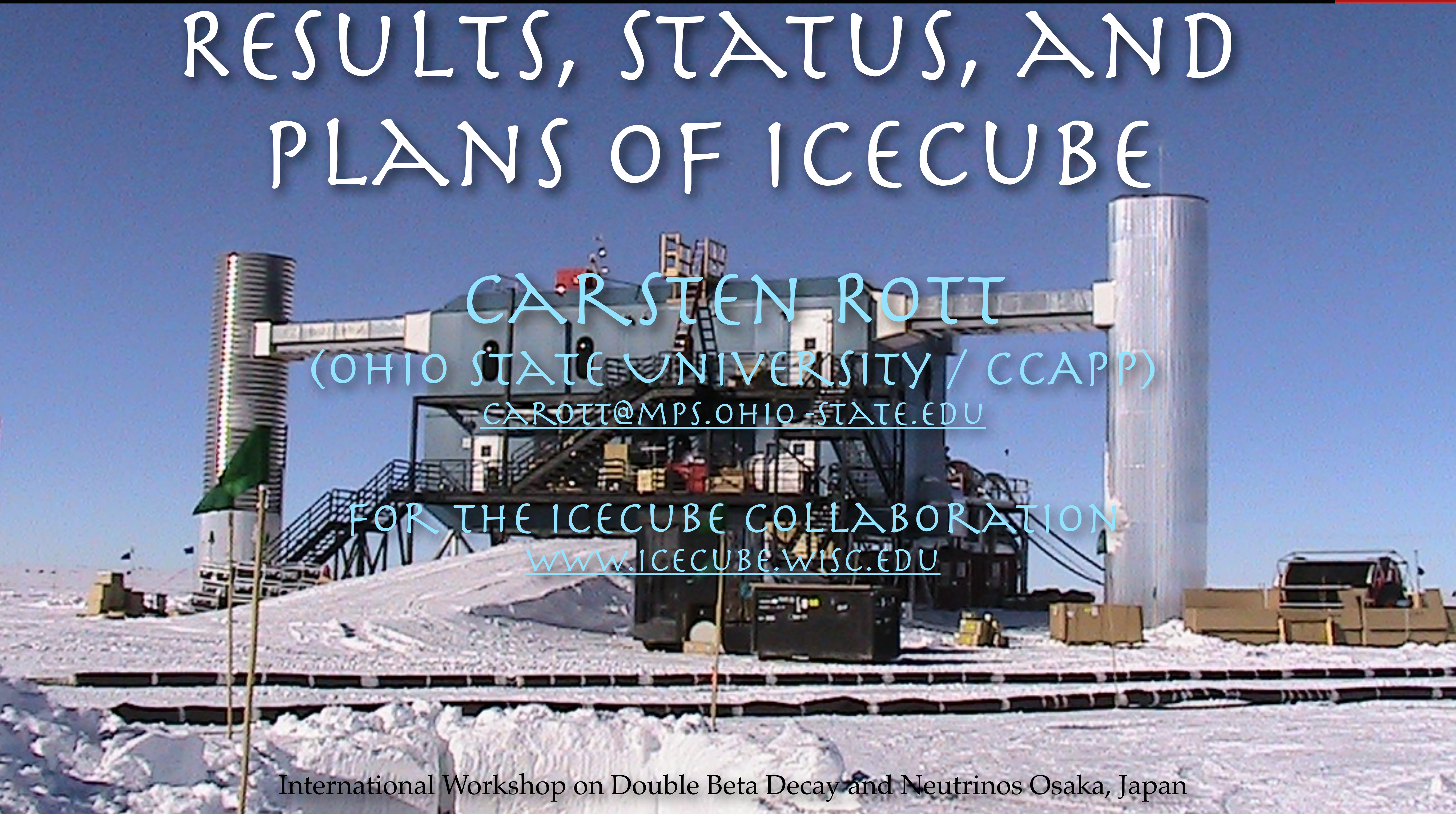
Results, Status, and Plans of IceCube



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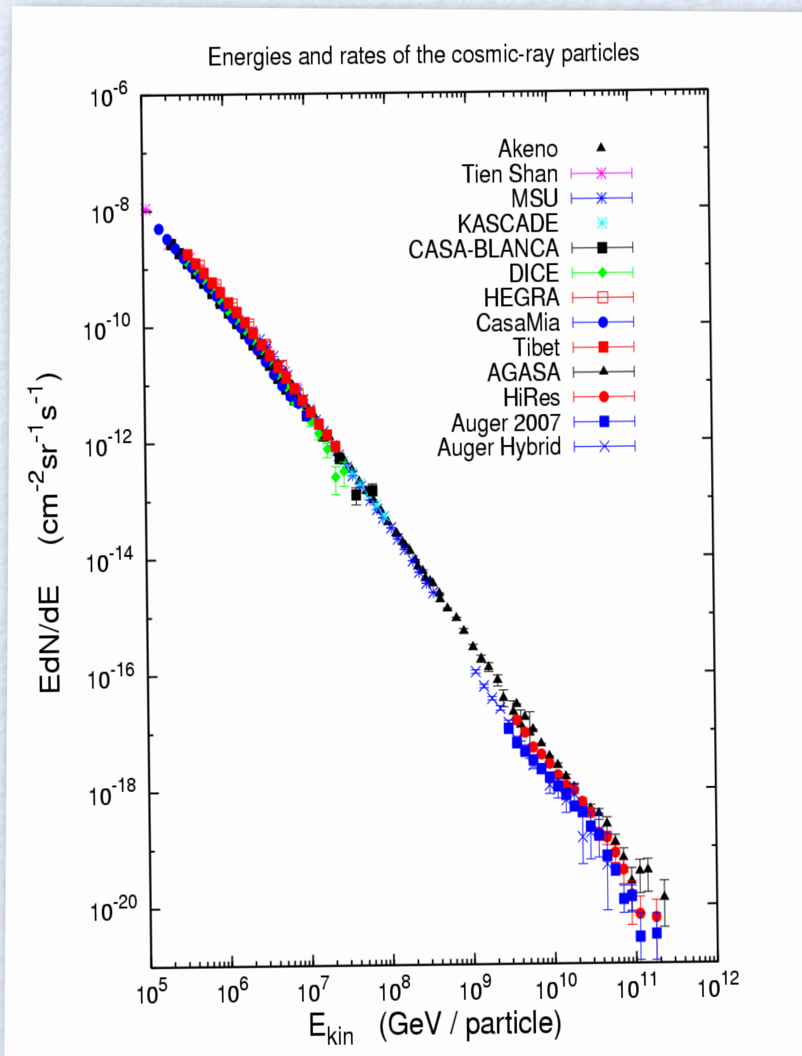
for the IceCube Collaboration
www.icecube.wisc.edu

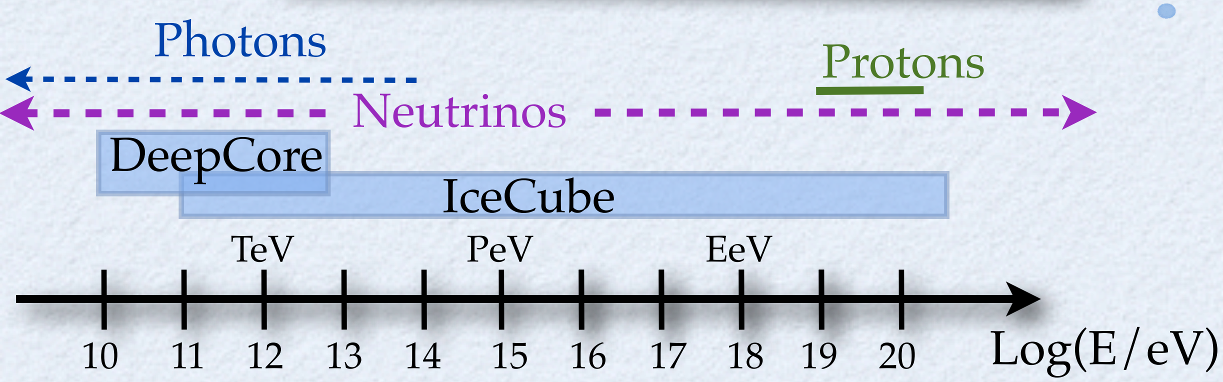
International Workshop on Double Beta Decay and Neutrinos Osaka, Japan

Overview

- The IceCube Neutrino Telescope
- Selected Results
- Neutrino Properties and DeepCore
- Future Plans and Conclusions

What makes Neutrinos so exciting as Messengers ?





Electrons

- Bend in Galactic magnetic fields

Protons

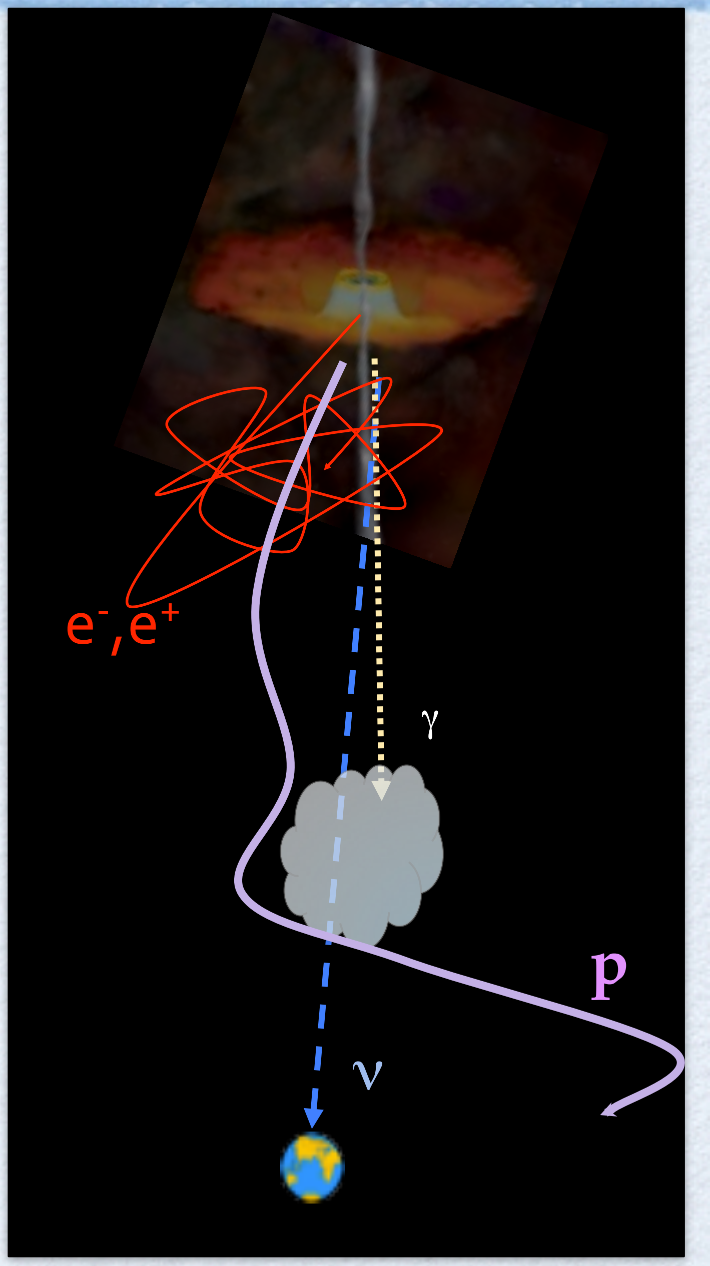
- bent below 10 EeV
- above 50EeV GZK cut-off

Photons

- scattered/absorbed above 50 TeV

Neutrinos

- Unobscured view
- Point back to their sources
- Cover entire energy spectrum

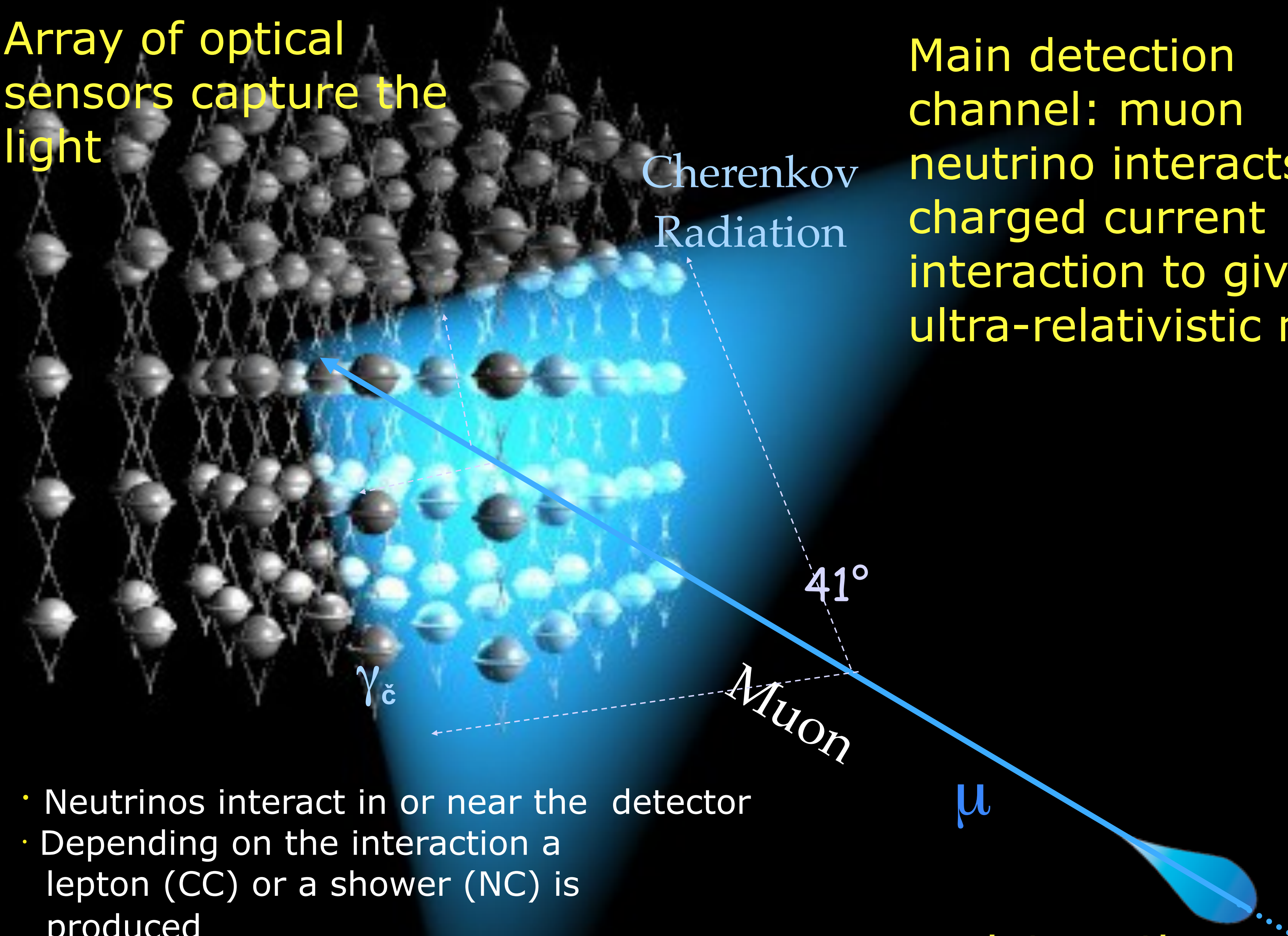


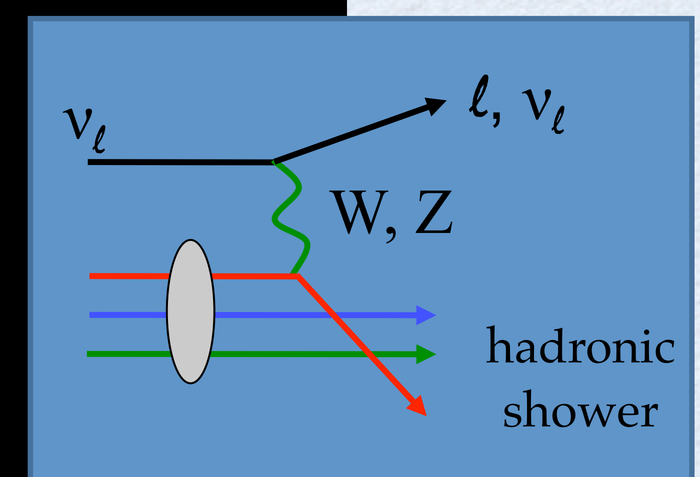
$$p + (p \text{ or } \gamma) \rightarrow \pi^0 \rightarrow \gamma\,\gamma$$
$$\rightarrow \pi^\pm \rightarrow \nu_e \nu_\mu \rightarrow \nu_e \nu_\mu \nu_\tau$$
$$(1{:}2{:}0) \qquad (1{:}1{:}1)$$

Detecting Neutrinos

Array of optical sensors capture the light

Main detection channel: muon neutrino interacts via charged current interaction to give ultra-relativistic muon





- Neutrinos interact in or near the detector
- Depending on the interaction a lepton (CC) or a shower (NC) is produced
- ***O*** (km) muons from ν_μ
- ***O*** (10m) cascades from ν_e, ν_τ, NC

The IceCube Collaboration

39 Institutions - 4 Continents - 250 Physicists

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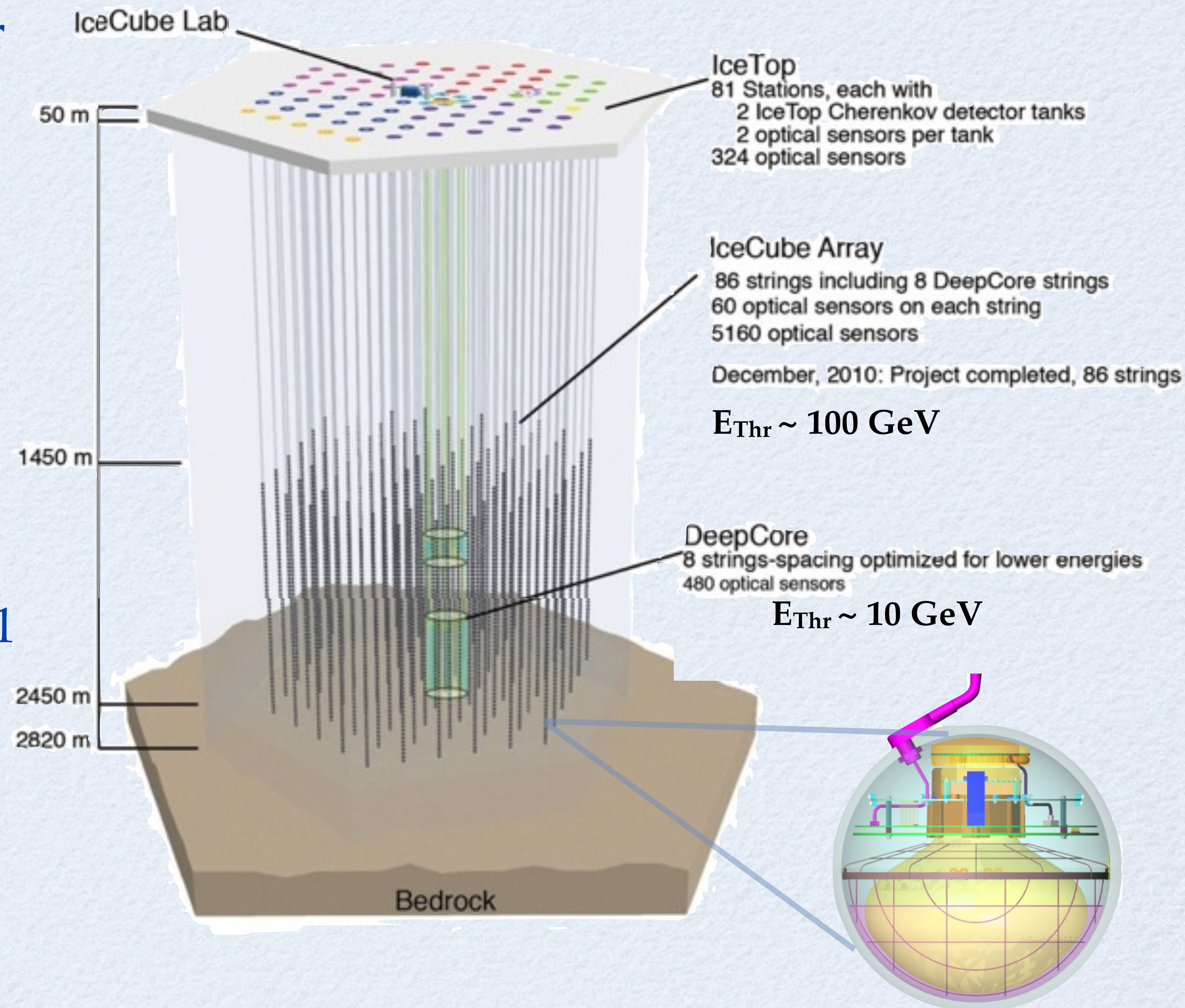
The IceCube Neutrino Telescope

- Gigaton Neutrino Detector at the Geographic South Pole
- 5160 Digital optical modules distributed over 86 strings
- Completed in December 2010, start of data taking with full detector May 2011
- Data acquired during the construction phase has been analysed



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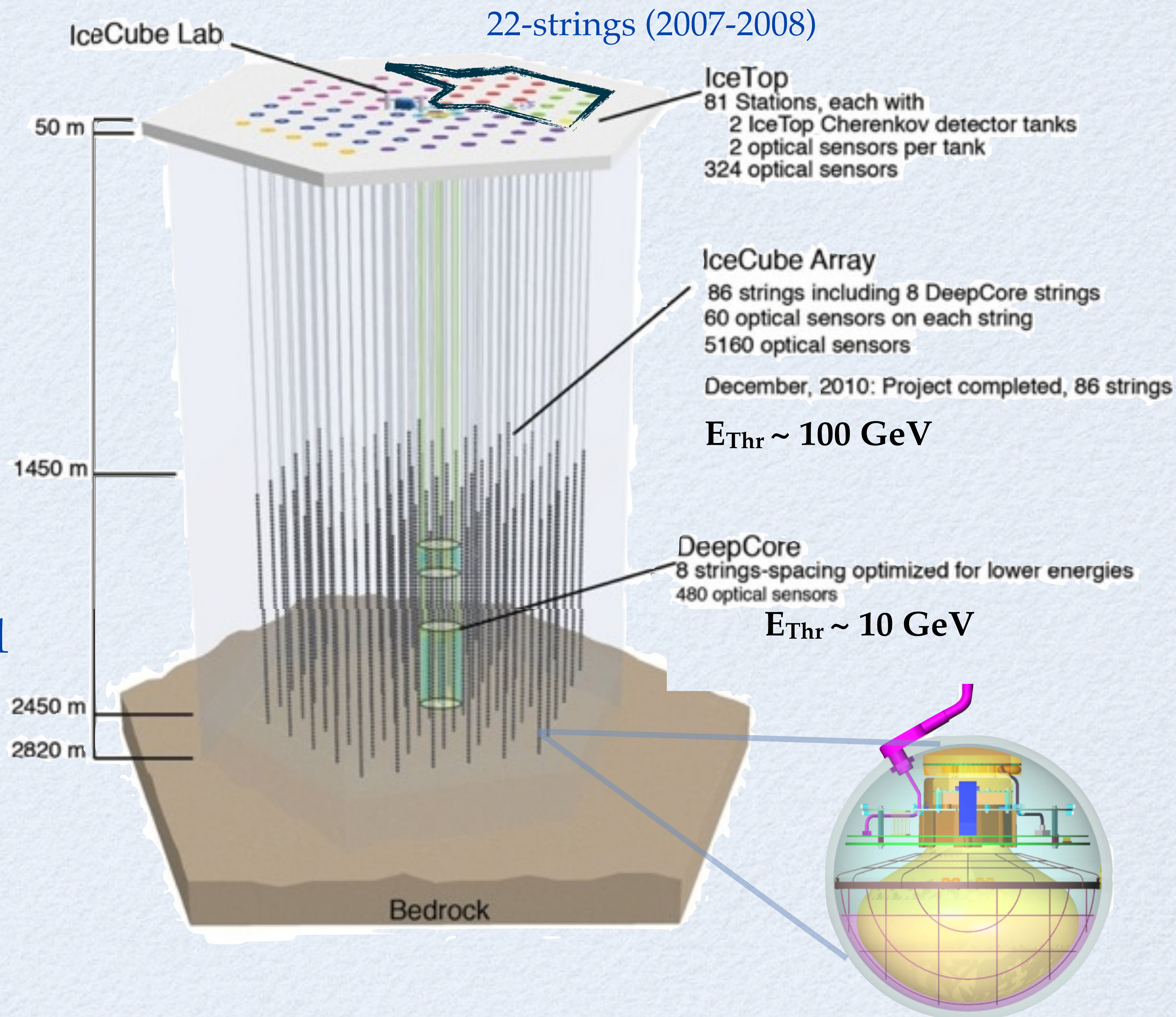

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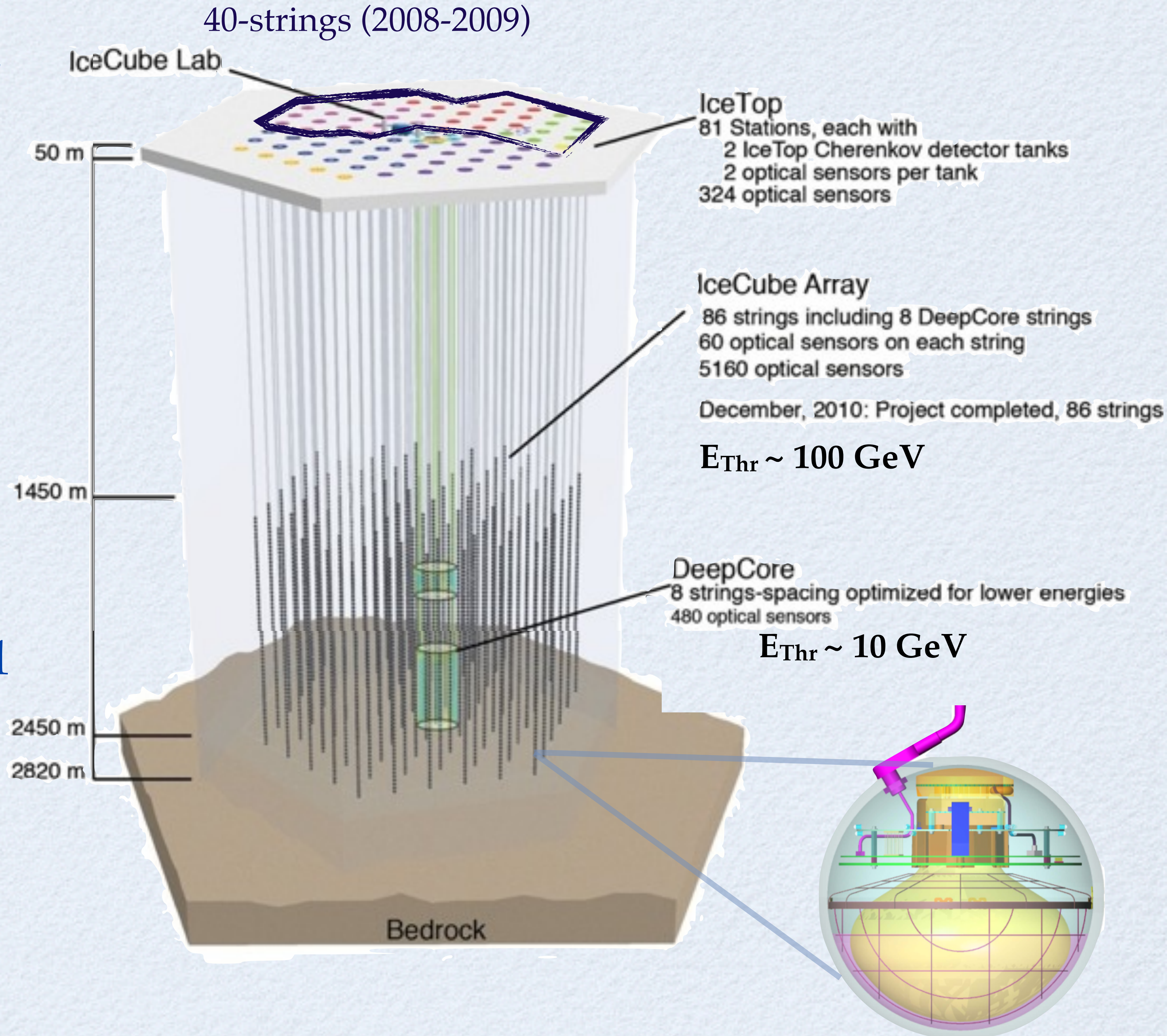

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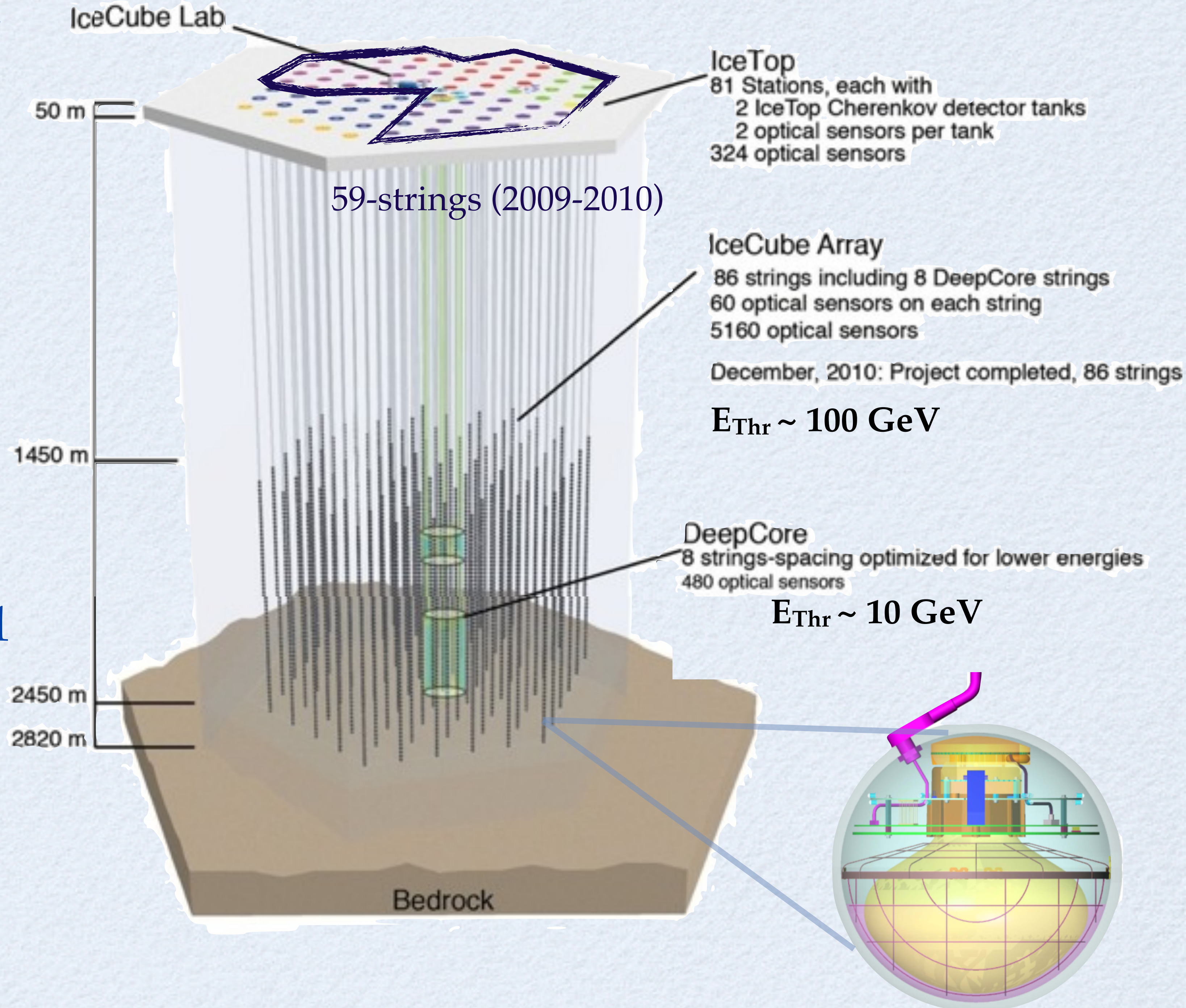

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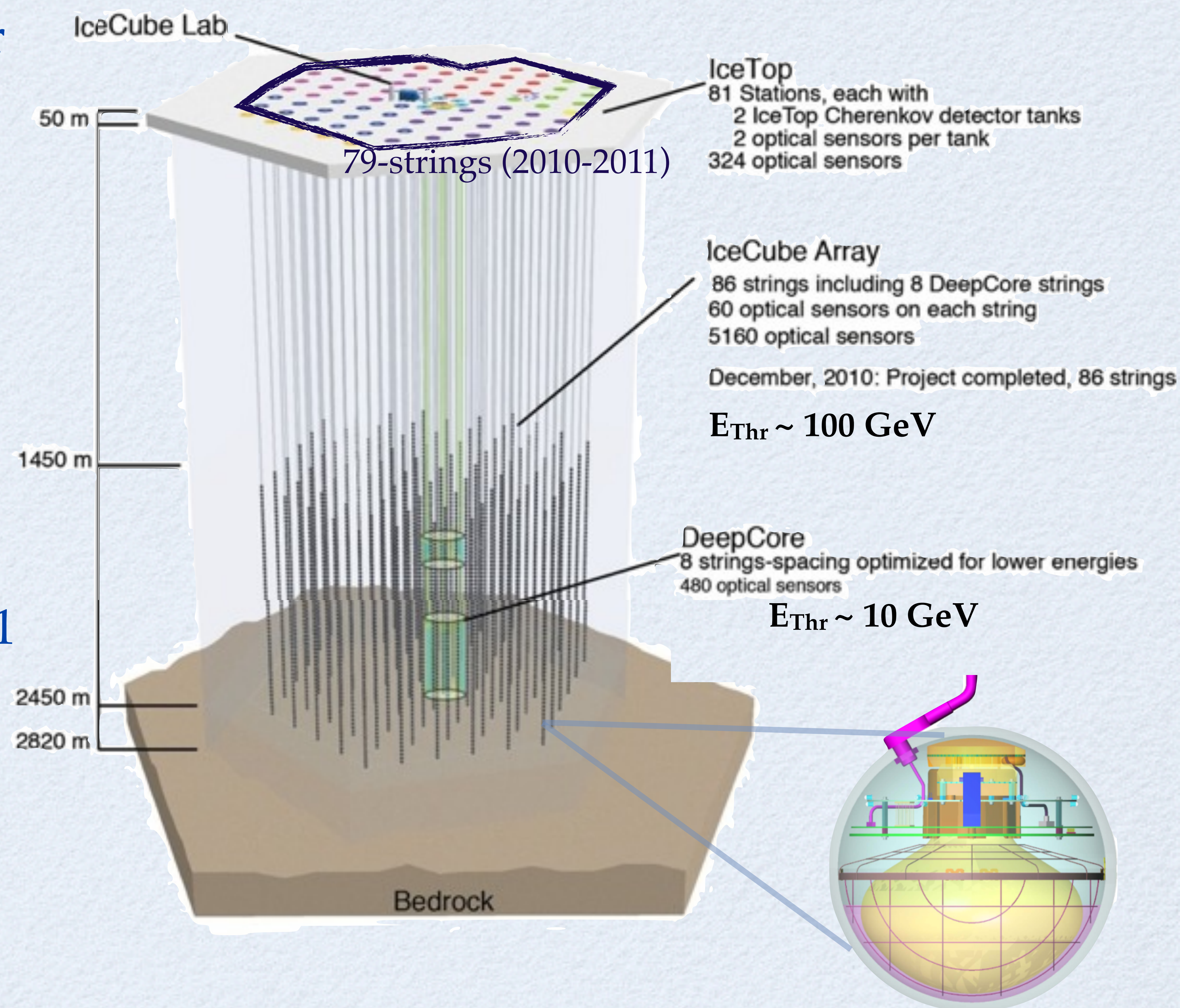

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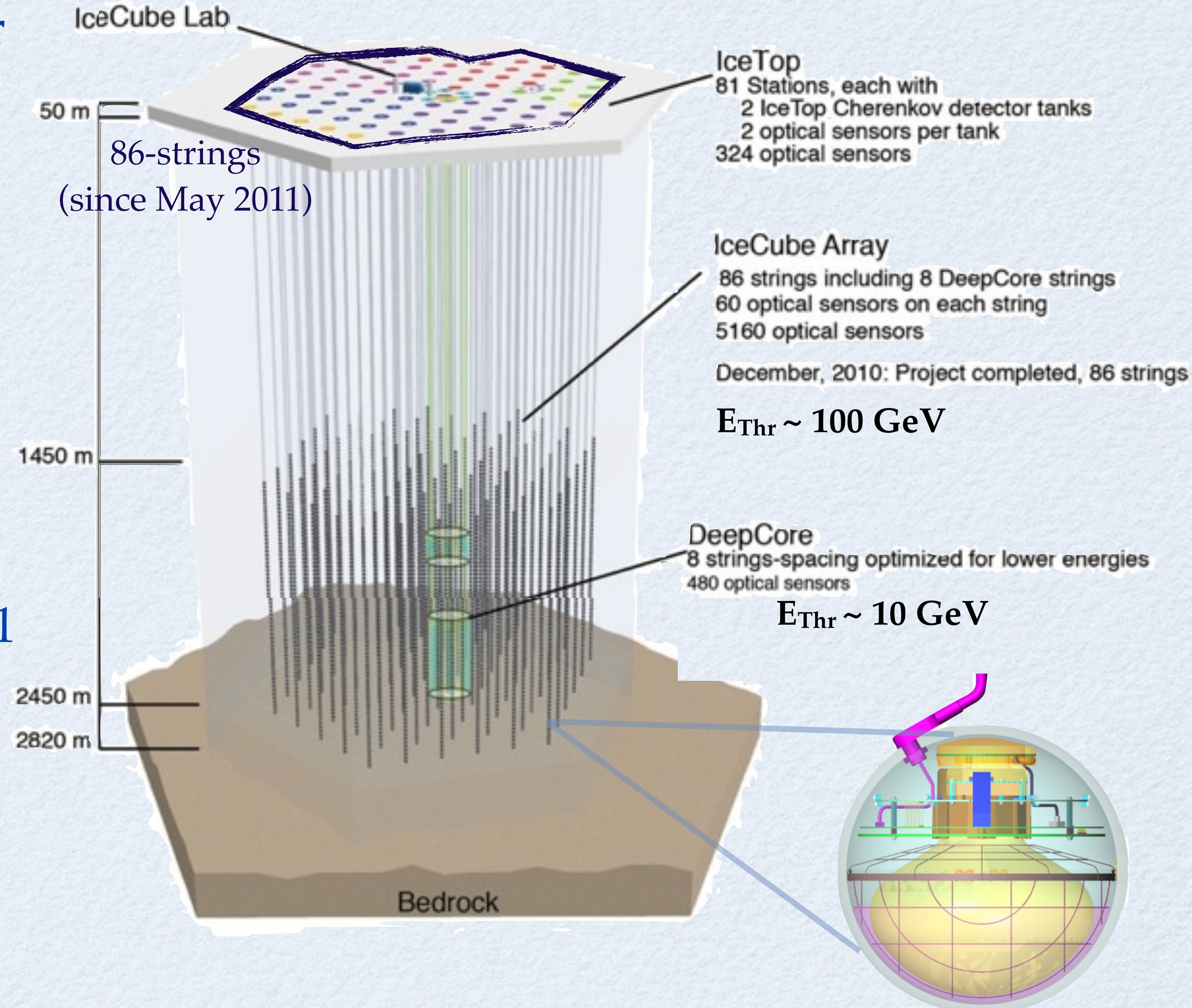

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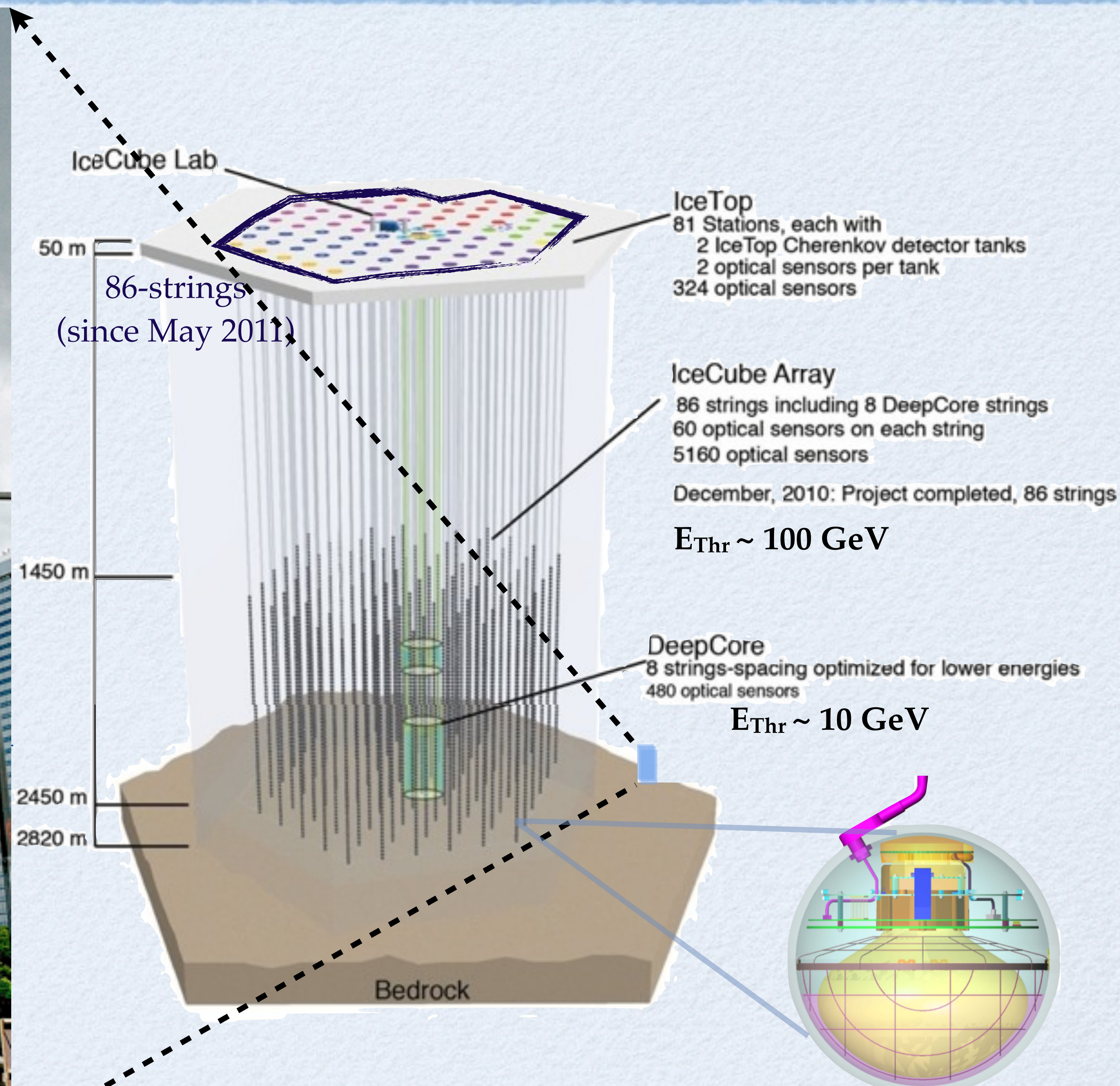
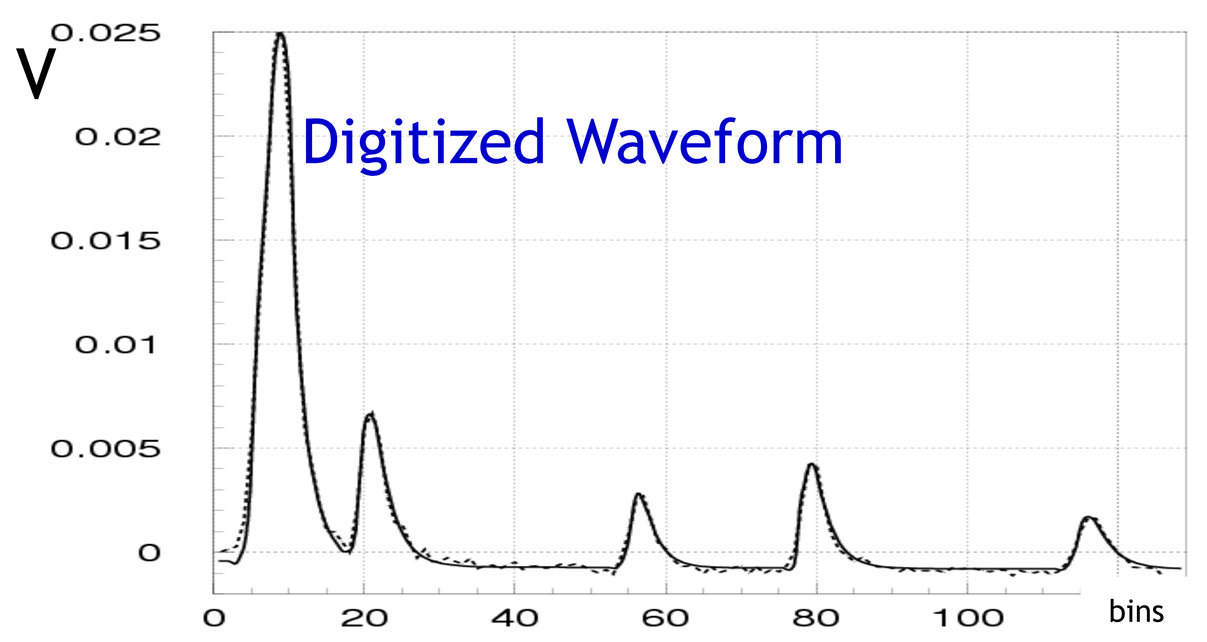


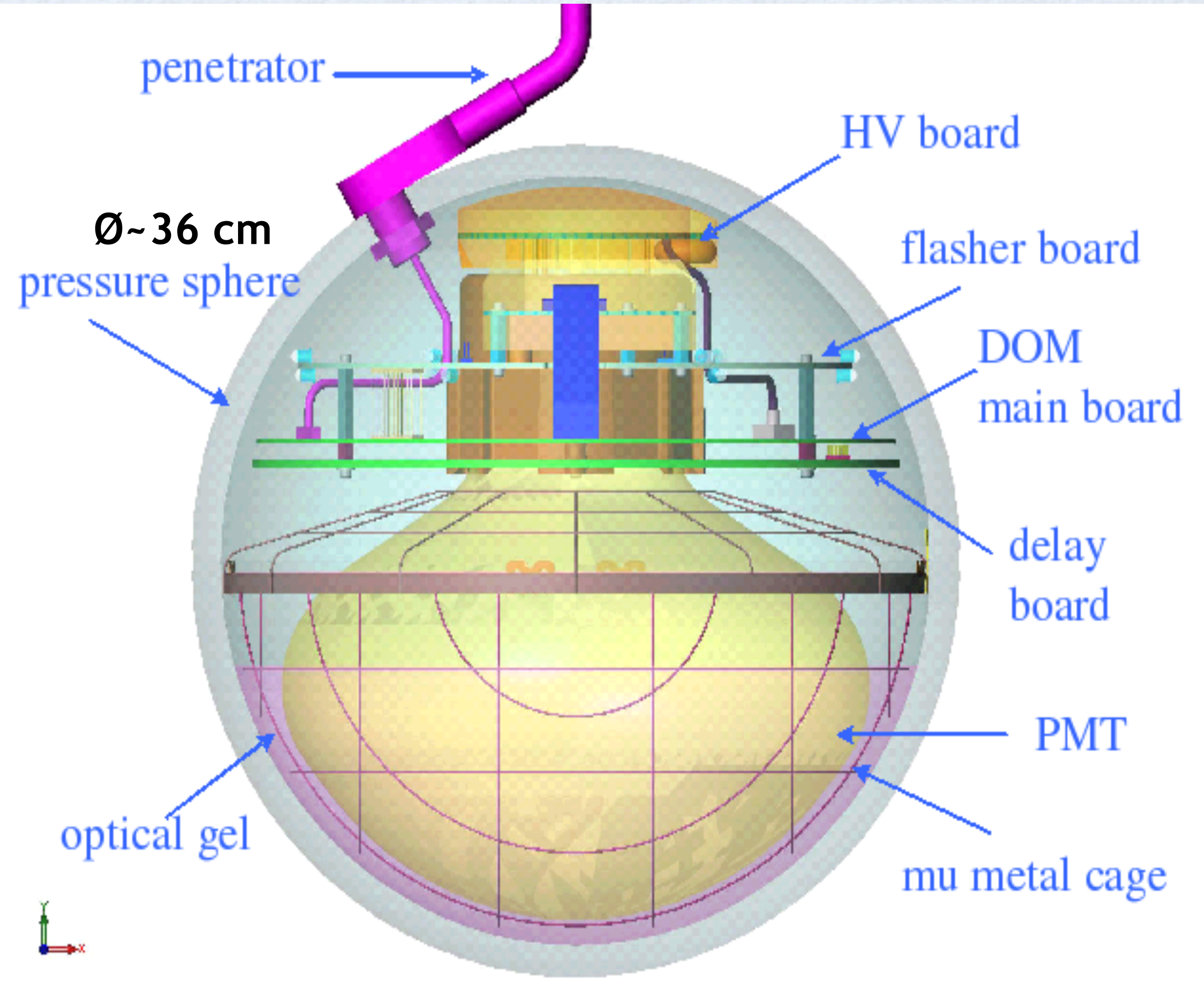
Digital Optical Module (DOM)

Measure individual photon arrival time:

- 2 ping-ponged four-channel ATWDs:
  - Analog Transient Waveform Digitizer
  - 200-700 Megasamples/s
  - 400 ns range
  - 400 pe / 15 ns
- fADC (fast 'ADC'):
  - 40 Megasamples/s
  - 6.4 μs range

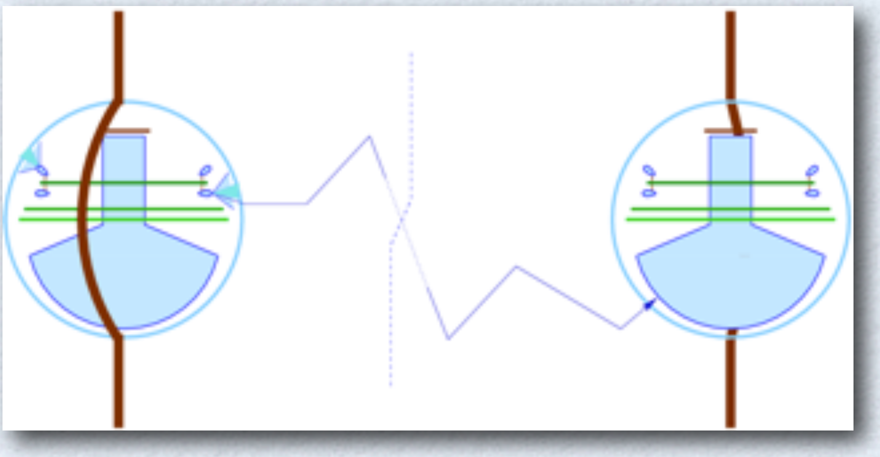


10 inch Hamamatsu PMT (R-7081-02)

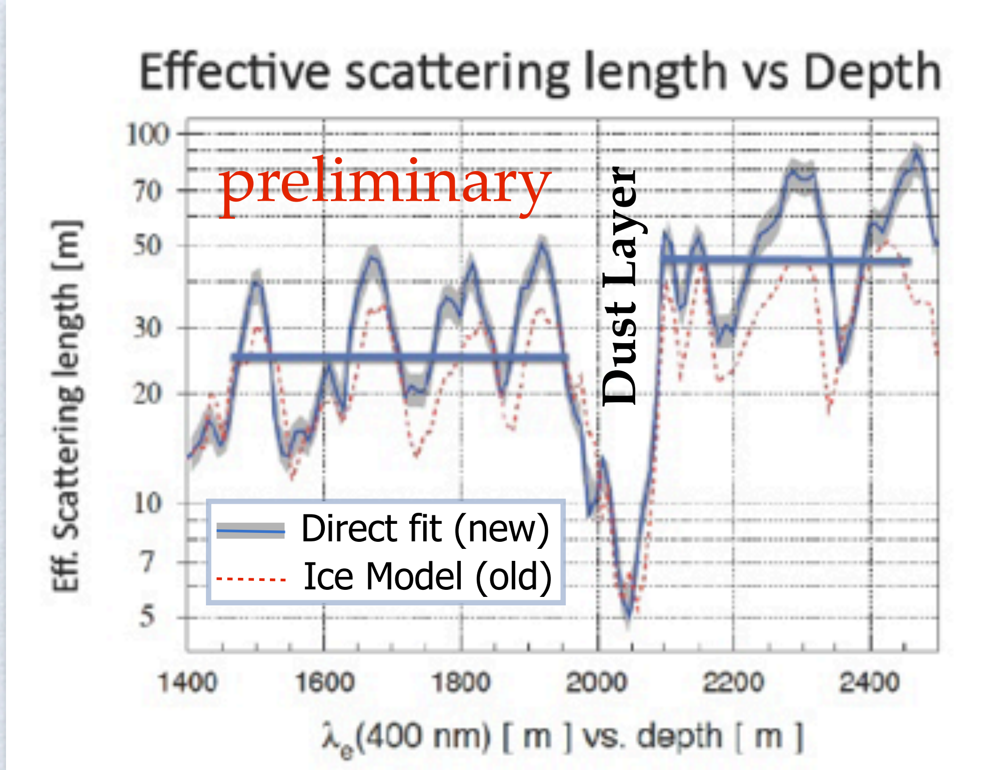


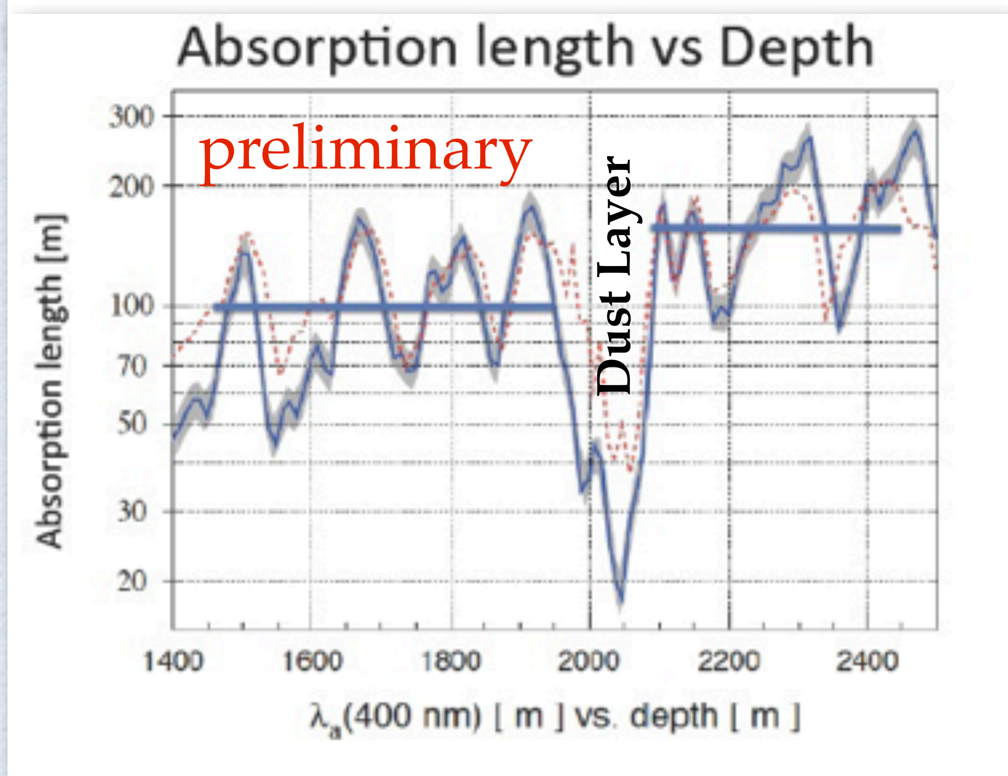
- Dark Noise rate ~ 350 Hz
- Local Coincidence rate ~ 15 Hz
- Deadtime < 1%
- Timing resolution ≤ 2 ns

Ice Properties



- Detailed understanding of the ice crucial to model light propagation in the detector medium
- Combination of in-situ measurements and LED flashers resulted in detailed knowledge of ice properties
- Newly deployed color LED flashers and ice camera will improve results further
- Ice below 2100m shows most favorable properties, making it an excellent detector medium





Signals in IceCube

South Pole

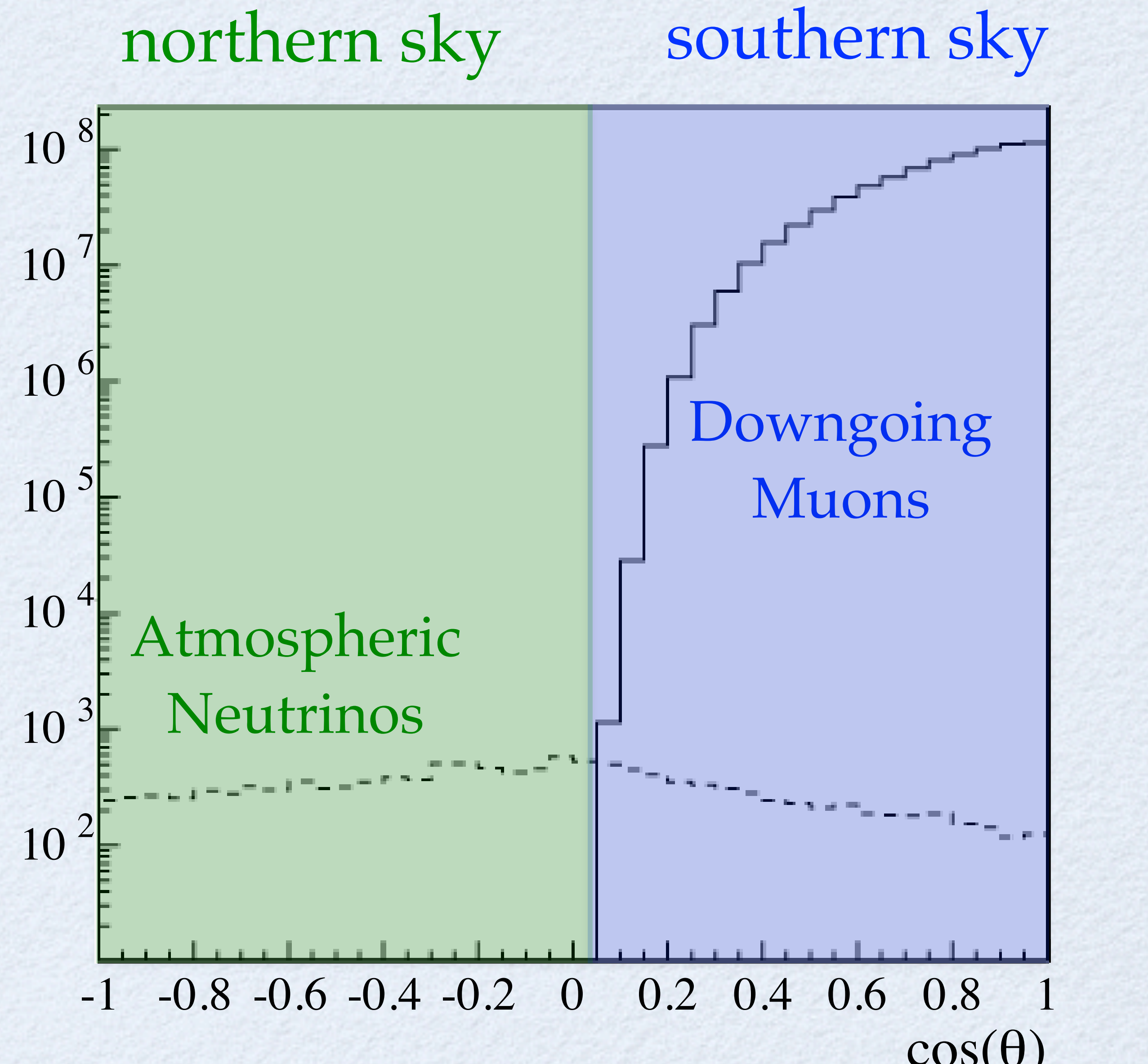
IceCube Depth: 1.5-2.5 km

North Pole

- Up-going events can be used to obtain “clean” neutrino sample
  - Earth is used as muon filter
- Atmospheric neutrinos create irreducible neutrino background to extra terrestrial neutrino fluxes

$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons

- $\pi^{+} \rightarrow \mu^{+} \nu_{\mu} \rightarrow e^{+} \nu_{e} \nu_{\mu} \nu_{\mu}$



Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

Signals in IceCube

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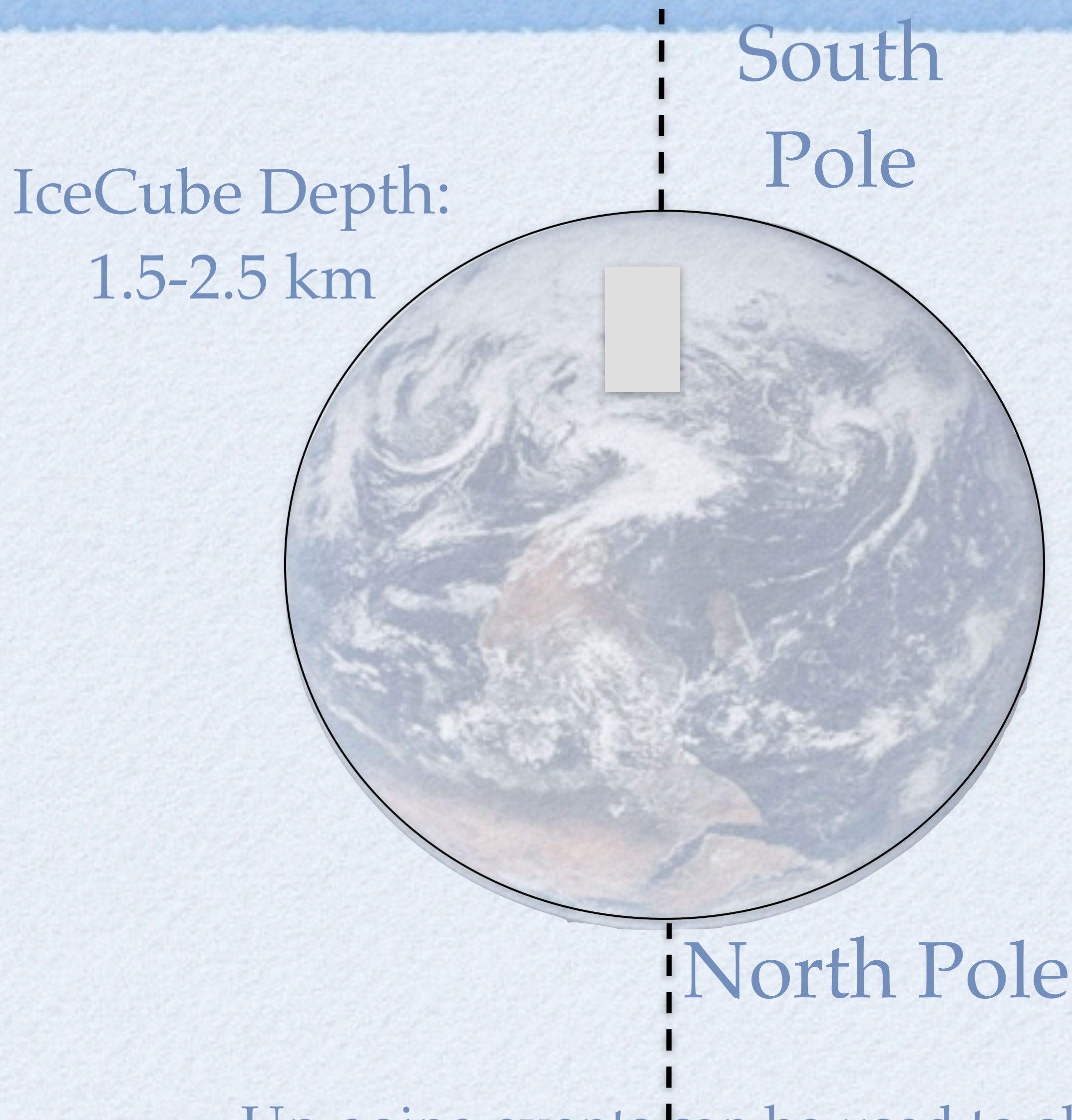

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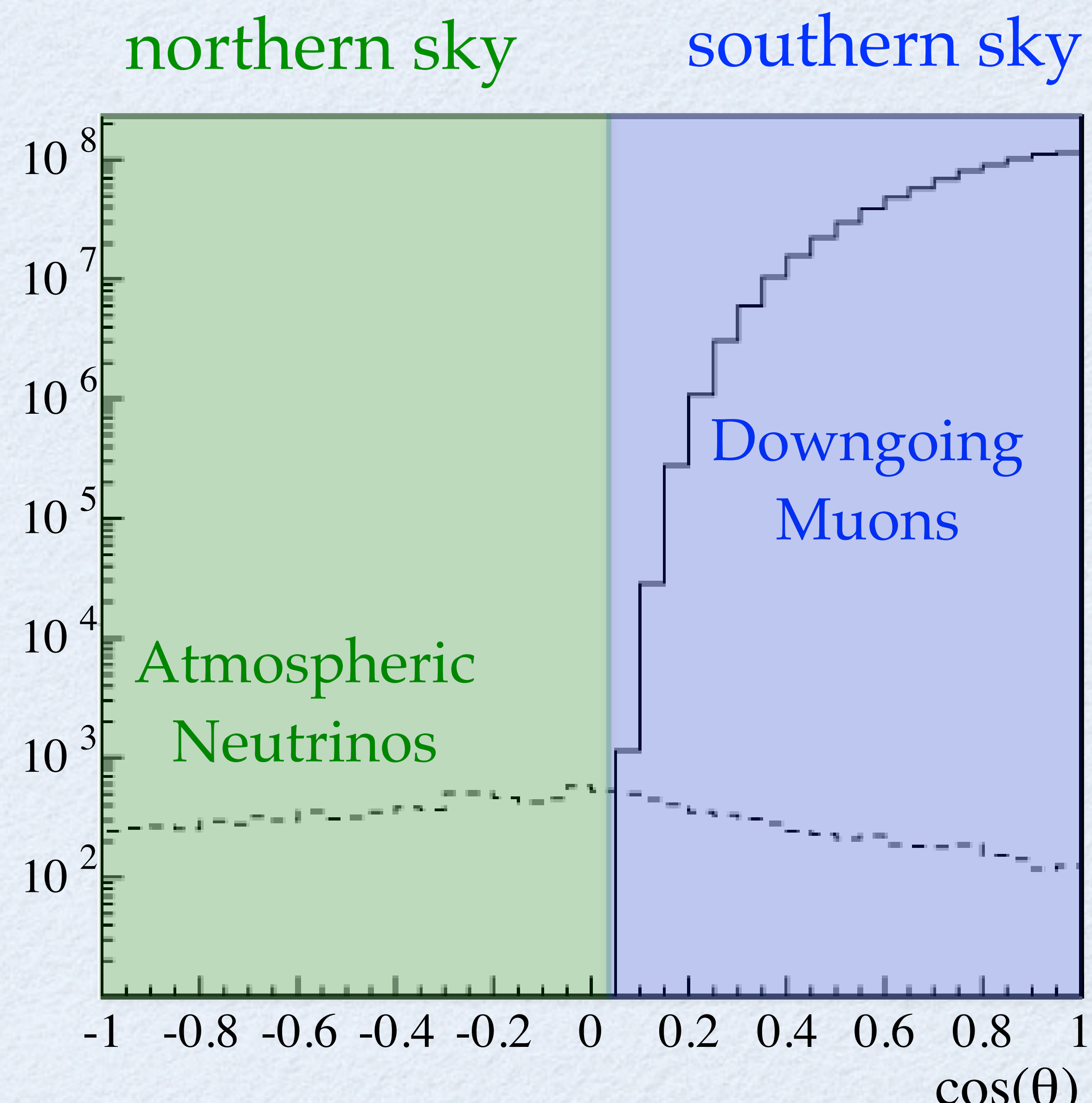

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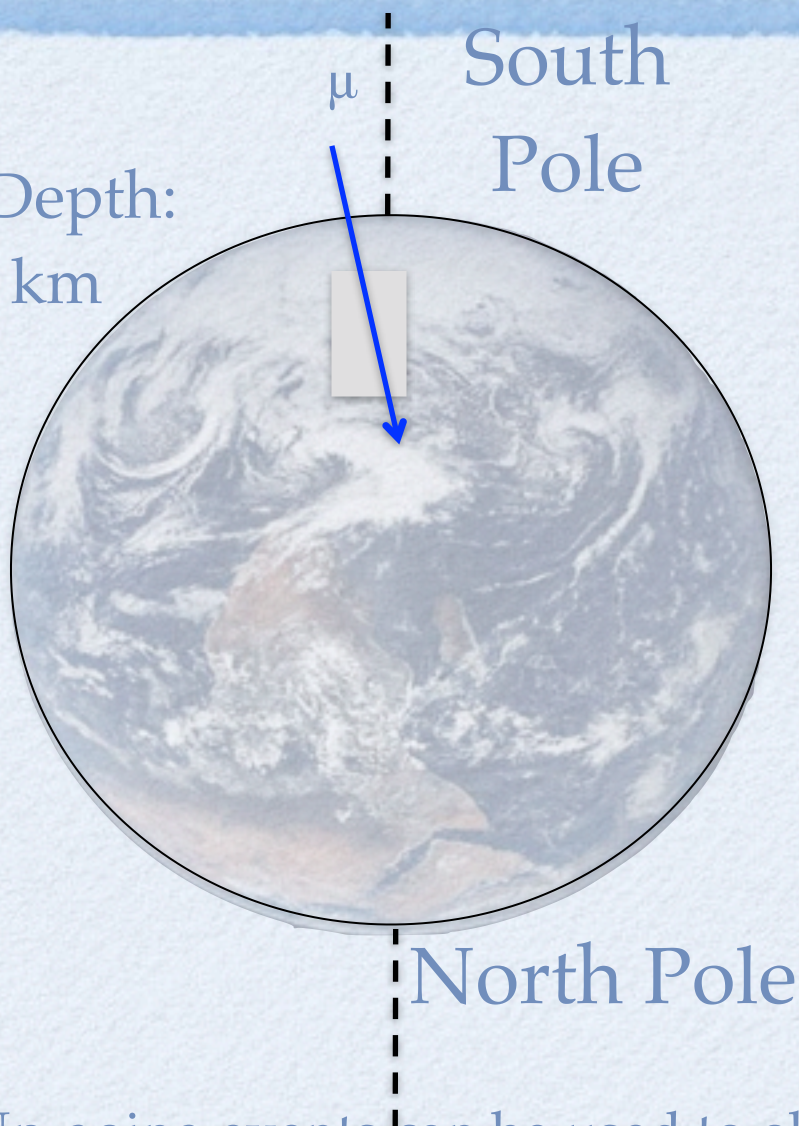

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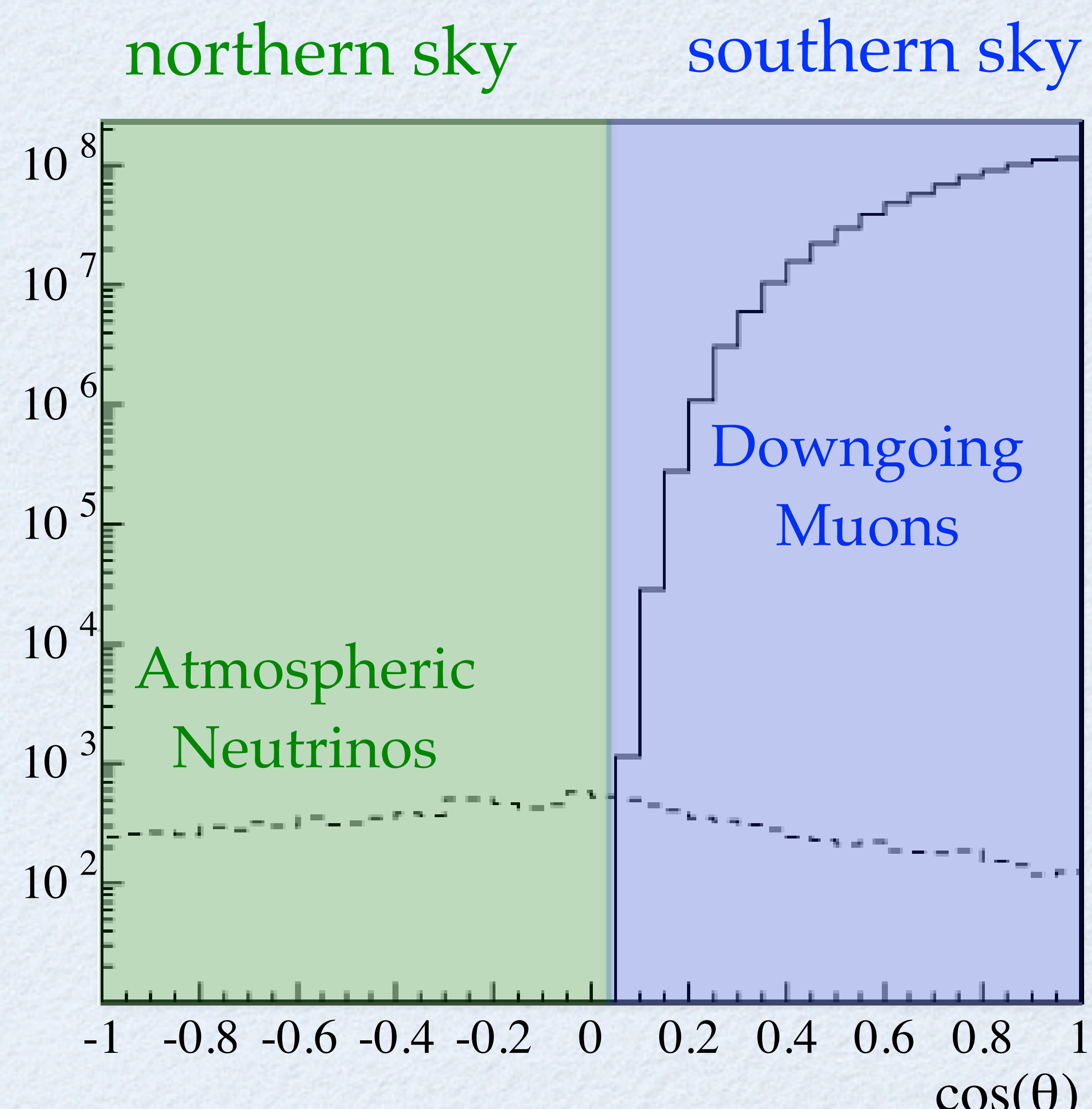

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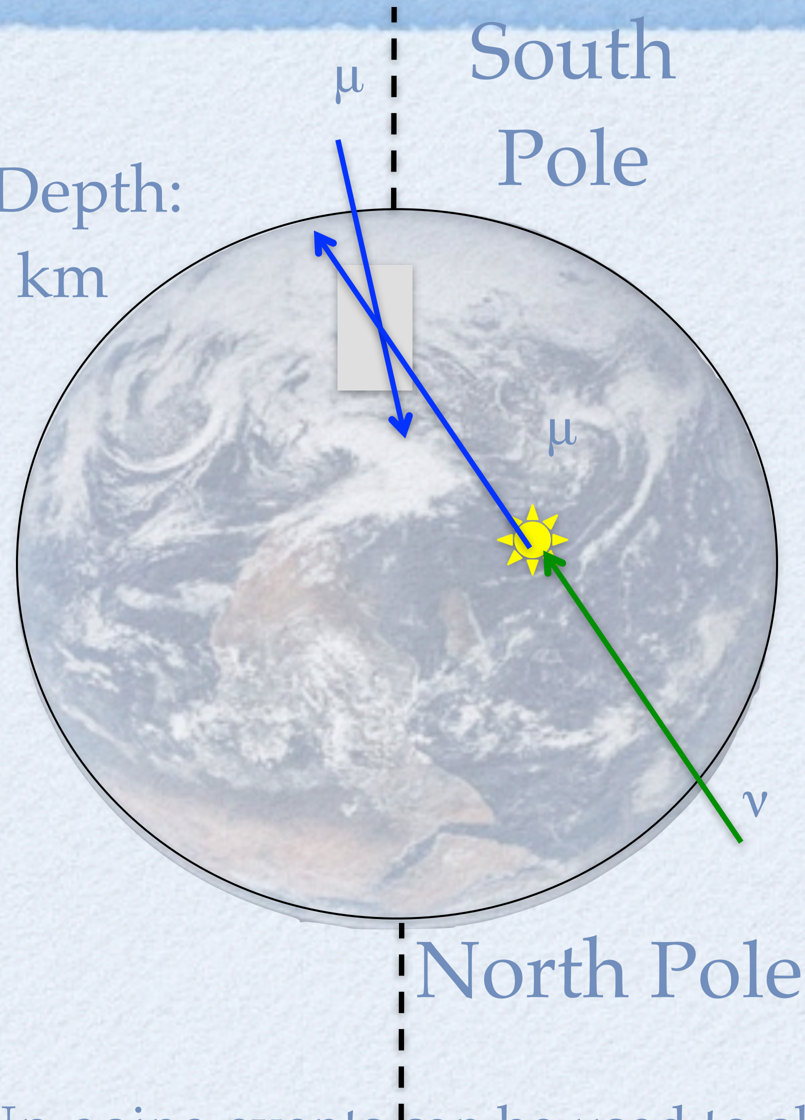

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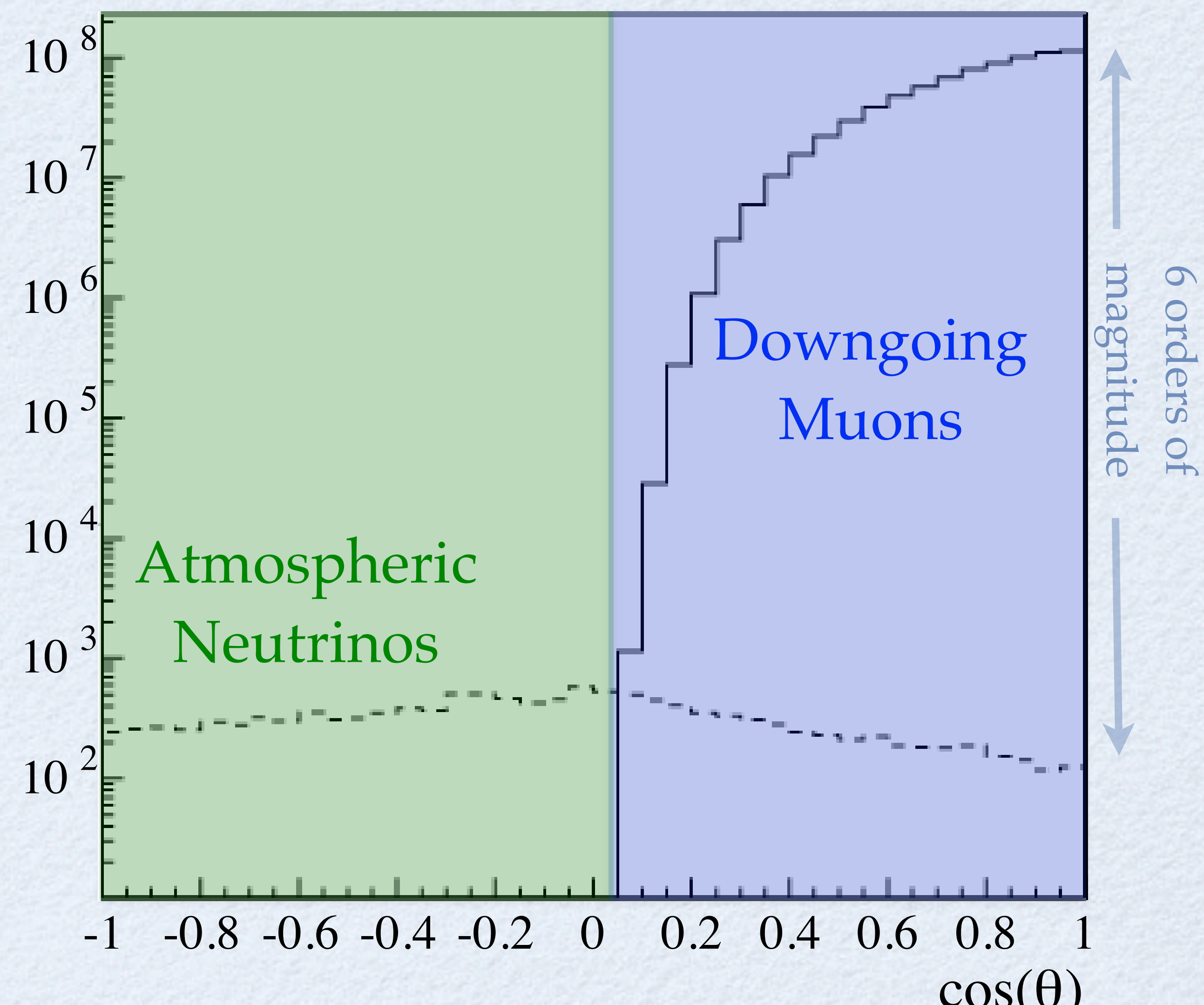

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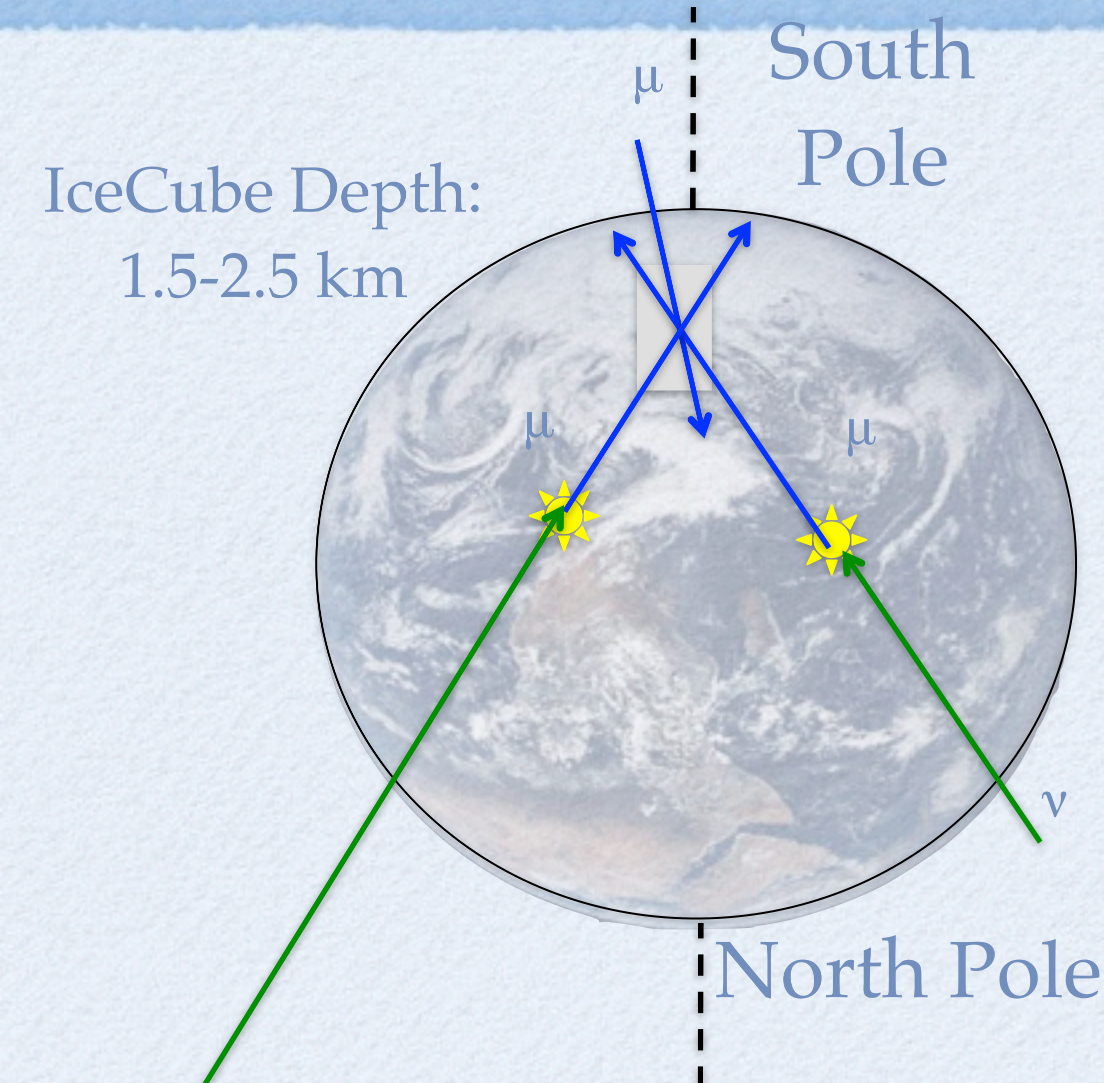
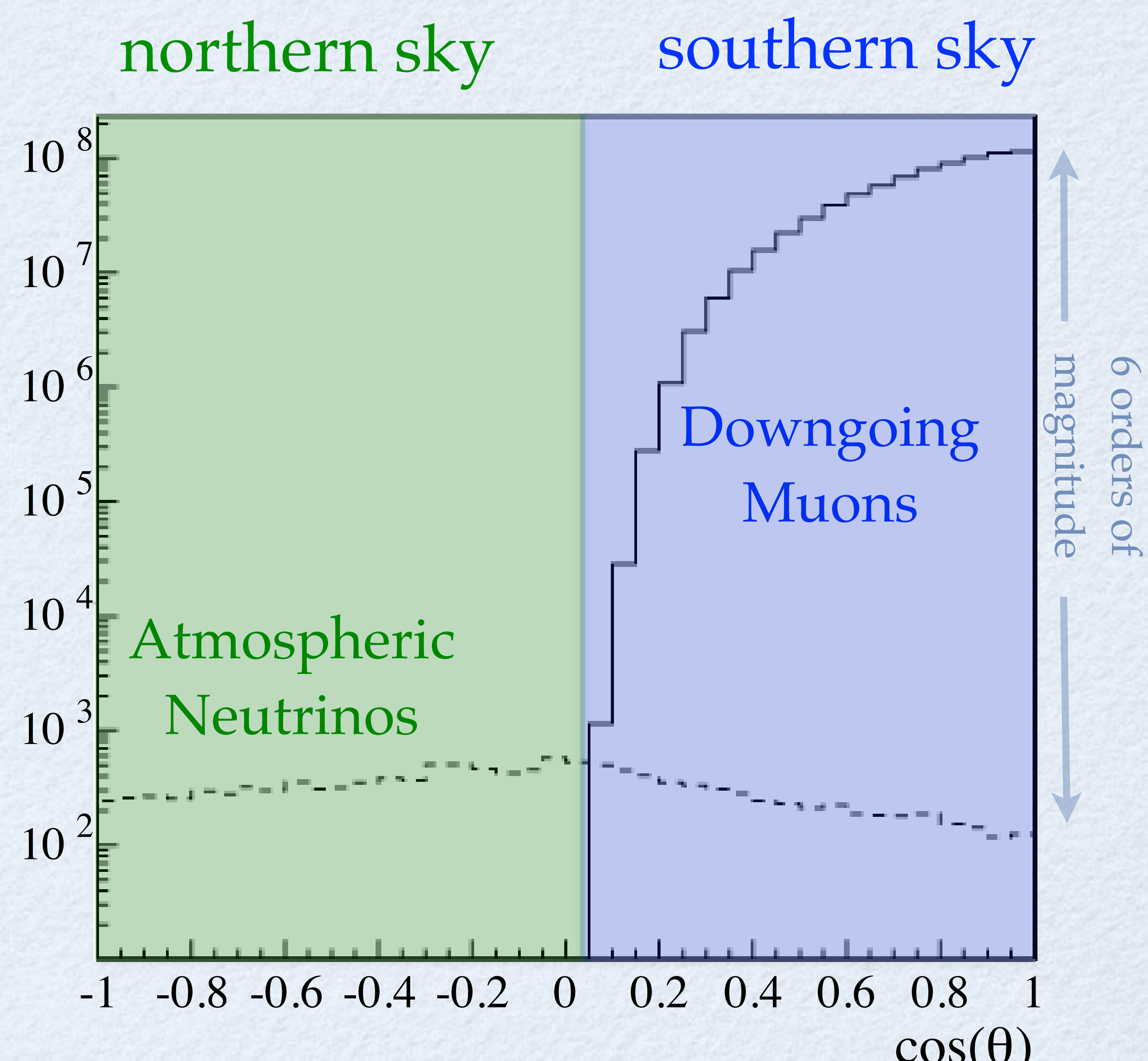
Signals in IceCube

IceCube Depth: 1.5-2.5 km



p + A → $\pi^\pm$ ($K^\pm$) + other hadrons

- π^+ → $\mu^+ \nu_\mu$ → $e^+ \nu_e \nu_\mu \nu_\mu$



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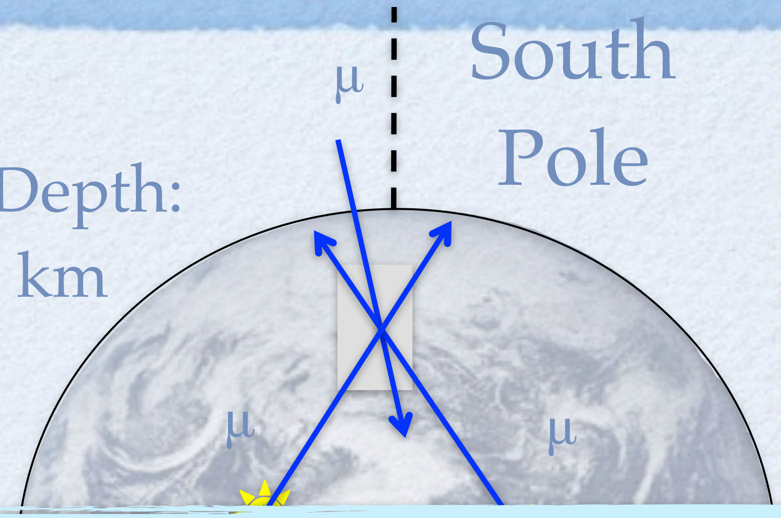
Signals in IceCube

ICECUBE

IceCube Depth: 1.5-2.5 km



$p + A \rightarrow \pi^{\pm} (K^{\pm})$ + other hadrons

- $\pi^+ \rightarrow \mu^+ \nu_\mu \rightarrow e^+ \nu_e \nu_\mu \nu_\mu$

Atmospheric muons ~ 10^{11} / year
Atmospheric neutrinos ~ 10^5 / year
Astrophysical neutrinos ~ ?? / year

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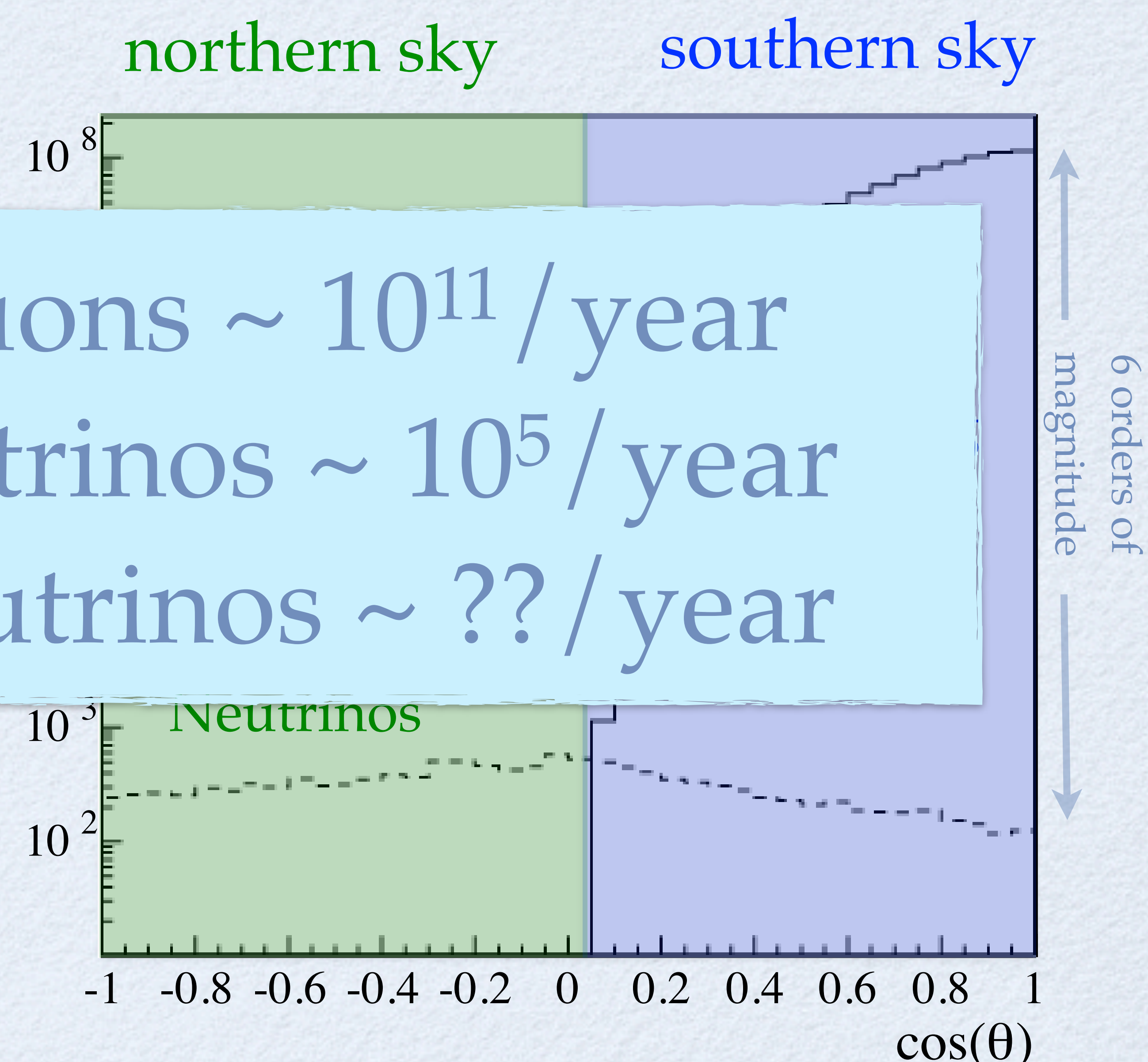
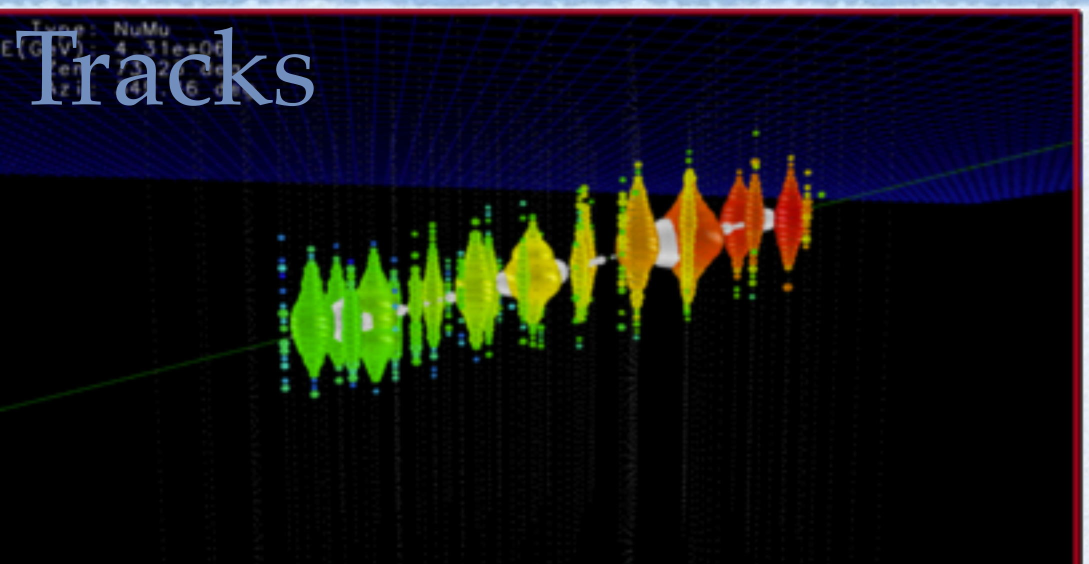
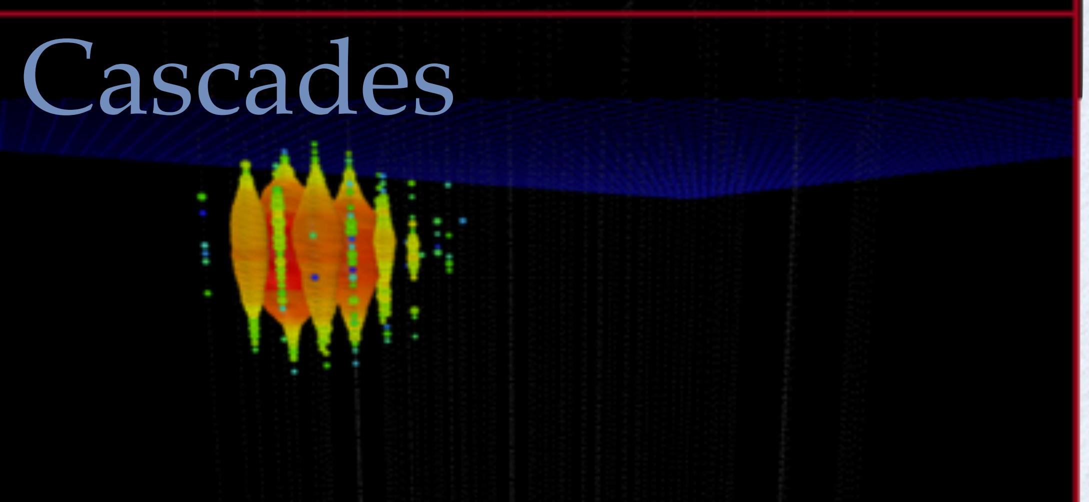
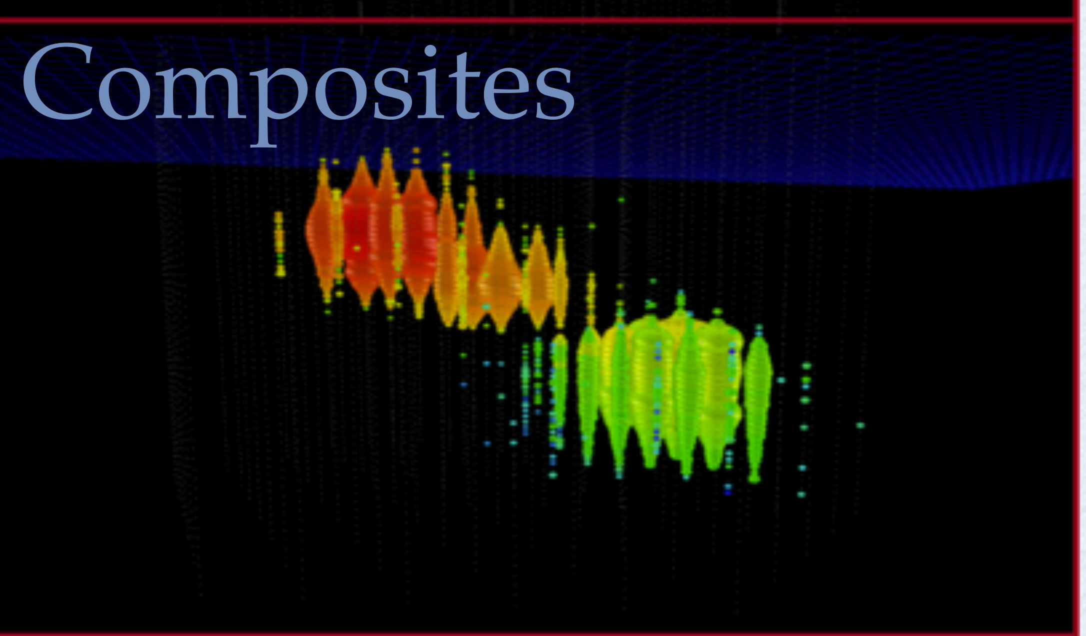


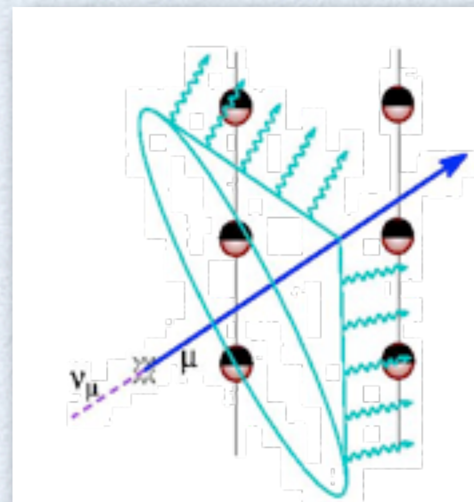
Atmospheric backgrounds for extra-terrestrial neutrino searches at the depth of IceCube

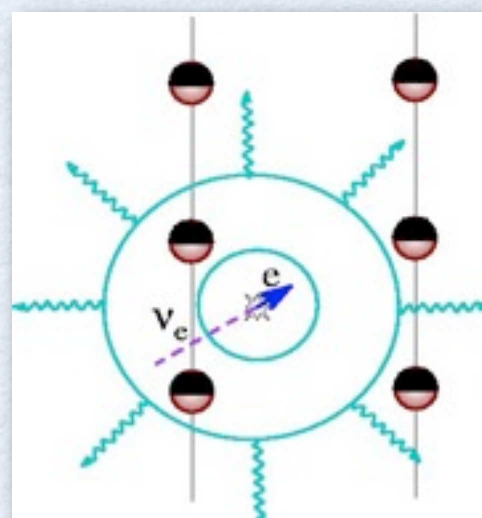
Neutrino Event Signatures









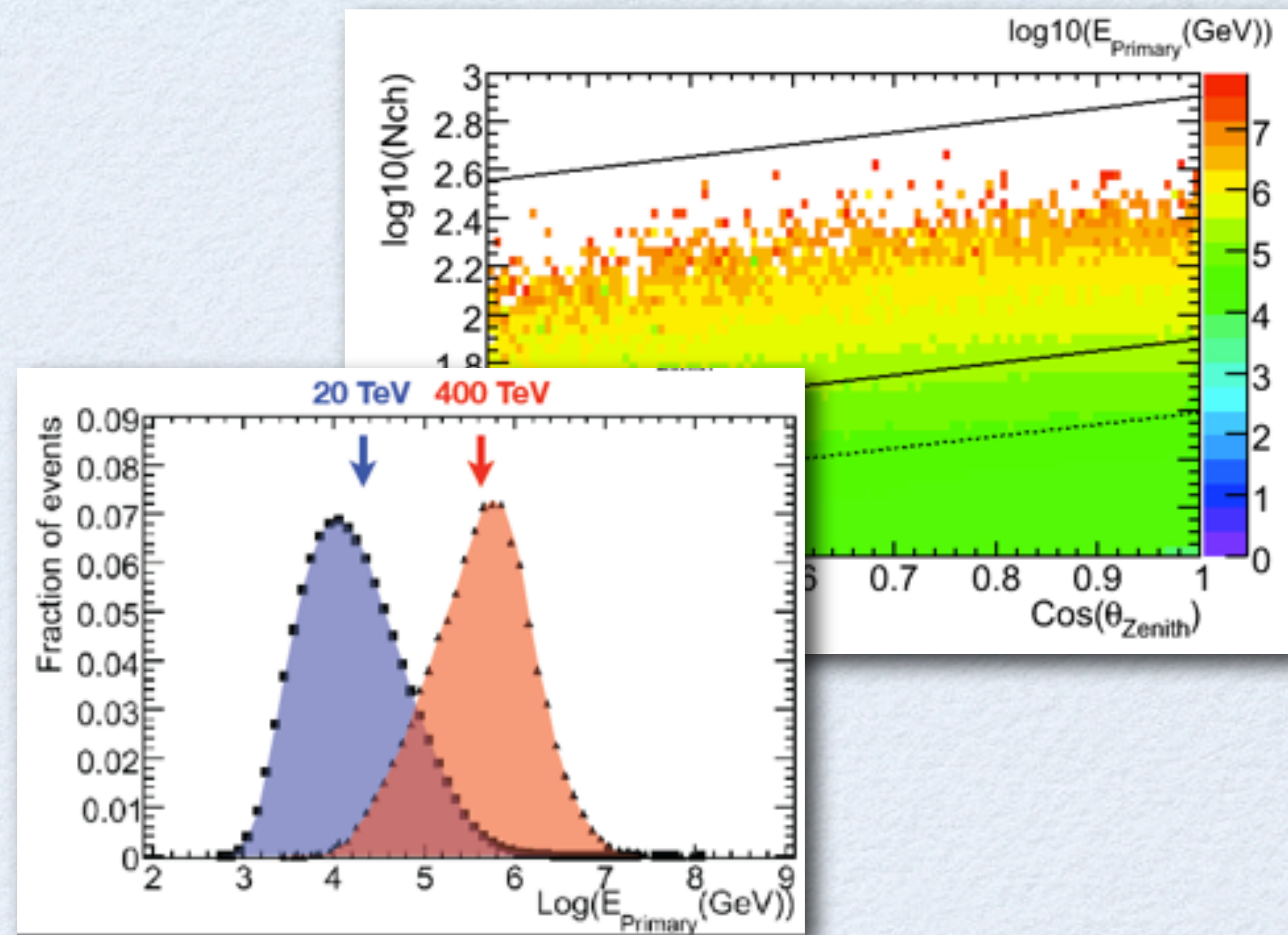


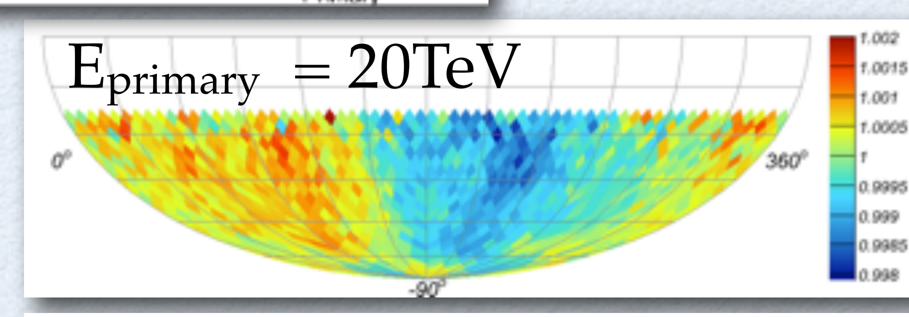
- Tracks
  - Down-going atm. muons
  - $\nu_\mu + N \rightarrow \mu + X$
  - pointing resolution ~1°
- Cascades
  - electro-magnetic and hadronic
  - $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
  - $\nu_{e,\mu,\tau} + N \rightarrow \nu_{e,\mu,\tau} + X$
  - good energy resolution
- Composites
  - tau double bangs, lollipop
  - starting tracks
  - good directional and energy resolution

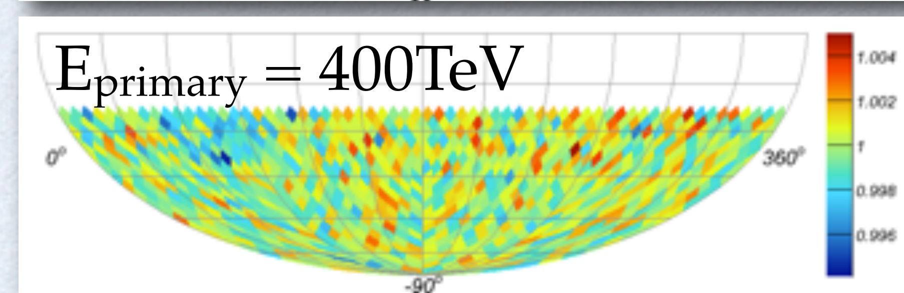
Cosmic Ray Anisotropy

arXiv:1109.1017
Astrophys.J. 718 (2010) L194

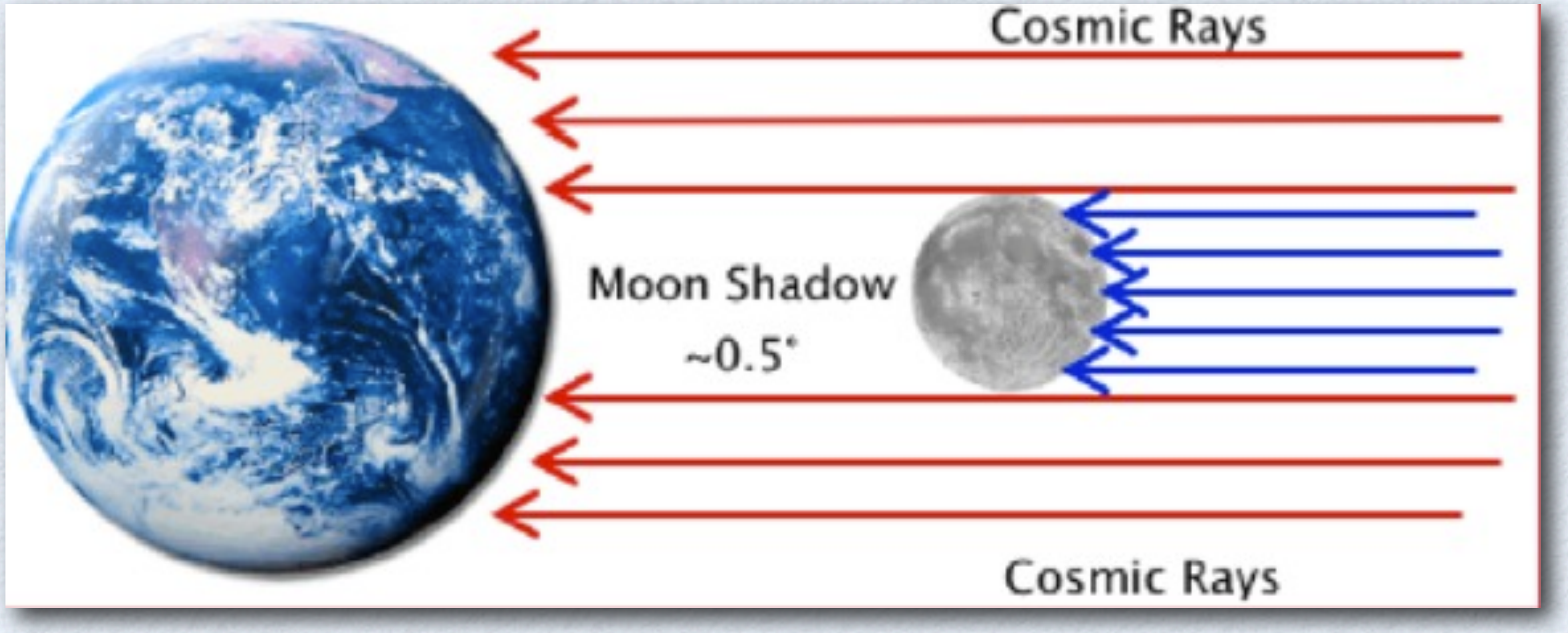
- An Anisotropies in the arrival direction of TeV (20TeV / 400TeV) cosmic rays have been observed
    - Wide angular scale range (10°-180°)
    - Strength in the 10^{-4}-10^{-3} range
- 20 TeV anisotropy matches that observed in the North
- Observation of anisotropy at 400 TeV (change in phase, size compared to 20 TeV)
- Preliminary results from IceTop at 400 TeV are consistent with IceCube results
- Origin of the anisotropy remains a mystery

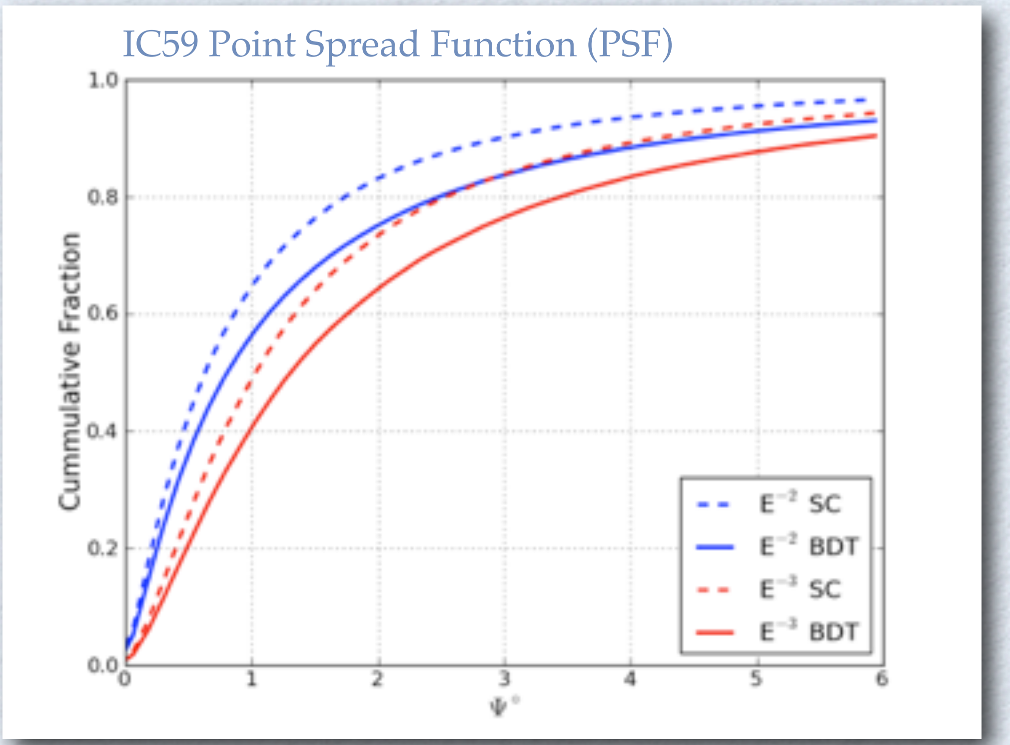


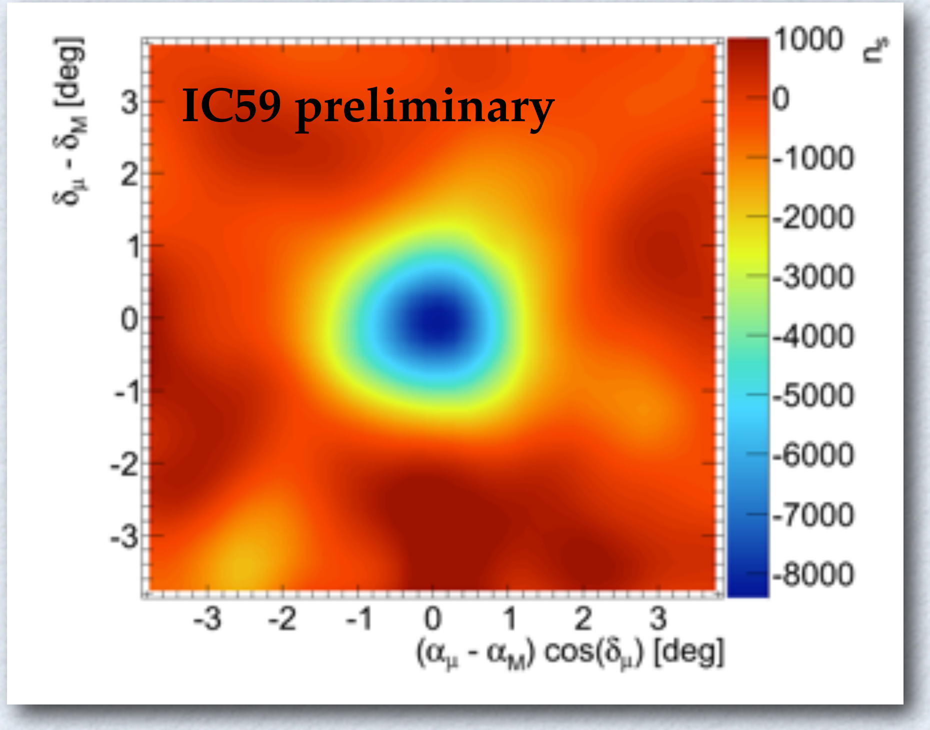




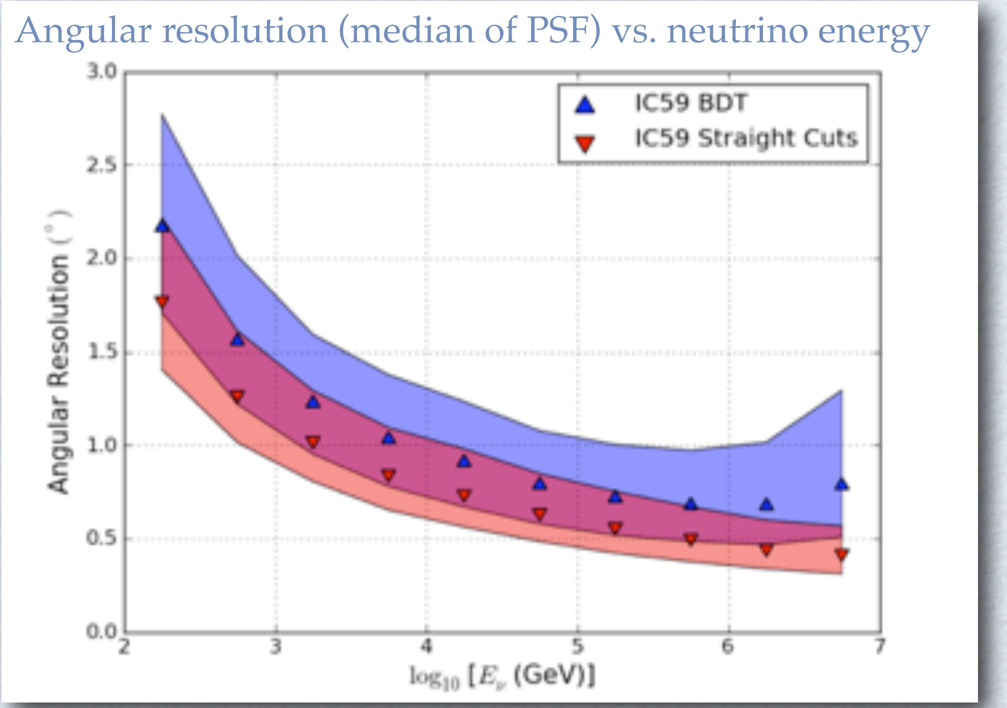
Muon Track Performance







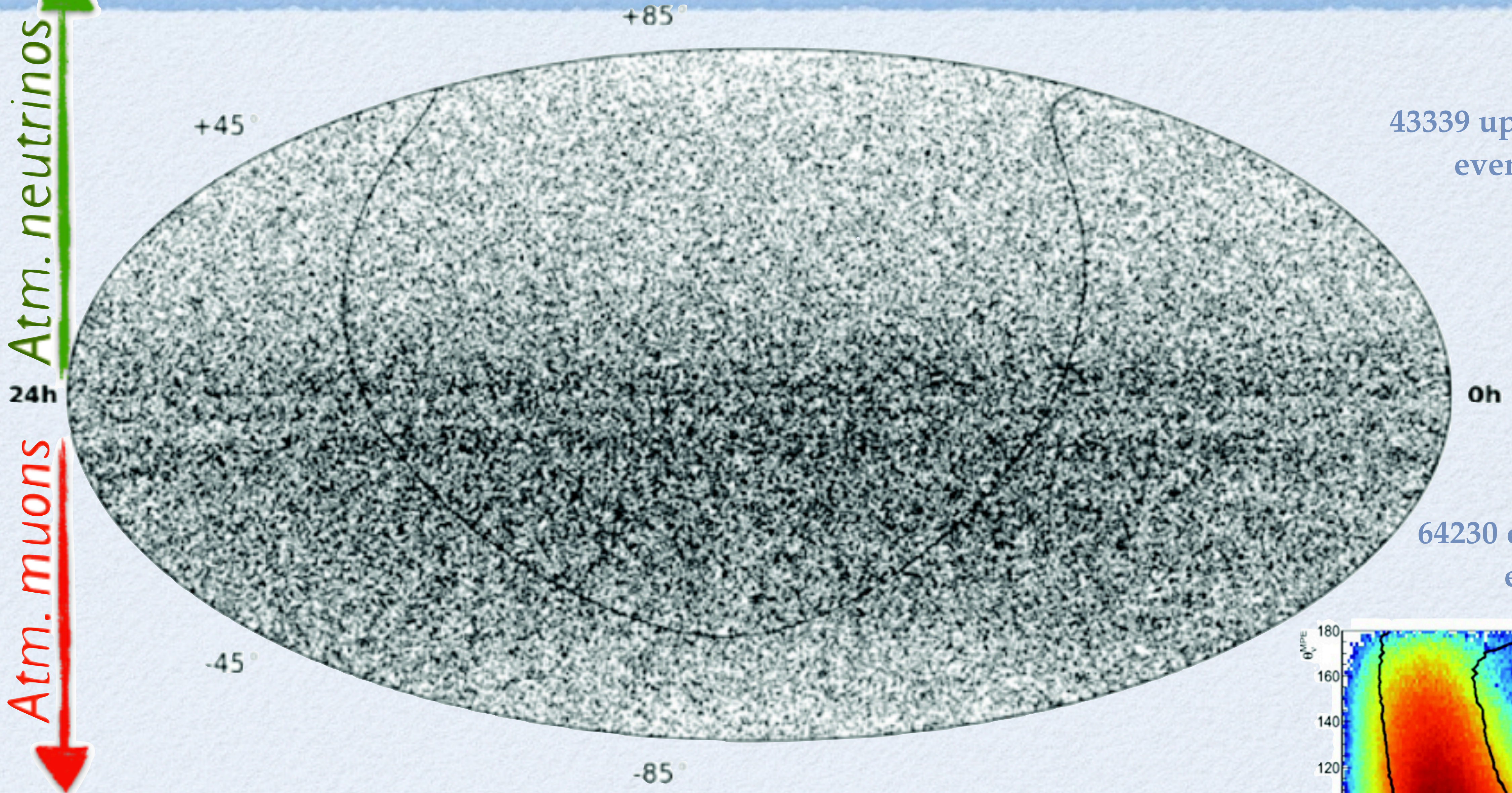
- Moon blocks cosmic rays, resulting in a deficit of down-ward going muons in the detector
- Using the 59-string this deficit has been observed 12σ significance
  - systematic pointing error <0.1°



Point Source Search

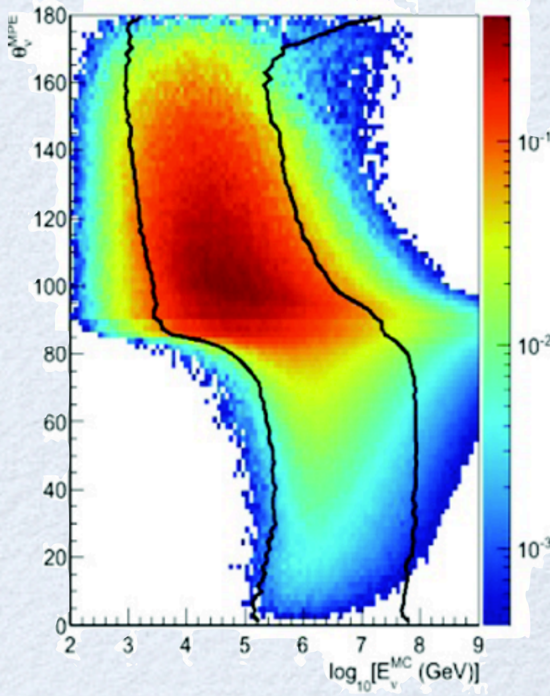
Atm. neutrinos

Atm. muons



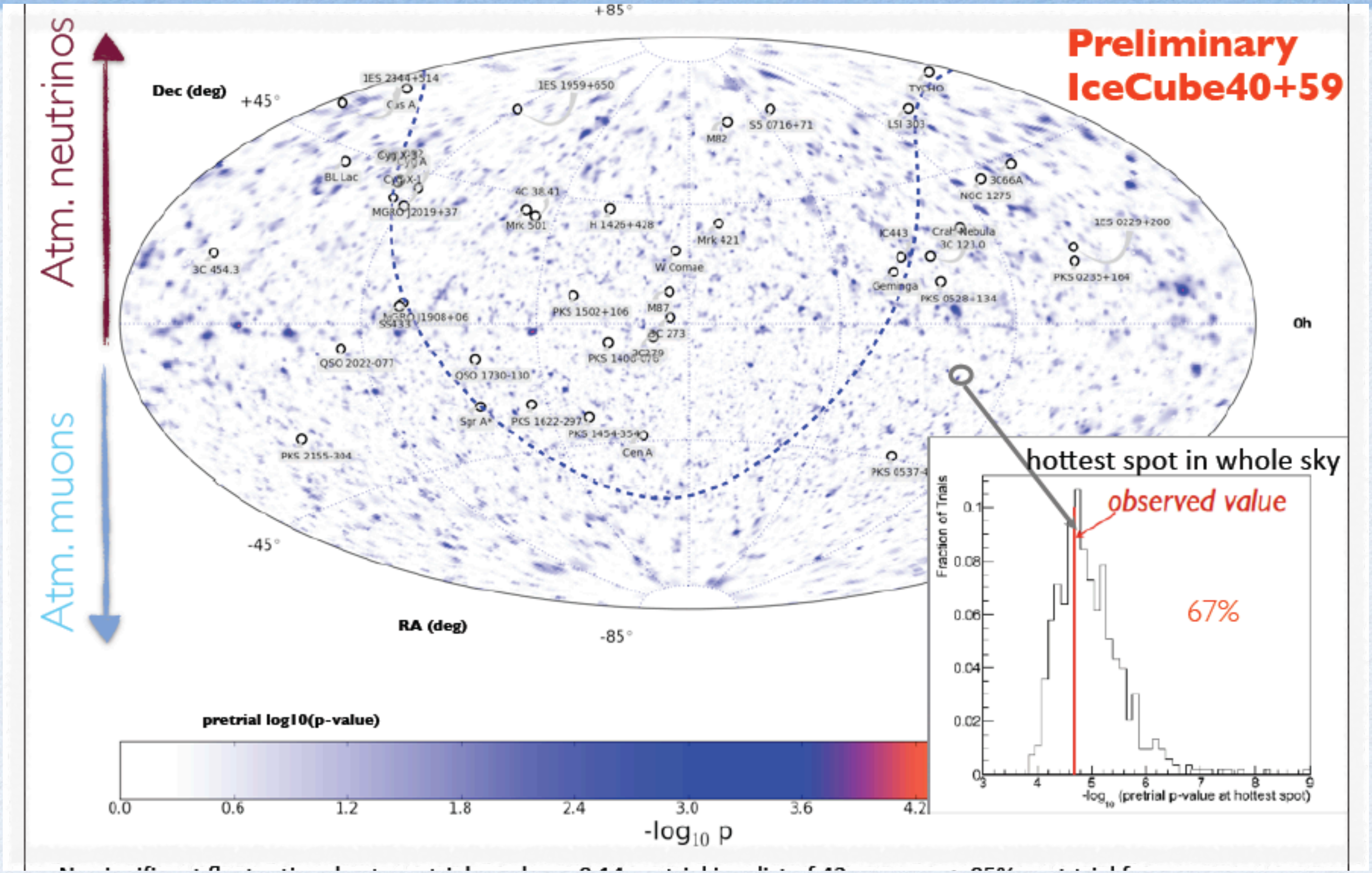
43339 up-going events

64230 down-going events



- Livetime: 375 days (40-string) + 348 (59-string)
- Total Events - 37290 (40-string) + 70279 (59-string)

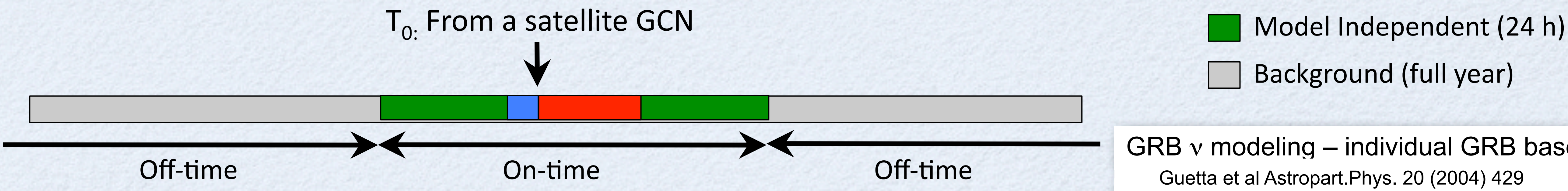
Point Source Search

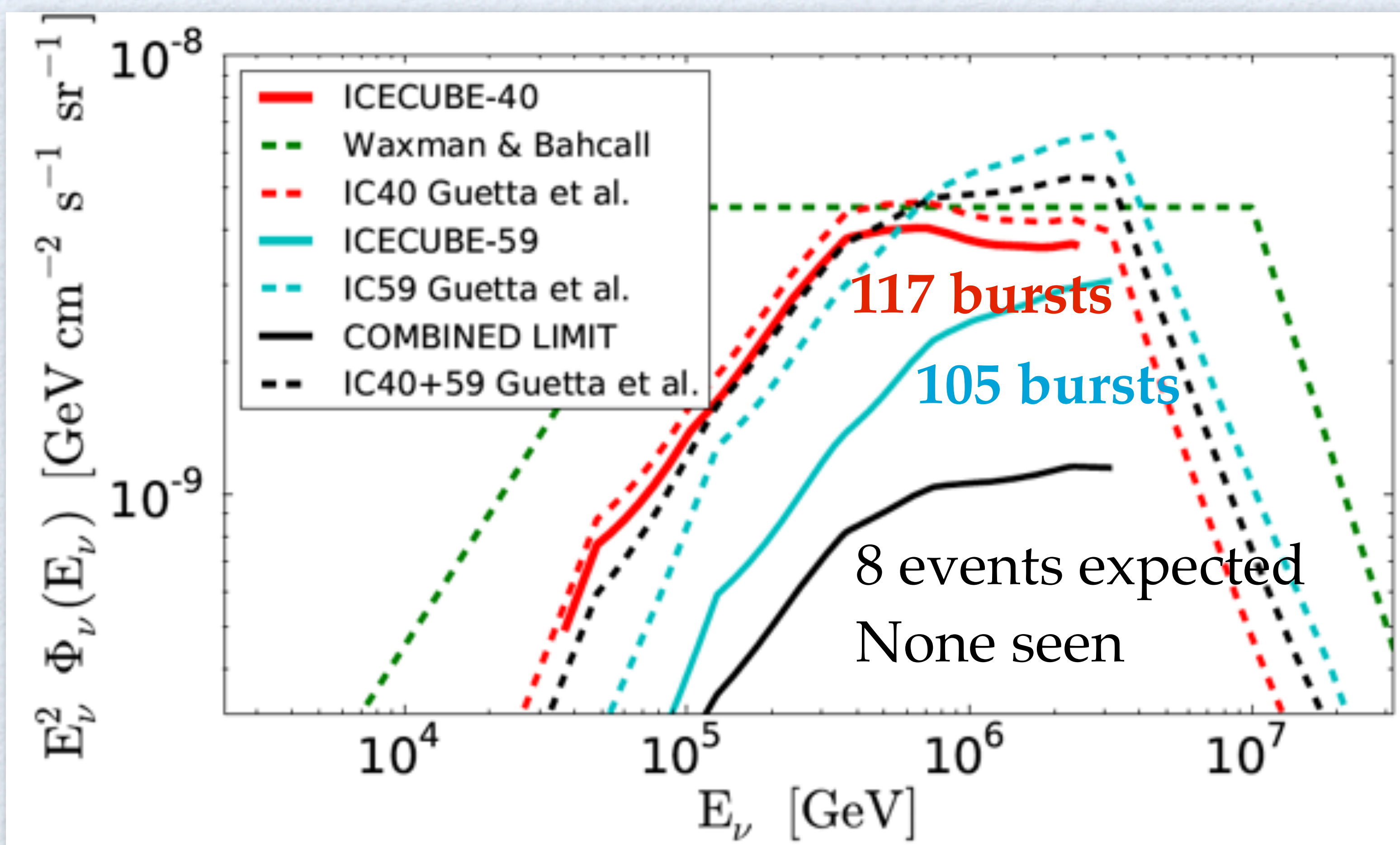


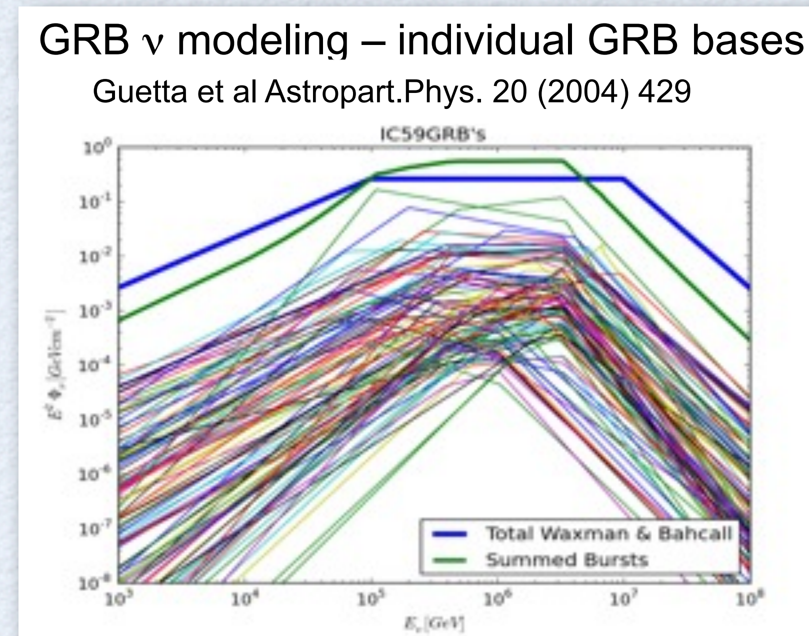
GRB Neutrino Search

Phys.Rev.Lett. 106 (2011) 141101

Brusts fromGRB Coordinates Network (... individually modeled spectra for each burst







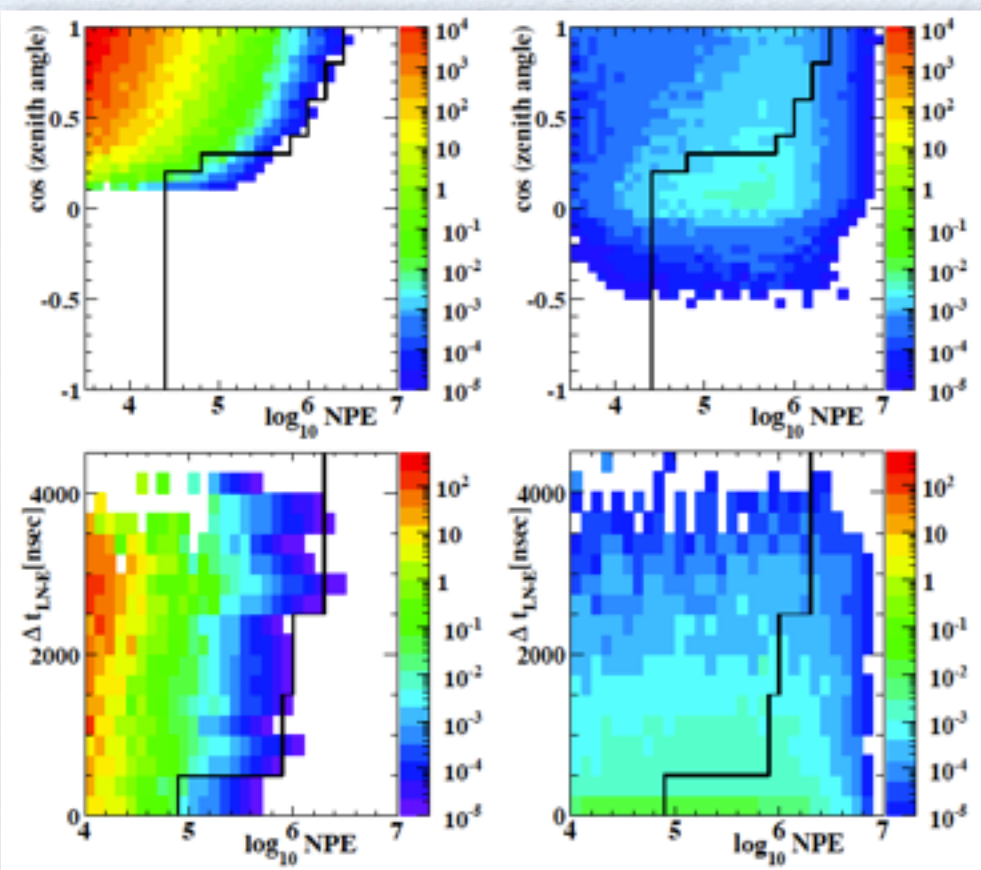
Disfavor Gamma Ray Bursts (GRBs) as dominant source of UHECRs

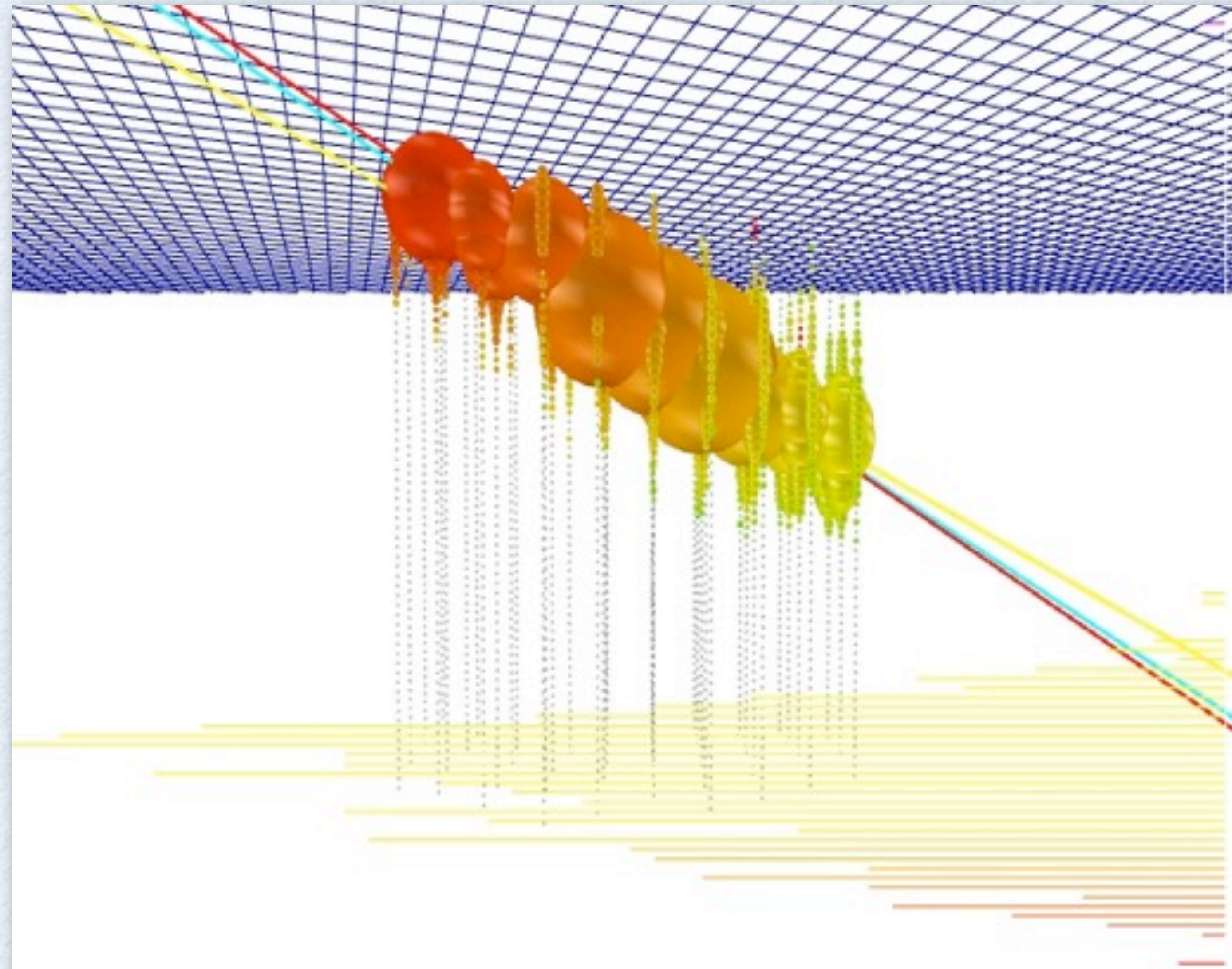
GZK Neutrino Search

Phys.Rev. D83 (2011) 092003

- In the Greisen-Zatsepin-Kuzmin (GZK) process UHECRs interact with CMB background photons to produce cosmogentic neutrinos
  - $p+\gamma_{CMB} \rightarrow \Delta \rightarrow \pi^{\pm} + X$
- Search for extremely bright down-going events

Background Expected Signal





The world's best all-flavor ν upper limits to date from 10^6 to 10^{10} GeV

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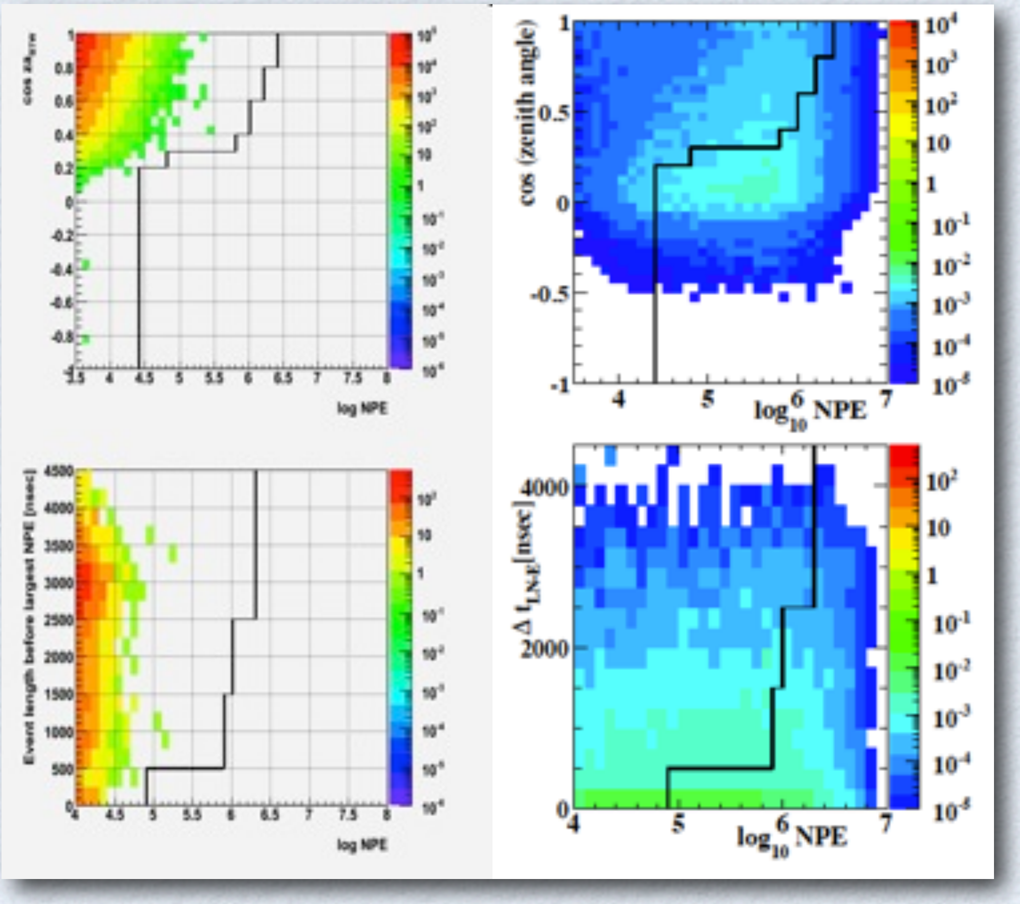
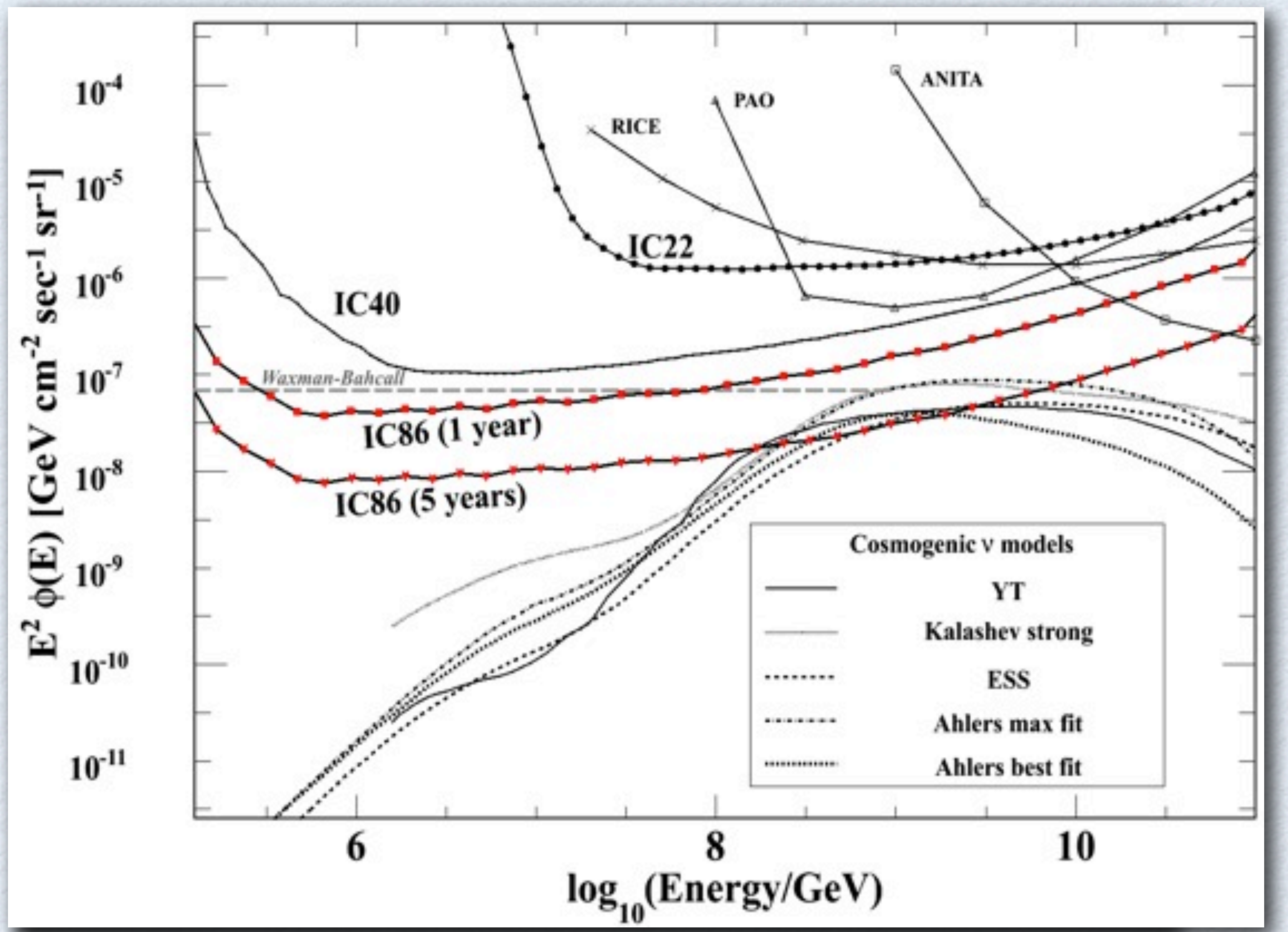
Observed Expected Signal

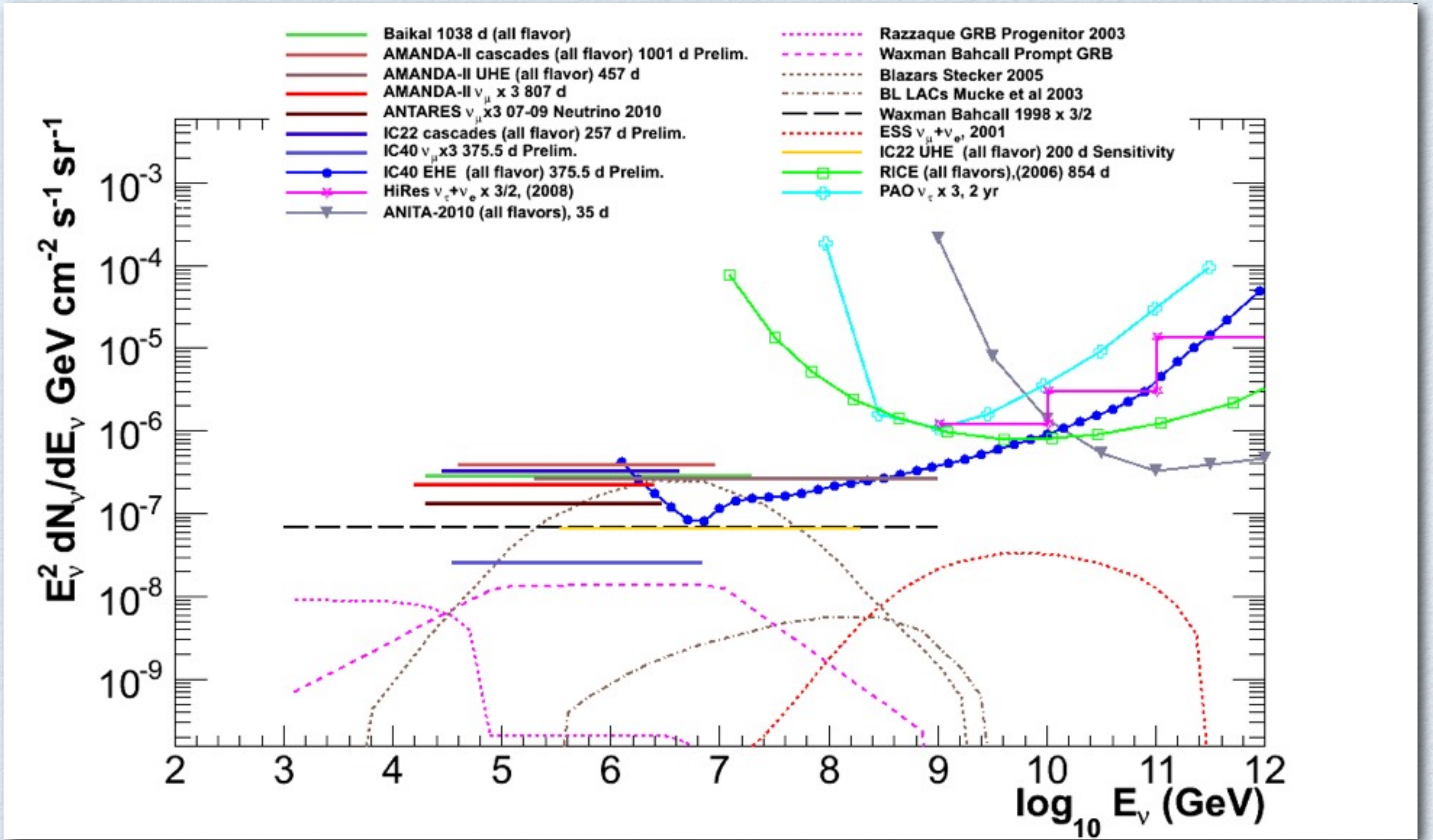




The world's best all-flavor ν upper limits to date from 10^6 to 10^{10} GeV

Search for diffuse fluxes

Phys.Rev. D84 (2011) 082001



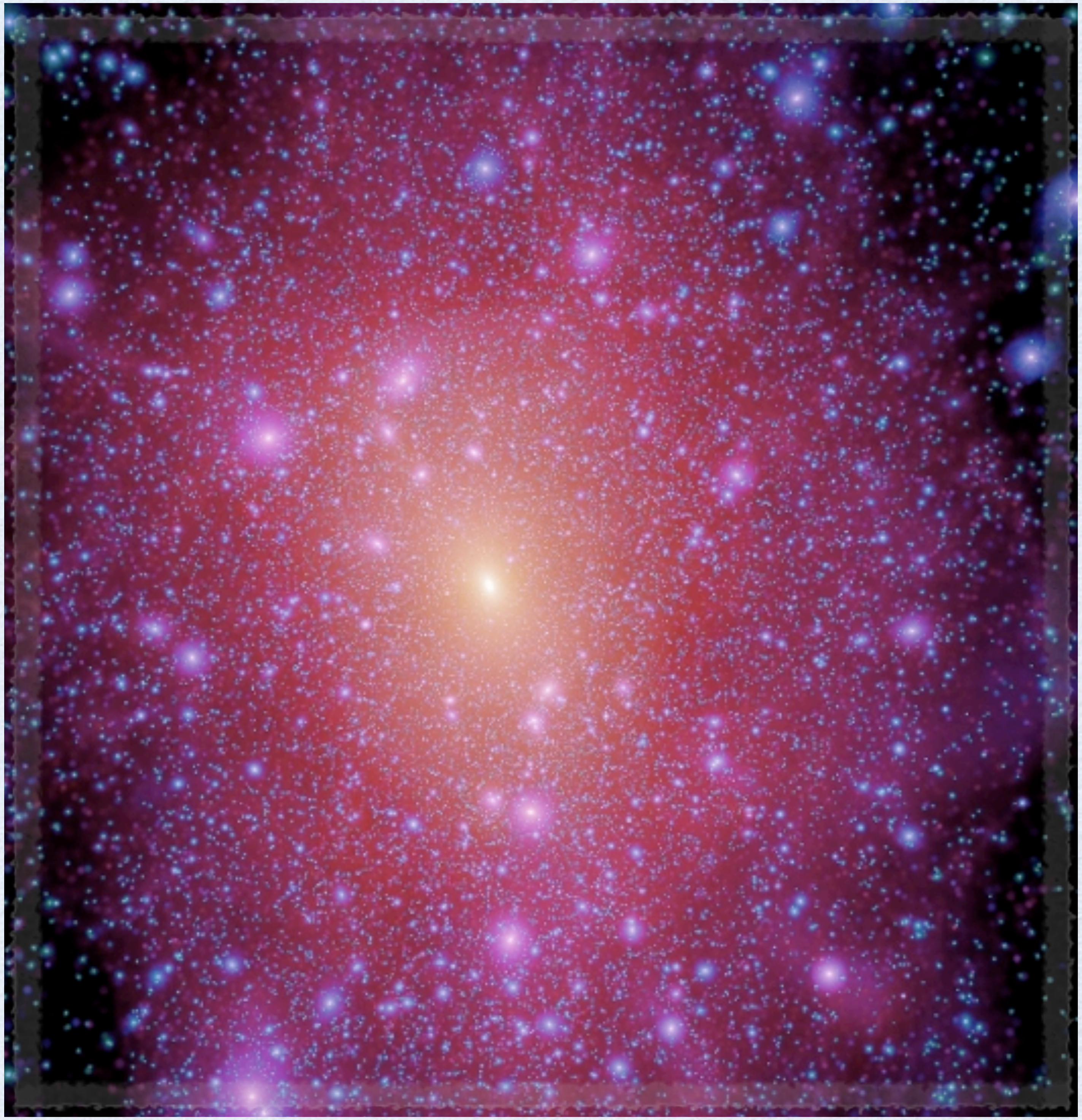
Dark Matter Halo WIMPs

Phys.Rev.D84:022004,2011

- Expected differential neutrino flux from dark matter self-annihilations is given by:

$$\frac{d\phi_\nu}{dE} = \frac{\langle \sigma_A v \rangle}{2} J(\psi) \frac{R_{\rm sc}\rho_{\rm sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

- Result is in general model independent
  - Any generic WIMP model works
- Obtain result as function of WIMP mass, dark matter distribution and annihilation channel



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distribution

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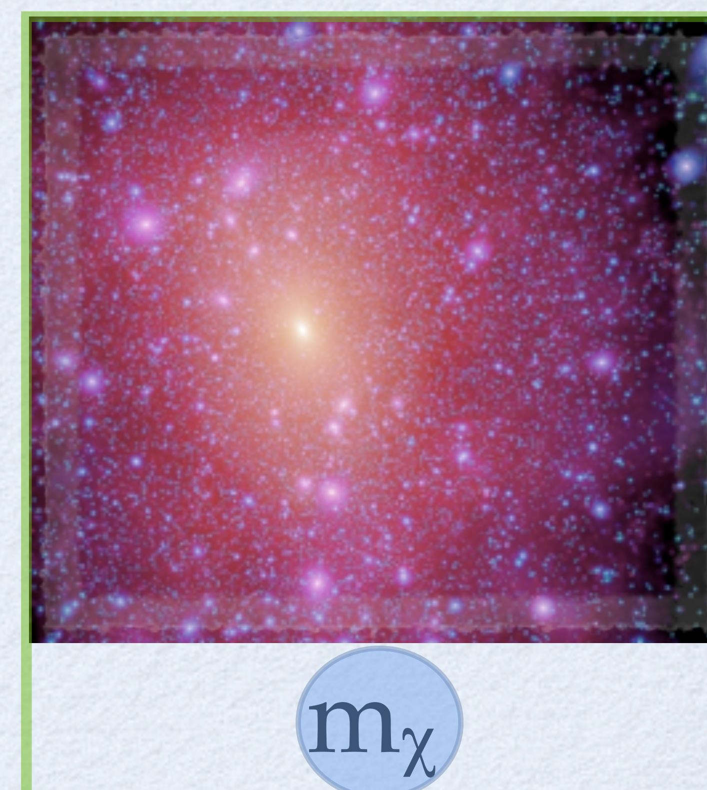

Dark Matter Halo WIMPs

Phys.Rev.D84:022004,2011

probe

distribution

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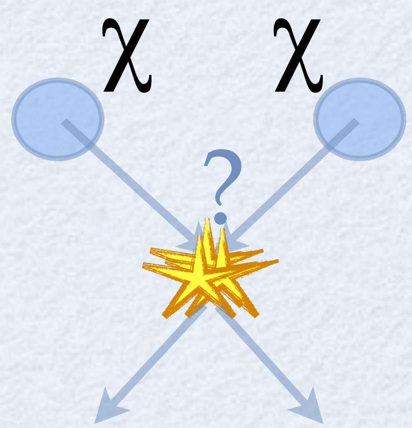

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Dark Matter Halo WIMPs

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probe — distribution — particle physics

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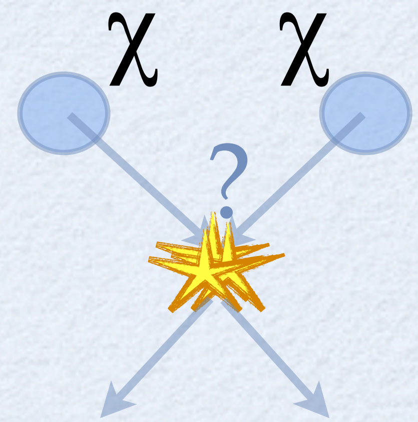

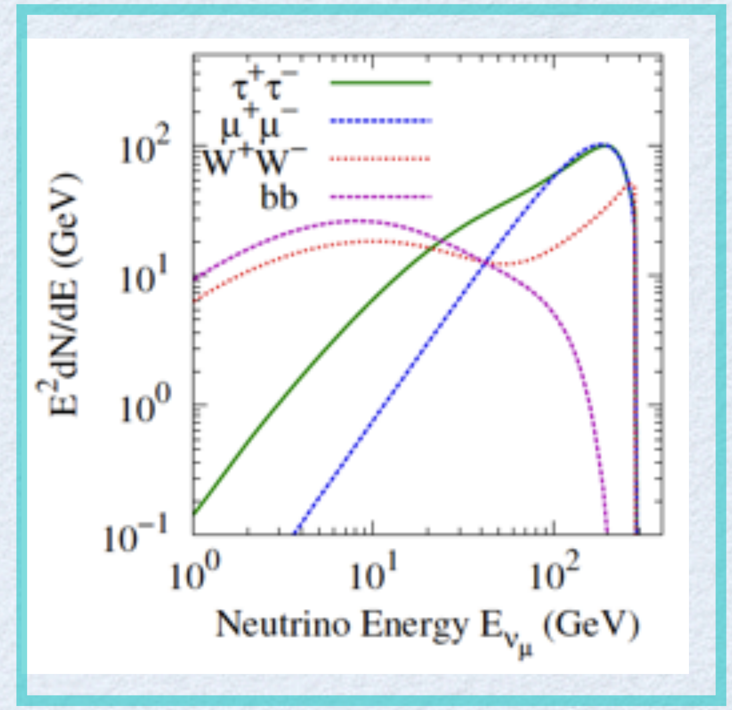

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Dark Matter Halo WIMPs

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measure — probe — distribution — particle physics

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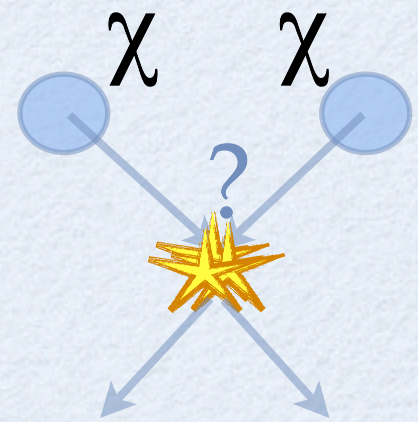

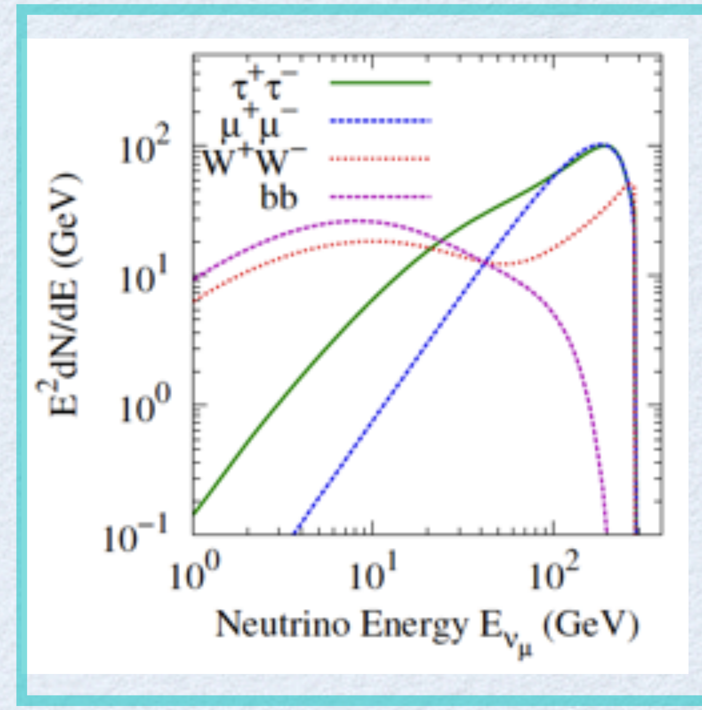

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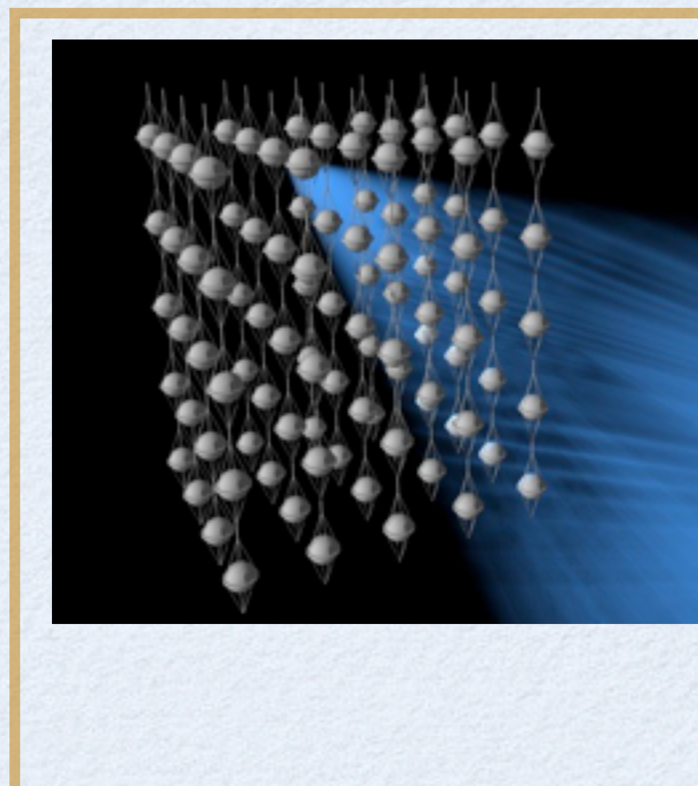

Dark Matter Halo WIMPs

Phys.Rev.D84:022004,2011

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- 5114 Events after selection from -5° to +85° declination
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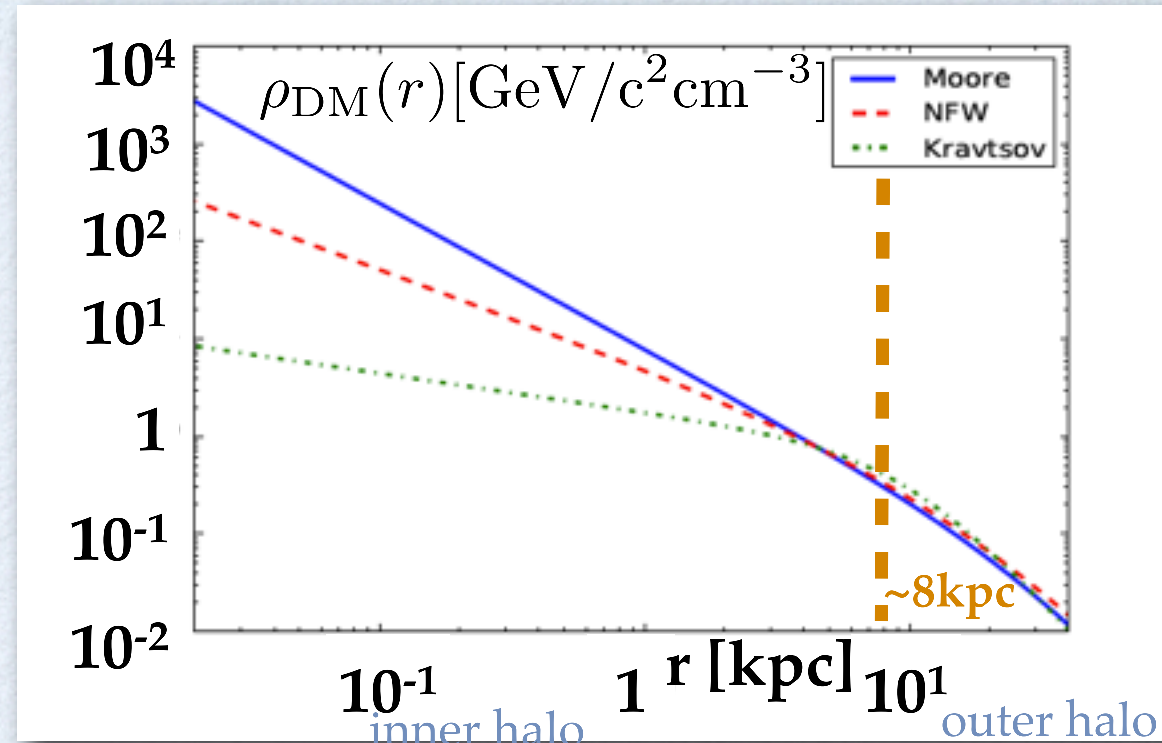

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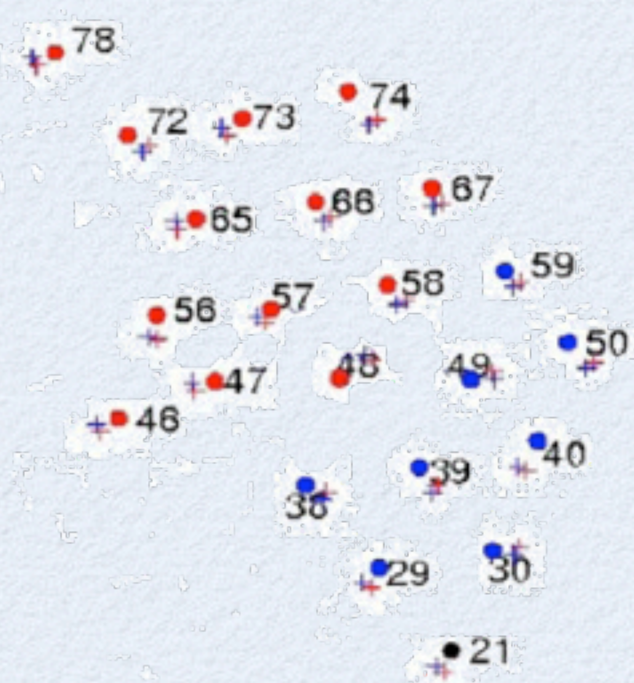

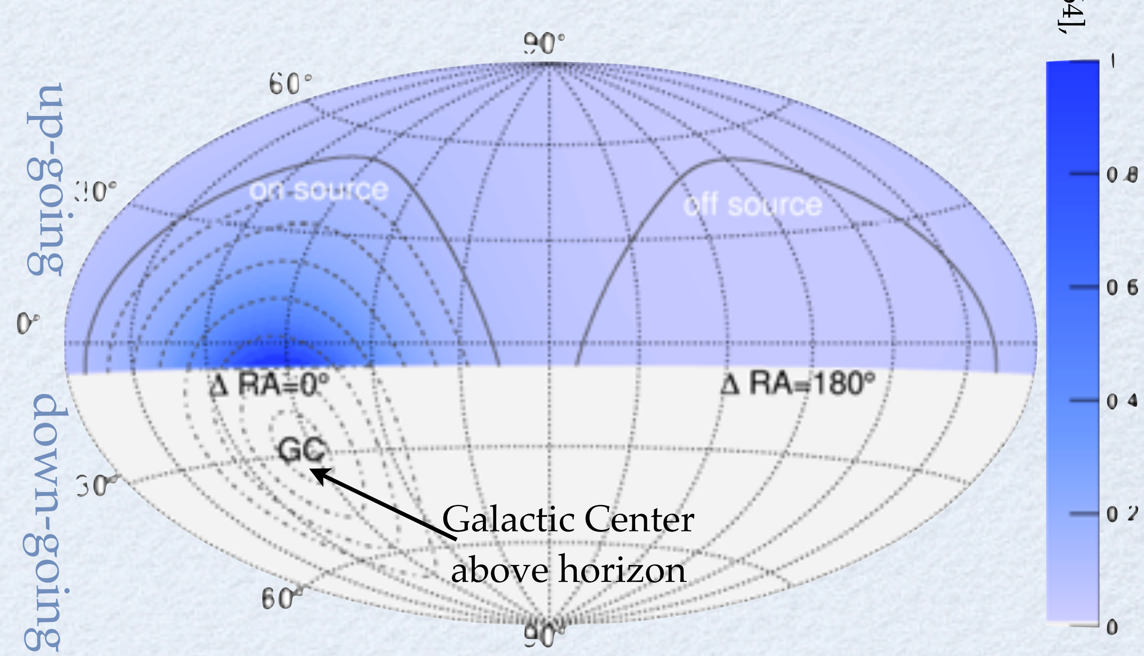

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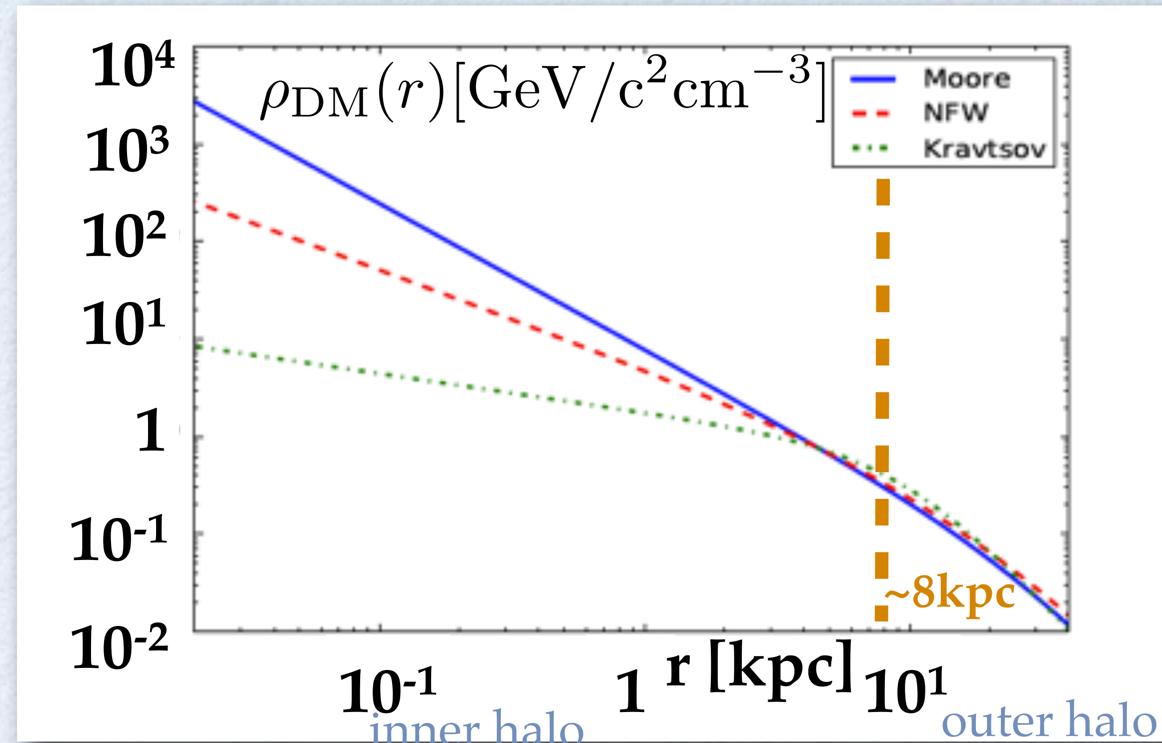

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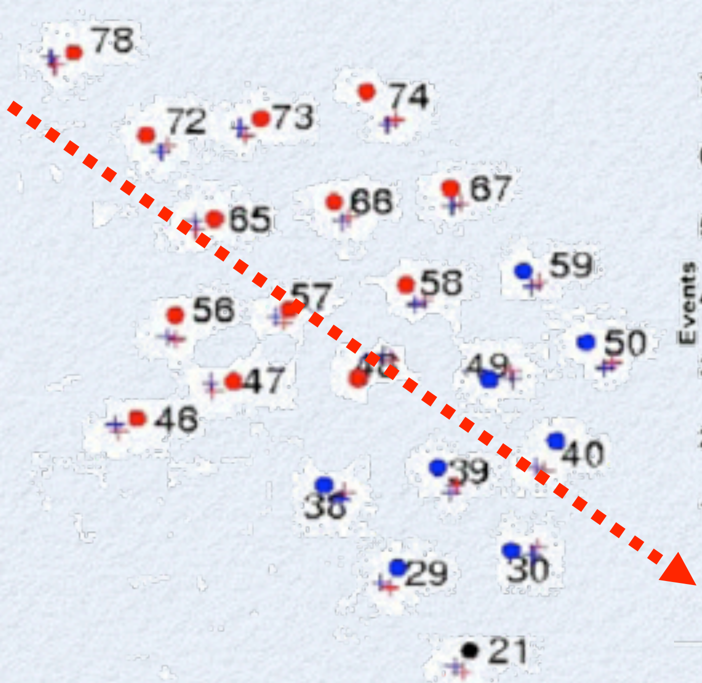

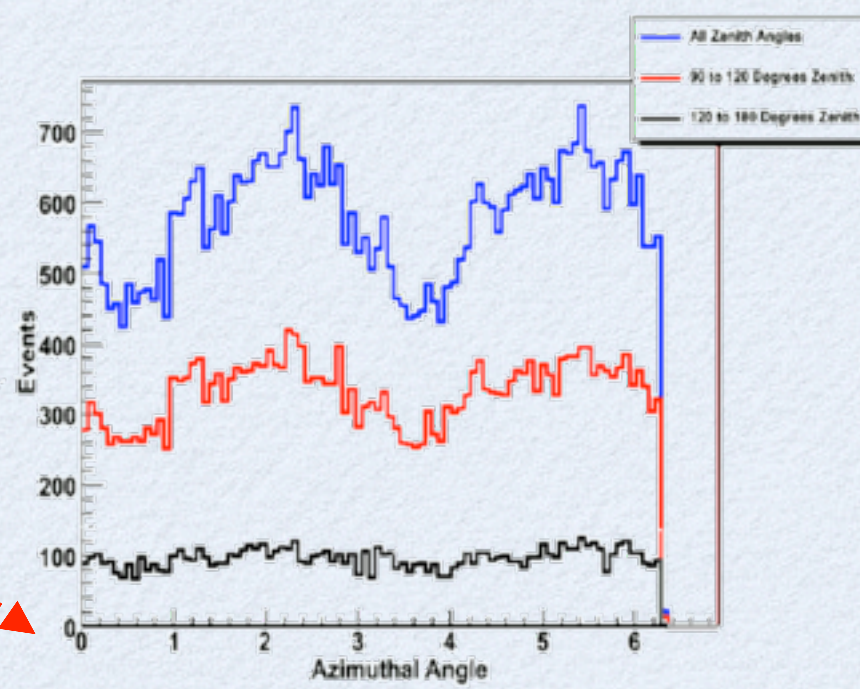

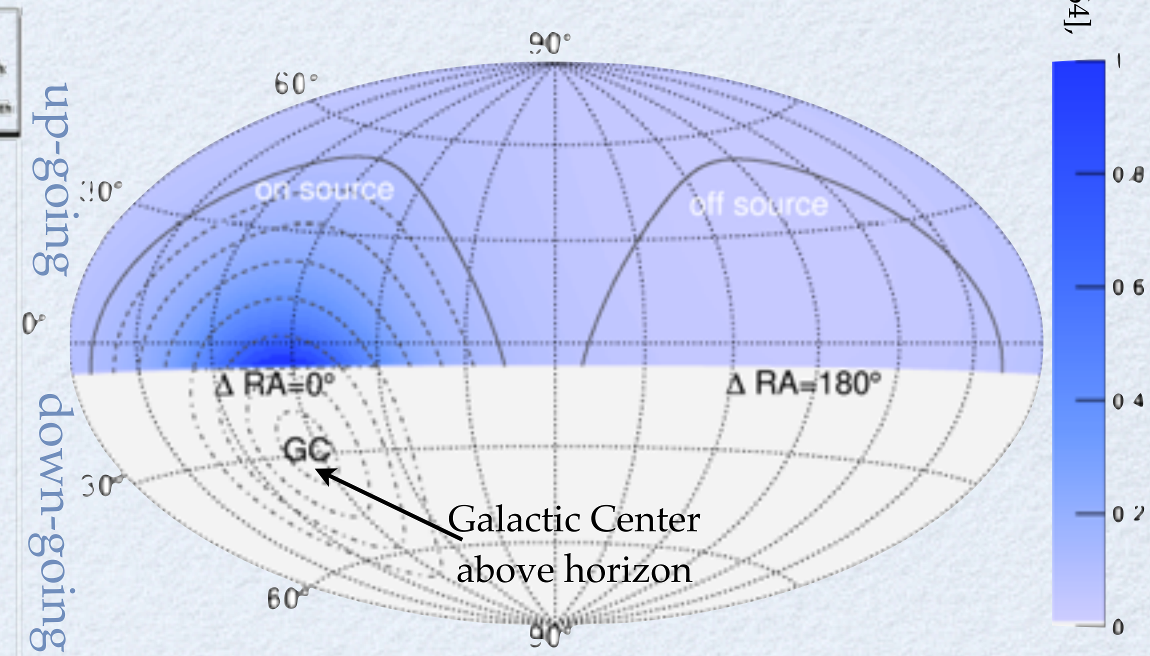

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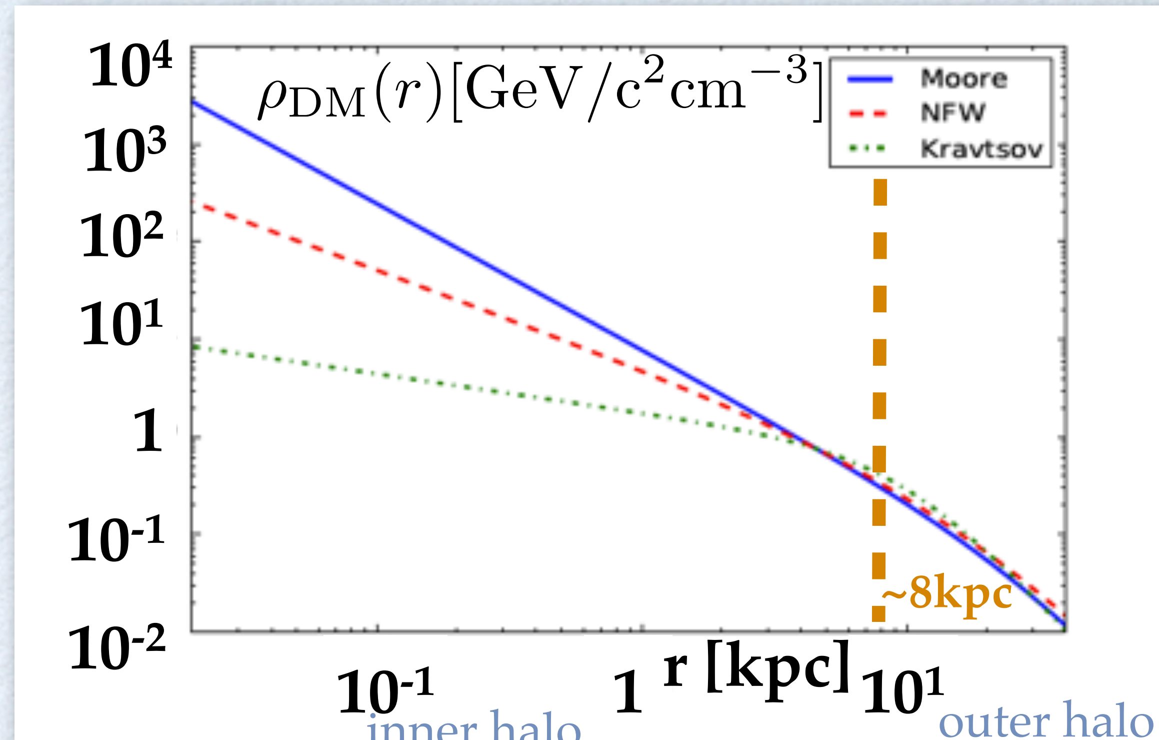

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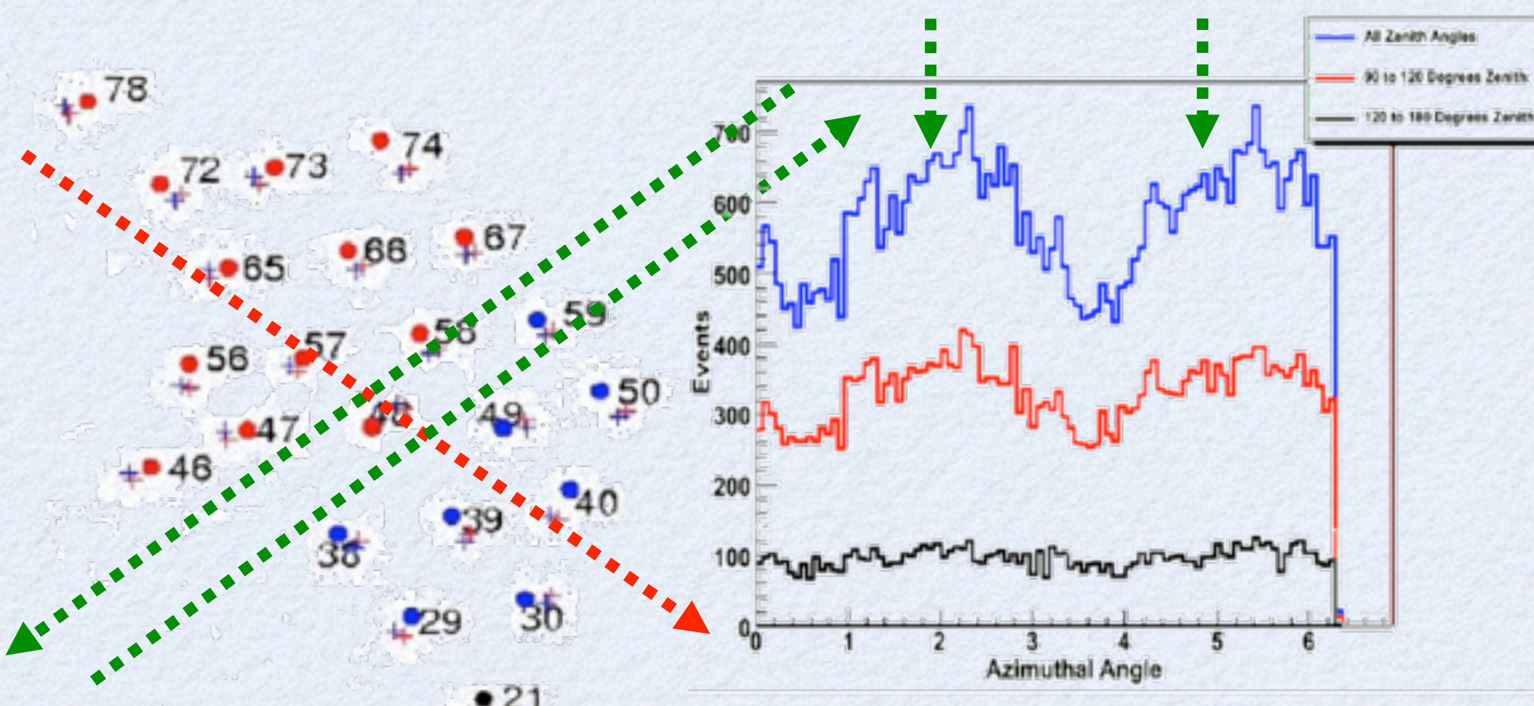

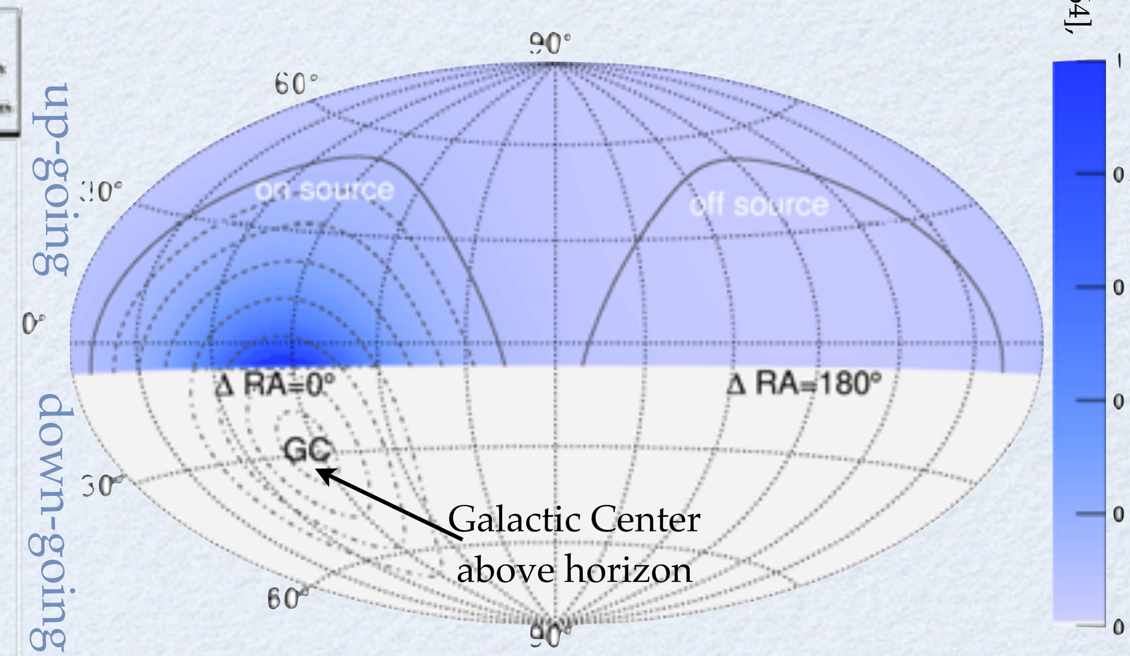

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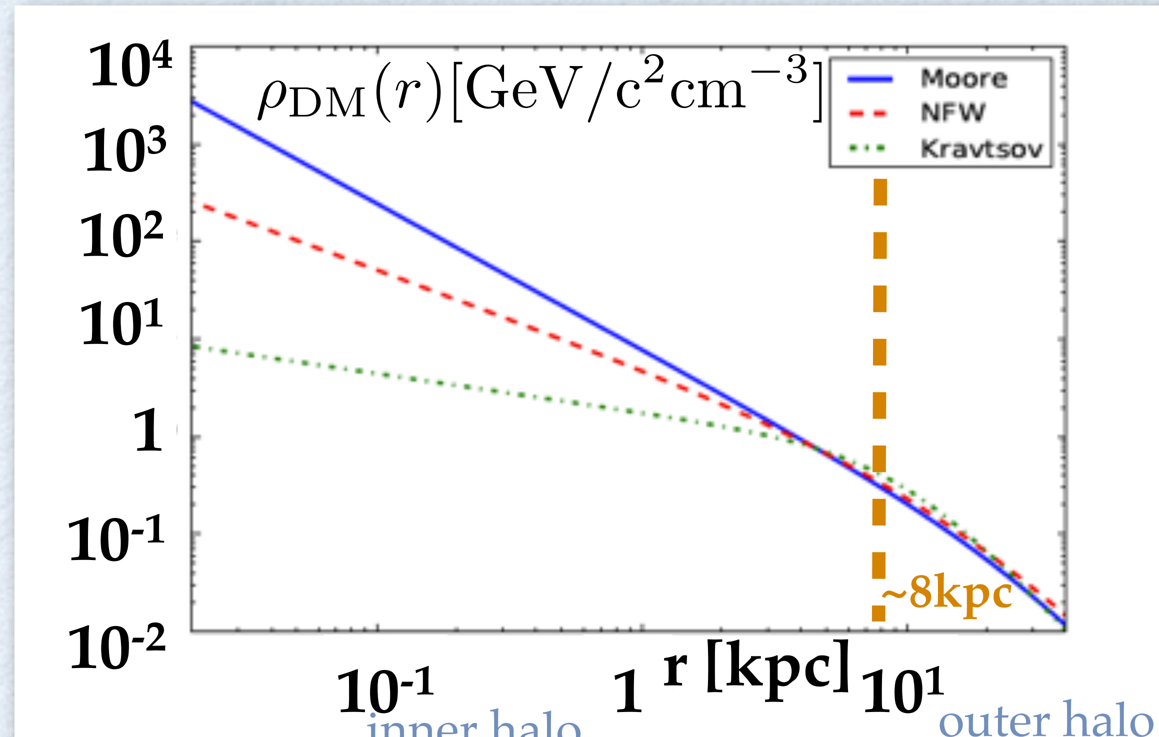

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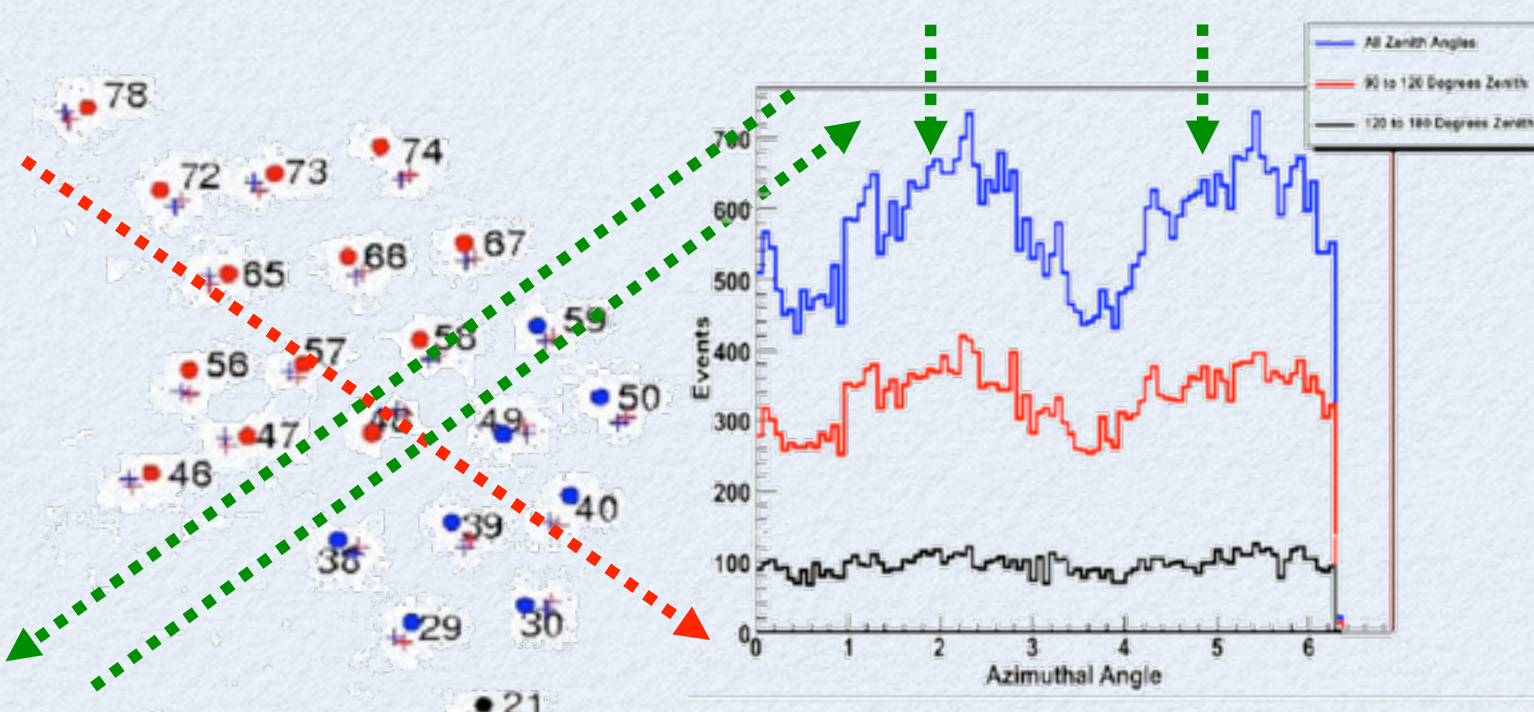

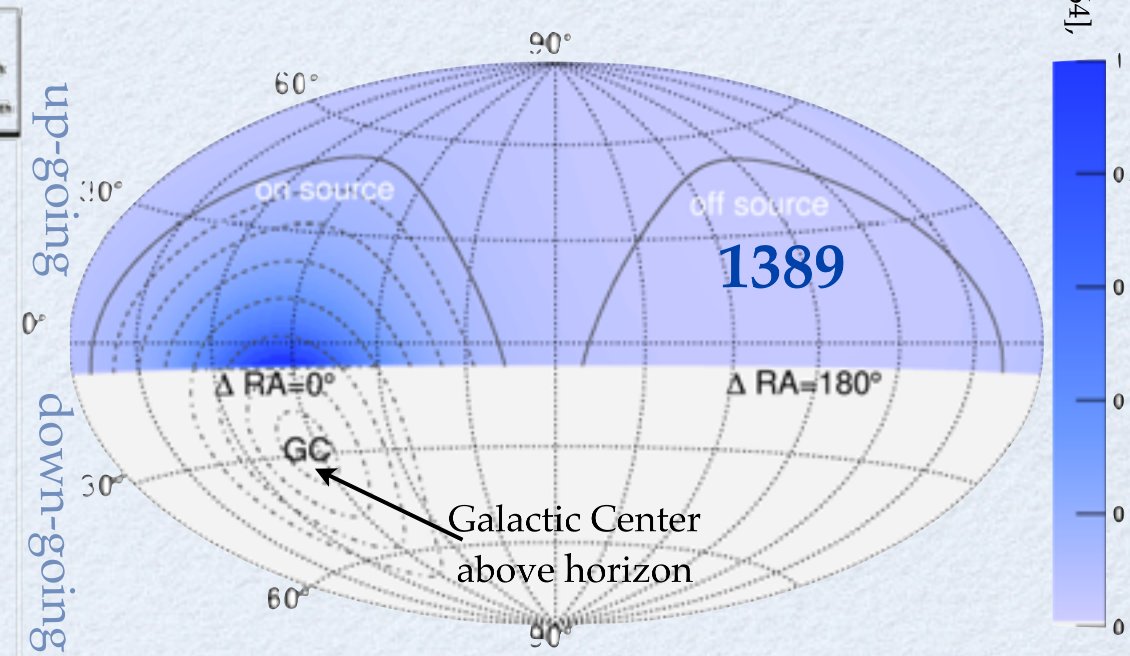

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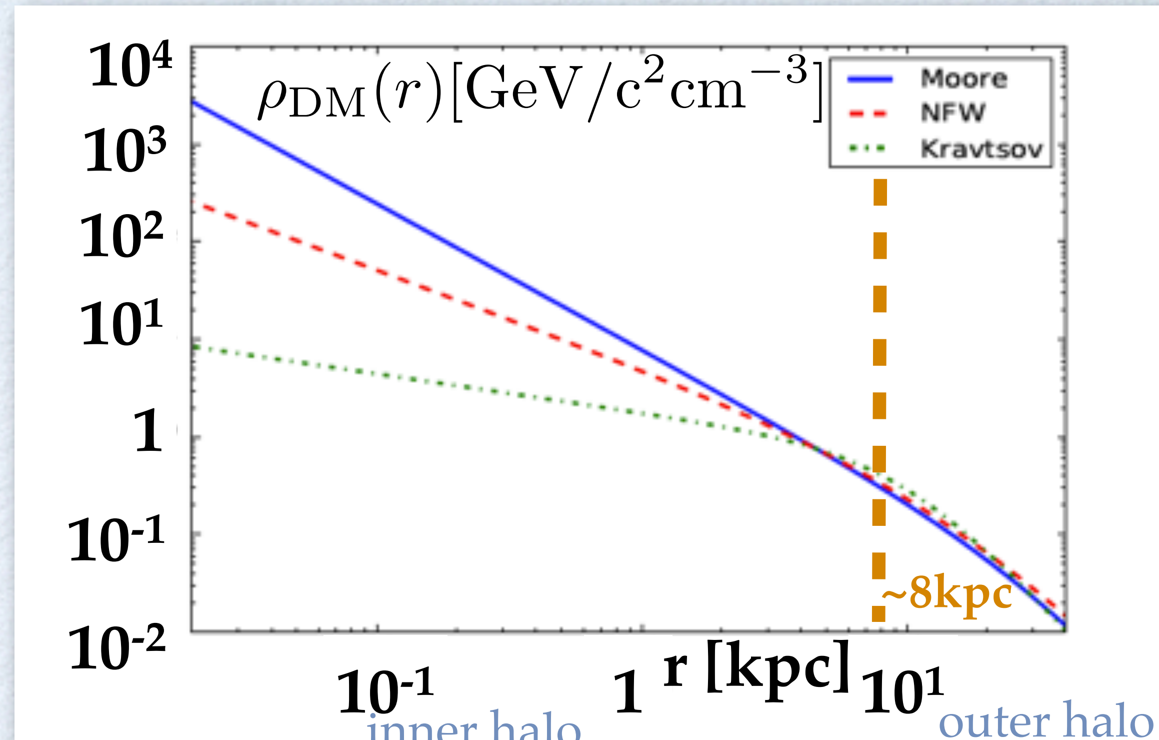

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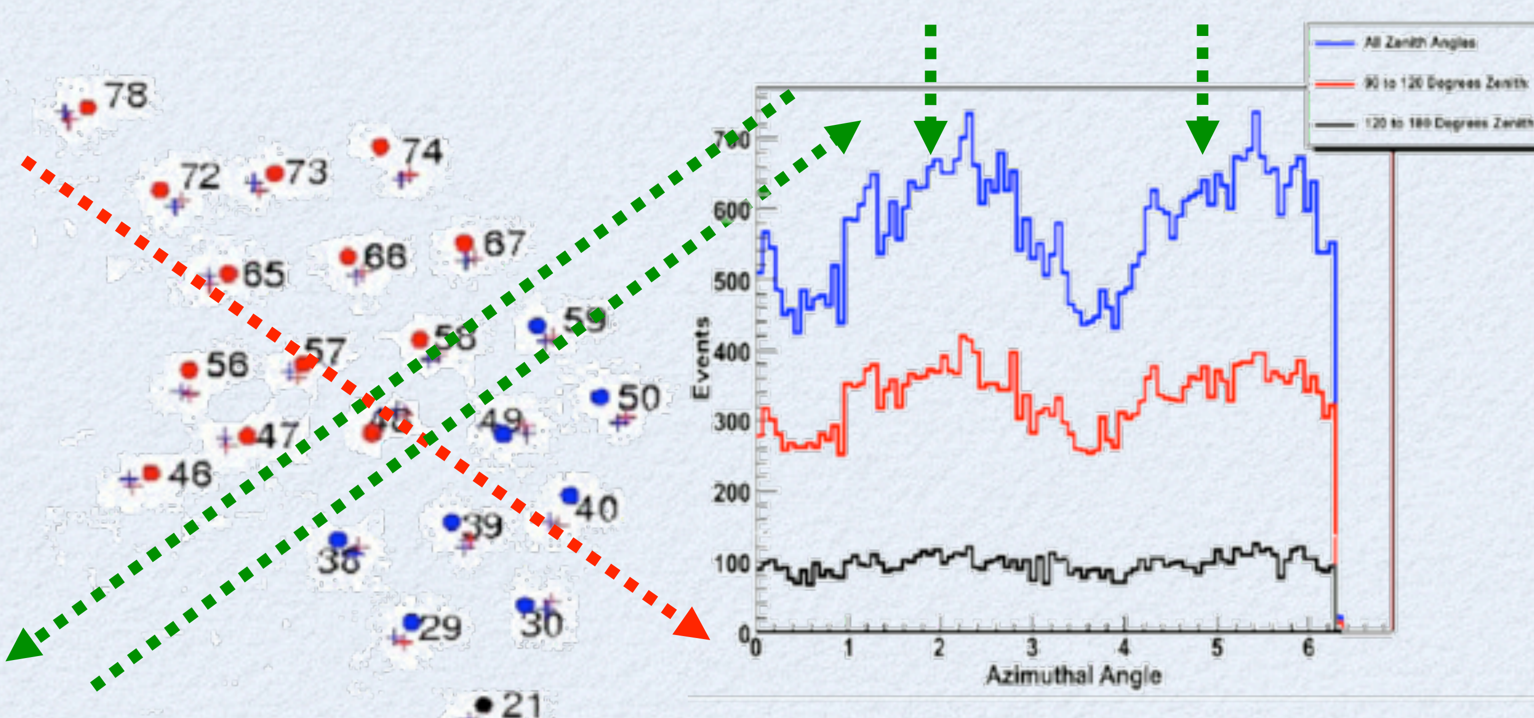
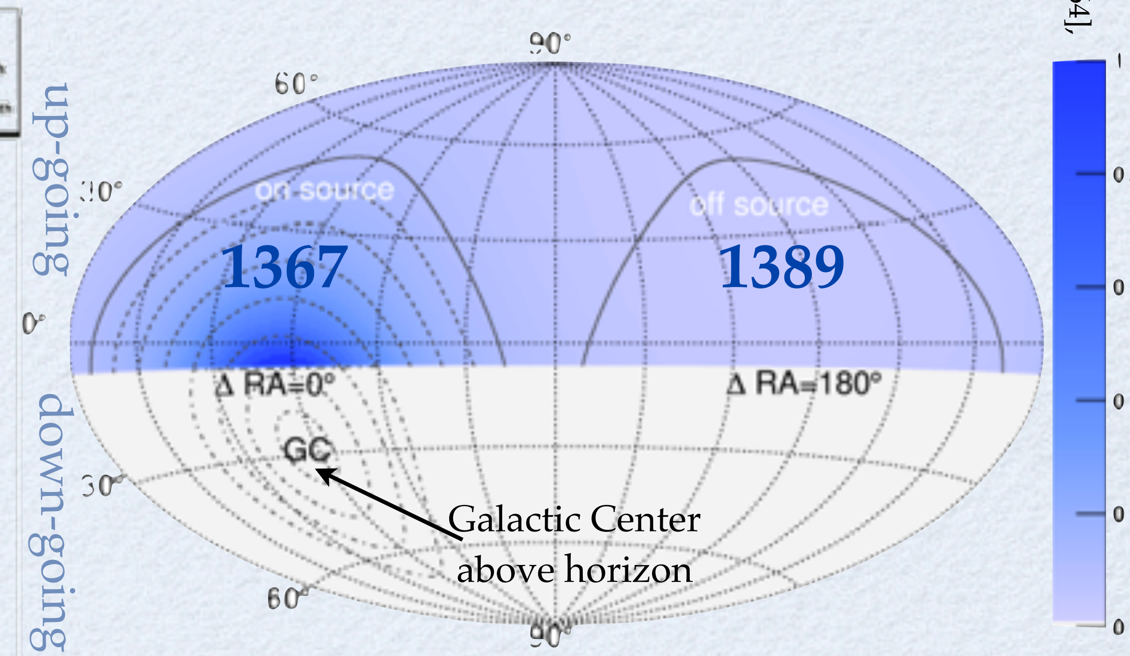
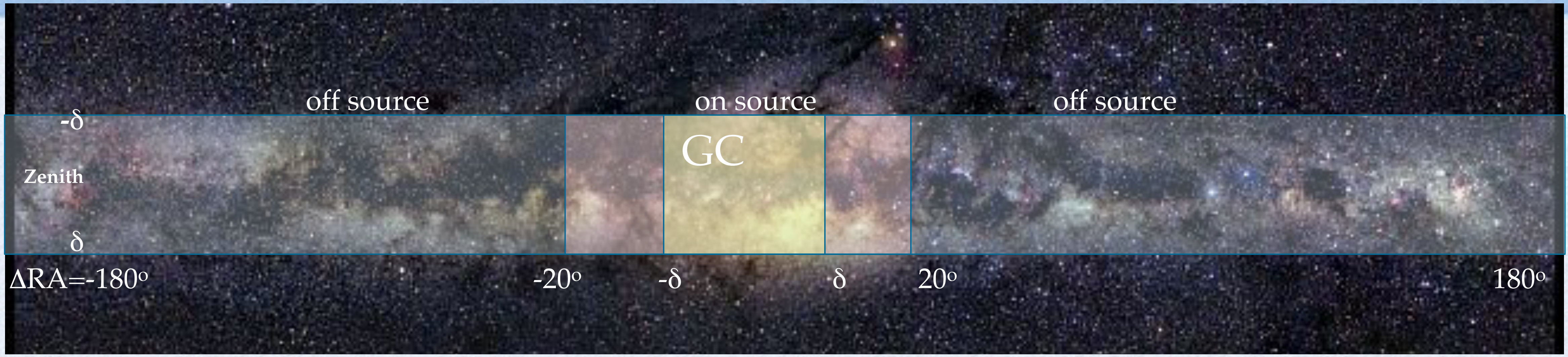




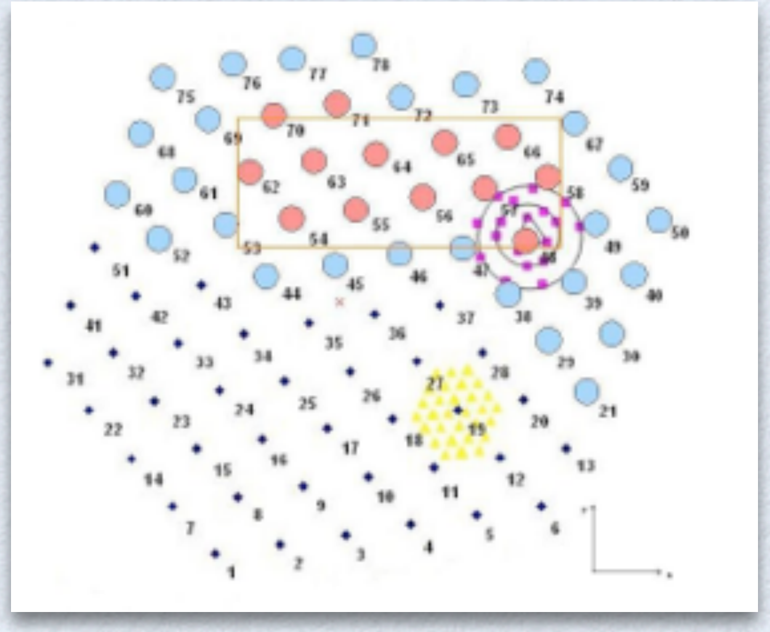
Galactic Center Analysis

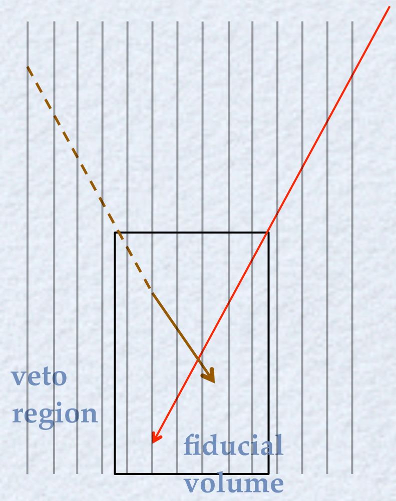
arXiv:1111.2738 [astro-ph.HE]



- Dark Matter profiles are peaked at the Galactic Center
- Using 367 days of IceCube 40 string data
- Optimize the size of the on-source region
  - → δ = 8°
- Compare the amount of events in the on- and off-source region
- Use likelihood ratio between infinite track assumption to starting track to distinguish neutrino events from down-going muon background

- Galactic Center is above the horizon → events are down-going in IceCube
  - Use starting events to reduce atmospheric muon background





Milky Way Halo Analyses

Analysis	Galactic Halo	Galactic Center
Detector configuration	22-strings	40-strings
Dataset	275days (June 2007 - March 2008)	367days (April 2008 - May 2009)
Signal	up-going muon neutrino candidate events (-5° - 85° in declination)	down-going muon neutrino candidate events centered around -30° in declination
Neutrino events	through-going	vertex contained
Background estimate	**1389** (dominated by atm. neutrinos)	**798842** (dominated by atm. muons)
Observed	**1367**	**798819**

- Observations in both analyses were consistent with background only expectations → constrain the self- annihilation cross section

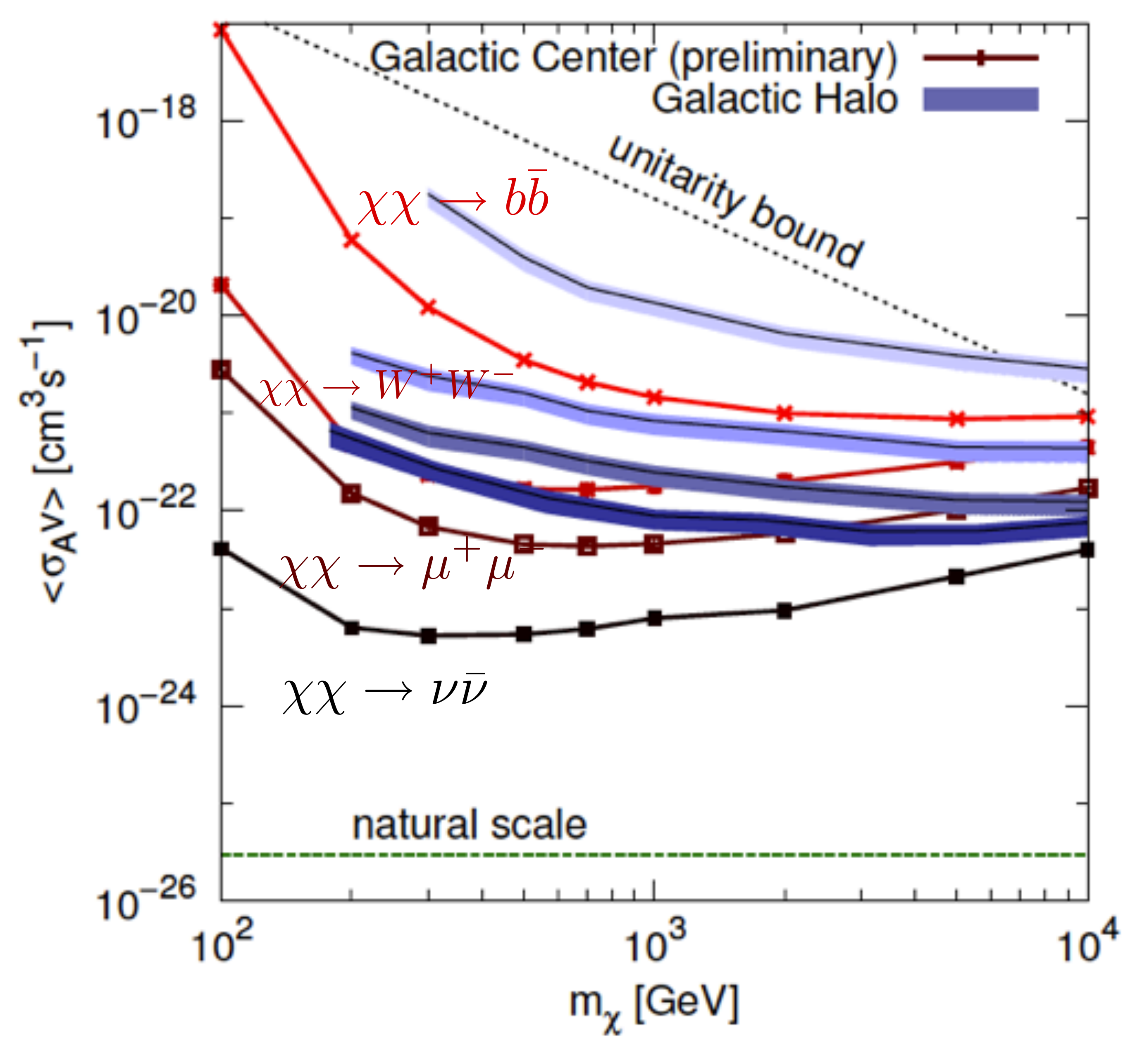
Halo WIMP Results

Phys.Rev.D84:022004,2011

- Limits computed at 90% C.L. as function of WIMP mass and for various annihilation channels assuming branching fractions of 100%

$$\langle\sigma_A v\rangle_{90} = \Delta N_{90} \times \frac{\langle\sigma_A v\rangle_0}{\Delta N^{sig}(\langle\sigma_A v\rangle_0)}$$

- Uncertainty due to the choice of halo model is small
- Limit depends on neutrino yield and spectrum for given annihilation channels
- Best limit for line channel



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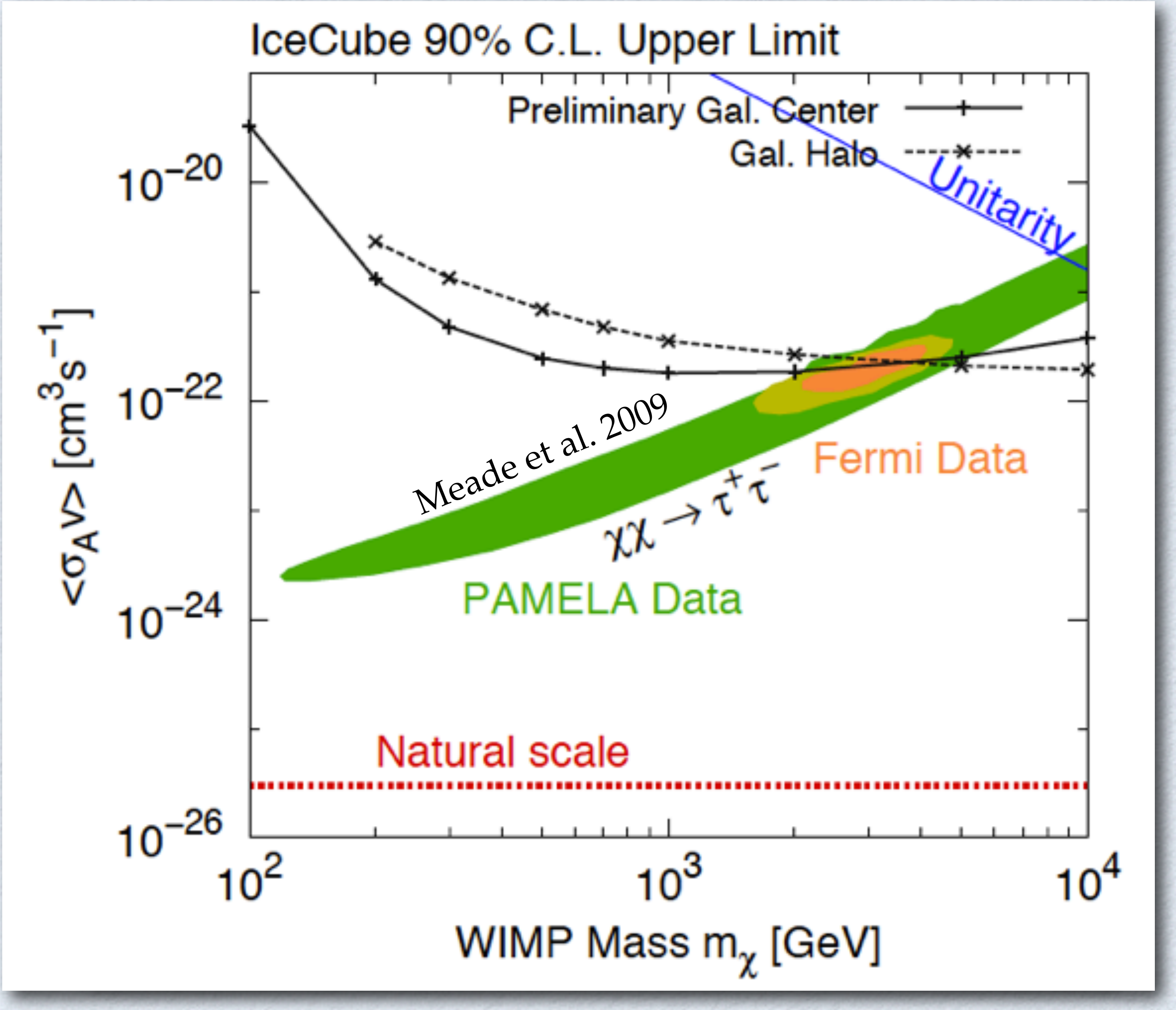
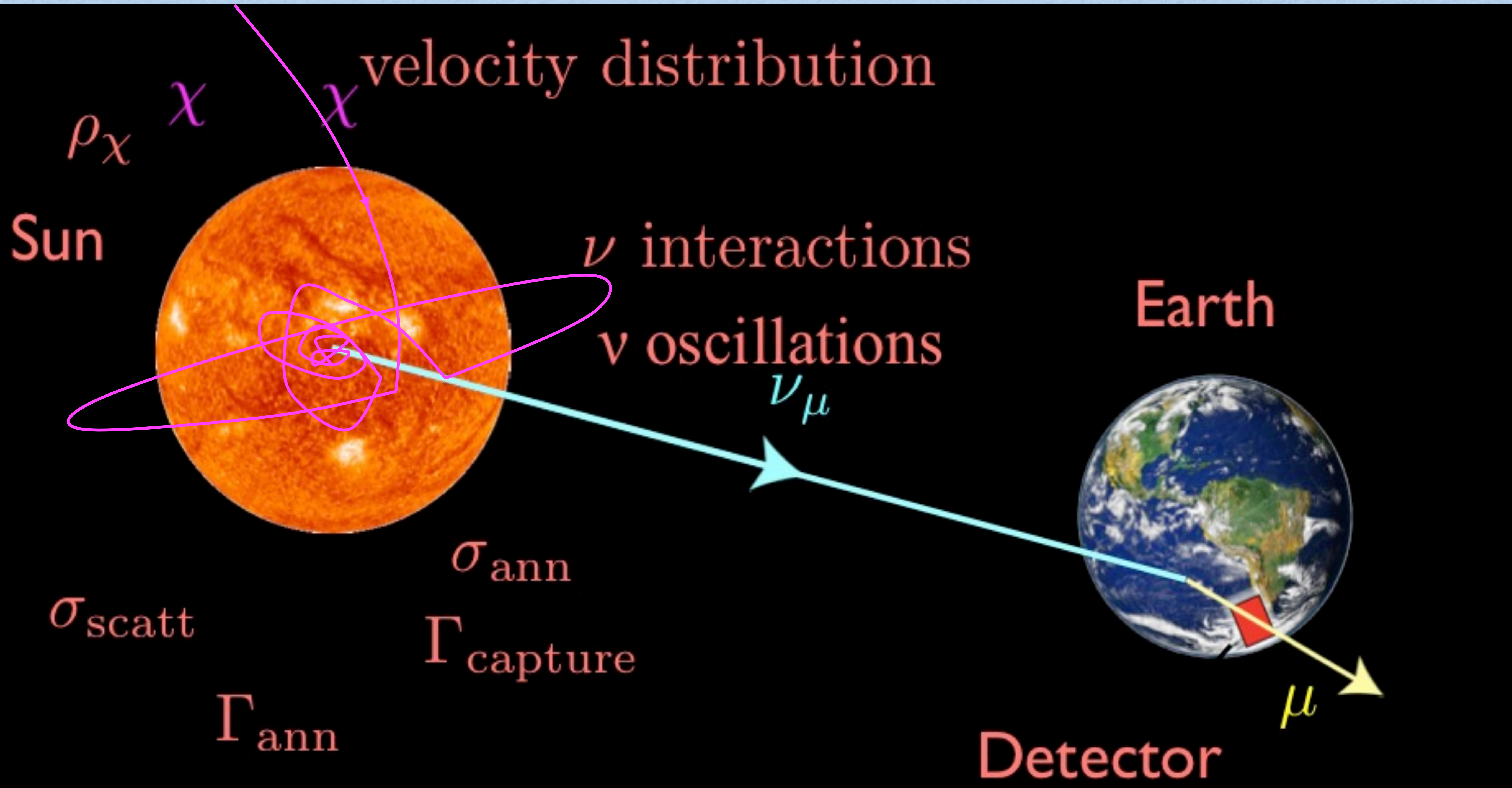


Solar WIMP signal

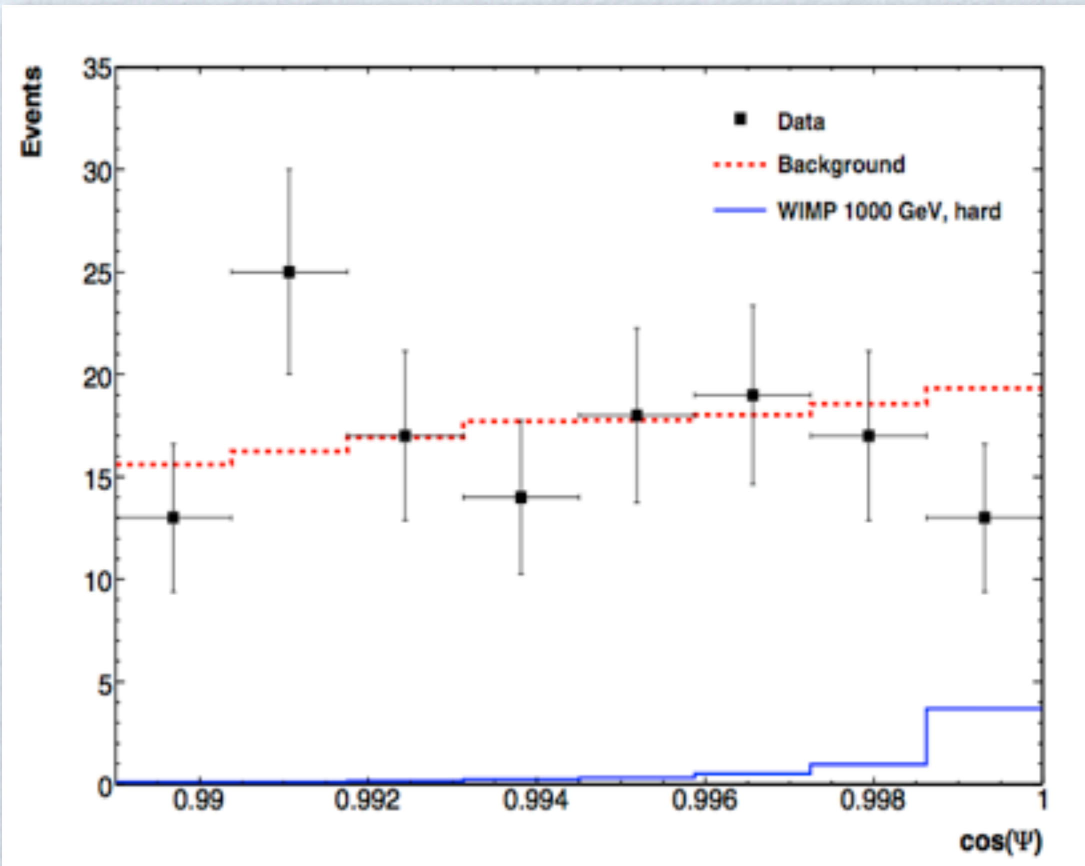


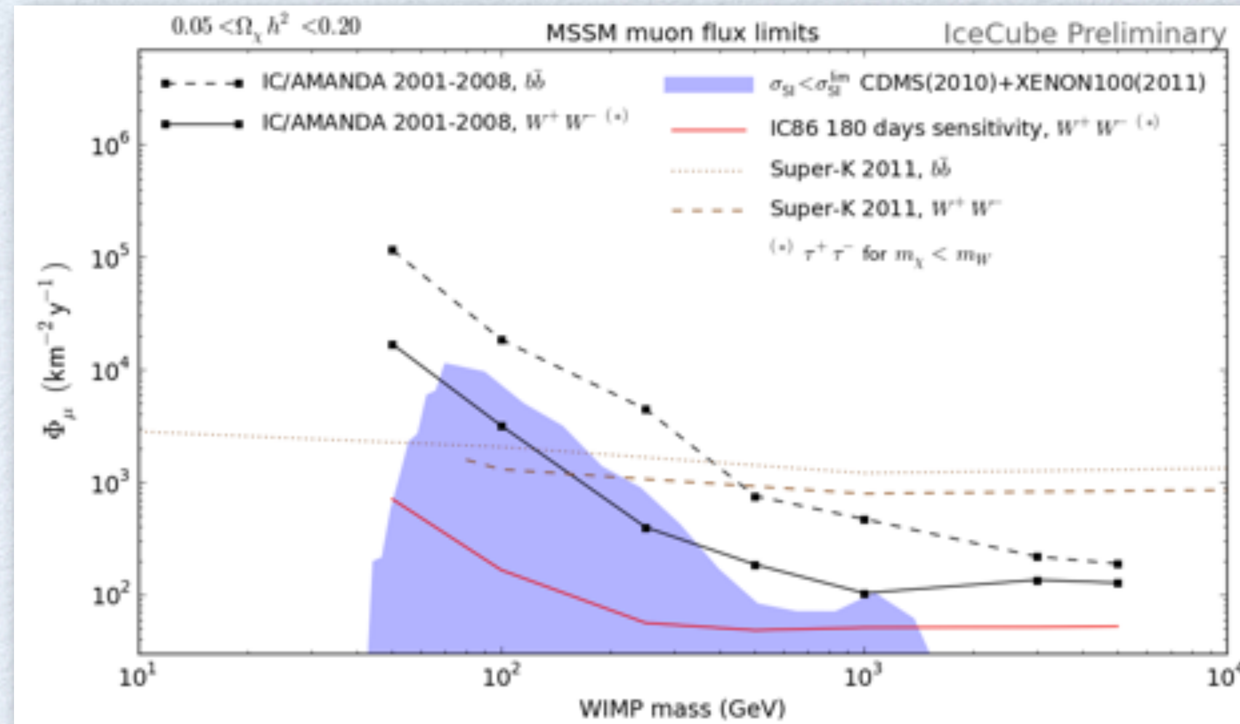
Freese '86
Krauss, Srednicki & Wilczek '86
Gaisser, Steigman & Tilav '86

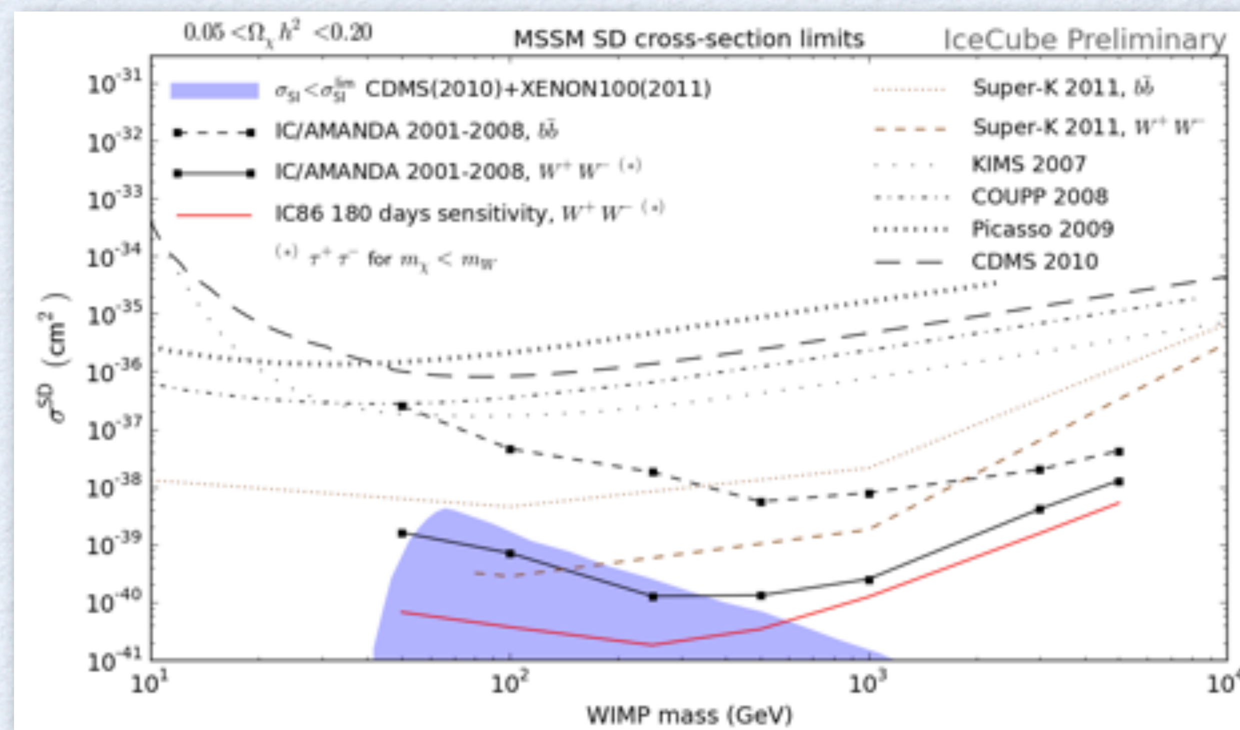
Silk, Olive and Srednicki '85
Gaisser, Steigman & Tilav '86

Solar WIMP Limits

Phys.Rev.Lett. 102 (2009) 201302





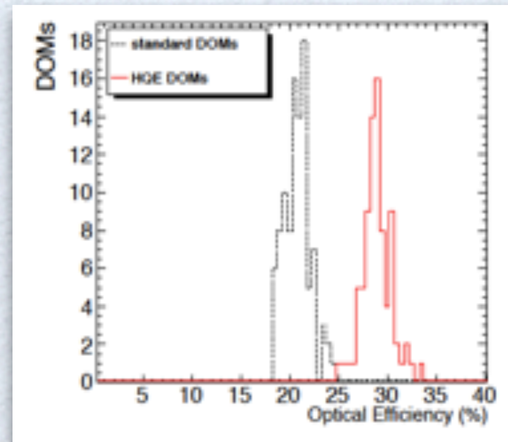


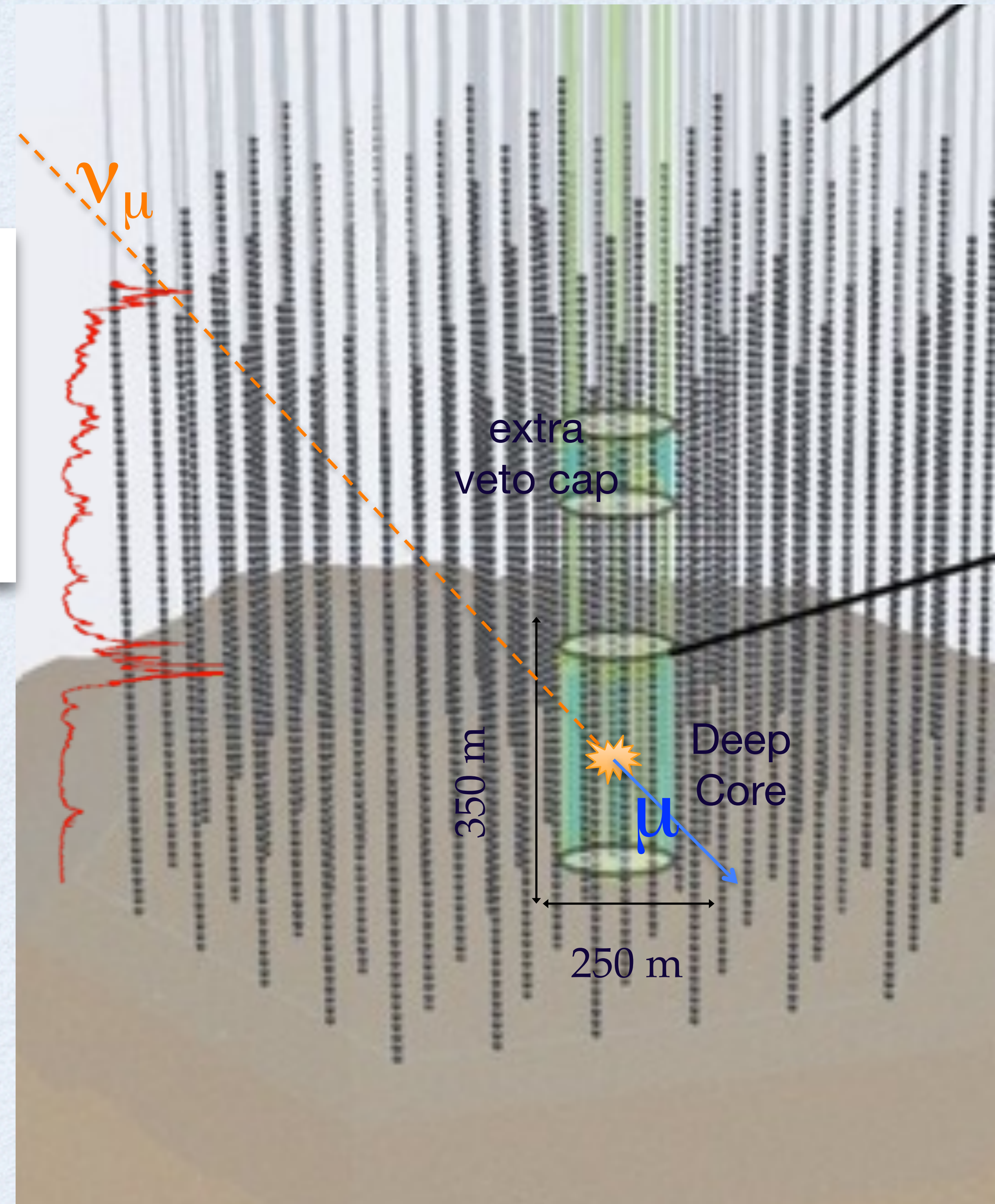
- Limits & Sensitivity:
  - Only data, when Sun is below the horizon
- Main systematic uncertainty
  - Photon propagation in the ice & absolute DOM efficiency (~20%)
- Relate muon flux to WIMP-Nucleon scattering cross section

DeepCore

arXiv:1109.6096 [astro-ph.IM]

- DeepCore deployed and taking data since June 2010
- 8 special strings plus 7/11 nearest standard IceCube strings
    - 72 m interstring spacing
    - 7 m DOM spacing on string
- High Q.E. PMTs (~40% better)
    - ~5x higher eff. photocathode density
- Clearest ice below 2100m
    - $\lambda_{atten} \approx$ 40-45 m
- Look for starting events in DeepCore to veto atmospheric muons
- Top and outer layers of IceCube can be used to veto down-going muon





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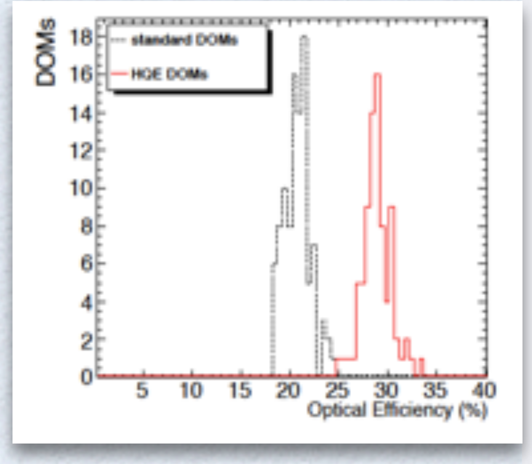

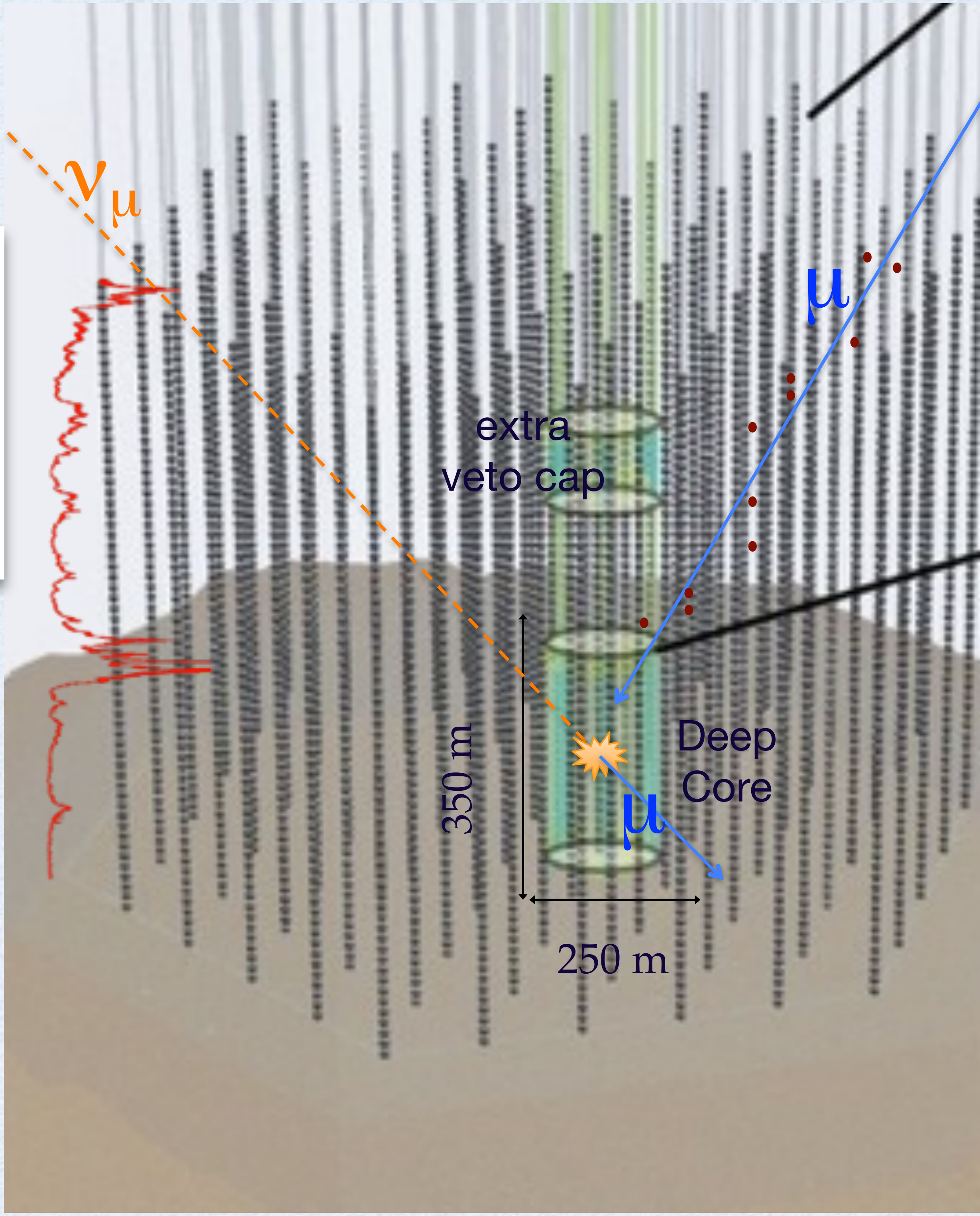

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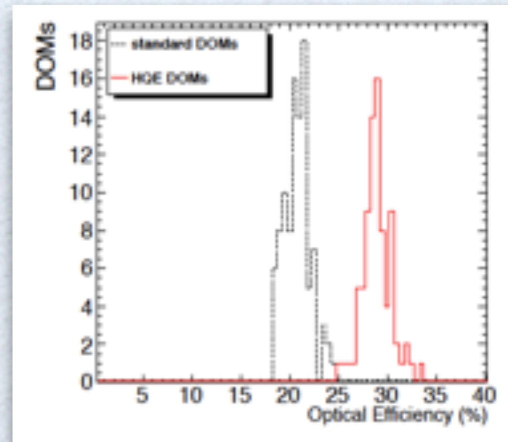

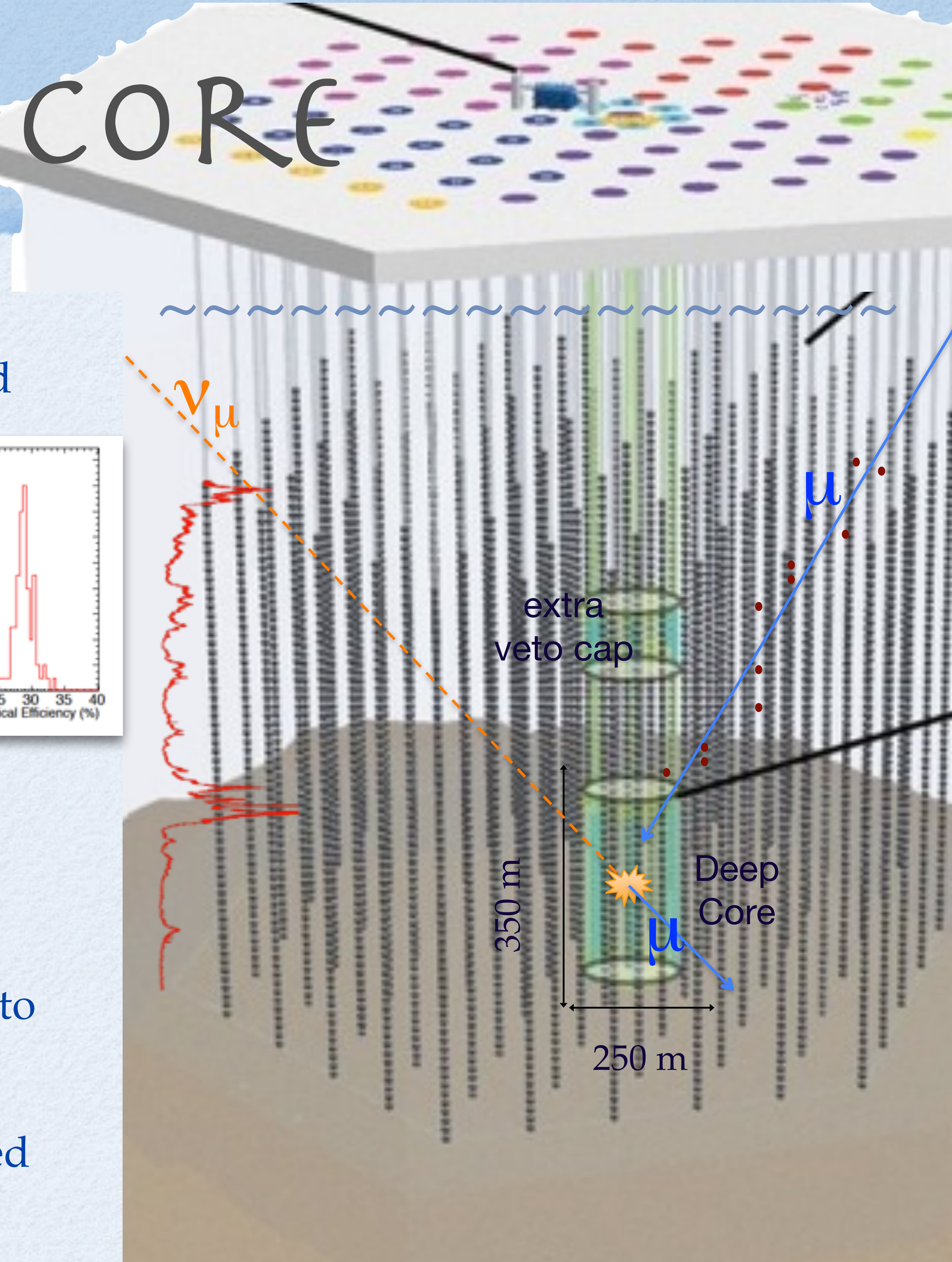

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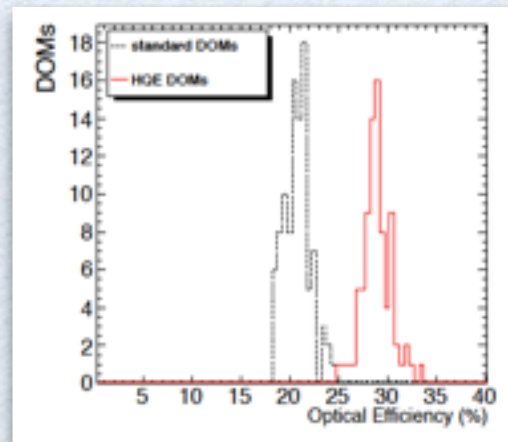
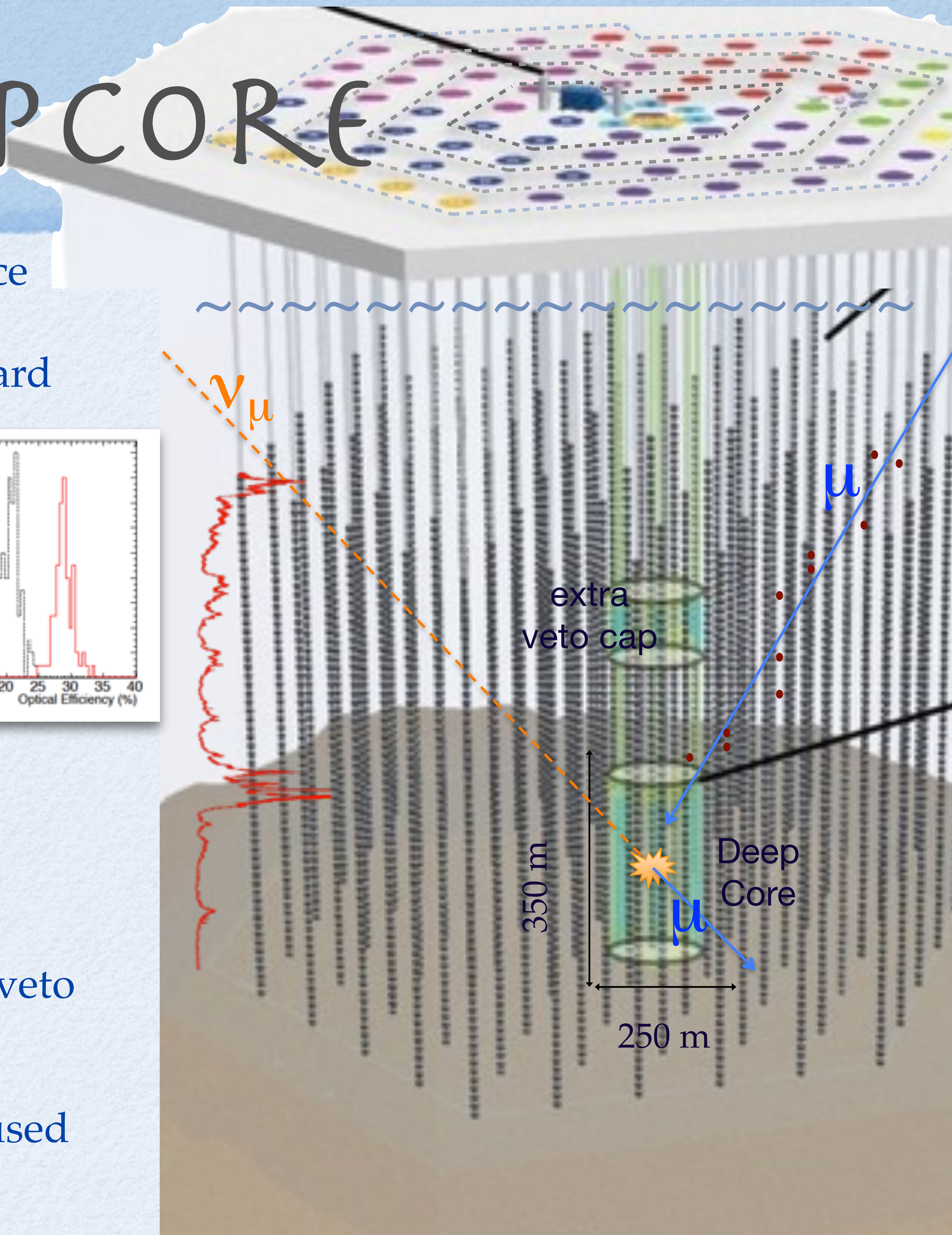
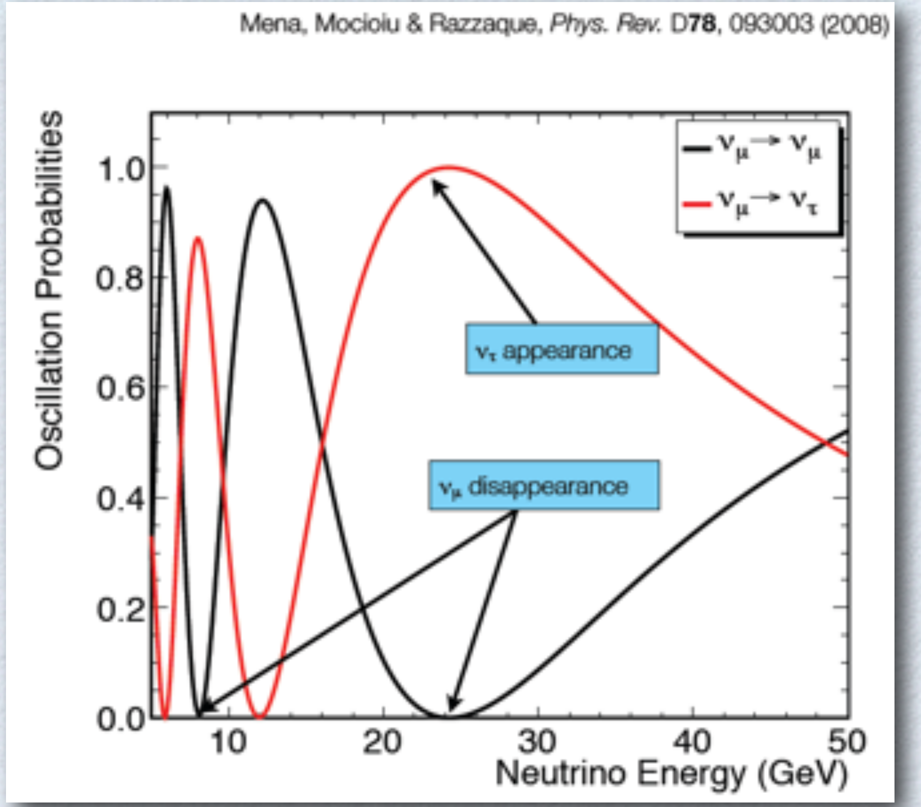
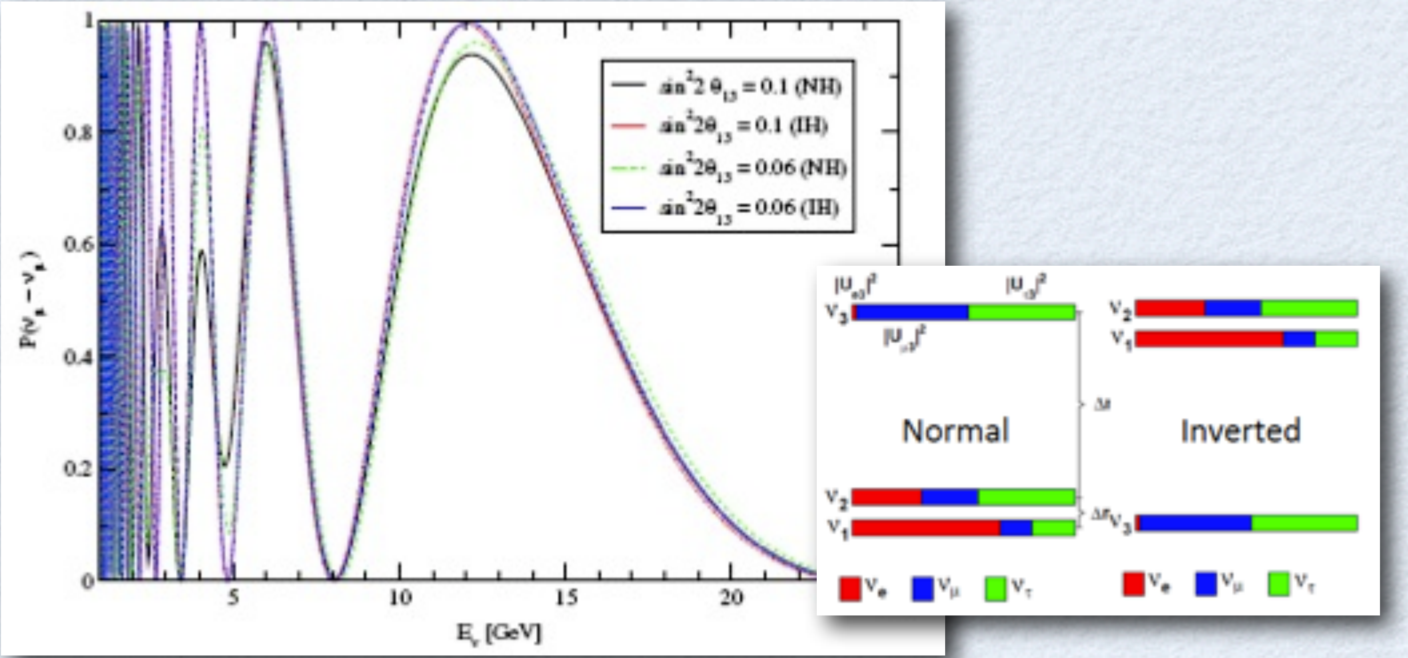




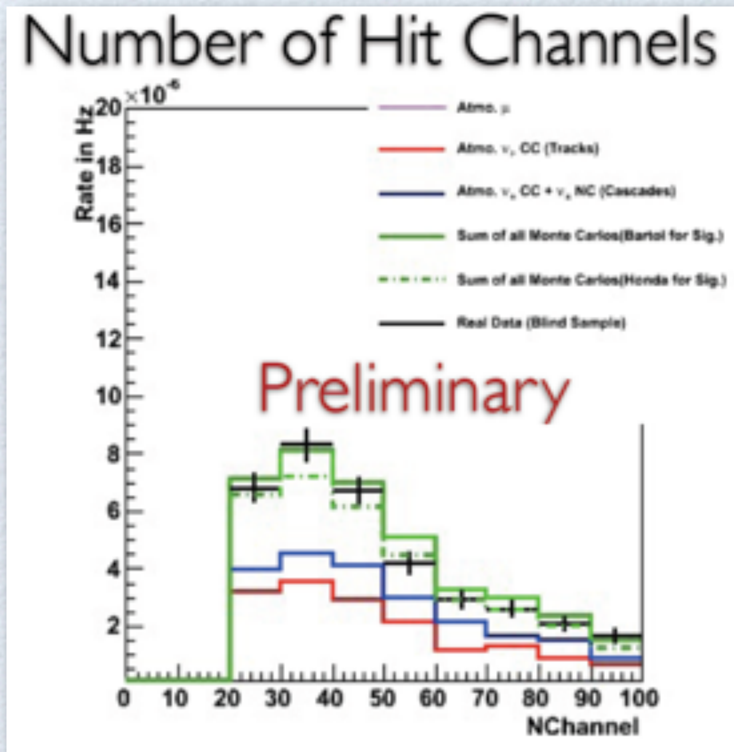
Atmospheric Neutrino Oscillations

- 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

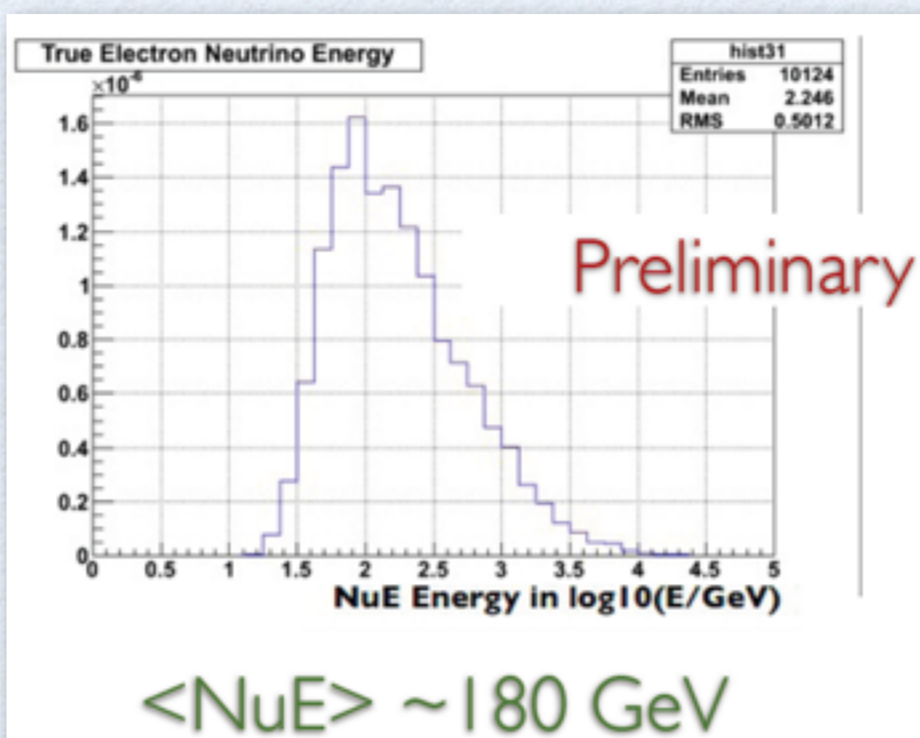


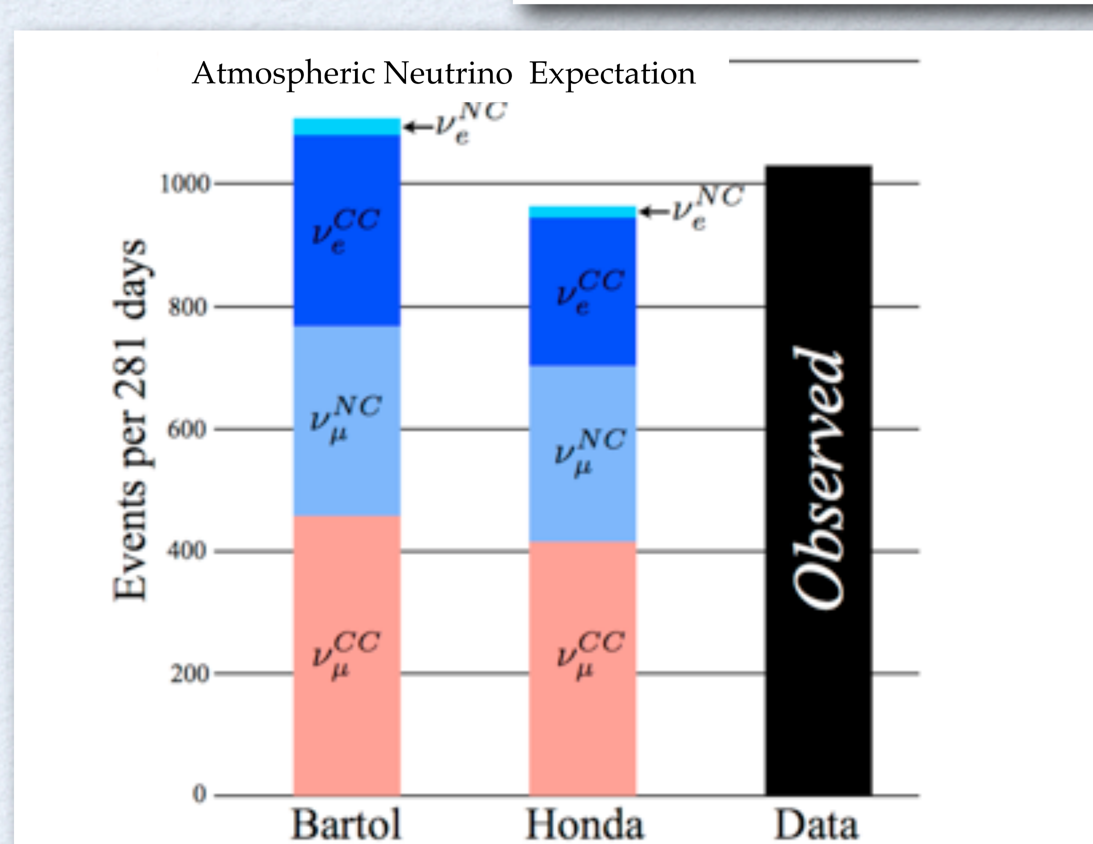


Cascades

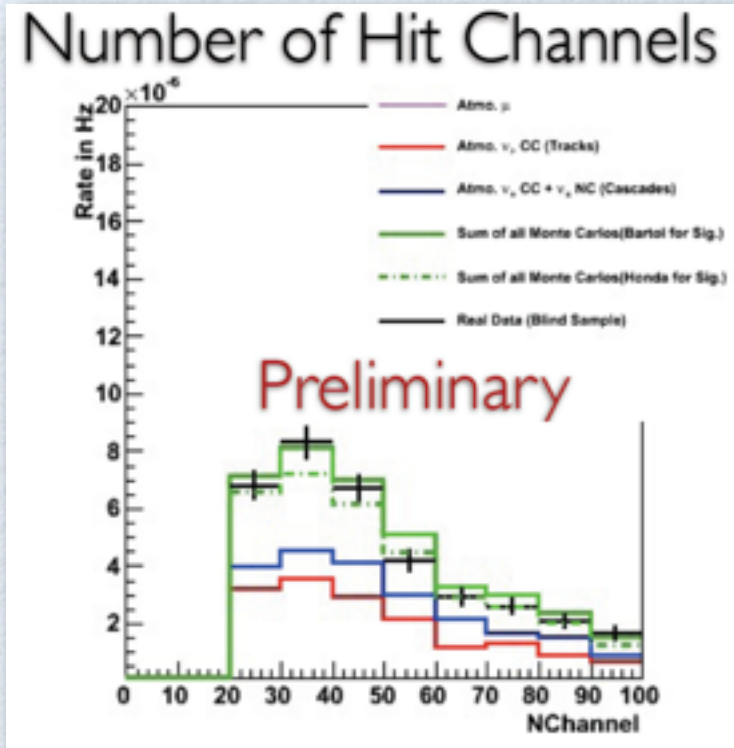


- Observation of cascades-like events consistent with expectation from atmospheric flux predictions
- The dominant background now is CC ν_μ events with short tracks

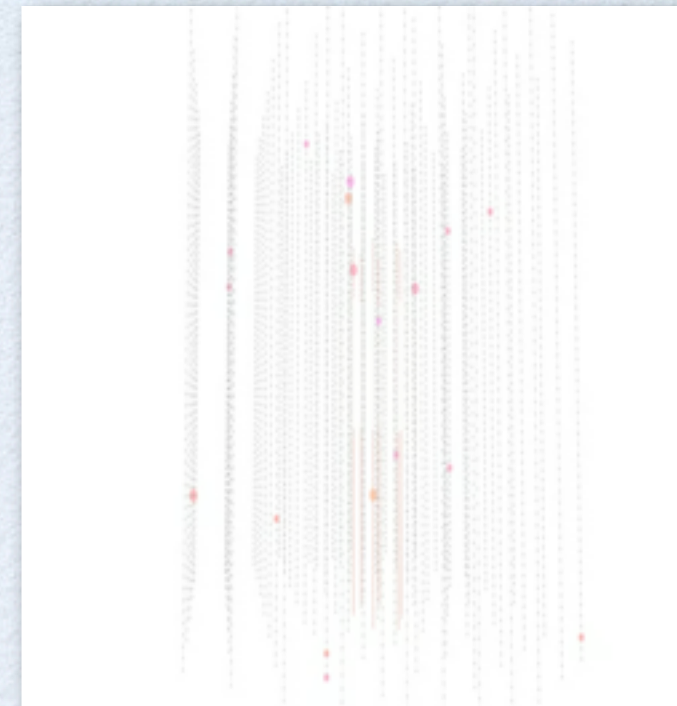


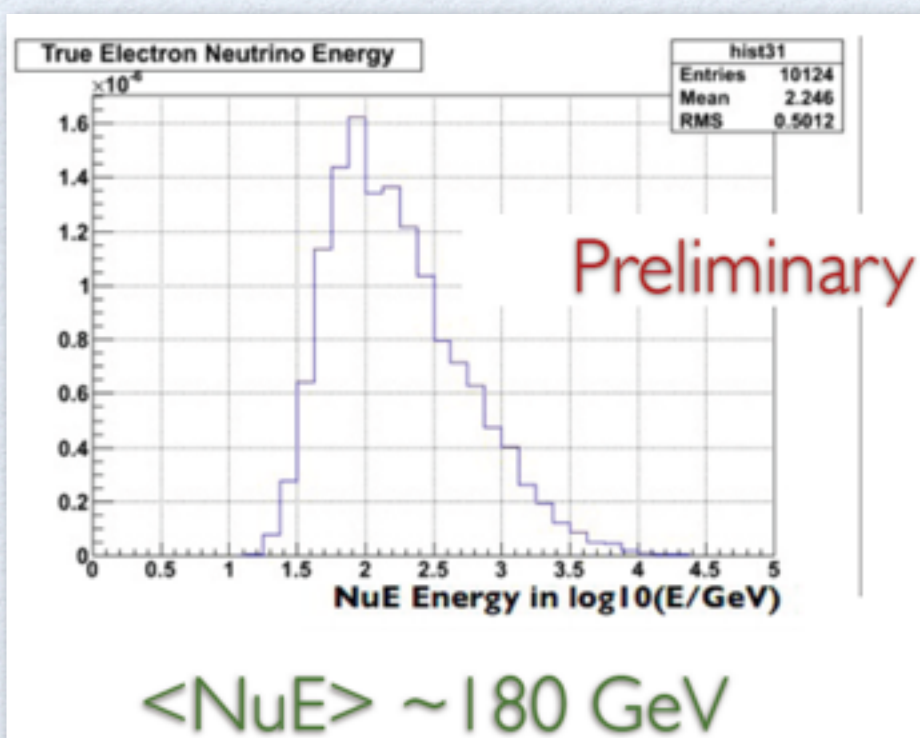


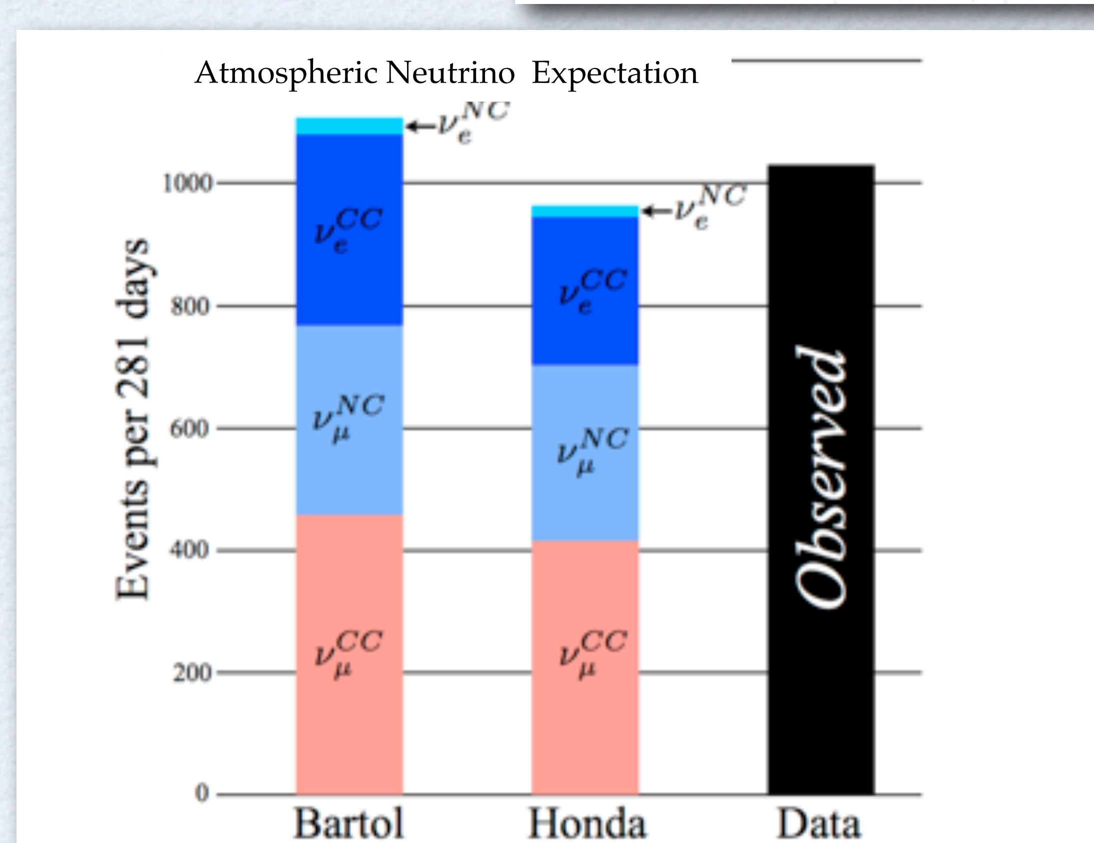
Cascades



- Observation of cascades-like events consistent with expectation from atmospheric flux predictions
- The dominant background now is CC ν_μ events with short tracks

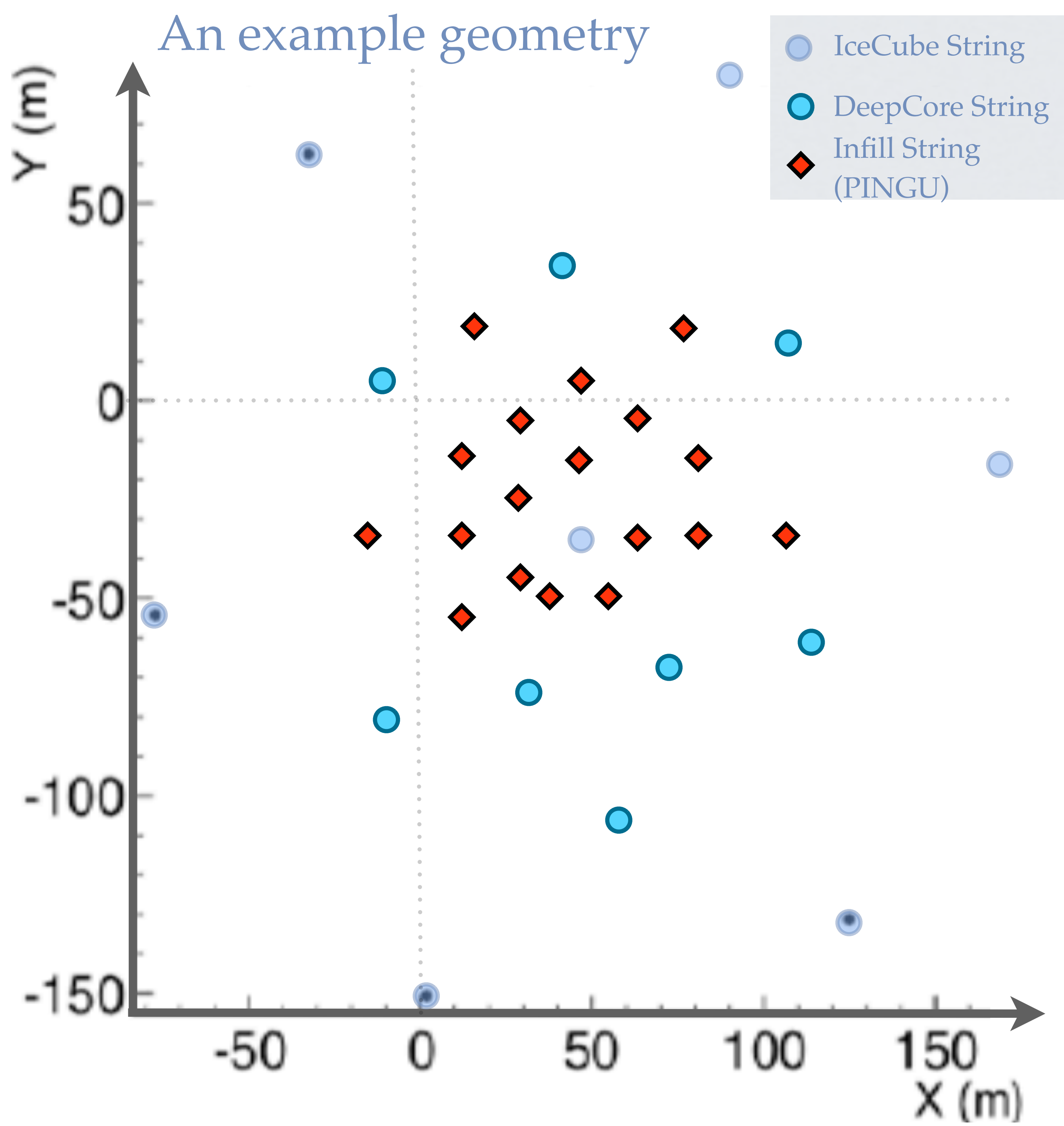






DeepCore and Beyond

- Test low mass WIMPs and precision measurements of neutrino oscillations
  - needs energy threshold of ~1GeV
- Developing a proposal to further in-fill DeepCore, called PINGU
  - Instrument a volume of about 10MT with 18-20 strings each containing 50-60 optical module
  - Rely on well established drilling technology
  - Create platform for calibration program and test technologies for future detectors
- Expected cost around \$25M - \$30M



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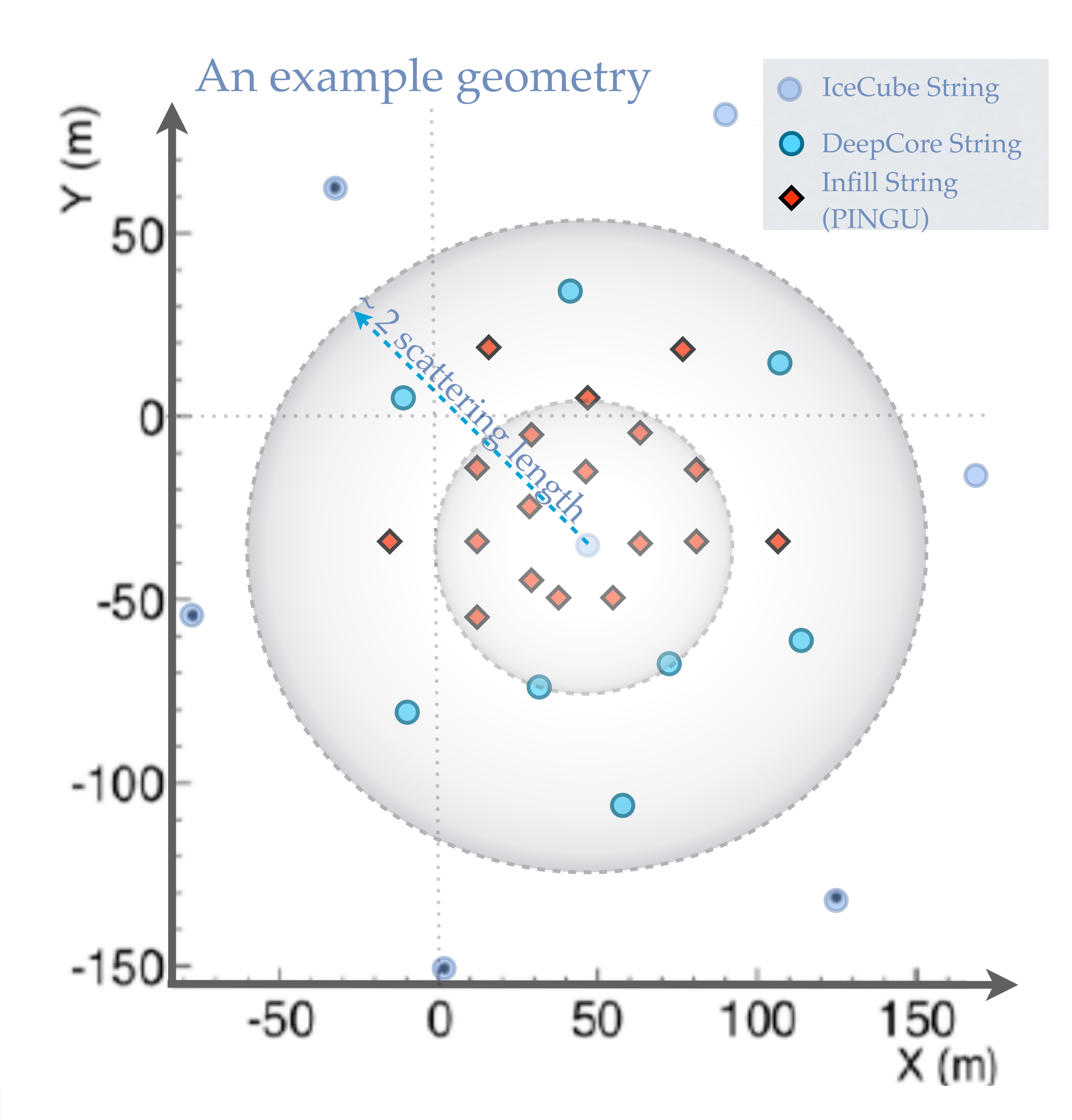
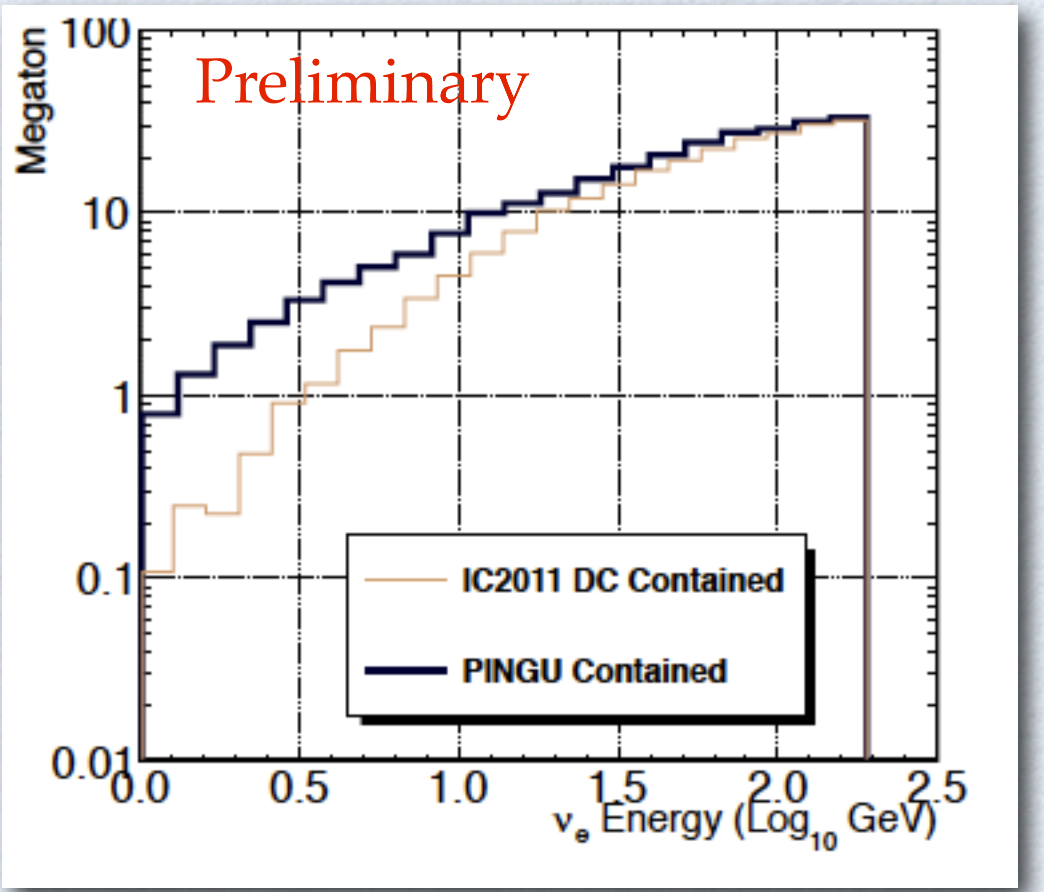
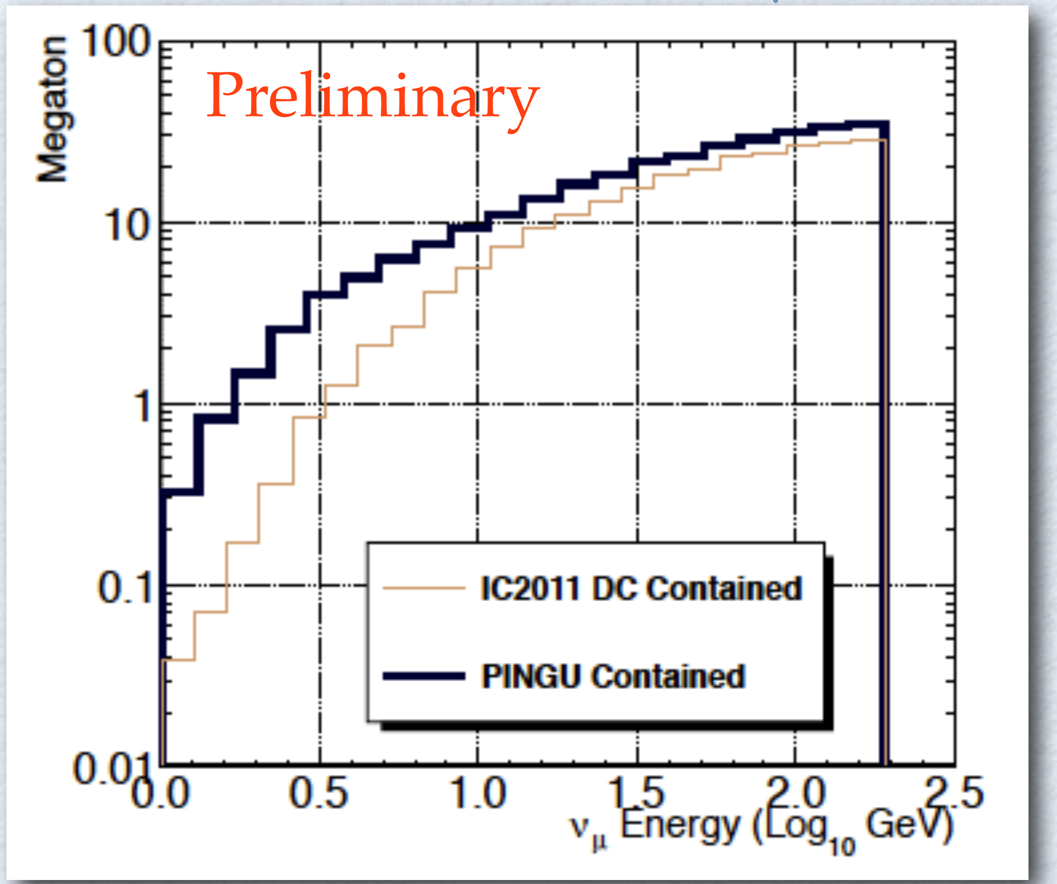


PINGU Effective Volumes

Effective Volume ν_e



Effective Volume ν_μ

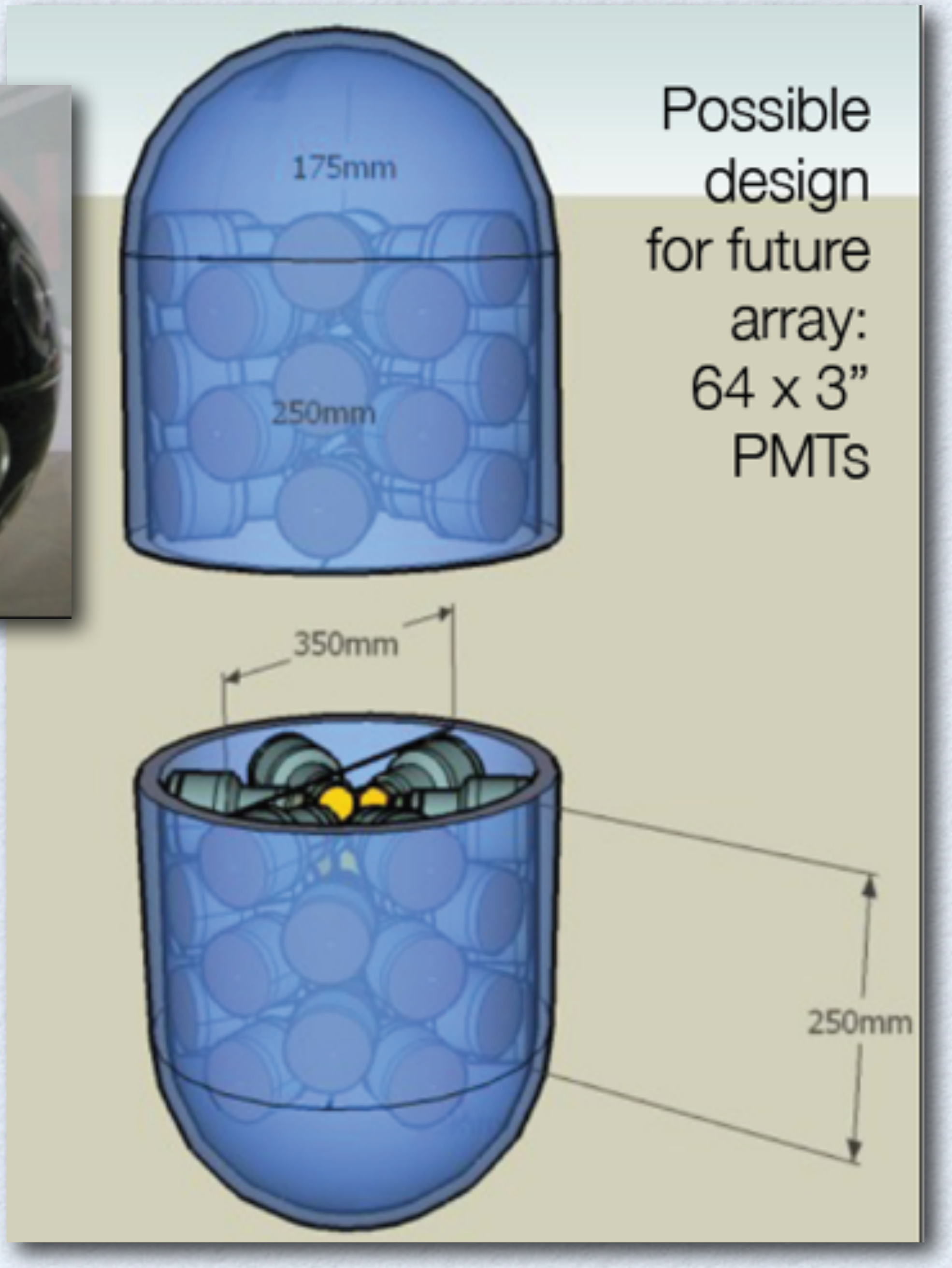


- Significant increase in effective volume below 10GeV, reach megaton size at few GeV
- Effective volume is at trigger level (analysis efficiencies not included)
  - Absolute scale lower, but improvement with respect to DeepCore expected to be much larger

R&D: Optical Module

- Multi-PMT Digital Optical Module (evolved KM3Net design)
  - Deployment Vessel
    - diameter similar to IceCube DOM
  - Sensors
    - 64 x 3" PMTs
  - Goal
    - pixelization
    - "isotropic" light acceptance
- R&D efforts have started

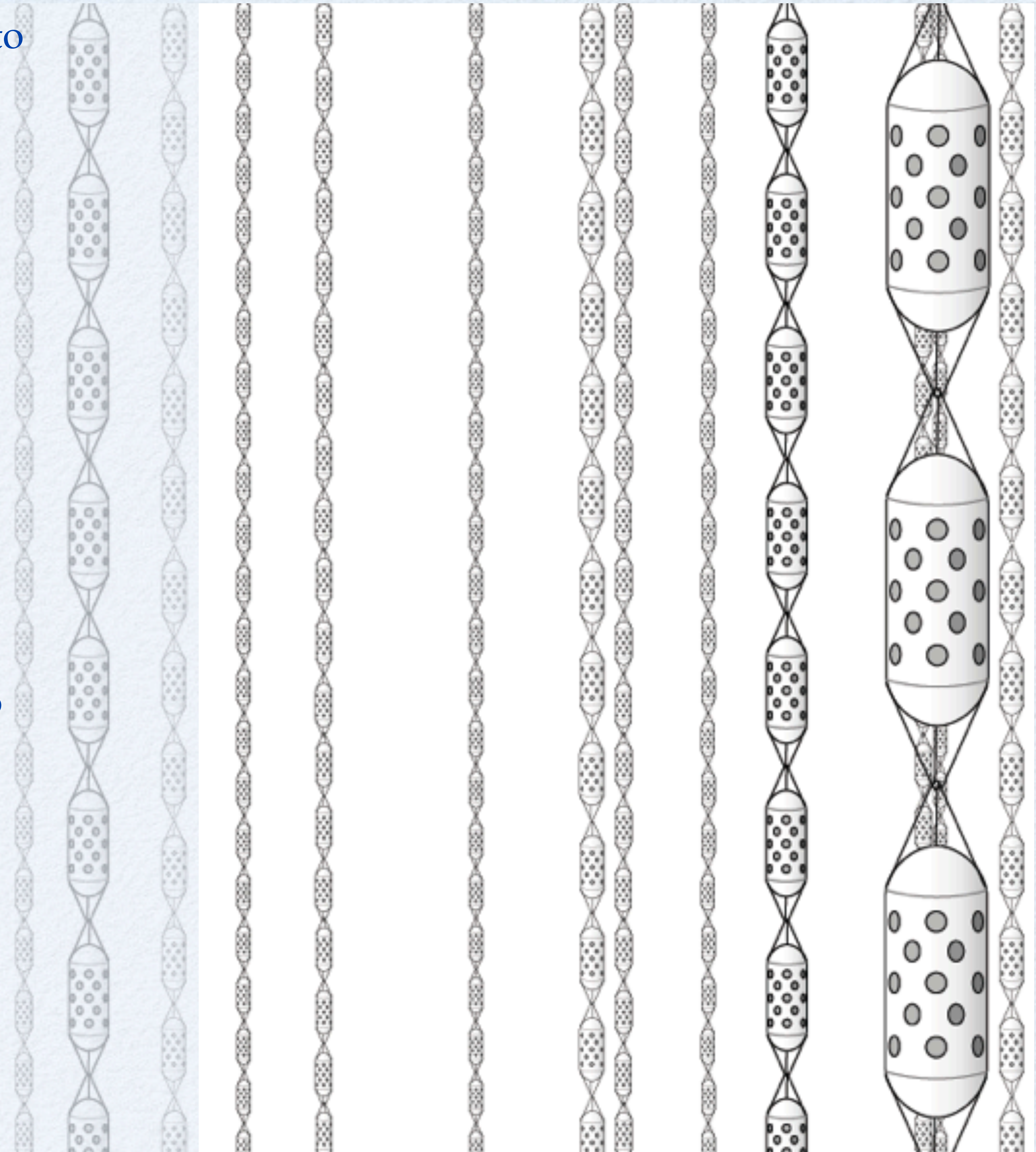
Courtesy E. de Wolf & P. Kooijman



Plan to deploy 3-4 strings of new Multi-PMT DOMs for PINGU

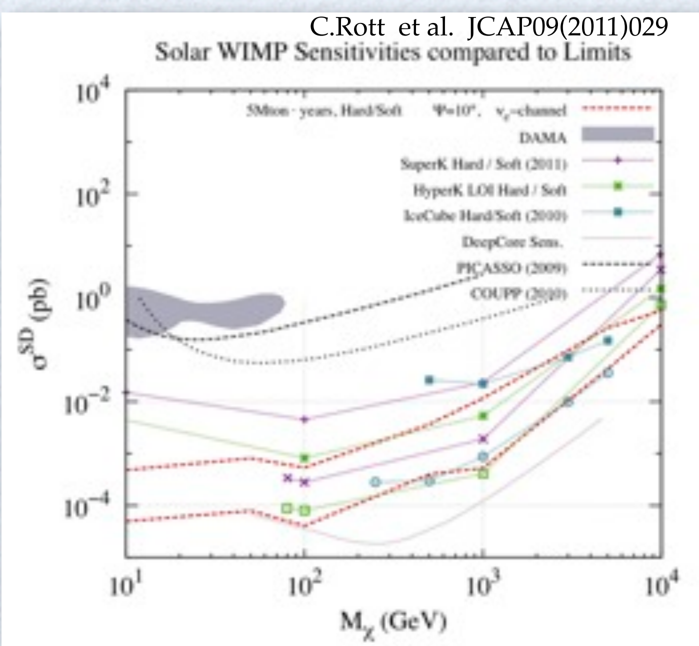
Beyond PINGU

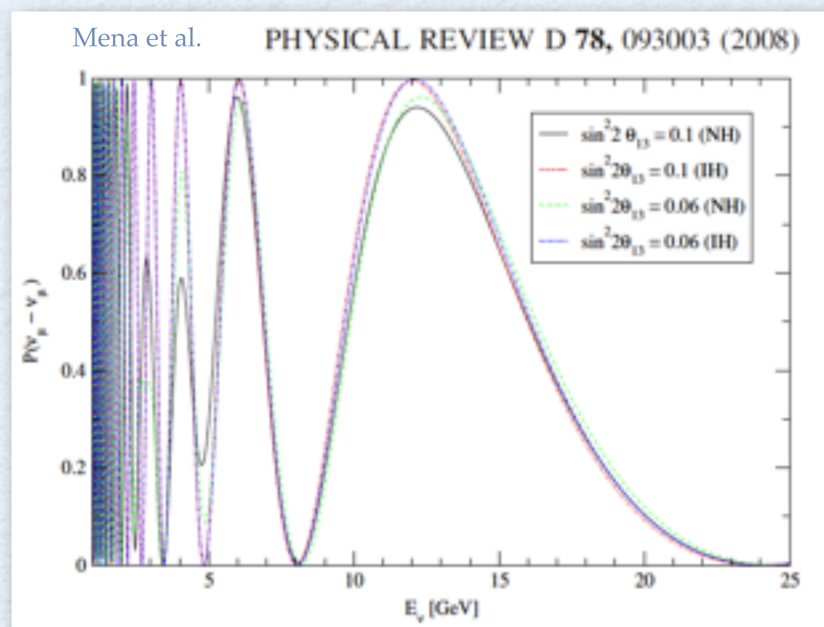
- Few hundred strings of "linear" detectors to be deployed within DeepCore
  - String spacings ~5 m, sensors spaced by ~1 m on a string
- An ambitious vision worth working towards:
  - ~5 MTon fiducial volume
  - Photo coverage ~10%
  - O(10 MeV) threshold for bursts
  - O(100 MeV) for single events
- IceCube and DeepCore provide active veto
  - No excavation is necessary, drilling/ deployment has been refined to an industrial process – deployment costs would be well below 10% of total
- Physics extraction from Cherenkov ring imaging in the ice

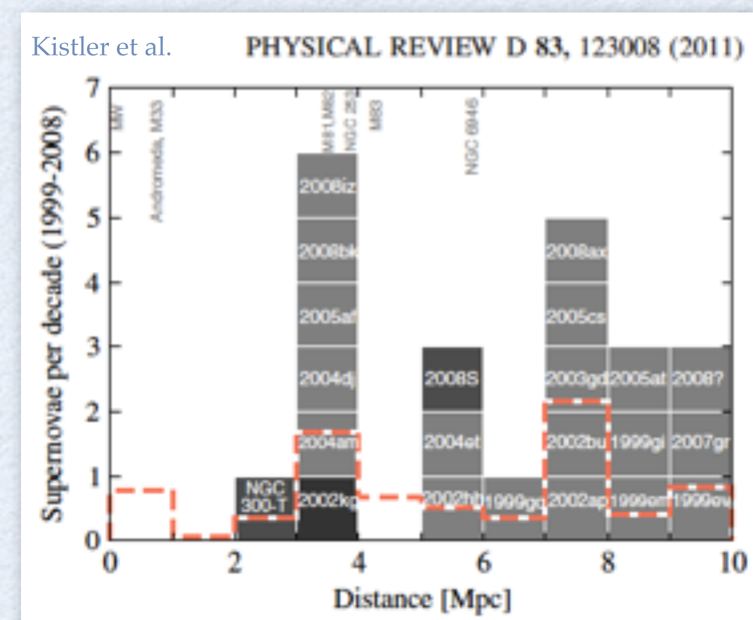


Main PINGU and beyond physics goals

- Dark Matter
  - Test low mass WIMP scenarios
- Neutrino Physics
  - Atmospheric neutrino oscillation physics
- Supernova neutrinos
  - Extend reach beyond Milky Way (?)







PINGU and Beyond Summary

- Aim to construct MT-size detector at the South Pole in two stages
  - Stage 1 (20 string Deep Core upgrade):
    - Improved Dark Matter Sensitivity, Neutrino Oscillations, Improved Supernova Sensitivity
    - Rely on proven IceCube technology and test new technologies
  - Stage 2 (100s of strings):
    - Dark Matter, Neutrino Oscillations, Supernova Detection beyond the Milky Way (?), Extensions reaching proton decay could possibly be contemplated
    - Technology decision based on stage 1 experience
- A PINGU white paper is in preparation

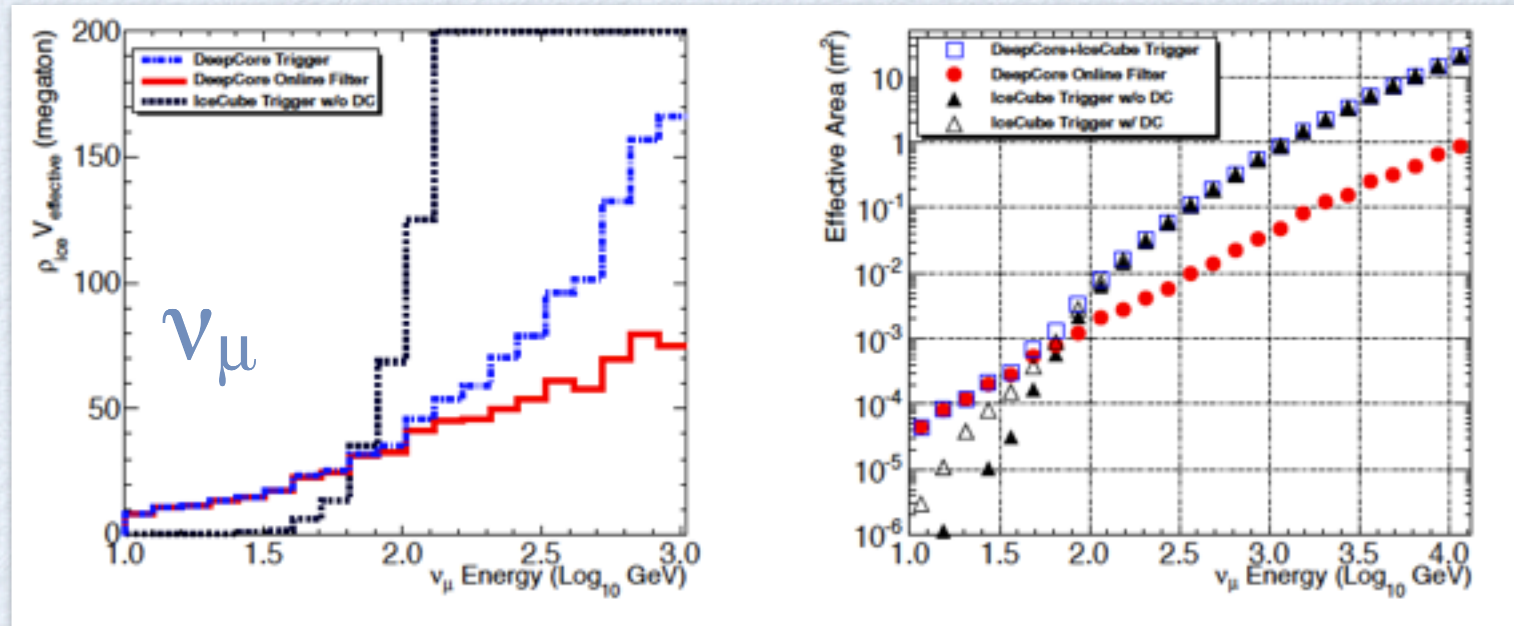
Conclusions

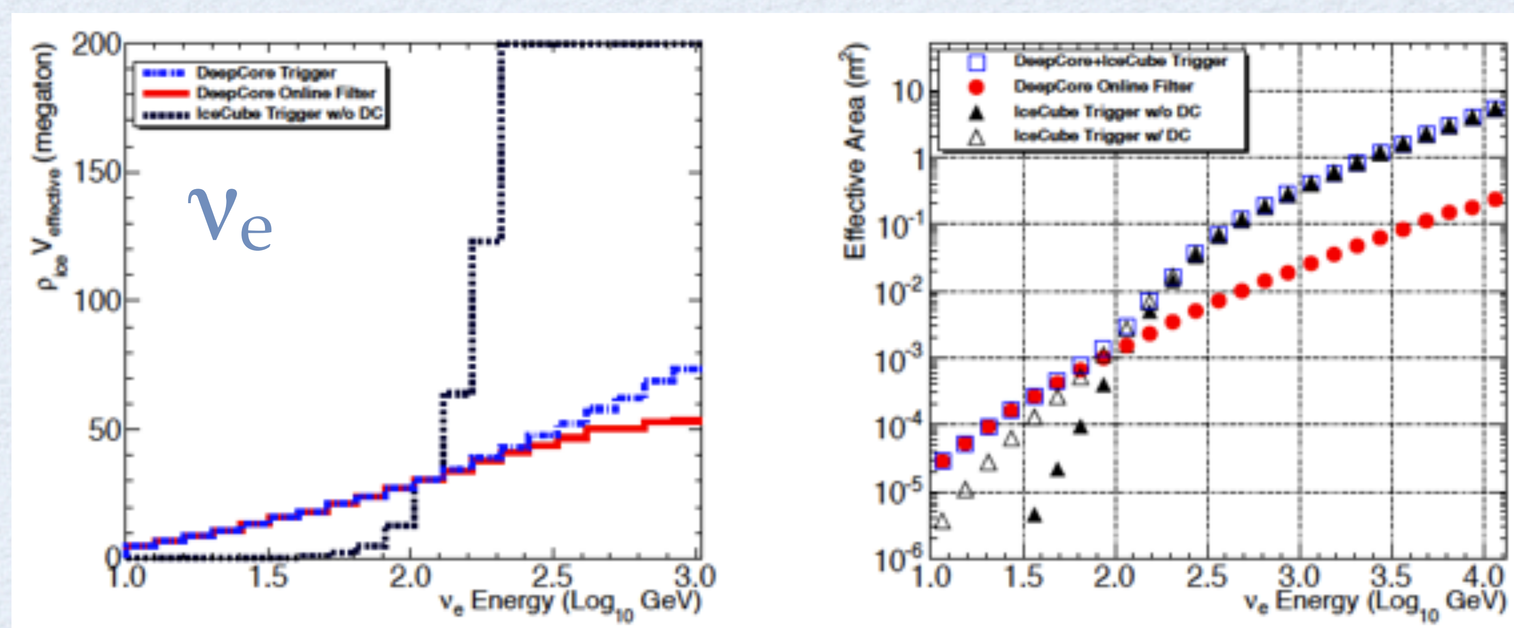
- The IceCube Neutrino Telescope was completed in December 2010 and we are acquiring data with the full detector configuration since May 2011
- The partially instrumented detector has been operating very stable and we produced already a variety of very competitive results
  - Observed CR anisotropy, measured the atmospheric neutrino spectrum, observation of cascades, ...
  - Set limits on diffuse and point-like fluxes of astrophysical neutrinos, WIMP-nucleon scattering cross sections, and ...
- Look forward to many years of exciting physics

BACKUP

DeepCore Effective Area/Volume

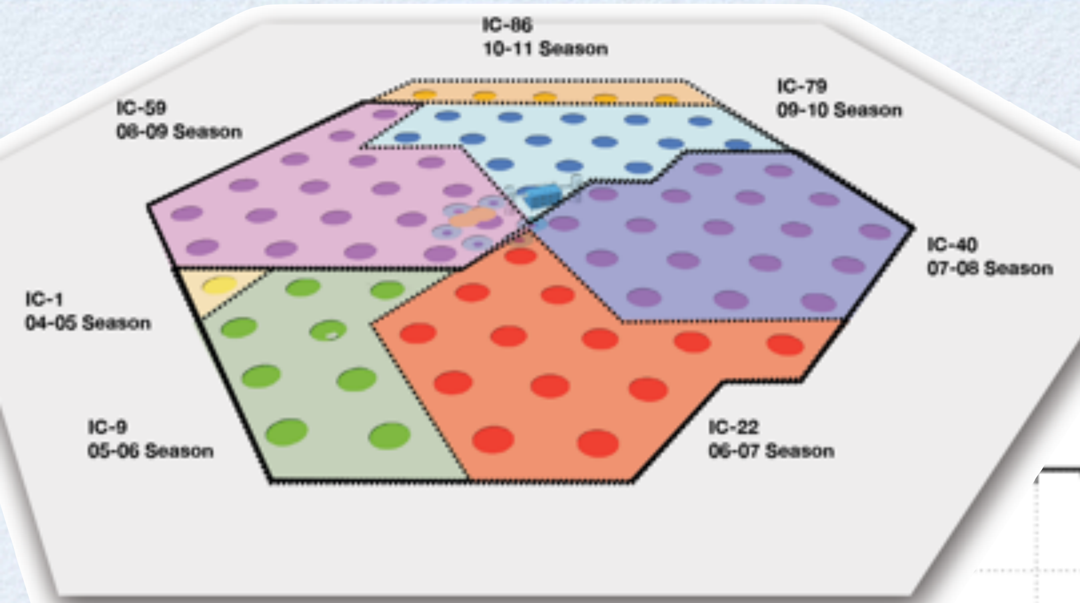
- DeepCore dominates energy response below 100GeV
- Effective area is trigger level, analysis cuts will further degrade this efficiency
- Once detector is fully efficiency, growth is driven by the neutrino cross section increase

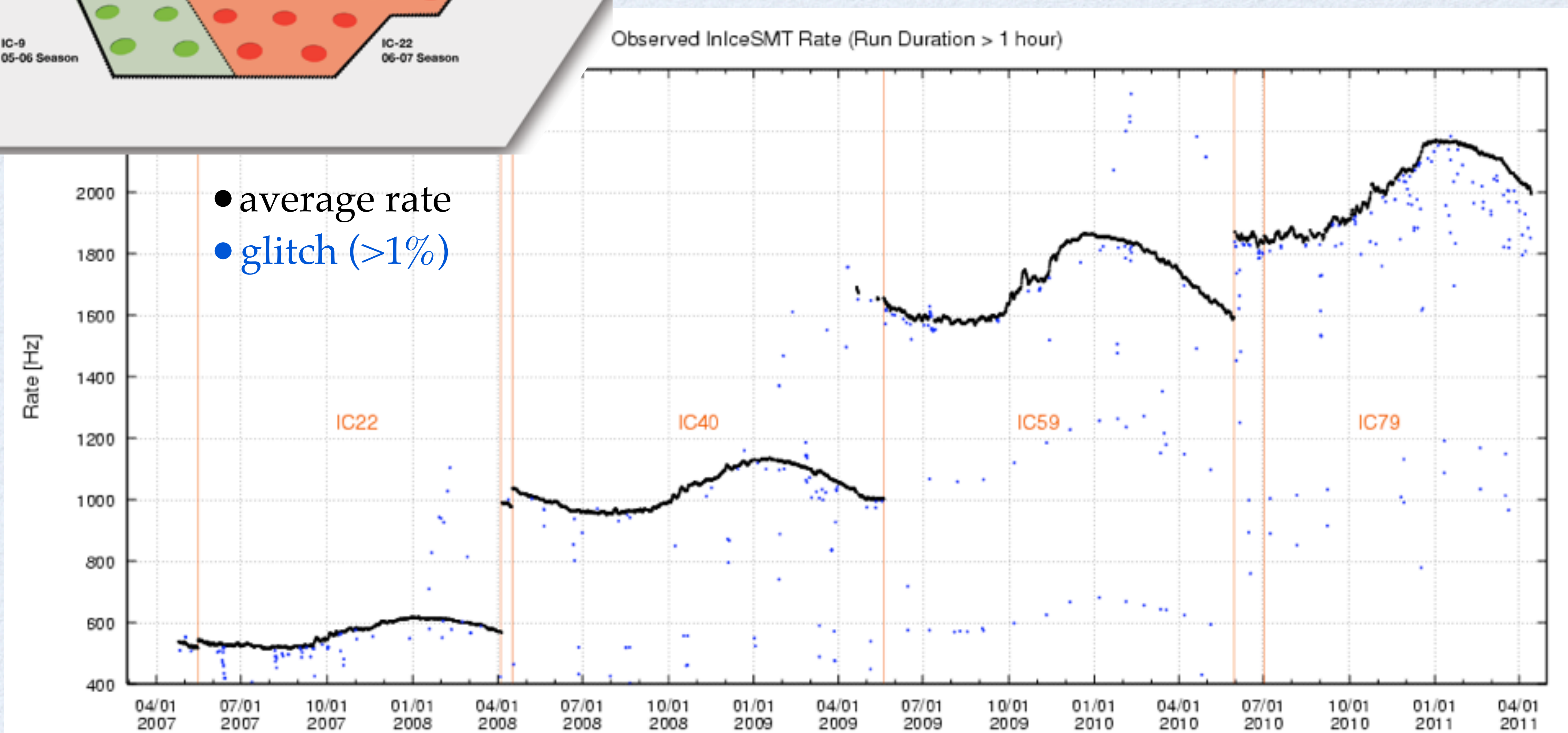




Growing IceCube and Seasonal Variations

- IceCube is functioning extremely well
  - >98% modules are working fine
  - uptime ~99%





ANTARES / IceCube Complementarity