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

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Trieste, Italy
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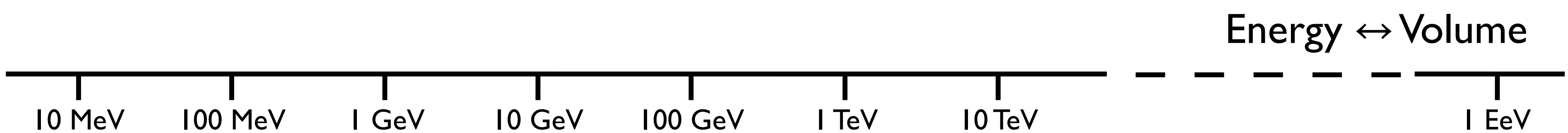
Outline

- 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



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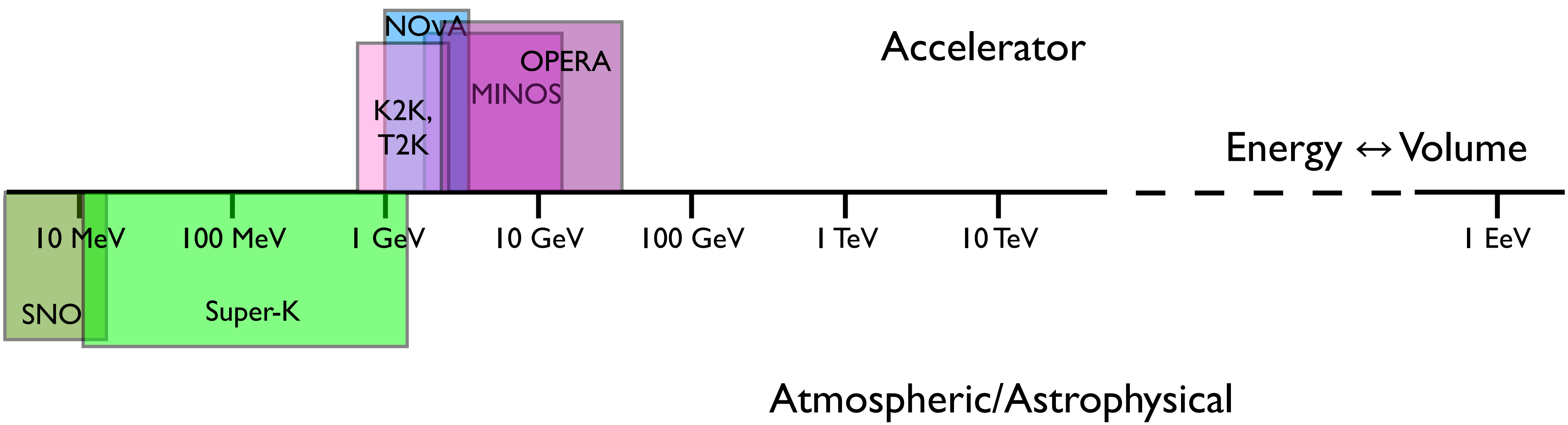

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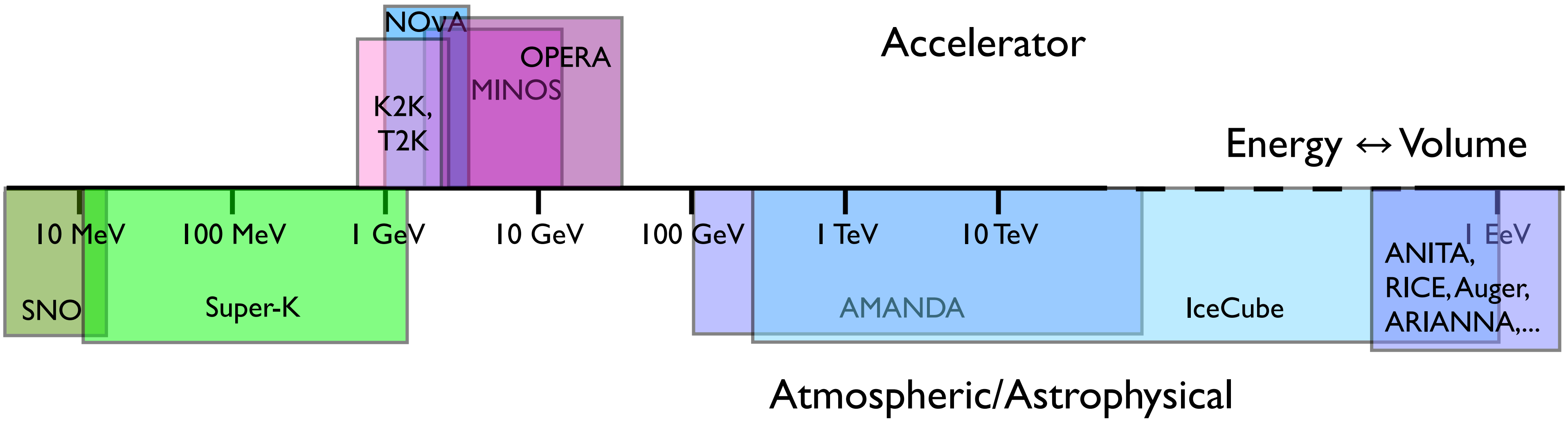

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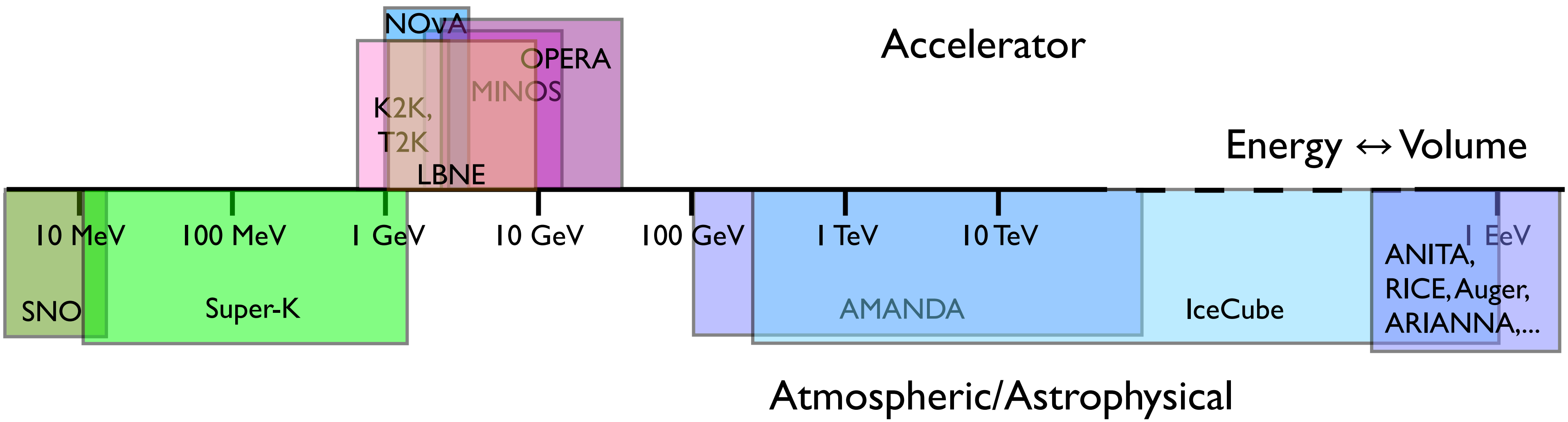

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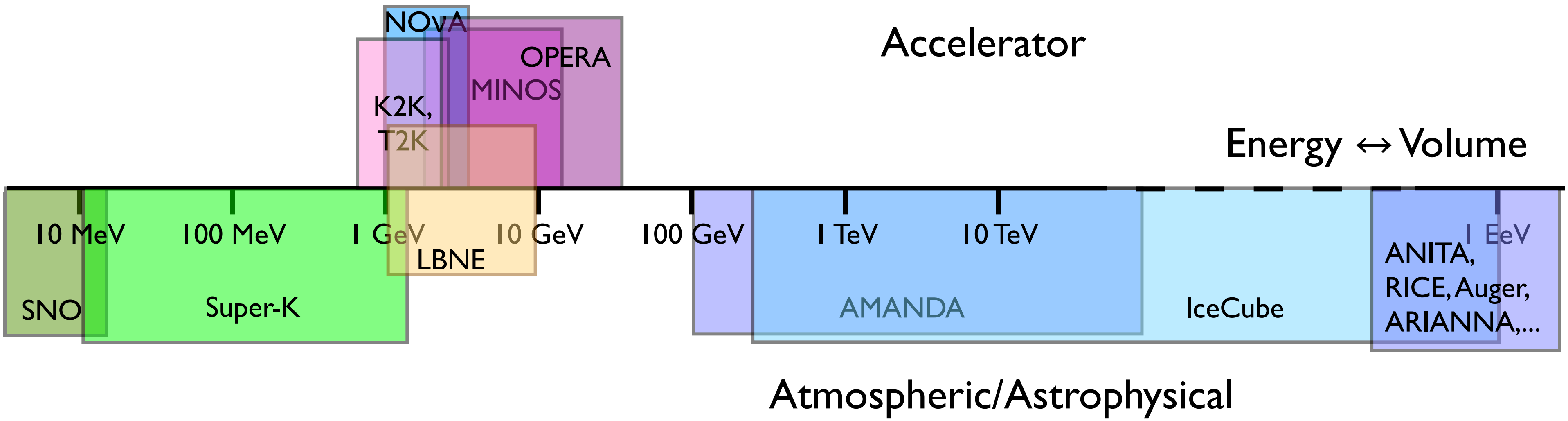

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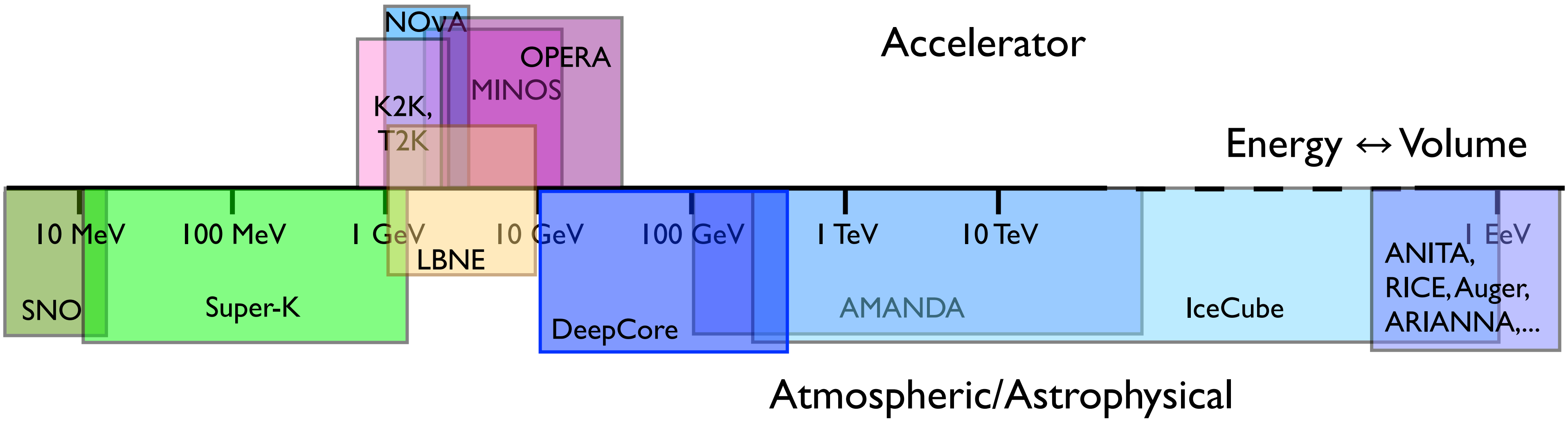

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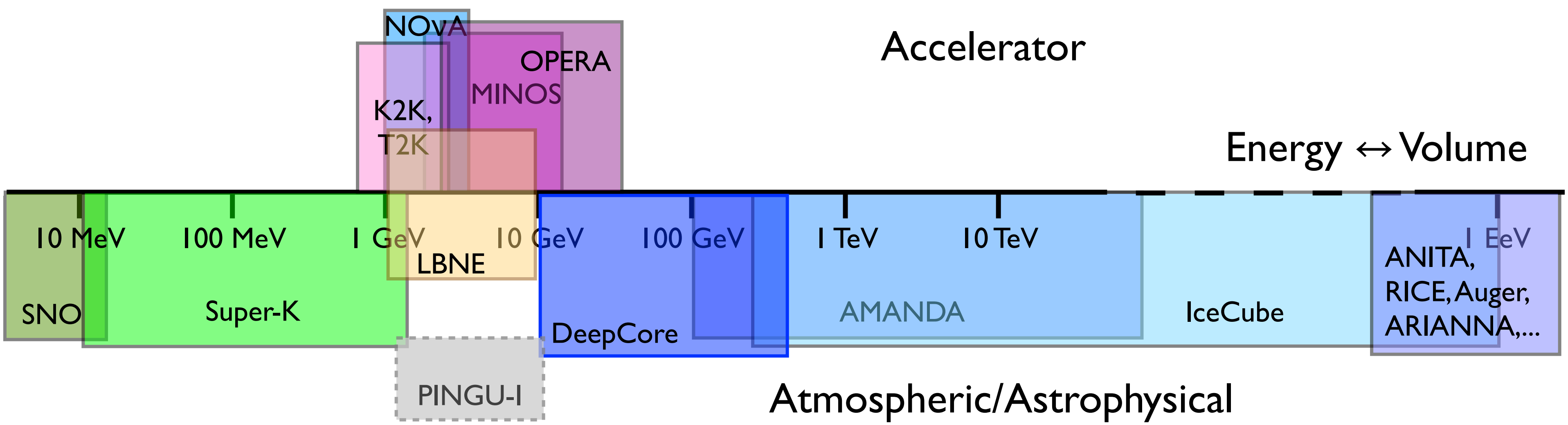

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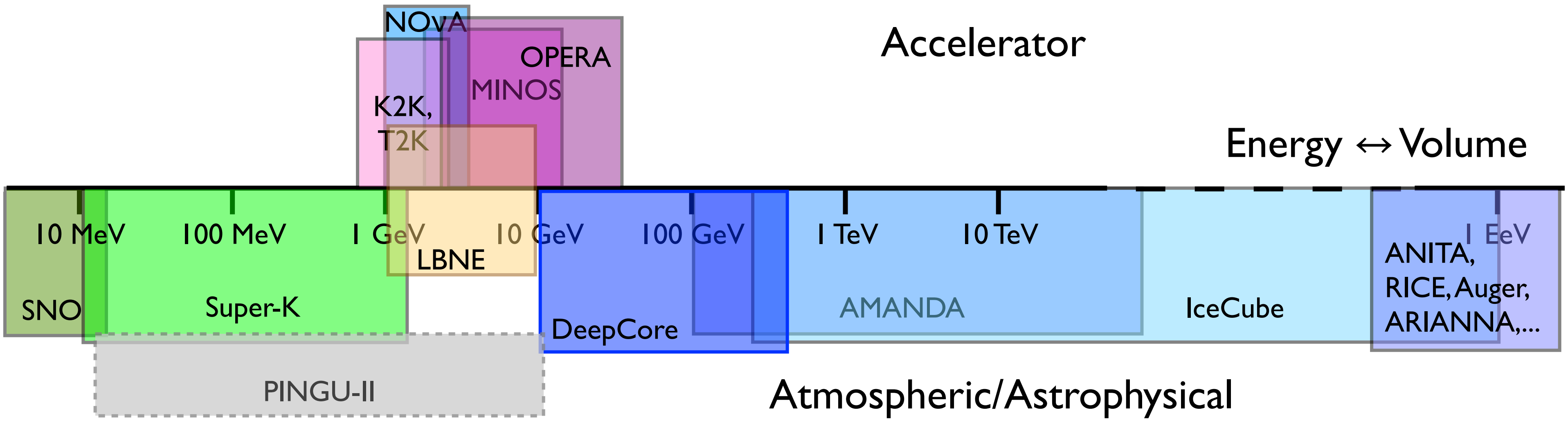

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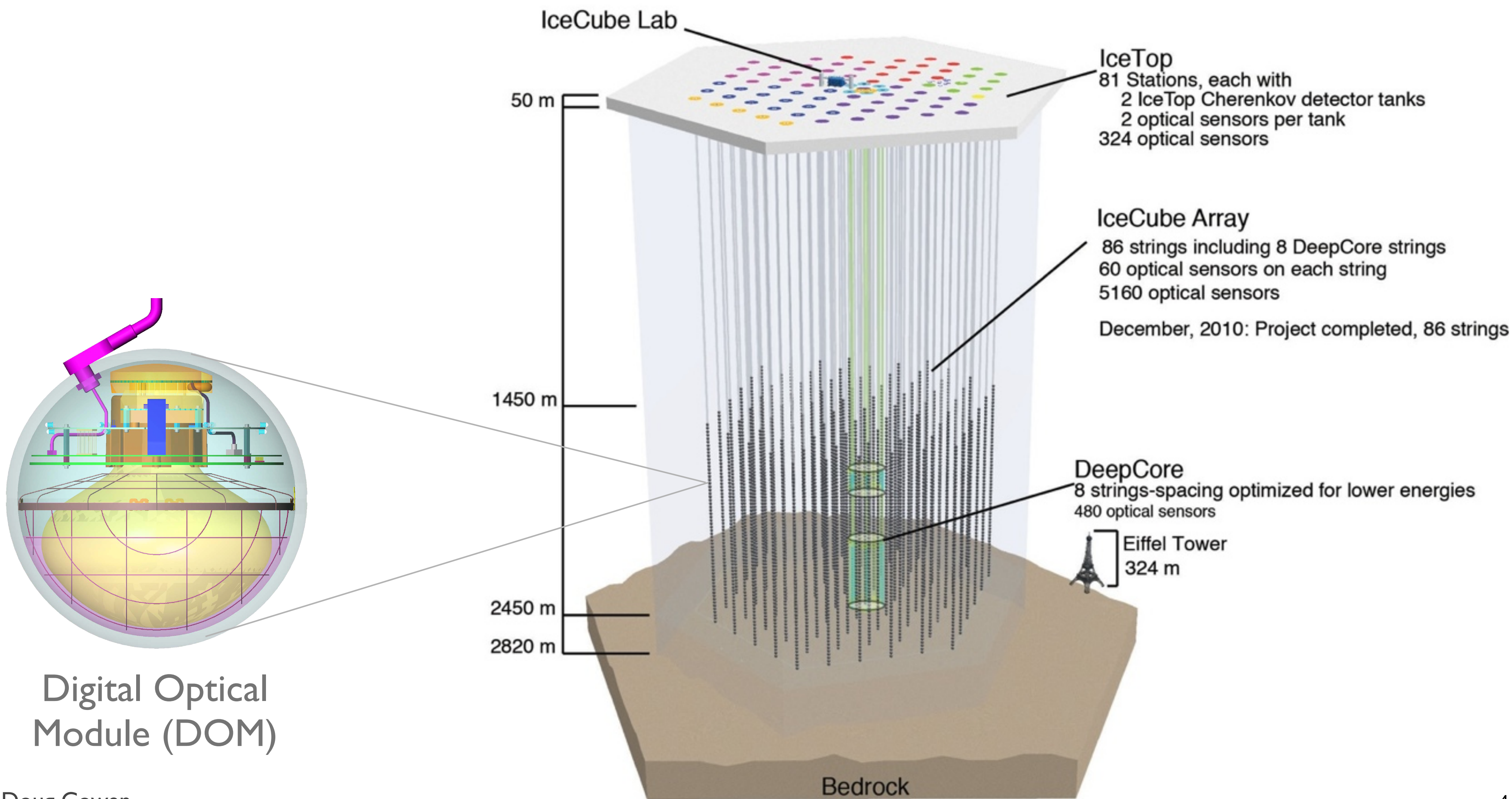
IceCube Status: Fully Constructed!



Digital Optical Module (DOM)

IceCube DeepCore: Introduction

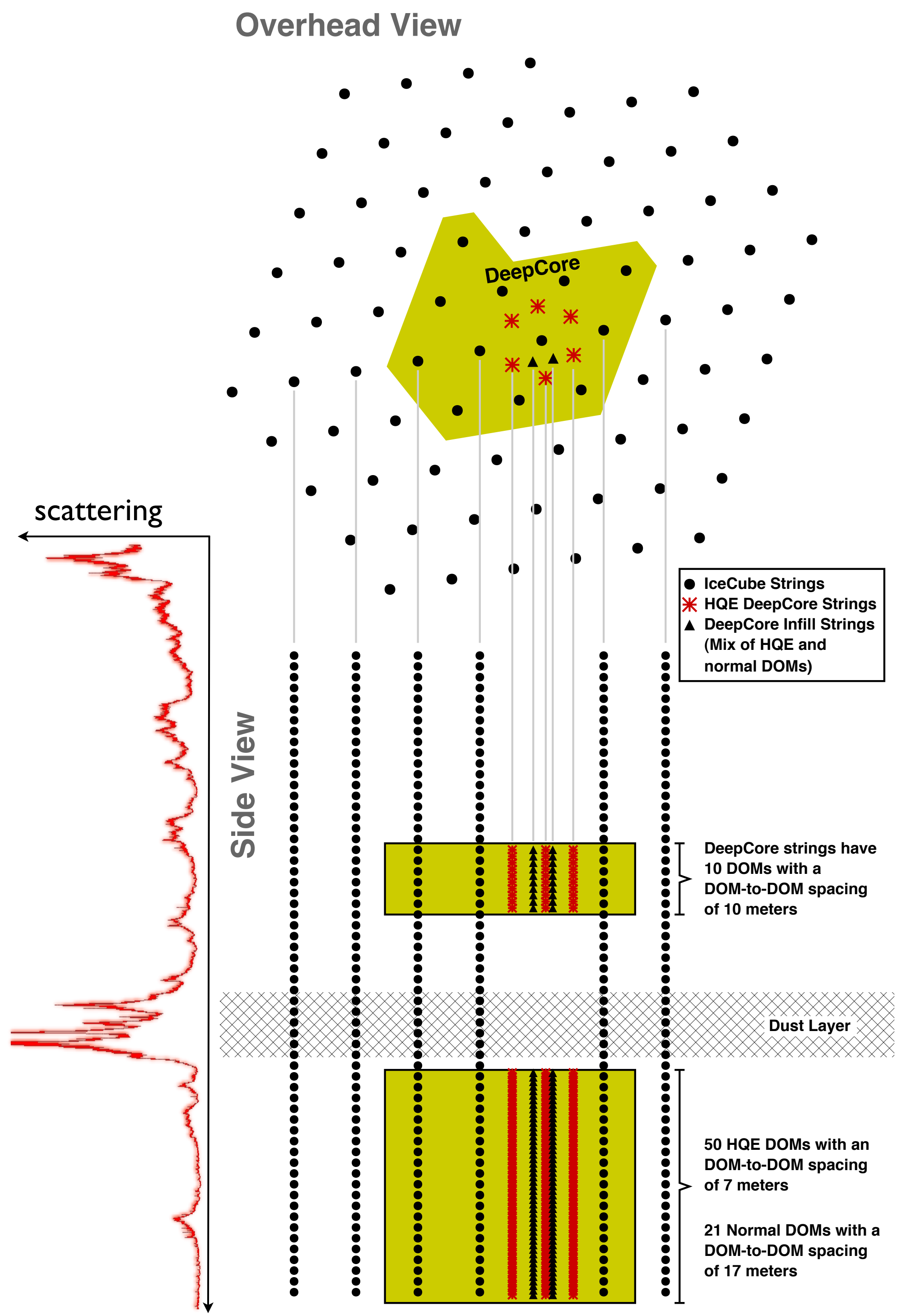
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
  - Significant improvement in capabilities from ~10 to ~300 GeV

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
  - λ_{eff} = 47 m (average)
  - λ_{abs} = 155 m (average)
- Result: ~30 MTon detector with ~10 GeV threshold, collecting $\mathcal{O}$(200k) 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 ~10^6
  - Vetoing algorithms expected to reach at least 10^6 level of background rejection

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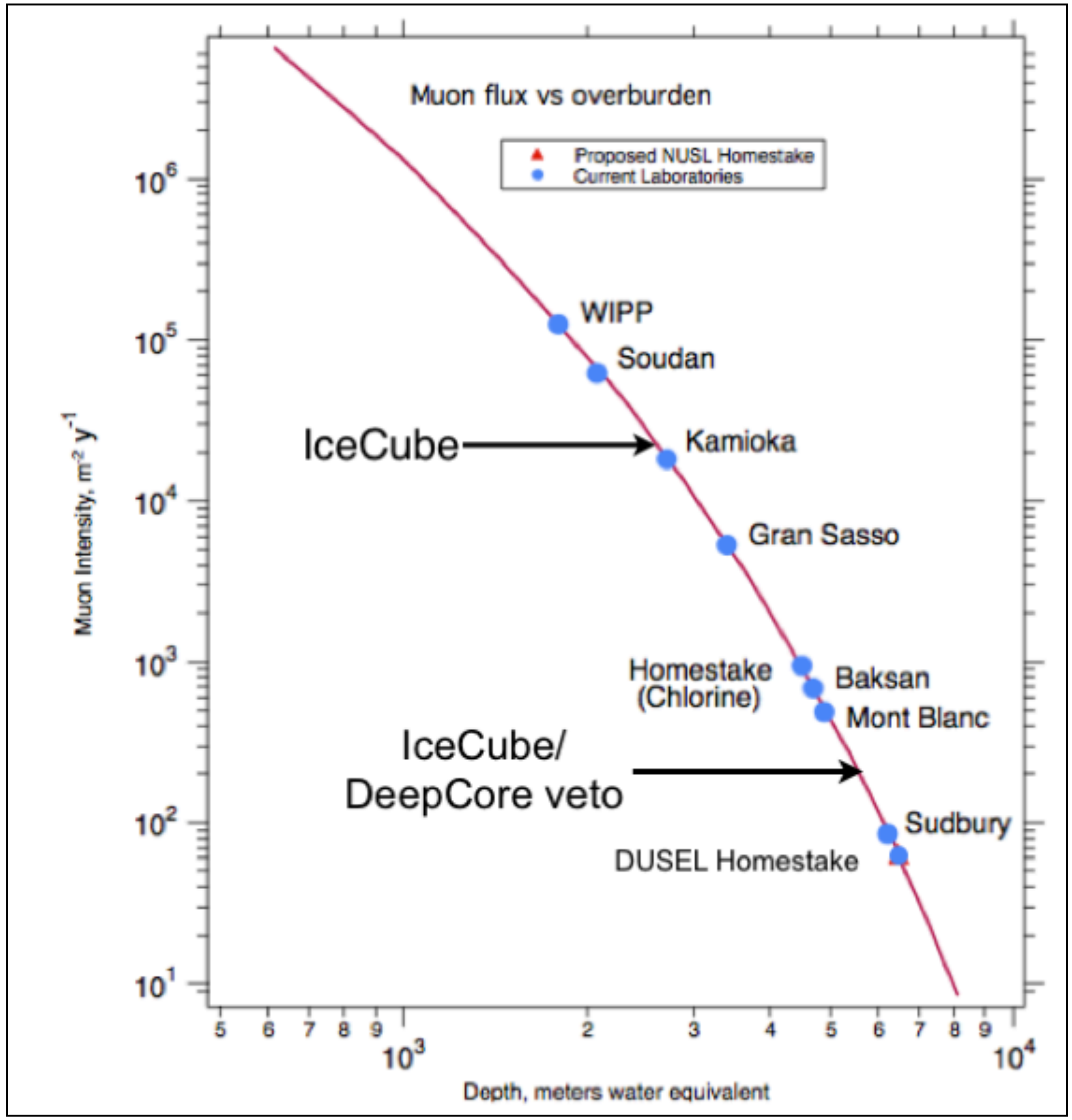
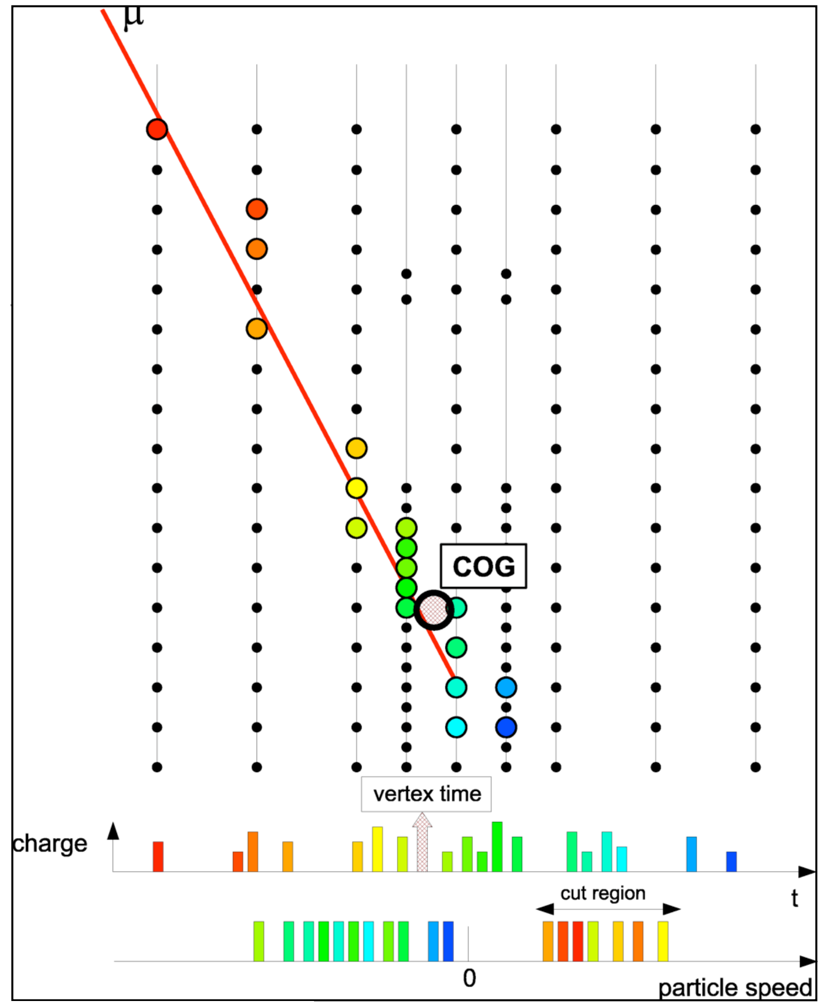
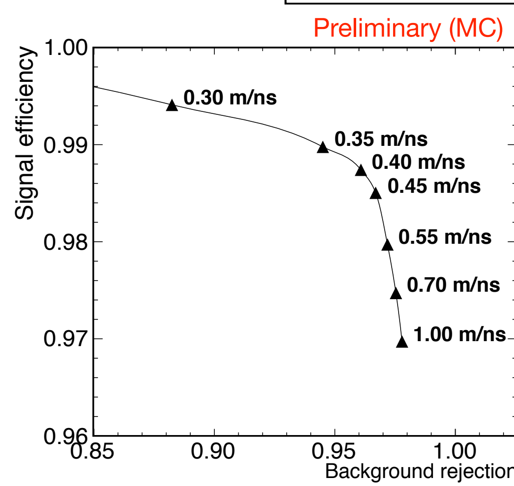


DeepCore:
Atmospheric Muon Online Filter

- First, trigger on 3 or more hits in DeepCore fiducial volume in 2.5μs (“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



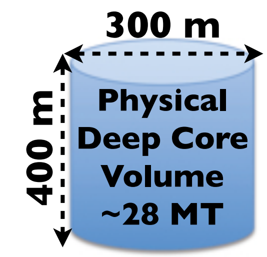


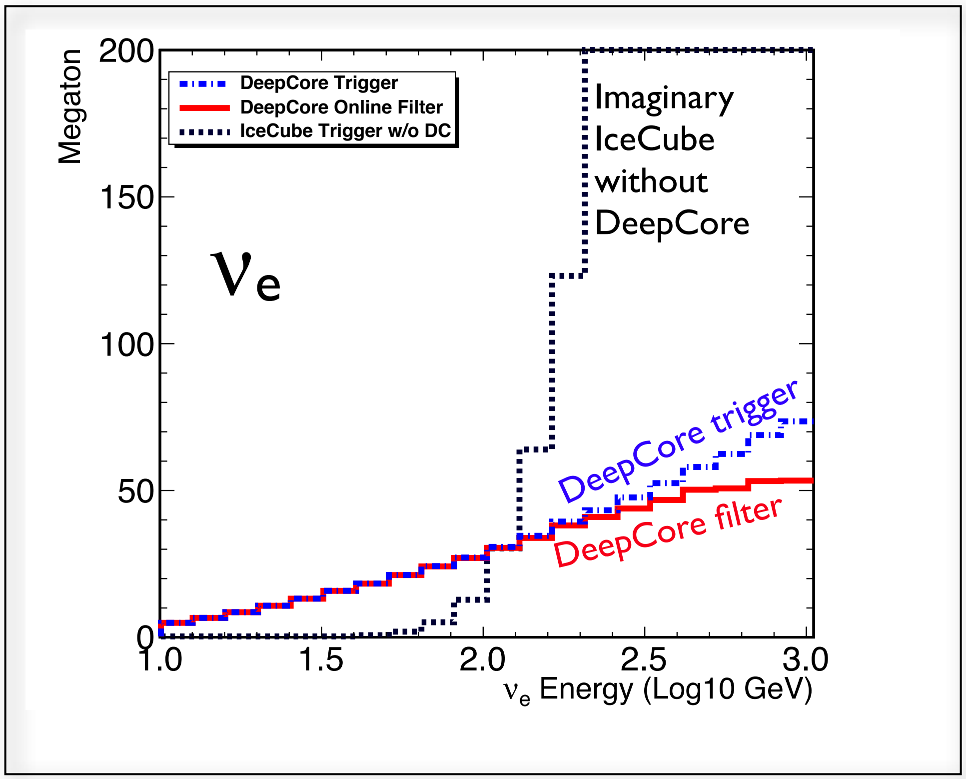
Require speed to be between 0.25-0.40 m/ns.

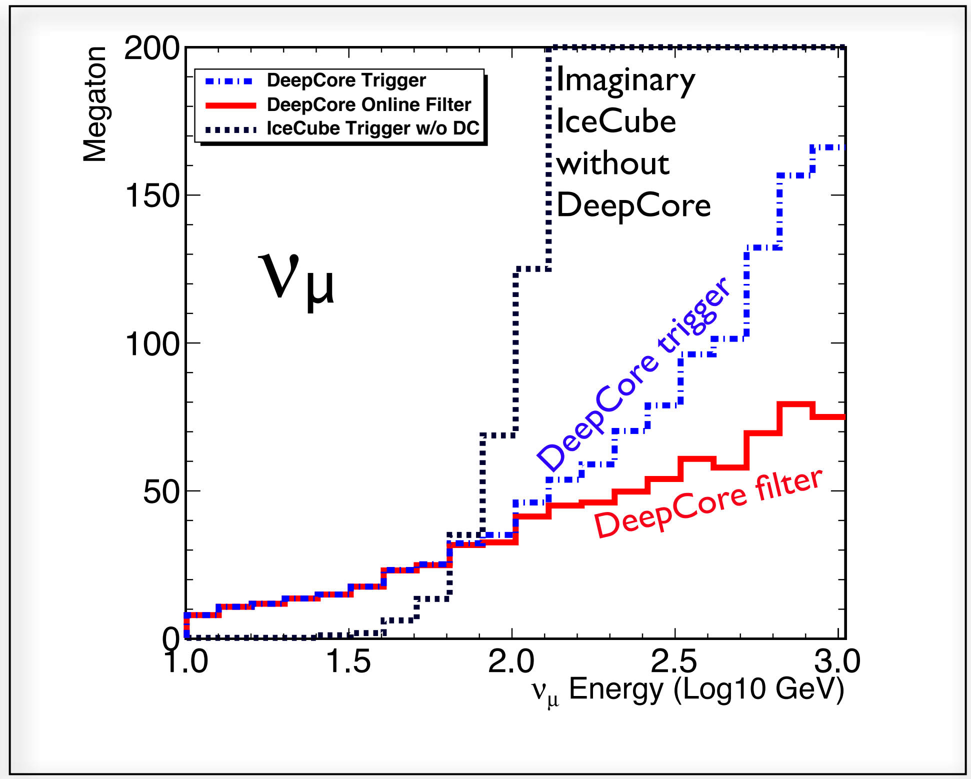
The value “0.40” was chosen by holding 0.25 constant and varying upper value, giving plot on left. (And similarly for 0.25.)

DeepCore: Lepton Effective Volume

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



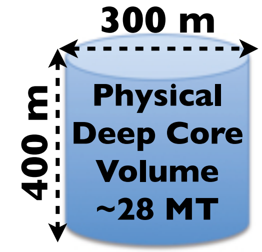


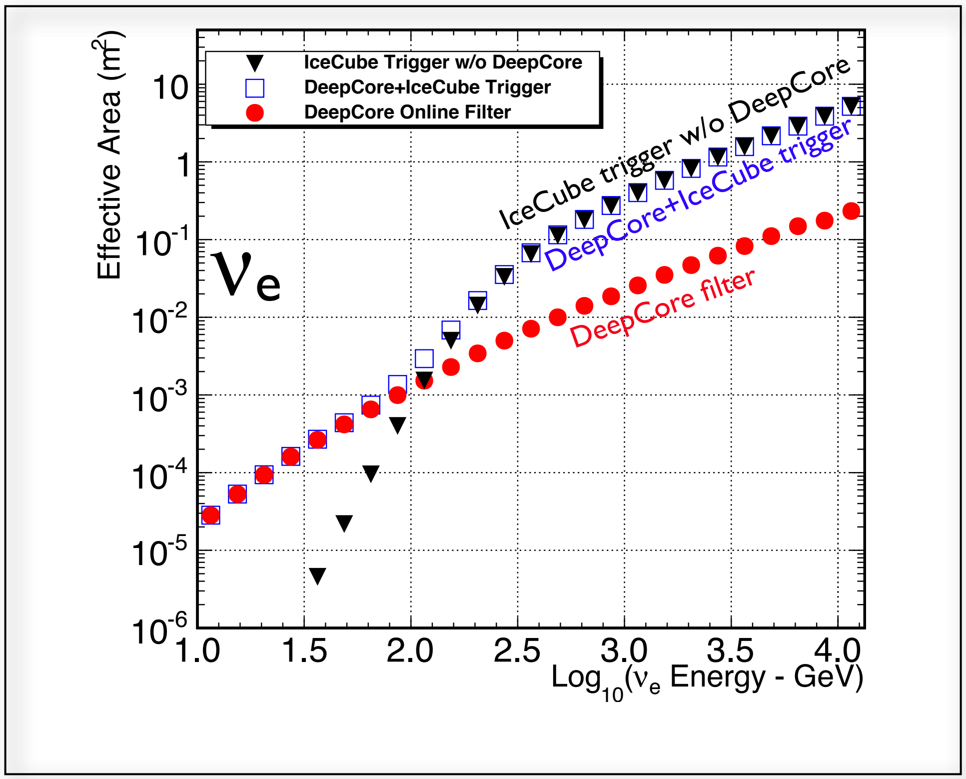


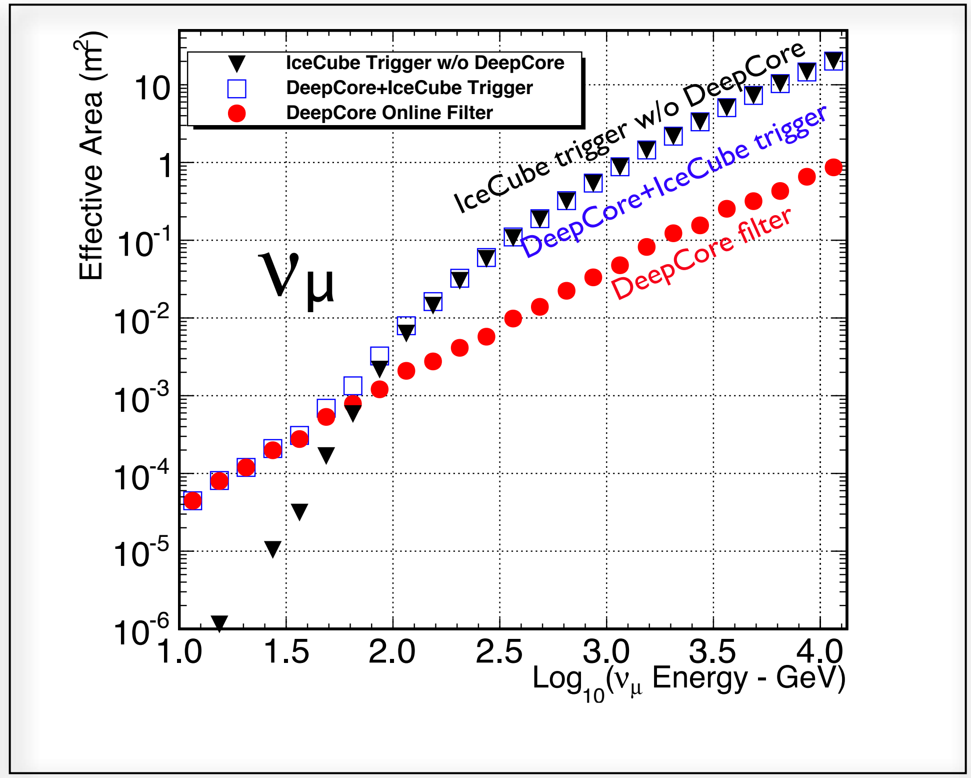
- Many events in IceCube will also trigger DeepCore
  - These events are rejected by the online veto algorithm
- Below ~100 GeV, DeepCore improves V_{eff} significantly
- Final V_{eff} will be lower than shown once we require good event reconstruction

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*)

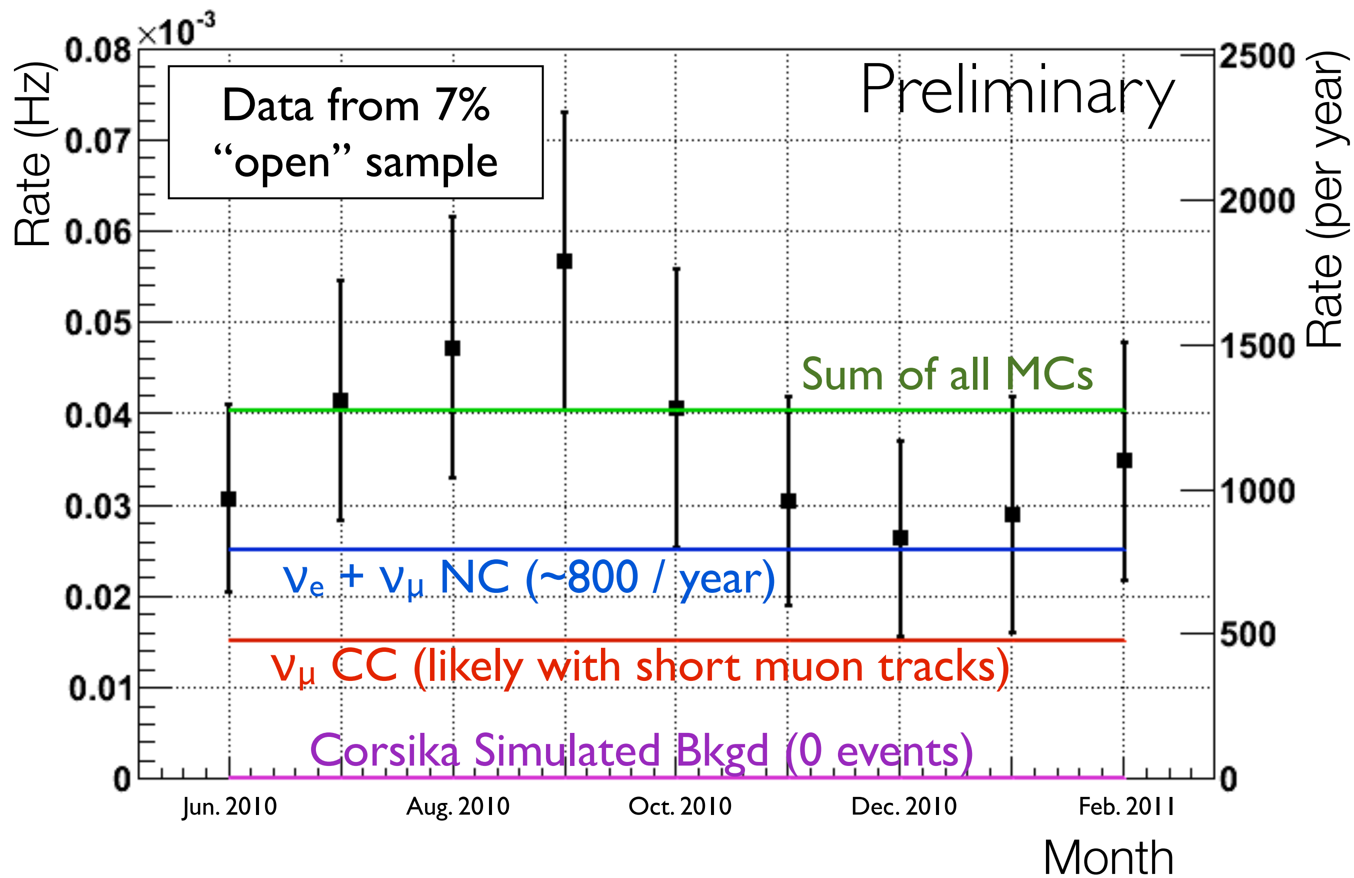
- Historical background:
  - First high energy neutrinos detected years ago by AMANDA
    - detected long muon tracks created by atmospheric ν_μ interactions
    - many IceCube analyses have grown in this fertile soil
  - In parallel, launched efforts to detect EM and hadronic showers produced by, e.g., 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 <u>very important milestone</u> 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*)

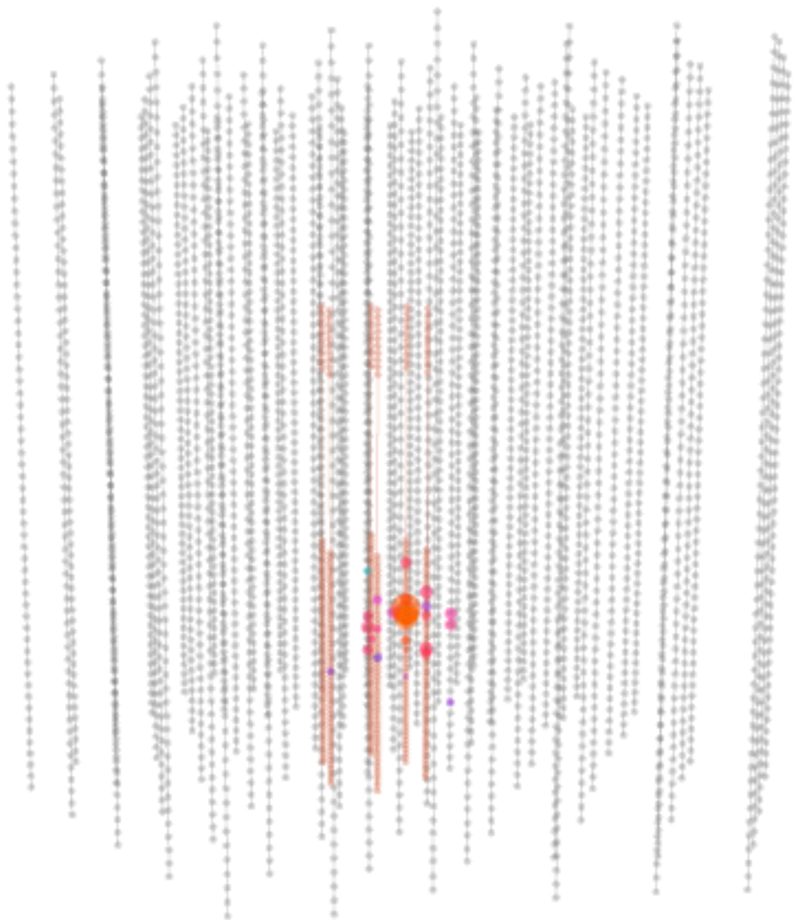
- With harsh cuts to eliminate the ν_μ background we expect to obtain a sample of ~800 neutrino-induced cascades per year
  - Approximately 500 background ν_μ CC events expected
  - Contamination from atmospheric muons still being evaluated

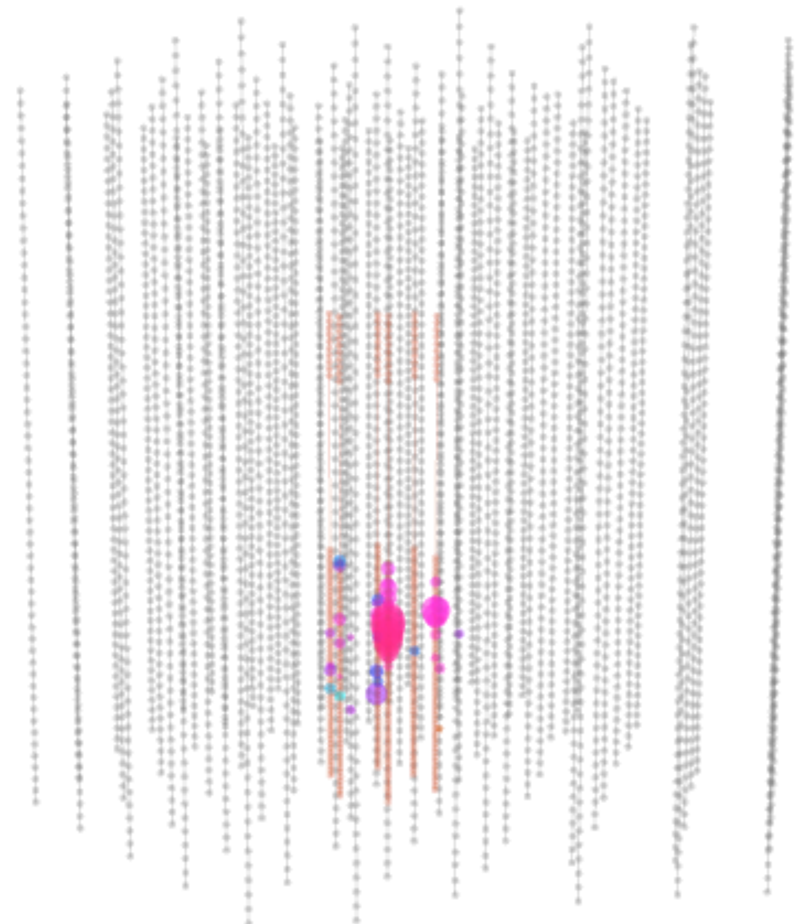


  - Efforts to increase ν_e yield and reduce ν_μ CC background ongoing

DeepCore:
First Results (*Preliminary*)

Two candidate events

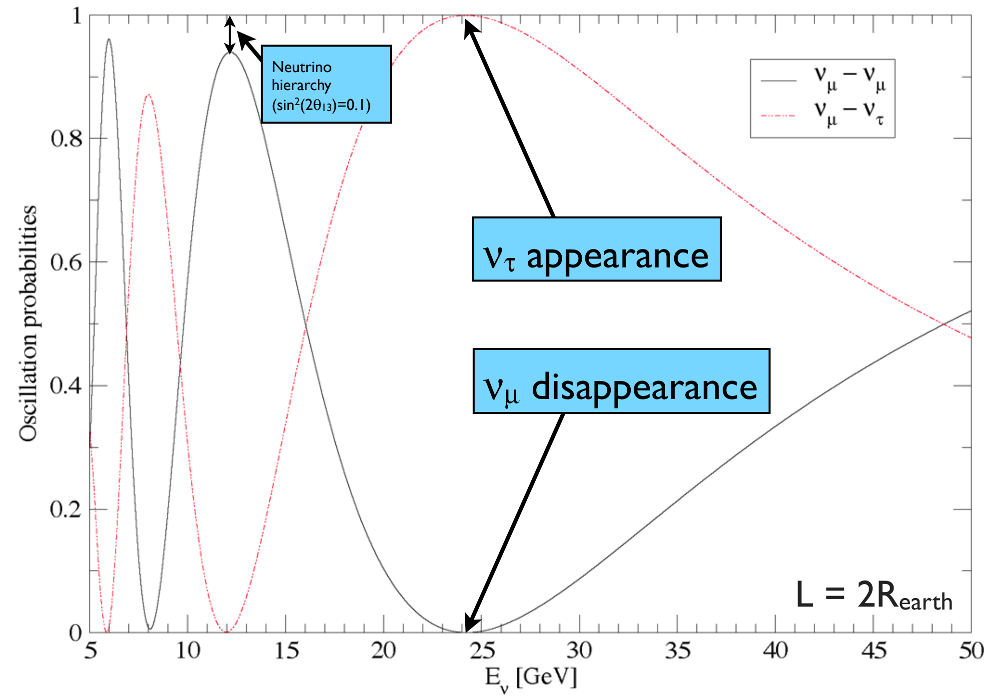




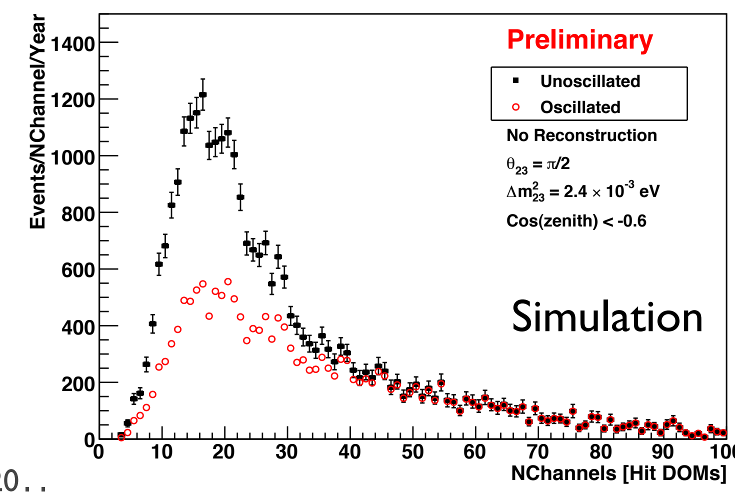
(Standard hit cleaning algorithm removed all noise hits in rest of detector.)

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

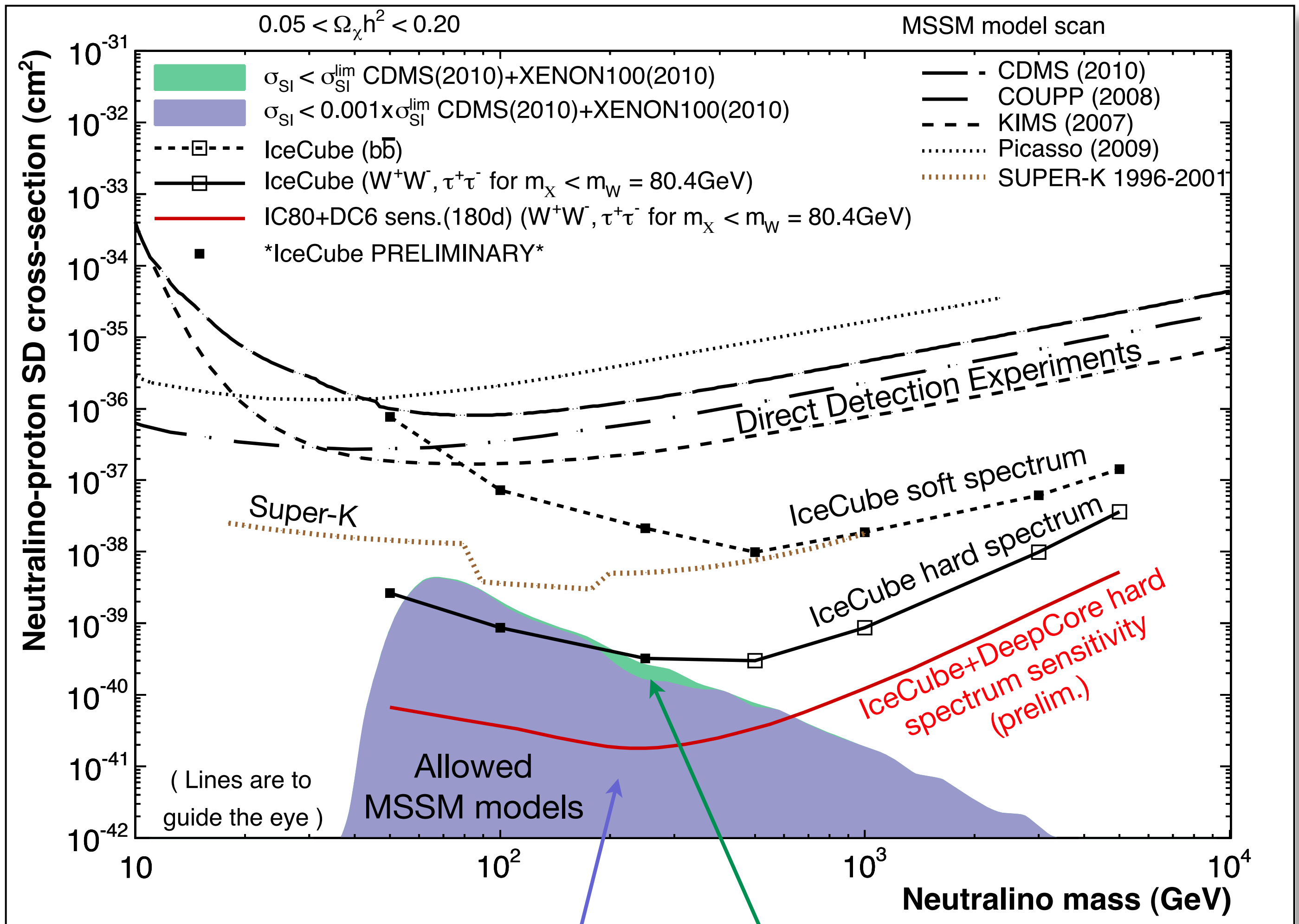


Mena, Mocioiu & Razzaque, *Phys. Rev.* **D78**, 093003 (2008)



Deep Core: Predicted Performance: WIMPs

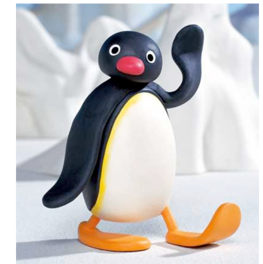
- Solar WIMP dark matter searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



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

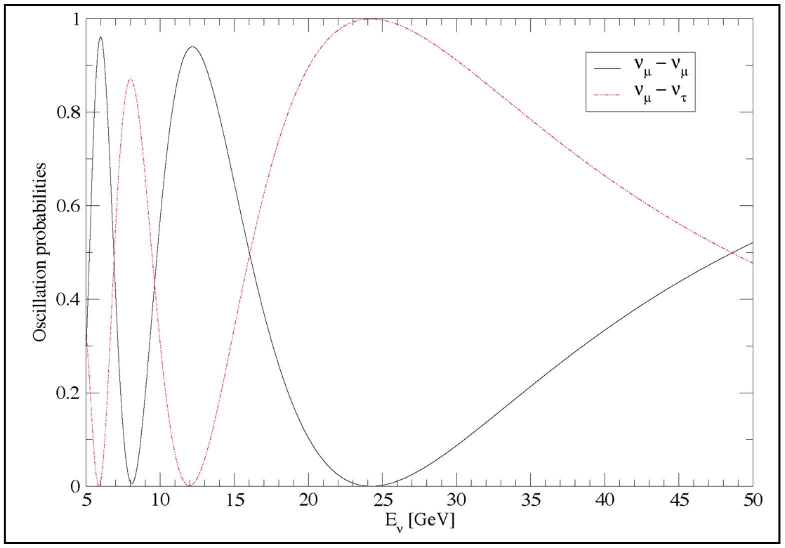


© The Pygos Group

- 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



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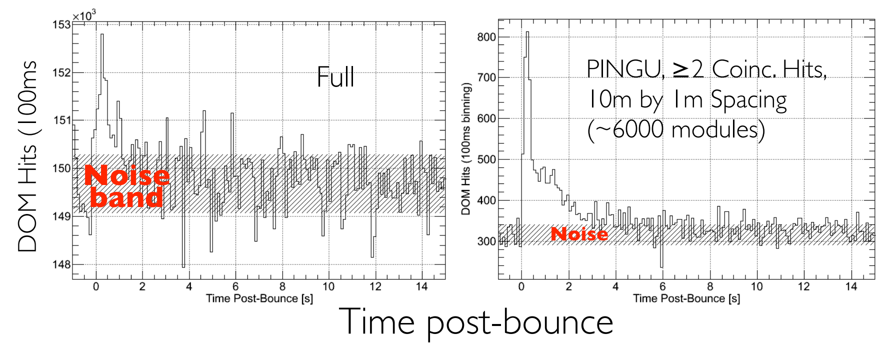
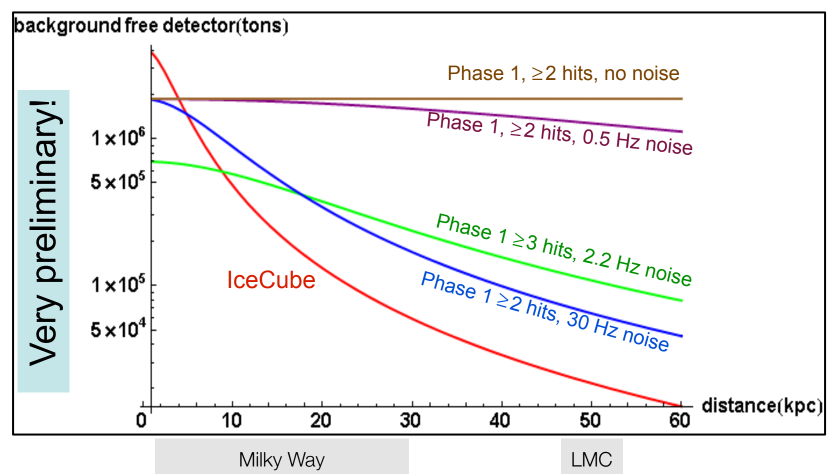




Equivalent size of a background free detector for beginning 0.38 s of **Lawrence Livermore** model, 1 m DOM and 10 m string distance, 18 strings (~6,000 DOMs) (figures from Lutz Koepke/Mainz)

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

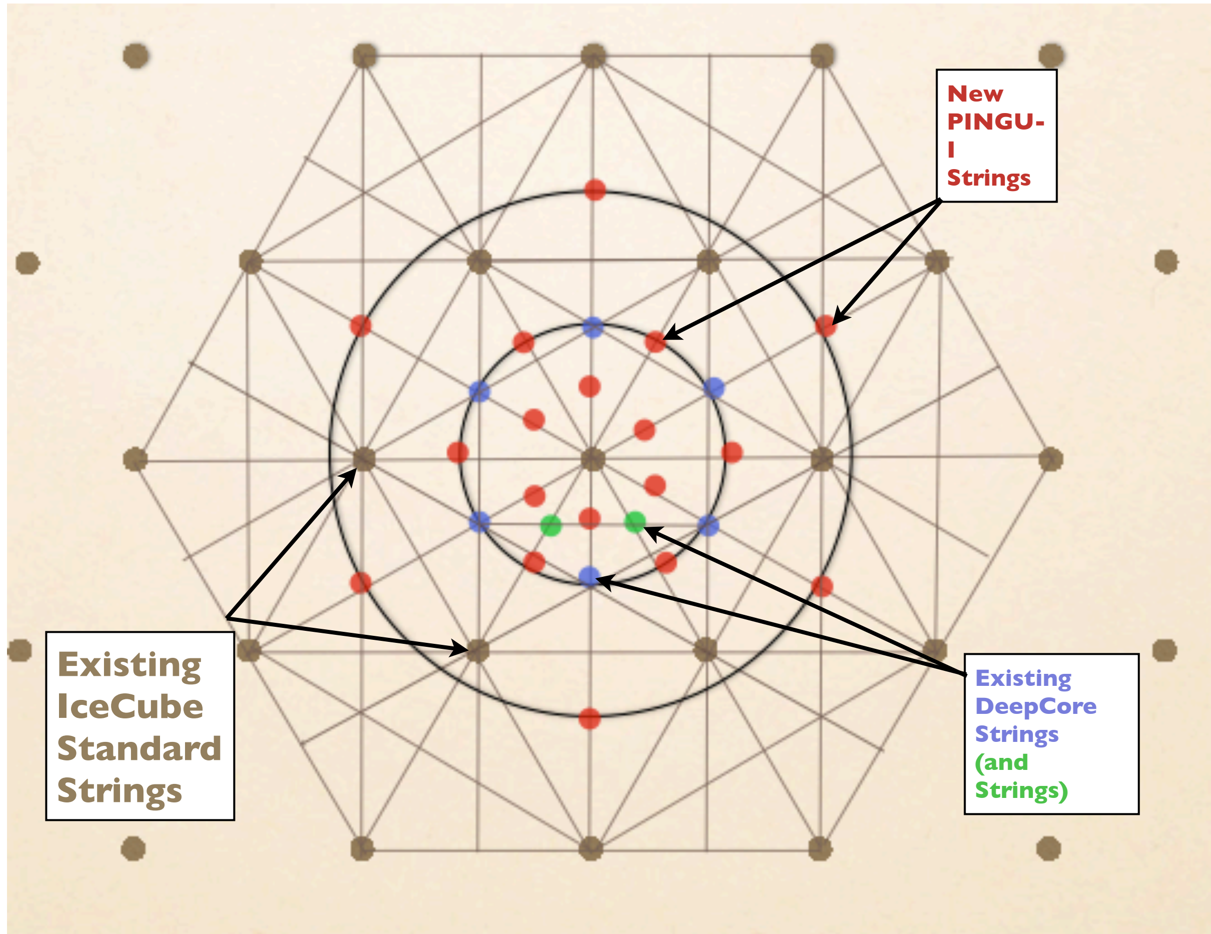


Image courtesy of A. Karle

- Price tag would likely be around $25M

PINGU-II: Physics Motivations for sub-GeV Energy Threshold

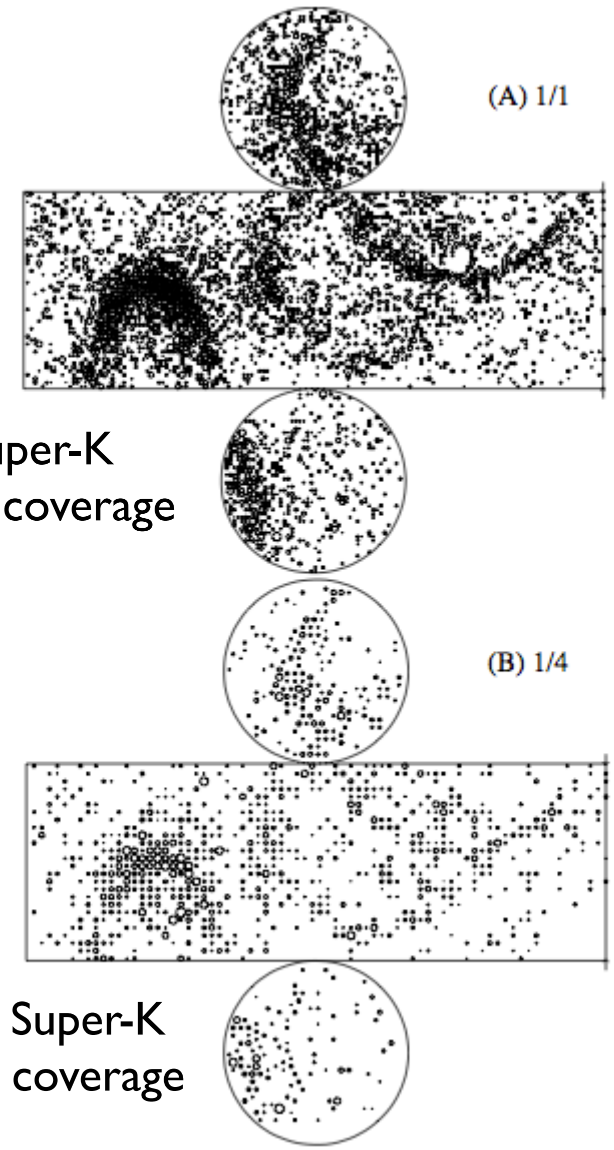
- Proton decay
  - Target $p \rightarrow \pi^0 + e^+$ channel
- Supernova neutrinos
  - Need to reach well beyond our galaxy to get statistical sample of SN neutrinos
- Plus improvements for WIMP, oscillation analyses over PINGU-I & DeepCore

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 $M_{GUT} << M_{Planck}$
- MC studies needed to understand:
  - energy resolution in a volume detector
  - possibilities for e/μ ID from Cherenkov rings
  - required photocathode coverage
    - preliminary MC calculations indicate 5-10% coverage may be within reach

Super-K PMT coverage

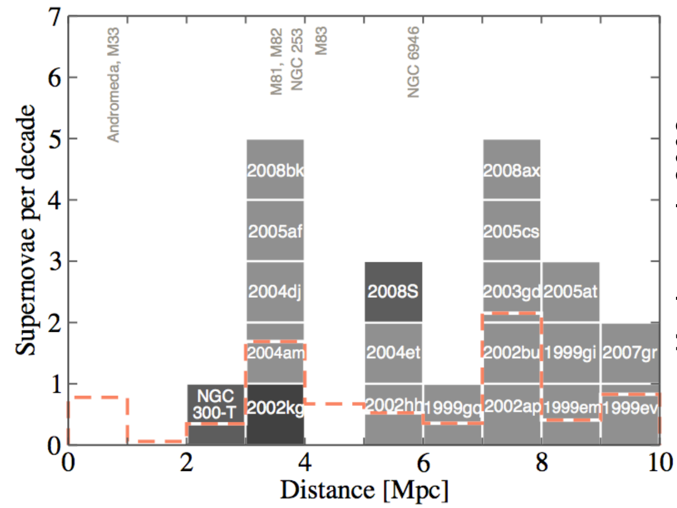


¼ of Super-K (10%) coverage

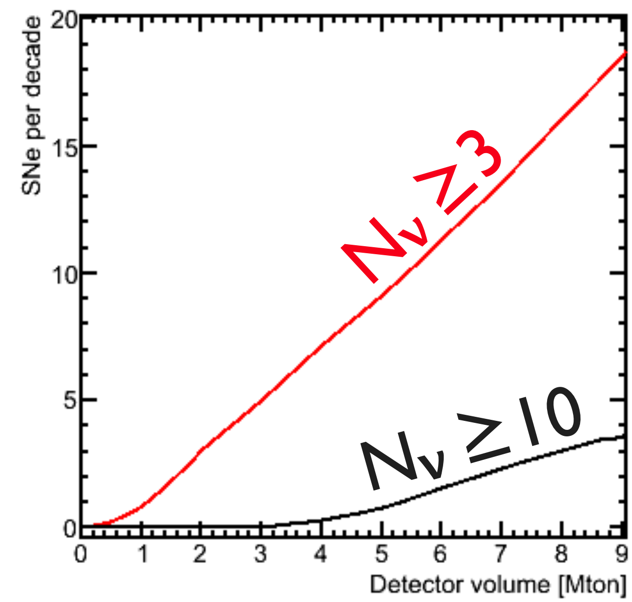
M. Shiozawa, NNN99

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 = ~1000x stronger signal
  - Caveats: LOTS of uncertainties (reconstruction, particle ID,...)



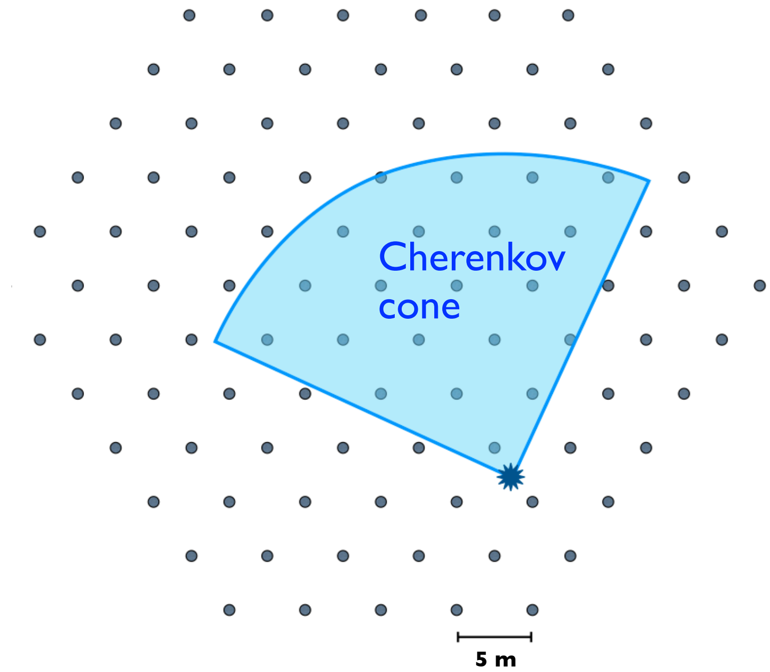
Kistler et al., 2008

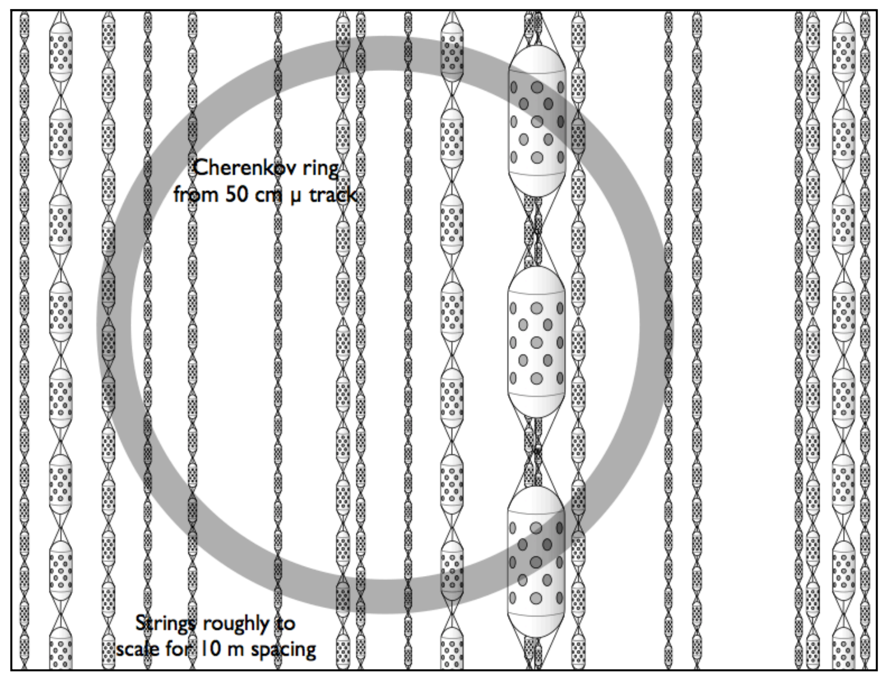


M. Kowalski (PINGU Workshop)

PINGU-II: Detector Concept

- $\mathcal{O}$(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

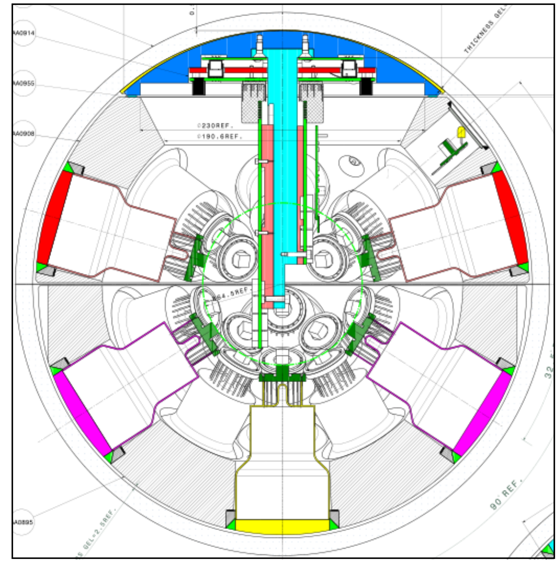




PINGU-II: Composite Digital Optical Module

Courtesy E. de Wolf & P. Kooijman

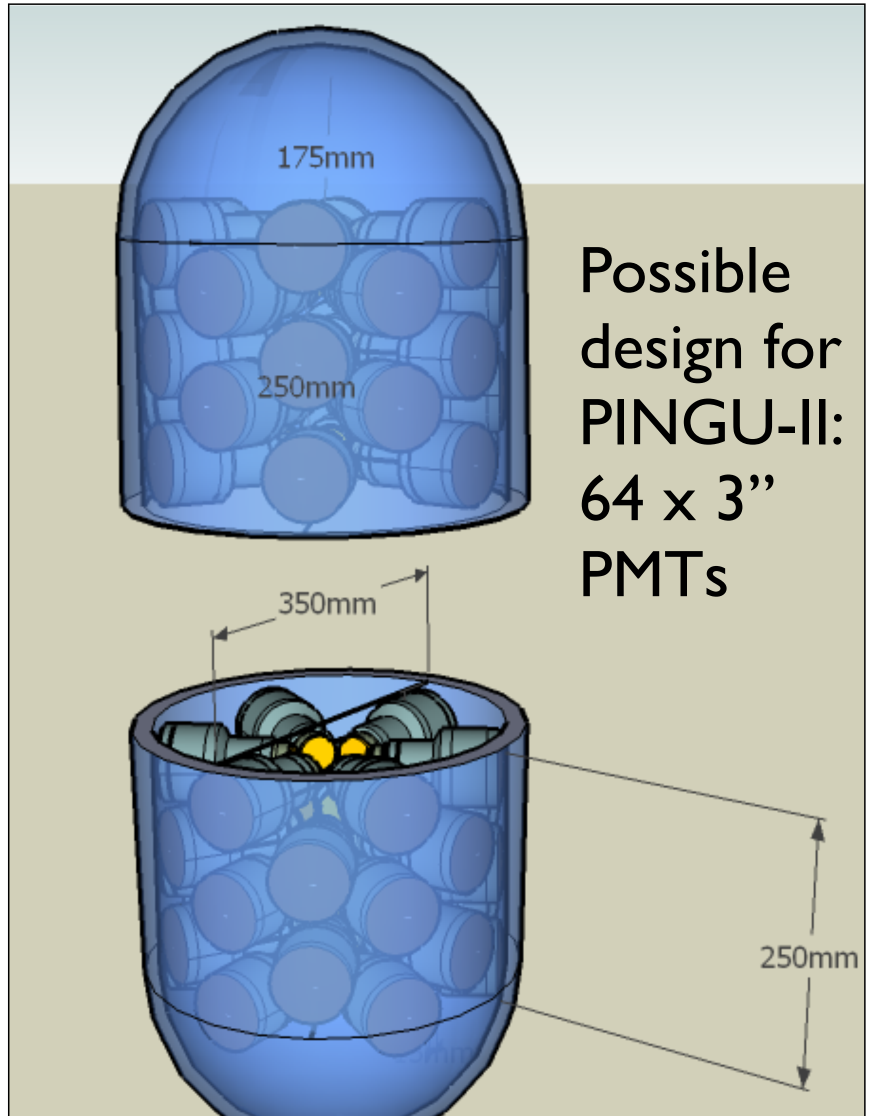
- Based on a KM3NeT proposed design
  - Glass sphere containing 31 3" PMTs and associated electronics
    - Effective photocathode area 4x that of standard 8" PMT, but
      - with better granularity
      - hopefully lower cost/area
  - Single connector simplifies deployment



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



Courtesy E. de Wolf & P. Kooijman

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_χ = ~50 GeV
- Future projects
  - PINGU-I
    - Extend reach of DeepCore lower by another ~10x
    - 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 ~10^{36} years
      - detect neutrinos from ~1 SN/yr
    - Cost: driven by photocathode area; not detector size
    - "Schedule": Begin deployment in 2018/19

The End