PINGU: the next upgrade of IceCube

Rezo Shanidze

for the IceCube collaboration

ORCA Workshop
Paris, 18 April 2012

HELMHOLTZ GEMEINSCHAFT

ICECUBE

DESY

The IceCube Collaboration

IceCube: 39 Institutions
~220 Collaborators

PINGU non IceCube Institutions (Universities):
Erlangen (Germany), Manchester (UK),
SKKU (S. Korea), Tokyo (Japan), Toronto (Canada)

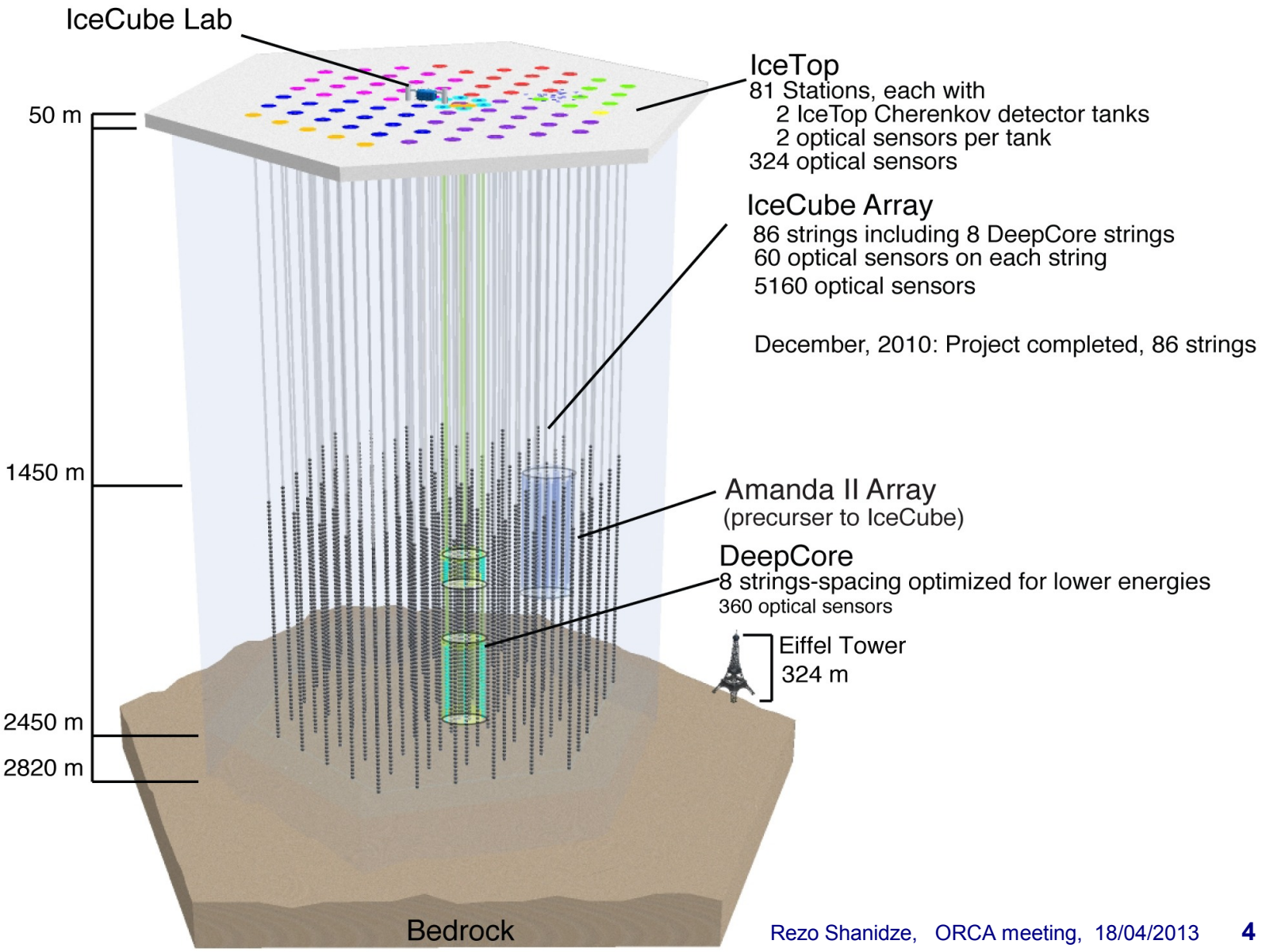
International Funding Agencies

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)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Outline

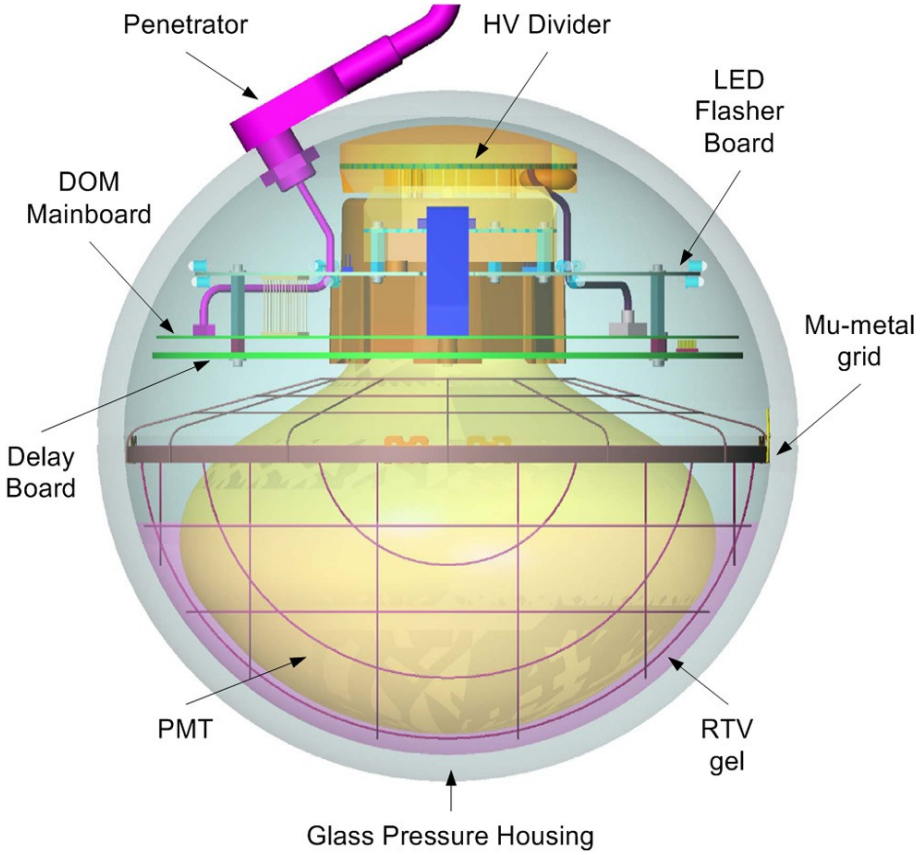
- IceCube neutrino observatory
- DeepCore: low energy subarray of IceCube
  - First results from DeepCore
- **PINGU** (**P**recision **I**ceCube **N**ext **G**eneration **U**pgrade):
  - Physics goals and design concept
  - Current status and timeline

IceCube neutrino observatory



IceCube DOM

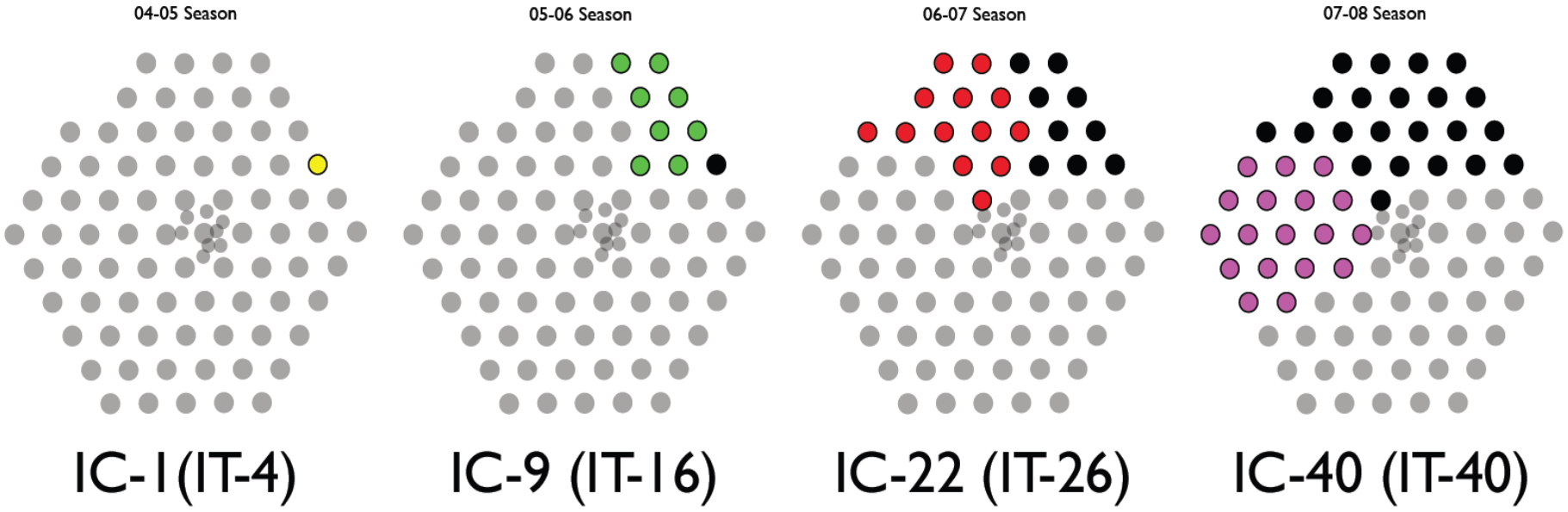
- Digital Optical Module (DOM)
  13 inch. pressure resistant (70 MPa) glass sphere:
  - PMT, HV generator and divider circuits,
  - LED flasher board,
  - Mainboard with signal processing electronics[1].

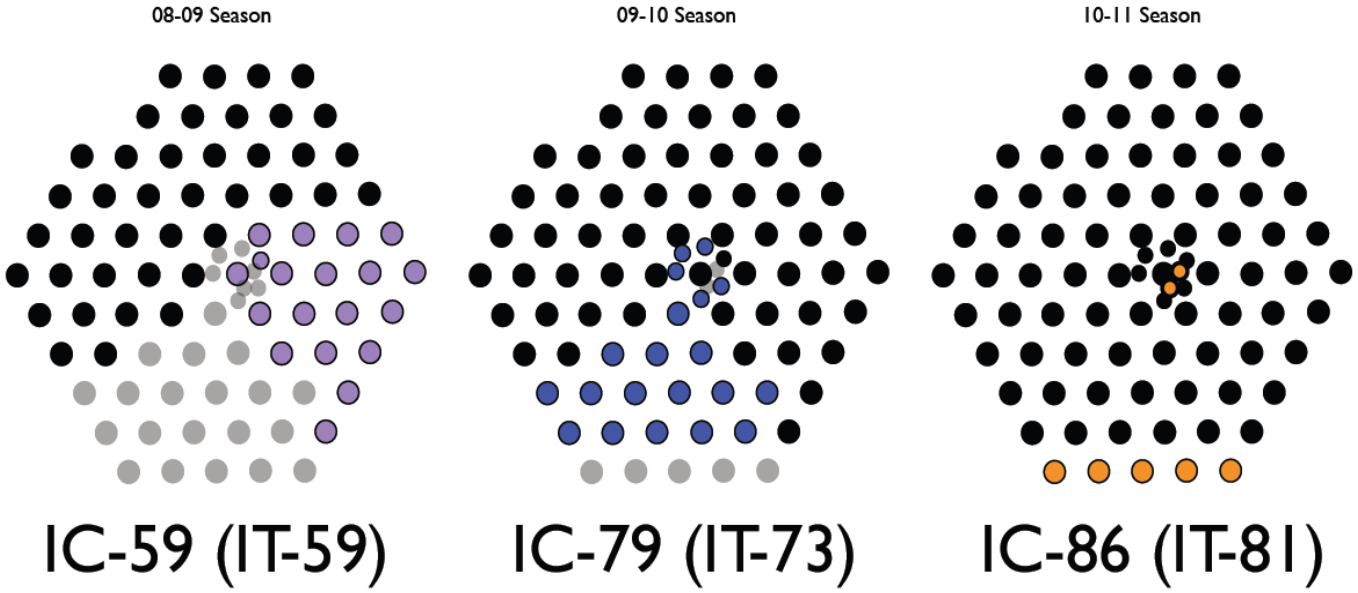


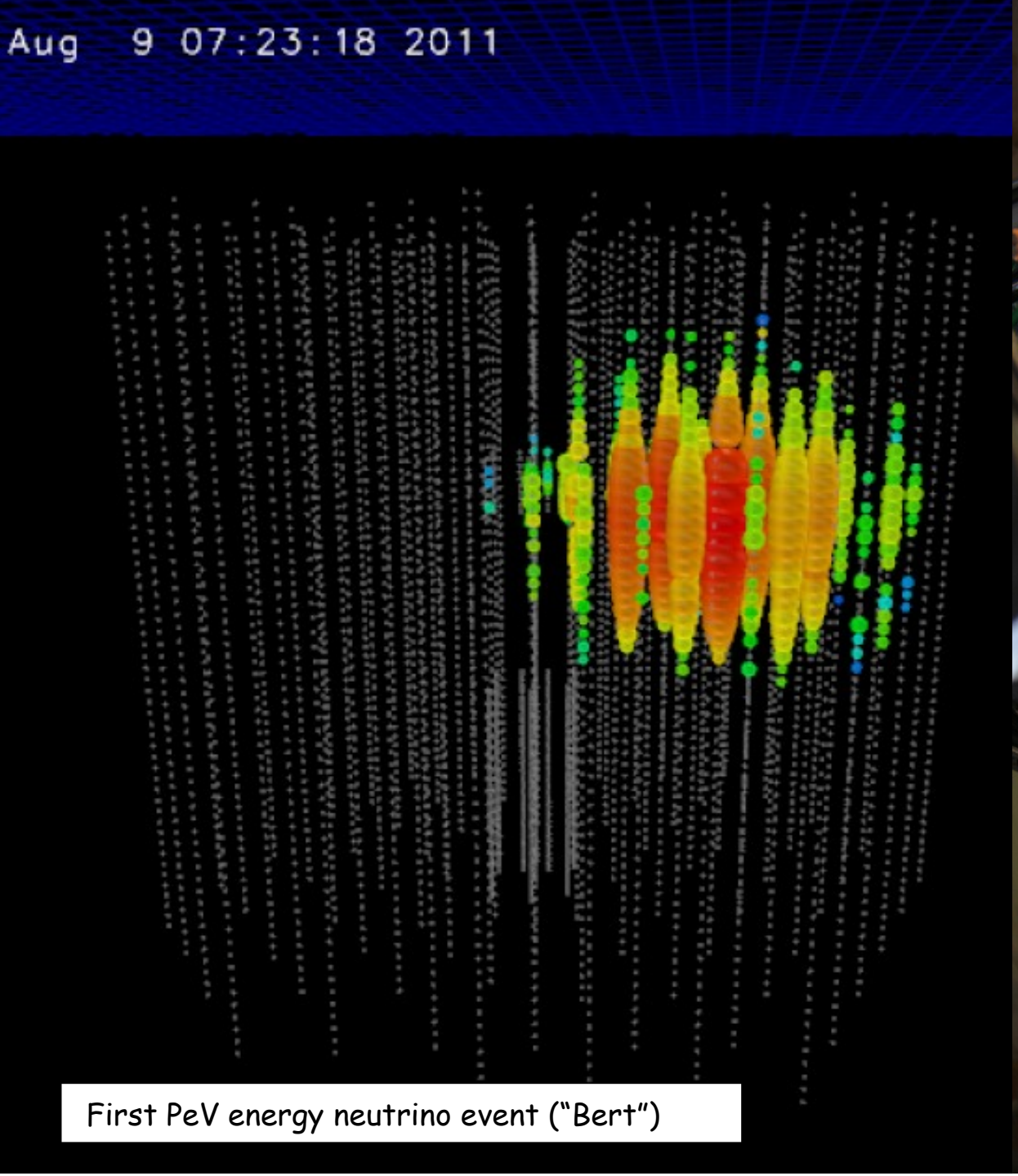
- PMT[2]:
  - Hamamatsu R7081-02
  - Q.E.(at 390 nm): 25%
  - Dark rate at (-40°): 500 Hz
  - TTS: 3.2 ns

[2]. NIM A601(2009), 294 [arXiv: 0810.4930]
[1.] NIM A618(2010), 139 [arXiv: 1002.2442]

The IceCube Observatory



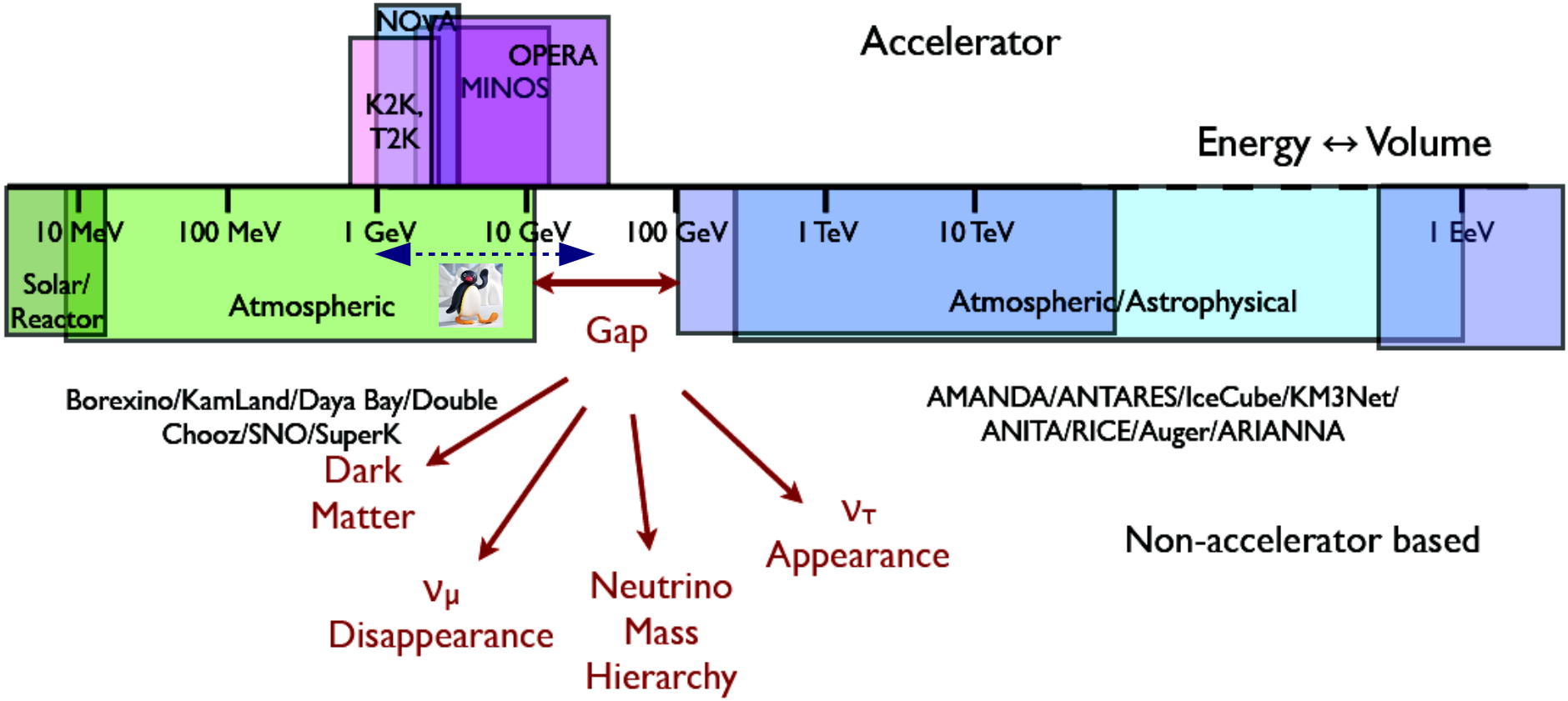




First PeV energy neutrino event ("Bert")

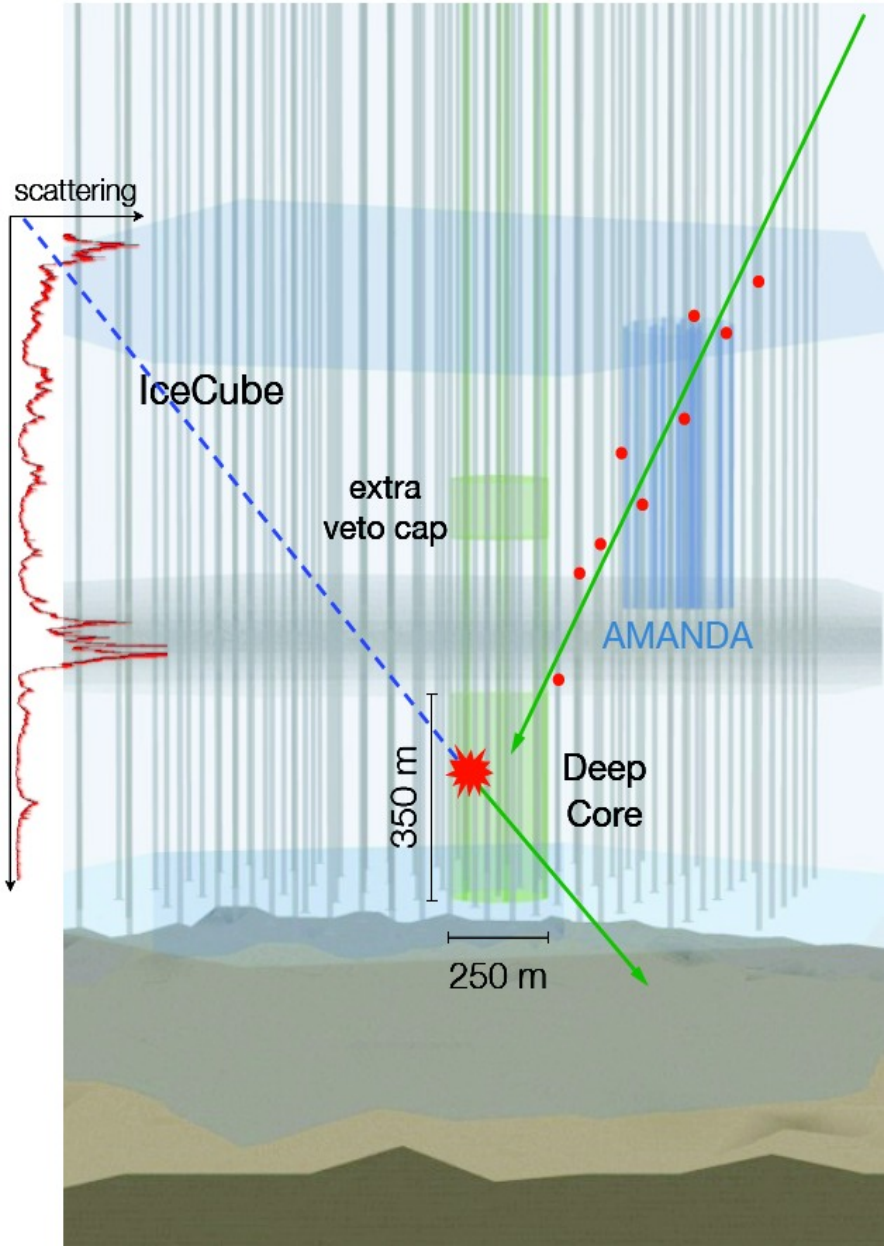
IceCube Completed:
December 18, 2010

The Neutrino Detector Spectrum



*boxes select primary detector physics energy regimes and are not absolute limits

IceCube/DeepCore



- IceCube/DeepCore[1]:

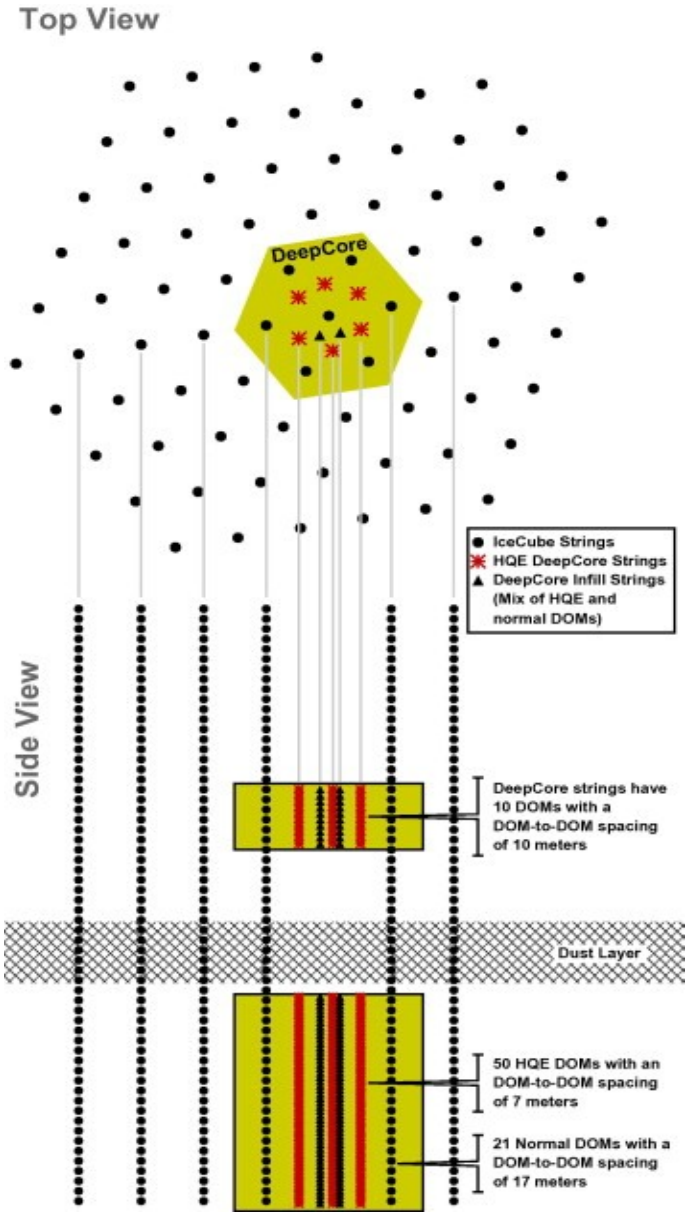
  More densely instrumented region at the center of IceCube, below ~2000m, in the clearest ice λ_{eff} > ~ 40-50 m

- Atmospheric-μ veto:

  Top and outer layers of IceCube provide an active veto for DeepCore.

[1] Astropart. Phys. 35(2012) 615

DeepCore configuration



- A schematic view of DeepCore configuration[1]

- String configuration (DOM-DOM distance):
  - IceCube : 17 m (60 DOMs)
  - DeepCore: 10 m (top 10 DOMs)
    7 m (bottom 50 DOMs)

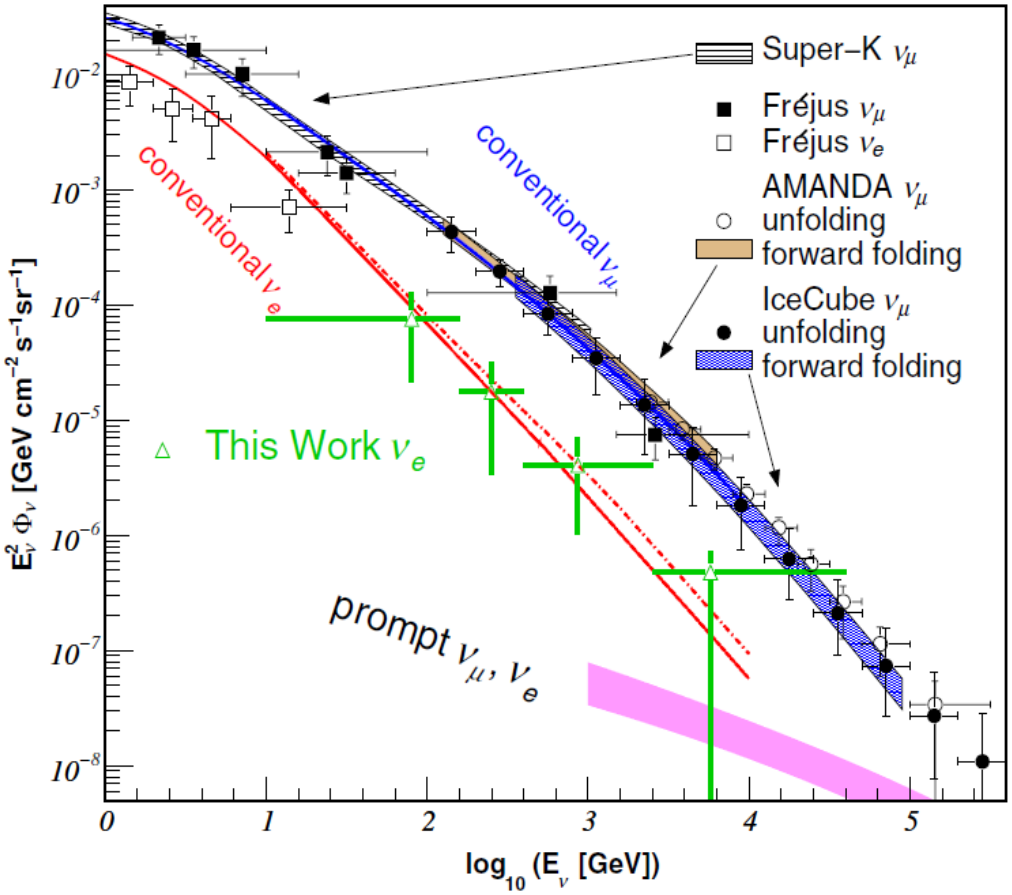
- HQE DOM:
  - Hamamtsu R7081MOD
  - "super bialkali" photocathode
  - ~ 40% higher QE at λ = 390 nm

[1] Astropart. Phys. 35(2012) 615

IceCube/DeepCore: ν_e-cascades

- Measurement of the atmospheric ν_e flux in IceCube[1]:

  First observation of ν_e-induced cascades in high energy neutrino telescopes



IC-79 (6 DC strings) data: 281 days

$N_{cascade} = 496 \pm 66(stat.) \pm 88(sys.)$

Energy range: ~80 GeV – 6 TeV

The conventional ν-fluxes:

HONDA(solid): ν_e (red) and ν_μ (blue)

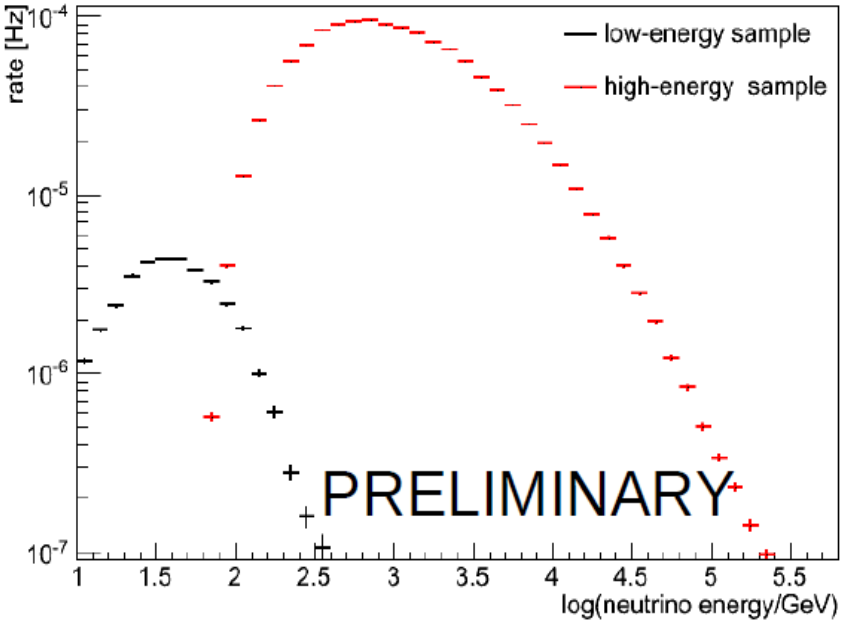
Bartol (dotted): ν_e (red) and ν_μ (blue)

[1] PRL 110(2013), 151105 [arXiv: 1212.4760]

Neutrino oscillations in IceCube/DeepCore

- Atmospheric neutrino oscillations in IceCube [1]:

  Oscillation signal extracted from a low-energy (20-100 GeV) ν_μ-sample collected By DeepCore in 2010-2011 (IC-79) .

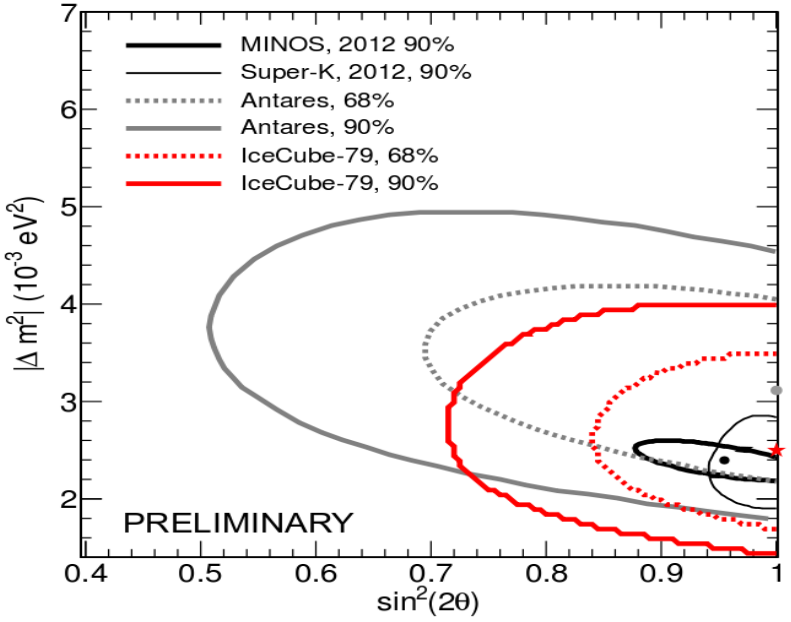


Energy distribution of the atmospheric neutrinos in the low-energy (DeepCore) and in the high-energy (IceCube) sample.

For 2-flavor formalism:

$\Delta m_{23}^2 = (2.5 \pm 0.6)\ 10^{-3}\ eV^2$

$\sin 2\Theta_{23}^2 > 0.92$ (max. mixing favored)

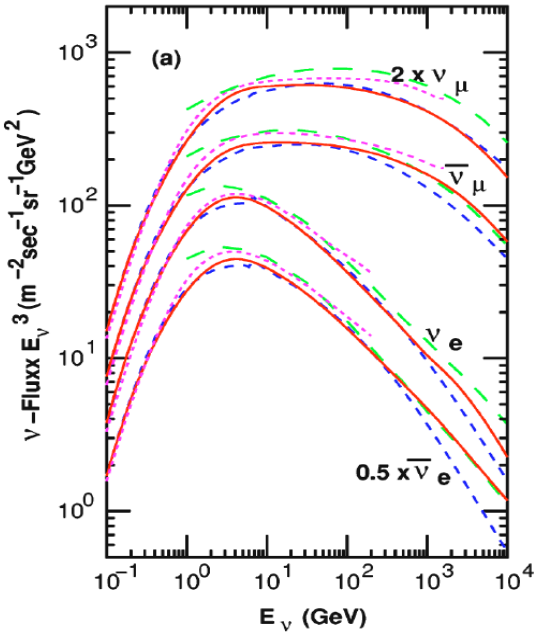


[1] ArXiv:1301.4339

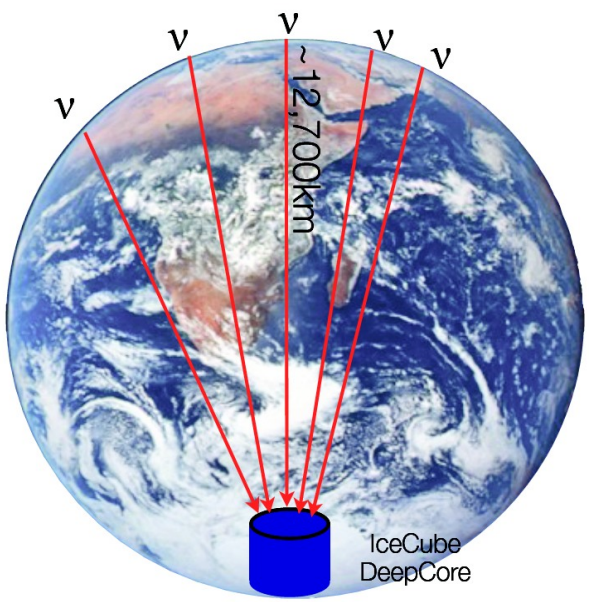
PINGU Physics Goals

- Neutrino mass hierarchy (NMH) determination with 5-15 GeV atmospheric neutrinos.
  (Fisrt detection of parametric oscillations)
- Other neutrino oscillation physics: maximal Θ_{23}, ν_τ appearence
- Low mass WIMP dark matter search via neutrinos
- Neutrino astrophysics with E ~10 GeV neutrinos
- R&D for possible next-to-next upgrade: megaton-scale Cherenkov ring-imaging Detector: "MICA"

NMH with atmospheric neutrinos



Many different baselines.

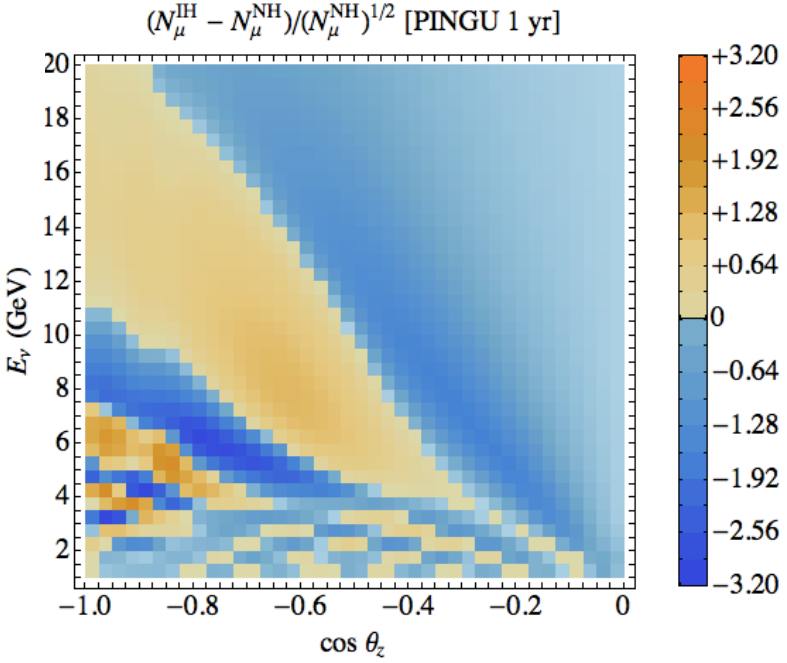


Difference in the neutrino and antineutrino fluxes and interaction cross-section, $\sigma(\nu)/\sigma(\bar{\nu}) \sim 2$ gives a possibility to detect NMH with the atmospheric neutrinos.

Atmospheric neutrinos: a mixture of muon, electron neutrino and antineutrino fluxes.
PR D70 (2004), 043008

Oscillation probability: modified in matter, depending on NMH, matter density profile and mixing angle Θ_{13} .

The effect is different for neutrinos and antineutrinos.



NHM measurement with neutrino telescopes

- O. Mena, I. Mocioiu, S. Razzaque, Phys. Rev. D78(2008), 093003 [arXiv:0803.3044]

  Neutrino mass hierarchy extraction using atmospheric neutrinos in ice

  First calculation for DeepCore, assuming $\sin^2(2\Theta_{13}) = 0.1$, $\delta = 0$

2012: $\sin^2 2\Theta_{13} = 0.089 \pm 0.10\ (\text{stat.}) \pm 0.005(\text{syst.})$

- E.Kh. Akhmedov, S.Razzaque and A.Yu. Smirnov, JHEP 1302(2013),082 [arXiv:1205.7071]

  Mass hierarchy, 2-3 mixing and CP-phase with Huge Atmospheric Neutrino Detectors

- S. K. Agarwalla, T. Li, O. Mena, and S. Palomares-Ruiz, arXiv:1212.2238

  Exploring the Earth matter effect with atmospheric neutrinos in ice

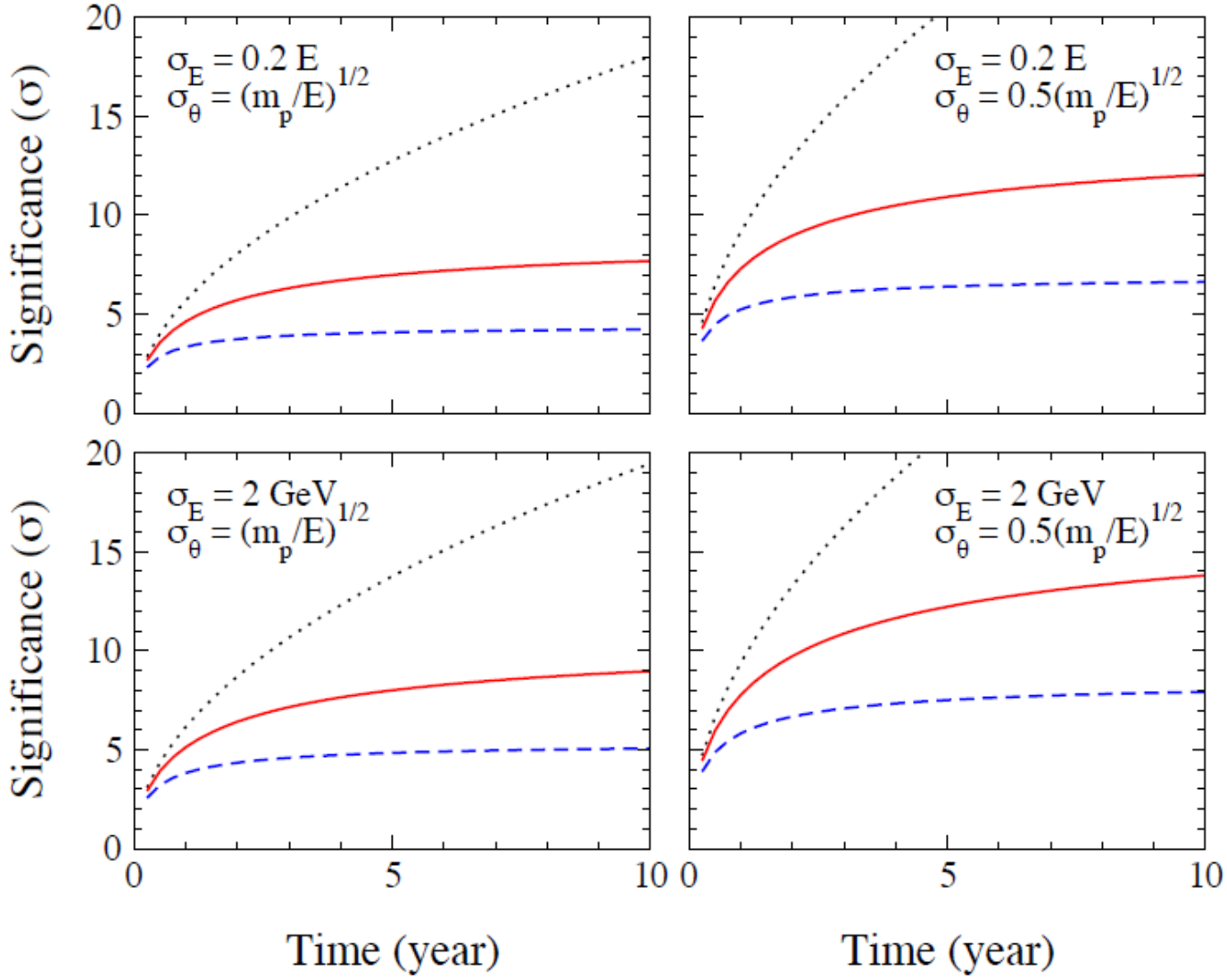
- M.Ribordy and A. Yu. Smirnov, arXiv:1303.0758

  Improving the neutrino mass hierarchy identification with inelasticity measurement in PINGU and ORCA

- T. Ohlsson, H. Zhang and S. Zhou, arXiv: 1303.6130

  Effects of non-standard neutrino interactions at PINGU

Estimation of NHM detection significance



no syst.
5% syst.
10% syst.

$$S^{tot} = \sqrt{\sum_{ij} S_{ij}^2} = \sqrt{\sum_{ij} \frac{(N_{ij}^{IH} - N_{ij}^{NH})^2}{\sigma_{ij}^2}}$$

N_{ij} - events in
$E \times \cos\Theta_\nu$ plane
[1-20GeV] x [-1,0]

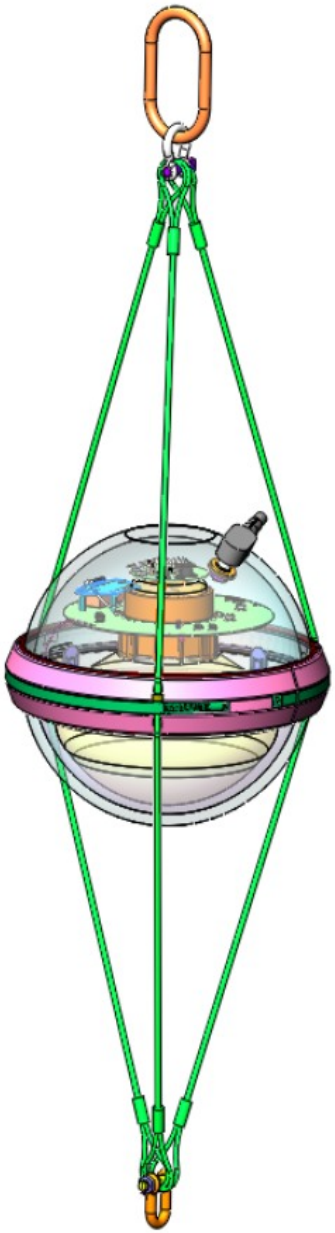
For $\rho V_{eff}(E)$ [Mton] =
$14.6 \times [\log(E_\nu/\mathrm{GeV})]^{1.8}$

E.Kh. Akhmedov et al., JHEP 1302(2013),082

PINGU design concept

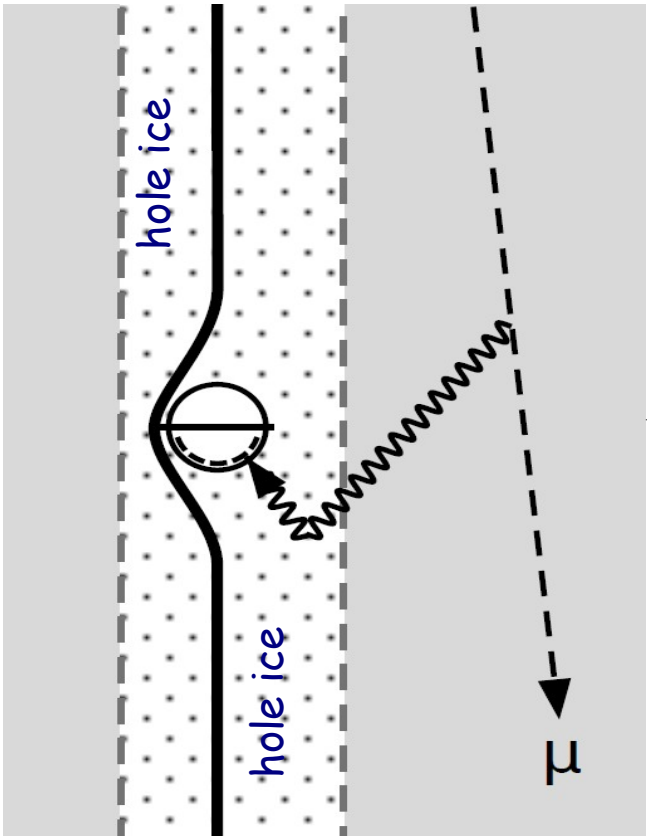
- Add in-fill strings to IceCube/DeepCore array
  - further increase module density
  - continue to exploit 2km depth and surrounding IceCube/DeepCore array as active cosmic ray muon veto
- Optimize and simplify IceCube module design for ~5 GeV E_ν events, reduced cost
- Co-deploy new calibration devices tuned for lower E_ν
- Improve refrozen hole ice clarity
- Goal: reach few GeV E_ν threshold

PINGU instrumentation



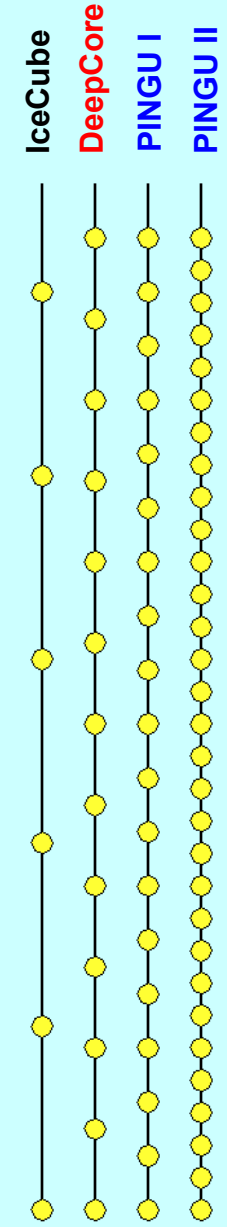
- PINGU hardware:
  IceCube hardware
  with various modifications
  to minimize cost and risk.

- PINGU DOM (PDOM):
  IceCube/DeepCore DOM
  ("HQE DOM") with
  updates and appropriate
  adaptations.



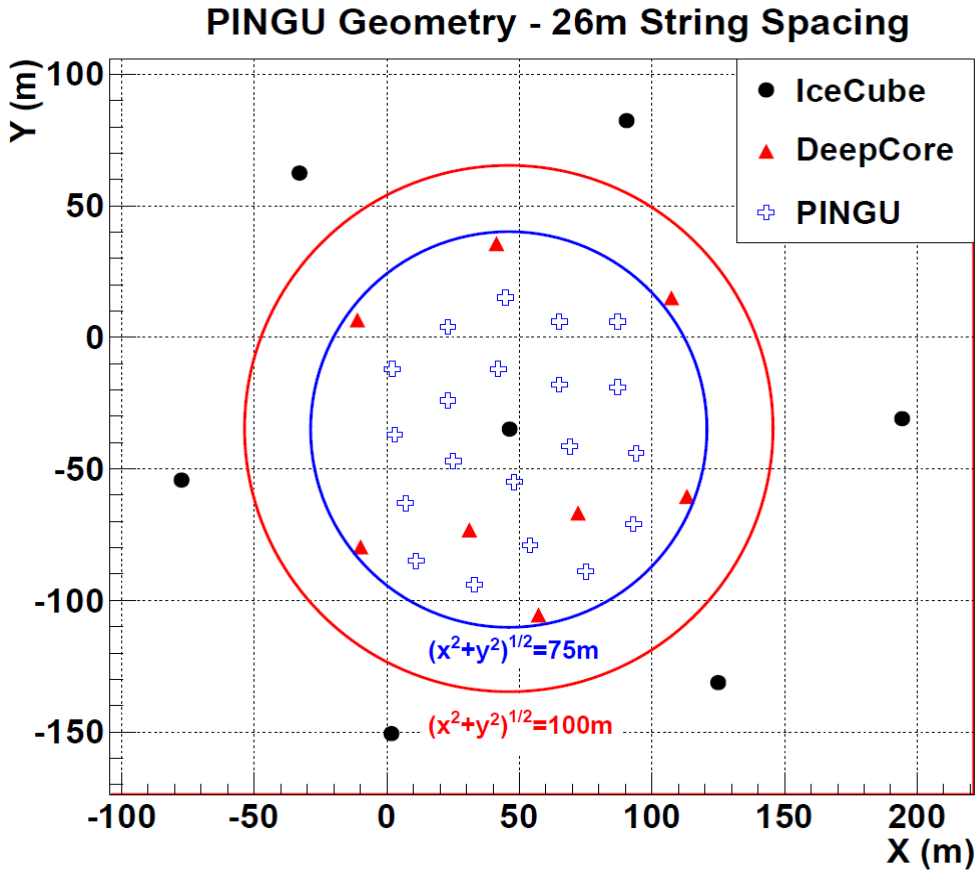
The drilling system will be upgraded to ensure the clarity of refrozen ice ("hole ice").

PINGU configuration



20, 40 string configurations are considered for PINGU.

PINGU string (I/II): 60 / 100 DOMs, spacing: 5 / 3 m

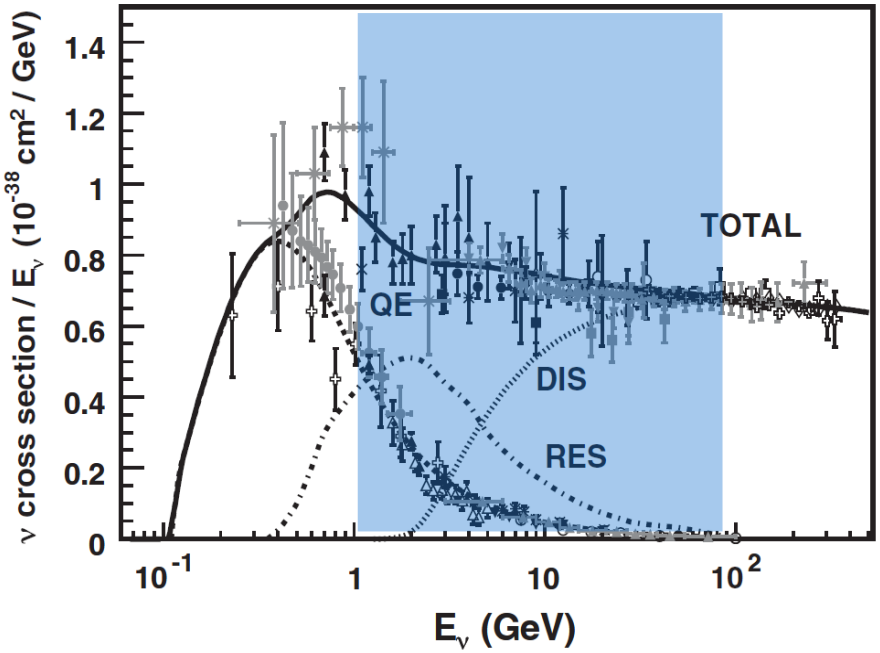


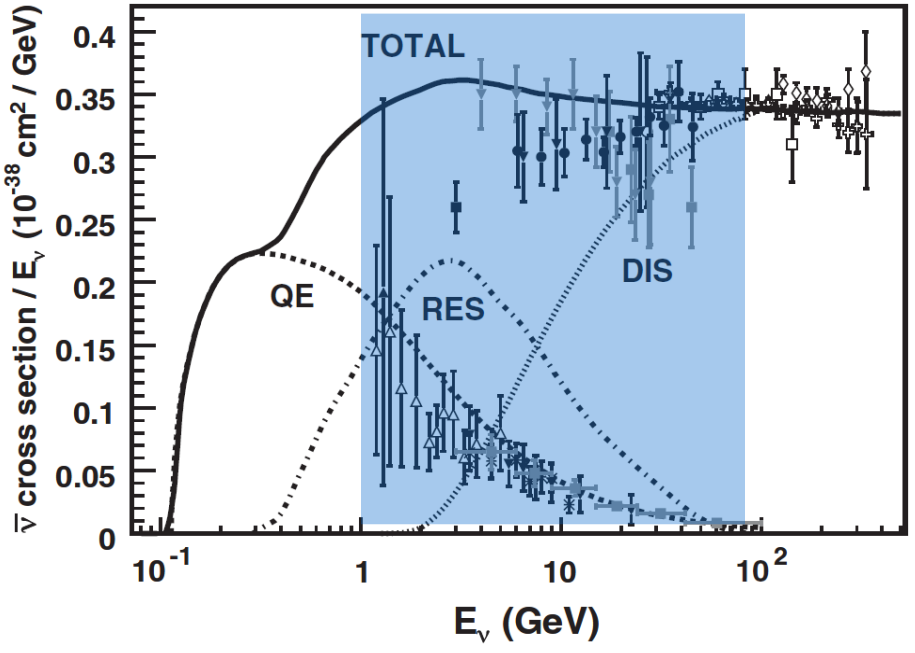
Higher density arrays were also simulated to completely explore the geometry parameter space.

Simulations for PINGU

- PINGU simulation chain (goal: production of multi-year triggered neutrino events for the mass hierarchy study):
  - Simulation of low energy (1-80 GeV) neutrino (ν_e, ν_μ, ν_τ) events: **GENIE**
  - Propagation of all particles produced in νN interactions: **Geant-4**
  - Propagation of the Cherenkov photons, generation of hits in the IceCube/DeepCore/PINGU DOMs and event triggering

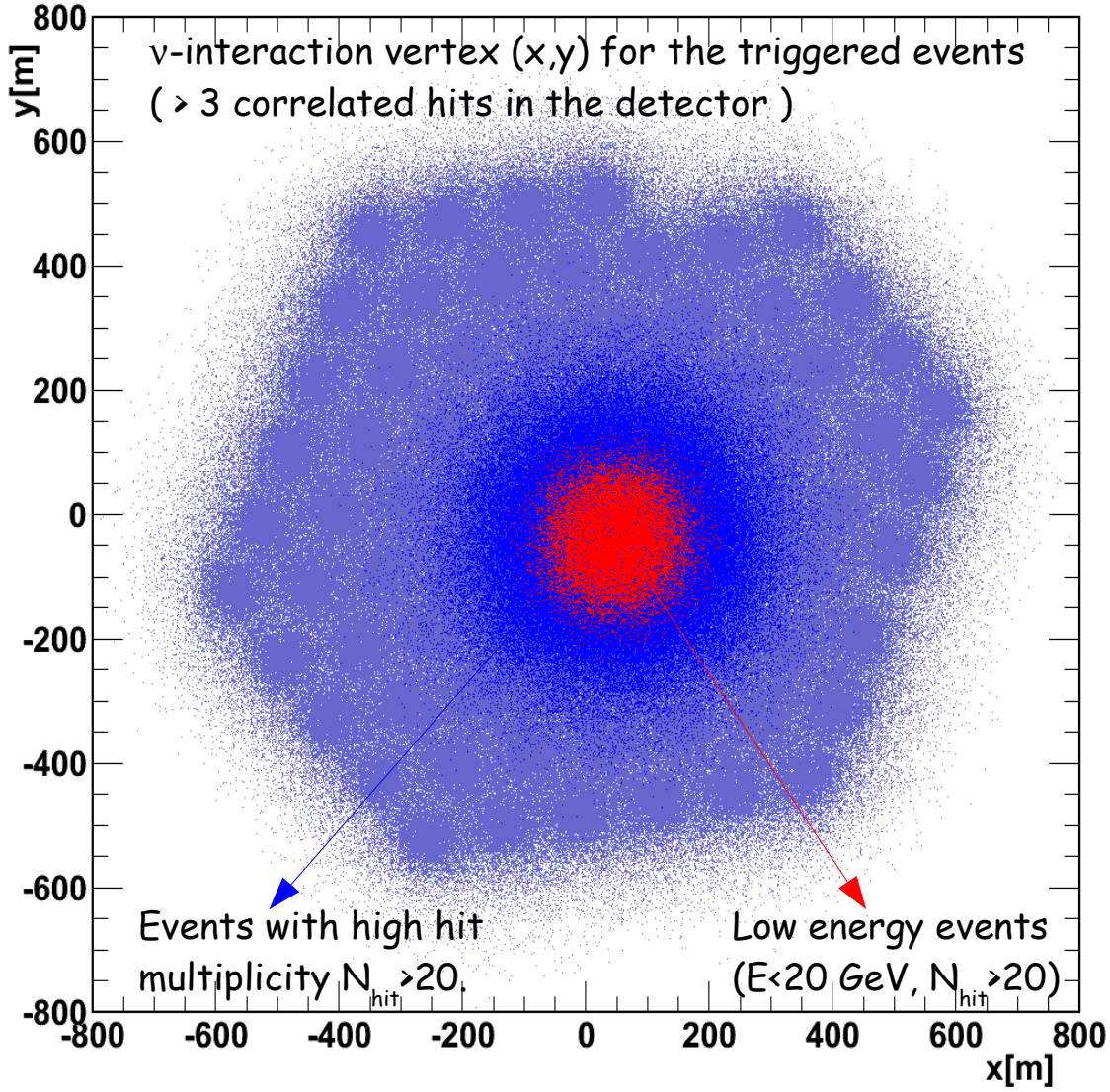
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84(2012) , 1307





Triggered low energy events

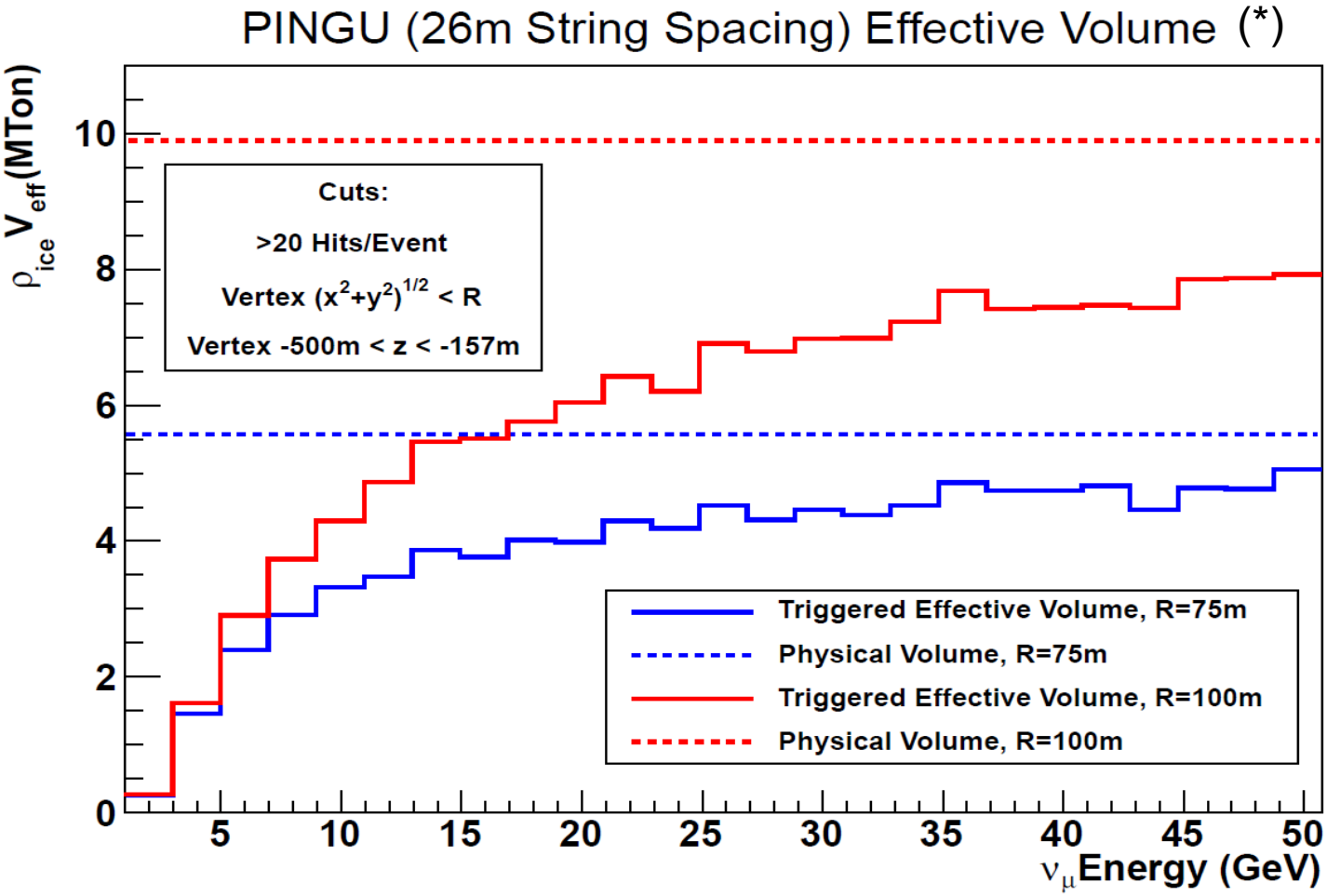
Simulated ν_μ-events: 1< E < 80 GeV, E0



- CC and NC interactions
- neutrinos and antineutrinos

Low energy (E<20 GeV) ν_μ-events with high hit multiplicity are localized in the DeepCore/PINGU volume

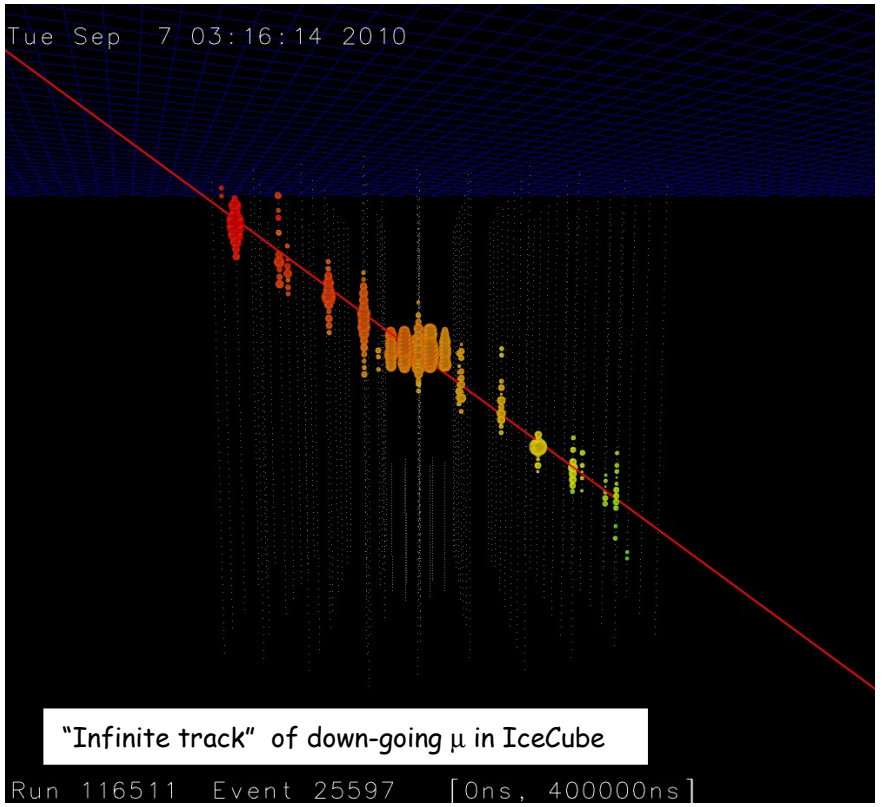
PINGU Effective volume



* No reconstruction has been done.
Effective volume will be lower after folding the reconstruction efficiency.

Event reconstruction

- Neutrino event reconstruction in IceCube/DeepCore:
  - Based on likelihood (LLH) reconstruction algorithms/strategies developed for IceCube[1], including tabulated PDFs.
  - New algorithm (developed for DeepCore):
    - Reconstruction with the direct (non-scattered) photons, similar to ANTARES[2].
  - "Contained events": with the interaction vertex in the DeepCore volume. ("starting point" reconstruction)
- Several IceCube/DeepCore algorithms are under study for PINGU.



"Infinite track" of down-going μ in IceCube

[1] NIM A524(2004), 169 [astro-ph:0407044

[2] Astopart. Phys. 34(2011), 652 [ArXiv: 1105.4116]

Reconstruction for PINGU

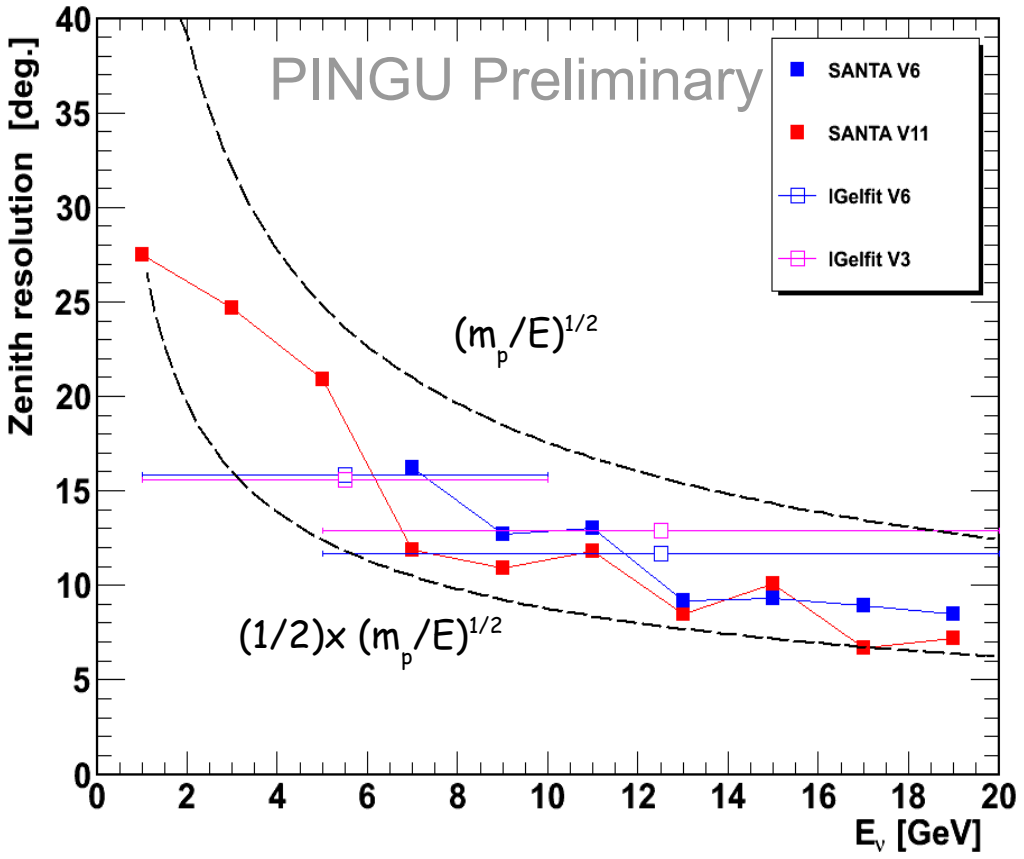
- Reconstruction with the different algorithms:
  - Reconstruction with non-scattered photons ("SANTA")
  - LLH reconstruction with "grid"-search strategy ("IgelFit").
  - Reconstruction of ν_μ-CC events with 8 parameters ("HybridRECO"):

    - ν_μ-interaction vertex and time
    - μ-Direction (zenith, azimuth)
    - μ-length and cascade energy

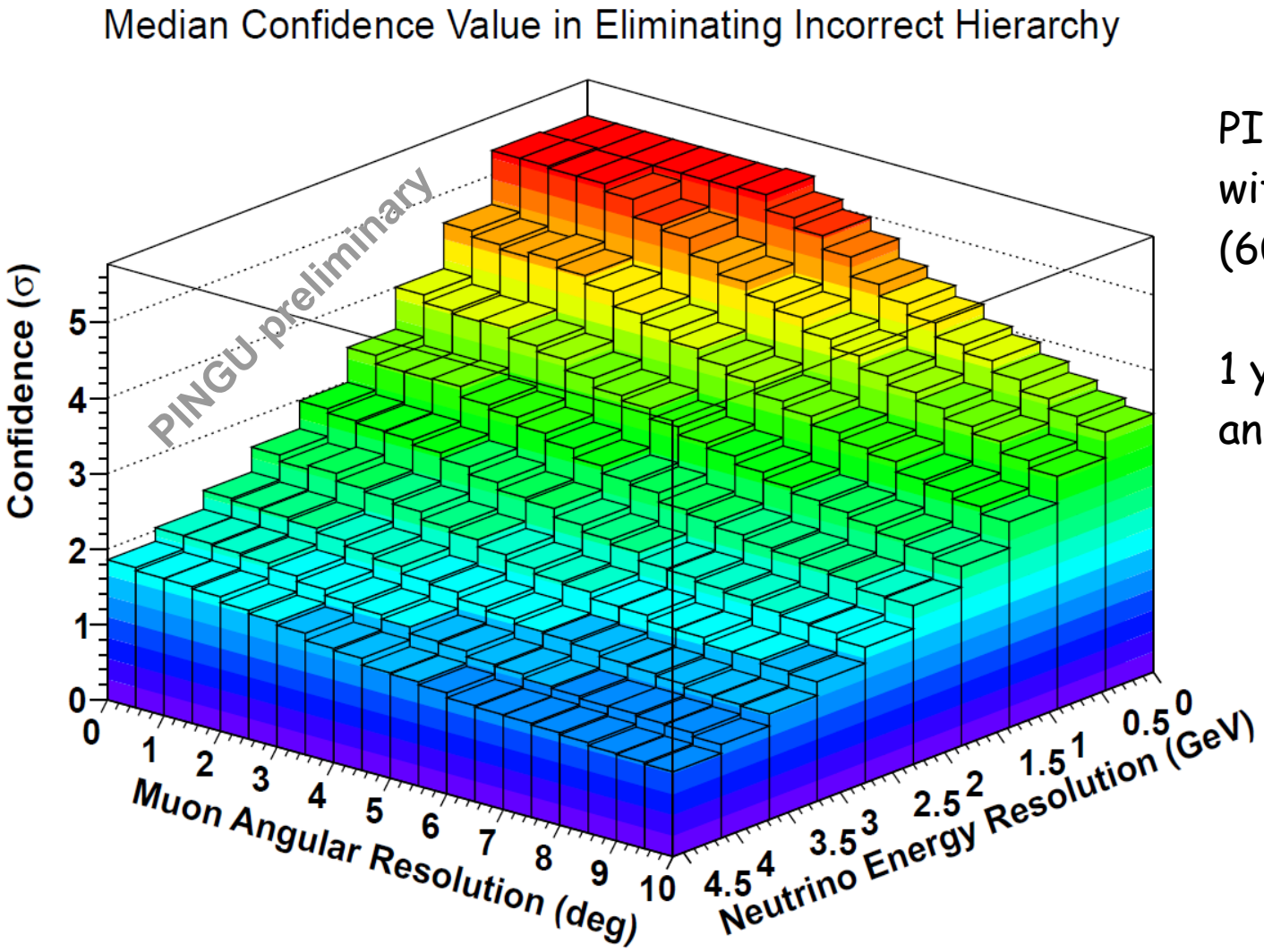
    with Markov chain algorithm for LLH minimization.

Figure presents (as an example) angular resolution obtained with 2 different algorithms, for the PINGU configurations with 20/40 strings (V6/V11).

Dashed lines correspond to the parameterization of angular resolution with $(m_p/E)^{1/2}$.



Statistical analysis for the NMH sensitivity



PINGU configuration with 20 strings (60 DOM/string)

1 year of data and N_{hit}>20

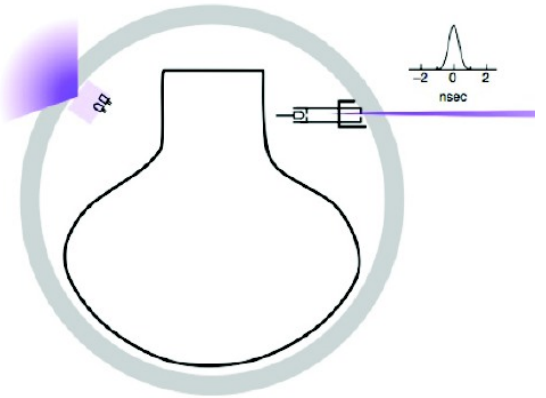
Dedicated study for NMH sensitivity is underway, including methods from [1,2].

[1] X. Qian et. al., PR D86(2012), 113011 [arXiv: 1210.3651]

[2] D. Franco et. al., JHEP 04(2013), 008 [arXiv: 1301. 4332]

Systematic uncertainties

- Theoretical (similar for the ORCA and PINGU)
  - Oscillation parameters (Θ_{12}, Θ_{13}, Θ_{23}, δ, Δm_{12}^2, Δm_{23}^2)
  - Muon and electron neutrino fluxes [$\Phi(\nu_\mu)$, $\Phi(\nu_e)$]
  - Neutrino cross-sections (σ_ν)
  - Earth density model (PREM)
- Experimental (DOM efficiency and ice properties)
  - Studies and simulations are underway with an aim to reach few % level via:
    - Improved lab measurements for calibration of the PMT/DOMs
    - Reduction of the impact of hole ice
    - Improved calibration devices (LED flasher)



PDOM with modified LED flasher

Conclusions

- IceCube/DeepCore and its potential new infill array PINGU could collect large statistics of low energy neutrino events and may be able to measure a variety of neutrino oscillation parameters with:
  - gratifyingly short time scale and modest cost
  - straightforward construction and low overall risk
- Currently addressing reconstruction and systematics challenges
- PINGU LoI is in preparation

Current PINGU timeline

Current Status

- Detailed Monte Carlo simulations nearing completion
- Low energy reconstruction algorithms from DeepCore applied to PINGU events
- Estimation of sensitivity to NMH reconstruction underway
- Letter of intent in preparation

Today (18/04/2013)

Spring 2013

Letter of Intent

Summer / Fall 2013

Submit proposals to international Agencies.

April 2014

Proposal results. Begin pre-spending on critical path items (cables, mainbords, drill refurbishment),

Austral Summer 2015/2016

Drill half-crew on ice to begin drill preparation. DOM production and testing Underway.

Austral Summer 2016/2017

Drill operational with full crew. Deploy 8 Strings.

Austral Summer 2017/2018

Deploy 12 Strings. Repack drill.

PINGU Complete

2018 February

Physcis data taking