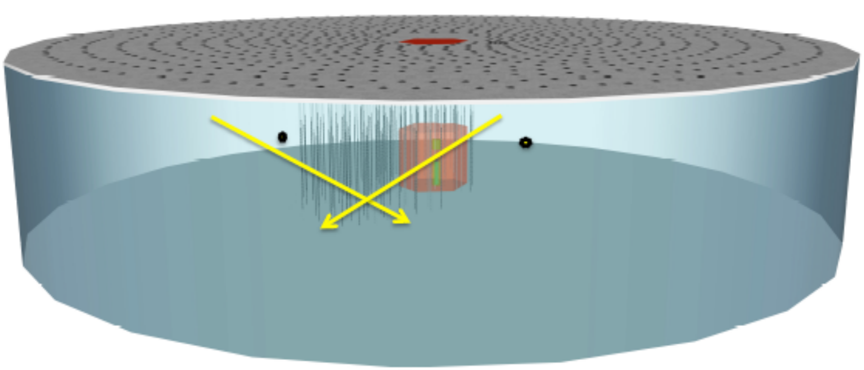
Larger spacing of strings:
~10 km^3 instrumented
Volume.
Cost comparable to IceCube.



Artist conception
Here: 120 strings at 300 m spacing



Air shower veto array



KM3NeT Picture Gallery

KM3NeT-Italy

KM3NeT-France

Important Ingredients

- Direction resolution (track/cascade)
- Energy resolution (track/cascade)

- Cascade versus track separation

- Atmospheric muon background rejection
- Neutral current backgrounds

- Effective volume
- Geometry optimisation
- Trigger efficiency and rates (atms mu@36Hz, K40@19Hz)

- Systematic uncertainties

KM3NeT cost breakdown

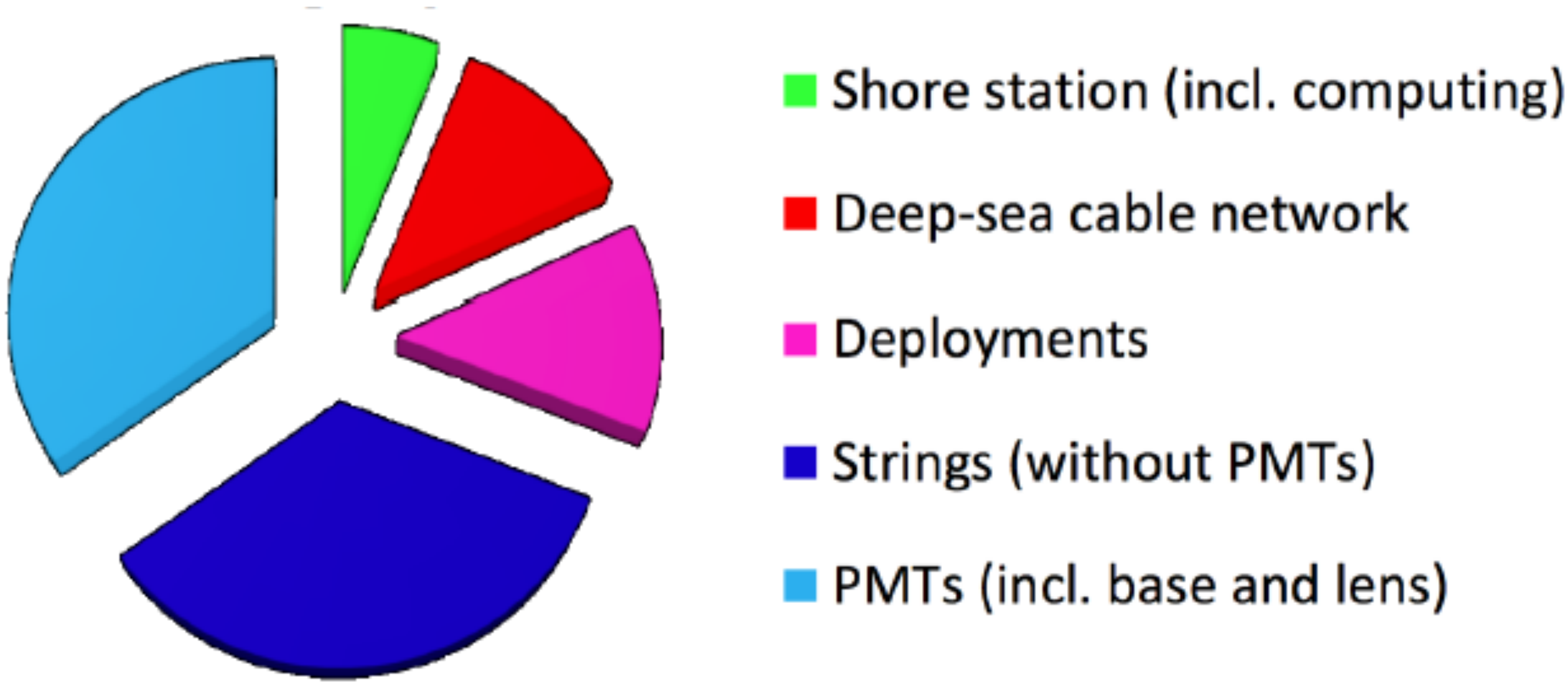
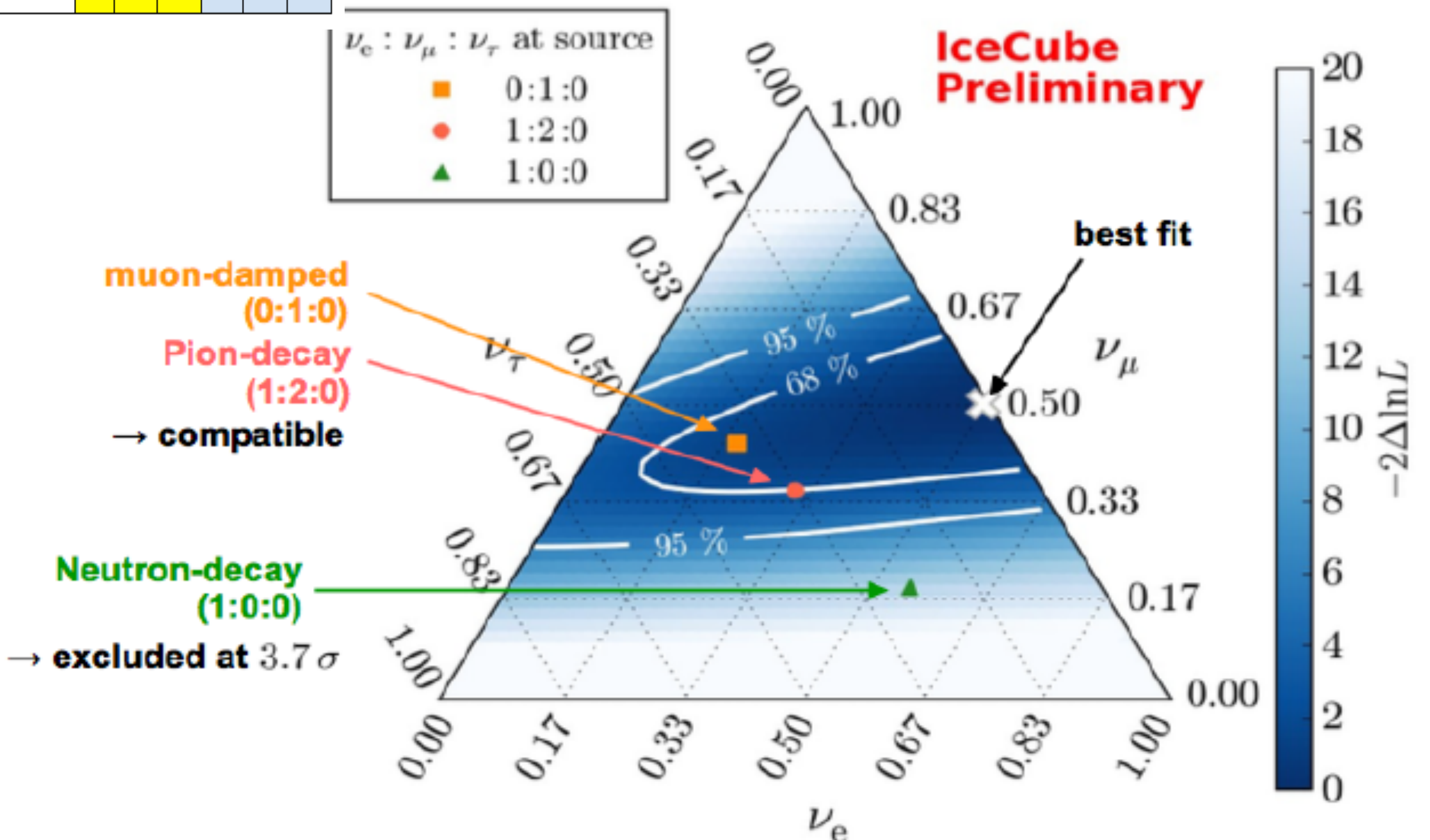


Figure 111: Breakdown of costs amongst the major items.

Phase 1 (funded) : 31 M€
Phase 2 + 95 M€

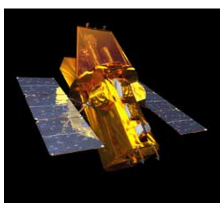
Flavour Ratios

	At source			At Earth		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
Pion decay	1	2	0	1	1	1
Muon-damped	0	1	0	0.2	.39	.39
Neutron-decay	1	0	0	.56	.22	.22



Slide: courtesy L. Mohrmann, IceCube (ICRC 15)

Multi-Messenger Program



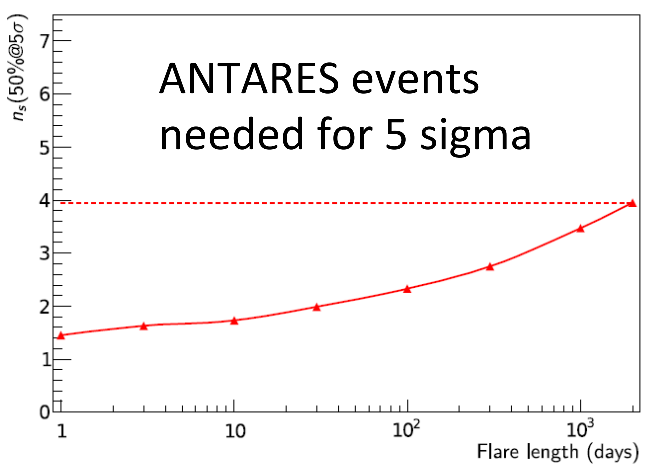
GeV-TeVγ-rays
Fermi / HESS
CTA

UHECR
Auger

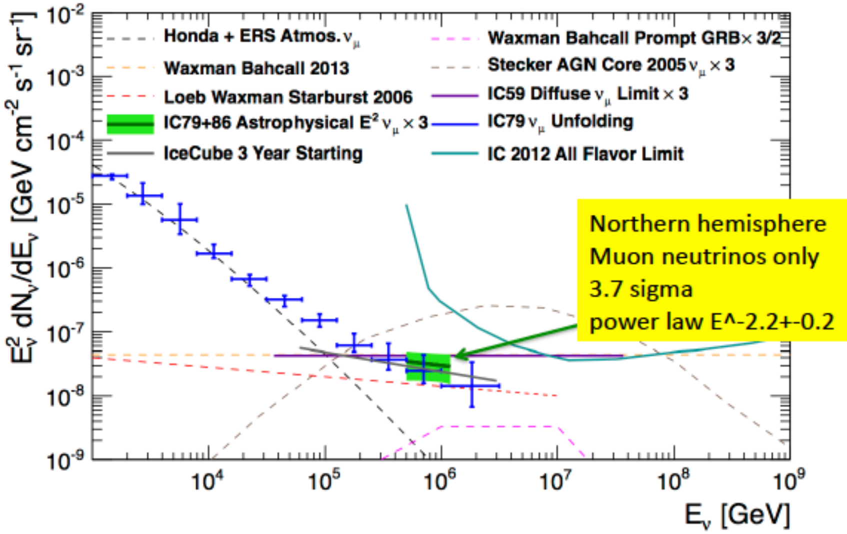
HE neutrinos

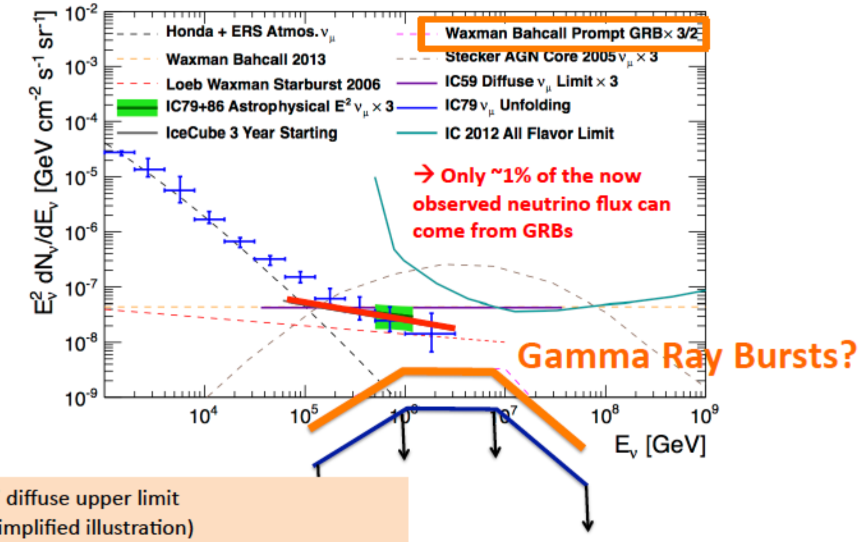
Optic / X-ray
TAROT, ROTSE /
Swift, ZADKO

Gravitational
Waves
Virgo / Ligo

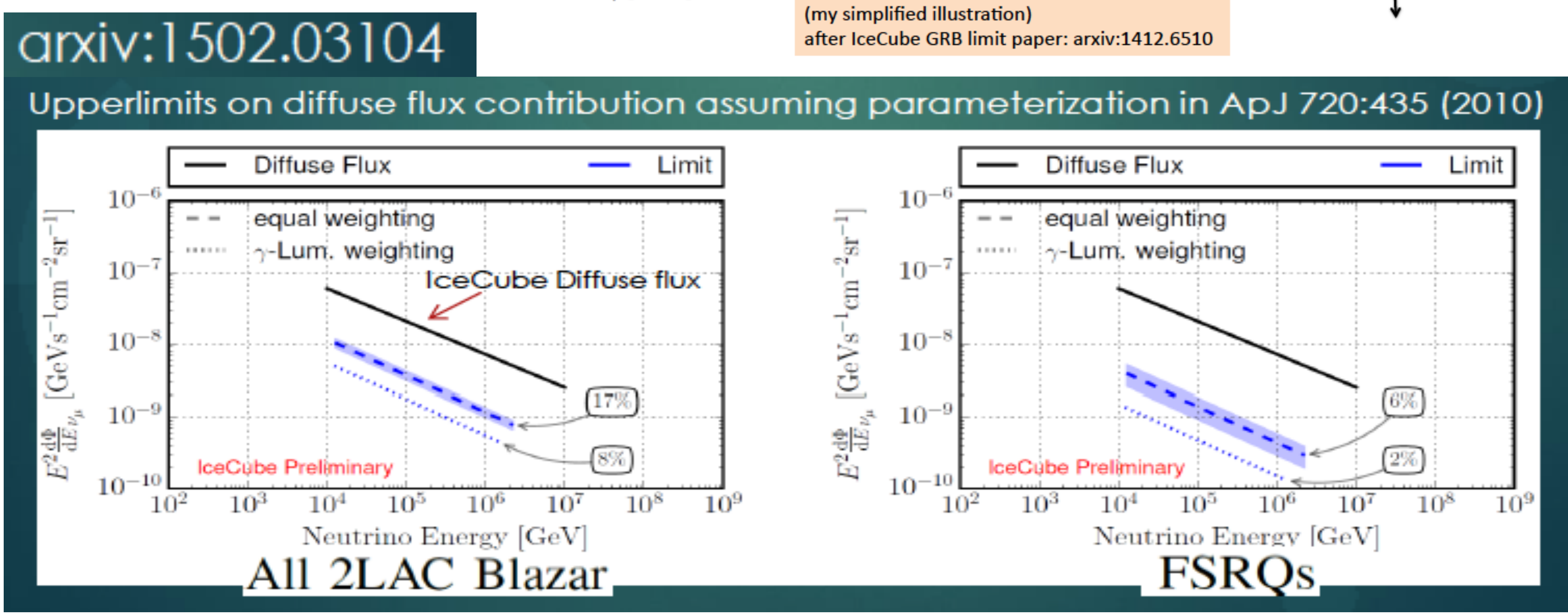


GRBs? Fermi-LAT Blazars?





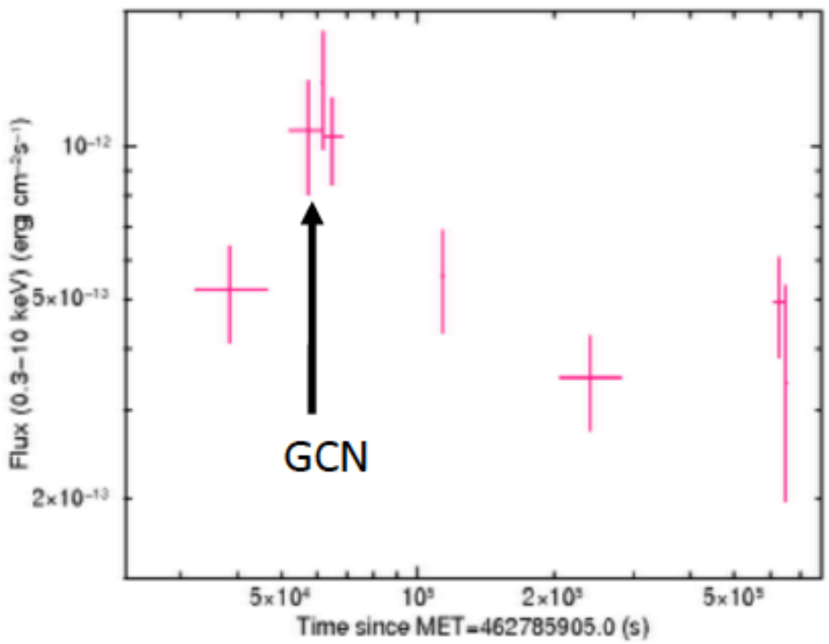
Quasi diffuse upper limit
(my simplified illustration)
after IceCube GRB limit paper: arxiv:1412.6510

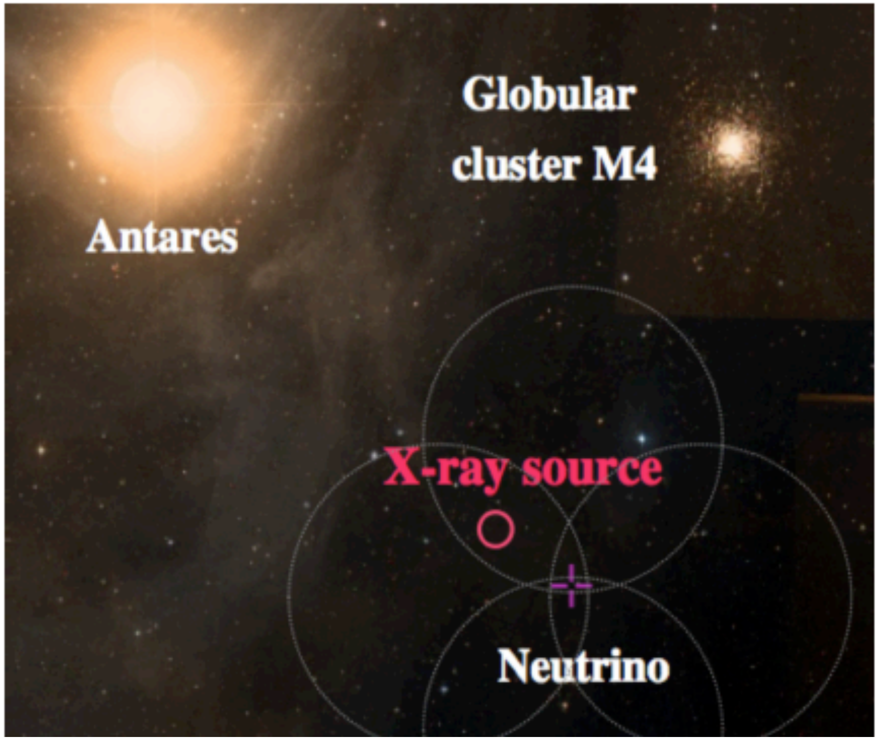


The ANT091501A alert

E=~50-100 TeV
Error box:18 arcmin
Sent in 10s to Swift (X) & Master (Opt)
Swift obs: +9h
Master obs: +10h

- **Swift:** uncatalogued x- ray source within 8 arcmin from the neutrino direction
- **Optical:** Bright star in Swift source location
- **Multiwavelength observations:** Star correlated with x-ray flare



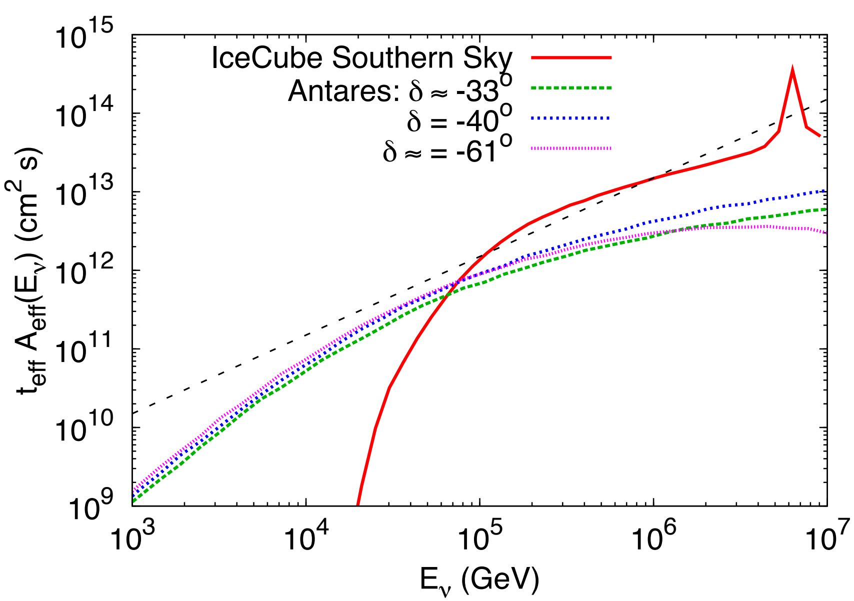


AGNs close to Ernie and Bert?

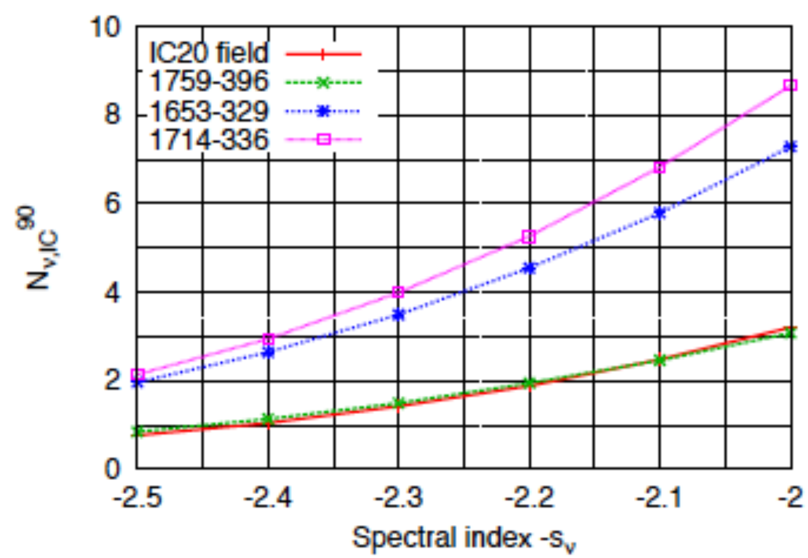
TANAMI collaboration reported observations of 6 bright blazars locally compatible with 2 first PeV IceCube events IC14 and IC20.

📖 Krauß, F. et al. 2014, A&A, 566, L7

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



ANTARES inferred limits

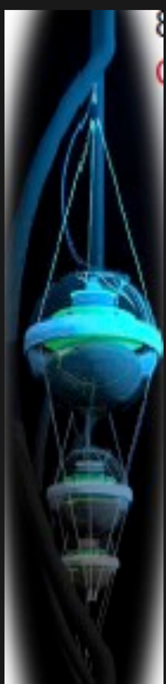


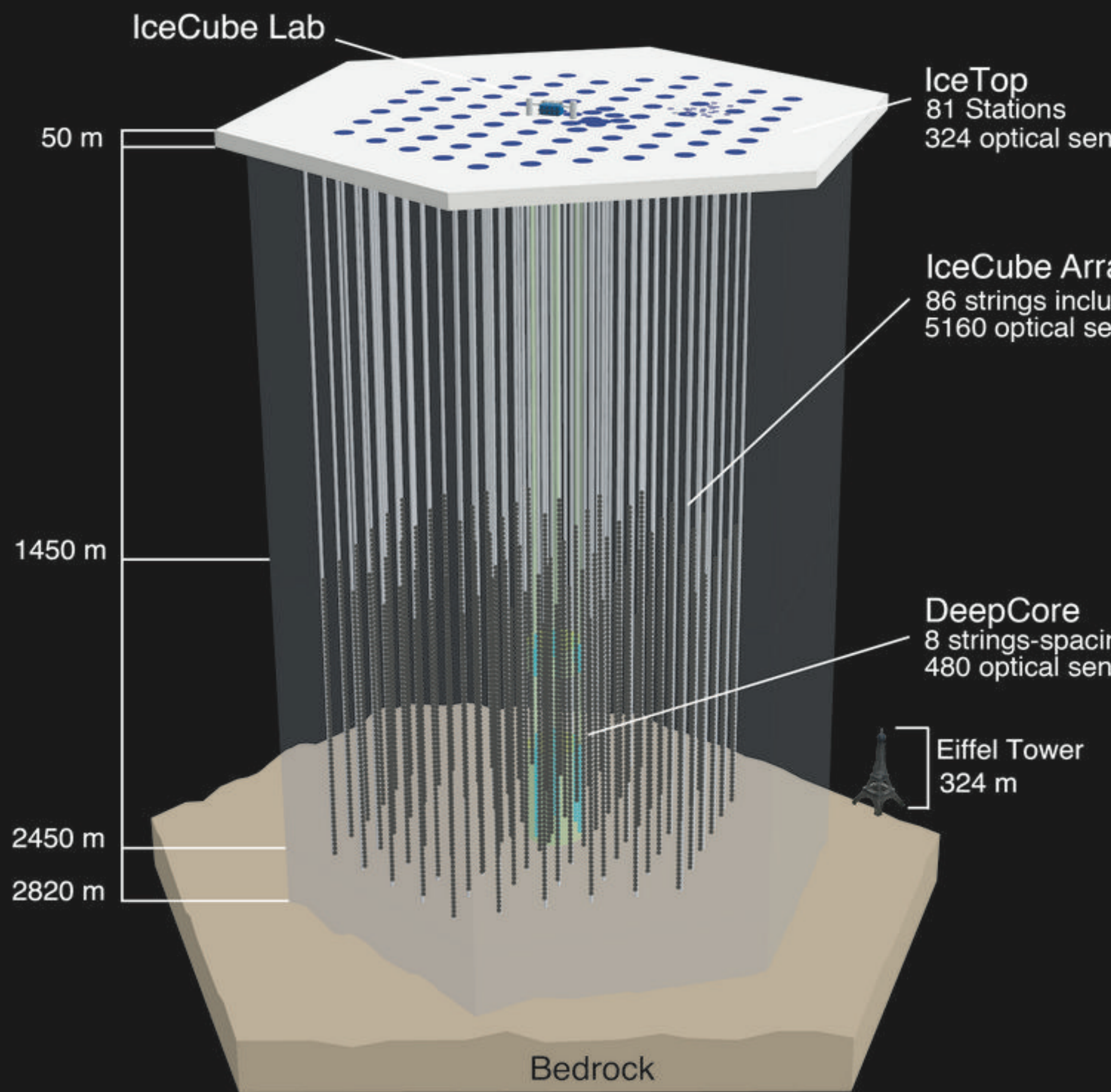
→ Relevant constraints on spectral index of potential source

📖 Antares, A&A 576, L8 (2015)

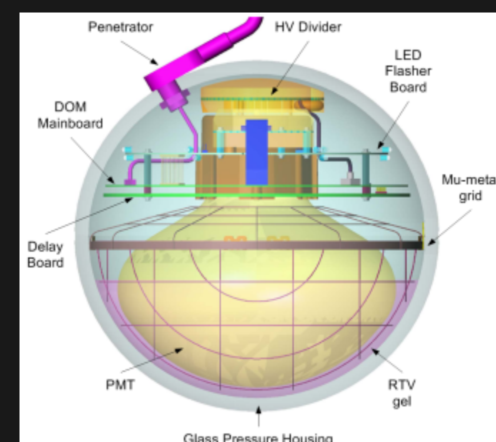
Highlighted in the Nature vol 520, April 2015

IceCube





IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



Penetrator
HV Divider
LED Flasher Board
DOM Mainboard
Mu-metal grid
Delay Board
PMT
RTV gel
Glass Pressure Housing