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

RICAP

26 May 2011

The IceCube Collaboration

36 institutions in 4 continents

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:
  - $50000 m^2$ scale: ANTARES, AMANDA (decommissioned)
  - Auger Detector (tau neutrinos, $E > 10^{18}$ eV)
  - IceCube (data from 50-75% size)
- Coming generation: km^3 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-km^3 scale!***

Motivation

Candidate sources (accelerators):

Cosmic ray related:

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

Other:

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

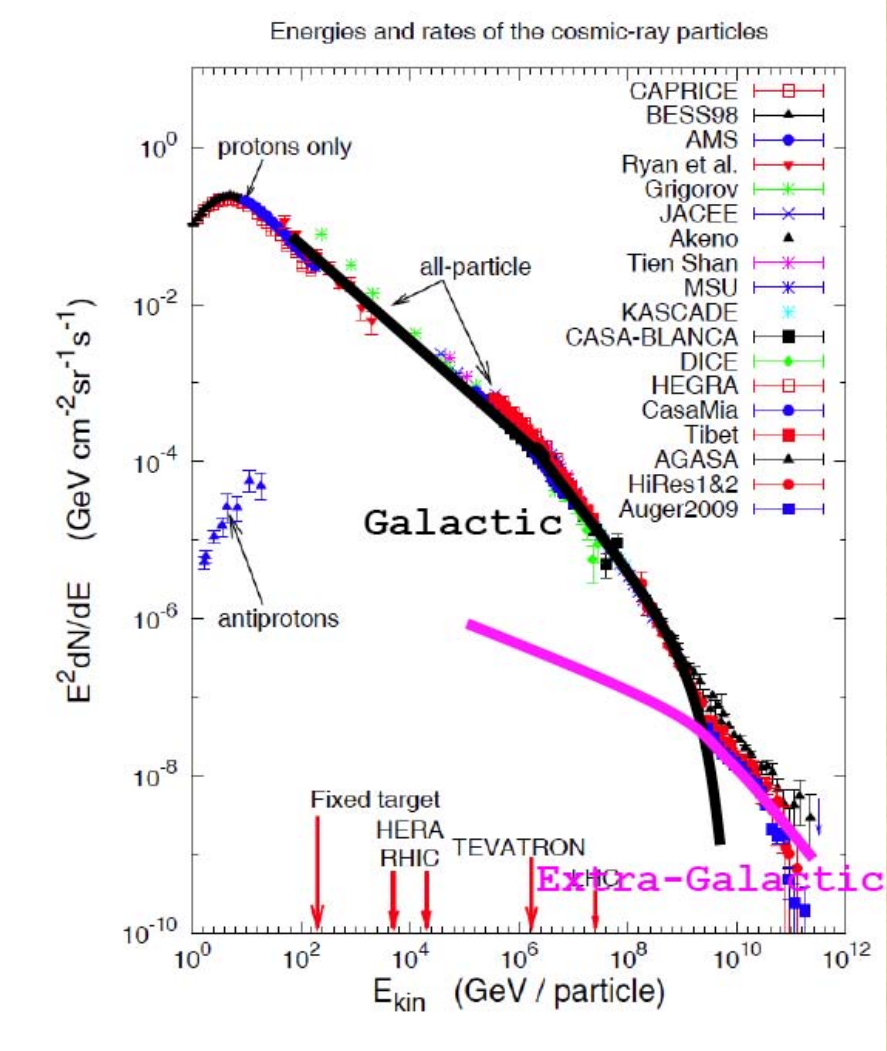
Guaranteed sources (known targets):

-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:

$\gamma + \gamma_{EBL+CMB} \rightarrow e^+ + e^-$

$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$

$\rightarrow \mu^+ + \nu_\mu$

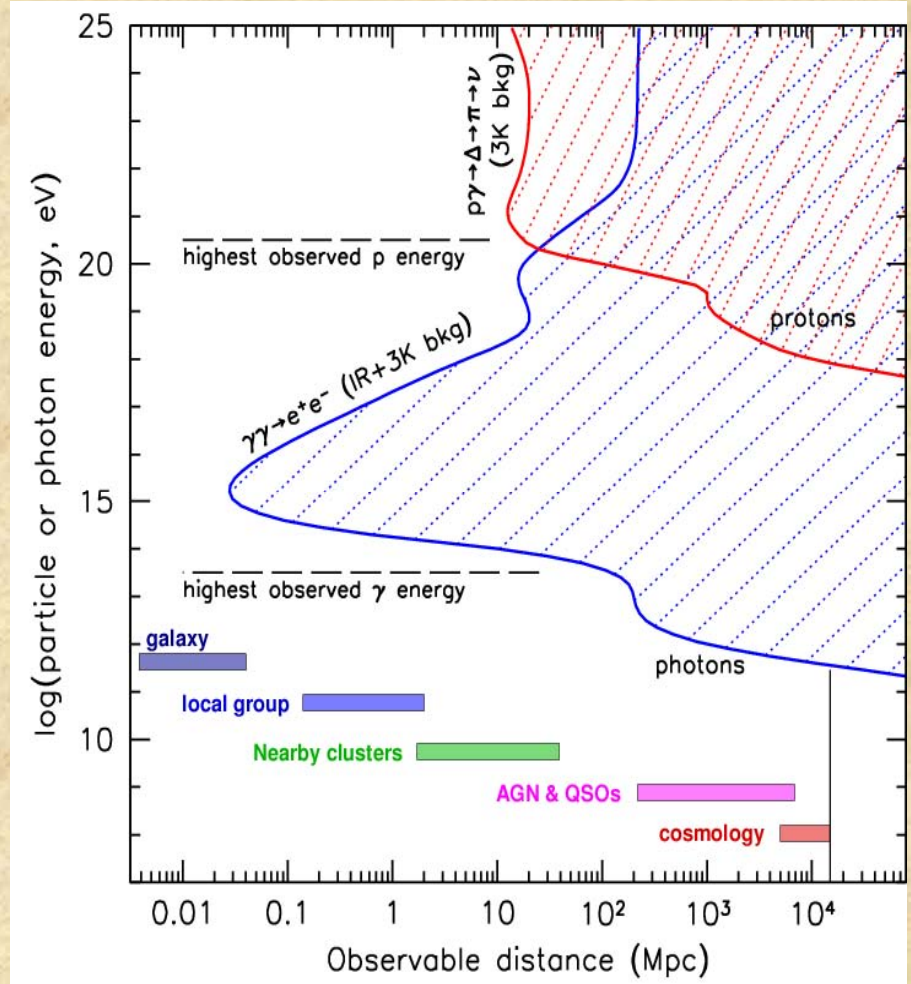
Cosmogenic neutrinos

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

- ***Not pointing back for distant sources***

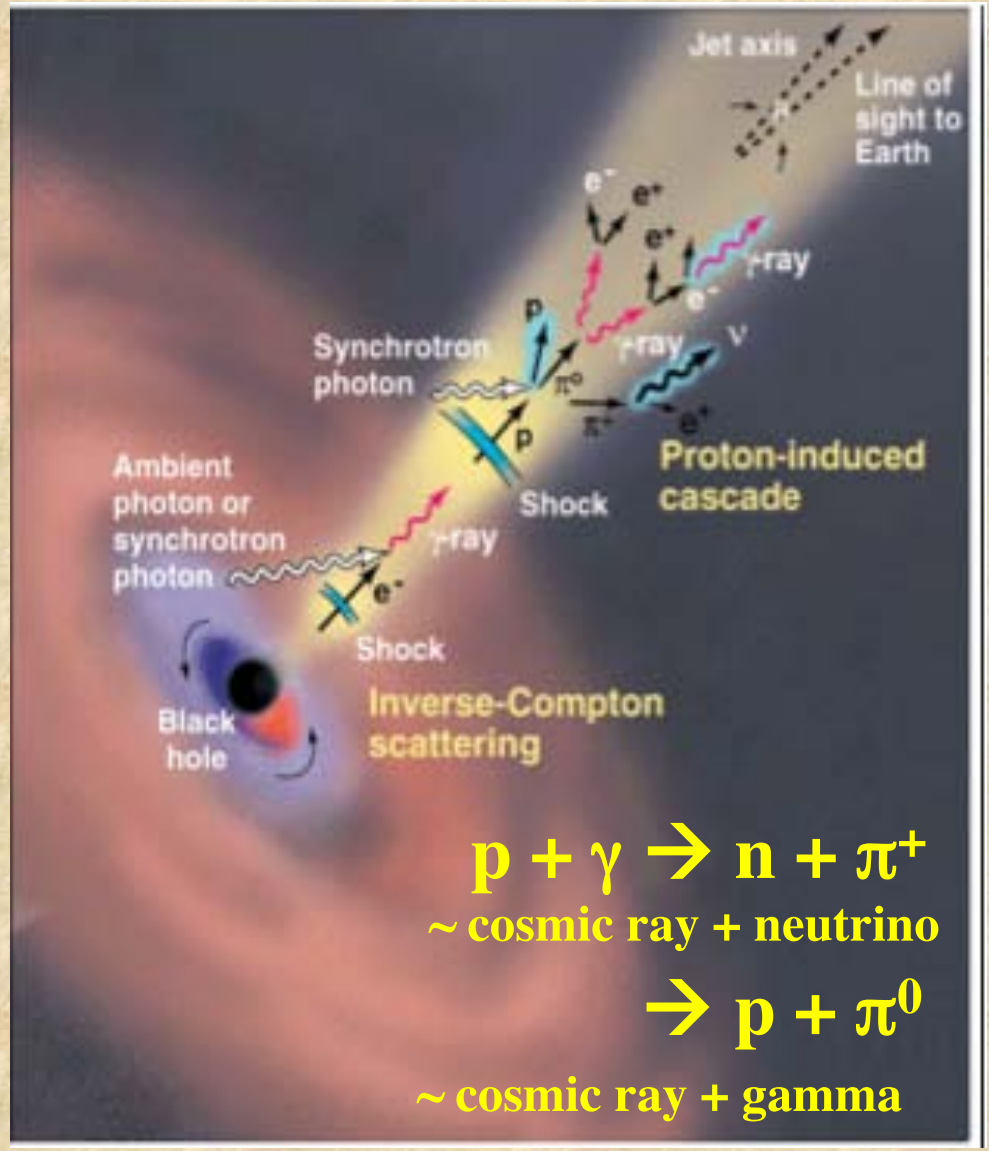
1)Neutrinos are a candidate for high energy (>10TeV) cosmic astronomy!

2)Neutrinos provide unambiguous evidence of hadronic acceleration!

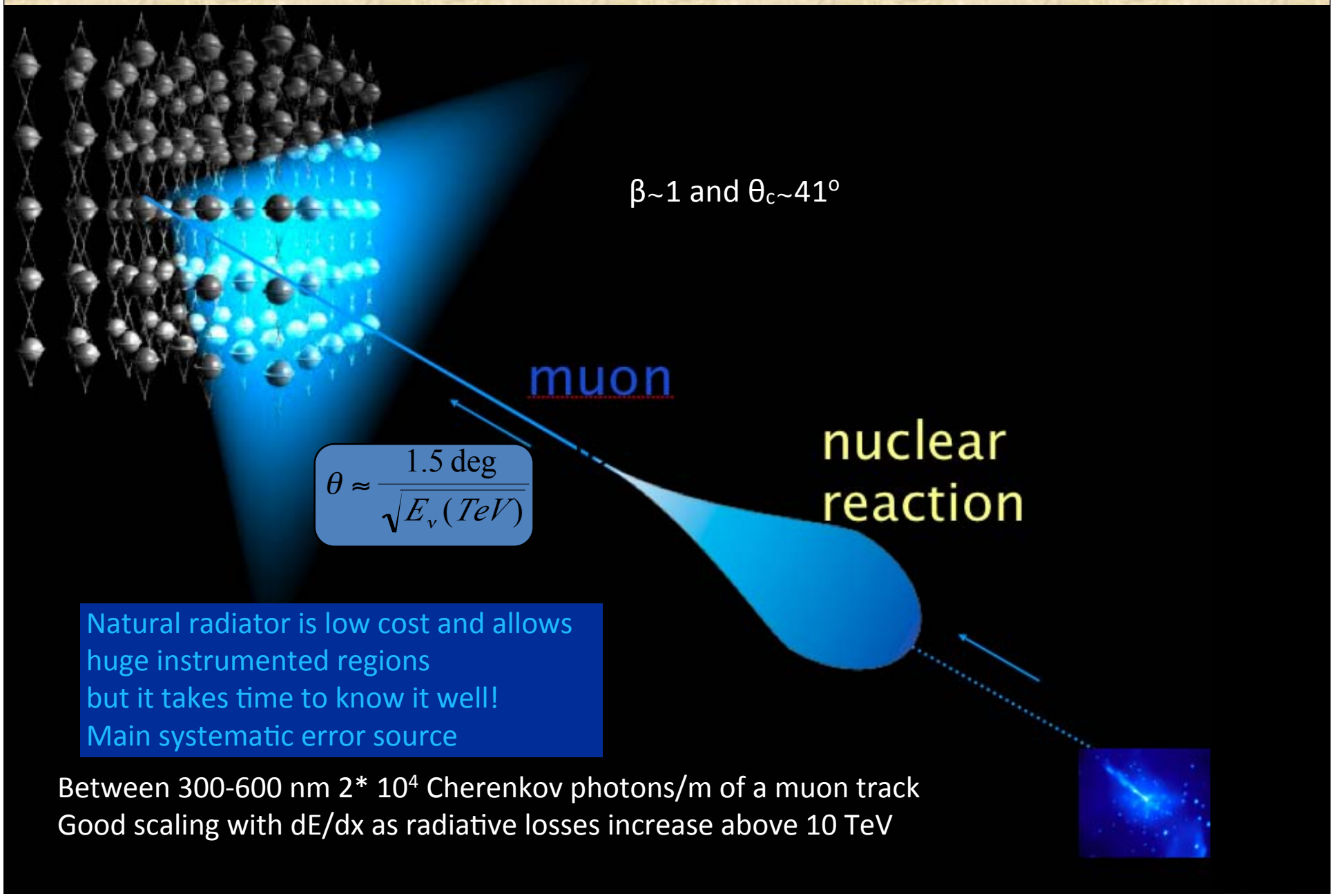


High Energy Particles in the Universe

- Cosmic Rays
  - Observed up to 10^21 eV
  - Diffuse, mass composition
- Gamma Rays
  - Observed up to ~100 TeV
  - Numerous TeV point sources resolved

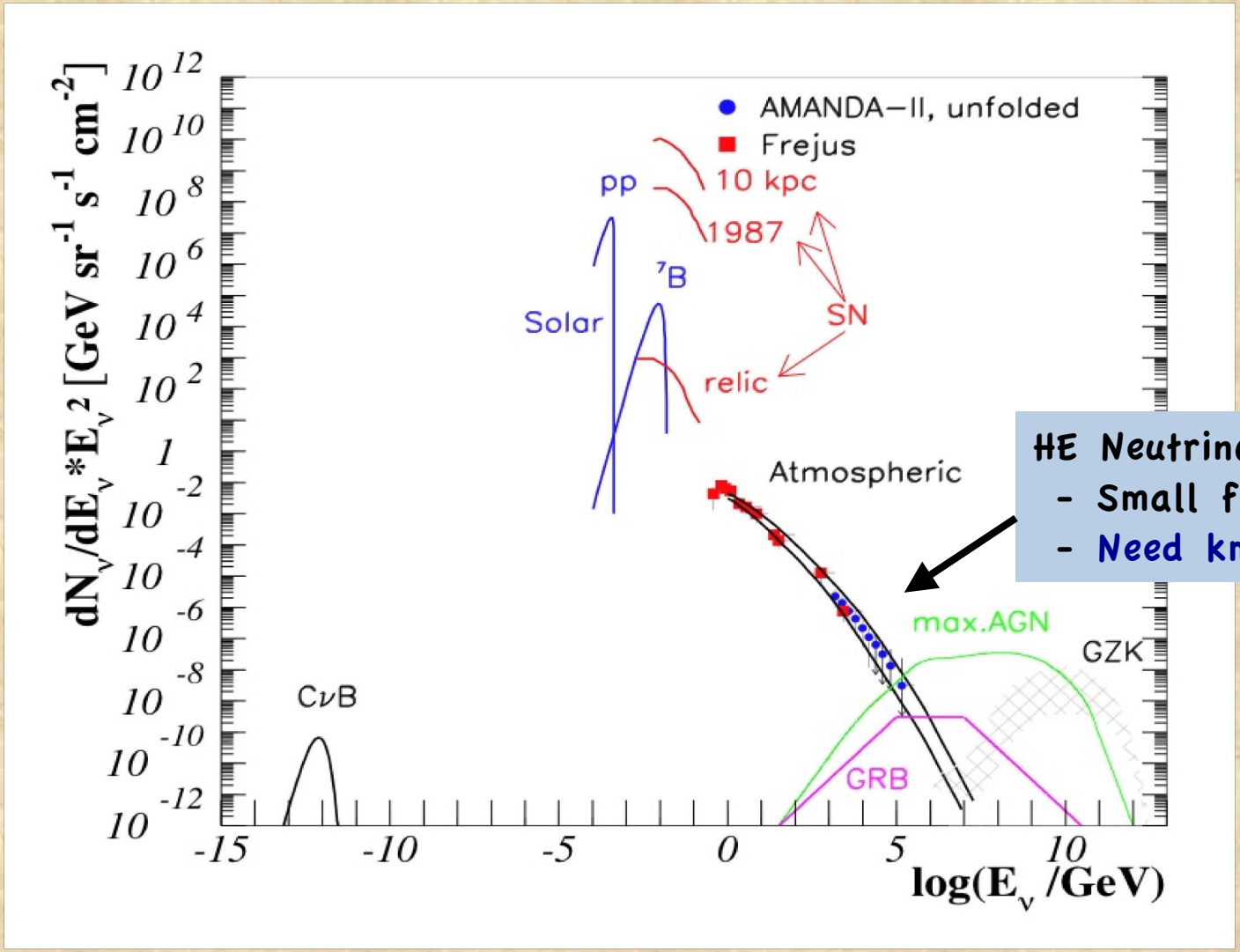


Concept of Large Neutrino Telescopes

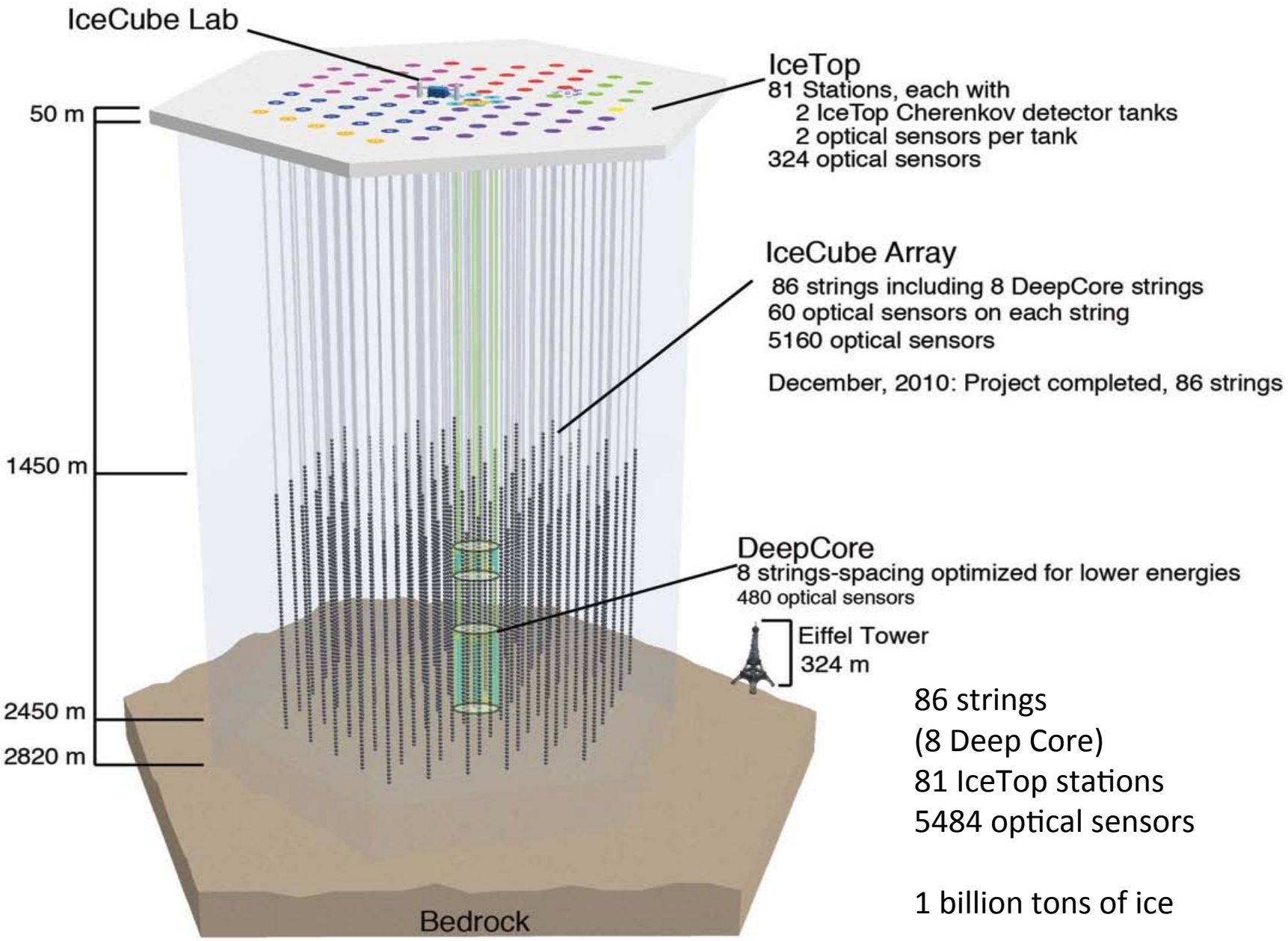


Between 300-600 nm 2* 10^4 Cherenkov photons/m of a muon track
Good scaling with dE/dx as radiative losses increase above 10 TeV

High Energy Neutrinos



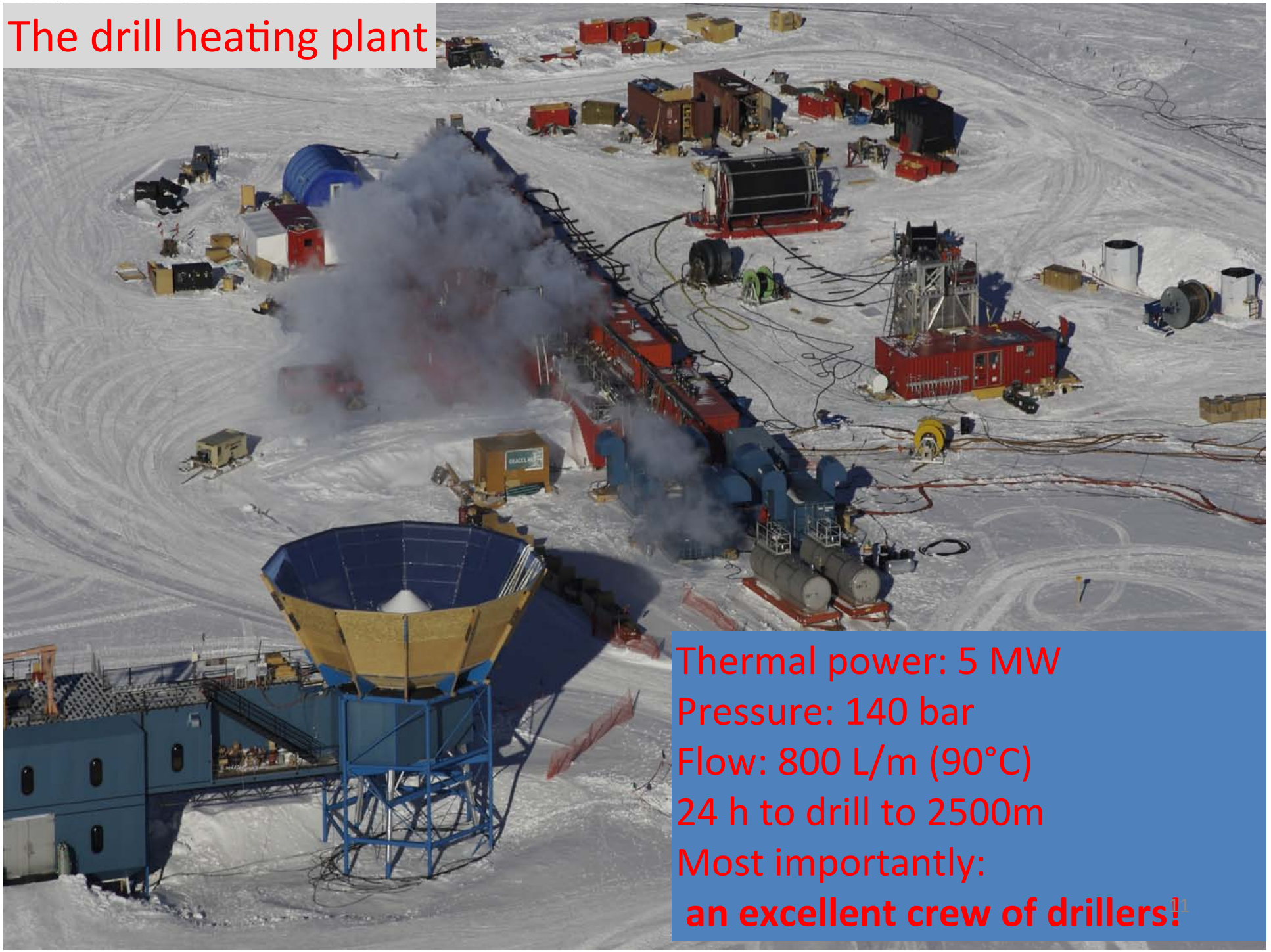
HE Neutrino astronomy:
- Small fluxes
- Need km scale detector



86 strings
(8 Deep Core)
81 IceTop stations
5484 optical sensors

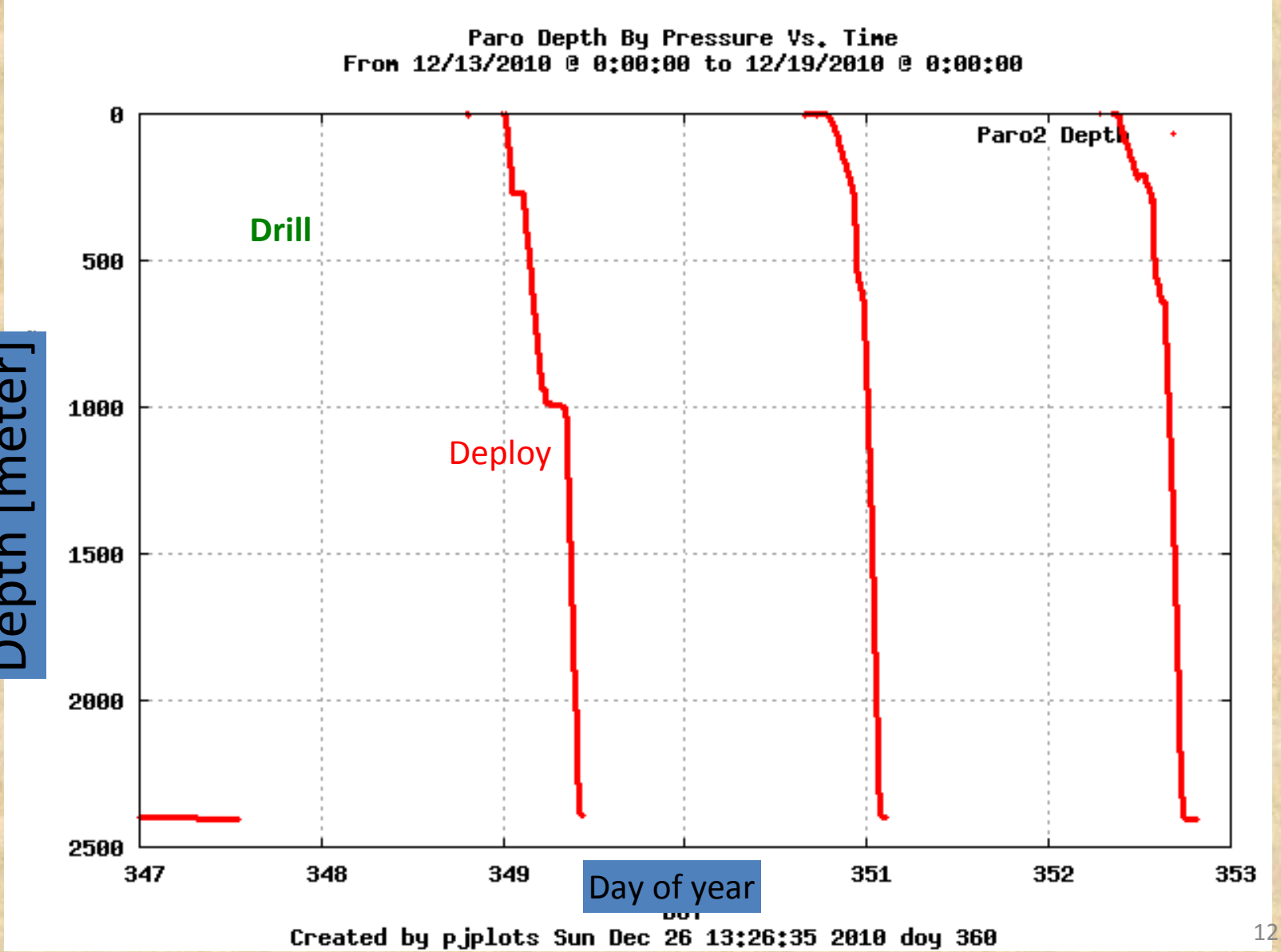
1 billion tons of ice

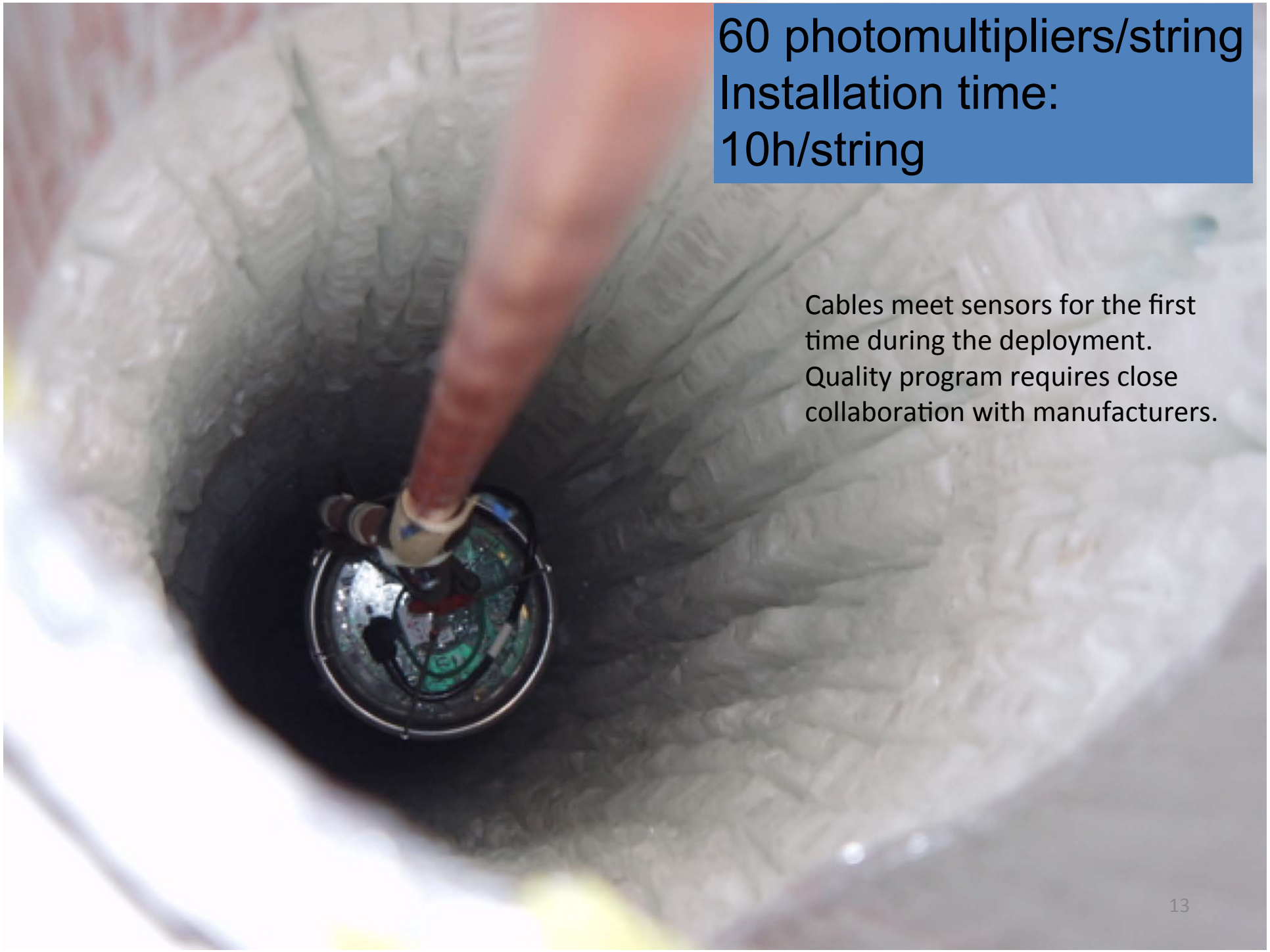
The drill heating plant



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!

Drilling and deployment Dec. 13-18, 2010





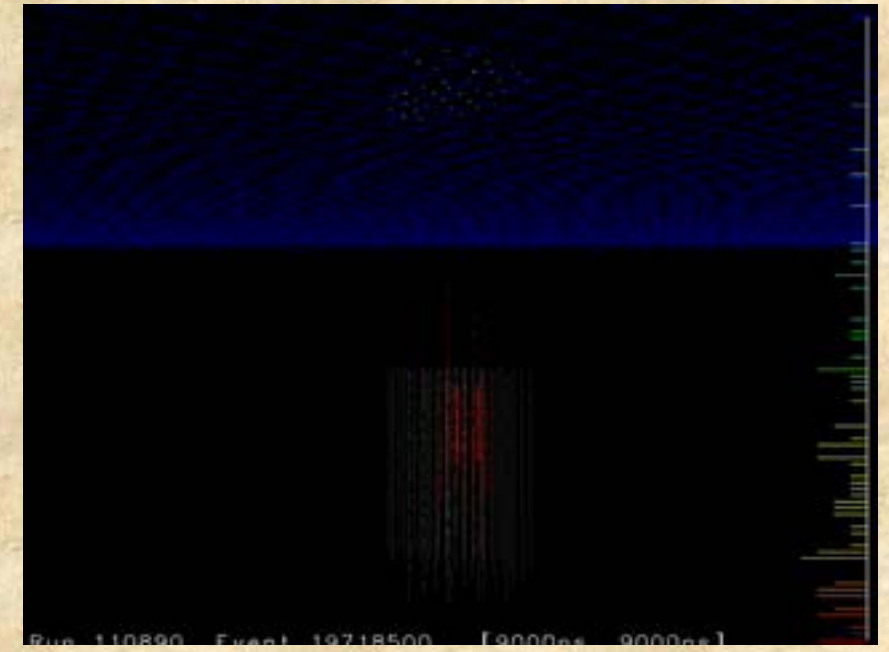
60 photomultipliers/string
Installation time:
10h/string

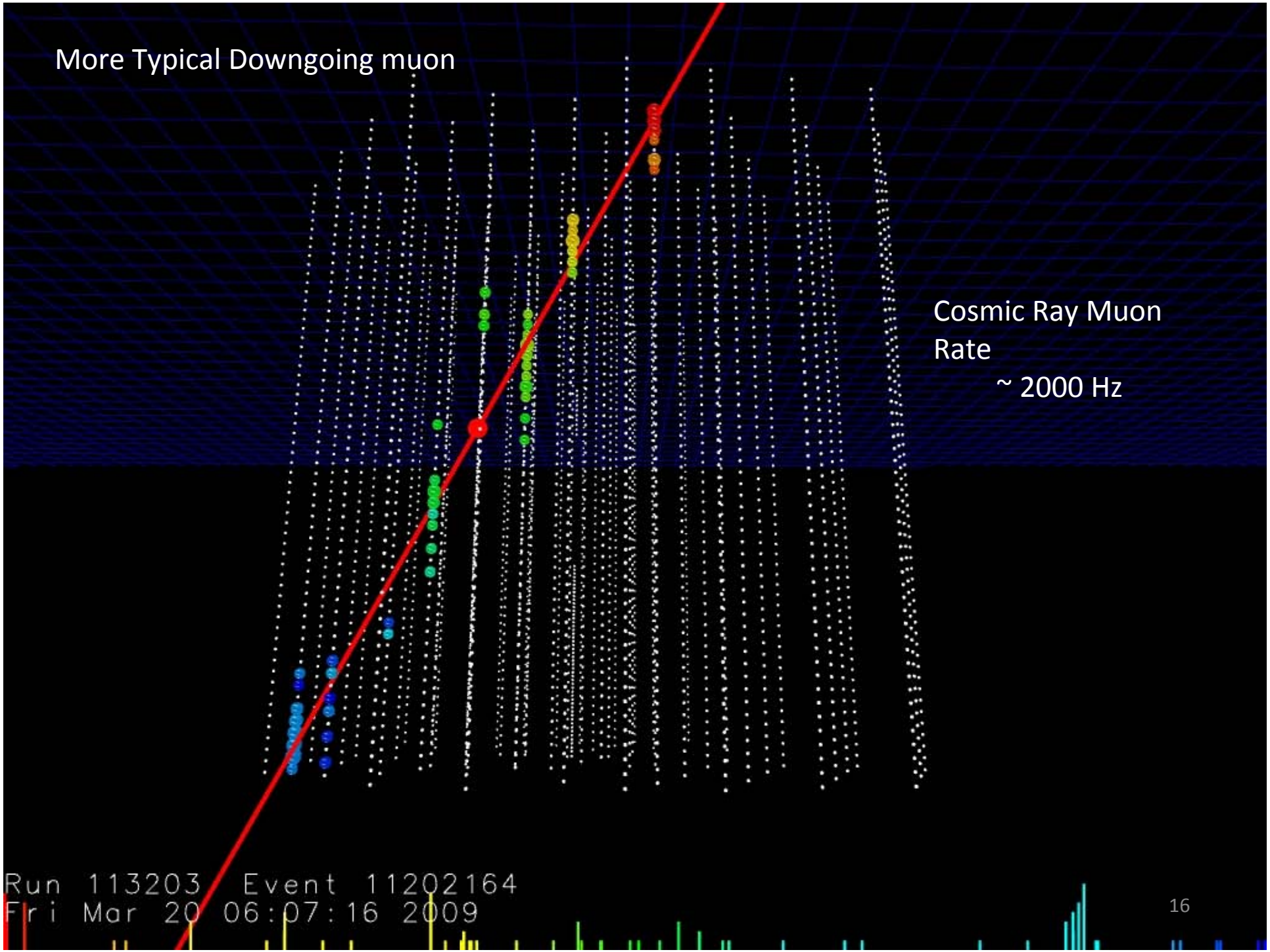
Cables meet sensors for the first time during the deployment.
Quality program requires close collaboration with manufacturers.

Operational support:
ICL maintenance
~60 kW power to electronics
90 GB/day
2 winterovers
summer population (around 5-7 pop Dec - Jan)

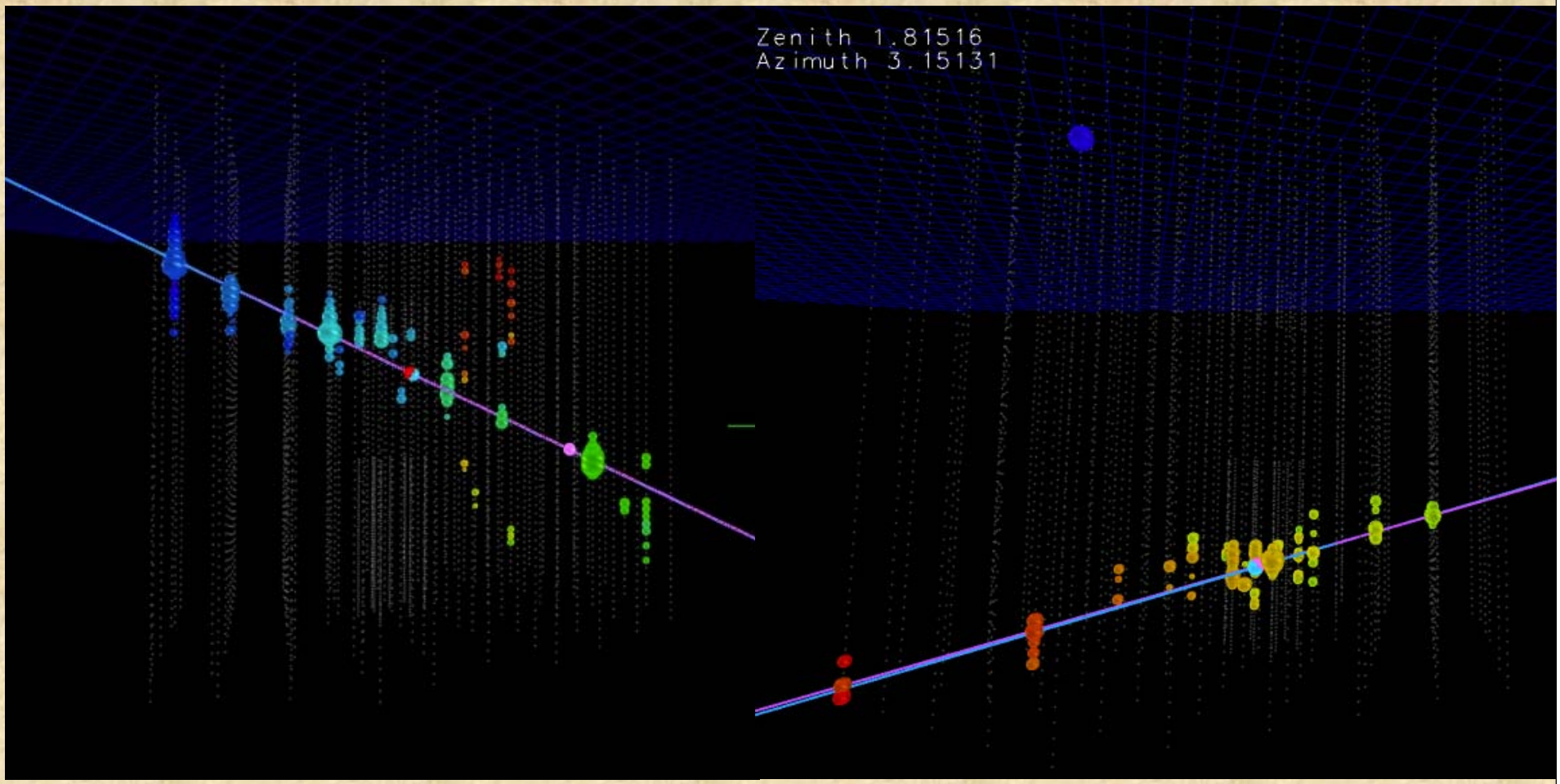
Muon Events from Data

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

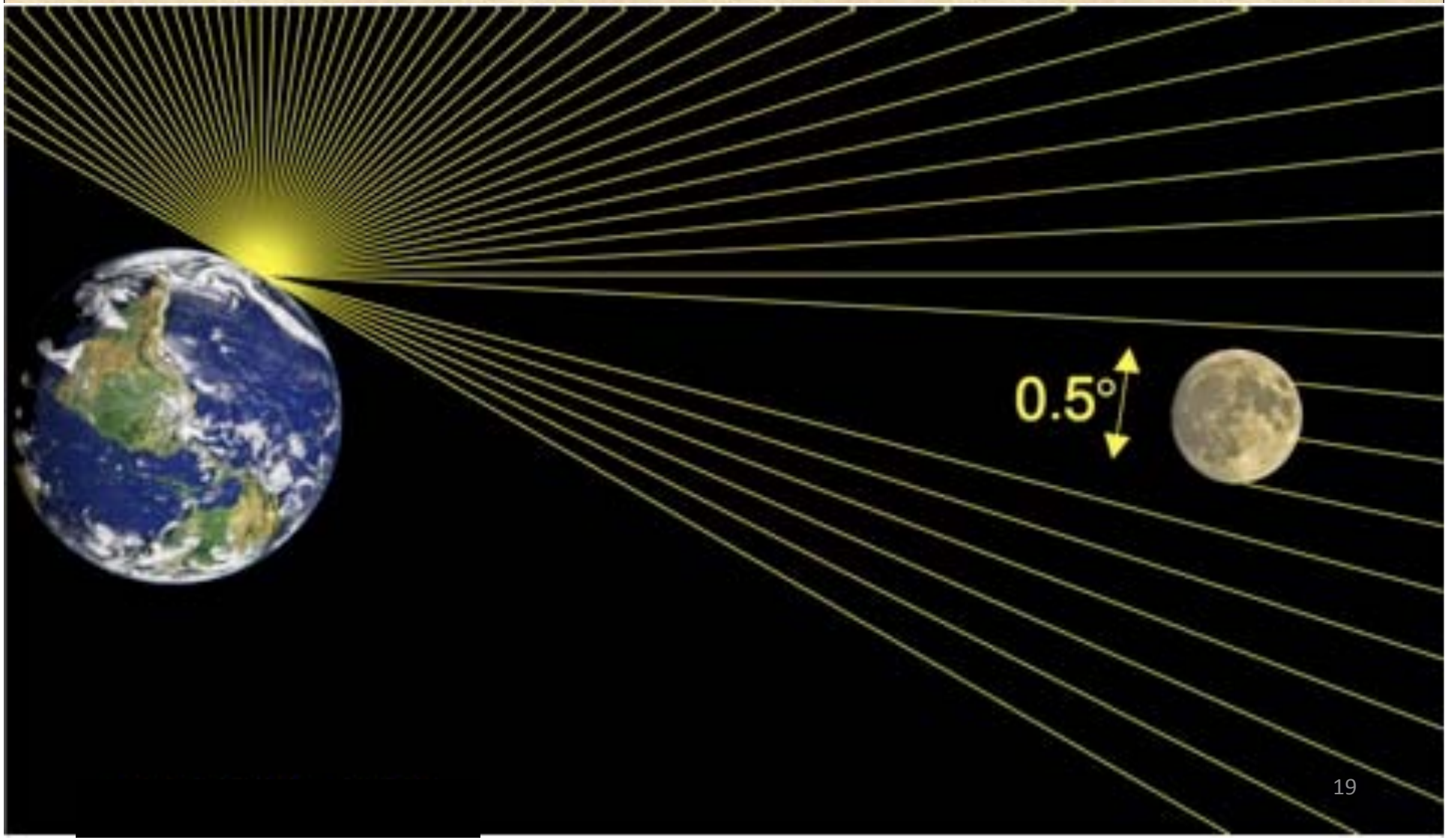
Strings	Data (year)	Livetime	μ rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	5 / day
IC40	2008-09	375 days	1100	38 / day
IC59	2009-10	360 days	1900	129 / day
IC79	2010-11	1 year	2250	
IC86	2011-	13 days	2700	

DeepCore Completed

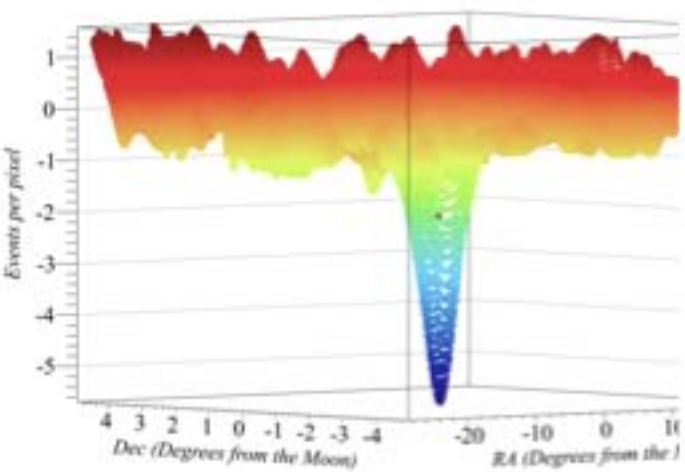
IC86 Run Start on May 13, 2011

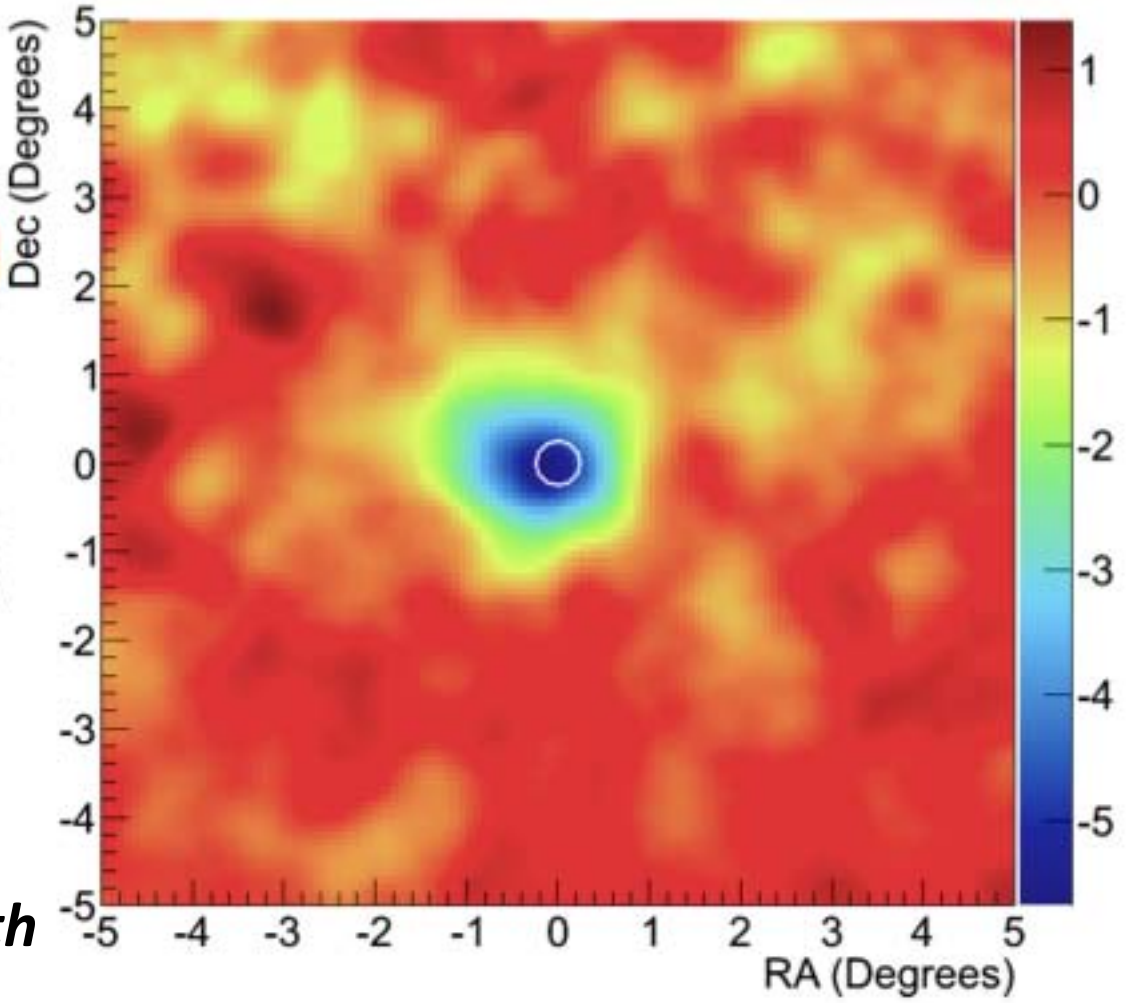
- Detector performance parameters increase faster than the number of strings
  - Longer muon tracks (km scale)
  - Improved analysis techniques

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
- Search for HE diffuse neutrinos
  - muons
  - Cascades
- Cosmic Ray anisotropy (Simona Toscano)
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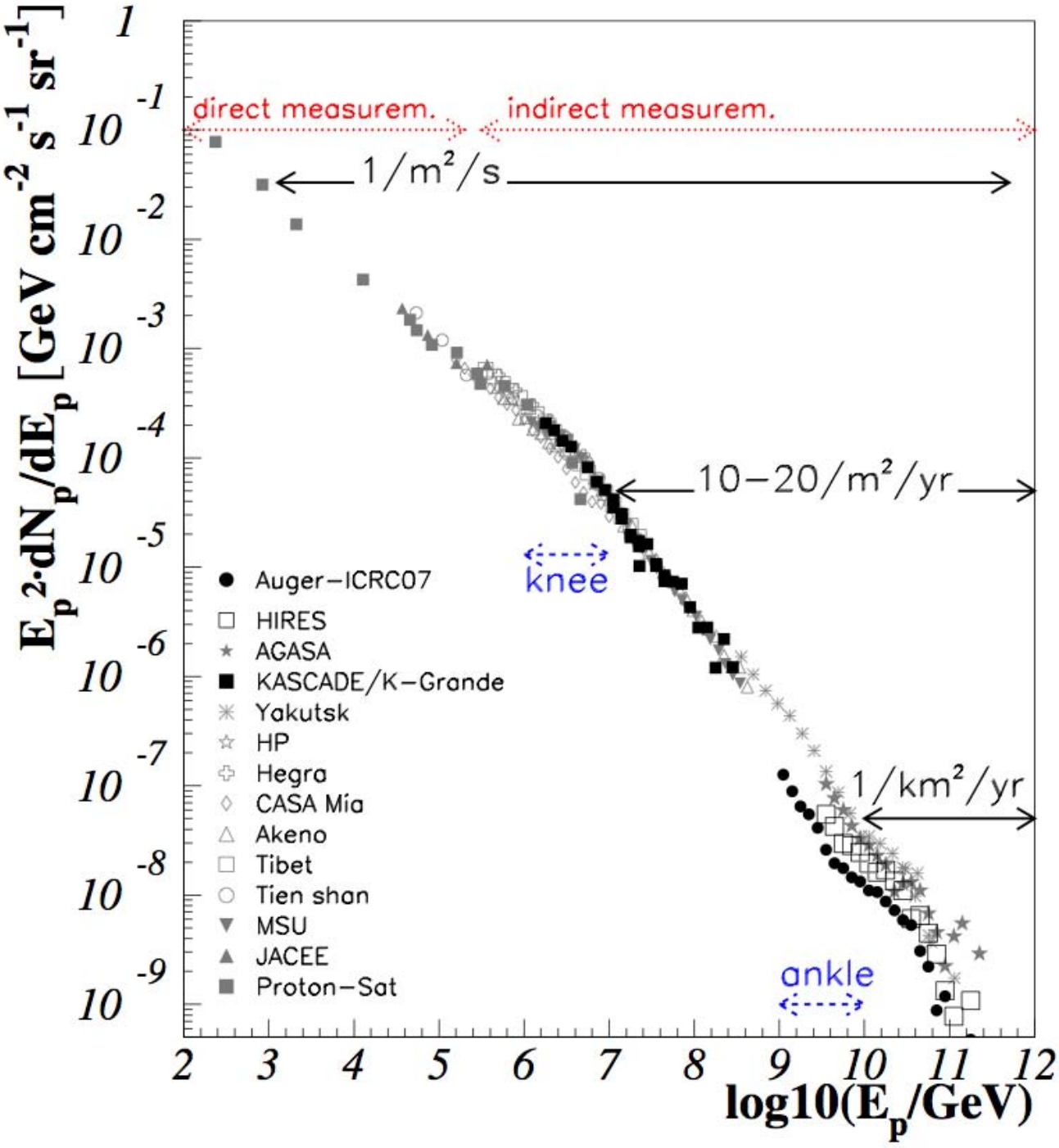
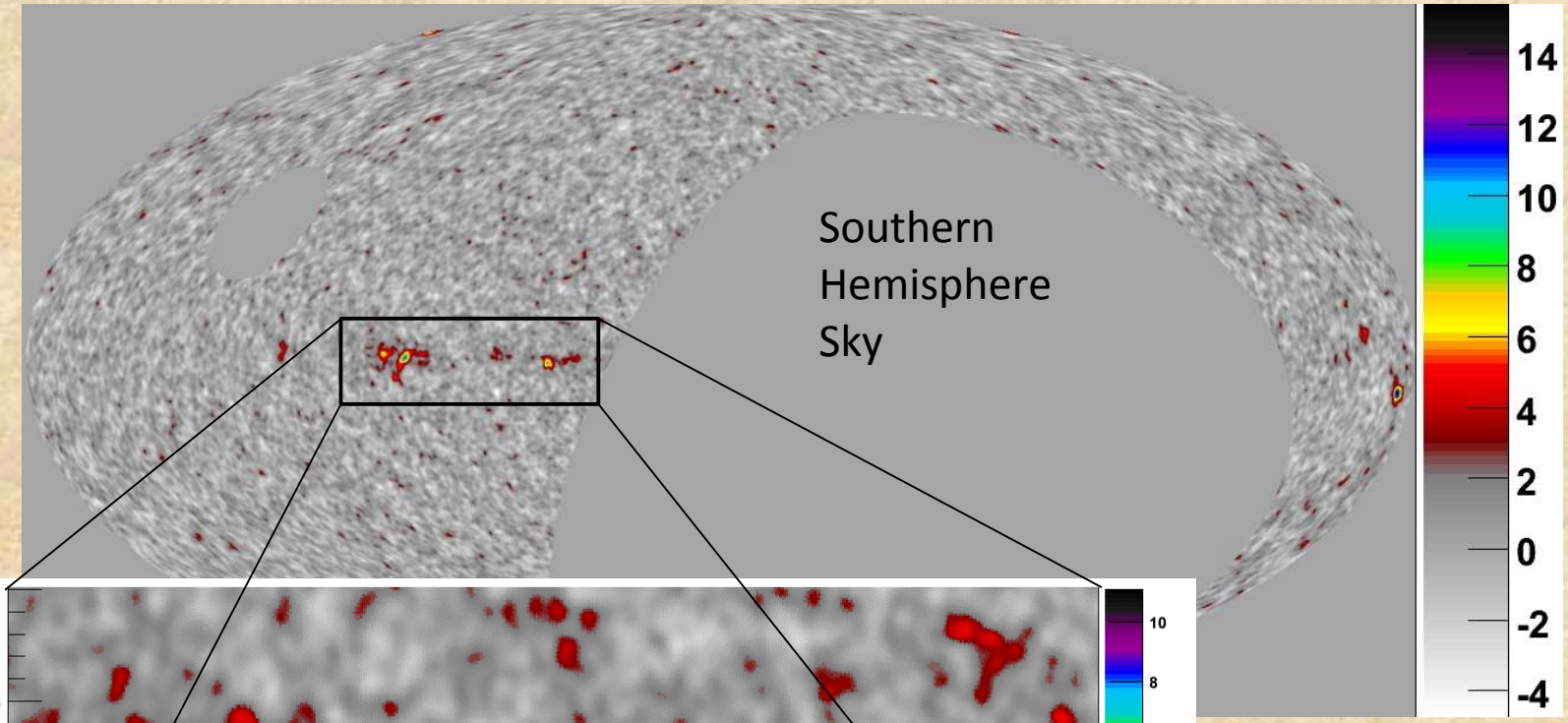
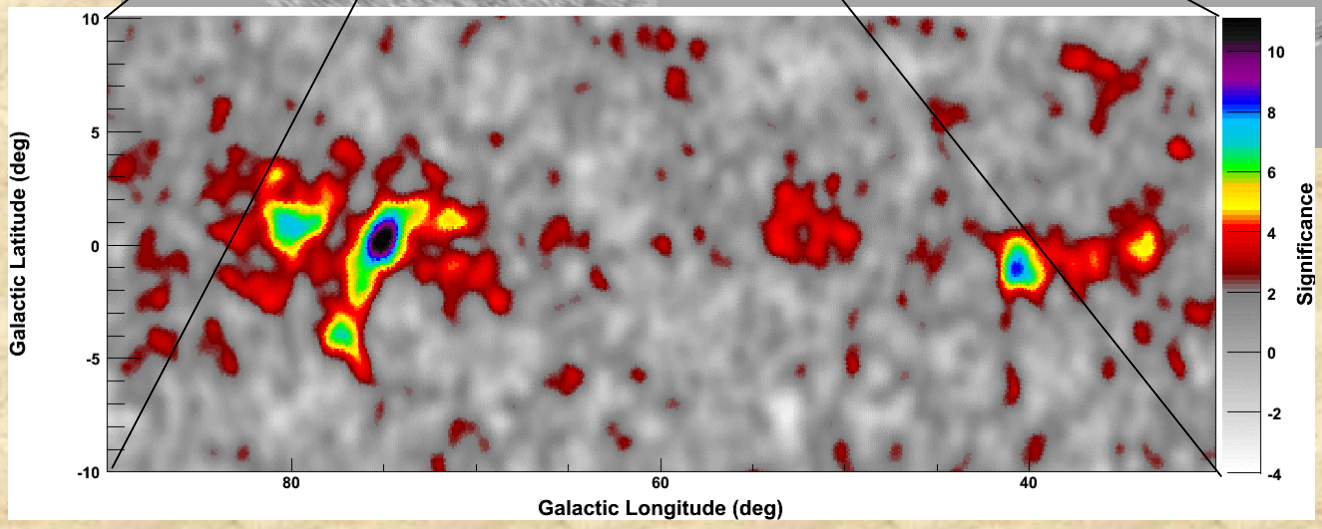
Galactic Cosmic Rays

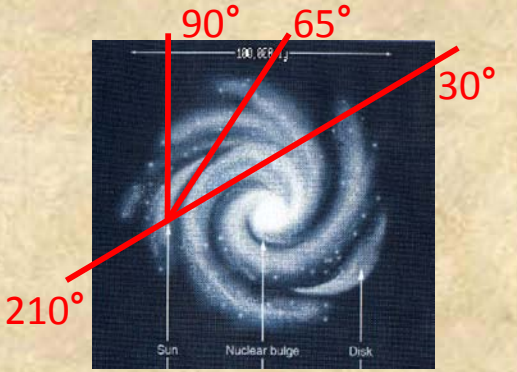


galactic plane in 10 TeV gamma rays :

supernova remnants in star forming regions

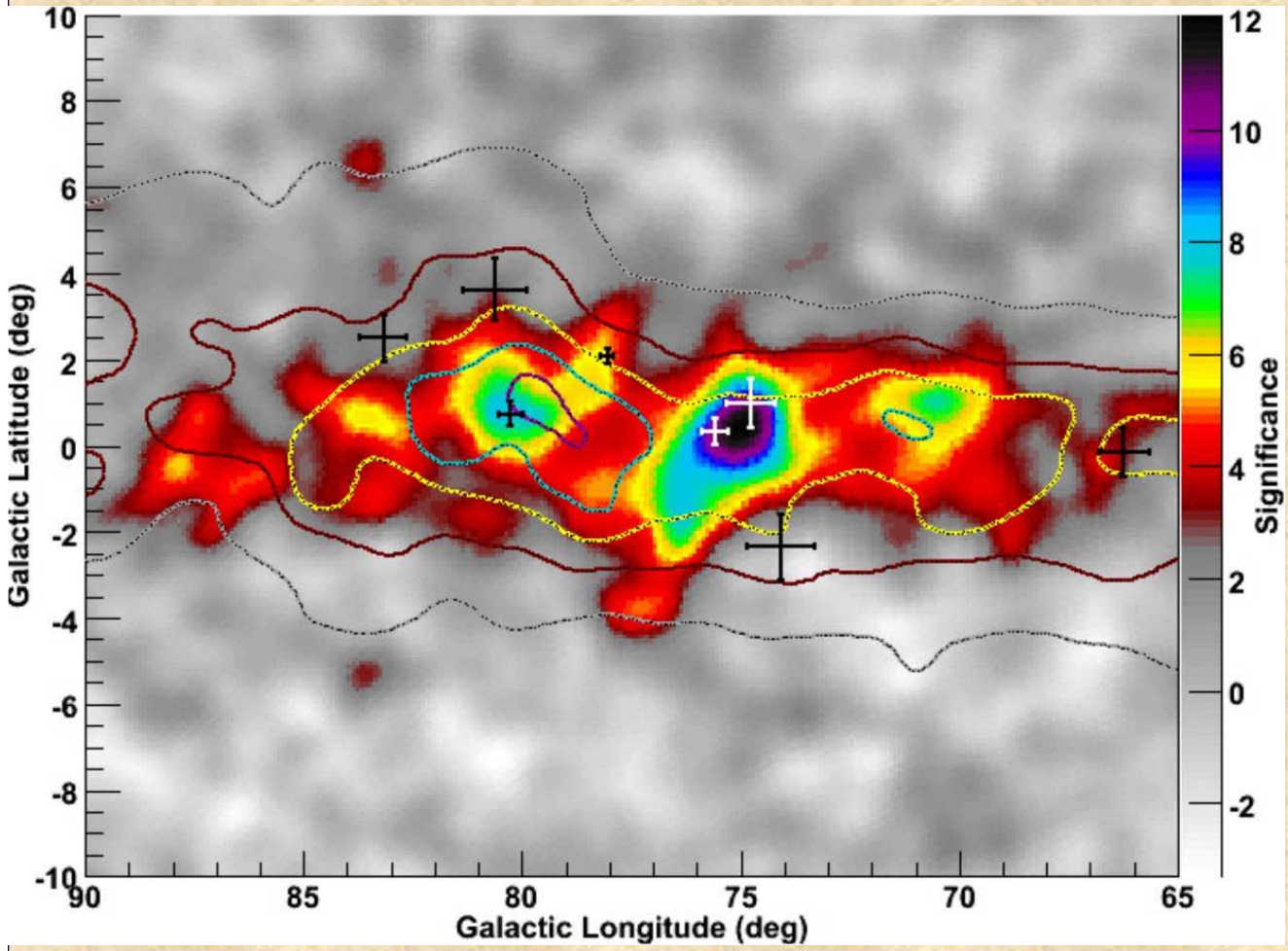






milagro

cygnus region : Milagro



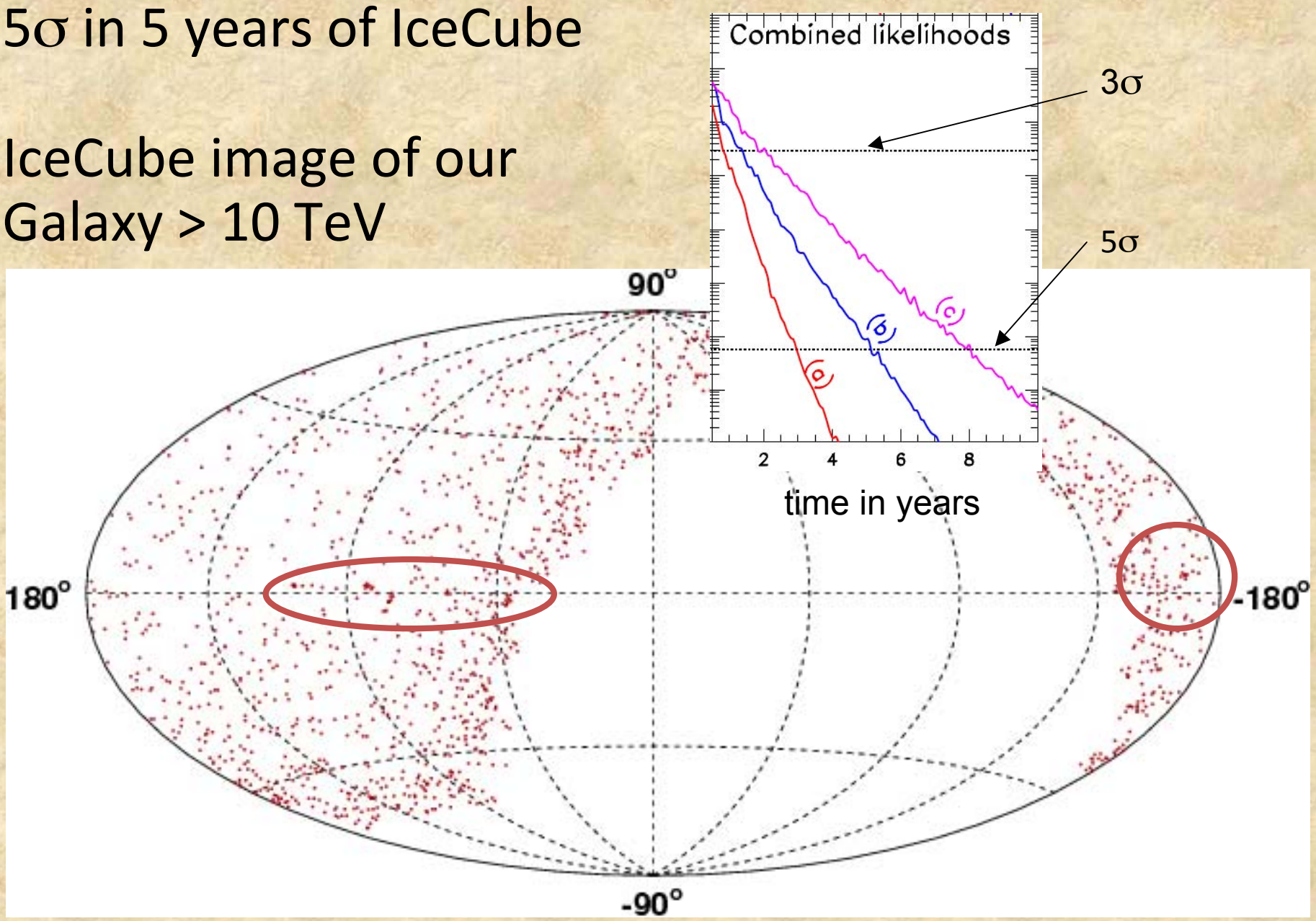
Milagro

translation of
TeV gamma rays
into
TeV neutrinos

3 ± 1 ν per year in IceCube per source

5σ in 5 years of IceCube

IceCube image of our Galaxy > 10 TeV



M. C. Gonzalez-Garcia, F. Halzen, and S. Mohapatra, Astropart. Phys. **31**, 437 2009; e-print arXiv:0902.1176.

20,000 atmospheric neutrinos later …

Preliminary

STACKING 6 MILAGRO SNR

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)

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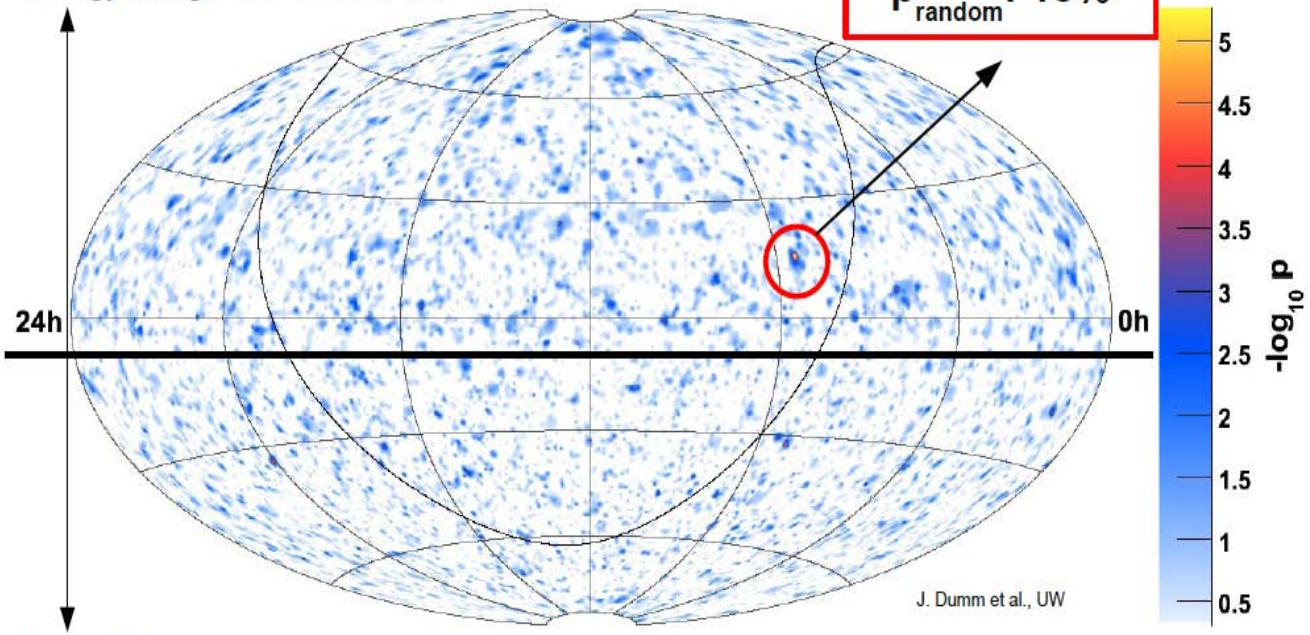
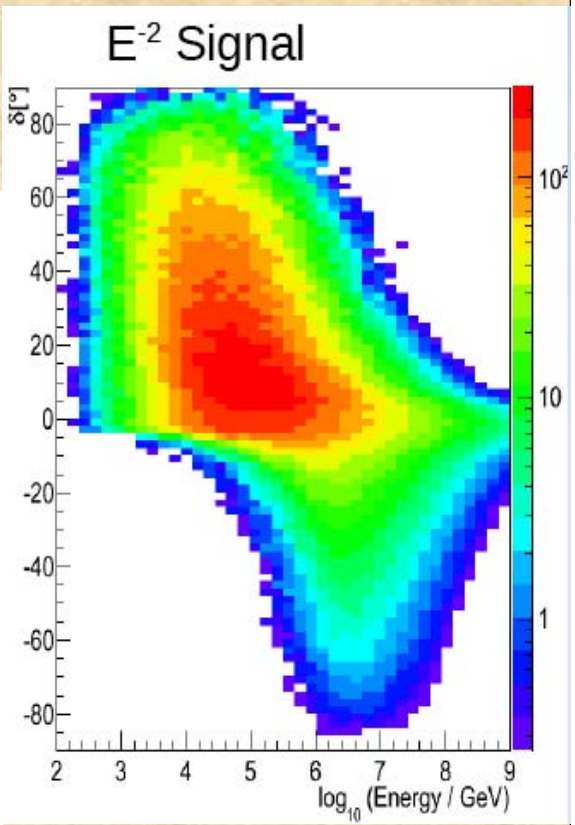
IC40 Point Source Search

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

$-\log_{10} p$: 5.28
p_{random}: 18%



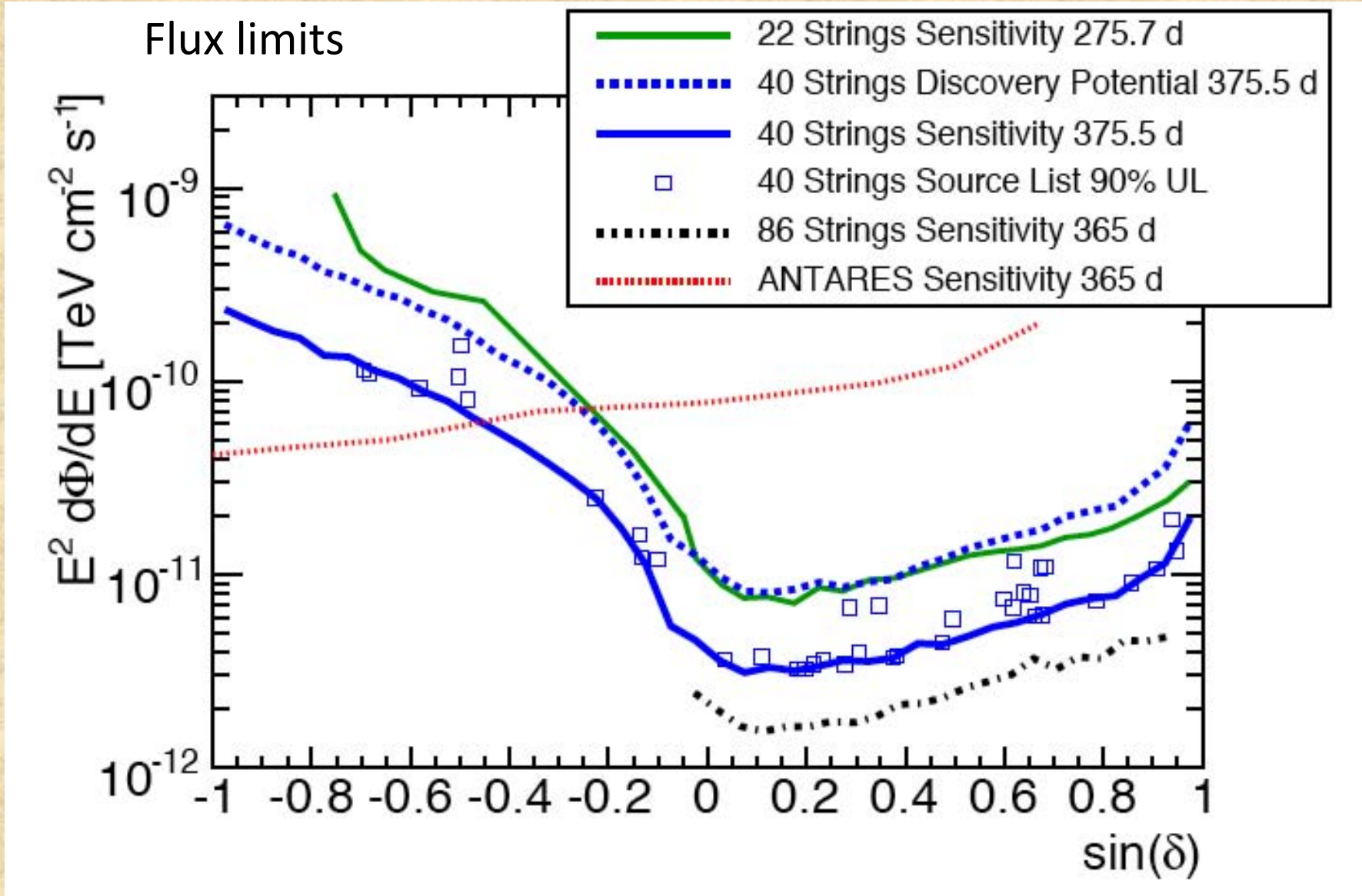
Above Horizon:
Data dominated by atmospheric **Muons**
Energy Range >PeV, increasing with angle



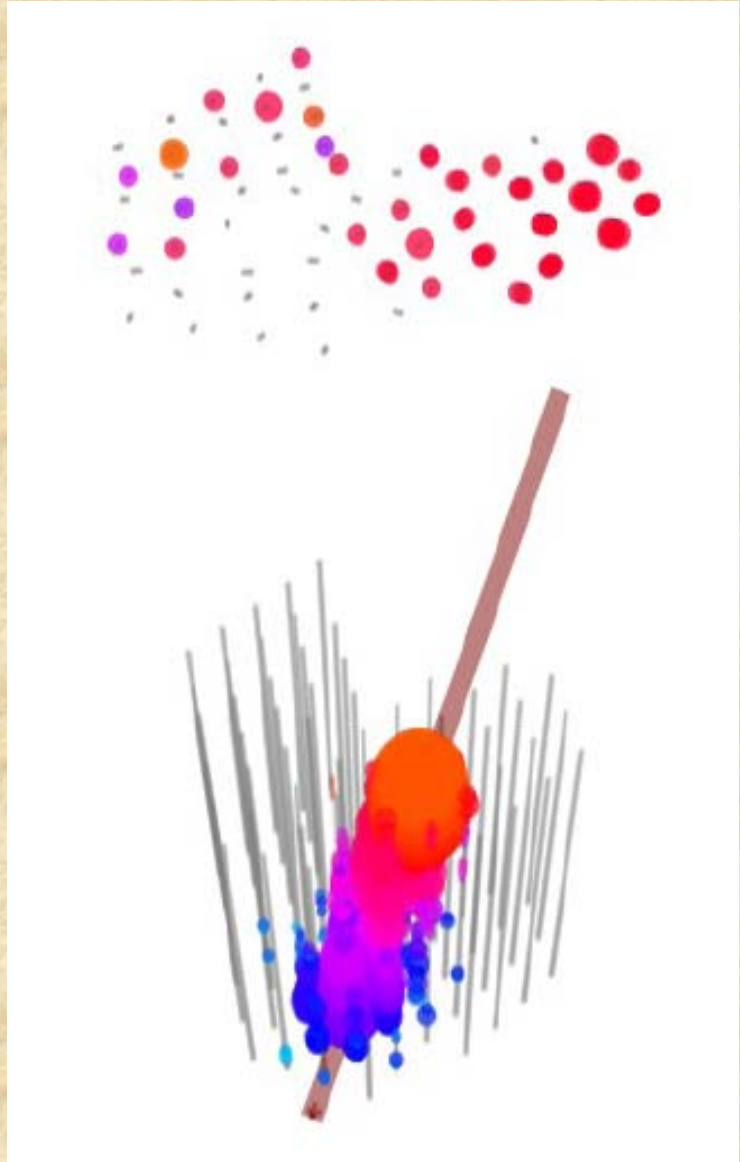
ApJ. 732:18,2011

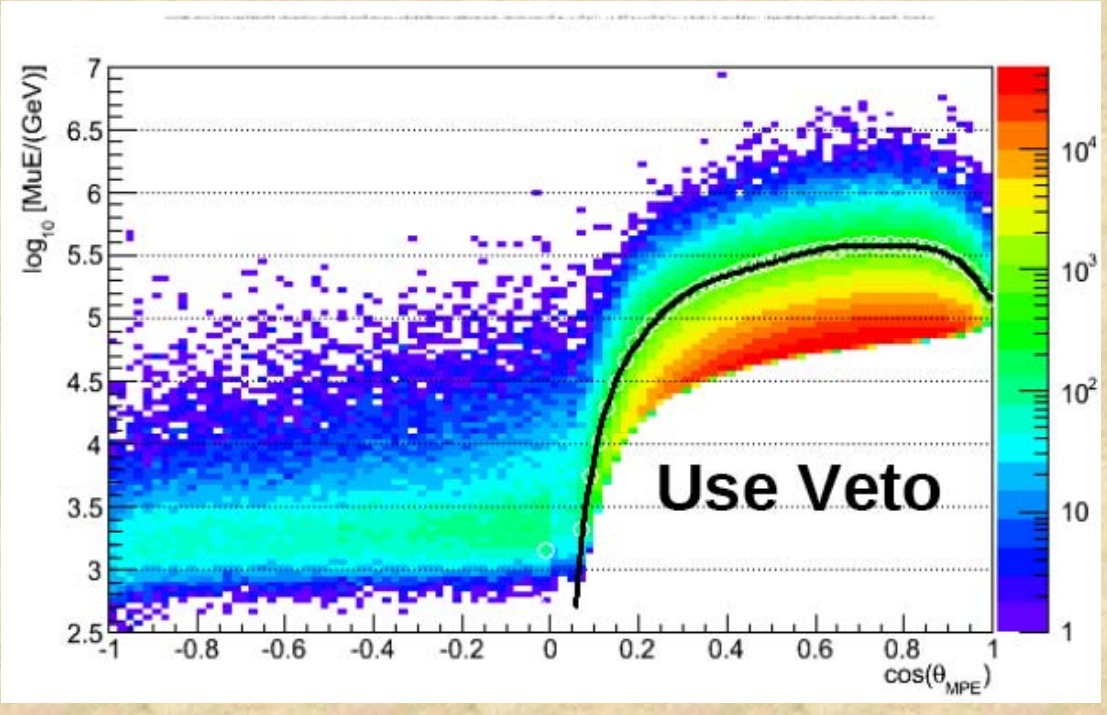
All sky search & source list

Flux limits



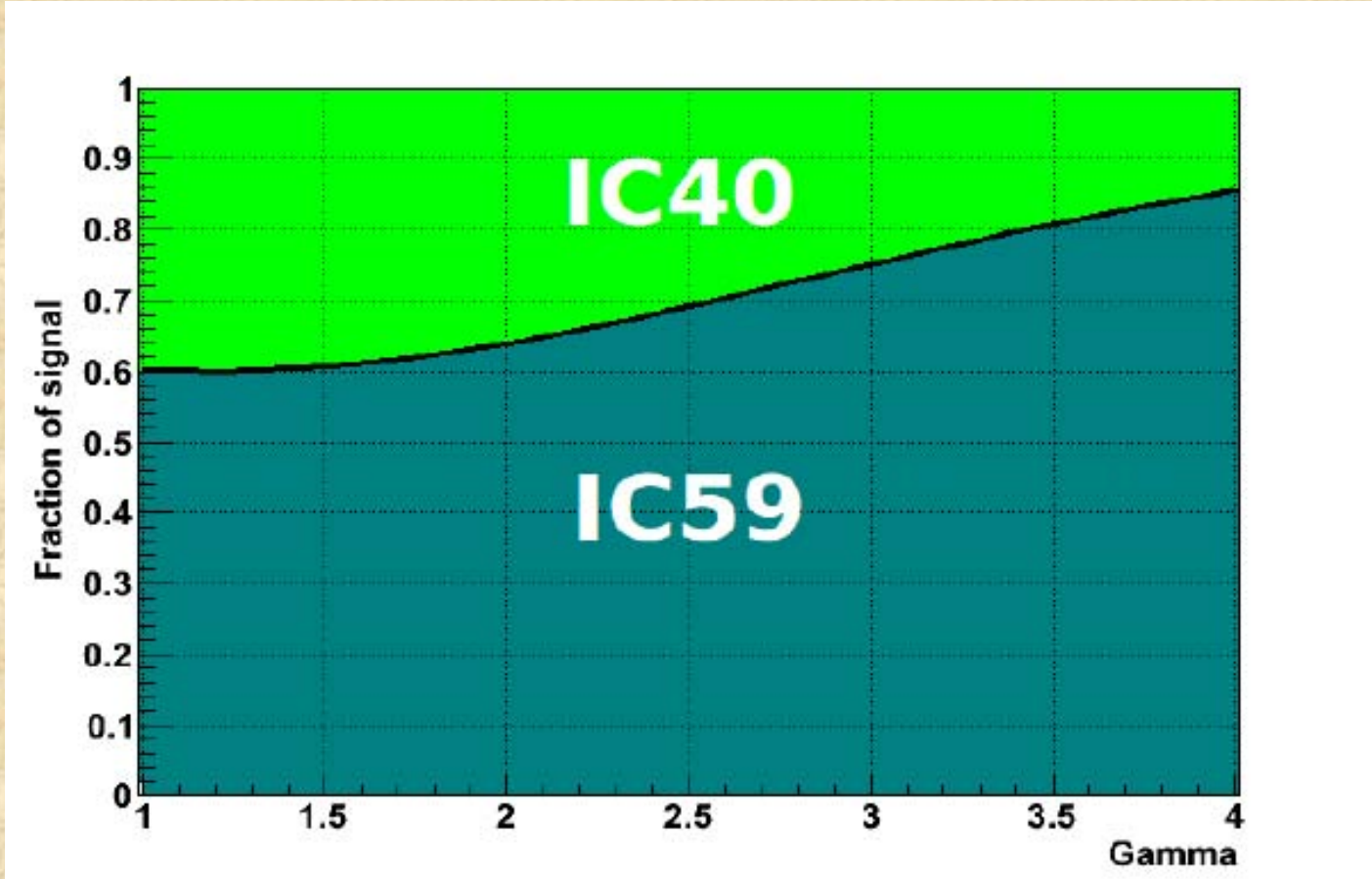
IC59 search - Improvements





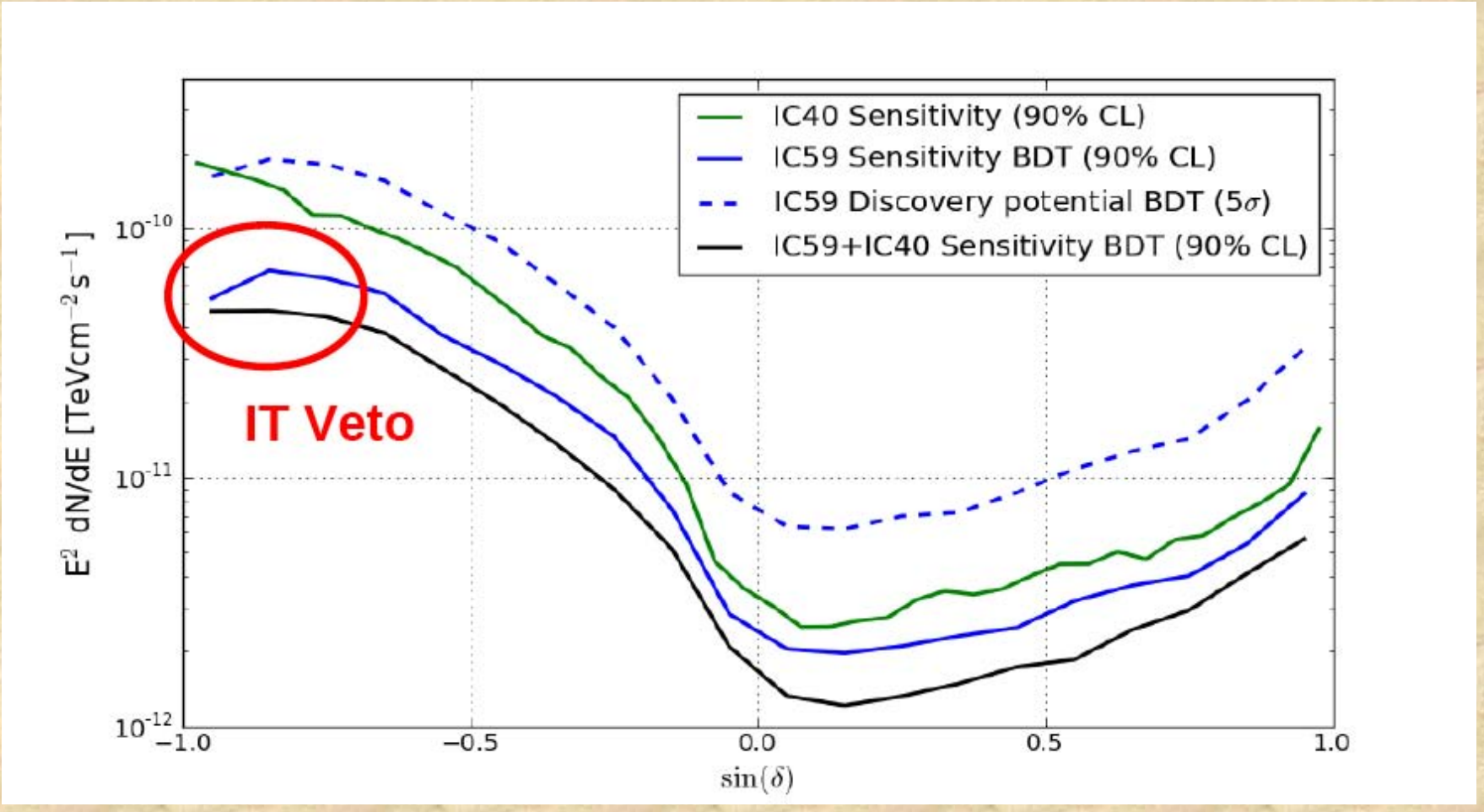
- Use IceTop as veto to reduce energy “cut” for downgoing
- Improved sensitivity using BDT
- Improved reconstruction

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

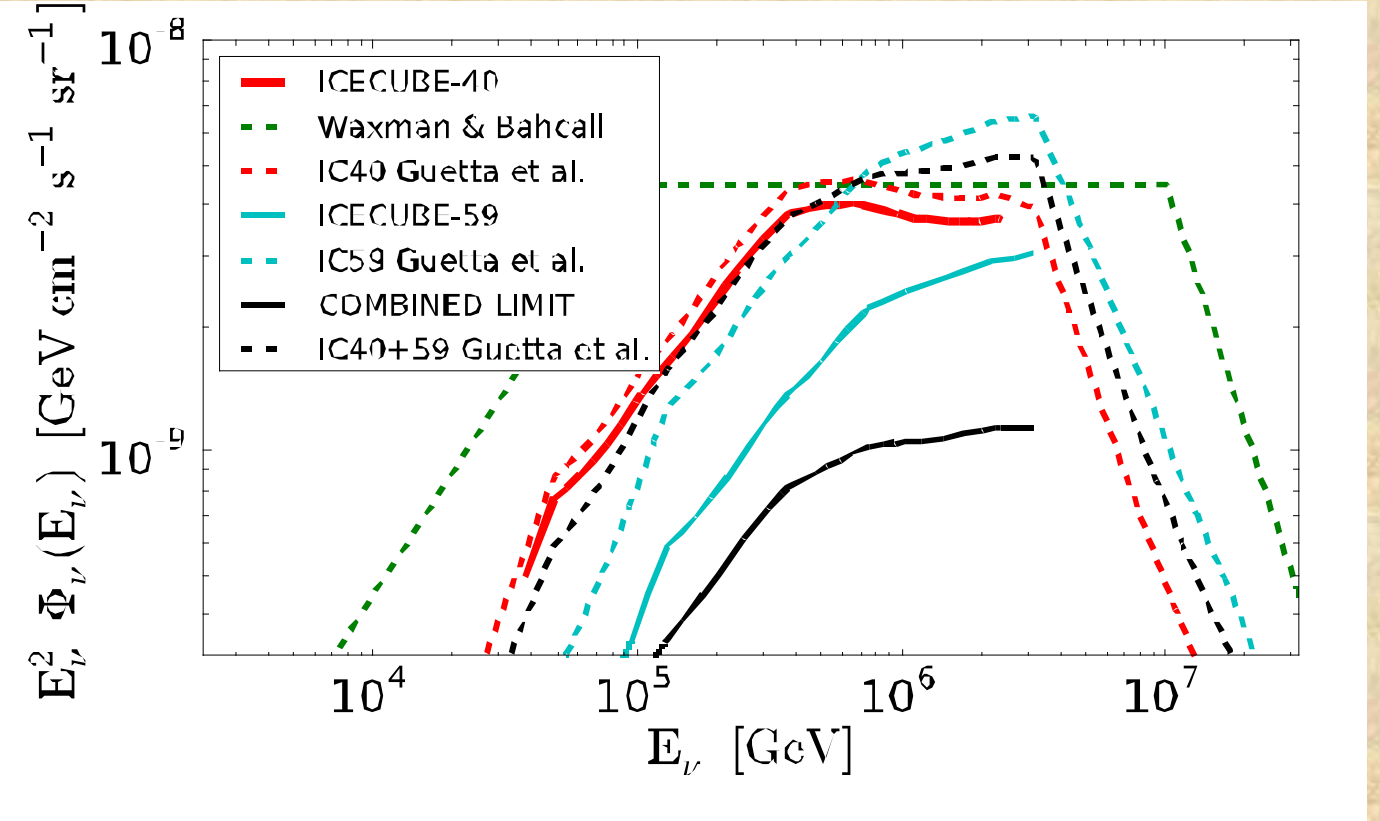
- Internal shocks in GRBs are a compelling candidate for the source of acceleration for UHECRs.
- Acceleration conditions required to produce the observed gamma rays would also be sufficient for UHECR production
- Observed gamma-ray burst energy injection rate into Universe well matched to observed UHECR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



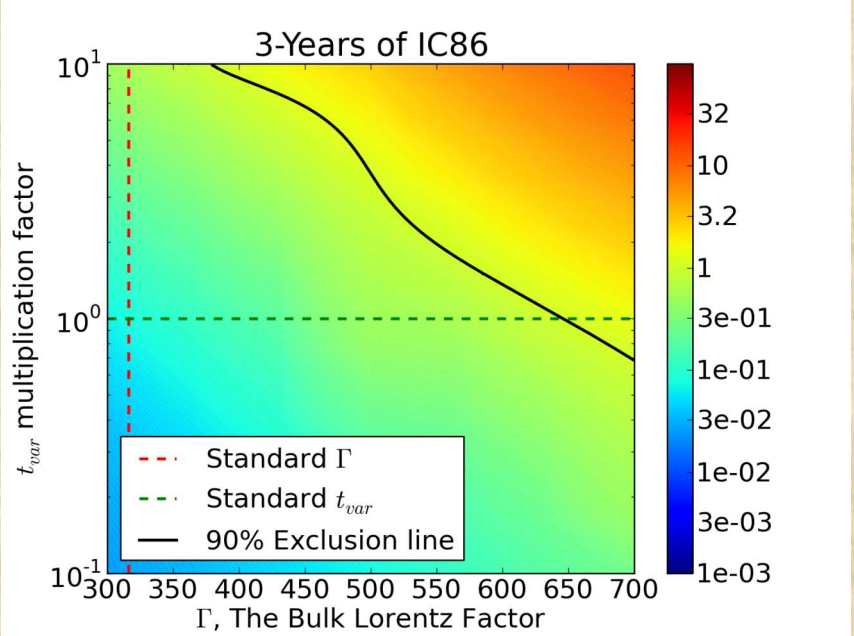
IC40: 117 Bursts

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
  - ***Km^3 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!

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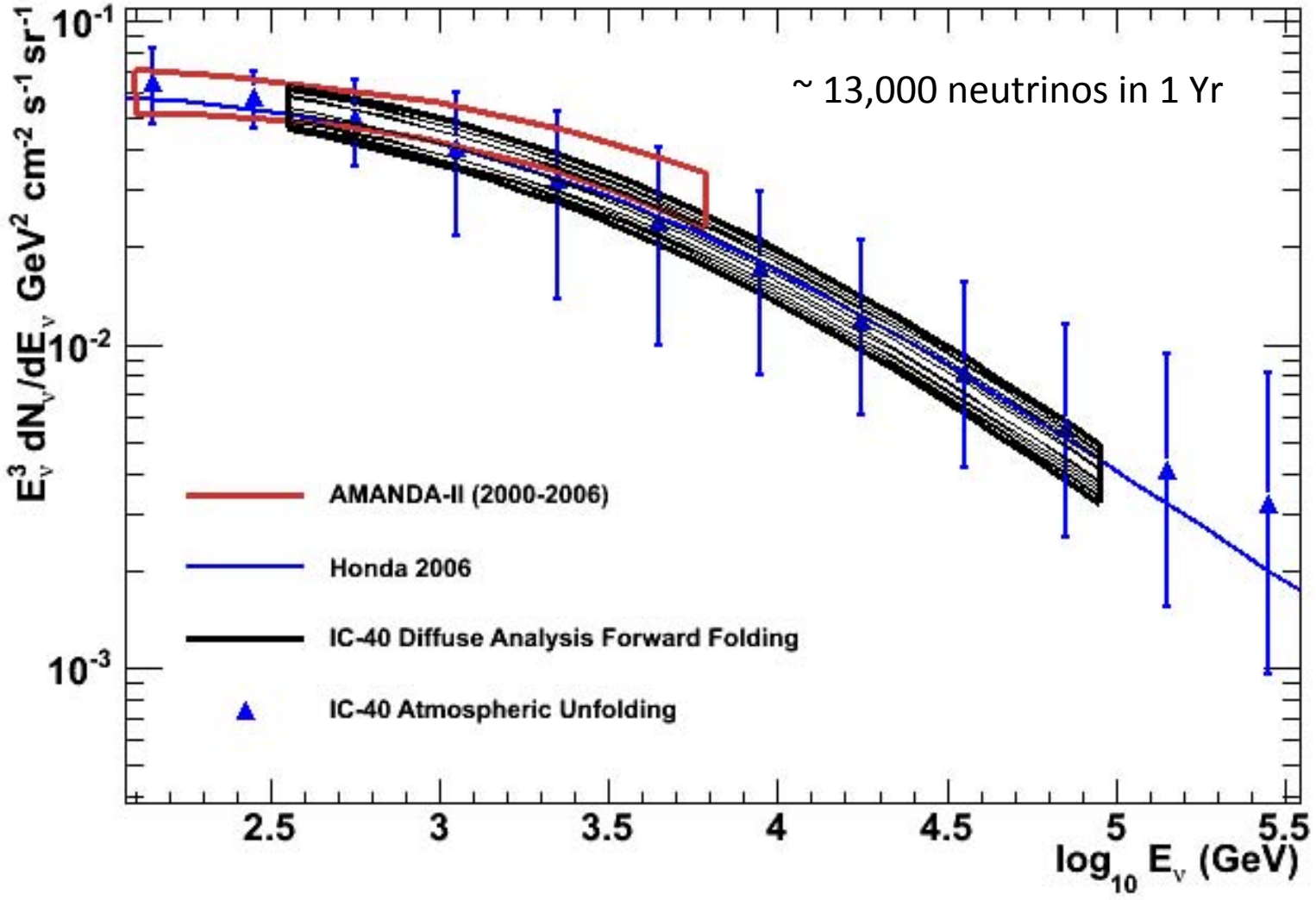
Atmospheric Neutrino Spectrum



PHYSICAL REVIEW D 83, 012001 (2011)

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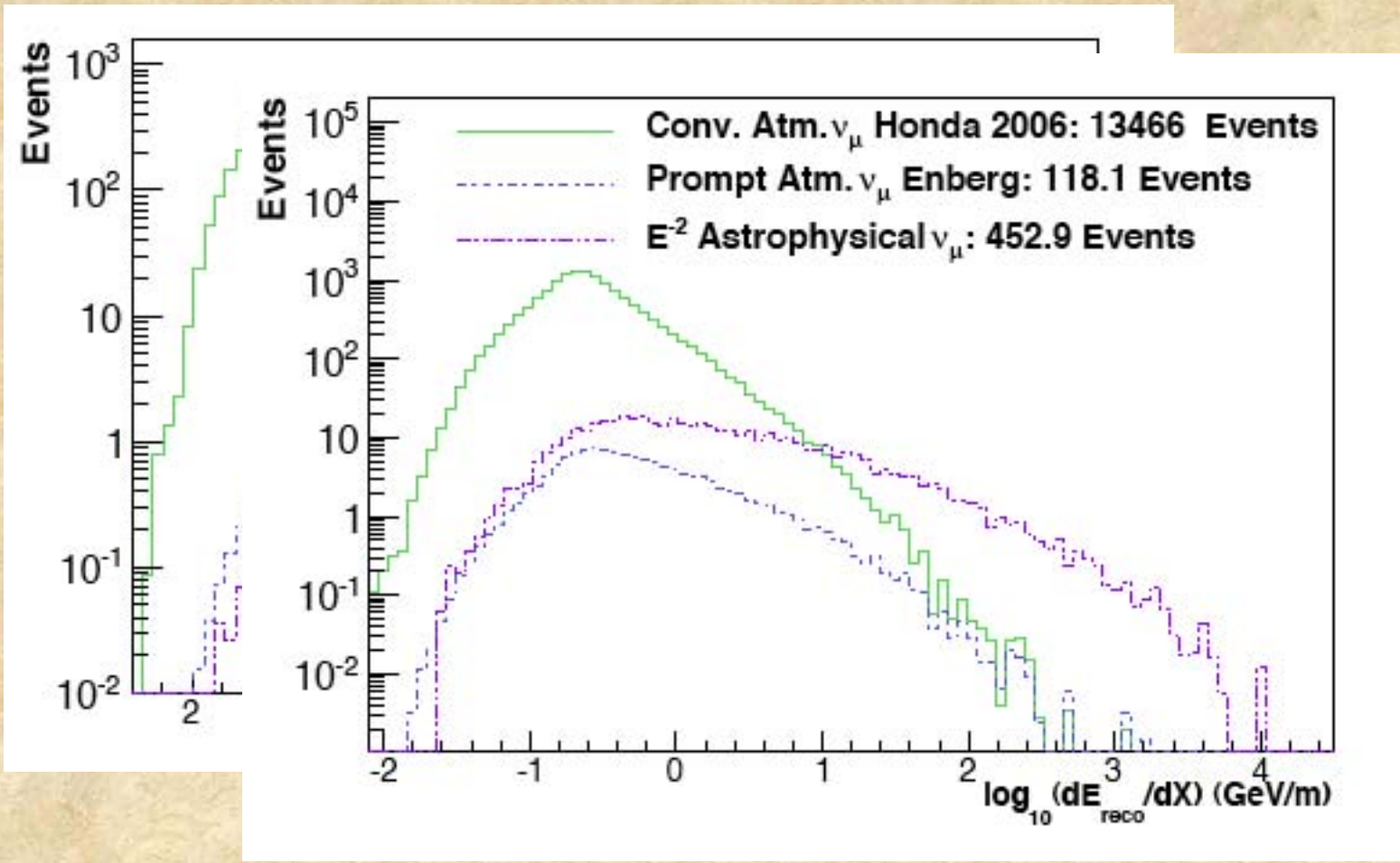
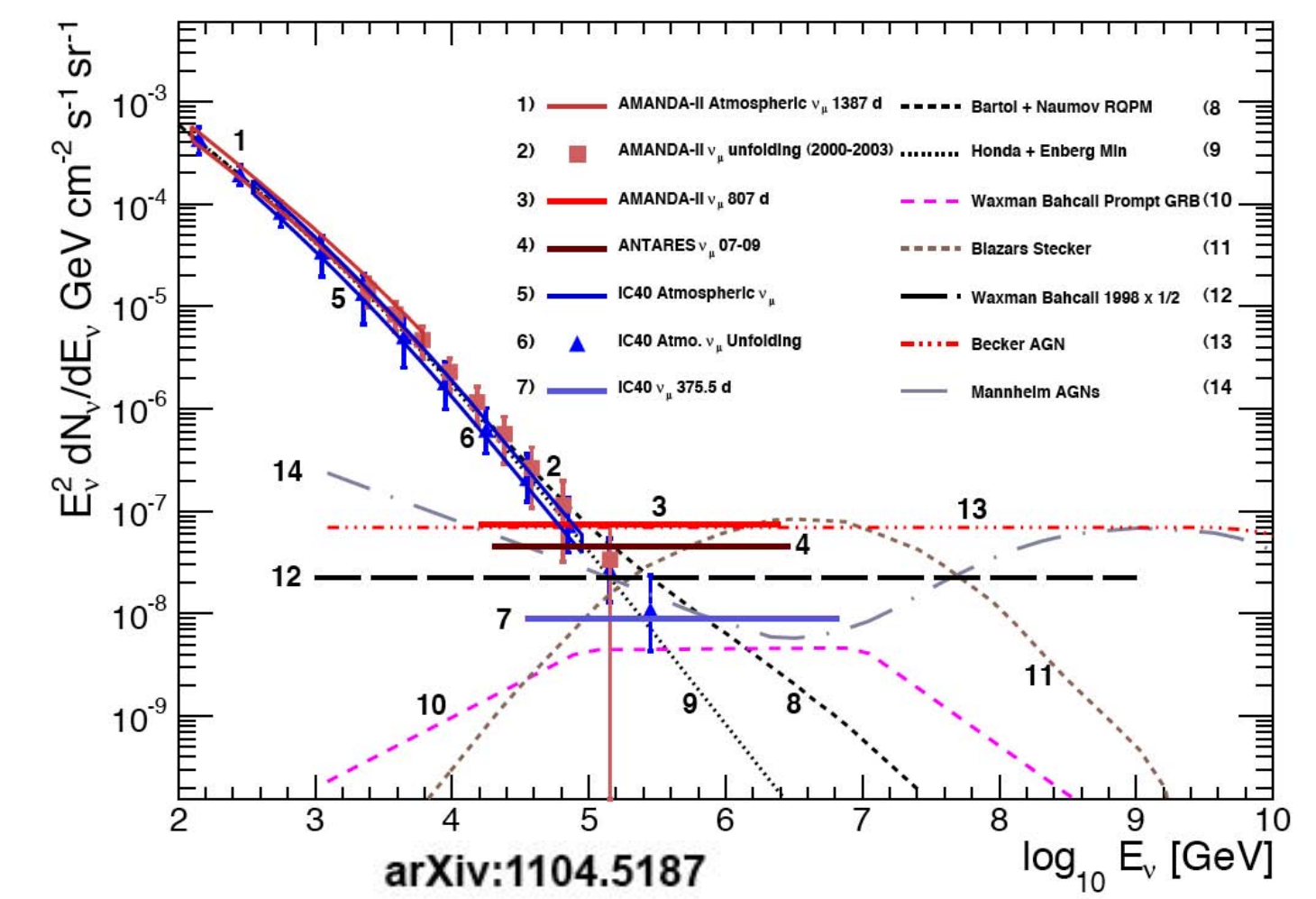
Search for Diffuse Neutrino flux with Muon neutrinos



IC40 muon neutrino diffuse flux limit



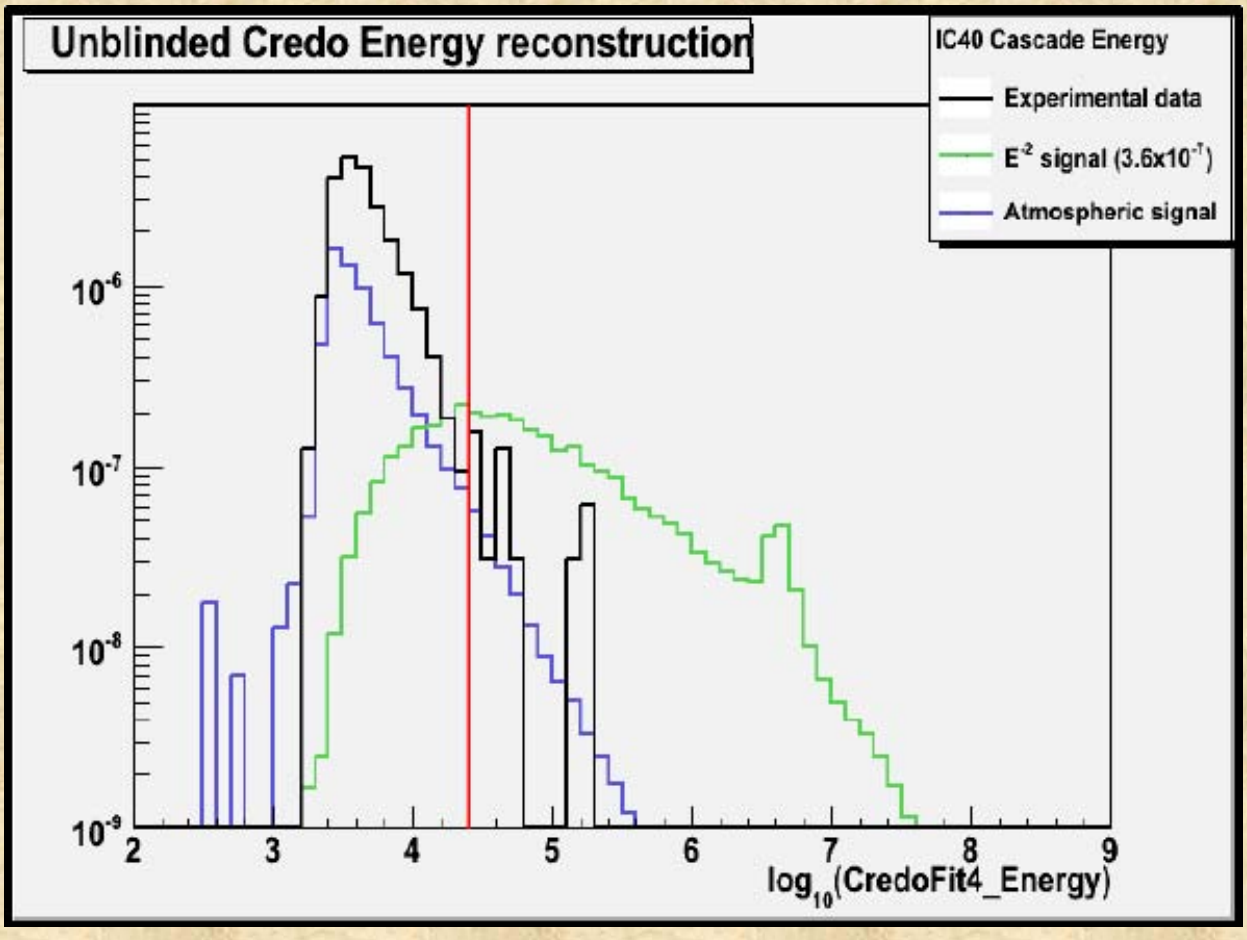
IceCube 40 has Reached the Waxman-Bahcall bound!

HE Cascades in IceCube

- The volume of IceCube is qualitatively different then 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 cr 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

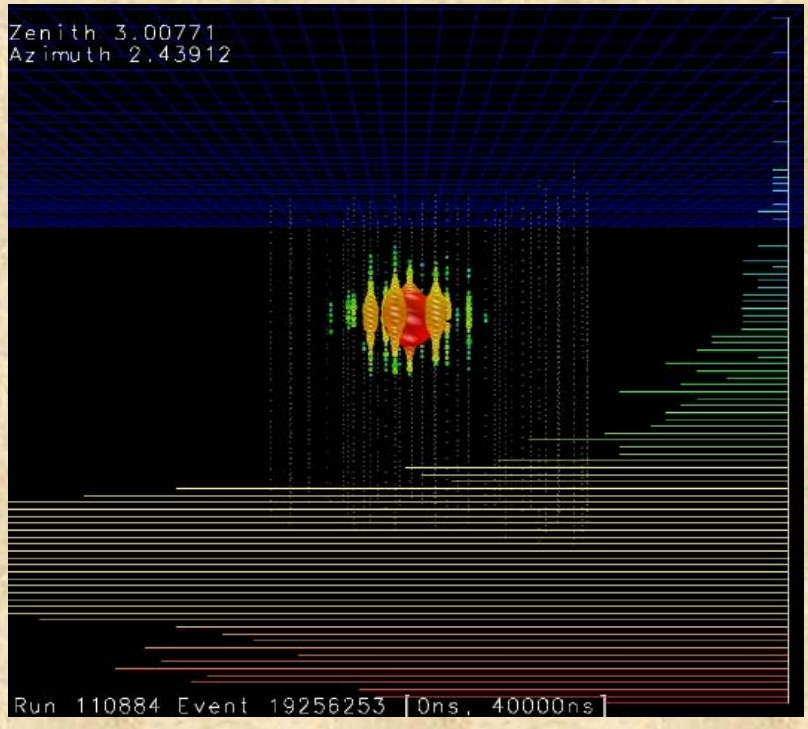
IC40 high energy cascades *(preliminary)*

- 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

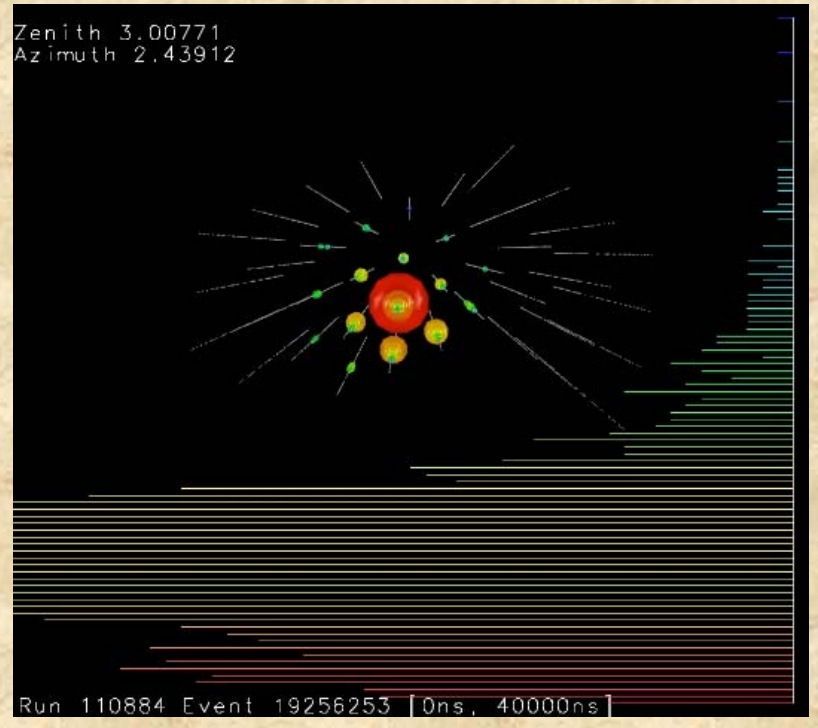


IC40 HE cascade event displays

Energy estimate = 175 TeV

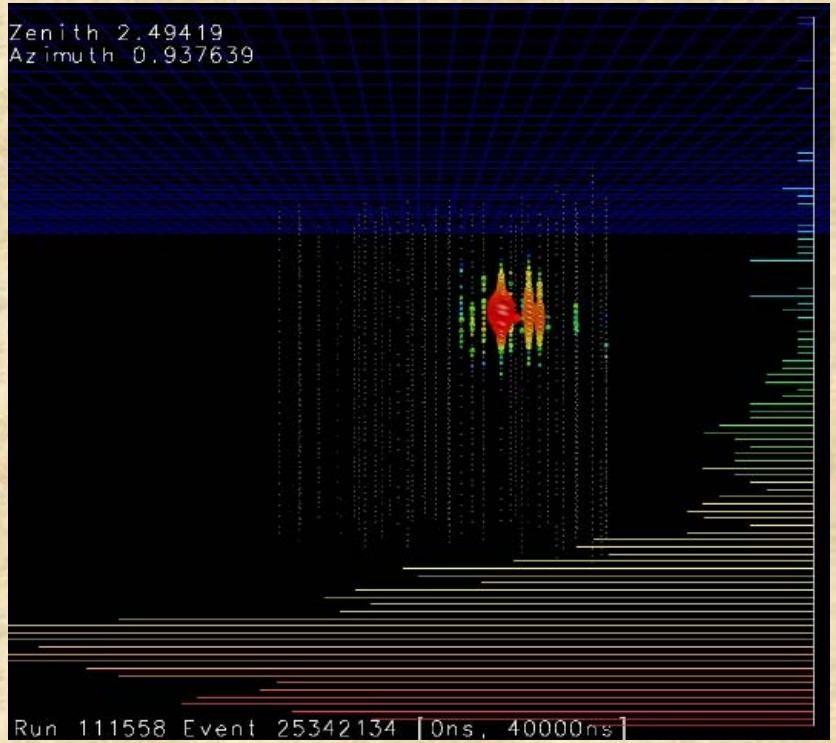


Side view

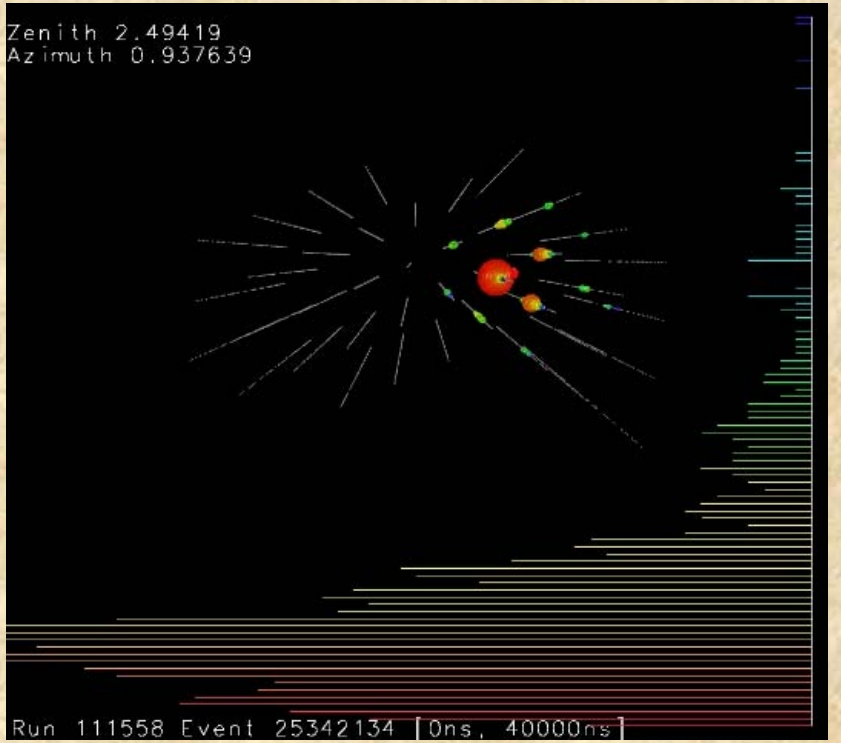


Top view

Energy estimate = 45 TeV



Side View



Top View

Several Cascade Analyses in progress with IceCube Data

HE atmoshepric neutrino/diffuse, EHE GZK, LE (deep core)

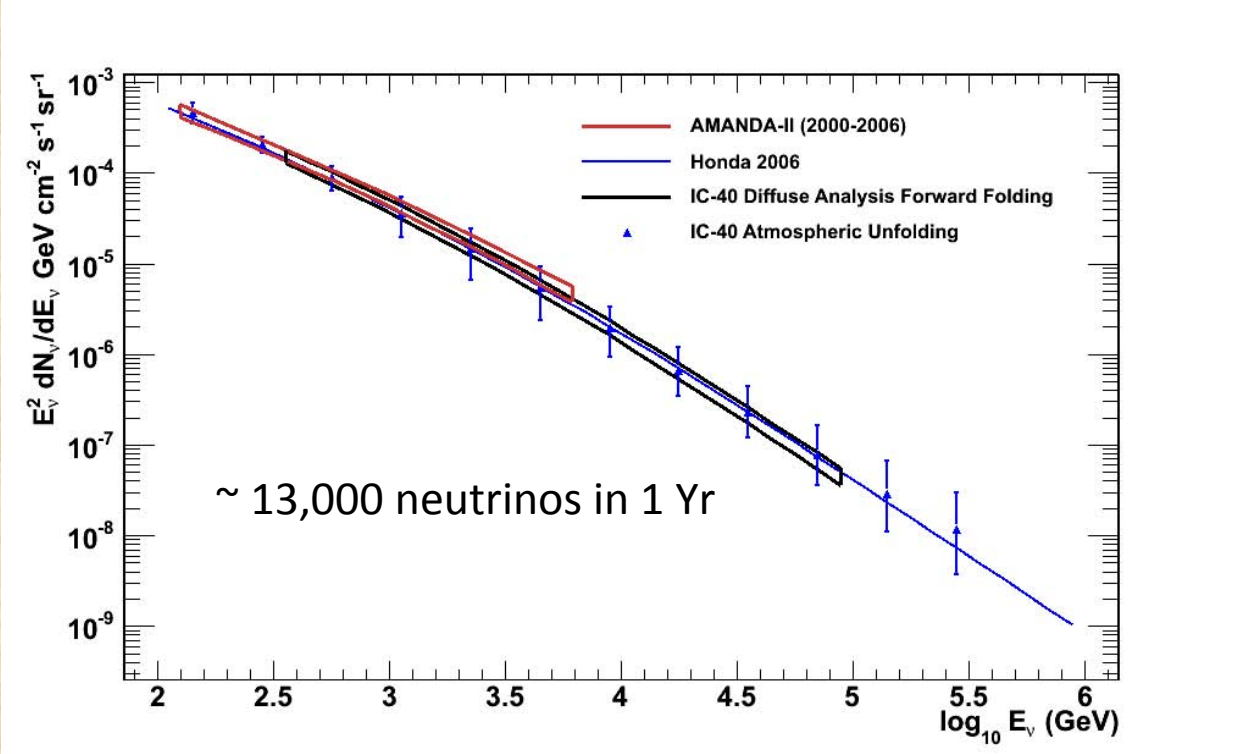
Stay tuned!

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

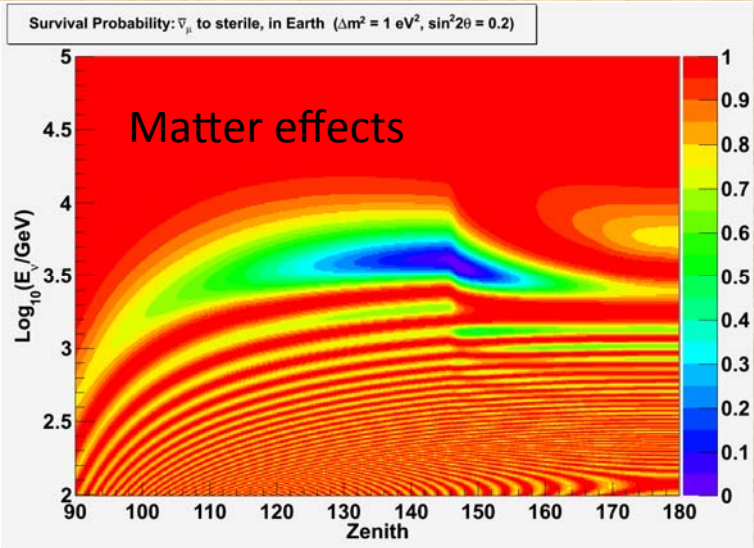
Atmospheric Neutrino Spectrum

- High statistics sample of atmospheric neutrinos
- ~13,000 events above ~100 GeV with >95% purity in IC40
- ~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

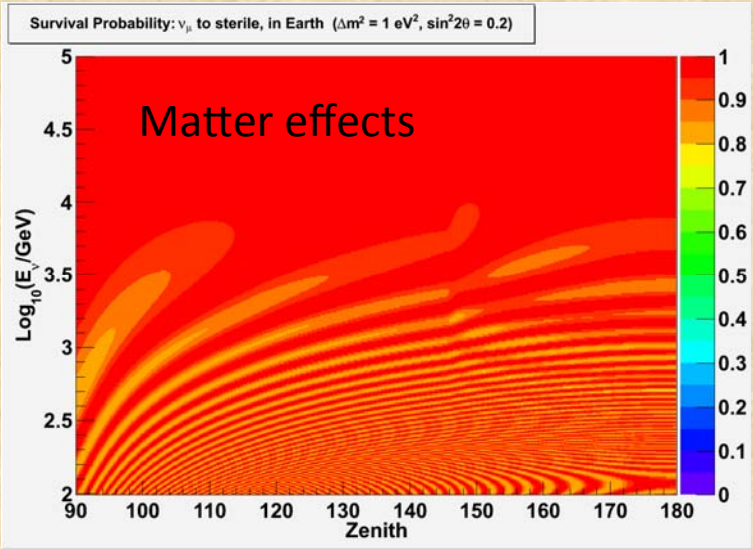


Non-standard oscillations effect on atmospheric neutrinos

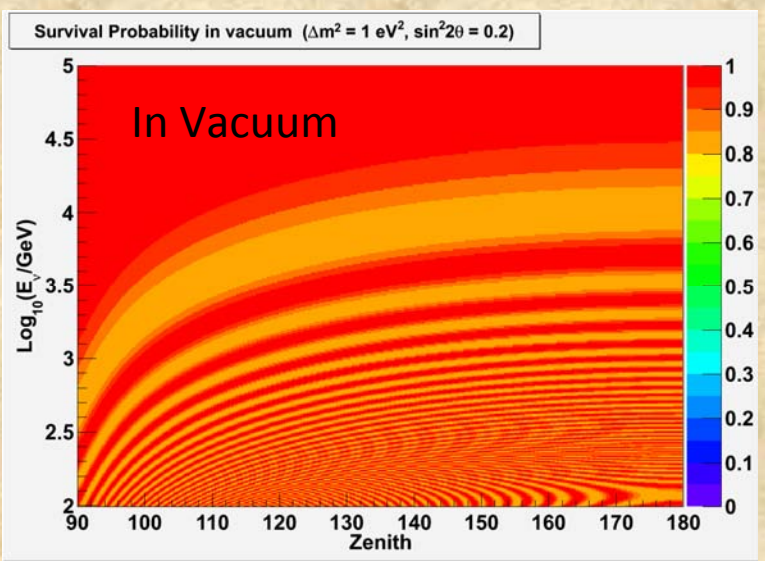
Antineutrinos



Neutrinos

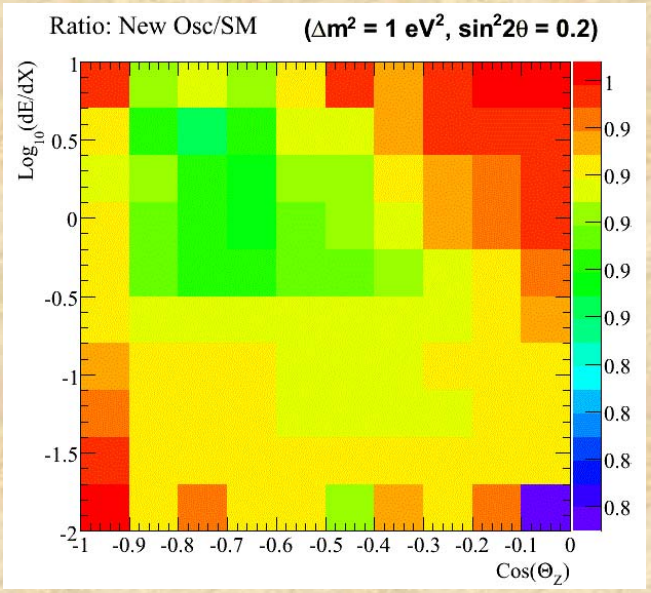


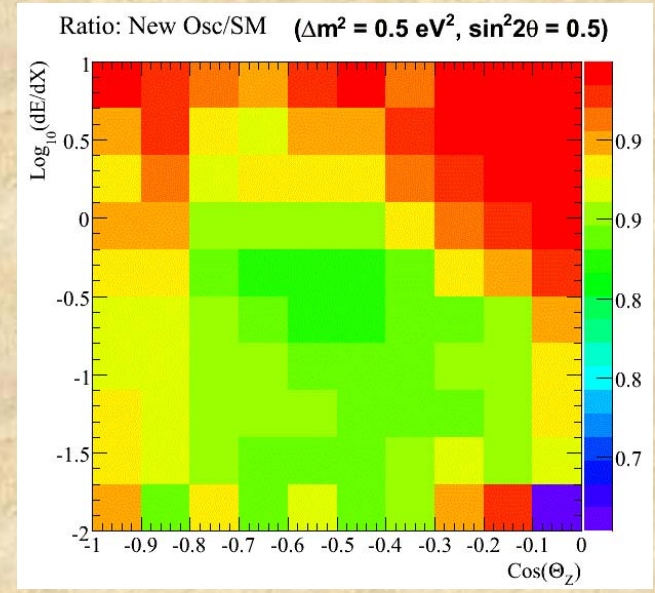
ν_μ --> ν_s oscillations



Effect in IceCube Detector

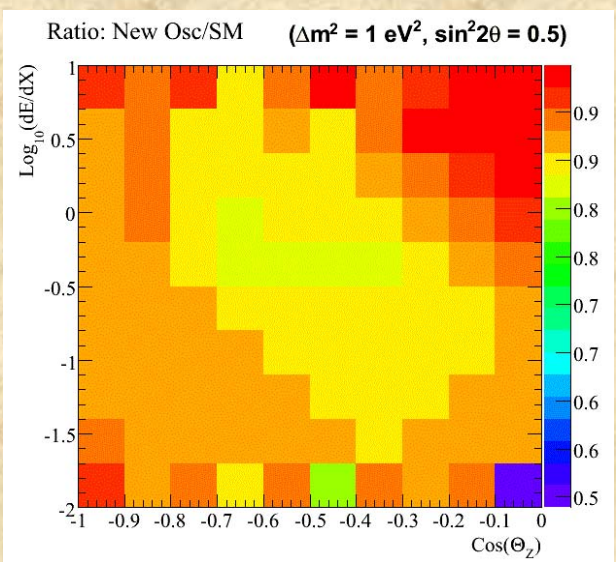
Effect with energy and angular resolutions of IceCue included
→ 10's %





40,000 events in IC59

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



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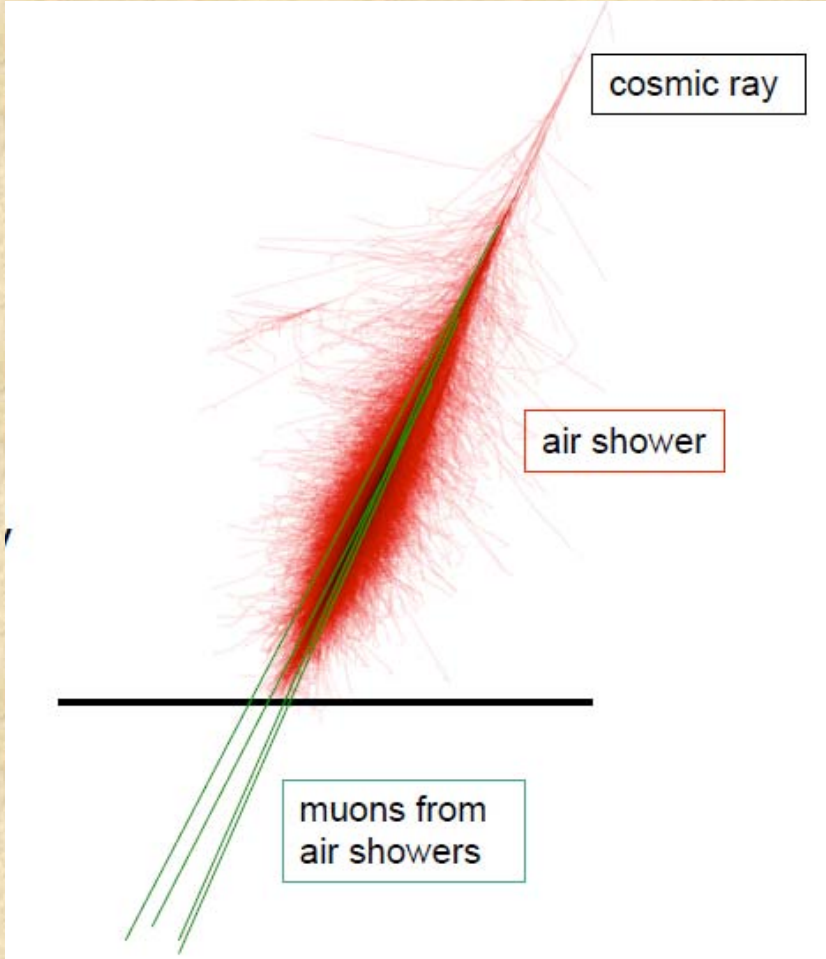
CR Muon Astronomy

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

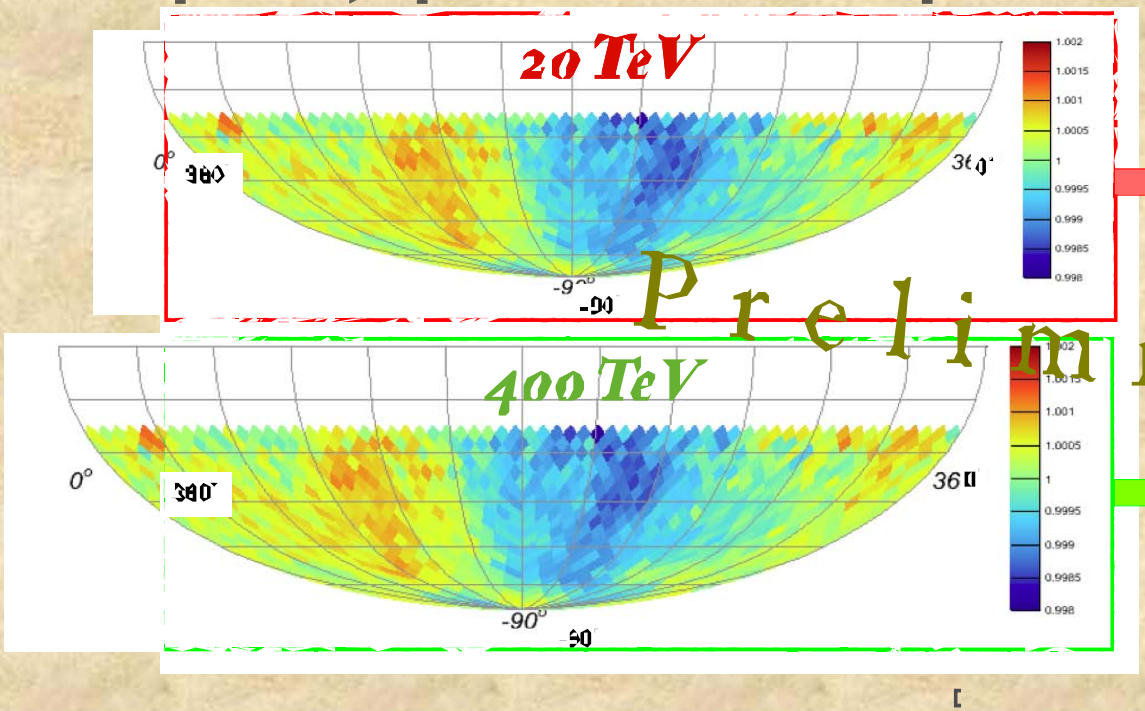
Recall the Moon Shadow

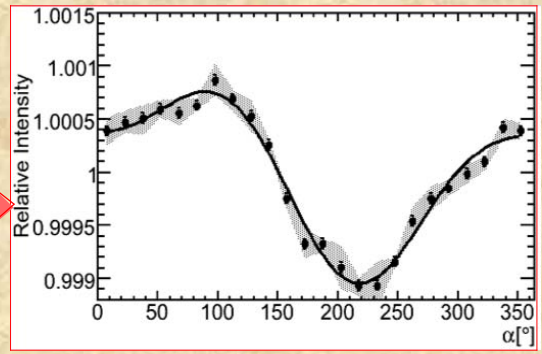


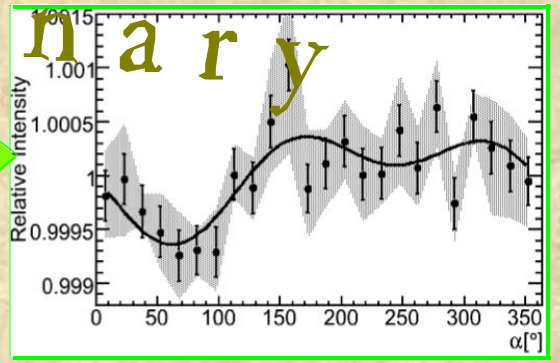
Large Scale anisotropy [paper in preparation]

- 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 NSide= 16, **pix resol ~ 3°***







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

Equatorial sky maps in HEALPix with NSide= 64, ***pix resol ~ 0.9°***

[submitted to ApJ: **arXiv:1105.2326**]

Sampling of IceCube Science Topics

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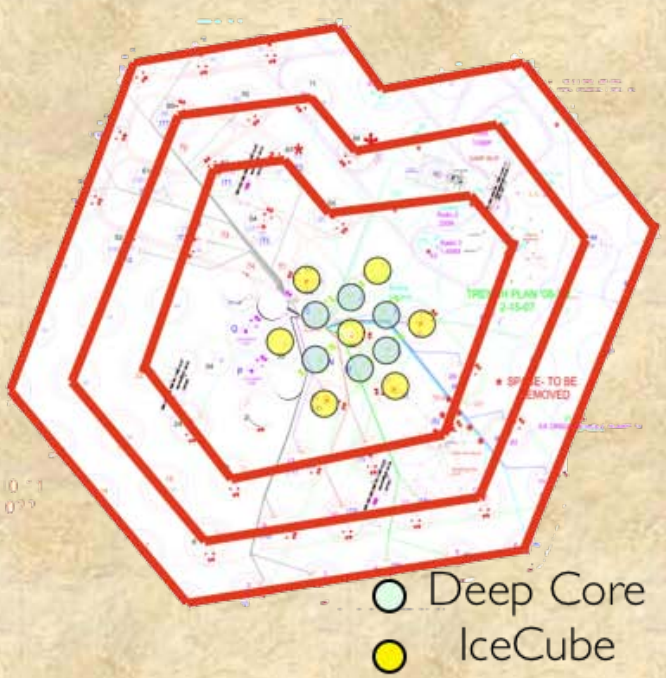
IceCube Deep Core (low energy & contained events)

Rejection rate

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

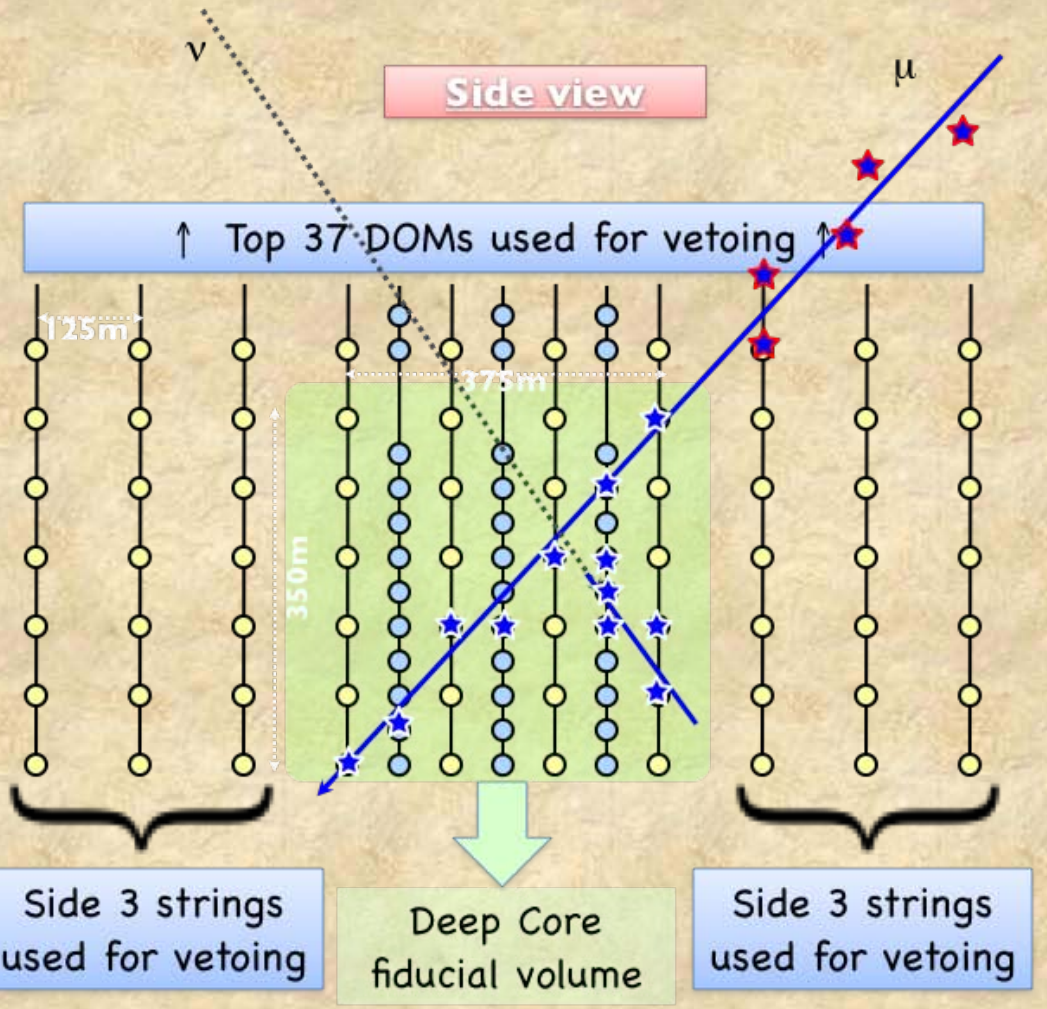
Top view



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

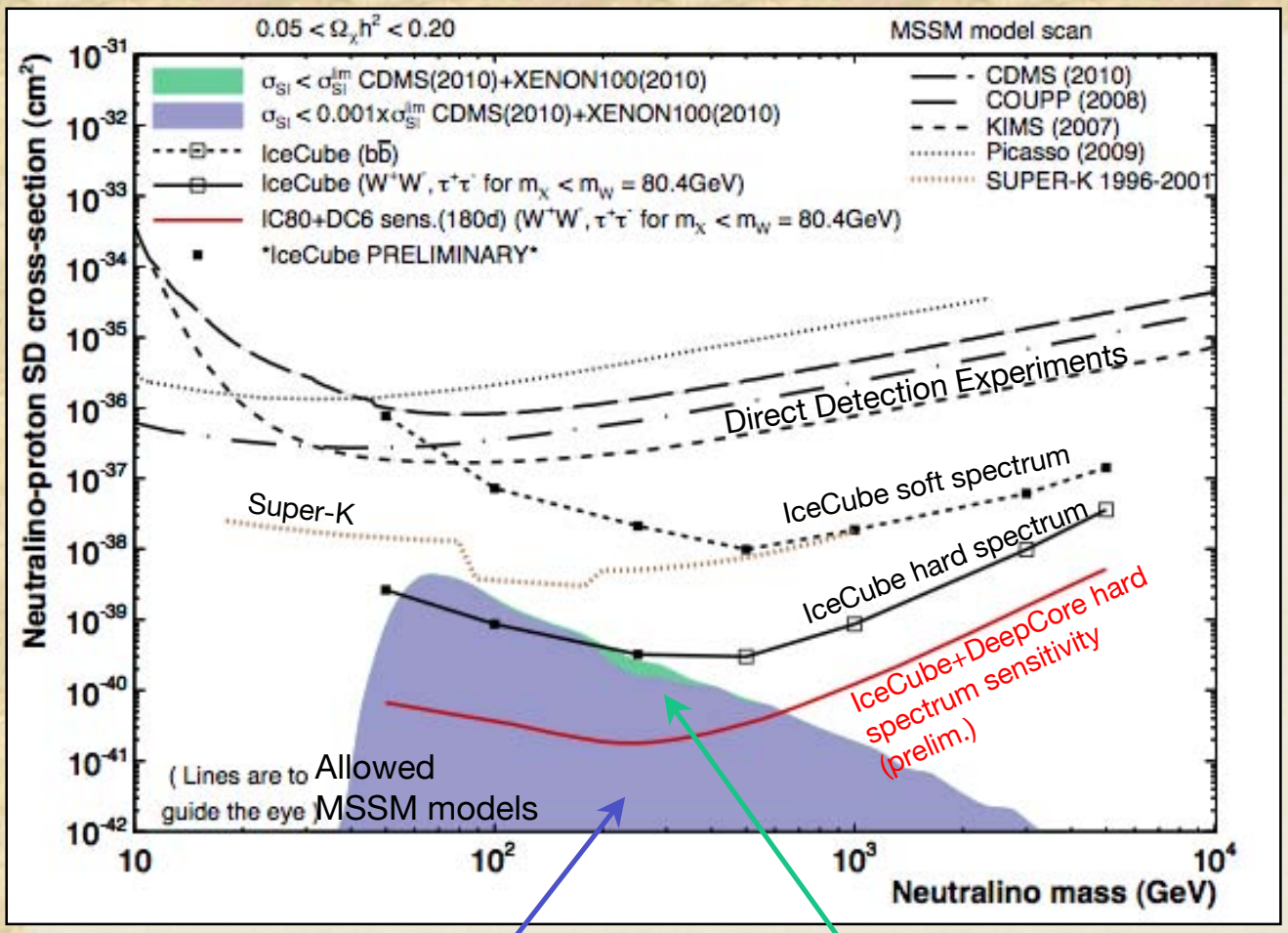
veto allows searches above horizon!

Side view



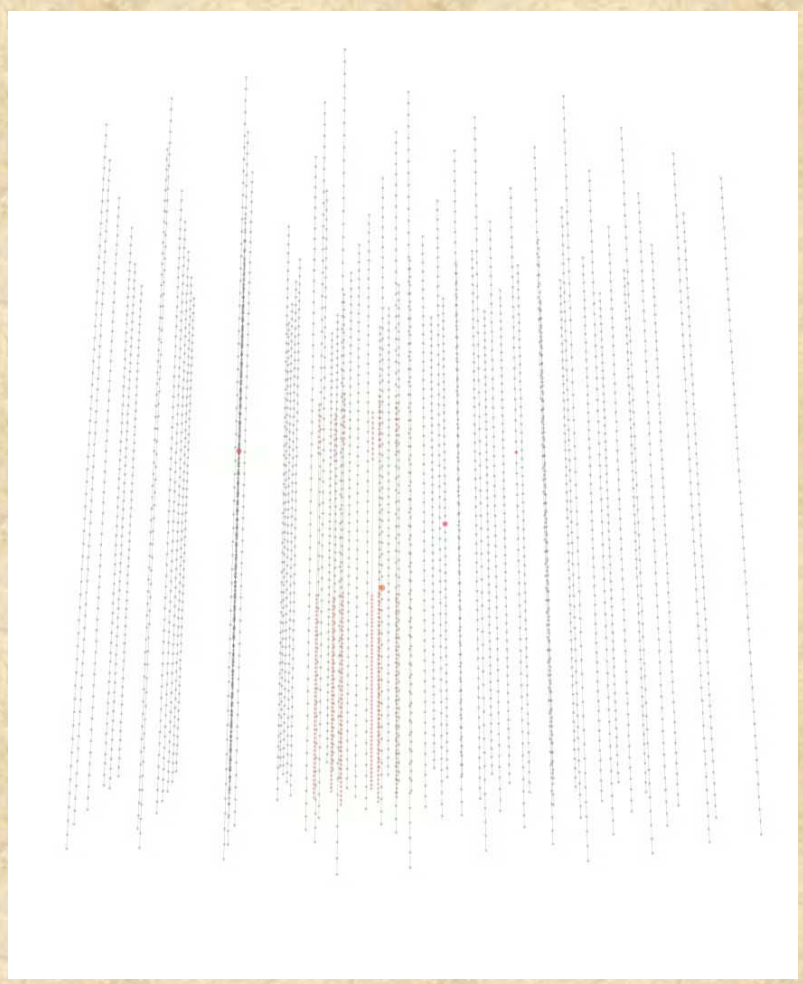
Sensitivity to MSSM WIMPs

- 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



Observation of Neutrino Cascades (Preliminary)

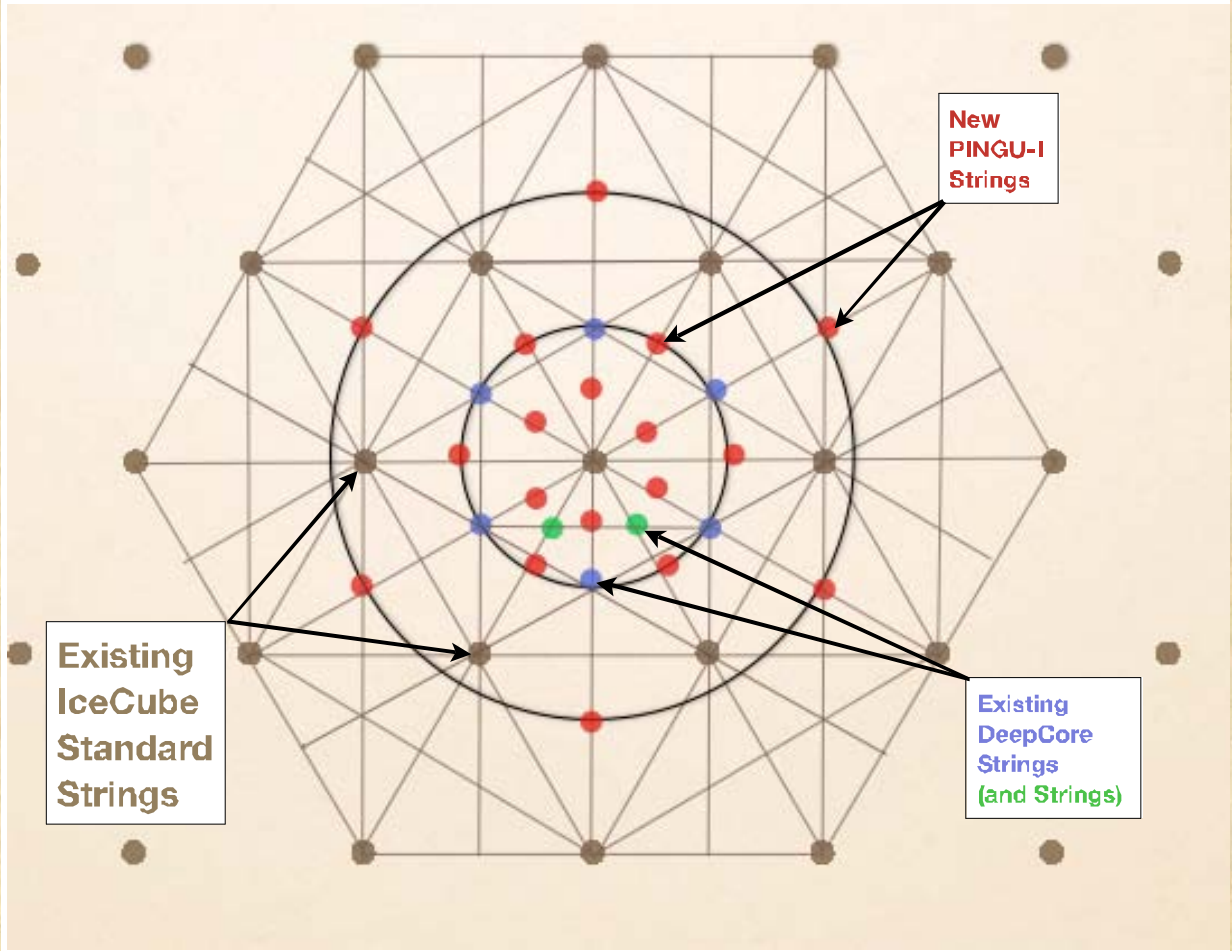
- Disappearing ν_μ should appear in IceCube as ν_τ cascades
  - Effectively identical to neutral current or ν_e CC events
  - Could observe ν_τ appearance as a distortion of the energy spectrum, if cascades can be separated from muon background
- We believe we see neutrino cascade events for the first 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*(1
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  Core
- Sub
  dete
- *MT*
- *Feas*
  Deco
- 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!