IceCube - DeepCore - PINGU

D. Jason Koskinen
Penn State

Implication of Neutrino Flavor Oscillations (INFO) 11
July 2011

Message

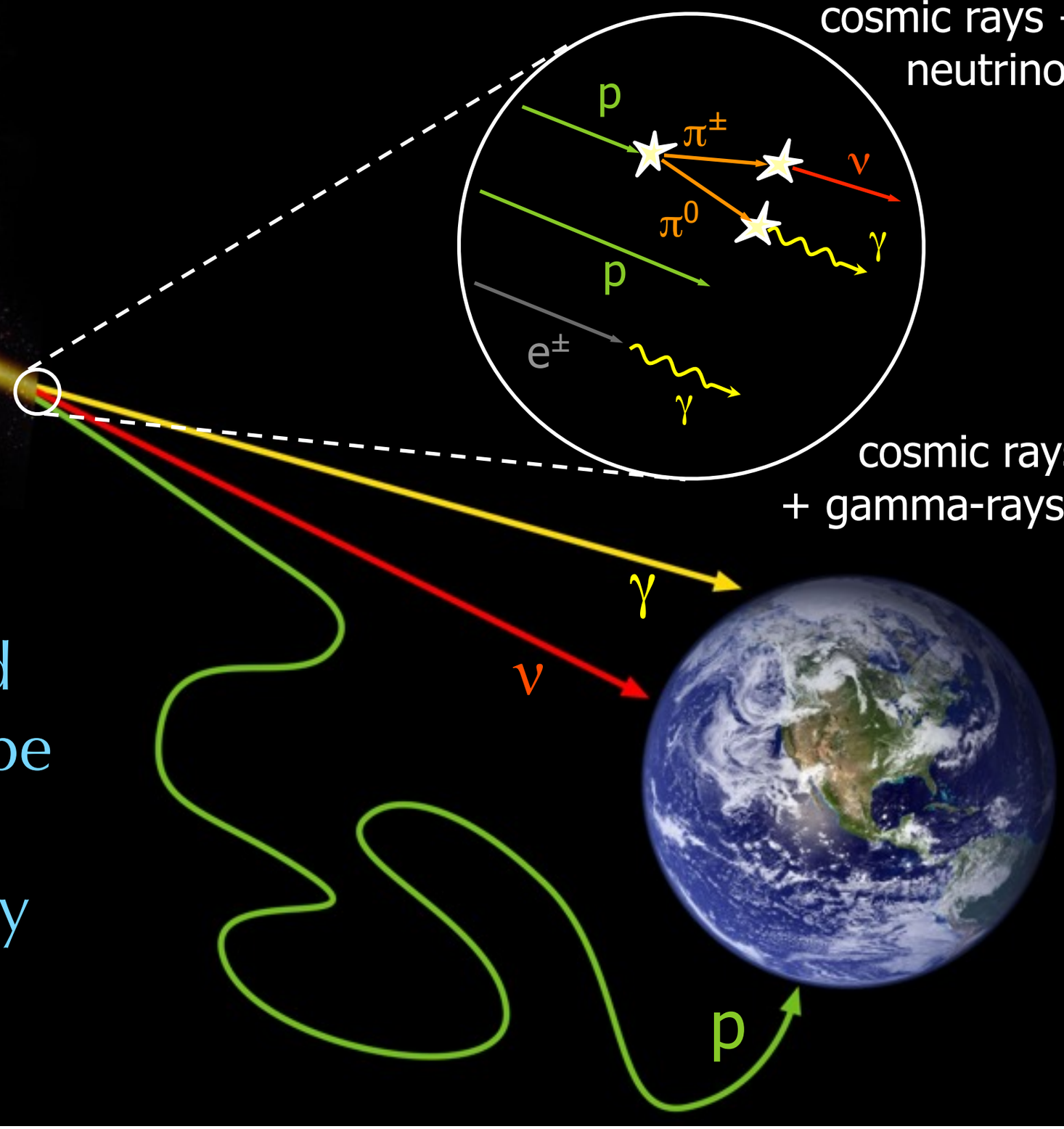
- IceCube astrophysical neutrino physics is alive and well
- DeepCore is an IceCube infill deployed to enhance sensitivity to neutrinos from ~10 GeV to ~300 GeV
  - Dark Matter
  - Neutrino Oscillations
- DeepCore is a multi-megaton scale neutrino detector at tens of GeV, which is situated inside a gigaton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

IceCube Classic

Particle Astrophysics

- 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)

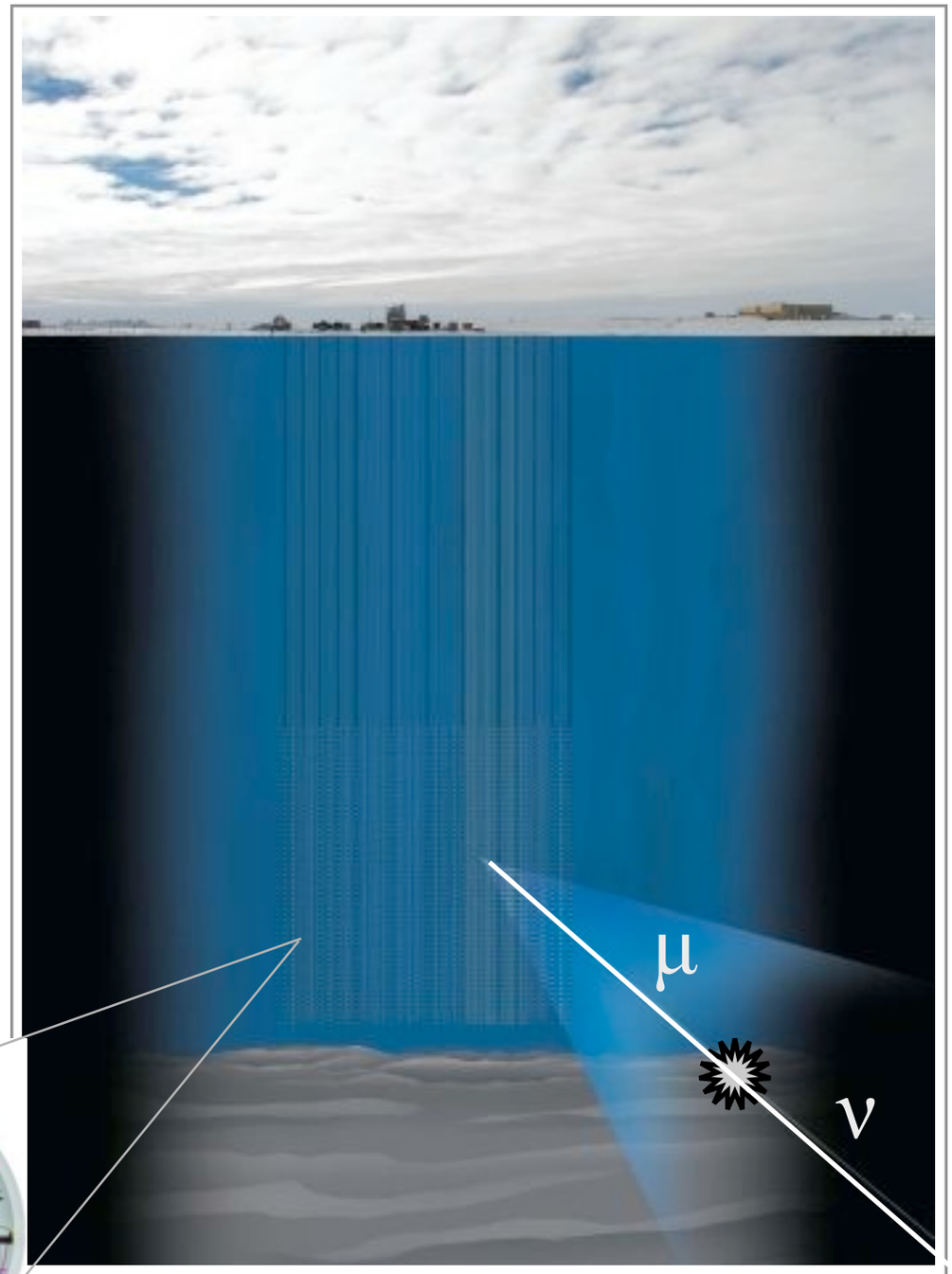
Multimessenger Astronomy

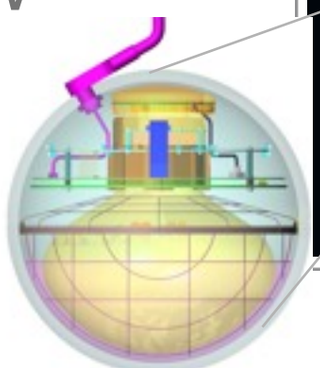


Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

IceCube

- ~1km^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
- Deployed 1.5-2.5km below the surface





IceCube DOM

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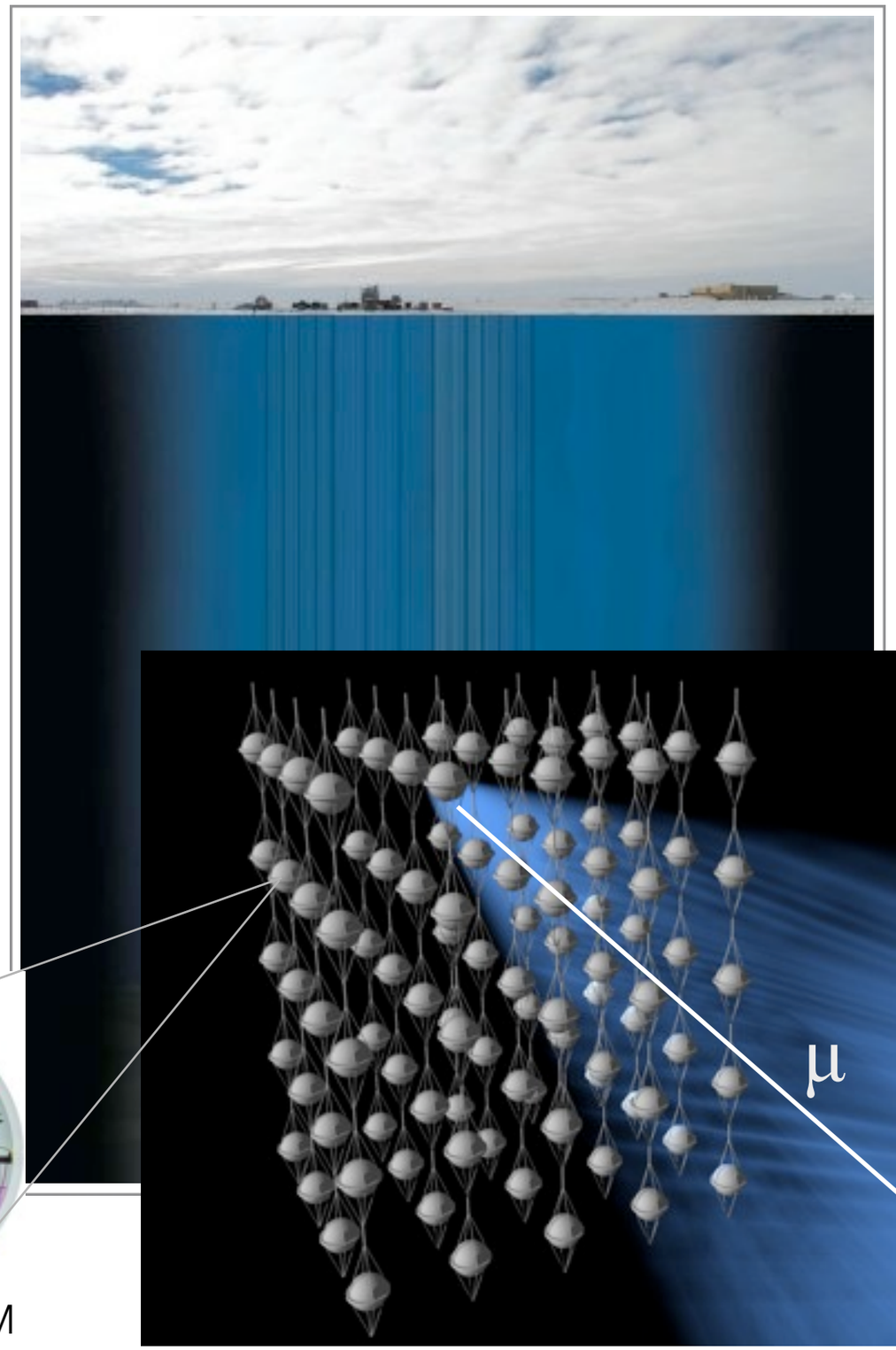
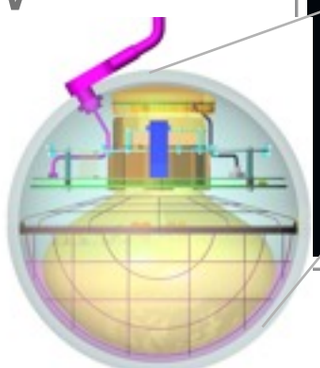
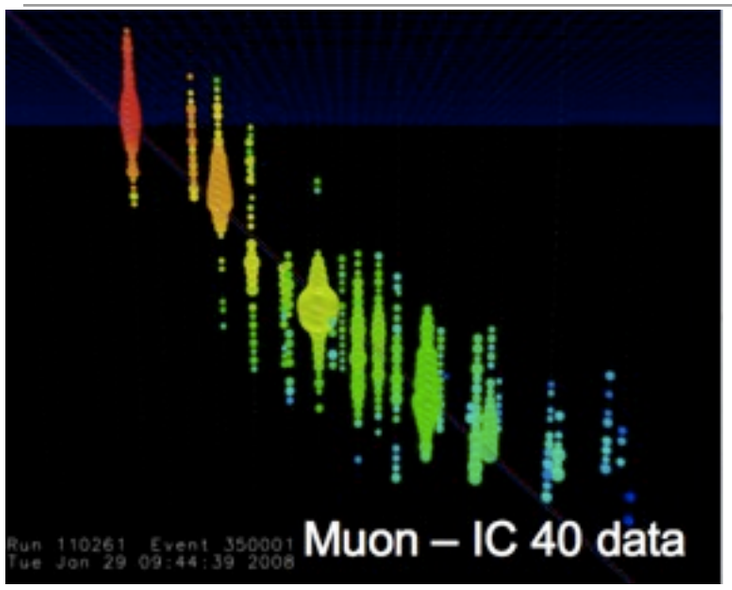




IceCube DOM

Detection Principles

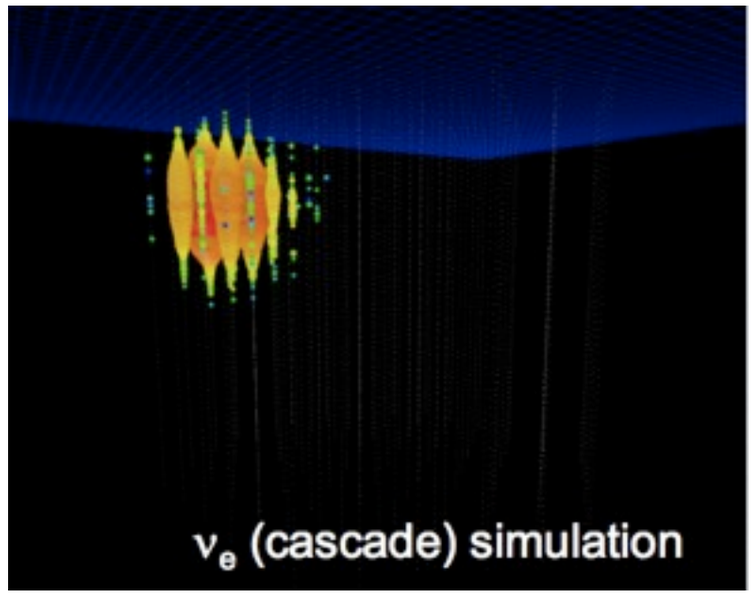


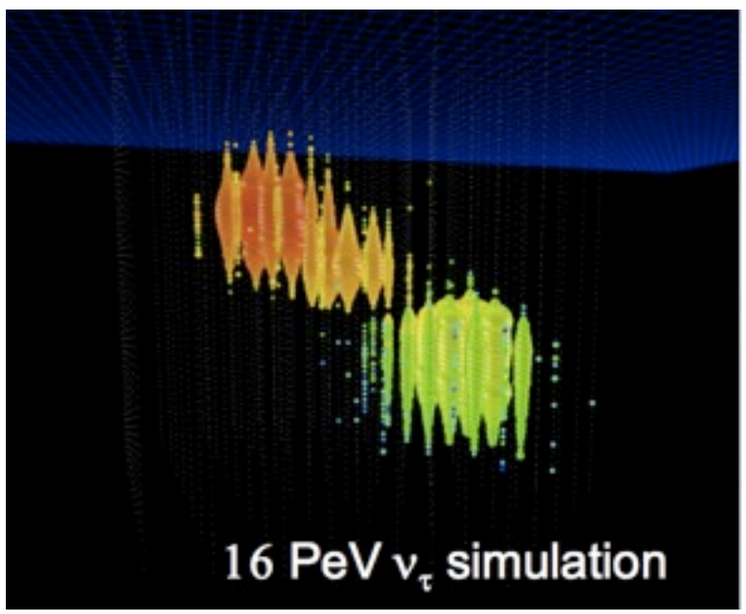
Tracks:

- 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

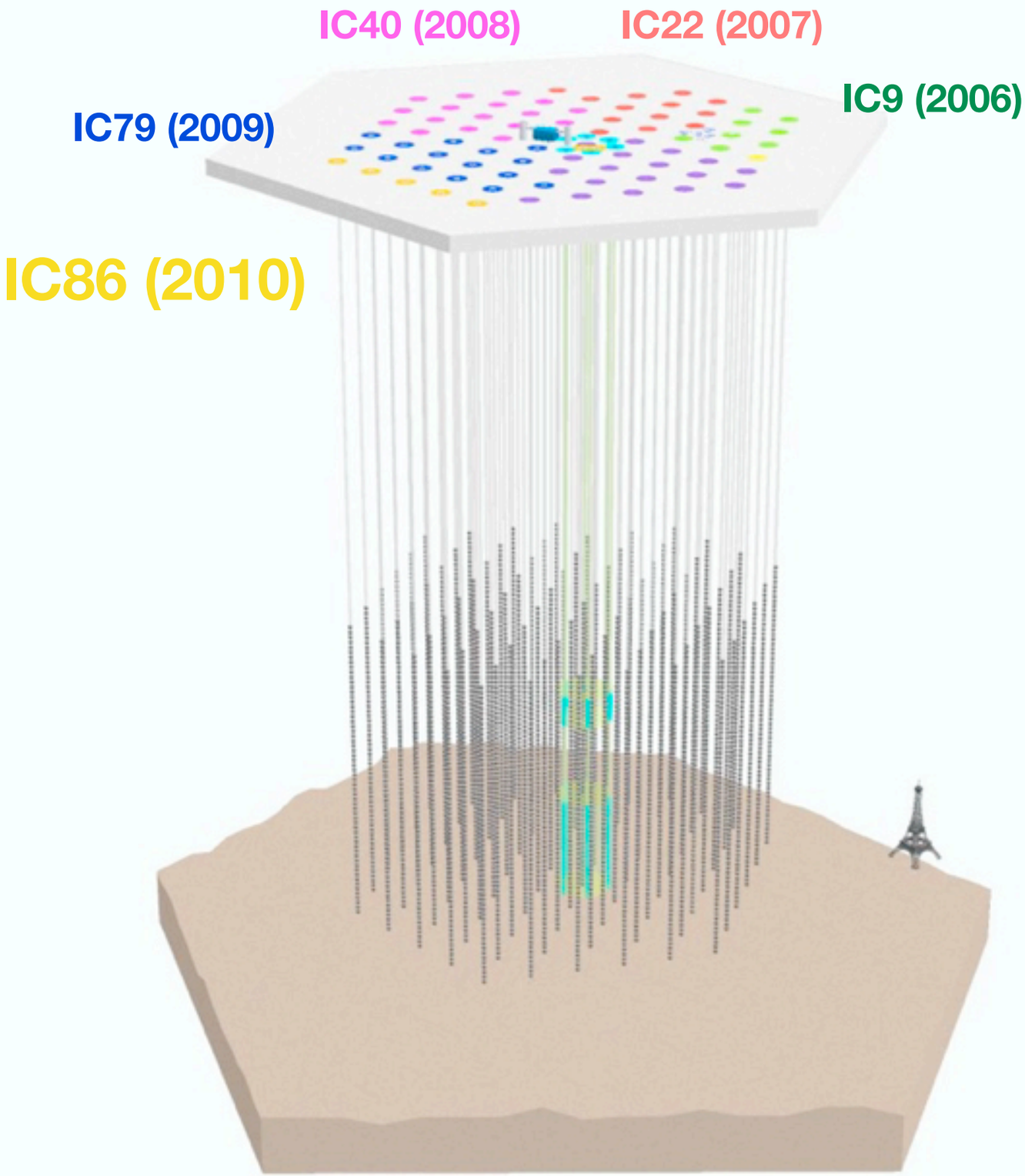
Collaboration

The IceCube Collaboration

36 institutions - 4 continents - ~250 Physicists

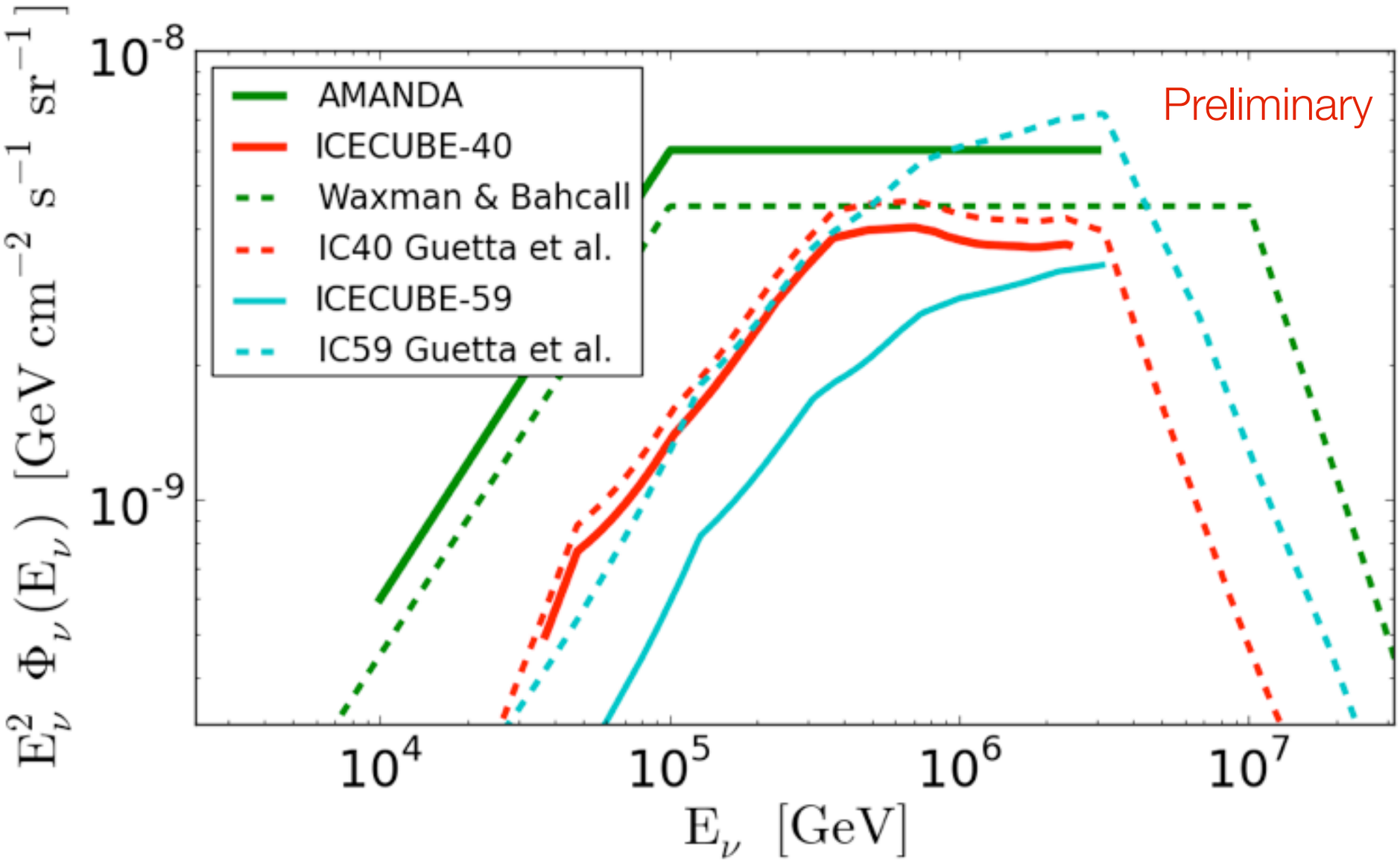
Data Sets by year

- IceCube
- DeepCore
- Beyond DeepCore



Gamma Ray Bursts

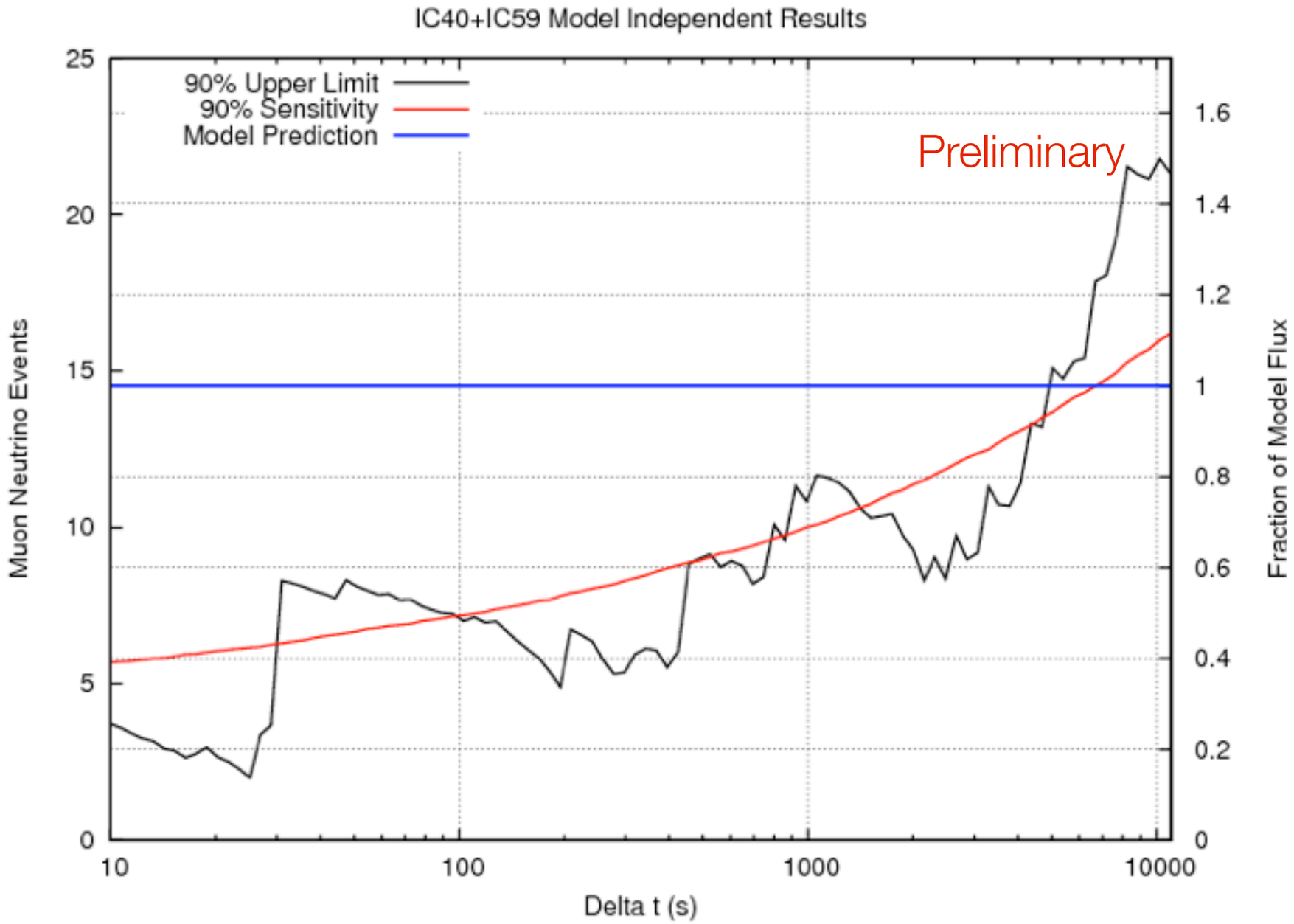
- Searches for neutrinos produced by p+γ interactions during the primary fireball



IC40 result
arXiv:1101.1448

GRB - Model Independent

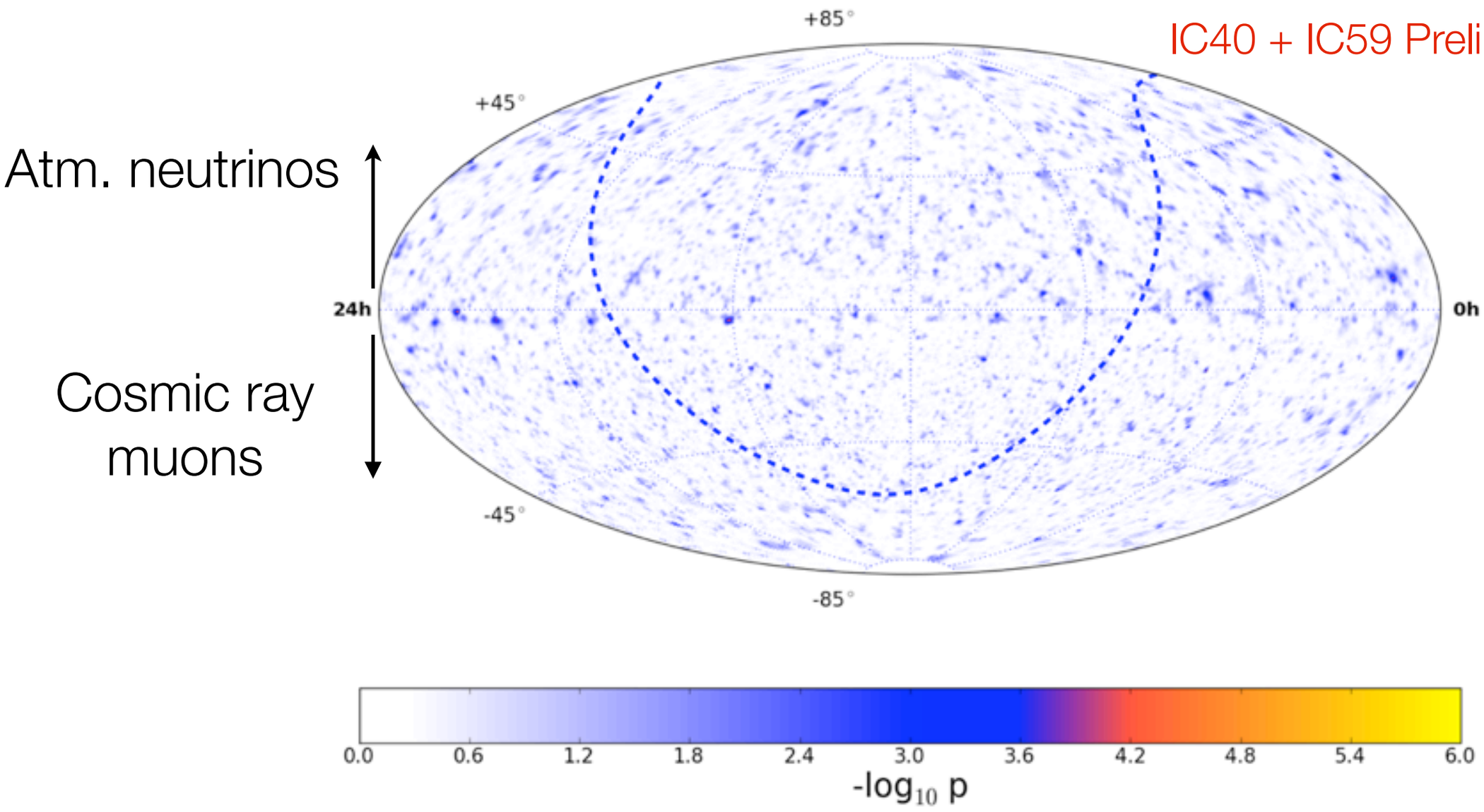
- IceCube
- DeepCore
- Beyond DeepCore



Astrophysical Point Source

- IceCube
- DeepCore
- Beyond DeepCore

- Sky Map consistent with background



Further Topics/Papers

- 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

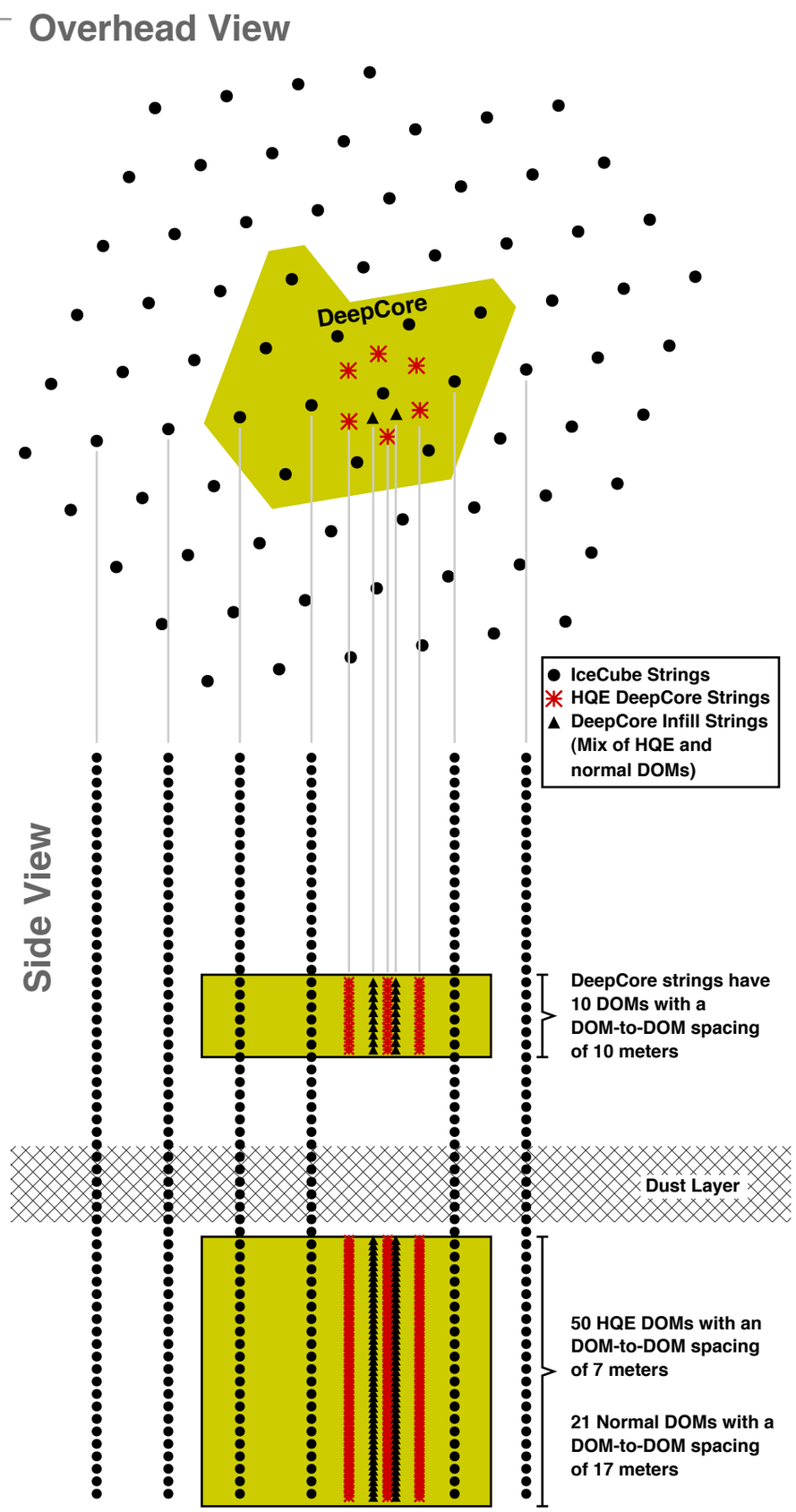
Below TeV+ Energies
DeepCore

IceCube

DeepCore

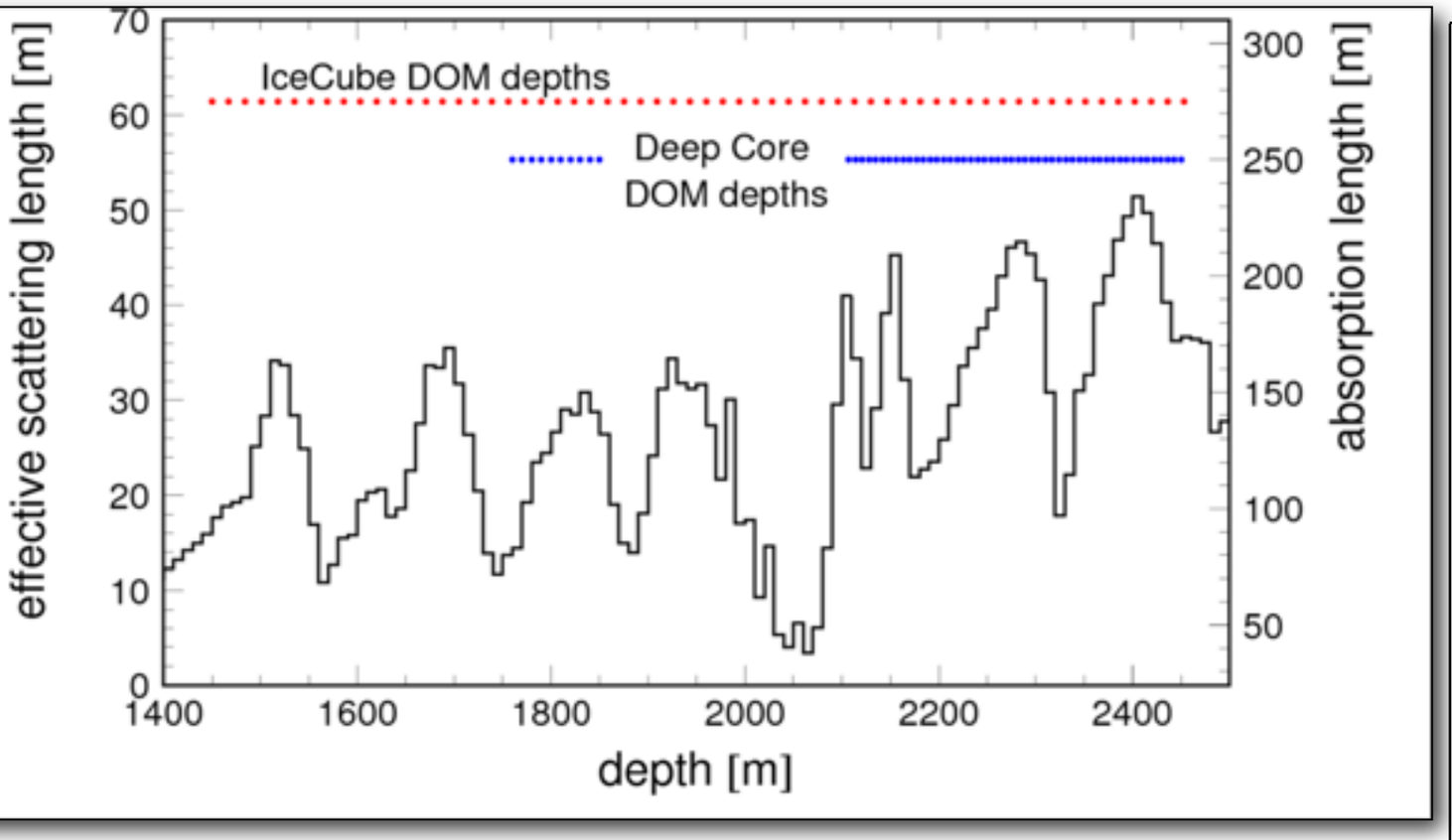
DeepCore

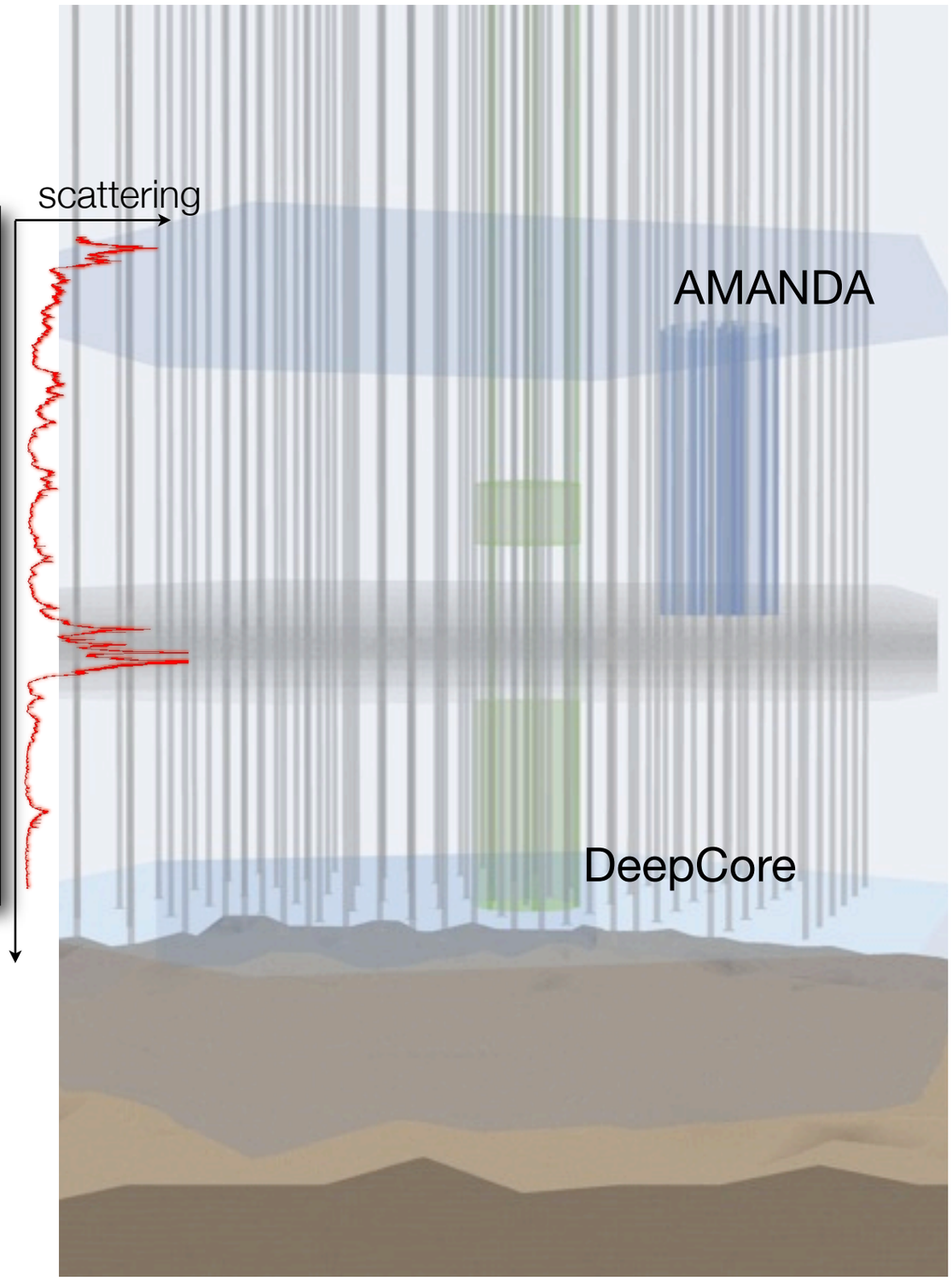
- 8 special Strings combined with 12 nearby standard IceCube Strings
- 72 m interstring spacing versus 125 m for IceCube
  - 7 m DOM spacing vs. 17 m
  - High Quantum Efficiency PMTs (35% higher QE)
- Deepest clearest ice
  - 40m scattering length
  - 140m absorption length



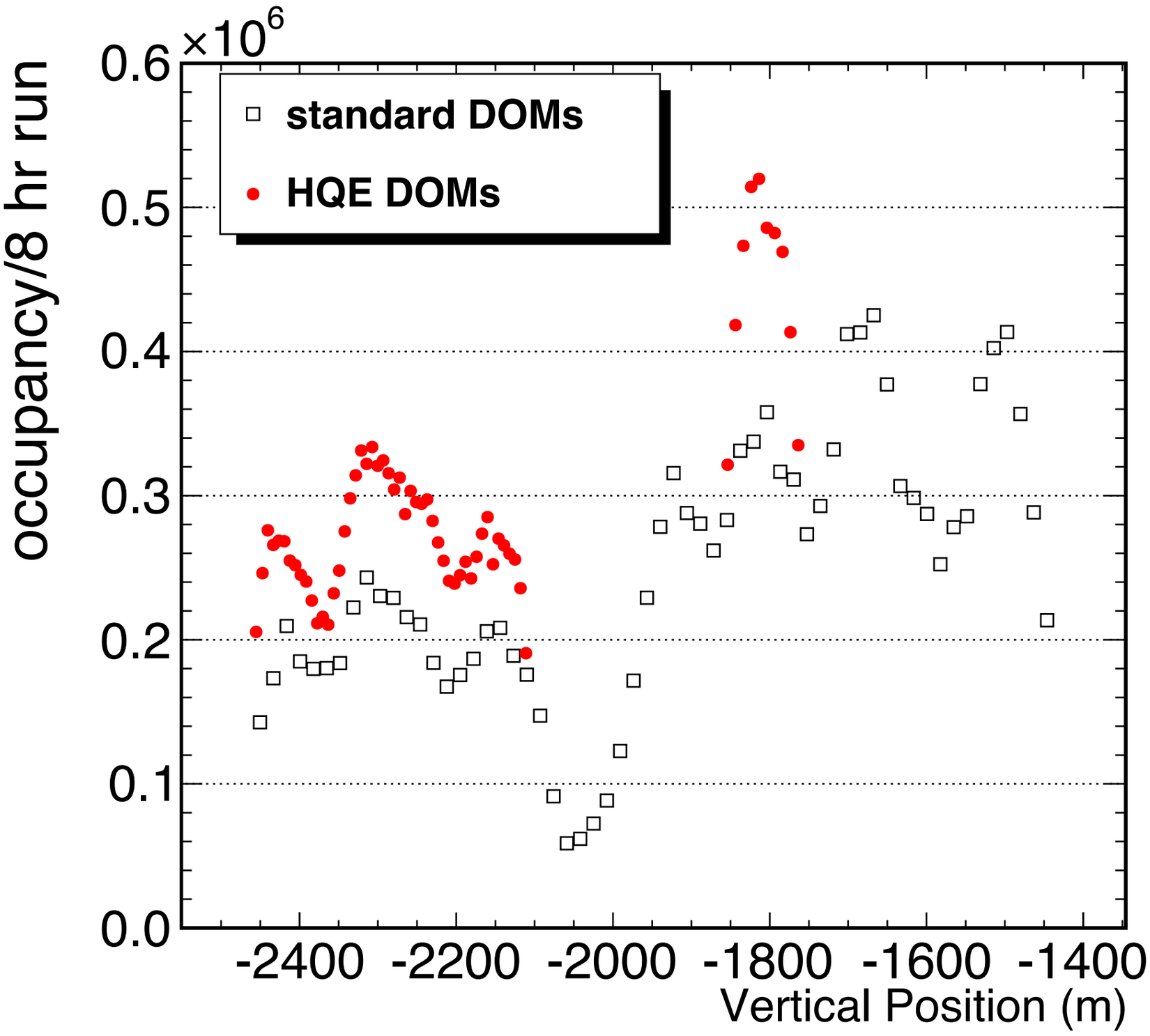
Dust at Depth

- IceCube
- DeepCore
- Beyond DeepCore



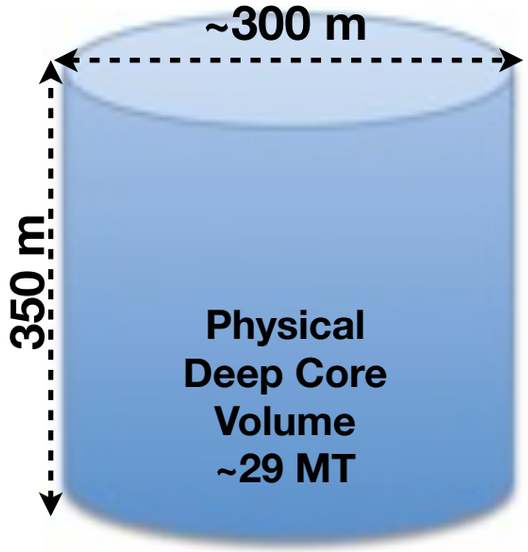


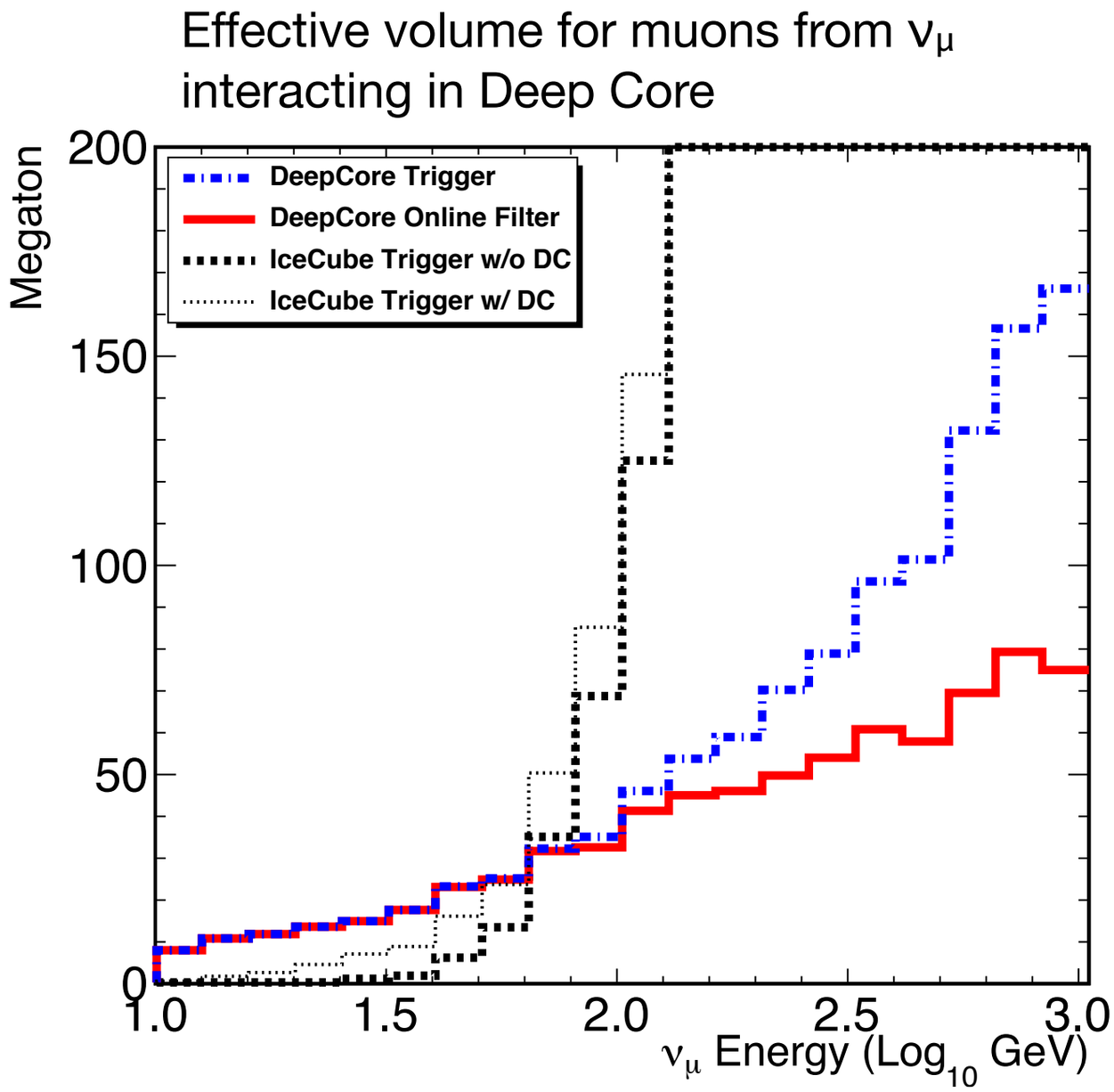
Better PMTs


standard DOMs
HQE DOMs
occupancy/8 hr run
×10^6
0.6
0.5
0.4
0.3
0.2
0.1
0.0
-2400
-2200
-2000
-1800
-1600
-1400
Vertical Position (m)

Size Matters

- Online Veto loosely constrains vertex to be within DeepCore volume
  - Physical volume is ~29 MTon





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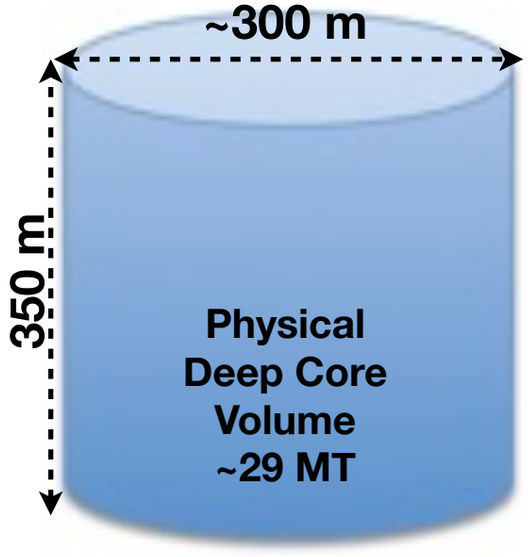

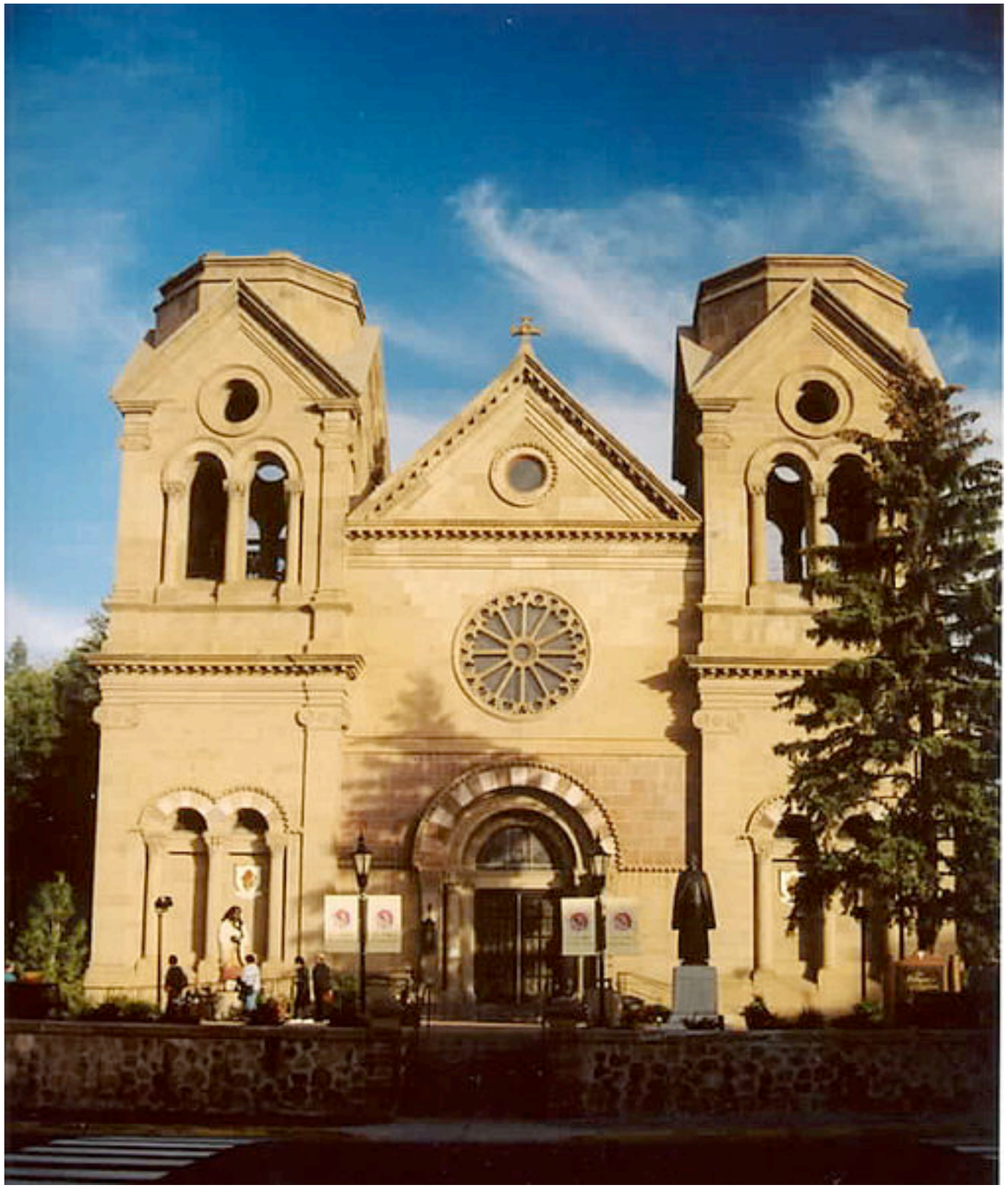

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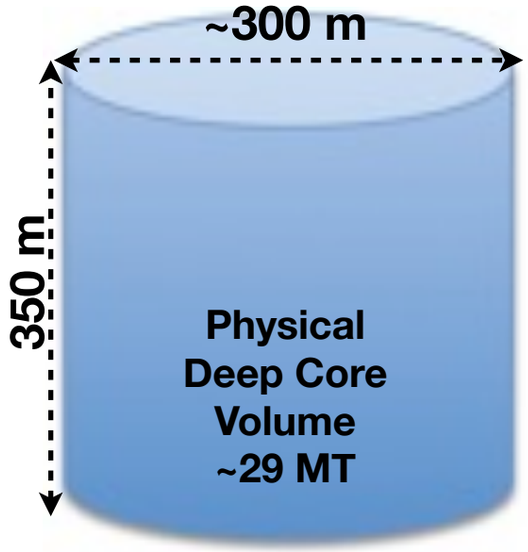
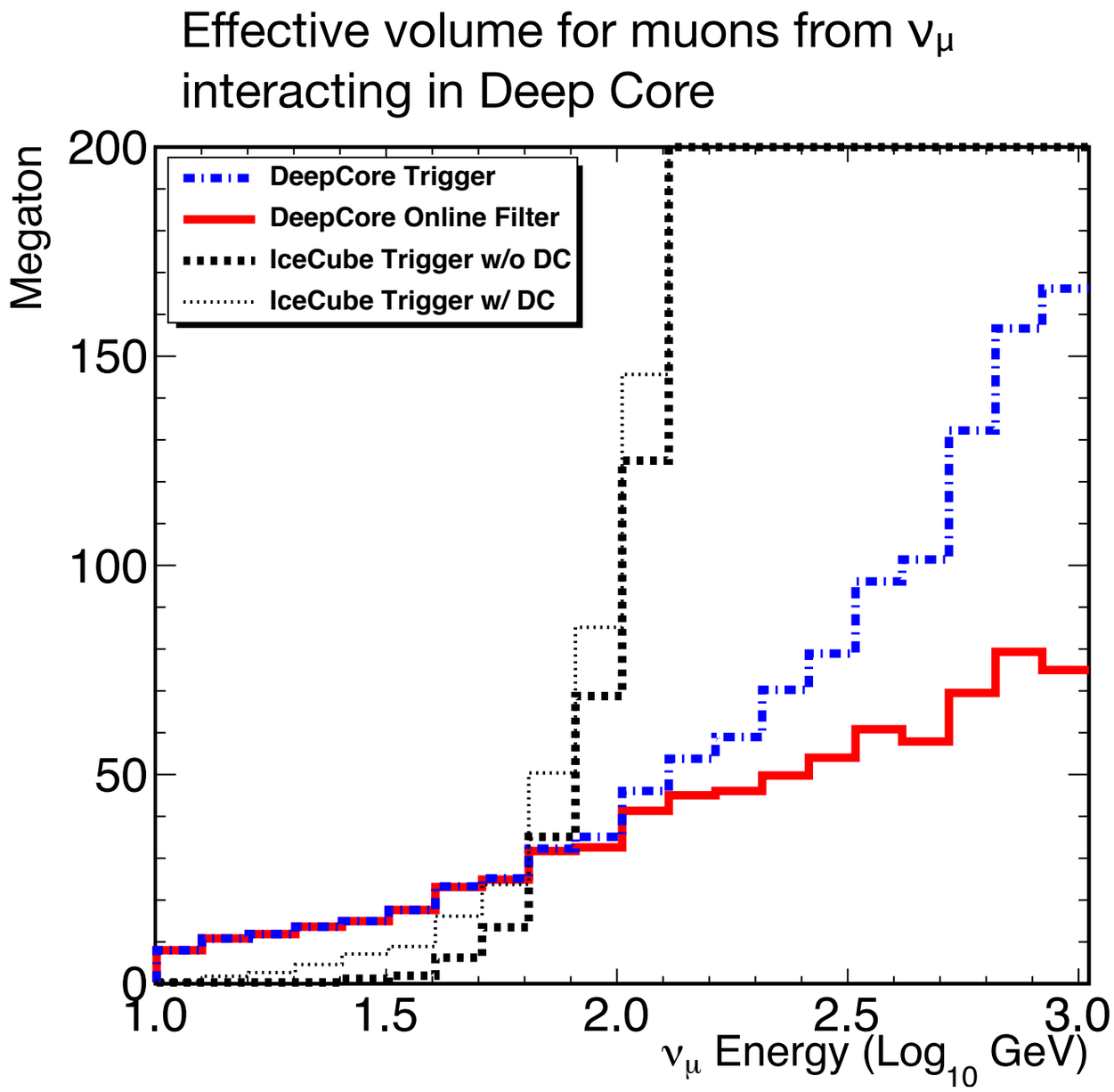
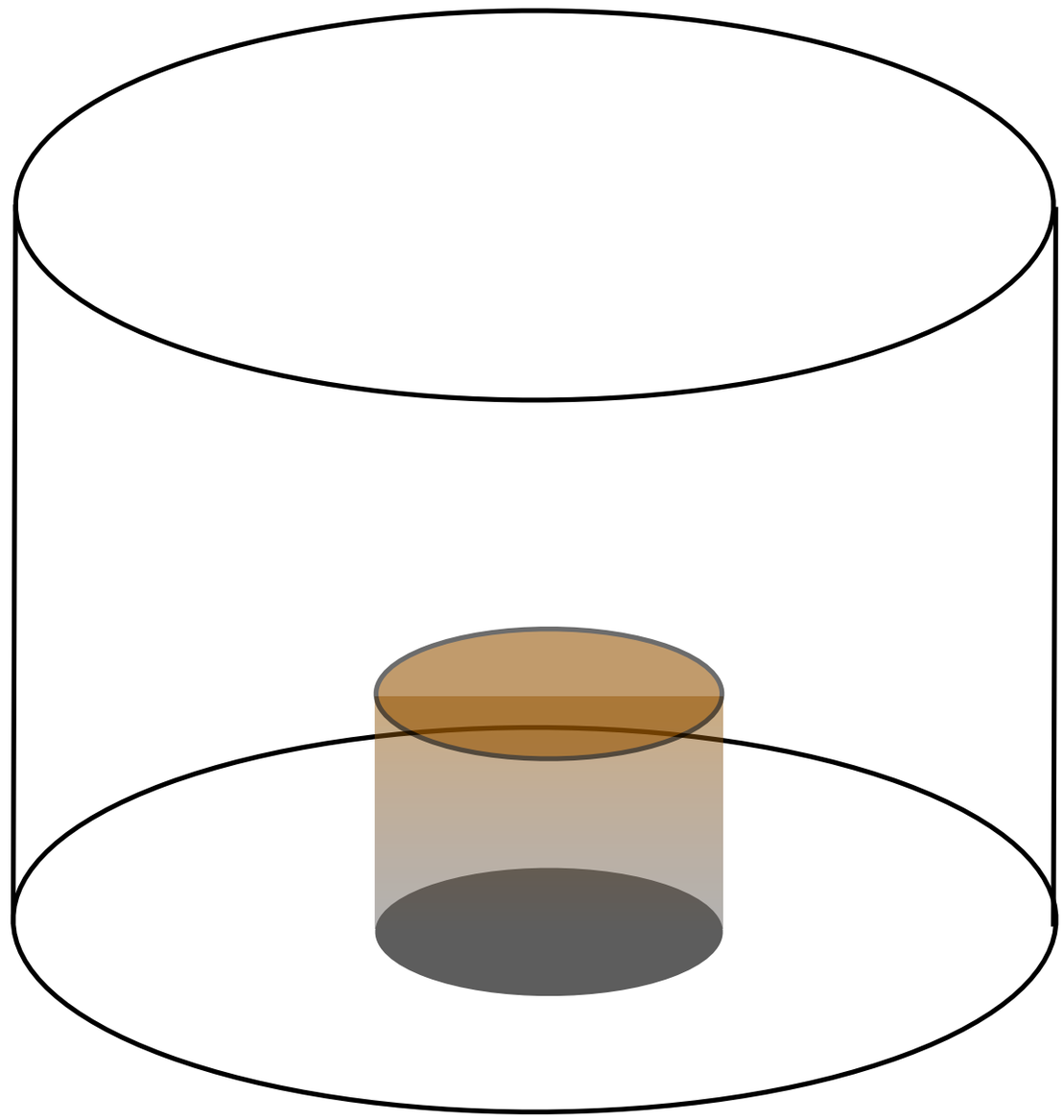




More Signal = More Bkg



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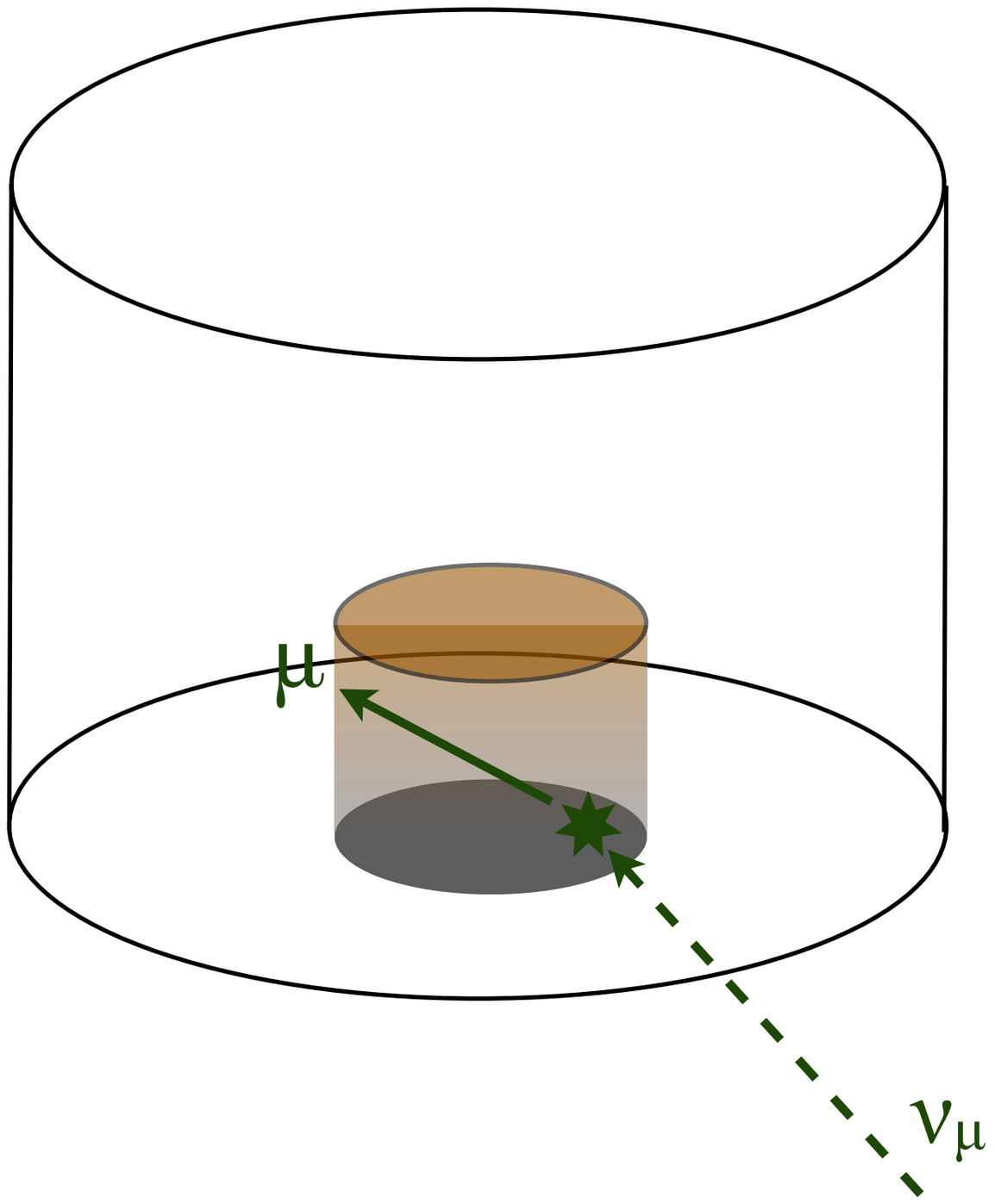

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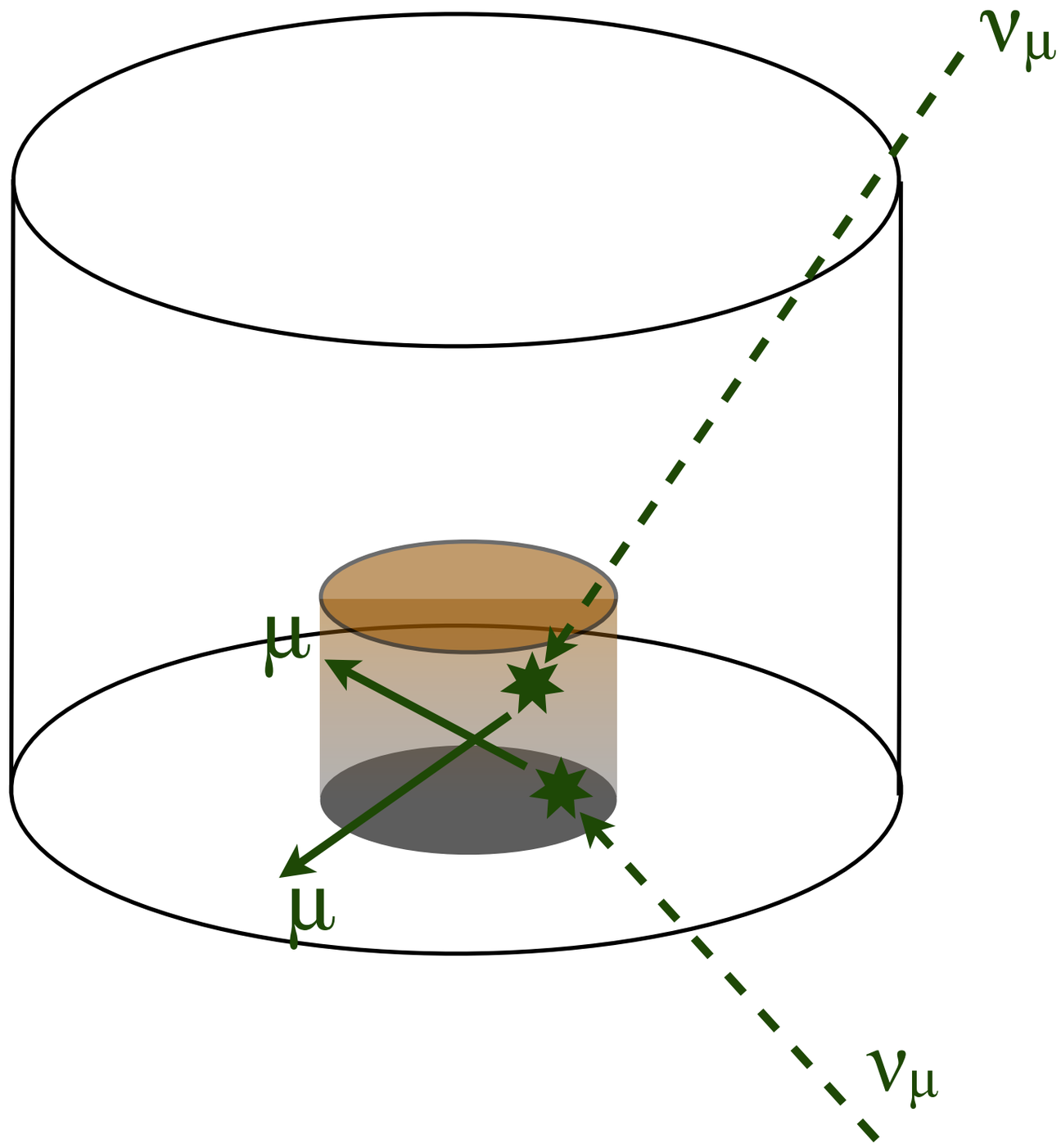
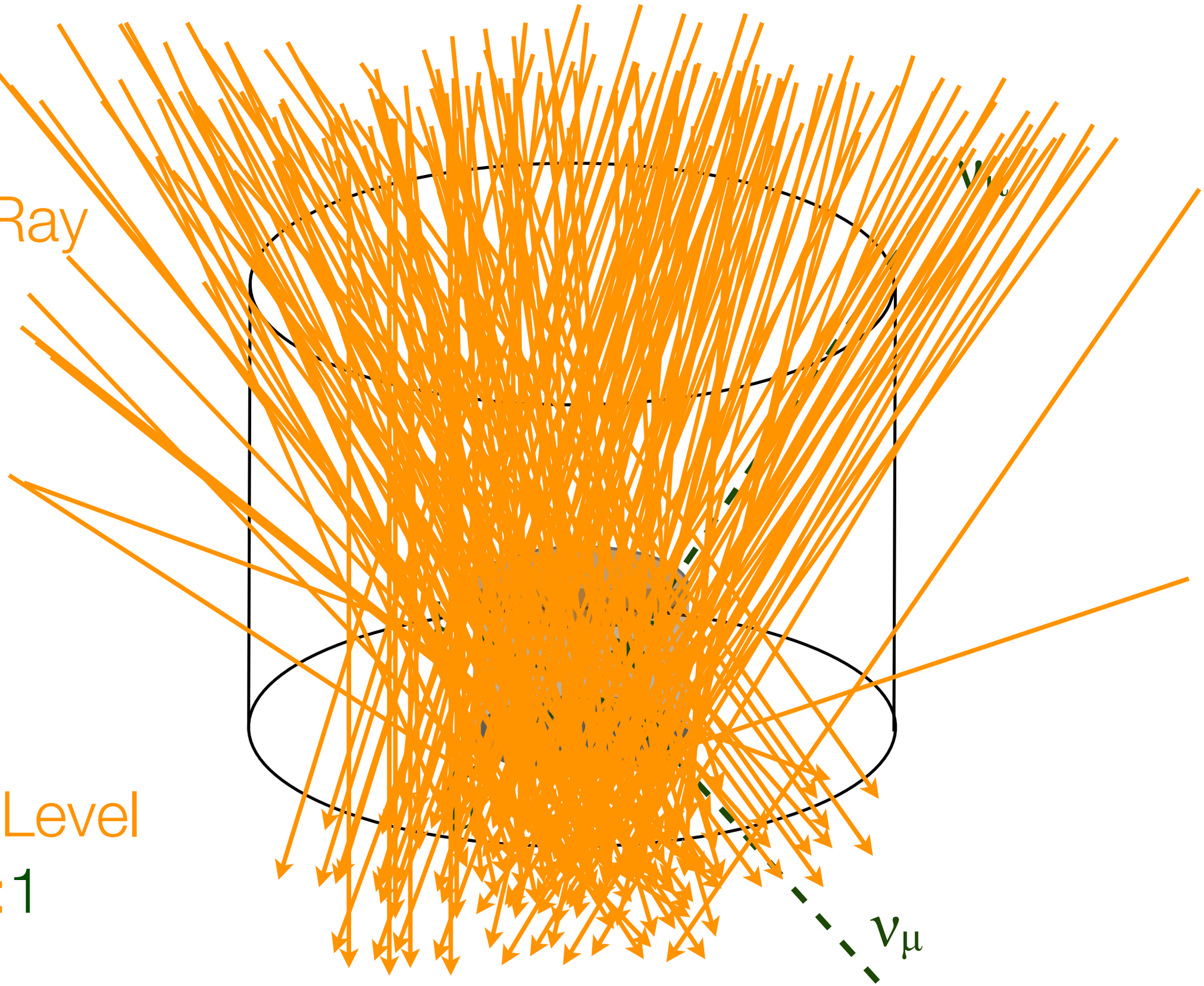


More Signal = More Bkg

- IceCube
- **DeepCore**
- Beyond DeepCore

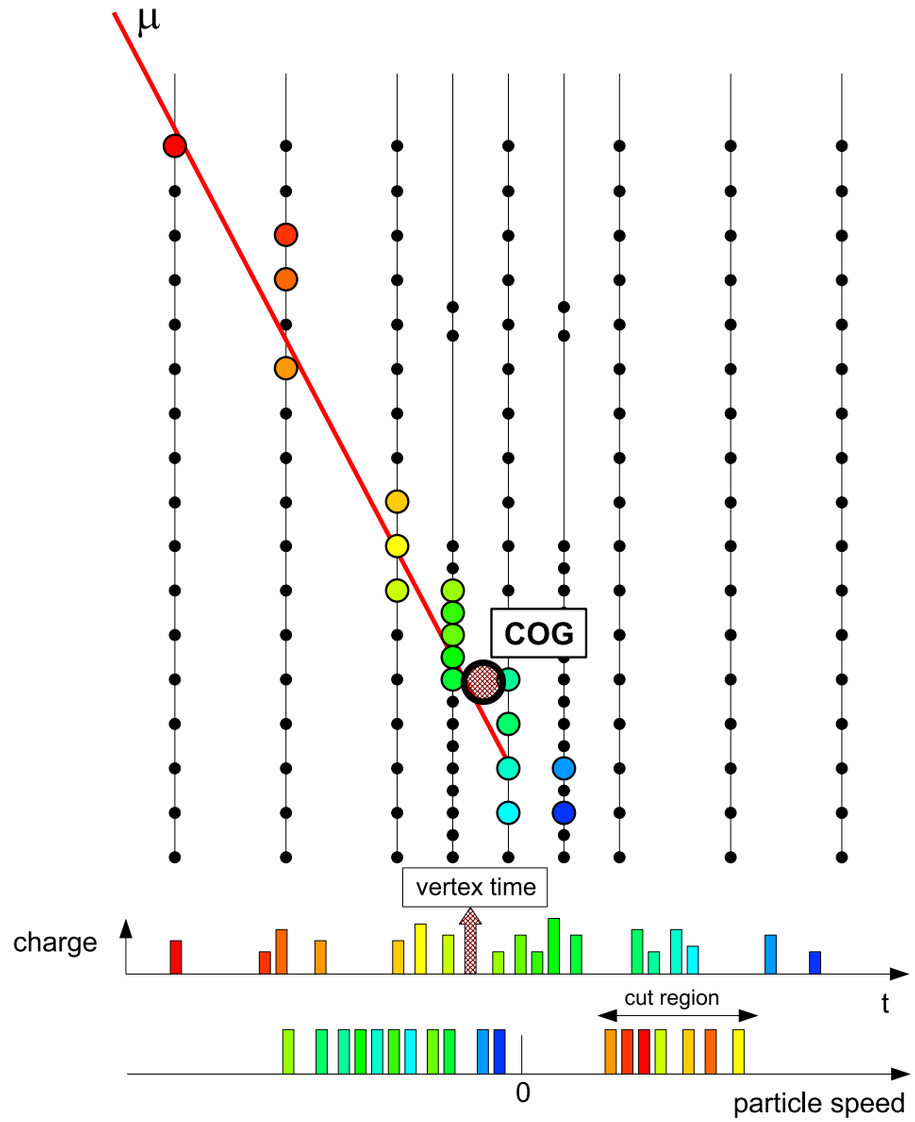
Cosmic Ray
μ



Trigger Level
10^6:1

Background Rejection

- 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 ~$8x10^3$ with neutrino retention of ~99%
  - Further rejection employed offline

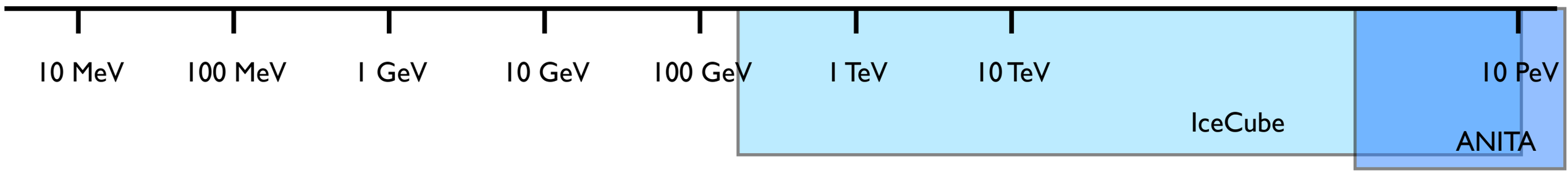


DeepCore Neutrinos

Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore

Accelerator based

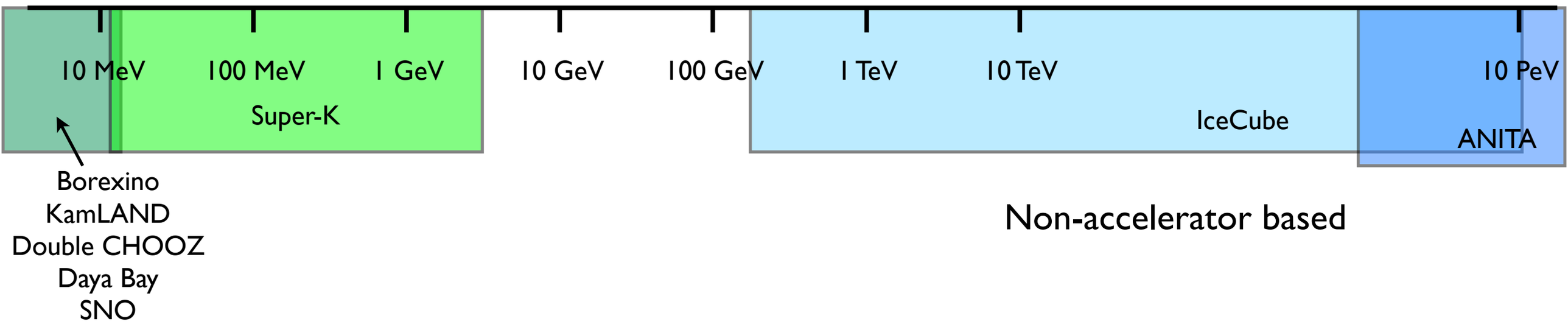


Non-accelerator based

Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore

Accelerator based

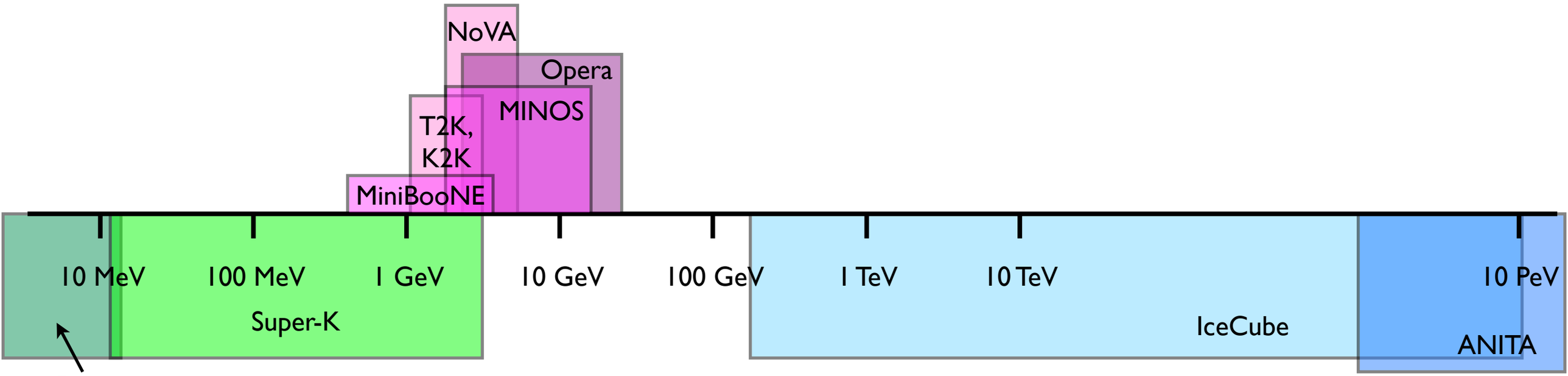


Non-accelerator based

Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore

Accelerator based



Non-accelerator based

Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore

Accelerator based

NoVA
Opera
MINOS
T2K,
K2K
MiniBooNE

10 MeV
100 MeV
1 GeV
10 GeV
100 GeV
1 TeV
10 TeV
10 PeV

Super-K
IceCube
ANITA

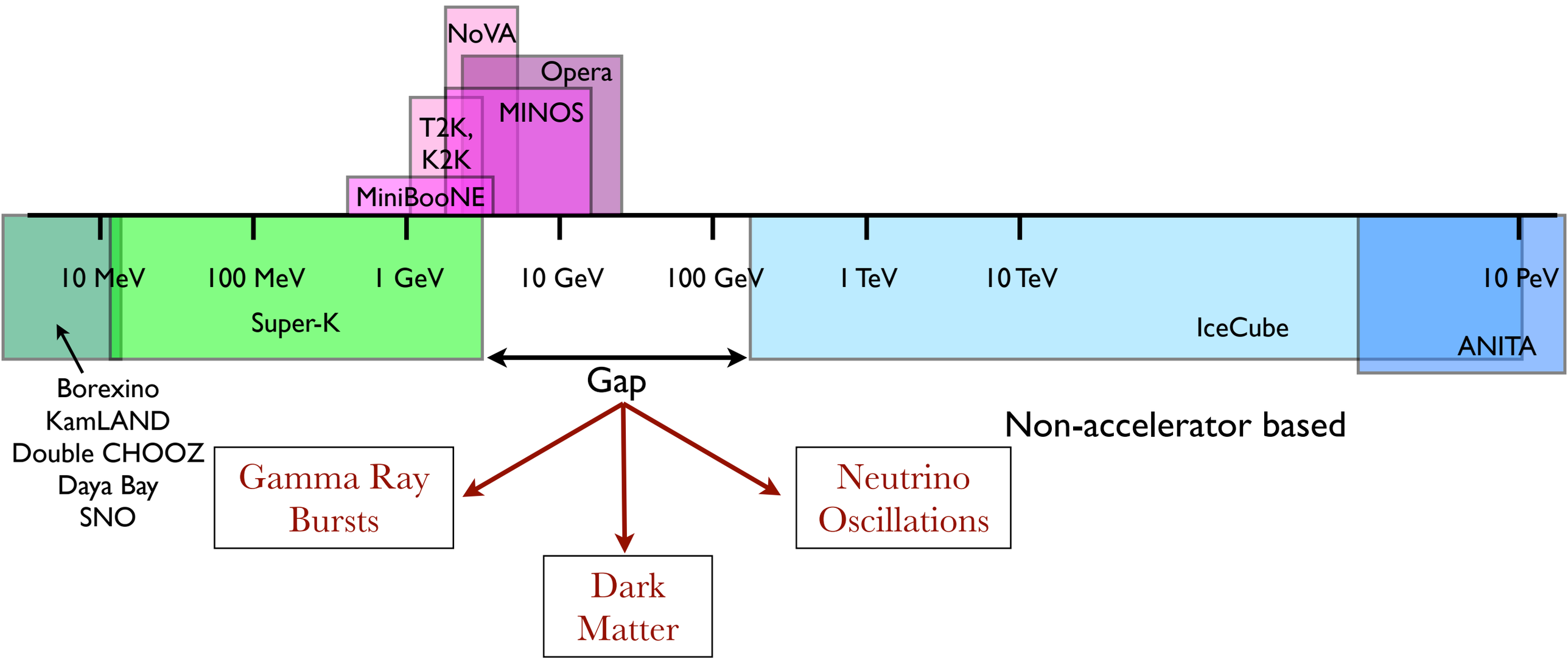
Gap

Borexino
KamLAND
Double CHOOZ
Daya Bay
SNO

Non-accelerator based

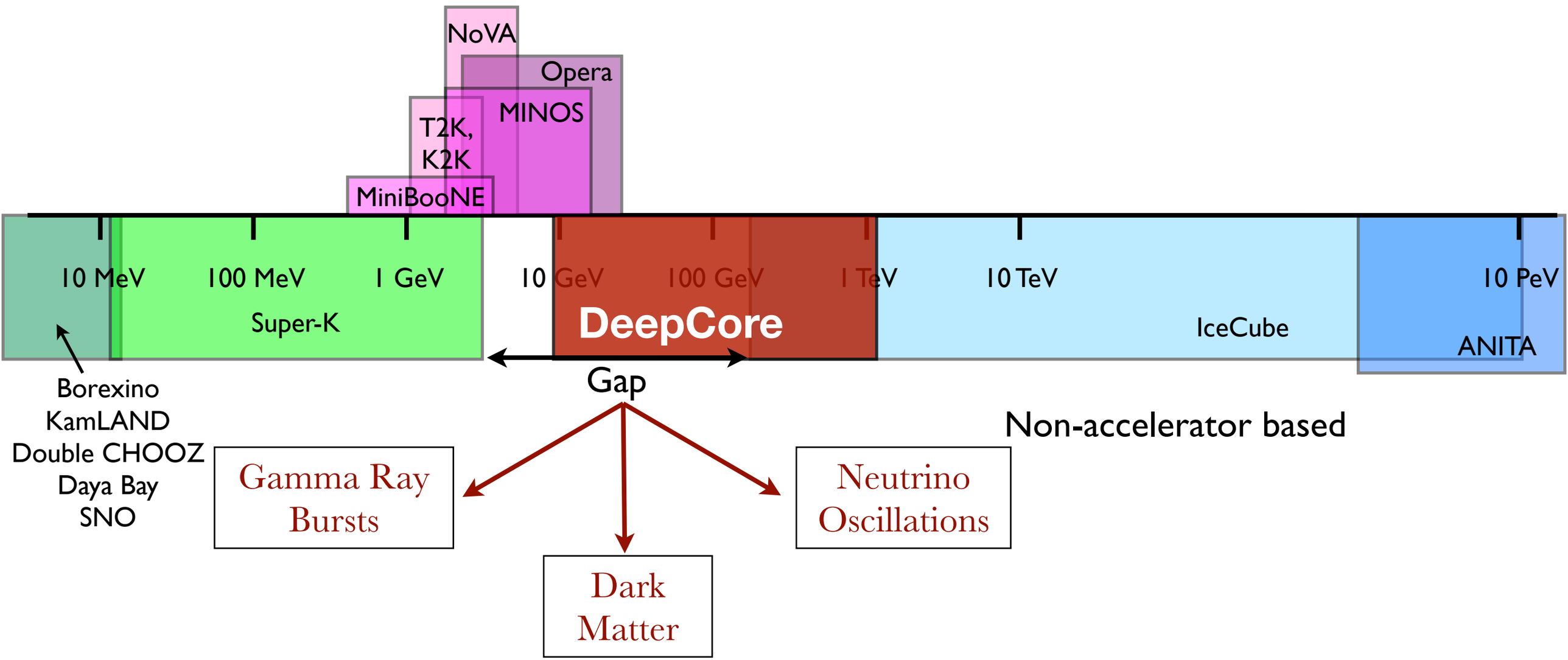
Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore



Experimental Landscape

- IceCube
- DeepCore
- Beyond DeepCore



Experimental Landscape

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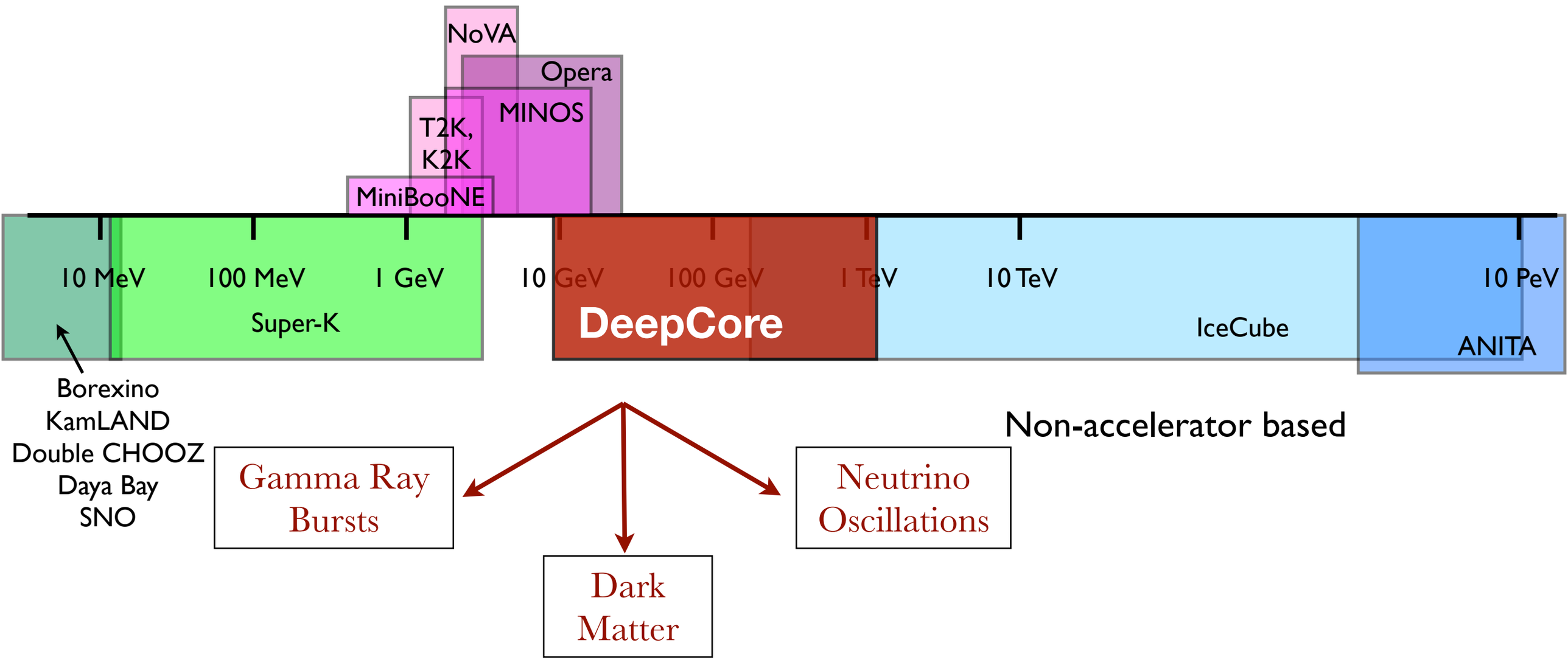
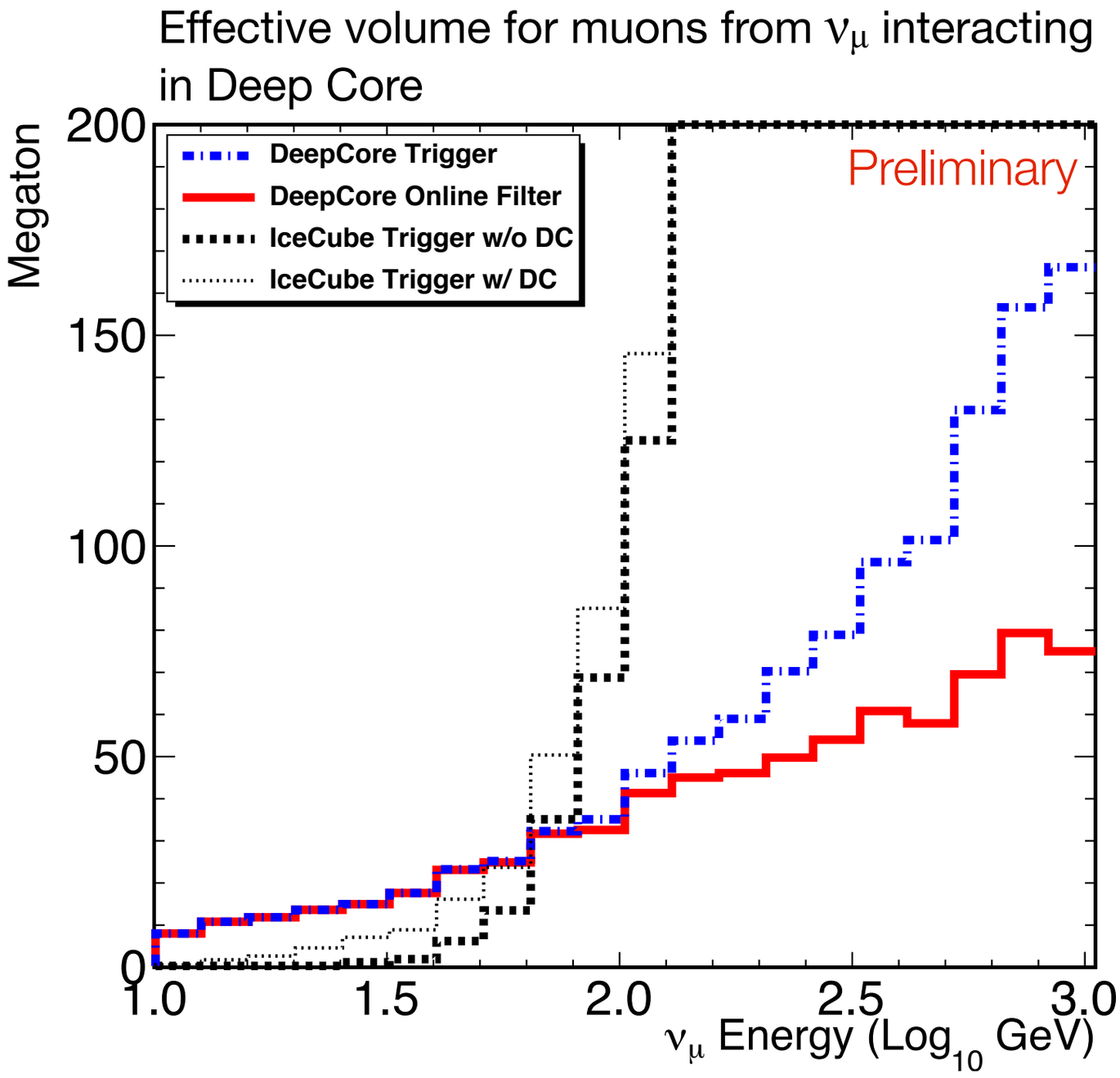


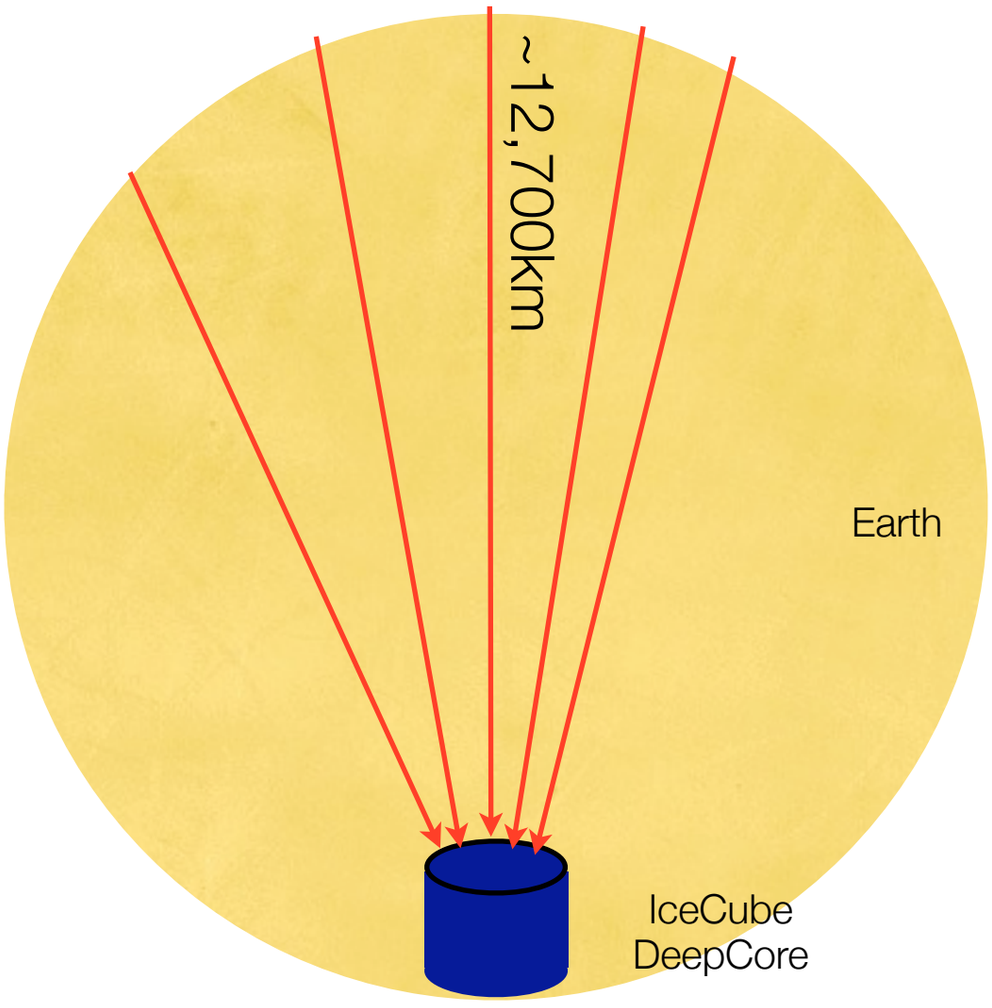
Oscillation

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

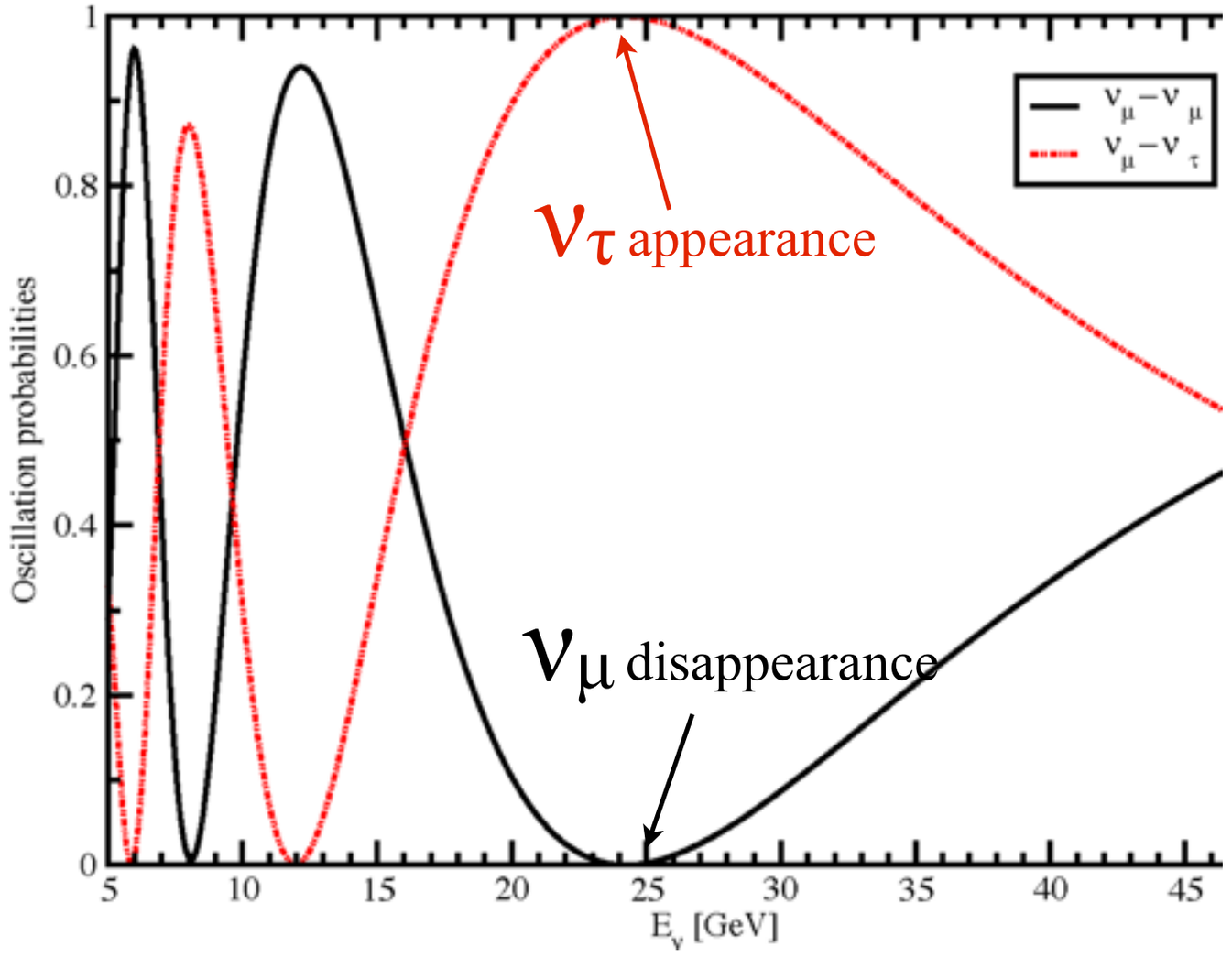


Neutrino Oscillation Source

- 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
  - Beam never turns off

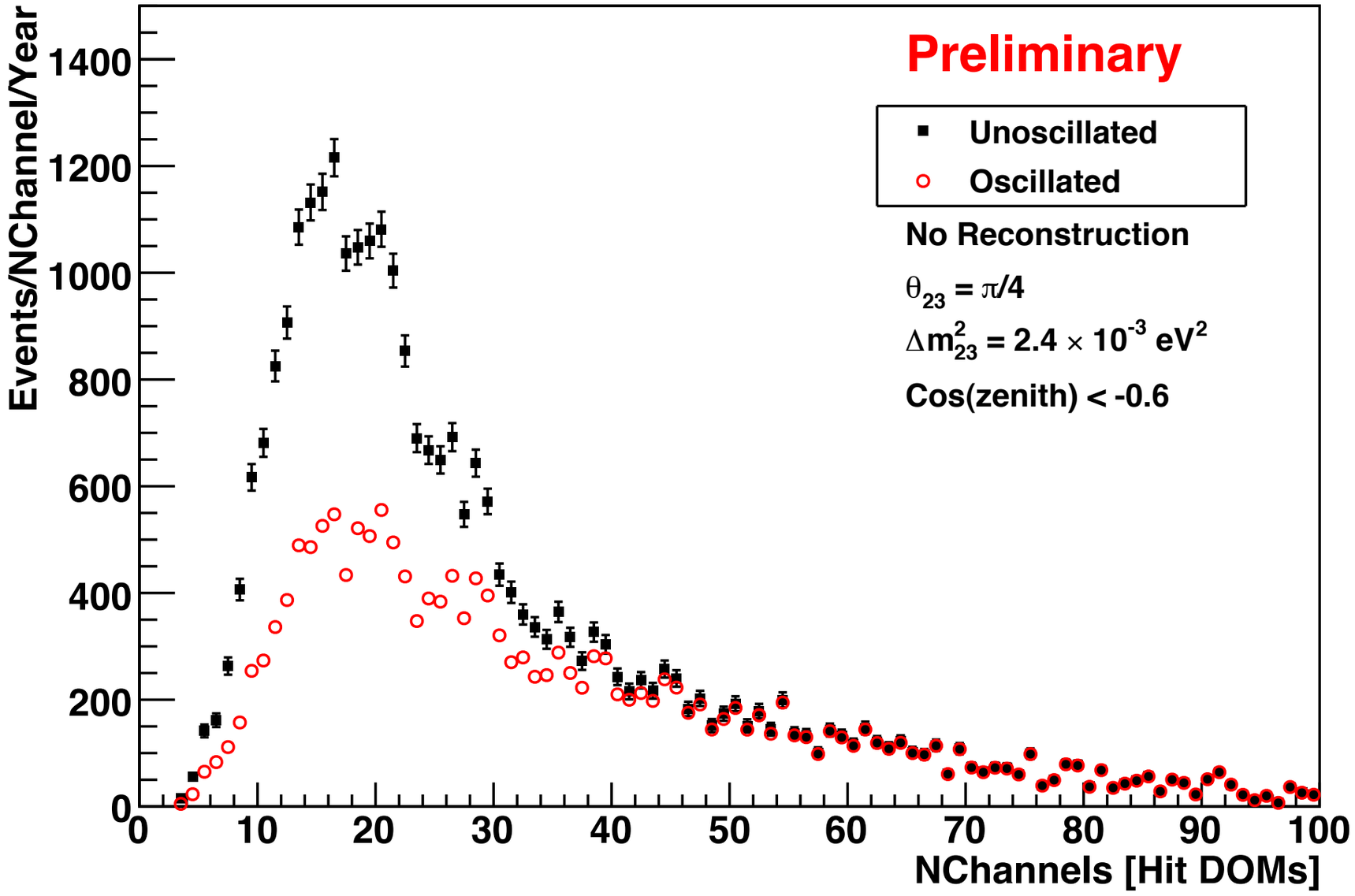


Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)



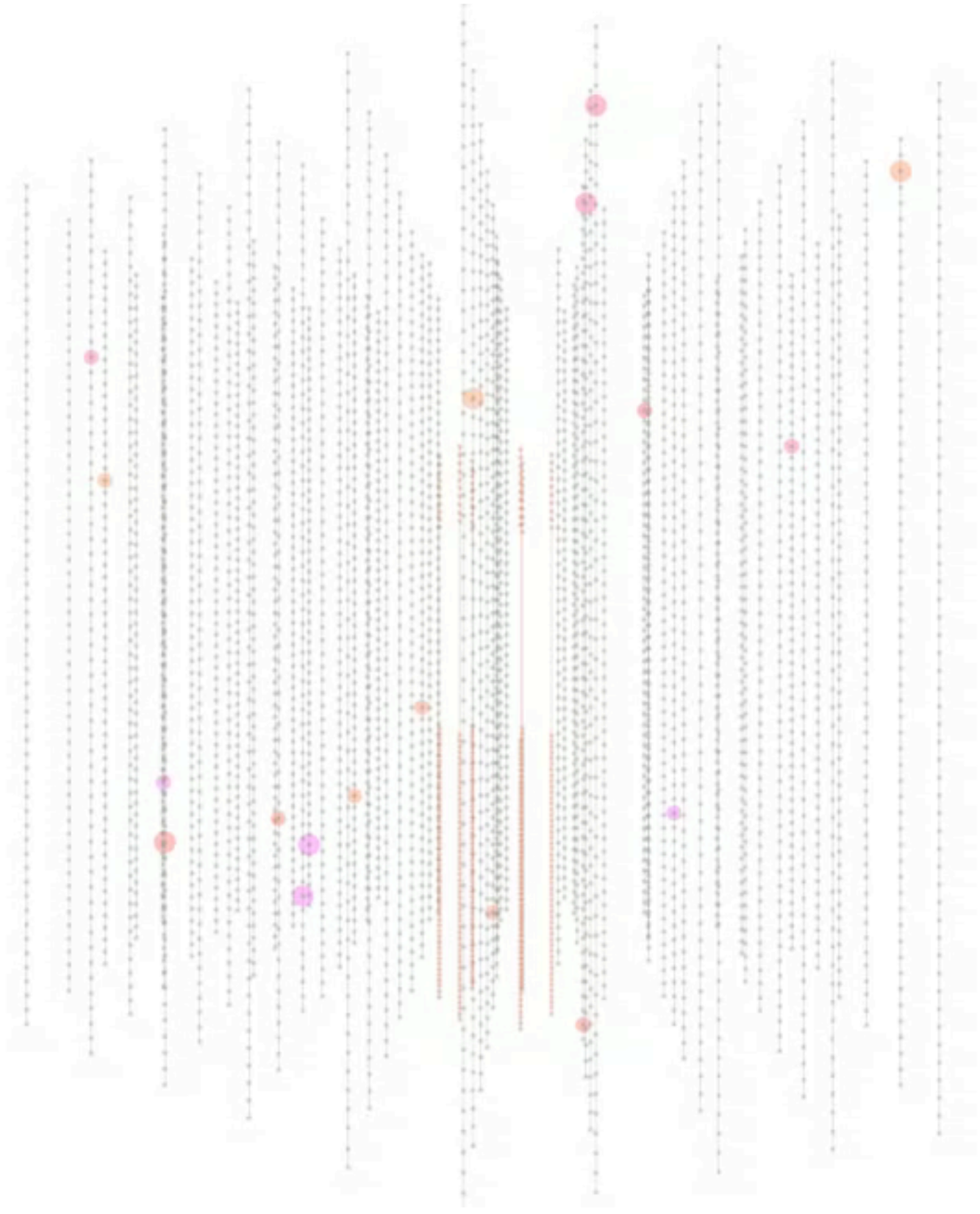
Muon Neutrino Disappearance

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



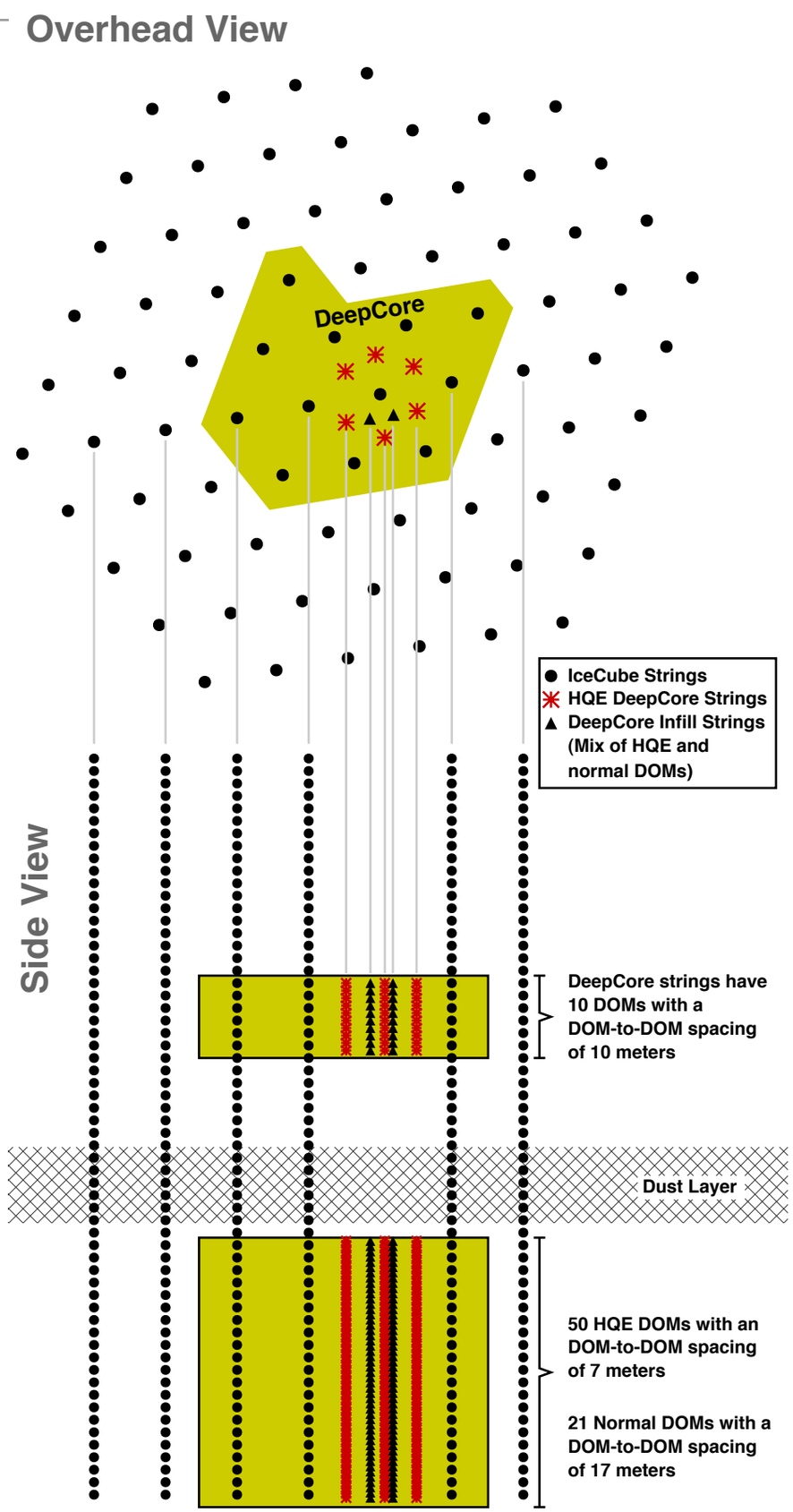
Neutrino Candidate

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



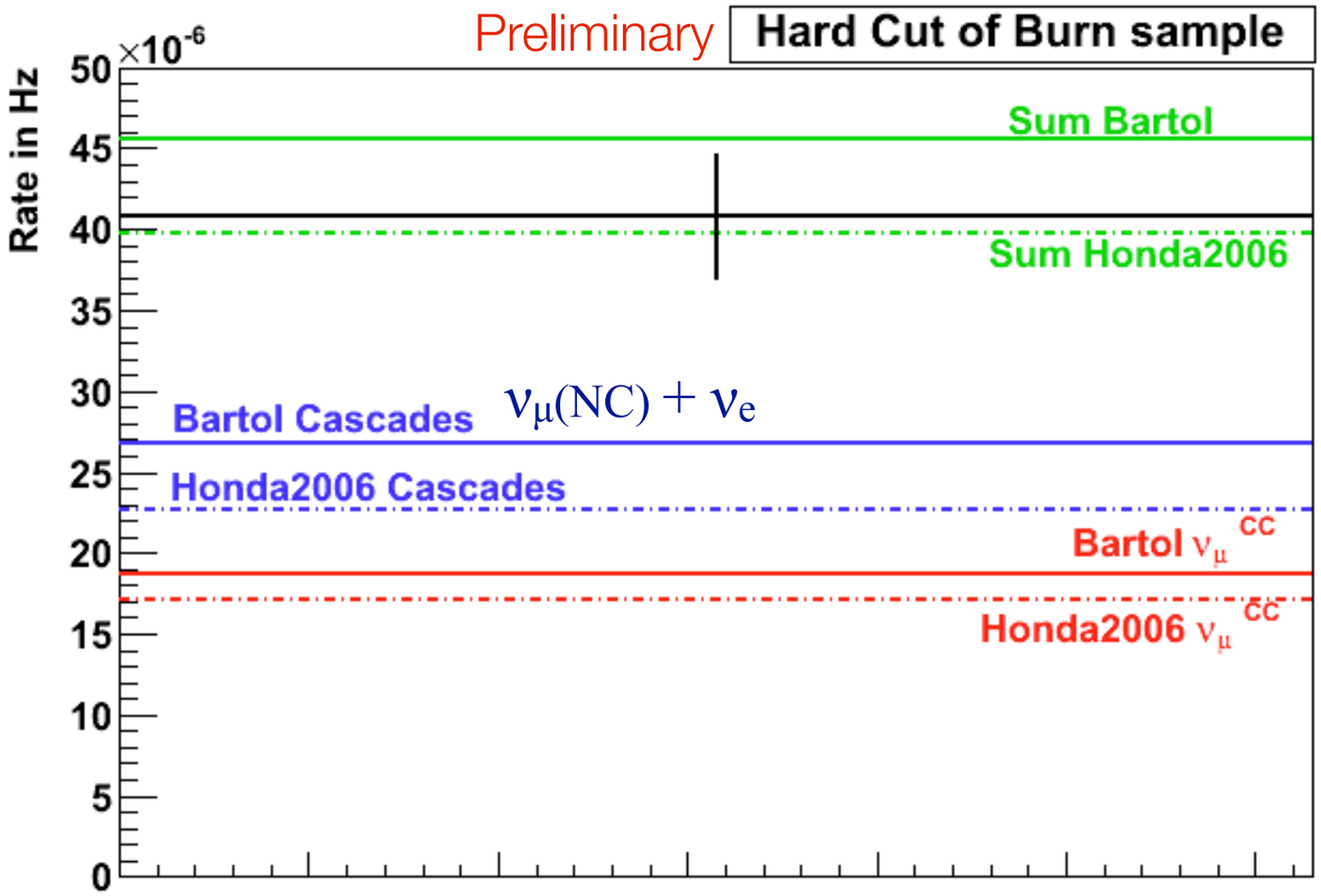
Tau Neutrino Appearance

- 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%



- DeepCore cascade candidate event

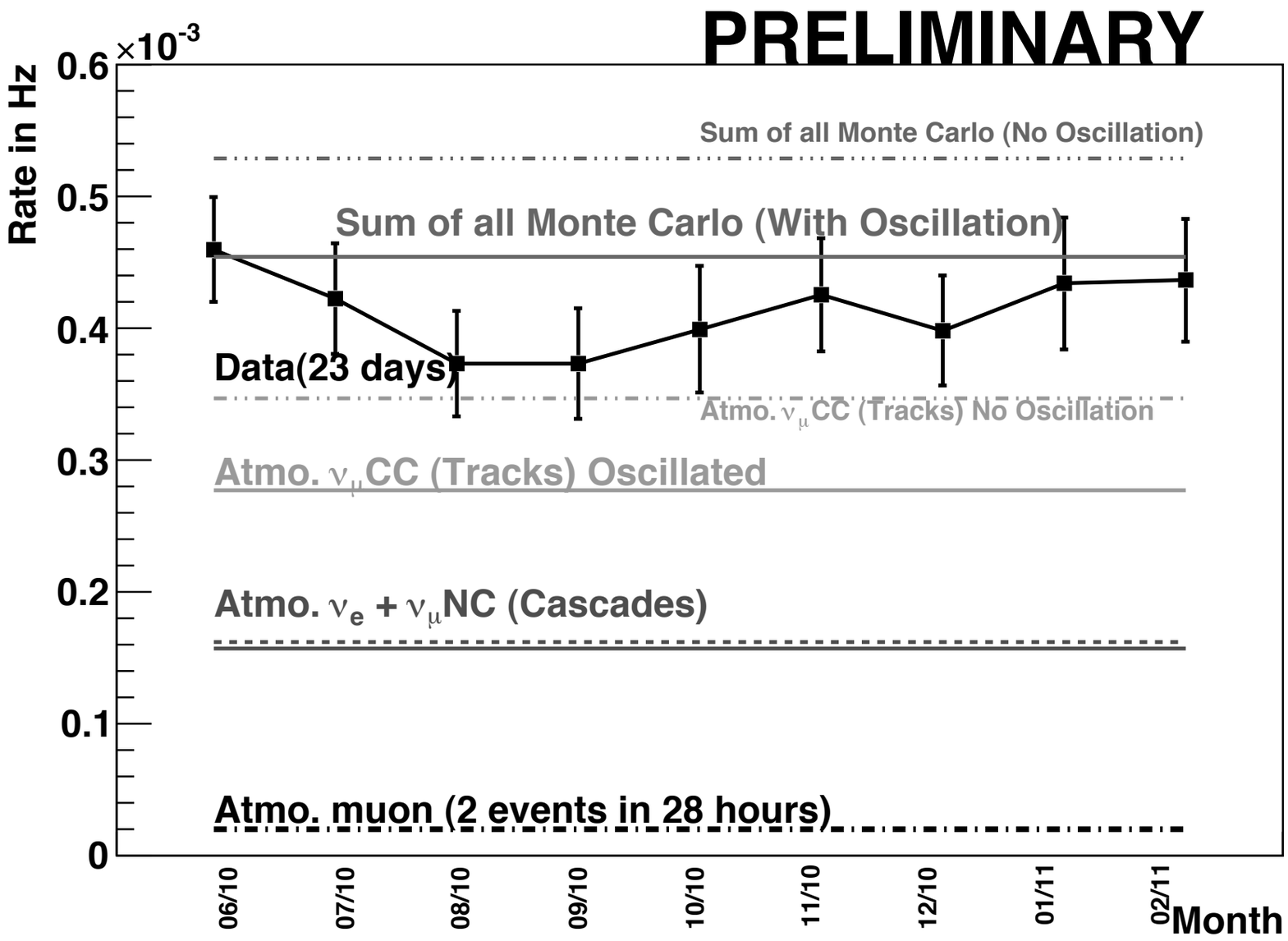
- First observation of neutrino induced cascades in IceCube
- 30.64 Days of IC79 livetime (10% open sample)
  - Tight cuts removed all cosmic ray muons from available 28 hours of CORSIKA
  - Inclusive rate over all



Full Burn ("Open") Sample

DeepCore Cascades - Loose Cuts

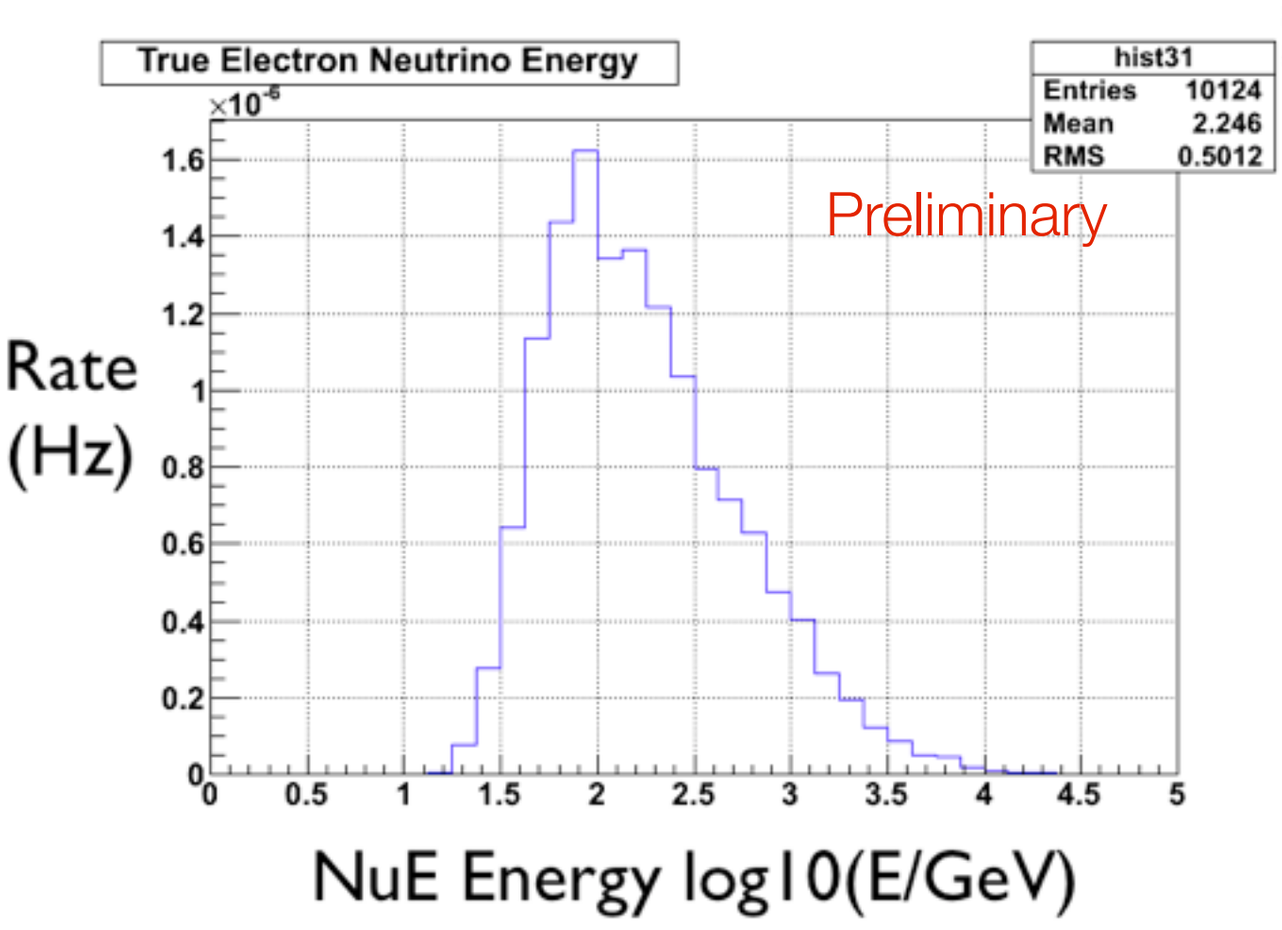
- Loose Cuts = More signal + non-zero atmospheric muon background
- Lower Energy Neutrinos



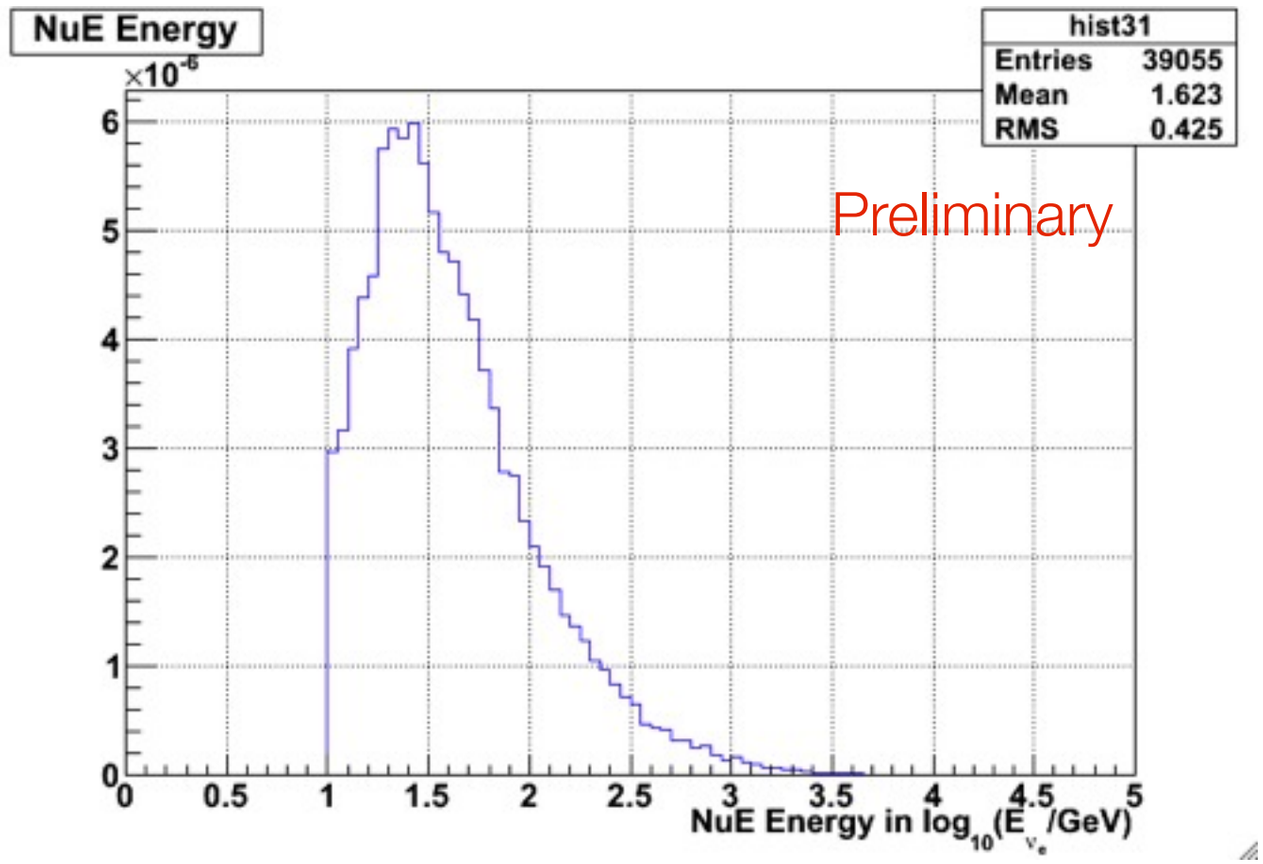
Energy Distribution

- IceCube
- DeepCore
- Beyond DeepCore

Hard Cut



Loose Cut



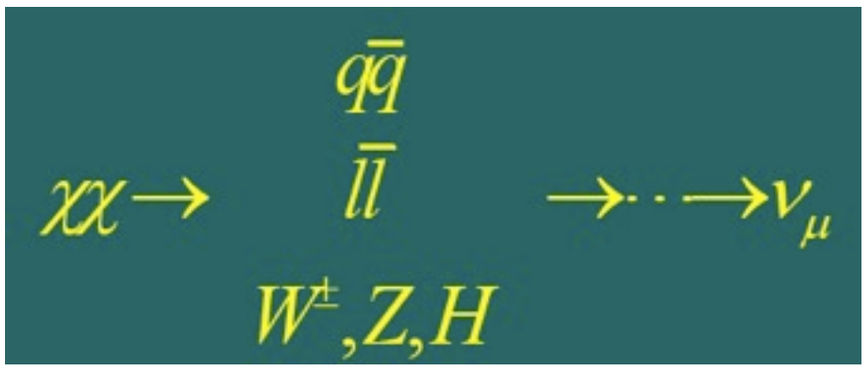
DeepCore

- 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

Indirect Dark Matter Search

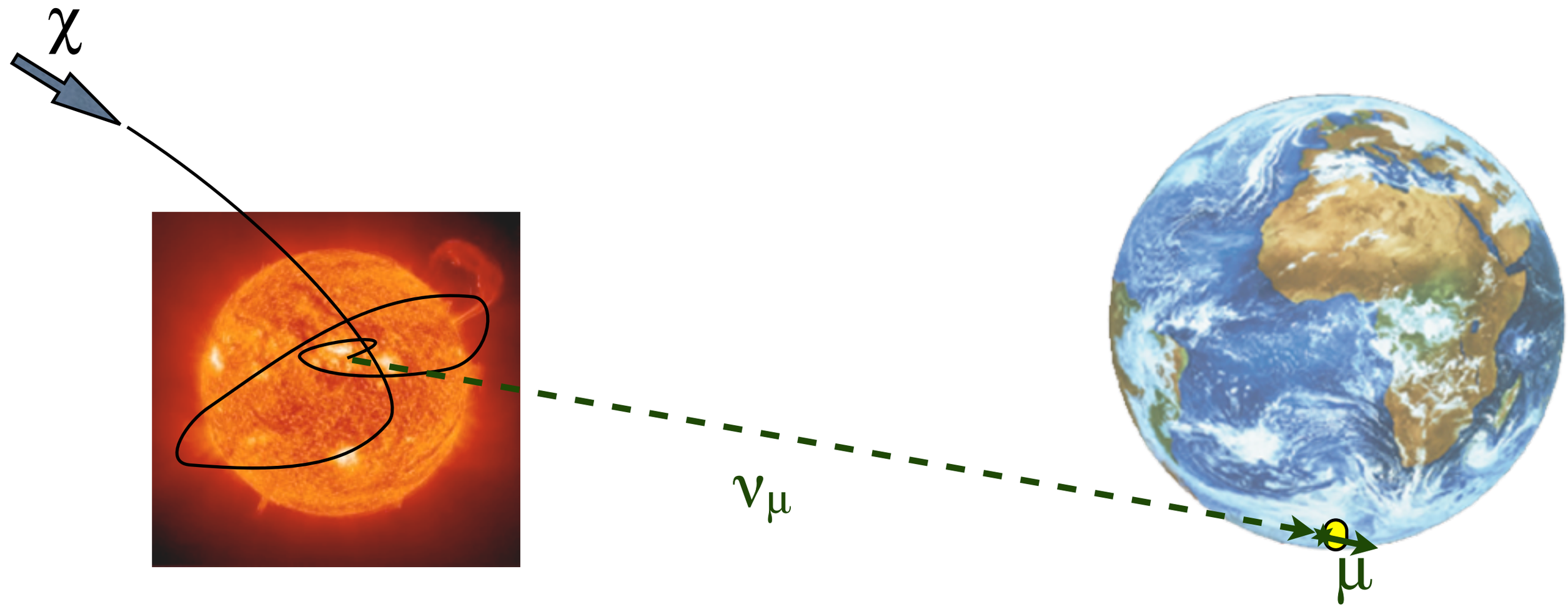
- Galaxy clustering, Gravitational lensing, Bullet Cluster galaxies, etc... strongly suggest existence of Dark Matter
- Popular candidate for Dark Matter particle is **W**eakly **I**nteracting **M**assive **P**article (WIMP)
- IceCube-DeepCore searches for Dark Matter self-annihilation creating neutrinos
  - 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).

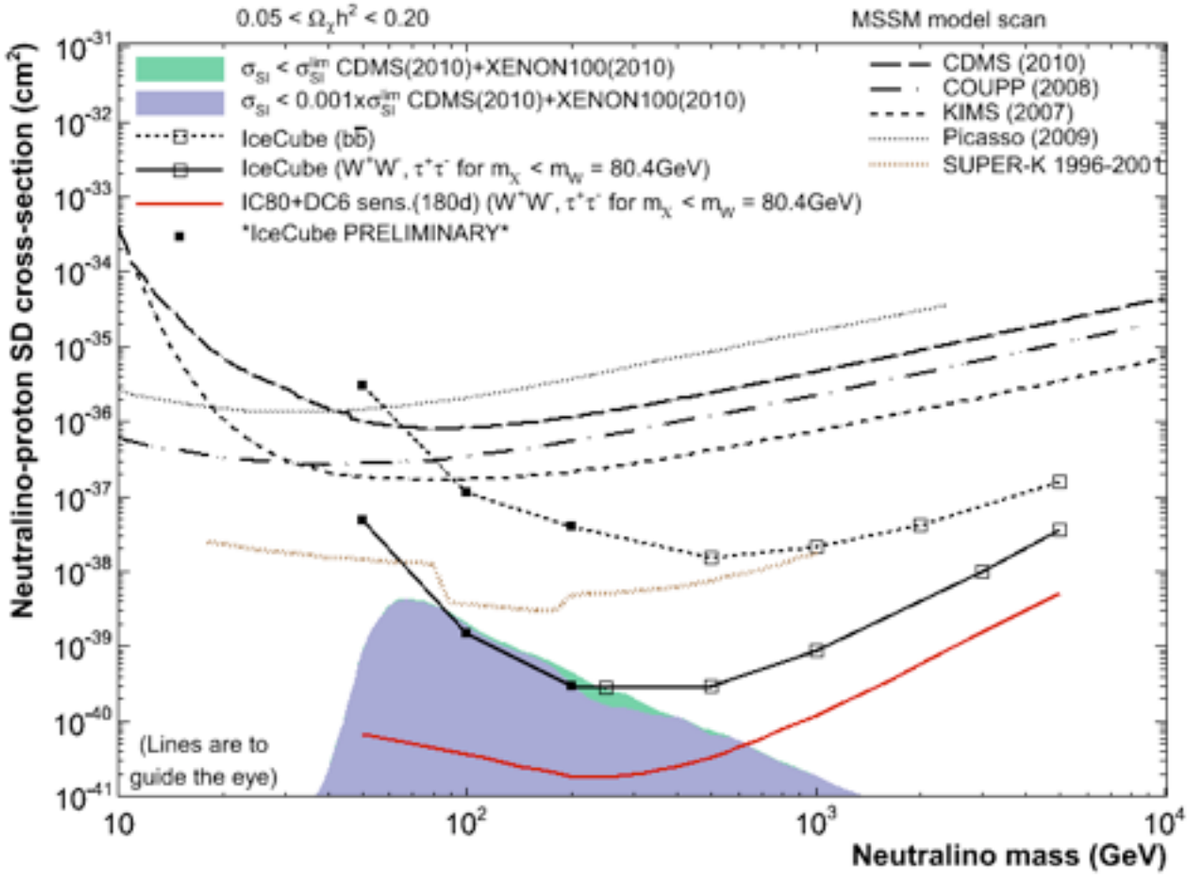
Solar Dark Matter

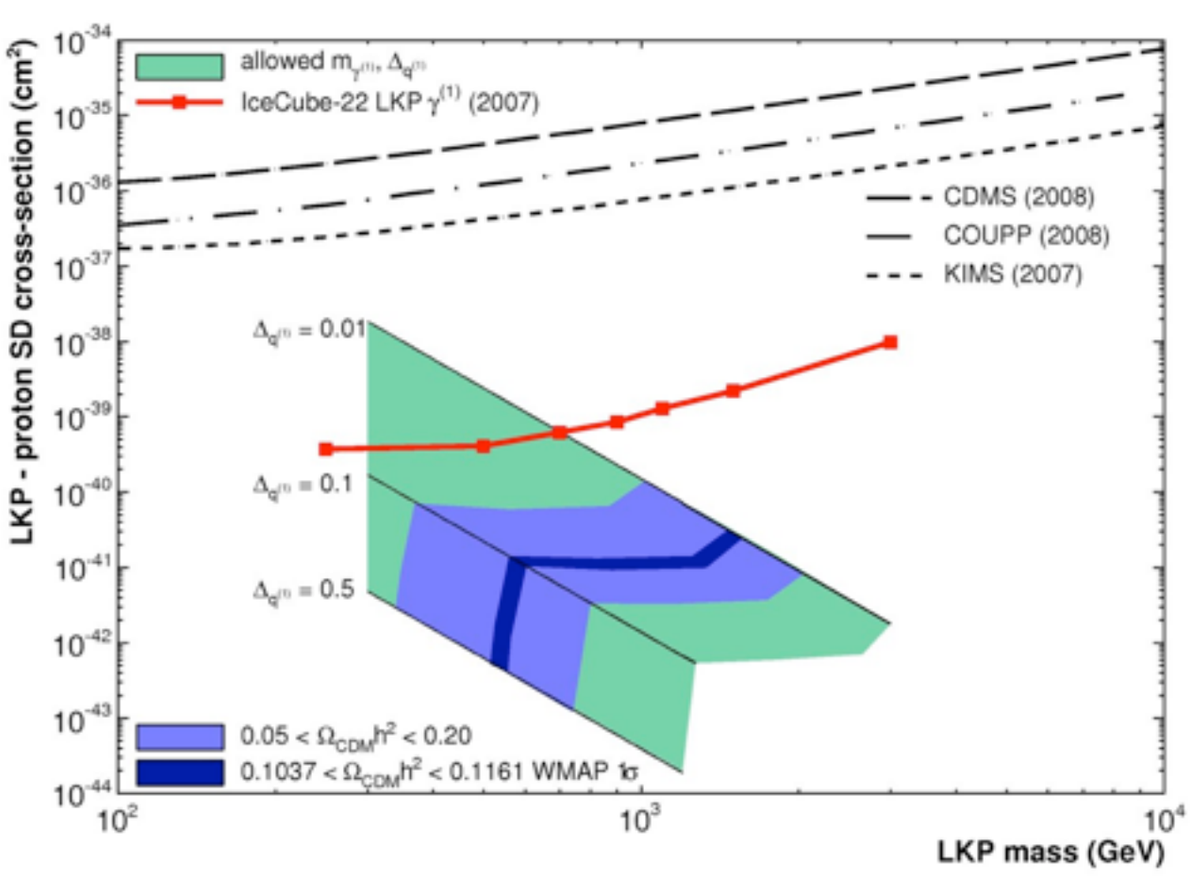
- Dark Matter gets trapped via Spin-Dependent (SD) collisions with nucleons
  - Spin-independent is well constrained by direct detection experiments
- Builds up, reaches equilibrium, starts annihilating



Solar Dark Matter Limits

- 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





DeepCore Dark Matter

- 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

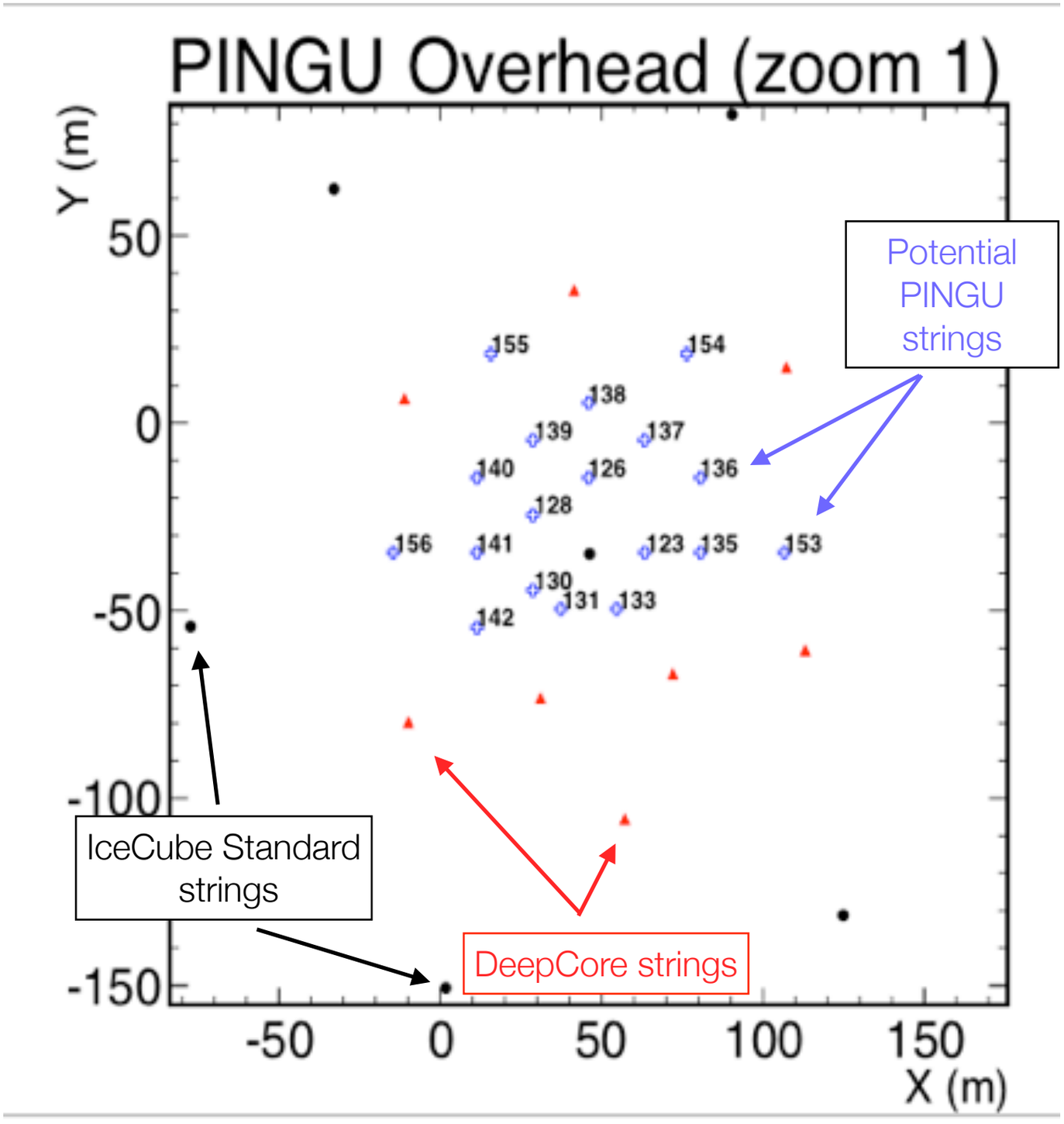
PINGU

Idea

- 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)

PINGU: Possible Geometry

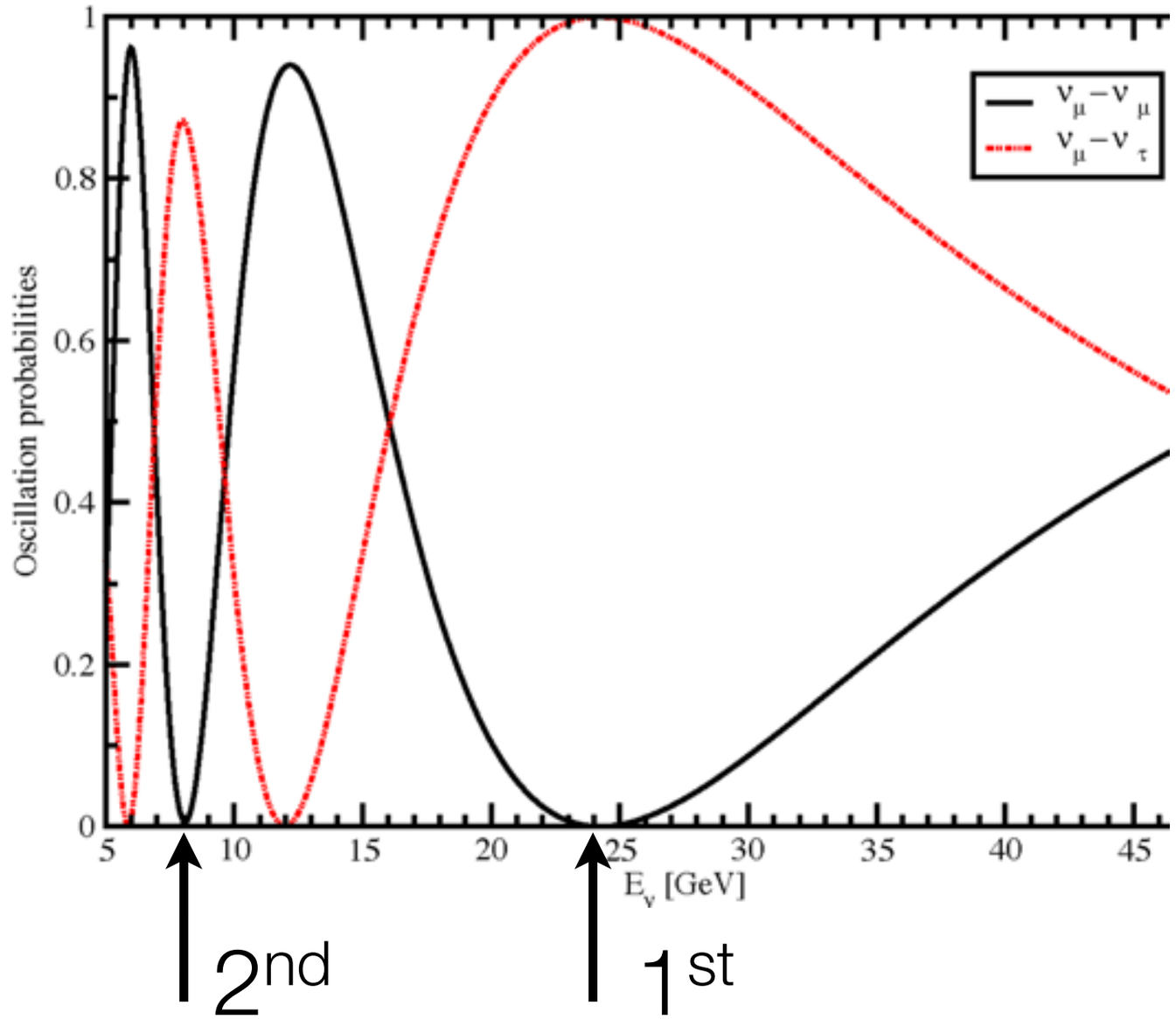
- Add 18-20 strings into DeepCore volume
- One of many possible geometries
- R & D for future water/ice cerenkov detectors



PINGU Oscillation Impact

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

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



PINGU Status

- 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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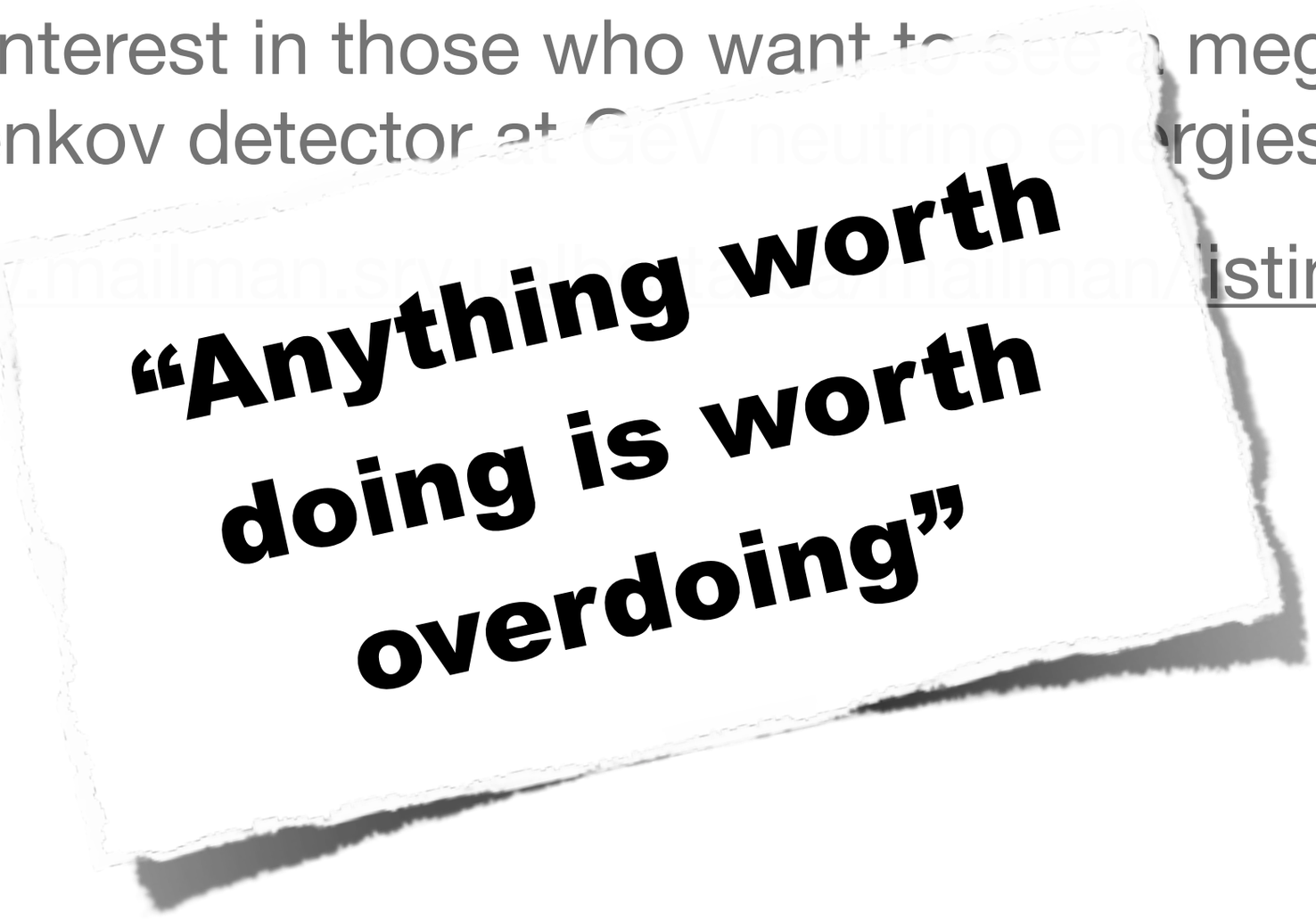


Really Beyond DeepCore

IceCube

DeepCore

PINGU

Really Beyond DeepCore

IceCube

DeepCore

PINGU

Really Beyond DeepCore

IceCube

DeepCore

PINGU

Low Energy Large Volume

- South Pole Infrastructure
  - No excavation
  - Deployment is a 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

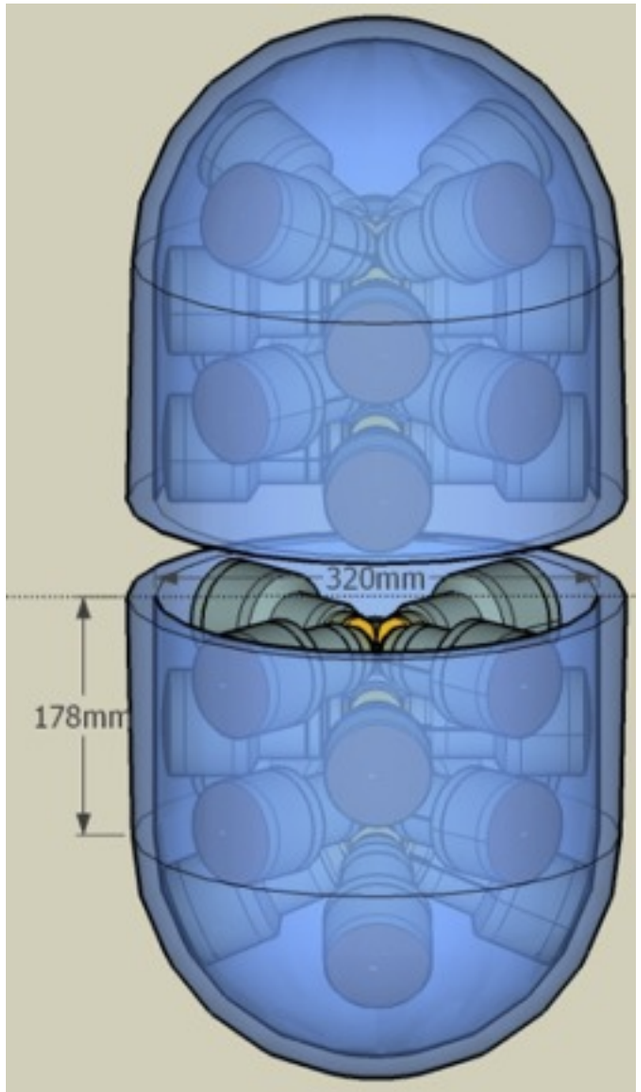
Possible Module

- Based on a KM3NeT proposed design

  P. Kooijman, *NIM* A**567** (2006), S. Kuch *NIM* A**567** (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

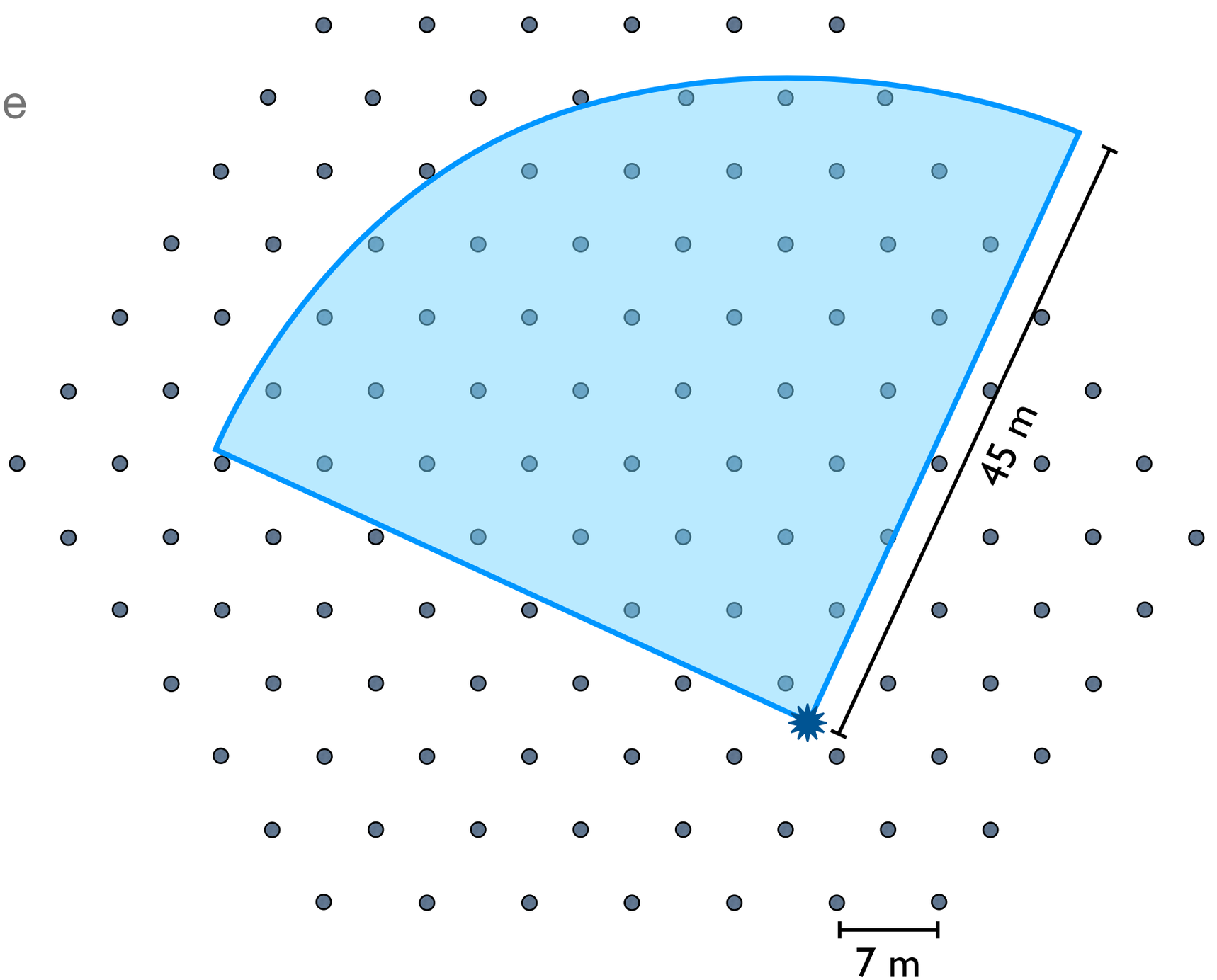
- Would allow spatial imaging of Cherenkov ring
  - KM3NeT has moved toward a 17” sphere instead – close PMT spacing not their goal – but the cylinder design was developed to the engineering stage

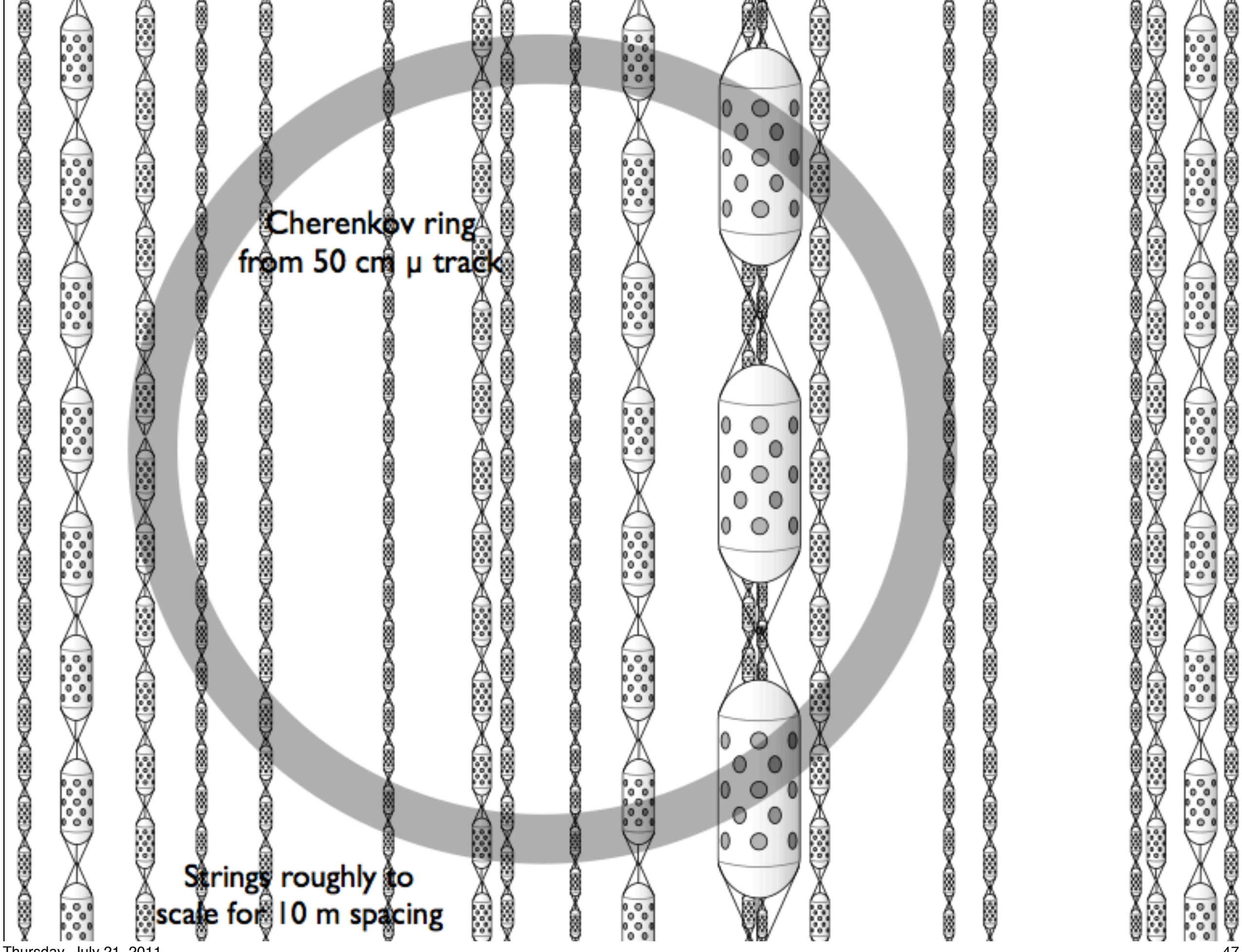


Courtesy P. Kooijman

Cerenkov Ring Imager

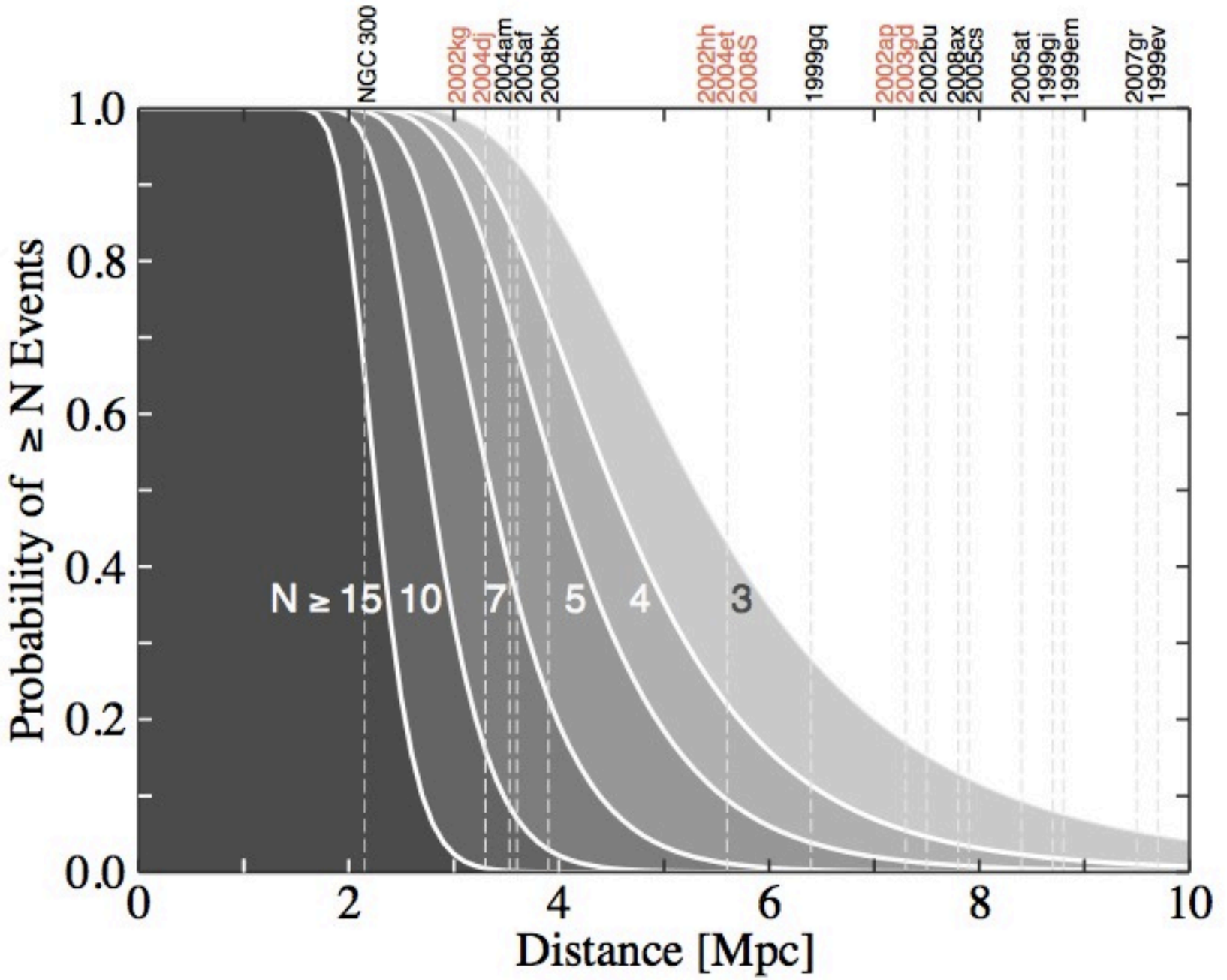
- 120 strings of 125 composite DOMs each
  - Instrumented volume of 250 m height, ~40 m radius
- 1 MegaTon fiducial volume, at depths of 2200-2450 m
  - Optical scattering length ≳40 m, absorption ≳140 m
- Inside IceCube and DeepCore for muon veto




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



Physics Opportunities

- IceCube
- DeepCore
- **Beyond DeepCore**

Physics Opportunities

- 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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  - Option for PINGU as well depending on beam characteristics
- Proton Decay
- Extra-galactic Supernova neutrino

Conclusion

- 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 at trigger
  - Phase 2 - Down to ~O(10) MeV

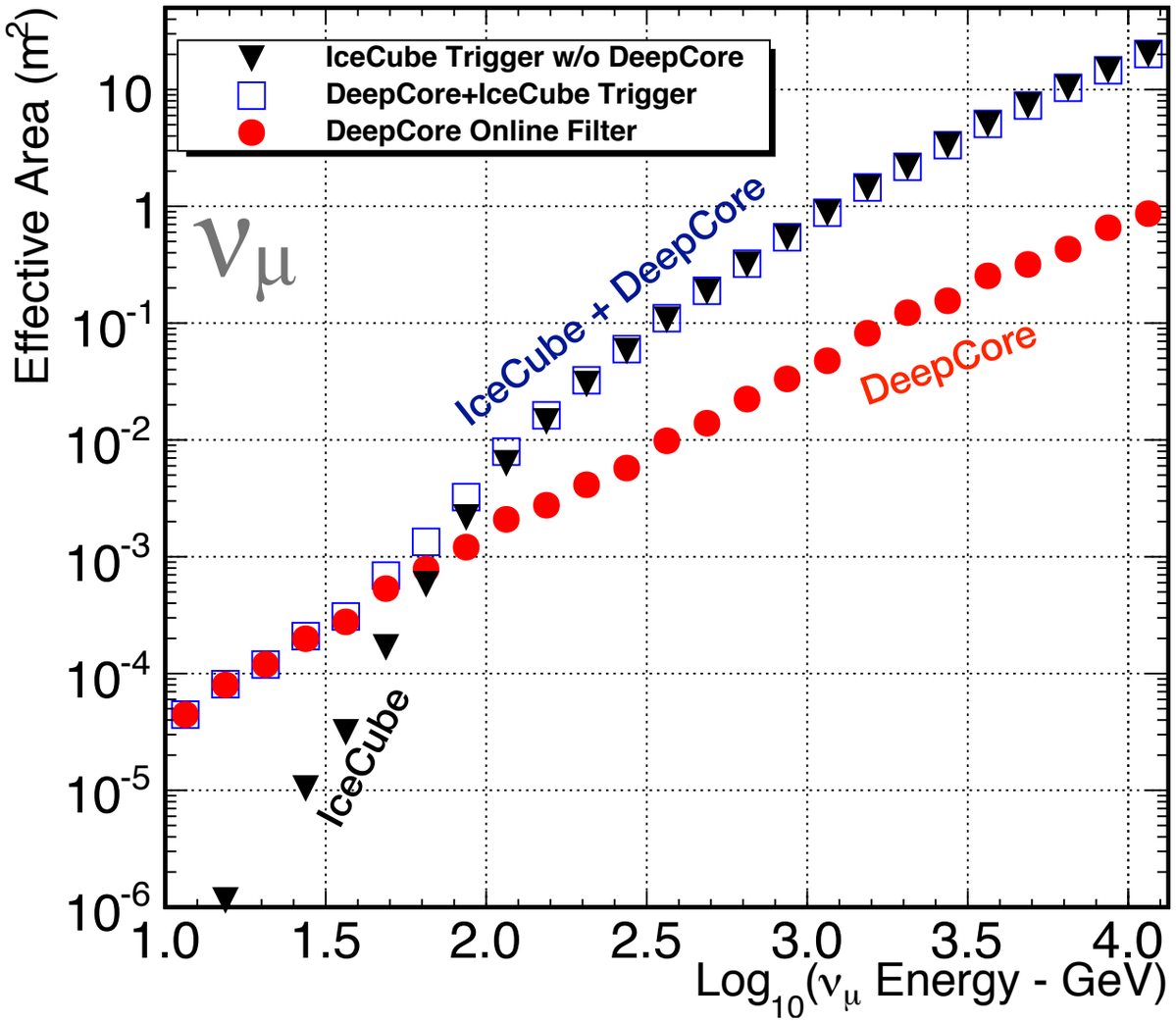
Thanks

Backup

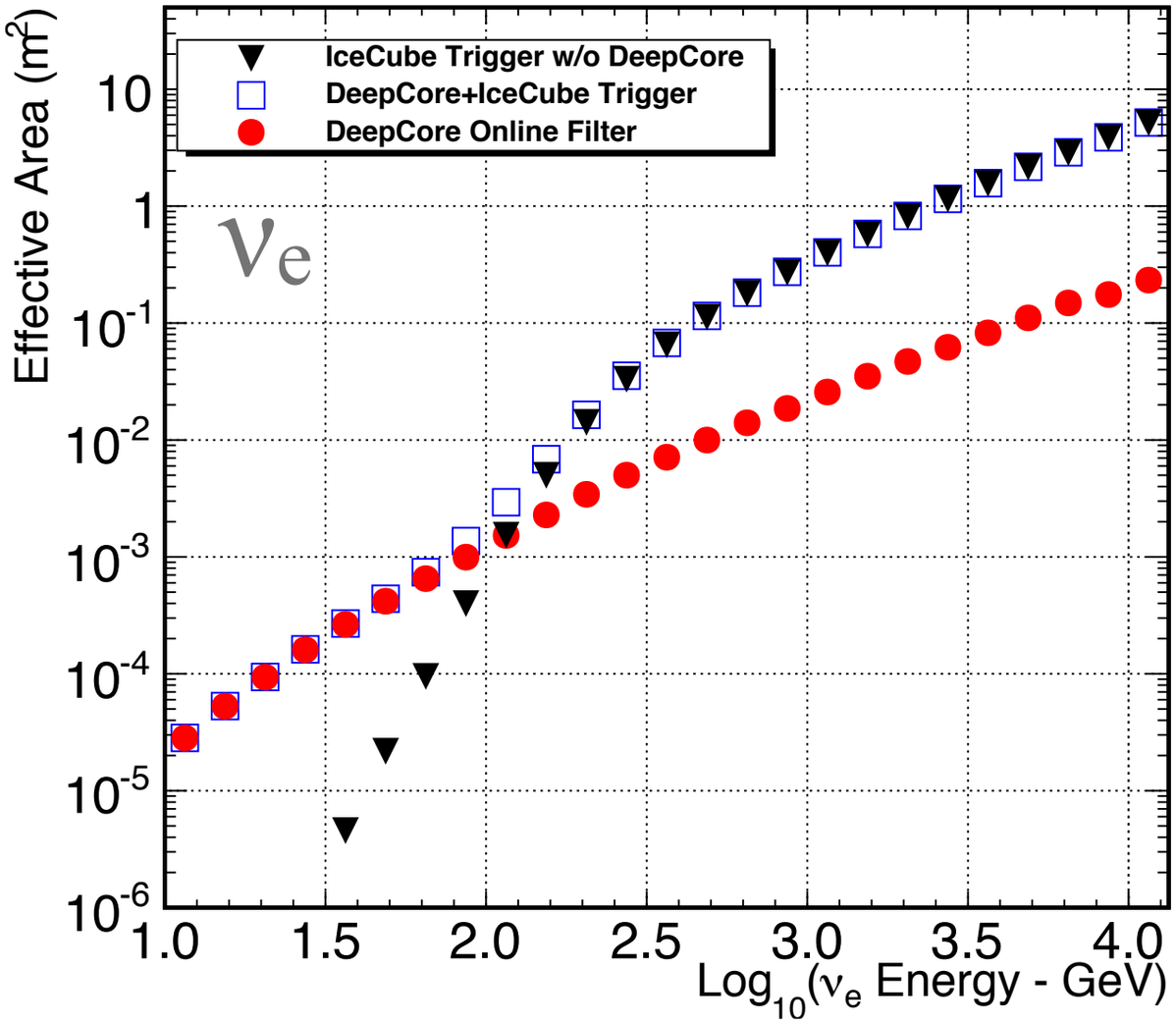
Effective Neutrino Area

- IceCube
- DeepCore
- Beyond DeepCore

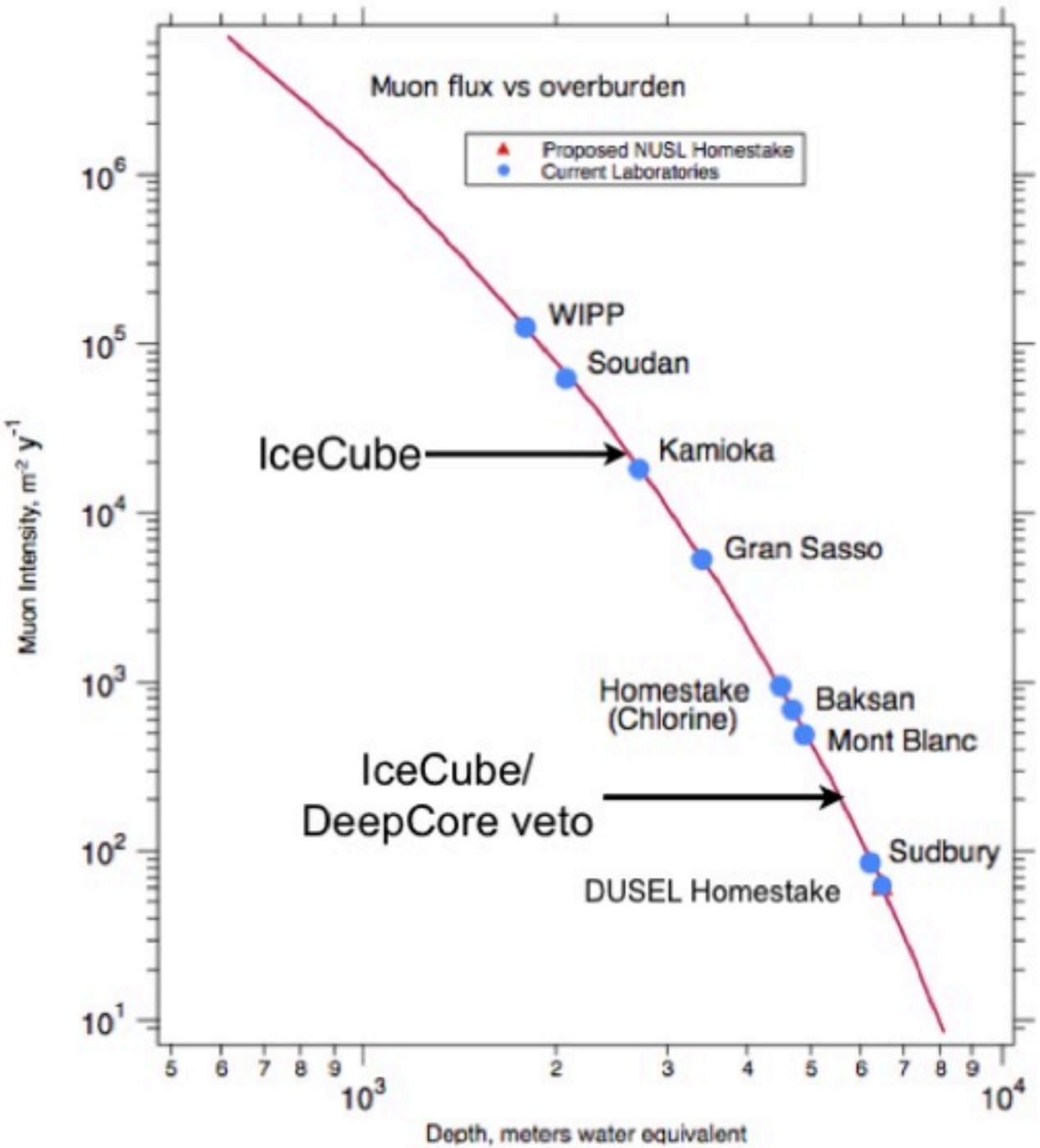
Preliminary



Preliminary

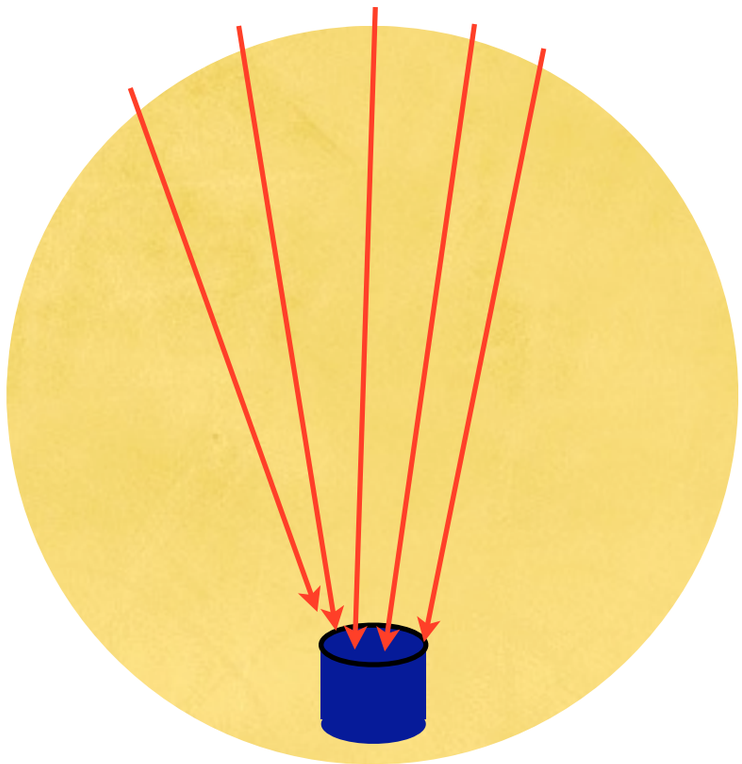


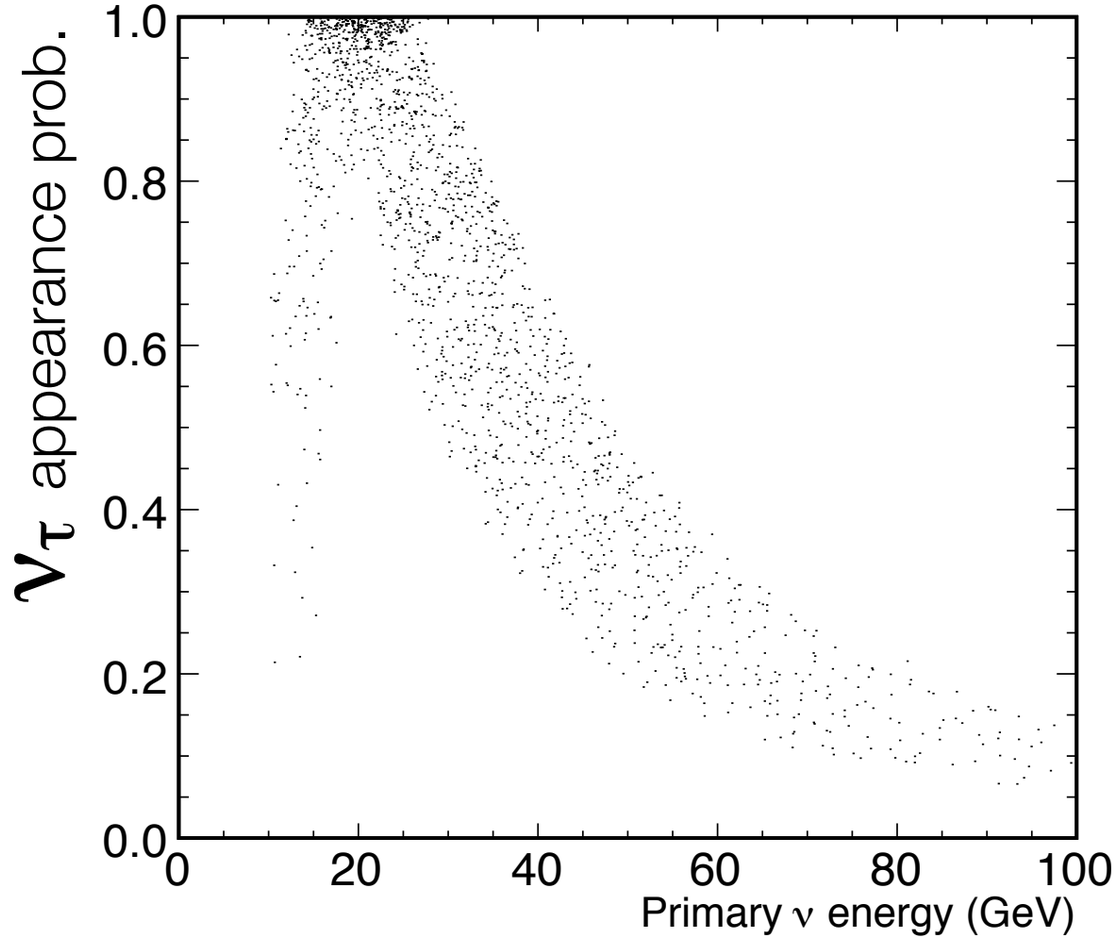
Active Veto


Muon flux vs overburden
Proposed NUSL Homestake
Current Laboratories
WIPP
Soudan
IceCube
Kamioka
Gran Sasso
Homestake
(Chlorine)
Baksan
Mont Blanc
IceCube/
DeepCore veto
Sudbury
DUSEL Homestake
Muon Intensity, m-2 y-1
Depth, meters water equivalent

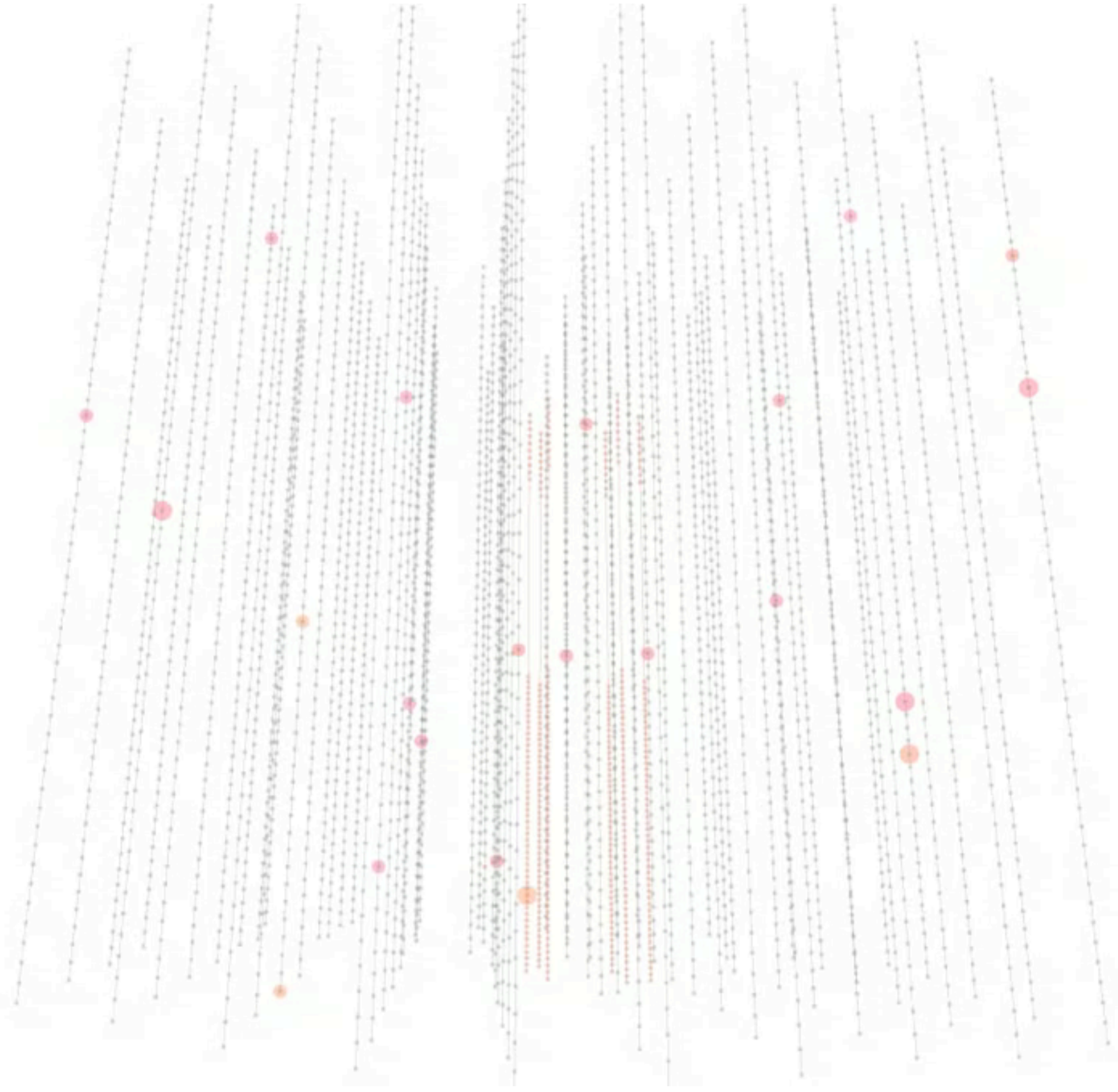
Tau Oscillation Smearing

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

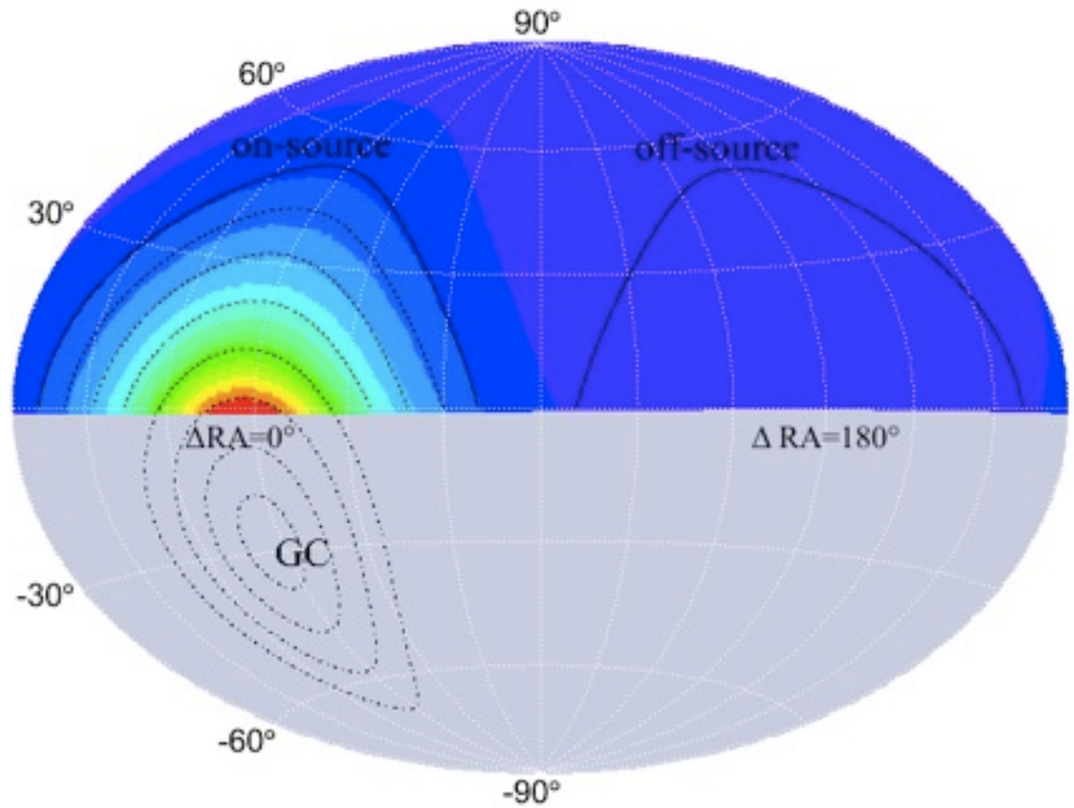




Neutrino Candidate 2

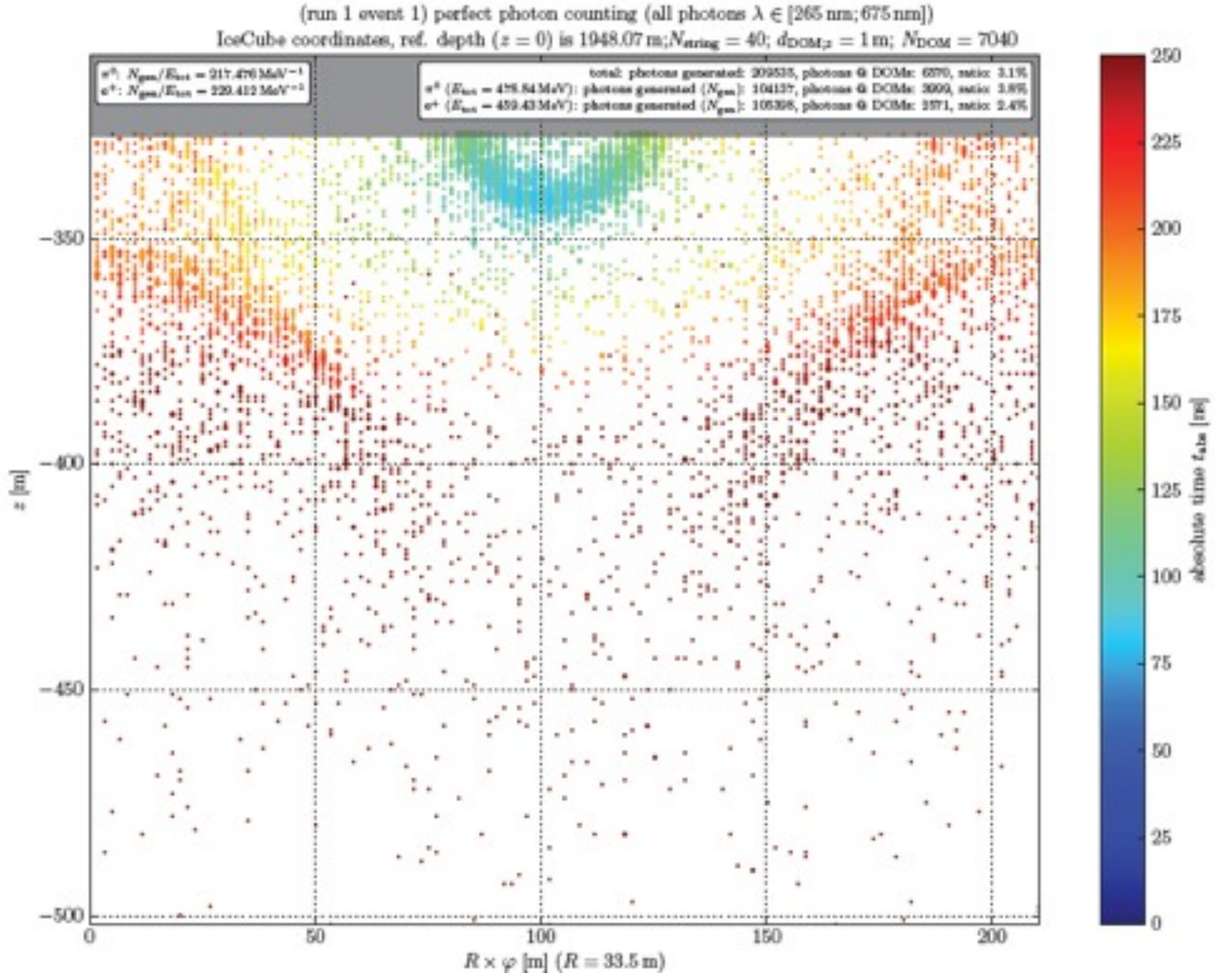


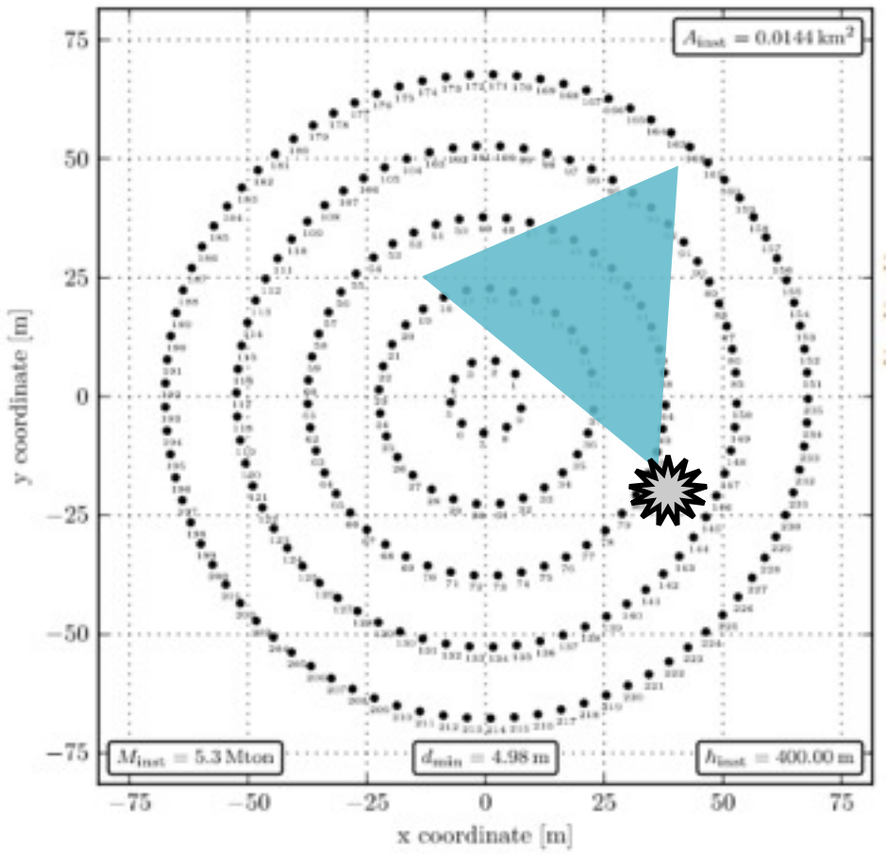
- Signal depends on Halo distribution(DM density) model and SUSY model(DM annihilation channels)
- on-source versus off-source anisotropy
- IC22 analysis did not observe a large scale anisotropy and has a 90% C.L. on WIMP self-annihilation cross-section of $\langle\sigma_A v\rangle$ 10^{-22} $cm^3 s^{-1}$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



BDC Conceptual Design

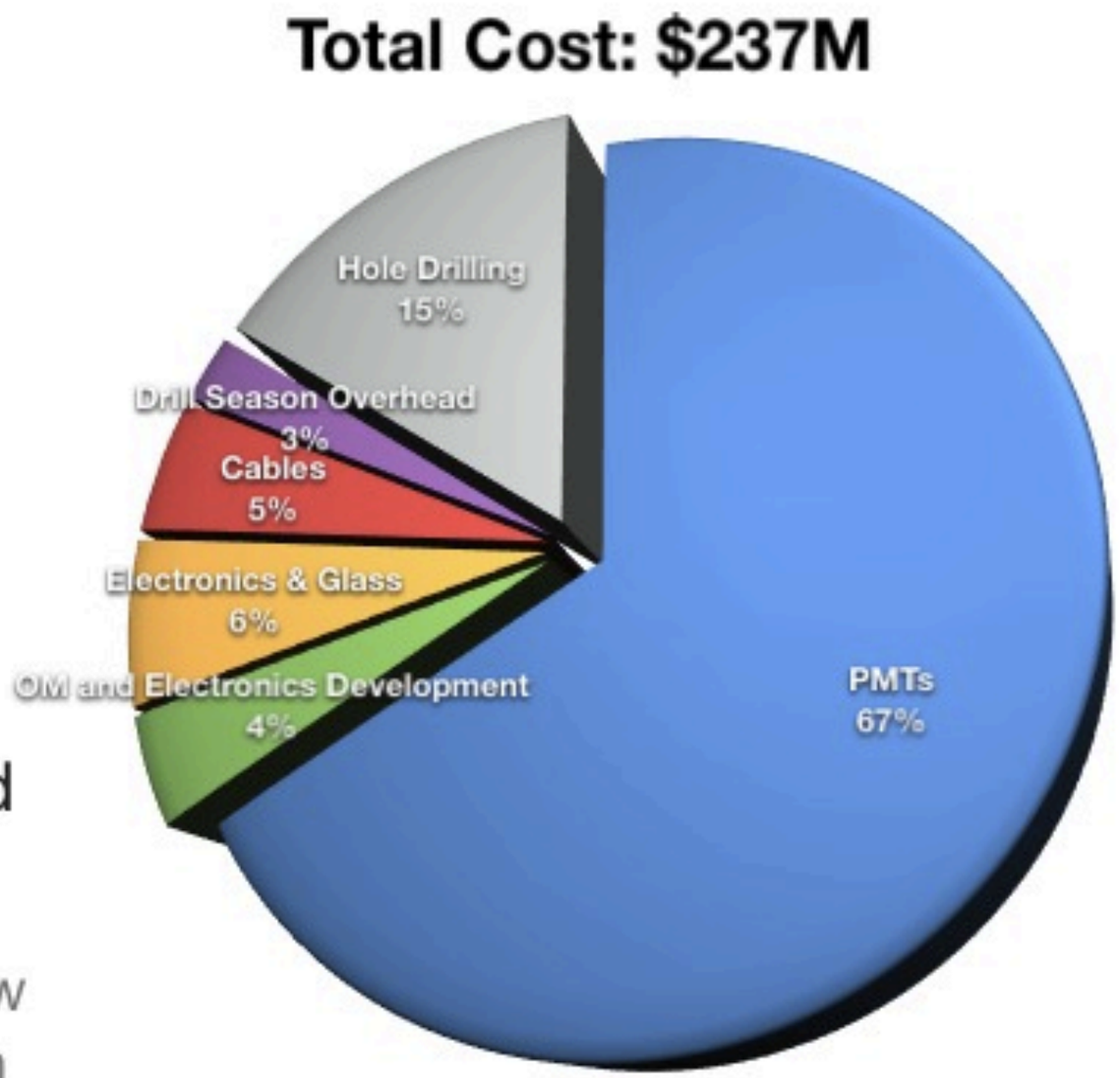
- At 100% photon collection efficiency, cylindrical deployment and 1 meter OM spacing, cerenkov ring from proton decay is visible
- Simulation and testing is under active development





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?



Tyce DeYoung Advances in Neutrino Technology Workshop September 16, 2010