IceCube results

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University of Wisconsin-Madison

For the IceCube Collaboration

MANTS, Munich 2013

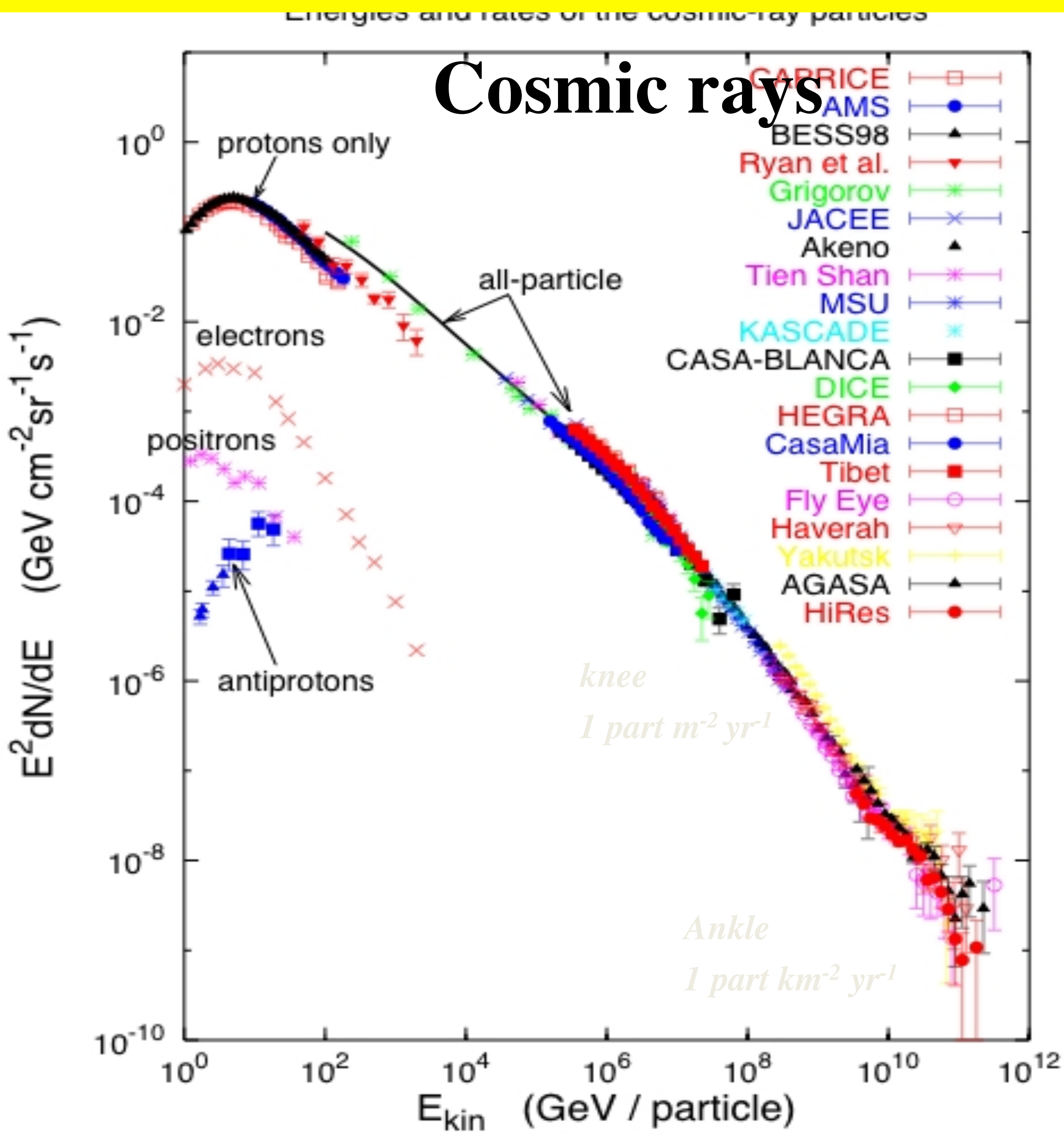
- Introduction
- Detector, events, techniques
- New results with contained vertex events
- Discussion, other channels

IceCube

WIPAC
Wisconsin IceCube Particle Astrophysics Center

NSF

Cosmic Rays and Neutrino Sources



Neutrino production from cosmic rays on known targets.

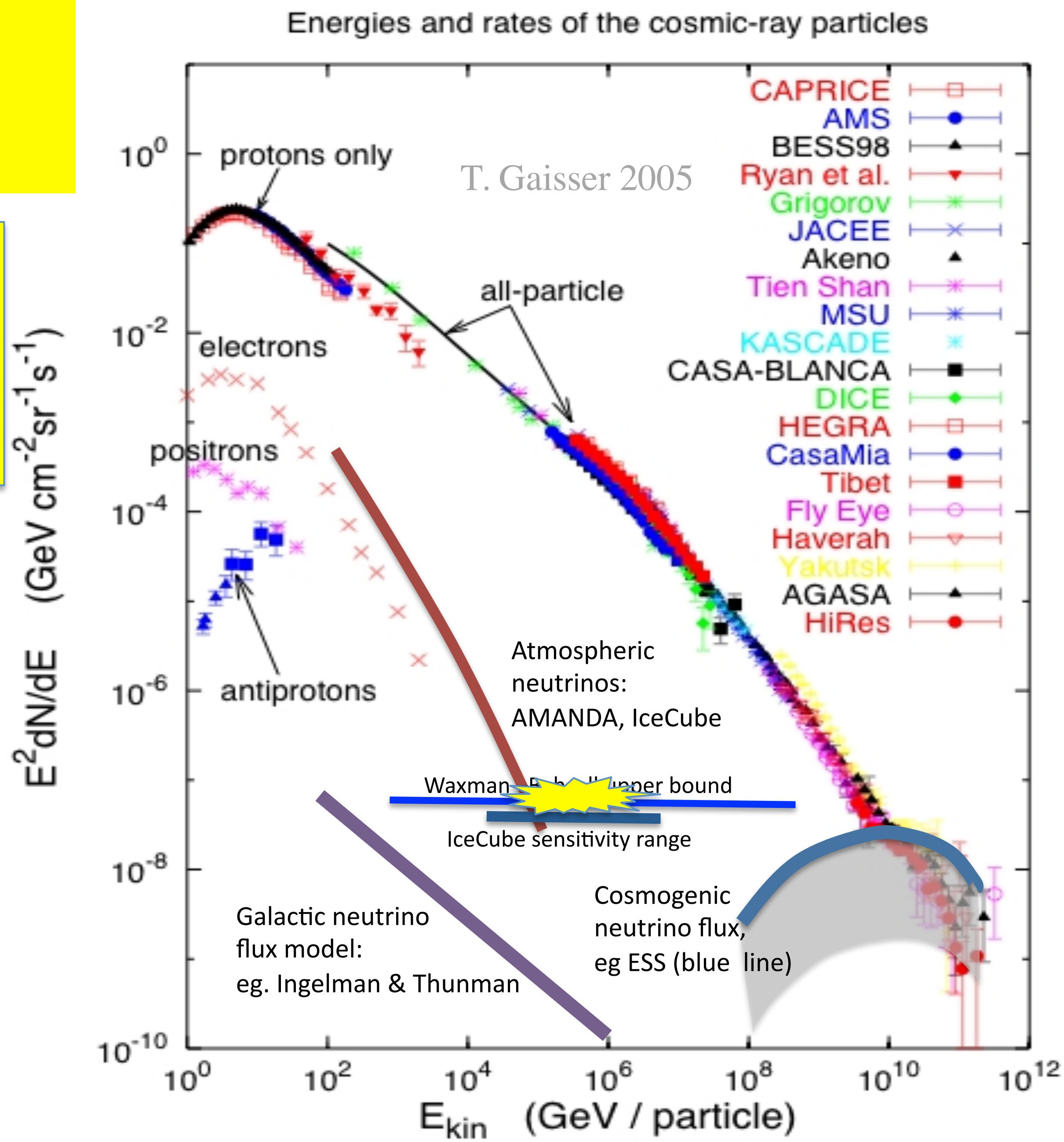
$$pp \to NN + pions; \qquad p\gamma \to p\pi^0, n\pi^+$$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

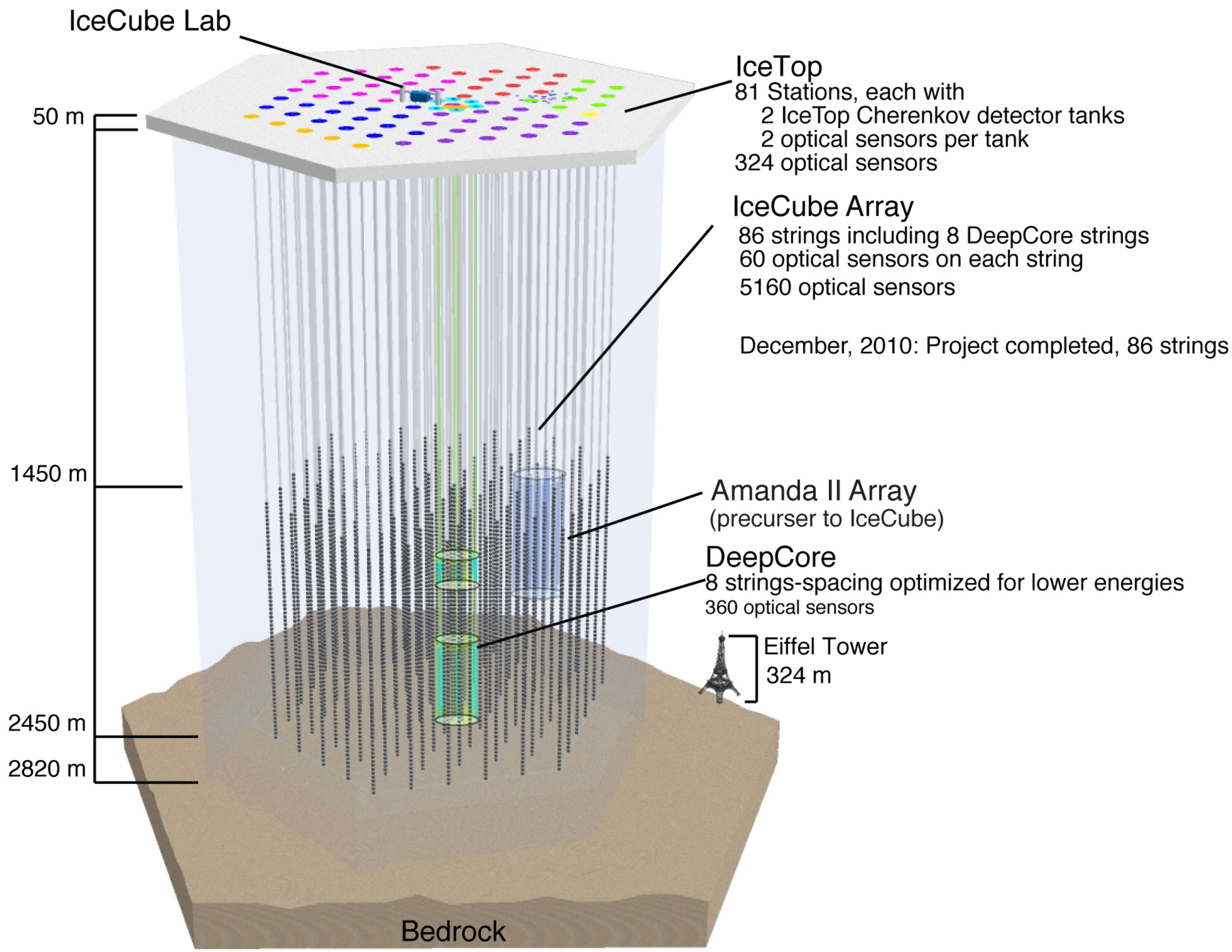
Known targets:

- Earth's atmosphere: Atmospheric neutrinos (from π and K decay)
- Interstellar matter in Galactic plane: Cosmic rays interacting with Interstellar matter, concentrated in the disk
- Cosmic Microwave background: UHE cosmic rays interact with photons in intergalactic photon fields.



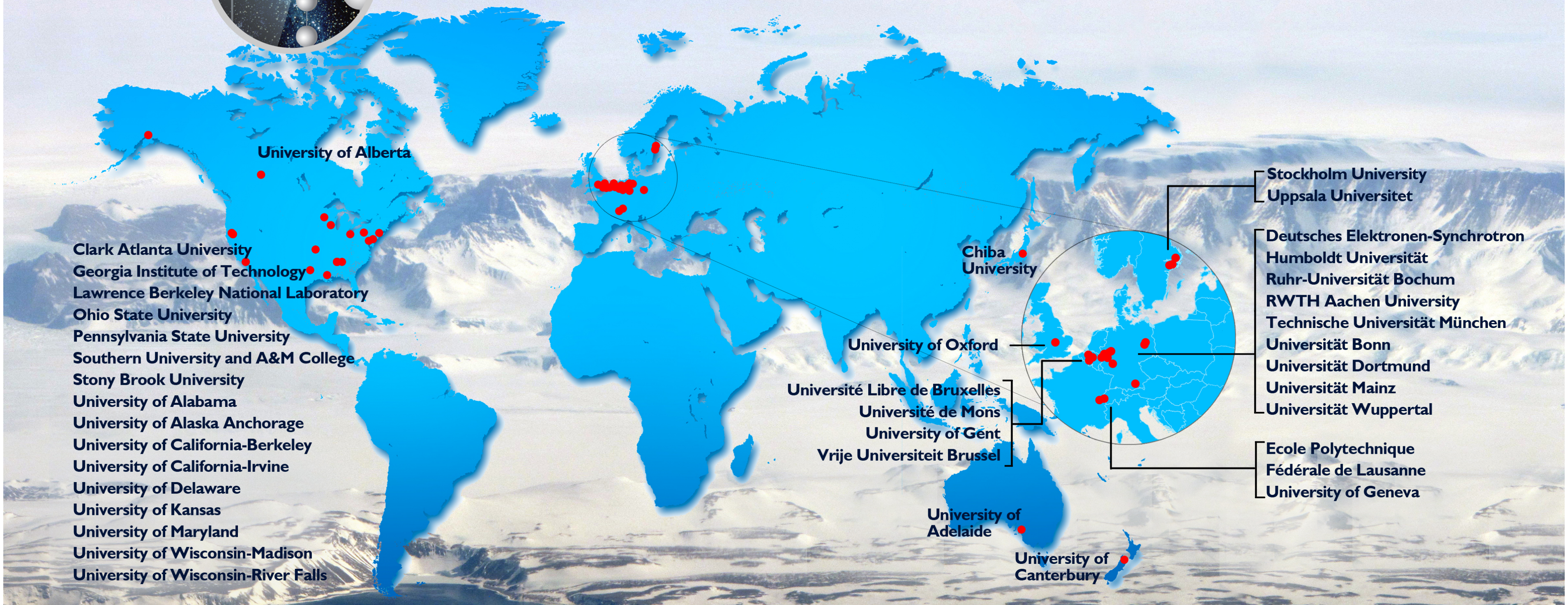
The IceCube Neutrino Observatory

- Total of 86 strings and 162 IceTop tanks;
- Full operation with all strings since May 2011.



A. Karle, UW-Madison

The IceCube Collaboration



International Funding Agencies

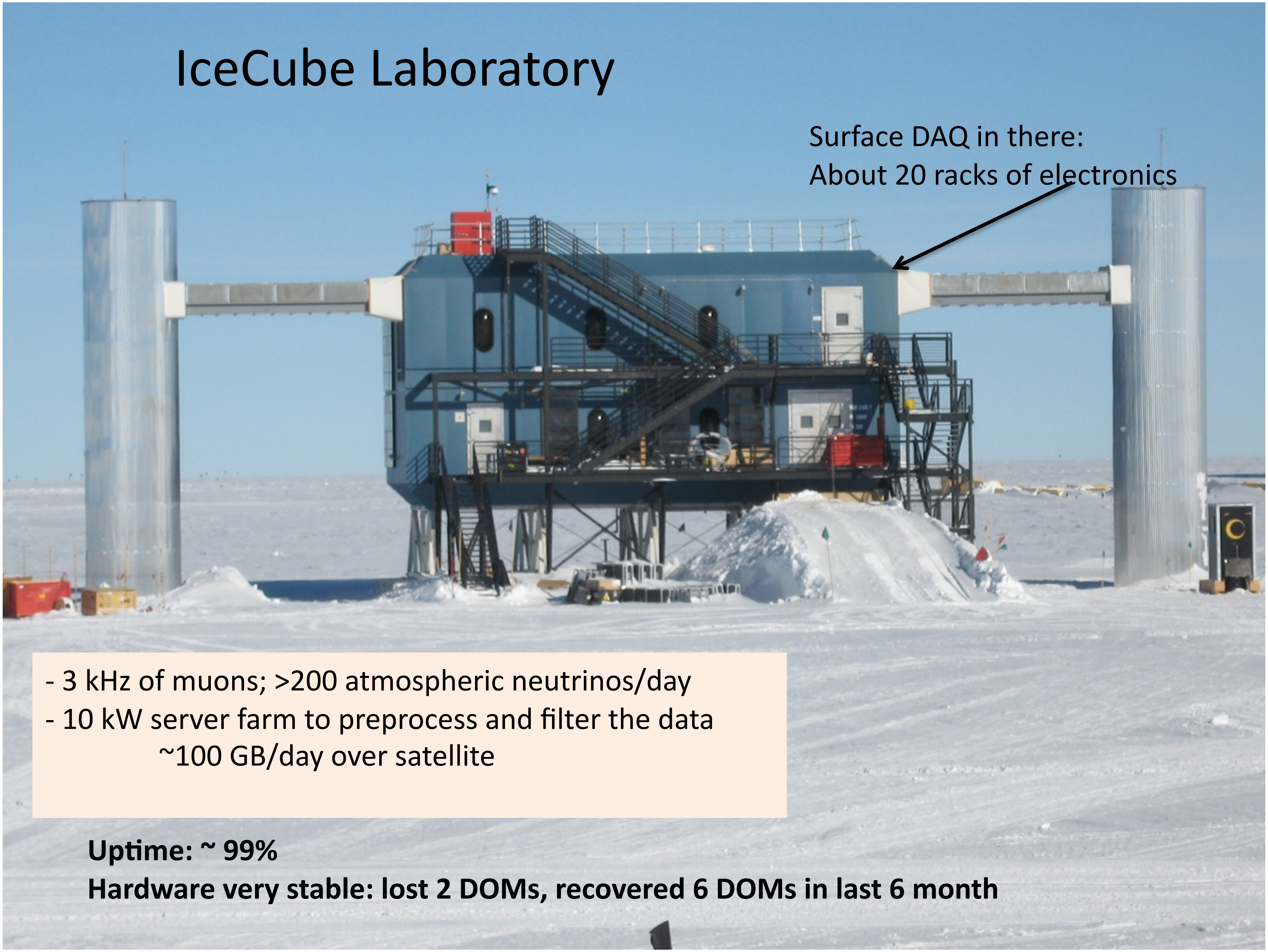
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)

Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)

Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

IceCube Laboratory



- 3 kHz of muons; >200 atmospheric neutrinos/day
- 10 kW server farm to preprocess and filter the data
  ~100 GB/day over satellite

Uptime: ~ 99%

Hardware very stable: lost 2 DOMs, recovered 6 DOMs in last 6 month

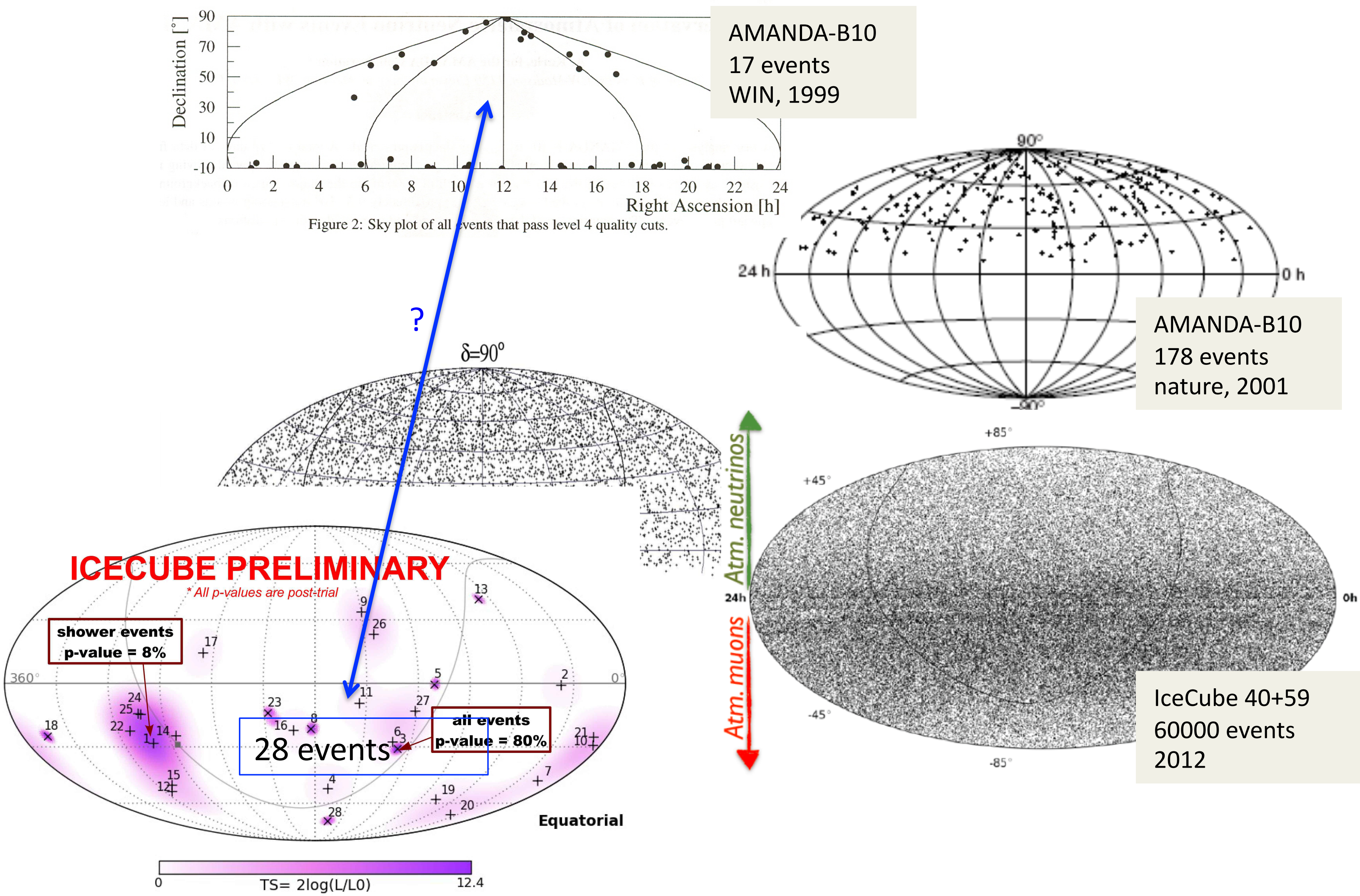
20 years of construction history of AMANDA and IceCube

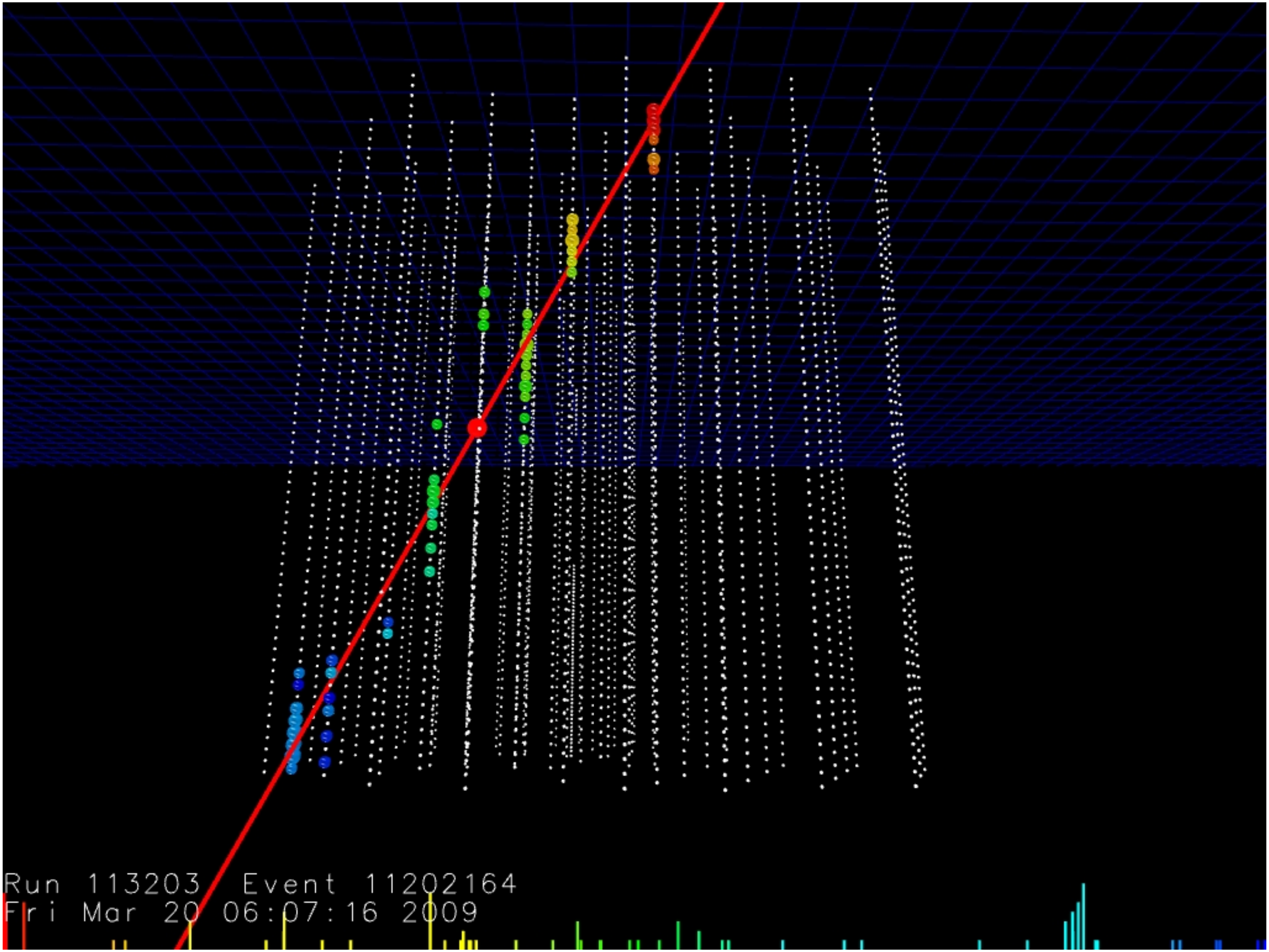
1991

2011

Season	Campaign	Sensors cum.	Strings	Depth (m)	Neutrinos per day	Resol. @100TeV
1991-1992	Exploratory	few		Shallow	-	
1992-1993						
1993-1994	AMANDA-A	80	4	800-1000	-	
1994-1995						
1995-1996	AMANDA-B4	86	4	1500-1950	~ 0.01	
1996-1997	AMANDA-B10	206	6/10	1500-1950	~ 1	4°
1997-1998						
1998-1999	AMANDA-II	306	3/13	1500-1950		
1999-2000	AMANDA-II	677	6/19	1500-1950	~ 5	2°
2001-2002						
2002-2003						
2003-2004	IceCube prep.					
2004-2005	IceCube 1	60	1/1	1450-2450		
2005-2006	IceCube 9	540	8/9	1450-2450		
2006-2007	IceCube 22	1320	13/22	1450-2450	18	1.5°
2007-2008	IceCube 40	2400	18/40	1450-2450	40	0.8°
2008-2009	IceCube 59	3540	19/59	1450-2450	120	0.6°
2009-2010	IceCube 79	4740	20/79	1450-2450	180	0.4°
2010-2011	IceCube 86	5160	7/86	1450-2450	>200	0.4°

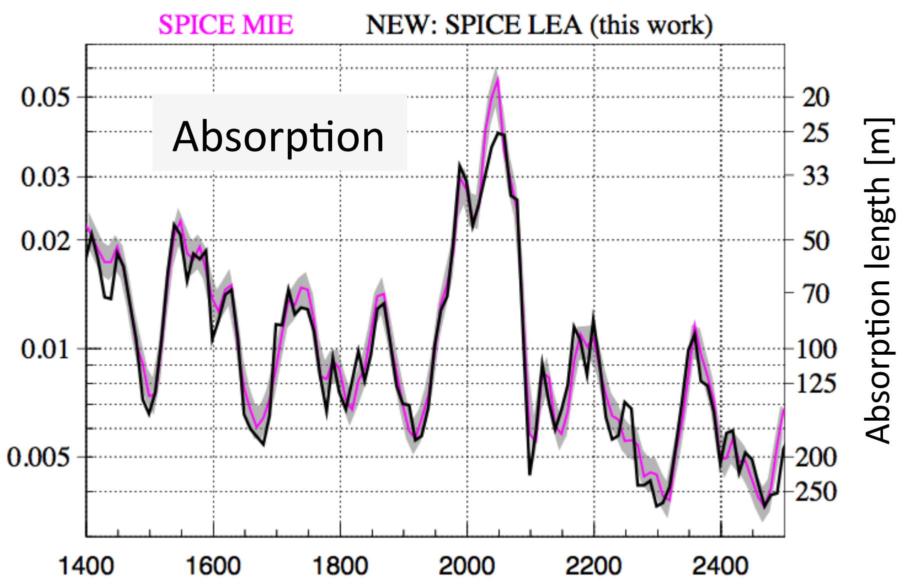
Neutrino Skymaps




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

Ice and detector response –
→ reduce systematic errors!

1. Vertical structure of ice parameters



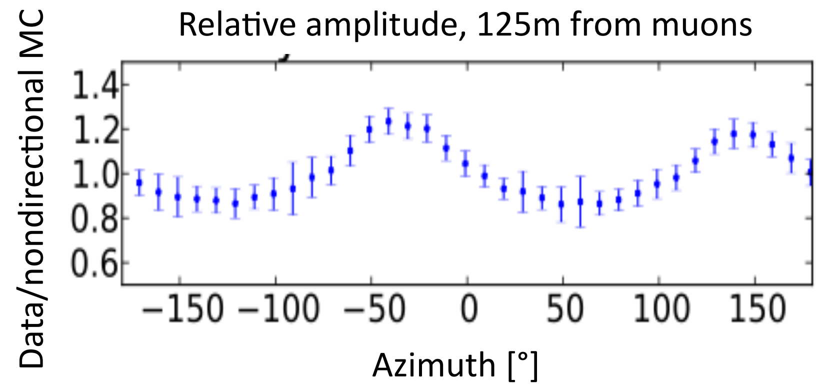
Scattering (eff.): 20 – 50 m
Absorption: 100 – 200 m

Measurement of South Pole ice transparency with the IceCube LED calibration system,

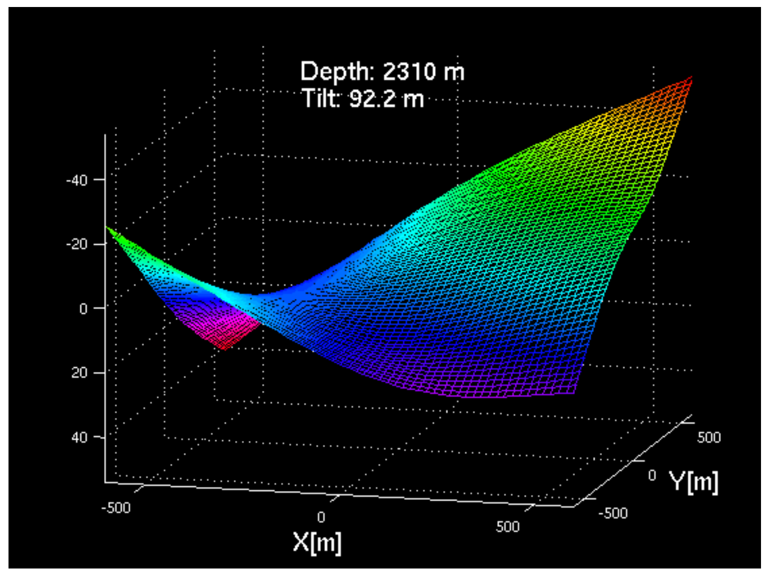
Aartsen et al., (IceCube Coll.), NIMA55353
http://arxiv.org/abs/1301.5361

2. Azimuthal variation in of scattering

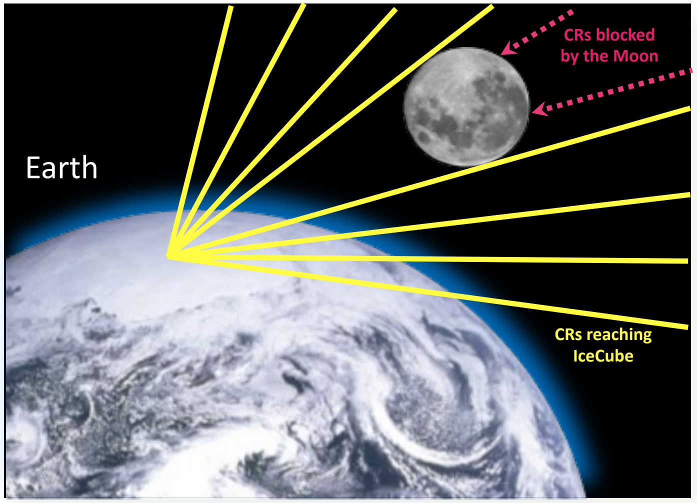
Less scattering in direction of ice flow:
→ up to ~10% /100m variation in amplitude



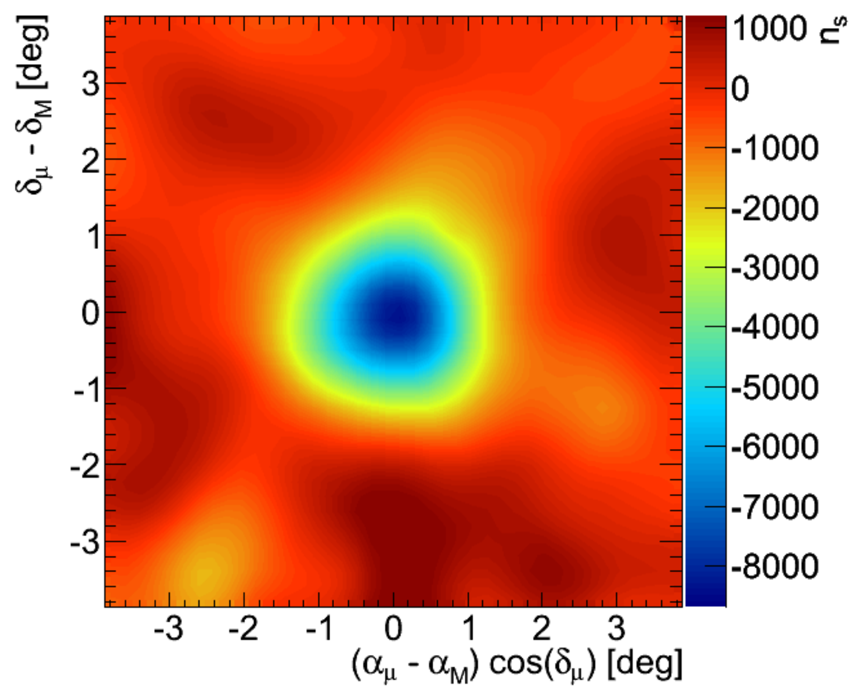
3. Ice layers are tilted – not planar



Moon shadow



- Moon blocks cosmic rays coming from its direction.
  → deficit of muons from direction of moon.



Deficit: ~ 8700 events
Significance: **13.9σ**

Observed shadow exactly matches expectations
on pointing (<0.1°) and angular resolution (0.7° for these events).

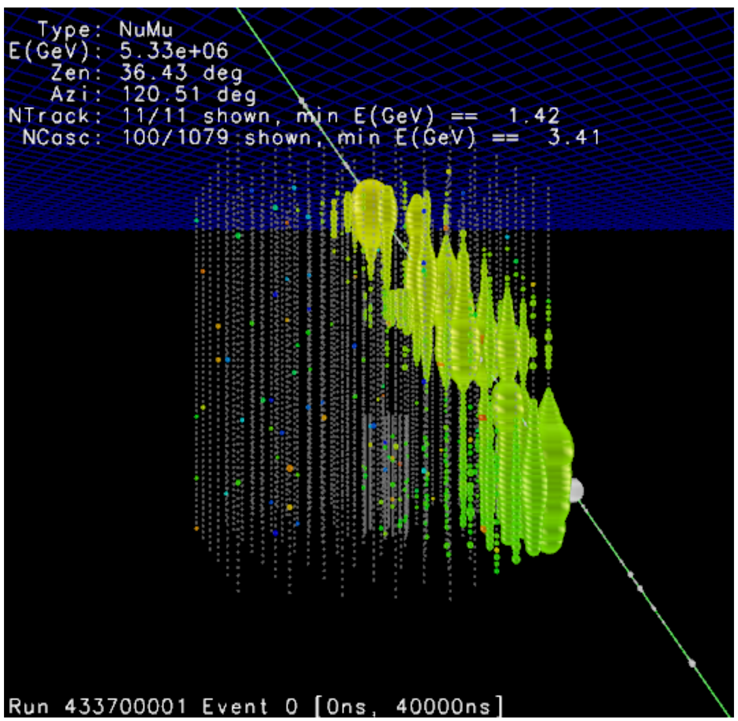
Improving event reconstruction: muons

Simulated Muon of 5 PeV energy

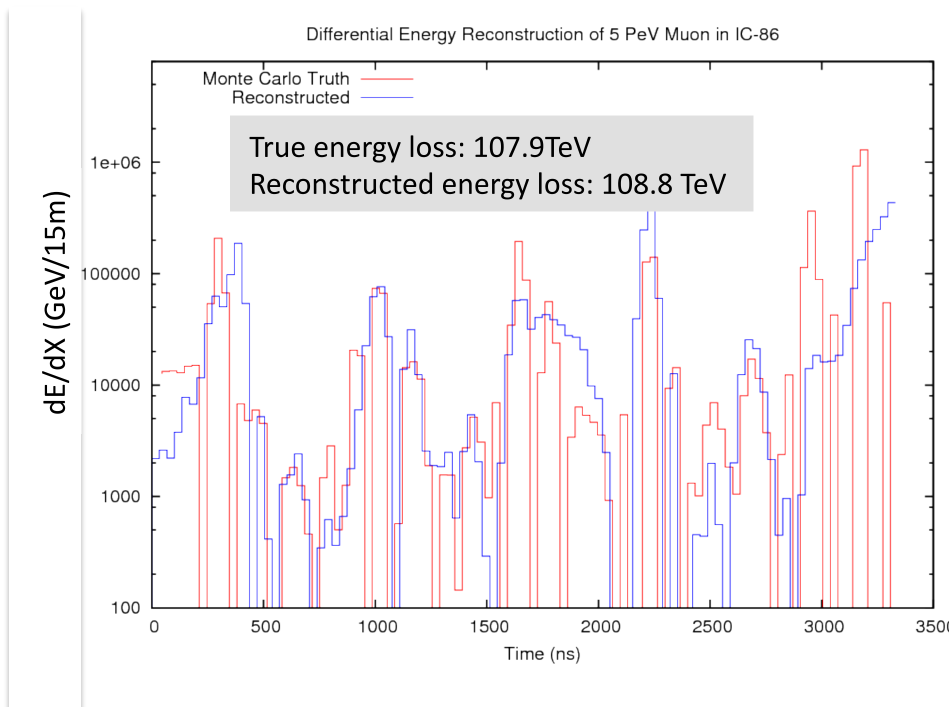
Improved tools allow to resolve stochastic energy losses along the km long tracks.

Muon energy resolution:
rms of log(E): ~0.3 - 0.25 for E>100 TeV

Limited by fluctuations in energy deposition.



Time (ns)

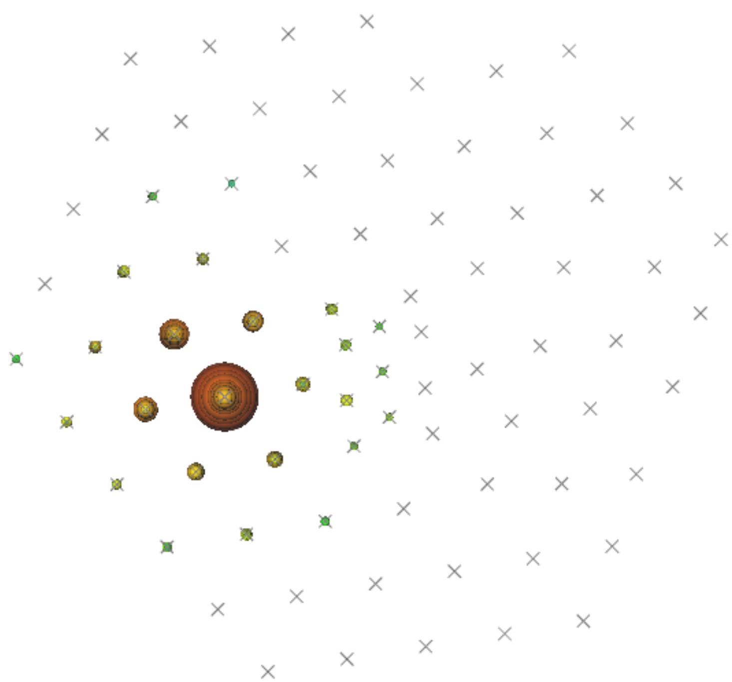


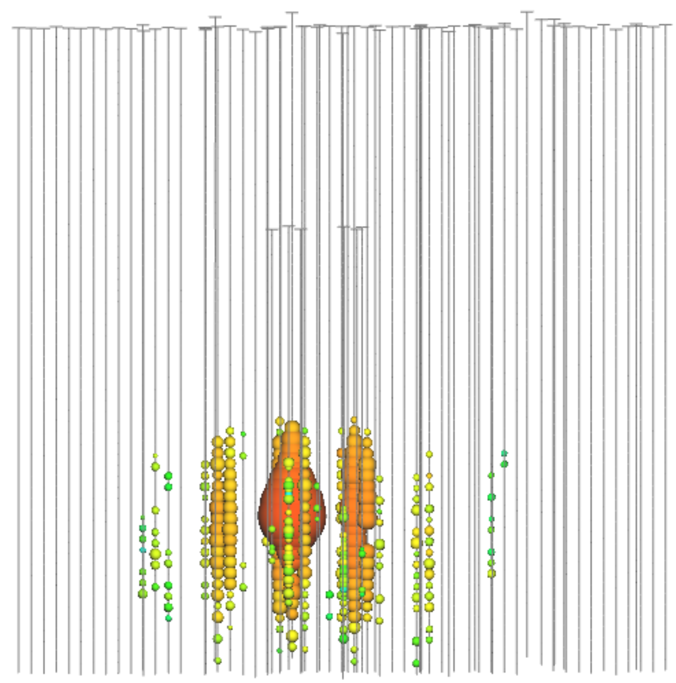
Improving event reconstruction: cascades

Resolution at E ≳ 100 TeV:

≈ ±15% deposited energy
(incl. all sys. errors)

≈ 10° angular resolution





Tau neutrinos

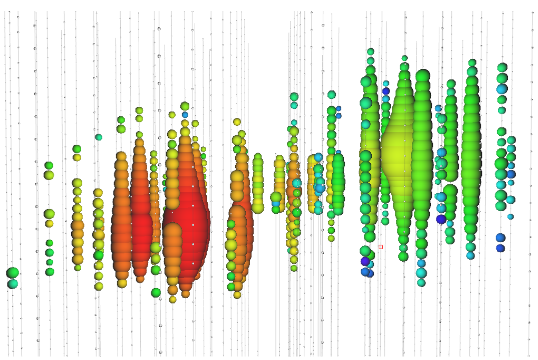
Charged Current tau neutrino:

$$\nu_\tau + N \rightarrow \tau + X$$

Double-bang signature from decaying tau, $l_\tau = \gamma c t_\tau \sim 50\ (E_\tau\ /\mathrm{PeV})\ \mathrm{m}$

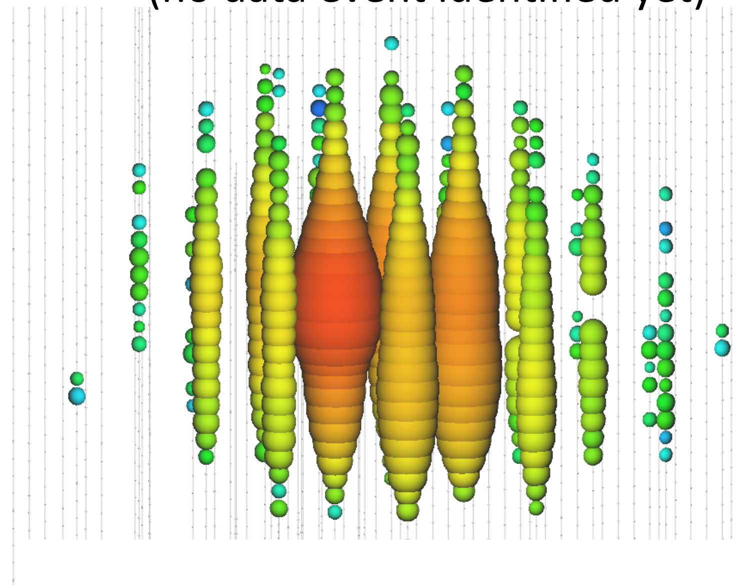
Can identify double bang above ~ PeV

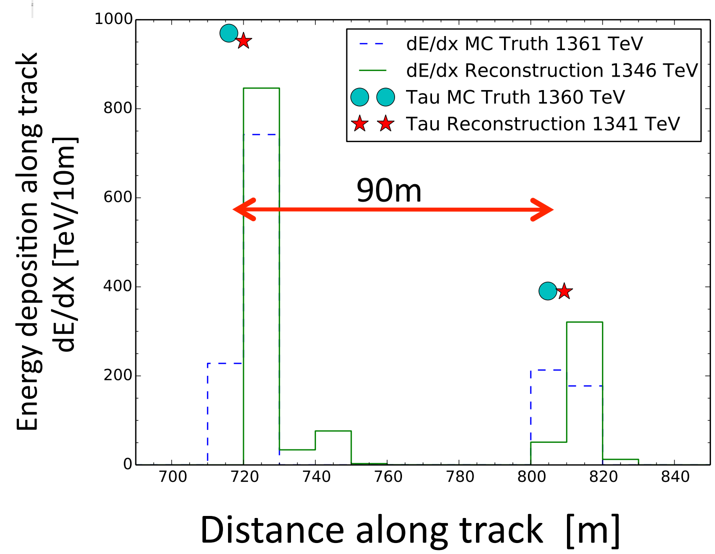
Lower energy id more limited possibilities.



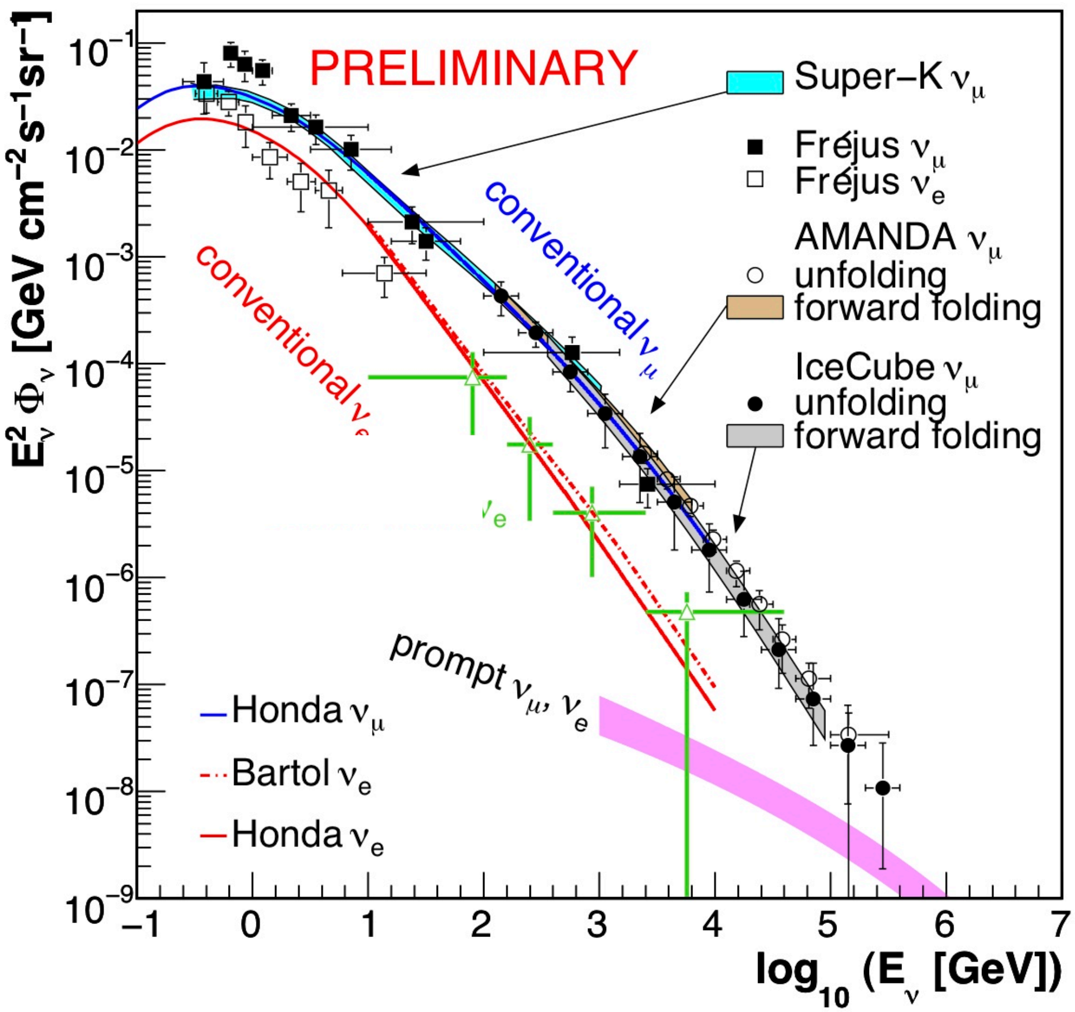
Event with ~400m decay length

Simulated event: 1.36 PeV
(no data event identified yet)





Atmospheric Neutrinos



Very large neutrino sample: > 50k events per year of purity,

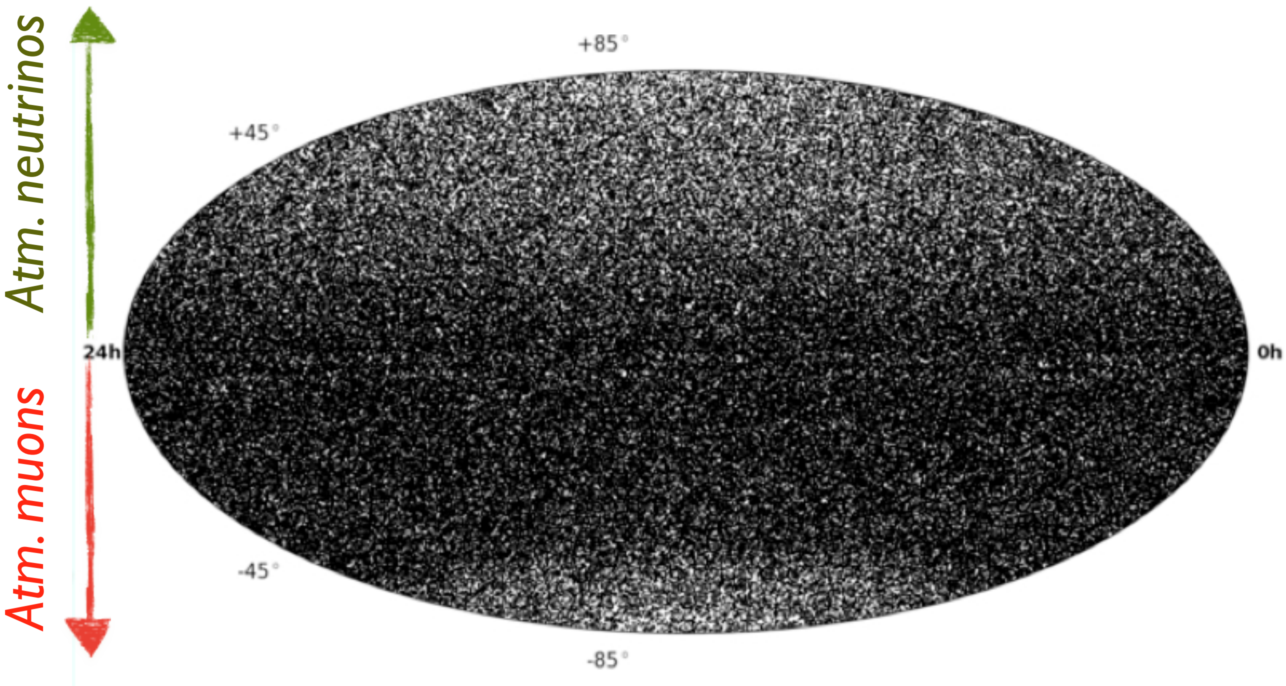
Muon neutrinos into 100's of TeV

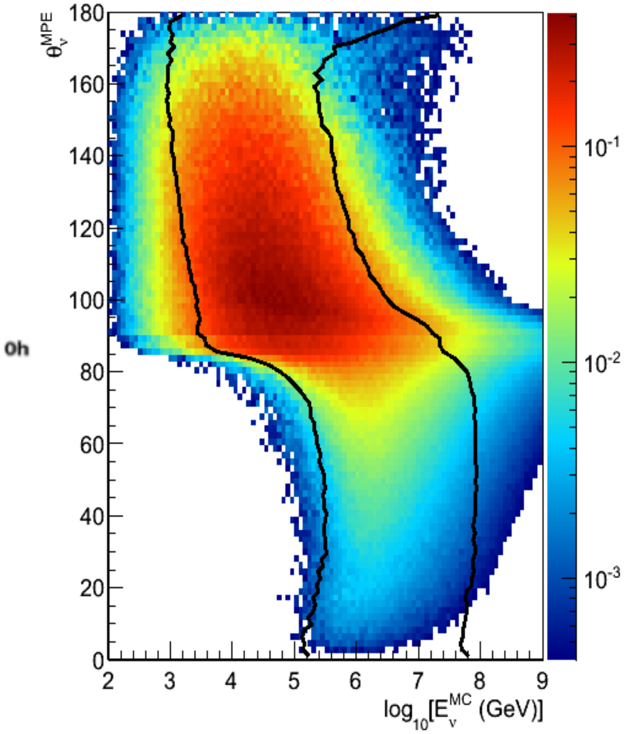
Electron neutrinos up to TeV energies

arXiv:1212.4760

Targeted multiflavor analysis under way to determine prompt neutrino flux.
(see: J.v. Santen at TAUP)

Point Source Search





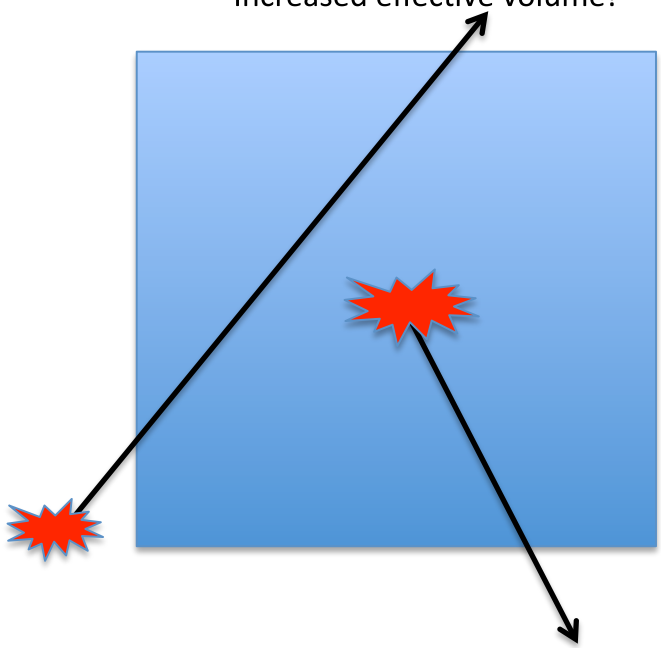
- *Total events (IC40+IC59+IC79+IC86-1): 394000 events*

  178k neutrino candidates in North, 216k atmospheric muons in South
- *Livetime:* 1371 days

See talk by J. Feintzeig

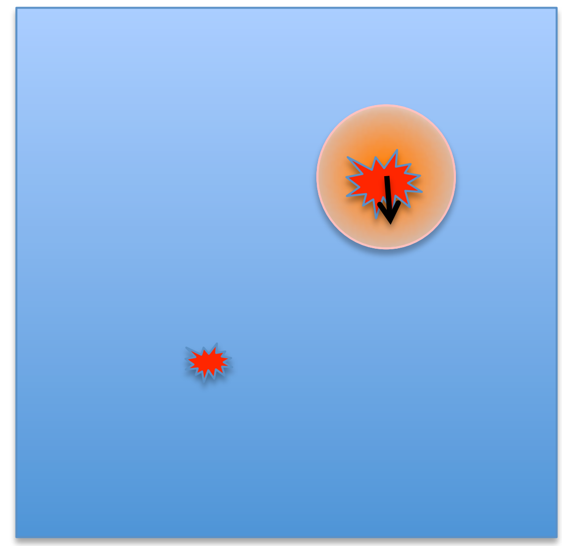
Event types – search strategies

- **Throughgoing muons** –
  - the workhorse for neutrino astronomy, good angular resolution
  - Vertex can be far outside the detector. Increased effective volume!



- Starting tracks: downgoing neutrino astronomy (reject background of throughgoing cosmic ray muons AND possibly atmospheric neutrinos)

- **Cascade events:**
  - ν_e, ν_τ **and neutral current**
  - High energy resolution (fully active calorimeter, all energy gets deposited in the detection volume)
  - Angular reconstruction above ~50TeV

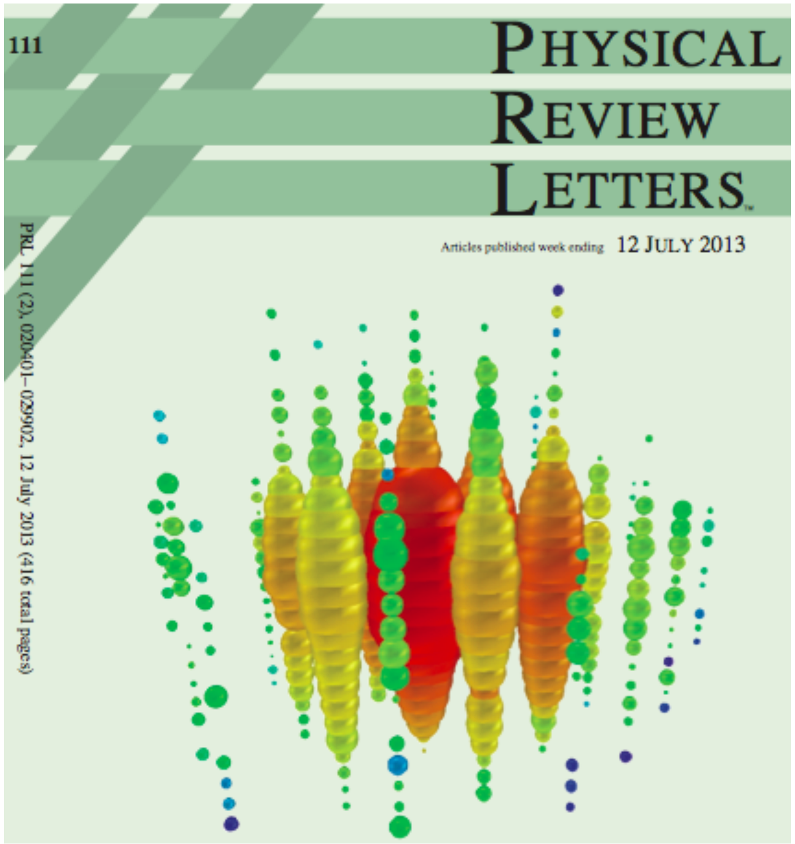


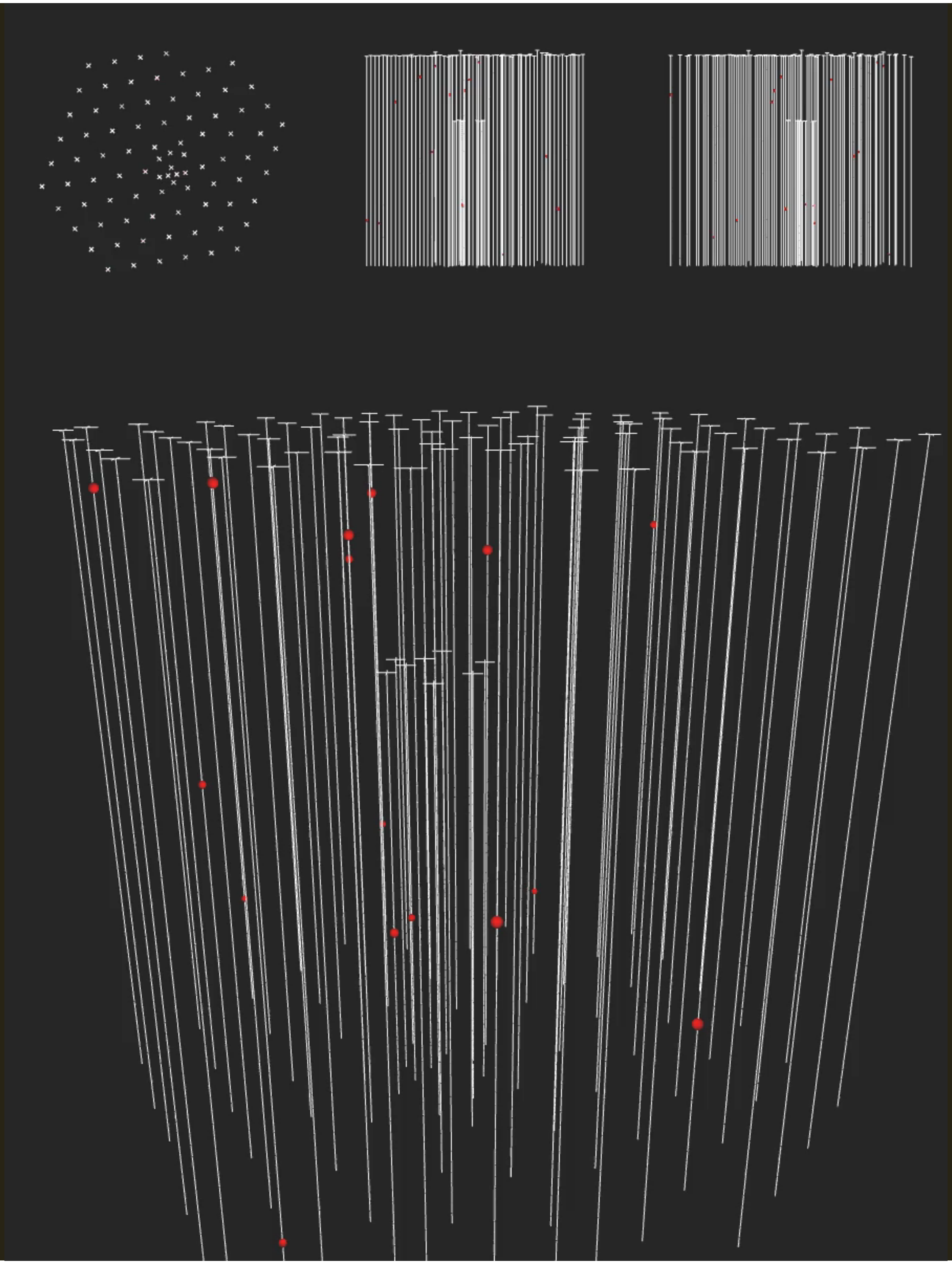
Bert and Ernie
Two gold plated events found at PeV energies

Events were found in GZK search in 2 year data set just above threshold.

→ Not GZK

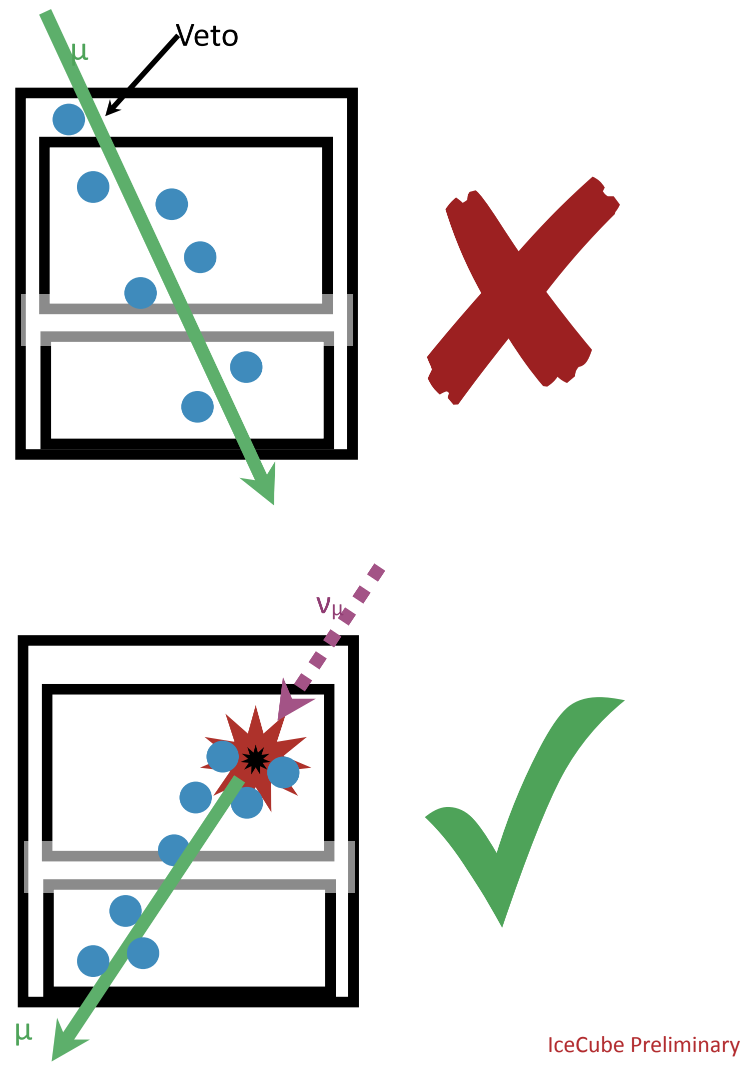
Significance above background: 2.8 sigma





Targeted High Energy Starting Event (HESE) search leads to evidence for an astrophysical neutrino flux

Related talks at this meeting by
Tom Gaisser, Nathan Whithorn, Claudio Kopper and
Jake Feintzeig.

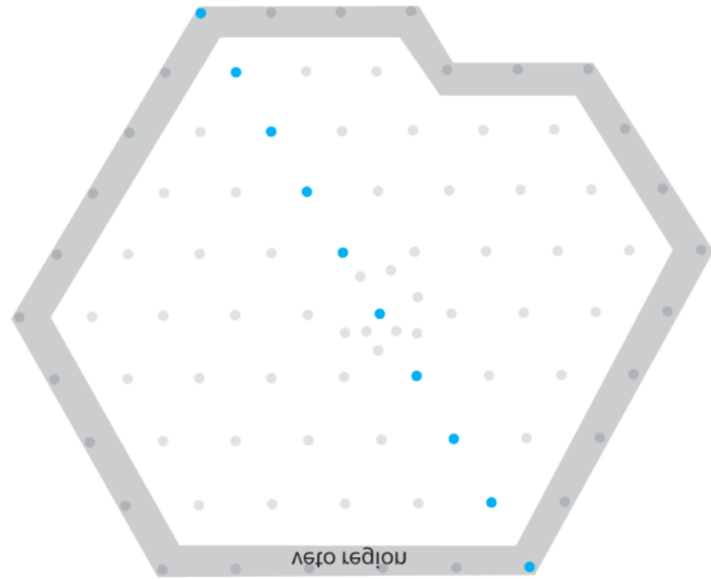


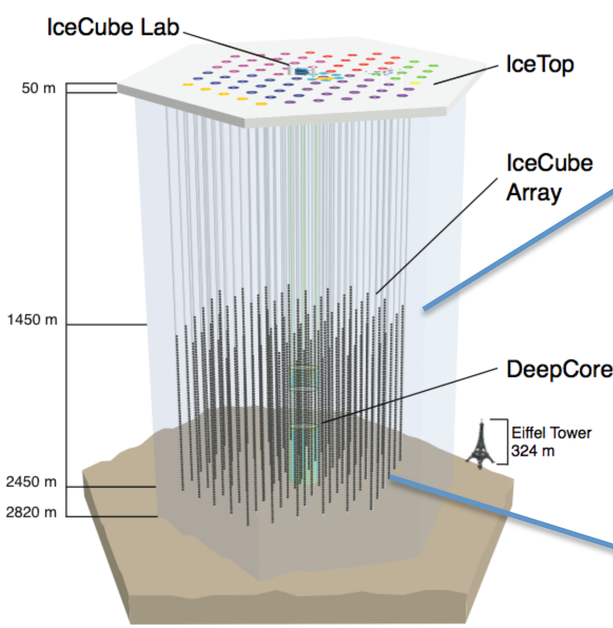
- Search for events with contained vertex – starting tracks - at high energies (cut: Q_{tot}>6000)
- Threshold: ~ 60 TeV
- Veto of downgoing atmospheric muons AND neutrinos
- Estimate background from data

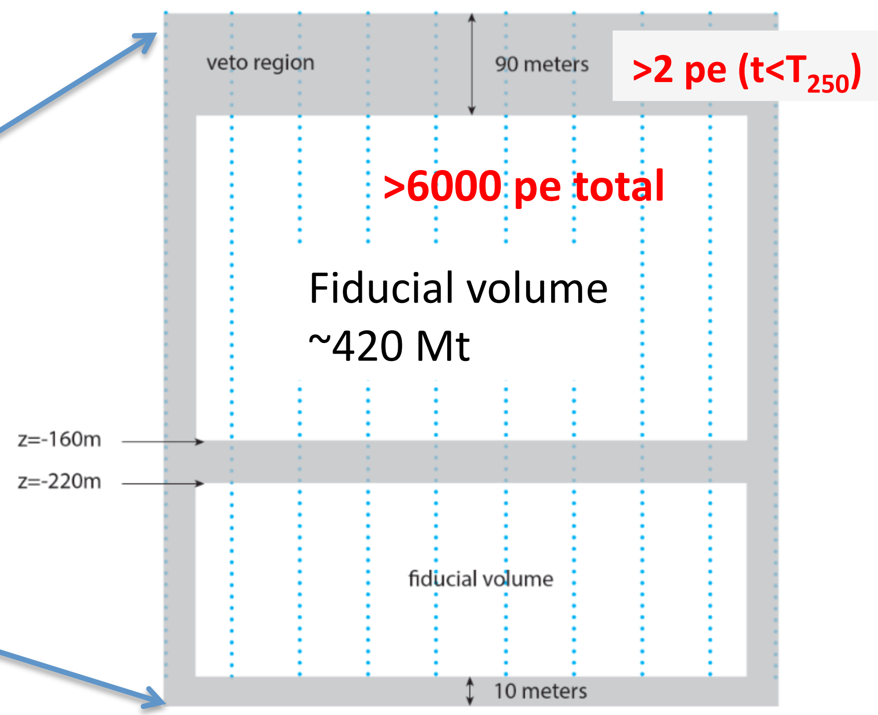
Veto region

The PMT signals of all PMTs
in the veto region are treated as Veto signals:
~2400 DOMs
Contained vertex events: "First light is in fiducial region"

Amongst the first 250 photoelectrons of an event, not more than 3.0 photoelectrons are allowed in the veto region.

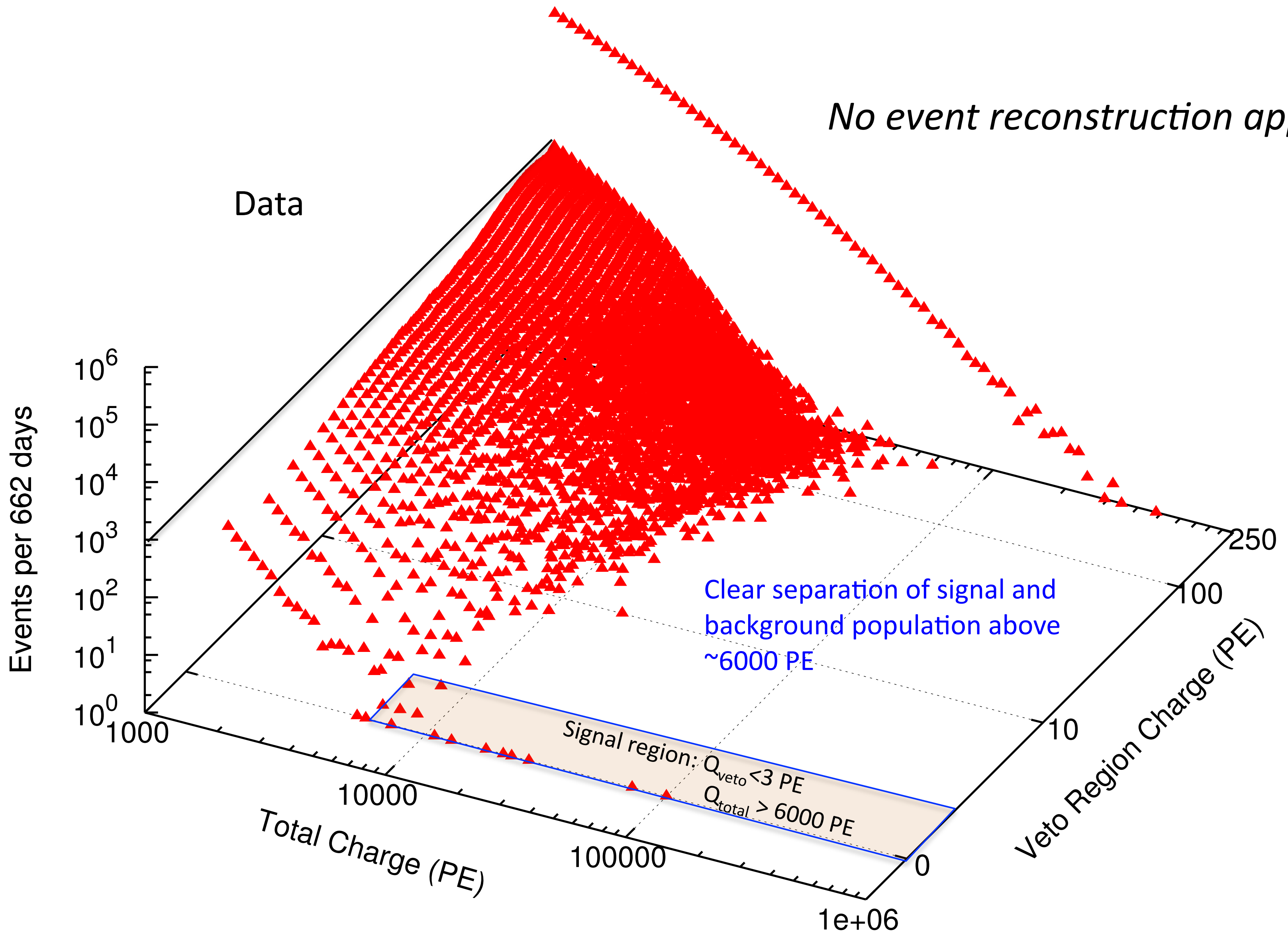






Event selection:
Compare total charge with charge in veto region

No event reconstruction applied.

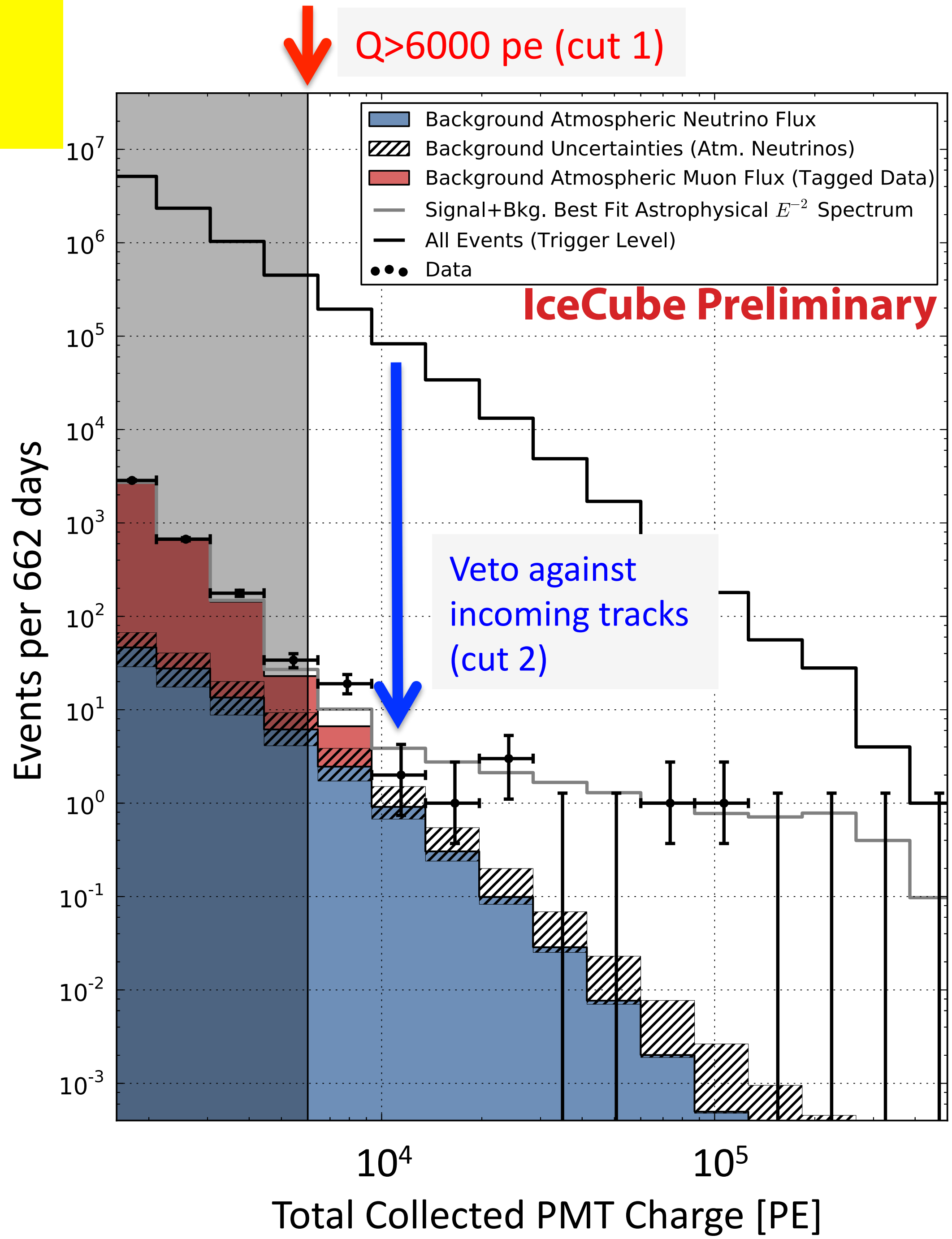


Energy distribution using total deposited charge.

After cut on total charge and application of veto:
28 events

(2 of them the original 2 PeV events reported earlier)

- Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Q_{tot}>6000)
- Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)

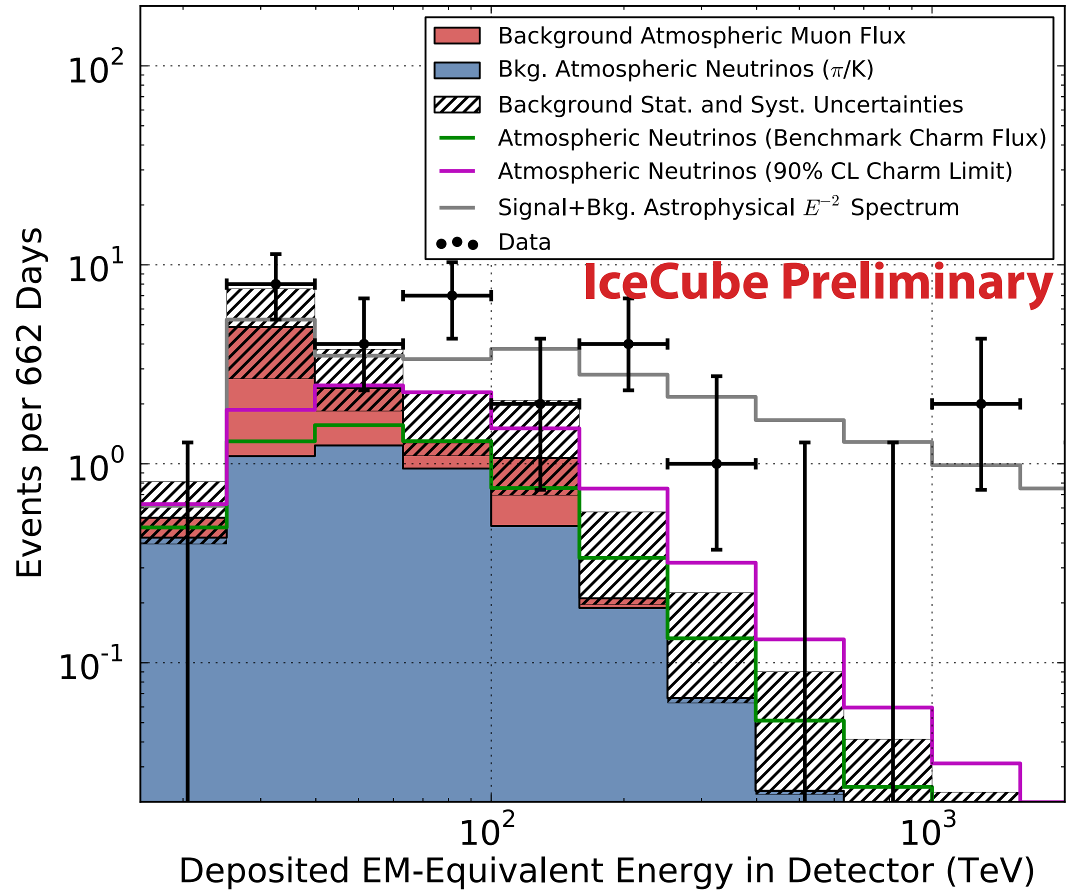


Energy distribution

- Harder than any expected atmospheric background
- Potential cutoff at about 2-5 PeV
  - at 1.6 (+1.5-0.4) PeV when fitting a hard cutoff
- Best fit (normalized to single flavor):

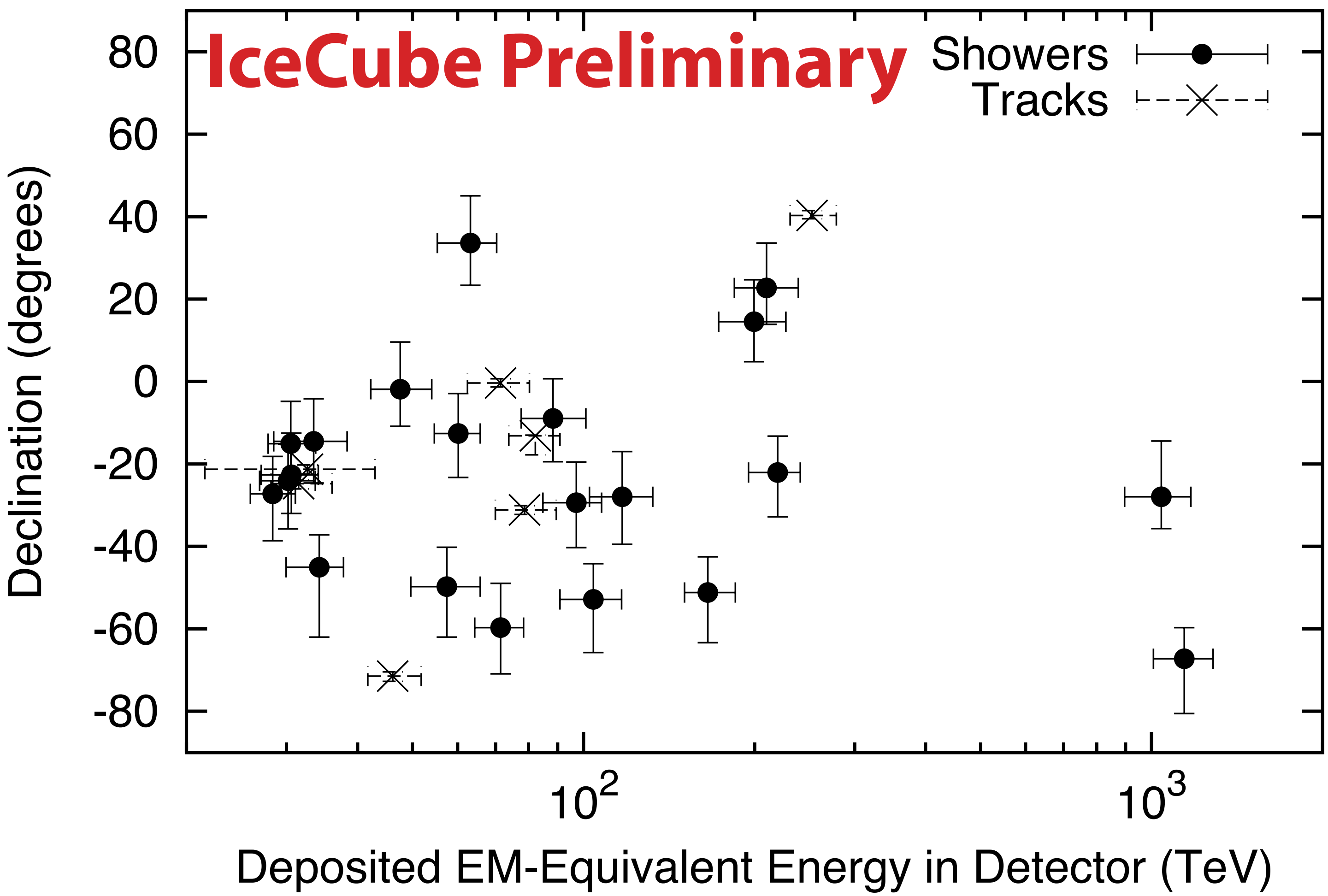
  $1.2 \pm 0.4 \times 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

- Inconsistent at 4 σ level with standard atmospheric backgrounds, astrophysical origin most compatible explanation, but no clear picture.



Note that the energy scale is the ***deposited energy****.*
Muons will carry away some energy.
Electron and tau neutrinos deposit ~all energy.

Declination vs energy

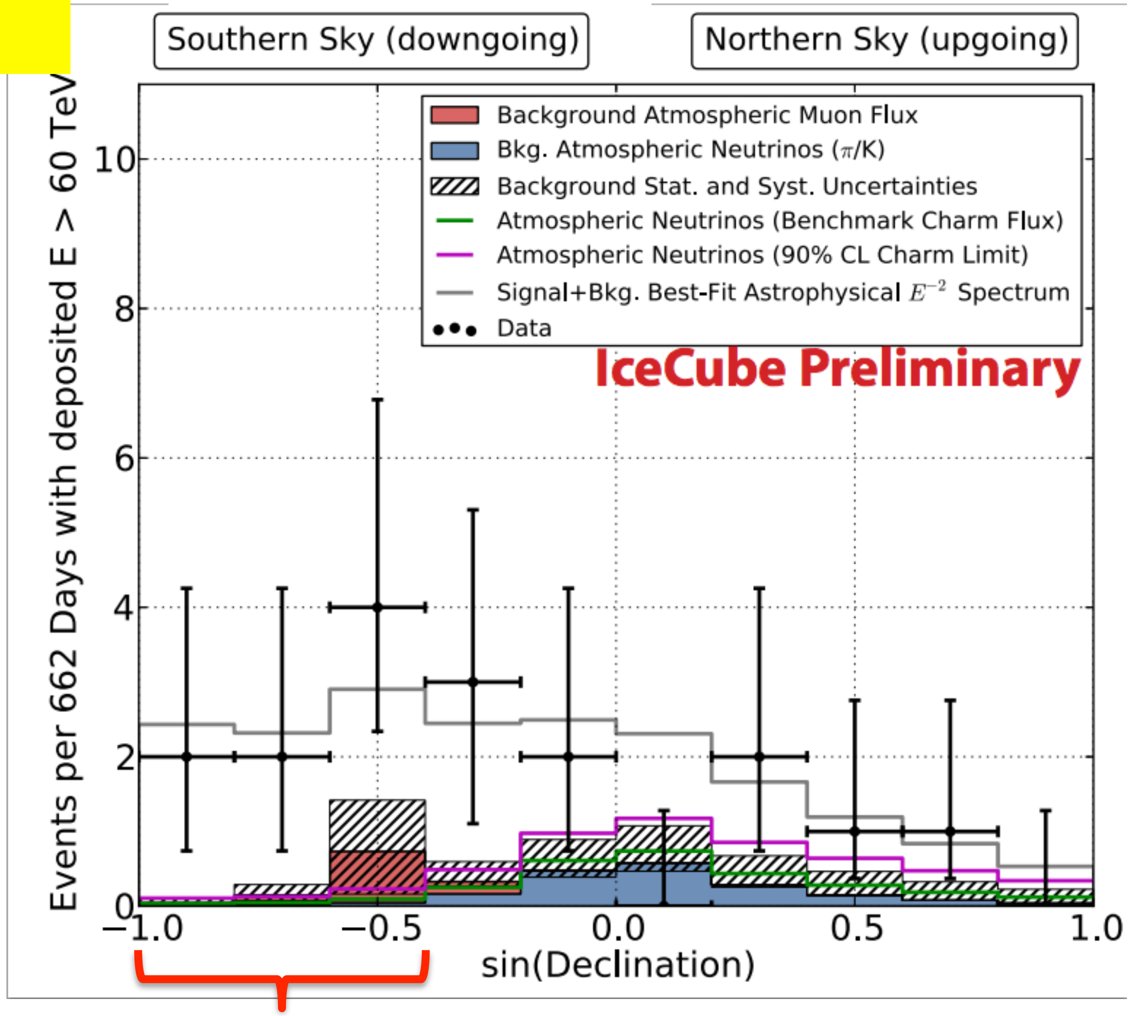


Most events in Southern hemisphere (downgoing).

Zenith angle, declination distribution

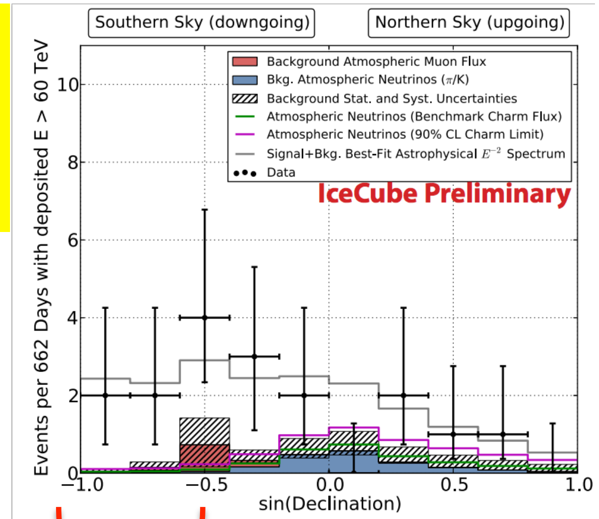
- Angular distribution does not fit atmospheric.
- Compatible with isotropic flux
- Absorption matters for upgoing events at higher energies

Deposited energy > 60 TeV



Very low background of downgoing atmospheric neutrinos due to veto.

Background free neutrino astronomy?

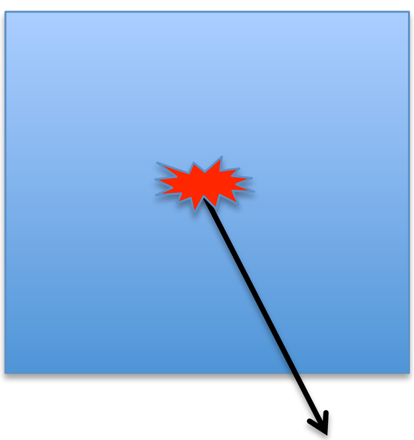


- Reject some of higher energy atmospheric neutrino background
- Downgoing energetic neutrinos with
  - E>100 TeV
  - zenith angle less then 50°

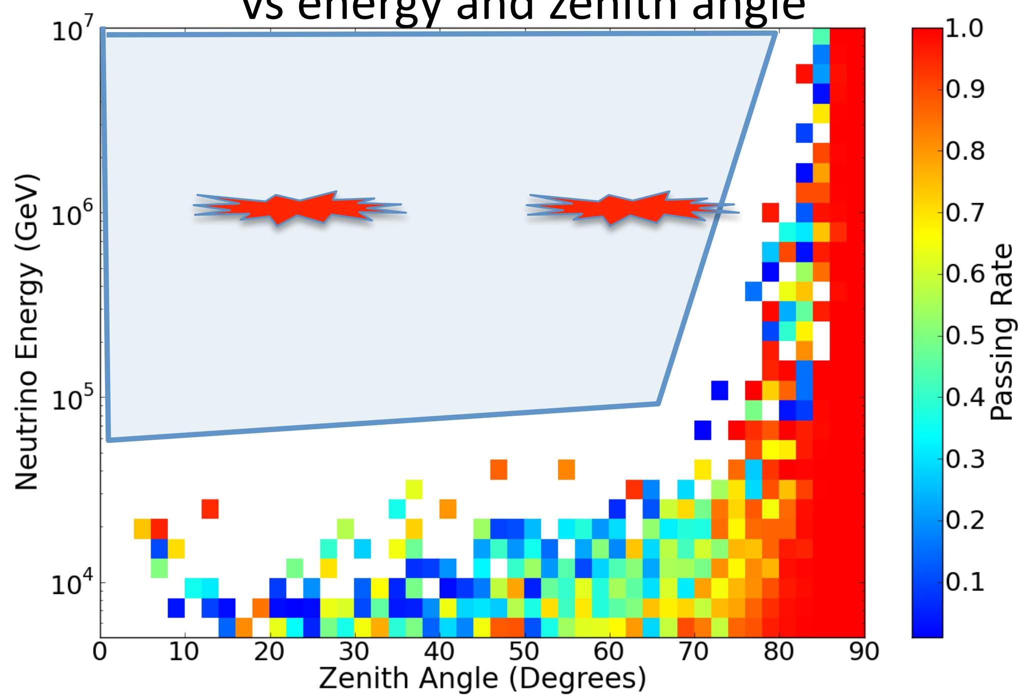
  will likely be accompanied by muons from the same air shower.

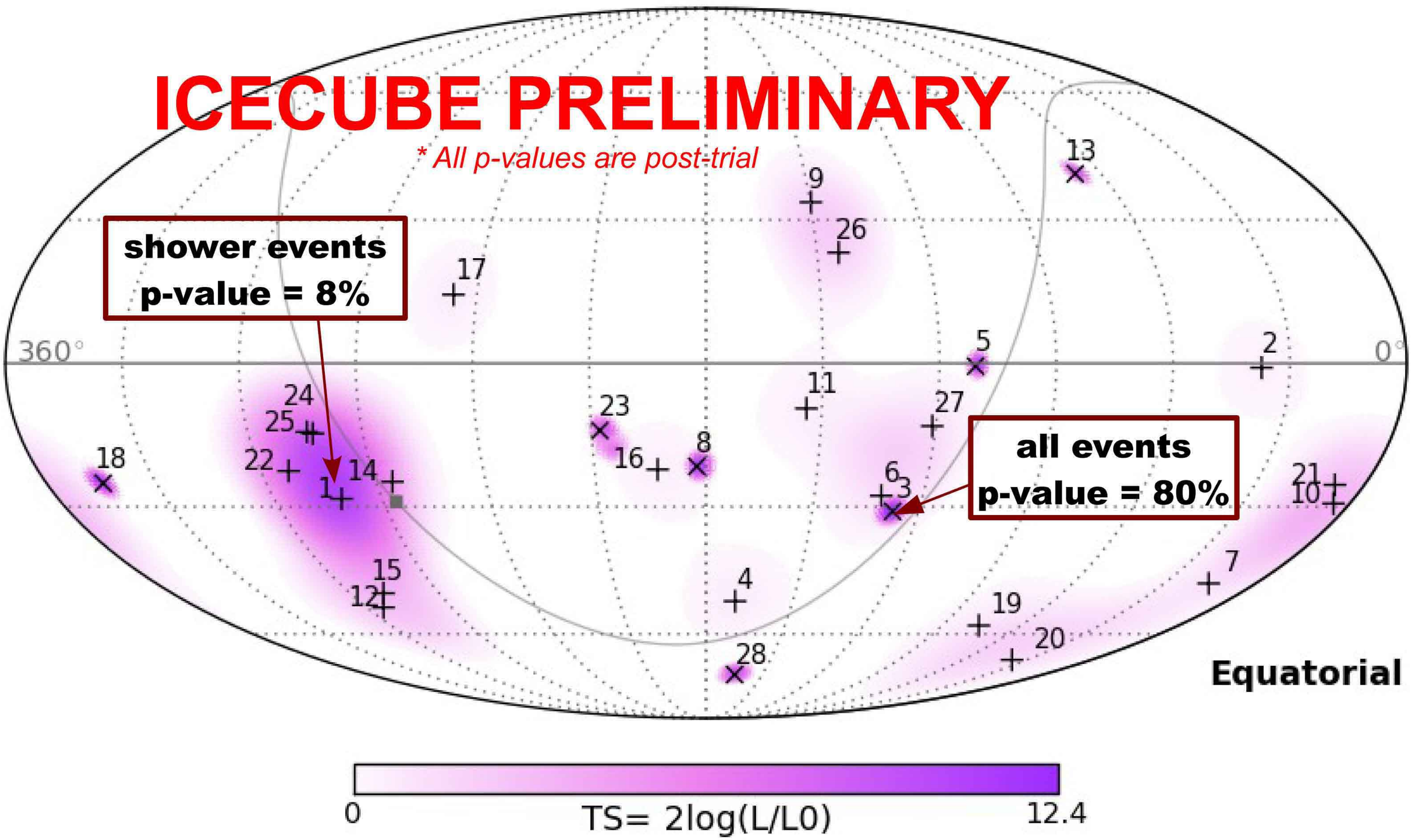
→ A starting neutrino in that region unlikely to be atmospheric.

→ Tom Gaisser's talk



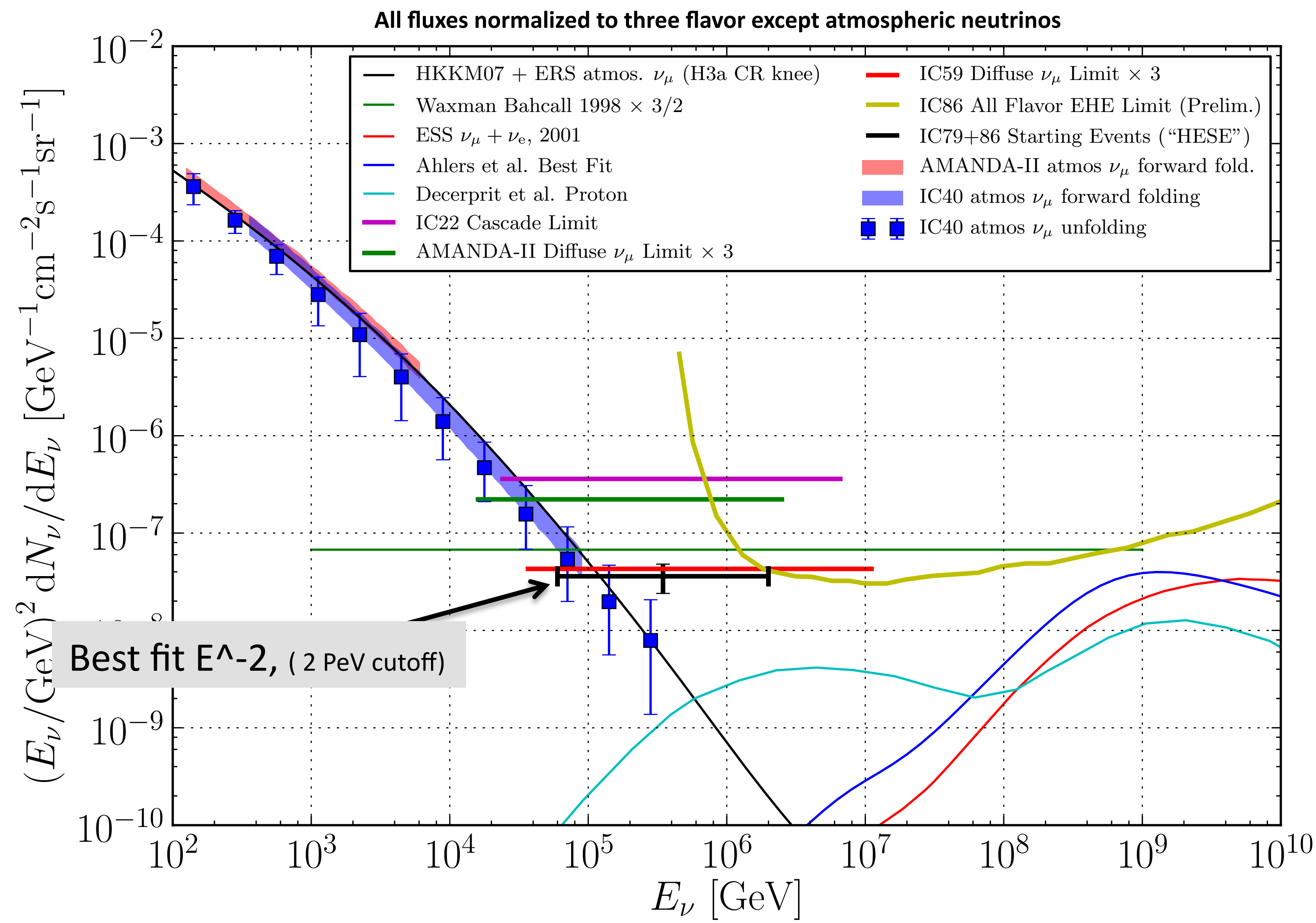
Veto probability vs energy and zenith angle





→ *No significant clustering of events that would be indicator of a point source.*

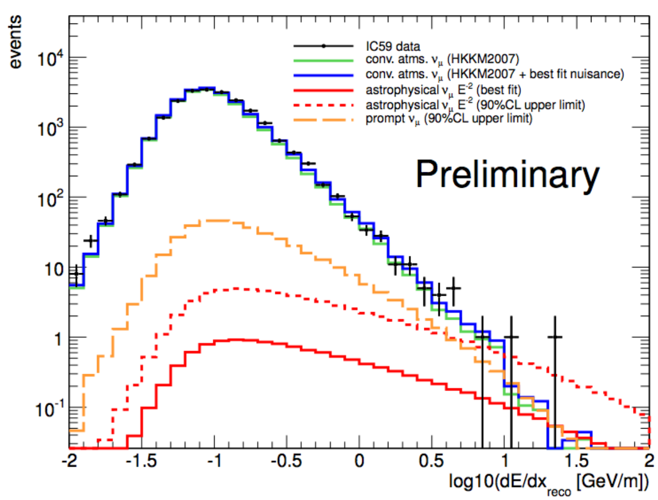
Neutrino fluxes – Limits, sensitivities of detectors



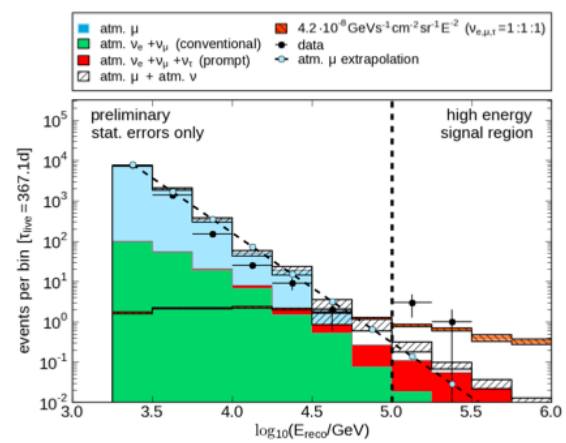
Other channels

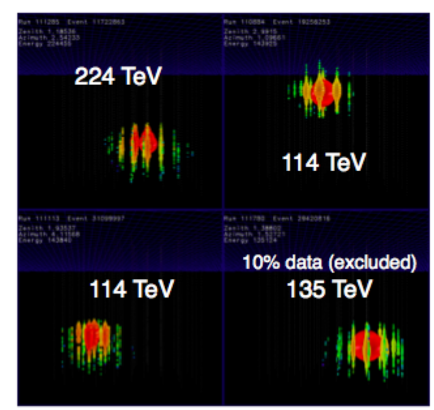
1. ν_μ signal: for upward going tracks (zenith>85°)
   - IC 40 (40 strings) published [Phys. Rev. D 84, 082001 (2011) **arXiv: 1104.5187v5], → upper limit**
   - Results from IC 59 search: → upper limit (2sigma tension to zero astrophys.)
2. Cascade search
   – Cascade only events, contained, 2 sigma level tension to zero astrophysical

Consistent with observed flux level

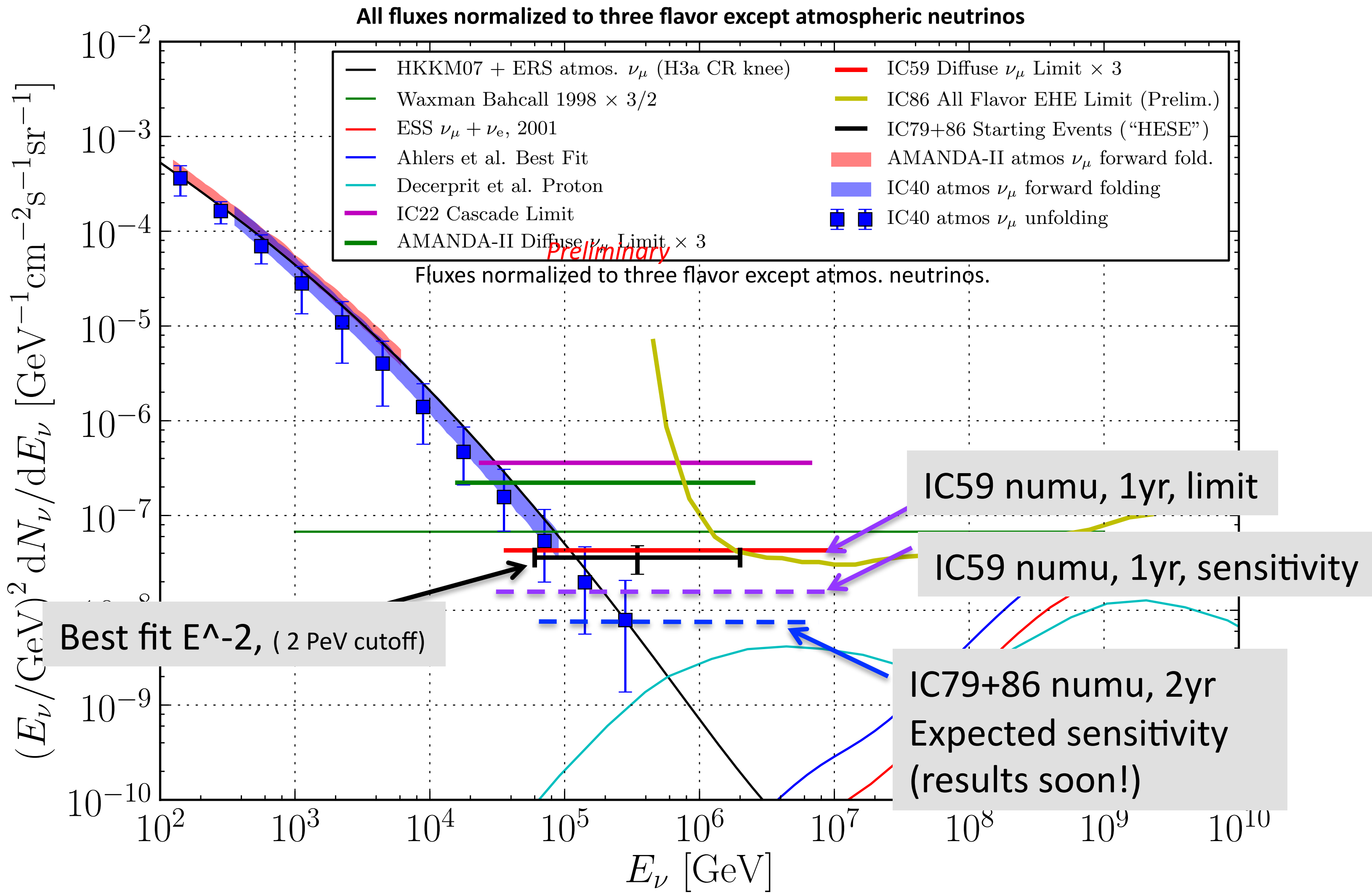


arXiv:1302.0127





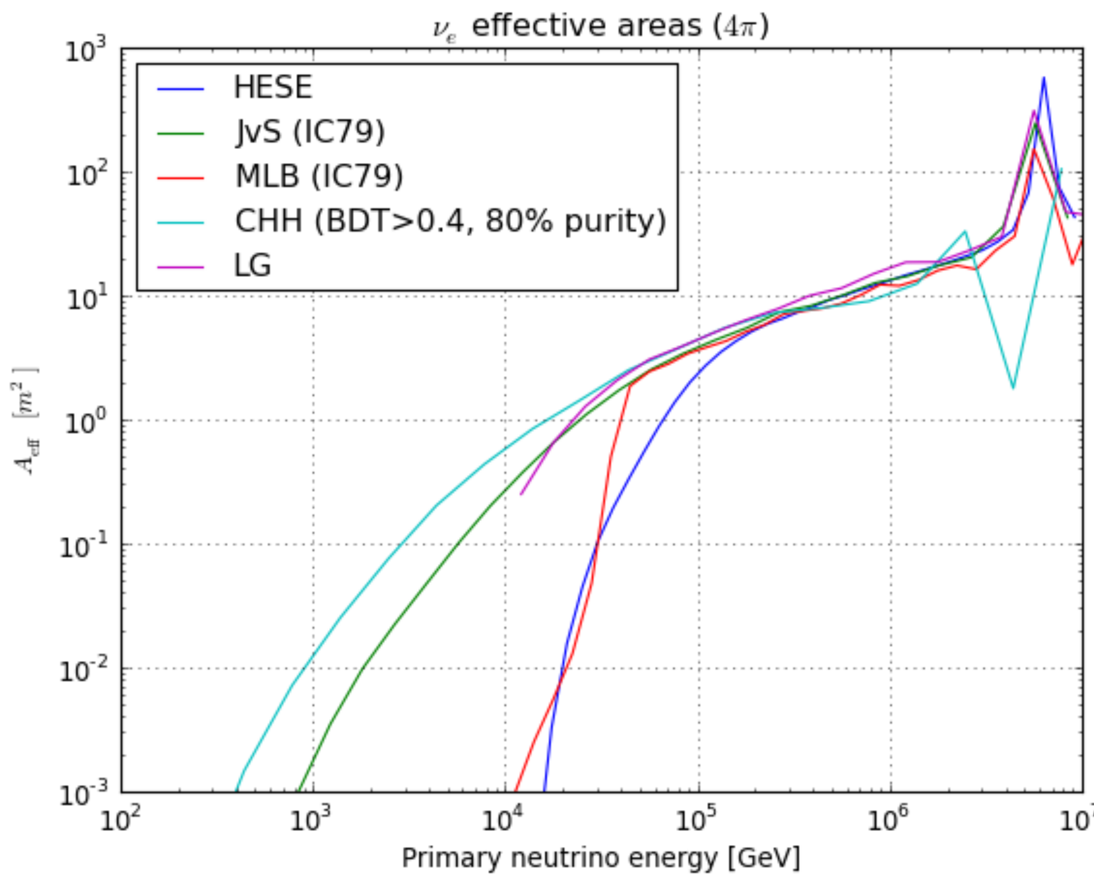
How do the searches for a diffuse muon neutrino flux fit in?

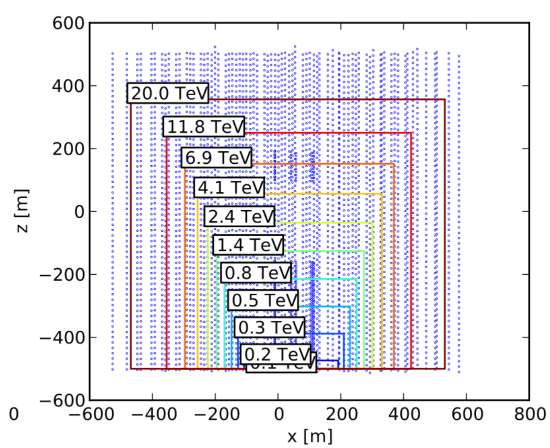


Future of veto strategies for contained vertex analyses

- Veto application for contained vertex are becoming powerful at
  - high energies (>100 TeV)
  - Low energies 10 – 100 GeV (Deep Core)

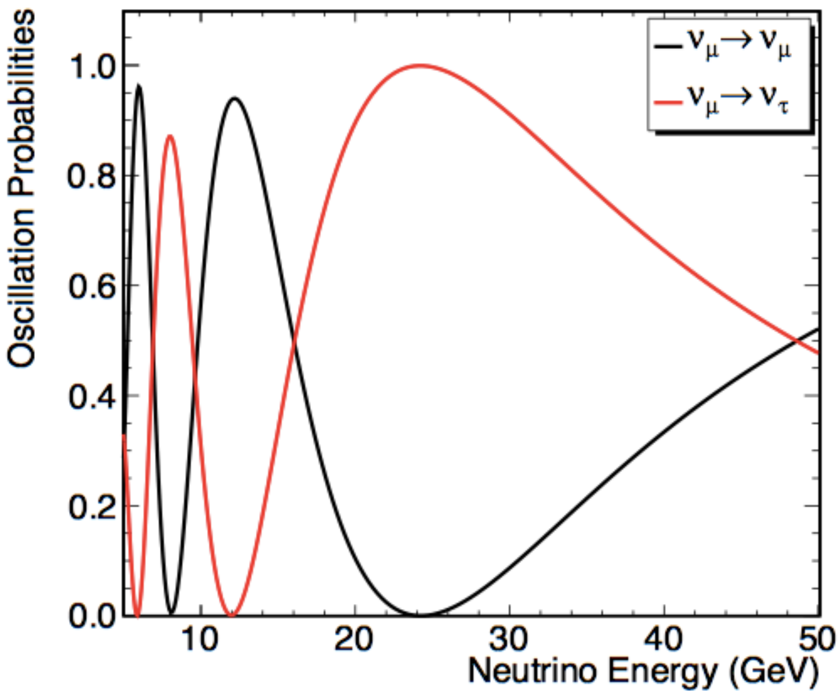
  Goal: close gap!

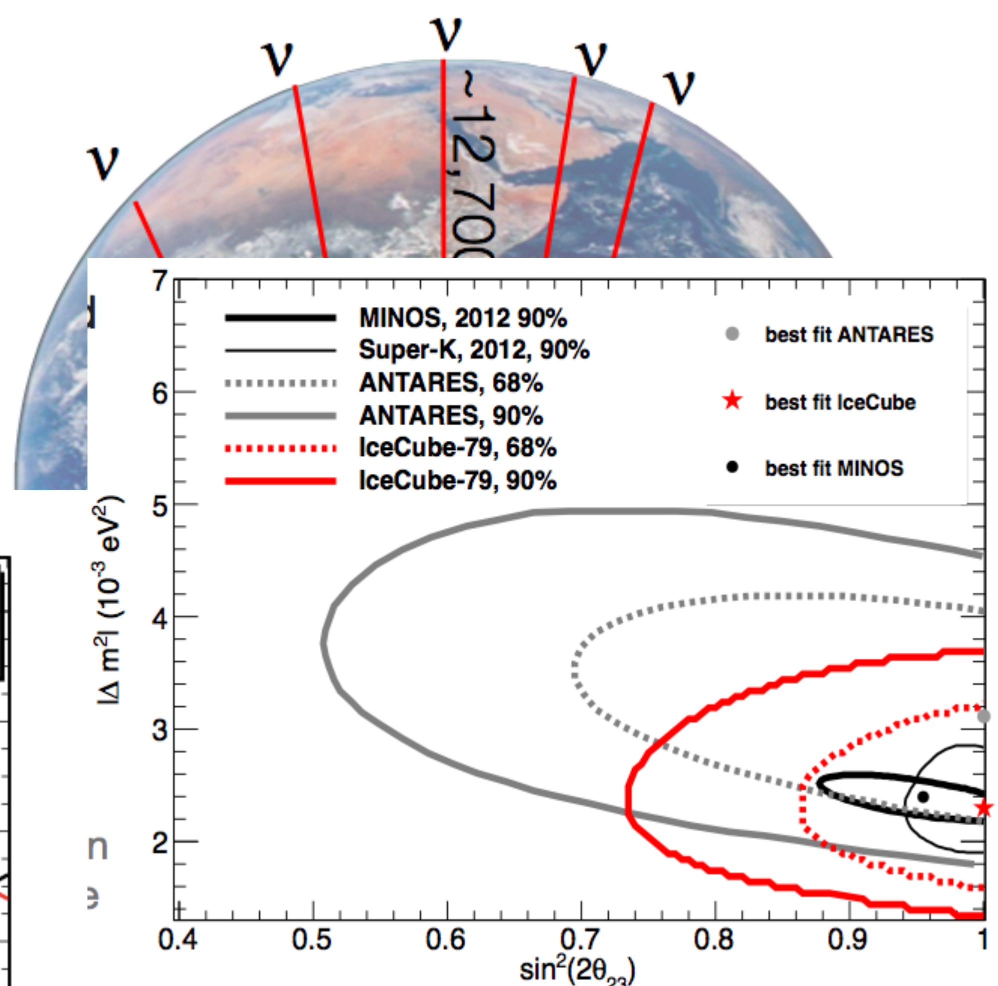




Neutrino oscillation analysis with IceCube-DeepCore

- First oscillation maximum around 24 GeV, i.e. DeepCore energies
- Hierarchy-dependent matter effects below 10 GeV – too low for DeepCore





arXiv:1305.3909 (accepted PRL)

Summary

- Evidence for high energy extraterrestrial neutrinos, no evidence for clustering. - publication very soon.
- Indication in other analysis channels for hard component in neutrino flux, possible indication of all flavor, isotropic flux component
- Significantly more data in the pipeline that may clarify some questions.
  - 1 more year starting track, 2 years diffuse muon neutrinos very soon
  - Extend cascades to lower energies
  - Global fit, other
- Publication and more data coming soon

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Neutrino oscillation analysis with IceCube-DeepCore

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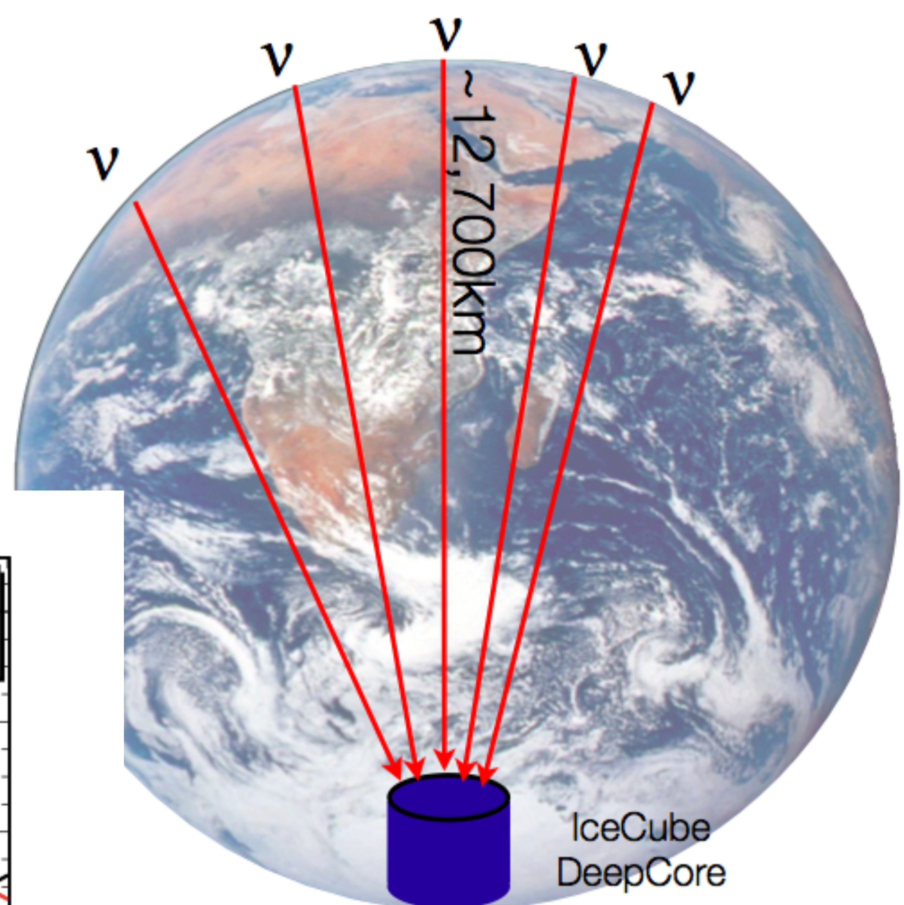

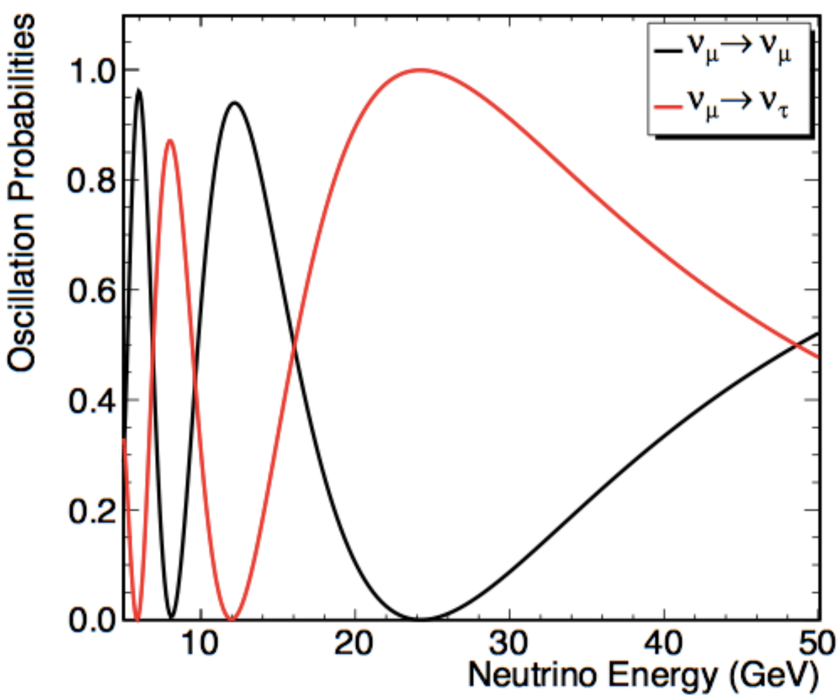

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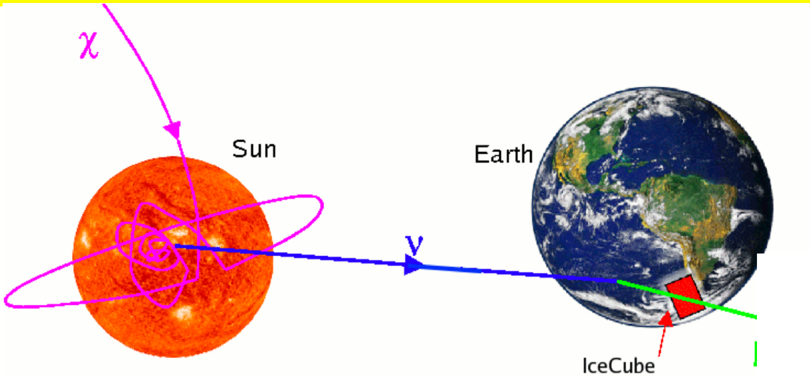
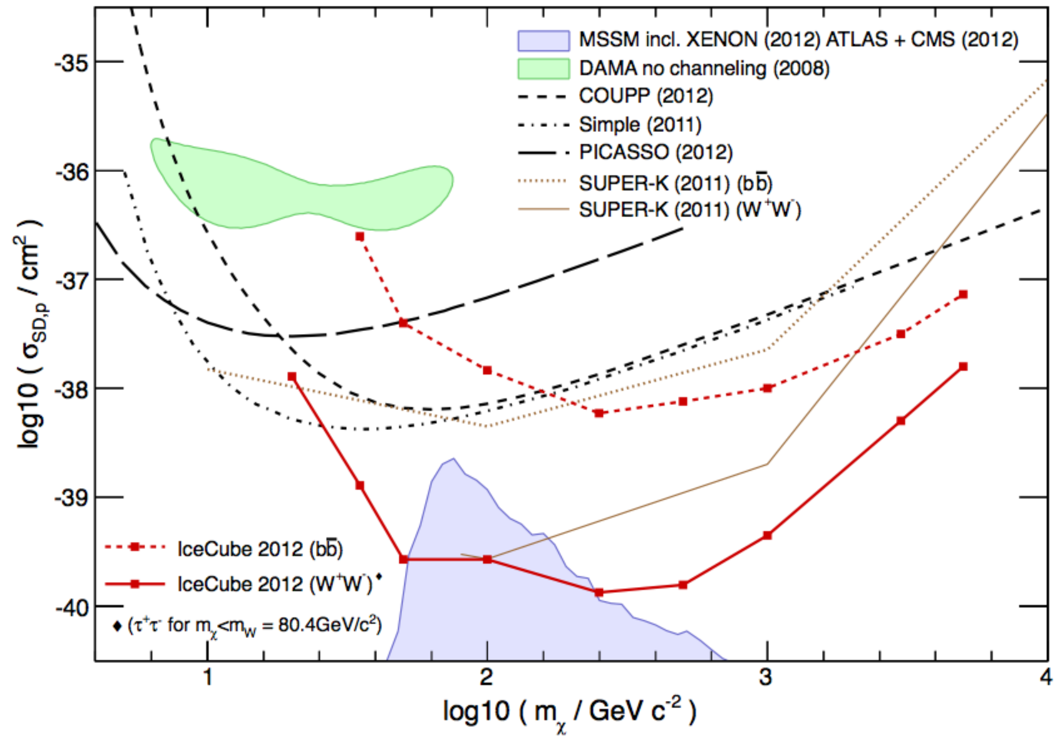
Dark matter: Indirect search, WIMPs in sun, galactic center, ….
Using IceCube-DeepCore (low energy subdetector)



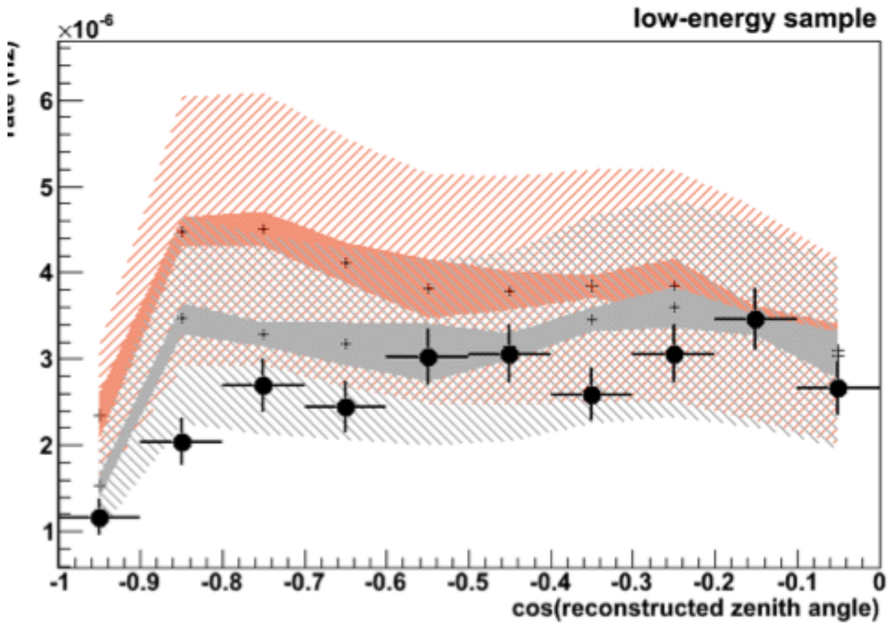
arXiv:1212.4097,
accepted PRL

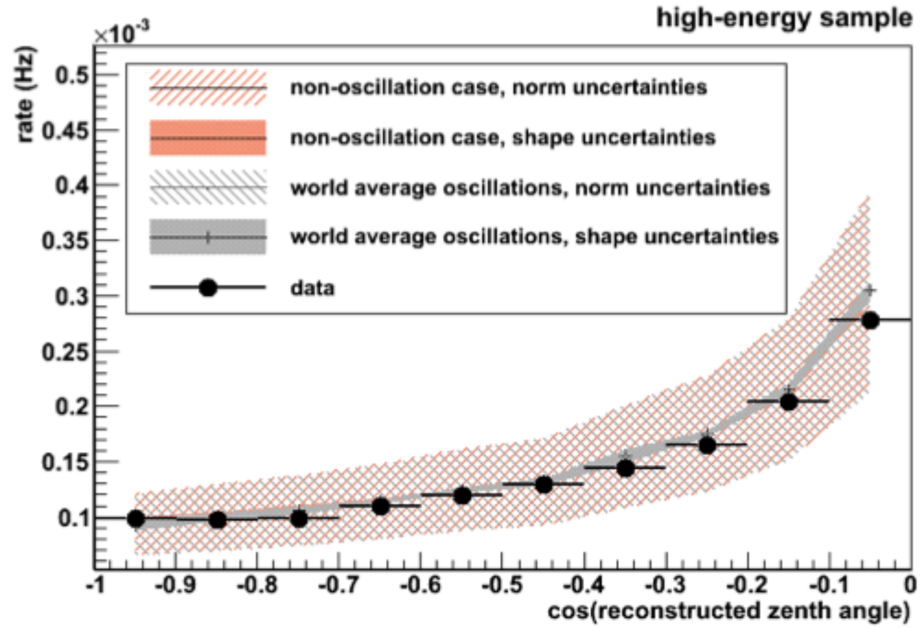


- Dark matter accumulates in the sun, annihilating to high energy neutrinos
- Equilibrium annihilation related to solar capture rate
- → probes scattering cross-section
- Sensitivity from $20GeV \leq m_\chi \leq 10T$
- High sensitivity to spin-dependent cross section due to proton target

Muon Neutrino Disappearance

arXiv:1305.3909 (accepted PRL)





Statistically significant angle-dependent suppression at low energy, high energy sample provides constraint on uncertainties in simultaneous fit

- Shaded bands show range of uncorrelated systematic uncertainties; hatched regions show overall normalization uncertainty

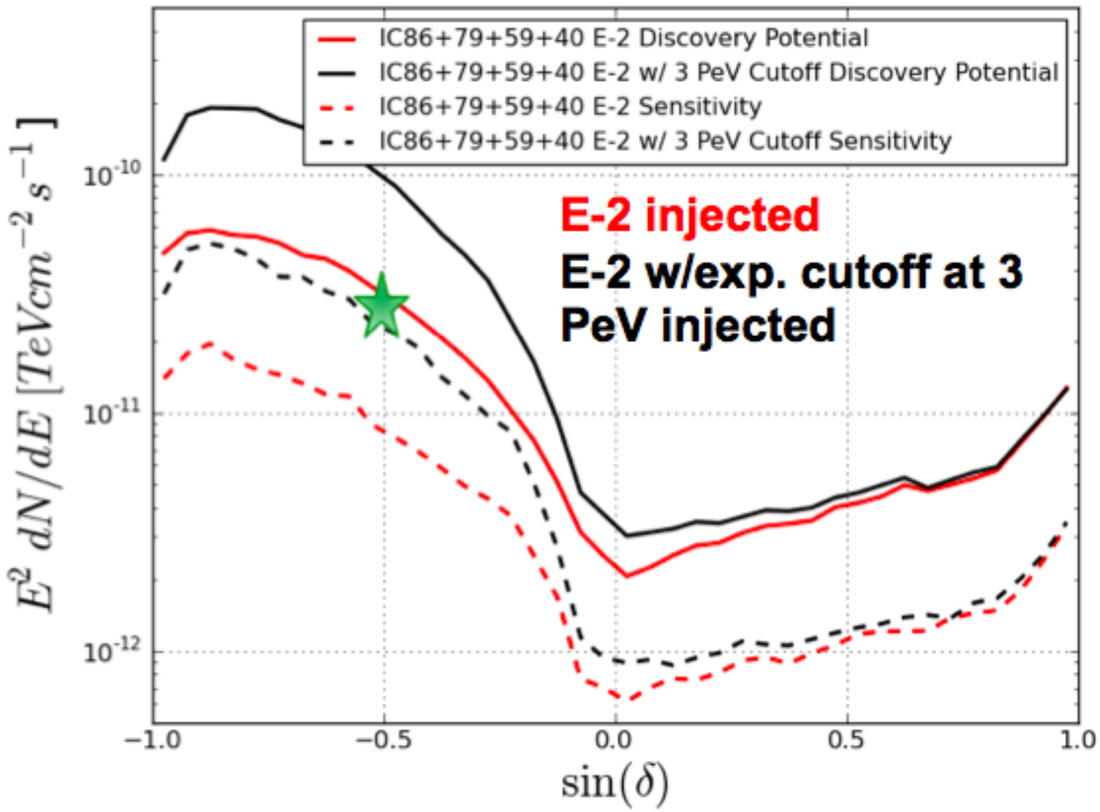
How does this result relate to high-energy starting event results?

- Back of the envelope:
  - Starting event best-fit flux is ~3 x 10^{-8} GeV/cm^2/s/sr
  - Convert to ν_μ PS flux → multiply by 4π, divide by 3 ≈ 12 x 10^{-8}
  - But only ~25% of events near hotspot: ~3 x 10^{-8} → **3 x 10^{-11} TeV/cm^{2}s**

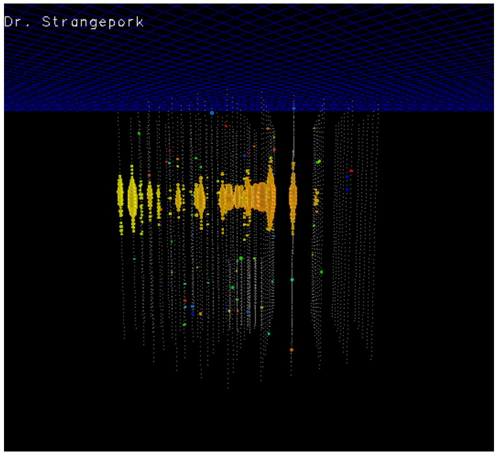
→For optimistic scenario, the high-energy starting event "hot spot" flux is at the edge of sensitivity

→ At 90% confidence level, there is no tension in results

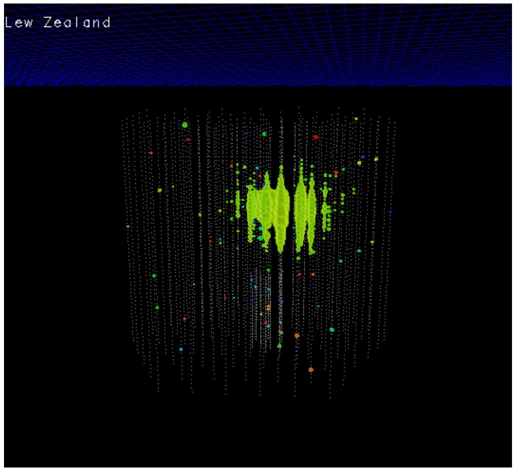
→ Sensitivity to actual flux can easily be worse (cutoff position/shape, source extension, flavor ratio, etc.)



→ Feintzeig



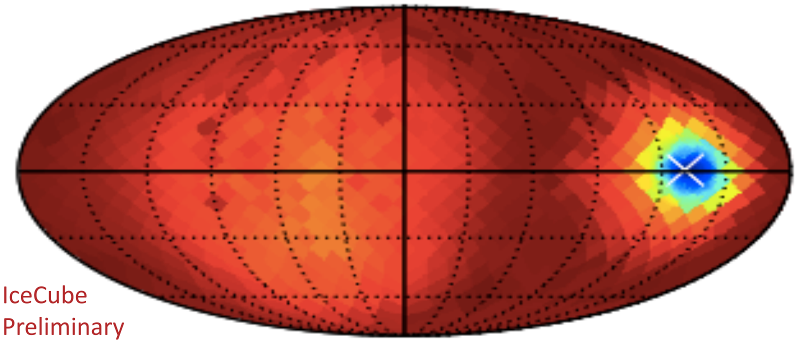
Event Reconstruction



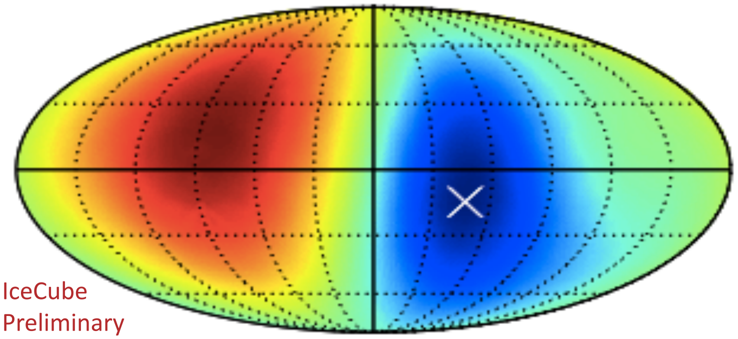
Generic full-sky likelihood scan for each event

Muon neutrino: ~1° resolution

Cascade (e, tau, NC) event: ~10° resolution



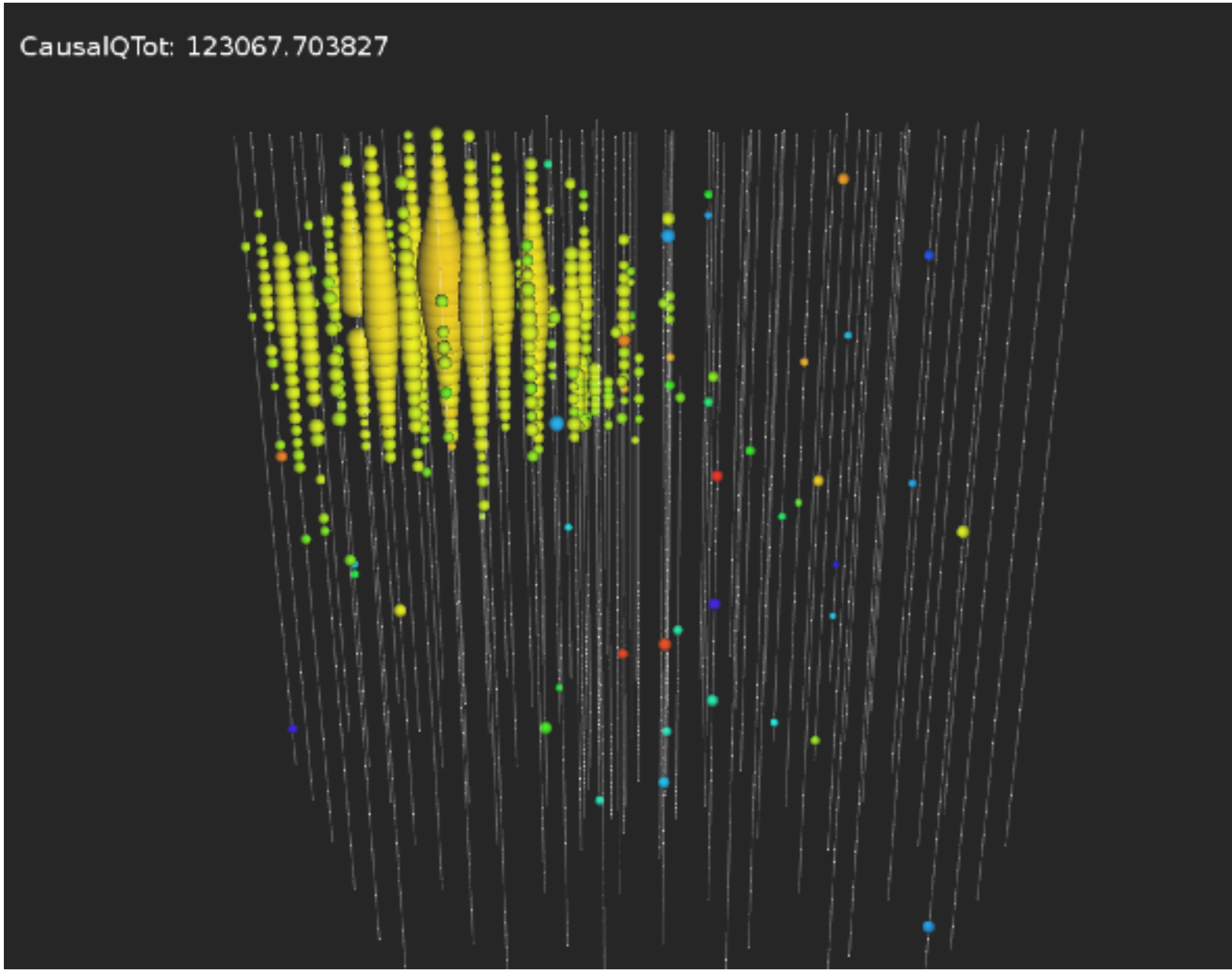
IceCube Preliminary



IceCube Preliminary

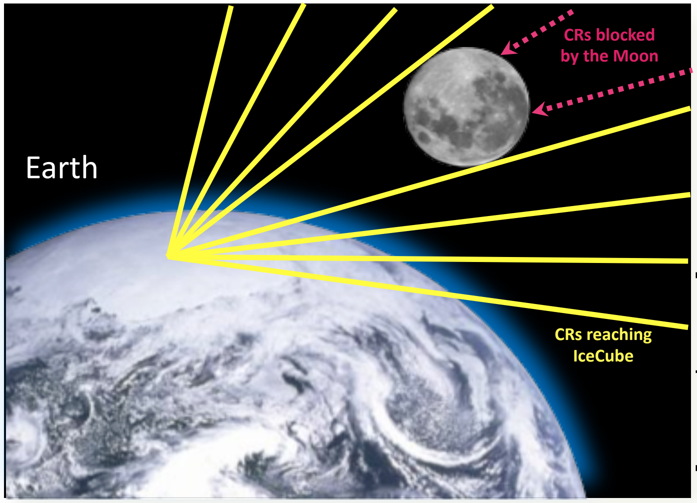
- Result: direction with uncertainty and estimate for deposited energy
- Use density maps of reconstructed events to construct zenith angle probabilities and skymaps

IceCube Preliminary


CausalQTot: 123067.703827

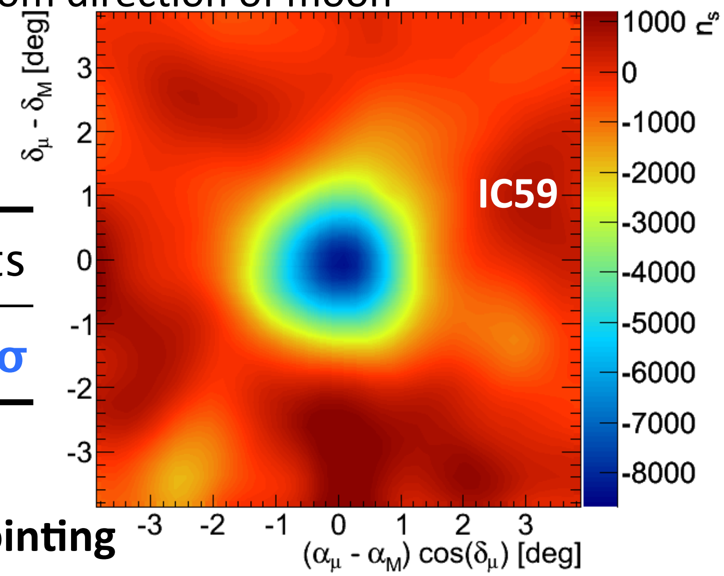
Moon shadow

- Moon blocks cosmic rays coming from its direction.
  → deficit of muons from direction of moon



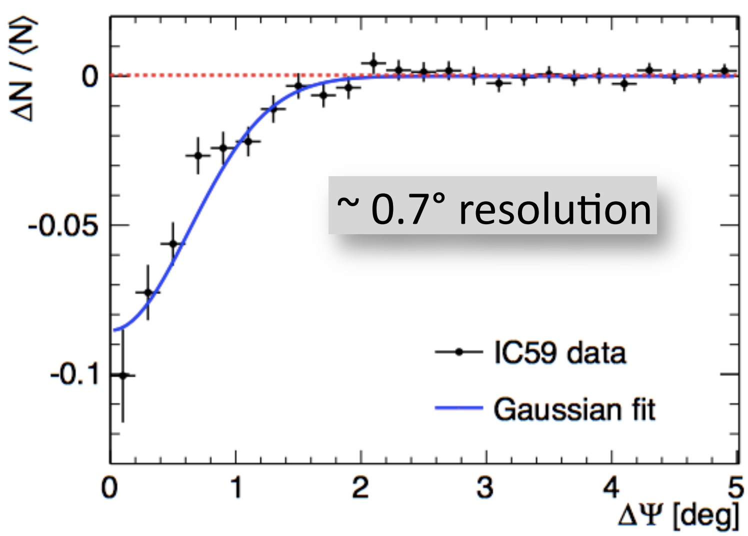
Deficit: ~ 8700 events

Significance: 13.9σ



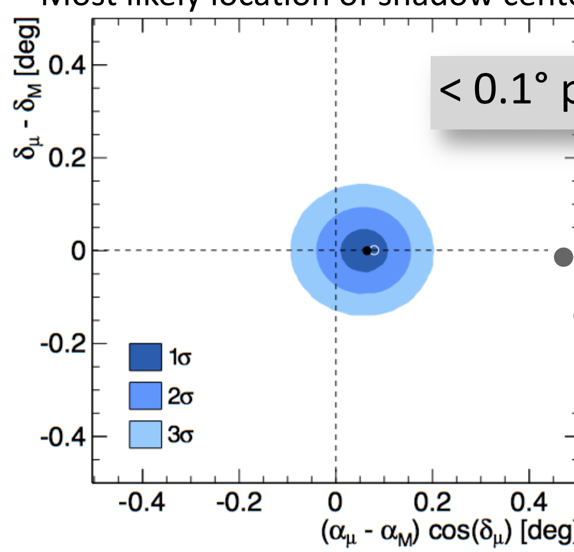
Resolution

Shadow profile vs. angular distance from the Moon



Absolute pointing

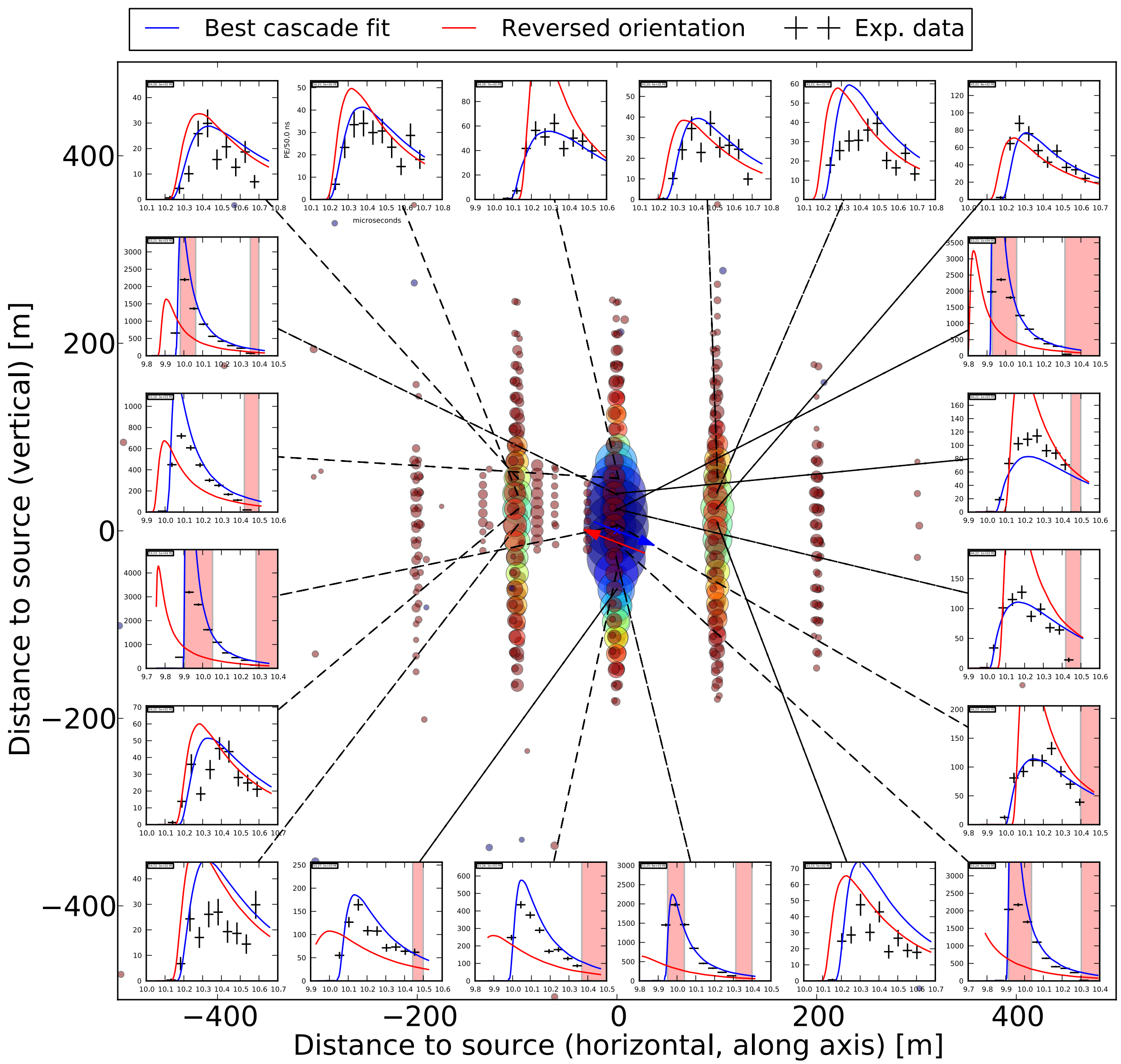
Most likely location of shadow center



< 0.1° pointing res.

- Accounts for magnetic deflection effects

Observed neutrino event at E=1.1x10^6 GeV



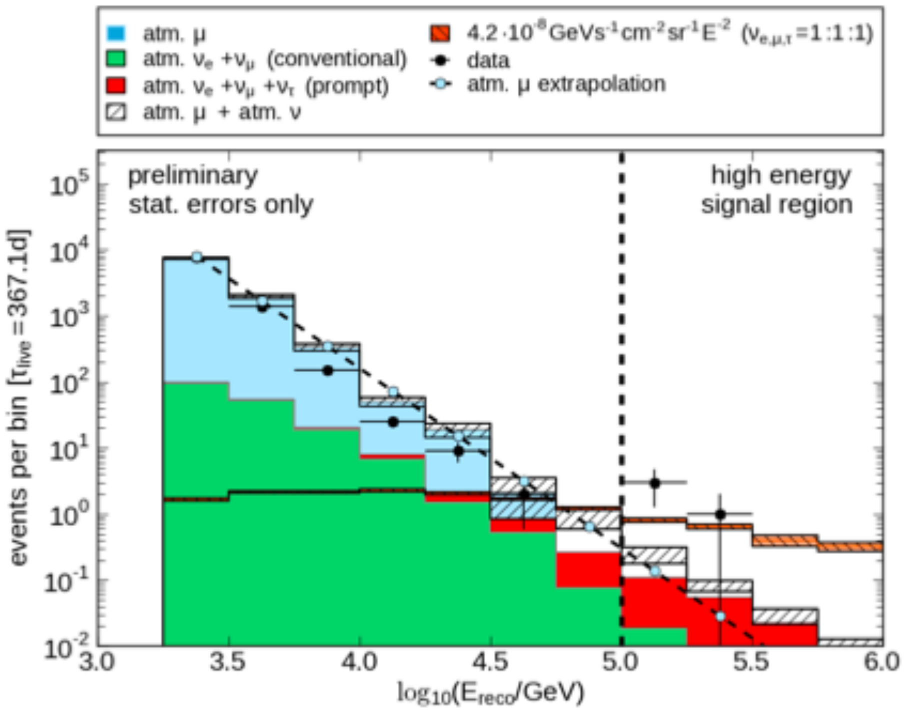
Shown is one event with best fit (blue) and forced reverse direction (red)

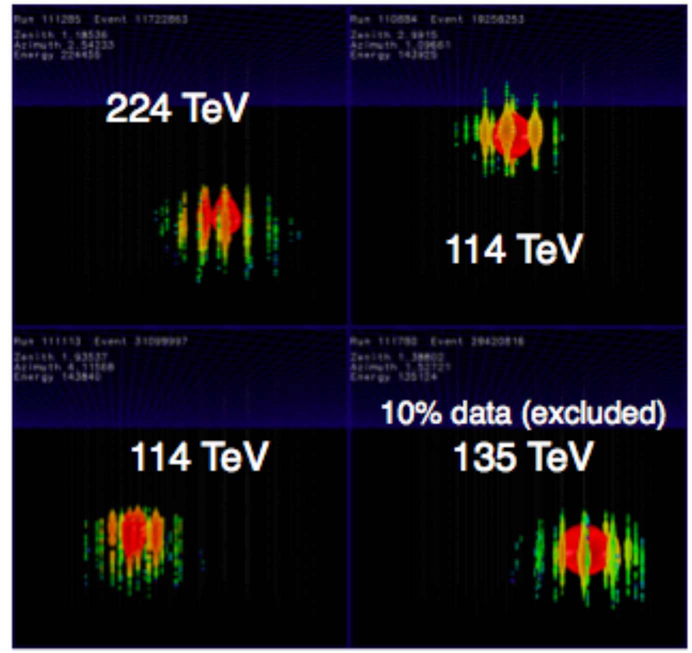
Event contains 354 waveforms and a total of > 90,000 photoelectrons

Widths of waveform related to direction of Cherenkov cone
Preliminary pointing established (blue line).
 independent reconstruction algorithms agree
Need to use most advanced ice models
Integrated charge proportional to energy.
Energy uncertainty: +15%/-13%

Cascade searches

Example: IC40 search for neutrino induced cascades





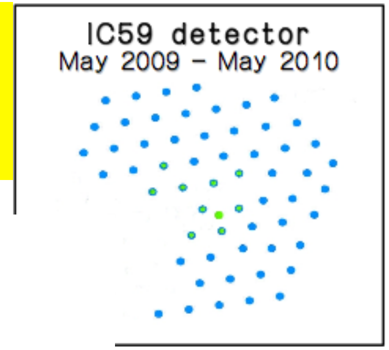
Tension with atmospheric background only assumption also on cascade channel:

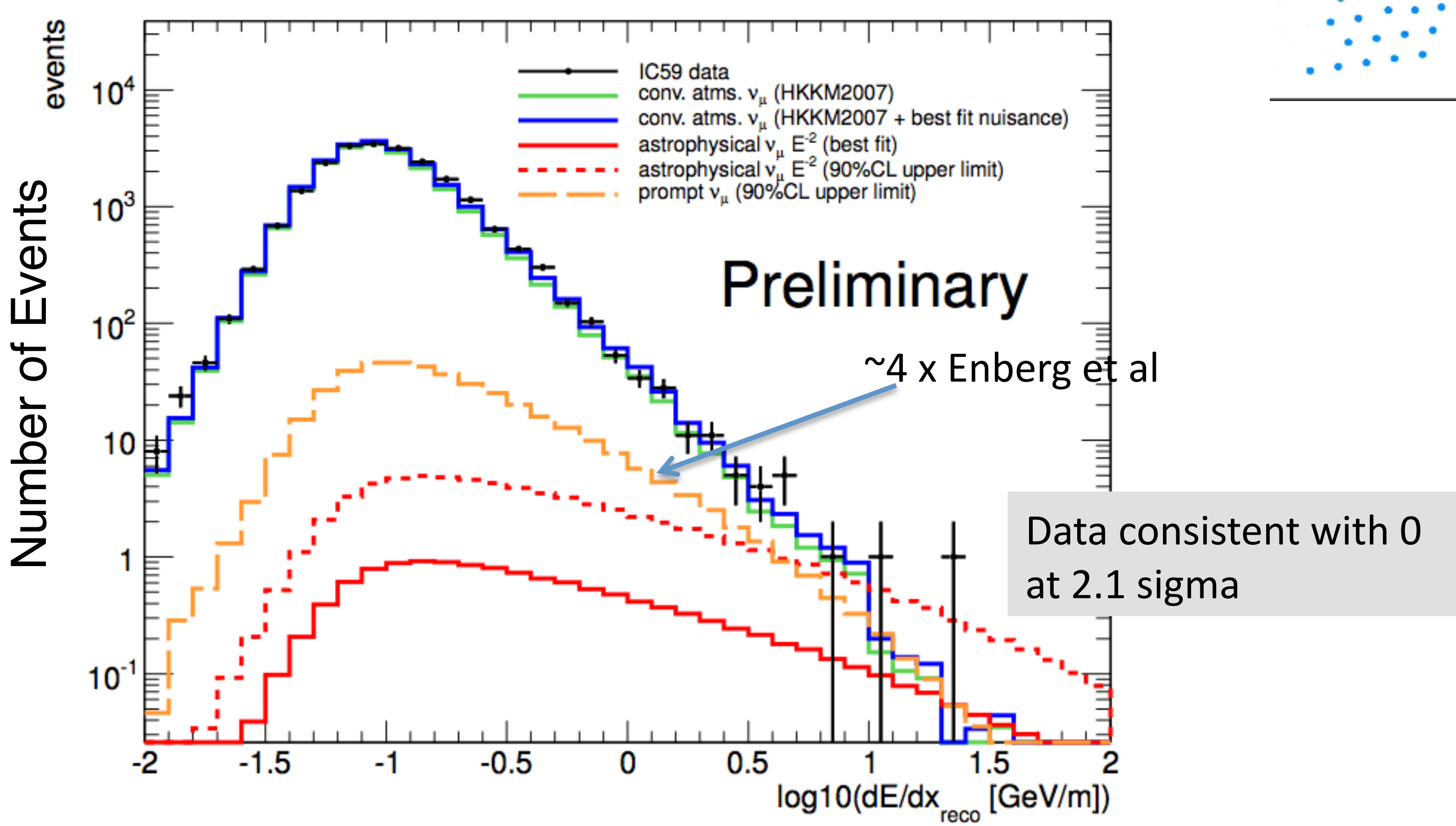
Observed 3 events with:

- 2.75σ excess over atm. μ
- $2.4\ \sigma$ excess over atm. μ and ν (conventional + prompt)

Bg estimate from extrapolation, statistical uncertainties only

IC 59 diffuse ν_μ flux



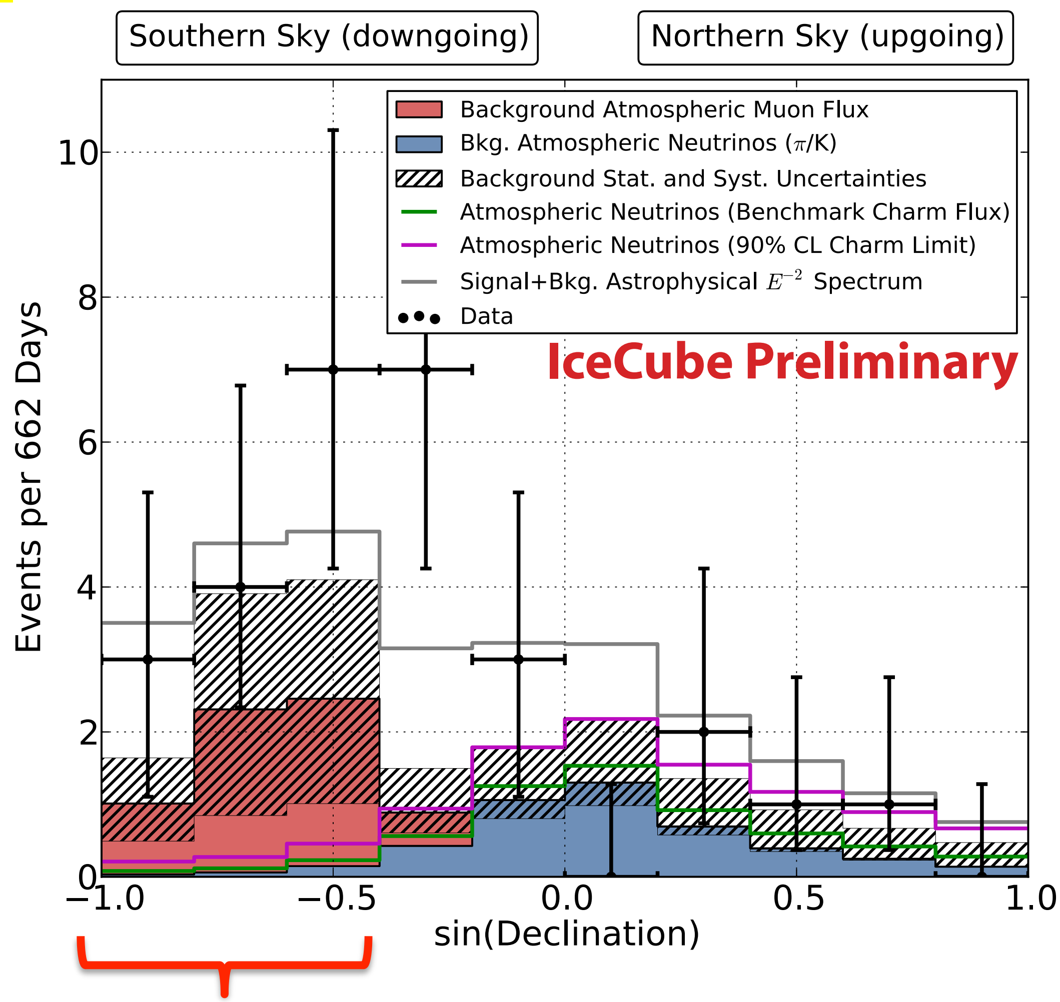


arXiv:1302.0127

Data from 2009-2010: 348 days of livetime with ~75% complete detector
Analysis looks for deviation from the expected atmospheric neutrino flux

Zenith angle, declination distribution

- Angular distribution does not fit atmospheric.
- Compatible with isotropic flux
- Absorption matters for upgoing events at higher energies



Very low background of downgoing atmospheric neutrinos due to veto.