IceCube

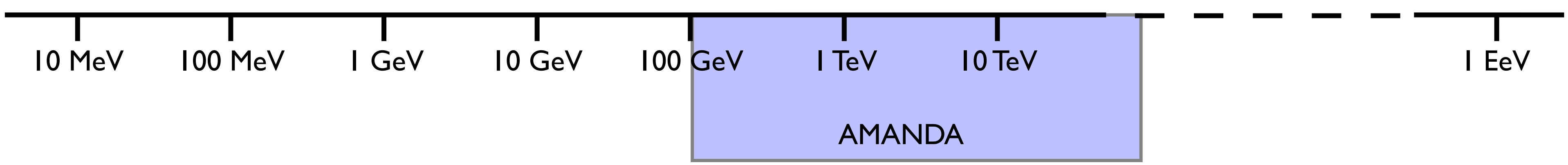
DeepCore Upgrades: A phased approach toward precision megaton neutrino detectors

Darren R. Grant
Department of Physics, Centre for Particle Physics
University of Alberta

Antarctic Science Symposium
Madison WI USA
April 27, 2011

UNIVERSITY OF ALBERTA

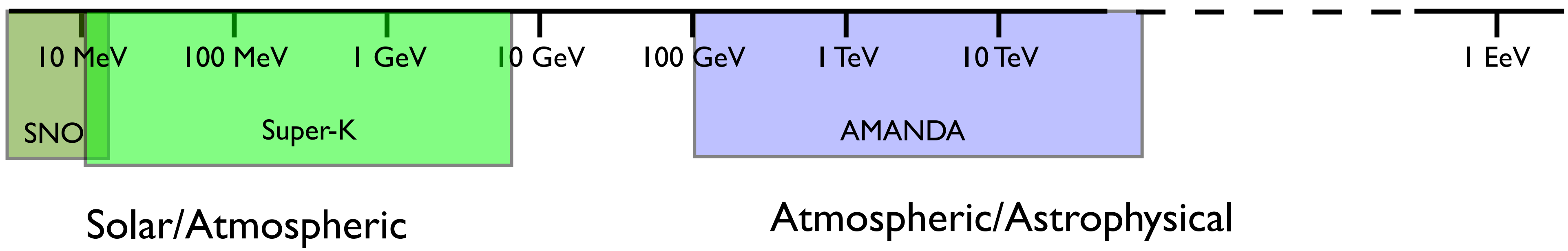
The Neutrino Detector Spectrum



Atmospheric/Astrophysical

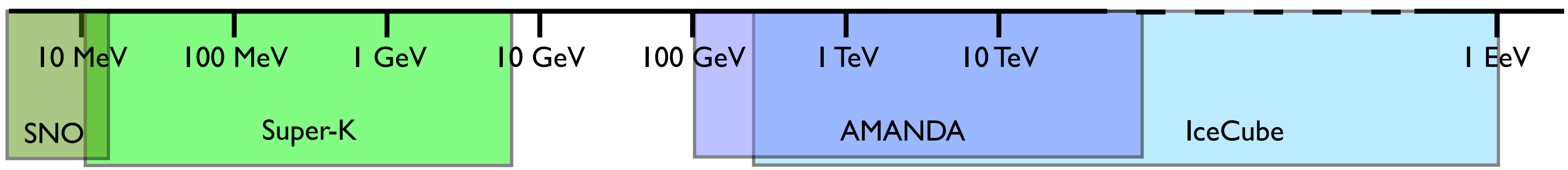
Non-accelerator based

The Neutrino Detector Spectrum



Non-accelerator based

The Neutrino Detector Spectrum

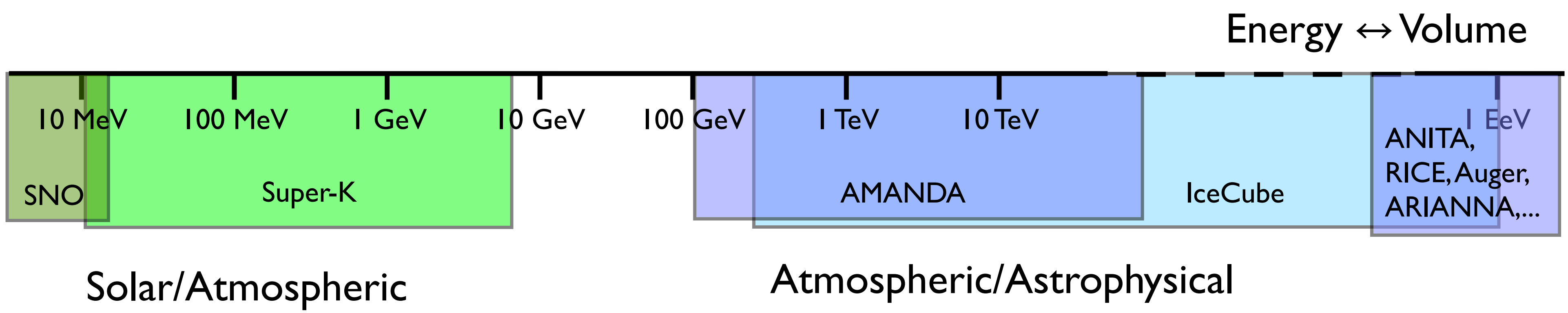


Solar/Atmospheric

Atmospheric/Astrophysical

Non-accelerator based

The Neutrino Detector Spectrum

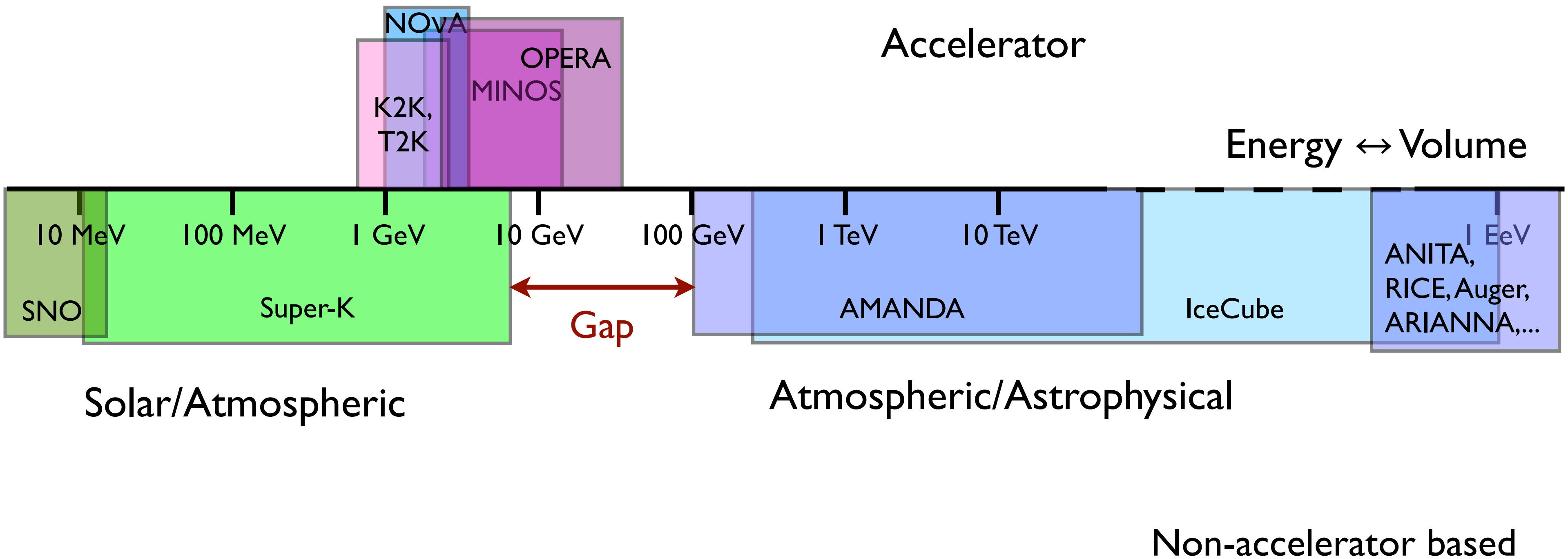


Non-accelerator based

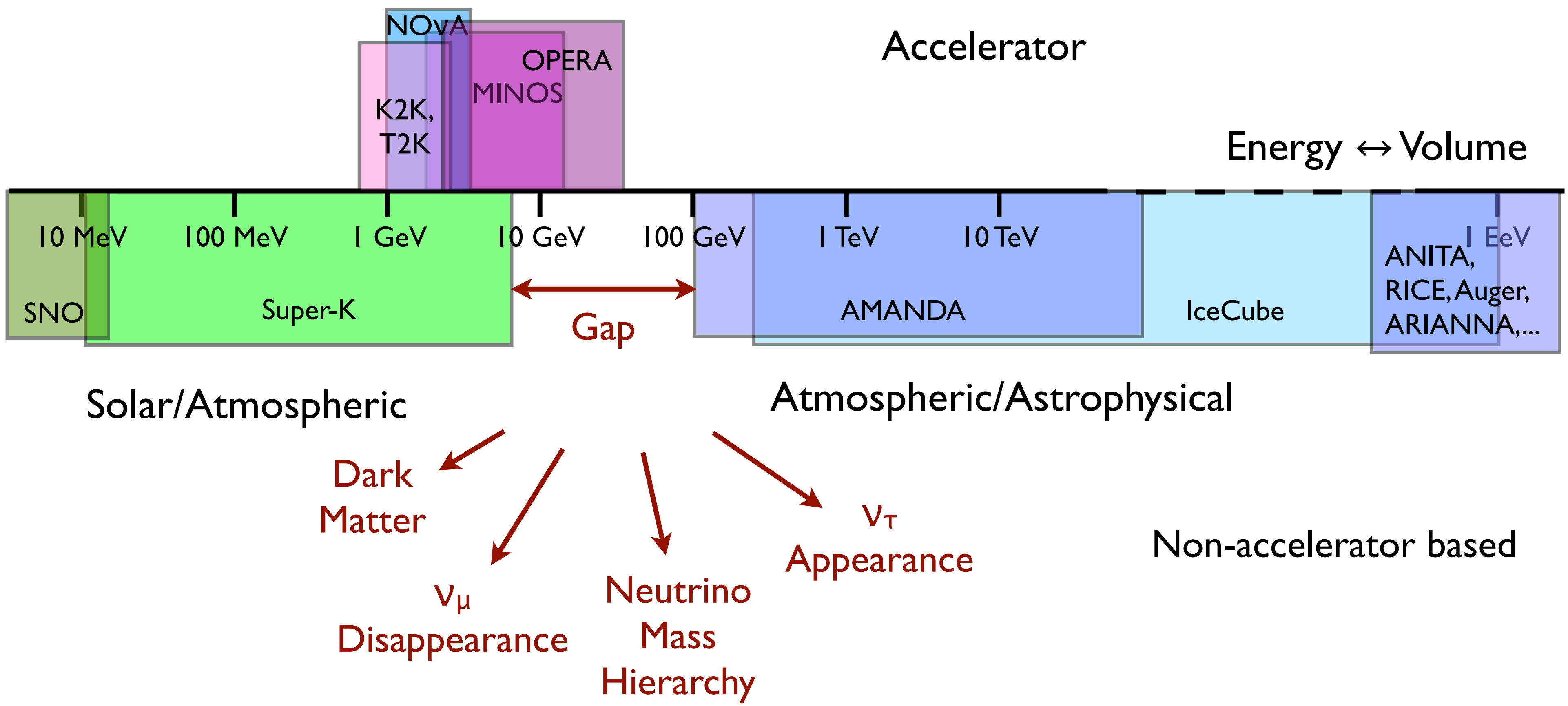
Historically, two main branches of the neutrino detector family tree:

- Relatively small (<<MTon), high precision experiments
- Very large (~GTon), low precision experiments

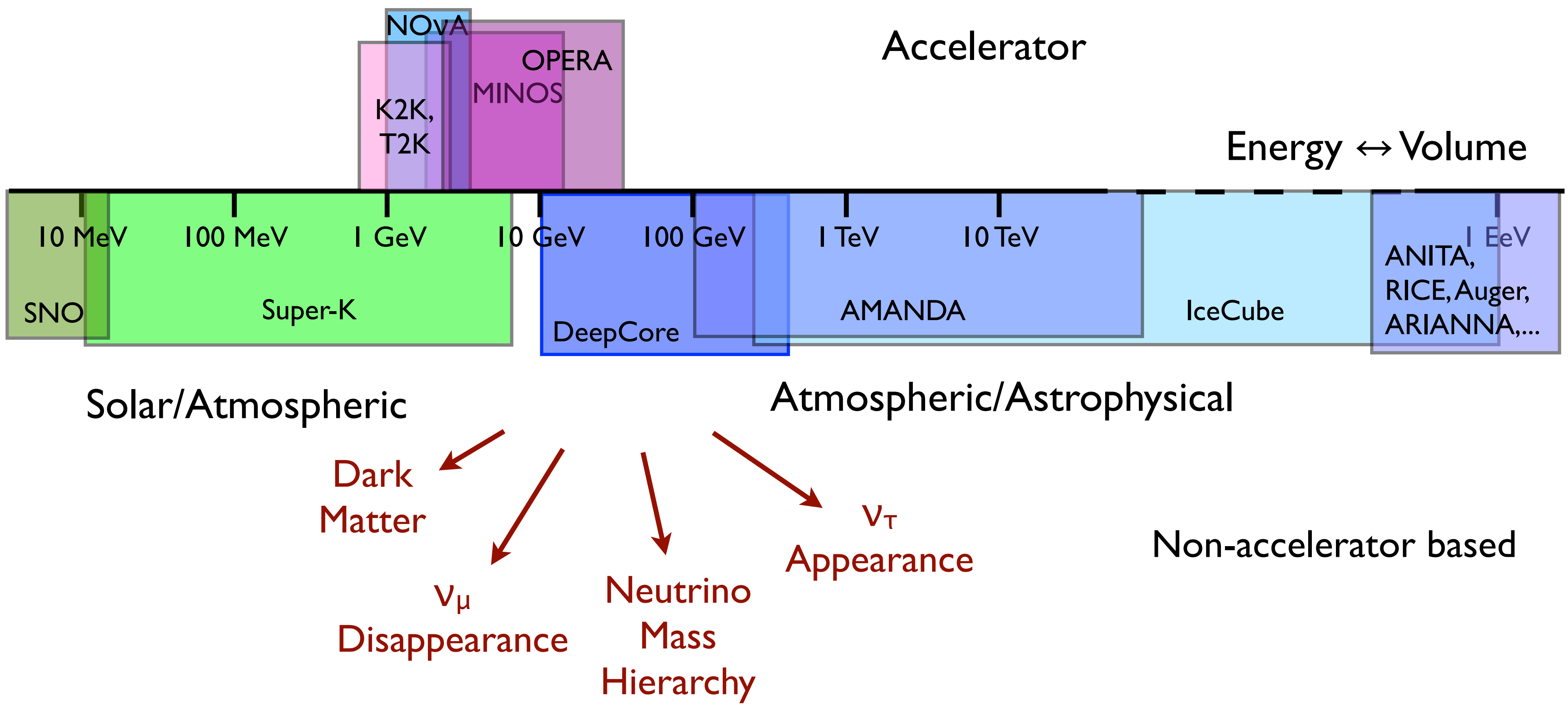
The Neutrino Detector Spectrum



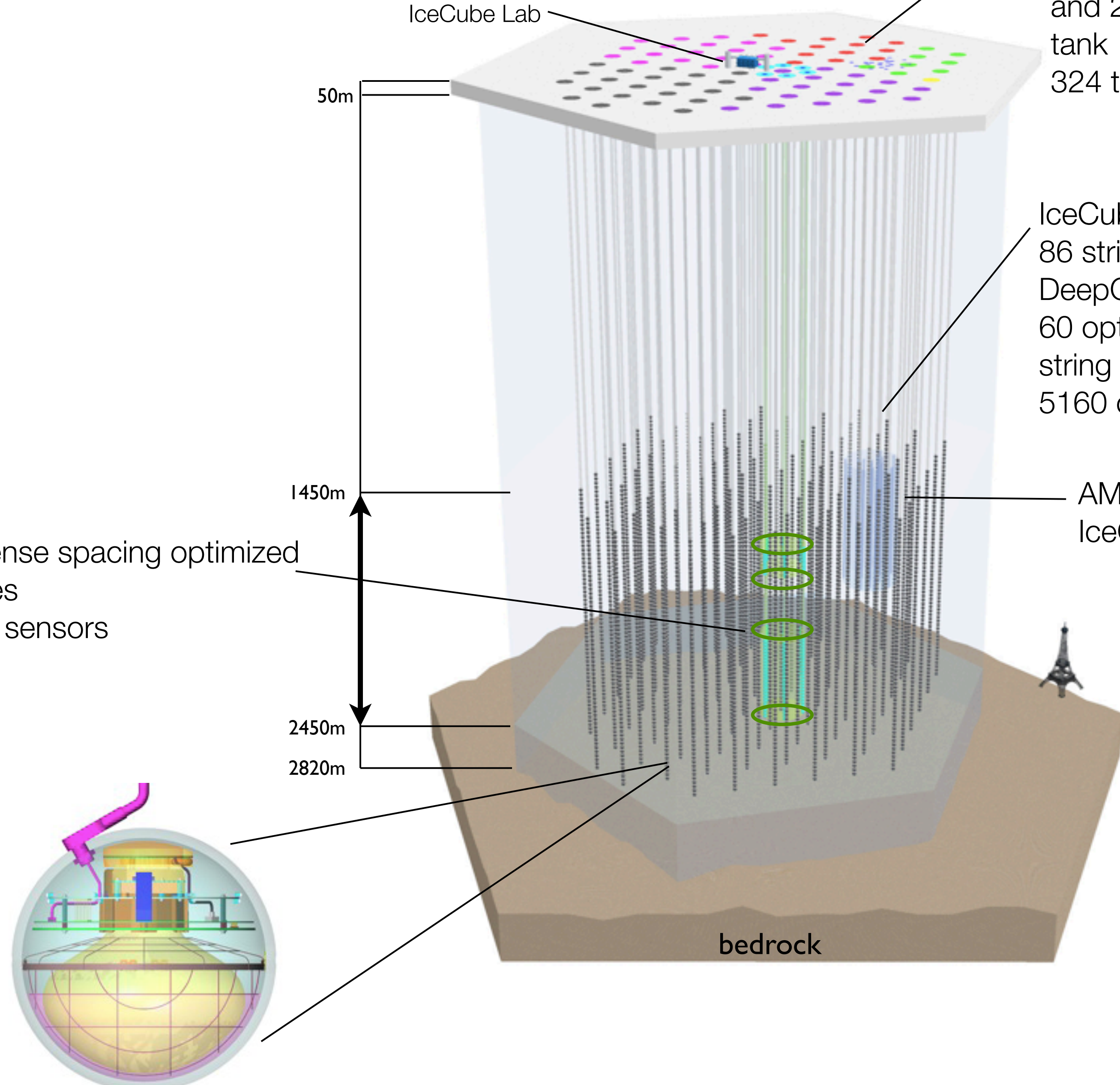
The Neutrino Detector Spectrum



The Neutrino Detector Spectrum



The IceCube Neutrino Observatory

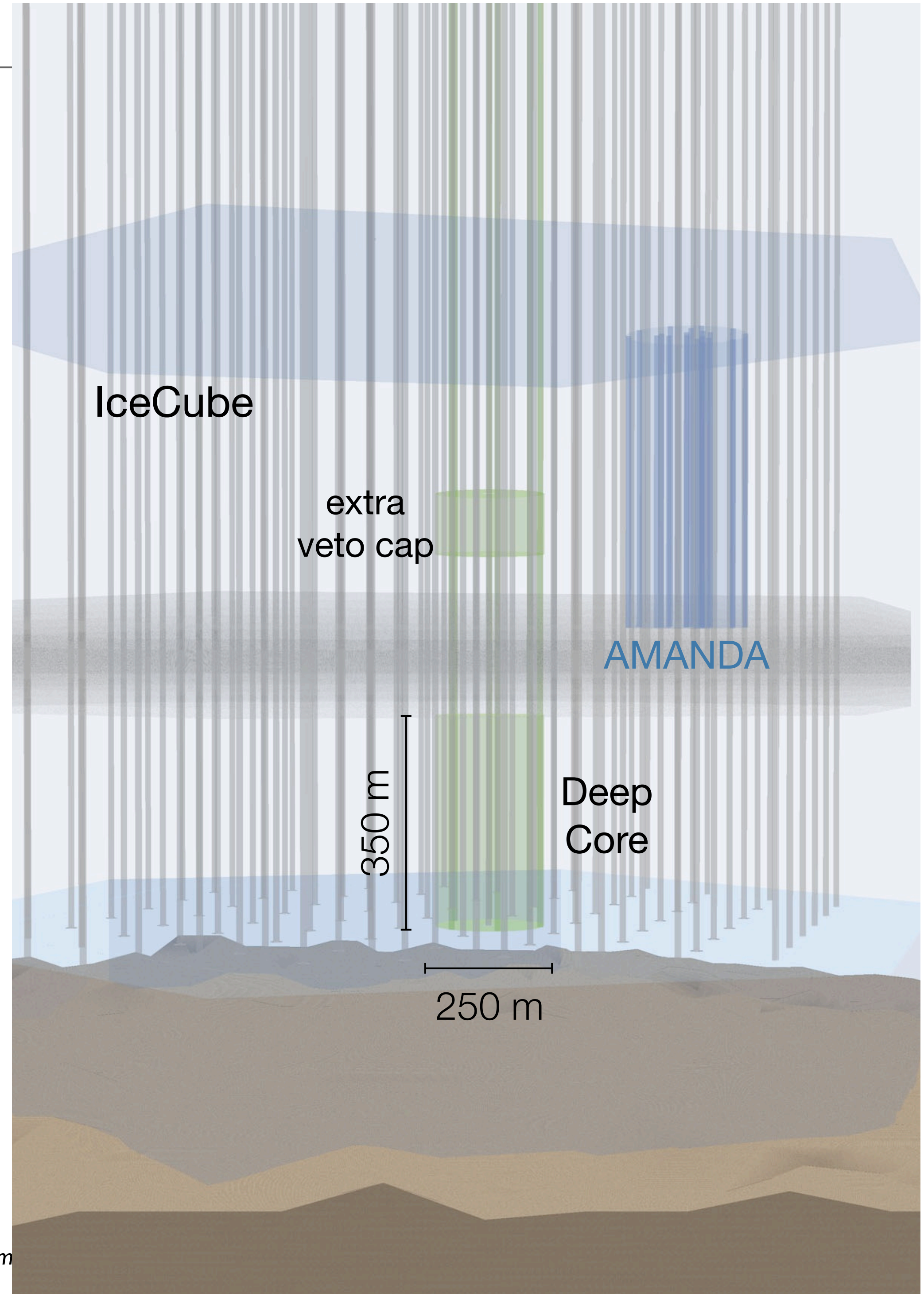


IceCube-DeepCore

- 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)

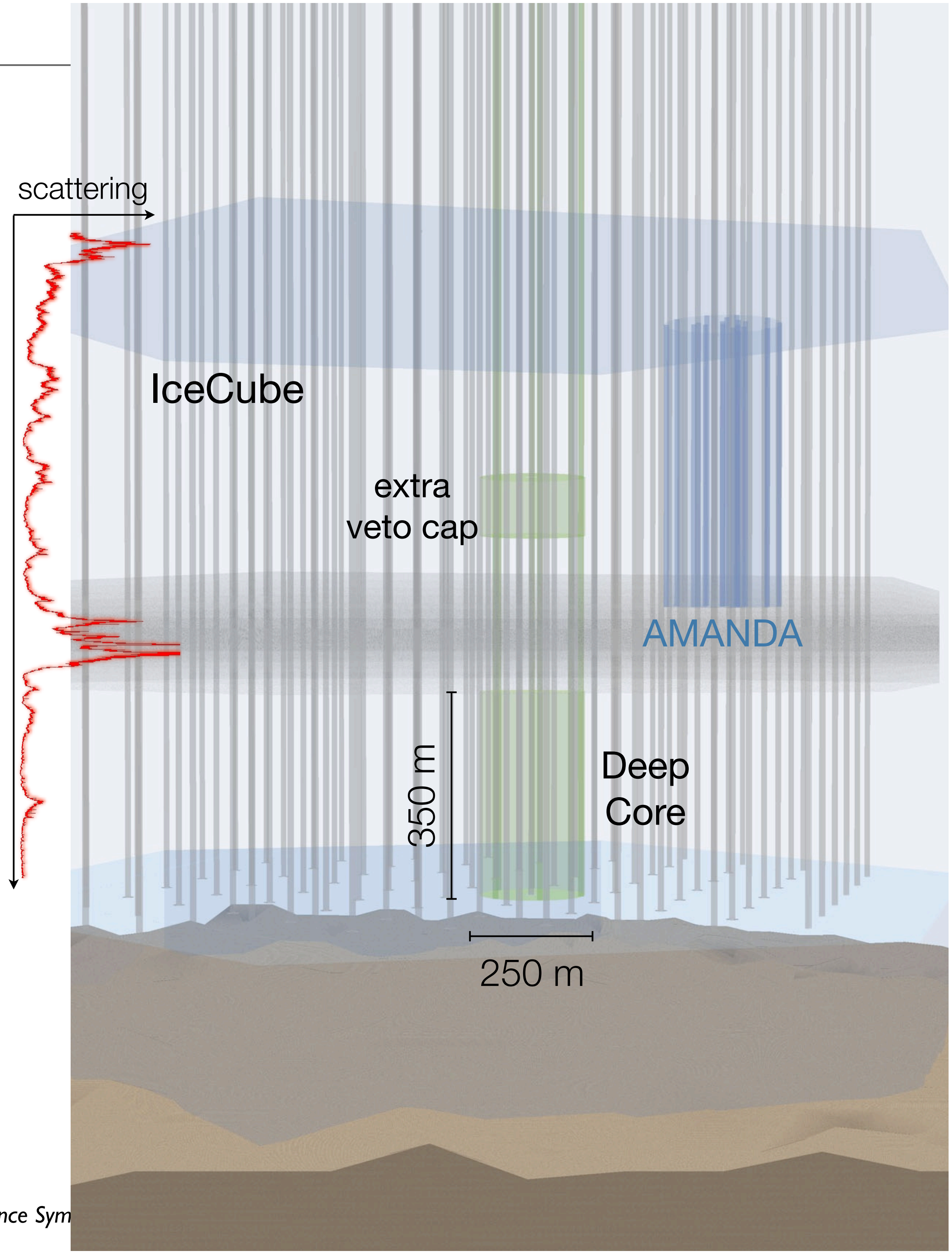
DeepCore Design

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



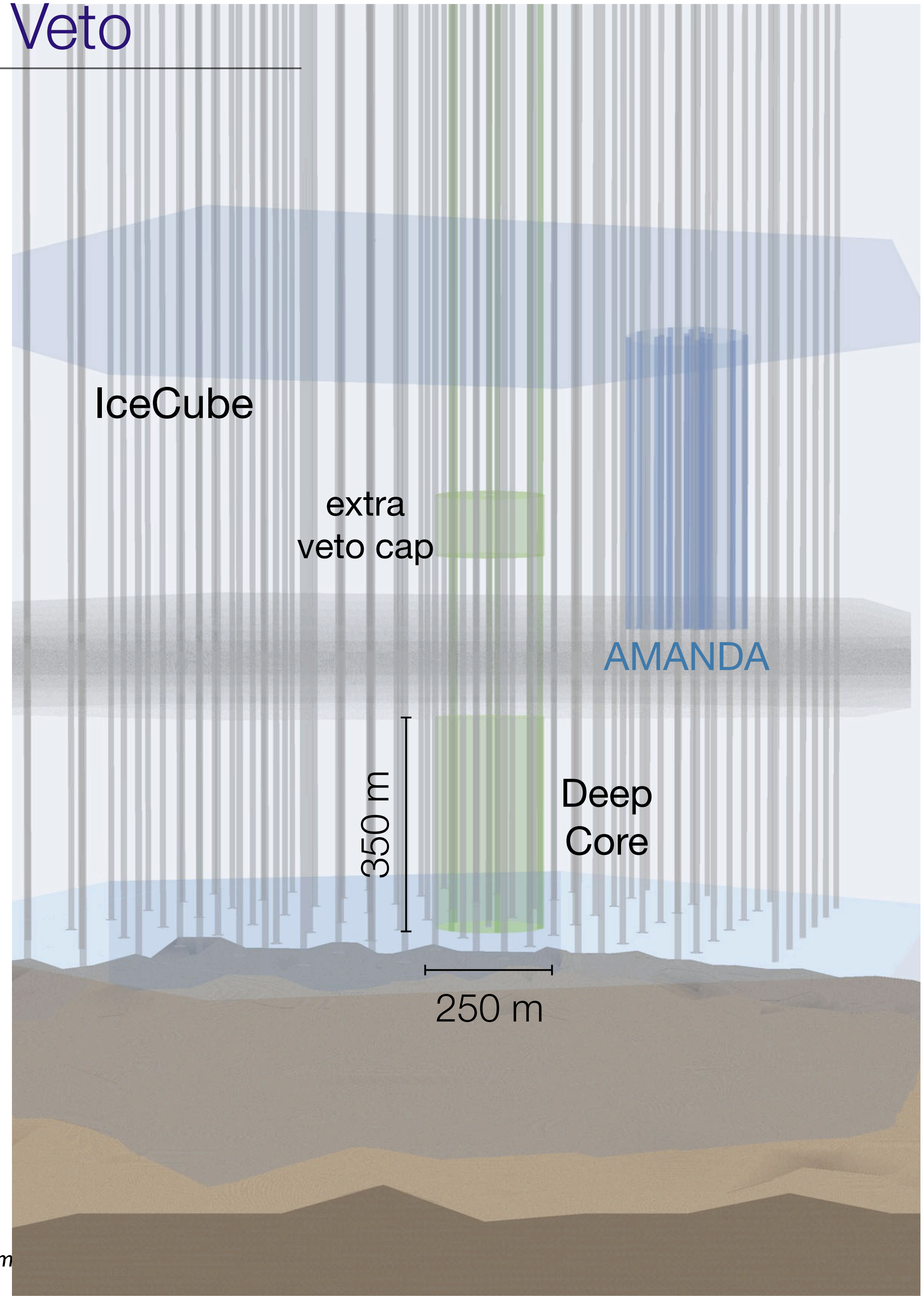
DeepCore Design

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



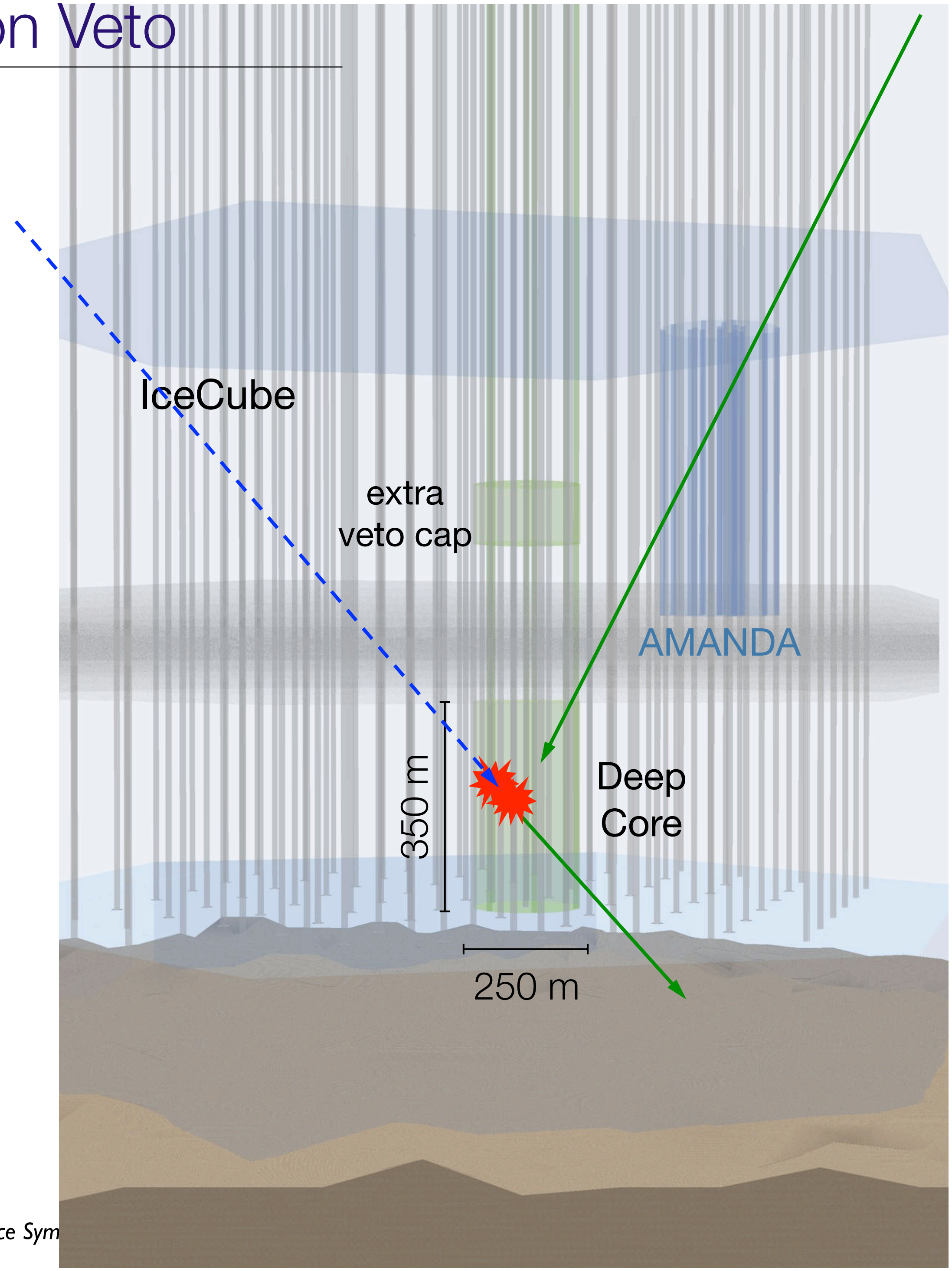
DeepCore Atmospheric Muon Veto

- 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



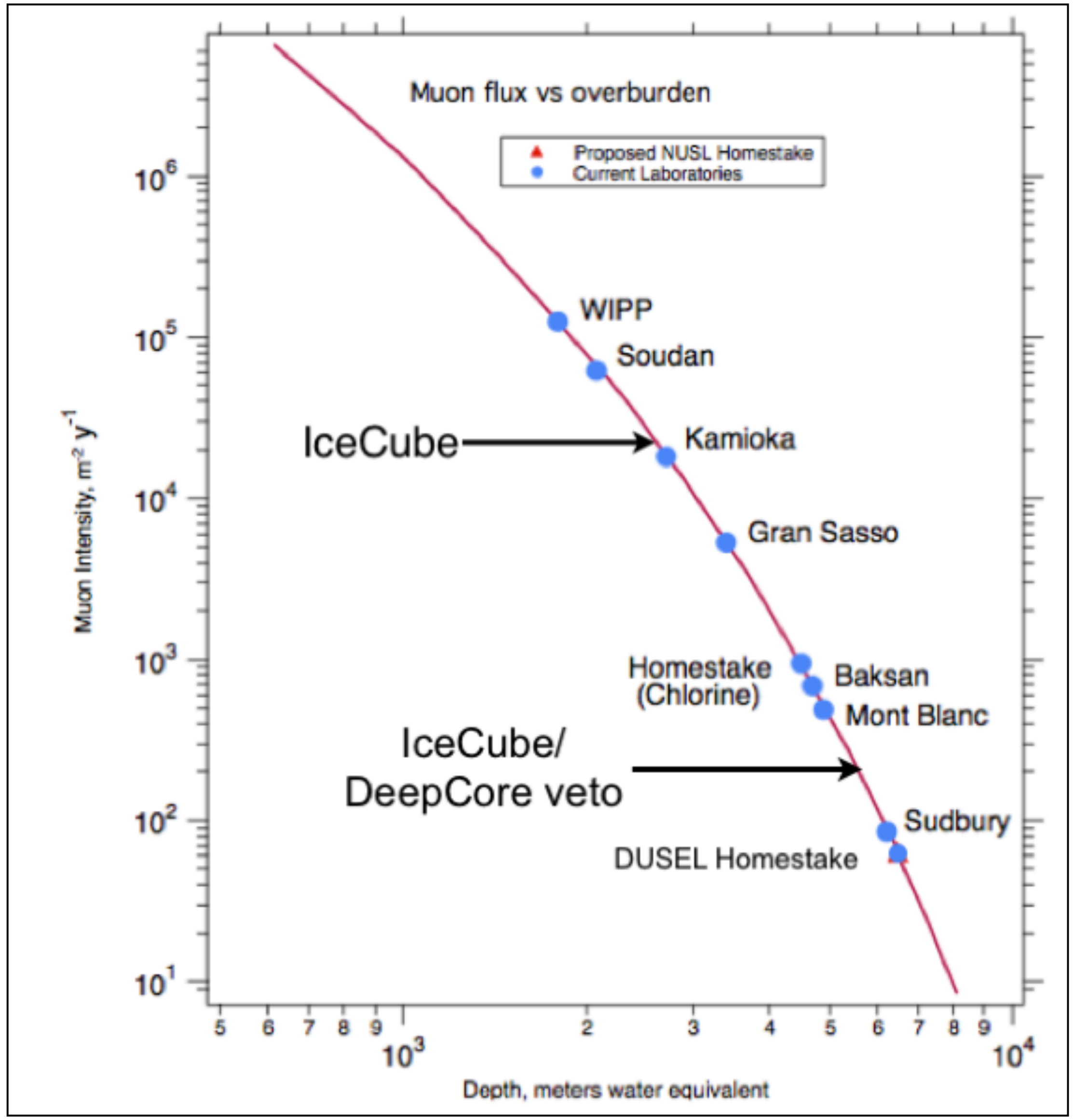
DeepCore Atmospheric Muon Veto

- 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



DeepCore Atmospheric Muon Veto

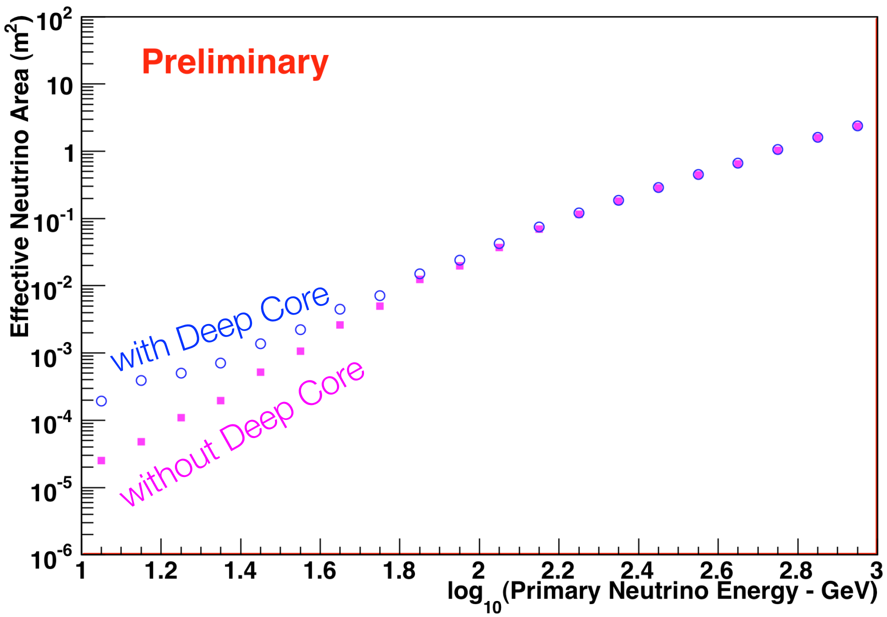
- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
- 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

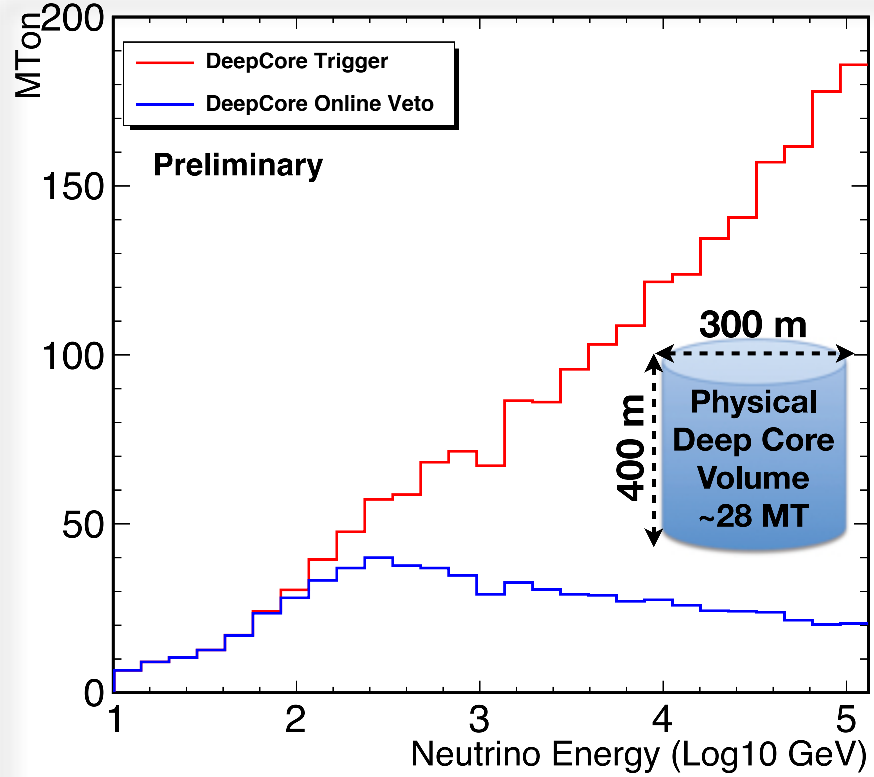


DeepCore Effective Area and Volume

Effective area for up-going ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase





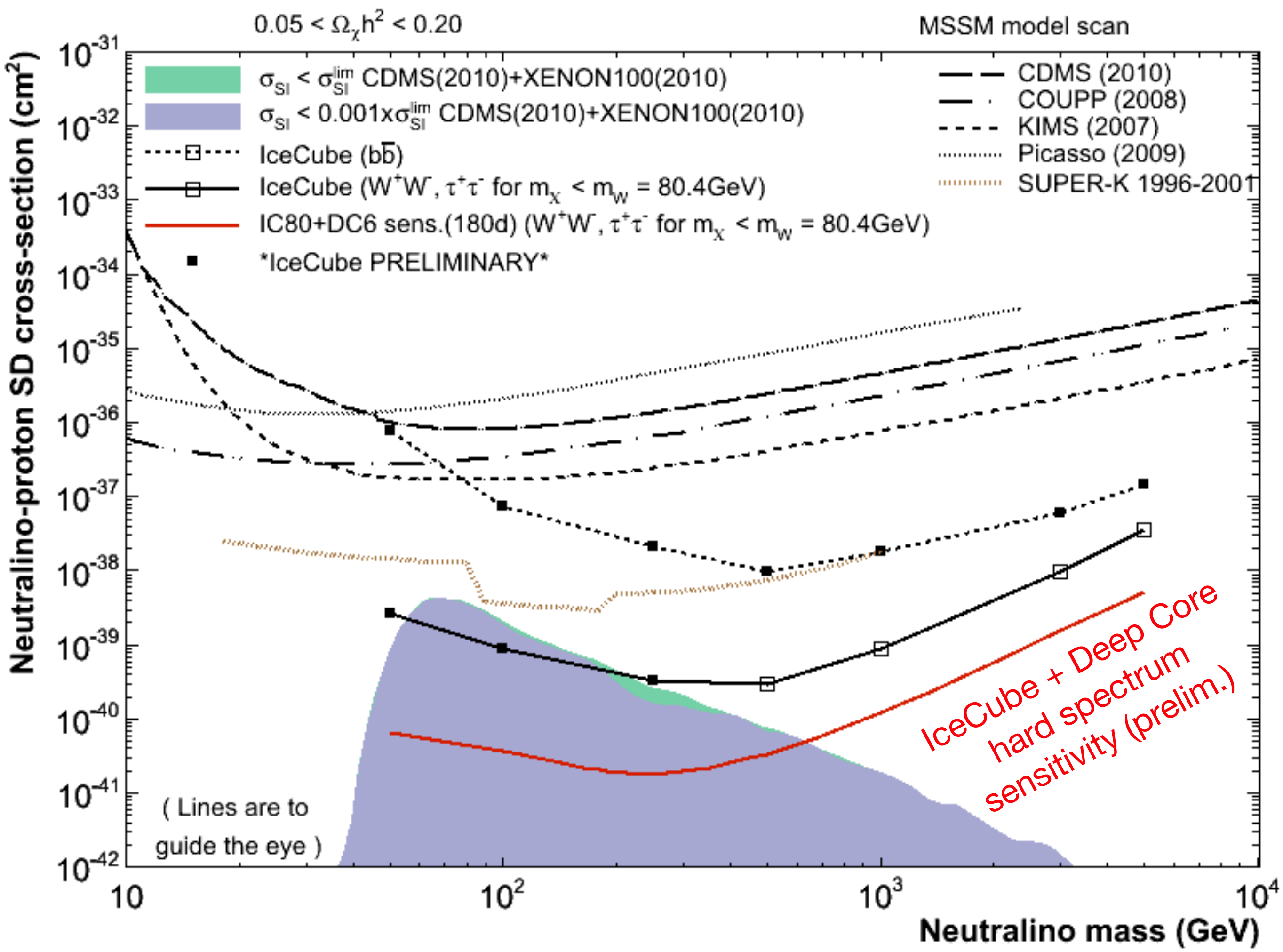
Effective volume for muons from ν_μ interacting in Deep Core

NB: full analysis efficiency *not* included yet

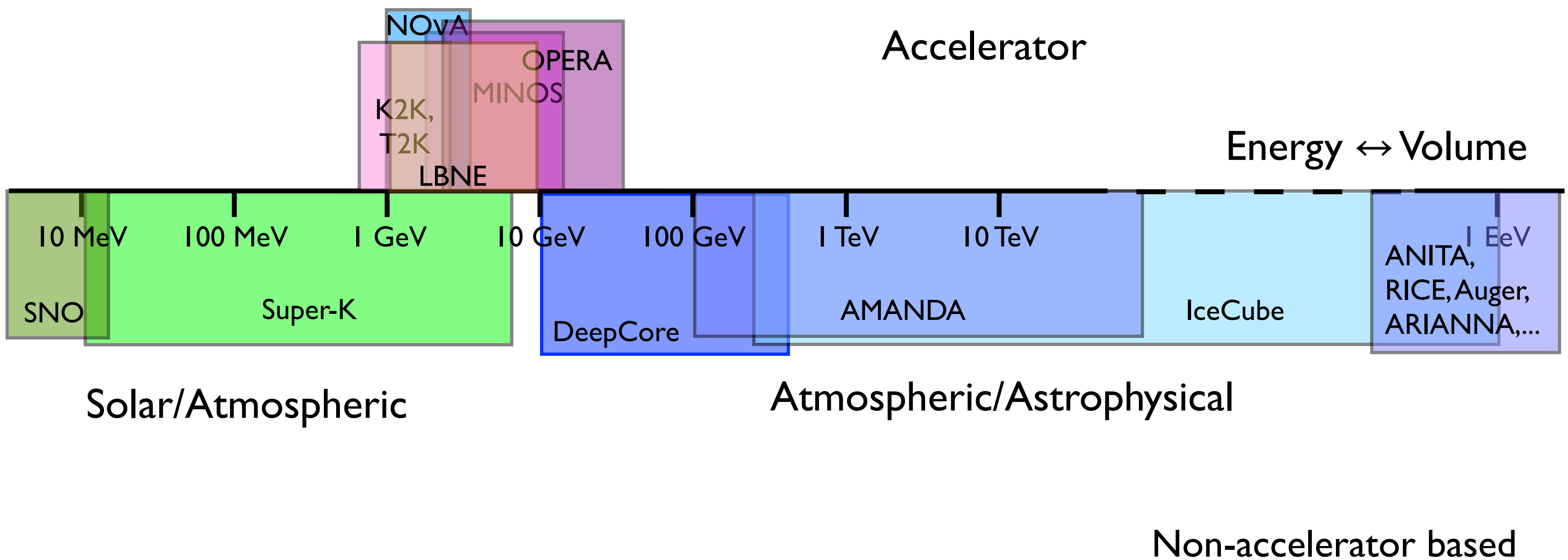
Trigger: ≥3 DOMs hit in 2.5μs;
Online Veto: No hits consistent with muons outside DeepCore volume

IceCube-DeepCore WIMP Sensitivity

- 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



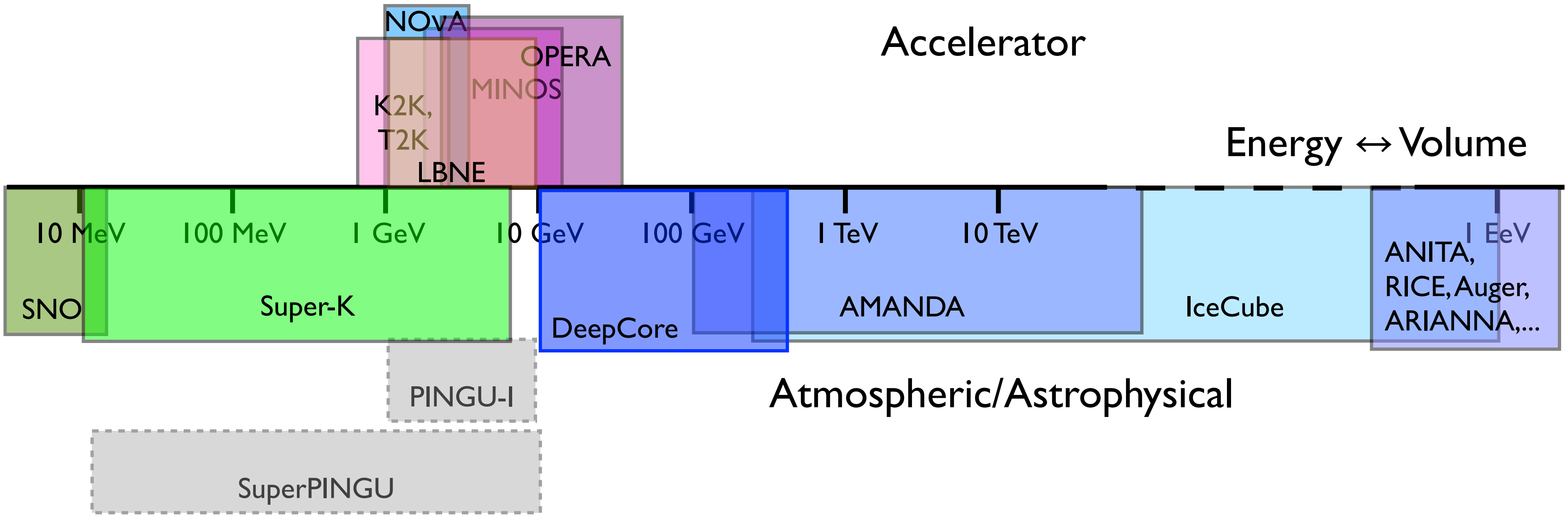
The Neutrino Detector Spectrum



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

Construction of the facilities for these detectors remain a technological challenge.

PINGU - Phased IceCube Next Generation Upgrade



~70 active members in feasibility studies:

- IceCube, KM3Net, Several neutrino experiments
- Photon detector developers
- Theorists

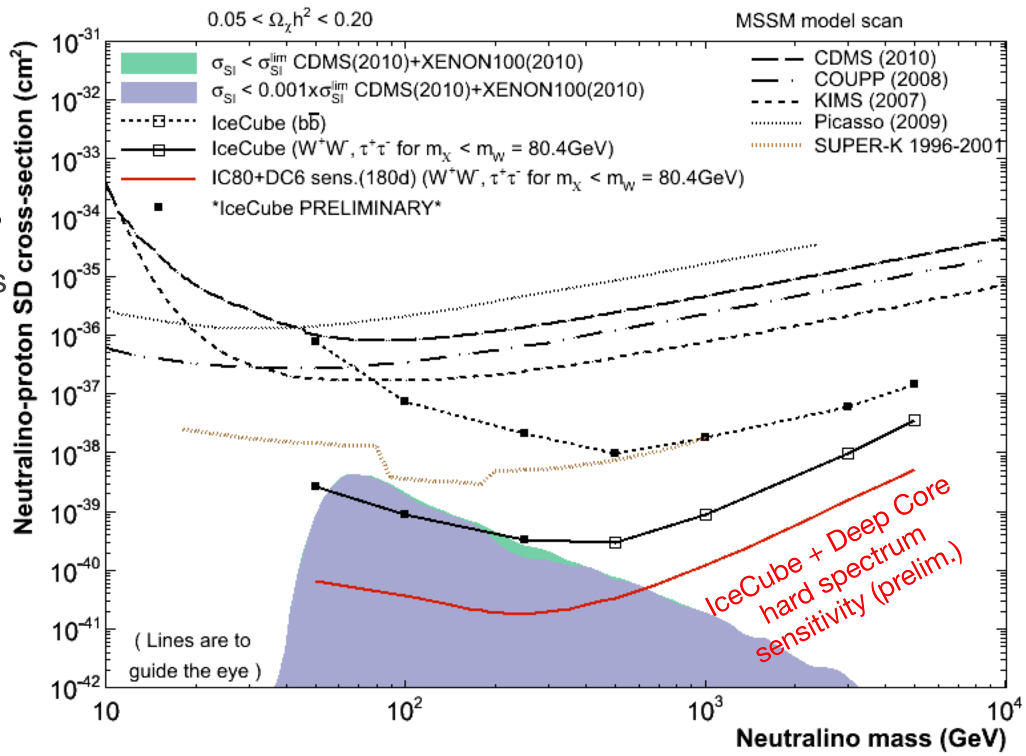
PINGU - Possible detector configurations

- 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 to IceCube, but in a much smaller volume

PINGU-I Physics

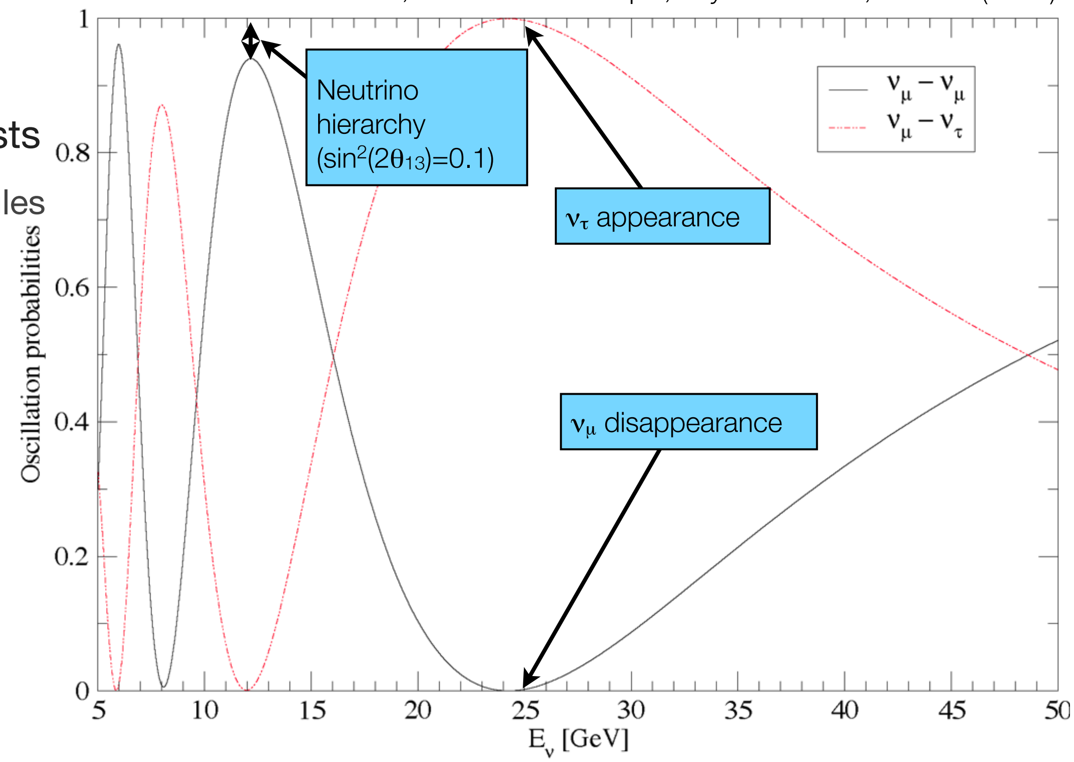
- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - will help pin down $(\Delta m_{23})^2$
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate 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 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

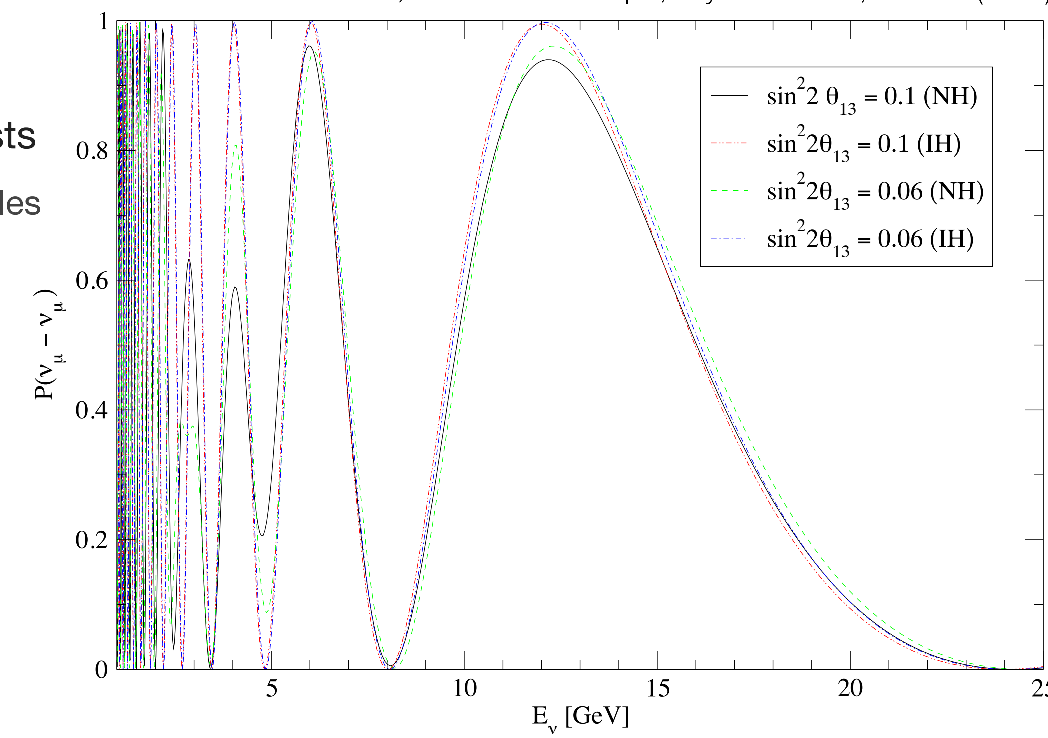
Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)



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

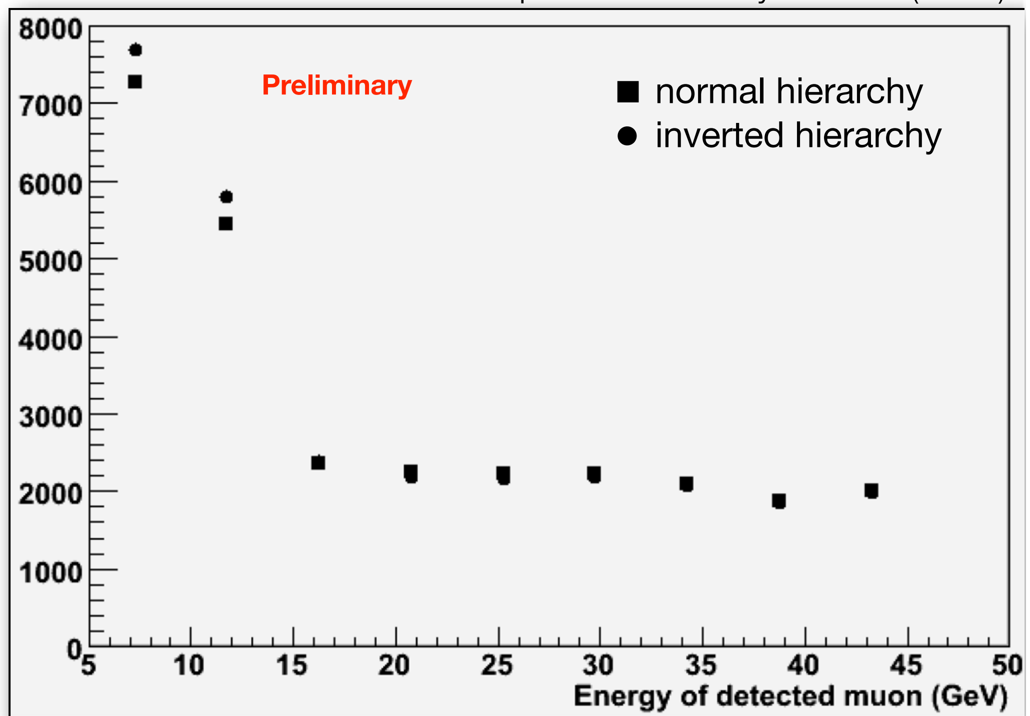
Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)



PINGU-I Physics

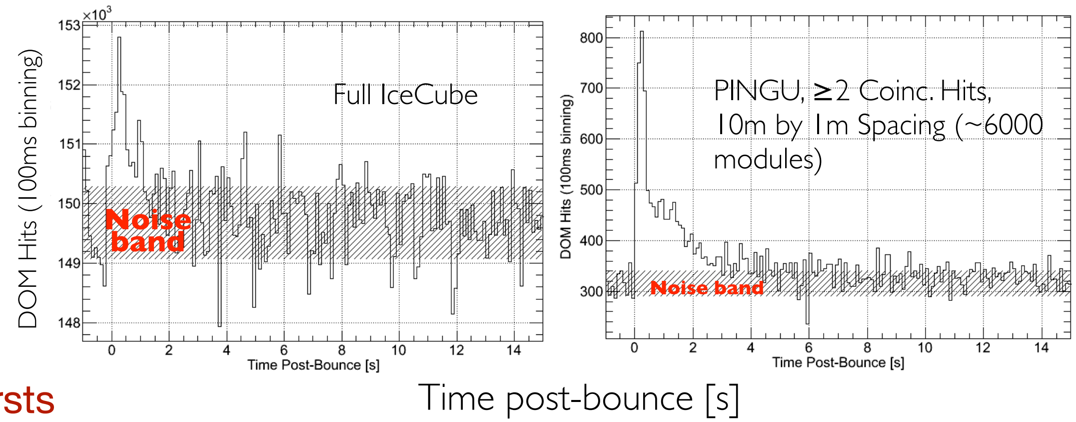
- Probe lower mass WIMPs
- Gain sensitivity to second oscillation peak/trough
  - will help pin down $(\Delta m_{23})^2$
  - enhanced sensitivity to neutrino mass hierarchy
- Gain increased sensitivity to supernova neutrino bursts
  - Extension of current search for coherent increase in singles rate 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
- Initiate an extensive calibration program
- Pathfinder technological R&D for SuperPINGU

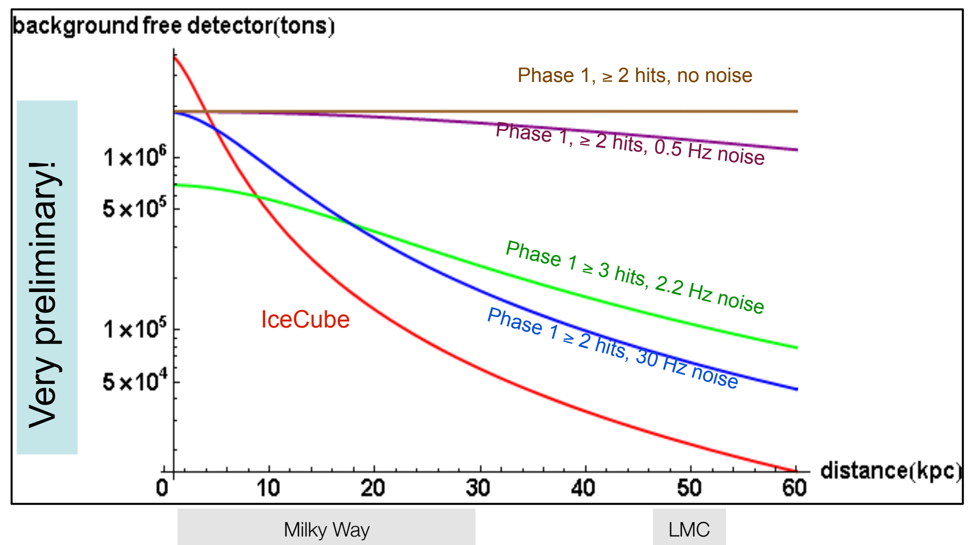
DeepCore Feasibility Studies (2008)



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
- Initiate an extensive calibration program
- Pathfinder technological R&D for SuperPINGU

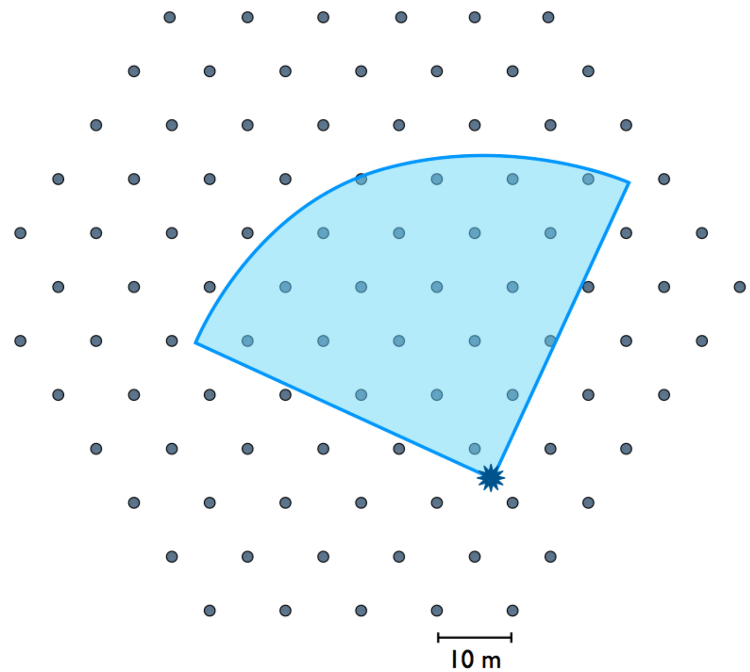


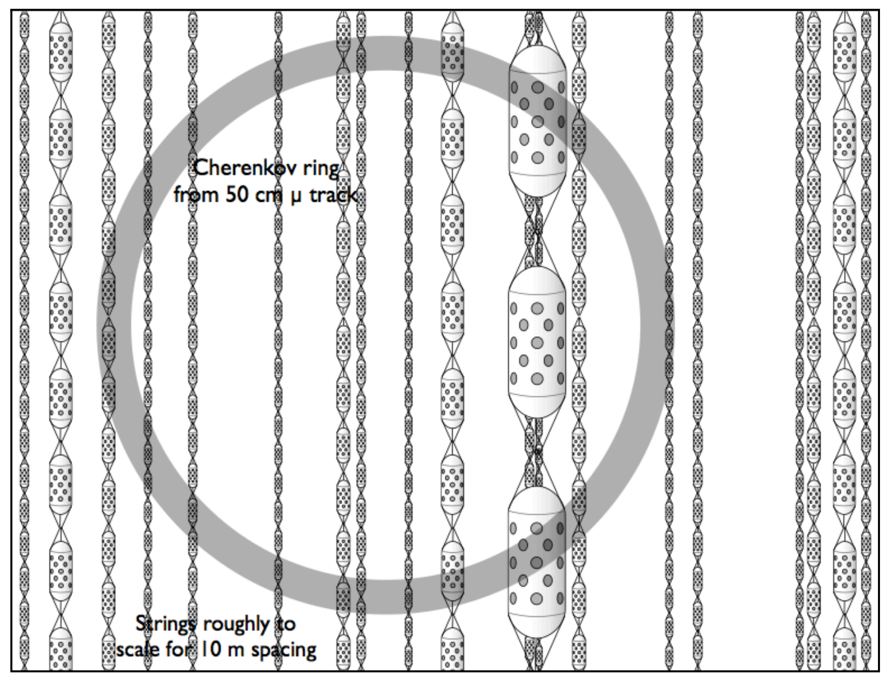


Equivalent size of a background free detector for beginning 0.38 s of **Lawrence Livermore** model, 1 m DOM and 10 m string distance, 18 strings (~6,000 DOMs) (figures from Lutz Koepke/Mainz)

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





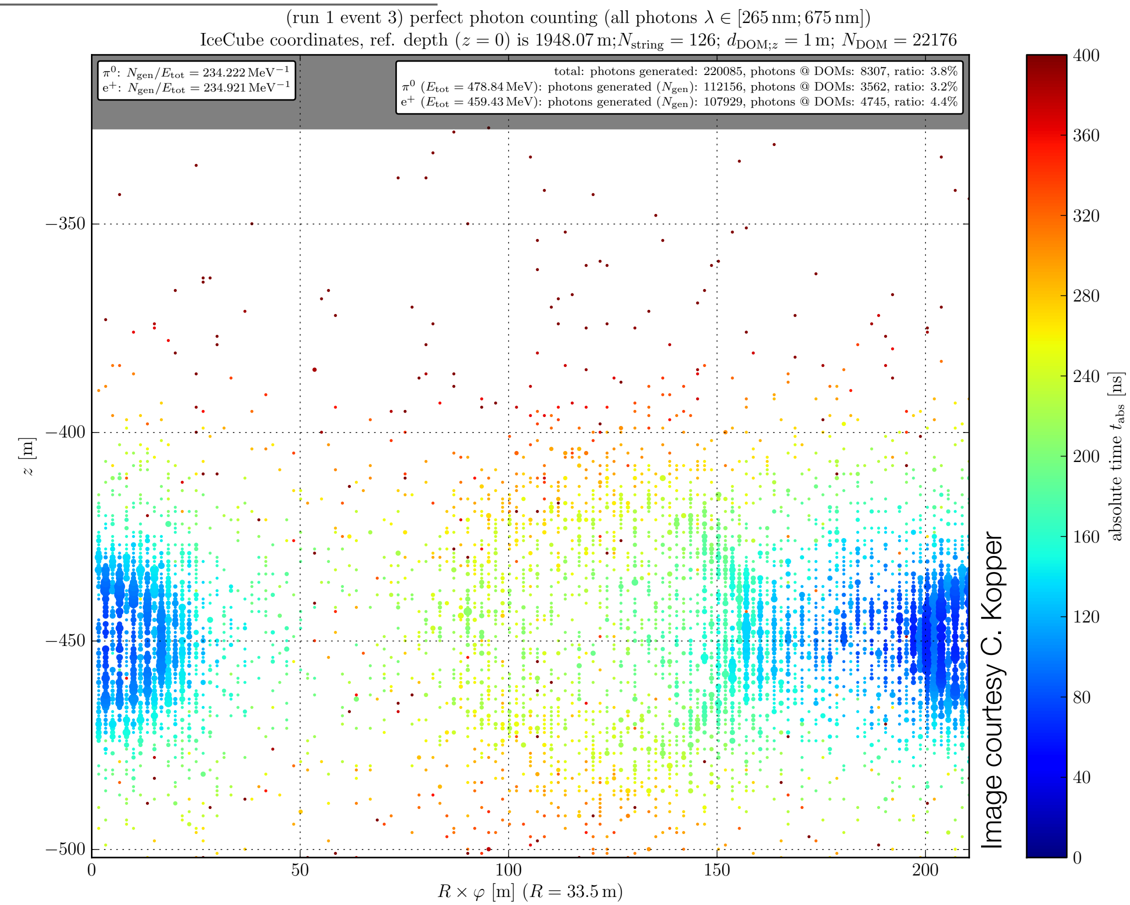
SuperPINGU Physics

- 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

SuperPINGU Proton Decay

Courtesy E. Resconi

- For fiducial volume of 1.5 MT ($5x10^{35}$ protons) with 10 MeV energy threshold
- $\tau_p \sim 10^{35}$-10^{36} yr for p → $\pi^0 + e^+$ 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



- First simulations underway. Above-strawman geometry (~750MT 15% photocathode coverage)
- ~240 photons per MeV deposited energy. 4-5% photons detected

SuperPINGU SuperNovae

- With a large-scale detector, O(5MT), designed for proton decay, you essentially confer sensitivity out to O(10 Mpc) and assure 1 supernova-per-year sensitivity.
  - 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,...)

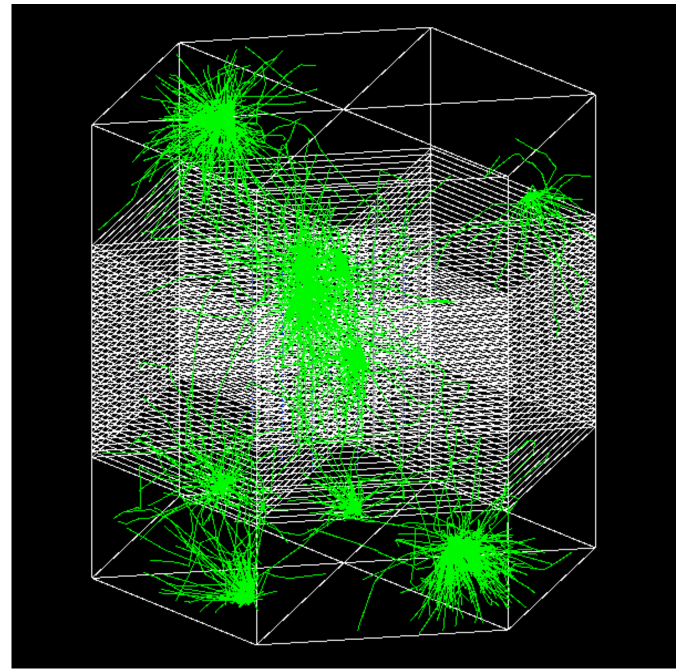


Figure: Lukas Schulte/Mainz

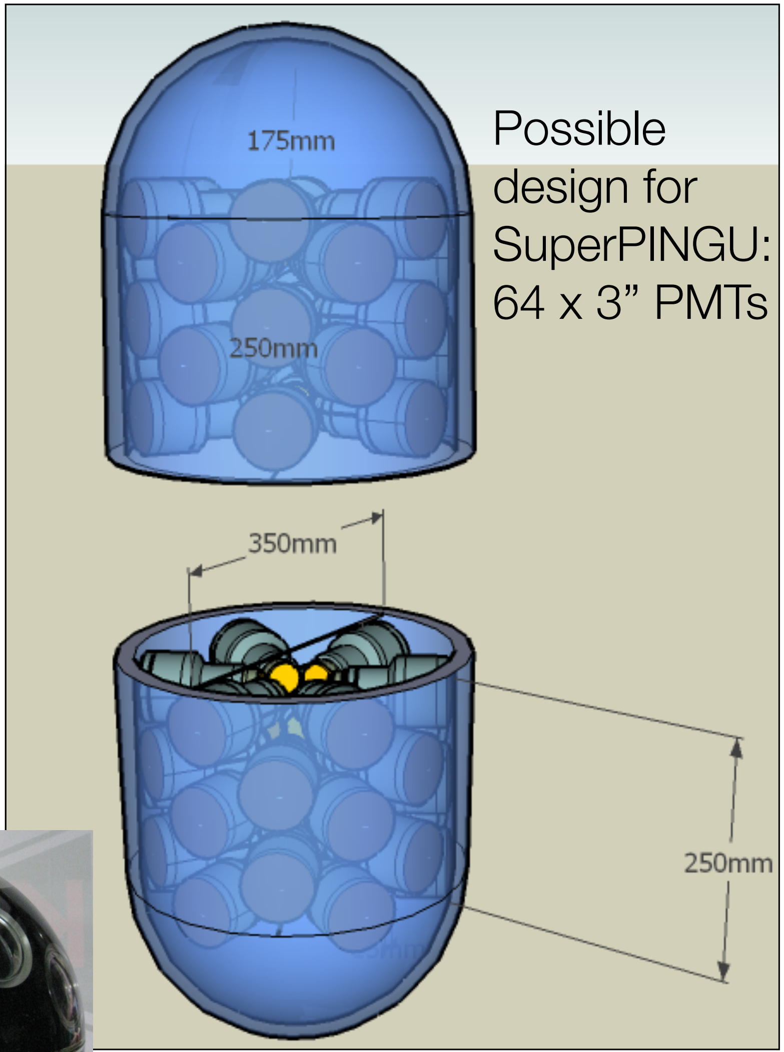
Geant4: γ's from SN ν's

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 >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



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

March 2011
First PINGU workshop - NIKHEF

Fall 2011
Complete simulation feasibility studies for 18 string detector with threshold <=1GeV. Targeted Physics: WIMPs, neutrino oscillations, supernovae
Letter of Intent

Spring 2012
Complete 1st DC analyses. Establish R&D plans as part of phase I
Submit 20 string Proposals

Summer 2012
Complete simulation feasibility studies

Fall 2012
R&D proposals to Agencies

Winter 2014/15
Begin deploying phase A

Winter 2015/16
Finish deploying Phase A including R&D strings

Spring/Fall 2016
Submit proposals to Agencies

Winter 2018/19
Start deployment phase B

2021

PINGU-I

SuperPINGU