Future atmospheric measurements with PINGU

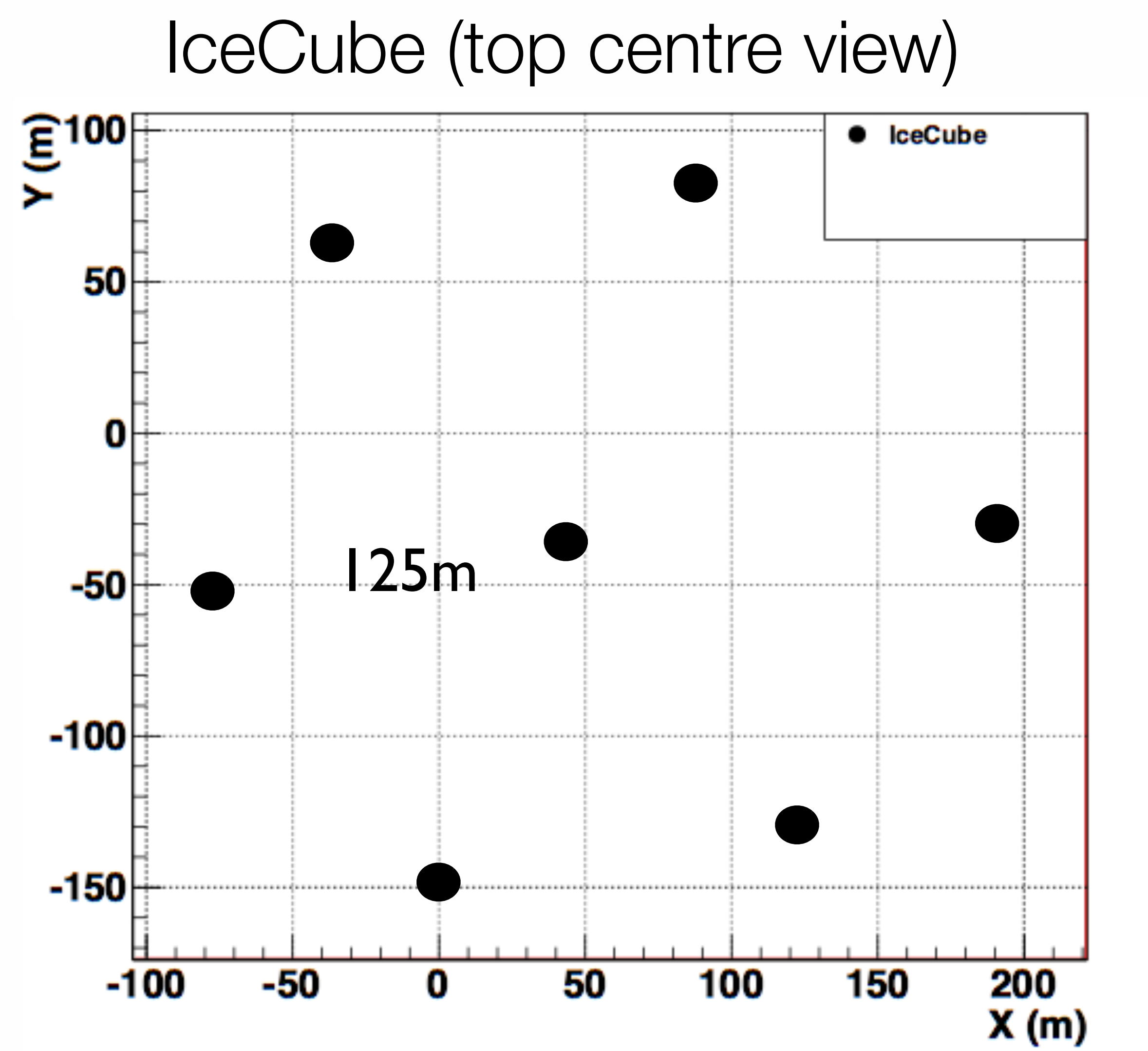
PRECISION ICECUBE NEXT GENERATION UPGRADE

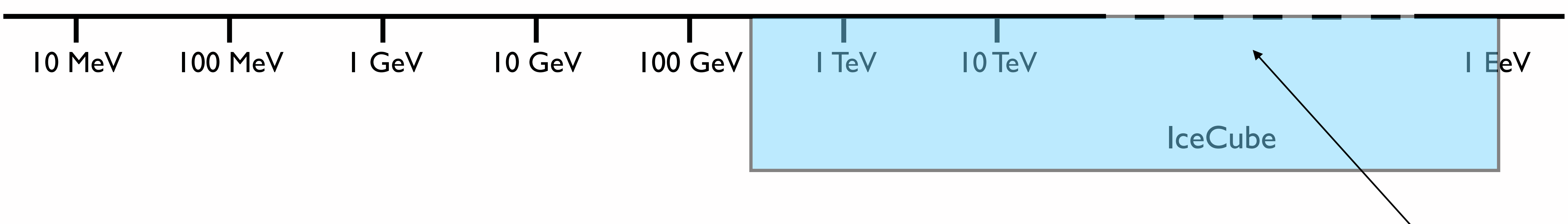
Neutrino 2014

Darren R. Grant
for the IceCube-PINGU collaboration

IceCube

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing





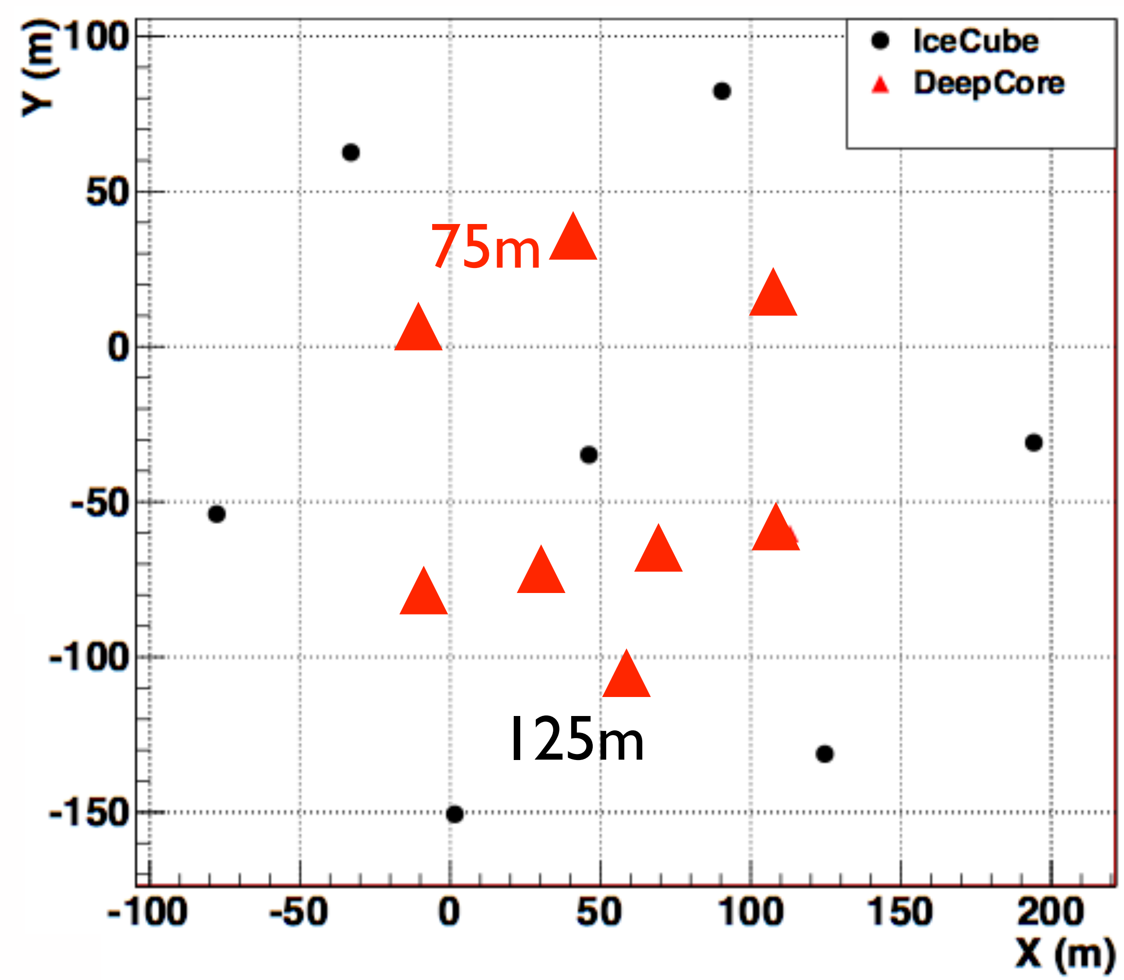
Astrophysical neutrinos are here; see talk yesterday by Gary Hill.

digital optical module - DOM

IceCube-DeepCore

- 78 Strings
  - 125m string spacing
  - 17m DOM spacing
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing

IceCube-DeepCore top view



Neutrino telescopes can efficiently measure atmospheric oscillations; see talk Juan Pablo Yáñez 25’ ago for the latest.

IceCube-DeepCore-PINGU

- 78 Strings
  - 125m string spacing
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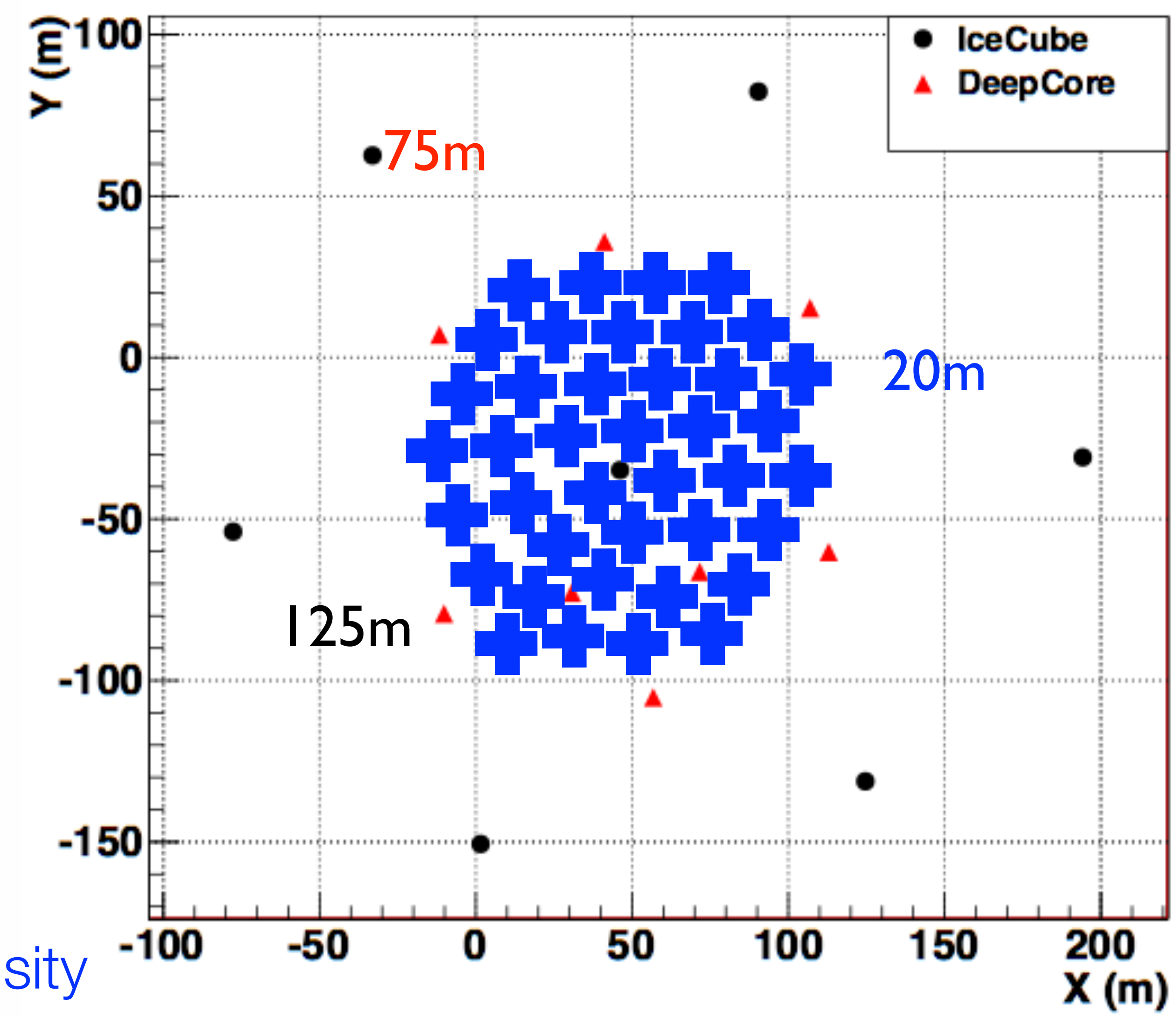
- Add 8 strings
  - 75m string spacing
  - 7m DOM spacing
- Add 40 strings (baseline target)
  - ~20m string spacing
  - 3-5m DOM spacing
  - ~20x higher photocathode density

IceCube-DeepCore-PINGU top view



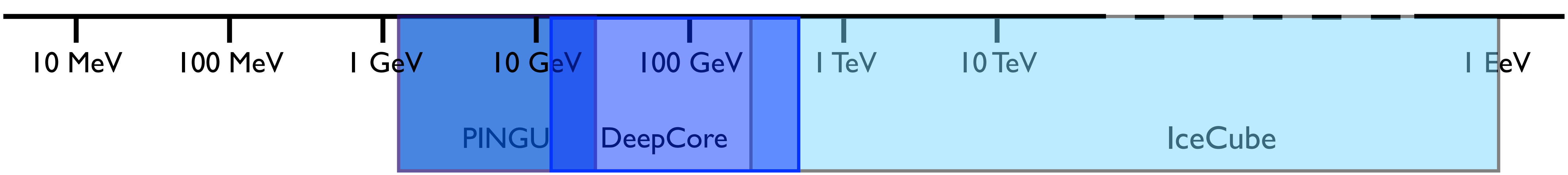


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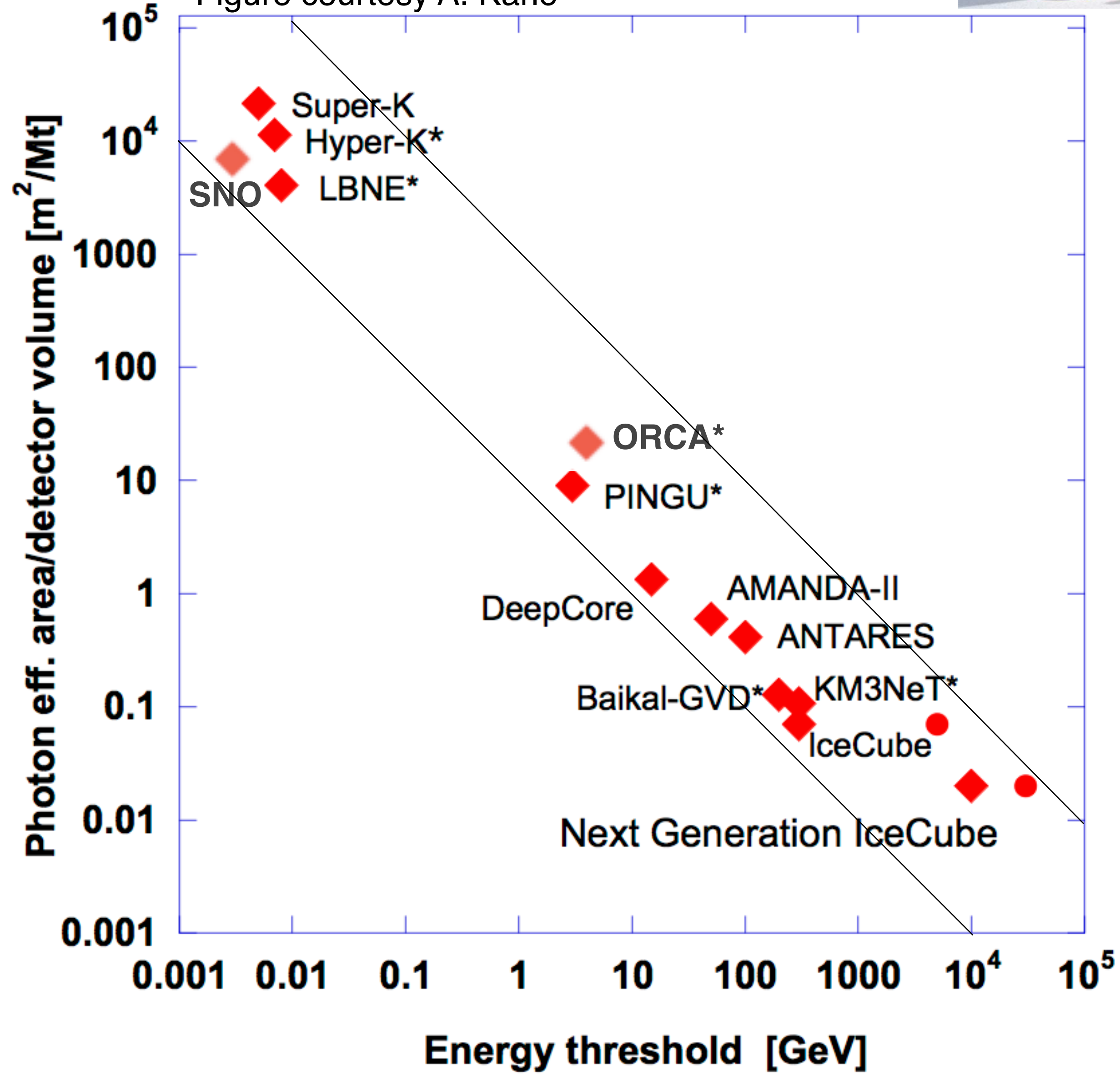
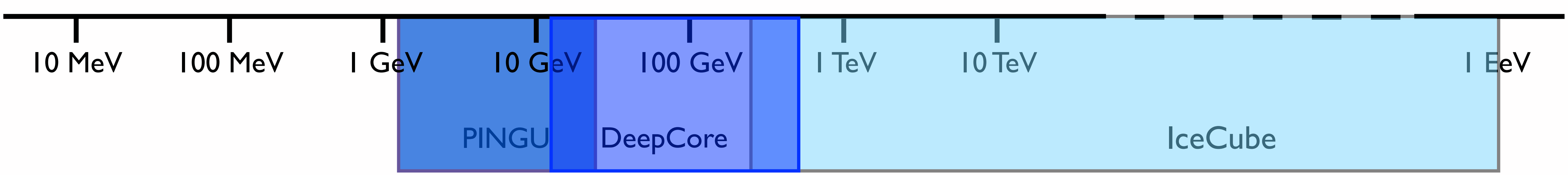
Figure courtesy A. Karle





digital optical module - DOM

The physics with future atmospheric neutrino detectors

Covered in today's talk

- Gain sensitivity to atmospheric neutrinos in the region below 10 GeV with very high statistics
  - Provide a definitive measurement of the neutrino mass hierarchy (NMH)
  - Will help pin down $(\Delta m_{23})^2$ and test maximal mixing, ν_τ appearance

Not discussed today

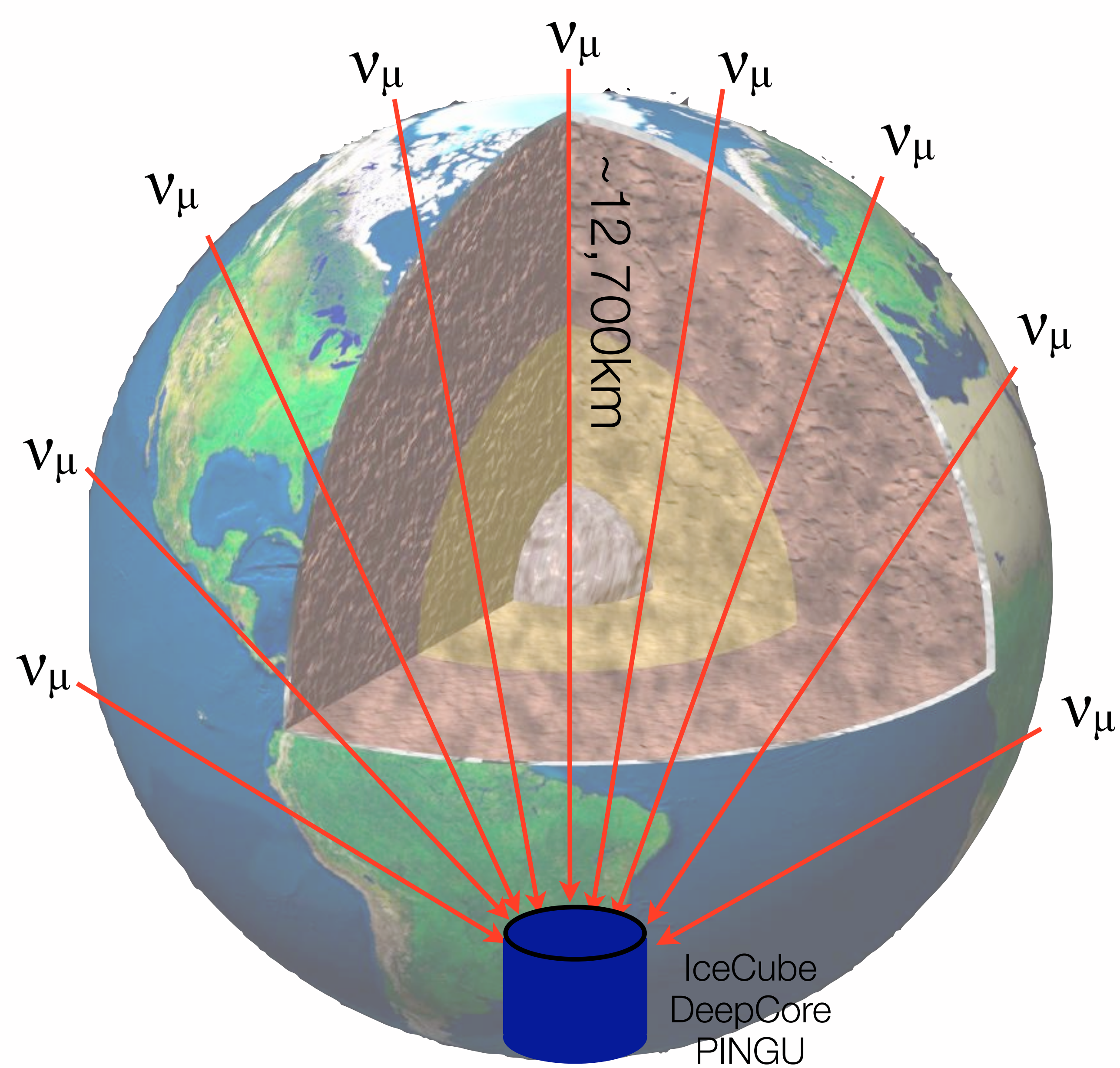
- Probe lower mass WIMPs
- Gain increased sensitivity to supernovae neutrino bursts, Earth tomography
- Initiate an extensive calibration program to improve systematics knowledge

see poster "New calibration methods for IceCube, DeepCore, and PINGU" by Martin Jurkovič et al.

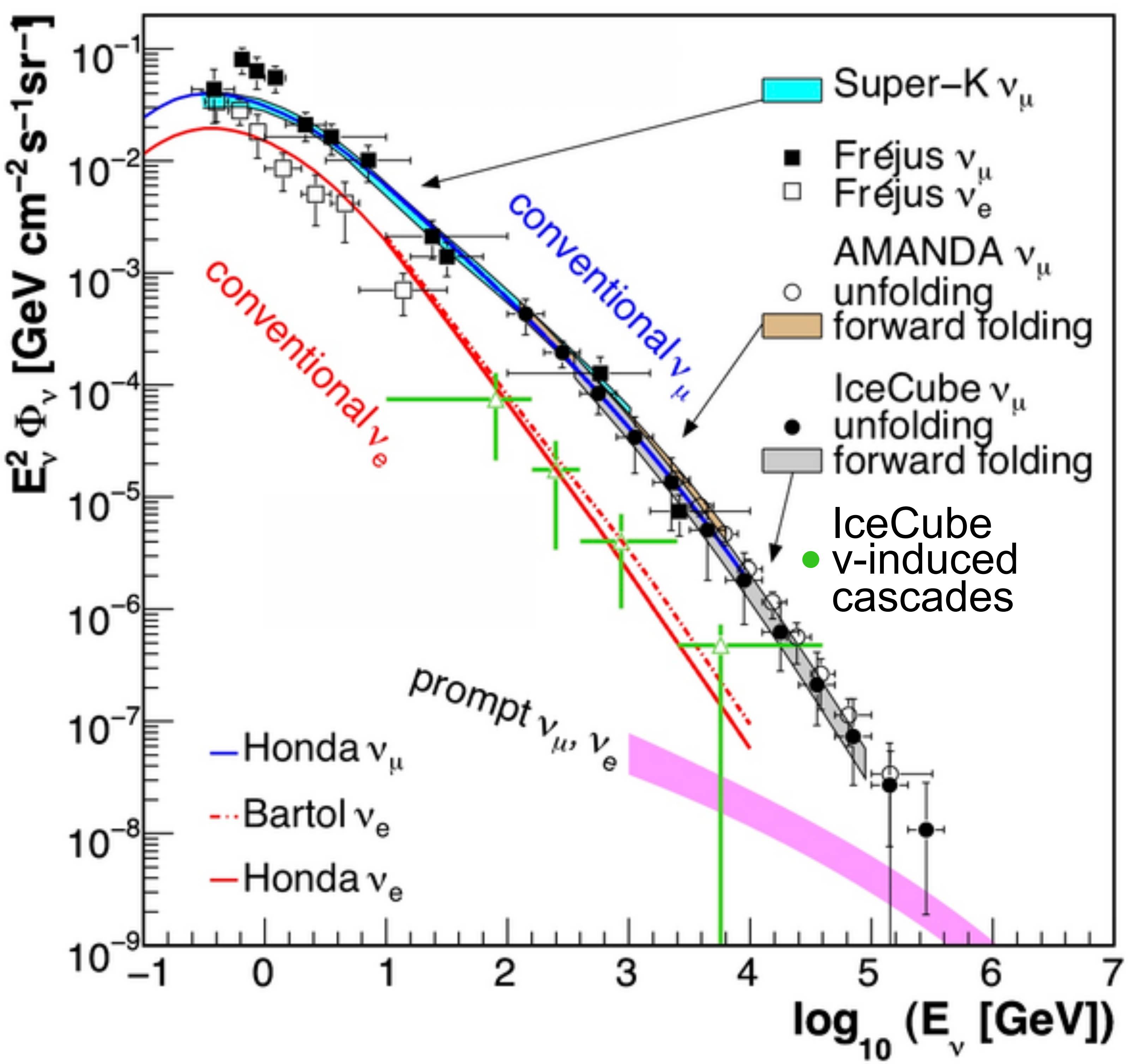
- Pathfinder technological R&D for the Megaton Ice Cherenkov Array (MICA)

Oscillations with Atmospheric Neutrinos

- Neutrinos oscillating over one Earth diameter have a ν_μ survival minimum at ~25 GeV
  - Hierarchy-dependent matter effects below ~12 GeV
- Neutrinos are available over a wide range of energies and baselines
  - Comparison of observations from different baselines and energies is crucial for controlling systematics
  - Essentially, a generalization of the up-down ratio approach



PINGU's Atmospheric ν Signal

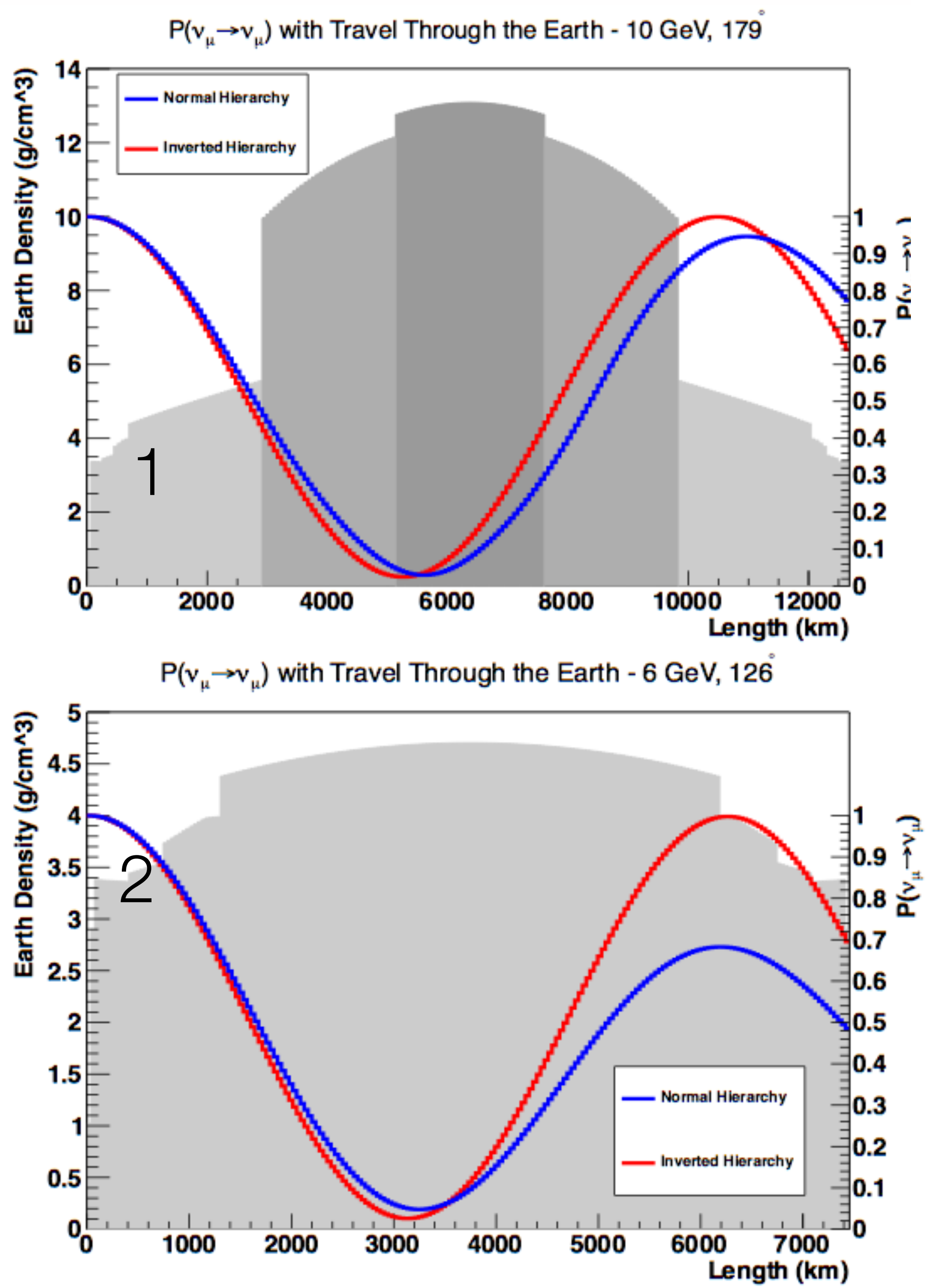


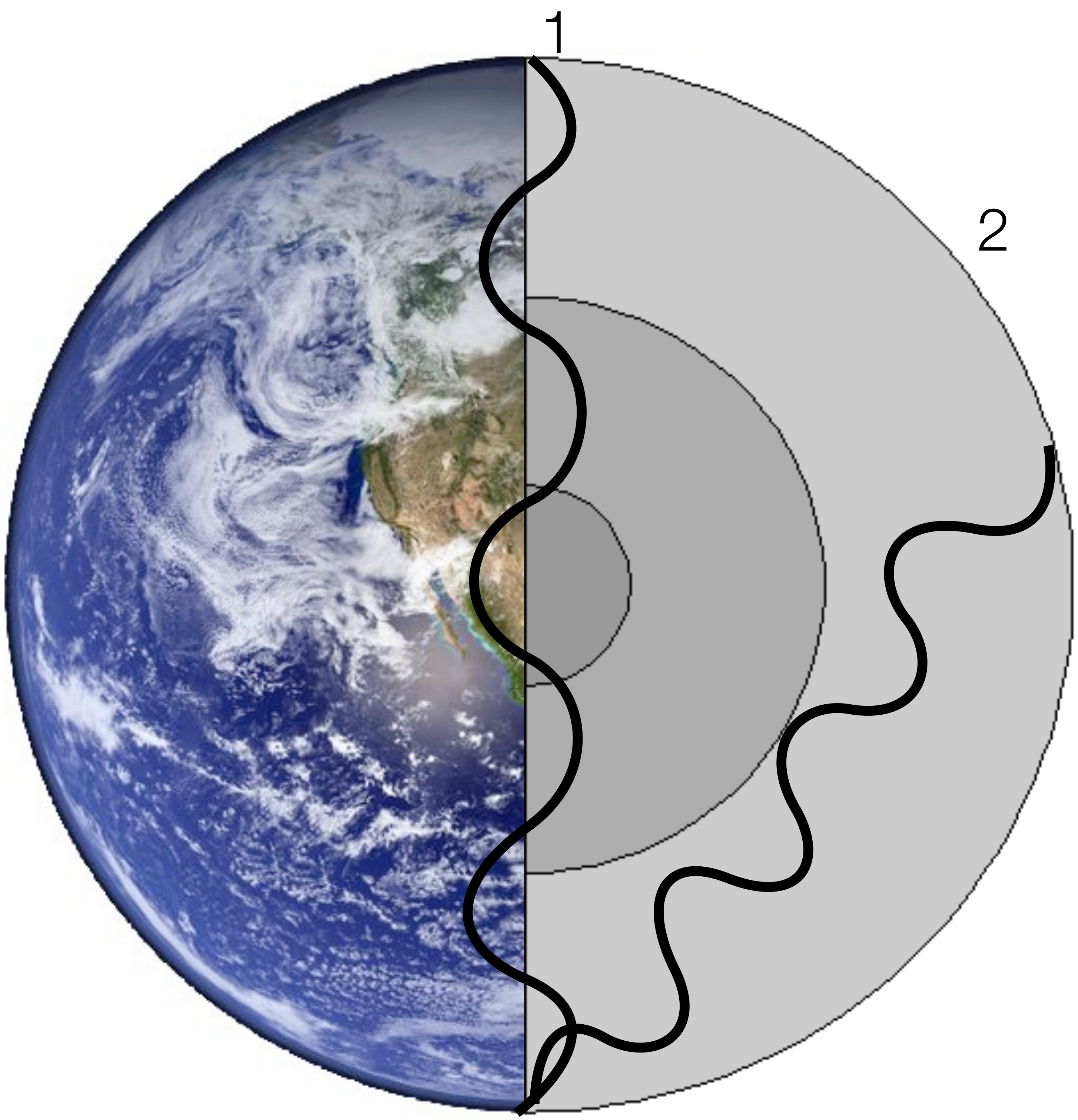
N(Events) Expected in PINGU per Year		
	Trigger Detector	Pass Baseline Analysis
ν_e CC	52k	26k
ν_μ CC	86k	35k
ν_τ CC	6.4k	2.7k
ν_x NC	17k	7.9k

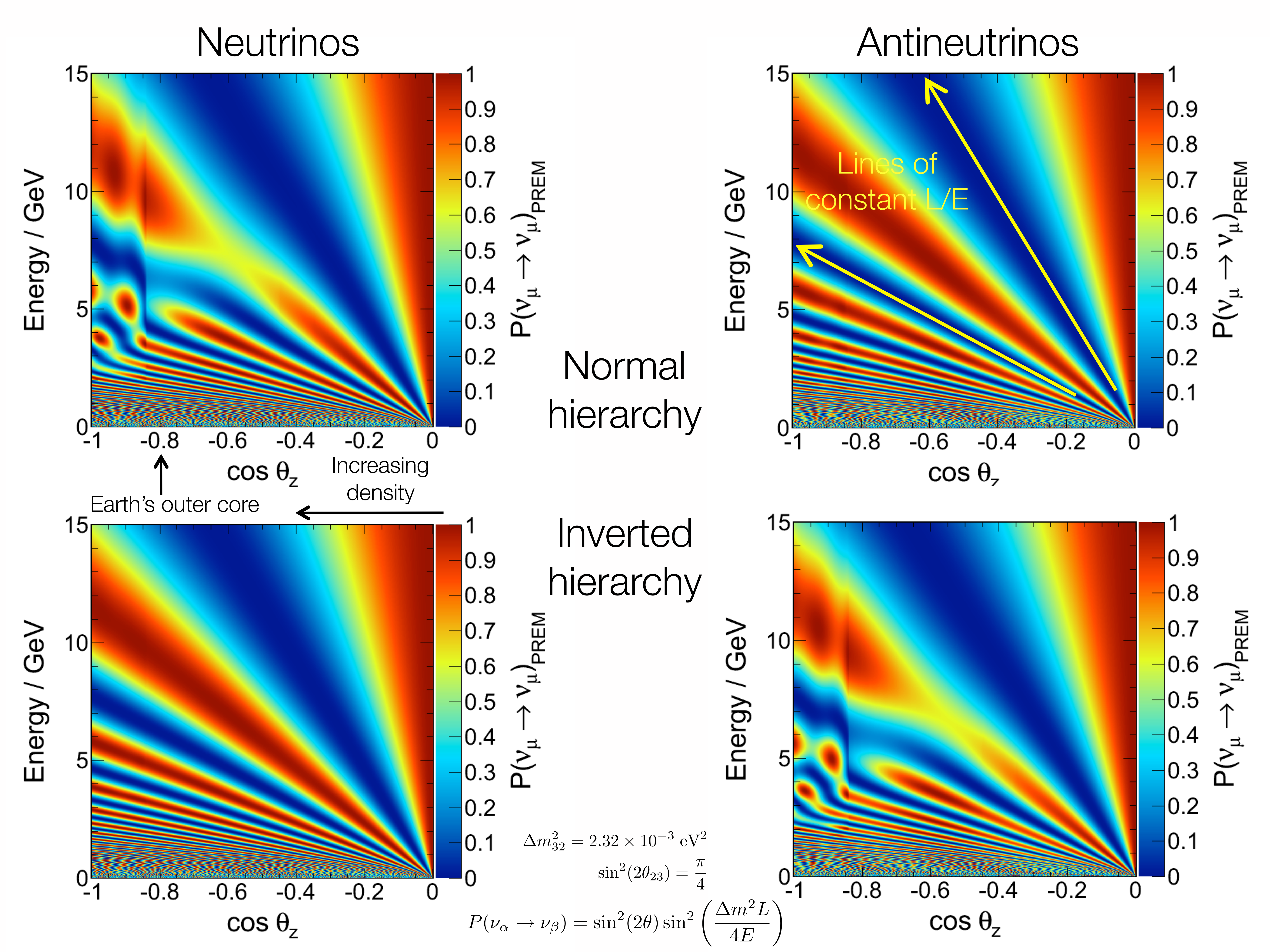
1 GeV < E < 80 GeV

Using atmospheric neutrinos to measure the NMH

Up to 20% differences in ν_μ survival probabilities for various energies and baselines, depending on the neutrino mass hierarchy

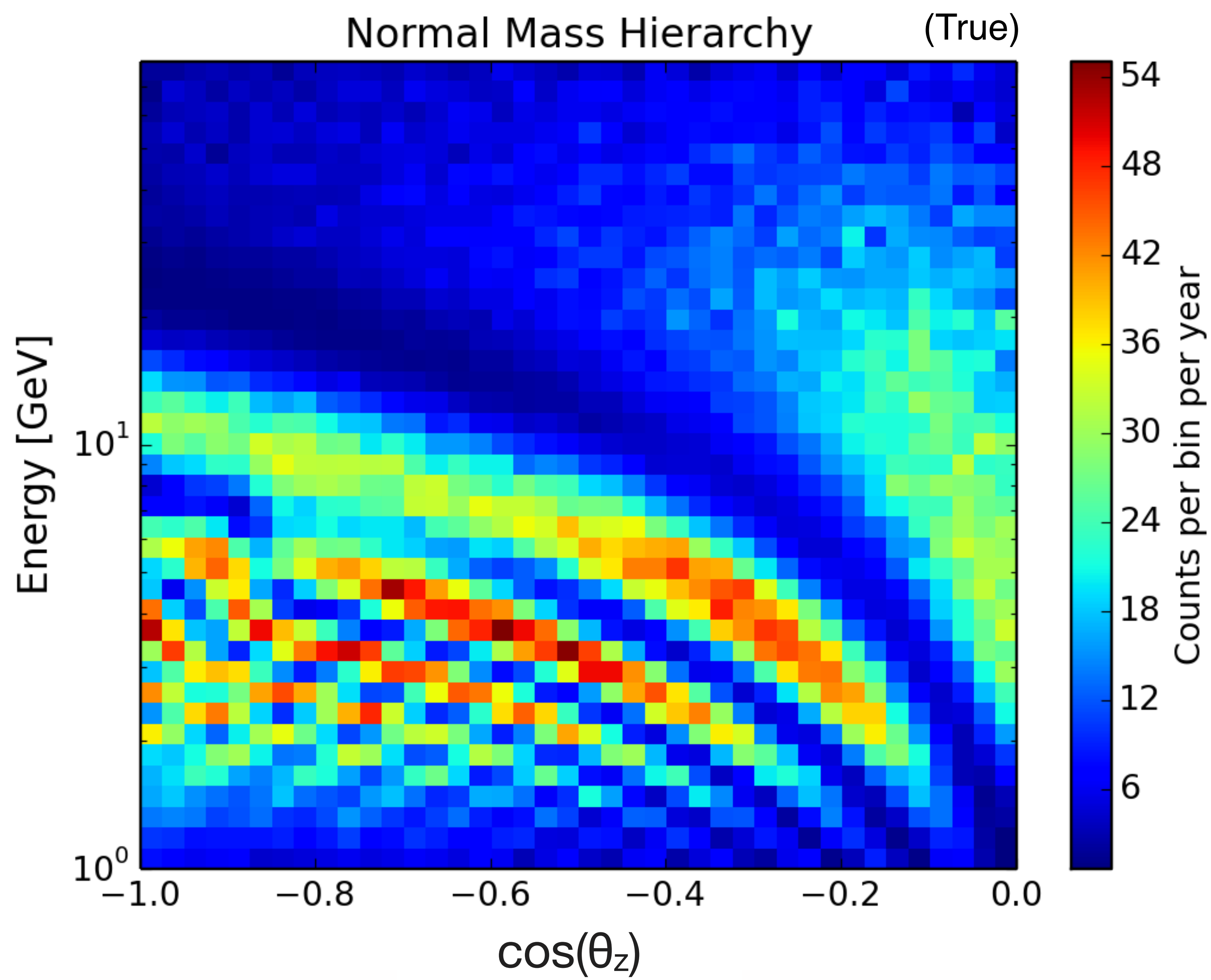





Neutrinos
Antineutrinos
Normal hierarchy
Inverted hierarchy
Lines of constant L/E
Earth's outer core
Increasing density
Energy / GeV
cos θ_z
$P(\nu_\mu \rightarrow \nu_\mu)_{PREM}$
$\Delta m^2_{32} = 2.32 \times 10^{-3}\ \mathrm{eV}^2$
$\sin^2(2\theta_{23}) = \frac{\pi}{4}$
$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$

PINGU and the NMH

- Cannot distinguish ν from $\bar{\nu}$ directly – rely instead on differences in fluxes, cross sections (and kinematics)
- Differences clearly visible in expected atm. muon (ν + $\bar{\nu}$) rate even with 1 year's data
  - Note: detector resolutions not yet included here



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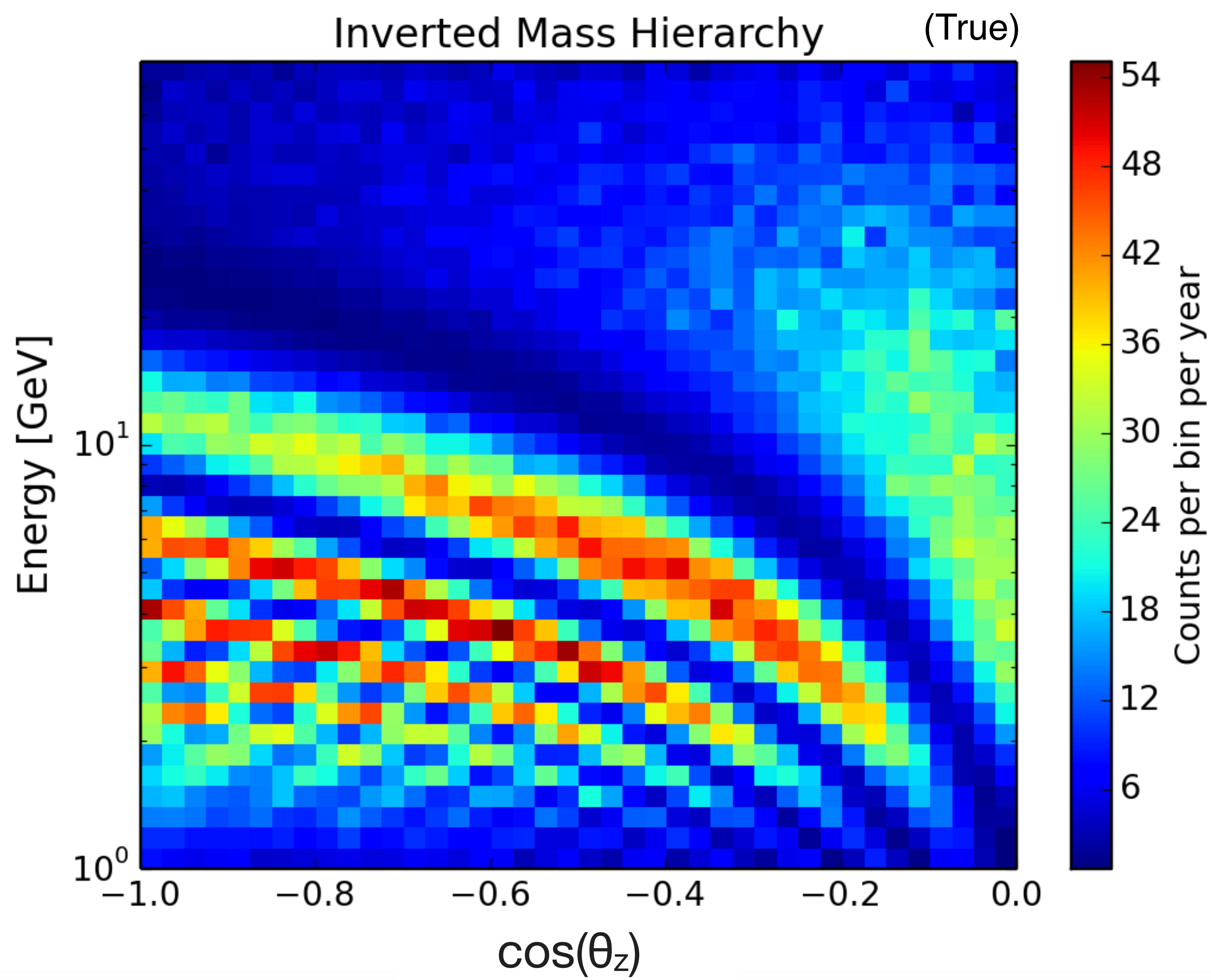
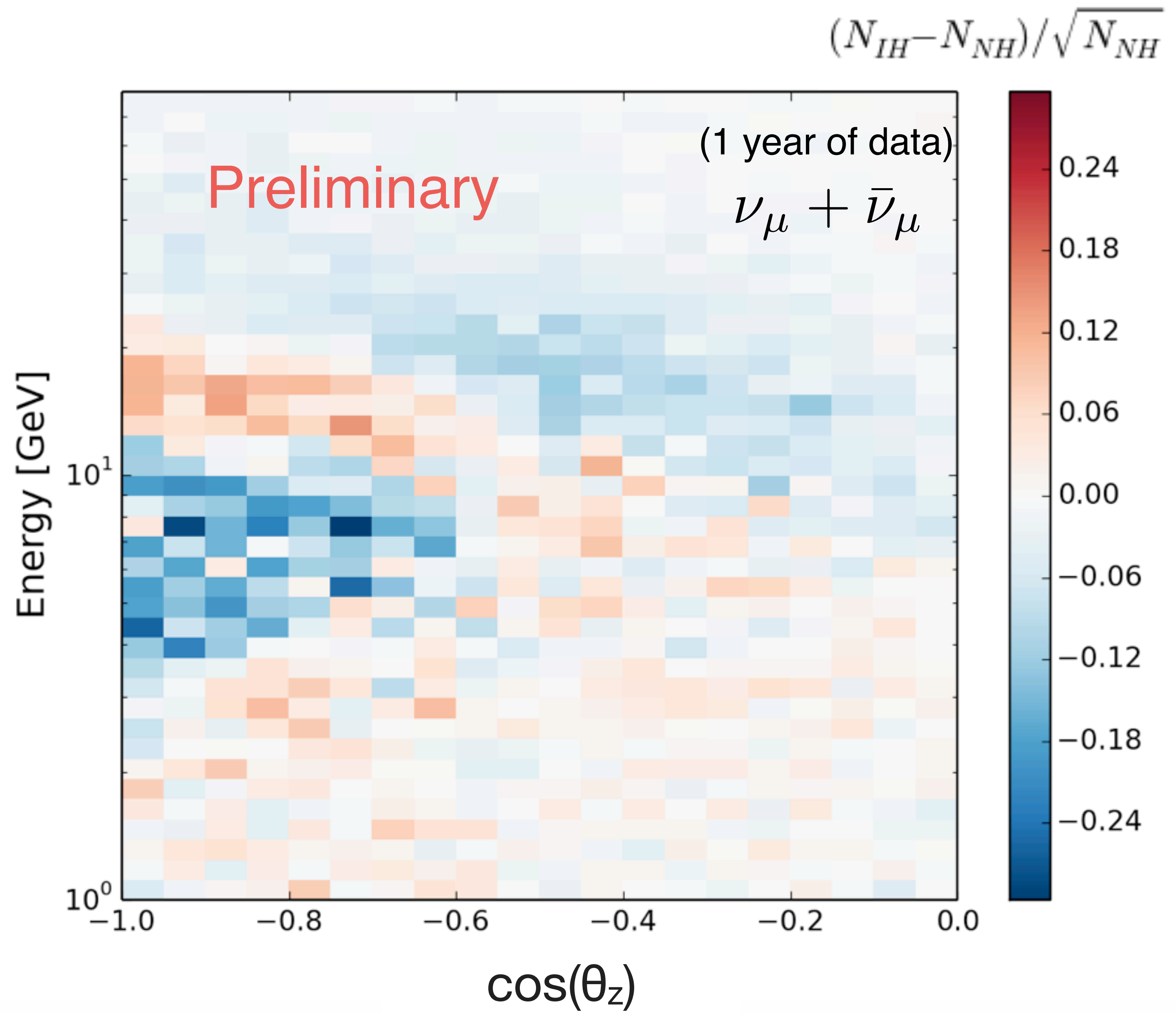


PINGU and the NMH

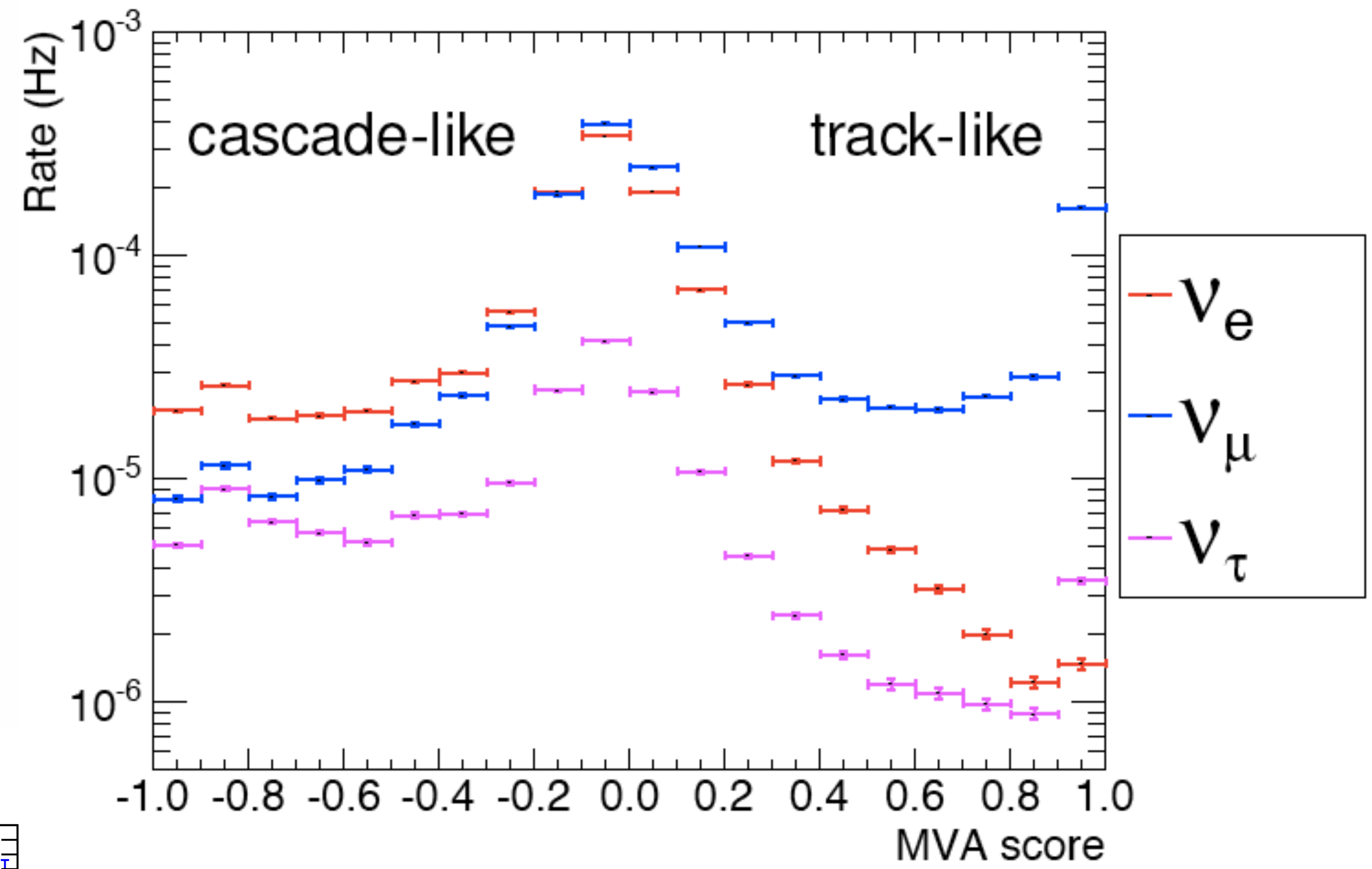
- Once detector resolutions are included the signature of the hierarchy is apparent by looking at the pattern of expected excesses and deficits in the E vs. cos(θ_z) plane
  - Structure of the pattern gives some protection against systematics
  - Note: reconstructions included in these plots, but not yet particle ID

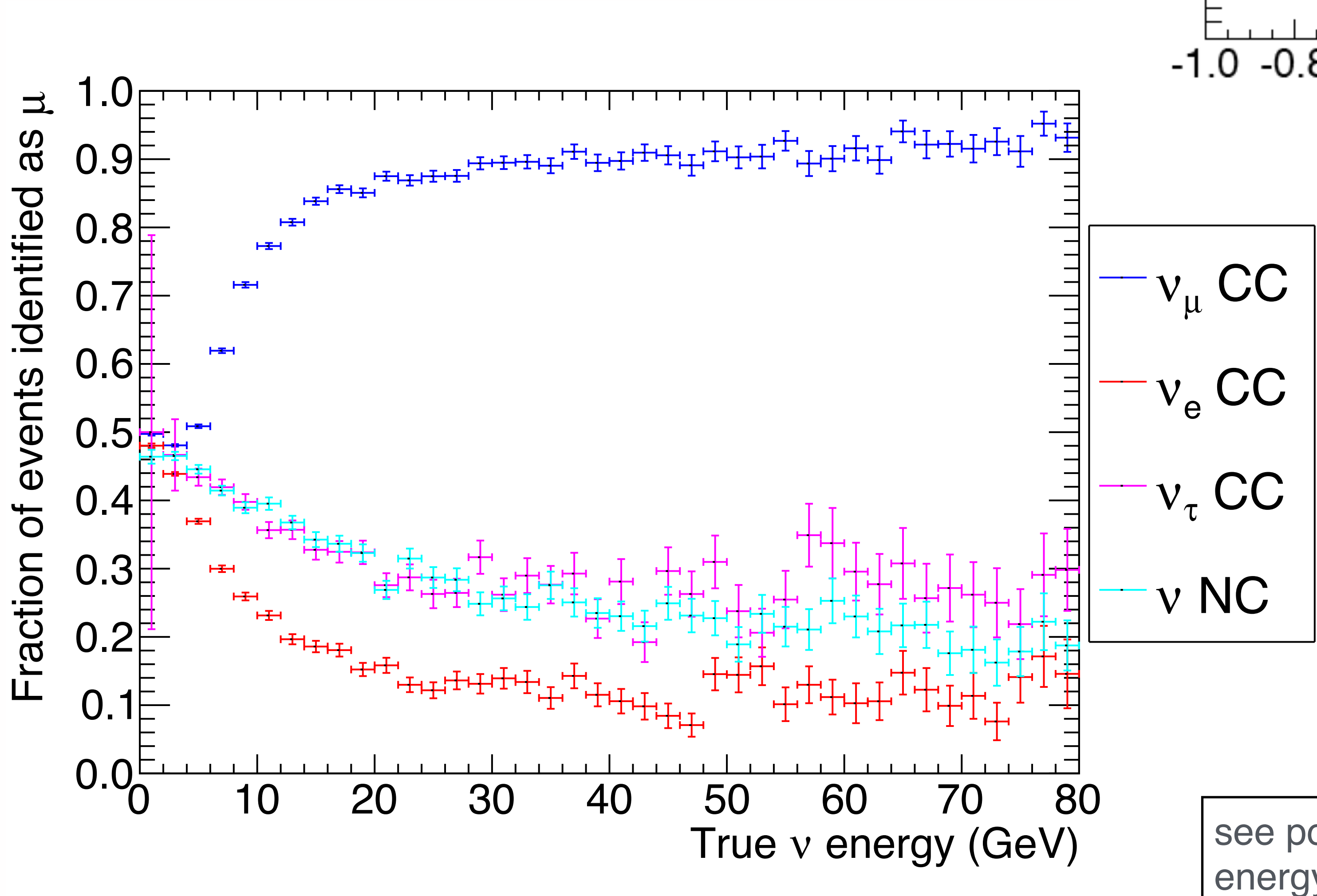
following JHEP, 2013(02):, pp. 1-39



PINGU Particle ID

- ν_μ CC events distinguishable by the presence of a muon track
  - Distinct signatures observable in both track (ν_μ CC) and cascade (ν_e and ν_τ CC, ν_x NC) channels

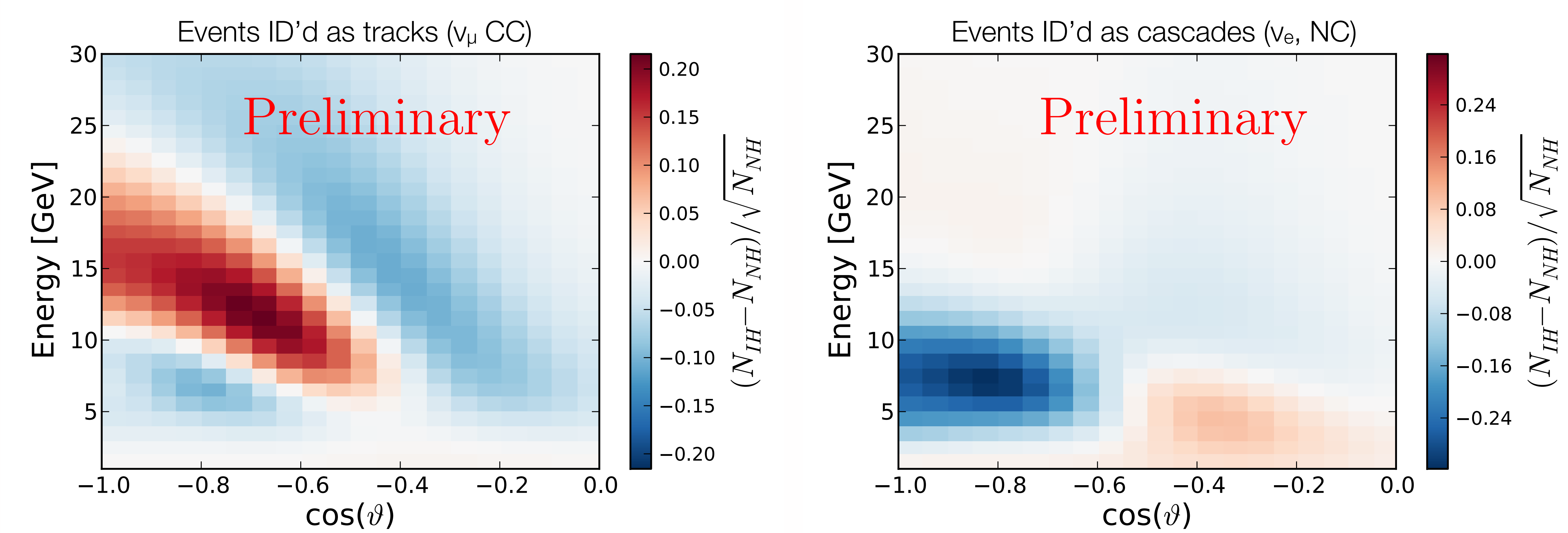




see poster "Event reconstruction and particle identification for low energy events in DeepCore and PINGU" by Tim Arlen et al.

PINGU and the NMH

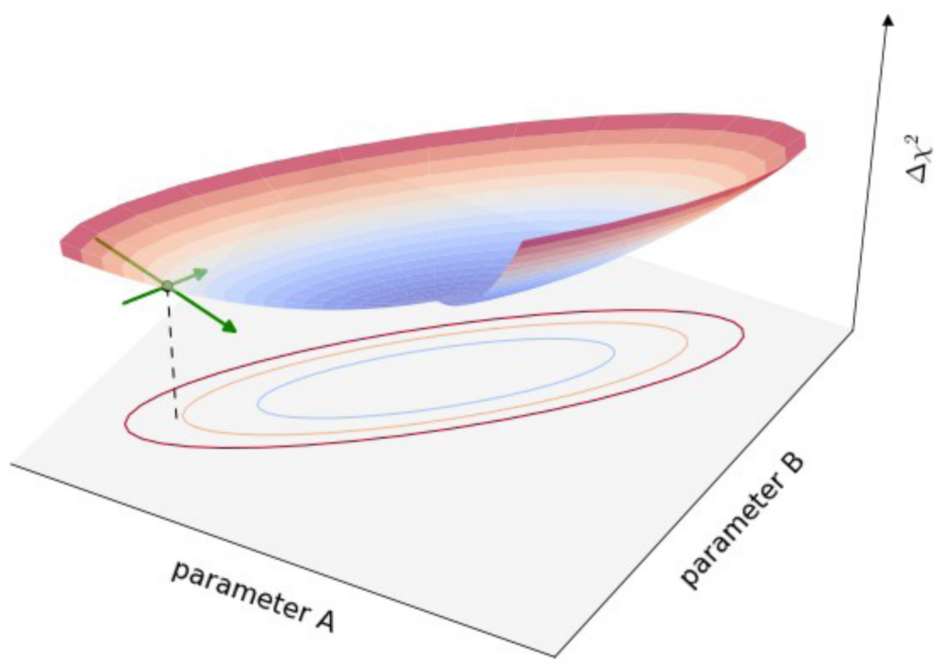
arXiv:1401.2046



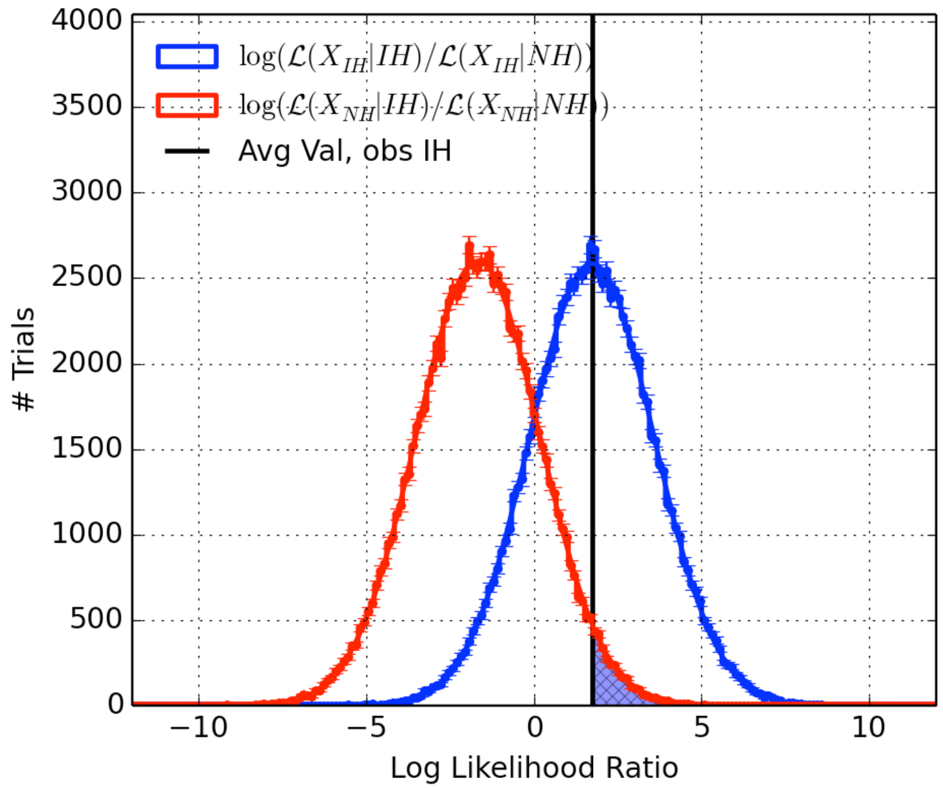
- Distinctive (and quite different) hierarchy-dependent signatures are visible in both the track and cascade channels
    - Full MC for detector efficiency, reconstruction, and particle ID included

PINGU and the NMH - extracting the sensitivity

Fisher Information Matrix



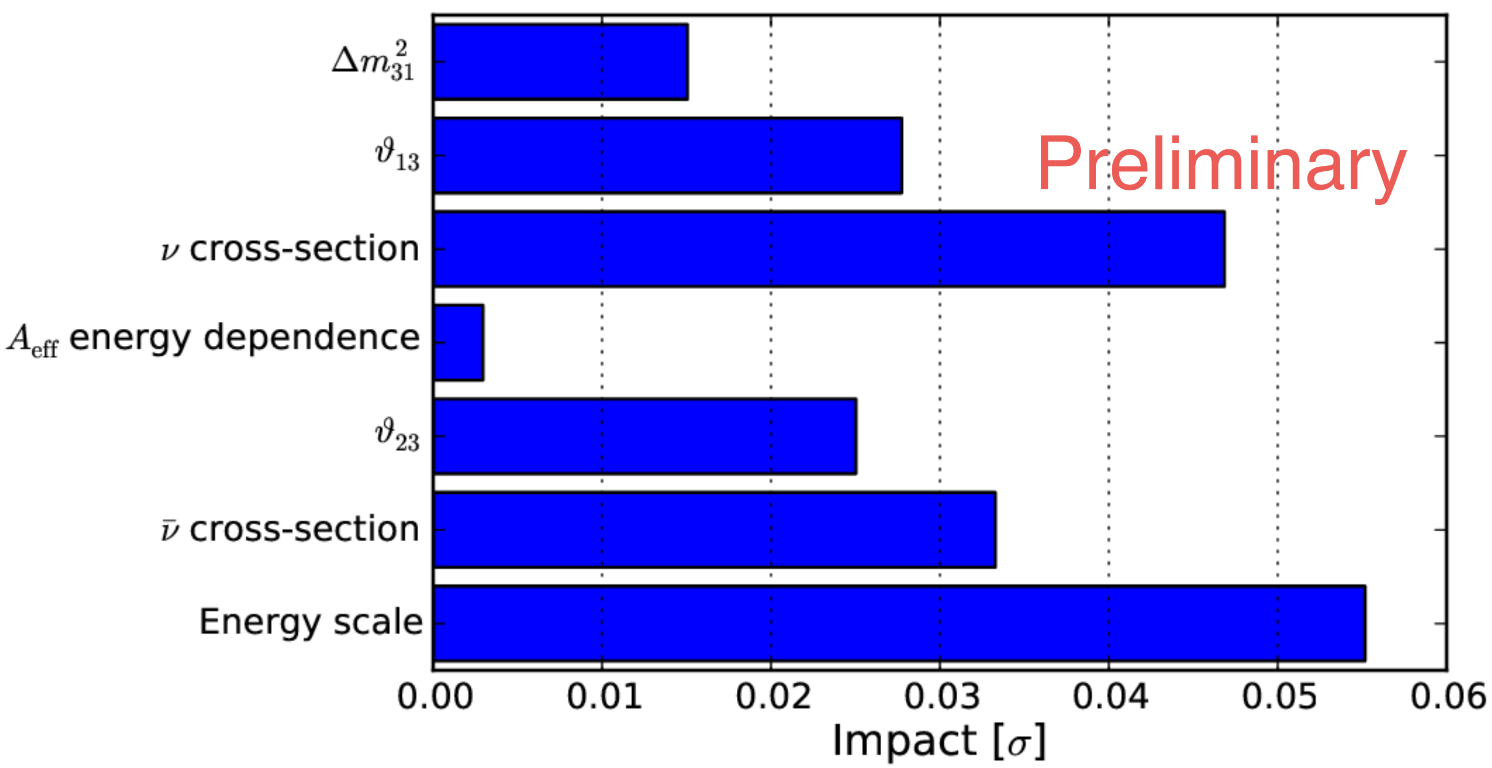
Likelihood Ratio Analysis



- Estimations from the full simulation operating on event histograms in Energy and cos(zenith)
  - Fast evaluation using the Fisher Information Matrix (FIM) where the gradients at each point fully describe the parabolic minimum (invert and obtain the full covariance matrix for the experiment
  - Full analysis from pseudo data sets applied as templates; LLR provides degree of agreement between pseudo set and one hierarchy vs. the other.
  - The Likelihood distributions are fit well by Gaussians; the two methods agree

see poster “Calculating PINGU’s sensitivity to the neutrino mass hierarchy” by Lukas Schulte et al.

PINGU and the NMH - applying the systematics



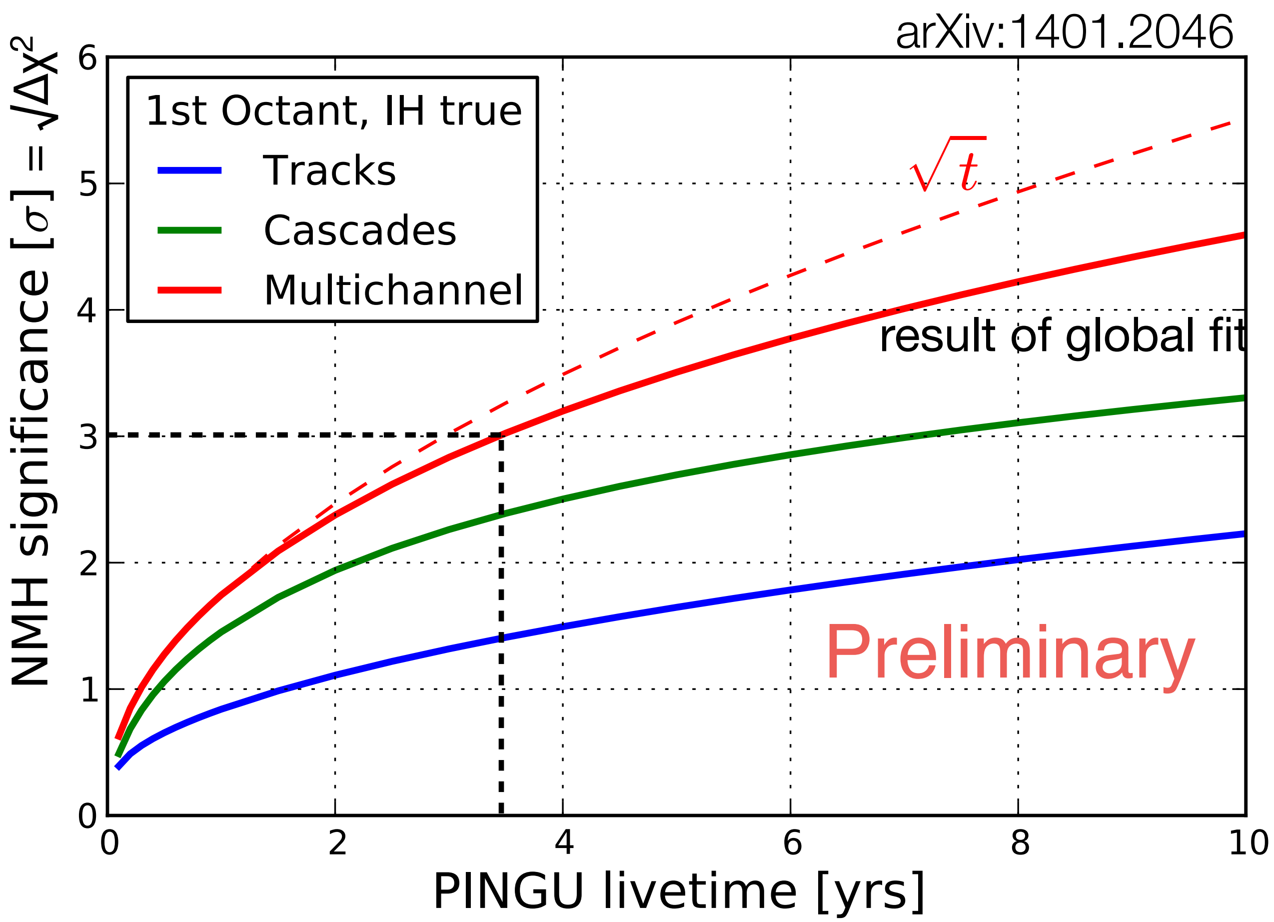
Parameter	Description
Δm^2_{31}, ϑ_{23}, ϑ_{13}	Oscillation parameters
ν / $\bar{\nu}$ cross-section	Cross-section/flux normalization (fully degenerate)
A_{eff} energy dependence	Degenerate with spectral index of atmospheric flux
Energy scale	E_{reco}/E_{true}

- Strongest impact from the Energy Scale and cross-section normalization, δ_{CP} has a minimal effect.
- Additional systematics currently being incorporated:
  - Particle ID performance
  - Cross-section details
  - Ice Model

see poster "Calculating PINGU's sensitivity to the neutrino mass hierarchy" by Lukas Schulte et al.

PINGU and the NMH - predicted sensitivity

- With baseline geometry, a determination of the mass hierarchy with 3σ significance appears possible with 3.5 years of data
  - Primary estimate uses parametric detector response model based on simulations
  - Vetted against full Monte Carlo studies with more limited statistics and range of systematics
- Optimization of detector geometry & analysis techniques and more detailed treatment of systematics underway



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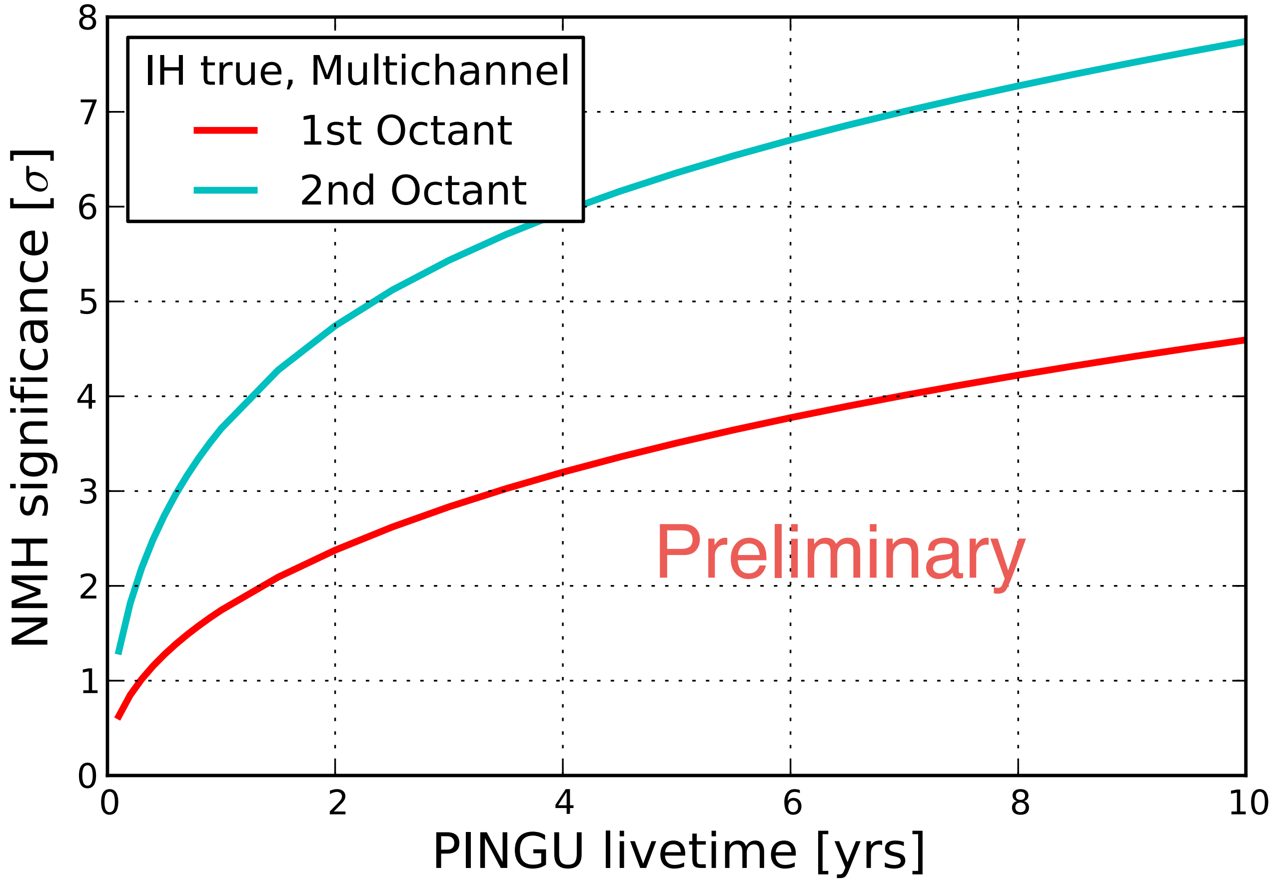
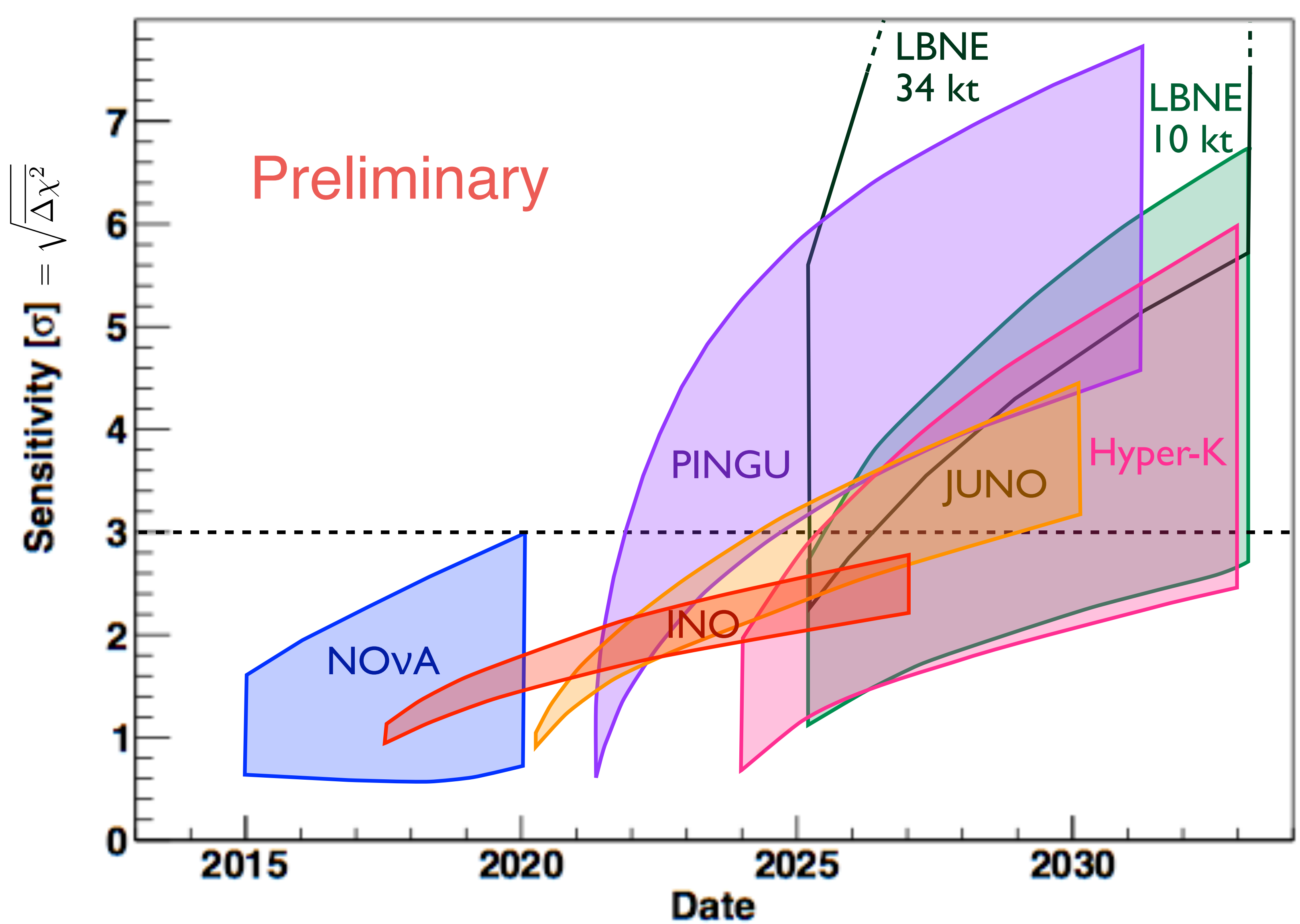


see poster "Calculating PINGU's sensitivity to the neutrino mass hierarchy" by Lukas Schulte et al.

PINGU and the NMH - in broad context

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

after Blennow et al., arXiv:1311.1822



- LBNE from LBNE-doc-8087-v10, Hyper-K from arXiv:1109.3262 (2011), all others from Blennow

PINGU and the NMH - comparison to ORCA

- ORCA uses a similar design philosophy to PINGU
- Assumed is the first octant with fits to the oscillation parameters
- Included is some misidentification of rate based on MC
- Not yet included are overall flux and interaction uncertainty, NC events

~3x the photocathode of PINGU DOM

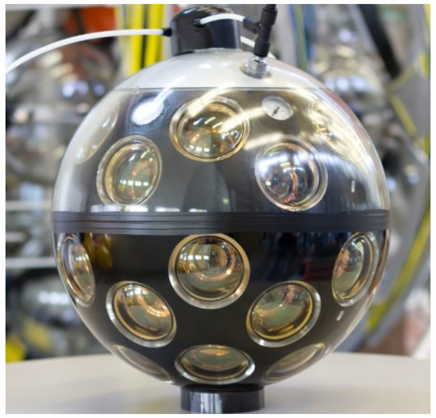
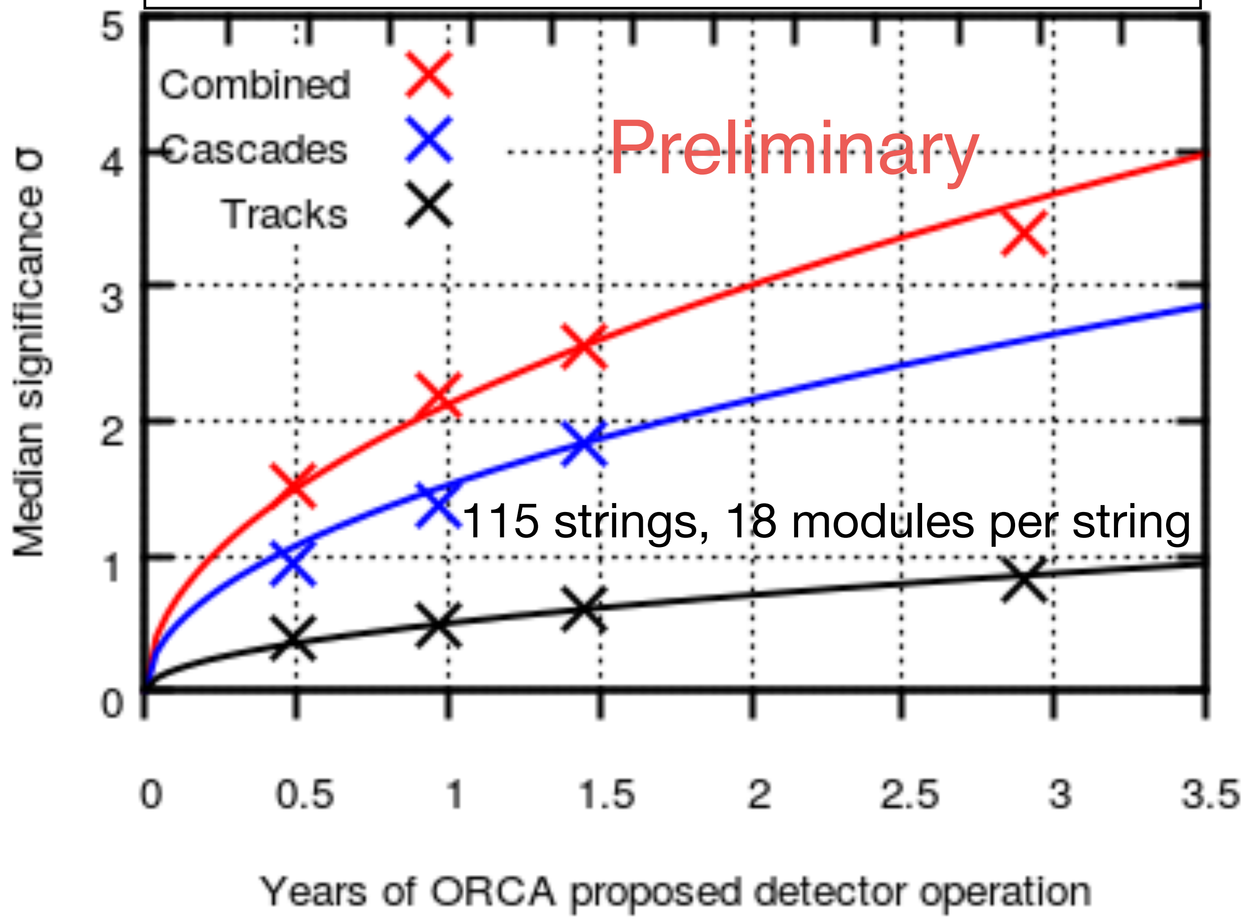


figure see talk yesterday Maarten de Jong; for details see poster Antoine Kouchner



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- Assumed is the first octant with fits to the oscillation parameters
- Included is some misidentification of rate based on MC
- Not yet included are overall flux and interaction uncertainty, NC events
- The individual track and cascade channels are similar; things are roughly consistent between the independent detector designs and analyses.

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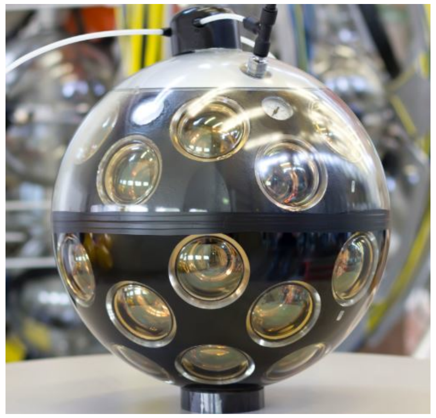

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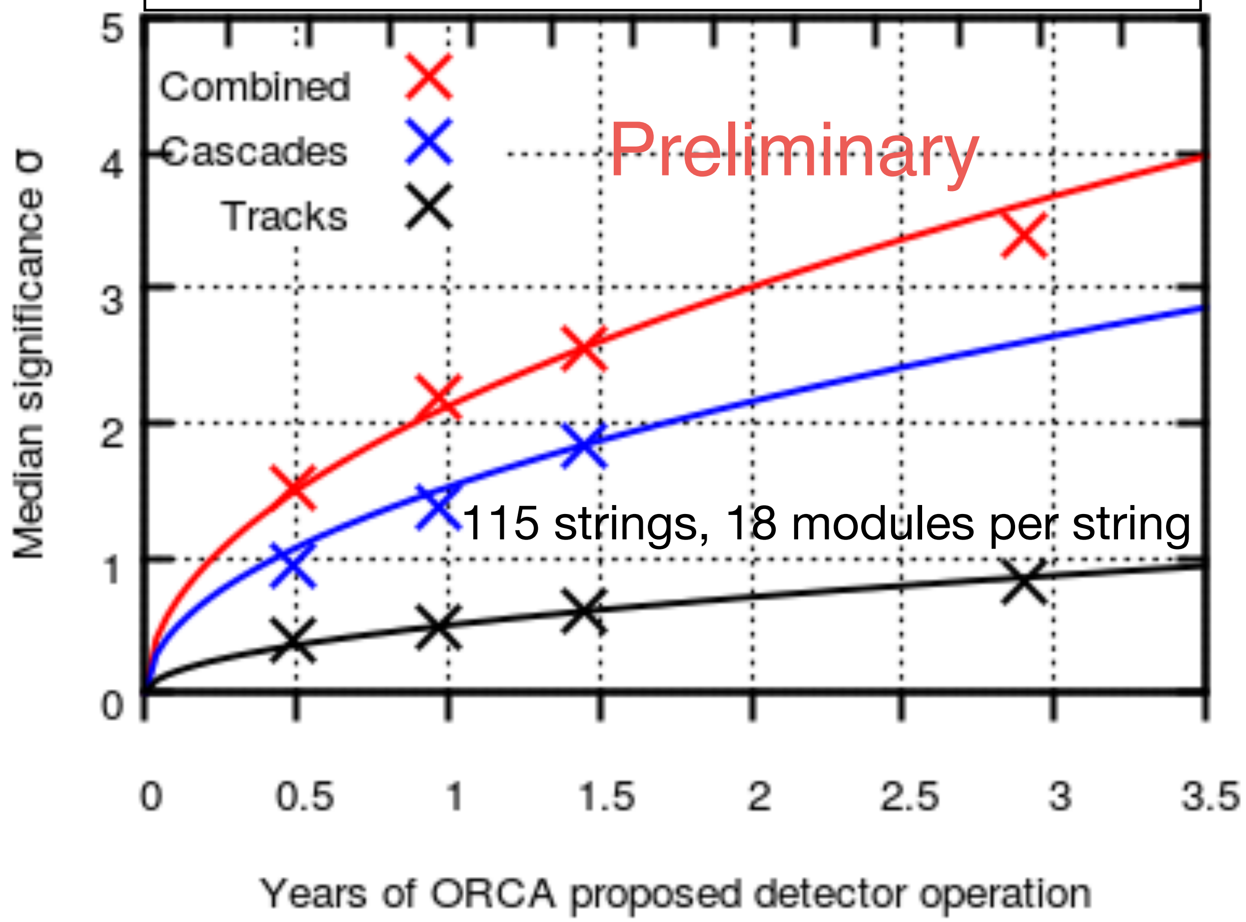
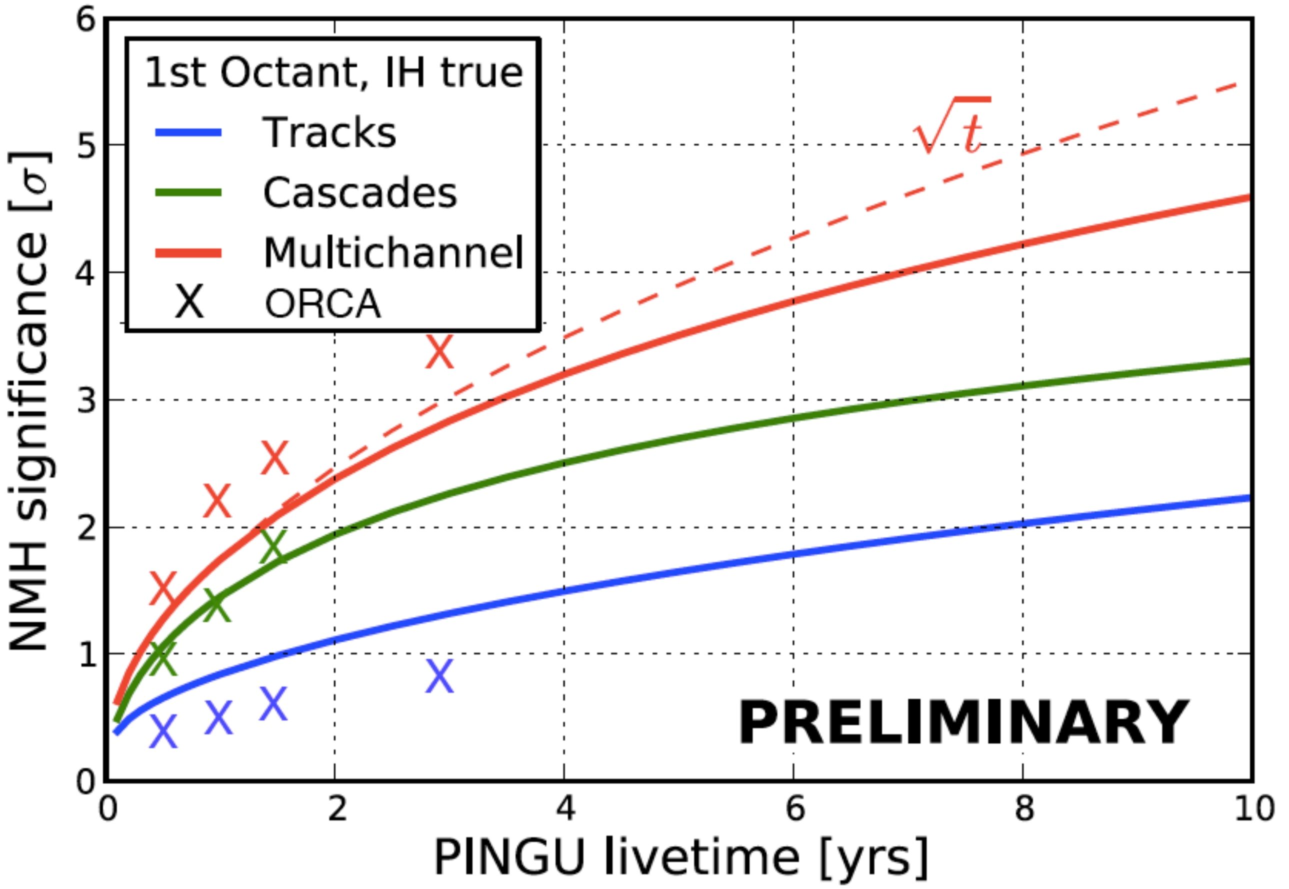


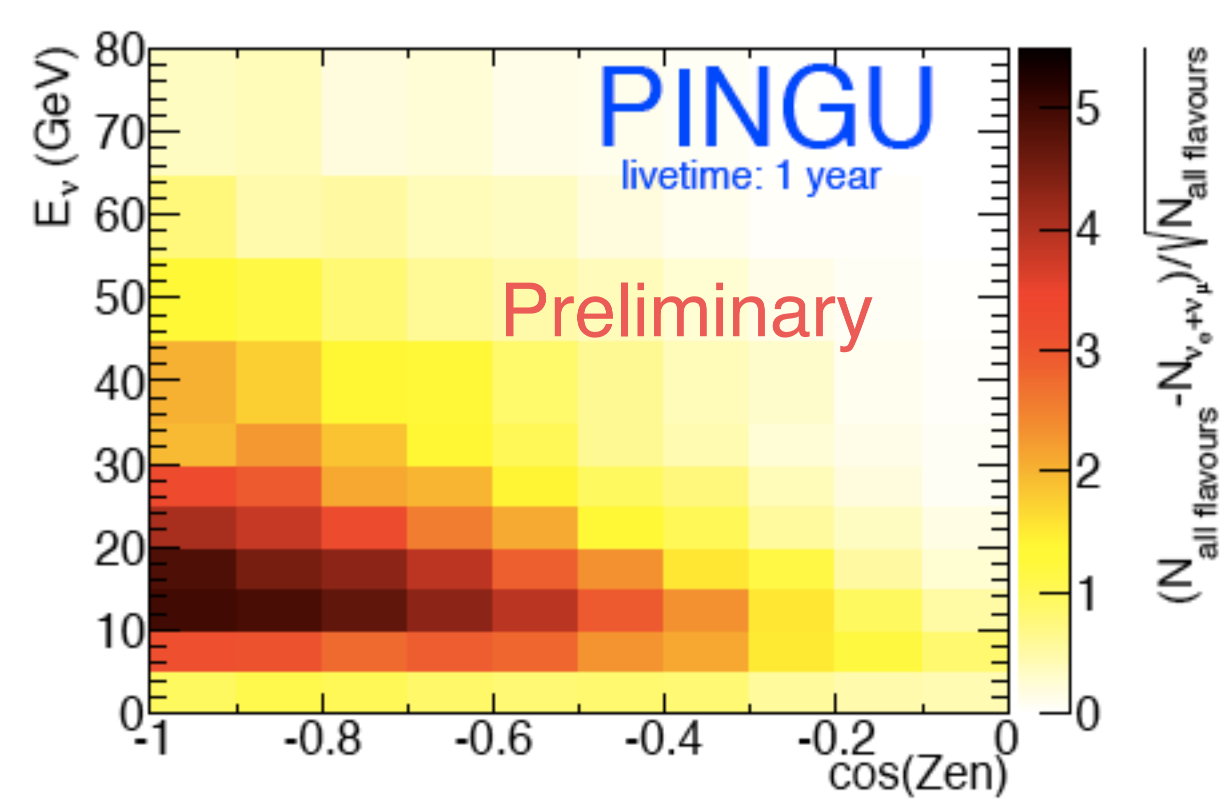


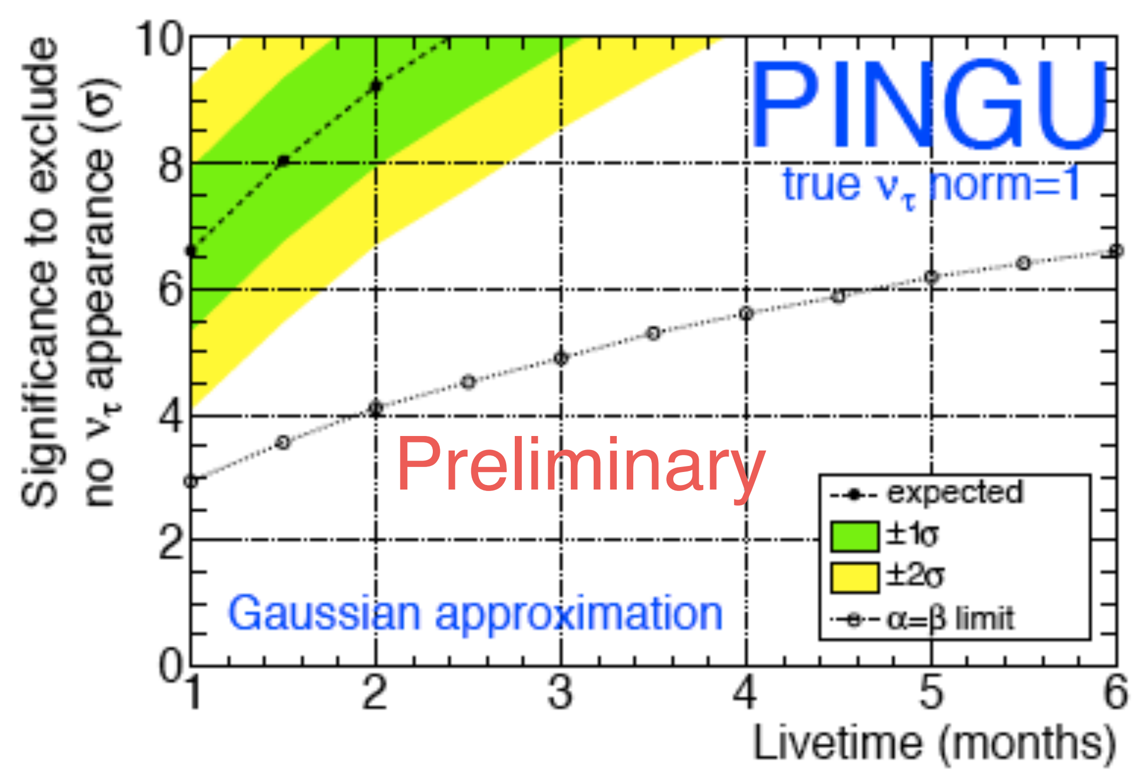
PINGU and non-NMH atmospheric measurements- ν_τ appearance

- Provides a test of the unitarity of the mixing matrix

- Selection of events currently uses same criteria as for the NMH analysis with the goal now to reject atmospheric muons. Improvements are under development.

- Same trained BDT as the NMH analysis for selecting “pure” cascade-like events



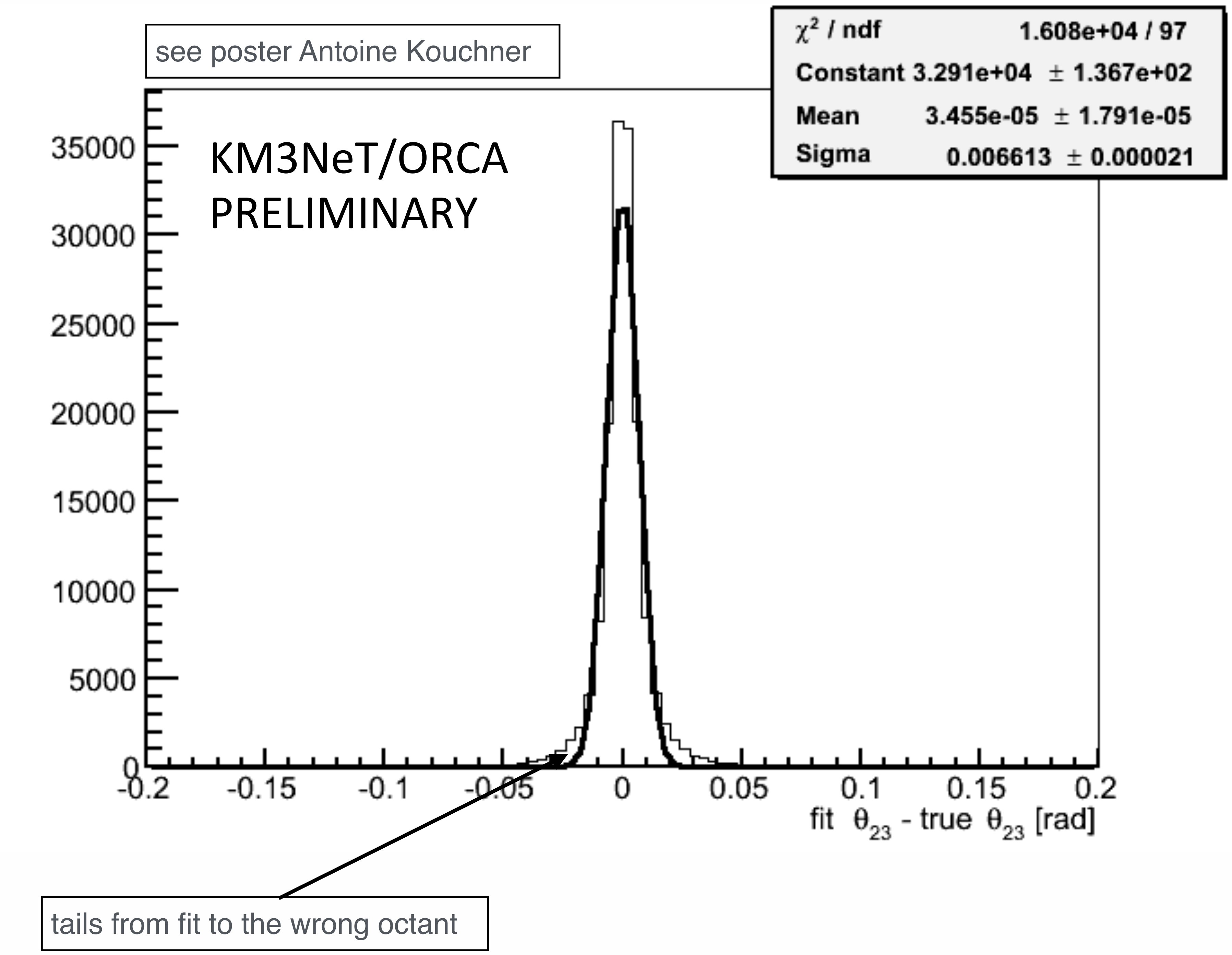


- 5σ exclusion of no ν_τ appearance expected after 1 month of data; 10% precision in the ν_τ normalization after 6 months.

see poster “Sensitivity to ν_τ appearance with DeepCore and PINGU” by Joao Pedro Athayde Marcondes de Andre

Sensitivity to θ_{23}

- Expected error on θ_{23} after 3 years of running the proposed ORCA detector can be reduced to 6.6 mrad (around a factor of 4 improvement over current sensitivity)

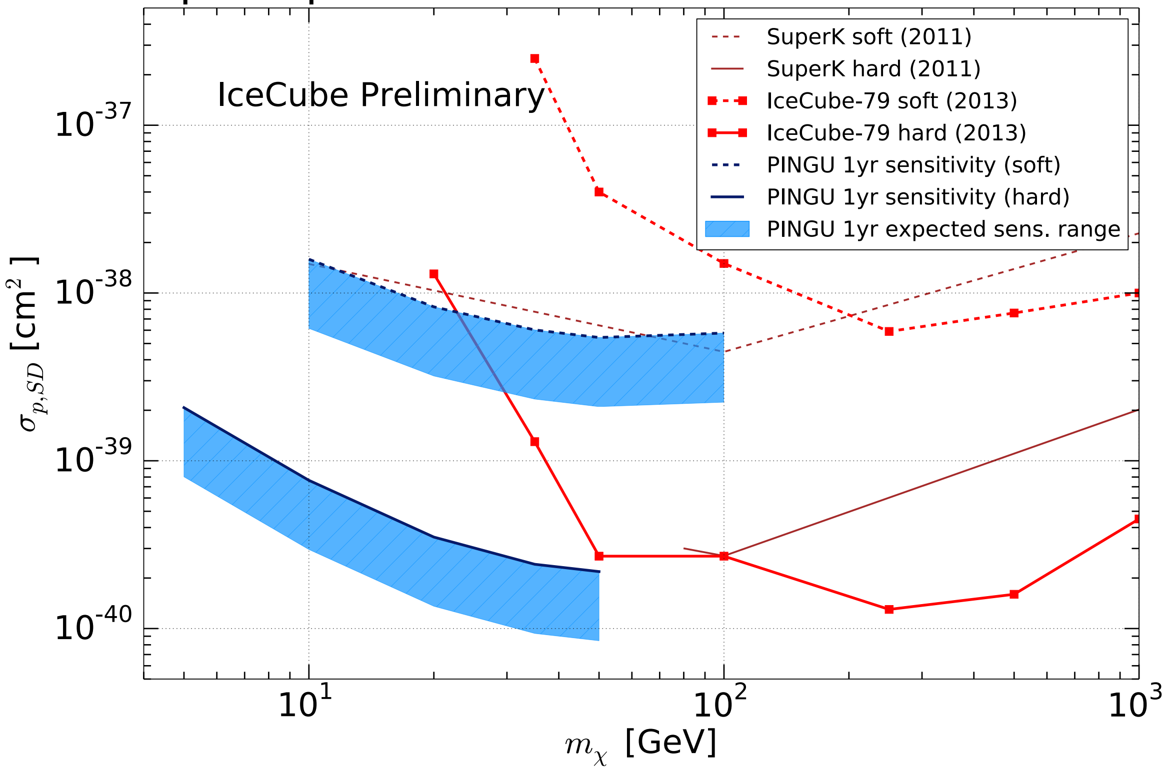


Summary and Outlook

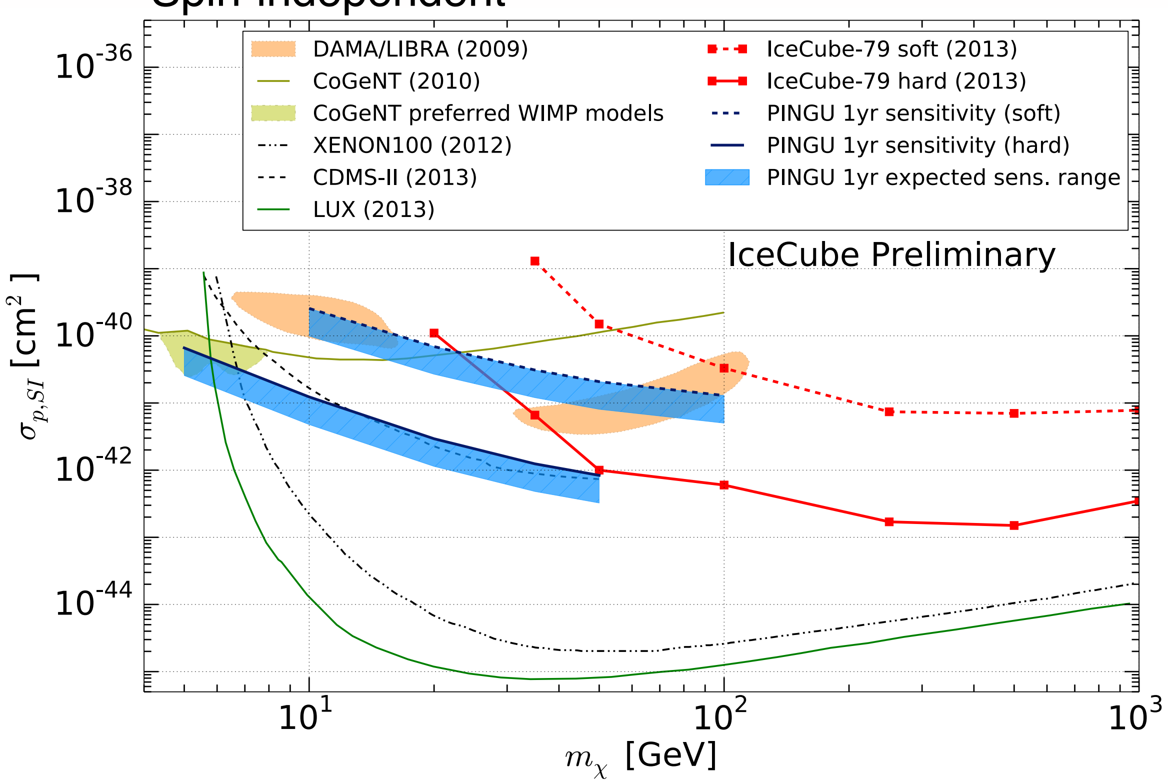
- IceCube and DeepCore paved the way: demonstration of a prolific low-energy neutrino physics in the Antarctic ice with leading sensitivity in the indirect dark matter search and a robust atmospheric neutrino oscillation programs of IceCube.
- PINGU is being optimized
  - String and optical module placement has a fairly broad minimum for the NMH sensitivity.
  - Additional detectors (increasing from 60 to 96 modules per string) improves the resolution at low energies, significantly moving the 3 year significance from 2.8σ to nearly 3.3σ for a 10% increase in project cost.
- Beyond a rich program in atmospheric neutrino measurements, PINGU will increase the sensitivity to the low-mass indirect WIMP searches, supernova neutrinos, Earth tomography…

PINGU indirect dark matter search

Spin-dependent



Spin-independent



Summary and Outlook

- PINGU advantages include:
  - Use of the similar hardware and deployment techniques as IceCube would significantly reduce project risk
  - Could be quick, dependent on funding (2 years of procurement and fabrication; 2-3 years of deployment)
  - Is a natural part of a Next Generation IceCube Observatory (high energy extension, surface veto array). P5 final draft report "...and we encourage continued work to understand systematics. PINGU could play a very important role as part of a larger upgrade of IceCube, or as a separate upgrade, but more work is required."
  - NSF MREFC, and international partner proposals are now in preparation (still early days; interested? come visit us)
- PINGU as a potential stepping stone: acting as a testbed for new photodetectors could lead to a multi-megaton fiducial detector (MICA) reaching a O(10 - 100 MeV) in the ice (supernova neutrinos, very low-mass WIMP searches, (potentially) proton decay).

The IceCube–PINGU Collaboration

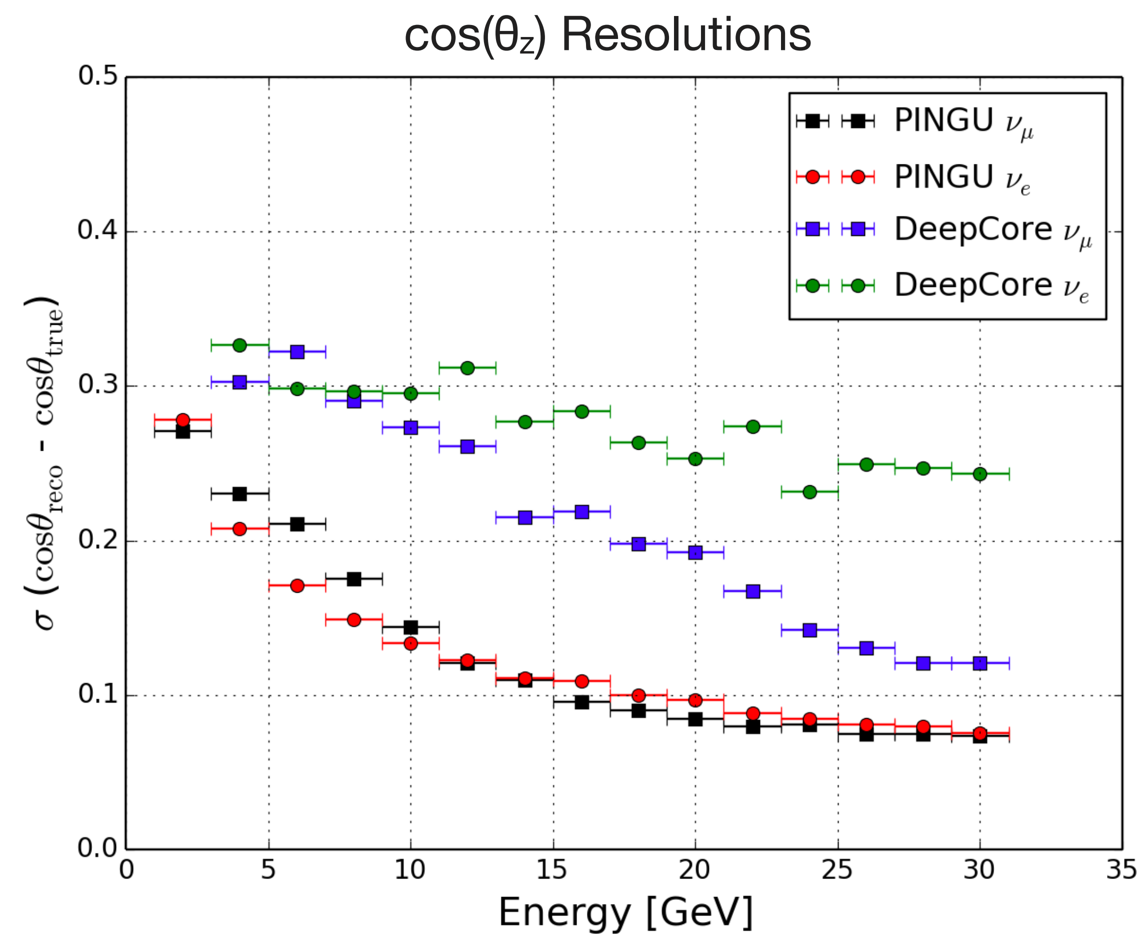
International Funding Agencies

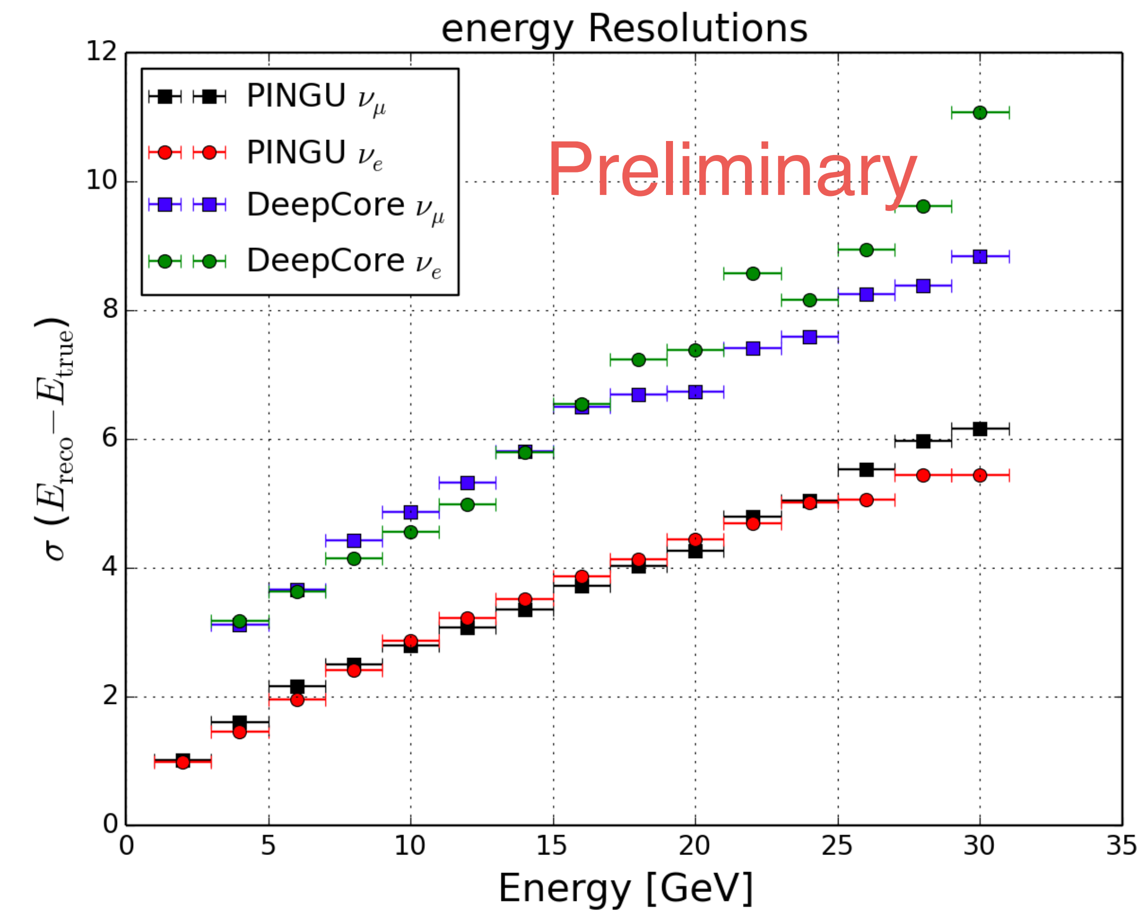
Fonds de la Recherche Scientifique (FRS–FNRS)
Fonds Wetenschappelijk Onderzoek–Vlaanderen (FWO–Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen–Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
NSF–Office of Polar Programs
NSF–Physics Division
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Backup slides

PINGU event reconstruction

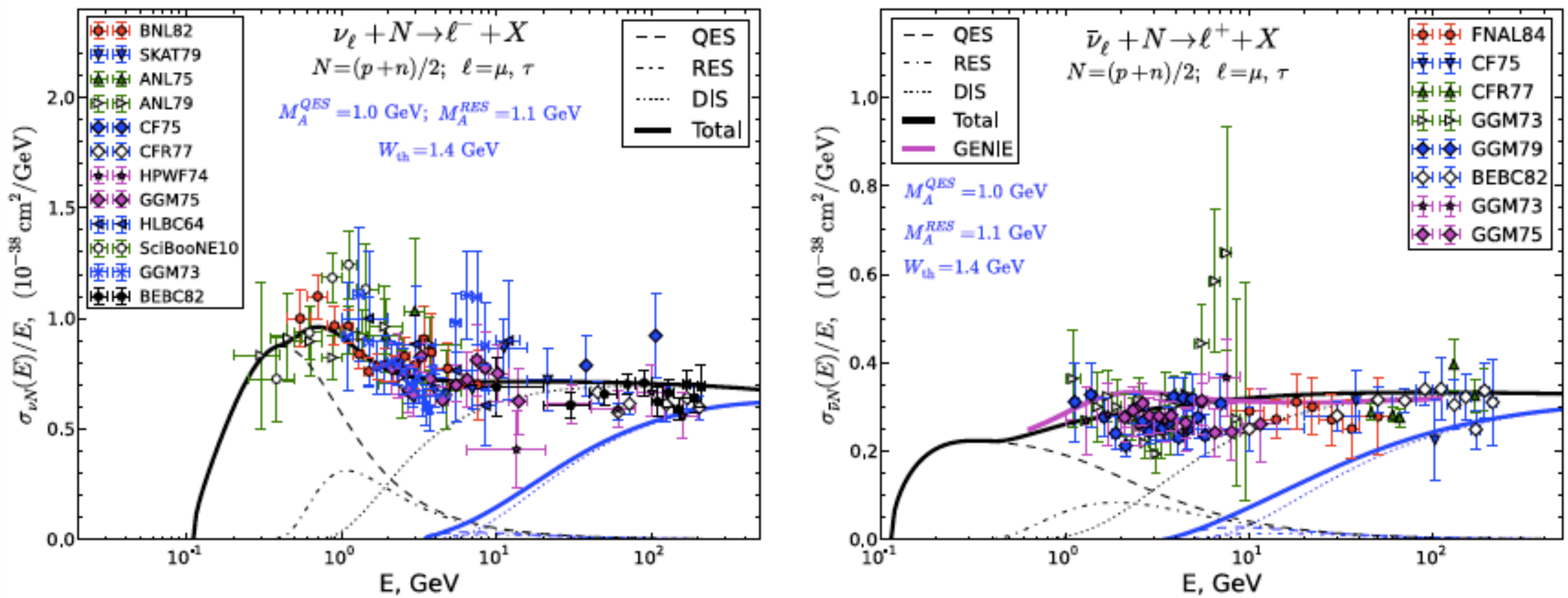
- Matter effects alter oscillation probabilities for neutrinos or antineutrinos traversing the Earth
  - Maximum effects seen for specific energies and baselines (= zenith angles) due to the Earth's density profile
  - Neutrino oscillation probabilities affected if hierarchy is normal, antineutrinos if inverted
  - Rates of all flavors are affected





see poster "Event reconstruction and particle identification for low energy events in DeepCore and PINGU" by Tim Arlen et al.

PINGU cross-section systematics under study

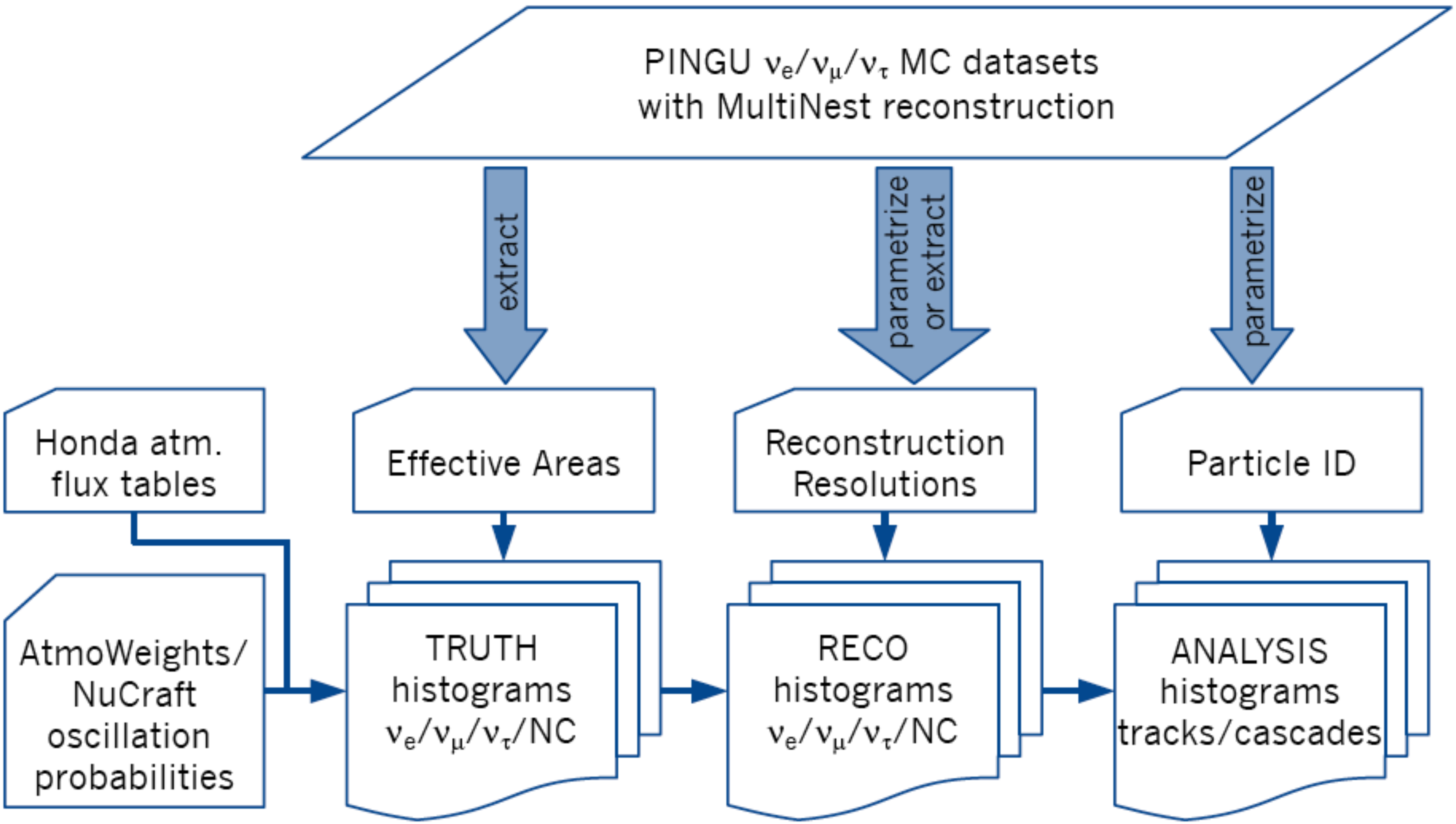


(a) Neutrino cross-sections

(b) Anti-neutrino cross-sections

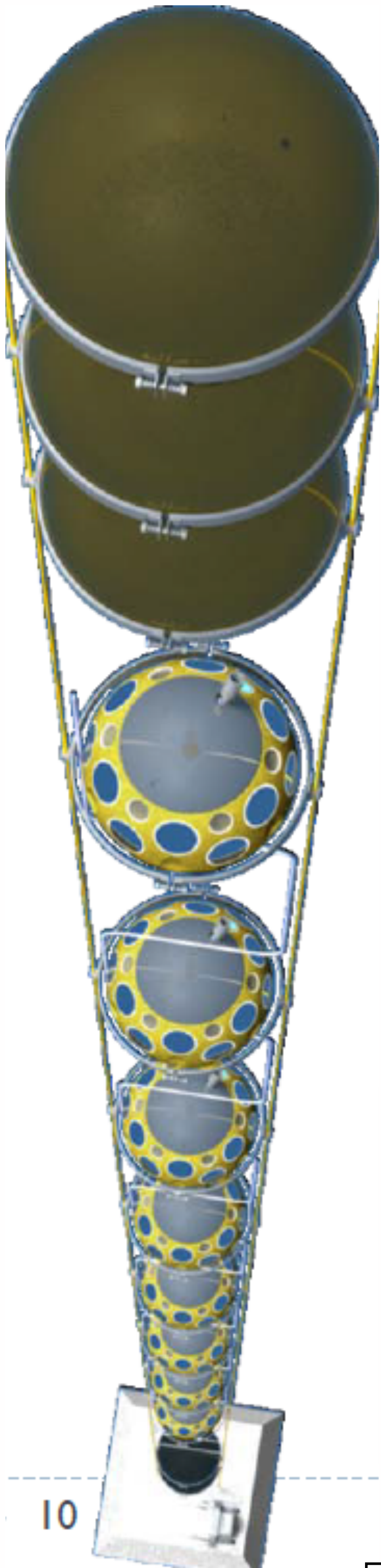
PINGU's energy region of interest is dominated by DIS with small contributions from QES and RES production

Generating fast MC sets for the PINGU FIM analysis



see poster "Calculating PINGU's sensitivity to the neutrino mass hierarchy" by Lukas Schulte et al.

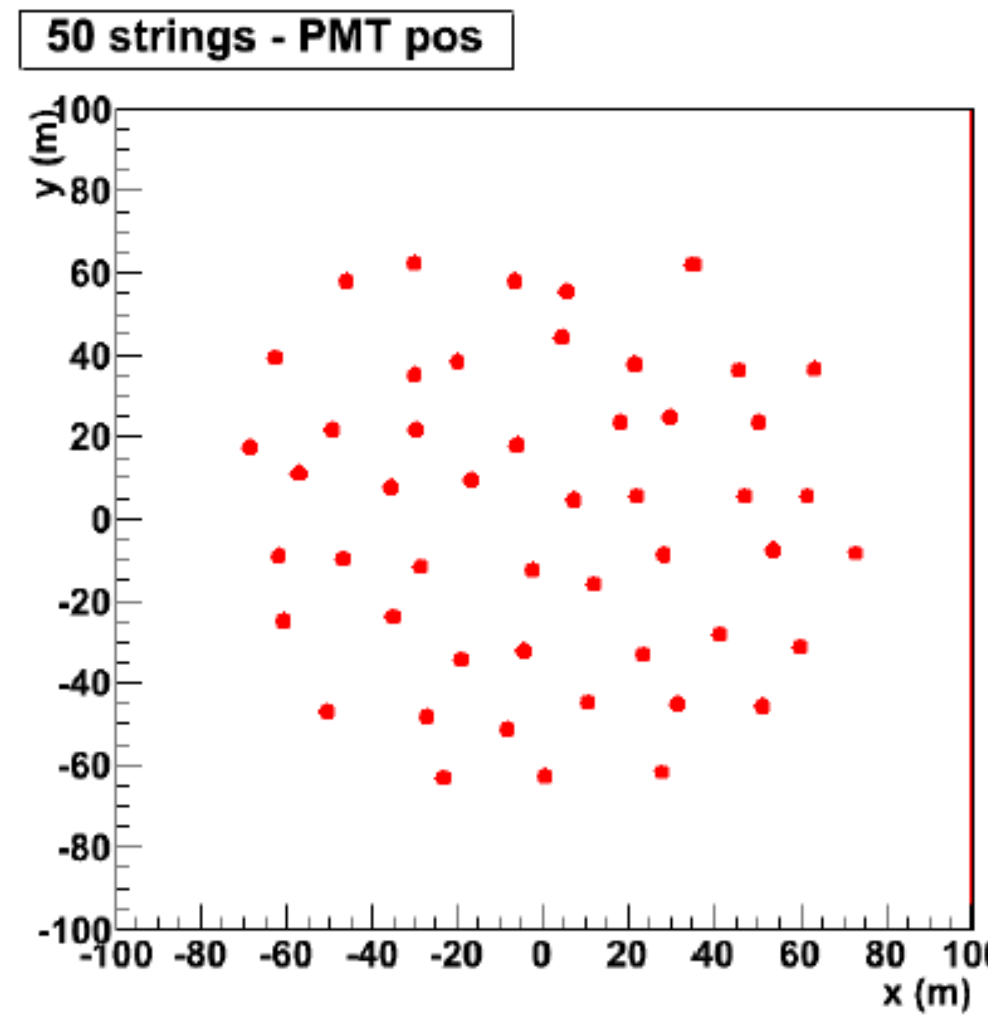
The reference detector



- ORCA detector:
  - 50 strings 20m spaced
  - 20 DOM/string spaced 6m

Instrumented volume:

$\Pi \times 70^2 \times 114 = 1.75$ Mt

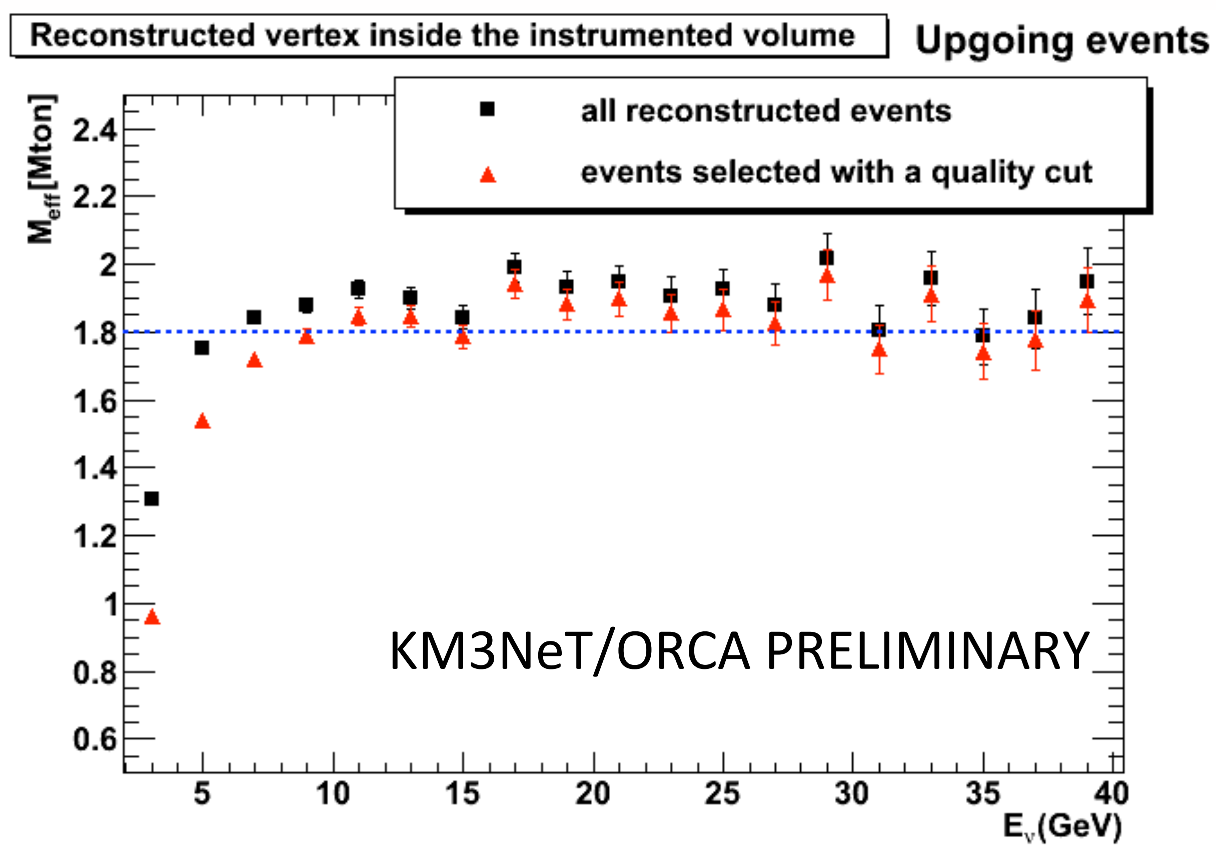


Multi-PMT DOM
31 small PMTs
Almost uniform coverage
Photon counting
Direction of photon
All electronics inside

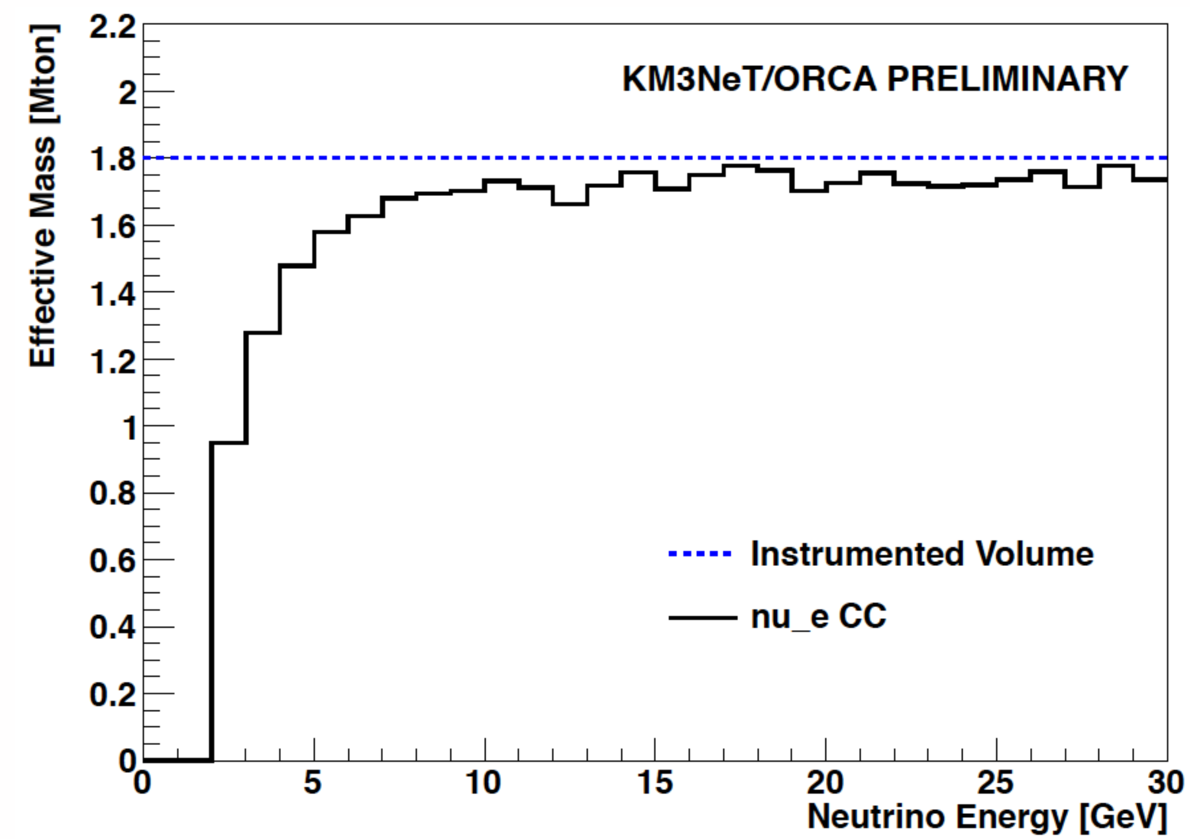
see poster Antoine Kouchner

ORCA - Performance

Reference detector - Fiducial volume



Muon Channel

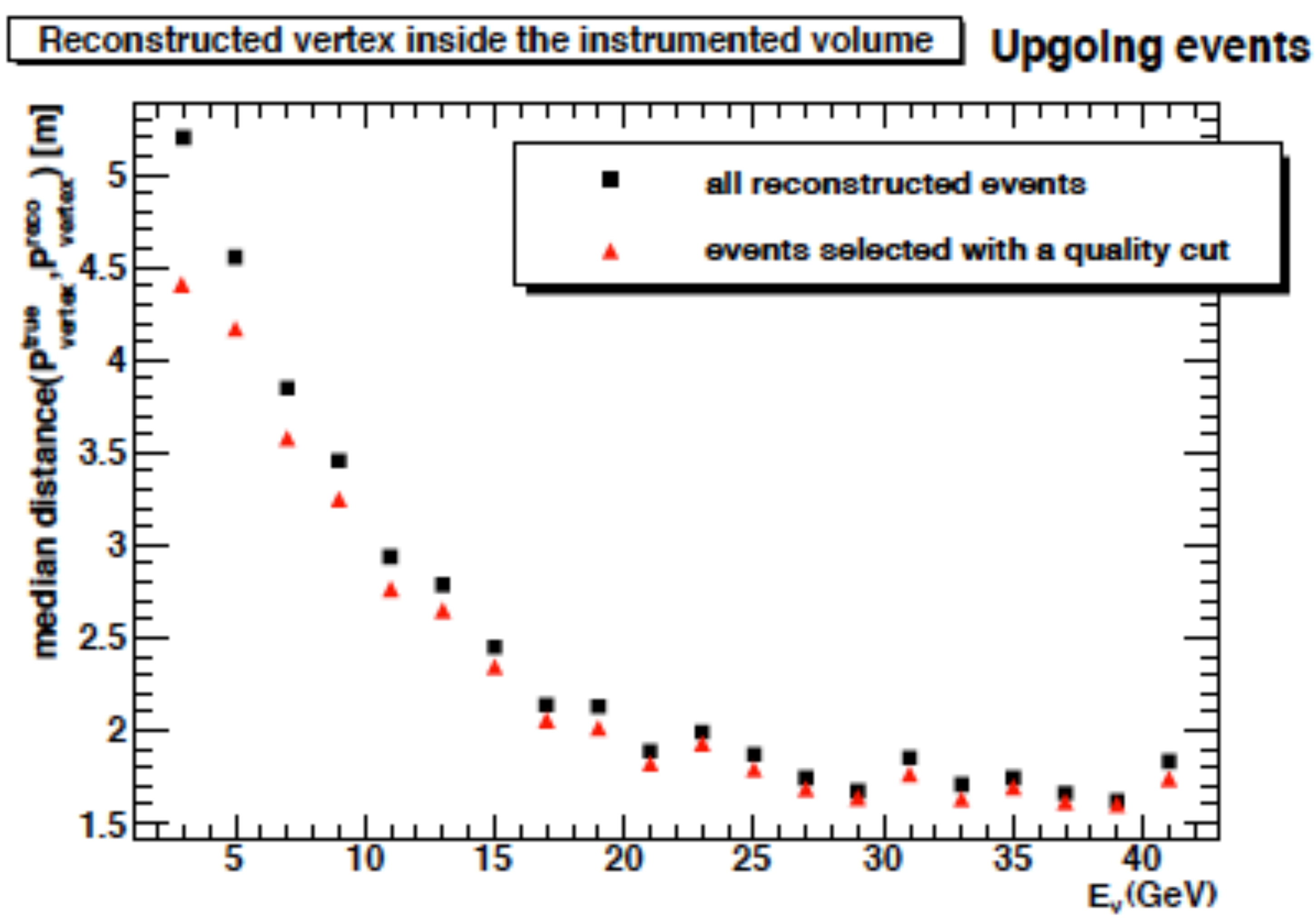


Cascade Channel

see poster Antoine Kouchner

ORCA - Performance in the muon channel

Reference detector - vertex reconstruction

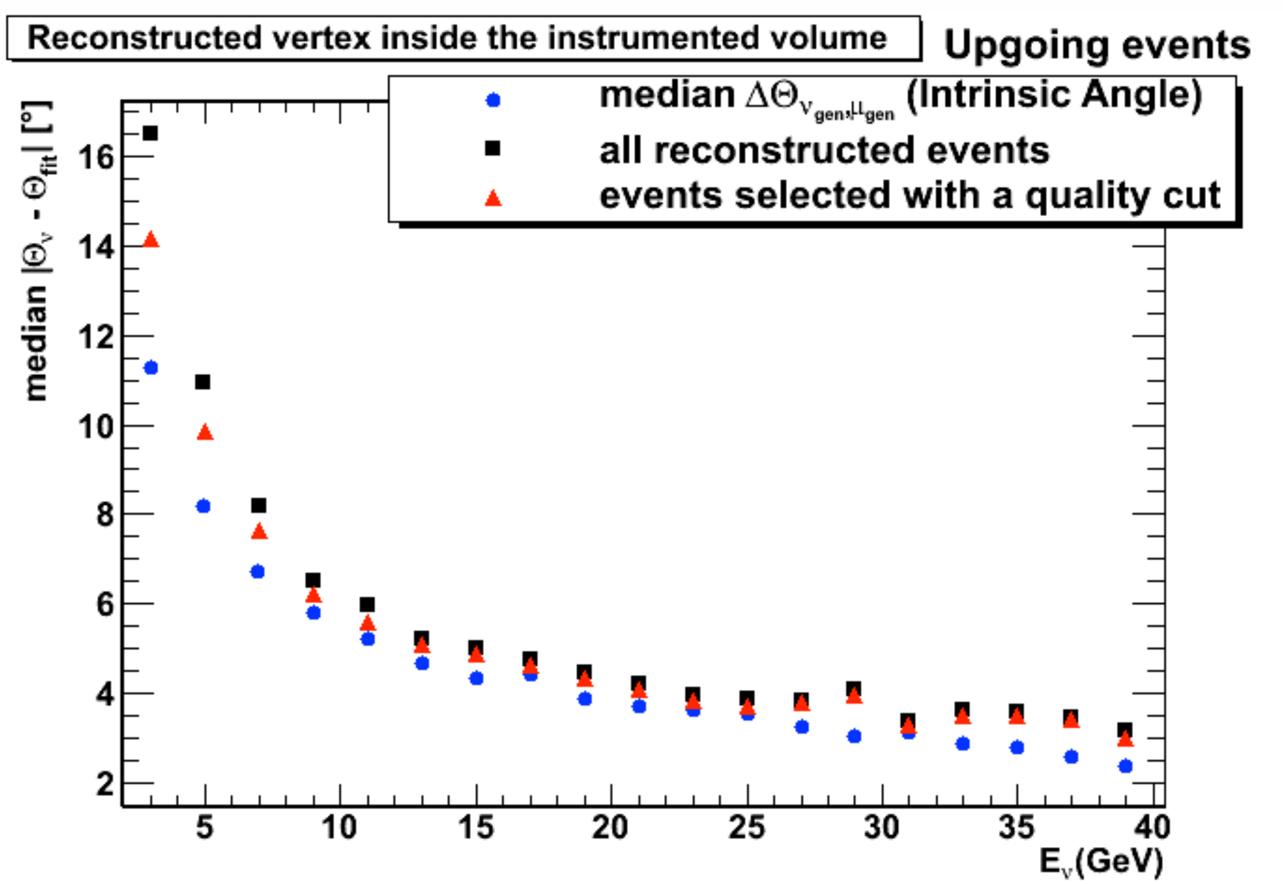


Muon Channel

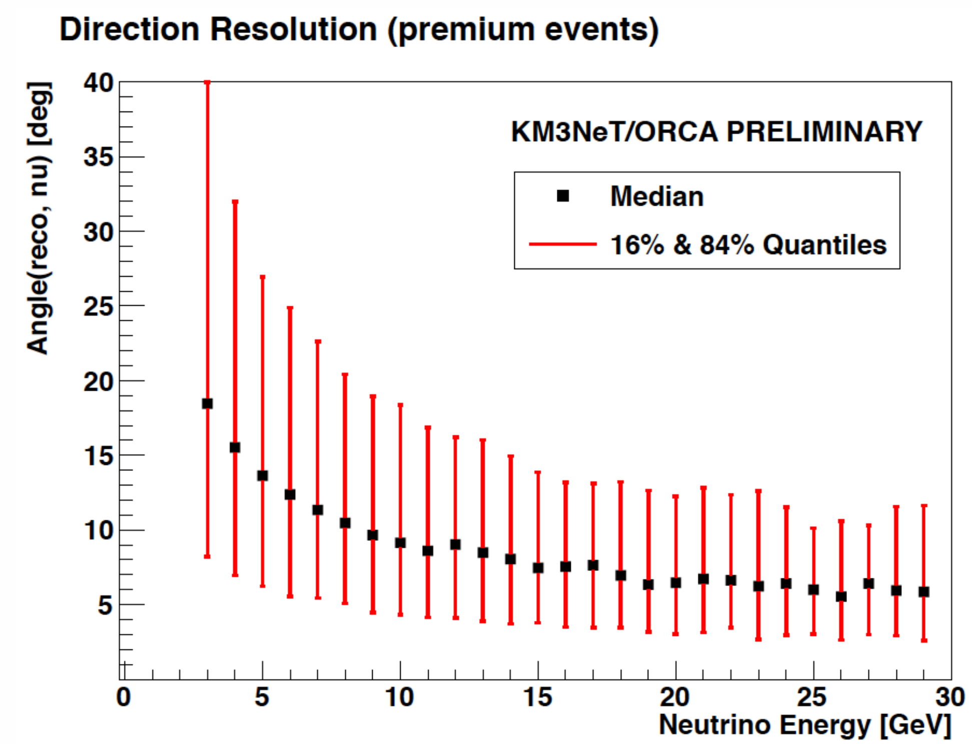
see poster Antoine Kouchner

ORCA - Performance in the muon channel

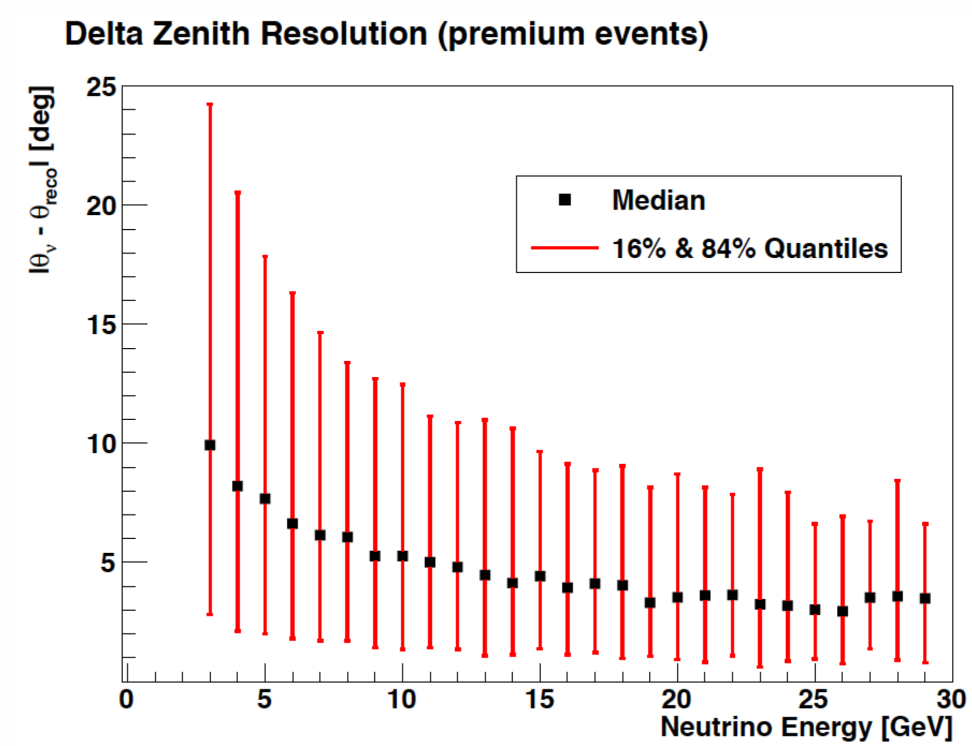
Reference detector - angular resolution



Muon Channel - Zenith Angle



Cascade Channel - Azimuthal Angle



Cascade Channel - Zenith Angle

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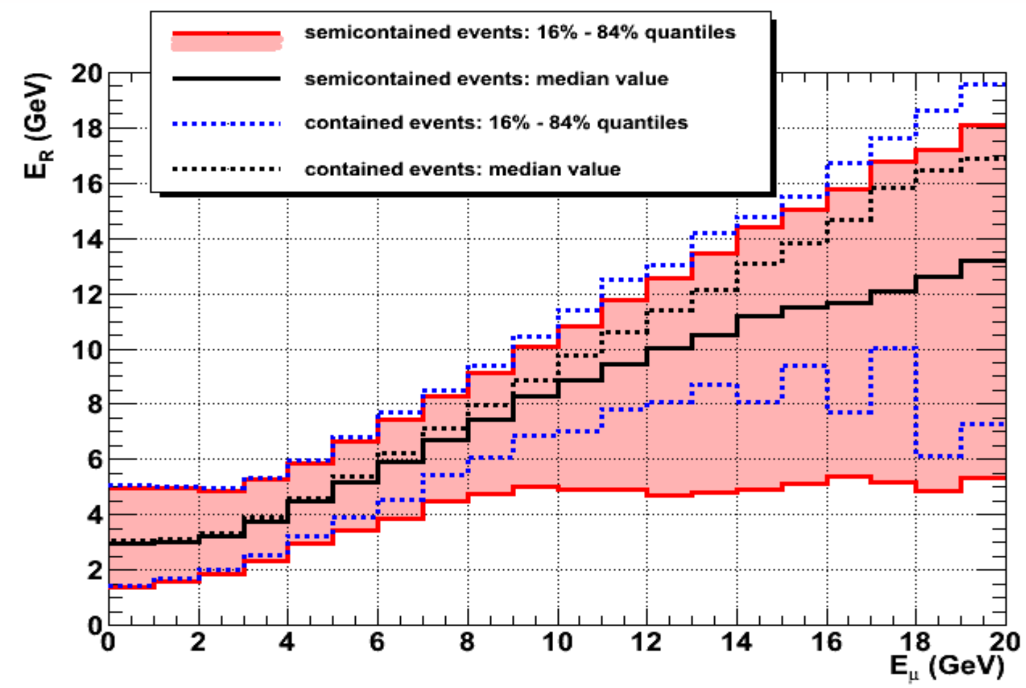
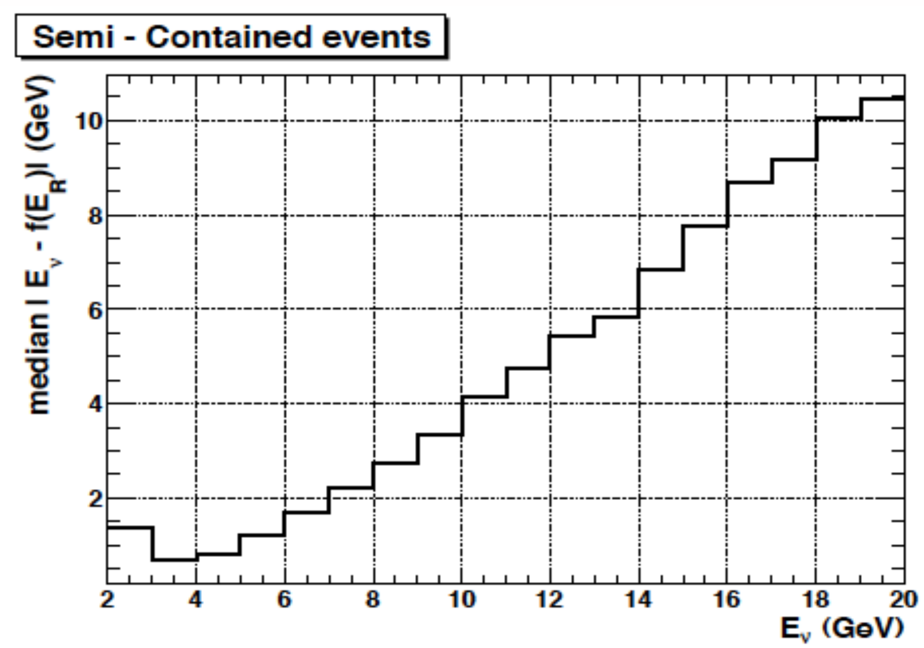
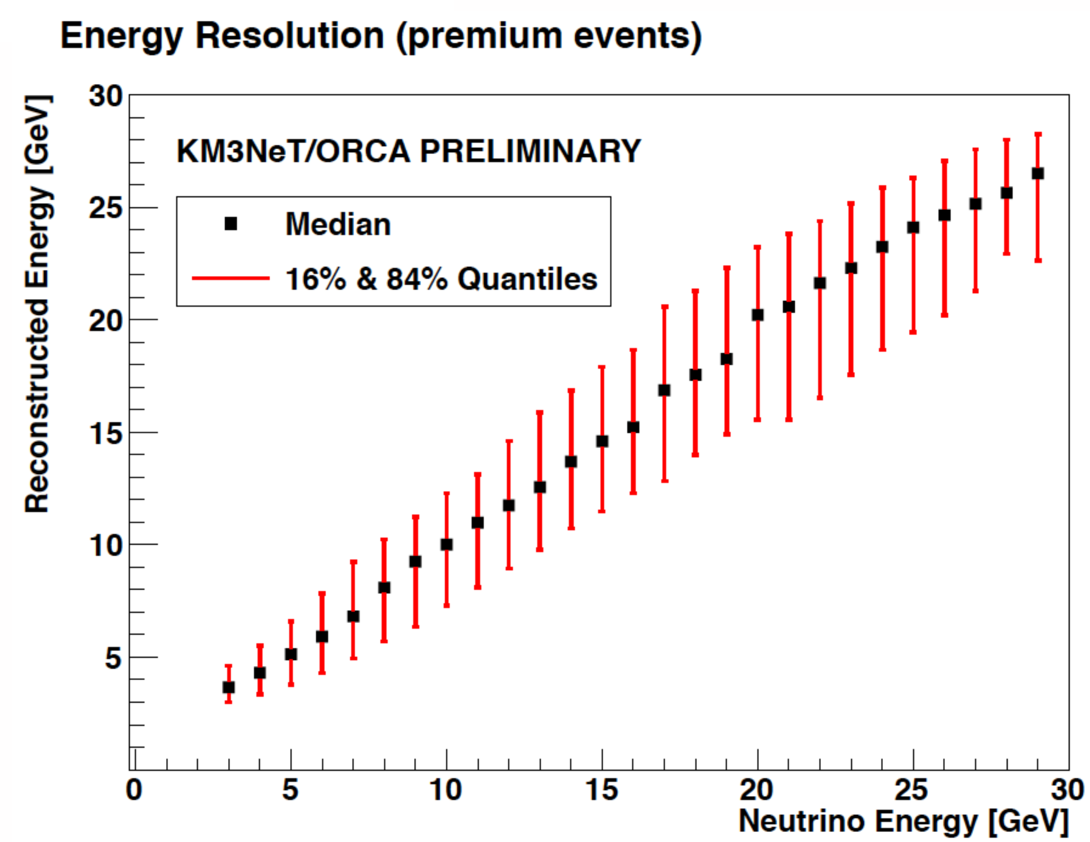
ORCA - Performance in the muon channel

Reference detector - Energy resolution





Muon Channel



- Muon channel currently uses only the length of the muon as the energy estimator. Expect improvements using hits from the initial hadronic cascade.

Cascade Channel

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ORCA - NMH sensitivity

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

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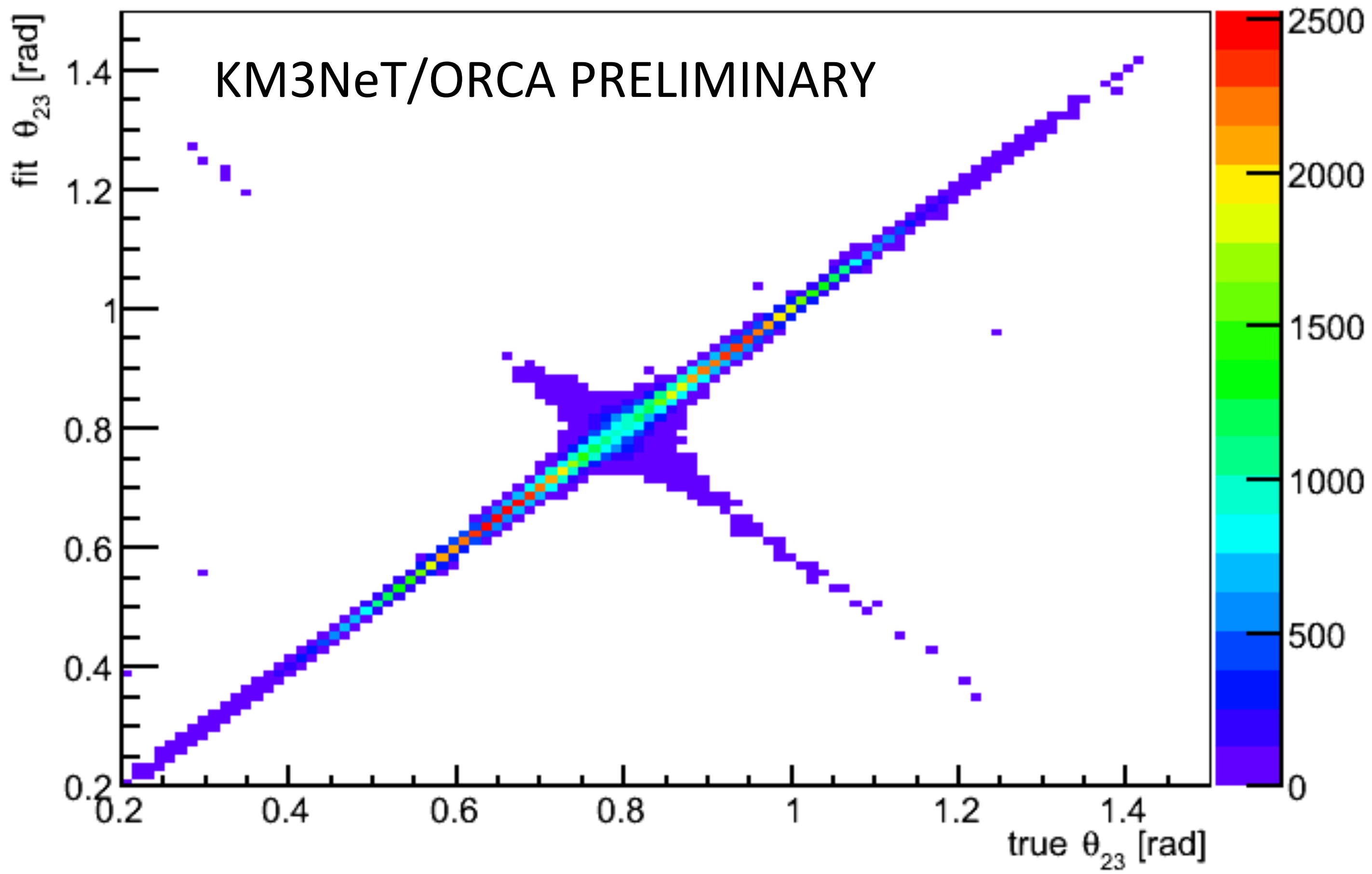
ORCA - sensitivity θ_{23}

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



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