IceCube-DeepCore-PINGU

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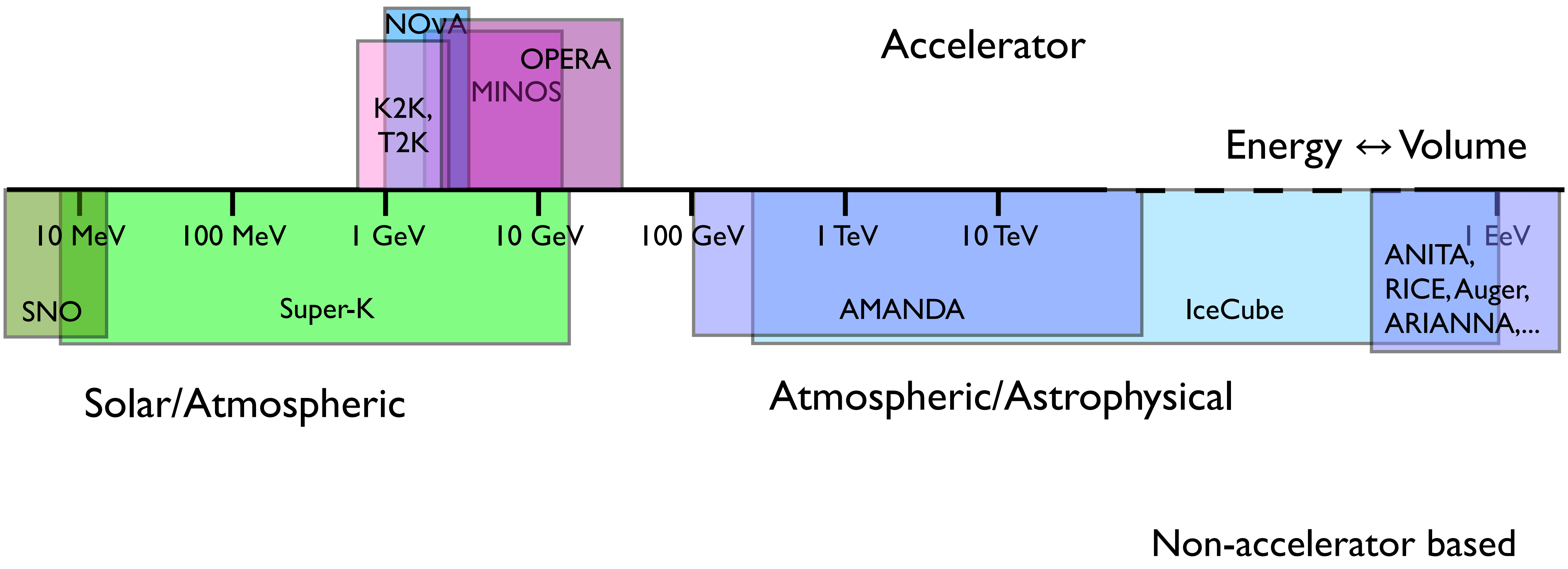
University of Alberta

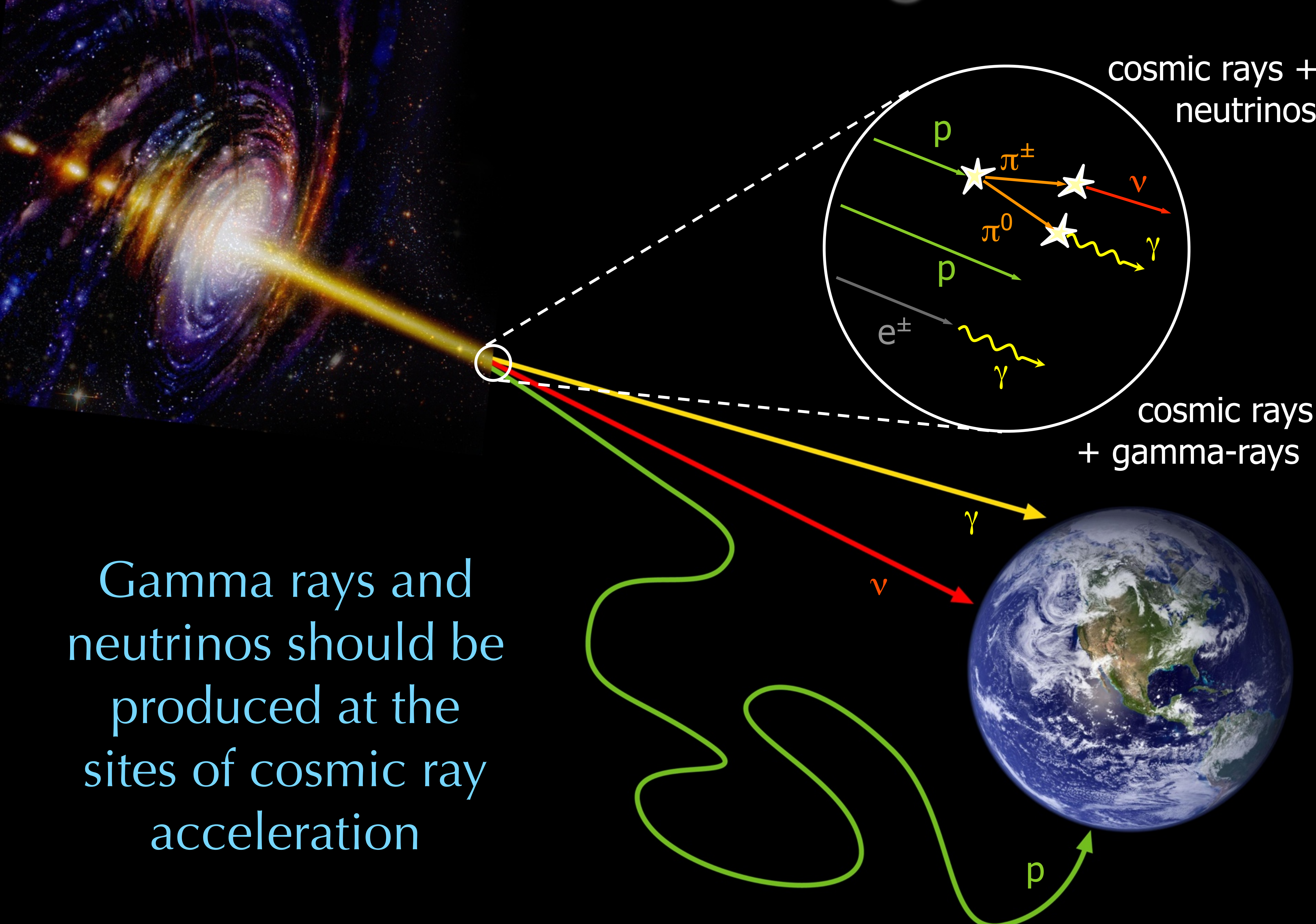
12th International Workshop on Next generation Nucleon Decay and Neutrino Detectors
Zurich, Switzerland

The Neutrino Detector Spectrum



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

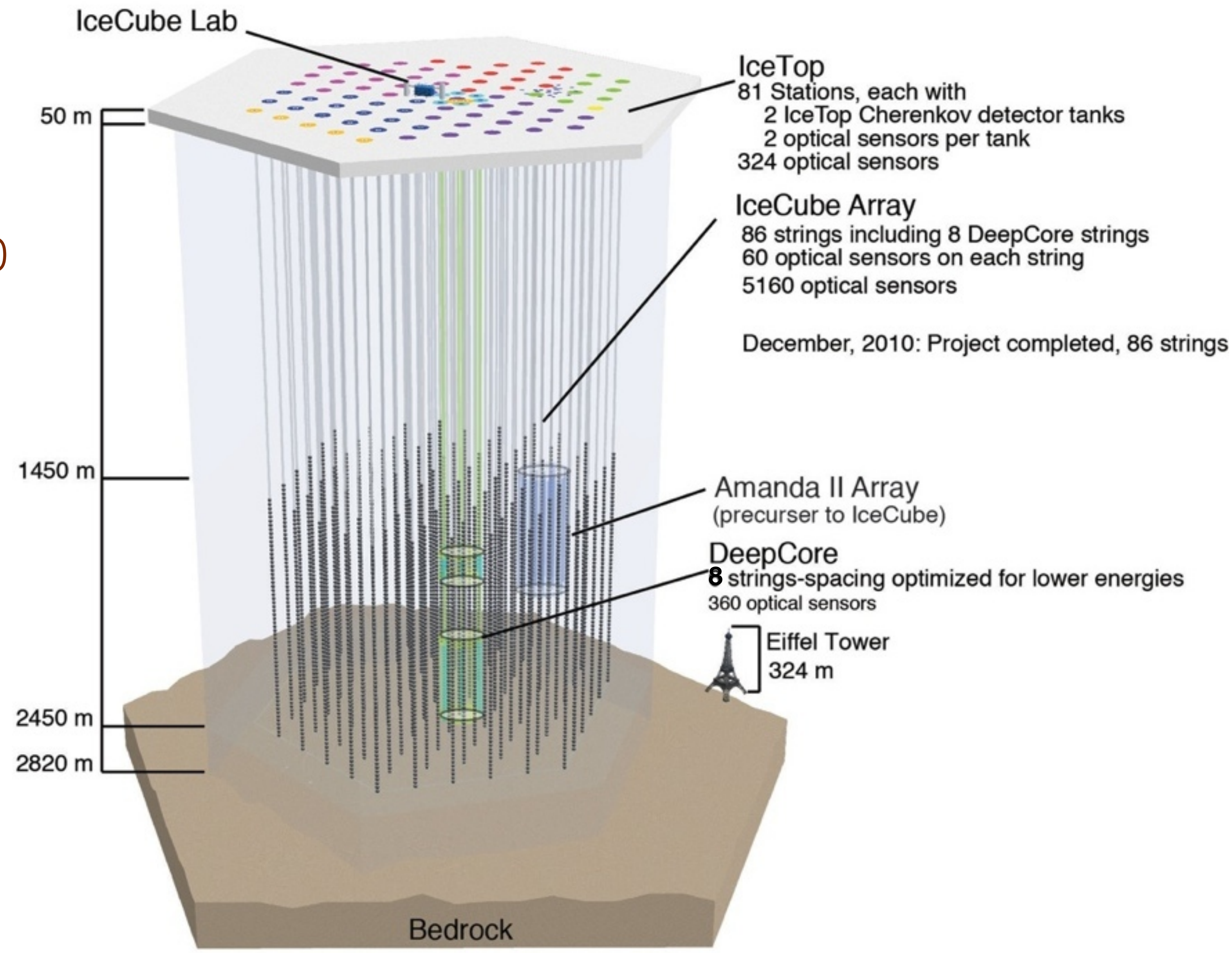
Multimessenger Astronomy



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

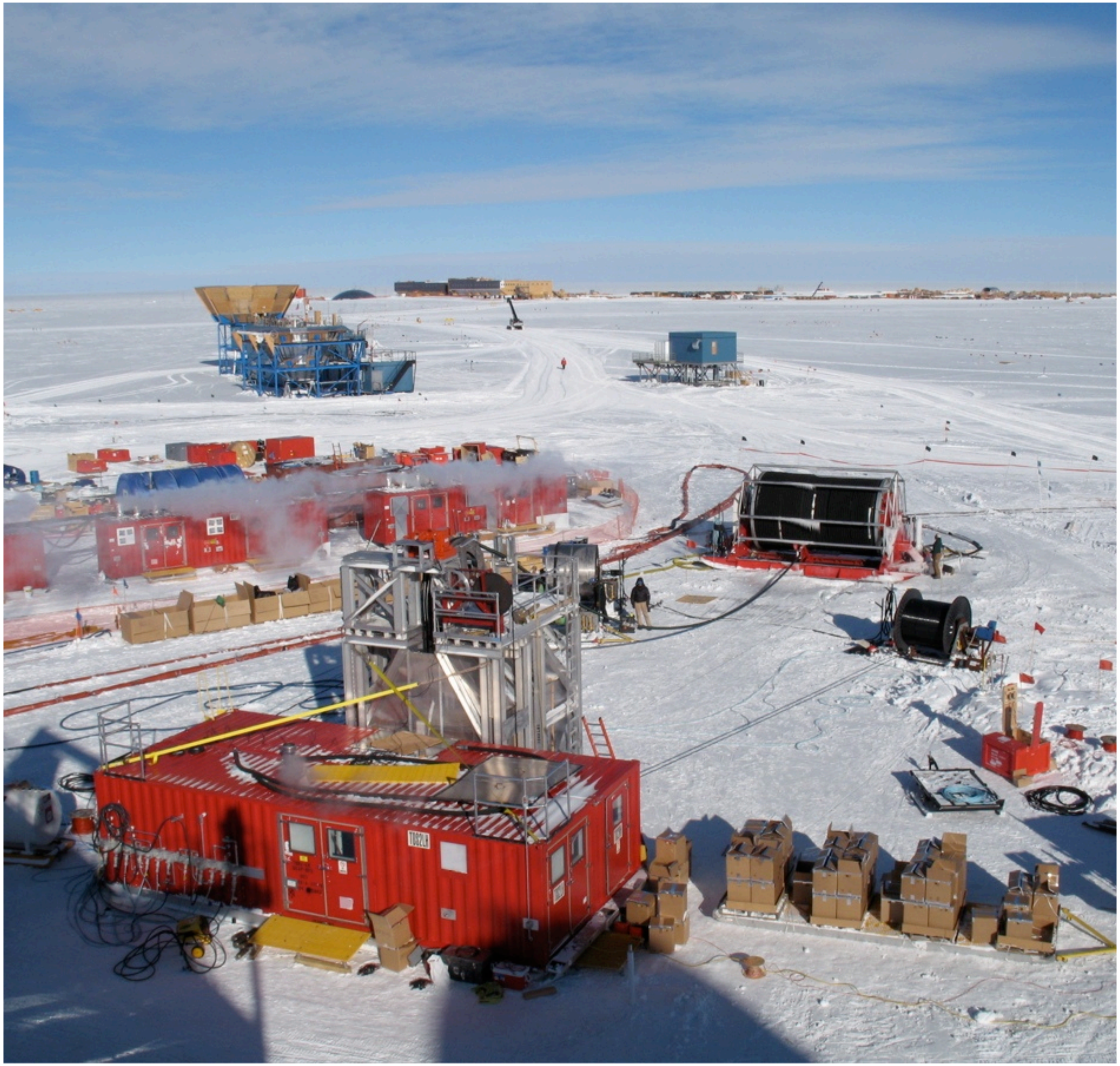
The IceCube Neutrino Observatory

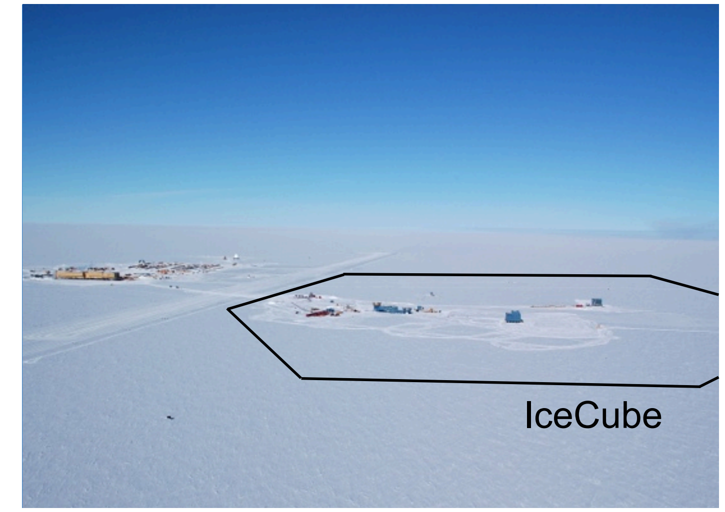
Completed
December 18, 2010

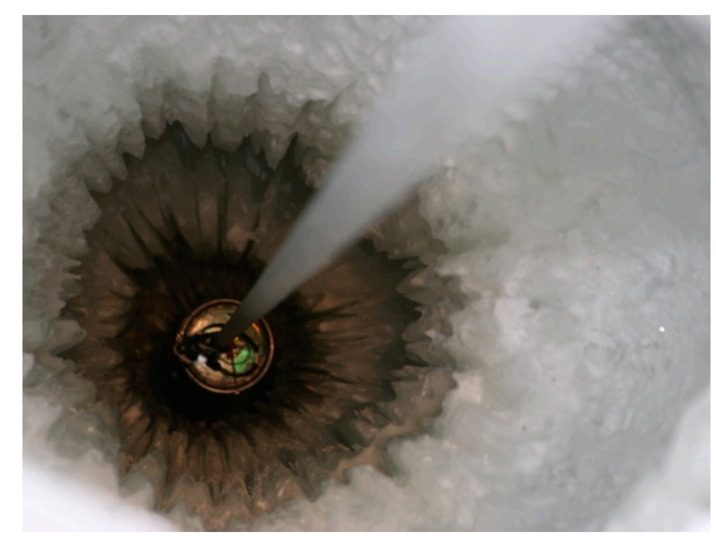


The IceCube Collaboration

36 institutions - 4 continents - ~250 Physicists

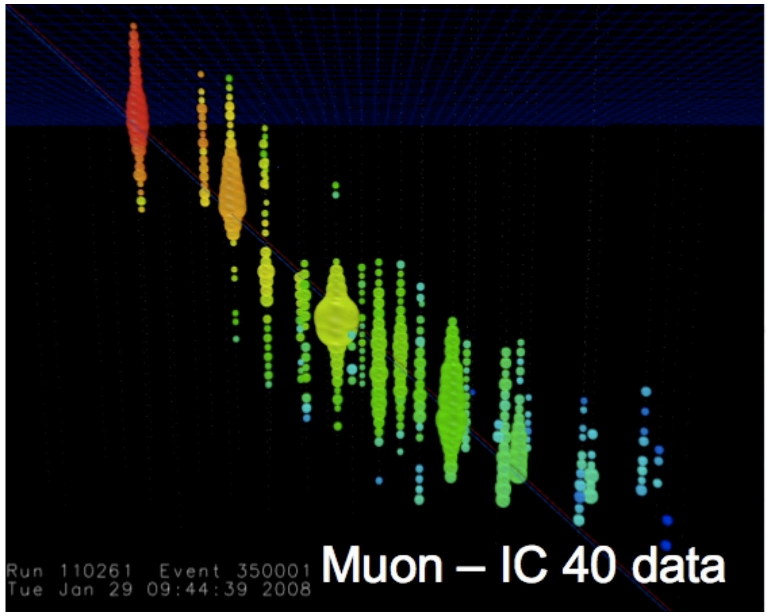






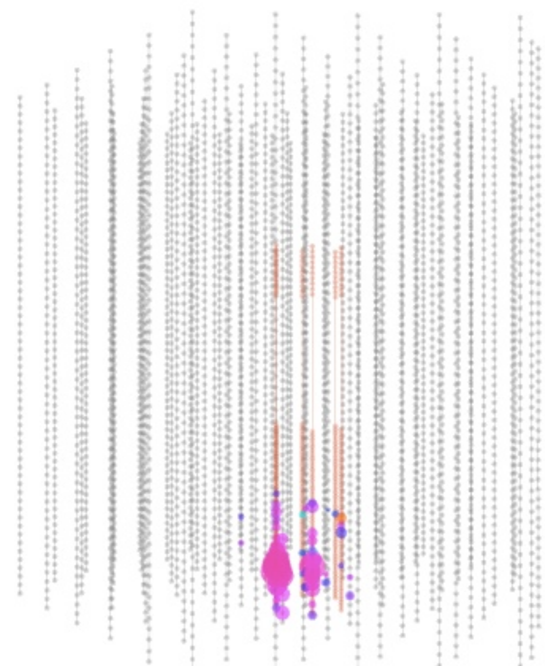
Amundsen-Scott South Pole Station, Antarctica

Neutrino Telescopes - Principle of Detection

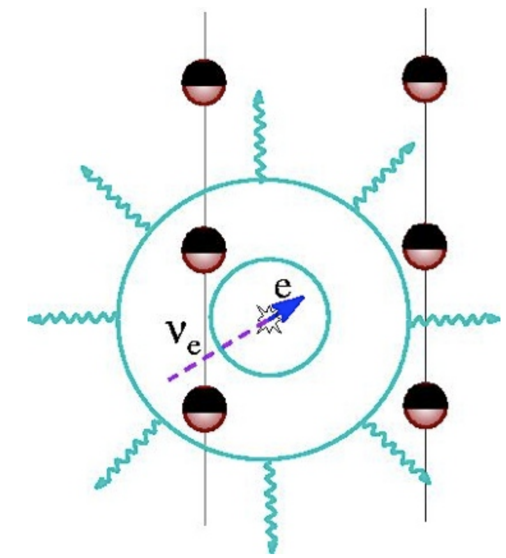


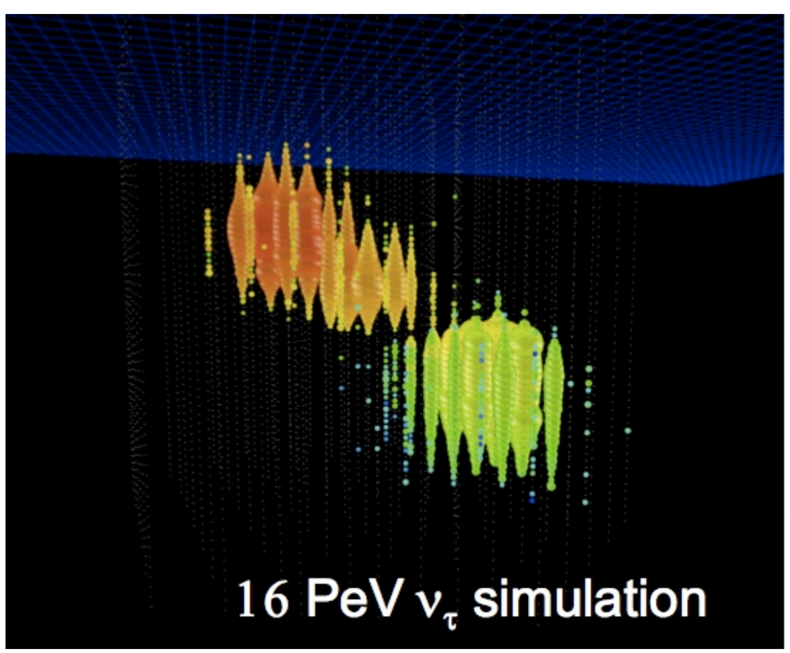
Tracks:
- through-going muons
- pointing resolution ~1°

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



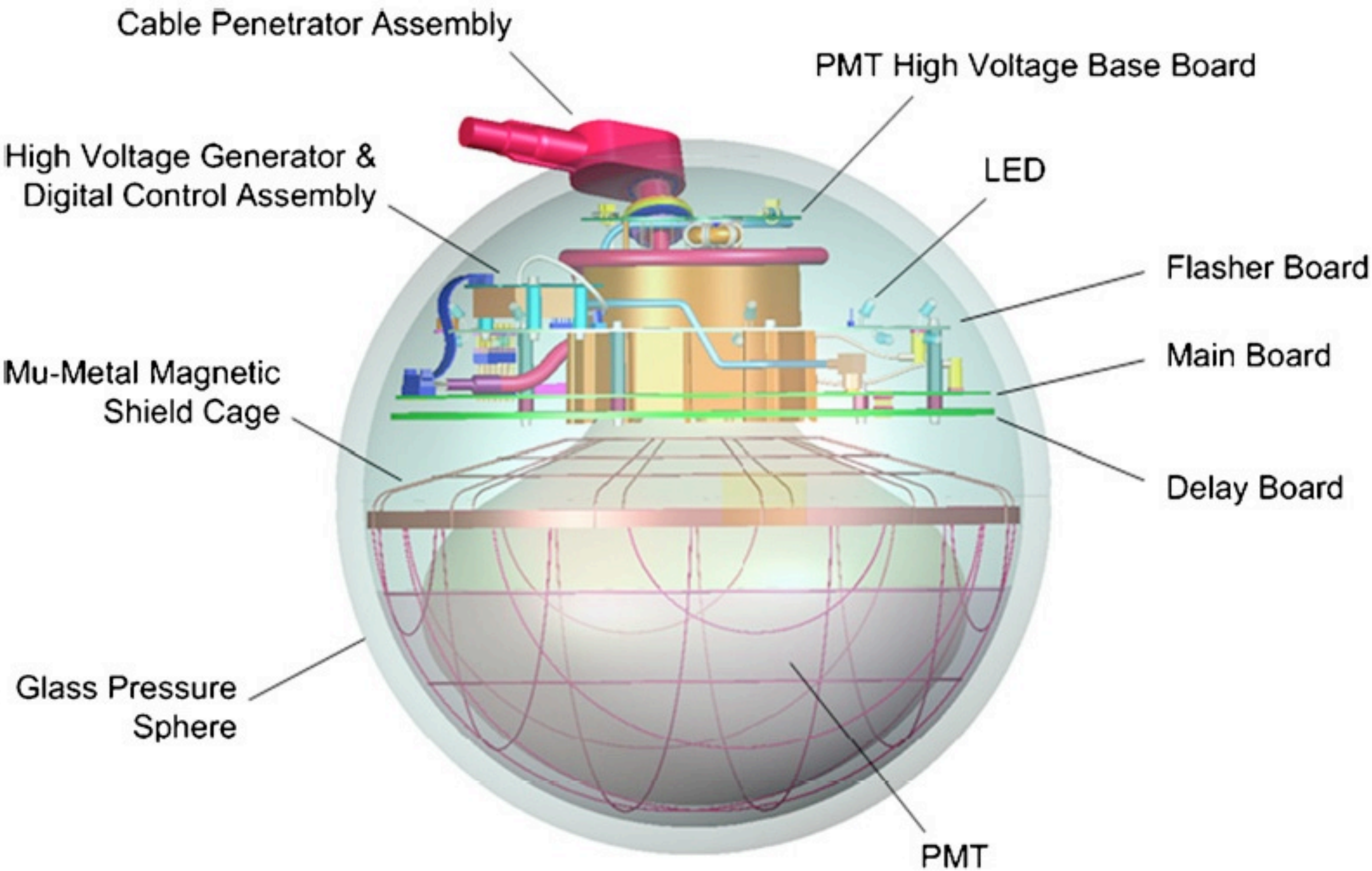
IC79 Cascade Event





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

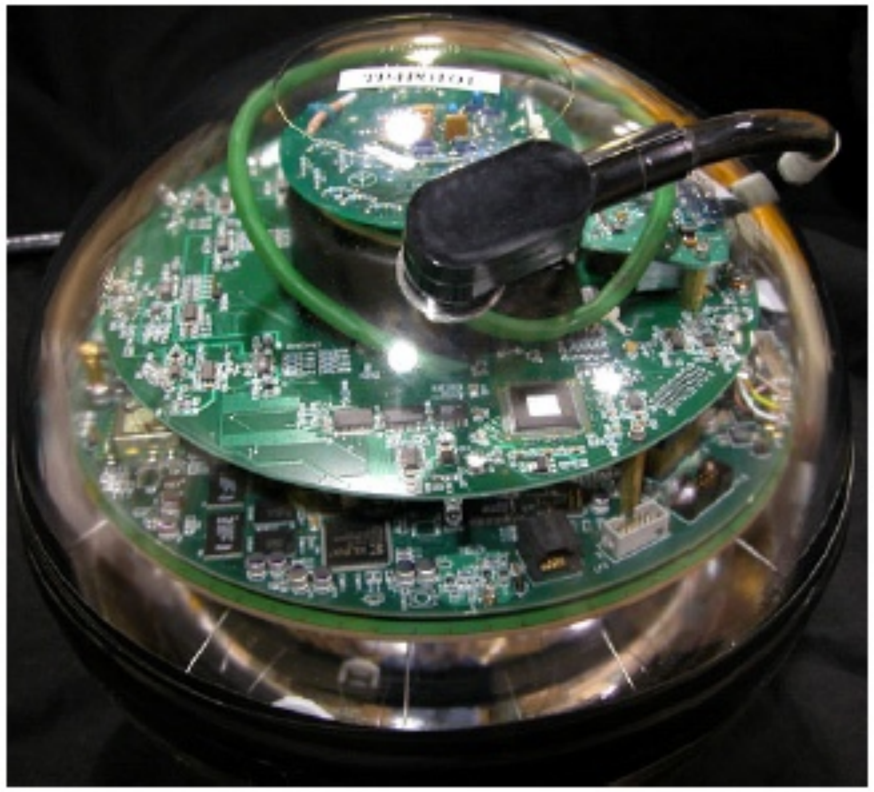
The Digital Optical Module (DOM)



IceCube Performance Parameters

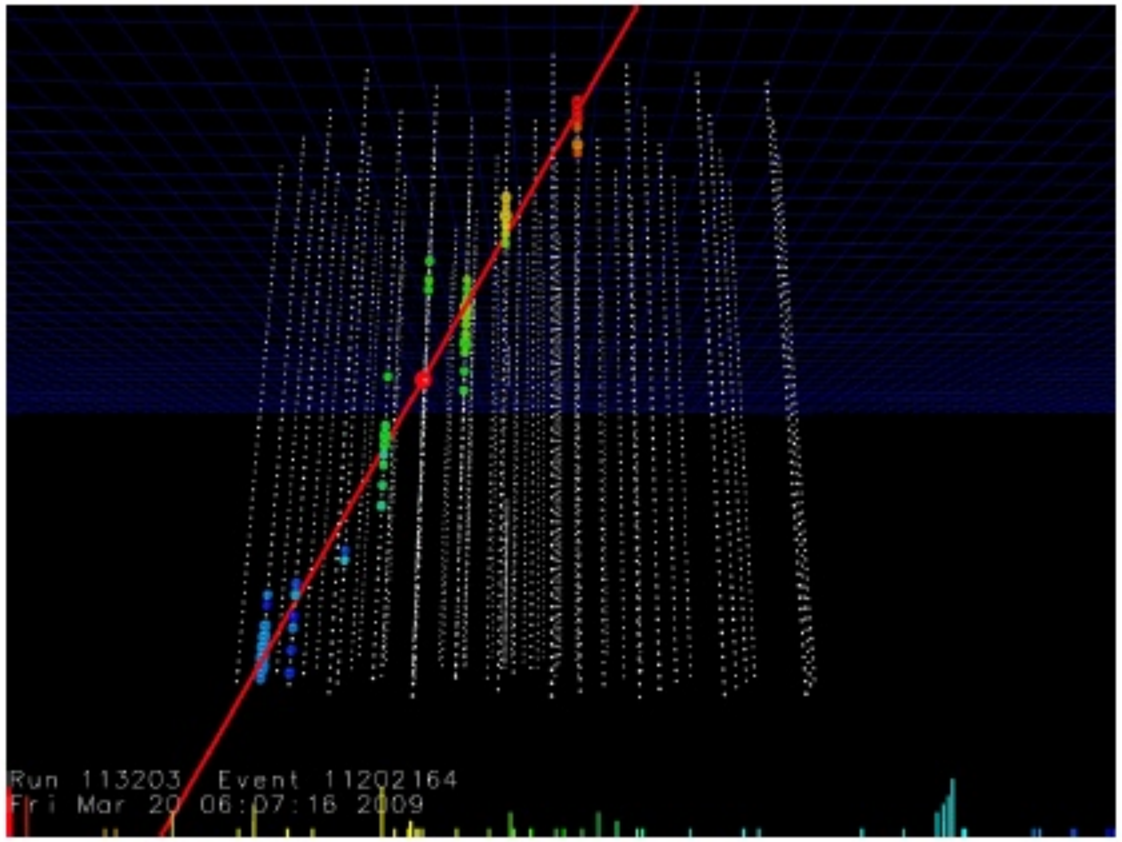
DOM Level

- time resolution
- charge response
- noise behavior
- reliability



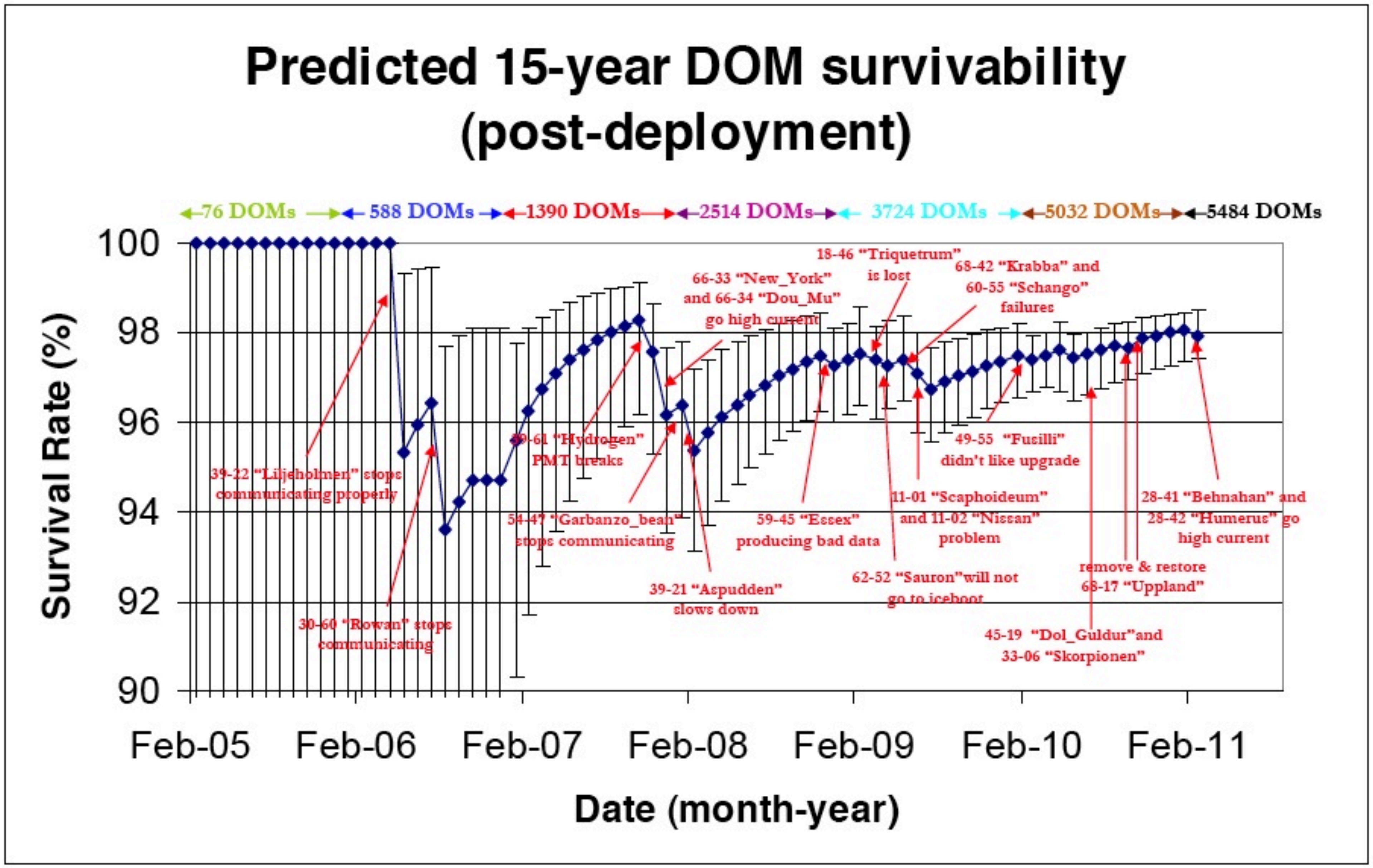
Detector level

- angular resolution
- energy resolution
- final sensitivity



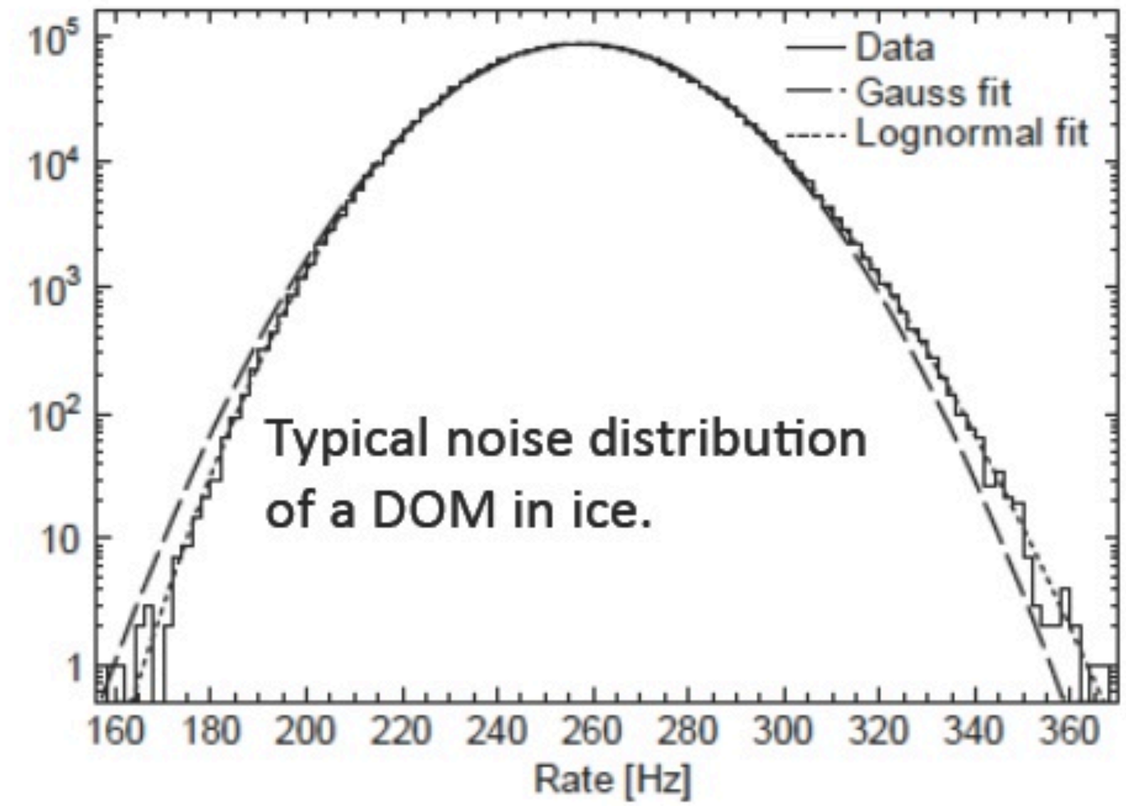
DOM Reliability

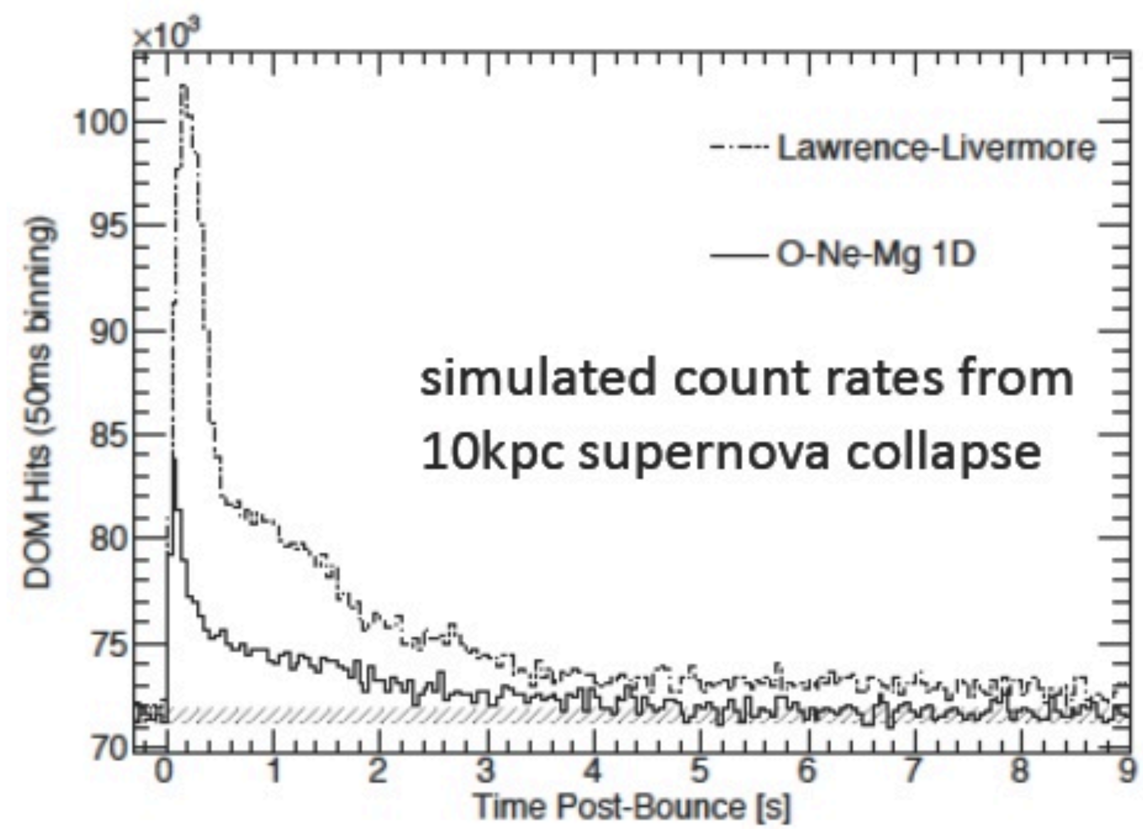
- ~14k years accumulated lifetime as of April 2011.
- 84 lost DOMs (fail commissioning) during deployments and freeze-in
- 19 lost DOMs after successful freeze-in and commissioning.



DOM Dark Noise

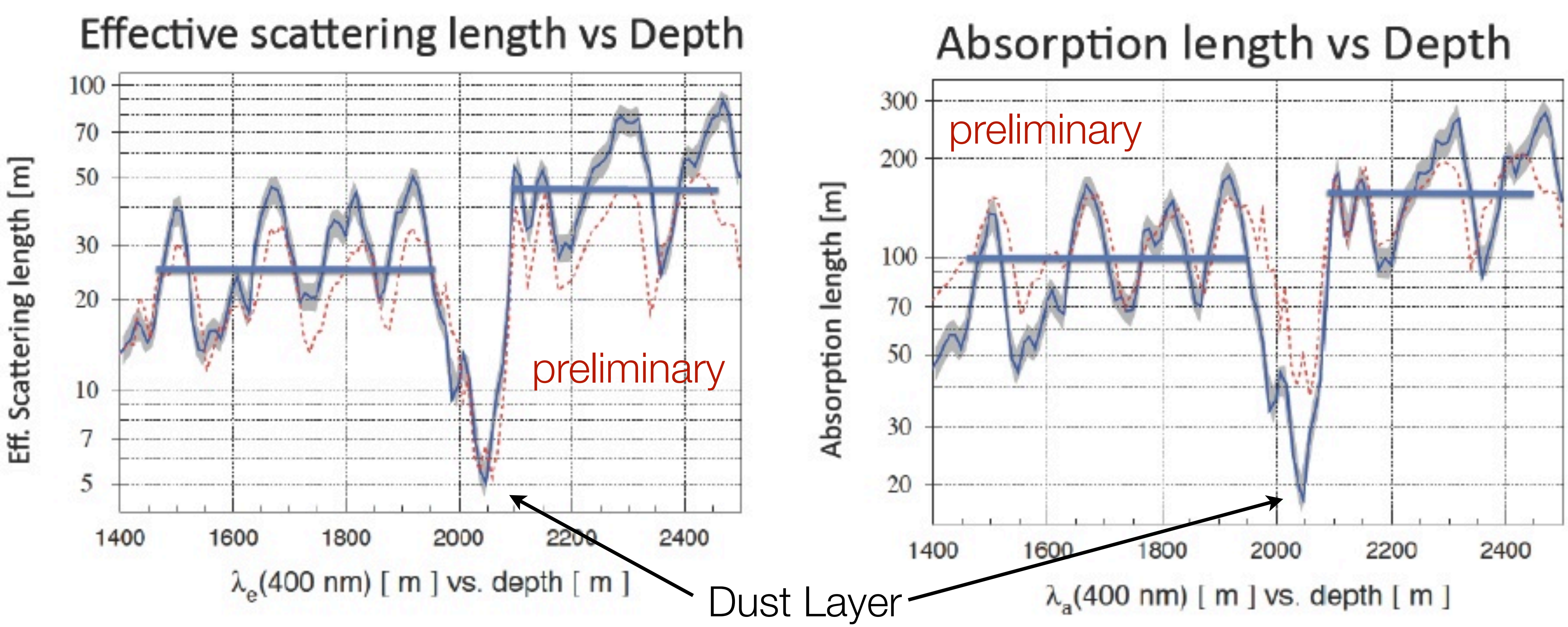
- Use of low-radioactivity glass for the pressure spheres and good PMT characteristics = very low noise rates.
- Average rate/sensor (including dead-time) = 286 Hz
- Sensor noise is stable and as expected. (Gaussian timing distribution is due to correlated hits from single DOM radioactivity and fluorescence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



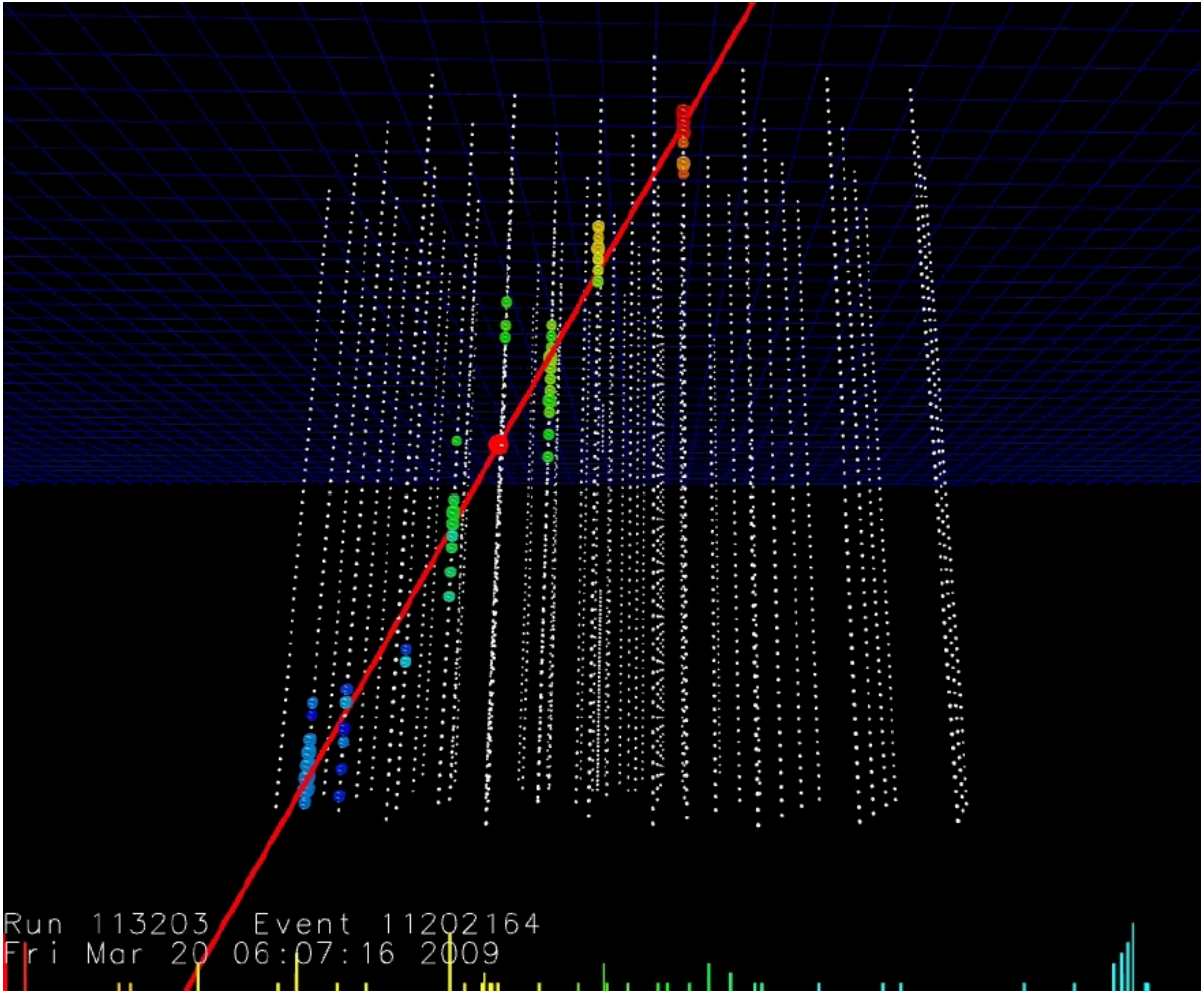


IceCube Calibrations

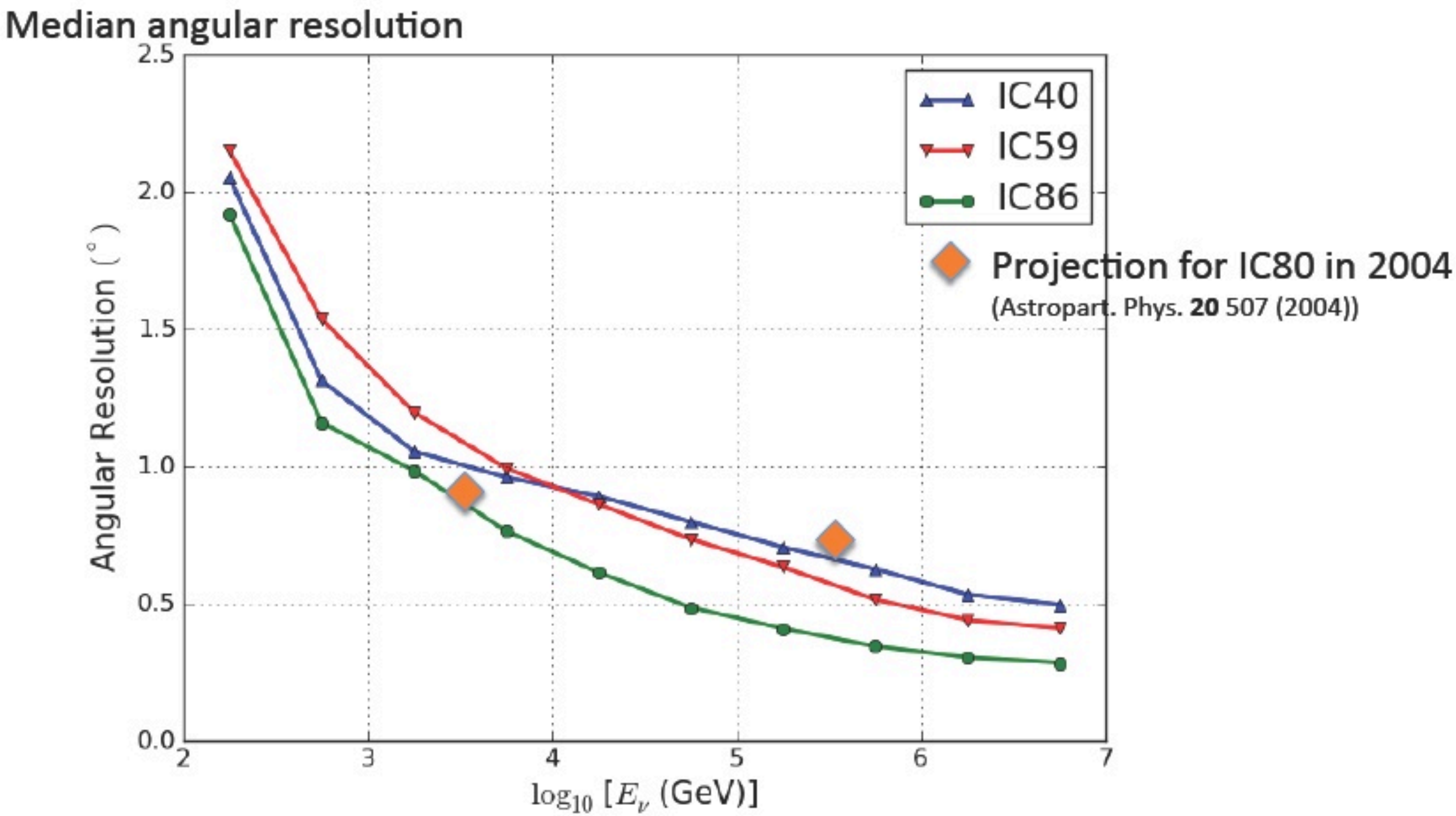
- Depth dependence of the optical properties of the ice is a challenge to analyze and the flasher measurements have been crucial in the knowledge obtained thus far.
- Special color LED DOMs were deployed and their data is being analyzed to provide multi-wavelength ice calibration.
- The deepest ice, below 2100 m, has better properties than expected making it an excellent medium for particle detection.



IceCube Detector Performance



IceCube Detector Performance - Angular Resolution



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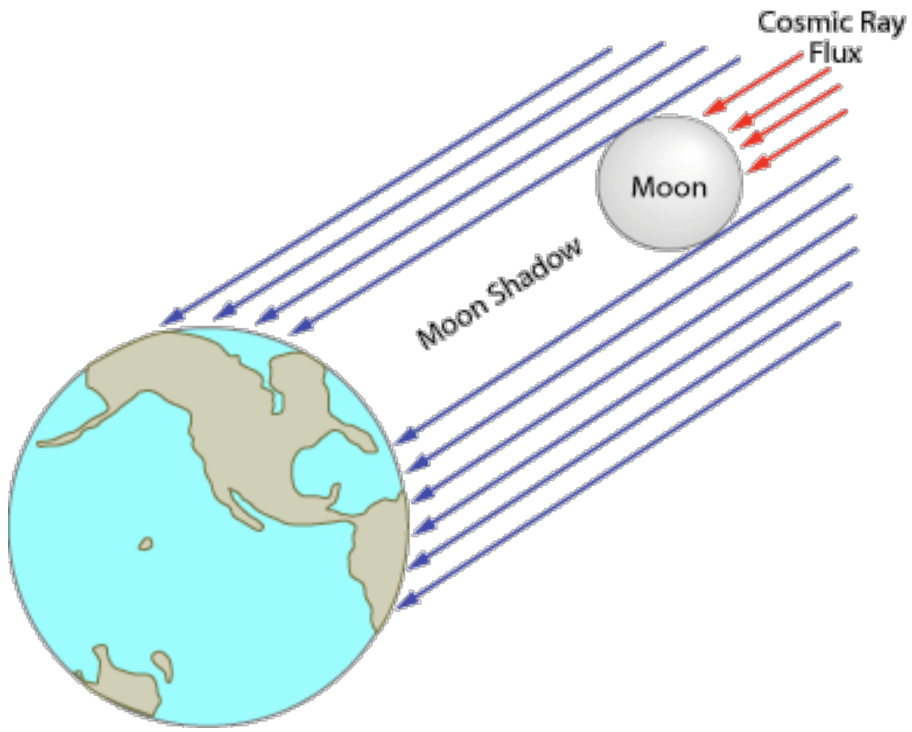
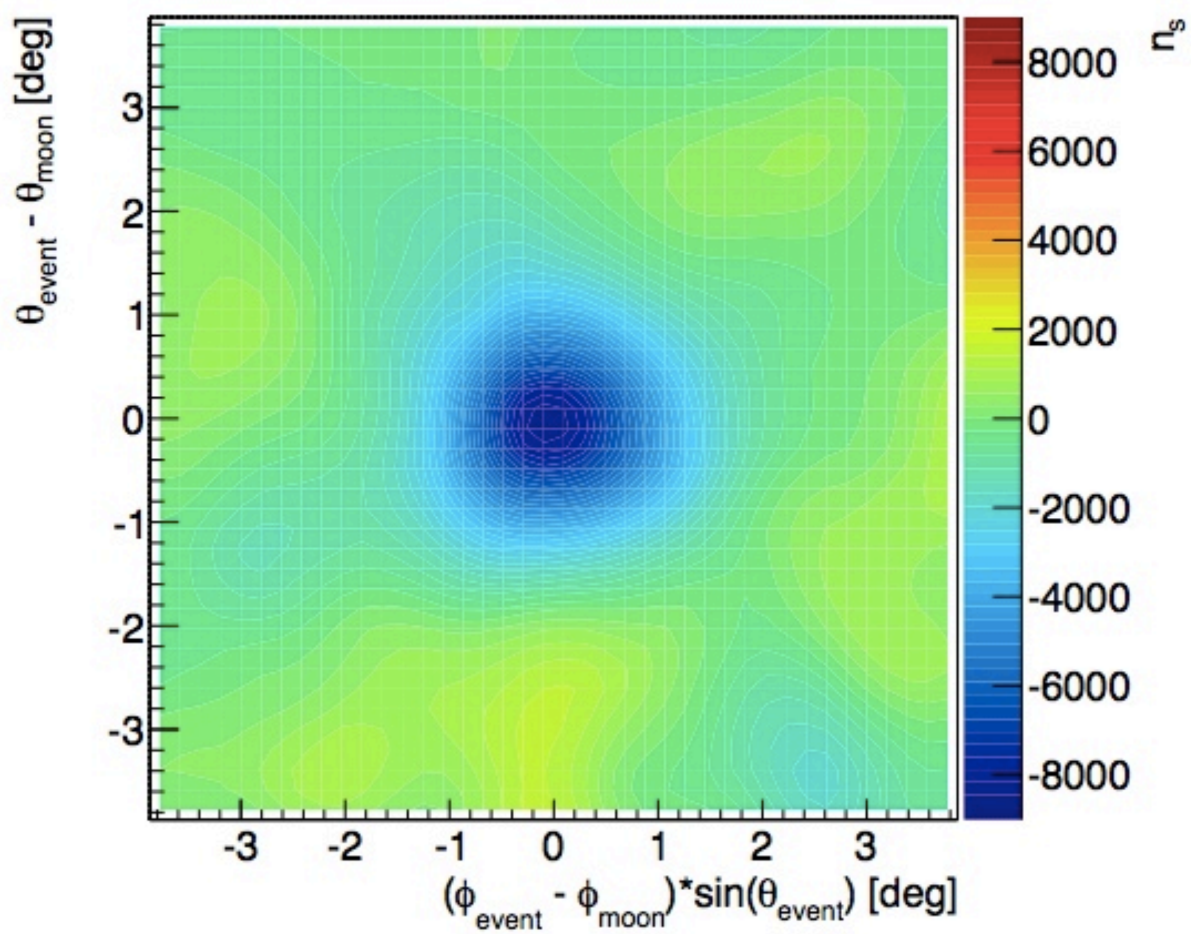
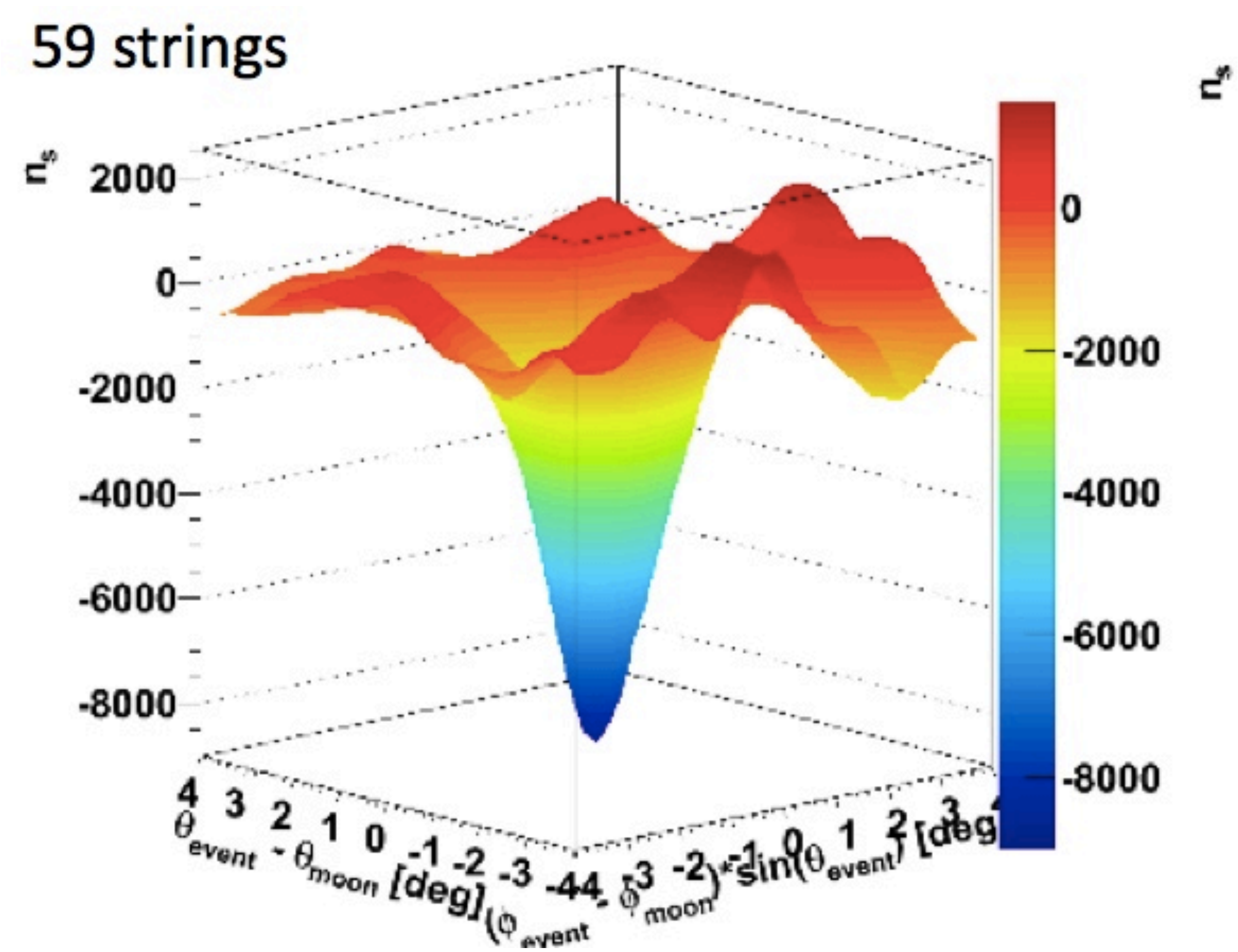


Existence of the moon - confirmed!

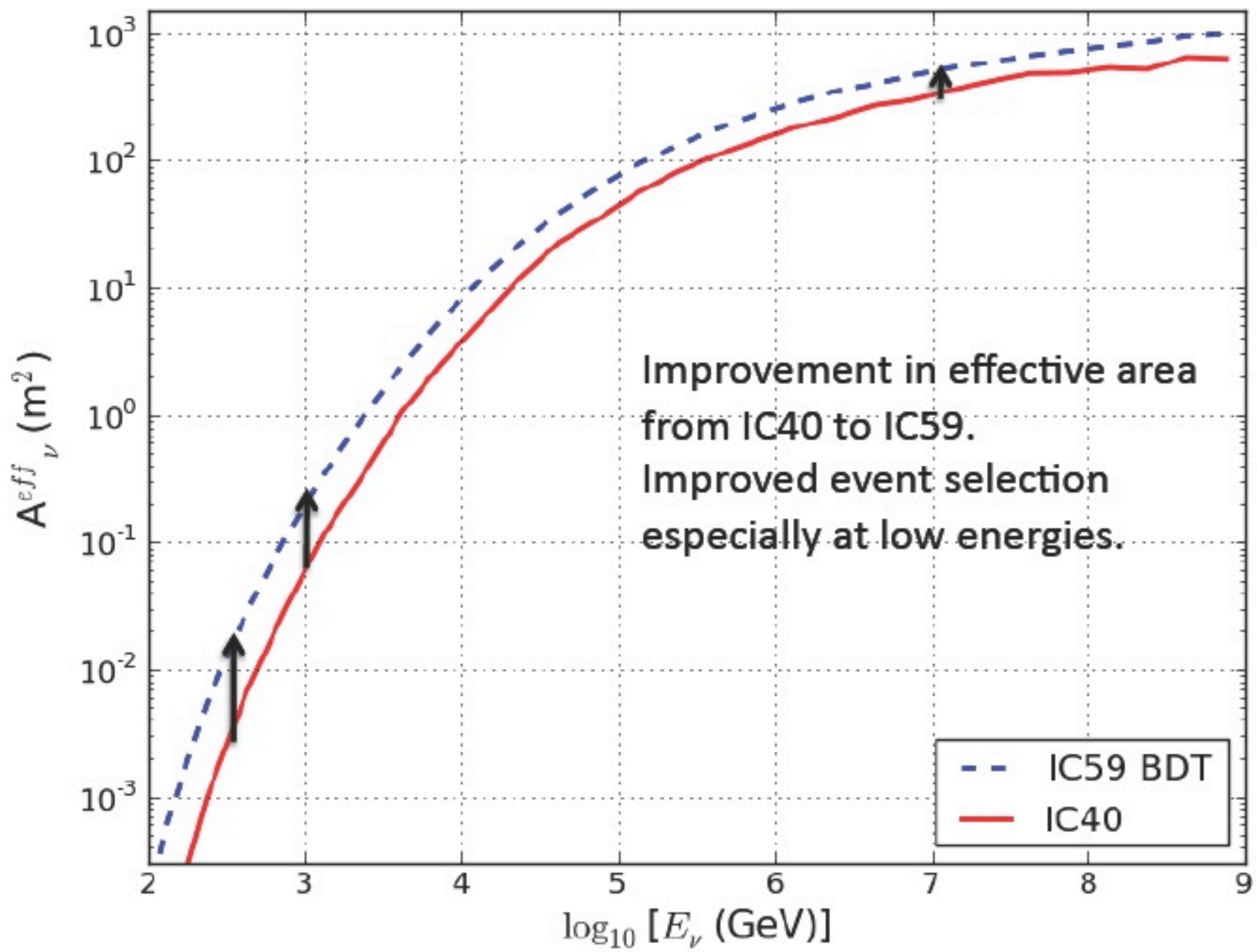
- Likelihood analysis determines deficit of events from direction of moon in the IceCube 59-string detector confirms pointing accuracy.
- Validates pointing capabilities with expected angular resolution for IceCube 80-string detector $<1^{\circ}$ at 1 TeV.



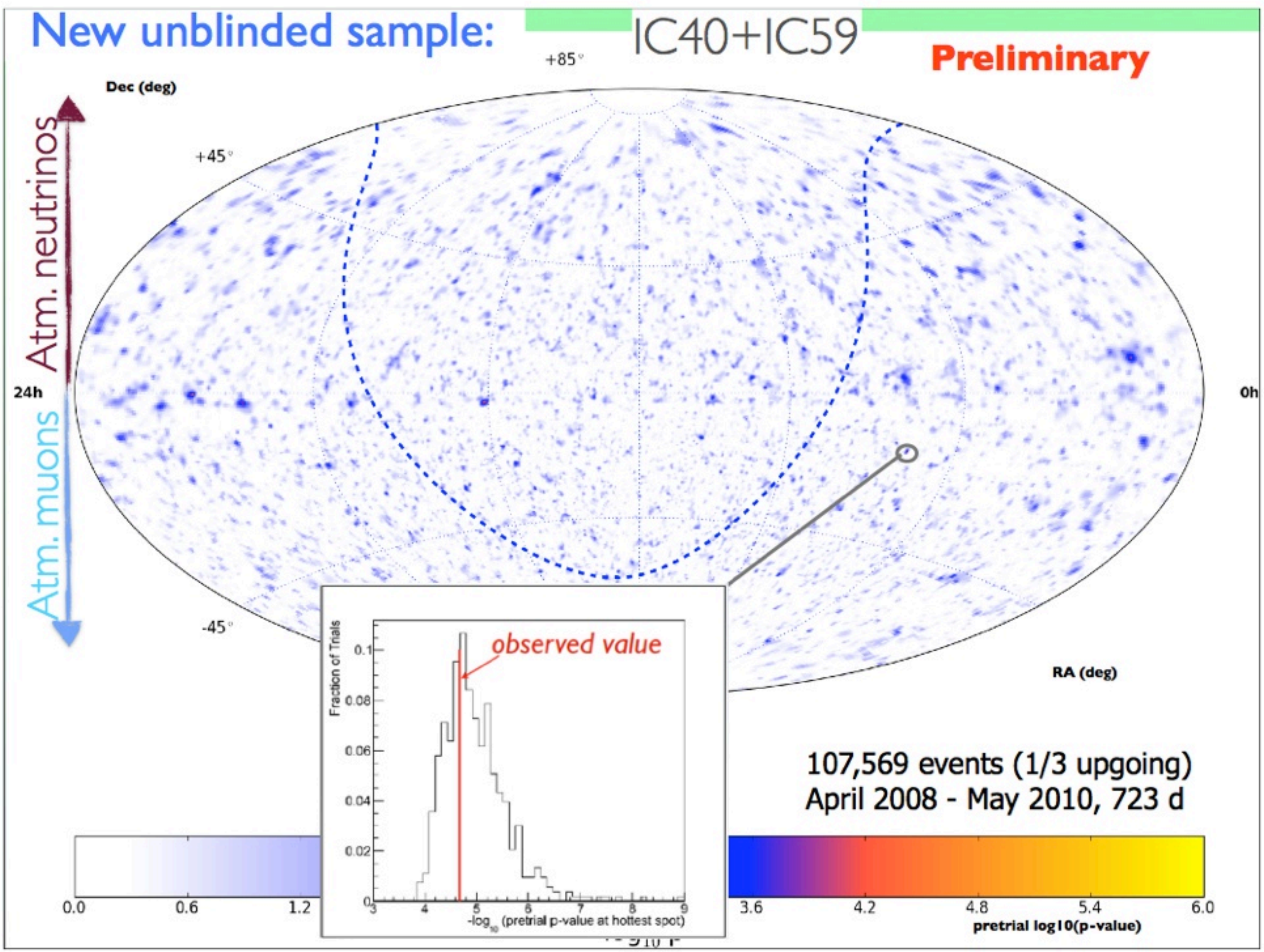


IceCube Detector Performance - Effective Neutrino Area

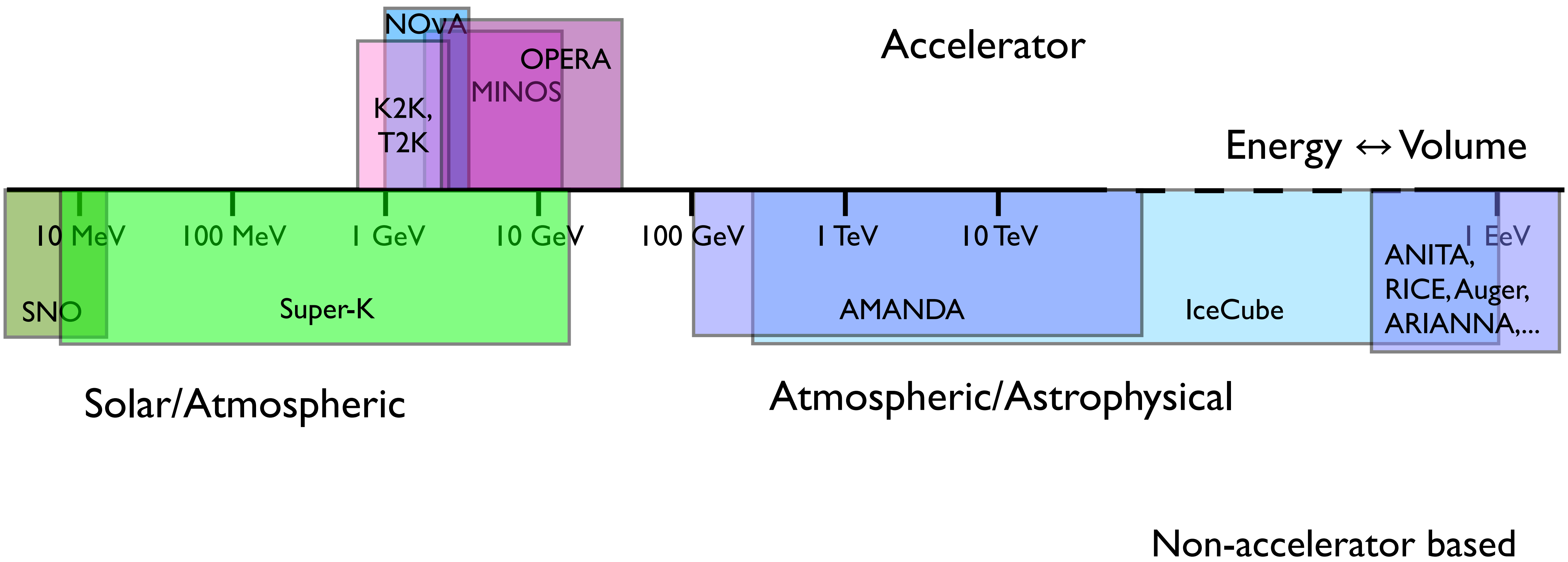
- The detector performance parameters increase faster than the number of strings
- This is an effect of longer muon tracks providing improved angular resolution (lever arm) and energy reconstruction.
- Improved analysis techniques and new ideas (data quality, detector modeling, background simulations)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



Most Recently from IceCube...



The Neutrino Detector Spectrum



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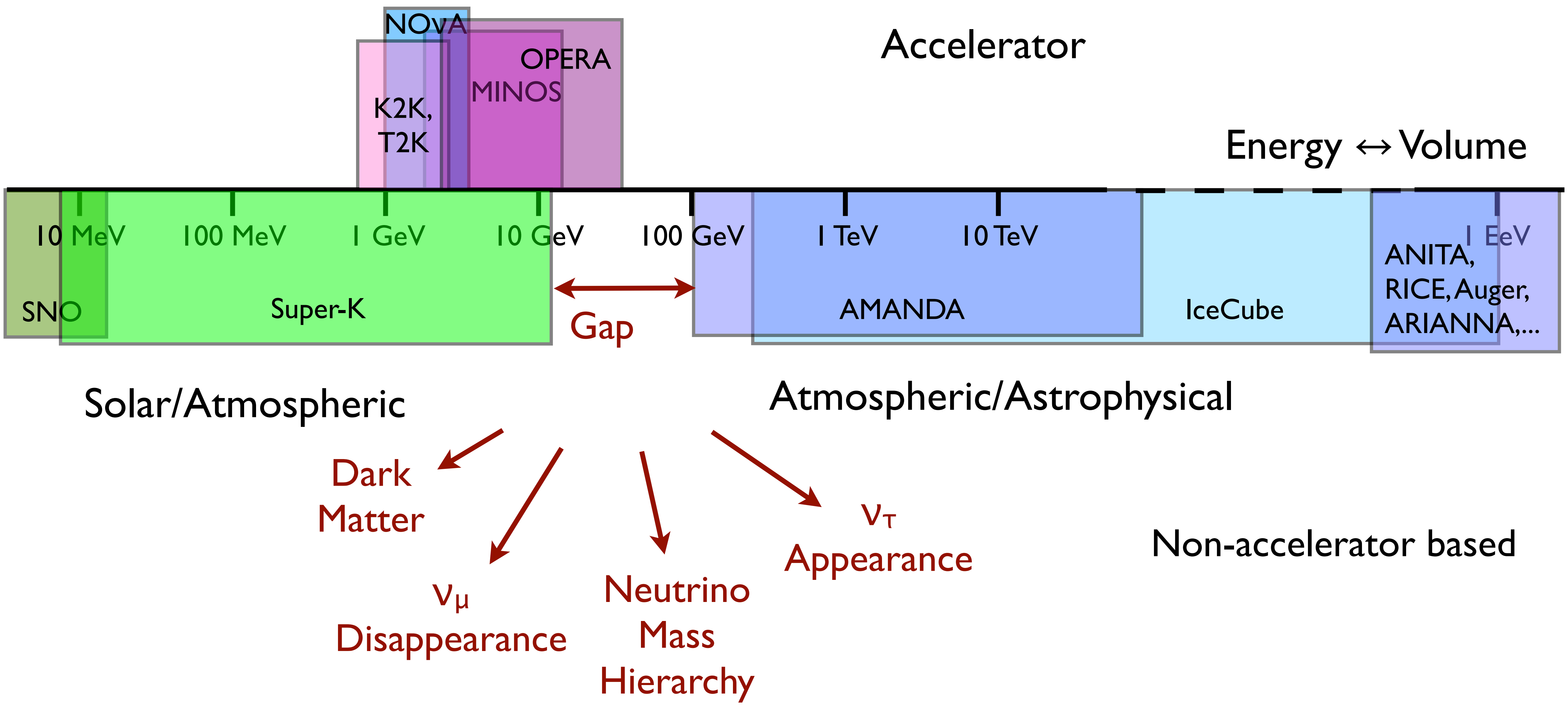

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IceCube

IceCube

IceCube

IceCube

IceCube-DeepCore

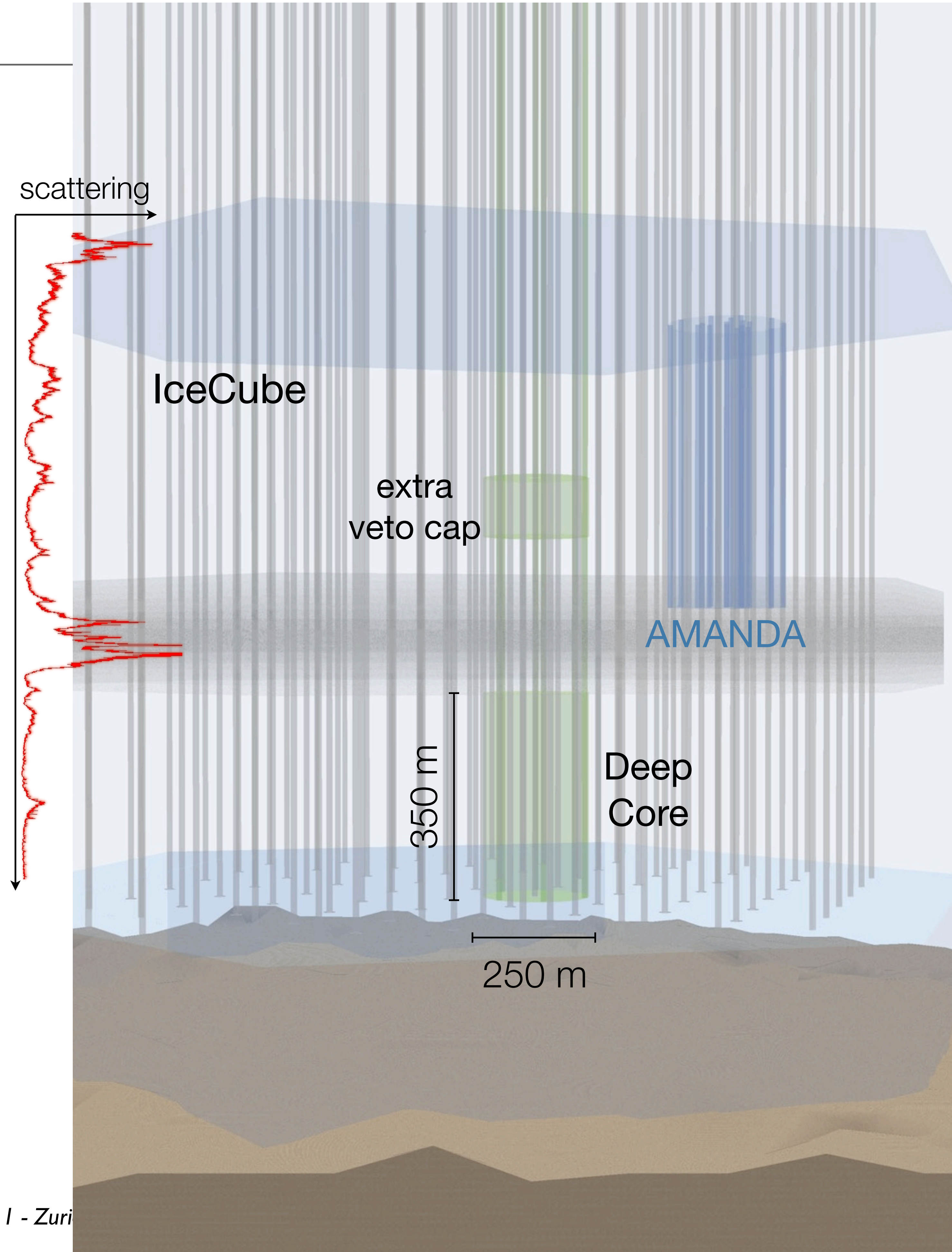
IceCube DeepCore

IceCube-DeepCore

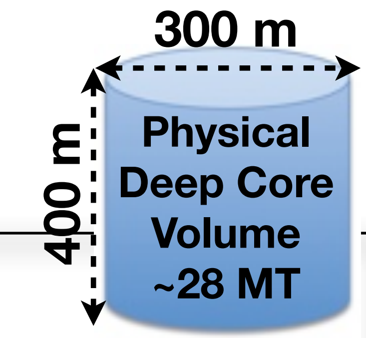
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
  - Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Scientific Motivations:
  - Indirect search for dark matter
  - Neutrino oscillations (e.g., ν_τ appearance)
  - Neutrino point 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(100k) physics quality atmospheric ν/yr

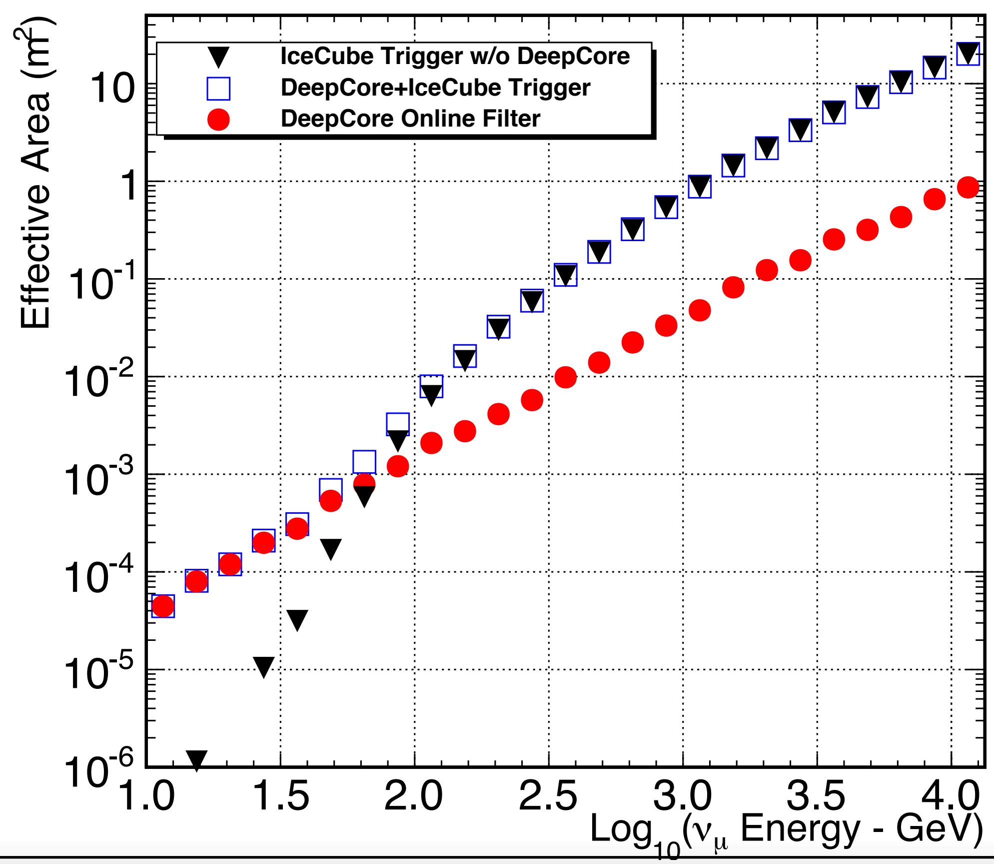


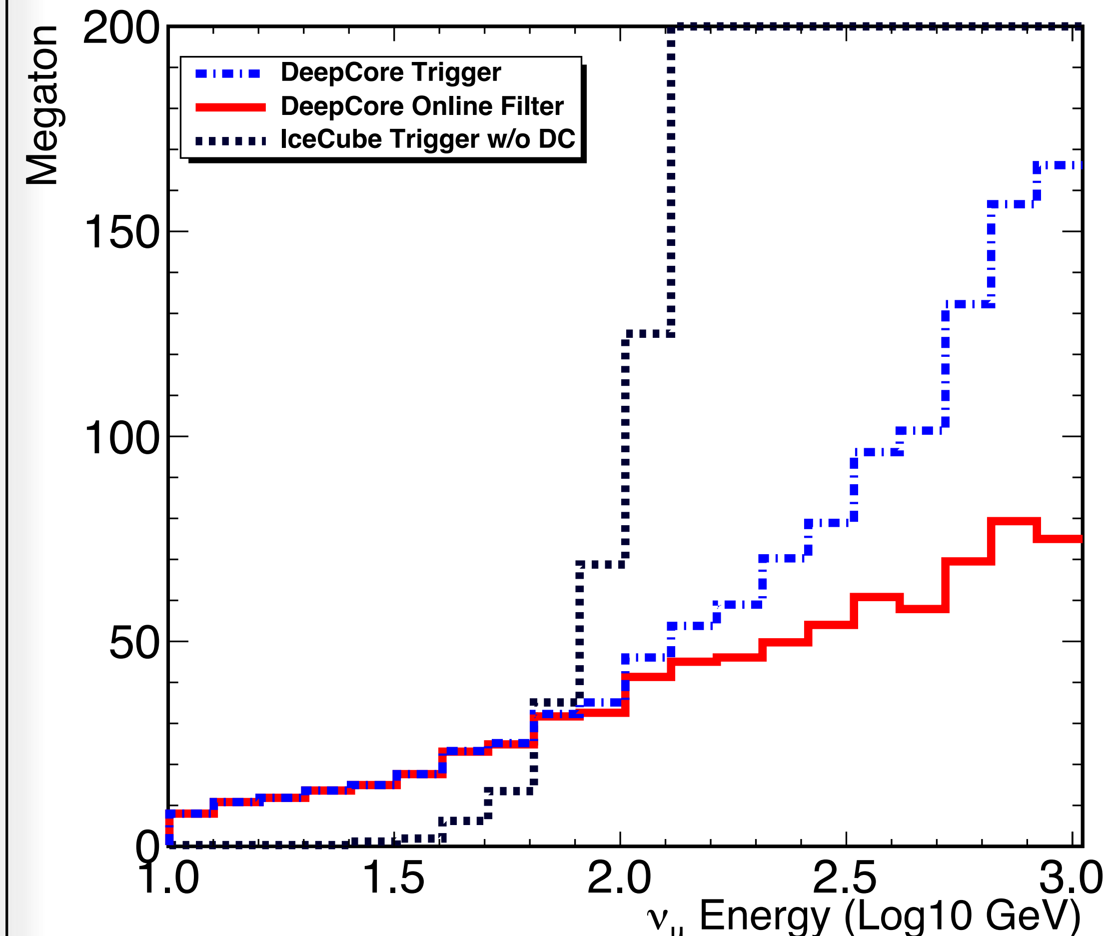
DeepCore Effective Area and Volume



Effective area for ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase





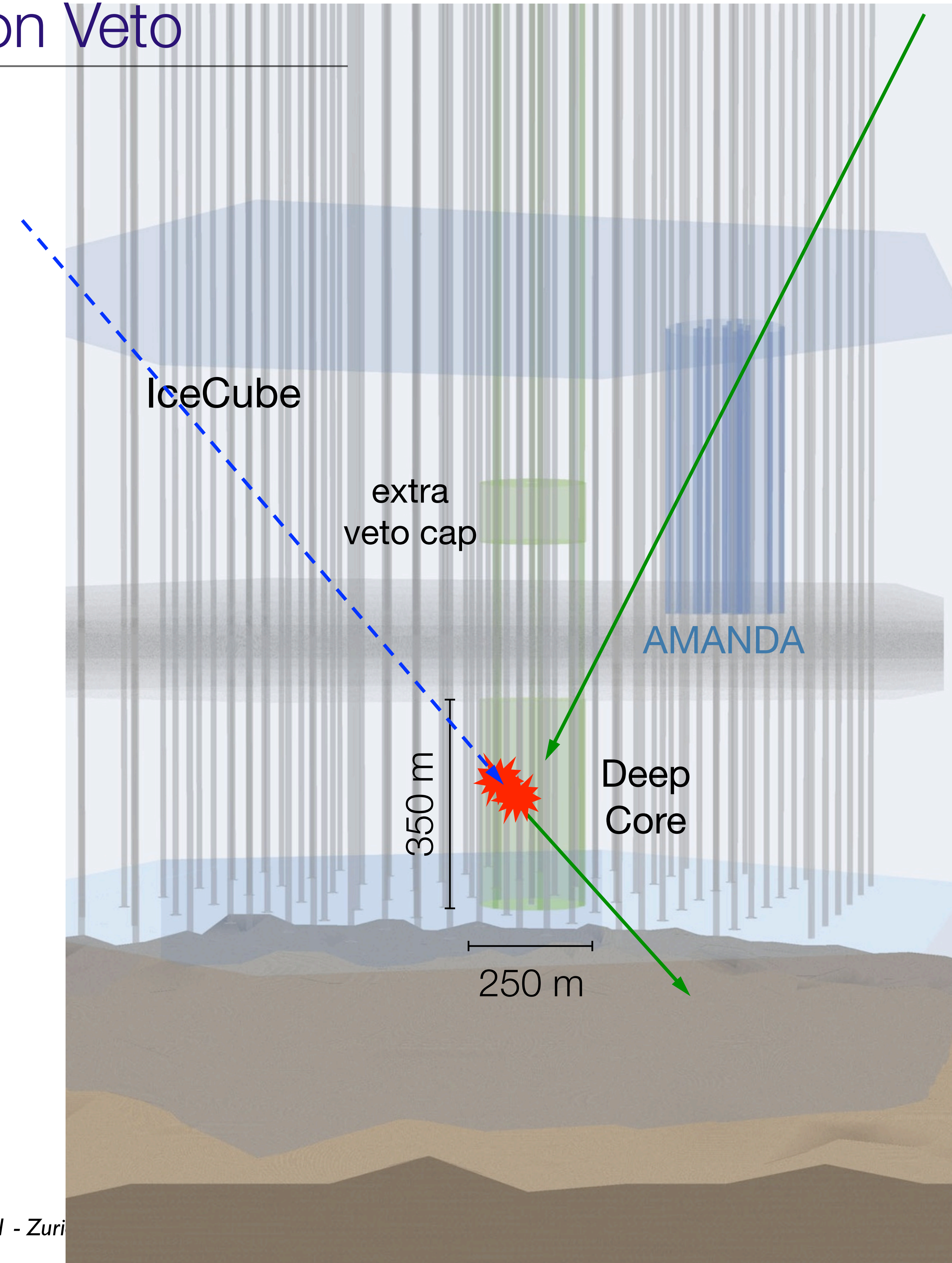
Effective volume for muons from ν_μ interacting in Deep Core

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

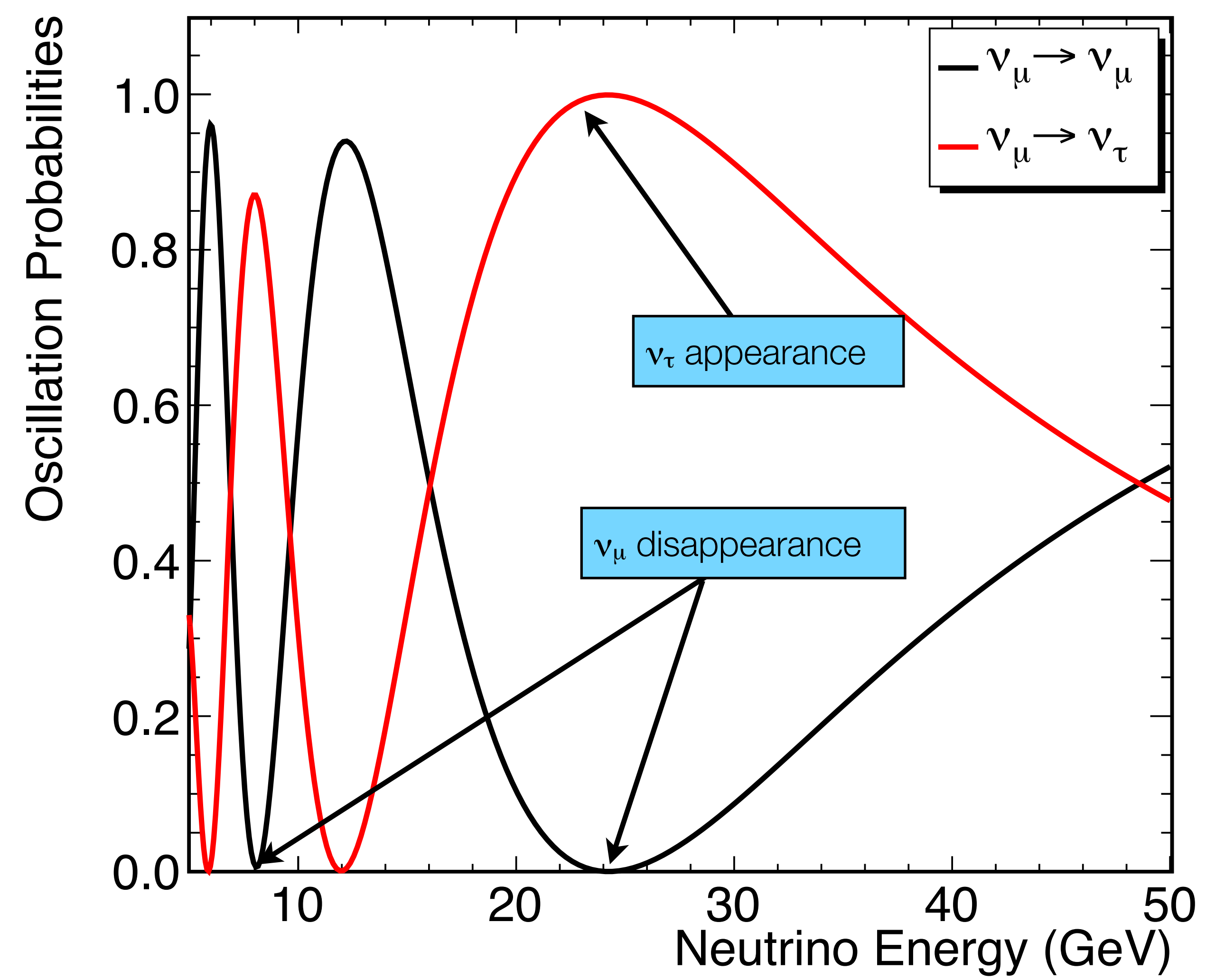
- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
- 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



Observation of Atmospheric Cascades

- Disappearing ν_μ should appear in IceCube as ν_τ cascades
  - Effectively identical to neutral current or ν_e CC events
  - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background
- First results from DeepCore are neutrino cascade events
  - The dominant background now is CC ν_μ events with short tracks

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



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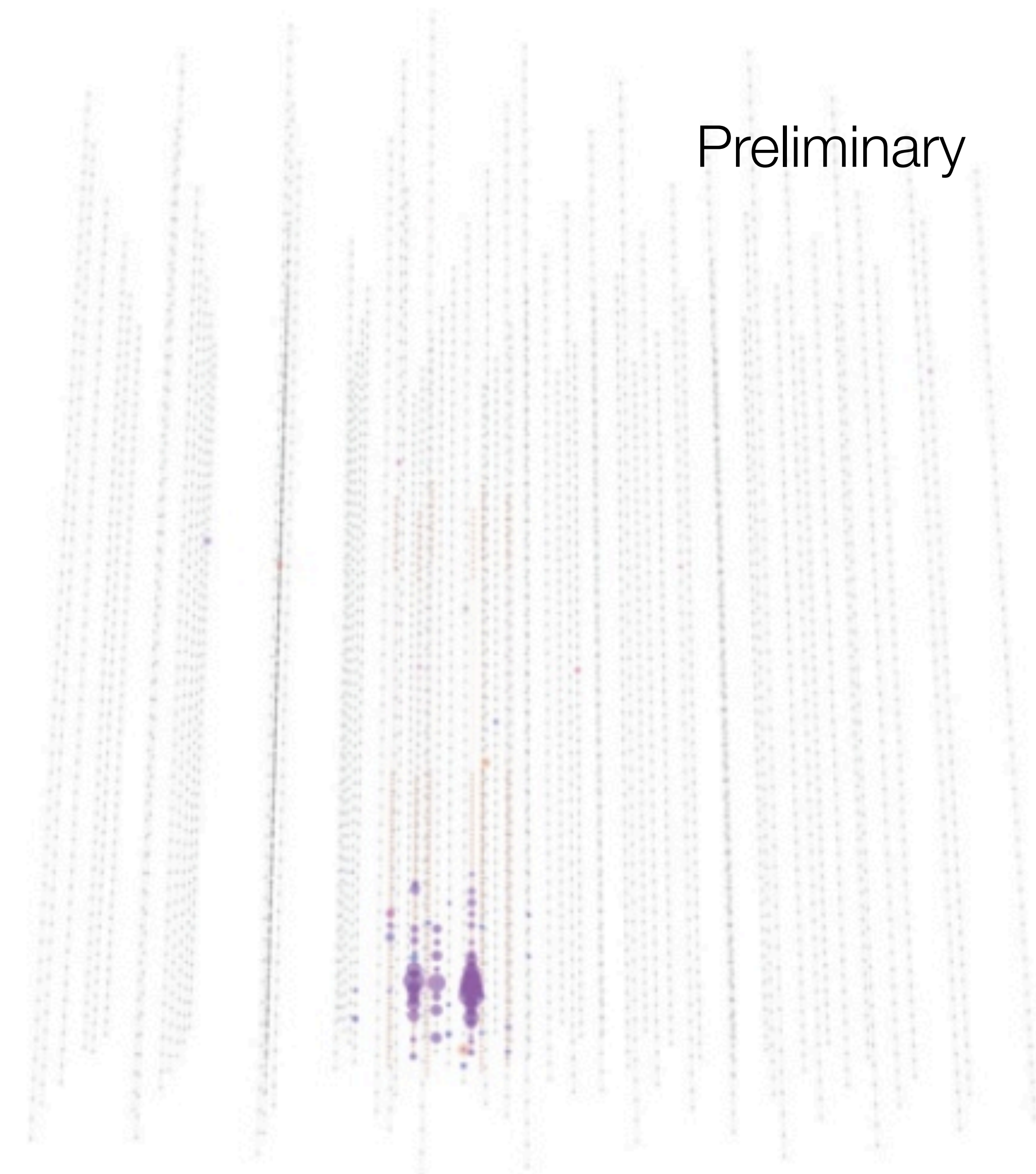


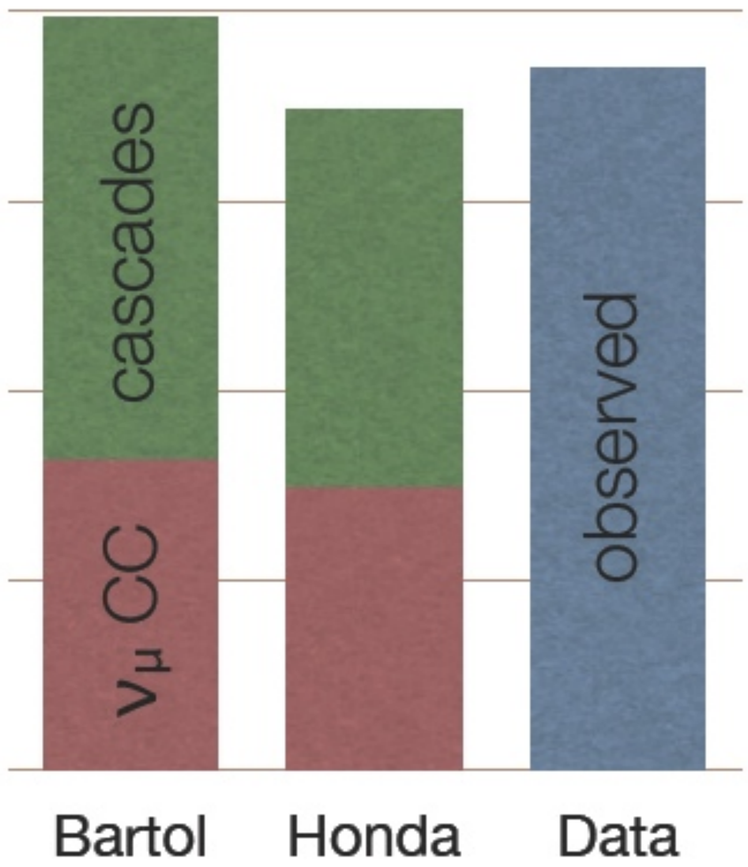
Candidate cascade event
Run 116020, Event 20788565, 2010/06/06

Observation of Atmospheric Cascades

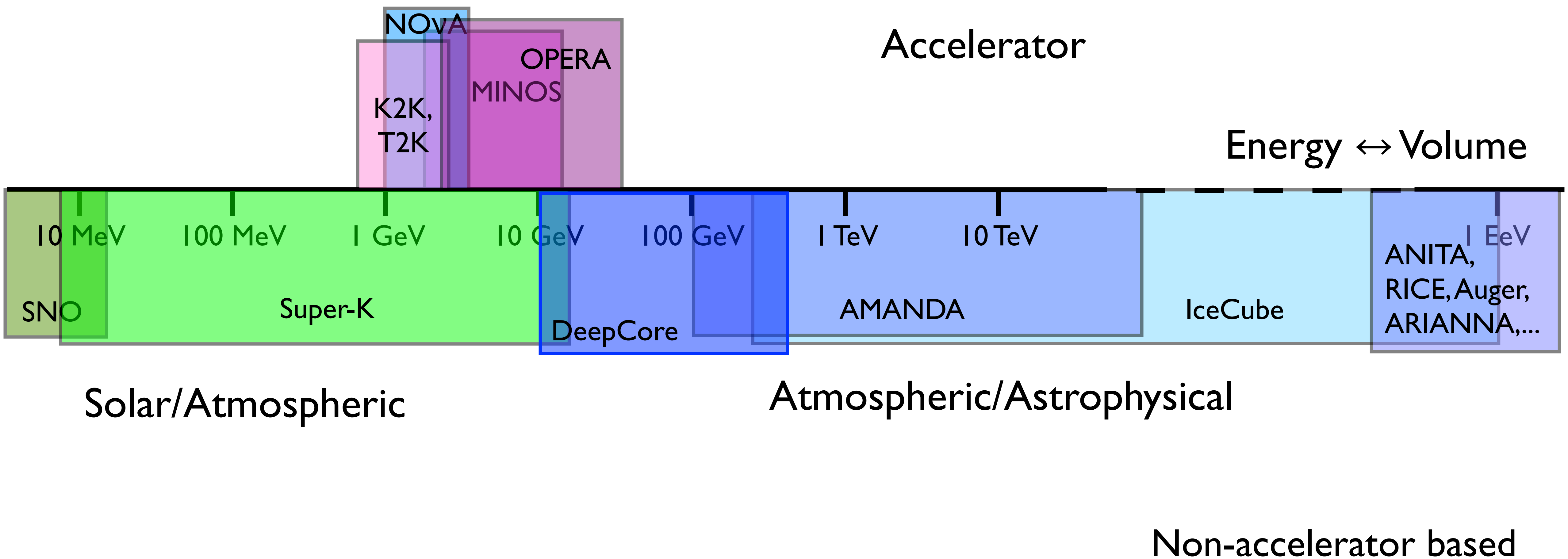
- A substantial sample of cascades has been obtained, final data set ~60% cascade events
  - Events have a mean energy ~180 GeV (not sensitive to oscillations with these first cuts)
  - Atmospheric muon background is being assessed (expected to be small)
- The potential to discriminate between atmospheric neutrino models exists and thus measuring air shower physics

preliminary!

	Cascades	CC ν_μ	Total
Bartol	650	454	1104
Honda	551	415	966
Data			1029



The Neutrino Detector Spectrum



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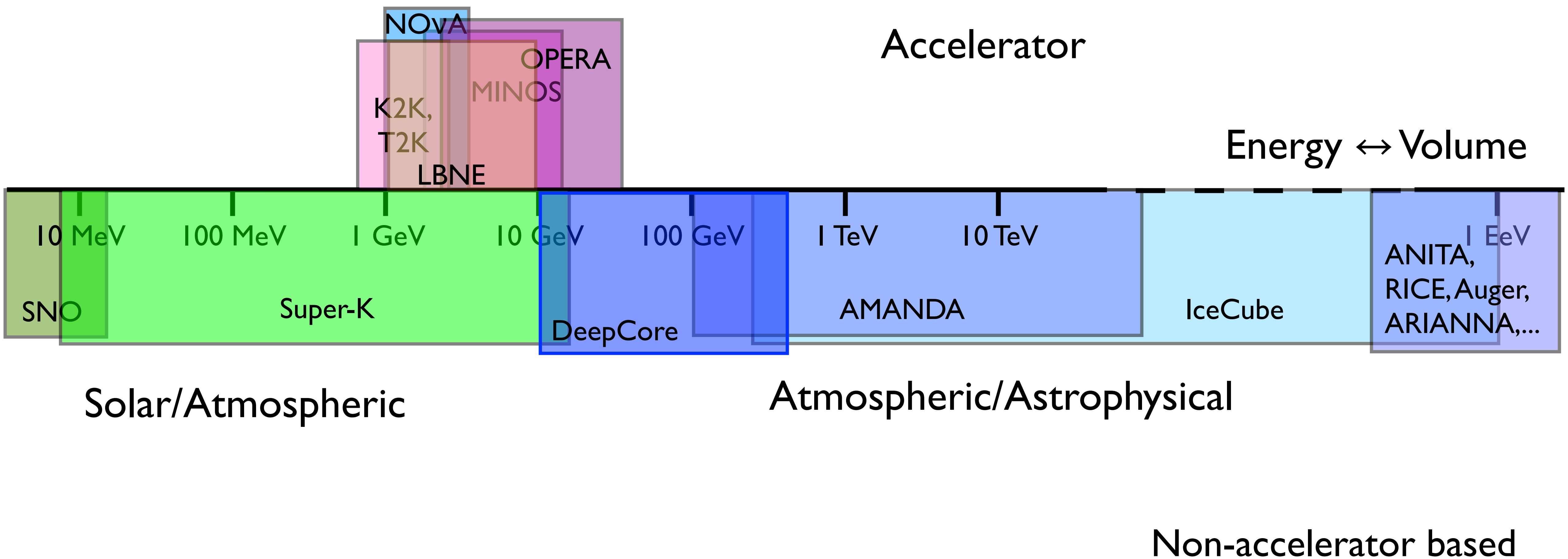


The underground community is preparing programs for large-scale detectors O(300 kT),with physics focused on long-baseline neutrinos, toward O(1MT), proton decay, supernova neutrinos.

Construction/Purification of the facilities for these detectors remain technological challenges of engineering.

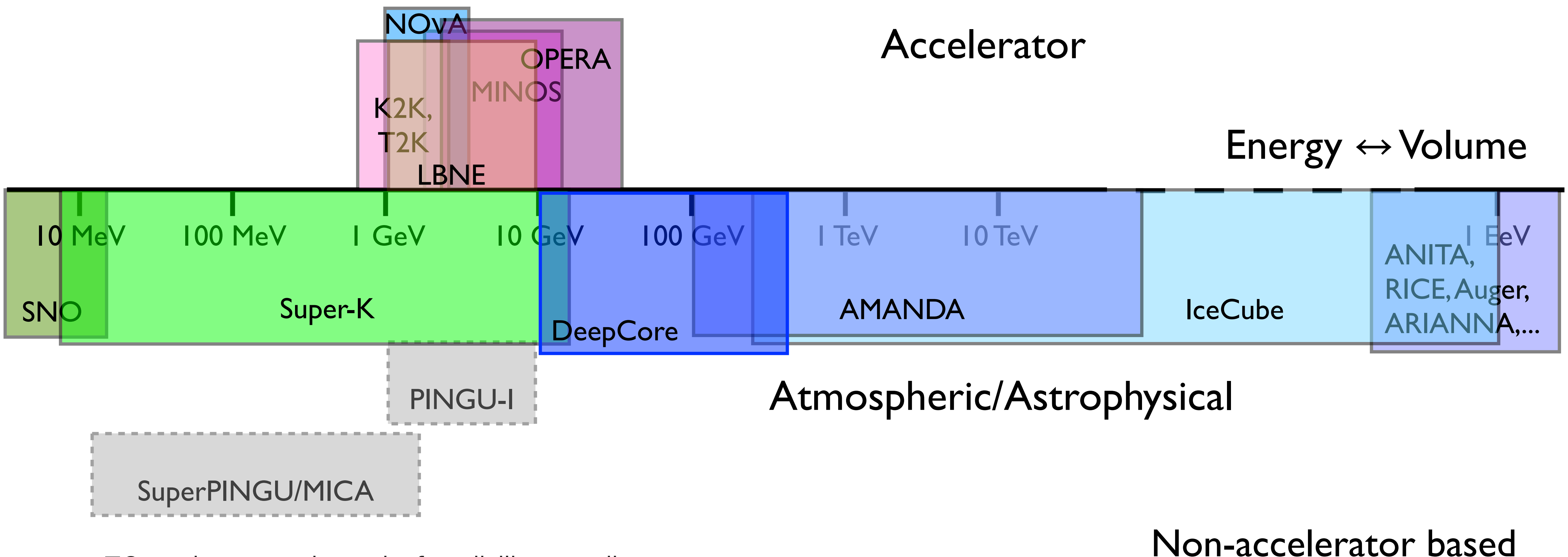
IceCube-DeepCore

IceCube-DeepCore

IceCube-DeepCore-PINGU

IceCube DeepCore PINGU

PINGU - Phased IceCube Next Generation Upgrade



~70 active members in feasibility studies:

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

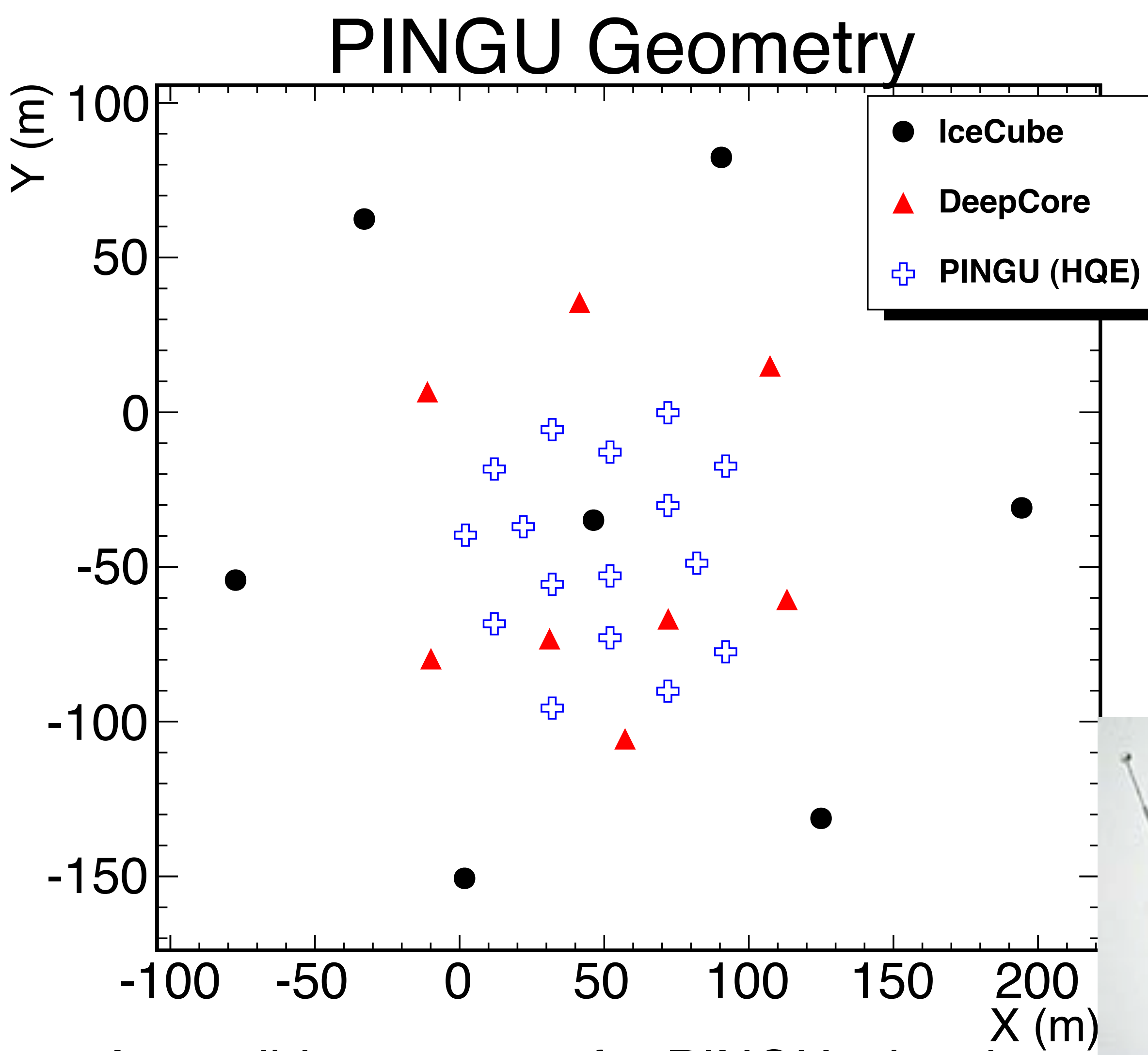
PINGU - Possible detector configurations

- 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

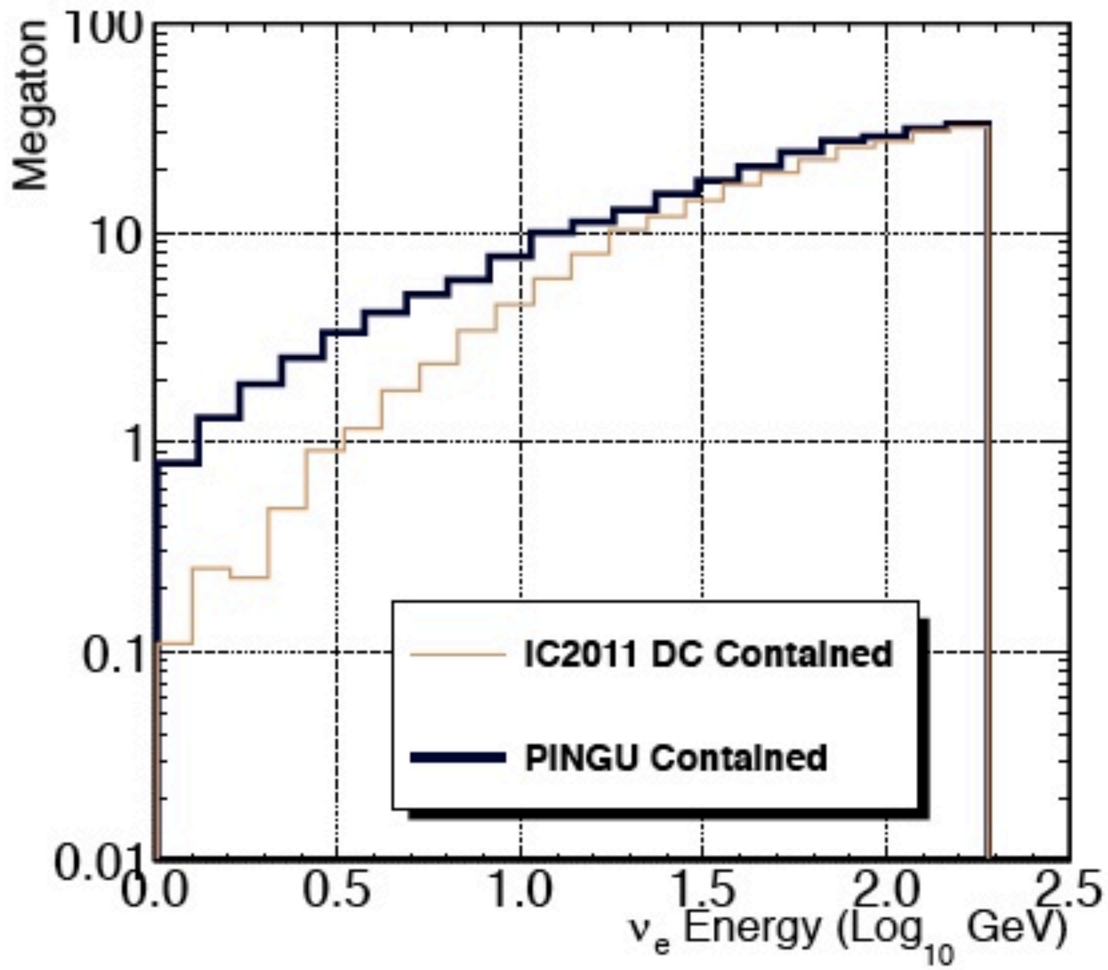
- Could continue to fill in the DeepCore volume
  - E.g., an additional 18-20 strings (~1000 DOMs) in the 30 MTon DeepCore volume
  - Could reach O(GeV) threshold in inner 10 MTon volume

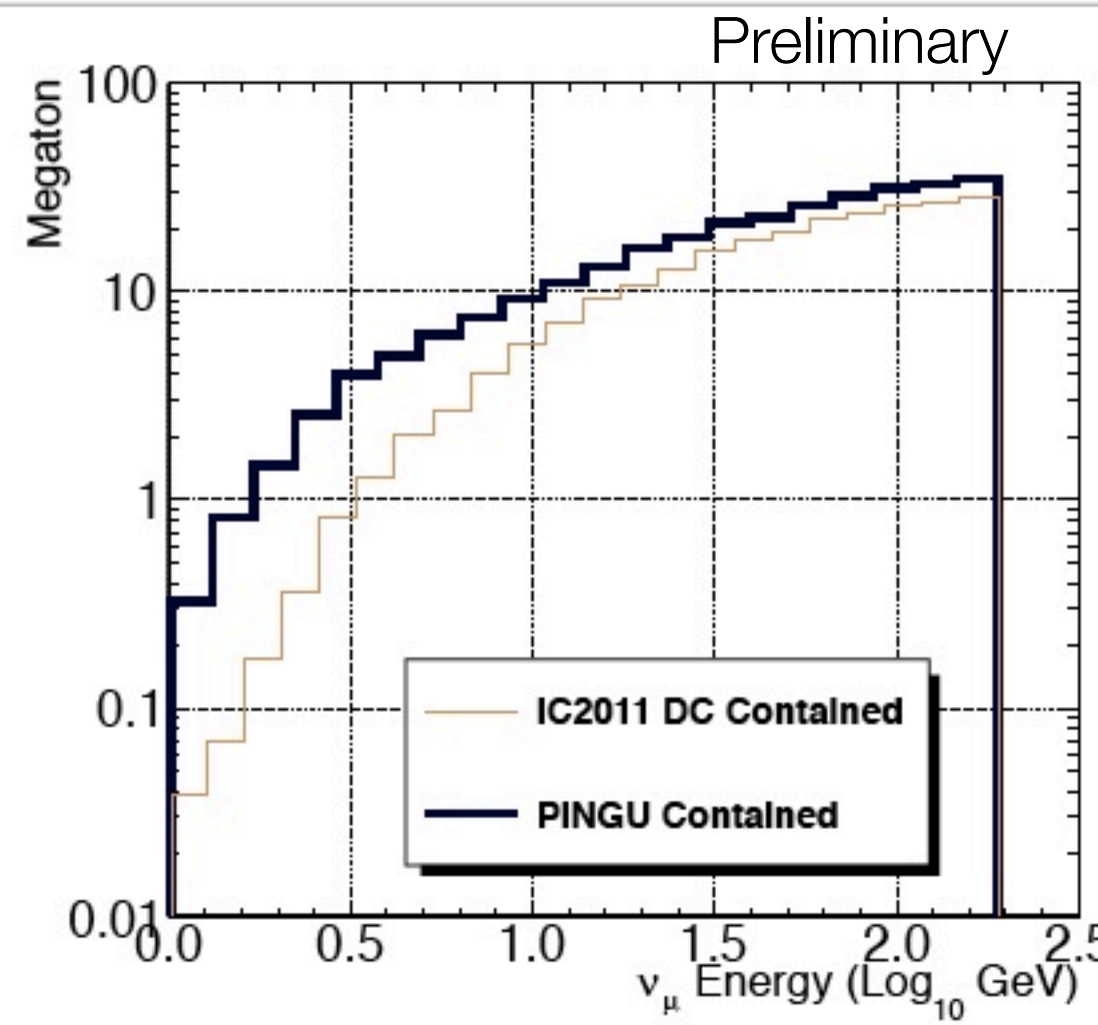


Aardman Animations

- Price tag would likely be around $25M

PINGU-I: Effective Volumes

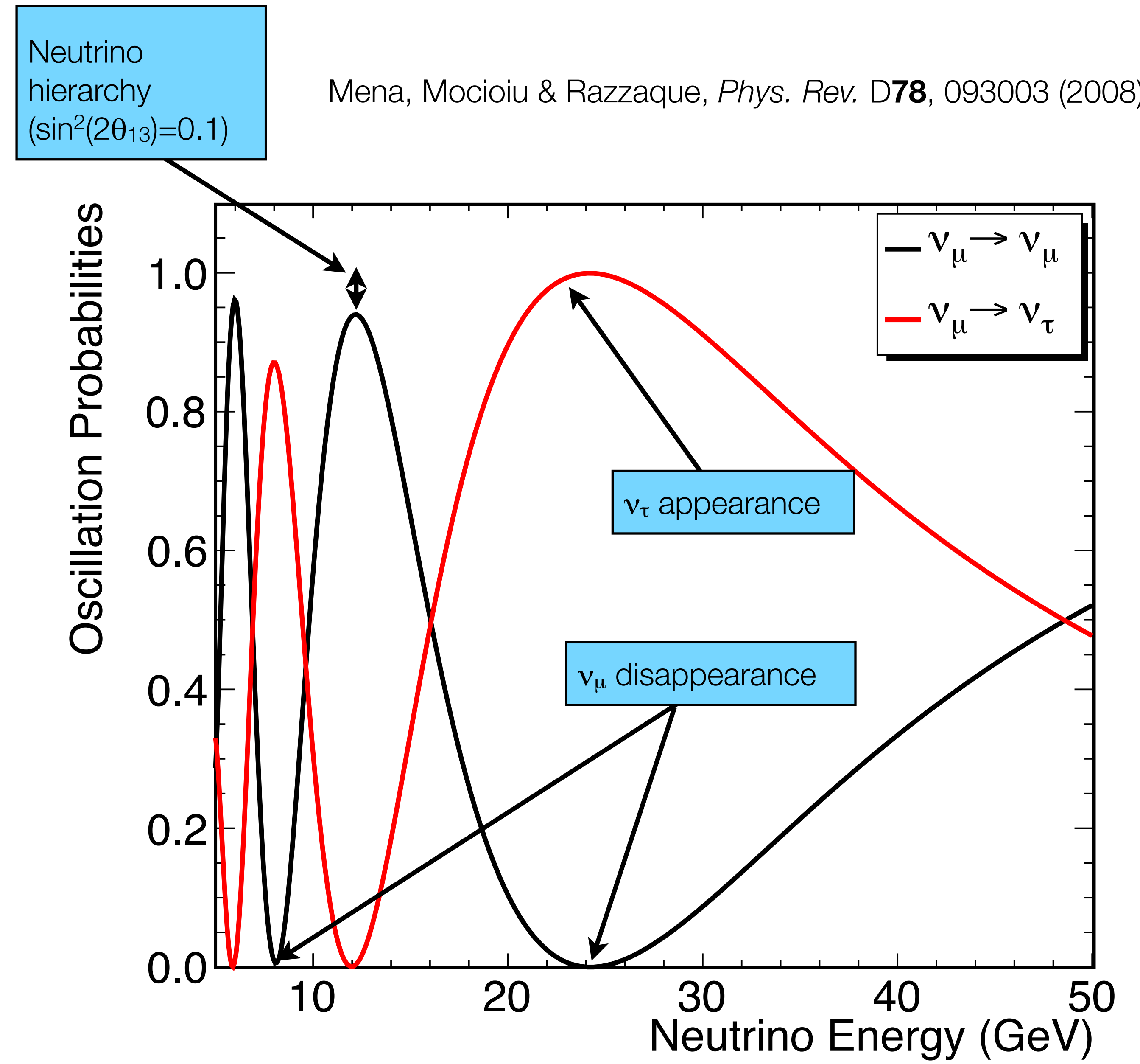




- Increased effective volume for energies below ~15 GeV
- Nearly and order of magnitude increase at 1 GeV (100s of kTon)
- Expected improvement over DeepCore > 10x despite above does not yet include analysis efficiencies

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

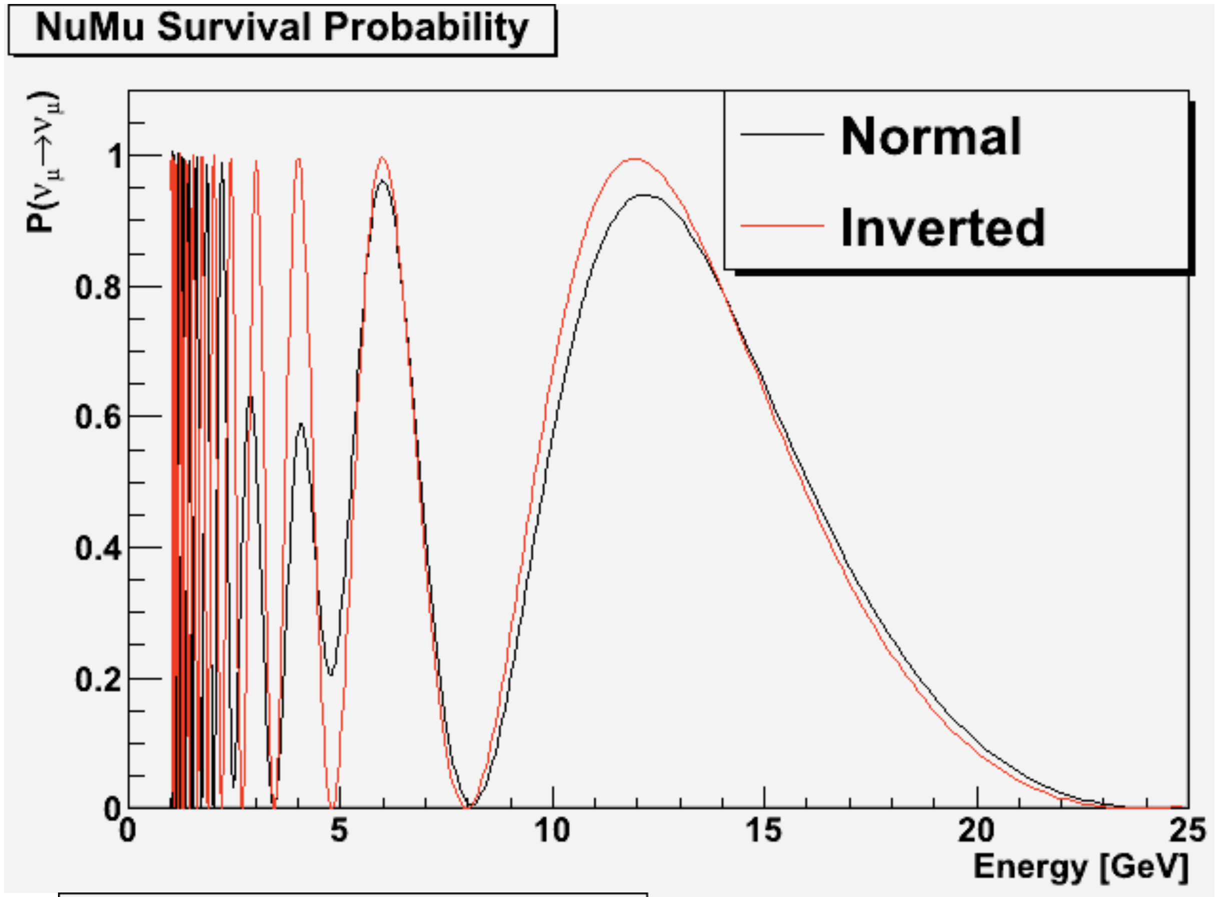


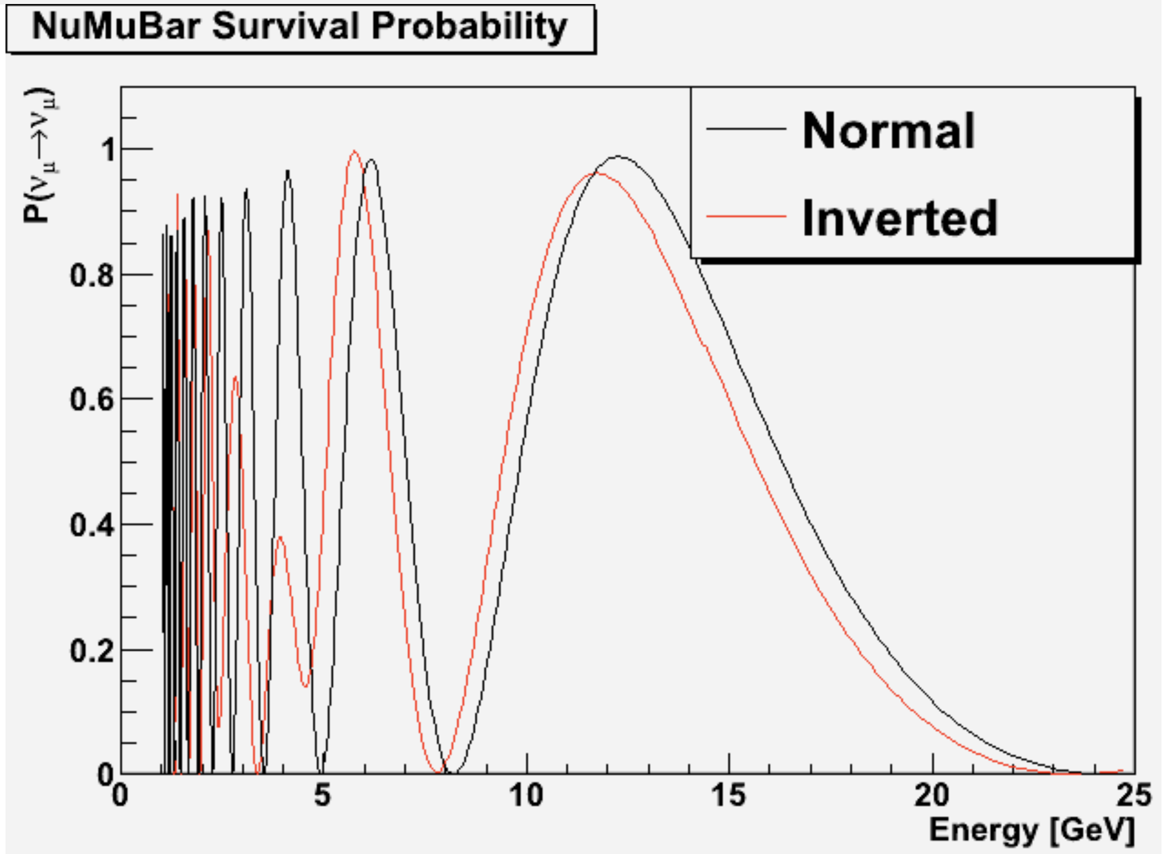
PINGU-I Neutrino Mass Hierarchy

Possible sensitivity to neutrino mass hierarchy via matter effects if θ_{13} is large

- Exploit asymmetries in the neutrino/anti-neutrino cross section, kinematics
- Effect is largest at energies below 5 GeV (for Earth diameter baseline)
- Control of systematics will be crucial

Recent results suggest that nature may be kind and provide a sufficiently large θ_{13}





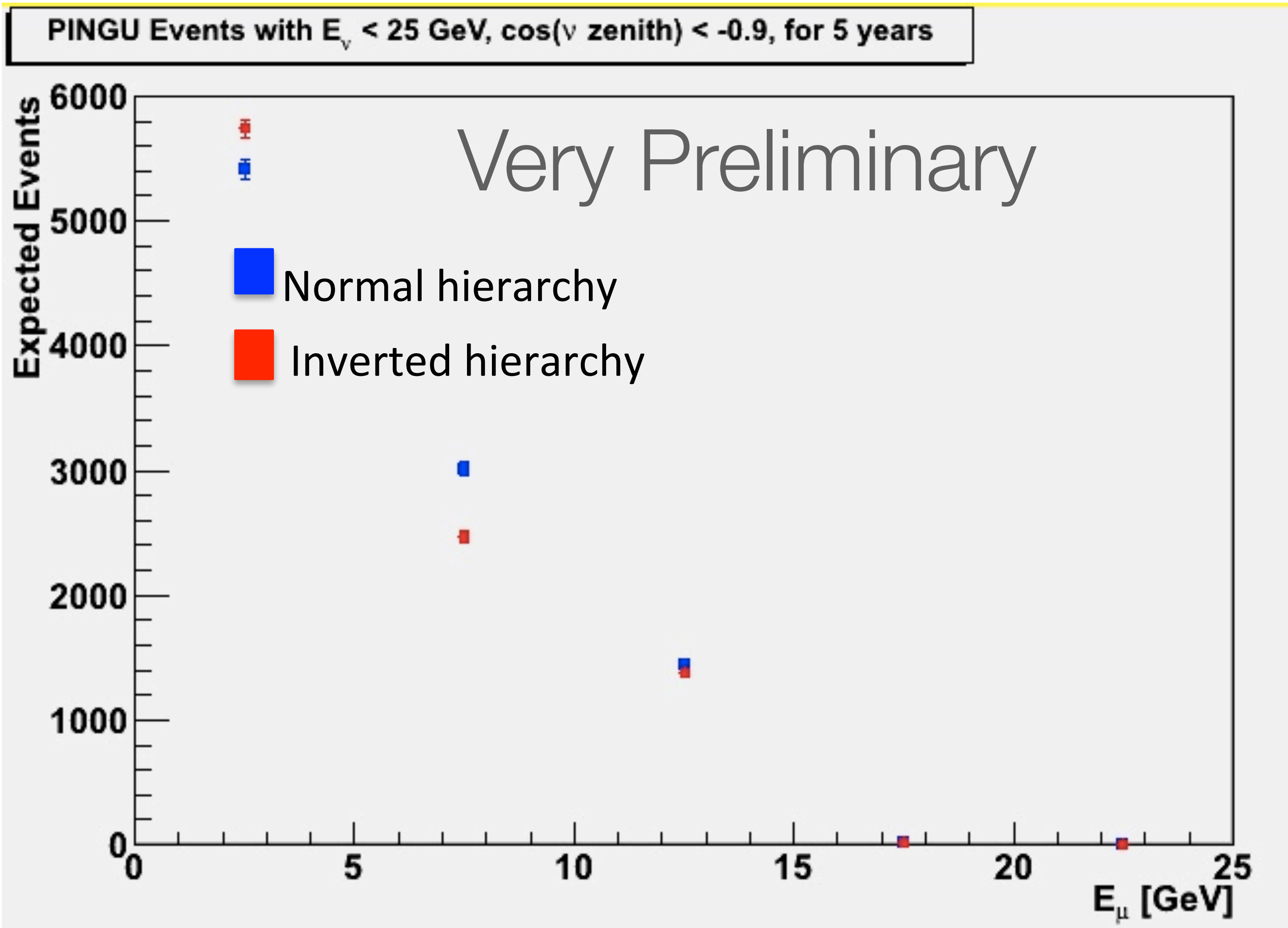
PINGU-I Neutrino Mass Hierarchy

Simulations of 20-string PINGU with 5 years of data and $\sin^2(2\theta_{13})$ = 0.1

Assumes perfect background rejection, selecting events within 25 degrees of vertical

Up to 20% (10 sigma) effects in several energy/angular bins

The signal is potentially there **if** the systematics can be controlled



PINGU-I Long Baseline Studies

Tang & Winter http://arxiv.org/pdf/1110.5908v1

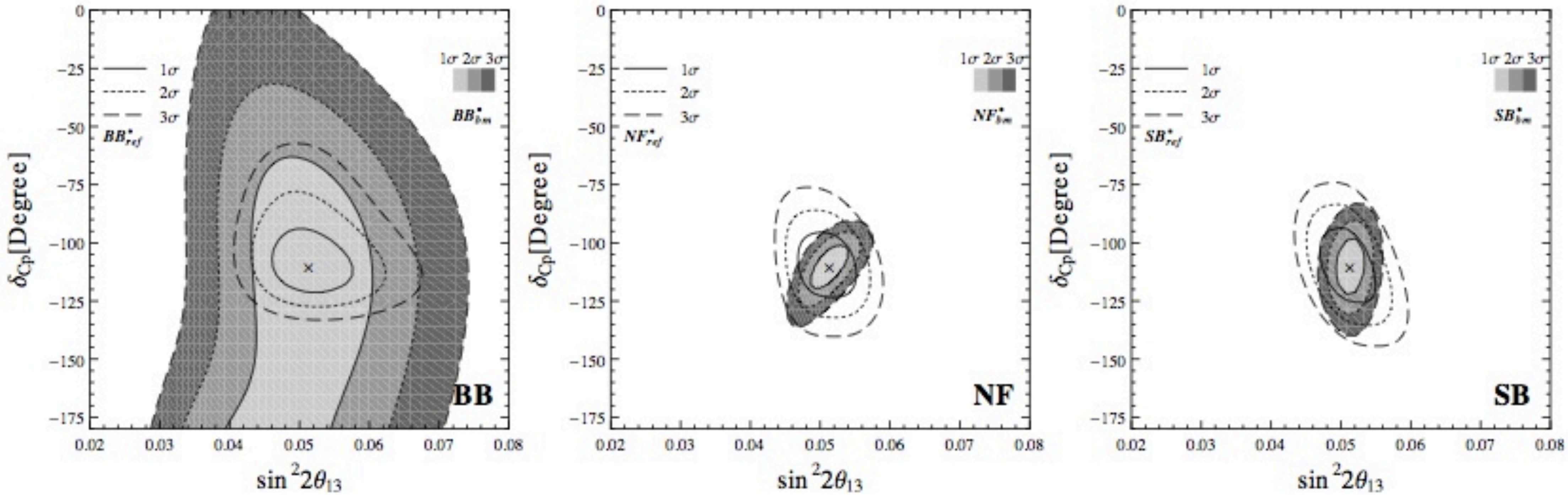
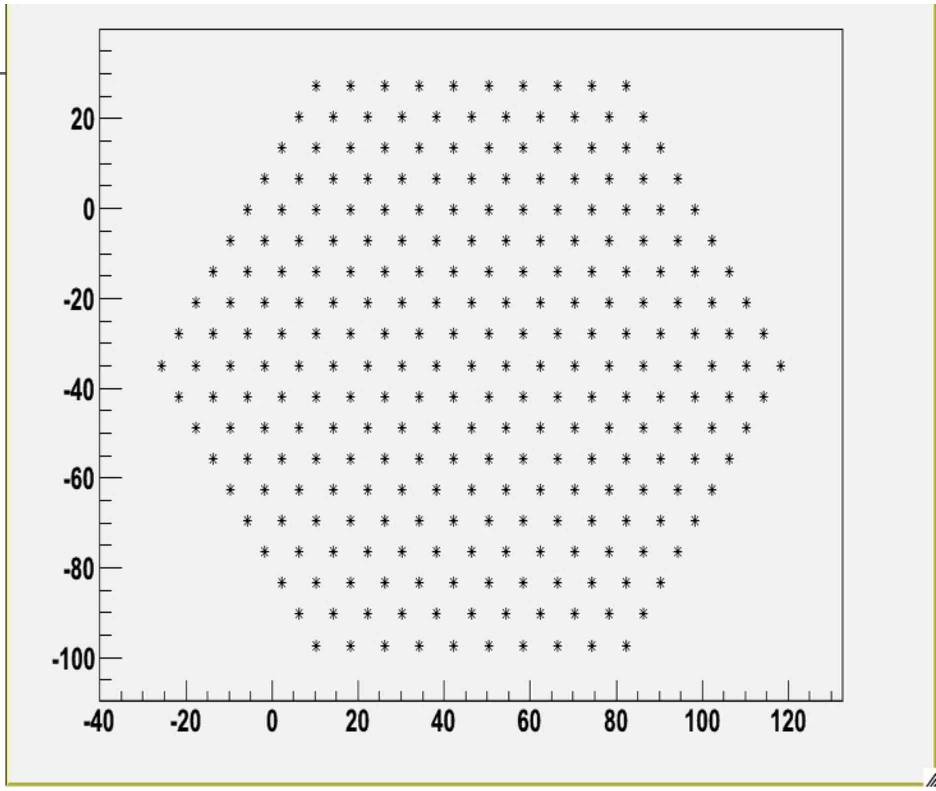


Figure 12: The precision measurements of CP phase $\delta_{\rm CP}$ and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the 1σ, 2σ and 3σ confidence levels (2 d.o.f.). Filled contours represent the PINGU benchmark setups, unfilled contours the reference setups. The crosses mark the best fit value of $\sin^2 2\theta_{13}$ and $\delta_{\rm CP}$. Here we assume the normal (true) hierarchy, the inverted (fit) hierarchy solution can be ruled out by the experiments.

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
- No excavation necessary: detection medium is the support structure

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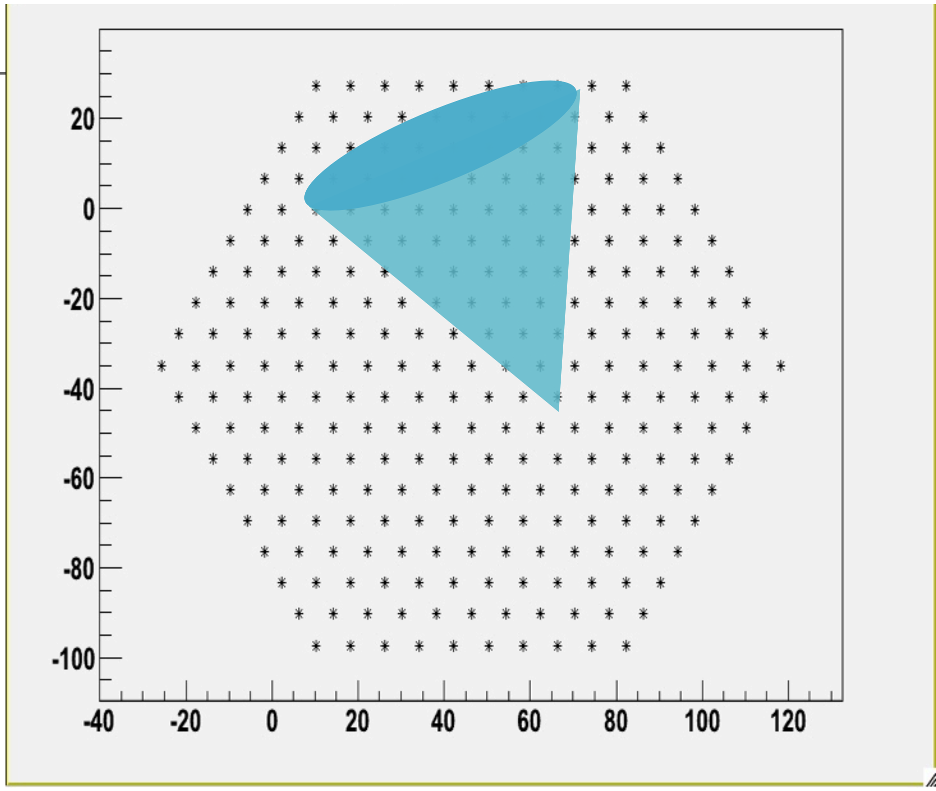

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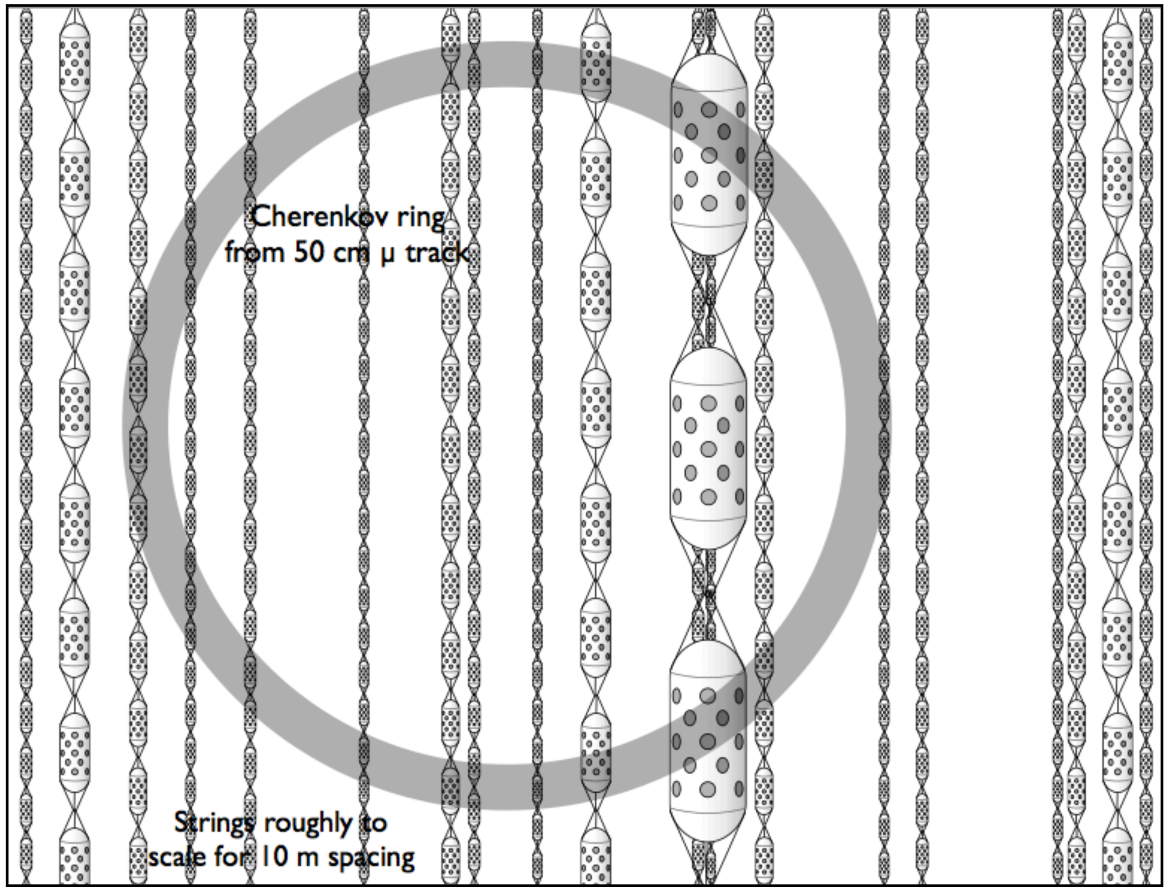
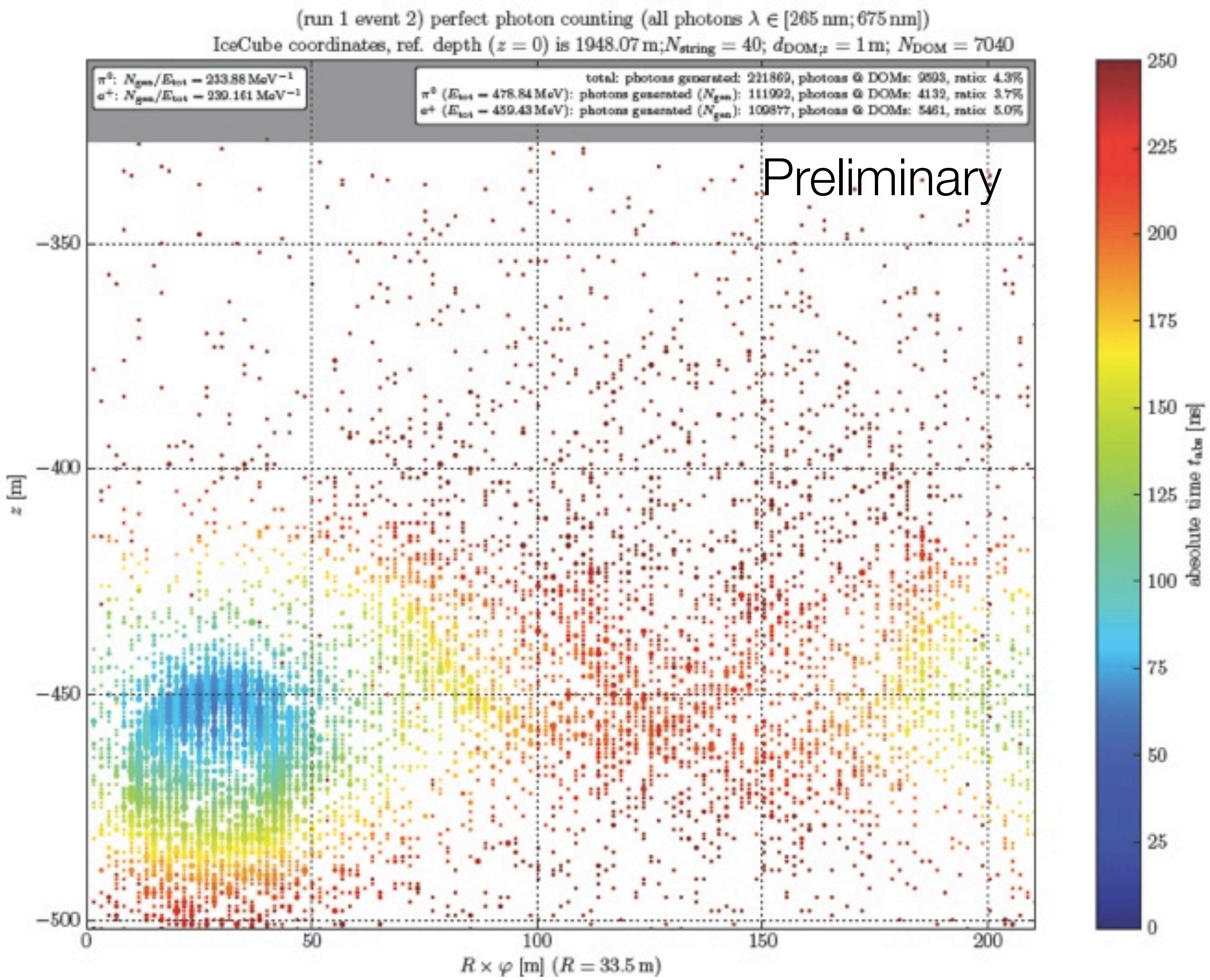


SuperPINGU Physics

- Proton decay
  - Studying sensitivity to p -> $\pi^0 + e^+$ channel
  - Requires energy threshold of ~100's of MeV
  - Background limited - depends on energy resolution, particle ring ID
- Supernova neutrinos
  - Need to reach well beyond our galaxy to get statistical sample of SN neutrinos
  - Background levels may be too high for a ~10 MeV threshold for individual events, but still allows for observation of bursts of events
- Plus improvements for WIMP, oscillation analyses over PINGU-I & DeepCore

SuperPINGU Proton Decay

- For fiducial volume of 1.5 MT (5×10^{35} protons) with 10 MeV energy threshold
- investigating $p \rightarrow \pi^0 + e^+$ channel as first step; clearly others to be studied
- Current predictions of SU(5) - 10^{36} yr sensitivity probe minimal realistic theory and SUSY SU(5) - 10^{36} yr would rule out MSSM defined for $M_{GUT} << M_{Planck}$
- Backgrounds will be key
- MC studies needed to understand:
- energy resolution in a volume detector
- possibilities for e/μ ID from Cherenkov rings
- required photocathode coverage



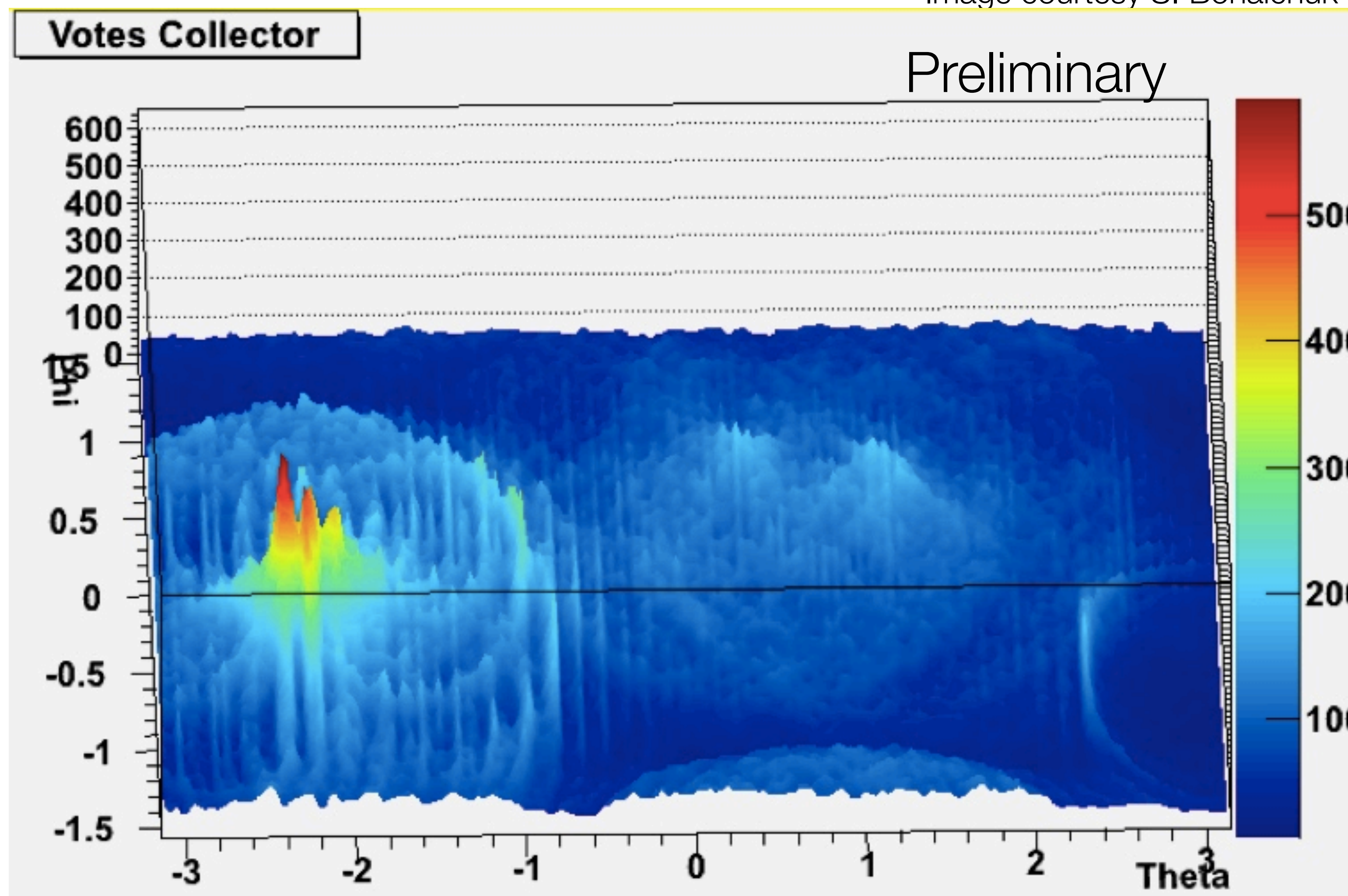
- First simulations underway. Above-strawman geometry (~750MT)
- ~240 photons per MeV deposited energy. 4-5% photons detected (assuming complete acceptance)

SuperPINGU Proton Decay

Courtesy E. Resconi

- For fiducial volume of 1.5 MT ($5x10^{35}$ protons) with 10 MeV energy threshold
- $\tau_p \sim 10^{35}$-10^{36} yr for $p \rightarrow \pi^0 + e^+$ channel
- SU(5) - 10^{36} yr sensitivity probe minimal realistic theory
- SUSY SU(5) - 10^{36} yr would rule out MSSM defined for $M_{GUT} << M_{Planck}$
- MC studies needed to understand:
- energy resolution in a volume detector
- possibilities for e/μ ID from Cherenkov rings
- required photocathode coverage

Image courtesy S. Bohaichuk



- First simulations underway. Above-strawman geometry (~750MT)
- ~240 photons per MeV deposited energy. 4-5% photons detected (assuming complete acceptance)

SuperPINGU SuperNovae

- With a large-scale detector, O(5MT), designed for proton decay, you essentially confer sensitivity out to O(10 Mpc).
  - Background constraints for proton decay are much larger than for supernova neutrinos (3000 photons per supernova neutrino with a 3% effective coverage = 30 photons/SN neutrino detected)
- Within the detector design ensure 10 MeV events detectable in burst mode.
- Caveat: LOTS of uncertainties (reconstruction, particle ID,...)

http://arxiv.org/abs/0810.1959v2

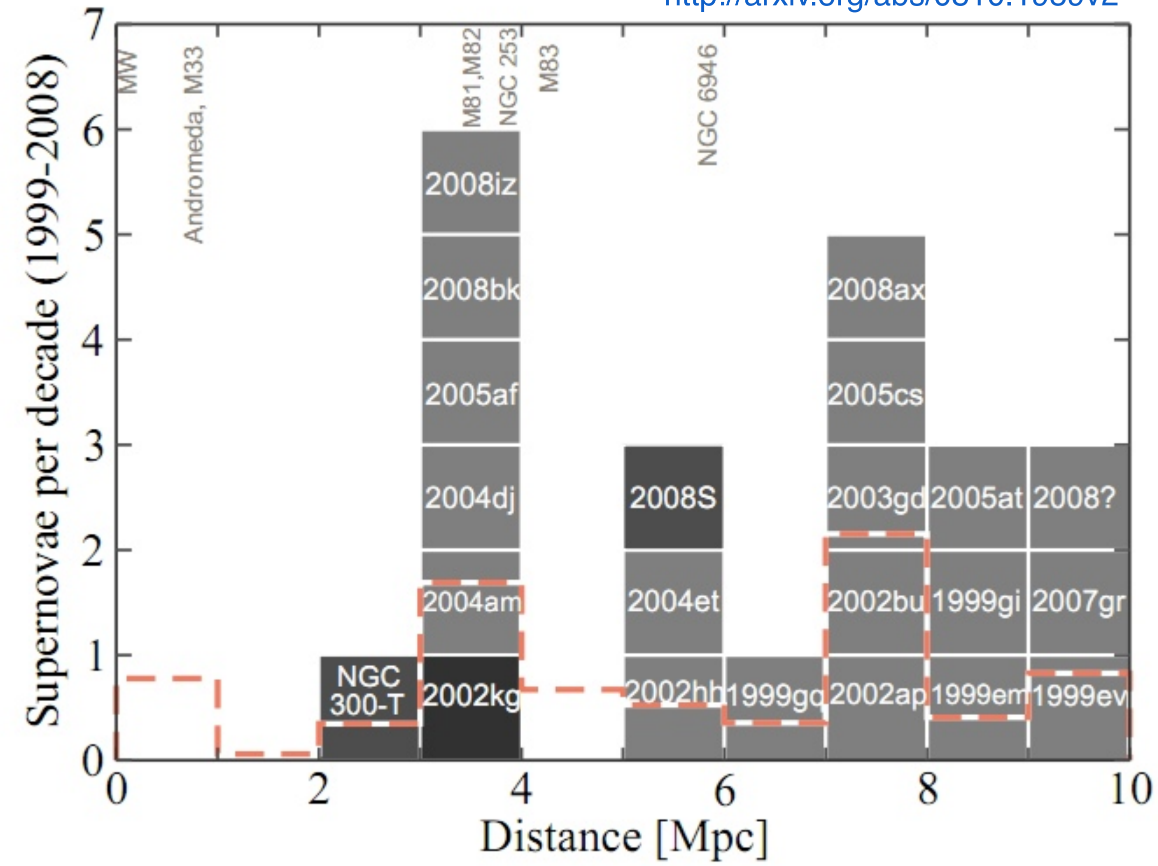
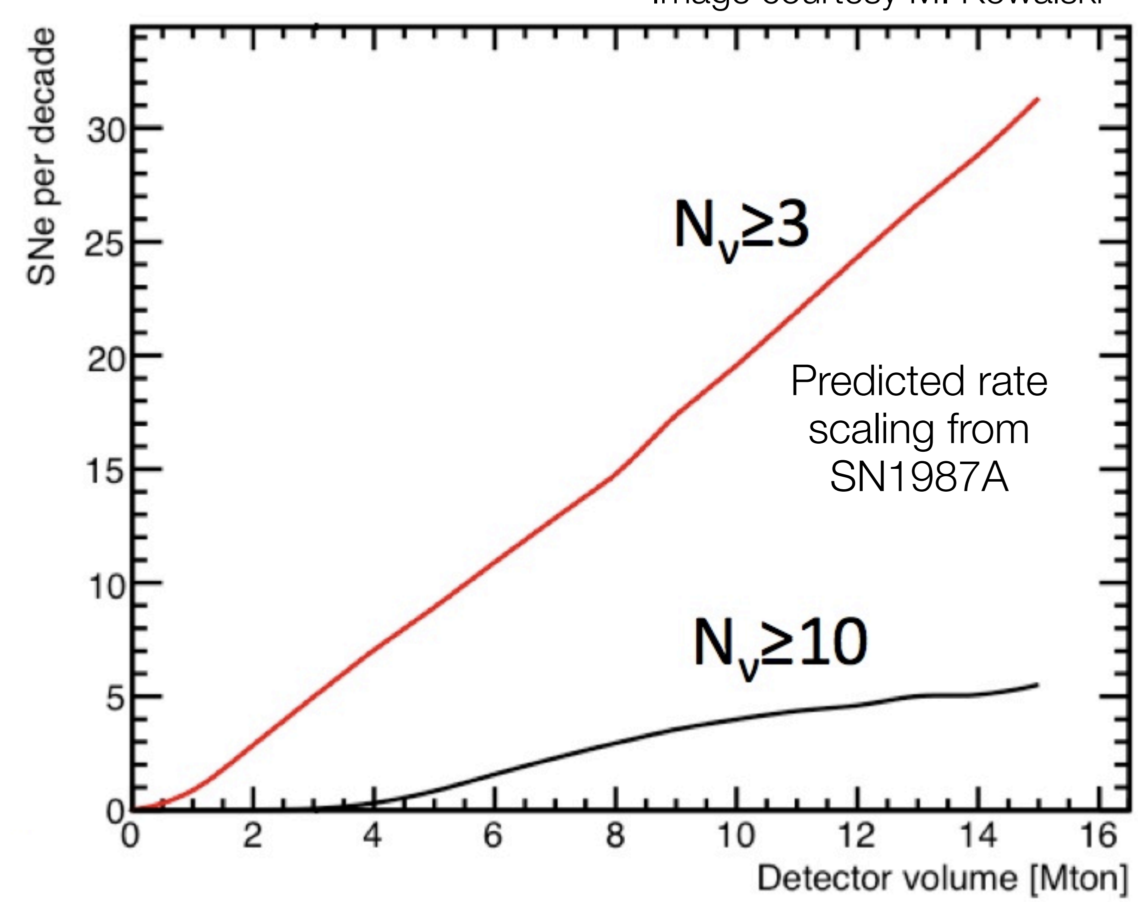


Image courtesy M. Kowalski



SuperPINGU SuperNovae

- With a large-scale detector, O(5MT), designed for proton decay, you essentially confer sensitivity out to O(10 Mpc).
    - Background constraints for proton decay are much larger than for supernova neutrinos (3000 photons per supernova neutrino with a 3% effective coverage = 100 photons/SN neutrino detected)
- Within the detector design ensure 10 MeV events detectable in burst mode.
- Caveat: LOTS of uncertainties (reconstruction, particle ID,...)

Preliminary

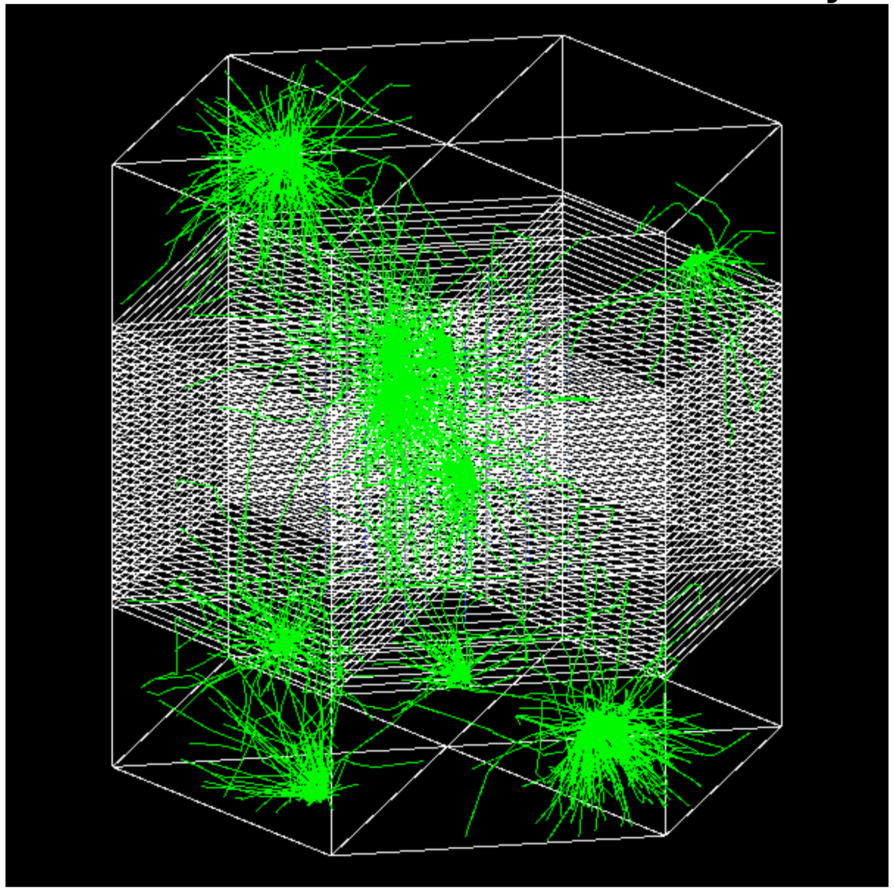


Figure: Lukas Schulte/Mainz

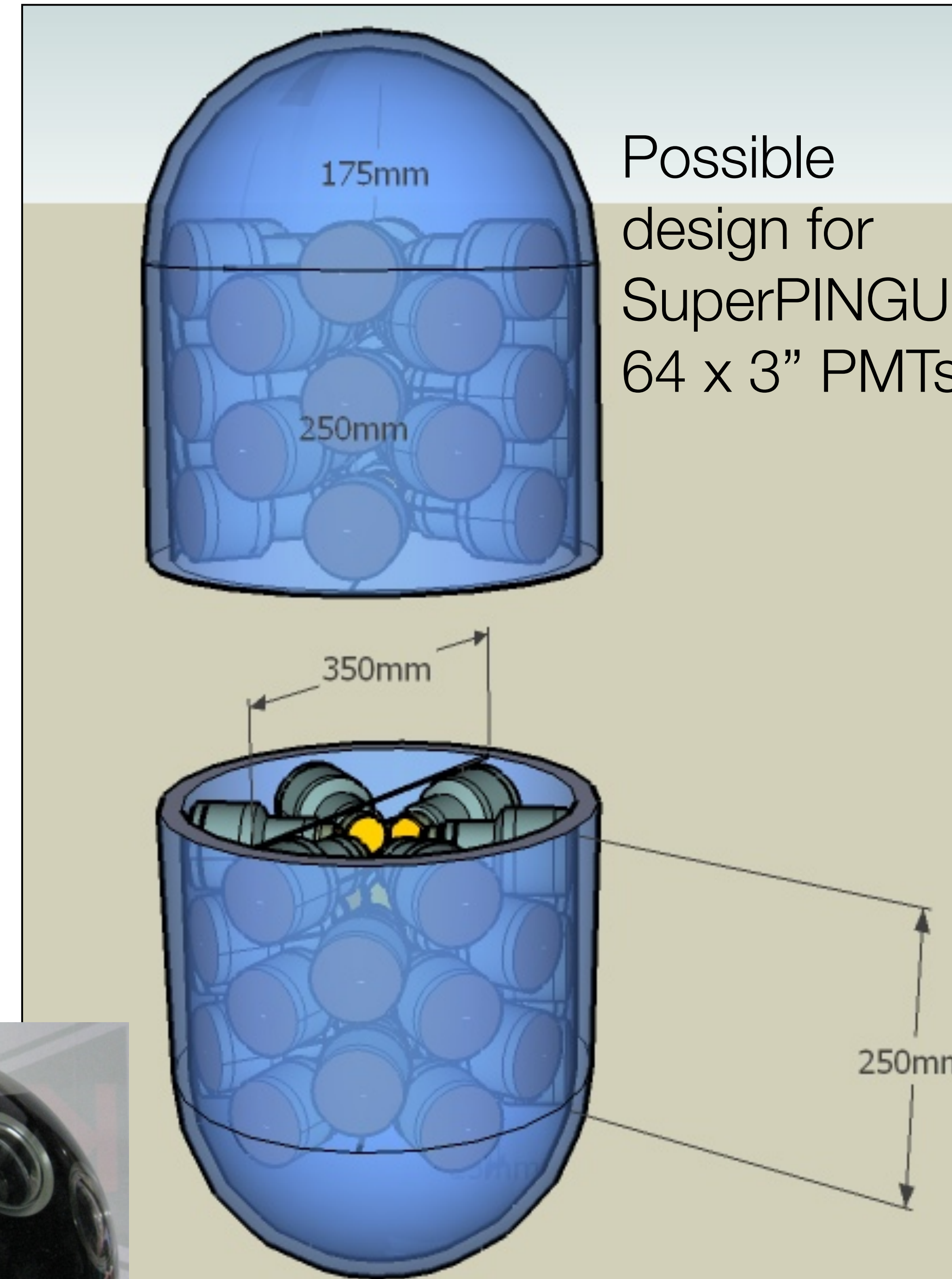
Geant4: γ's from SN ν's

SuperPINGU Detector R&D

Courtesy E. de Wolf & P. Kooijman

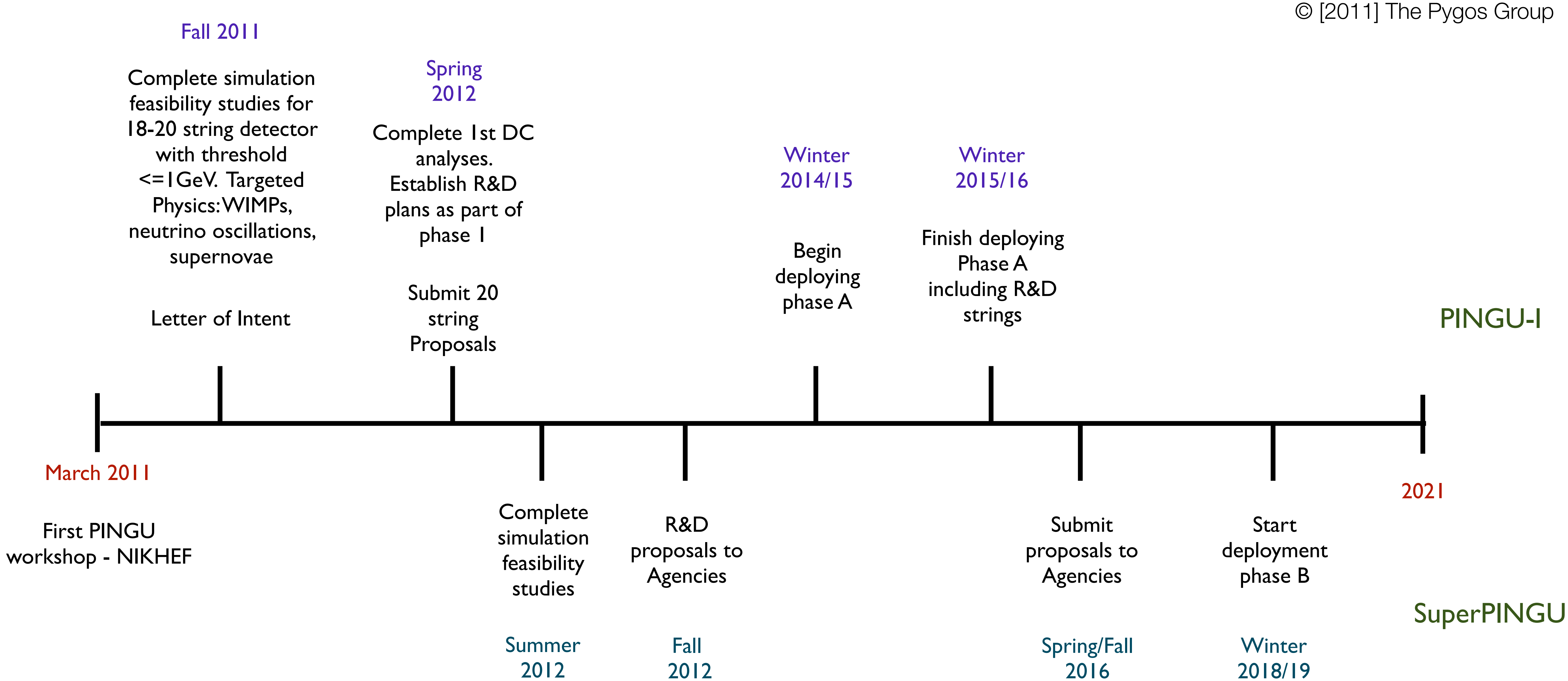
Composite Digital Optical Module

- Glass cylinder containing 64 3” PMTs and associated electronics
    - Effective photocathode area >5x 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



PINGU Timeline

- Detailed Monte Carlo simulations underway
- New specialized reconstruction algorithms for lower energies and for Cherenkov rings need to be developed
- Low energy reconstruction will follow work on DeepCore now underway
- Cherenkov ring reconstruction can modify existing algorithms from experiments like SuperK



Summary

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

- 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.

- DeepCore has been running for 1 year and has just commenced taking data in its final configuration. First results are now appearing!

- Expect significant improvement in sensitivity to dark matter, potential for neutrino oscillations. Preliminary analysis suggests we may have detected atmospheric electron neutrinos for the first time in a high-energy telescope.

- Towards the 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!