

Status and Recent Results from the IceCube km^3 Neutrino Detector

RICAP

26 May 2011



Neutrino Telescopes – A Brief Heritage

(See Tom Gaisser's Review Talk, 25 May)

Telescopes for TeV energies:

- ***First envisioned by Greisen, Markov 1960***
- Pioneering effort: DUMAND near Hawaii
- First and second generation telescopes in 90's, proof of principle : Baikal, AMANDA (S Pole), NESTOR (Greece).
- Current generation experiments and initiatives:
 - 50000m² scale: ANTARES, AMANDA (decommissioned)
 - Auger Detector (tau neutrinos, $E > 10^{18}$ eV)
 - IceCube (data from 50-75% size)
- Coming generation: km³ scale (and larger)
 - IceCube completed construction ***Dec 18, 2010 !***
 - ***Data Taking Began May 13, 2011***
 - Based on NESTOR, NEMO, ANTARES experience's → km³NeT project, Mediterranean Sea. ***Multi-km³ scale!***

Motivation

Candidate sources (accelerators):

Cosmic ray related:

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

Other:

- Dark Matter, Oscillations, ...
- Exotics, New Physics, ...

Guaranteed sources (known targets):

-Atmospheric neutrinos (from π and K decay)

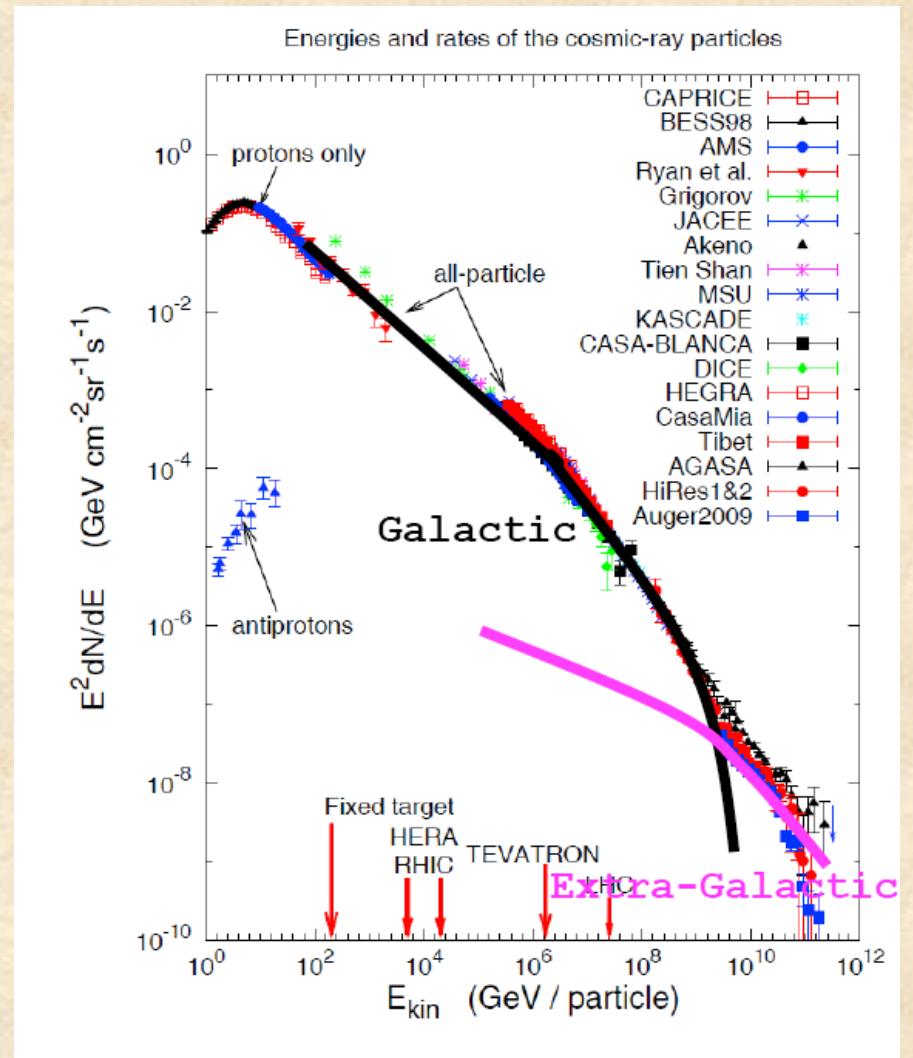
-Galactic plane:

CR interacting with ISM, concentrated on the disk

-Cosmogenic neutrinos (GZK)

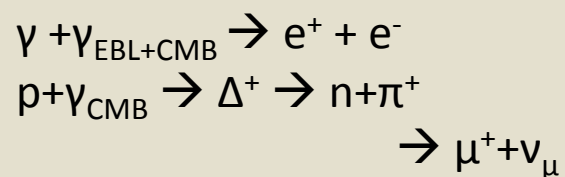
$$p \gamma \rightarrow \Delta^+ \rightarrow n \pi^+ (p \pi^0)$$

Cosmic rays



Neutrinos provide a Window on the HE Universe

Universe opaque to to high energy (>10's TeV) photons:



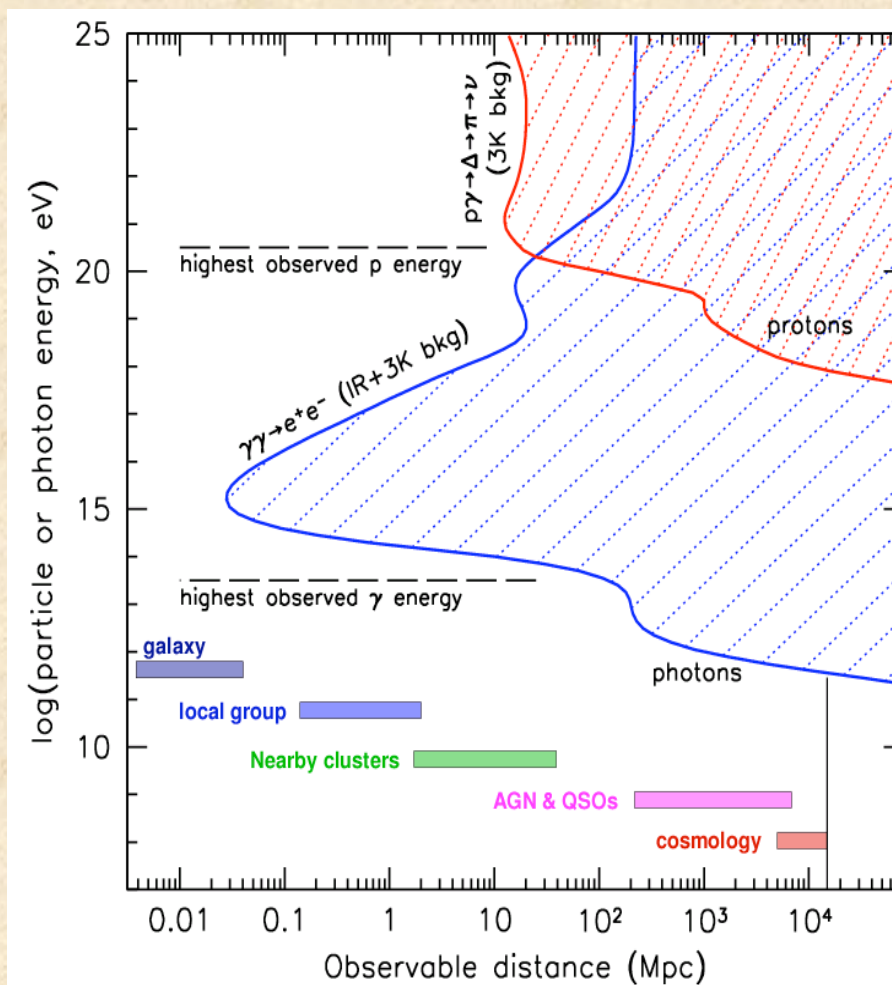
Cosmogenic neutrinos

Protons deflected by magnetic field for $E < 10^{19}$ eV

- *Not pointing back for distant sources*

1) *Neutrinos are a candidate for high energy (>10TeV) cosmic astronomy!*

2) *Neutrinos provide unambiguous evidence of hadronic acceleration!*



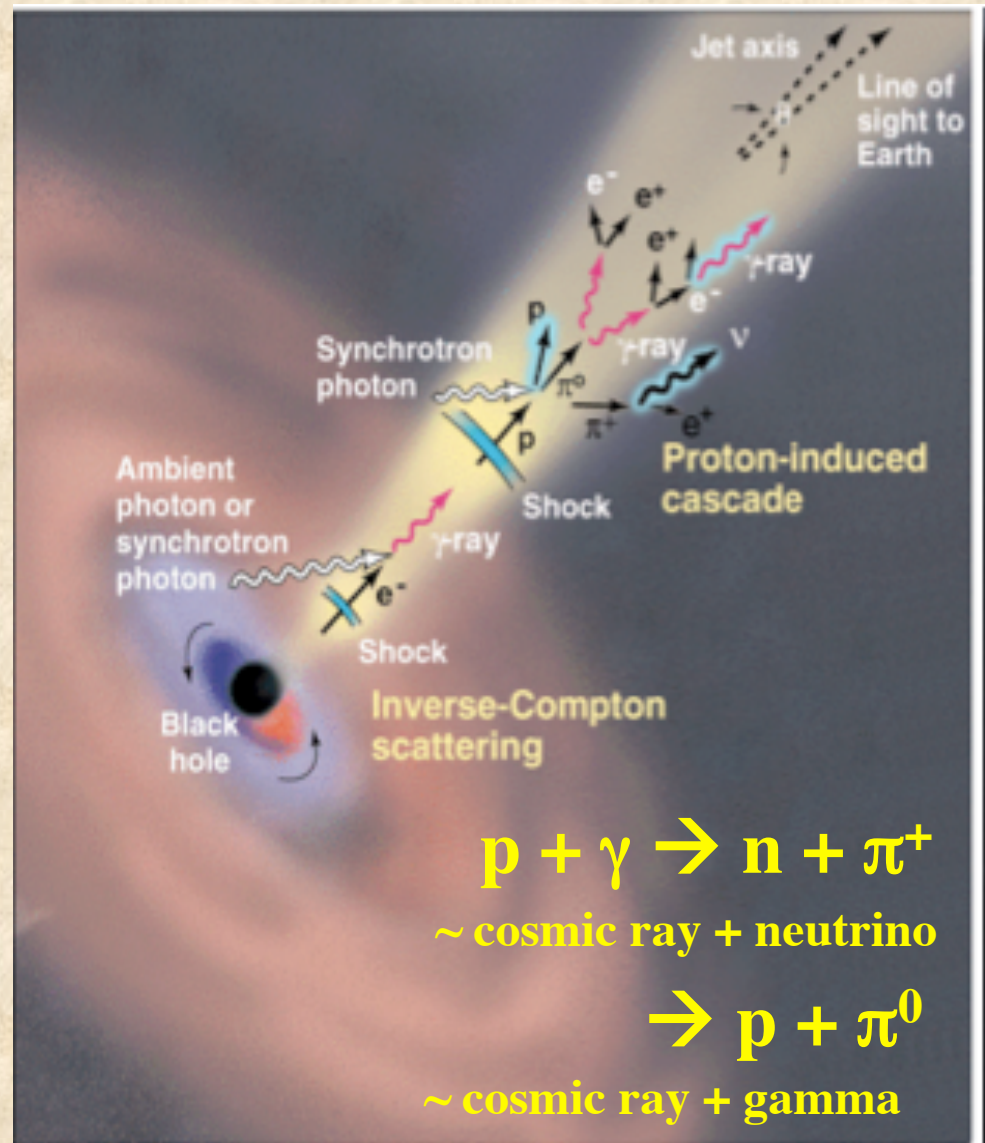
High Energy Particles in the Universe

- **Cosmic Rays**

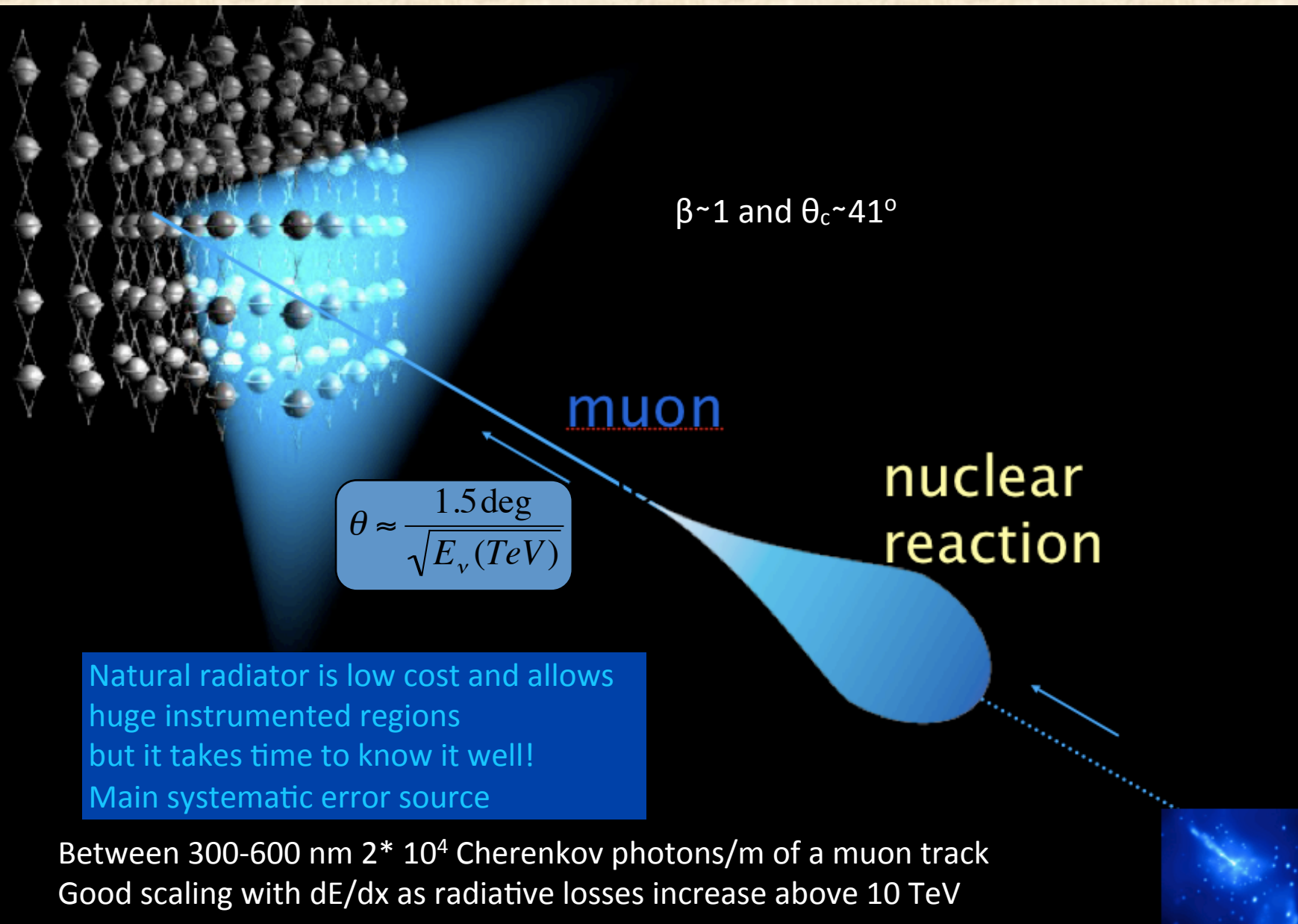
- Observed up to 10^{21} eV
- Diffuse, mass composition

- **Gamma Rays**

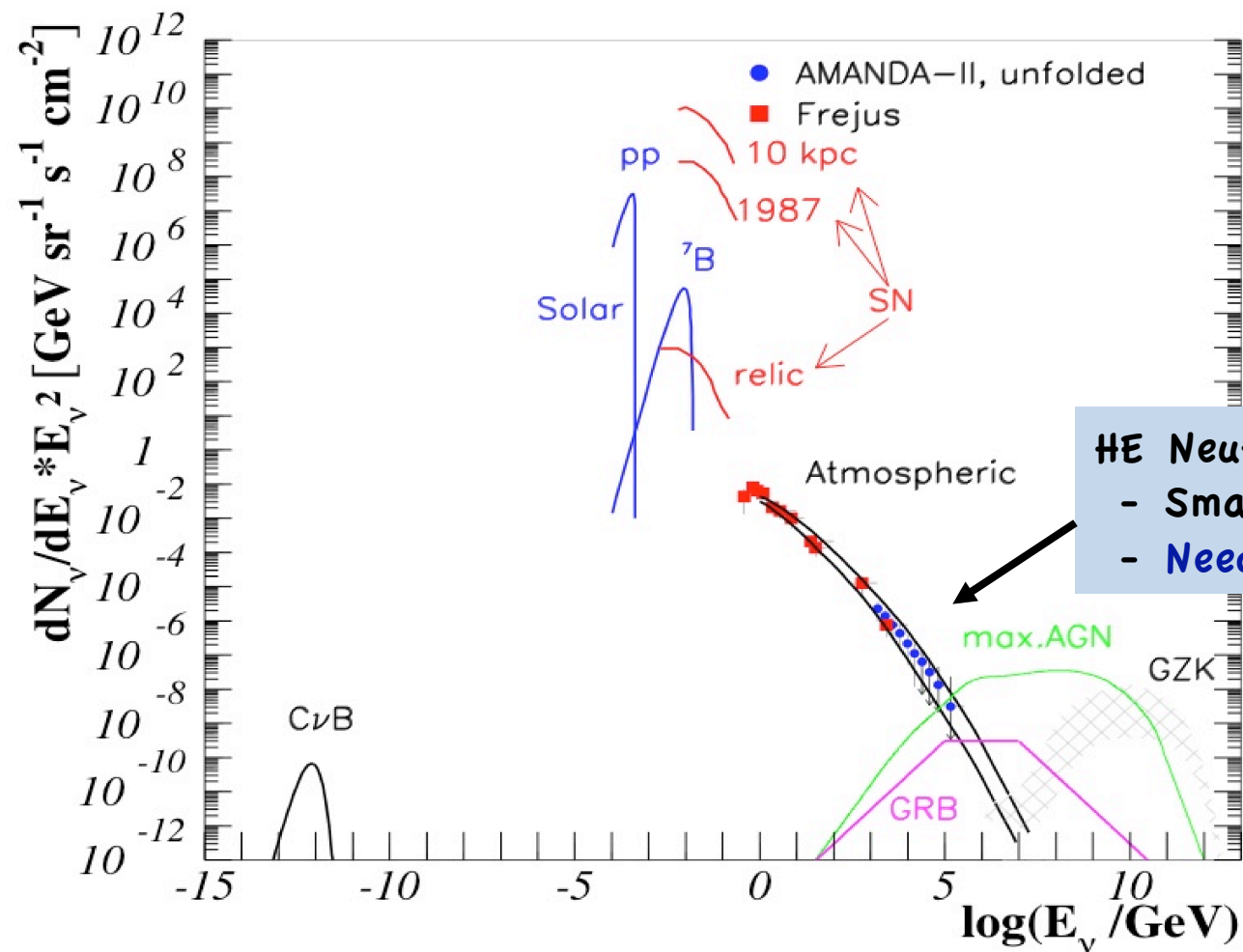
- Observed up to ~ 100 TeV
- Numerous TeV point sources resolved



Concept of Large Neutrino Telescopes

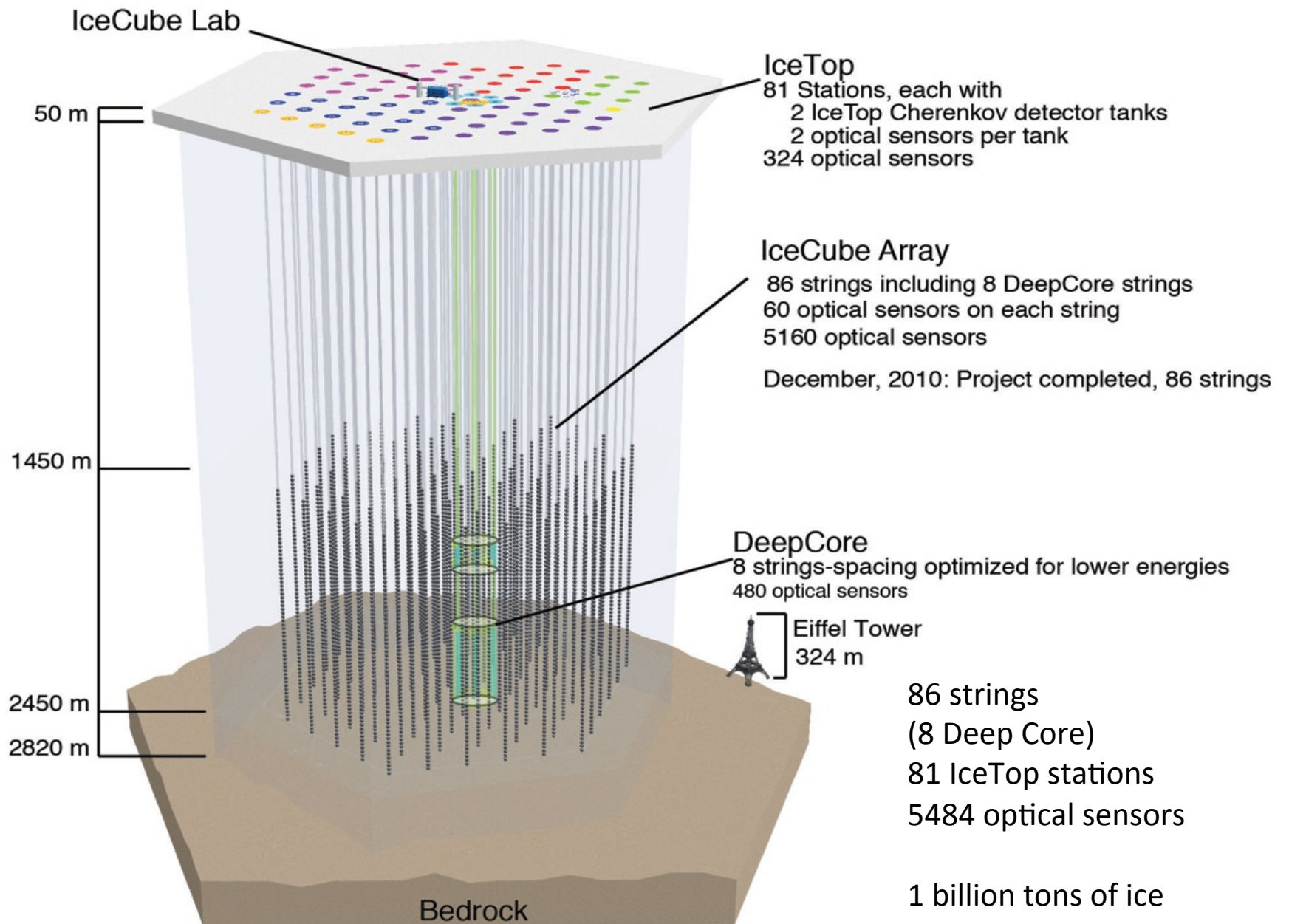


High Energy Neutrinos



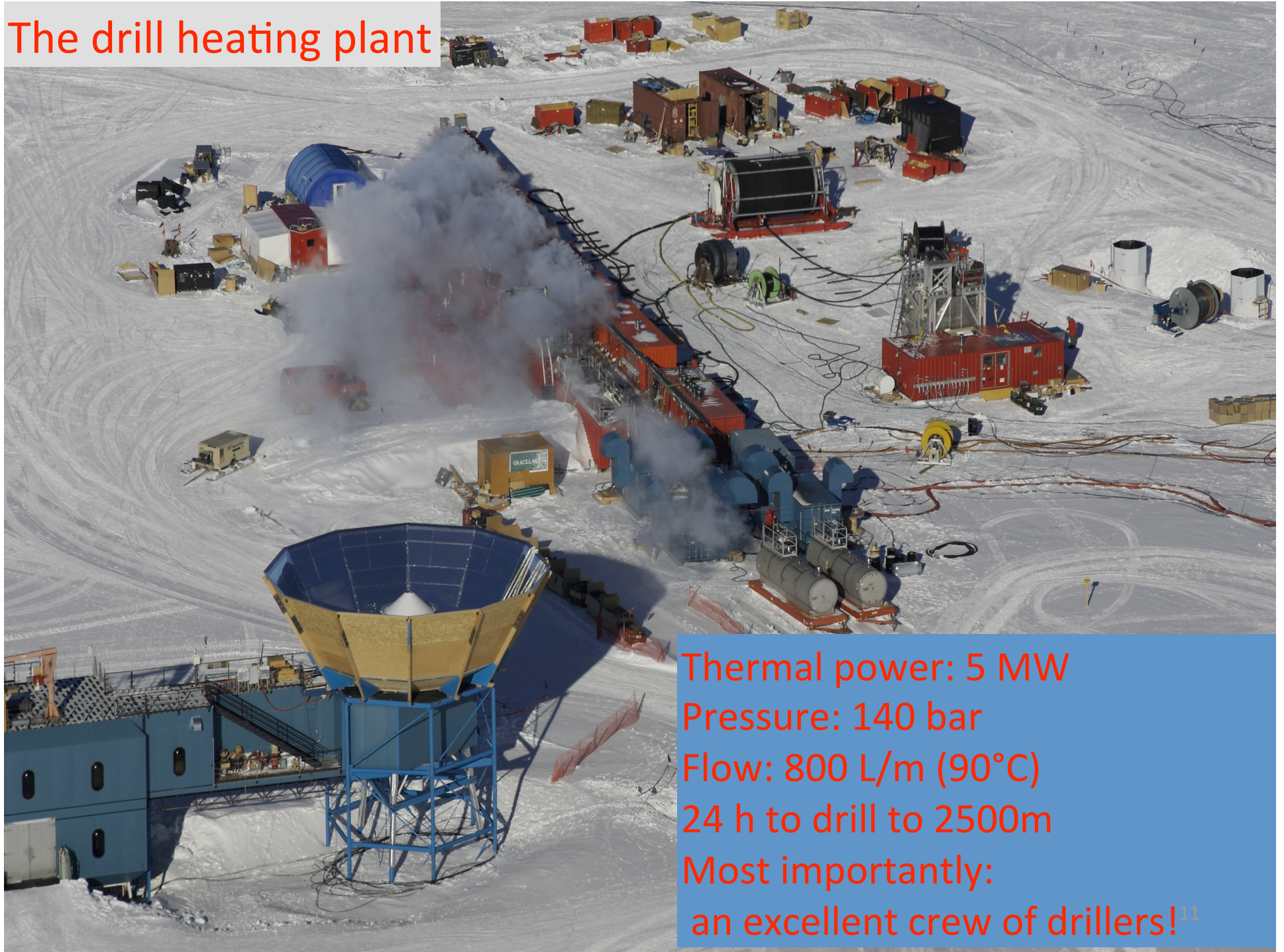
HE Neutrino astronomy:

- Small fluxes
- Need km scale detector





The drill heating plant



Thermal power: 5 MW

Pressure: 140 bar

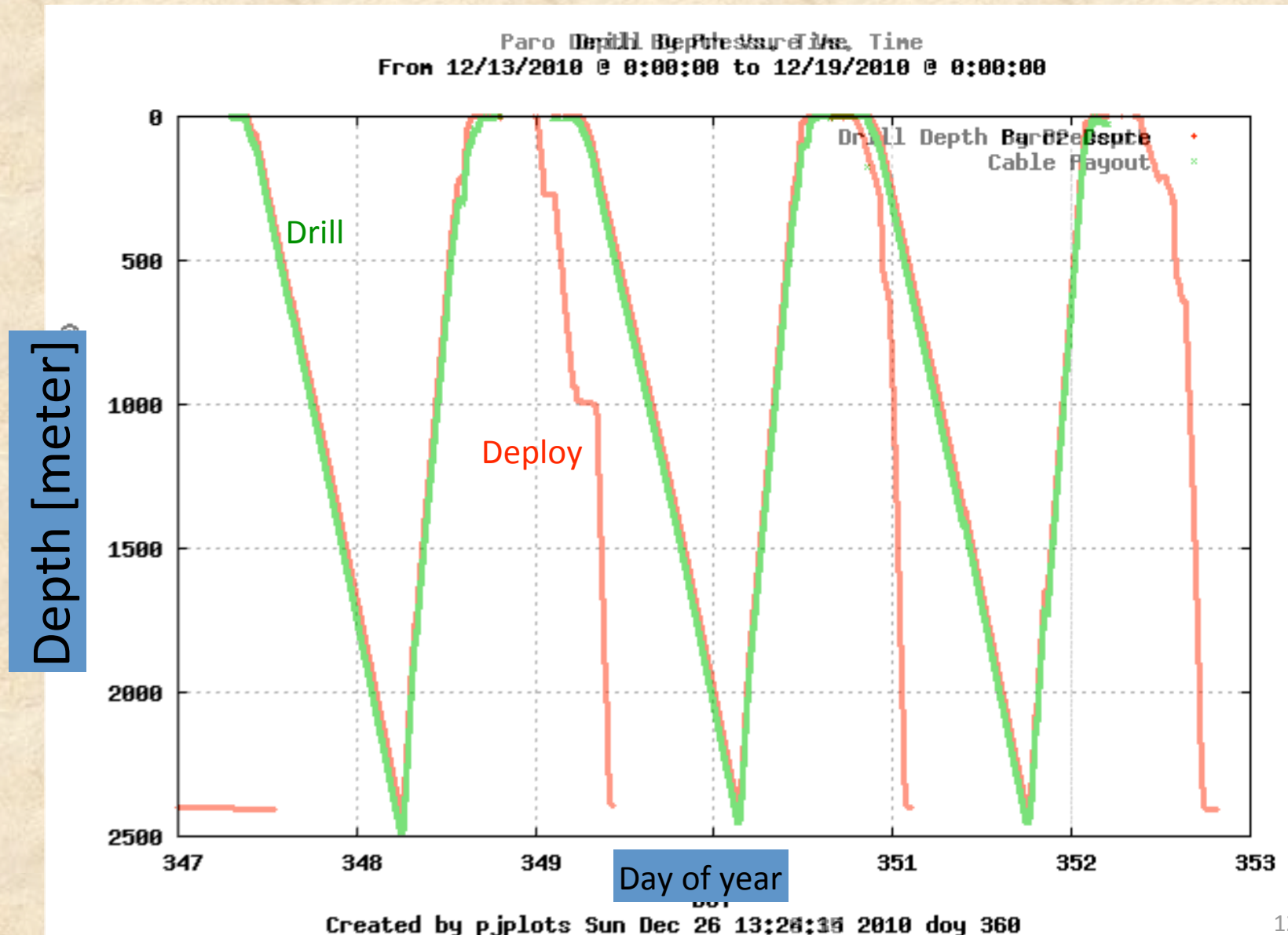
Flow: 800 L/m (90°C)

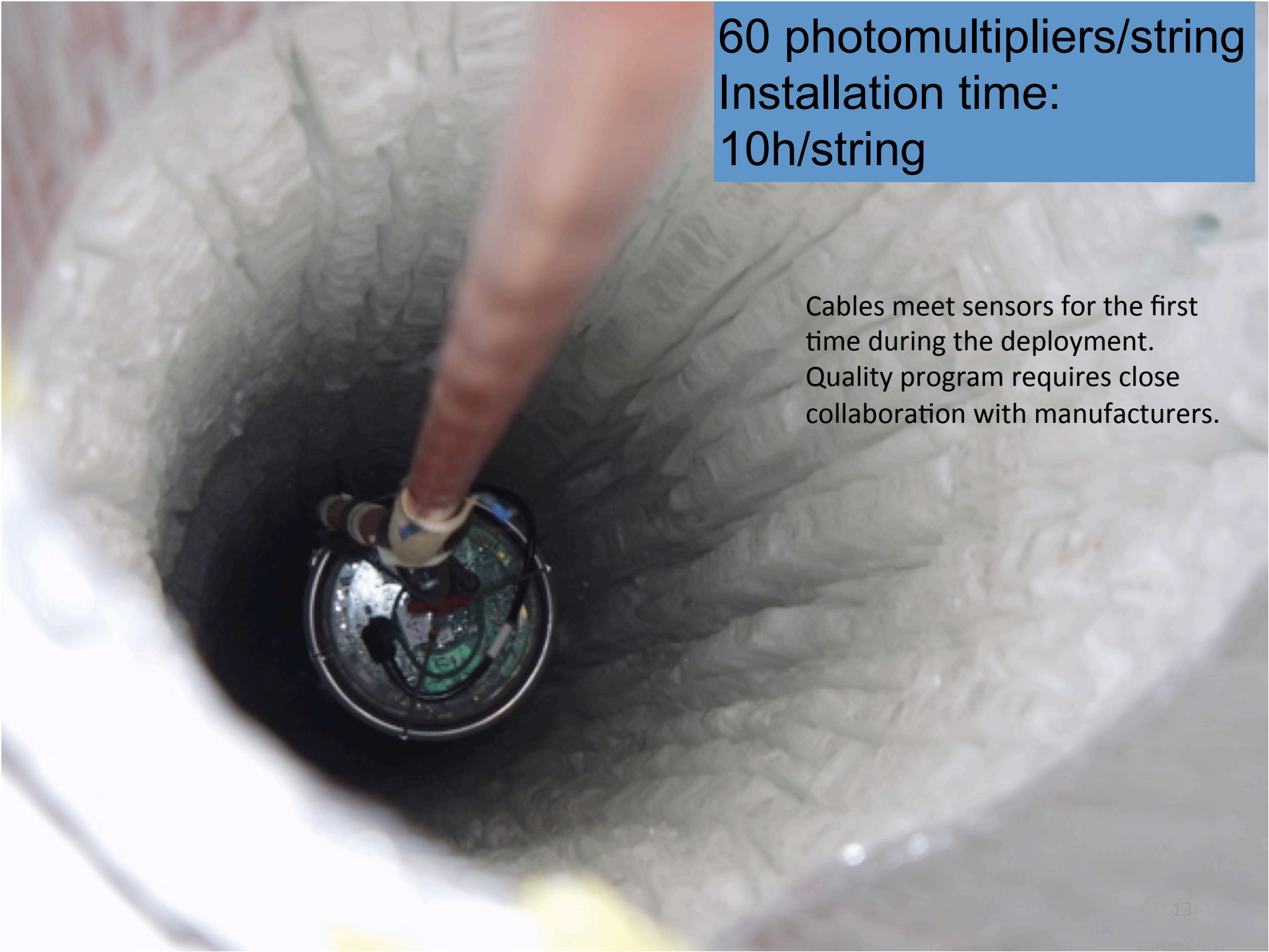
24 h to drill to 2500m

Most importantly:

an excellent crew of drillers!¹¹

Drilling and deployment Dec. 13-18, 2010





60 photomultipliers/string
Installation time:
10h/string

Cables meet sensors for the first time during the deployment.
Quality program requires close collaboration with manufacturers.



Operational support:

ICL maintenance

~60 kW power to electronics

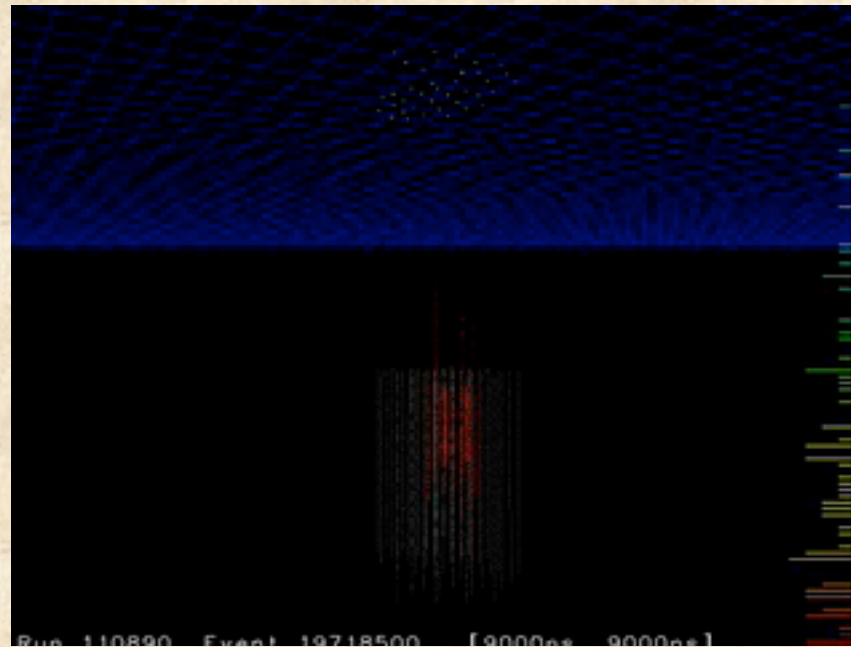
90 GB/day

2 winterovers

summer population (around 5-7 pop Dec - Jan)

Muon Events from Data

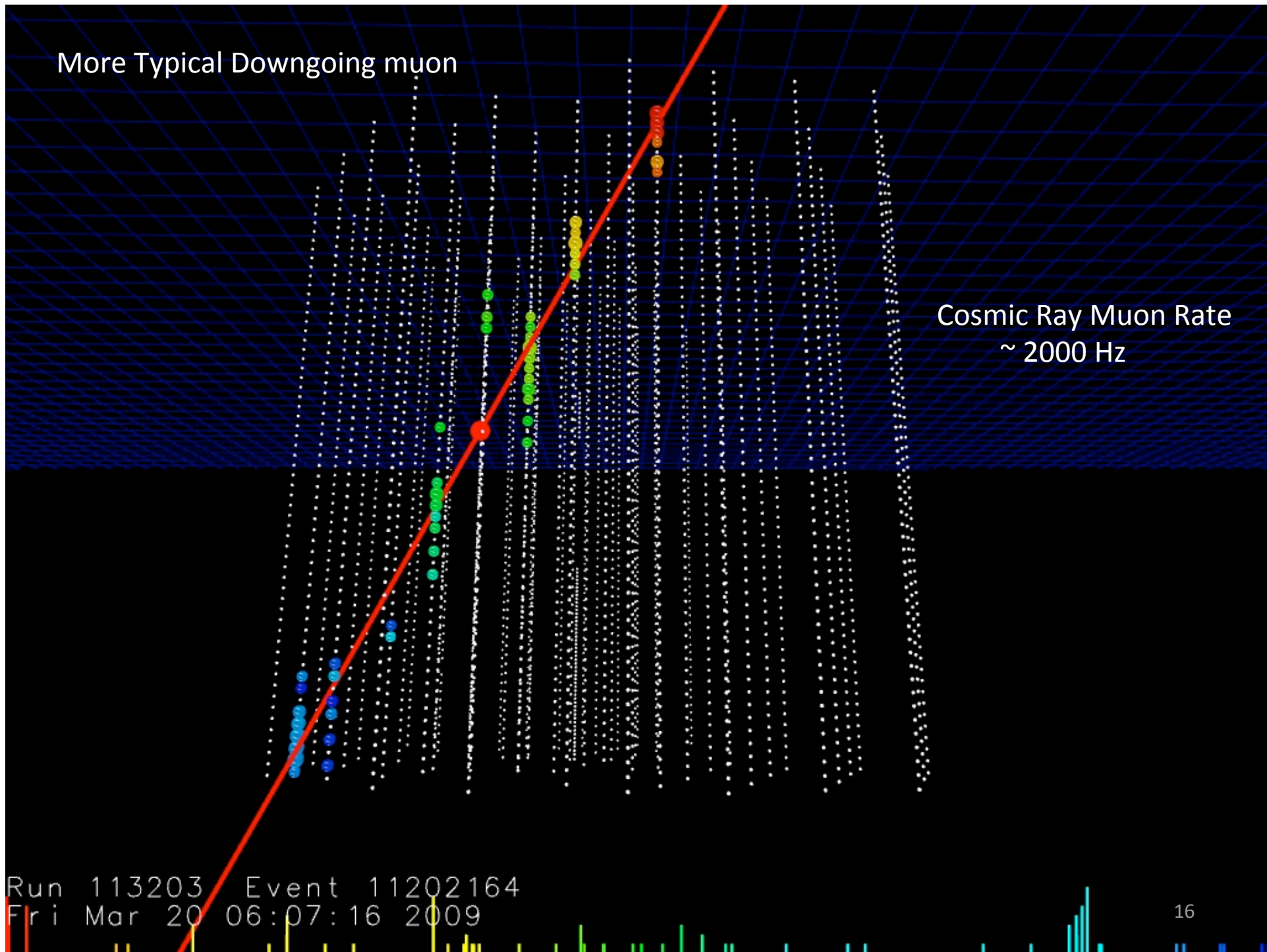
Downgoing muon bundle



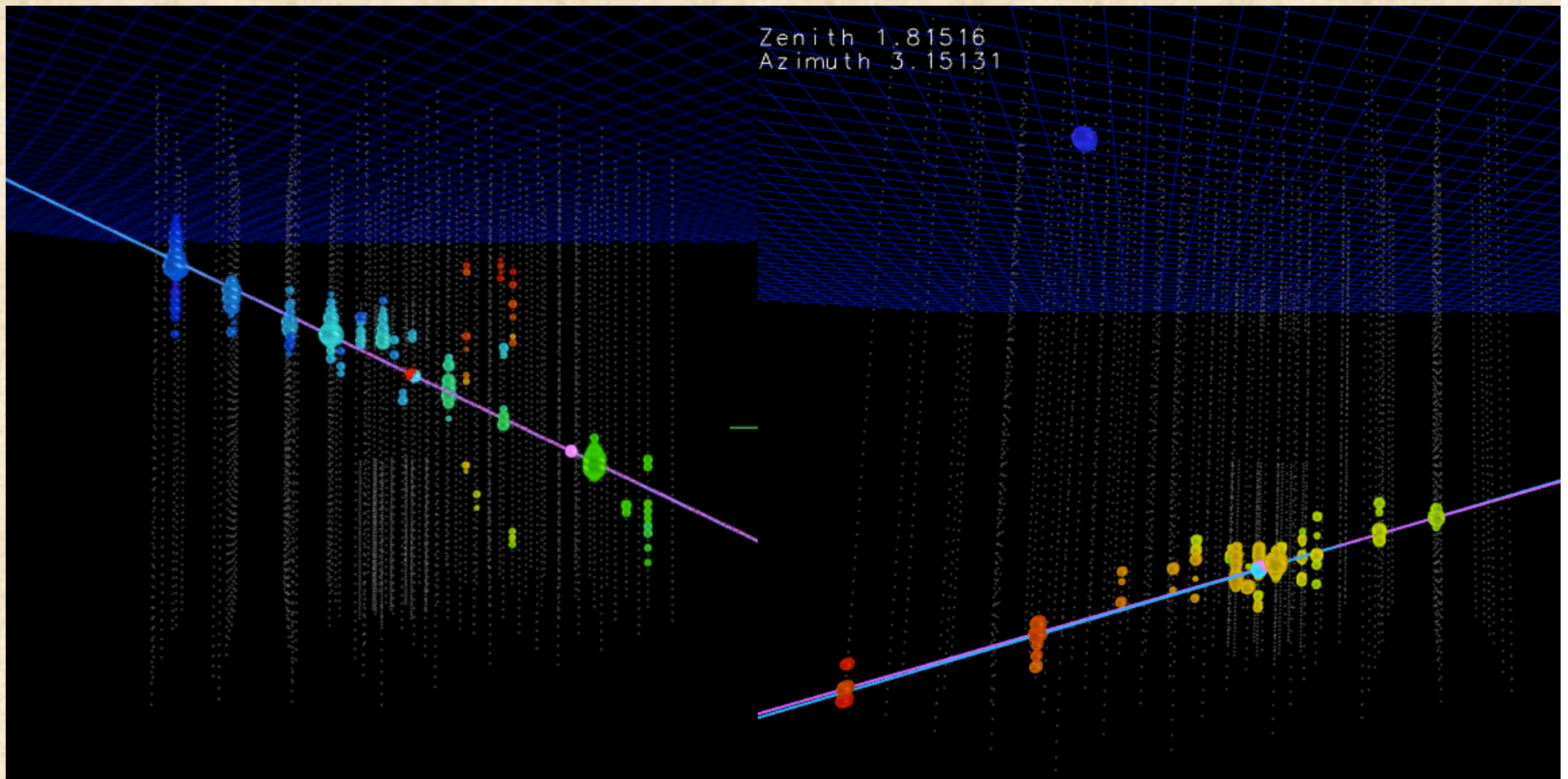
More Typical Downgoing muon

Cosmic Ray Muon Rate
~ 2000 Hz

Run 113203 Event 11202164
Fri Mar 20 06:07:16 2009



86 String Upgoing muon “Neutrinos”



From recent early commissioning runs for 86 string setup

IceCube Detector Status, Rates

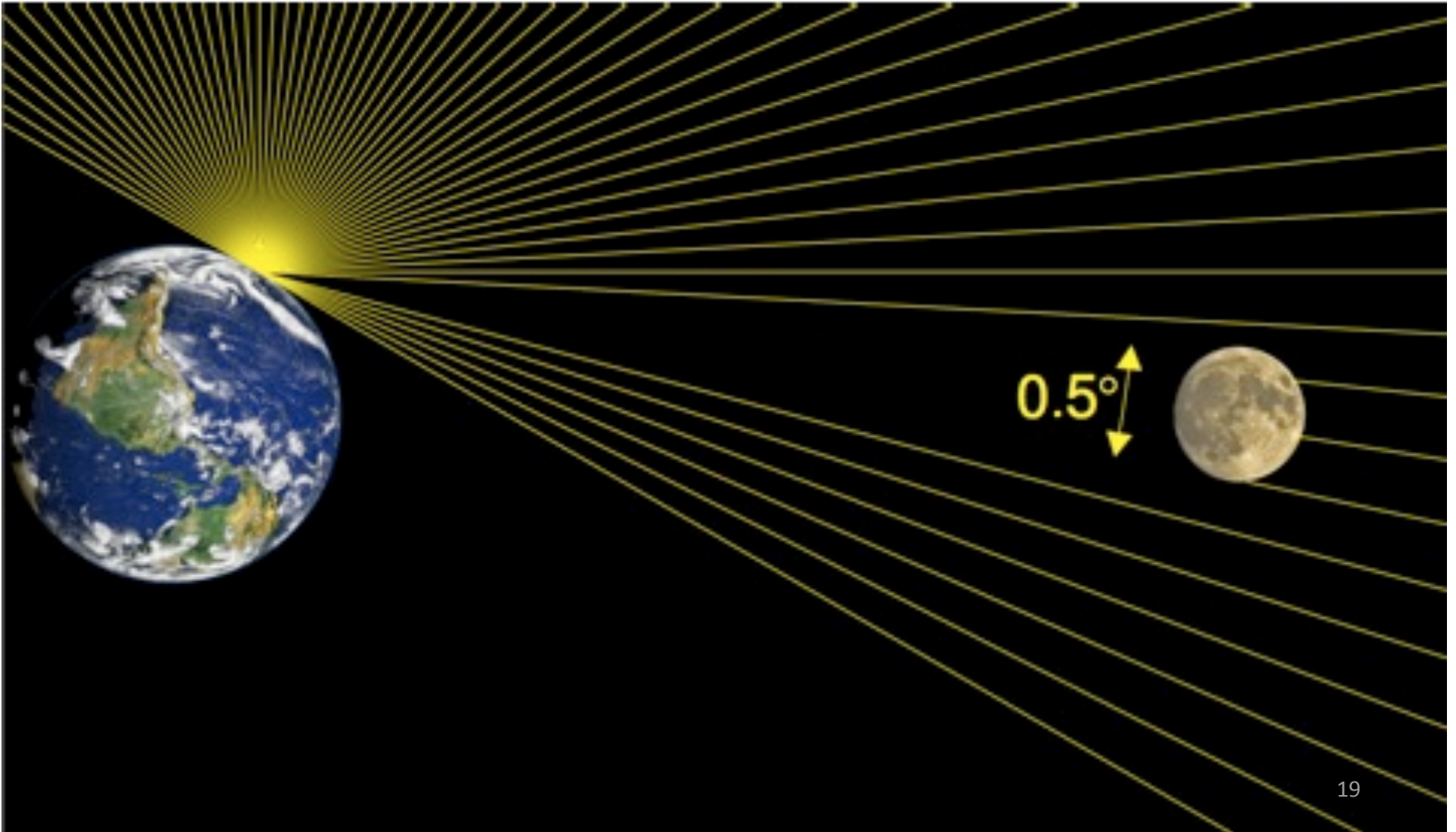
Strings	Data (year)	Livetime	μ rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	5 / day
IC40	2008-09	375 days	1100	38 / day
IC59	2009-10	360 days	1900	129 / day
IC79	2010-11	1 year	2250	
IC86	2011-	13 days	2700	

DeepCore
Completed

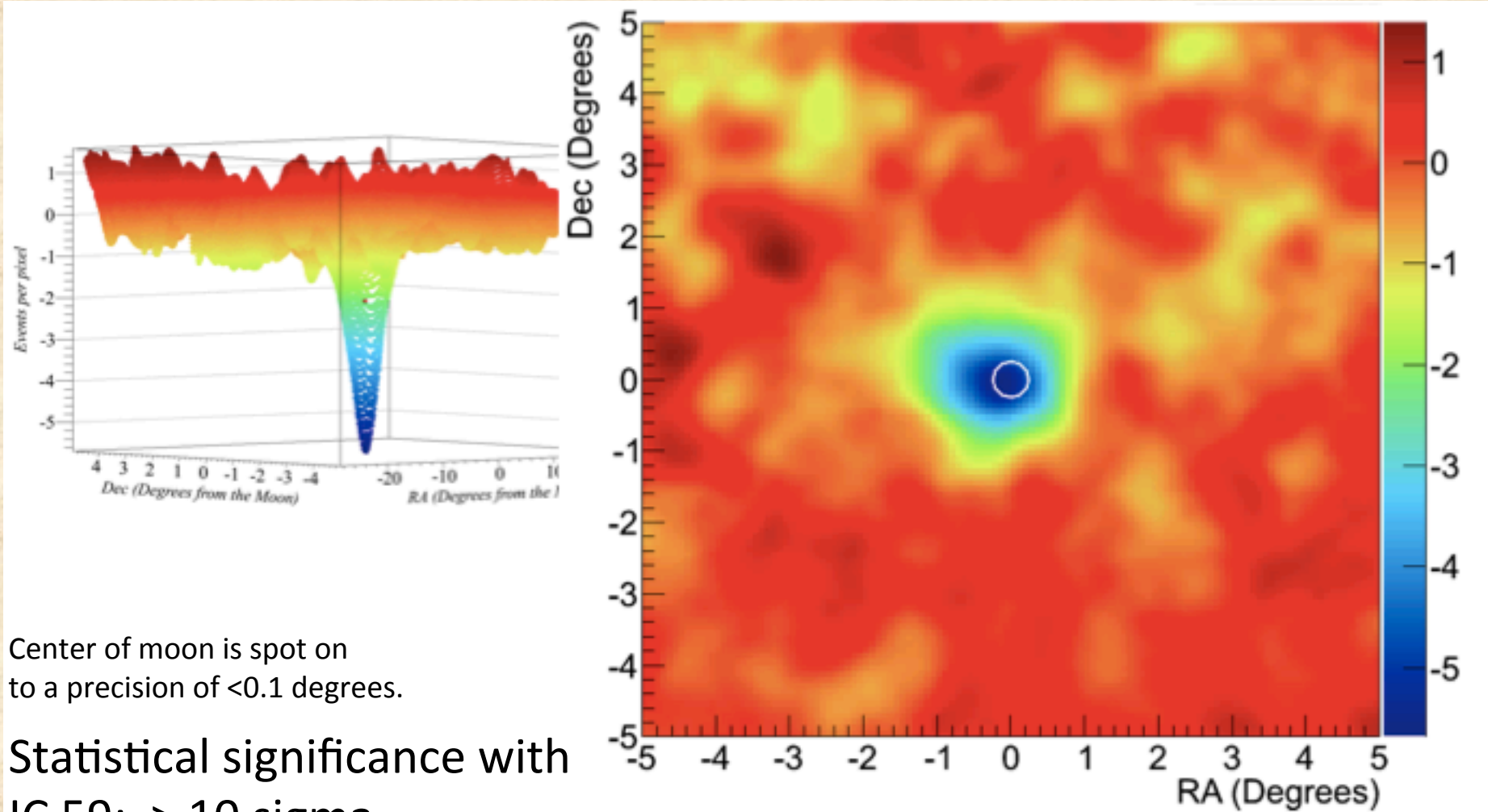
IC86 Run Start on May 13, 2011

- Detector performance parameters increase faster than the number of strings
 - Longer muon tracks (km scale)
 - Improved analysis techniques

Moon Shadow of Cosmic Rays using muons in the IceCube Detector



Moon shadow observed in muons – Check on IceCube pointing



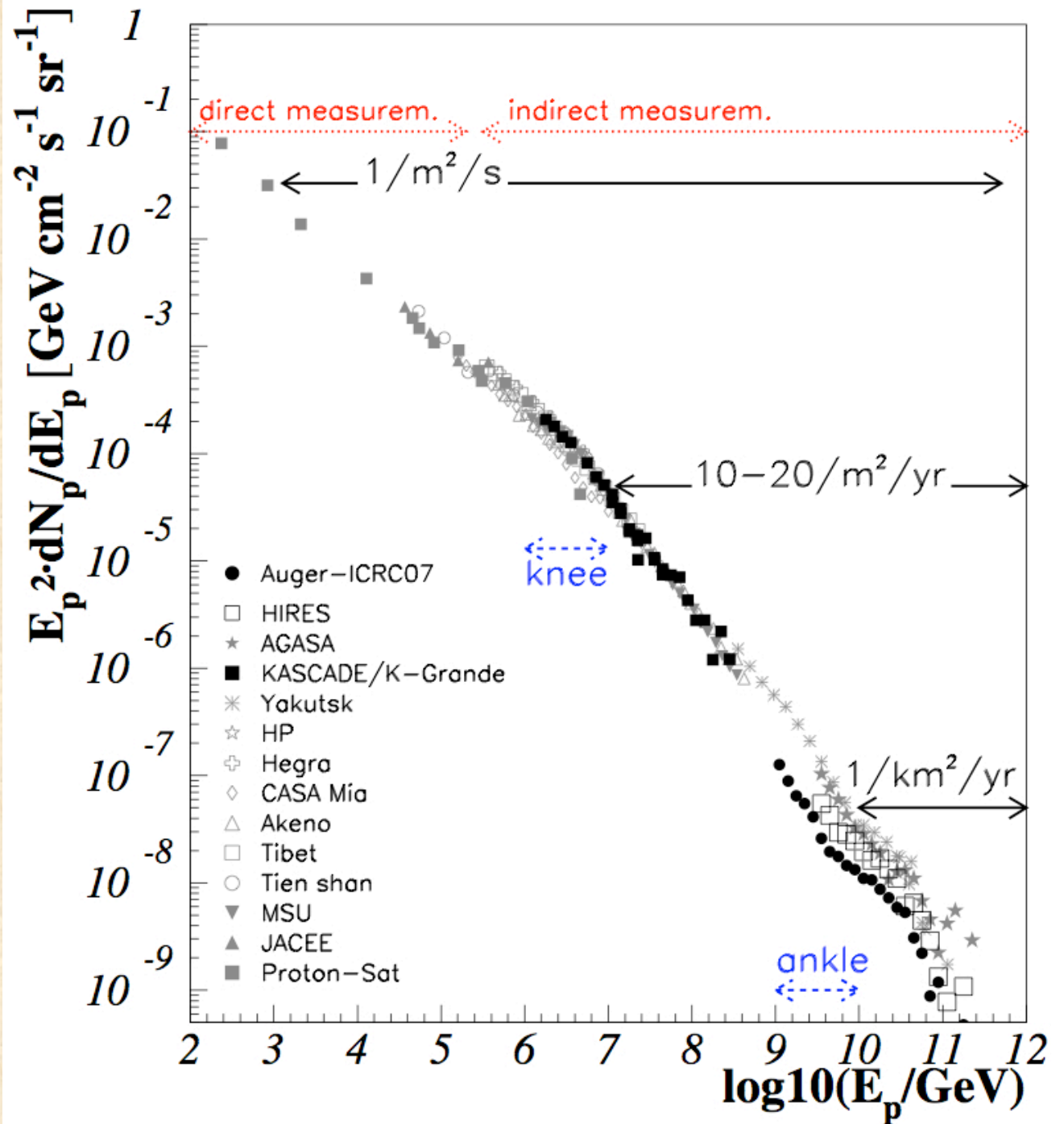
Center of moon is spot on
to a precision of <0.1 degrees.

Statistical significance with
IC 59: > 10 sigma

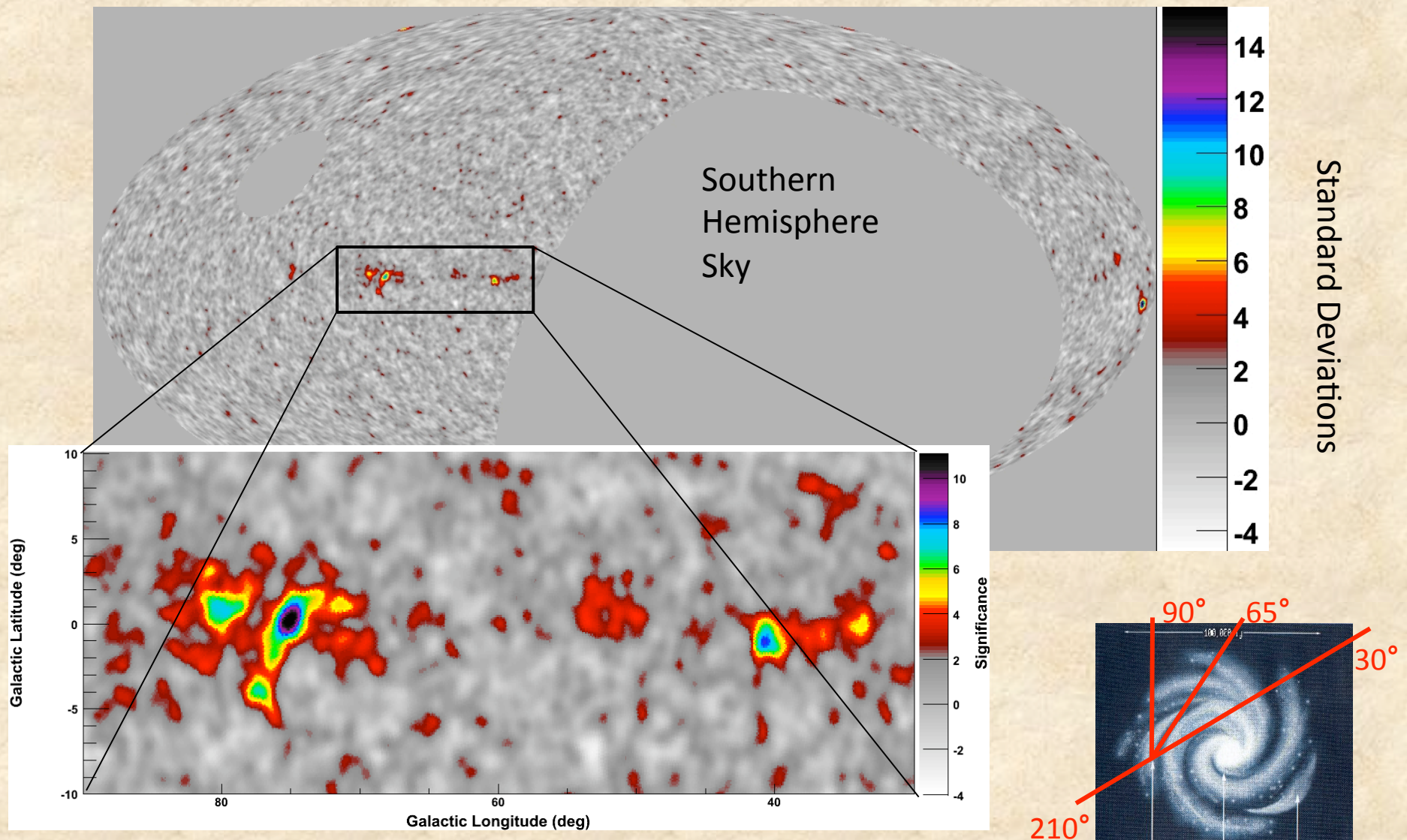
Sampling of IceCube Science Topics

- Search for sources of Galactic cosmic rays
- Search for the extragalactic cosmic rays – All sky point source
- Search for the extragalactic cosmic rays – gamma ray bursts
- Atmospheric neutrino spectrum
 - Non-standard neutrino oscillations
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Galactic Cosmic Rays

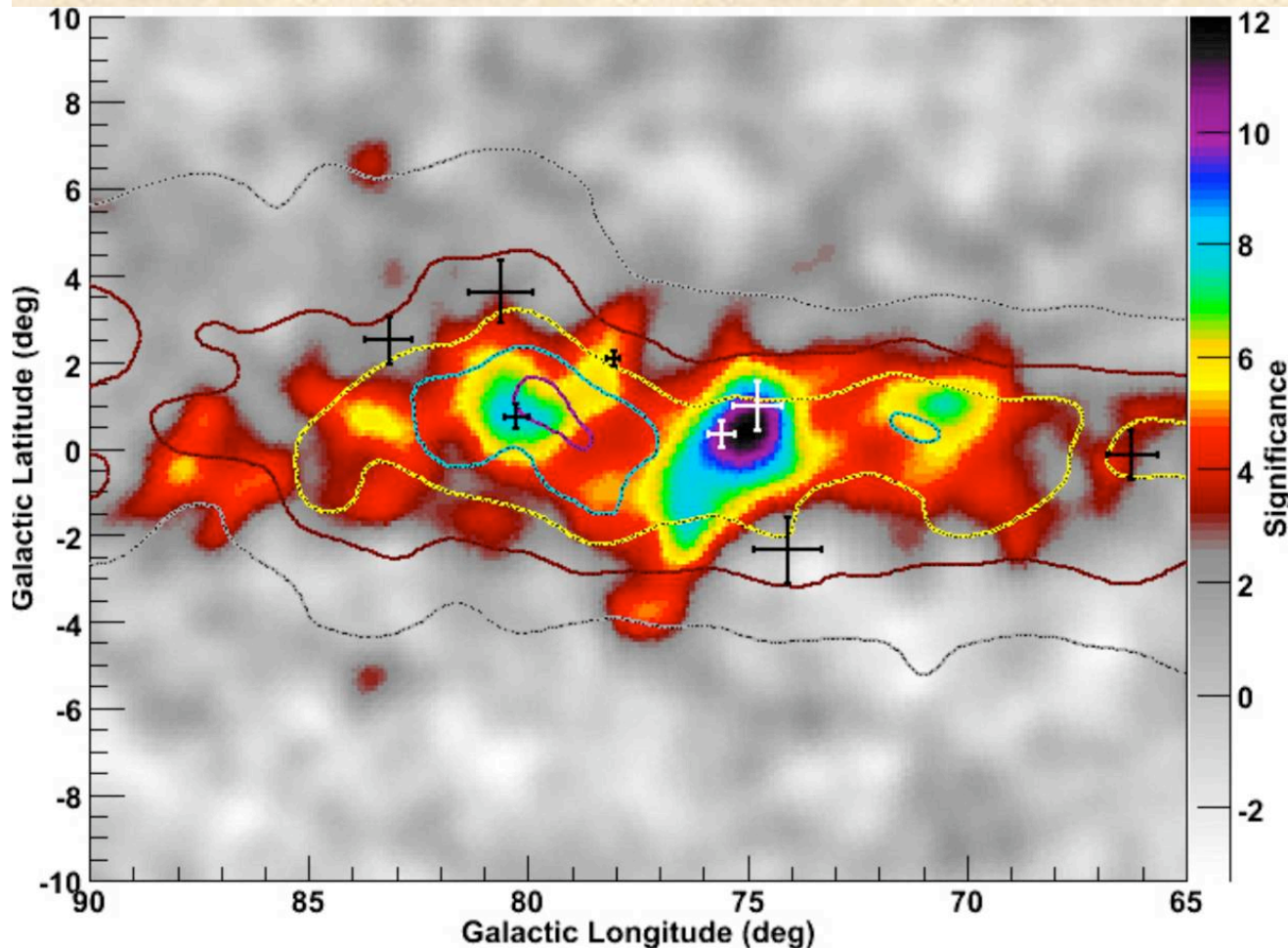


galactic plane in 10 TeV gamma rays : supernova remnants in star forming regions



milagro

cygnus region : Milagro



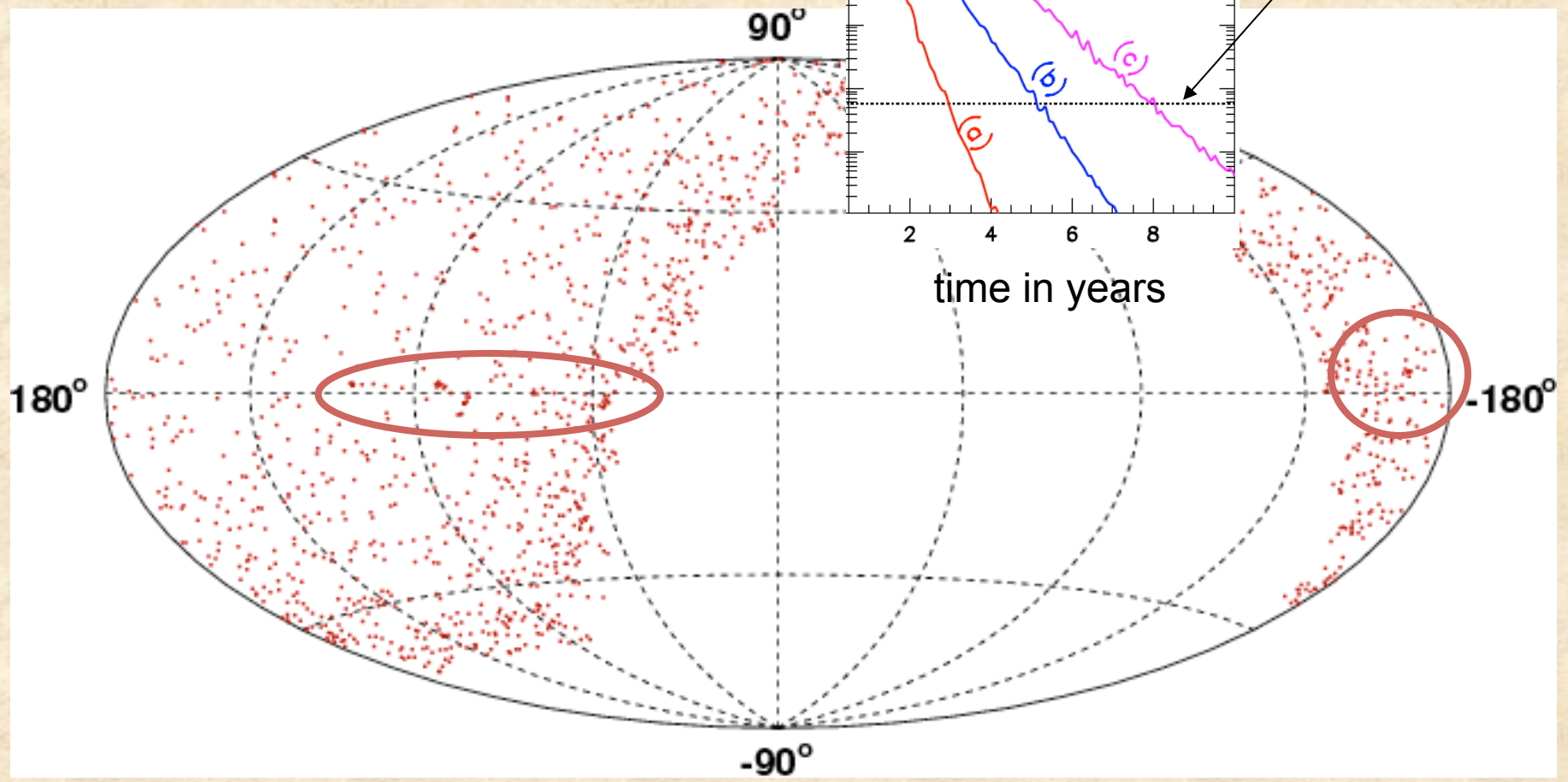
Milagro

translation of
TeV gamma rays
into
TeV neutrinos

$3 \pm 1 \nu$ per year in IceCube per source

5σ in 5 years of IceCube

IceCube image of our
Galaxy > 10 TeV



20,000 atmospheric neutrinos later ...

STACKING 6 MILAGRO SNR

Preliminary

IC40 Stacking Search	Med. Sensitivity	90% Upper Limit
Milagro 6 SNR	2.05 * prediction	5.50 * prediction

3.0 events in IC40 predicted by flux from Halzen, Kappes, O'Murchadha (2008)

p-values of 6 Milagro SNR stacked searches:

AMANDA 7-yr	22-strings	40-strings
20%	27%	2.3%

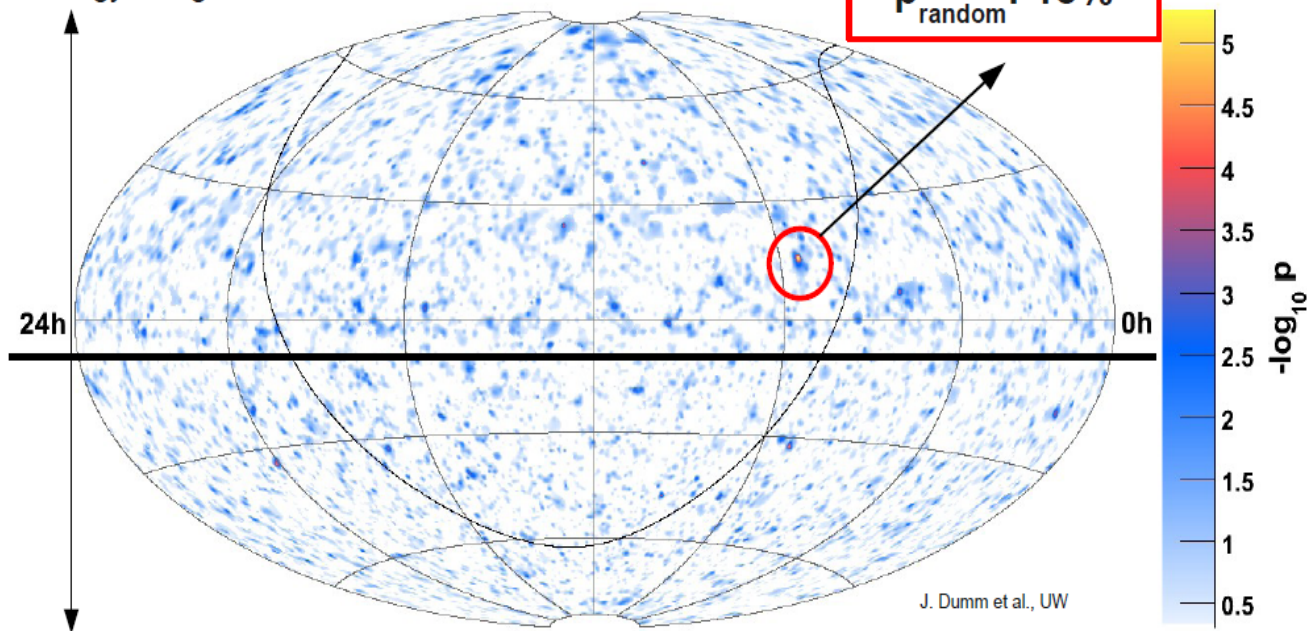
(a posteriori)

Sampling of IceCube Science Topics

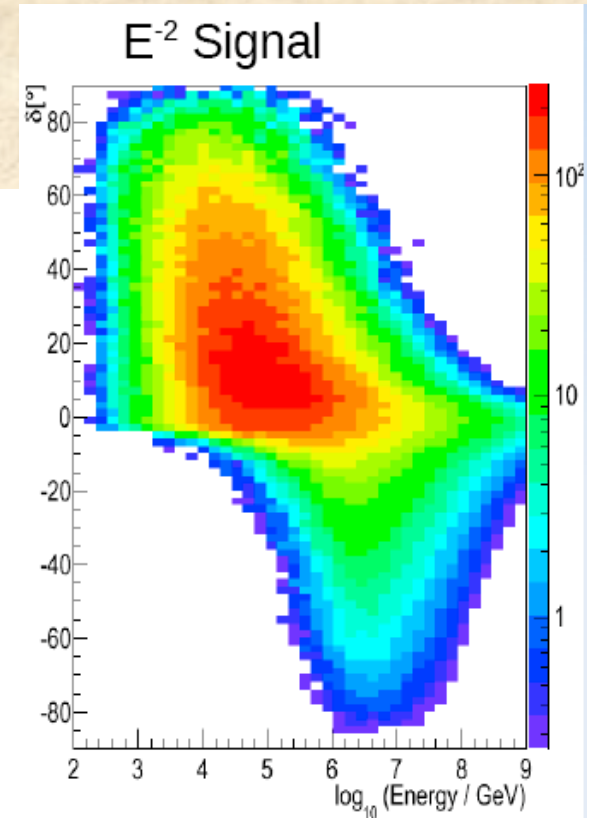
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IC40 Point Source Search

Below Horizon:
Data dominated by atmospheric **Neutrinos**
Energy Range 10s-100s of TeV

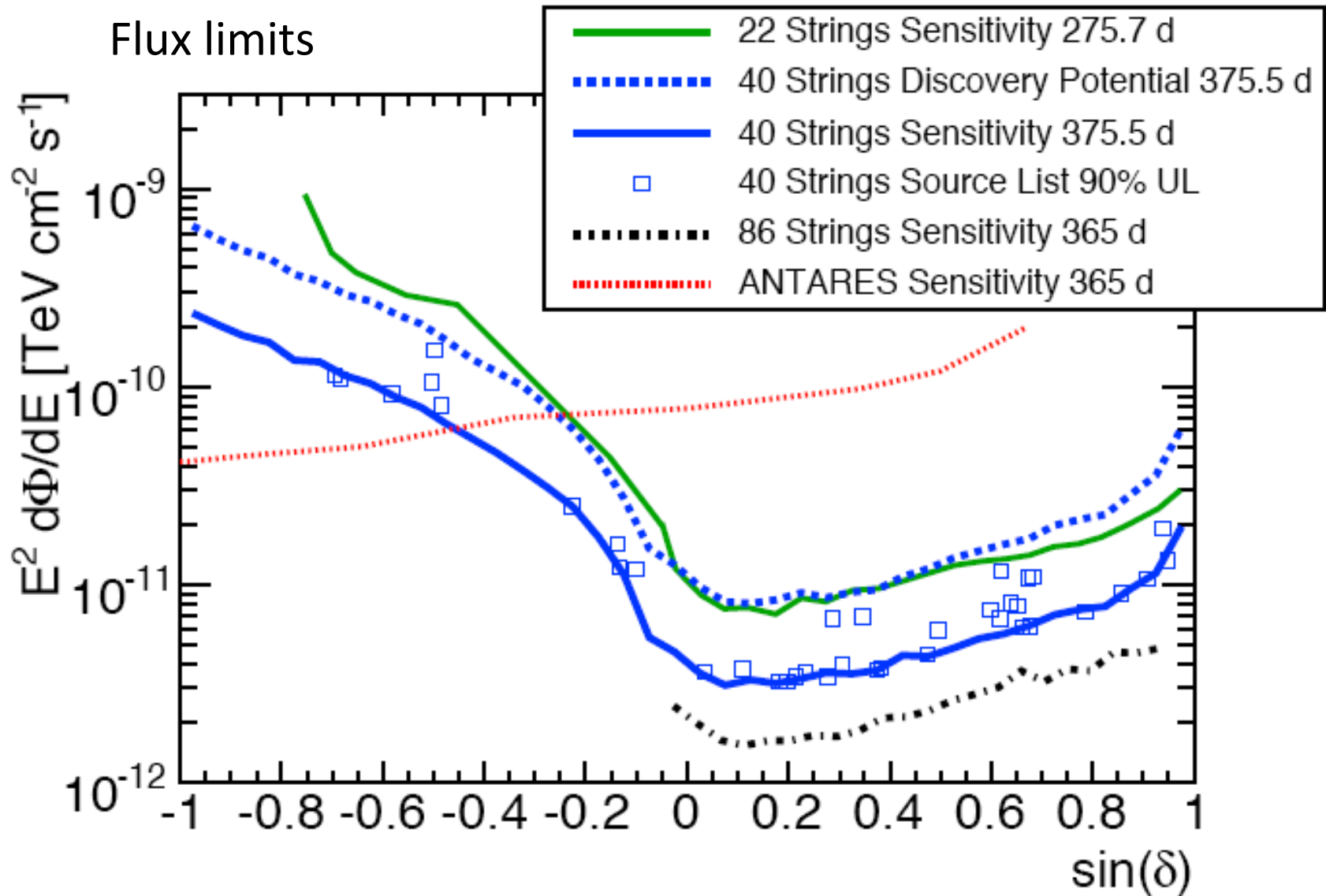


Above Horizon:
Data dominated by atmospheric **Muons**
Energy Range >PeV, increasing with angle

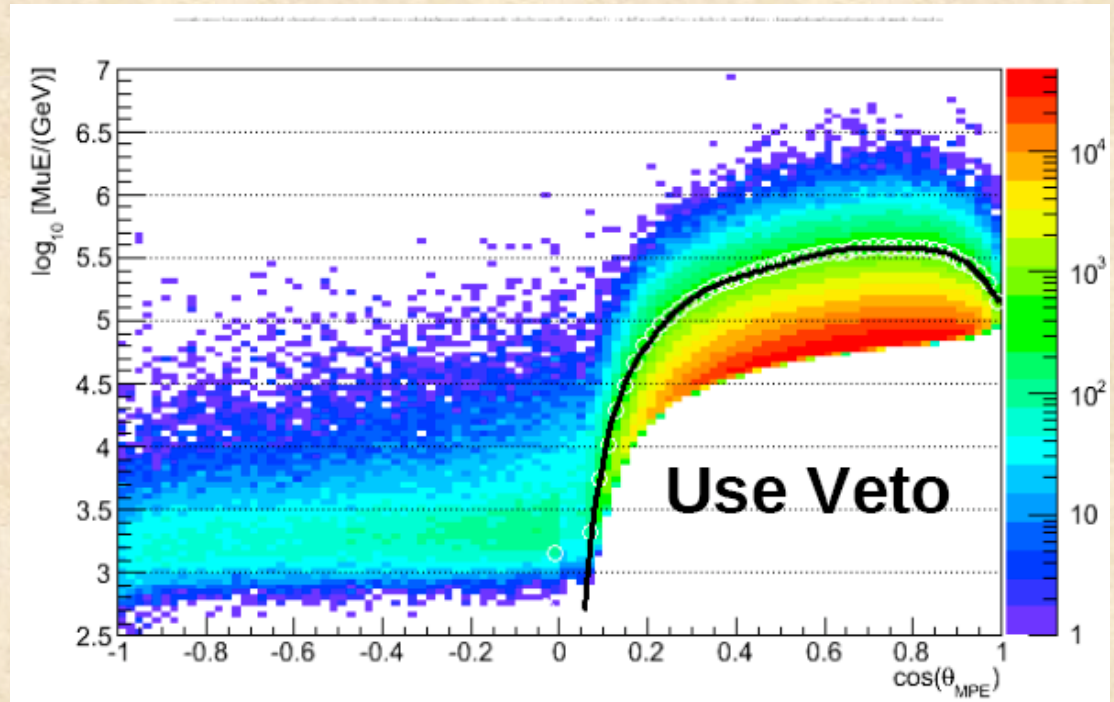
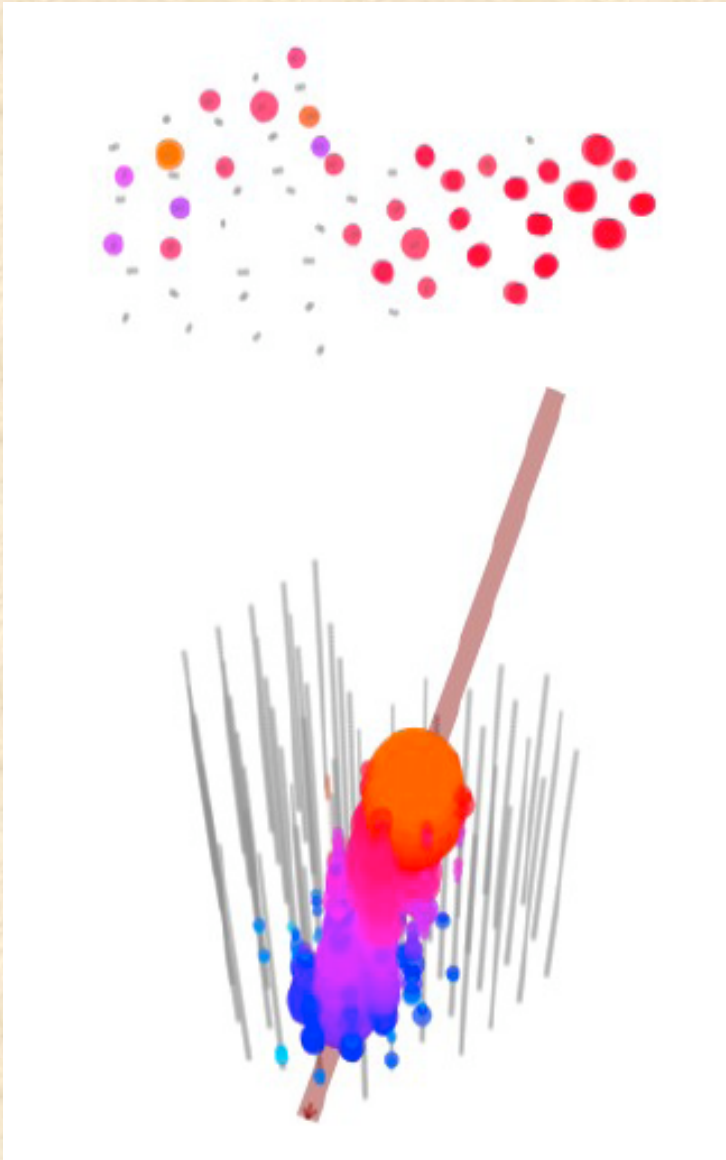


ApJ. 732:18,2011

All sky search & source list

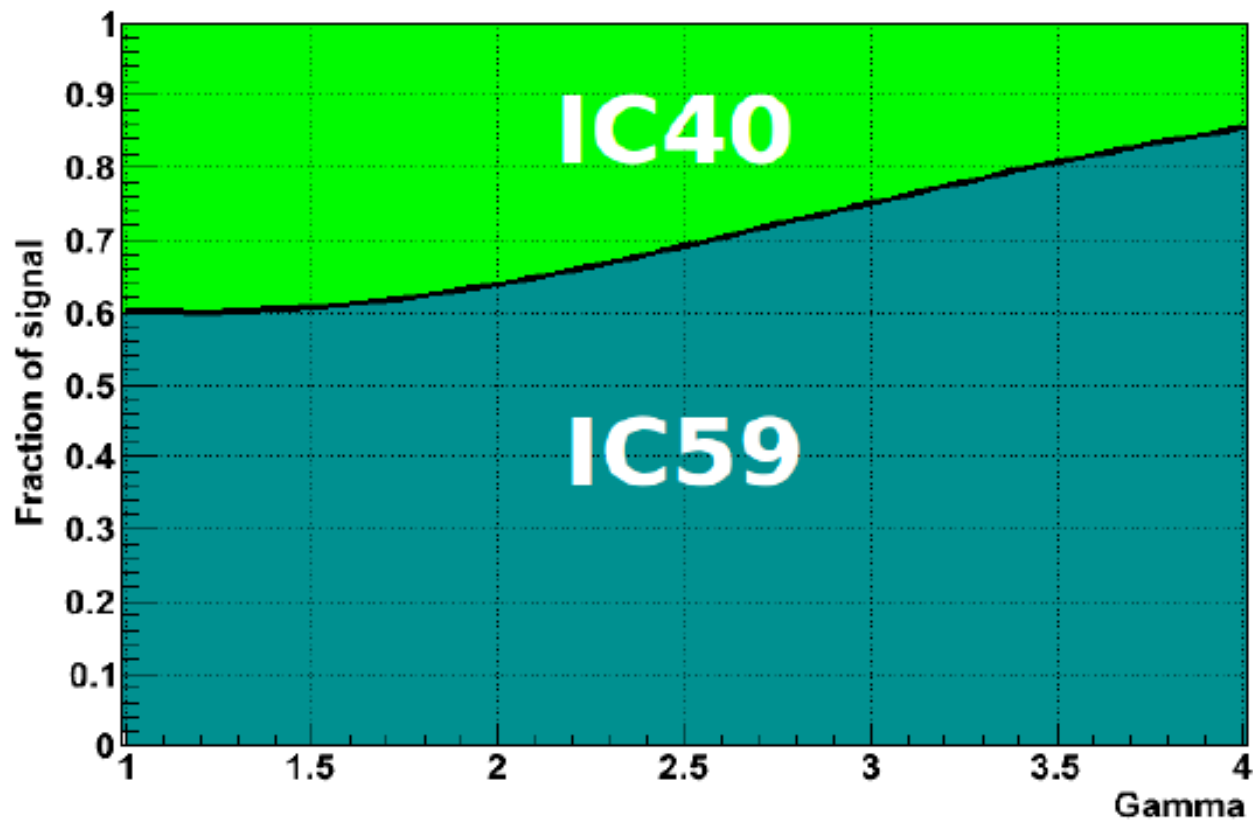


IC59 search - Improvements



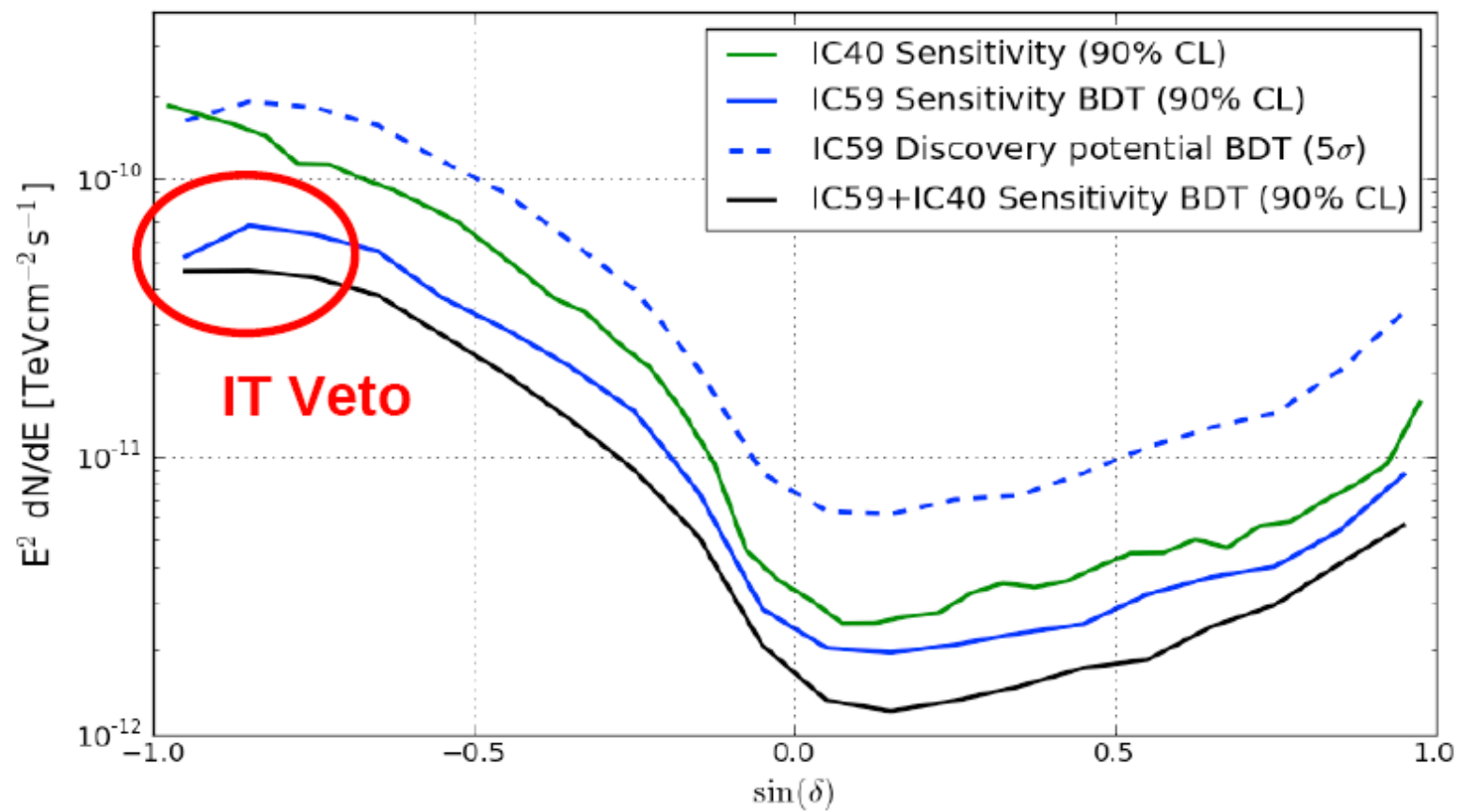
- Use IceTop as veto to reduce energy “cut” for downgoing
- Improved sensitivity using BDT
- Improved reconstruction

Combining IC59 with IC40



Increased effective area and improvements in reconstruction and analysis

Expected sensitivity IC59+IC40

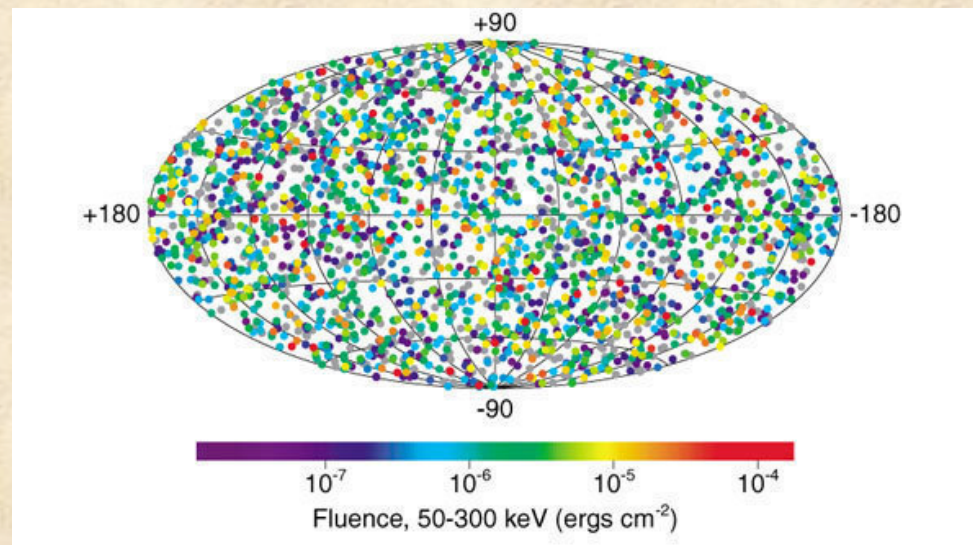


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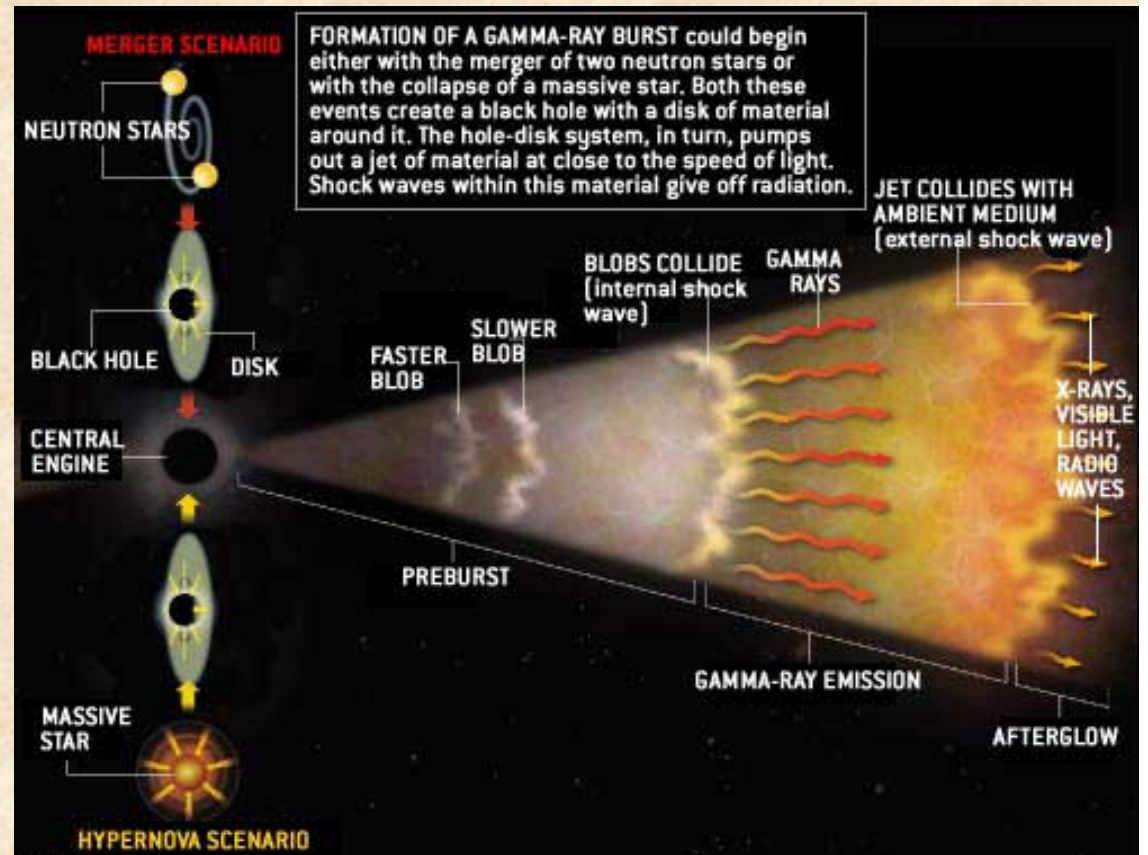
Gamma Ray Bursts

- Gamma-Ray Bursts are short bursts of gamma rays, a few seconds in duration
- Brighter than rest of gamma ray sky
- Afterglow lasting much longer
- First observed in Vela satellites (1960s)
- Several generations of satellite-based observations have shown:
- Extra-galactic origin
- Gamma-ray emission beamed



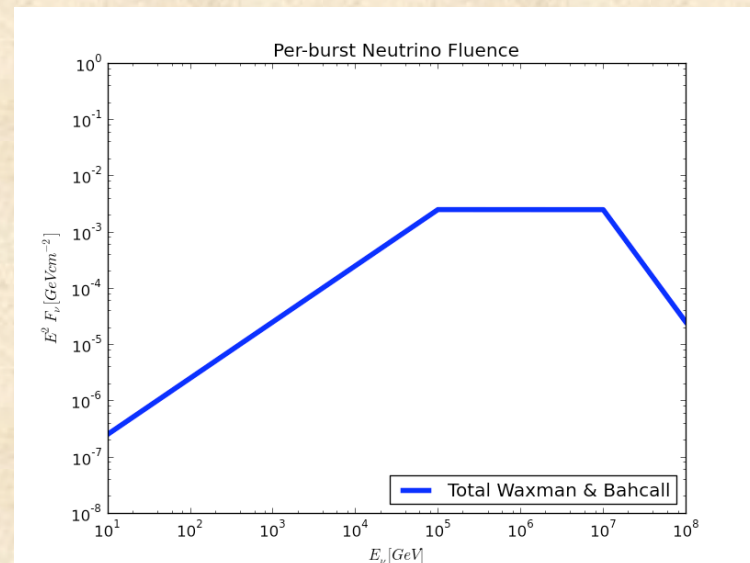
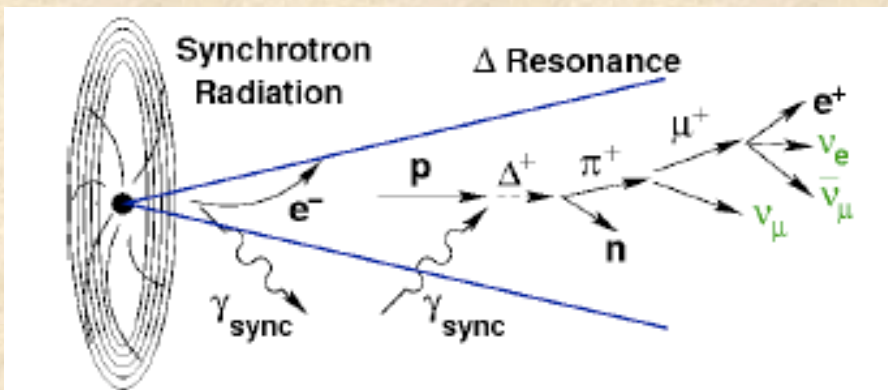
Gamma Ray Bursts

- Fireball model is successful at explaining the observed photons
- Prompt gamma rays
- Afterglows
- Realistic to believe that baryons are also accelerated
- Produce high-energy neutrinos



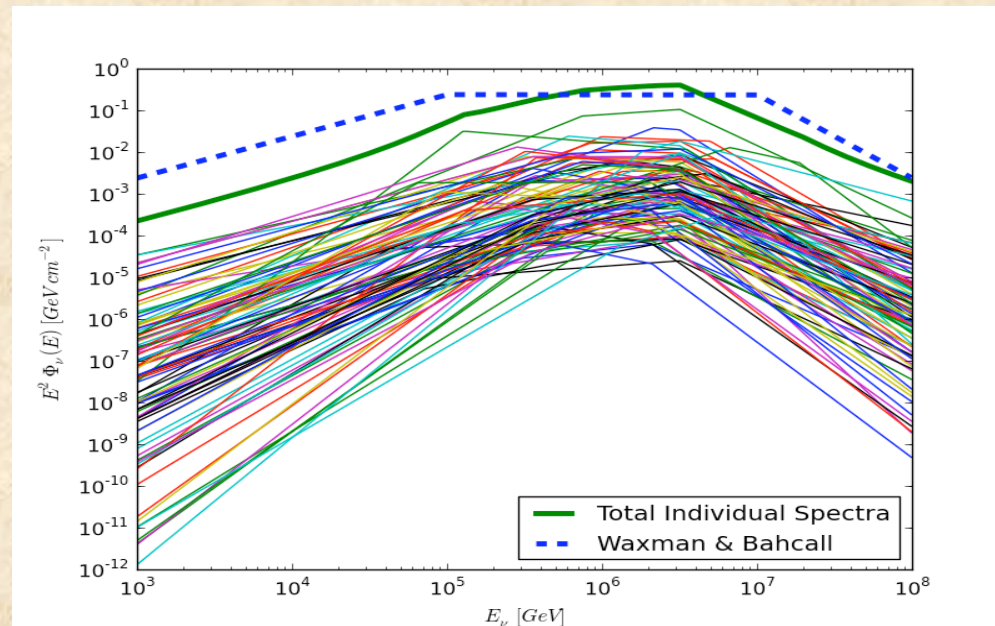
GRB Neutrino predictions

- Internal shocks in GRBs are a compelling candidate for the source of acceleration for UHECRs.
- Acceleration conditions required to produce the observed gamma rays would also be sufficient for UHECR production
- Observed gamma-ray burst energy injection rate into Universe well matched to observed UHECR energy
- Waxman-Bahcall modeled neutrino production from photon-hadron interactions in fireball



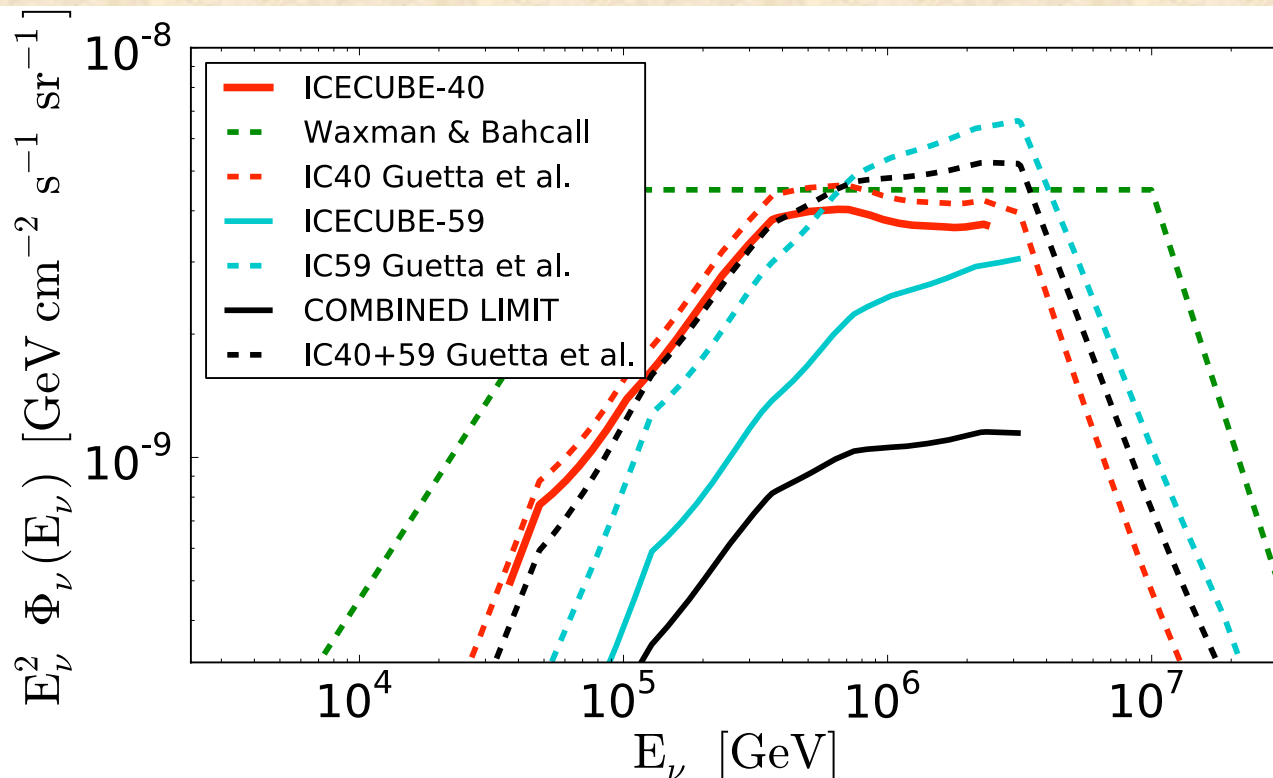
IceCube GRB Search

- IceCube performs a stacked for a neutrino signal in coincidence with observed GRB gamma signals
- All Northern hemisphere GRB bursts are considered where good IceCube data exists.
- Combination of spatial and time correlation required for a signal yield low background (***~Background Free Search***)
- Per-burst neutrino fluence and spectra are calculated based on the measured gamma-ray spectra
- Parameterization of Guetta, et al. (Astropart.Phys. 20 (2004) 429-455)



GRB Results

- IC59, IC40, IC22 and AMANDA have all searched for neutrinos in coincidence with reported gamma-ray bursts
- ***No observed signal, 90% CL upper limits set.***



IC40: 117 Bursts

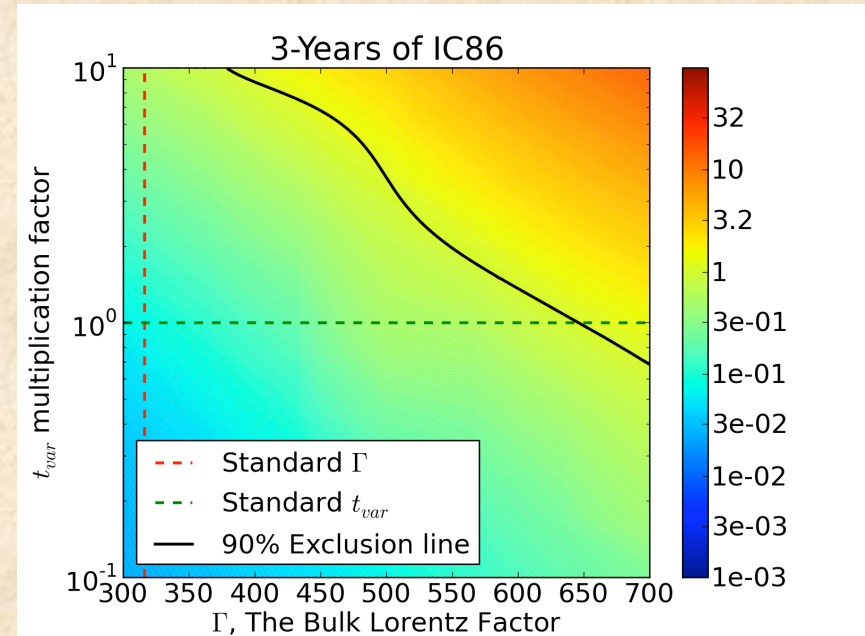
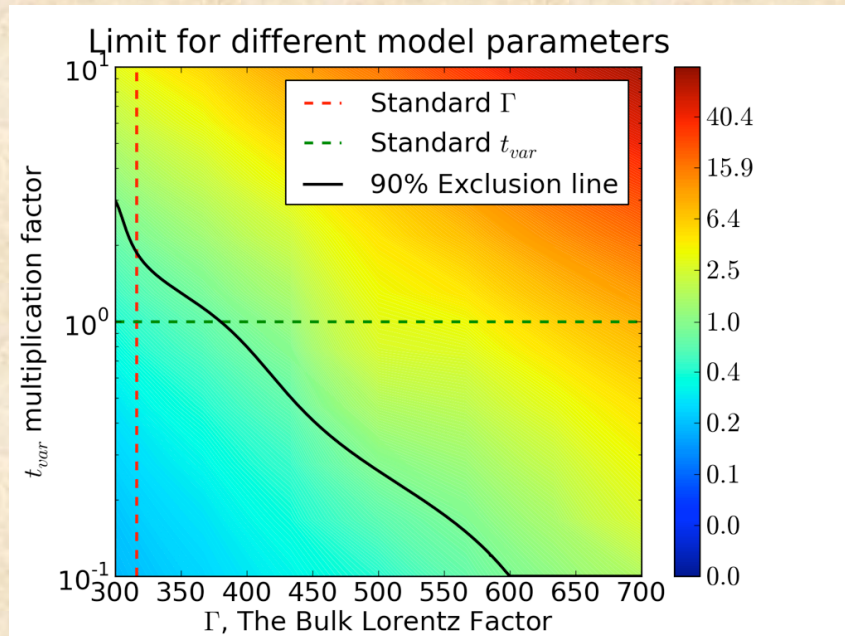
**IC59: 109 Bursts
(preliminary)**

IceCube GRB Summary

- Three successive seasons without a GRB neutrino discovery
- IC40 90% CL upper limit: 0.82 modeled flux
- IC59 90% CL upper limit: 0.46 modeled flux
- Combined search results
 - Expect almost 10 neutrinos from model, see 0
 - Combined limit is 0.22 modeled flux
- *Where are the neutrinos?*
- *Do we already rule out GRB as CR source?*
- Input assumptions in modeled GRB neutrino flux
 - Bulk Lorentz factor, fraction of energy in electrons relative to protons, dynamics of time structure
- Ongoing work to place limits on UHECR production in GRBs
 - *Km³ detector gives sensitivity of Astrophysical Interest!*

GRB astrophysics in IceCube

Current & Future

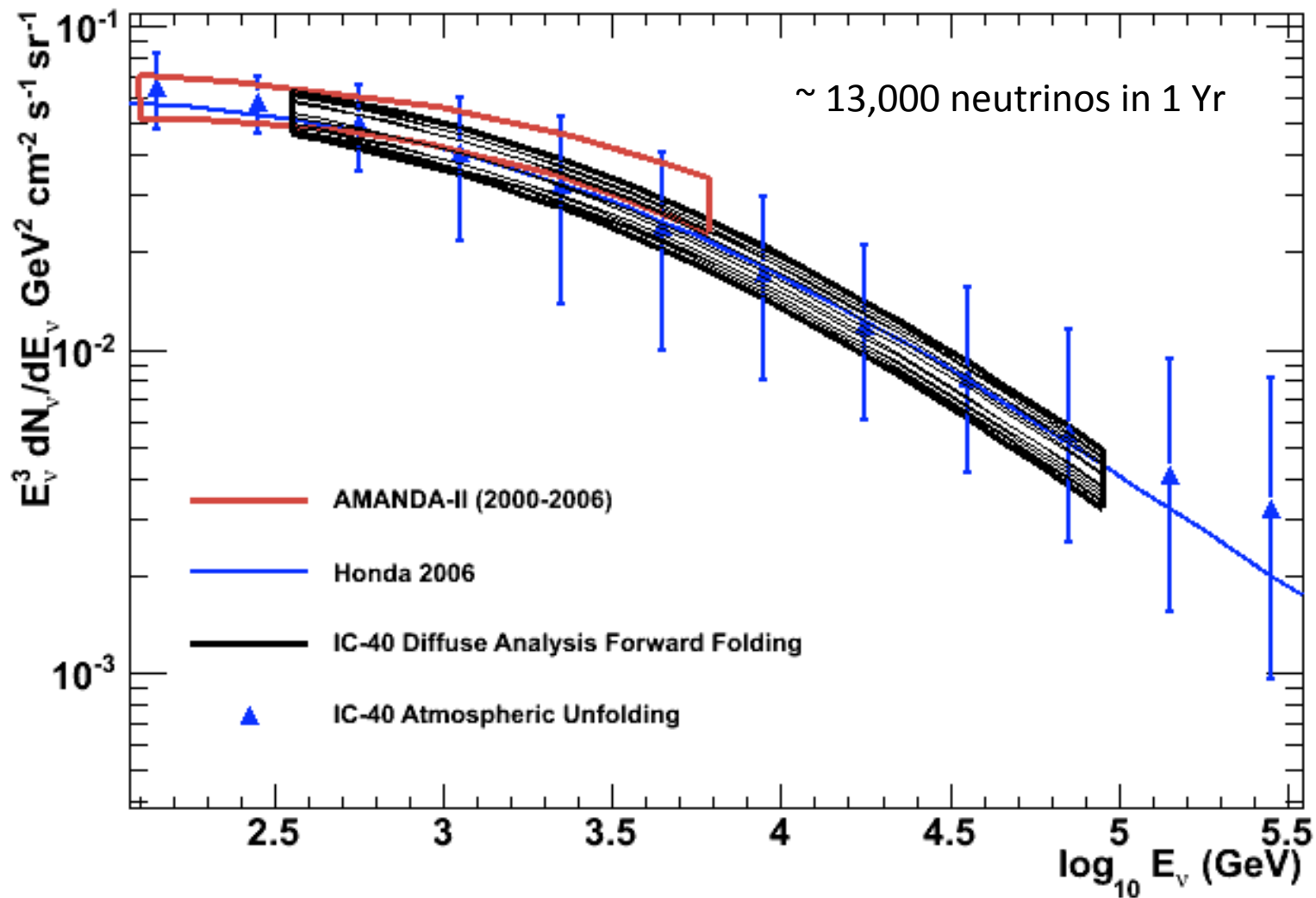


3 years of IceCube will see neutrinos from GRBs or rule out the fireball model!

Sampling of IceCube Science Topics

- Search for sources of Galactic cosmic rays
- Search for the extragalactic cosmic rays – All sky point source
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- **Atmospheric neutrino spectrum**
 - Non-standard neutrino oscillations
- Search for HE diffuse neutrinos
 - muons
 - Cascades
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Atmospheric Neutrino Spectrum

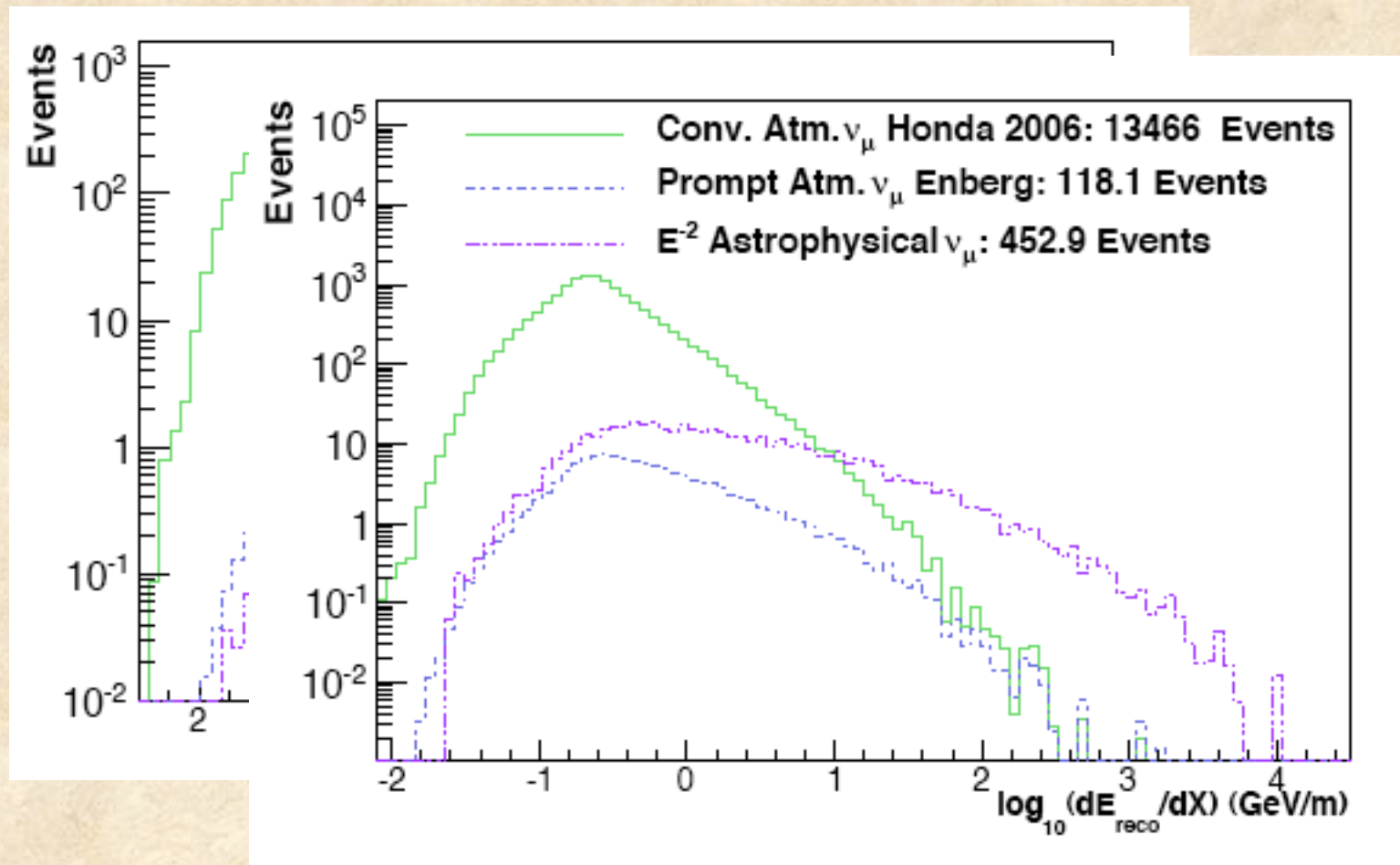


PHYSICAL REVIEW D 83, 012001 (2011)

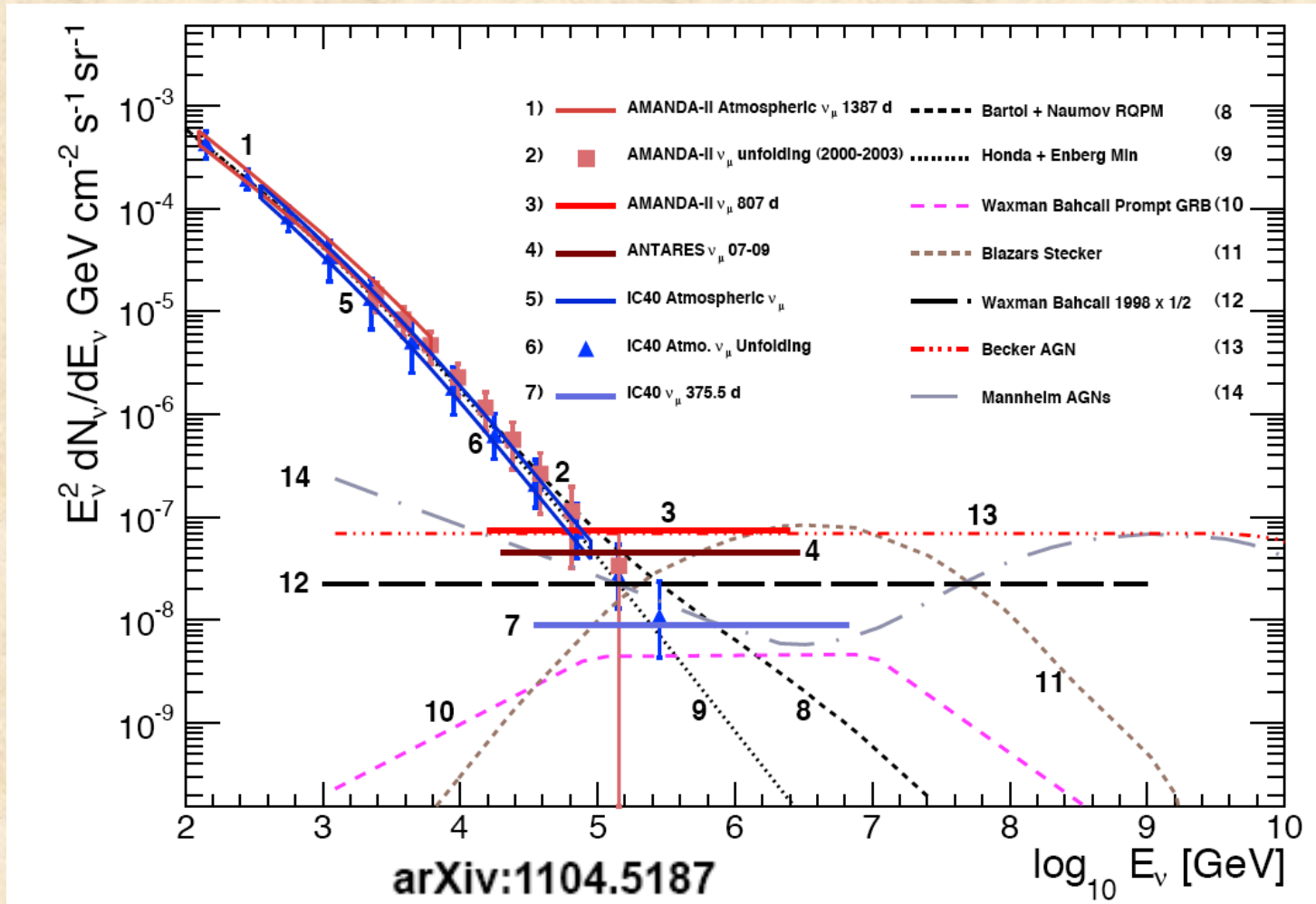
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Search for Diffuse Neutrino flux with Muon neutrinos



IC40 muon neutrino diffuse flux limit



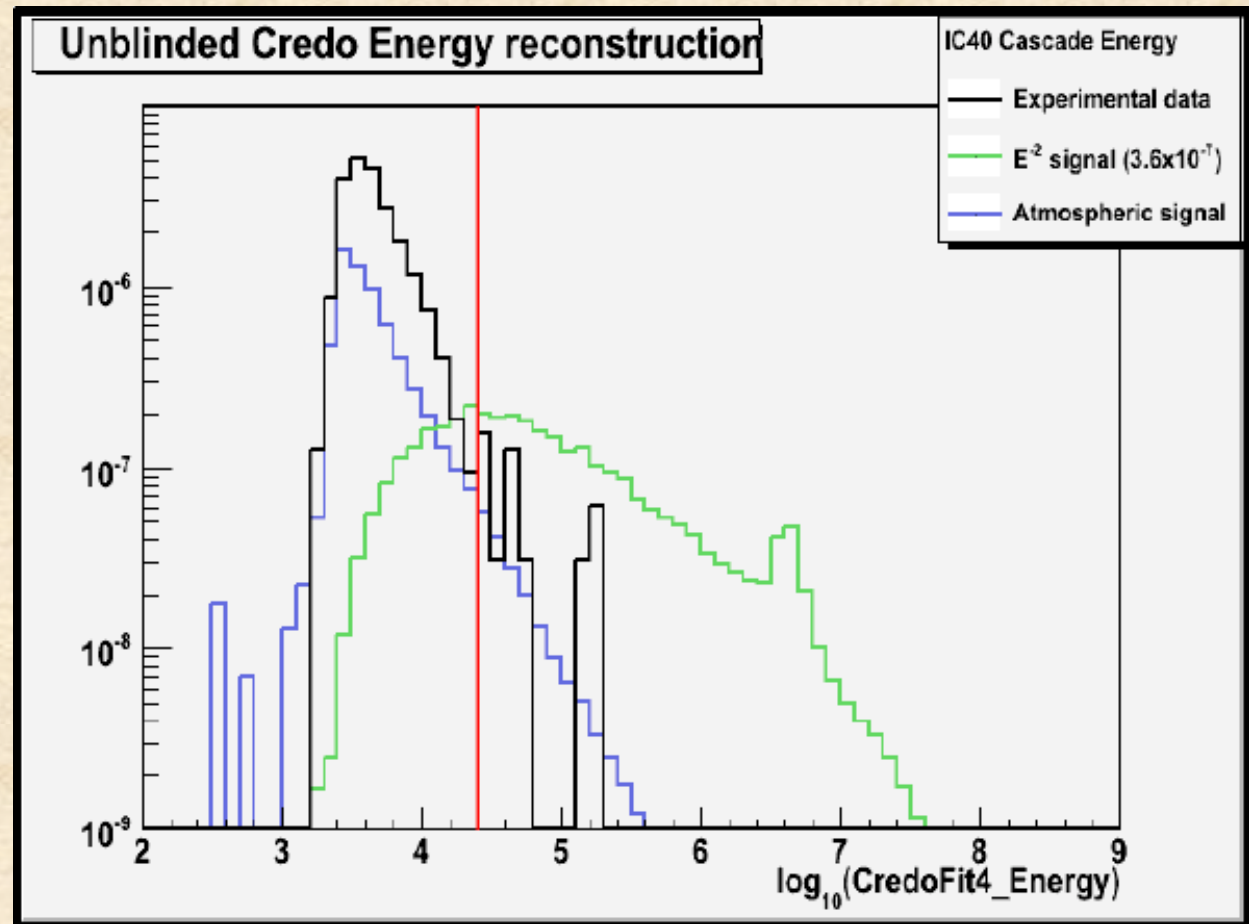
IceCube 40 has Reached the Waxman-Bahcall bound!

HE Cascades in IceCube

- The volume of IceCube is qualitatively different than previous generations of detectors
 - Ability to contain high energy cascade events
 - Advantage is that all sky is covered at all energies
 - Muon astronomy constrained to low energy contained events and higher energy events (above or induced muon spectrum)
 - Disadvantage is reduced ability to point for astronomy
 - But, for diffuse analysis pointing not critical!
- IC40 is sufficient to start sensitive searches using cascades
 - Early work, not yet as mature as muon neutrino
 - Preliminary results → work in progress

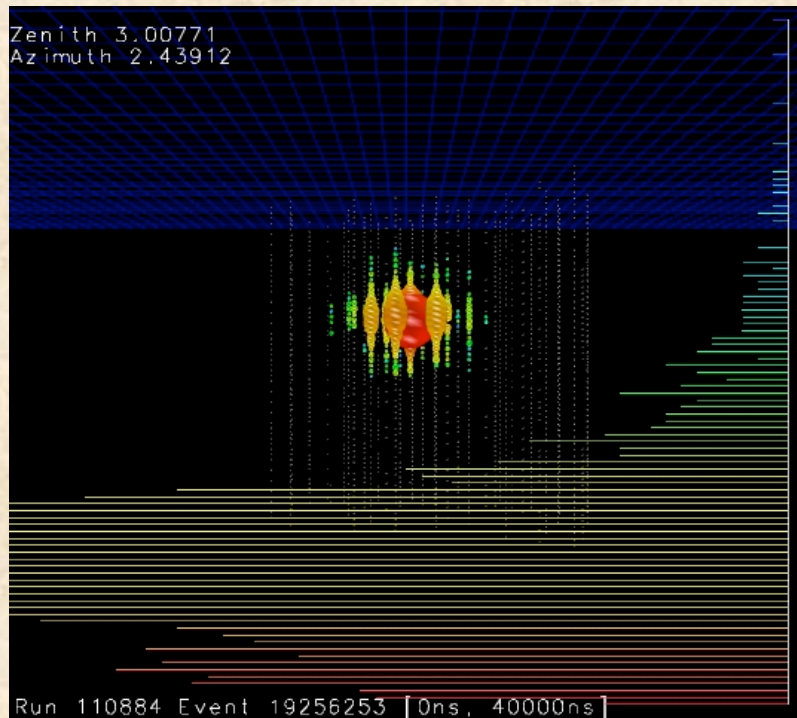
IC40 high energy cascades *(preliminary)*

- 14 events pass cuts
- Detailed examination of the 14 events indicates ~4 events look like background from high energy cosmic rays
- Generating more monte carlo to make a better estimate for CR backgrounds and expected number of atmospheric neutrino events

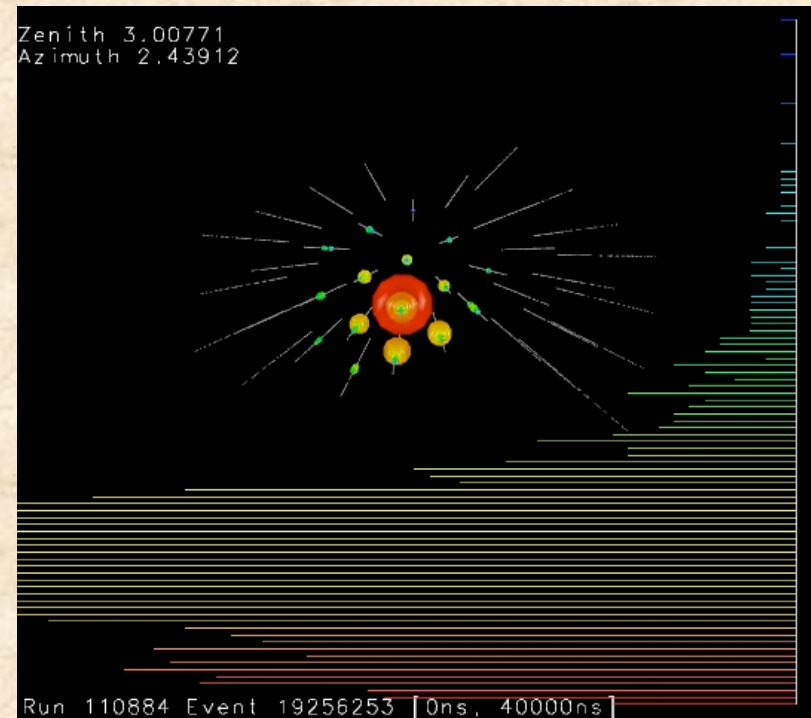


IC40 HE cascade event displays

Energy estimate = 175 TeV

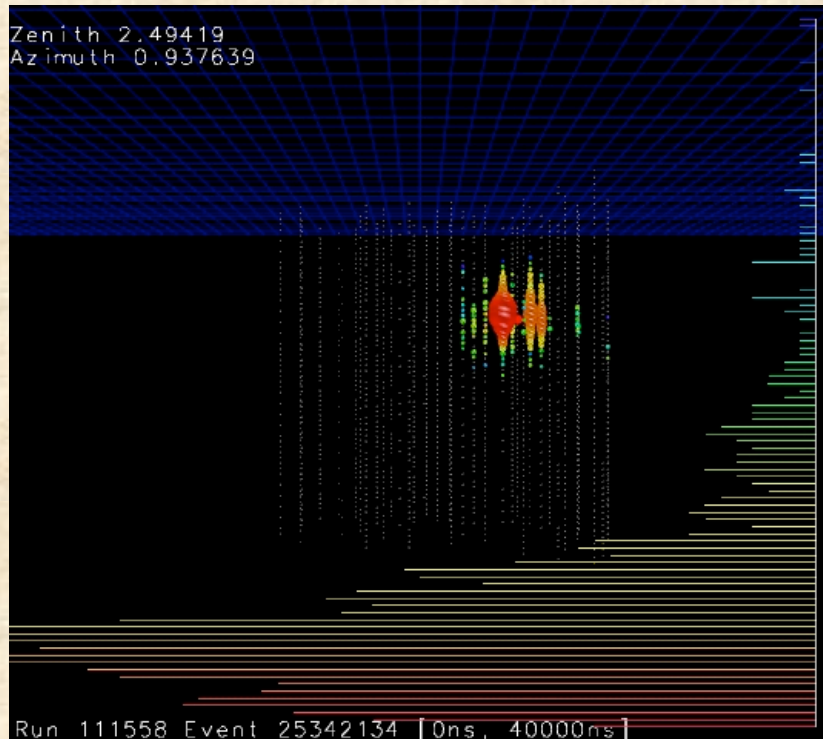


Side view

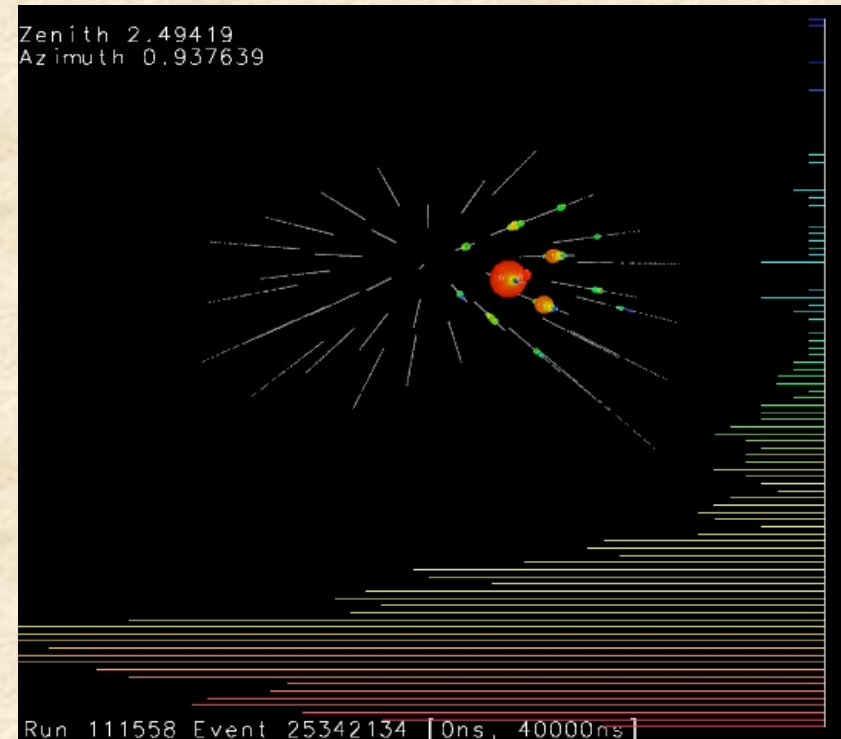


Top view

Energy estimate = 45 TeV



Side View



Top View

*Several Cascade Analyses in progress with IceCube Data
HE atmospheric neutrino/diffuse, EHE GZK, LE (deep core)*

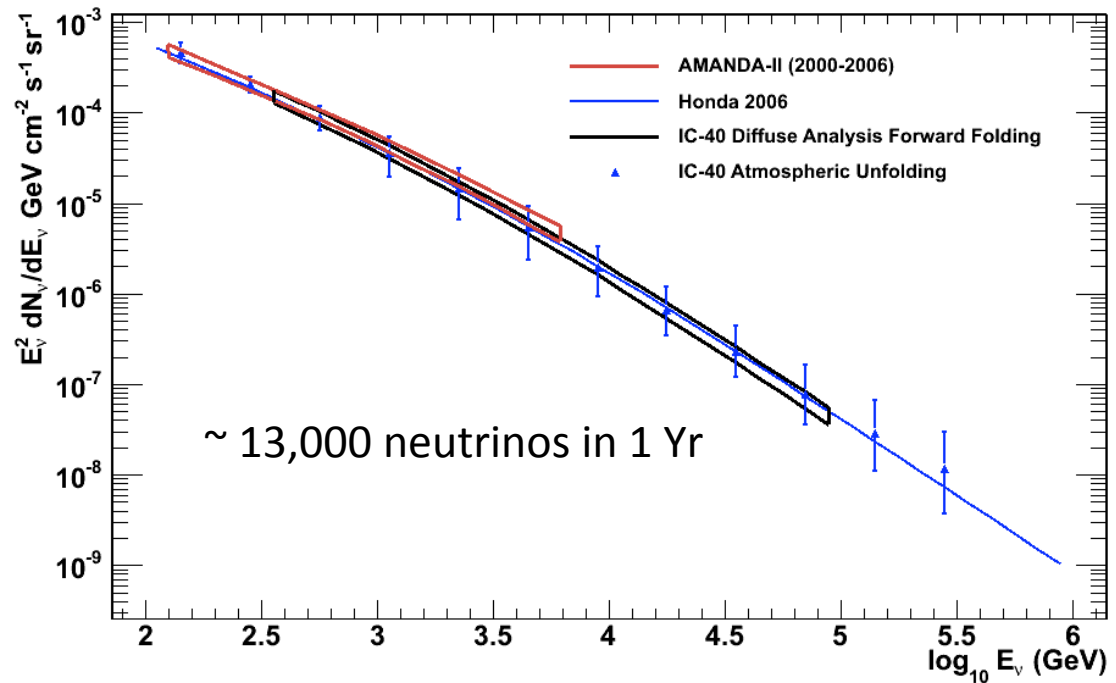
Stay tuned!

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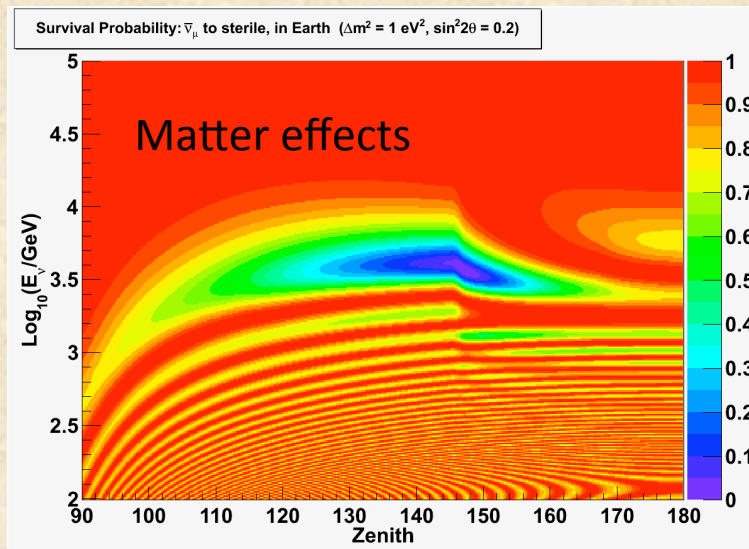
Atmospheric Neutrino Spectrum

- High statistics sample of atmospheric neutrinos
- $\sim 13,000$ events above ~ 100 GeV with $>95\%$ purity in IC40
- $\sim 40,000$ events in IC59
- *IC79 even higher, and Deep Core improves $E < 100$ GeV*
- Use the HE sample (~ 100 GeV and higher) to search for non-standard oscillations as a test of the MiniBooNe antineutrino results

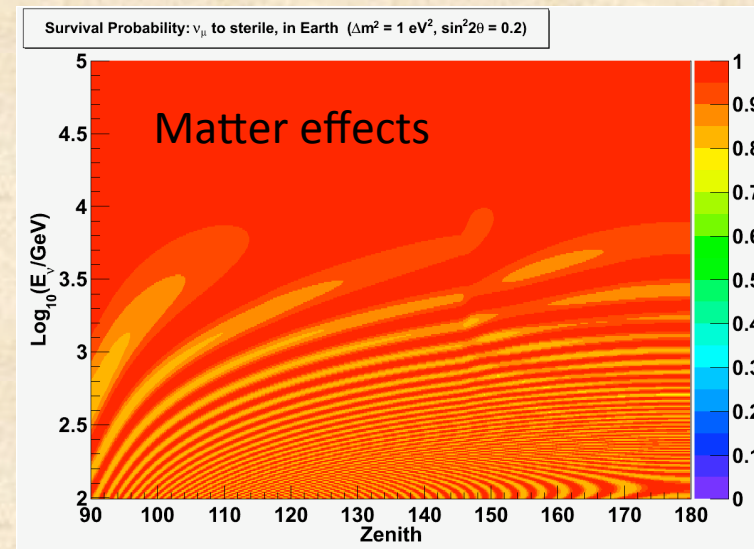


Non-standard oscillations effect on atmospheric neutrinos

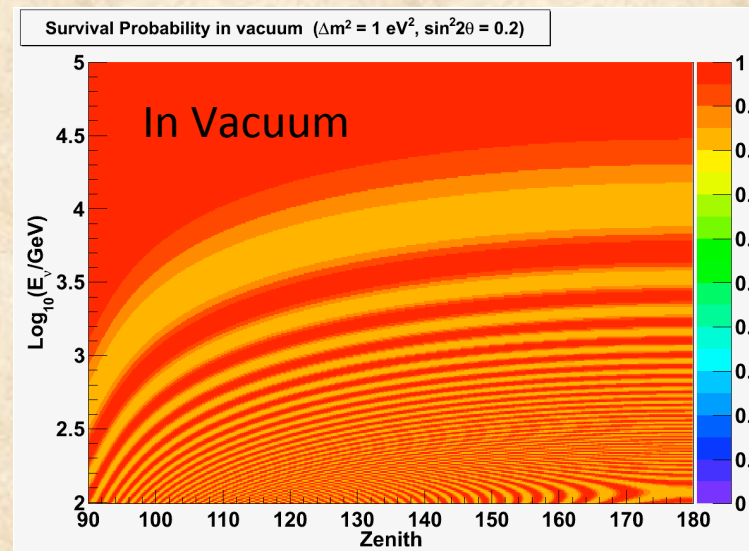
Antineutrinos



Neutrinos

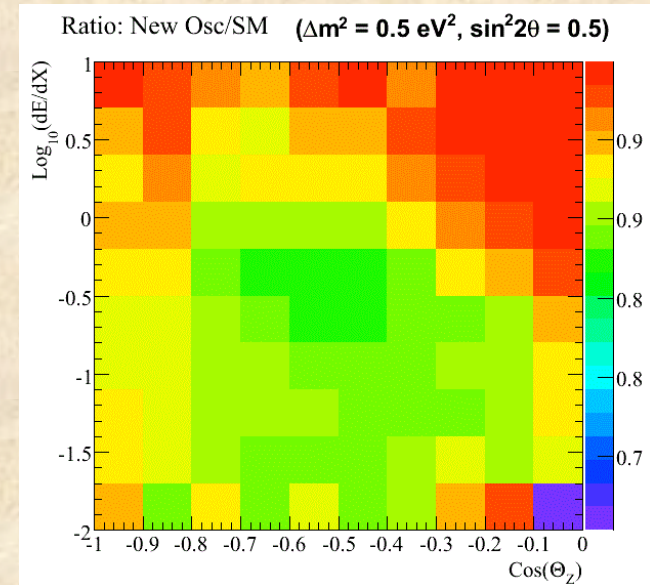
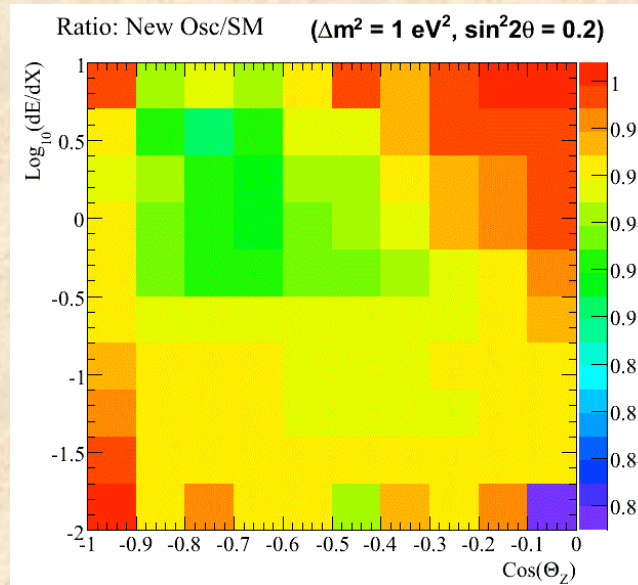


$\nu_\mu \rightarrow \nu_s$ oscillations



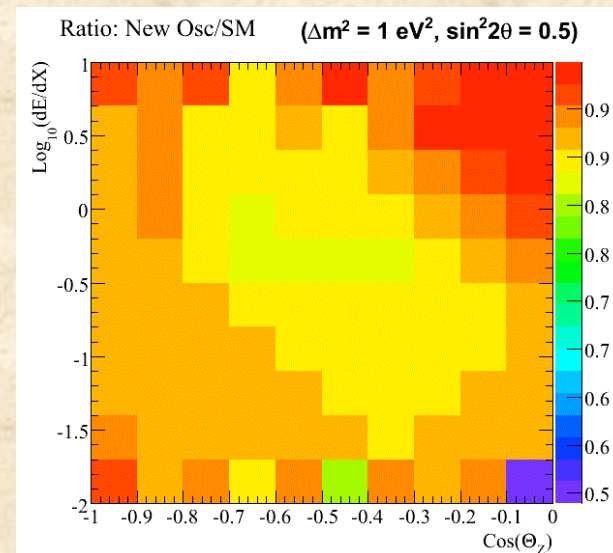
Effect in IceCube Detector

Effect with energy
and angular
resolutions of
IceCube included
→ 10's %



40,000 events in IC59

Not statistically limited!
Large number of systematic effects that
have to be understood!



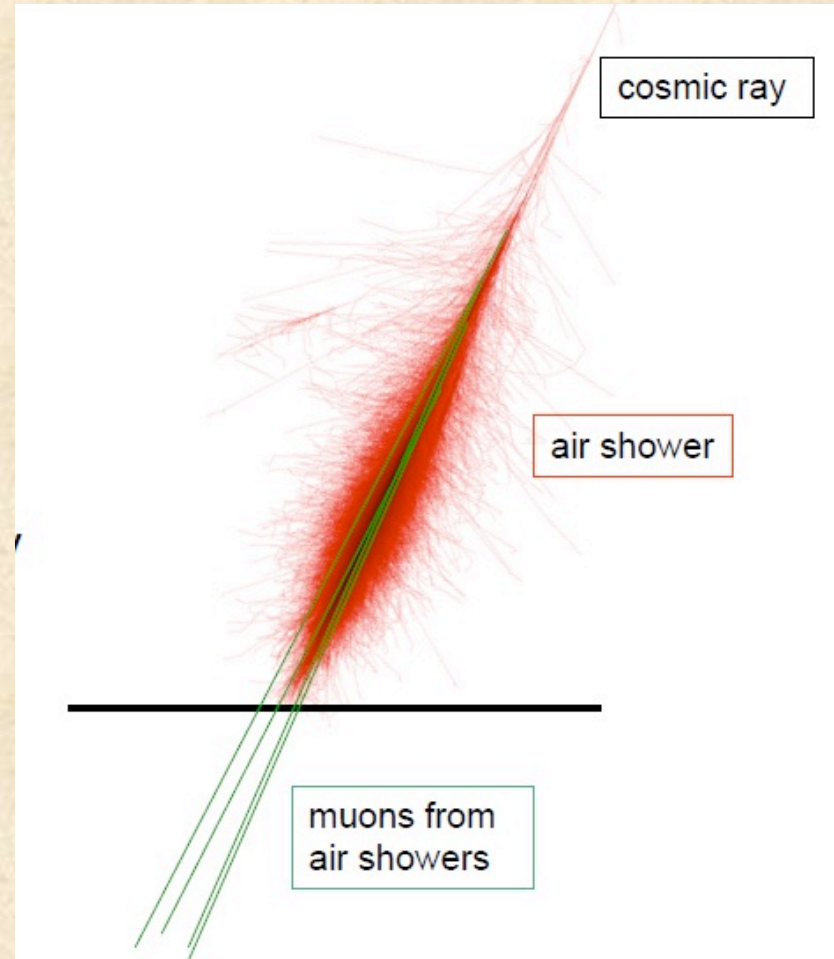
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CR Muon Astronomy

Use large sample (~ 2 kHz) of down going cosmic ray muons to make a map of the southern hemisphere

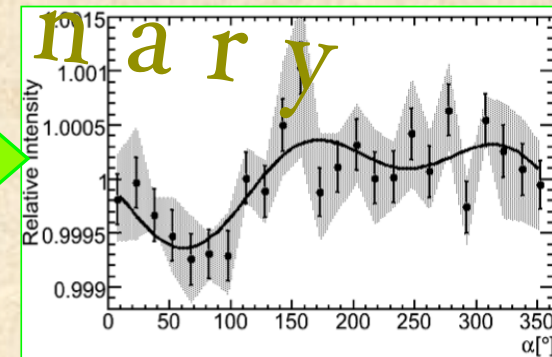
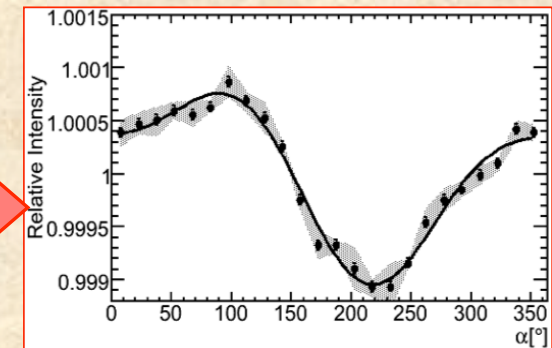
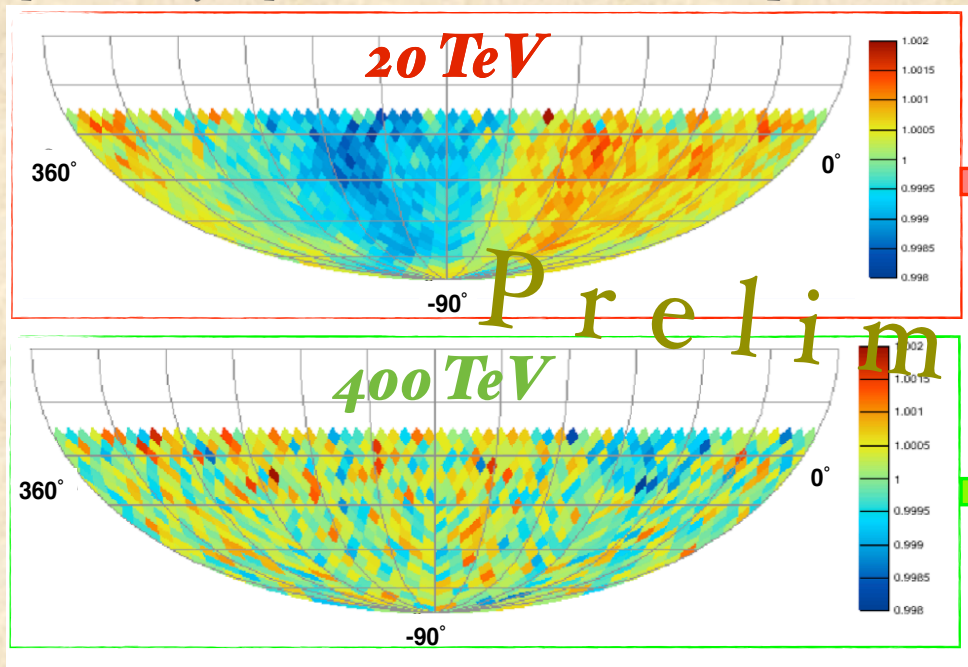
Recall the Moon Shadow



Large Scale anisotropy [paper in preparation]

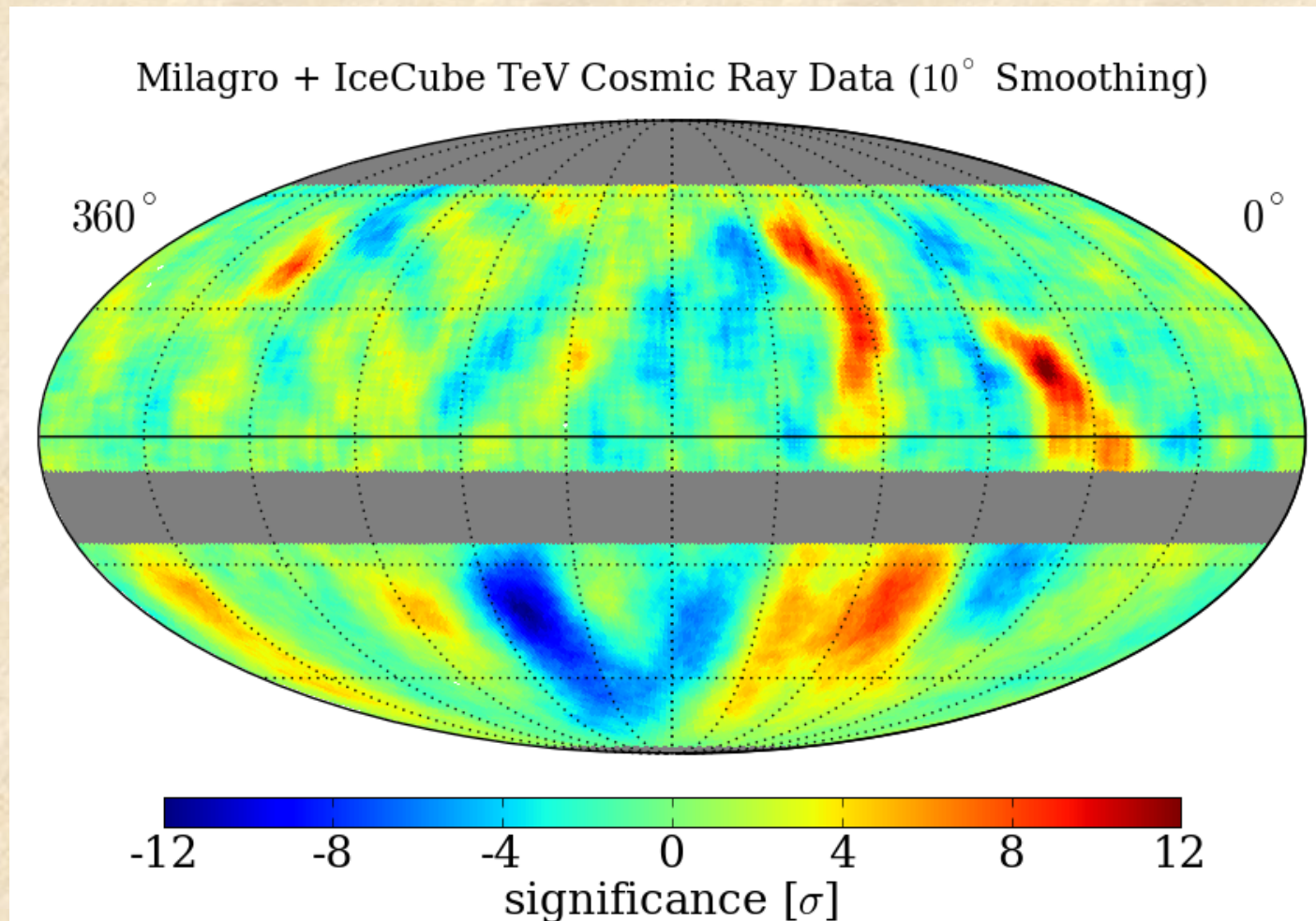
- * First observation of sidereal anisotropy @ 400 TeV in southern hemisphere.
- * Sidereal anisotropy at 20 TeV confirms previous observation.
- * Indication of a persistence of anisotropy @ 400 TeV: evidence of a “dip”.

Equatorial sky maps in HEALPix with $N_{\text{Side}} = 16$, $\text{pix resol} \sim 3^\circ$



- *Nearby CR sources?*
- *Something Else?*

*Equatorial sky maps in HEALPix
with $N_{\text{Side}}=64$, **pix resol** $\sim 0.9^\circ$*



[submitted to ApJ: [arXiv:1105.2326](https://arxiv.org/abs/1105.2326)]

Sampling of IceCube Science Topics

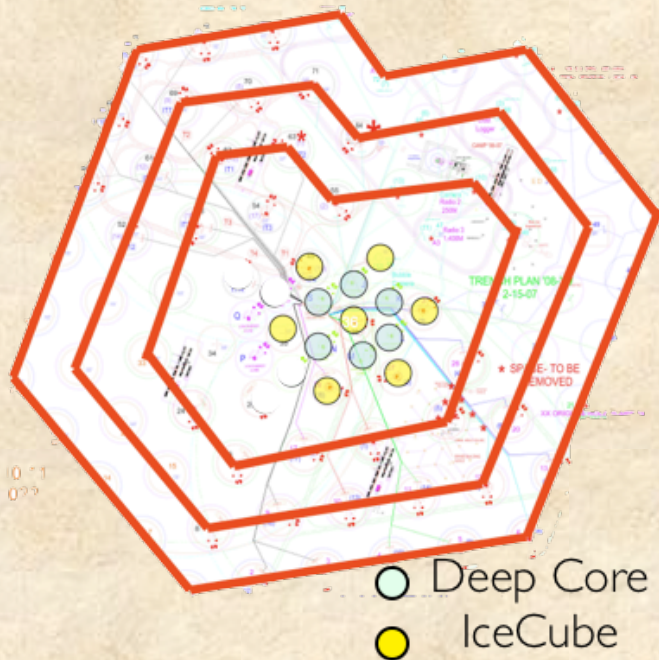
- Search for sources of Galactic cosmic rays
- Search for the extragalactic cosmic rays – All sky point source
- Search for the extragalactic cosmic rays – gamma ray bursts
- Atmospheric neutrino spectrum
 - Non-standard neutrino oscillations
- Search for HE diffuse neutrinos
 - muons
 - Cascades
- Cosmic Ray anisotropy (Simona Toscano)
- **IceCube at low energy with Deep Core LE (Tyce DeYoung)**
 - Indirect Search for Dark Matter
 - Neutrino oscillation Physics

IceCube Deep Core (low energy & contained events)

Rejection rate

$$\phi(\mu) / \phi(\nu_{\text{atm}}) \approx 10^6$$

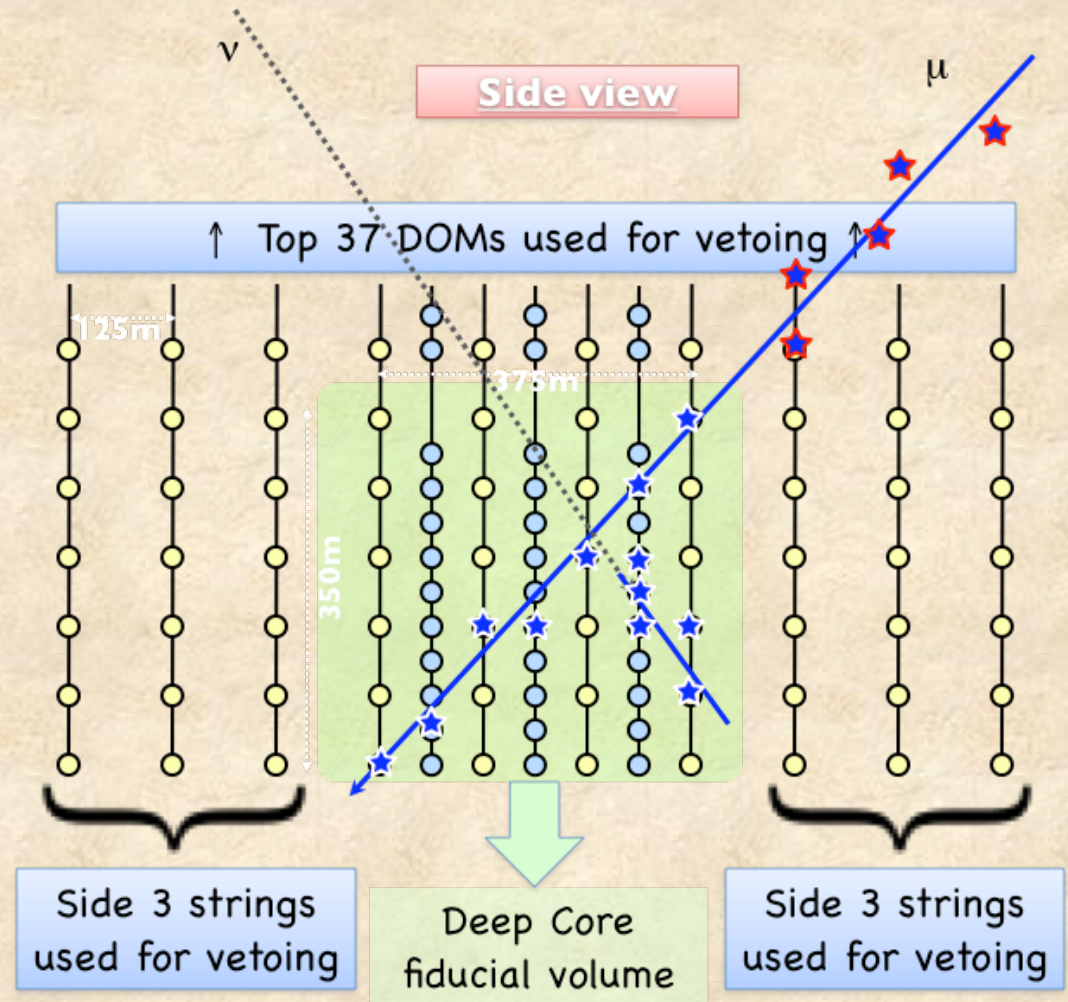
Top view



375 m thick active veto:
3 full IceCube string
layers surround Deep Core

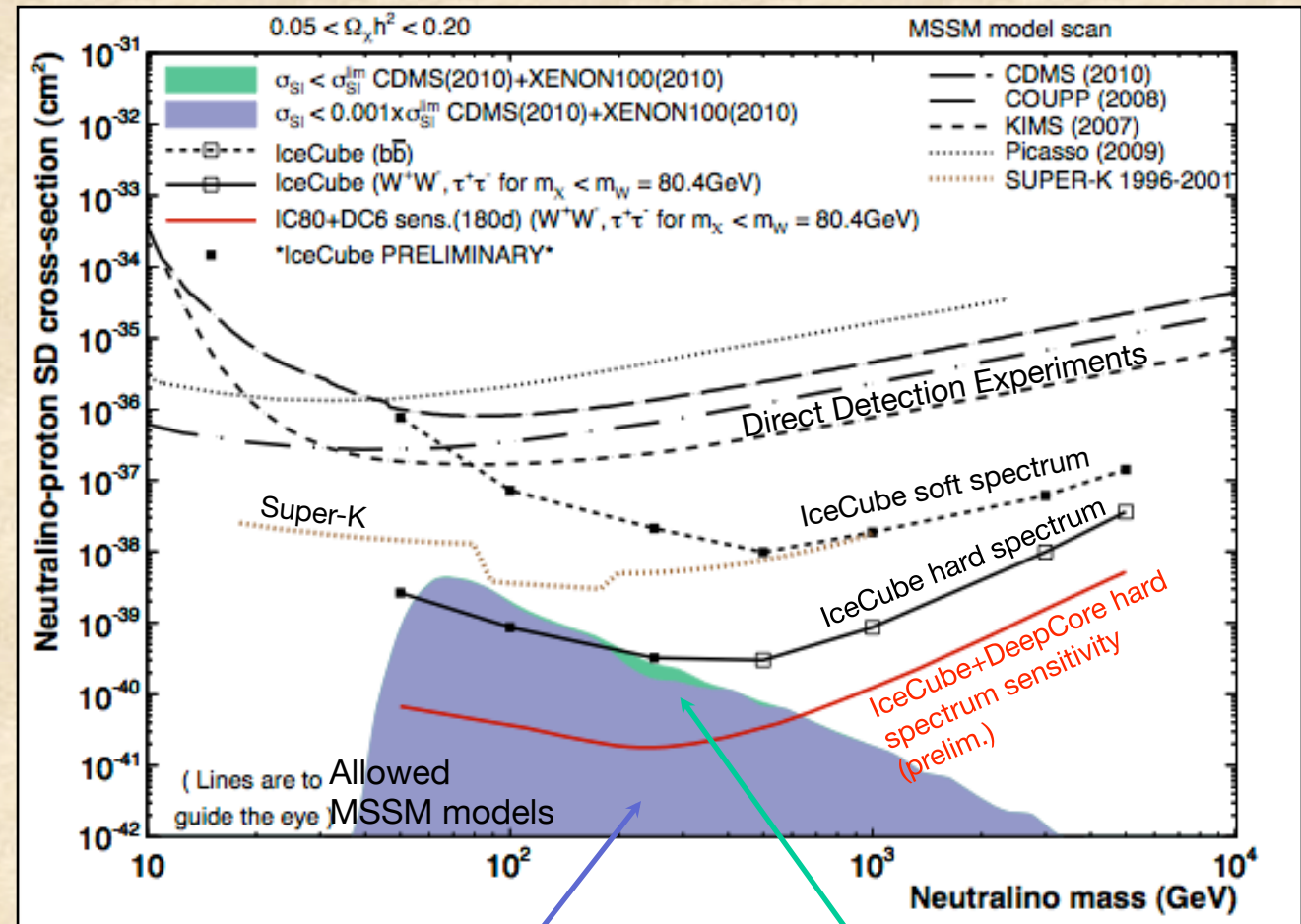
veto allows searches above horizon!

Side view



Sensitivity to MSSM WIMPs

- Solar WIMP dark matter searches probe SD scattering cross section
 - SI cross section constrained well by direct search experiments
- DeepCore will probe large region of allowed phase space



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

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

Observation of Neutrino Cascades (Preliminary)

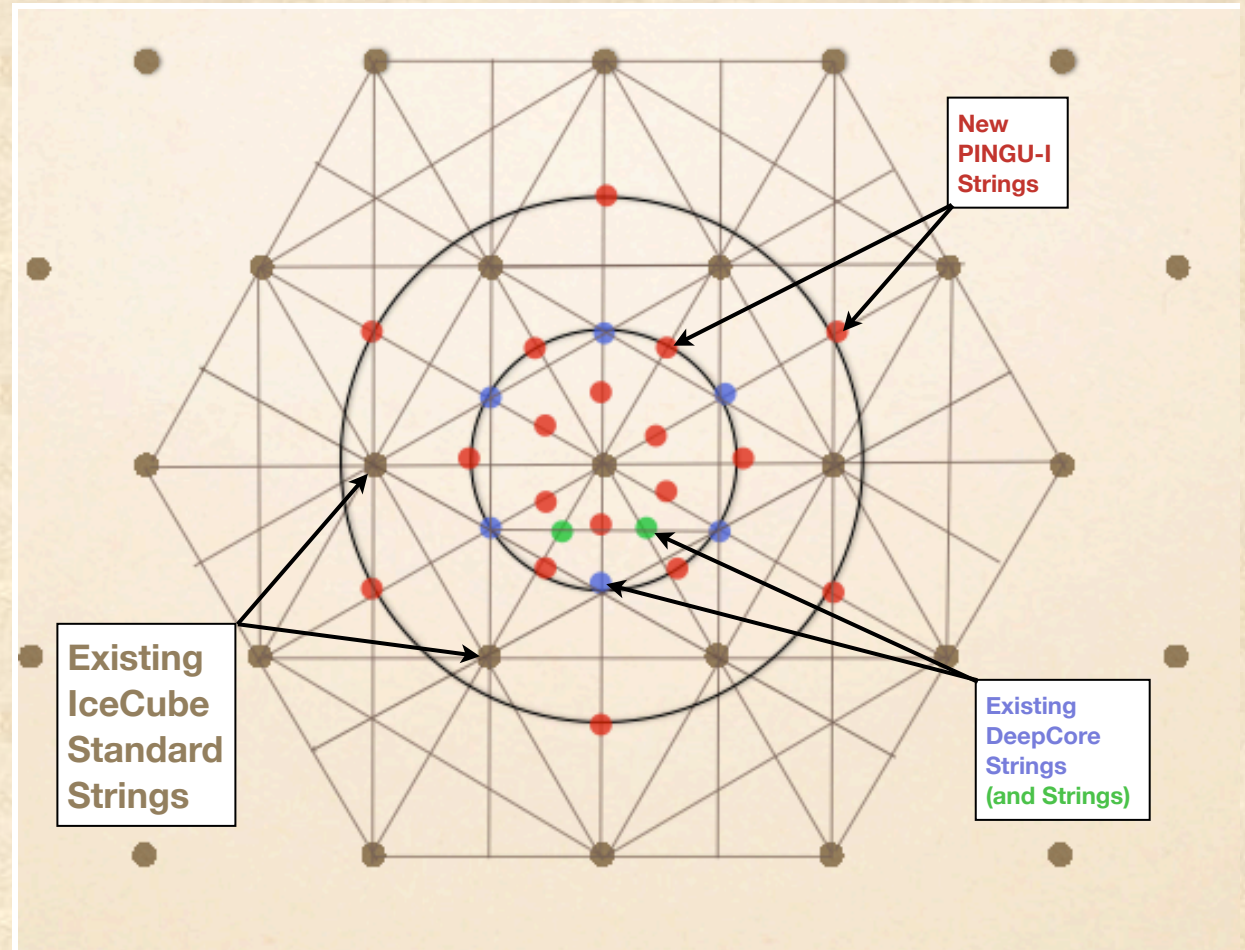
- Disappearing ν_μ should appear in IceCube as ν_τ cascades
 - Effectively identical to neutral current or ν_e CC events
 - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background
- We believe we see neutrino cascade events for the first time
 - The dominant background now is CC ν_μ events with short tracks



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

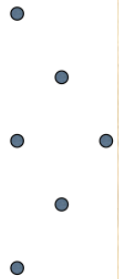
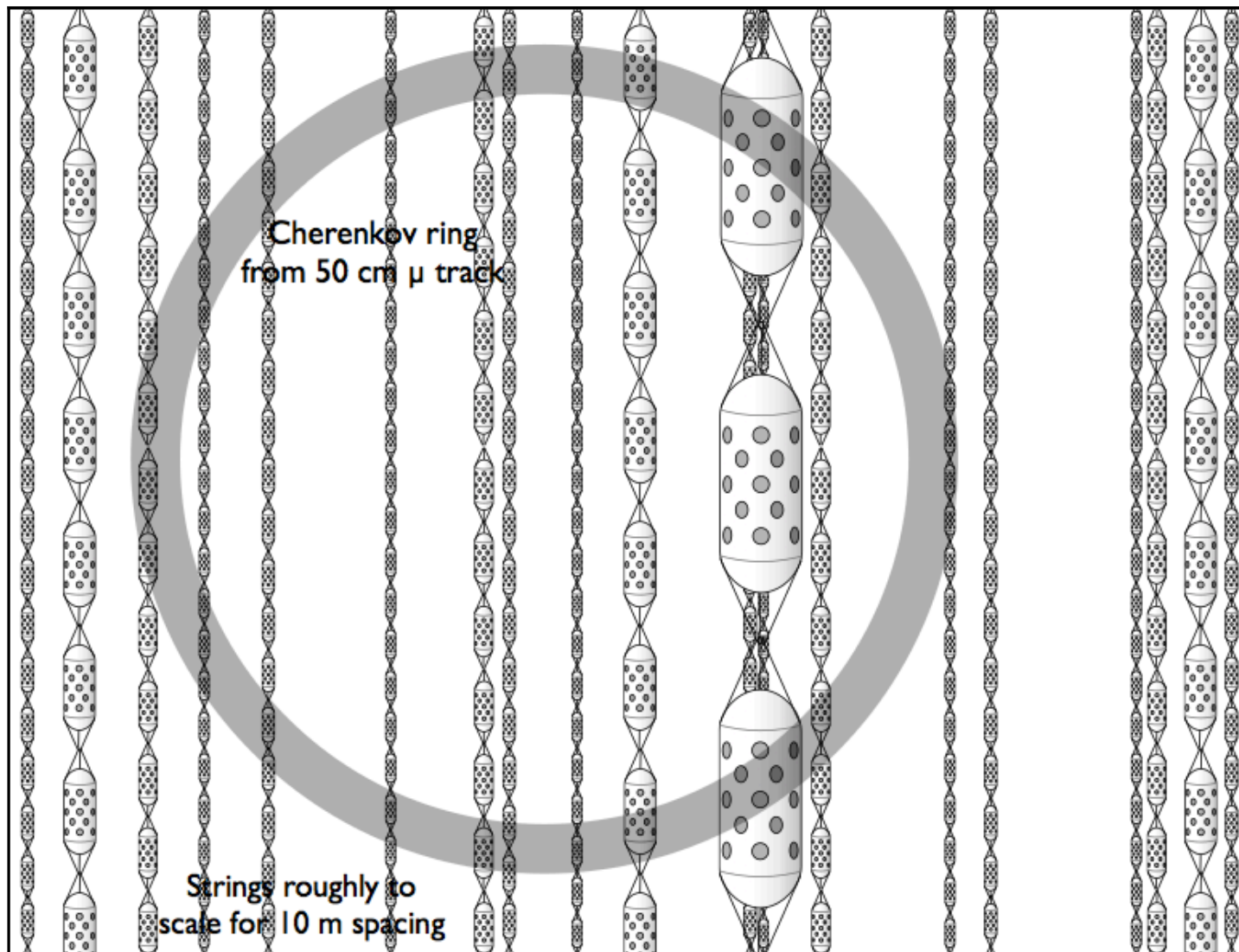
Beyond Deep Core (Phase 1)?

- 18 additional strings (~1000 DOMs) in the 30MT Deep Core Volume
- Few GeV threshold in inner 10 MT??
- Cost ~\$30M
- Enhance LE capability
 - Oscillation
 - Galactic center



Beyond Deep Core (Phase 2)??

- $O(10)$ cent Core
- Sub dete
- *MT*
- *Feas*
Dec
- Seri
non-



Summary

- IceCube detector completed construction Dec 2010
 - Run start May 13, 2011
 - The era of km^3 neutrino astronomy has begun!
- The 40 and 59 string data have already surpassed the expected performance of the full IceCube on a number of searches
- No neutrinos seen from GRB at .2 of prediction
 - Setting important limits on astrophysics of fireball model
 - Within 3 years we will see events or rule out
- Cascade searches reaching maturity
- Deep Core extension at Low energies (IC79 and later)
 - Wimp sensitivity
 - Neutrino oscillations
 - Galactic center

Stay tuned over the next few years!