Particle physics with IceCube-DeepCore and beyond

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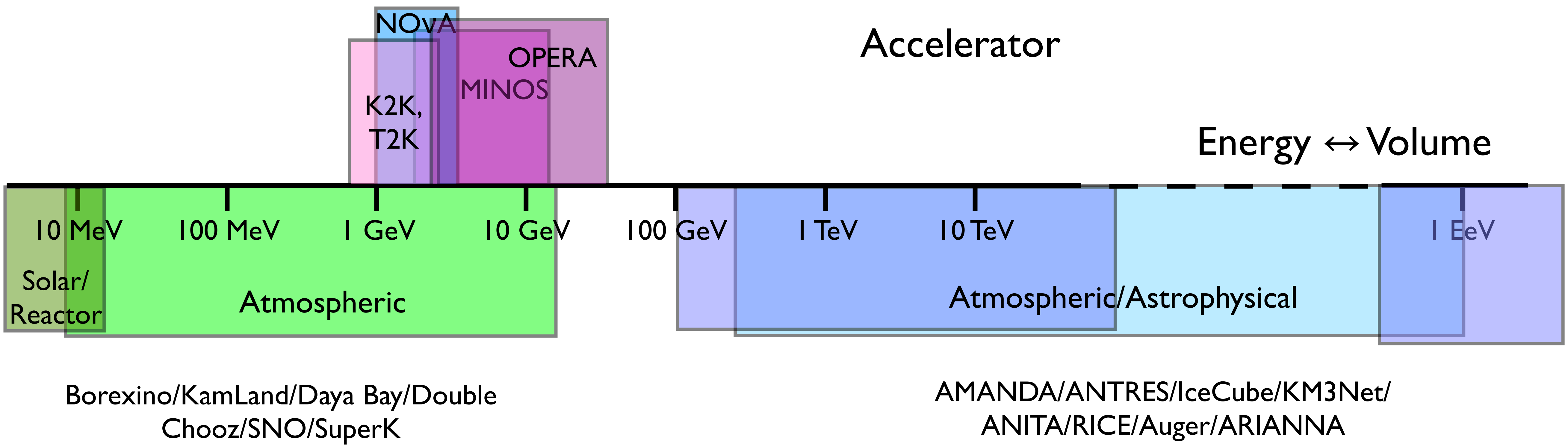
University of Alberta

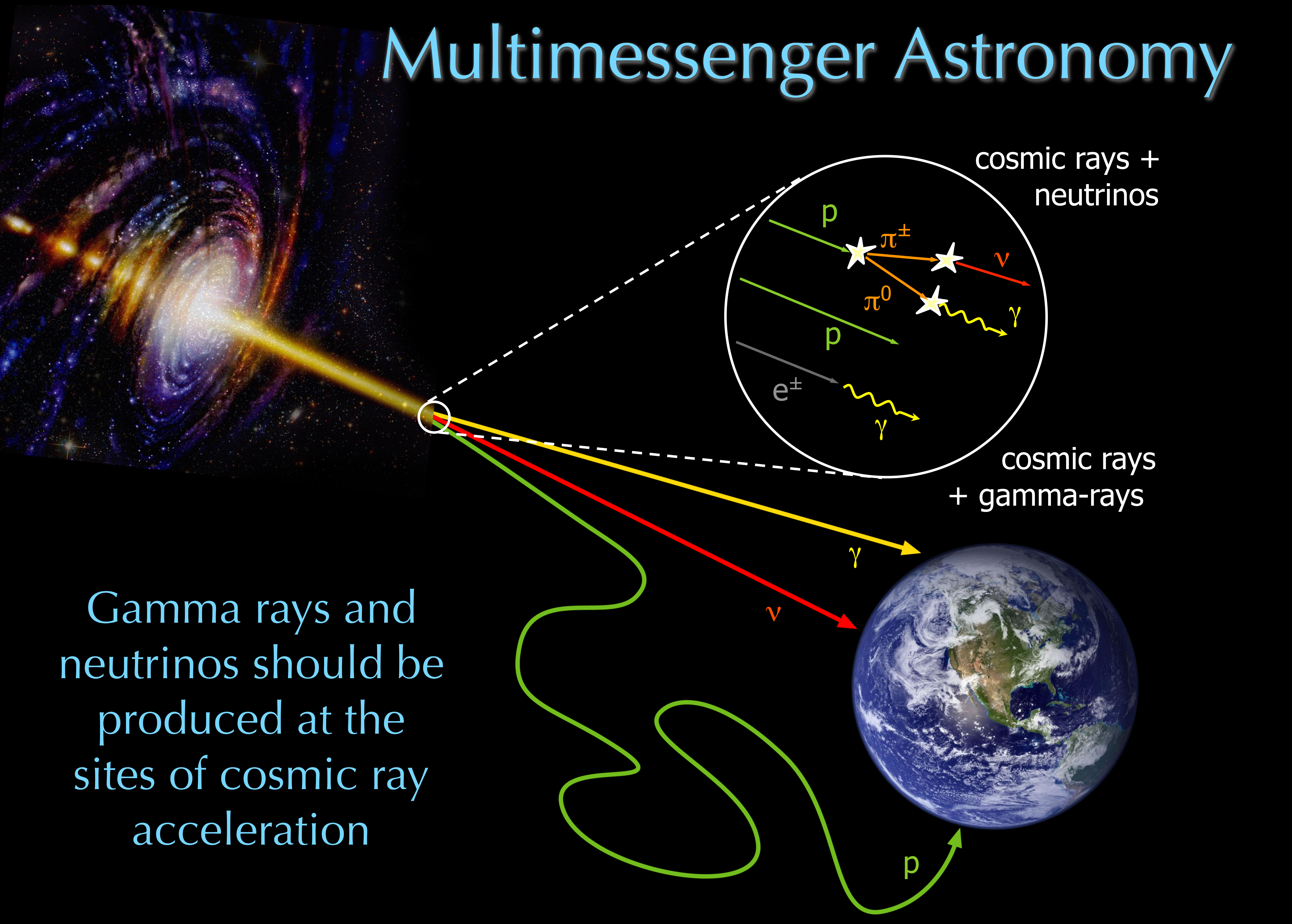
Winter Nuclear and Particle Physics Conference 2012
Mont Tremblant Quebec

The Neutrino Detector Spectrum



** boxes select primary detector physics energy regimes and are not absolute limits*

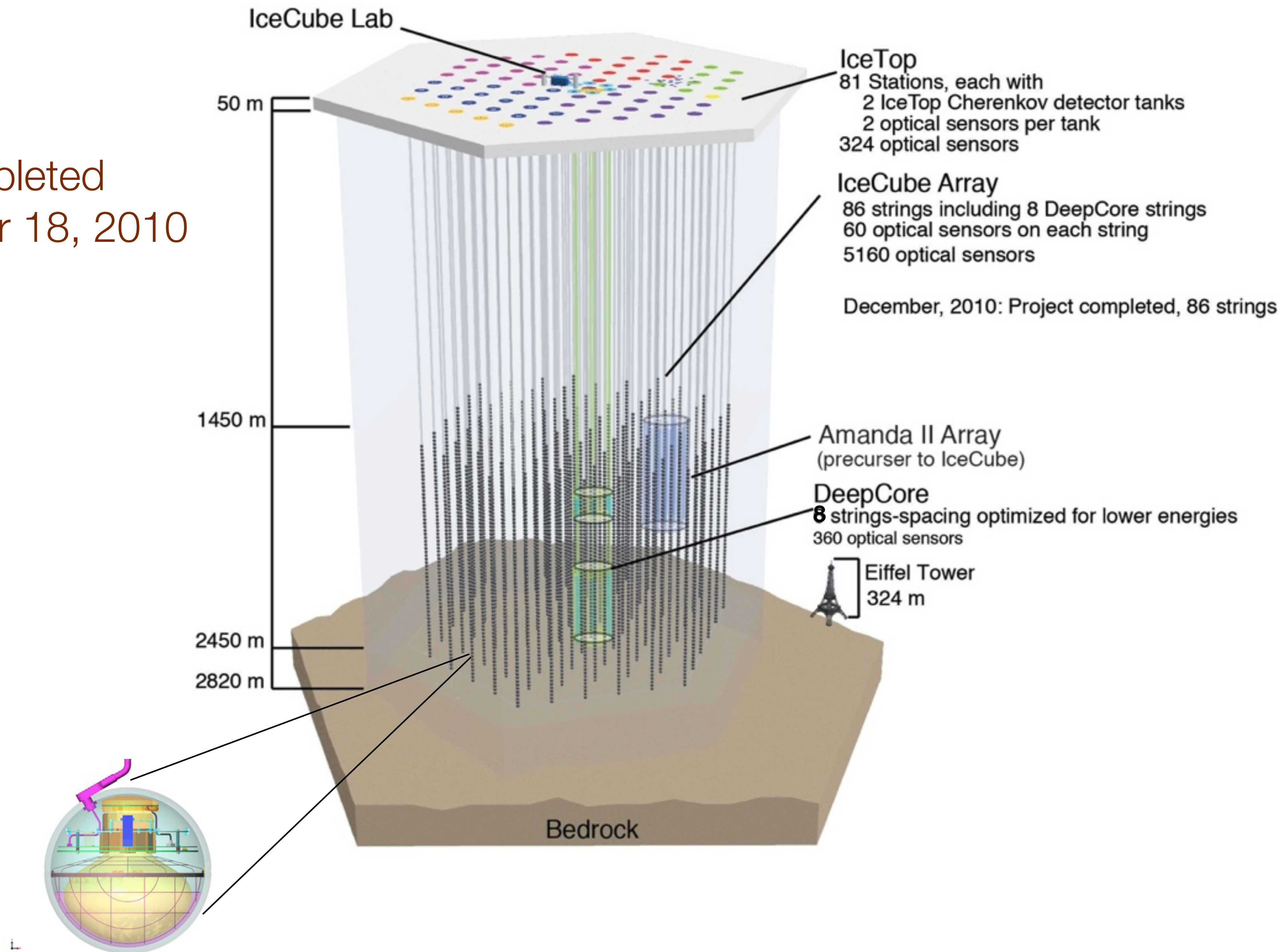
Multimessenger Astronomy



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

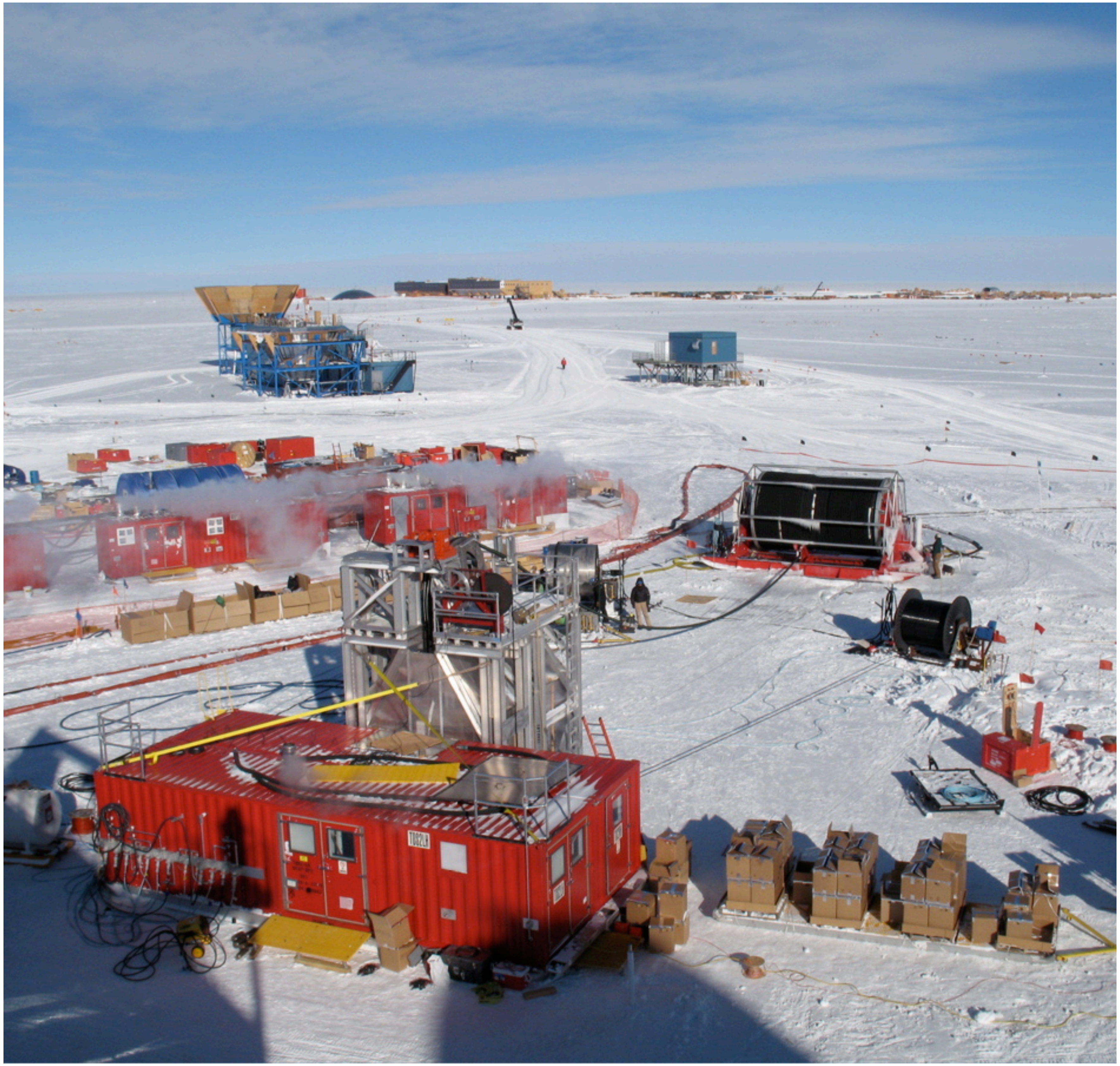
The IceCube Neutrino Observatory

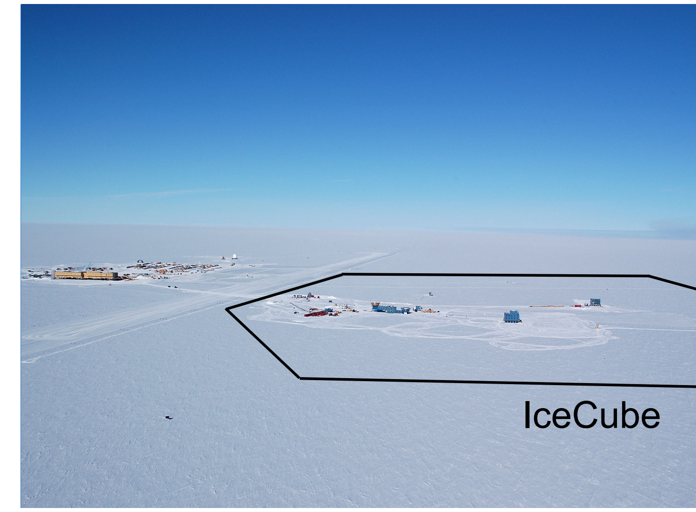
Completed
December 18, 2010

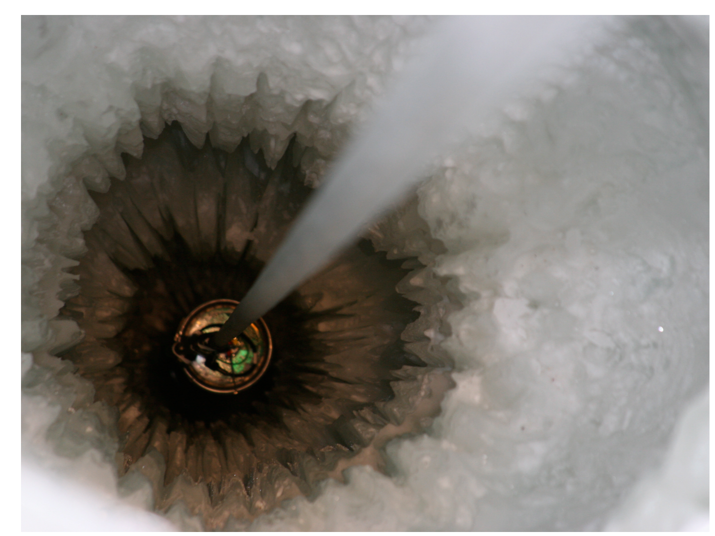


The IceCube Collaboration

38 institutions - 4 continents - ~250 Physicists

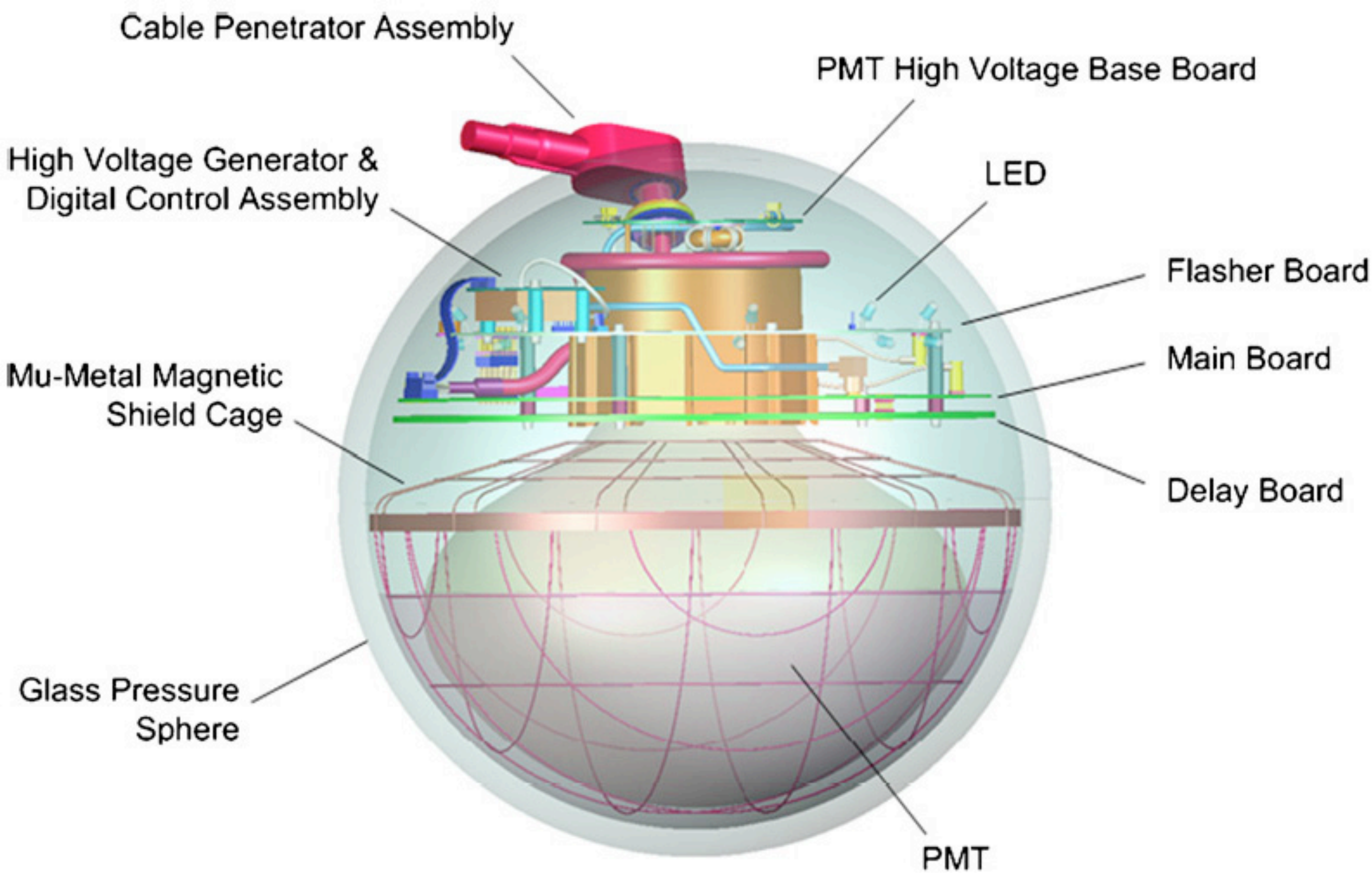




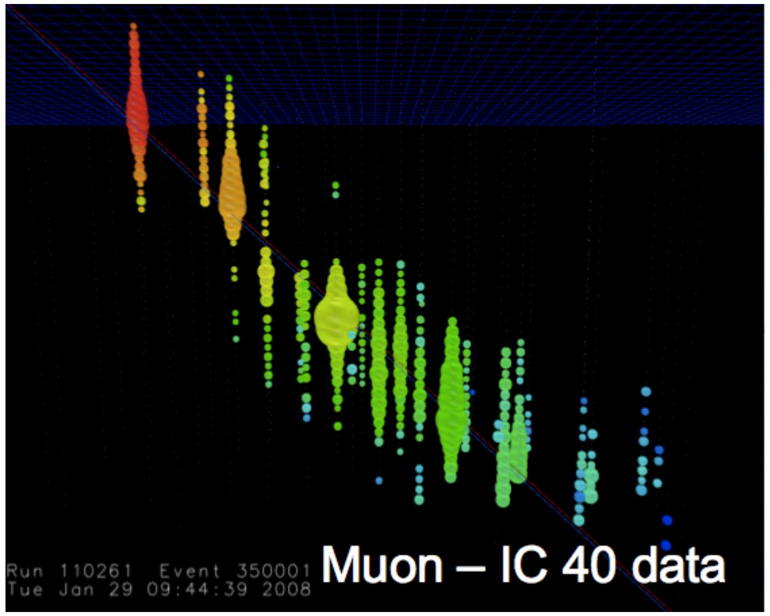


Amundsen-Scott South Pole Station, Antarctica

The Digital Optical Module (DOM)



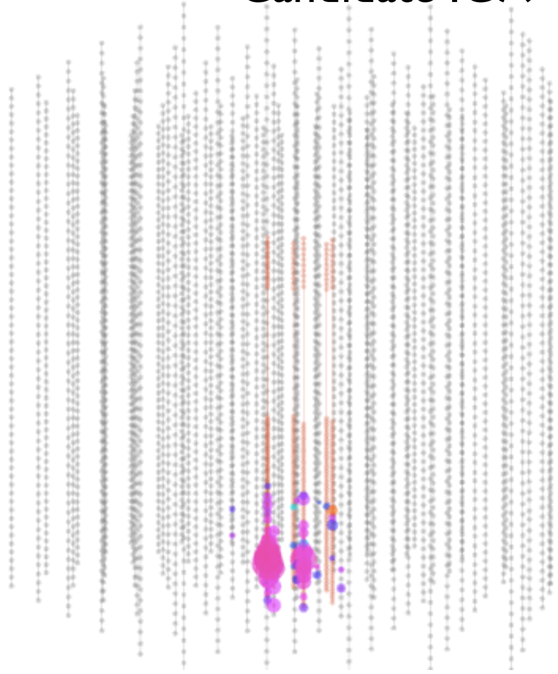
Neutrino Telescopes - Principle of Detection

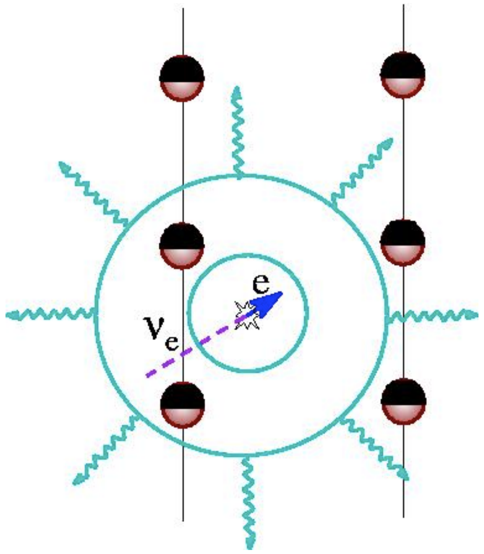


Tracks:

- through-going muons
- pointing resolution ~1°

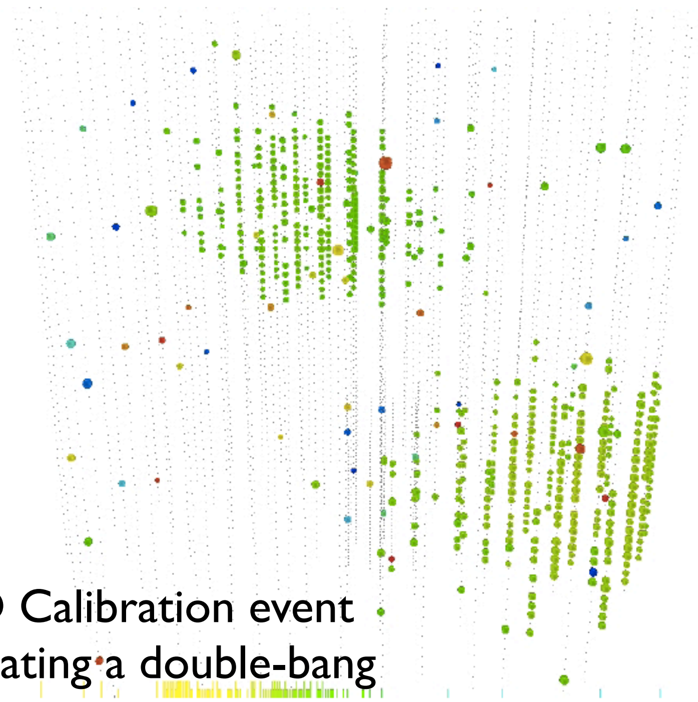
Candidate IC79 Cascade





Cascades:

- Neutral current for all flavors
- Charged current for ν_e and low-E ν_τ
- Energy resolution ~10% in log(E)

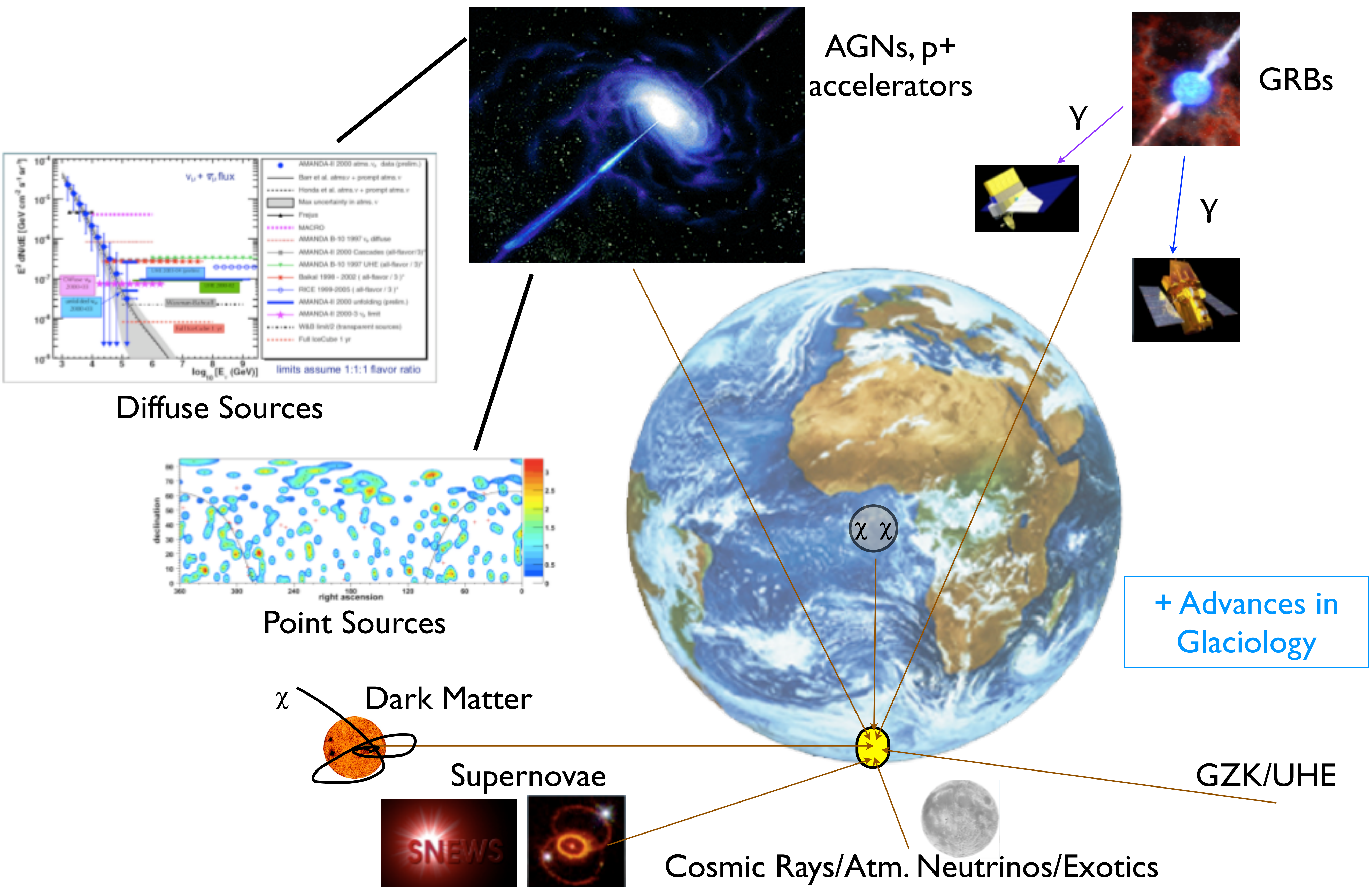


LED Calibration event simulating a double-bang

Composites:

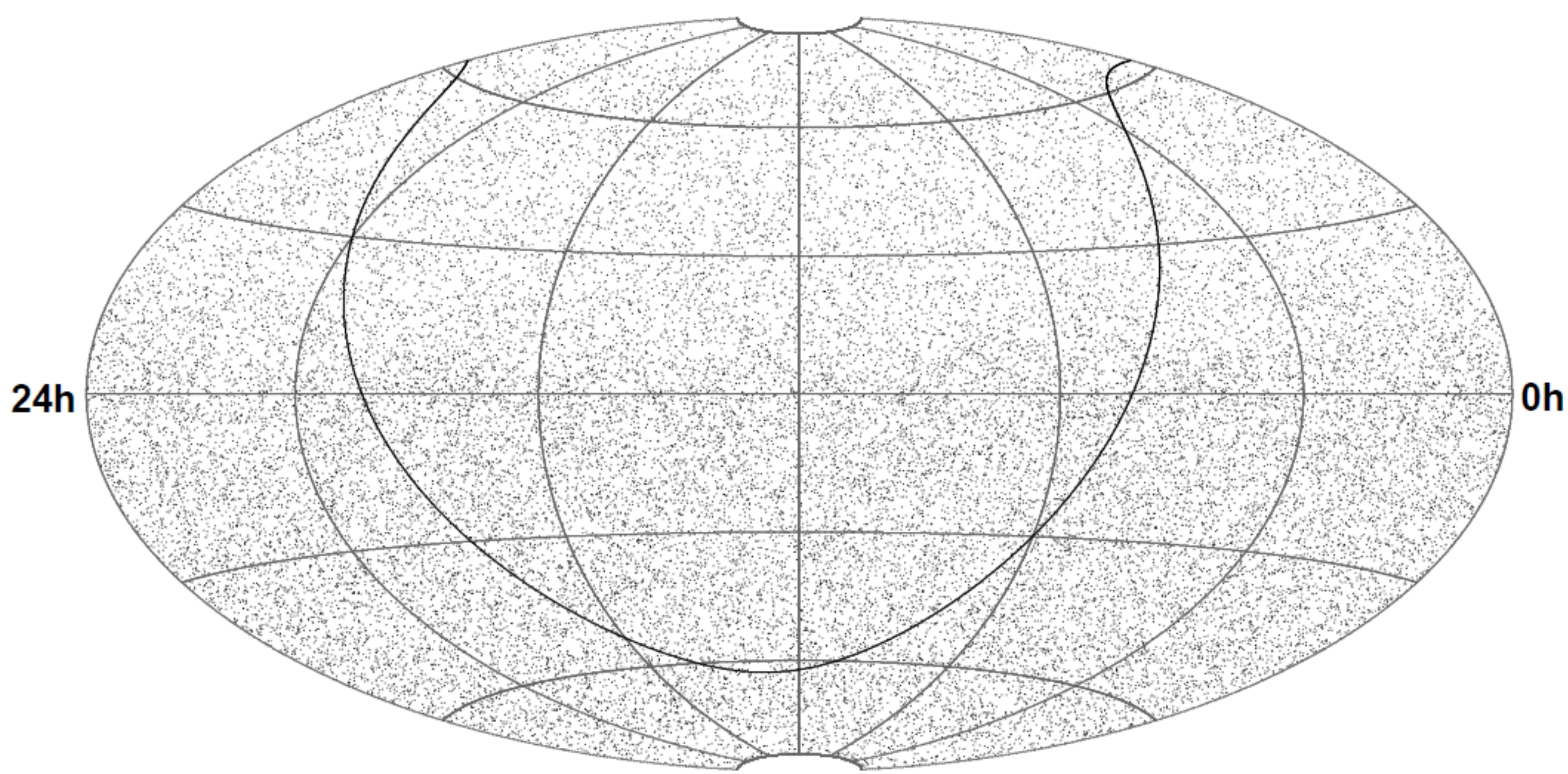
- Starting tracks
- high-E ν_τ (Double Bangs)
- Good directional and energy resolution

The IceCube Neutrino Observatory - A Wealth of Science...



Identify and reconstruct your best candidates (IceCube 40-string Detector)

- Operated for 375.5 days
  - Northern sky - 14139 events
  - Southern sky - 23151 events
  - Search for clustering of events in direction and energy.



Perform the Point Source Search (IceCube 40-strings)

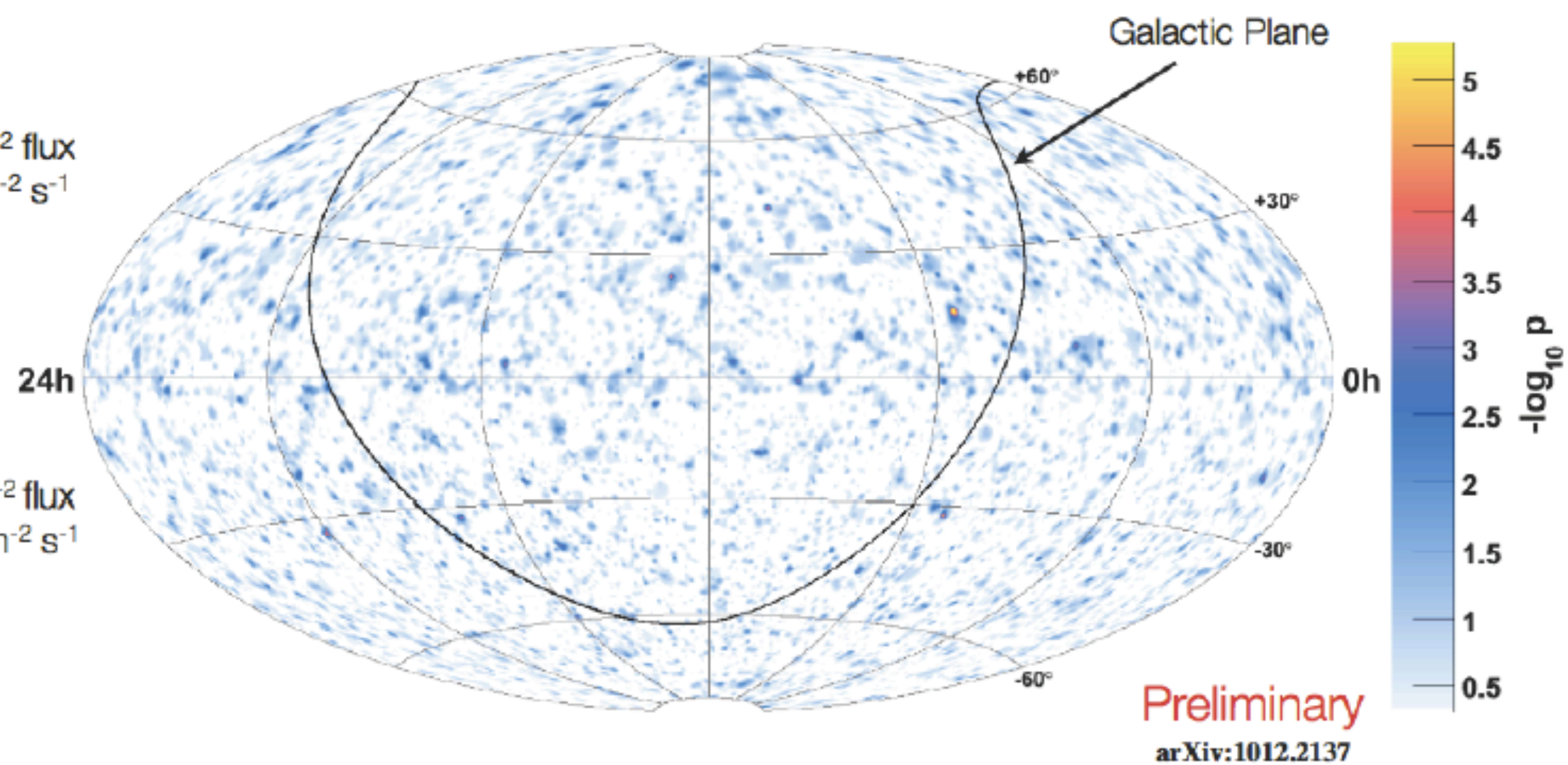
- Search for an excess of astrophysical neutrinos from a common direction over the atmospheric neutrino background

- All sky search with >37K neutrino candidates (~23k from southern hemisphere atmospheric neutrinos

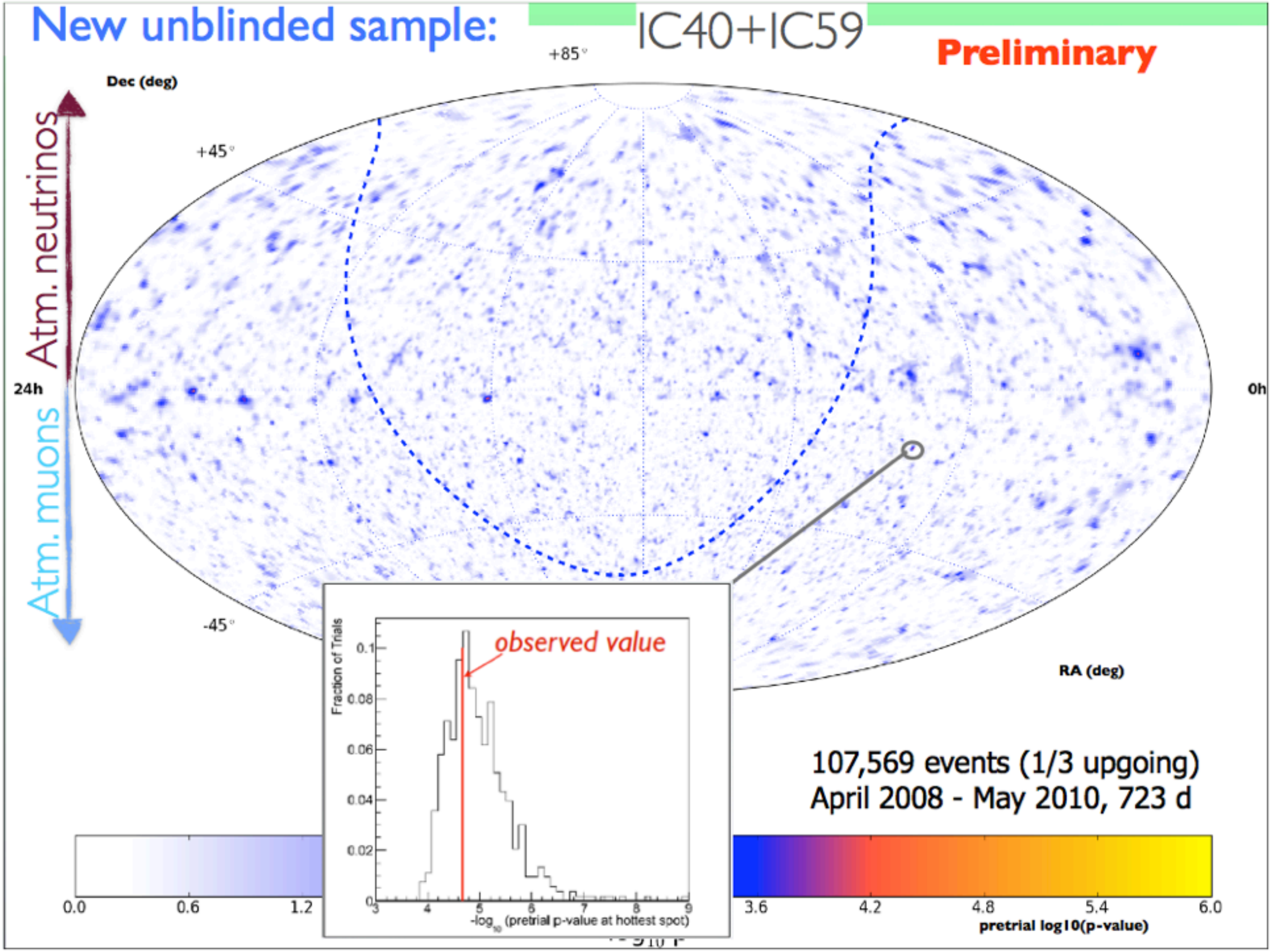
- Hottest spot in the 40-string data set was not statistically significant (96% of scrambled sky maps have higher significance)

Northern Sky Limit for E^{-2} flux
$\Phi^{90} = 2\text{-}20 \times 10^{-12}$ TeV cm^{-2} s^{-1}
TeV-PeV sensitivity

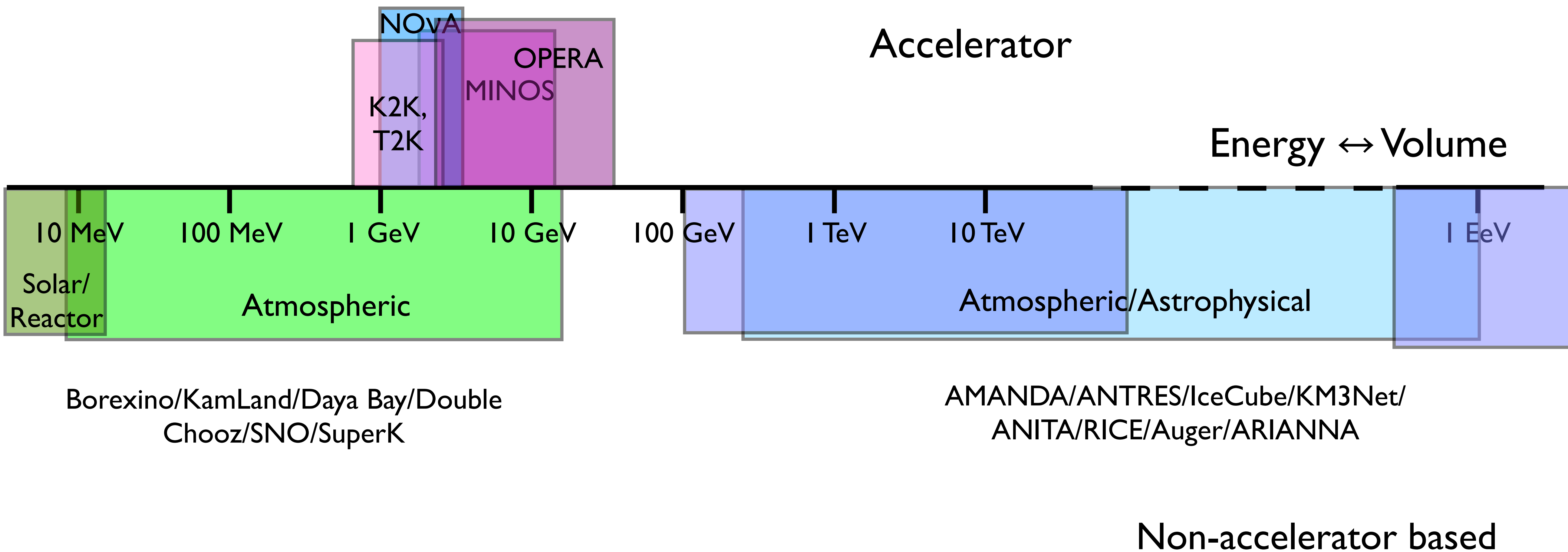
Southern Sky Limit for E^{-2} flux
$\Phi^{90} = 3\text{-}700 \times 10^{-12}$ TeV cm^{-2} s^{-1}
1 PeV < sensitivity



Most Recently from IceCube Point Source Searches...



The Neutrino Detector Spectrum



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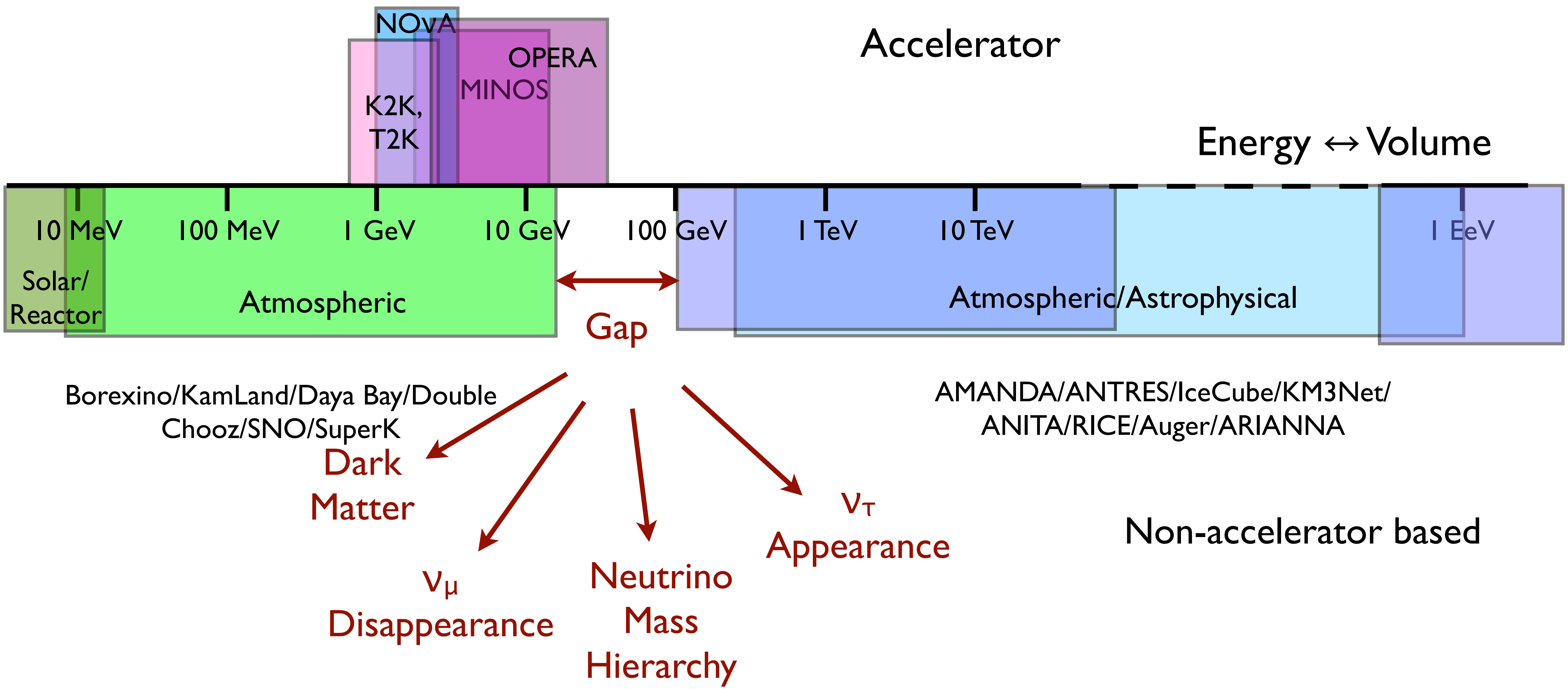


** boxes select primary detector physics energy regimes and are not absolute limits*

IceCube

IceCube

IceCube

IceCube-DeepCore

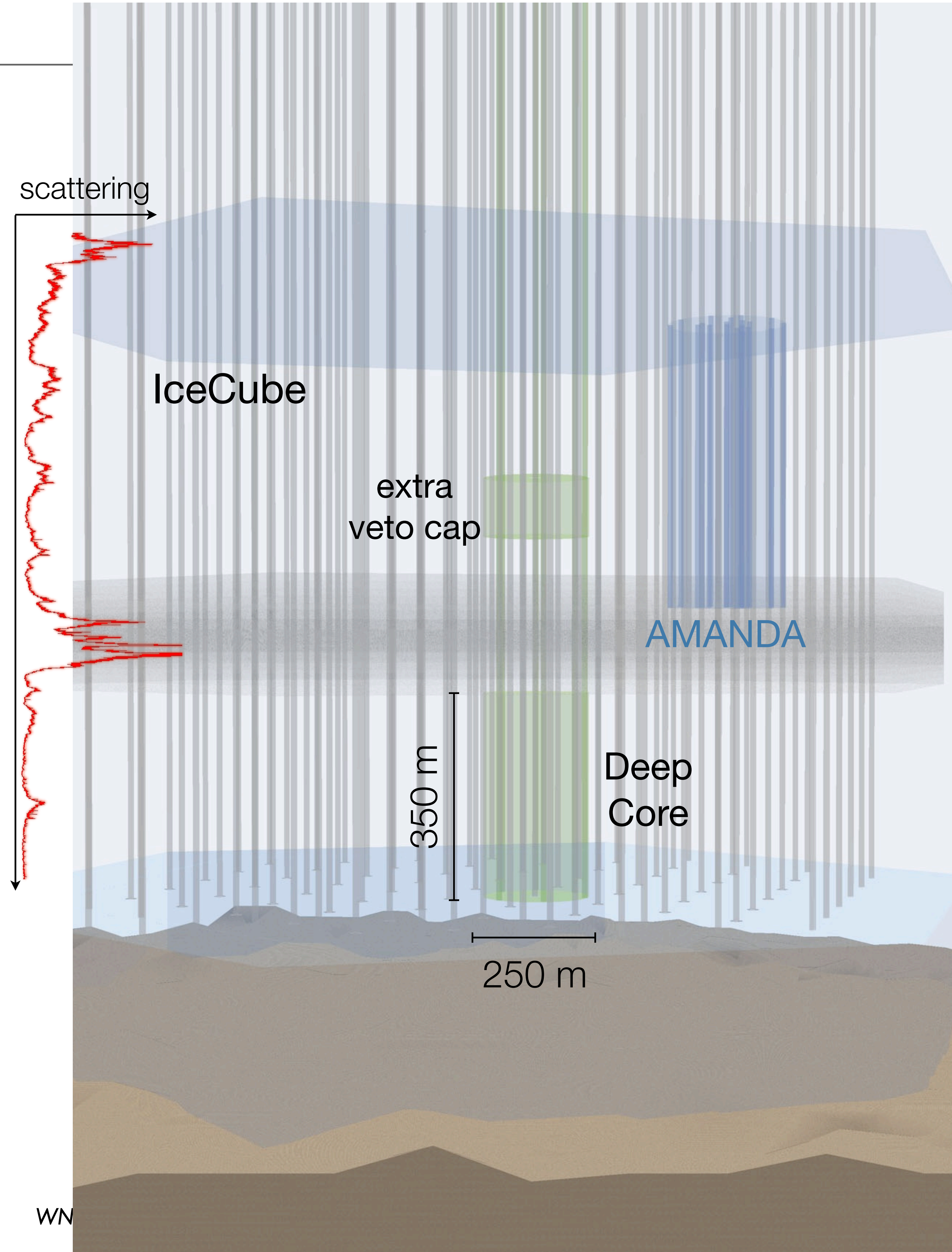
IceCube DeepCore

IceCube-DeepCore

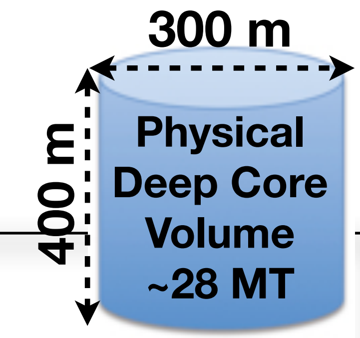
- IceCube extended its "low" energy response with a densely instrumented infill array: DeepCore http://arxiv.org/abs/1109.6096
  - Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Scientific Motivations:
  - Indirect search for dark matter
  - Neutrino oscillations (e.g., ν_τ 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(100k) physics quality atmospheric ν/yr

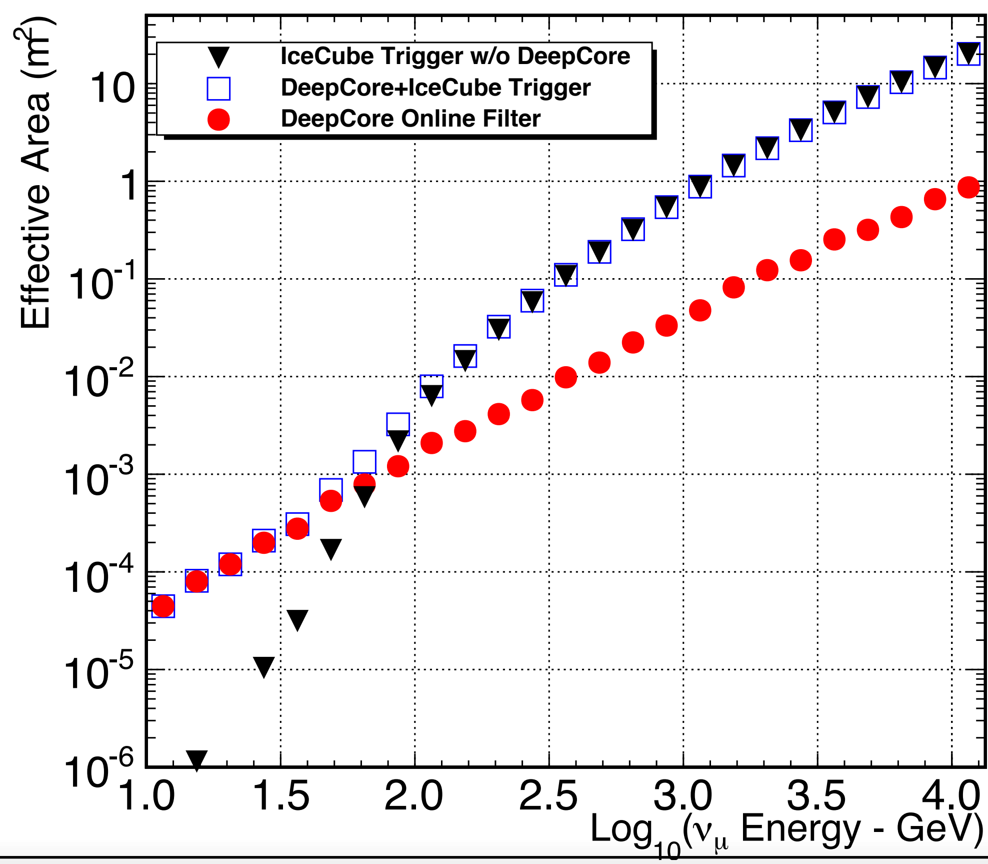


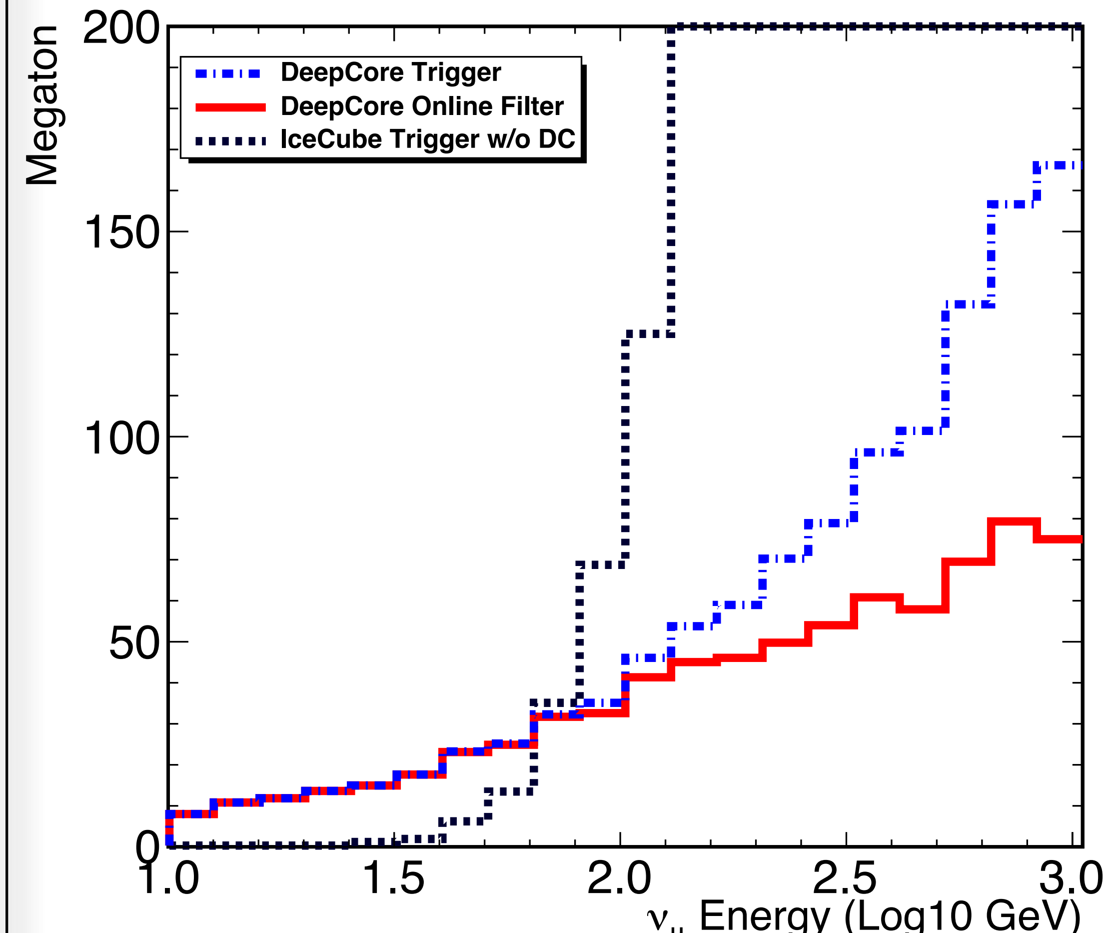
DeepCore Effective Area and Volume



Effective area for ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase





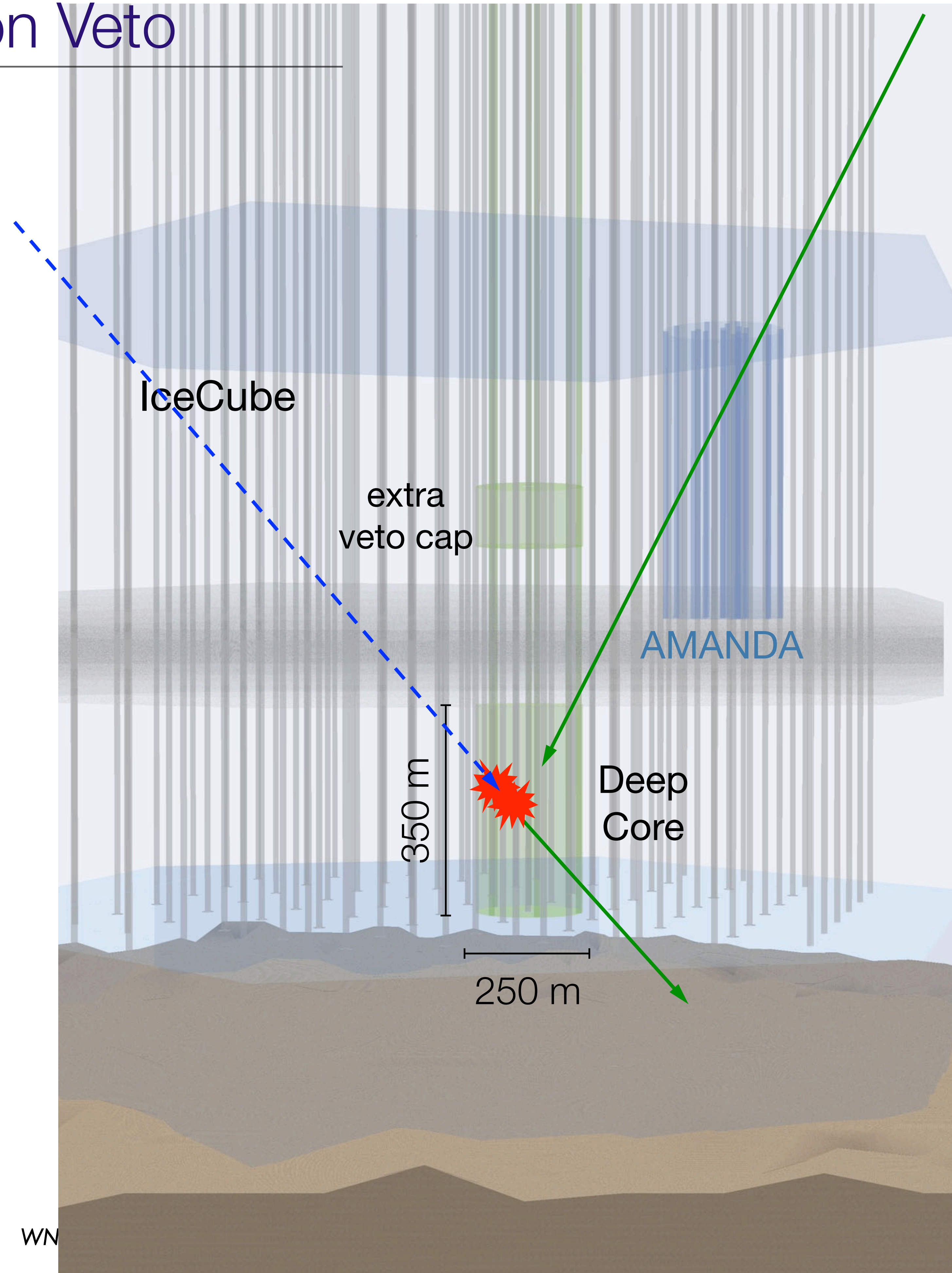
Effective volume for muons from ν_μ interacting in Deep Core

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 Atmospheric Muon Veto

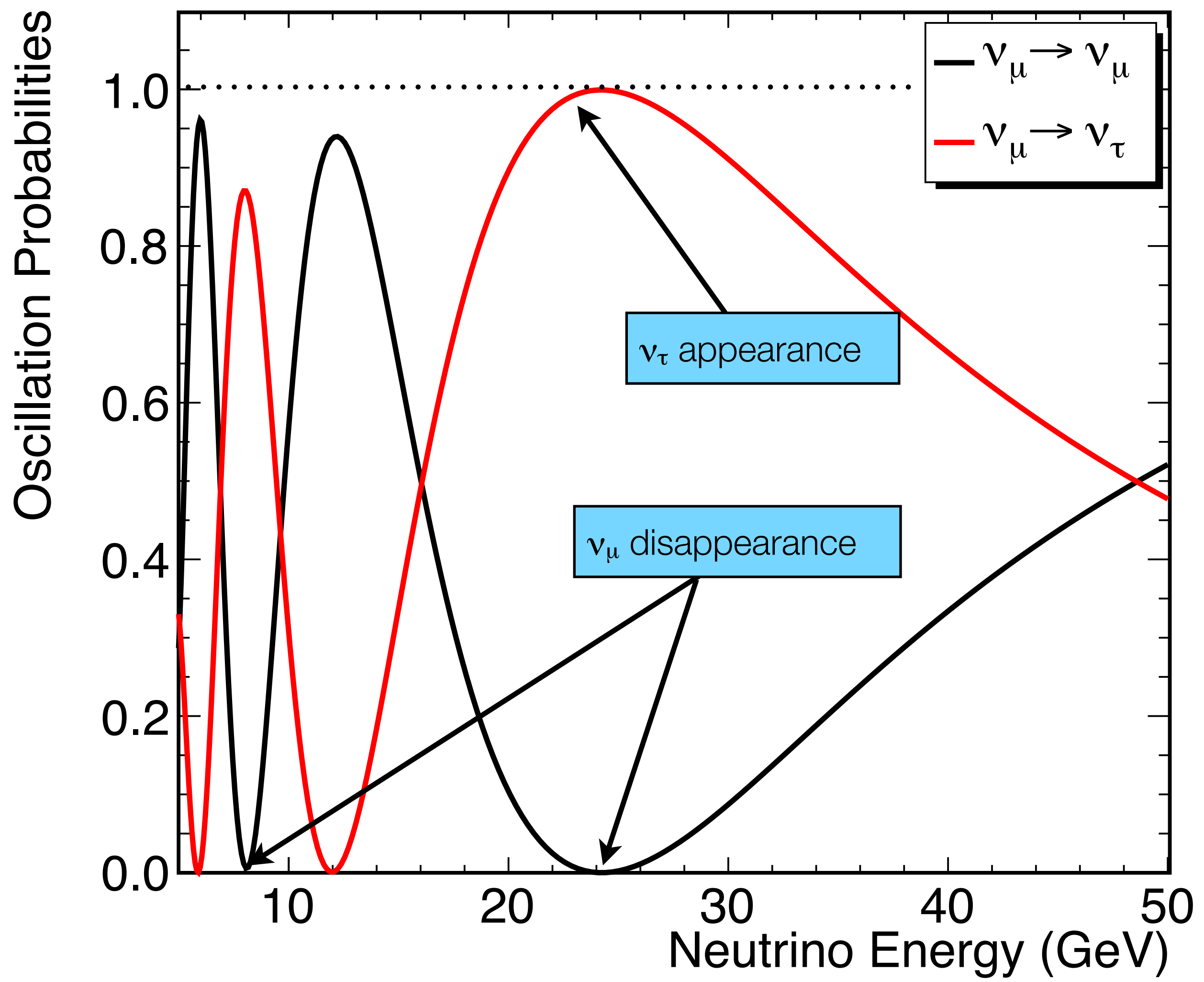
- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective μ-free depth much greater
-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



First from DeepCore - Observation of Atmospheric Cascades

- Disappearing ν_μ should appear in IceCube as ν_τ cascades
    - Effectively identical to neutral current or ν_e CC events
    - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background

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



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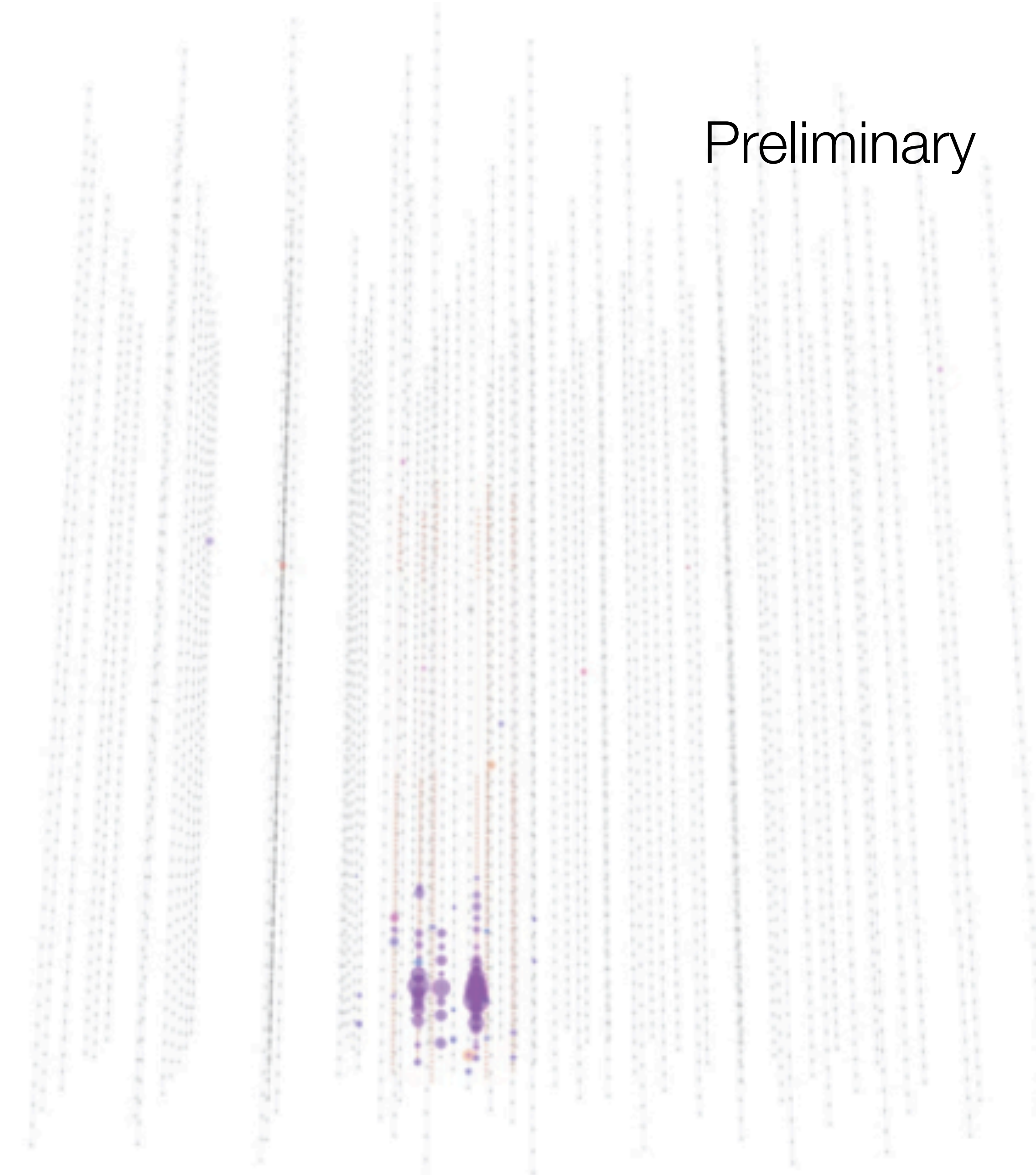
    - Effectively identical to neutral current or ν_e CC events
    - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background
- First results from DeepCore are neutrino cascade events
    - The dominant background now is CC ν_μ events with short tracks



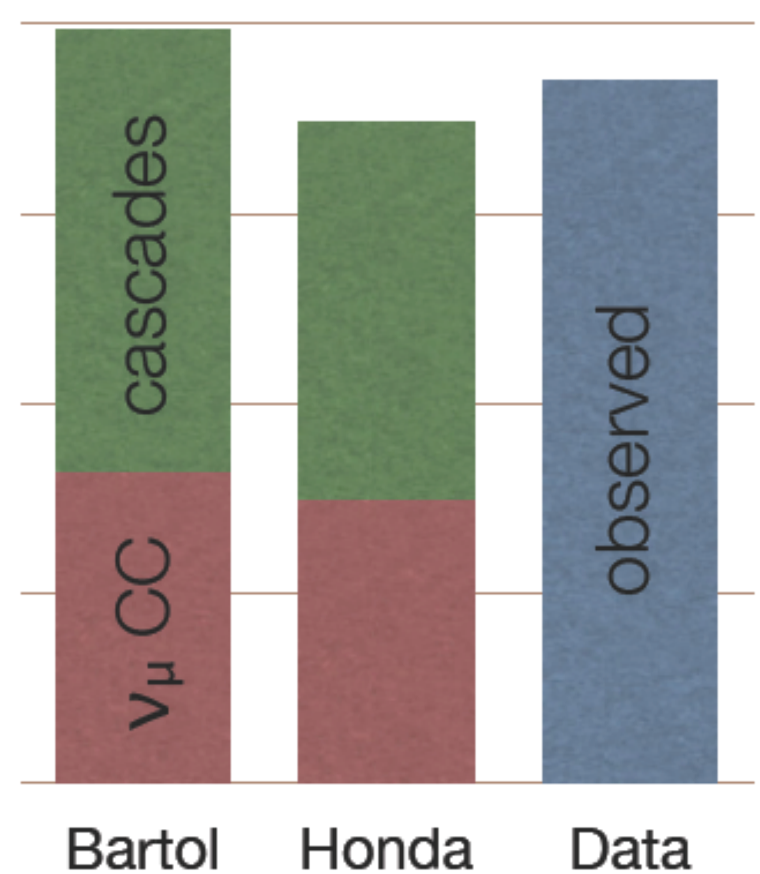
Candidate cascade event
Run 116020, Event 20788565, 2010/06/06

First from DeepCore - Observation of Atmospheric Cascades

- A substantial sample of cascades has been obtained, final data set ~60% cascade events
  - Events have a mean energy ~200 GeV (not sensitive to oscillations with these first cuts)
  - Atmospheric muon background is being assessed (expected to be small)
- The potential to discriminate between atmospheric neutrino models exists and thus measuring air shower physics

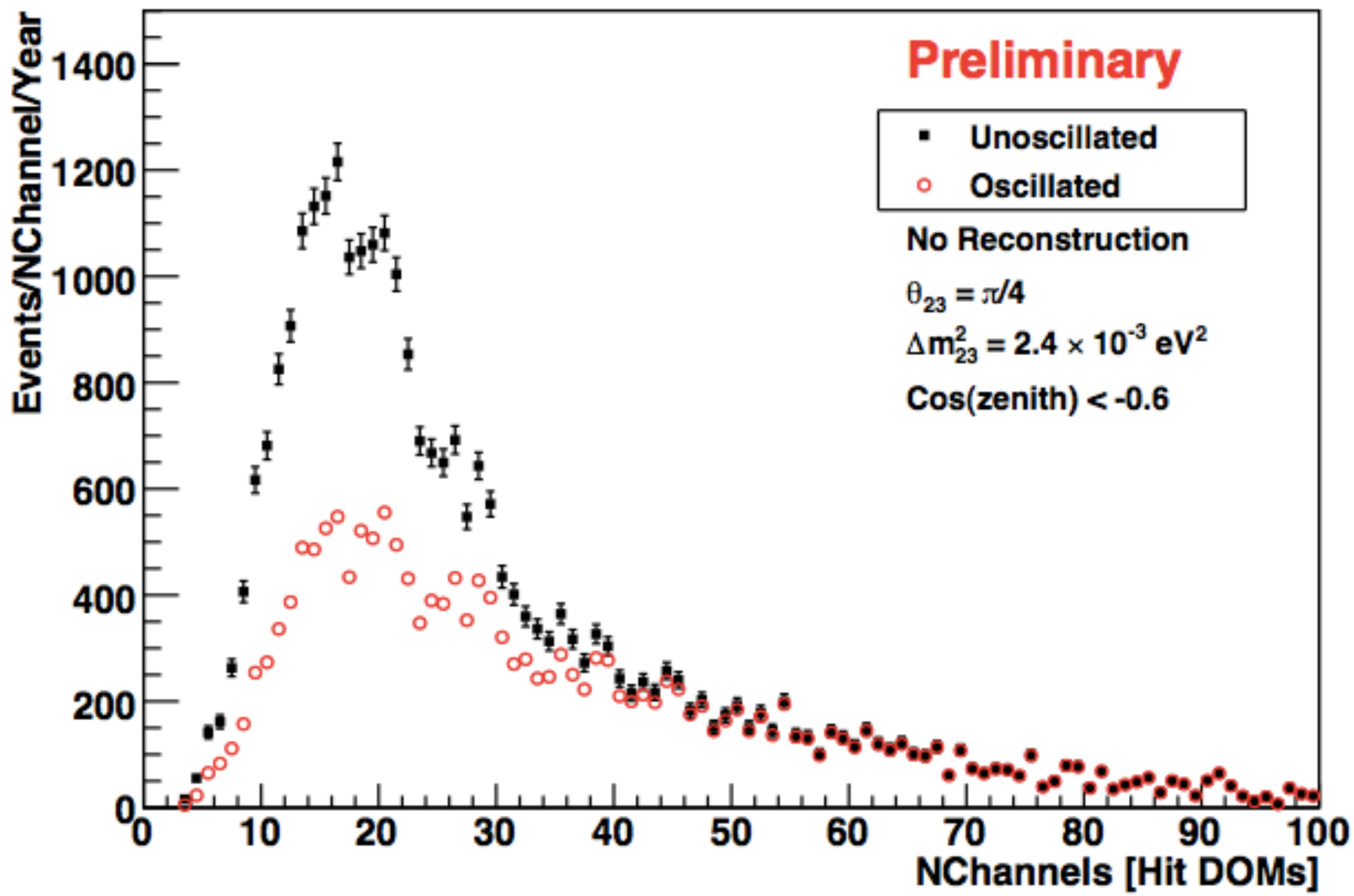
preliminary!

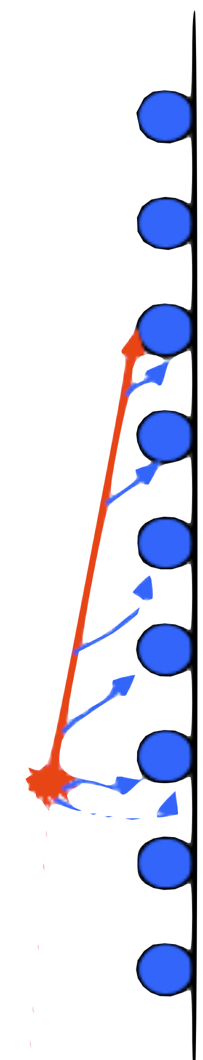
	Cascades	CC ν_μ	Total
Bartol	650	454	1104
Honda	551	415	966
Data			1029



Muon-neutrino disappearance

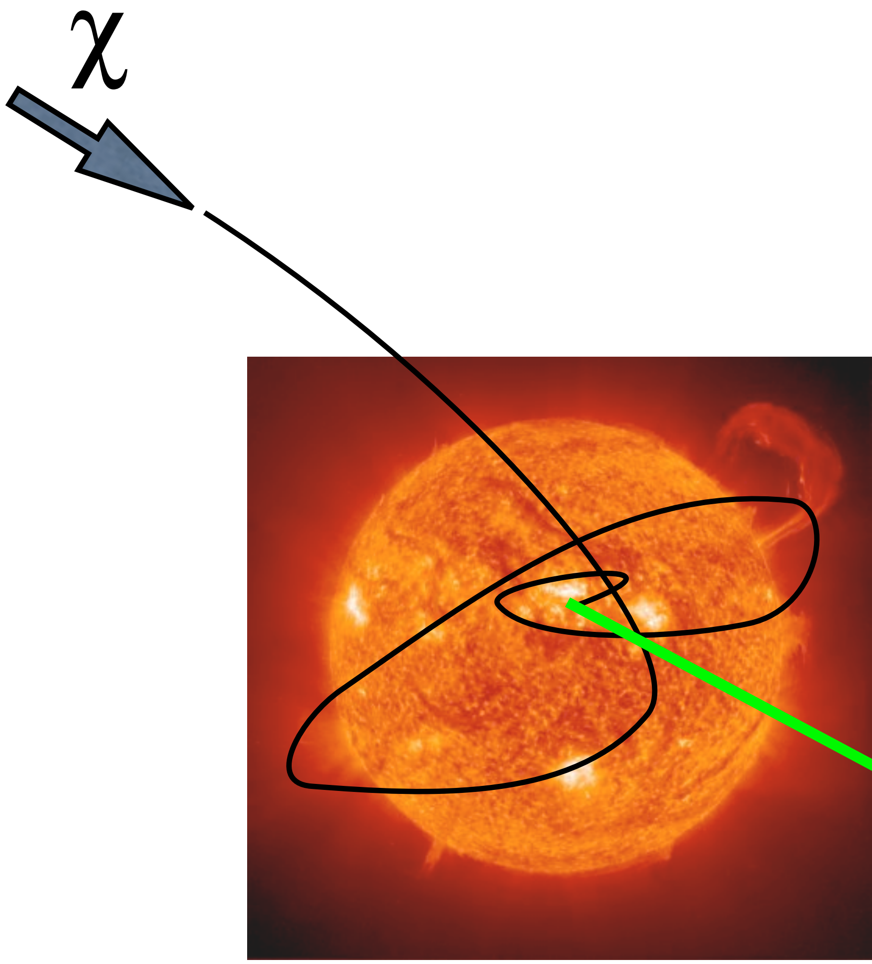
- Full detector simulation of signal
  - 3-flavor oscillations, PREM
  - 1 year DC
  - No BG
  - cos(θ)<-0.6



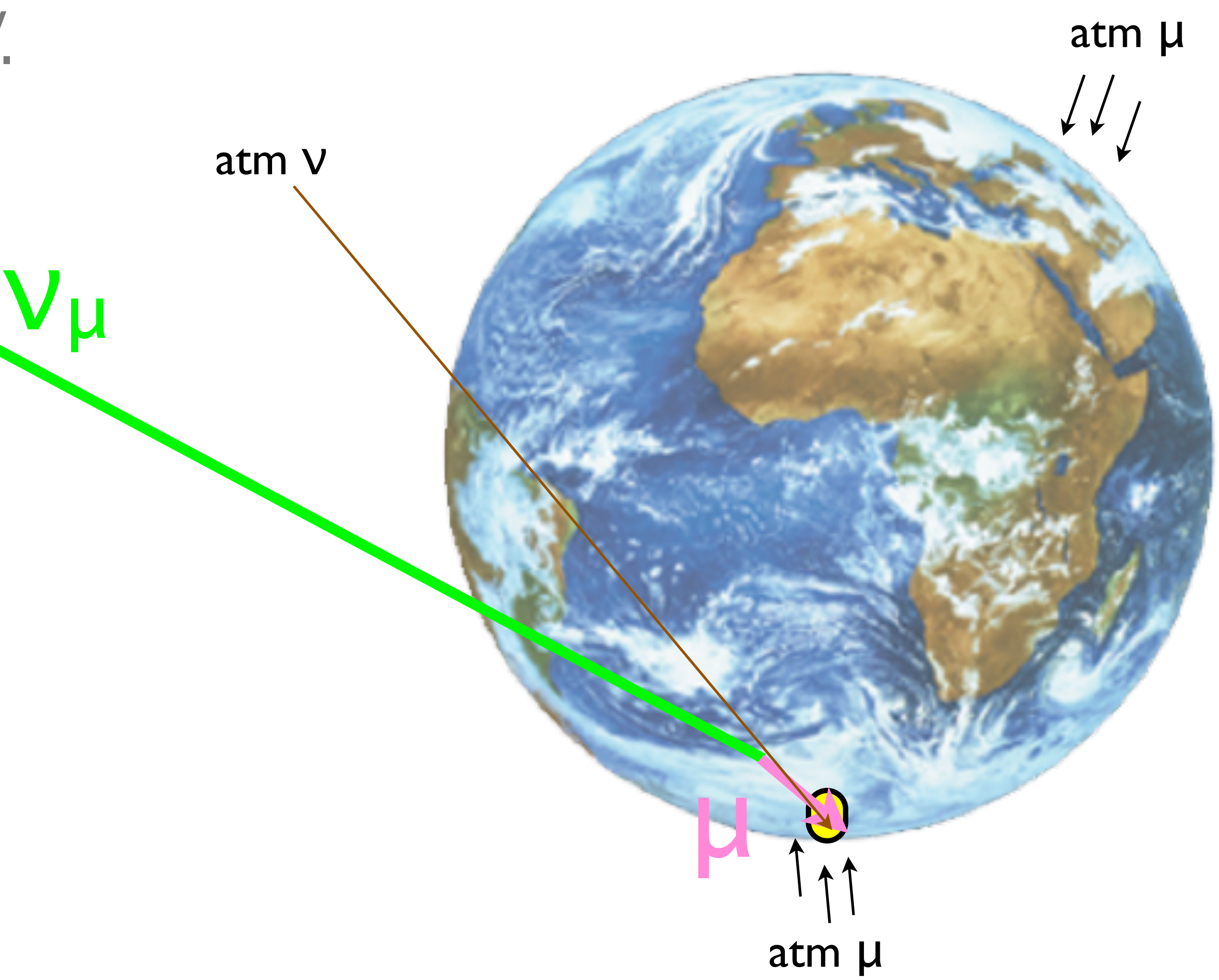


- Number of hit channels used as simple energy estimator

Indirect Dark Matter Searches



- Search for neutrinos produced in the annihilation of dark matter collected in massive astrophysical objects (Sun, centre of Earth...)
- Resultant neutrino energies of order GeV - TeV.



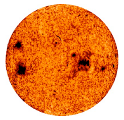
$$\chi\chi \rightarrow \begin{array}{c} q\bar{q} \\ l\bar{l} \\ W^{\pm}, Z, H \end{array} \rightarrow \cdots \rightarrow \nu_{\mu}$$

Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86
Freese, '86

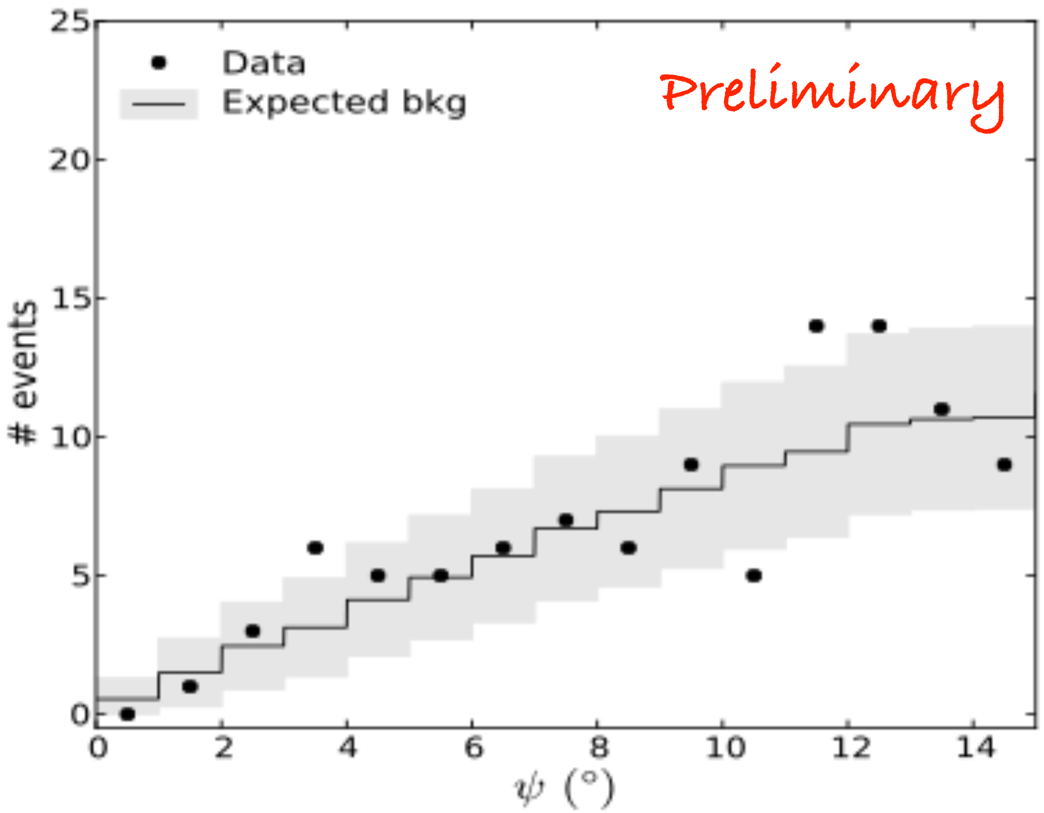
Krauss, Srednicki & Wilczek, '86
Gaisser, Steigman & Tilav, '86

Indirect Dark Matter Searches

Solar WIMP search

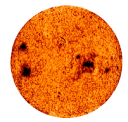


- We utilize data when the Sun is below the horizon (March - September), resulting in near-horizontal muon tracks.
    - AMANDA-II (2001 - 2006)
    - IceCube 22 and 40-strings (2007-2009)
    - Total exposure 1065 days.
- Several levels of filtering are applied to remove atmospheric muon backgrounds.
- Signal selection efficiency order of 20%, dependent on the neutrino energy.
- Angular resolution:
    - AMANDA (<500 GeV) 4 - 5 degrees
    - IceCube-22 (>500 GeV) 3 degrees
- Examine angular distribution Ψ for Sun and muon track.

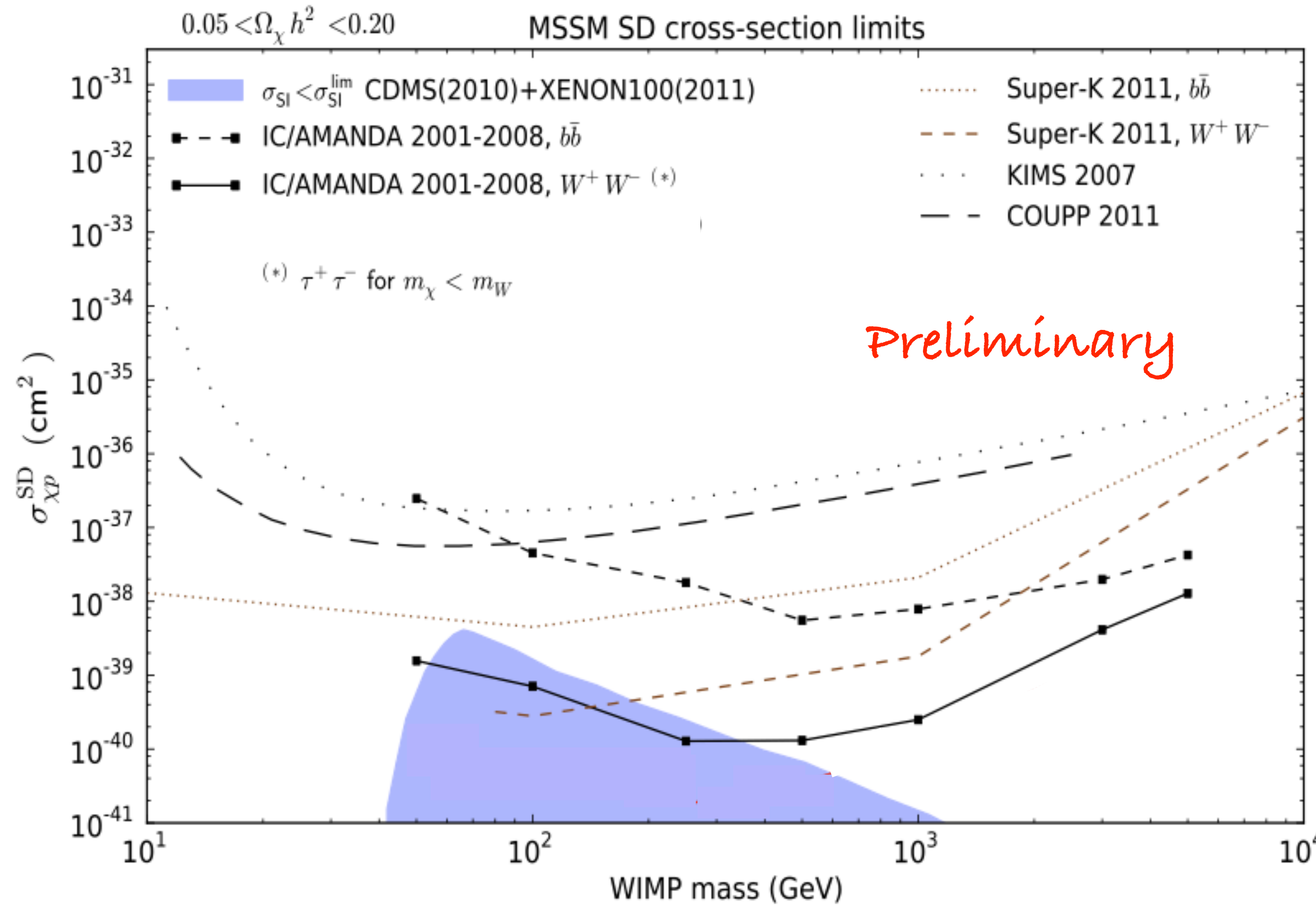


Observed flux in live days is consistent with background expectations.

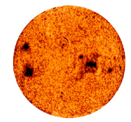
Indirect Dark Matter Searches

Solar WIMP search 

- Solar WIMP searches probe SD scattering cross section
  - SI cross section constrained well by direct search experiments
- Requires models of solar dark matter population distributions, annihilation modes



Indirect Dark Matter Searches

Solar WIMP search 

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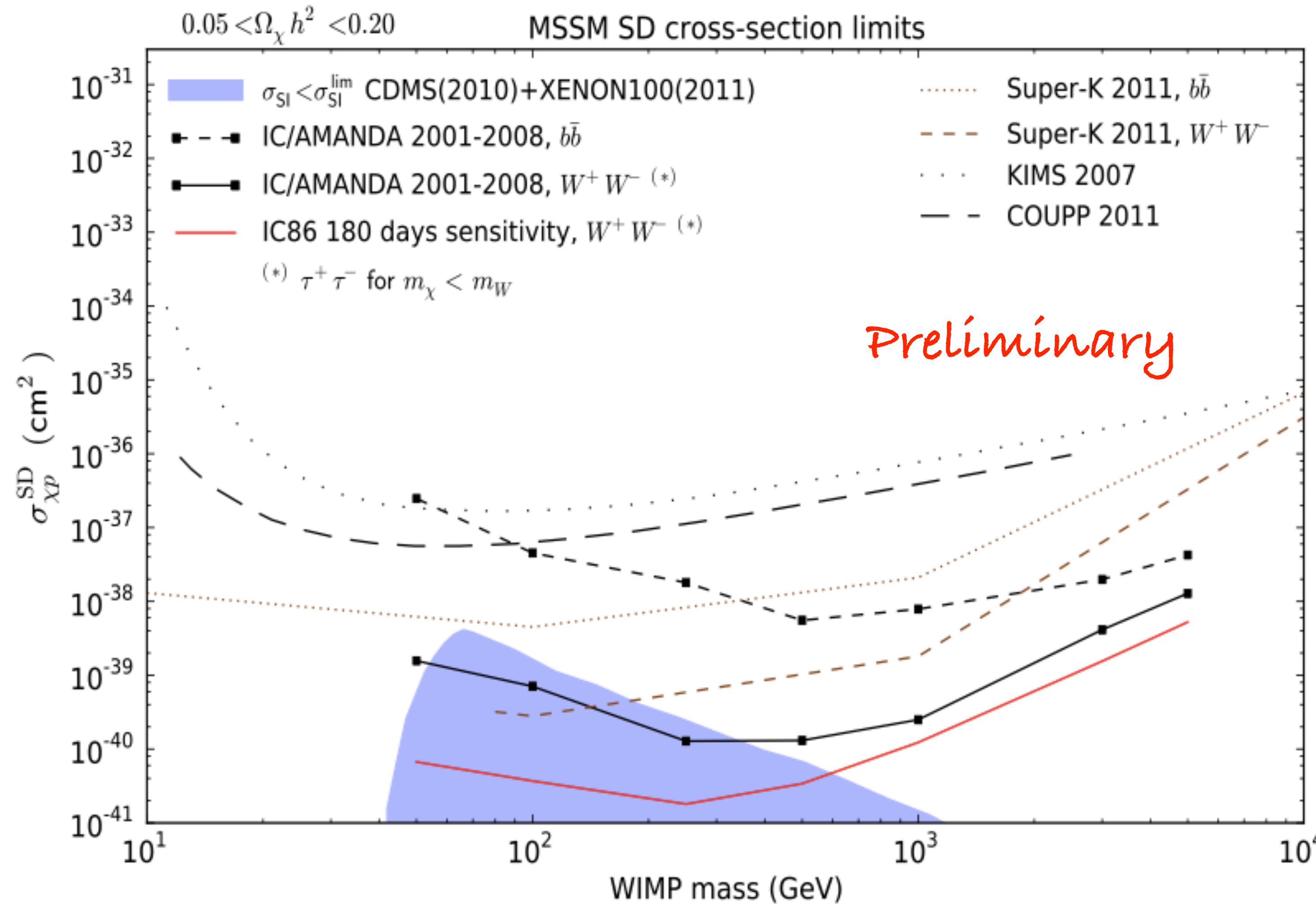
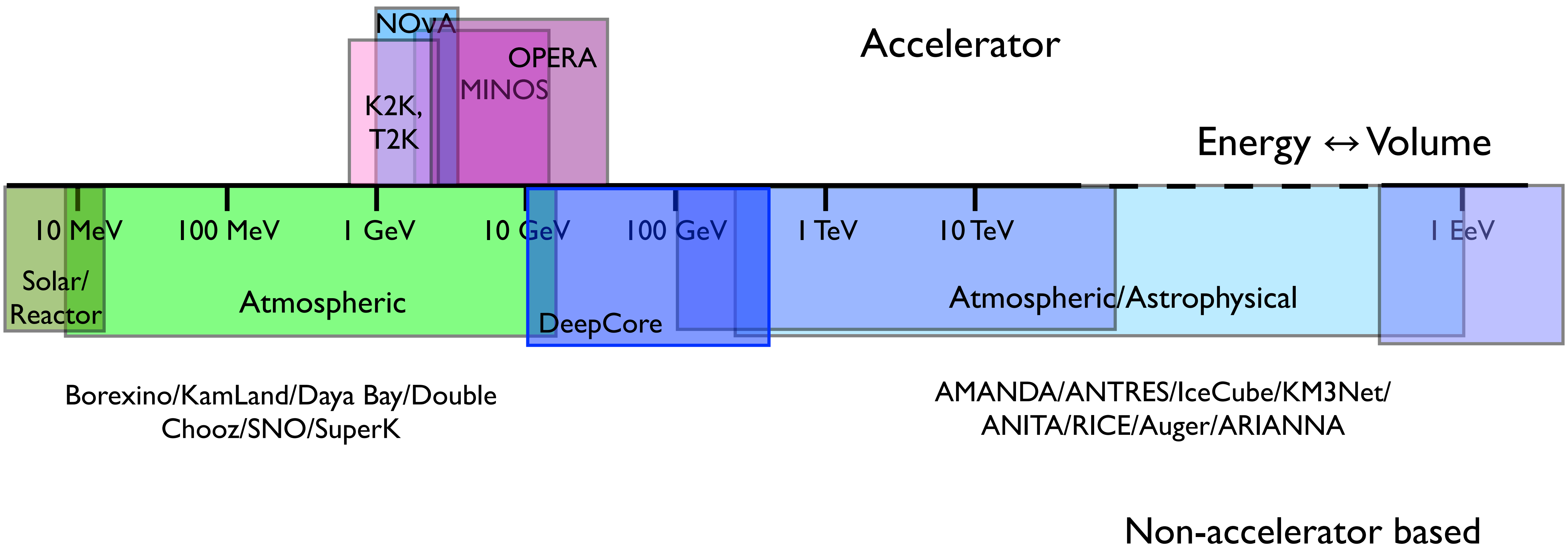


The Neutrino Detector Spectrum



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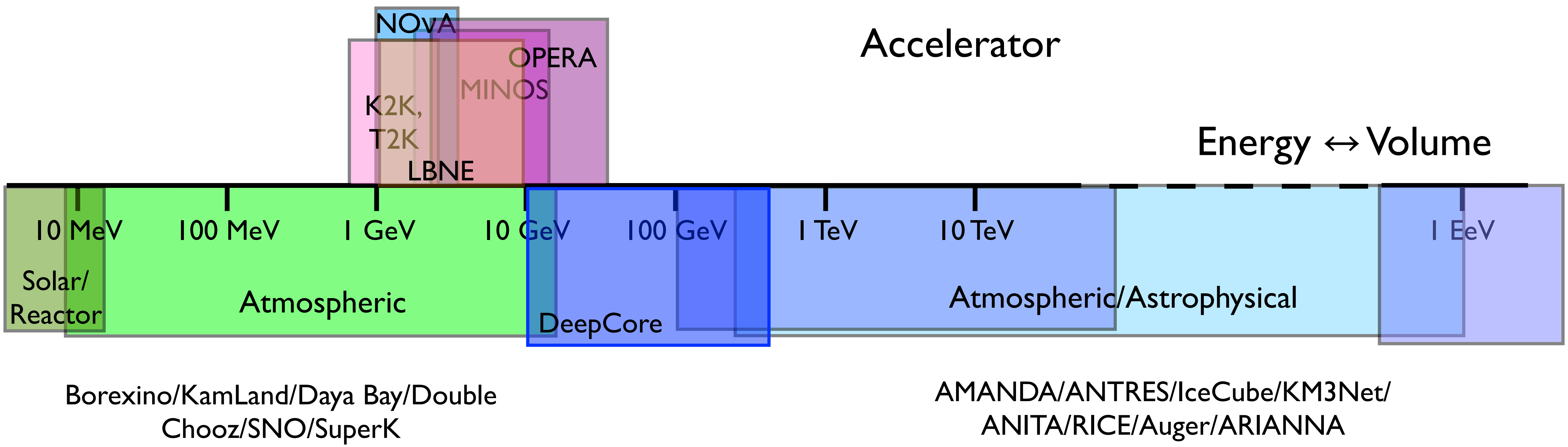


The underground community is preparing programs for large-scale detectors O(300 kT),with physics focused on long-baseline neutrinos, toward O(1MT), proton decay, supernova neutrinos.

Construction/Purification of the facilities for these detectors remain technological challenges of engineering.

IceCube-DeepCore

IceCube DeepCore

IceCube-DeepCore

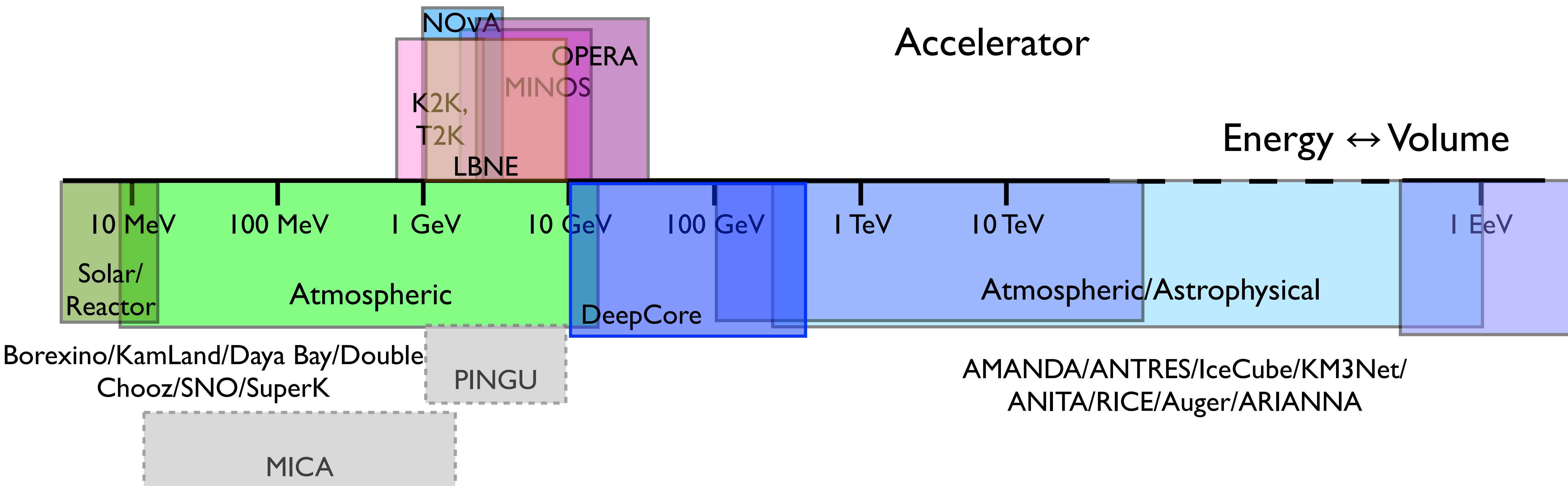
IceCube DeepCore

IceCube-DeepCore-PINGU

IceCube DeepCore PINGU/MICA

PINGU/MICA

(Precision IceCube Next Generation Upgrade/Multimegaton Ice Cherenkov Array)



Non-accelerator based

~70 active members in feasibility studies:

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

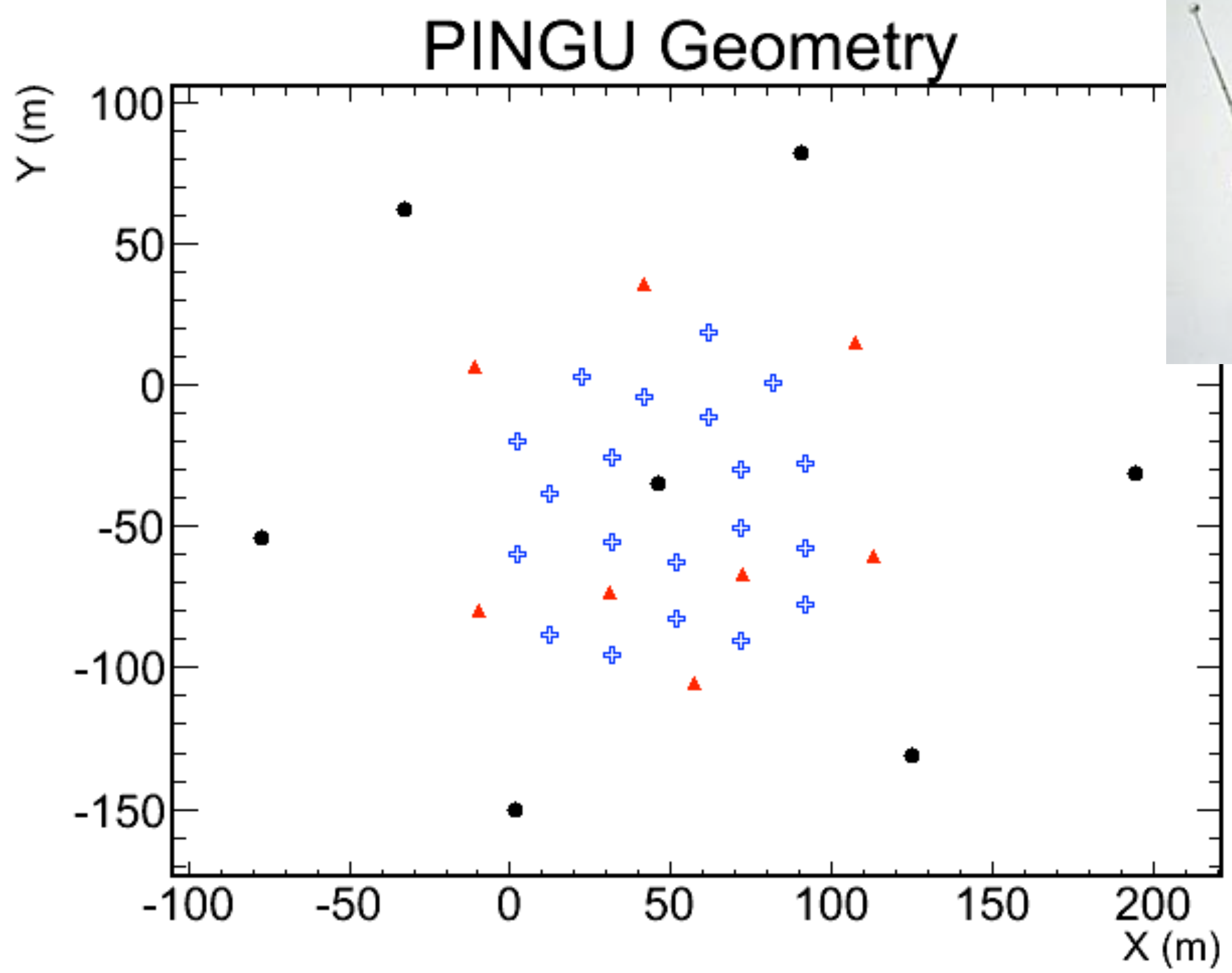
PINGU - Possible detector configurations

- First stage (“PINGU”)
- 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 (“MICA”)
- Using new photon detection technology, build detector that can reconstruct Cherenkov rings for events well below 1 GeV
  - proton decay, supernova neutrinos, PINGU topics
- Comparable in scope (budget/strings) to IceCube, but in a much smaller volume

PINGU: Possible Geometry

- Could continue to fill in the DeepCore volume
  - E.g., an additional 20 strings (~1200 DOMs) in the 30 MTon DeepCore volume
  - Could reach O(GeV) threshold in inner 10 MTon volume

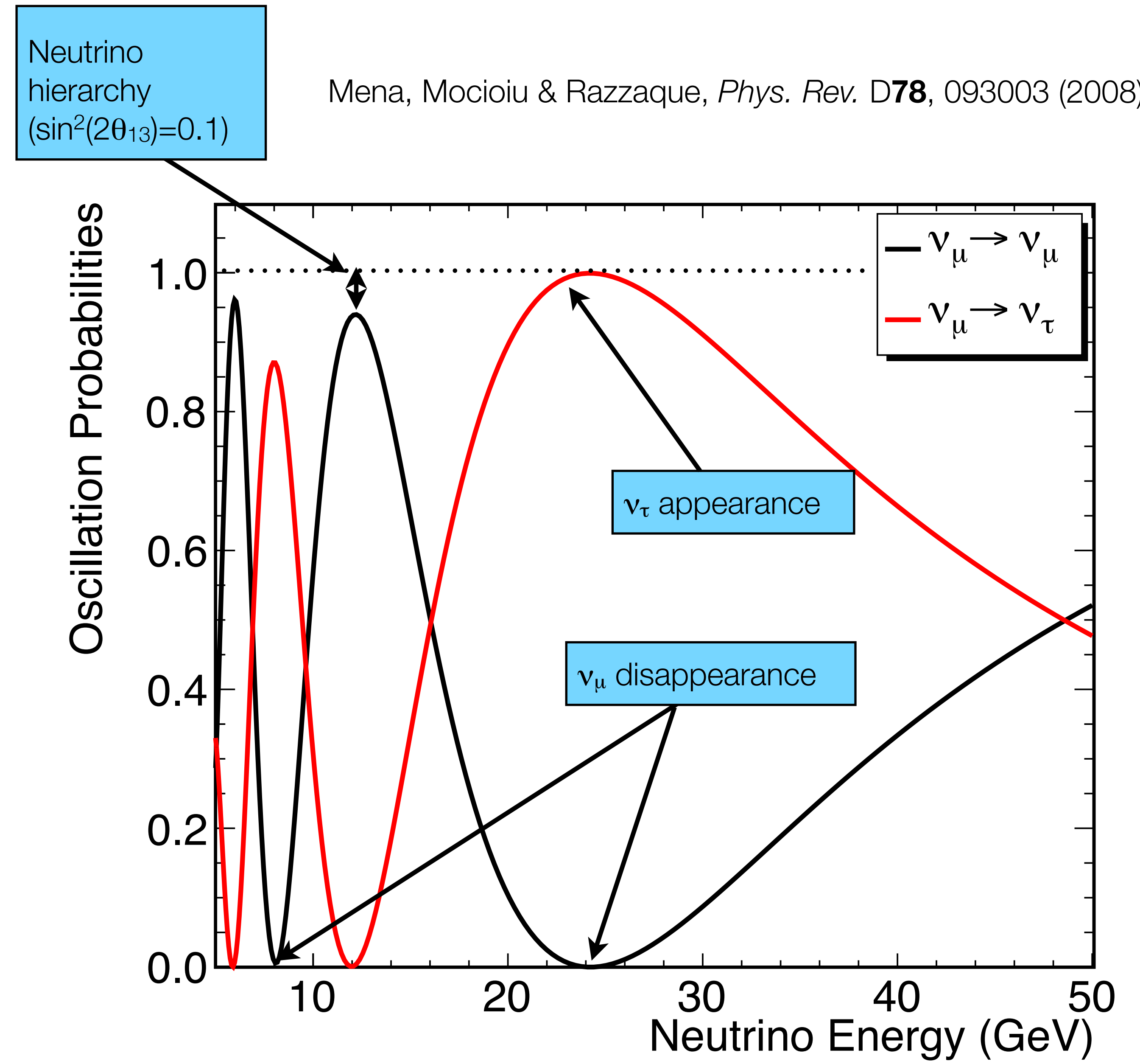


Aardman Animations

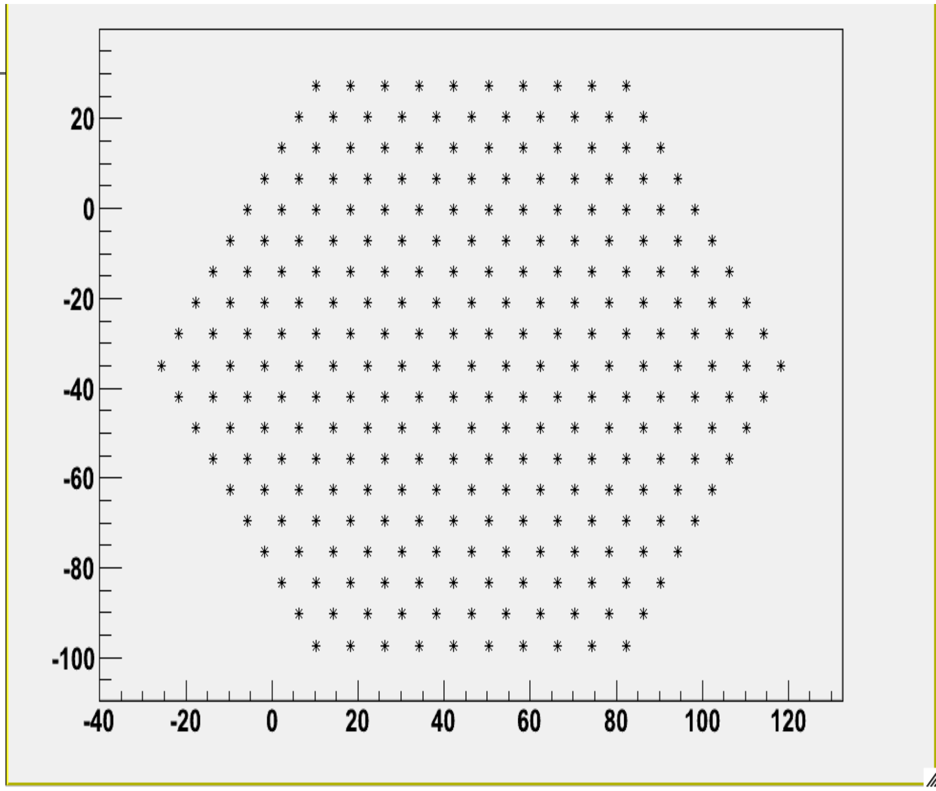
- Price tag would likely be around $25M

PINGU 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 MICA



MICA 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
- No excavation necessary: detection medium is the support structure

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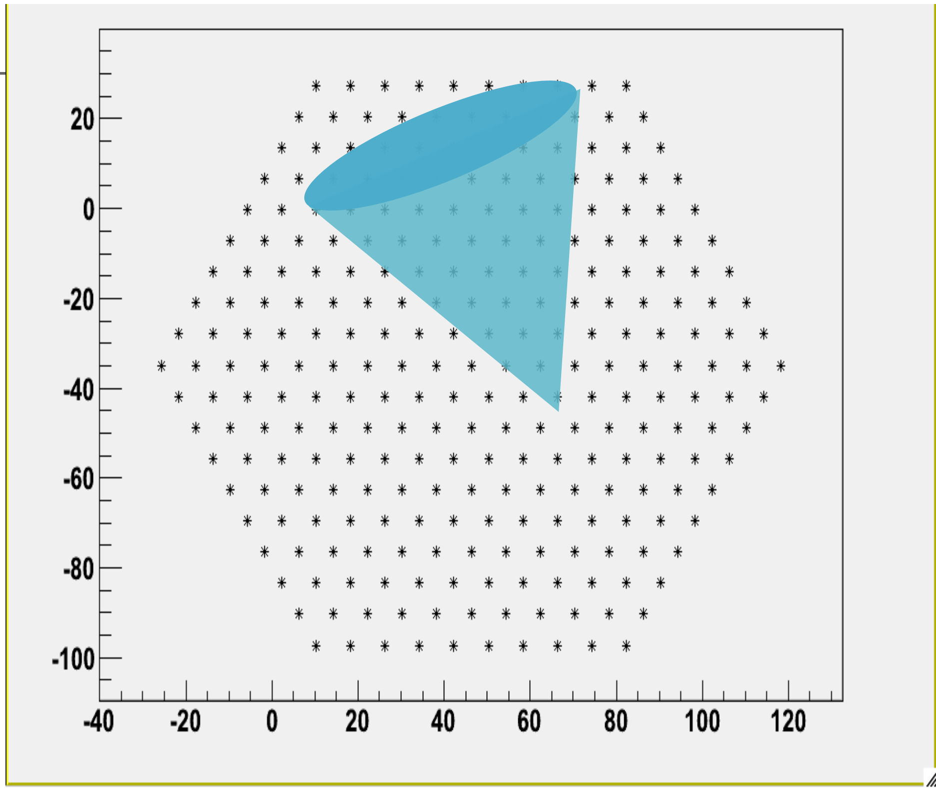

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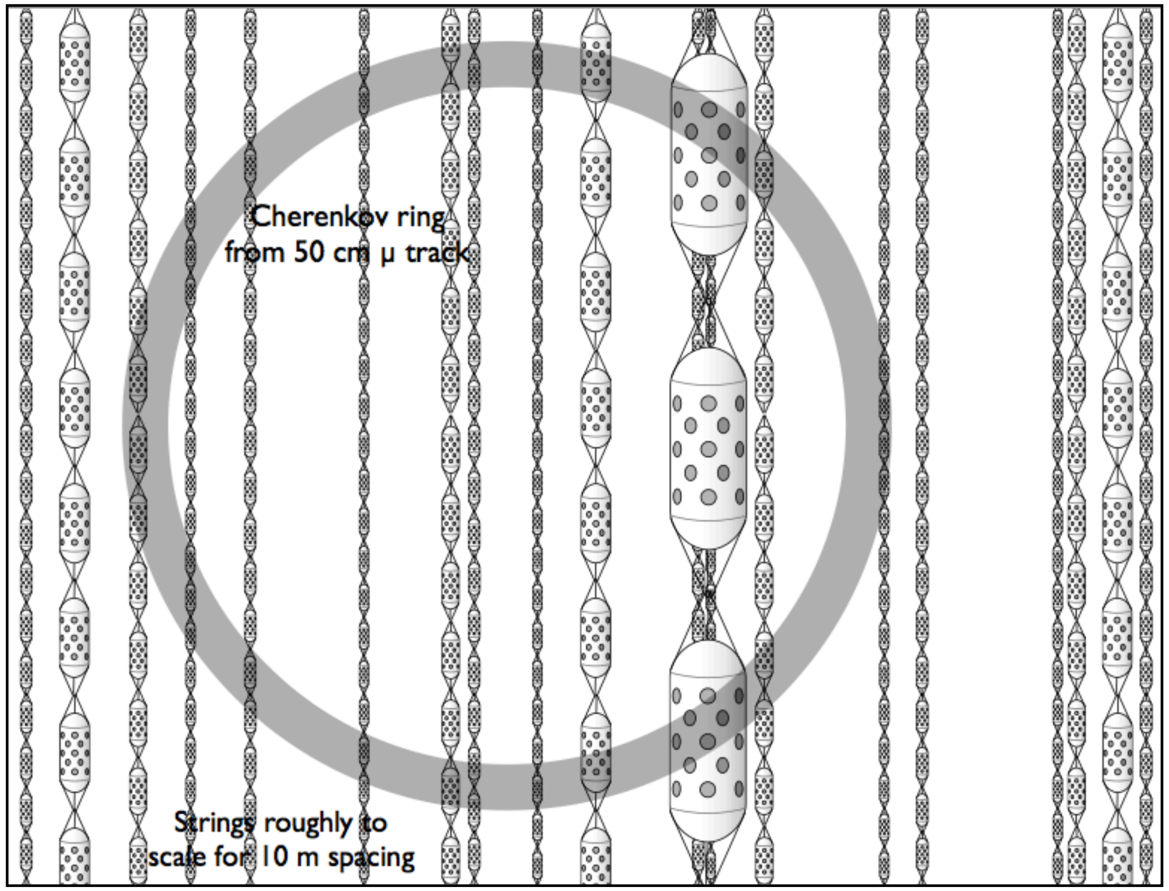

MICA Physics

- Proton decay
  - Studying sensitivity to p -> $\pi^0 + e^+$ channel
  - Requires energy threshold of ~100's of MeV
  - Background limited - depends on energy resolution, particle ring ID
- Supernova neutrinos
  - Need to reach well beyond our galaxy to get statistical sample of SN neutrinos
  - Background levels may be too high for a ~10 MeV threshold for individual events, but still allows for observation of bursts of events
- Plus improvements for WIMP, oscillation analyses over PINGU & DeepCore

Summary

- IceCube completed construction in December 2010 on schedule and within budget.

- The detector is exceeding the initial performance goals.   It is now has sensitivity to neutrinos of all flavors in a very wide energy range (10 GeV to 10^9 GeV) in both hemispheres. Recent results have started stringently testing the models for astrophysical neutrinos.

- DeepCore has been running for >1 year and has just commenced taking data in its final configuration. First results are now appearing!

- Expect significant improvement in sensitivity to dark matter, potential for neutrino oscillations. Preliminary analysis suggests we may have detected atmospheric electron neutrinos for the first time in a high-energy telescope.

- Towards the future, South Pole ice may be prove to be an attractive alternative for large-scale precision neutrino detectors (and direct detection dark matter with DM-Ice). Feasibility studies underway - stay tuned (or join in)!