Toward Precision Neutrino Physics with DeepCore and Beyond

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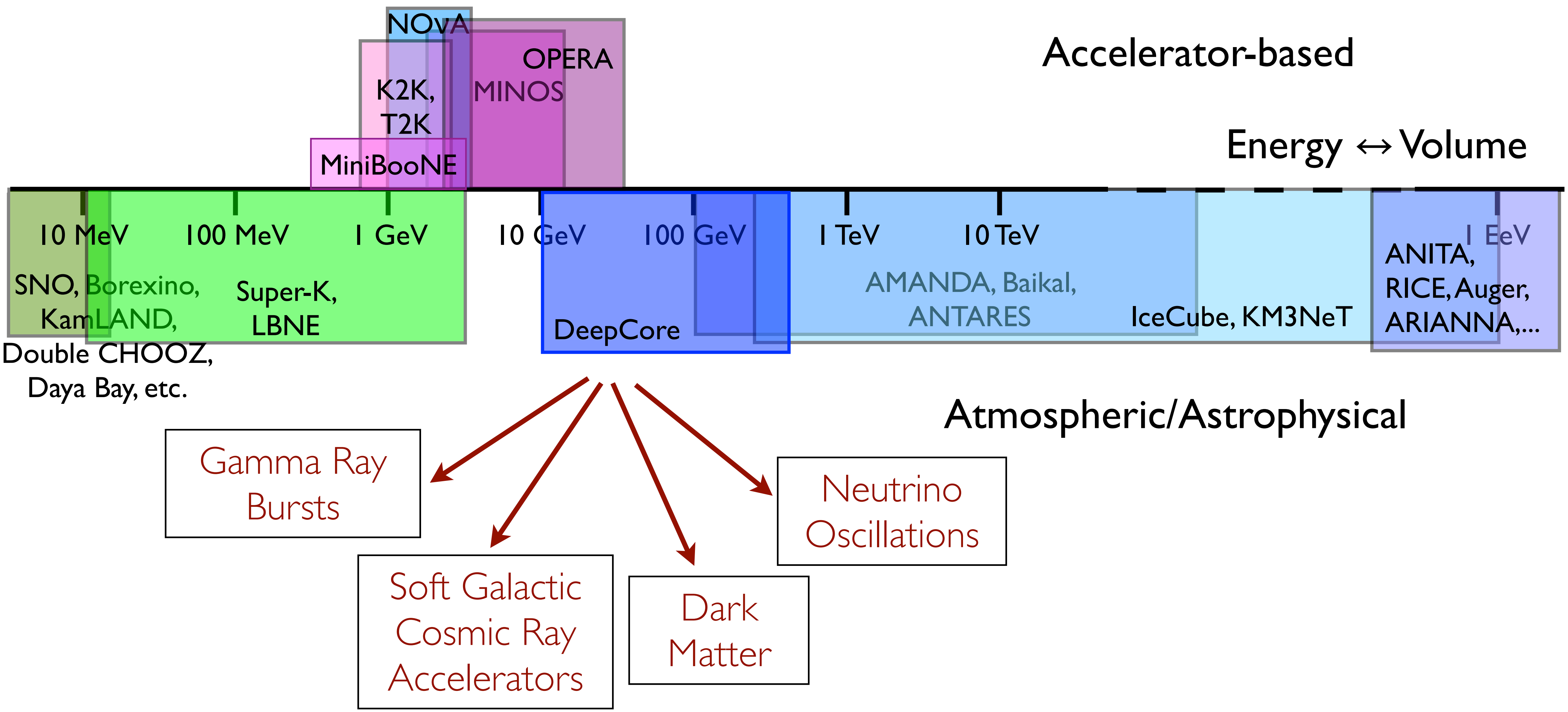
The Neutrino Detector Spectrum

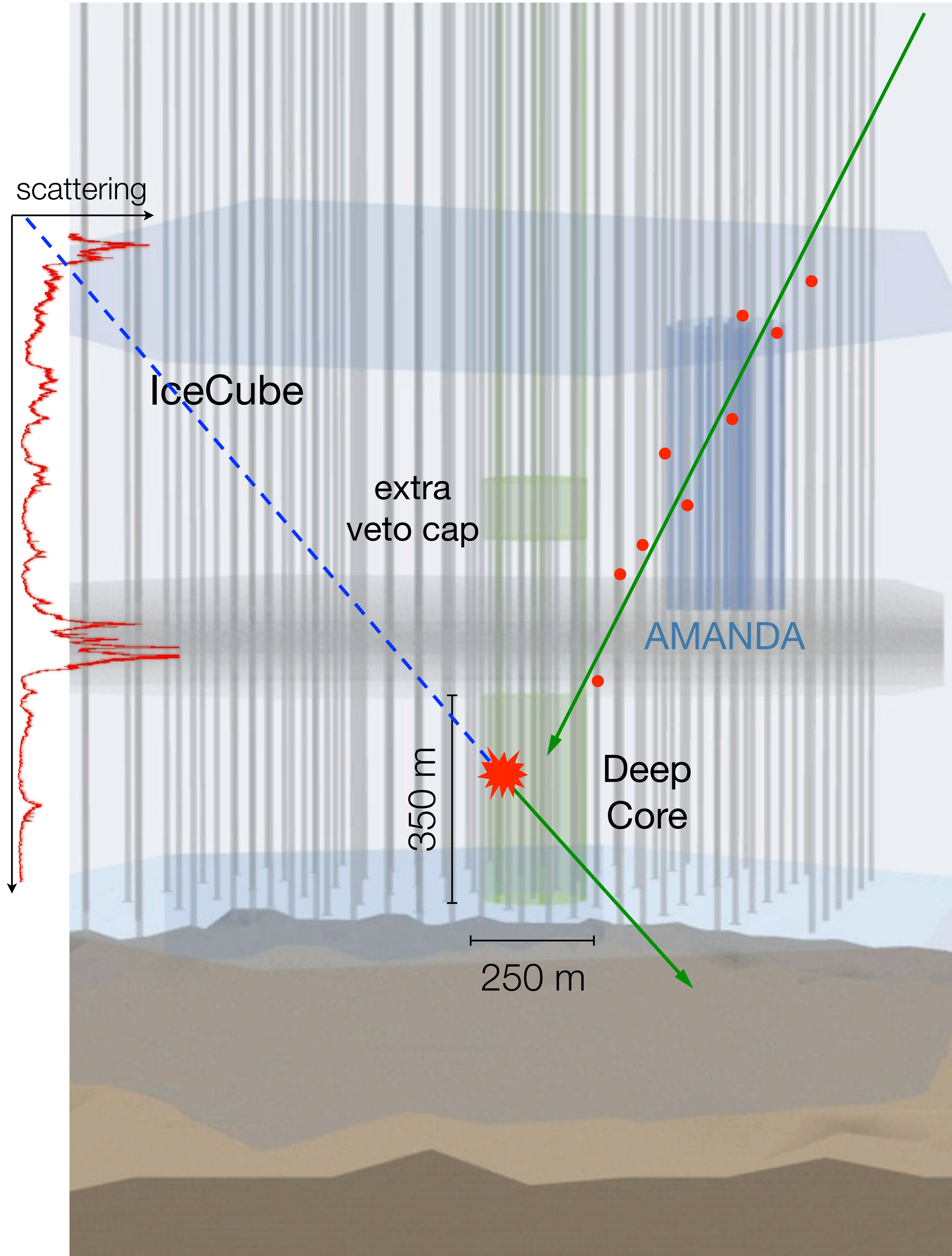


IceCube DeepCore

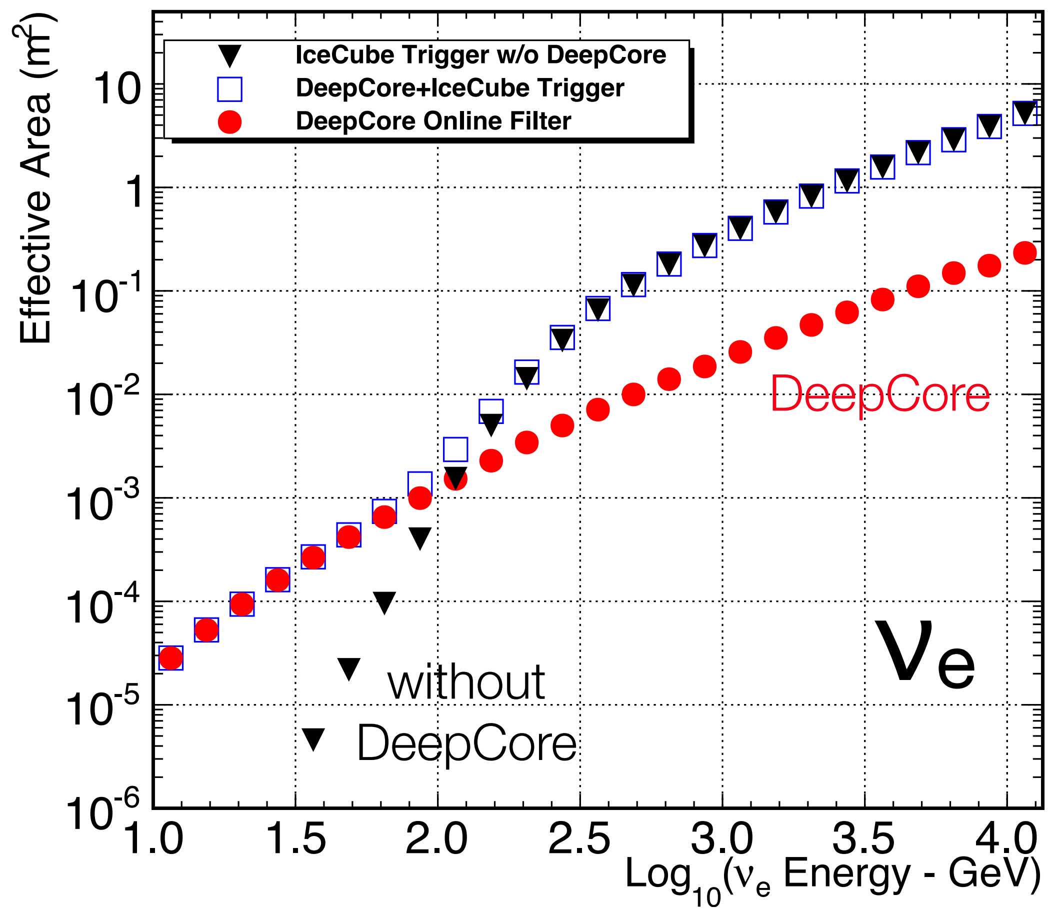
- IceCube collaboration decided to augment “low” energy response with a densely instrumented infill array: DeepCore
  - Significant improvement in capabilities from ~10 GeV to ~100 GeV (ν_μ)
- Primary scientific rationale was the indirect search for dark matter
- Particle physics using atmospheric neutrinos
  - Neutrino oscillations, including tau neutrino appearance
- Neutrino sources in Southern Hemisphere?
  - Galactic cosmic ray accelerators, dark matter in the Galactic center
- Neutrino astronomy at low energies (e.g. GRBs)?

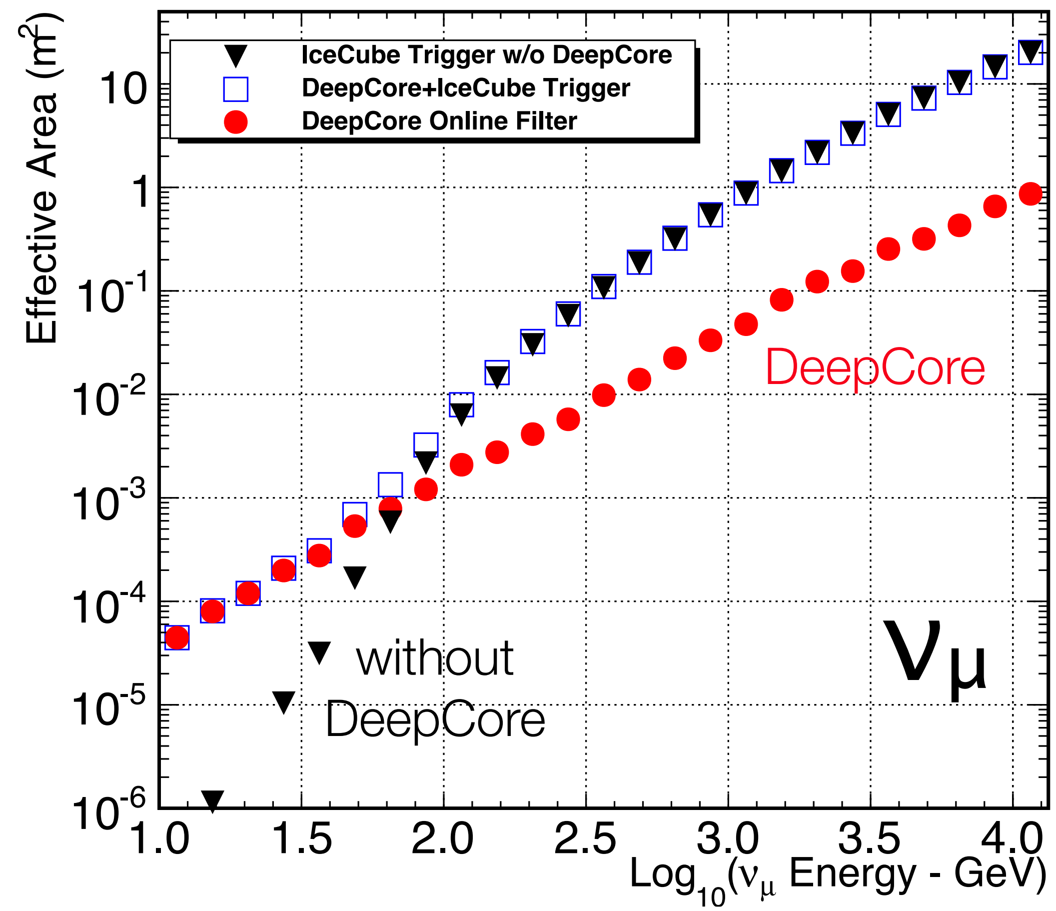
IceCube DeepCore

- Eight special strings plus 12 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 40-45 m
- 30 MTon detector with ~10 GeV threshold, $\mathcal{O}(10^5)$ atm. ν / year
- IceCube is an active veto against cosmic ray muon background



DeepCore Neutrino Effective Area



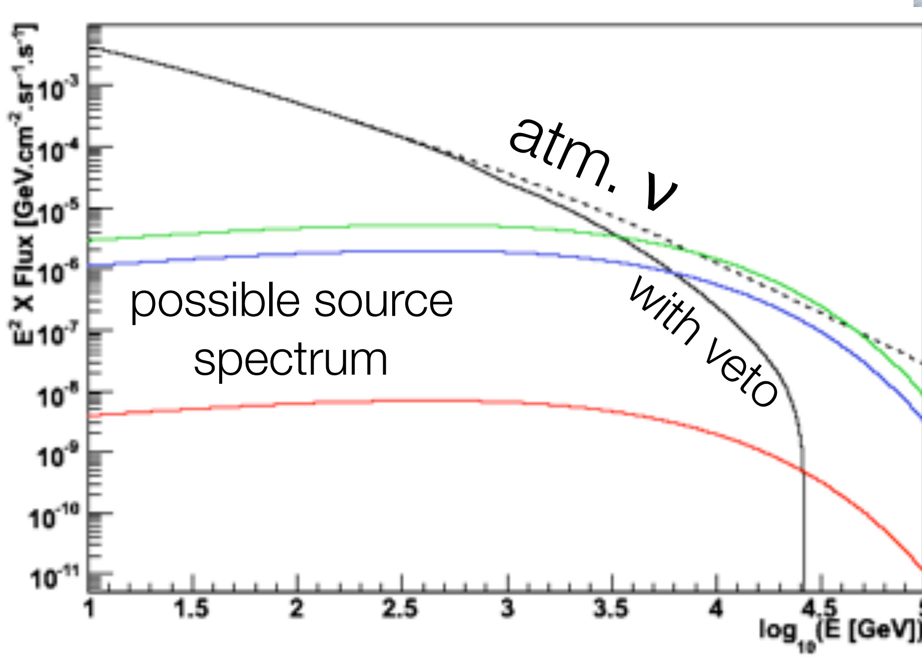


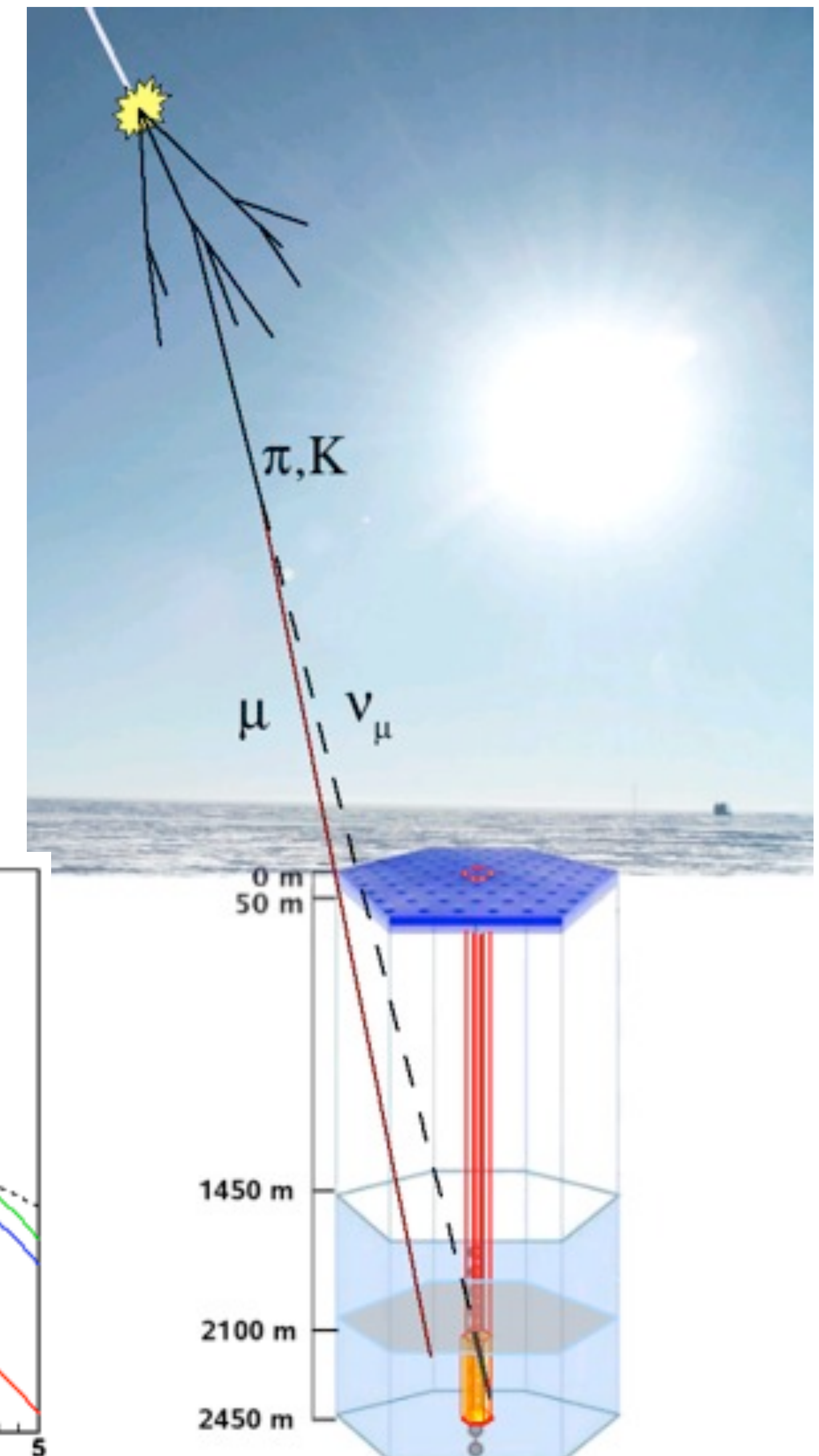
- DeepCore dominates total response for E_ν below ~100 GeV
  - Improved trigger efficiency overcomes much smaller volume
  - Linear growth at high energy reflects neutrino cross section, not detector efficiency
  - Analysis efficiencies *not* included! First analyses accepted low (<10%) efficiency, expected to improve considerably in the future

Neutrino Astronomy with DeepCore

- Atmospheric neutrino veto?
  - May enhance observability of Galactic sources in the ~10 TeV band (Schönert et al. 2009)
  - Still difficult at these energies due to loss of muon range factor, rising neutrino cross section

- Sensitivity to low energy neutrinos from transients?
  - E.g. choked or magnetically dominated GRBs (e.g., Ando & Beacom 2005; Razzaque, Meszaros & Waxman 2005; Meszaros & Rees 2011)



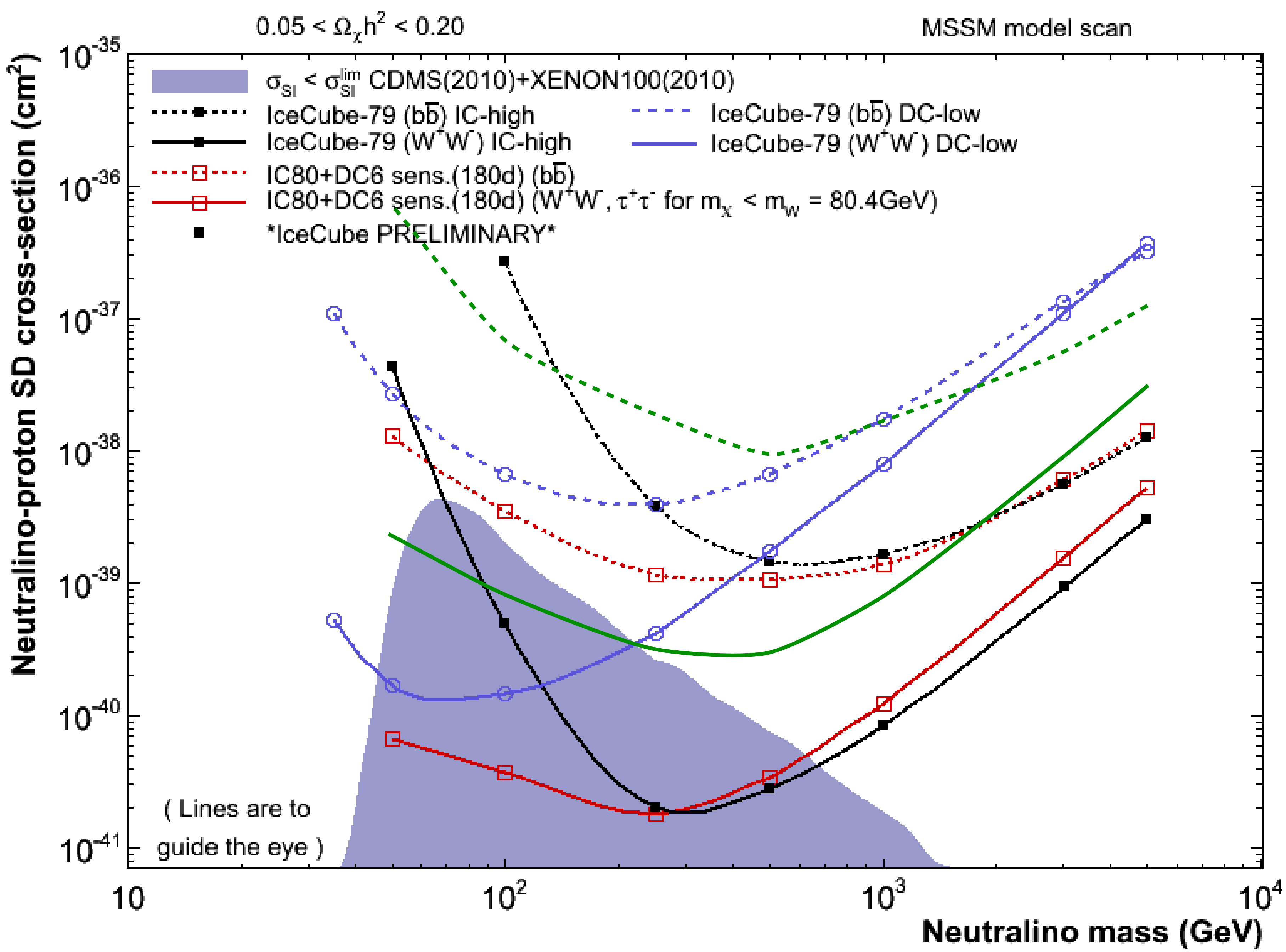


Search for Solar Dark Matter

M. Danninger, TAUP 2011

- Solar WIMP dark matter searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- DeepCore is essential to low mass WIMPs
- For non-SUSY DM, even lower energies are of interest

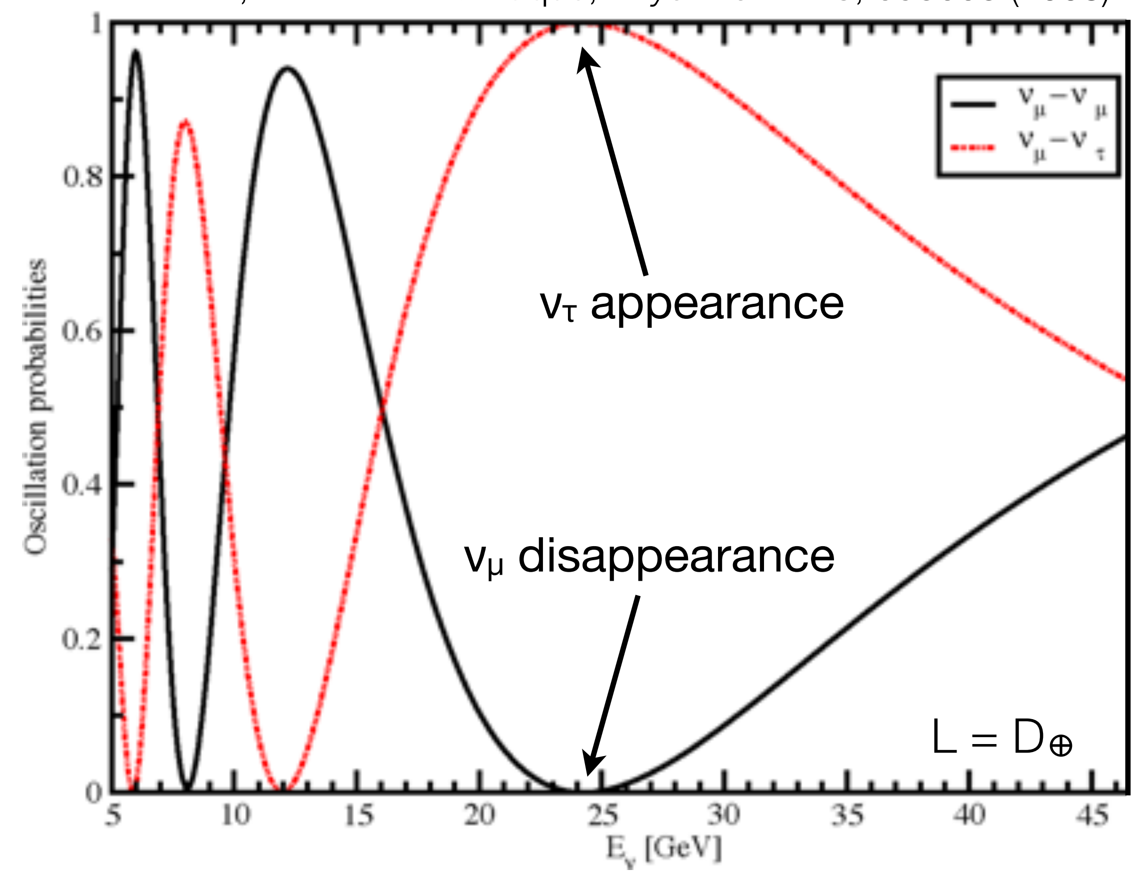
Preliminary sensitivities

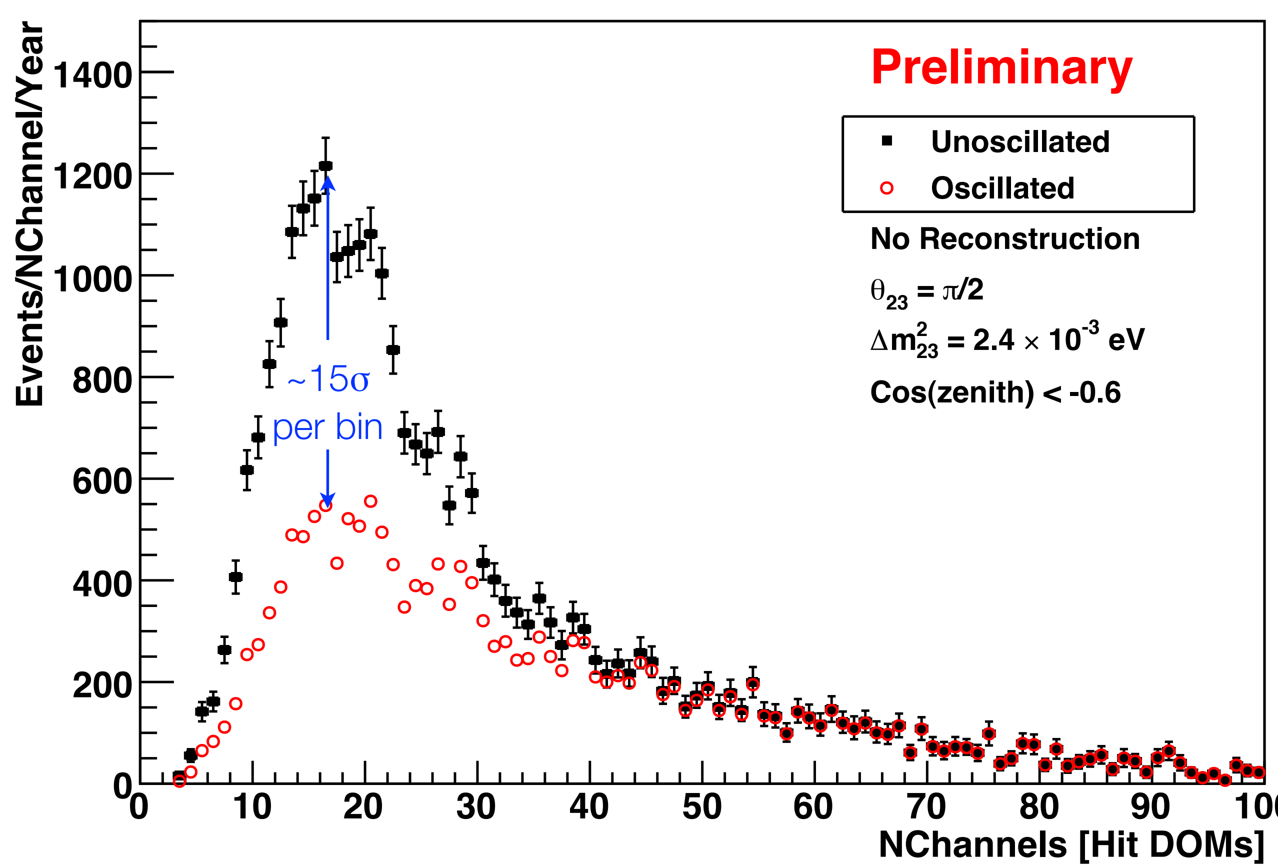


Neutrino Oscillations

- Atmospheric neutrinos from Northern Hemisphere oscillating over one earth diameter have ν_μ oscillation minimum at ~25 GeV
  - Higher energy region than accelerator-based experiments
- Plot of ν_μ disappearance shows only simulated signal (no BG), simple energy estimator
  - Analysis efficiencies not included yet – work ongoing
  - Magnitude of the signal may help overcome poorer control of systematics

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

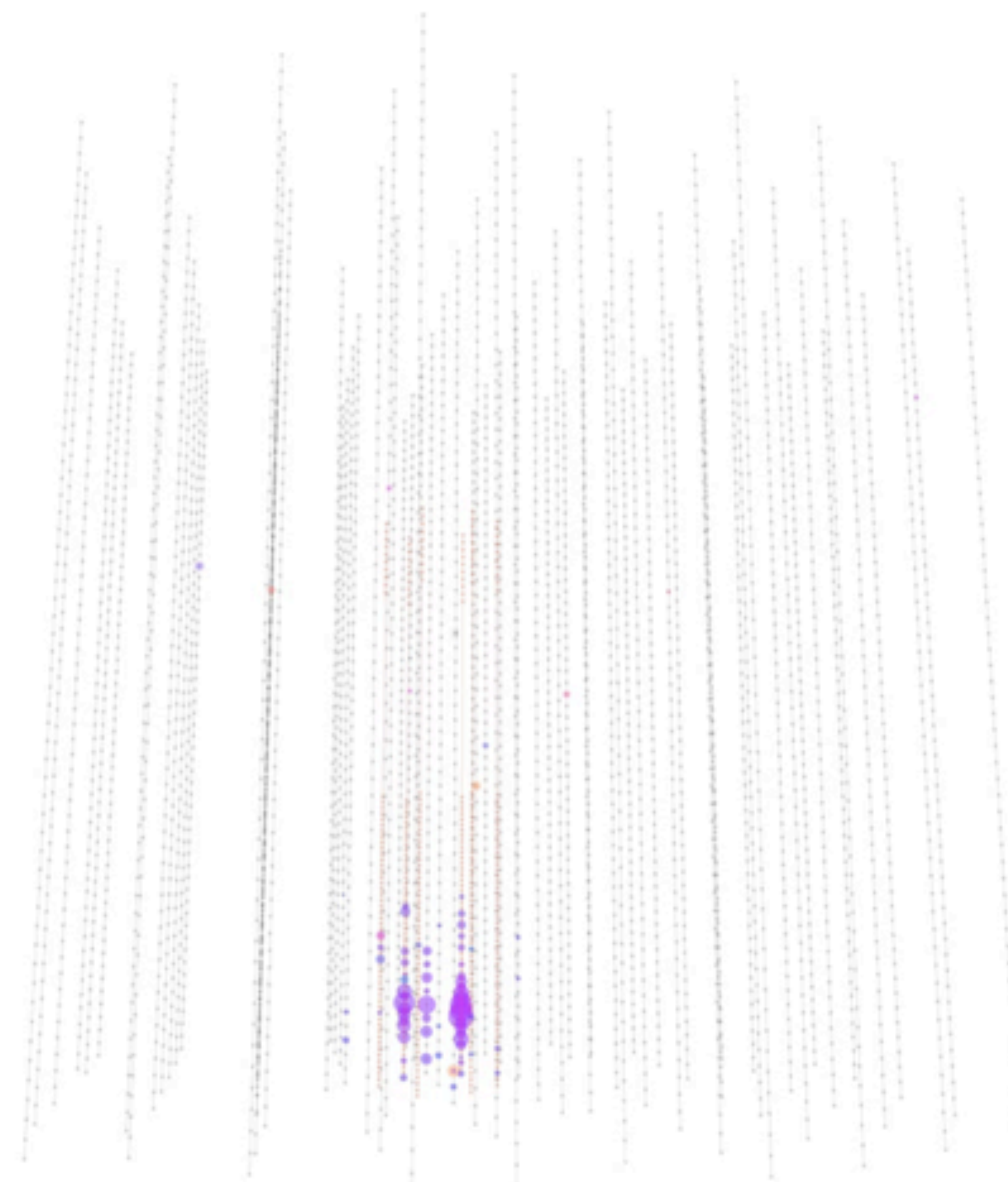




Observation of Neutrino Cascades

Preliminary

- 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
- We believe we see neutrino cascade events for the first time
  - The dominant background now is CC ν_μ events with short tracks



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

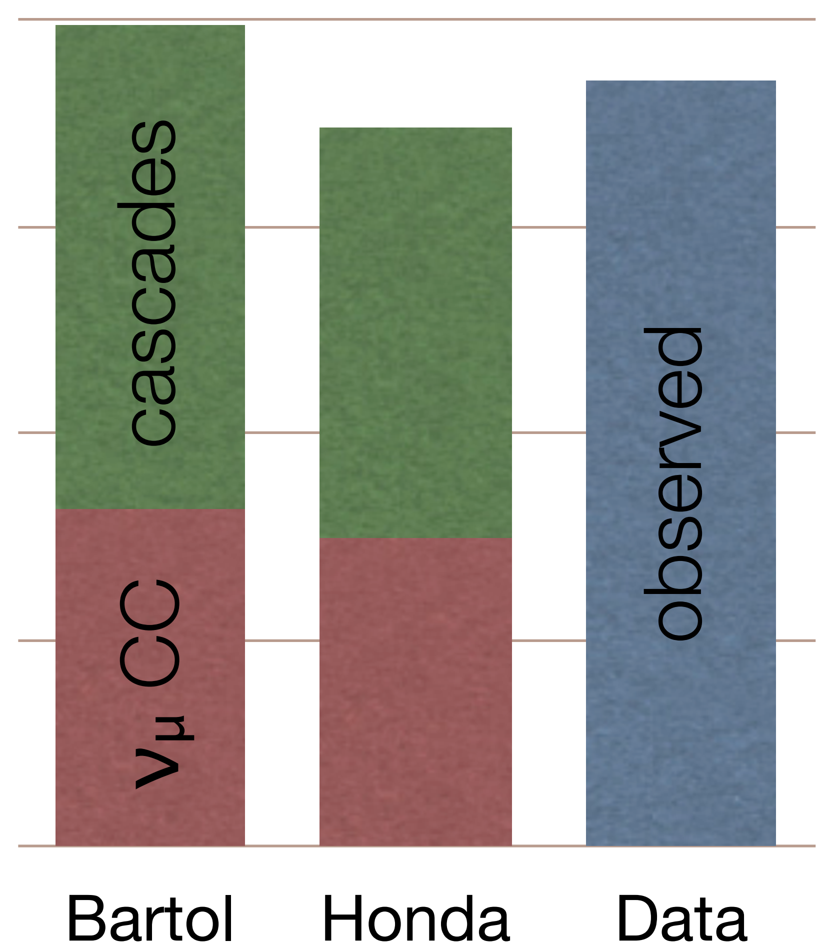
Observation of Atmospheric Cascades

C. H. Ha, TAUP 2011

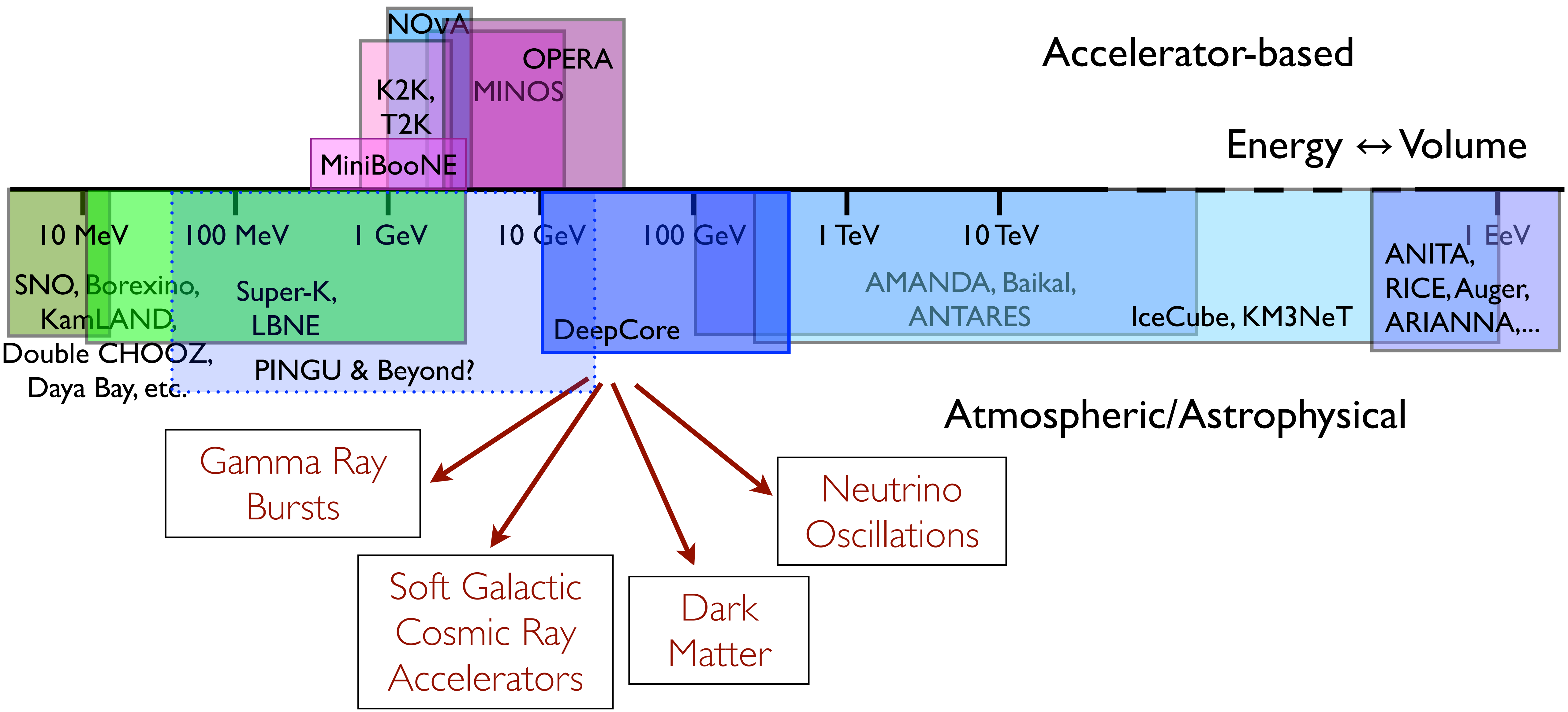
- Substantial sample of cascades, final data set ~60% cascades
  - Mean energy ~180 GeV, not sensitive to oscillations (with these cuts)
  - Atmospheric muon background being assessed, but ν_μ CC dominant
  - Represents about 5x enrichment of cascades over ν_μ CC, but better neutrino particle ID clearly desirable
  - Potential to discriminate between Bartol, Honda atmospheric neutrino models – measuring air shower physics!

preliminary!

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



Beyond DeepCore

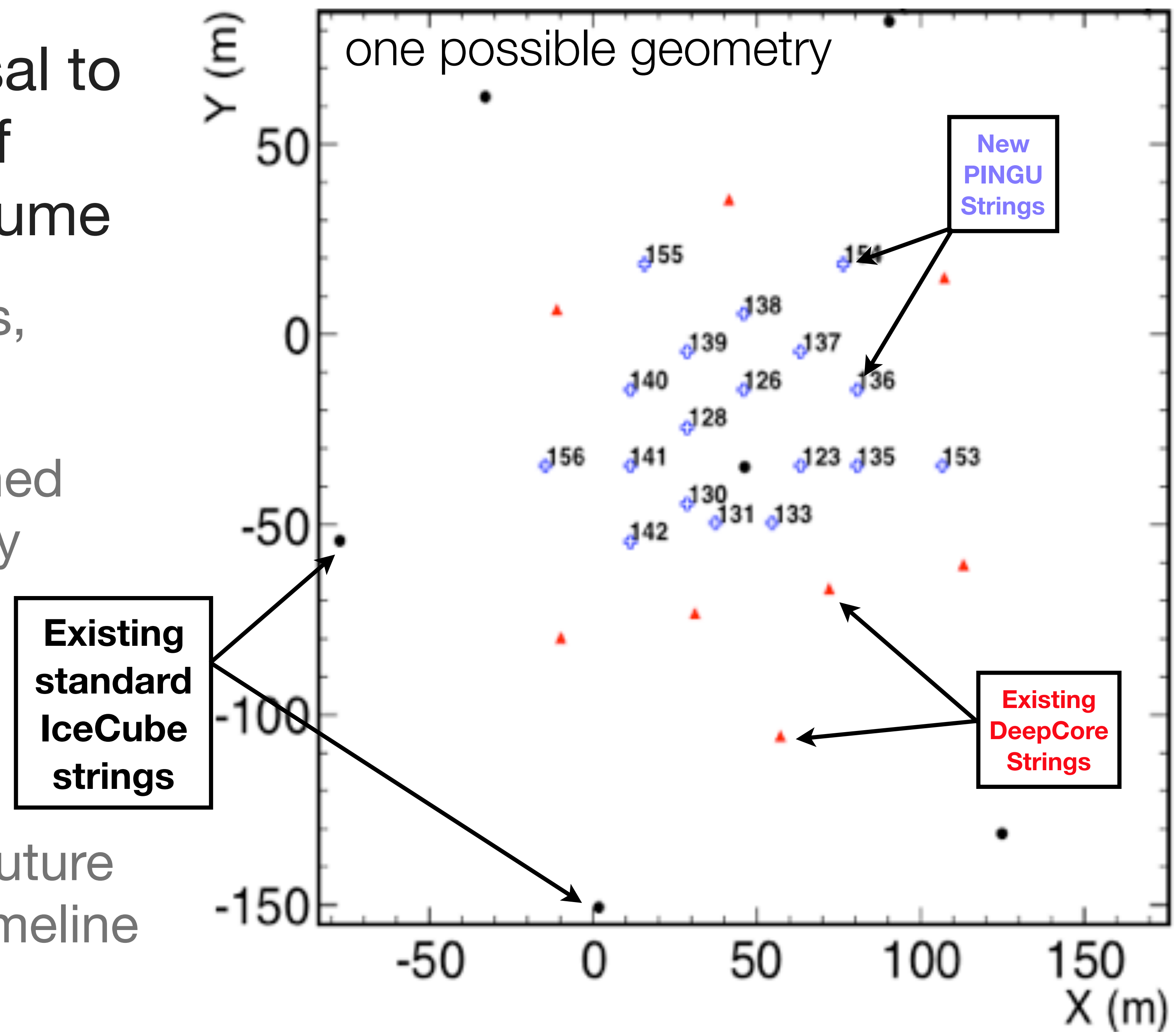


Toward Precision Particle Physics in Ice

- First stage (“PINGU”)
  - Add ~20 further infill strings to DeepCore, extend energy reach to ~1 GeV
  - Improved sensitivity to DeepCore physics, and test bed for next stage
  - Use mostly standard IceCube technology, include some R&D toward new types of photodetectors
  - Include additional calibration devices with an eye toward few-% systematics
- Ideas beyond PINGU
  - Using new photon detection technology, can we build a detector that can reconstruct Cherenkov rings for events well below 1 GeV?
  - PINGU topics, plus proton decay, supernova neutrinos
  - At least comparable in scope to IceCube, but in a much smaller volume

Beyond DeepCore: PINGU

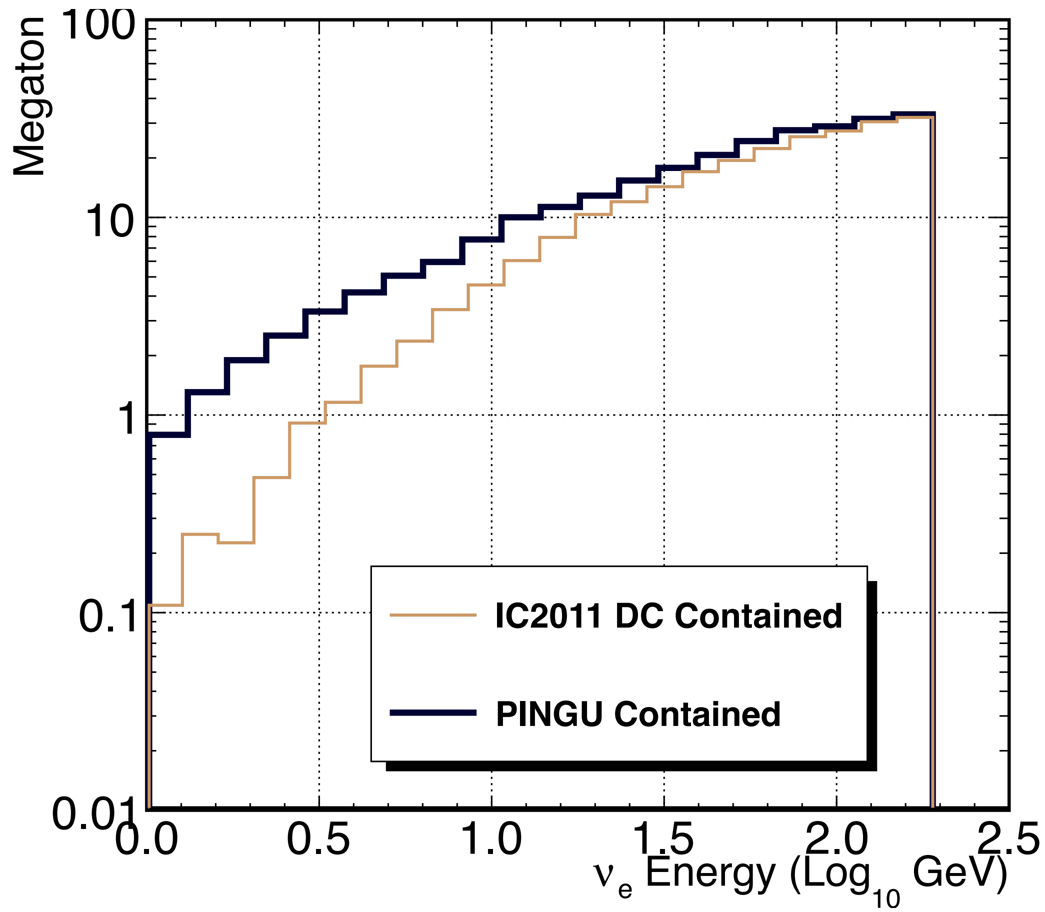
- Now developing a proposal to further increase density of instrumentation in DC volume
  - An additional 18-20 strings, 1000-1200 DOMs
  - Make use of well-established IceCube drilling technology
  - Might get to a threshold of ~1 GeV in a ~10 MTon volume
  - Also an R&D platform for future detectors on a ~decade timeline

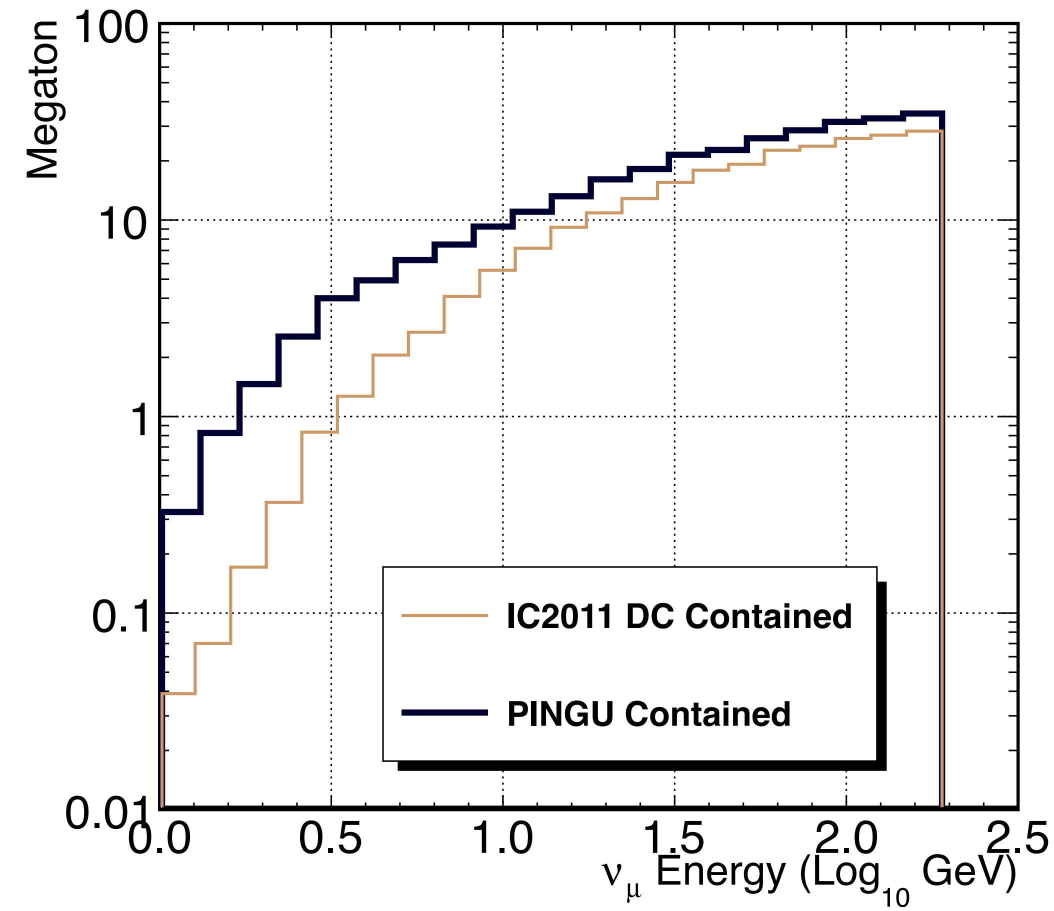


- Price tag expected to be around \$25M – \$30M

PINGU Effective Volumes

Preliminary



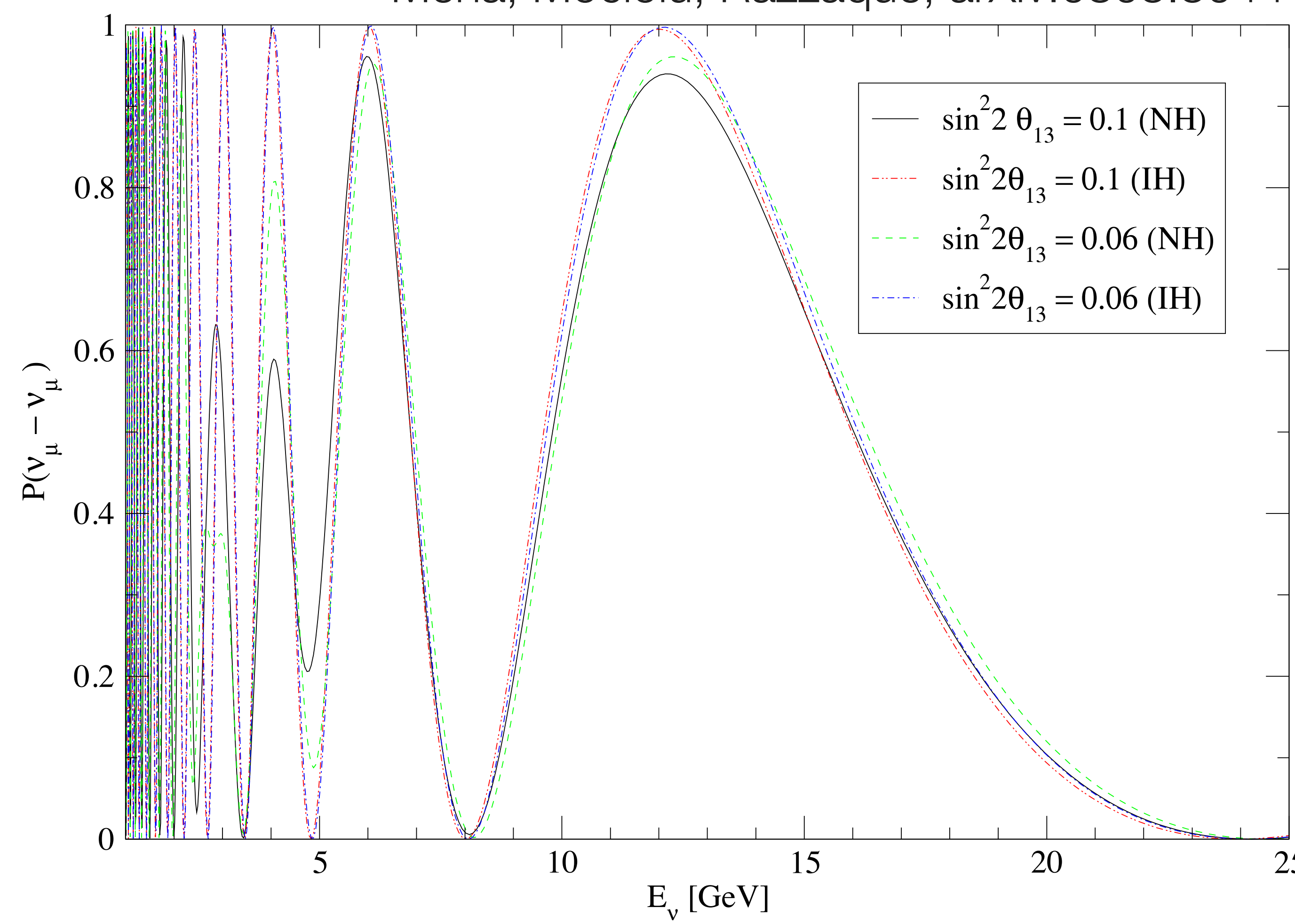


- Increased effective volume for energies below ~15 GeV
- Nearly an order of magnitude increase at 1 GeV (100's of kton)
- Does not include analysis efficiencies, reconstruction precision
  - Absolute scale lower, but improvement over DeepCore likely >10x

PINGU Neutrino Physics

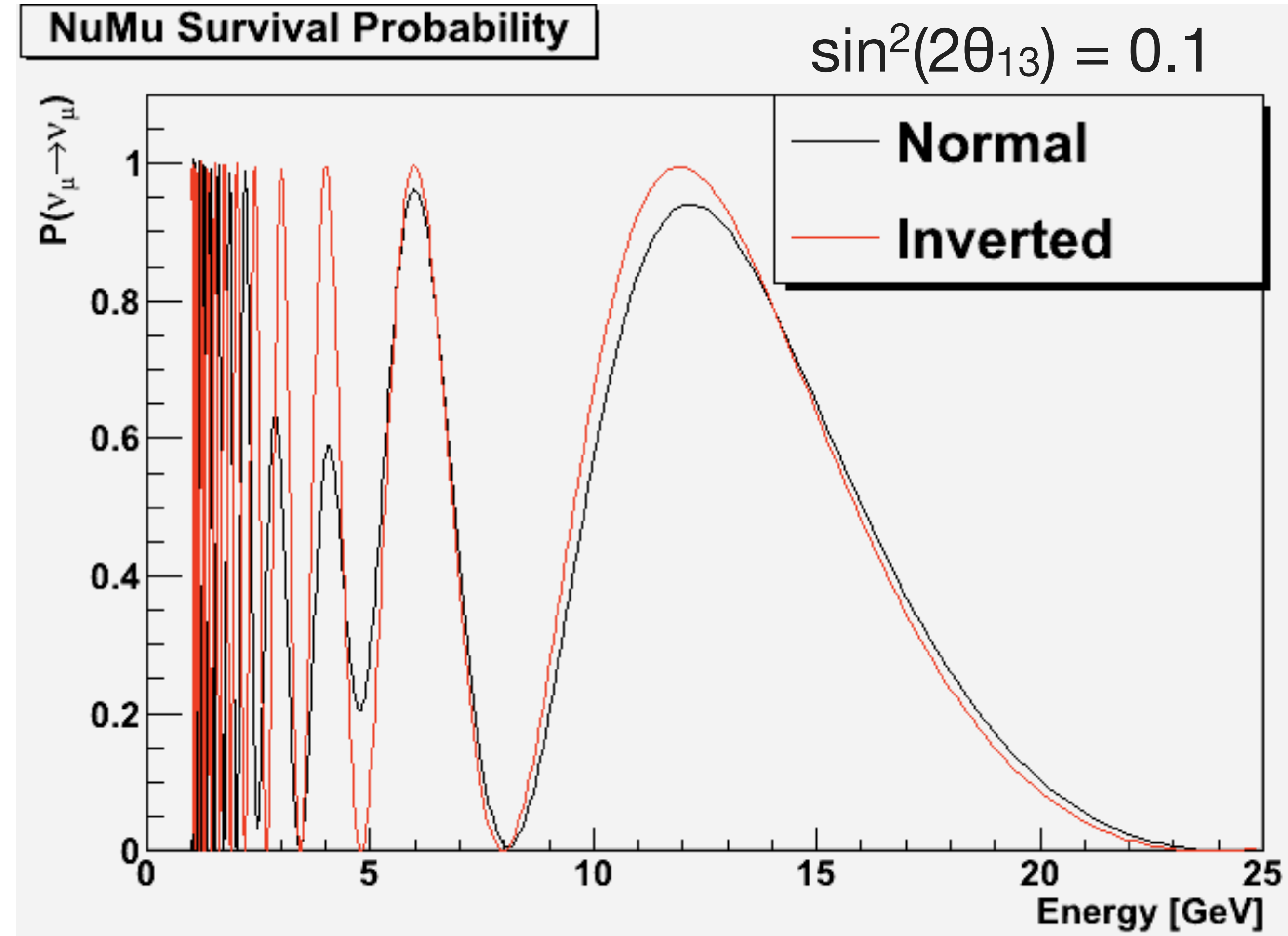
- Sensitivity to 2nd oscillation peak/trough, and lower?
  - Measuring full minimum and 2nd peak would improve extraction of Δm_{23}^2 and $\sin^2(2\theta_{23})$ in a very large data set
  - Limited by systematic uncertainties, not statistics
- Plan for a robust calibration program to refine understanding of systematics

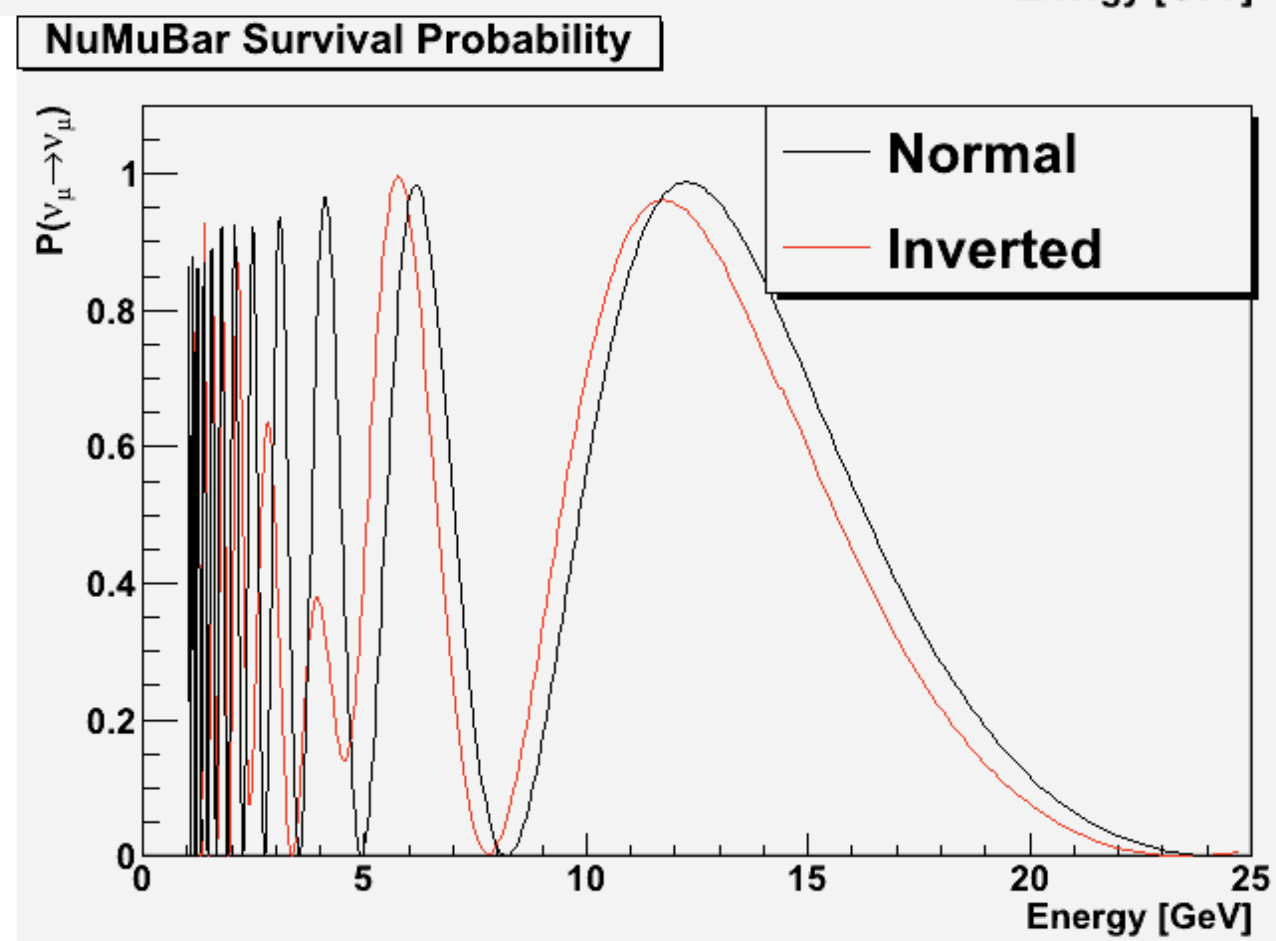
Mena, Mocioiu, Razzaque, arXiv:0803.3044



Probing the Neutrino Mass Hierarchy?

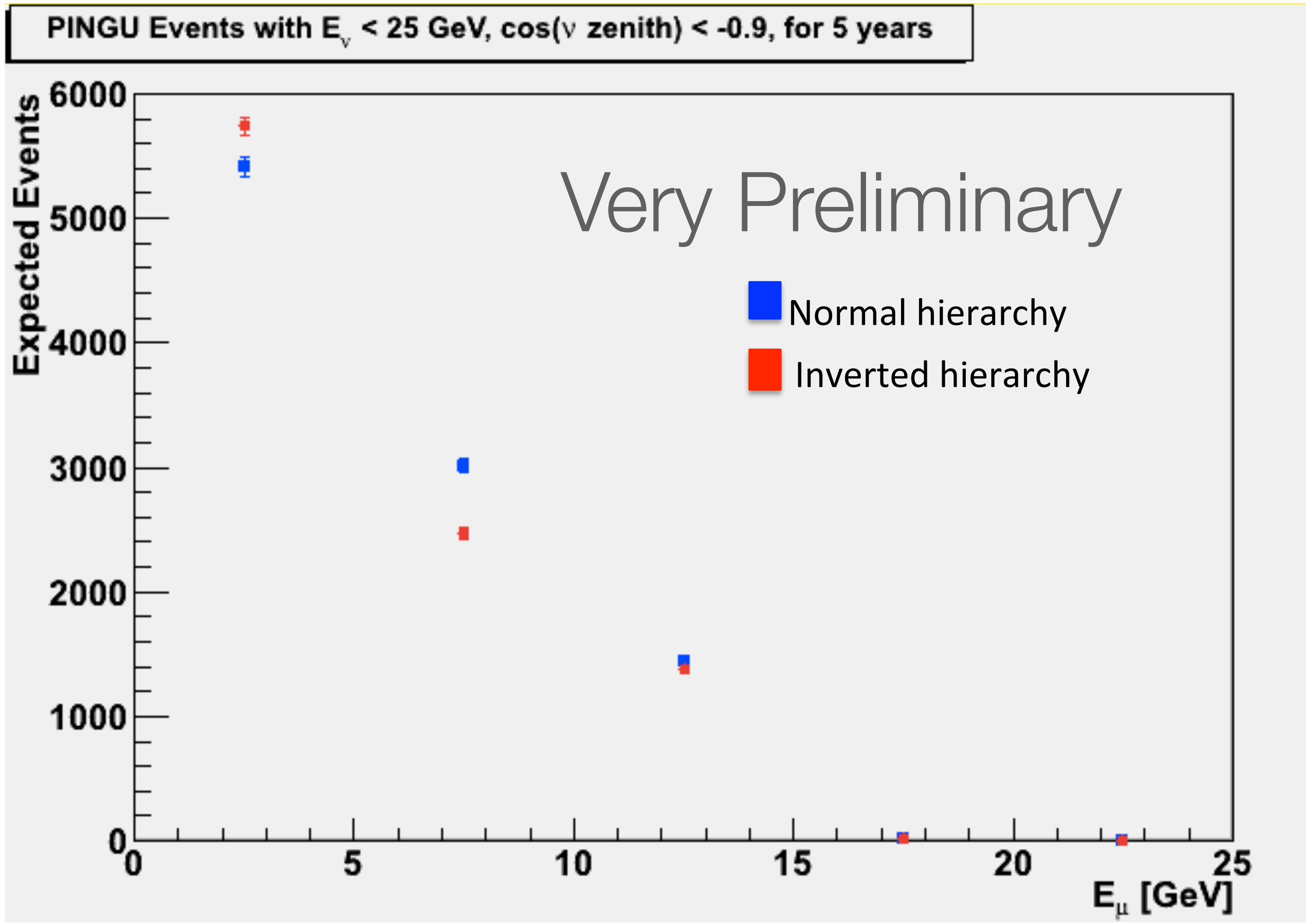
- Possible sensitivity to neutrino mass hierarchy via matter effects if θ_{13} is large
  - Exploit asymmetries in ν / $\bar{\nu}$ cross section, kinematics
  - Effect is largest at energies below 5 GeV (for Earth diameter baseline)
  - Control of systematics crucial
- Recent results suggest that nature may have been kind to us by giving us a large θ_{13}





PINGU Hierarchy Measurement?

- Simulations of 20-string PINGU for 5 years with $\sin^2(2\theta_{13}) = 0.1$
- Assumes perfect background rejection, select events within 25° of vertical
  - 5 GeV muon energy bins – ~25 m length resolution



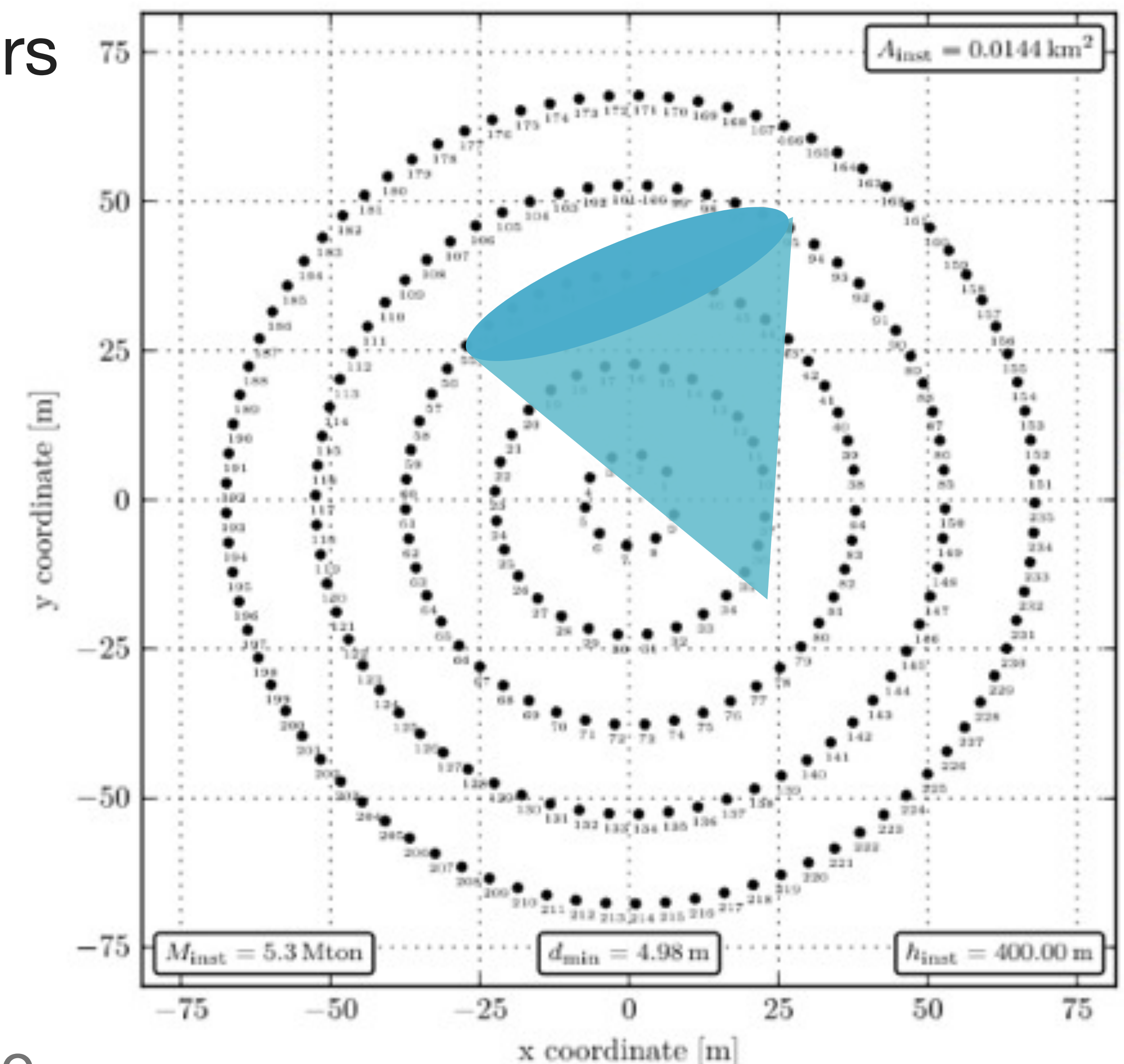
- Up to 20% (=10σ) effects in several energy/angle bins
  - Signal is potentially there, <u>if</u> systematics can be controlled

Beyond PINGU: A Megaton Ice Cherenkov Array

- Underground detectors such as Super-K have made tremendous contributions to particle physics, but are approaching the limits of feasible detector size
  - Physics reach determined by photocathode coverage, radiopurity, optical quality of the medium
  - Costs driven primarily by photocathode coverage, purification, and civil engineering – and the latter is coming to dominate
- Ice offers one great advantage: the medium is the support structure
  - Installation costs low (on the scale of a next-generation detector)
  - Deep ice has reasonably good optical quality, very high radiopurity
  - But the maximum density of instrumentation is determined by installation procedure, and the optical properties must be assessed *in situ*

Megaton Ice Cherenkov Array

- Few hundred strings of "linear" detectors to be deployed within DeepCore
  - String spacings ~5 m, sensors spaced by ~1 m on a string
- Goals: ~5 MTon fiducial volume
  - O(10 MeV) threshold for bursts
  - O(100 MeV) for single events
- Physics extraction from Cherenkov ring imaging in the ice
  - IceCube and DeepCore provide active veto

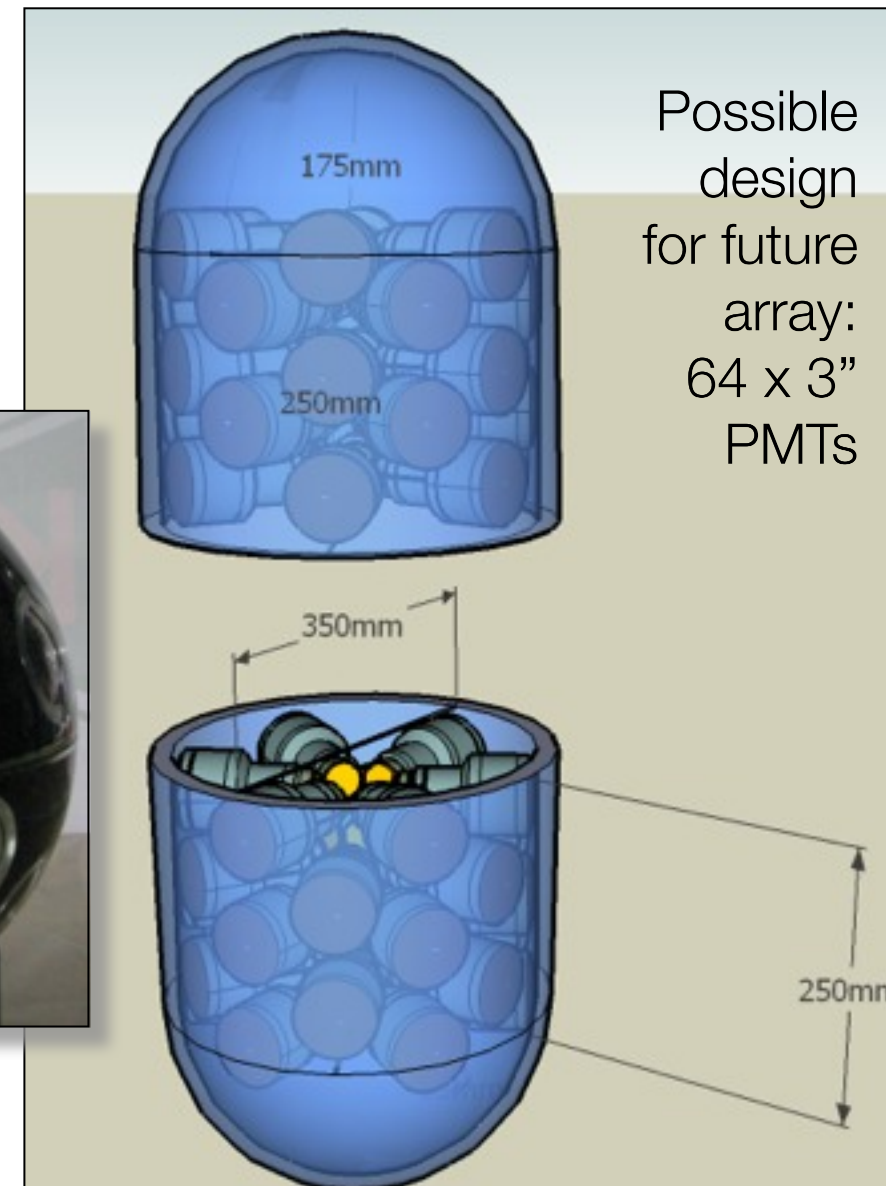


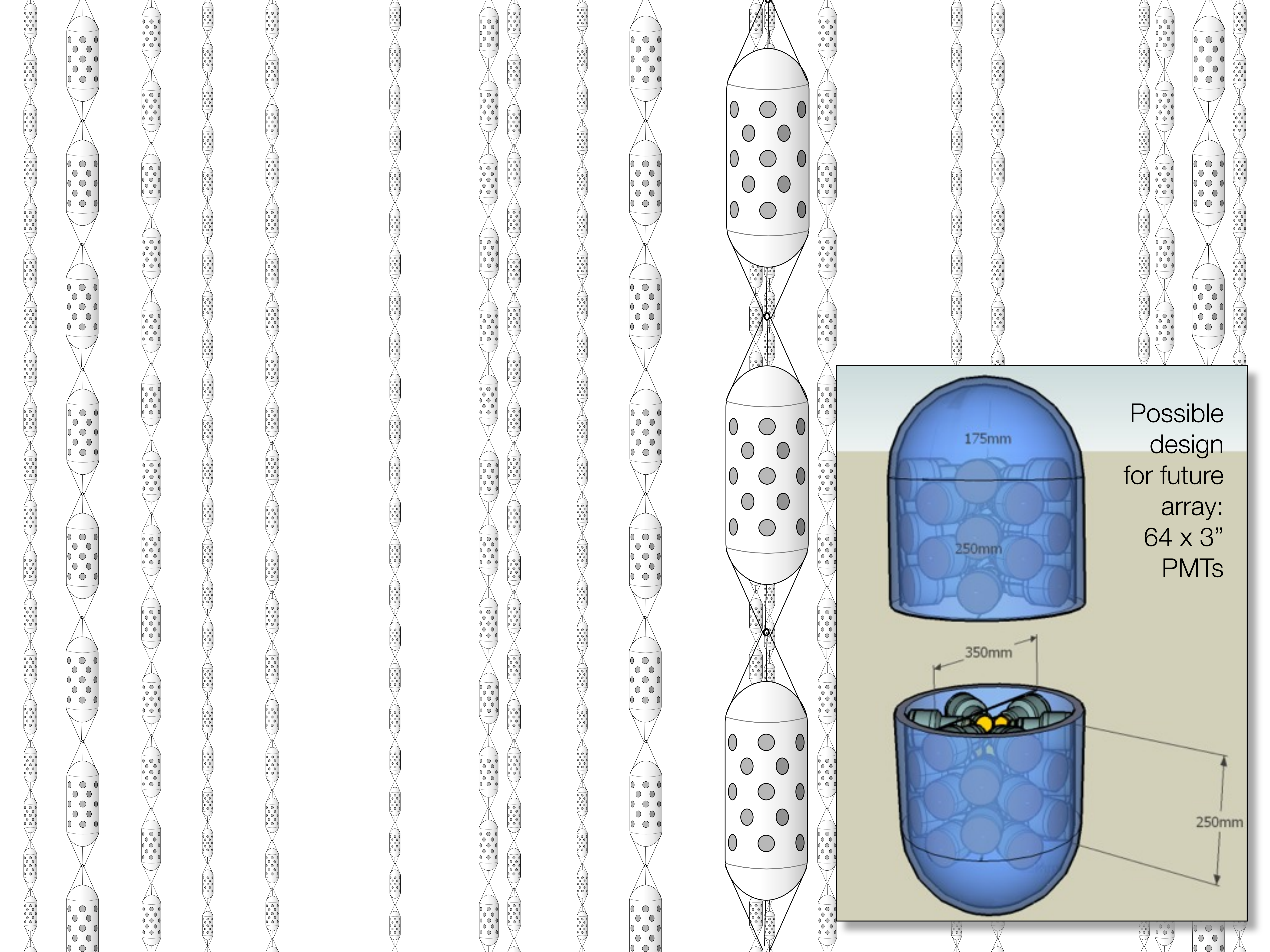
- No excavation is necessary, drilling/deployment has been refined to an industrial process – deployment costs would be well below 10% of total

R&D: Multi-PMT Digital Optical Module

P. Kooijman &
E. de Wolf

- Based on a KM3NeT design
- Glass cylinder containing 64 3” PMTs and associated electronics
  - Effective photocathode area >6x that of a standard IceCube 10” PMT
  - Diameter similar to IceCube DOM, single connector
- Might enable Cherenkov ring imaging in the ice
  - Feasible to build a multi-MTon detector in ice with an energy threshold of 10’s of MeV?
- R&D beginning (U. Katz/P. Kooijman)




Possible design for future array: 64 x 3” PMTs
175mm
250mm
350mm
250mm

Physics Goals

- 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 – requires multi-MTon effective volume
  - Background levels may be too high for a ~10 MeV threshold for individual events, but still allow observations of a burst of neutrinos
- Plus improvements for dark matter, neutrino physics compared to PINGU and DeepCore

Proton Decay

- Studying use of ring imaging algorithms from underground detectors (e.g. Super-K) in a volume-instrumented detector
  - Need to understand energy resolution, e/μ ring identification, required photocathode coverage
  - Photocathode density equivalent to ~10-15% coverage is technically feasible based on deployment technology (but would be expensive)
  - What information do we gain from always having segmented photodetectors near the event vertex? How can we incorporate it?
- Proton lifetimes of 10^{36} years are theoretically interesting, current limits are around several times 10^{34} years
  - Need to assess detector performance before we understand our sensitivity

Supernovae

- Work in progress to assess the ability to detect SN neutrinos
- Background constraints more difficult but threshold may be lowered for bursts of events

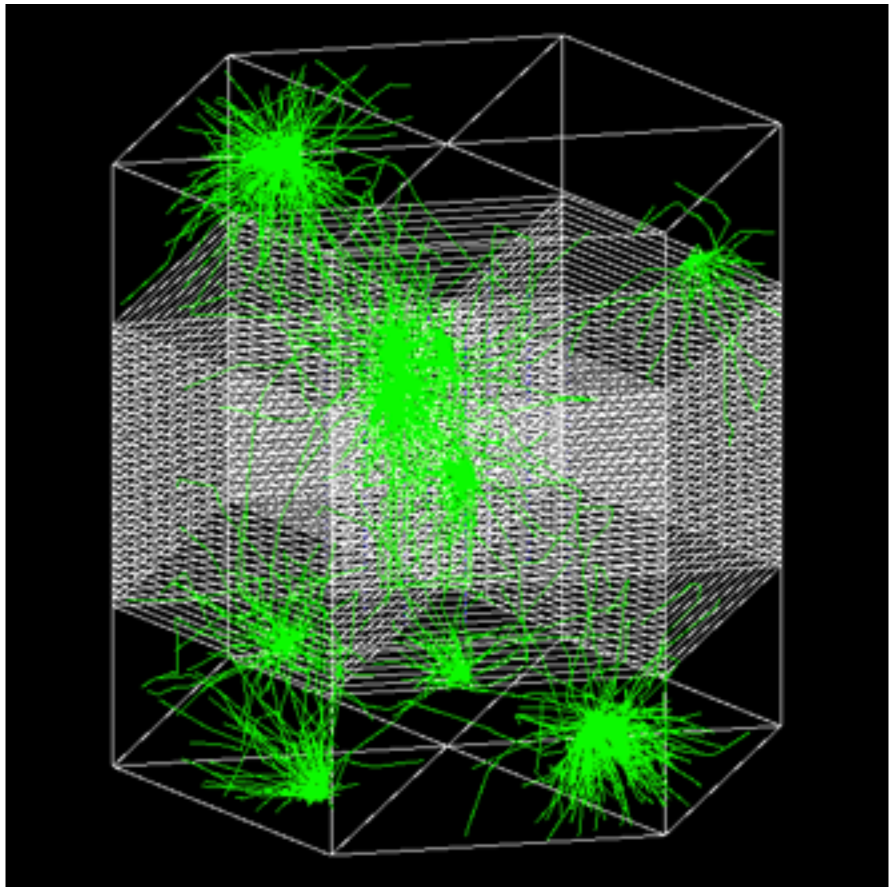
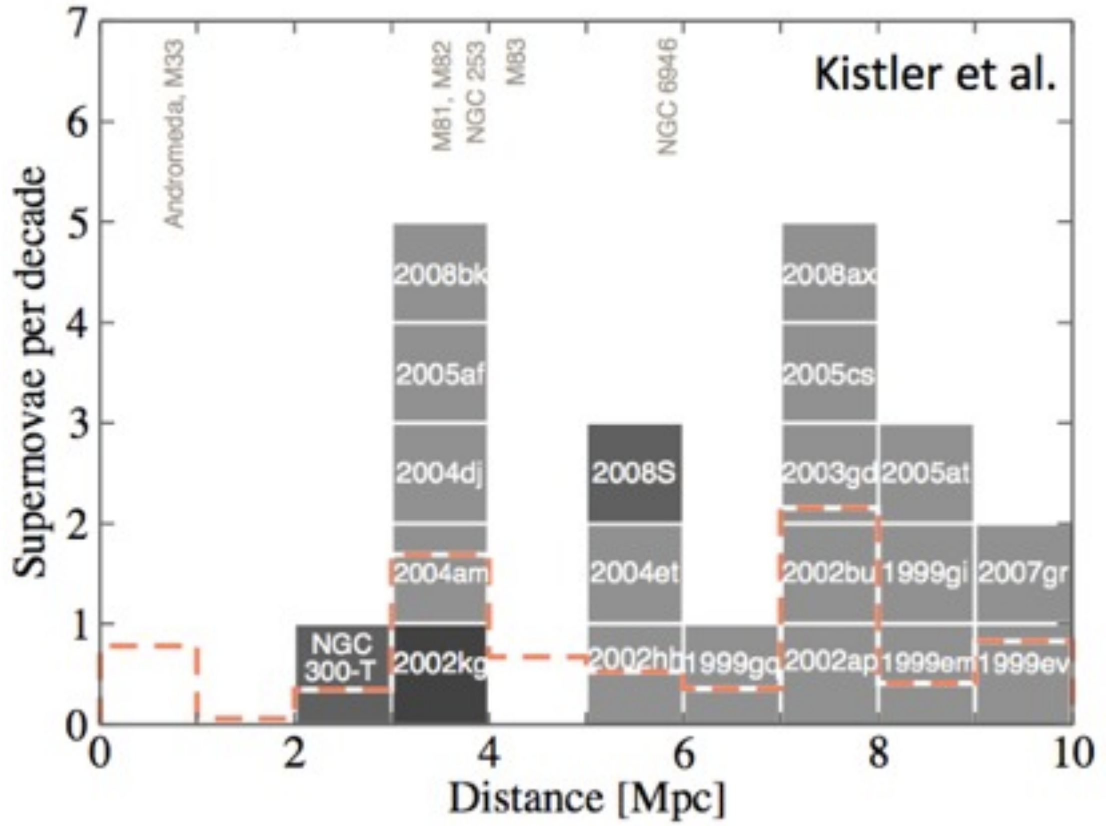
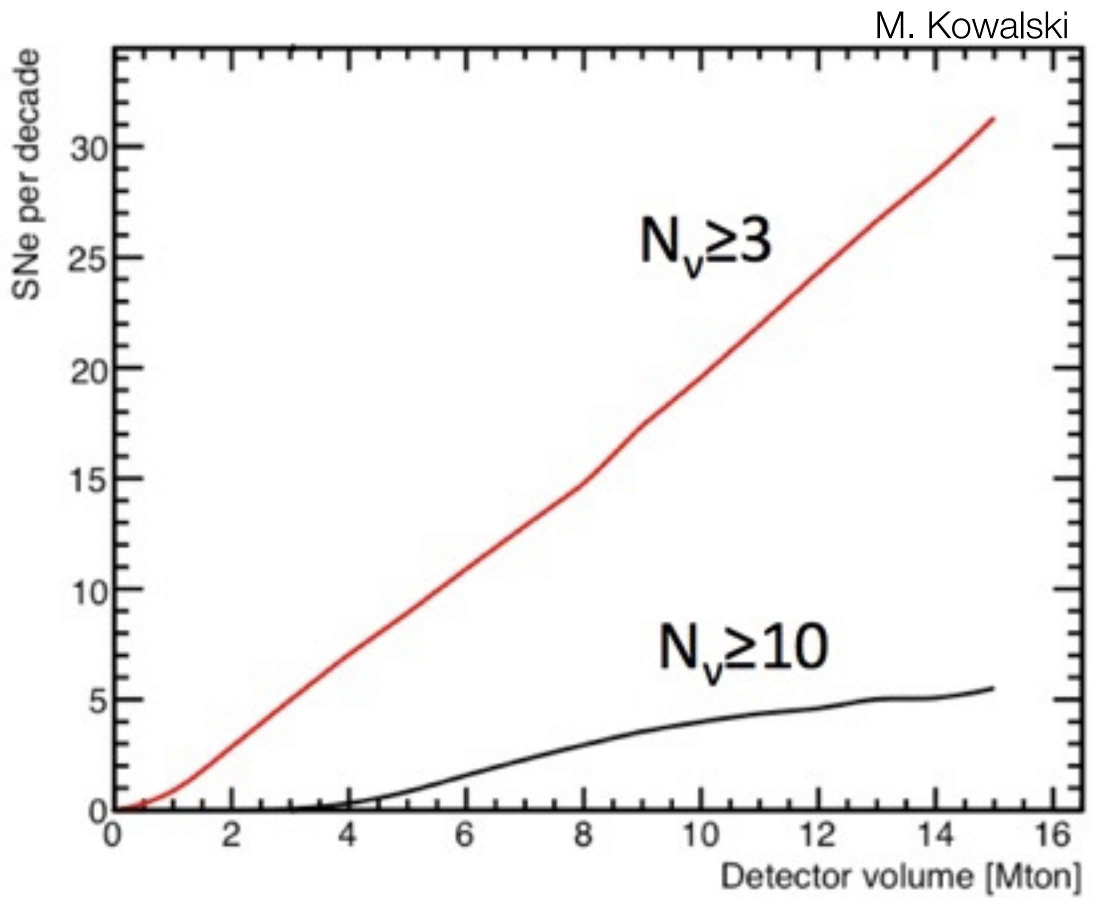


Figure: Lukas Schulte/Mainz

Geant4: γ's from SN ν's





Timeline

- Detailed Monte Carlo simulations underway
  - Low energy reconstruction will follow work on DeepCore now underway
  - Cherenkov ring reconstruction can modify existing algorithms from experiments like SuperK
- We aim for a PINGU proposal soon, deploy within next few years