Extending IceCube with Deep Core

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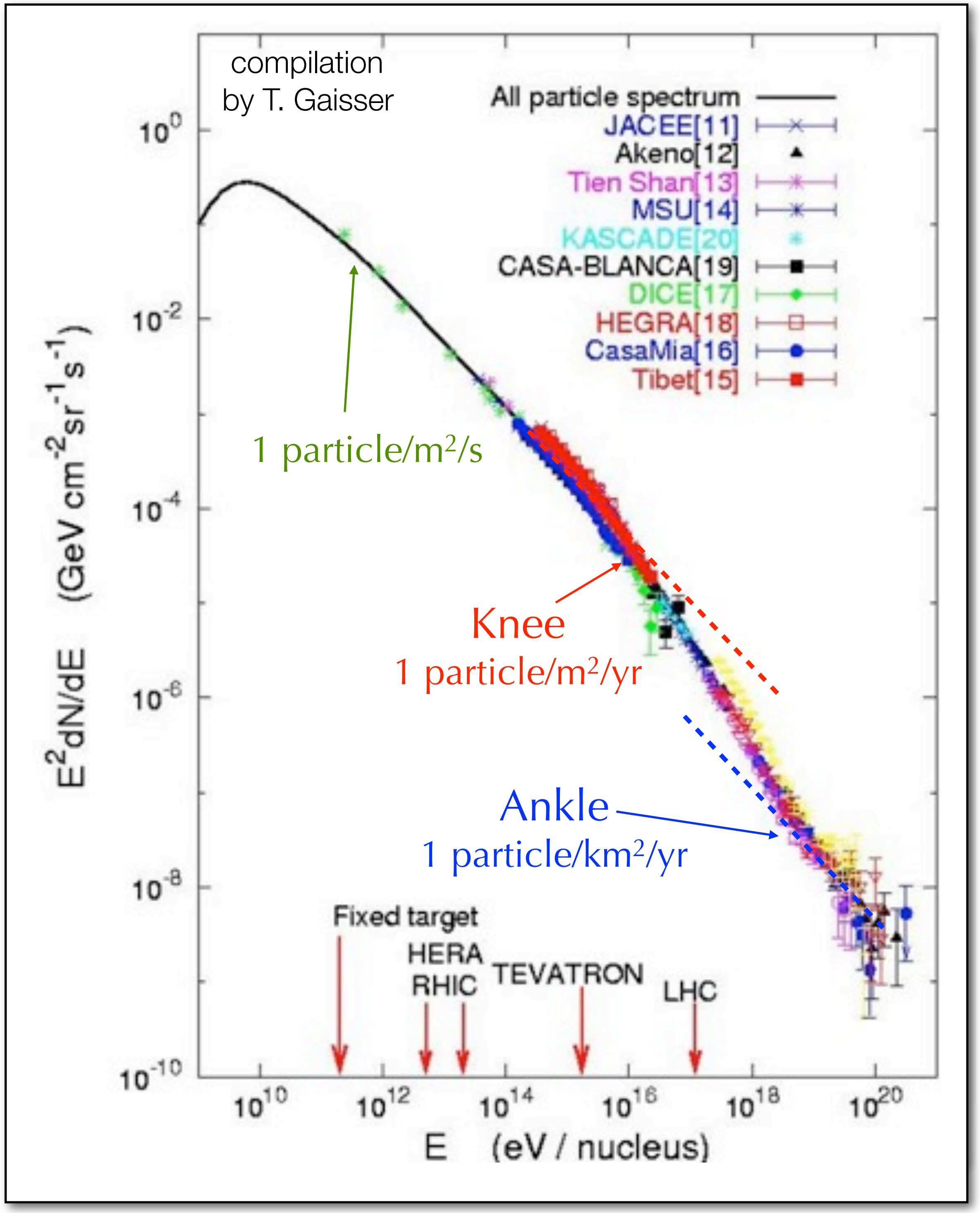
Outline

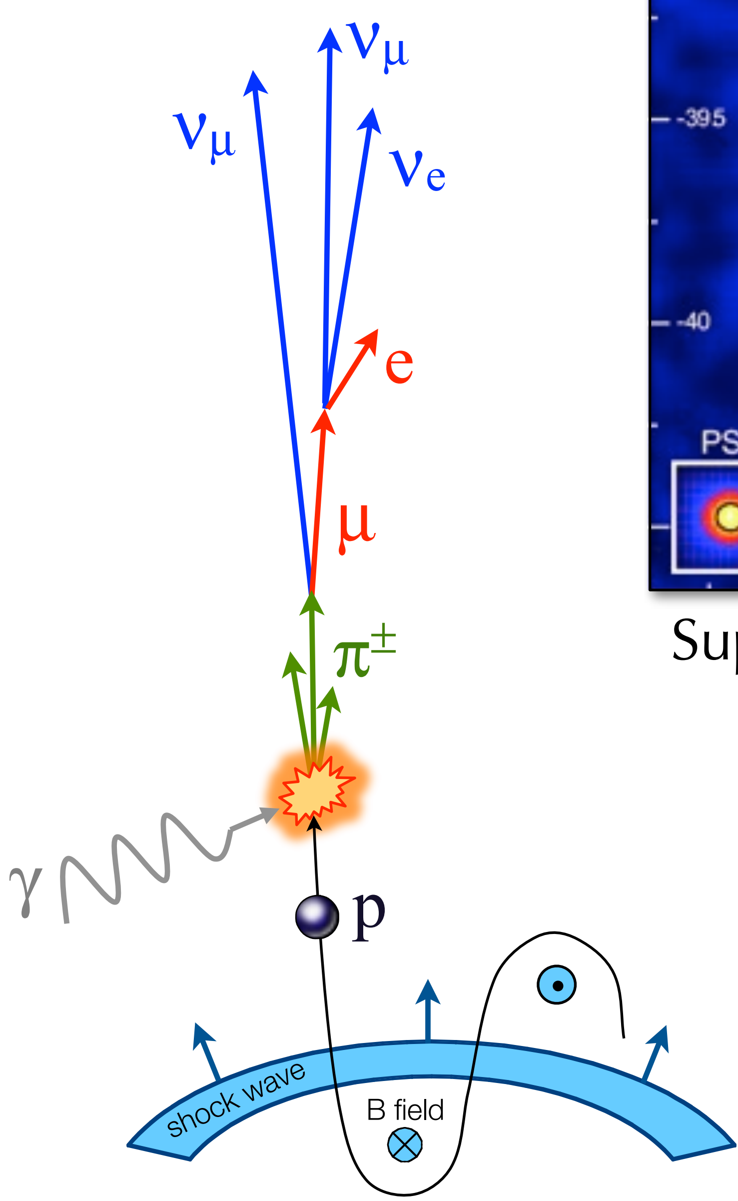
- The IceCube Detector
  - How and Why to Build a Neutrino Telescope
- Deep Core: the IceCube Low Energy Extension
- Science Goals of Deep Core
  - Neutrino Physics
  - Galactic Neutrino Astronomy
  - Dark Matter Searches

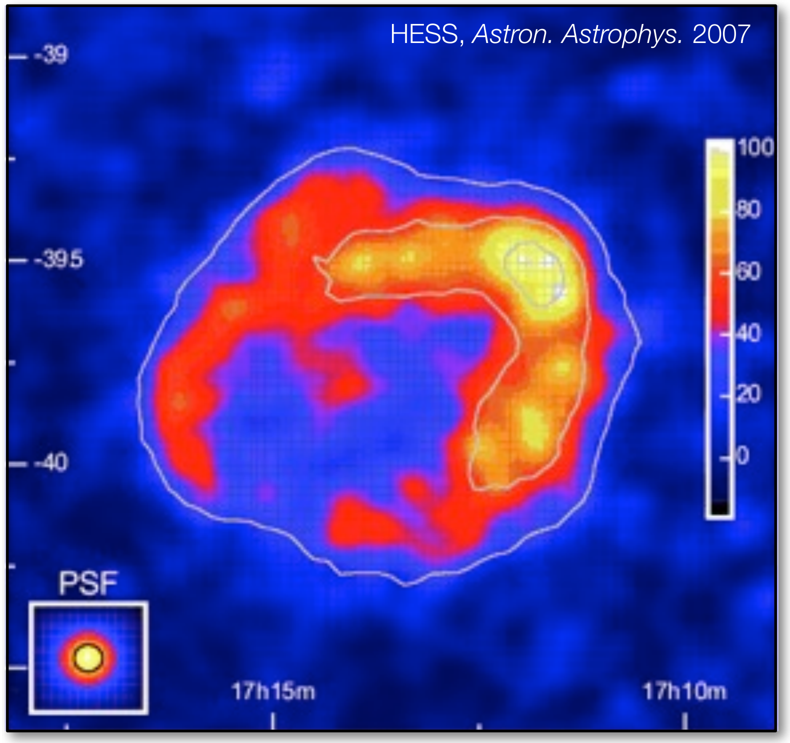
Cosmic Rays and the High Energy Universe

- Radiation of cosmic origin first established in 1912
  - Victor Hess carries electroscopes to 5000 m altitude (!) in a balloon
- What are they?
  - Charged particles, so they don't point back to their sources
  - Clues from spectrum, composition
- Where do they come from?
  - Astrophysical accelerators?
  - How are they accelerated?

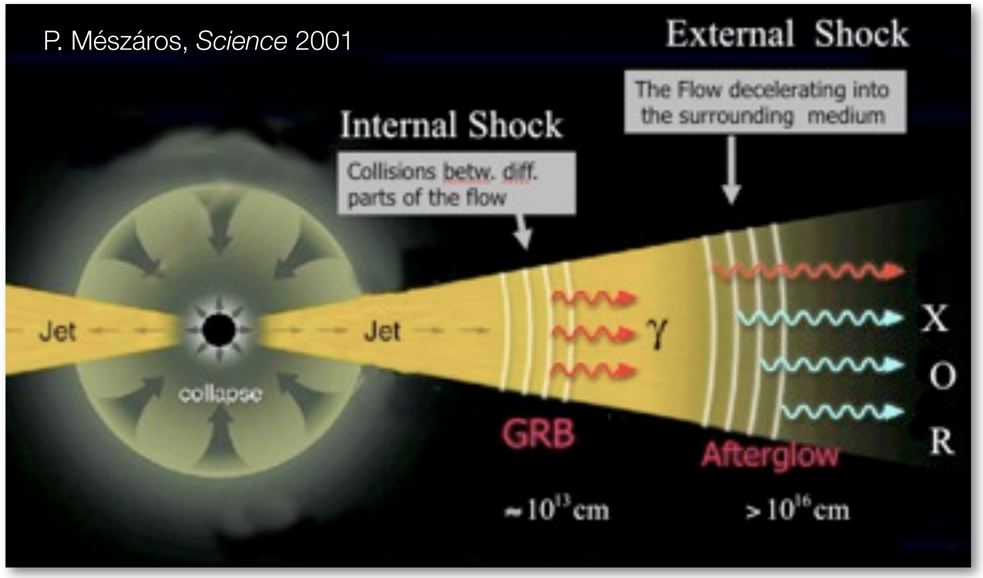


Potential Cosmic Ray Accelerators

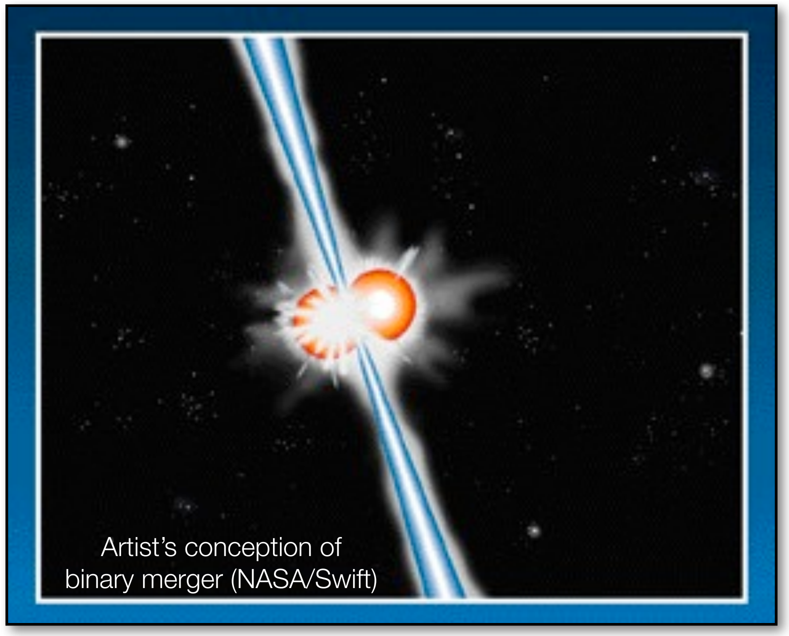




Supernova Remnants

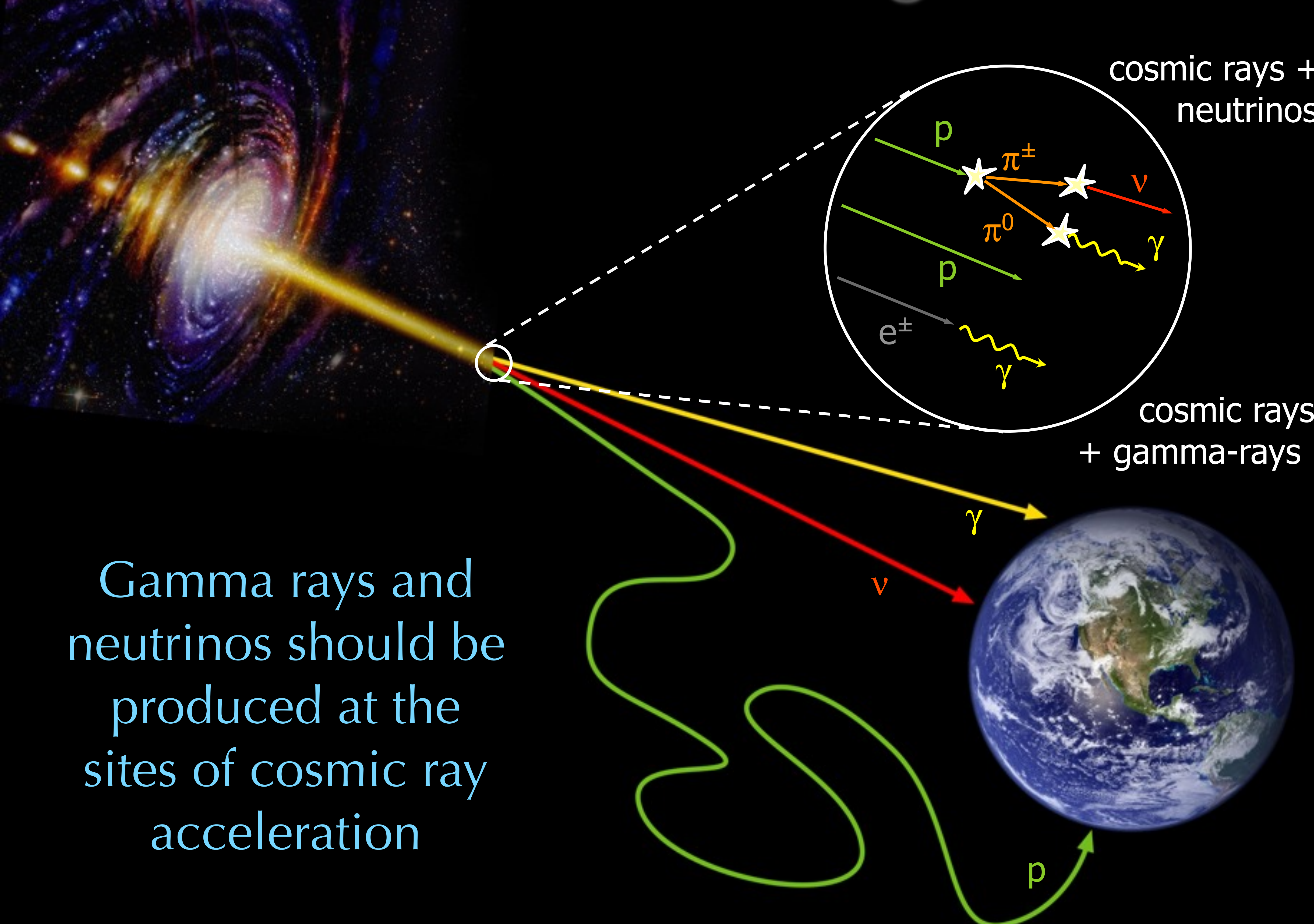


Gamma Ray Bursts



Active Galactic Nuclei

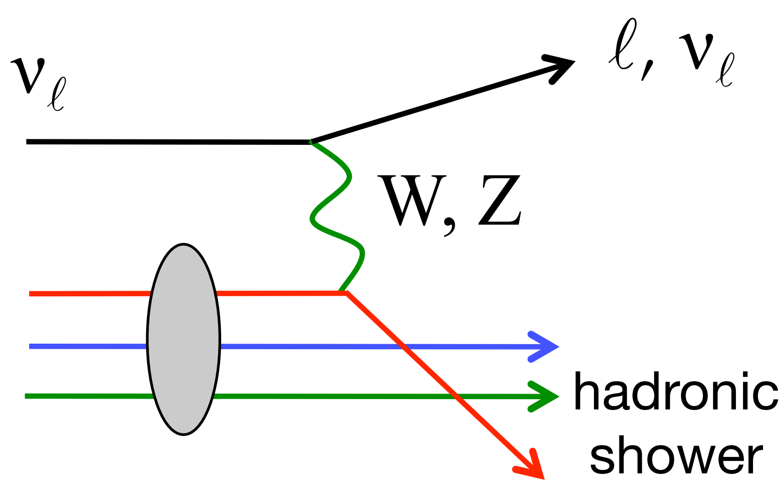
Multimessenger Astronomy



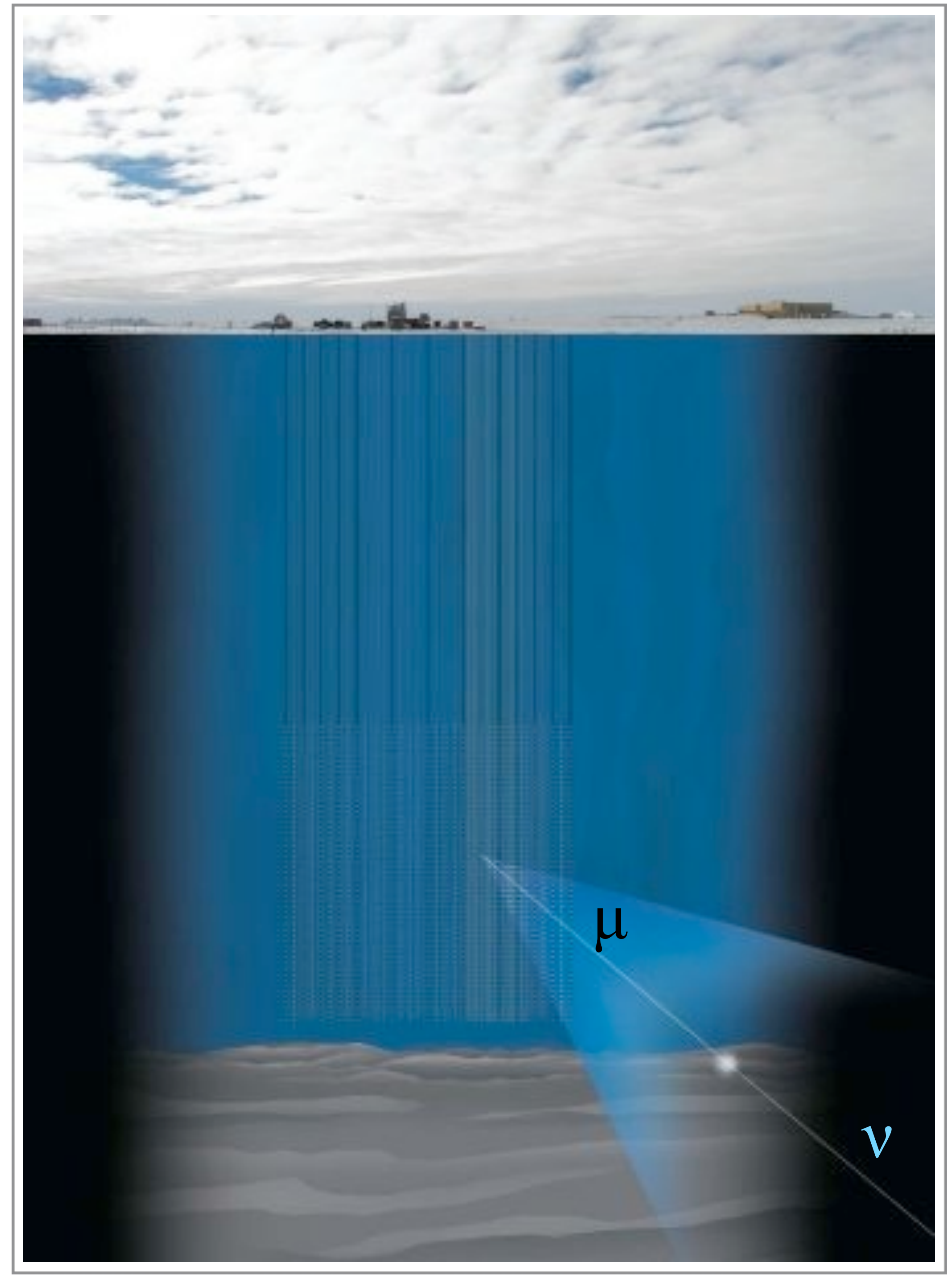
Gamma rays and neutrinos should be produced at the sites of cosmic ray acceleration

High Energy Neutrino Telescopes

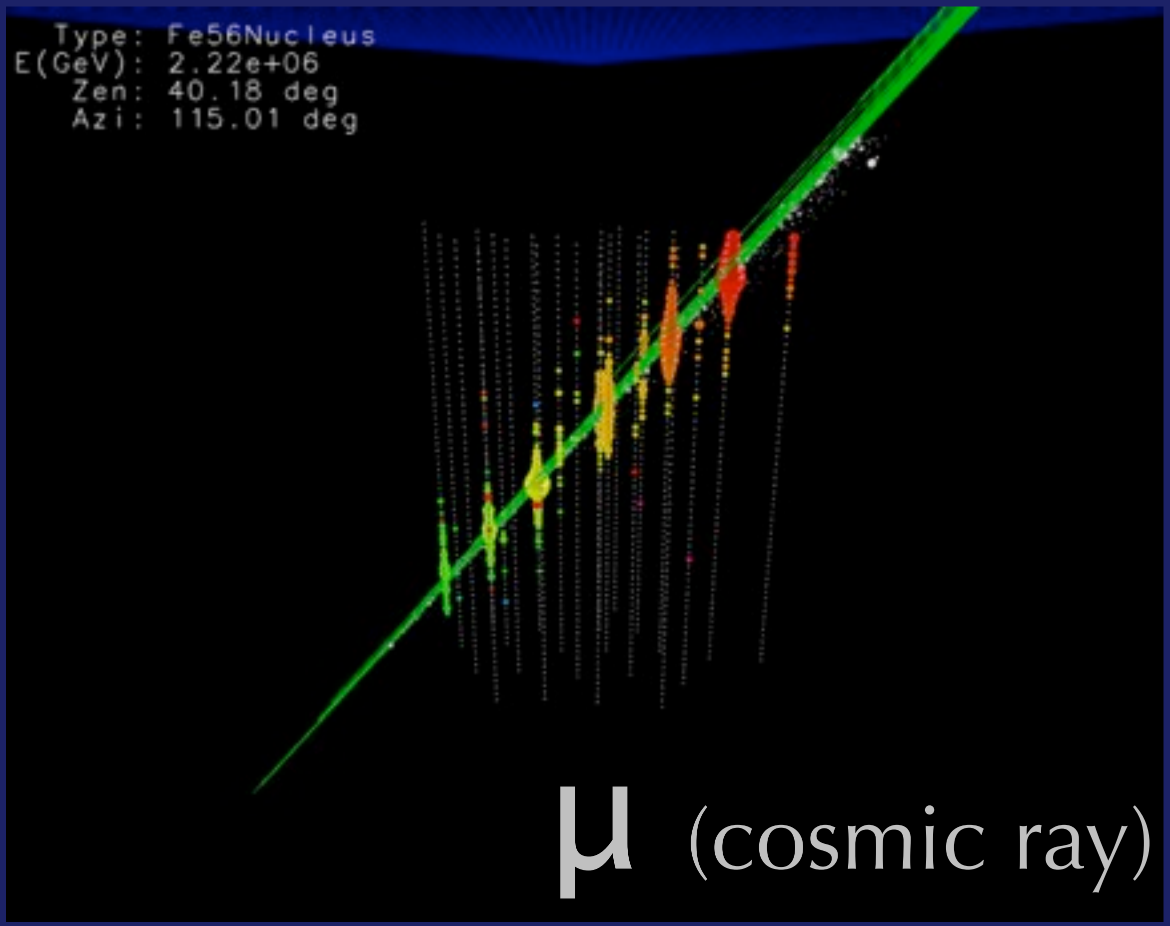
- Neutrinos interact in or near the detector

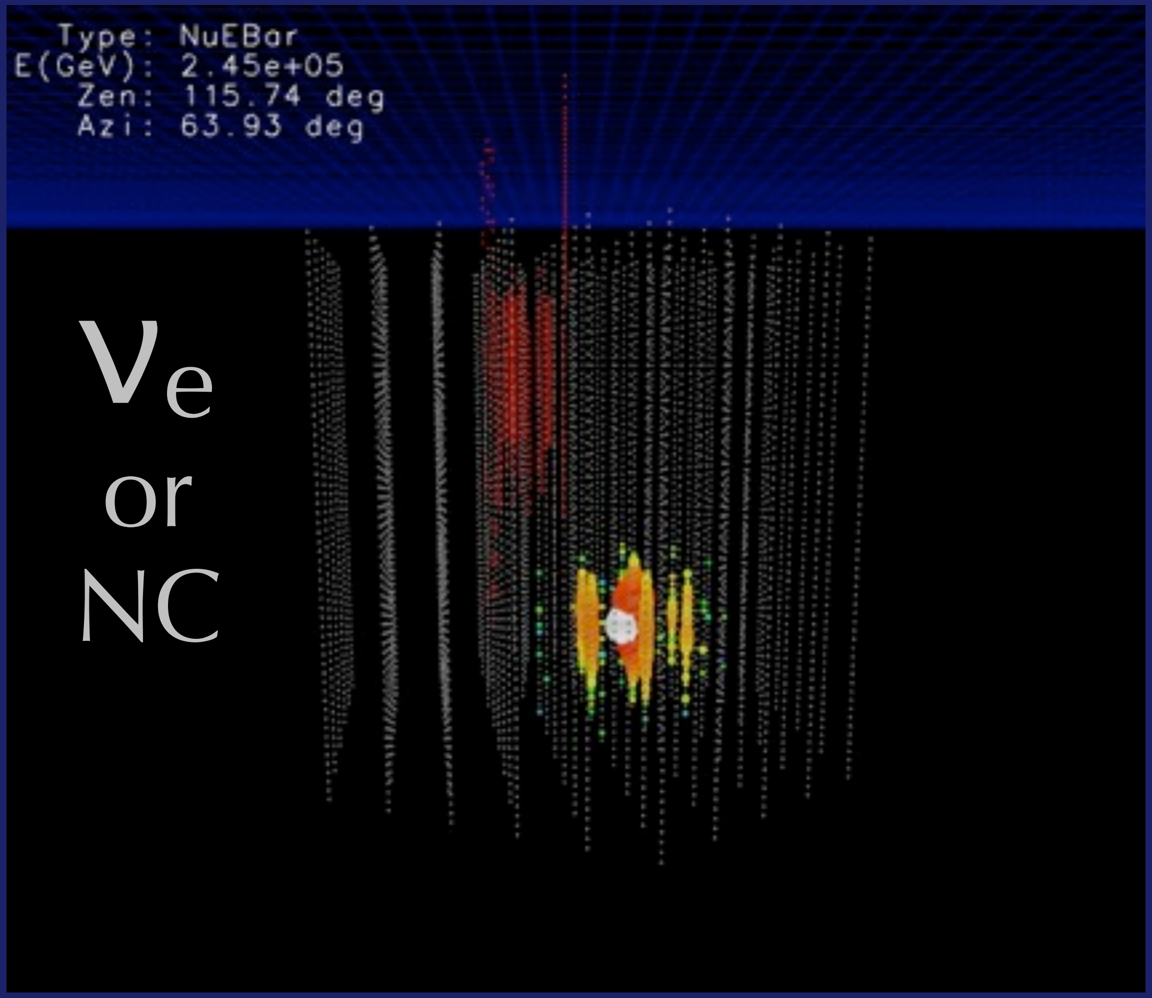


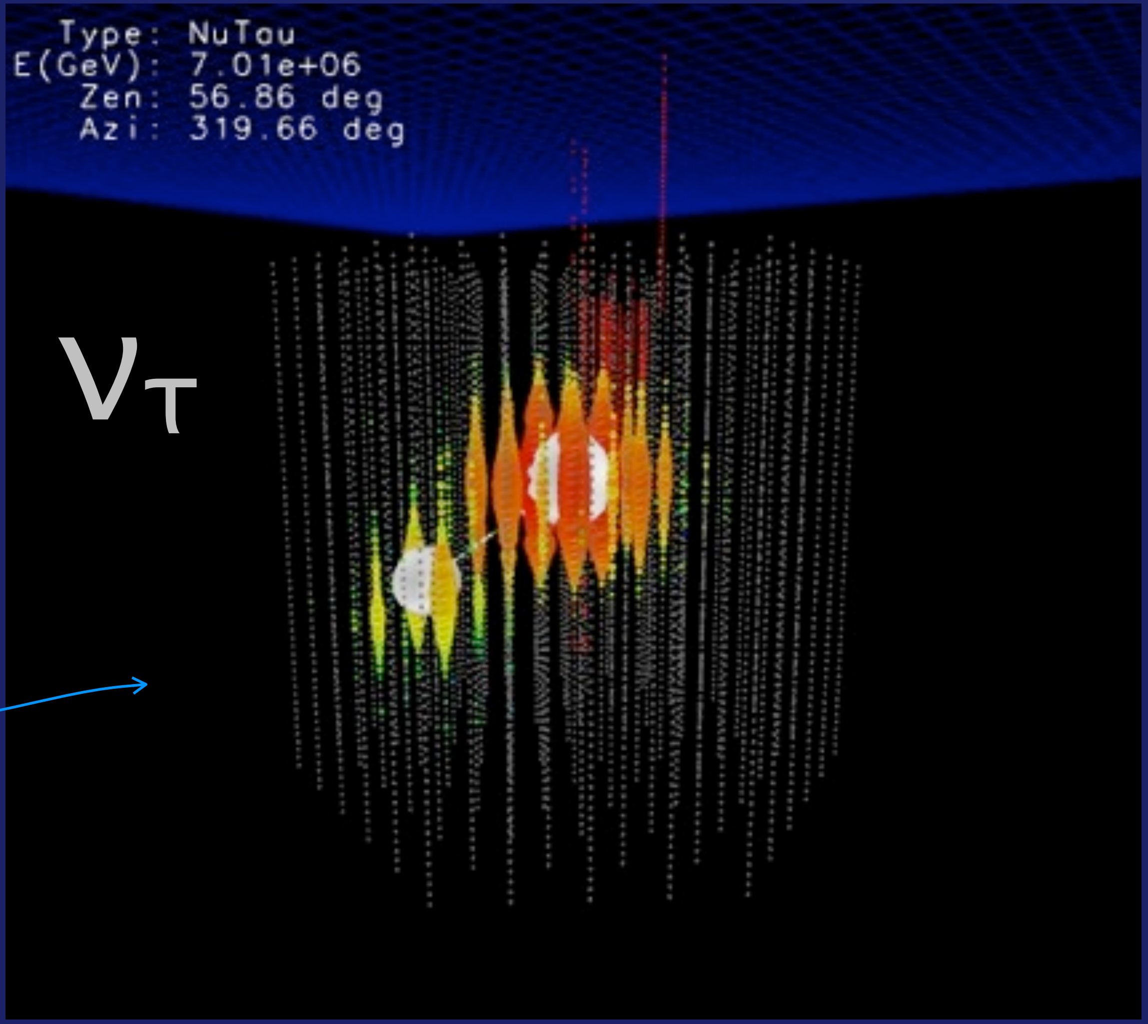
- $\mathcal{O}$(km) muon tracks from ν_μ CC
- $\mathcal{O}$(10 m) cascades from ν_e CC, low energy ν_τ CC, and ν_x NC
- Cherenkov radiation detected by 3D array of optical sensors (OMs)



Neutrino Signatures







"Double Bang":

One of several tau signatures : lollipop, inverted lollipop, etc…

(Learned & Pakvasa, Beacom et al.,…)

The IceCube Collaboration

IceCube

University of Alabama
University of Alaska, Anchorage
University of California, Berkeley
University of California, Irvine
Clark-Atlanta University
Bartol Research Institute, University of Delaware
Georgia Institute of Technology
University of Kansas
Lawrence Berkeley Natl. Laboratory
University of Maryland
Ohio State University
Pennsylvania State University
Southern University and A&M College
University of Wisconsin, Madison
University of Wisconsin, River Falls

RWTH Aachen
Ruhr-Universität Bochum
Universität Bonn
DESY, Zeuthen
Universität Dortmund
MPIfK Heidelberg
Humboldt Universität, Berlin
Universität Mainz
BUGH Wuppertal

Stockholms Universitet
Uppsala Universitet

Vrije Universiteit Brussel
Université Libre de Bruxelles
Universiteit Gent
Université de Mons-Hainaut

University of Alberta

Chiba University

University of Canterbury

EPF Lausanne

Oxford University

University of the West Indies

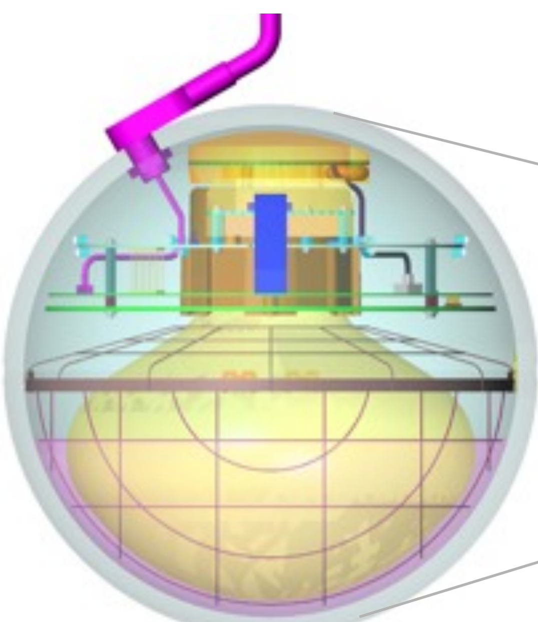
IceCube

5160 DOMs on 86 strings

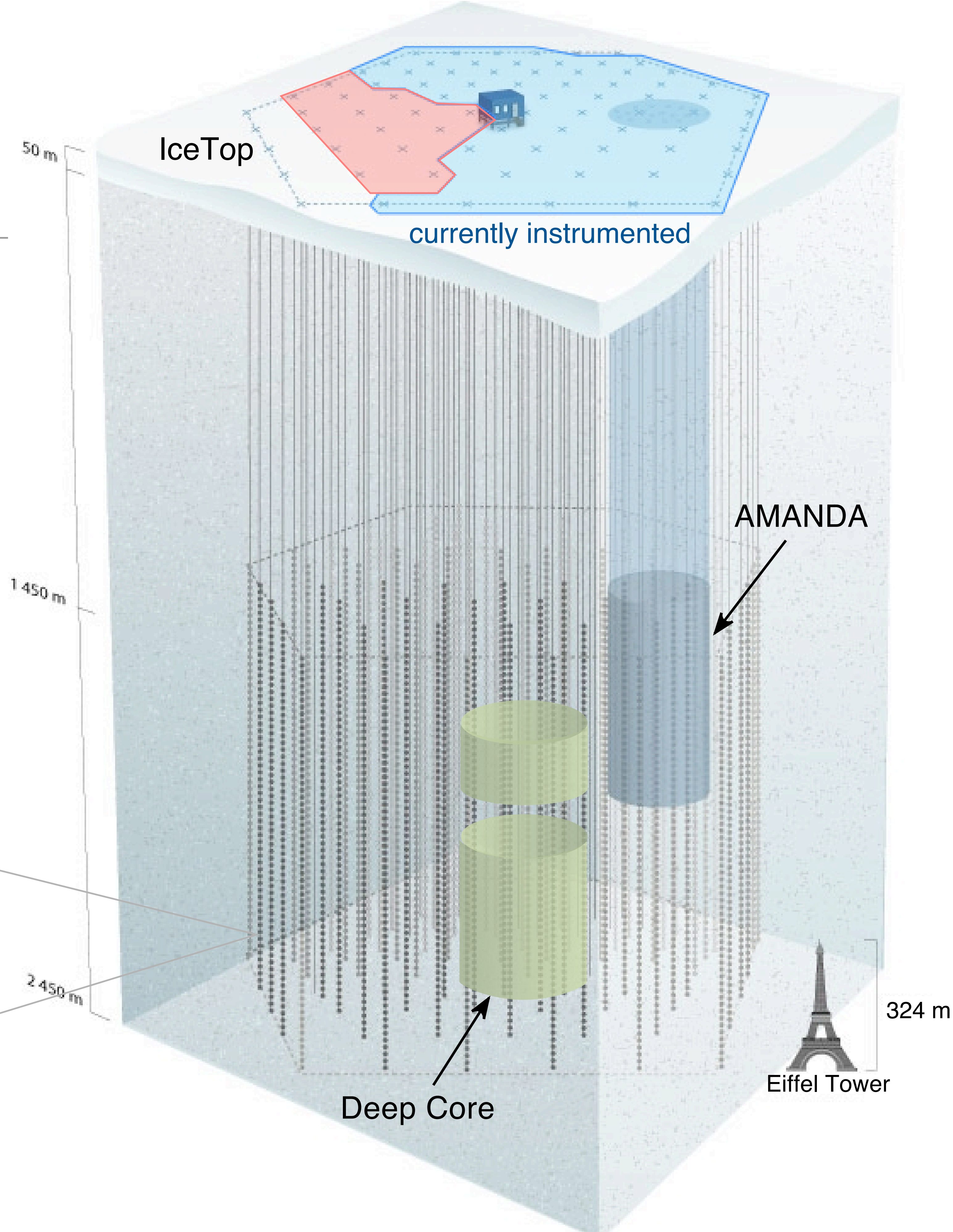
160 Ice-Cherenkov tank surface array (IceTop)

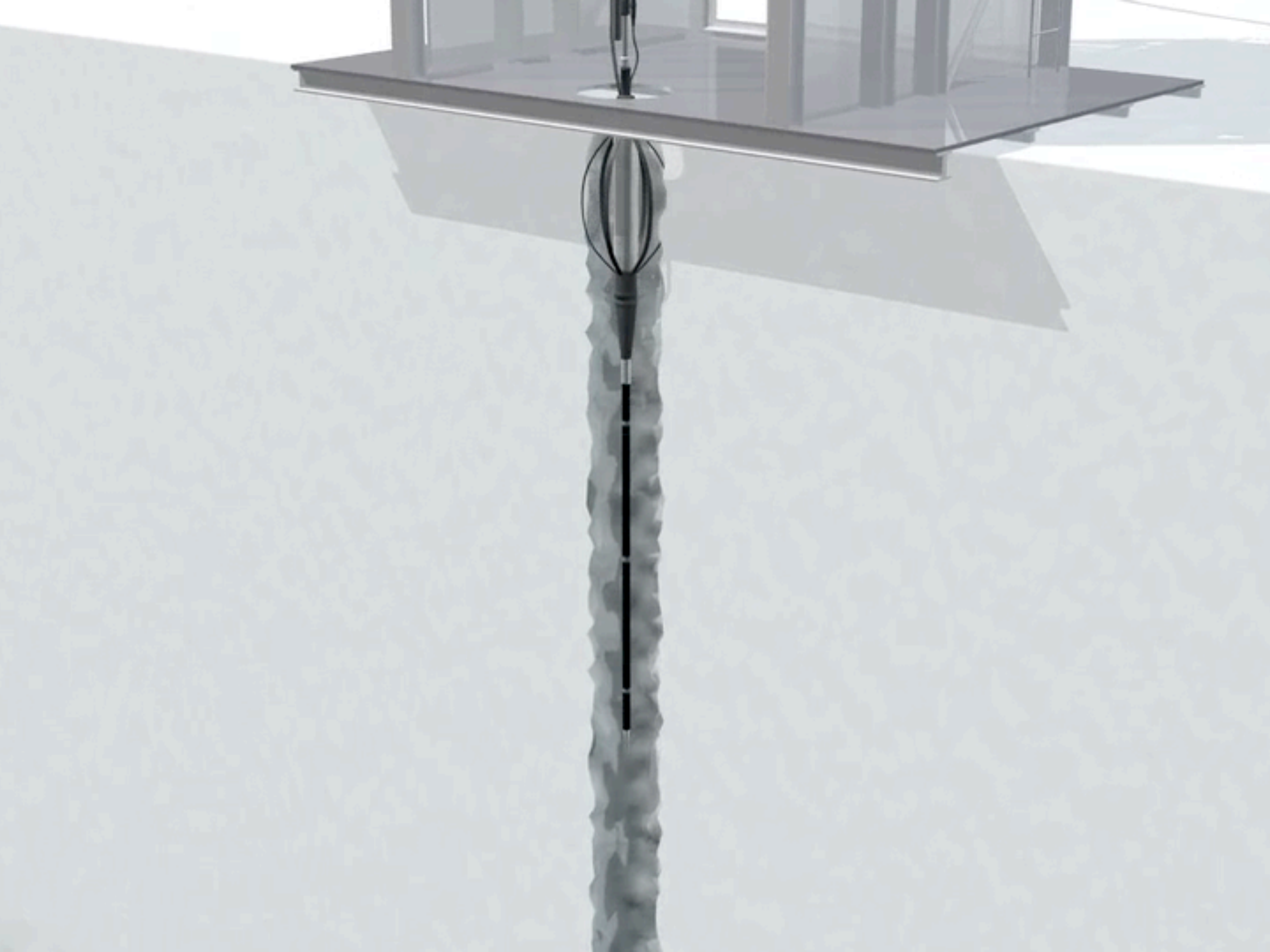
Surrounds existing AMANDA detector (677 OMs)

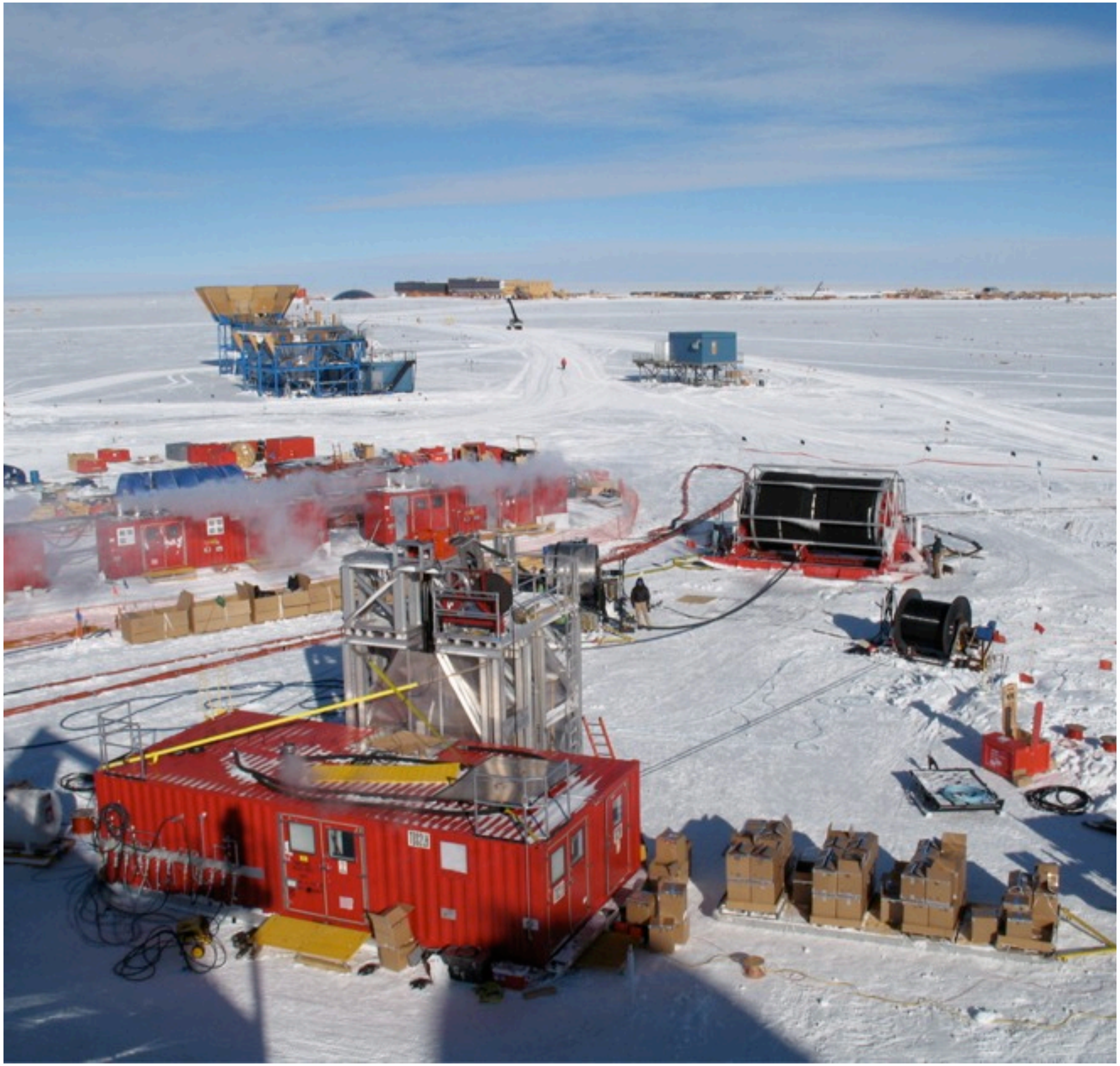
~~59~~ 79! strings deployed to date in ~~5~~ 6 construction seasons

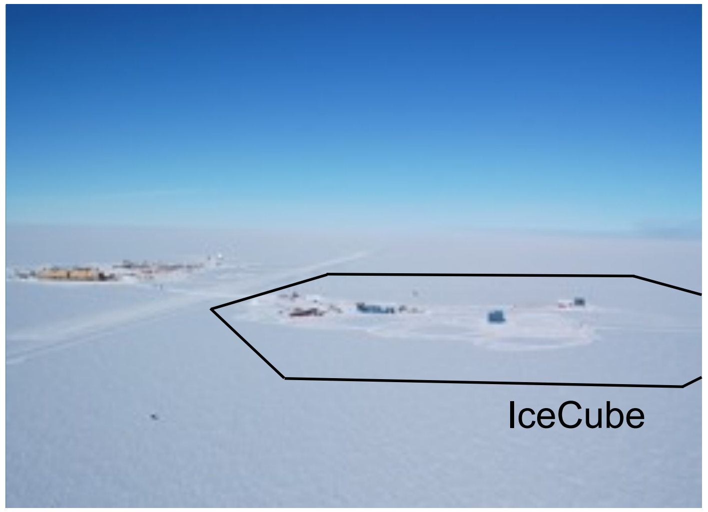


Digital Optical Module (DOM)



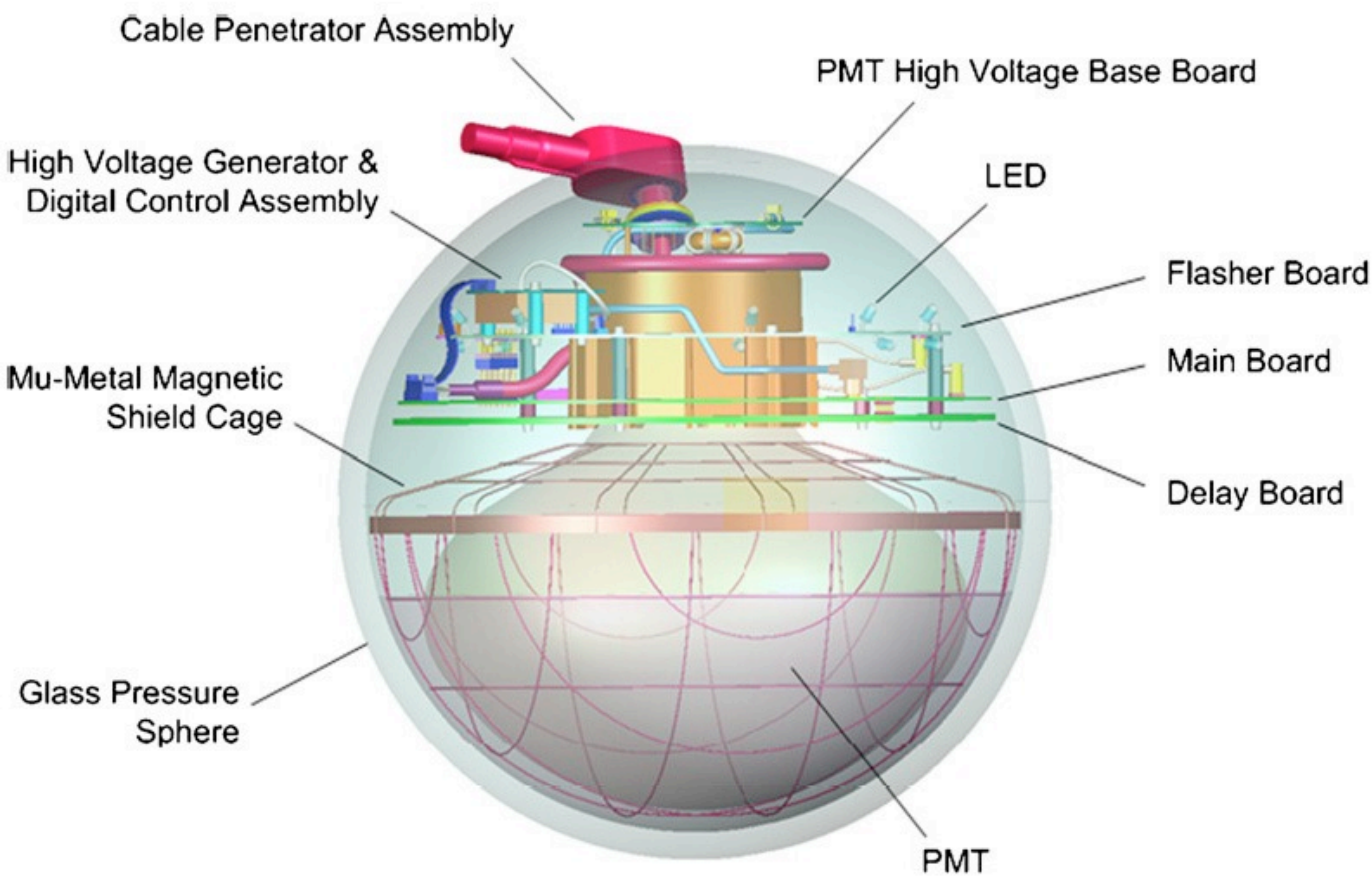






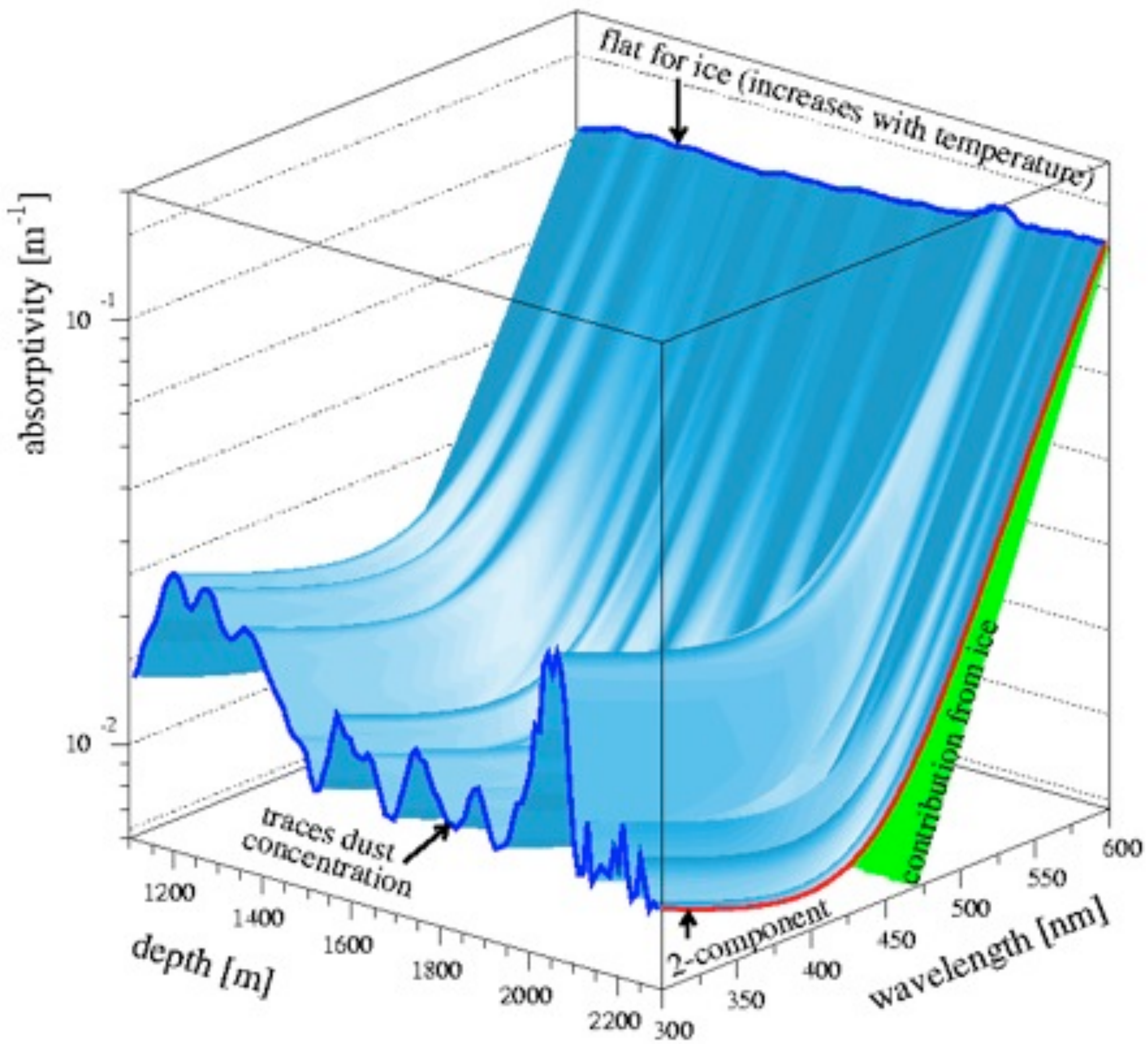
Amundsen-Scott South Pole Station, Antarctica

The Digital Optical Module (DOM)

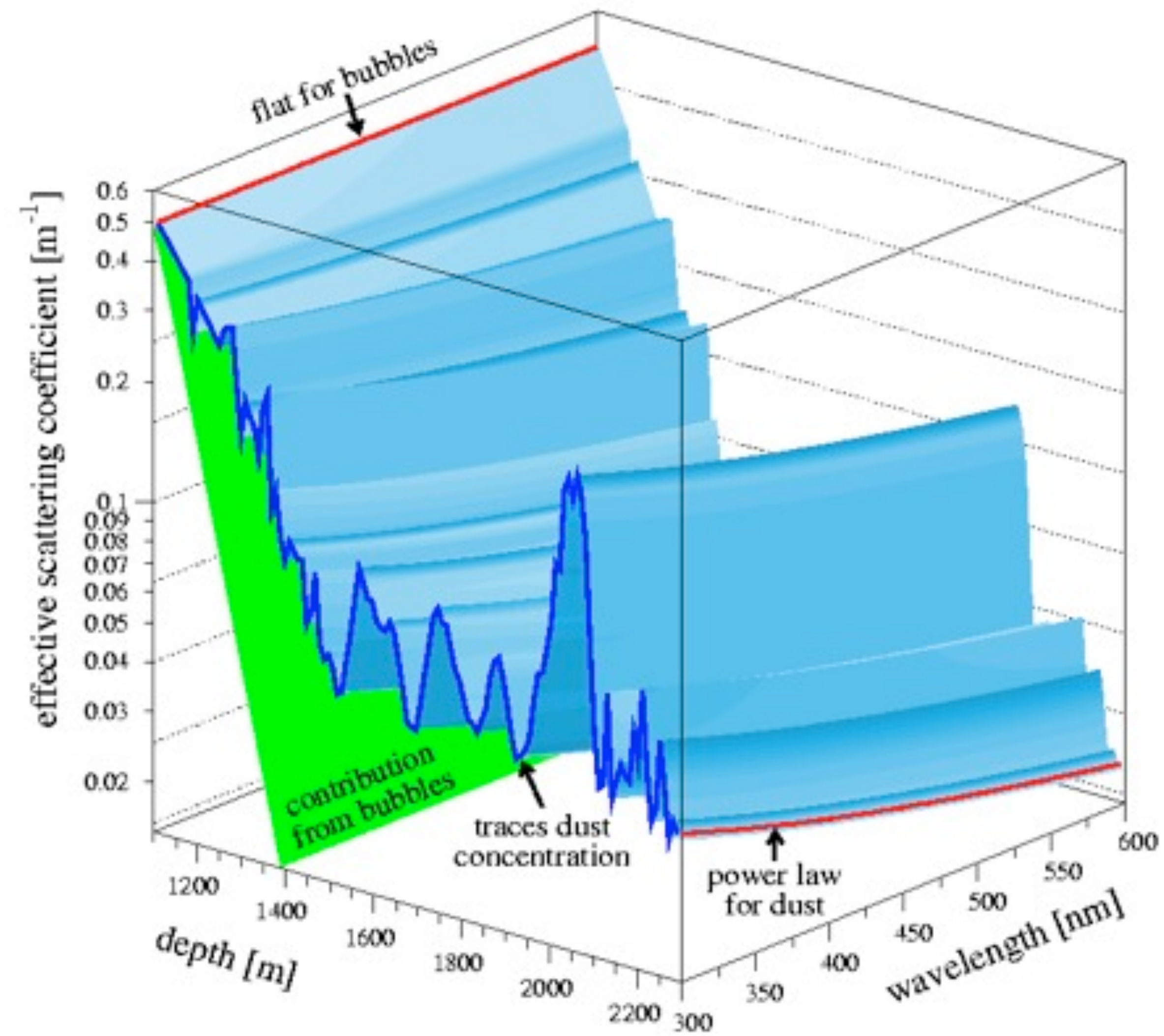


Optical Properties of South Pole Ice

Absorption



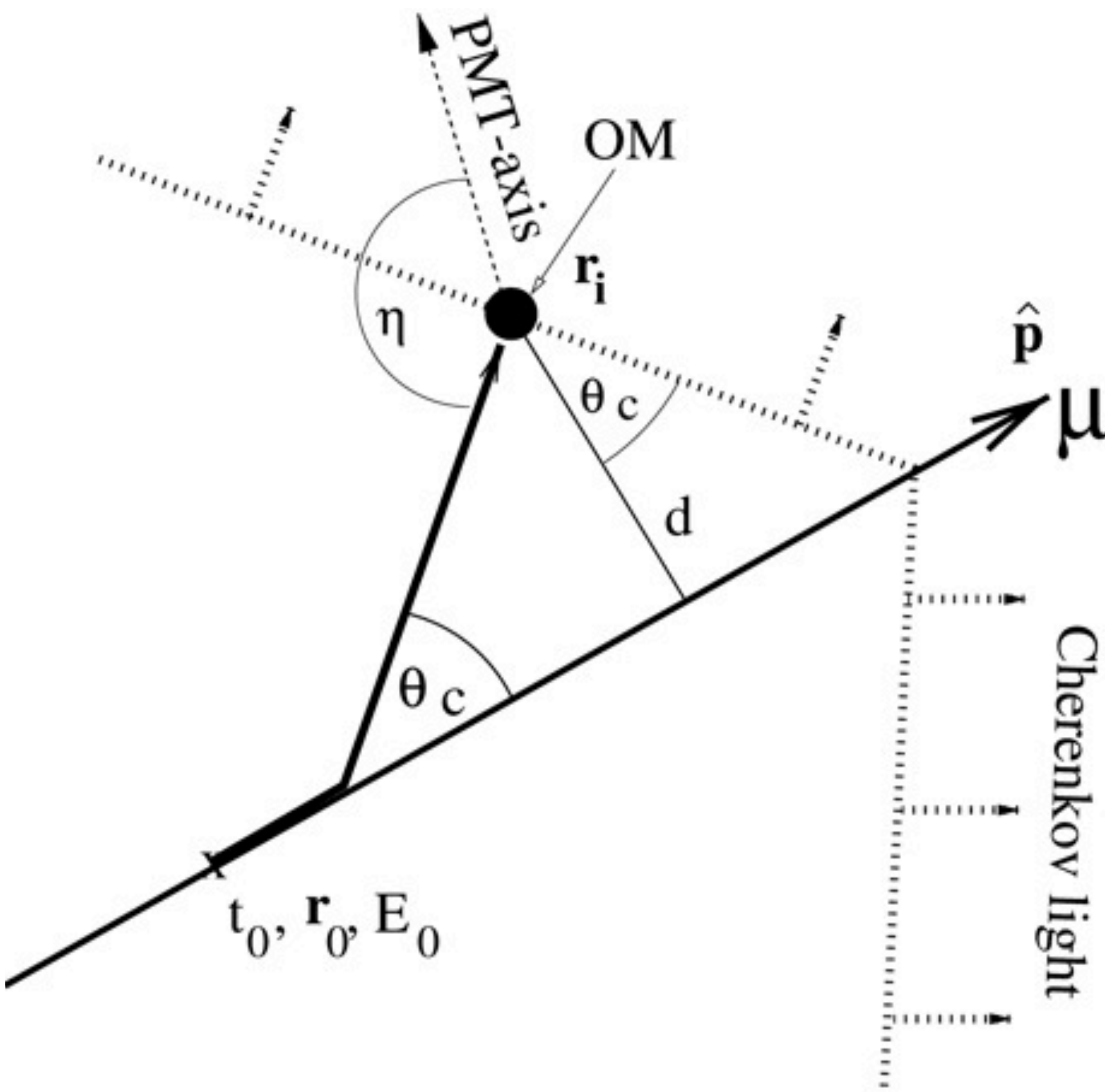
Scattering

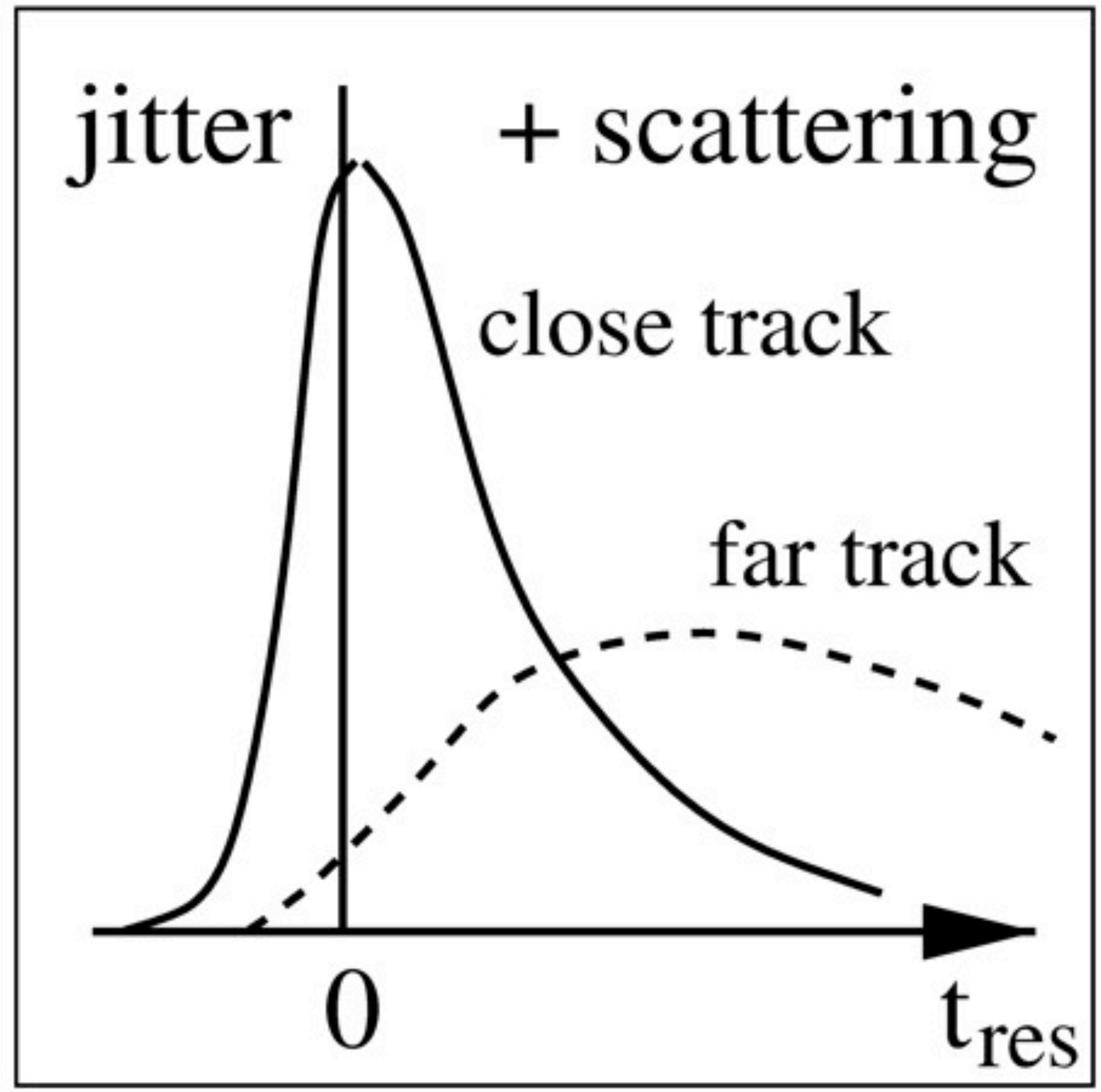


- One of the clearest natural materials known
- Absorption lengths > 100 m, effective scattering lengths 20-50 m

Likelihood Reconstruction of Events

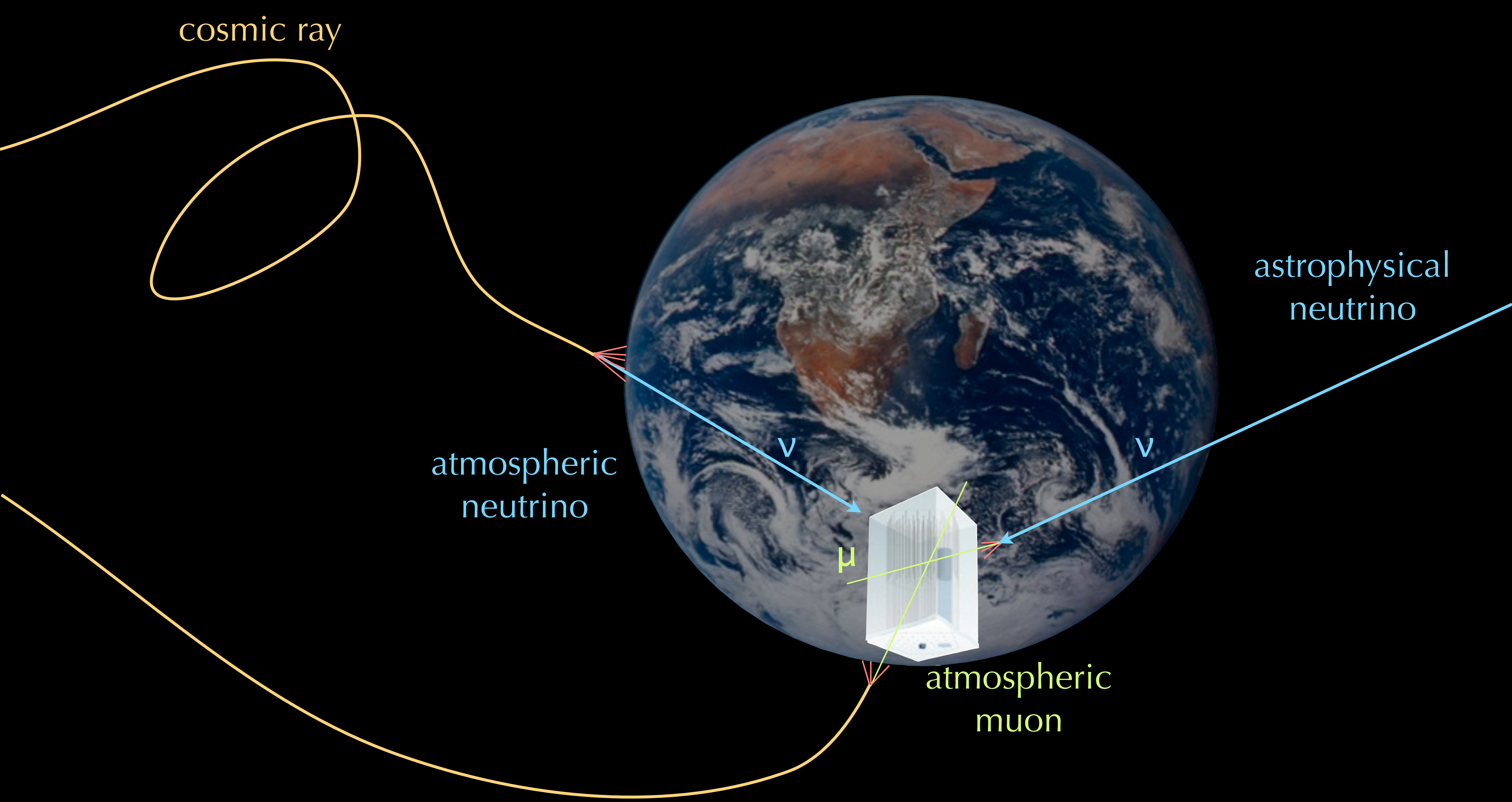
J. Ahrens et al., *Nucl. Inst. & Meth.* A**524**, 169 (2004)



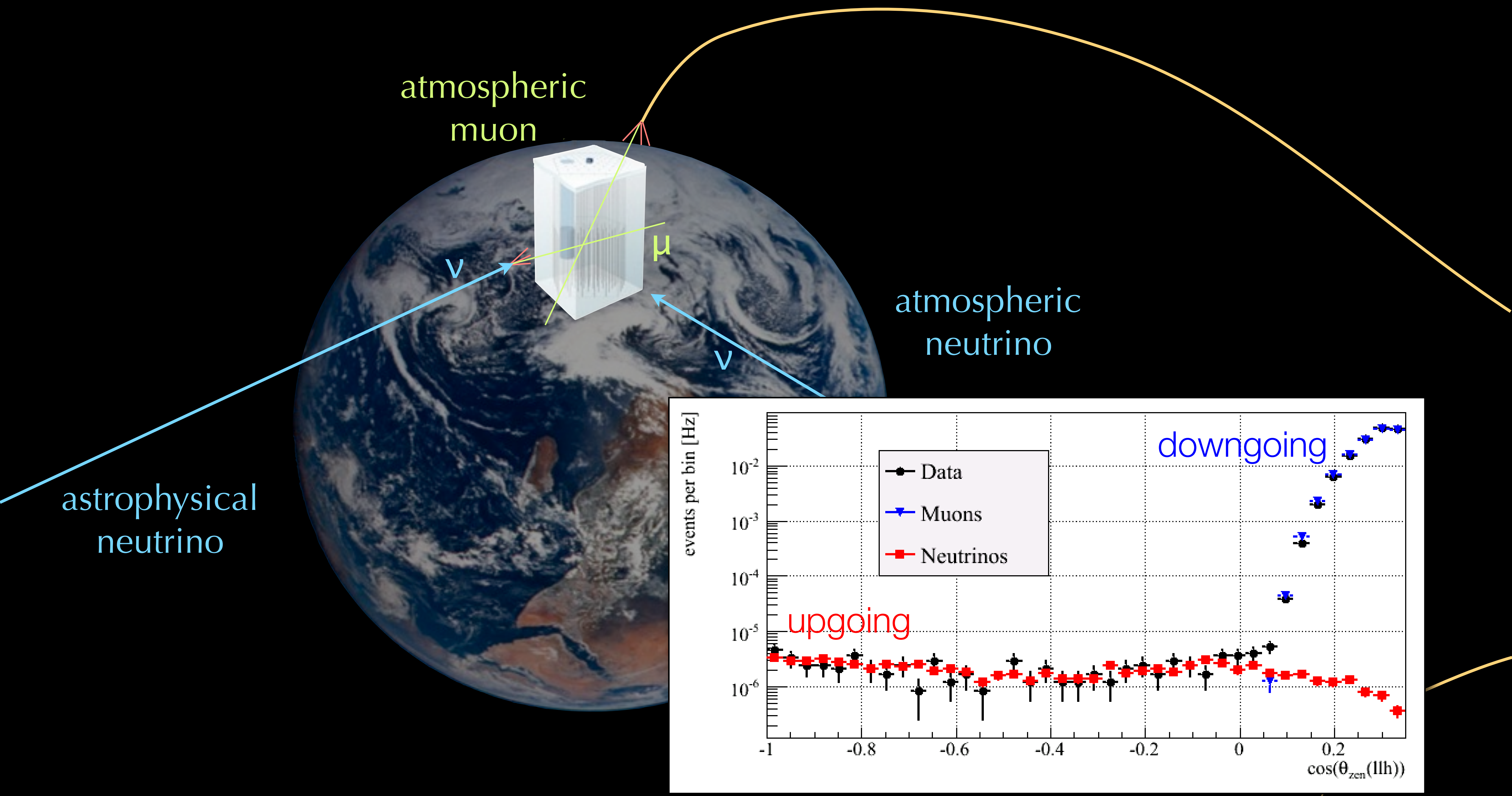


- Intermediate regime between diffusion, free streaming – difficult
- Requires detailed numerical description of light propagation

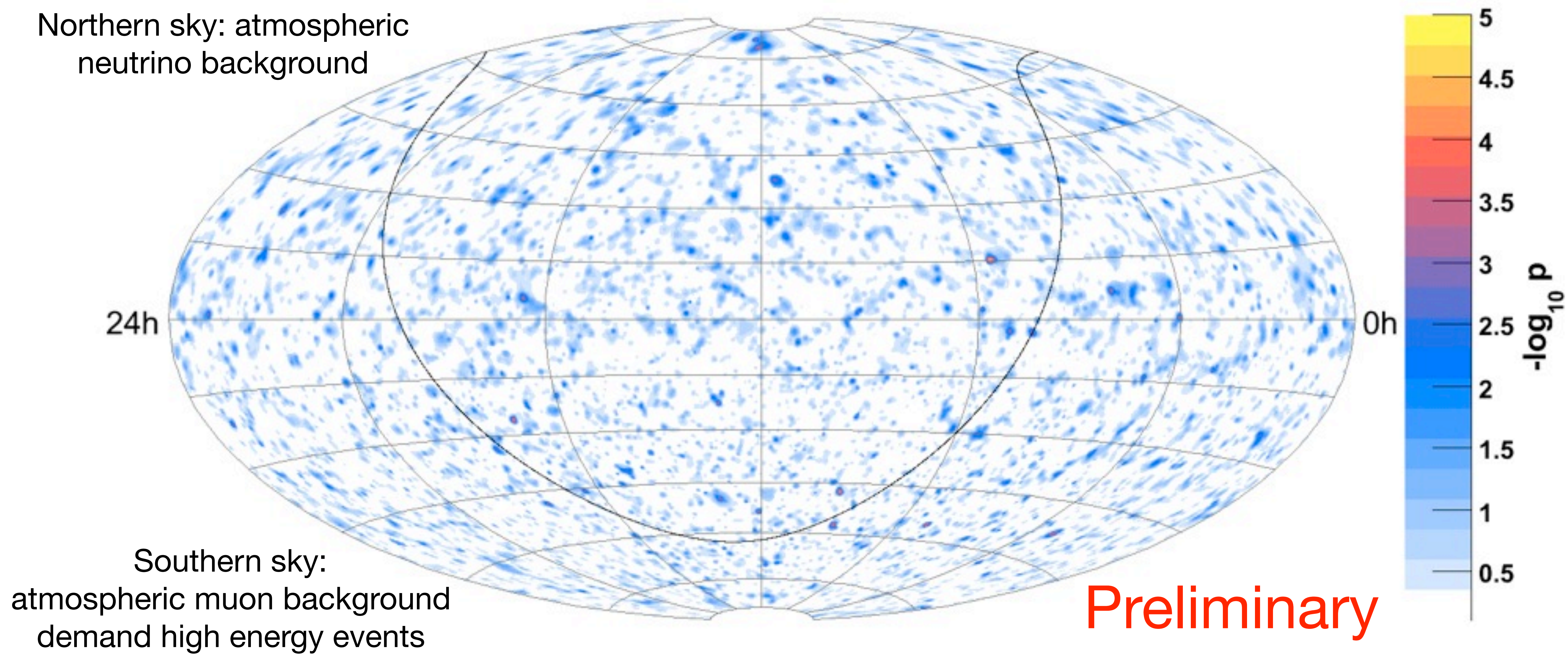
Signals and Backgrounds



Signals and Backgrounds



IceCube 2008 (40 String) Full Sky Source Search

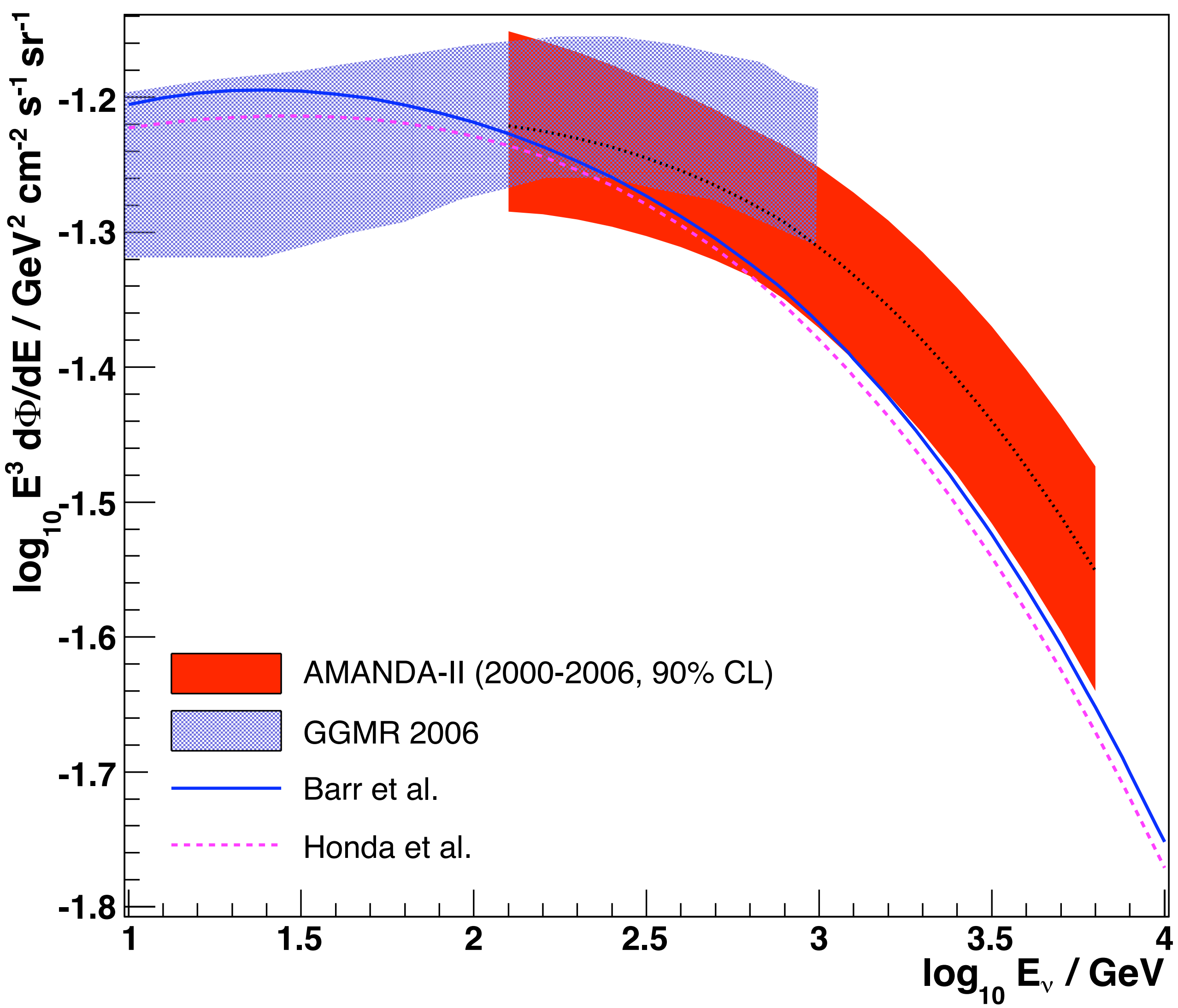


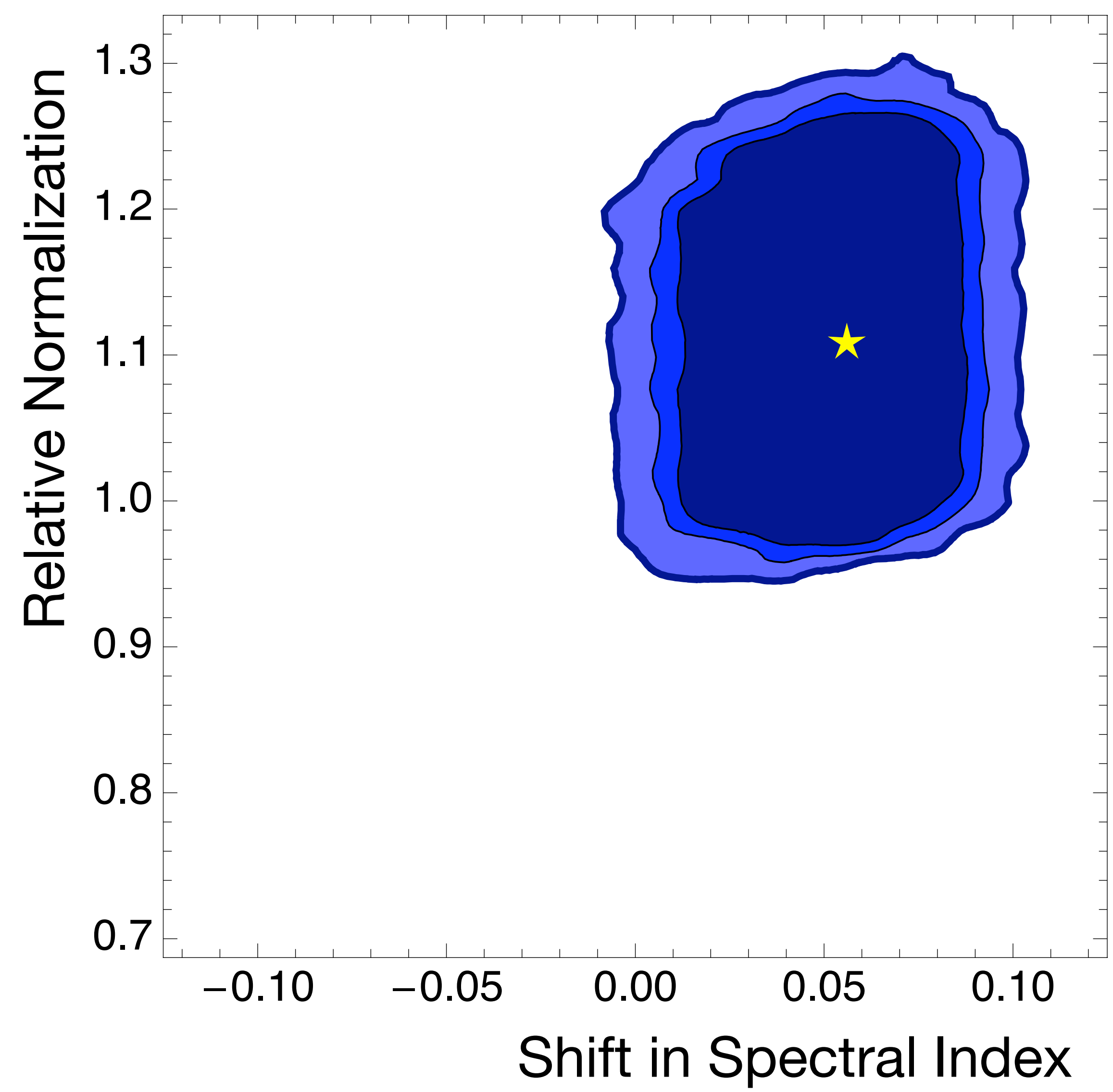
Based on only 1st six months of 2008 data (remainder forthcoming)

17,777 events: 6,796 upgoing and 10,981 downgoing

Maximum deviation 3.7 x 10^{-5}, seen in 61% of randomized sky maps

Atmospheric Muon Neutrino Observations



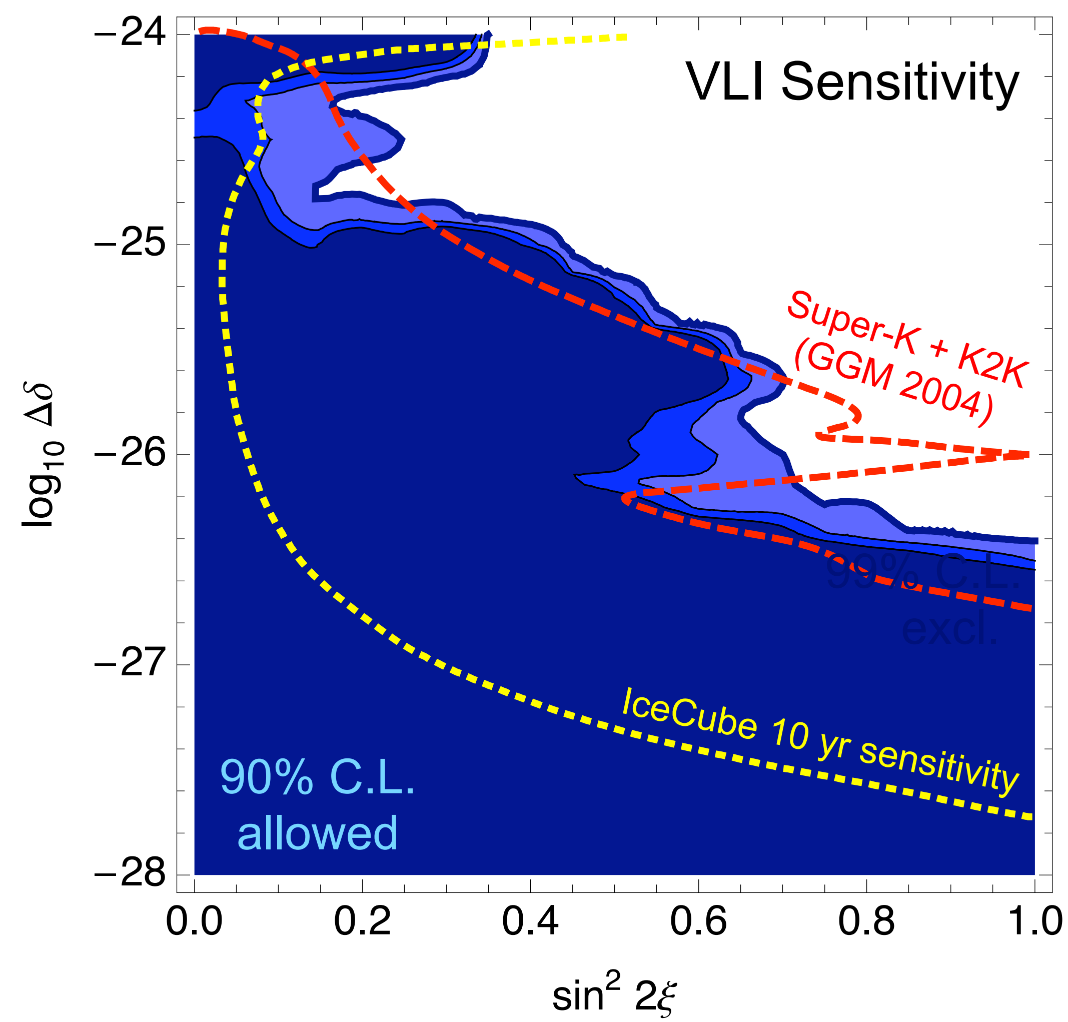


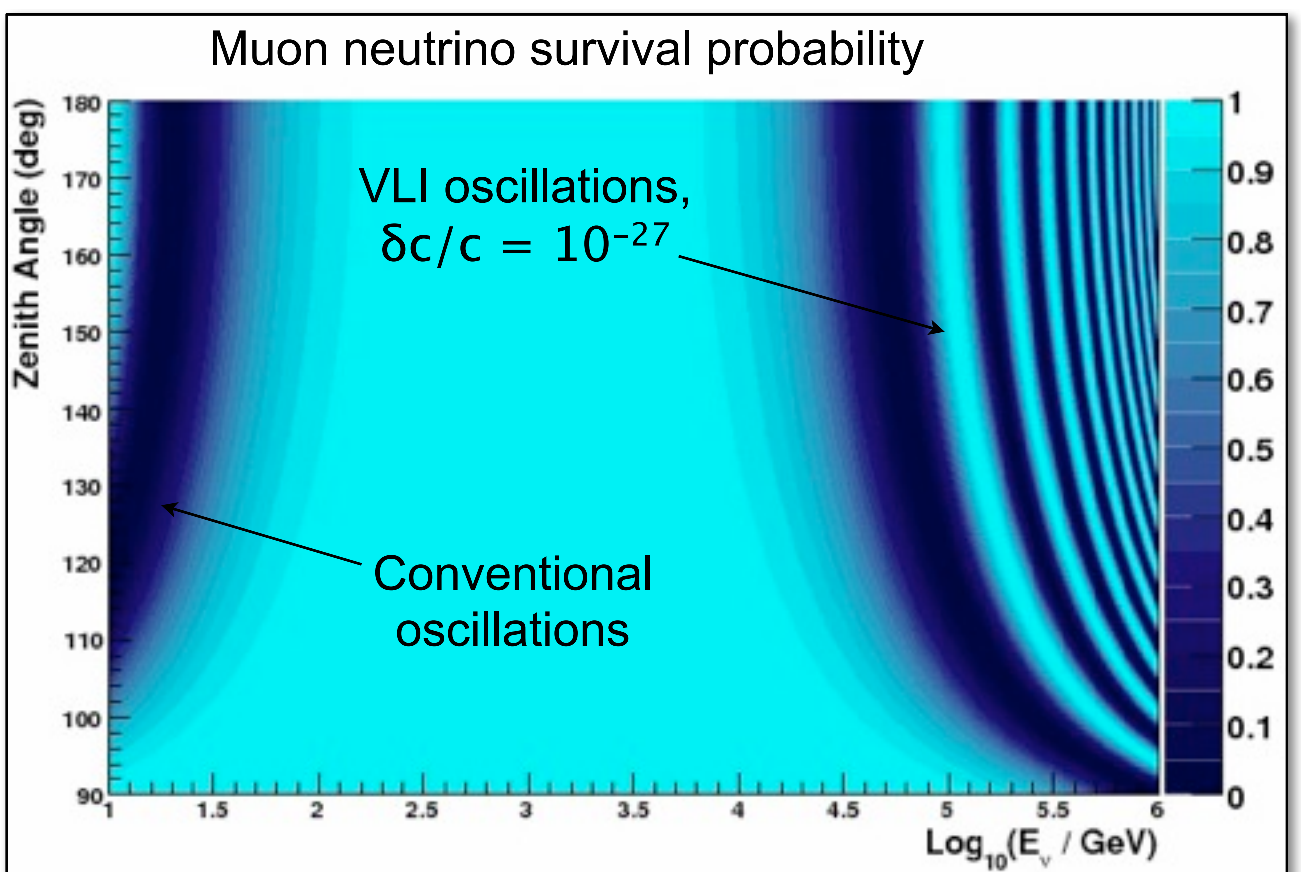
Based on complete 7-year AMANDA-II data set (3.8 years exposure)

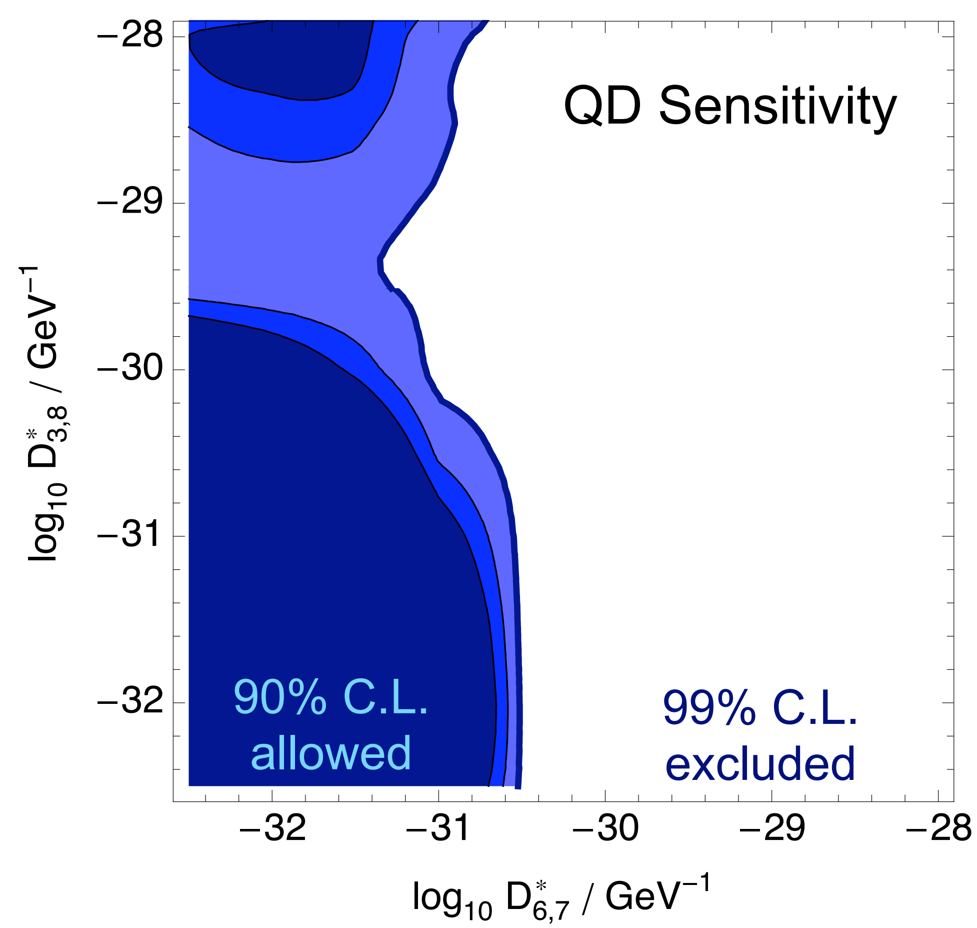
Abbasi et al., Phys. Rev. D **79**, 102005 (2009), arXiv:0902.0675

Using Atmospherics to Search for PBSM

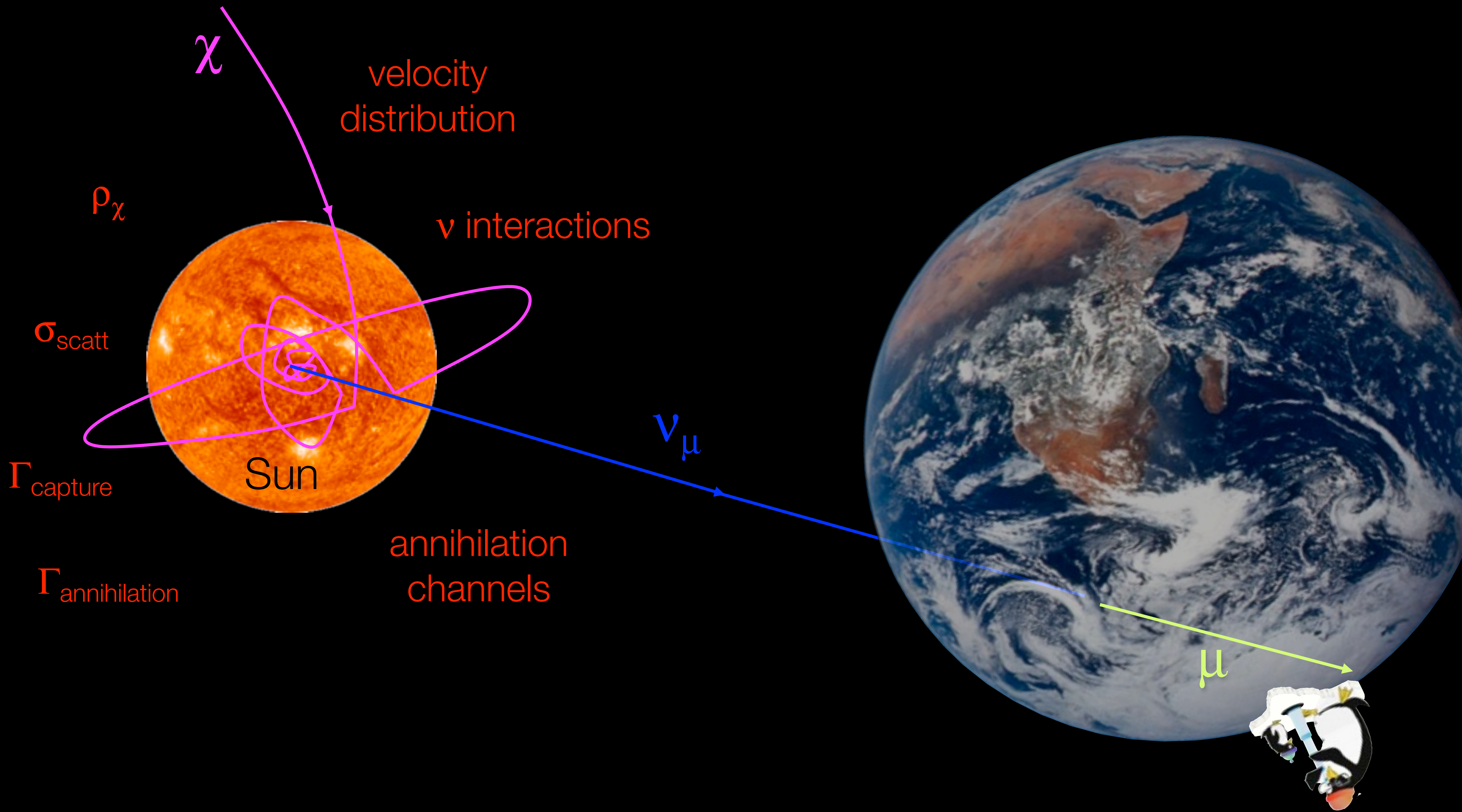
- Use large sample of atmospheric neutrinos, look for ν_μ disappearance
  - Violation of Lorentz invariance
  - Quantum decoherence







Indirect Detection of Solar Dark Matter



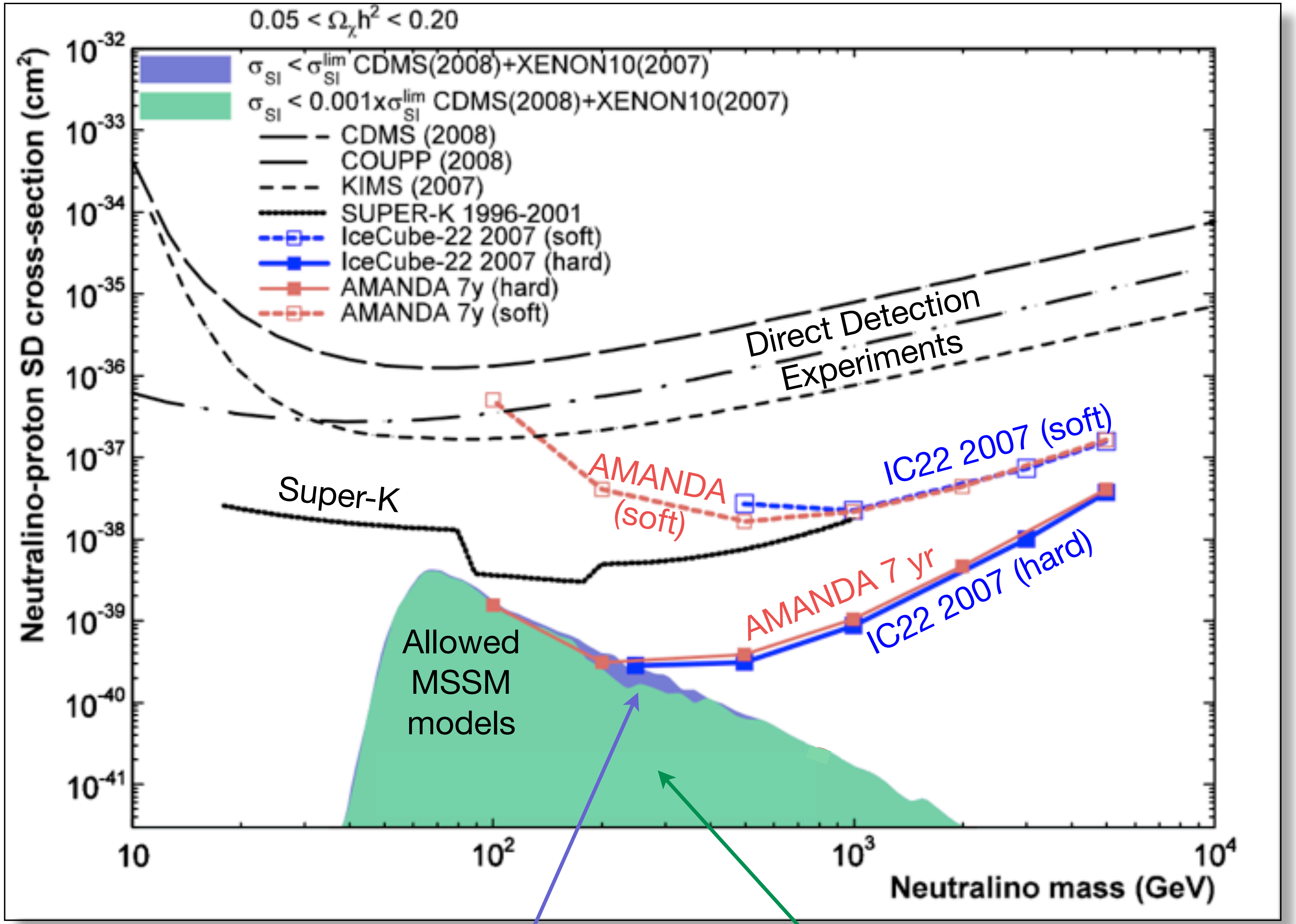
Silk, Olive and Srednicki, '85
Gaisser, Steigman & Tilav, '86
Freese, '86

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

WIMP Searches

Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009)
arXiv:0902.2460

- 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 mode
    - hard W^+W^-, soft $b\bar{b}$

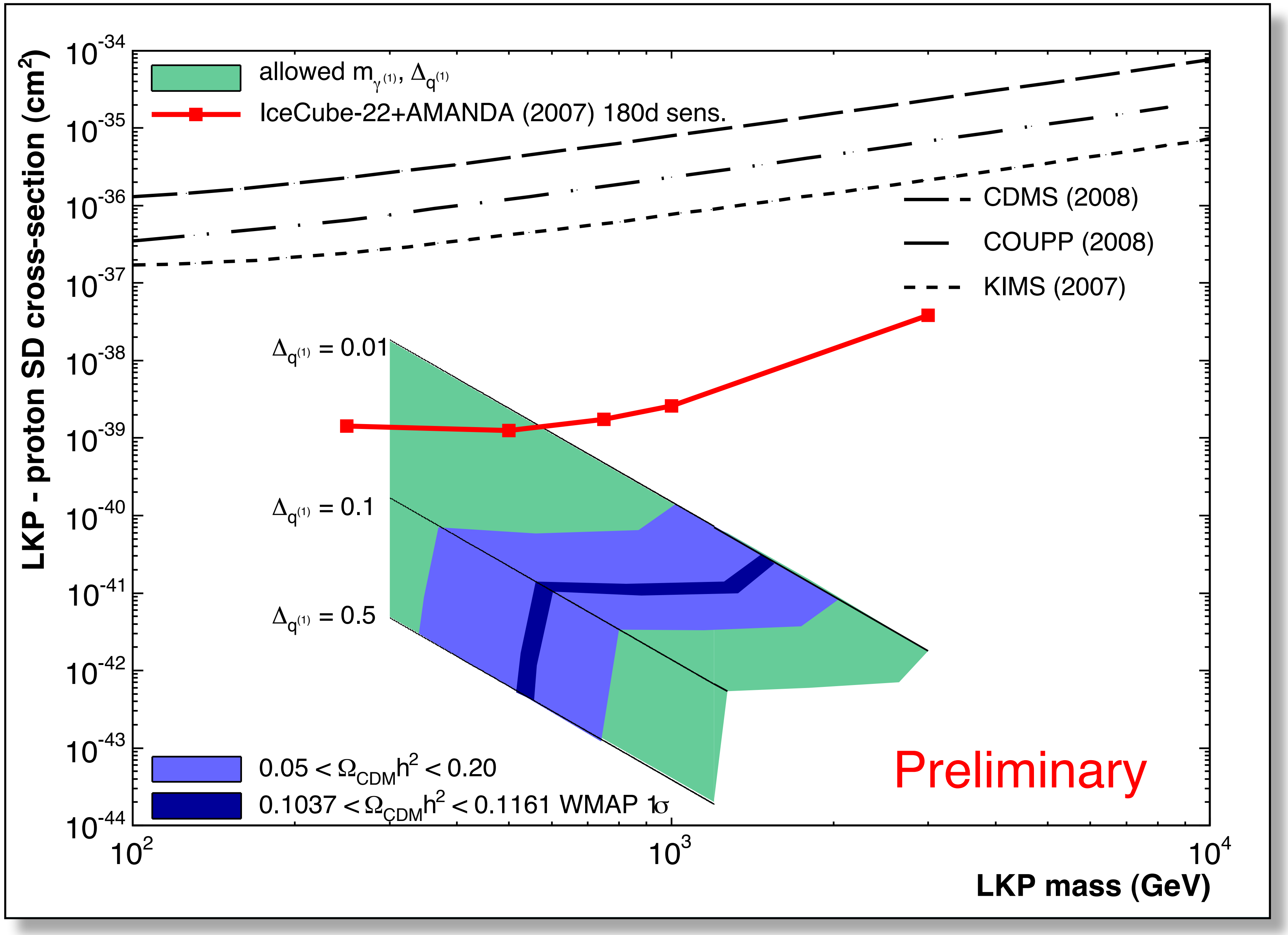


Corresponding σ_{SI} within factor 10^3 of current direct limits

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

Search for Kaluza-Klein Dark Matter

- Can place similar limits on Kaluza-Klein dark matter particles
  - Low masses excluded by colliders
  - High masses would overclose the universe
  - Best-fit WMAP cold dark matter parameters shown in blue



And now for something completely different…

- IceCube collaboration decided to augment "low" energy response with a densely instrumented infill array: Deep Core
  - Significant improvement in capabilities from ~10 GeV to ~300 GeV (ν_μ)
- Primary scientific rationale is the indirect search for dark matter
- Particle physics using atmospheric neutrinos
  - Neutrino oscillations, including tau neutrino appearance
- Neutrino sources in Southern Hemisphere
  - Galactic cosmic ray sources
  - Dark matter in the Galactic center

IceCube

5160 DOMs on 86 strings

160 Ice-Cherenkov tank surface array (IceTop)

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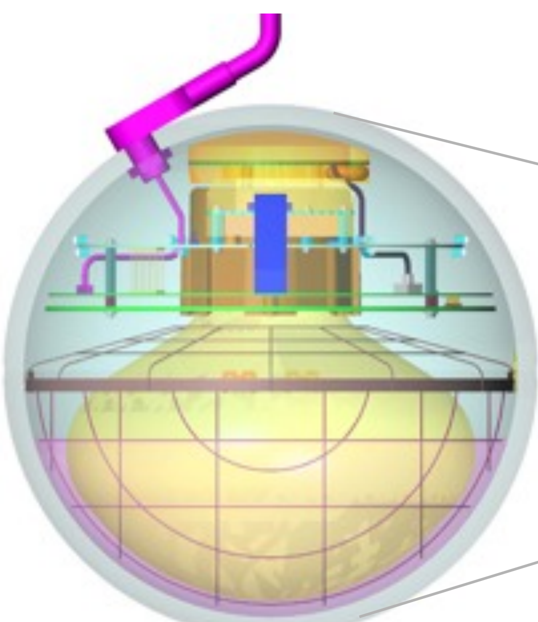
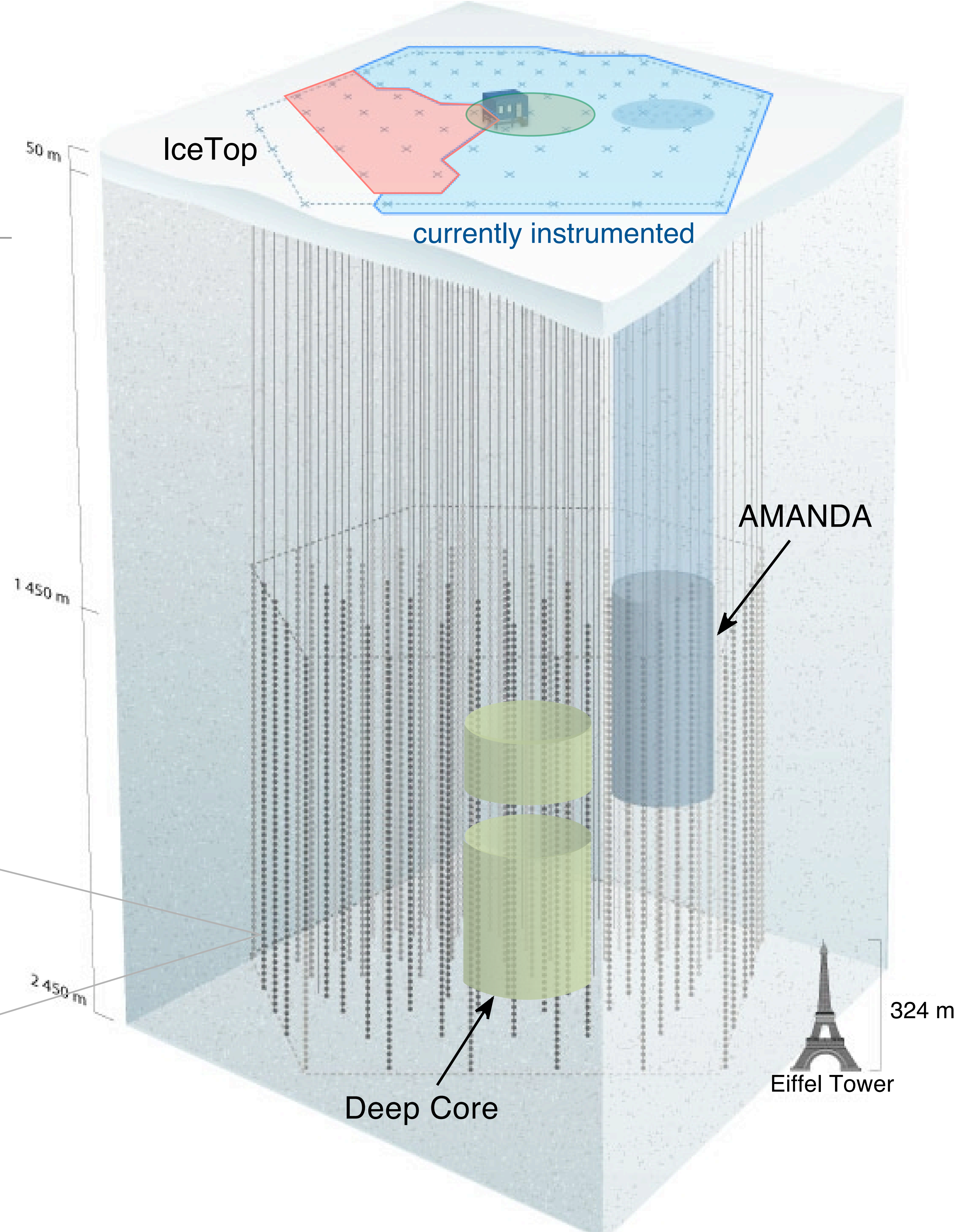
79! ~~59~~ strings deployed to date in ~~5~~ 6 construction seasons



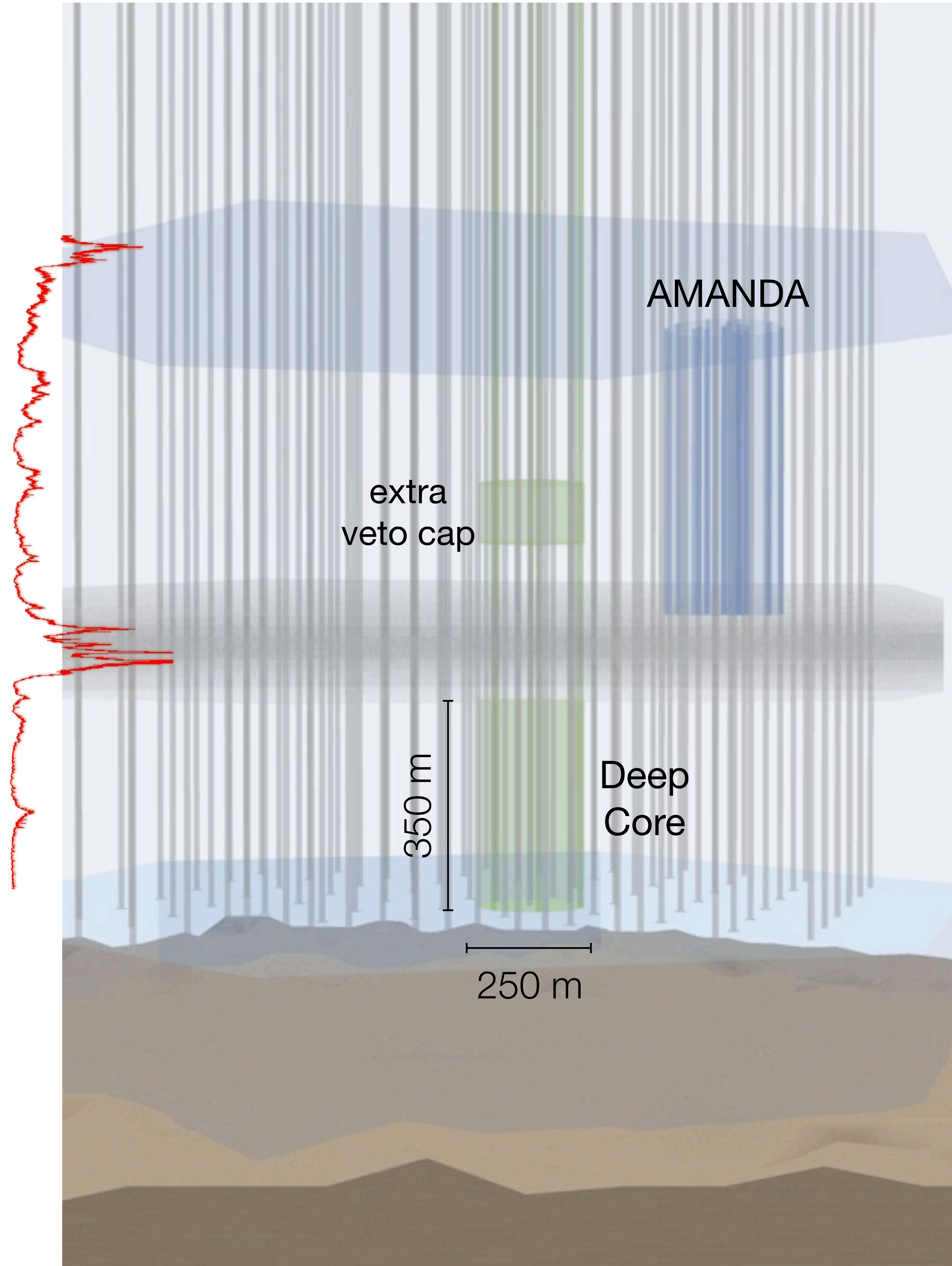
Digital Optical Module (DOM)



IceCube Deep Core

Eight

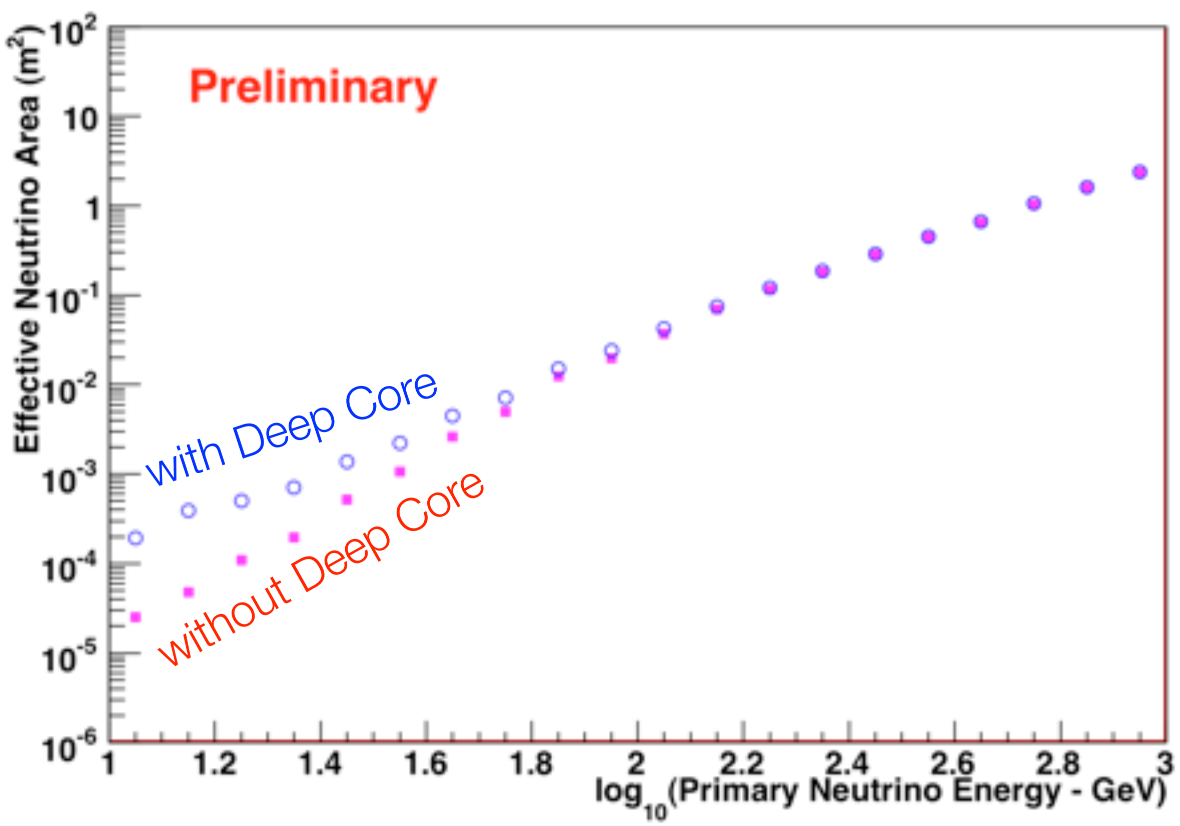
- ~~Six~~ special strings plus 7 nearest standard IceCube strings
  - 72 m interstring spacing
  - 7 m DOM spacing
  - High Q.E. PMTs
  - ~5x higher effective photocathode density
- In the clearest ice, below 2100 m
  - $\lambda_{atten} \approx$ 40-50 m (cf. 20-25 m in shallower ice)

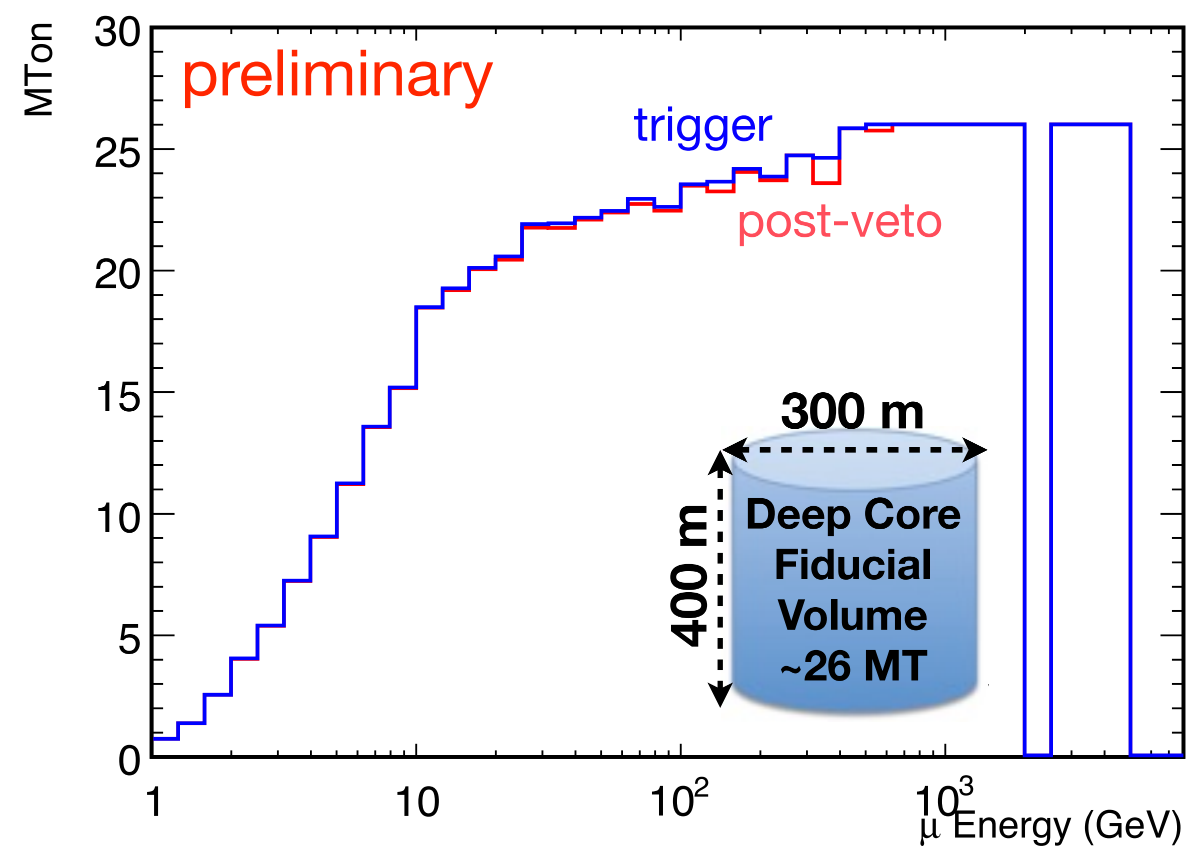


Deep Core Effective Area & Effective Volume

Effective area for upgoing ν_μ at trigger level

Reconstruction efficiencies not included yet – relative effect likely to increase



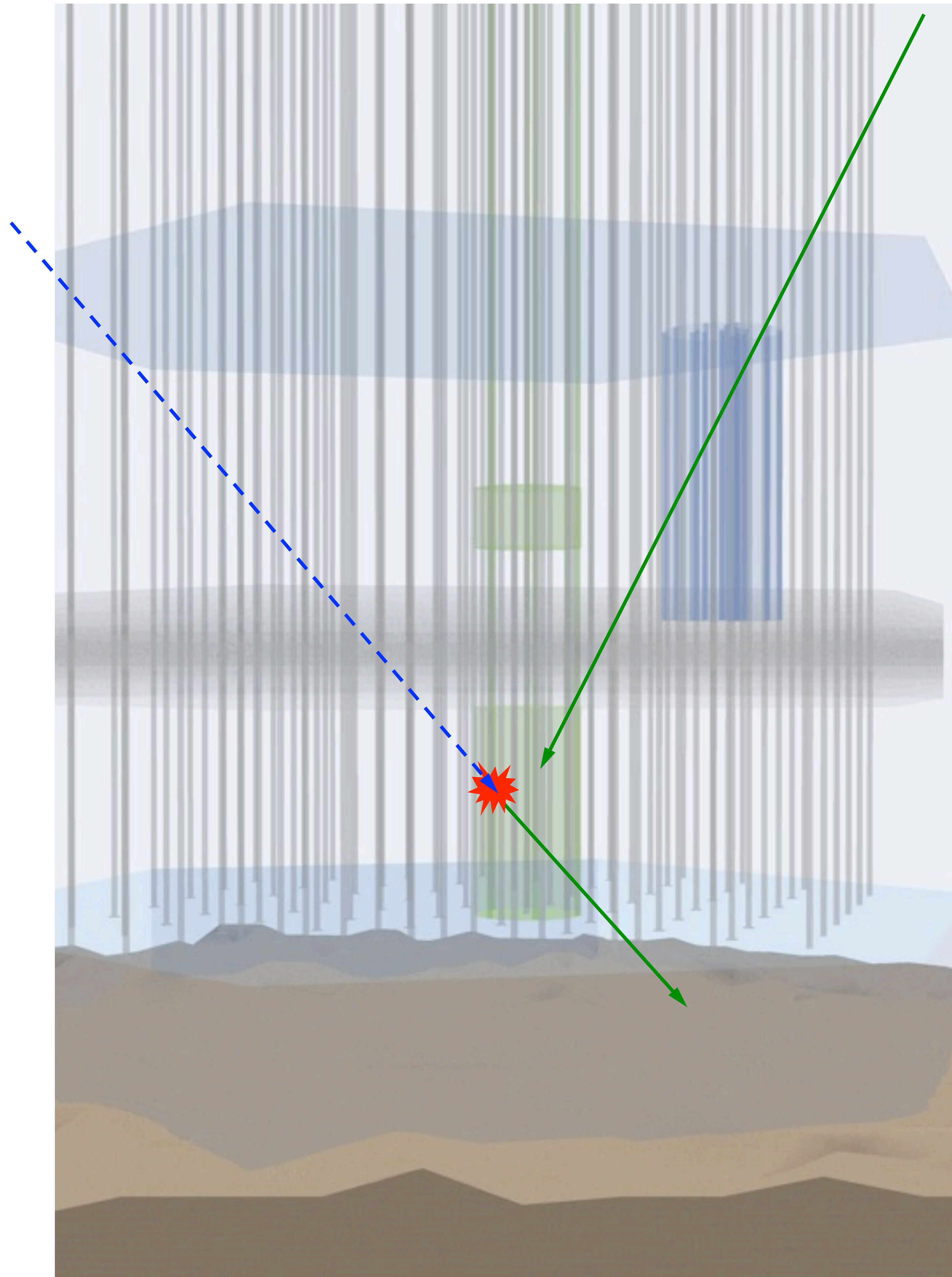


Effective volume for muons from ν_μ interacting in Deep Core

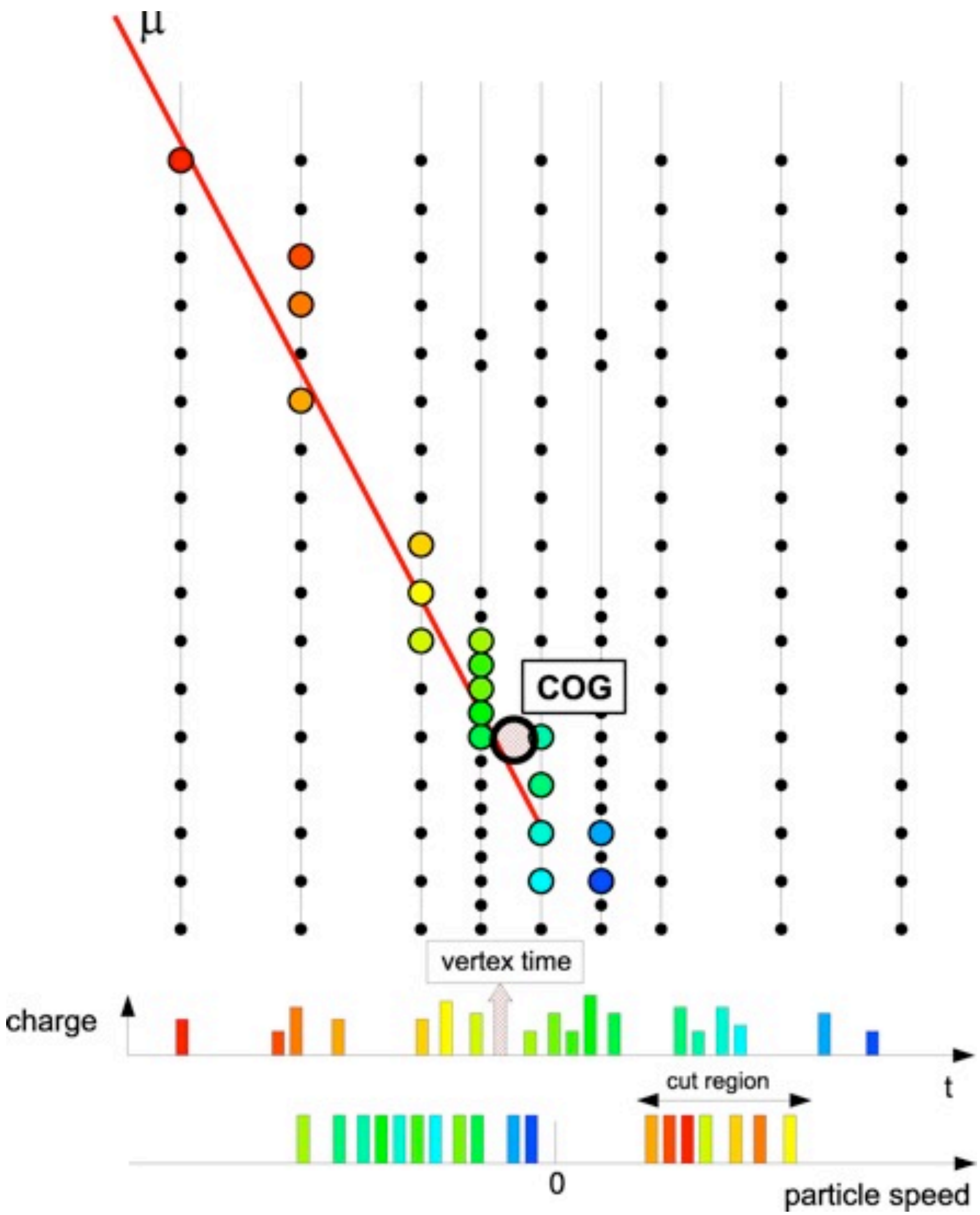
NB: full analysis efficiency *not* included yet

Atmospheric Muon Veto

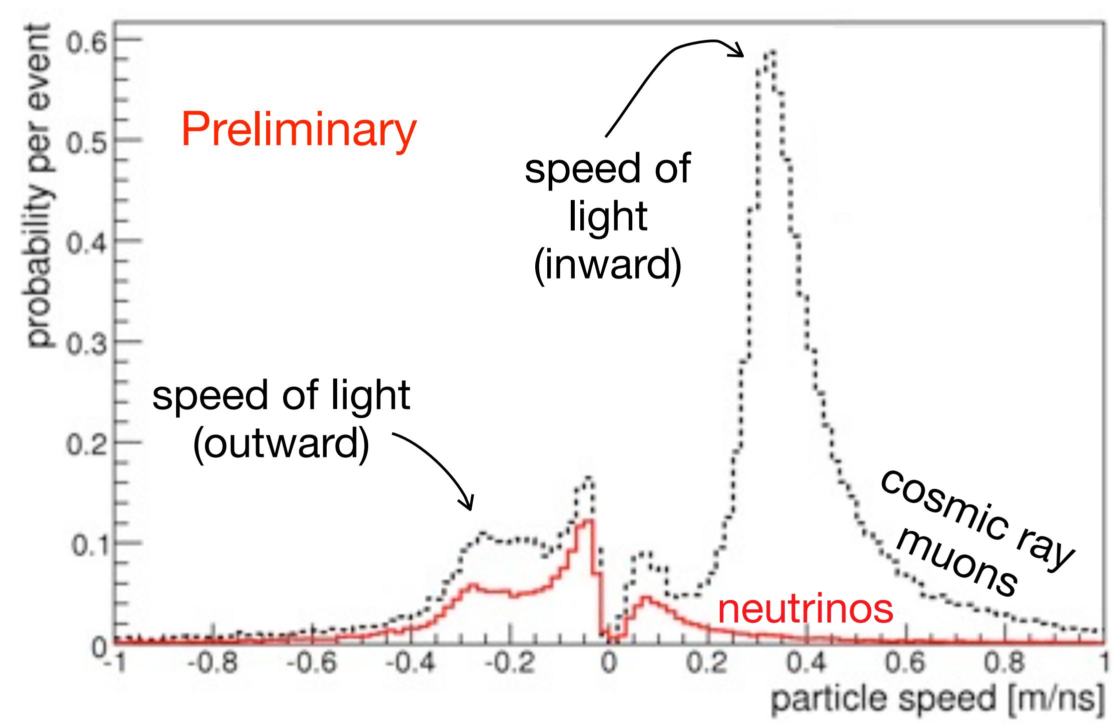
- Top and outer layers of IceCube can be used to detect and veto atmospheric muon background
  - Try to identify atmospheric muons entering Deep Core
  - 3 rows of strings on all sides
  - Downgoing neutrinos accessible if they interact in the Deep Core volume
  - Atm. μ/ν trigger ratio is ~10^6
  - Development of specialized algorithms continues, final sensitivities still TBD



Cosmic Ray Muon Veto

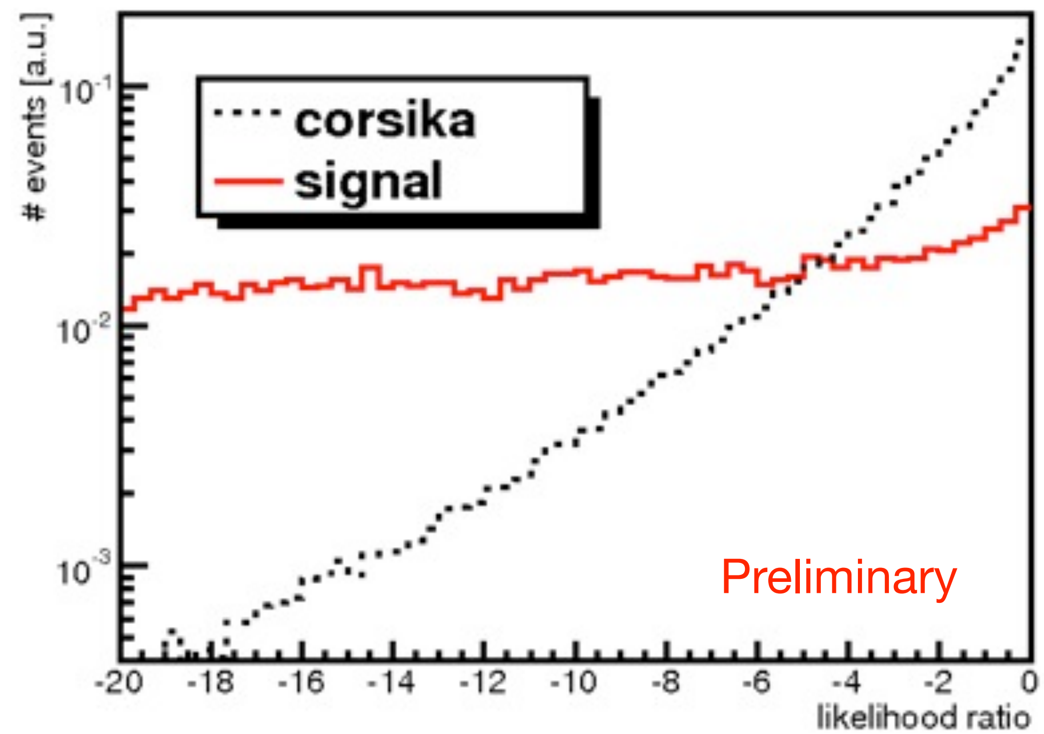


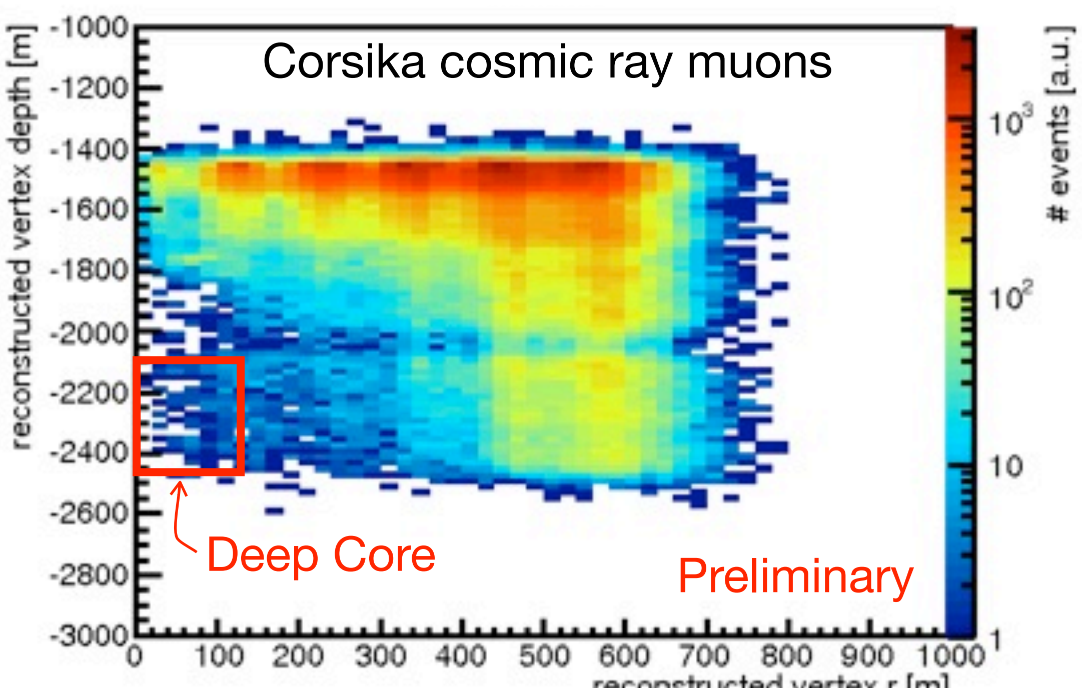
- Stage 1 veto: look for hits in veto regions consistent with speed-of-light travel time to hits in fiducial volume
  - Achieves 6 x 10^{-3} rejection of cosmic ray muon background
  - Loss of <1% of fiducial neutrinos

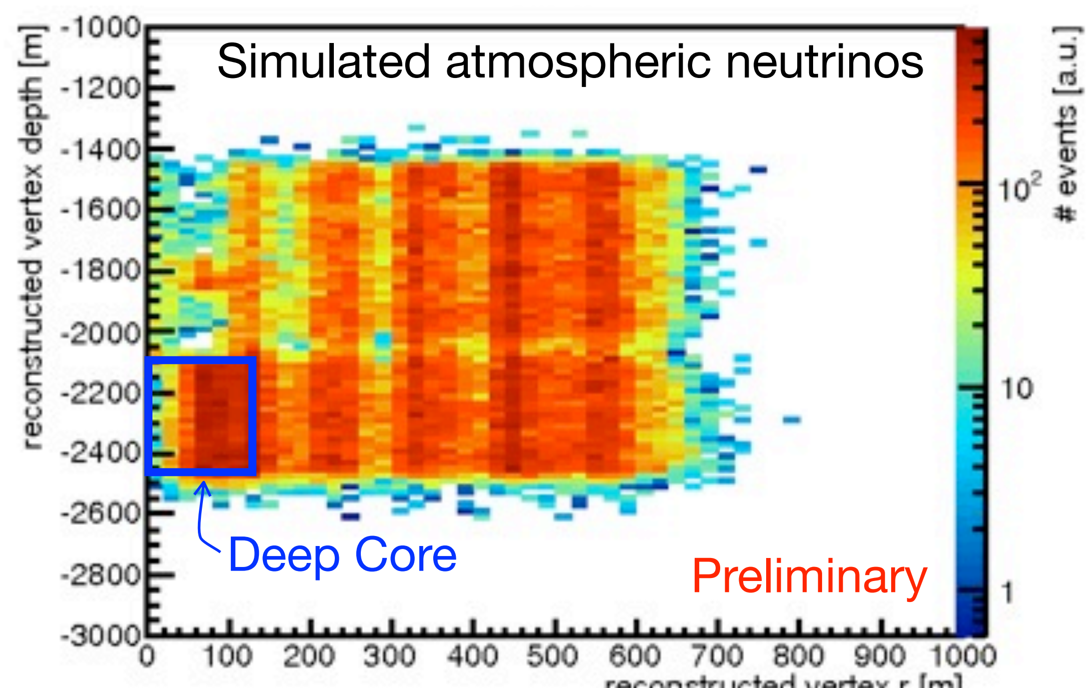


Cosmic Ray Muon Veto

- One stage 2 veto approach:
  - likelihood ratio for starting track vs. through-going track hypothesis
  - position of reconstructed starting point
- Preliminary studies indicate total background rejection < 10^{-6} possible

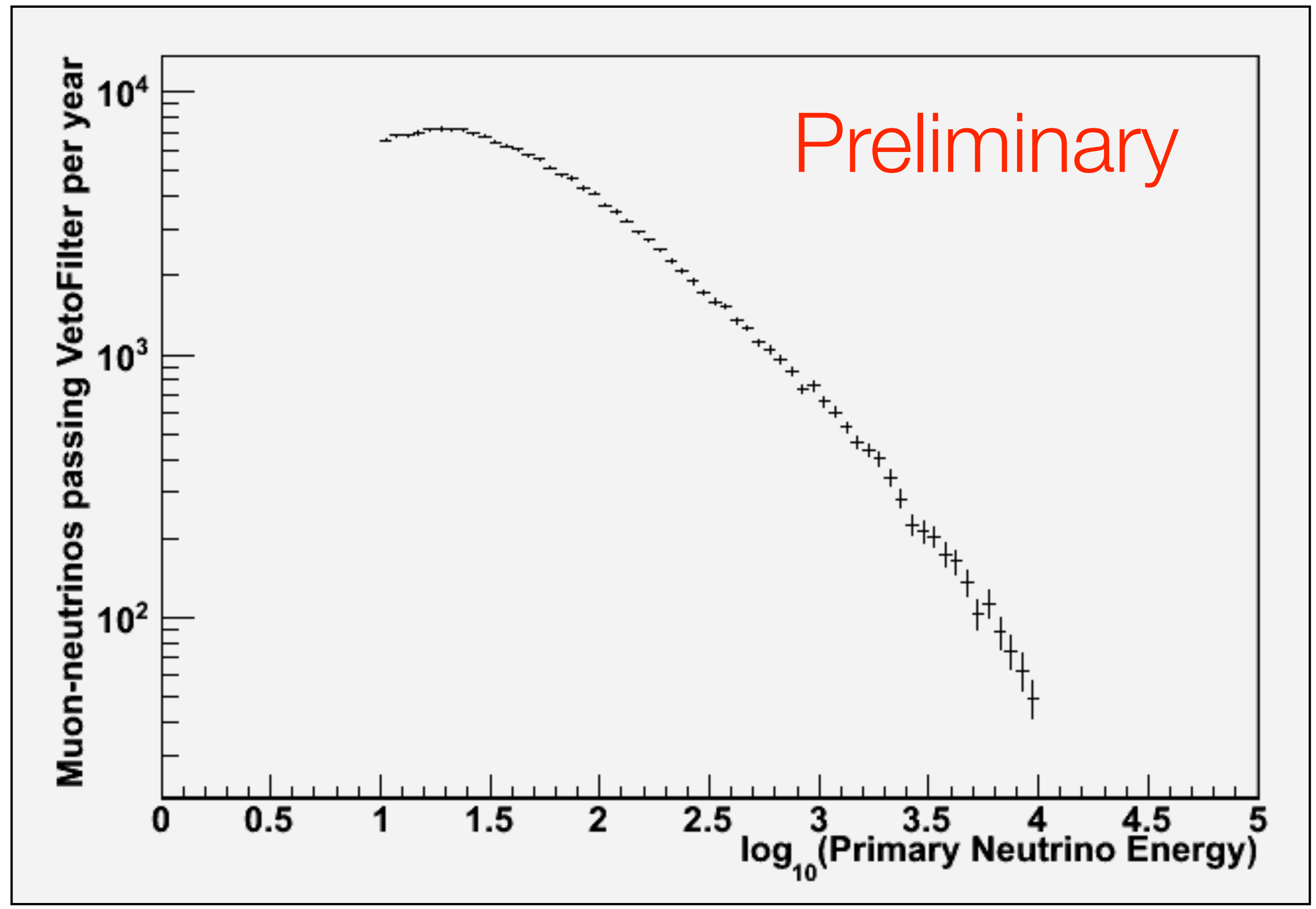






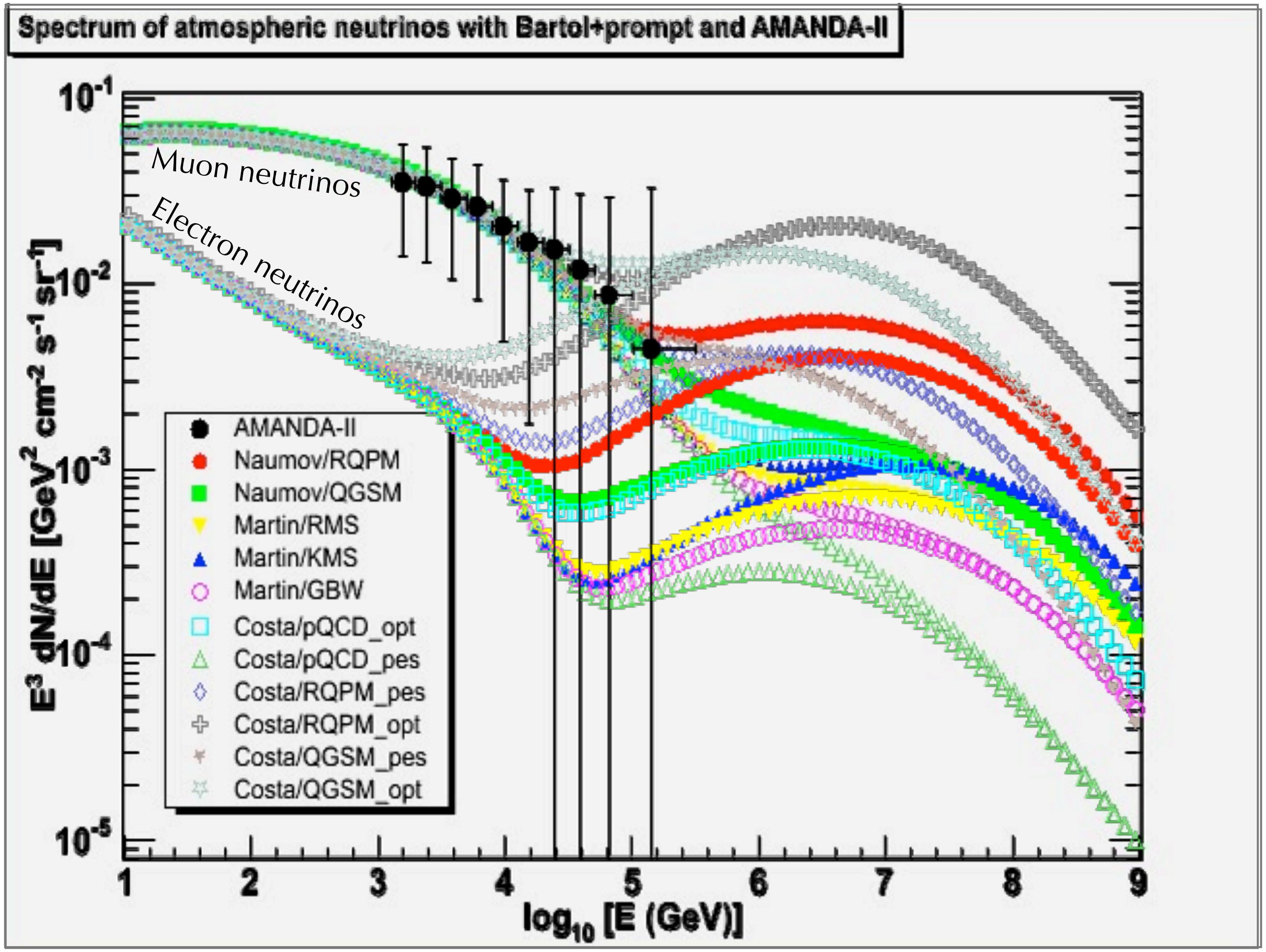
World's Largest Neutrino Data Set

- Expect >200,000 ν_μ events per year above 10 GeV (filter level)
    - Additional ~20,000 ν_e events per year
- Need to refine our Monte Carlos to handle correctly neutrino interactions below 10 GeV



- Additional atmospheric neutrinos at higher energies from standard IceCube filters

QCD: Prompt Electron Neutrinos



Expect ~10 conventional ν_e events per bin per year at 10^4 GeV in Deep Core

Lower conventional ν_e flux means prompt component visible at lower energy

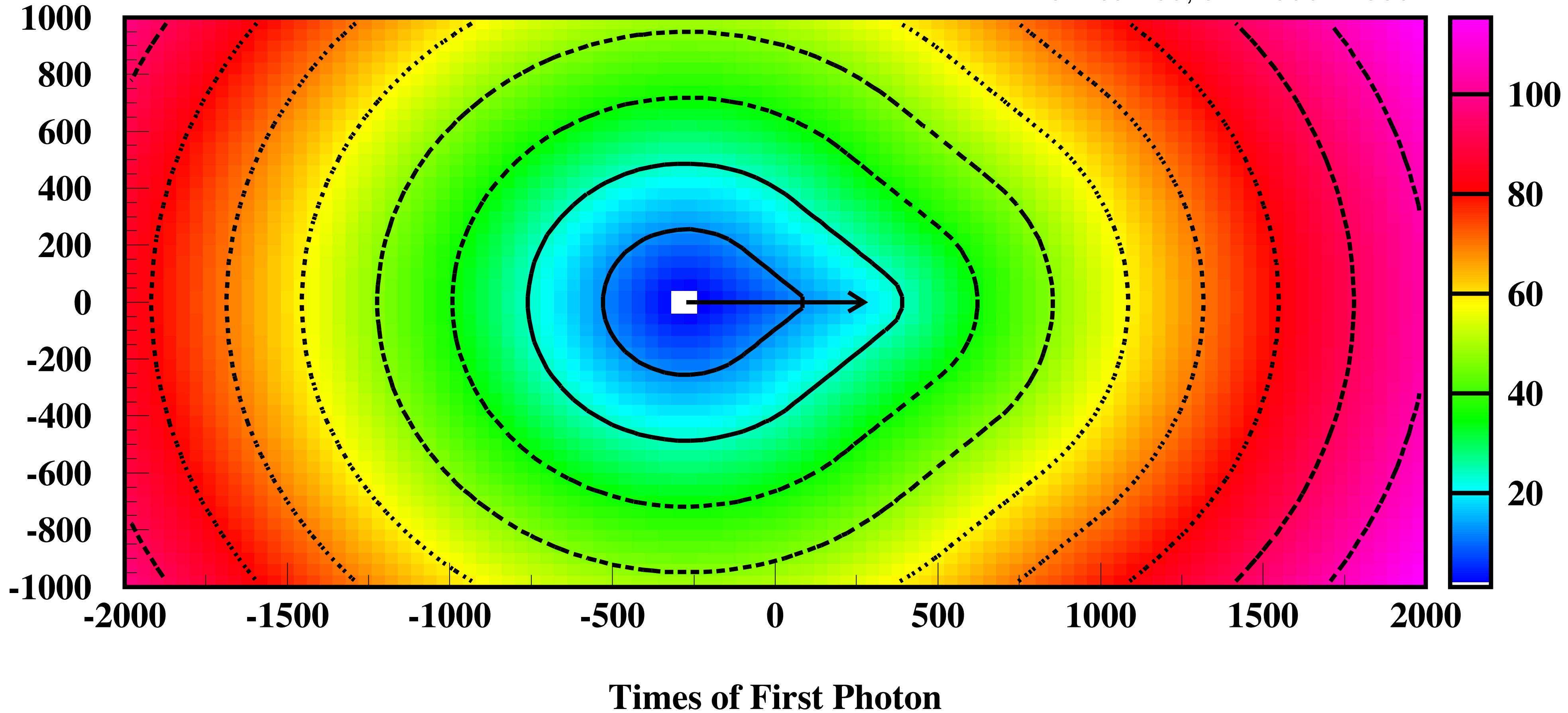
Spectral measurements easier in ν_e channel (full containment)

Neutrino Physics with Deep Core

- Caveat: preliminary studies
  - Full detector simulation of signal (only)
  - Assume high suppression of atmospheric muons by veto – trigger level
  - Specialized reconstruction algorithms for low energy events needed, now under development

Track Fitting in Deep Core

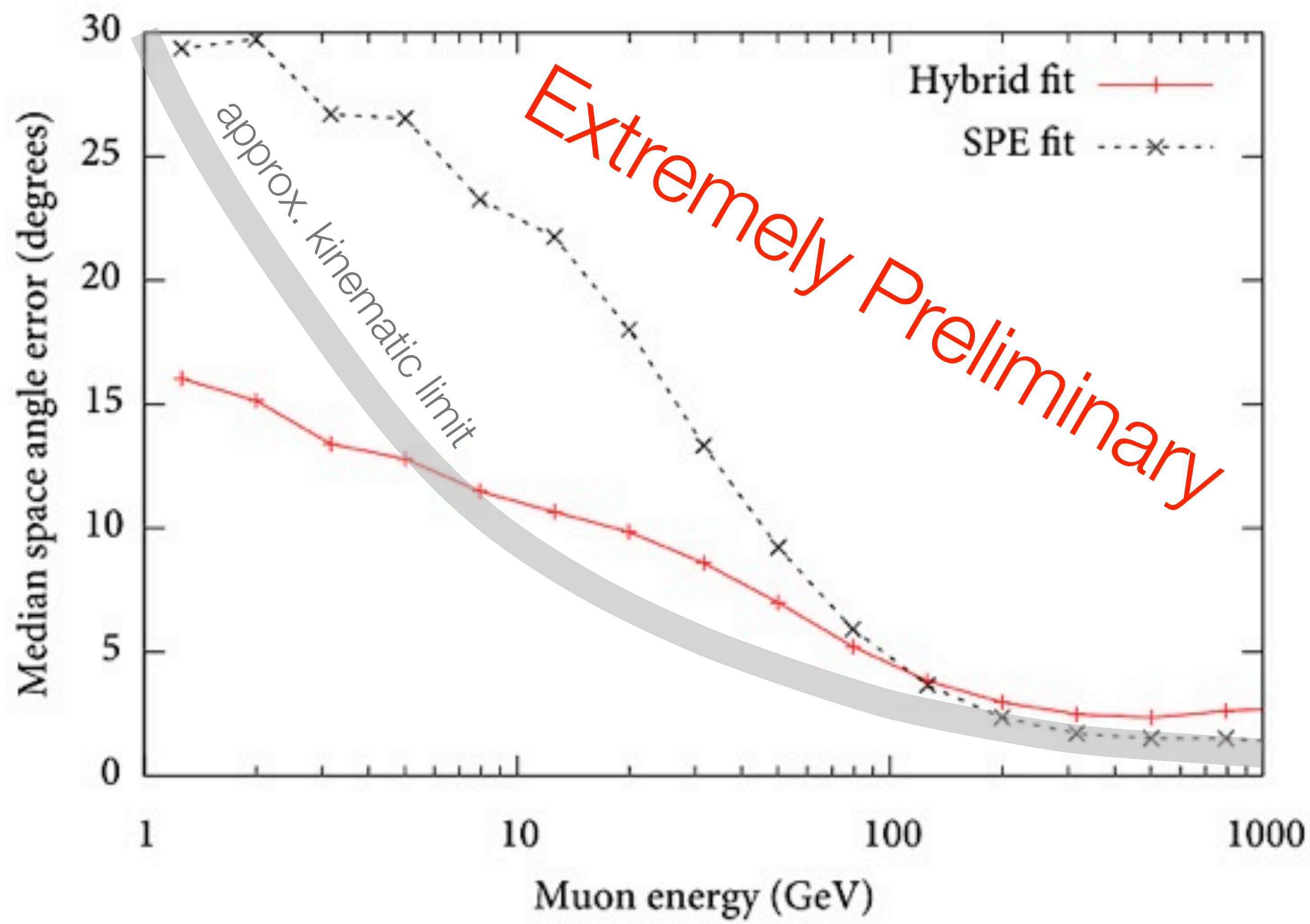
J. Learned, arXiv:0902.4009



- Topology is fundamentally different
  - Instead of entering from one side, light expands outward in all directions
  - More fit parameters: (θ, φ, x, y, t, E) → (θ, φ, x, y, z, t, E_{μ}, E_{casc})

Track Reconstruction Performance

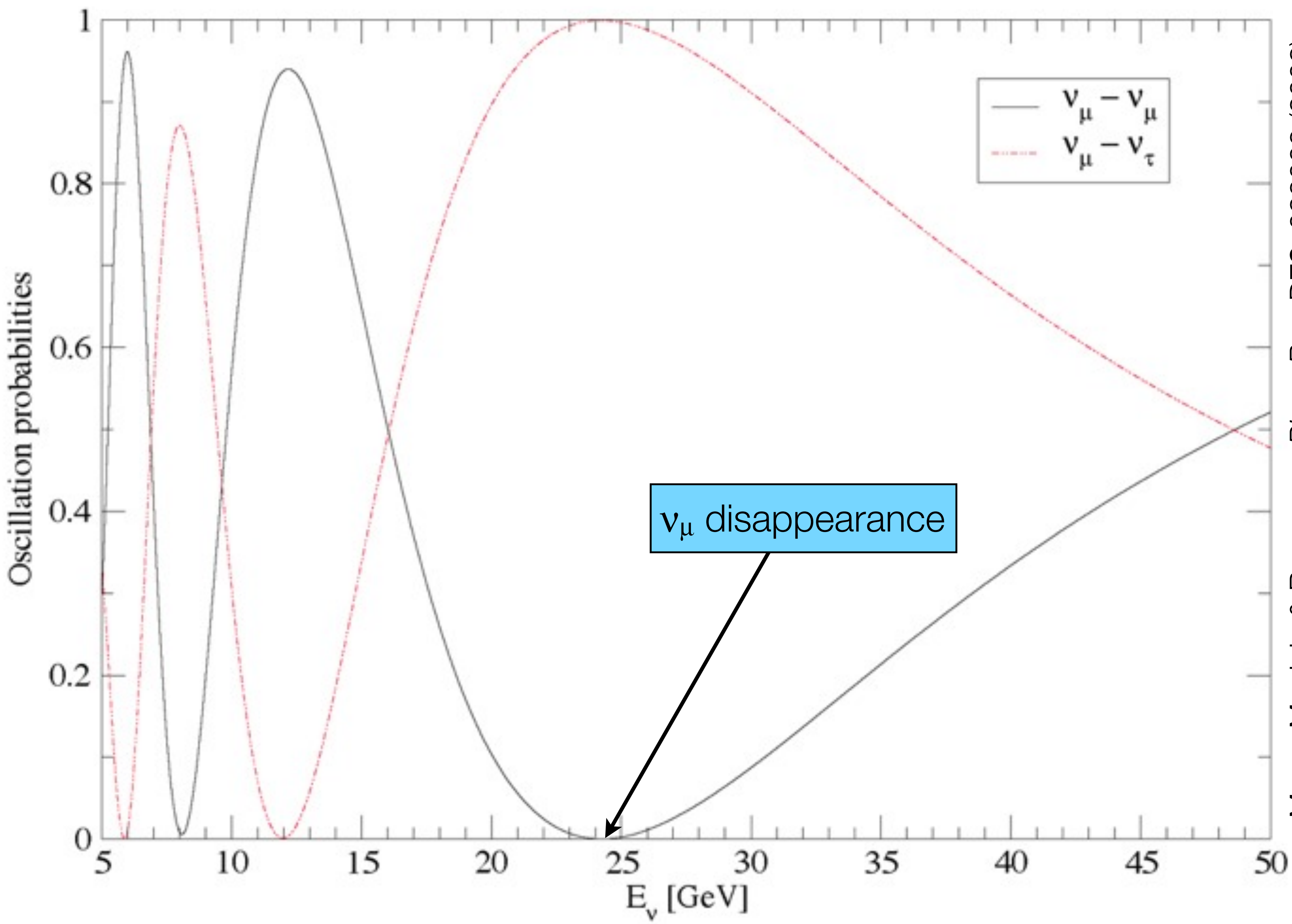
- Study of likelihood space for muon neutrino events in Deep Core
  - Not a real reconstruction (started with MC truth), just an estimate of how sharply peaked and correctly located the likelihood optima are
  - Suggests that we should be able to reconstruct events with reasonable accuracy



Neutrino Physics with Deep Core

- Caveat: preliminary studies
  - Full detector simulation of signal (only)
  - Assume high suppression of atmospheric muons by veto – trigger level
  - Specialized reconstruction algorithms for low energy events needed, now under development
  - Mainly using low level quantities, assumptions seem reasonable, but…
- Three possible measurements
  - Muon neutrino disappearance — Feasible
  - Tau neutrino appearance — Reasonable
  - Neutrino mass hierarchy? — Hard

Neutrino Oscillations

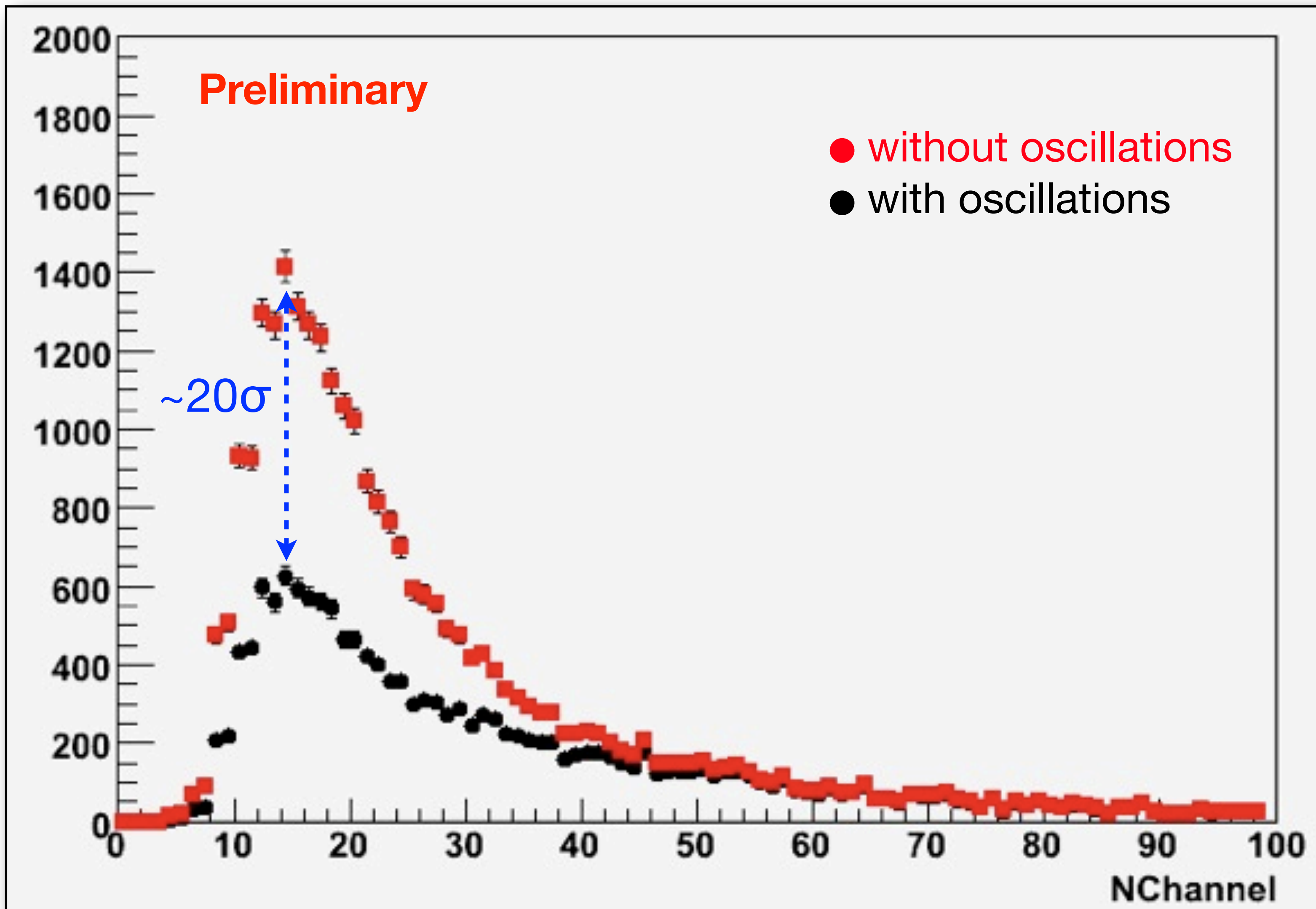


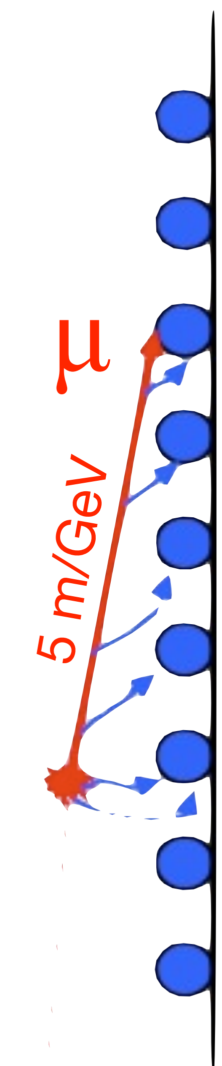
Mena, Mocioiu & Razzaque, *Phys. Rev.* D**78**, 093003 (2008)

For vertically upgoing neutrinos (L = Earth diameter)

Muon Neutrino Disappearance

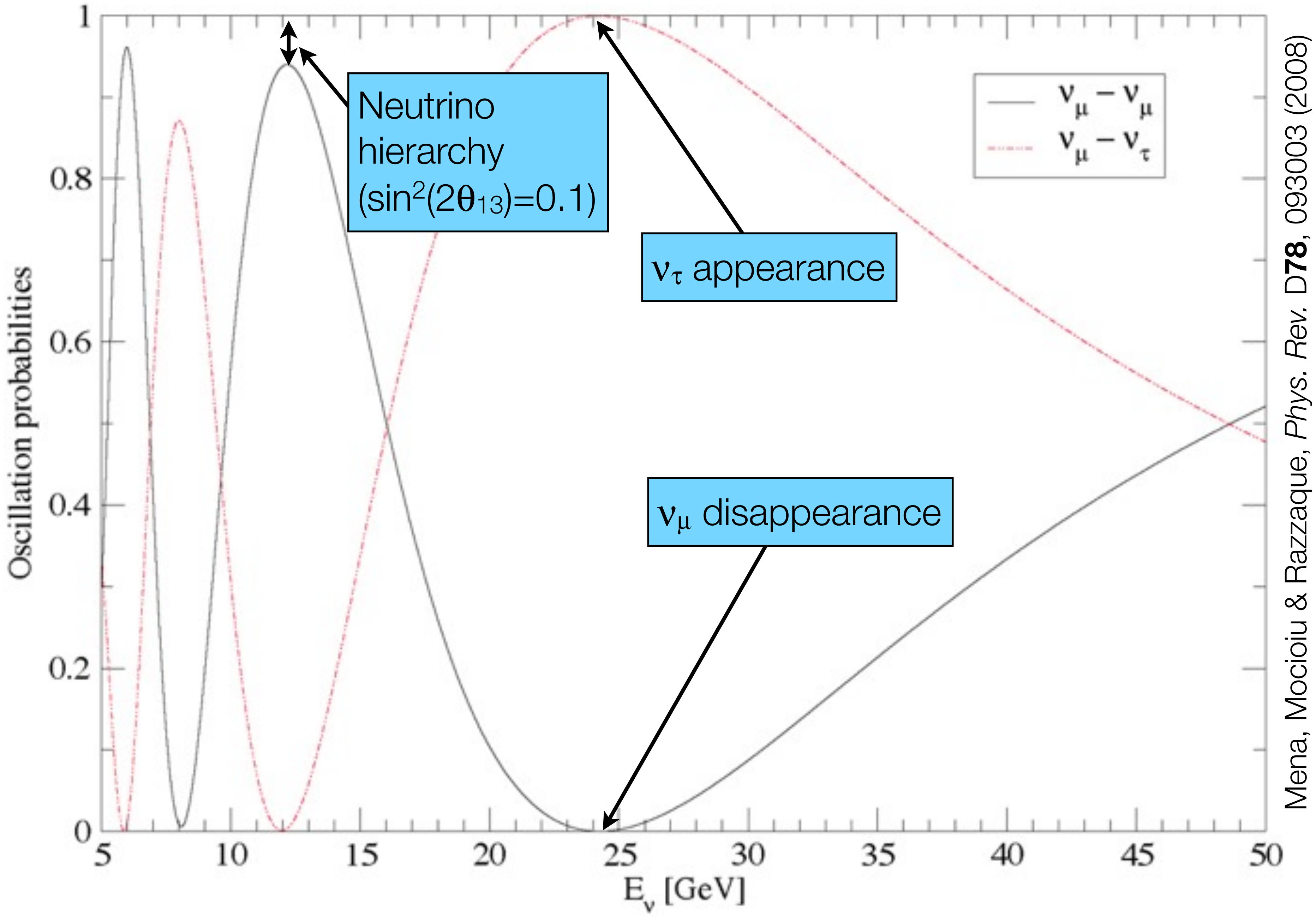
- Full detector simulation of signal
  - 3-flavor oscillations, PREM
  - 1 year DC
  - No BG
  - cos(θ)<-0.6





- Number of hit channels used as simple energy estimator

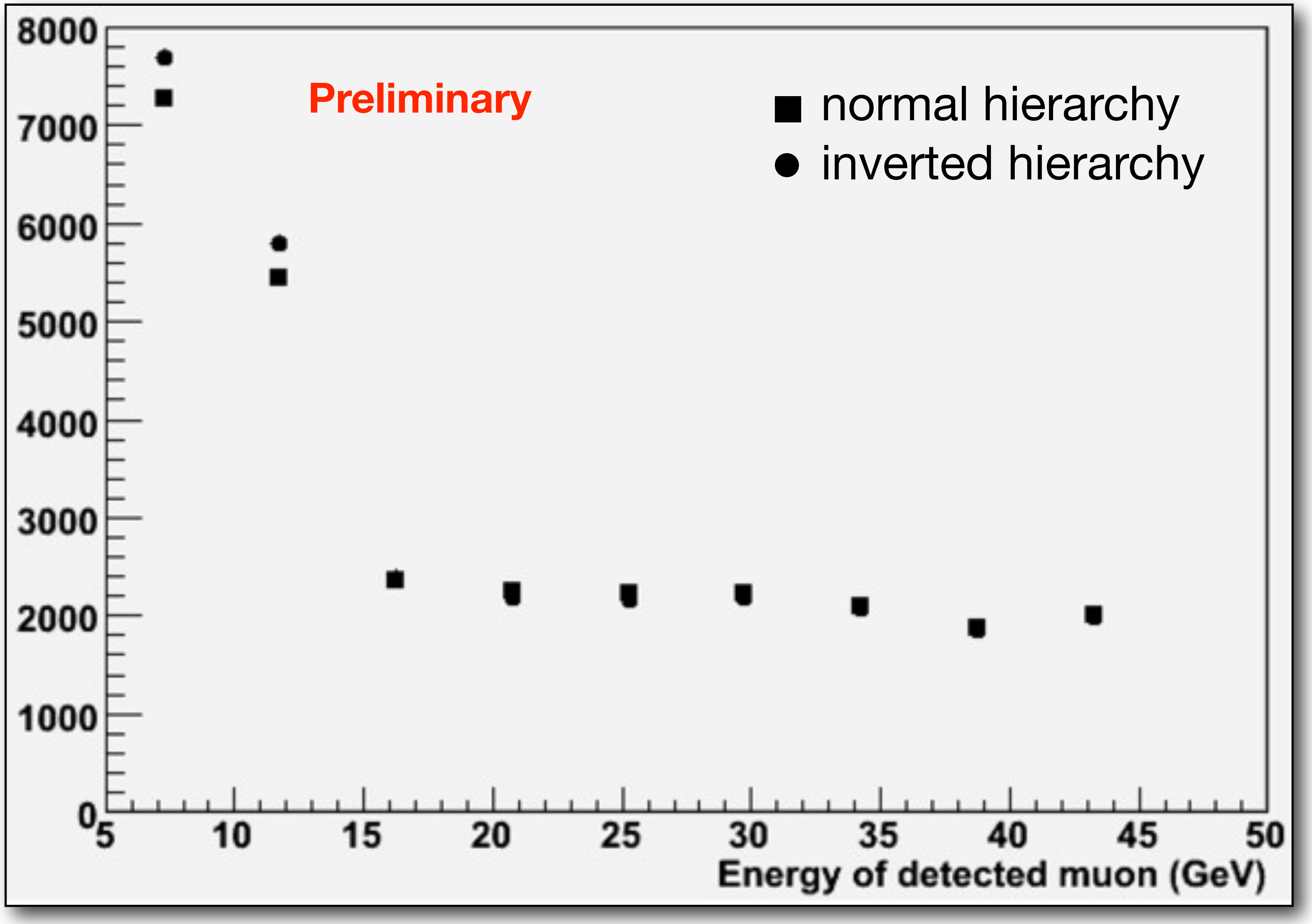
Neutrino Oscillations



For vertically upgoing neutrinos (L = Earth diameter)

Neutrino Mass Hierarchy?

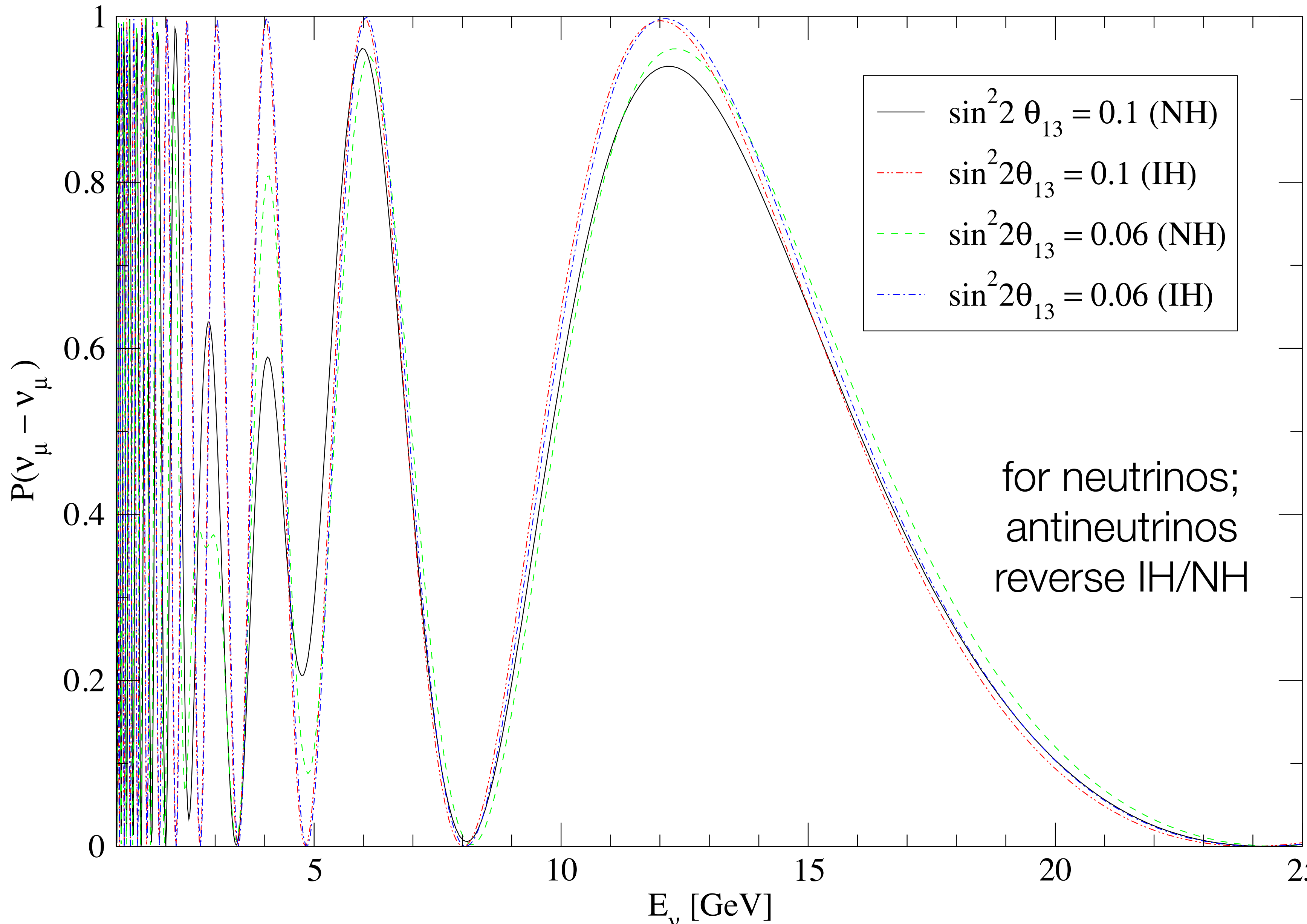
- Exploit asymmetries between neutrinos and antineutrinos (Mena, Mocioiu, Razzaque arXiv:0803.3044)
    - Resonance in effective θ_{13} angle in Earth at 10 GeV for Earth diameter
    - $P_{\mu\mu}$ max at 12 GeV
    - Asymmetries in $P_{\mu\mu}$, $\sigma_{\nu N}$, $\langle y \rangle$



- 5 year prediction for IceCube + Deep Core, $\cos(\theta) < -0.7$, muon threshold 5 GeV (~25 m), similar assumptions as previous studies

Neutrino Mass Hierarchy?

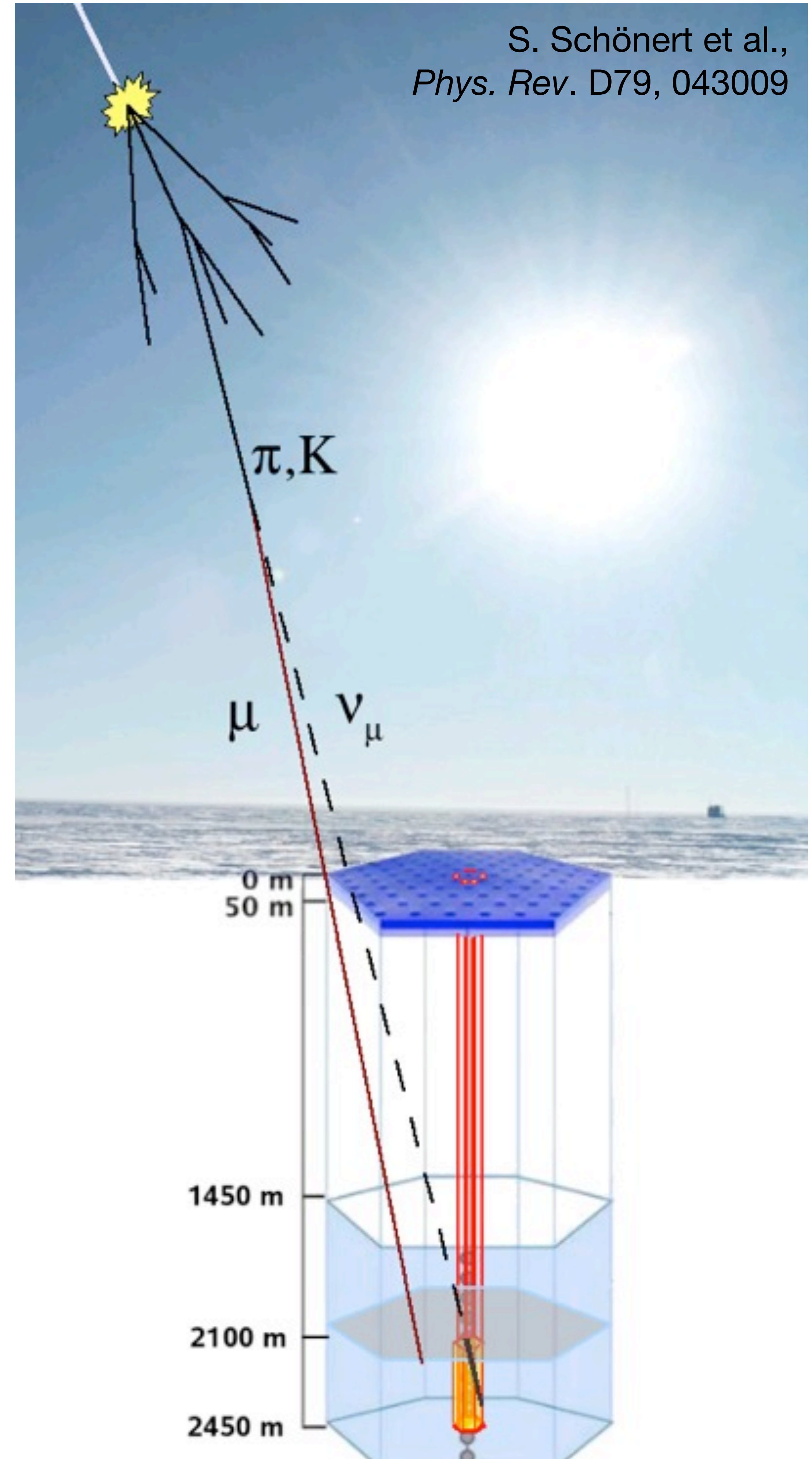
- Requires large θ_{13}
  - Universal issue
- Also some dependence on hierarchy (easier to see effect if hierarchy is normal)



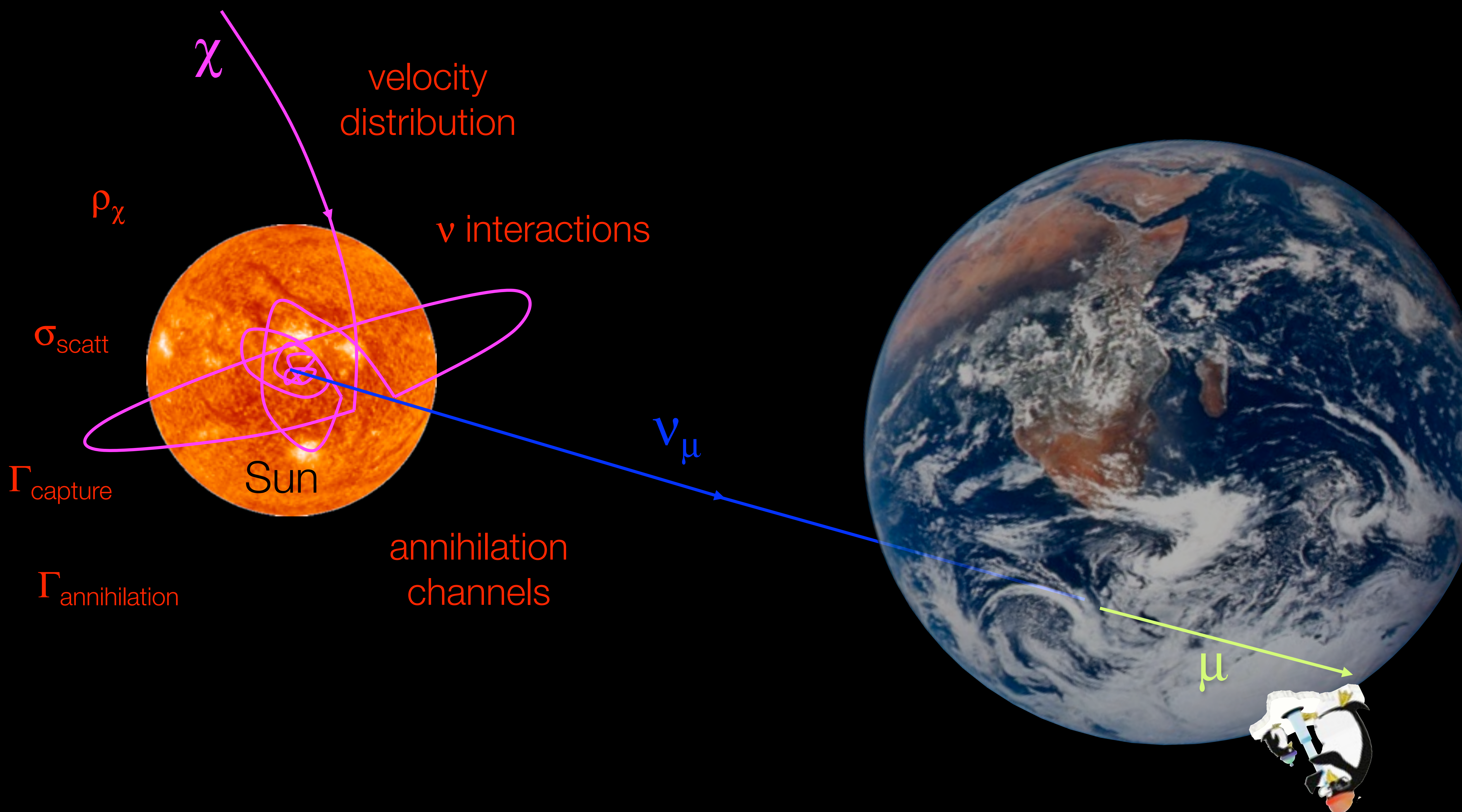
- Very difficult measurement, control of systematics crucial, *and* Nature must be kind to us – precise range in θ_{13} under study

Atmospheric Neutrino Veto

- Atmospheric neutrinos will often be accompanied by muons produced in the same air shower
- These will likely be “accidentally” rejected by the muon veto
- Will improve sensitivity to searches for astrophysical neutrinos from sources in the southern sky (Galactic Center)
- Sensitivity skewed to lower energies (lose benefit of muon range) but many Galactic gamma sources cut off



Indirect Detection of Solar Dark Matter

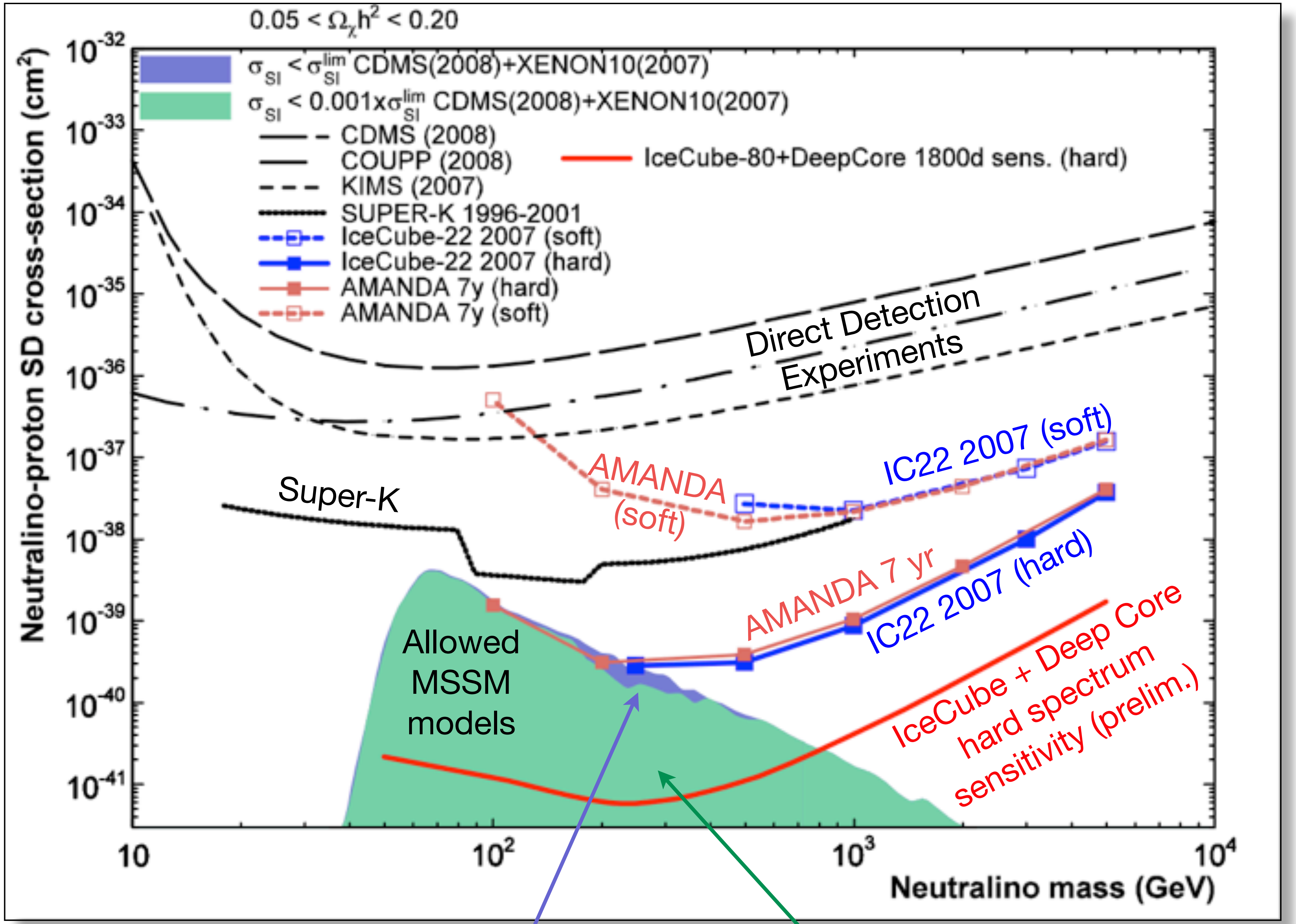


Silk, Olive and Srednicki, ’85
Gaisser, Steigman & Tilav, ’86
Freese, ’86

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

Solar WIMP Searches with Deep Core

- Initial study based on std. IceCube analysis
- Does not include any of the improved techniques discussed
- Even so, probes large region of allowed phase space

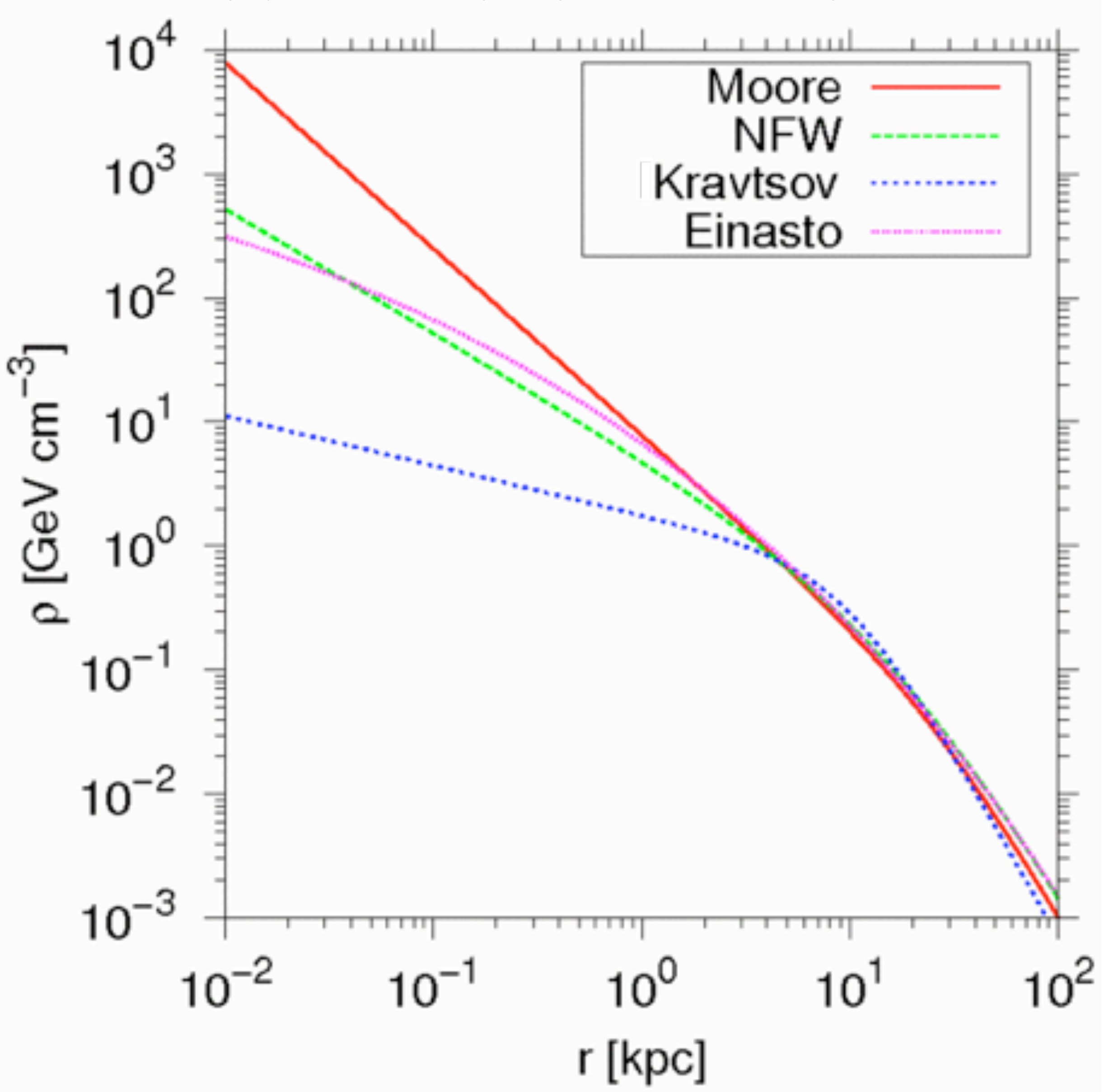


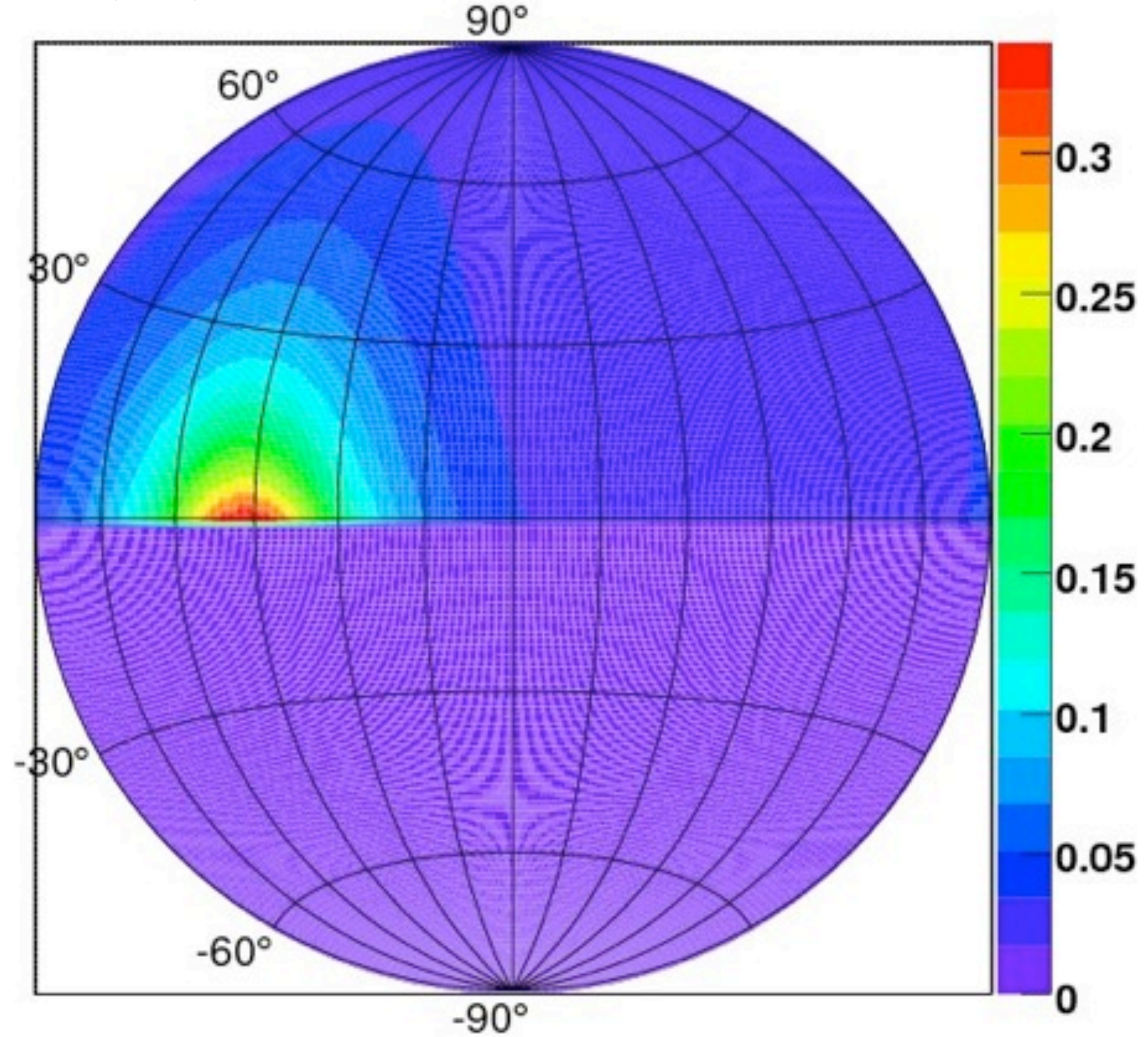
Corresponding σ_{SI} within factor 10^3 of current direct limits

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

Dark Matter Annihilation in the Galactic Halo

Moore et al. *MNRAS* **310**, 1147 (1999)
Kravtsov et al. *Astrophys*. *J*. **502**, 48 (1998)
Navarro, Frenk, White, *Astrophys*. *J*. **490**, 493 (1997)
J. Einasto, Trudy Inst. Astroz. Alma-Ata **5**, 87 (1965)



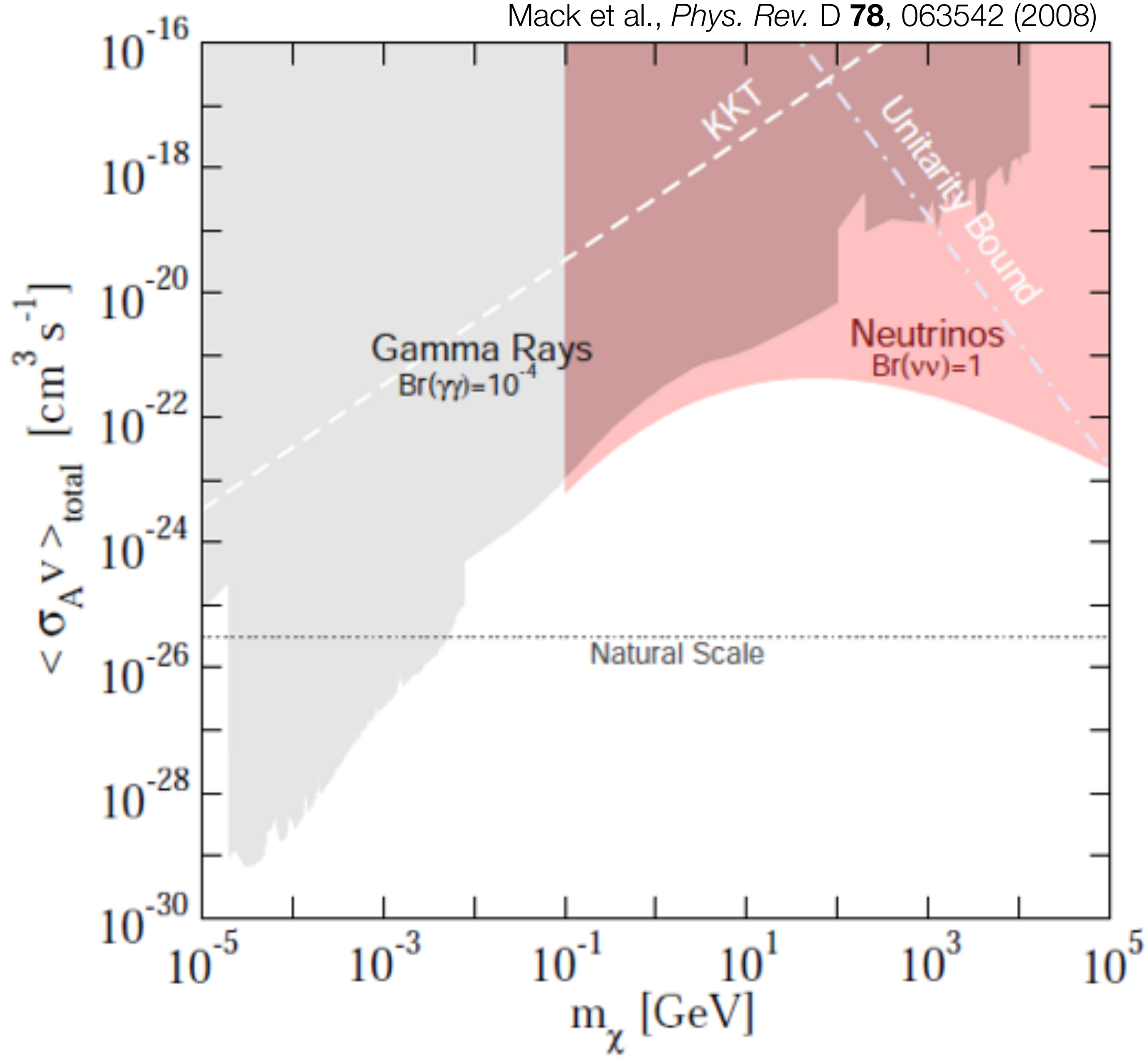


- Halo density and annihilation rate highest near Galactic center
- Ability to view southern sky will improve sensitivity greatly

Neutrino and Gamma Ray Limits on Dark Matter Annihilation

- Consider $\chi\chi \rightarrow \nu\nu$ the least detectable dark matter annihilation channel
  - Limits assuming $Br(\nu\nu) = 1$ are thus most conservative
  - Typical predictions for $Br(\gamma\gamma)$ are around $10^{-3} - 10^{-4}$
- For high mass WIMPs, limits that neutrino flux must be lower than atmospheric flux are most constraining

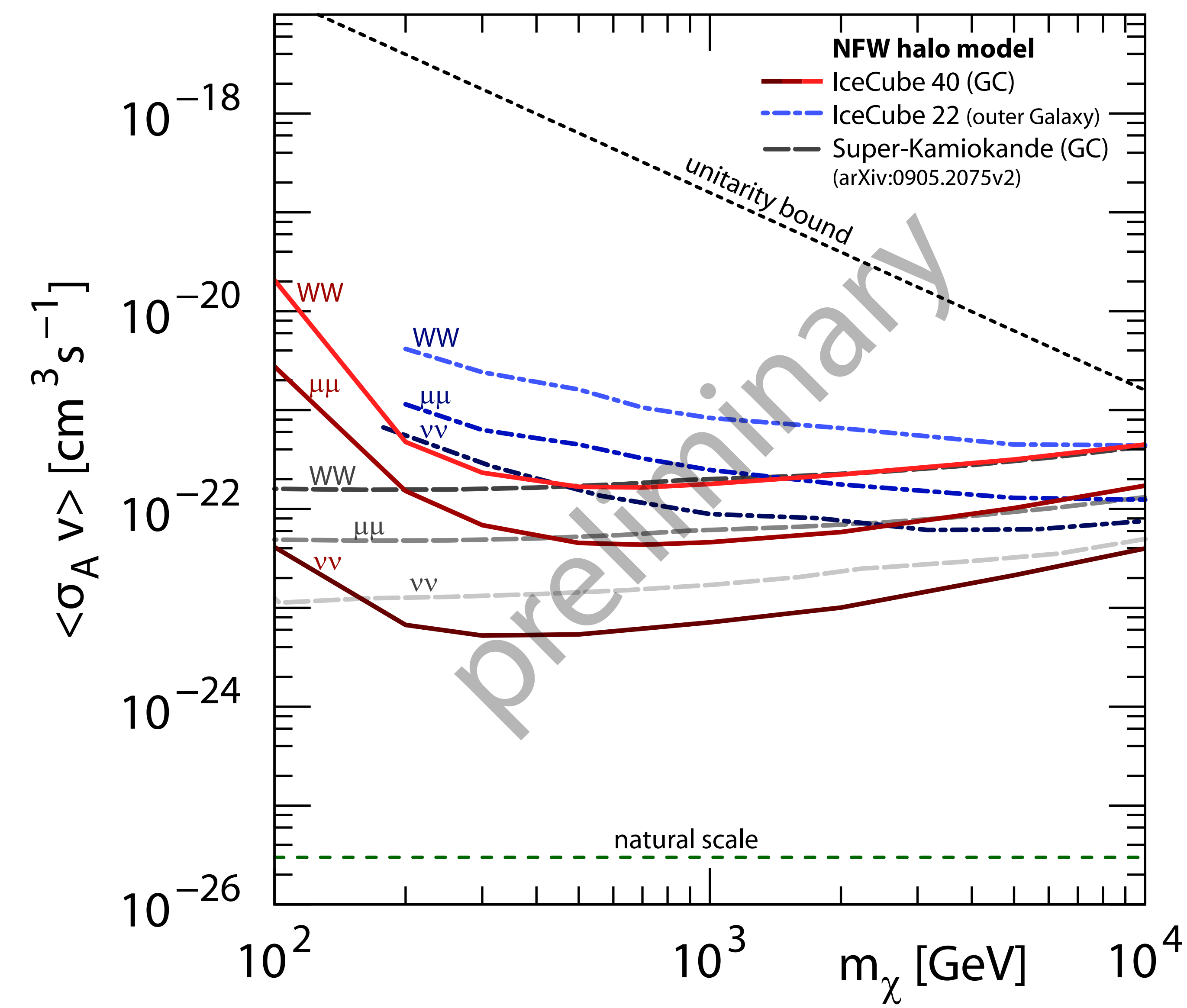
Mack et al., *Phys. Rev.* D **78**, 063542 (2008)



IceCube Limits on Dark Matter Annihilation

- Sensitivity depends strongly on annihilation channel (affects neutrino energy spectrum)
- IceCube 2008 (40-string) sensitivity already better than Super-Kamiokande for WIMP masses above a few hundred GeV
- Natural scale for thermal relics still several orders of magnitude lower

Limits (90% C.L.) on the self annihilation cross section (χχ -> WW, μμ, νν)



Summary

- IceCube construction is nearly complete
  - 79 of a planned 86 strings now operating
  - Rapidly increasing sensitivity to astrophysical neutrino sources
  - Also being used to obtain important results in fundamental physics
- Deep Core underway
  - Deployment completed last month
  - Reduce threshold to ~10 GeV
  - Sensitivity to neutrino oscillations
  - Atmospheric neutrino veto may allow observation of Galactic objects
  - Significant sensitivity to dark matter in the Sun, Galactic halo