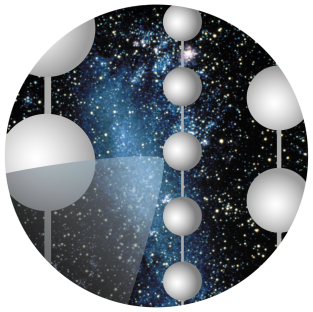


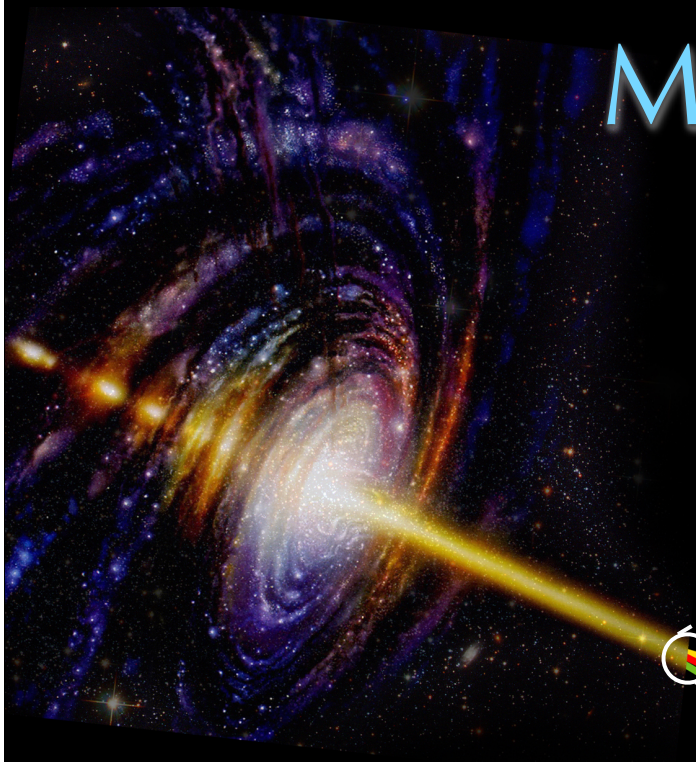
IceCube-DeepCore and beyond: towards precision neutrino physics at the South Pole

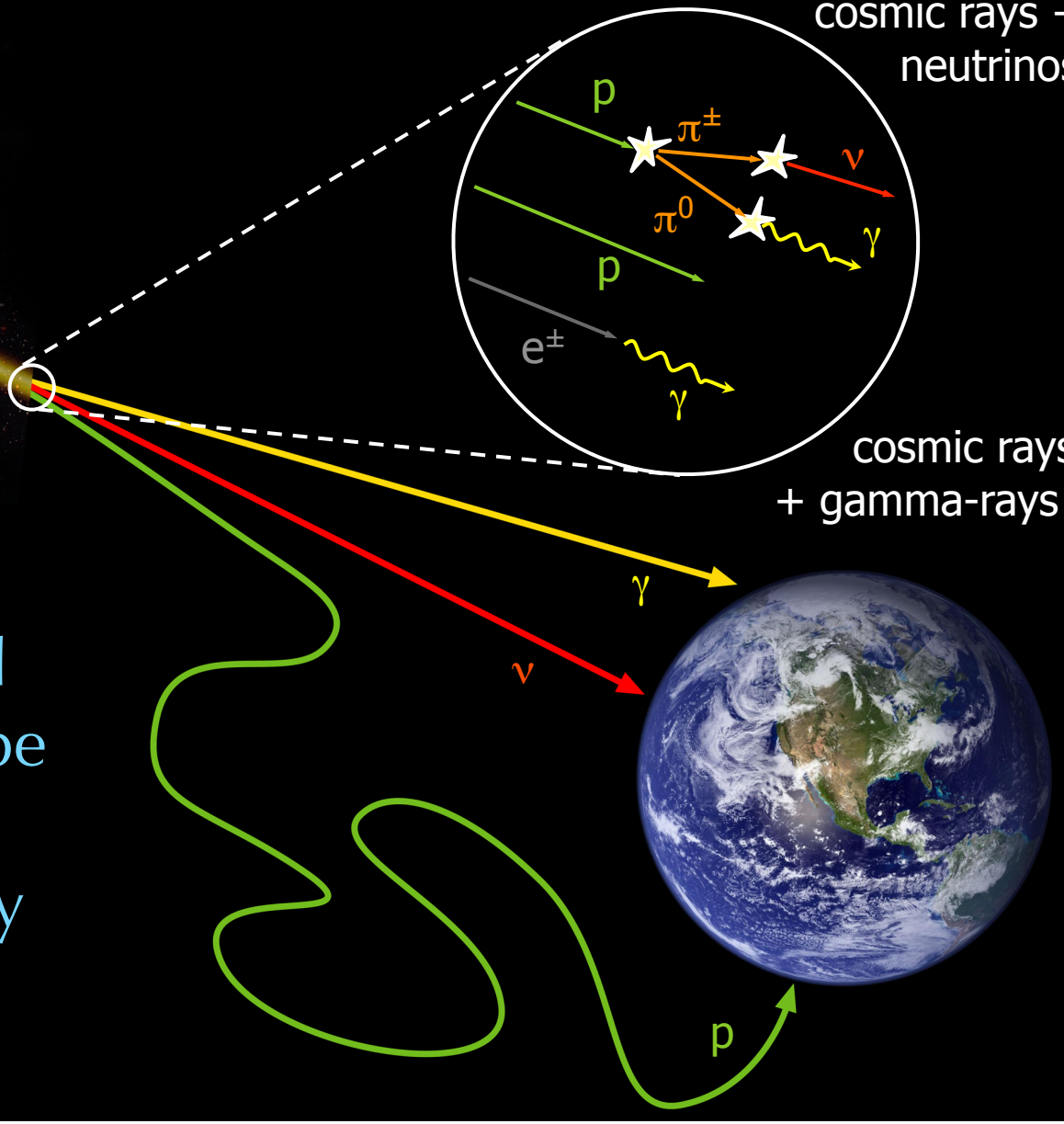
Darren R. Grant (for the IceCube Collaboration)
Department of Physics, Centre for Particle Physics
University of Alberta

Technology and Instrumentation in Particle Physics 2011
Chicago IL USA
June 11, 2011

UNIVERSITY OF ALBERTA

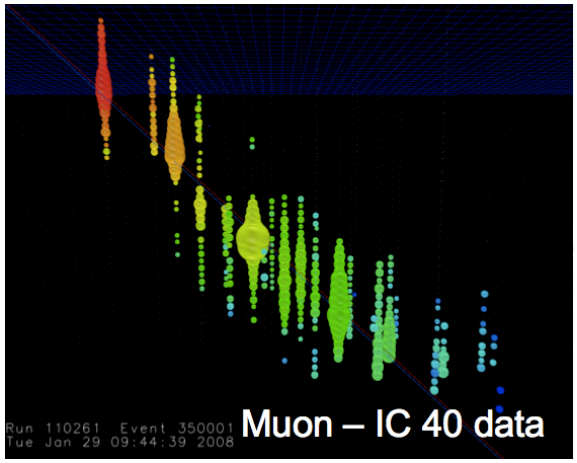
Multimessenger Astronomy



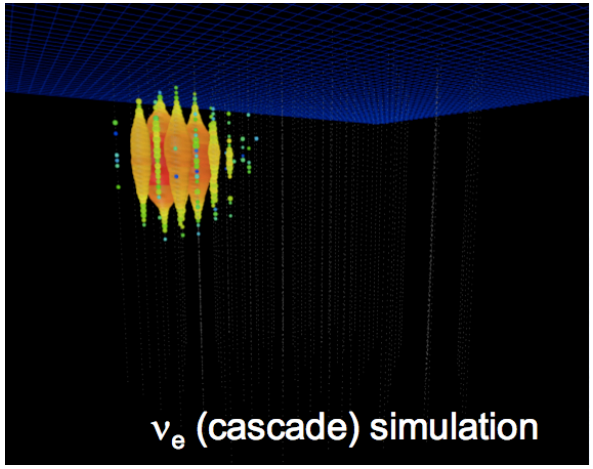


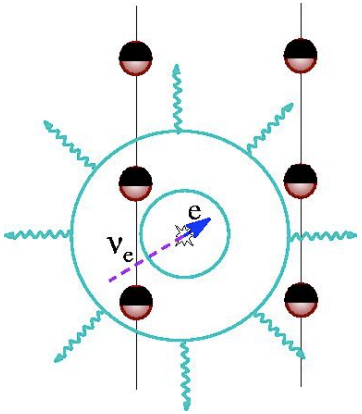
Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

Neutrino Telescopes - Principle of Detection

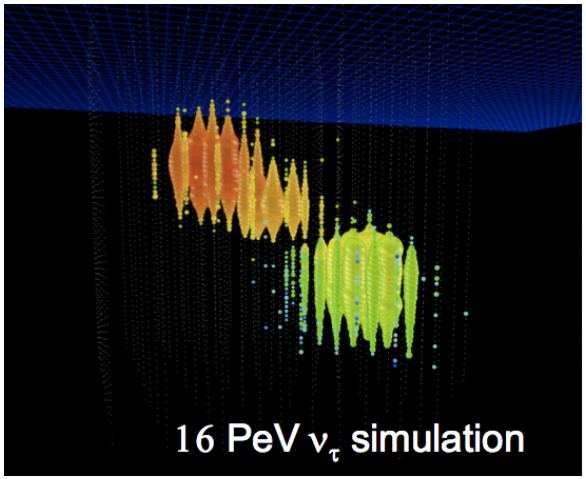


Tracks:
- through-going muons
- pointing resolution ~1°





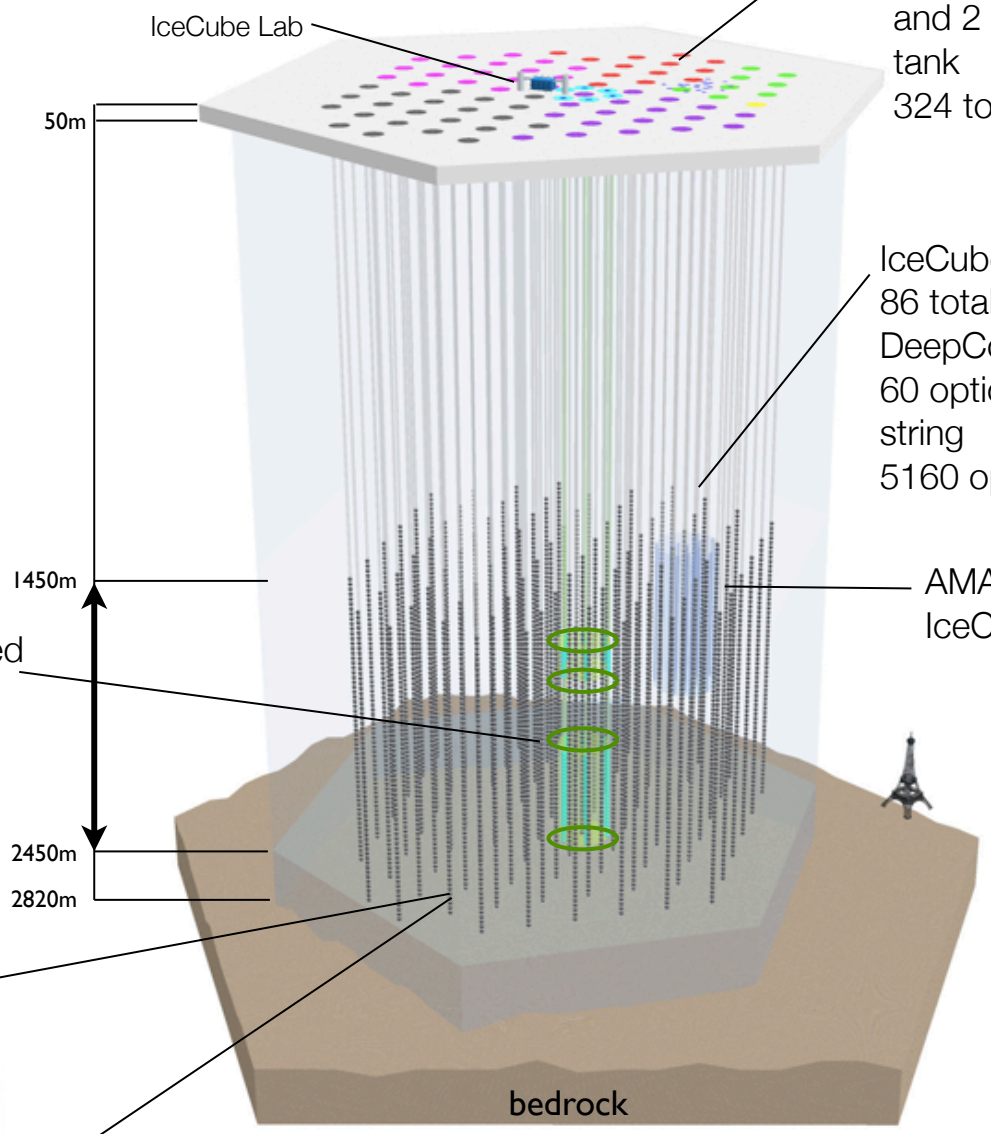
Cascades:
- Neutral current for all flavors
- Charged current for ν_e and low-E ν_τ
- Energy resolution ~10% in log(E)



Composites:
- Starting tracks
- high-E ν_τ (Double Bangs)
- Good directional and energy resolution

The IceCube Neutrino Observatory

Completed
December 18, 2010

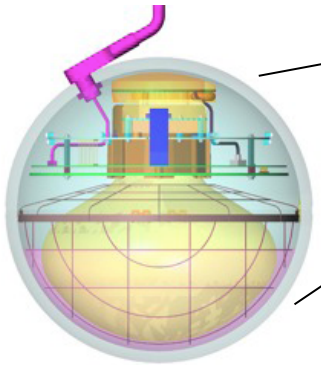


IceTop
81 Stations, each with 2 Cherenkov detector tanks and 2 optical sensors per tank
324 total optical sensors.

IceCube Array
86 total strings, including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

AMANDA-II Array
IceCube pre-cursor

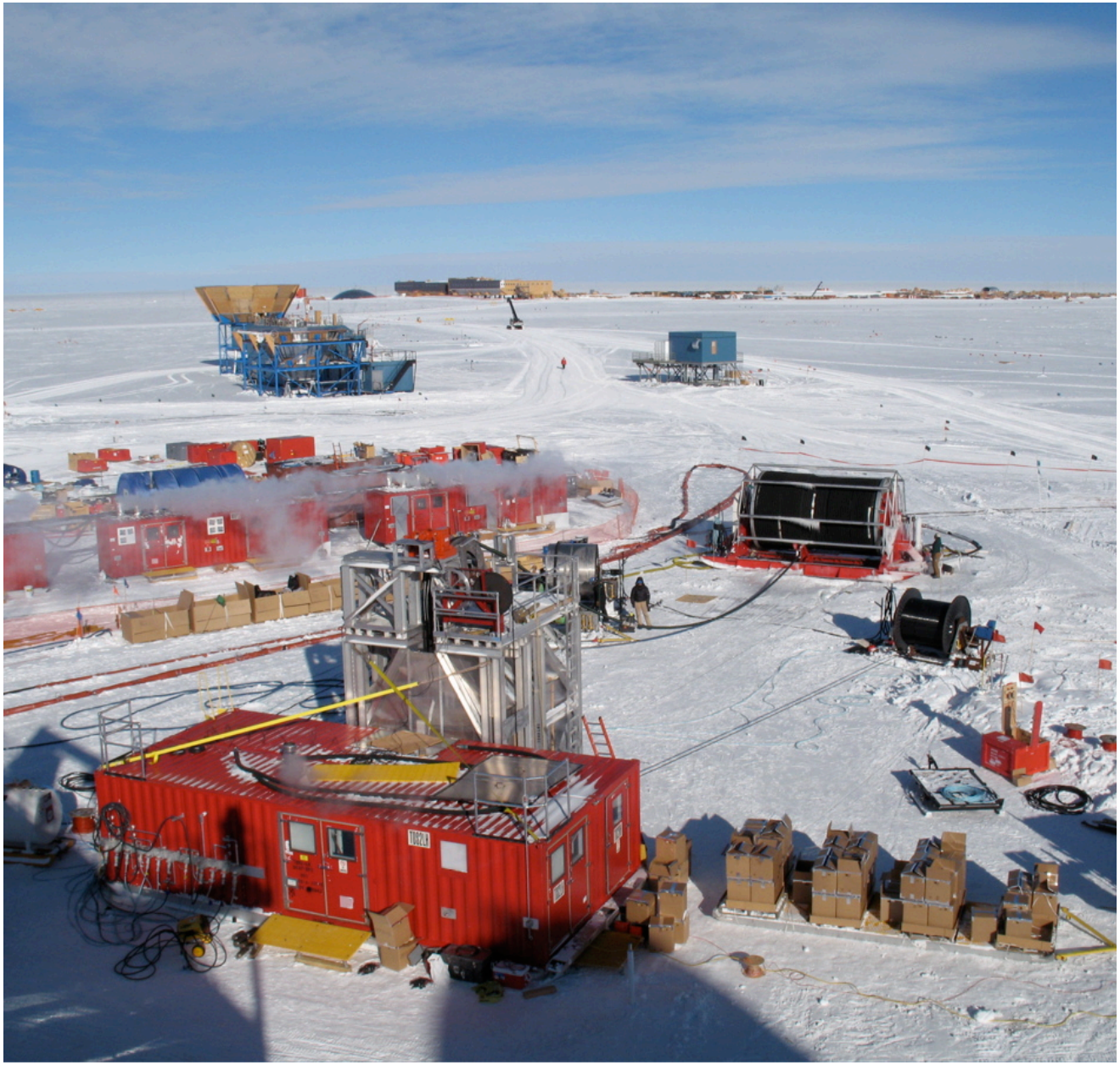
DeepCore Array
8 strings with dense spacing optimized for lower energies
480 total optical sensors

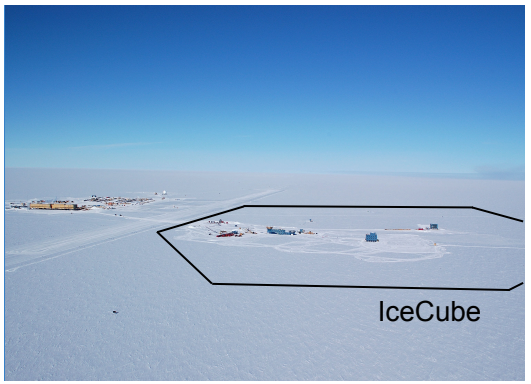


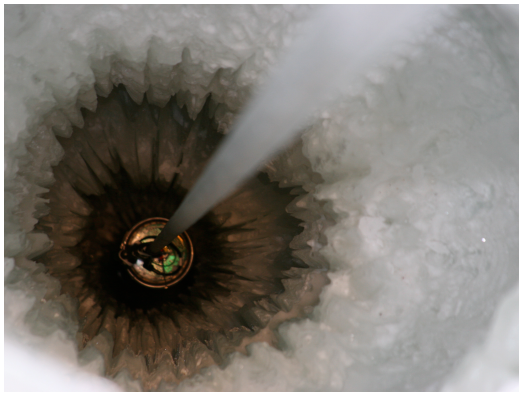
Digital Optical Module

The IceCube Collaboration

36 institutions - 4 continents - ~250 Physicists







Amundsen-Scott South Pole Station, Antarctica

IceCube module design specs

- Stable and reliable operation (minimal personnel at the South Pole and modules are inaccessible)
- High dynamic range (deposited energy may vary by ~10^6)
- Complex waveform information
- Low power dissipation

IceCube module design specs

- Stable and reliable operation (minimal personnel at the South Pole and modules are inaccessible)
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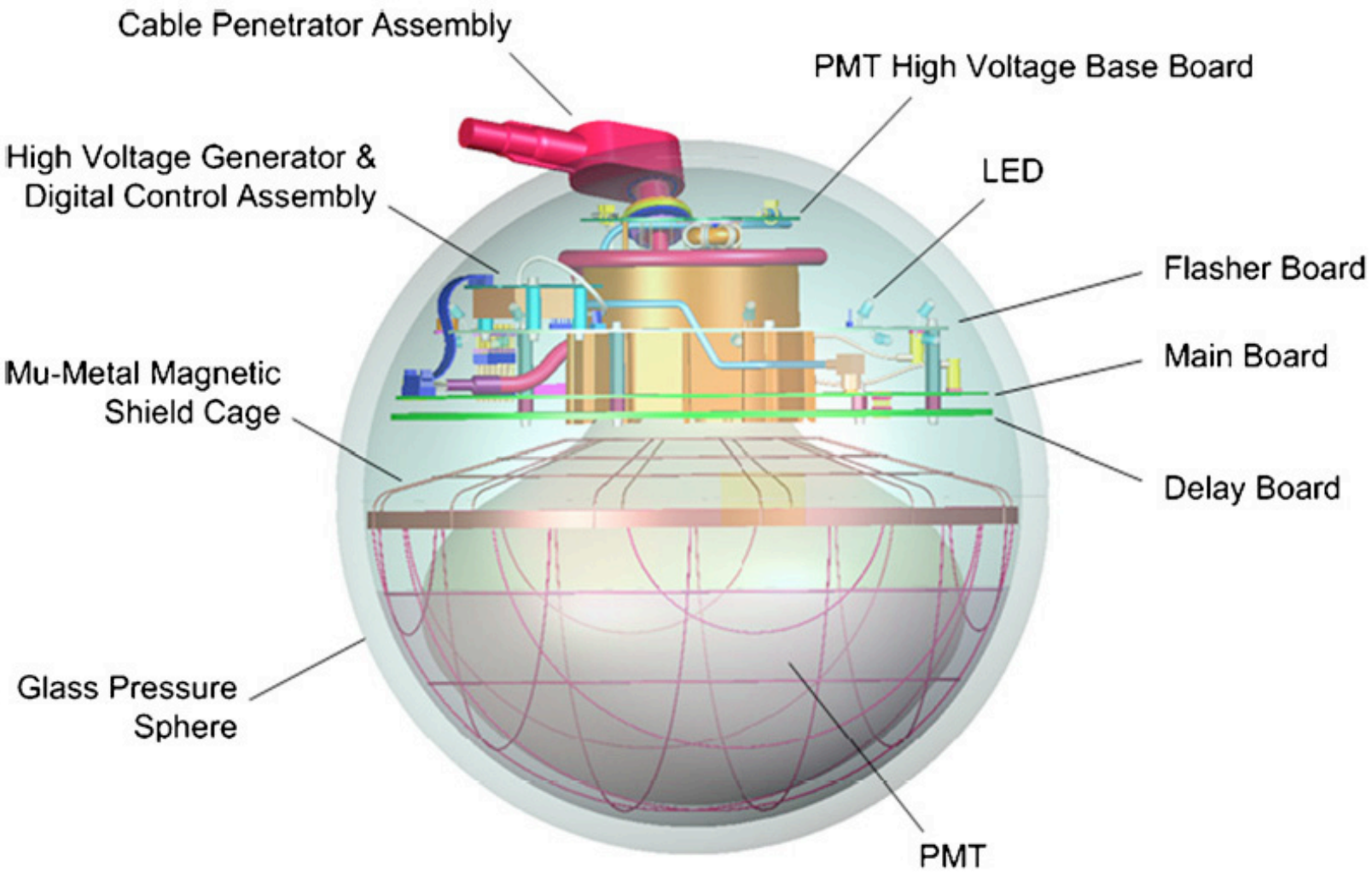
- Complex waveform information
- Low power dissipation

Waveform Digitization for the entire detector

Each optical module becomes a semi-autonomous data acquisition platform linked in an all-digital decentralized network

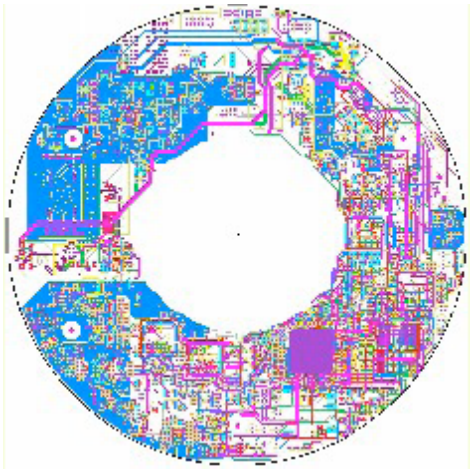
- The ice is a relatively quiet environment -> low information rate and need to digitize only ~0.1% of the time

The Digital Optical Module (DOM)



Digital Optical Module Main Board Design

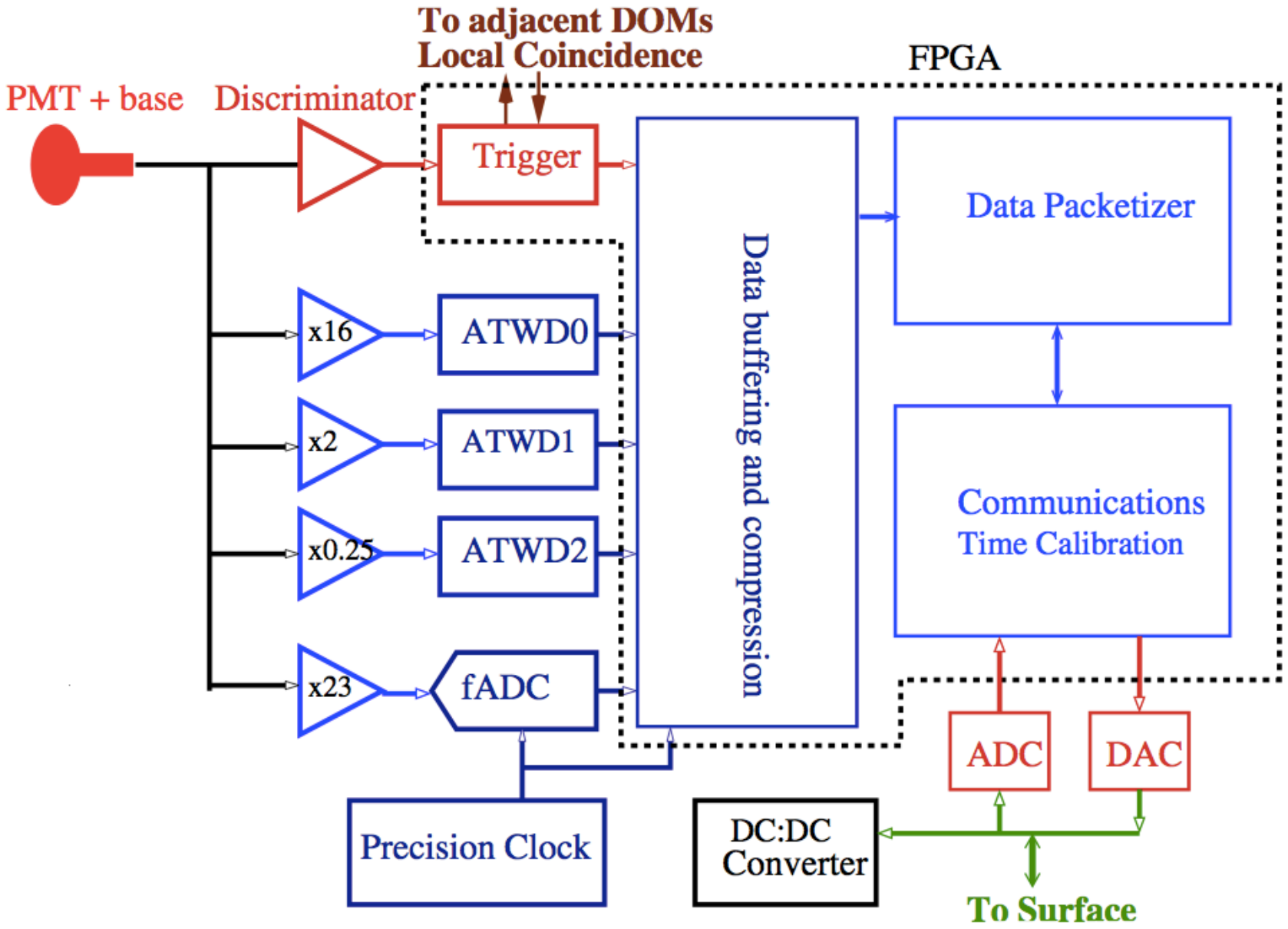
- Pulse waveform sampling: 300 MSPS
- Wide dynamic range: 200 pe/10 ns
- Hit timing accuracy: 2 ns rms
- Low dead-time: << 1%
- Low power consumption: <5 W
- Adequate CPU and memory
- Built-in calibration, monitoring and debugging capabilities
- Remotely reprogrammable software and firmware.
- Off-board interfaces: PMT Power and flasher boards.
- Long lifetime, high reliability with optimized



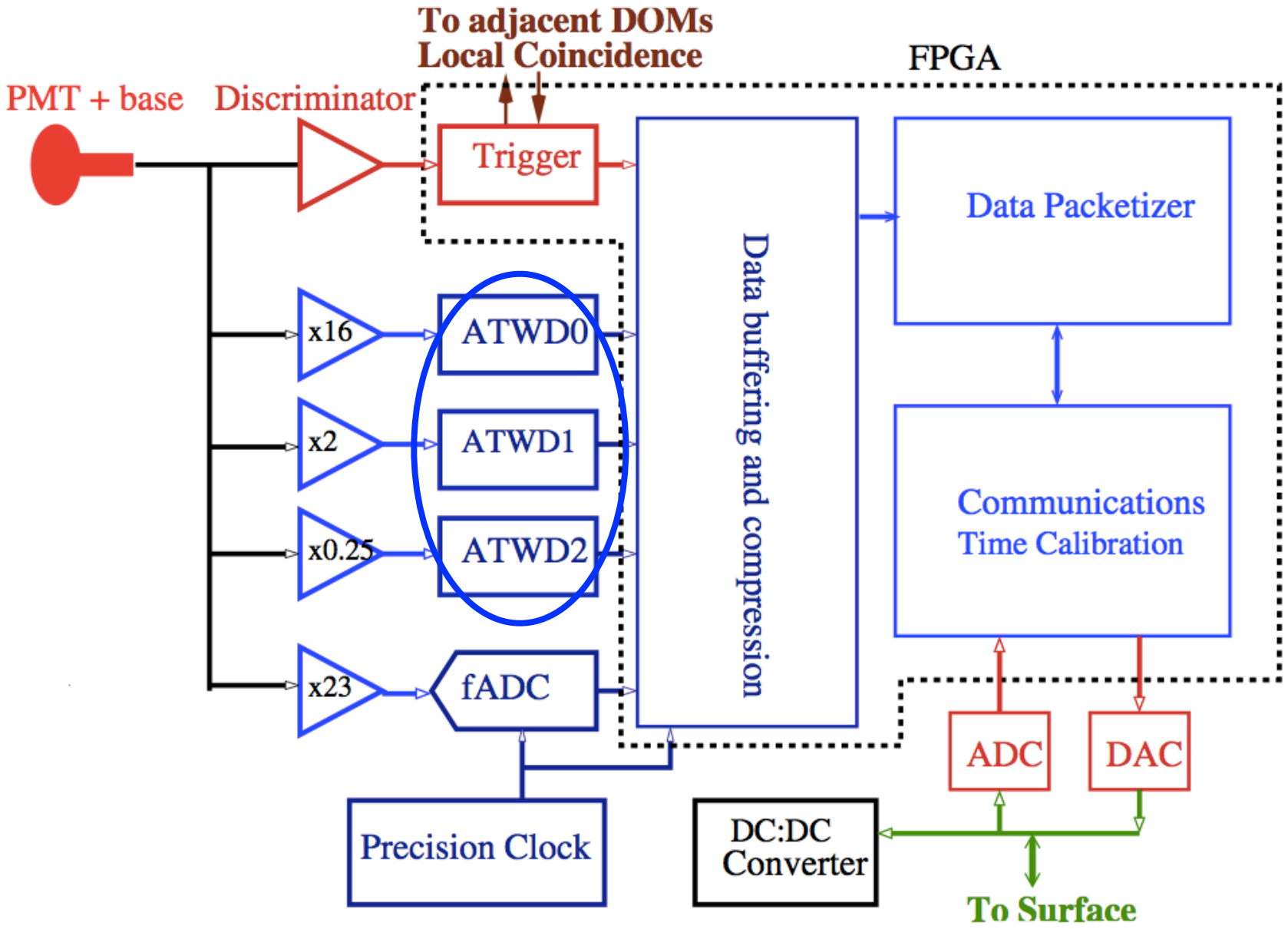
Engineer: Jerry Przybylski, LBNL

Goal: “as simple as possible”

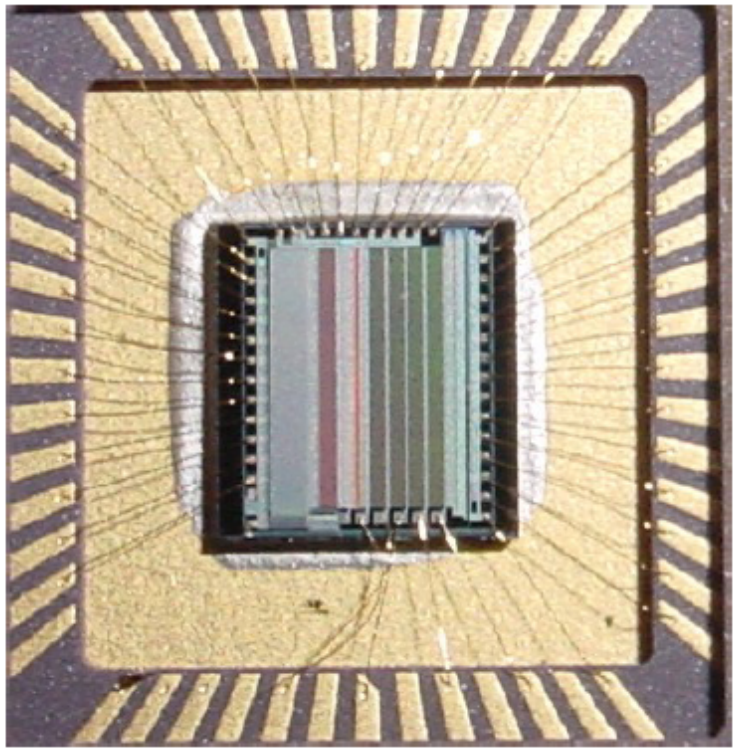
Digital Optical Module Main Board Design



Digital Optical Module Main Board Design

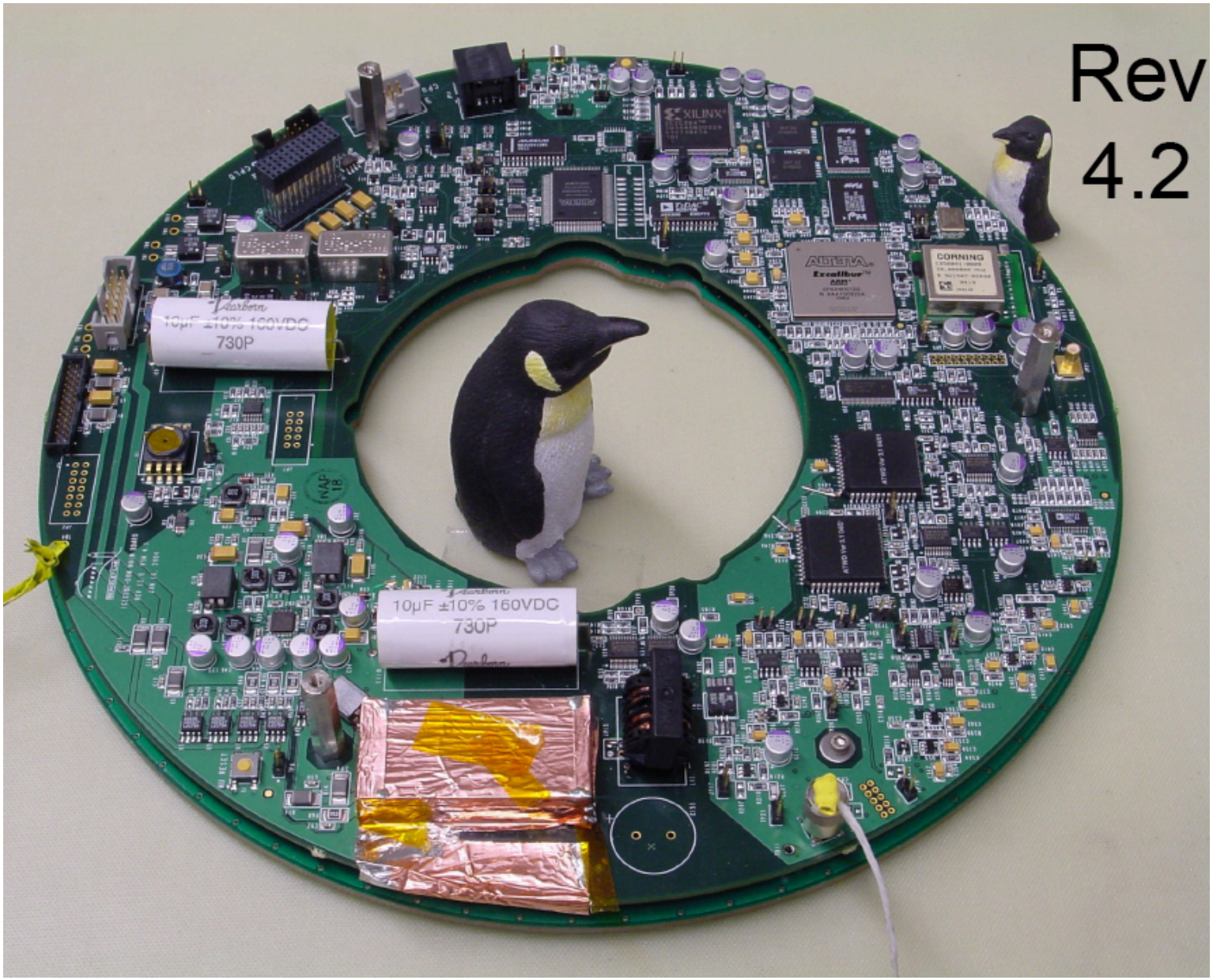


IceCube ATWD



- Adopted from Analog Transient Wave Recorder (ATWR) designed by Stuart Kleinfelder.
- Switched-capacitors = low power
- 4 input channels (3 for PMT signal and 1 for calibrations etc), 256 samples per channel
- synchronous sampling: variable from 200-1000 MHz
- 10 bit S/N
- For the ATWR there was no internal ADC and readout was slow.
- Solution: ATWD - 128 channel common-ramp Wilkinson ADC added by Stuart. Improved the readout speed greatly (Also used for the KamLand experiment)

DOM Mainboard



DOM Flasher board

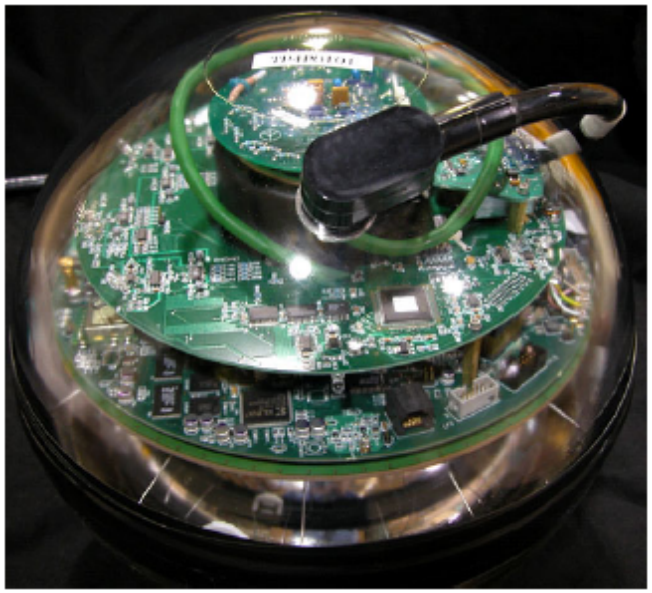
PMTs and pressure vessels

R7081-02 Hamamatsu (252mm) PMTs

IceCube Performance Parameters

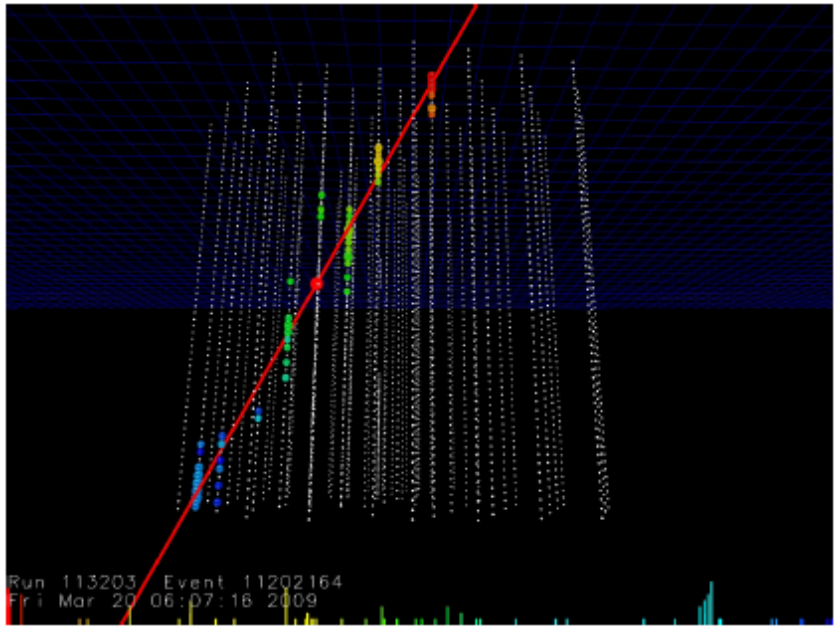
DOM Level

- time resolution
- charge response
- noise behavior
- reliability



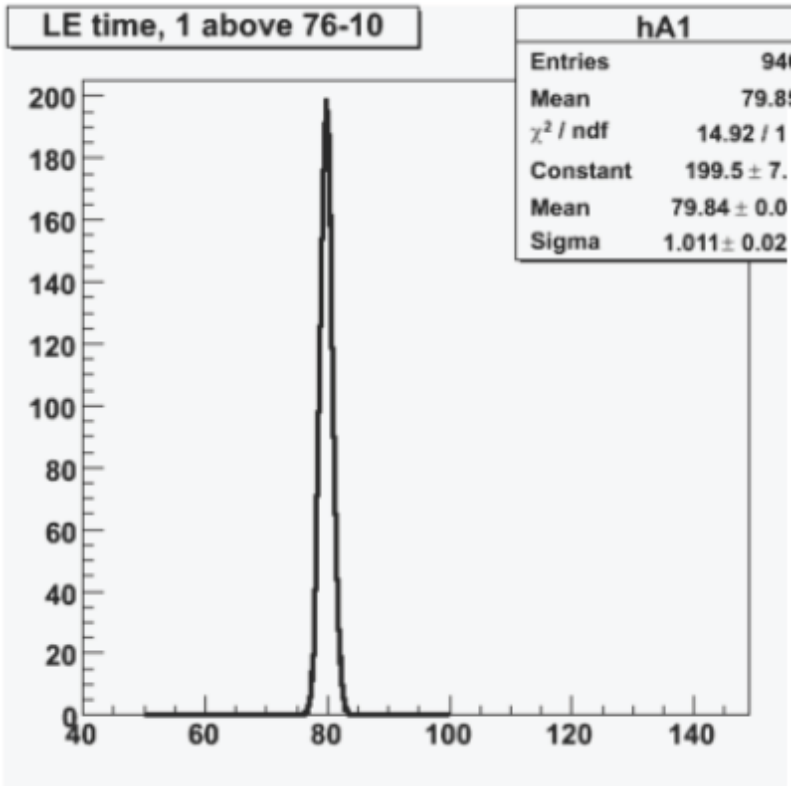
Detector level

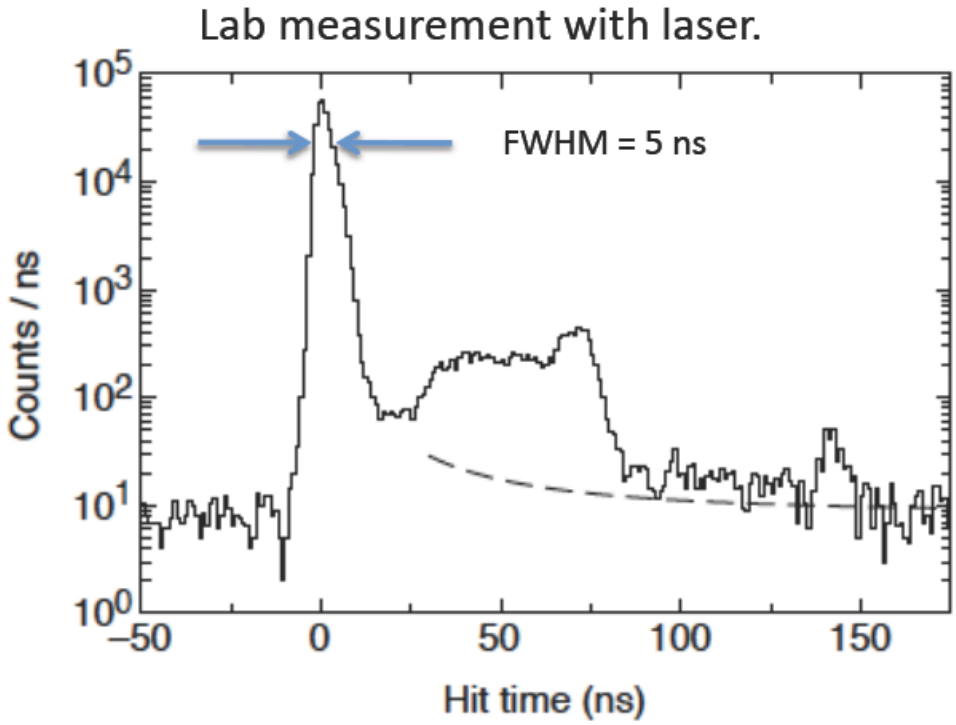
- angular resolution
- energy resolution
- final sensitivity



DOM Time Resolution

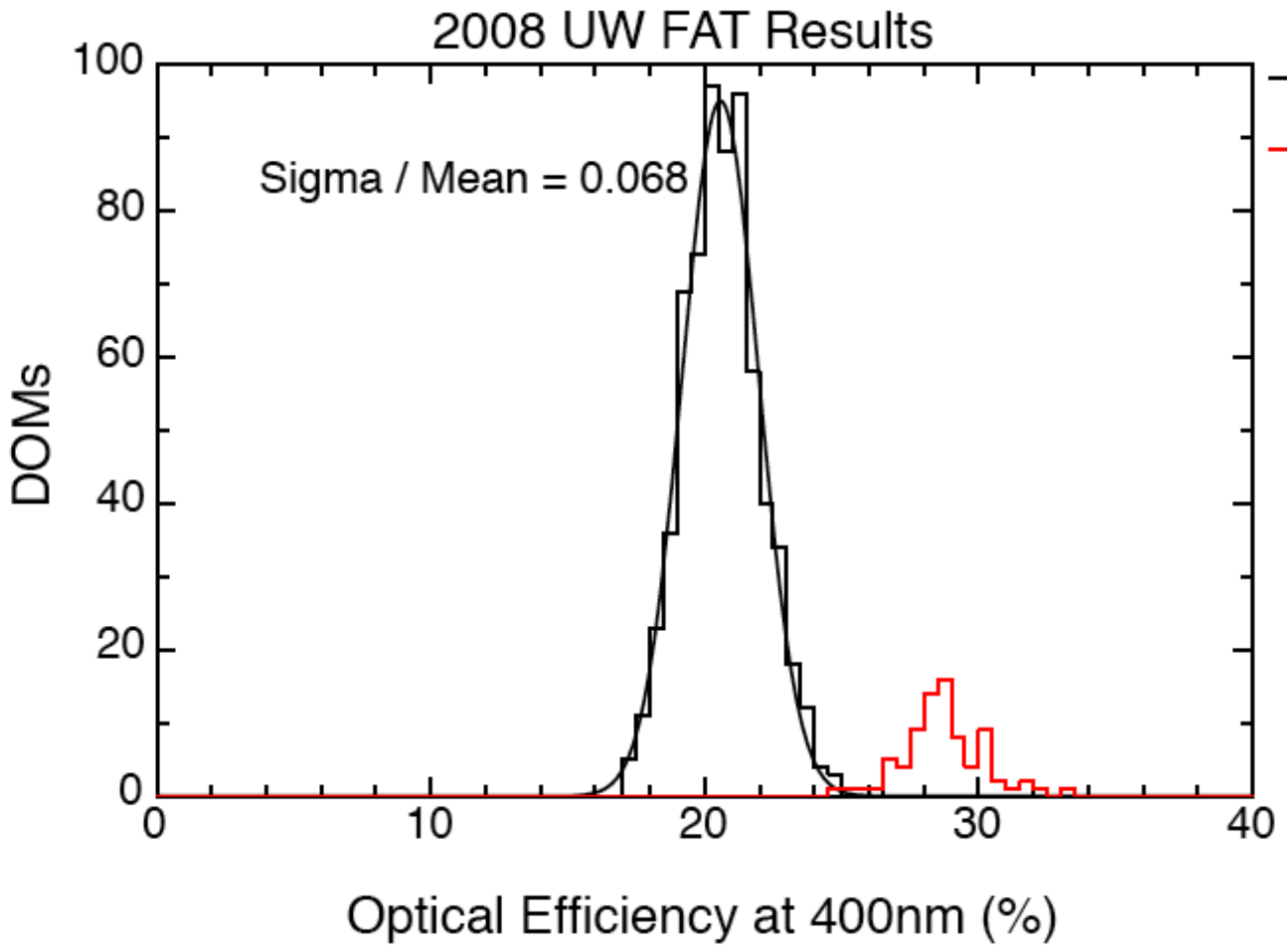
The time difference between neighboring DOMs fired with flasher pulses is ~1 ns (including clock timing).





Single photoelectron pulse resolution is limited by the PMT. RMS in the peak is ~ 2 ns.

DOM Sensitivity



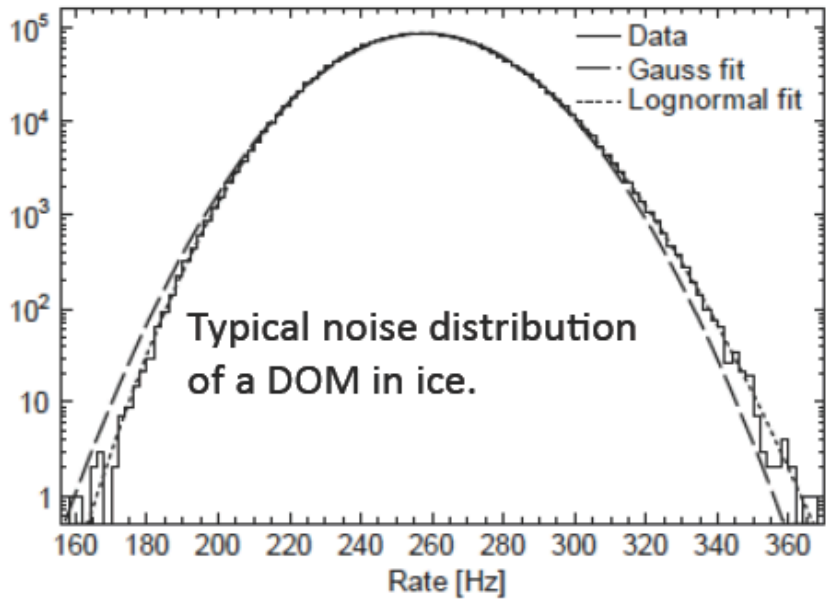
Standard DOMs

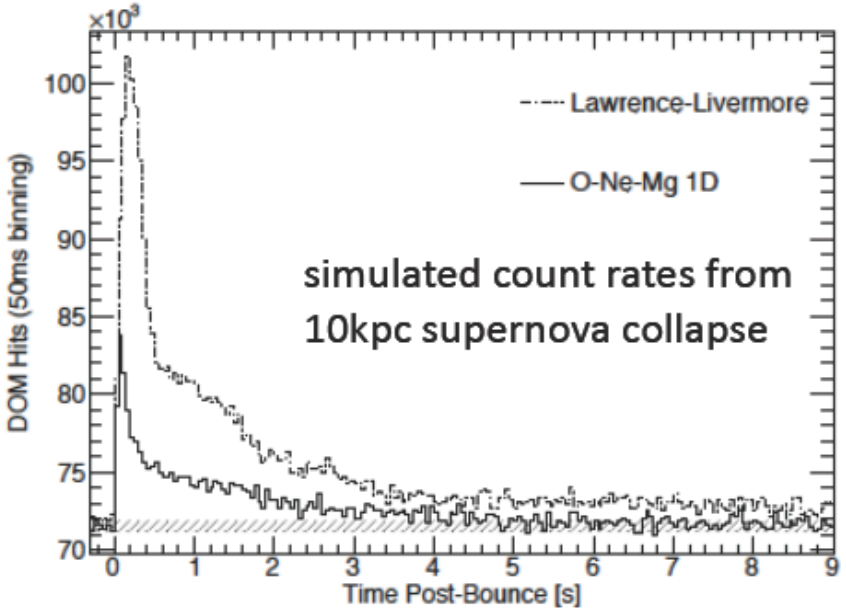
High-QE DOMs

High QE DOMs primarily used on Deep Core strings.
1.35 times phototdetection efficiency

DOM Dark Noise

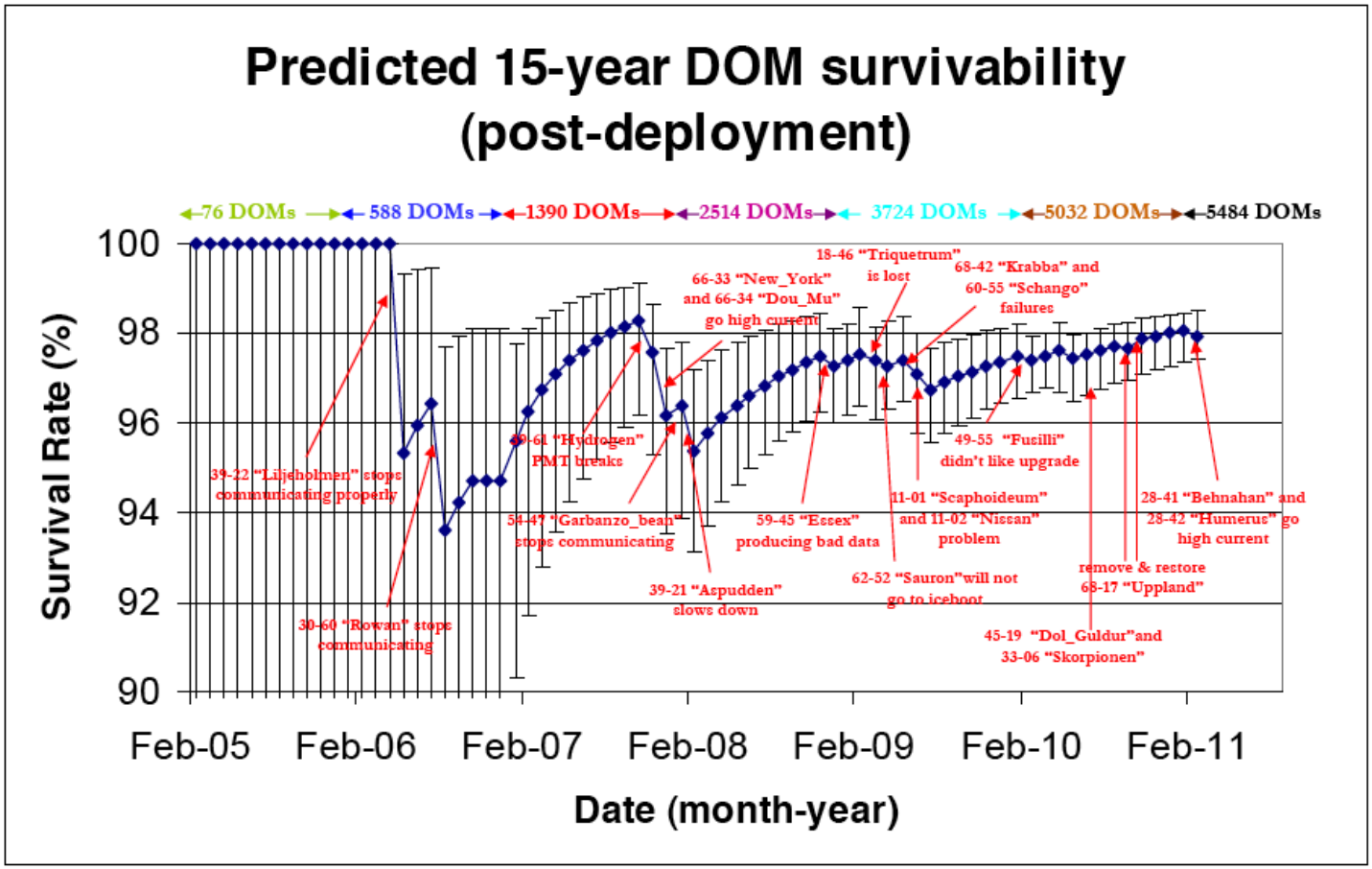
- Use of low-radioactivity glass for the pressure spheres and good PMT characteristics = very low noise rates.
- Average rate/sensor (including dead-time) = 286 Hz
- Sensor noise is stable and as expected. (Gaussian timing distribution is due to correlated hits from single DOM radioactivity and fluorescence in the glass and from multi-DOM cosmic-ray muons.)
- This is a critical parameter for high resolution of neutrino emission time profile of a galactic supernova core collapse.





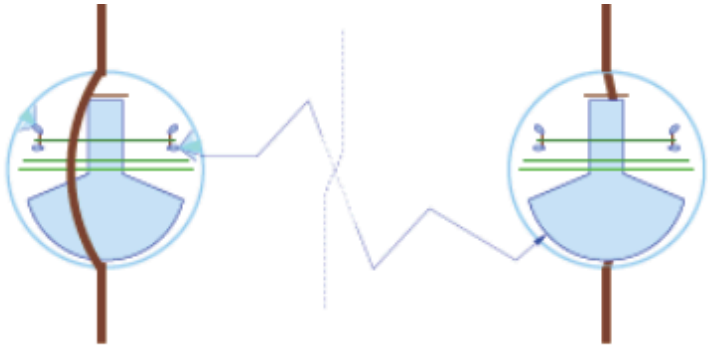
DOM Reliability

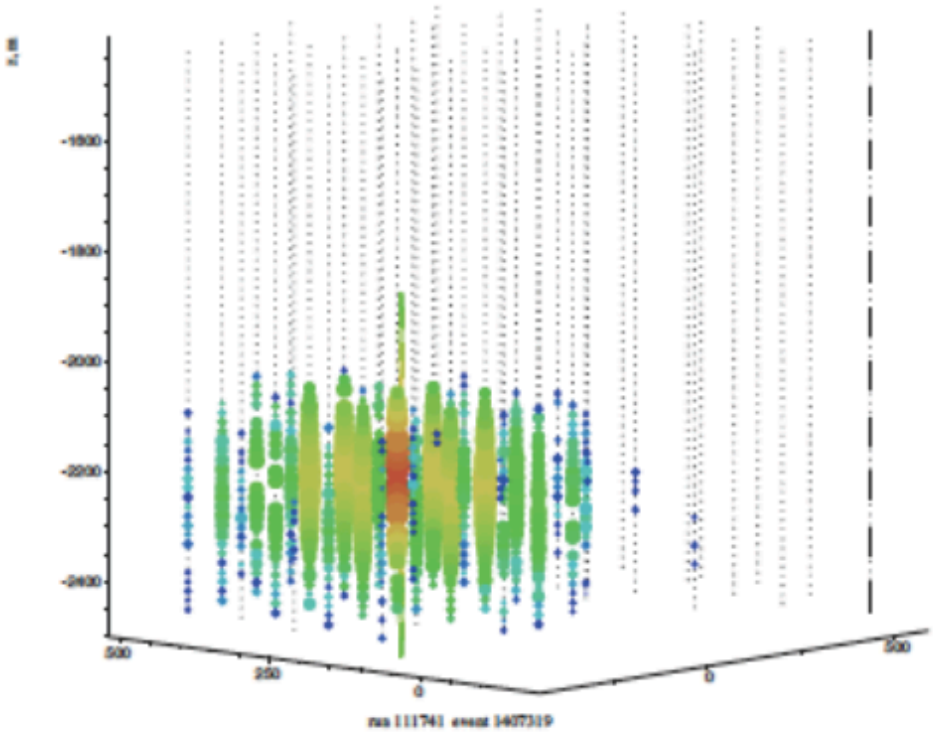
- ~14k years accumulated lifetime as of April 2011.
- 84 lost DOMs (fail commissioning) during deployments and freeze-in
- 19 lost DOMs after successful freeze-in and commissioning.



IceCube Calibrations

- All sensors are equipped with a set of 12 LED flashers.
- A 30 ns pulse of $0(10^9)$ photons at 400 nm are visible to a distance of 600 m.
- The measurements are used to calibrate the detector in time, geometry and optical properties of the ice.



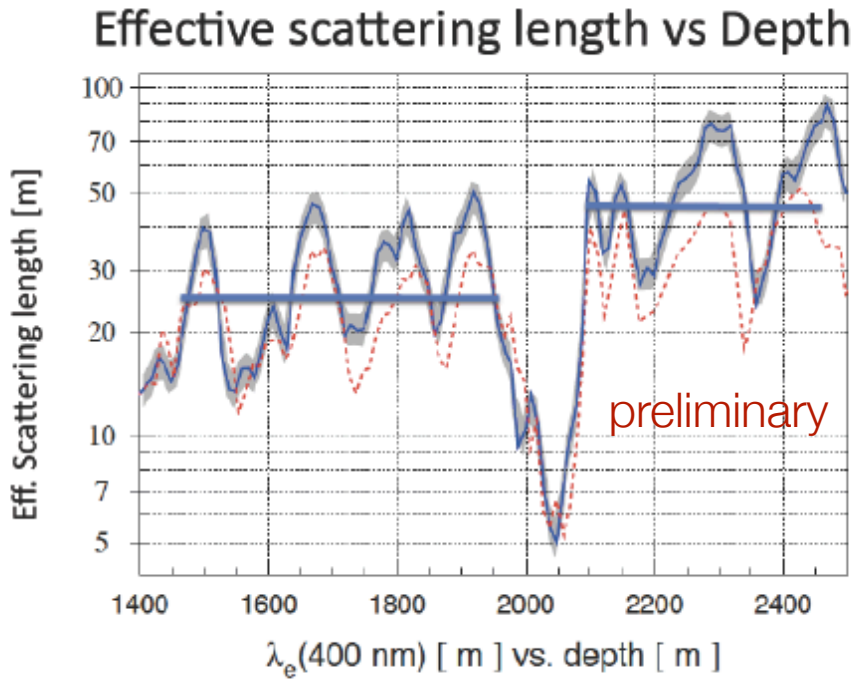


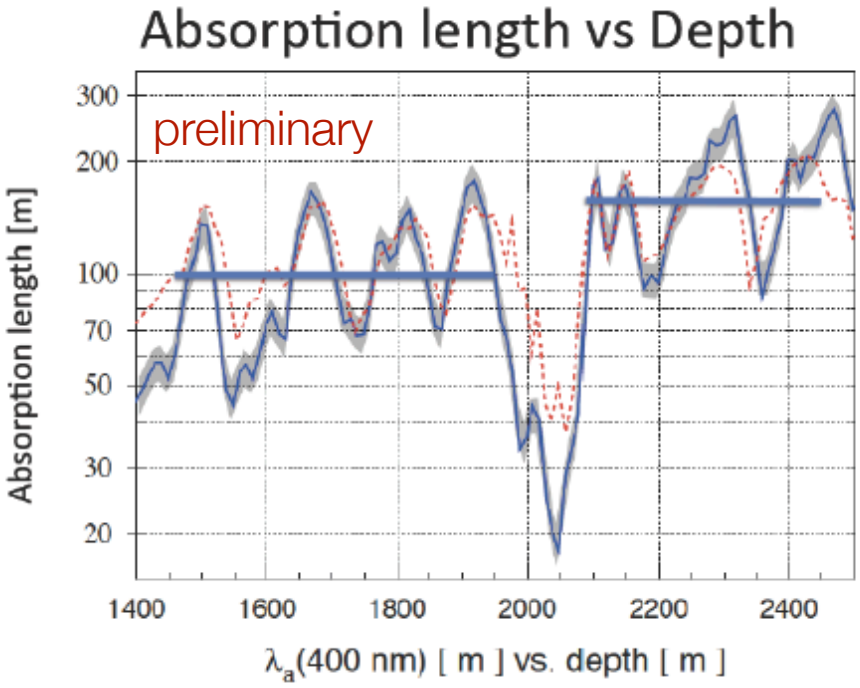
IceCube Calibration

- Depth dependence of the ice is a challenge to analyze and the flasher measurements have been crucial in the knowledge obtained thus far.

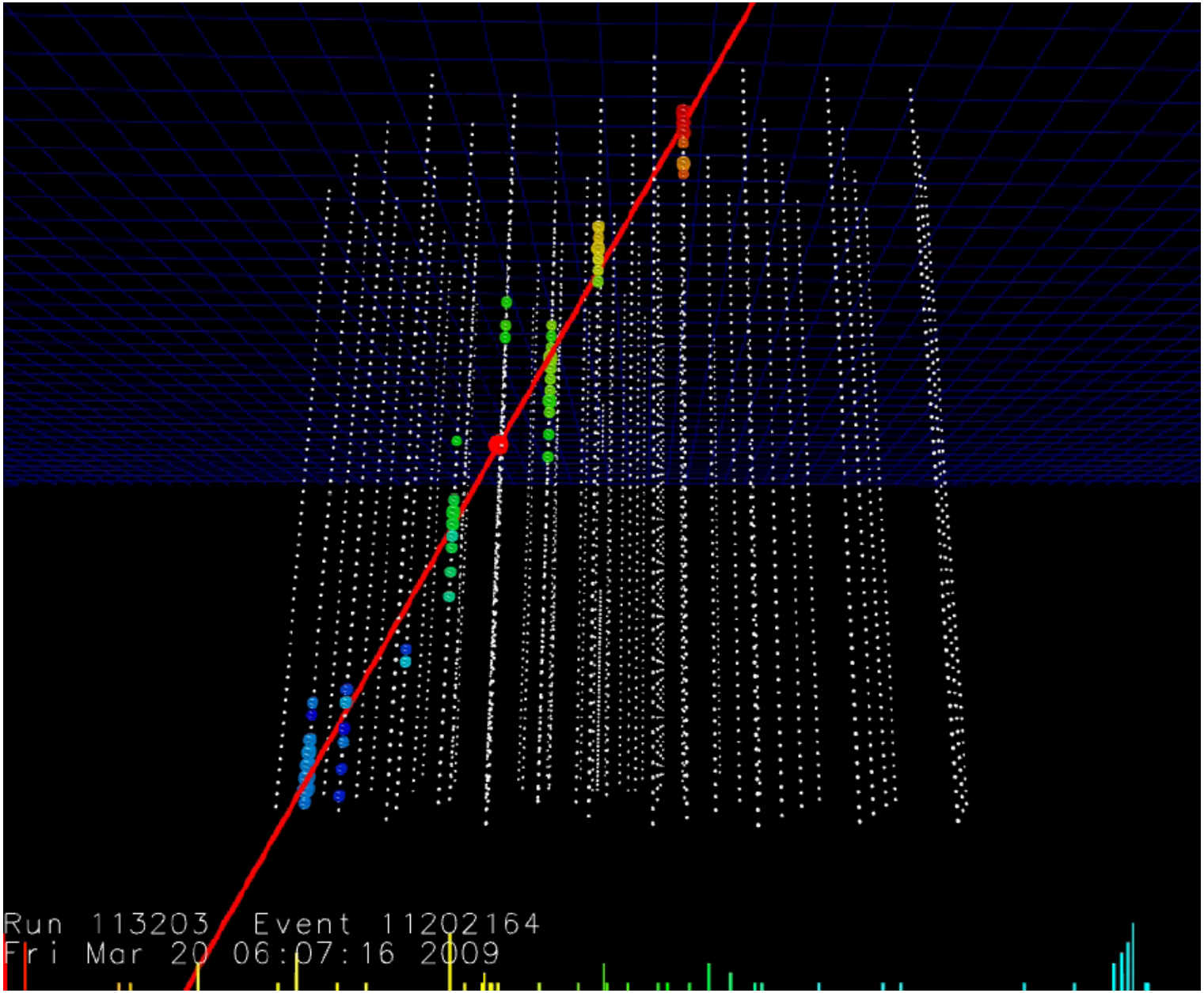
- Special color LED DOMs were deployed and their data is being analyzed to provide multi-wavelength ice calibration.

- The deepest ice, below 2100 m, has better properties than expected making it an excellent medium for particle detection.

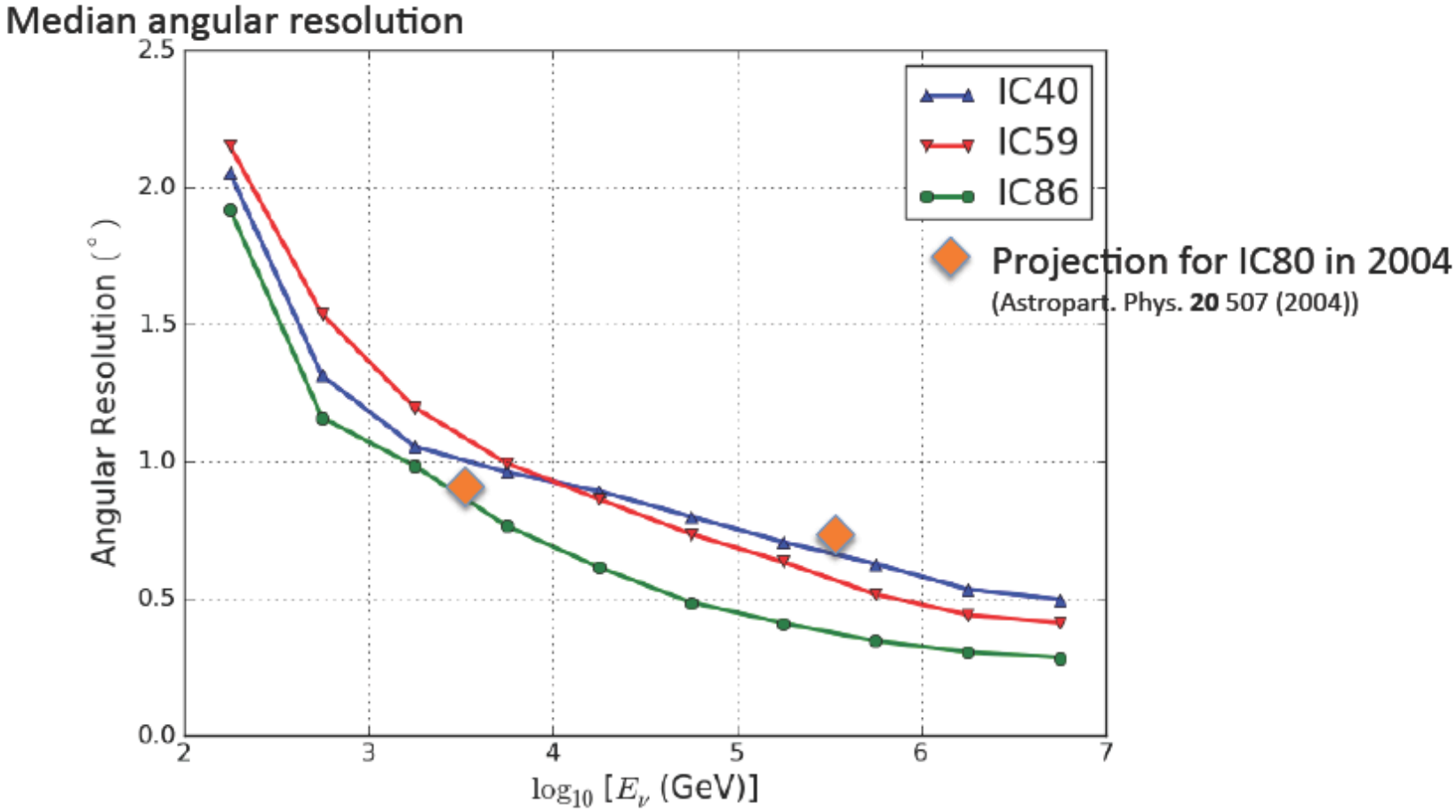




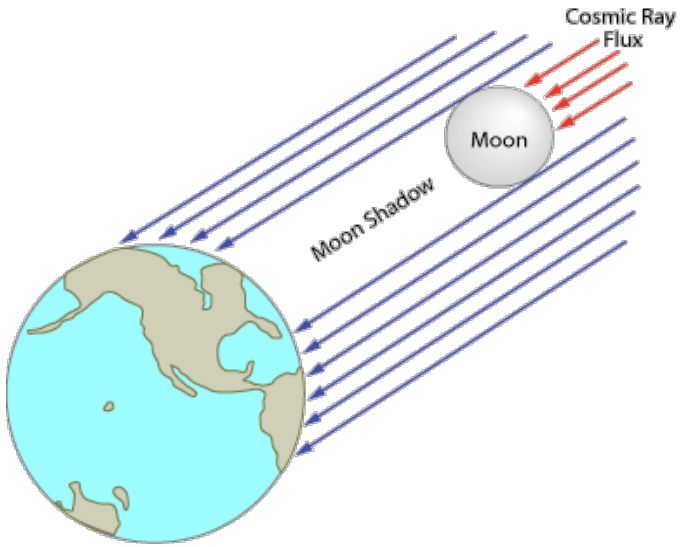
IceCube Detector Performance



IceCube Detector Performance - Angular Resolution

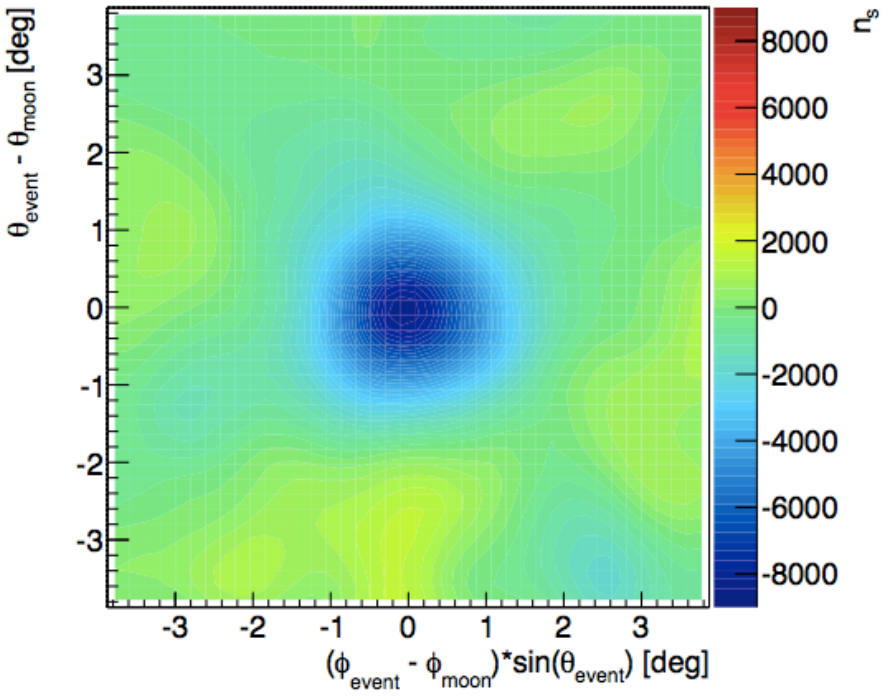


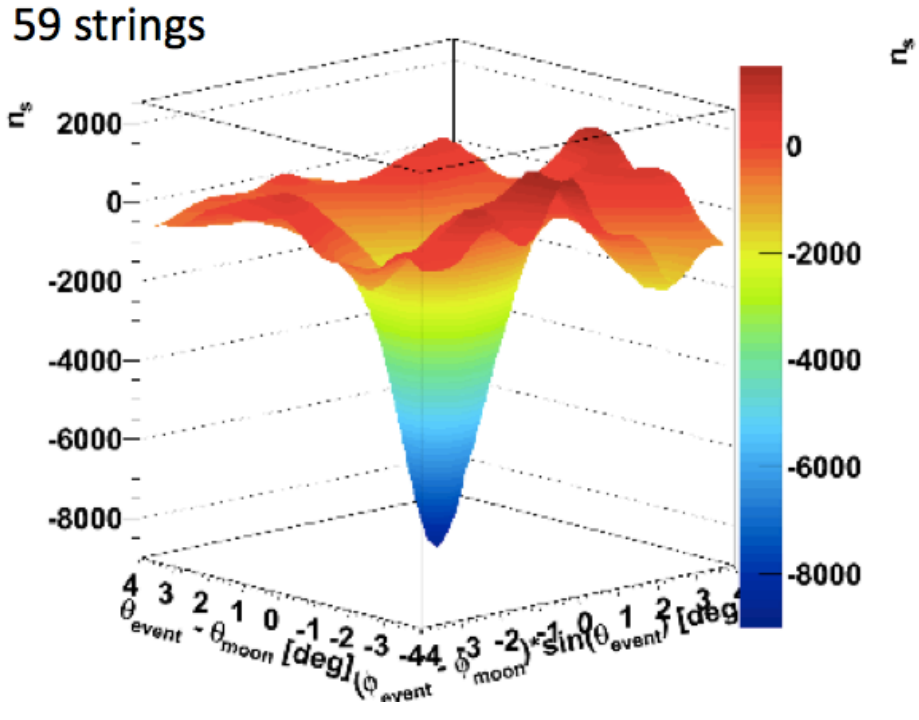
IceCube Detector Performance - Angular Resolution



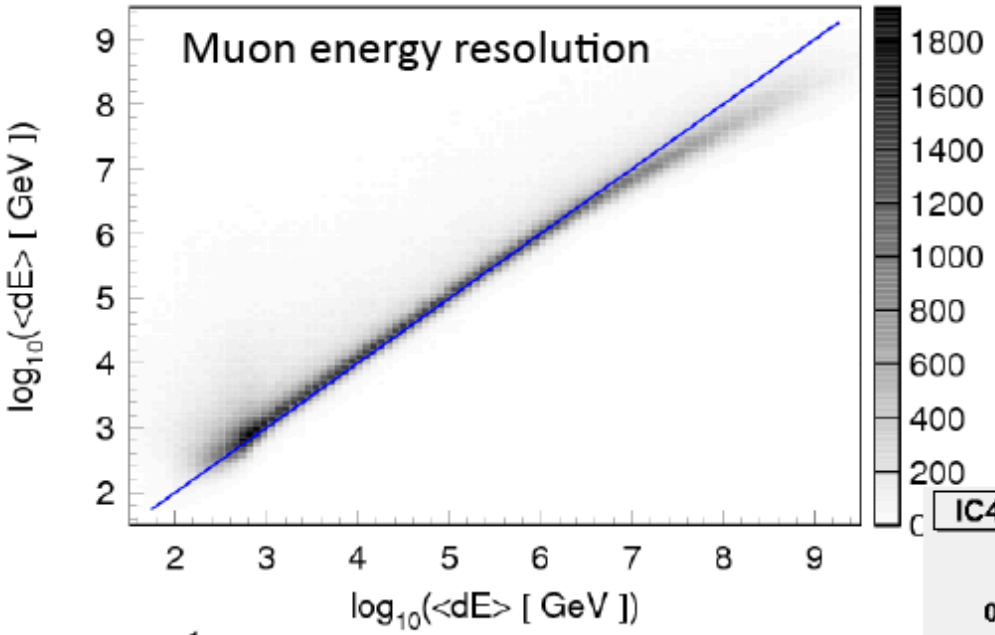
Existence of the moon - confirmed!

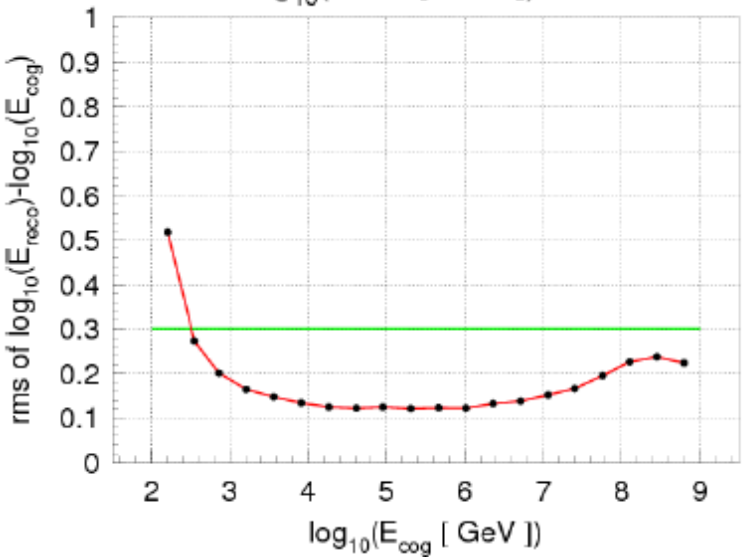
- Likelihood analysis determines deficit of events from direction of moon in the IceCube 59-string detector confirms pointing accuracy.
- Validates pointing capabilities with expected angular resolution for IceCube 80-string detector <1° at 1 TeV.





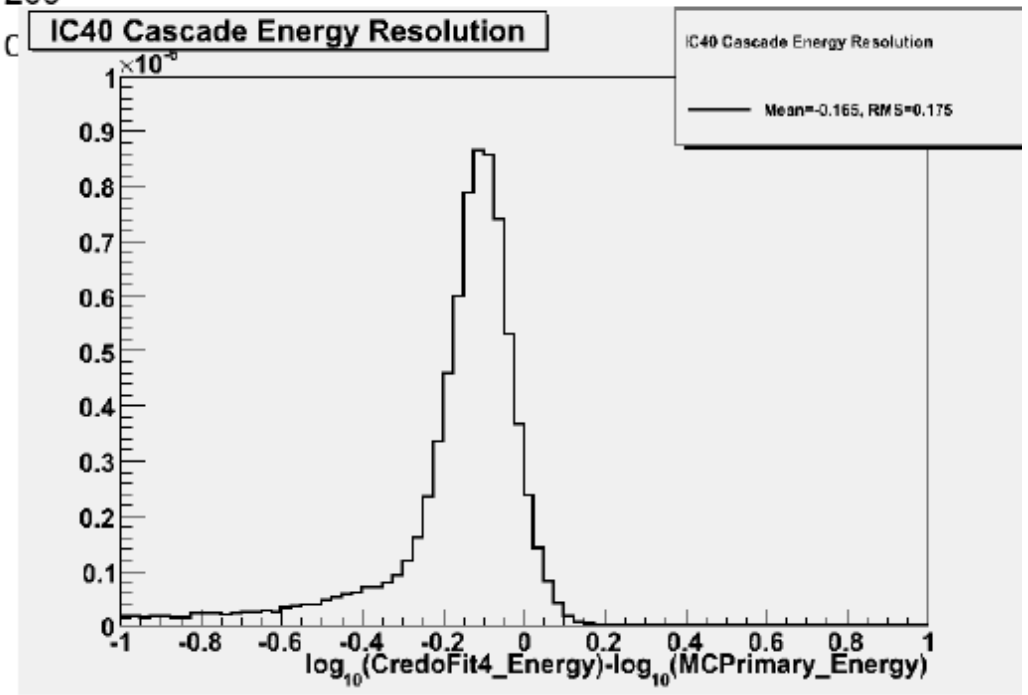
IceCube Detector Performance - Energy Resolution





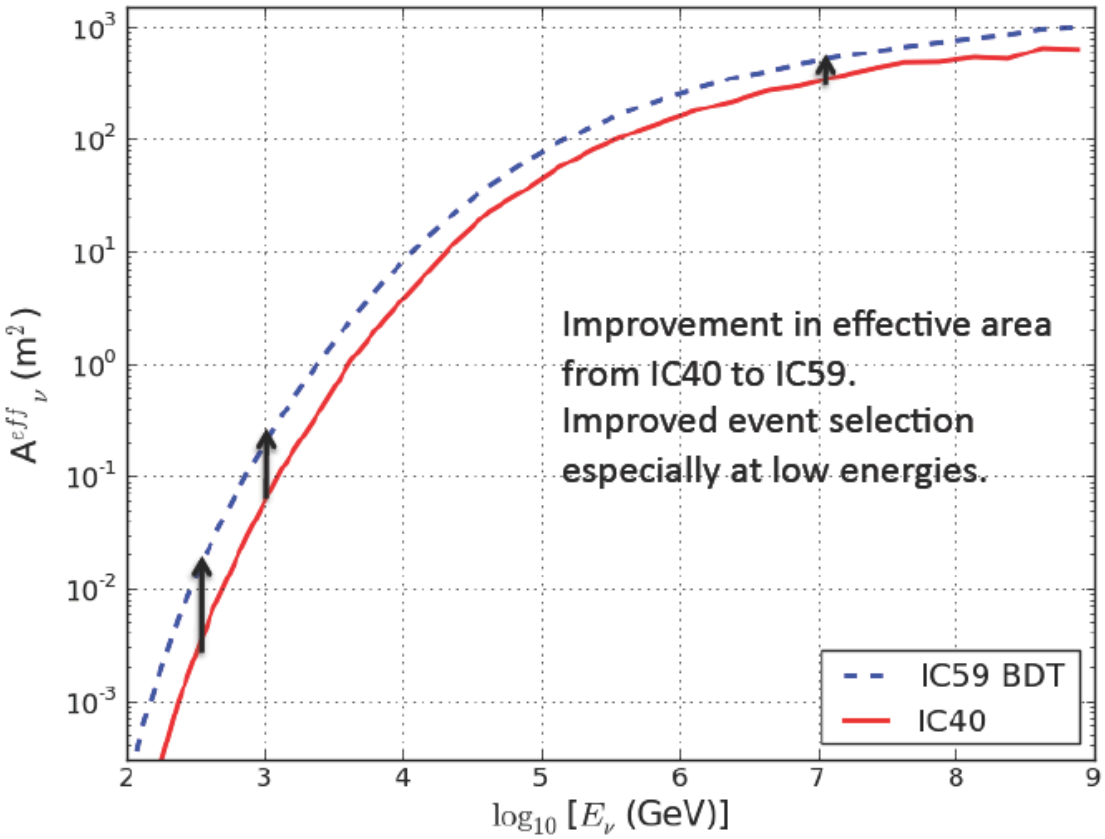
Muon energy: rms of log(E) ~ 0.15
Muon neutrino: 0.3 (inevitable physics fluctuations from neutrino energy to muon energy at detector)

Electron neutrino cascades:
rms of log(E): ~ 0.175
sigma of peak: 0.07

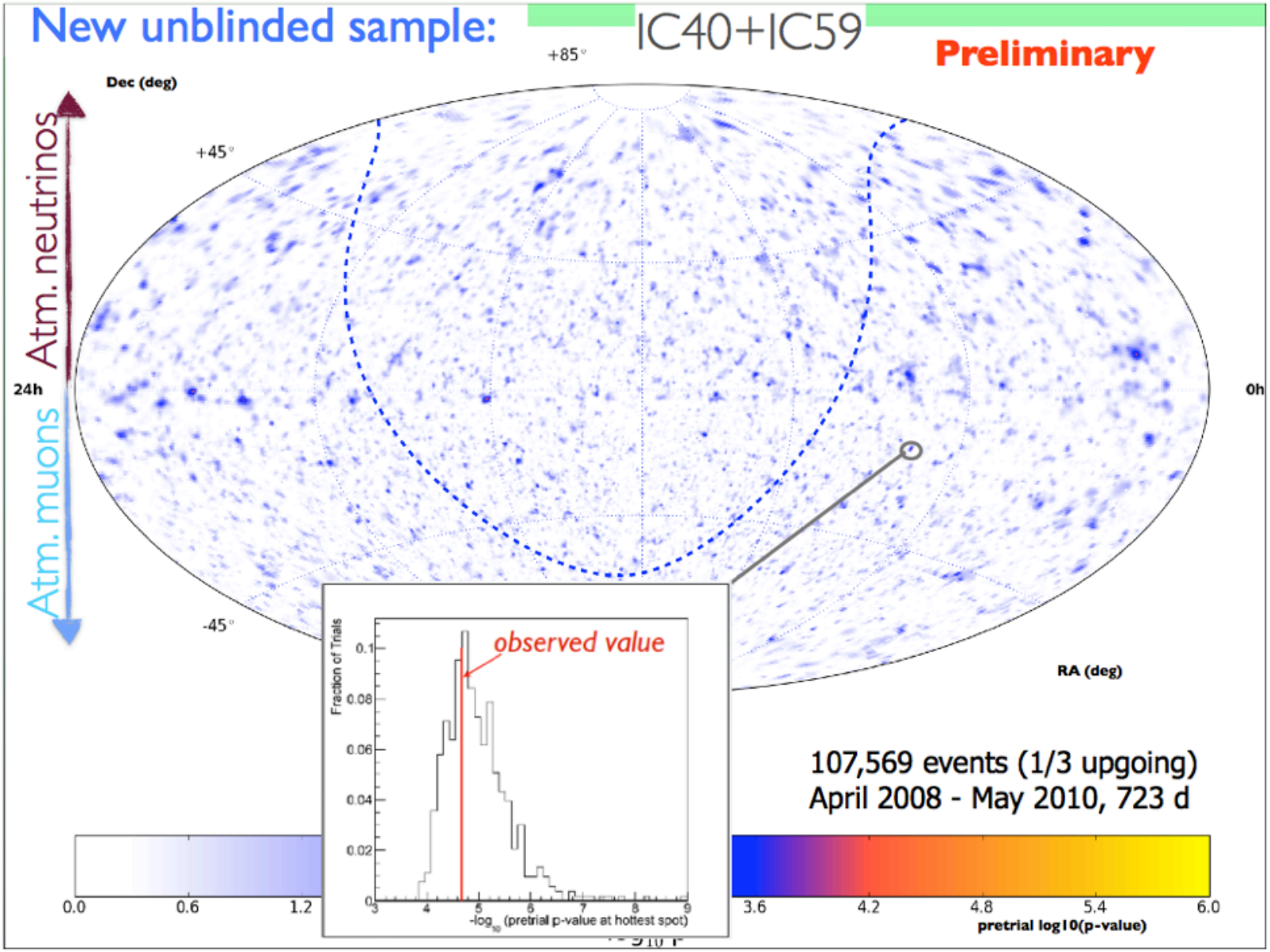


IceCube Detector Performance - Effective Neutrino Area

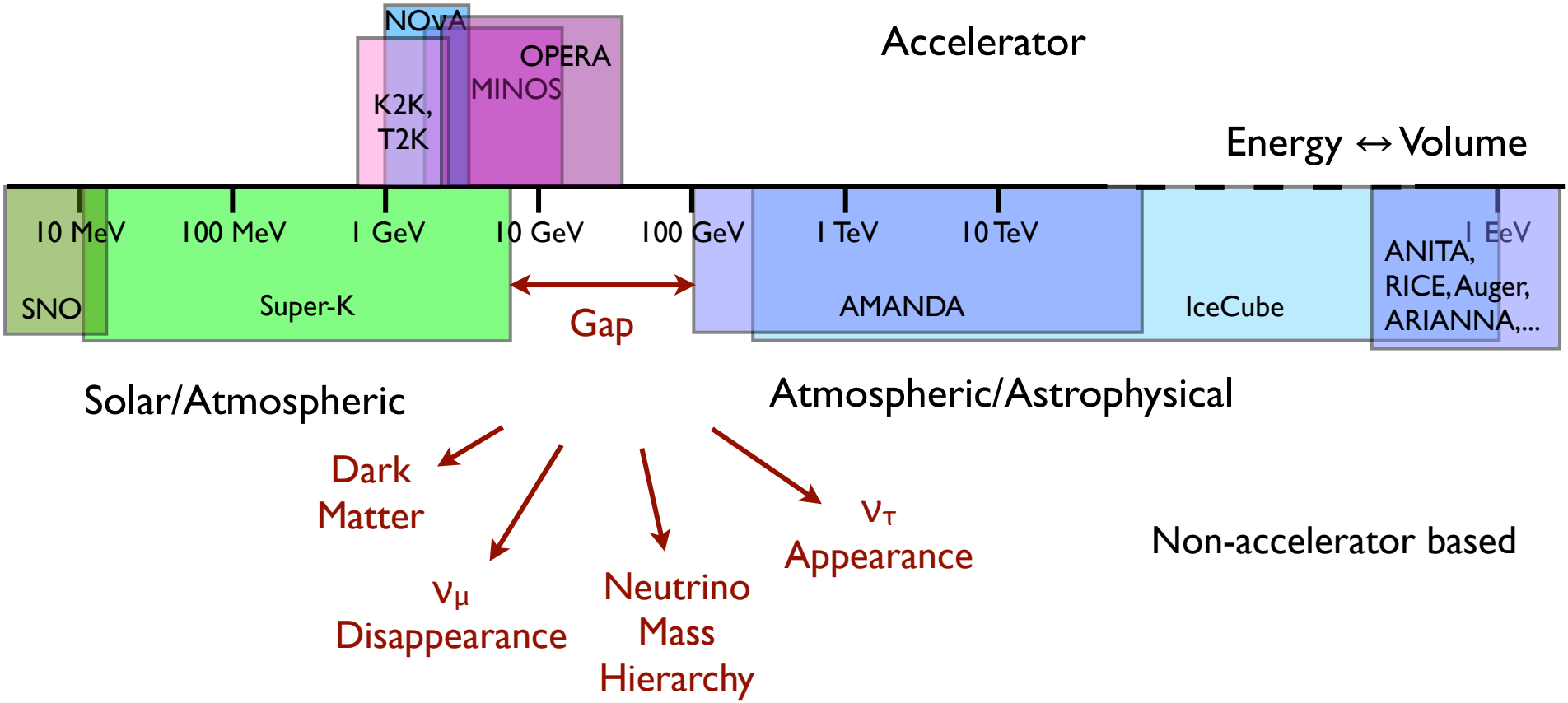
- The detector performance parameters increase faster than the number of strings
- This is an effect of longer muon tracks providing improved angular resolution (lever arm) and energy reconstruction.
- Improved analysis techniques and new ideas (data quality, detector modeling, background simulations) underway will continue to push the improvements for IC86.



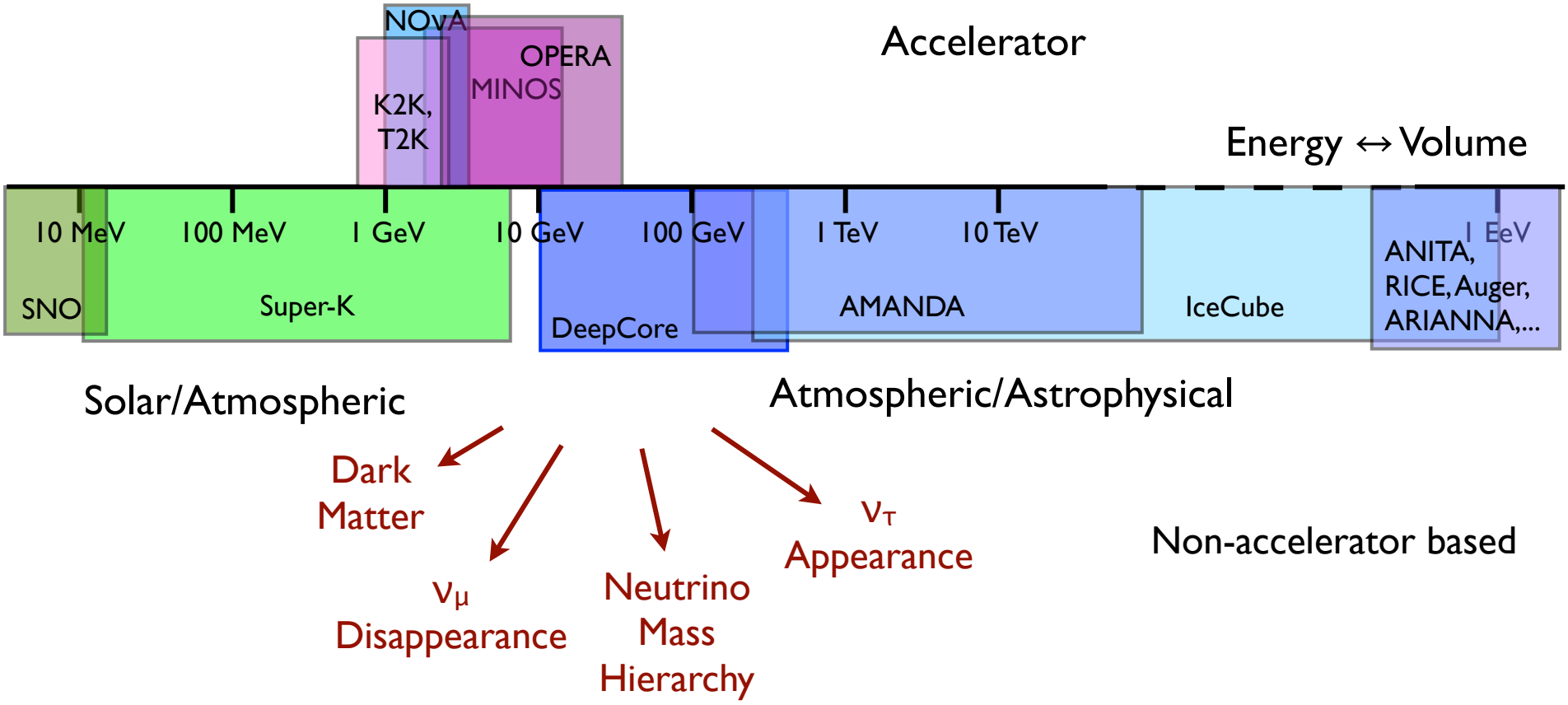
Most Recently from IceCube...



The Neutrino Detector Spectrum



The Neutrino Detector Spectrum

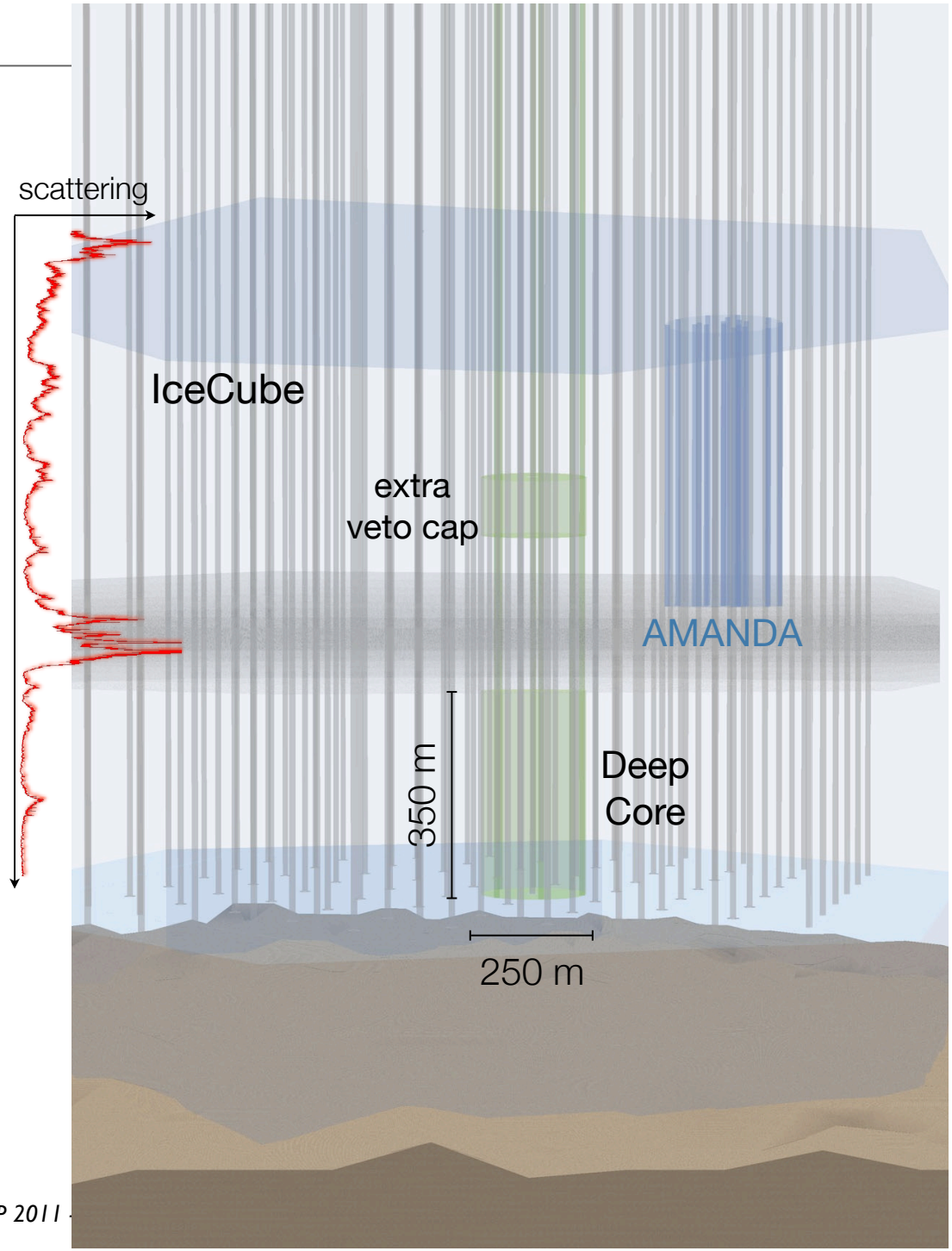


IceCube-DeepCore

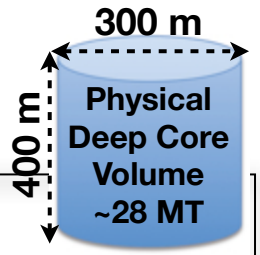
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
- Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Scientific Motivations:
- Indirect search for dark matter
- Neutrino oscillations (e.g., ν_τ appearance)
- Neutrino point sources in the southern hemisphere (e.g., galactic center)

DeepCore Design

- Eight special strings plus seven nearest standard IceCube strings
- 72 m inter-string horizontal spacing (six with 42 m spacing)
- 7 m DOM vertical spacing
- ~35% higher Q.E. PMTs
- ~5x higher effective photocathode density
- Deployed mainly in the clearest ice, below 2100 m
- $\lambda_{eff} > \sim 50$ m
- Result: 30 MTon detector with ~10 GeV threshold, will collect O(200k) atmospheric ν/yr

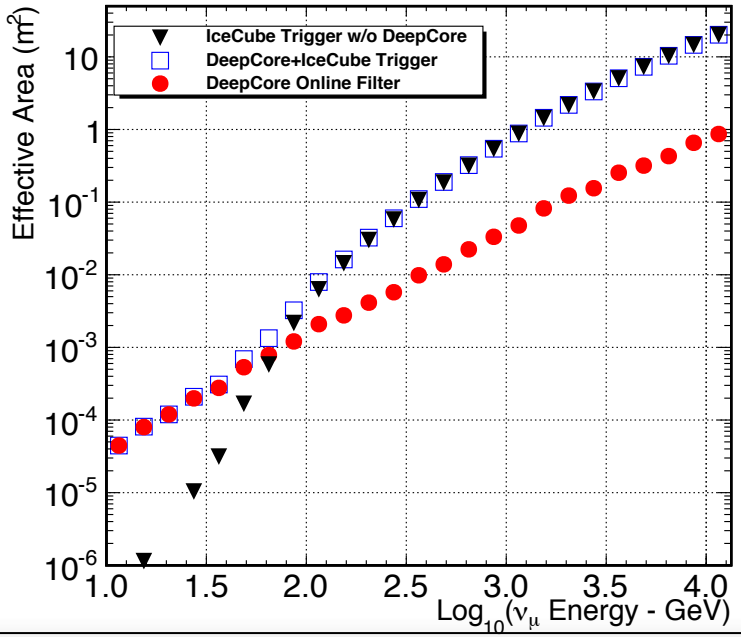


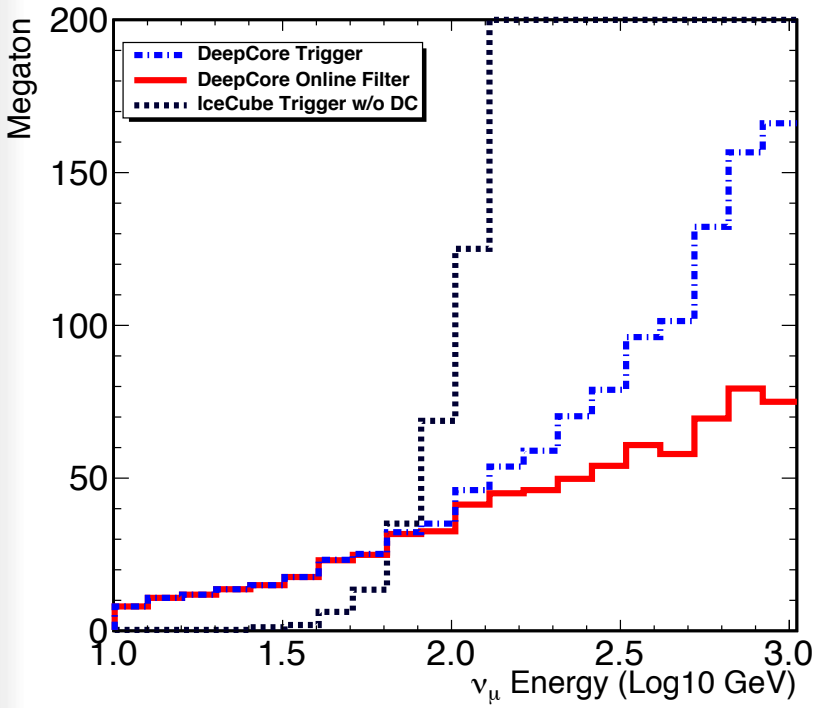
DeepCore Effective Area and Volume



Effective area for up-going ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase





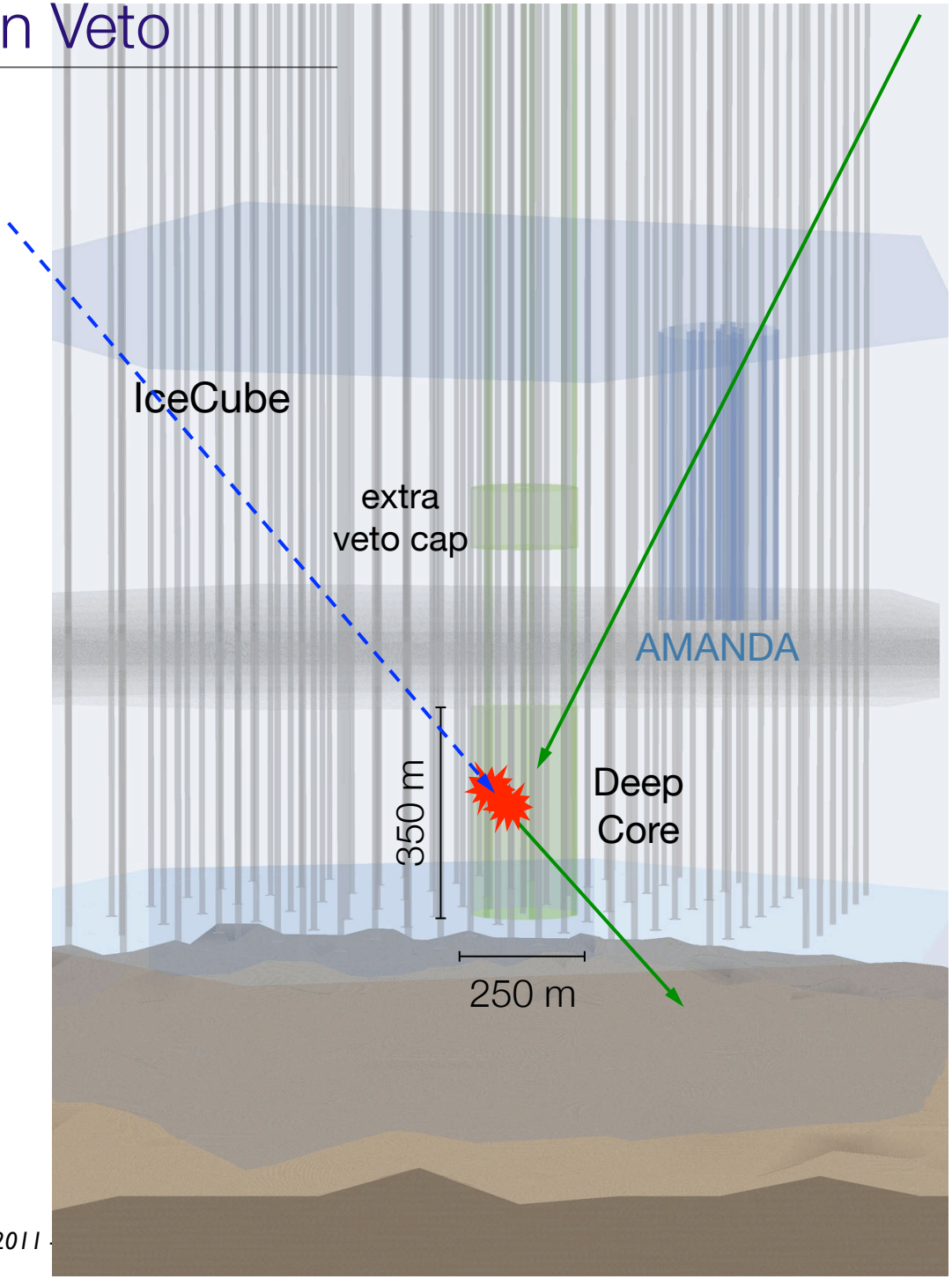
Effective volume for muons from ν_μ interacting in Deep Core

NB: full analysis efficiency *not* included yet

Trigger: ≥3 DOMs hit in 2.5μs;
Online Veto: No hits consistent with muons outside DeepCore volume

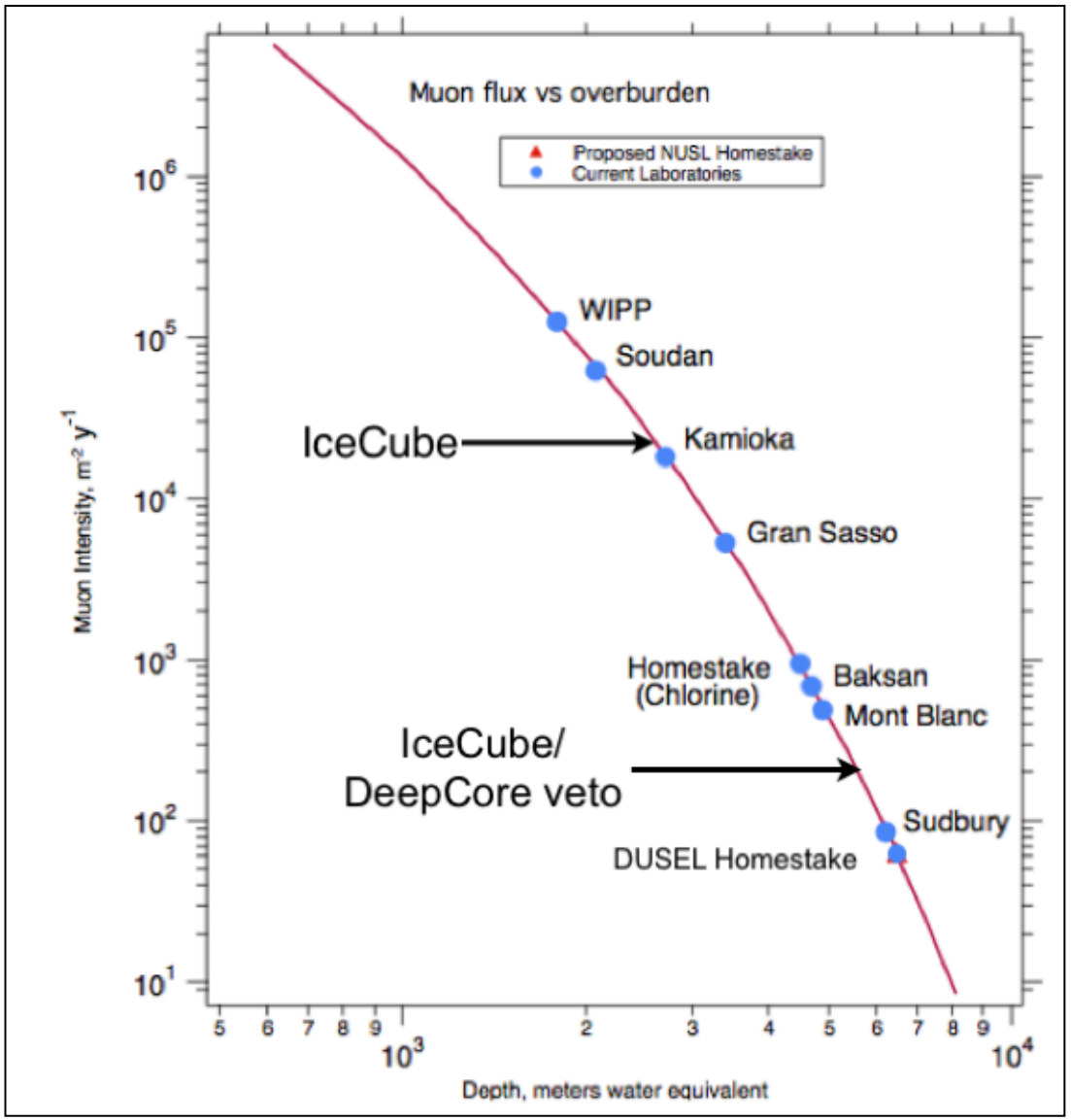
DeepCore Atmospheric Muon Veto

- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
- Can use to distinguish atmospheric μ from atmospheric or cosmological ν
- Atm. μ/ν trigger ratio is ~10^6
- Vetoing algorithms expected to reach at least 10^6 level of background rejection



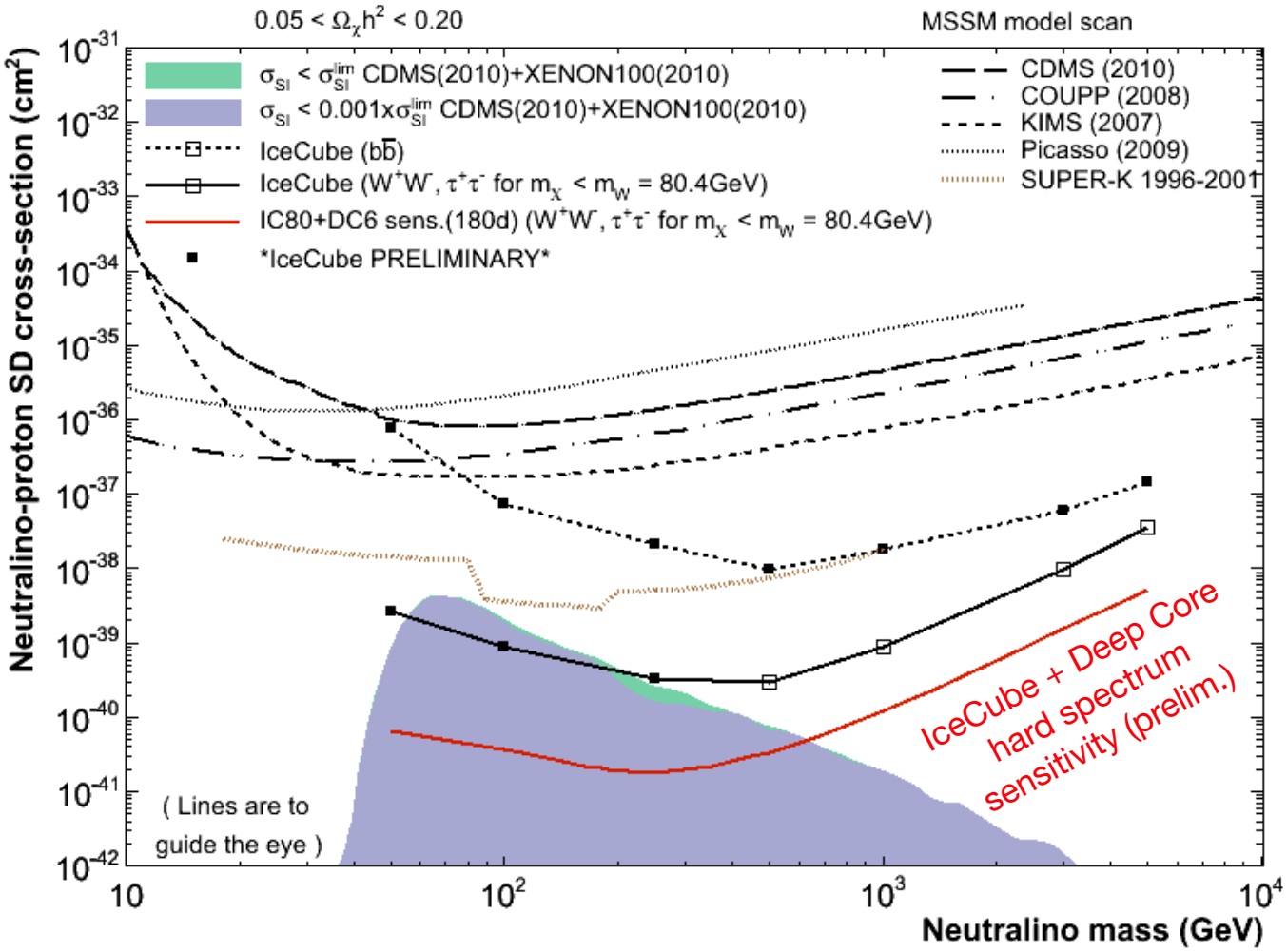
DeepCore Atmospheric Muon Veto

- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
- Can use to distinguish atmospheric μ from atmospheric or cosmological ν
- Atm. μ/ν trigger ratio is ~10^6
- Vetoing algorithms expected to reach at least 10^6 level of background rejection



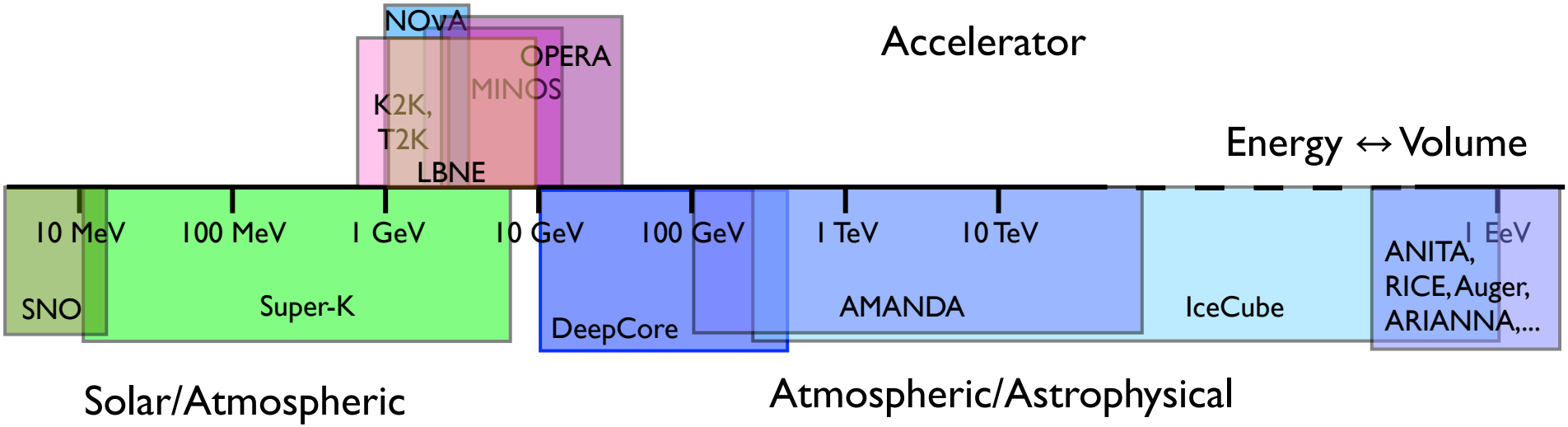
IceCube-DeepCore WIMP Sensitivity

- Solar WIMP dark matter searches probe SD scattering cross section
- SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



IC22 (1 year) + AMANDA (6 years)

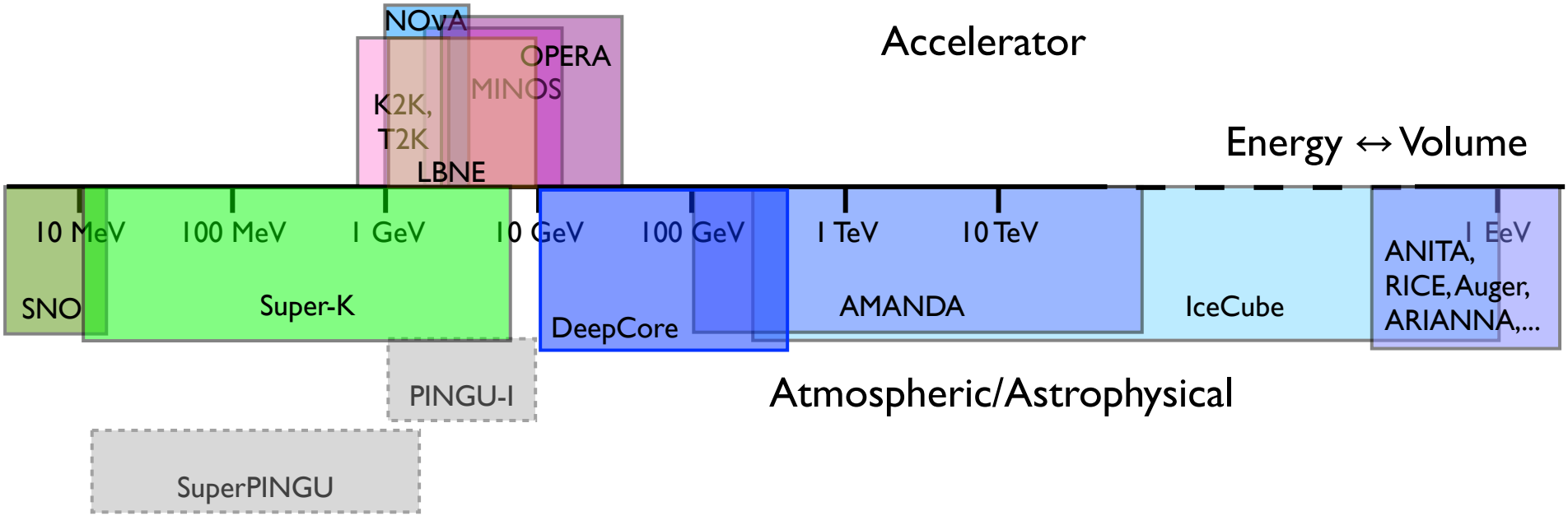
The Neutrino Detector Spectrum



The underground community is preparing programs for large-scale detectors O(300 kT),with physics focused on long-baseline neutrinos, toward O(1MT), proton decay, supernova neutrinos.

Construction of the facilities for these detectors remain a technological challenge.

PINGU - Phased IceCube Next Generation Upgrade



~70 active members in feasibility studies:

- IceCube, KM3Net, Several neutrino experiments
- Photon detector developers
- Theorists

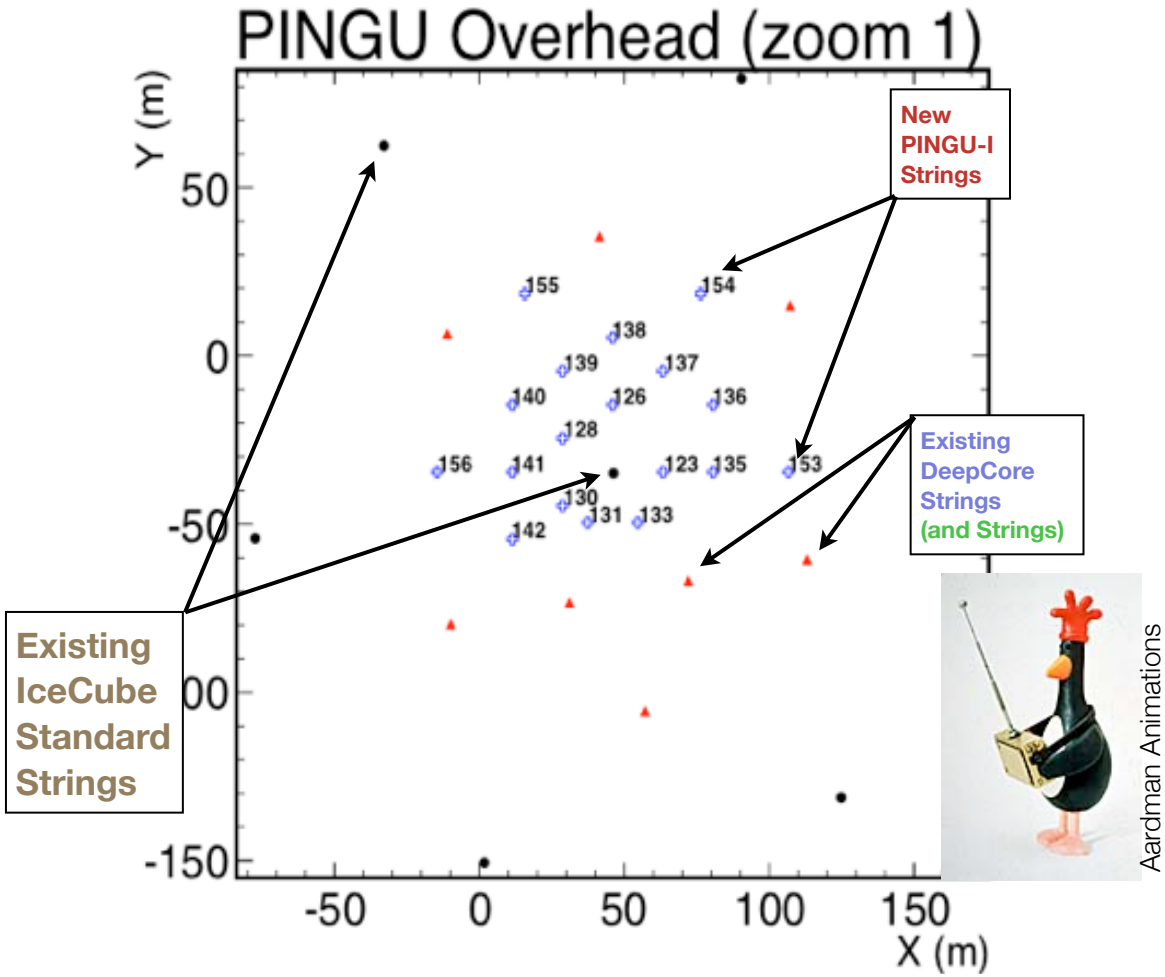
PINGU - Possible detector configurations

- First stage ("PINGU-I")
- Add ~20 in-fill strings to DeepCore to extend energy reach to ~1 GeV
  - improves WIMP search, neutrino oscillation measurements, other low energy physics
  - test bed for physics signals addressed by next stage
- Use mostly standard IceCube technology
- Include some new photon detection technology as R&D for next step

- Second stage ("SuperPINGU")
- Using new photon detection technology, build detector that can reconstruct Cherenkov rings for events well below 1 GeV
  - proton decay, supernova neutrinos, PINGU-I topics
- Comparable in scope (budget/strings) to IceCube, but in a much smaller volume

PINGU-I: Possible Geometry

- Could continue to fill in the DeepCore volume
  - E.g., an additional 18-20 strings (~1000 DOMs) in the 30 MTon DeepCore volume
  - Could reach O(GeV) threshold in inner 10 MTon volume

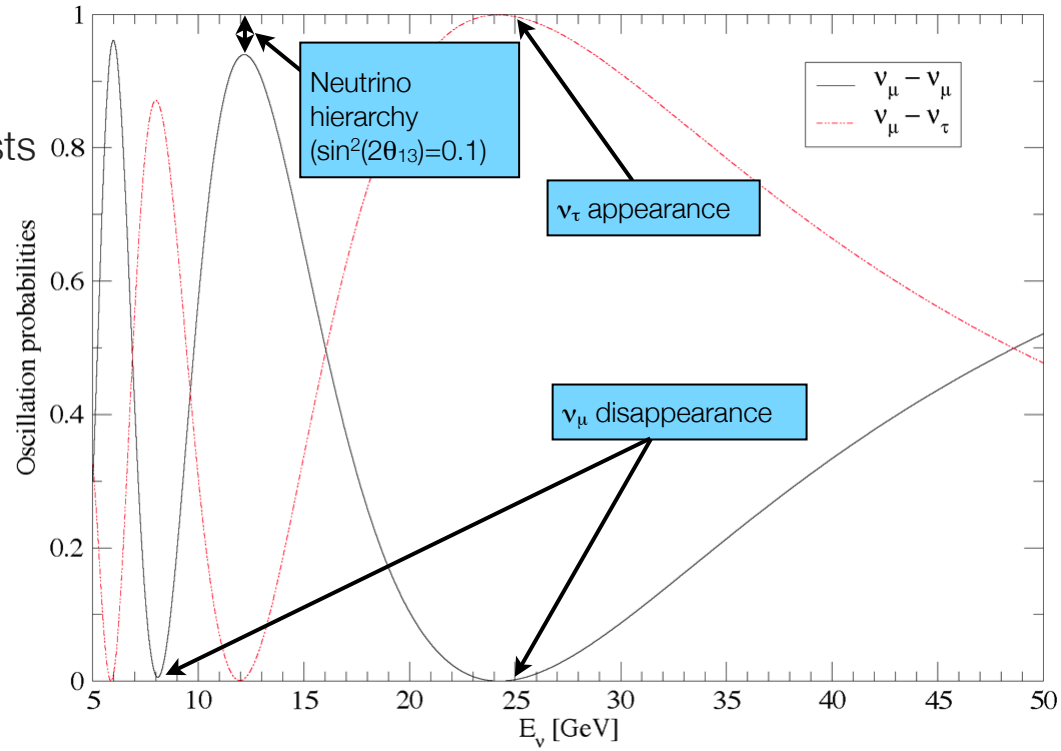


- Price tag would likely be around $25M

PINGU-I Physics

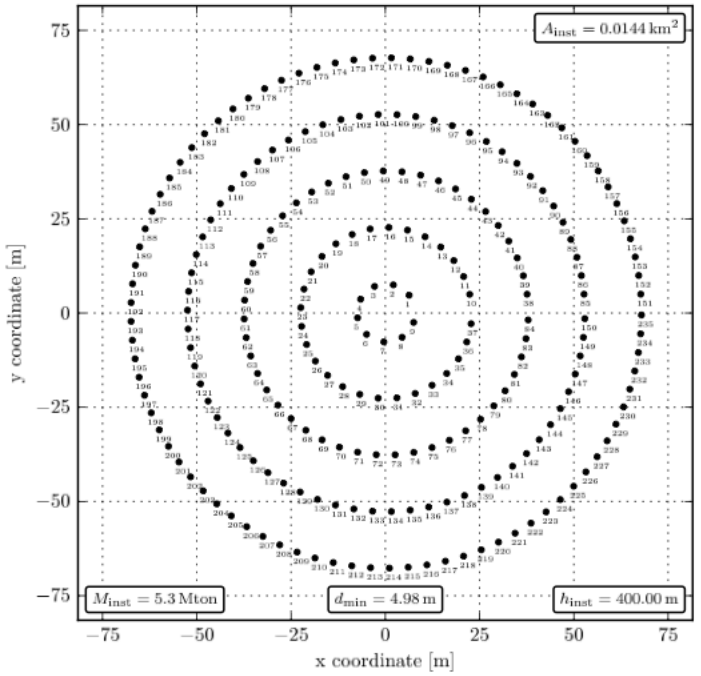
- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - will help pin down $(\Delta m_{23})^2$
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate across entire detector volume
  - Only 2±1 core collapse SN/century in Milky Way
    - need to reach out to our neighboring galaxies
- Gain depends strongly on noise reduction via coincident photon detection (e.g., in neighbor DOMs)
- Begin initial in-situ studies of sensitivity to proton decay
- Extensive calibration program
- Pathfinder technological R&D for SuperPINGU

Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)



SuperPINGU Conceptual Detector

- O(few hundred) strings of “linear” detectors within DeepCore fiducial volume
- Goals: ~5 MTon scale with energy sensitivity of:
  - O(10 MeV) for bursts
  - O(100 MeV) for single events
- Physics extraction from Cherenkov ring imaging in the ice
- IceCube and DeepCore provide active veto



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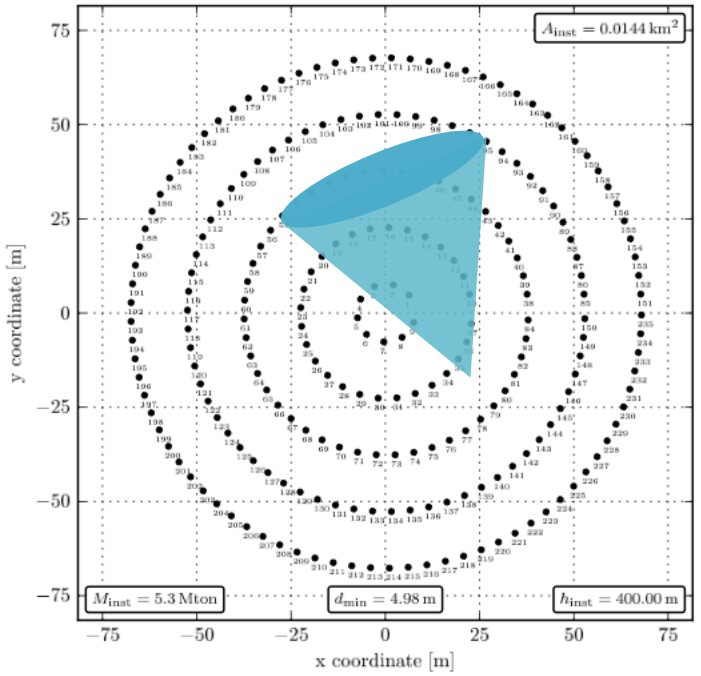
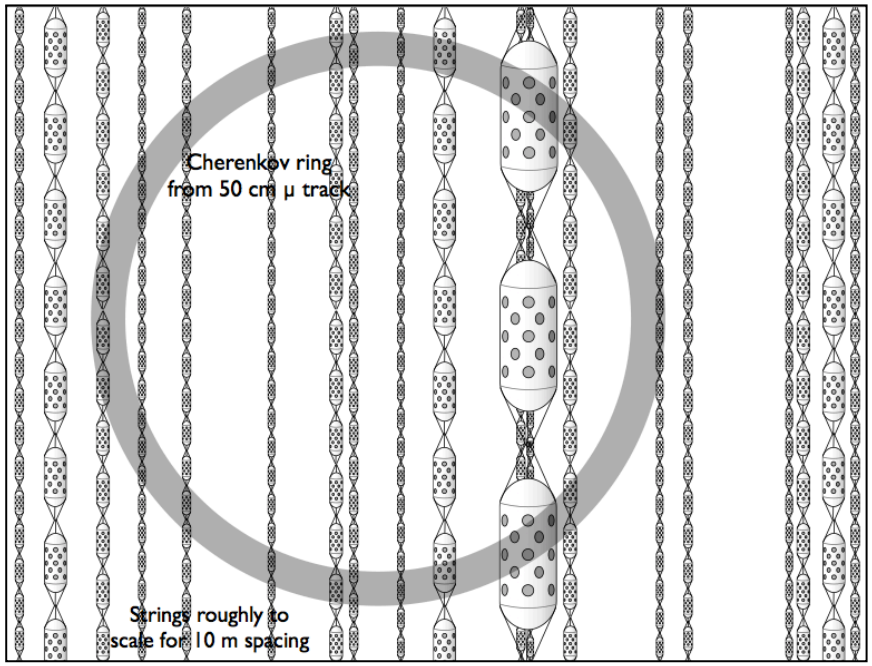


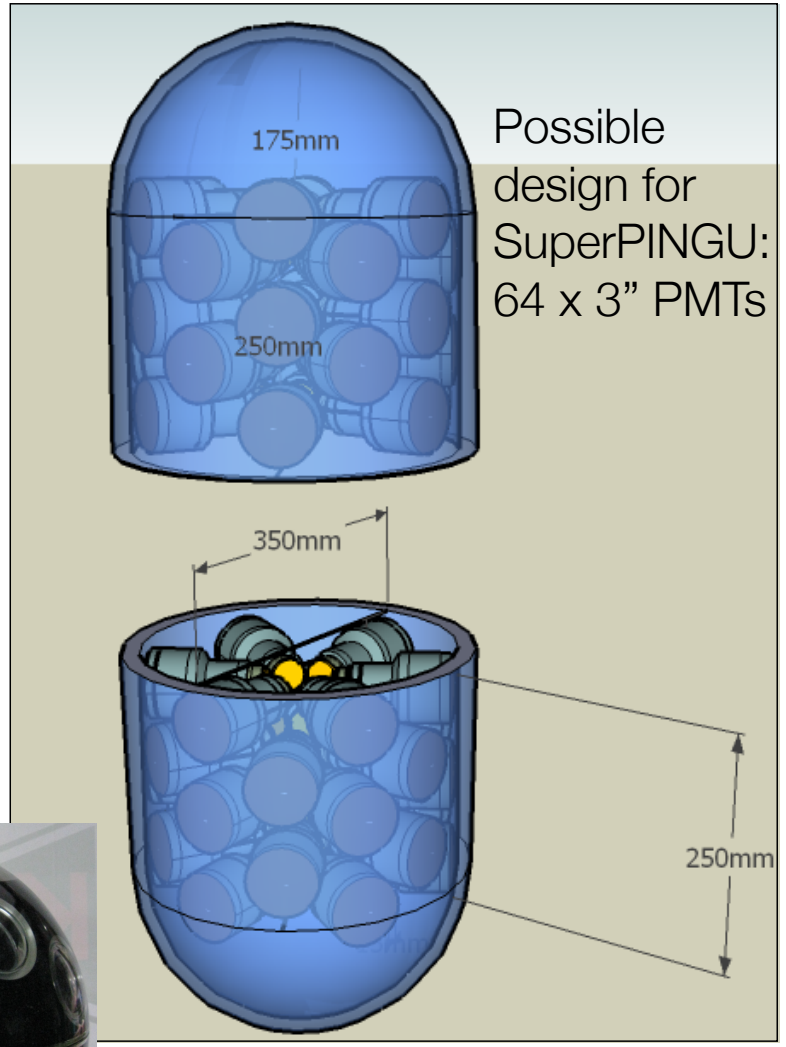


SuperPINGU Detector R&D

Courtesy E. de Wolf & P. Kooijman

Composite Digital Optical Module

- Glass cylinder containing 64 3” PMTs and associated electronics
  - Effective photocathode area >6x that of a 10” PMT
  - Diameter comparable to IceCube DOM so (modulo much tighter vertical spacing) drilling requirement would also be similar
  - Single connector
- Might enable Cherenkov ring imaging in the ice



Possible design for SuperPINGU: 64 x 3” PMTs

Summary

- IceCube completed construction in December 2010 on schedule and within budget.

Nuclear Instruments and Methods in Physics Research A 601 (2009) 294–316

- The detector is exceeding the initial performance goals. It is now has sensitivity to neutrinos of all flavors in a very wide energy range (10 GeV to 10^9 GeV) in both hemispheres.

- Operation of the sensors show very stable running and the hardware technology show very good reliability with very few failures per year expected for the full IceCube data operation.

- IceCube is just entered its era of highest sensitivity running. Active development underway for improvements of the performance parameters.

- Toward the distant future, South Pole ice may be prove to be an attractive alternative for large-scale precision neutrino detectors. Simulations for feasibility studies underway - stay tuned!