



IceCube - DeepCore - PINGU

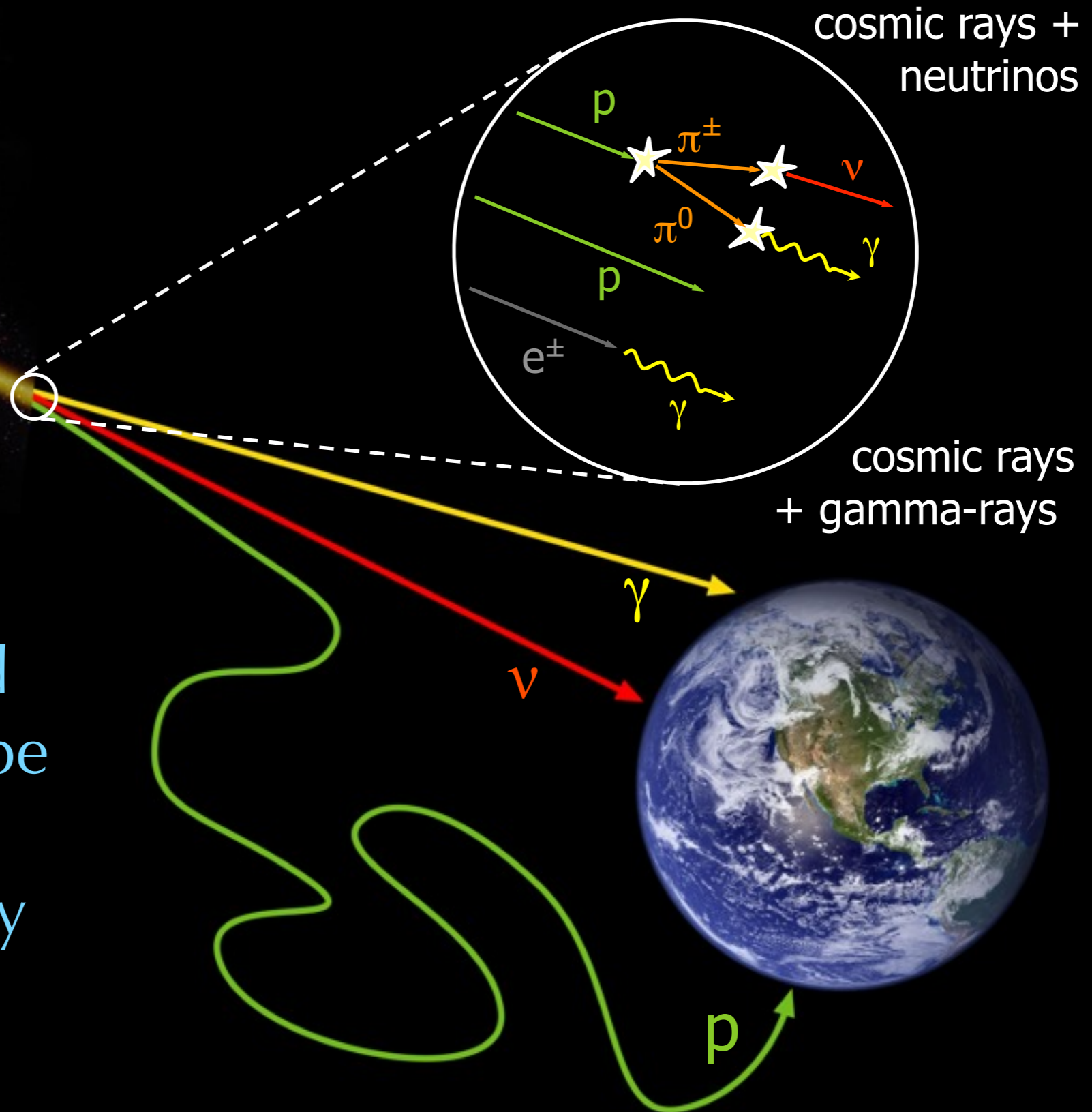
D. Jason Koskinen
Penn State

- IceCube astrophysical neutrino physics is alive and well
- DeepCore is an IceCube infill deployed to enhance sensitivity to neutrinos from ~ 10 GeV to ~ 300 GeV
 - Dark Matter
 - Neutrino Oscillations
- DeepCore is a multi-megaton scale neutrino detector at tens of GeV, which is situated inside a gigaton sized “veto”
- Proposed phased extensions
 - Phase 1 (PINGU) - Down to ~ 1 GeV
 - Phase 2 (BeyondDC) - Down to ~ 15 MeV

IceCube Classic

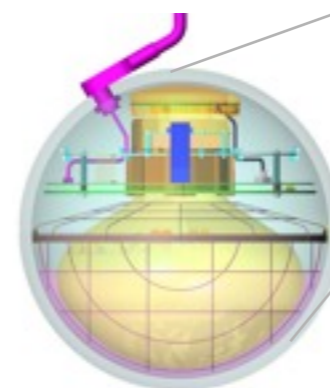
- Neutrinos are long distance cosmic messengers
 - Photons interact with CMB
 - Charged cosmic rays lose directionality through magnetic deflection
- The cosmic laboratory
 - Complementarity with cosmic rays
 - Astrophysical objects and Cosmic Ray acceleration, leptonic or baryonic? (GRB, SNR, PWN)

Multimessenger Astronomy

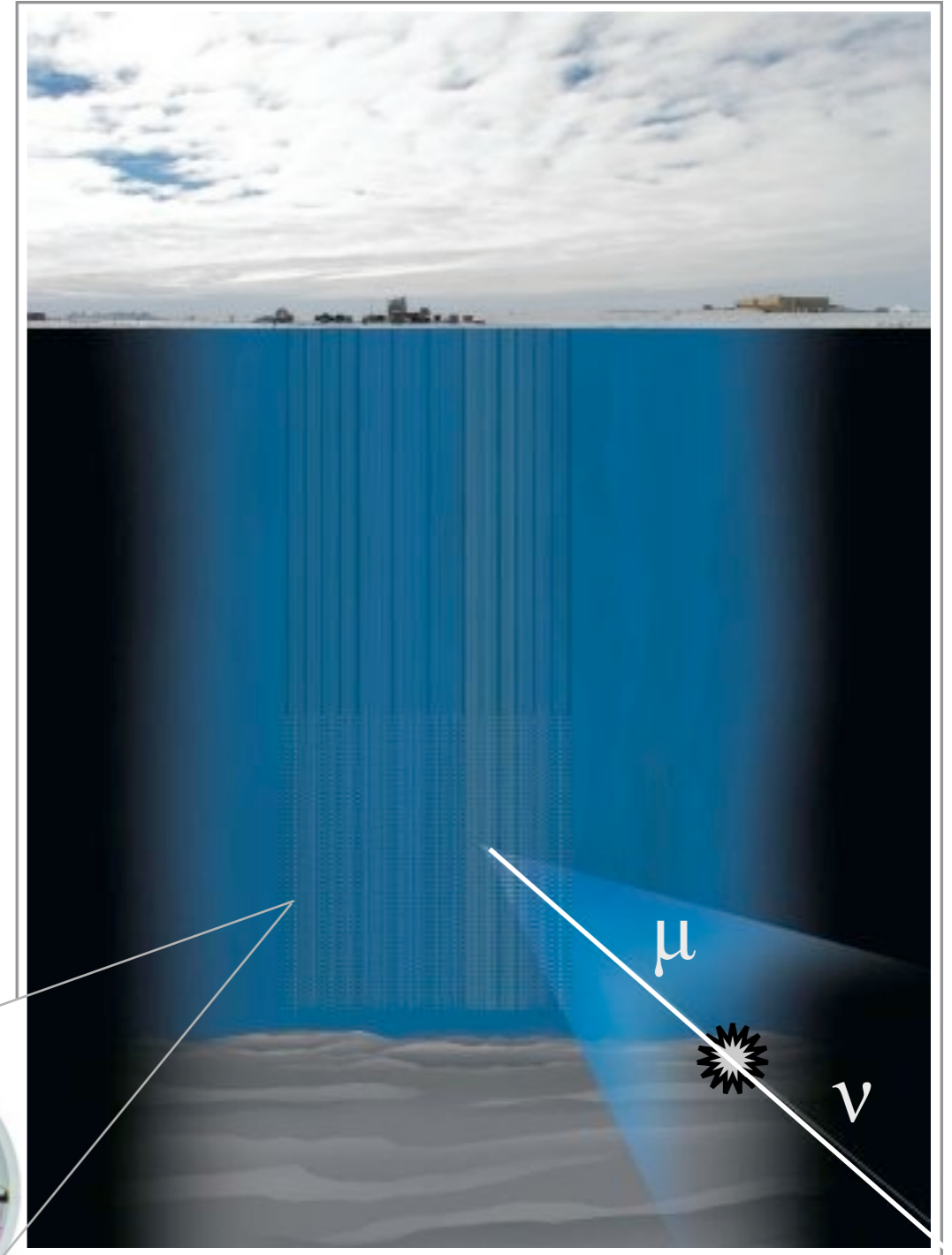


Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

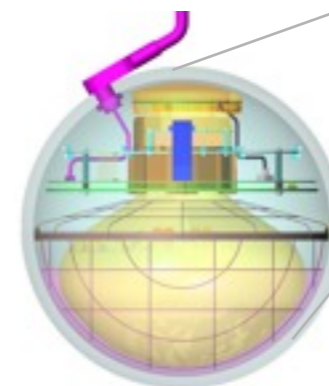
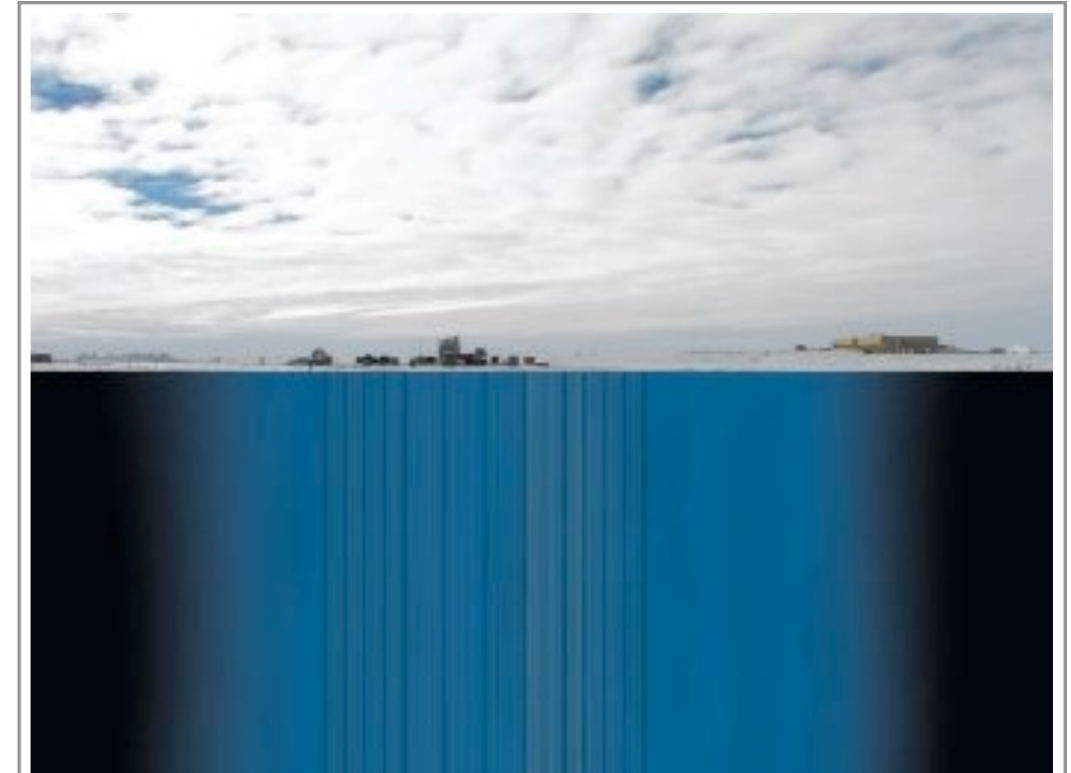
- $\sim 1\text{km}^3$ of instrumented ice
- Uses 5160 Digital Optical Modules (DOMs) across 86 strings within the ice to detect Cherenkov radiation
- 160 Cherenkov tank surface array (IceTop)
- Completed Dec. 18, 2010



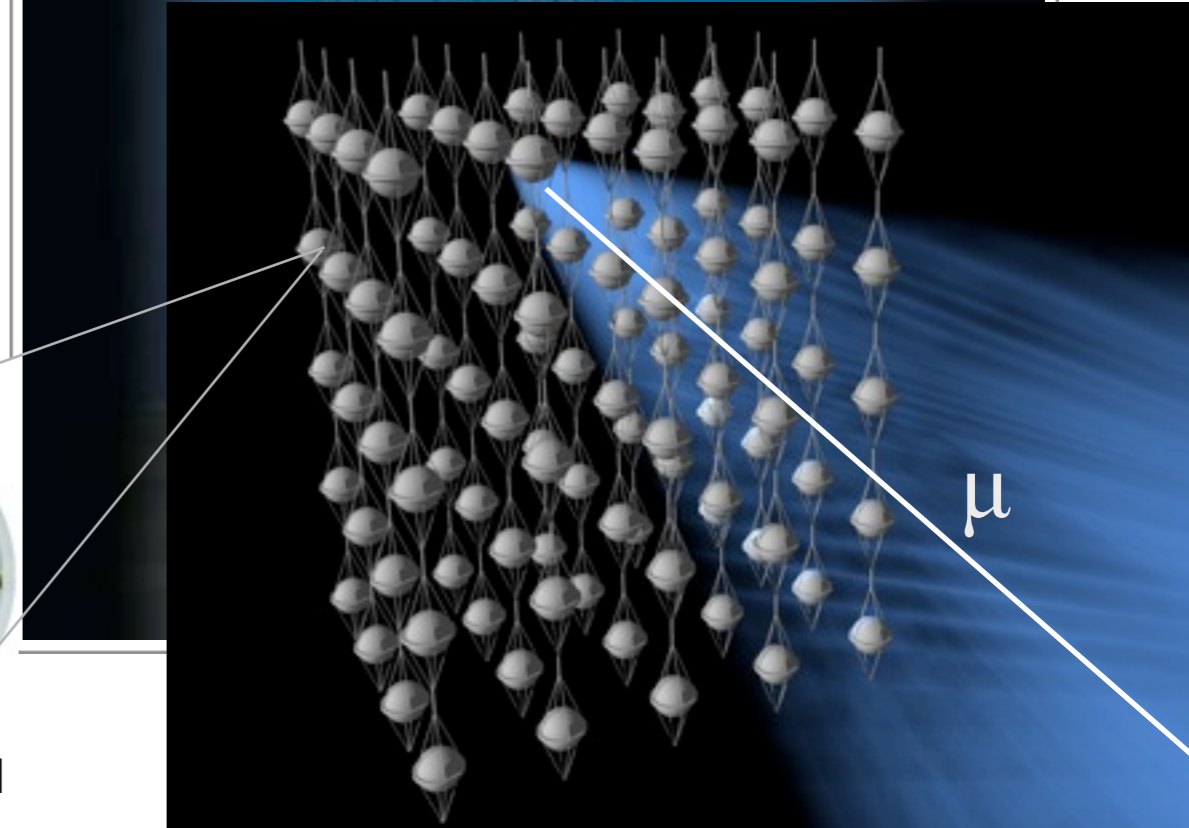
IceCube DOM

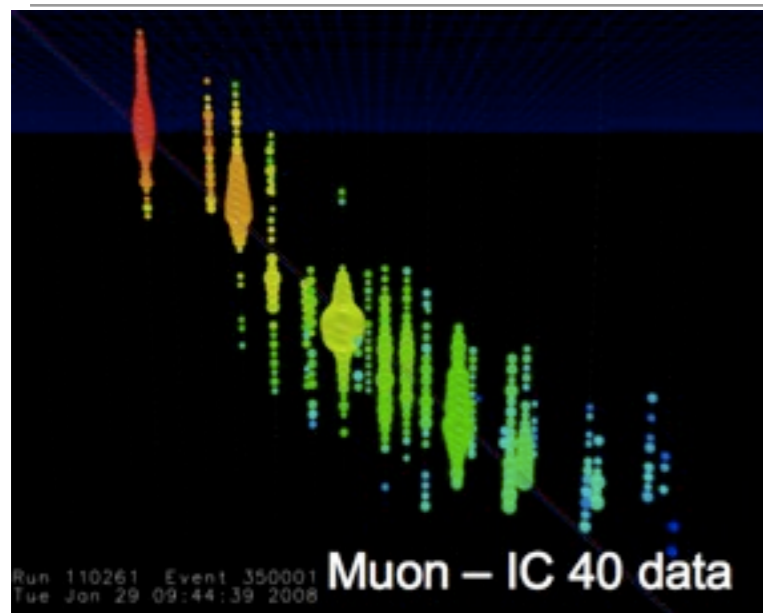


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IceCube DOM



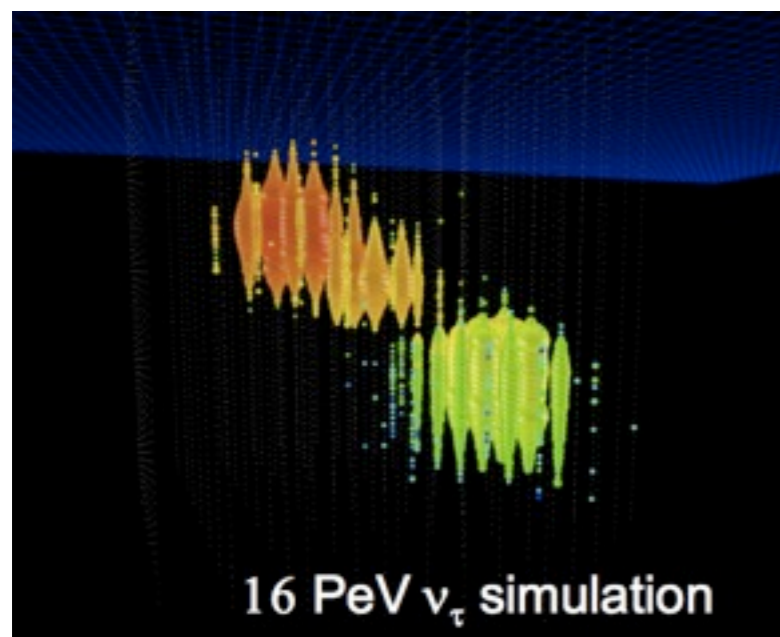
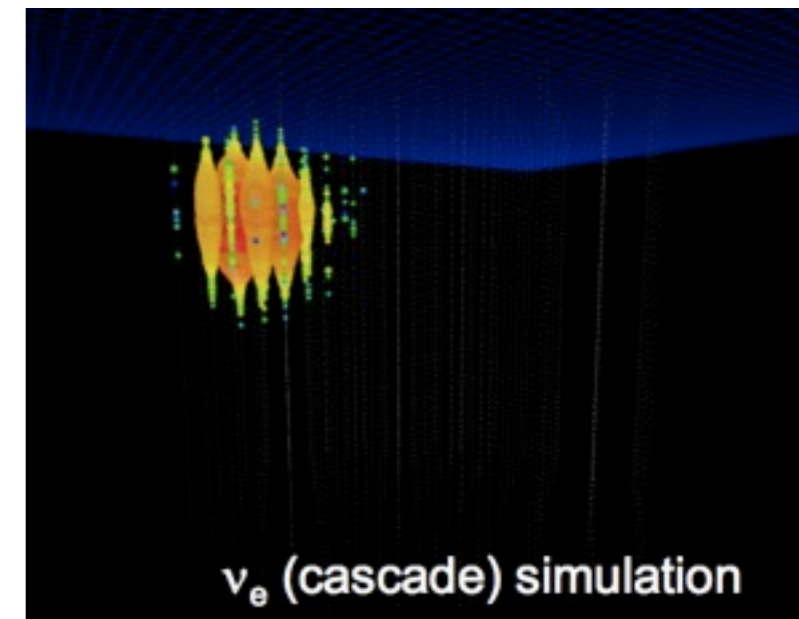


Tracks:

- through-going muons

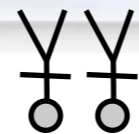
Cascades:

- Neutral current for all flavors
- Charged current for ν_e and low-E ν_τ



Composites:

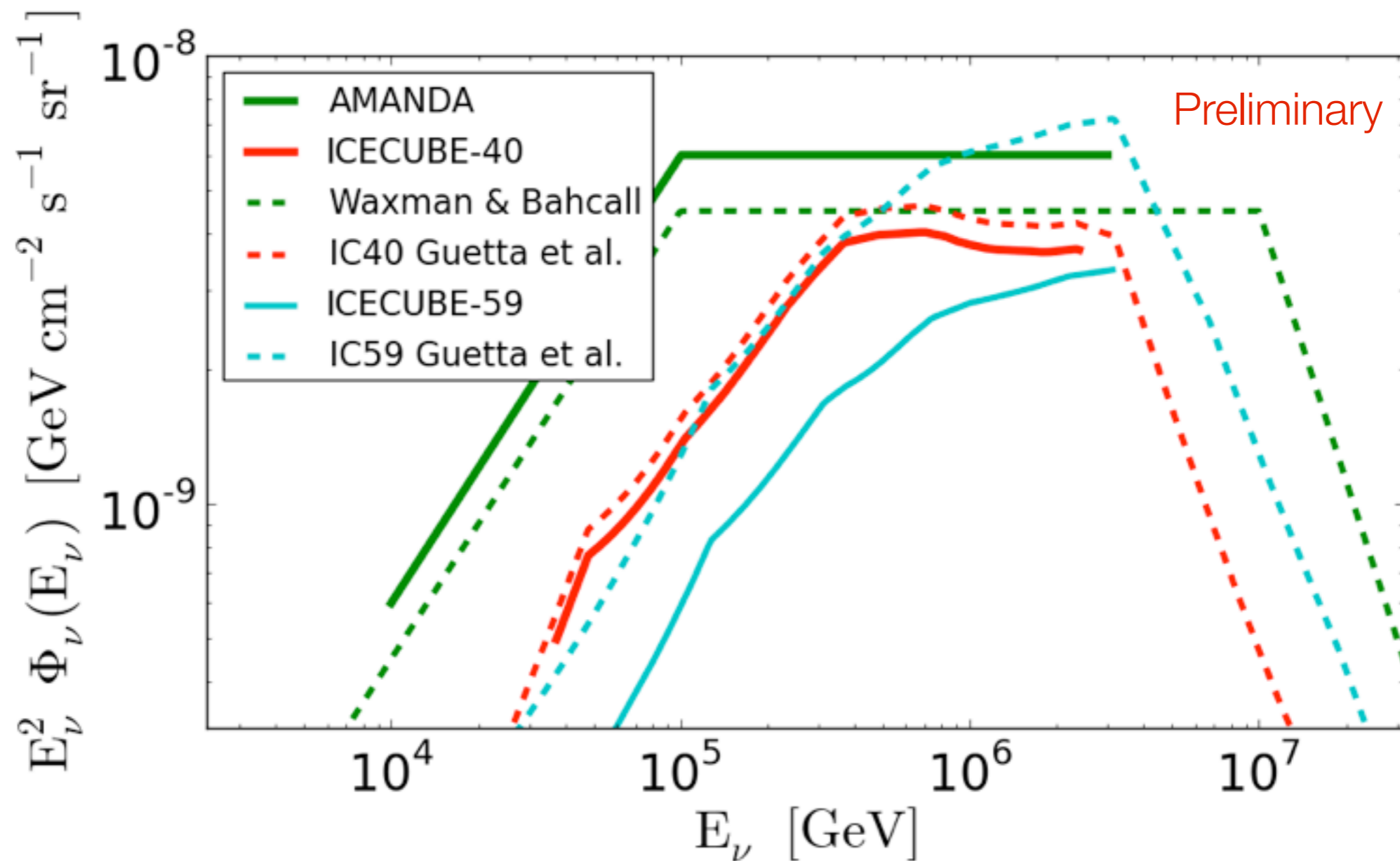
- Starting tracks
- high-E (PeV) ν_τ (Double Bangs)
- Good directional and energy resolution



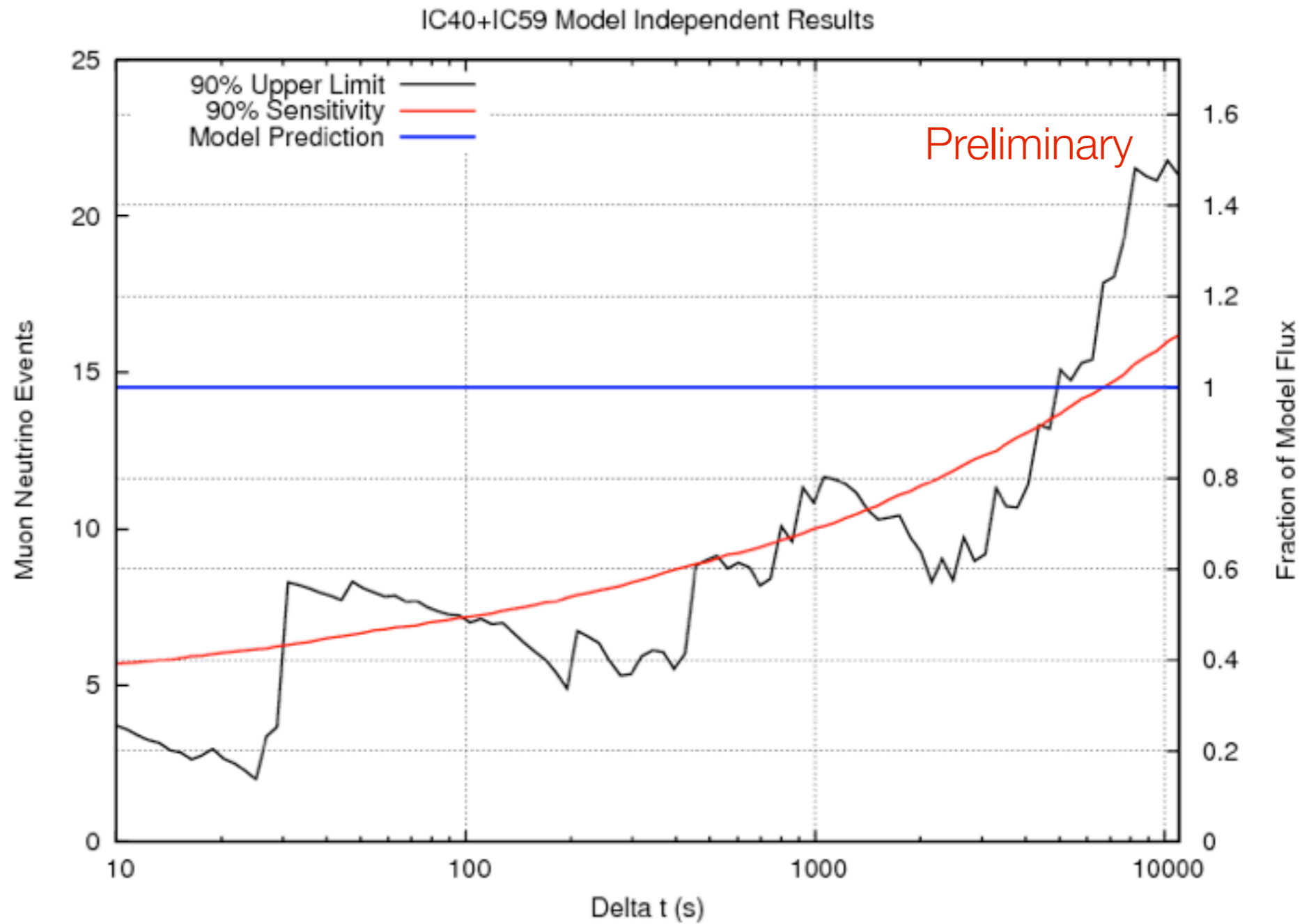
The IceCube Collaboration

36 institutions - 4 continents - ~250 Physicists

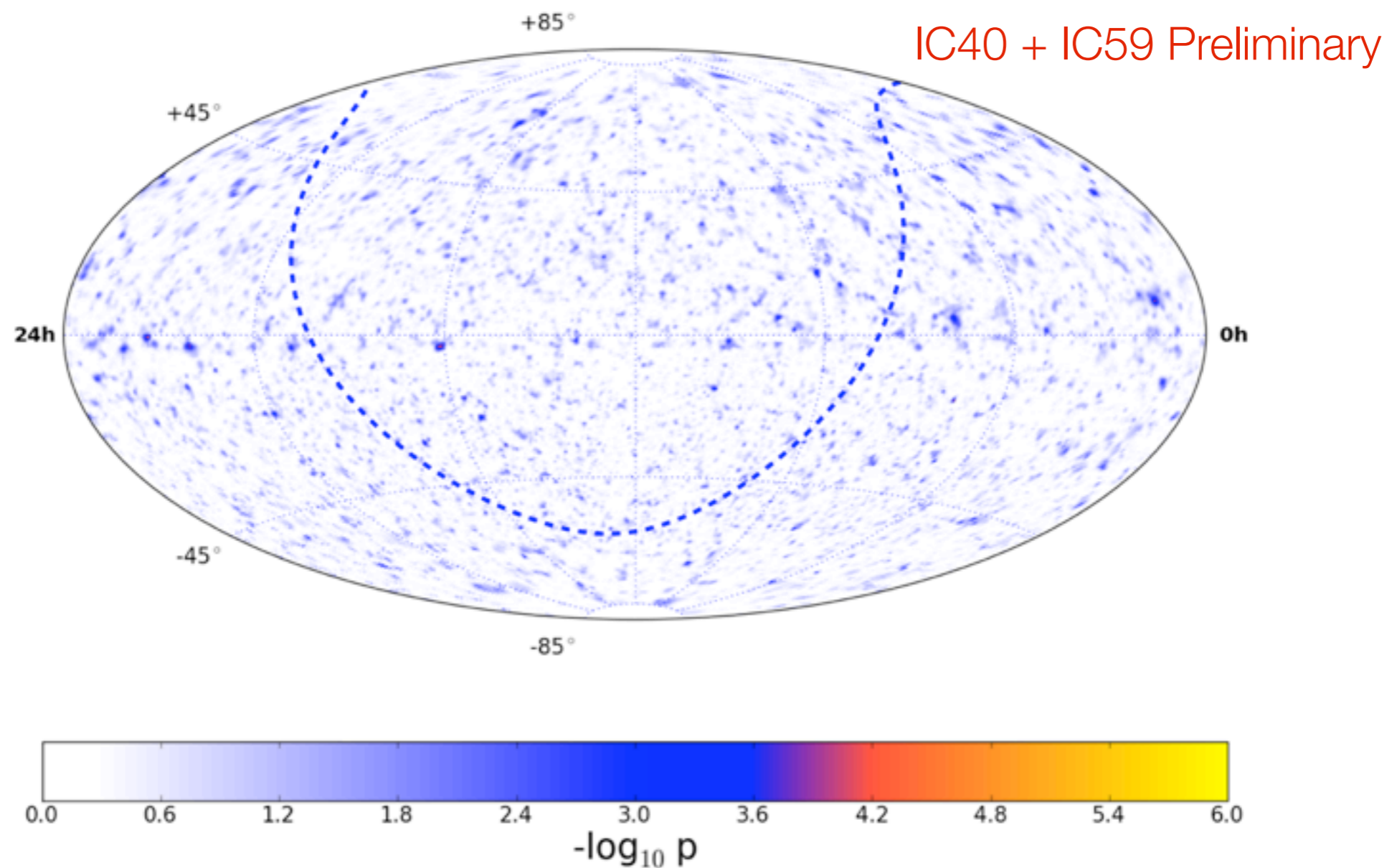
- Searches for neutrinos produced by $p+\gamma$ interactions during the primary fireball



IC40 result
arXiv:1101.1448



- Sky Map consistent with background
- Full IC86 deployment offers large increase in sensitivity



-
- IC59 Cosmic Ray Anisotropy - **arXiv:1105.2326**
 - IC40 Diffuse Flux - **arXiv:1104.5187**
 - IC40 Atmospheric Neutrino Spectrum - **arXiv:1010.3980v1**
 - Supernova 2008D - **arXiv:1101.3942**
 - IC22 Neutrino Induced Cascades - **arXiv:1101.1692**
 - Neutrino Emission Constraints on 2010 Crab Flare - **arXiv:1106.3484**

Below TeV+ Energies DeepCore



IceCube

Below TeV+ Energies DeepCore



IceCube

Below TeV+ Energies DeepCore



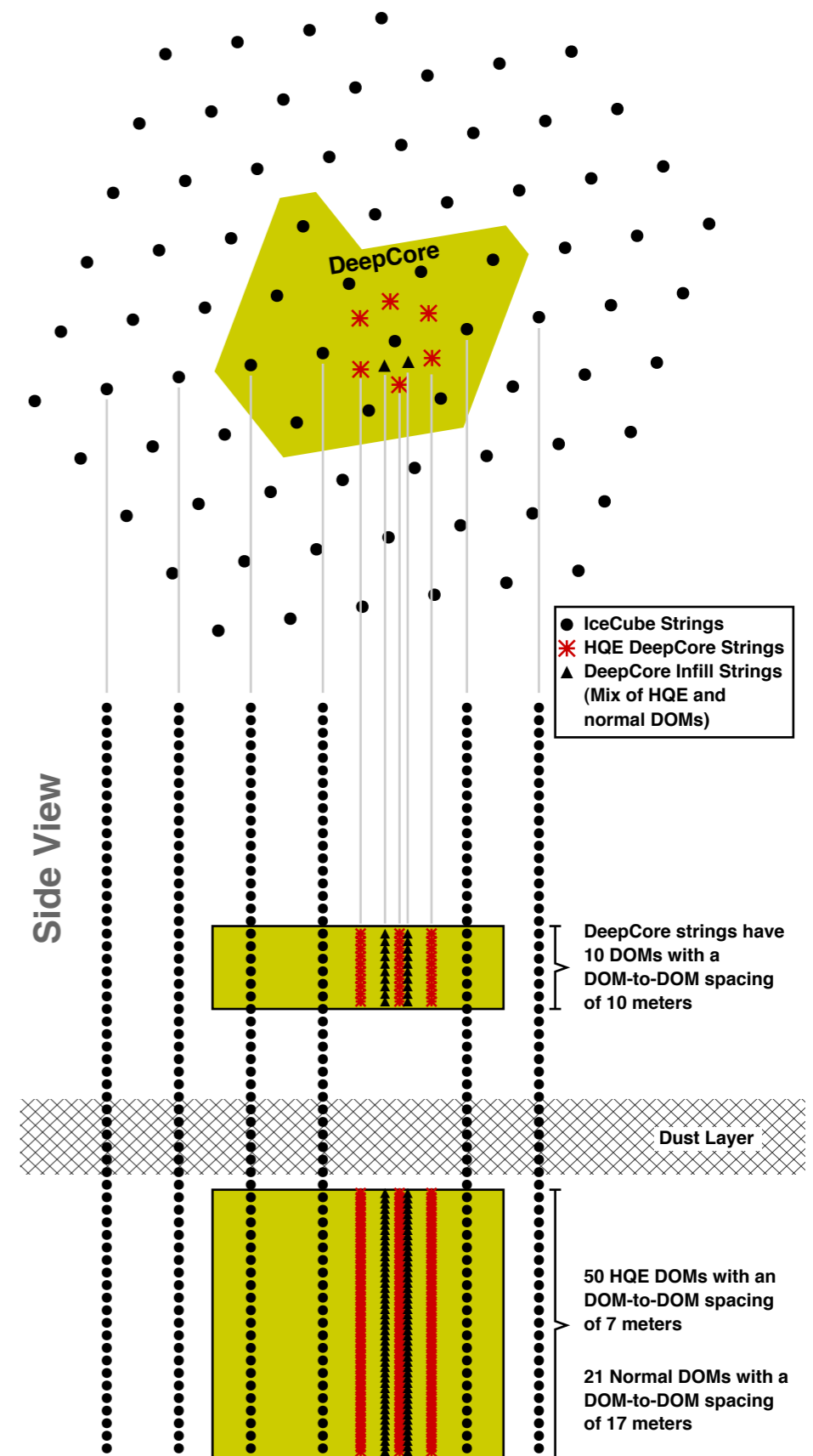
IceCube

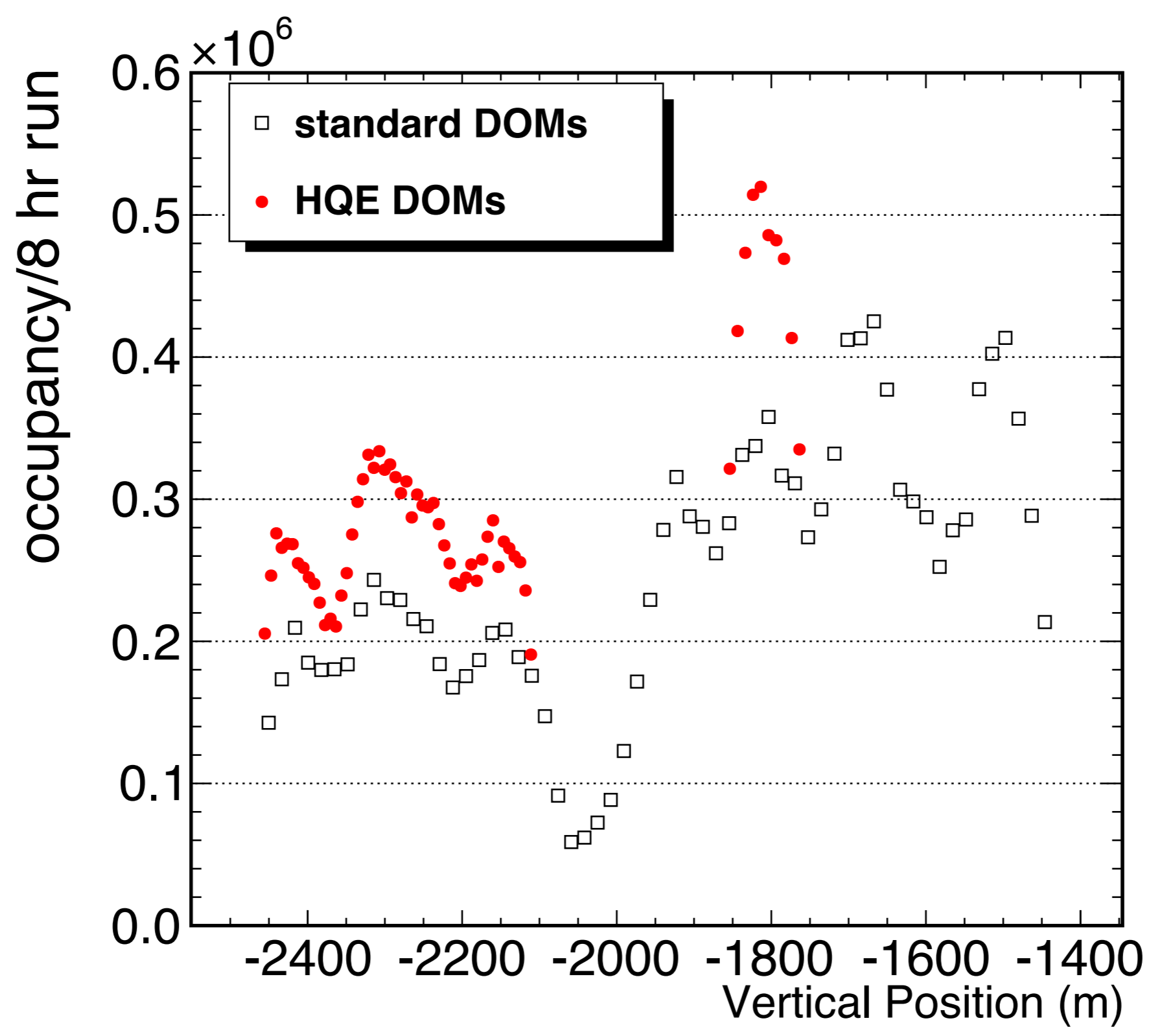


DeepCore

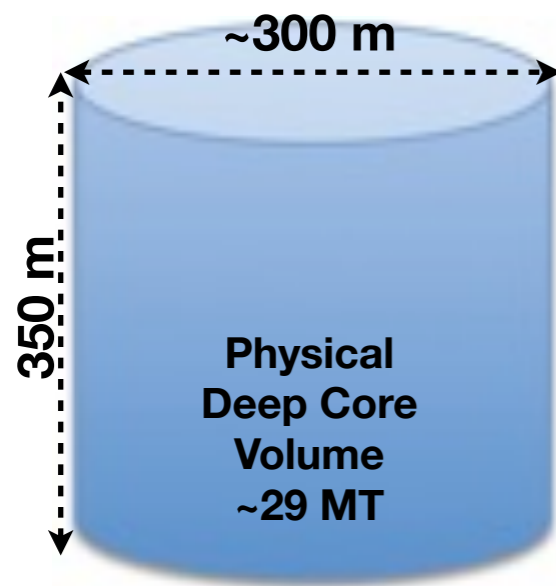
- 8 special Strings combined with 12 nearby standard IceCube Strings
- 72 m interstring spacing versus 125 m for IceCube
 - 7 m DOM spacing vs. 17 m
 - High Quantum Efficiency PMTs (35% higher QE)
- Deepest clearest ice
 - 40m scattering length
 - 140m absorption length

Overhead View

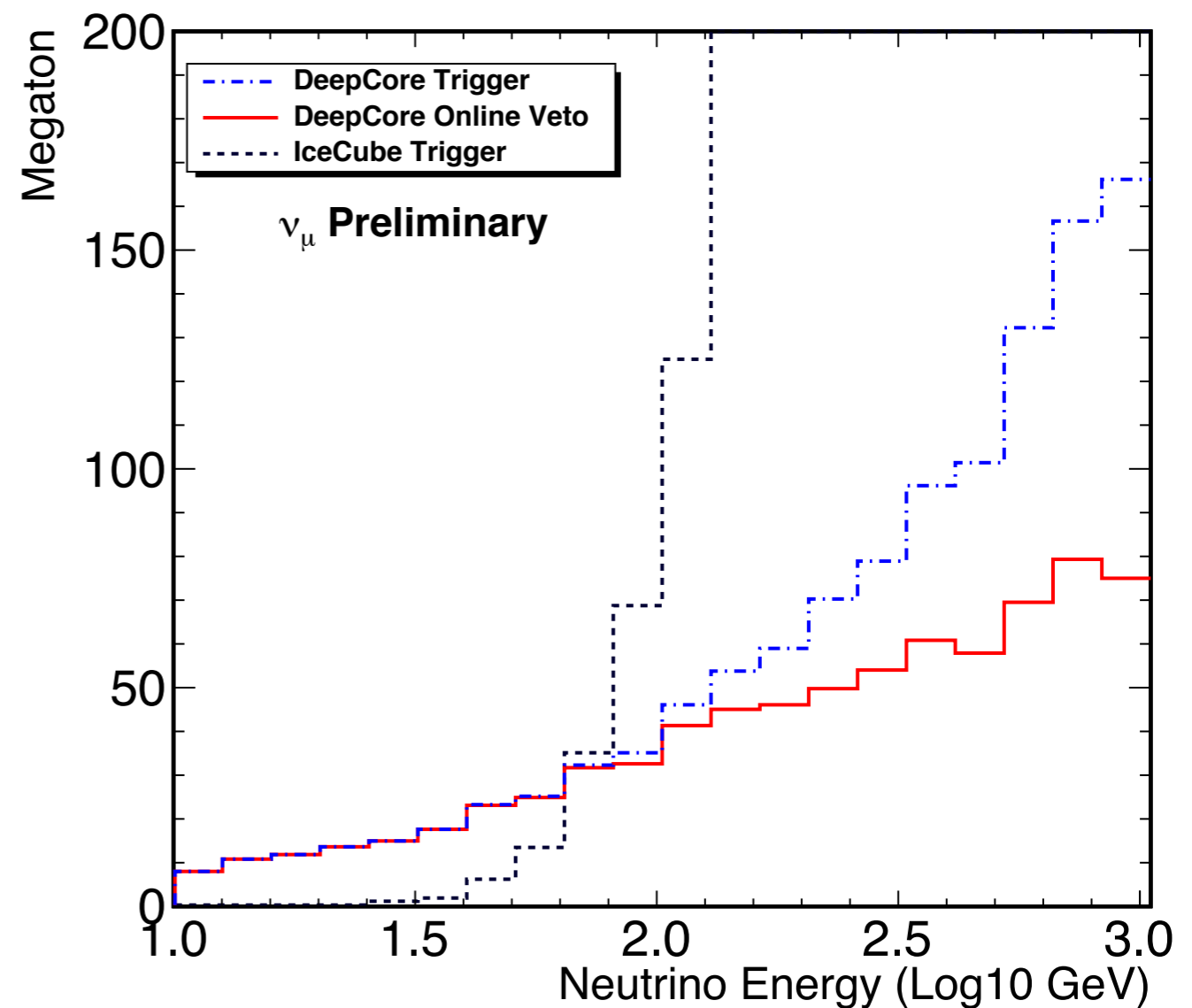




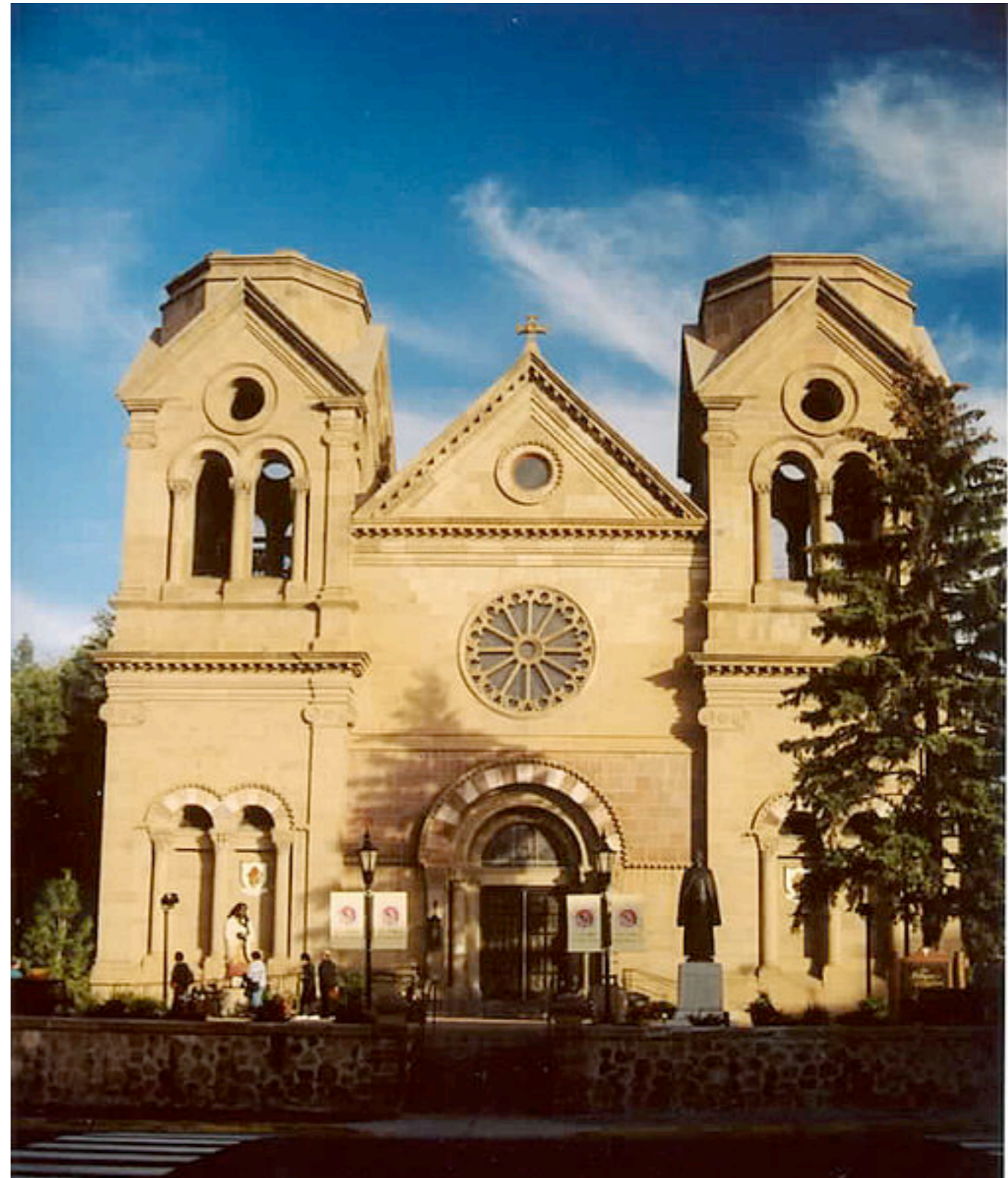
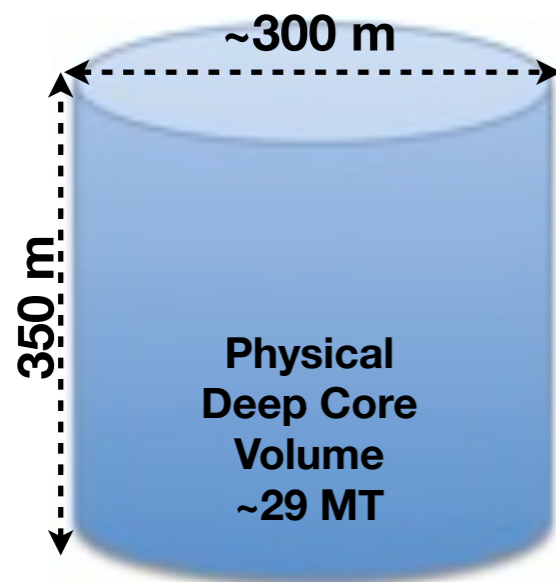
- Online Veto loosely constrains vertex to be within DeepCore volume
- Physical volume is ~28Mton



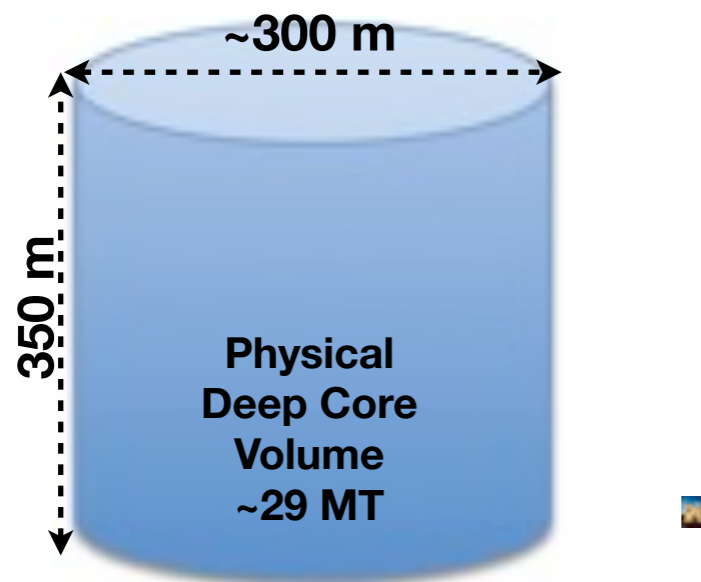
Effective volume for muons from ν_μ interacting in Deep Core



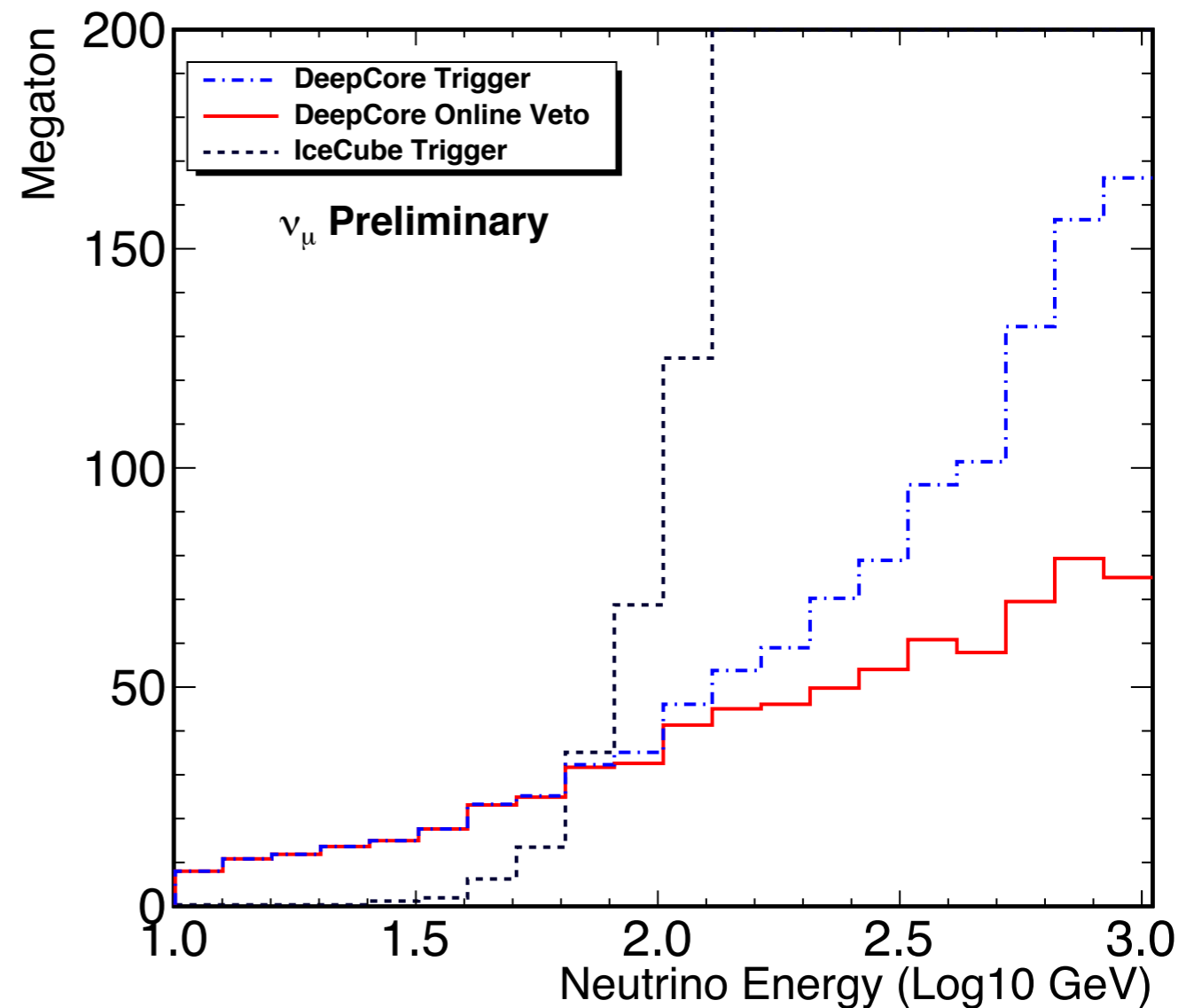
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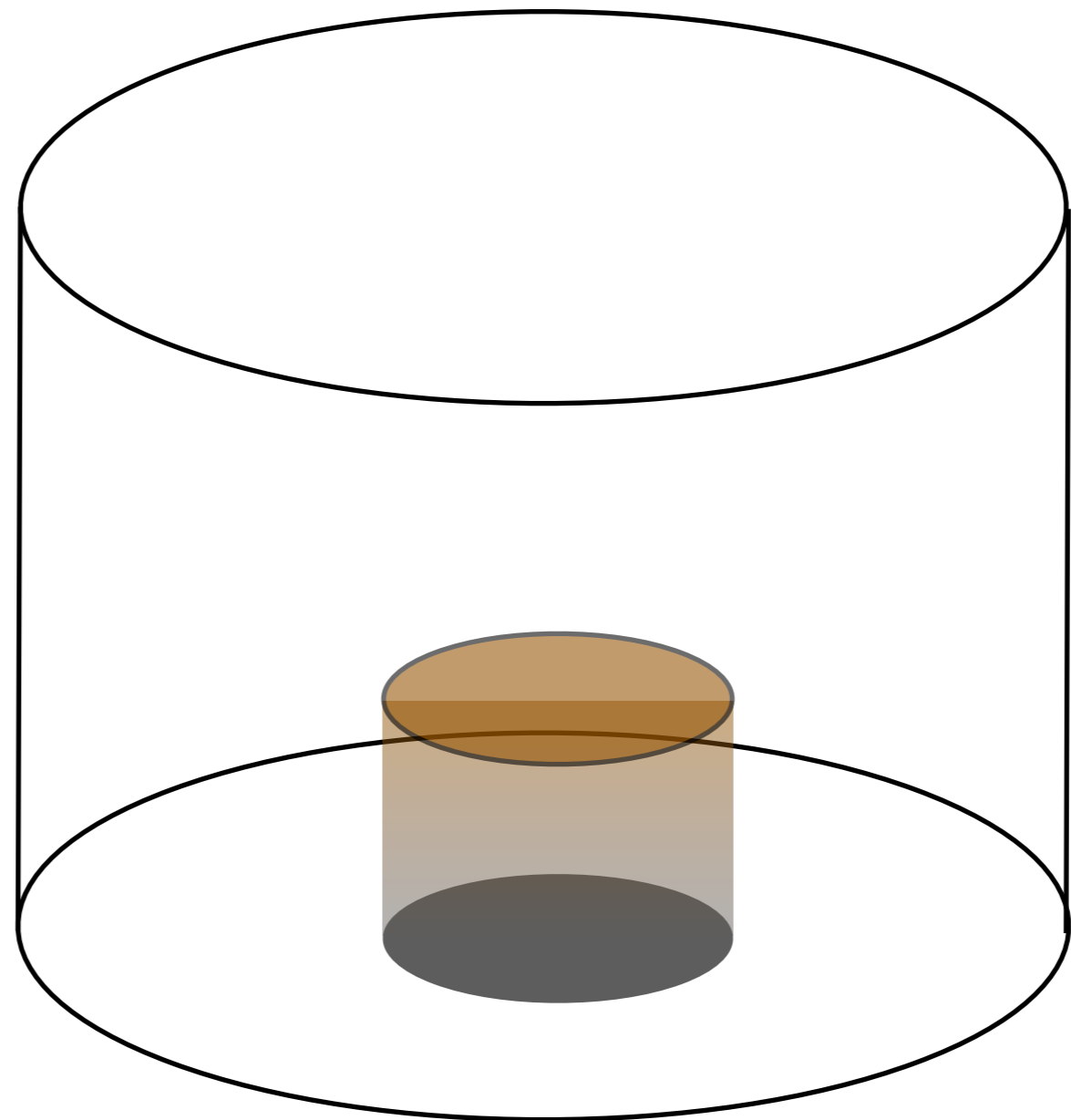


Effective volume for muons from ν_μ interacting in Deep Core



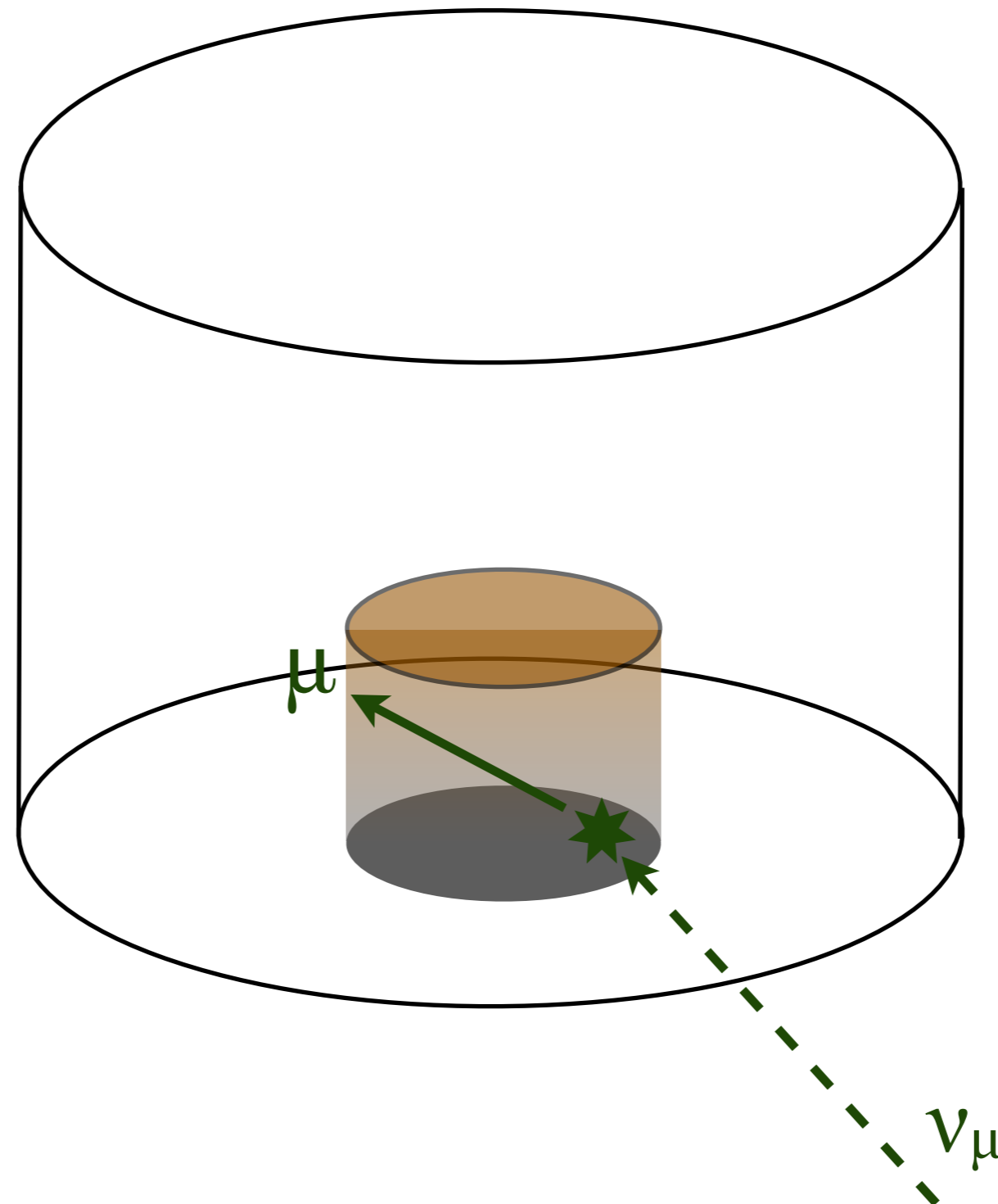
More Signal = More Bkg

- IceCube
- DeepCore
- Beyond DeepCore



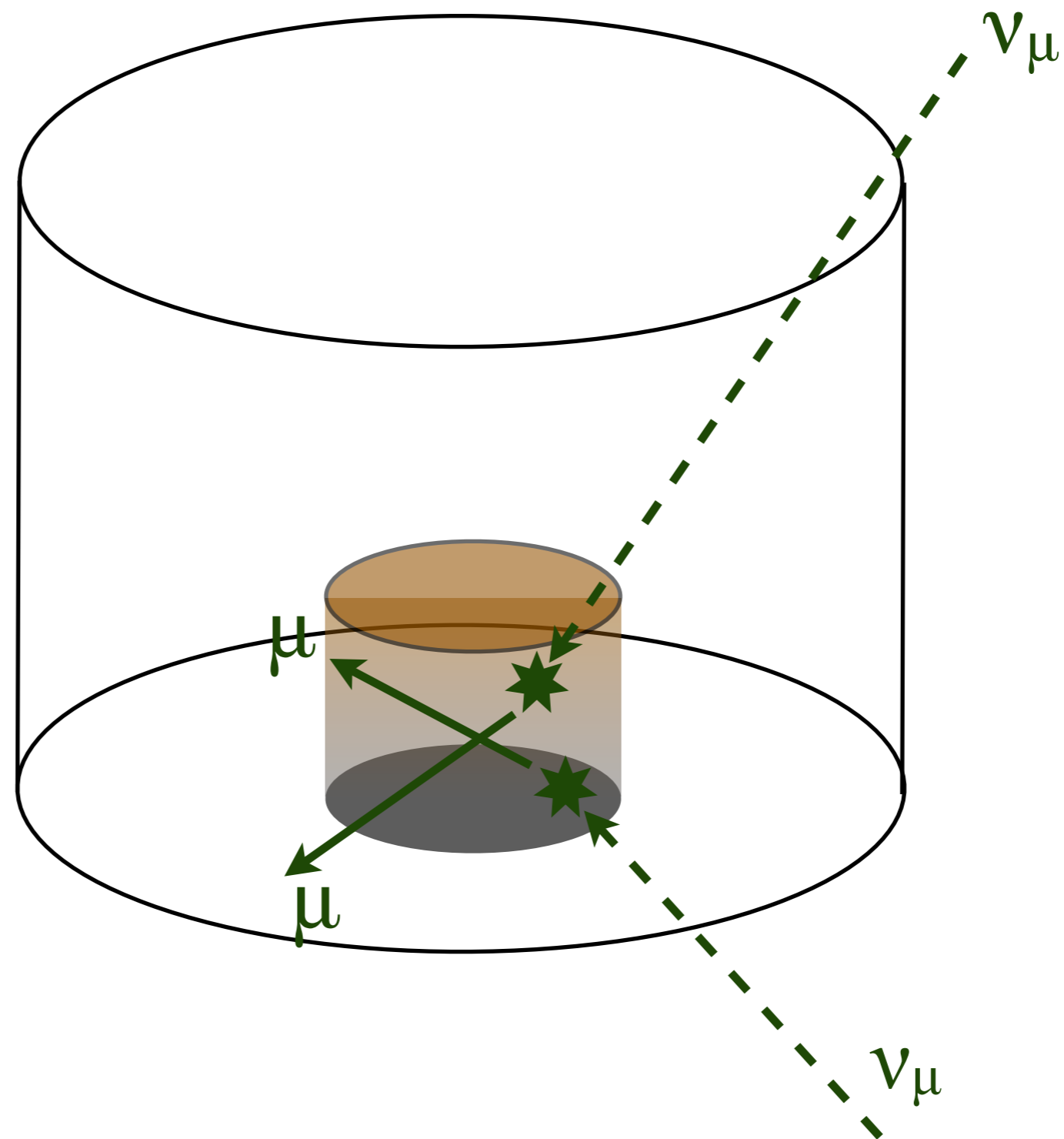
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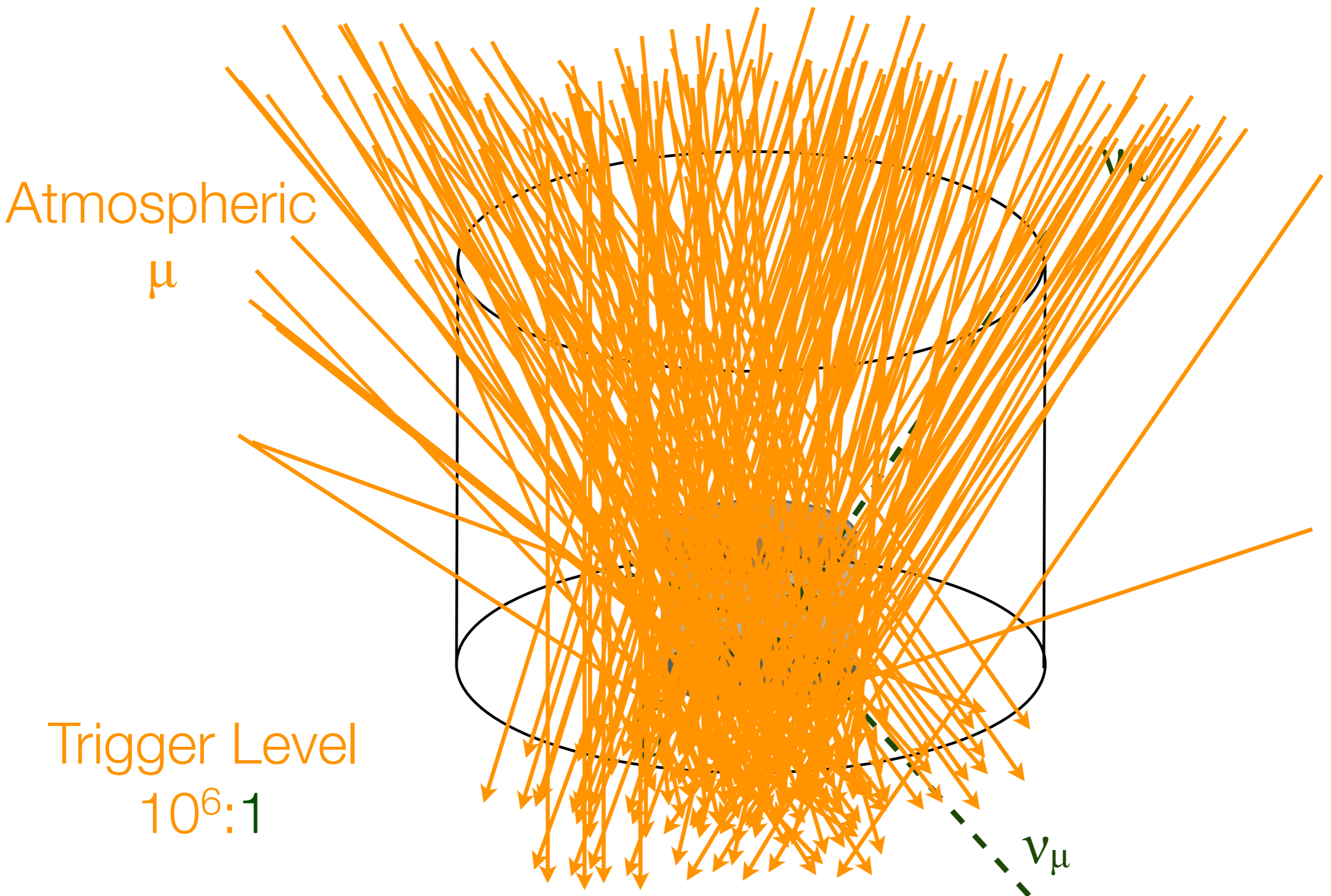
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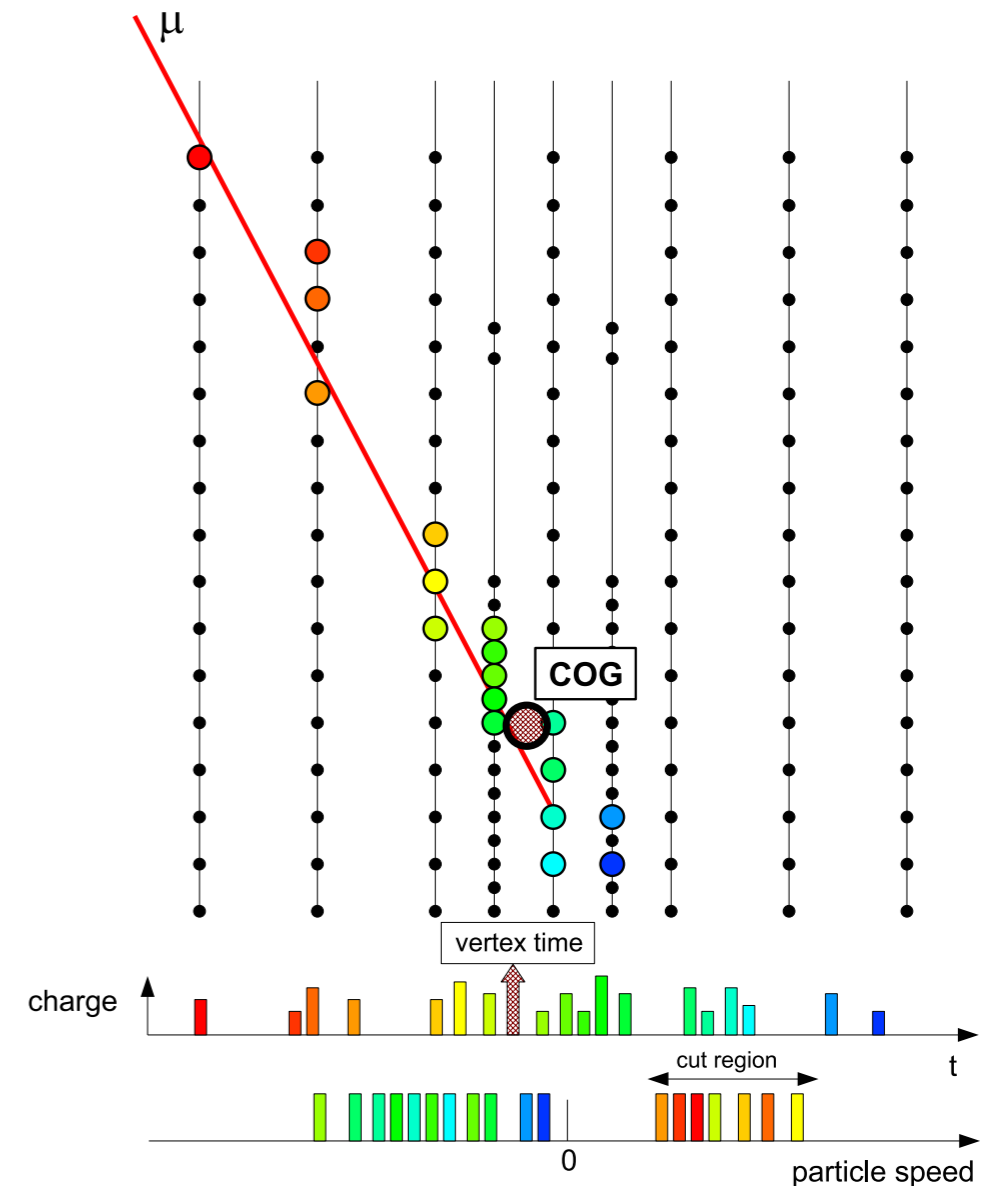


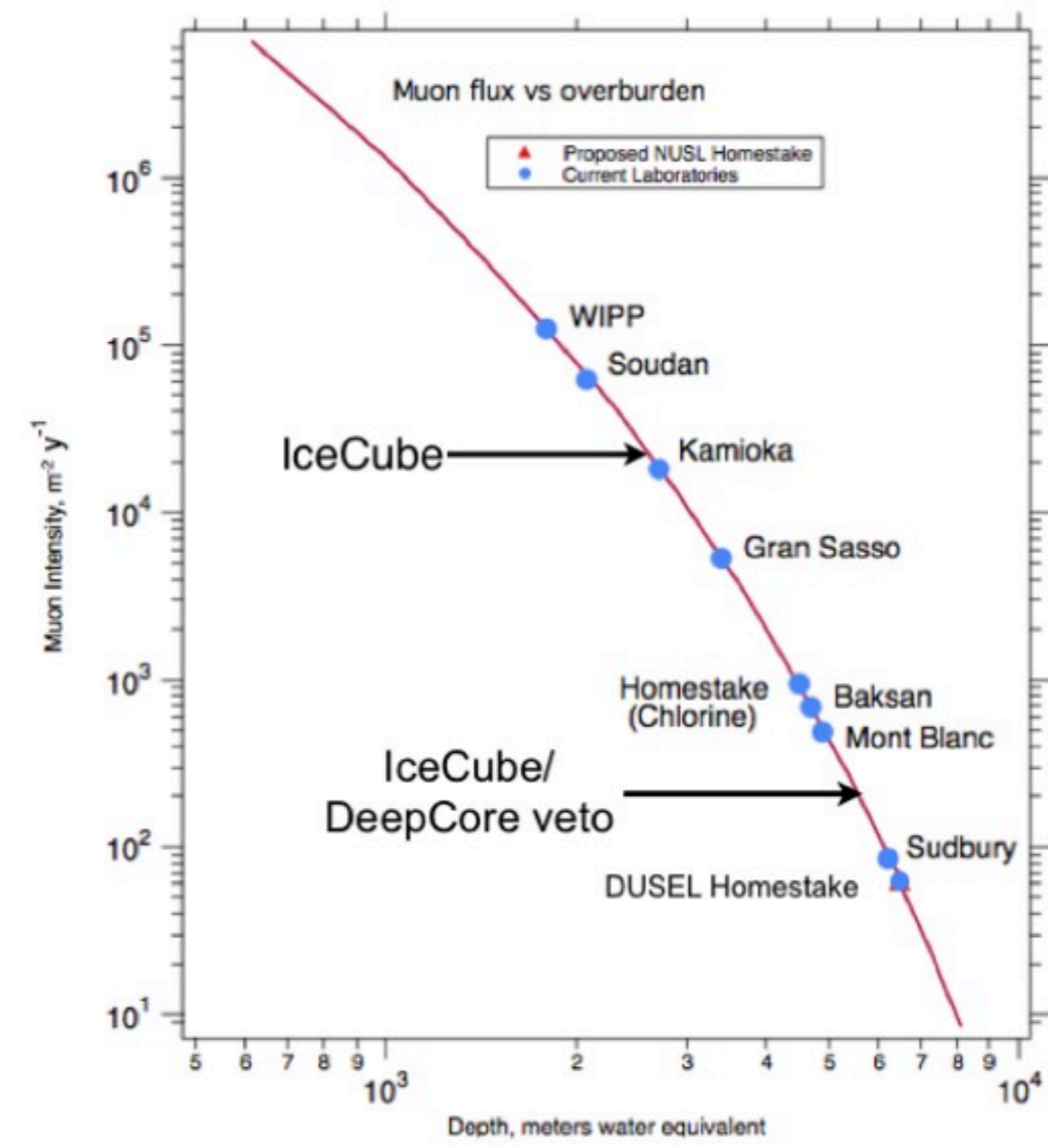
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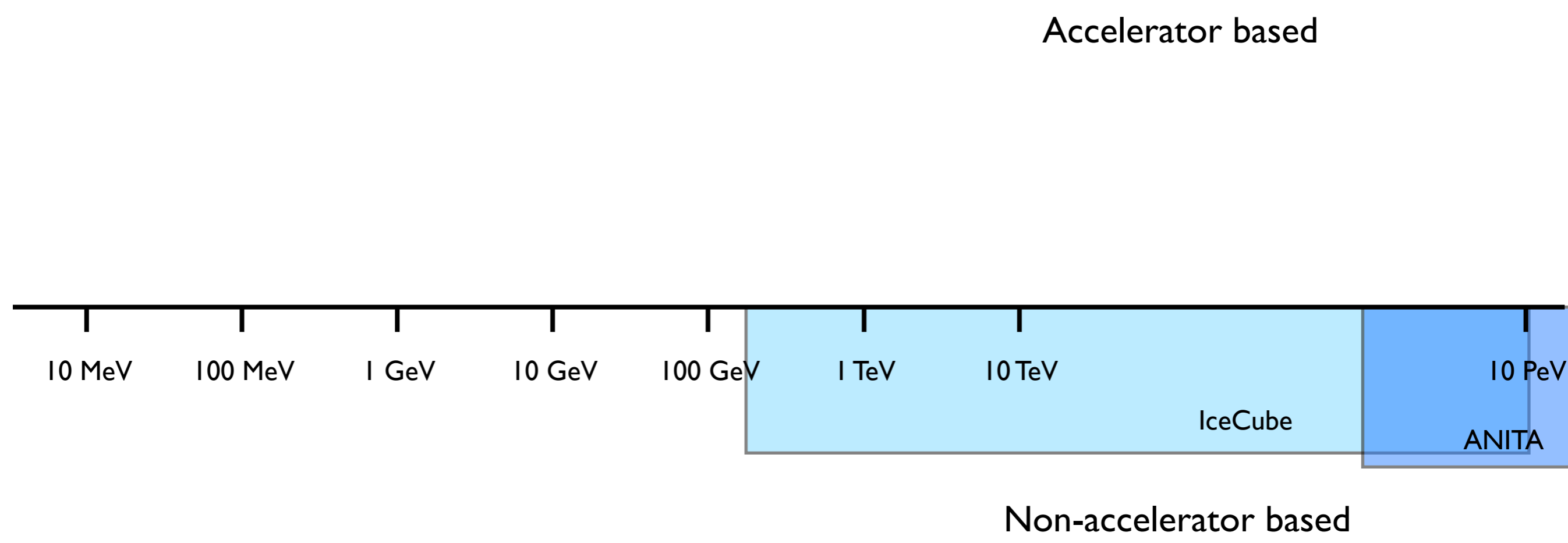
- Trigger level background to signal ratio is $10^6:1$
- DeepCore uses IceCube as an active veto to reject down-going atmospheric muons and neutrinos
 - Atmospheric muon rejection of $\sim 8 \times 10^3$ with neutrino retention of $\sim 99\%$
 - Further rejection employed offline





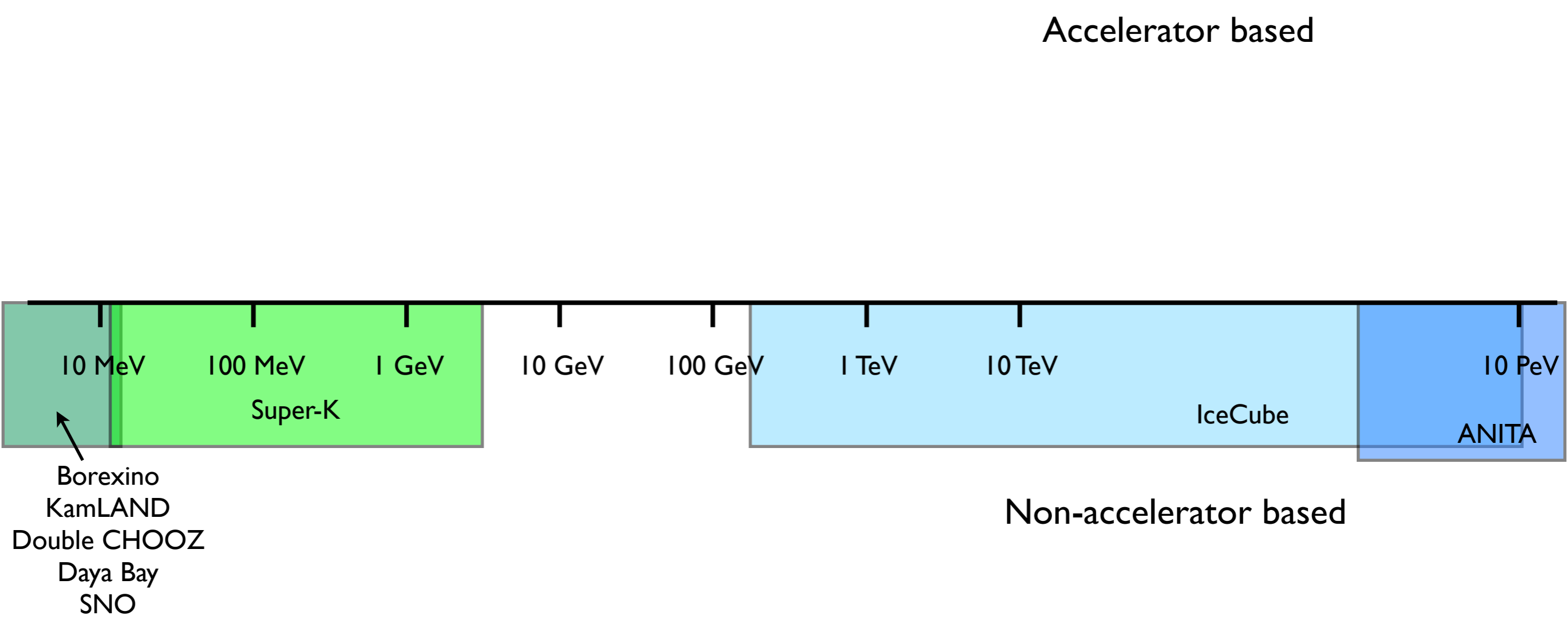
Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore



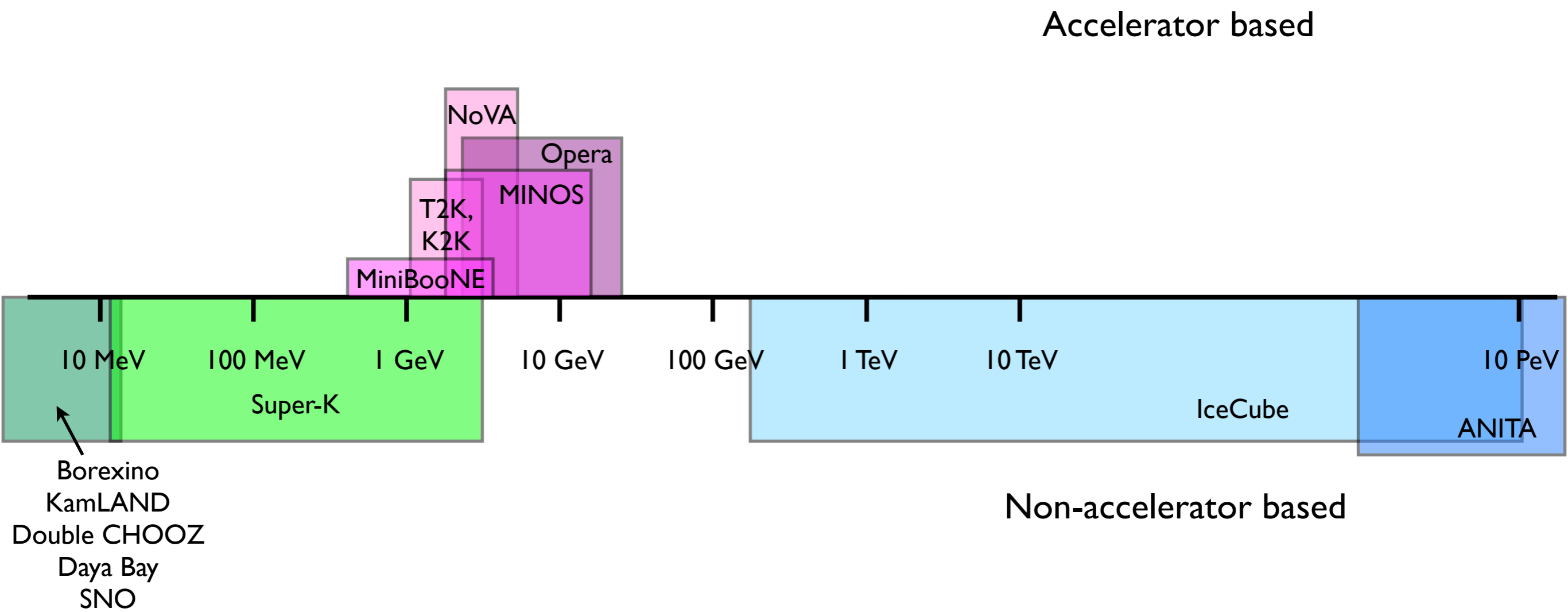
Experimental Landscape

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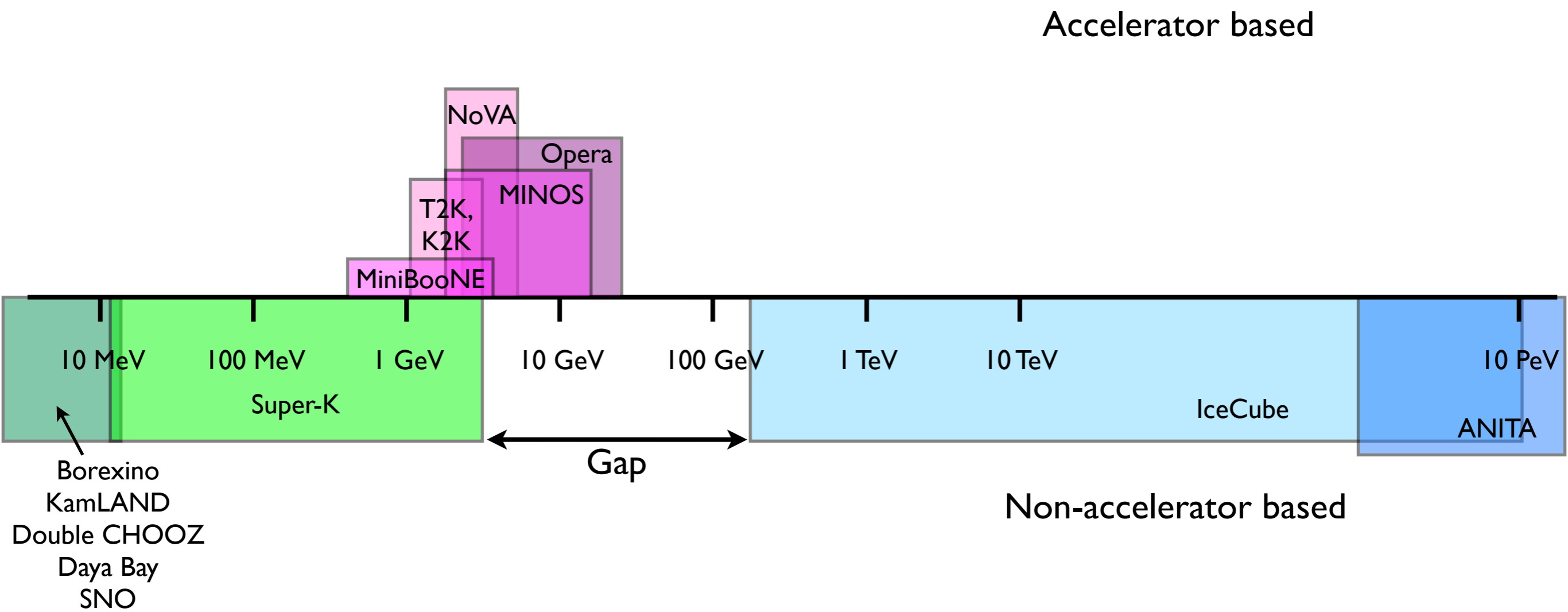
Experimental Landscape

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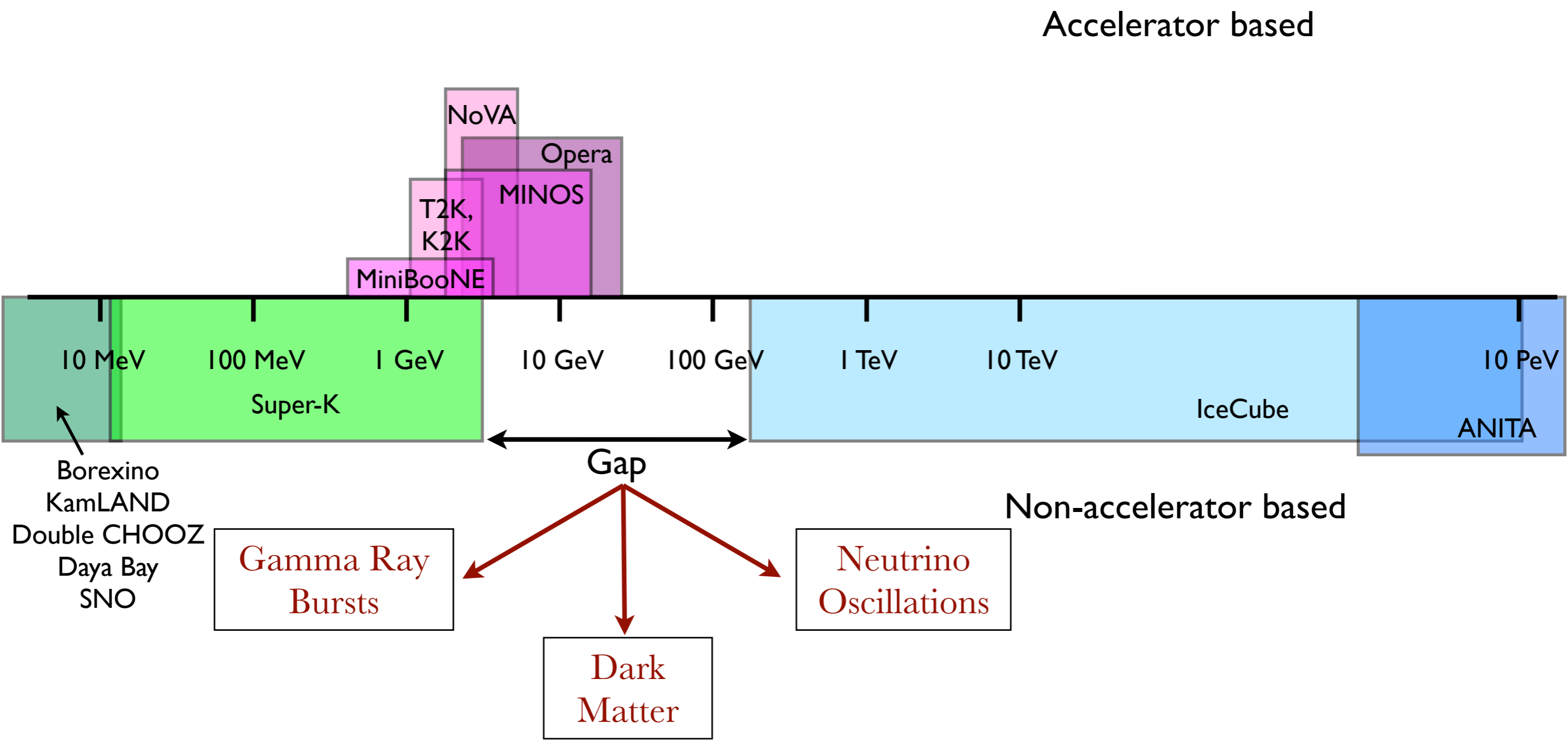
Experimental Landscape

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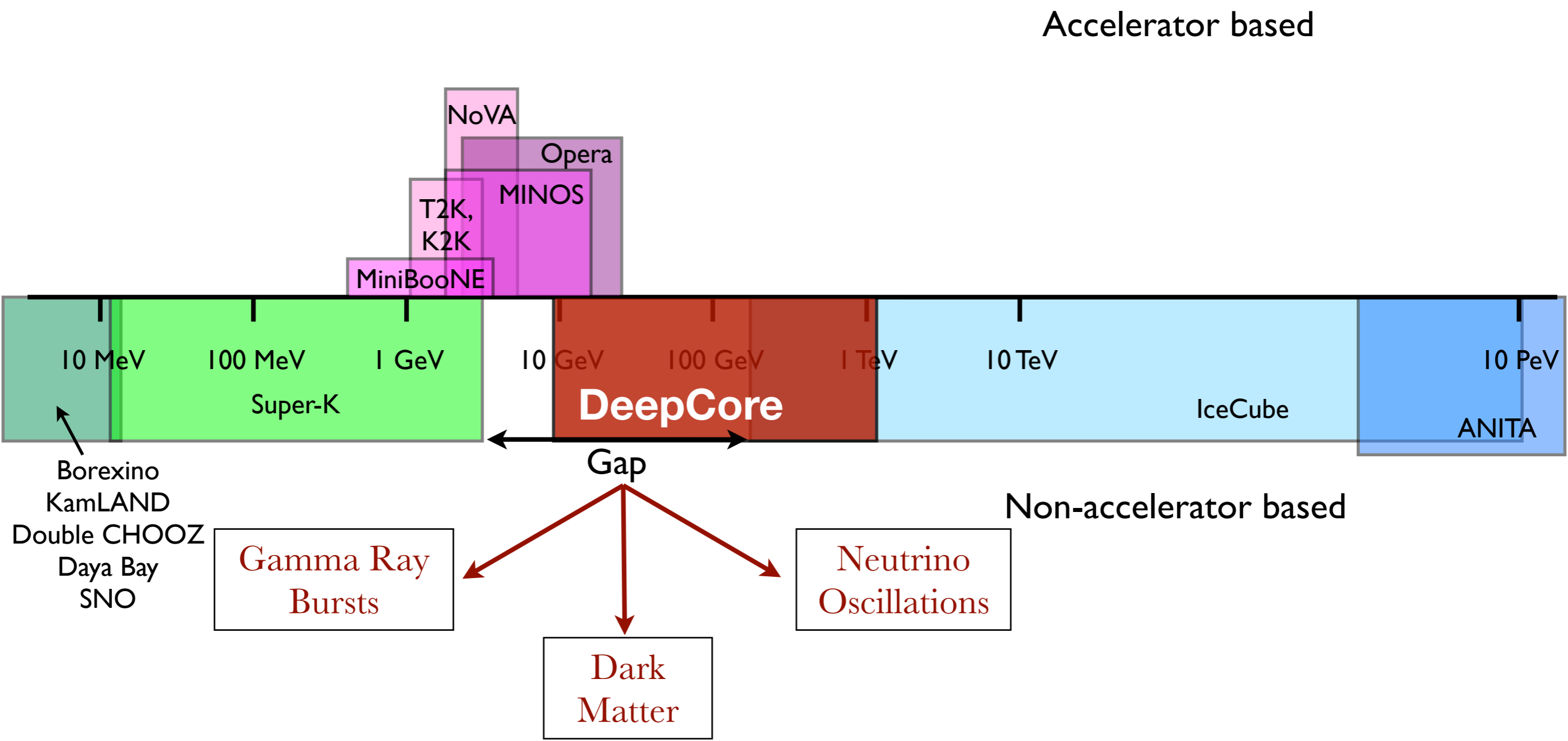
Experimental Landscape

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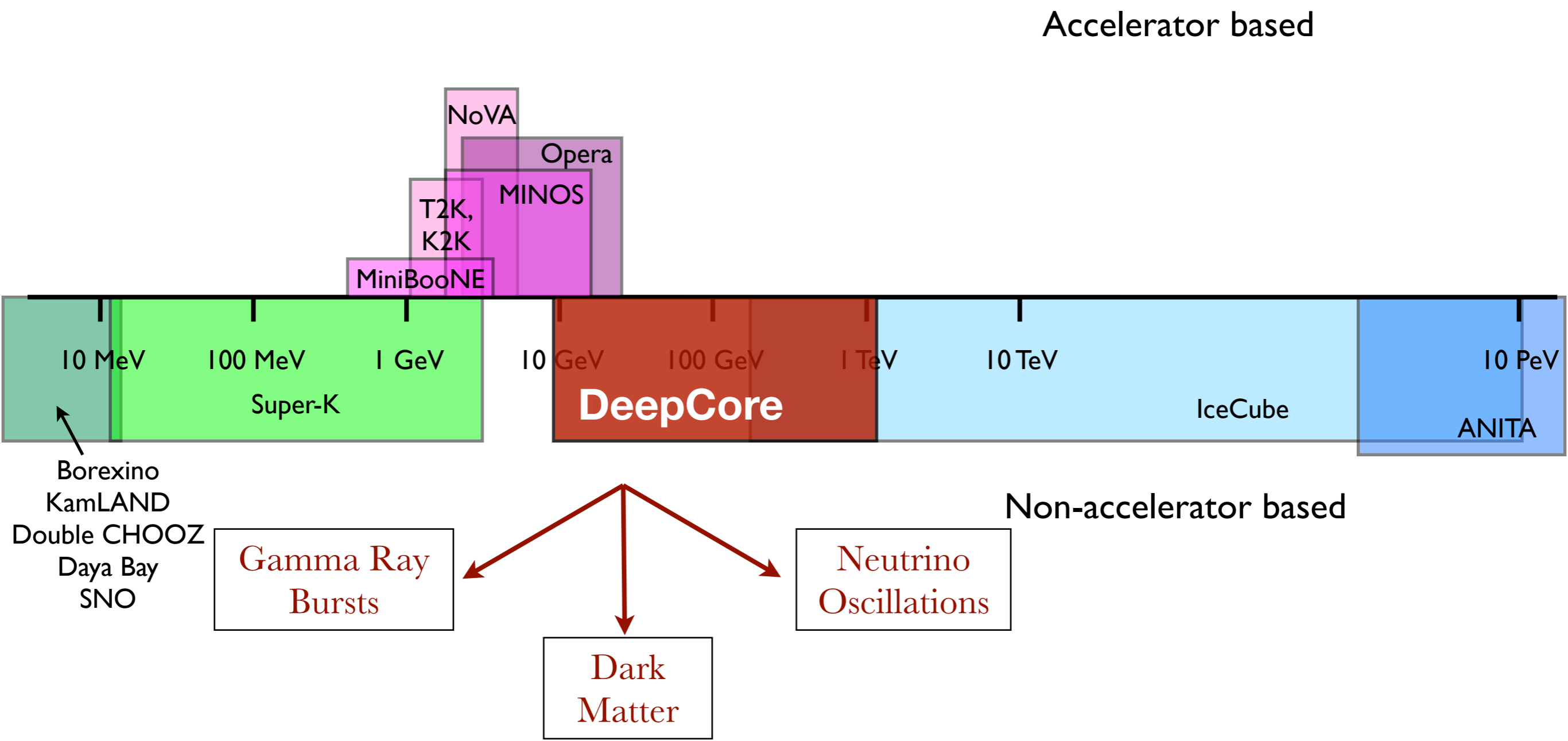
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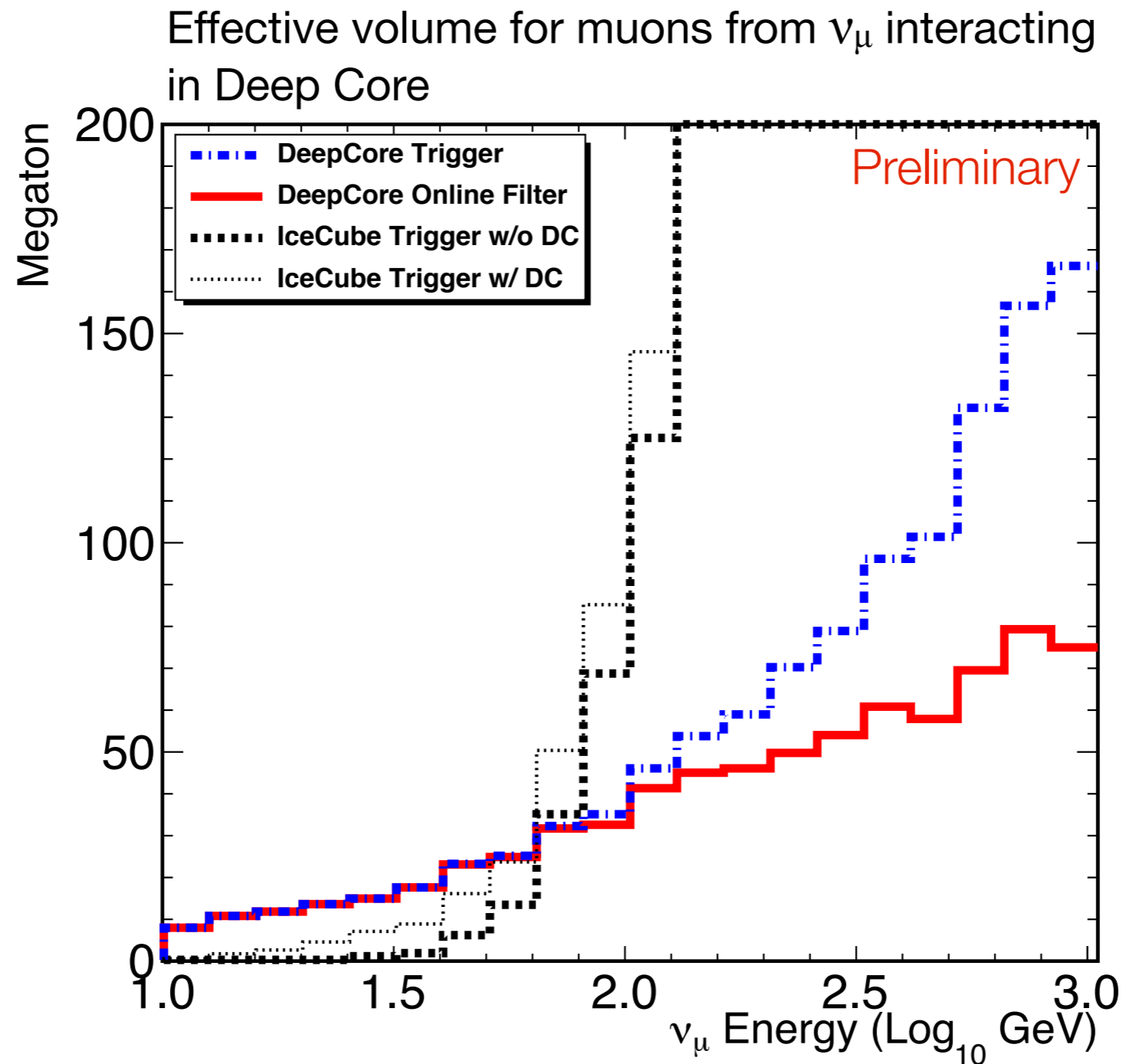
Experimental Landscape

- IceCube
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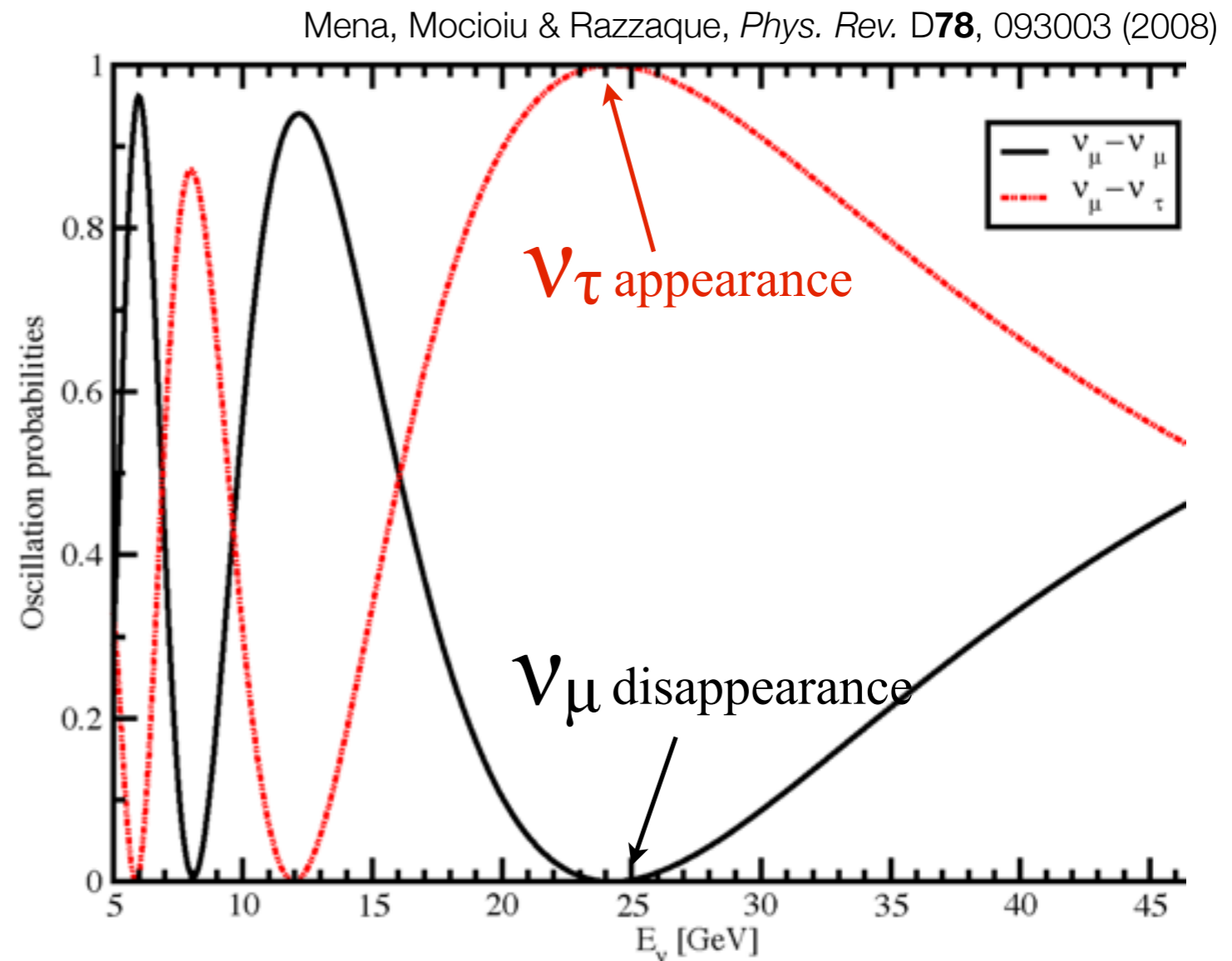
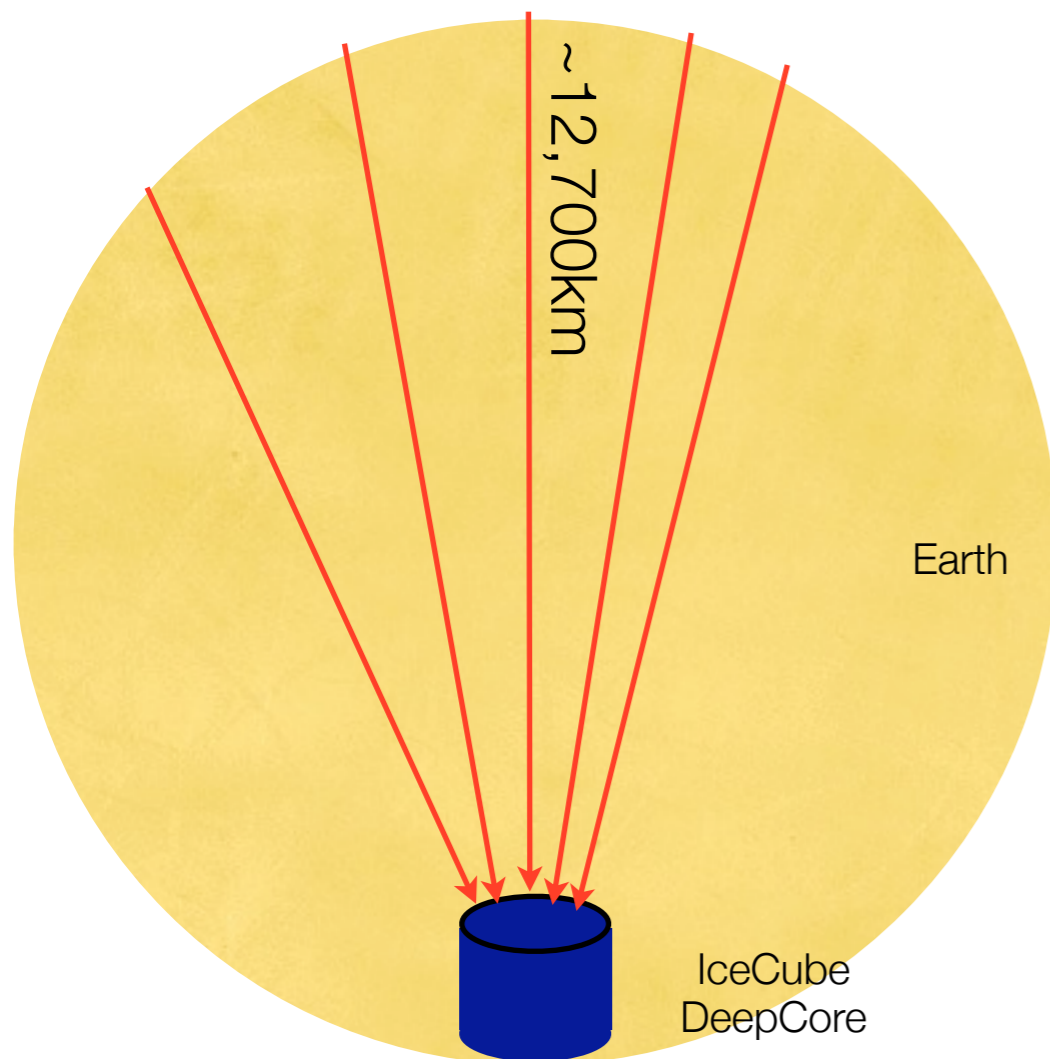


DeepCore Neutrinos

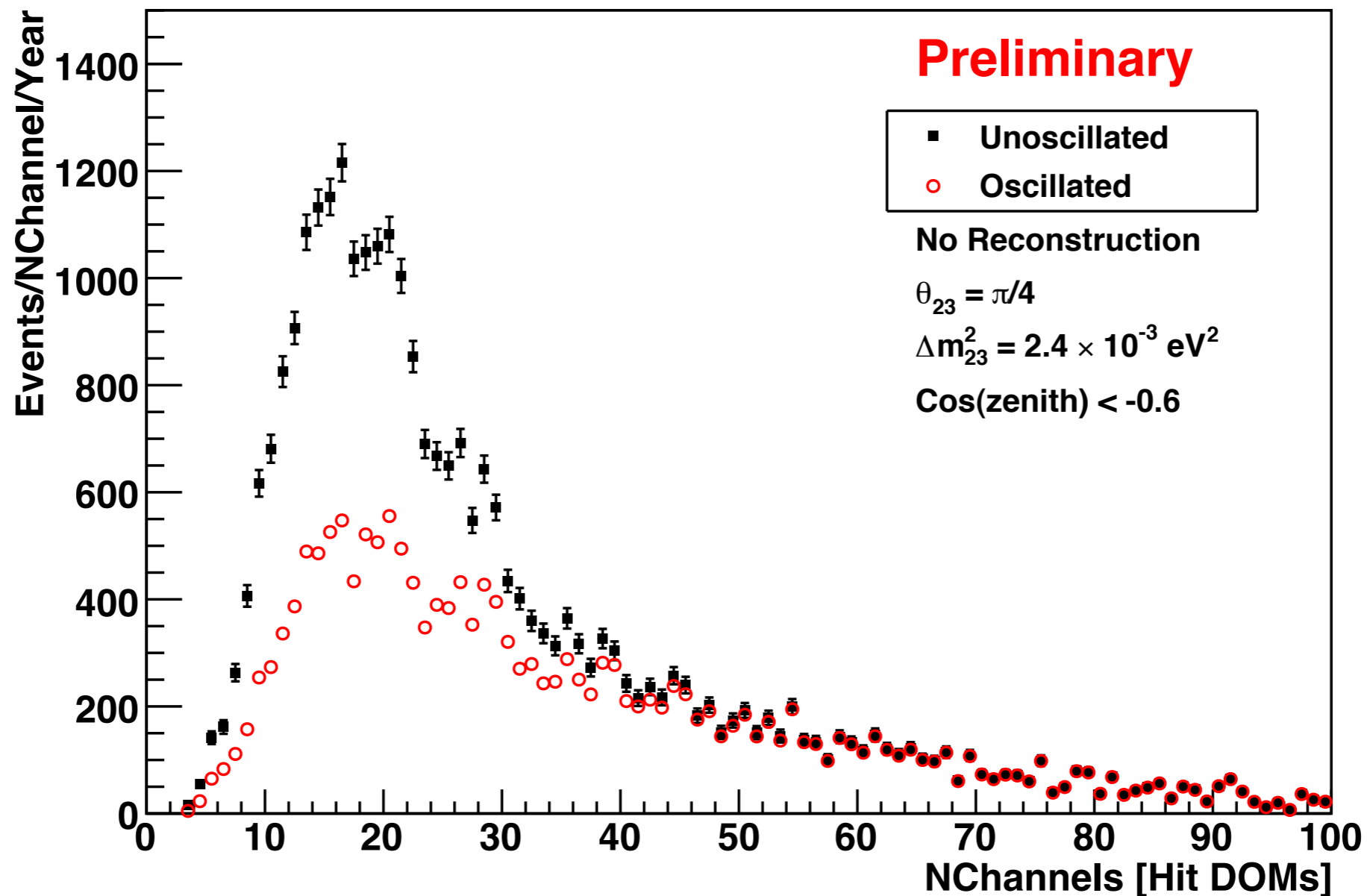
- DeepCore, being a multi-MTon detector, will collect tens of thousands of oscillated neutrinos at trigger level



- Northern Hemisphere neutrinos oscillating over one earth radii produces ν_μ (ν_τ) oscillation minimum(maximum) at ~ 25 GeV
 - Higher energy region than accelerator based experiments

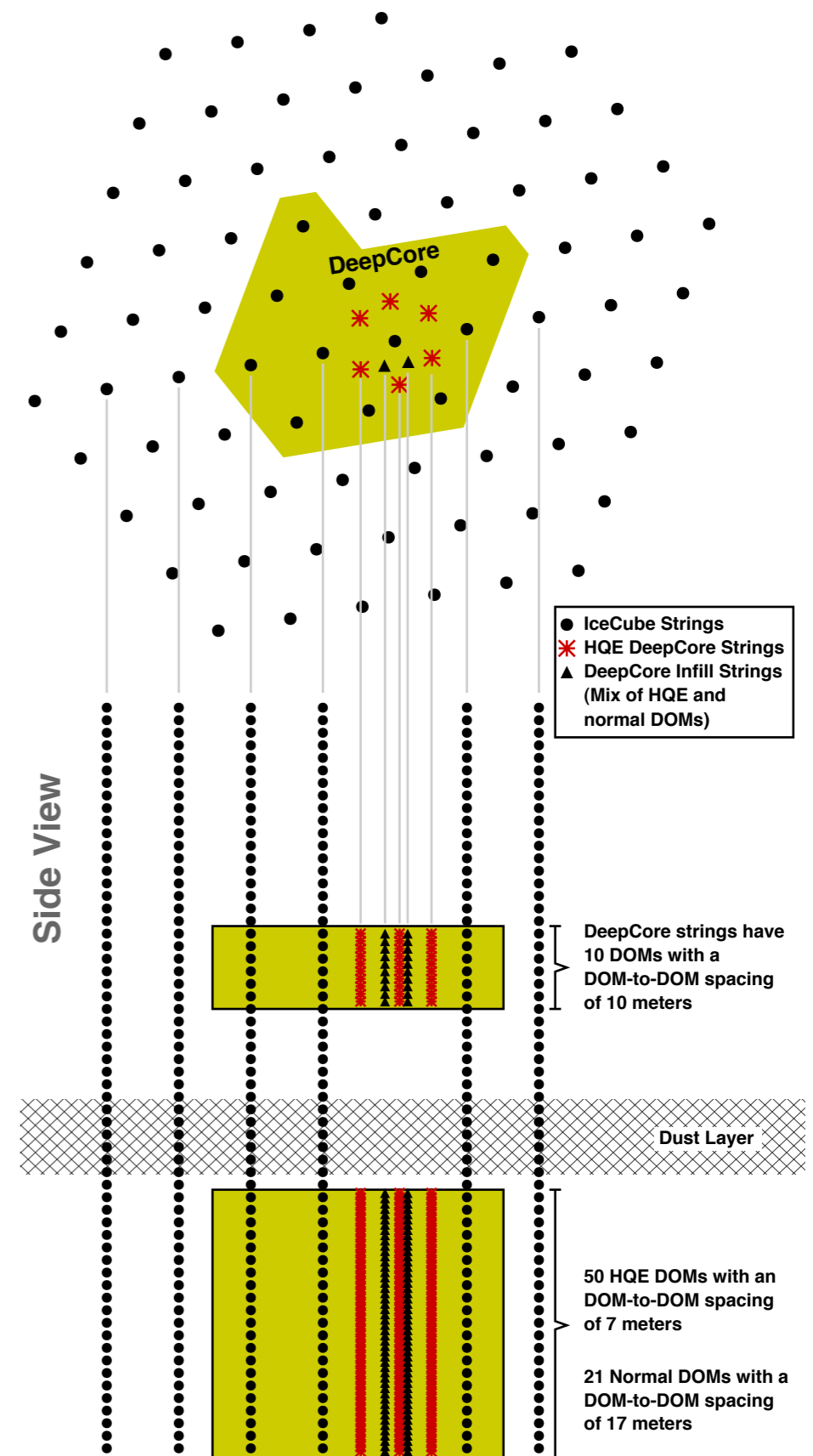


- 1 year data with 79 strings
- Monte Carlo signal only

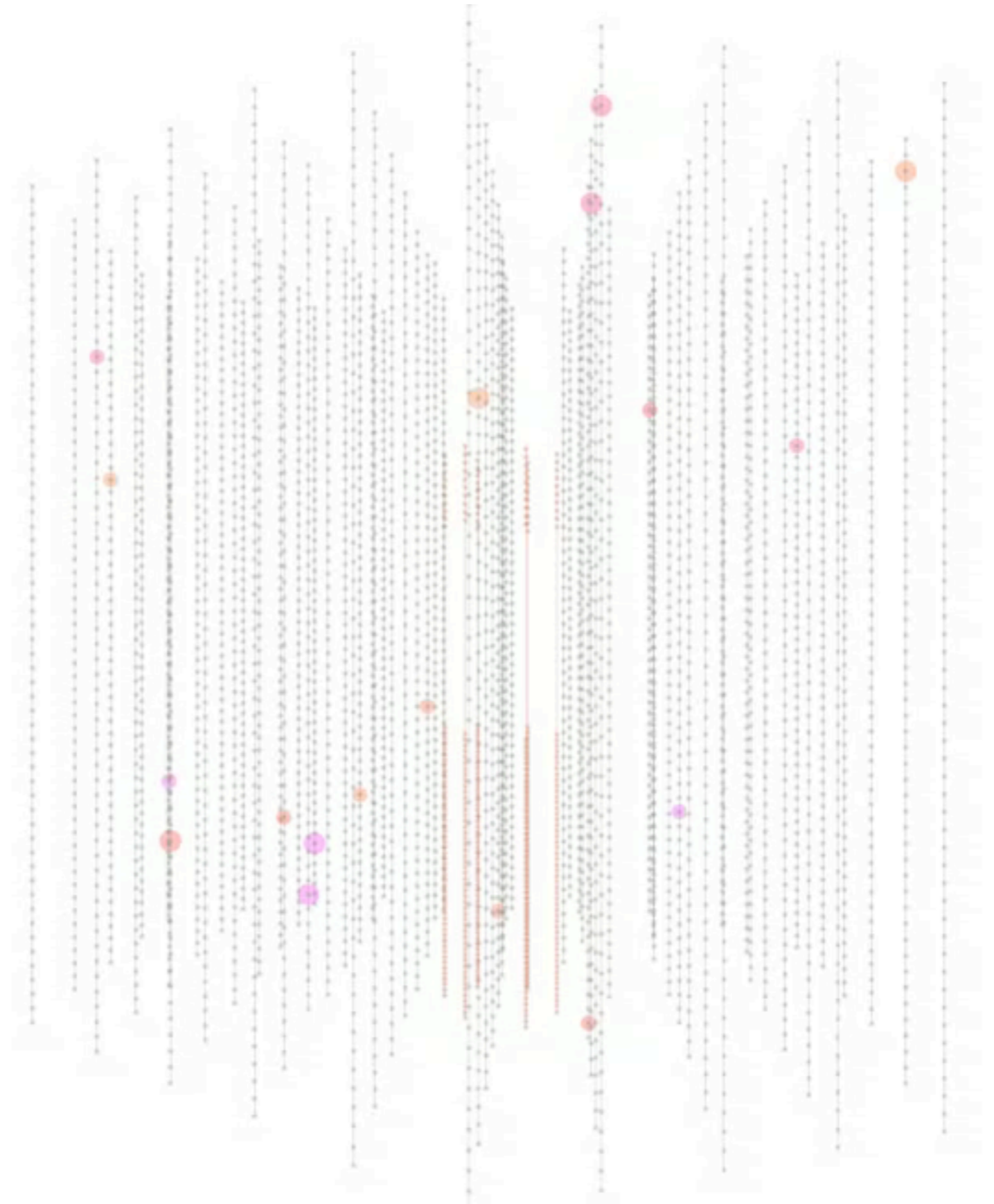


- Neutral Current, Charged Current ν_e , low energy ν_μ CC and CC ν_τ events produce cascade-like signatures
- Look for statistical excess in up-going cascade events
- DeepCore has been infilled with 2 additional strings
 - Increases ν_τ event rate by $> 15\%$

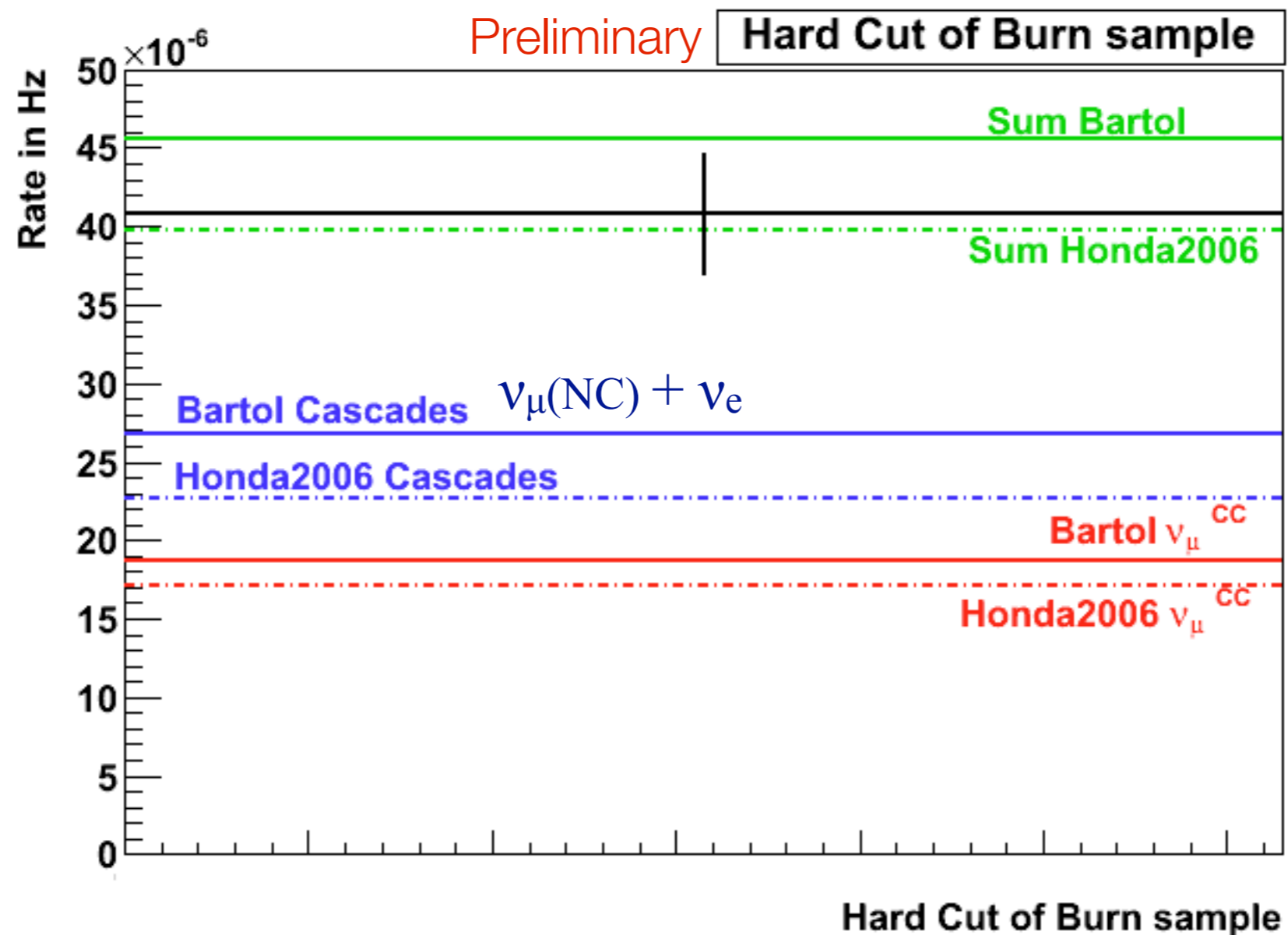
Overhead View



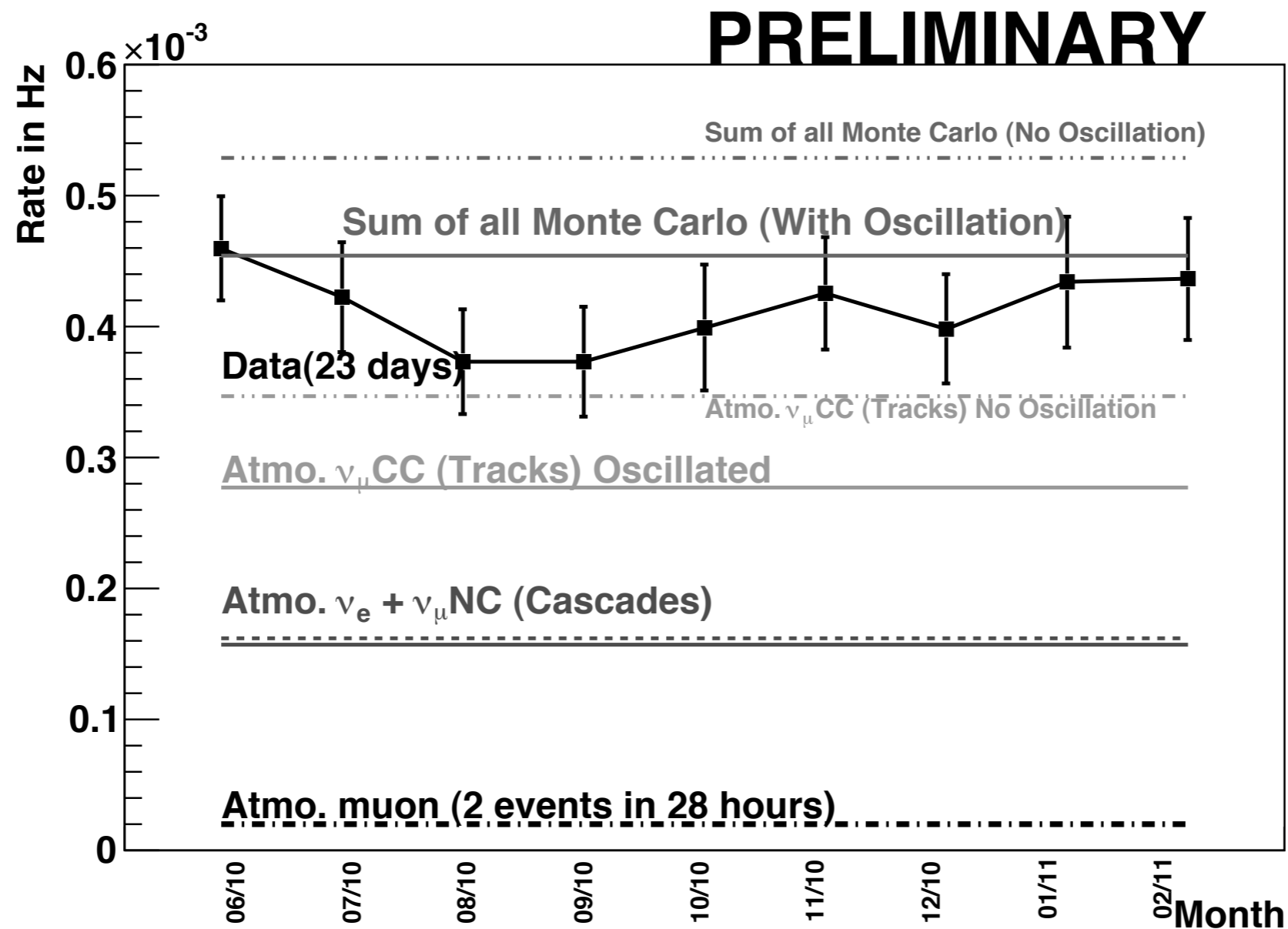
- 8 hours of real data
- Specific DeepCore vetoes and a Boosted Decision Tree
- Up-Going muon neutrino candidate
 - ~15 GeV from track length



- First observation of neutrino induced cascades in IceCube
- 30.64 Days of livetime (10% open sample)
 - Tight cuts removed all cosmic ray muons from available 28 hours of CORSIKA

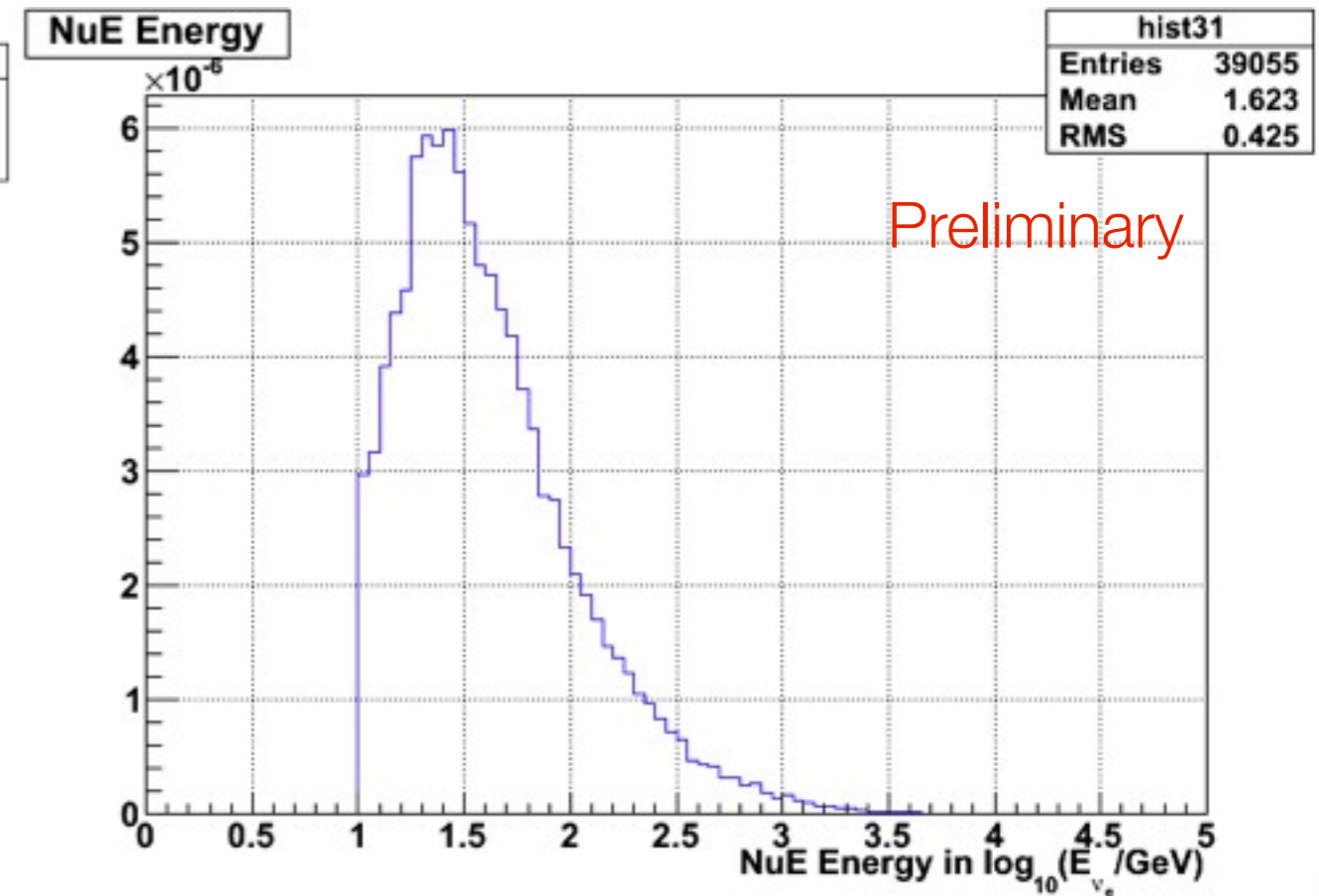
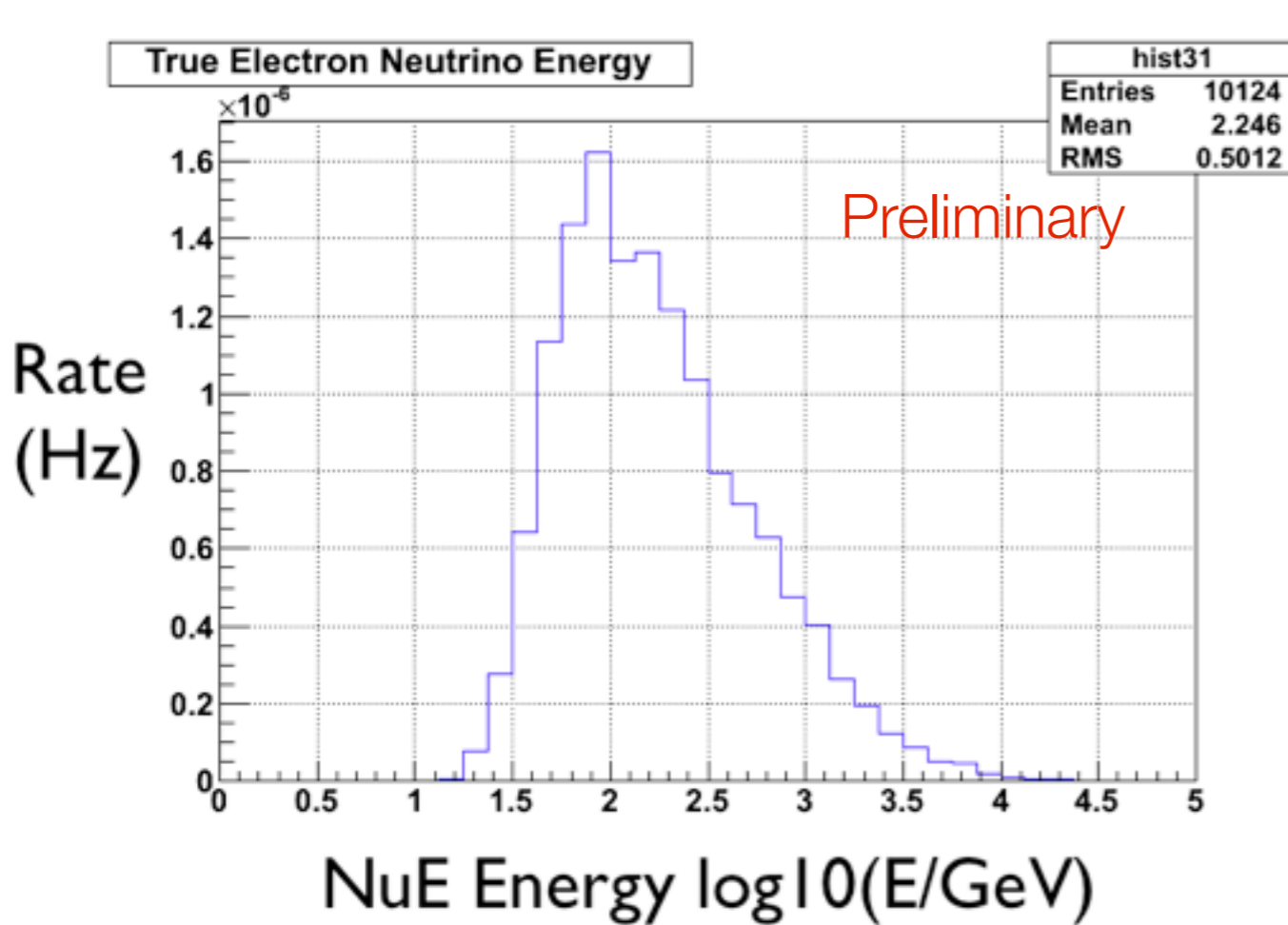


- Loose Cuts = More signal + non-zero atmospheric muon background
- Lower Energy Neutrinos



Hard Cut

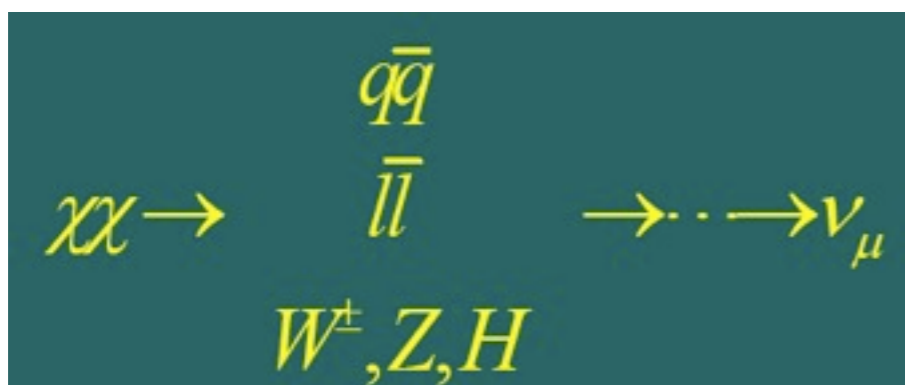
Loose Cut



-
- 1 year of physics quality data with 80% deployment
 - 100% deployed in Dec. 2010
 - Opens up energy region for neutrino oscillation studies
 - First observation of neutrino induced cascades

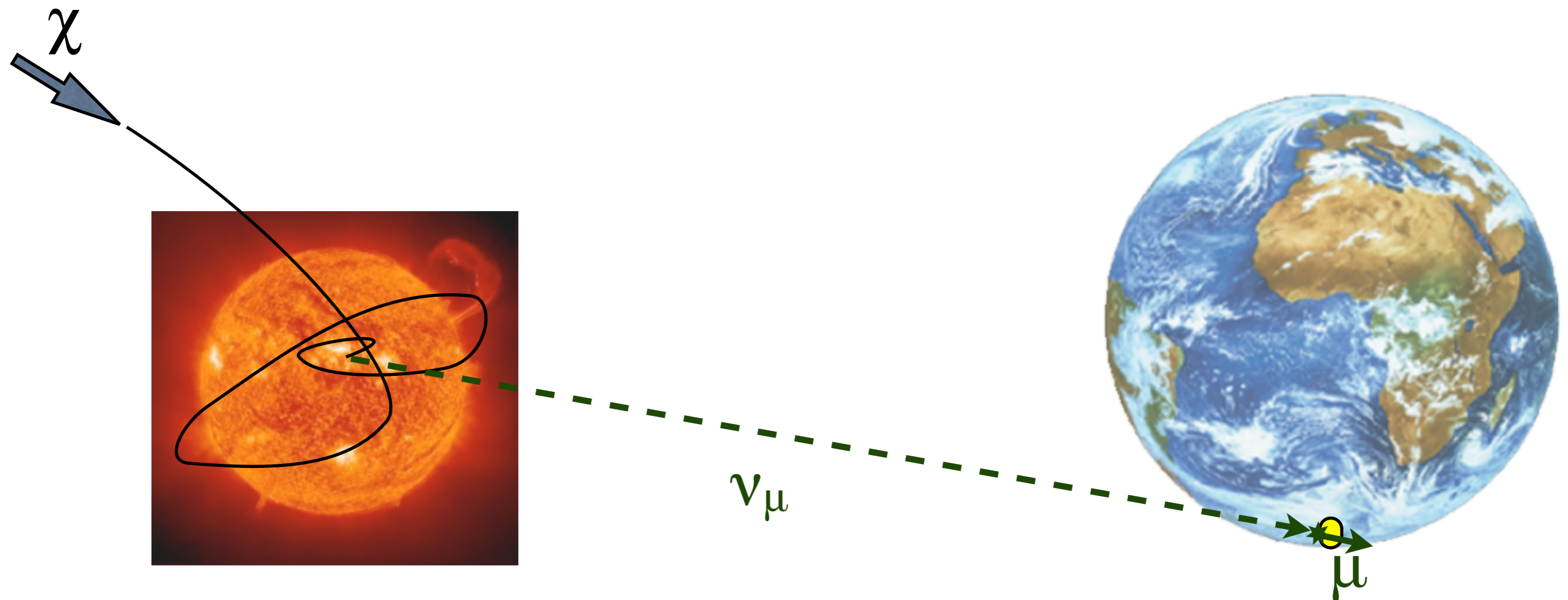
DeepCore Dark Matter

- Galaxy clustering, Gravitational lensing, Bullet Cluster galaxies, etc... strongly suggest existence of Dark Matter
- Popular candidate for Dark Matter particle is **Weakly Interacting Massive Particle (WIMP)**
- IceCube-DeepCore searches for Dark Matter self-annihilation creating neutrinos
 - Point towards galactic objects where Dark Matter clumps (Sun, Galactic Halo)

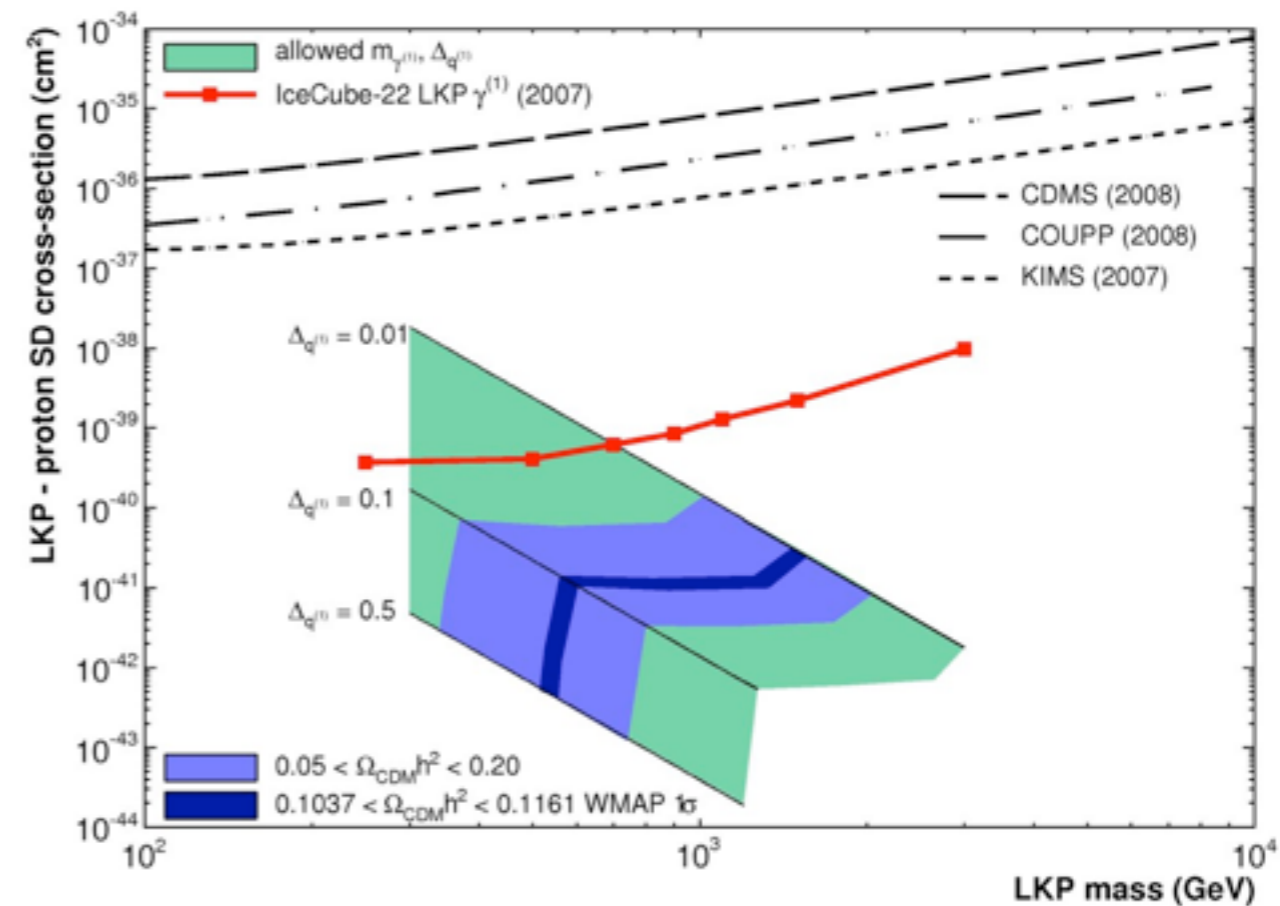
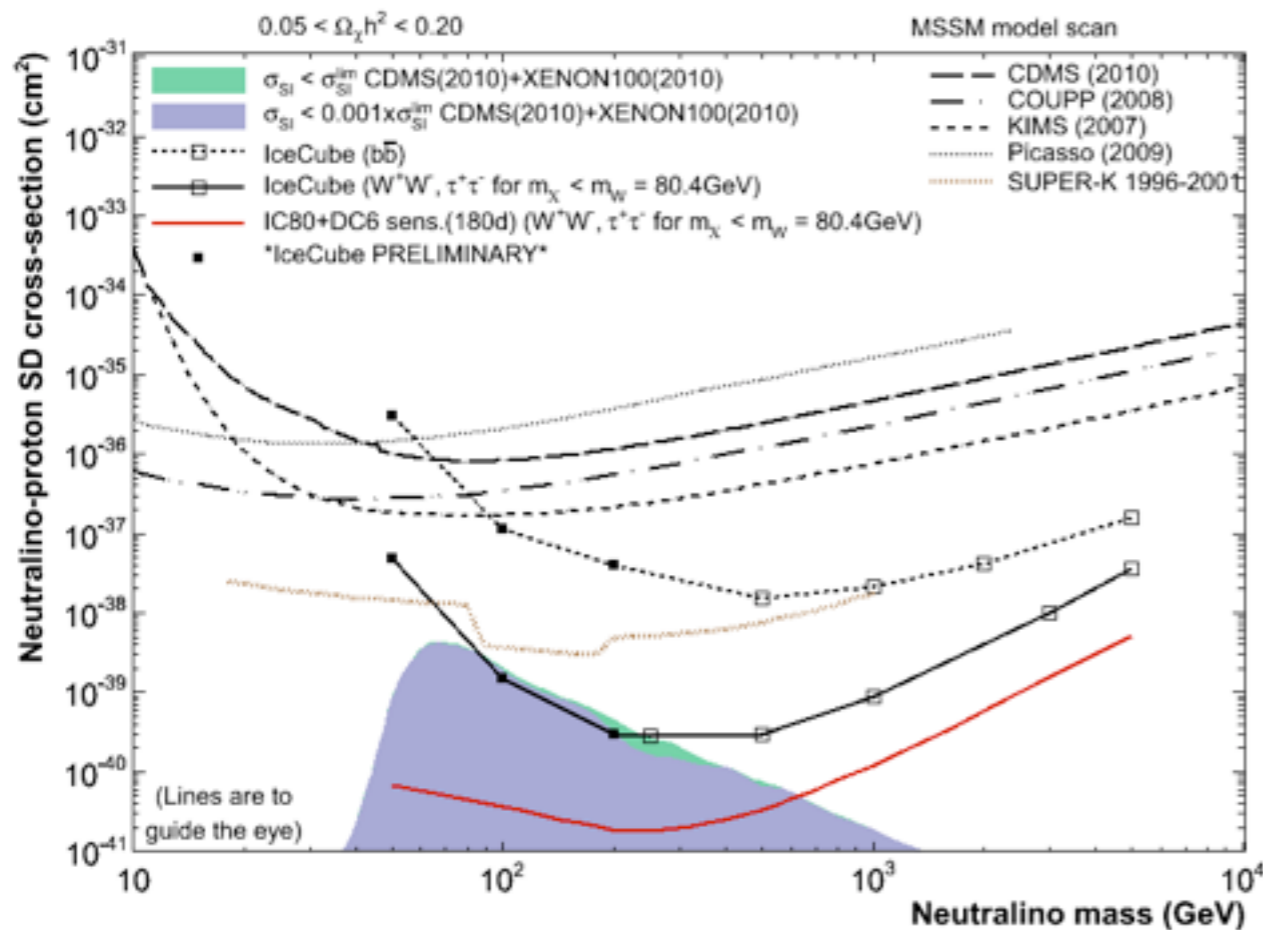


W. H. Press and D. N. Spergel. *Astrophys. J.* **296**, 679, (1985)
T. Gaisser, G. Steigman and S. Tilav. *Phys. Rev. D* **34**, 2206, (1986)
A. Gould. *Ap. J.* 328, 919, (1988).

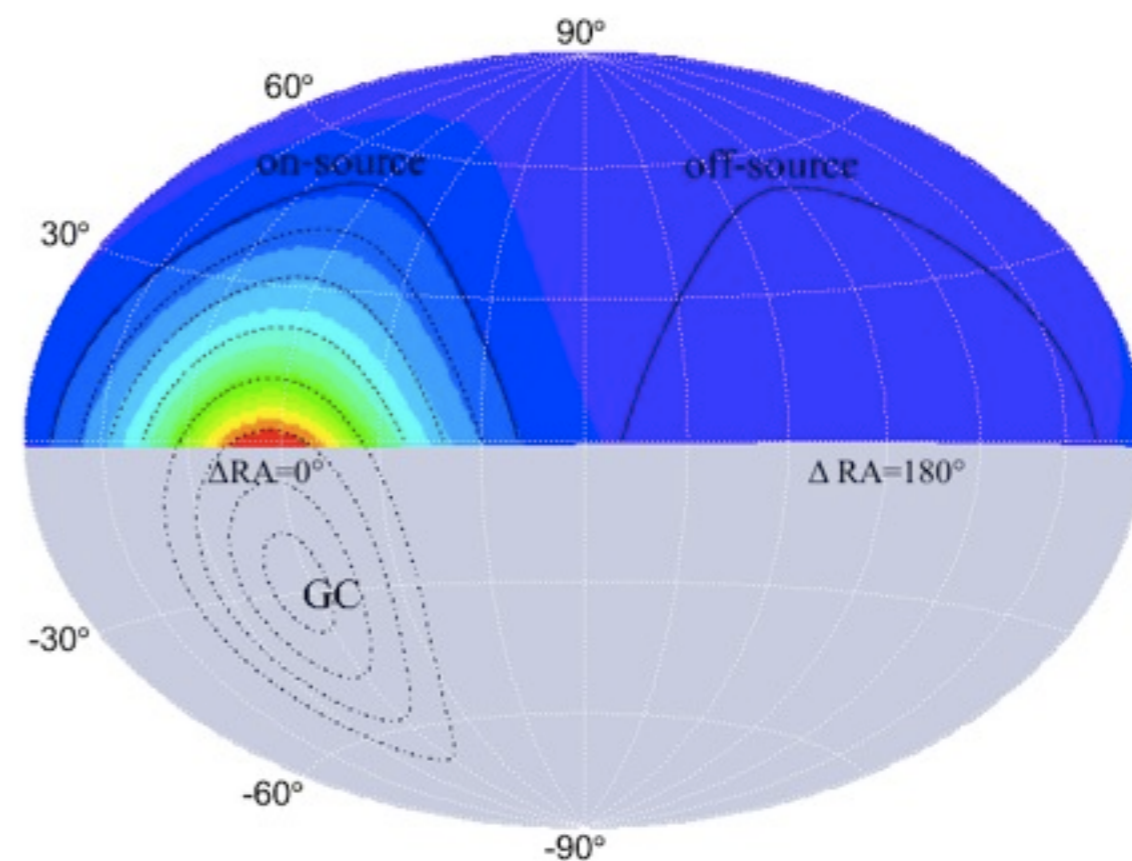
- Dark Matter gets trapped via Spin-Dependent (SD) collisions with nucleons
 - Spin-independent is well constrained by direct detection experiments
- Builds up, reaches equilibrium, starts annihilating



- Look for neutrino excess when the Sun is below the horizon
- Neutrino flux translates to cross-section
- DeepCore will provide order of magnitude+ improvement in spin dependent searches for Dark Matter
- Limits on MSSM model Dark Matter and Kaluza-Klein model



- Signal depends on Halo distribution(DM density) model and SUSY model(DM annihilation channels)
- on-source versus off-source anisotropy
- IC22 analysis did not observe a large scale anisotropy and has a 90% C.L. on WIMP self-annihilation cross-section of $\langle\sigma_{AV}\rangle 10^{-22} \text{ cm}^3\text{s}^{-1}$ in the WIMP mass range of 200 GeV-10 TeV



-
- Current IceCube-only analyses of spin dependent WIMP are probing phase space
 - Inclusion of DeepCore will improve WIMP Dark Matter sensitivity by 2 orders of magnitude

Beyond DeepCore



IceCube



DeepCore

Beyond DeepCore



IceCube



DeepCore

Beyond DeepCore



IceCube

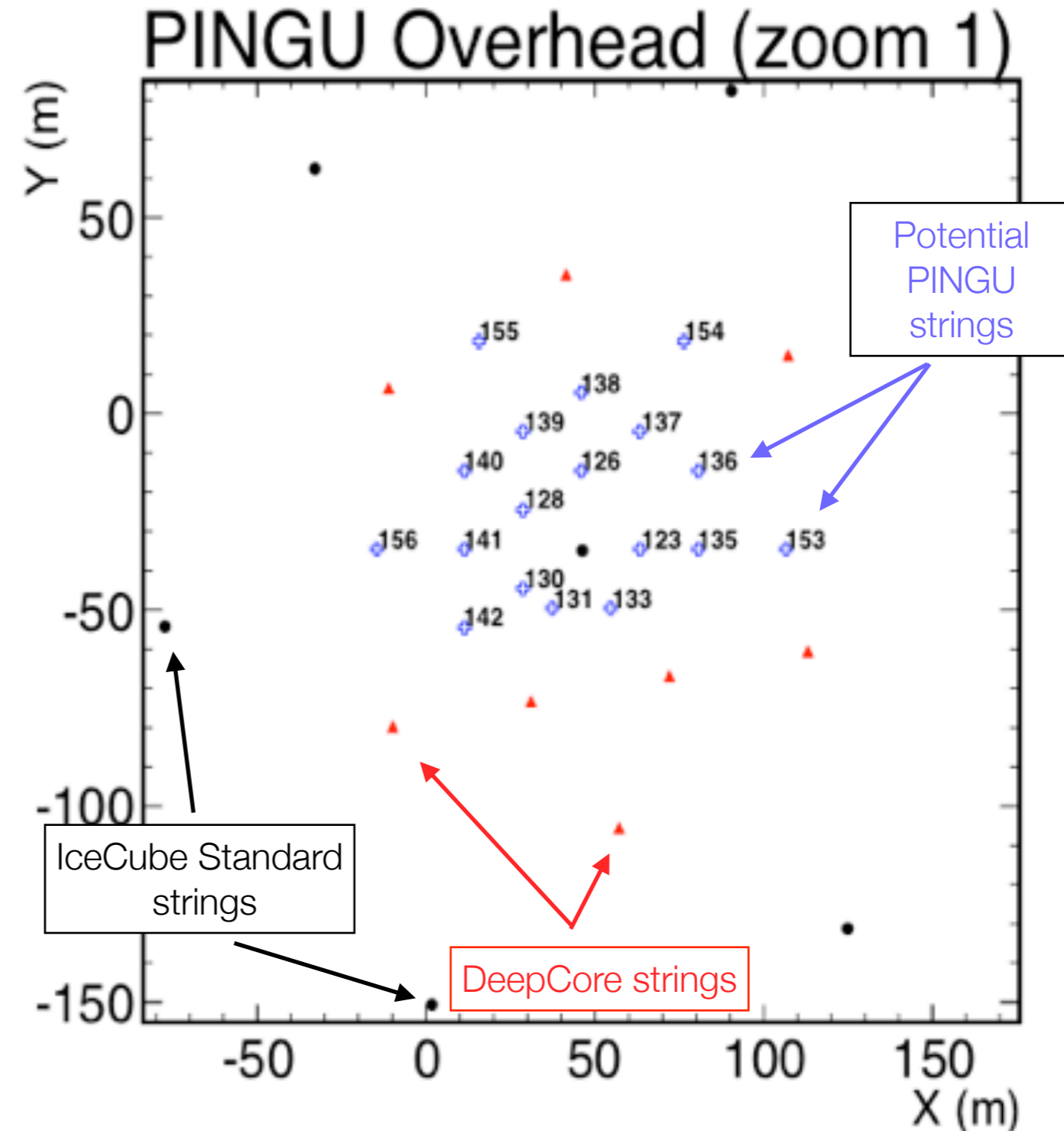


DeepCore

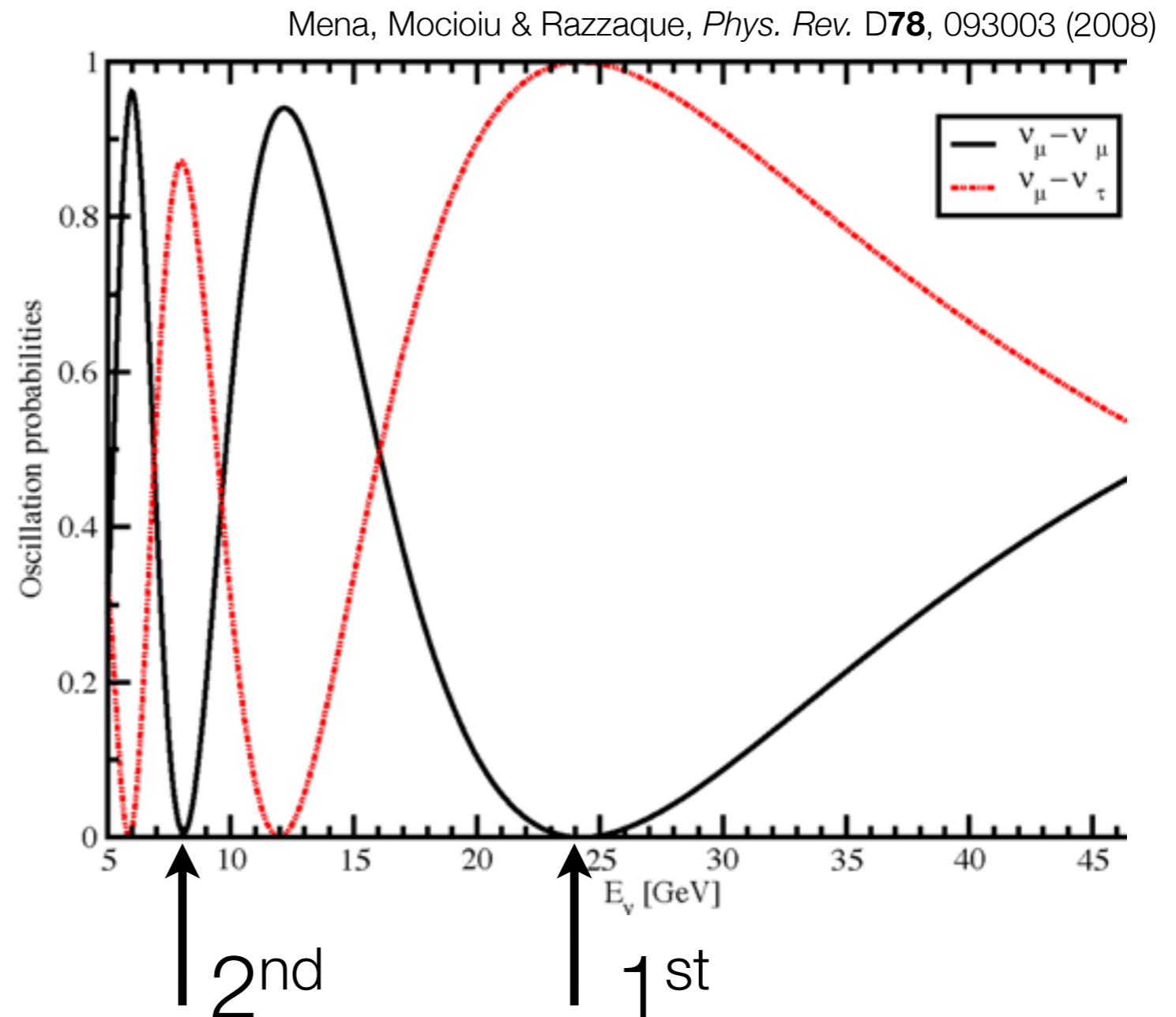


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- Using existing and familiar technology (hot water drill, HQE PMT DOMs) infill DeepCore with 18-20 more Strings
 - Drive neutrino energy reach down to few GeV while maintaining multi-megaton scale size
 - Improves Dark Matter sensitivity and Neutrino Oscillation analyses
 - Phased IceCube Next Generation Upgrade (PINGU)

- Add 18-20 strings into DeepCore volume
- One of many possible geometries
- R & D for future water/ice cerenkov detectors



- With an infill that achieves \sim GeV resolution, the 2nd oscillation minimum becomes accessible
- Improve Cascade reconstruction
 - Tau appearance



- Monte Carlo is now available using GENIE neutrino generator for GeV neutrinos
- Soliciting interest in those who want to see a megaton water cerenkov detector at GeV neutrino energies
- <http://www.mailman.srv.ualberta.ca/mailman/listinfo/beyonddc>

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- <http://www.beyonddc.org>

“Anything worth doing is worth overdoing”

Really Beyond DeepCore



IceCube



DeepCore



PINGU

Really Beyond DeepCore



IceCube



DeepCore



PINGU

Really Beyond DeepCore



IceCube



DeepCore



PINGU



- South Pole Infrastructure
 - No excavation
 - Deployment is now a precision process
- Unchanging, low-background medium
- Use IceCube and DeepCore (maybe PINGU) as active veto
- Move from GeV to MeV
 - Cerenkov Ring Imaging
 - Single PMT Module is no longer feasible

- Based on a KM3NeT proposed design

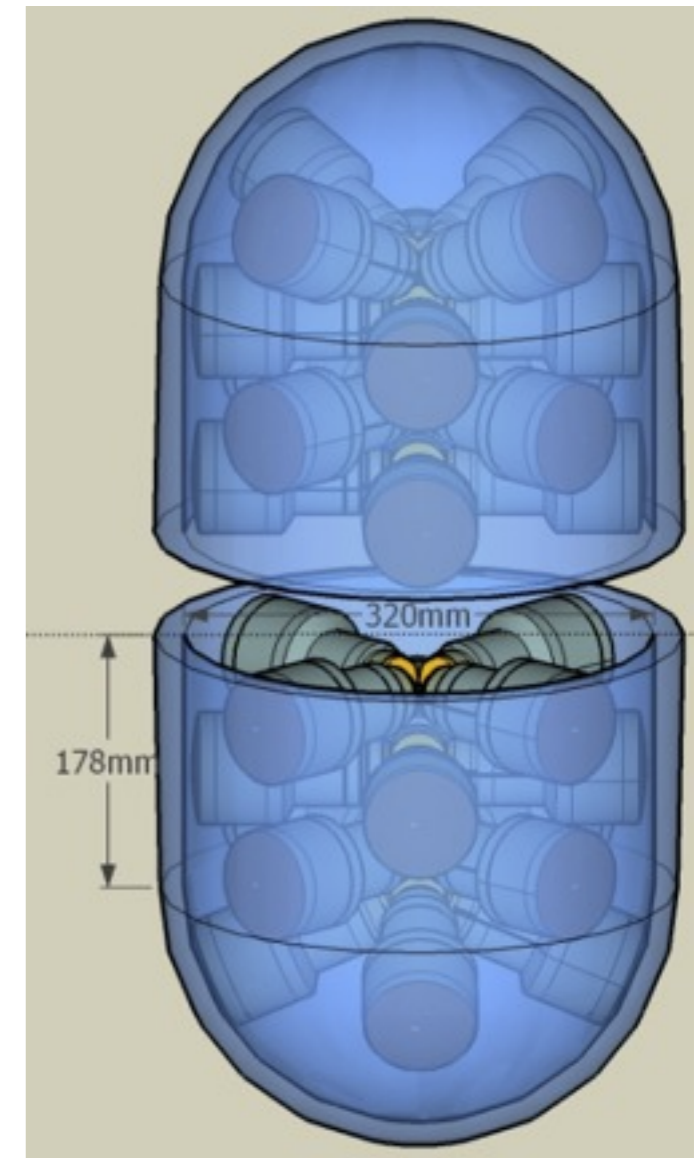
P. Kooijman, *NIM A567* (2006), S. Kuch *NIM A567* (2006), KM3NeT TDR

- One meter glass cylinder containing 30 3" PMTs and associated electronics

- Comparable width to IceCube DOM
- Effective photocathode area of 265 sq. in. – 3.4x that of standard 10" IceCube PMT, but granular

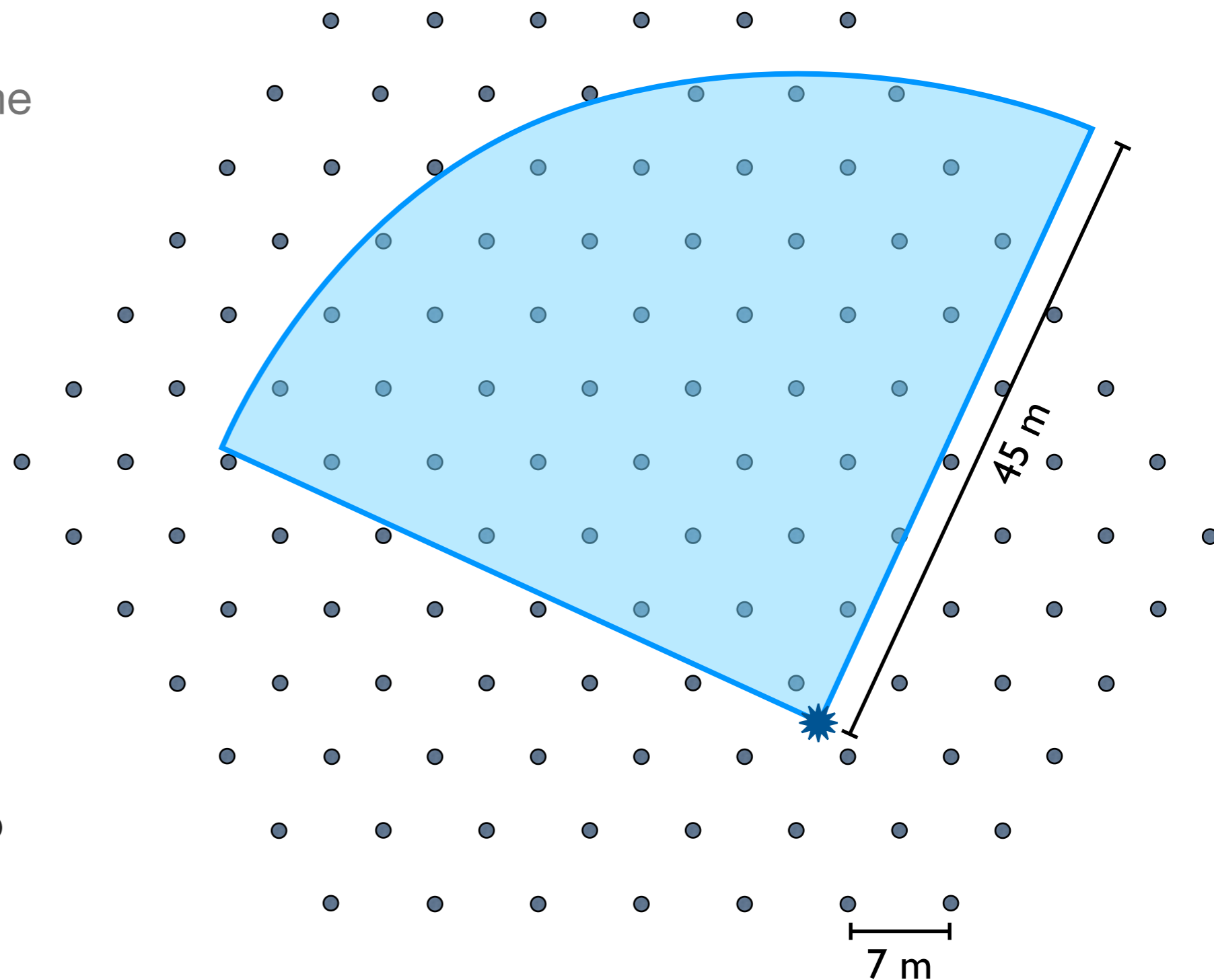
- Would allow spatial imaging of Cherenkov ring

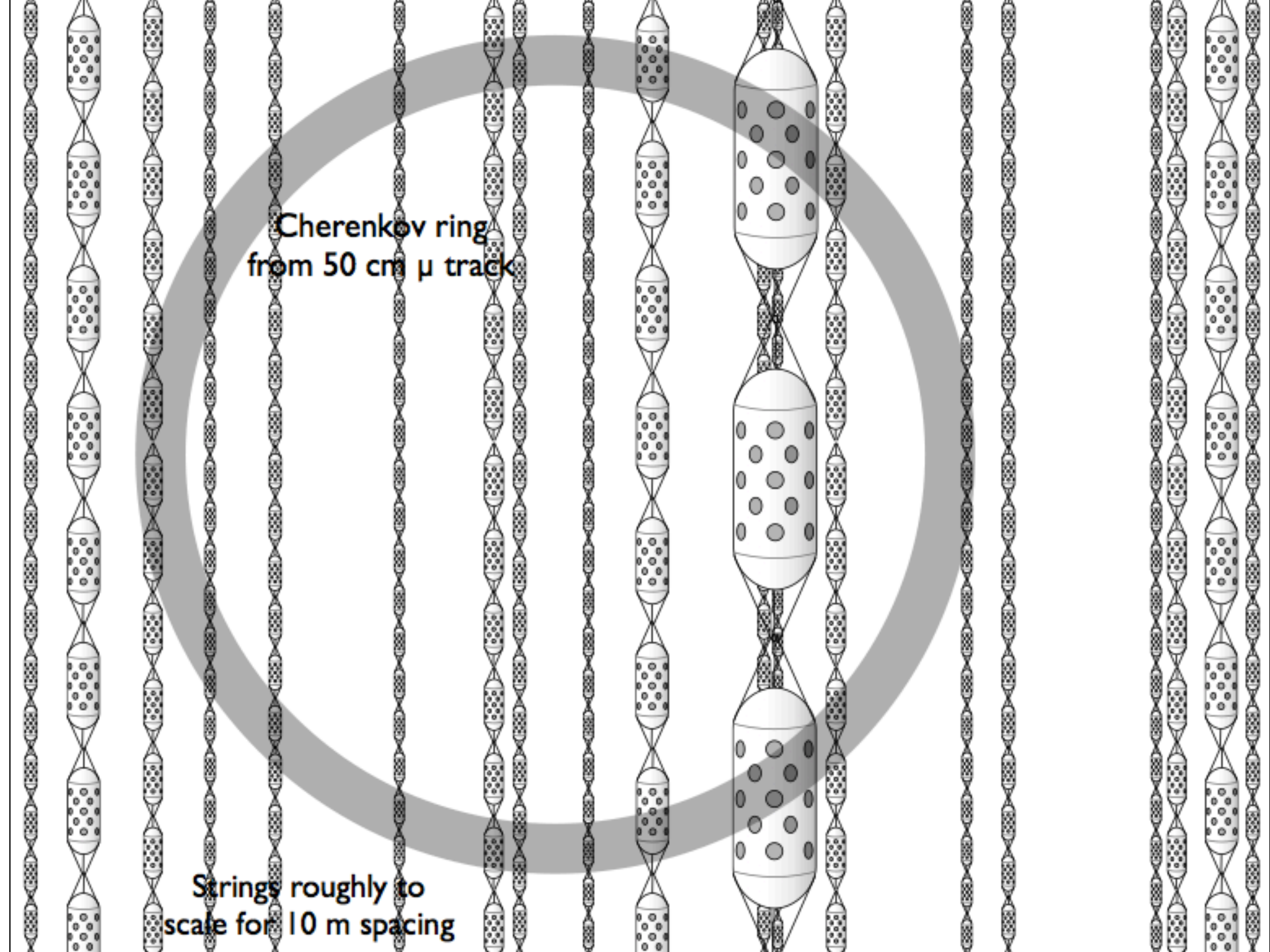
- KM3NeT has moved toward a 17" sphere instead – close PMT spacing not their goal – but the cylinder design was developed to the engineering stage



Courtesy P. Kooijman

- 120 strings of 125 composite DOMs each
 - Instrumented volume of 250 m height, ~40 m radius
- 1 MegaTon fiducial volume, at depths of 2200-2450 m
 - Optical scattering length ≥ 40 m, absorption ≥ 140 m
- Inside IceCube and DeepCore for muon veto





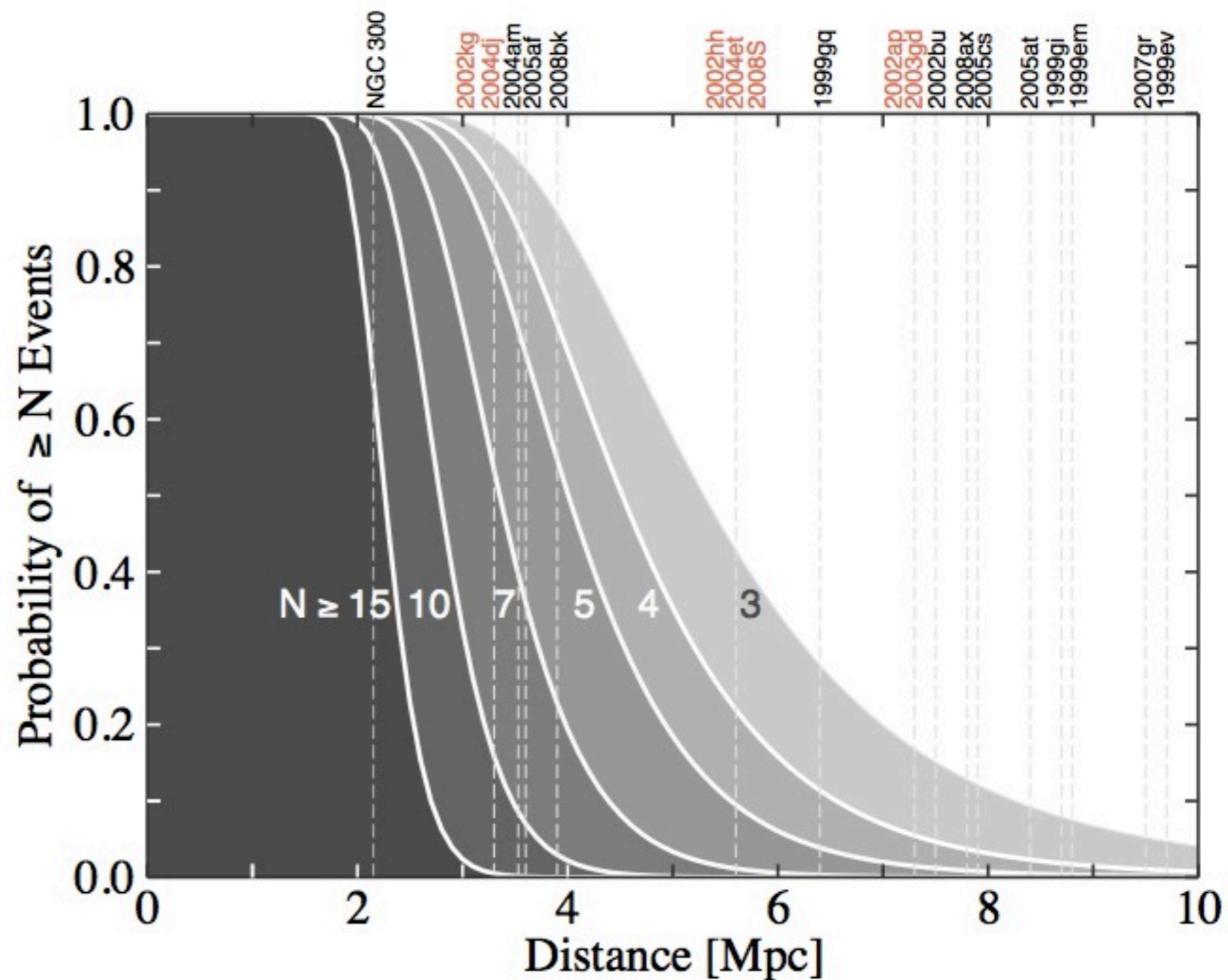
The diagram illustrates a detector setup with vertical strings of photomultiplier tubes (PMTs) arranged in a grid. A central vertical string is highlighted with a larger, shaded PMT tube, representing a track. A large, semi-transparent gray ring is centered on this track, representing a Cherenkov ring. The ring's radius is approximately 10 meters. The strings are spaced 10 meters apart. The text 'Cherenkov ring from 50 cm μ track' is centered within the ring, and 'Strings roughly to scale for 10 m spacing' is located at the bottom left.

Cherenkov ring
from 50 cm μ track

Strings roughly to
scale for 10 m spacing

- Extend core-collapse SN search beyond Milky Way
- 5 megaton detector with sensitivity down to 15 MeV

Kistler et. al.
arXiv:0810.1959



-
- Solar Neutrinos

-
- Solar Neutrinos
 - Detector for Neutrino Factory, Beta beam or Super Beam
 - Mass Hierarchy, Small θ_{13} (10^{-4} - 10^{-3}), Lepton CP Violation
 - Option for PINGU as well depending on beam characteristics

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- Solar Neutrinos
 - Detector for Neutrino Factory, Beta beam or Super Beam
 - Mass Hierarchy, Small θ_{13} (10^{-4} - 10^{-3}), Lepton CP Violation
 - Option for PINGU as well depending on beam characteristics
 - Proton Decay

- Solar Neutrinos
- Detector for Neutrino Factory, Beta beam or Super Beam
 - Mass Hierarchy, Small θ_{13} (10^{-4} - 10^{-3}), Lepton CP Violation
 - Option for PINGU as well depending on beam characteristics
- Proton Decay
- Extra-galactic Supernova neutrino

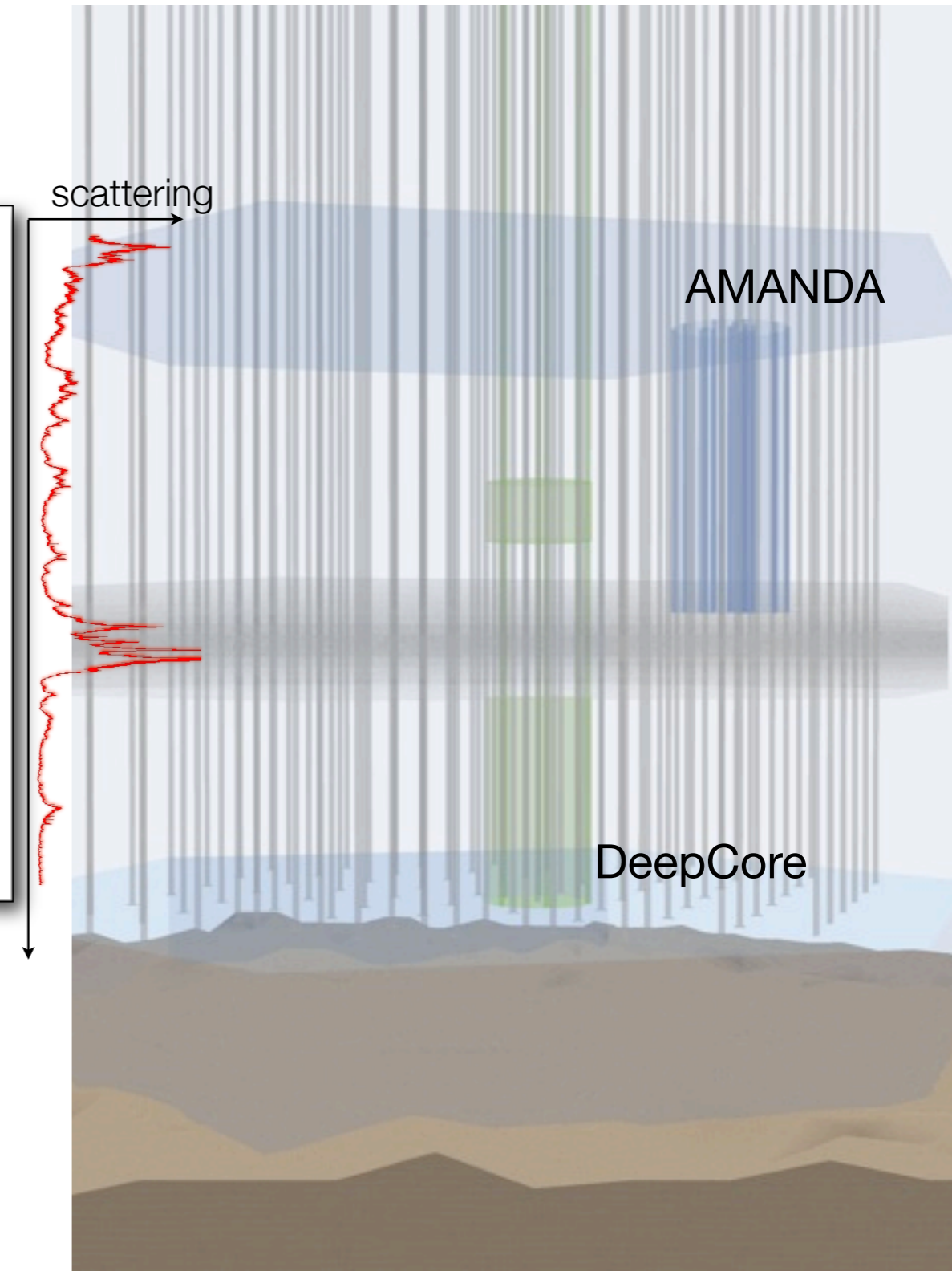
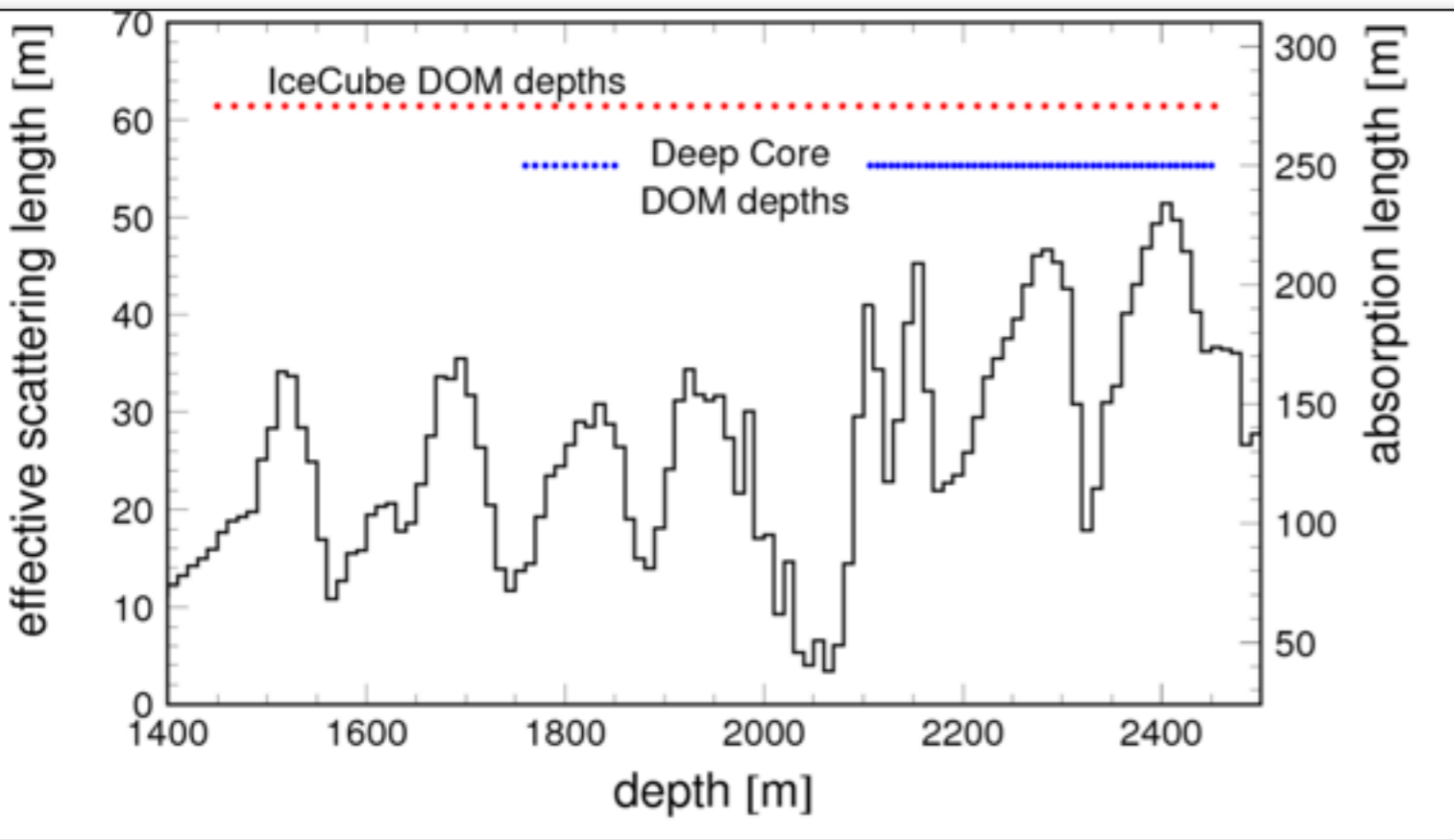
- IceCube astrophysical neutrino searches are alive and well
- DeepCore extends IceCube sensitivity to neutrinos down to ~ 10 GeV
- Phased extensions aim to provide lower energy reaches at megaton sizes in a water(ice) cerenkov detector
 - PINGU - ~ 1 GeV
 - Phase 2 - Down to ~ 15 MeV

Thanks

Backup

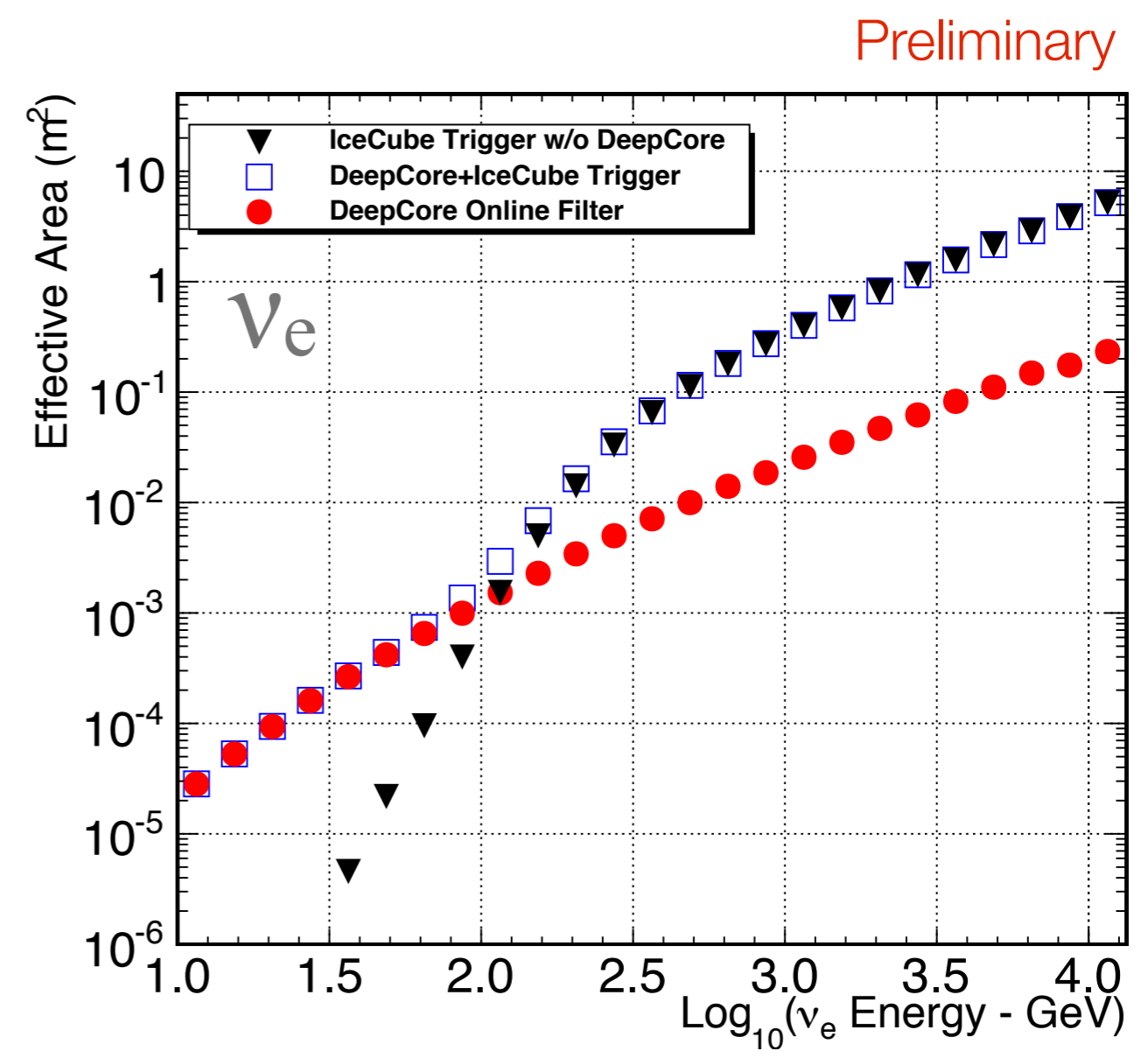
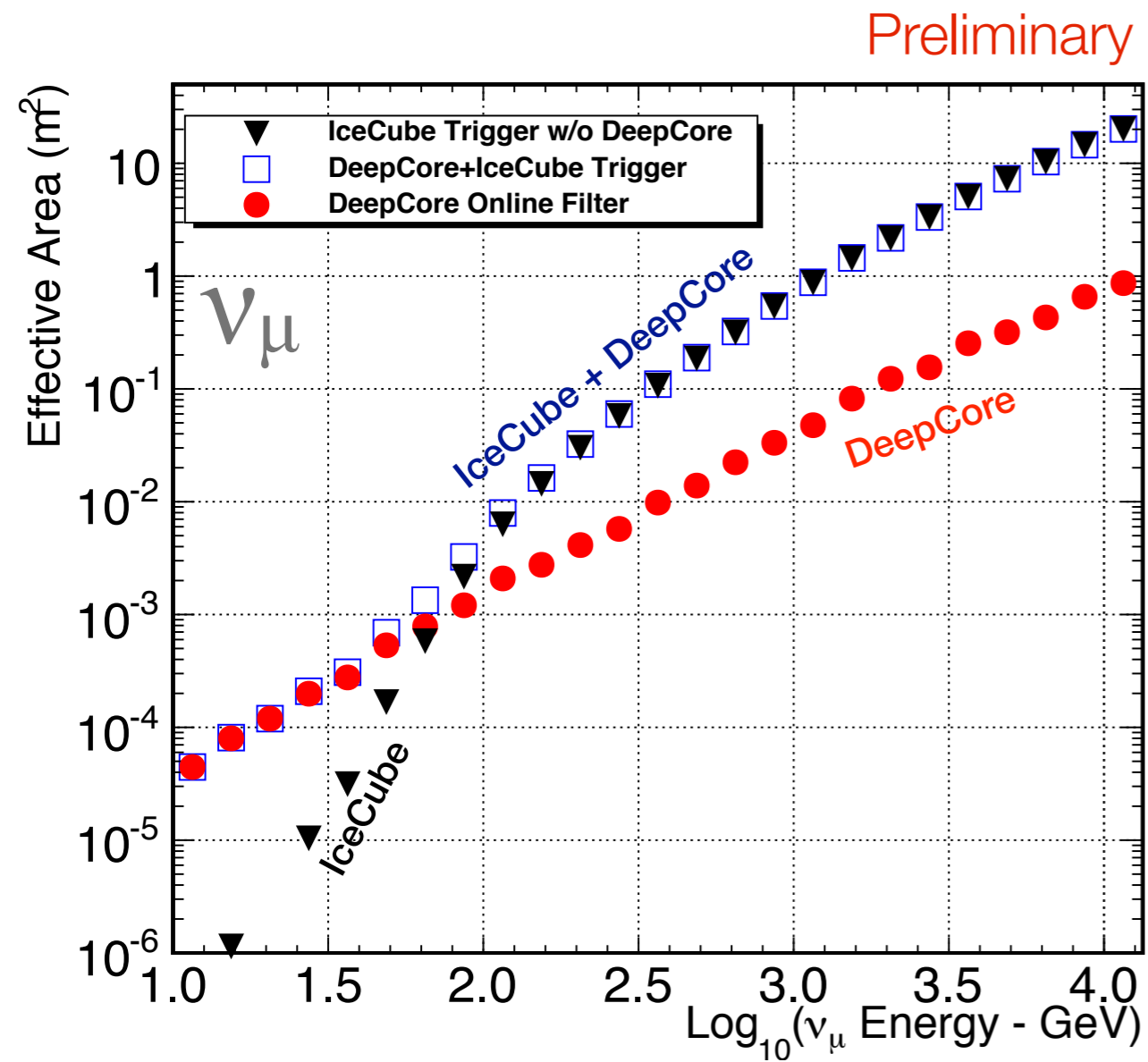
Dust at Depth

- IceCube
- DeepCore
- Beyond DeepCore

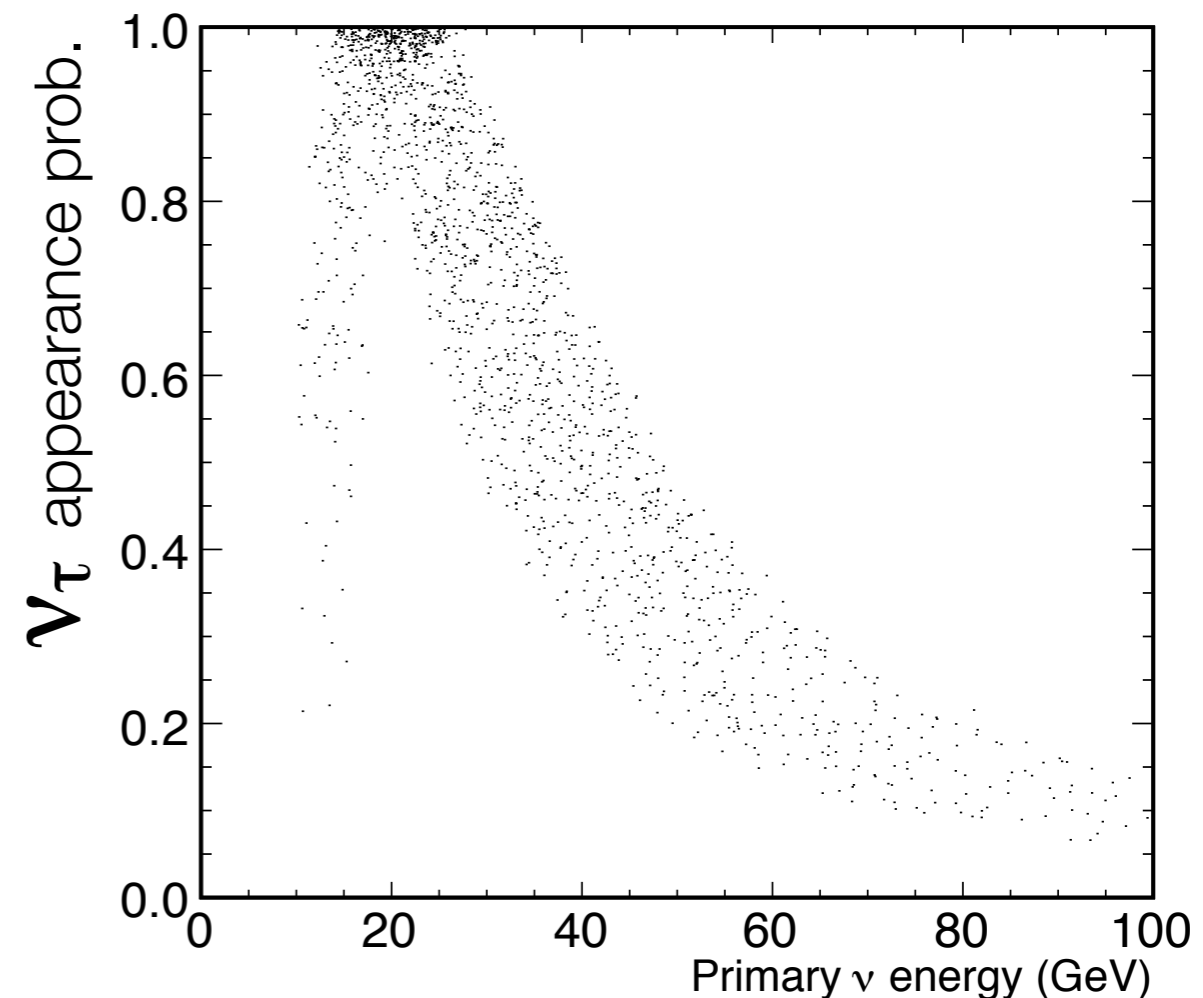
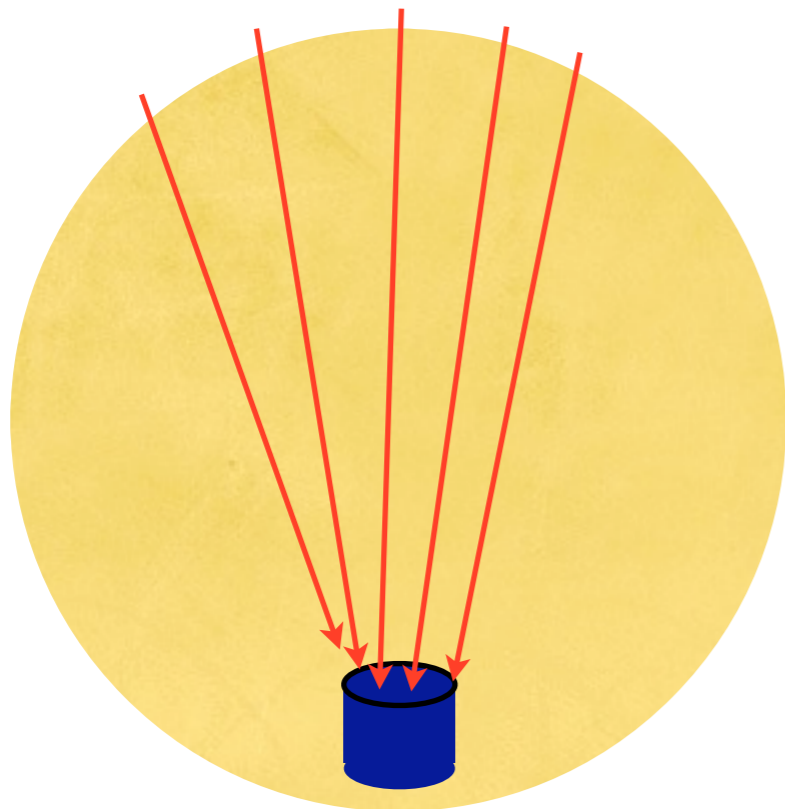


Effective Neutrino Area

- IceCube
- DeepCore
- Beyond DeepCore

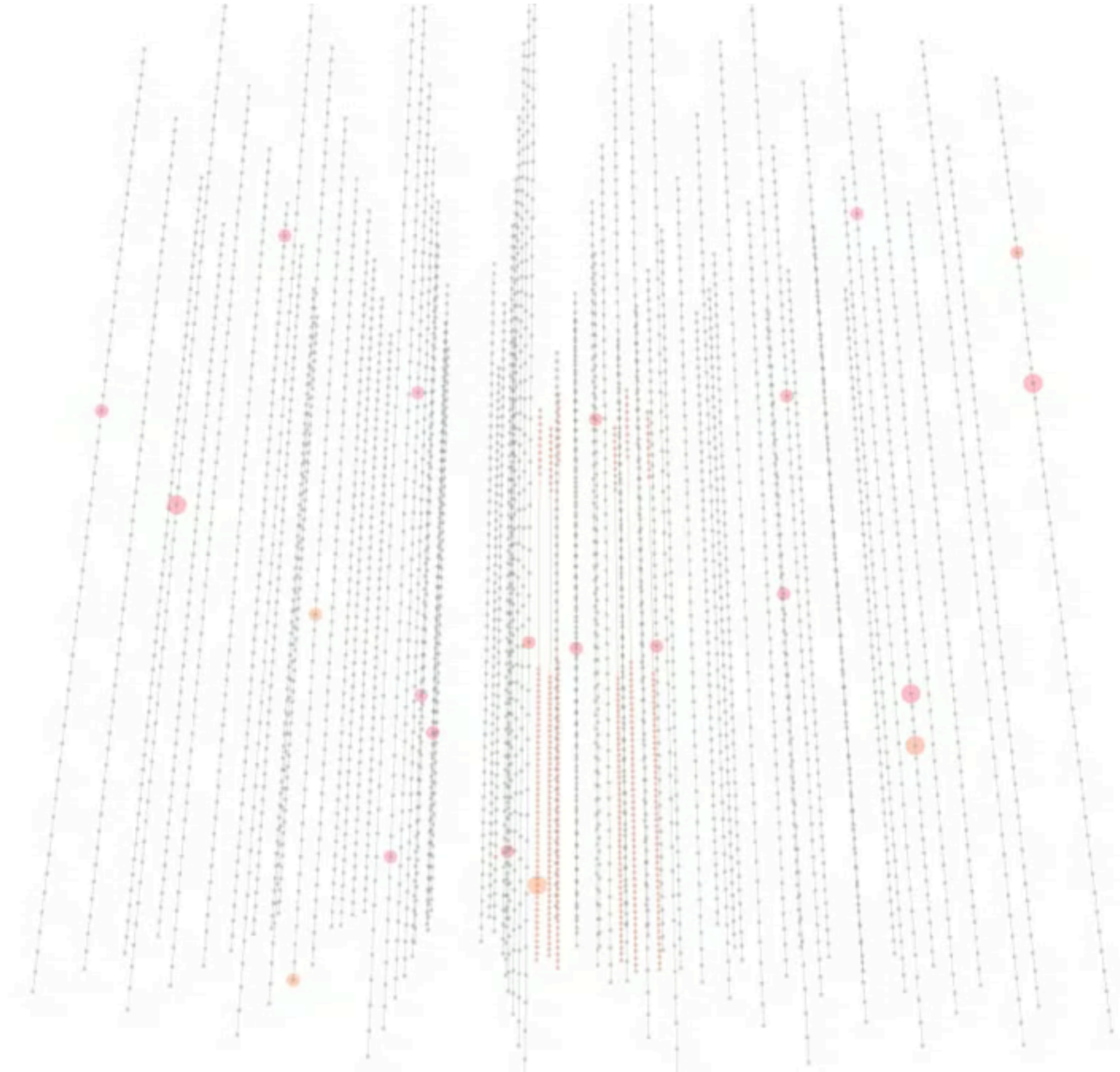


- ν_τ events, in addition to neutral current and ν_e events, produce cascades
- Signal will be smeared
 - Neutrino-lepton opening angle
 - Zenith angle resolution



Neutrino Candidate 2

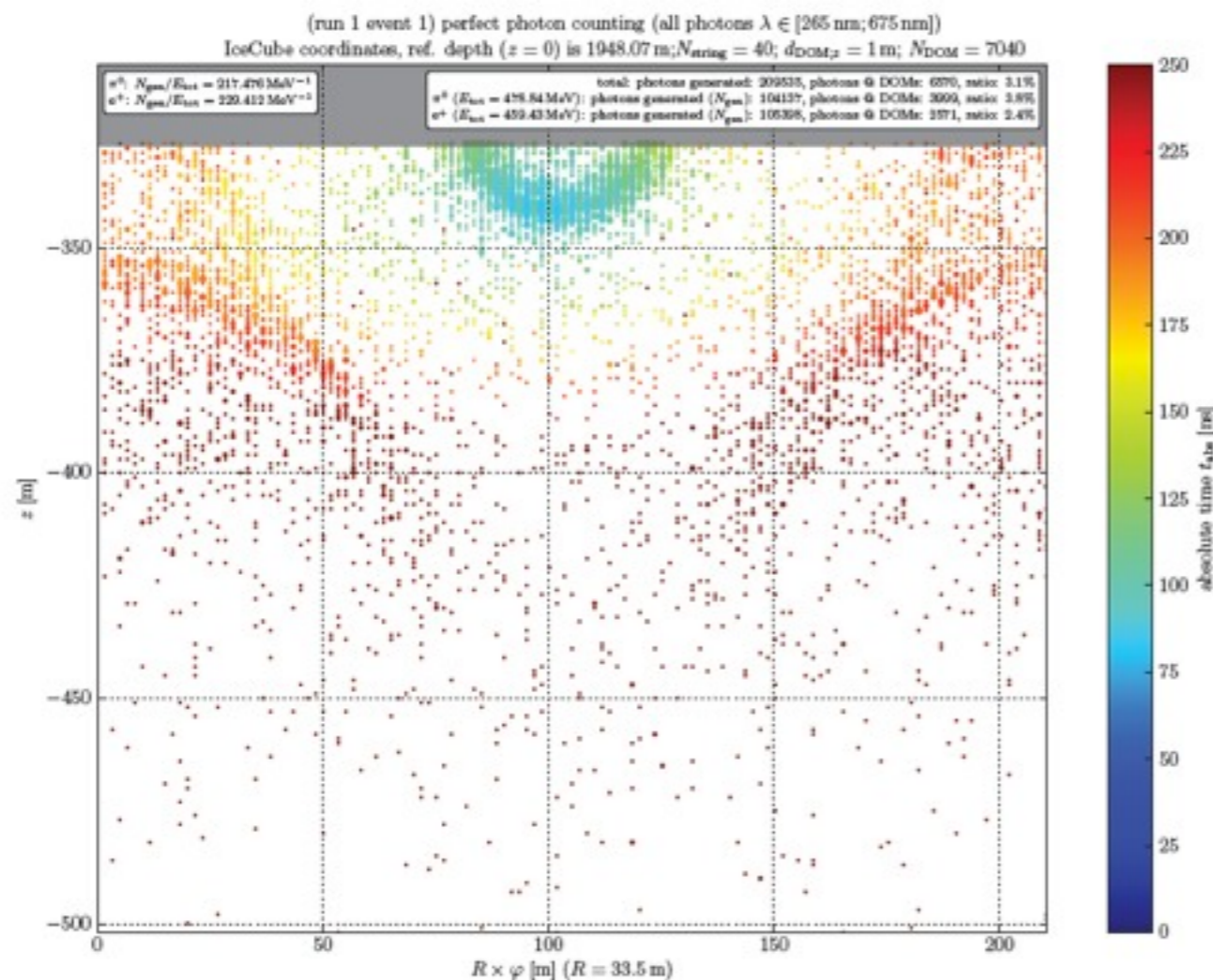
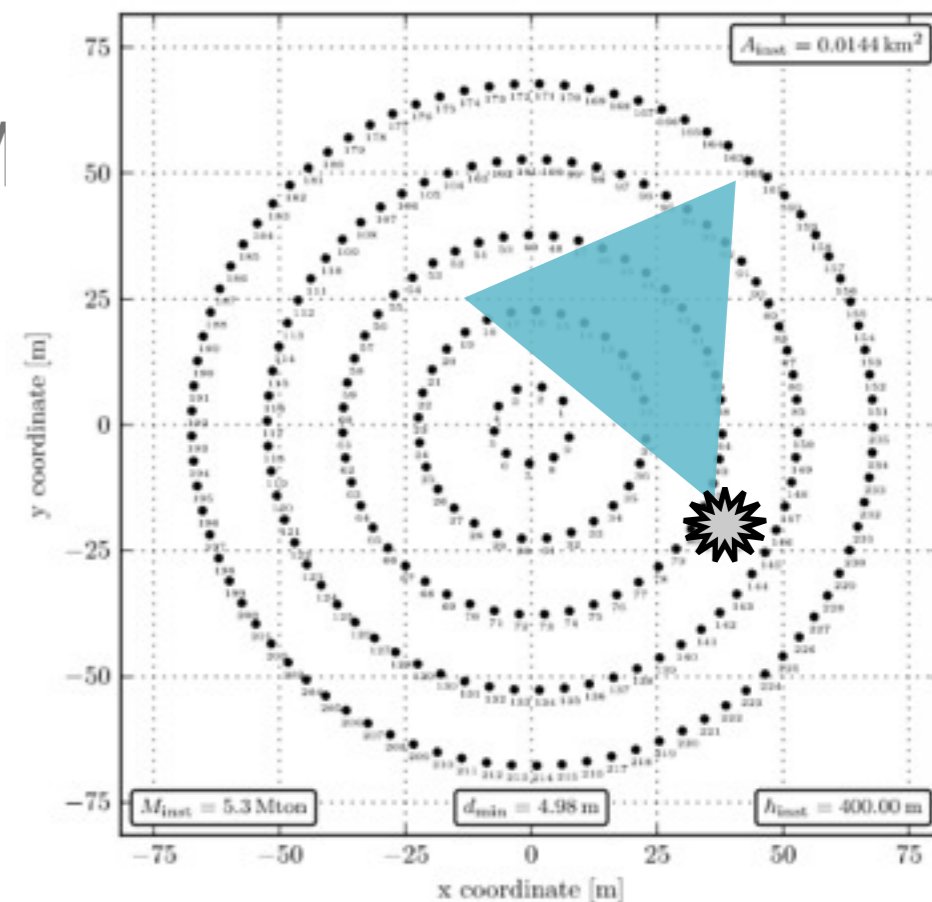
- IceCube
- DeepCore
- Beyond DeepCore



BDC Conceptual Design

- IceCube
- DeepCore
- Beyond DeepCore

- At 100% photon collection efficiency, cylindrical deployment and 1 meter OM spacing, cerenkov ring from proton decay is visible
- Simulation and testing is under active development



Cost Estimate for a One Megaton Detector

- Costs are driven completely by total photocathode area
 - Is there a more cost-efficient way to collect Cherenkov photons?
- Costs seem competitive, even if management, contingency, personnel, etc. increase the total
- Scaling up to larger volume would be roughly linear in cost
 - Scaling *down* might be harder – how much photocathode can we pack in per unit volume?

