Towards GeV and sub-GeV Cherenkov Detectors in the South Pole Ice Cap

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Astrophysics from the South Pole: Status and Future Prospects
Washington, DC
April 4, 2011

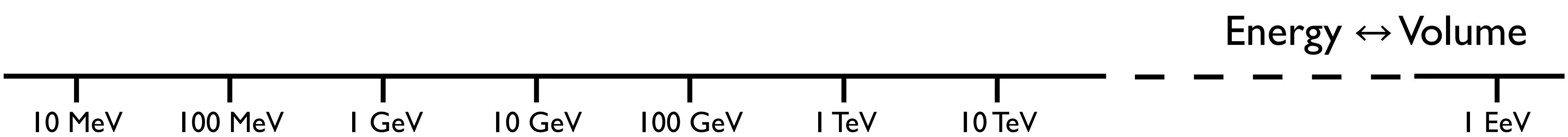
Thanks to Tyce DeYoung and Darren Grant
for numerous slides

Outline

- Neutrino detectors
- IceCube and its DeepCore sub-array
  - Design
  - First results
  - Predicted performance
- PINGU* (Phased IceCube Next Generation Upgrade)
  - PINGU-I: Extending DeepCore to E_{ν}~1 GeV
    - physics motivations, possible designs
  - PINGU-II: A new GeV to sub-GeV Mton-scale Cherenkov ring-imaging detector
    - physics motivations, possible designs

*Provisional
Identifier
Not
Granted
Usage (yet)

The Neutrino Detector Spectrum



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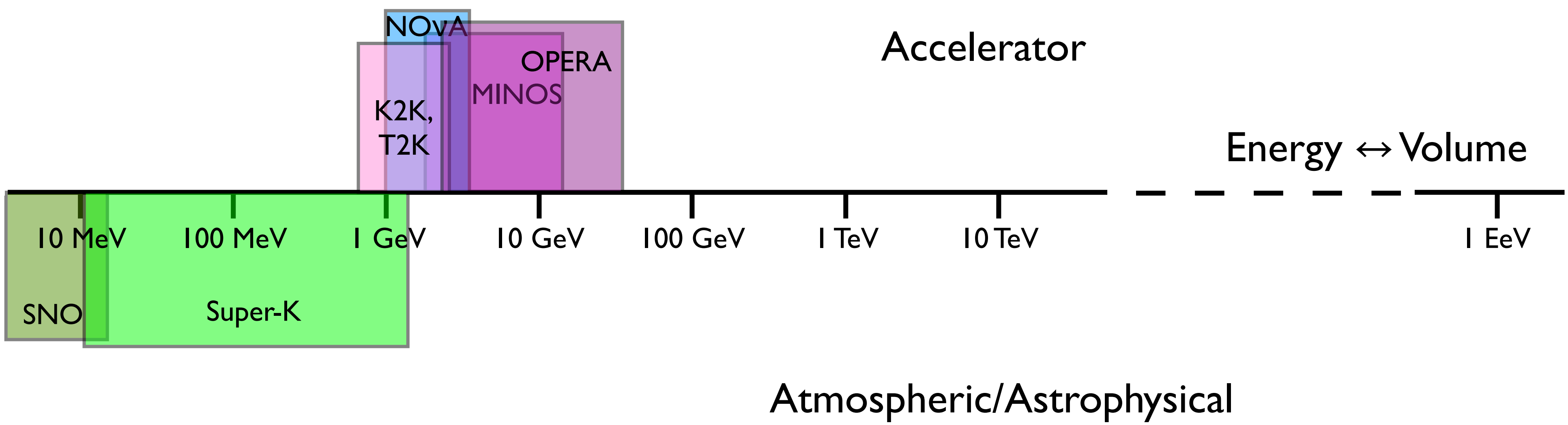

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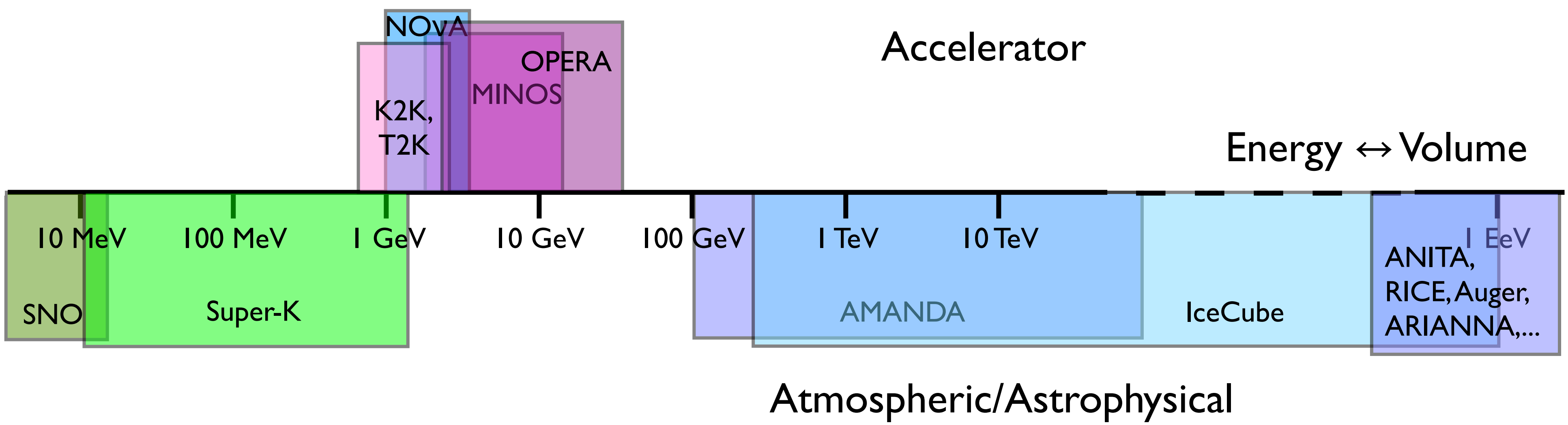

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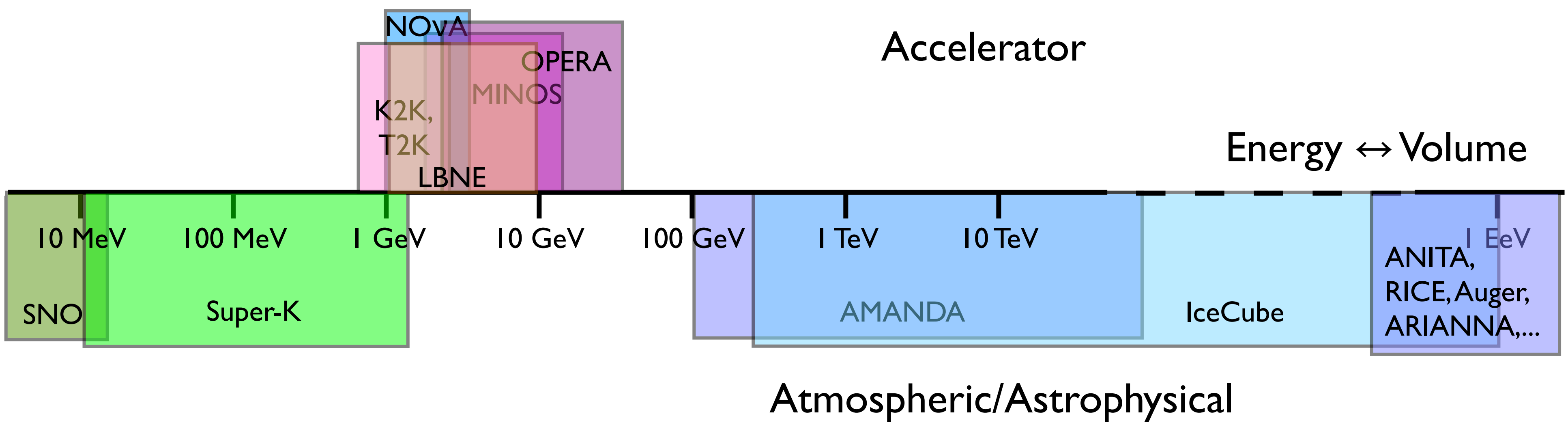

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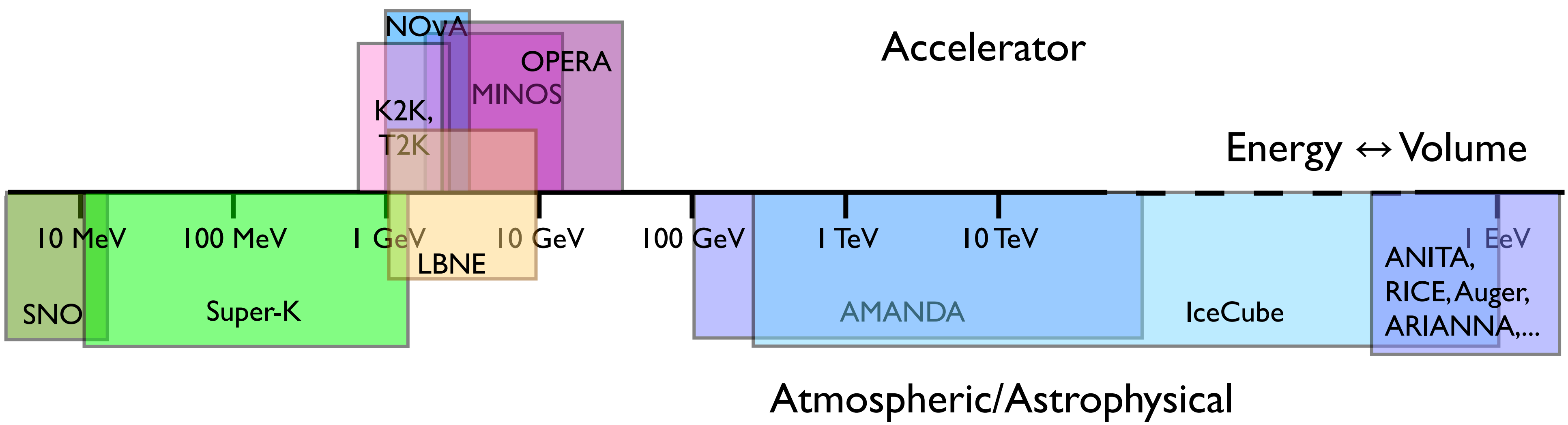

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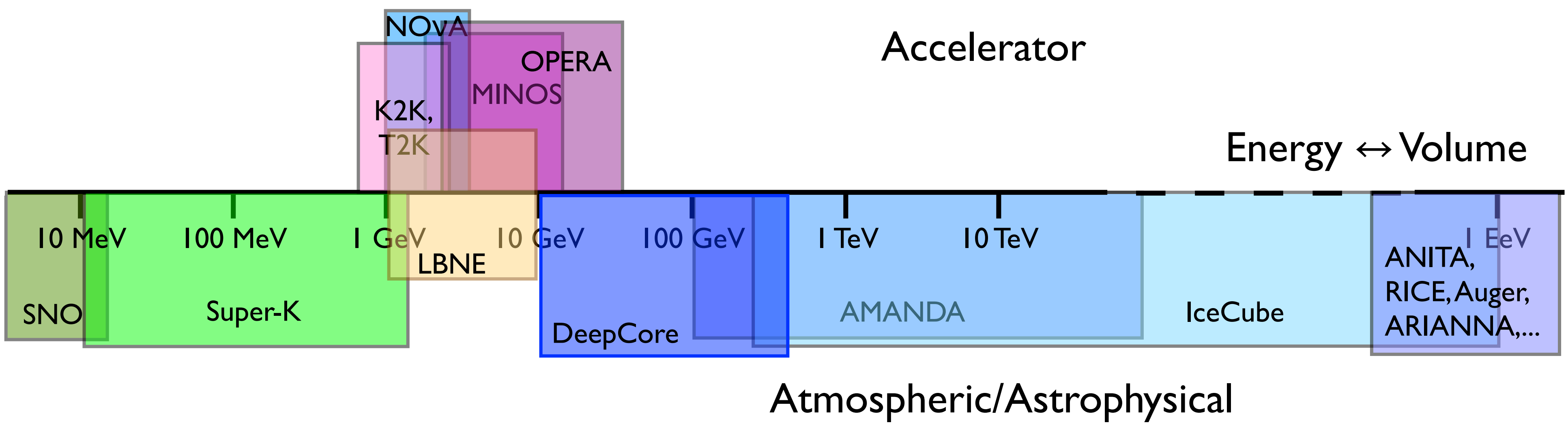

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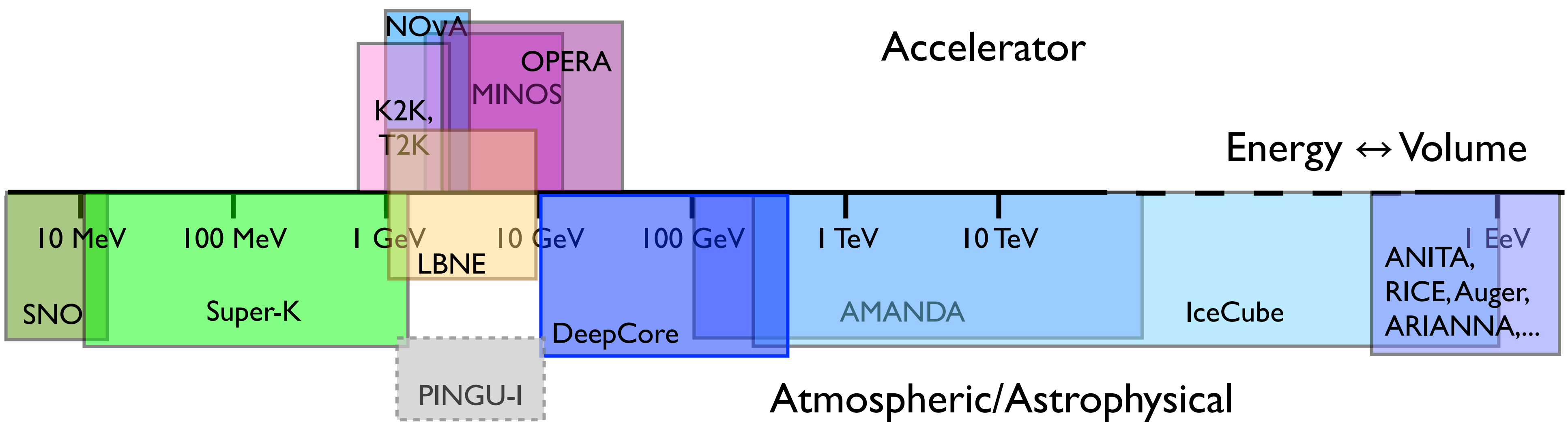

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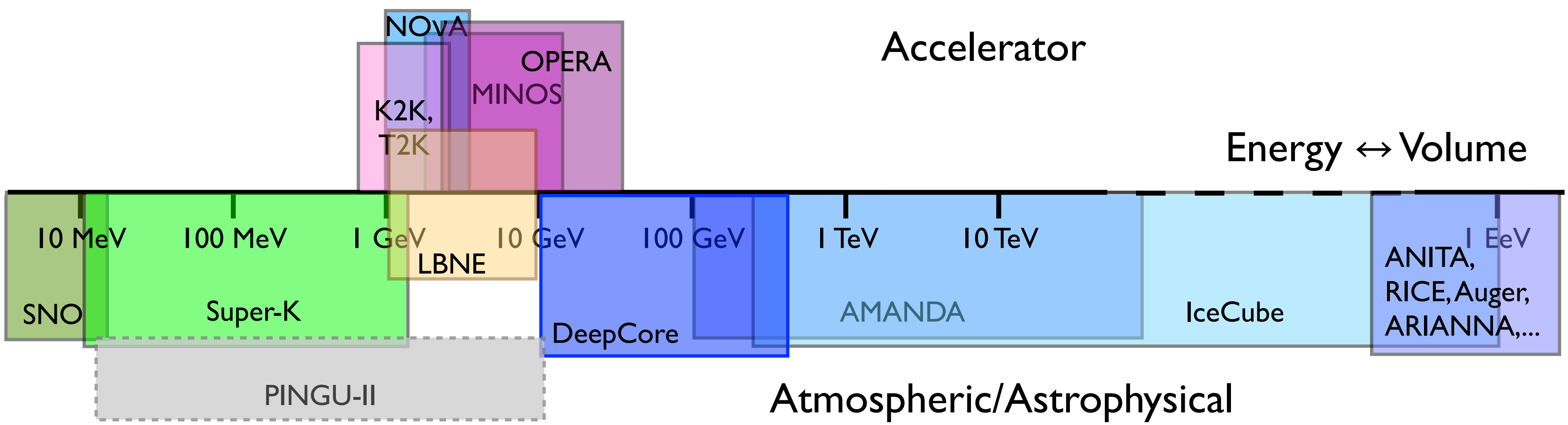

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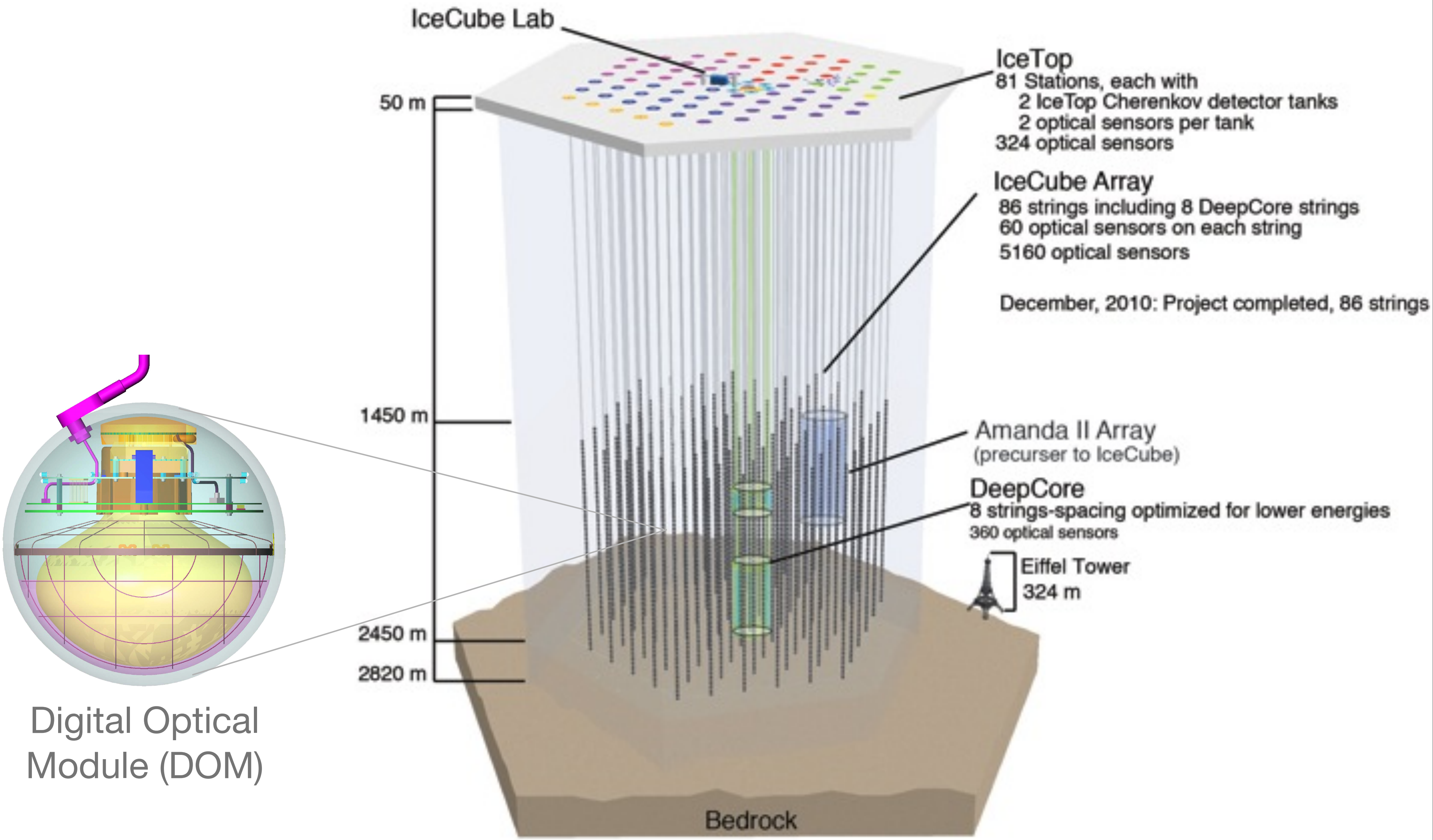
IceCube Status: Fully Constructed!



IceCube DeepCore: Introduction

- 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)

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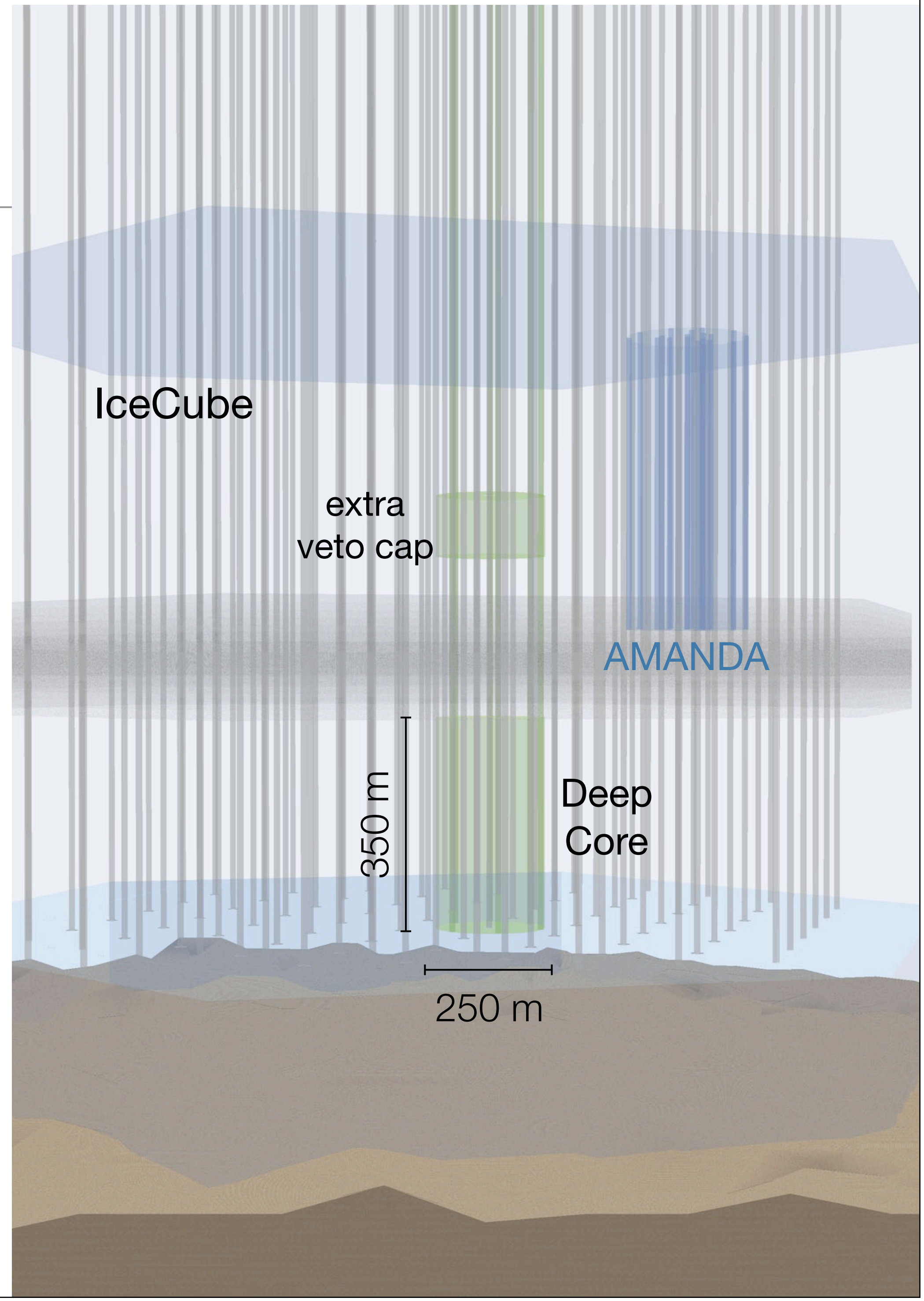
- IceCube extended its “low” energy response with a densely instrumented infill array: DeepCore
  - Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Scientific Motivations:
  - Indirect search for dark matter
  - Neutrino oscillations (e.g., ν_τ appearance)
  - Neutrino point sources in the southern hemisphere (e.g., galactic center)

DeepCore: Design

- Eight special strings plus seven nearest standard IceCube strings
  - 72 m interstring horizontal spacing (six with 42 m spacing)
  - 7 m DOM vertical spacing
  - ~40% higher Q.E. PMTs
  - ~5x higher effective photocathode density



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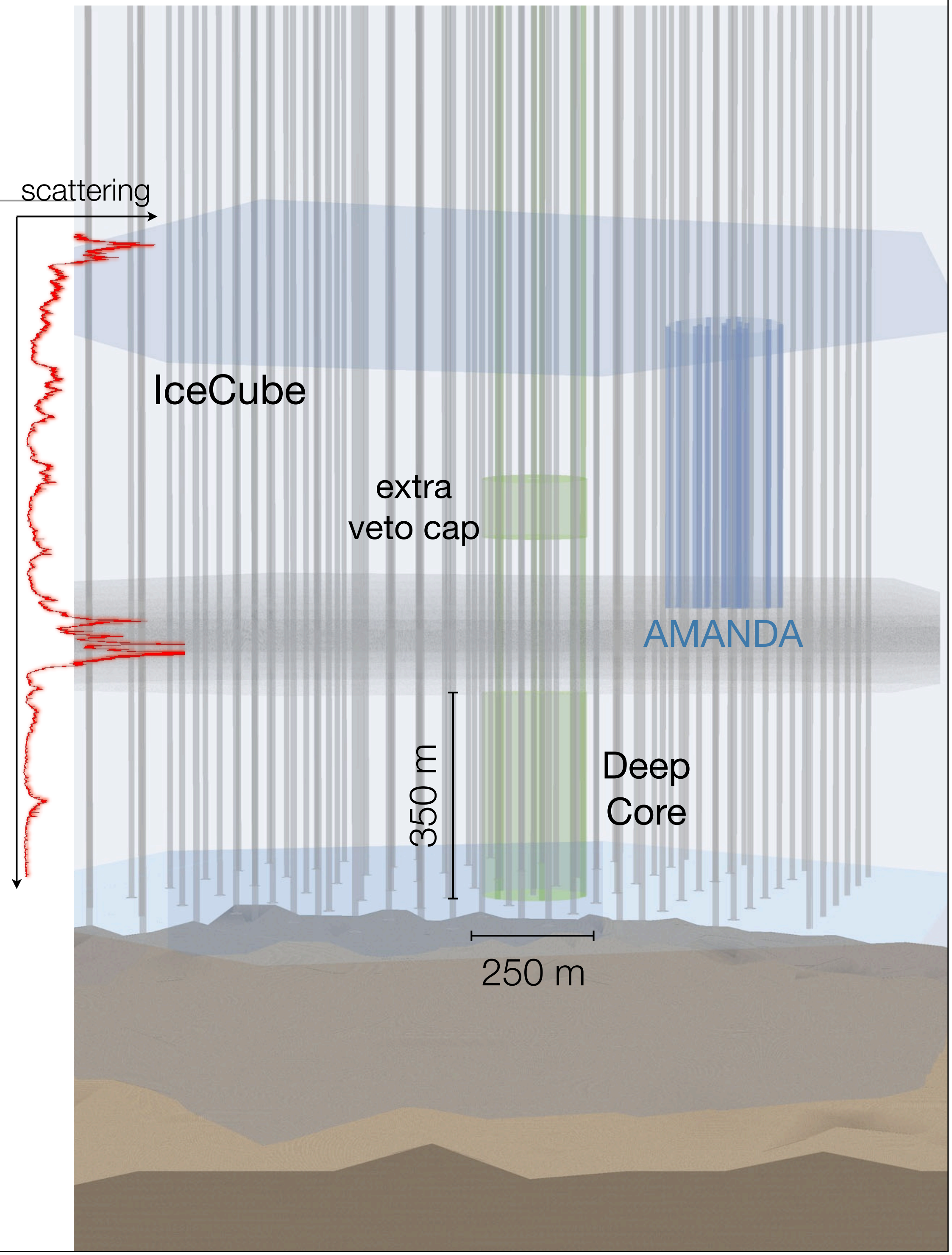
  - $\lambda_{eff} > \sim 50$ m



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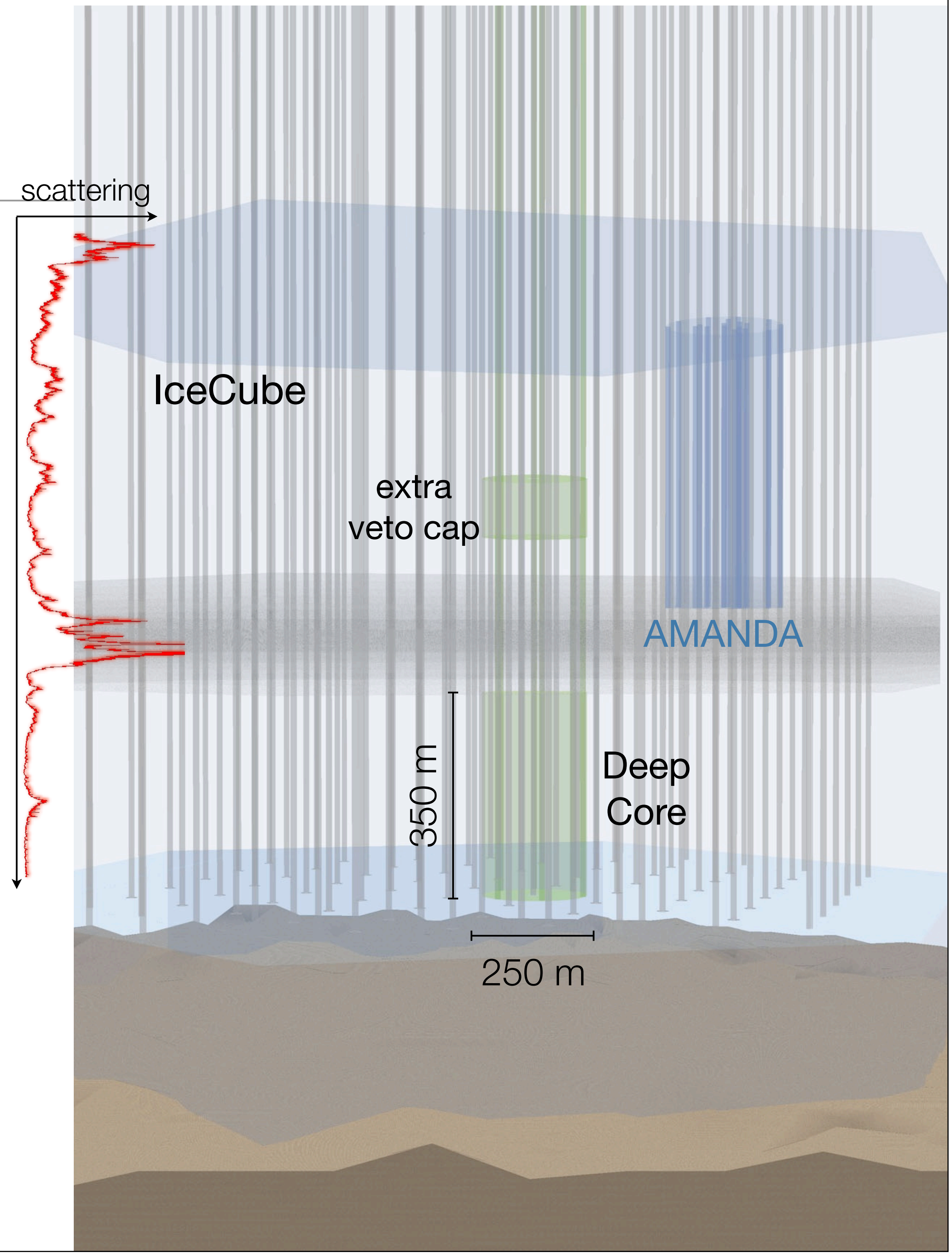
  - λ_{eff} > ~50 m
- Result: 30 MTon detector with ~10 GeV threshold, will collect $\mathcal{O}$(200k) atmospheric ν/yr



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
- 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

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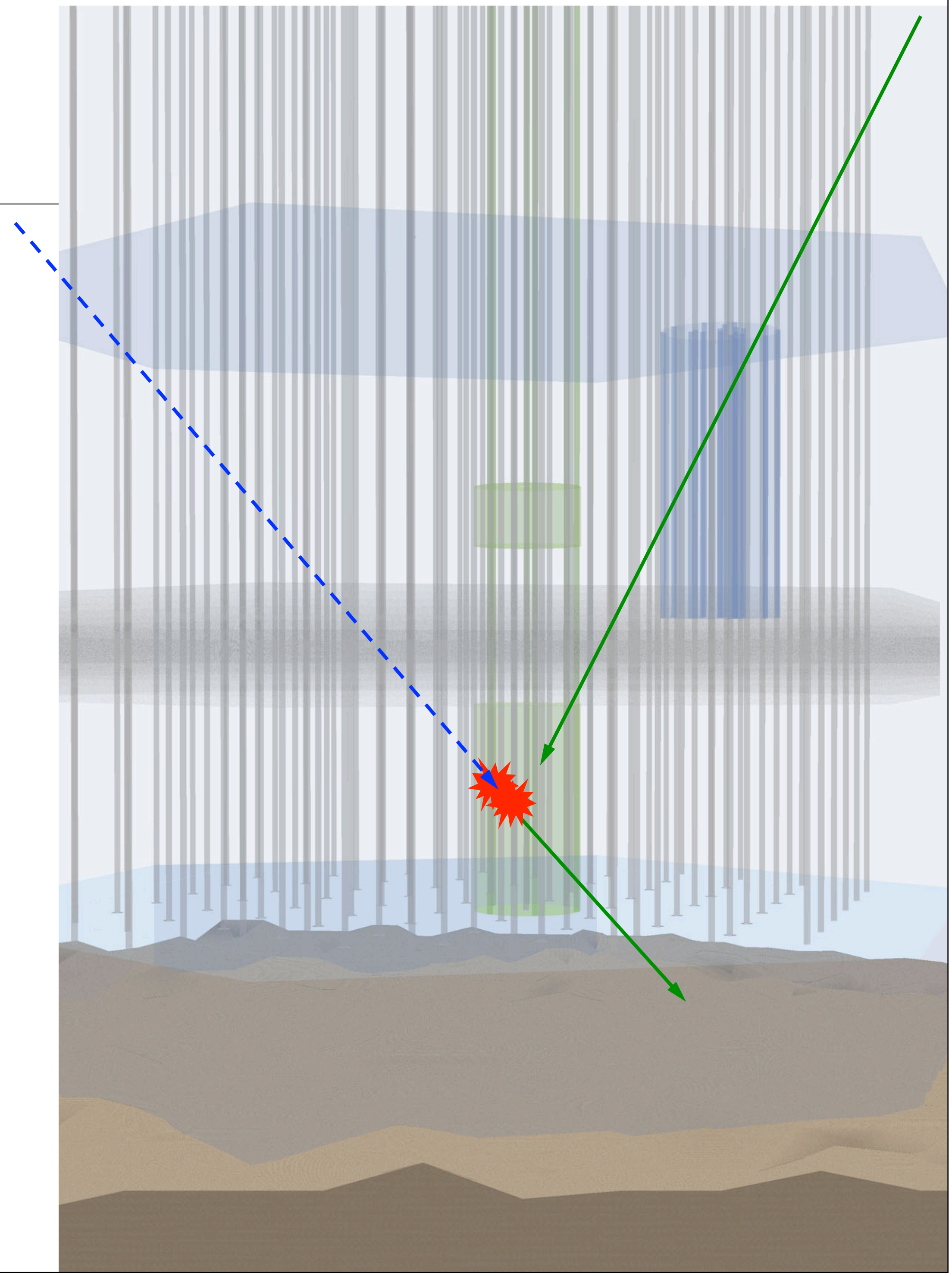

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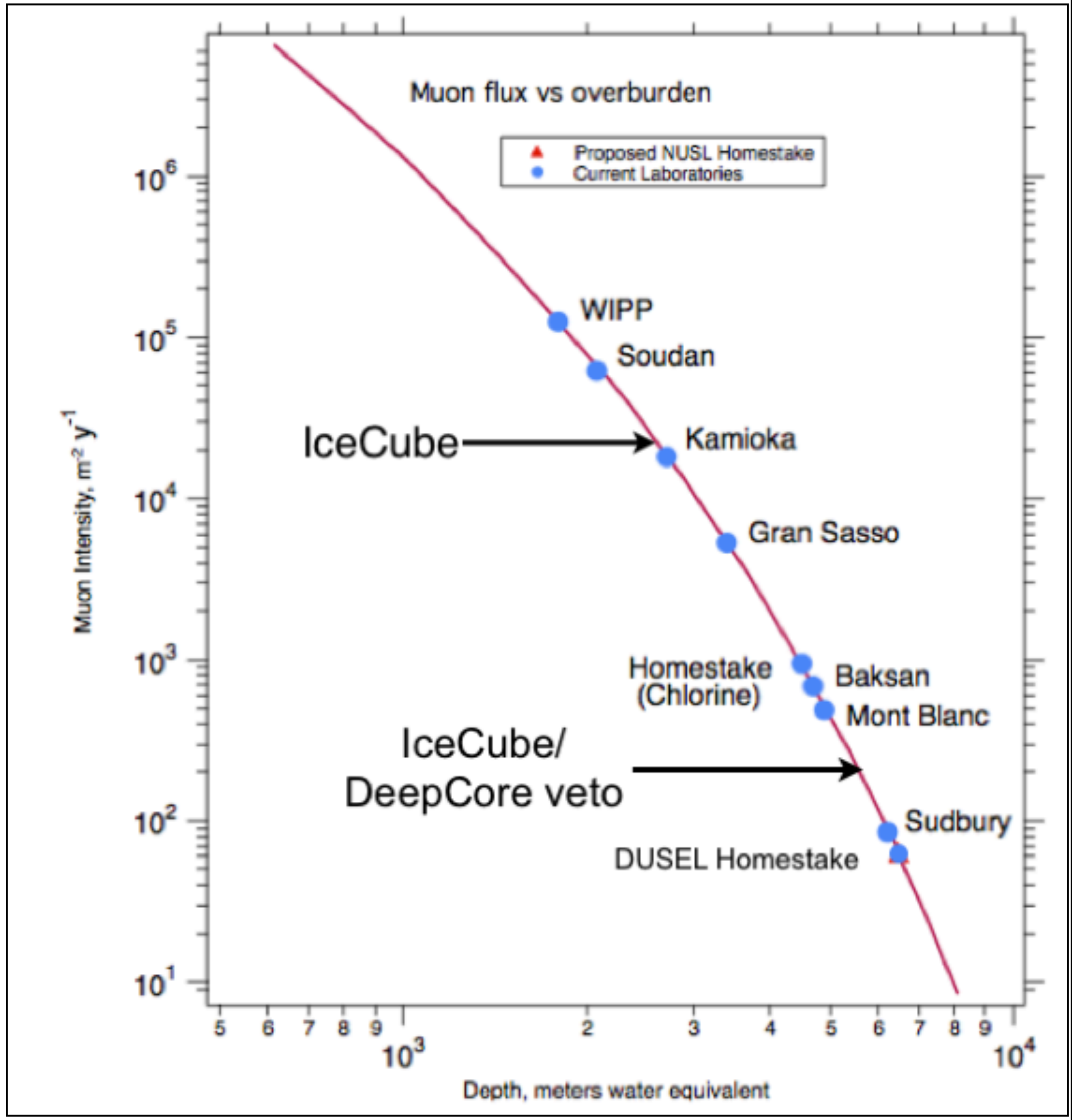
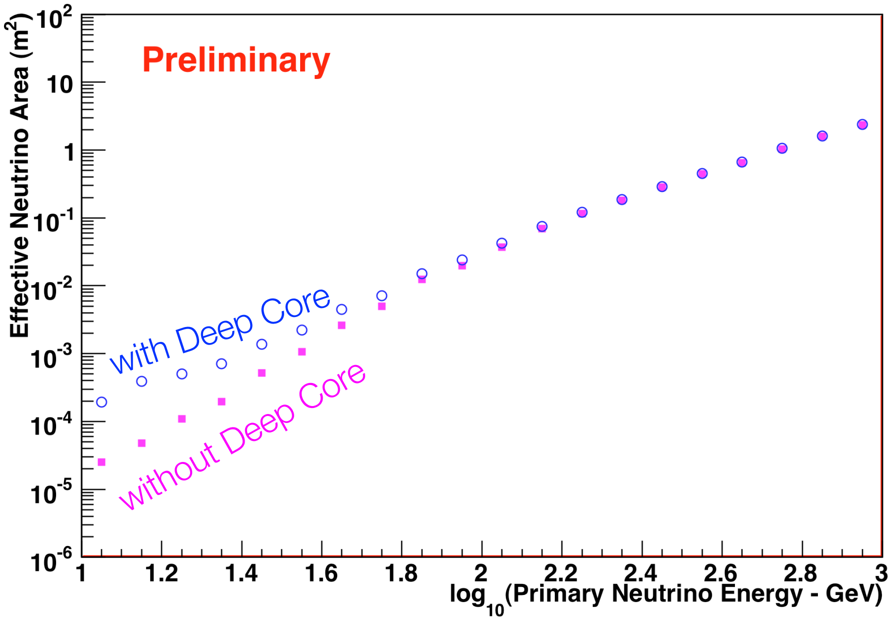
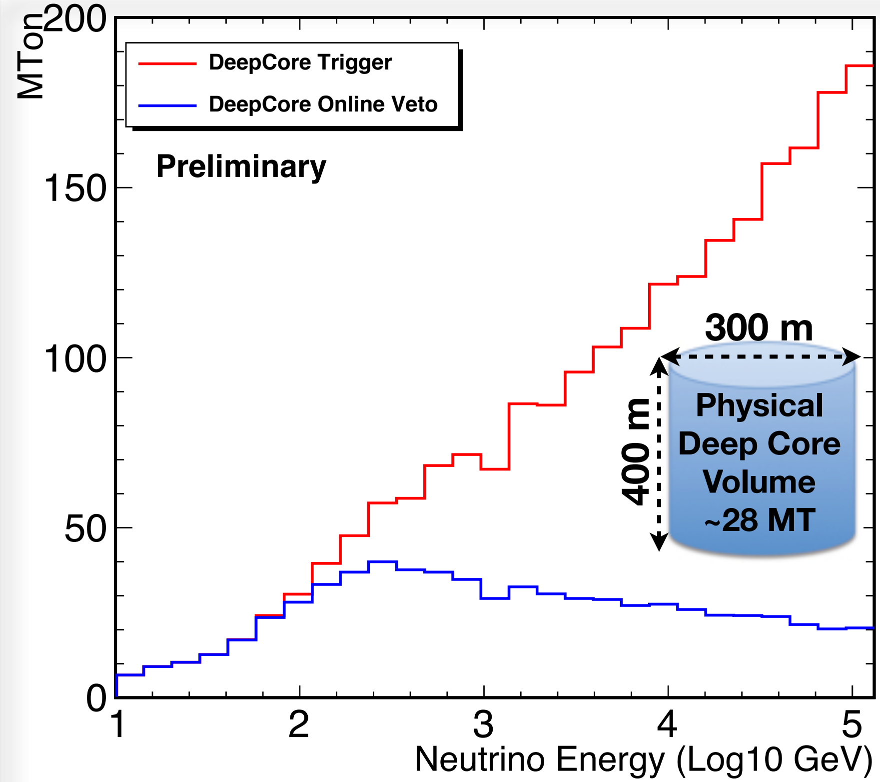


DeepCore:
Effective Area & Effective Volume

Effective area for upgoing 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

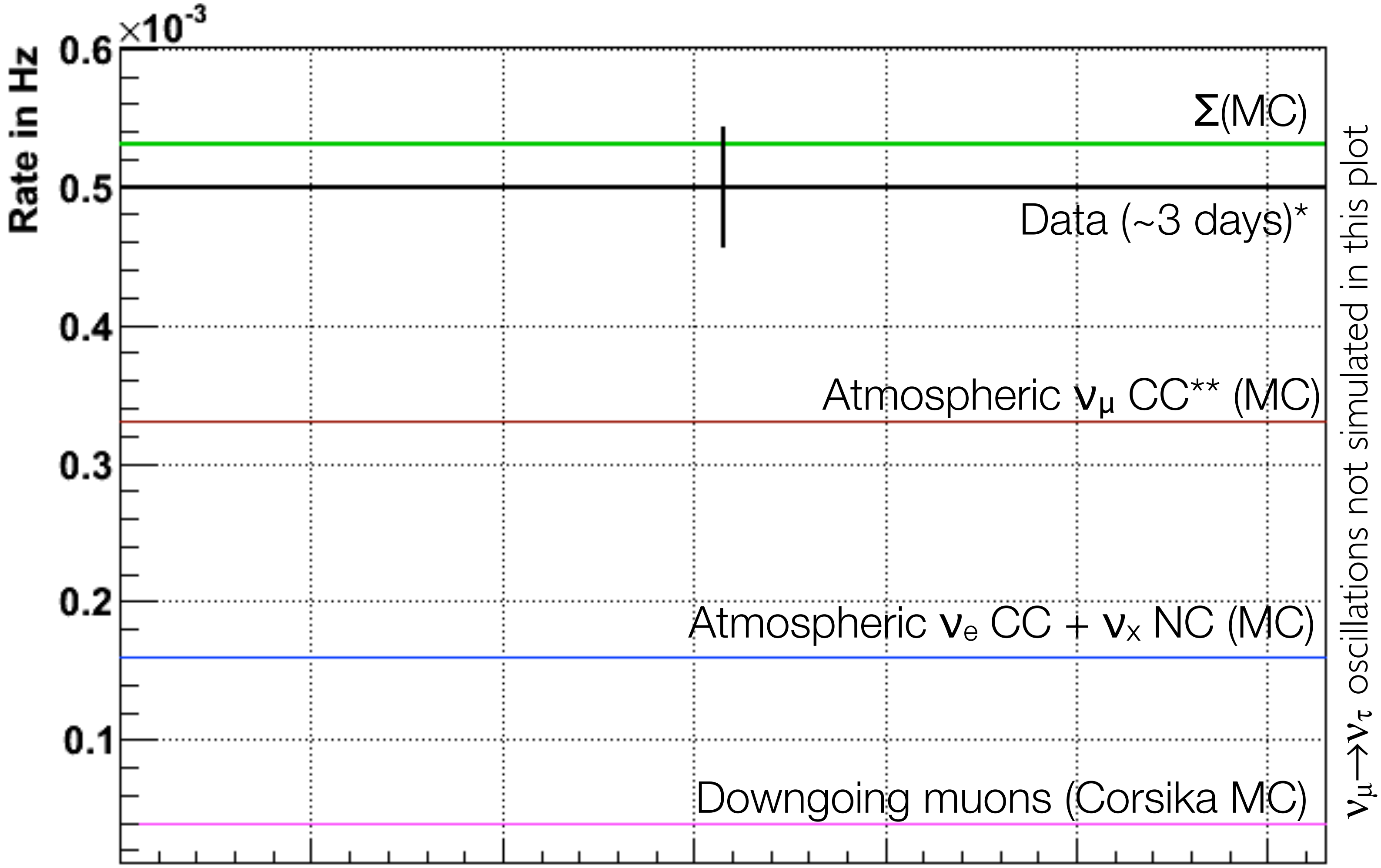
DeepCore:
First Results (*Very Preliminary*)

- Historical background:
  - Feasibility of high energy neutrino astronomy shown 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 (*Very Preliminary*)

- Enter DeepCore with its potent combination of
  - Vetoing capability
    - 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 new, high 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 (*Very Preliminary*)

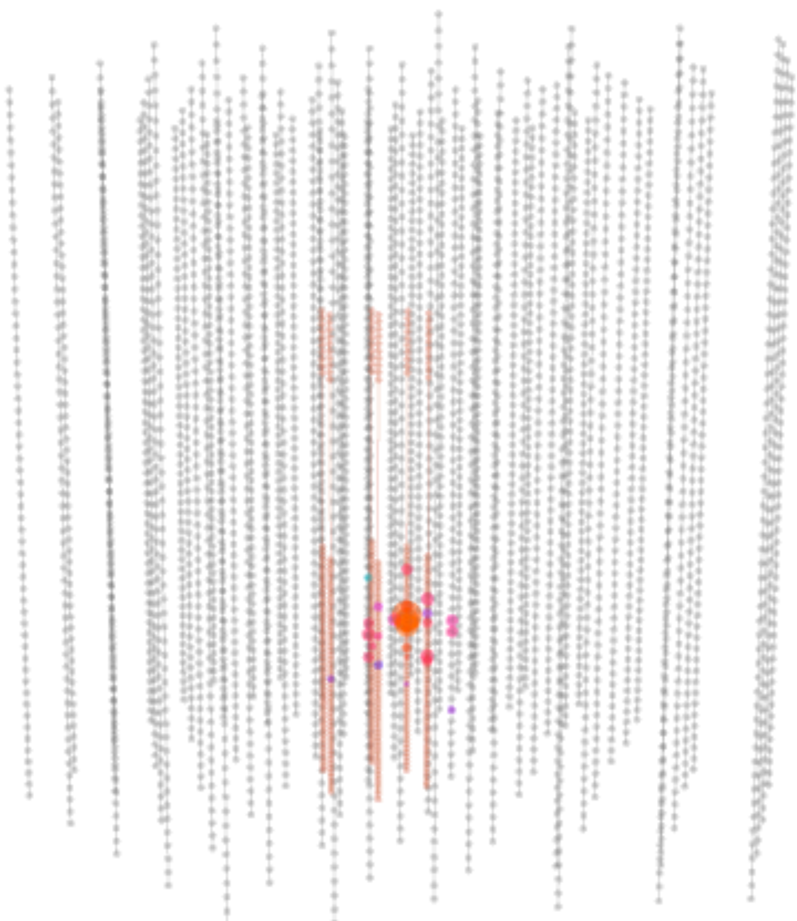
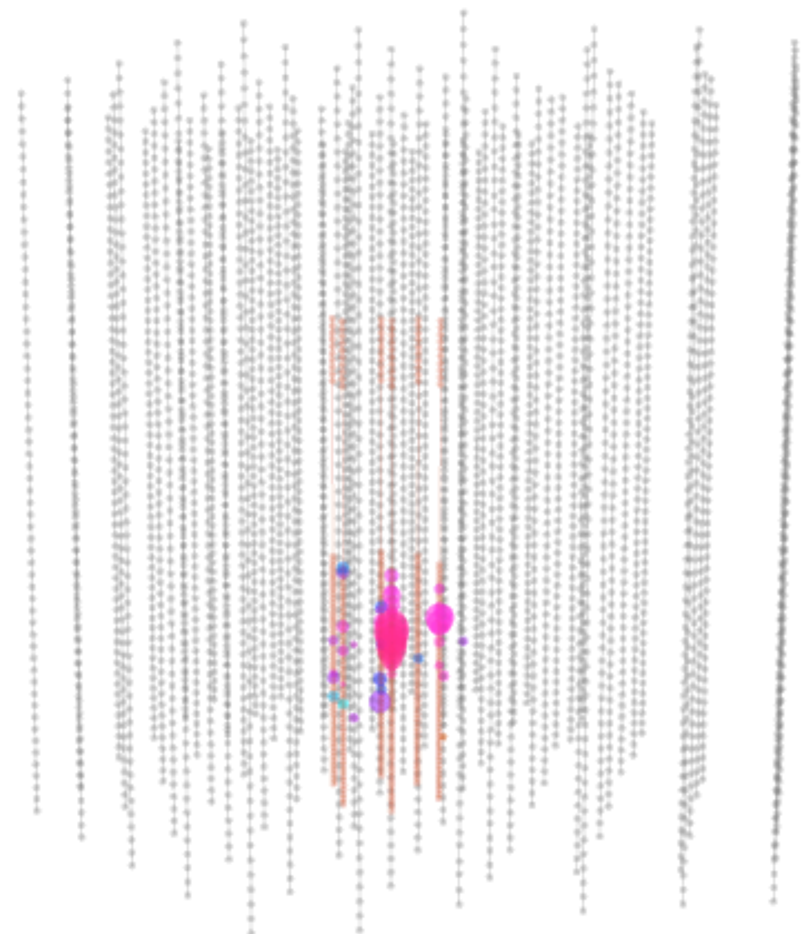


*Have ~100x more data available.

**Stubby tracks. Further purification of sample in progress.

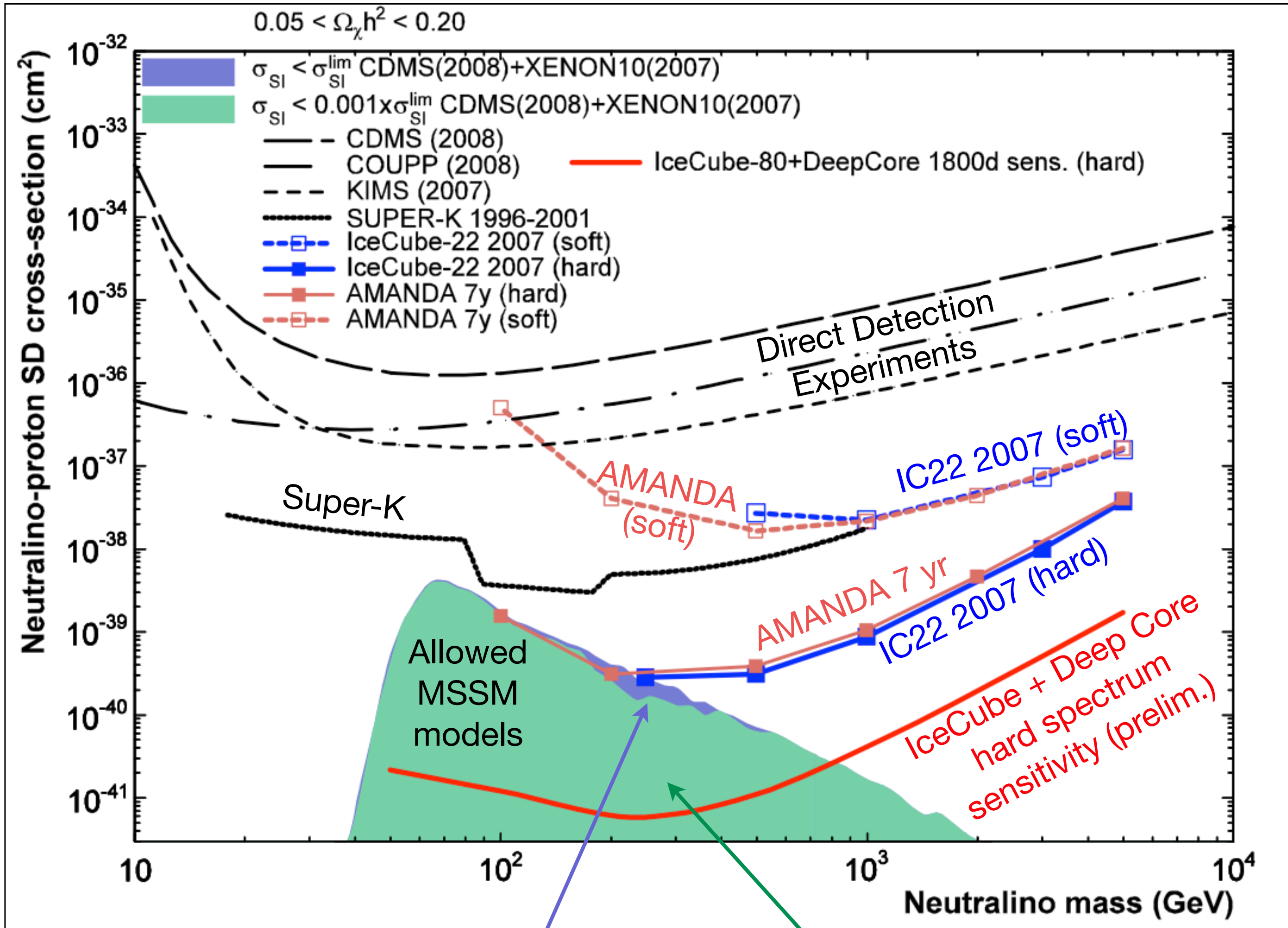
DeepCore:
First Results (*Very Preliminary*)

Two candidate events

Deep Core: Predicted Performance: WIMPs

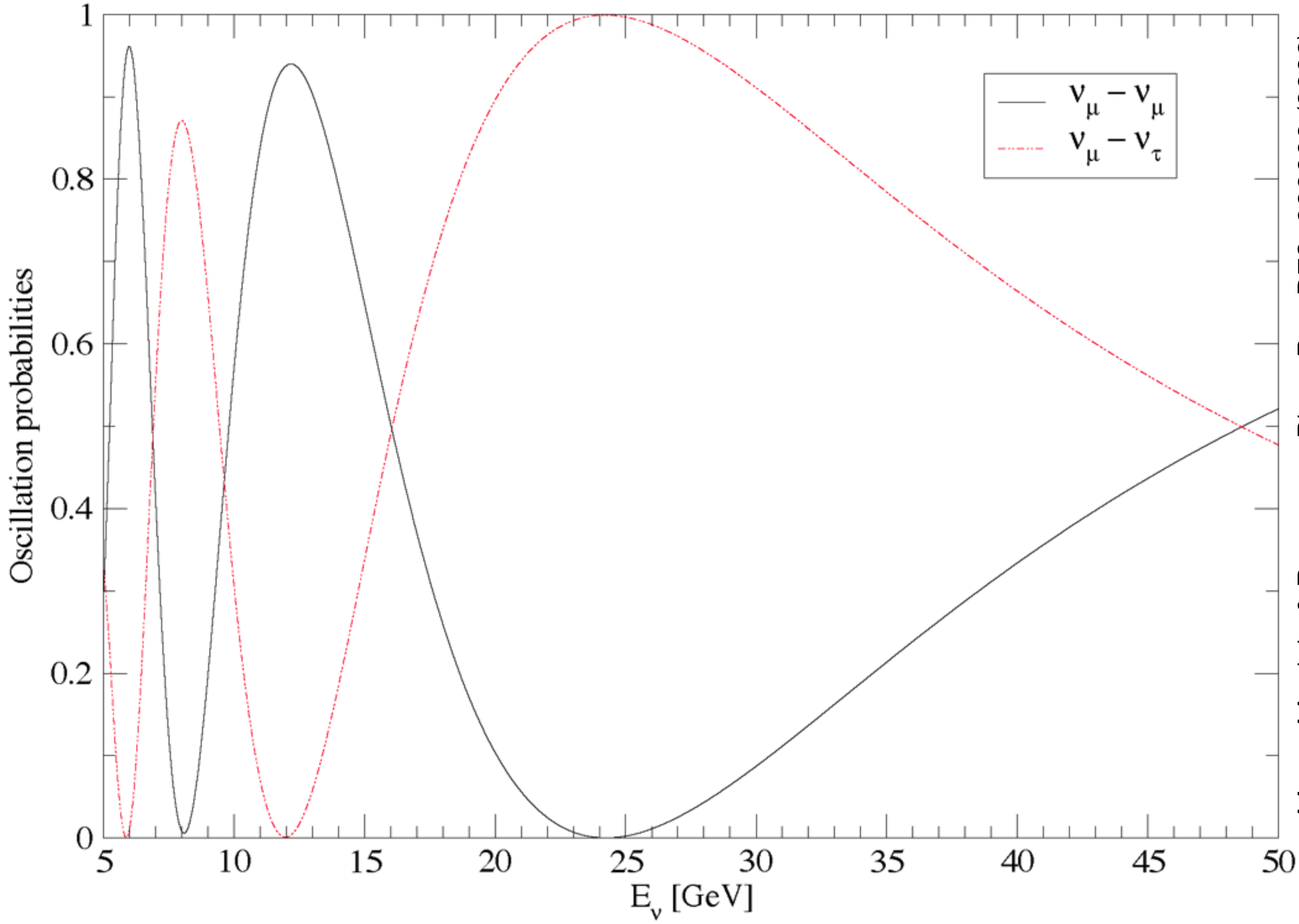
- Solar WIMP dark matter searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



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

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

DeepCore:
Predicted Performance: ν Oscillations



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

(For vertically upgoing neutrinos; L = Earth diameter)

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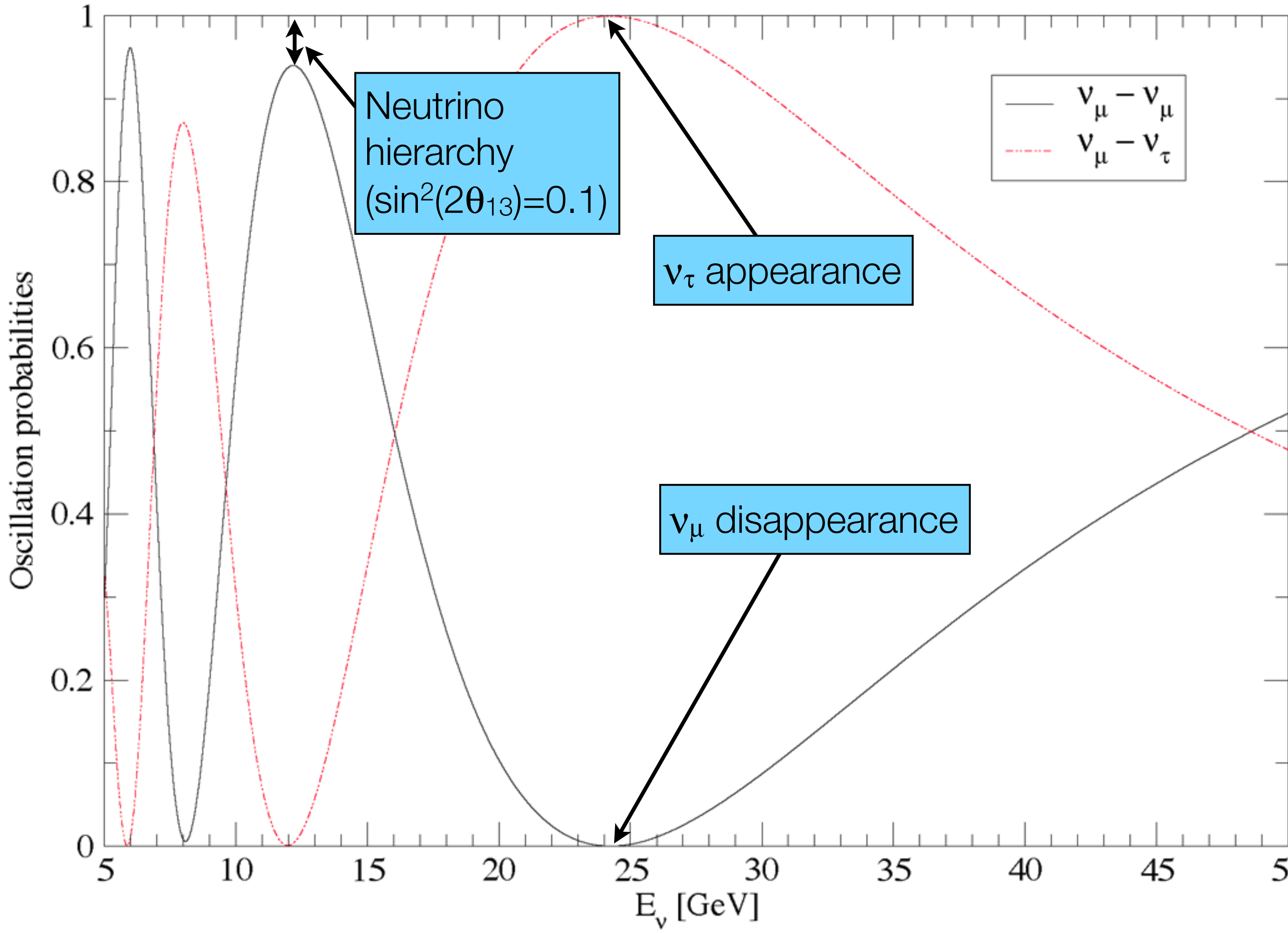

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PINGU: Phased IceCube Next Generation Upgrade

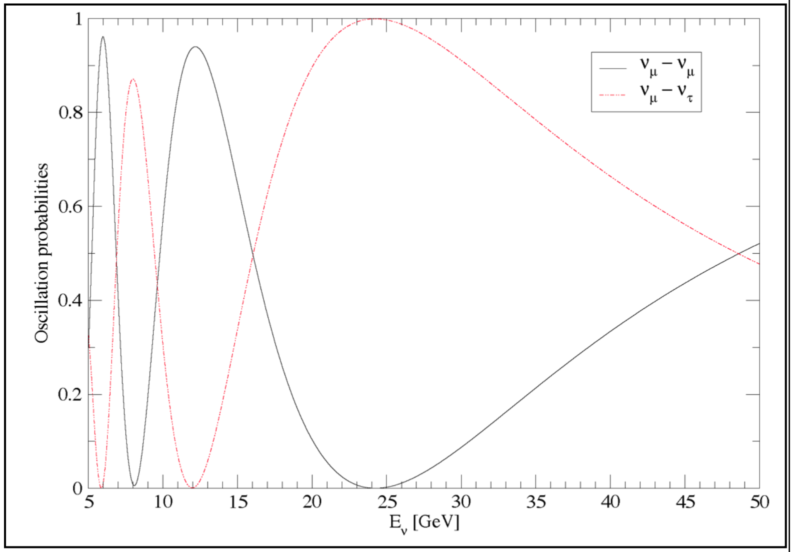
- Proto-collaboration of ~70 members from
  - IceCube, KM3Net
  - Several other neutrino experiments
  - Photon detector developers
  - Theorists
- Semi-monthly conference calls for past few months
- First meeting held 19-20 March at NIKHEF in Amsterdam
  - ~30 participants
  - Main discussion points:
    - physics drivers
    - detector design options
    - new photon detector configurations and technologies
    - timelines, collaboration issues

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 (“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

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
    - 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
- Pathfinder technological R&D for PINGU-II



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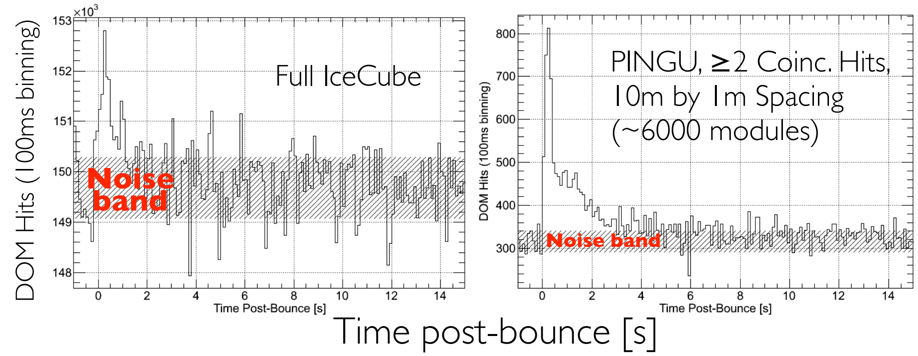
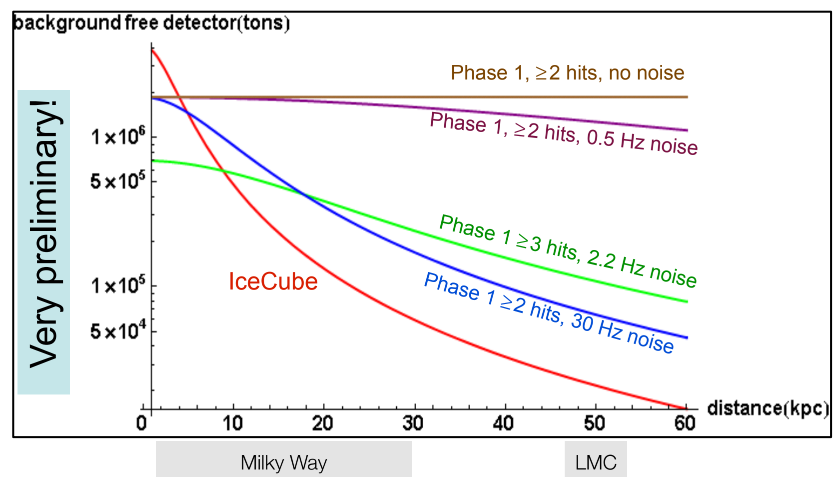




Equivalent size of a background free detector for beginning 0.38 s of **Lawrence Livermore** model, 1 m DOM and 10 m string distance, 18 strings (~6,000 DOMs) (figures from Lutz Koepke/Mainz)

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

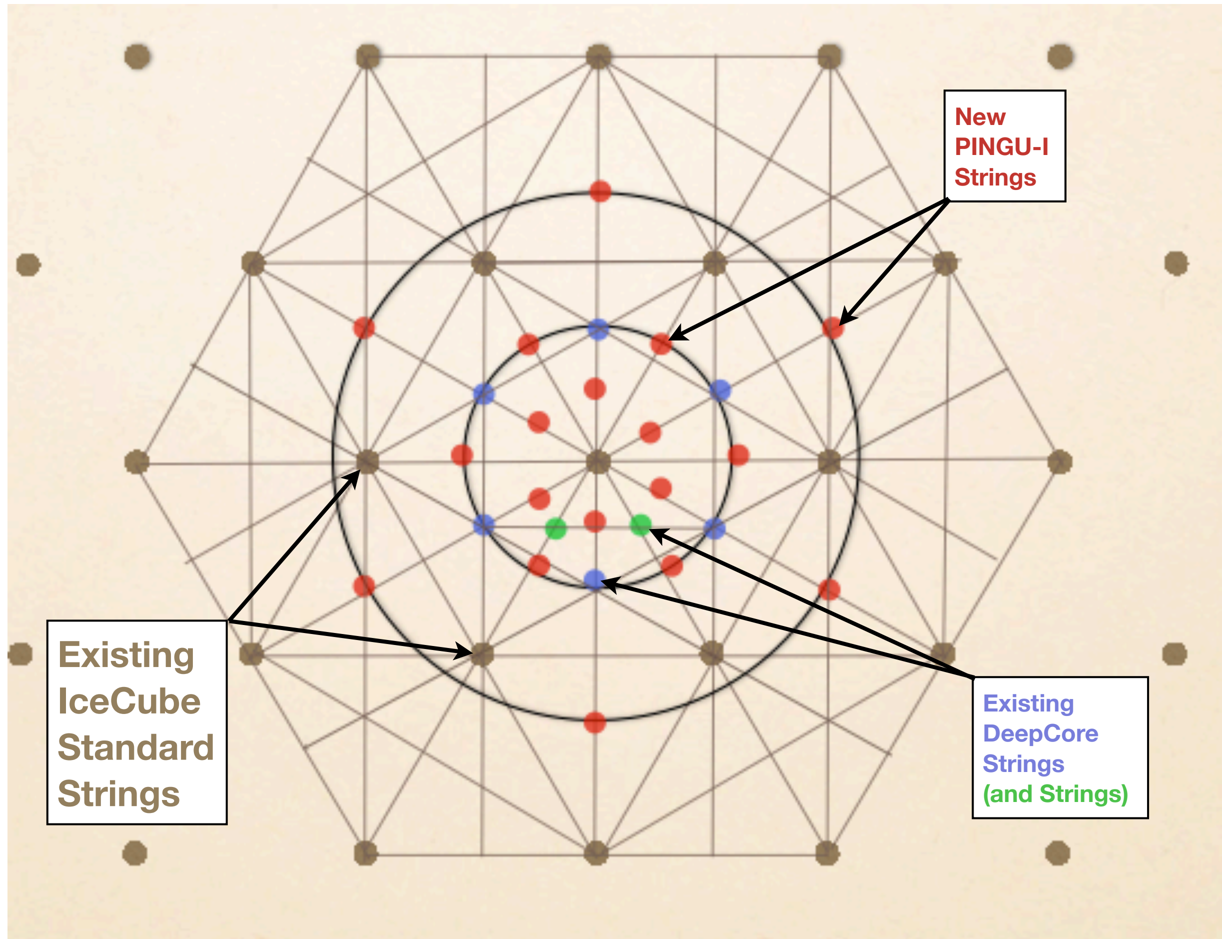


image courtesy of A. Karle

- Price tag would likely be around $20M

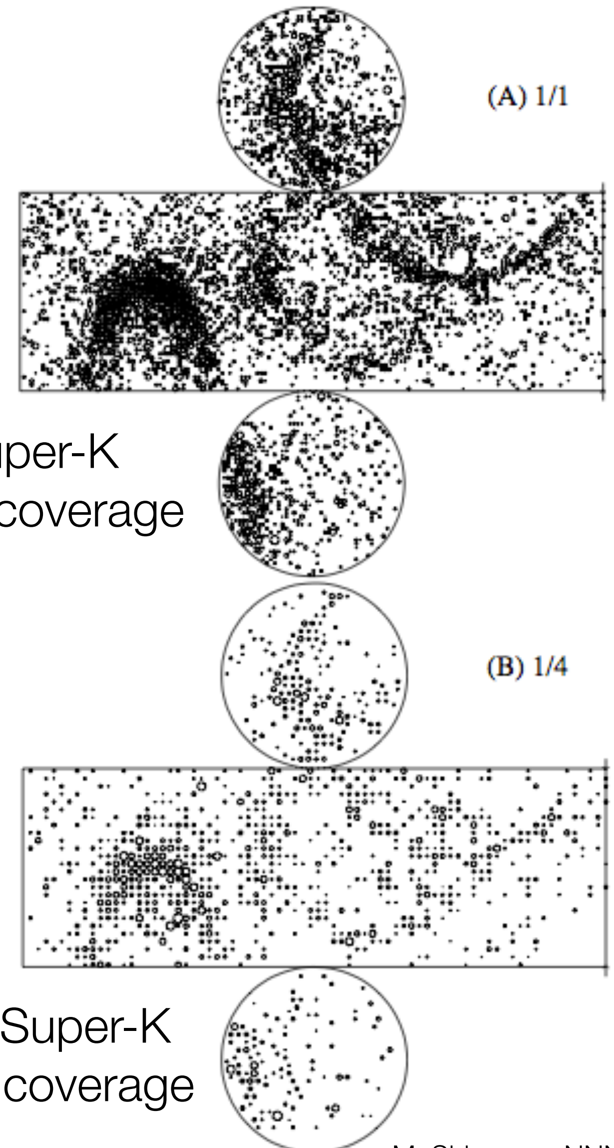
PINGU-II: Physics Motivations for sub-GeV Energy Threshold

- 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

Courtesy E. Resconi

- For fiducial volume of 1.5 MT (5×10^{35} protons) with 10 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 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
    - back-of-the-envelope calculations indicate 10% coverage is feasible



Super-K PMT coverage

¼ of Super-K (10%) coverage

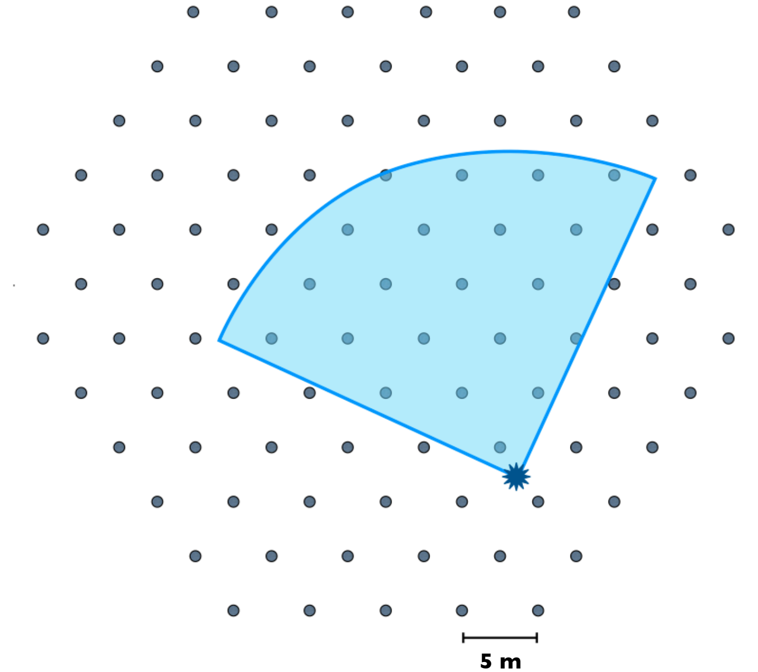
M. Shiozawa, NNN99

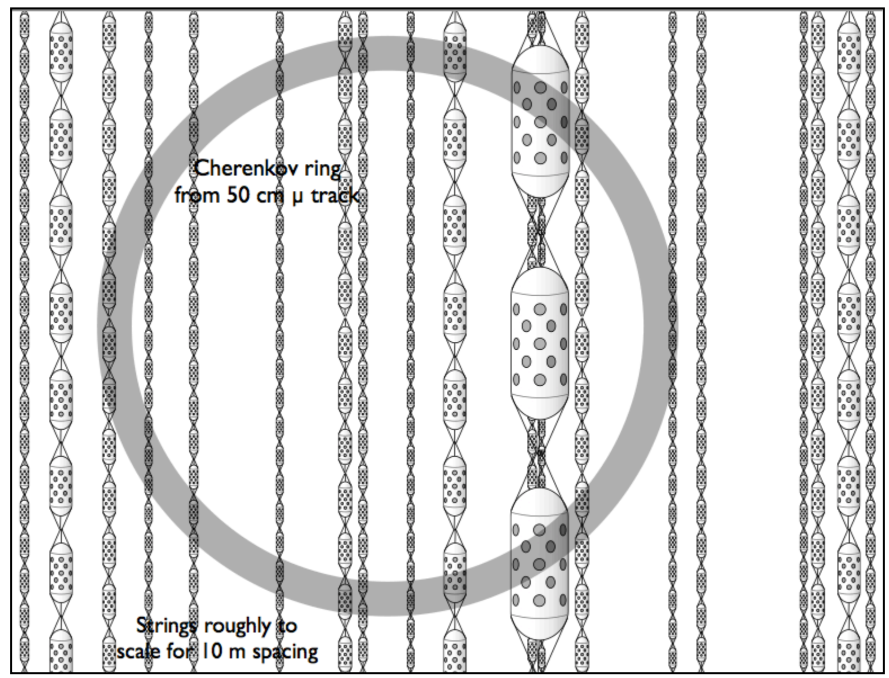
PINGU-II: Supernova Neutrinos

- Expect ~200 Cherenkov photons per MeV
  - A detector in the ice could reach down as low as 10 MeV
  - Would confer sensitivity out to ~1 Mpc, giving ~0.5 SN/yr
  - Caveat: LOTS of uncertainties (reconstruction, particle ID,...)

PINGU-II: Detector Concept

- $\mathcal{O}$(few hundred) strings of "linear detectors within DeepCore fiducial volume
  - Goals: few MTon scale with energy sensitivity of:
    - $\mathcal{O}$(10 MeV) for bursts
    - $\mathcal{O}$(100 MeV) for single events
- Physics extraction from Cherenkov ring imaging in the ice
- IceCube and DeepCore provide active vetoing

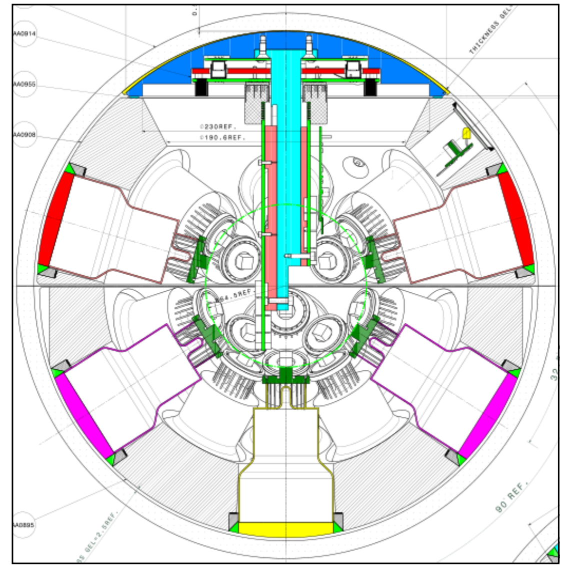




PINGU-II:
Composite Digital Optical Module

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 granular
  - Single connector

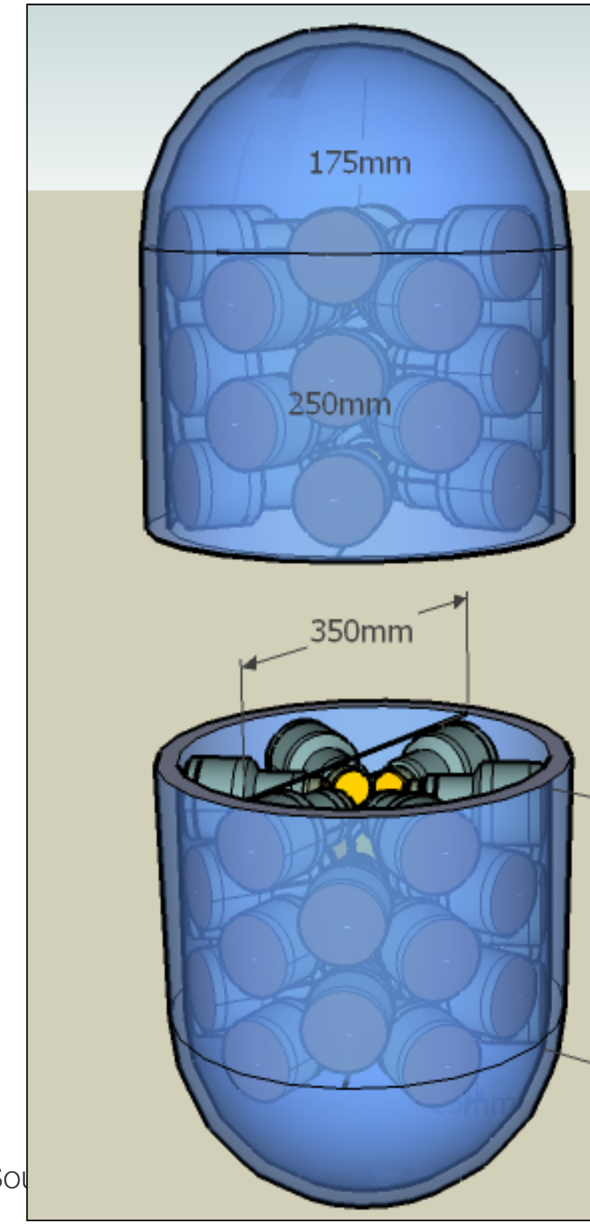


P. Kooijman, NIM A567 (2006), S. Kuch NIM A567 (2006), KM3NeT TDR

PINGU-II: Composite Digital Optical Module

Courtesy E. de Wolf & P. Kooijman

- Glass cylinder containing 64 3" PMTs and associated electronics
  - Effective photocathode area >6x that of a 10" PMT
  - Diameter comparable to IceCube DOM so (modulo much tighter vertical spacing) drilling requirement would be similar, too
  - Single connector
- Might enable Cherenkov ring imaging in the ice



Possible design for PINGU-II: 64 x 3" PMTs

PINGU-I & -II: Near-Term Work

- Detailed Monte Carlo simulations underway
  - GENIE ν simulation from E_ν = 0.6-200 GeV
    - neutrinos generated per dataset using full IceCube simulation
    - can re-cast into many possible geometries inside DeepCore volume
  - Also simulating proton decay and SN neutrinos
- New specialized reconstruction algorithms for lower energies and for Cherenkov rings need to be developed
  - Low energy reco will follow work on DeepCore now underway
  - Cherenkov ring reconstruction can modify existing algorithms from experiments like SuperK

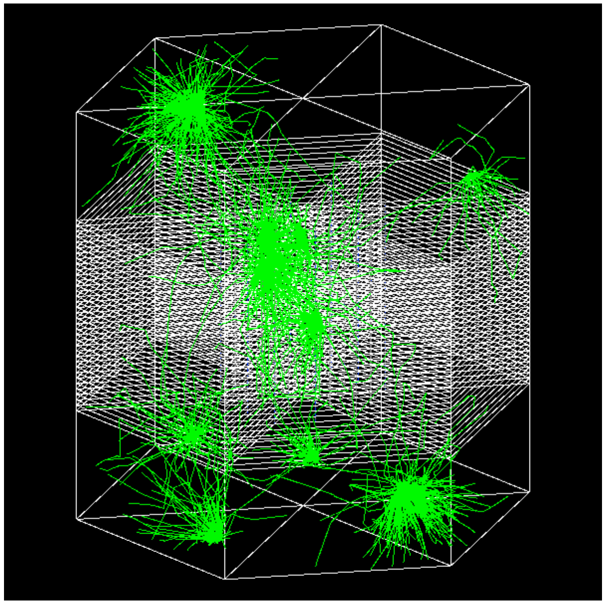


Figure: Lukas Schulte/Mainz

Geant4: γ's from SN ν's

PINGU-I & PINGU-II: Very Rough Schedule

- Step 0
  - Submit LoI to NSF
- PINGU-I
  - Prerequisites: Results from DeepCore demonstrating ability to reconstruct low energy events
  - Cost: well understood based on IceCube experience
  - Schedule: Deploy in two seasons starting 2014/15
- PINGU-II
  - Cost: driven chiefly by photocathode area; not by detector size.
    - Drilling costs can be estimated with reasonable accuracy based on IceCube experience
  - "Schedule": Begin deployment in 2018/19

The End

- (Backup slides follow.)