IceCube: Diffuse [and Point Source] Results for GRB and AGN Searches

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For the IceCube Collaboration

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The IceCube Collaboration

39 Institutions
~220 collaborators

International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
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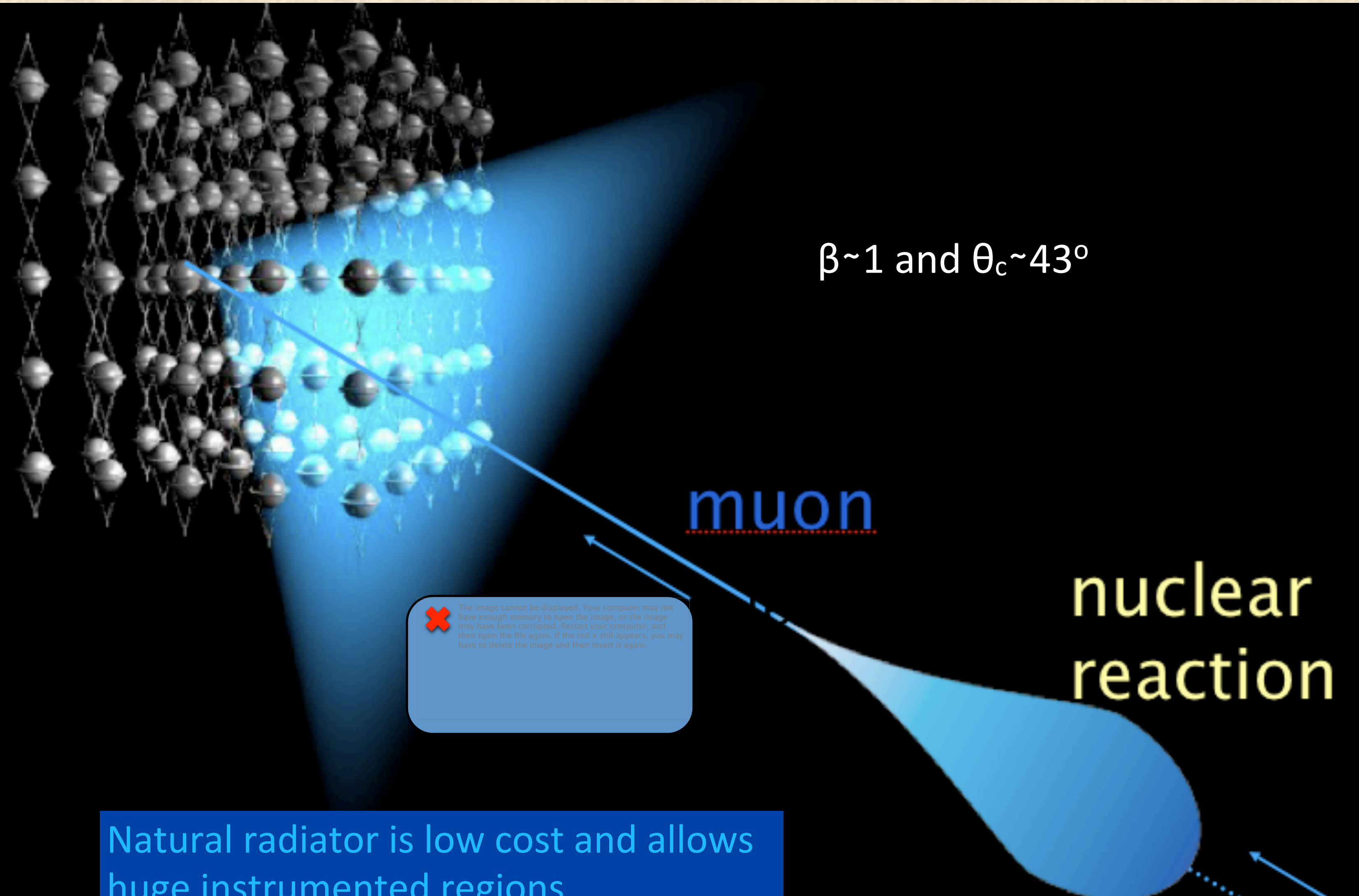
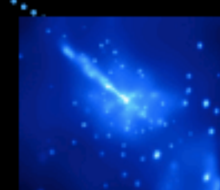
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Concept of Large Neutrino Telescopes



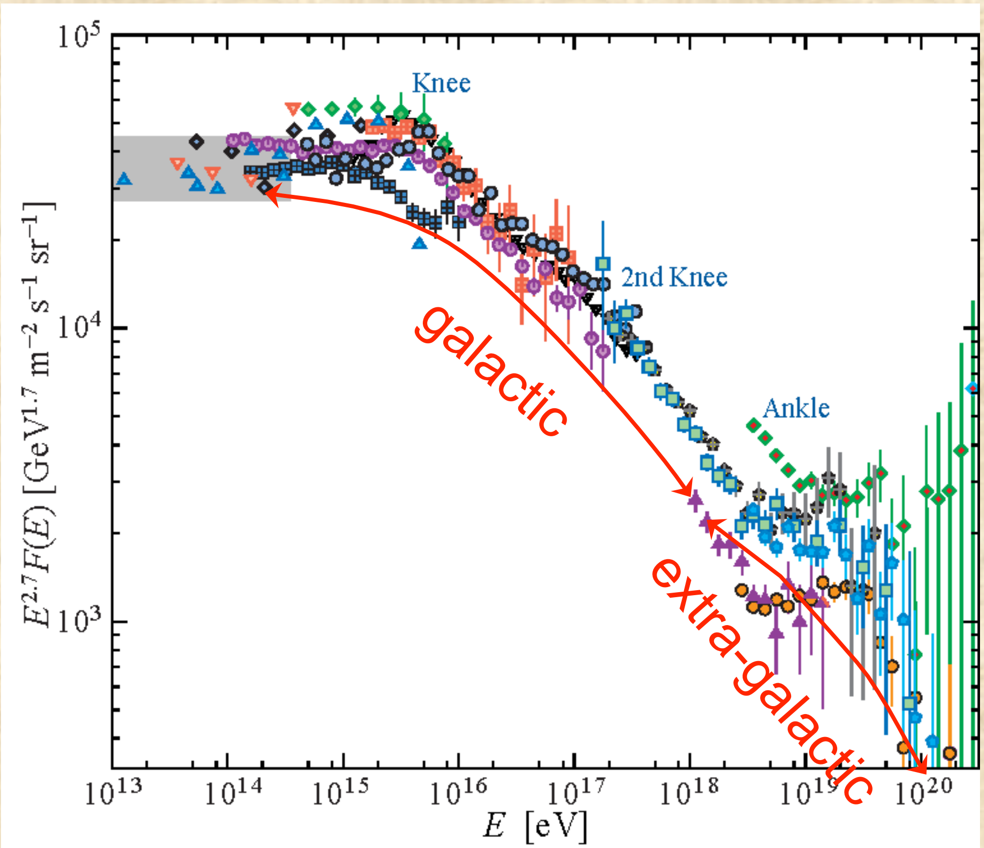
Natural radiator is low cost and allows huge instrumented regions
→ Deep sea or lake
→ Deep clear Ice

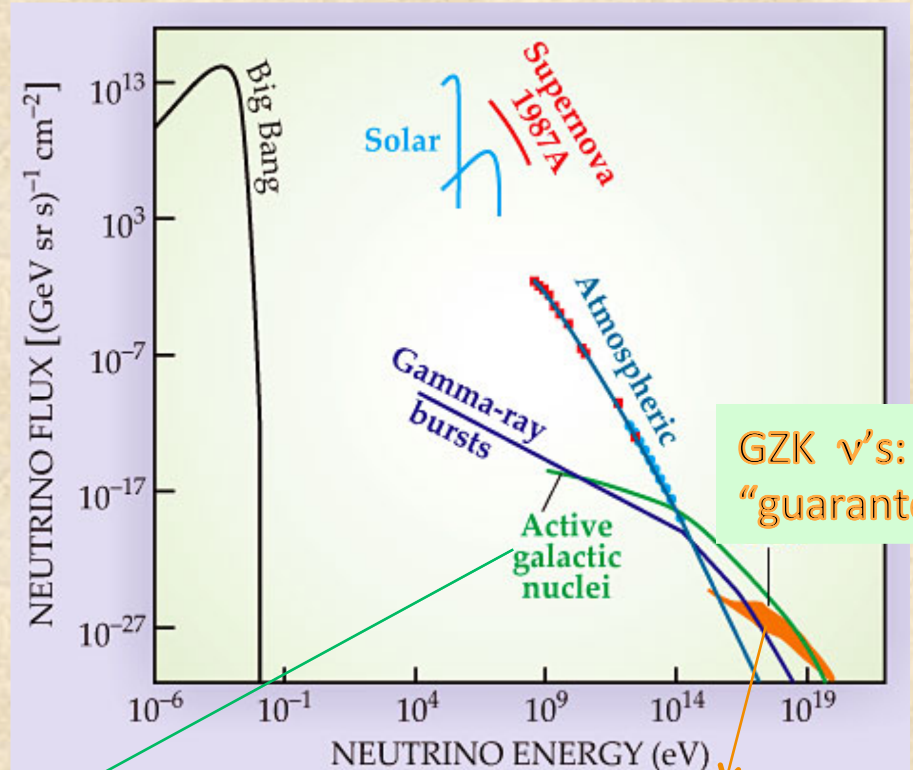


Between 300-600 nm 2* 10^4 Cherenkov photons/m of a muon track
Good scaling with dE/dx as radiative losses increase above 10 TeV

Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays

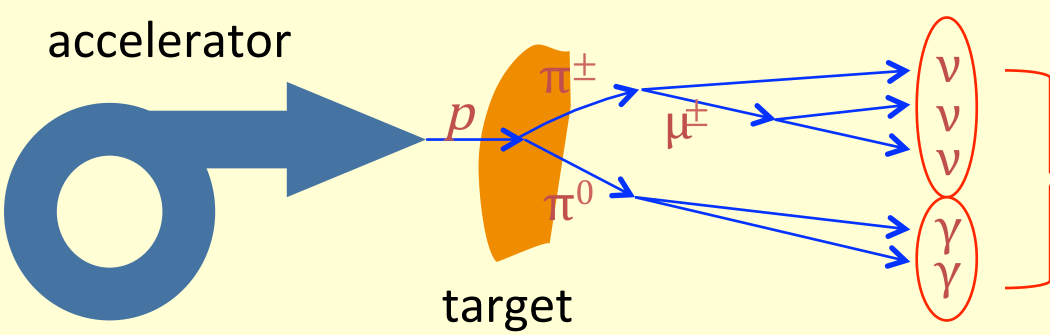




GZK ν's: "guaranteed"

$$\gamma_{cmb}\, p \;\rightarrow \Delta^{+} \;\rightarrow\; \begin{matrix} n\,\pi^{+} \;\rightarrow n\,\mu\nu \\ p\,\pi^{0} \;\rightarrow p\,\gamma\gamma \end{matrix}$$

CR – ν connection



the **γ – ν** connection
for hadronic accelerators

Neutrinos Provide a Unique Window on the HE Universe

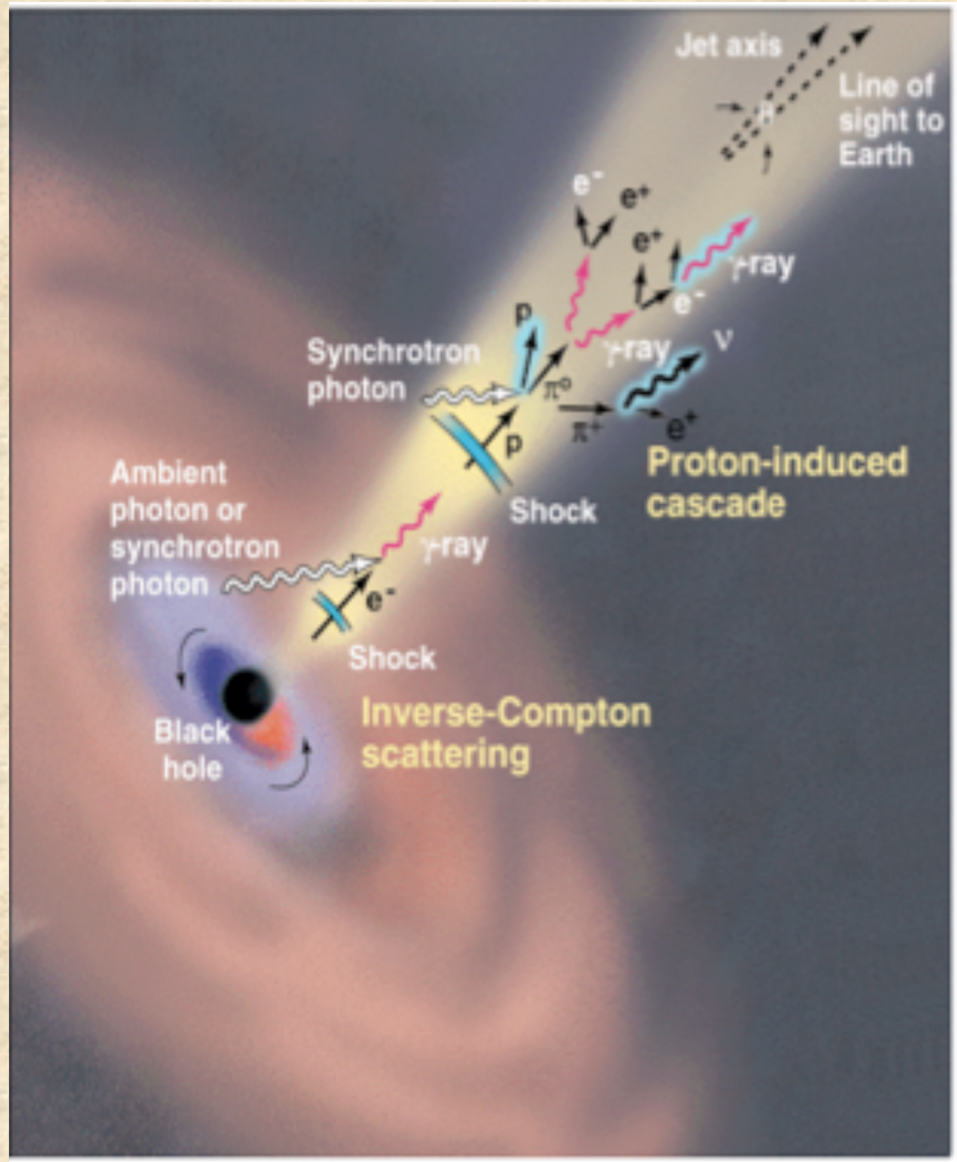
Universe opaque to high energy (>10's TeV) photons:

$\gamma + \gamma_{EBL+CMB} \rightarrow e^{+} + e^{-}$
$p+\gamma_{CMB} \rightarrow \Delta^{+} \rightarrow n+\pi^{+}$
$\rightarrow \mu^{+}+\nu_{\mu}$

Cosmogenic "GZK" 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!



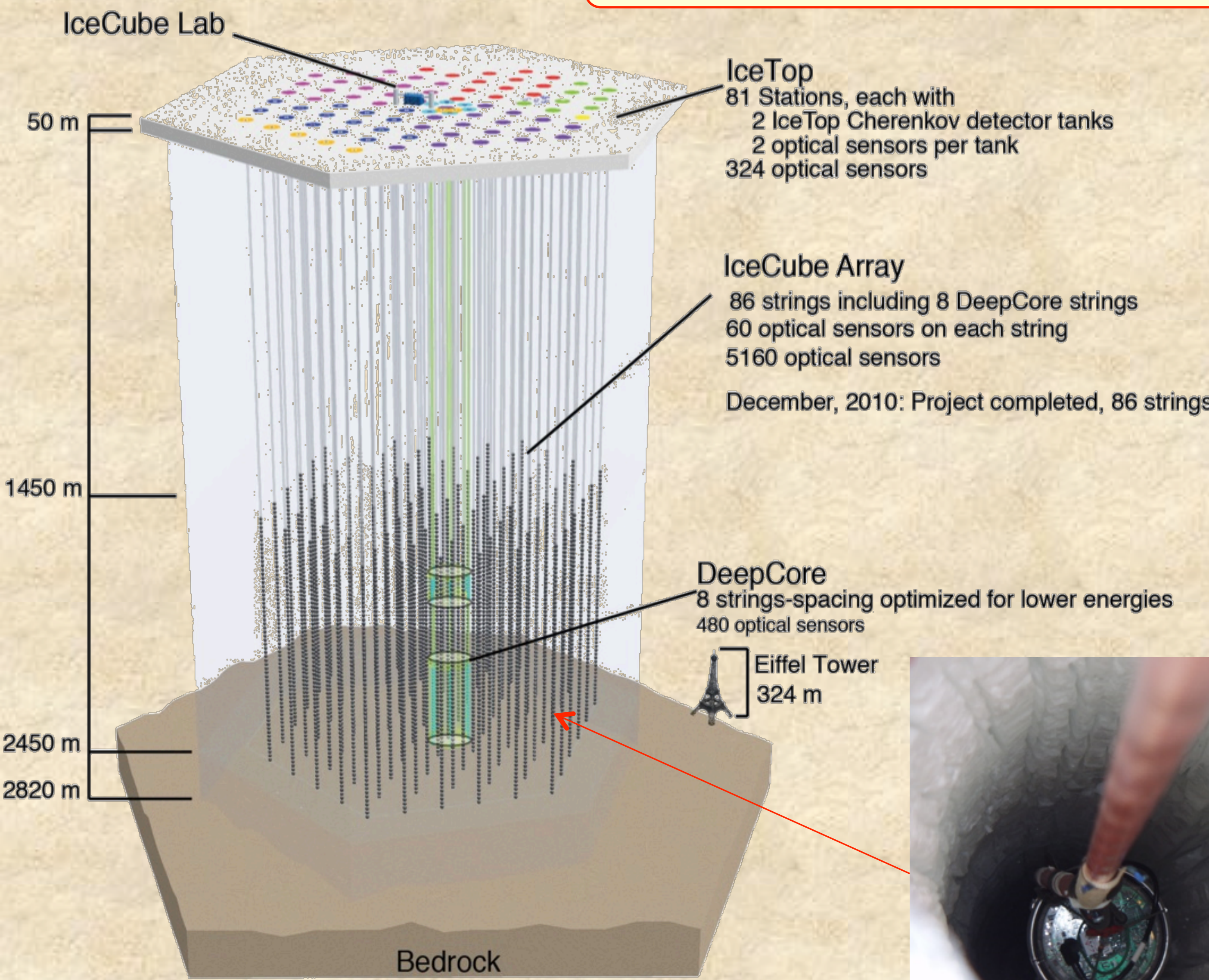
Neutrino Telescopes – A Brief Heritage

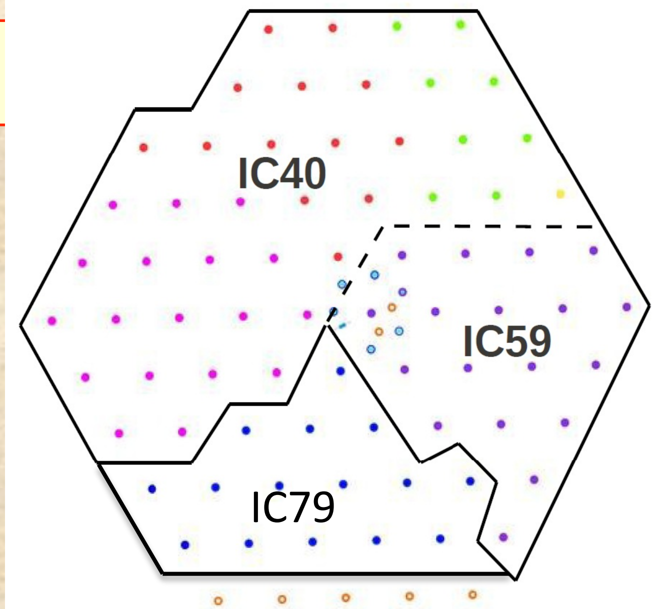
Telescopes for TeV energies:

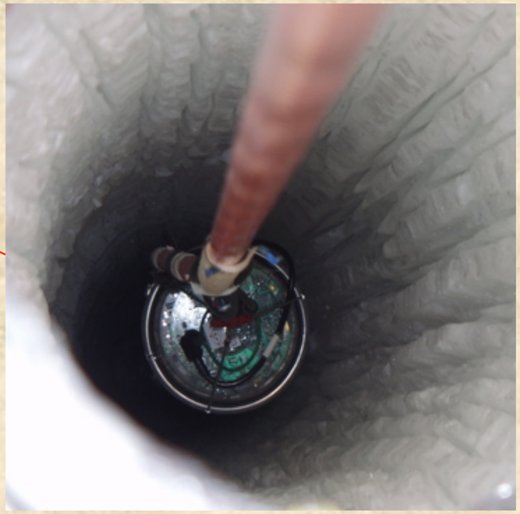
- ***First envisioned by Greisen, Markov 1960***
  - ***Conceptually simple but technically challenging***
- Pioneering effort: DUMAND near Hawaii
- First and second generation in 90's
  - proof of principle : Baikal, AMANDA, NESTOR.
- Current generation experiments
  - IceCube, ANTARES, Auger
- ***The Era of km^3 Scale Detectors is Finally Here***
  - IceCube completed construction ***Dec 18, 2010 !***
    - *IC 86-string Data Taking Began May 13, 2011*
  - km3NeT project in Mediterranean, GVD in Bakail

IceCube Detector

Detector Completion Dec 2010





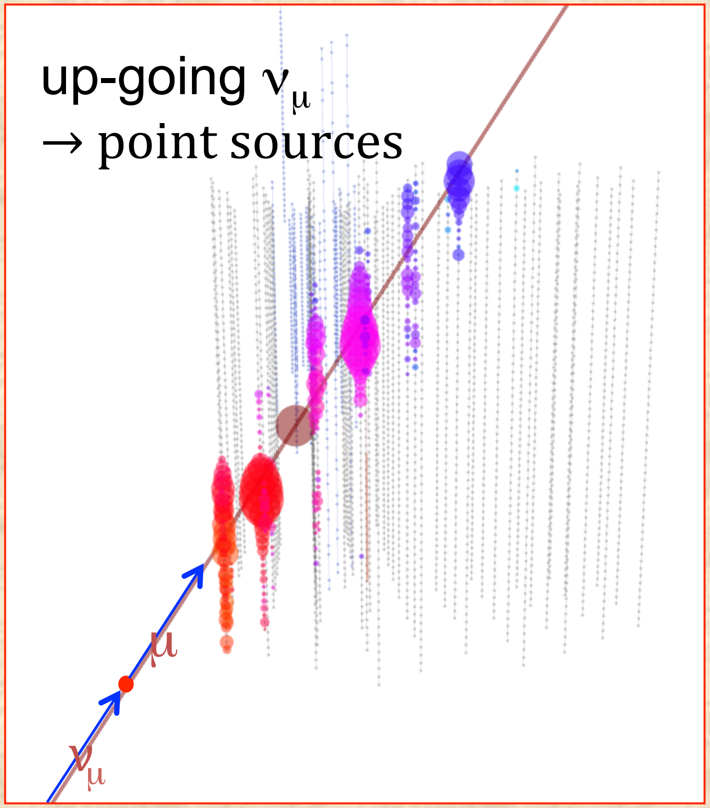


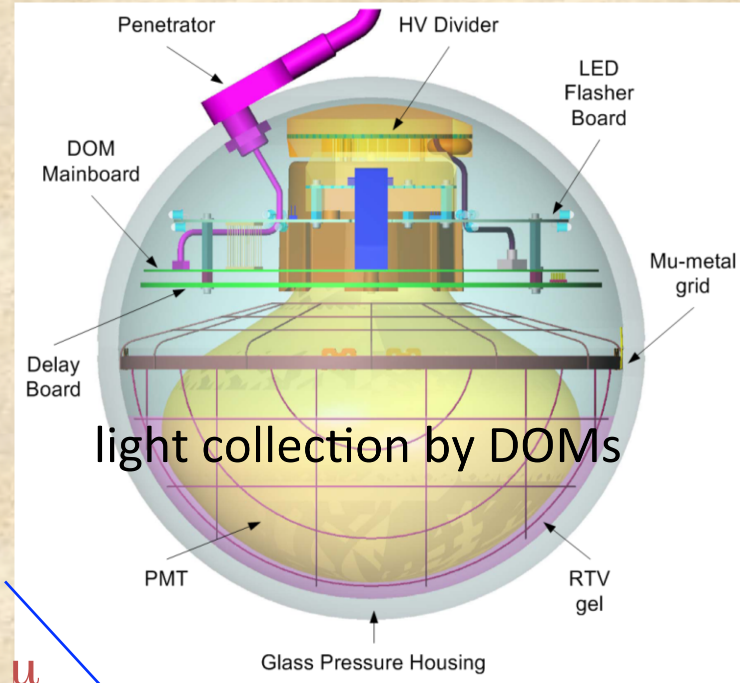
9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

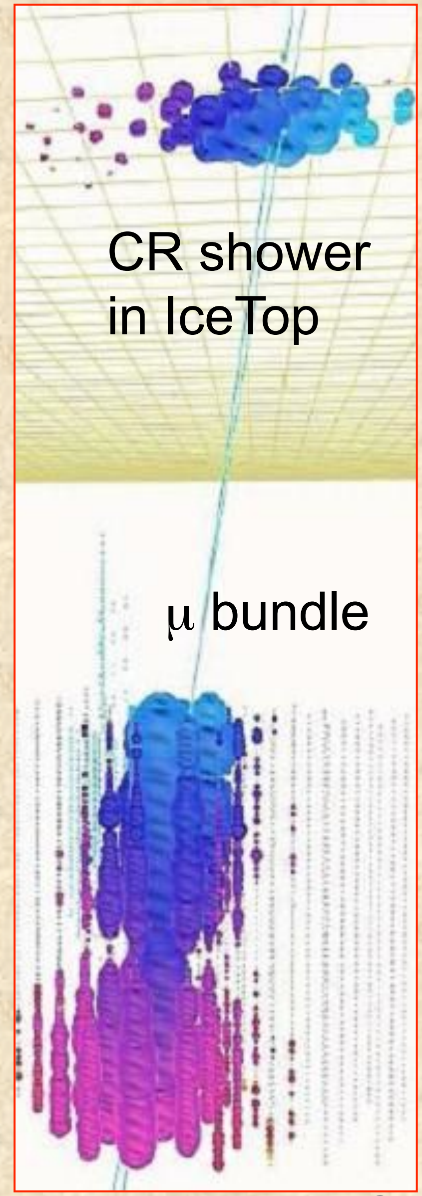
IceCube at South Pole

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

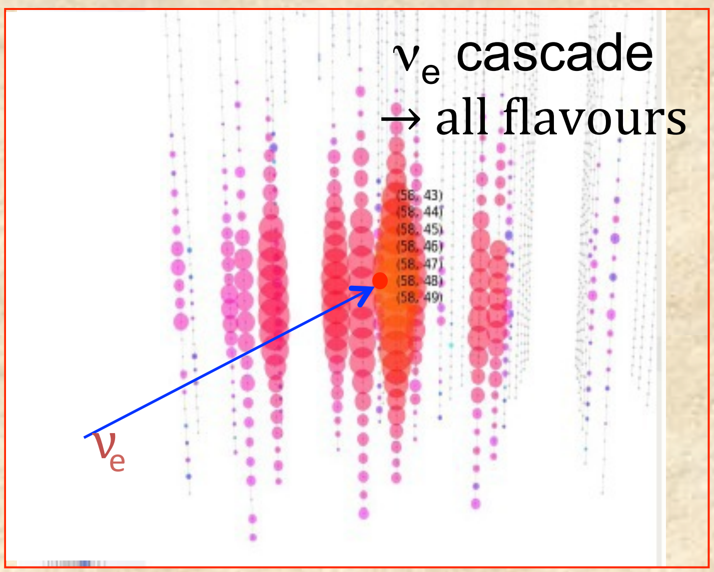
Detection Methods

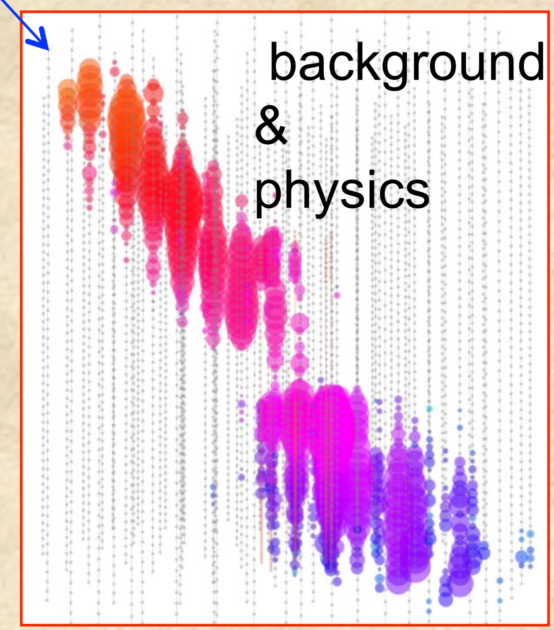






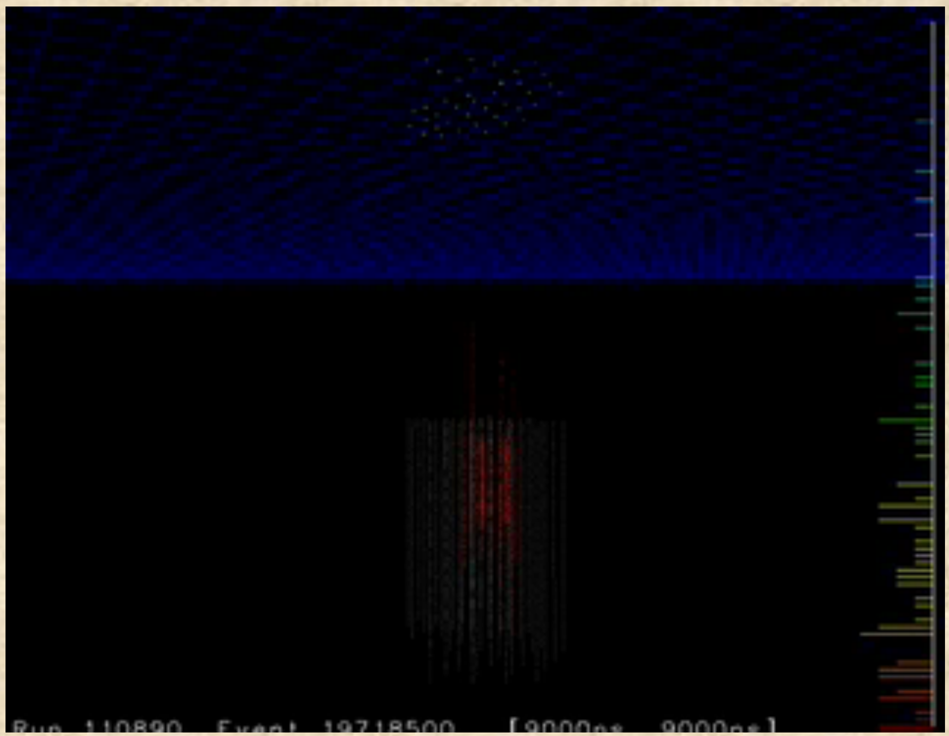
μ





Muon Events from Data

Downgoing muon bundle



IceCube Detector Status, Rates

Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	~5 / day
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	~100/day
IC86-I	2011- 2012	~ year	2700	processing
IC86-II	current		2700	running

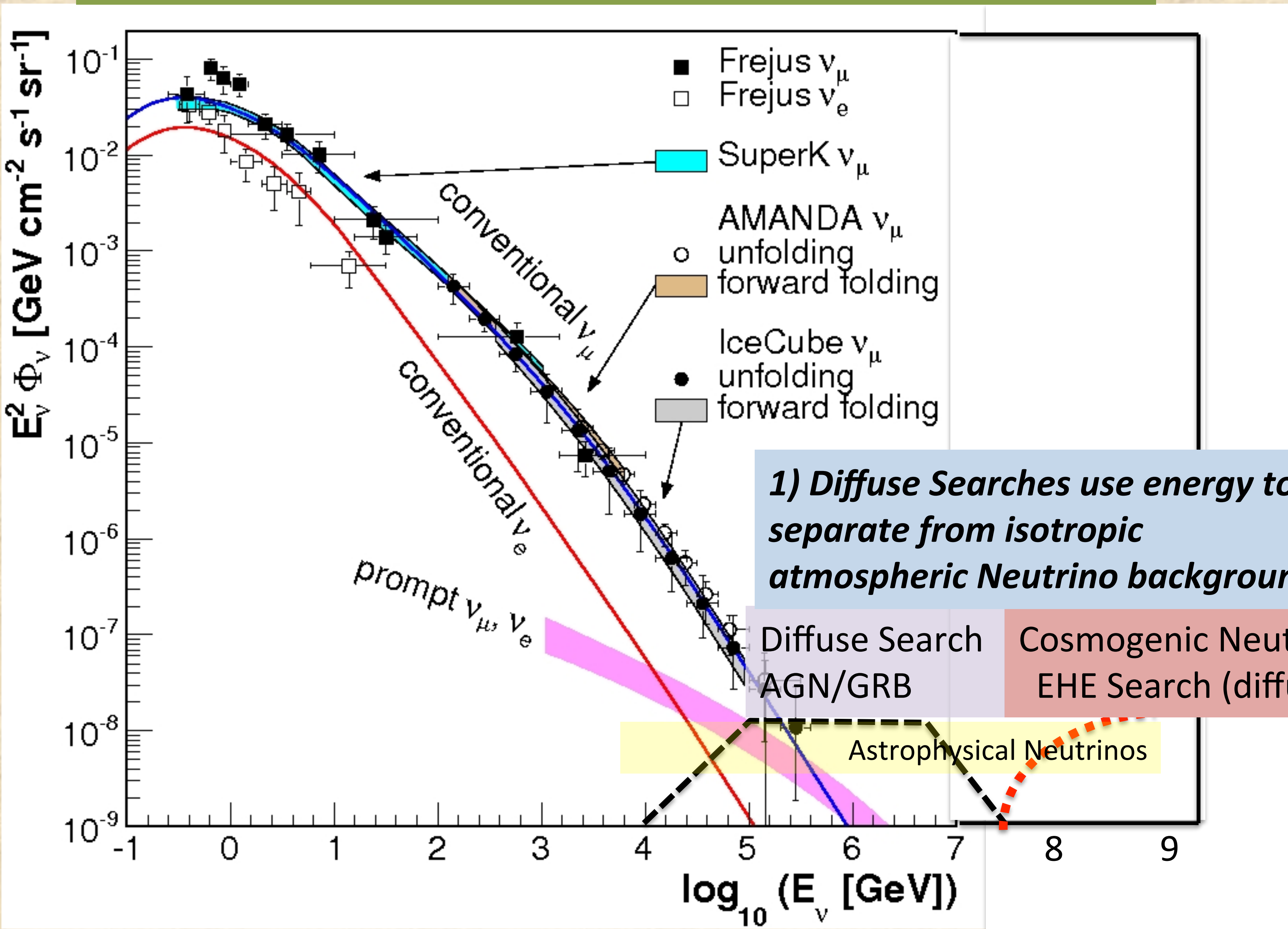
DeepCore Installed → IC79

Run transition typically mid May

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

IC86 achieving ~ 99% uptime

Search Strategies for Astrophysical Neutrinos



1) Diffuse Searches use energy to separate from isotropic atmospheric Neutrino background

Diffuse Search AGN/GRB

Cosmogenic Neutrino EHE Search (diffuse)

IceCube Diffuse Neutrino Searches

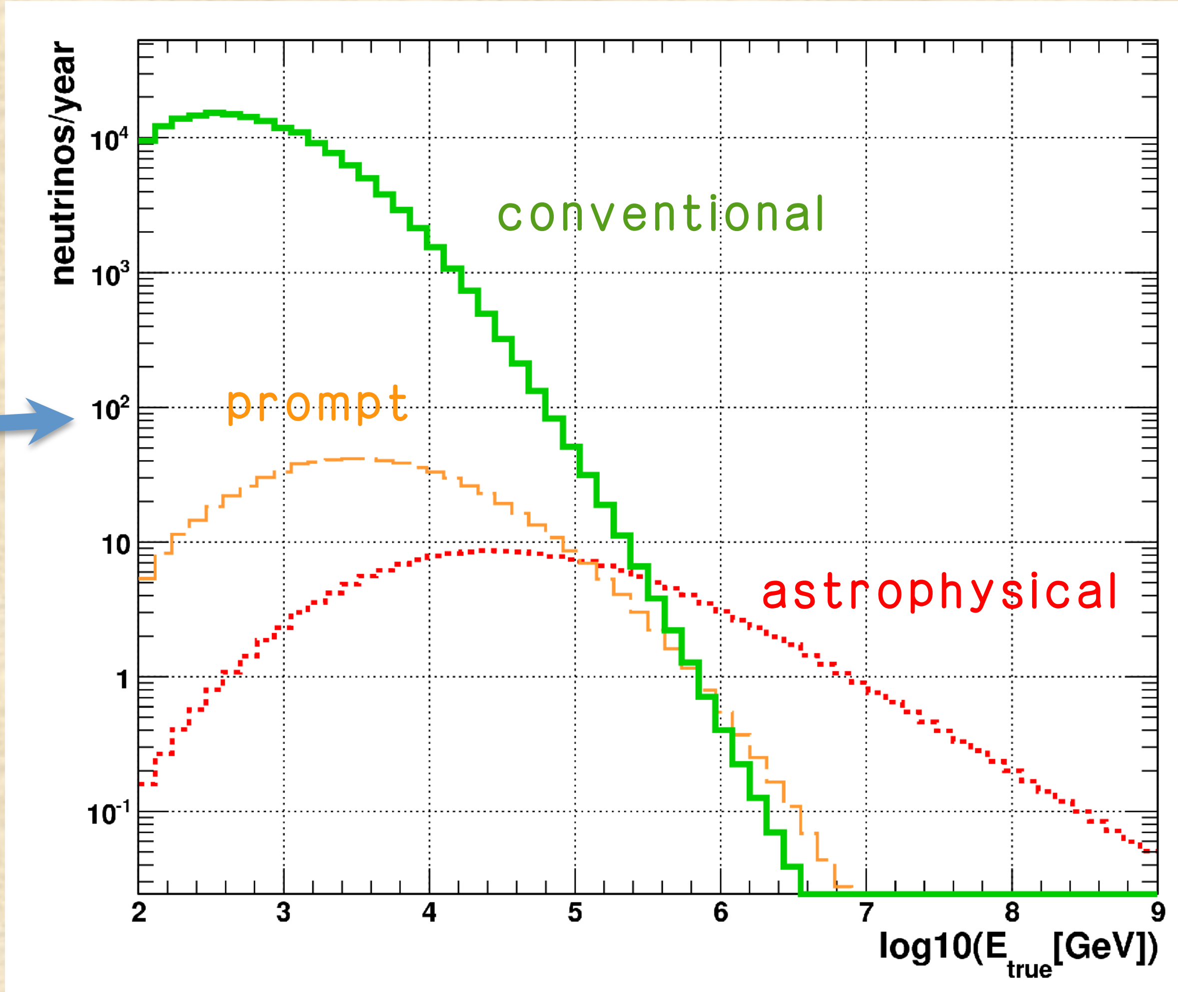
- Look for neutrino events at high energy, above the rapidly falling atmospheric neutrino spectrum.
  - ν_{μ} signal looks for upward going tracks
  - Cascade events (CC ν_{e} and ν_{τ}, NC $\nu_{\mu,\tau,e}$) contained showers
- ν_{μ} diffuse search
  - IC 40-string published [Phys. Rev. D 84, 082001 (2011) **arXiv:1104.5187v5]**
  - New Results from IC 59-string ν_{μ} search
- Cascade search
  - updated Results for IC 40-string search

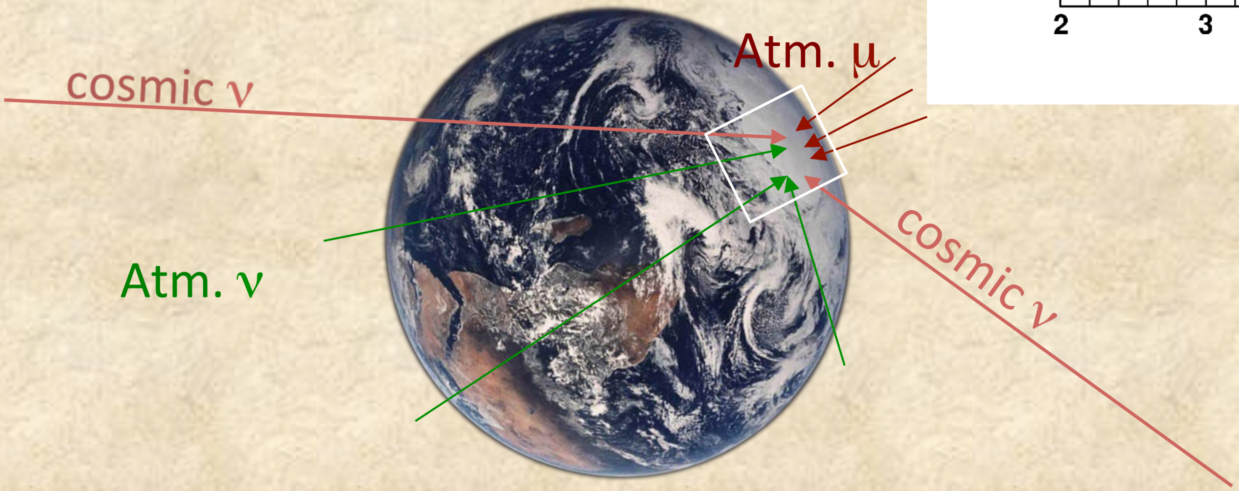
IC 59-string diffuse ν_μ Search

Search for upward going tracks at energies above atmospheric neutrino spectrum.

Relative rates in IceCube (at trigger level, before analysis cuts)

Conventional ν_μ: Honda 2006
Prompt ν_μ: Engberg et al.
Astrophysical E^{-2}: at IC40 limit





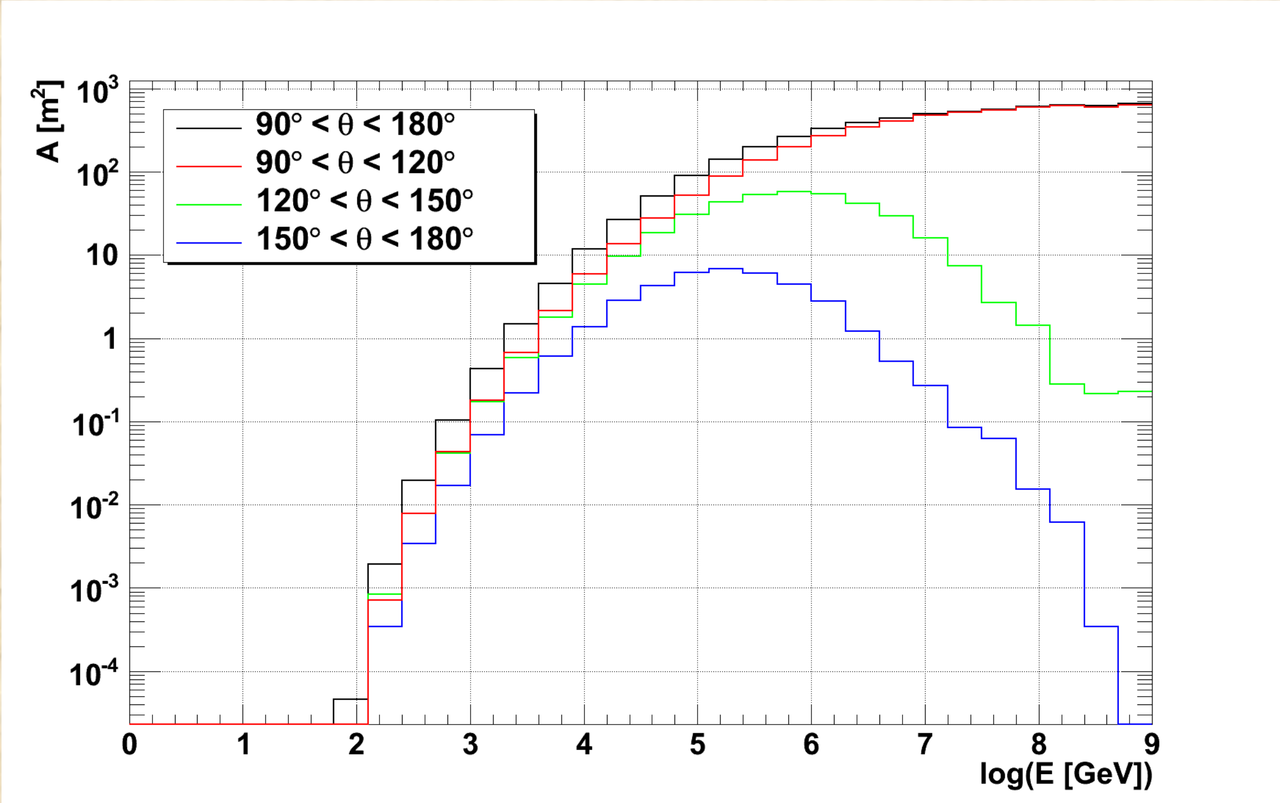
IC 59-string diffuse ν_{μ} effective area

Analysis cuts to reject

- Down-going events
- mis-reconstructed CR muons
- multiple CR muons

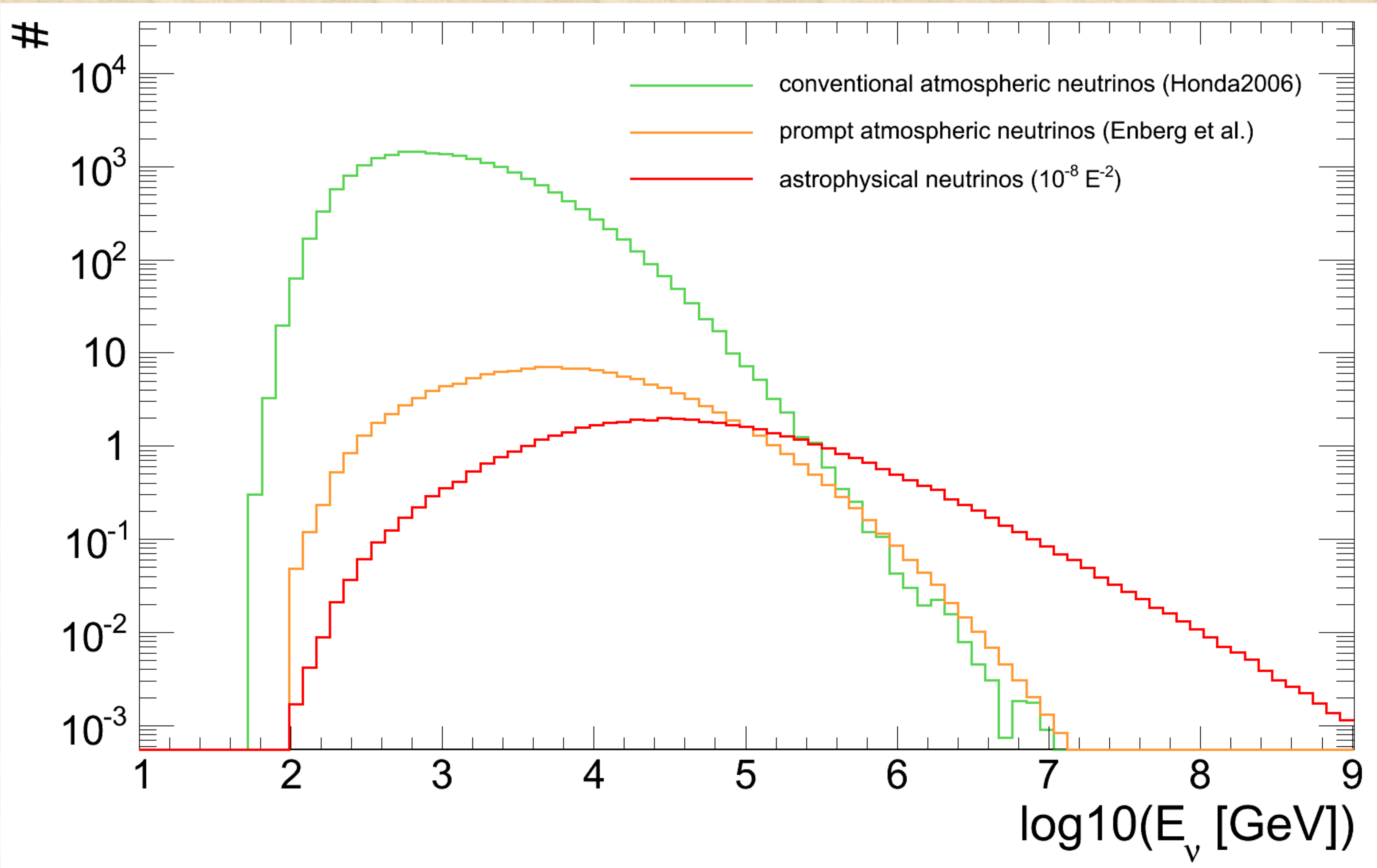
Achieve:

- ν purity of 99.8%
- Atm. ν efficiency ~12%
- E^{-2} ν efficiency ~30%



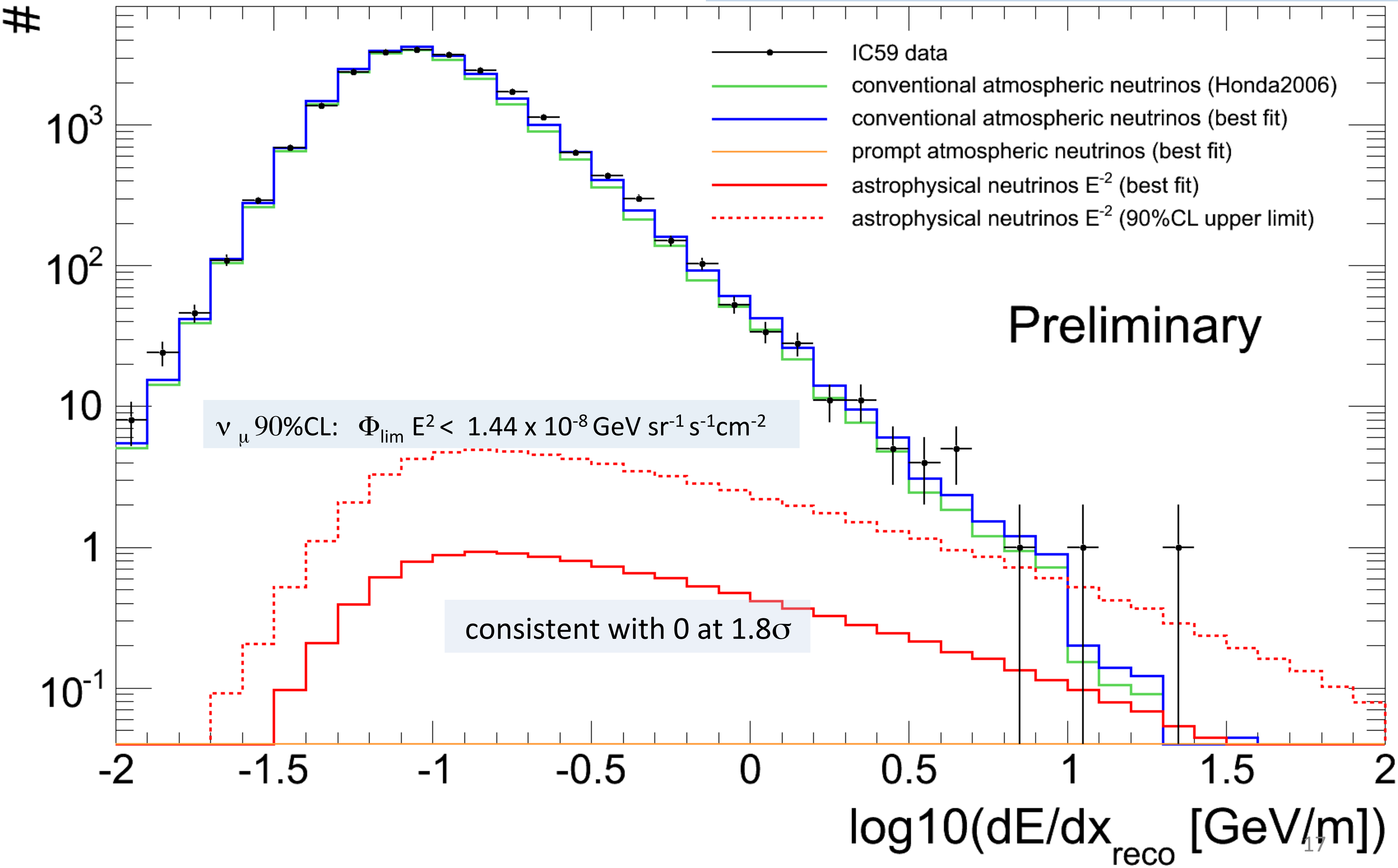
ν_{μ} effective area (m^2) vs. ν_{μ} energy (GeV) for various zenith angle ranges

Neutrino Fluxes at analysis level

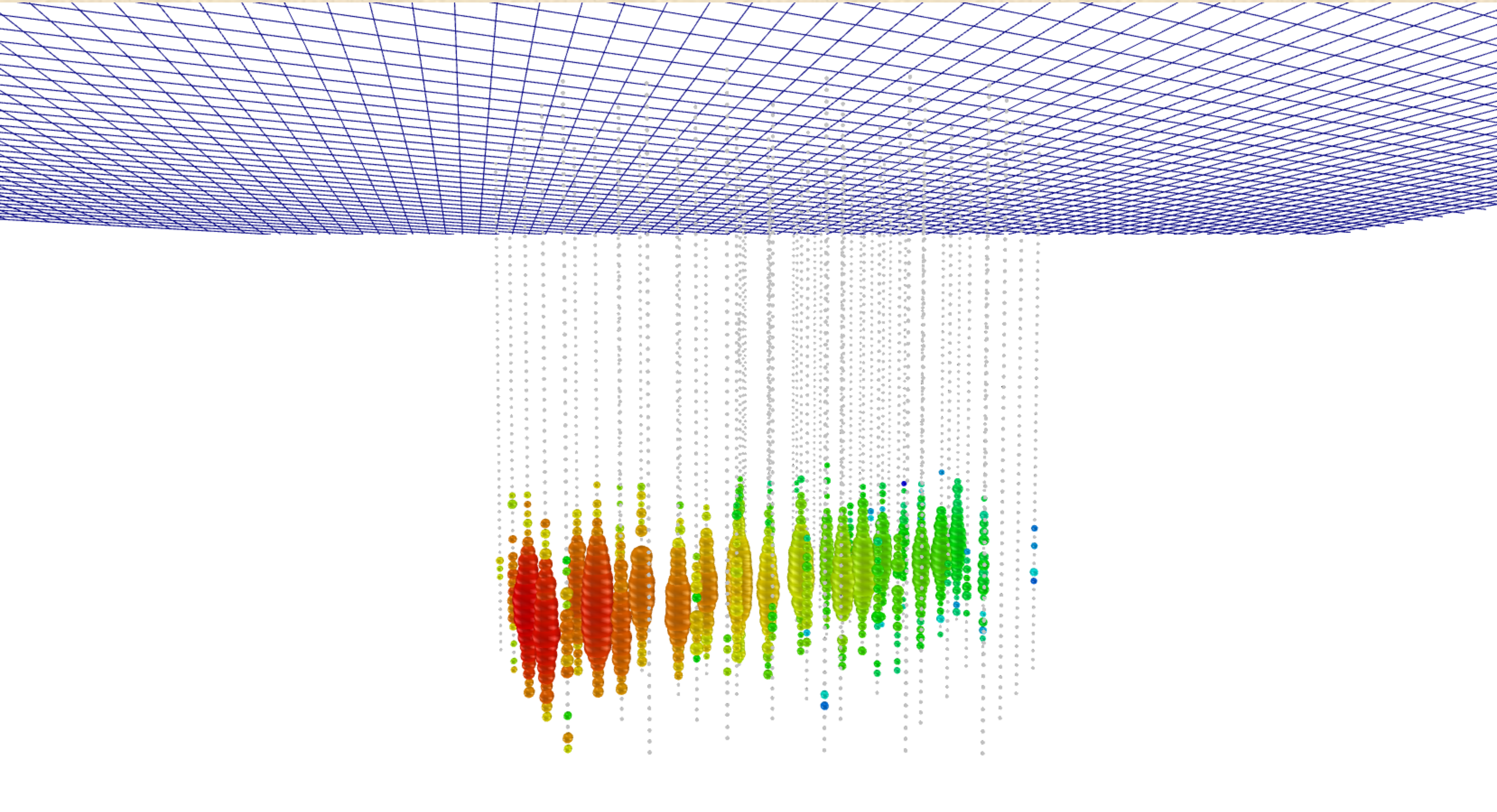


IC59 Diffuse ν_μ Search fit to data

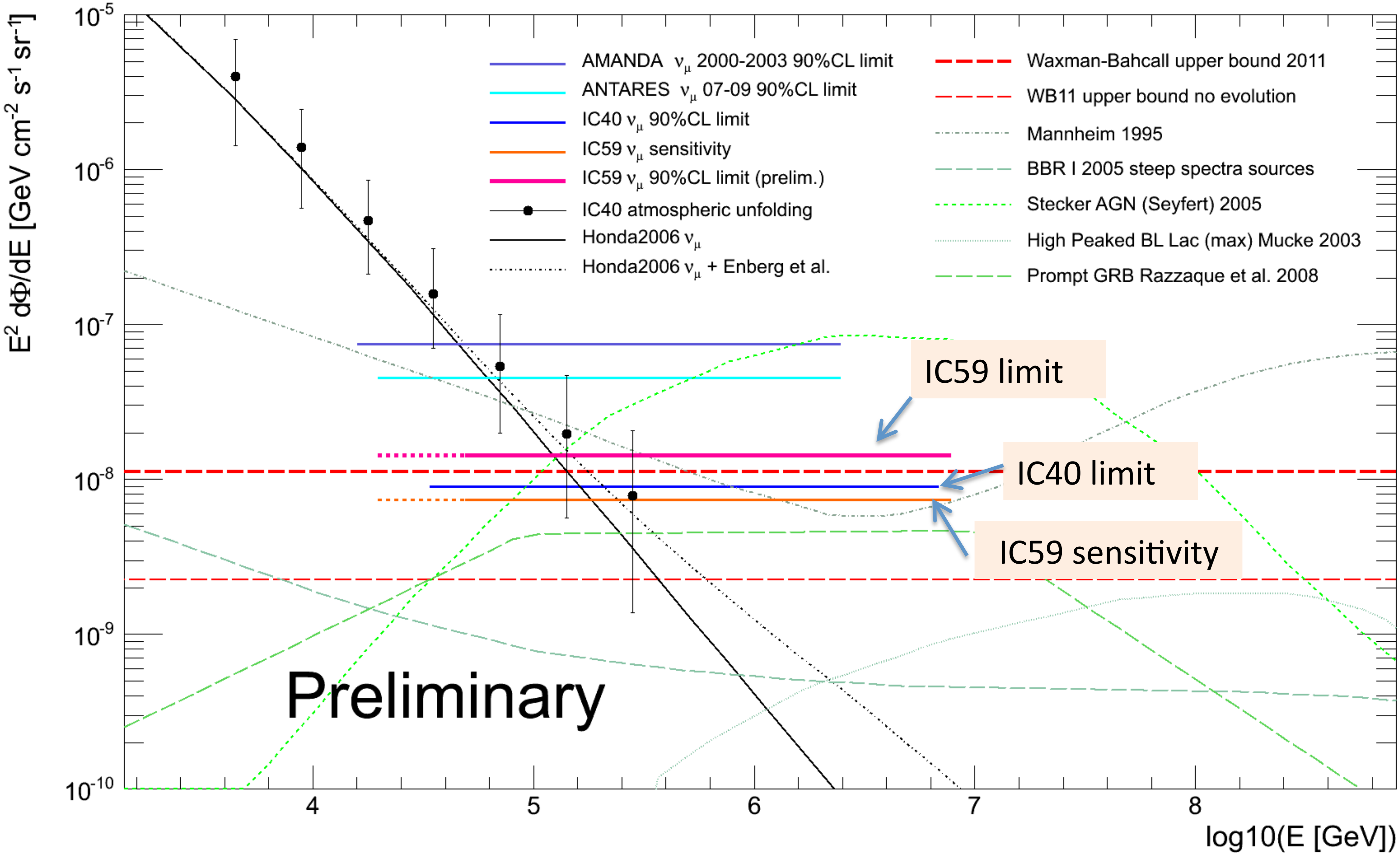
Livetime: 348 days Events: 21943



Highest Energy event in IC59 Diffuse muon neutrino sample



Current ν_μ Diffuse limits (single flavor)

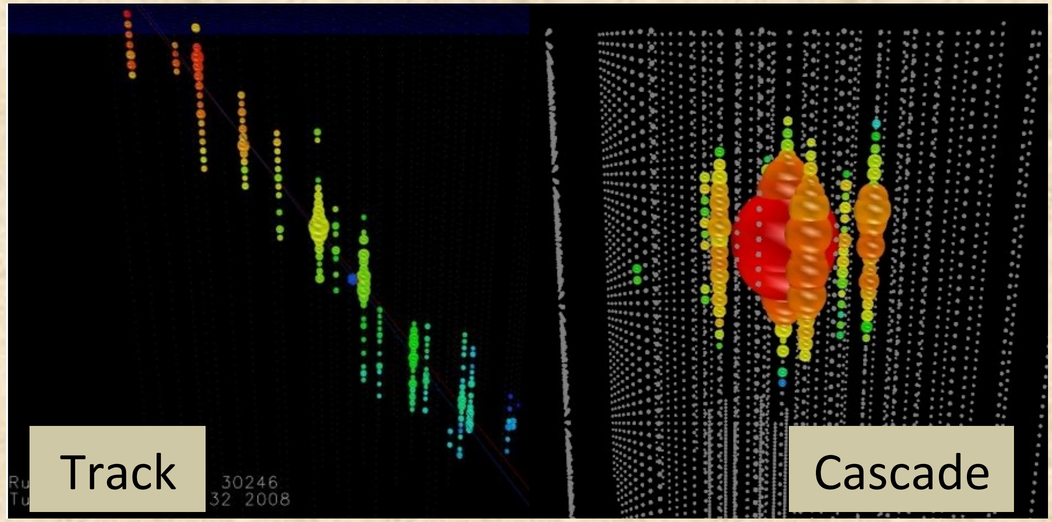


IC40 ν Cascade Diffuse Search

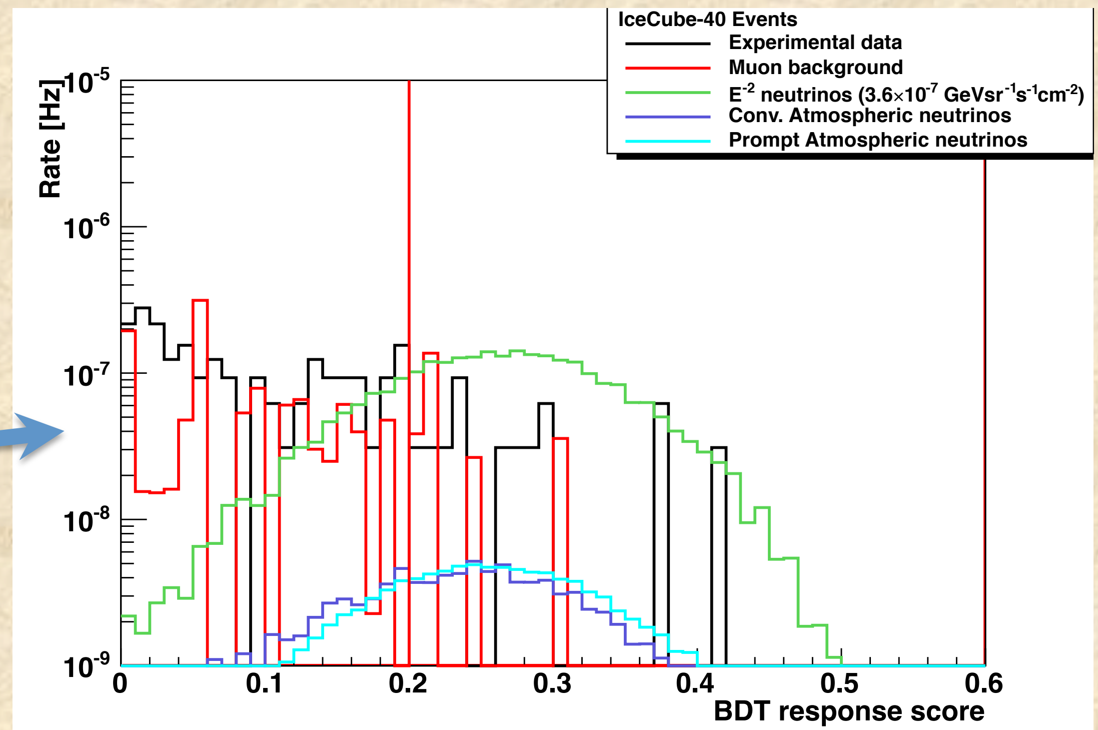
signal: ν induced particle showers (ν_e CC + all-flavor NC)

background: atm. μ

difficult background: atm. μ with catastrophic energy losses

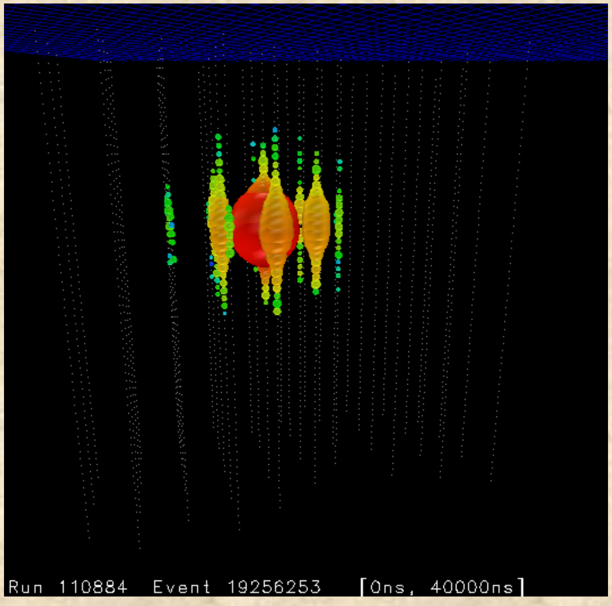


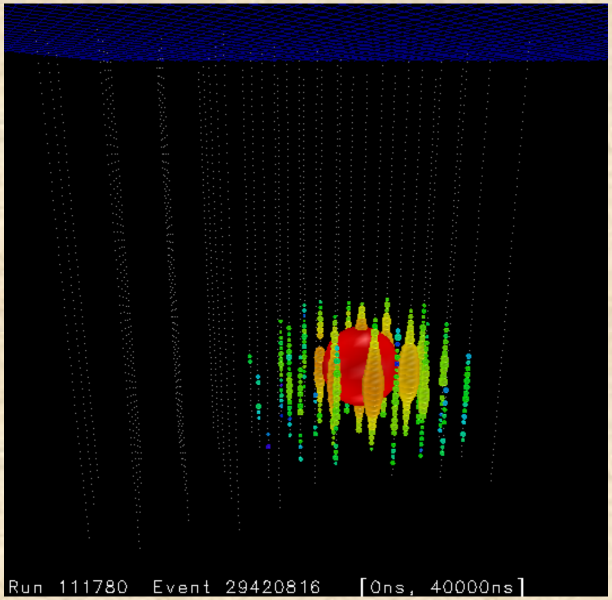
The analysis uses a Boosted Decision Tree optimized for removing atmospheric μ's



Will Improve with full Volume of IceCube, which is qualitatively a better detector for cascades!

IceCube 40-string search for neutrinos using cascade events

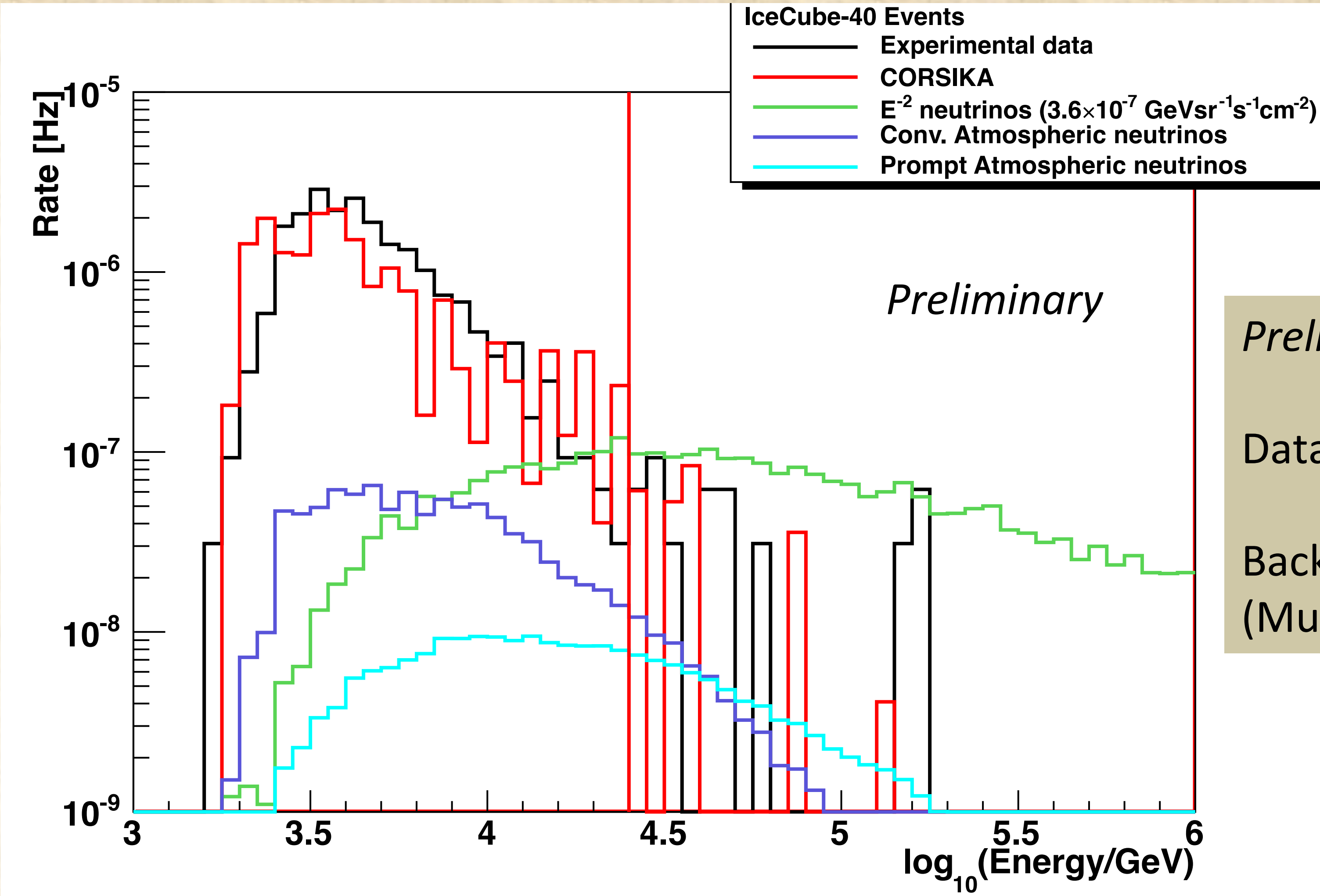




Found 14 “cascade” events after cuts in a total livetime of 373.6 days

Run	Date	BDT response	Energy
110860	18th April 2008	0.268	29 TeV
110862	19th April 2008	0.375	31 TeV
110884	23rd April 2008	0.416	175 TeV
110964	10th May 2008	0.230	27 TeV
111076	29th May 2008	0.225	41 TeV
111113	5th June 2008	0.380	174 TeV
111281	7th July 2008	0.293	31 TeV
111558	30th August 2008	0.232	45 TeV
111780	16th October 2008	0.236	144 TeV
111917	8th November 2008	0.279	32 TeV
112406	14th January 2009	0.203	47 TeV
112782	6th February 2009	0.219	57 TeV
113693	12th May 2009	0.295	40 TeV
113802	17th May 2009	0,281	27 TeV

IC40 Diffuse Cascade Search Results



Preliminary

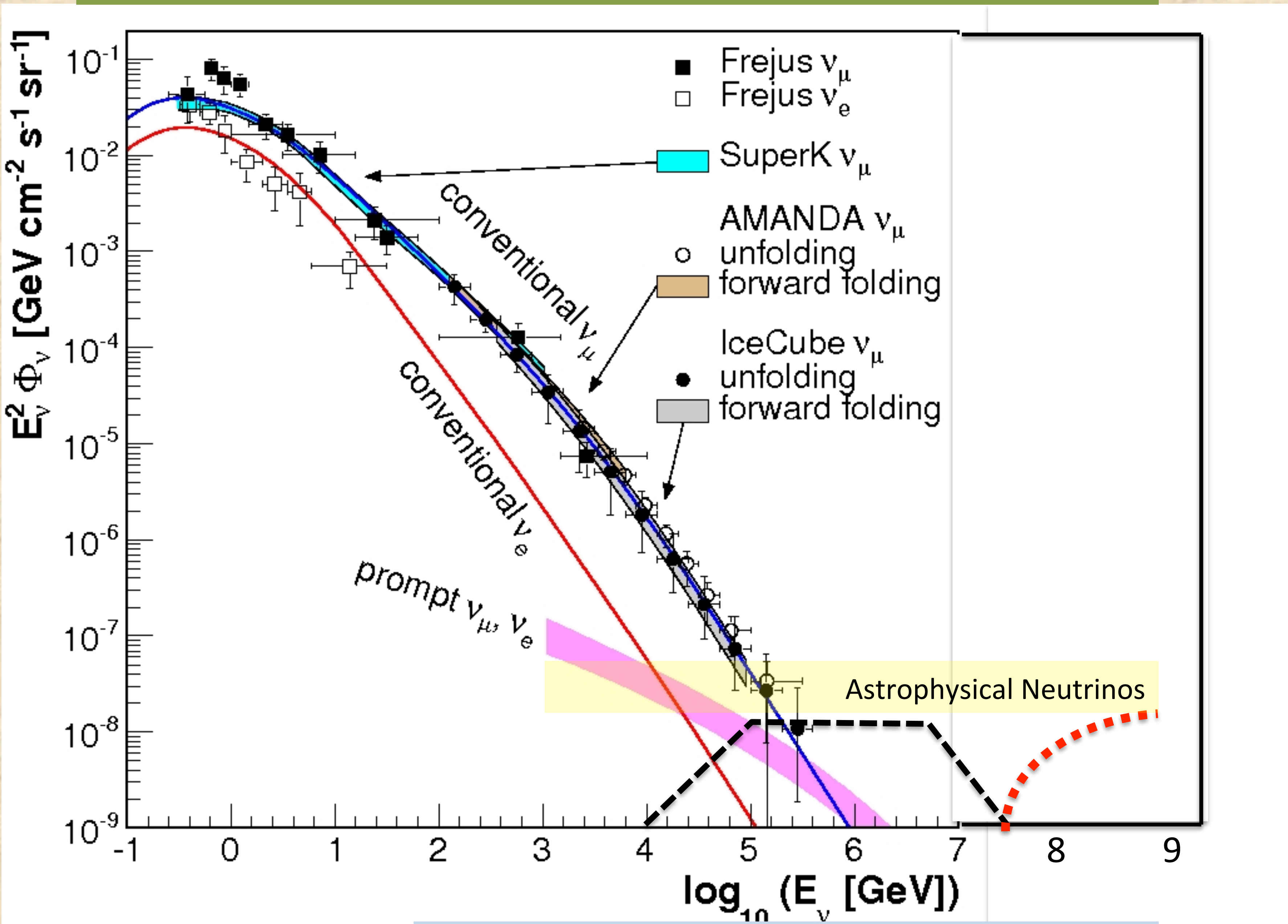
Data: 14 events

Backgrnd: 11.6 events
(Muons & Atm. Neutrinos)

Summary of IceCube diffuse astrophysical neutrino searches

- Progress in both muon and cascade channels
- IC 40-string data
  - ν_μ results published
  - Preliminary results for cascade search
- IC 59-string data
  - ν_μ preliminary results
- IceCube has achieved sensitivity below Waxman-Bahcall with data from partial detector
  - Upward fluctuation in 59-string data?
- We have accumulated 2+ years of data with “full” detector (79, 86)
  - Sensitivity well below W-B.

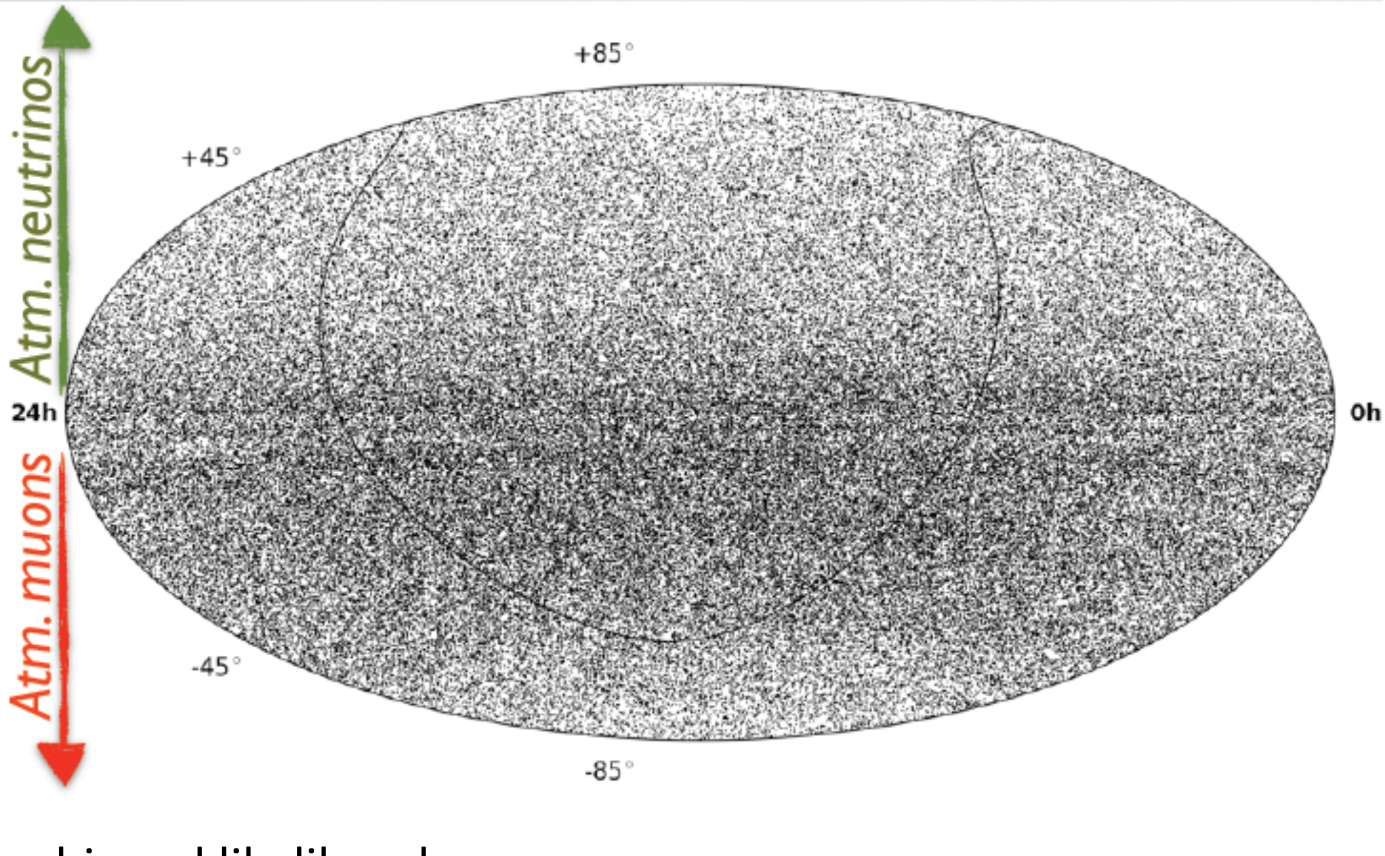
Search Strategies for Astrophysical Neutrinos

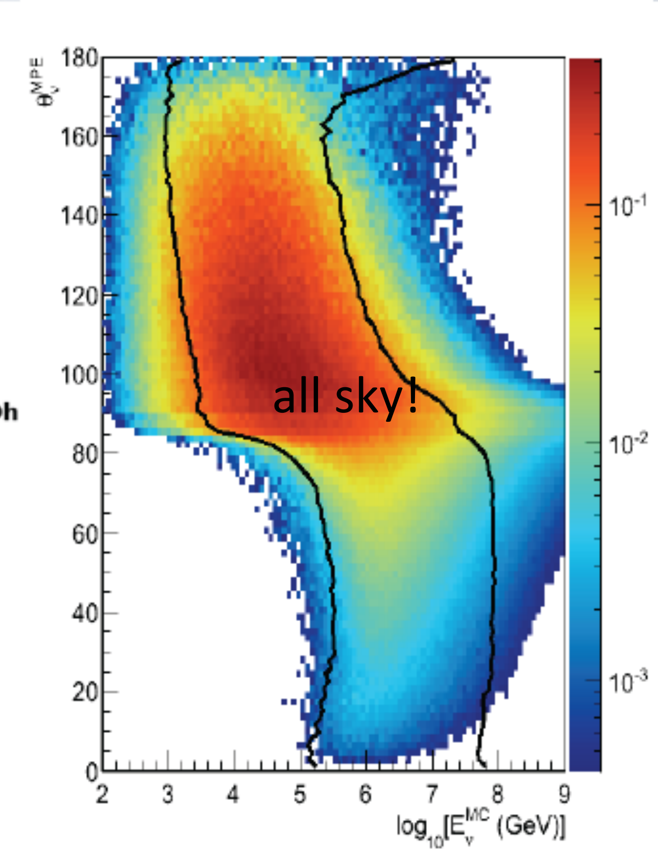


2) Point Source & GRB search use direction [and] timing to look for signal above isotropic atmospheric neutrino background

Point Source Search in Skymap (IC40+59)

43339 up-going + 64230 down-going from 723 days





unbinned likelihood

$$L(n_s, \gamma) = \prod_{i=1}^{N} \left(\frac{n_s}{N} S_i + \left(1 - \frac{n_s}{N}\right) B_i \right)$$

signal term contains angular and energy pdf

test statistics:

$$\lambda = \frac{L(\hat{n}_s, \hat{\gamma})}{L(n_s = 0)} \Rightarrow \text{p} - \text{value}$$

IceCube selected sources

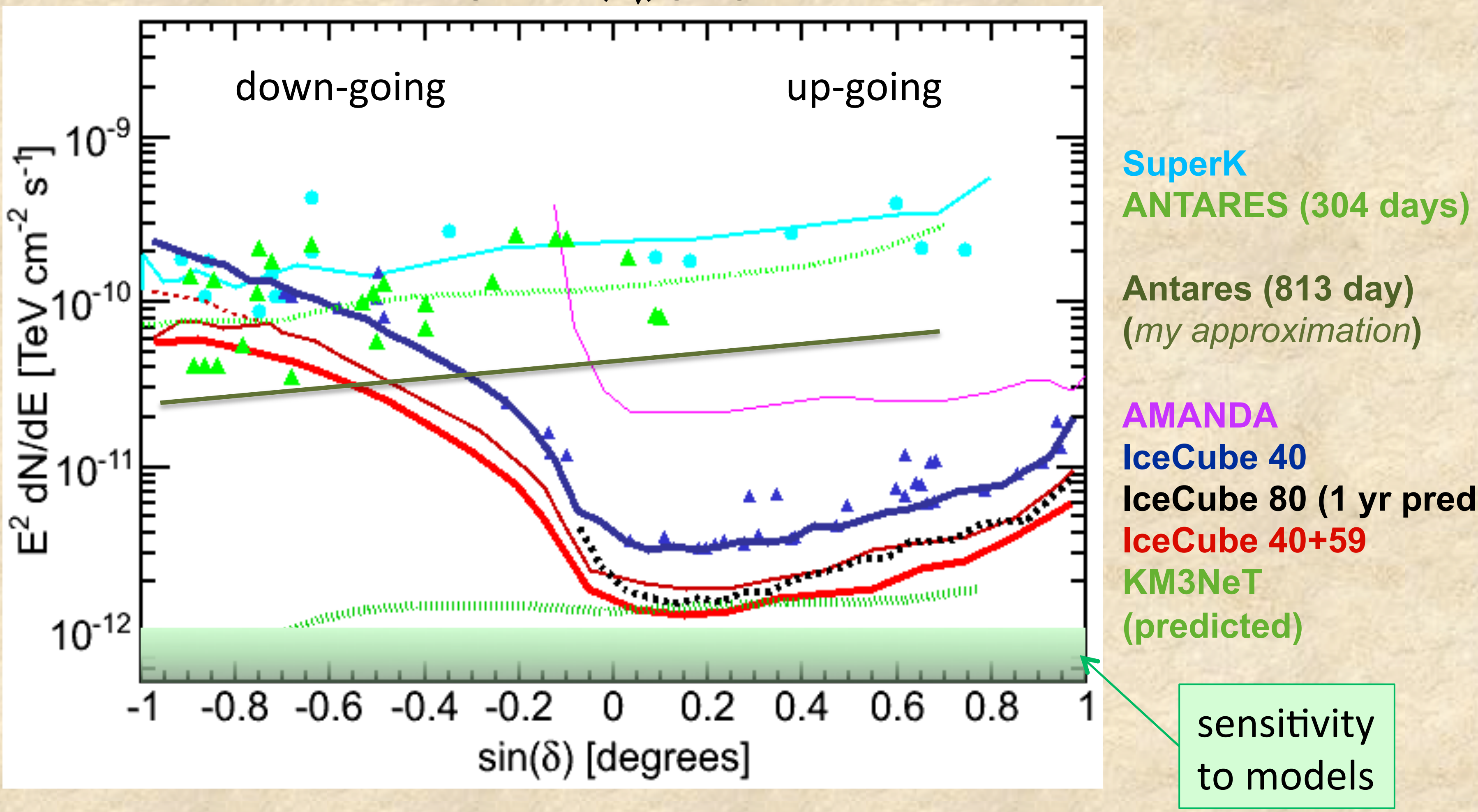
(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

No significant detections at this point

Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	--
MGRO J2019+37	305.22	36.83	PWN	-	--
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	--
IC443	94.18	22.53	SNR	1.5 kpc	--
Geminga	98.48	17.77	Pulsar	100 pc	--
Crab Nebula	83.63	22.01	SNR	2 kpc	--
1ES 1959+650	300.00	65.15	HBL	z = 0.048	--
1ES 2344+514	356.77	51.70	HBL	z = 0.044	--
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	--
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	--
W Comae	185.38	28.23	HBL	z = 0.1020	--
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	--
3C 123.0	69.27	29.67	FRII	1038 Mpc	--
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3
PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	--
3C 273	187.28	2.05	FSRQ	z = 0.158	--
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	--
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	***201.37***	***-43.02***	***FRI***	***3.8 Mpc***	***0.14***
PKS 1454-354	***224.36***	***-35.65***	***FSRQ***	***z = 1.42***	***0.14***
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	--
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	--
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	--
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	--
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	--
Cyg X-3	308.11	40.96	MQSO	9 kpc	--
LSI 303	40.13	61.23	MQSO	2 kpc	--
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

Neutrino Point Source Upper Limits

90% CL sensitivity for $\Phi(E_\nu)$ proportional to E^{-2}

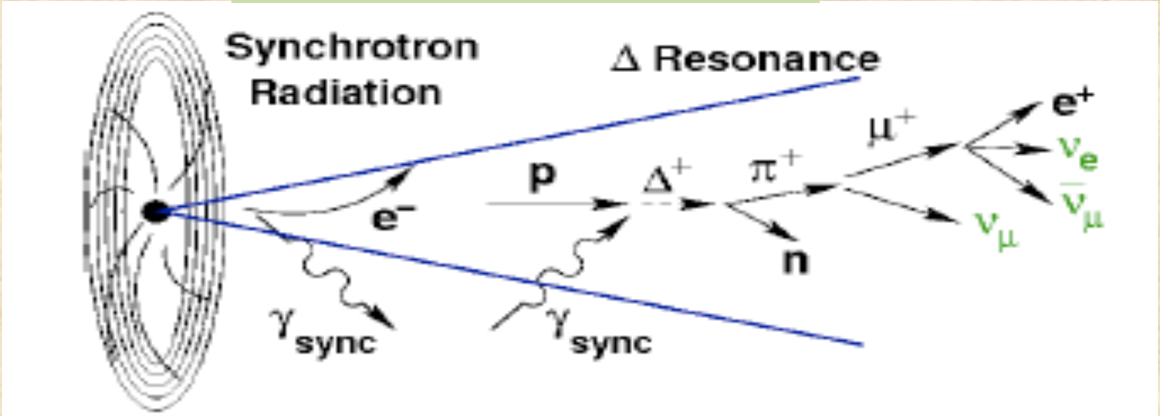


IceCube was designed to need several years data of full detector for sensitivity to point source detection

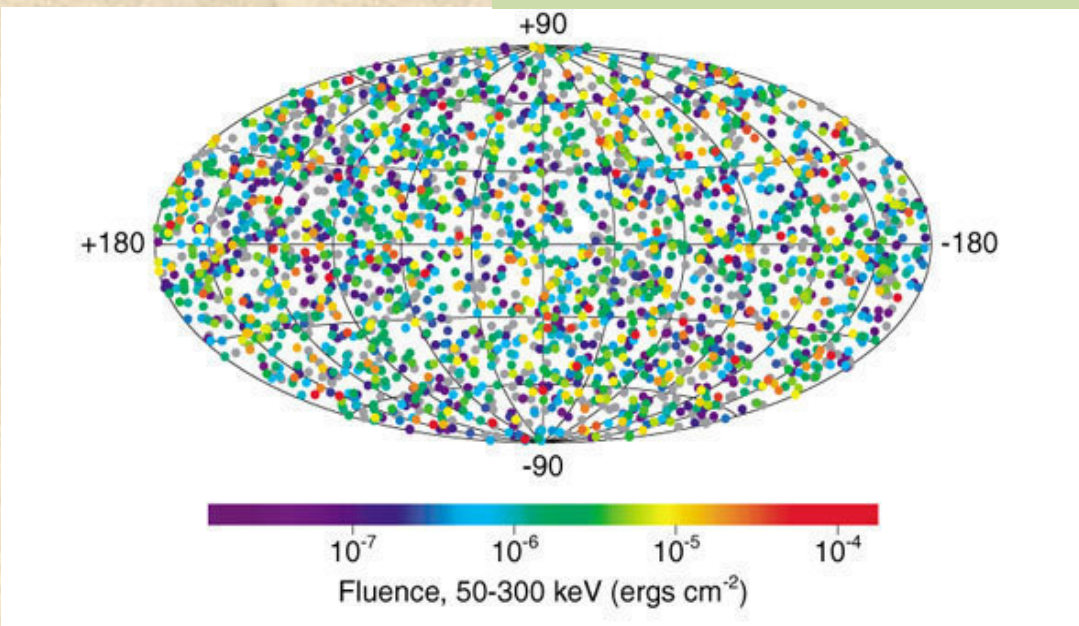
Gamma Ray Bursts

- 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
- Several generations of satellite-based observations have shown:
  - Extra-galactic origin
  - Gamma-ray emission beamed
- 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

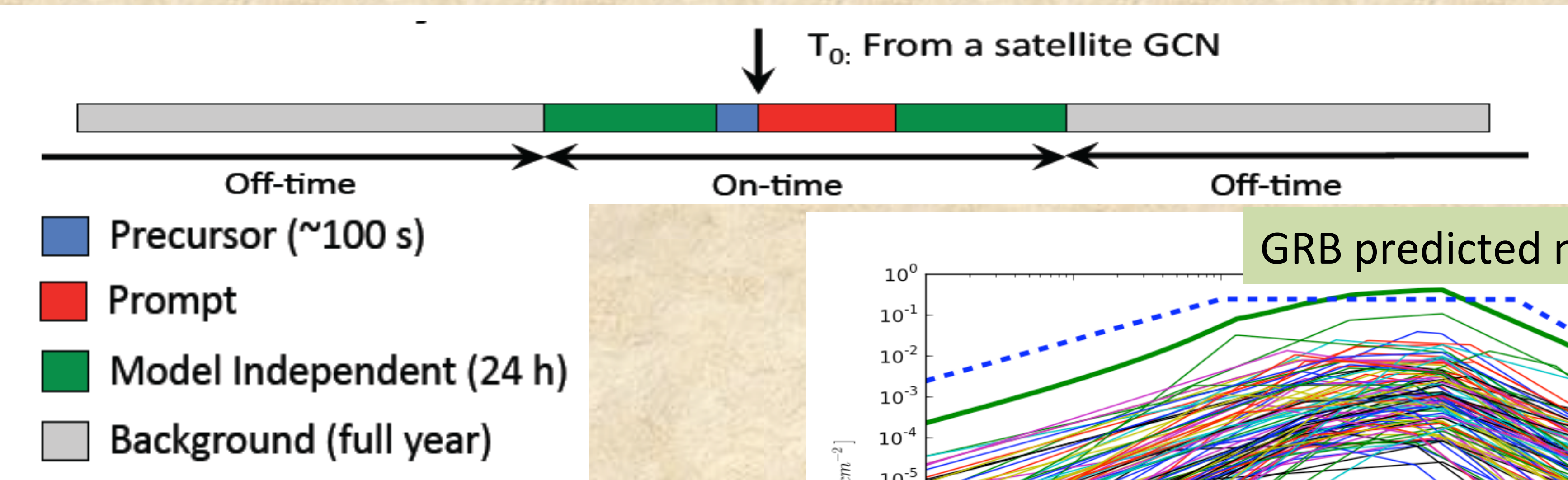
Beamed emission in Jet



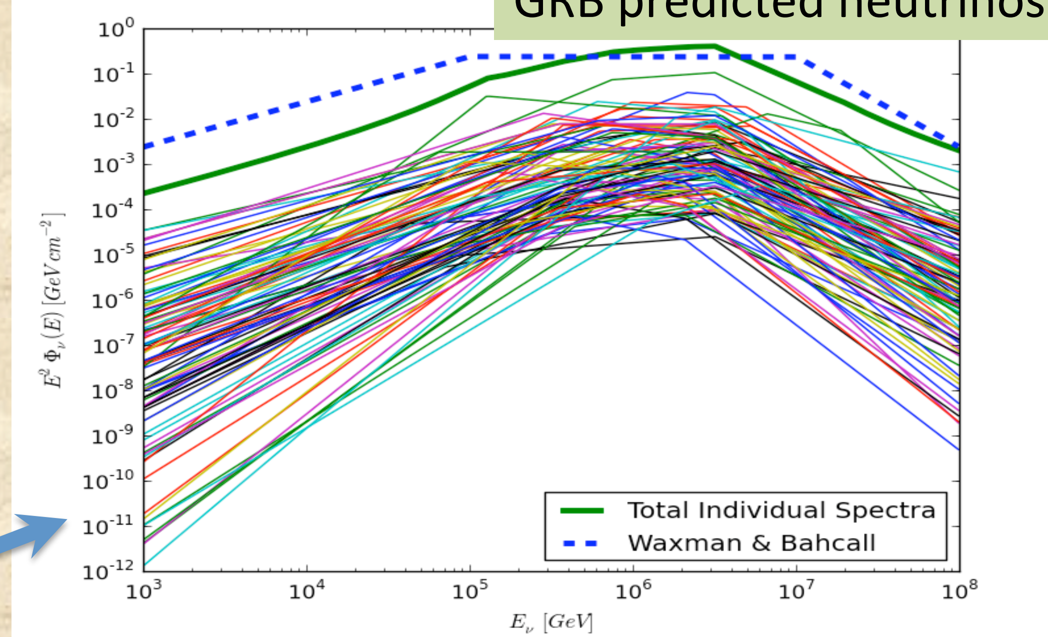
GRB in Gamma-Rays



- Model dependent stacked search for a neutrino signal in coincidence with observed GRB gamma signals
  - Northern hemisphere GRB bursts are considered.
  - Spatial & time correlation yields very low background ***(~Background Free Search)***
  - Per-burst neutrino fluence and spectra are calculated based on the measured gamma-ray spectra. (Guetta, et al. (2004))
- Model independent search more generic on wider time-scale
  - Up to ± 1 day and with generic (E^{-2}) spectrum
  - Includes Southern hemisphere for IC59

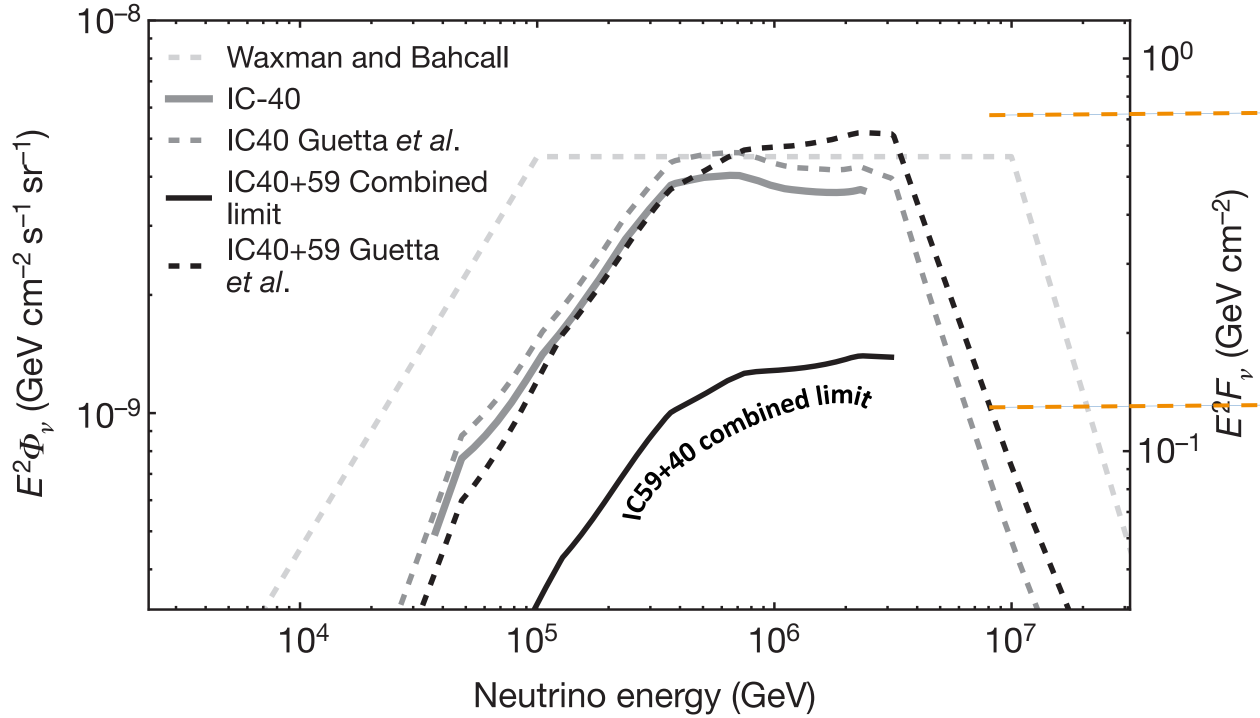


GRB predicted neutrinos



per-burst predicted neutrino flux for Guetta et al fireball (model dependent search)

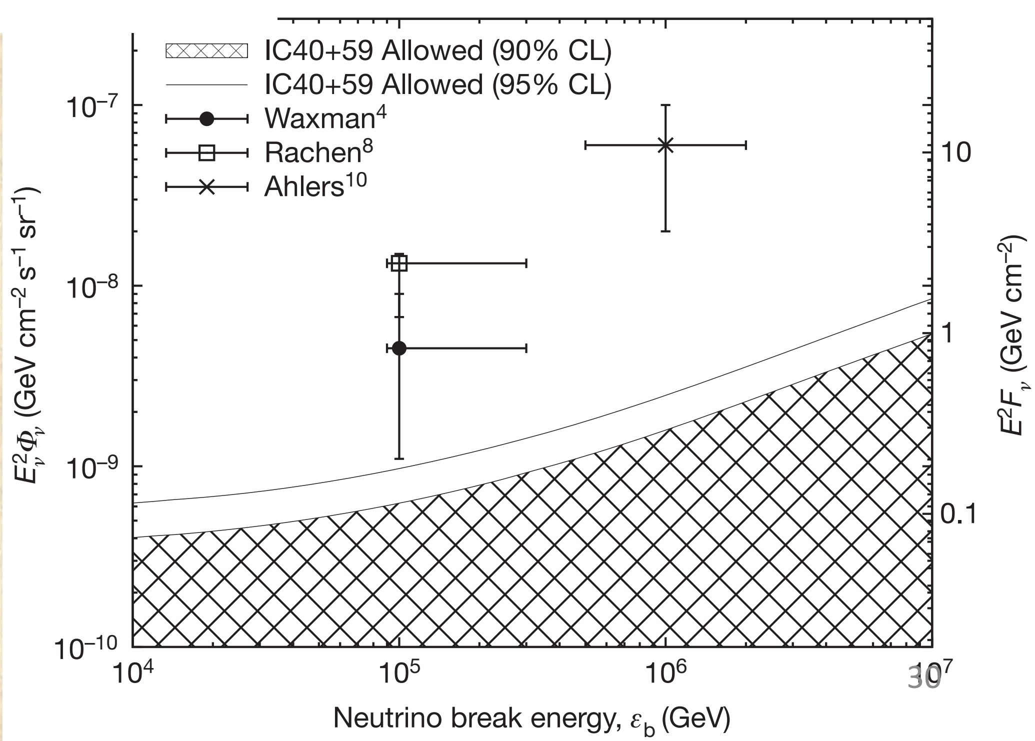
IC40 + IC59 GRB Search Results



90% c.l. = 0.27 model

8.4 events expected
0 events observed

Nature **Vol 484**, 351 (2012)

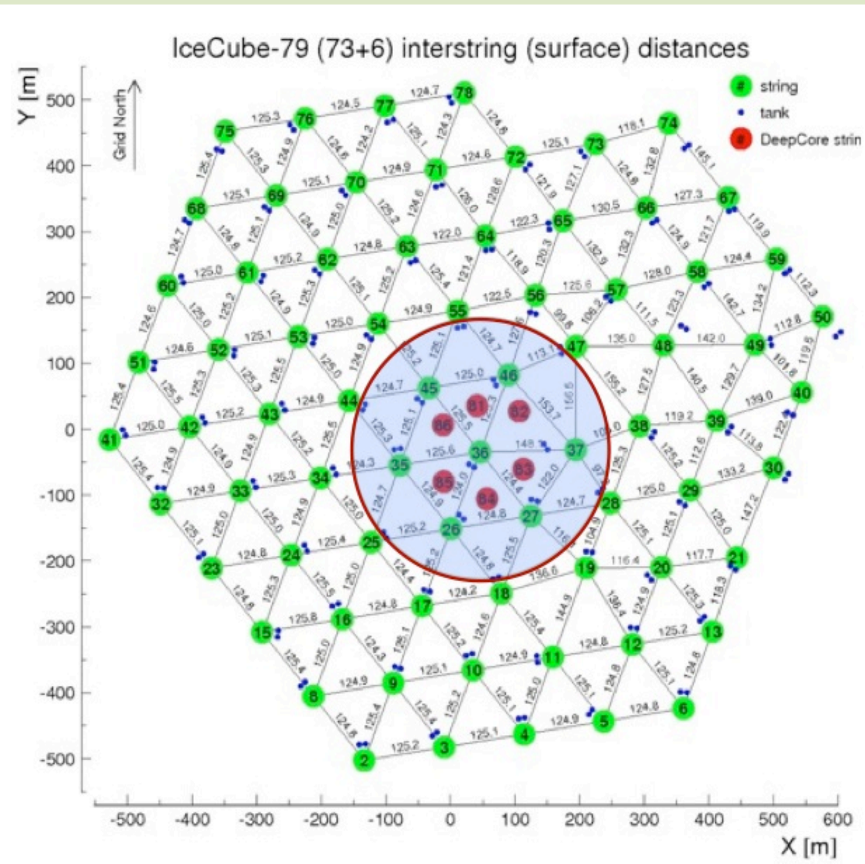


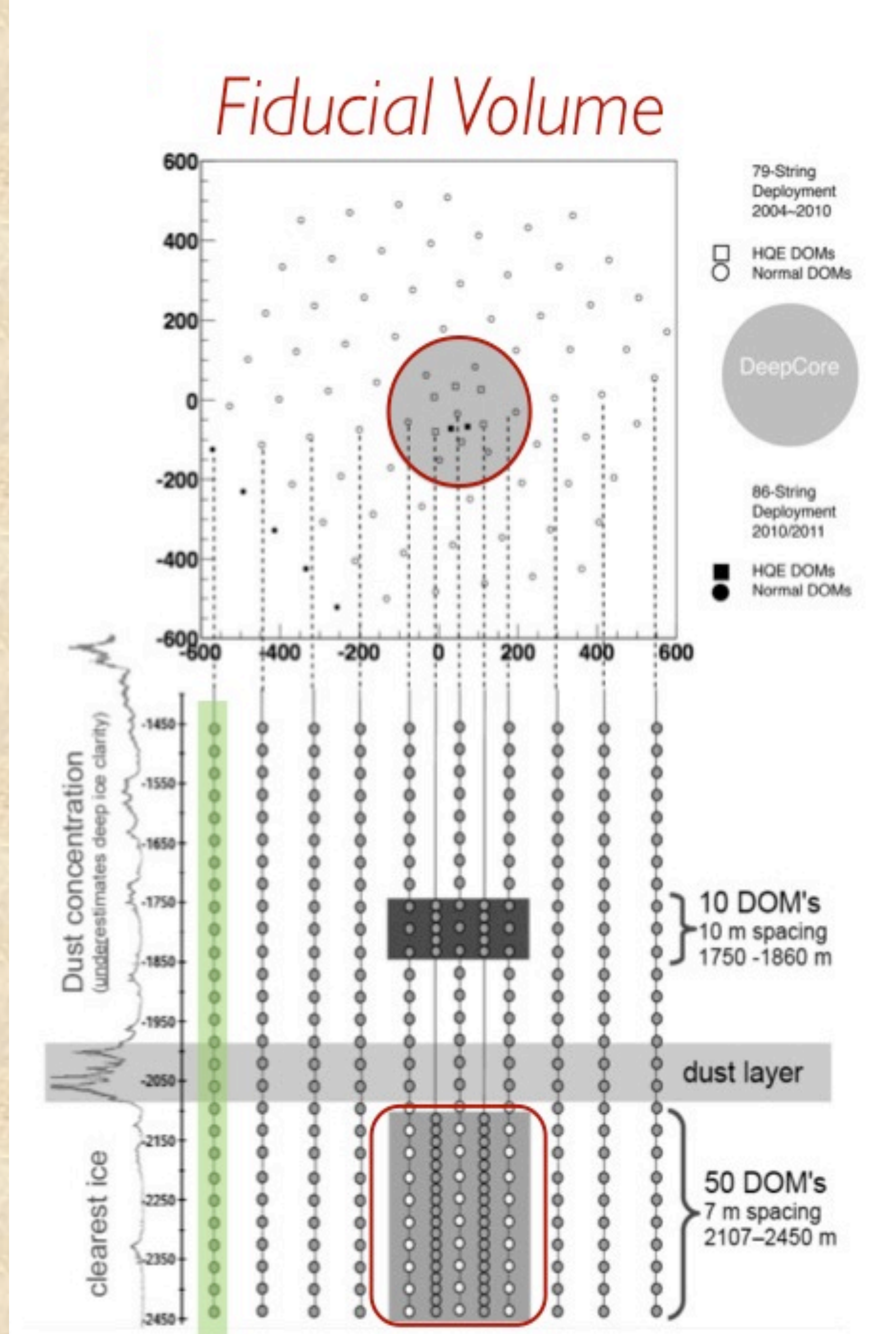
IceCube GRB Summary

- 3 Yrs (IC22, 40, 59) without a GRB neutrino detection
- Combined (IC40, IC59) search results → *Nature Paper*
  - *Guetta et al fireball:* Expect 8.4 events, see 0 → *0.27*
  - *Model independent search: no detection*
- ***Where are the neutrinos?***
  - GRB fireball neutrino flux
    - Theory in Fireball model is being revisited
    - Recalculations change predicted neutrino significantly
  - GRBs as the origin of cosmic rays excluded in some models
    - E.g. neutron models where neutrino flux is strongly coupled to the observed cosmic ray flux
- IC79, 86-I already recorded 86-2 will go near real-time
  - Sensitivity scales linearly with exposure
  - Waiting for neutrinos from GRBs!

IceCube Deep Core (low energy & contained events)

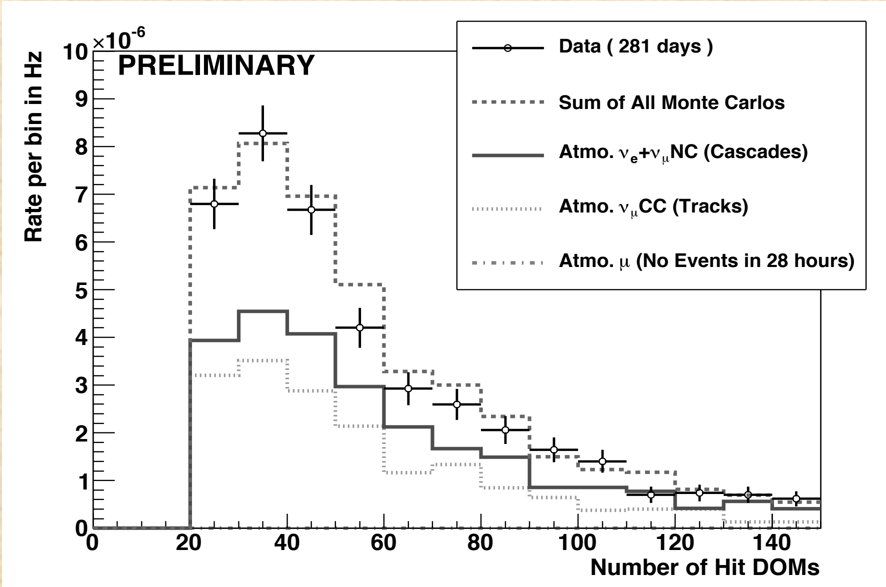
Motivation:
- Low mass WIMP search (indirect DM)
- Neutrino oscillation physics
  - extend LE, ν_μ disappearance, ν_τ appearance
- southern hemisphere →4π detector

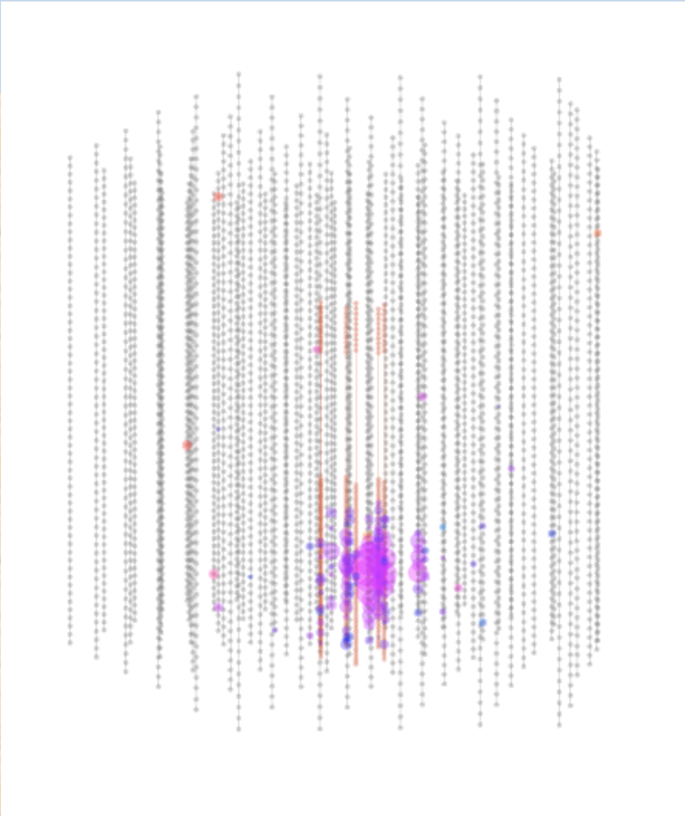


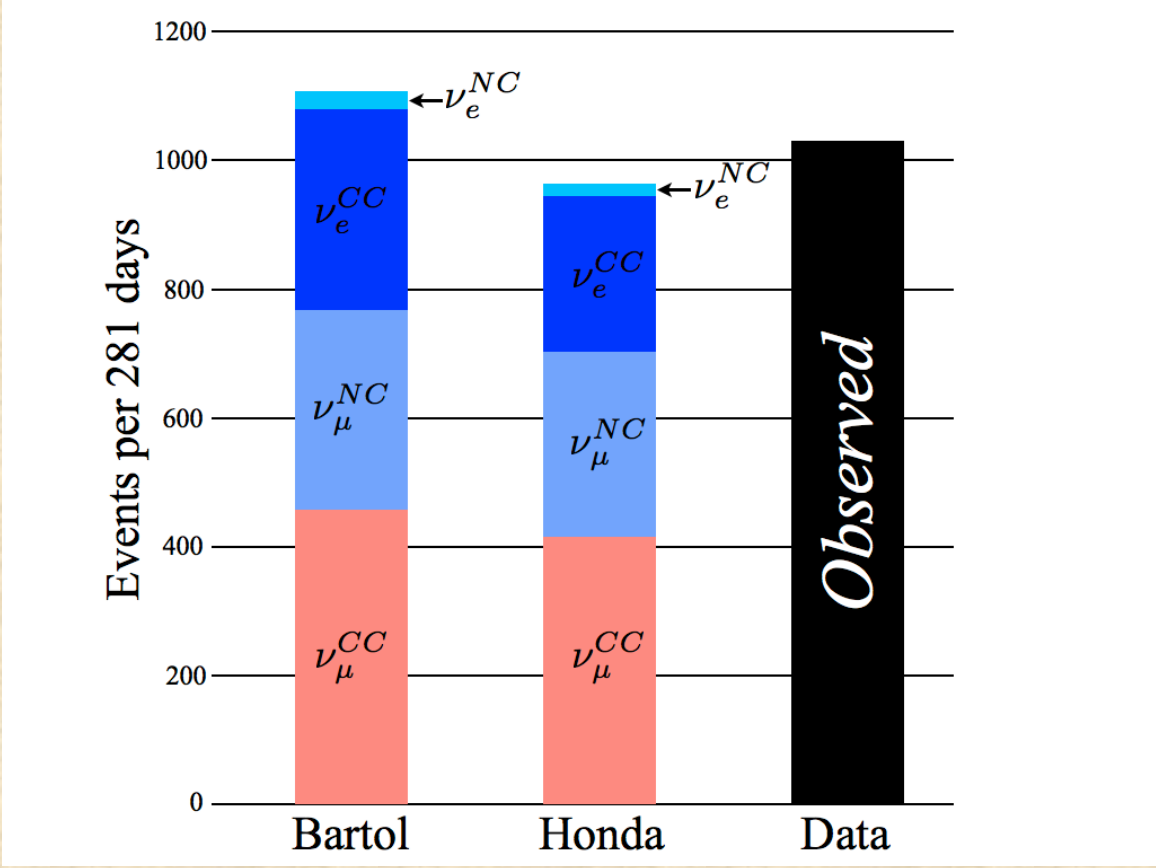


Low Energy Cascades (DeepCore)

- Cascades are the signature of neutral current, ν_e and ν_τ
- First observation of atmospheric neutrino-induced cascades in IC79 with DeepCore

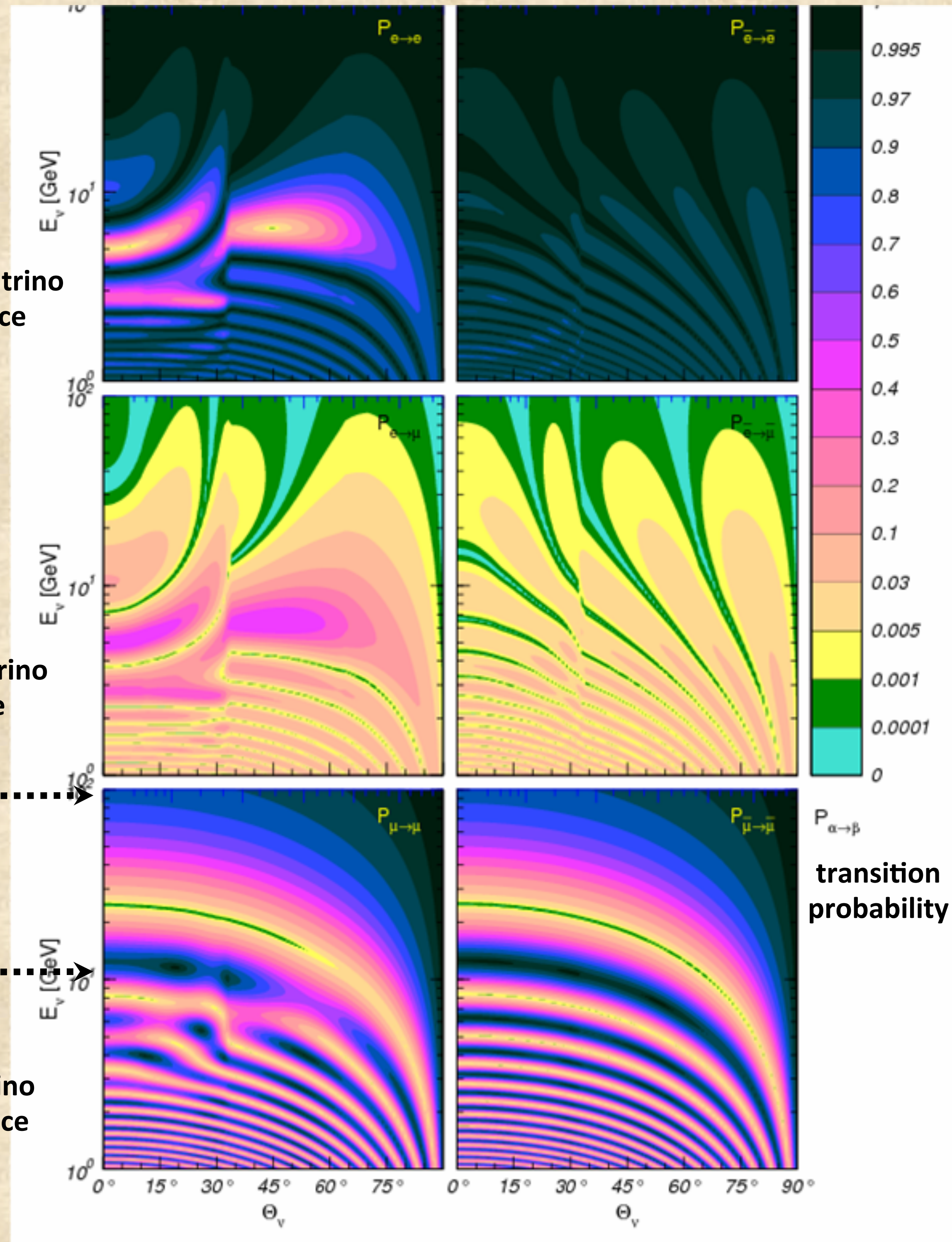






Standard Atmospheric Neutrino Oscillation in the energy region of interest for DeepCore

neutrino energy–nadir angle plane



electron neutrino disappearance

muon neutrino appearance

DeepCore energy region

muon neutrino disappearance

transition probability

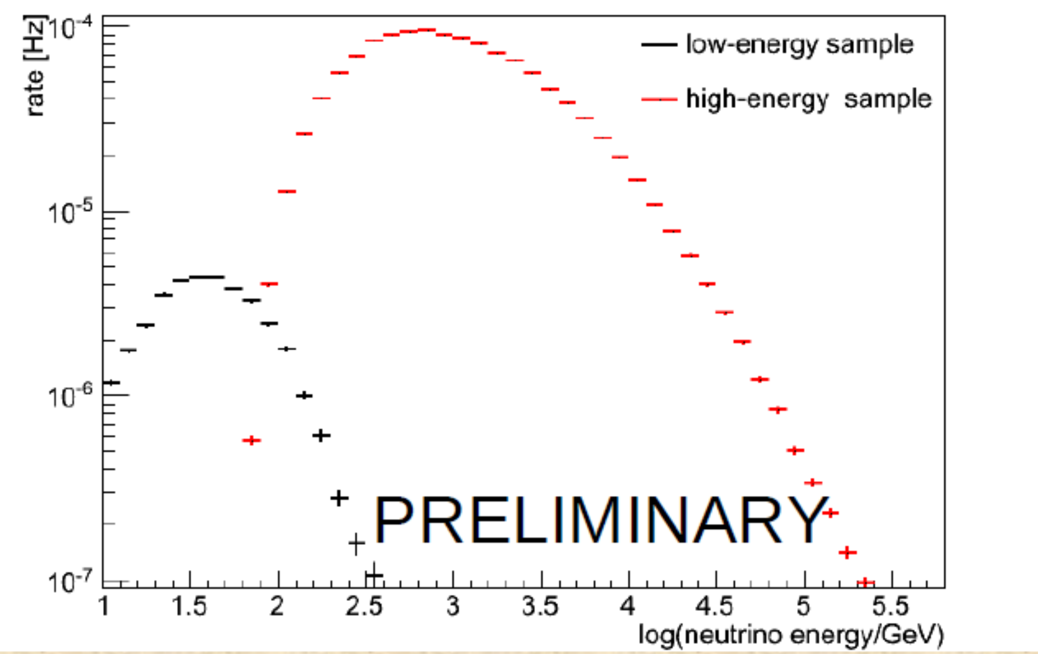
Neutrino oscillogram of the Earth from Akhmedov-Maltoni-Smirnov modified from arXiv:hep-ph/0612285v2 (private communication).

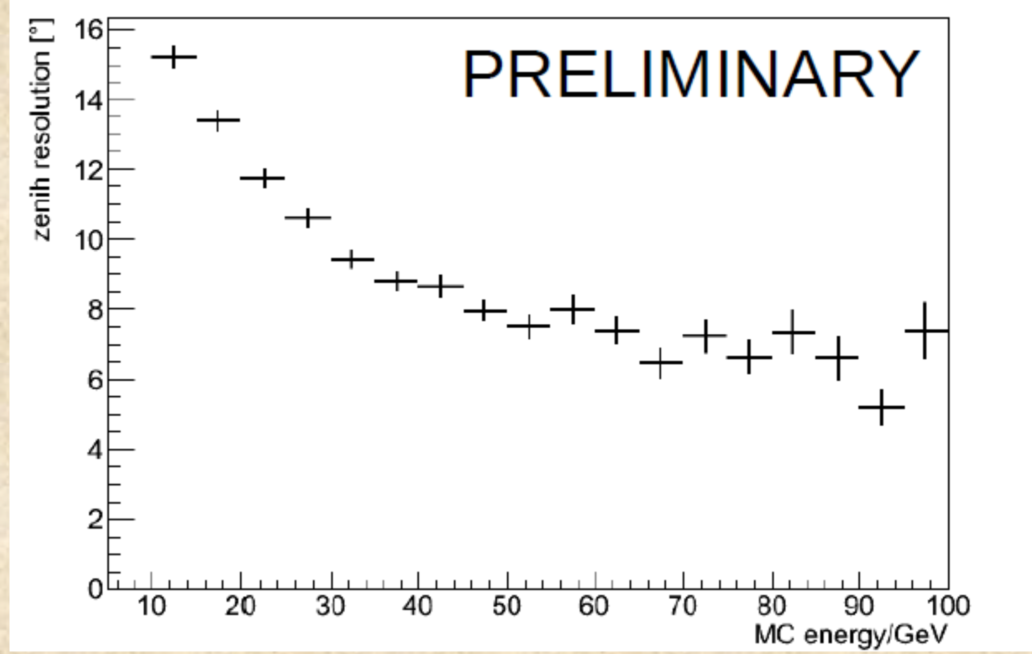
IceCube: First Step in Neutrino Oscillation Physics

- Strategy was to make **simple** cuts and reconstruction in Deep Core to extend sample to Low energies and look for consistency with standard neutrino oscillations.
- Not optimized for DeepCore efficiency, angular resolution,…
- Ongoing Work: more "sophisticated" analysis for measurement of oscillation parameters

	Data (317.9 days)	MC, std oscillation	MC, no oscillation
Low energy	719	789 +- 28 (stat)	1015 +- 32 (stat)
High energy	39639	33710 +- 770 (stat)	33810 +- 770 (stat)

IceCube DeepCore 79 Strings

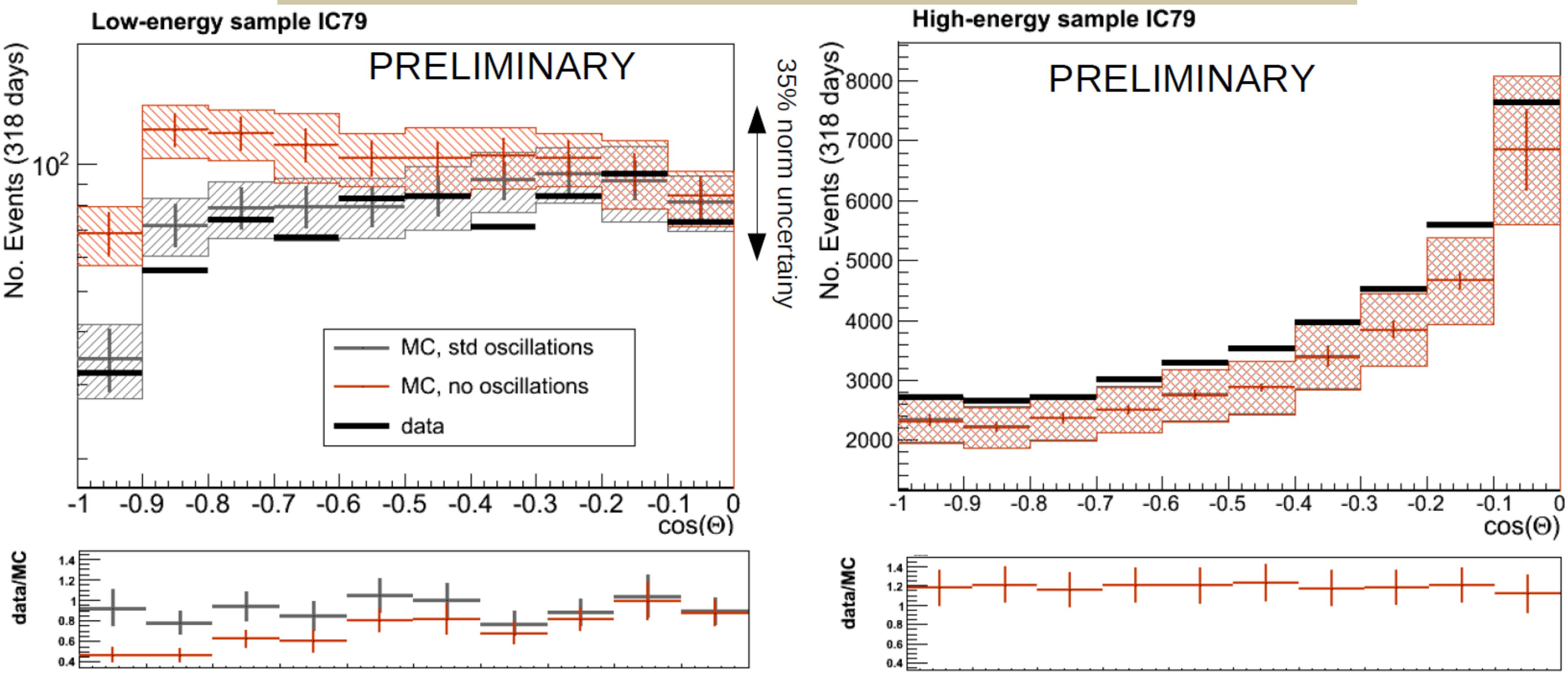




Zenith Angle Distribution

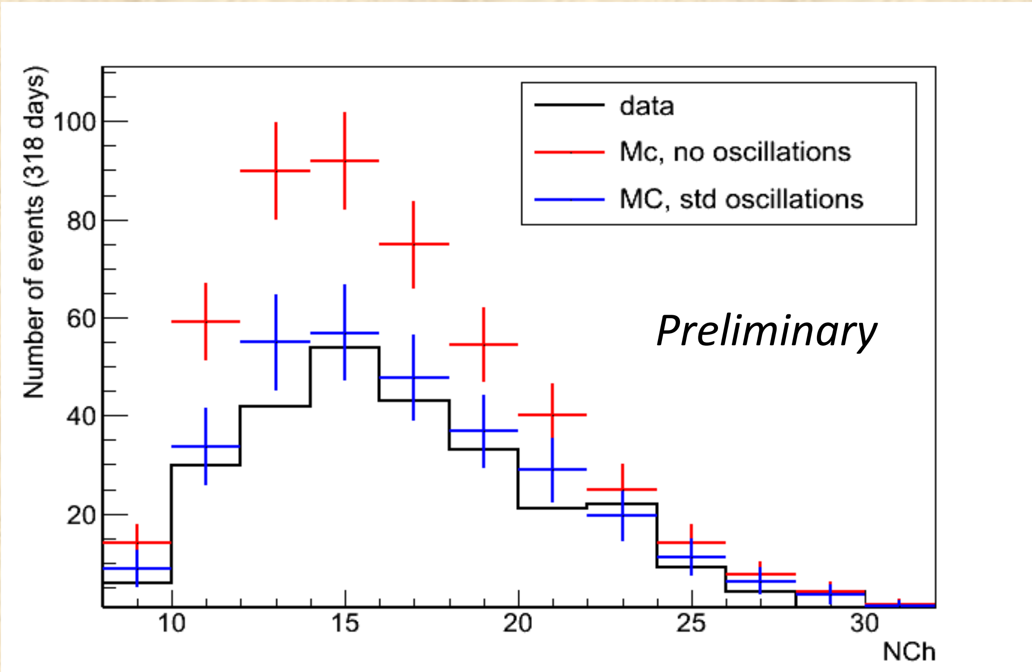
IceCube ν_μ disappearance

$\chi^2 = 52.7$ (no oscillation) $\chi^2 = 19.4$ (std. oscillation) dof=20



delta chi-square = 33.3, p-value = 1 x 10^{-8}

Cross Check: The energy-proxy “Nchannel” distribution of the LE sample



Distribution of the number of hit DOMs for vertical events (cos(theta)<-0.55) of the low-energy event selection. *Errors are statistical only.*

- IceCube DeepCore has now explored the energy region where standard neutrino oscillation are expected with IC79
- the non-oscillation hypothesis is rejected with high statistical significance.
- Data are in good agreement with standard oscillation expected from global best fit mixing parameters available from the literature.
- Systematic effects have been investigated and factorized in normalization, correlated and uncorrelated terms.

IceCube and Neutrino Oscillations

- We plan to investigate the oscillation parameters and test non standard oscillation scenarios (like sterile neutrinos).
- More sophisticated reconstruction methods and an improved knowledge of the optical properties of the Antarctic deep ice will provide a reduction of the overall systematic uncertainty.
- The observation of atmospheric neutrino oscillation provide a starting point for the feasibility study of a next infill phase, Precision IceCube Next Generation Upgrade → PINGU.
- With 20 additional strings and a set of new calibration instruments, PINGU will target precise measurements in the atmospheric neutrino sector.

Neutrino Oscillations in PINGU?

PINGU is a concept for even higher density infill to DeepCore that lowers the energy range of IceCube to several GeV range with MT's effective volume

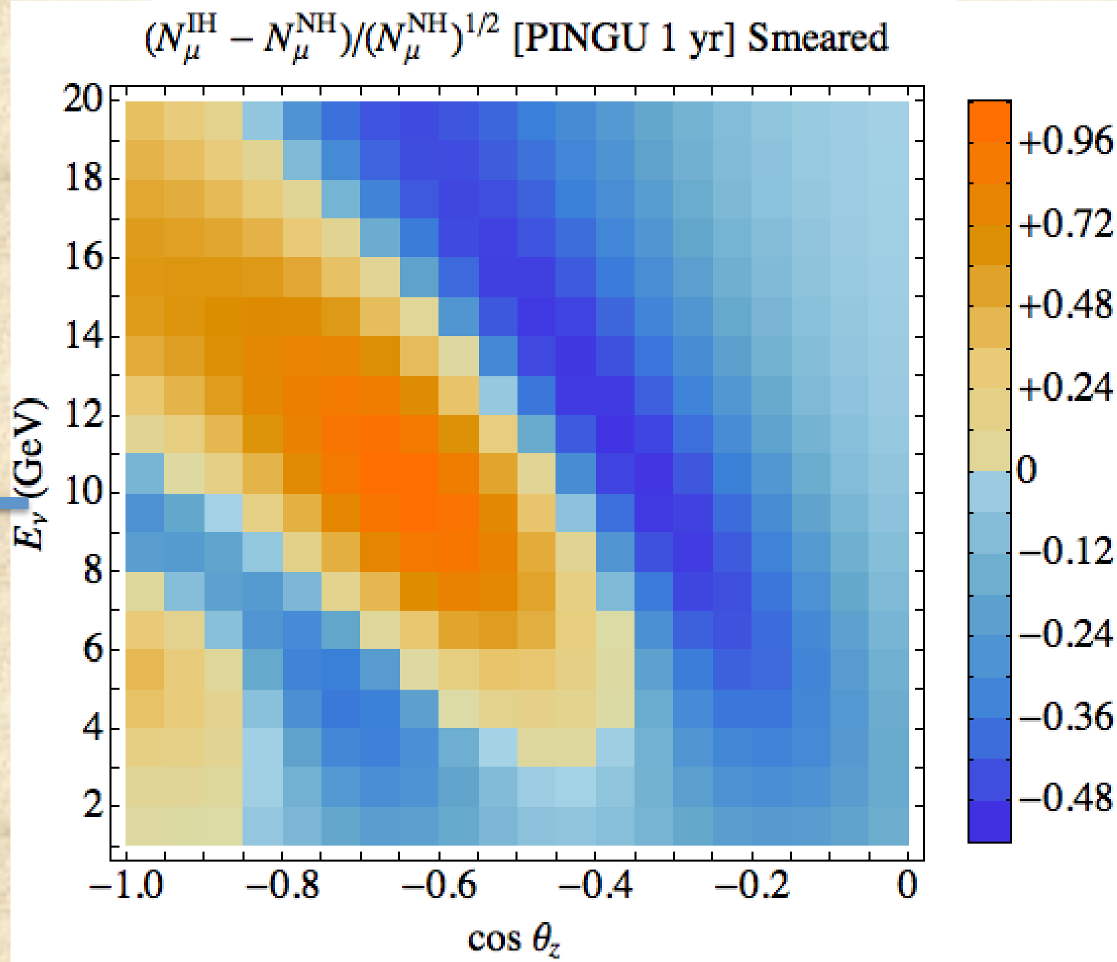
Ref: E. Kh. Akhmedov, S. Razzaque, A. Y. Smirnov arXiv:1205.7071 [hep-ph]

Statistical significance of Normal versus Inverted Mass Hierarchy.

Sets PINGU requirements on:

1) Energy Resolution
2) Angular Resolution
3) Systematic Errors

σ_E = 2 GeV, σ_θ = 11.25°



We are currently studying the feasibility of reaching the needed requirements.

3σ – 11σ in 5 Years of running

Includes systematic error ≤ 10%

Other Talks and Posters

- **Talks**

  IceCube: ultra-high energy neutrinos (A. Ishihara)

  A review of future experiments (A. Karle)

  A review of indirect WIMP search exp. (C. Rott)

- **Posters**
  - 11 – 2, Search for Neutrinos from The Galactic Plane and Other Astro-physical Extended Sources with IceCube. Naoko Kurahashi
  - 12 – 3, A search for the extremely high energy cosmogenic neutrinos with the IceCube 2010-2011 data. Keiichi Mase
  - 13 – 1, Searches for Neutrinos from GRBs with IceCube. Erik Blaufuss
  - 14 – 2, Extending IceCube-DeepCore with PINGU. Elisa Resconi, Darren R Grant
  - 15 – 3, Search for High-Energy Neutrino Point Sources with IceCube. Sirin Odrowski
  - 25 – 1, Supernova detection with IceCube and beyond. Ronald Bruijn
  - 29 – 2, Towards an extragalactic Supernova neutrino detector at the South Pole. Markus Voge
  - 40 – 1, Atmospheric neutrino oscillations with IceCube/DeepCore. Andreas Gross
  - 73 – 1, Determining the dark matter properties with neutrinos in Ice-Cube/DeepCore. C. R. Das
  - 74 – 2, Search for Dark Matter Captured in the Sun with the IceCube Neutrino Observatory. M. Danninger, C. Rott and E. Strahler
  - 75 – 3, Search for Dark Matter in Galactic and Extragalactic Halos with the IceCube Neutrino Observatory. Carsten Rott
  - 76 – 1, Search for Secluded Dark Matter using the IceCube Neutrino Observatory. Jonathan Miller

Summary

- ***IceCube has completed construction and has already surpassed expected performance.***

The era of km^3 neutrino telescopes has begun!

Neutrinos observed from ~10 GeV to ~1 PeV (5 orders of magnitude)

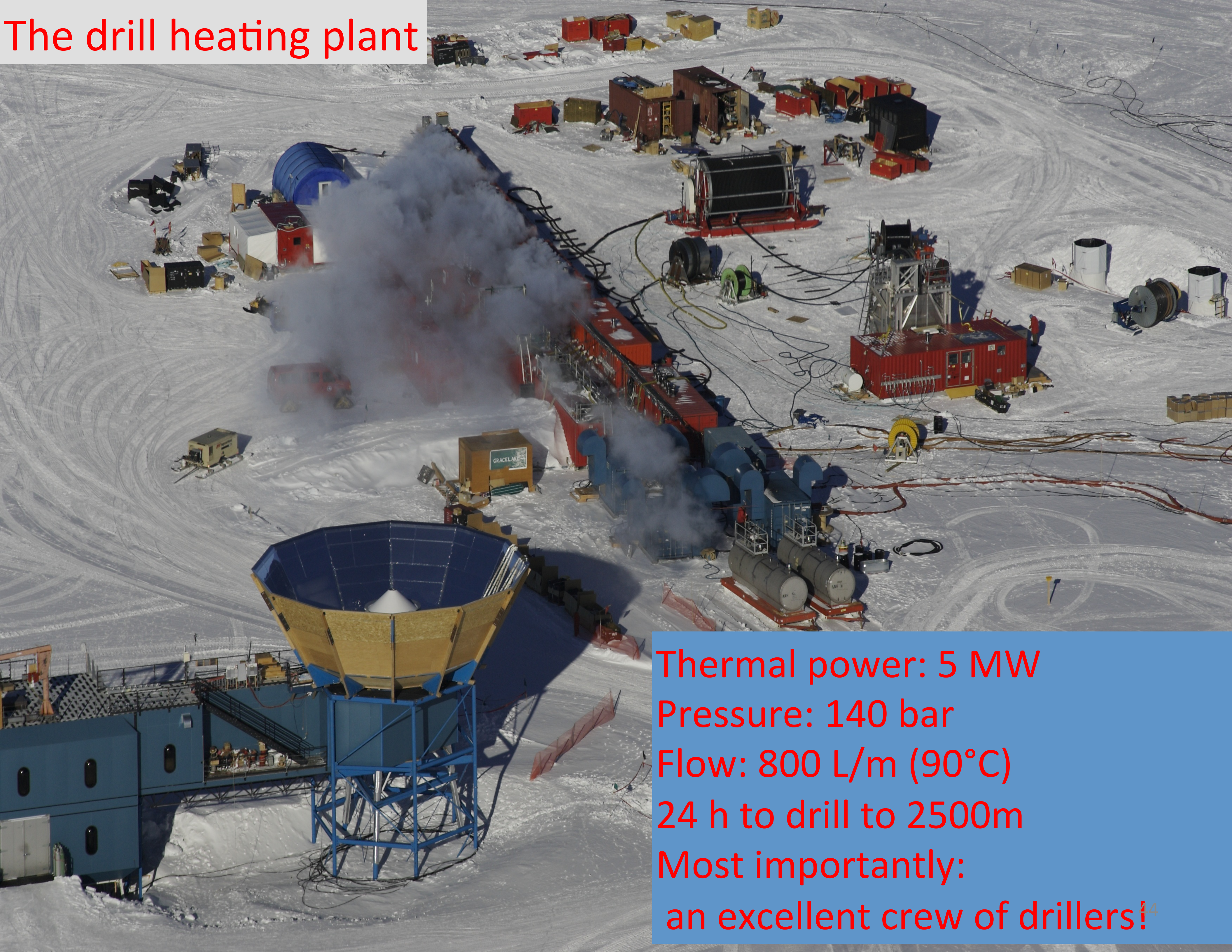
- ***After decades… IceCube detector (IC40 59, 79, 86) at sensitivities of Astrophysical importance***
  - **GRB limits challenging the models** *(Nature paper)*
  - **Diffuse at W-B bound: first HE astrophysical neutrinos?**
  - **EHE: in the range of GZK predictions** → *A. Ishihara's Talk*
  - point source limits all sky, time (in)dependent, candidate list,
  - WIMP limits (C. Rott's Talk), Monopole limit well below "Parker Bound"
  - Multi-messenger follow-up program (optical, X-ray, γ-ray, Gravity)
- ***Measurements:***
  - atmospheric neutrino and muon spectrum, lorentz invariance, neutrino oscillations
  - cosmic ray anisotropy on various angular scales, CR composition: IceCube/IceTop has unique capabilities
- ***Future Upgrades: exploit existing facility and infrastructure:*** → *A. Karle's Talk*
  - DeepCore: low energy extension (PINGU) → atmospheric neutrino oscillations,
  - Non-IceCube opportunities: high energy GZK with radio, DM-Ice

Stay tuned !

Thank You

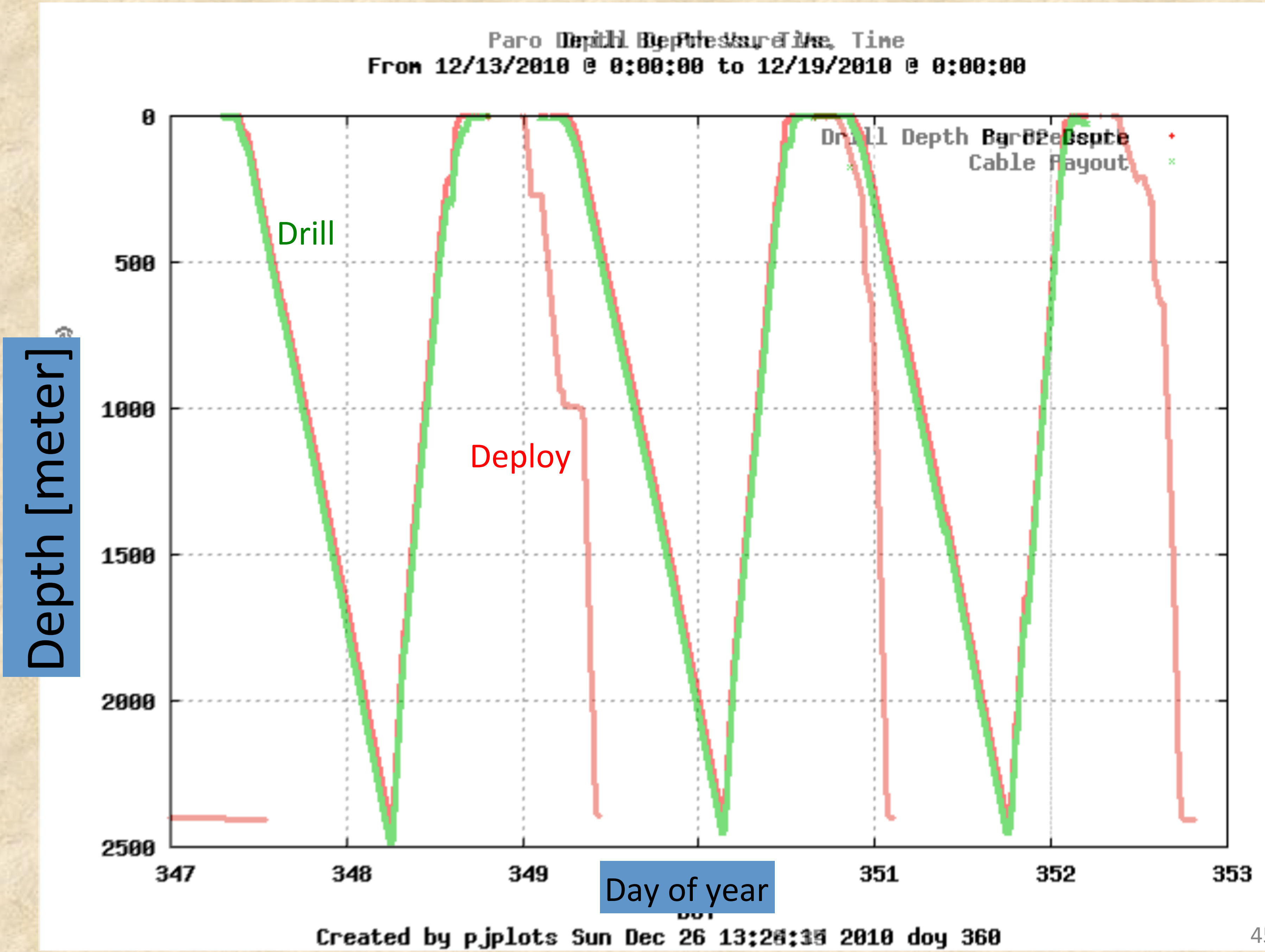
Backup

The drill heating plant



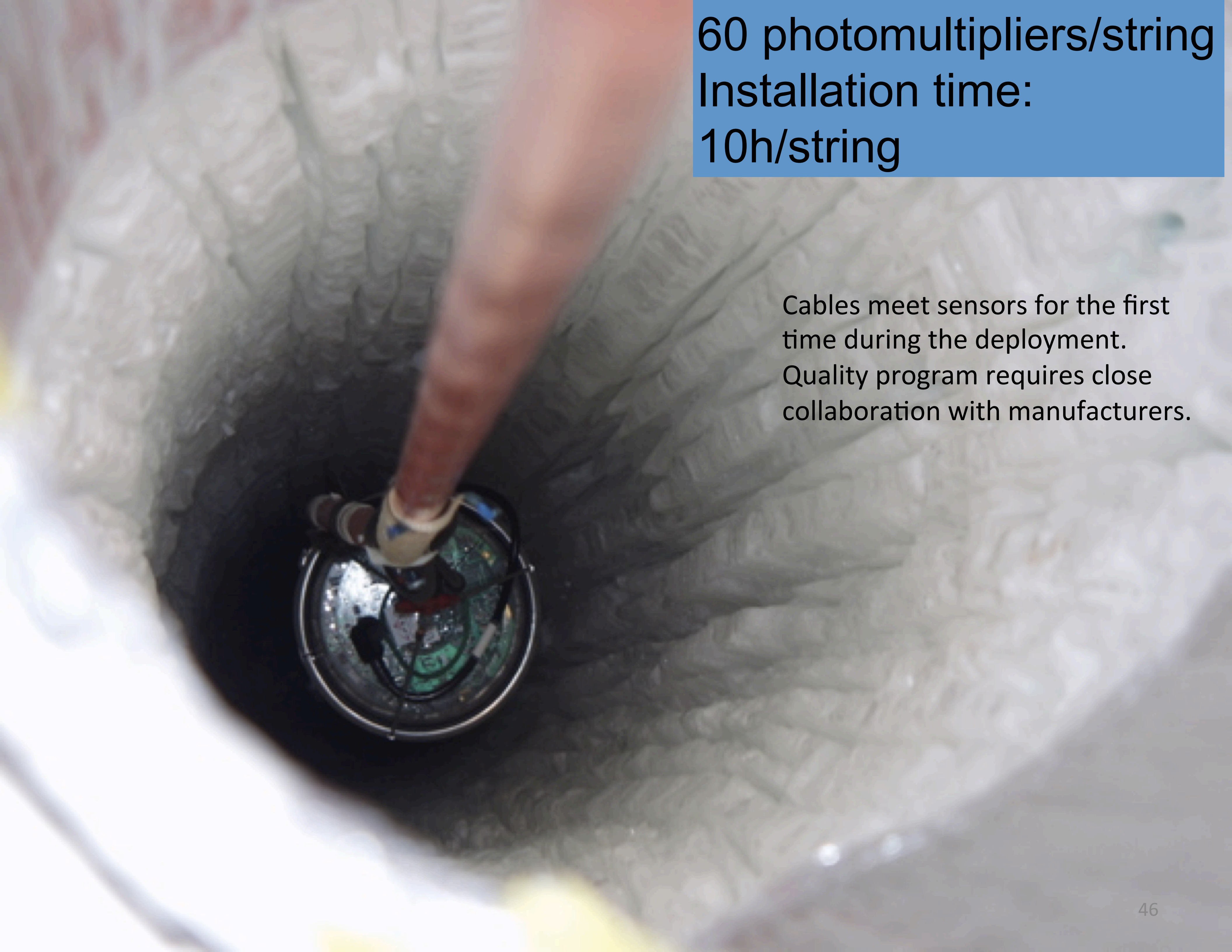
Thermal power: 5 MW
Pressure: 140 bar
Flow: 800 L/m (90°C)
24 h to drill to 2500m
Most importantly:
an excellent crew of drillers!

Drilling and deployment Dec. 13-18, 2010

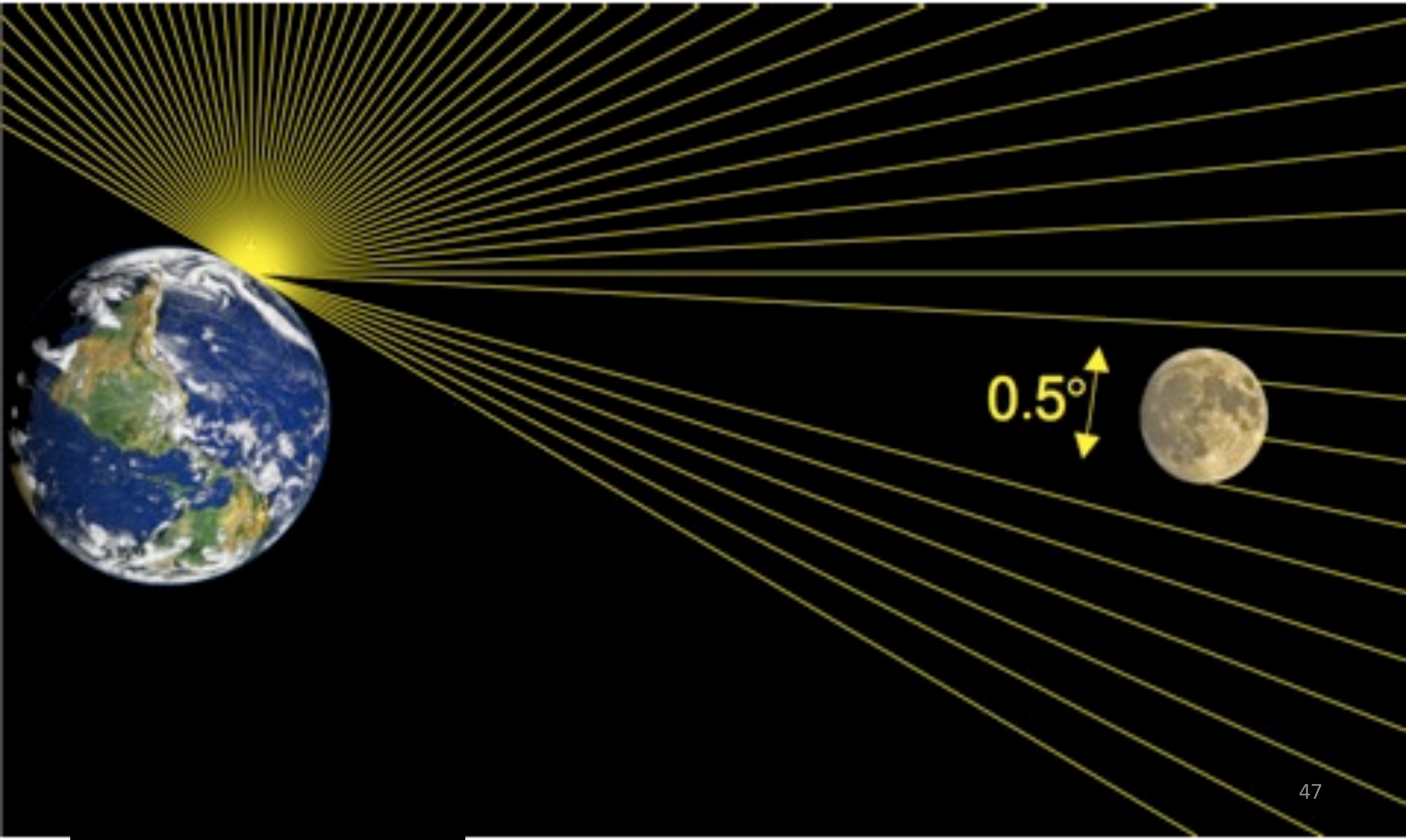


60 photomultipliers/string
Installation time:
10h/string

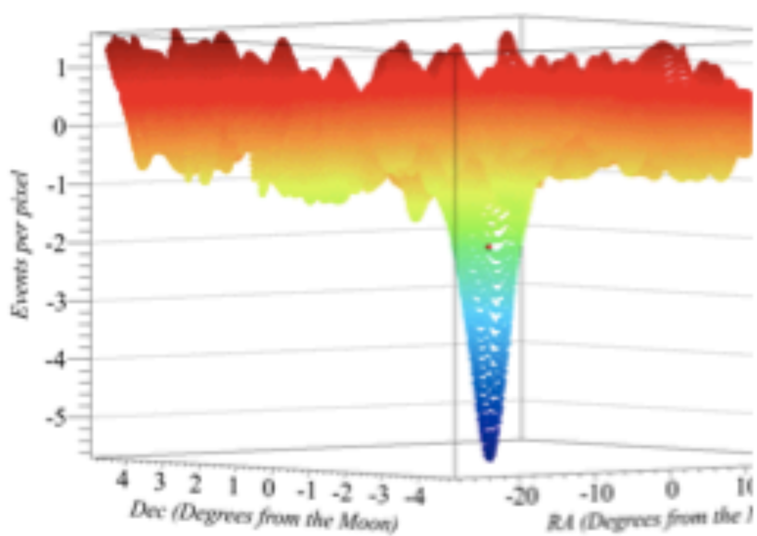
Cables meet sensors for the first time during the deployment. Quality program requires close collaboration with manufacturers.

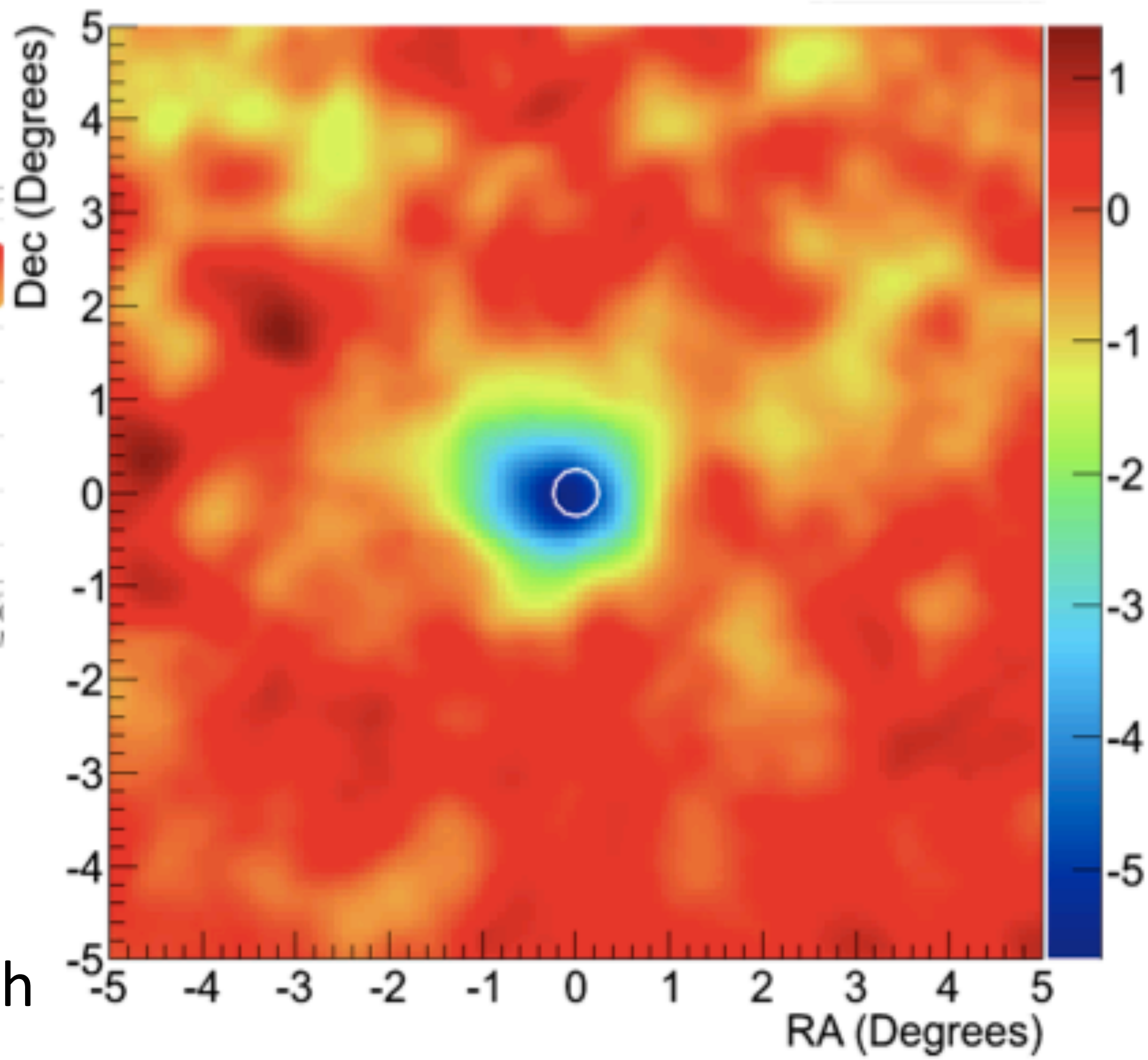


Moon Shadow of Cosmic Rays using muons in the IceCube Detector



Moon shadow observed in muons – Check on IceCube pointing

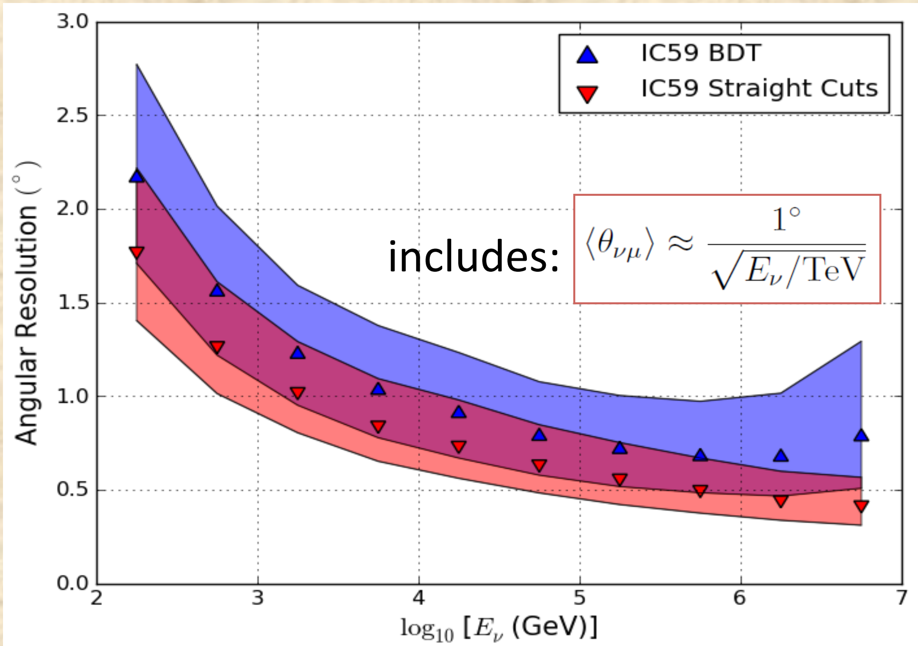




Center of moon is spot on to a precision of <0.1 degrees.

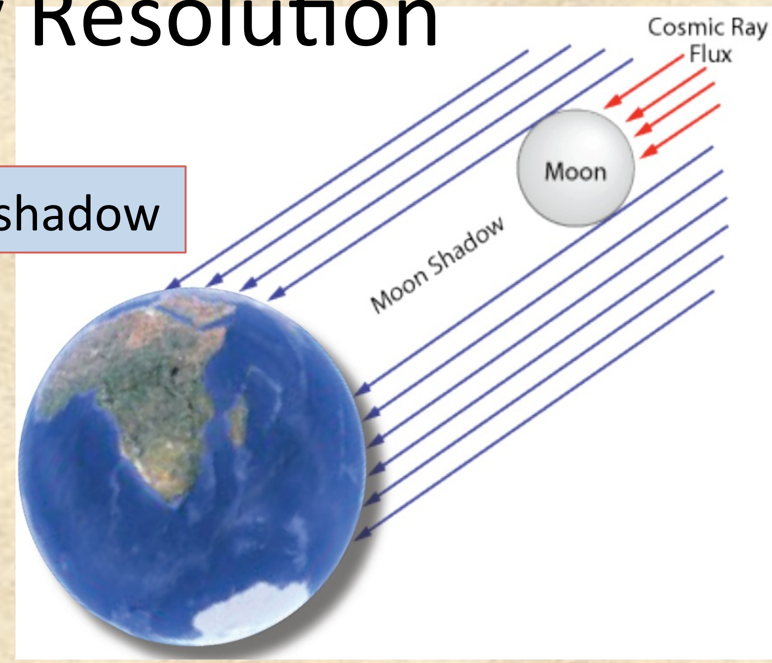
Statistical significance with IC 59: > 10 sigma

ν_μ Angular and Energy Resolution

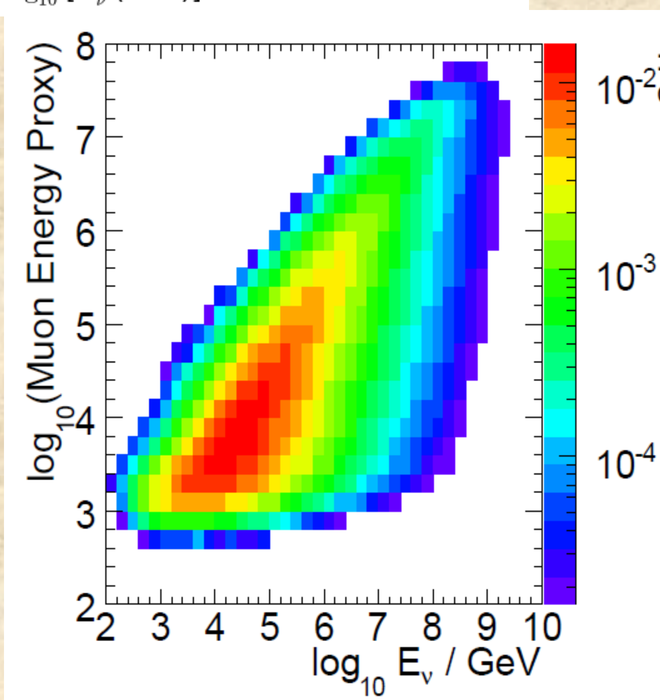


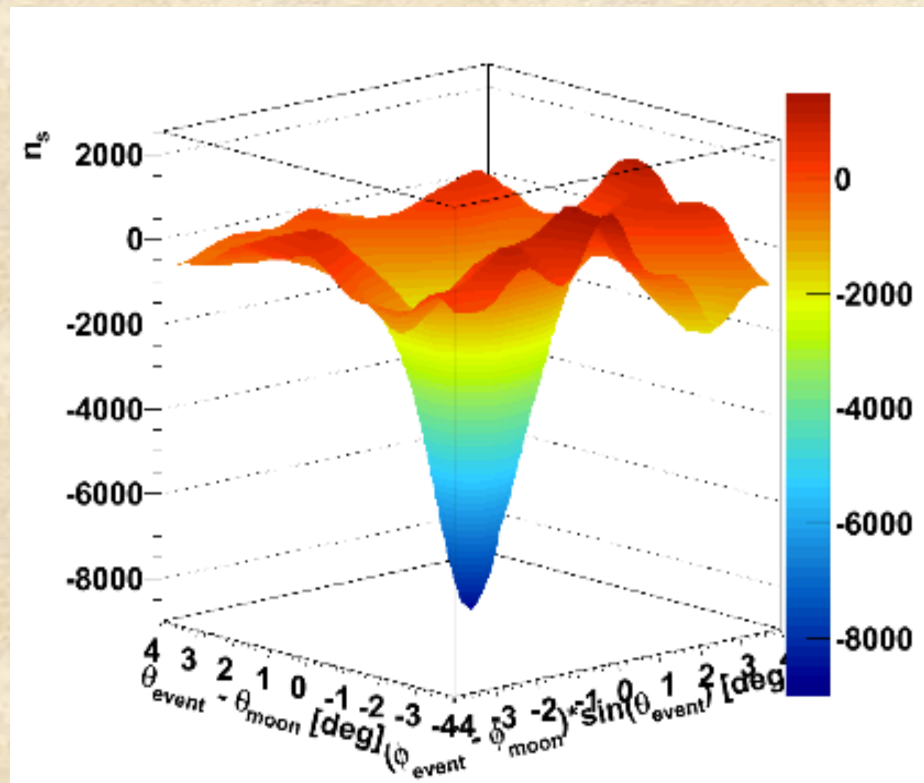
includes: $\langle\theta_{\nu\mu}\rangle \approx \frac{1^\circ}{\sqrt{E_\nu/\mathrm{TeV}}}$

Moon shadow



ν_μ energy estimated from dE/dx of muon (bremsstr.)





Results of fit *(Preliminary)*

- **astrophysical norm [10^{-8} E^2 GeV cm^{-1} s^{-1} sr^{-1}]**: 0.27 + 0.59 (consistent with zero)
- **prompt norm [Enberg + Gaisser knee]**: 0 + 1.216
- **conventional norm [Honda]**: 1.068 +/- 0.020
  (increased normalization by 7%)
- **DOM efficiency scaling factor**: 0.996 +/- 0.013
- **Delta gamma ($E^{-(gamma\ +\ Delta\ gamma)}$)**: -0.037 +/- 0.023
  (spectrum is harder than our input default)
- **Pion-Kaon ratio**: 1.133 +/- 0.105
  (~ 13% more kaons than in the Honda2006 standard)

Significance Skymap (IC40+59)

Hottest spot:

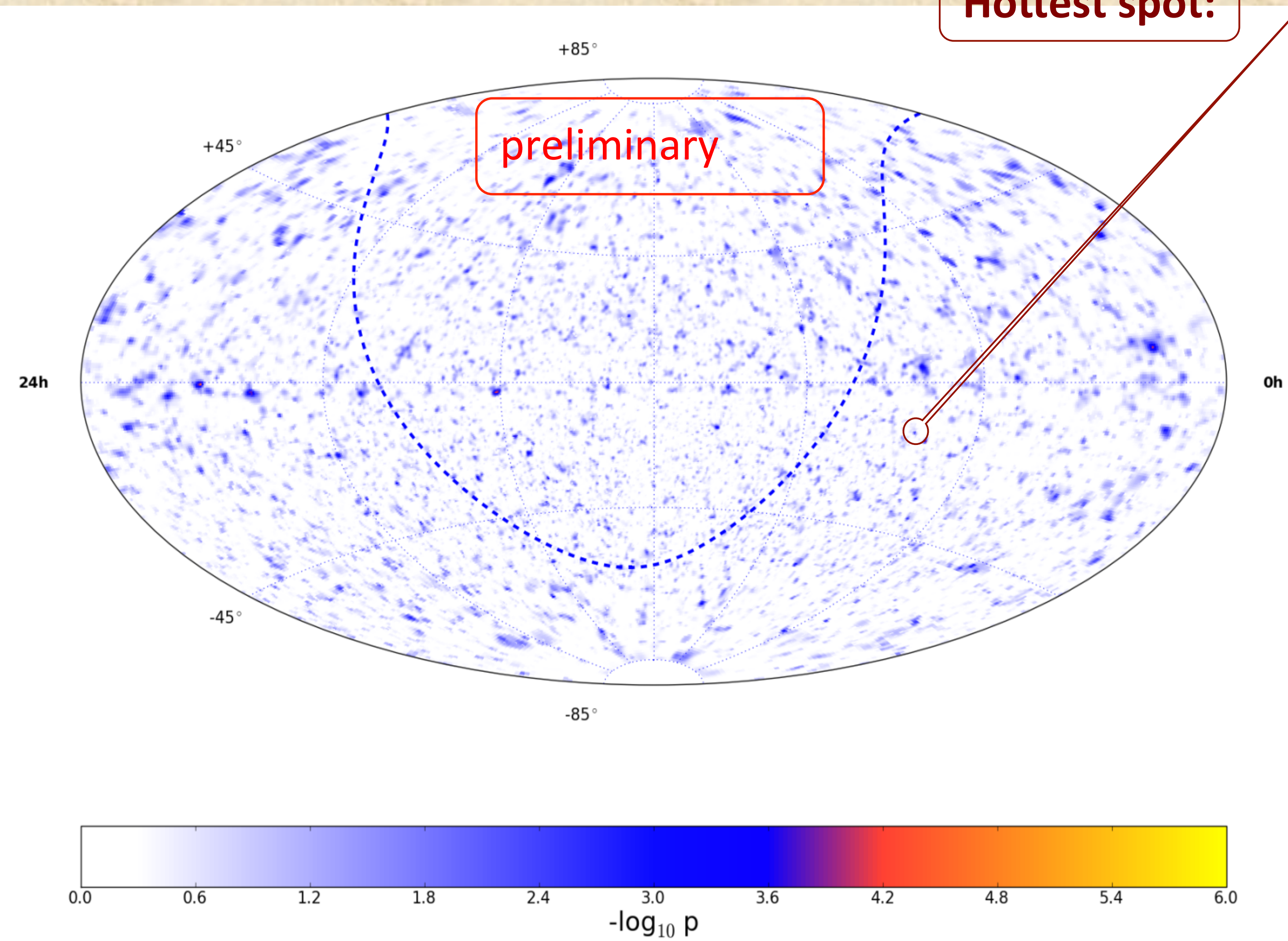
ra: 75.45 dec: - 18.15

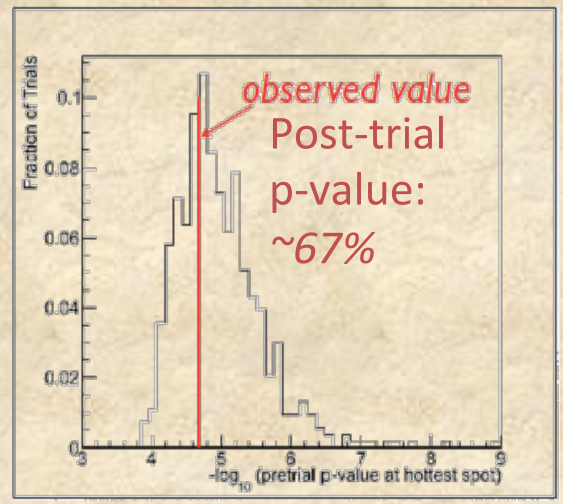
$-\log_{10} p = 4.65$

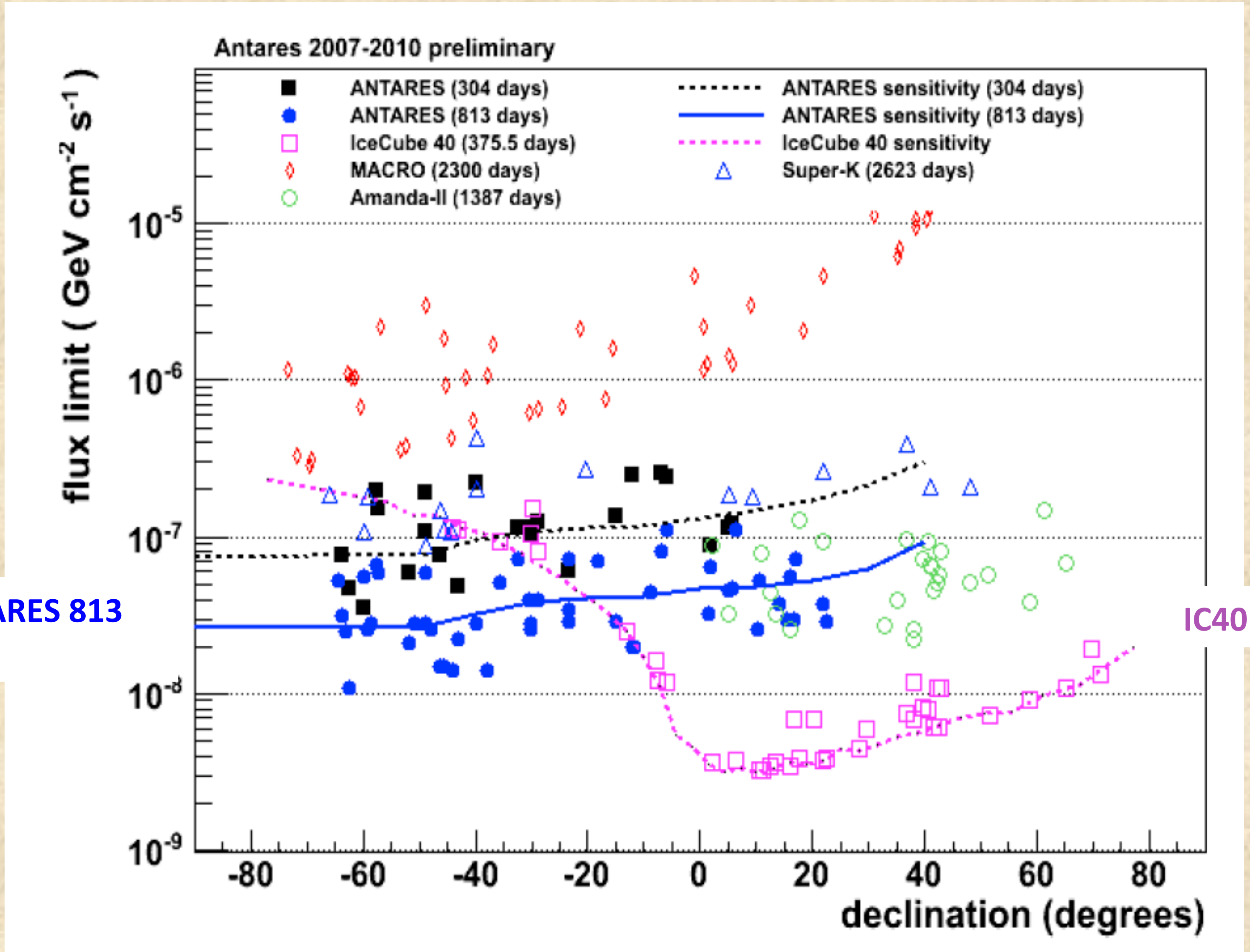
$\hat{n}_s = 18.3$

$\hat{\gamma} = 3.9$

but: $\mathcal{O}(100000)$ **trials**







ANTARES 813 days

IC40 1 year