University of Manchester, School of Physics and Astronomy
Seminar, 27 February 2013

Neutrino Telescopes and the Neutrino Mass Hierarchy

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The plan for the next 50 minutes:

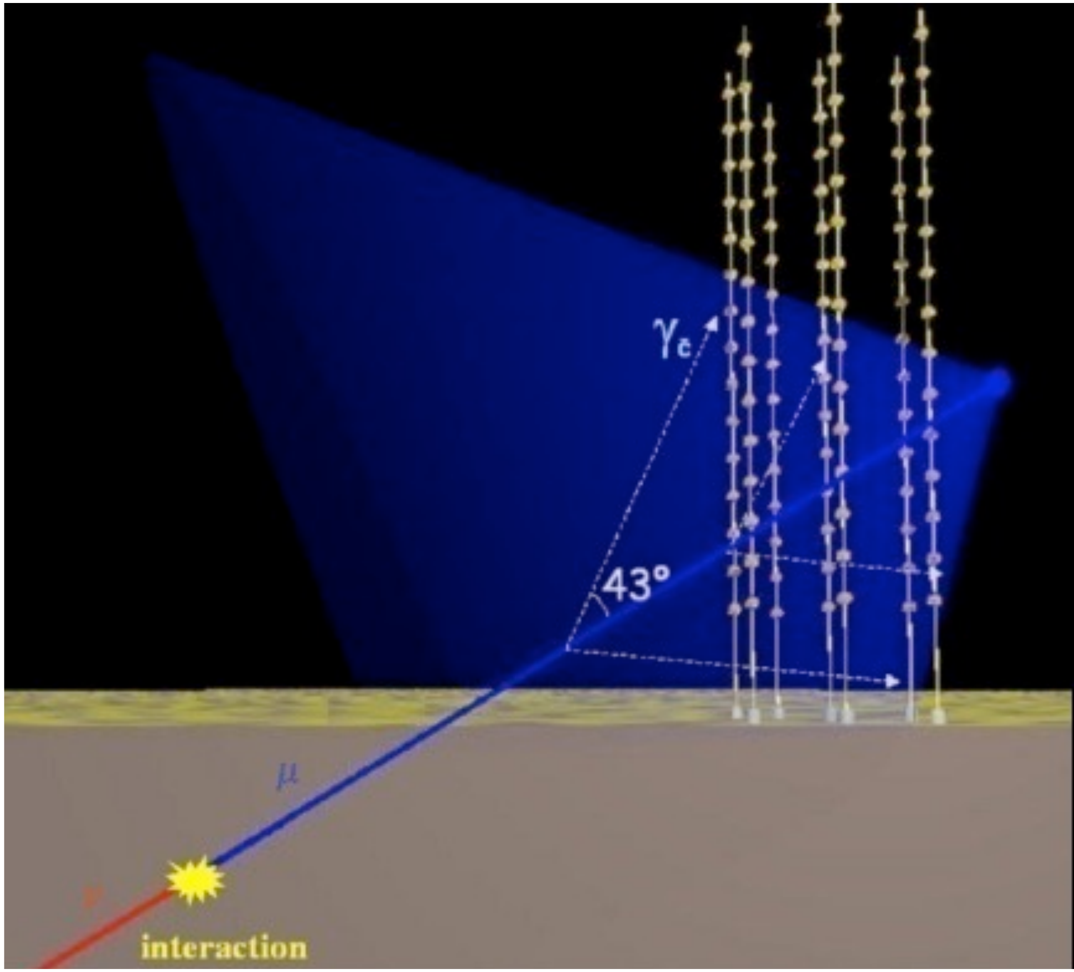
- Introduction
- Present and future neutrino telescopes: ANTARES, IceCube, KM3NeT
- Studying low-energy neutrinos: Towards PINGU and ORCA
- A measurement of the neutrino mass hierarchy?
- Summary

Sincere thanks to all colleagues who allowed me to use their material and apologies to those who find out that I did so without asking

Introduction

How does a neutrino telescope work?

- Neutrino interacts in the (vicinity of) the telescope
- Charged secondaries cross the detector volume (water or ice) and stimulate Cherenkov emission recorded by a 3D-array of photo-sensors
- Most important channel:
  $\nu_\mu + N \rightarrow \mu + X$
- Energy range :
  10(0) GeV – some PeV
- Angular resolution:
  <1°(0.3°) for E>1(10) TeV
- Δ[log(E)] ~ 0.3



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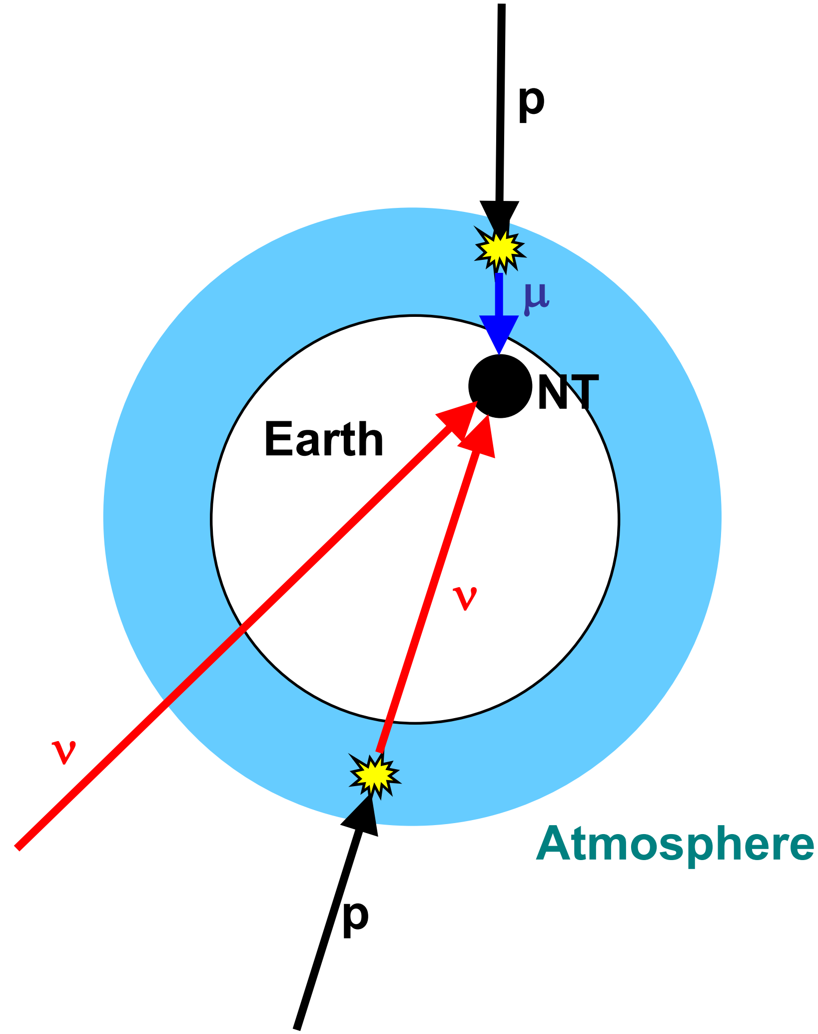
Backgrounds, or maybe not

- Atmospheric neutrinos from cosmic-ray interactions in atmosphere
  - irreducible
  - important calibration source
  - allow for oscillation studies
- Atmospheric muons from cosmic-ray interactions in atmosphere above NT
  - penetrate to NT
  - exceed neutrino event rate by several orders of magnitude
- Random light from K40 decays and bioluminescence



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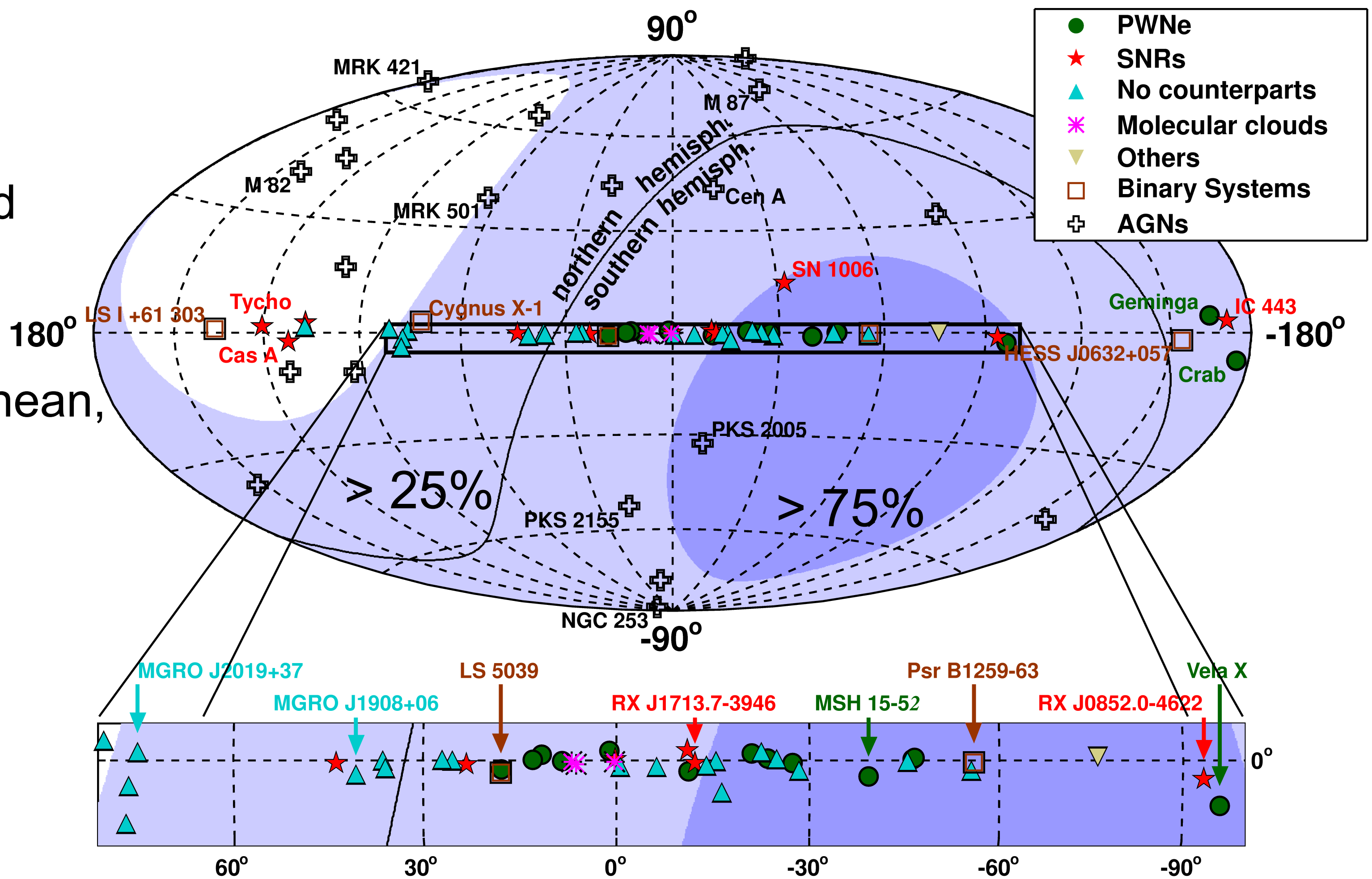
The neutrino telescope world map

South Pole and Mediterranean fields of view

Galactic coordinates

2π downward sensitivity assumed

In Mediterranean, visibility of given source can be limited to less than 24h per day



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Neutrino oscillations and mass hierarchy (1)

- Neutrino flavour and mass eigenstates are not the same:

$$[\text{mass}] \rightarrow \qquad |\nu_i\rangle = \sum_{\alpha=1}^{3} U_{i\alpha}|\nu_\alpha\rangle \qquad \leftarrow [\text{flavour}]$$

- Consequence: Neutrino oscillations
Unrealistic but didactically useful case: 2 flavours, vacuum

$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2\left(1.267\frac{\Delta m^2/\text{eV}^2 \cdot L/\text{km}}{E_\nu/\text{GeV}}\right)$$

- No information on sign of Δm^2
- In the above units:

$L/E \ll 1/\Delta m^2 \quad \rightarrow$ no effect
$L/E \sim 1/\Delta m^2 \quad \rightarrow$ observe oscillations
$L/E \gg 1/\Delta m^2 \quad \rightarrow$ observe averaged oscillations

Neutrino oscillations and mass hierarchy (2)

- Neutrino propagation in matter different for ν_e and $\nu_{\mu,\tau}$:
  $\nu_e e^- \to \nu_e e^-$ and $\overline{\nu}_e e^- \to \overline{\nu}_e e^-$ W and Z exchange
  $\nu_{\mu,\tau} e^- \to \nu_{\mu,\tau} e^-$ and $\overline{\nu}_{\mu,\tau} e^- \to \overline{\nu}_{\mu,\tau} e^-$ Z exchange only
  Result: Modification of oscillation pattern
- Dominant cause of solar neutrino oscillations (MSW effect)
- For atmospheric ν_μ and $\overline{\nu}_\mu$:
  Matter effect depends on sign of Δm^2_{13}
  Same effect for $\Delta m^2_{13} > 0, \nu_\mu$ and $\Delta m^2_{13} < 0, \overline{\nu}_\mu$
- Atmospheric neutrinos offer just the right $L \lesssim 2R_E$ and $E = \mathcal{O}(\text{a few GeV})$ to measure the effect.
- In neutrino telescope: ν_μ and $\overline{\nu}_\mu$ cannot be distinguished, but net effect since $\sigma(\nu_\mu N) \approx 2\sigma(\overline{\nu}_\mu N)$

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Present and future neutrino telescopes: IceCube, ANTARES, KM3NeT

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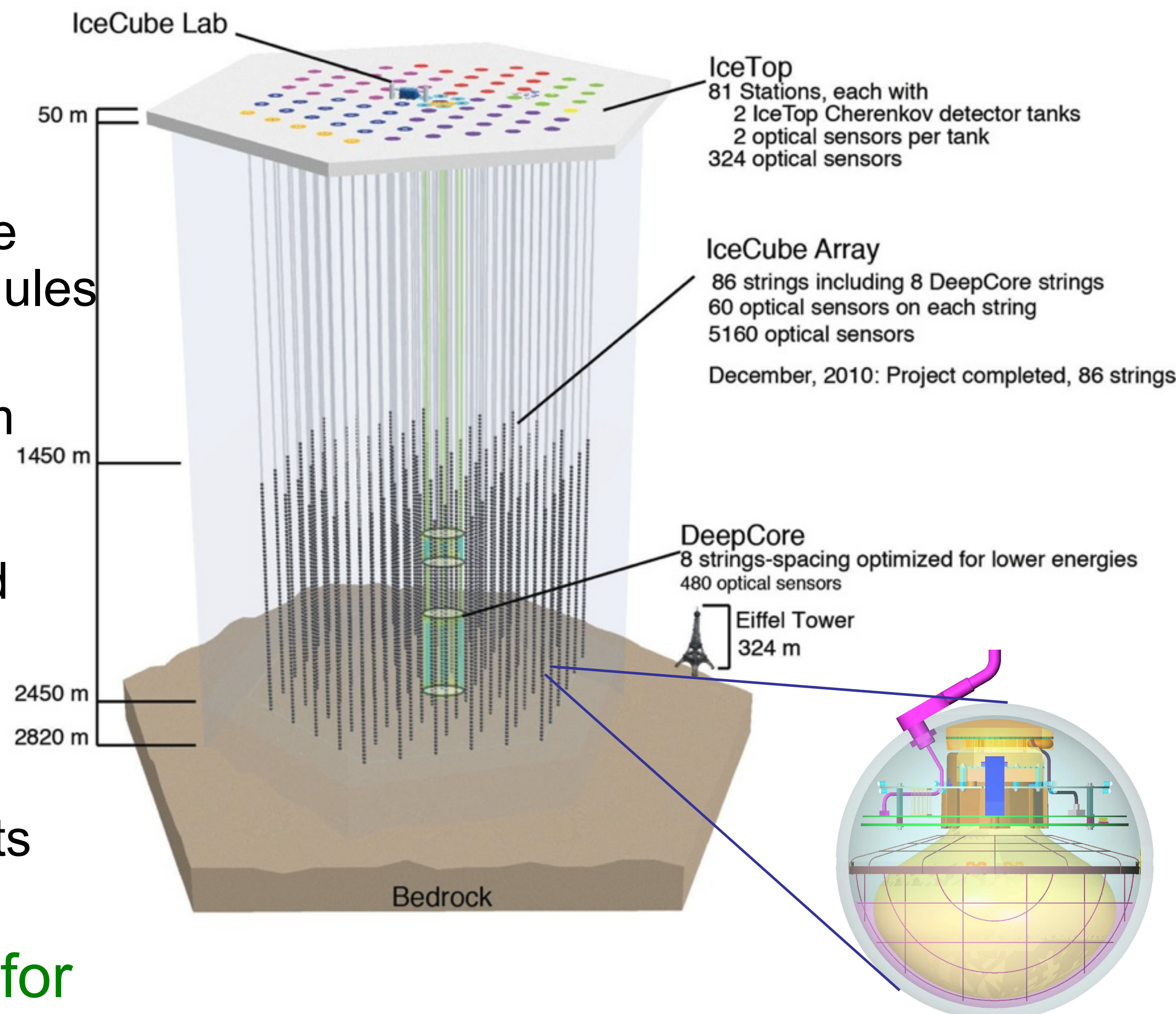
IceCube: a km^3 detector in the Antarctic ice

IceCube as of February 2013

- 86 strings altogether
  - 125 m horizontal spacing
  - 17 m vertical distance between Optical Modules
  - 1 km^3 instrumented volume, depth 2450m
- Deep Core
  - densely instrumented region in clearest ice
  - atmospheric muon veto by IceCube
  - first Deep Core results emerging
- PINGU/MICA: Plans for future low-energy extensions



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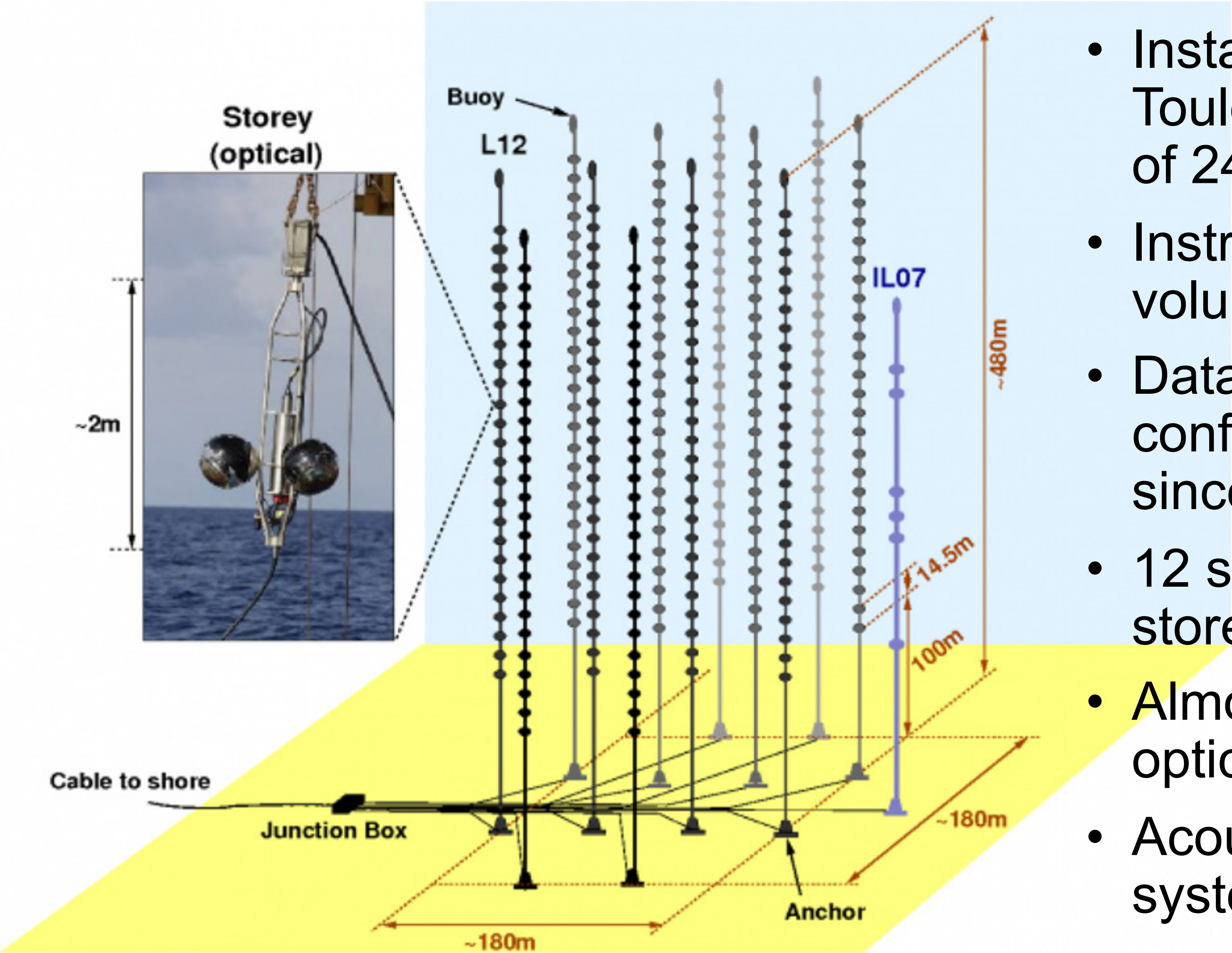
ANTARES: The first NT in the deep sea



- Installed near Toulon at a depth of 2475m
- Instrumented volume ~0.01km^3
- Data taking in full configuration since 2008
- 12 strings with 25 storey each
- Almost 900 optical modules
- Acoustic sensor system

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ANTARES achievements

- Proof of feasibility and long-term operation of a deep-sea neutrino telescope
- Position and orientation calibration of optical modules with required accuracy
    - acoustic positioning by triangulation
    - compasses and tilt-meters
- Time synchronisation at nanosecond level
- Use of optical technologies for readout
- All data to shore: Every PMT hit above threshold (typically 0.3 pe) is digitised and transmitted to shore
- Trigger/filter logic by computer farm on-shore

The KM3NeT project (1)

- Multi-km^3 NT in Mediterranean Sea, exceeding IceCube substantially in sensitivity
- Nodes for earth/sea science instrumentation
- EU-funded Design Study / Prep. Phase (2006-12)
- Central physics goals (by priority):
  - Galactic neutrino “point sources” (energy 1-100 TeV)
  - Extragalactic sources
  - High-energy diffuse neutrino flux
- Next steps
  - ~40 M€ available for first construction phase
  - final prototyping 2012/13
  - start of construction 2014

The KM3NeT project (2)

- Decisions taken:
  - Technology: Strings with multi-PMT optical modules
  - 5 building blocks of ~120 strings each
    (no sensitivity loss for Galactic sources, advantageous for earth & sea sciences)
  - Multi-site installation (France, Greece, Italy)
- Collaboration established
- … and the neutrino mass hierarchy?
  - Feasibility study ongoing:
    Oscillation Research with Cosmics in the Abyss (ORCA)
  - Idea: Densely instrumented detector using KM3NeT technology and funds.

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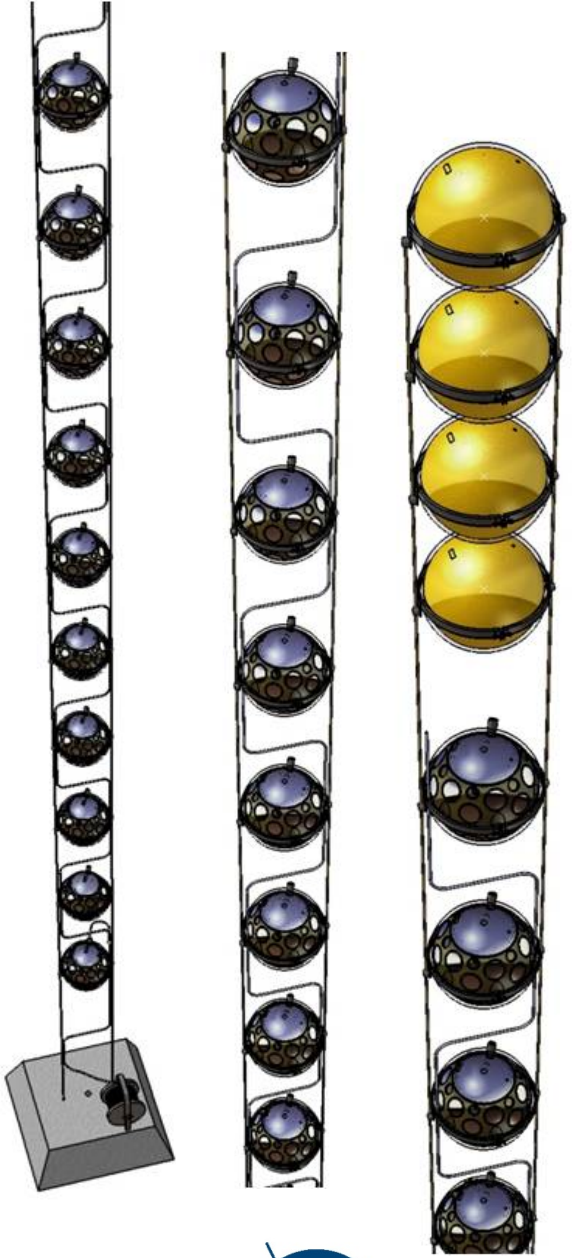
Detection units: Strings

- Mooring line:
  - Buoy (empty glass spheres, net buoyancy 2250N)
  - 2 Dyneema ropes (4 mm diameter)
  - 18 storeys (one OM each), 30-36m distance, 100m anchor-first storey
- Electro-optical backbone:
  - Flexible hose ~ 6mm diameter
  - Oil-filled
  - fibres and copper wires
  - At each storey: 1 fibre+2 wires
  - Break out box with fuses at each storey: One single pressure transition



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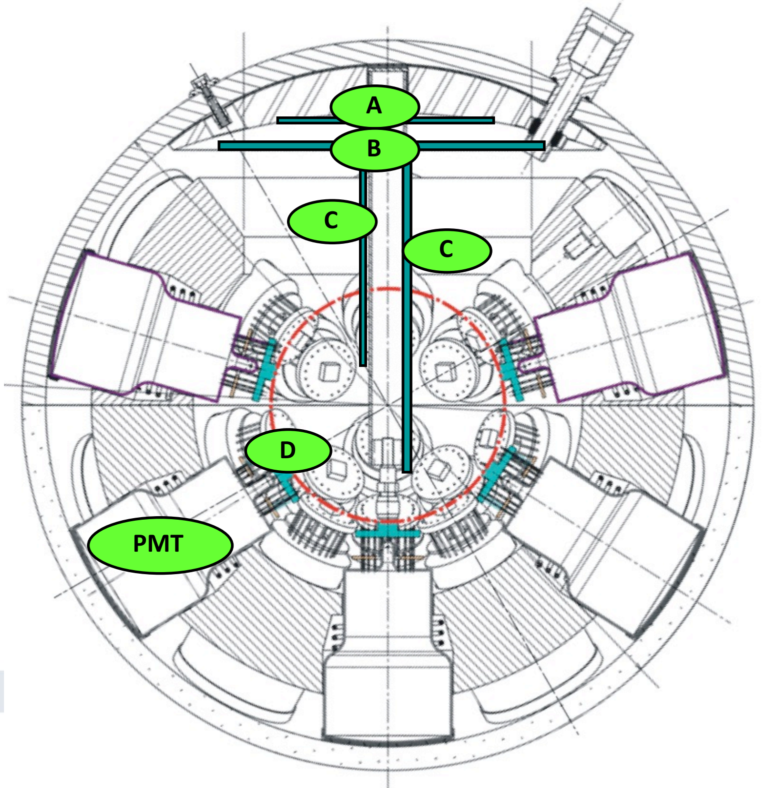
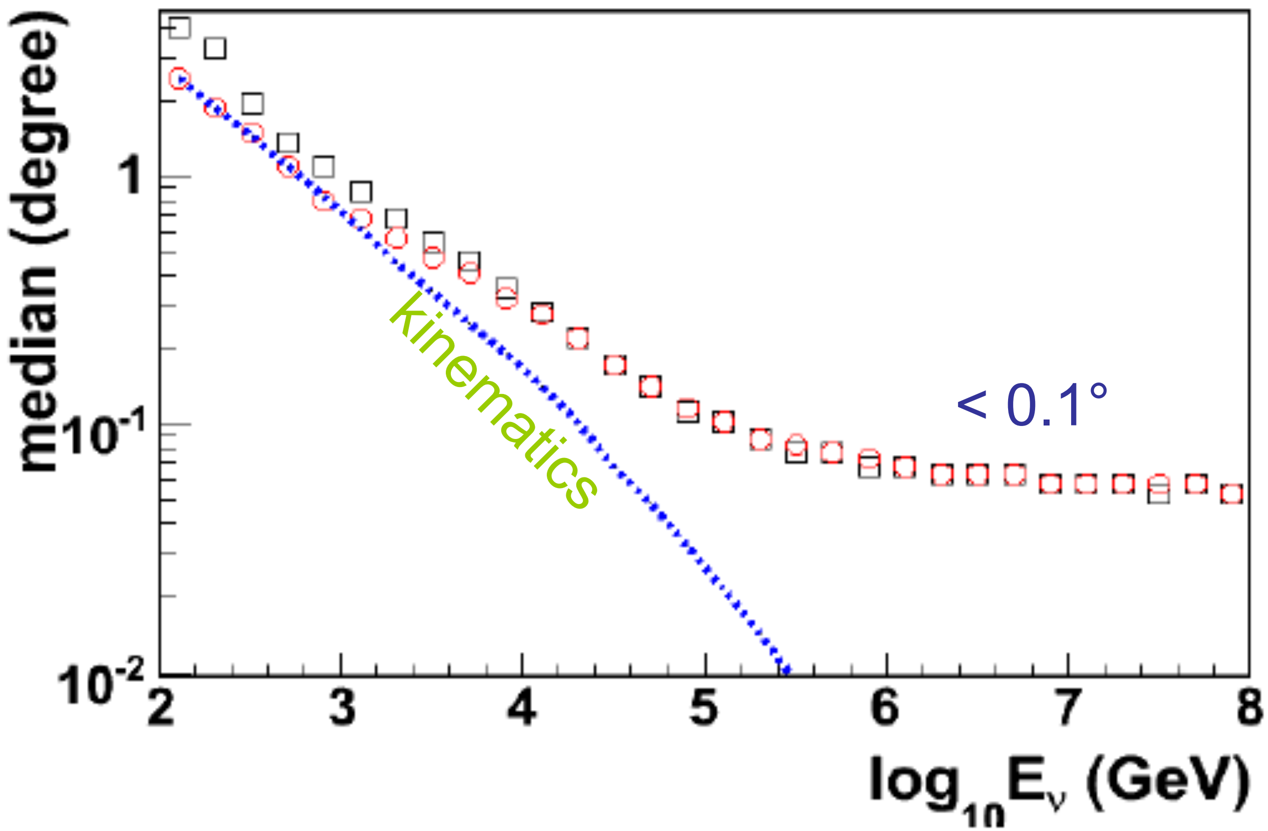
OM with many small PMTs

- 31 3-inch PMTs in 17-inch glass sphere (cathode area~ 3x10" PMTs)
  - 19 in lower, 12 in upper hemisphere
  - Suspended by compressible foam core
- 31 PMT bases (total ~140 mW) (**D**)
- Front-end electronics (**B,C**)
- Al cooling shield and stem (**A**)
- Single penetrator
- 2mm optical gel
- Advantages:
  - increased photocathode area
  - improved 1-vs-2 photo-electron separation → better sensitivity to coincidences
  - directionality



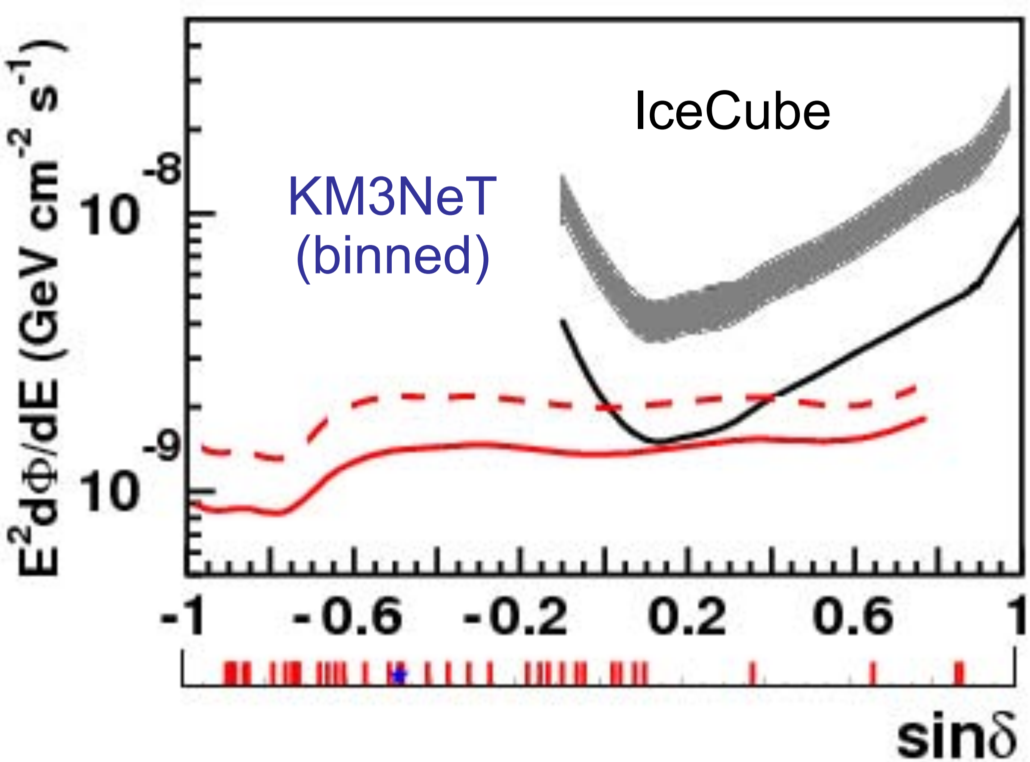
Angular resolution

- Investigate distribution of angle between incoming neutrino and reconstructed muon
- Dominated by kinematics up to ~1TeV



Point source sensitivity (1 year)

Expected exclusion limits / 5σ detection
(for E^{-2} source spectra, from Technical Design Report)



R. Abbasi et al. Astro-ph (2009) scaled – unbinned method

Discovery at 5σ with 50%

☐ Observed Galactic TeV-γ sources (SNR, unidentified, microquasars)
F. Aharonian et al. Rep. Prog. Phys. (2008)
Abdo et al., MILAGRO, Astrophys. J. 658 L33-L36 (2007)

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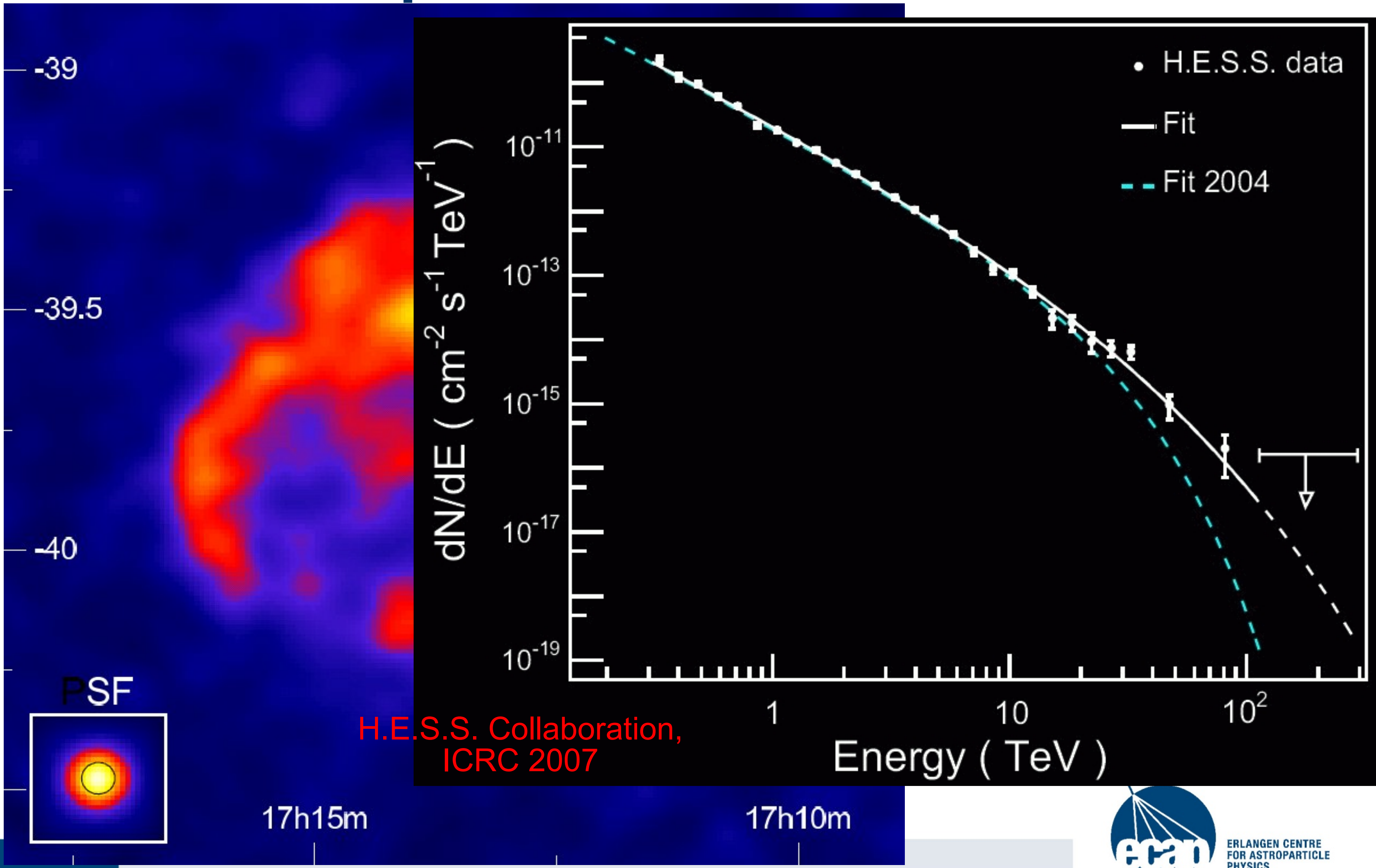
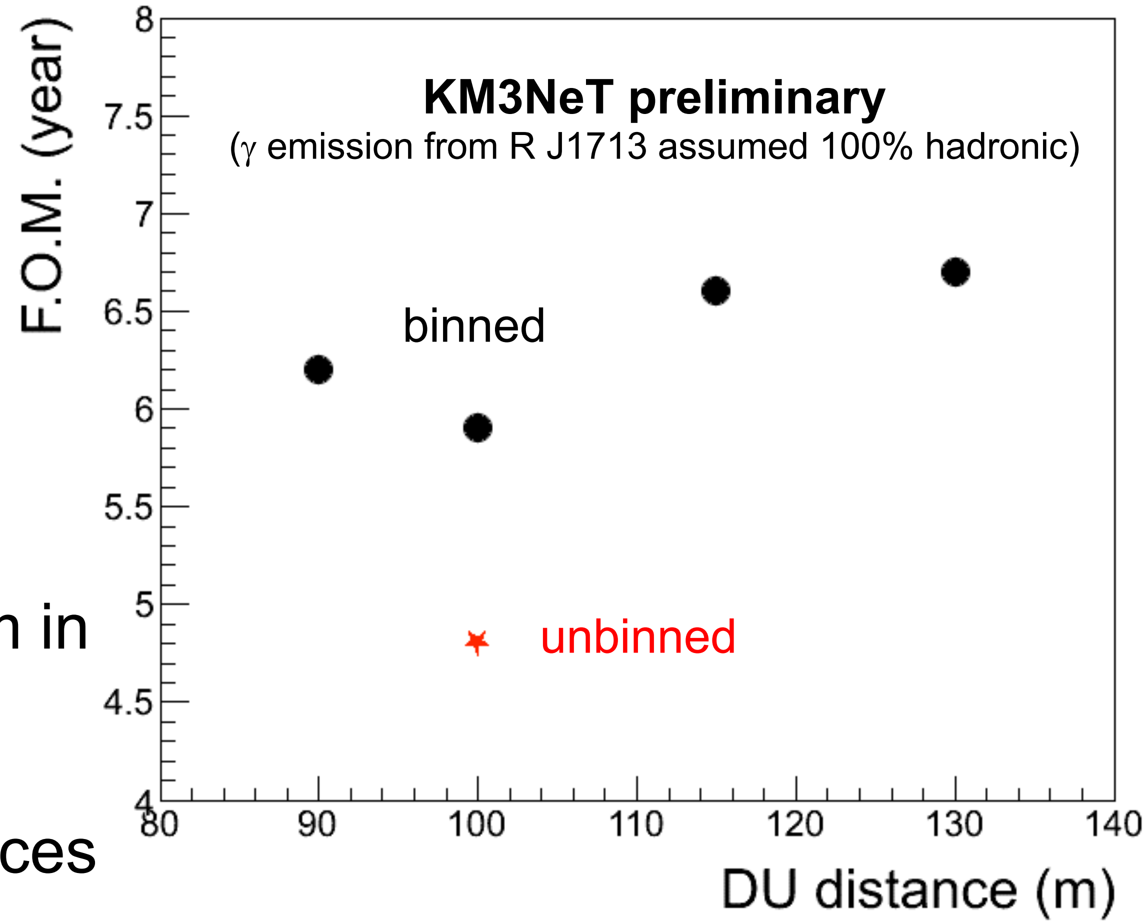
RX J1713: A prime candidate source



H.E.S.S. Collaboration, ICRC 2007

RX J1713: A prime candidate source

- Figure of merit (FOM): time to make an observation at 5σ with 50% probability
- KM3NeT analysis very conservative; ~20% improvement by unbinned analysis
- Clear (but flat) optimum in horizontal distance between DUs
- Further candidate sources with similar or better discovery chances



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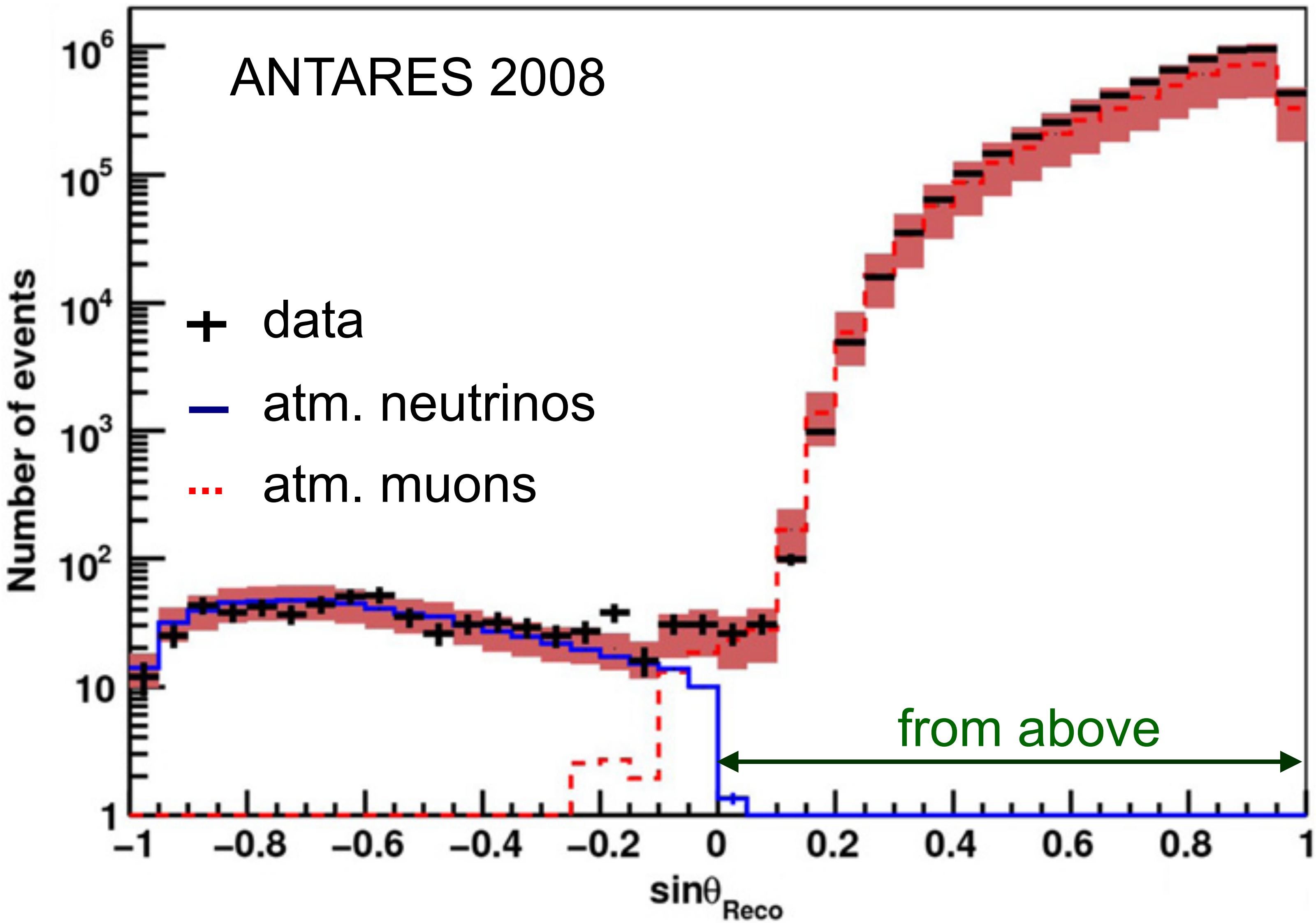
From TeV to GeV: Can neutrino telescopes measure low-energy neutrinos?

Understanding detector and signals



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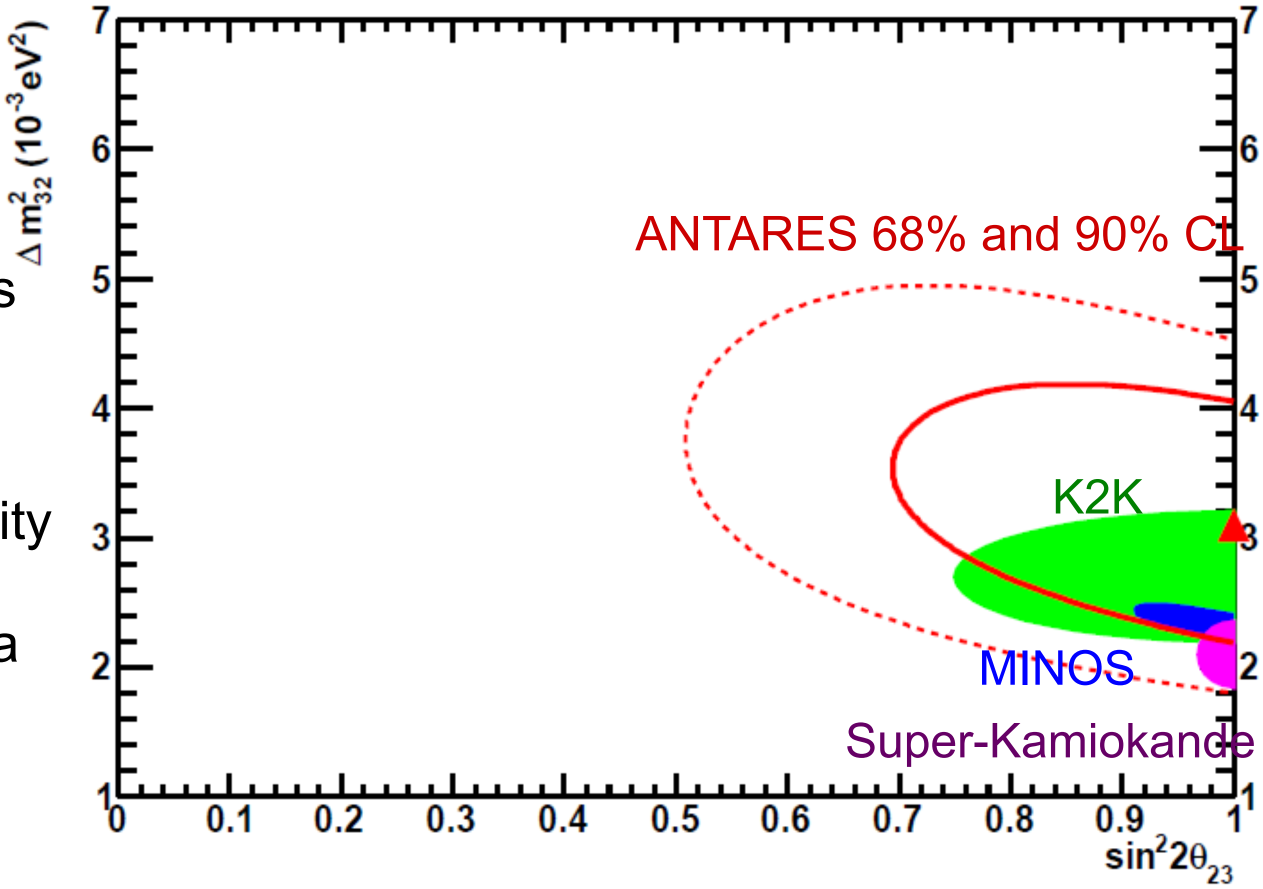
ANTARES: Oscillations at 20 GeV

- Measure distribution of reconstructed $E/\cos\theta \propto E/L$
- Expected oscillation signal at lowest values
- Significant signal observed
- Demonstrates capability to reconstruct events down to 20 GeV with a detector optimised for the TeV range
- Results agree nicely with other experiments



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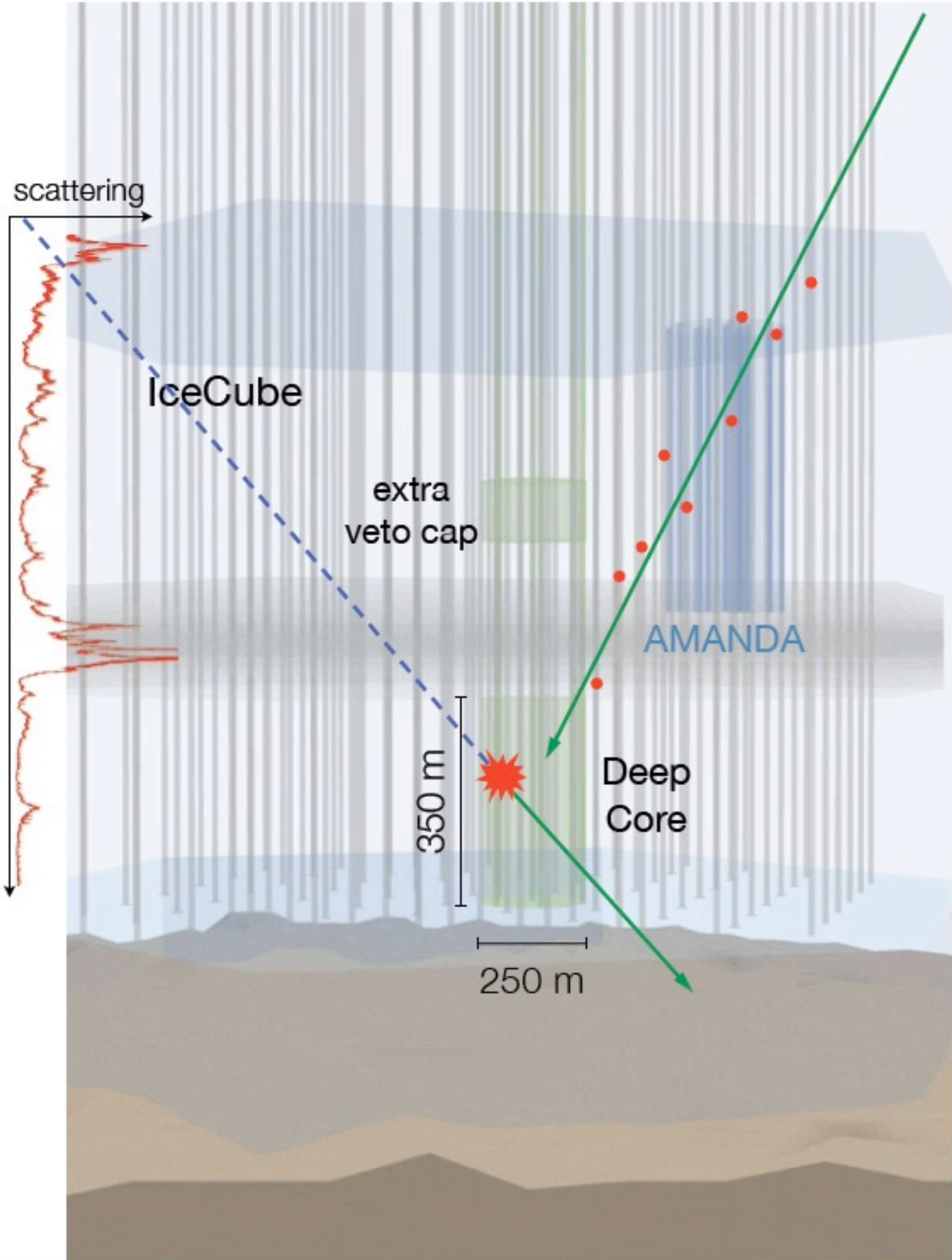
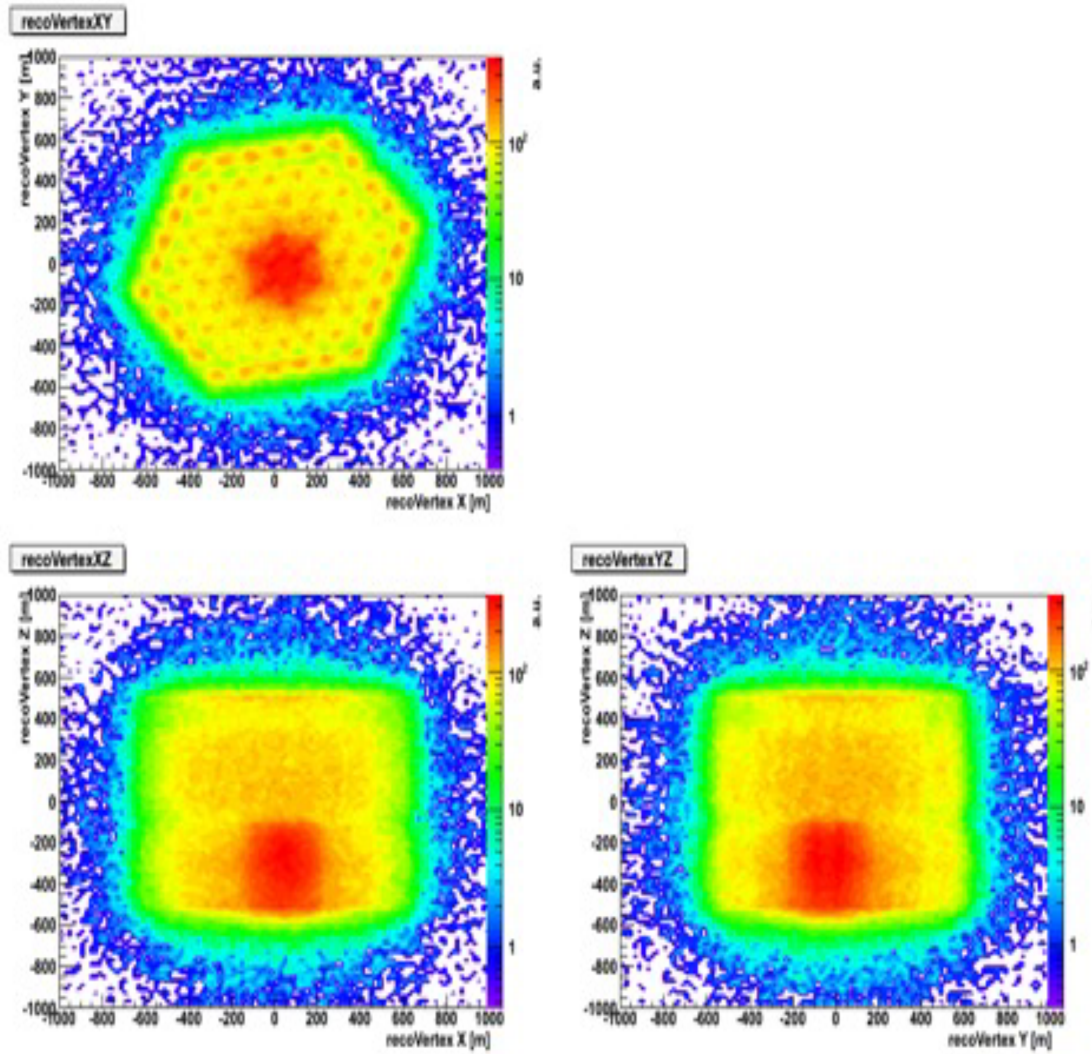
Deep Core

- 8 extra strings + 12 standard strings in clearest ice (~5 times higher photocathode density)
- Photomultipliers with high quantum efficiency
- Rest of IceCube provides active veto against penetrating muons

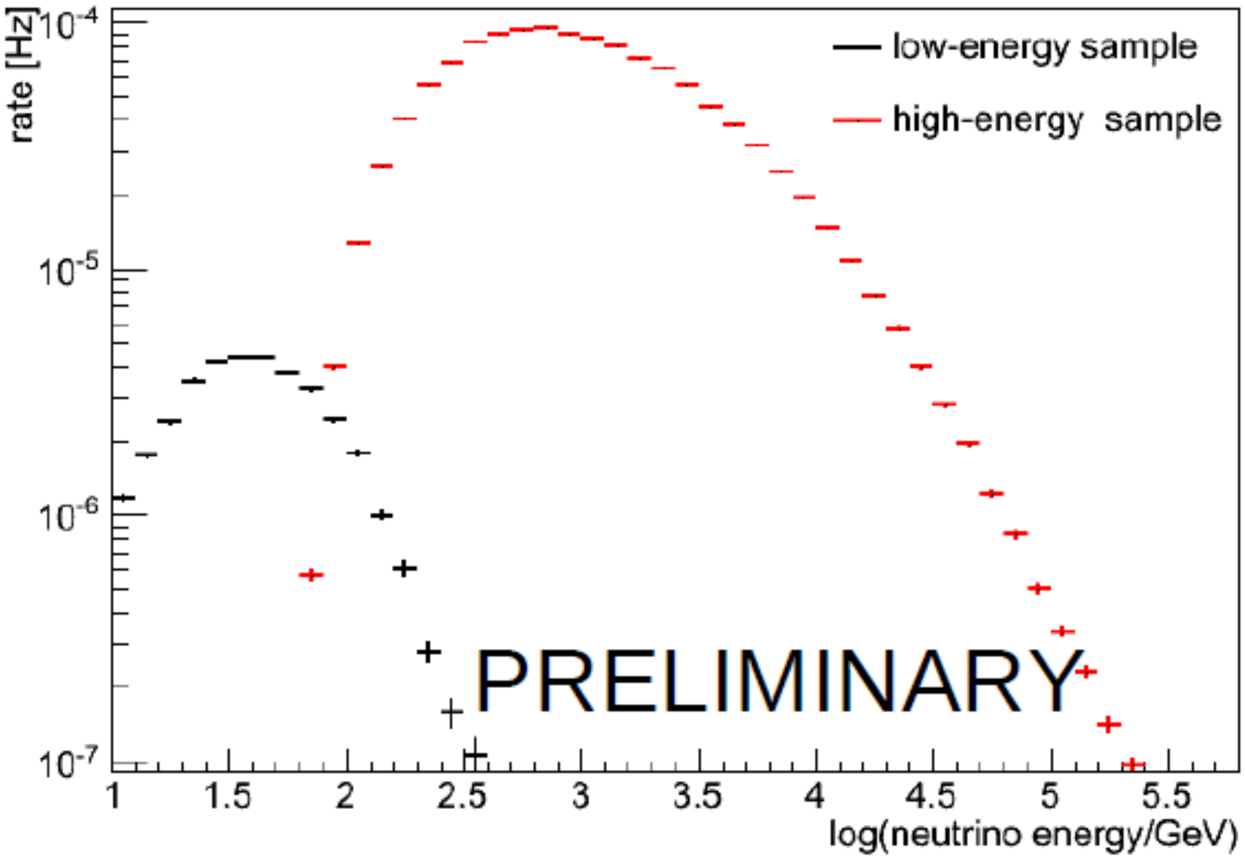


Deep Core and the muon veto

- From Deep Core design study (2008).
- Simulation of ν_μ interactions for 80+12 strings (4π, 5 GeV – 50 TeV, E^{-2} spectrum).
- Use surrounding man detector as veto to select events with vertex in Deep Core volume.



Deep Core low-energy event sample



Deep Core extends IceCube energy range to ~ 10 GeV

(from ν_μ oscillation analysis)

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A first Deep Core result from 2012 …

- Identification of cascades, mainly from

$$\nu_e + N \rightarrow e + X$$

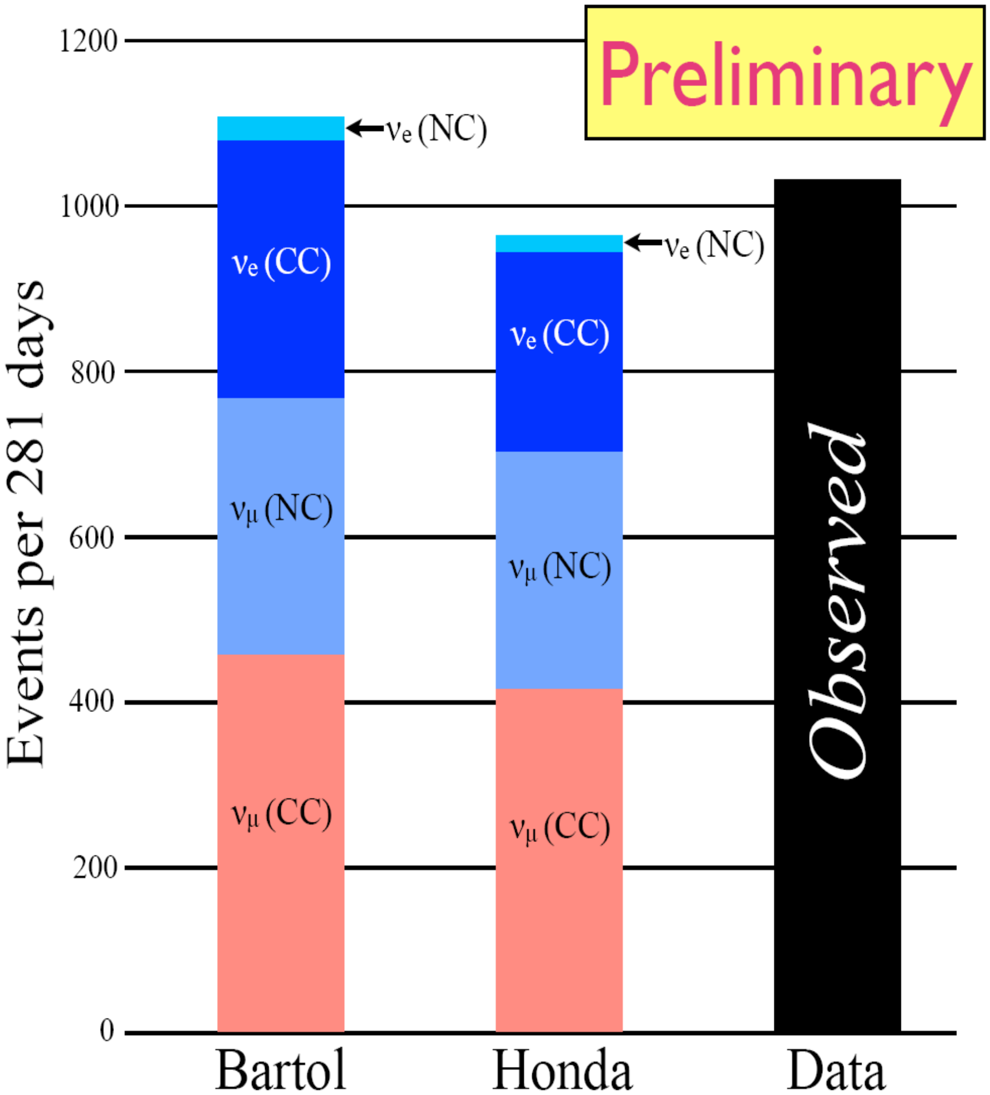
$$\nu_x + N \rightarrow \nu_x + X$$

- Main background:

$$\nu_\mu + N \rightarrow \mu + X$$

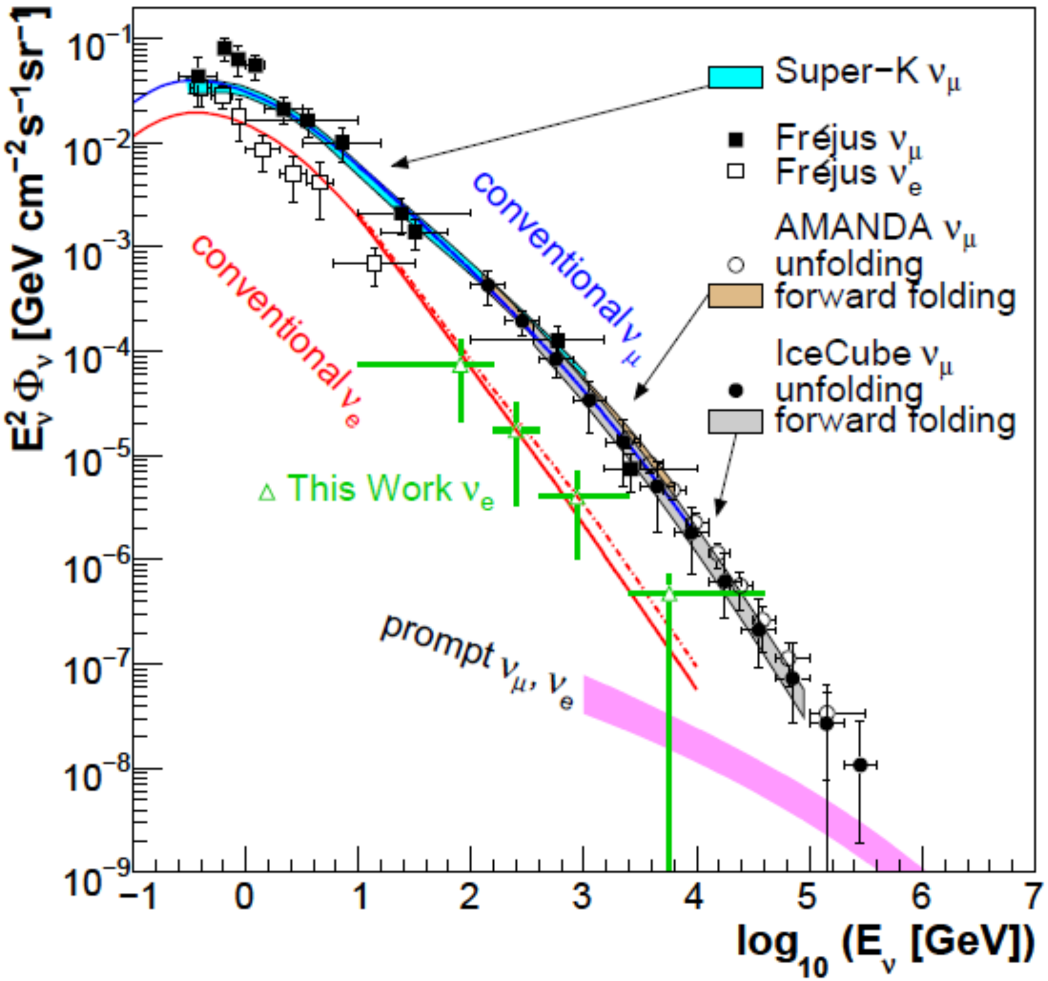
with short μ track

- Very difficult in IceCube
- Success in Deep Core! (see arXiv:1201.0801)



… and much more since then!

- Measurement of atmospheric ν_e flux (arXiv 1212.4760)
- Search for dark matter annihilation in Sun (arXiv 1212.4097)
- Atmospheric neutrino oscillations (arXiv 1301.4339)



What we learn

- Deep Core:
  - A close look at neutrino events above O(10 GeV); event identification and reconstruction possible.
  - The atmospheric muon veto works well.
  - Rich new physics results.
- ANTARES:
  - Event selection and reconstruction down to 20 GeV.
  - But not optimised for these energies!

Can we build on this success and go one step further?

PINGU & ORCA

PINGU and ORCA and their strategic context

- PINGU: Phased IceCube Next-Generation Upgrade
  - Extension of existing detector towards lower energies
  - Main focus: Mass hierarchy
    … but also other physics topics such as dark matter
  - May be proposed/endorsed even if mass hierarchy measurement is not possible
- ORCA: Oscillation Research with Cosmics in the Abyss
  - Would imply a major change of paradigm in KM3NeT
  - Will not be pursued if mass hierarchy measurement is not possible
- Both currently concentrate on feasibility studies; detector configurations not yet determined

The major experimental questions

- What are the trigger/event selection efficiencies?
- How and how efficiently can we separate different event classes?
- How can we reconstruct thes… d what resolutions can we reach … θ ?
- How can we control t… ounds?
- What are the d… stematic effects and how can we co…
- What precis… calibration is needed and how can it be achieved?

Questions under investigation,
no firm conclusions yet

A proposal requires knowing the answers!

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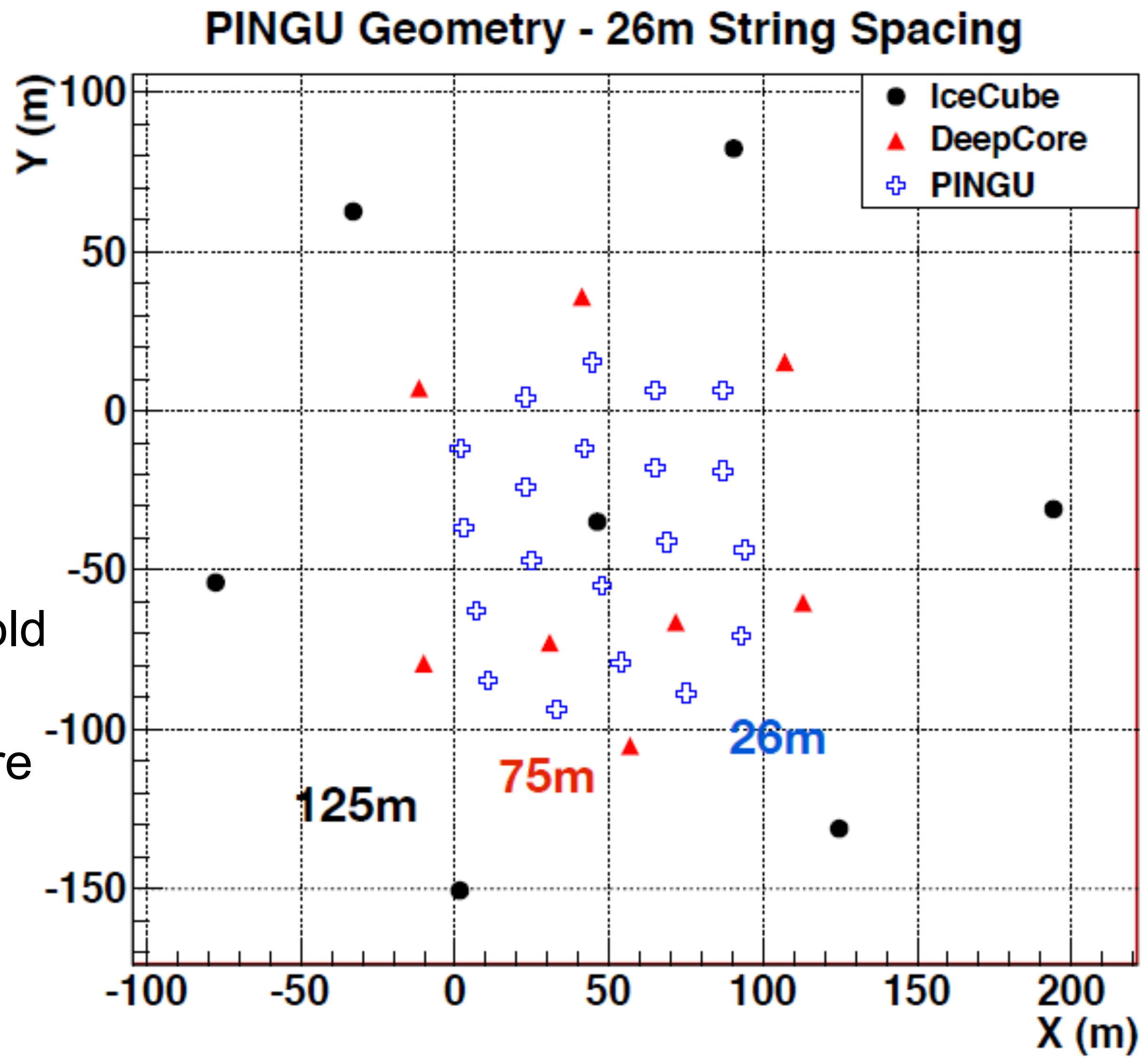
How PINGU might look like

- Add ~20 strings in Deep Core region, each with 60 OMs, 6m vertical distance
- Denser configurations also under investigation
- Instrumented volume ~5-6 Mton
- Expected energy threshold at ~1 GeV
- R&D opportunity for future developments
- IceCube plus further groups



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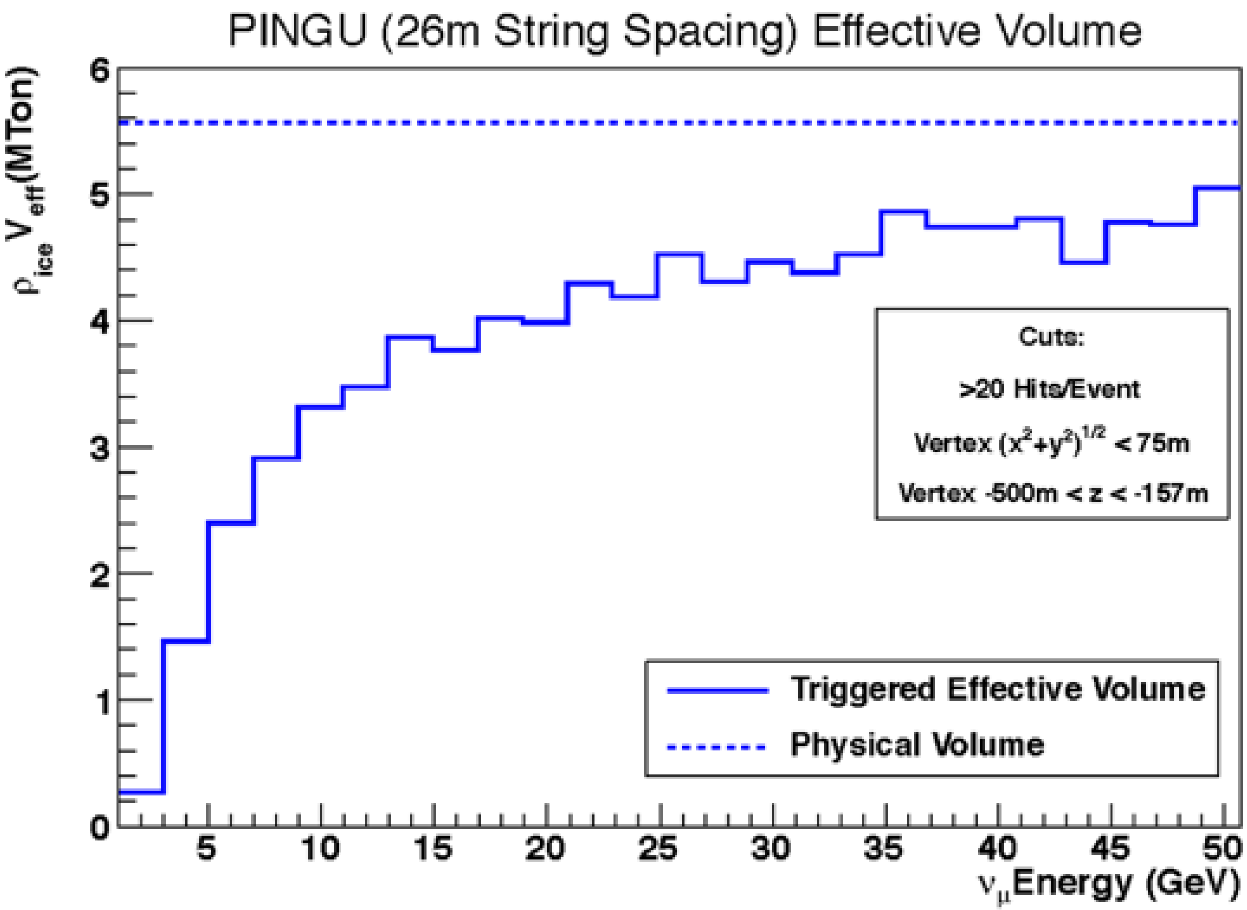
PINGU: Estimate of effective volume

- Require 20 hits inside PINGU volume
- Constrain generation vertex
- Gives rough estimate of reconstructable events
- Quality cuts and reconstruction efficiency not included



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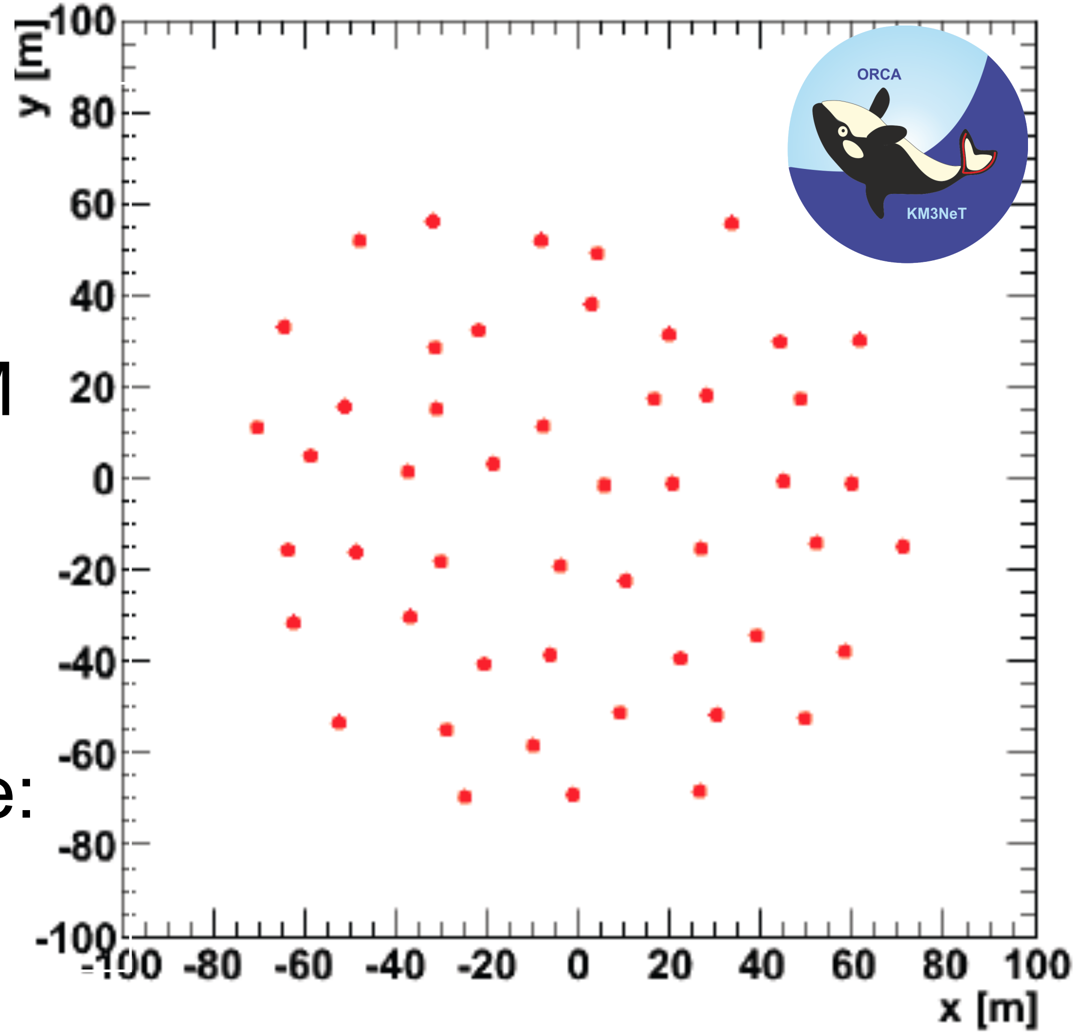
PINGU: Hardware issues

- Mostly standard IceCube technology
- Upgrade/improve optical modules (electronics, flasher, power supply)
- DAQ under study
- Improve flasher calibration system (better time resolution, better control of intensity)
- Add degassing system to hot-water drill to avoid bubbles in refreezing water

- Also: Prototype tests of new components for possible future use

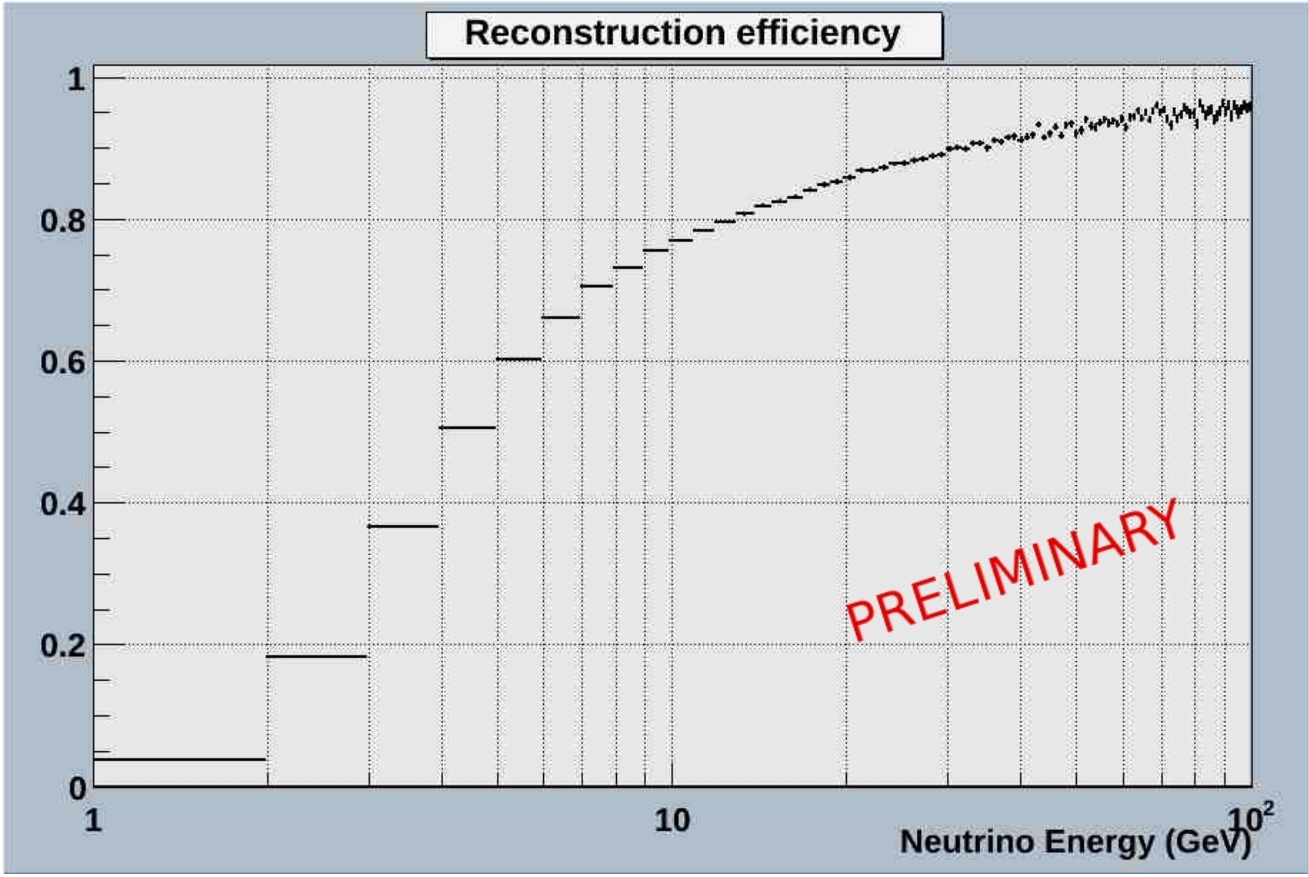
ORCA: A detector layout used for simulations

- 50 strings,
  20 OMs each
- KM3NeT design:
  31 3-inch PMTs / OM
- 20 m horizontal distance
- 6 m vertical distance
- Instrumented volume:
  1.75 Mton water



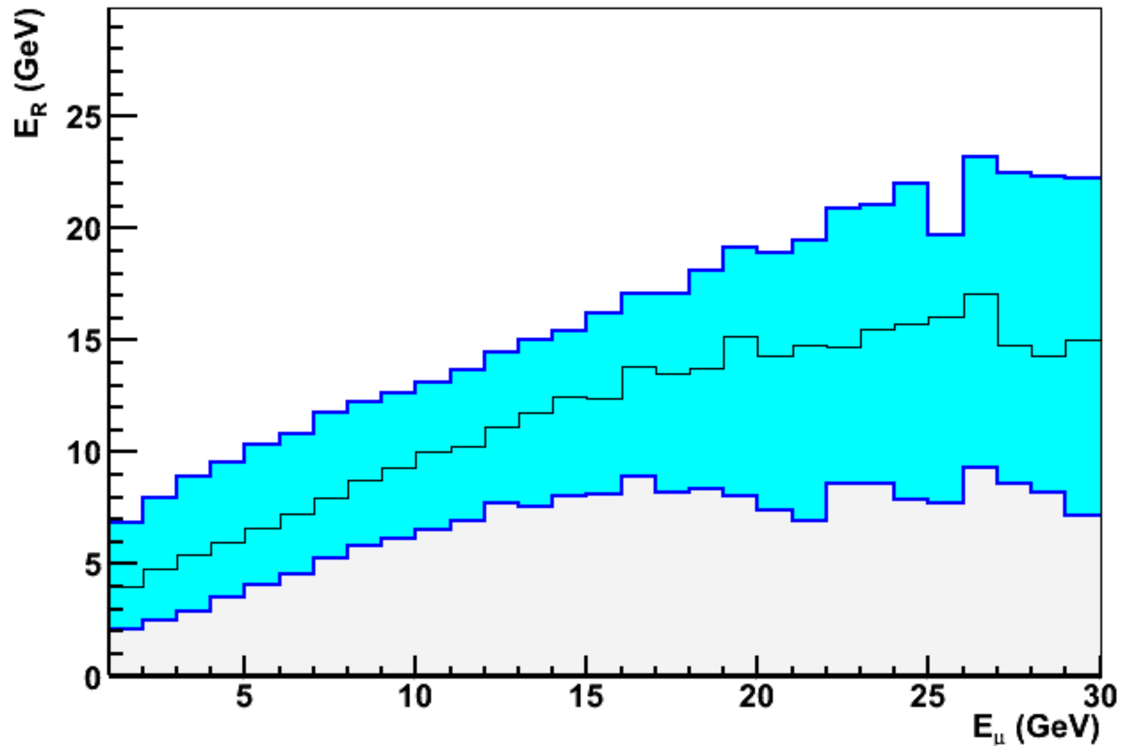
ORCA reconstruction efficiency

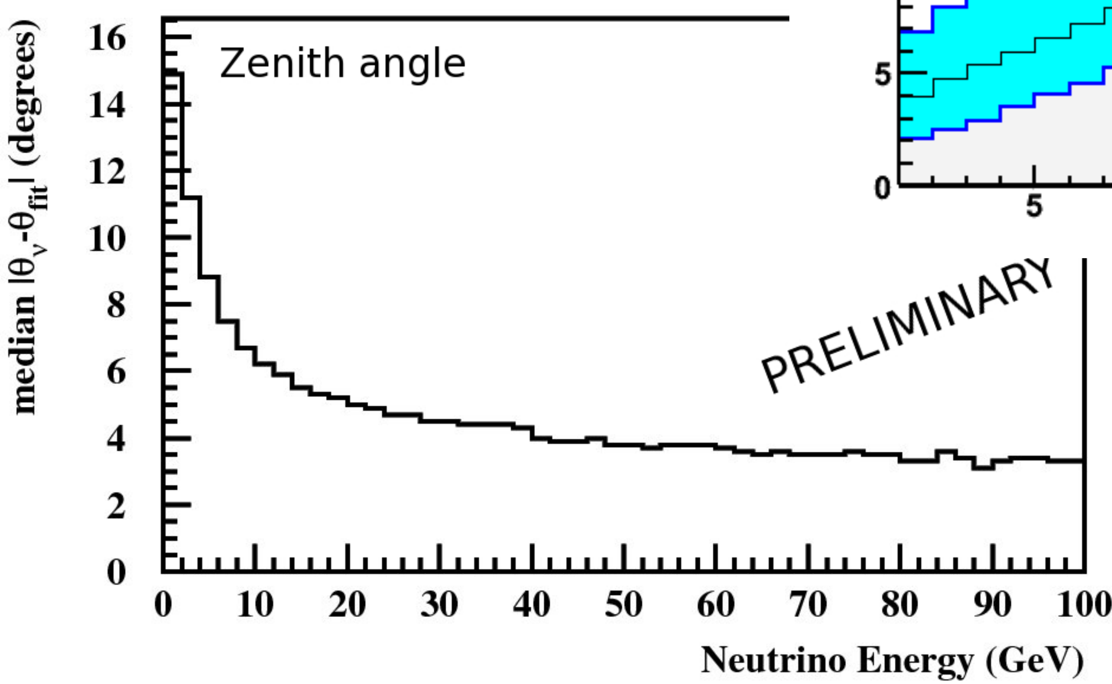
- Up-going events generated inside detector volume
- 4 L1 required (large hit or local coincidence
- No quality cuts, no background rejection



ORCA energy and zenith resolutions

- E_μ reconstructed from μ track length
- Shaded region: 16% and 84% quantiles as function of E_μ^{true}





- Median of zenith angle difference $\nu - \text{rec. } \mu$

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ORCA: Hardware and construction issues

- Use agreed KM3NeT technology;
  no major modifications required,
  but cable lengths etc. to be adapted
- String length restricted to avoid entanglement due to deep-sea currents
- Deployment requires care and studies (operation of deep-sea submersibles (ROVs) between deployed strings is impossible)
- New deployment scheme proposed (several strings in one sea operation)
- Very tight time constraints since most of the funding must be spent until March 2015

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PINGU and ORCA systematics

PINGU (ice):

- inhomogeneity of ice
- light scattering in ice
- atmospheric muons (less deep than water)
- position/orientation calibration of optical modules

ORCA (water):

- optical background from K40 and bioluminescence
- missing veto detector
- temporal variations of data taking conditions

Systematics are complementary – it may be useful/necessary to make both experiments

Measuring the neutrino mass hierarchy

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The full 3-flavour neutrino oscillation picture

- Parameterisation of mixing matrix (up to Majorana phases that are not discussed here):

$$U_{\mathrm{PNMS}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \cdot \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \cdot \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

with $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$

- Neutrino oscillation parameters:

$\sin^2(2\theta_{23}) = 0.97; \quad |\Delta m^2_{23}| = 2.35 \times 10^{-3}\,\mathrm{eV}^2$ atmos. + acc.

$\sin^2(2\theta_{12}) = 0.86; \quad \Delta m^2_{12} = 7.58 \times 10^{-5}\,\mathrm{eV}^2$ solar + reactor

$\sin^2(2\theta_{13}) = 0.096;$ reactor (new!)

- Unknown: sign of Δm^2_{23}
  CP-violating phase δ

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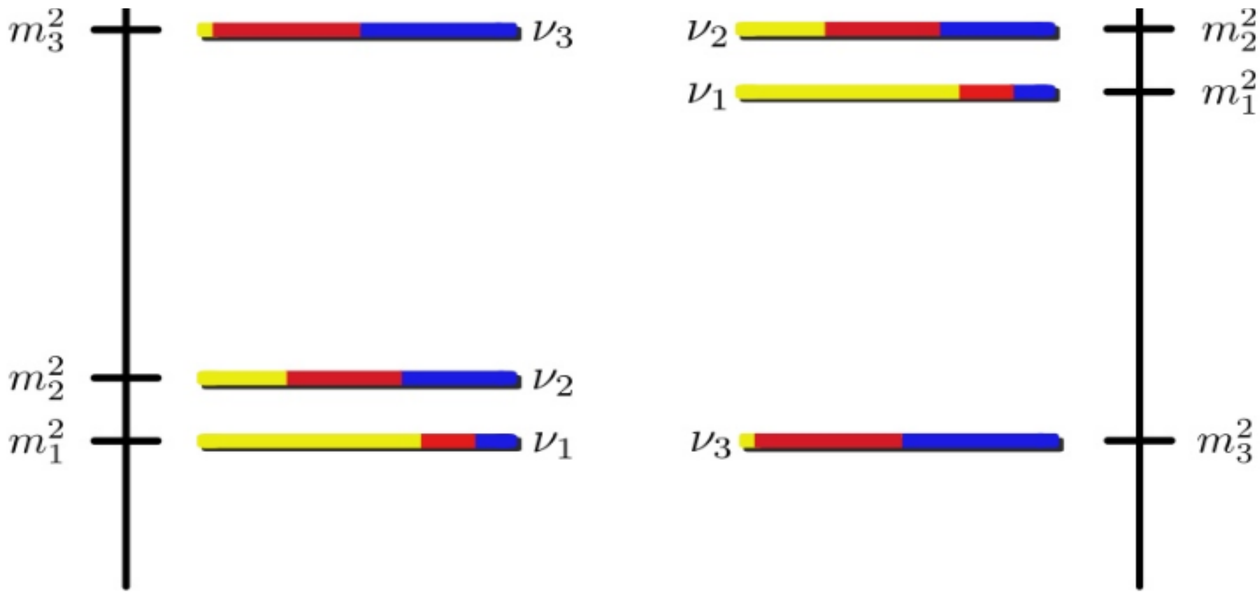
Neutrino mass hierarchy

- Depending on sign of Δm^2_{23} :
  "normal hierarchy" or "inverted hierarchy"
  (NH) (IH)



- A fundamental parameter of particle physics!

Mass hierarchy and atmospheric neutrinos

- Determining the sign of Δm^2_{23} requires matter effect. Oscillation of ν_e and/or $\overline{\nu}_e$ must be involved.
- 3-flavour oscillations of $\nu_e \leftrightarrow \nu_\mu$ in matter:

$$P_{e\to\mu} \approx P_{\mu\to e} \approx \sin^2\theta_{23}\sin^2(2\theta^{\text{eff}}_{13})\sin^2\left(\frac{\Delta^{\text{eff}}_{13}L}{2}\right)$$

$$\Delta_{13} = \frac{\Delta m^2_{13}}{2E_\nu} \qquad \sin^2(2\theta^{\text{eff}}_{13}) = \frac{\Delta^2_{13}\sin^2(2\theta_{13})}{\Delta^{\text{eff}}_{13}L}$$

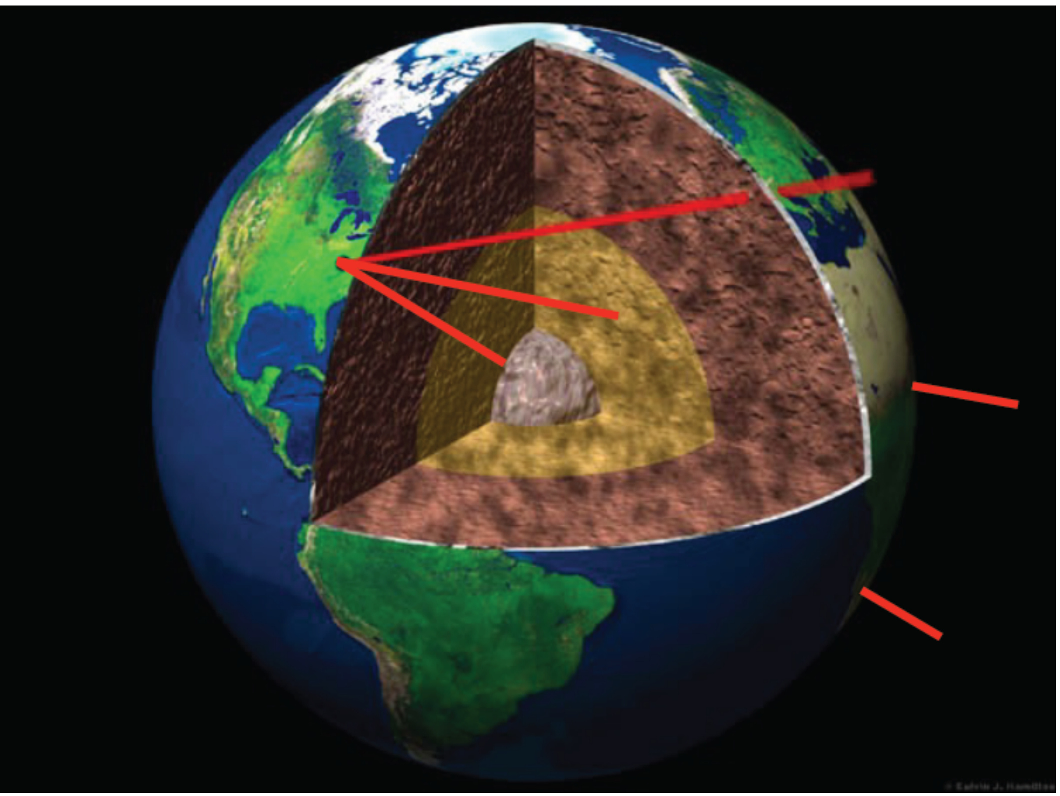
$$\Delta^{\text{eff}}_{13} = \sqrt{[\Delta_{13}\cos(2\theta_{13}) - A]^2 + \Delta^2_{13}\sin^2(2\theta_{13})}$$

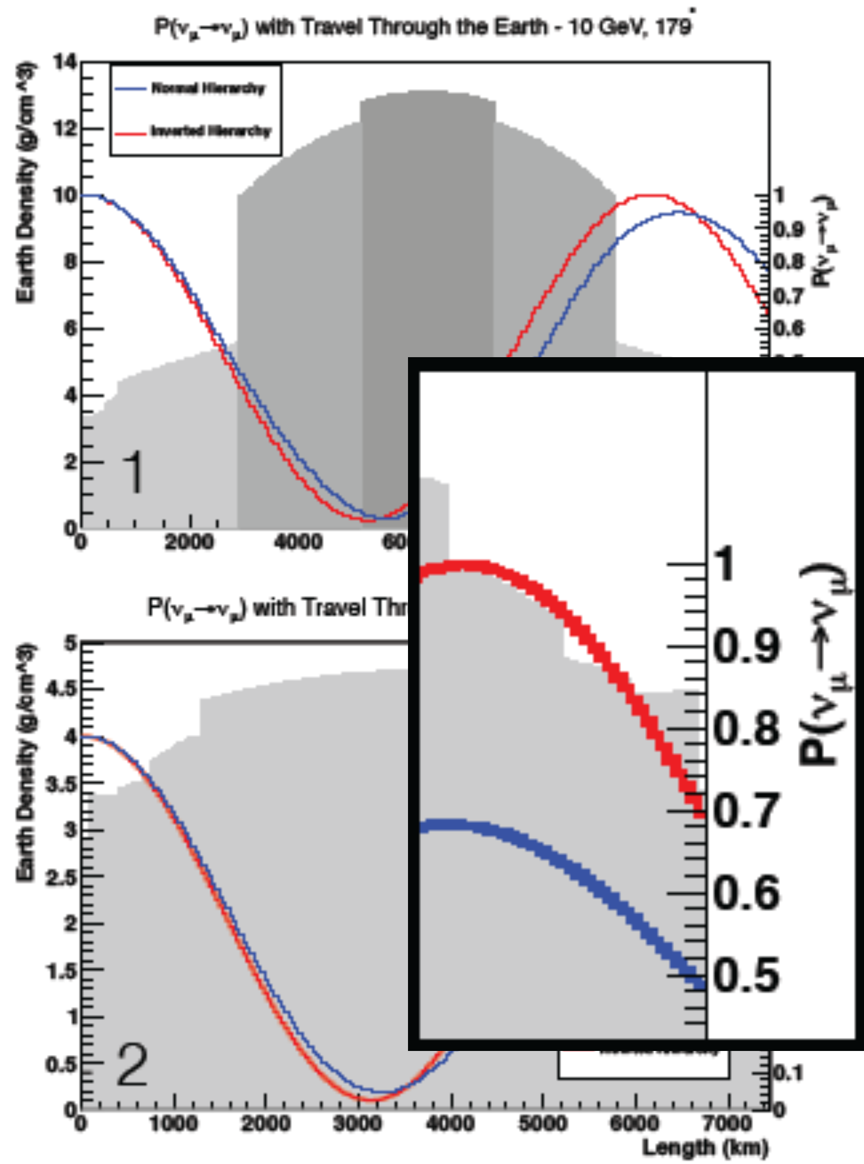
$$A = \sqrt{2}G_F N_e \text{ for } \nu \text{ and } A = -\sqrt{2}G_F N_e \text{ for } \overline{\nu}$$

- "Matter resonance" for $A = \Delta_{13}\cos(2\theta_{23})$ (maximal mixing, minimal oscillation frequency). This is the case for $E_\nu \approx 30\,\text{GeV}/\rho[\text{g cm}^{-3}]$

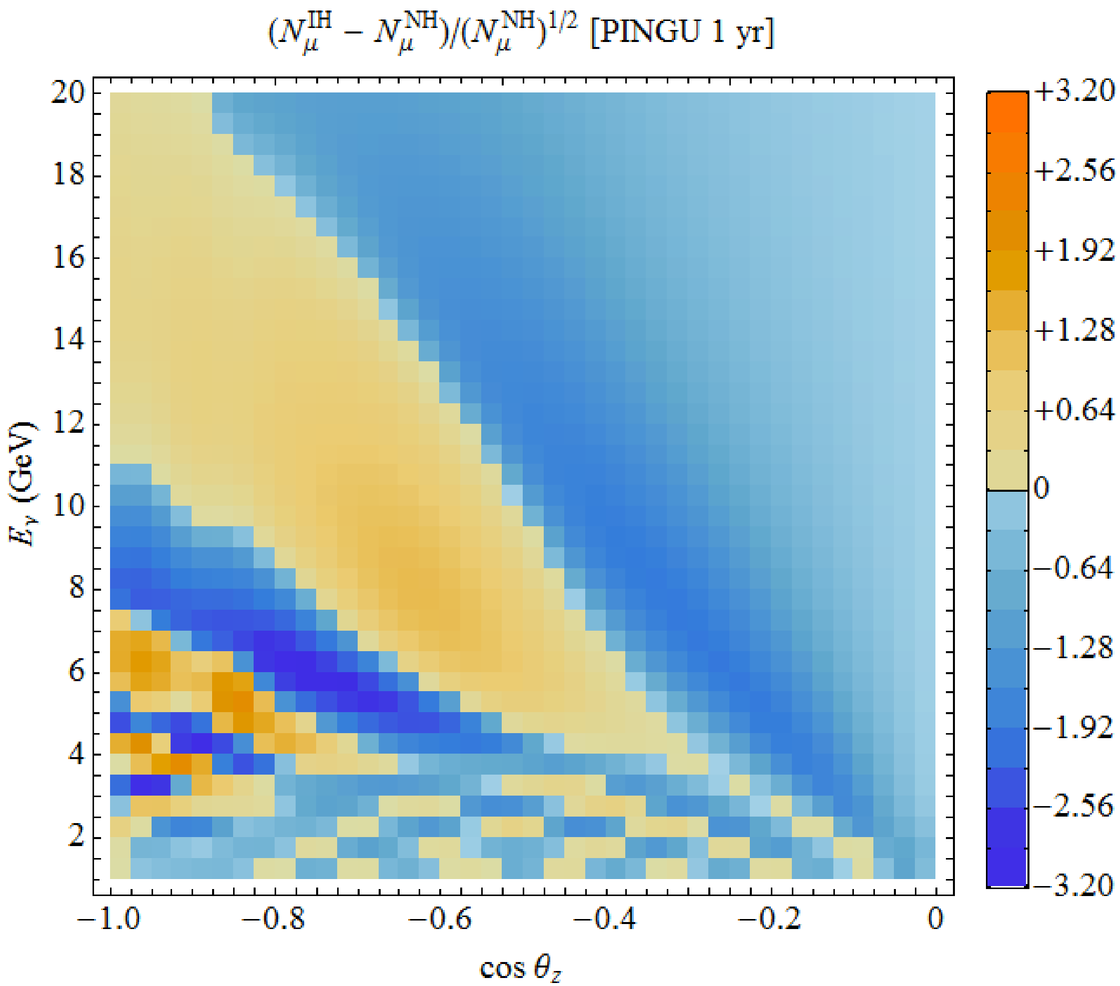
Neutrino oscillations in Earth

- Earth density 4-13 g/cm^3
- Relevant: $E_\nu \sim 3\text{–}10\,\text{GeV}$





The Akhmedov/Razzaque/Smirnov paper (1)



JHEP 1302 (2013) 082; arXiv 1205.7071

Significance for perfect resolution:

$$S_{\text{tot}} = \sqrt{\sum_{\text{bins}} \frac{(N_i^{\text{NH}} - N_i^{\text{IH}})^2}{\sigma_i}}$$

with $\sigma_i = N_i^{\text{NH}} + f(N_i^{\text{NH}})^2$

Uncorrelated system. errors assumed (f)

Result (5 years):

$f = 0.00$: $S_{\text{tot}} = 45.5\sigma$

$f = 0.05$: $S_{\text{tot}} = 28.9\sigma$

$f = 0.10$: $S_{\text{tot}} = 18.8\sigma$

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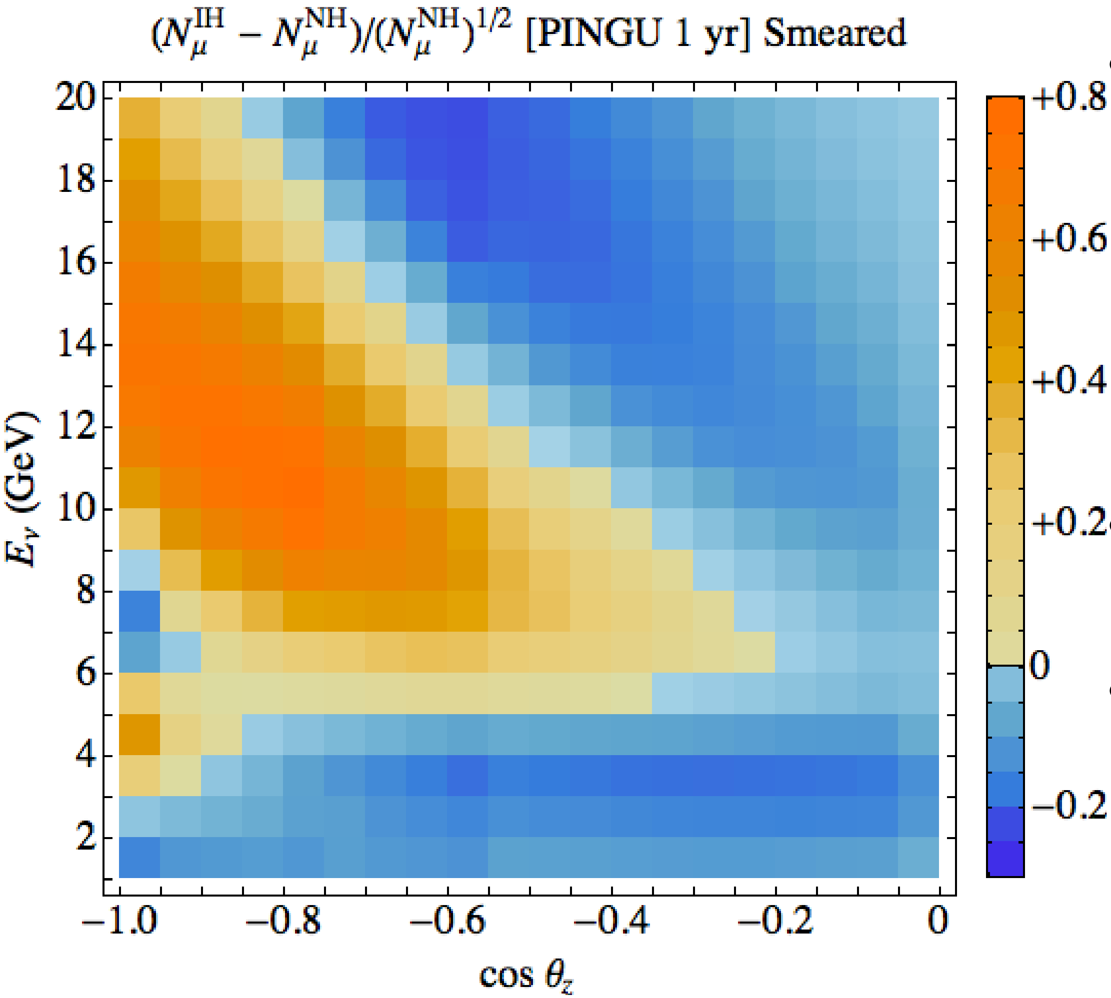
The Akhmedov/Razzaque/Smirnov paper (2)



- Taking into account experimental resolutions

  $\sigma_E = 0.2 E_\nu; \sigma_\theta = \sqrt{m_p/E_\nu}$

  (just an example) deteriorates result
- Remaining significances in the range 3…15σ
- Not yet included:
  - Non-Gaussian tails
  - Inefficiencies
  - Backgrounds
  - …

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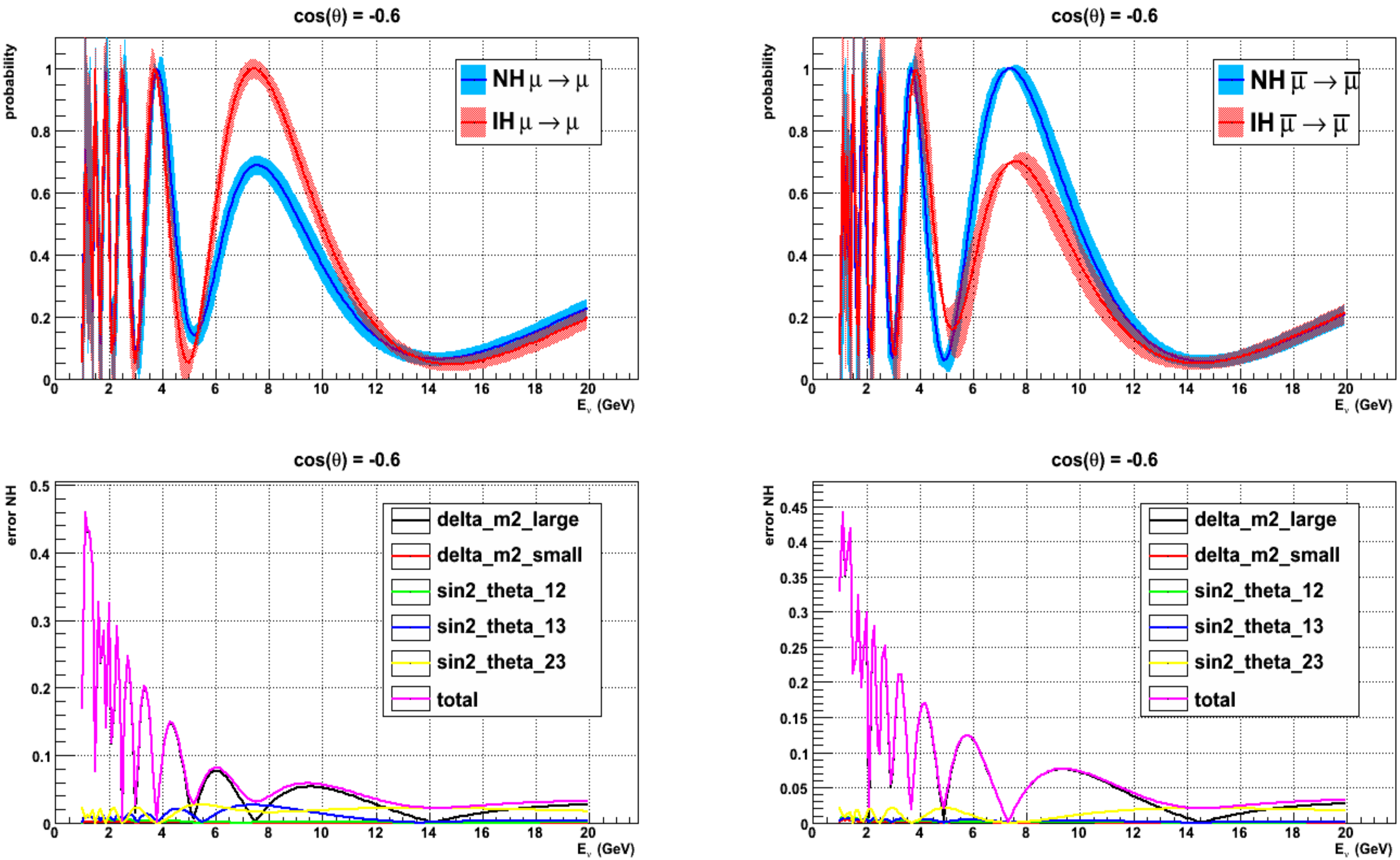
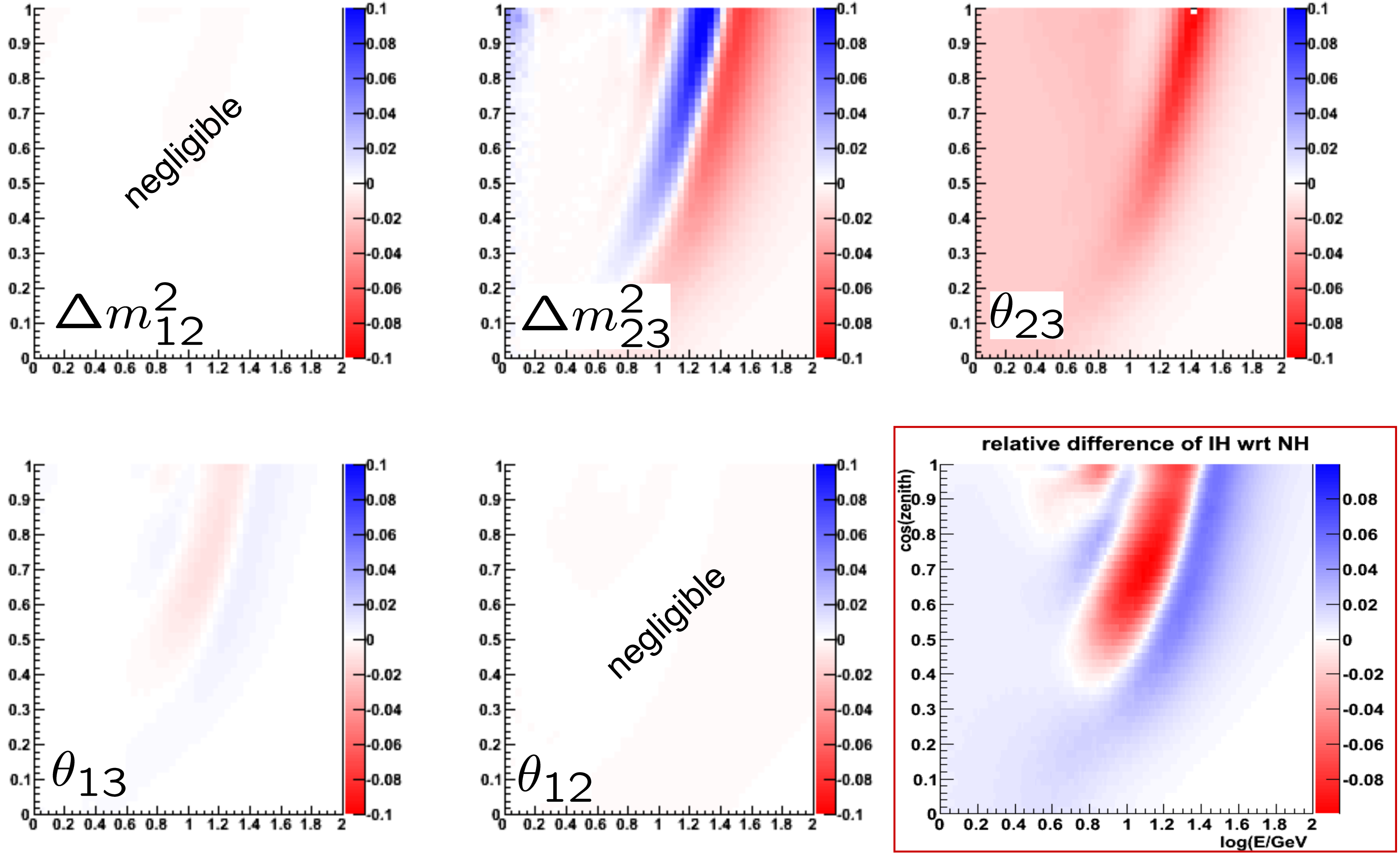
Impact of oscillation uncertainties (1)



Impact of oscillation uncertainties (3)



A toy analysis (ORCA)

- Neutrino interactions generated in detector volume
- Require at least PMT 15 hits
- Use true muon direction for zenith
- Assume 20% Gaussian uncertainty on E_ν
- No backgrounds, flavour misidentification etc.
- Assume hierarchy (NH or IH), pick oscillation parameters within experimental uncertainties, generate “toy experiment”
- Perform log-likelihood fit (free parameters: $\Delta m^2_{23}, \theta_{23}, \theta_{13}$), assuming both NH and IH
- Investigate log-likelihood ratio NH/IH

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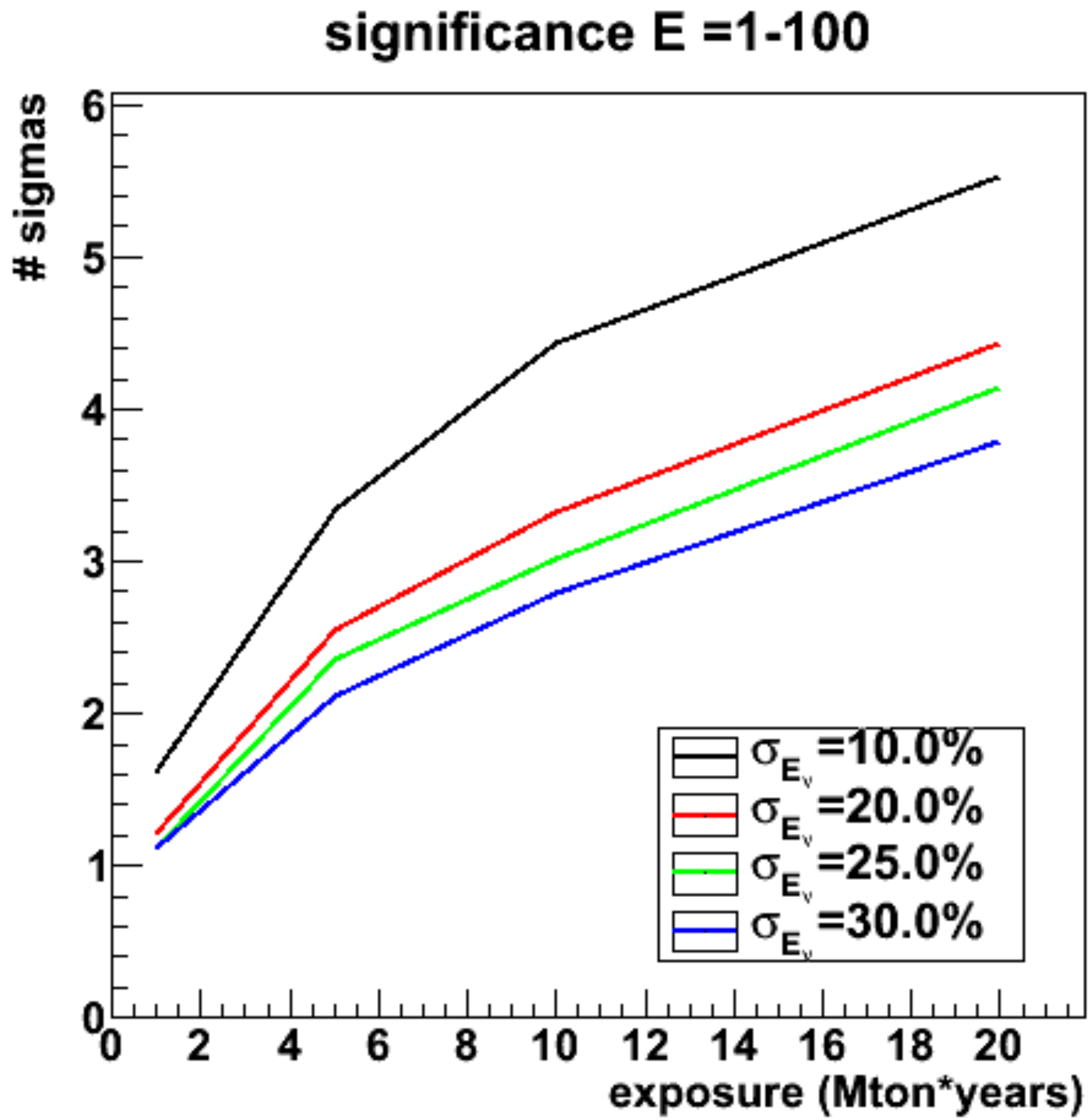
Results of toy analysis:

- Distribution of log-likelihood ratio NH/IH for toy experiments
- Experimental determination of mass hierarchy at 4-5σ level requires ~20 Mton-years
- Improved determination of $\Delta m^2_{23}, \theta_{23}$ seems possible



Summary and outlook

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- Neutrino telescopes in deep ice and water provide increasing sensitivity to cosmic neutrinos (>1TeV).
- They have demonstrated that low-energy measurements are possible (some 10 GeV).
- Even lower energies can be studied with densely instrumented configurations.
- A determination of the neutrino mass hierarchy with atmospheric neutrinos may be in reach but is experimentally difficult.
- If possible, this approach will be significantly faster and cheaper than any alternative.
- We will know more in a year – stay tuned.
- Help is more than welcome!

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