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

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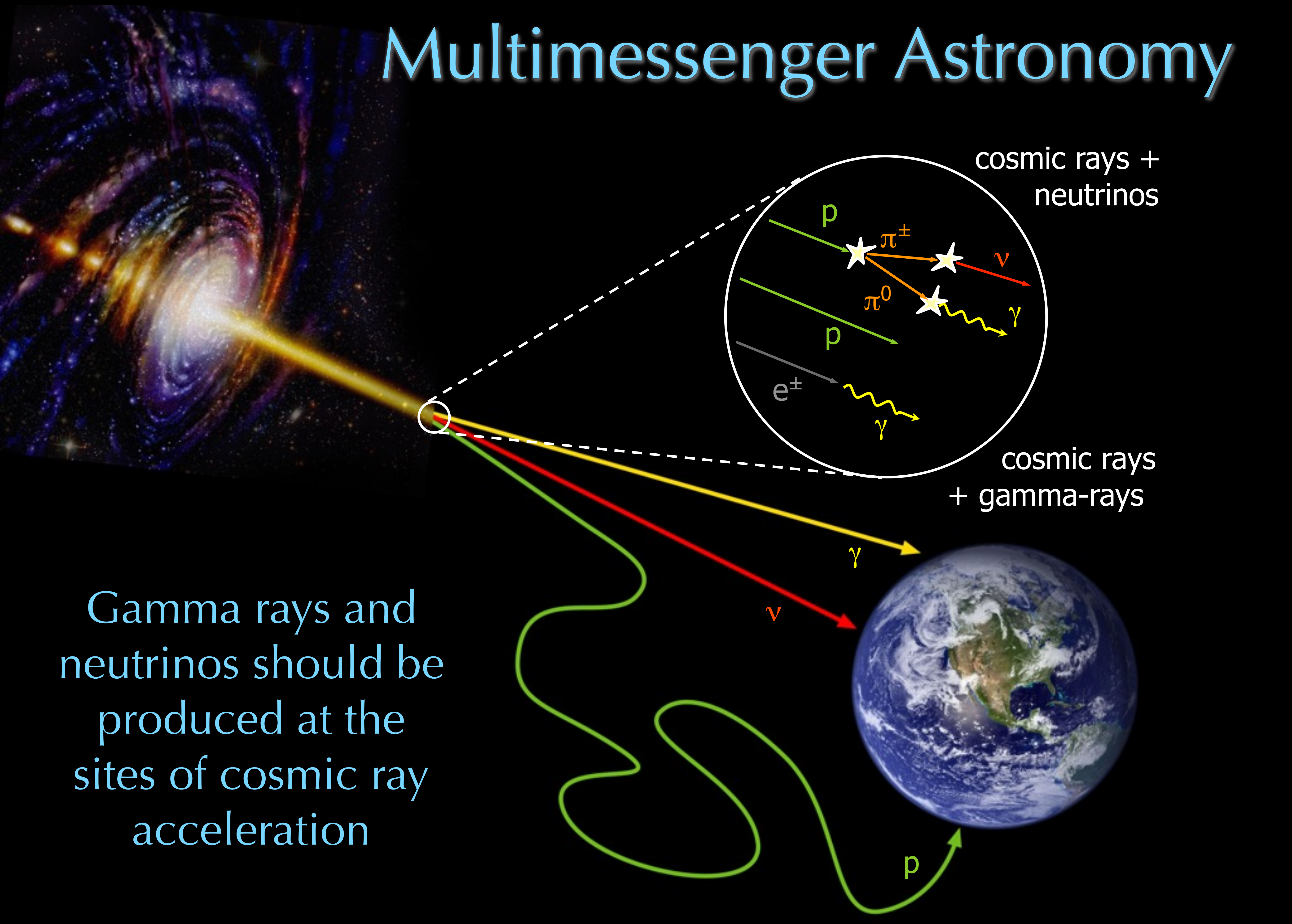
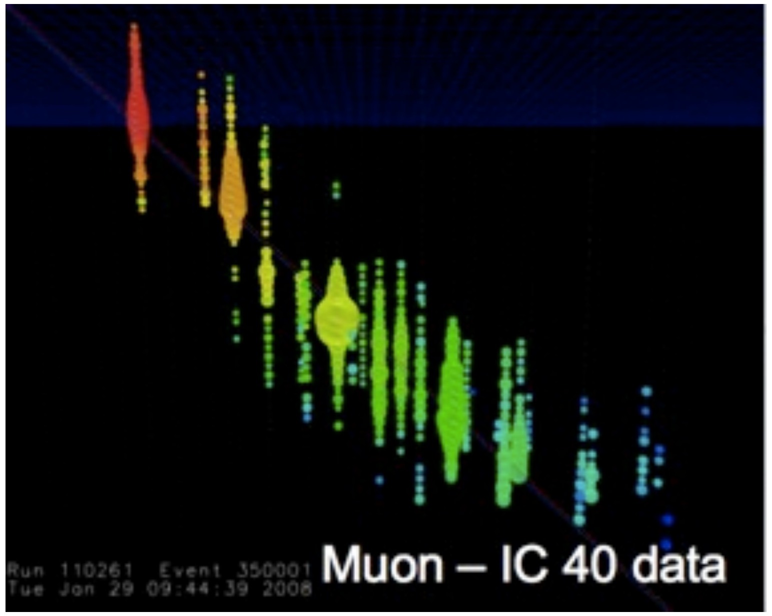
Multimessenger Astronomy



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

Neutrino Telescopes - Principle of Detection

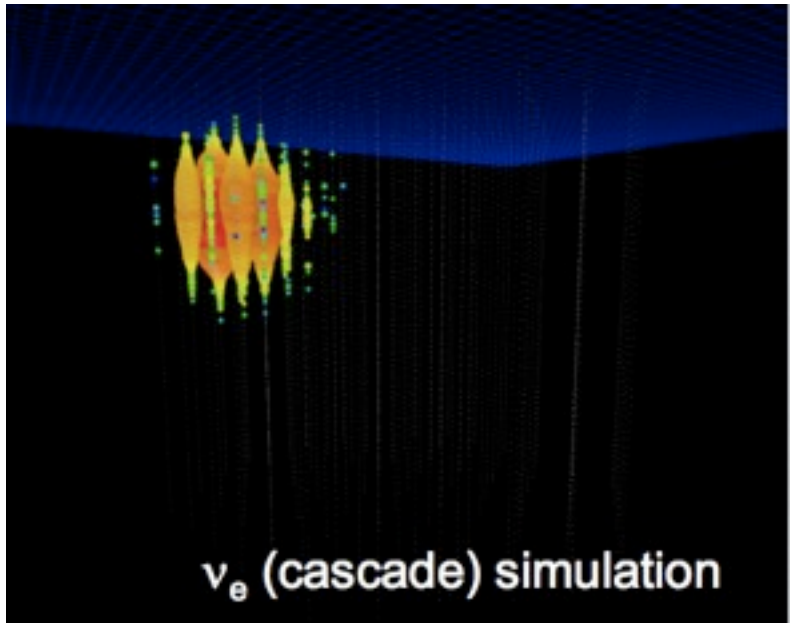


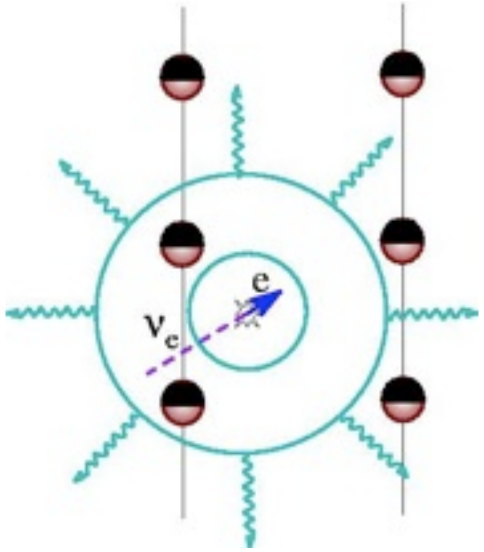
Tracks:

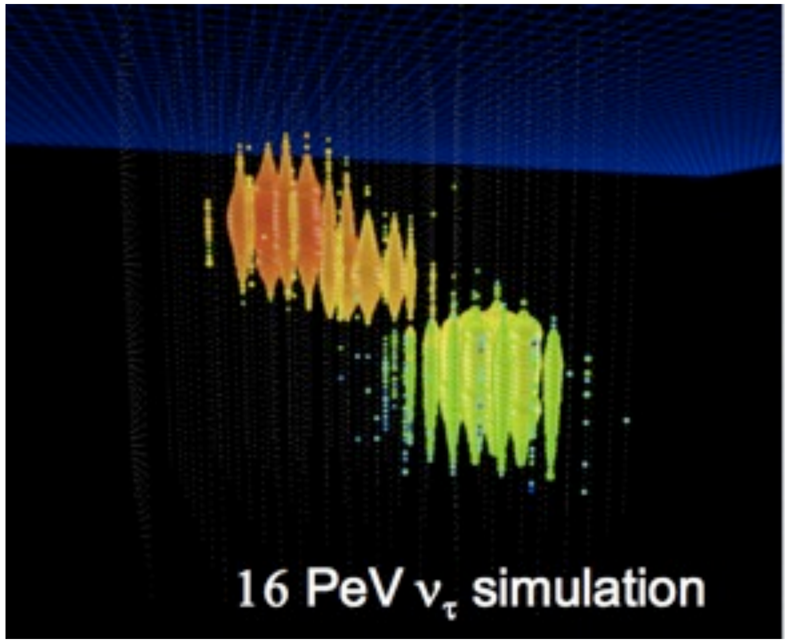
- through-going muons
- pointing resolution ~1°

Cascades:

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





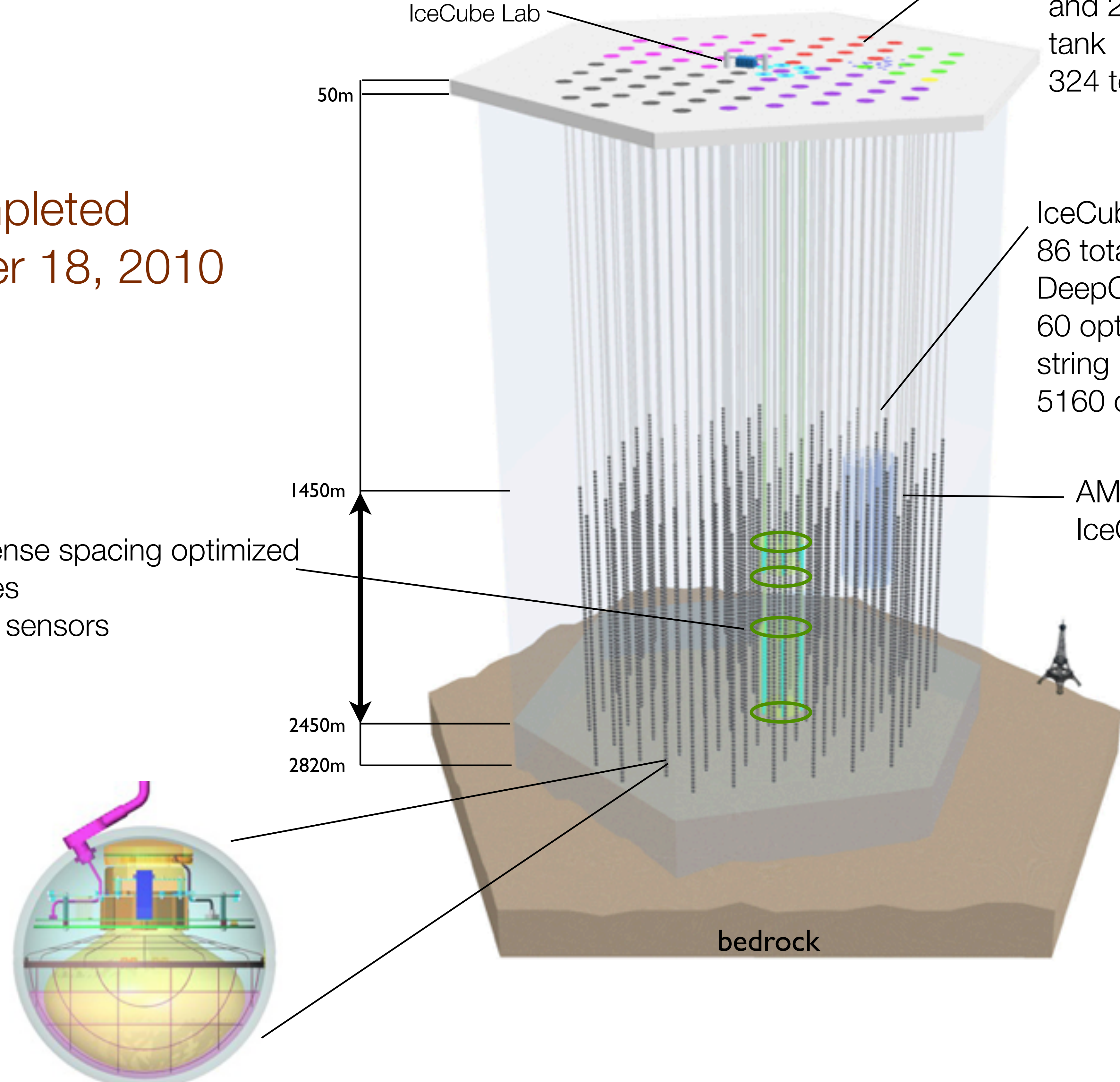


Composites:

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

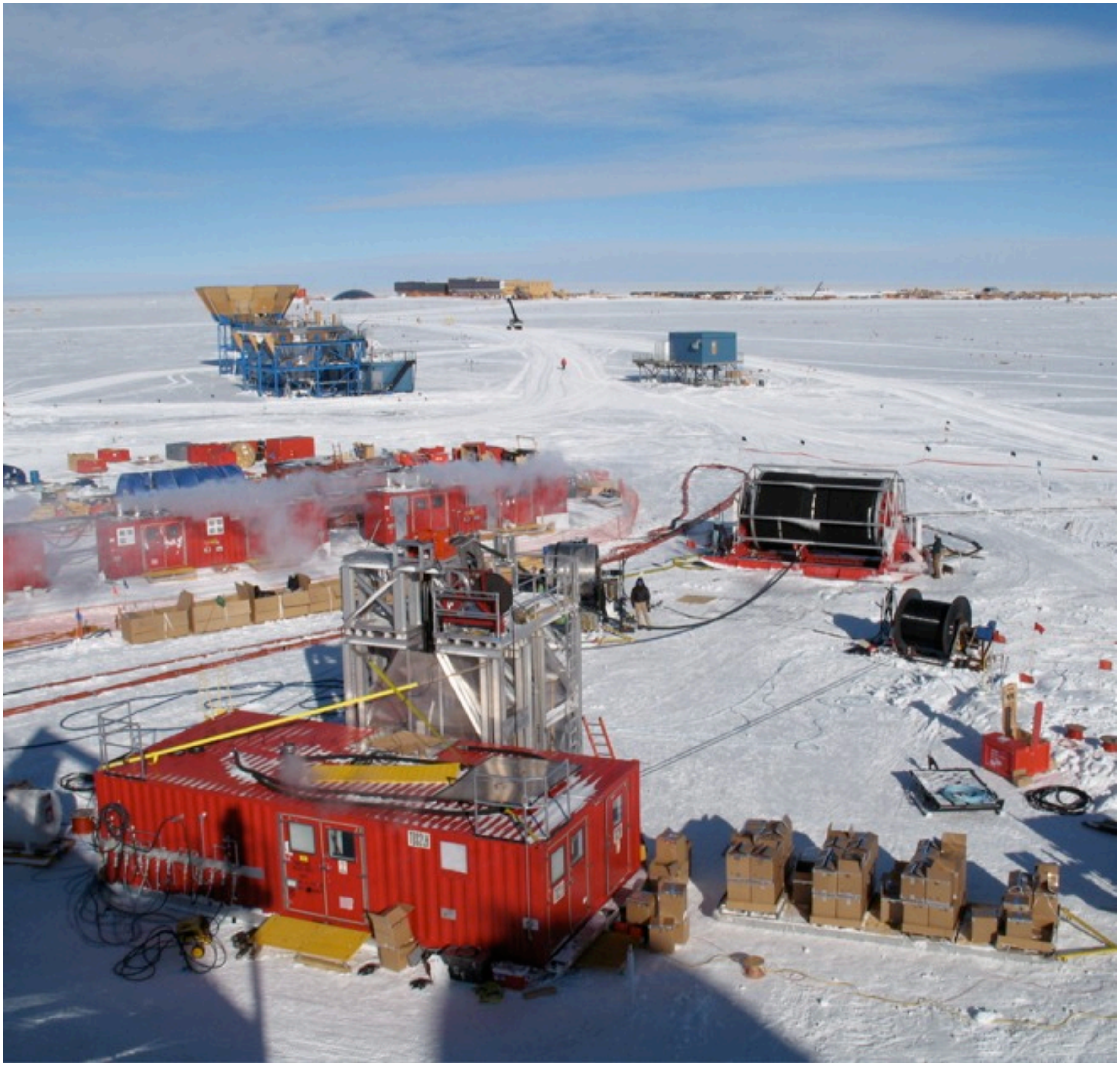
The IceCube Neutrino Observatory

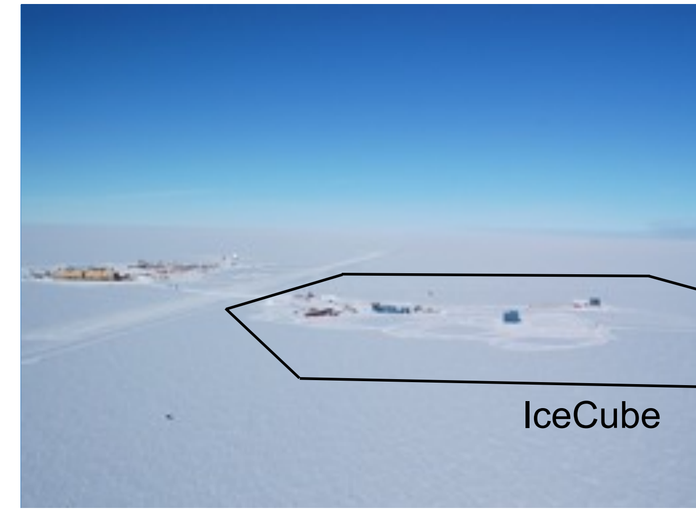
Completed
December 18, 2010

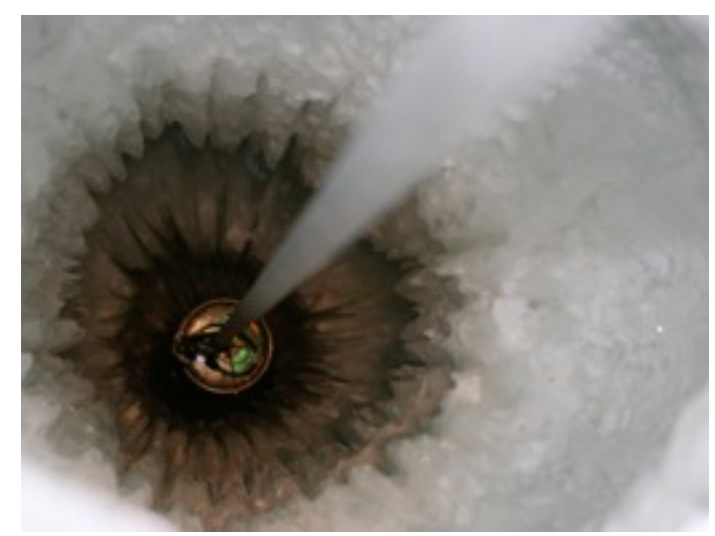


The IceCube Collaboration

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 $\sim 10^6$)
- Complex waveform information
- Low power dissipation

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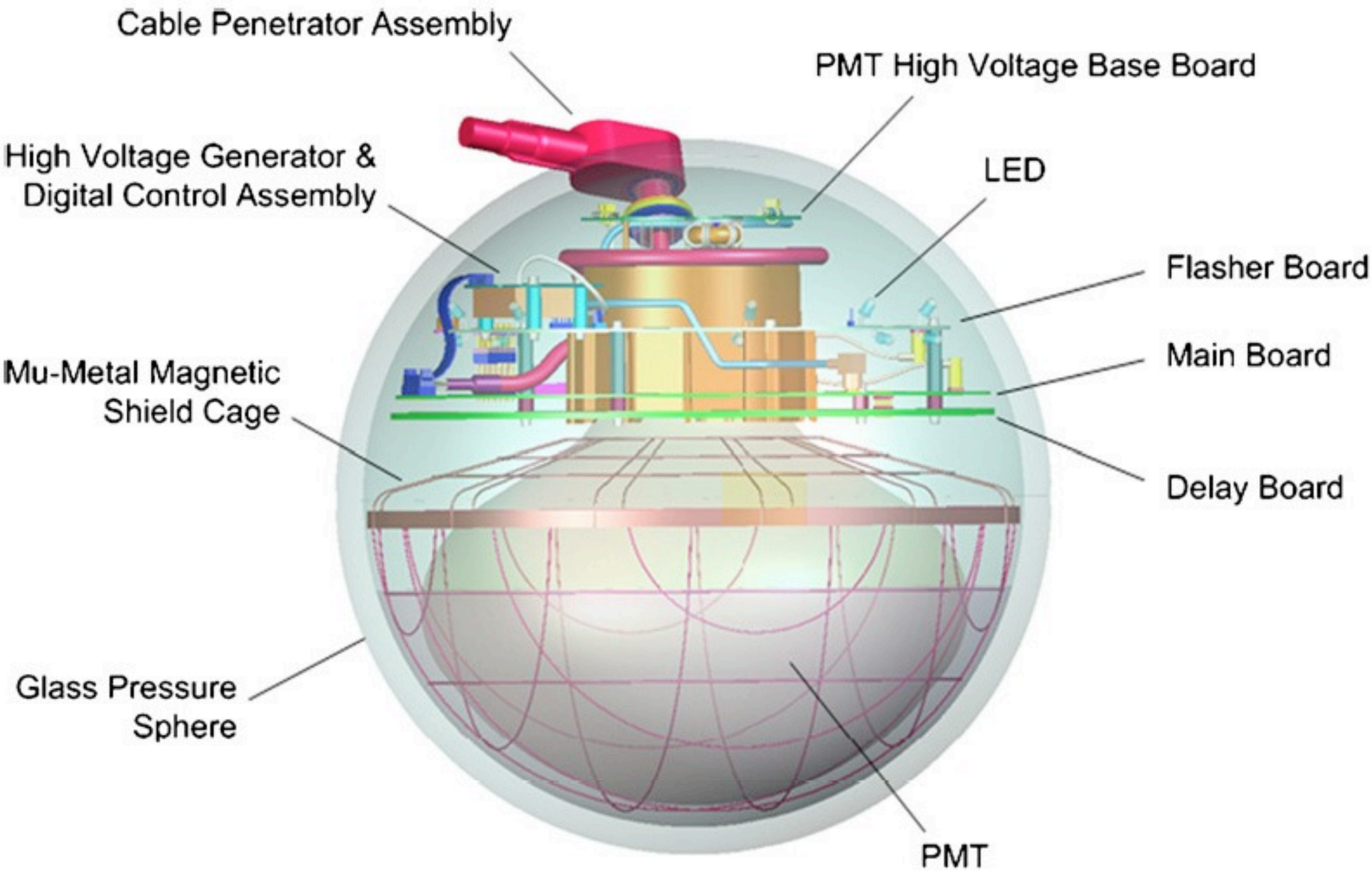
Waveform Digitization for the entire detector

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

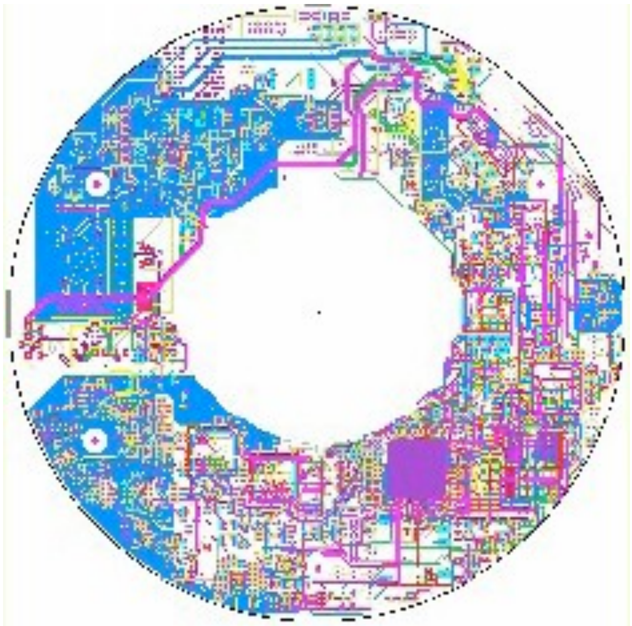
- The ice is a relatively quiet environment -> low information rate and need to digitize only ~0.1% of the time

The Digital Optical Module (DOM)



Digital Optical Module Main Board Design

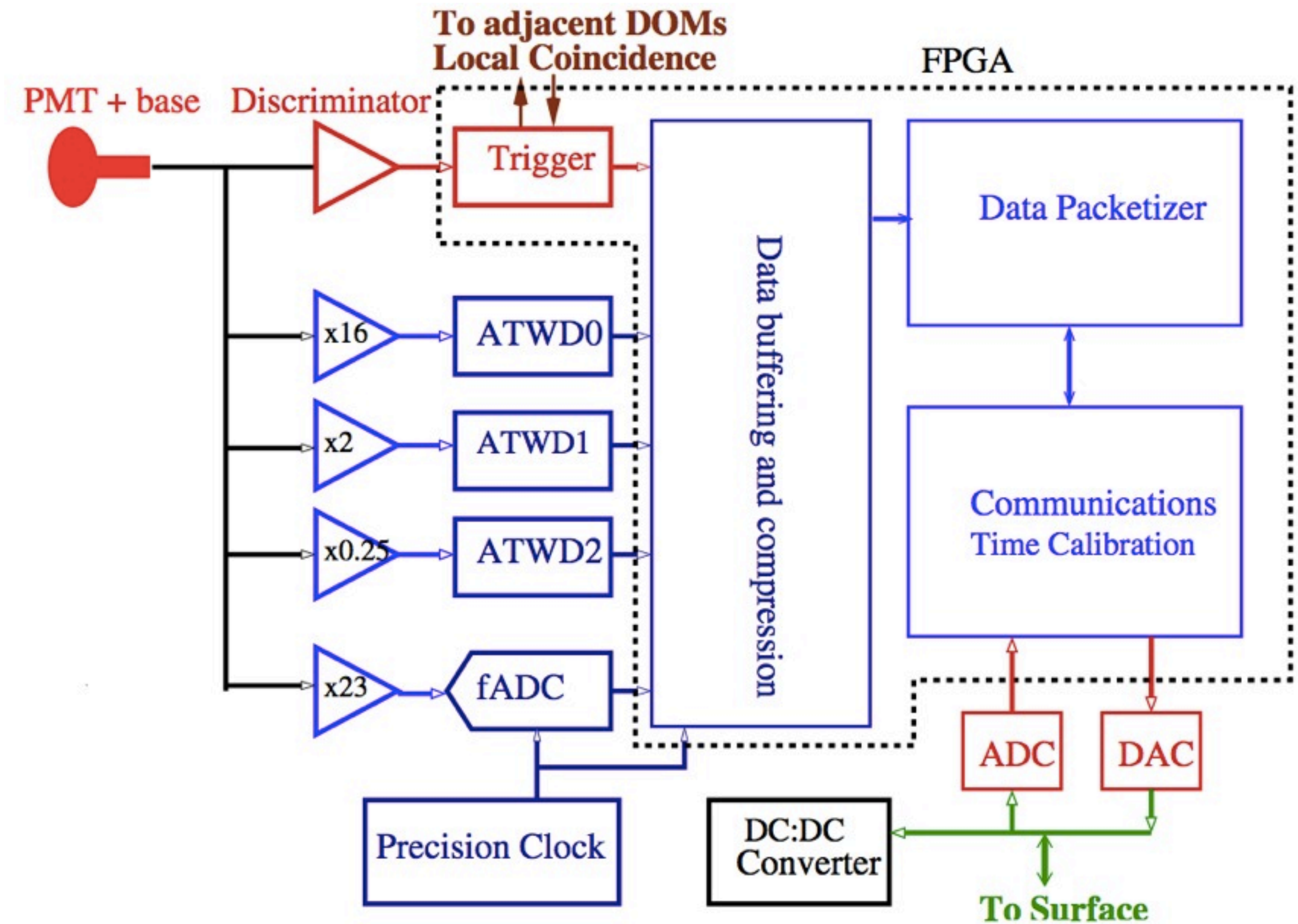
- Pulse waveform sampling: 300 MSPS
- Wide dynamic range: 200 pe/10 ns
- Hit timing accuracy: 2 ns rms
- Low dead-time: << 1%
- Low power consumption: <5 W
- Adequate CPU and memory
- Built-in calibration, monitoring and debugging capabilities
- Remotely reprogrammable software and firmware.
- Off-board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



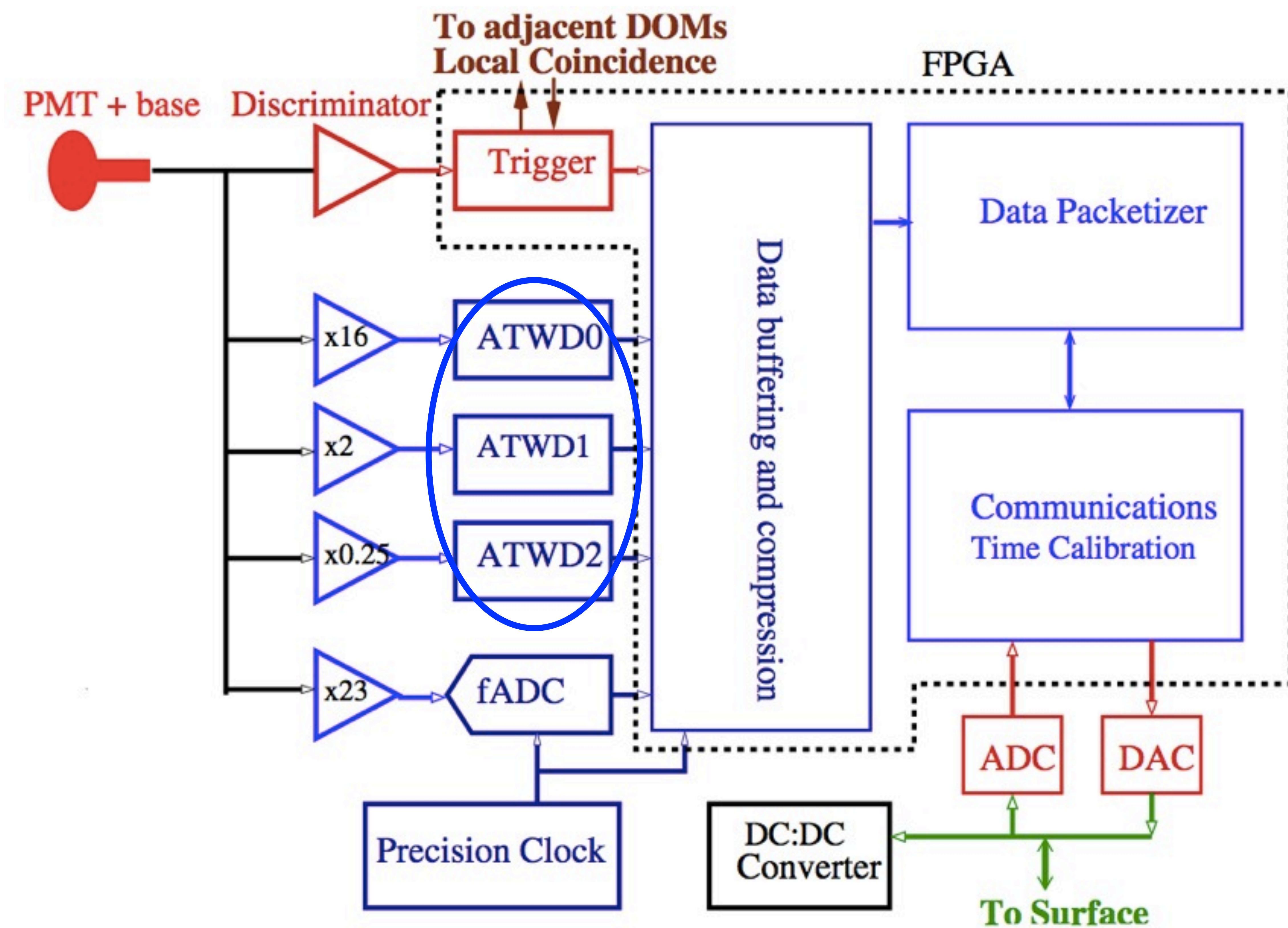
Engineer: Jerry Przybylski, LBNL

Goal: "as simple as possible"

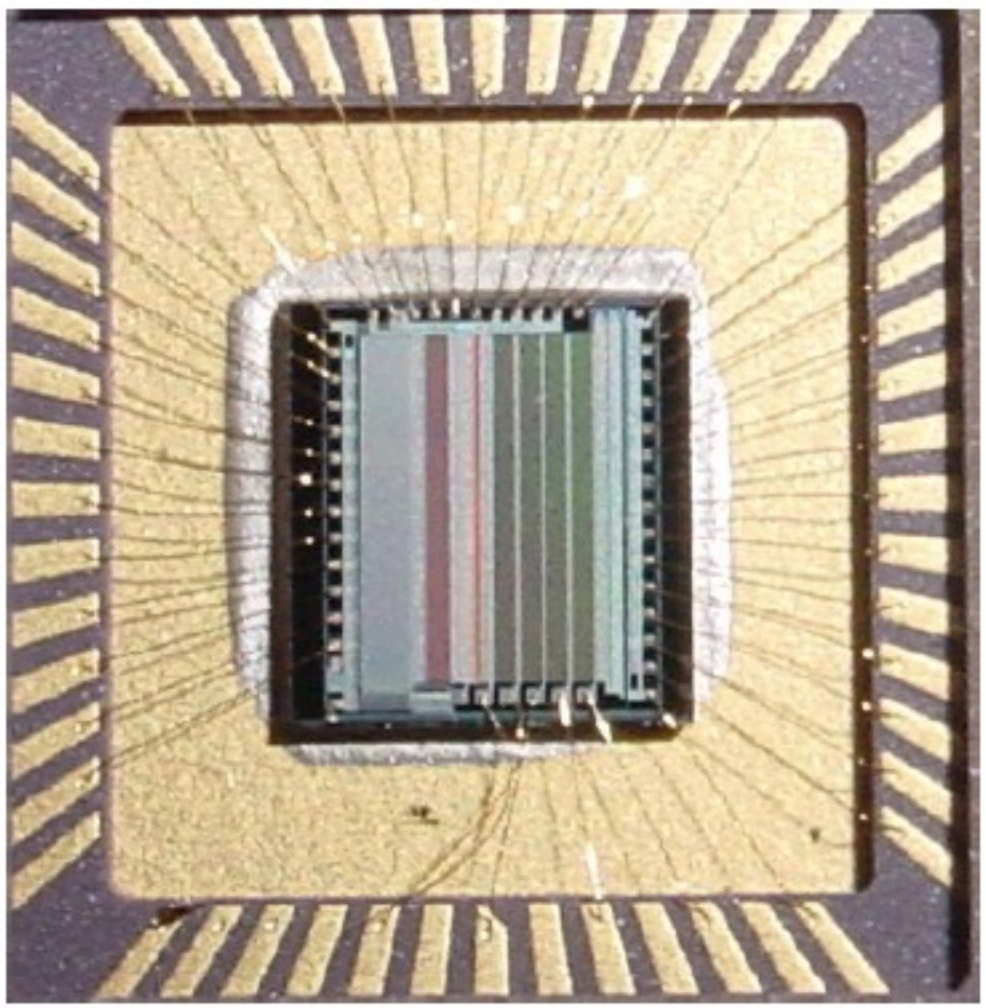
Digital Optical Module Main Board Design



Digital Optical Module Main Board Design

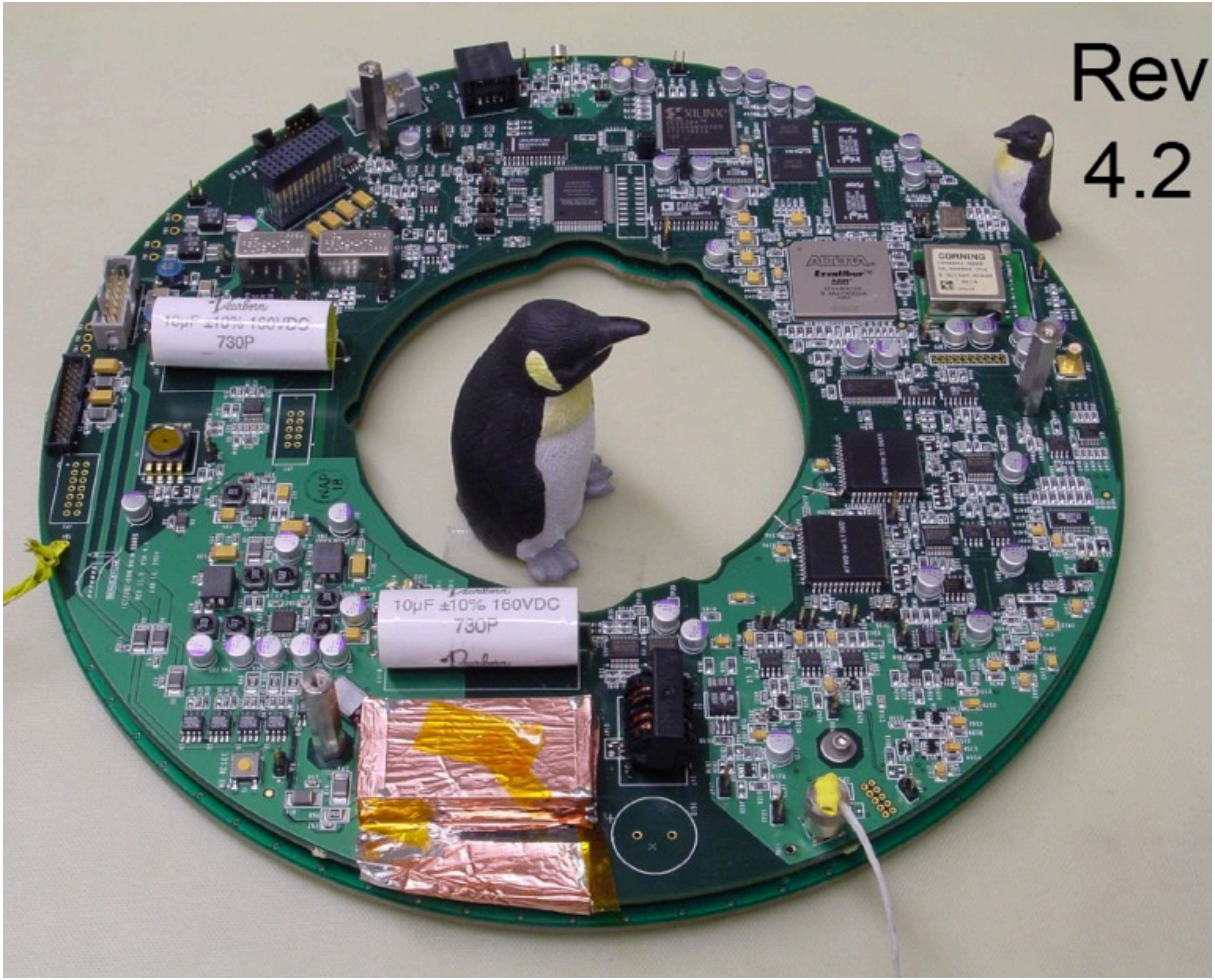


IceCube ATWD



- 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

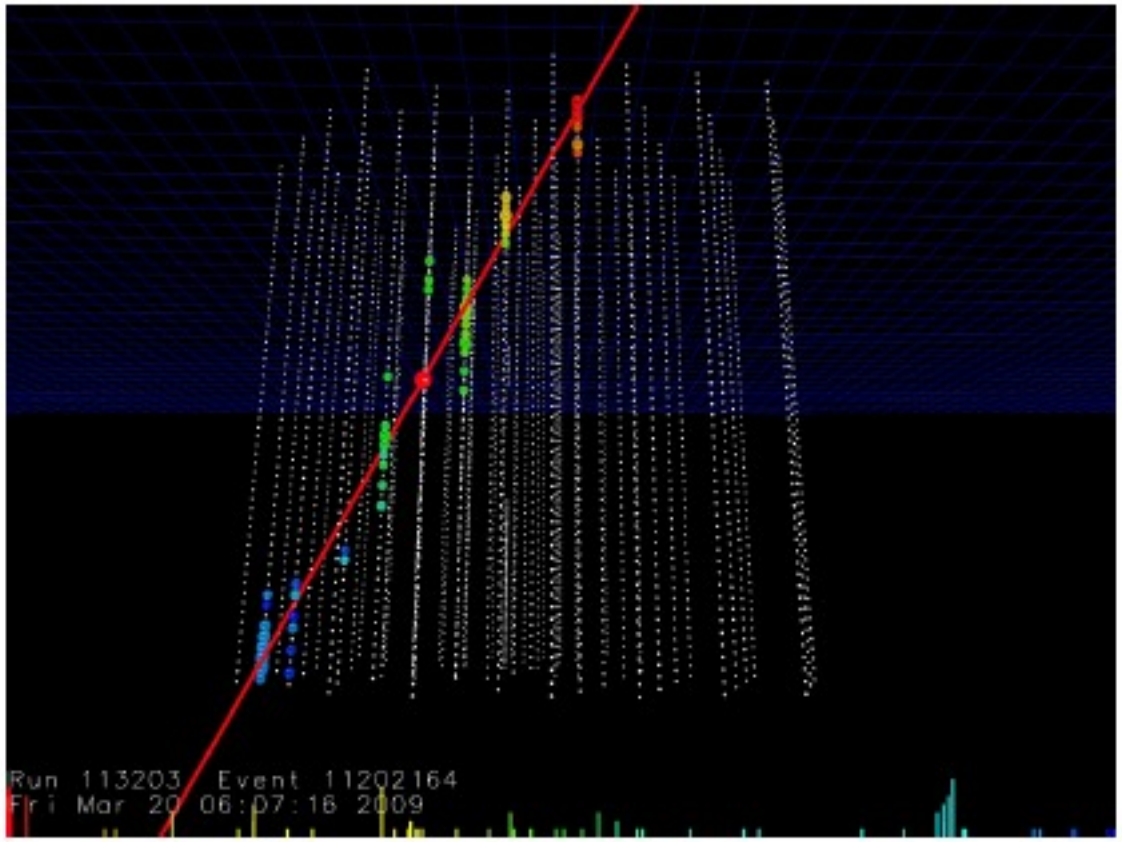
IceCube Performance Parameters

DOM Level

- time resolution
- charge response
- noise behavior
- reliability

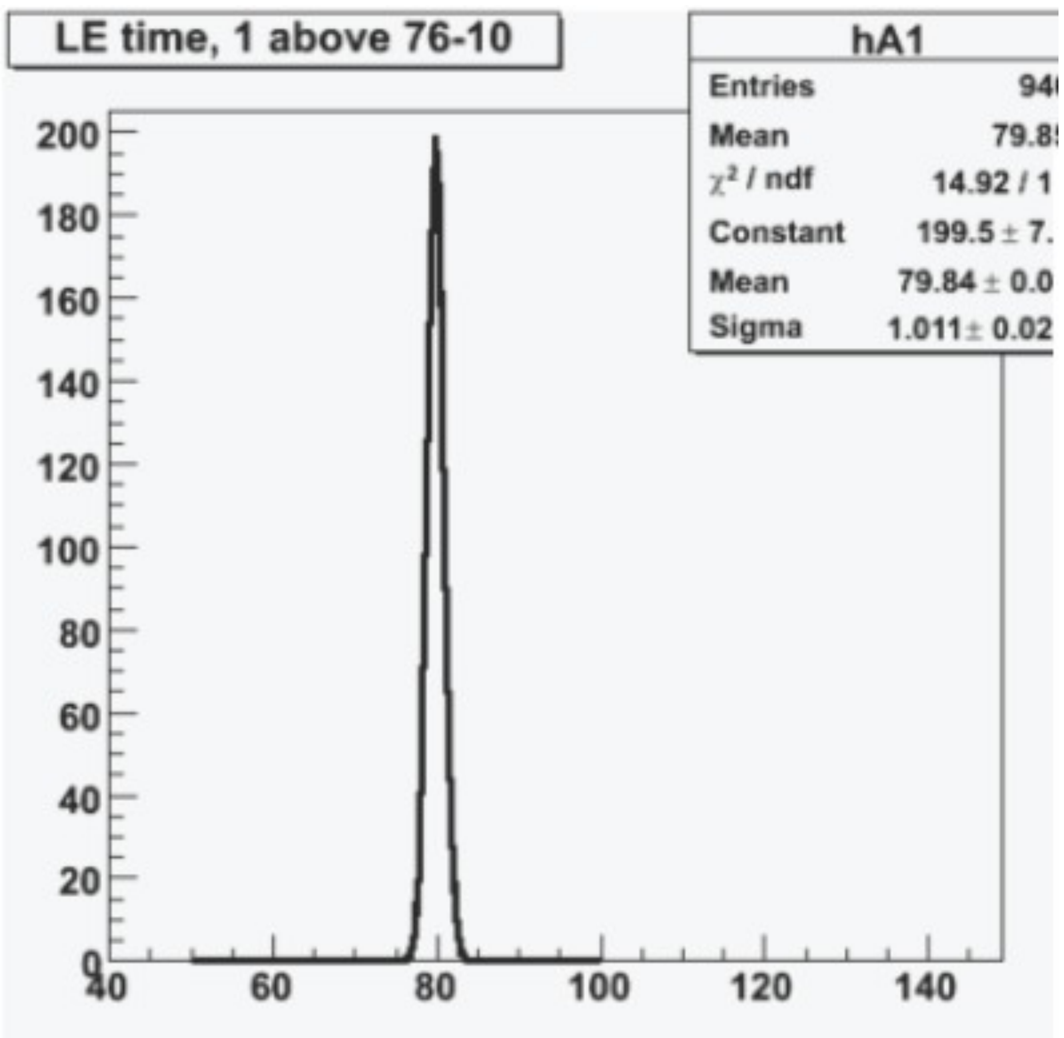
Detector level

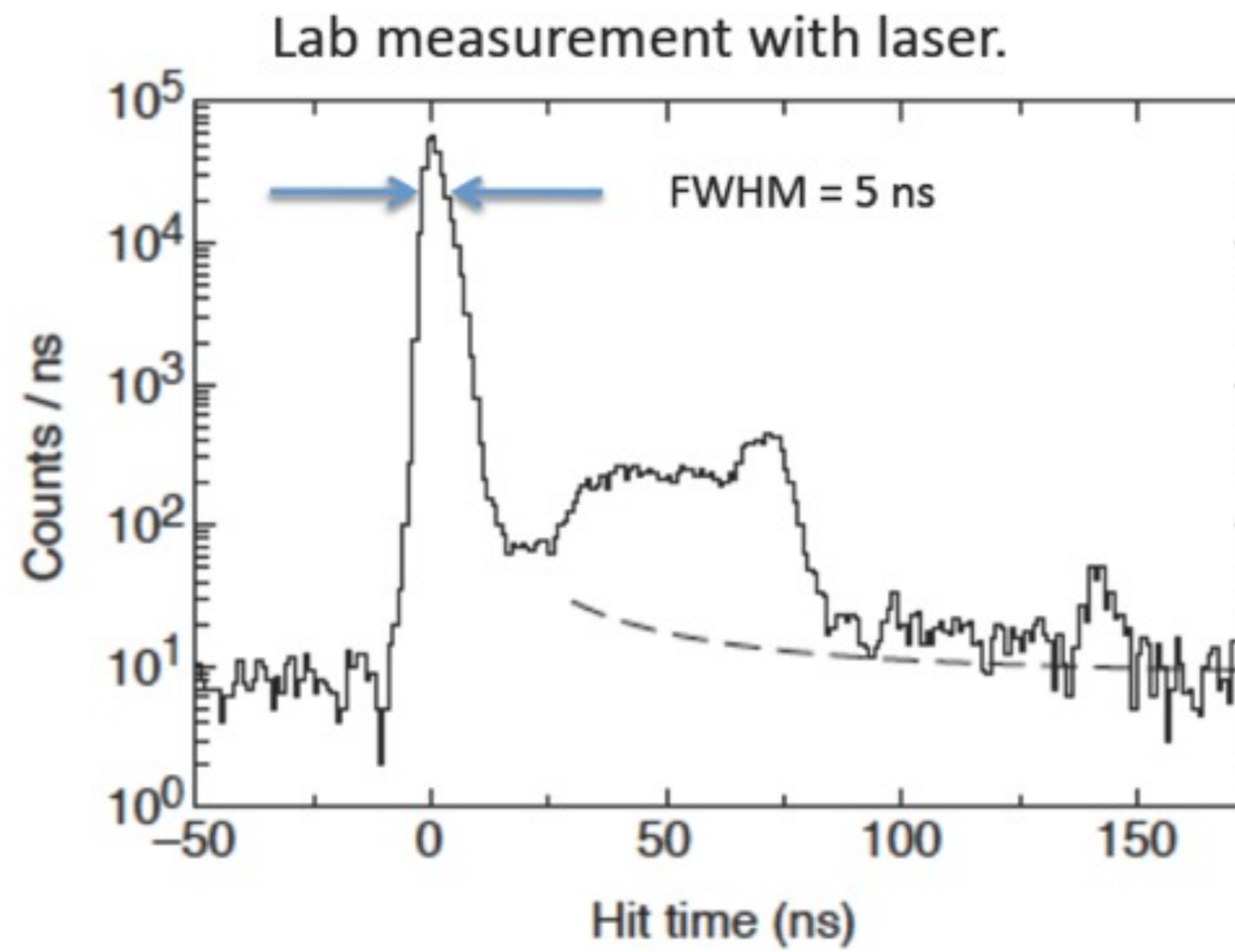
- angular resolution
- energy resolution
- final sensitivity



DOM Time Resolution

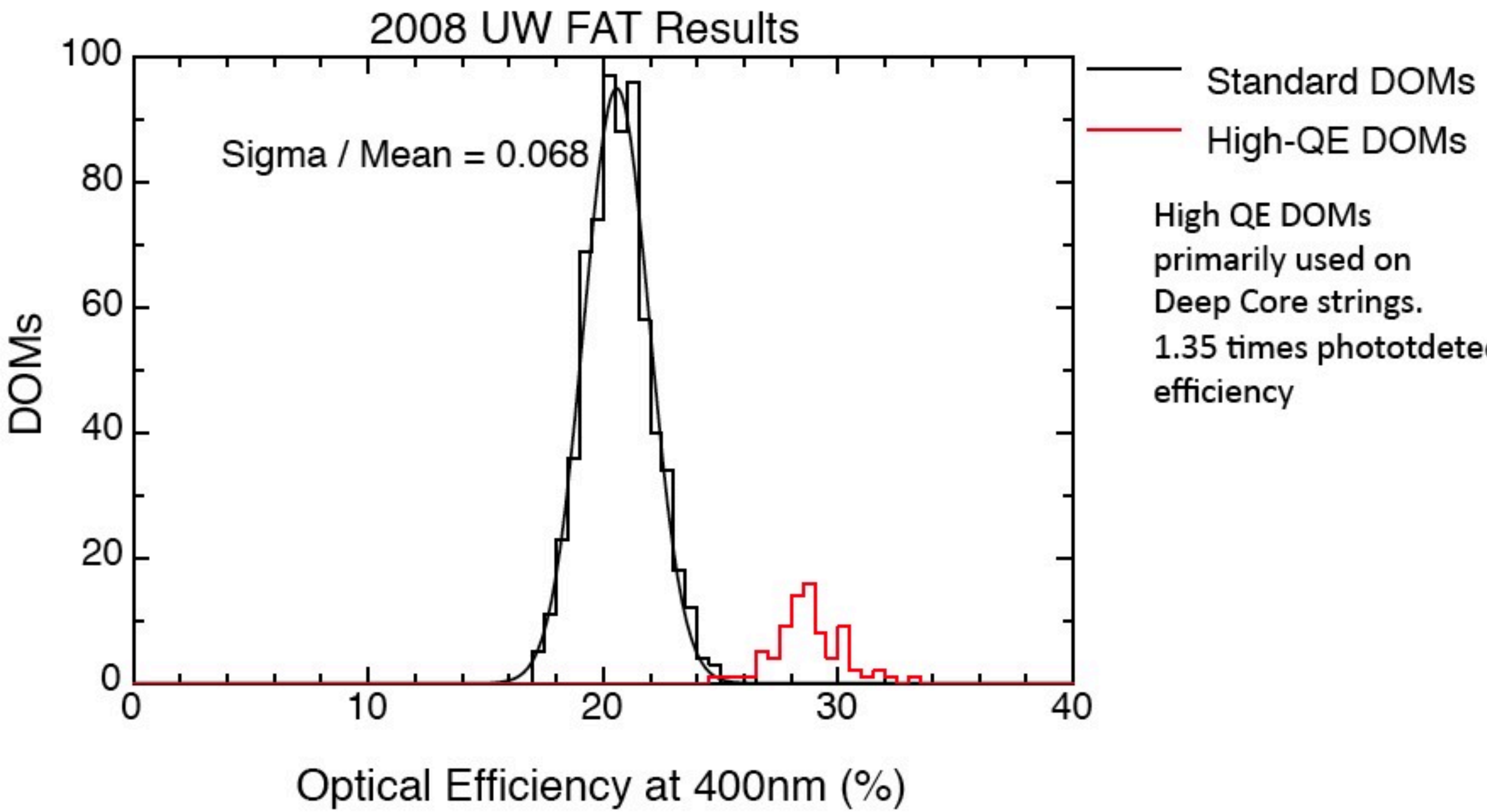
The time difference between neighboring DOMs fired with flasher pulses is ~1 ns (including clock timing).





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

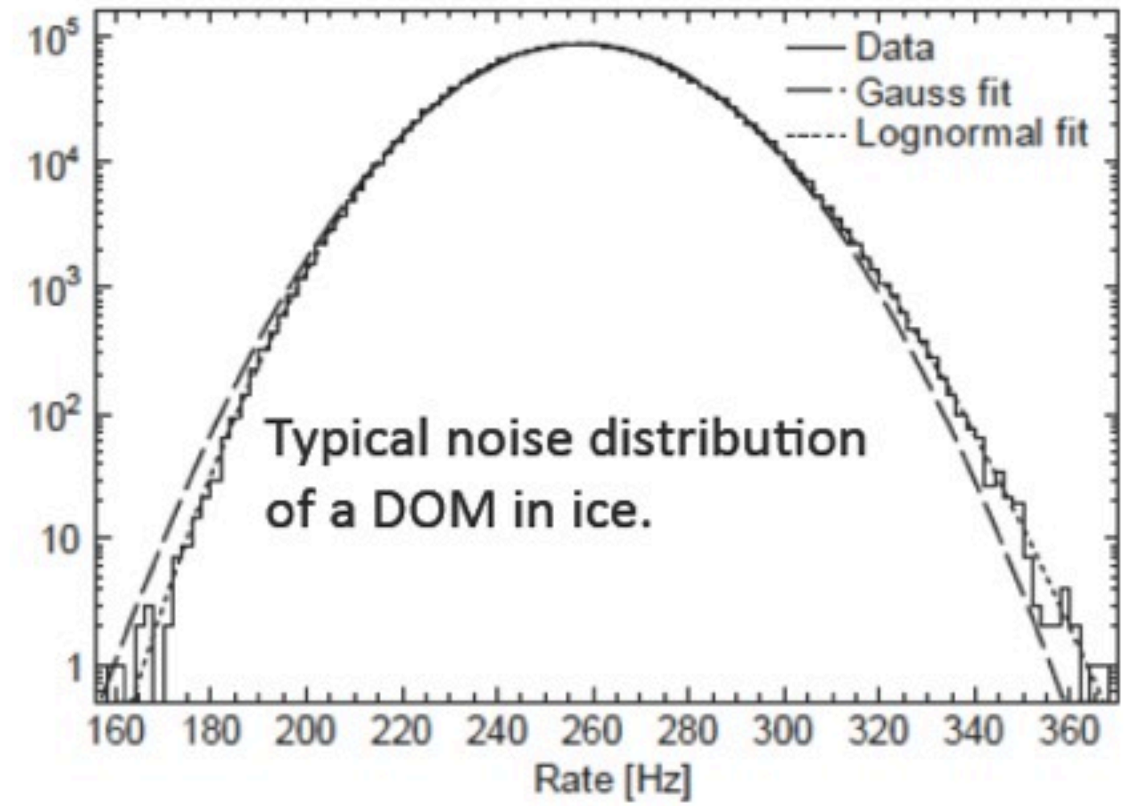
DOM Sensitivity

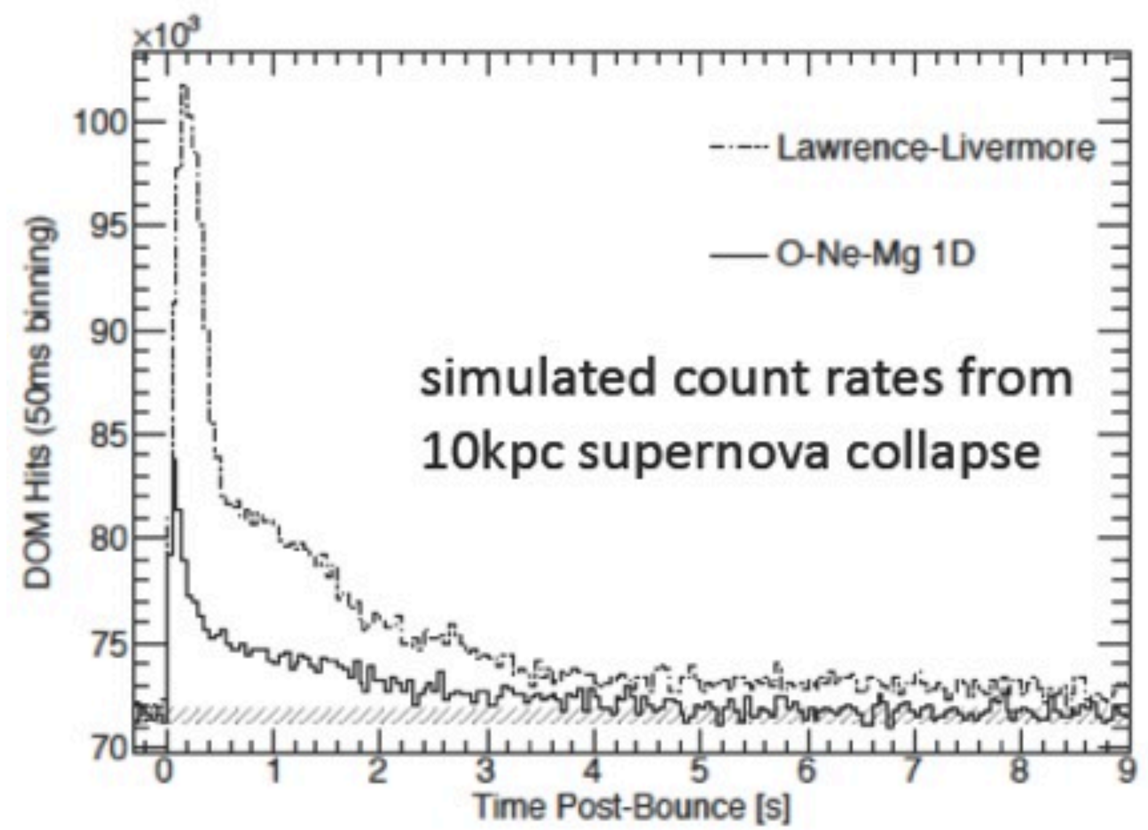


High QE DOMs primarily used on Deep Core strings.
1.35 times phototdetection efficiency

DOM Dark Noise

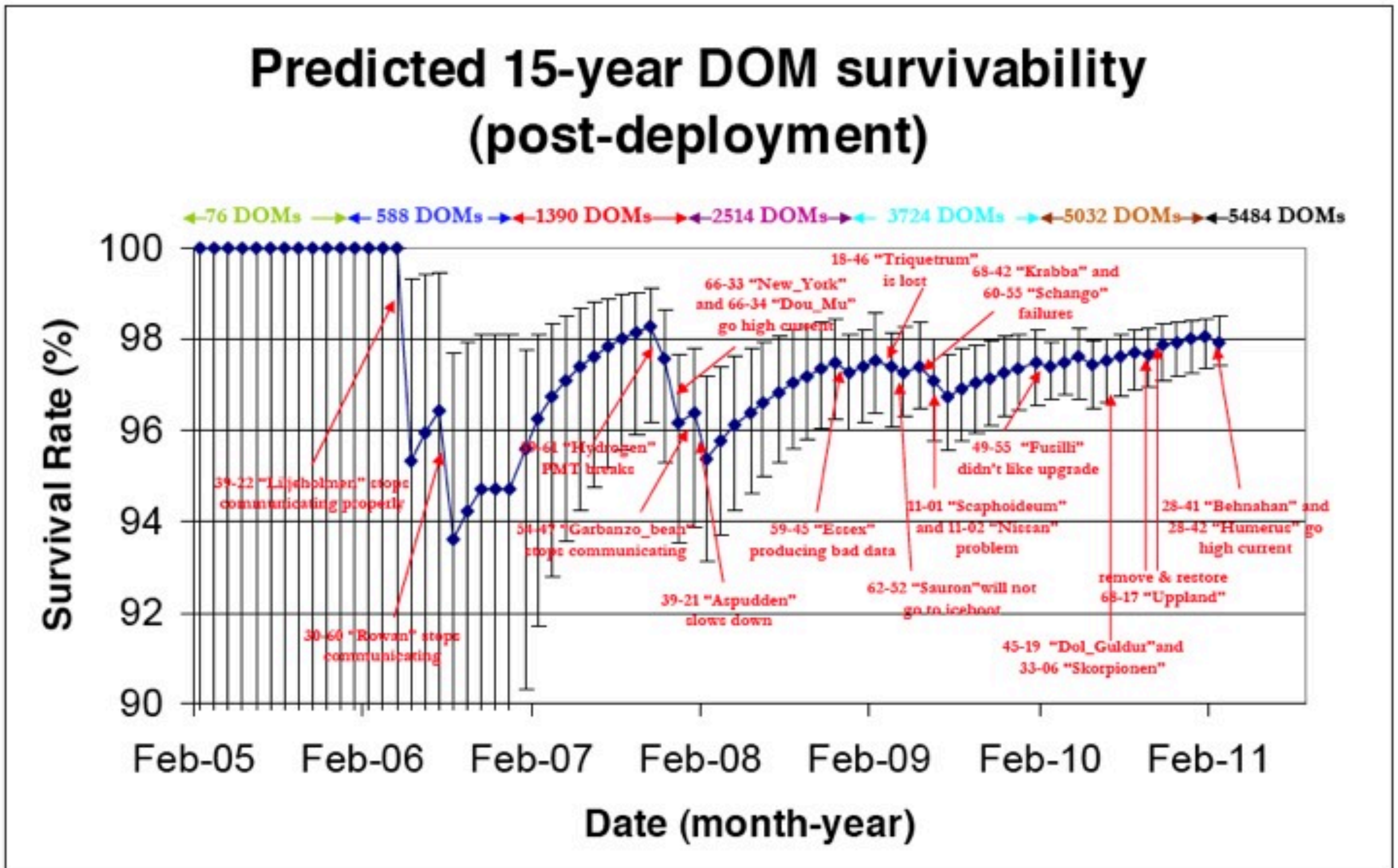
- Use of low-radioactivity glass for the pressure spheres and good PMT characteristics = very low noise rates.
- Average rate/sensor (including dead-time) = 286 Hz
- Sensor noise is stable and as expected. (Gaussian timing distribution is due to correlated hits from single DOM radioactivity and fluorescence 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.





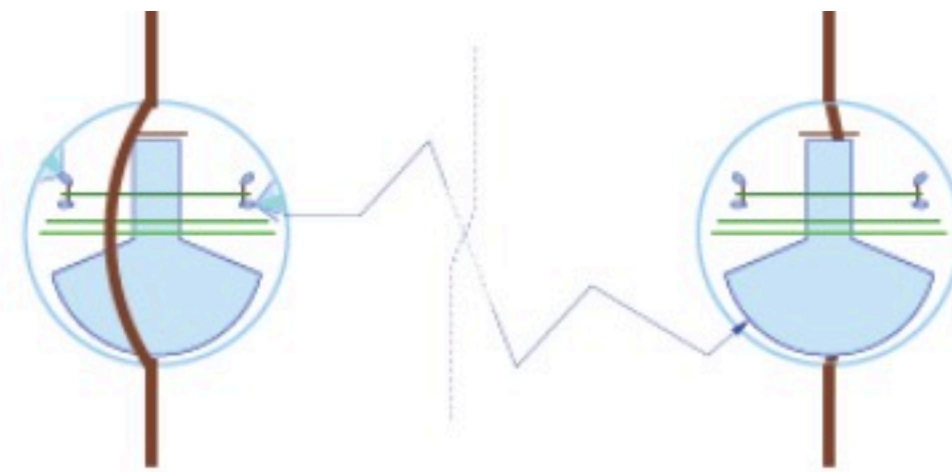
DOM Reliability

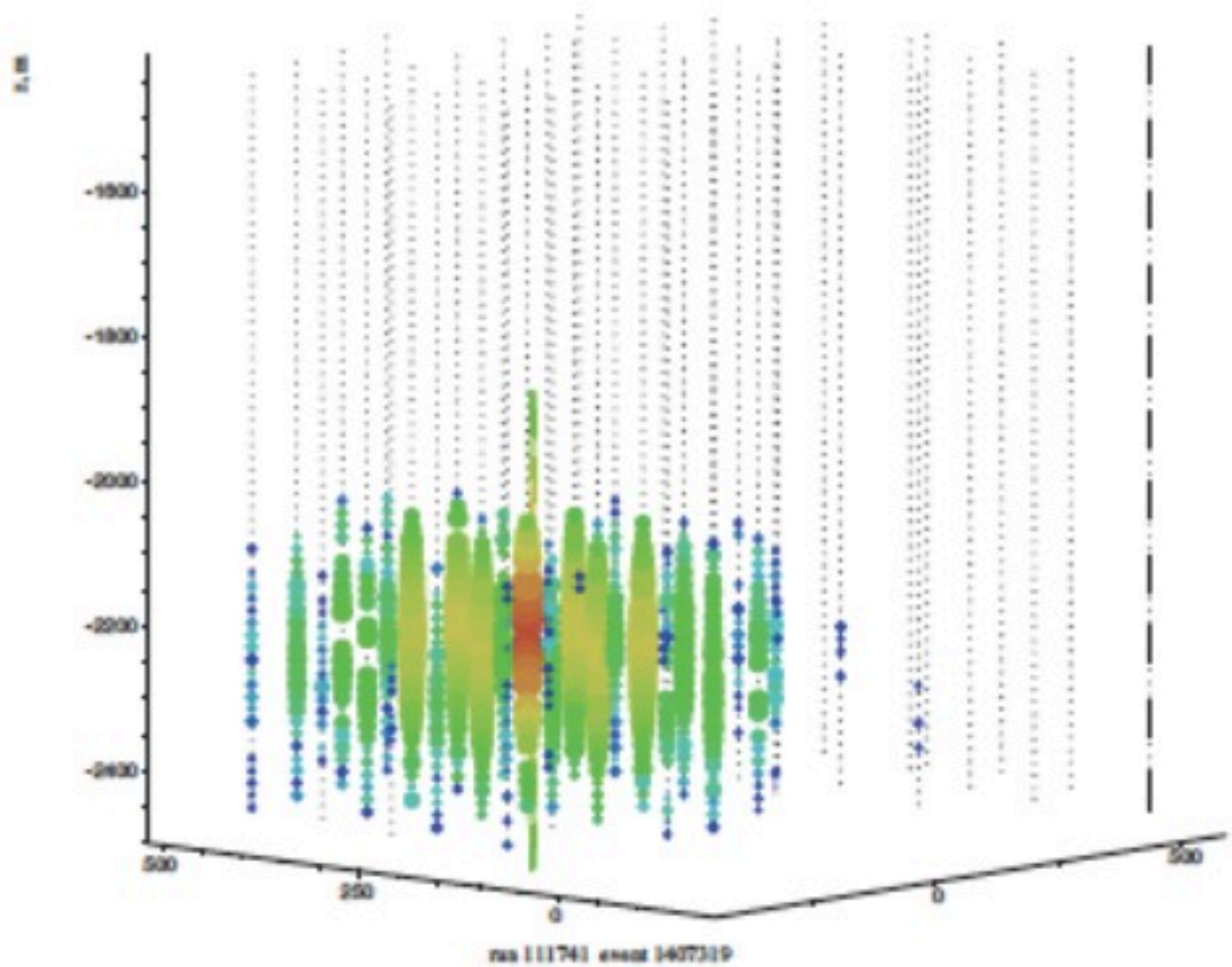
- ~14k years accumulated lifetime as of April 2011.
- 84 lost DOMs (fail commissioning) during deployments and freeze-in
- 19 lost DOMs after successful freeze-in and commissioning.



IceCube Calibrations

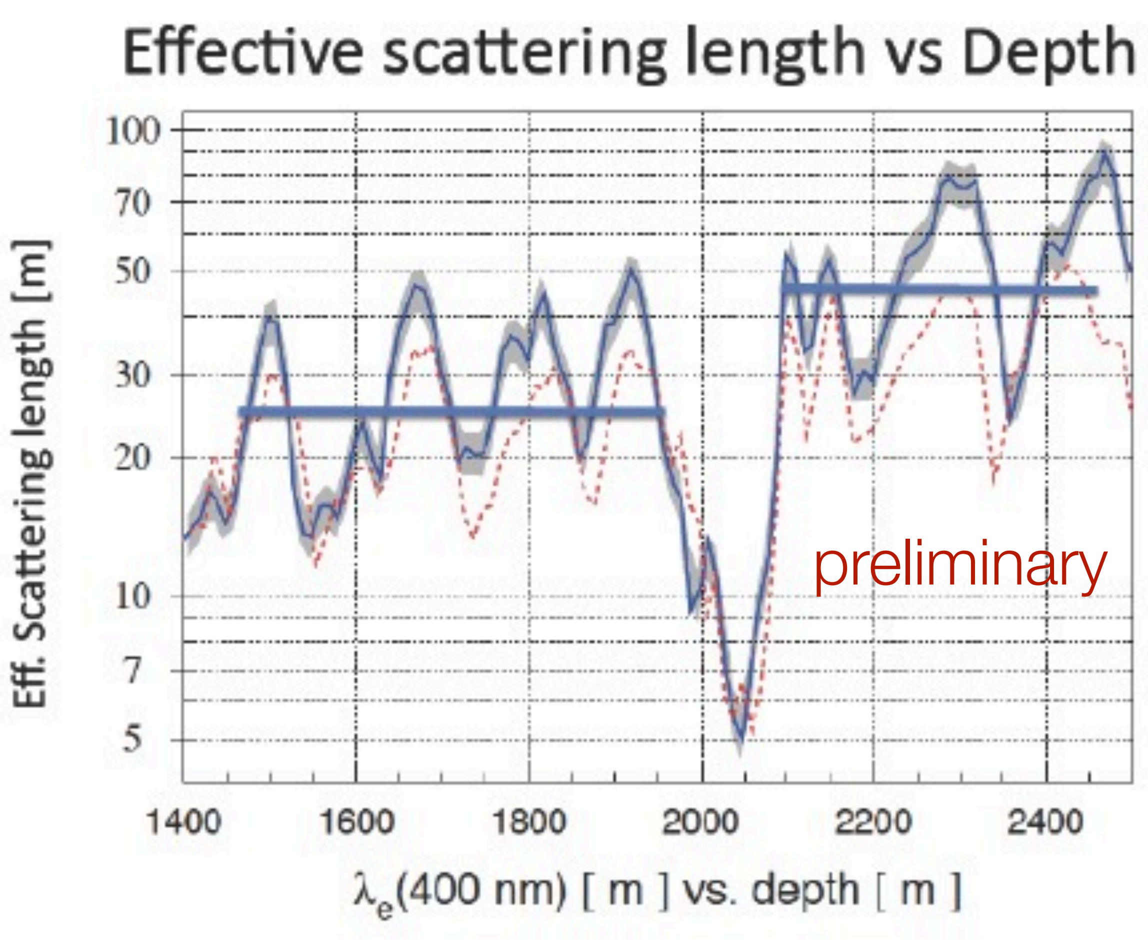
- All sensors are equipped with a set of 12 LED flashers.
- A 30 ns pulse of 0(10^9) photons at 400 nm are visible to a distance of 600 m.
- The measurements are used to calibrate the detector in time, geometry and optical properties of the ice.

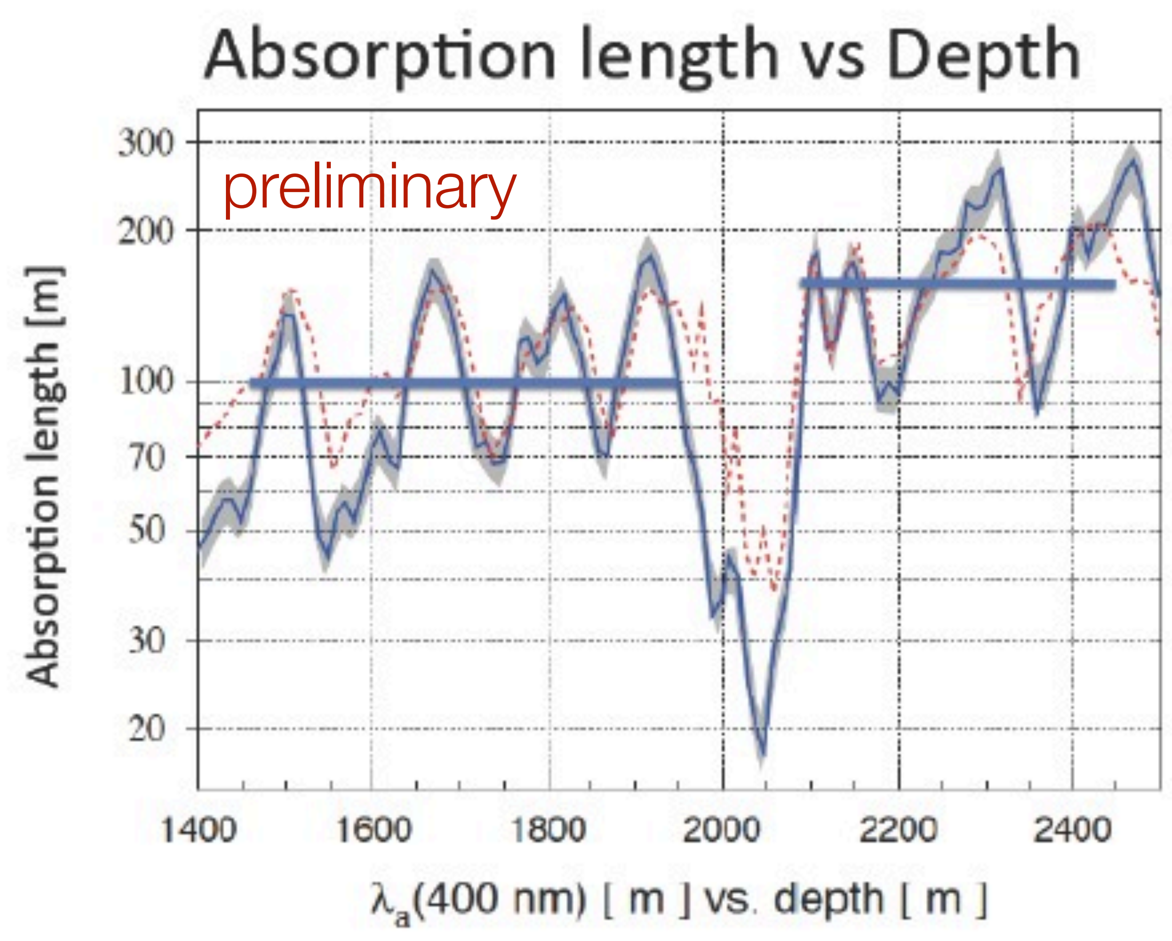




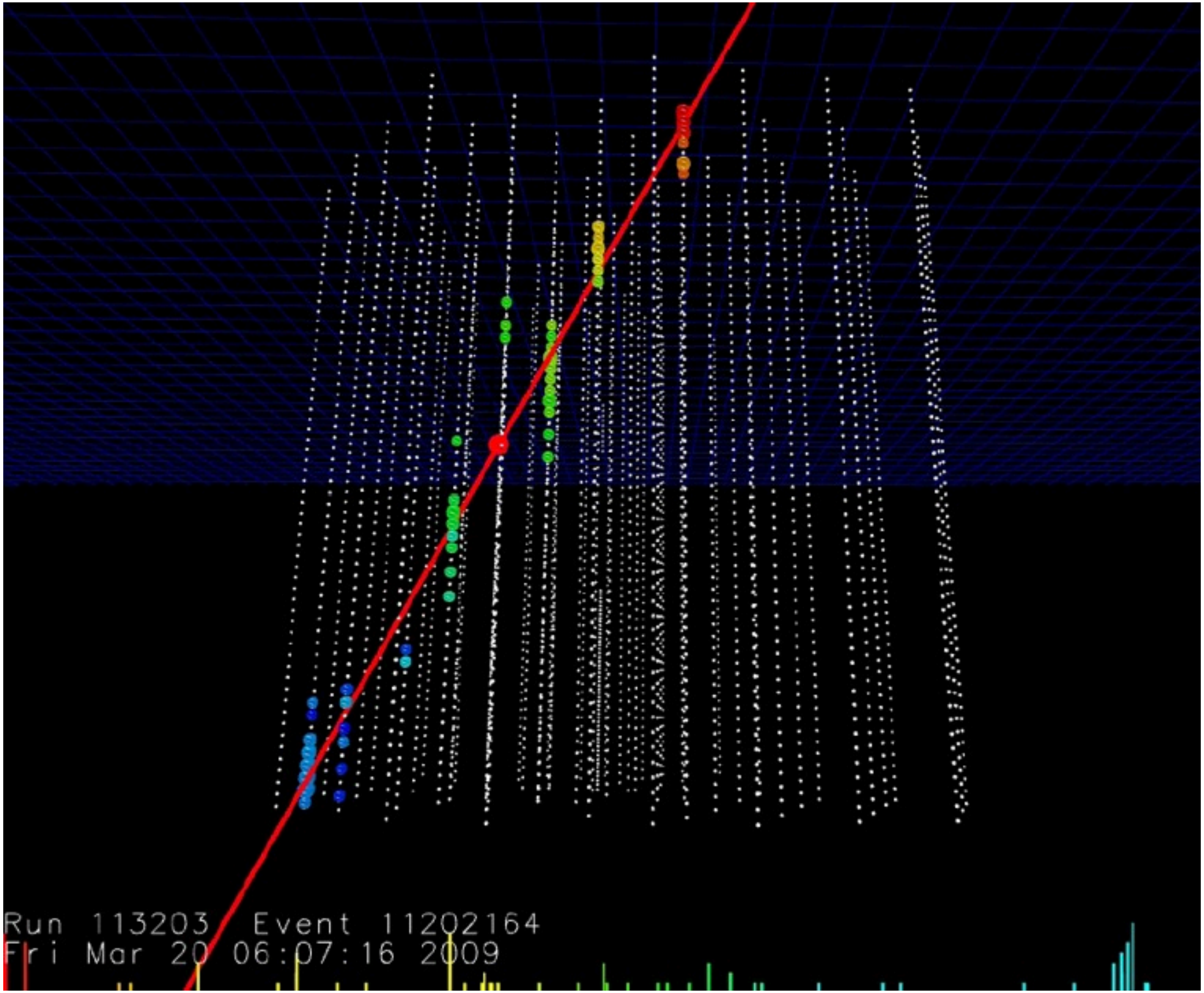
IceCube Calibrations

- 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.

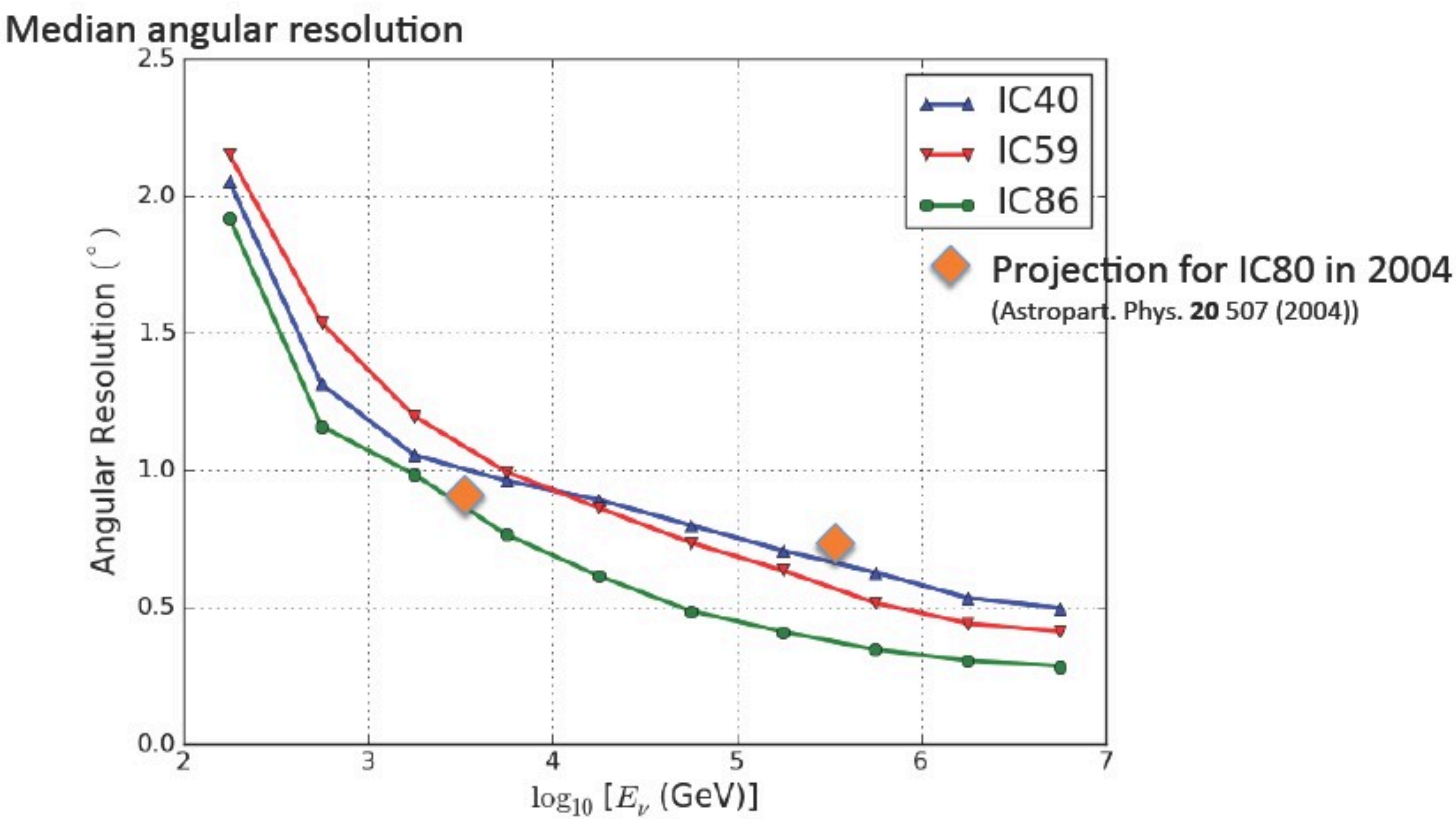




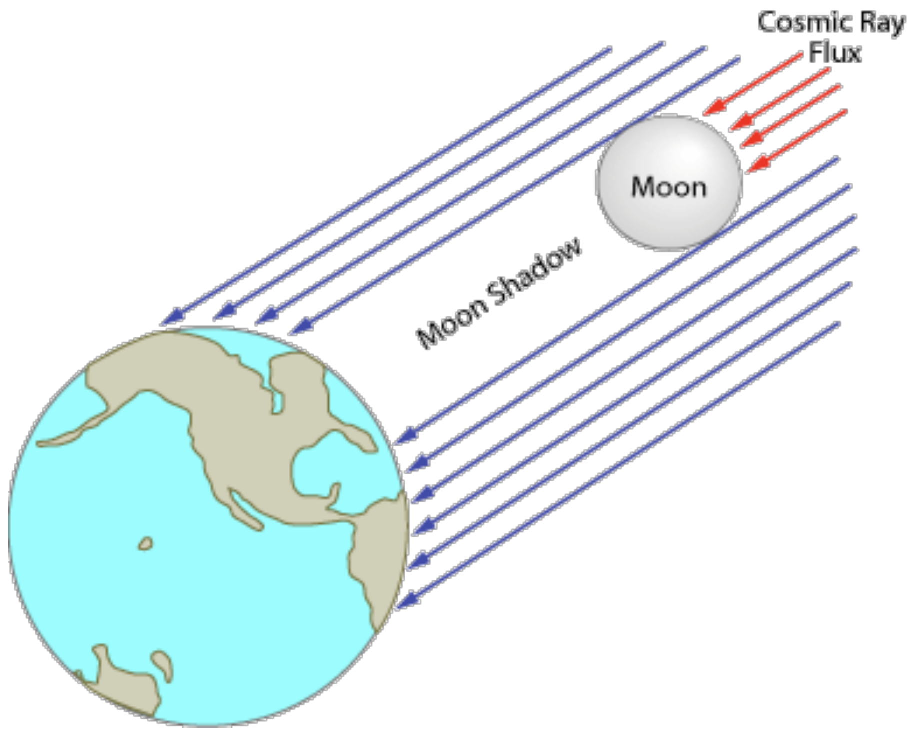
IceCube Detector Performance



IceCube Detector Performance - Angular Resolution

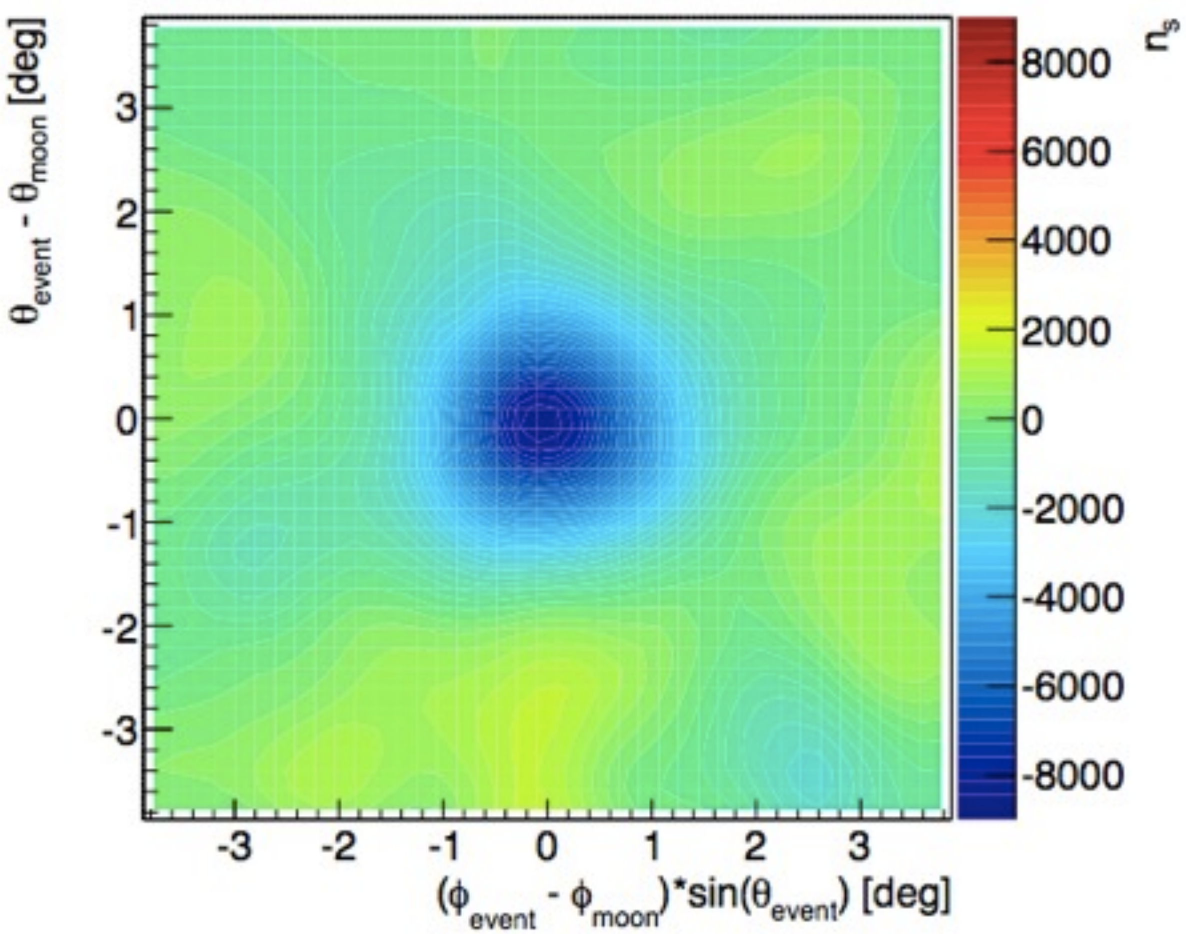


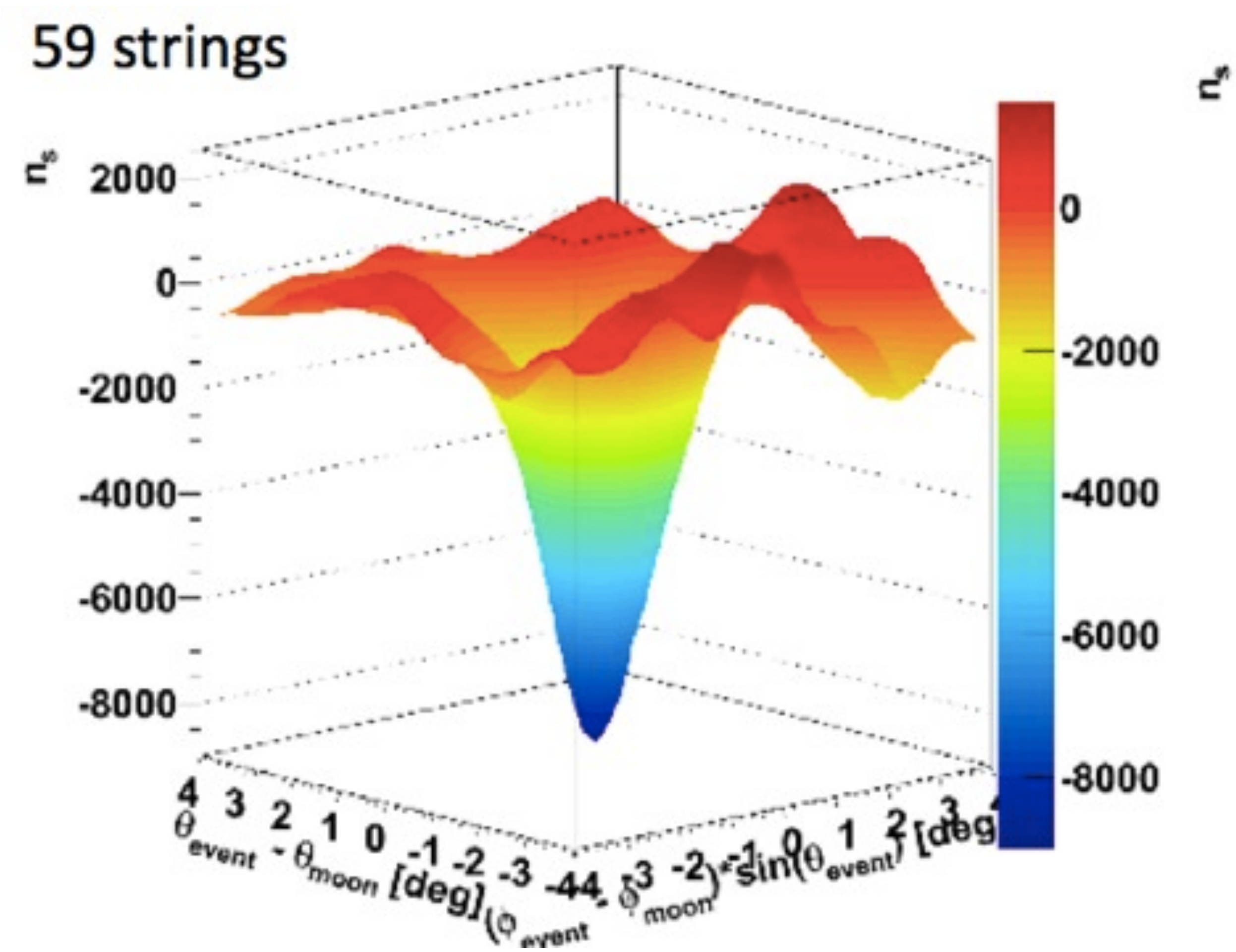
IceCube Detector Performance - Angular Resolution



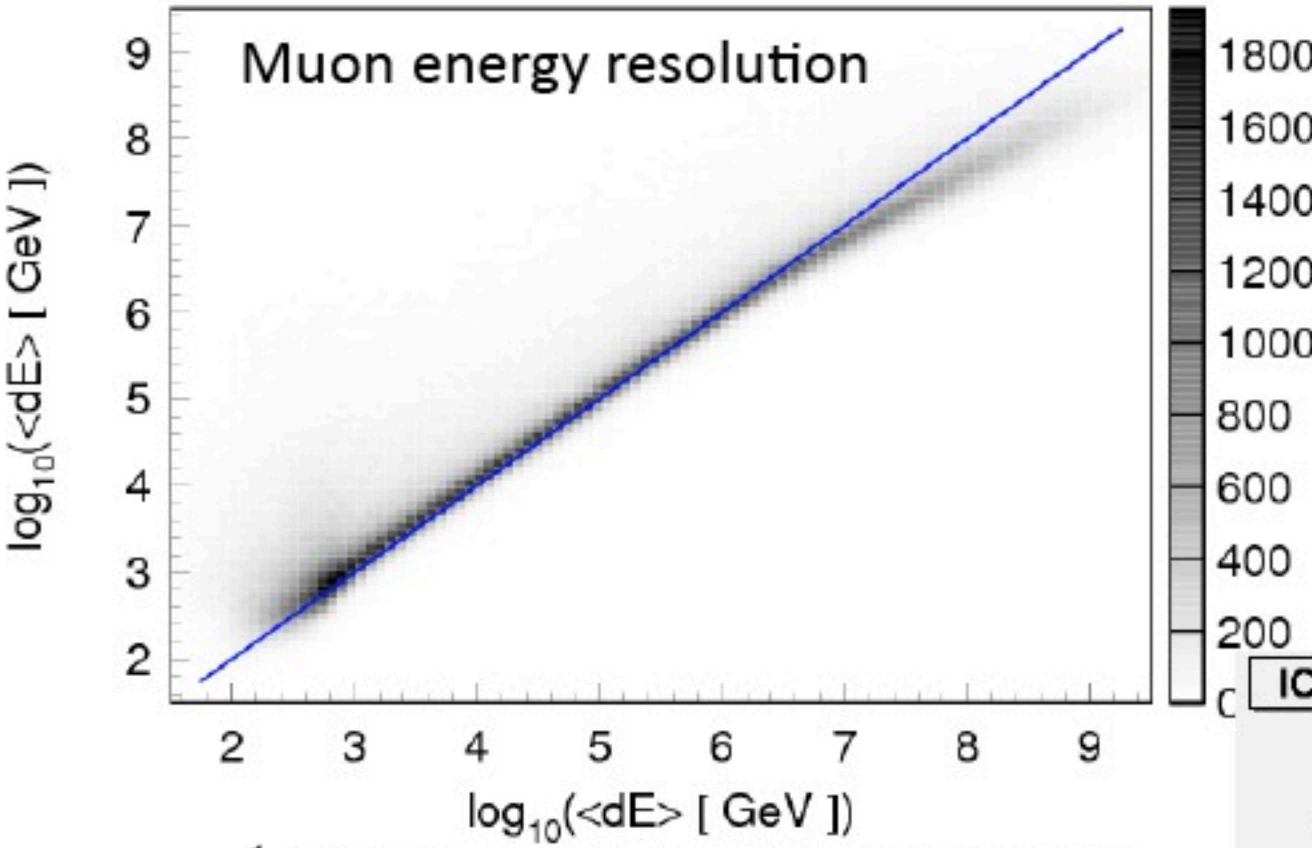
Existence of the moon - confirmed!

- 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.



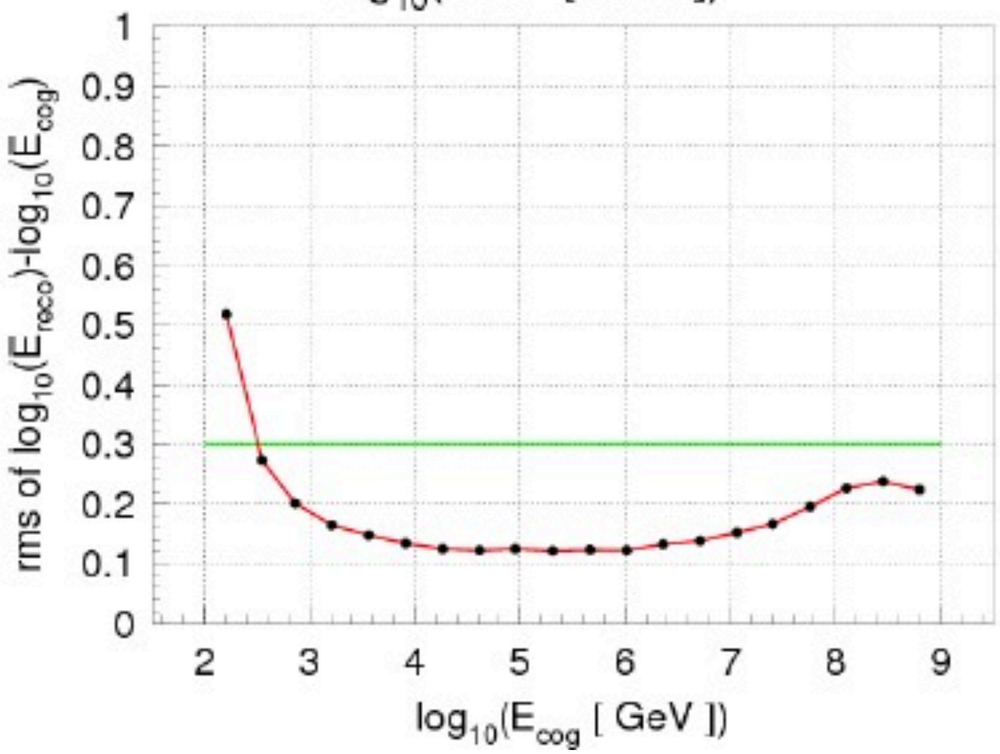


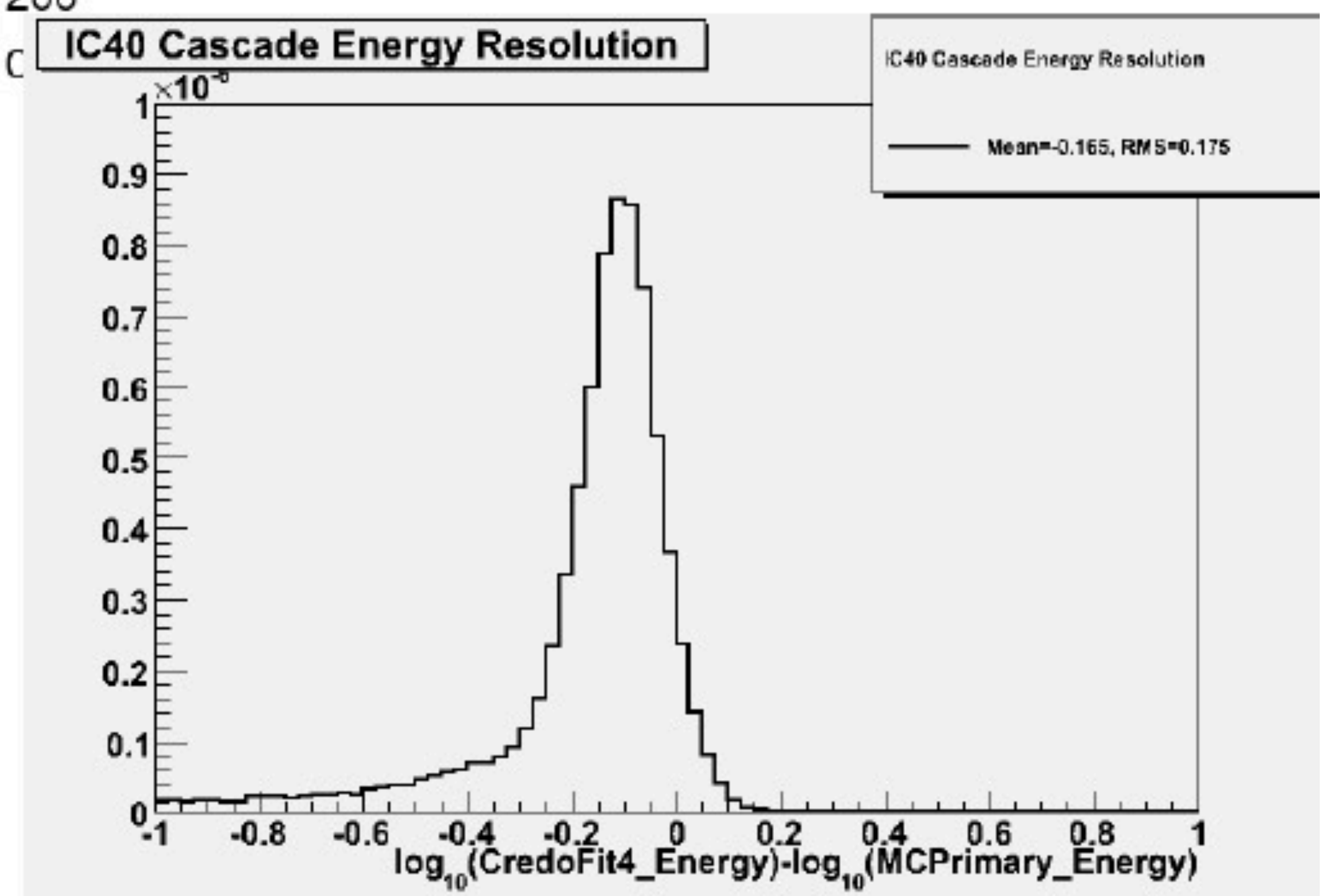
IceCube Detector Performance - Energy Resolution



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

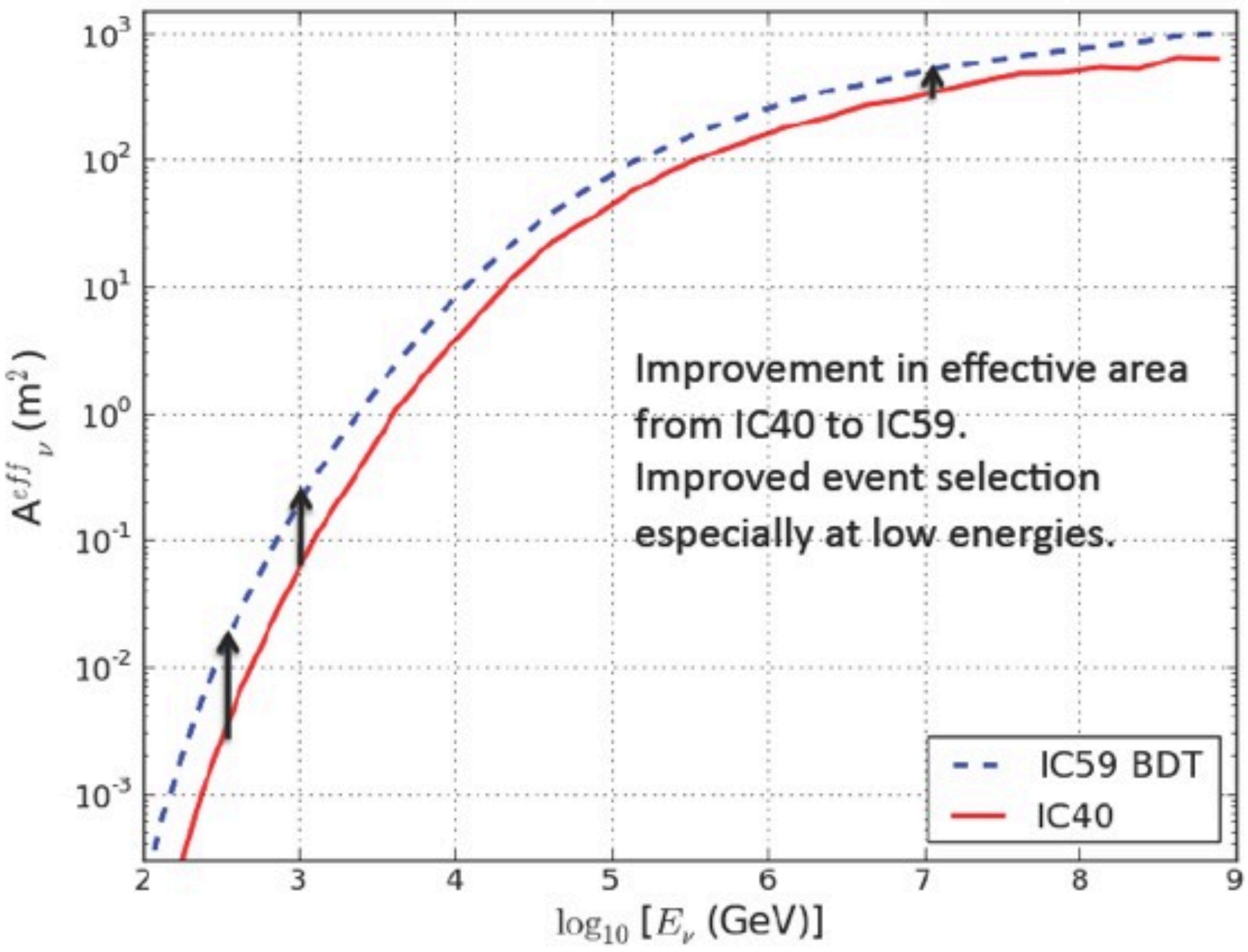
Electron neutrino cascades:
rms of log(E): ~ 0.175
sigma of peak: 0.07



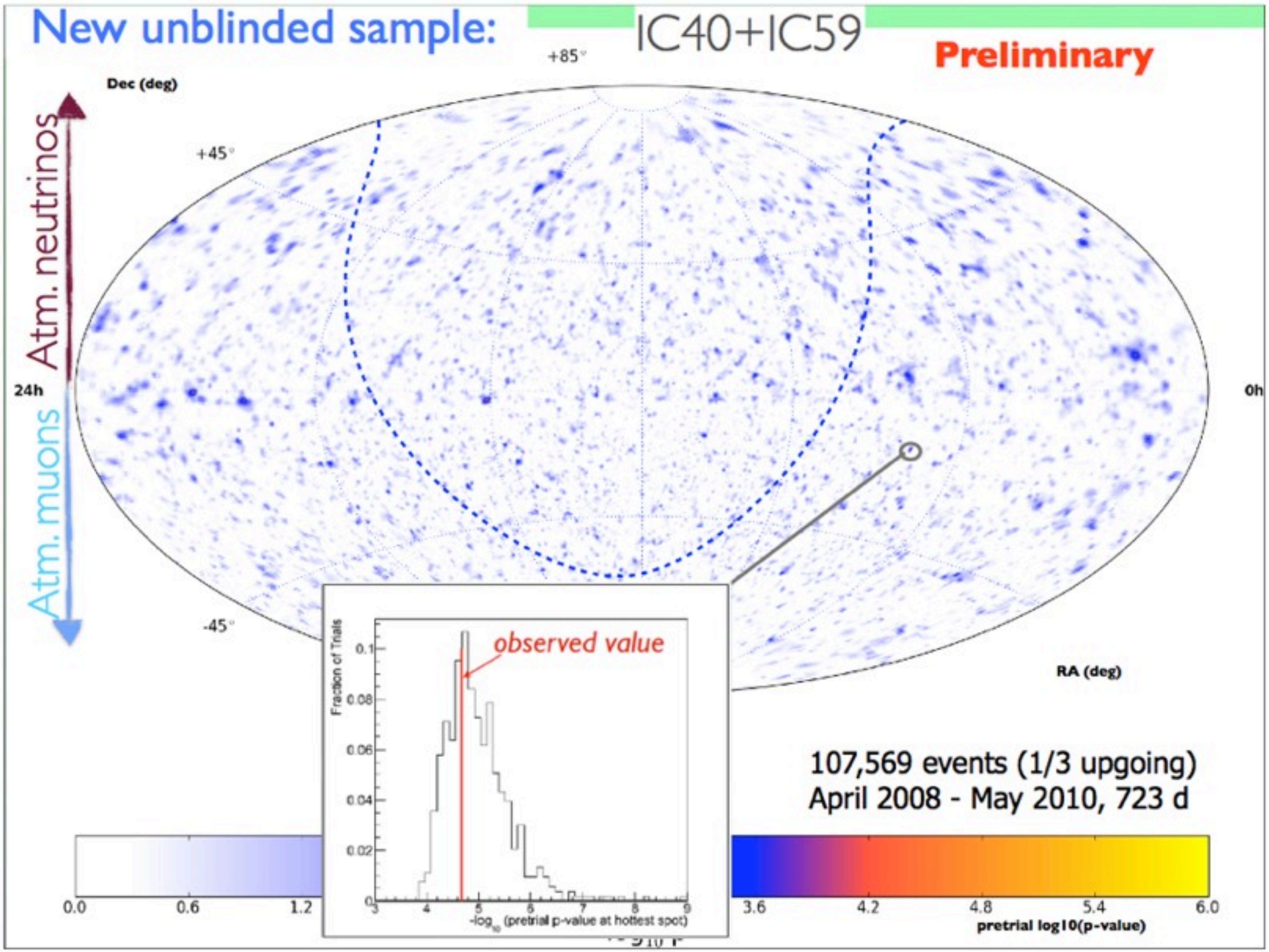


IceCube Detector Performance - Effective Neutrino Area

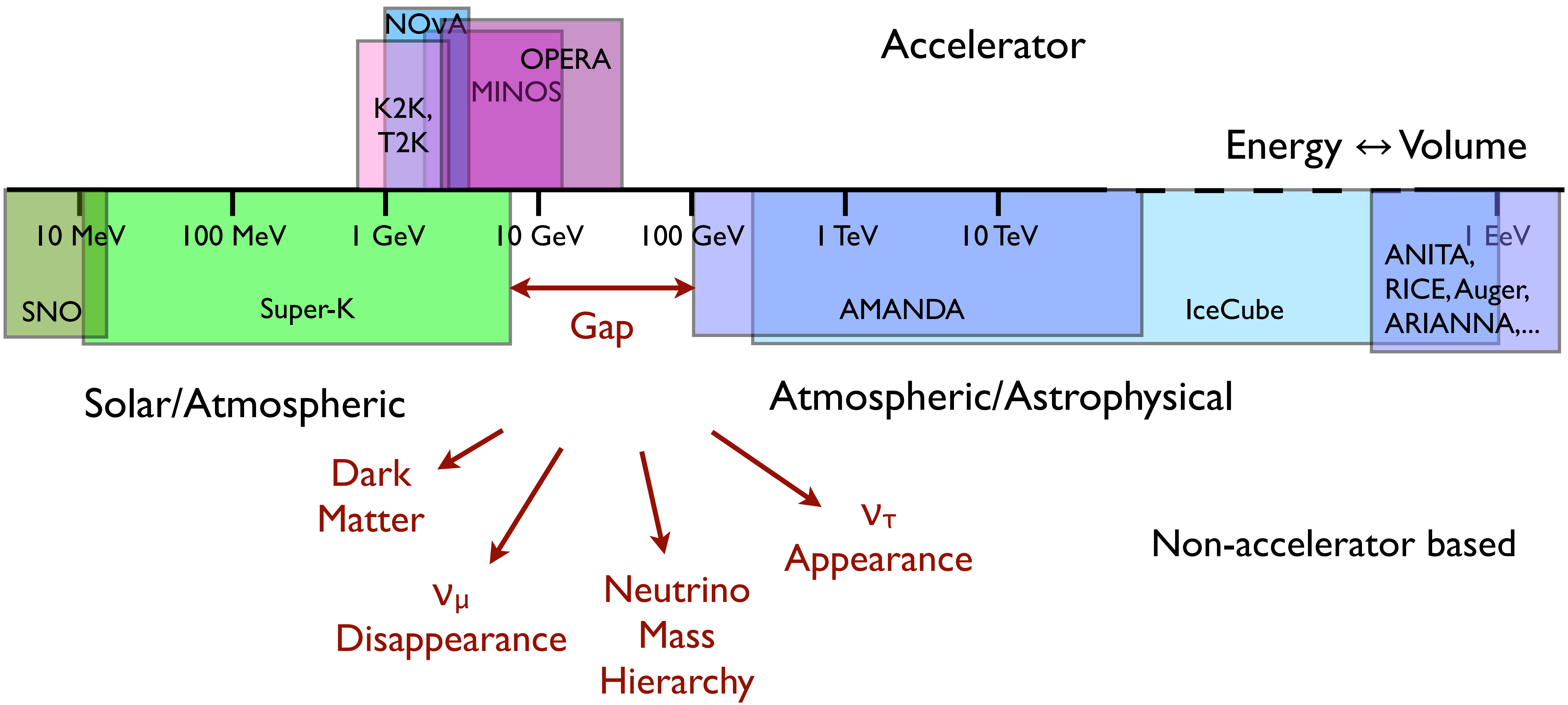
- The detector performance parameters increase faster than the number of strings
- This is an effect of longer muon tracks providing improved angular resolution (lever arm) and energy reconstruction.
- Improved analysis techniques and new ideas (data quality, detector modeling, background simulations)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



Most Recently from IceCube...



The Neutrino Detector Spectrum



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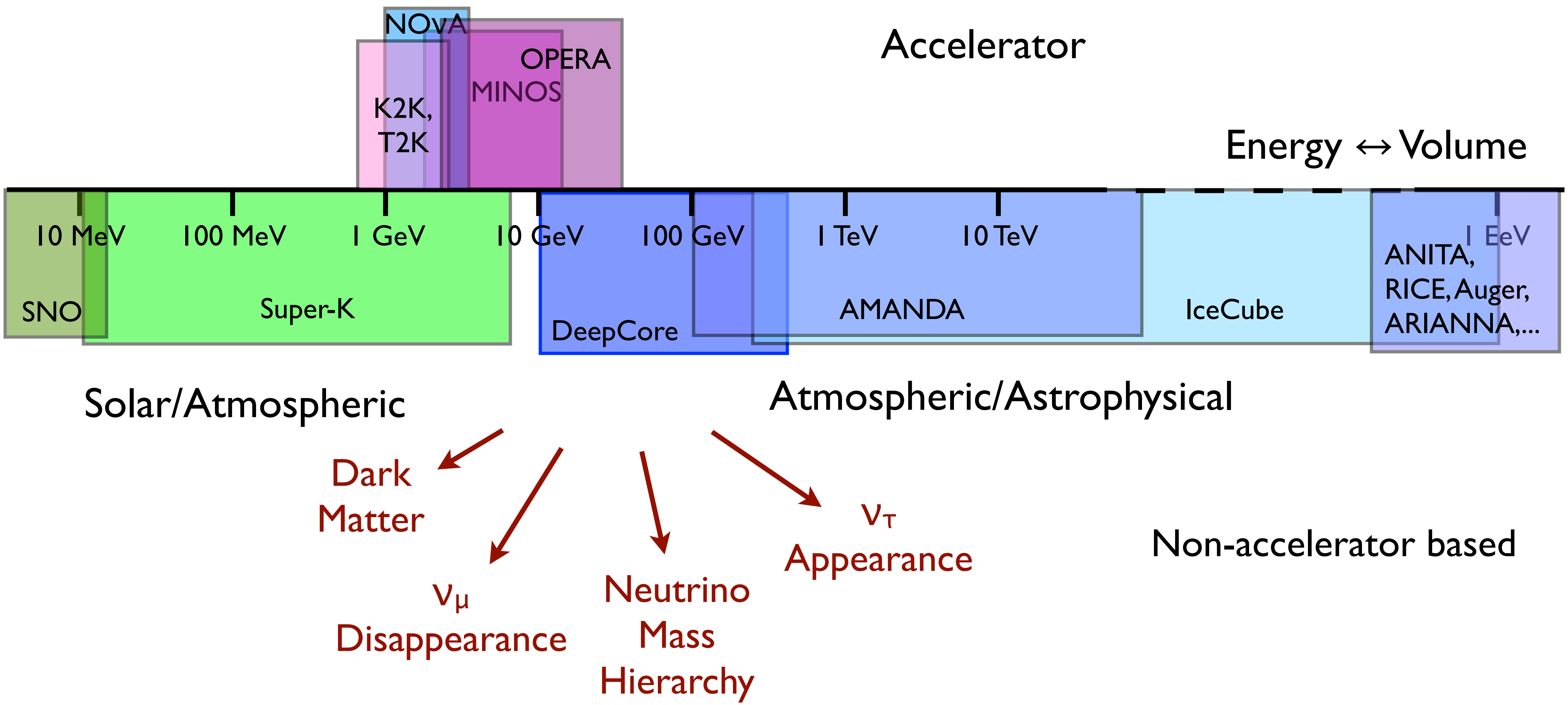
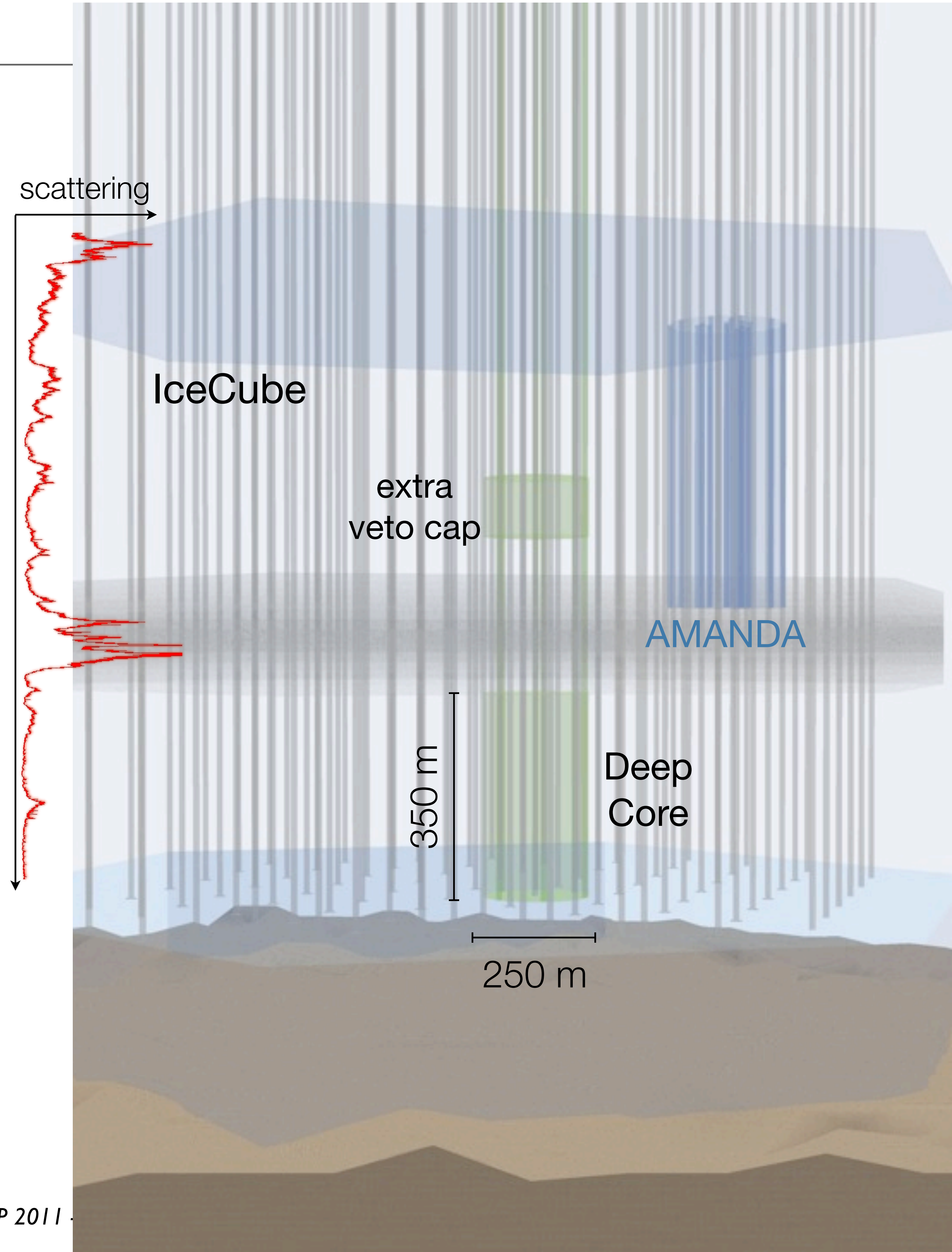


IceCube-DeepCore

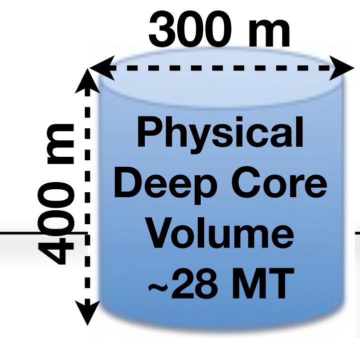
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
  - Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Scientific Motivations:
  - Indirect search for dark matter
  - Neutrino oscillations (e.g., ν_τ appearance)
  - Neutrino point 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
- λ_{eff} > ~50 m
- Result: 30 MTon detector with ~10 GeV threshold, will collect O(200k) atmospheric ν/yr

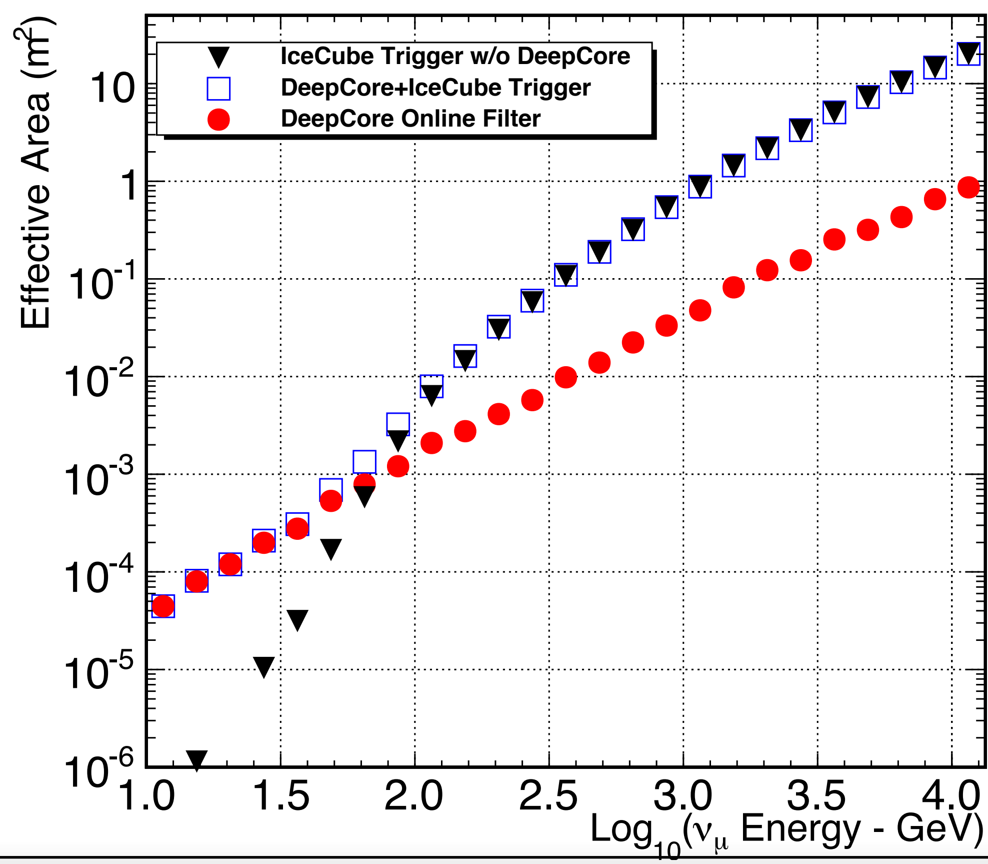


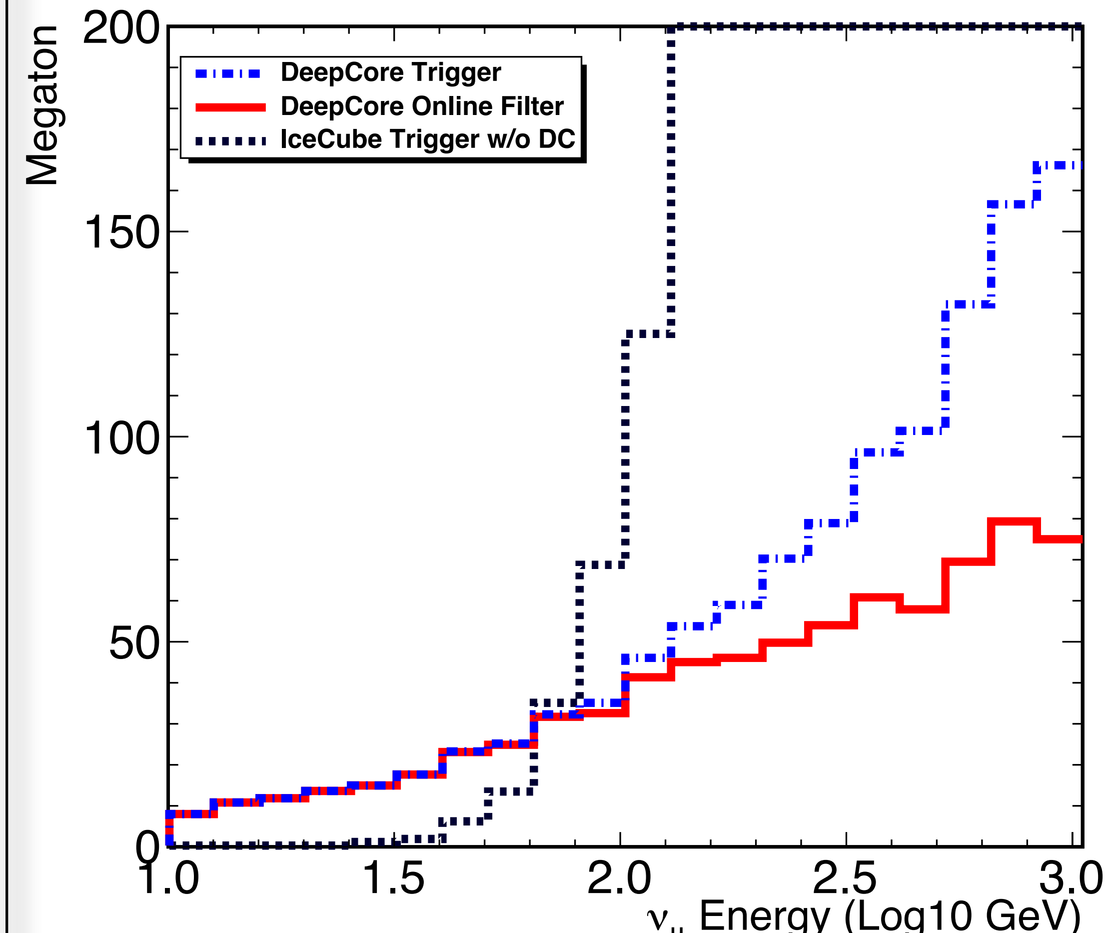
DeepCore Effective Area and Volume



Effective area for up-going ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase





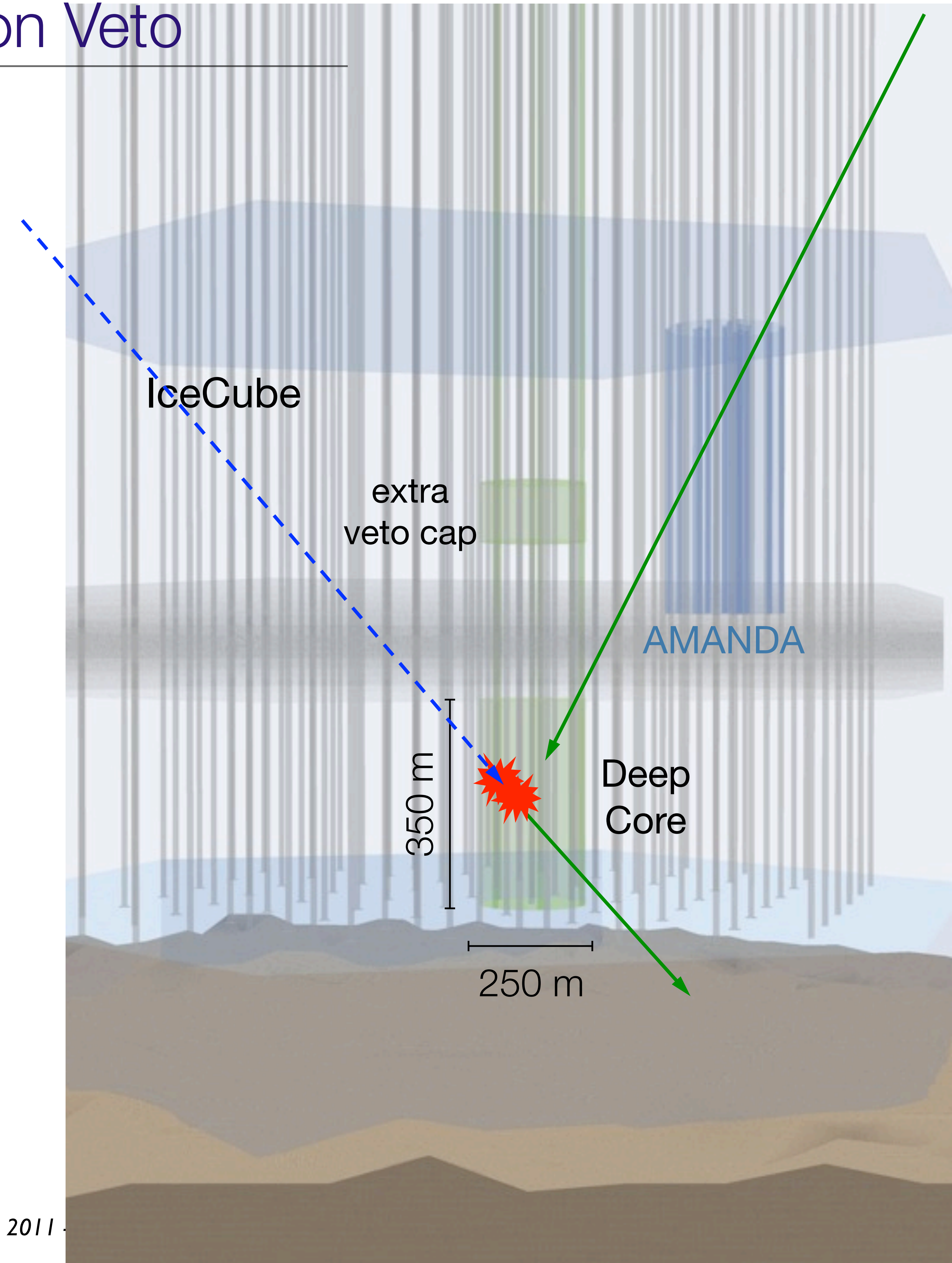
Effective volume for muons from ν_μ interacting in Deep Core

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



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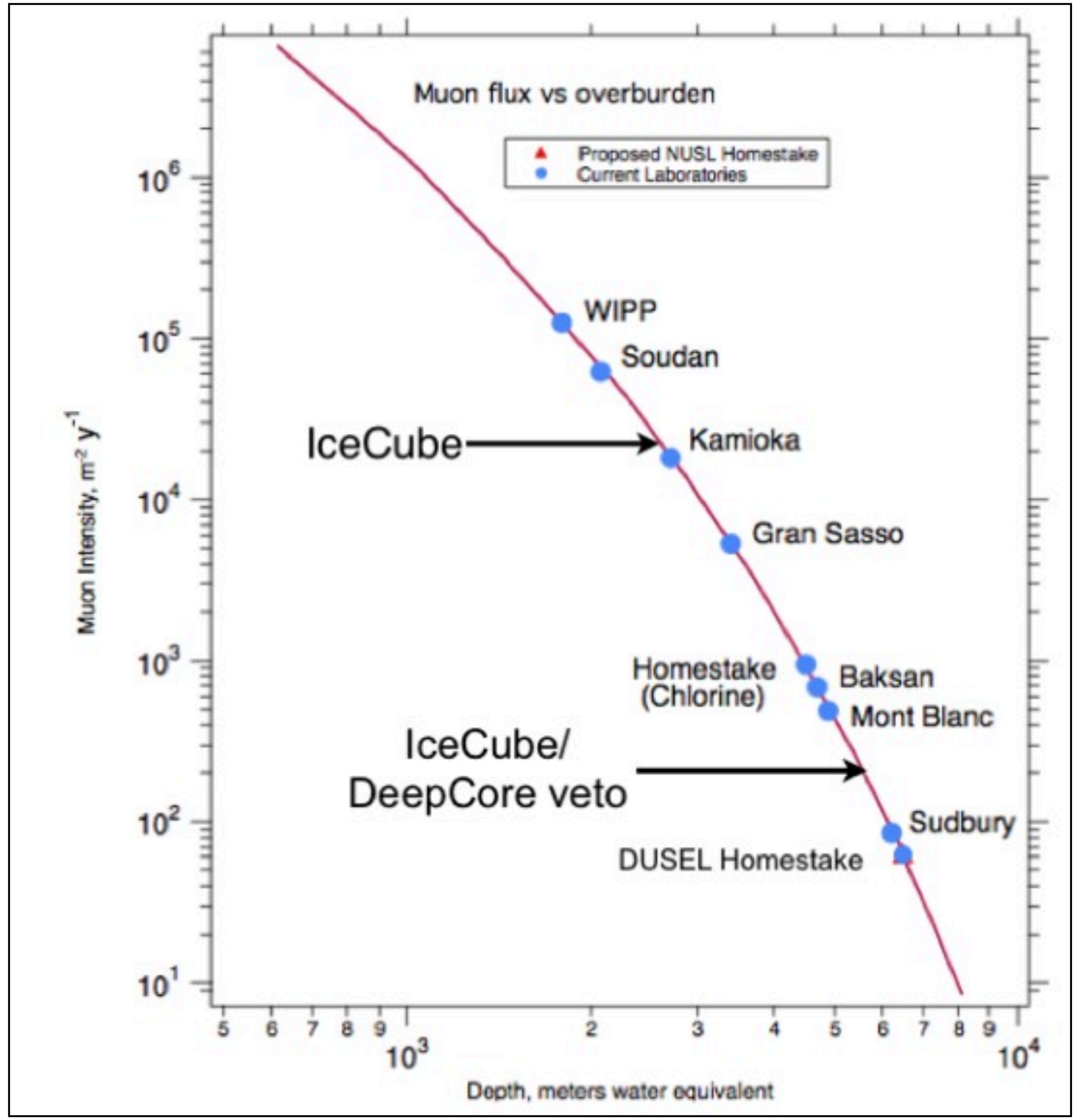
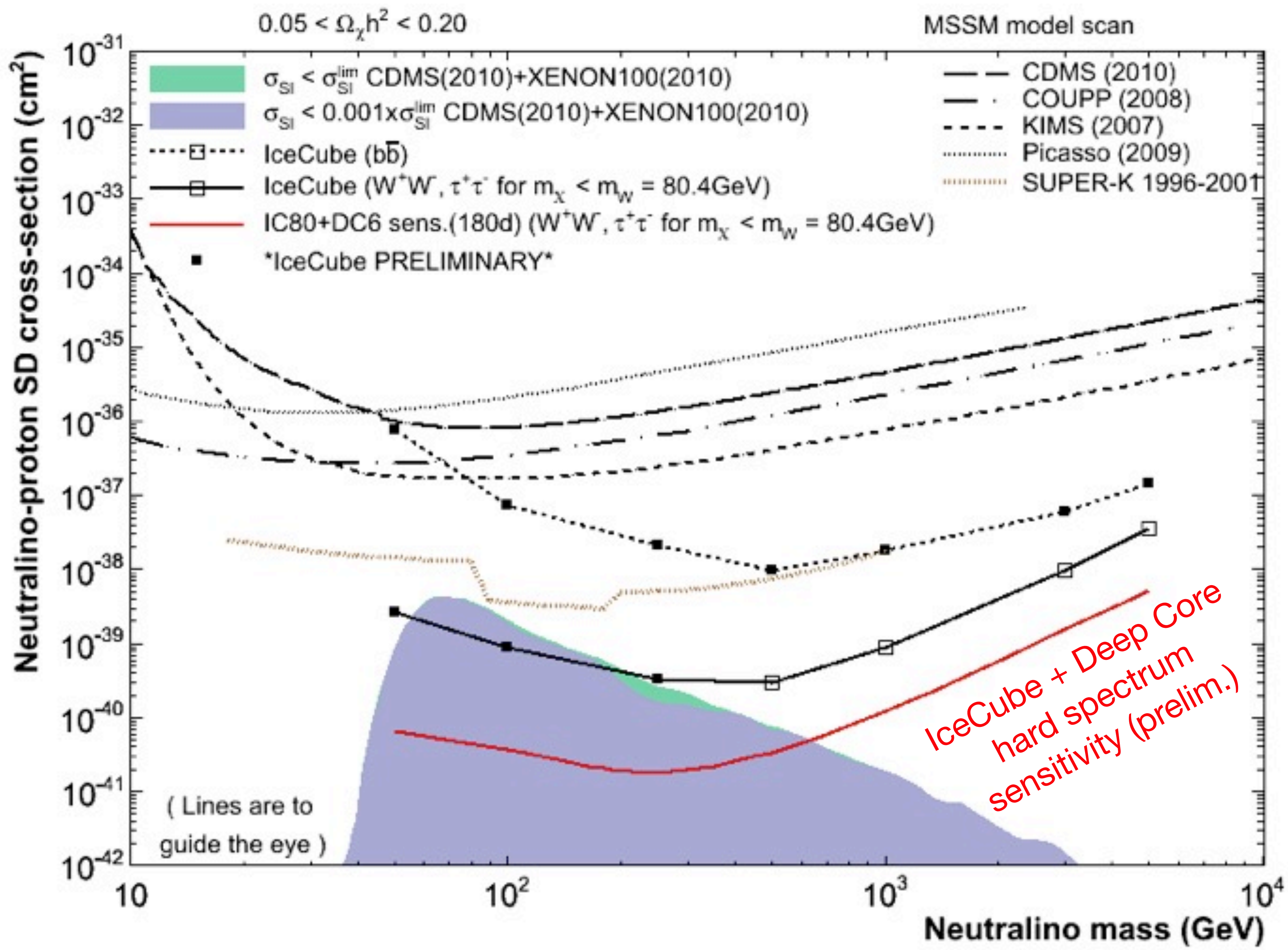


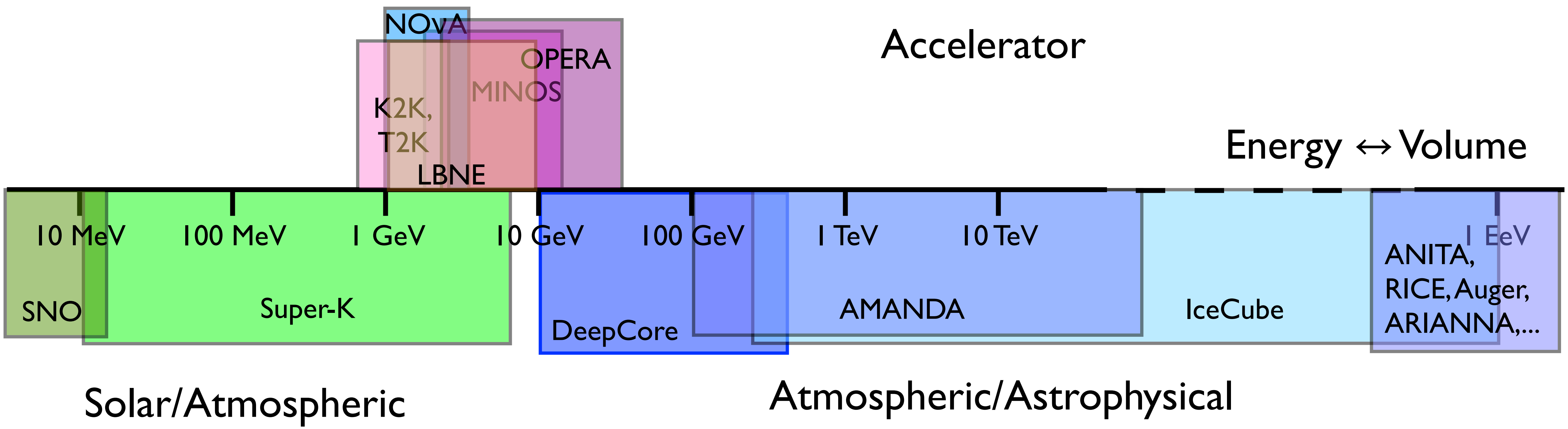
IceCube-DeepCore WIMP Sensitivity

- 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)

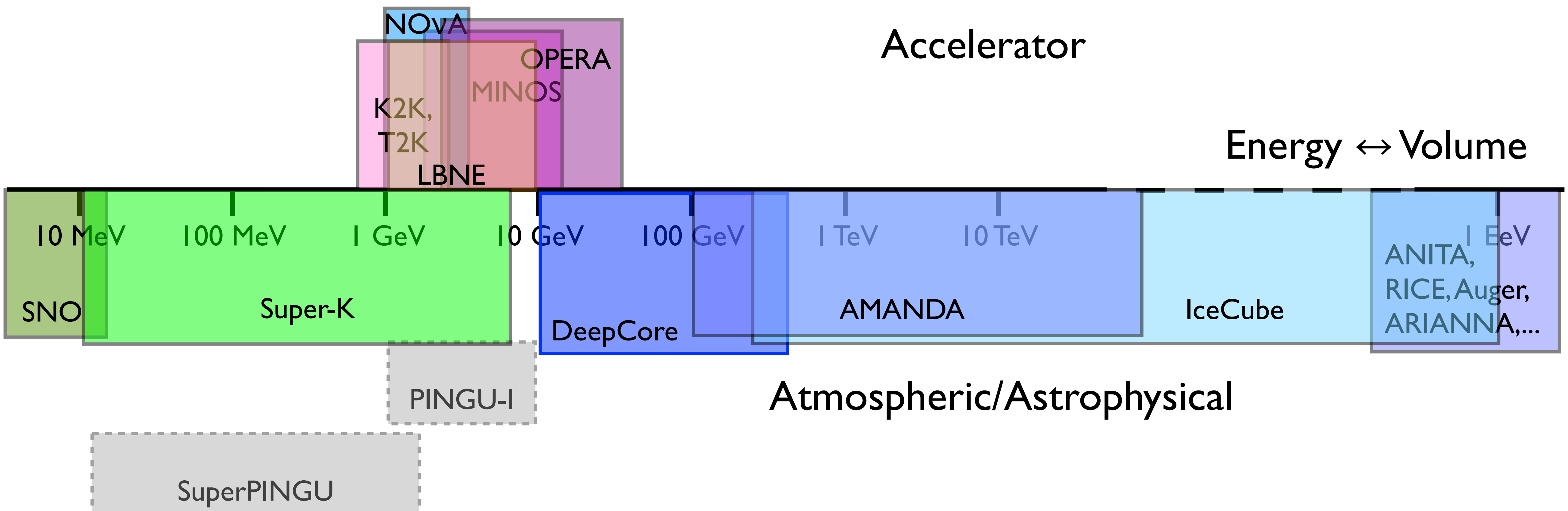
The Neutrino Detector Spectrum



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



Non-accelerator based

~70 active members in feasibility studies:

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

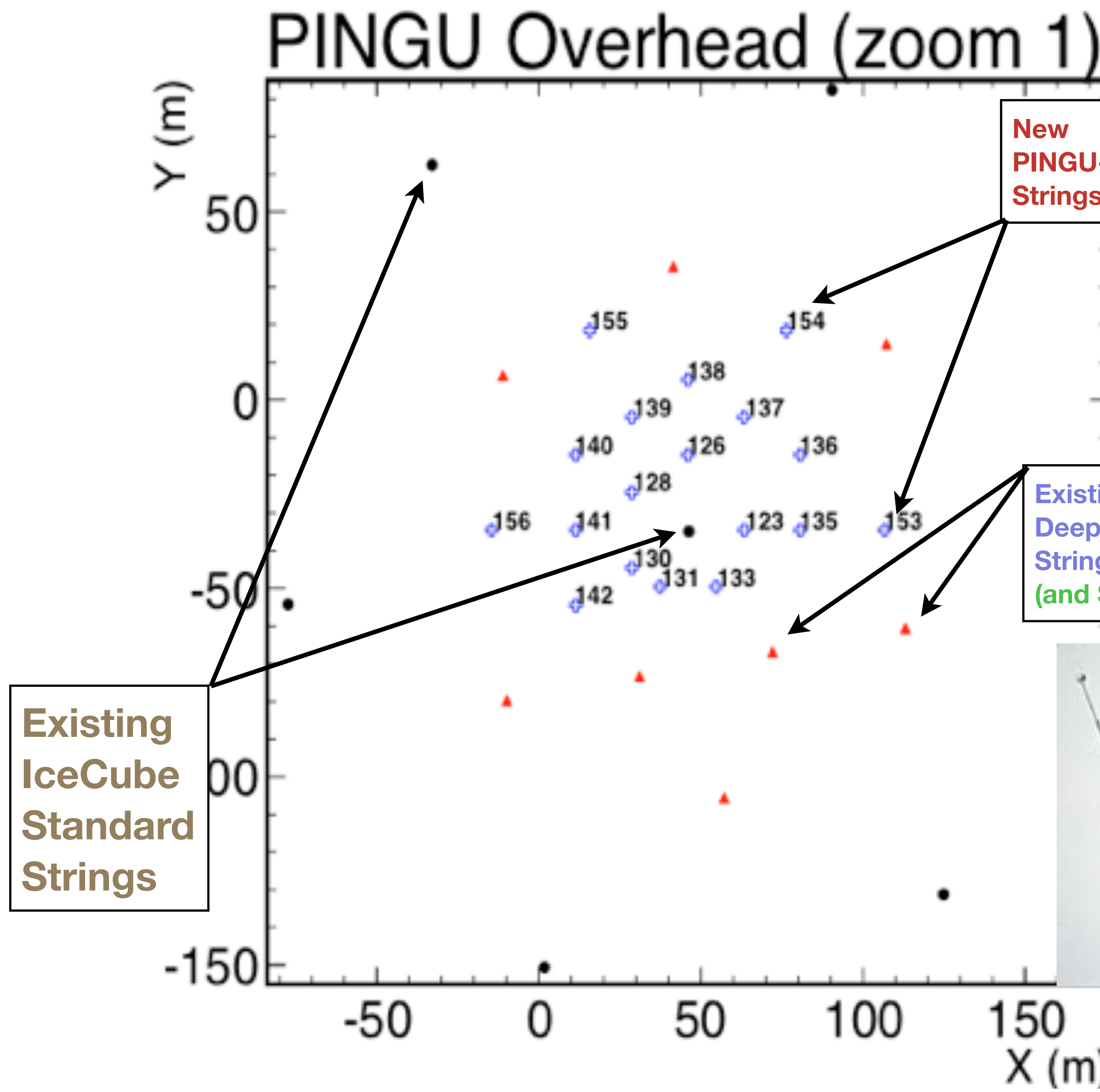
PINGU - Possible detector configurations

- 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



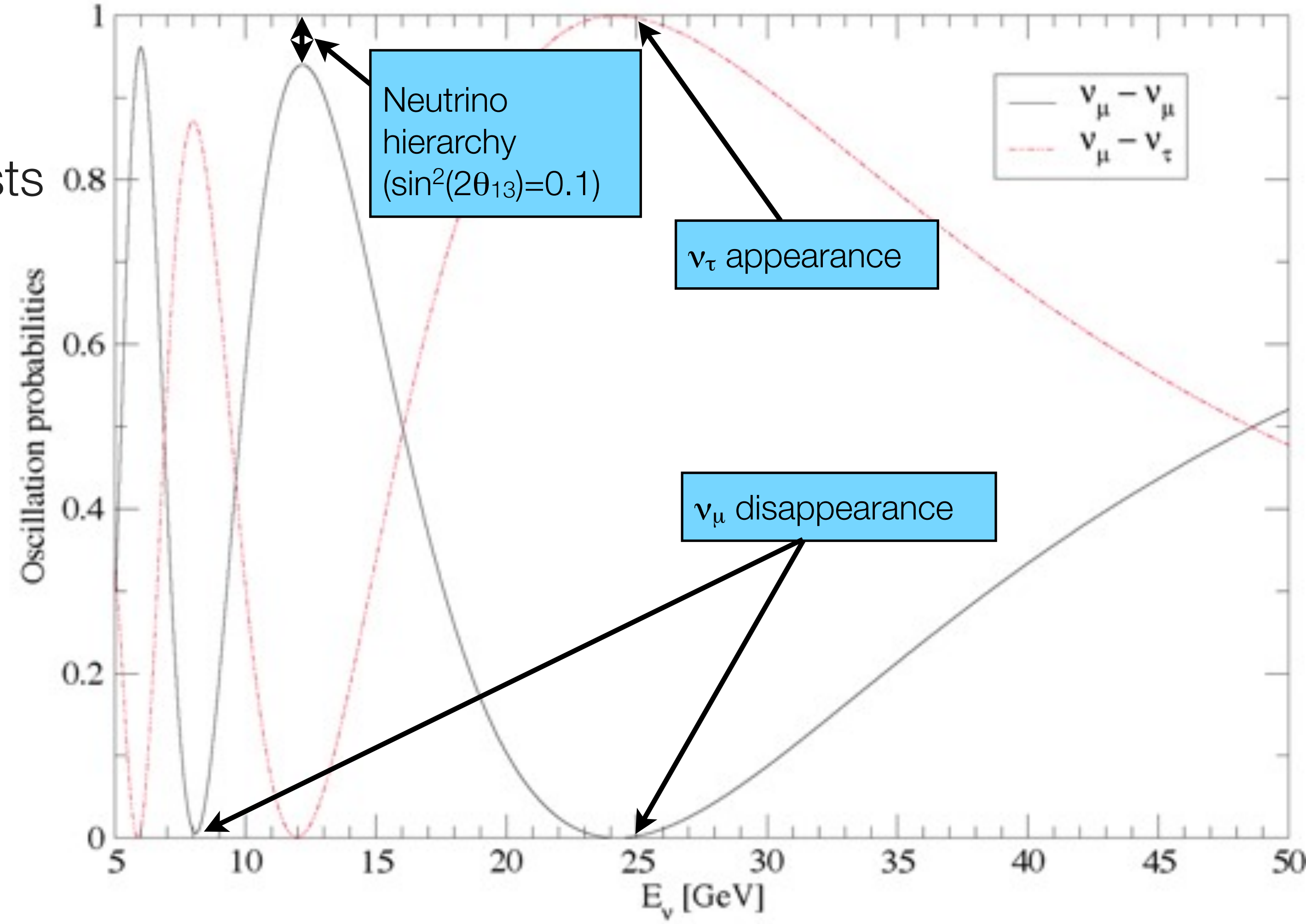
Aardman Animations

- Price tag would likely be around $25M

PINGU-I Physics

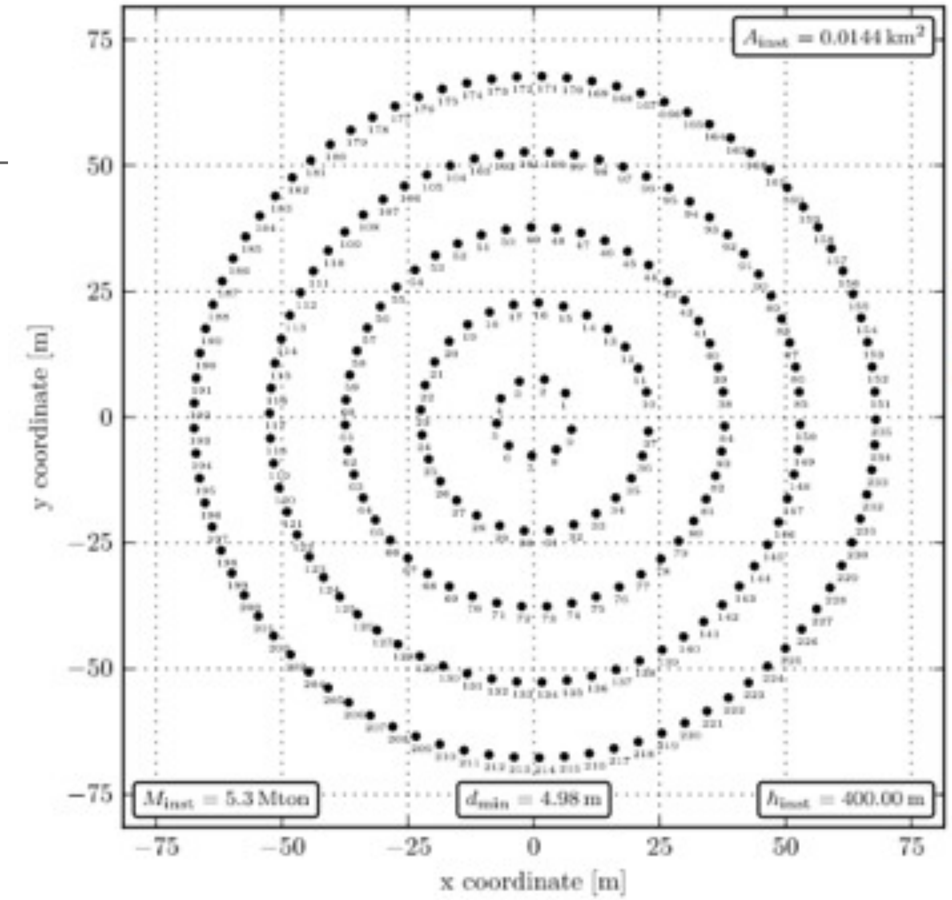
- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - will help pin down $(\Delta m_{23})^2$
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate 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)

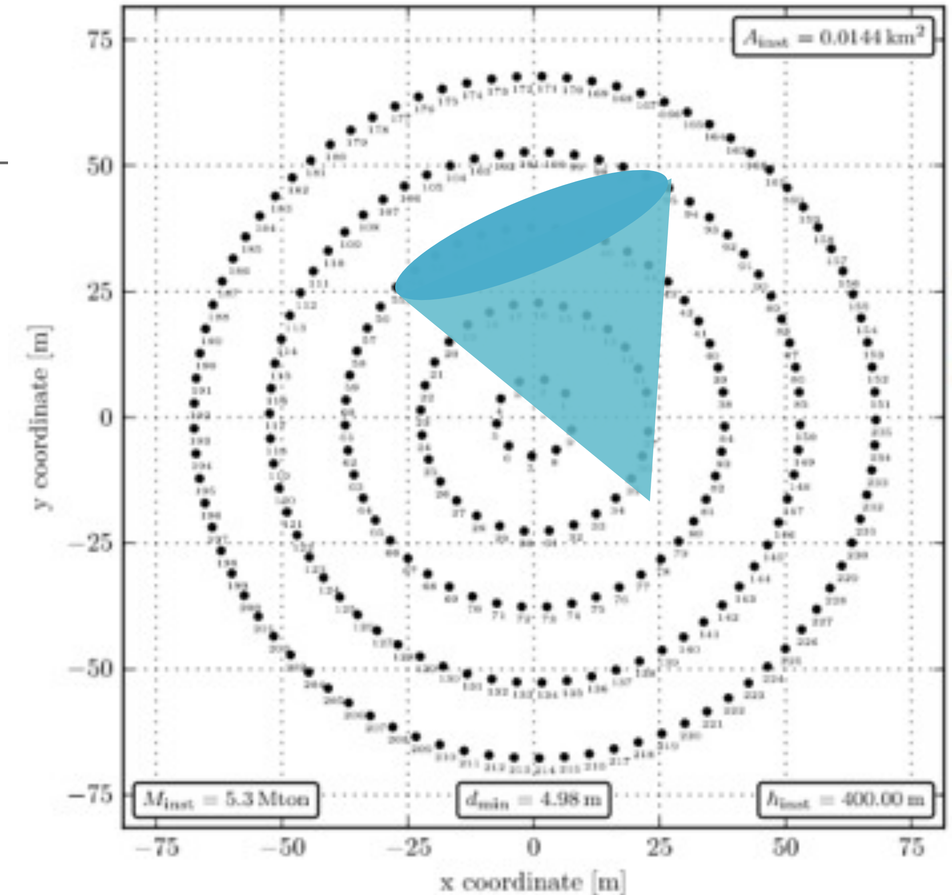


SuperPINGU Conceptual Detector

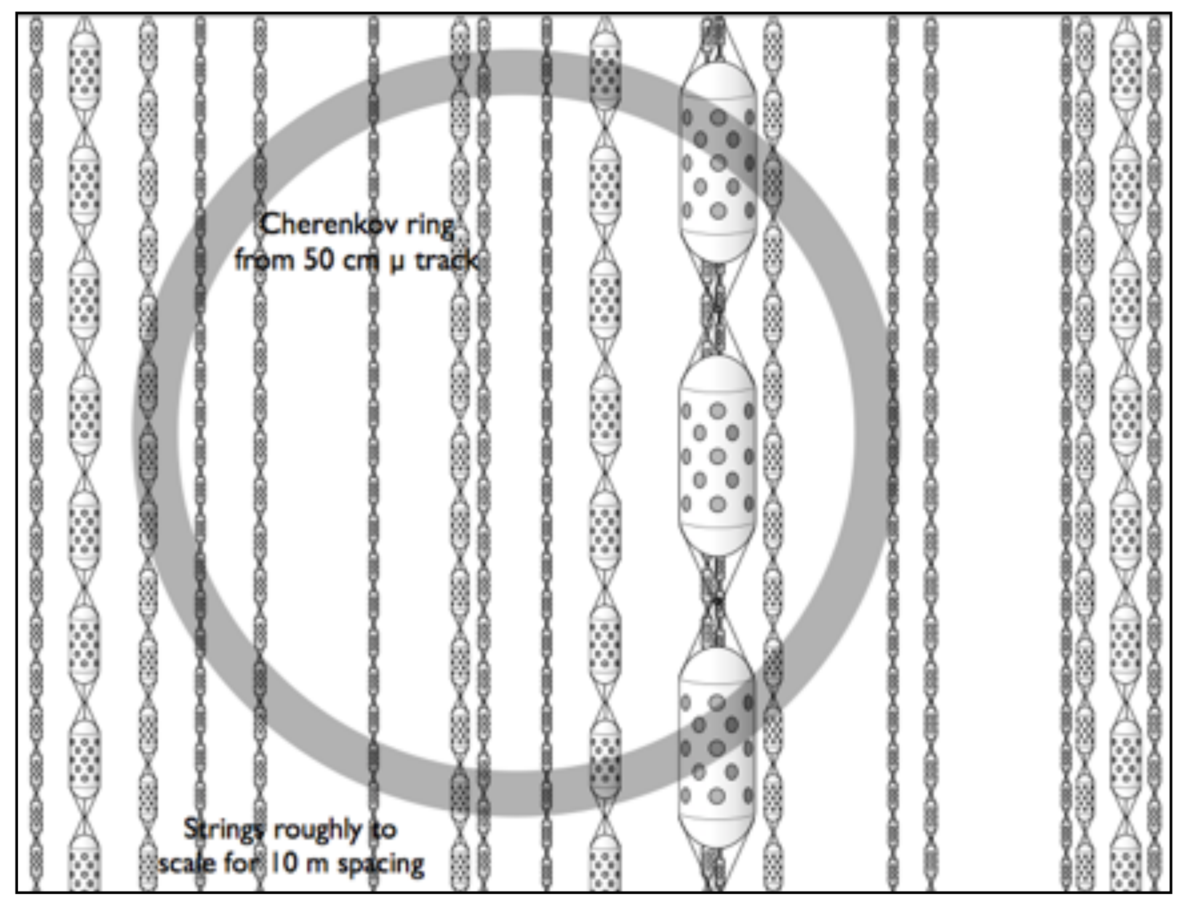
- O(few hundred) strings of “linear” detectors within DeepCore fiducial volume
- Goals: ~5 MTon scale with energy sensitivity of:
  - O(10 MeV) for bursts
  - O(100 MeV) for single events
- Physics extraction from Cherenkov ring imaging in the ice
- IceCube and DeepCore provide active veto



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

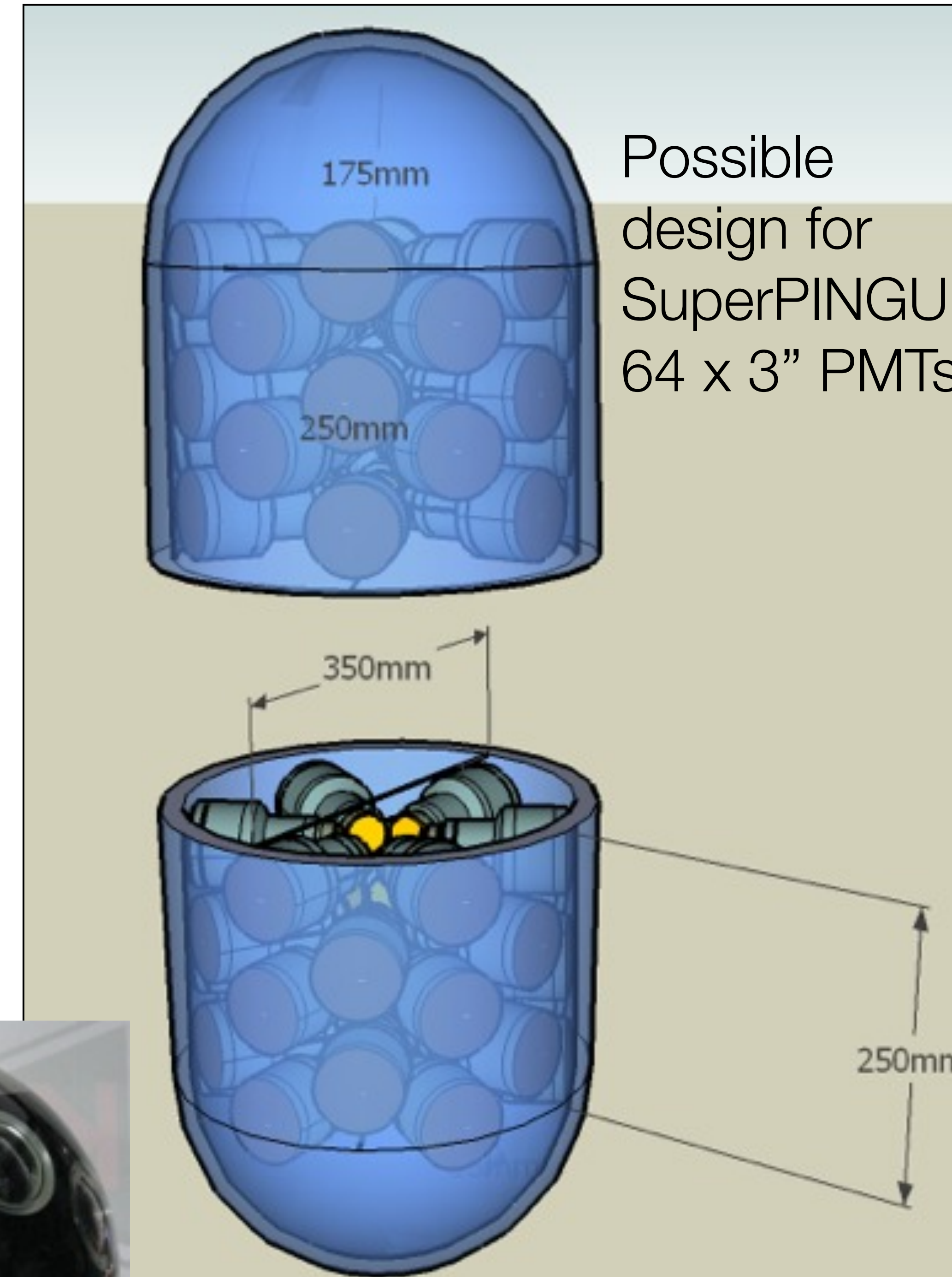


SuperPINGU Detector R&D

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



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!