

I c e C u b e

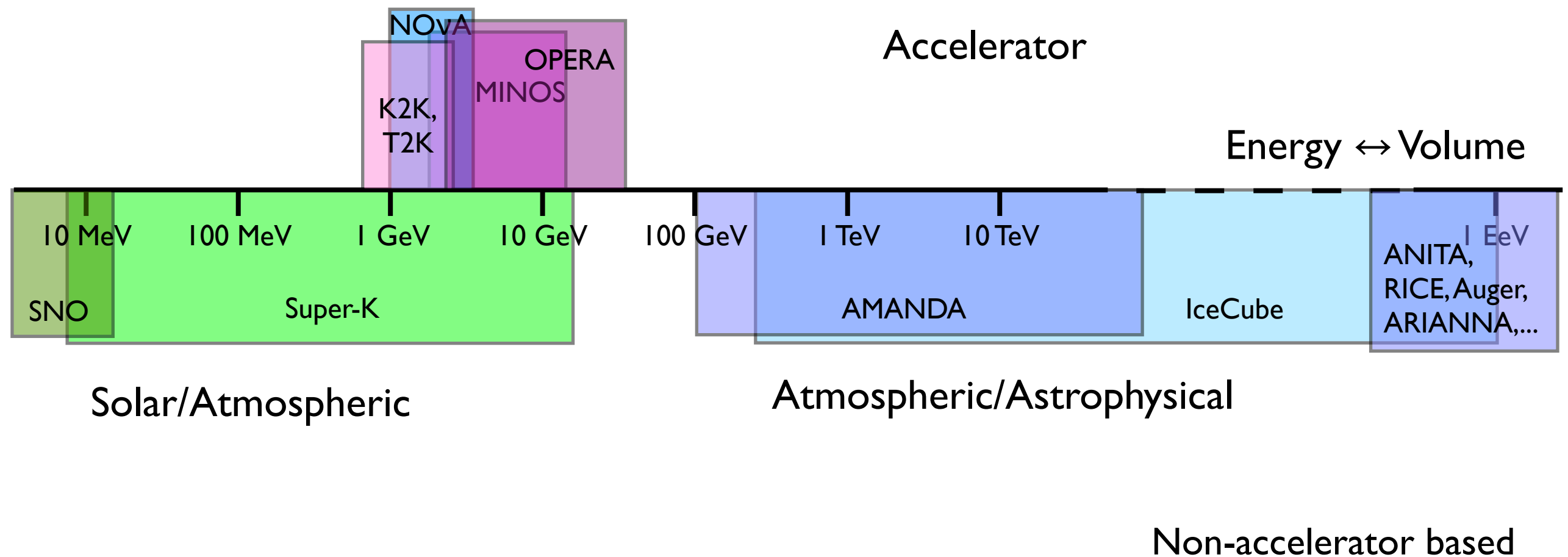
IceCube-DeepCore-PINGU

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

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

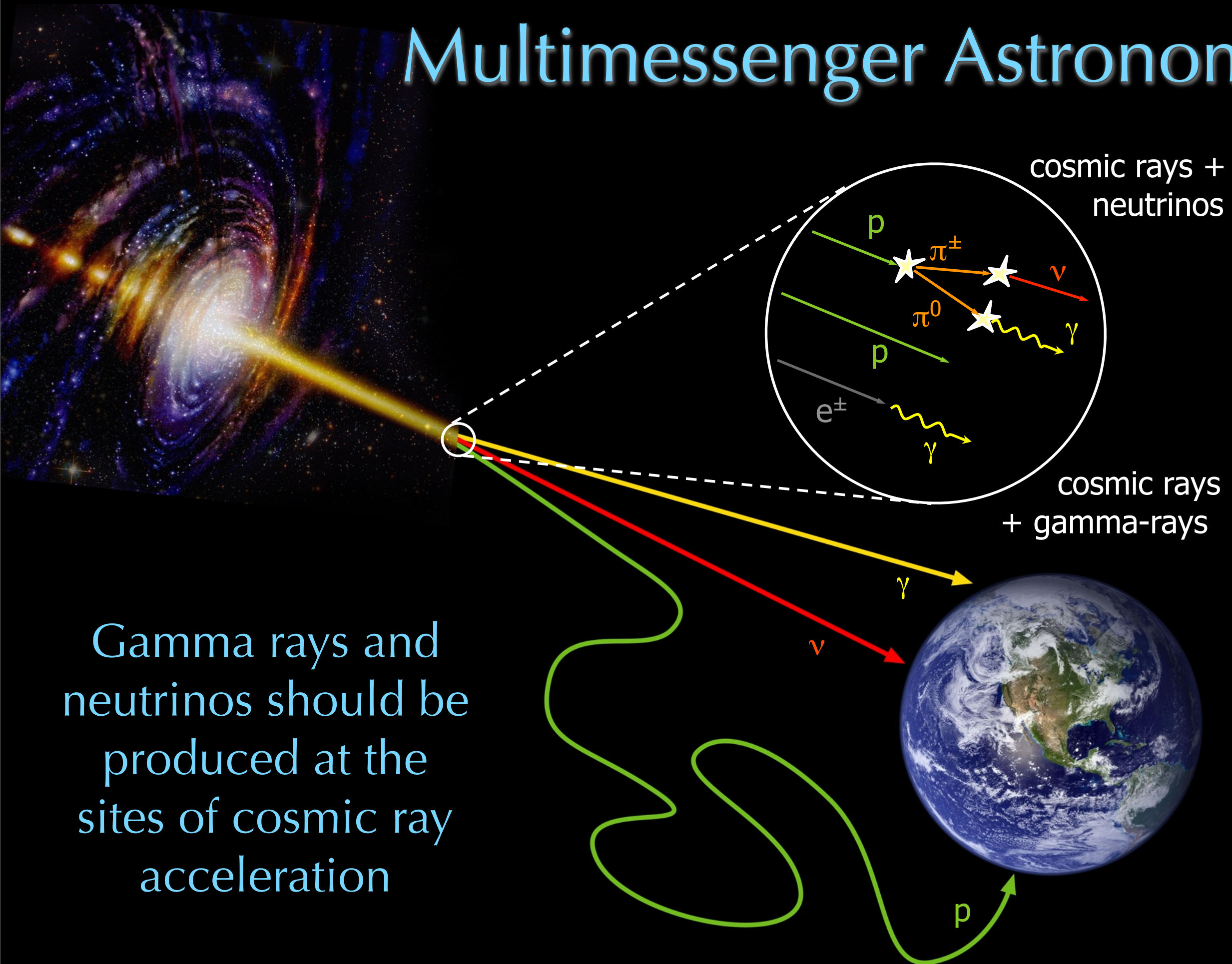


The Neutrino Detector Spectrum



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

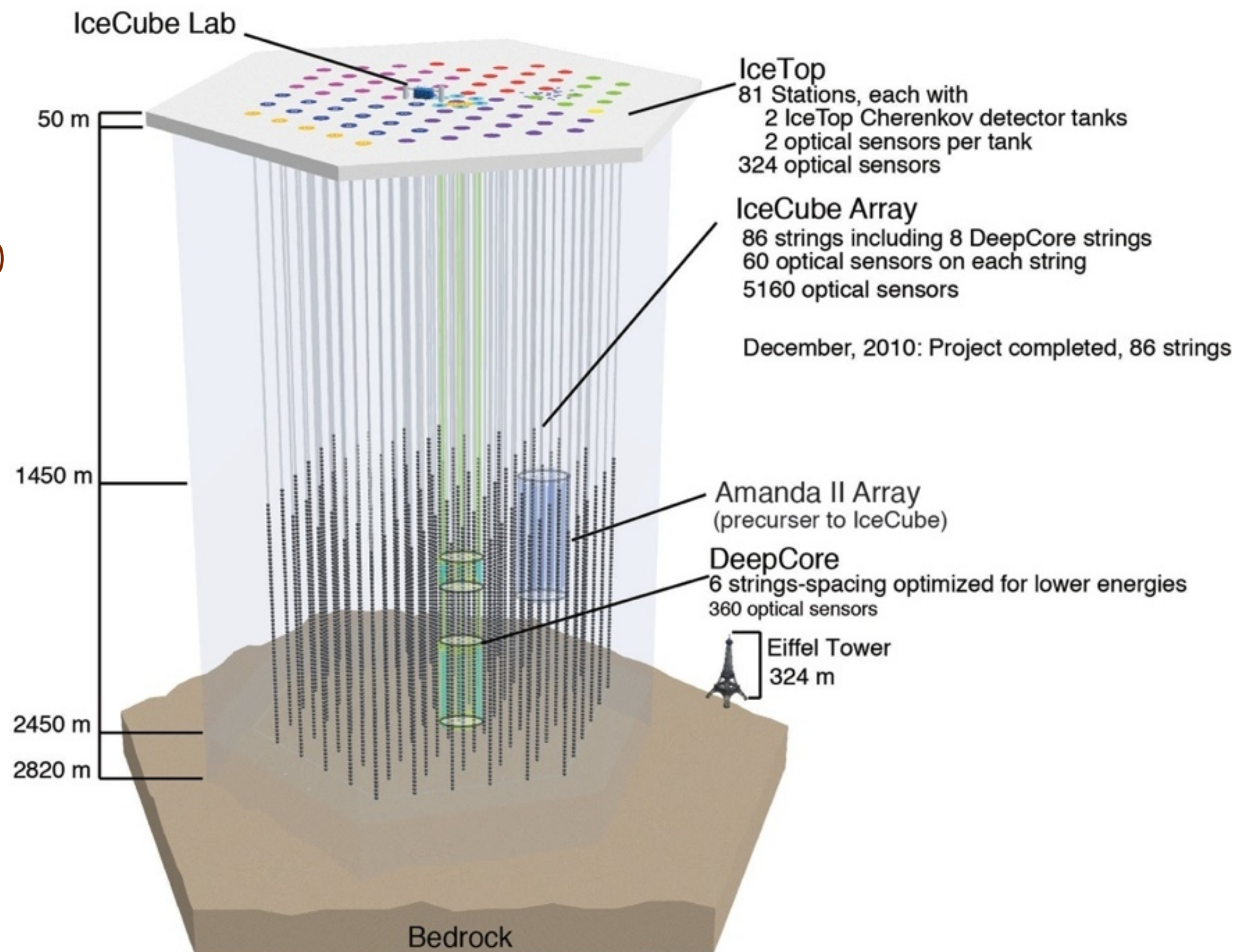
Multimessenger Astronomy



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

The IceCube Neutrino Observatory

Completed
December 18, 2010





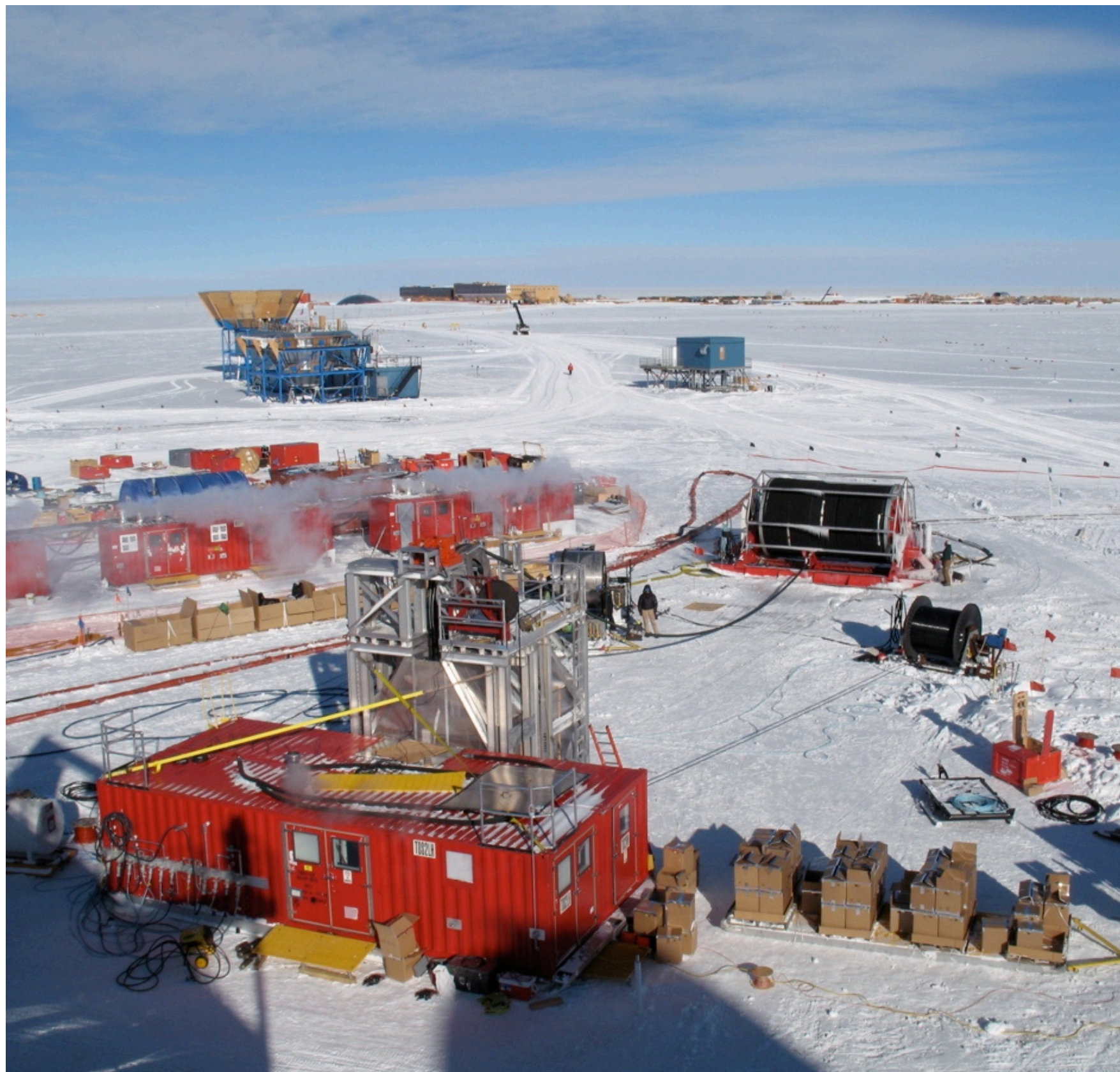
The IceCube Collaboration

36 institutions - 4 continents - ~250 Physicists

Nov 7, 2011

NNNI - Zurich Switzerland

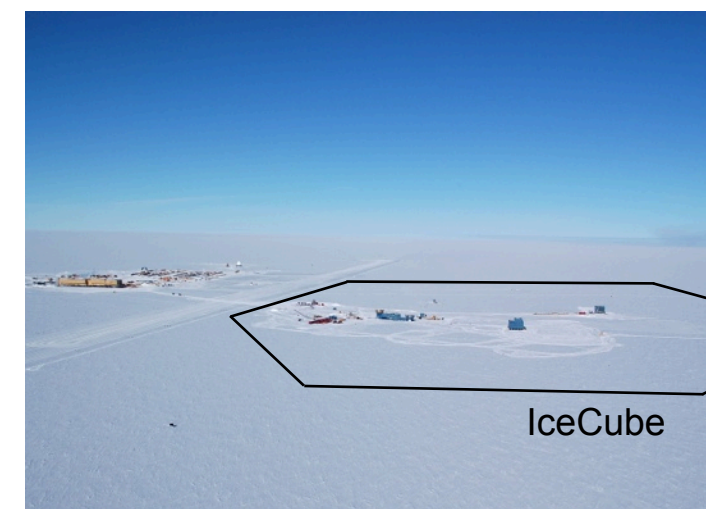
Darren R. Grant - University of Alberta



Amundsen-Scott South Pole Station, Antarctica

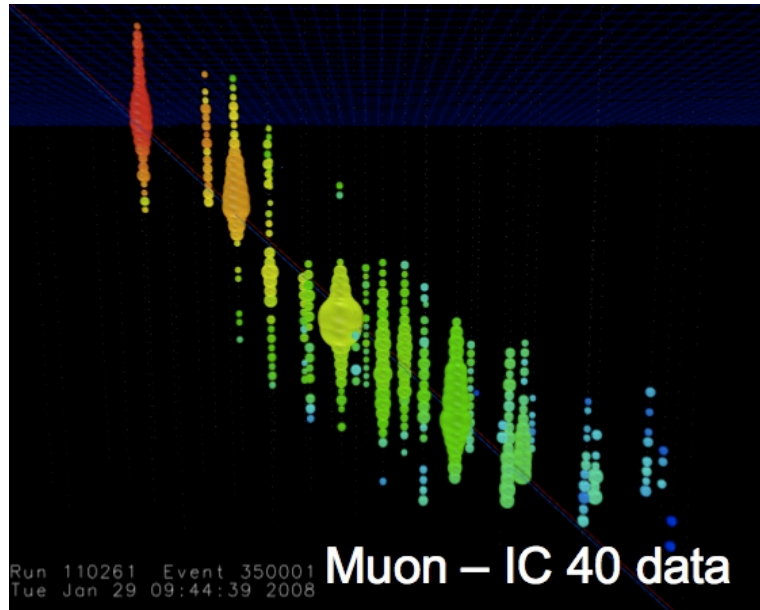
Nov 7, 2011

NNN11 - Zurich Switzerland



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Neutrino Telescopes - Principle of Detection

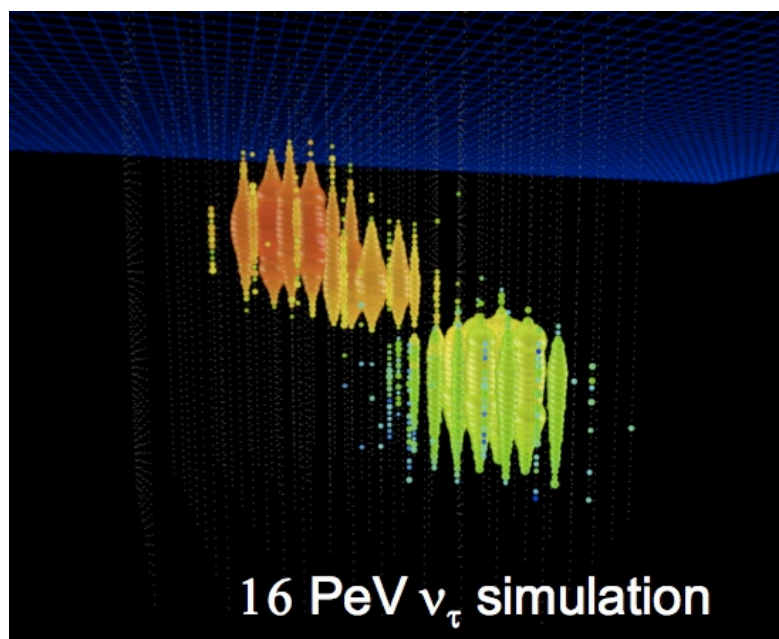


Tracks:

- through-going muons
- pointing resolution $\sim 1^\circ$

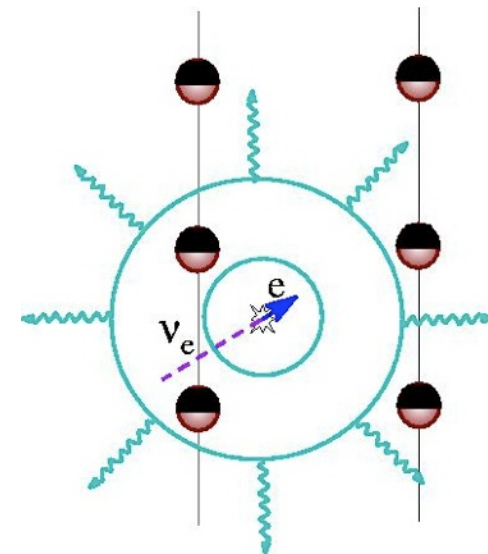
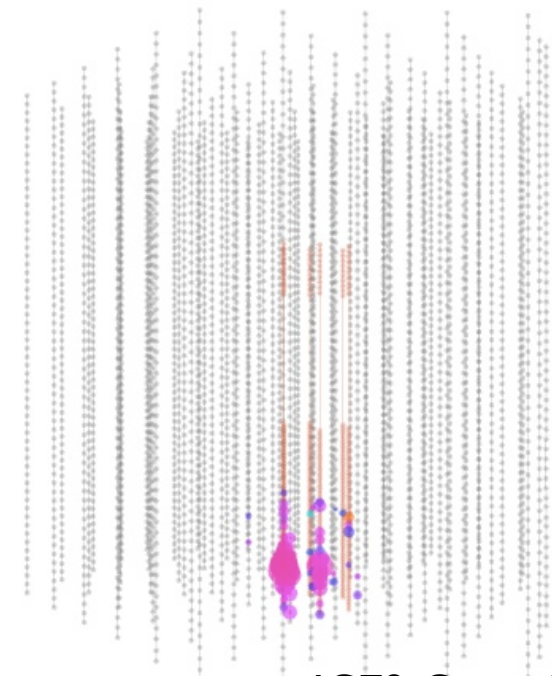
Cascades:

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

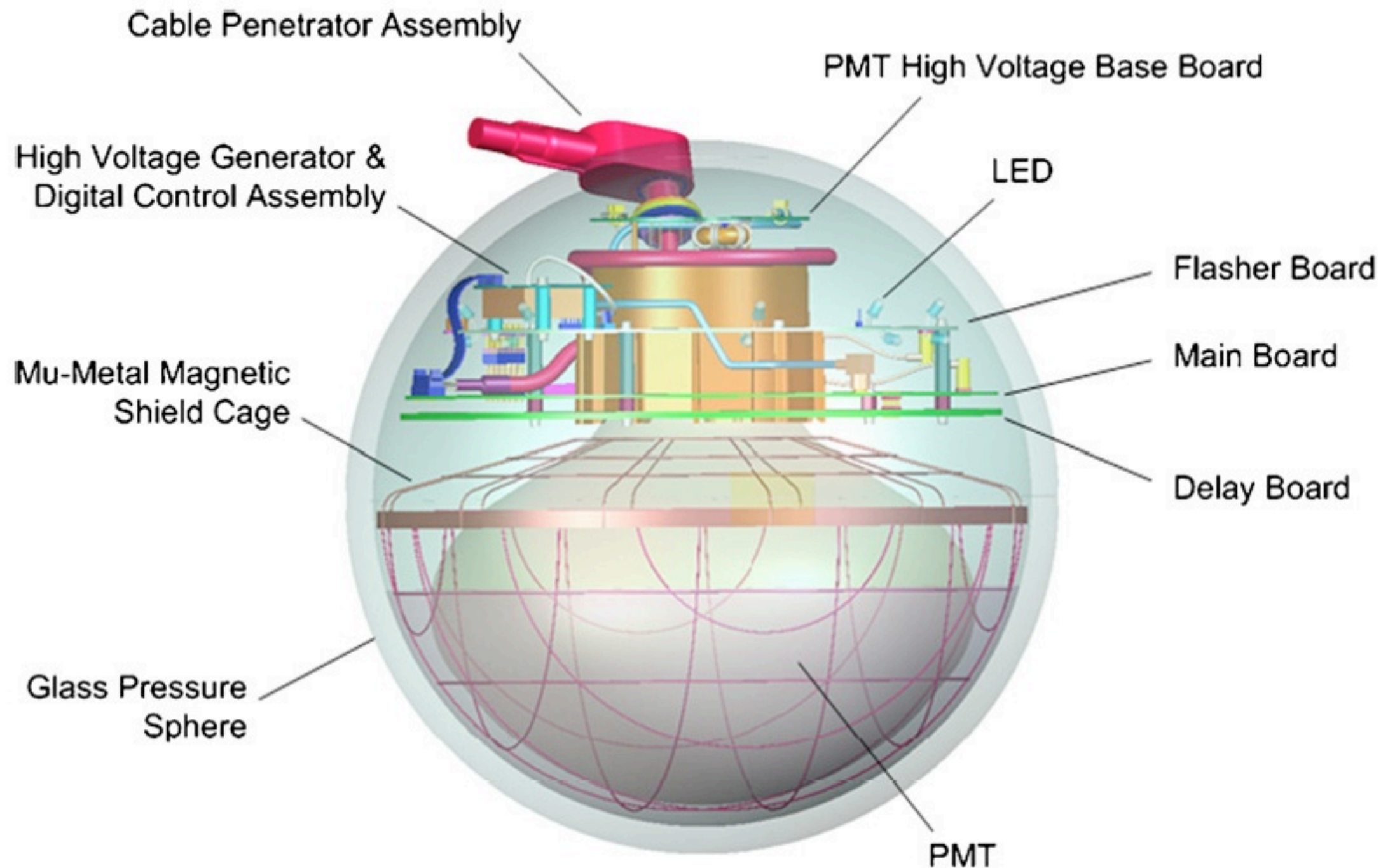


Composites:

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



The Digital Optical Module (DOM)



IceCube Performance Parameters

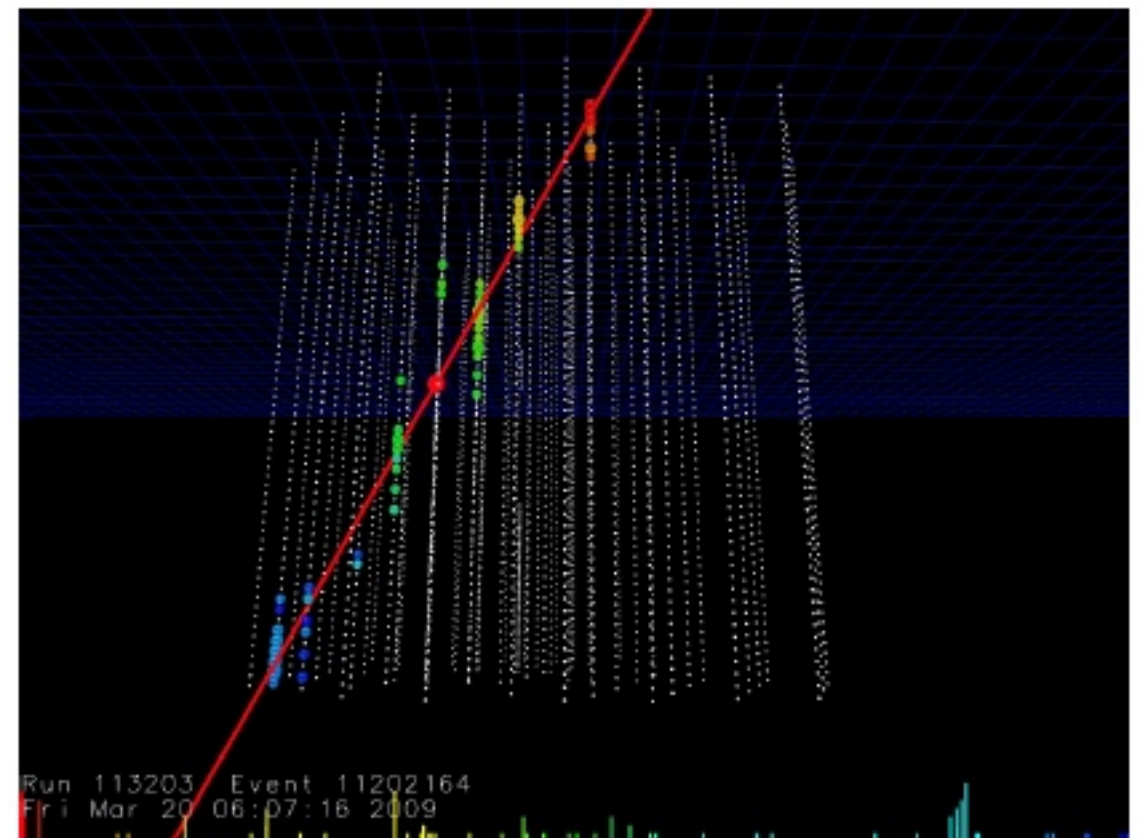
DOM Level

- time resolution
- charge response
- noise behavior
- reliability



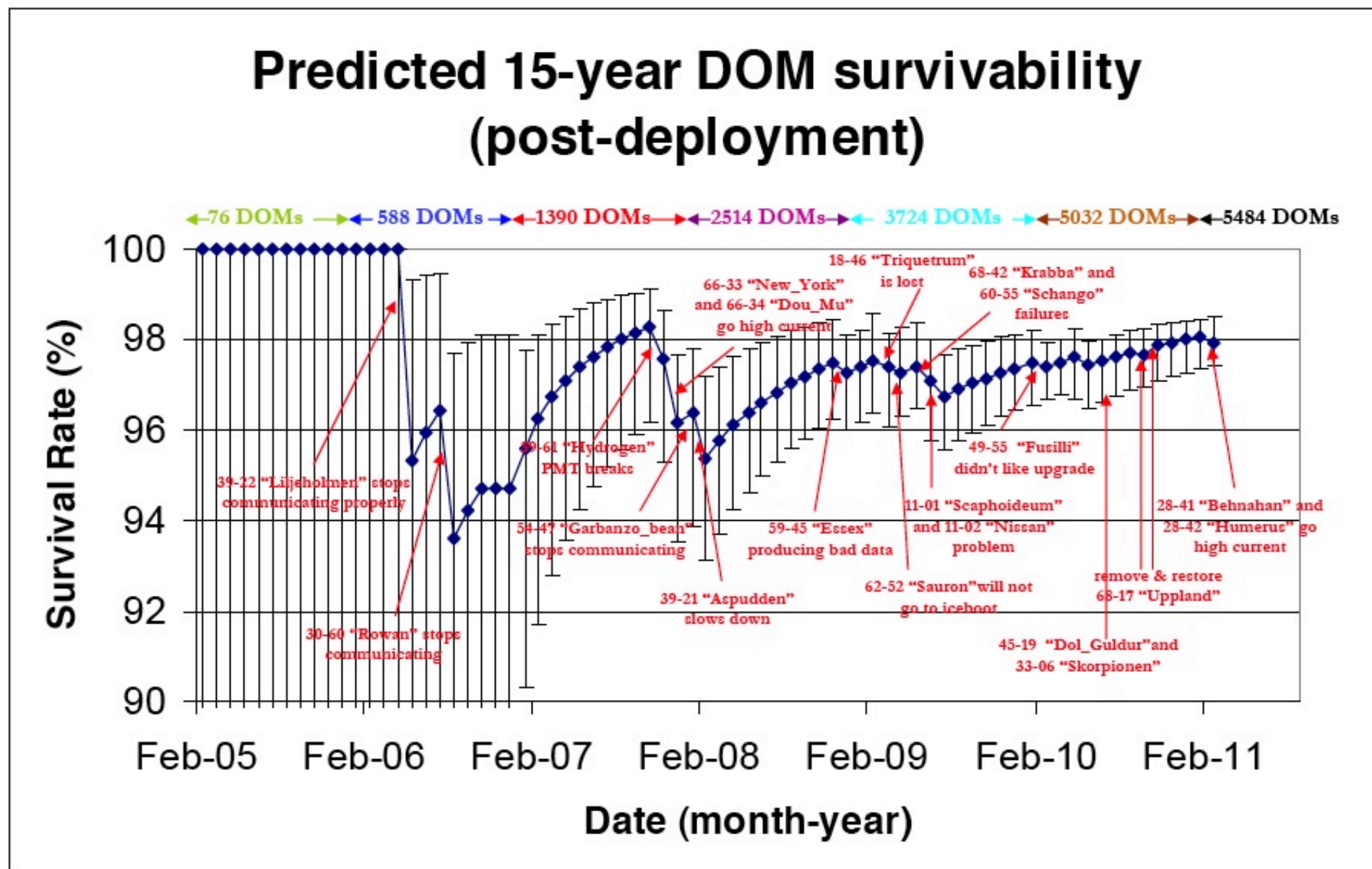
Detector level

- angular resolution
- energy resolution
- final sensitivity



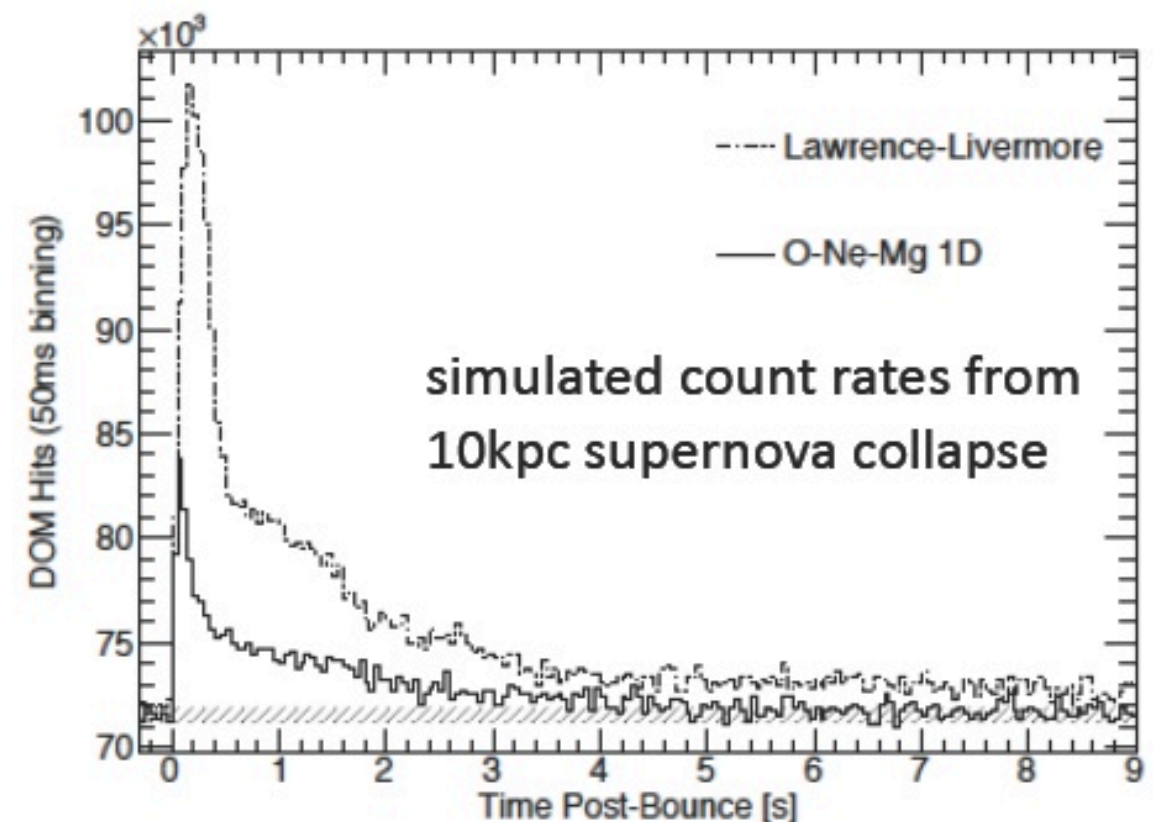
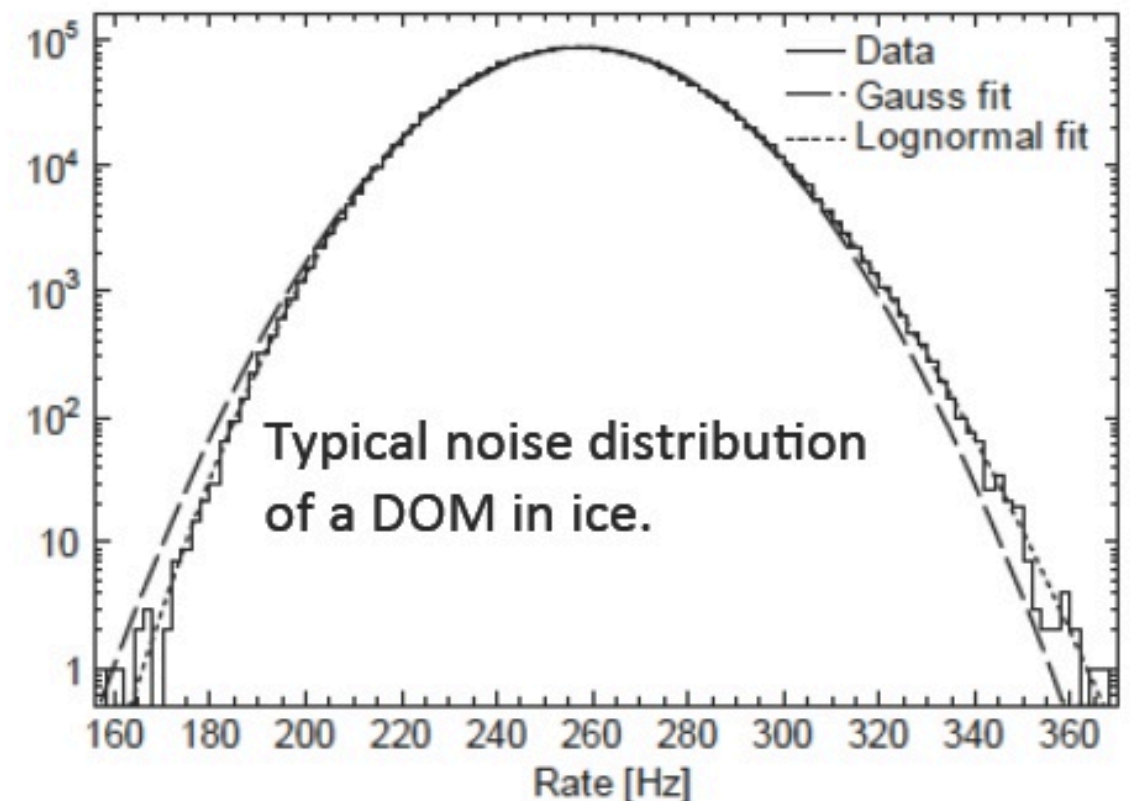
DOM Reliability

- ~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.



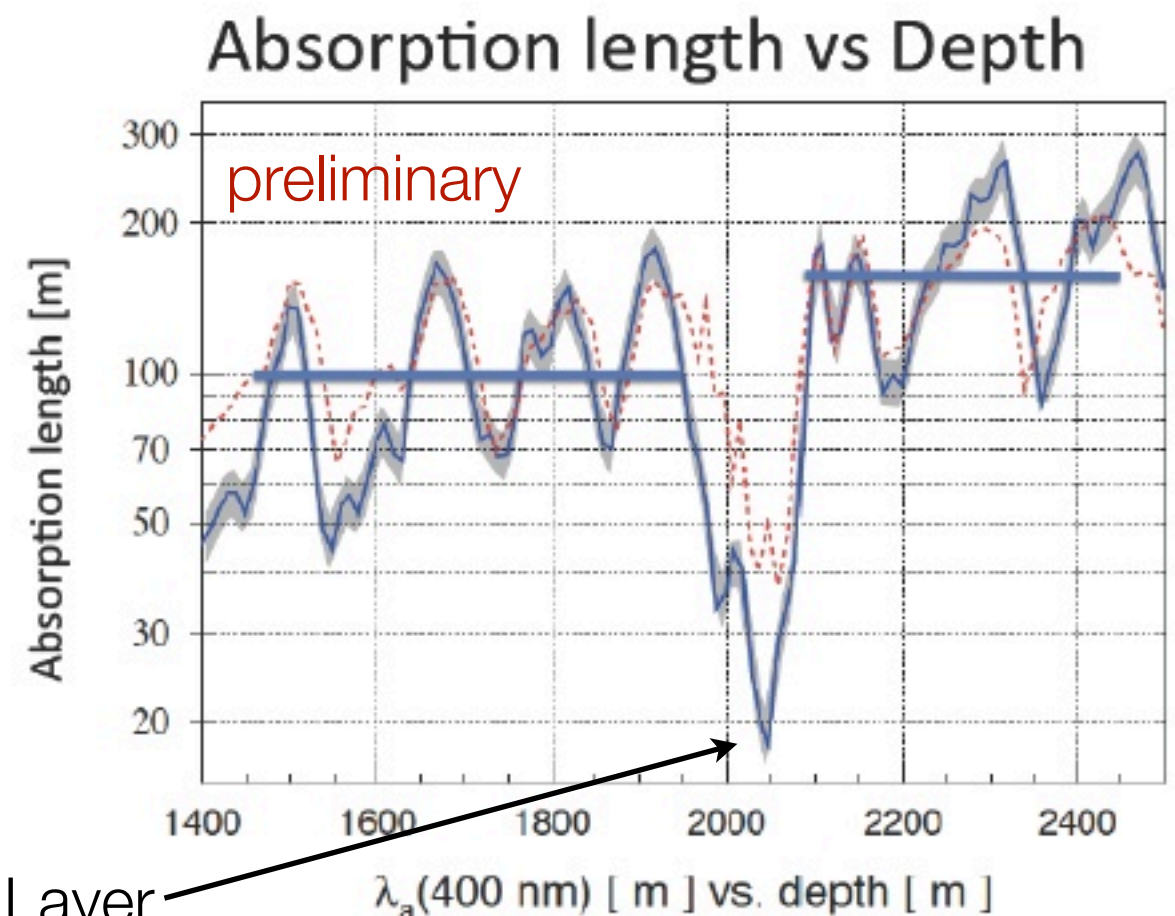
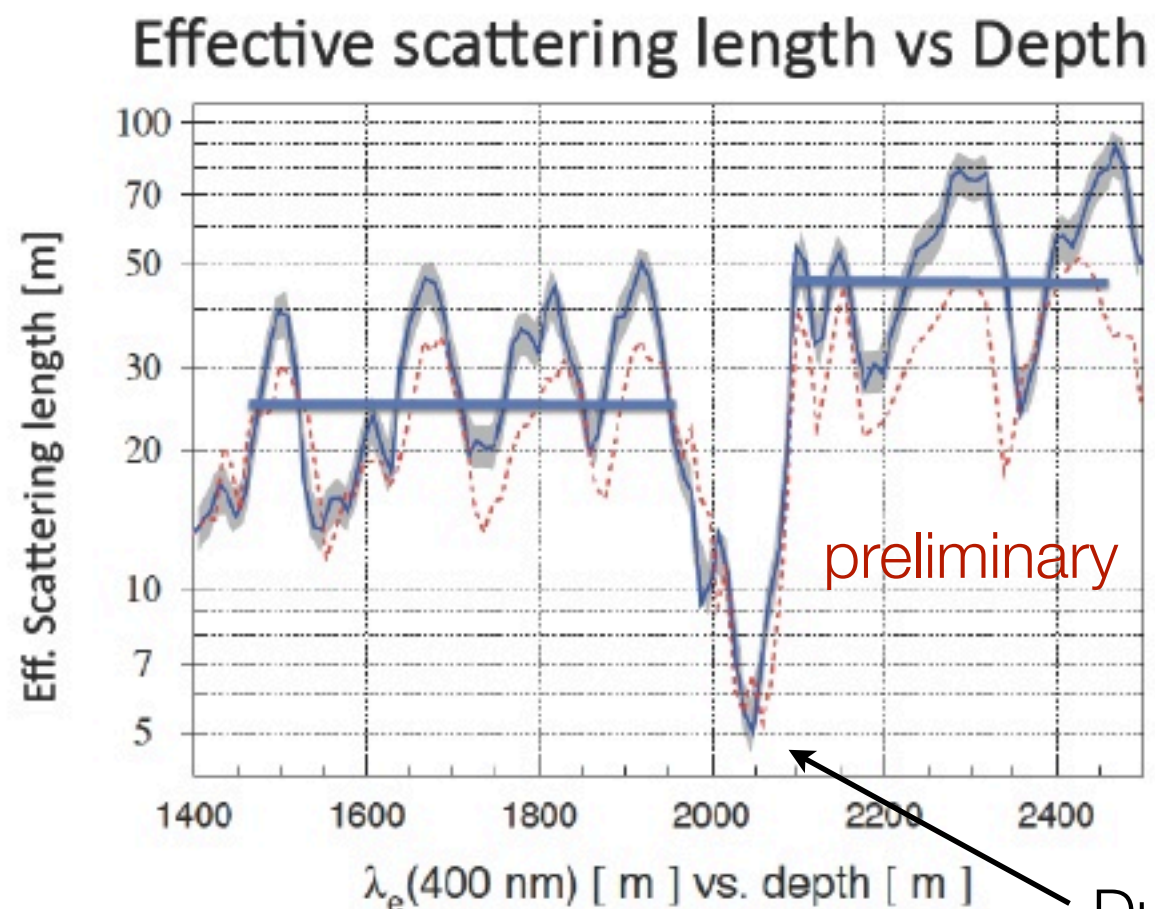
DOM Dark Noise

- 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.



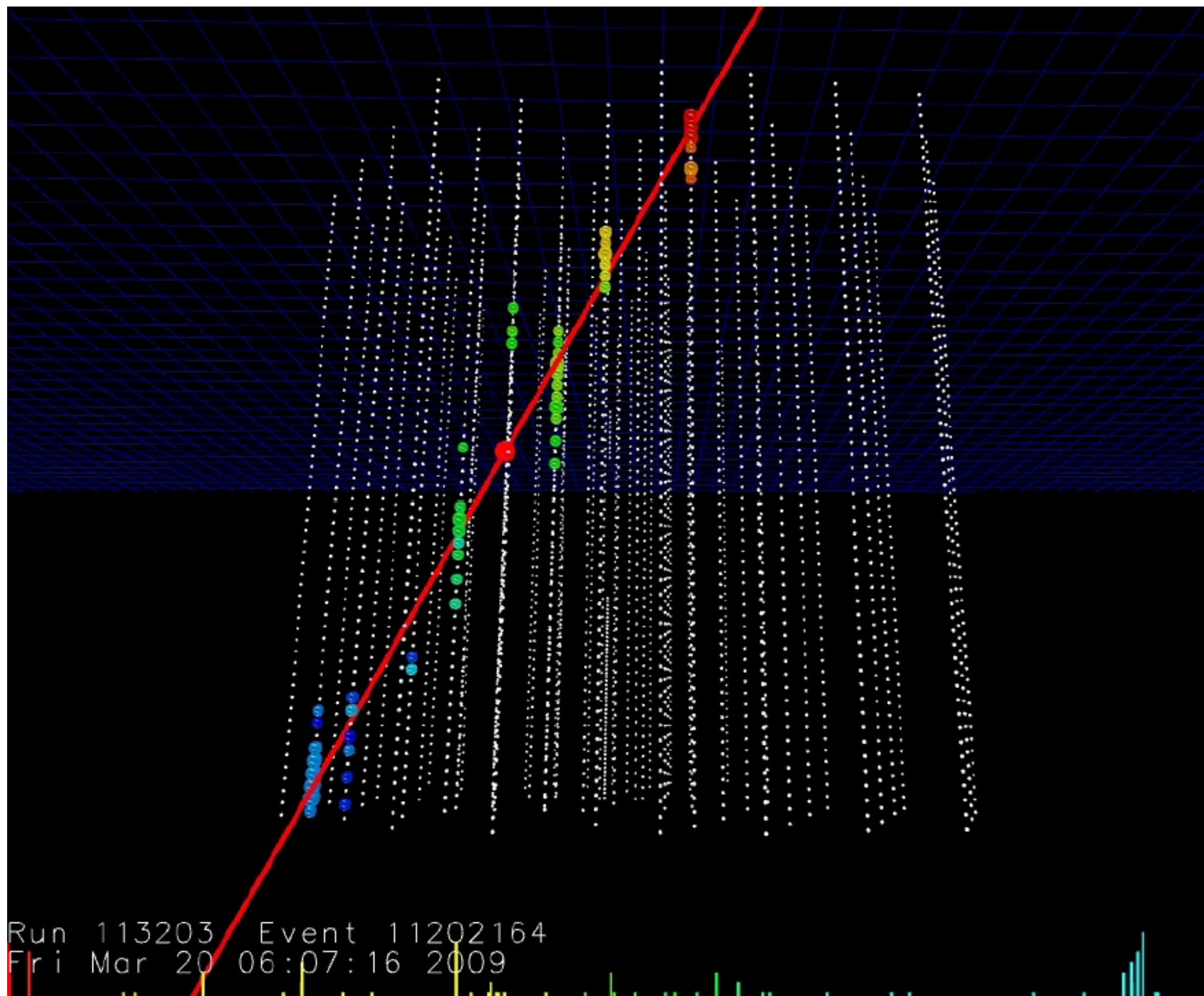
IceCube Calibrations

- 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.



Dust Layer

IceCube Detector Performance



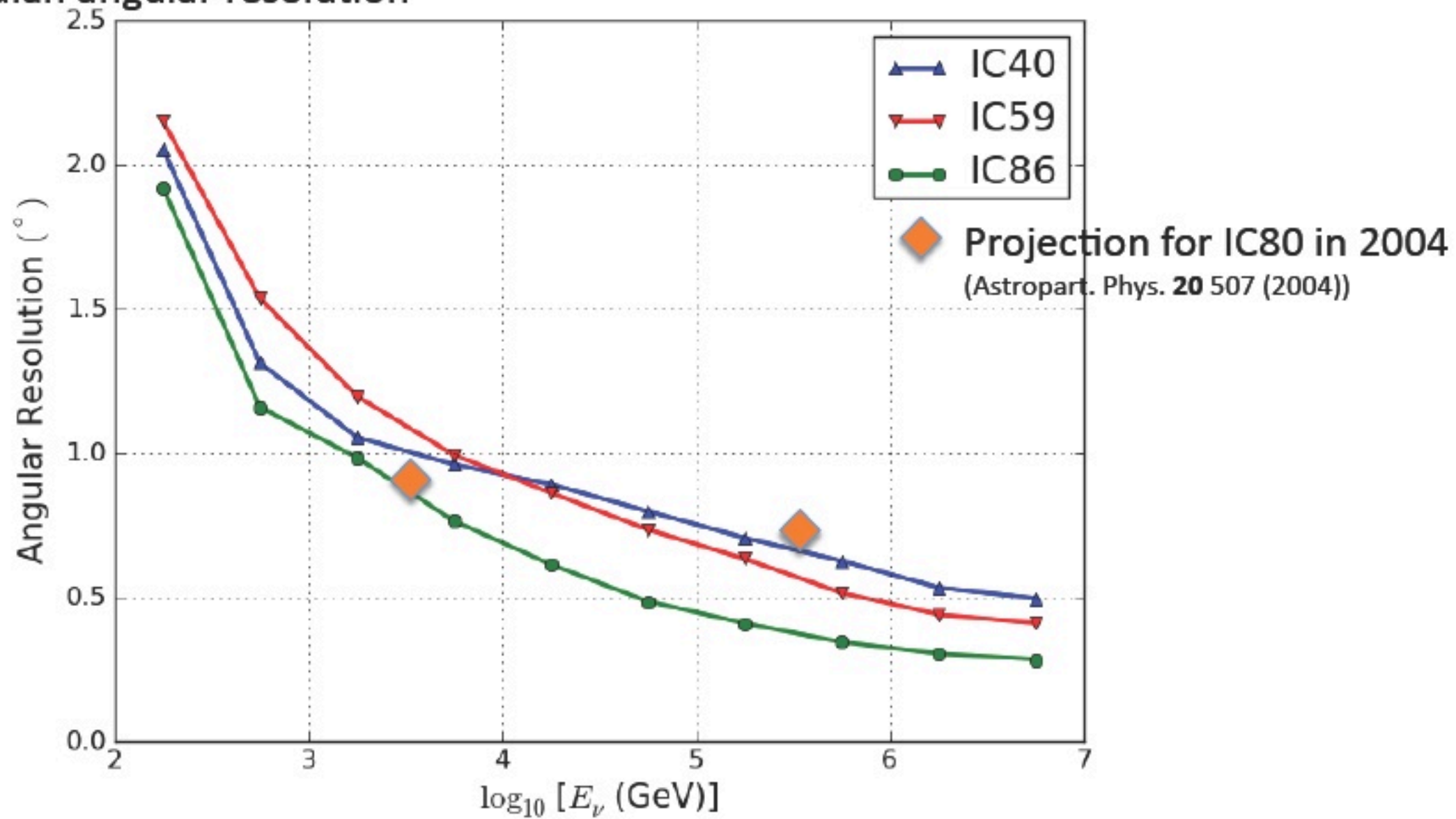
Nov 7, 2011

NNN11 - Zurich Switzerland

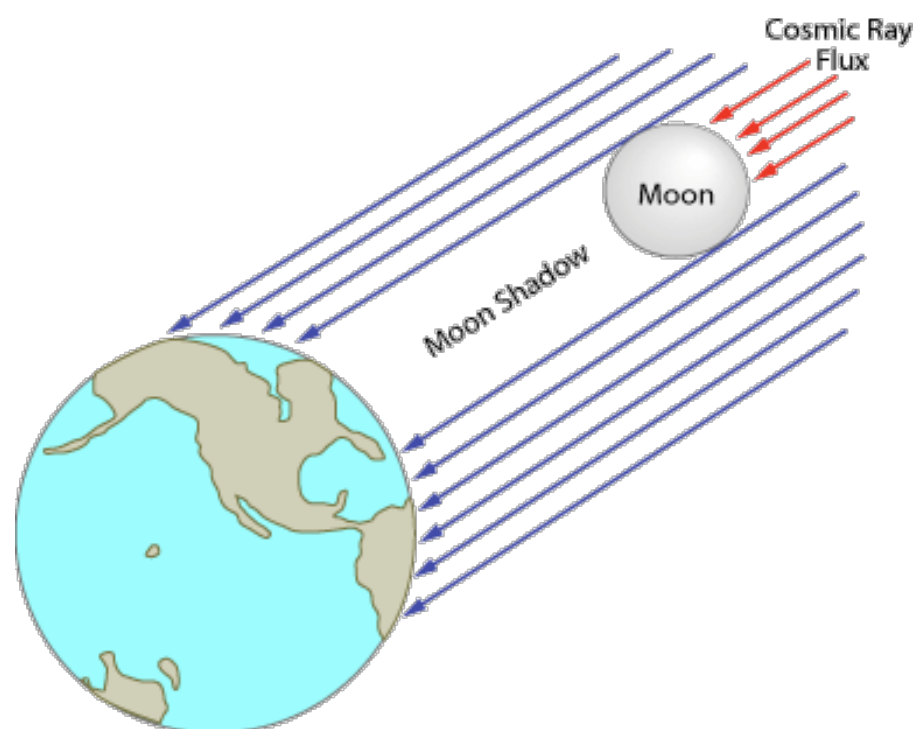
Darren R. Grant - University of Alberta

IceCube Detector Performance - Angular Resolution

Median angular resolution

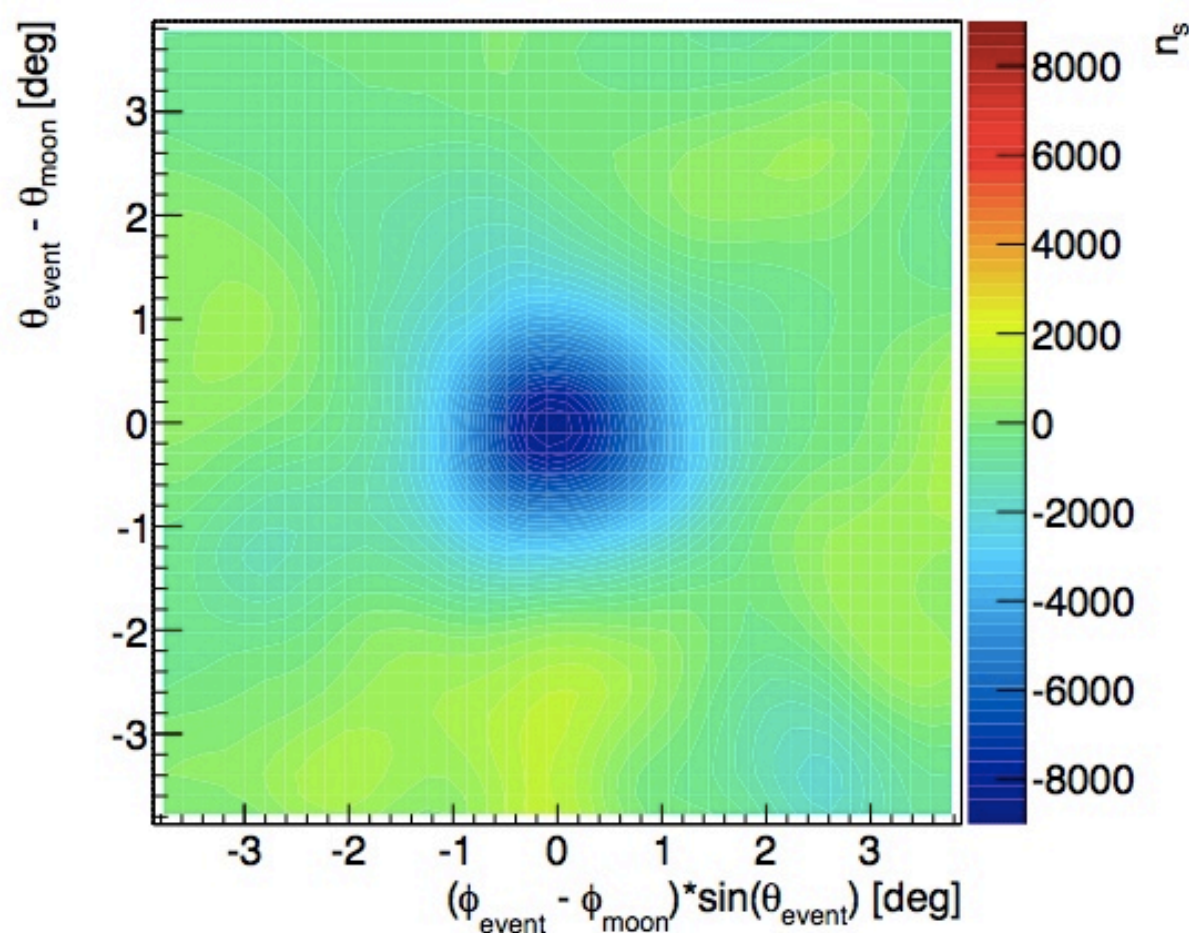


IceCube Detector Performance - Angular Resolution

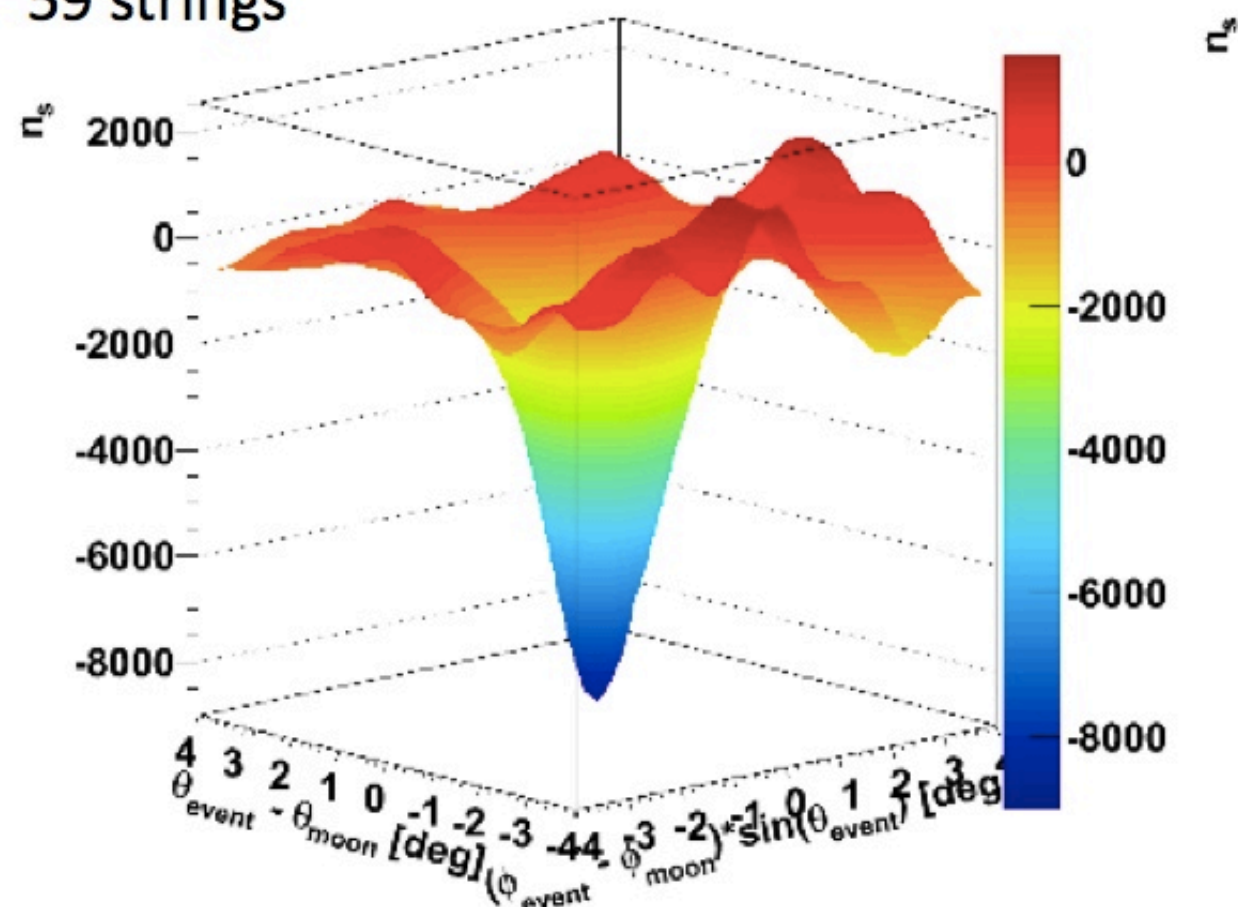


Existence of the moon - confirmed!

- 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 $< 1^\circ$ at 1 TeV.

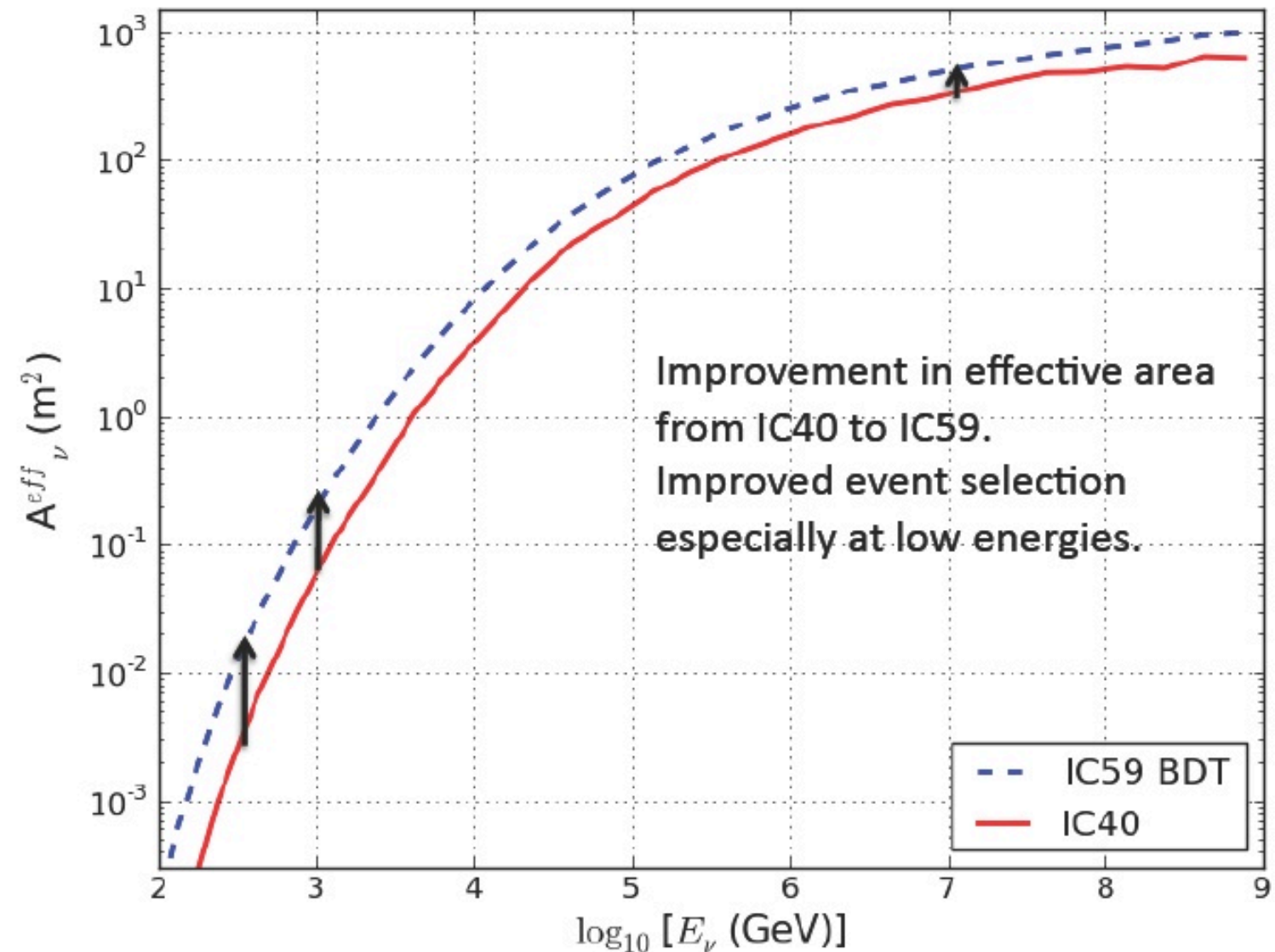


59 strings

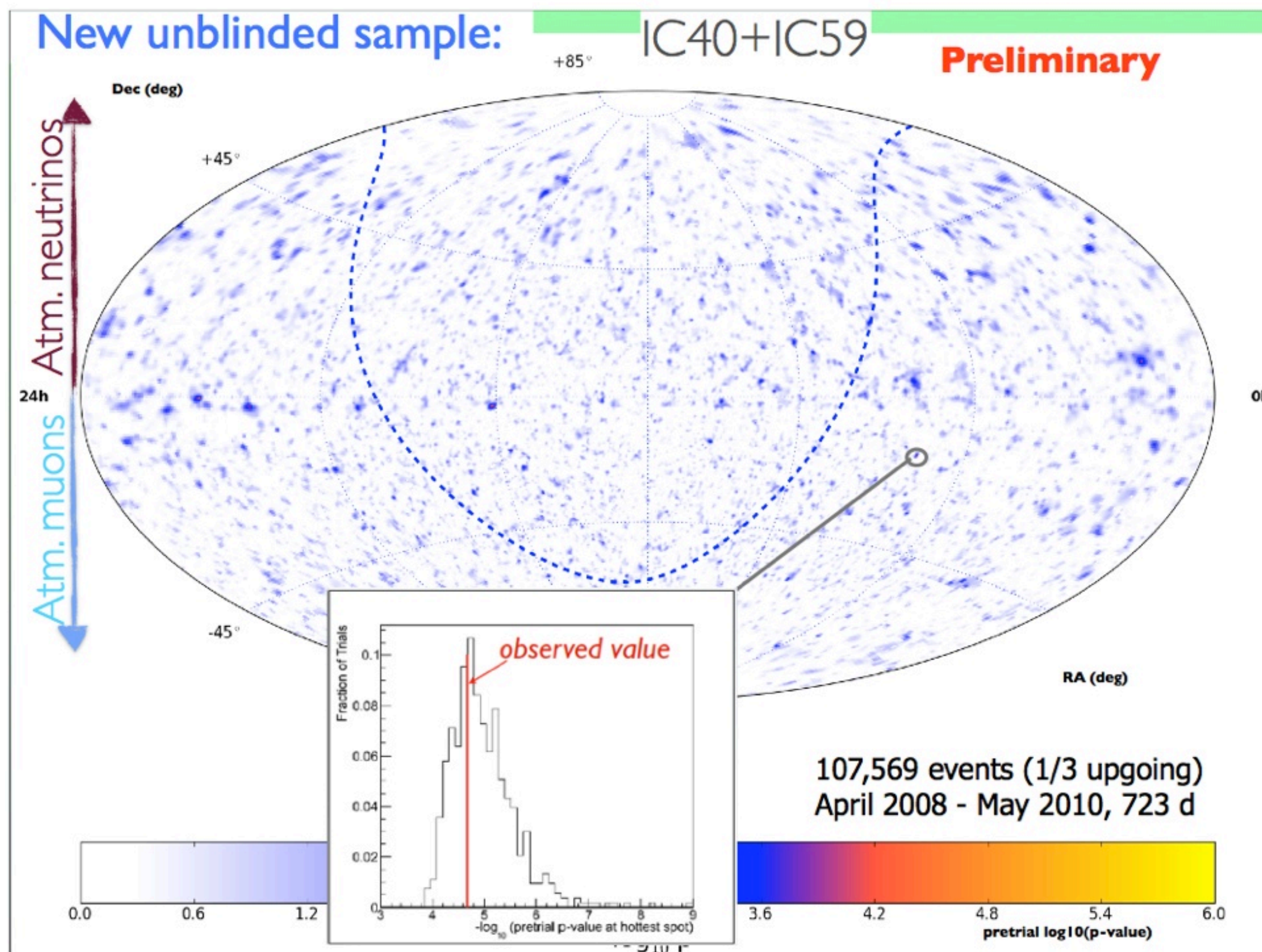


IceCube Detector Performance - Effective Neutrino Area

- 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...

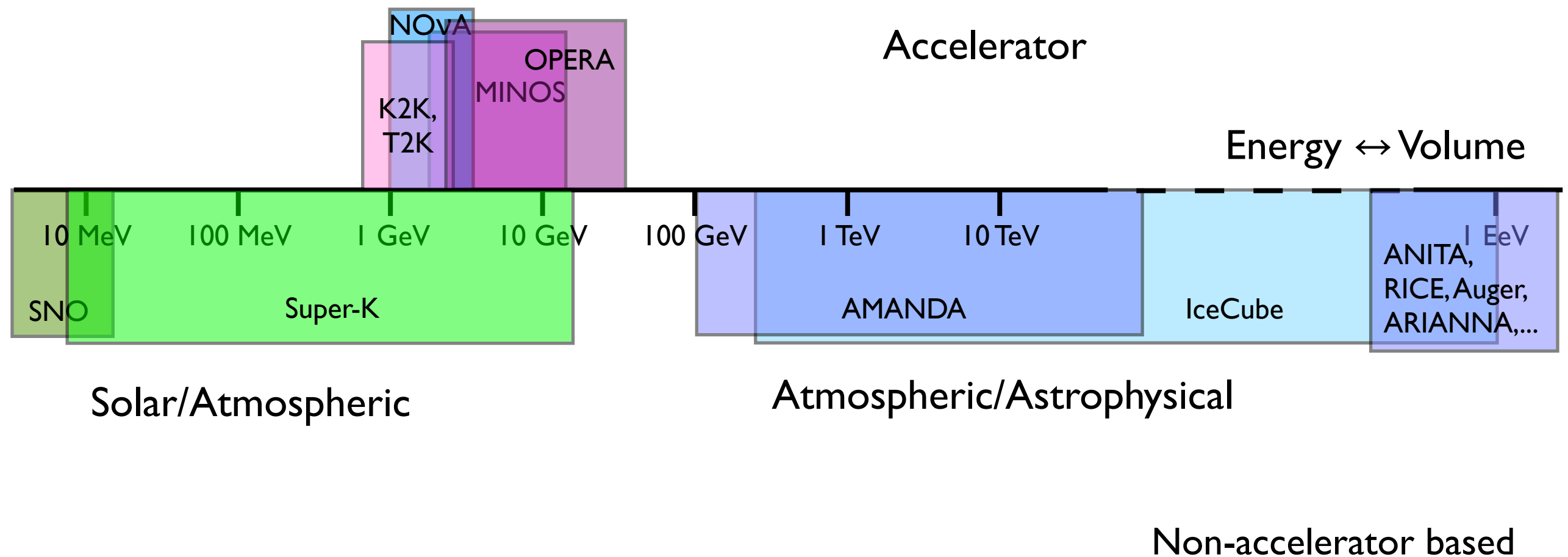


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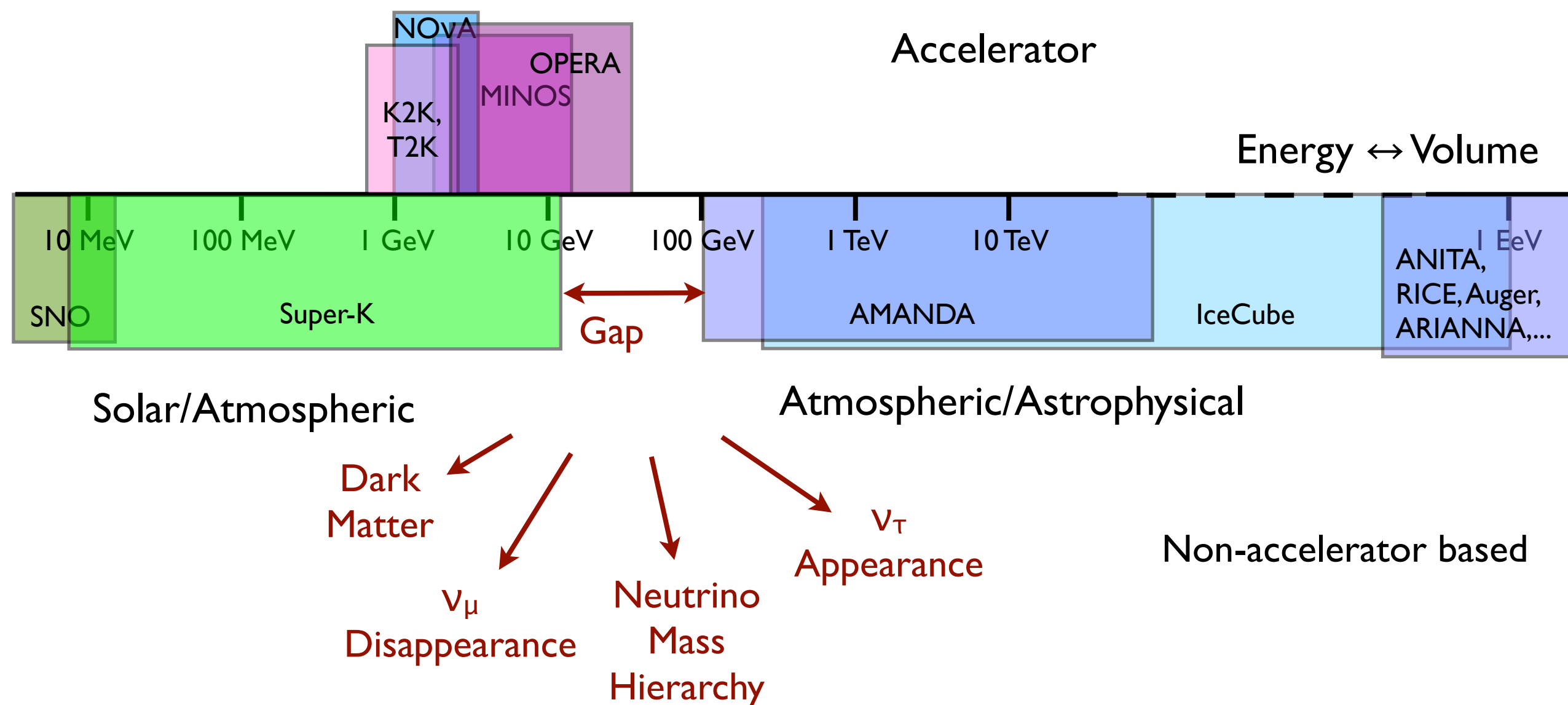
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The Neutrino Detector Spectrum



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

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IceCube

IceCube



IceCube

IceCube-DeepCore



IceCube



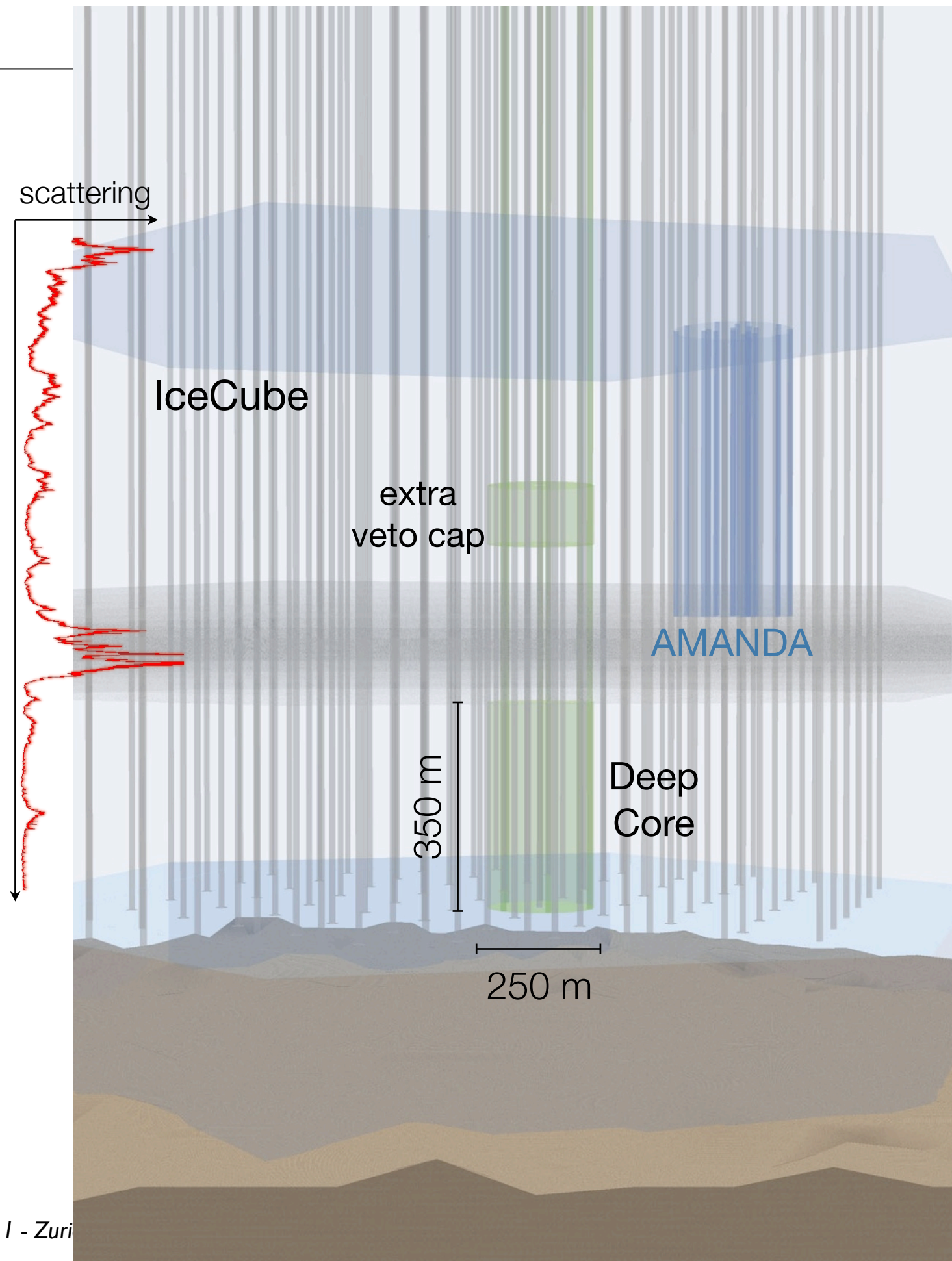
DeepCore

IceCube-DeepCore

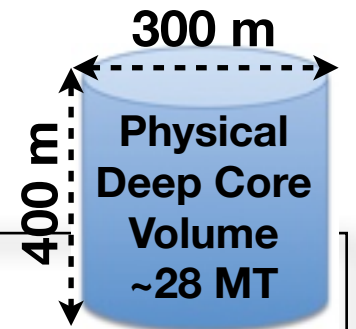
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
- Significant improvement in capabilities from ~ 10 GeV to ~ 300 GeV (ν_μ)
- Scientific Motivations:
 - Indirect search for dark matter
 - Neutrino oscillations (e.g., ν_τ appearance)
 - Neutrino point sources 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
- $\lambda_{\text{eff}} > \sim 50 \text{ m}$
- Result: 30 Mton detector with ~10 GeV threshold, will collect O(100k) physics quality atmospheric ν/yr

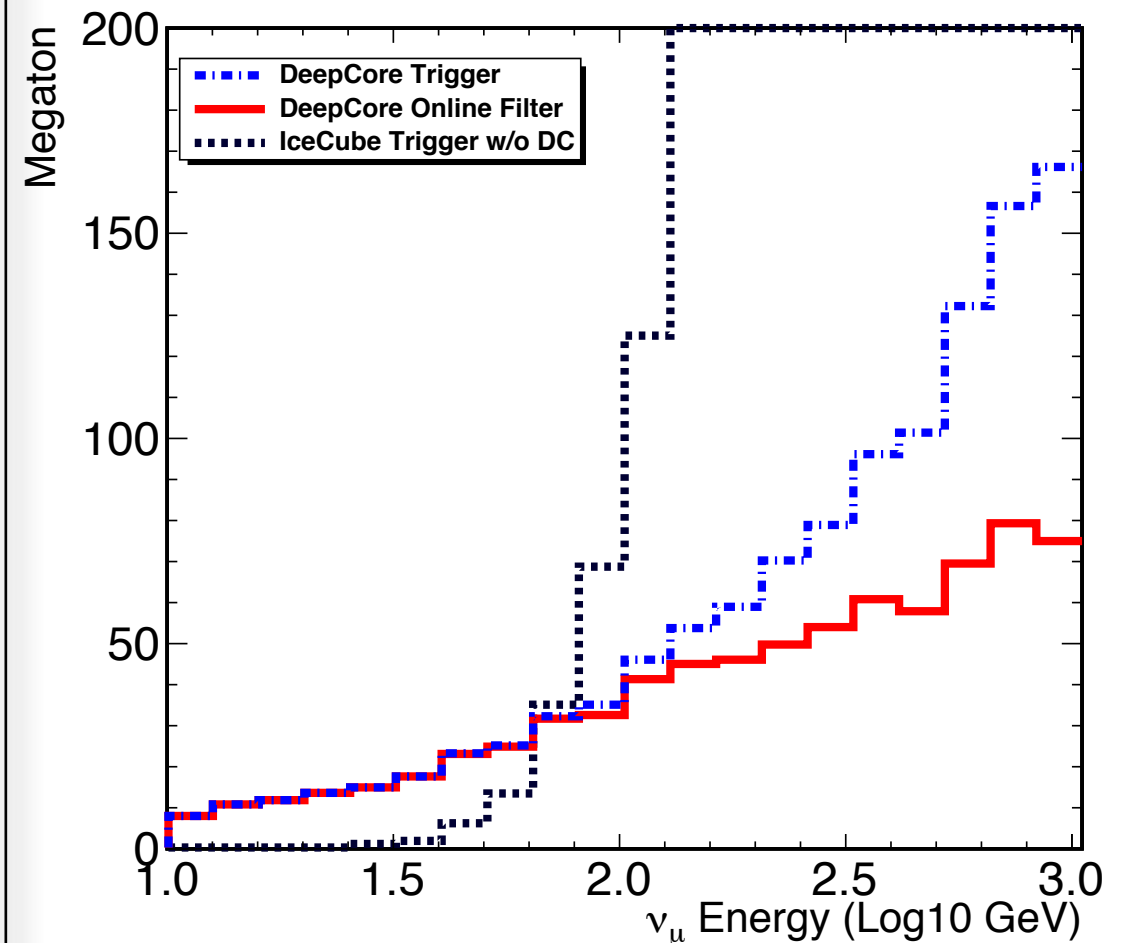
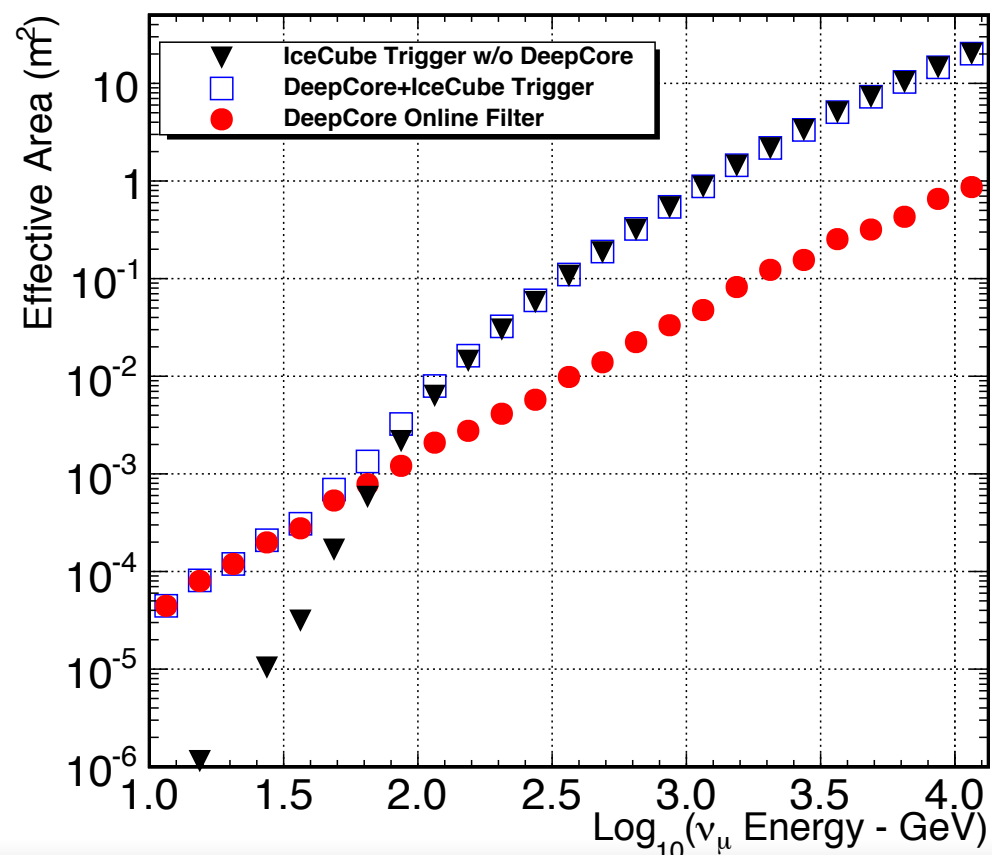


DeepCore Effective Area and Volume



Effective area for up-going ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase



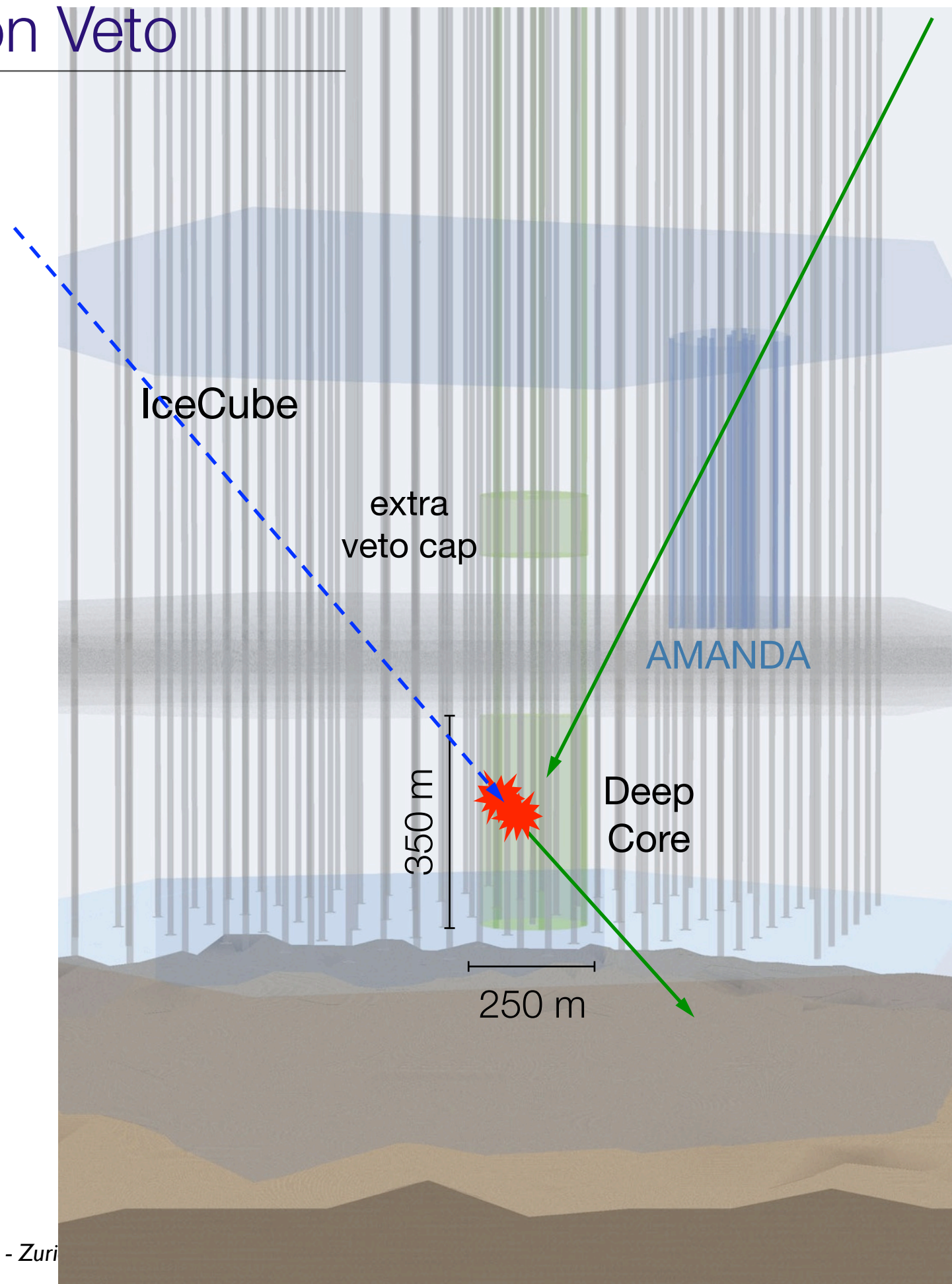
Effective volume for muons from ν_μ interacting in Deep Core

NB: full analysis efficiency *not* included yet

Trigger: ≥ 3 DOMs hit in $2.5\mu\text{s}$;
Online Veto: No hits consistent with muons outside DeepCore volume

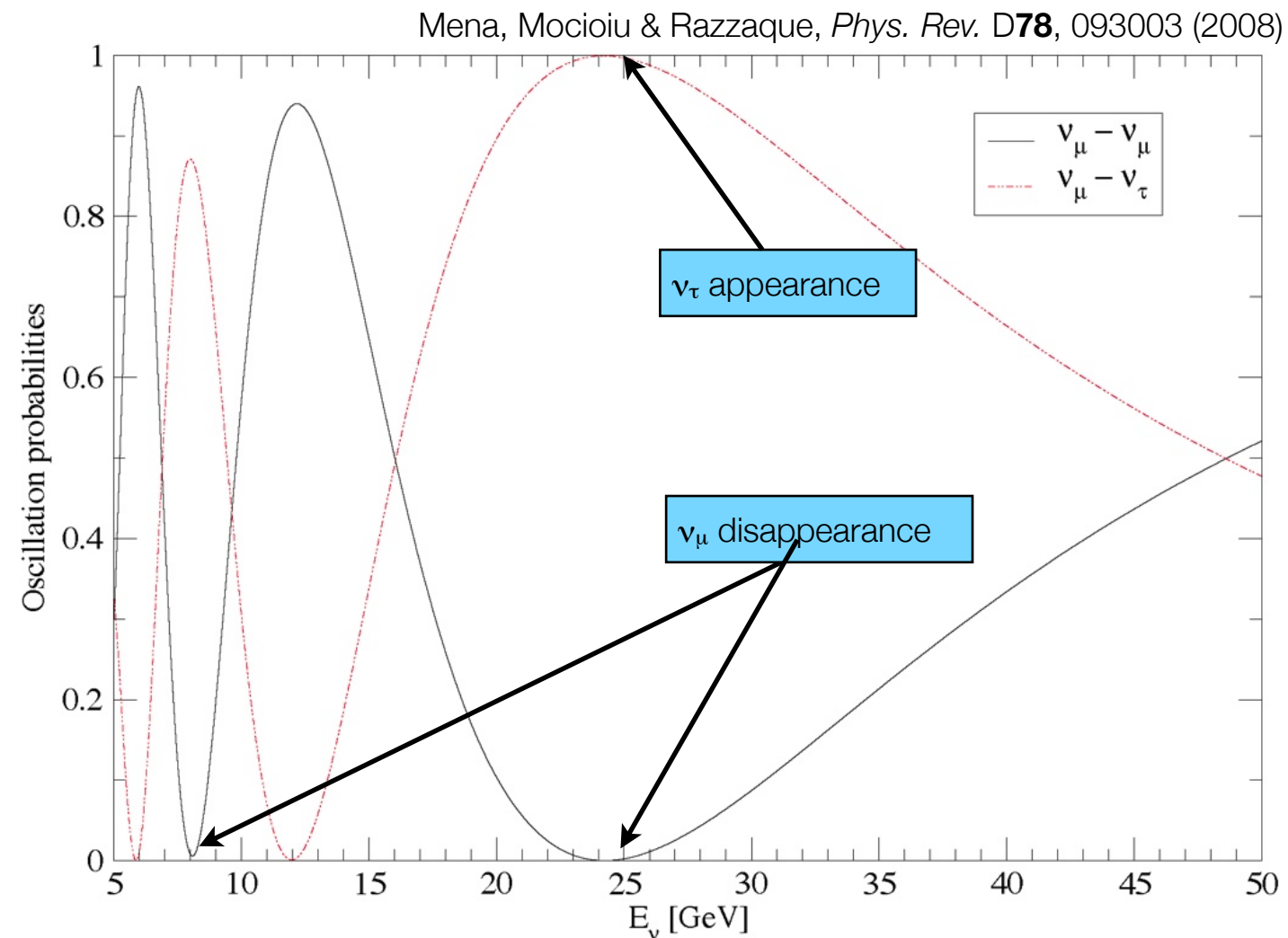
DeepCore Atmospheric Muon Veto

- 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 $\sim 10^6$
- Vetoing algorithms expected to reach at least 10^6 level of background rejection



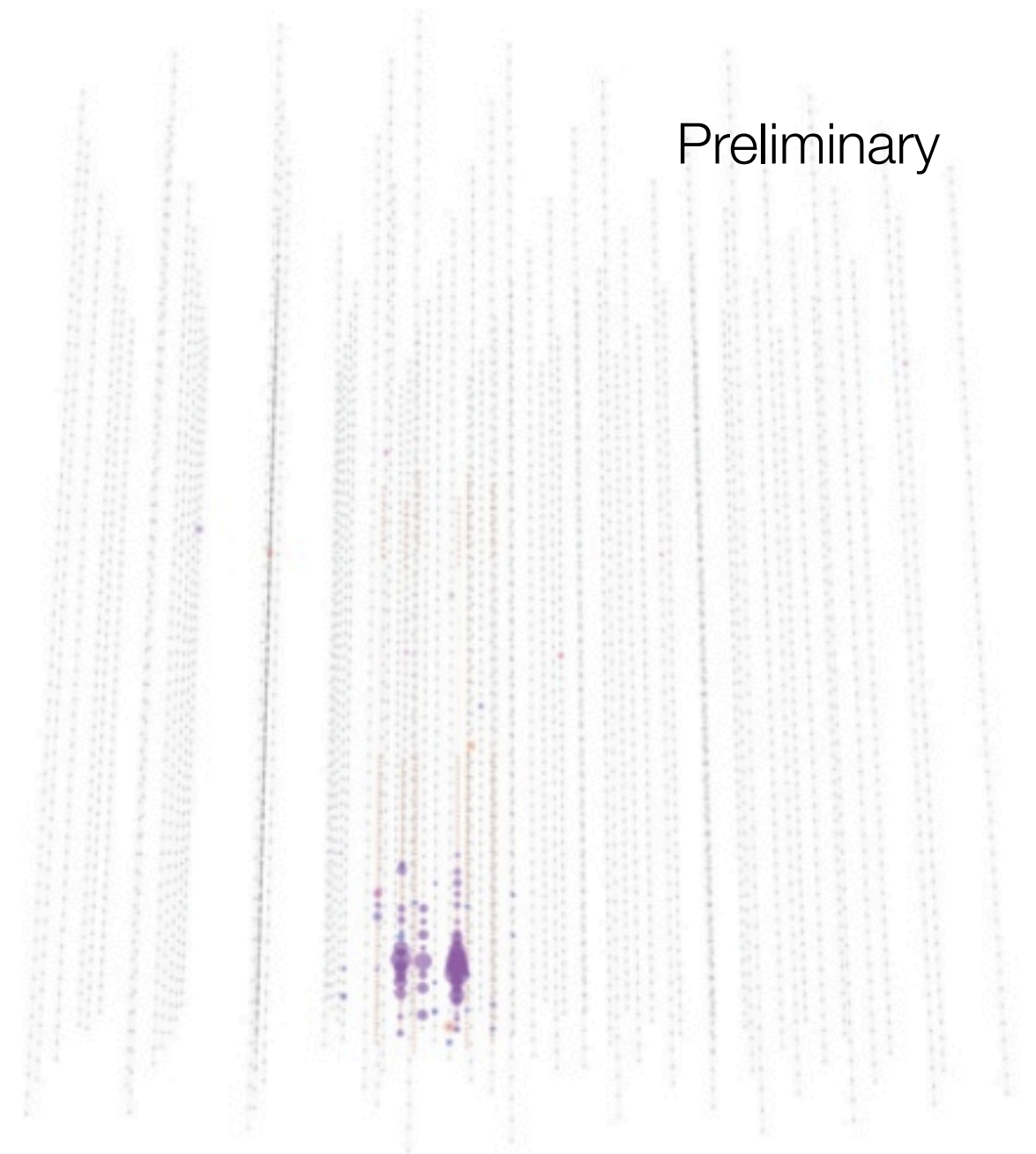
Observation of Atmospheric Cascades

- 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



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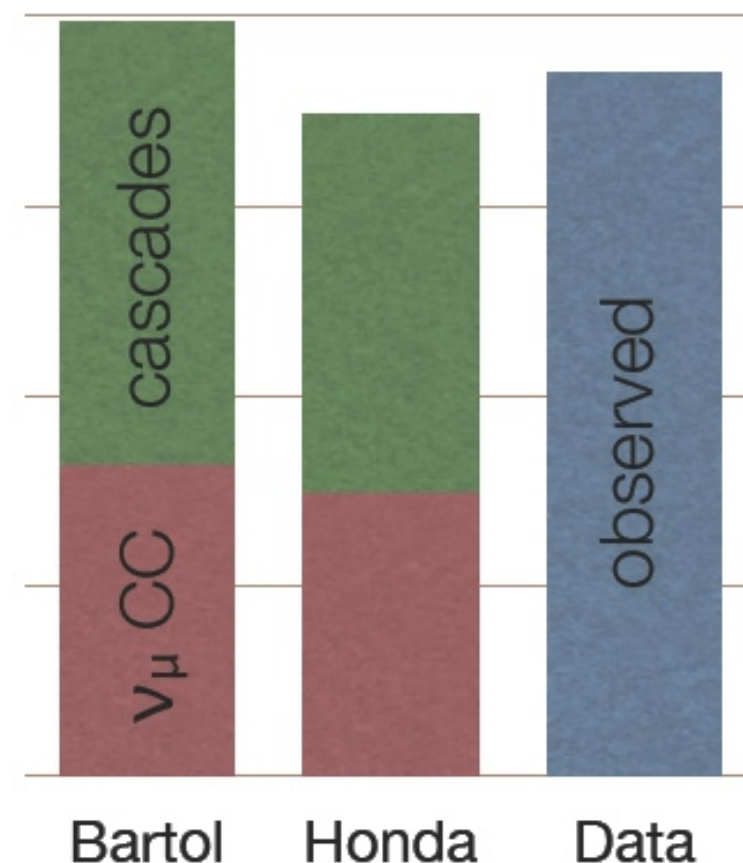
Candidate cascade event
Run 116020, Event 20788565, 2010/06/06

Observation of Atmospheric Cascades

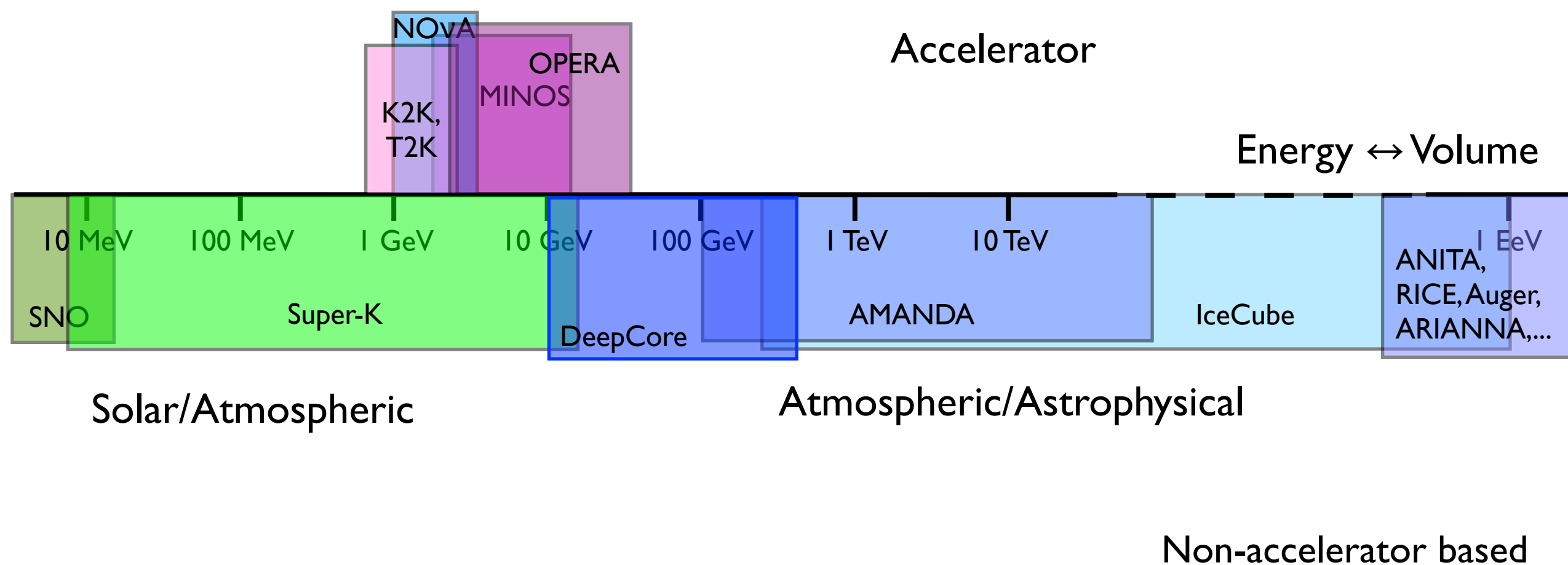
- A substantial sample of cascades has been obtained, final data set ~60% cascade events
 - Events have a mean energy ~180 GeV (not sensitive to oscillations with these first cuts)
 - Atmospheric muon background is being assessed (expected to be small)
- The potential to discriminate between atmospheric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

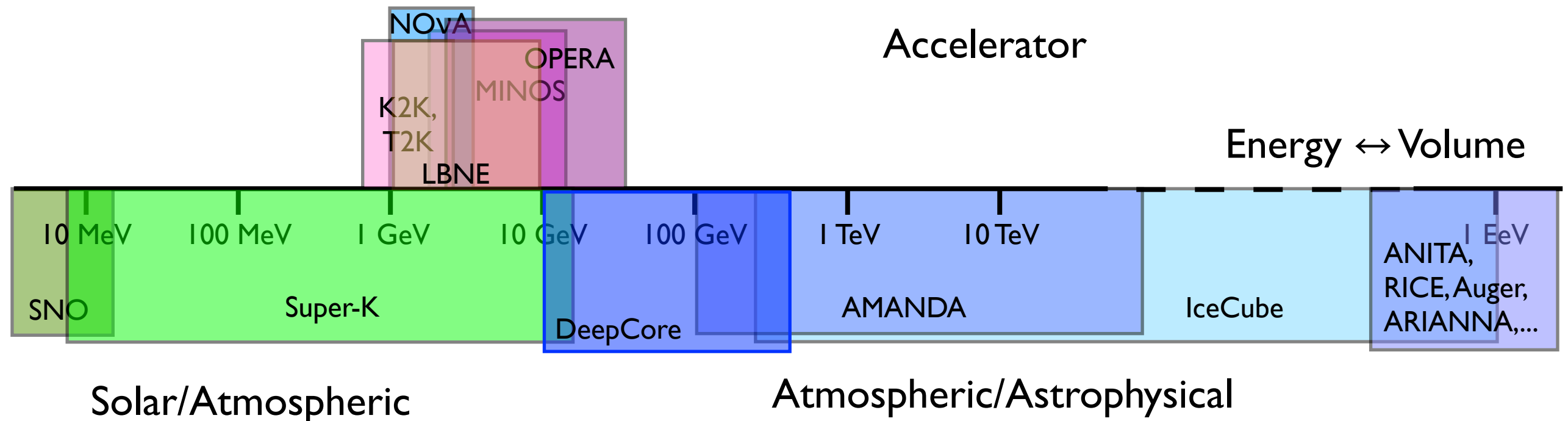


The Neutrino Detector Spectrum



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

The Neutrino Detector Spectrum



Non-accelerator based

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

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

IceCube-DeepCore



IceCube



DeepCore

IceCube-DeepCore



IceCube



DeepCore

IceCube-DeepCore-PINGU



IceCube

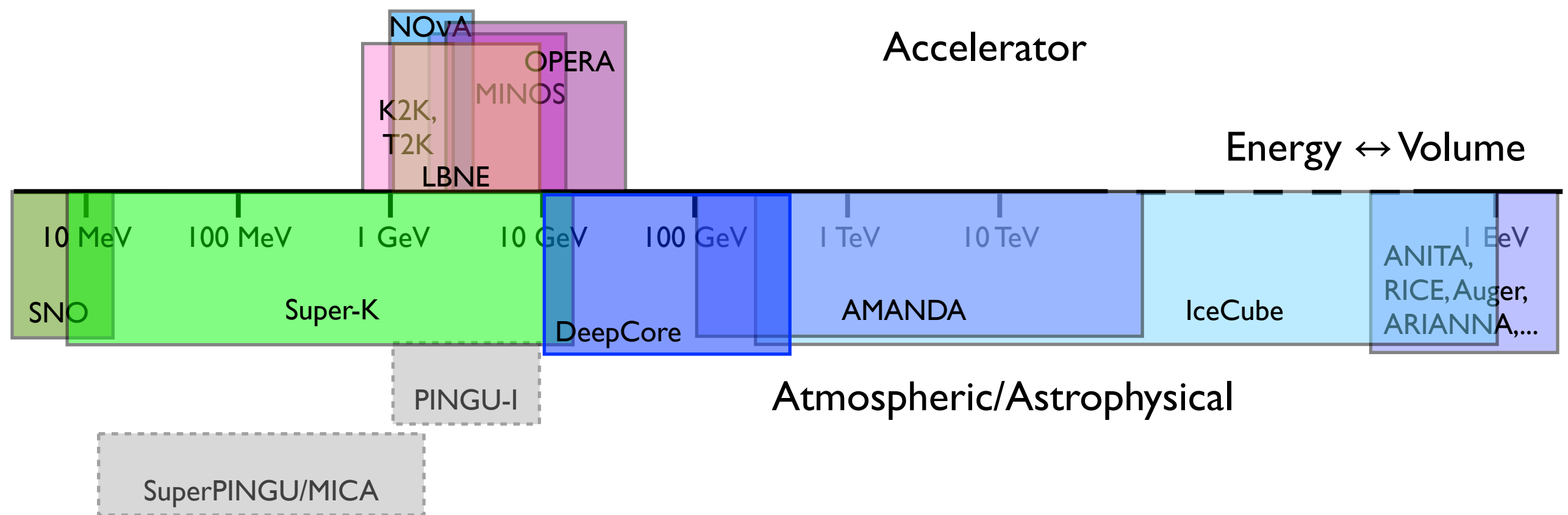


DeepCore



PINGU

PINGU - Phased IceCube Next Generation Upgrade



~70 active members in feasibility studies:

IceCube, KM3Net, Several neutrino experiments

Photon detector developers

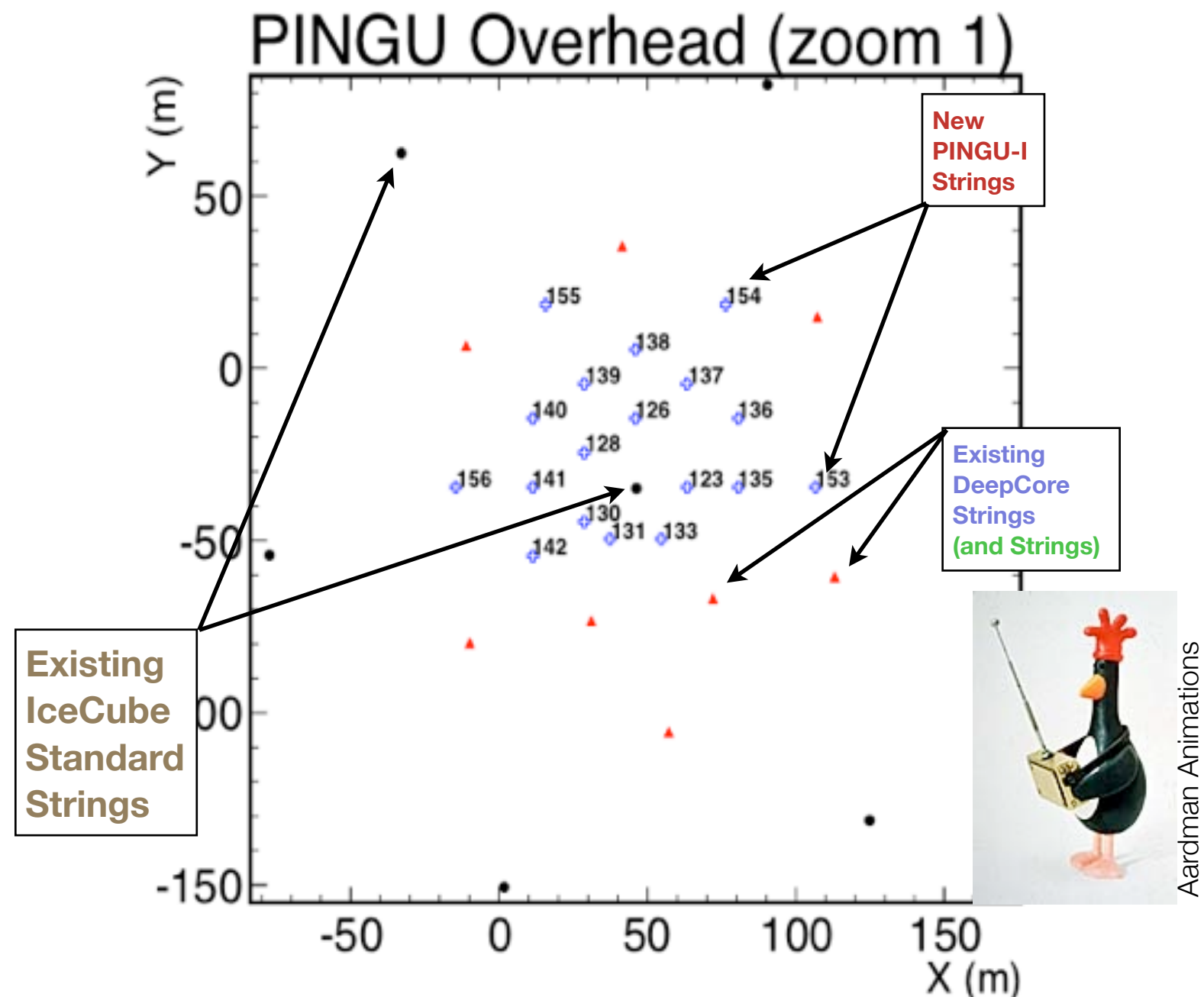
Theorists

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

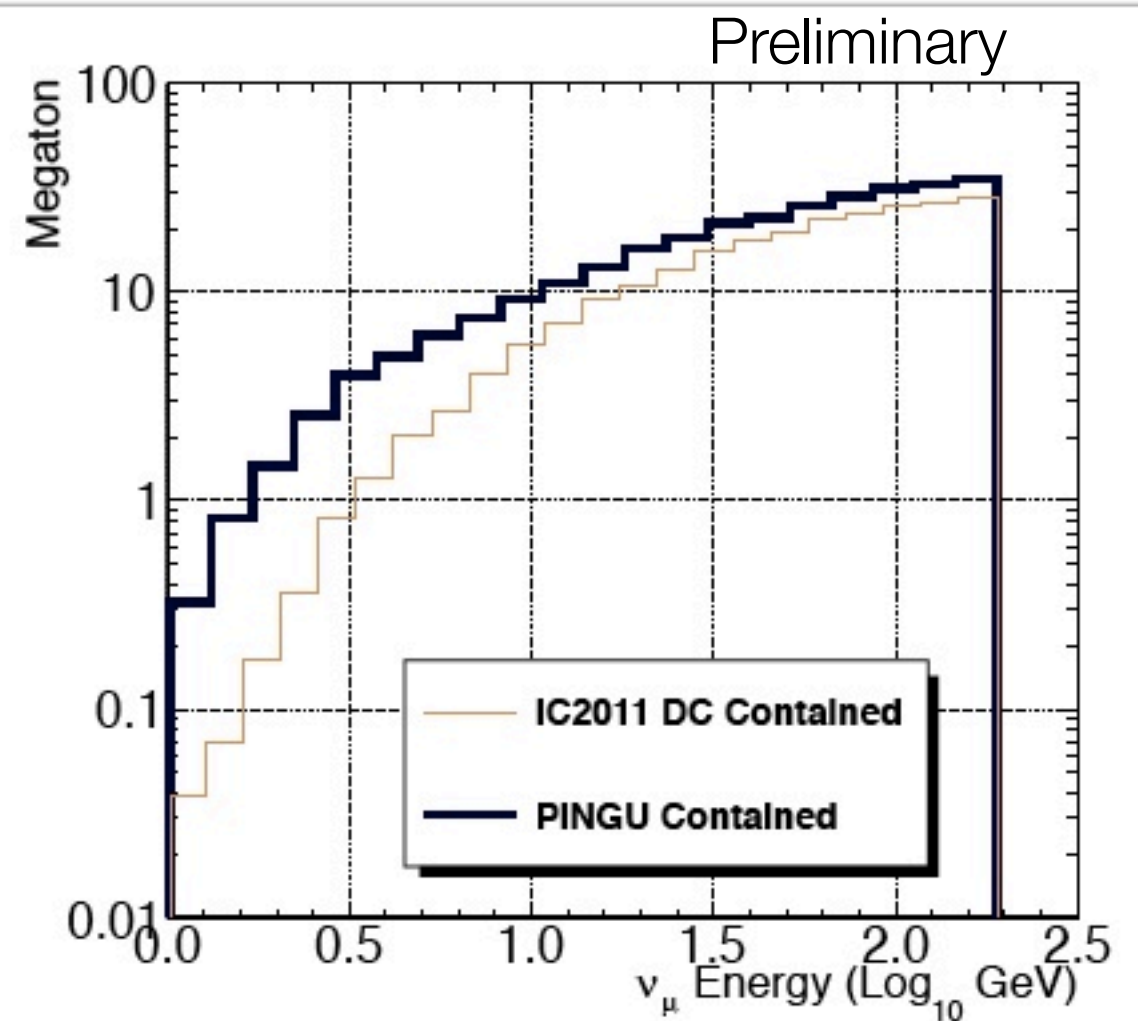
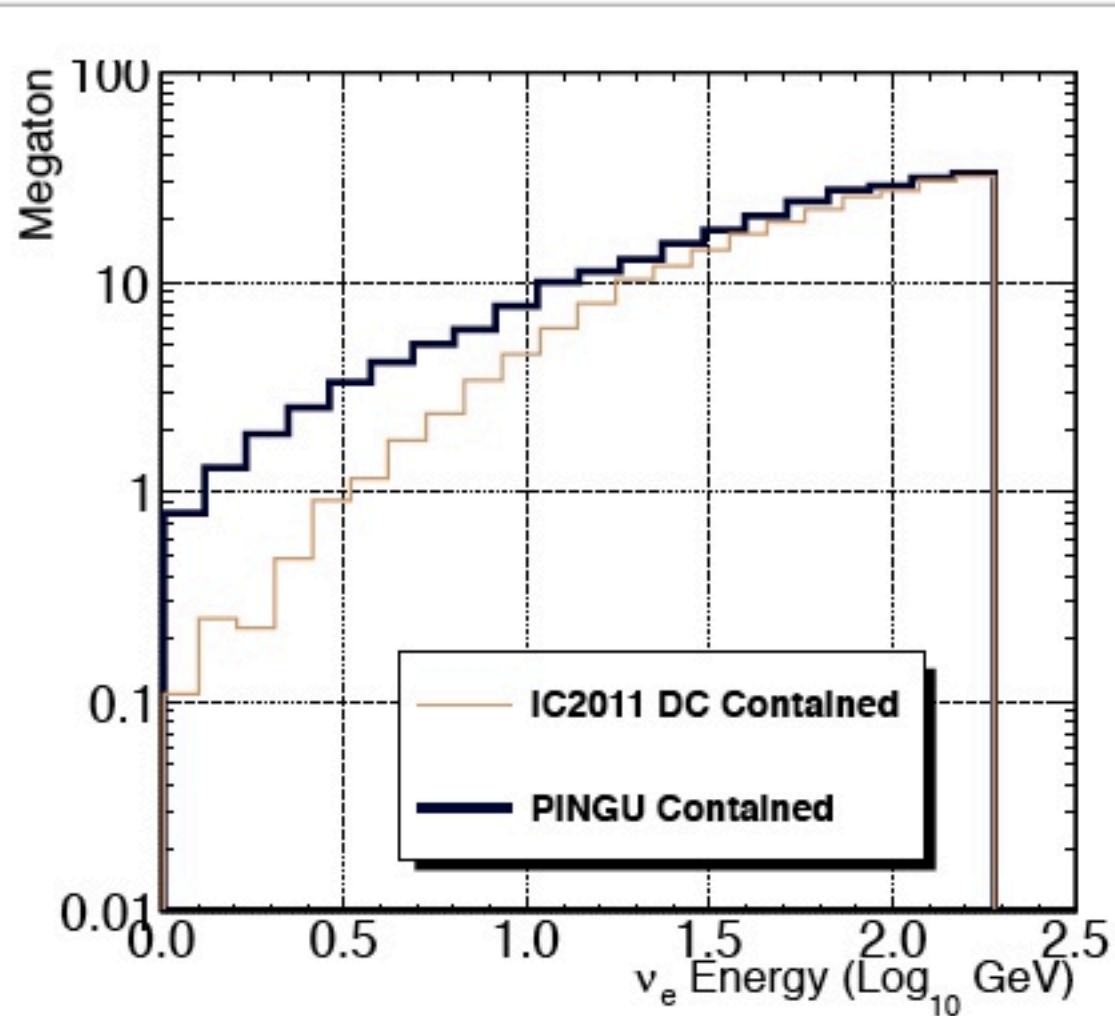
PINGU-I: Possible Geometry

- 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



- Price tag would likely be around \$25M

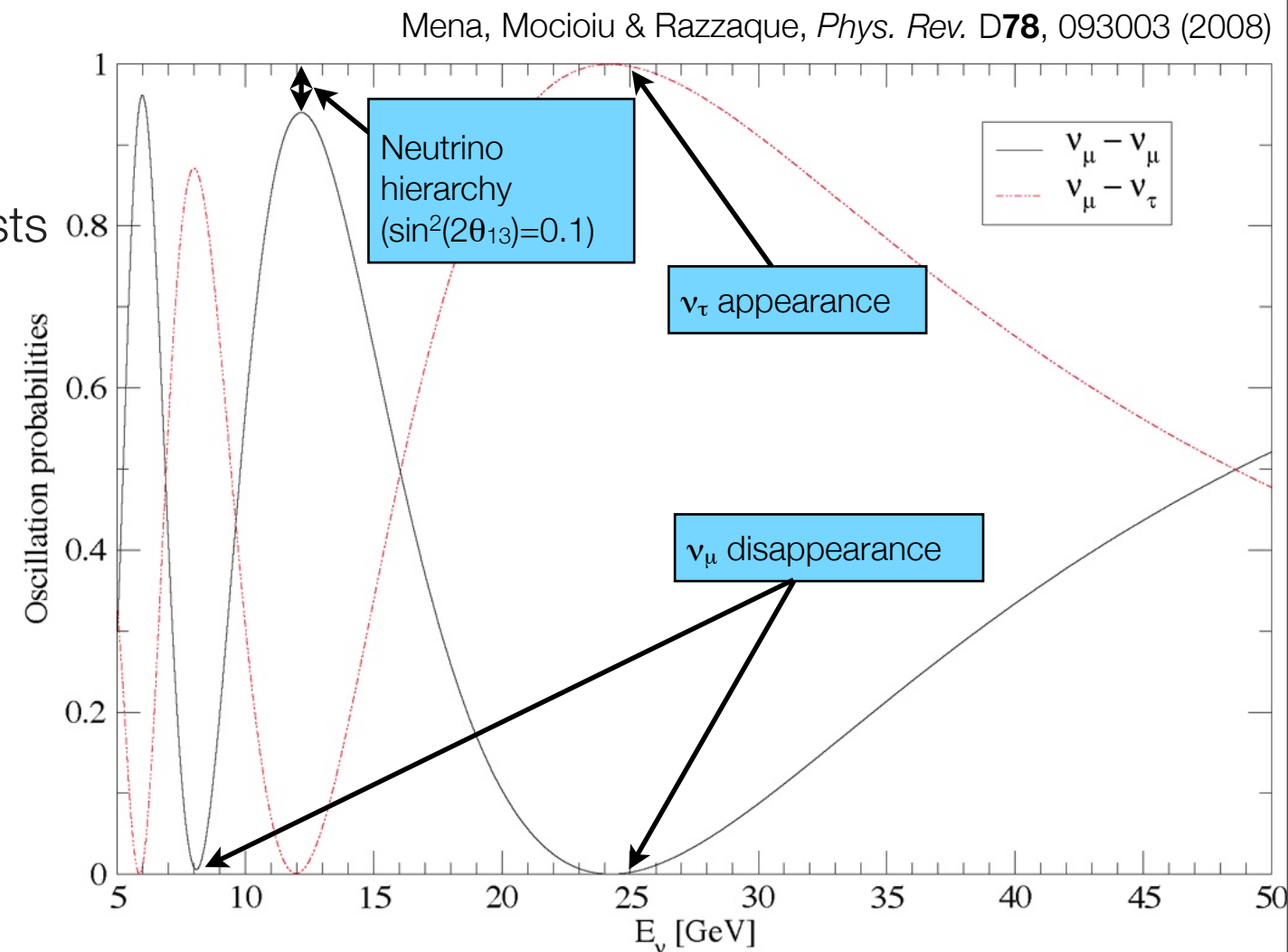
PINGU-I: Effective Volumes



- Increased effective volume for energies below ~ 15 GeV
- Nearly and order of magnitude increase at 1 GeV (100s of kTon)
- Expected improvement over DeepCore $> 10\times$ 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

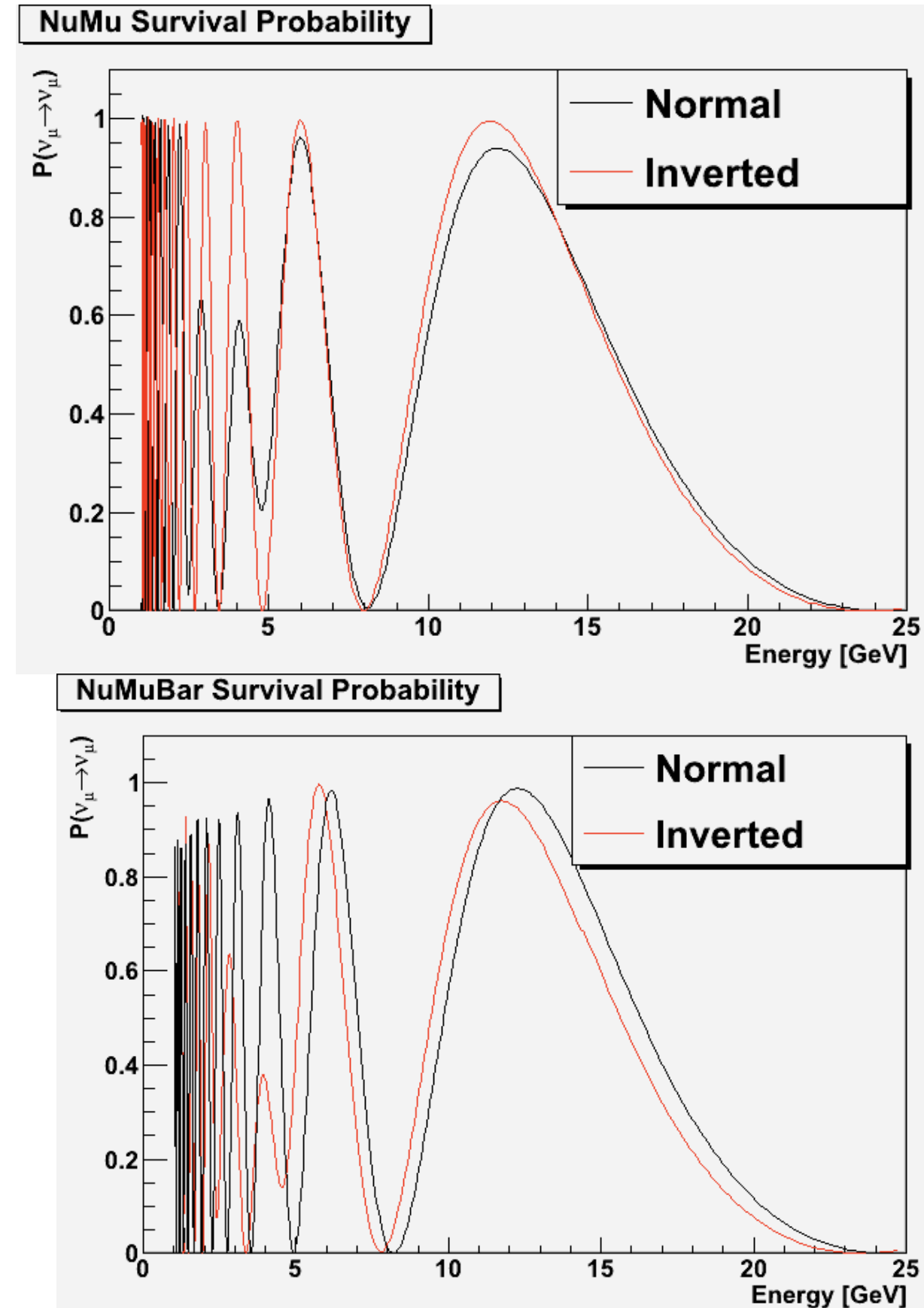
Possible sensitivity to neutrino mass hierarchy via matter effects if θ_{13} is large

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}



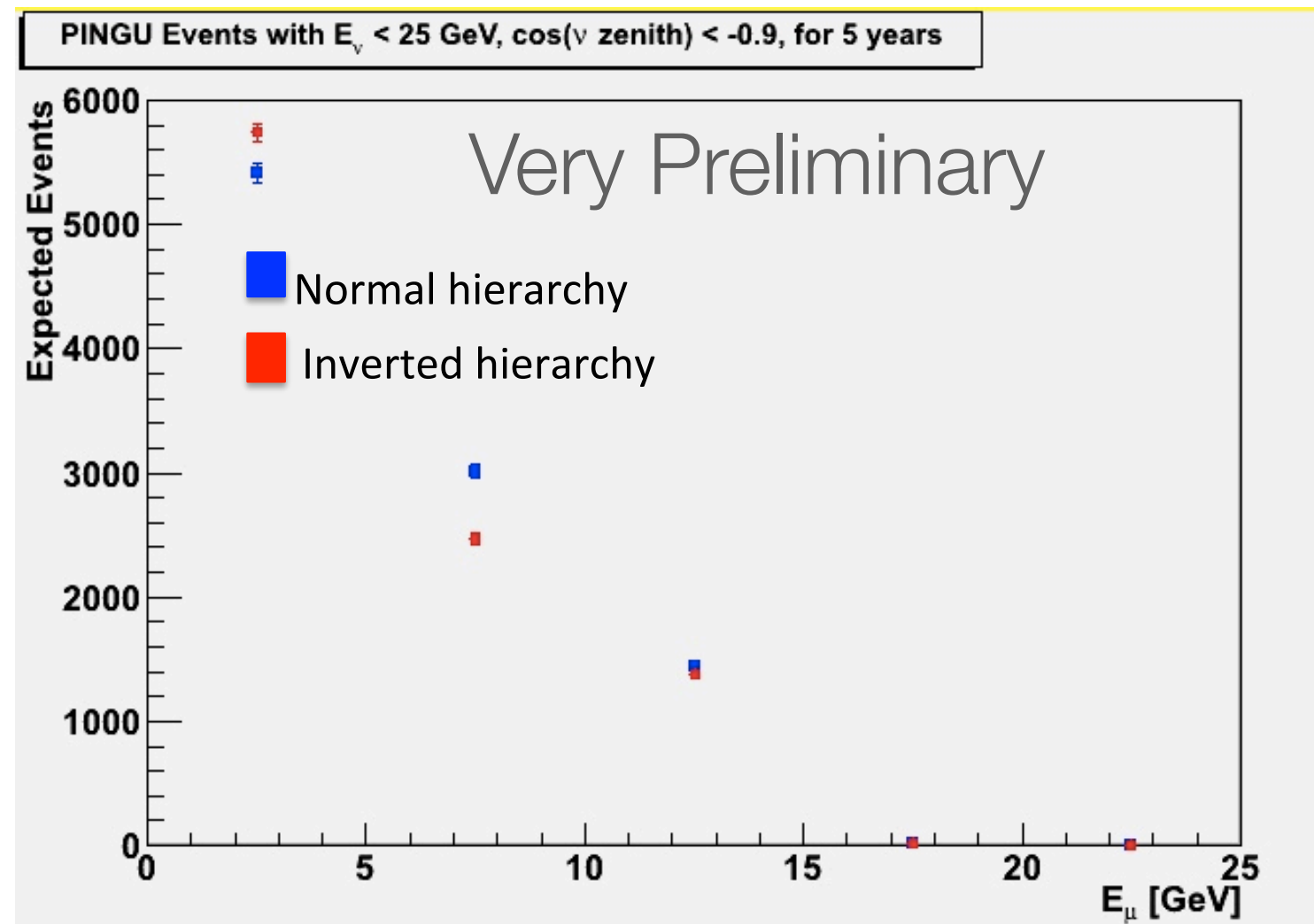
PINGU-I Neutrino Mass Hierarchy

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>

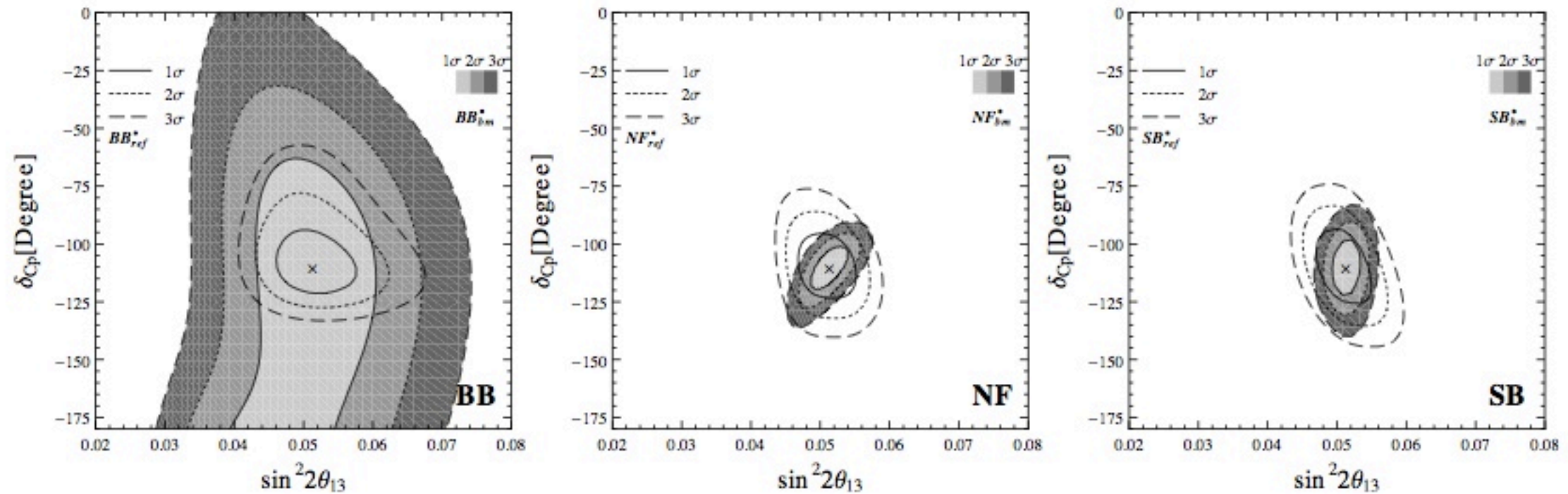
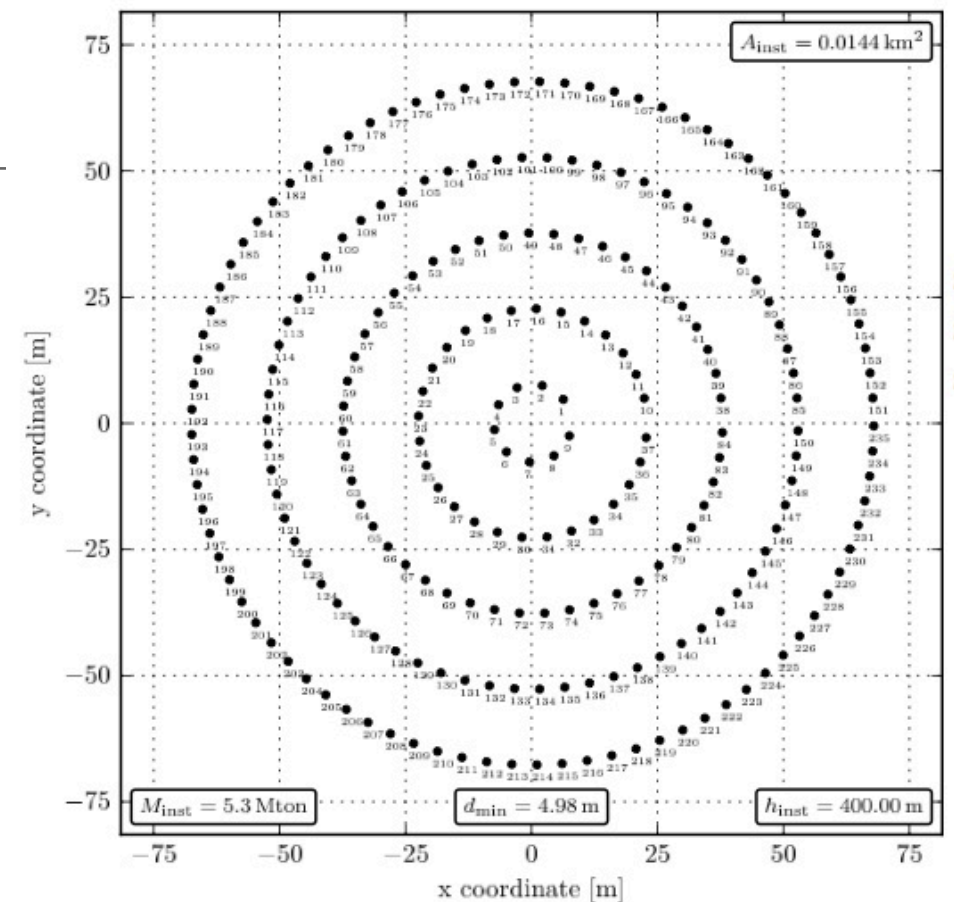


Figure 12: The precision measurements of CP phase δ_{CP} and $\sin^2 2\theta_{13}$ for three single-baseline neutrino experiments: Beta Beam (BB), Neutrino Factory (NF), and SuperBeam (SB). The contours represent the 1 σ , 2 σ and 3 σ confidence levels (2 d.o.f.). Filled contours represent the PINGU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

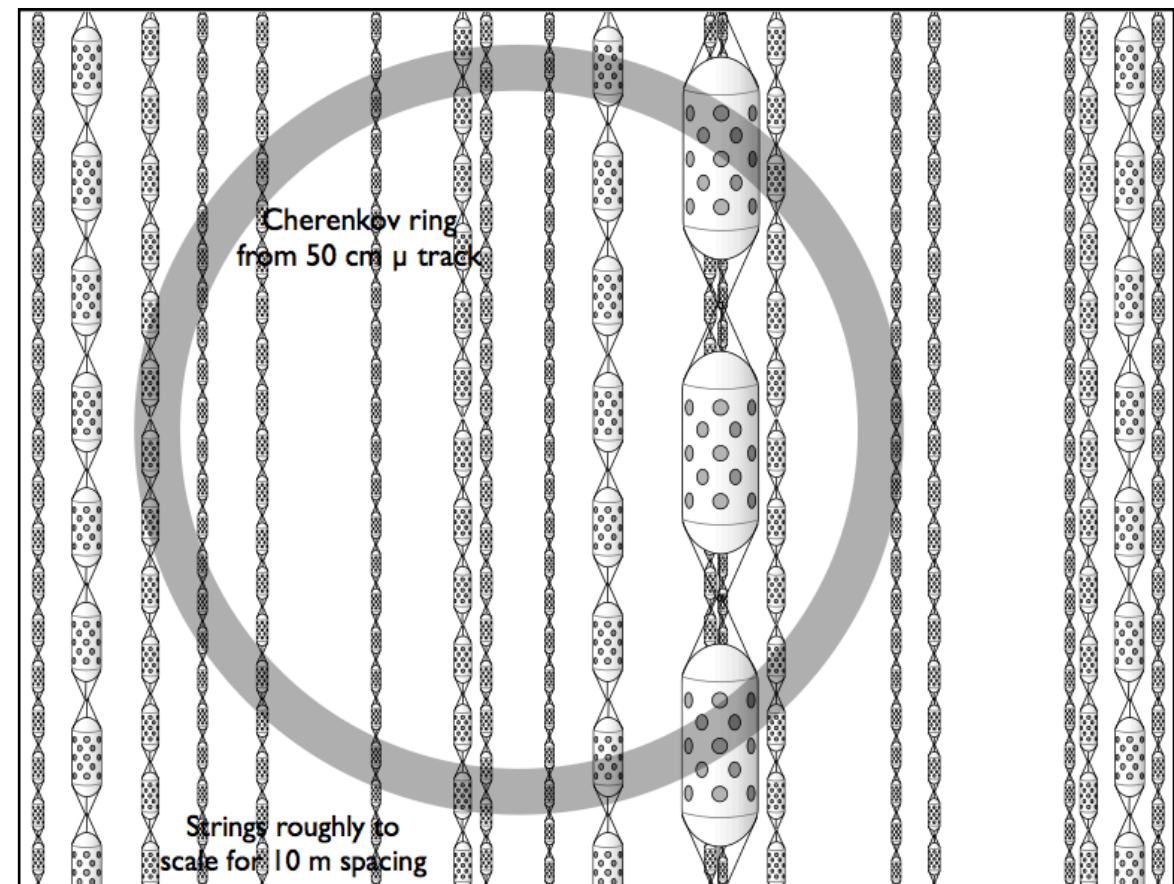
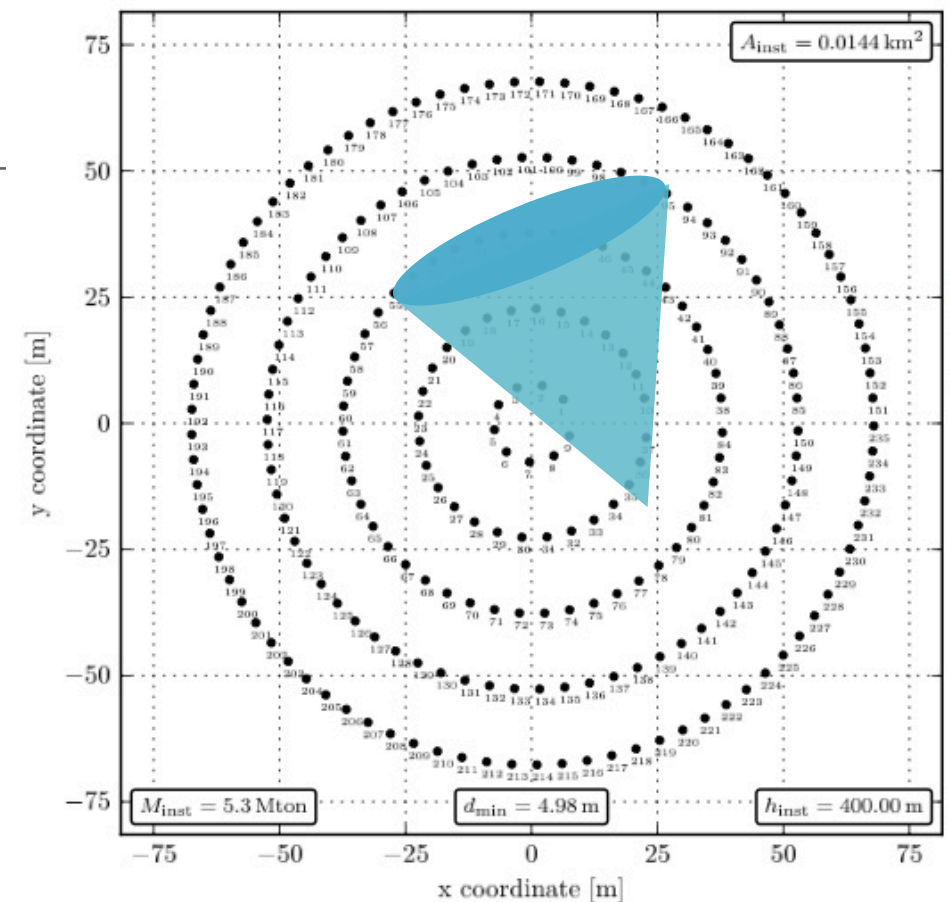
SuperPINGU Conceptual Detector

- 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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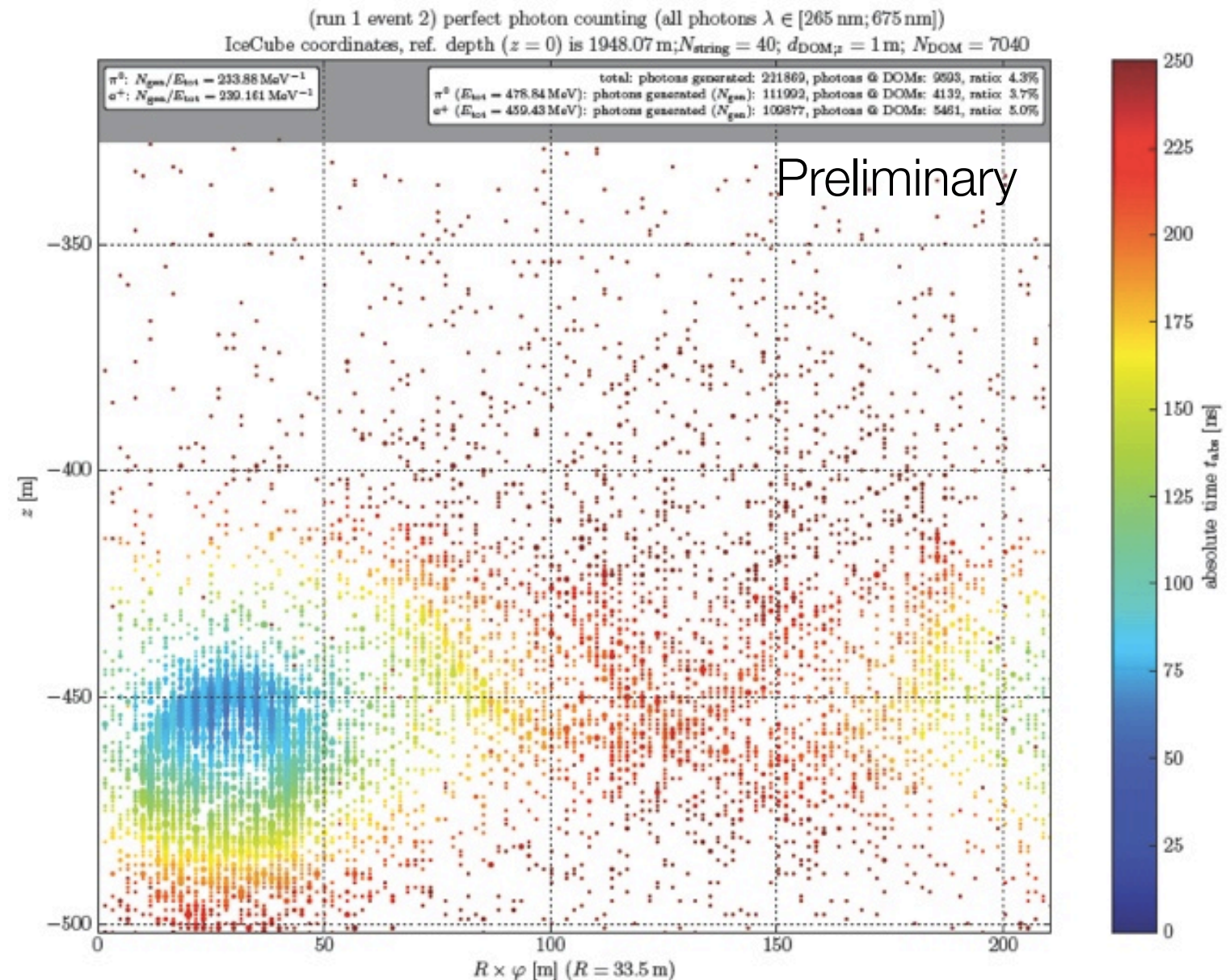


SuperPINGU Physics

- Proton decay
 - Studying sensitivity to $p \rightarrow \pi^0 + e^+$ 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 $M_{\text{GUT}} \ll M_{\text{Planck}}$
- 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



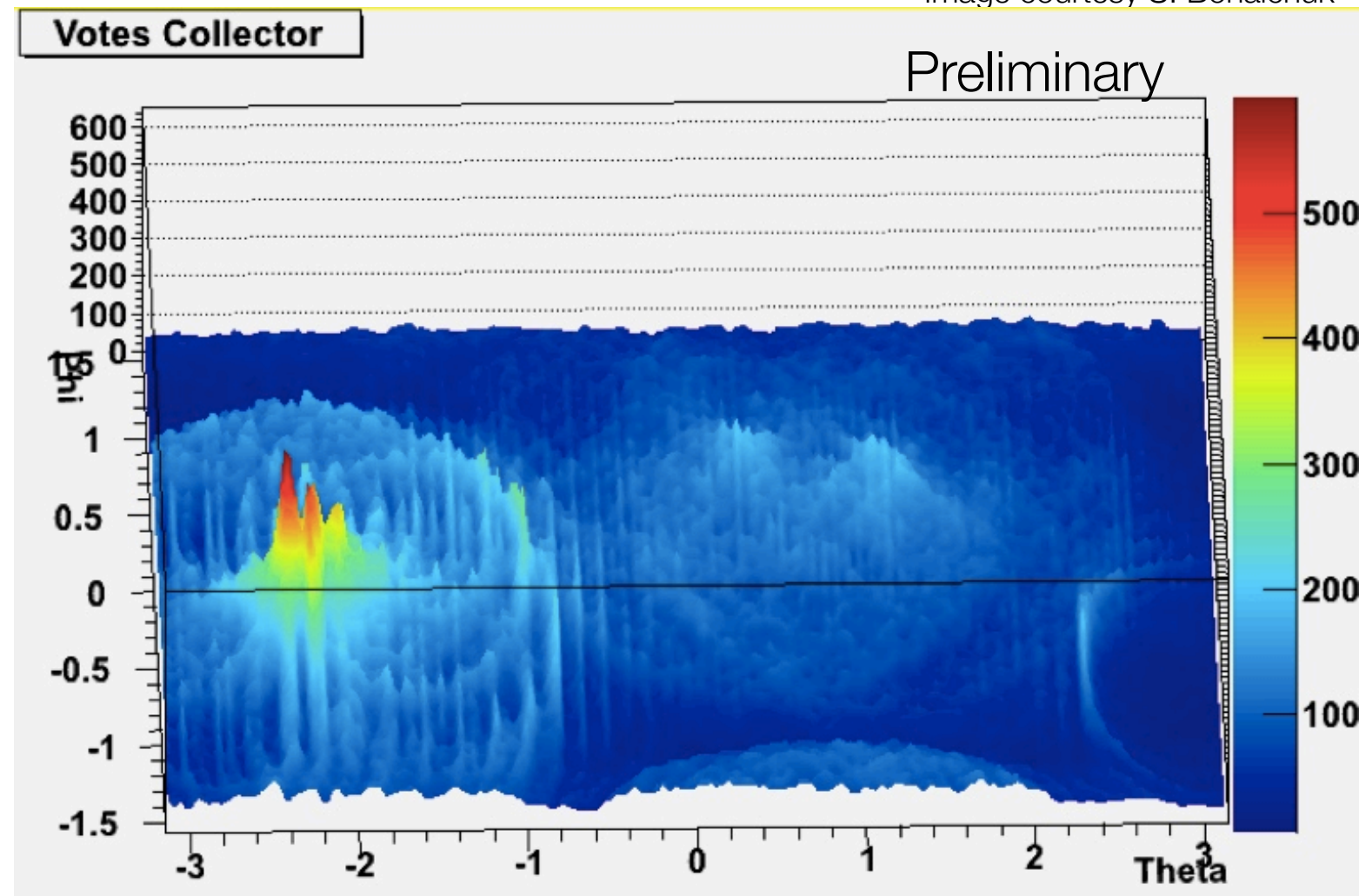
- First simulations underway. Above-strawman geometry ($\sim 750 \text{ MT}$)
- ~ 240 photons per MeV deposited energy. 4-5% photons detected (assuming complete acceptance)

SuperPINGU Proton Decay

Courtesy E. Resconi

- For fiducial volume of 1.5 MT (5×10^{35} protons) with 10 MeV energy threshold
- $\tau_p \sim 10^{35} - 10^{36}$ yr for $p \rightarrow \pi^0 + e^+$ channel
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Image courtesy S. Bohaichuk



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SuperPINGU SuperNovae

- With a large-scale detector, $O(5\text{MT})$, designed for proton decay, you essentially confer sensitivity out to $O(10\text{ Mpc})$.
- 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,...)

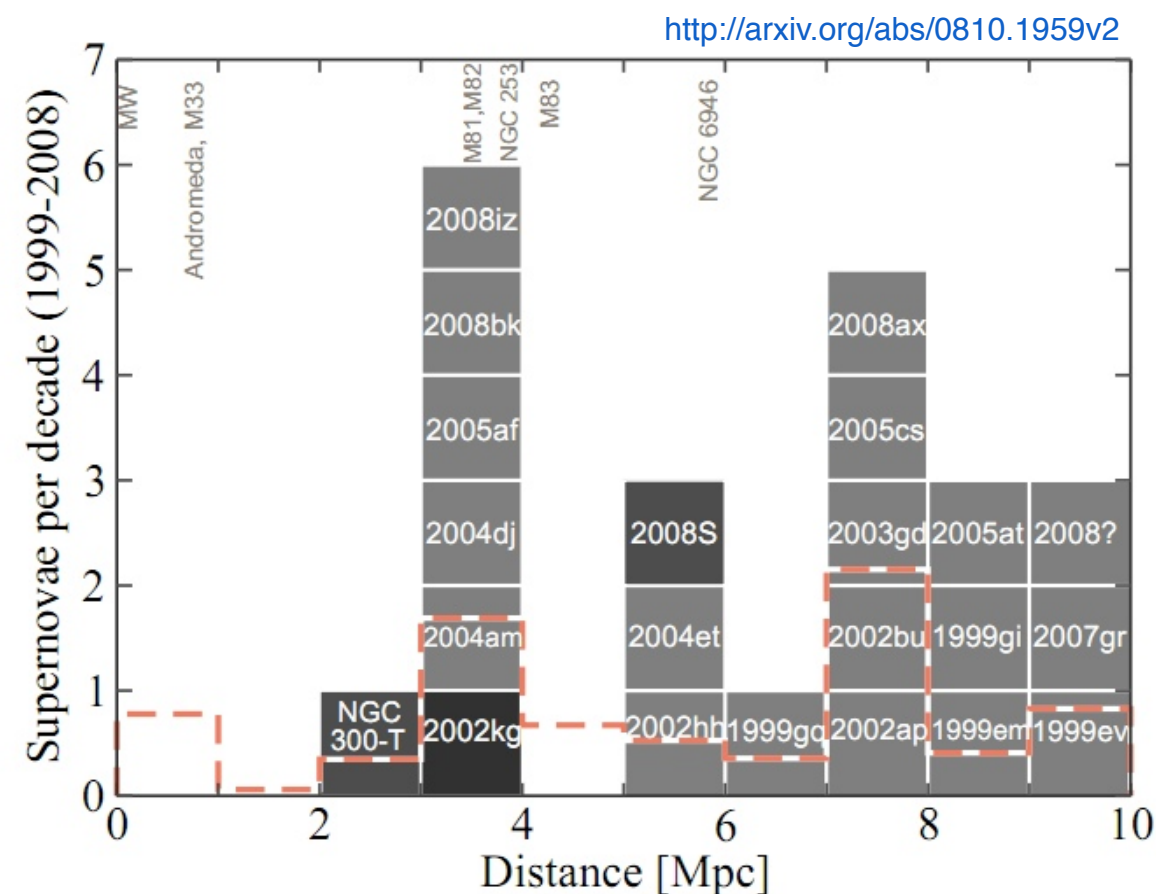
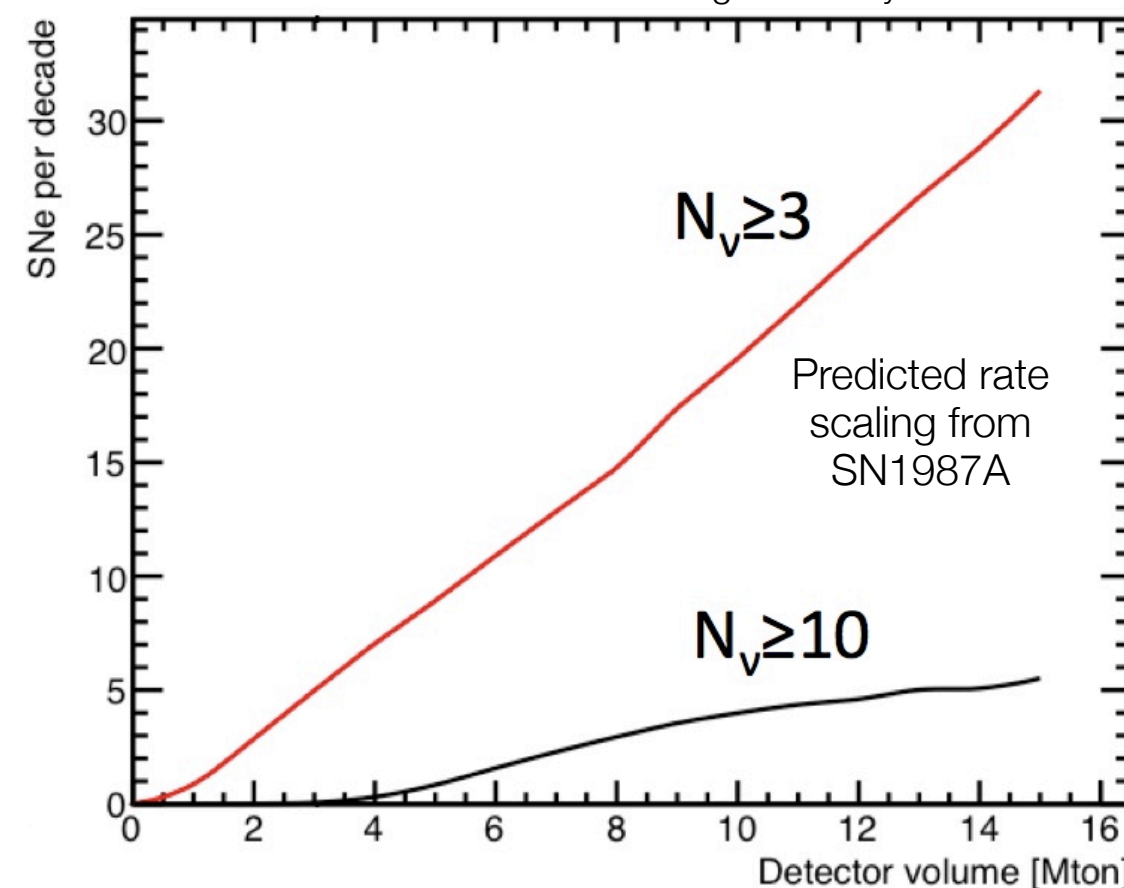
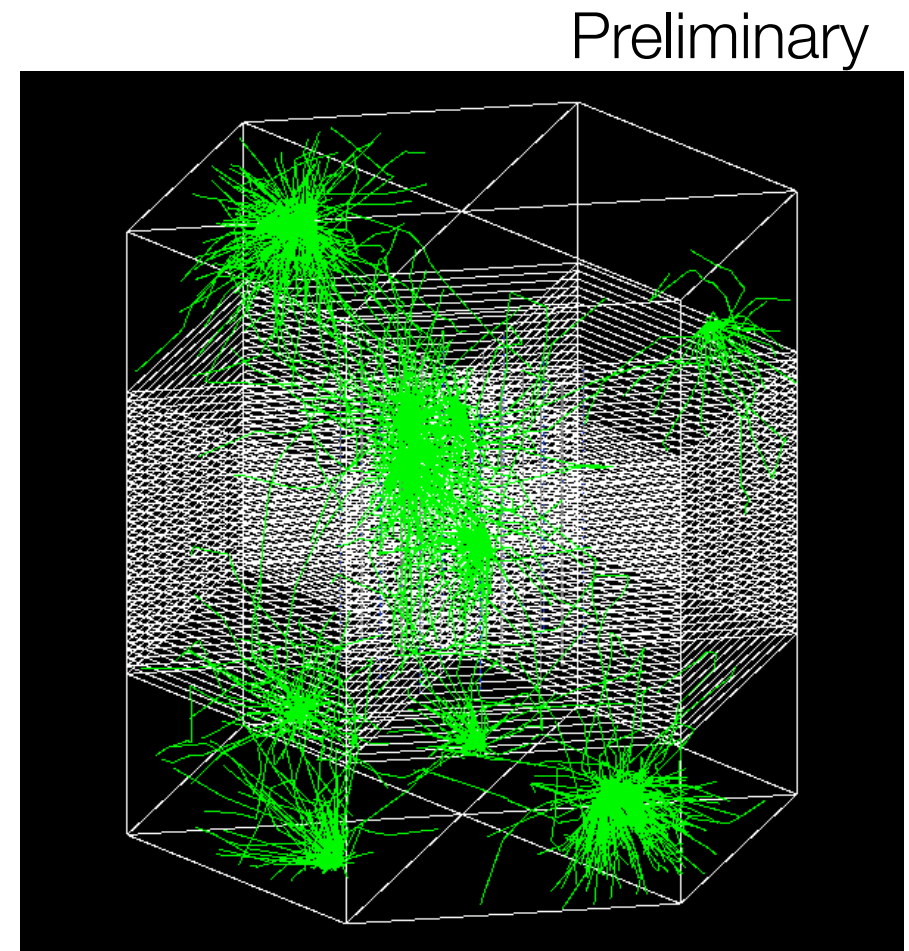


Image courtesy M. Kowalski



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Geant4: γ 's from SN ν 's

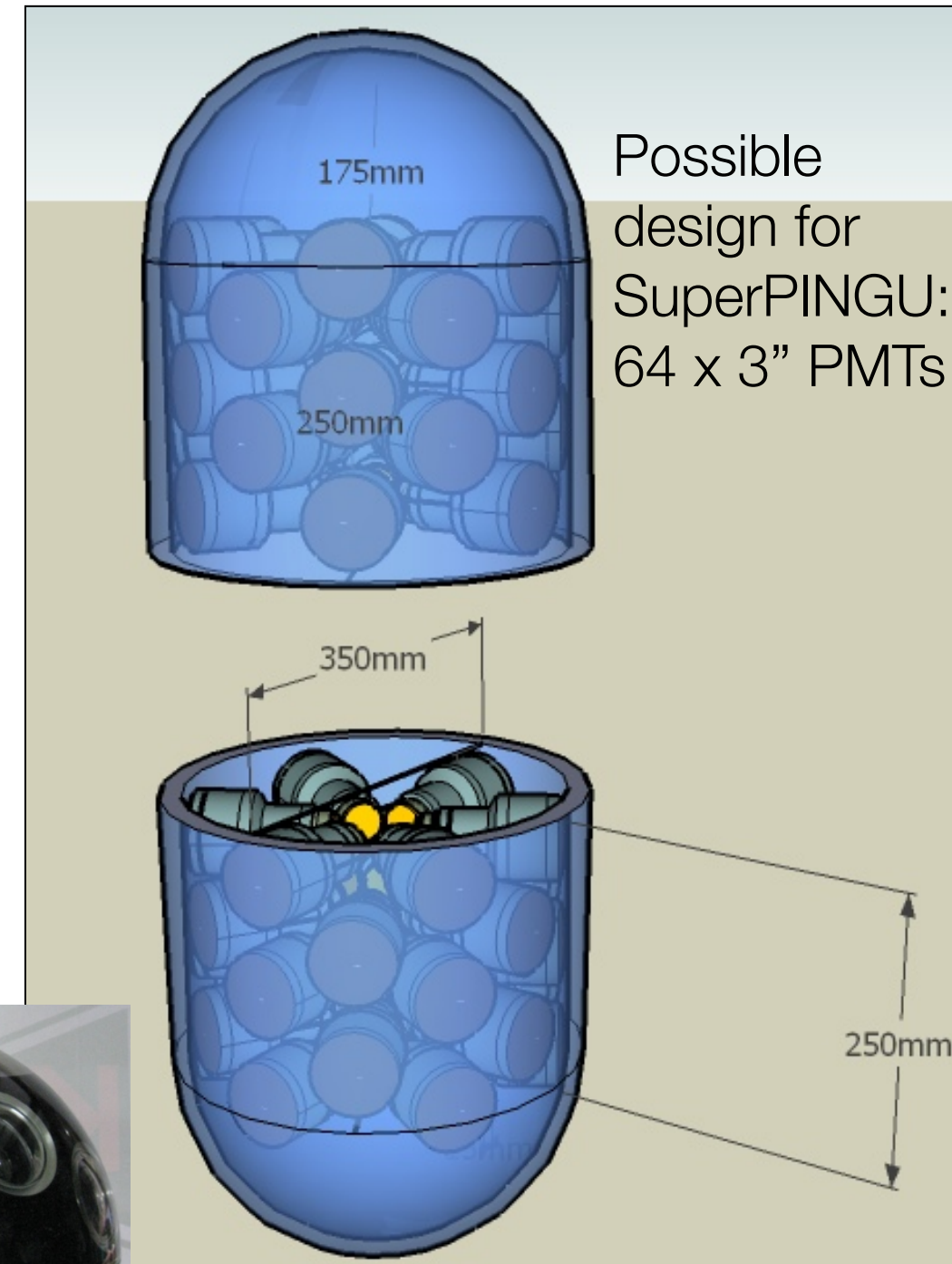
Figure: Lukas Schulte/Mainz

SuperPINGU Detector R&D

Courtesy E. de Wolf & P. Kooijman

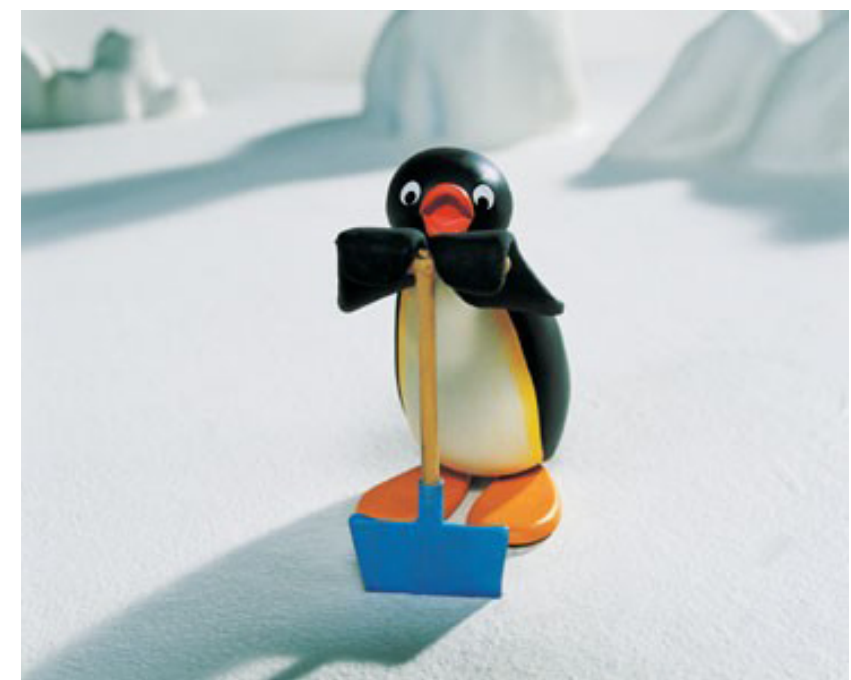
Composite Digital Optical Module

- Glass cylinder containing 64 3" PMTs and associated electronics
 - Effective photocathode area $>5\times$ 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

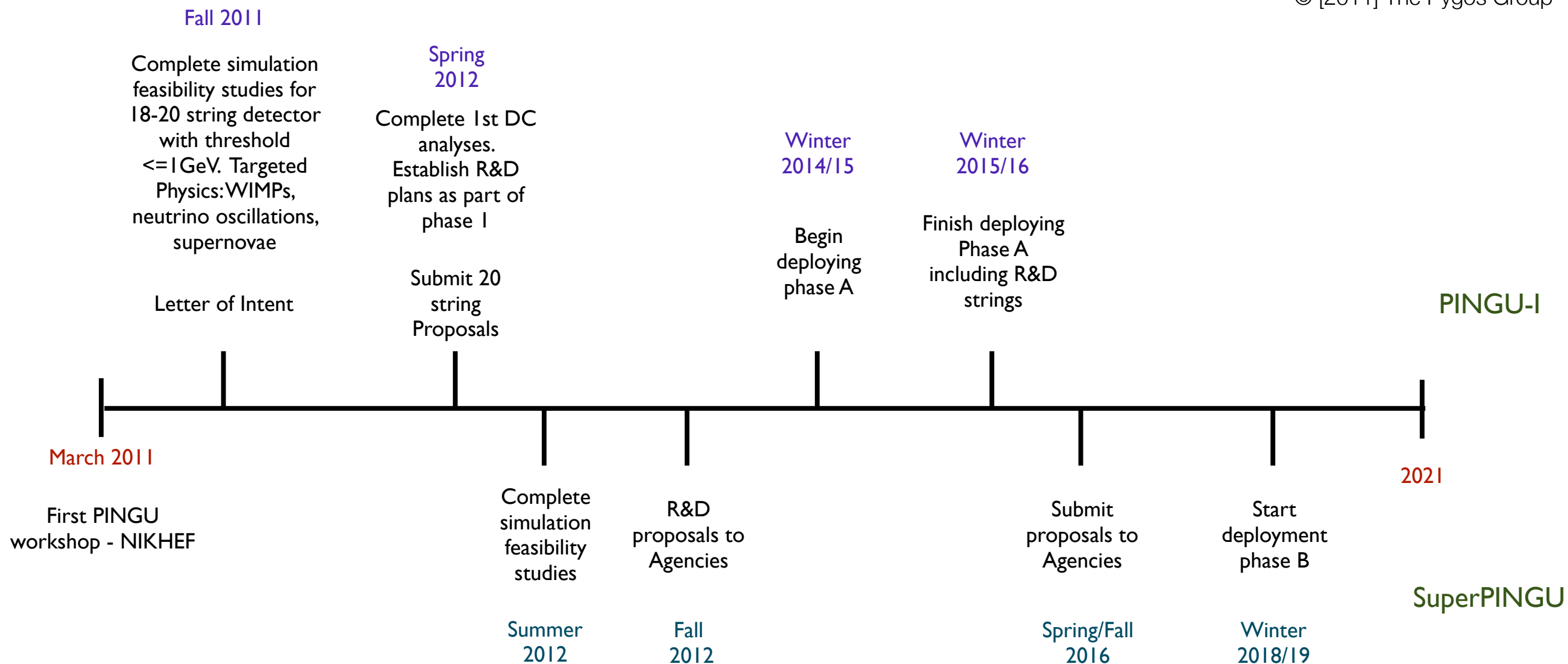


PINGU Timeline

- 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



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Nov 7, 2011

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Summary

- IceCube completed construction in December 2010 on schedule and within budget.
- The detector is exceeding the initial performance goals. It 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 prove to be an attractive alternative for large-scale precision neutrino detectors. Simulations for feasibility studies underway - stay tuned!

