Recent Results from the IceCube Neutrino Telescope

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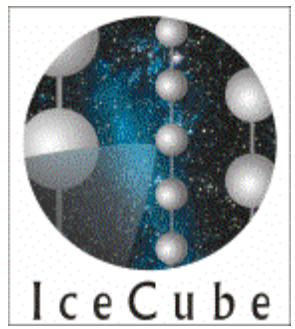
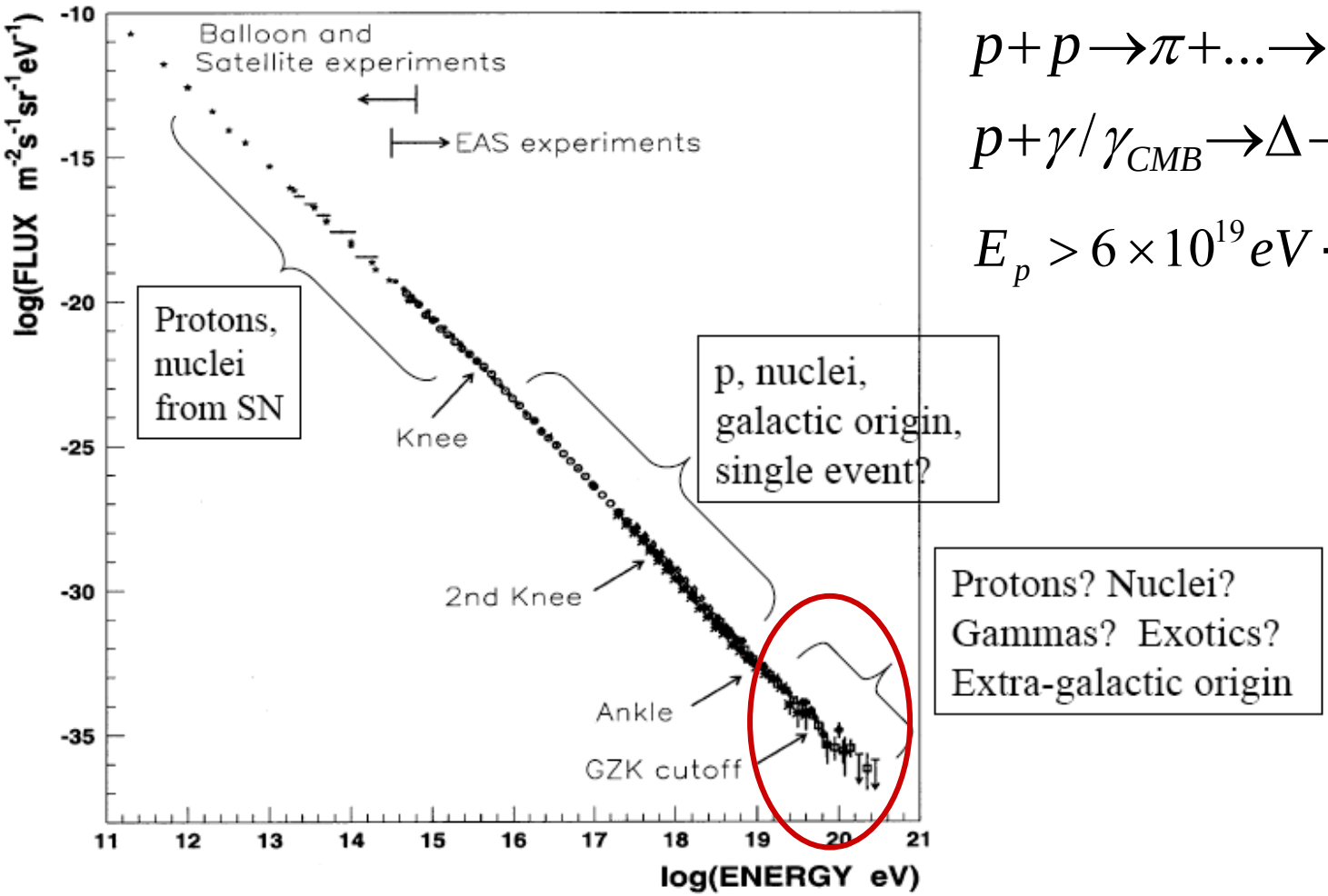


Overview

- Neutrino Astronomy
- The IceCube Detector
- Recent Results (Selected)
- Summary and Outlook

Neutrino Sources and Cosmic Rays

What is the origin of Cosmic Rays with Energy up to 10^{20} eV ?



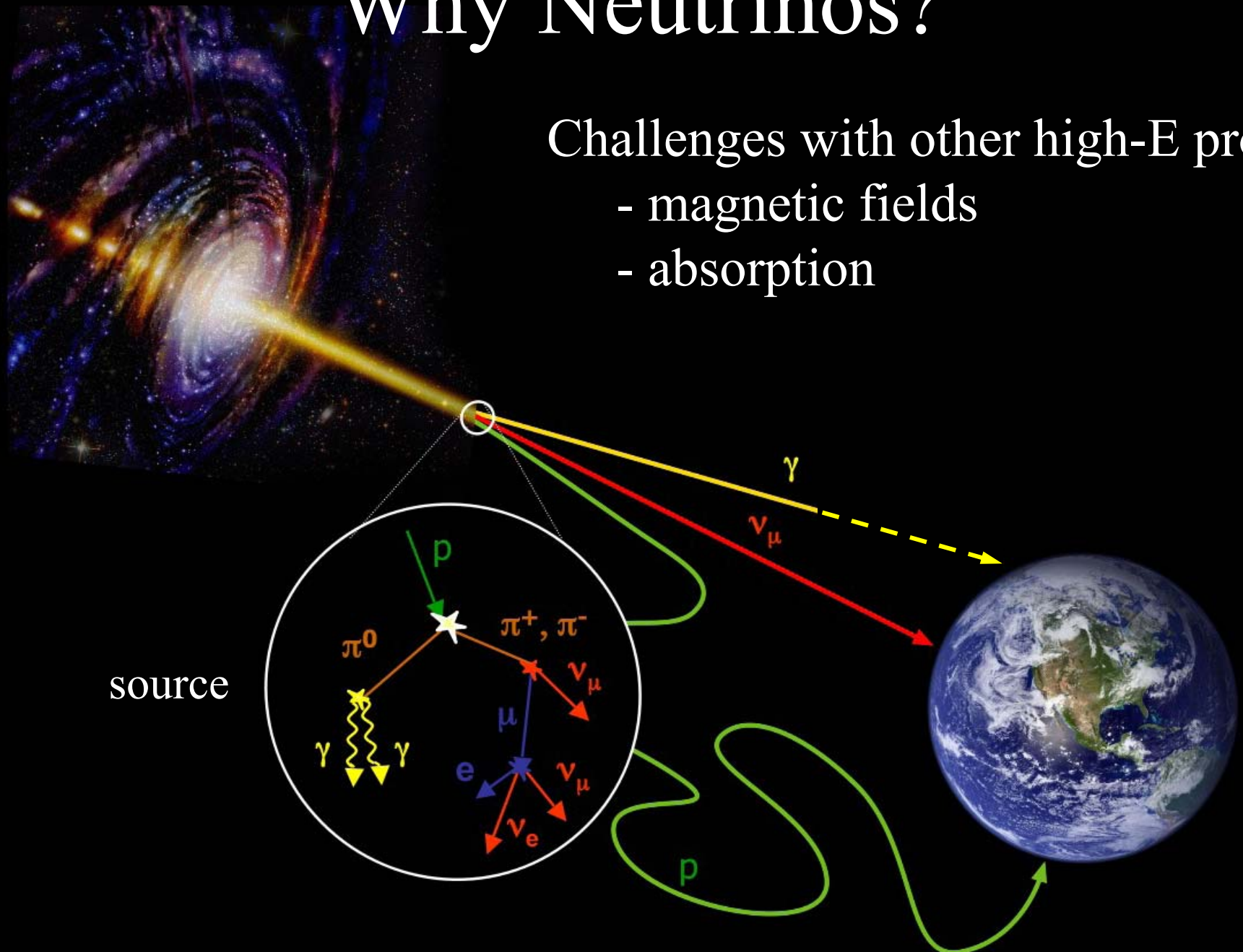
$$p+p \rightarrow \pi+... \rightarrow \nu+... \quad \text{or}$$

$$p+\gamma/\gamma_{CMB} \rightarrow \Delta \rightarrow \pi+n \rightarrow \nu+...$$

$$E_p > 6\times10^{19} eV \rightarrow \text{GZK cutoff}$$

Why Neutrinos?

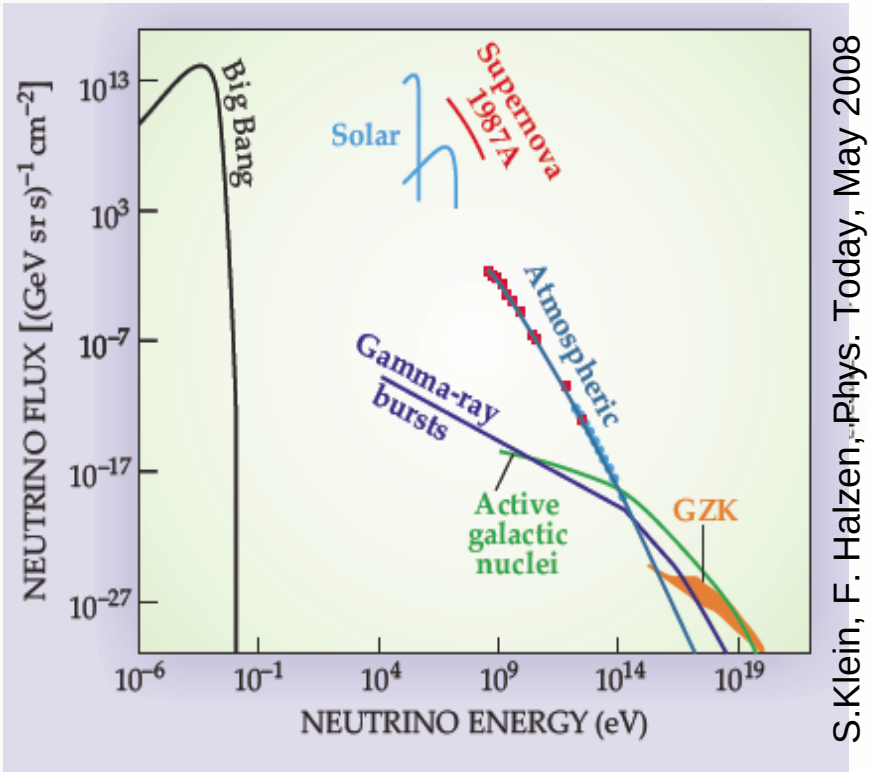
Challenges with other high-E probes
- magnetic fields
- absorption



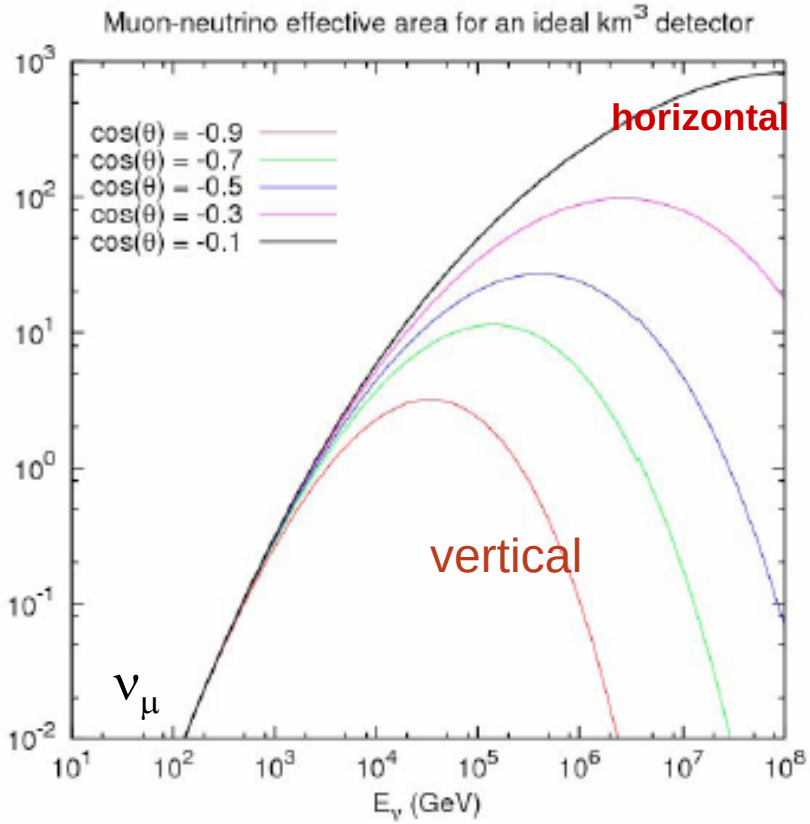
Why a 1 km^3 Detector?

Rate = Neutrino flux x Neutrino Effective Area

= Neutrino flux x Neutrino Cross Section x Absorption in Earth x Size of detector x (Range of muon for ν_μ)



S.Klein, F. Halzen, Phys. Today, May 2008



Expected GZK neutrino rate in 1 km^3 detector: ~ 1 per year

Scientific Goals of IceCube

- General: detect neutrinos (all flavors) between ~10^{10} eV and 10^{20} eV, as well as low energy ν's from supernovae

- Astronomy
  - Astrophysical neutrino point sources
  - Diffuse astrophysical flux from all sources
- New Physics
  - Dark Matter
  - Neutrino Oscillations
  - Exotics (Monopoles, etc…)
- Cosmic Rays
  - Spectrum
  - Composition
  - Anisotropy

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This Talk

A Neutrino Telescope at the South Pole

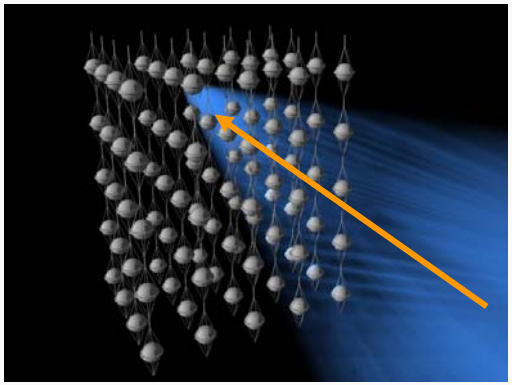
Counting House

Amundsen–Scott Station

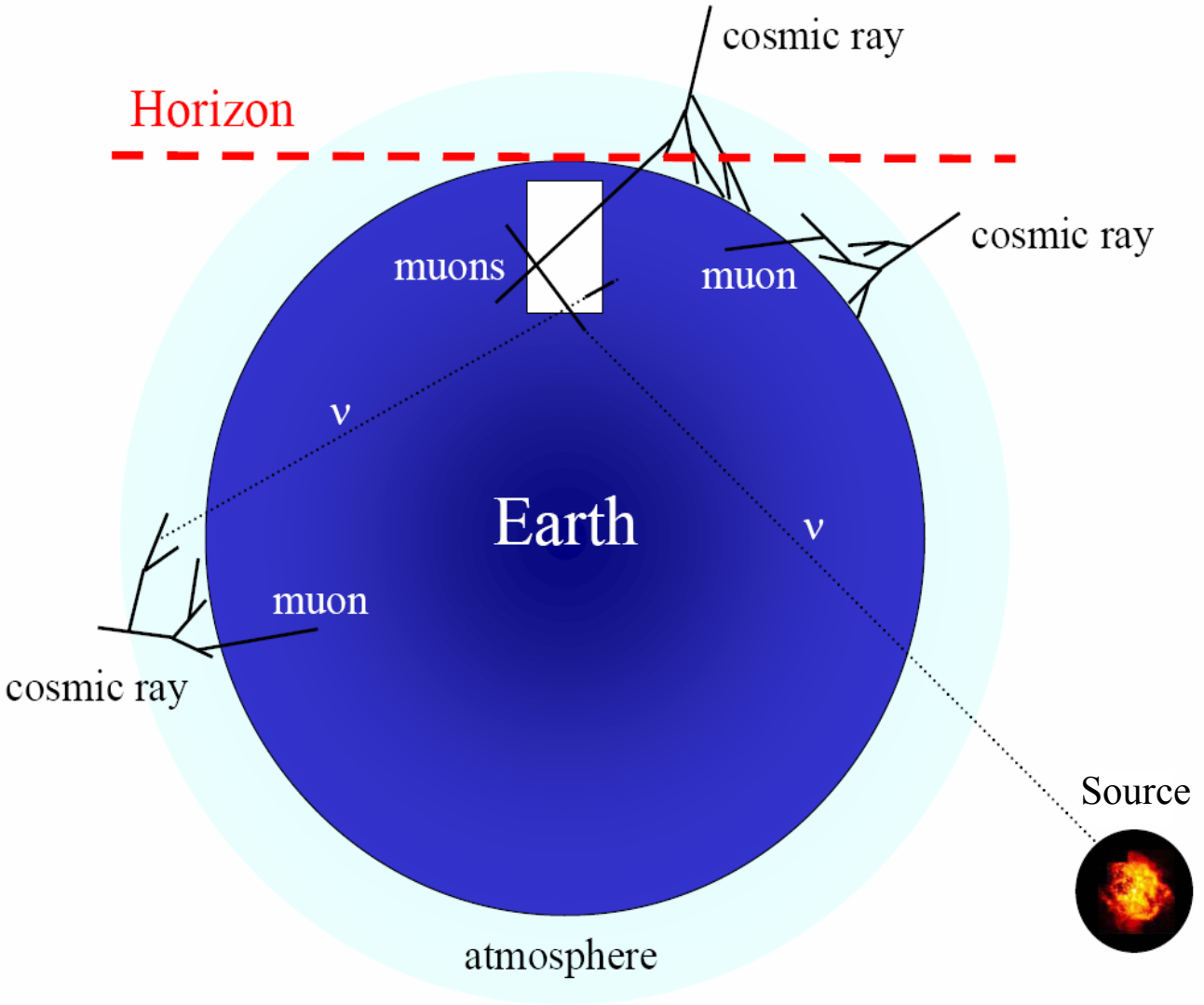
South Pole

IceCube

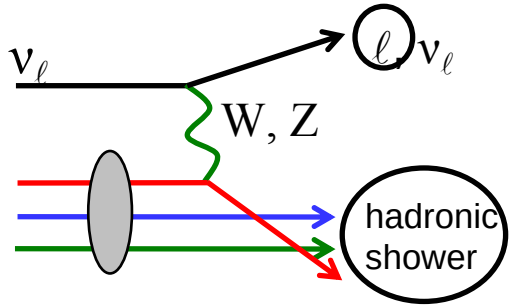
Principles of Neutrino Detection

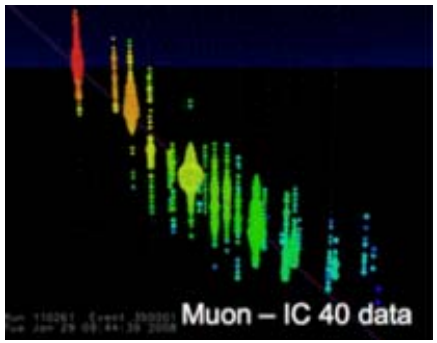


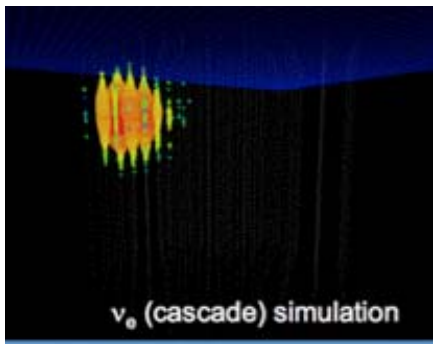
- Array of optical sensors
- High energy daughter lepton emits Cherenkov light
- Record light arrival times, amplitudes

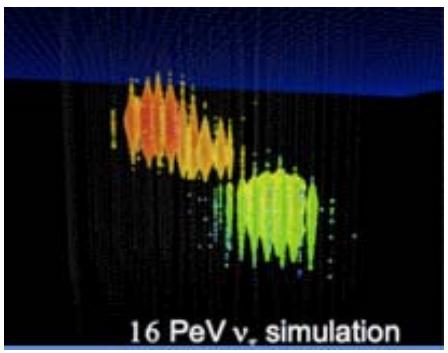


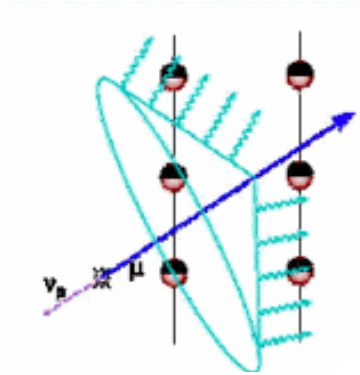
Neutrino Signatures

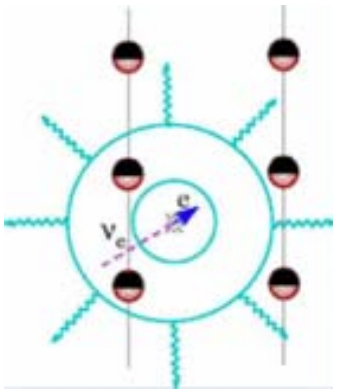












Tracks:

- $\nu_\mu + N \rightarrow \mu + X$
- pointing resolution ~1°
- used for point source and diffuse flux searches

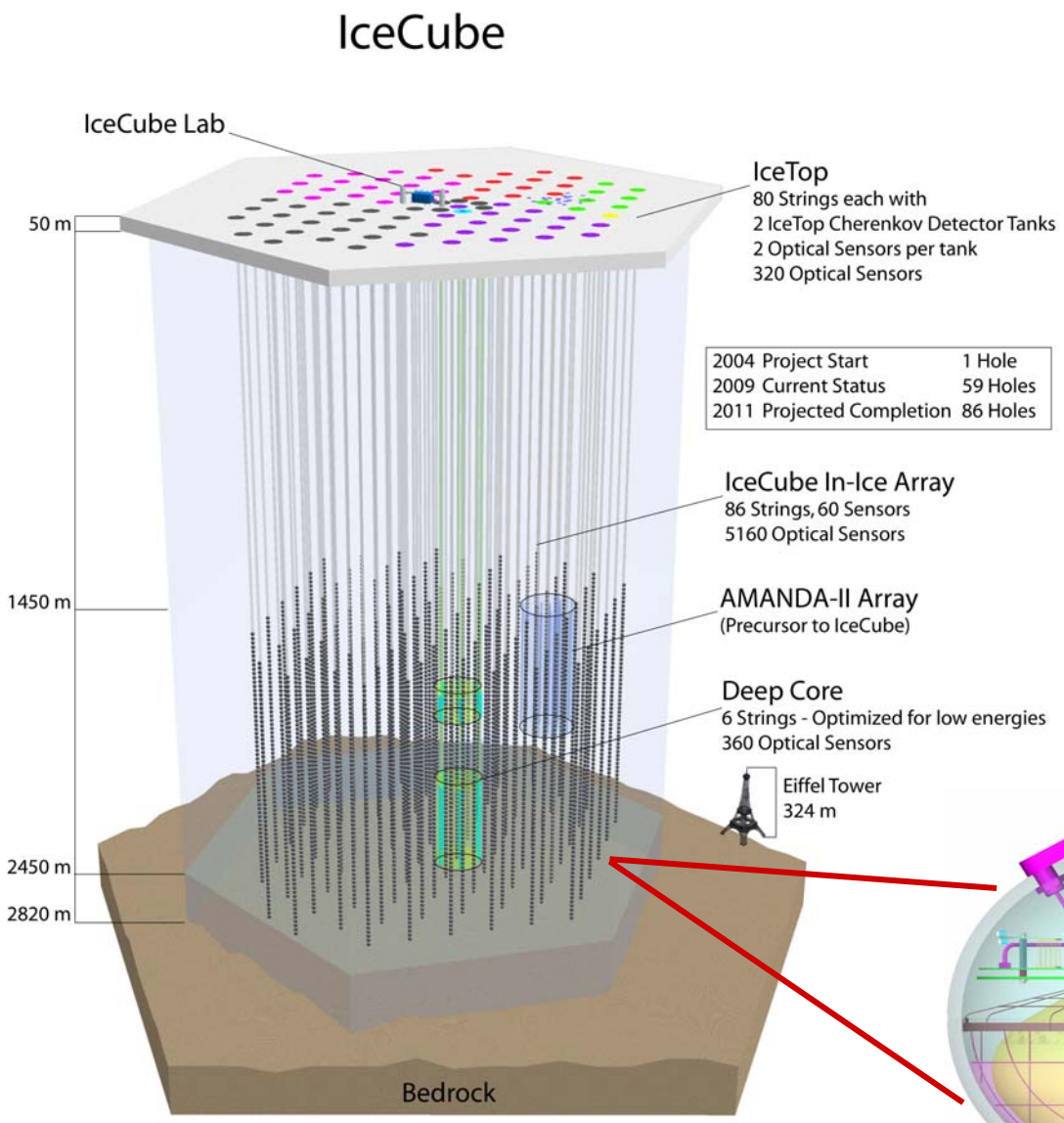
Cascades:

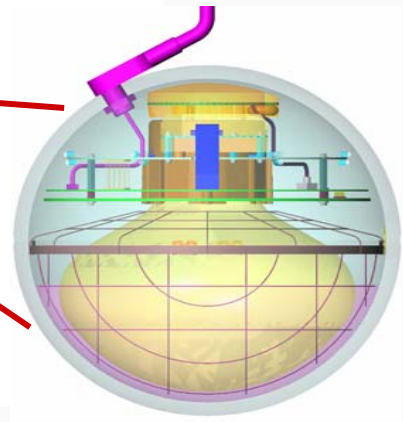
- e-m and hadronic cascades
- $\nu_{e(\tau)} + N \rightarrow e(\tau) + X$
- $\nu_f + N \rightarrow \nu_f + X \quad f = e, \mu, \tau$
- energy resolution 10% in log(E)
- used for diffuse flux searches

Composites

- starting tracks
- tau double bangs
- good directional and energy resolution

The IceCube Detector



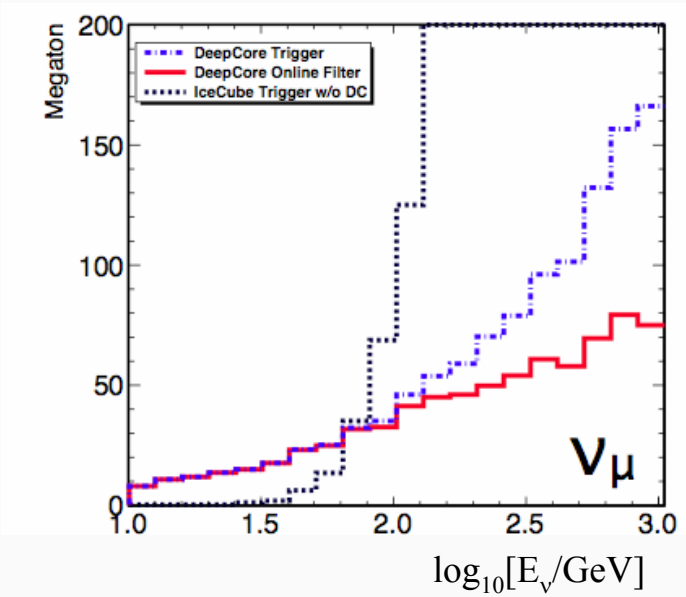


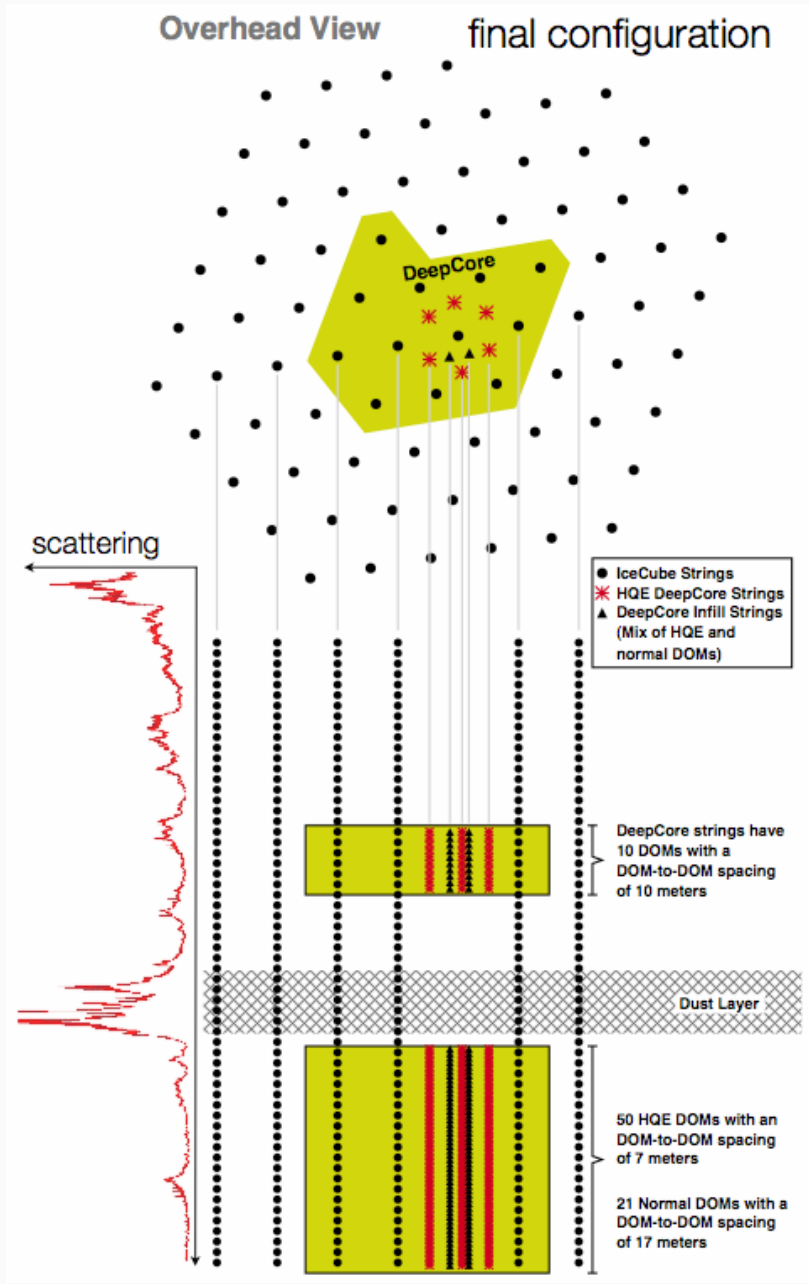
Digital Optical Module (DOM)

- Detector completion in 2010-2011
- 1450 m – 2450 m
- 80 strings
  - 60 DOMS each
  - 125 m horizontal
  - 17 m vertical
- +6 DeepCore strings

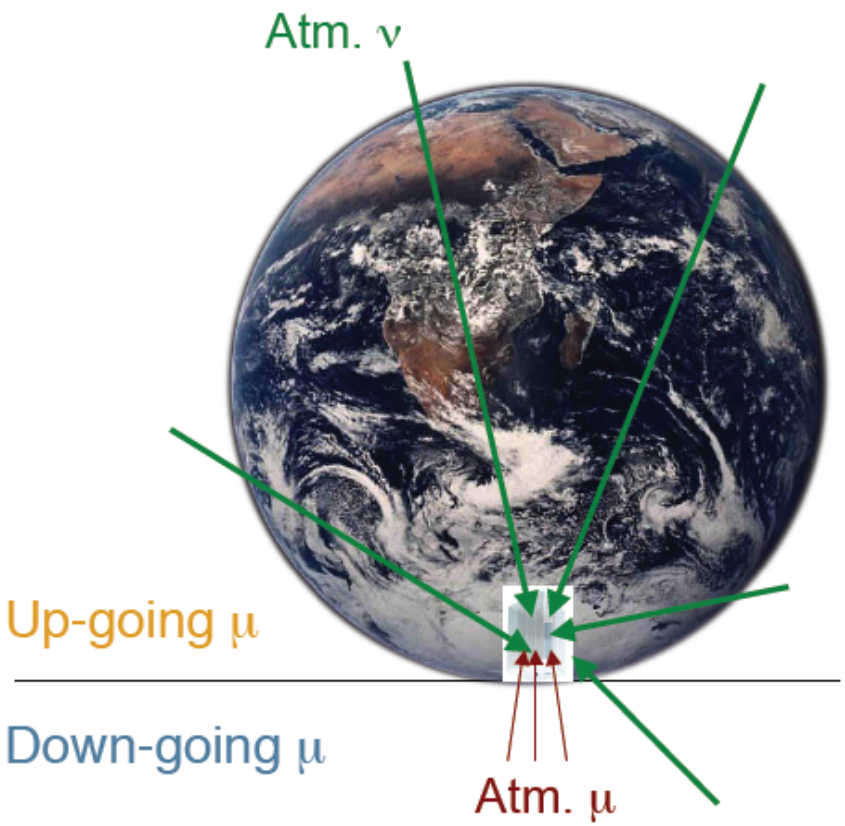
More about DeepCore

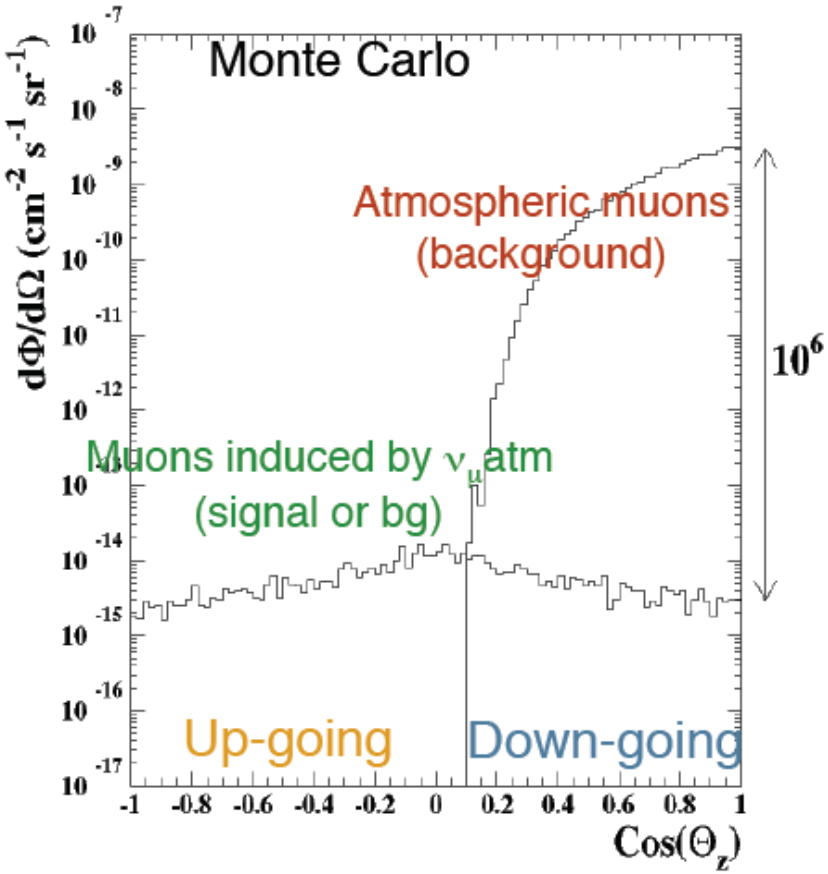
- Deployed in deepest, clearest ice
- High QE PMTs
- More densely spaced
  - 72 m horizontal
  - 7 m vertical
- Lowers energy threshold to ~10 GeV
- IceCube as active veto (muon shield)





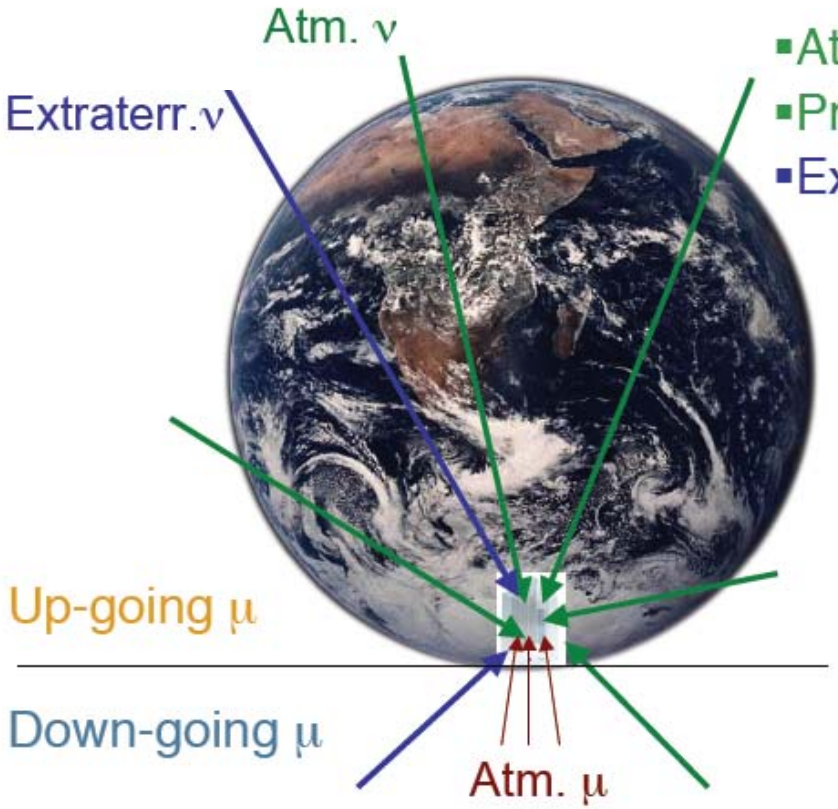
Background Rejection (low energy)



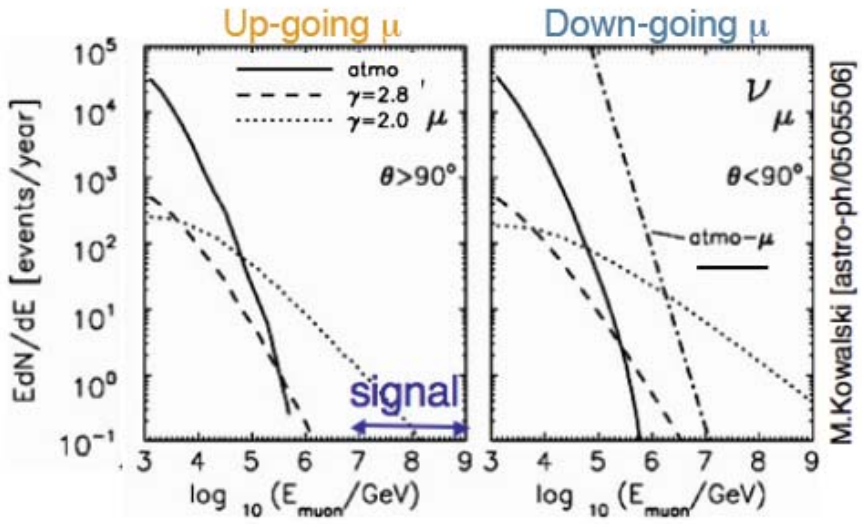


- Reject muon backgrounds by <u>direction</u>
- Topology helps remove mis-reconstructed muons

Background Rejection (high energy)



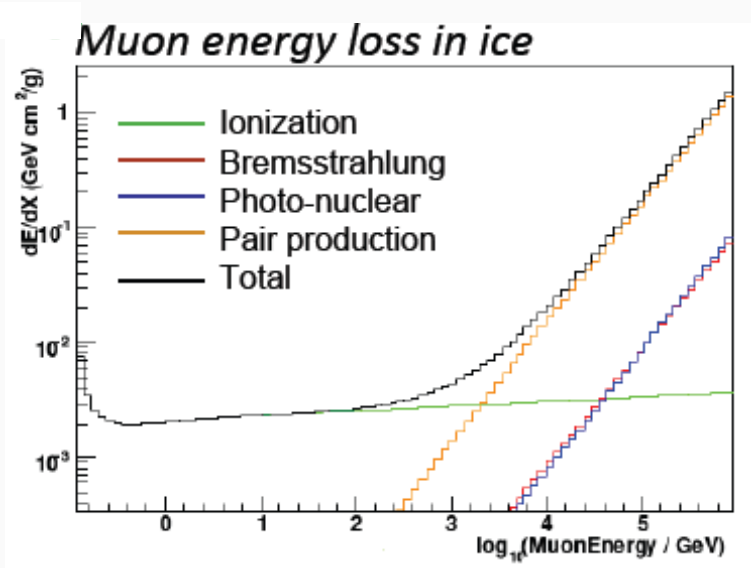
- Atm. ν: $dN/dE \sim E^{-3.7}$ bg ν
- Prompt atm. ν: $dN/dE \sim E^{-2.8}$ bg ν
- Extraterrestrial ν: $dN/dE \sim E^{-2.0}$ (model) signal ν

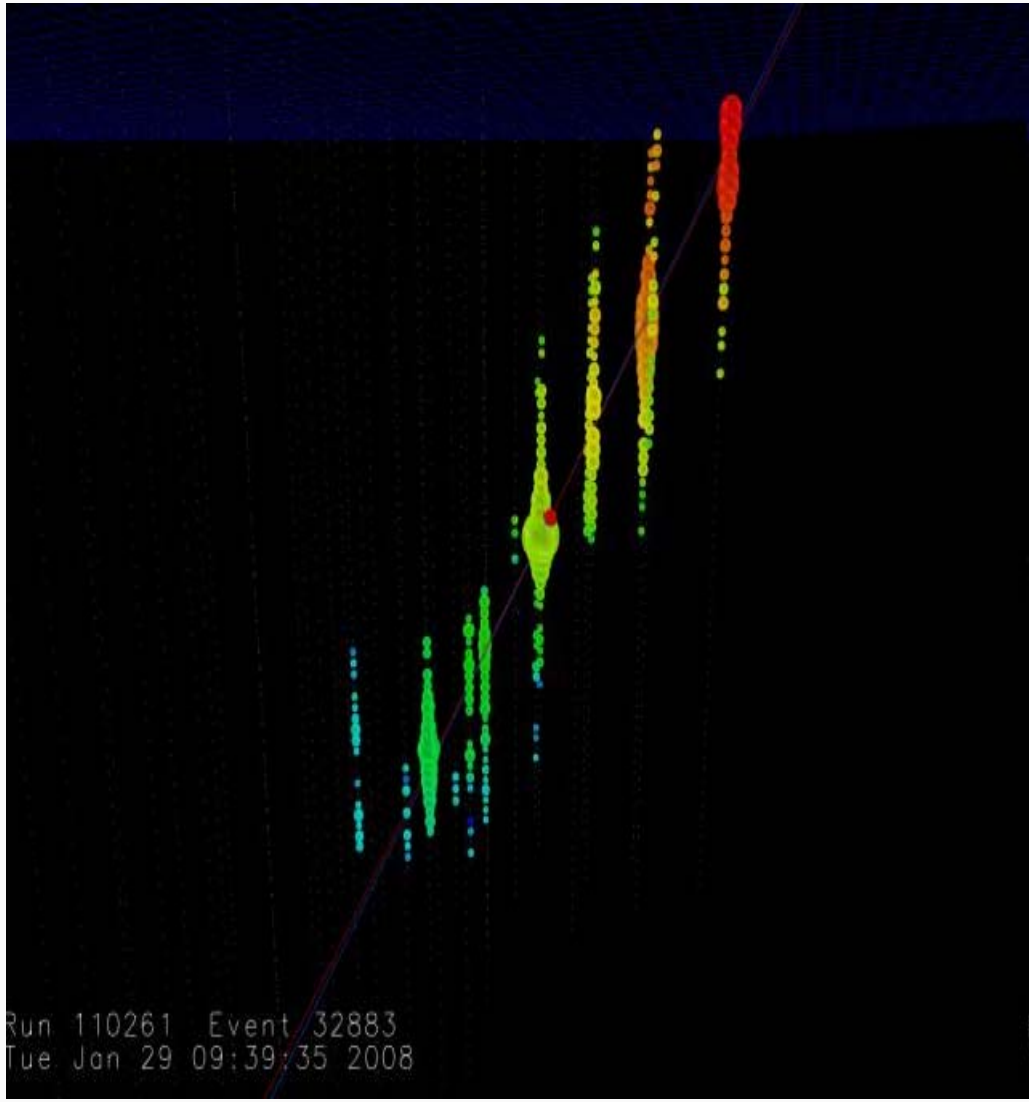


- Dominated by well-reconstructed atm. muons
- Reject backgrounds by <u>energy</u>

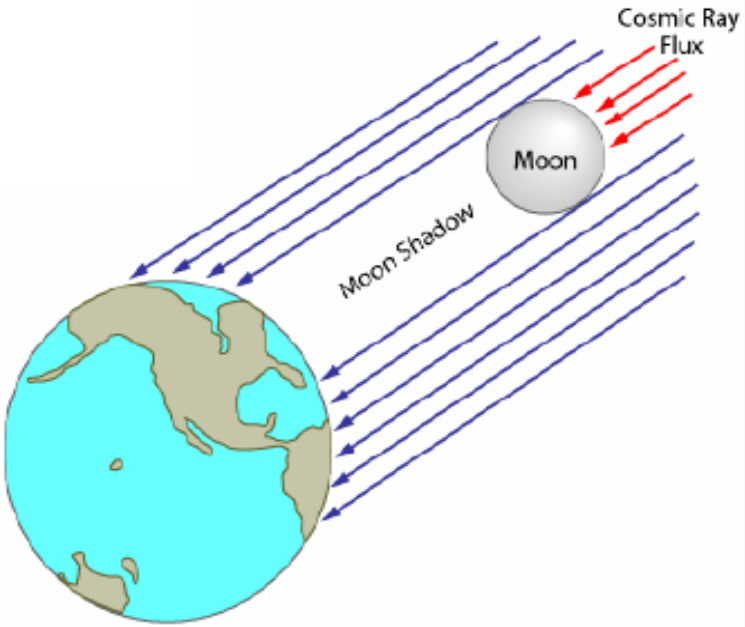
Reconstructing Direction and Energy

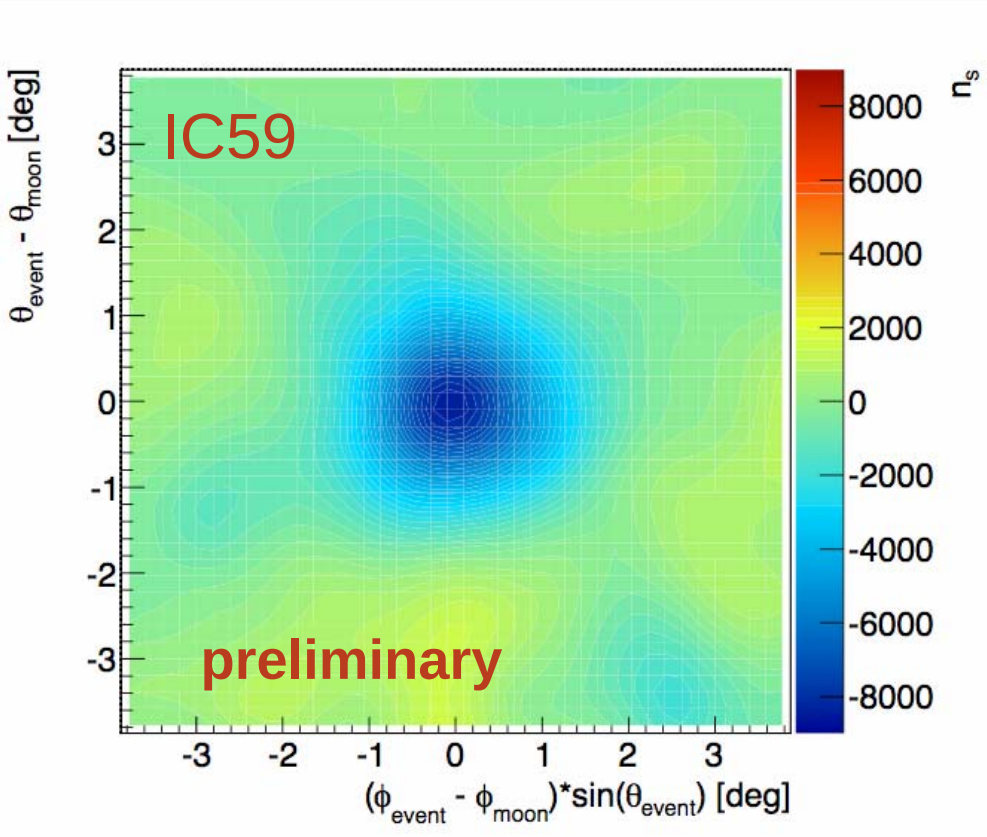
- Likelihood Based
  - Arrival times / intensities
  - Detailed ice properties
- Spatial Resolution
  - IceCube: < 1 degree
- Energy Resolution
  - 0.3 in $\ln(E_{reco}/E_{true})$





Angular Resolution: the Moon's Shadow



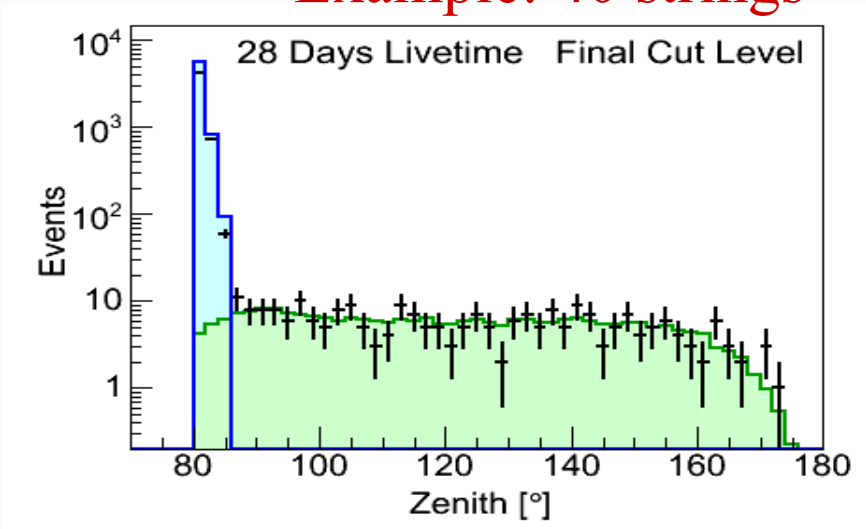


- Moon Shadow seen in muons at 10σ
- Systematic pointing error < 0.1°

Atmospheric Muon Neutrinos

- High-purity atmospheric neutrino sample achieved after quality cuts

Example: 40 strings

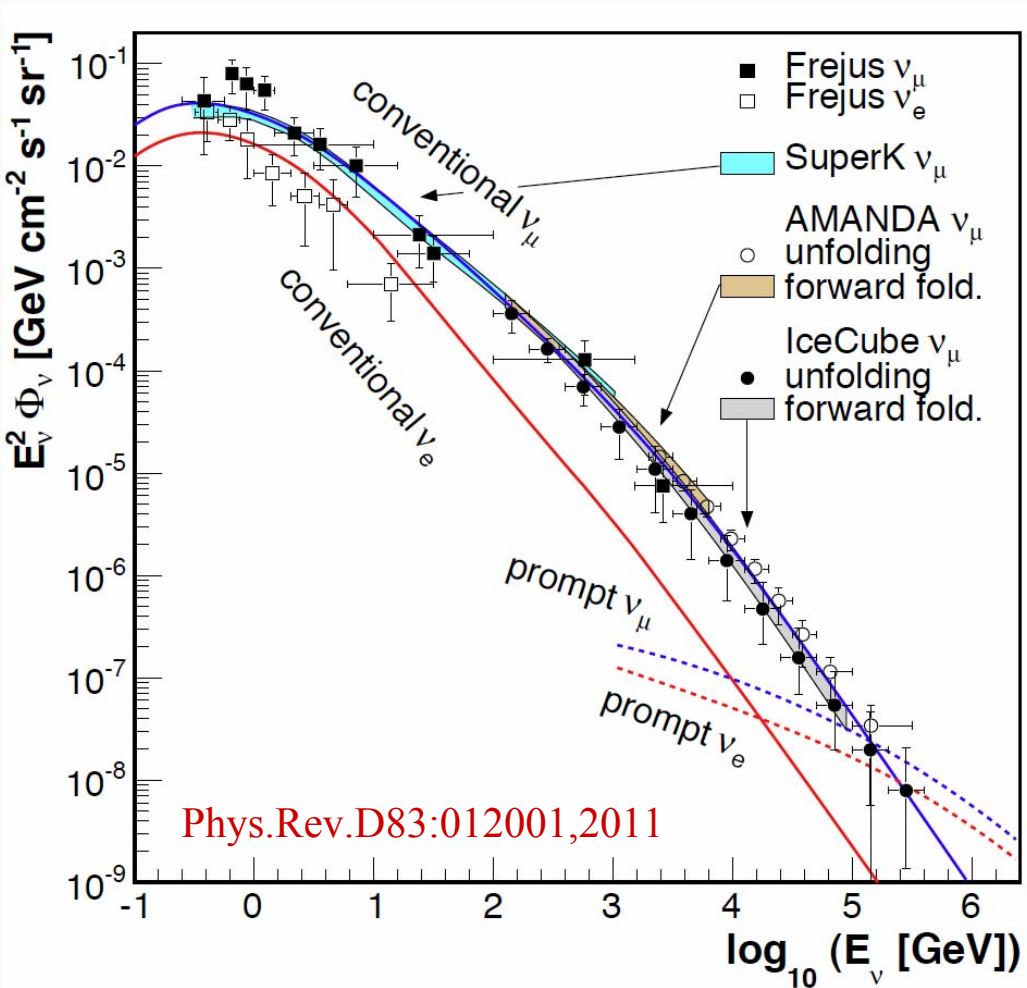


Strings	Year	Livetime	ν_μ rates
IC22	2007	275 days	28/day
IC40	2008	375 days	110/day
IC59	2009	360 days	160/day
IC79	2010	1 year	
IC86	**2011-**	**Since 05/13/2011**	**220/day***

*estimated

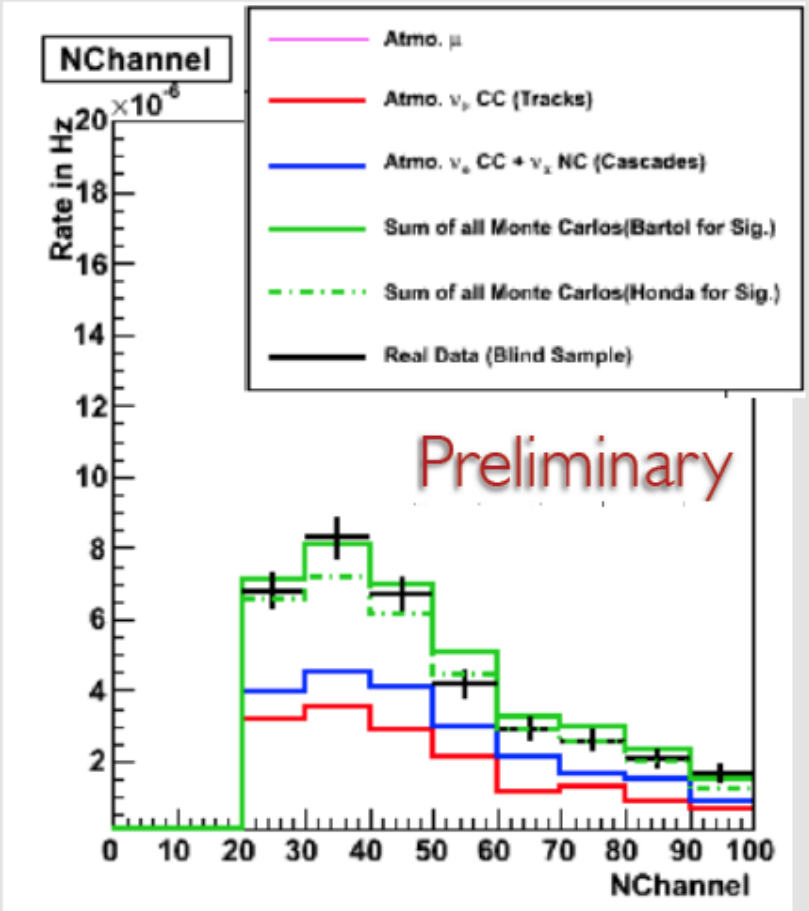
Atmospheric Neutrino Energy Spectrum

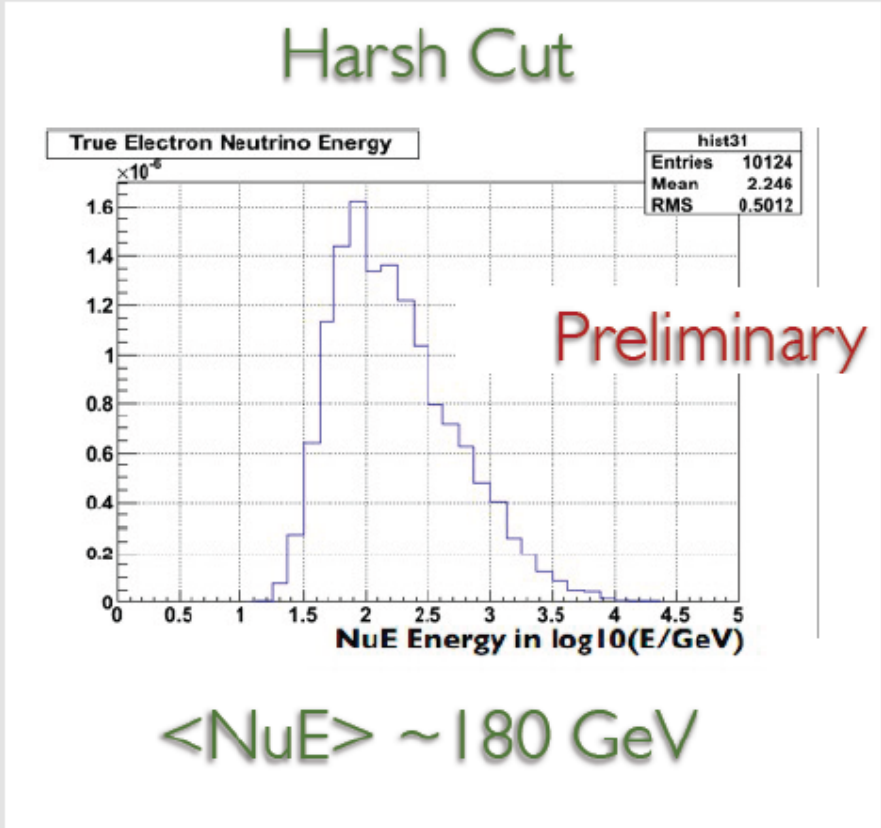
- IC40: high statistics sample of HE (E>100 GeV) atm. ν_μ (13000, 95% purity); flux consistent with previous measurements in the overlap region
- 40000 ν_μ in IC59
  - Extend to > 1 PeV
  - Probe charm contribution?
- No atm. ν_e observed so far in conventional analysis
- DeepCore: extension to lower energies / higher rates



Low Energy Atmospheric Neutrinos

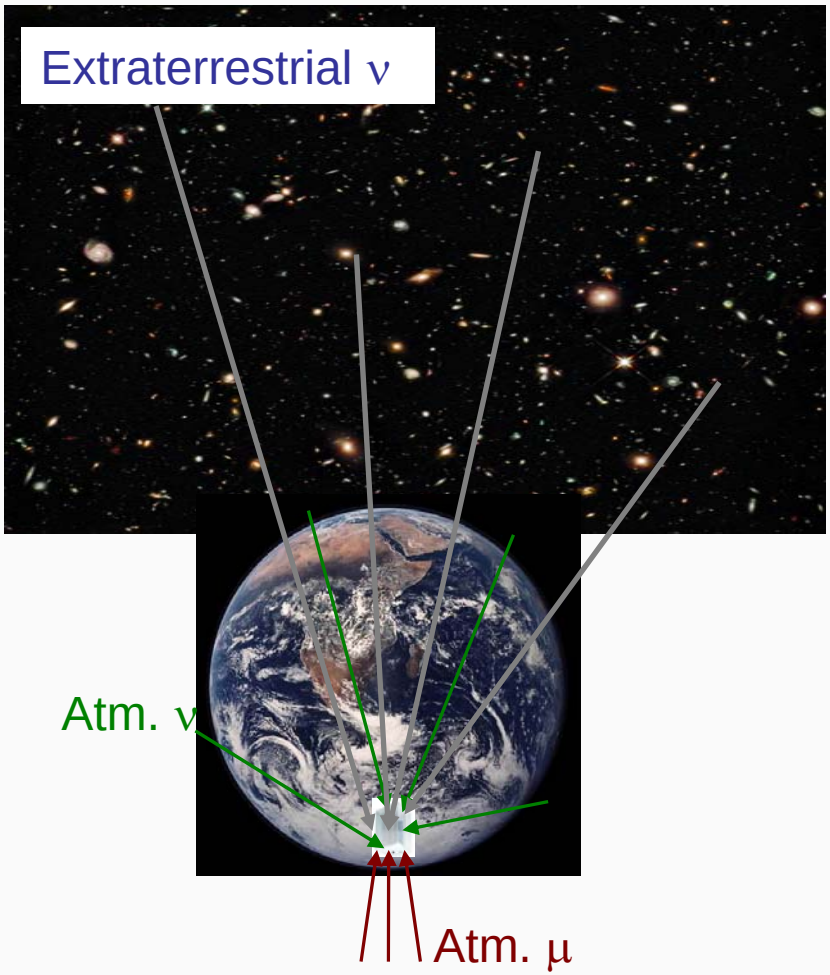
- 10% of 79-string data, 60% purity



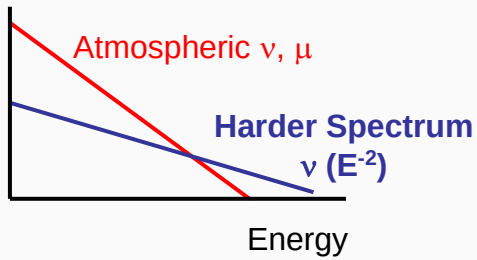


Diffuse Searches

Diffuse flux : integrated flux from all unresolved extraterrestrial sources



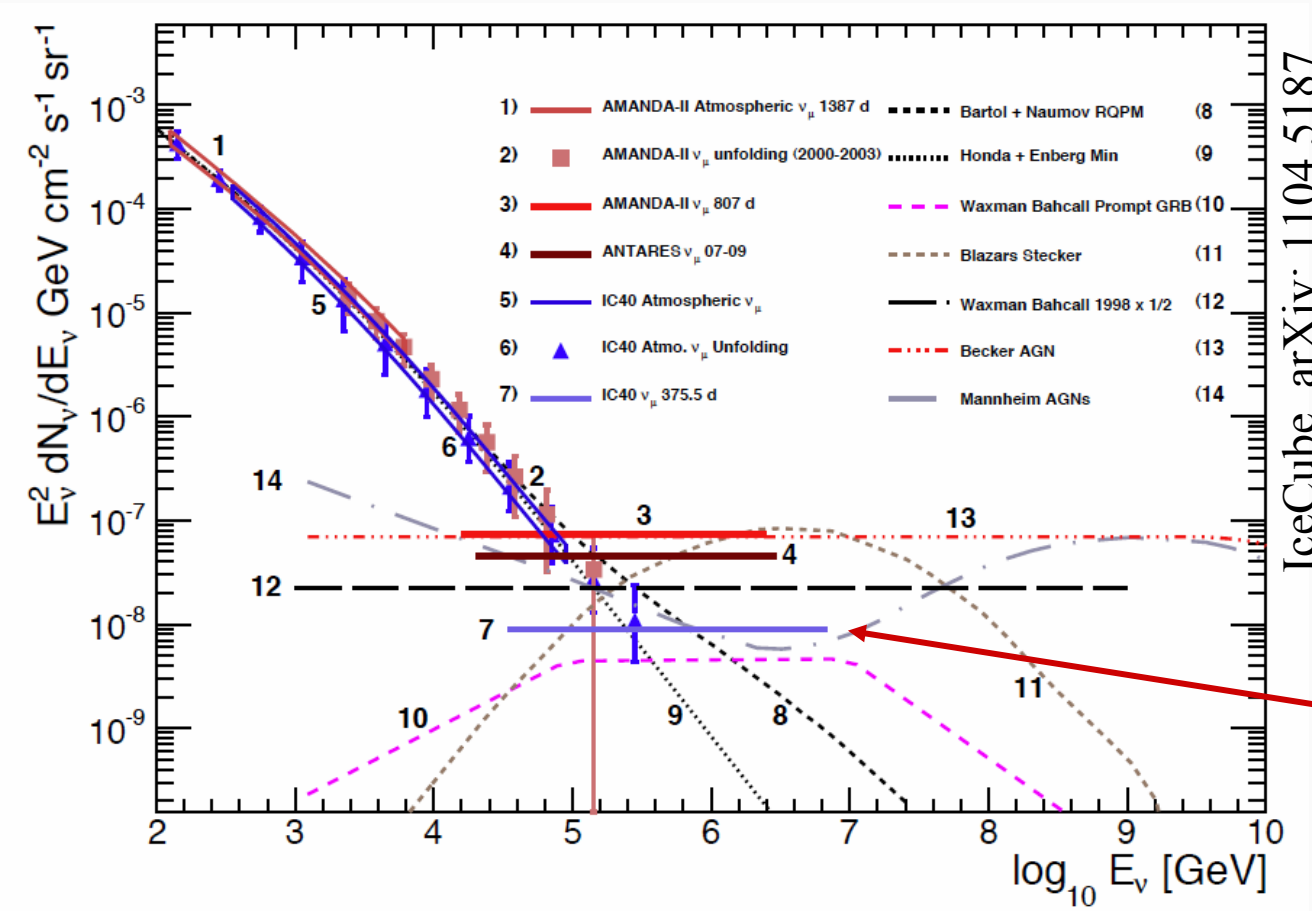
- Search for excess of astrophysical neutrinos with a harder spectrum than background atmospheric neutrinos



- Advantage over point sources: sensitive to weaker fluxes
- Disadvantage: high background
- Sensitive to all three flavors of neutrinos

Muon Neutrino Diffuse Flux Limit

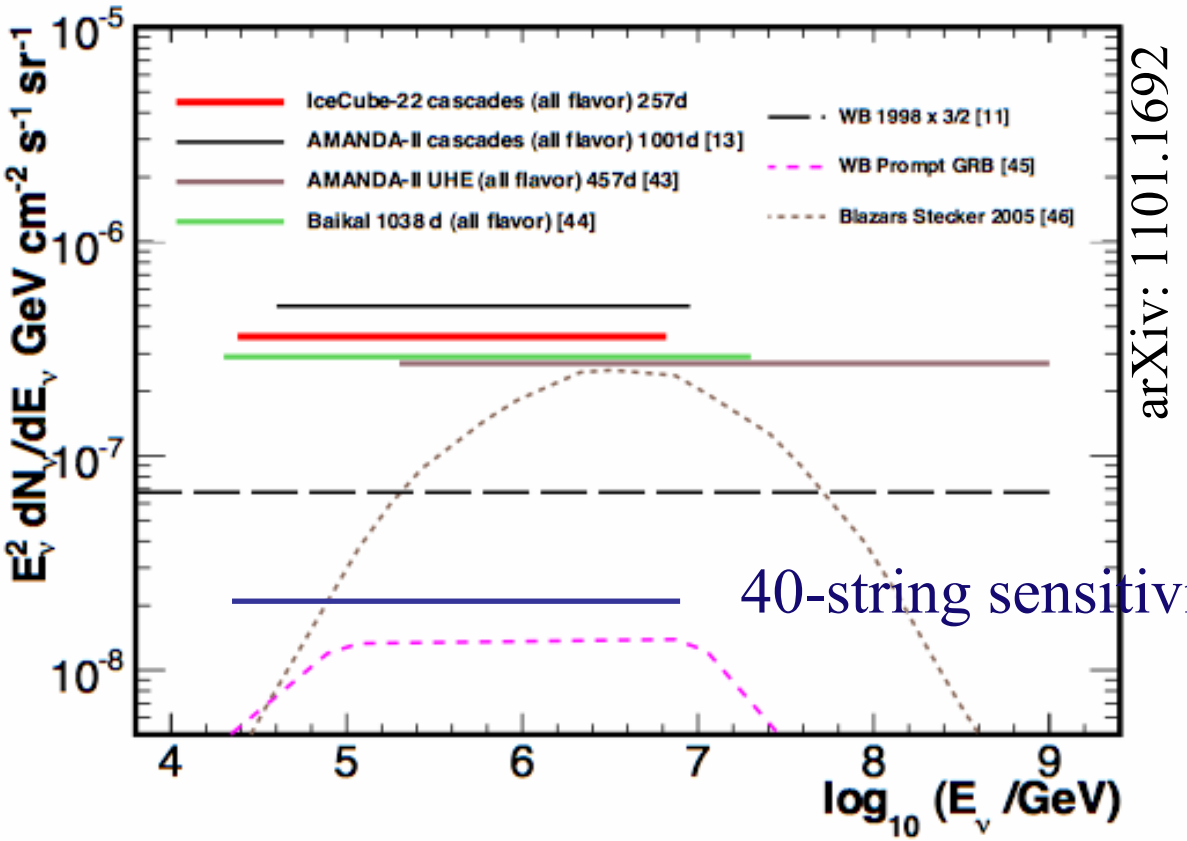
- Upper limit on diffuse flux of <u>muon</u> neutrinos produced with an E^{-2} energy spectrum
  - 375.5 days of 40-string data



Latest results fall below the Waxman-Bahcall upper bound

Cascade Diffuse Flux Limit

- Upper limit on diffuse flux from cascades (all flavor) produced with an E^{-2} energy spectrum
  - 257 days of 22-string data

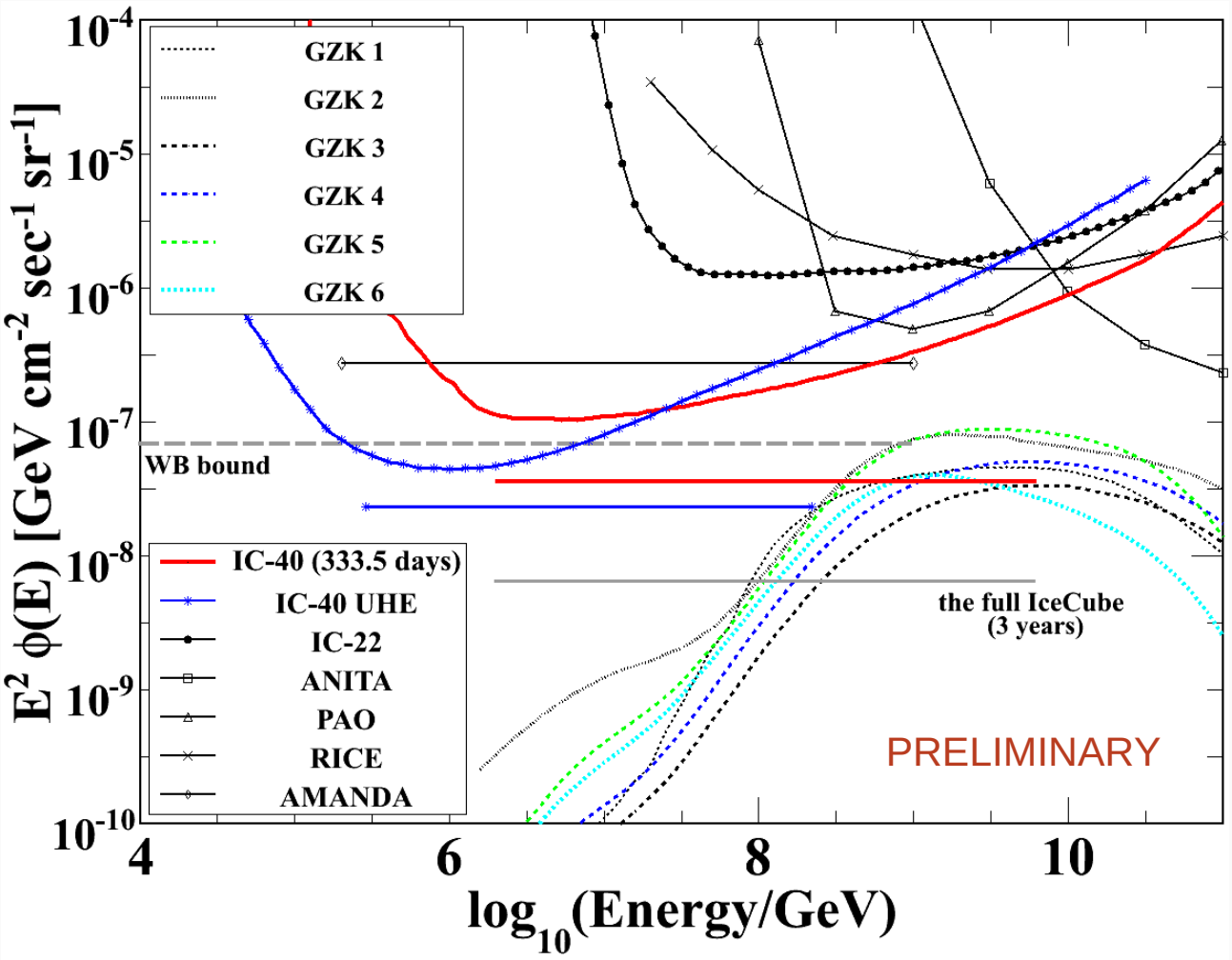


arXiv: 1101.1692

40-string sensitivity (337 days)

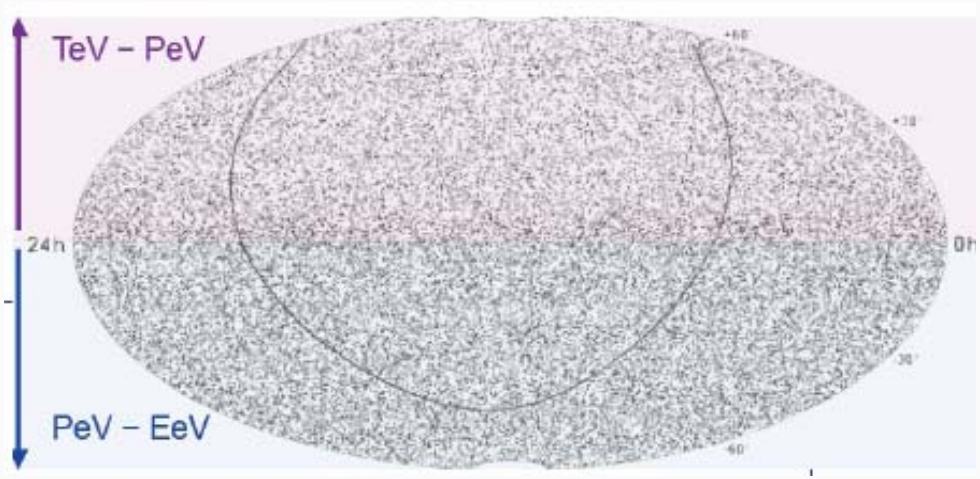
EHE Diffuse Flux Limits (GZK)

- 40-string data, analyses optimized for various energies
- Leading all flavor limits from 10^6 to 10^{10} GeV

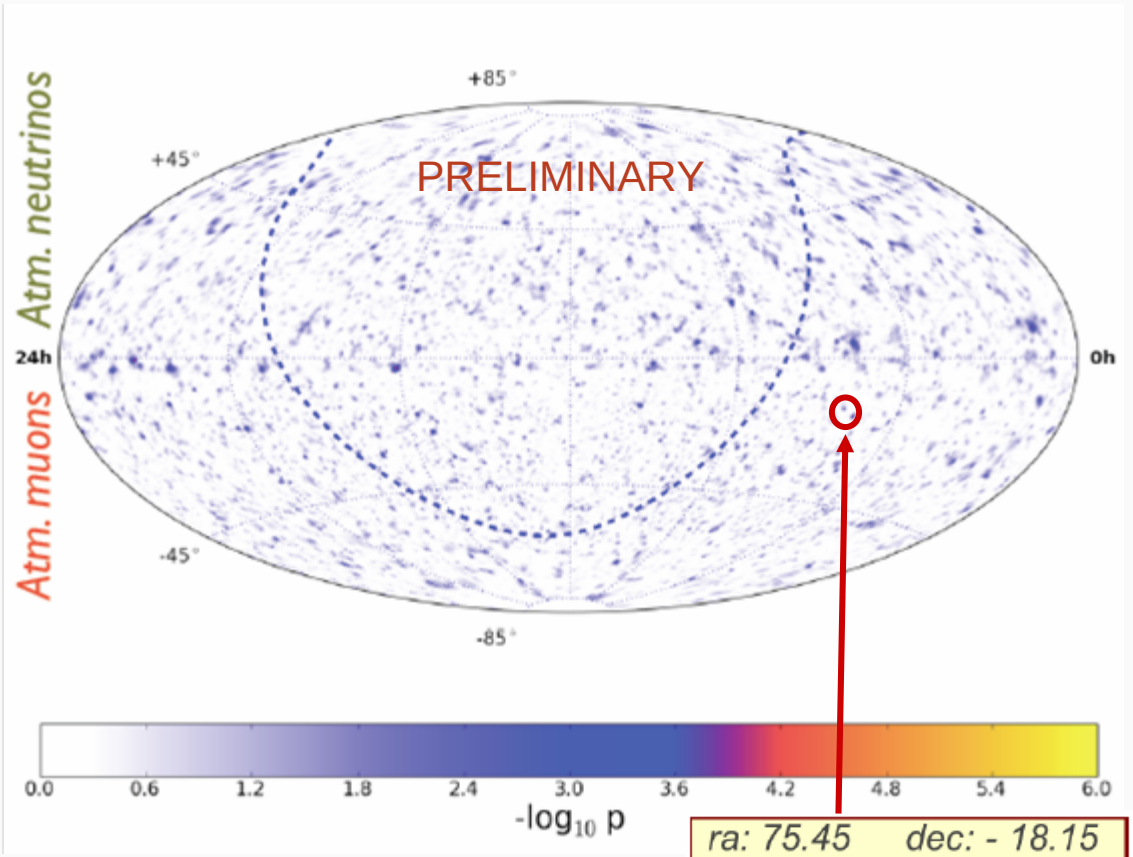


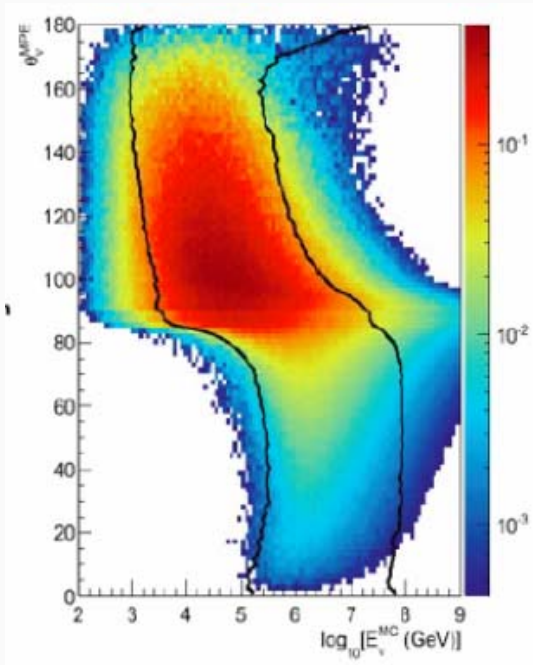
Point Source Searches

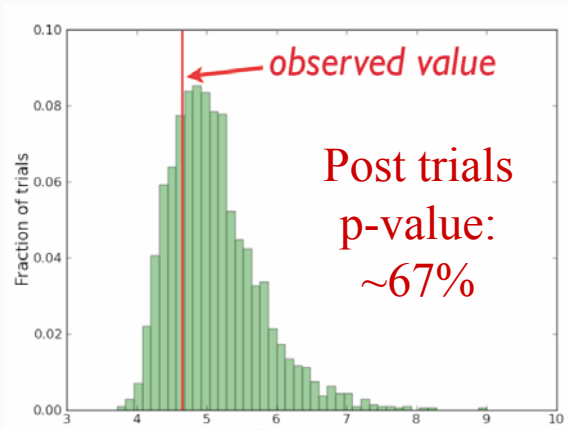
- Time integrated (all sky)
- Source Lists (single, stacking)
- Transients
  - Flares
  - GRBs
  - SN
- Follow up
  - Send alerts to optical, x-ray, gamma telescopes



40+59-string All Sky Point Source Search







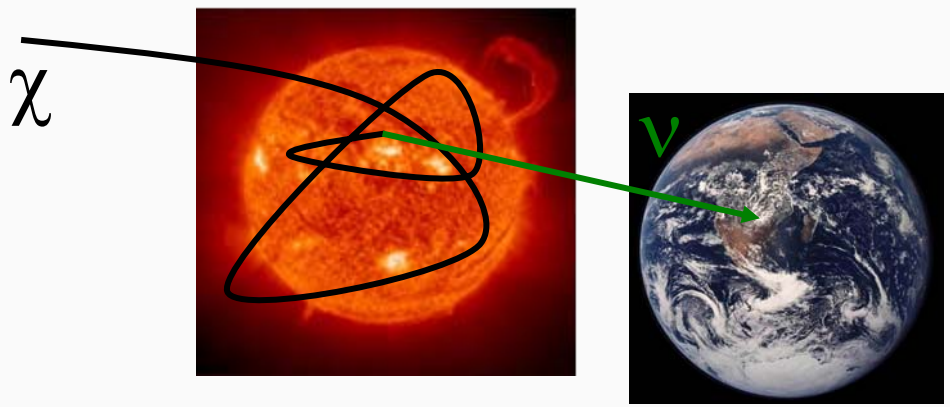
- Total Events: 43329 (upgoing) + 64230 (downgoing)
- Livetime: 375 days (40-string) + 348 days (59-string)

Indirect Dark Matter Searches

- Various candidates: MSSM (neutralino), UED (LKP), …
- Capture in center of massive objects (Sun, Earth, GC)
- Annihilation leads to SM particles, neutrinos

$$\chi\chi \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \ldots \rightarrow \nu s$$

- Event rates and energies depend on DM model and astrophysics (relative velocities, galactic density profile)
  - few to 10^3 events per year
  - GeV to TeV energies



Dark Matter Annihilation in the Sun

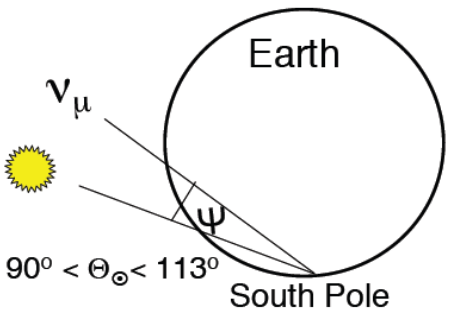
- 90% C.L. upper limits on SD and SI WIMP-nucleon scattering cross sections, assuming equilibrium between annihilation and capture

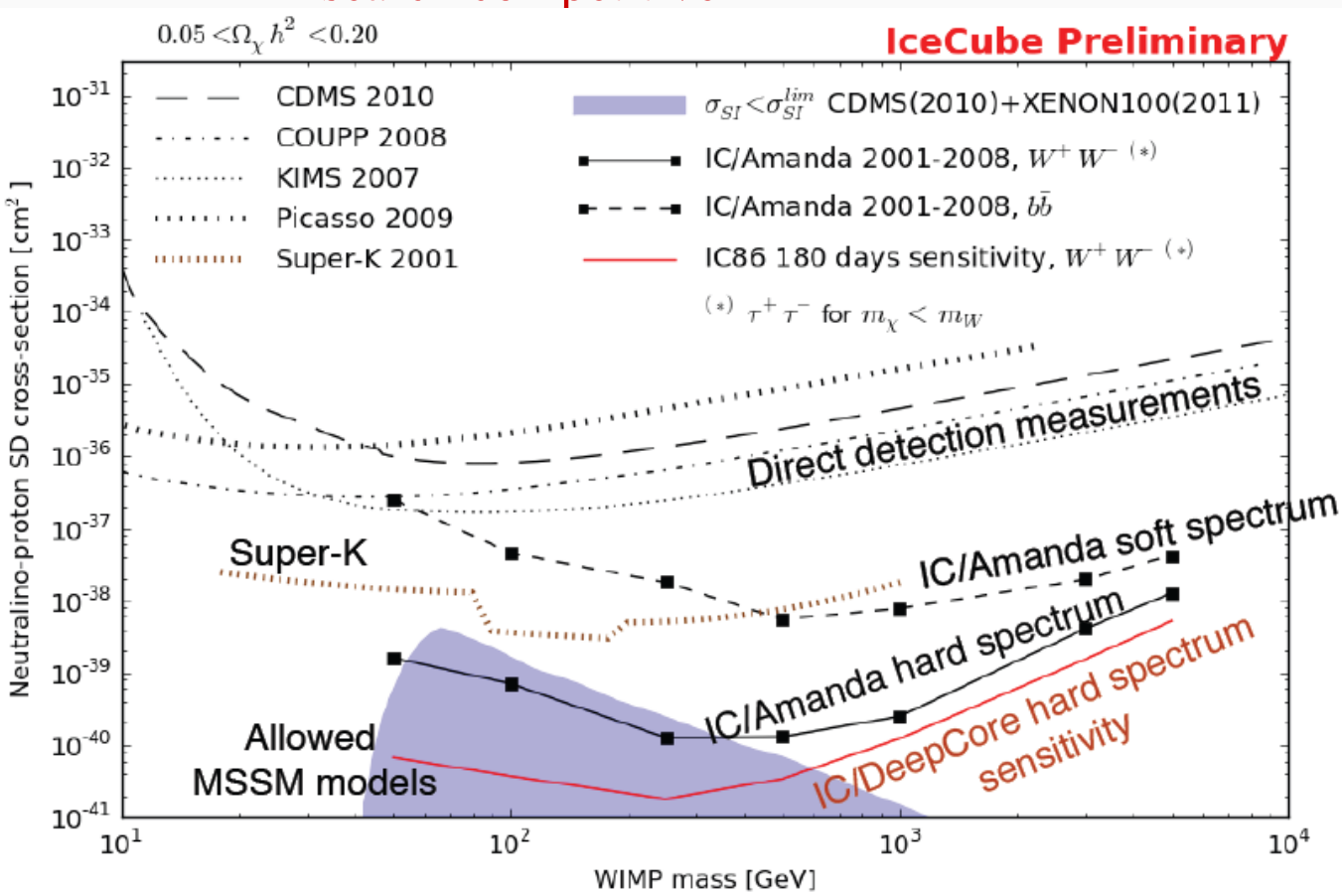
$$\sigma^{SI} = \lambda_{SI}(m_\chi)\Gamma_A \quad \text{and} \quad \sigma^{SD} = 0$$

$$\sigma^{SI} = 0 \quad \text{and} \quad \sigma^{SD} = \lambda_{SD}(m_\chi)\Gamma_A$$

- Well constrained by direct searches
- Solar capture dominated by σ^{SD}, indirect search competitive

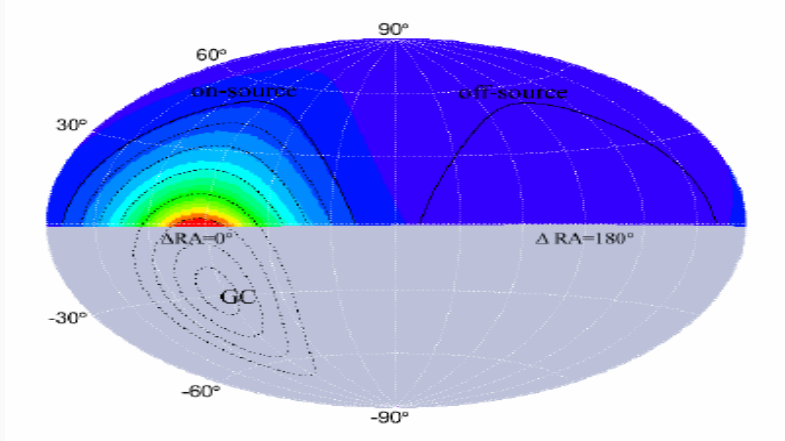
AMA+IC22+IC40 (2011-2008)





Dark Matter Annihilation in the Galaxy

- Halo (22-string)
  - northern hemisphere anisotropy
- Galactic Center (40-string)
  - Excess of down-going events from direction of GC
- Results consistent with background → limit on $<\sigma_A v>$



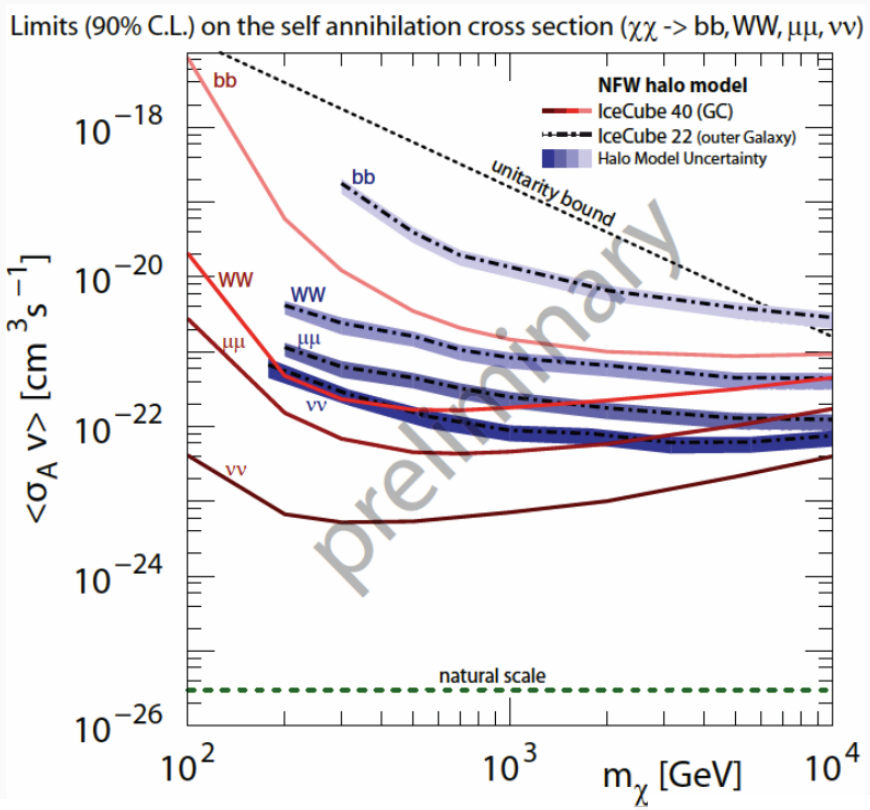
$$\frac{d\Phi_\nu}{dE} = \frac{<\sigma_A \upsilon>}{2} J(\psi) \frac{R_{sc}\rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}$$

Measure

Constrain

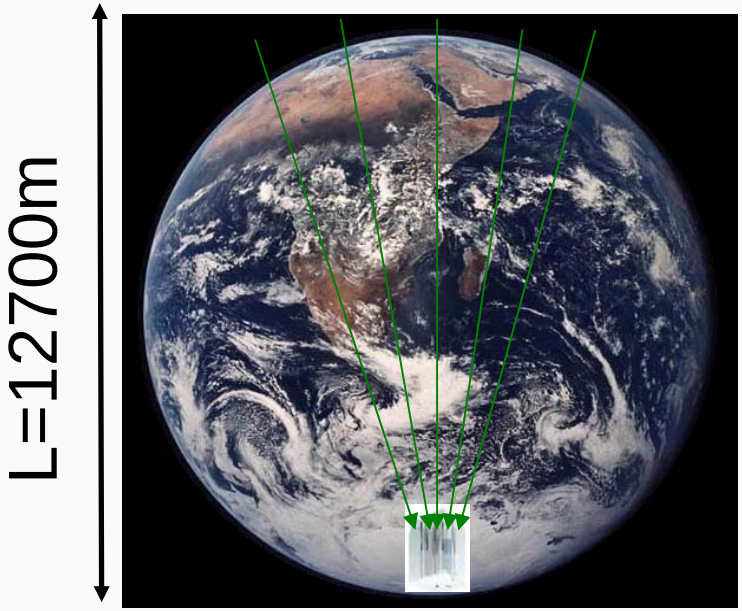
Halo

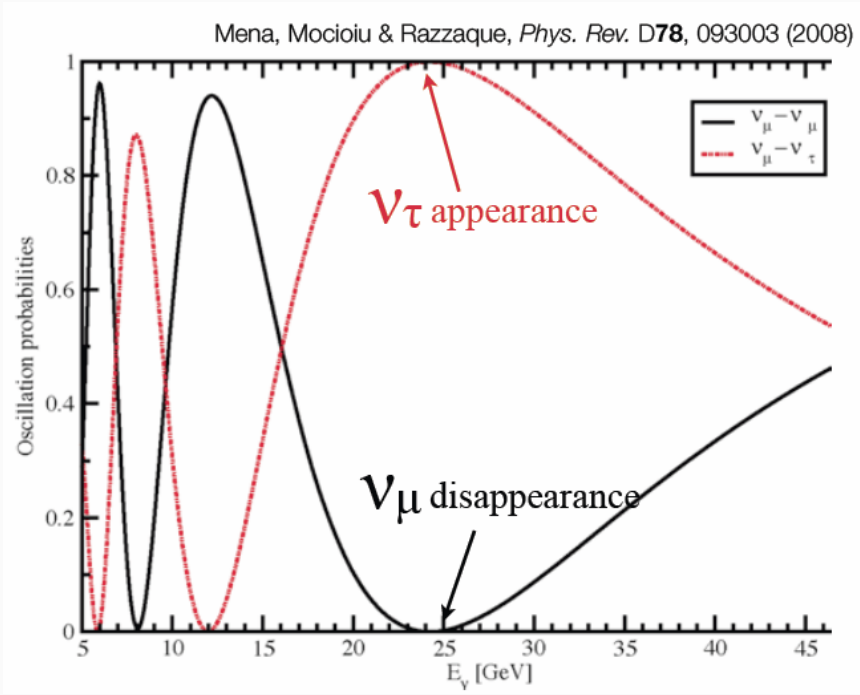
SUSY



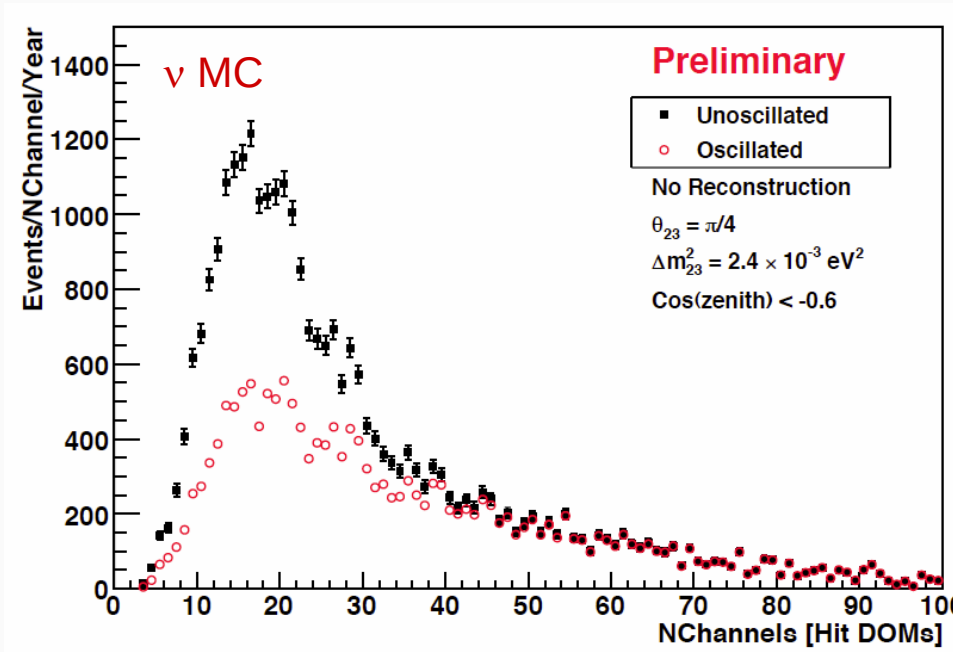
Neutrino Oscillations

Atm. ν





- DeepCore accesses 1st peak
- ν_μ disappearance MC
  - 3-flavor oscillations
  - Signal simulation only
  - 1 year 79-string livetime



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No astrophysical neutrino sources yet, but…

New 79 and 86 string results coming soon