



*The Abdus Salam
International Centre for Theoretical Physics*



2246-36

**Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the
Neutrino Sky**

20 - 24 June 2011

First results from IceCube/DeepCore and prospects for low energy physics in Ice

Doug COWEN
*Pennsylvania State University
USA*

First Results from IceCube/DeepCore and Prospects for Low Energy Physics in the Ice

Doug Cowen
IceCube Collaboration
and
Department of Physics
Penn State University

NuSky
Trieste, Italy
June 2011

Outline

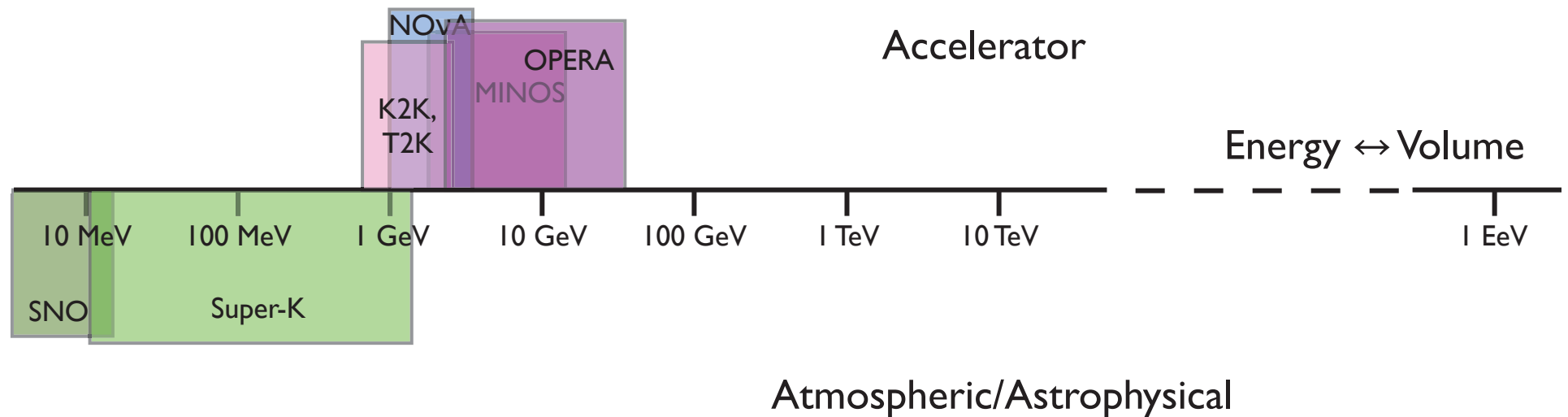
- Neutrino detectors
- IceCube and its DeepCore sub-array
 - Design
 - First results
 - Predicted performance
- PINGU (Phased IceCube Next Generation Upgrade)
 - PINGU-I: A possible enhancement to DeepCore down to $E_\nu \sim 1$ GeV
 - physics motivations, possible designs
 - PINGU-II: A possible GeV to sub-GeV Mton-scale Cherenkov ring-imaging detector
 - physics motivations, possible designs

The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

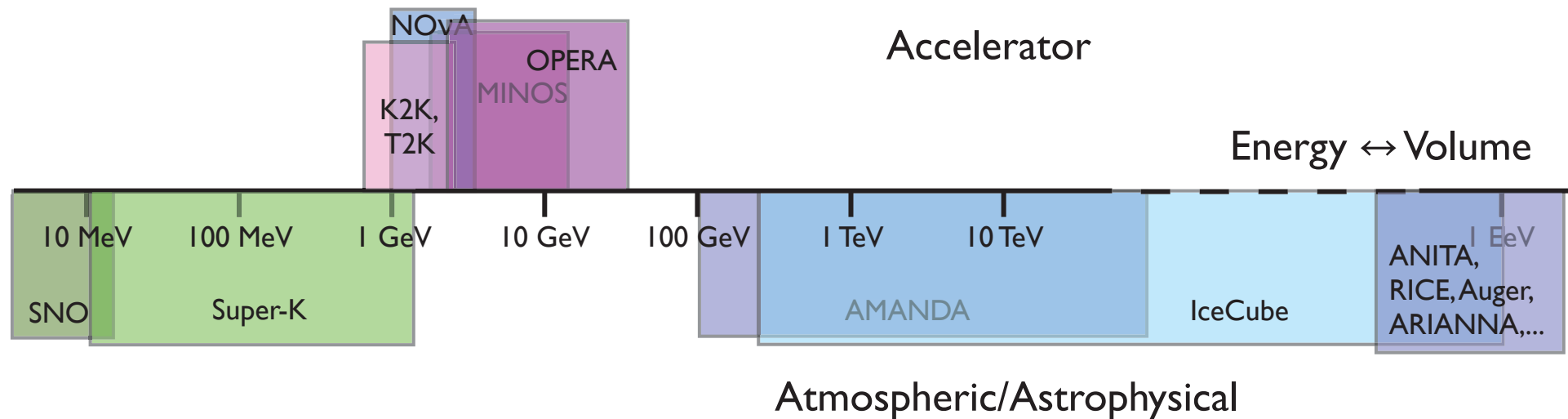
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments

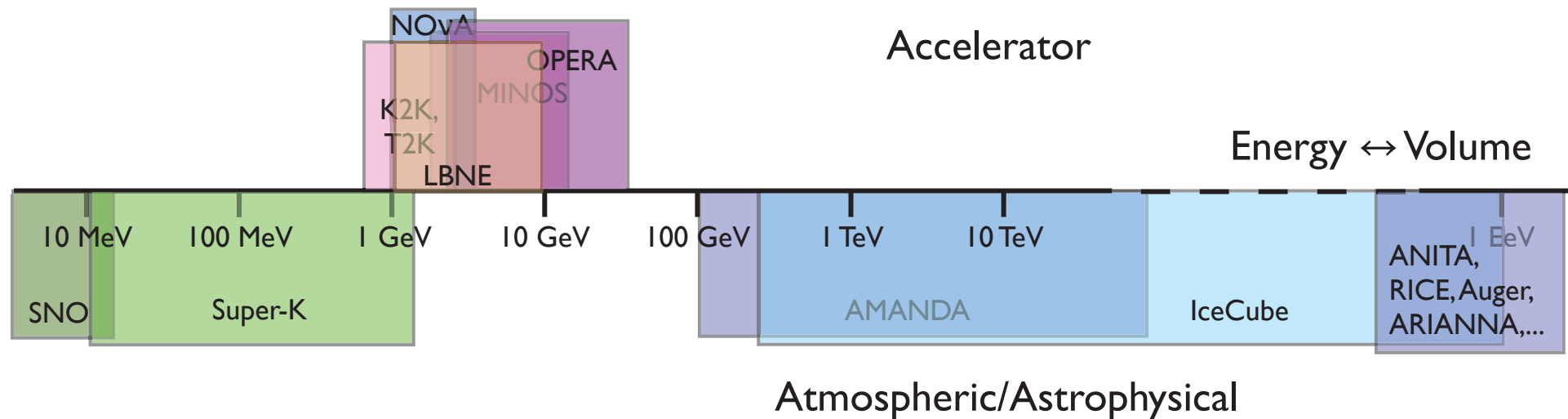
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments
- Very large (\sim Gton), low precision experiments

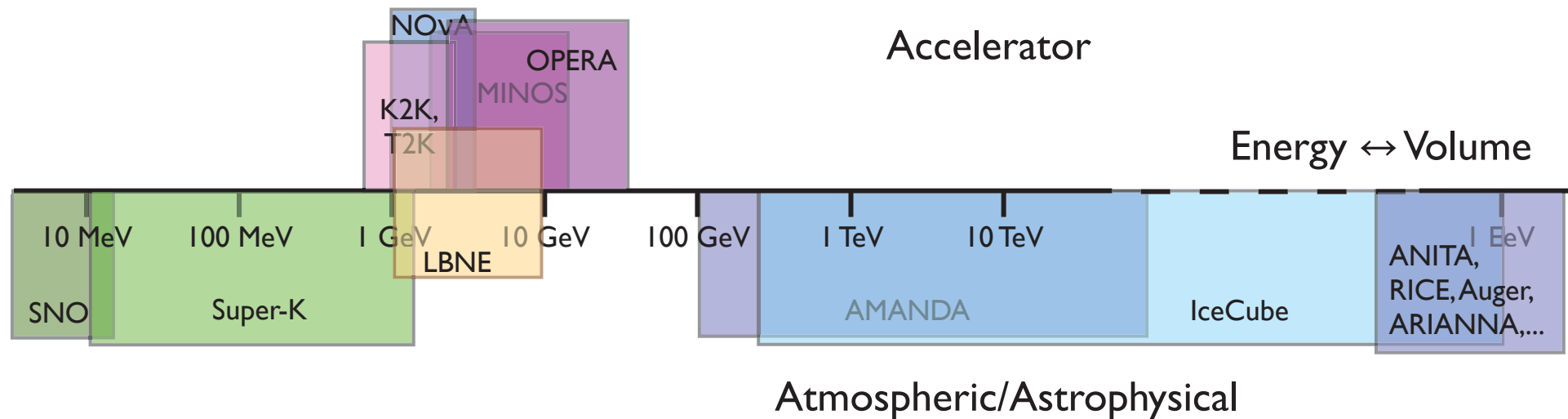
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll MTon), high precision experiments
- Very large (\sim GTon), low precision experiments

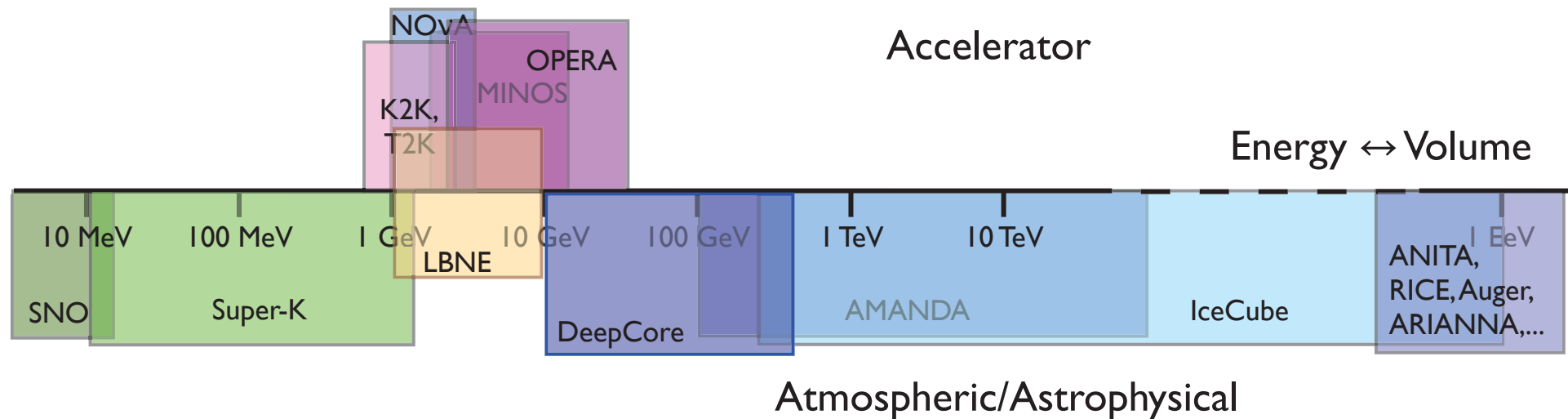
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments
- Very large (\sim Gton), low precision experiments

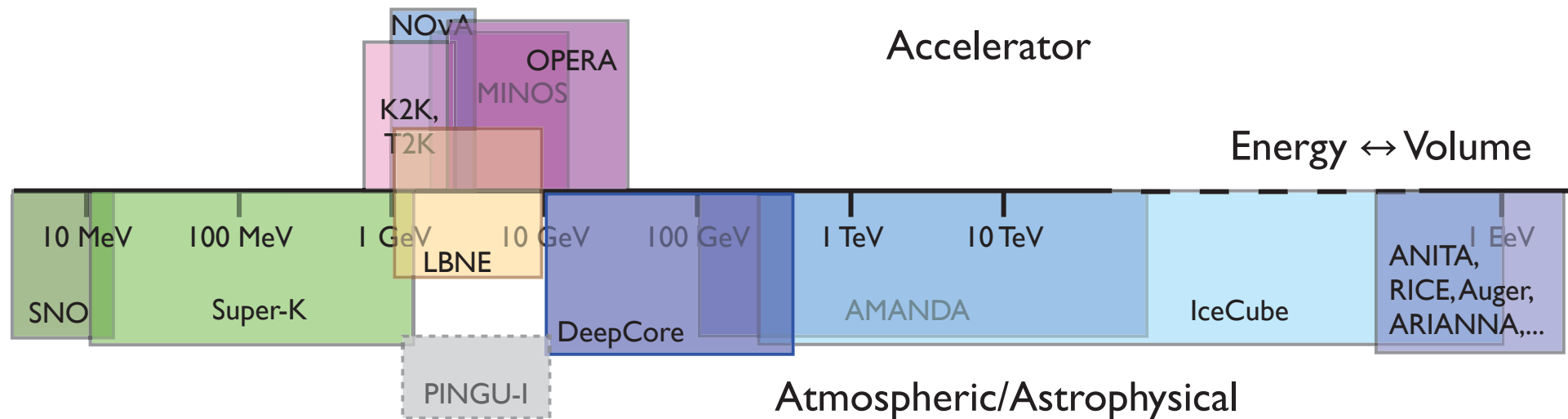
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments
- Very large (\sim Gton), low precision experiments

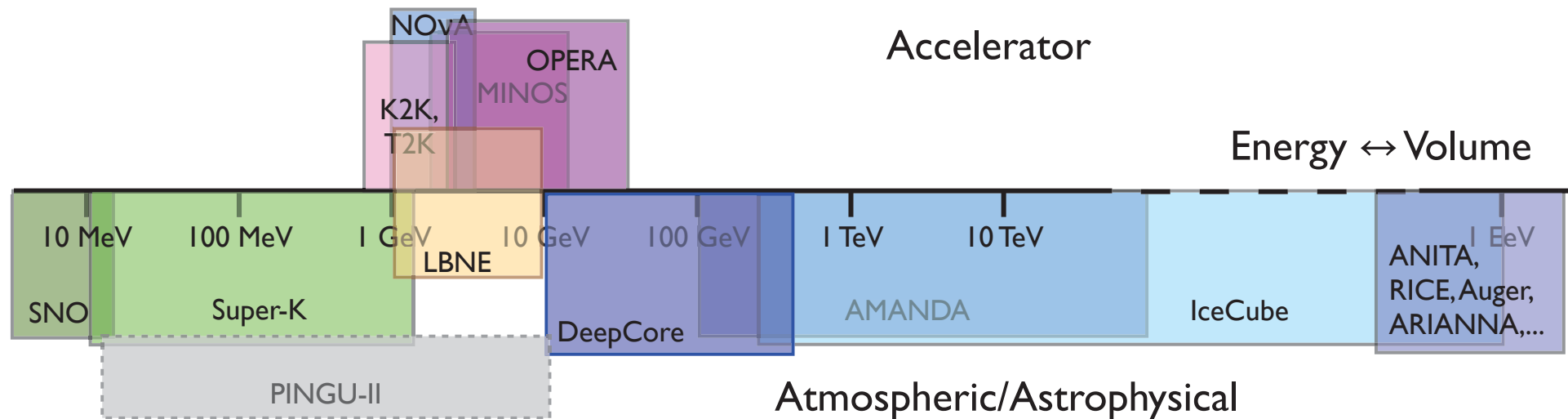
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments
- Very large (\sim Gton), low precision experiments

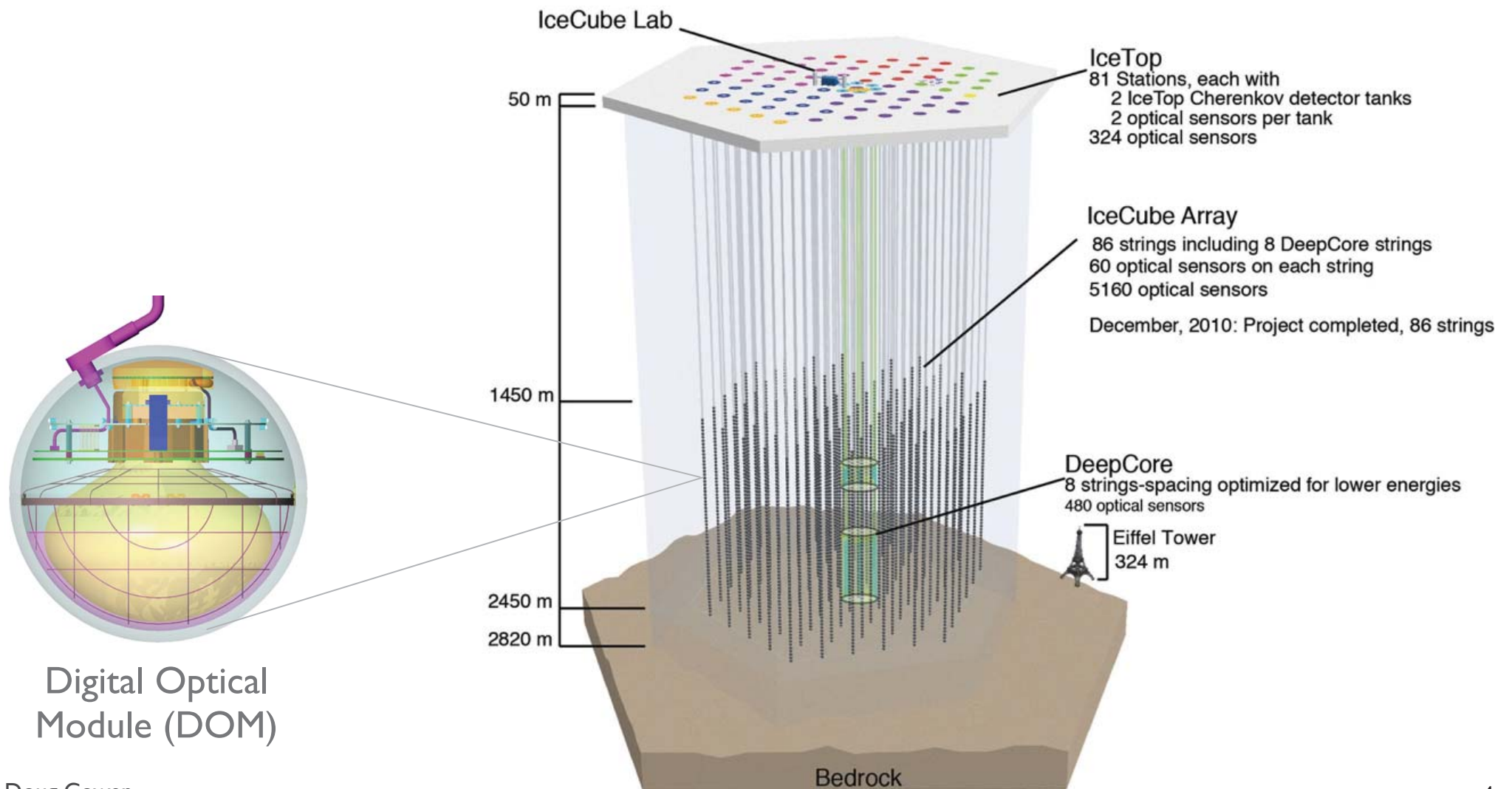
The Neutrino Detector Spectrum



Historically, two main branches of the neutrino detector family tree:

- Relatively small (\ll Mton), high precision experiments
- Very large (\sim Gton), low precision experiments

IceCube Status: Fully Constructed!

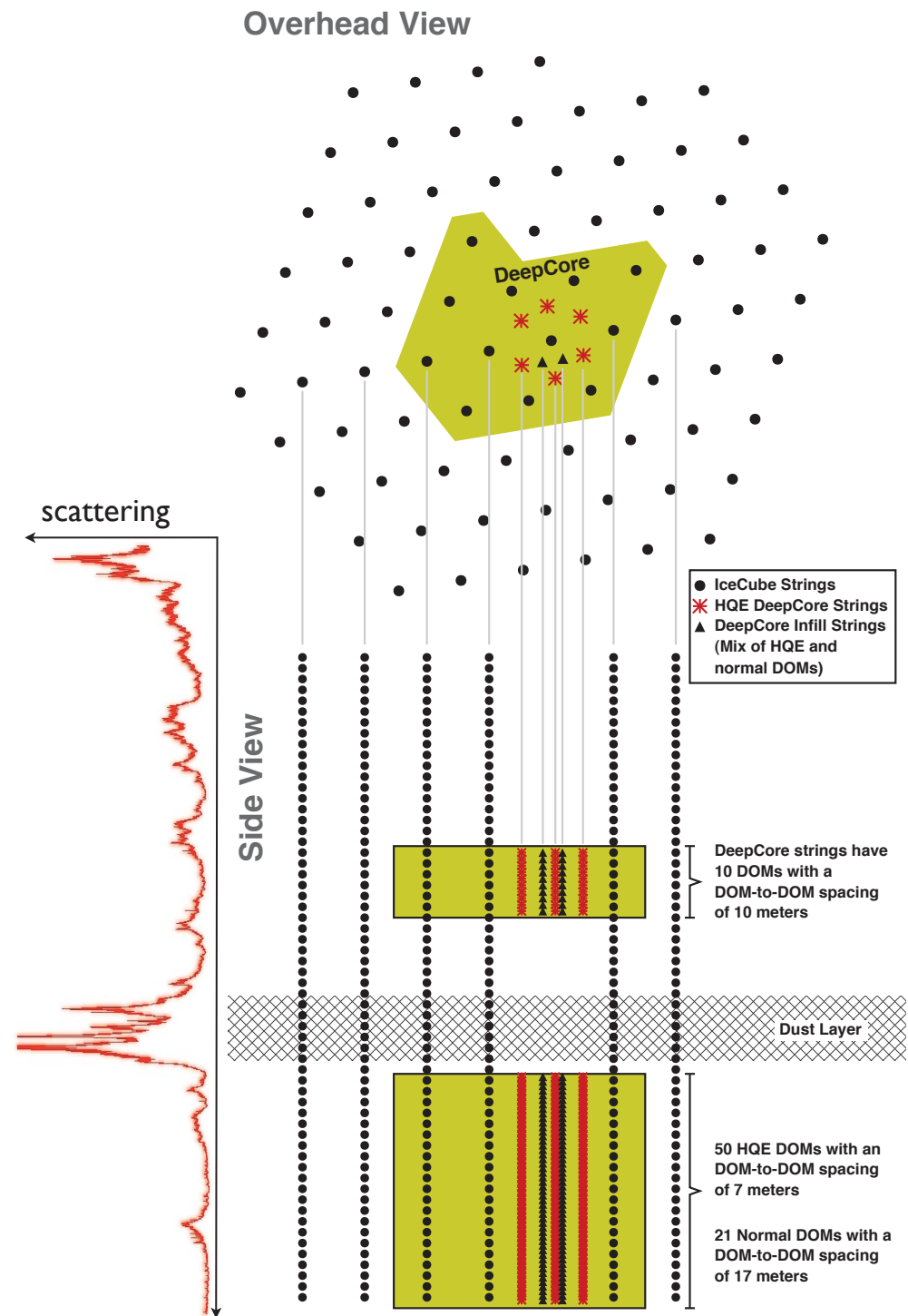


IceCube DeepCore: Introduction

- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
 - Significant improvement in capabilities from ~ 10 to ~ 300 GeV
- 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)

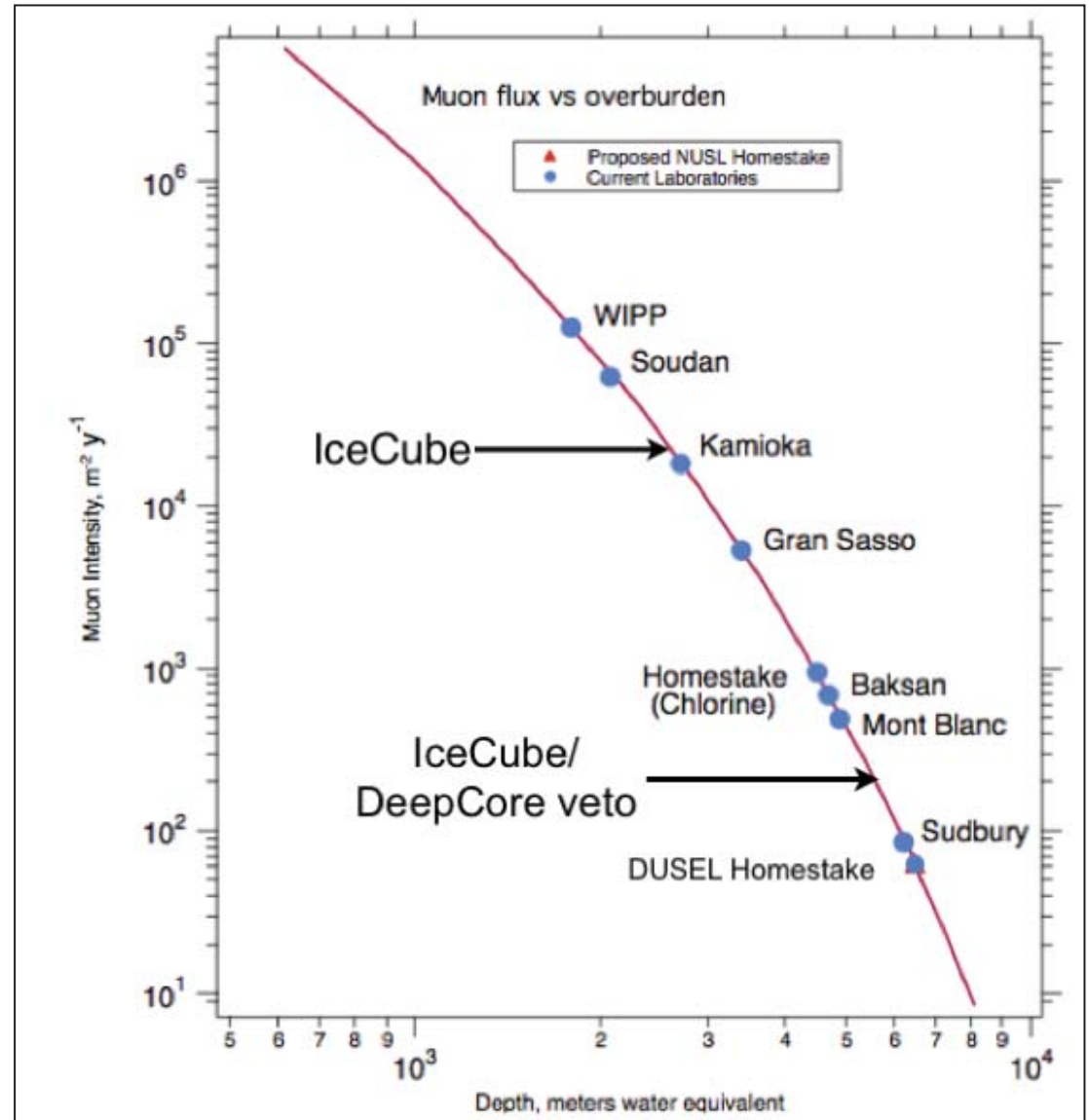
DeepCore: Design

- Eight special strings plus 12 nearby standard IceCube strings
 - 72 m interstring horizontal spacing (six with 42 m spacing)
 - 7 m DOM vertical spacing
 - ~40% higher Q.E. PMTs
 - ~5x higher effective photocathode density
- Deployed mainly in the clearest ice, below 2100 m
 - $\lambda_{\text{eff}} = 47$ m (average)
 - $\lambda_{\text{abs}} = 155$ m (average)
- Result: ~30 Mton detector with ~10 GeV threshold, collecting $\mathcal{O}(200\text{k})$ atmospheric ν/yr



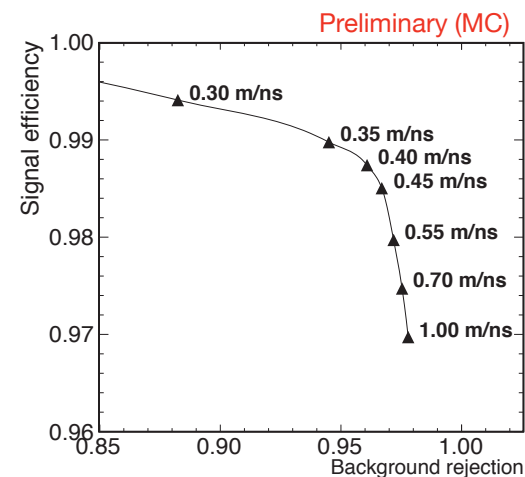
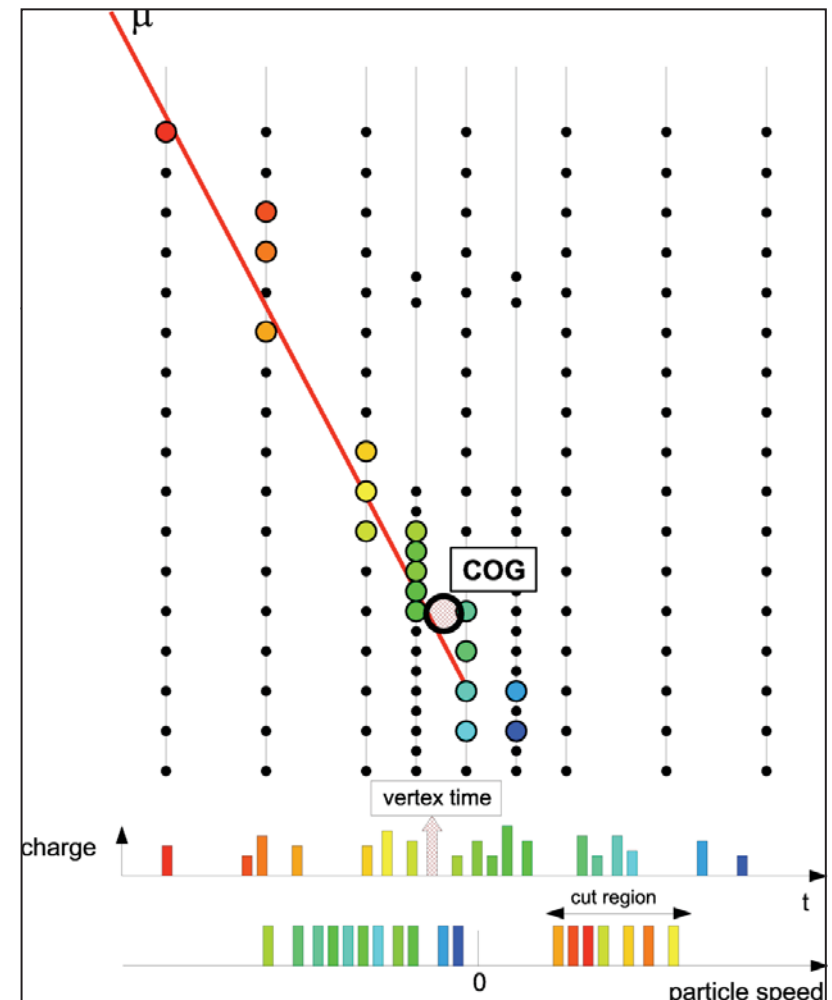
DeepCore: Atmospheric Muon Veto

- 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
- Use veto 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



DeepCore: Atmospheric Muon Online Filter

- First, trigger on 3 or more hits in DeepCore fiducial volume in $2.5\mu\text{s}$ (“SMT3”)
- Then, look for hits in veto region consistent with speed-of-light travel time to hits in DeepCore
 - Achieves >2 orders of magnitude rejection of cosmic ray muon background
- Loss of $<2\%$ of fiducial neutrinos

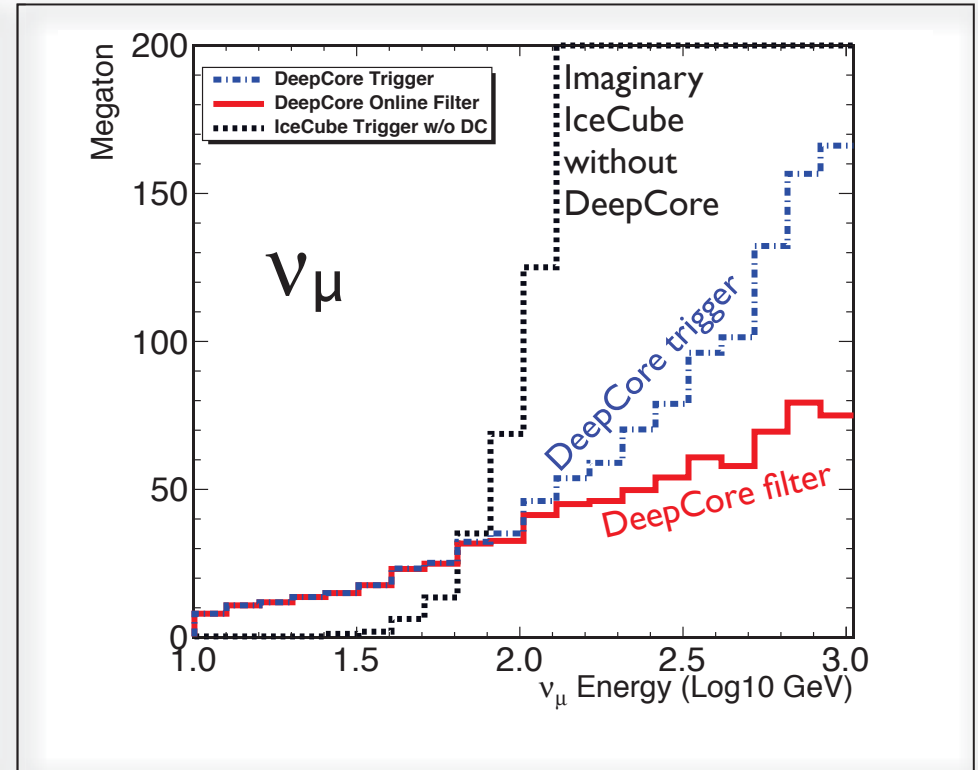
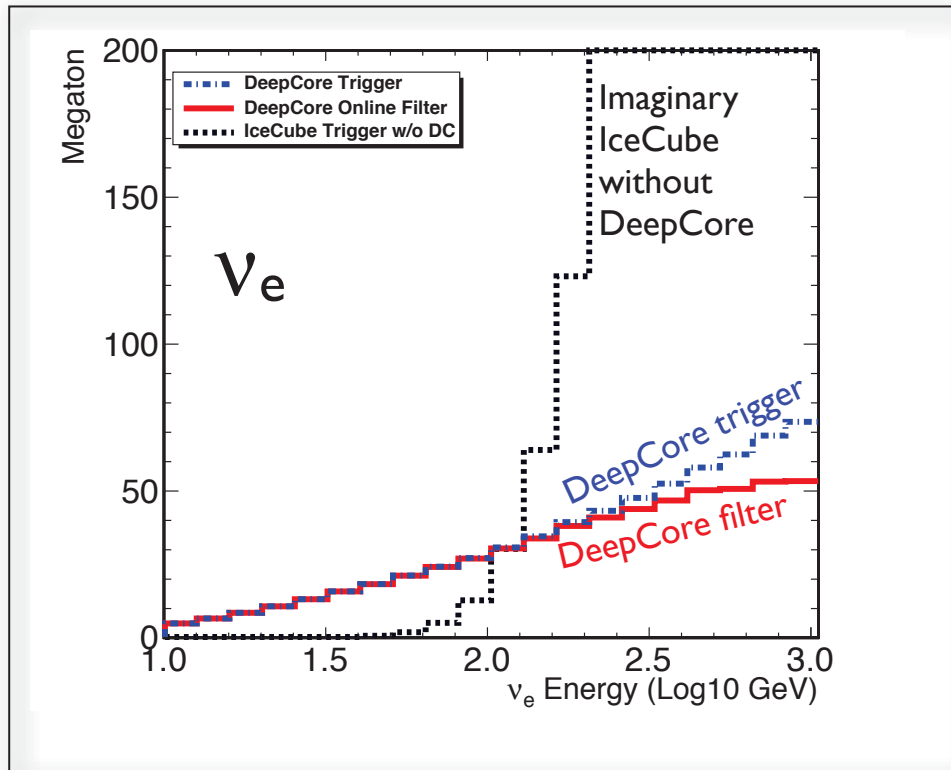
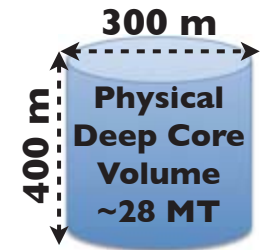


Require speed to be between 0.25-0.40 m/ns.

The value “0.40” was chosen by holding 0.25 constant and varying upper value, giving plot on left. (And similarly for 0.25.)

DeepCore: Lepton Effective Volume

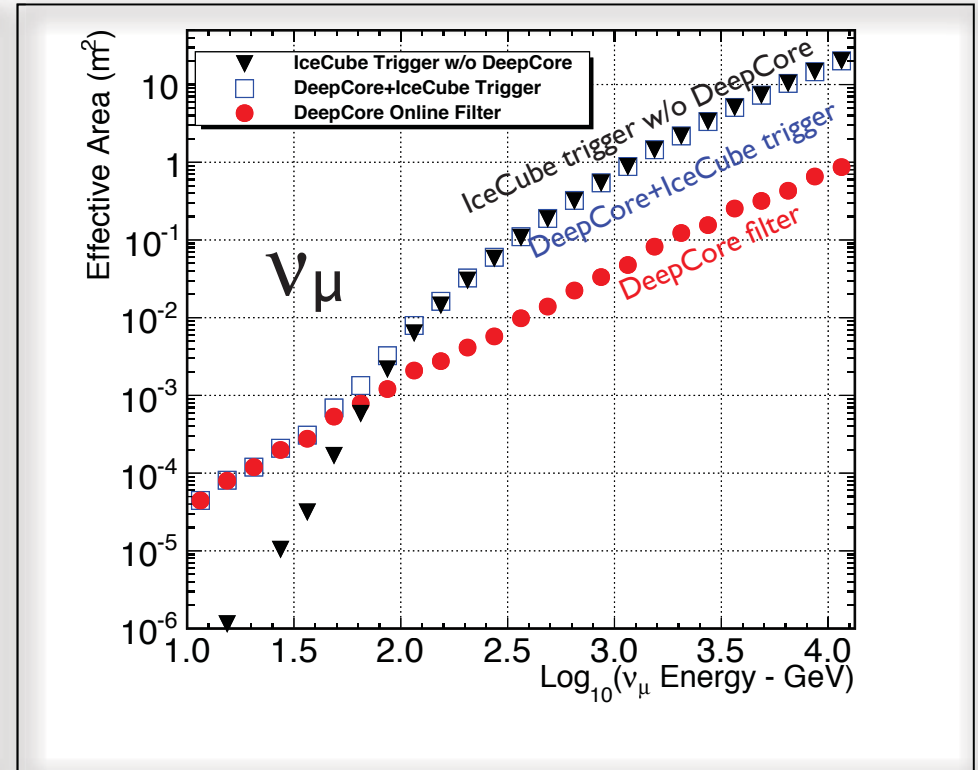
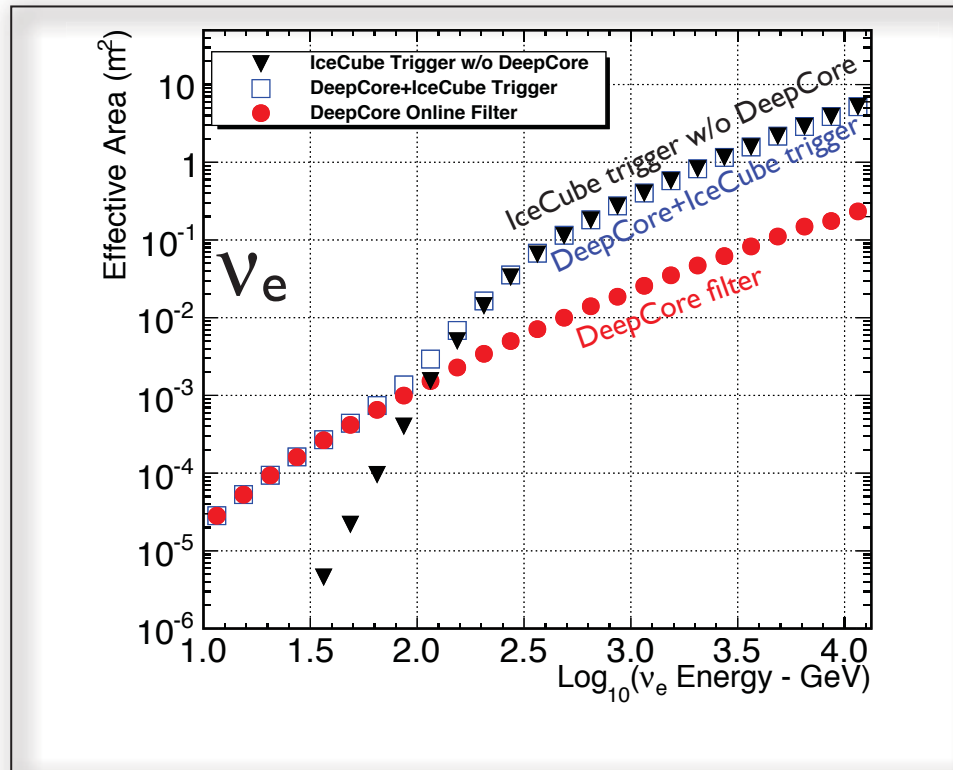
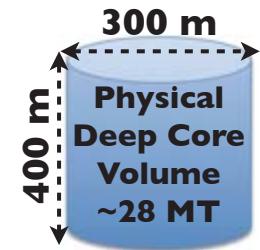
$$V_{eff} = \frac{N_{acc}}{N_{gen}} V_{gen}$$



- Many events in IceCube will also trigger DeepCore
 - These events are rejected by the online veto algorithm
- Below ~100 GeV, DeepCore improves V_{eff} significantly
- Final V_{eff} will be lower than shown once we require good event reconstruction

DeepCore: Neutrino Effective Area

$$A_{eff} = \frac{N_{acc}}{N_{gen}} A_{gen}$$



- Below ~100 GeV, DeepCore improves A_{eff} significantly
 - Improved trigger efficiency of DeepCore overcomes its smaller volume relative to IceCube
 - Linear growth in A_{eff} is due to neutrino cross section, not detector efficiency
- Final A_{eff} will be lower than shown once we require good event reconstruction

DeepCore:

First Results (*Preliminary*)

- Historical background:
 - First high energy neutrinos detected years ago by AMANDA
 - detected long muon tracks created by atmospheric ν_μ interactions
 - many IceCube analyses have grown in this fertile soil
 - In parallel, launched efforts to detect EM and hadronic showers produced by, e.g., ν_e
 - in many channels, searches for high energy ν -induced showers had comparable strength to their ν_μ track-based companions
 - but the actual detection of *lower energy atmospheric* ν_e has been much more challenging

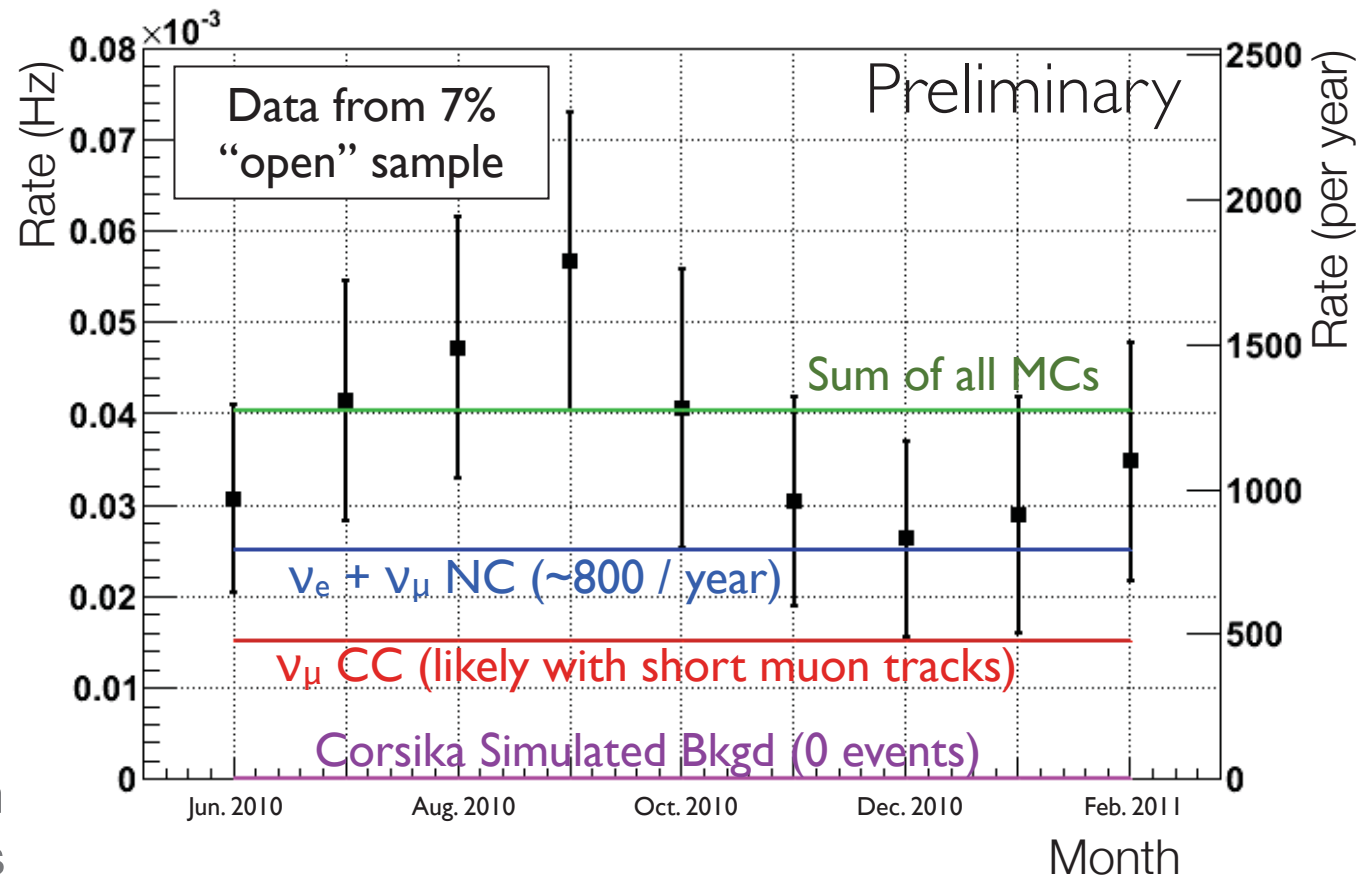
DeepCore:

First Results (*Preliminary*)

- Enter DeepCore with its potent combination of
 - Vetoing from surrounding IceCube strings
 - beats down copious cosmic-ray background
 - Lower energy threshold
 - increases event rate
- With just one year of DeepCore data, we may have first detection of ν_e in a previously inaccessible energy regime
 - Expected to see them, so this is not a fundamental discovery
 - But it is a very important milestone for IceCube
 - clearly highlights DeepCore's design advantages
 - opens up a new and important analysis channel
 - lights the path for further extensions with lower E_ν thresholds

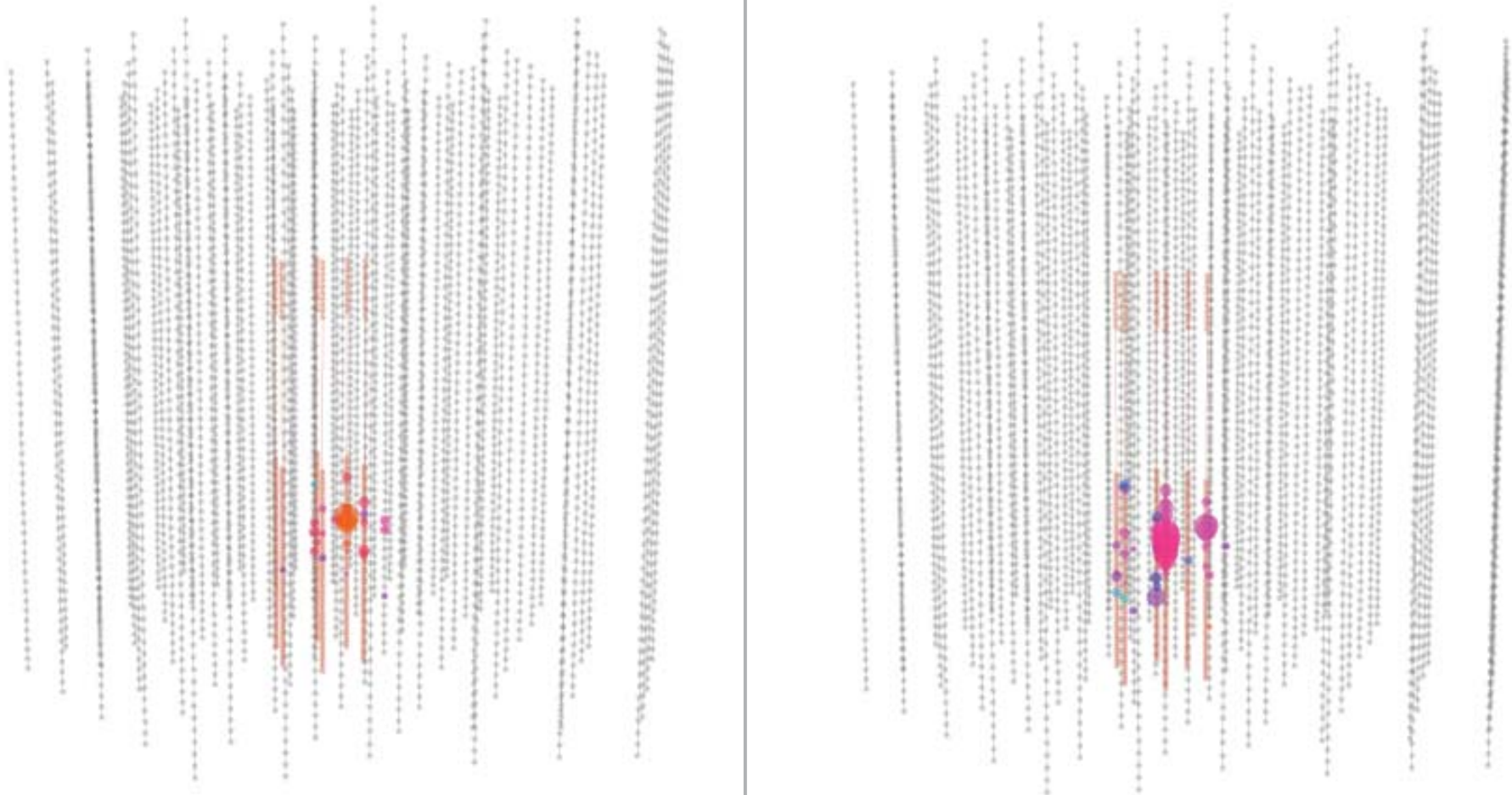
DeepCore: First Results (*Preliminary*)

- With harsh cuts to eliminate the ν_μ background we expect to obtain a sample of ~ 800 neutrino-induced cascades per year
 - Approximately 500 background ν_μ CC events expected
 - Contamination from atmospheric muons still being evaluated
 - Efforts to increase ν_e yield and reduce ν_μ CC background ongoing



DeepCore: First Results (*Preliminary*)

Two candidate events

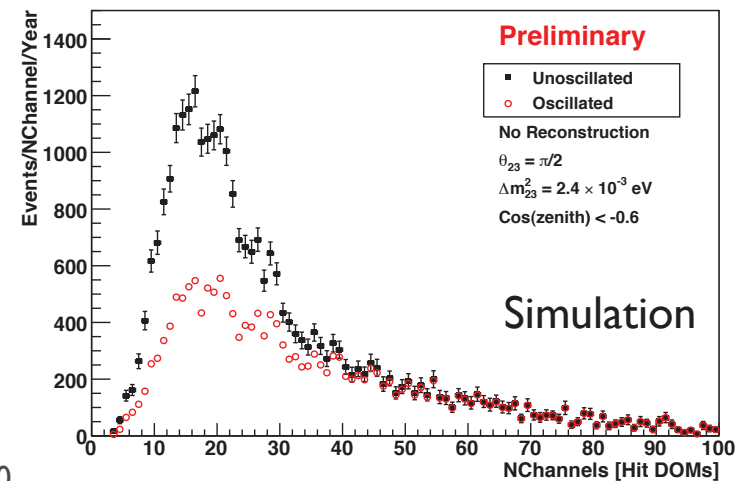
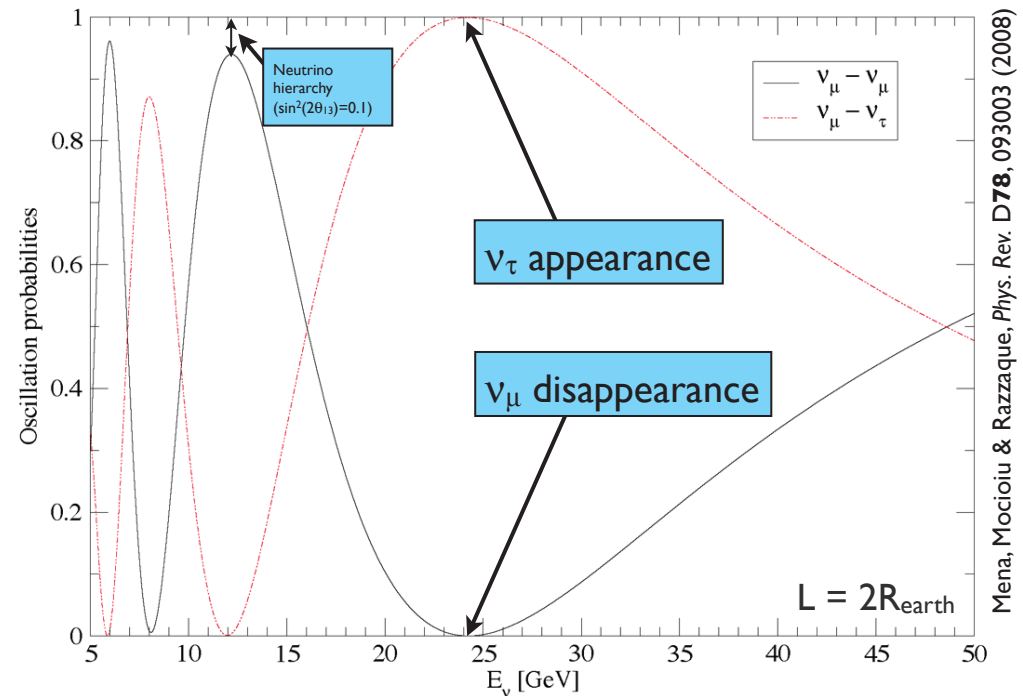


(Standard hit cleaning algorithm removed all noise hits in rest of detector.)

DeepCore:

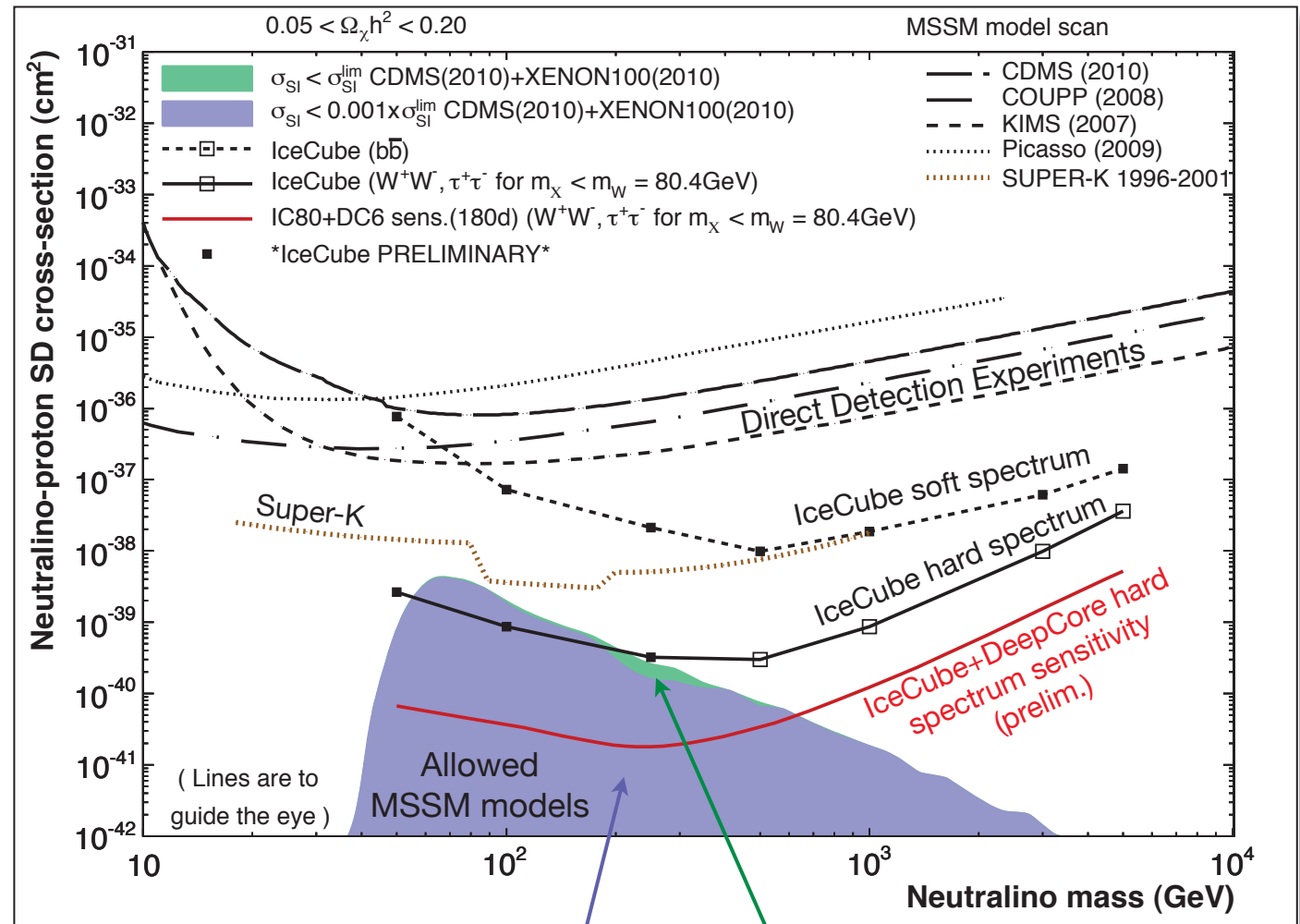
Predicted Performance: ν Oscillations

- 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
- ν_μ disappearance (see lower plot)
 - Analysis efficiencies not included yet – work ongoing
 - Uses number of hit DOMs as a crude energy estimator
- ν_τ appearance
 - Will have cascade sensitivity, working on energy resolution and particle ID to extract ν_τ appearance.
 - excess event rate over finite range in E
 - energy spectrum distortion



Deep Core: Predicted Performance: WIMPs

- 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



Corresponding σ_{SI} more than factor 10^3 beyond current direct limits

Corresponding σ_{SI} within factor 10^3 of current direct limits

PINGU: Phased IceCube Next Generation Upgrade

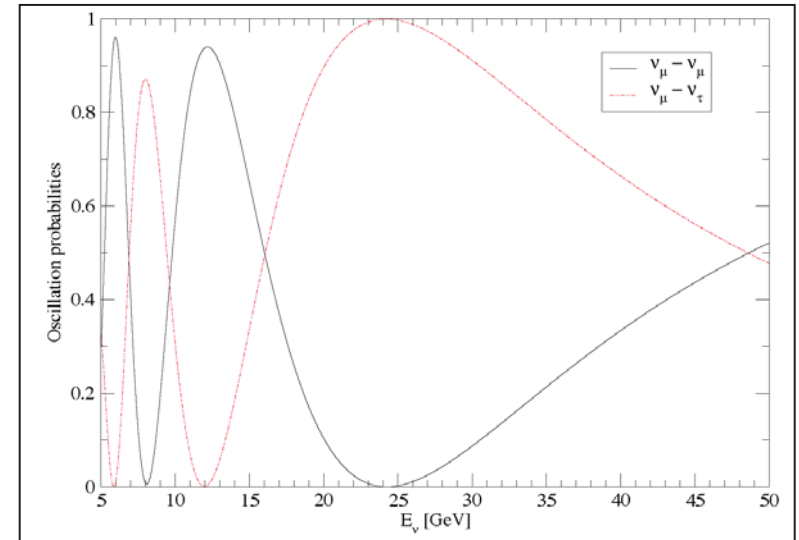


- First stage (“PINGU-I”)
 - Add ~20 in-fill strings to DeepCore to extend energy reach down to ~1 GeV
 - improves WIMP search, neutrino oscillation measurements, other low energy physics
 - test bed for physics signals addressed by next stage
 - Use mostly standard IceCube technology
 - Include some new photon detection technology as R&D for next step
 - Add new calibration devices designed with low energy signals in mind
- Second stage (“PINGU-II”)
 - 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 to IceCube, but in a much smaller volume
 - Detection medium is the support structure; no costly excavation required to build detector

PINGU-I:

Physics Motivations for ~ 1 GeV Energy Threshold

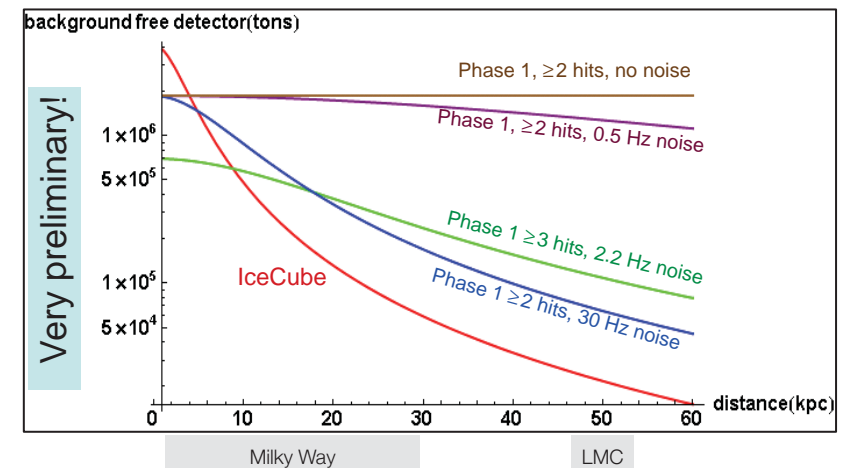
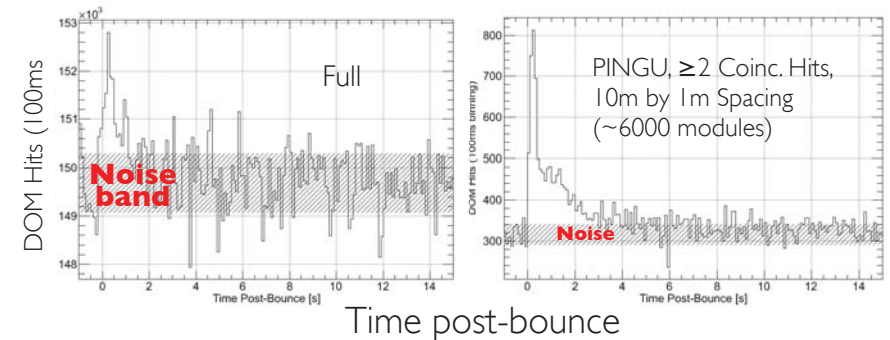
- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
 - will help pin down $(\Delta m_{23})^2$
- Gain increased sensitivity to supernova neutrino bursts
 - Extension of current search for coherent increase in singles rate across entire detector volume
 - Only 2 ± 1 core collapse SN/century in Milky Way
 - 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
- Pathfinder technological R&D for PINGU-II



PINGU-I:

Physics Motivations for ~ 1 GeV Energy Threshold

- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
 - will help pin down $(\Delta m_{23})^2$
- 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
 - 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
- Pathfinder technological R&D for PINGU-II



Equivalent size of a background free detector for beginning 0.38 s of **Lawrence Livermore** model, 1 m DOM and 10 m string distance, 18 strings ($\sim 6,000$ DOMs) (figures from Lutz Koepke/Mainz)

PINGU-I: Possible Geometry

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

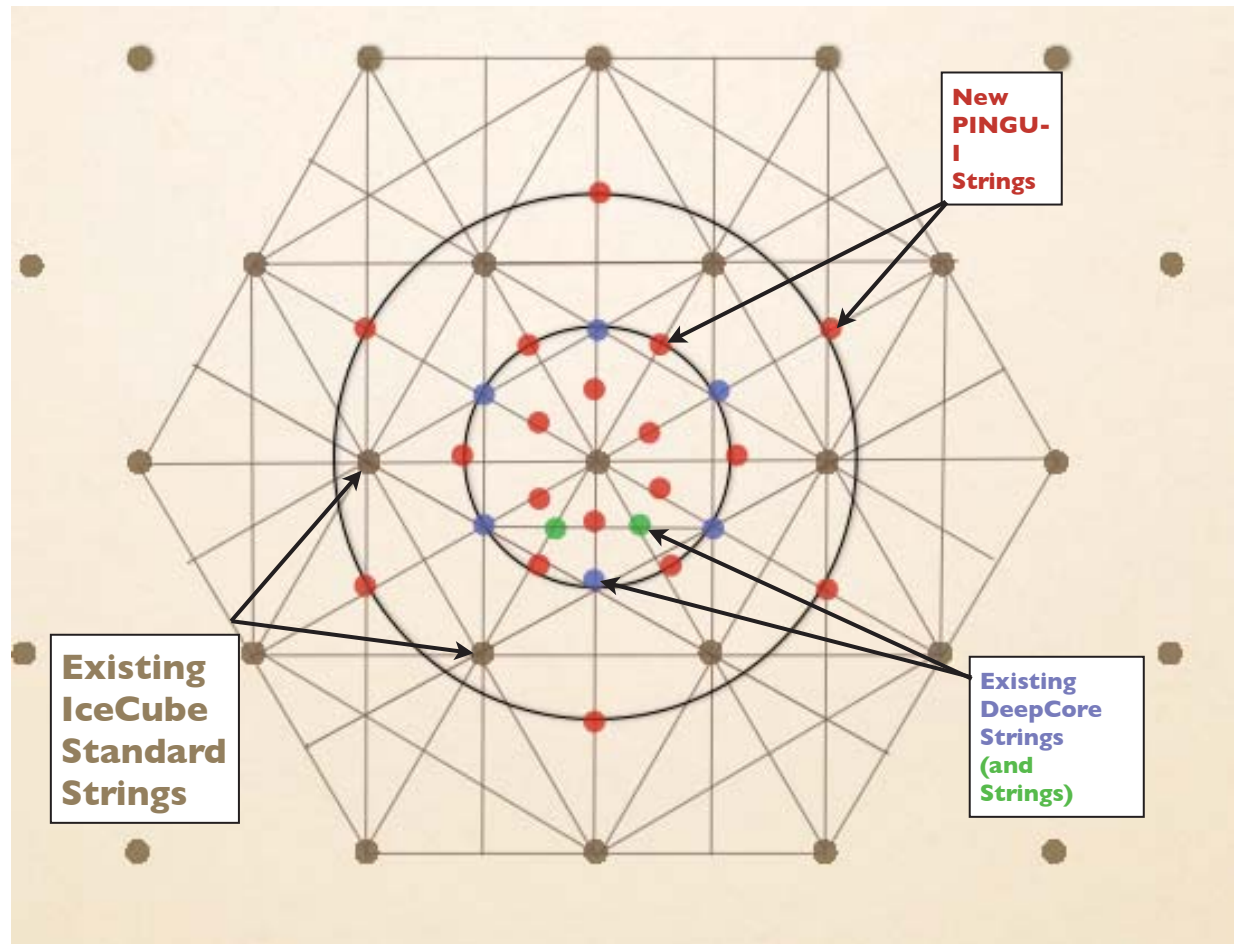


Image courtesy of A. Karle

- Price tag would likely be around \$25M

PINGU-II:

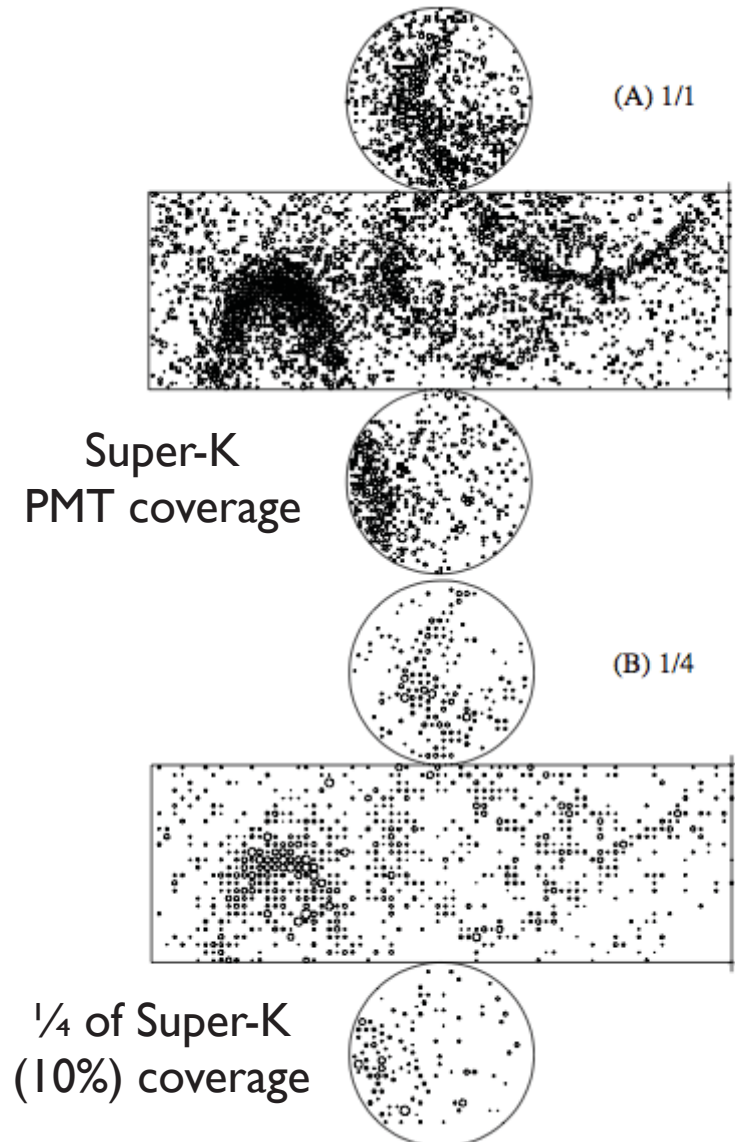
Physics Motivations for sub-GeV Energy Threshold

- Proton decay
 - Target $p \rightarrow \pi^0 + e^+$ channel
- Supernova neutrinos
 - Need to reach well beyond our galaxy to get statistical sample of SN neutrinos
- Plus improvements for WIMP, oscillation analyses over PINGU-I & DeepCore

PINGU-II: Proton Decay

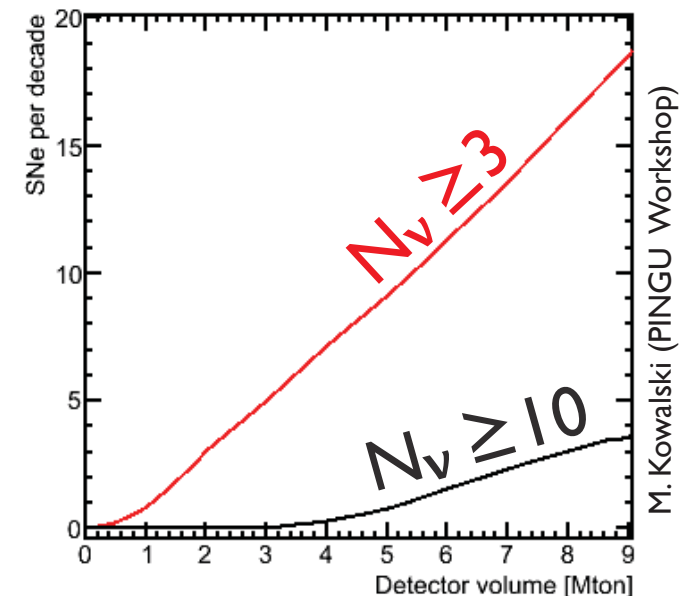
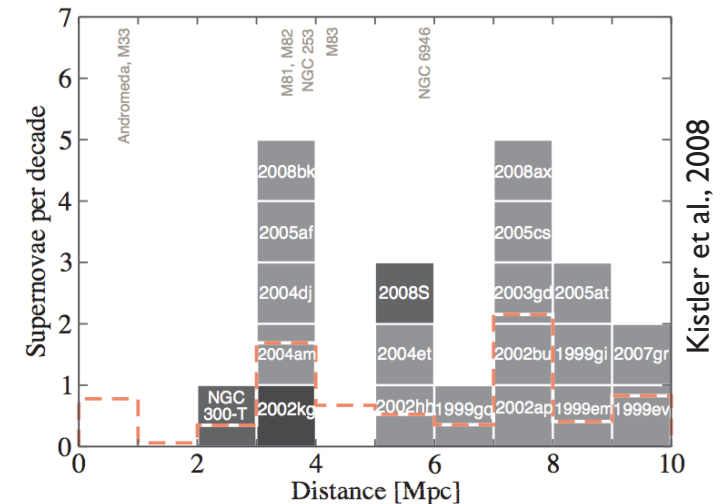
Thanks to E. Resconi

- For fiducial volume of 1.5 MT (5×10^{35} protons) with ~ 100 MeV energy threshold (expect ~ 200 photons/MeV)
 - $\tau_p \sim 10^{35} - 10^{36}$ yr for $p \rightarrow \pi^0 + e^+$ channel
 - SU(5) - 10^{36} yr sensitivity probes minimal realistic theory
 - SUSY SU(5) - 10^{36} yr would rule out MSSM defined for $M_{\text{GUT}} \ll M_{\text{Planck}}$
- MC studies needed to understand:
 - energy resolution in a volume detector
 - possibilities for e/μ ID from Cherenkov rings
 - required photocathode coverage
 - preliminary MC calculations indicate 5-10% coverage may be within reach



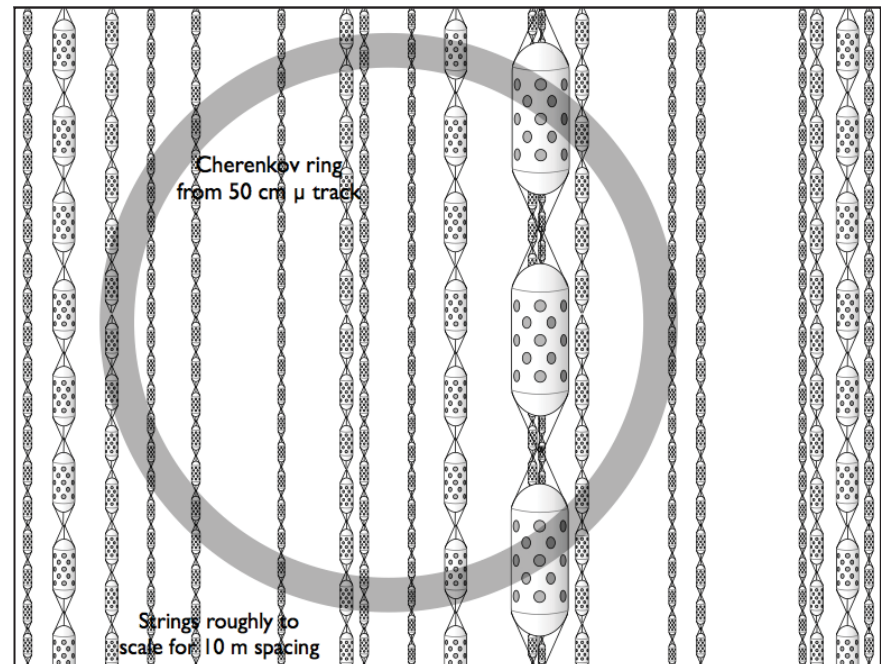
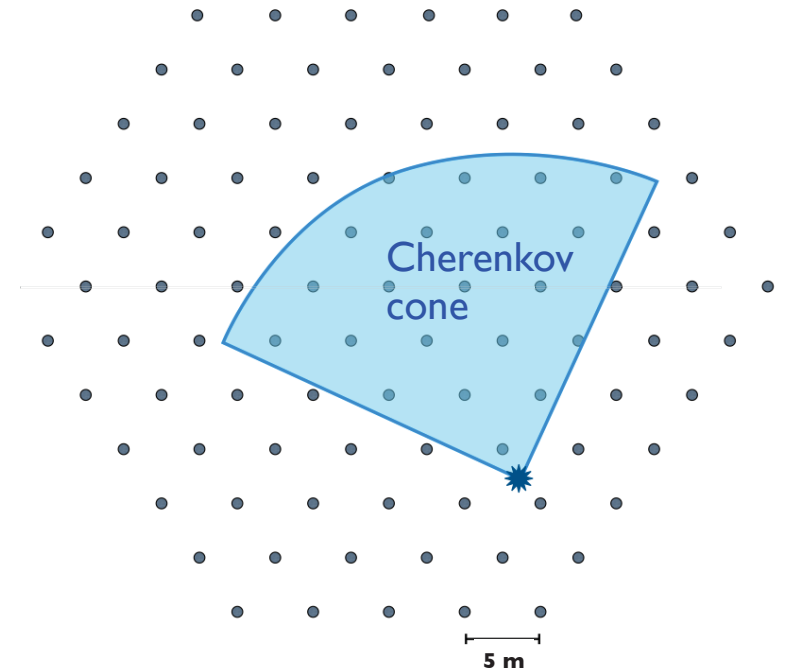
PINGU-II: Supernova Neutrinos

- With ~ 200 Cherenkov photons per MeV:
 - A detector in the ice could reach down as low as 10 MeV
 - Would confer sensitivity out beyond ~ 1 Mpc, giving neutrino bursts from ~ 1 SN/yr (!!!)
 - $N_\nu \sim 20 \times (D/\text{Mpc})^{-2} \times (V/\text{Mton})$
 - Other benefits:
 - Neutrinos would provide early triggers for optical observations
 - Similarly, gravitational wave detectors would gain background reduction of $\sim 10^6$
 - significance gain = $\sim 1000\times$ stronger signal
 - Caveats: LOTS of uncertainties (reconstruction, particle ID,...)



PINGU-II: Detector Concept

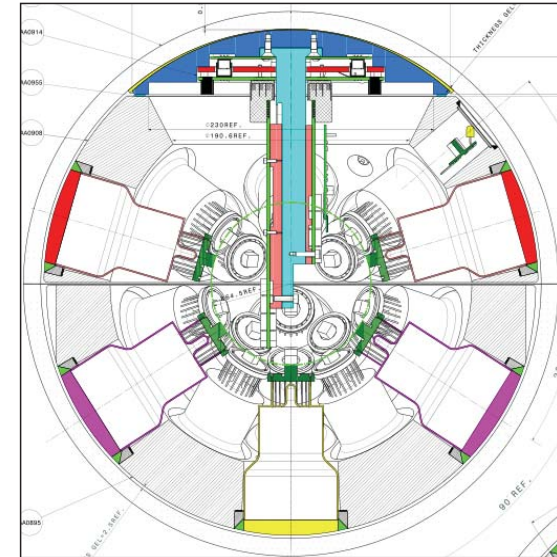
- $\mathcal{O}(\text{few hundred})$ strings of “line” detectors within DeepCore fiducial volume
- Physics extraction from Cherenkov ring imaging in the ice
 - Need high quality measurement of particle momenta and energy for sensitivity to proton decay
 - We don’t yet know if this is feasible; MC studies are underway
- Surrounding IceCube & DeepCore detectors provide active vetoing



PINGU-II: Composite Digital Optical Module

Courtesy E. de Wolf & P. Kooijman

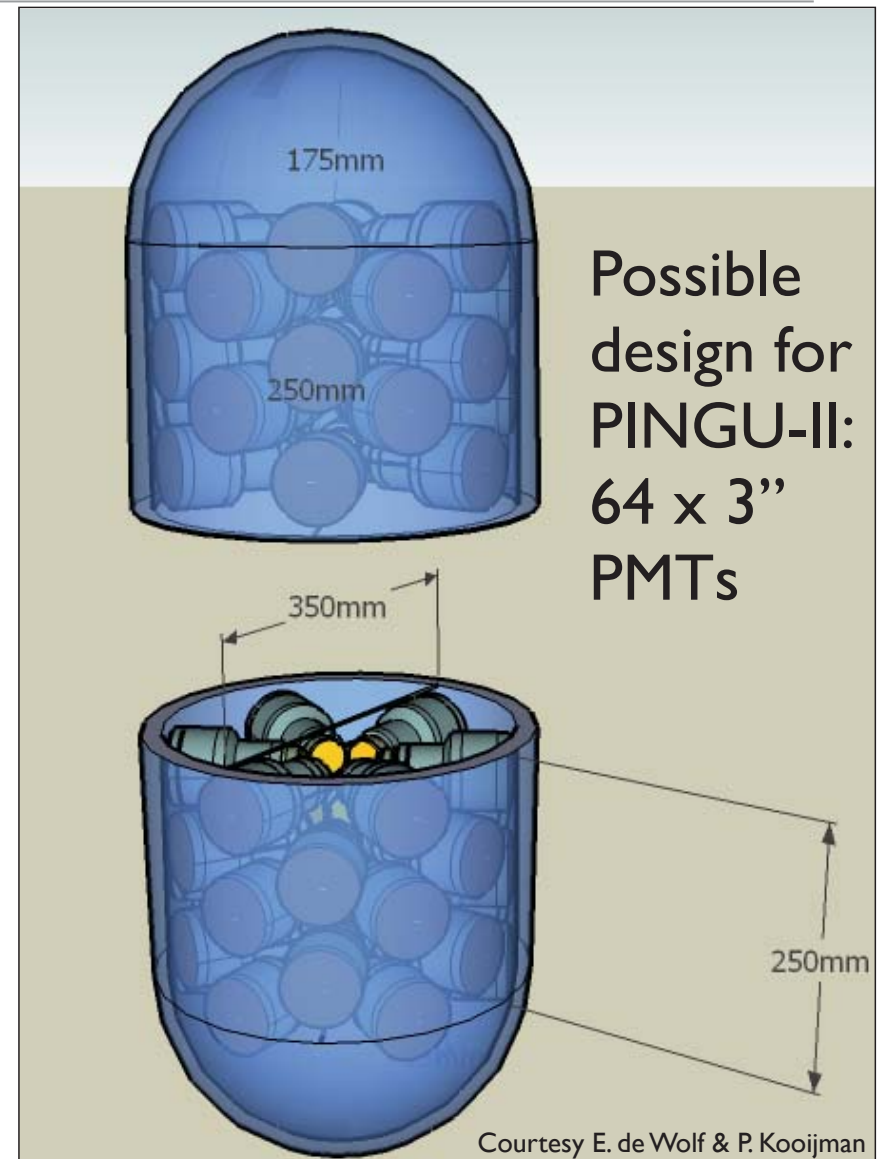
- Based on a KM3NeT proposed design
 - Glass sphere containing 31 3" PMTs and associated electronics
 - Effective photocathode area 4x that of standard 8" PMT, but
 - with better granularity
 - hopefully lower cost/area
 - Single connector simplifies deployment



P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR

PINGU-II: 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 drilling requirement would be similar (modulo much tighter vertical spacing)
 - Single connector
- Would be a big step towards enabling Cherenkov ring imaging in the ice
 - imagine connecting "stripes" of light created by Cherenkov rings as they intersect with the sides of many such cylinders



Conclusions

- DeepCore is working very well and has one year of data
 - Energy threshold as low as 10 GeV (10x lower than IceCube)
 - Strong evidence for high energy ν_{atm} cascades
 - High-E, high-stats ν_{μ} disappearance and ν_{τ} appearance analyses underway
 - Sensitivity to WIMPs down to $M_{\chi} = \sim 50$ GeV
- Future projects
 - PINGU-I
 - Extend reach of DeepCore lower by another $\sim 10\times$
 - Cost: well understood based on IceCube experience
 - Possible schedule: Deploy in 2 seasons starting 2014/15
 - Submit proposals to funding agencies in < 1 year
 - PINGU-II
 - Completely new detector with sub-GeV threshold
 - proton decay to $\sim 10^{36}$ years
 - detect neutrinos from ~ 1 SN/yr
 - Cost: driven by photocathode area; not detector size
 - “Schedule”: Begin deployment in 2018/19



© The Pygos Group

The End
