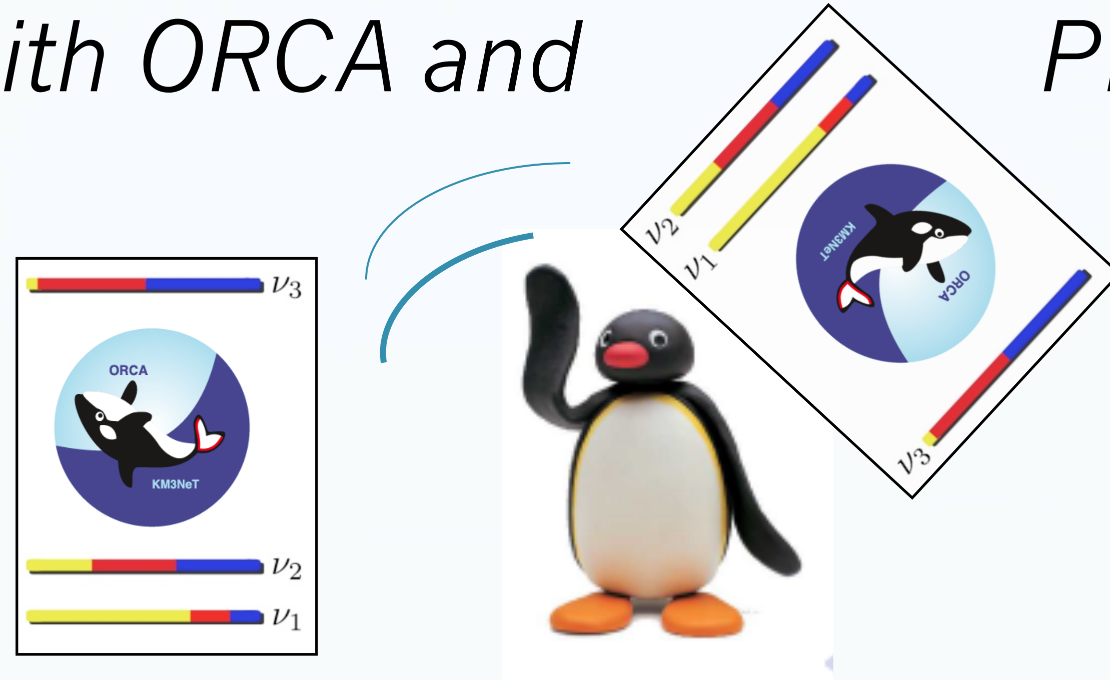
Measuring the neutrino mass hierarchy with ORCA and PINGU



Second International Meeting on Large Neutrino Infrastructures

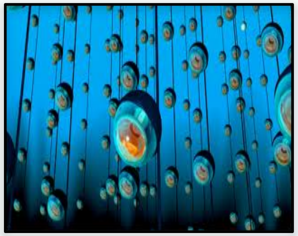
Antoine Kouchner

University Paris 7 Diderot- AstroParticle and Cosmology

Fermilab, Batavia, Illinois

April 20-21, 2015

Outline

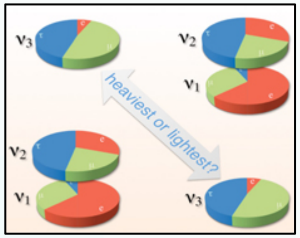


Neutrino Telescopes and Atmospheric Neutrinos

Neutrino Telescopes today

Atmospheric neutrinos: first achievements

Future detectors



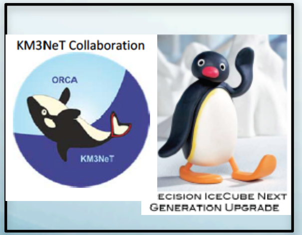
Sensitivity of ORCA and PINGU to the NMH

Matter effects

Baseline designs

Monte Carlo Performances

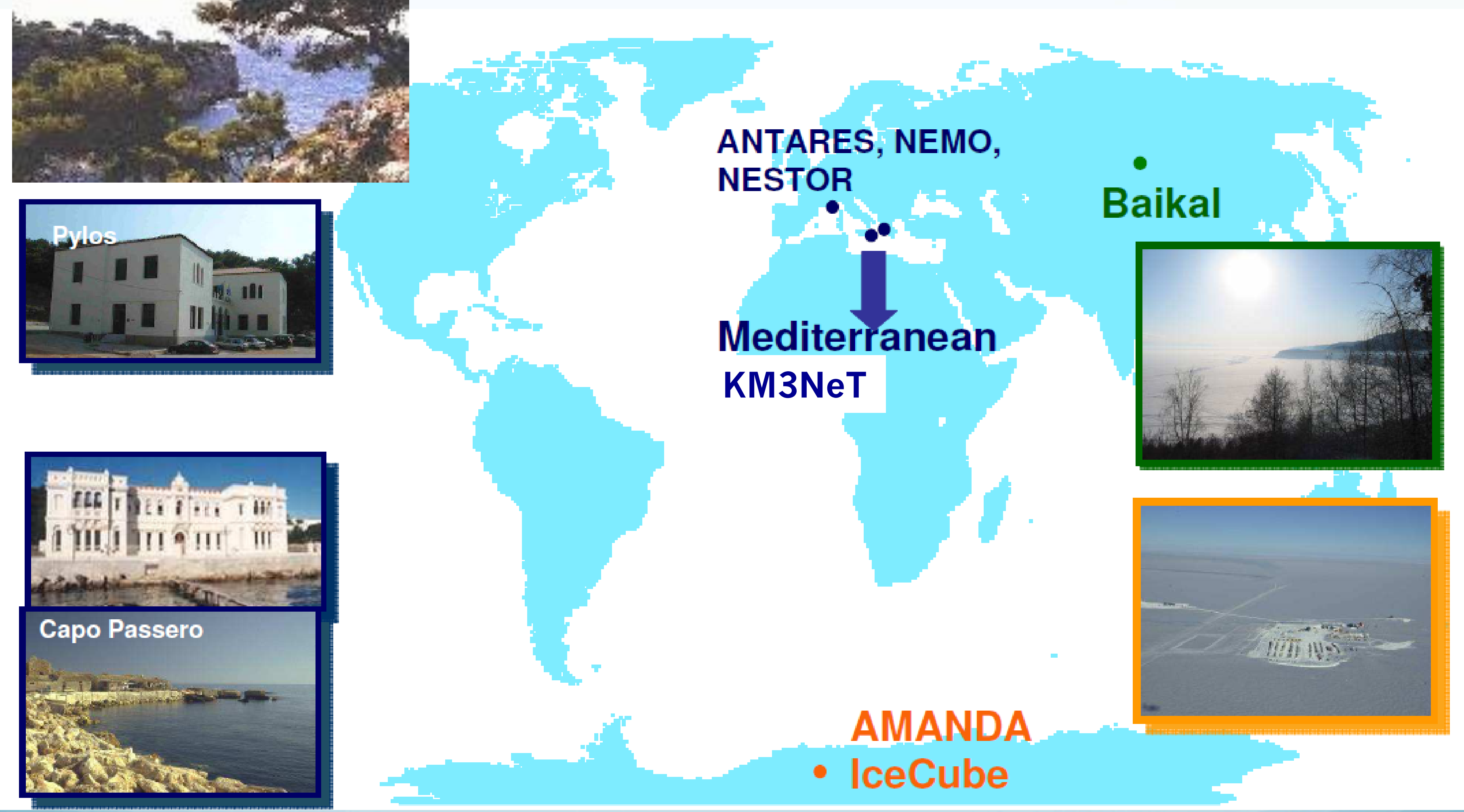
Sensitivity to the NMH



Not covered : Dark Matter searches, Low-Energy Astrophysics

Neutrino Telescopes (natural media)

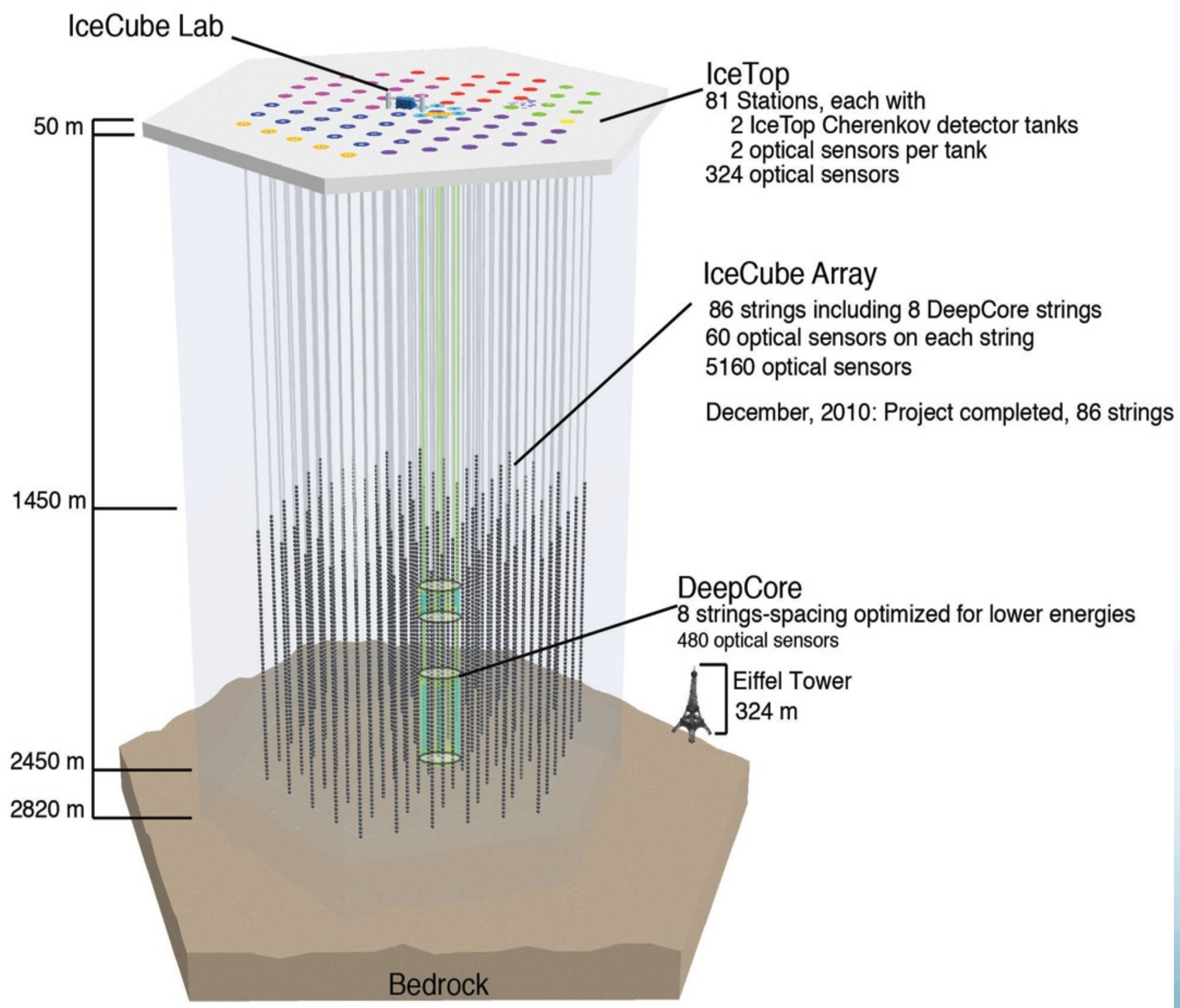
{ANTARES, BAIKAL, ICECUBE} currently running

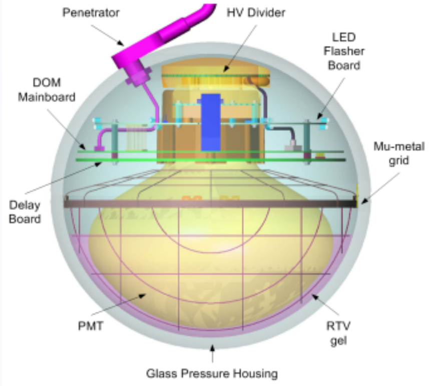


From $O(10\ \mathrm{GeV})$ to PeV neutrinos

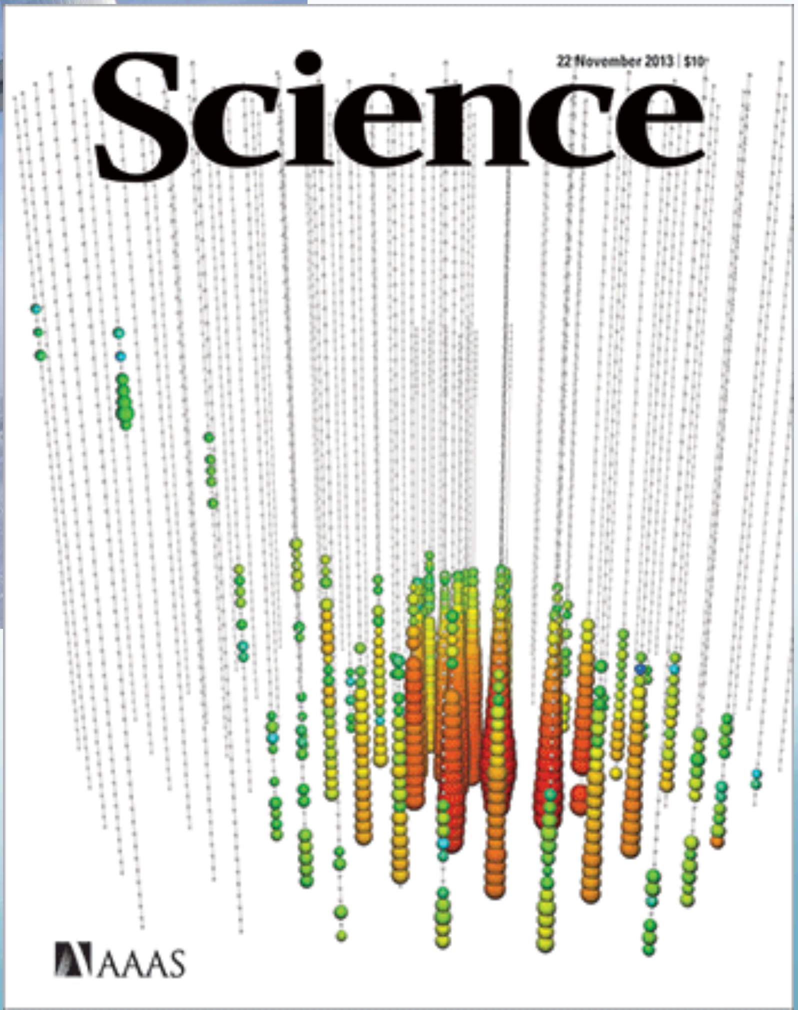
IceCube: world largest NT

Completed since December 2010.





First HE detection…2013!



IceCube has opened the field of High-Energy Neutrino Astronomy

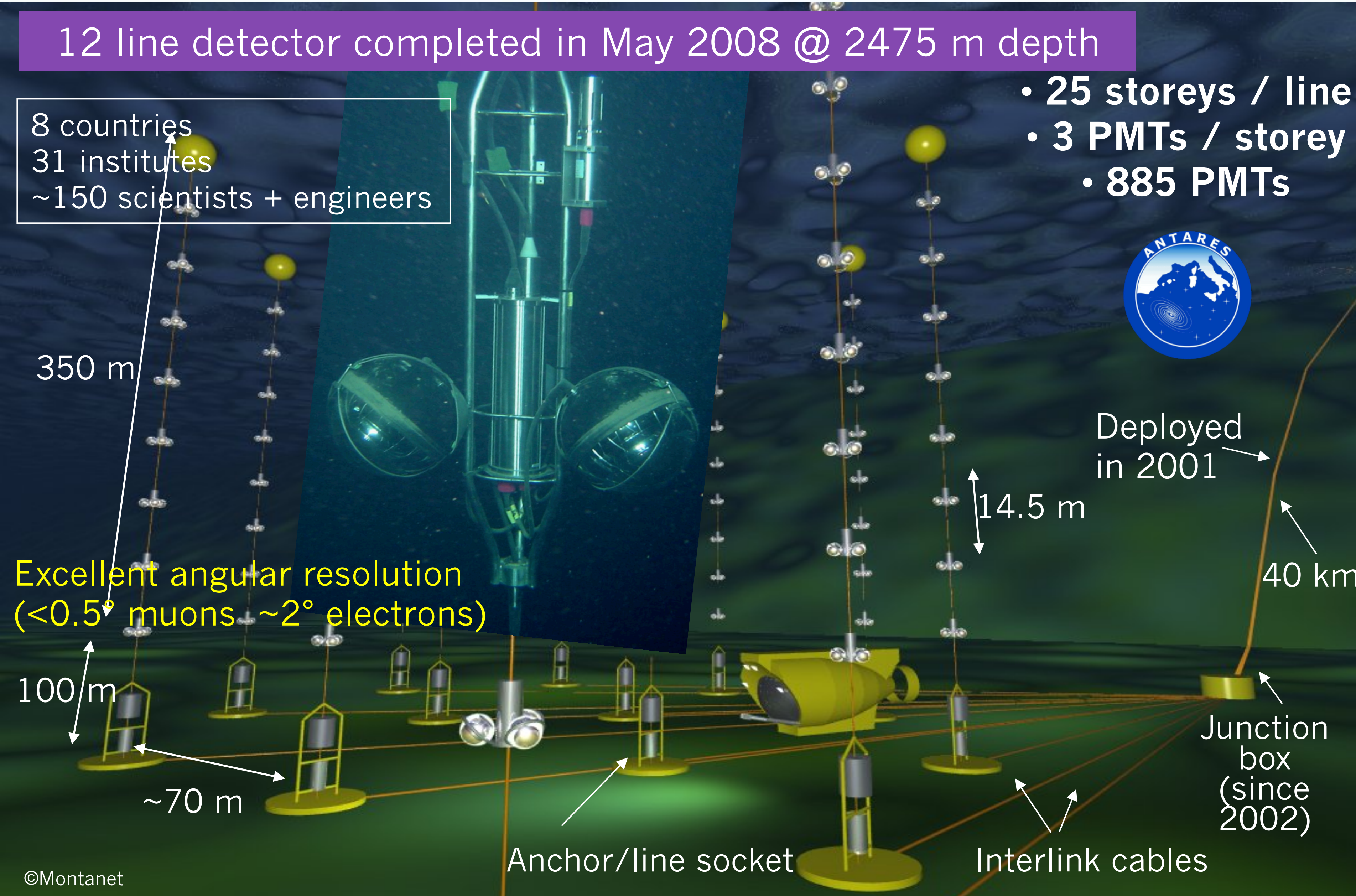
ANTARES: world 1st deep-sea NT

12 line detector completed in May 2008 @ 2475 m depth

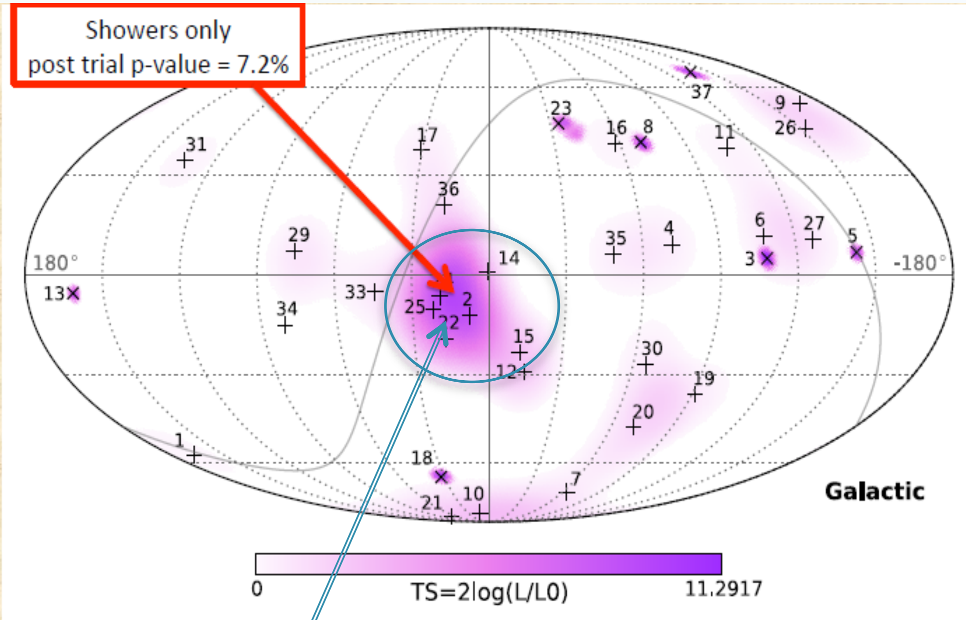
- 25 storeys / line
- 3 PMTs / storey
- 885 PMTs

8 countries
31 institutes
~150 scientists + engineers

Excellent angular resolution
(<0.5° muons, ~2° electrons)



Sources of the IceCube cosmic signal?

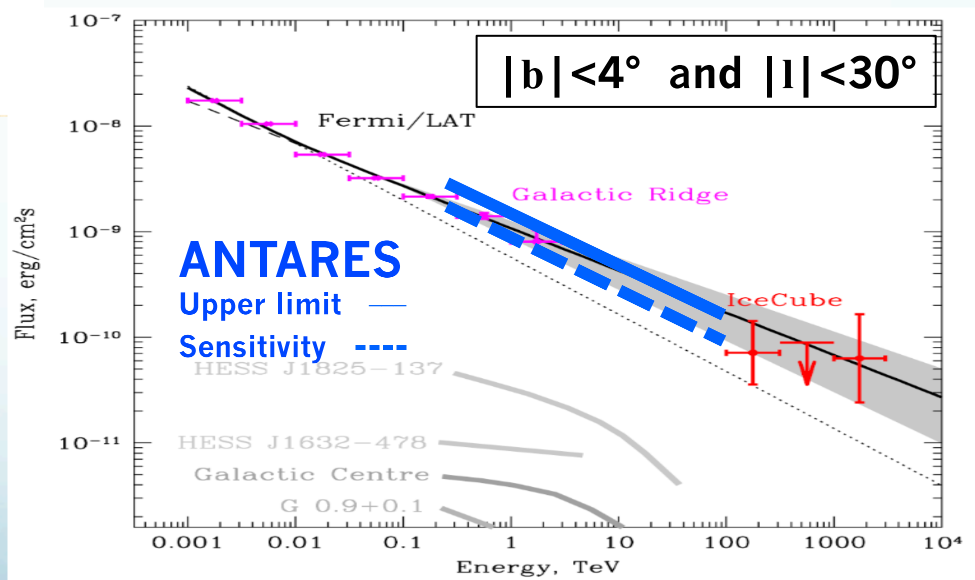


Hypothesized Galactic Source ?
📖 *Gonzalez-Garcia et al, APP 57 (2014)*
Point Source $\Phi = 6 \times 10^{-8} E^{-2}$ GeV cm^{-2} s^{-1}

+ Common point-source search with combined ANTARES/IceCube datasets → Upper Limits

ANTARES and IceCube signal

- Excludes single point-source (E^{-2}) as origin of cluster within 20° off GC
  📖 Astrophys. J. Lett. 786:L5 (2014)
- Constrains blazar origin of 2 PeV events
  📖 A&A 576, L8 (2015) – Highlighted in *Nature* April 15
- Sensitivity to Galactic Ridge



« Extrapolation of the spectrum of diffuse γ-ray emission from the Galactic Ridge, as observed by Fermi telescope »
📖 A. Neronov et al. Phys. Rev. D89, 103002 (2014)

First achievements on neutrino oscillation

ANTARES | IceCube/DeepCore

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

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

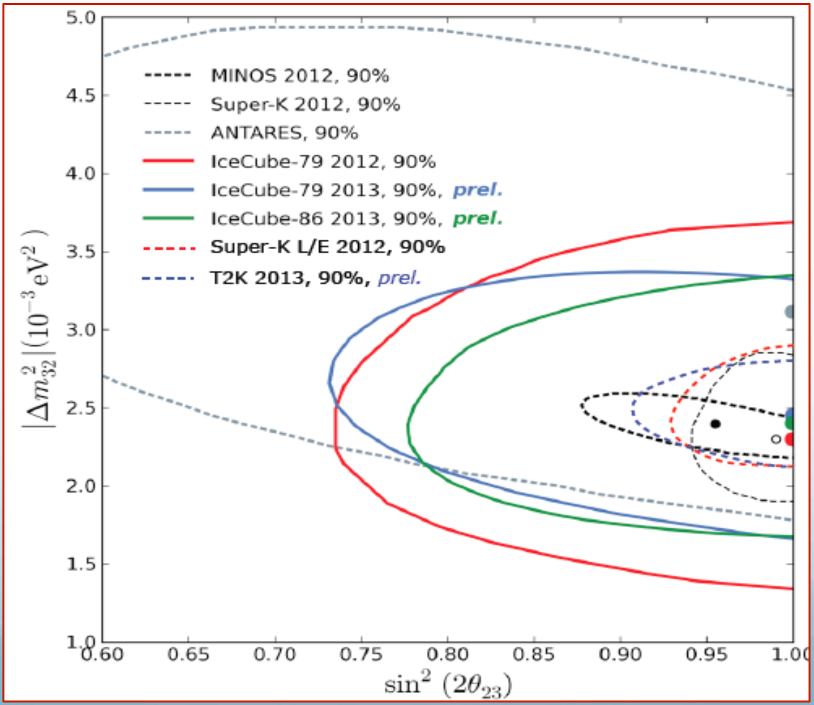
Larger effect on

Single lines ← low energy → DeepCore

than

Multi lines ← higher energy events → IceCube

2008-2010 data (863 days)



IC79 data (319 days)

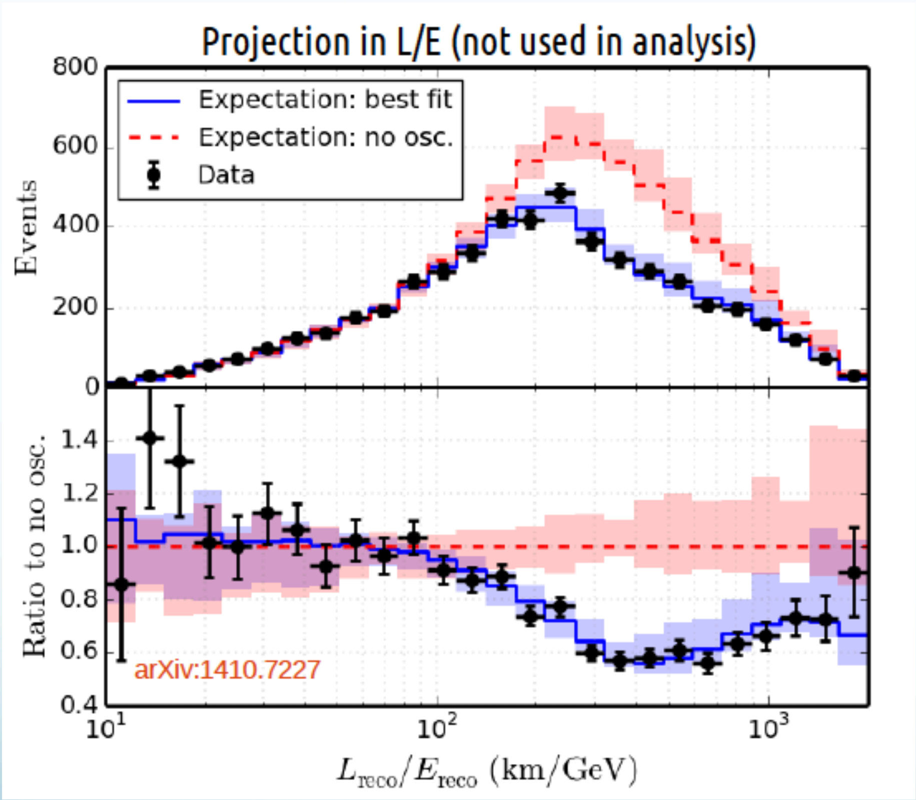
📖 Phys. Lett. B 714 (2012) 22.

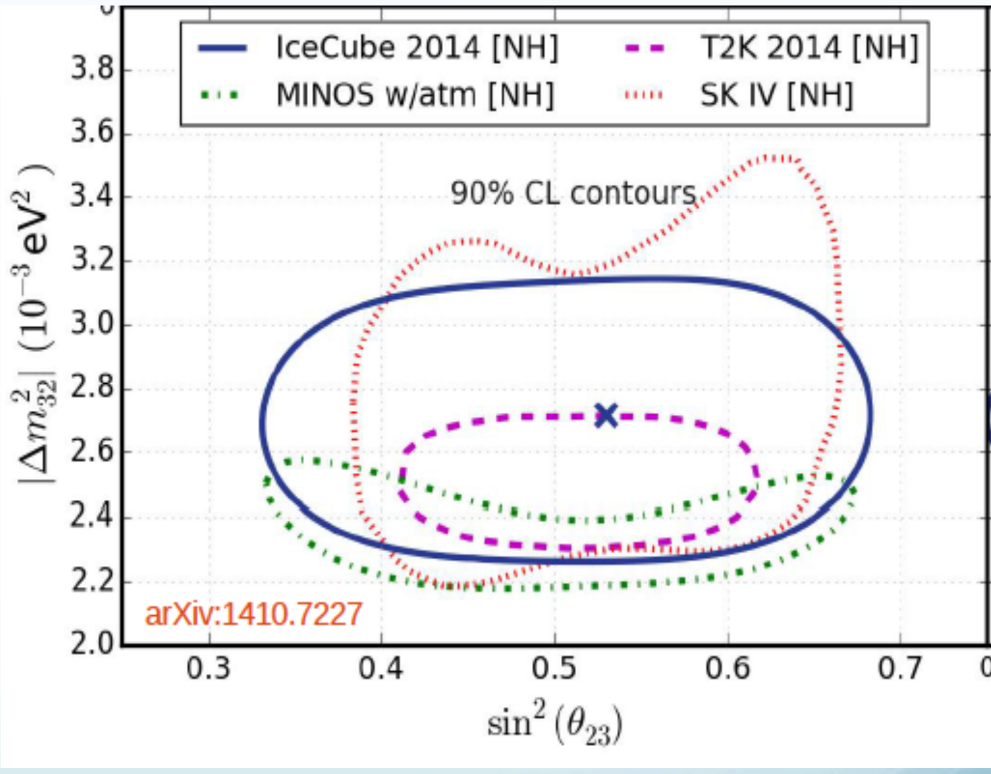
📖 PRL111, 081801 (2013)

Latest results with DeepCore

Full 3 neutrino oscillation scheme (5174 events in 3 years)

PHYSICAL REVIEW D 91, 072004 (2015)



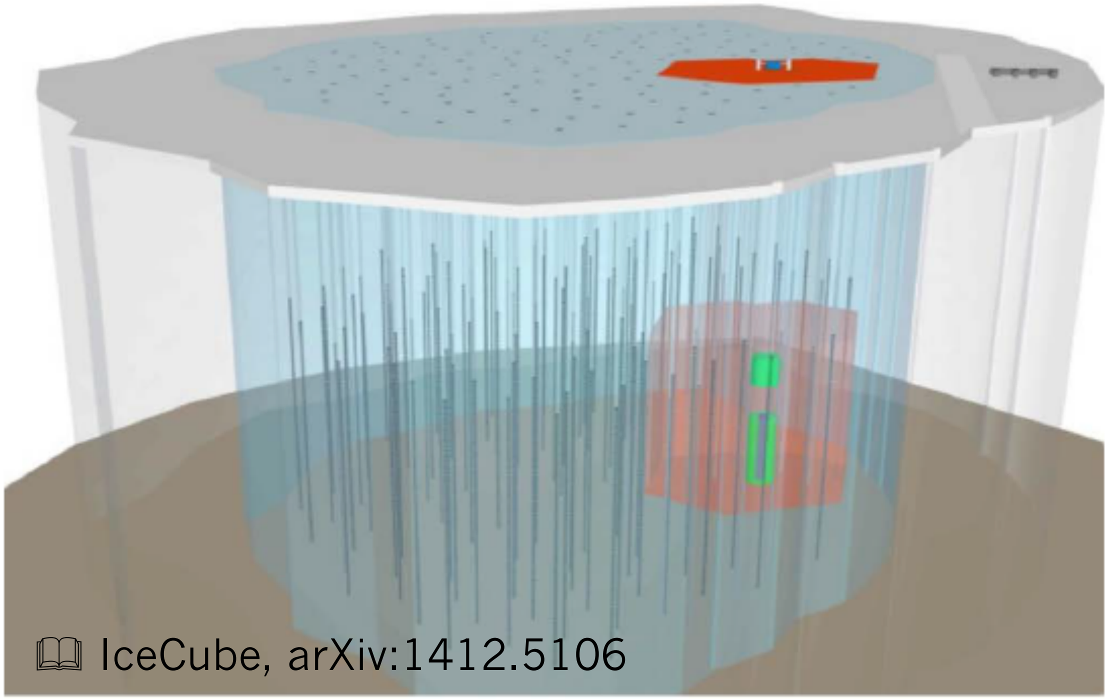


IceCube now competes with SK and LBL experiments !

Marginal sensitivity to matter effects
But great confidence for next steps

PINGU as part of IceCube Gen2

- Next generation neutrino experiments at the South Pole
  - IceCube Gen2 – larger spacing, bigger volume, surface veto → point sources
  - PINGU – denser DeepCore, matter effects in oscillations → neutrino mass hierarchy



📖 IceCube, arXiv:1412.5106

IceCube Gen2
→ +120 strings, 7,200 DOMs

IceCube
→ 86 strings, 5,160 DOMs

DeepCore
→ 8+7 strings, 500 DOMs

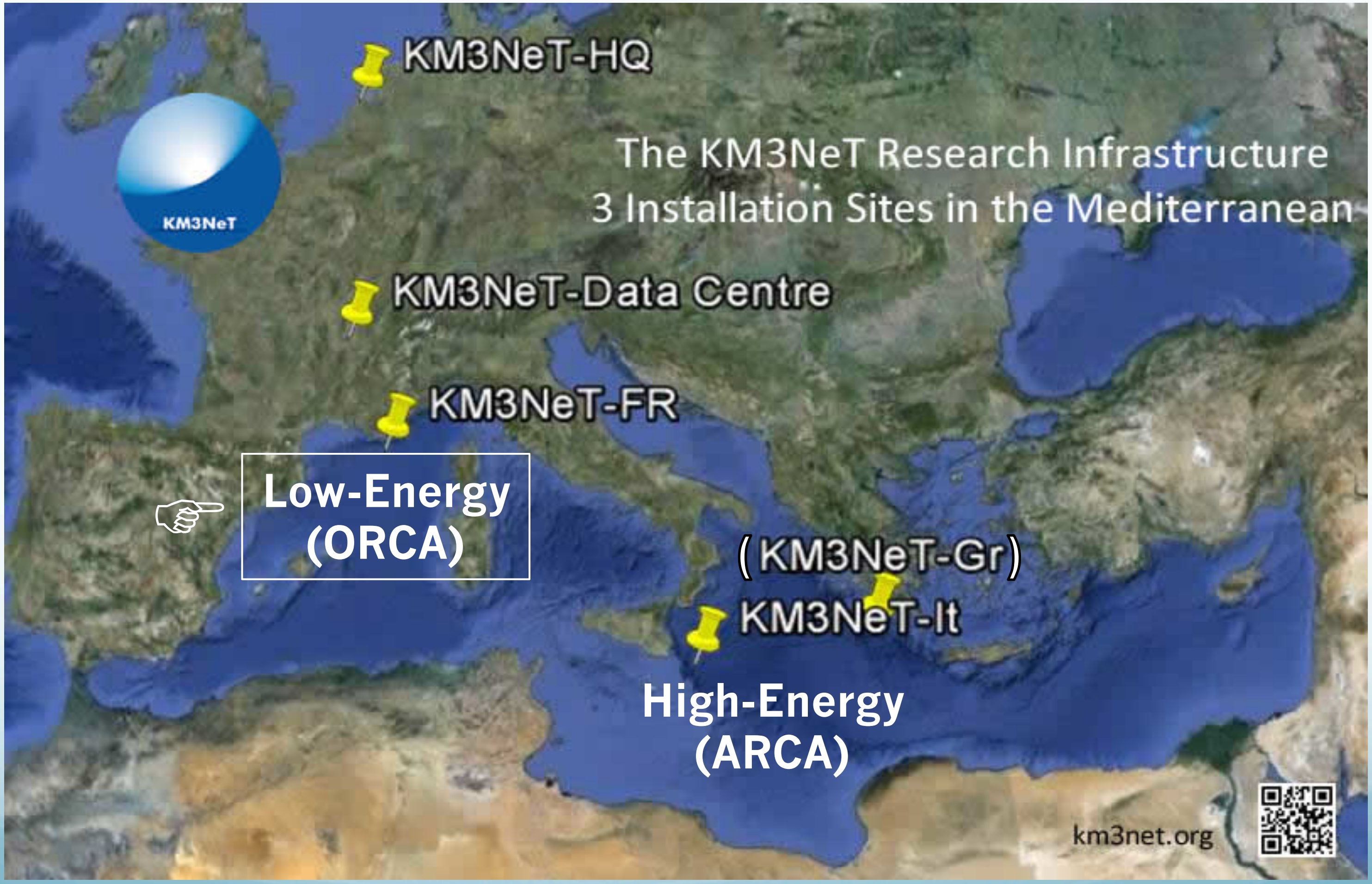
PINGU
→ +40 strings, 3,600 DOMs

10” R7081-02 High-QE
+ electronics upgrade

With PINGU, atmospheric muon background can be vetoed by IC/DC

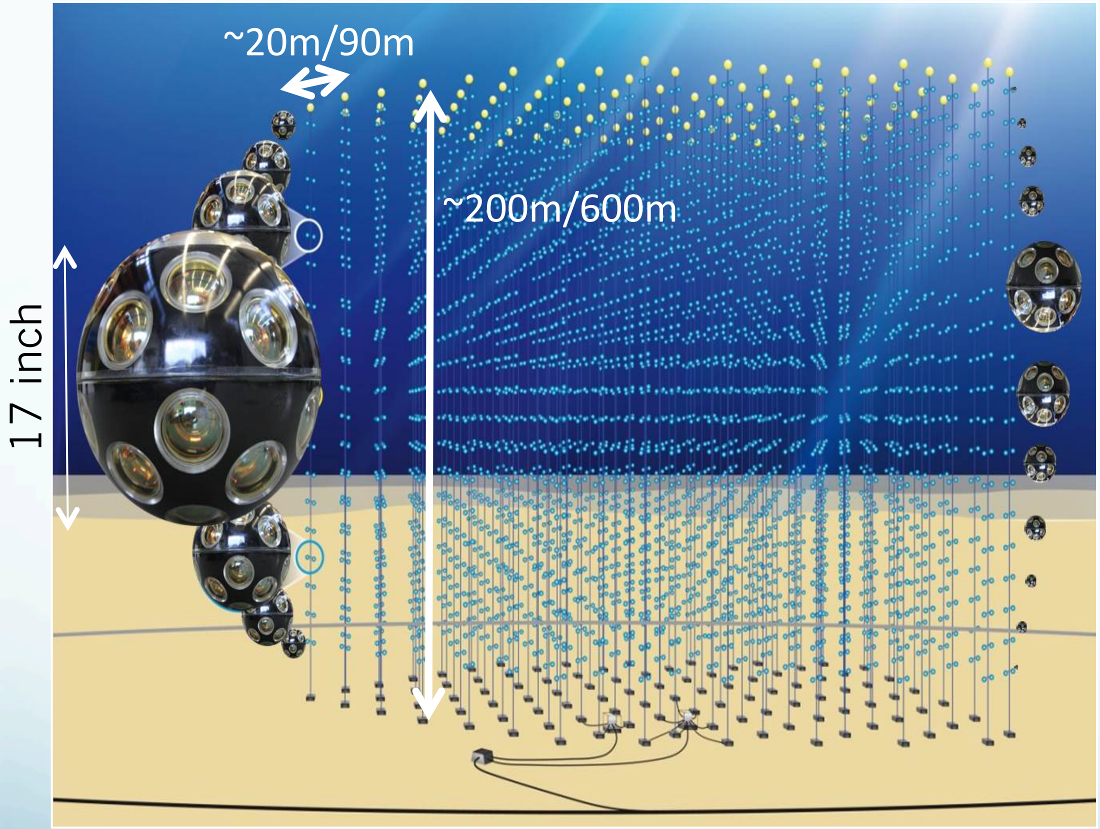
KM3NeT: Next generation Med. NT

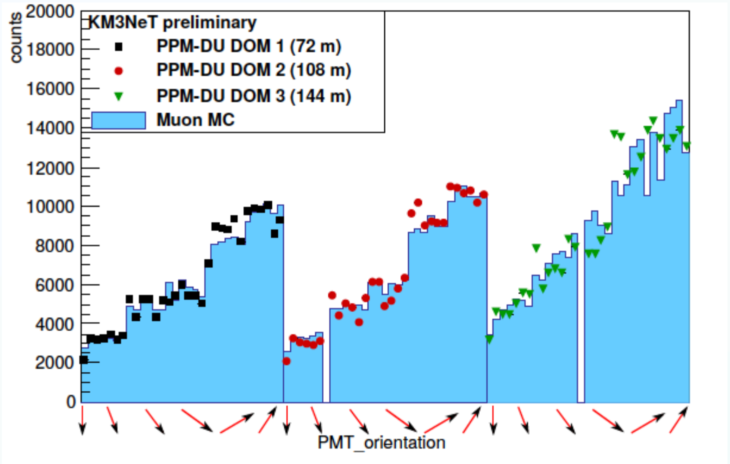
KM3NeT is a distributed research infrastructure with 2 main physics topics:
Low-Energy studies of atmospheric neutrinos – High-Energy search for cosmic neutrinos



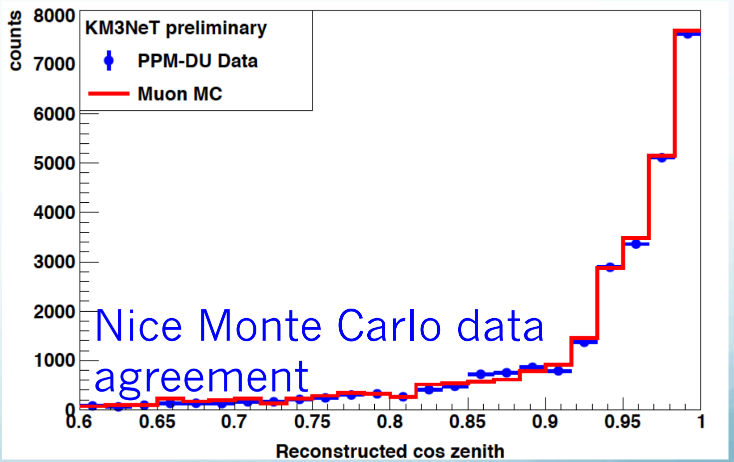
Detector technology

First in-situ prototype: 🕮 Eur. Phys. J. C (2014) 74:3056





Results of mini-line @ Capo Passero



- 31 3” PMTs
- Digital photon counting
- Directional information

- Wide angle of view
- More photocathode than 1 ANTARES storey
- Cost reduction wrt ANTARES

A phased implementation

PHASE 1:

Shore and deep-sea infrastructure at KM3NeT-Fr & KM3NeT-It

31 lines deployed by end 2016 (**3-4 x ANTARES sensitivity**)

Proof of feasibility of network of distributed neutrino telescopes and more?

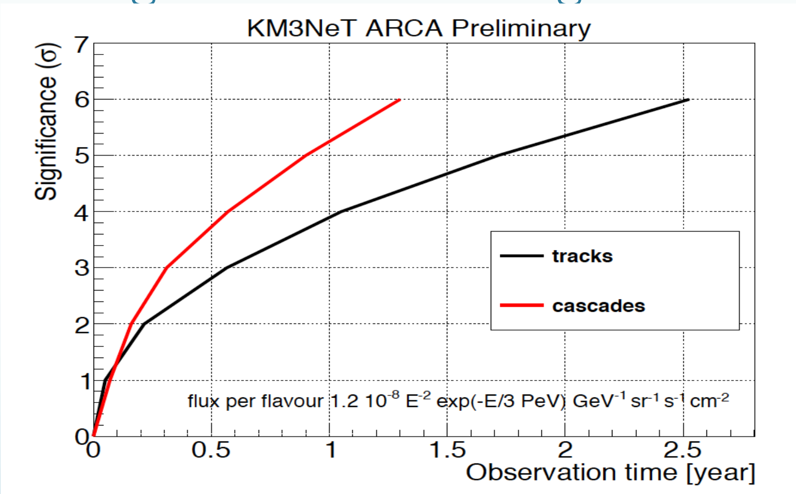
ORCA demonstrator

31 M€ FUNDED ONGOING

2016 PHASE 2: ARCA (+80-90 M€) and ORCA (+40 M€)

230 lines (2 building blocks in Italy) + 115 lines (1 building block) in France

Investigation of IceCube signal *Neutrino Mass Hierarchy*



ARCA and ORCA Letters of Intent in preparation → Summer 2015

2020 KM3NeT NEXT: *Neutrino astronomy*

6 building blocks

220-250 M€ ESFRI Roadmap

NMH with LBL experiments

- « Standard approach » :probe $\nu_\mu \leftrightarrow \nu_e$ governed by Δm^2_{31}

$$P_{3\nu}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\, P_{2\nu} = \sin^2\theta_{23}\,\sin^2 2\theta_{13}^{m}\,\sin^2\left(\frac{\Delta m^{m\,2}_{31} L}{4E_\nu}\right)$$

[Neglecting solar (> a few GeV and >1000's km) and CP violation effects]

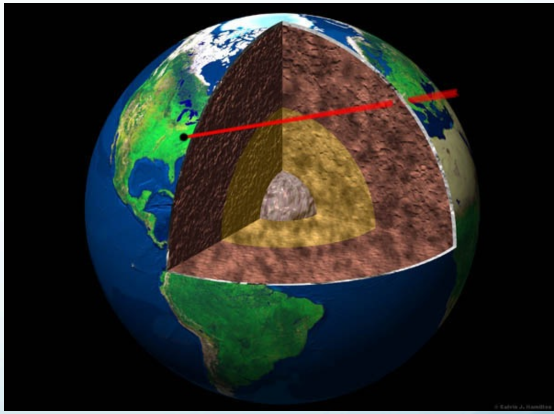
- Matter effects (MSW) come to the rescue

Only electron neutrinos interact through CC with electrons
→ Additional potential A in the Hamiltonian $A \equiv \pm\sqrt{2}G_F N_e$ (−)+ for (anti-)neutrinos

$$\sin^2 2\theta^m_{13} \equiv \sin^2 2\theta_{13}\left(\frac{\Delta m^2_{31}}{\Delta^m m^2_{31}}\right)^2$$

$$\Delta^m m^2_{31} \equiv \sqrt{(\Delta m^2_{31}\cos 2\theta_{13} - 2E_\nu A)^2 + (\Delta m^2_{31}\sin 2\theta_{13})^2}$$

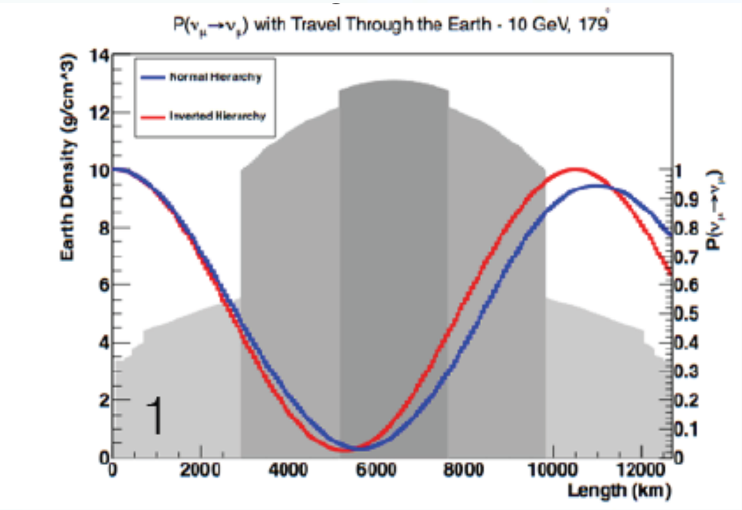
$$E_{\rm res} \equiv \frac{\Delta m^2_{31}\cos 2\theta_{13}}{2\sqrt{2}G_F N_e} \simeq 7\,\mathrm{GeV}\left(\frac{4.5\,\mathrm{g/cm^3}}{\rho}\right)\left(\frac{\Delta m^2_{31}}{2.4\times 10^{-3}\,\mathrm{eV^2}}\right)\cos 2\theta_{13}$$

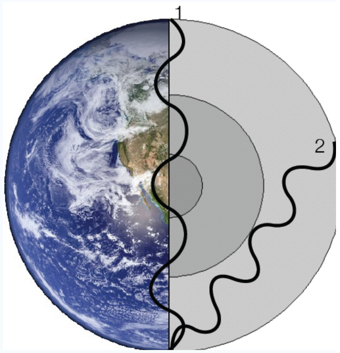


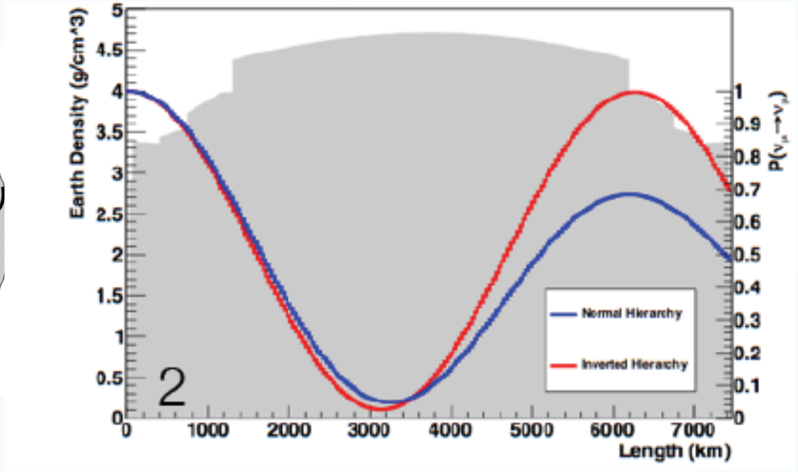
Resonance energy Earth: Mantle E_{res} ~ 7 GeV & Core E_{res} ~ 3 GeV

- Also parametric resonance (e.g mantle-core)

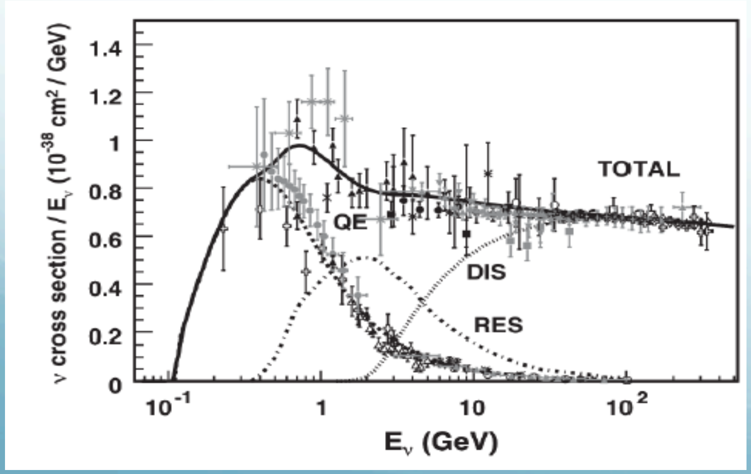
Matter Effects and Mass Hierarchy



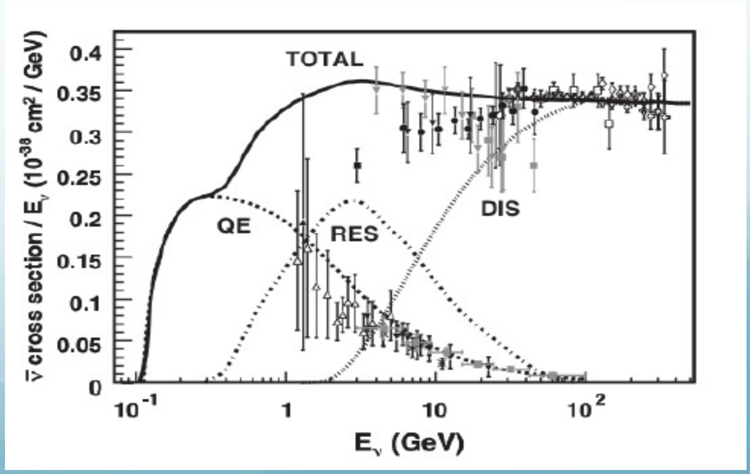




Requirements:
- $\Delta m^2_{13} \sim$ A matter potential must be significant but not overwhelming
- L large enough – matter effects are absent near the origin
- Distinction between neutrinos and anti-neutrinos → cross-sections!



$$\sigma(\nu) \approx 2\sigma(\bar{\nu})$$

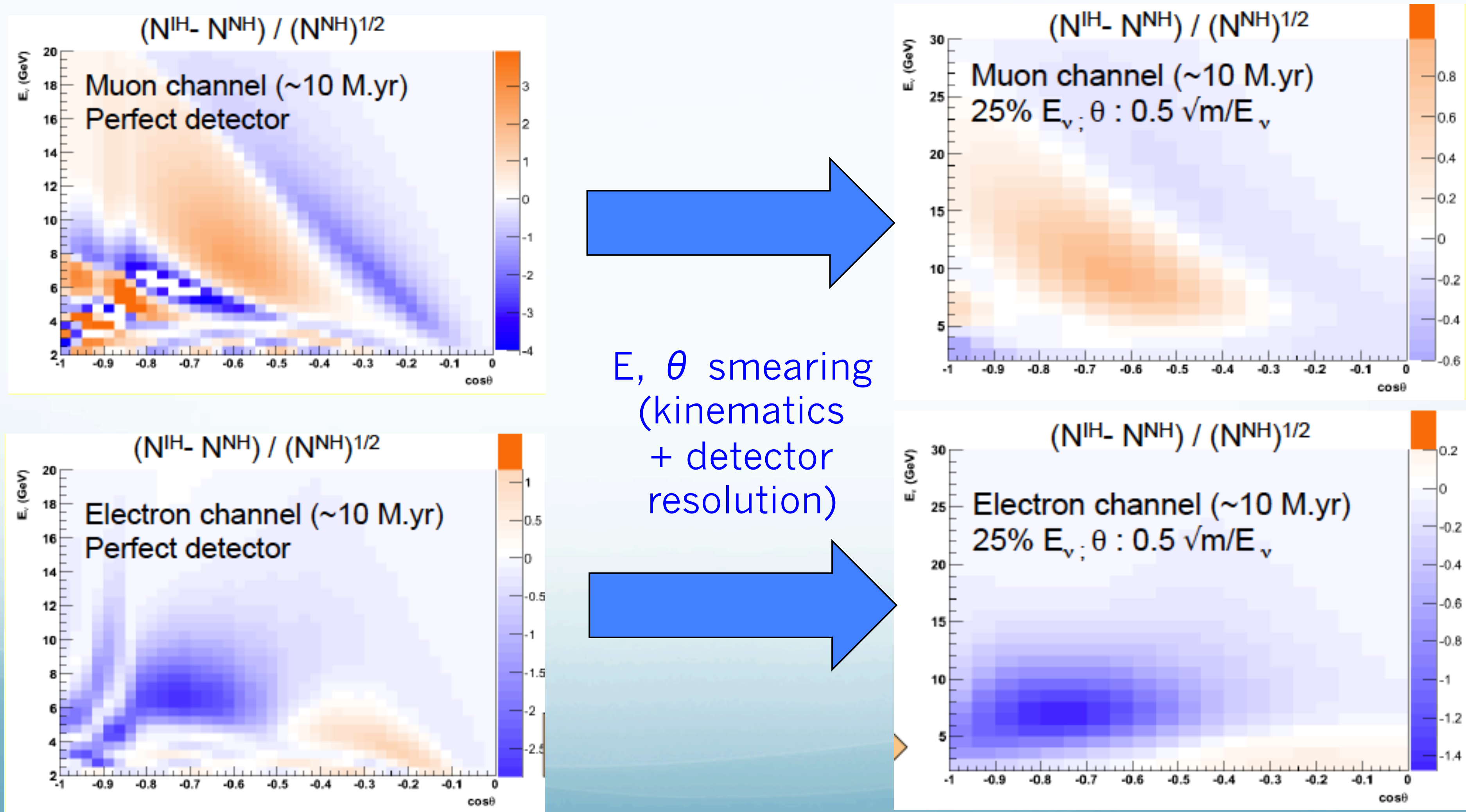


Muon versus Electron channels

Both muon- and electron-channels contribute to net hierarchy asymmetry

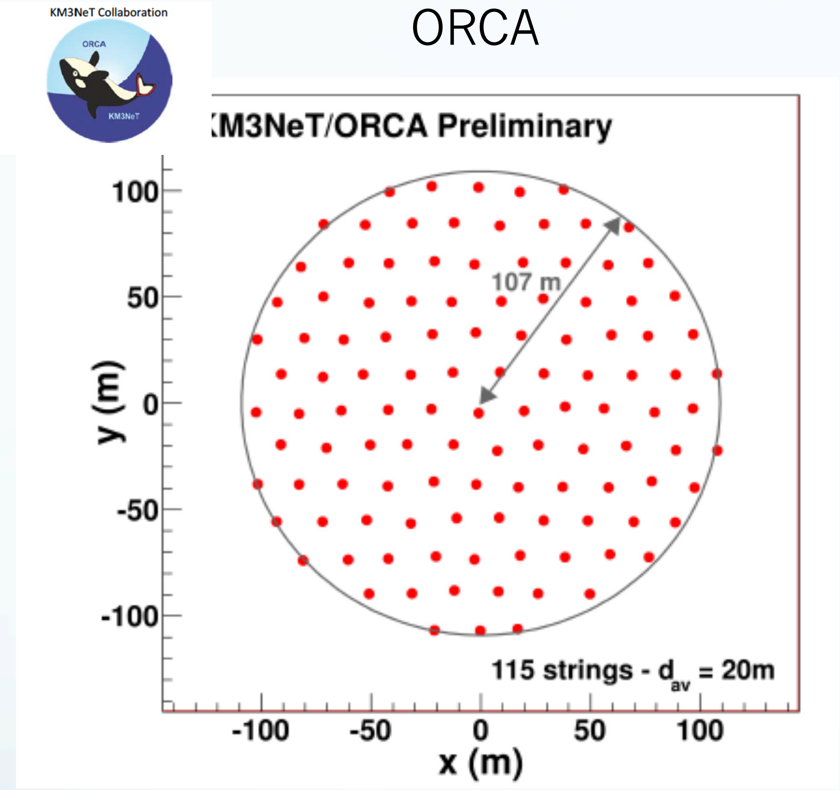
electron channel more robust against detector resolution effects:

(Significances a la Akhmedov et al. 📖 JHEP 02 (2013) 082)



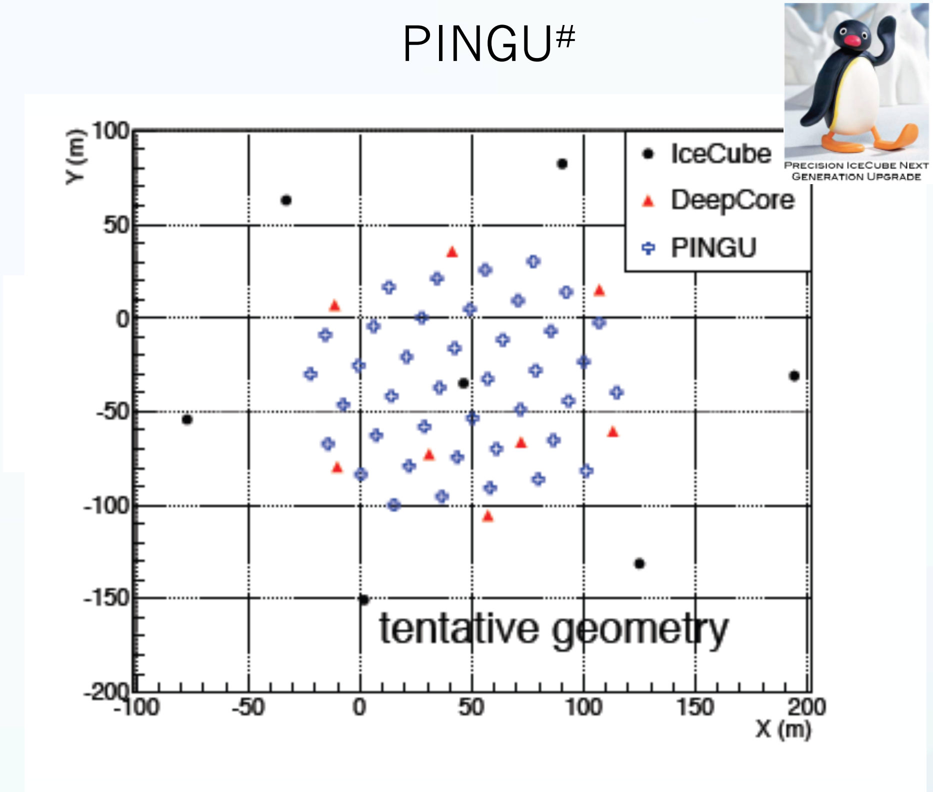
Proposed Low Energy Extensions

ORCA



115 lines, 20m spaced,
18 OM/line 6m spaced
Instrumented volume ~3.8 Mt, 2070 OM

PINGU#



40 strings, 20-25m spaced,
Up to 96 OM/string 3m spaced
Instrumented volume ~ 6 Mt, 3840 OM

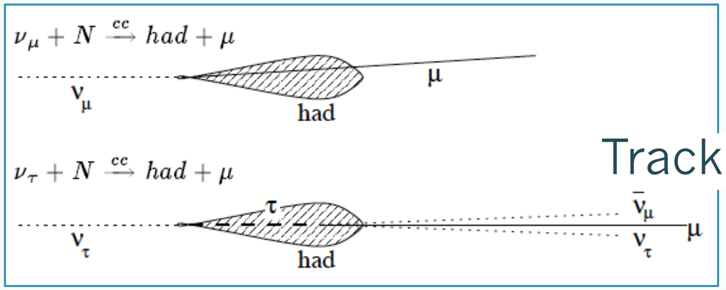
#First performances evaluated with 60 DOMs/string

Optimized layouts still under study

A. Kouchner, Phys. Dark Universe 4 (2014) 60-74

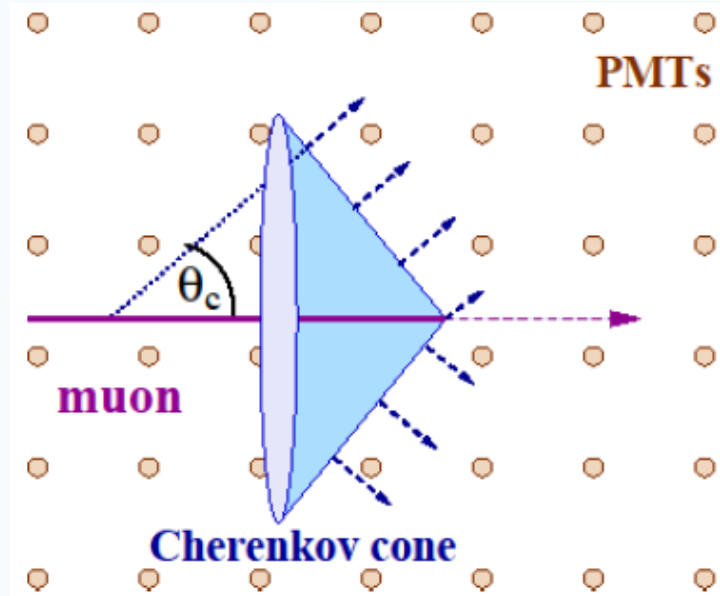
PINGU LOI arXiv:1401.2046

Event topologies

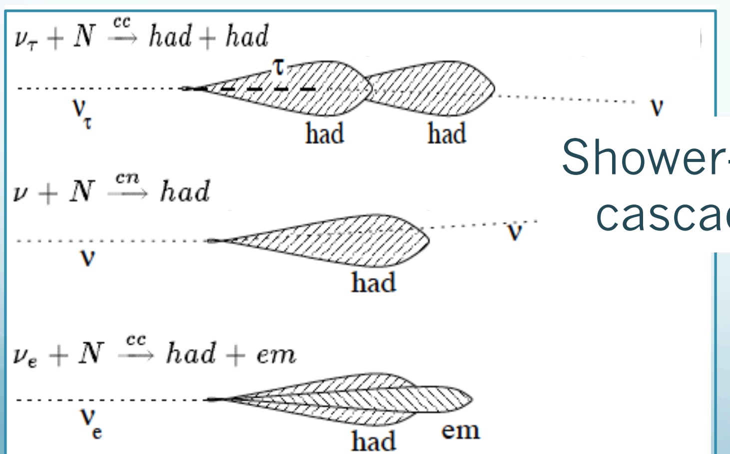


Track-like

Track-like contains both a cascade and one track

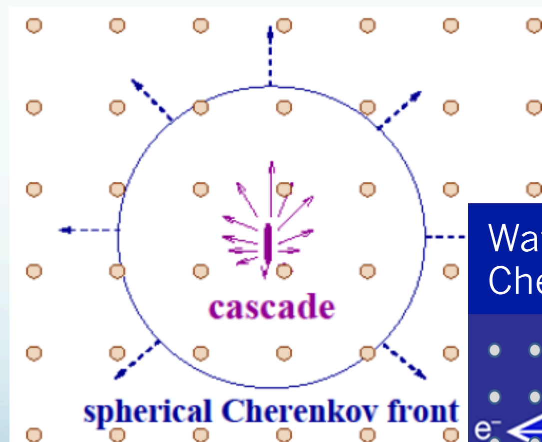


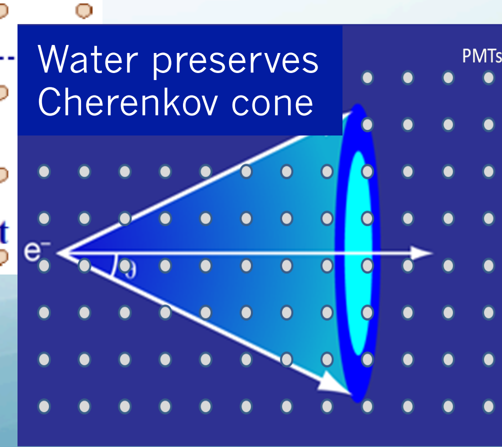
Not to scale



Shower-like
cascade

No track is identified



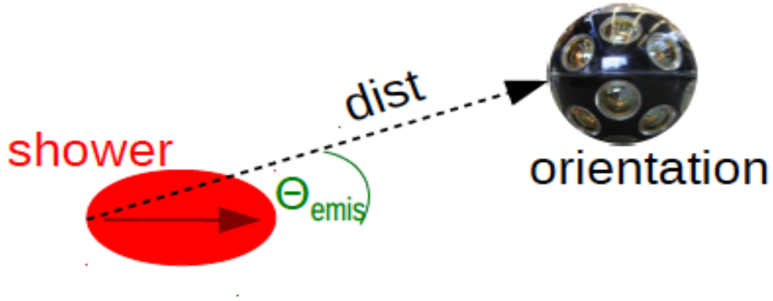


ORCA shower reconstruction (ν_e)

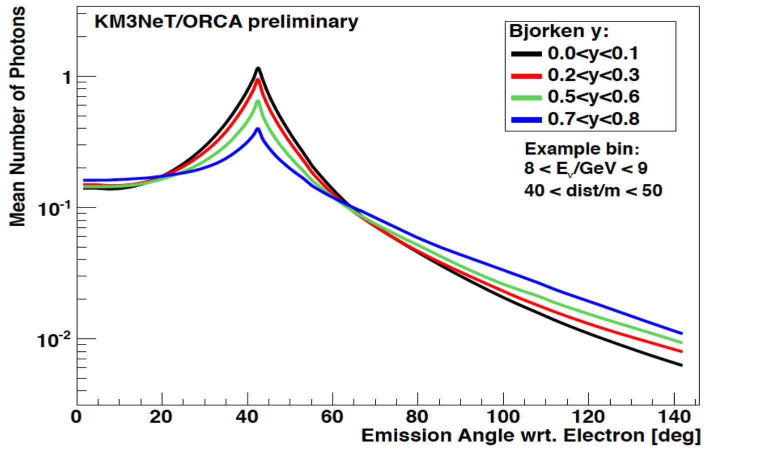
- 1. Vertex fit:
  - maximum likelihood method based on time residuals
  - two fits: first robust prefit then more precise fit

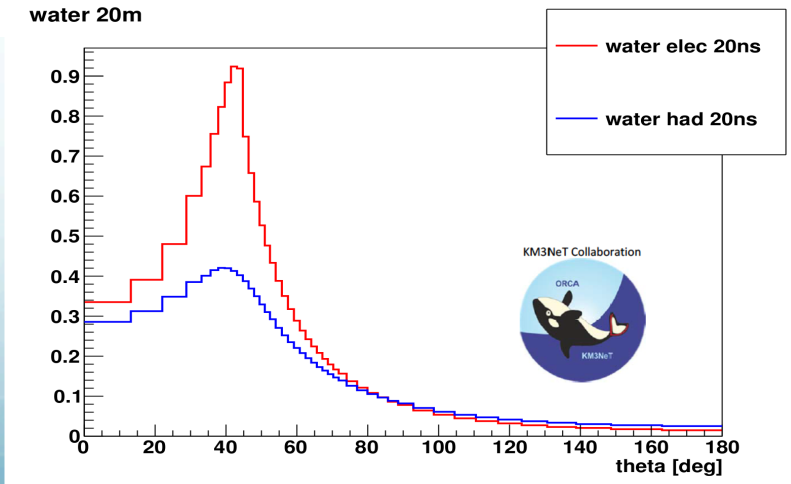
Res. (σ): 0.5-1 m

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



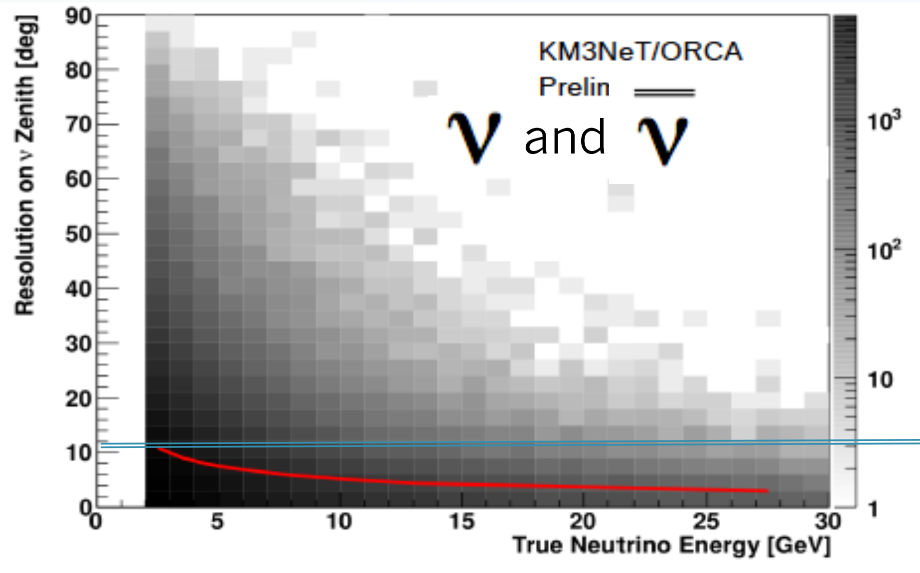
  - maximum likelihood method based probability that hits have been created by certain shower hypothesis (E_ν, Bjorken y, direction)

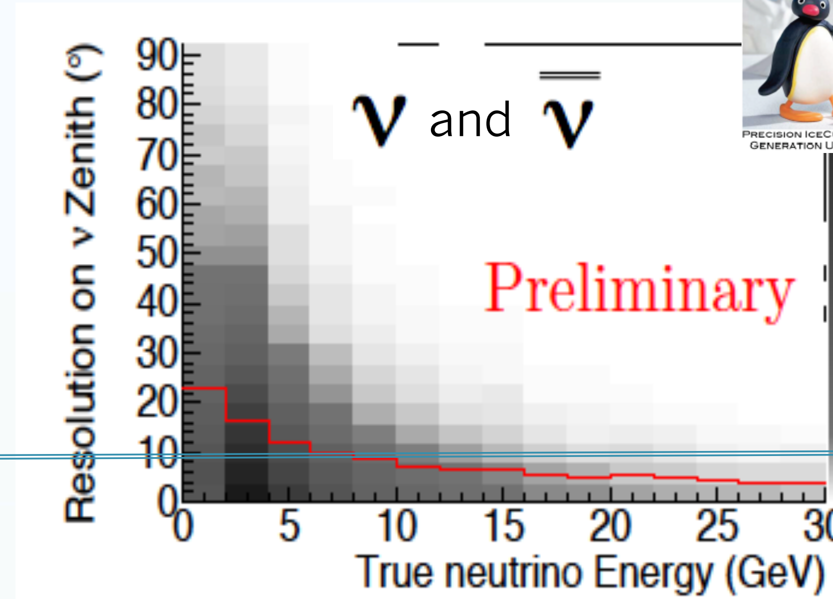


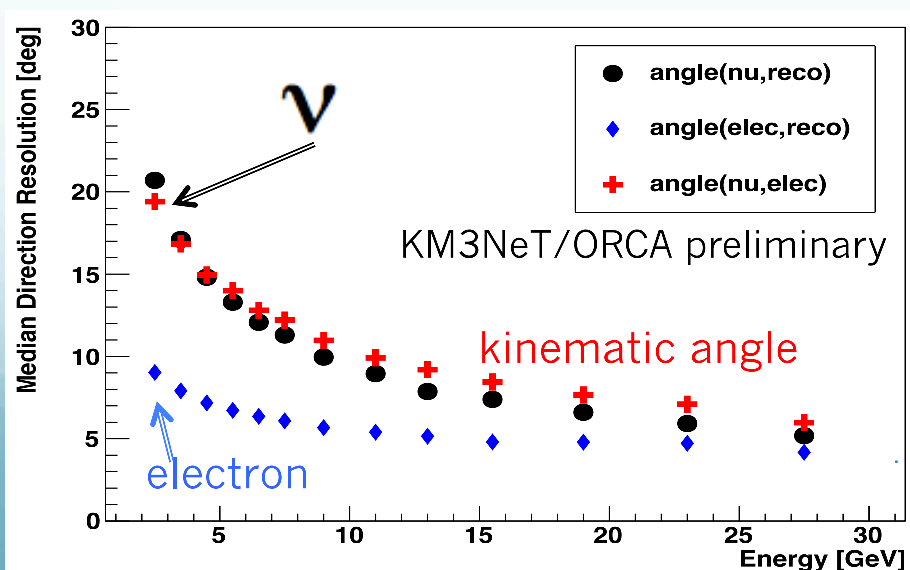


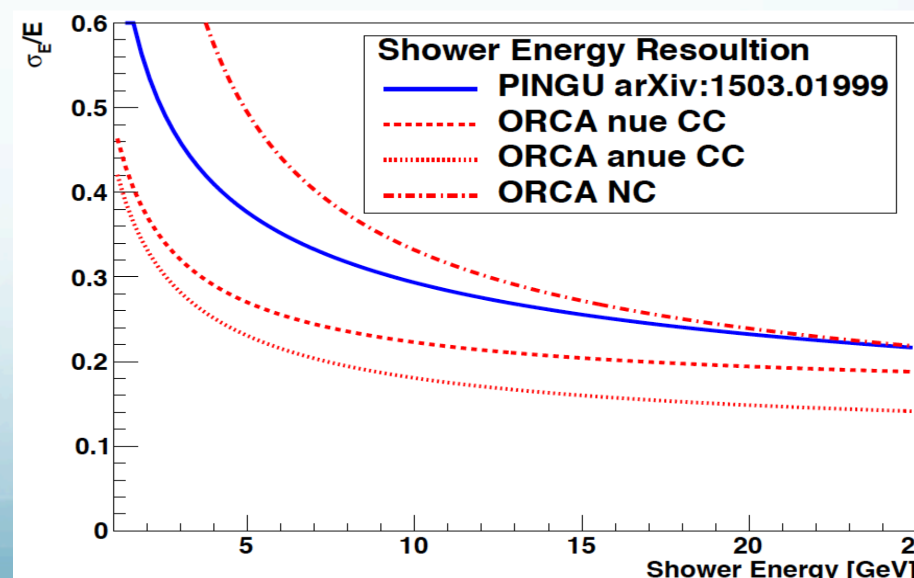
KM3NeT Collaboration

Preliminary performances (ν_e)



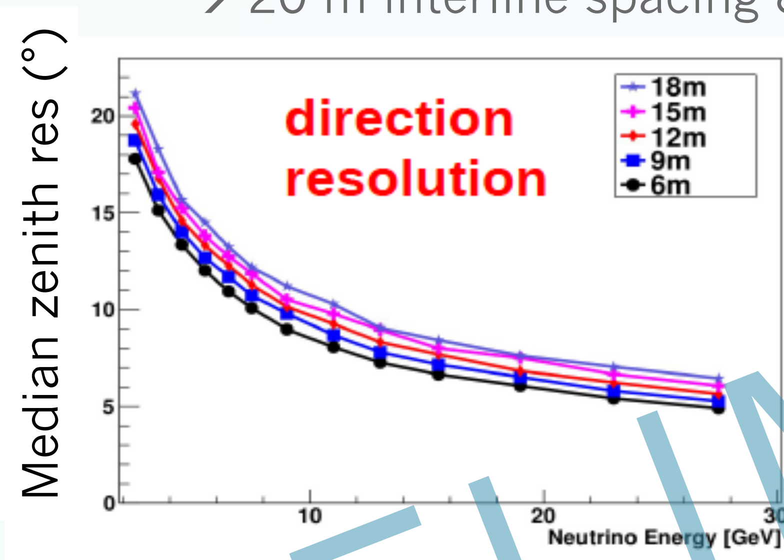


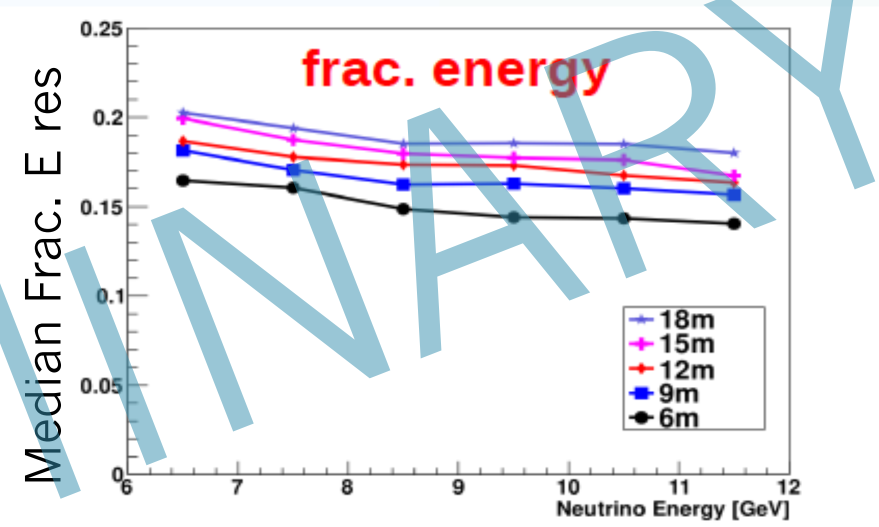


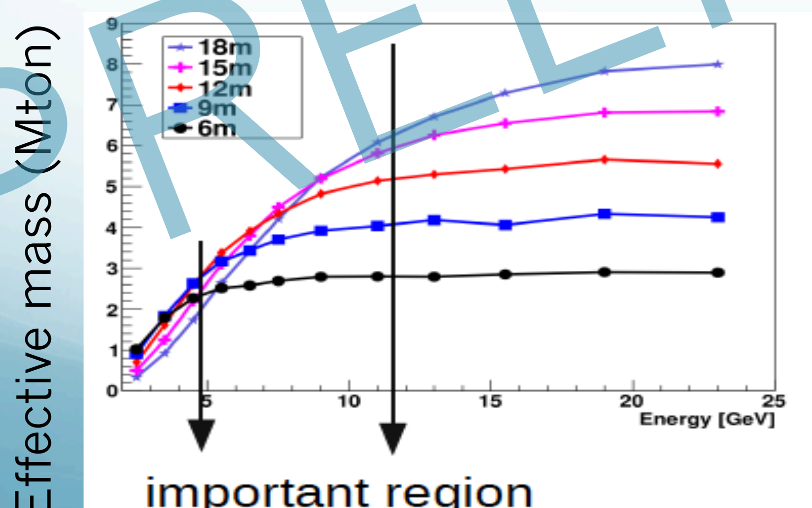


ORCA Layout Optimization

- Switch off DOMs in proposed 115 line detector
  → 20 m interline spacing & 6,9,12,18m spacing inter-DOM







Examples for shower reconstruction

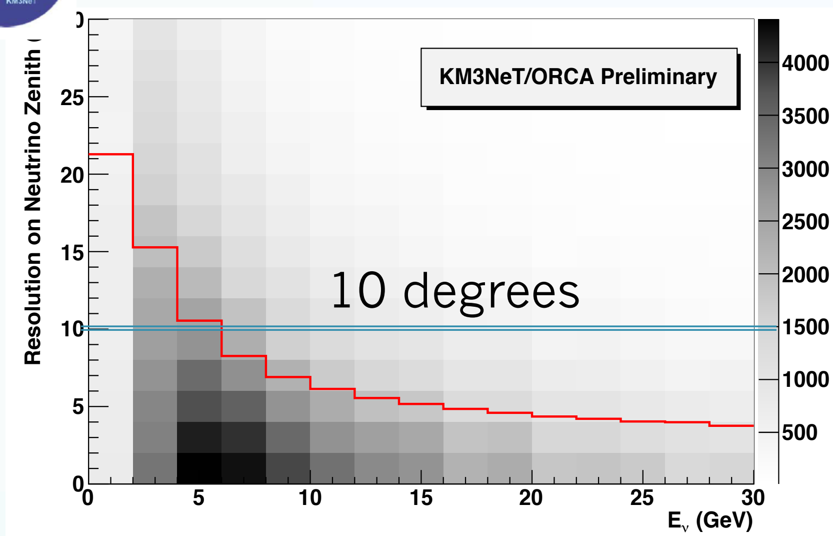
All relevant quantities must be studied in details before adopting an optimum spacing

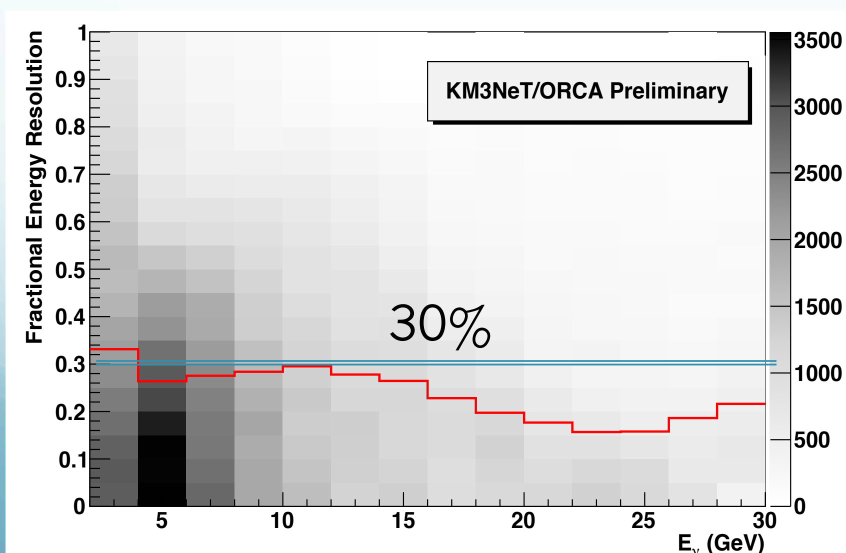
But substantial improvement possible

Work in progress

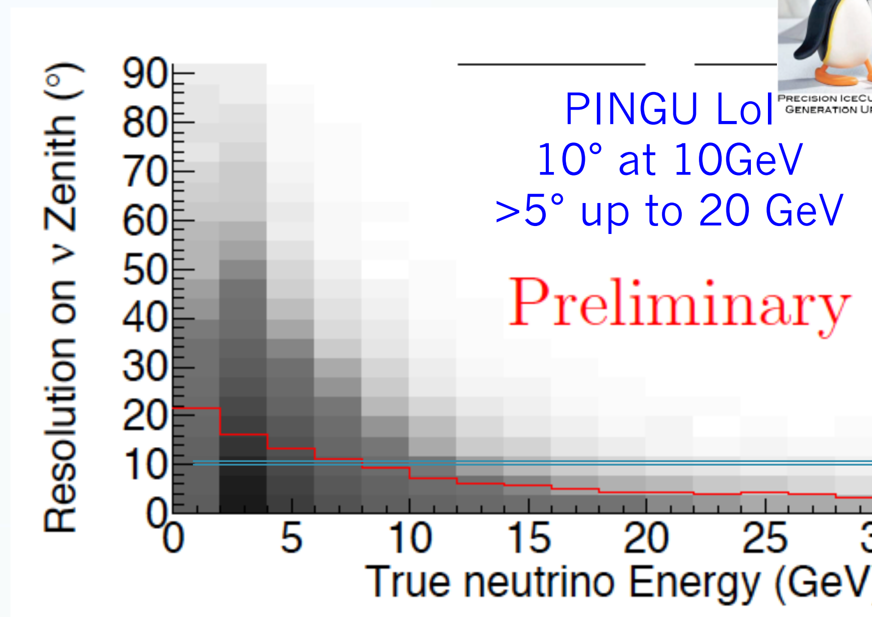
Preliminary performances (ν_μ)

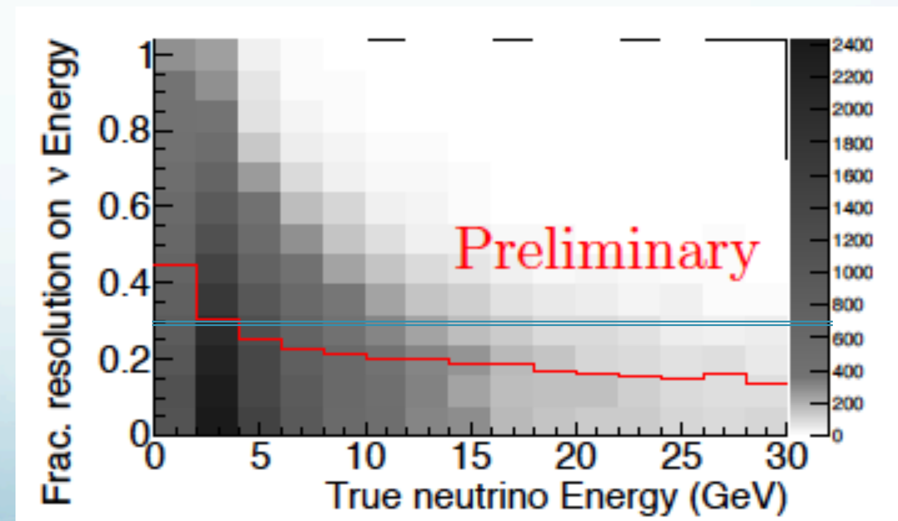
KM3NeT Collaboration





PRECISION ICECUBE NEXT GENERATION UPGRADE

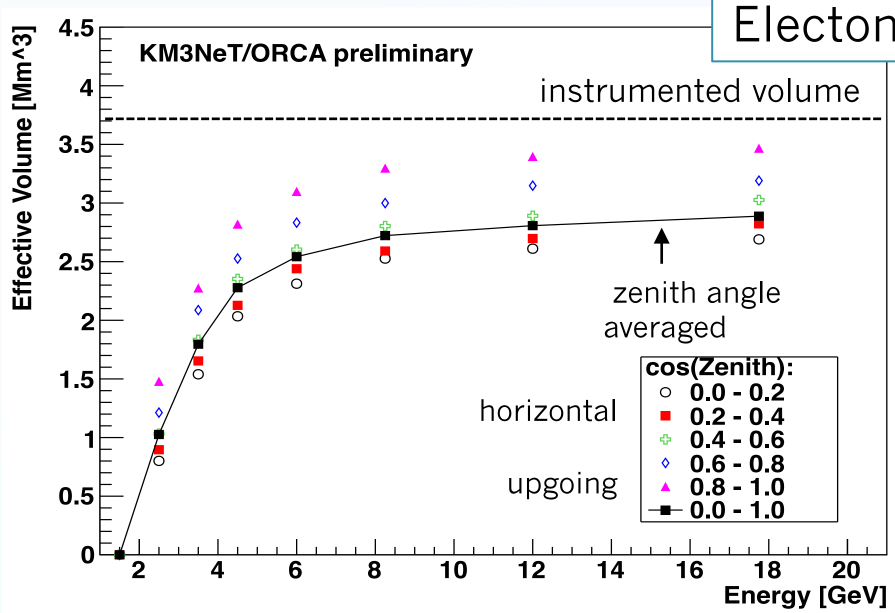


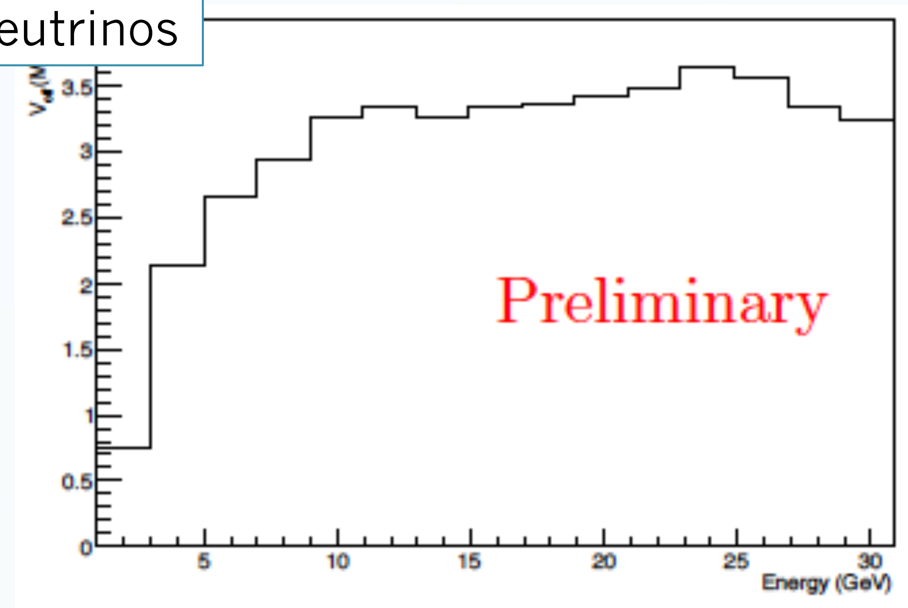


(b) $|E_{\nu,\mathrm{reco}} - E_{\nu,\mathrm{true}}|/E_{\nu,\mathrm{true}}$ vs. $E_{\nu,\mathrm{true}}$.

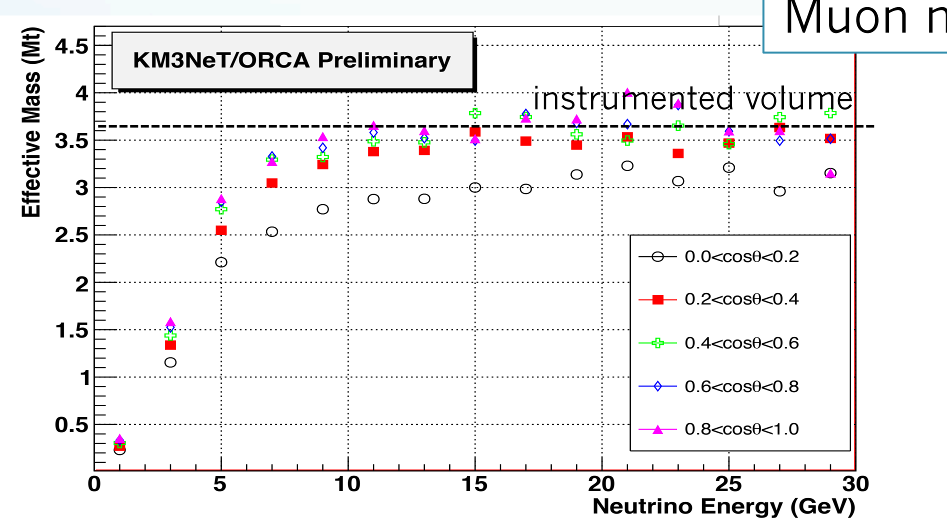
Similar Effective Masses

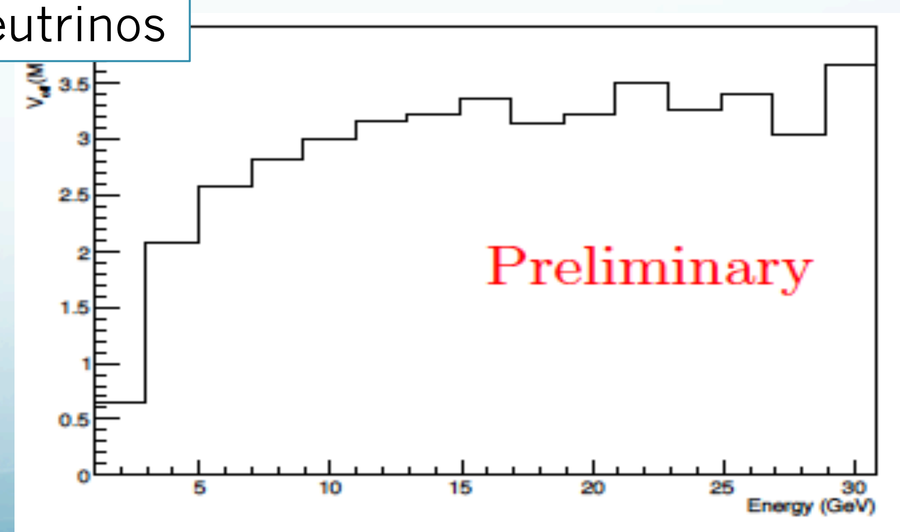
Electon neutrinos





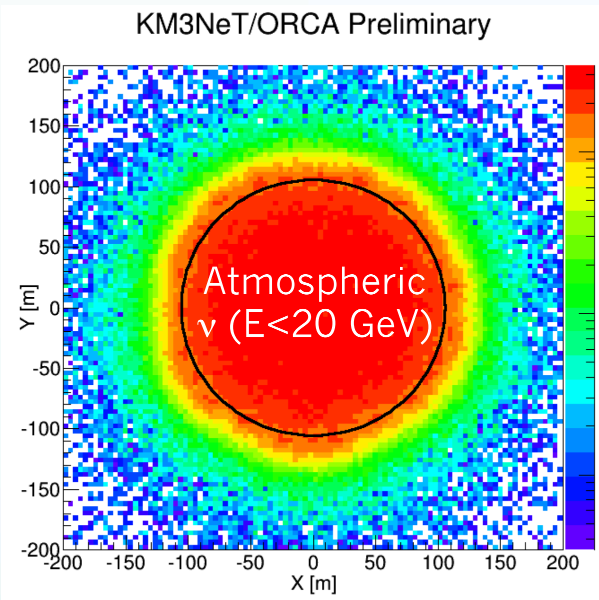
Muon neutrinos

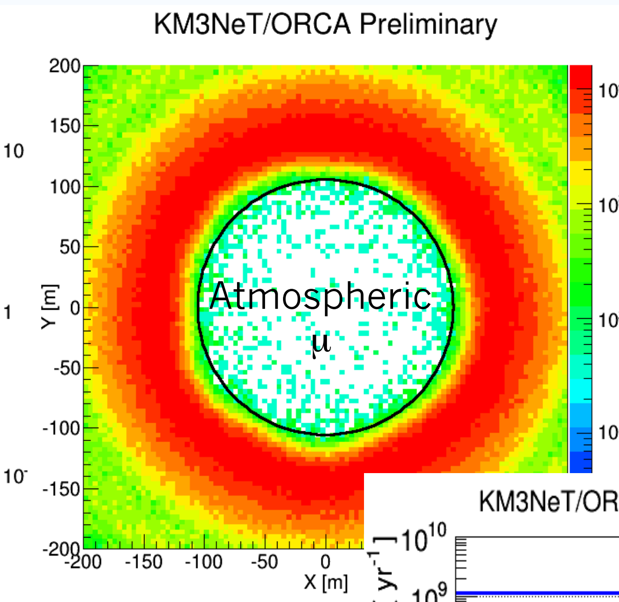




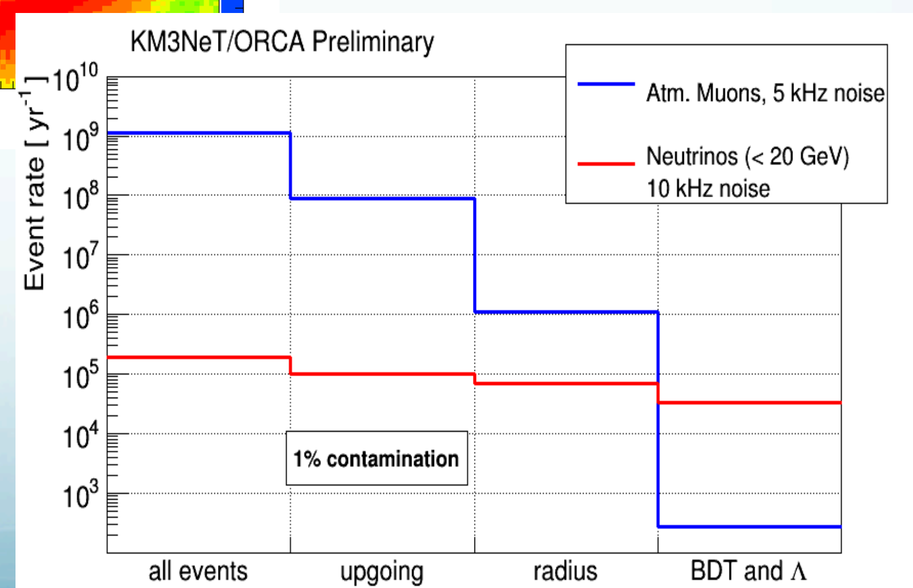
Atmospheric muon rejection

- 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





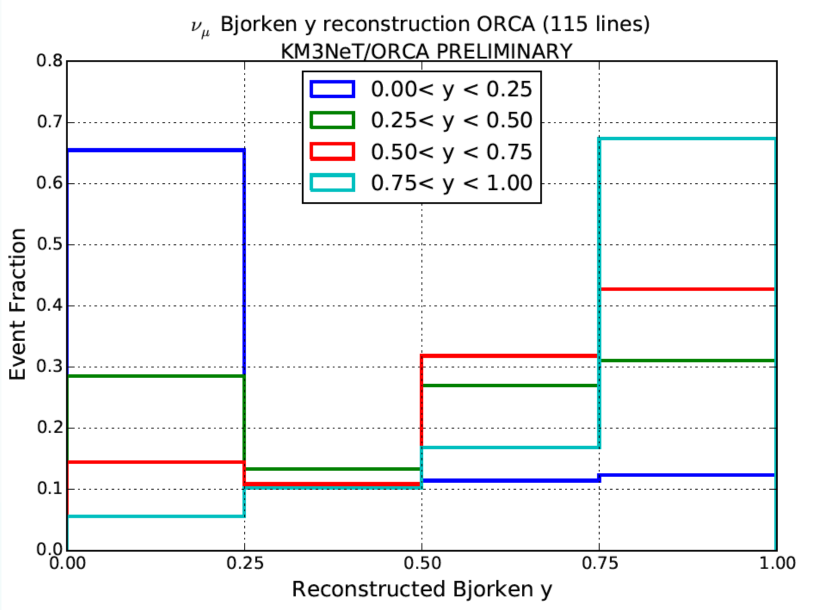
Instrumental veto not mandatory (though not impossible)



1% contamination achievable without too strong signal loss

Work in progress

ORCA Sensitivity to Inelasticity

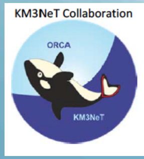


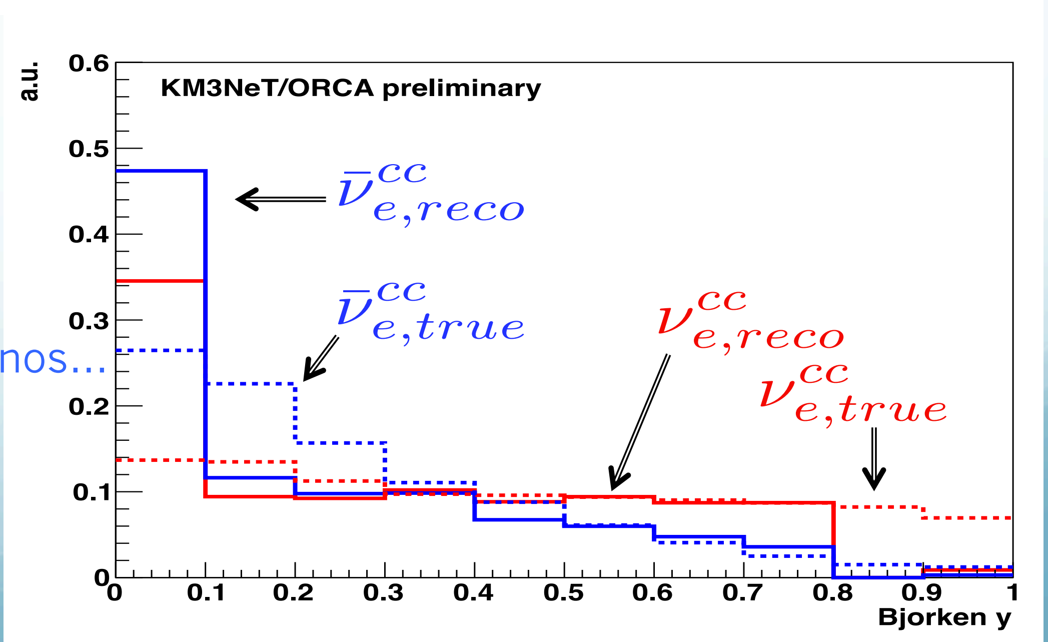
- Use PDFs on the time residuals under the track (low-y) and shower (high-y) hypothesis
- Select y-interval corresponding to highest likelihood

"total significance ... may increase by (20 - 50)%, thus effectively increasing the volume ... by factor 1.5 – 2"
📖 Ribordy & Smirnov PRD, 87. 113007
(**muon channel only**)

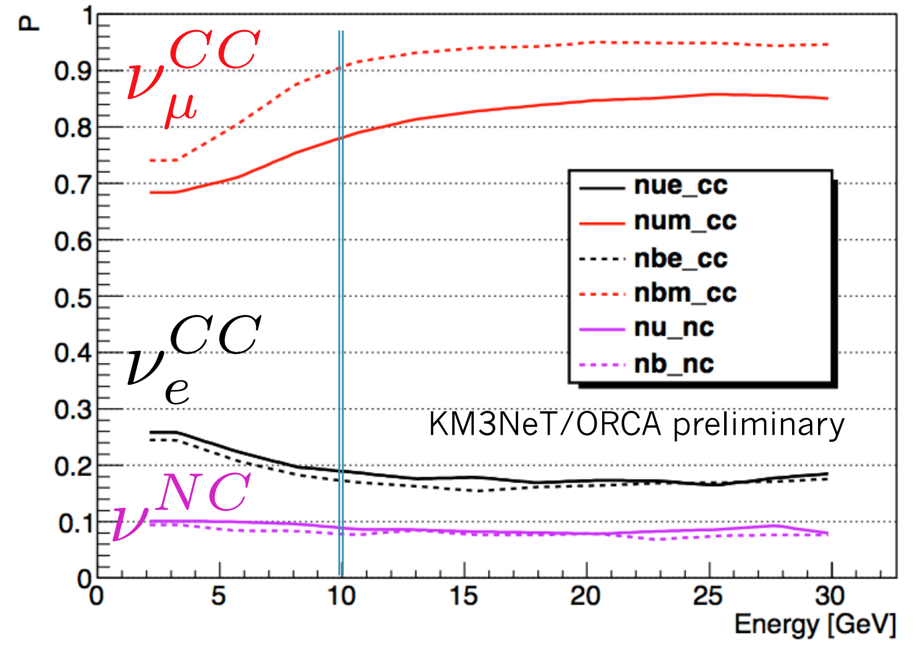
Work in progress

Should be further exploited
PID, NC rejection, neutrinos/anti-neutrinos...





Flavour (mis)-identification



Probabilities to classify as track-like

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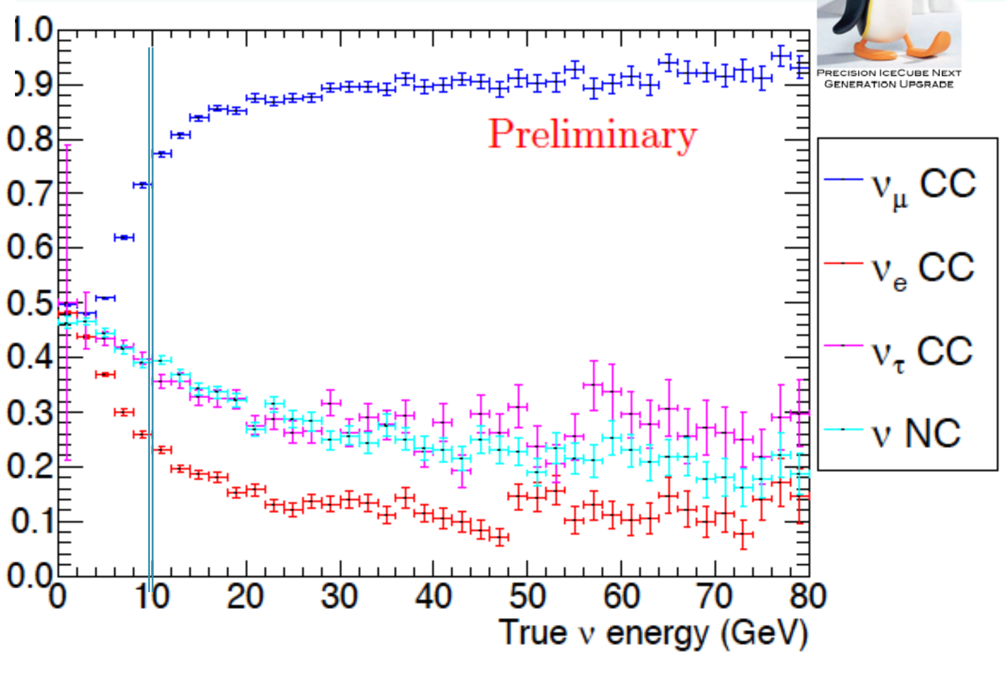


Precision IceCube Next Generation Upgrade

KM3NeT Collaboration

Sensitivity studies

PRECISION ICECUBE NEXT GENERATION UPGRADE

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

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

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

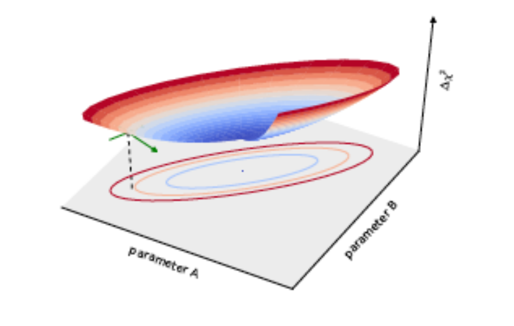
1) Fit parameters assuming NH
2) Fit parameters assuming IH
3) Compute $\Delta \log L = \log(L(\text{NH})/L(\text{IH}))$

θ_{23} , Δm^2 and normalization fitted from data

- ✓ Track vs shower event classification
- ✓ Full MC detector response matrices including misidentified and NC events
- ✓ Atmospheric muon contamination
- ✓ Neutral current event contamination

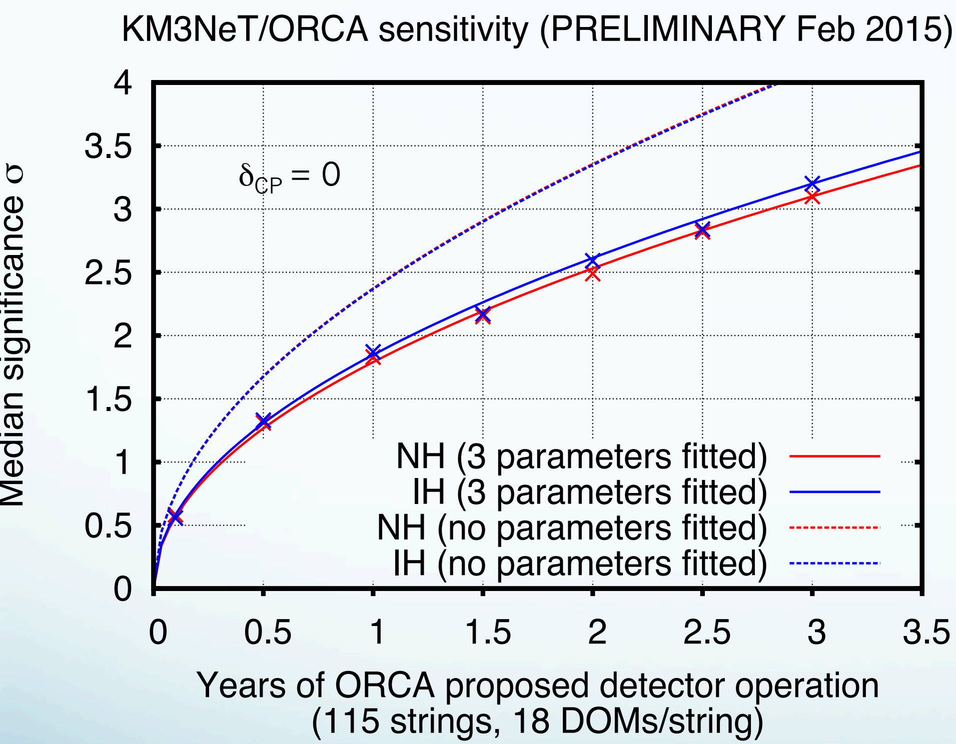
Fisher Information Matrix (FIM)

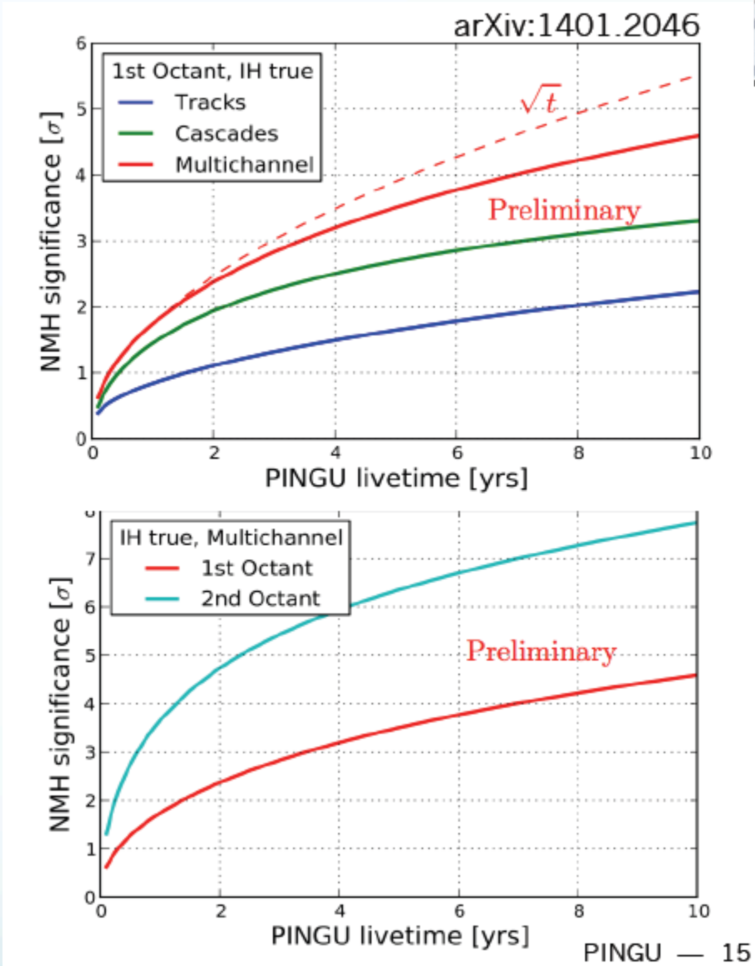
- Used in PINGU analysis
- Use 'fiducial' values (fixed true values)
- Evaluate bin-by-bin first-order derivatives of expected number of events
  $\Rightarrow$ probe small region around fiducial values
- Covariance matrix from derivatives
- Yields individual and combined uncertainties



Runs faster → easier for sys. studies

Current Sensitivities (median)





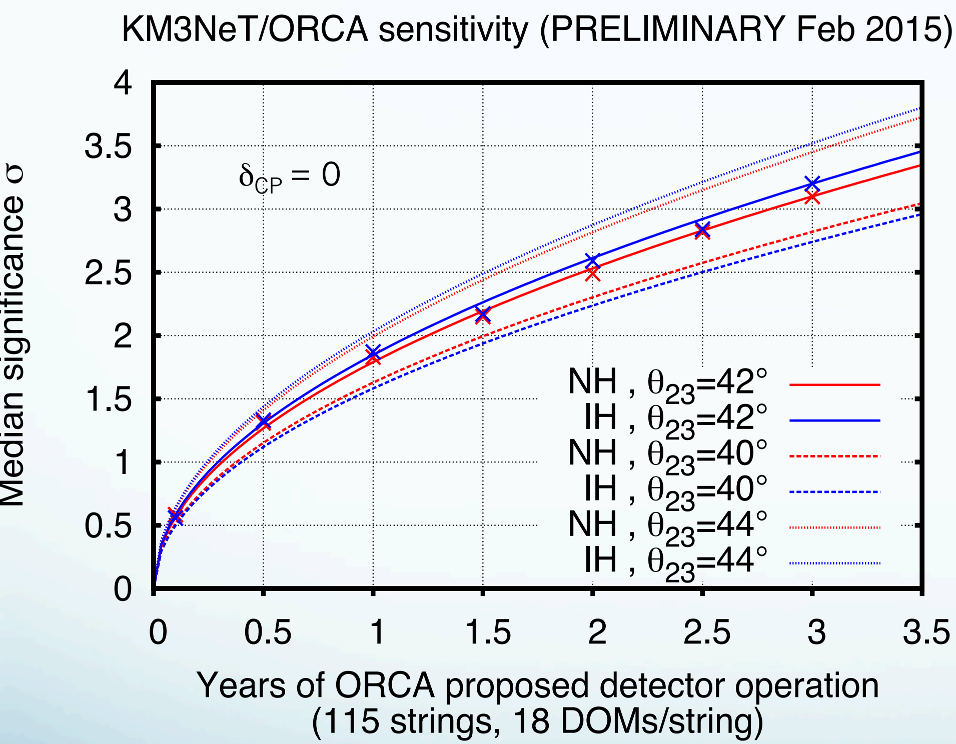
Oscillation parameters

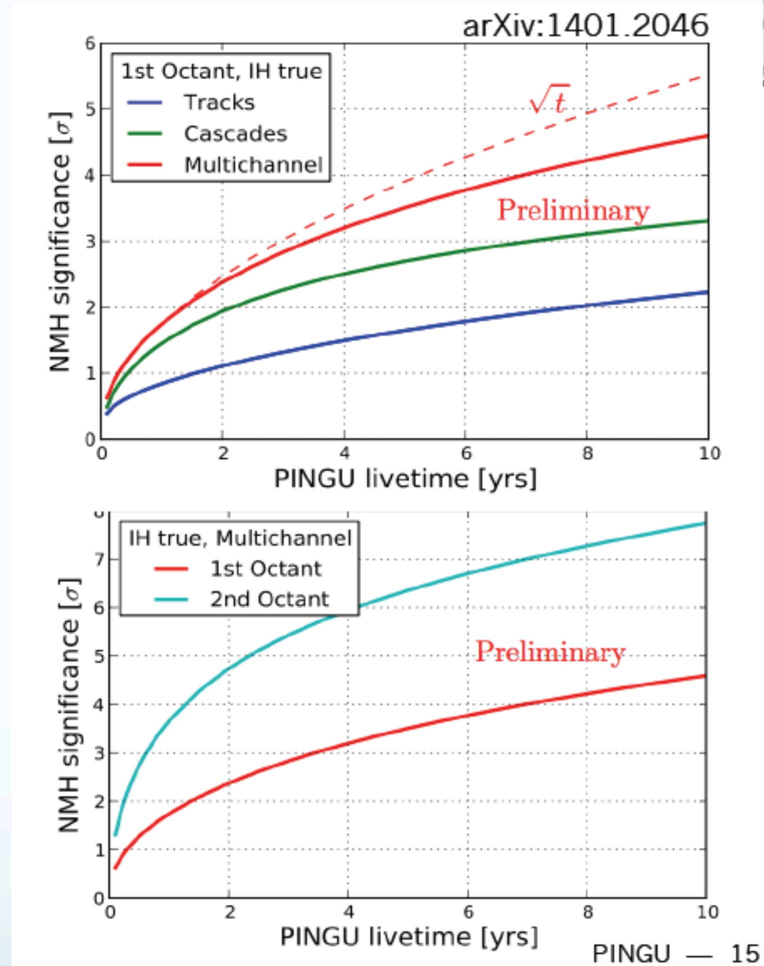
- mass splittings
- mixing angles
- CP-phase

Effective uncertainties

- overall efficiency
  - energy dependent
- energy scale
- x-section uncertainty

ORCA Updated Sensitivity





Oscillation parameters

- mass splittings
- mixing angles
- CP-phase

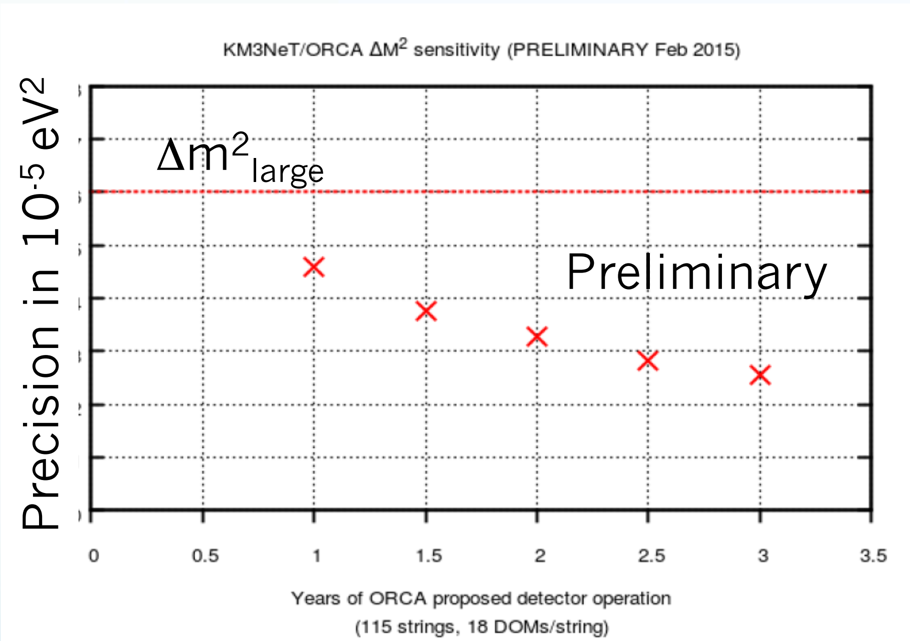
Effective uncertainties

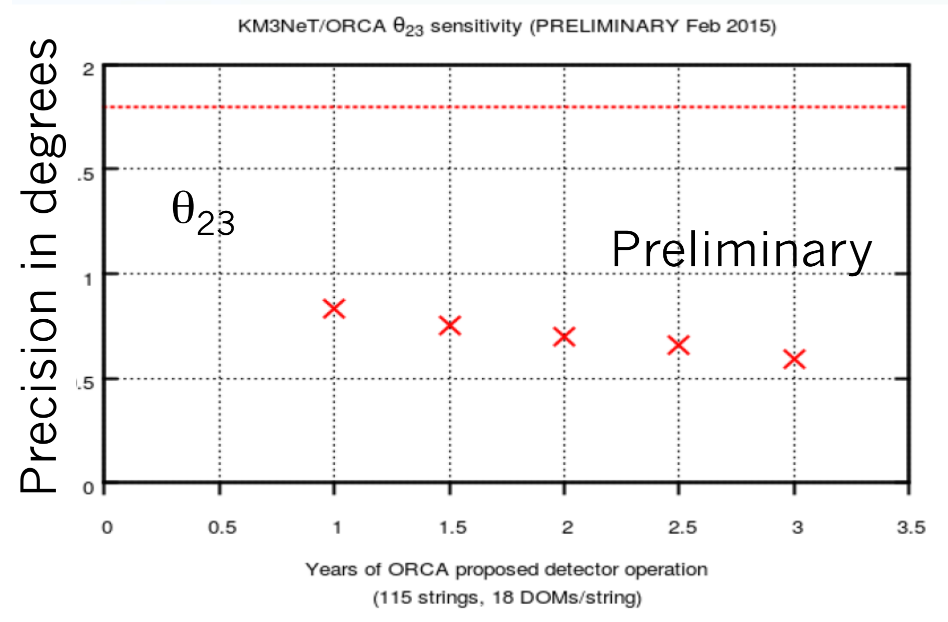
- overall efficiency
  - energy dependent
- energy scale
- x-section uncertainty

Sensitivity to PMNS parameters

KM3NeT Collaboration

Red dotted line : approximate current best value





Similar to PINGU's projections

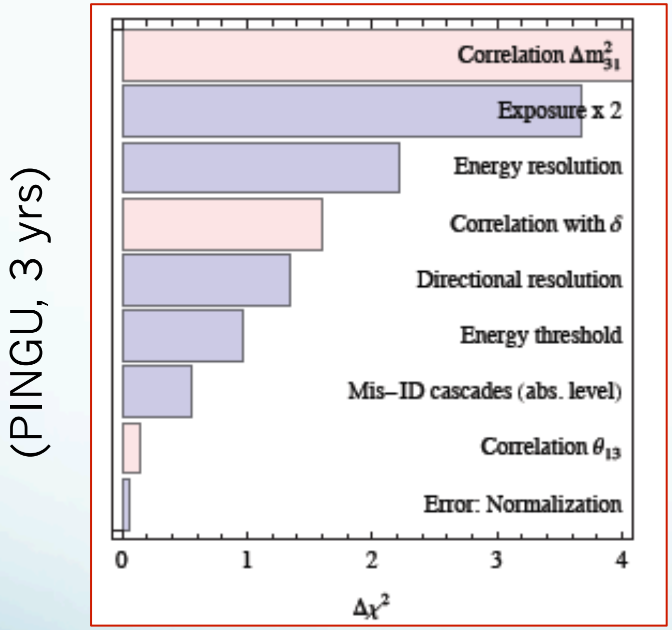
Studies of systematics

Several studies → same conclusions

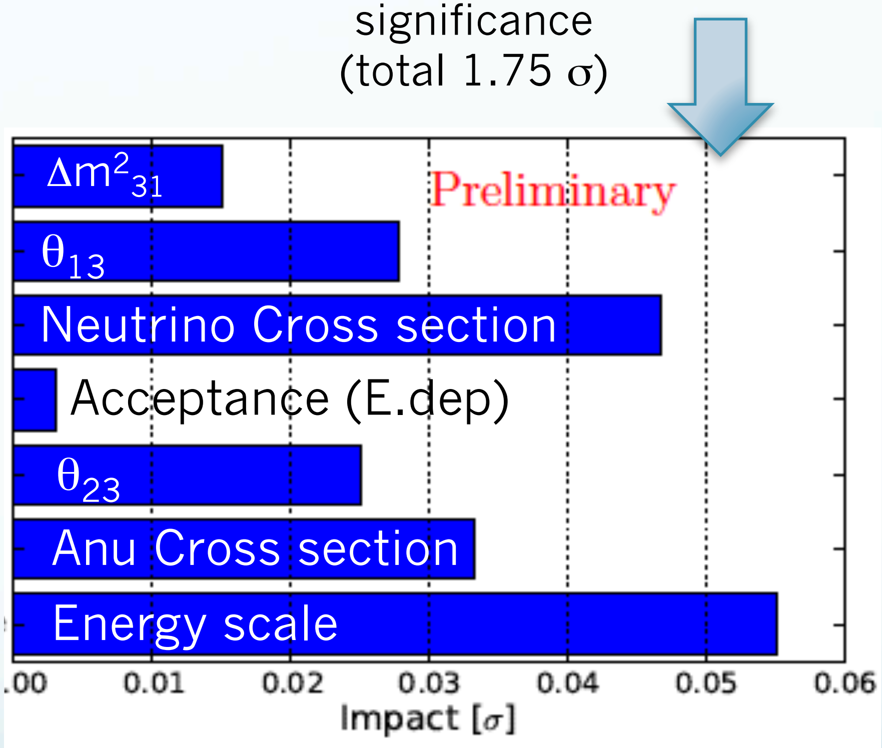
📖 D. Franco et al, JHEP 04 (2013) 008

📖 PINGU LoIarXiv1401.2046

📖 W. Winter, PRD 88 (2013) 013013



Impact (increase) on 1year significance (total 1.75 σ)



📖 Capozzi et al. arXiv1503.01999

Including E, zenith resolution/shape uncertainties +additional uncorrelated uncertainties

Total 5yrs loss in sensitivity from 24% to 40% under very pessimistic assumptions

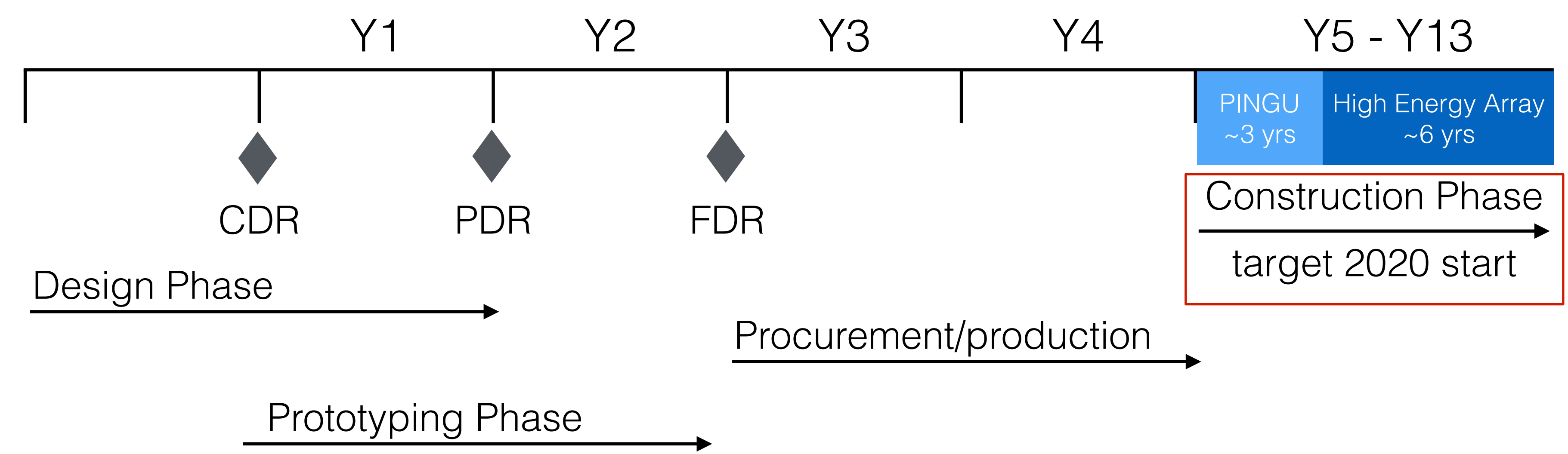
Updates coming up in PINGU, suite of systematics being studied in ORCA

PINGU costs & timeline

Cost of PINGU component	
Hardware	48 M$
Logistics	23 M$
Contingency	16 M$
Total (US accounting)	88 M$

Timeline driven by NSF MREFC funding process not by technology

Updated letter of Intent under internal review



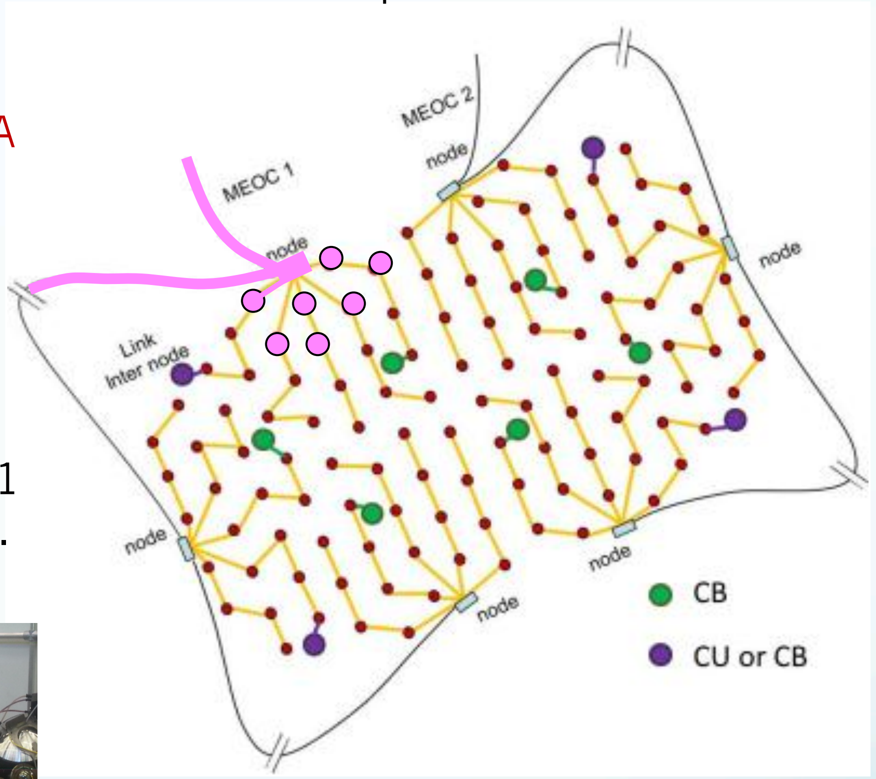
ORCA costs & timeline

Modular ring of up to 6 nodes with double connection to shore for up to 120 detection units + Sea Science instruments

Possibility to redirect the ANTARES cable to ORCA

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

Phase 2 (~40 M€ wo contingency) : 2017 deploy 1 building block 115 strings in French KM3NeT site. Completion by 2020



Requested funds
France:
12.4 M€ (NUMerEnv-CNRS/CPER/FEDER, 5 yrs)

The Netherlands: 5+5 M€ (FOM, 5 yrs)
Greece, Germany, Spain, Romania, Poland, UK ... under discussion

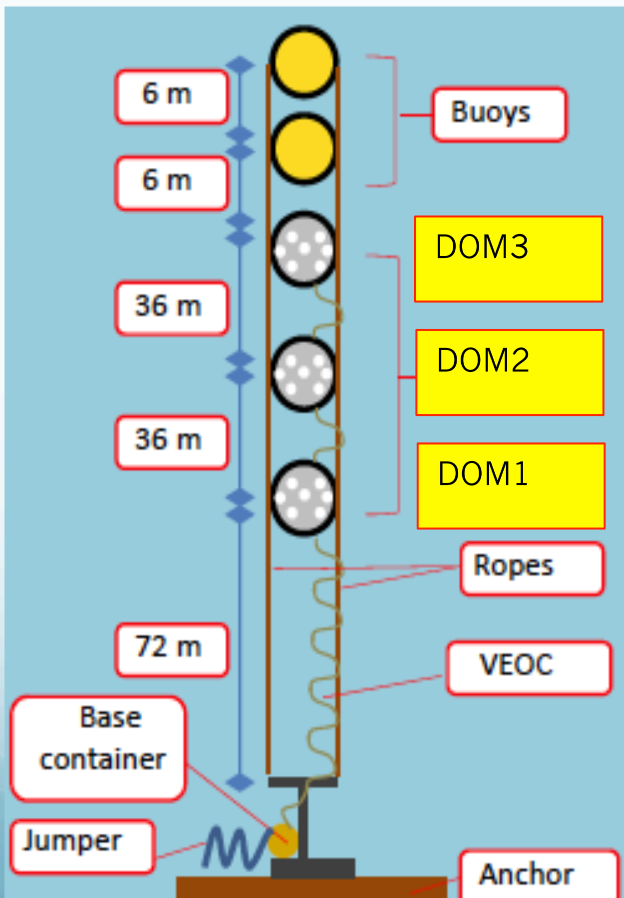
Summary

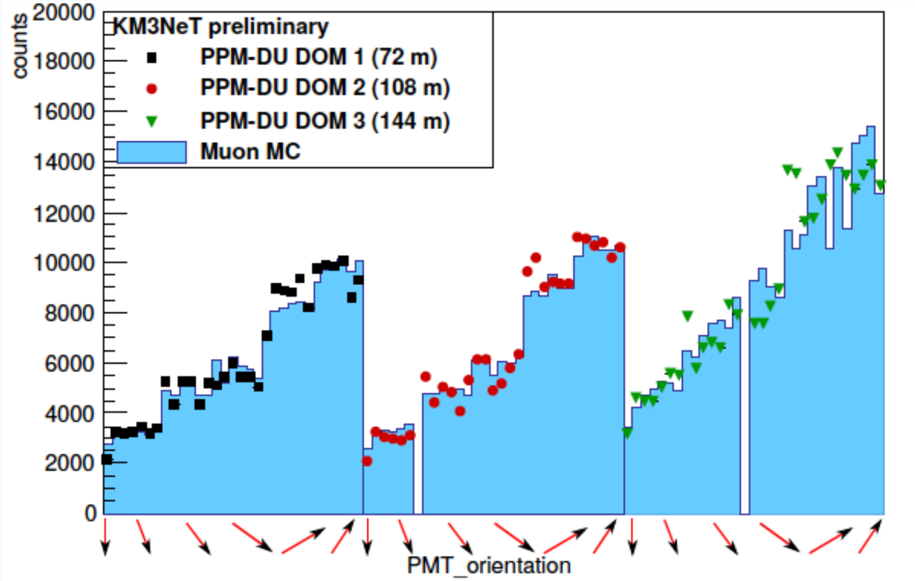
- Atmospheric Neutrinos have still a major role to play for precision measurements and determination of unknown parameters such as the mass hierarchy.
- Low energy (GeV) extensions of Neutrino Telescopes may be faster and cheaper than other alternatives…
- …but challenging, as systematics must be carefully controlled.
- Preliminary ORCA/PINGU sensitivities are quite promising. ORCA will proceed with a demonstrator for first time with ~GeV threshold. Running detectors circa 2020.
- Cooperation between ORCA and PINGU to evaluate systematics and compare sensitivities planned (annual common meetings).

New collaborators are welcome to join the endeavour !

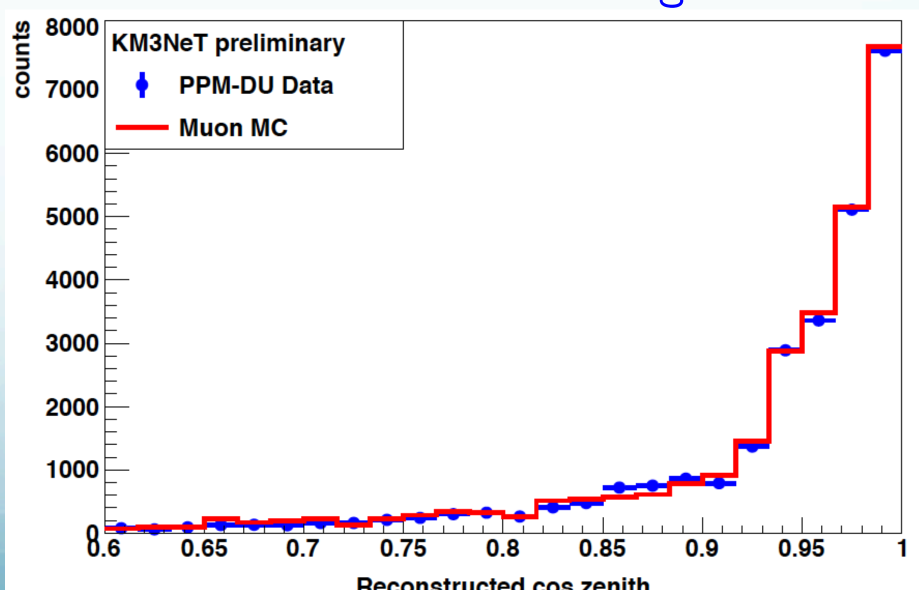
KM3NeT mini-line @ Capo Passero

Smooth operation and data taking since May 2014





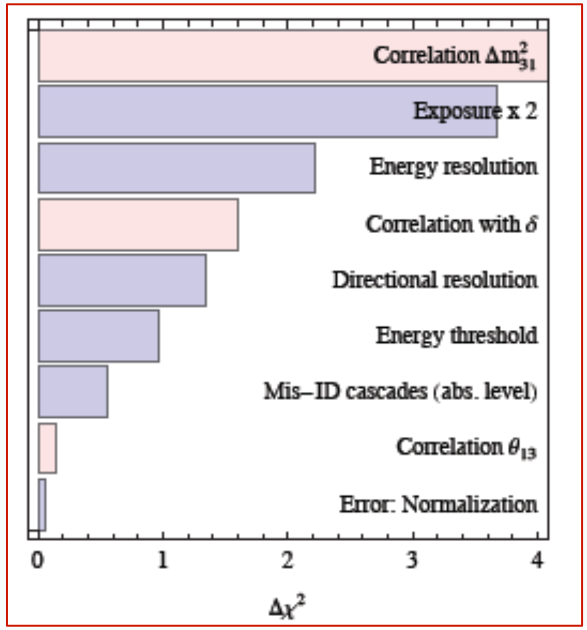
Nice Monte Carlo data agreement



Studies of systematics

W. Winter, PRD 88 (2013) 013013

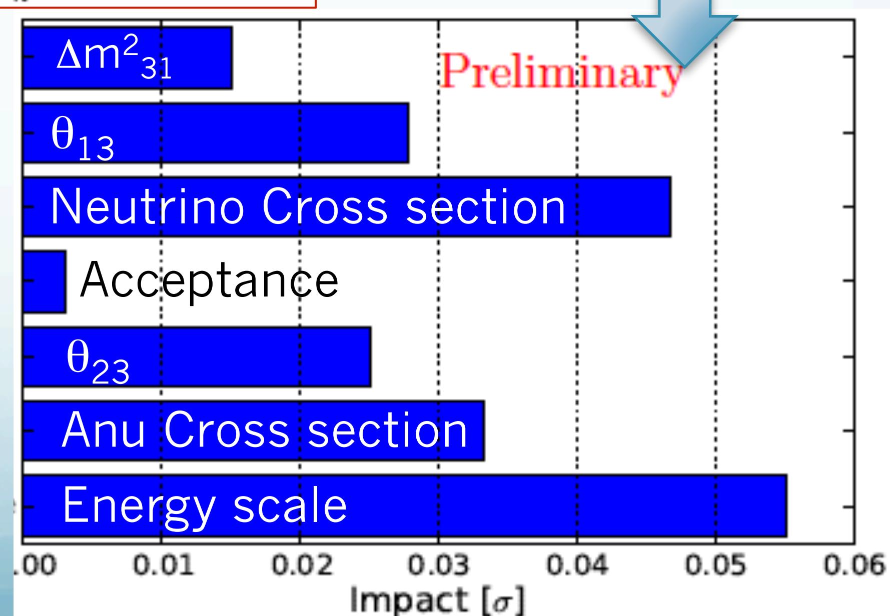
Systematics	Opt.	Def.	Cons.
Experiment properties:			
Fiducial mass and energy threshold	(*)	12/2012	12/2012
Energy res. $\Delta E/E$	0.15	0.25	0.35
Dir. resolution $\Delta\theta_z$	$0.5\sqrt{\frac{m_p}{E}}$	$0.6\sqrt{\frac{m_p}{E}}$	$\sqrt{\frac{m_p}{E}}$
Cascade mis-ID frac.	0.01	0.05	0.1
Systematical uncertainties:			
Normalization	0.10	0.25	0.35
mis-ID cascades	0.05	0.075	0.10
Cross sections (DIS)	0.05	0.075	0.10
Matter density	0.005	0.01	0.05
Uncertainties of atmospheric neutrino flux:			
Normalization	Included in "Normalization"		
Slope error (zenith bias)	0.01	0.04	0.10
Flavor ν_e/ν_μ	0.005	0.01	0.02
Polarity $\bar{\nu}_\mu/\nu_\mu$	0.01	0.02	0.03
Polarity $\bar{\nu}_e/\nu_e$	0.01	0.025	0.03
BG down-going	0.05	0.075	0.10



Need more work

PINGU LoI
arXiv1401.2046

Impact on 1year significance (total 1.75 σ)



Several other studies → same conclusions

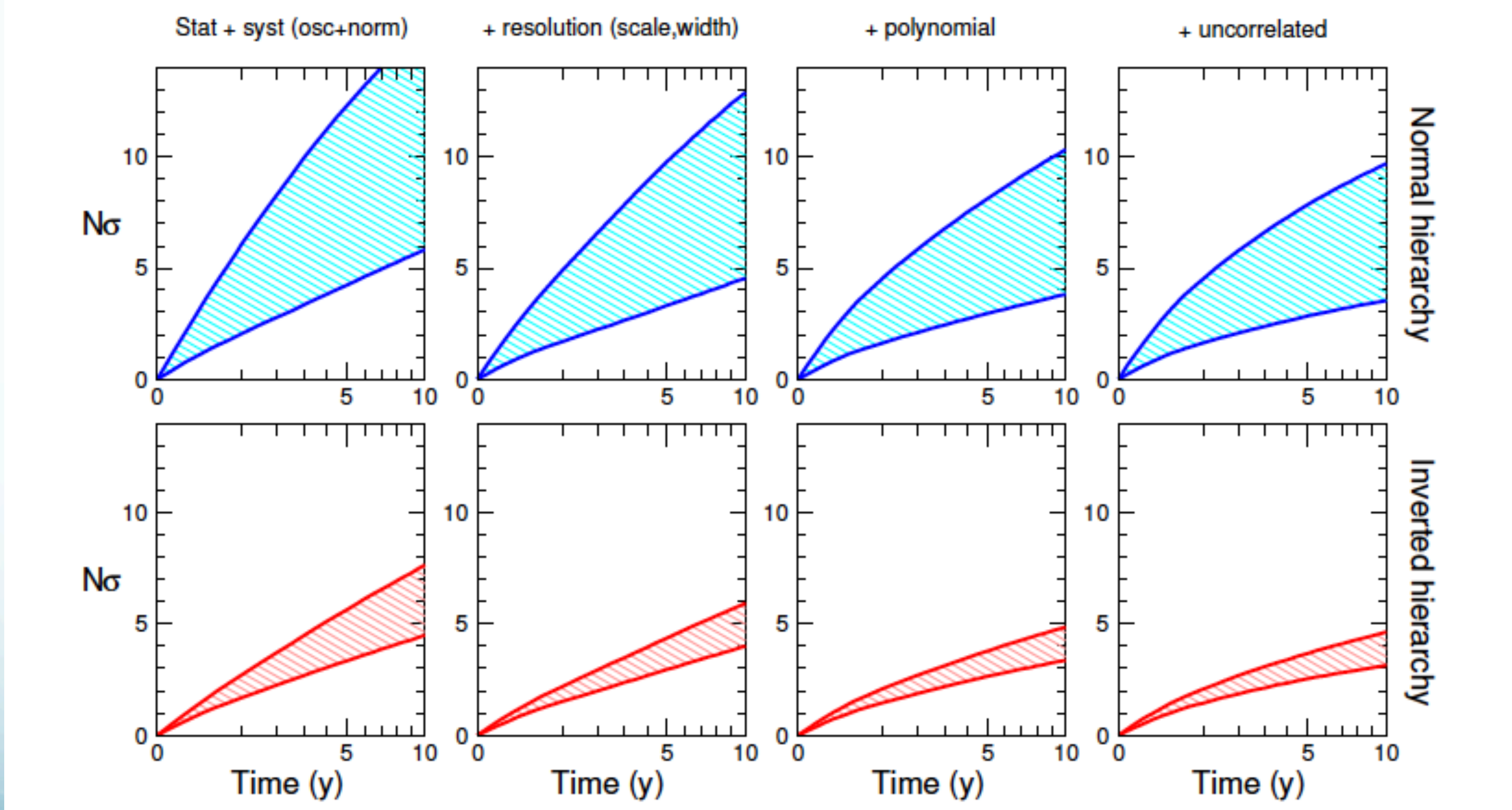
e.g D. Franco et al, JHEP 04 (2013) 008

Studies of systematics

$\sin^2\theta_{23}$ in [0.4; 0.6]

📖 Capozzi et al. arXiv1503.01999
PINGU resolutions and effective masses

(μ and e indep !?) Shape 1.5% Residual 1.5%



Total 5yrs loss in sensitivity from 24% to 40%

Worst case 3σ in 10 years

PINGU envisaged technology

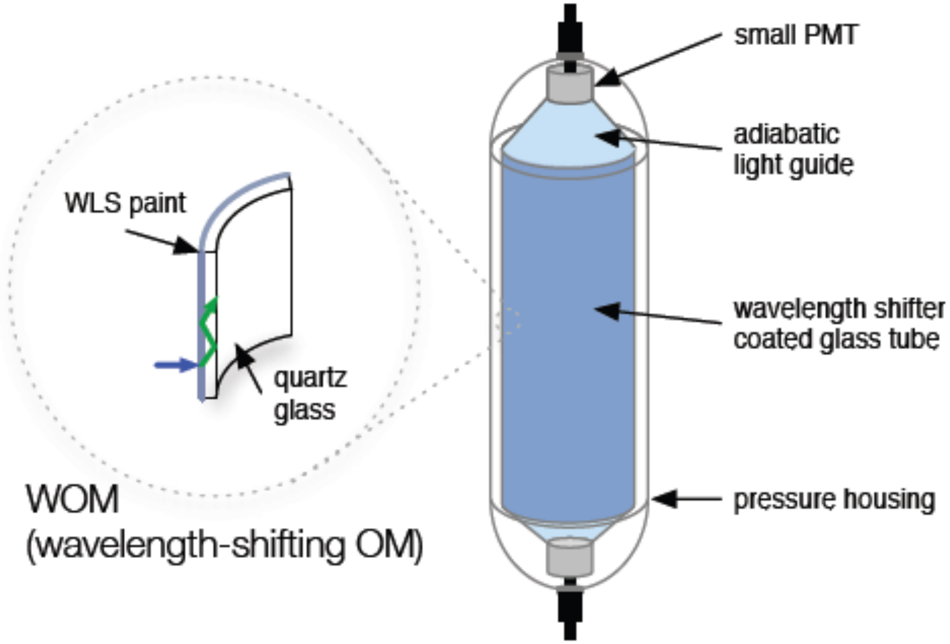
Optical modules

- baseline design
  - electronics upgrade on IceCube DOM

10” R7081-02
High-QE

mDOM
(multi-PMT DOM)

- exploratory designs
  - larger photosensitive area
  - lower noise
  - directional sensitivity



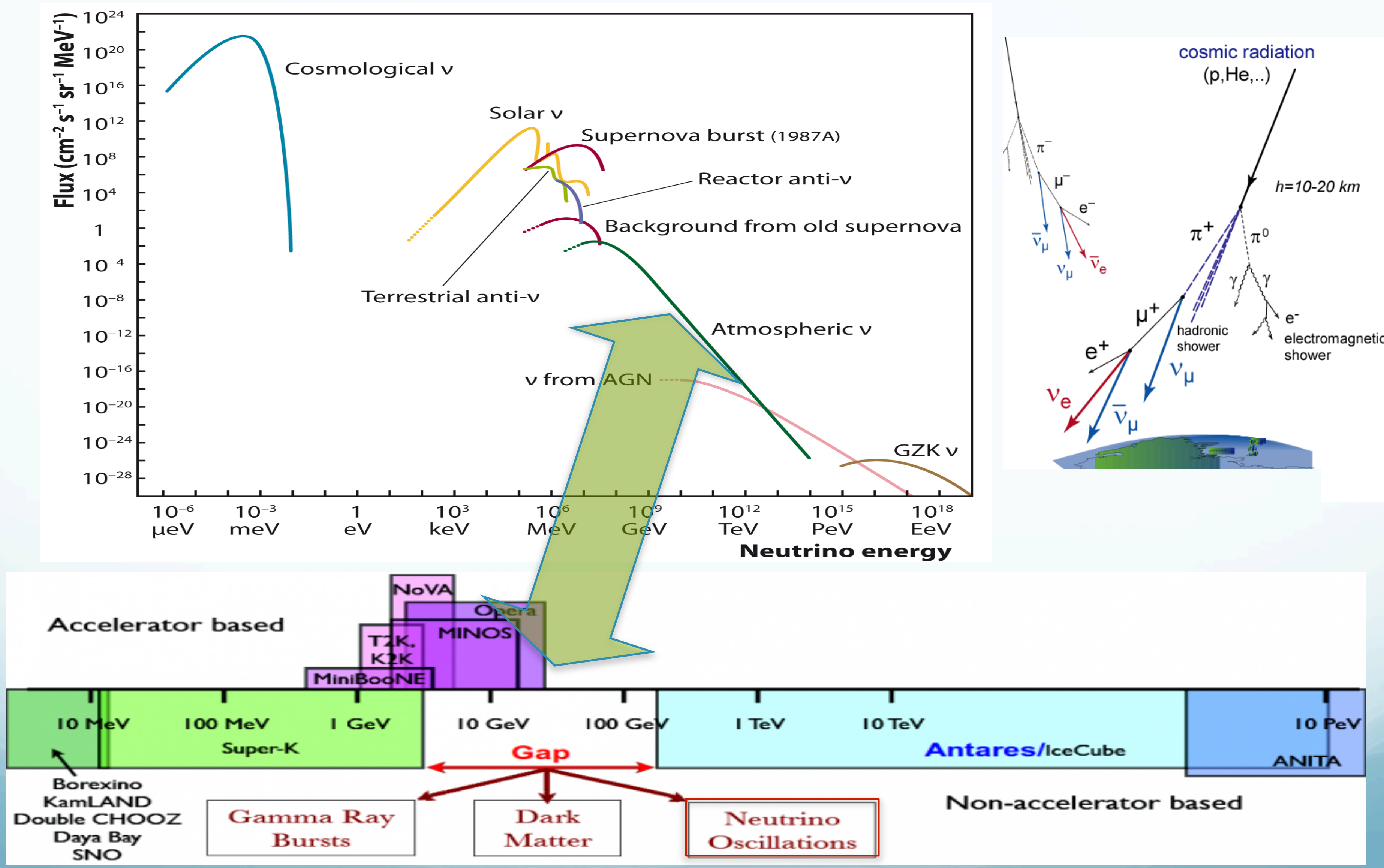
WOM
(wavelength-shifting OM)

Calibration devices

- calibrated light sources
- digital cameras
  - hole ice studies

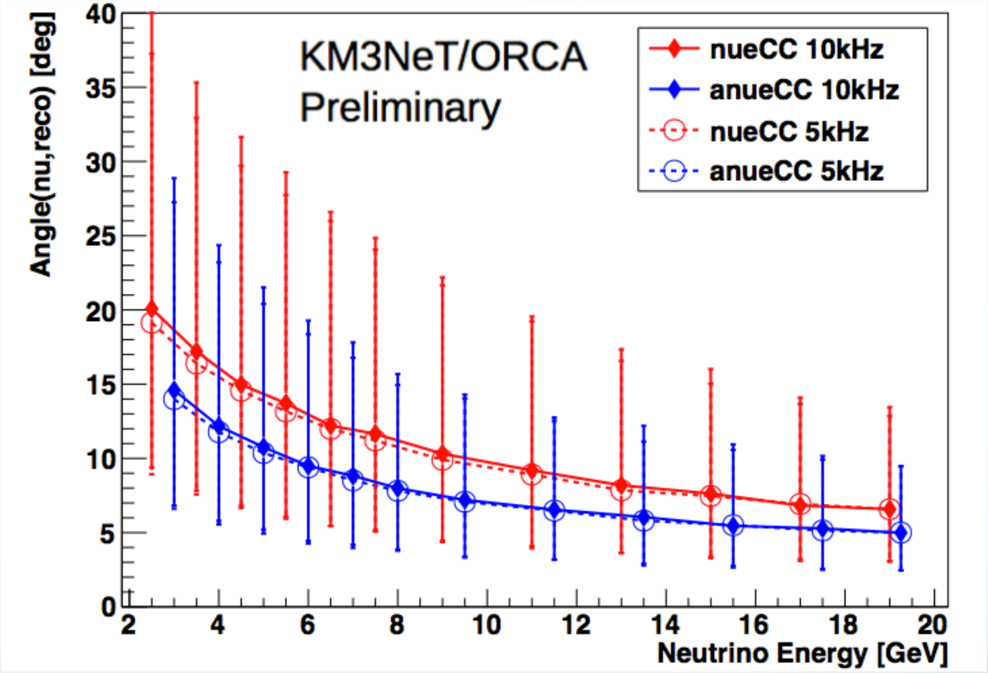
From S. Boser, Neutel, Venice 2015

Neutrinos on Earth



ν_e^{CC} : median directional resolution

- error bars: 15% and 85% quantiles
- neutrinos and anti-neutrinos
- negligible differences between 5 and 10 kHz single PMT optical background rates



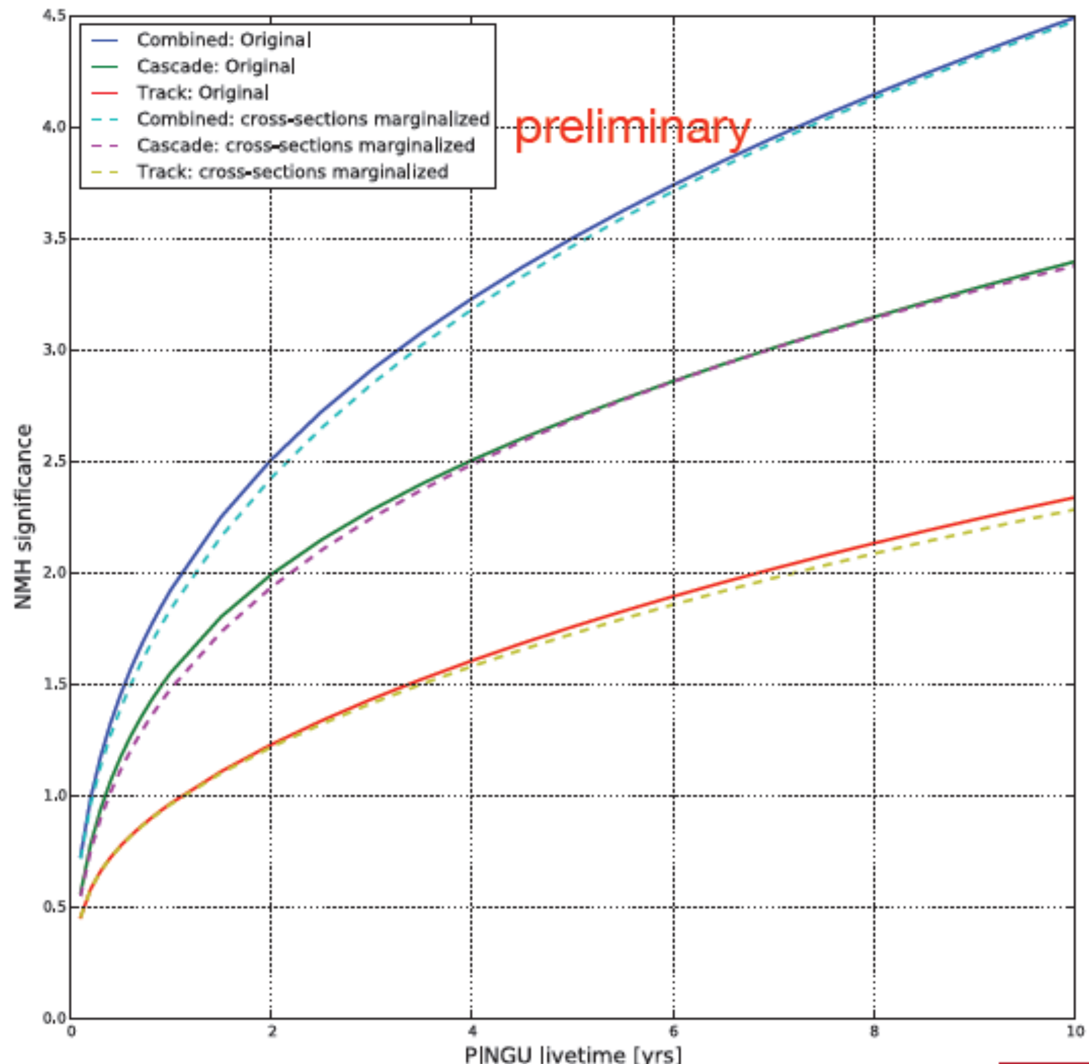
Neutrino Interaction Uncertainties

GENIE parameters

- biggest effects from uncertainty in:
  - Bodek-Yang higher twist parameters
  - axial mass term for hadron resonance production
- ad hoc scalings still included
  - may be over-counting

Result

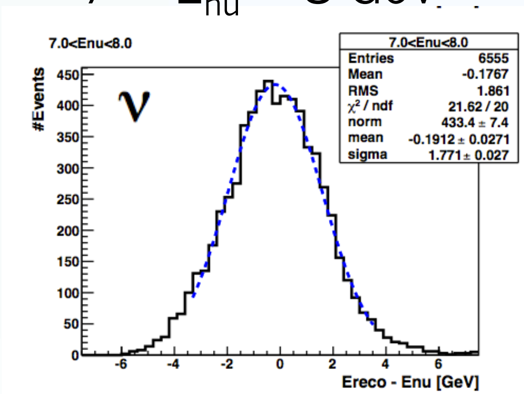
- small additional effect to effective x-section uncertainties



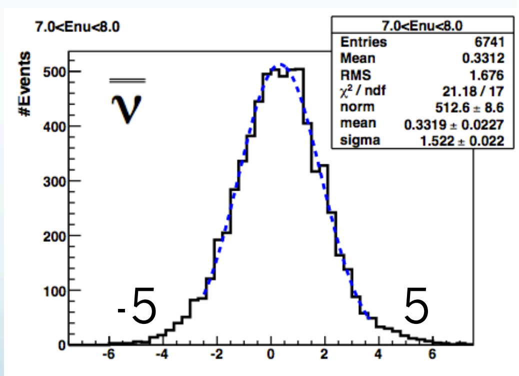
Preliminary performances (ν_e)

7 < E_{nu} < 8 GeV

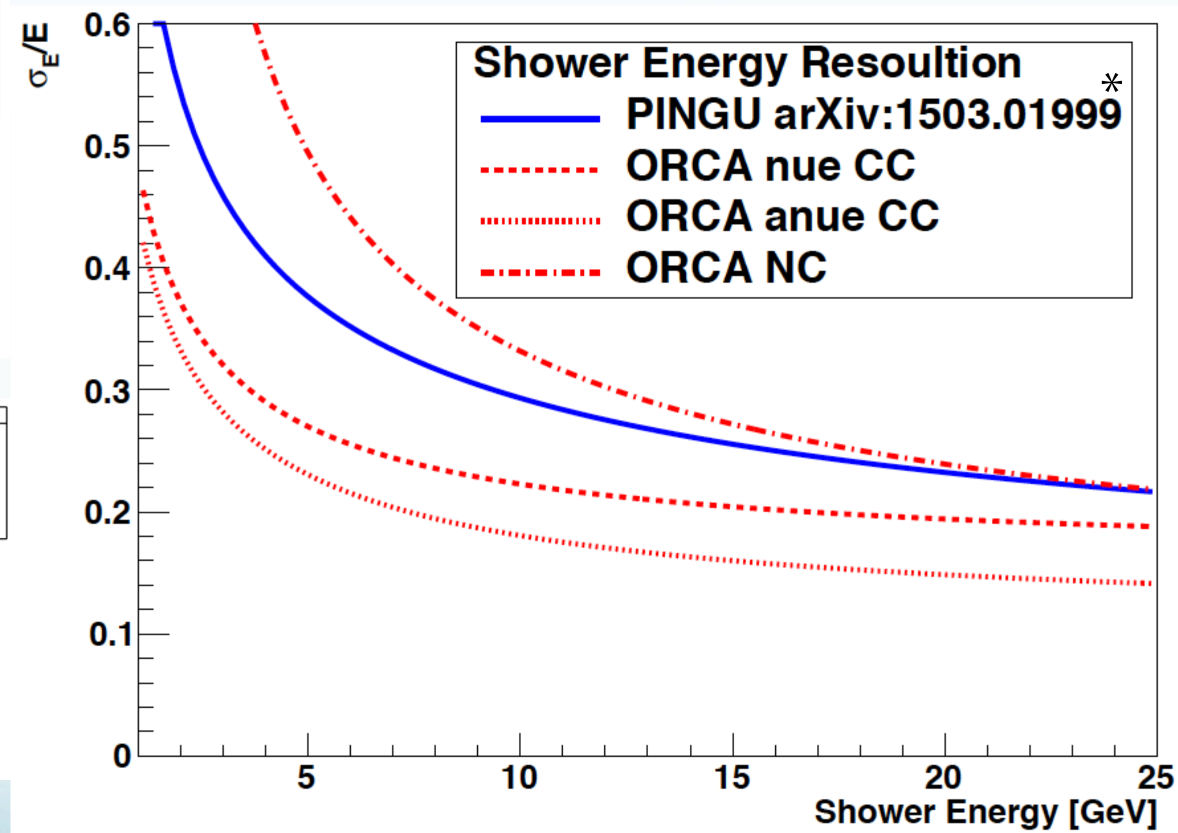
σ/E
~ 24%



σ/E
~ 20%

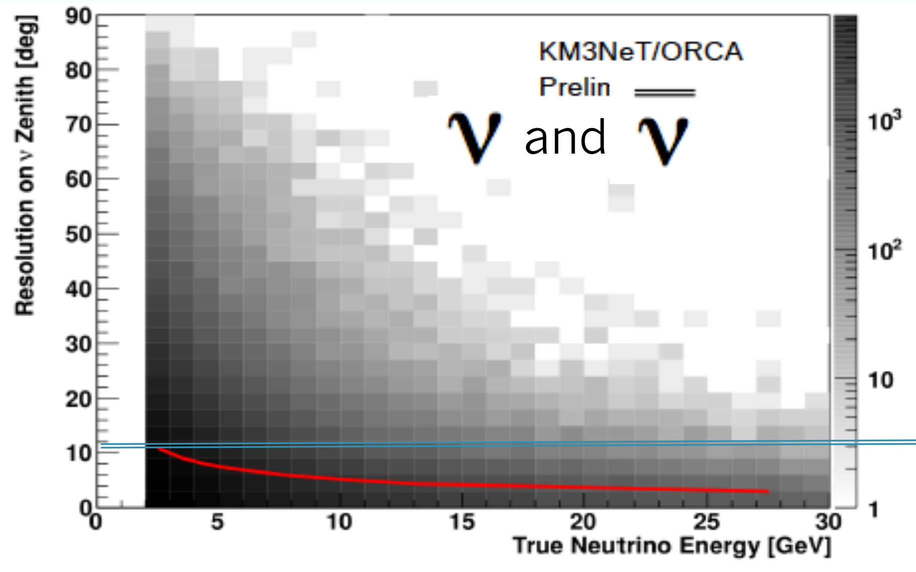


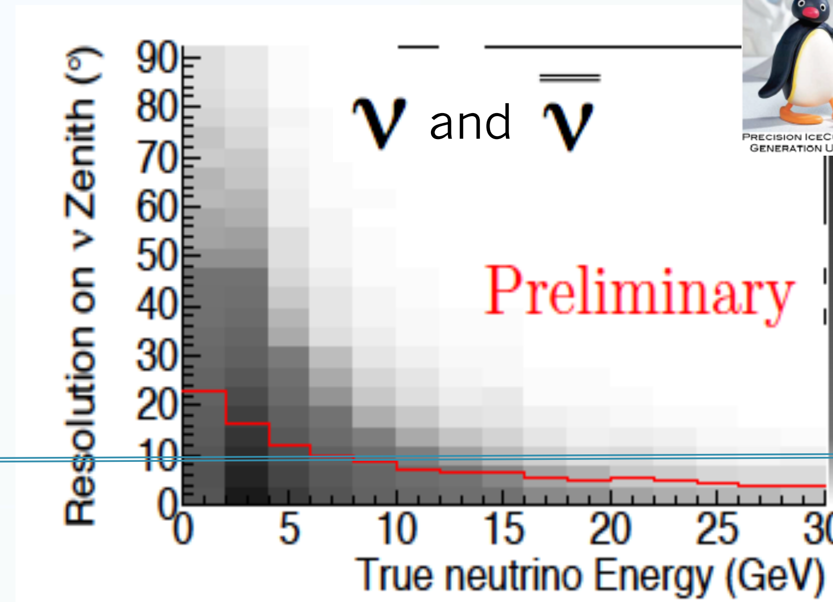
$E_{reco} - E_{nu}$ [GeV]

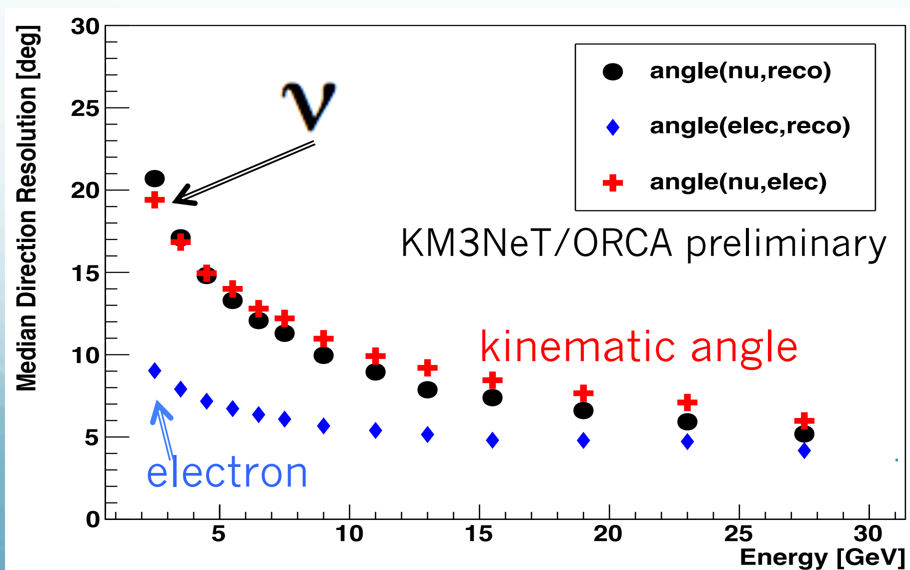


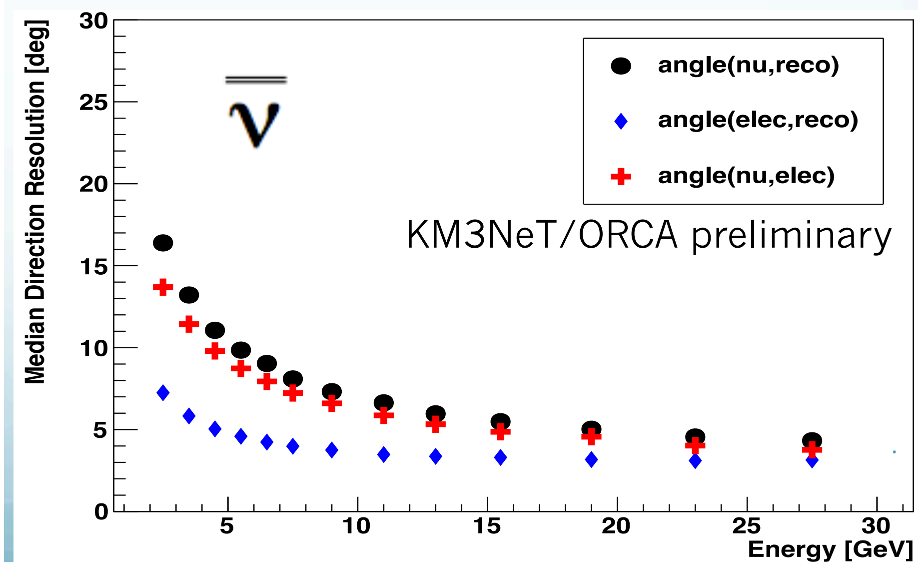
*Possibly underestimated for PINGU

Preliminary performances (ν_e)



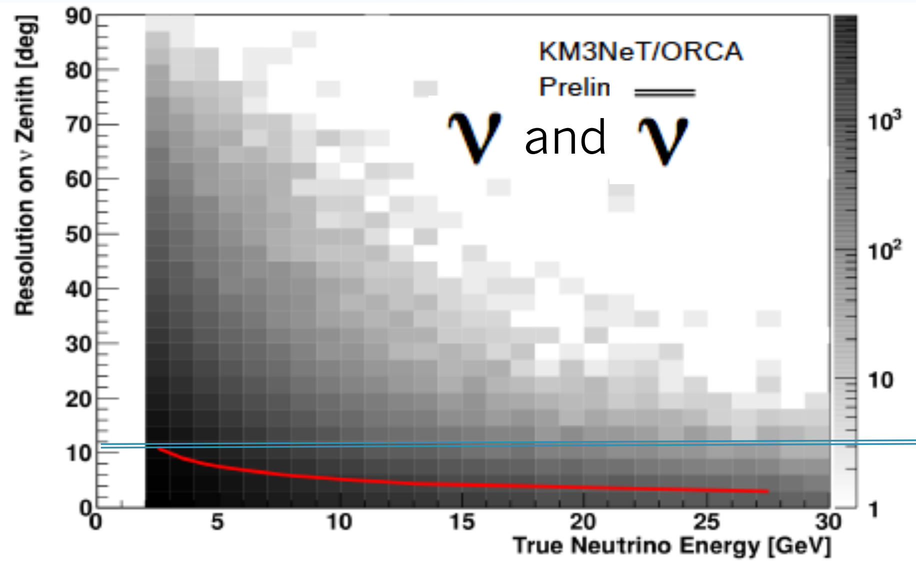


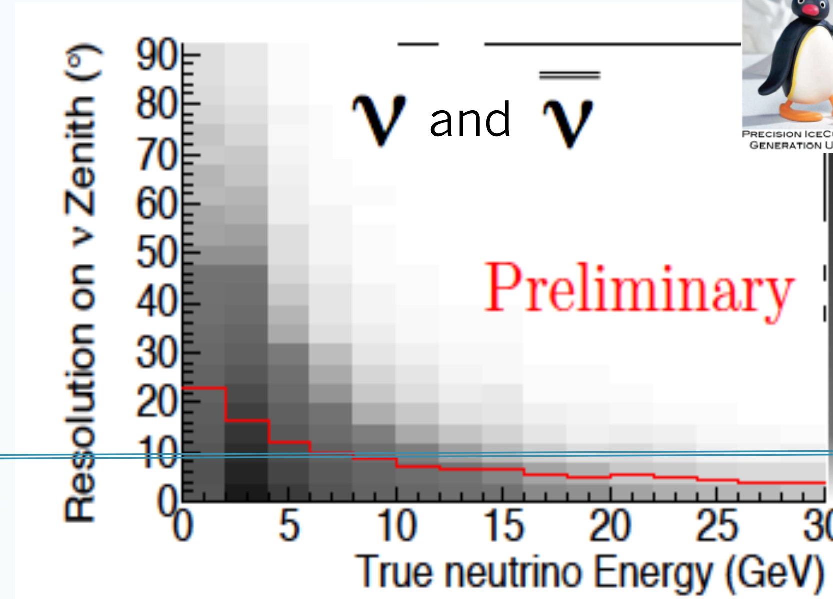


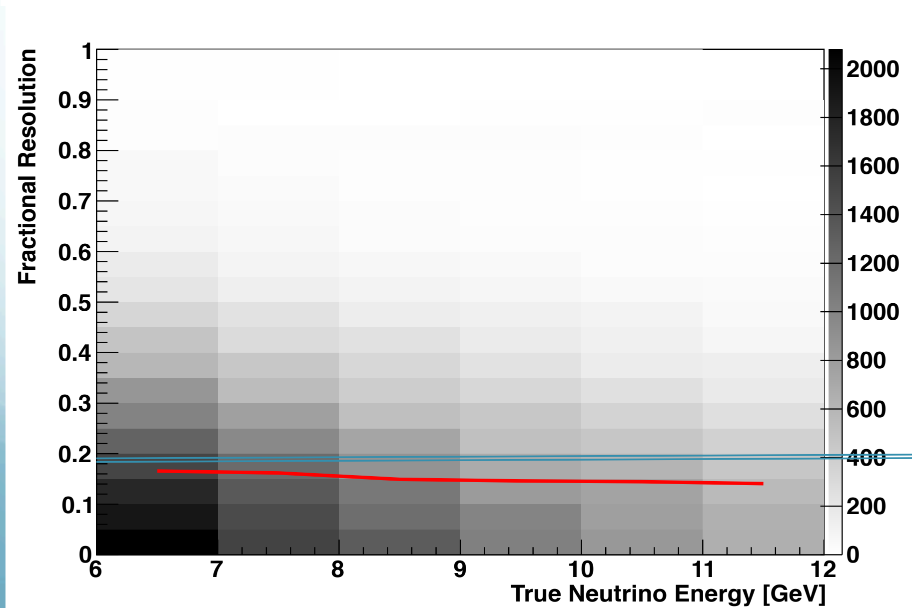


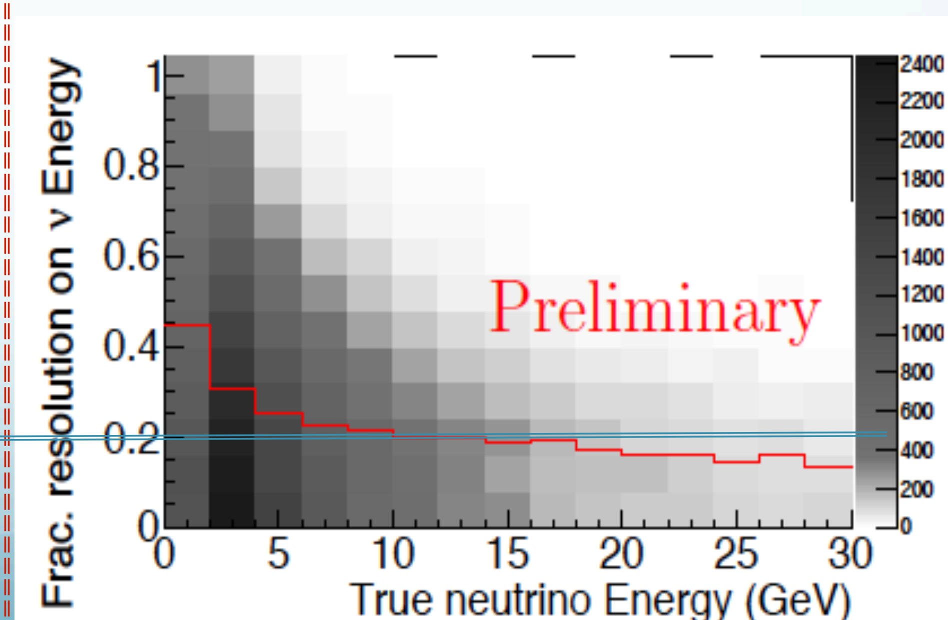
KM3NeT Collaboration

Preliminary performances (ν_e)









PRECISION ICECUBE NEXT GENERATION UPGRADE