Cosmic Rays with IceCube/IceTop

spectrum, composition and anisotropy

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4th Workshop on Air Shower Detection at High Altitude
Napoli, Jan 31st -Feb 1st, 2013

Outline

- primary spectrum and composition with IceTop
- coincident IceCube/IceTop events
- cosmic ray anisotropy
- muons in IceCube
  - bundles and inclusive spectrum
  - high pt muons

The IceCube Collaboration

International Funding Agencies

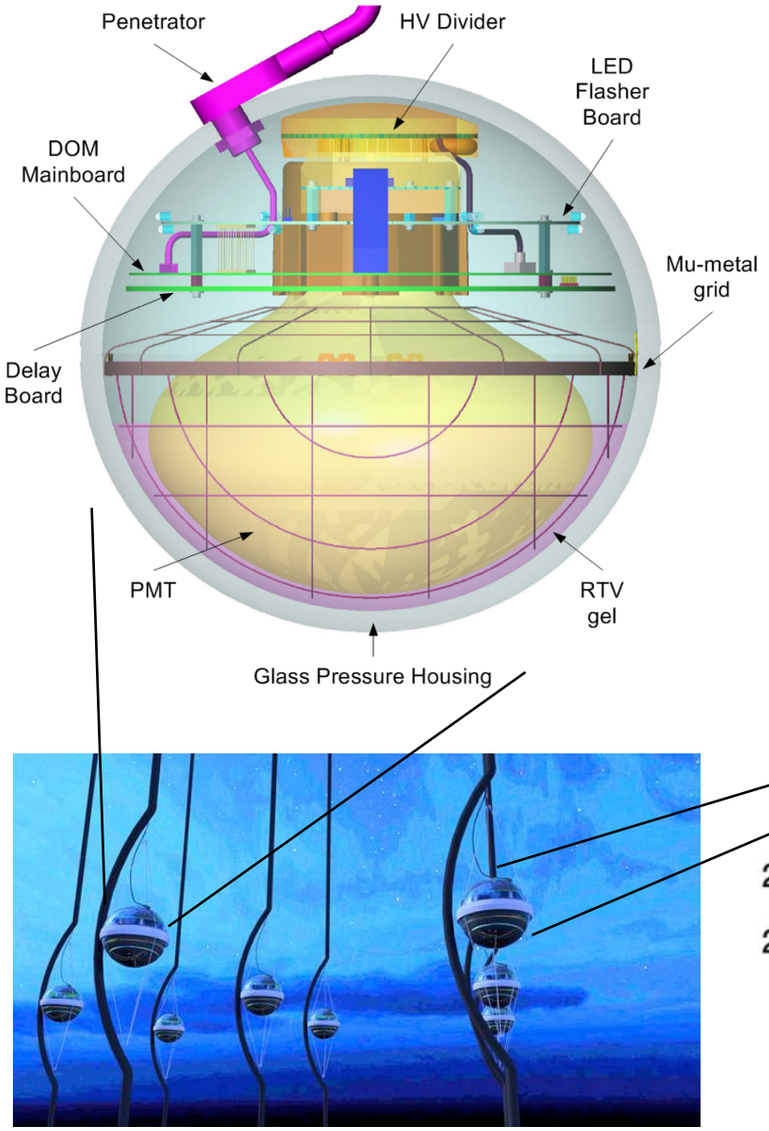
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

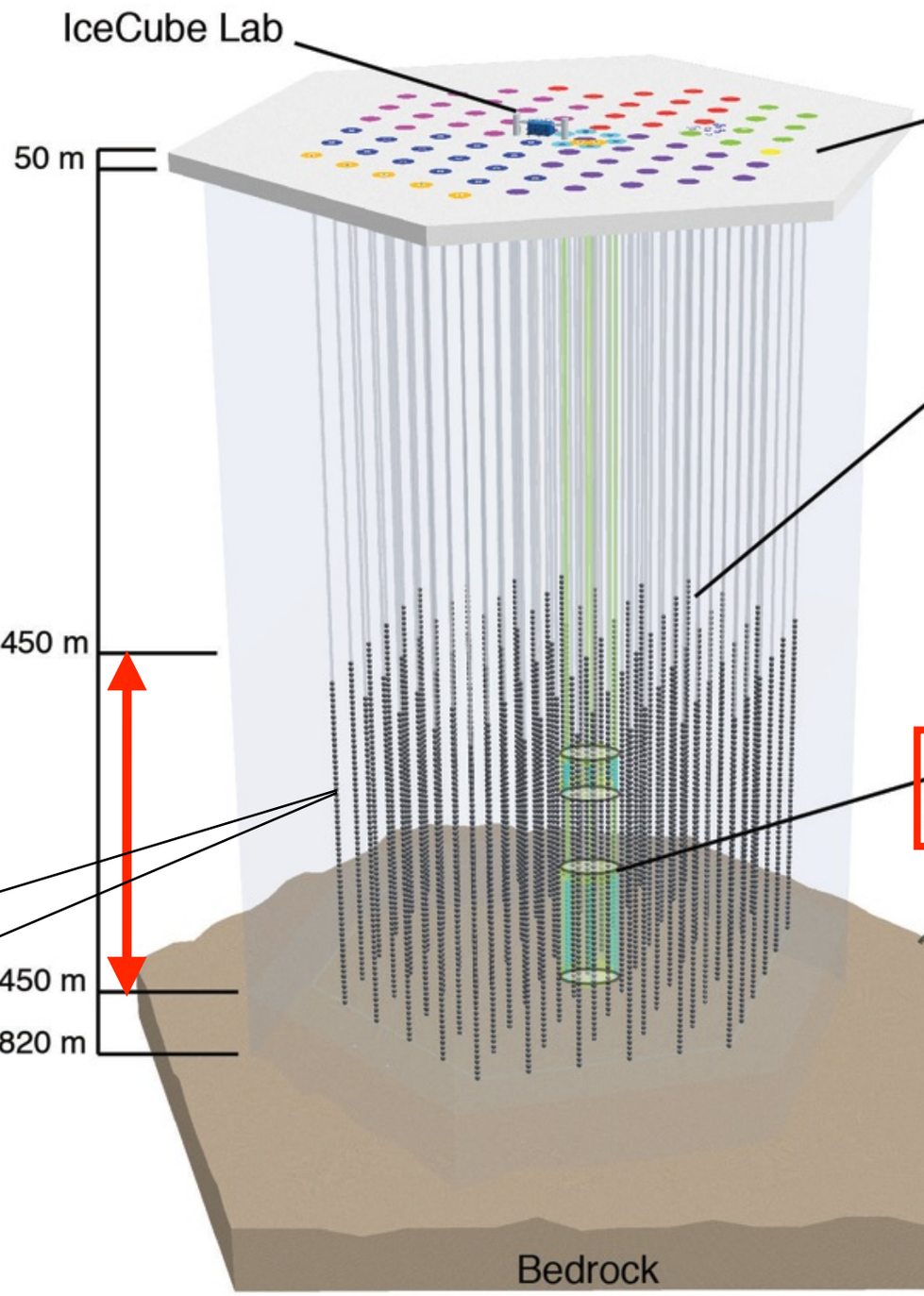
IceCube Observatory

air shower detection @ 2835 m altitude (680 g/cm^2)

muon detection @ 1450-2450 m depth

Digital Optical Module - DOM
with 10” PMT &
local DAQ electronics





IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors

IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors

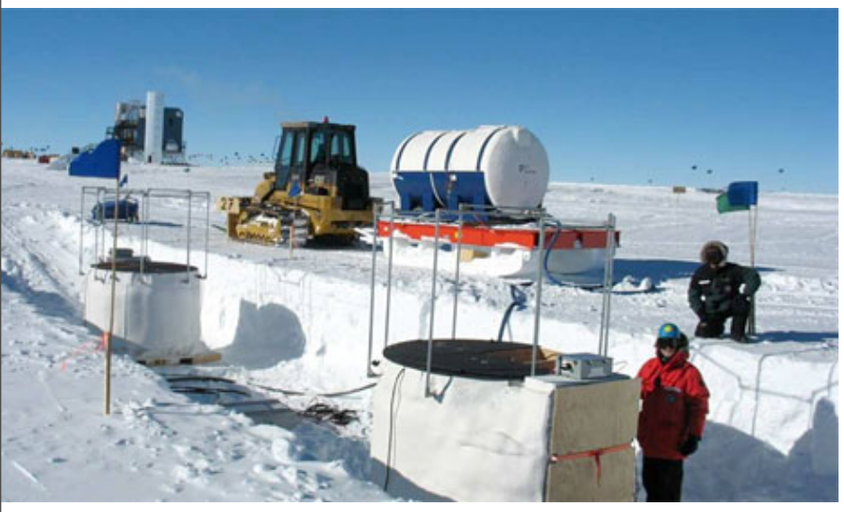
Eiffel Tower
324 m

IceCube Observatory

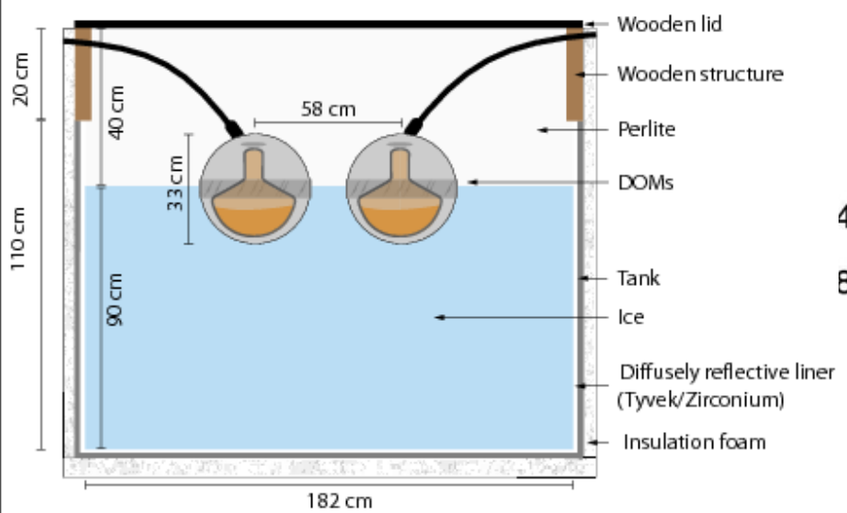
air shower detection @ 2835 m altitude (680 g/cm^2)

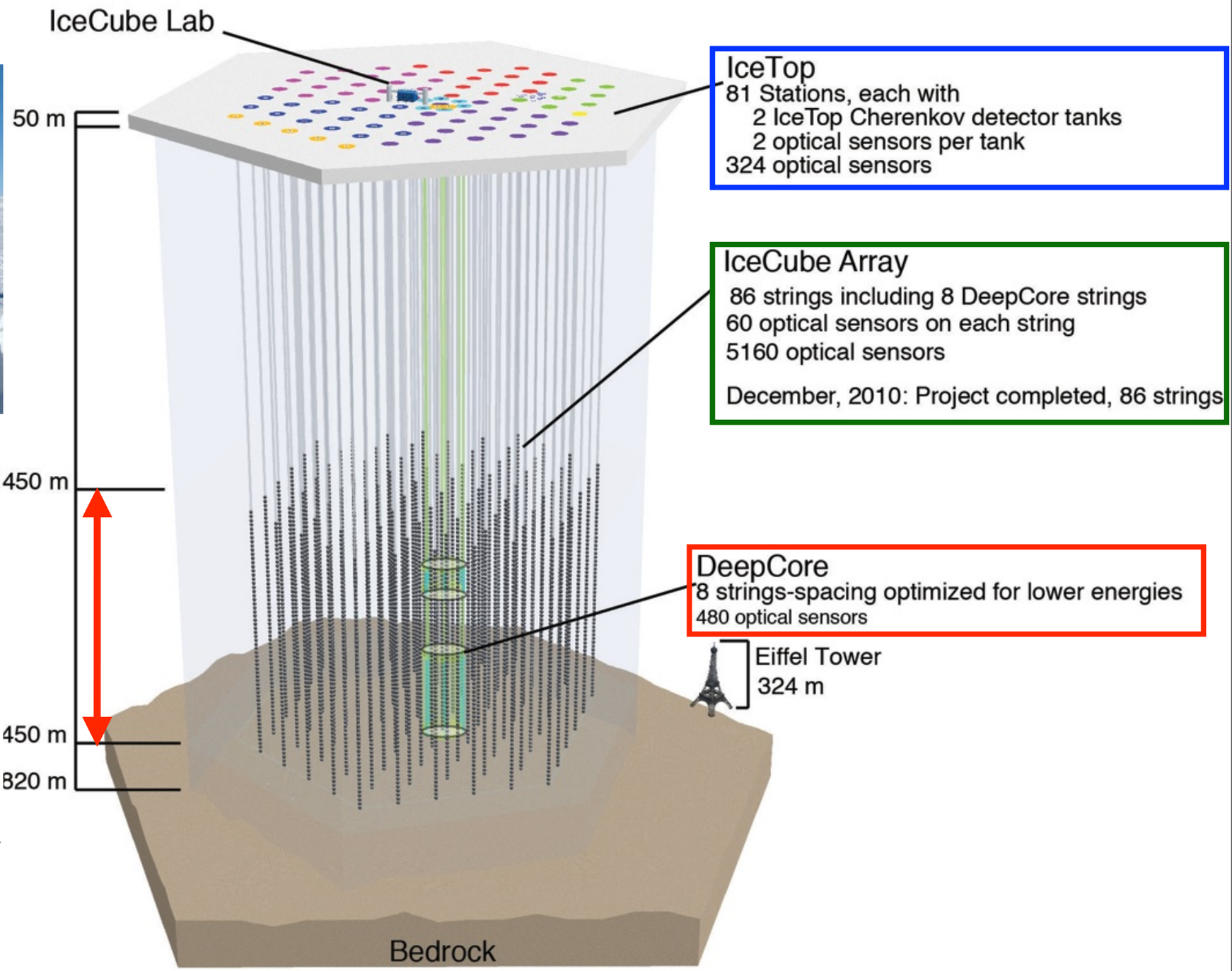
muon detection @ 1450-2450 m depth

the two tanks of one IceTop station



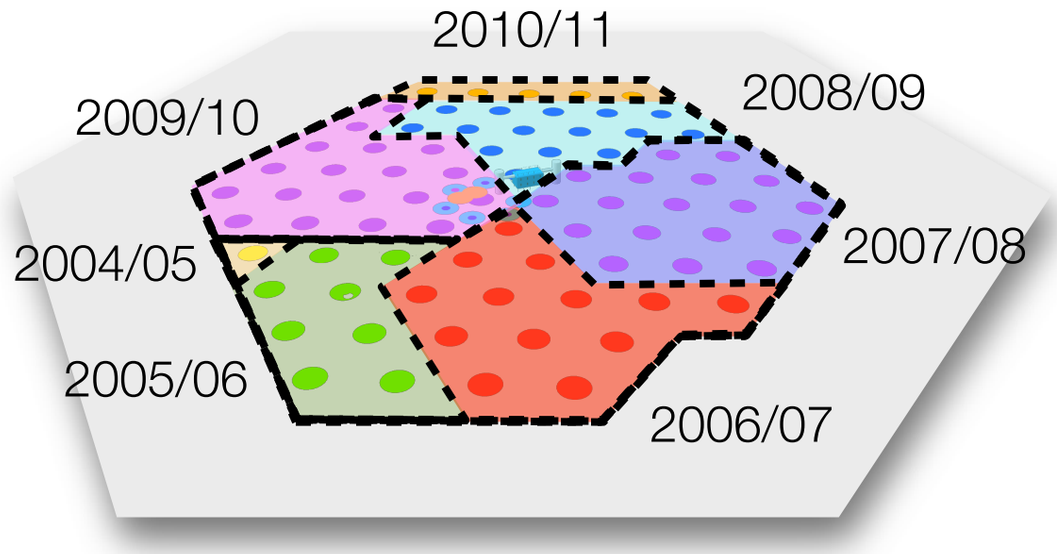
the two DOMs in one IceTop tank

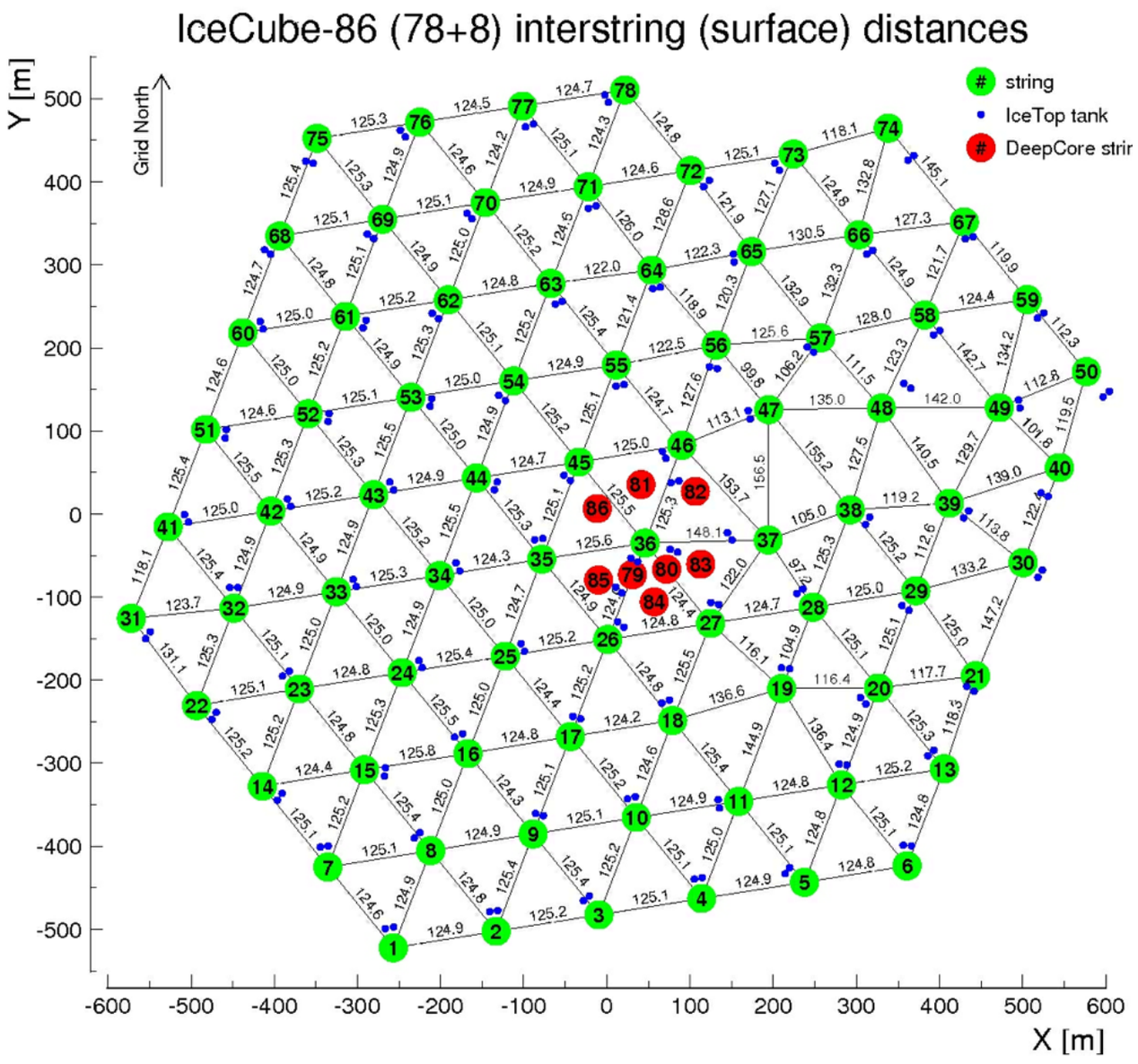




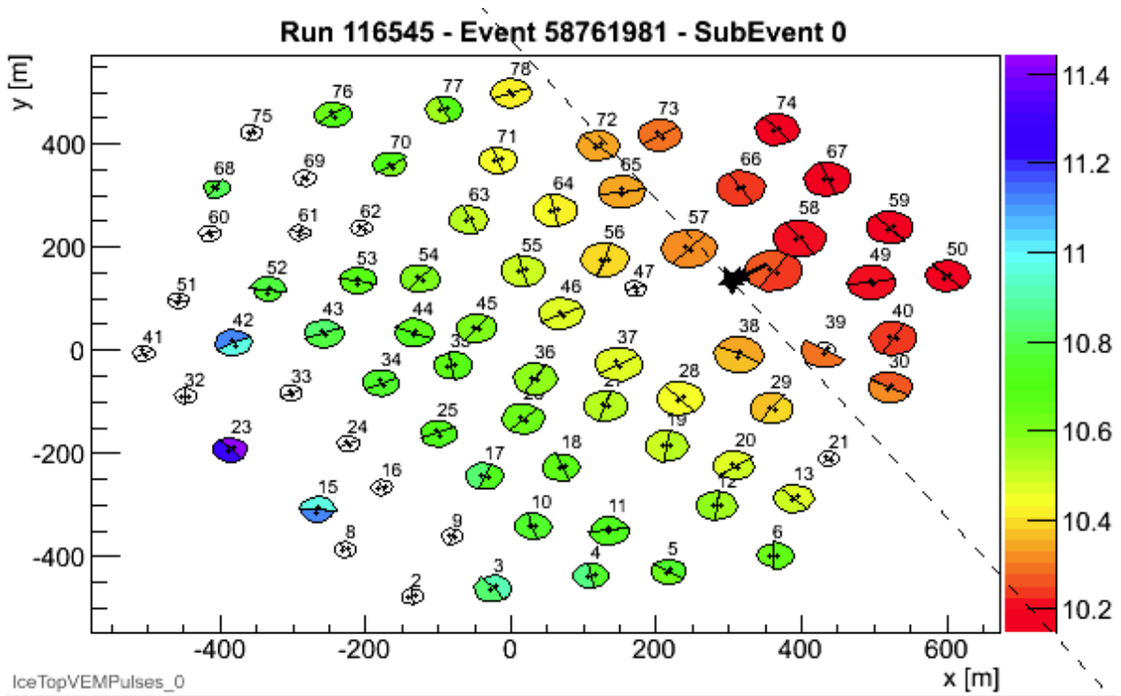
growing observatory

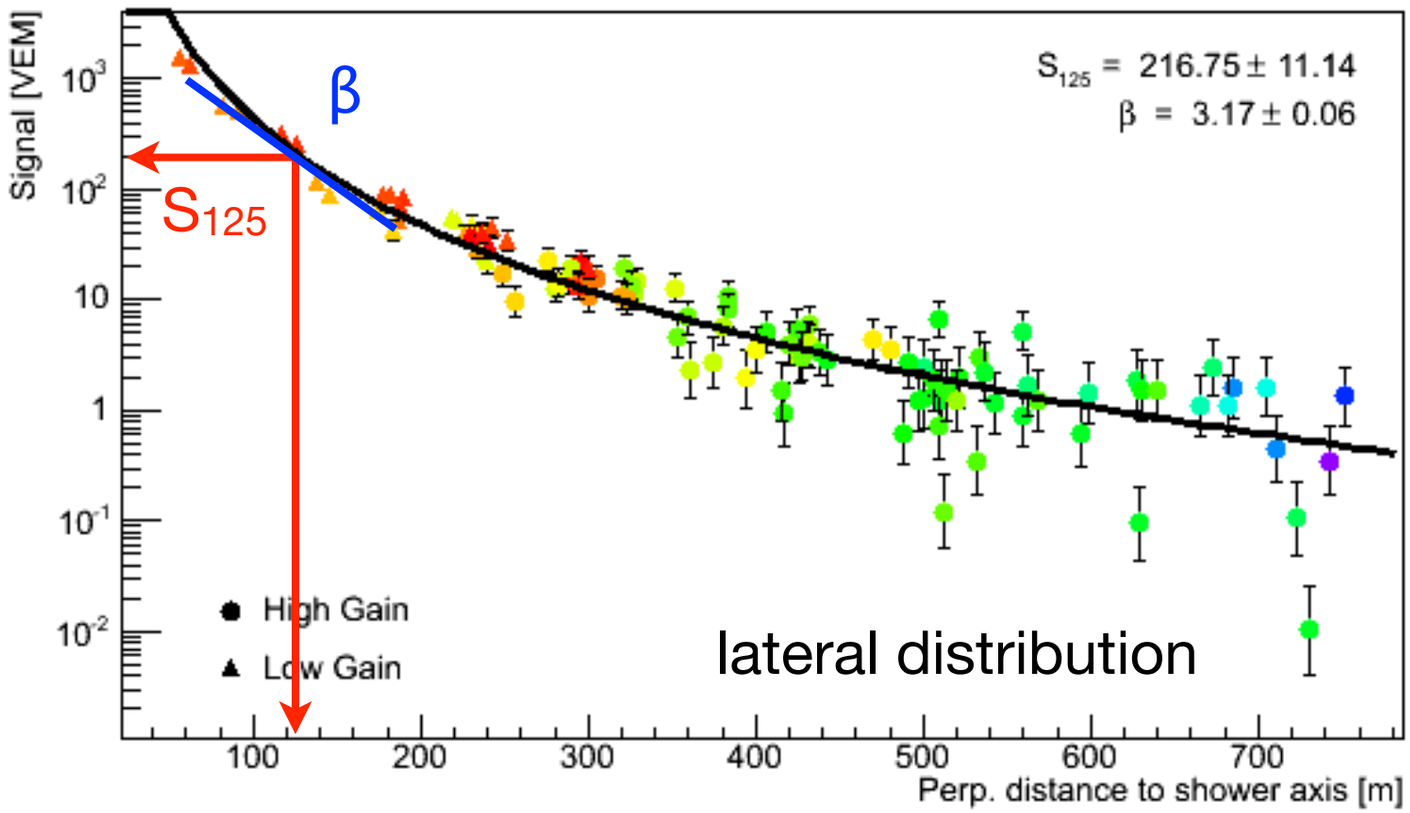
season	no. strings no. stations	array configuration
2004-2005	1 string 4 stations	
2005-2006	9 strings 16 stations	
2006-2007	22 strings 26 stations	IT26/IC22
2007-2008	40 strings 40 stations	IT40/IC40
2008-2009	59 strings 59 stations	IT59/IC59
2009-2010	79 strings 73 stations	IT73/IC79
2010-2011	86 strings 81 stations	IT81/IC86

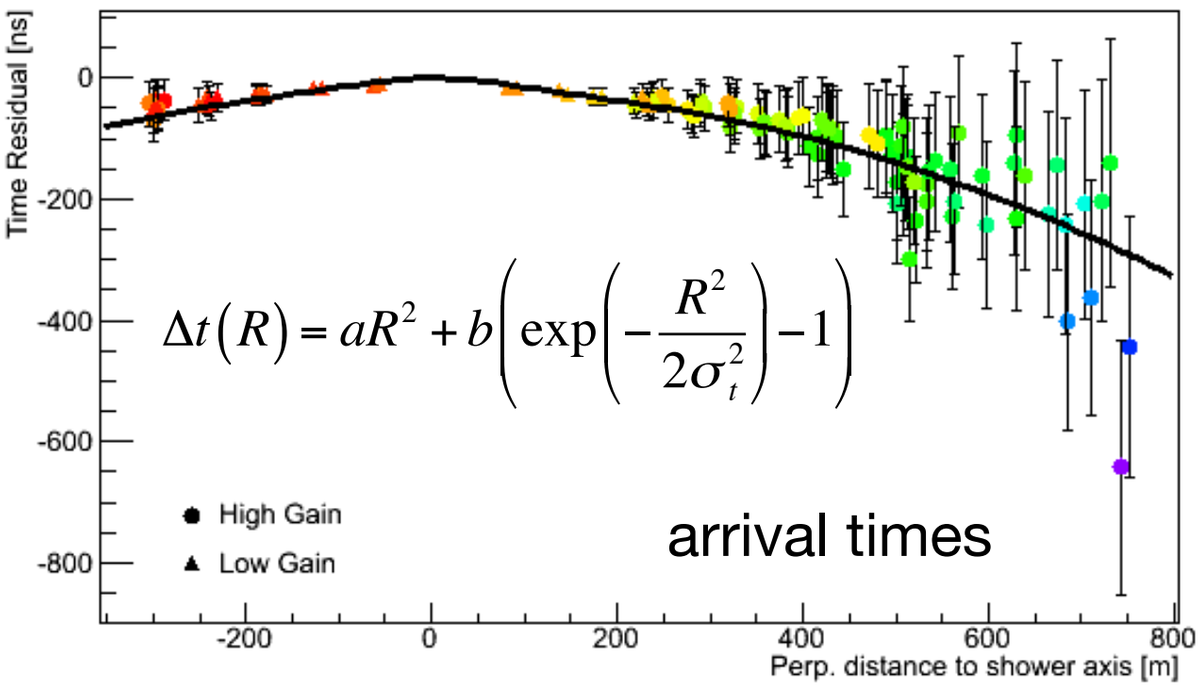




IceTop shower reconstruction







$$S(R) = S_{125}\left(\frac{R}{125m}\right)^{-\beta-\kappa\log(R/125m)}$$

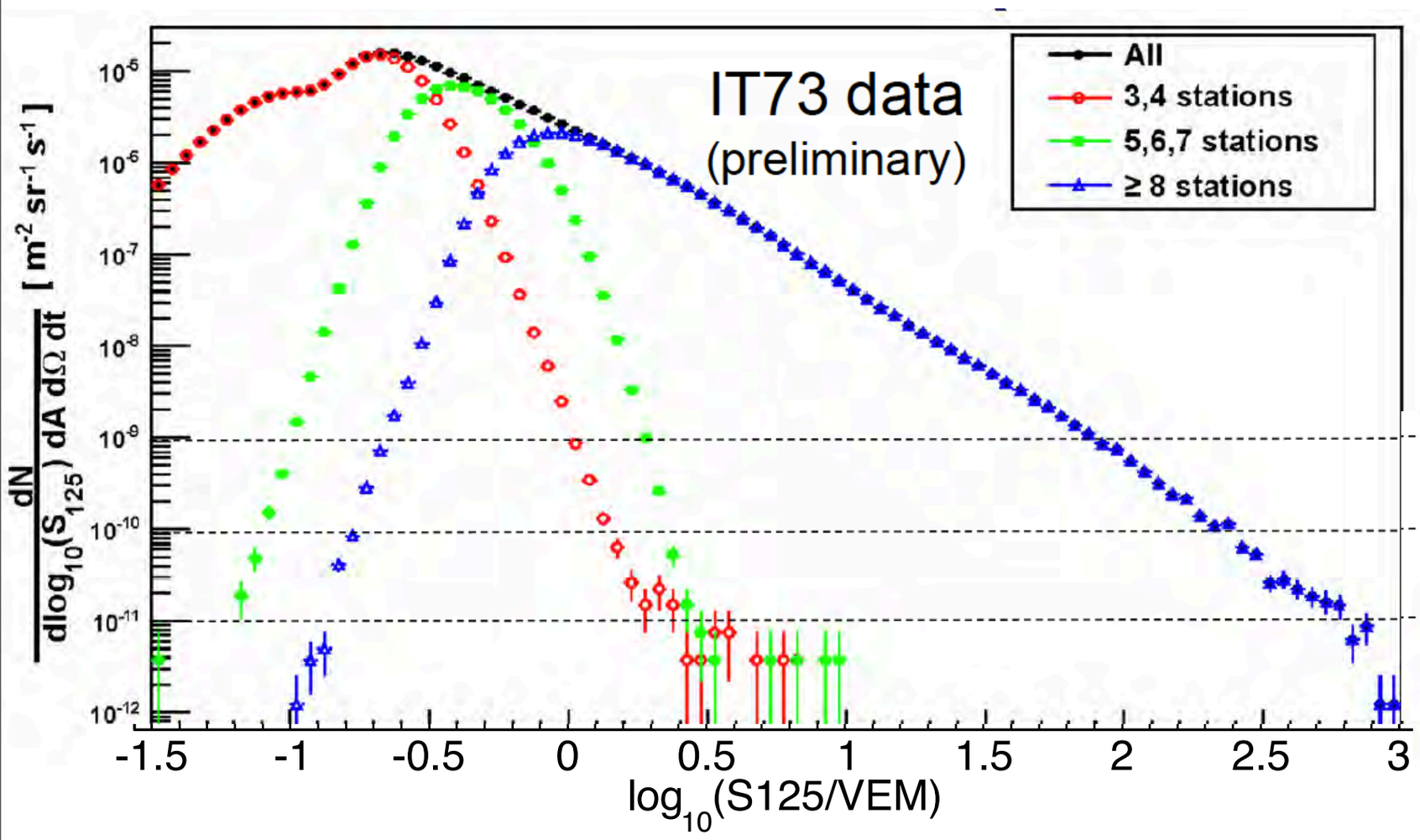
S_{125} : signal at r = 125m

β : slope at r = 125m

κ = 0.303 fixed

IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011



events per bin per year

($\Delta \log_{10} S_{125} = 0.05$)

$\cos\theta \geq 0.8$

IceTop-only all-particle spectrum

IceTop-73
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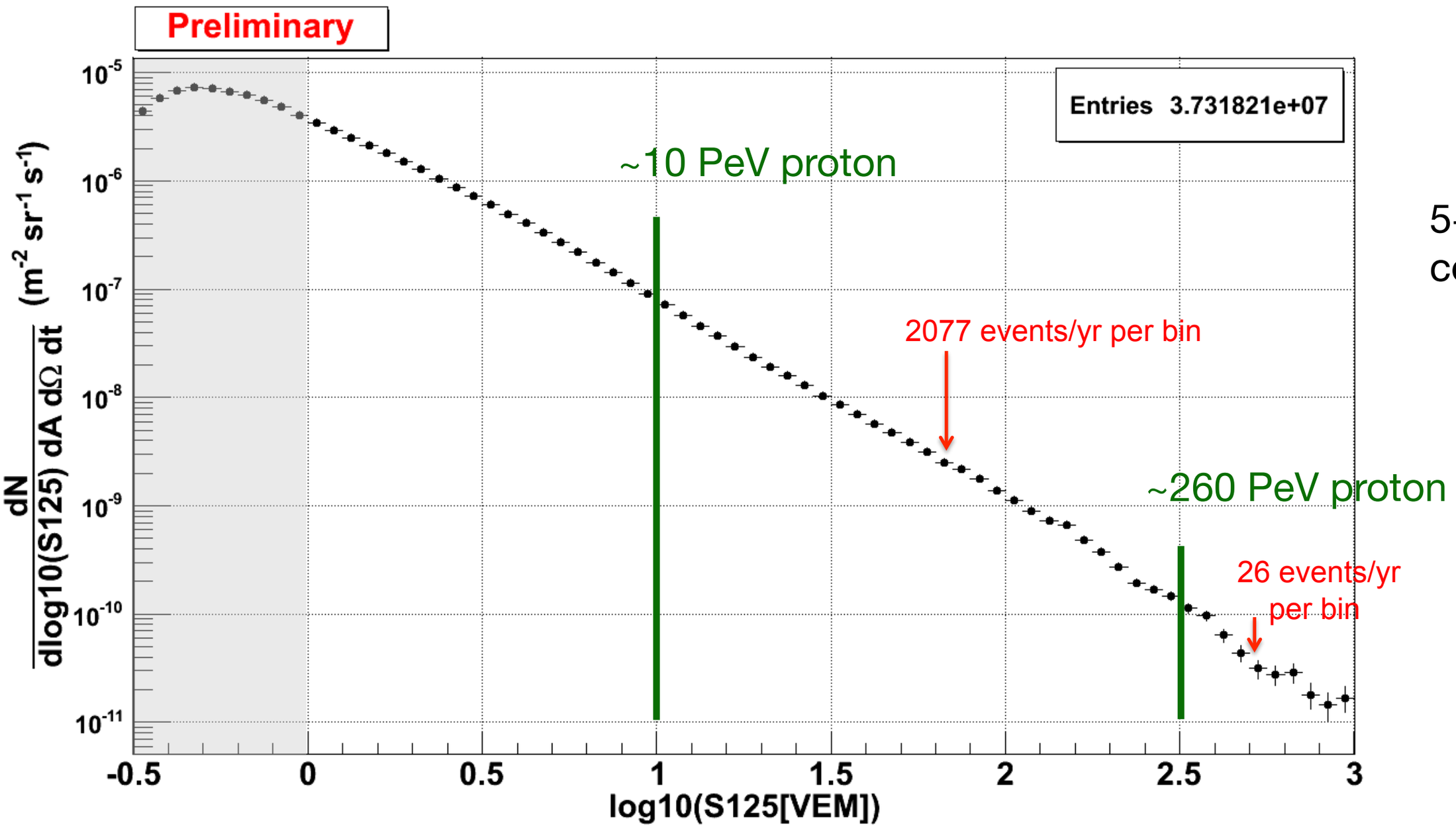
Jun 2010 - May 2011



5+ stations
cosθ≥0.8

IceTop-only all-particle spectrum
effect of snow accumulation

IceTop-73
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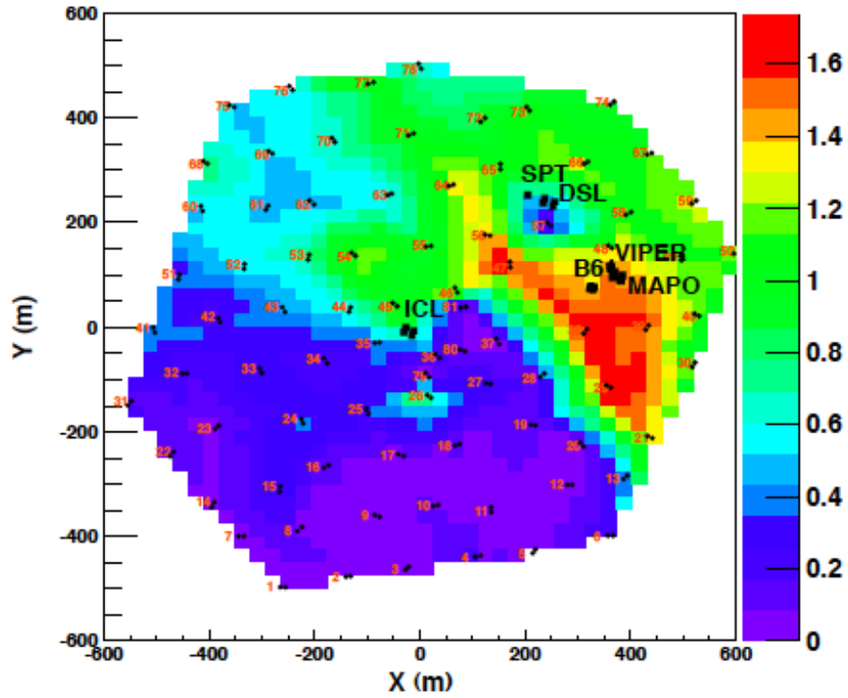
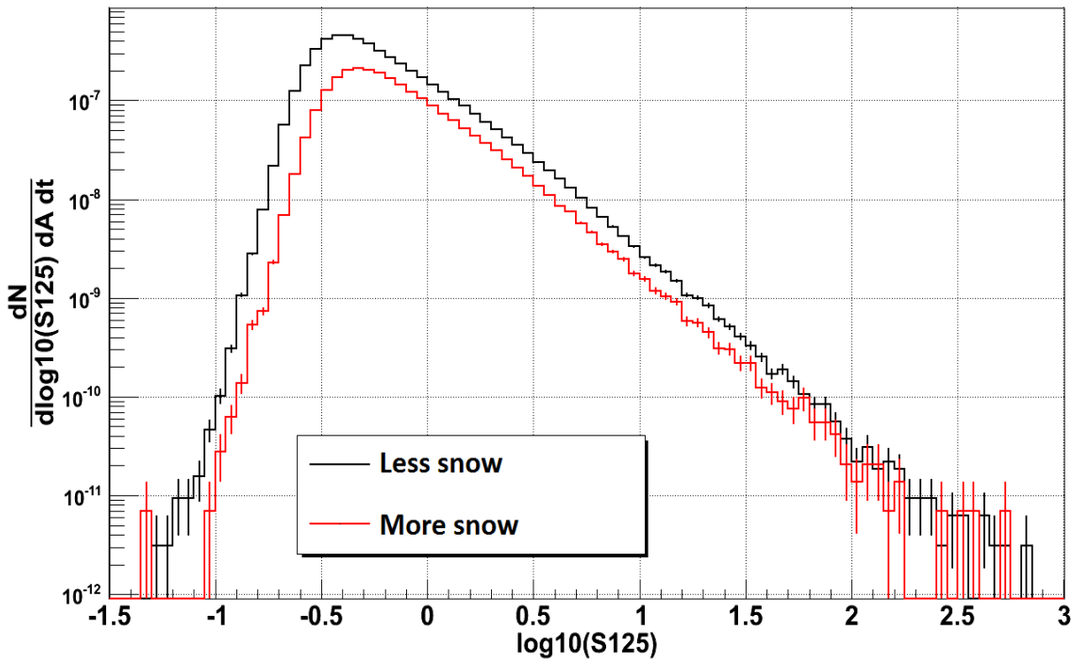
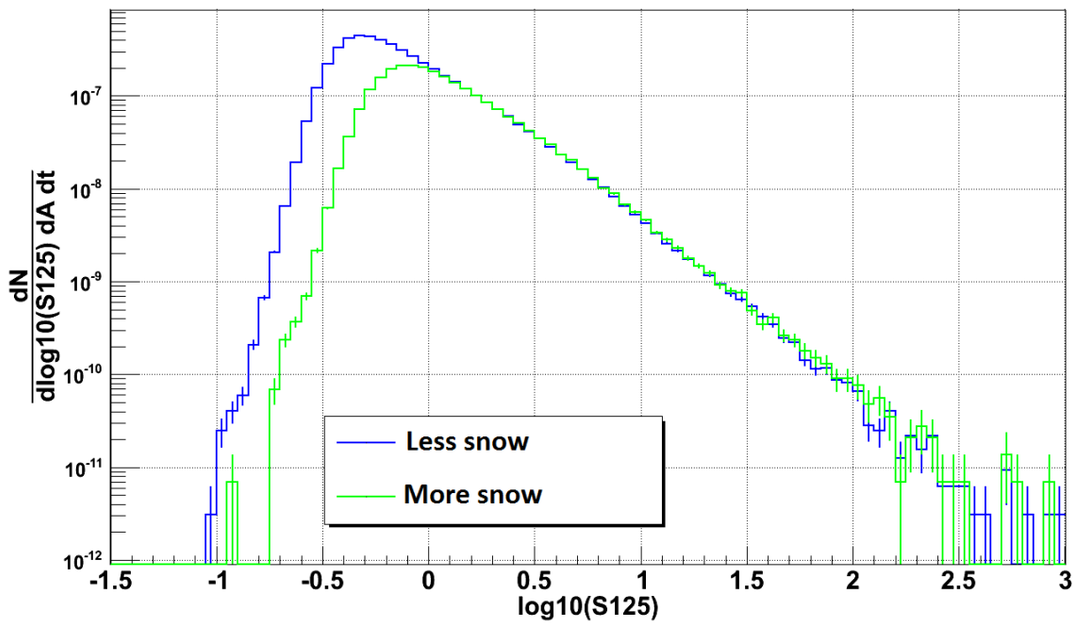
Jun 2010 - May 2011





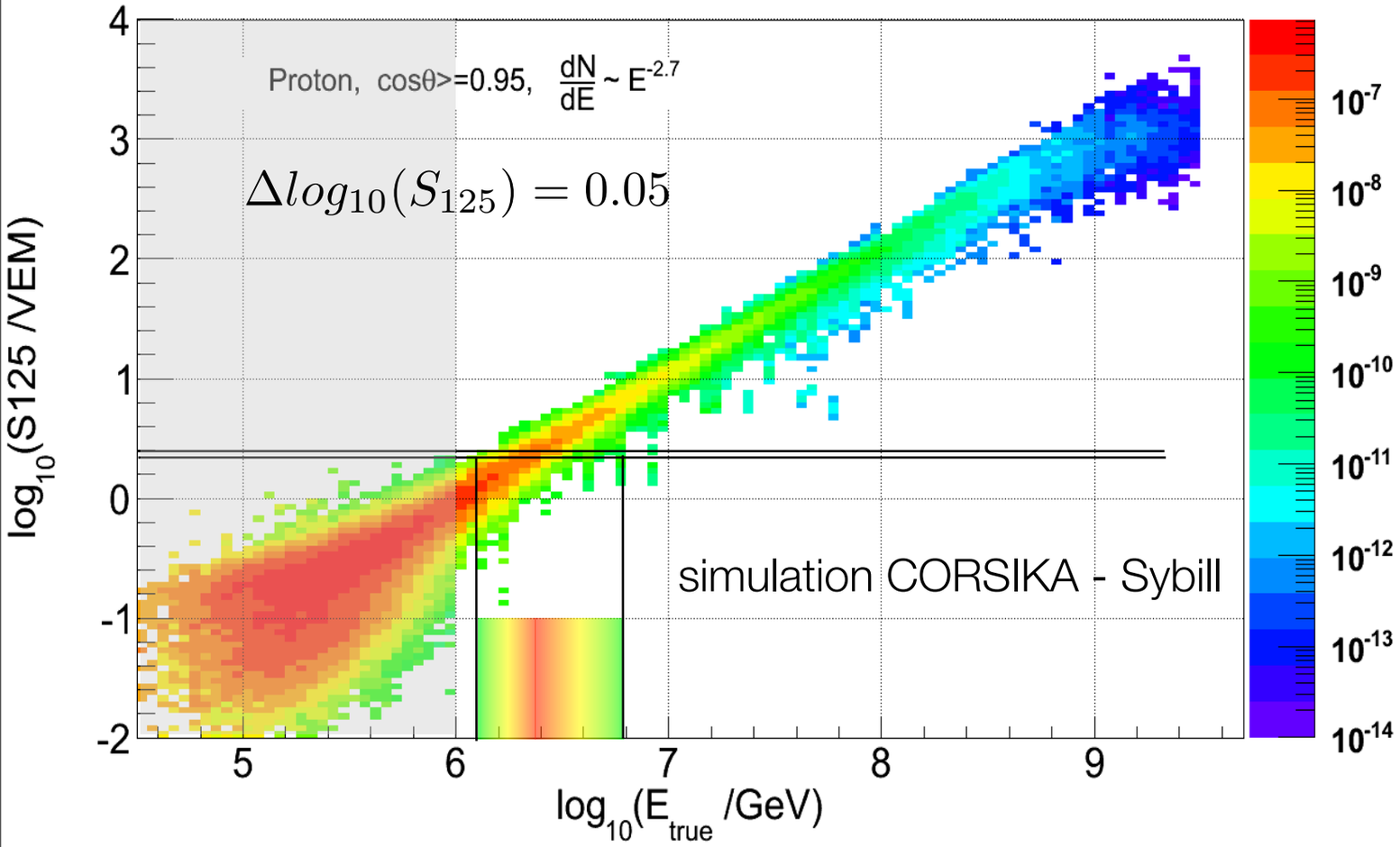
Snow corrected

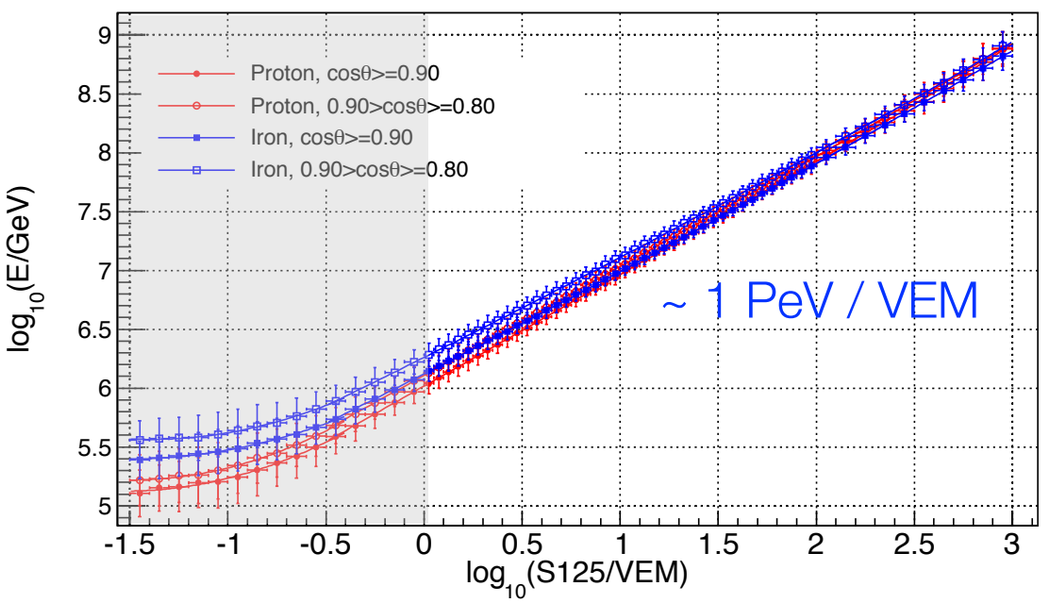


$$S_{corr} = S_0 e^{\frac{z\cos\theta}{\lambda}}$$

IceTop-only all-particle spectrum estimating primary energy

IceTop-73
326 days livetime
Jun 2010 - May 2011





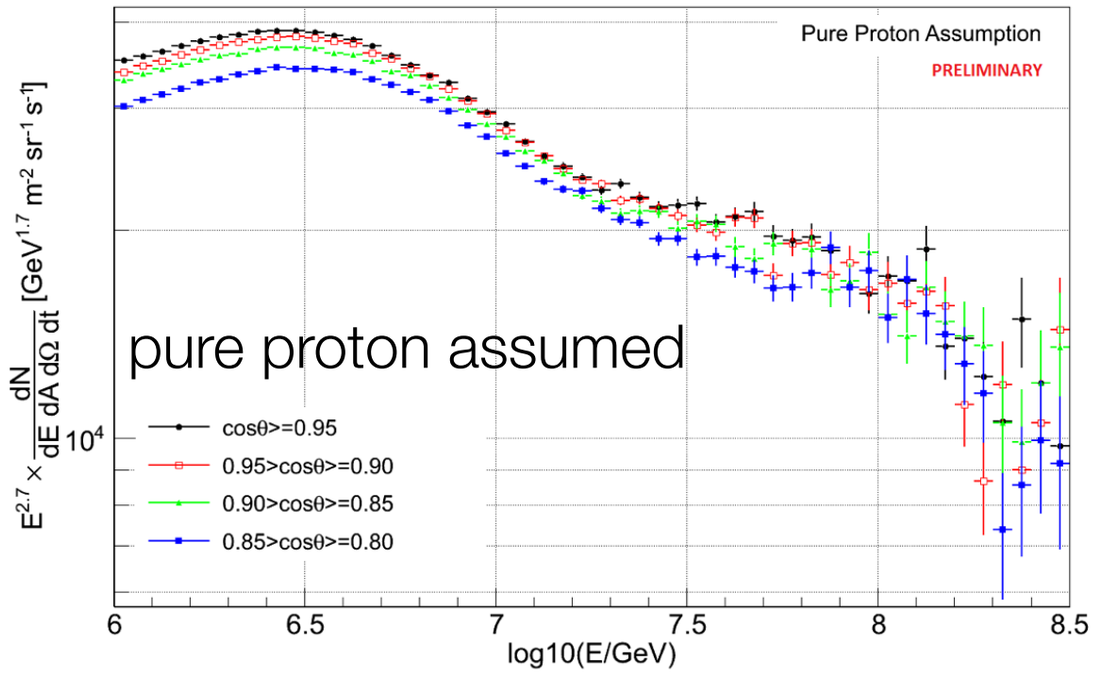
the relationship between S_{125} and primary energy depends on **mass** and **zenith angle**

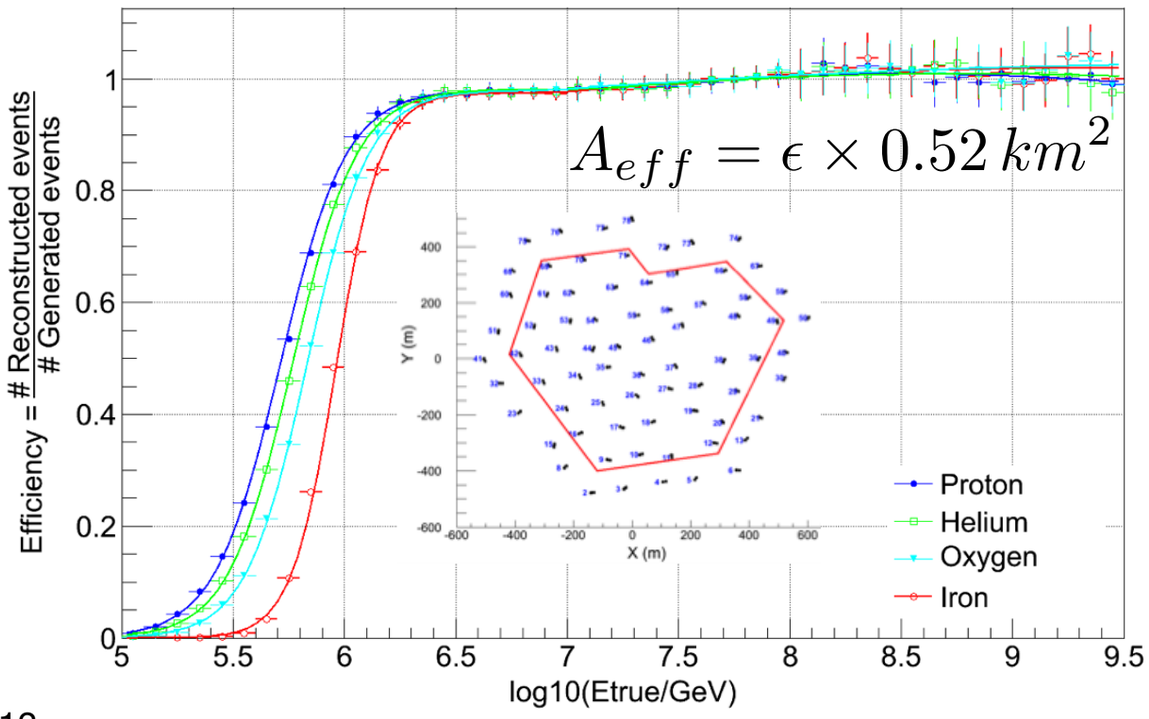
IceTop-only all-particle spectrum resolutions

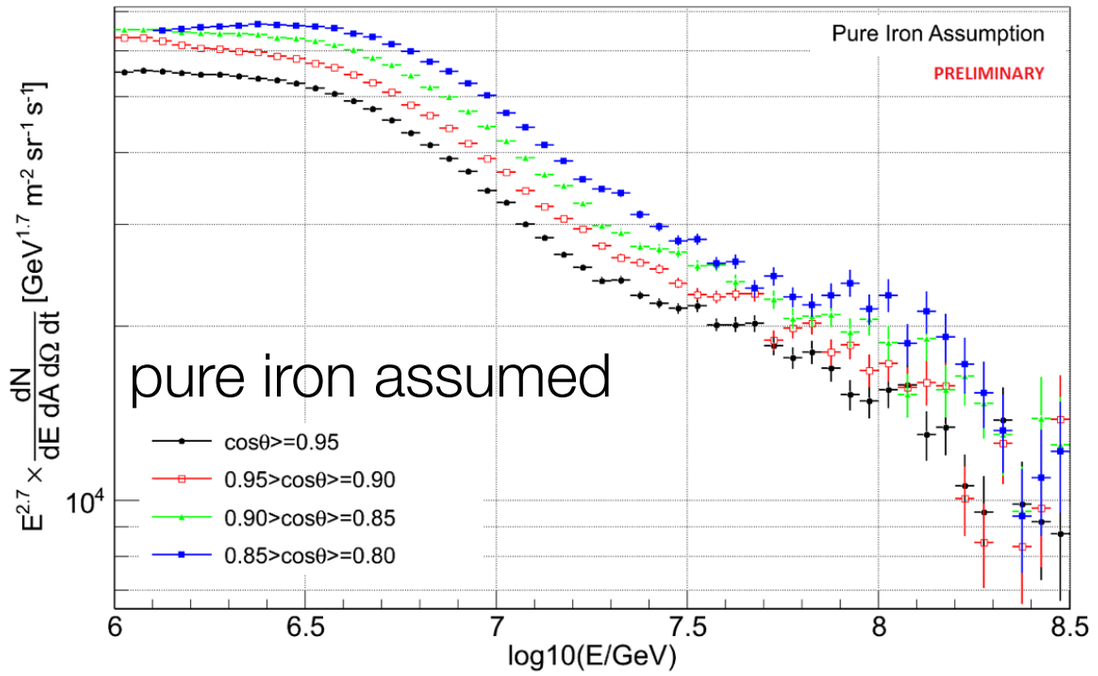
IceTop-73
326 days livetime
Jun 2010 - May 2011

$$\frac{dN}{d\,ln(E)} = \frac{N_{events}\,/\,bin}{\epsilon\,A\,\Delta\Omega\,T\,ln(E_{i+1}/E_i)}$$

inferred all-particle spectrum depends on assumed composition







IceTop-only all-particle spectrum

IceTop-73
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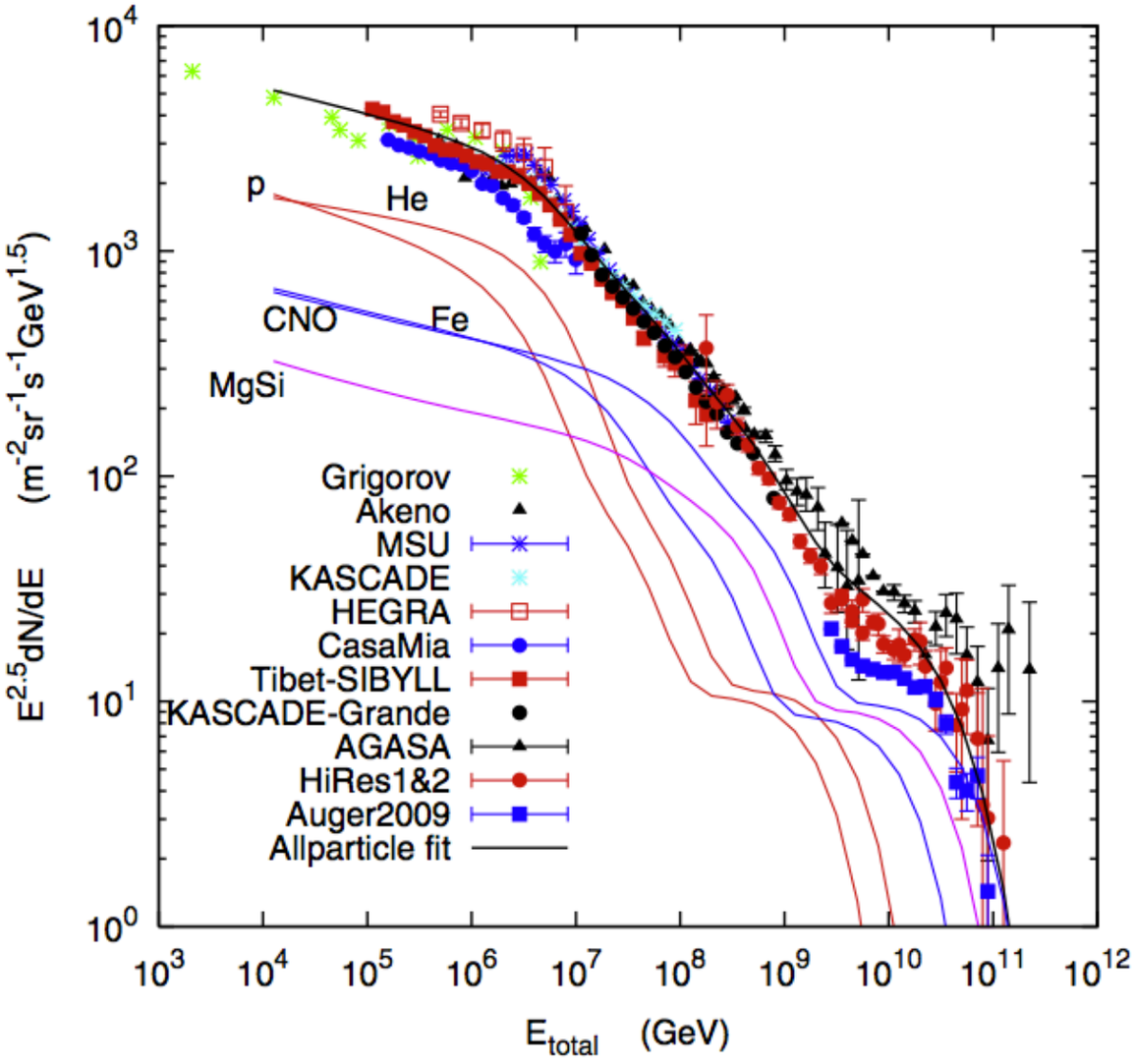
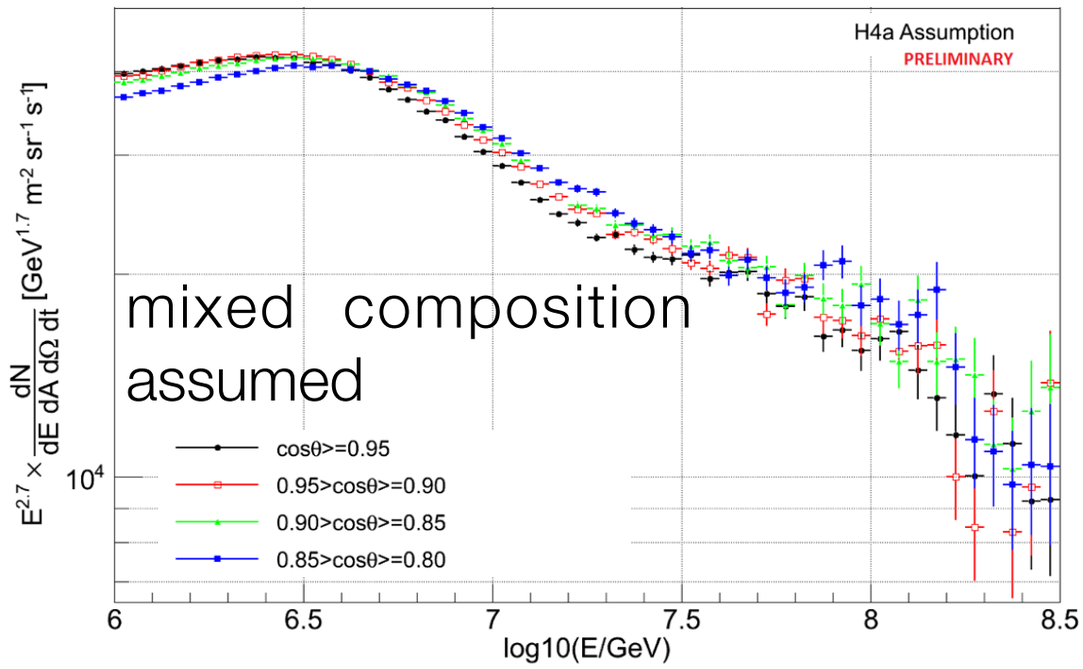
$$\frac{dN}{d\,ln(E)} = \frac{N_{events}\,/\,bin}{\epsilon\,A\,\Delta\Omega\,T\,ln(E_{i+1}/E_i)}$$



Gaisser, Astropart. Phys. 35 (2012) 801



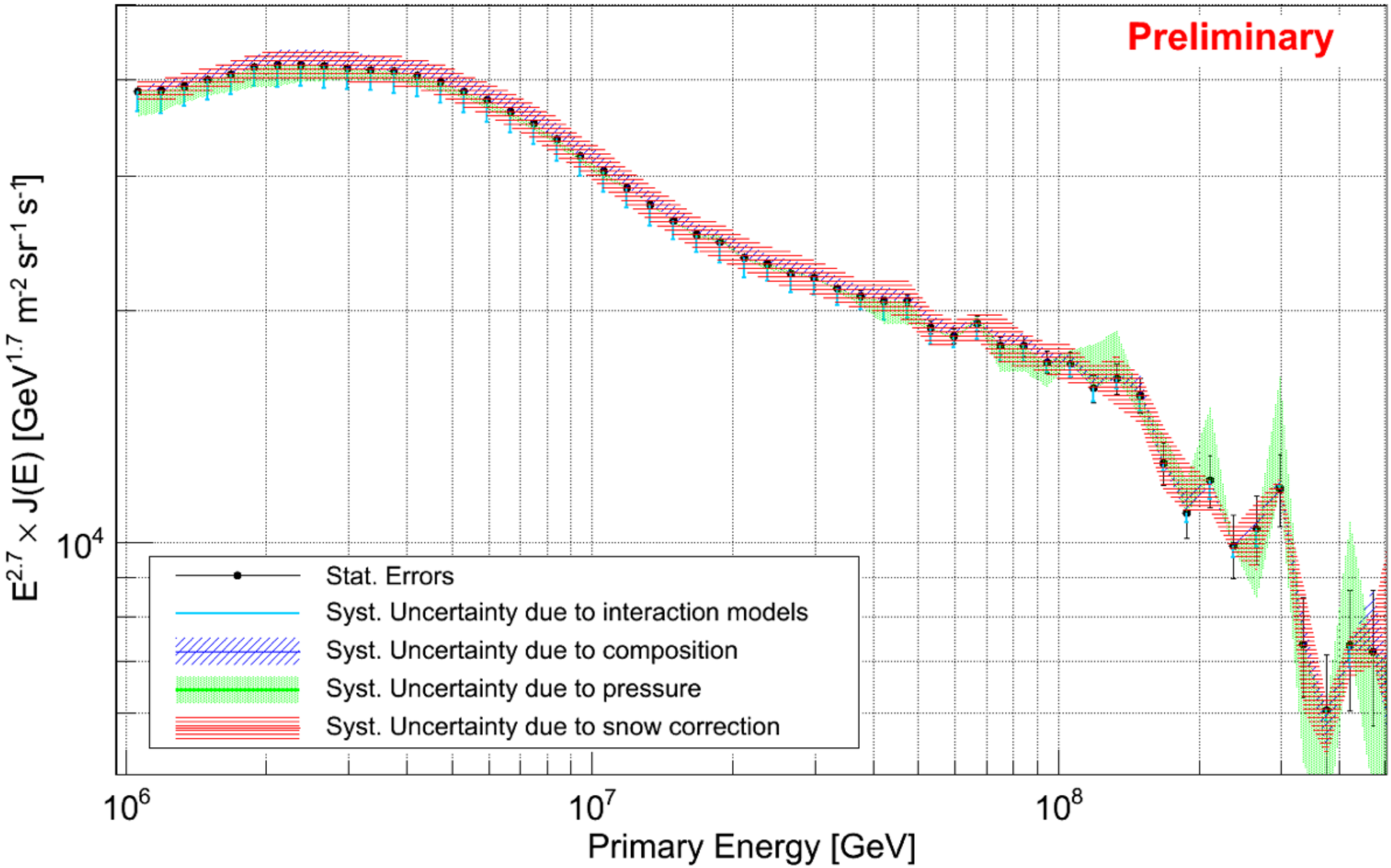
5 nuclear components

3 populations

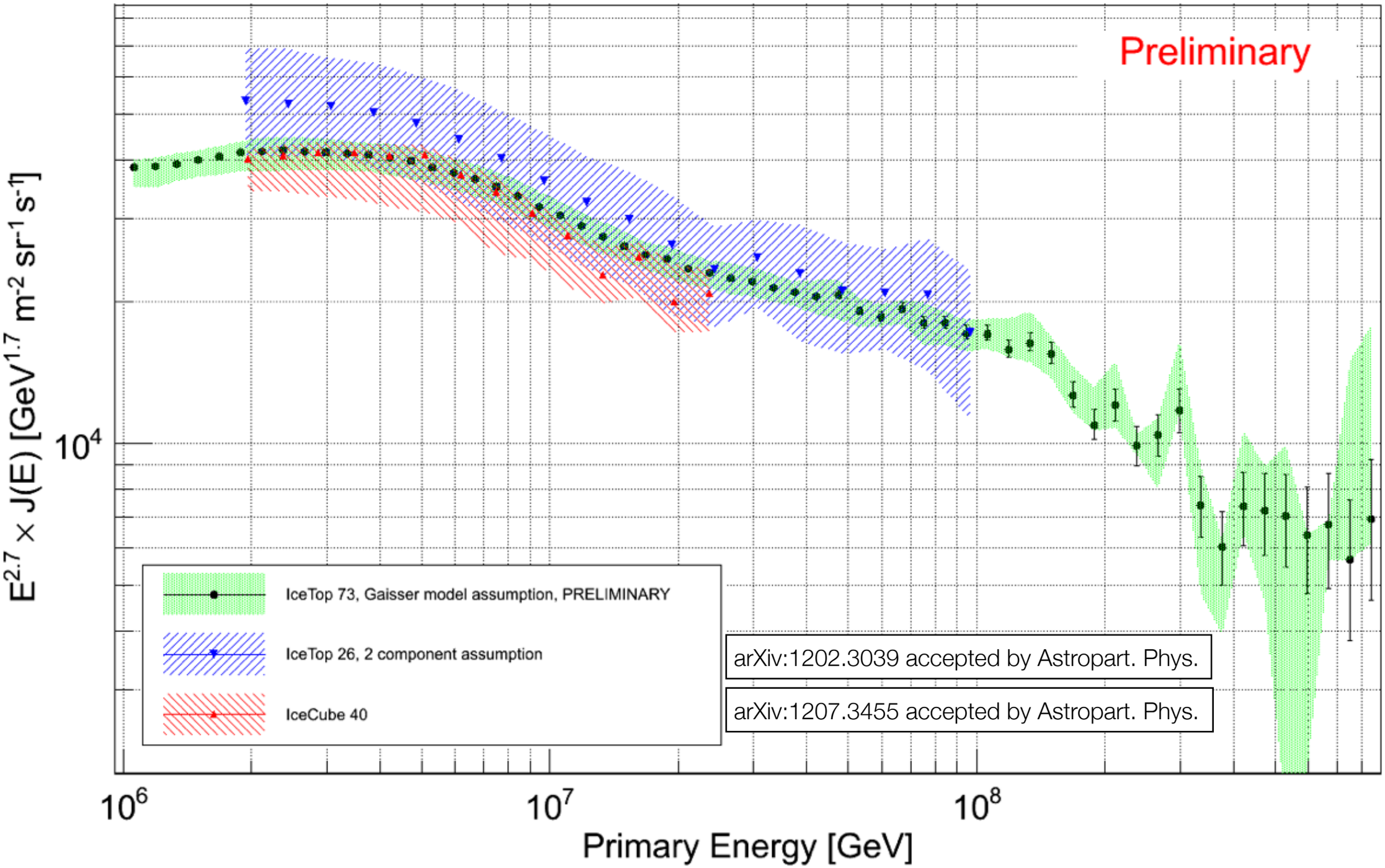
- galactic (e.g. SNR) - CREAM
- galactic II - Hillas
- extragalactic (p or mixed)

IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011



IceTop-only all-particle spectrum



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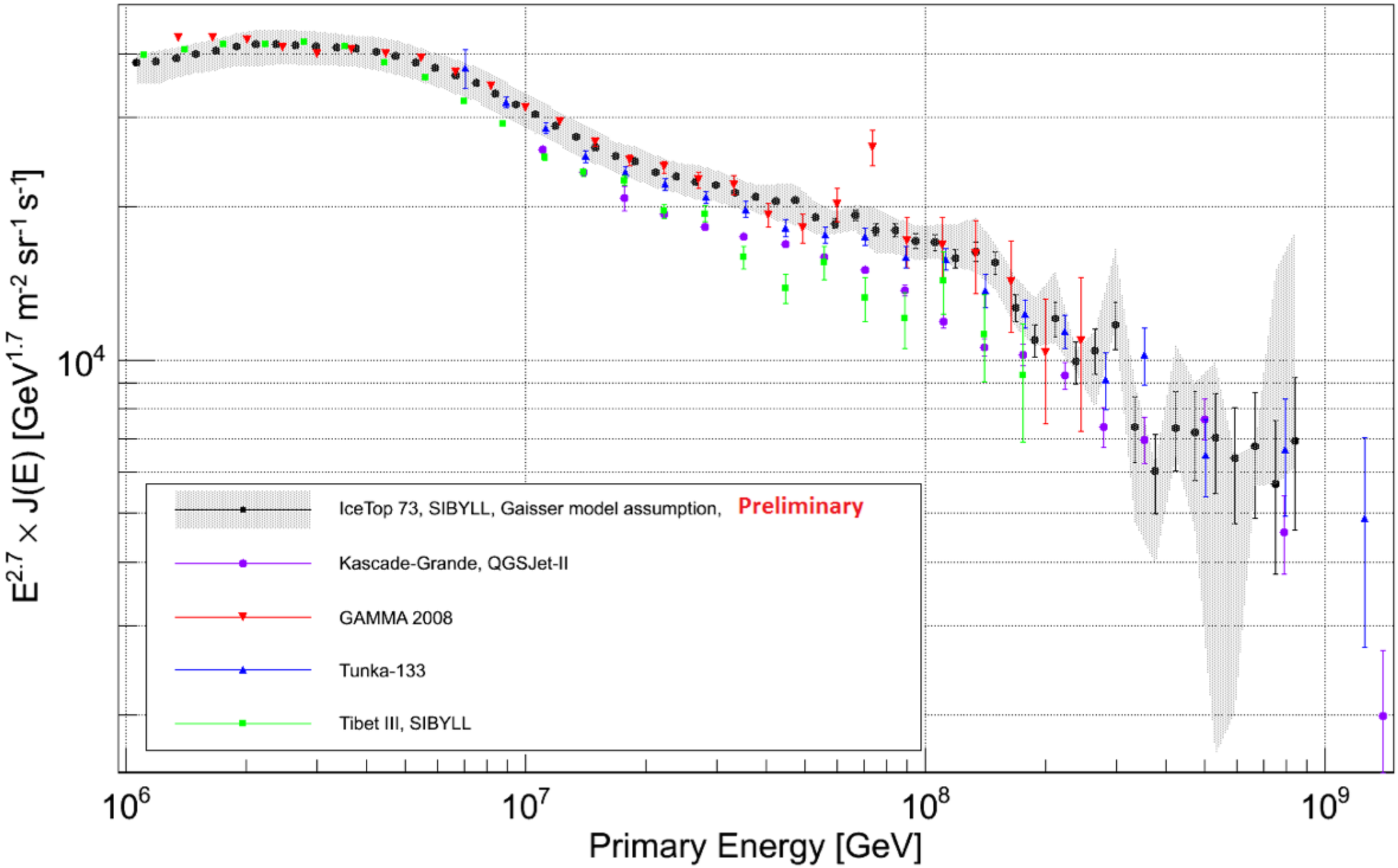

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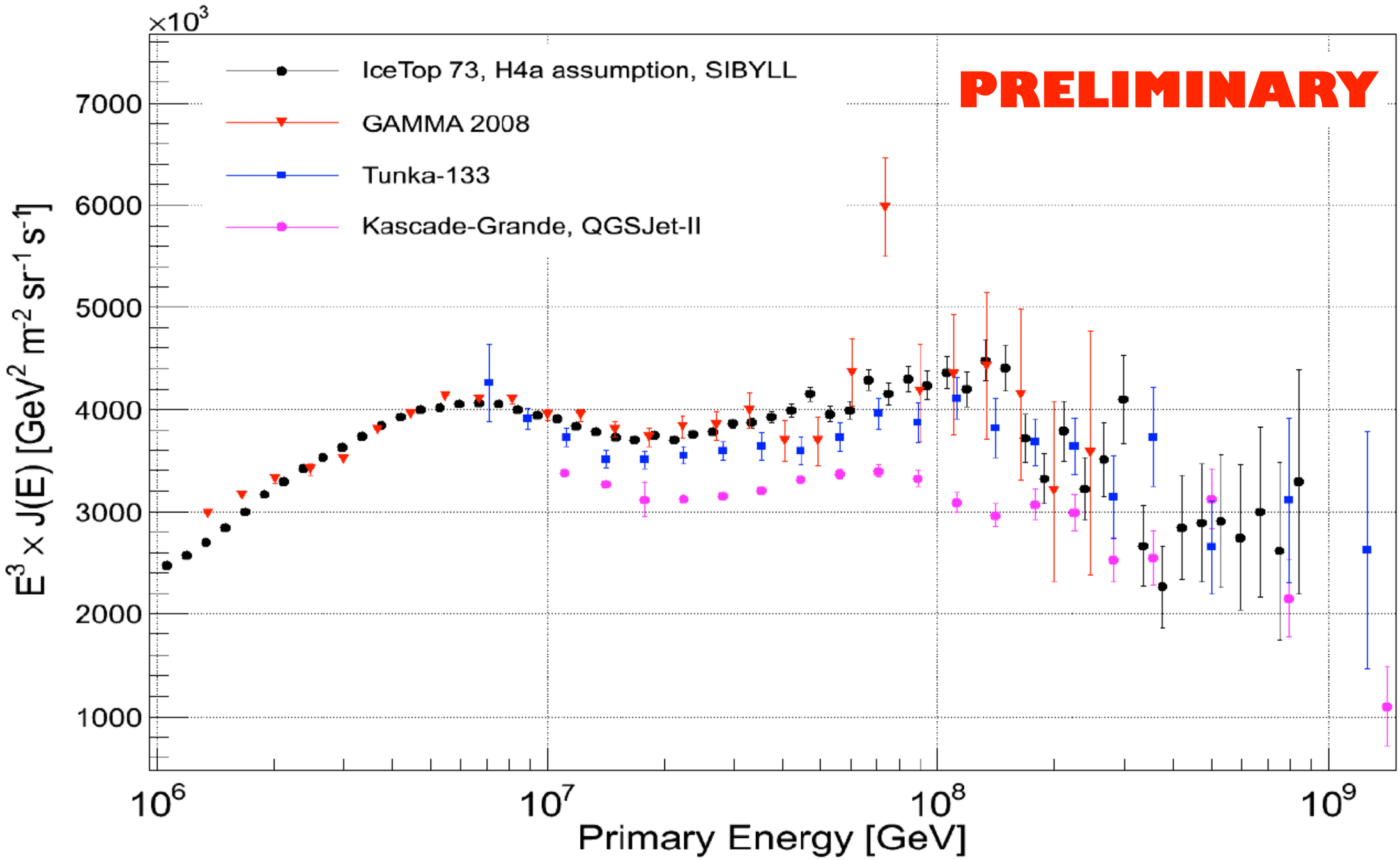

IceTop-only all-particle spectrum

IceTop-73
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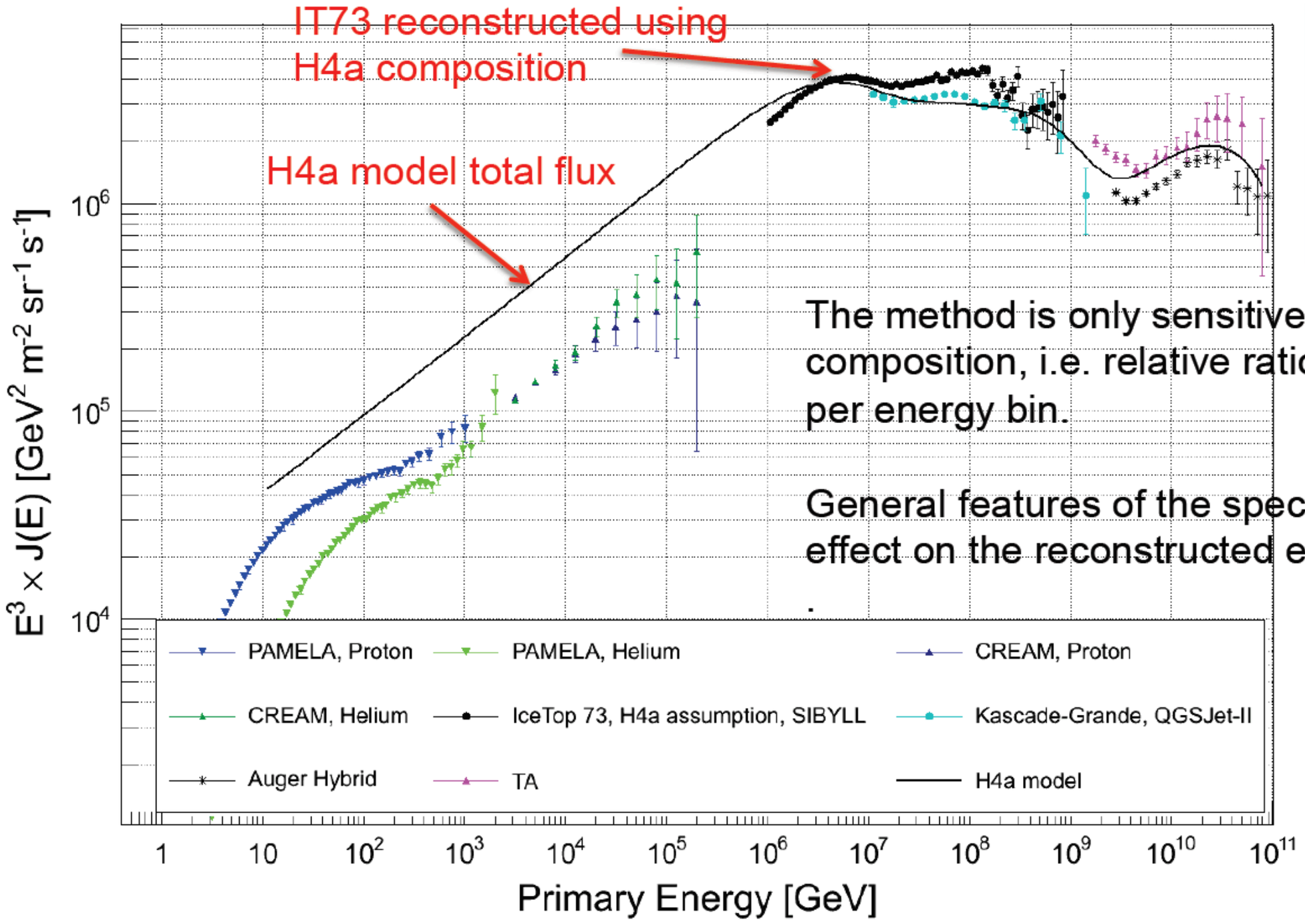
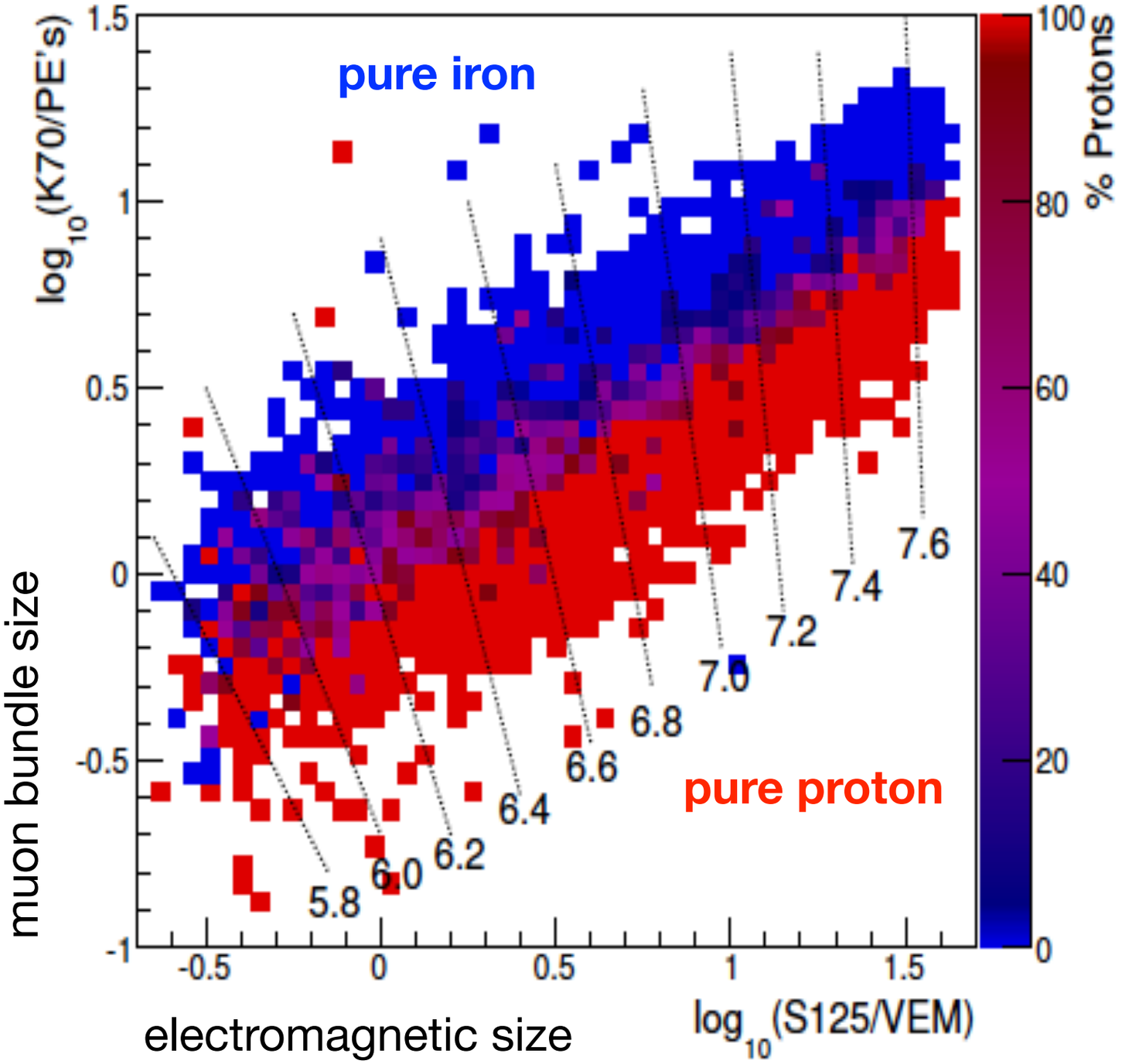


The method is only sensitive to composition, i.e. relative ratio of elements per energy bin.

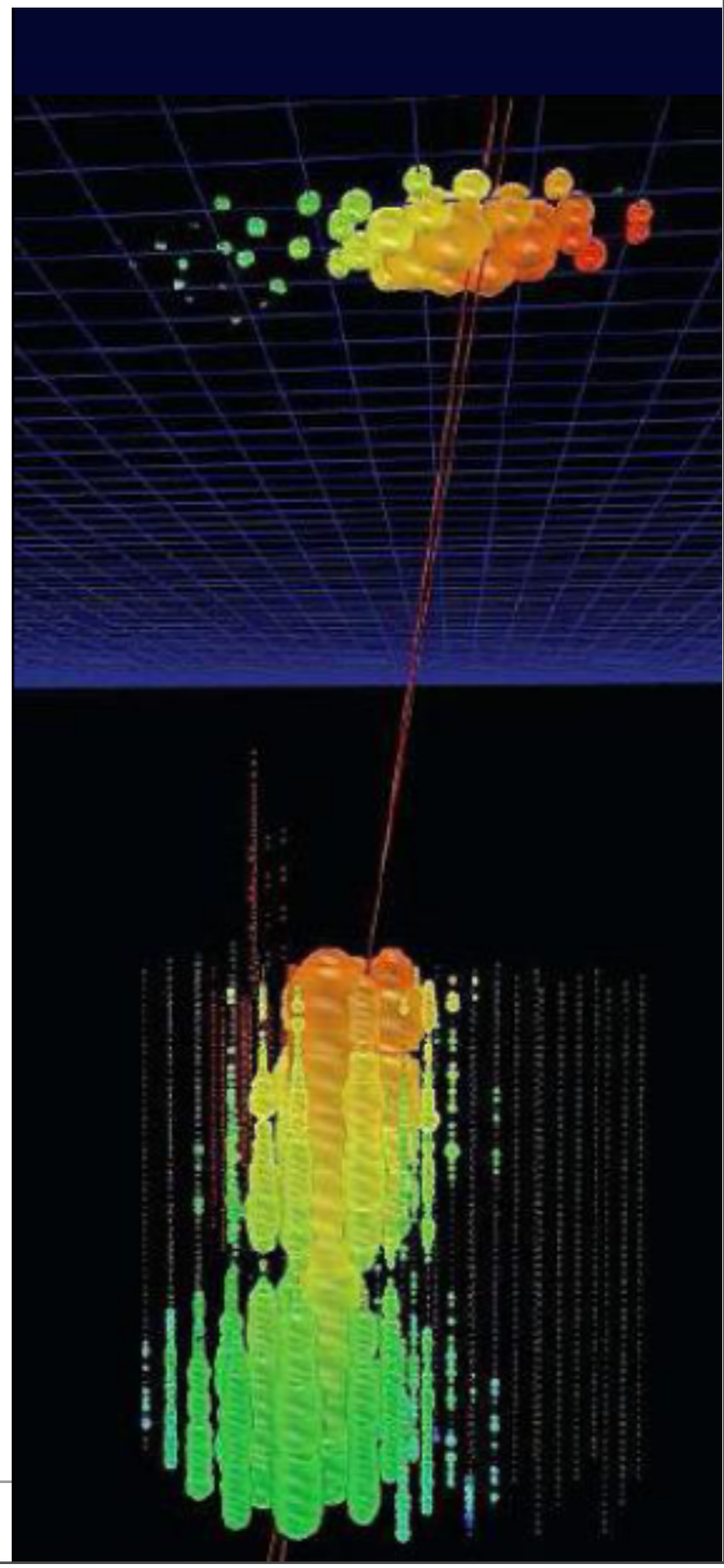
General features of the spectrum have little effect on the reconstructed energy

.

IceTop/IceCube spectrum & composition



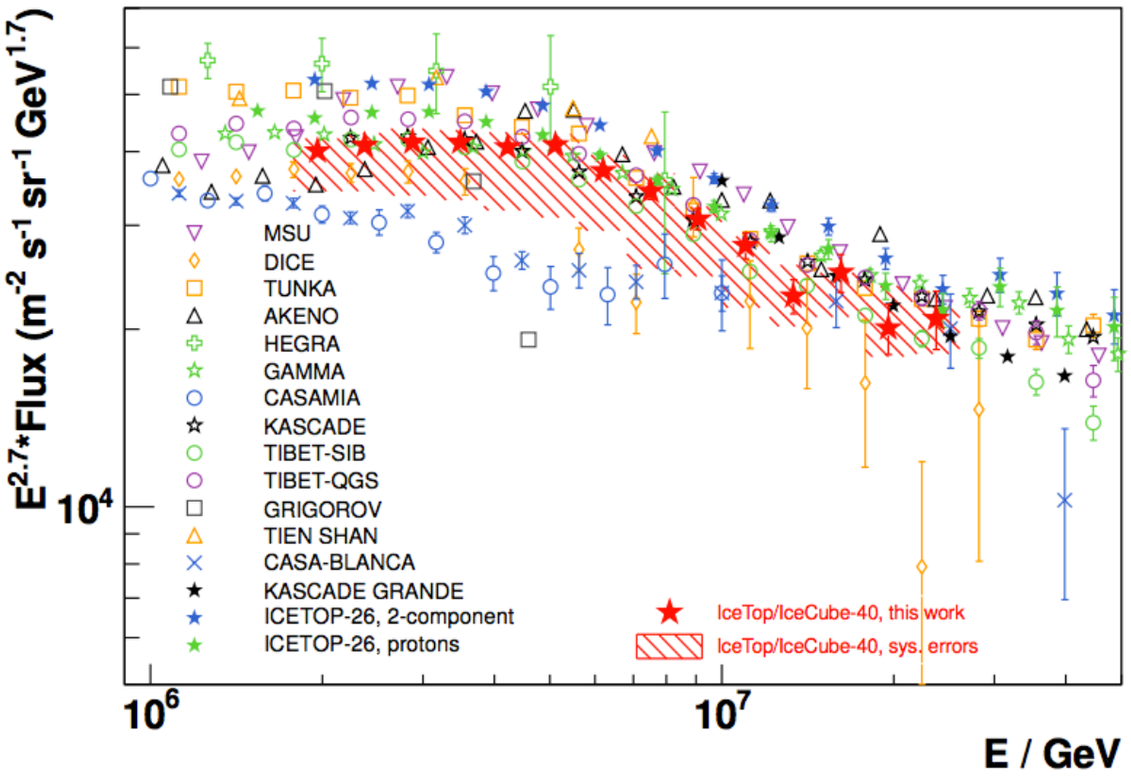
IT-40/IC-40

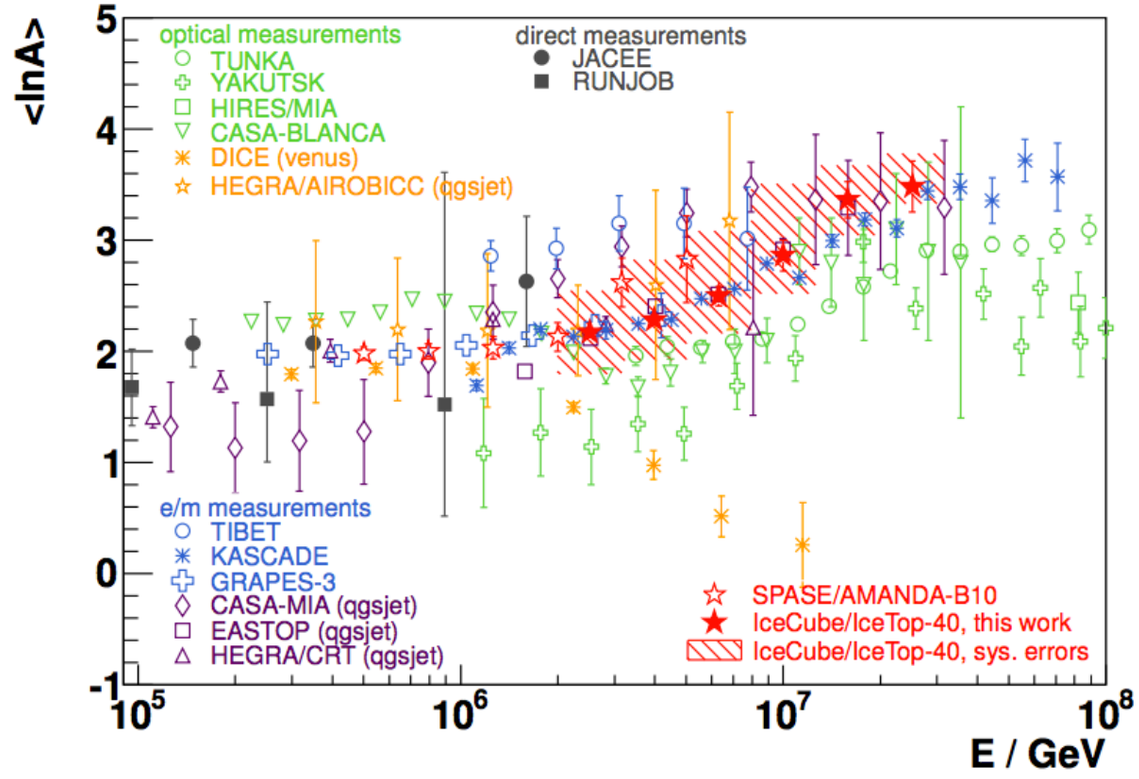


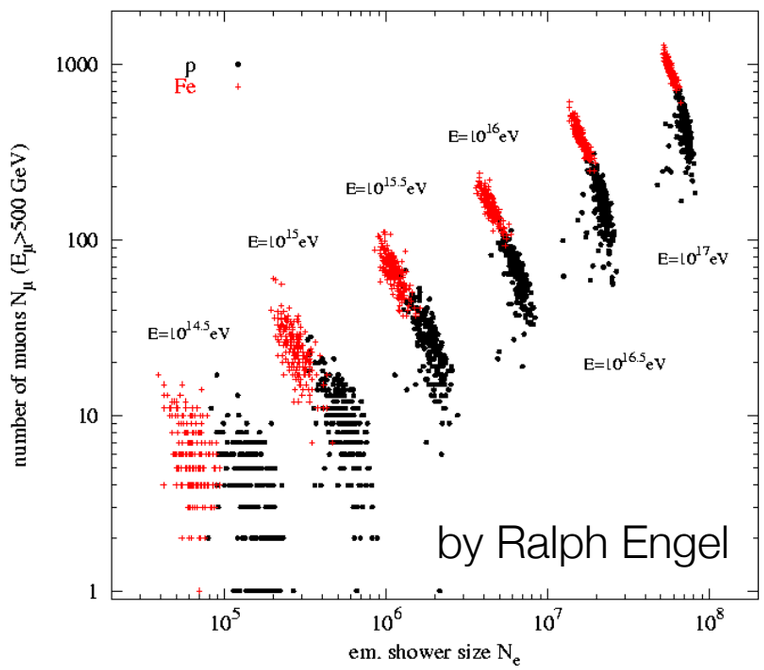
IceTop/IceCube spectrum & composition

IT-40/IC-40

arXiv:1207.3455 accepted by Astropart. Phys.







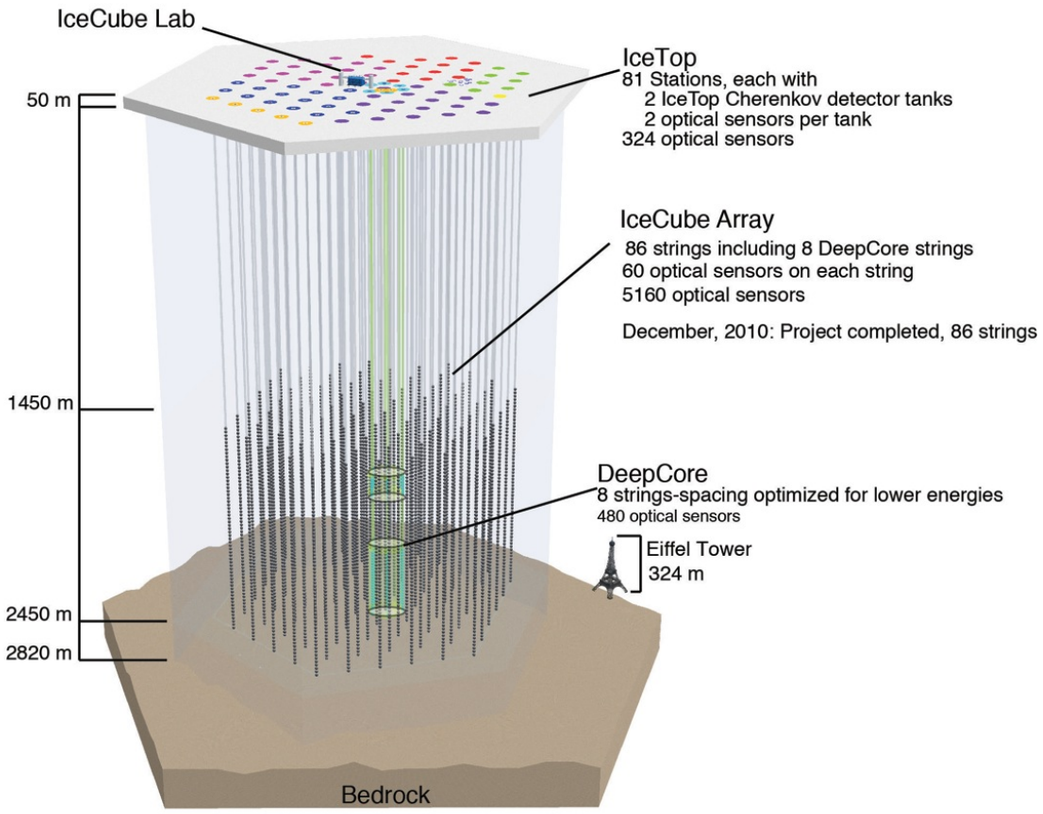
mass-independent primary energy resolution of 0.05 in logE

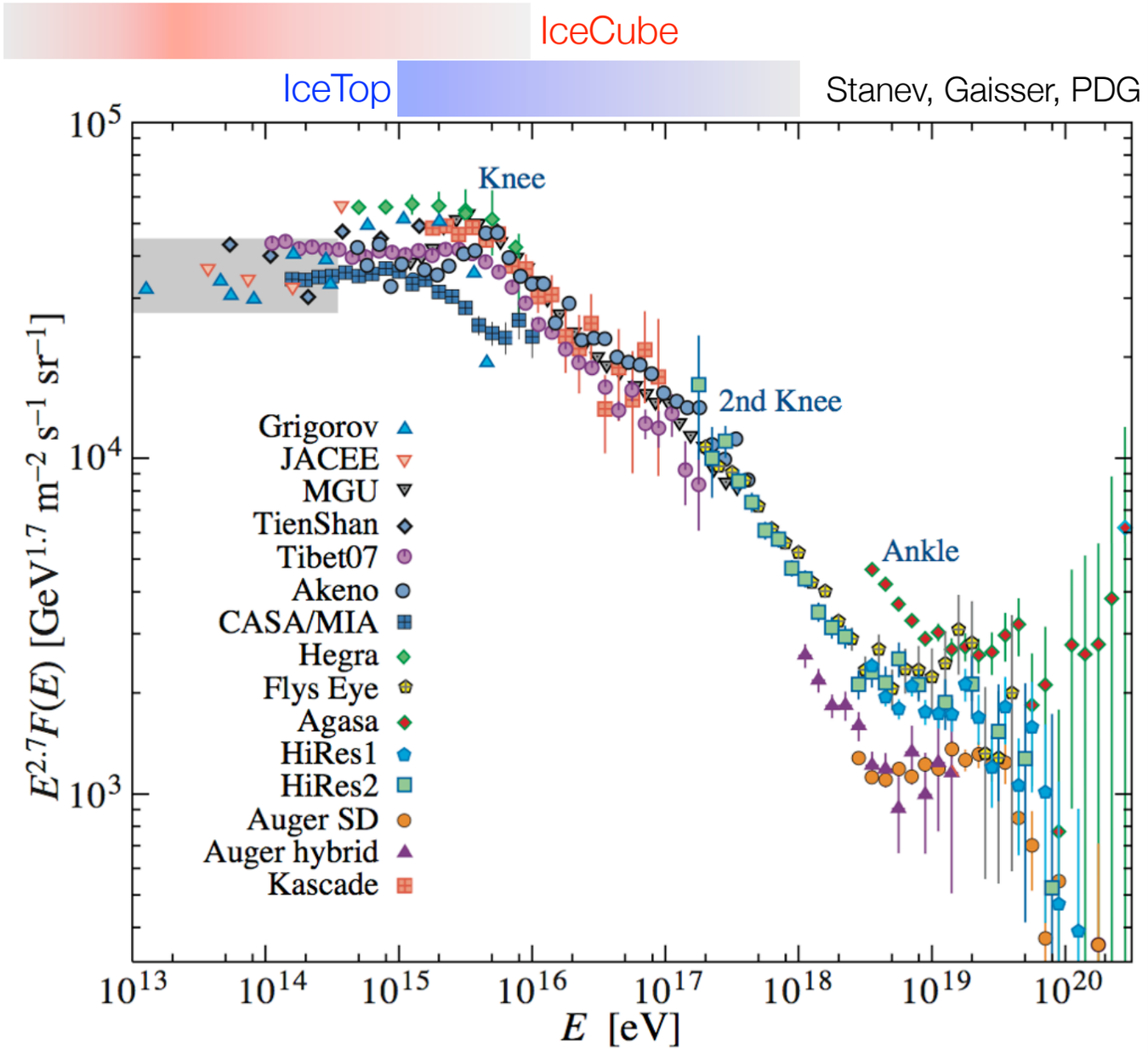
simultaneous EM and hadronic component measurement for spectrum/mass unfolding

experimental systematic uncertainties important

- study extended to IC53/IC59 & IT73/IC79

cosmic ray anisotropy

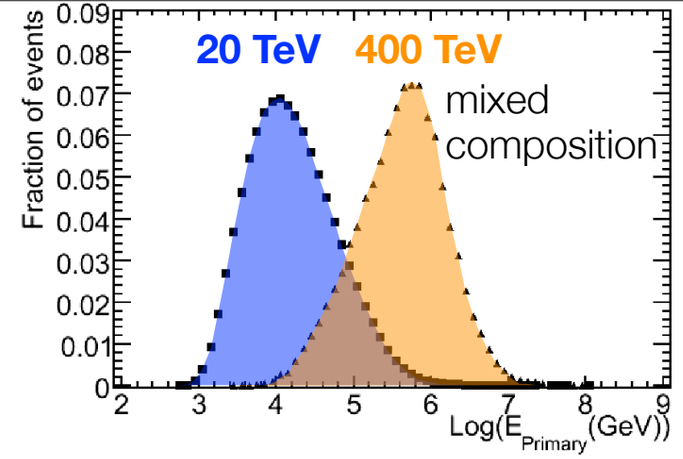




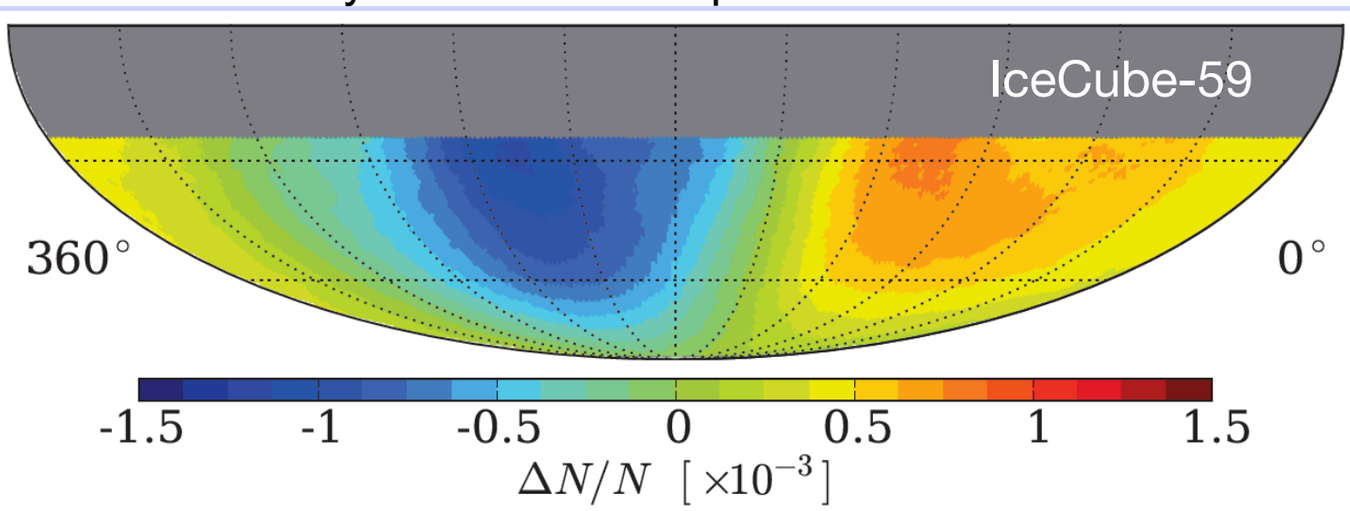
IceCube - μ bundle rate ~ **2.5 kHz**
8×10^{10} events/yr
sensitive to asymmetries O(10^{-5})

IceTop - CR rate ~ **10 Hz**
3×10^{8} events/yr
sensitive to asymmetries O(10^{-4})

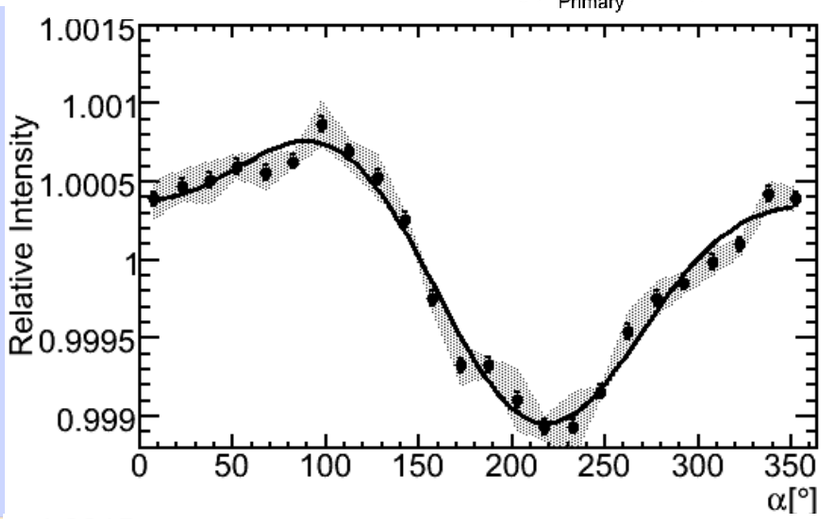
cosmic ray anisotropy large scale
IceCube

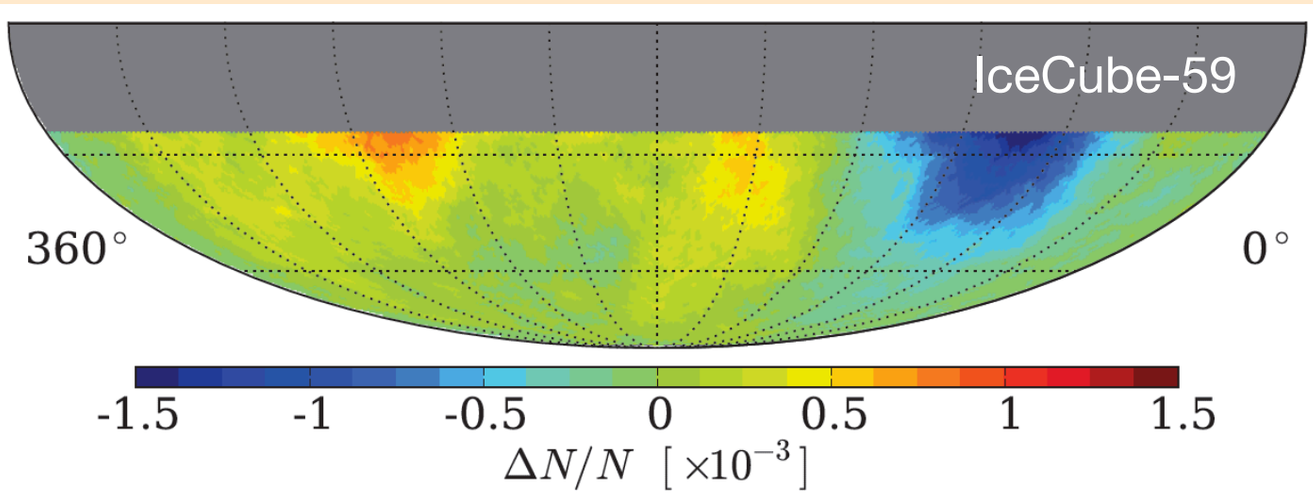


relative intensity equatorial coordinates



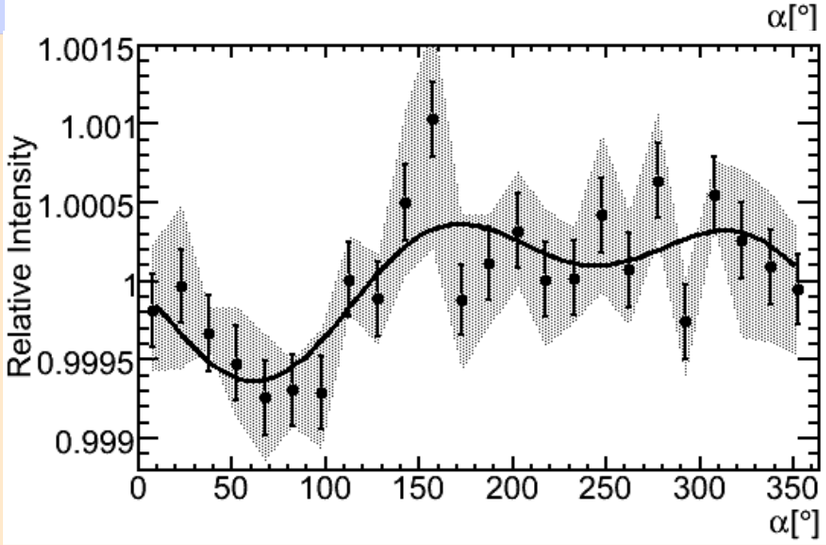
20 TeV





400 TeV

deficit
6.3 σ_{post}



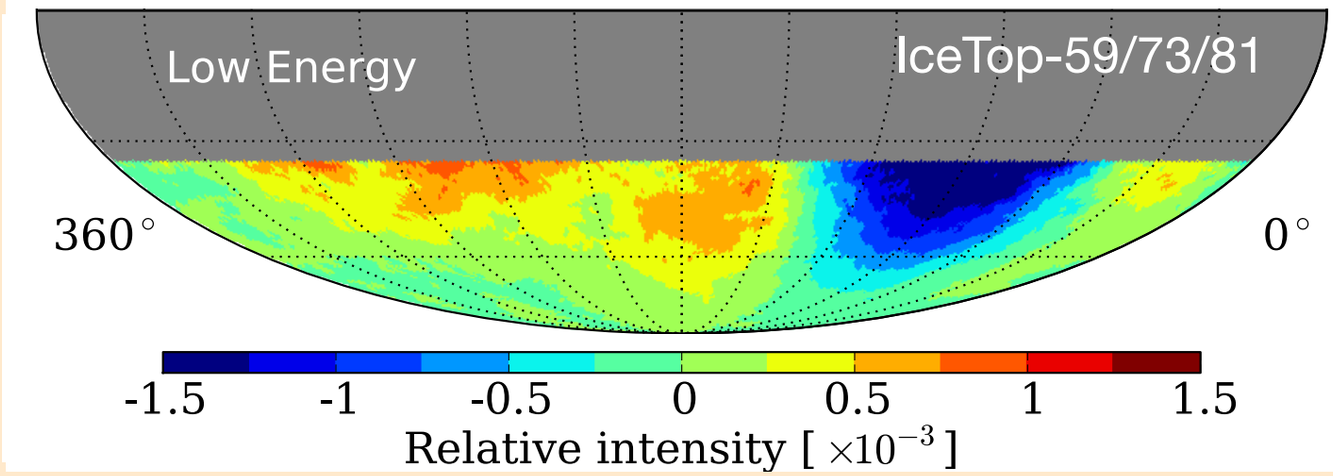
NOTE: anisotropy is not a dipole
topology changes at high energy

IC59 Abbasi et al., ApJ, **746**, 33, 2012

IC22 Abbasi et al., ApJ, **718**, L194, 2010

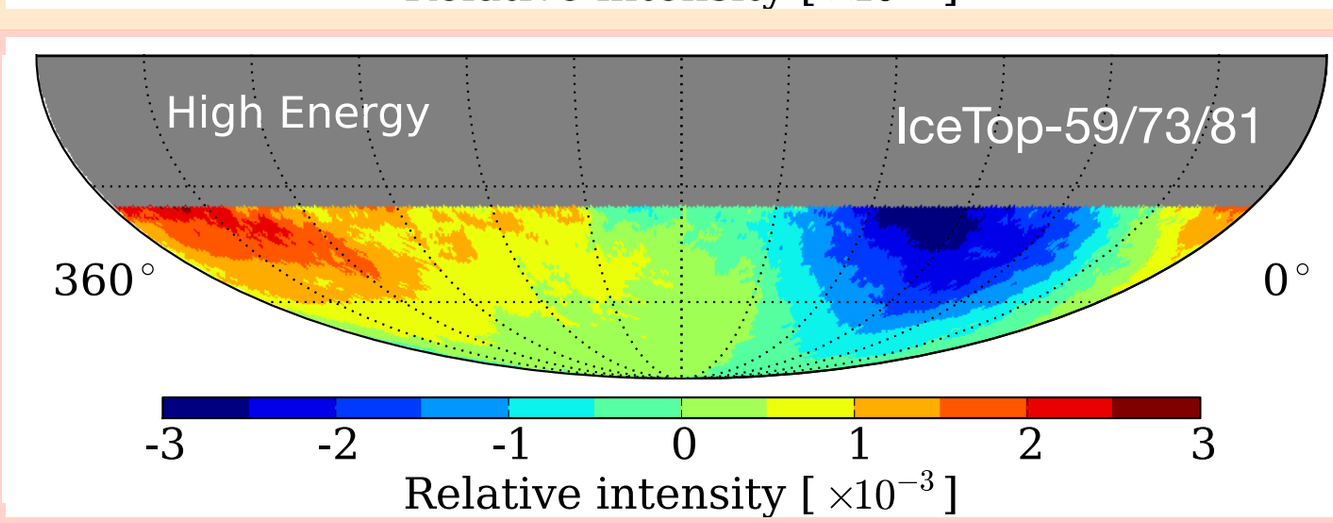
cosmic ray anisotropy large scale
IceTop

relative intensity equatorial coordinates



deficit
7 σ_{post}

400 TeV



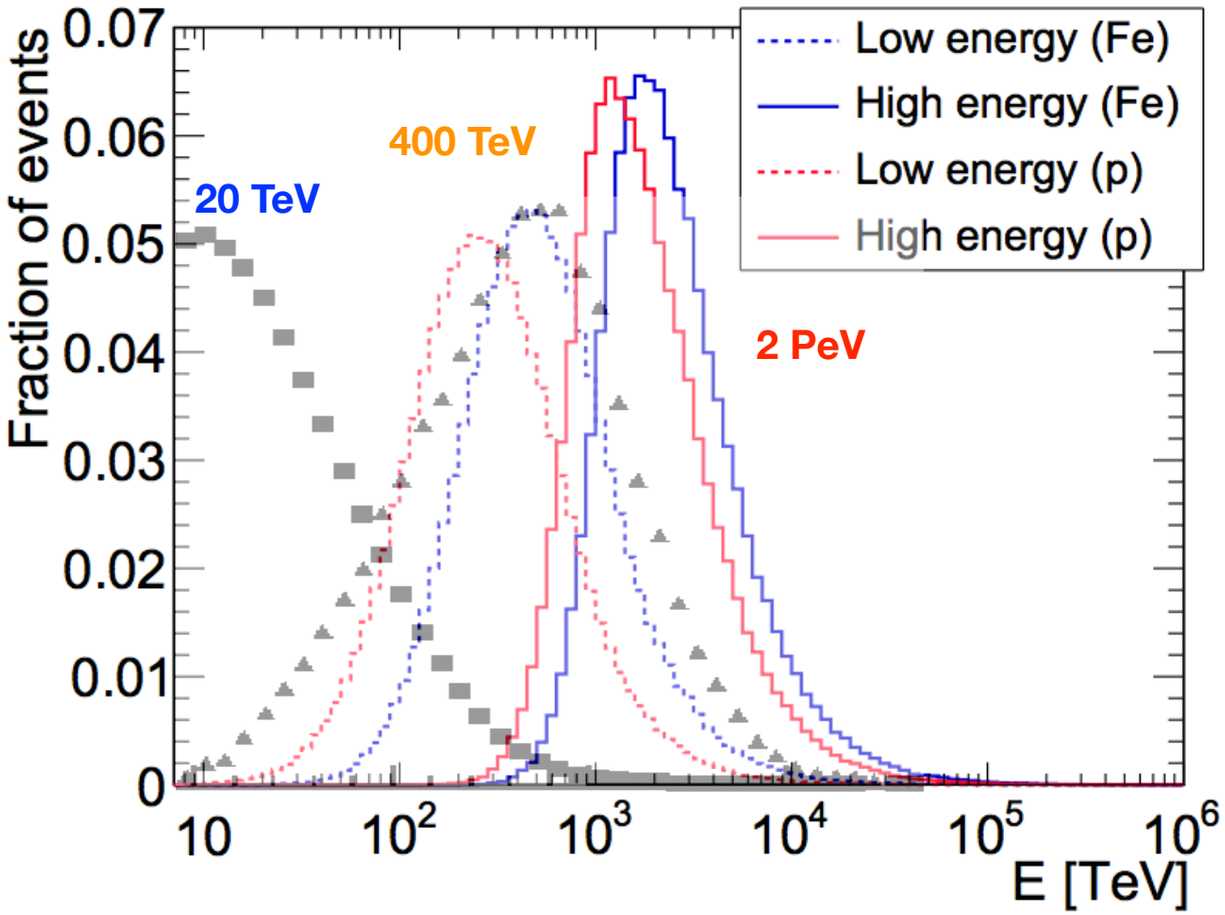
2 PeV

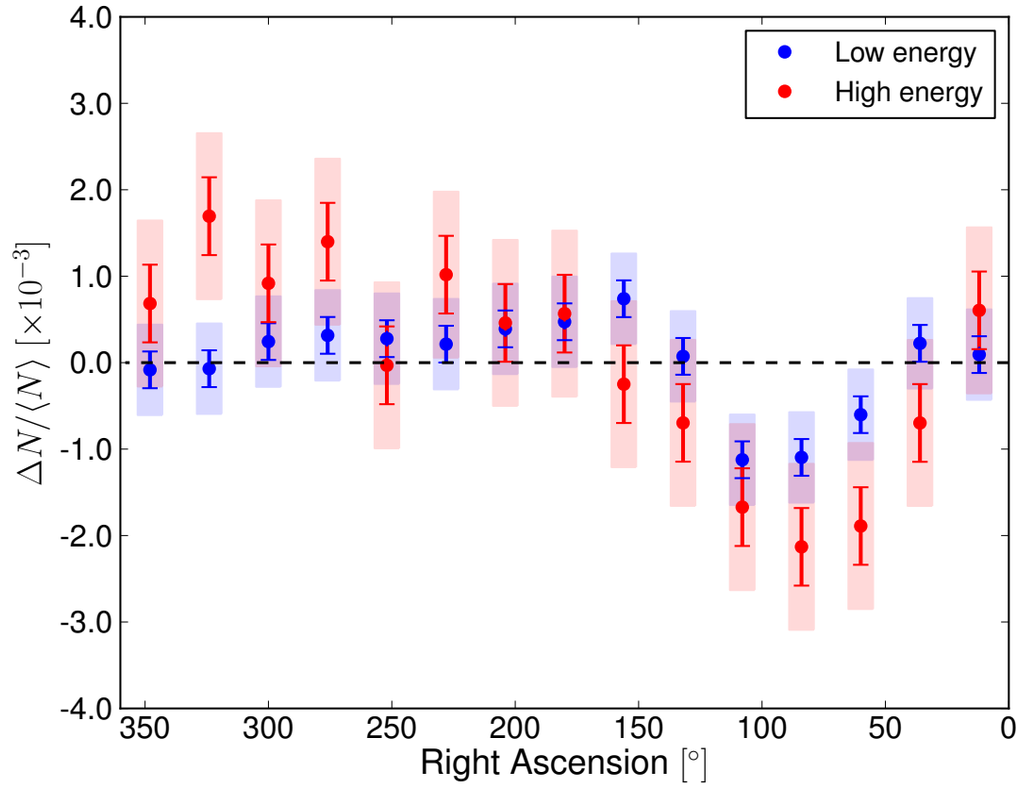
Aartsen et al., arXiv:1210.5278 accepted to ApJ

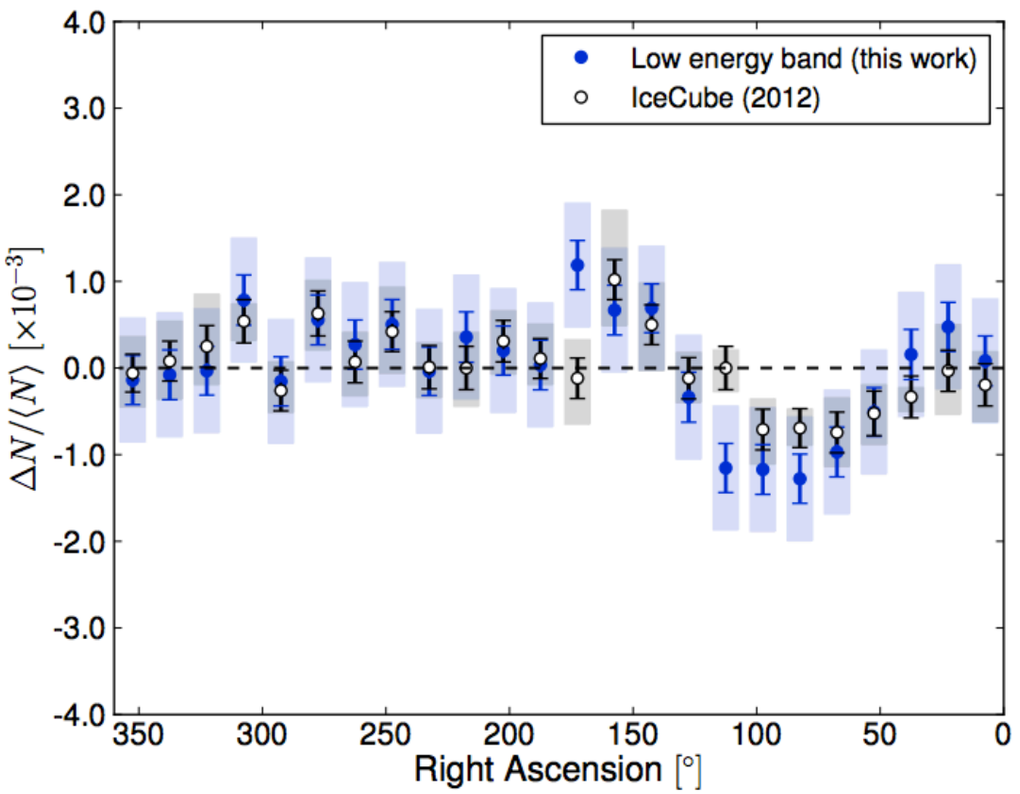
NOTE: global topology does not change

deficit amplitude increases with energy

cosmic ray anisotropy large scale
IceCube & IceTop







NOTE: different energy response distribution

IceTop with *sharper* low energy threshold

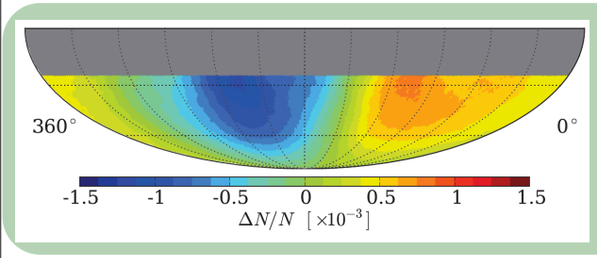
might explain IC/IT amplitude differences

cosmic ray anisotropy large scale

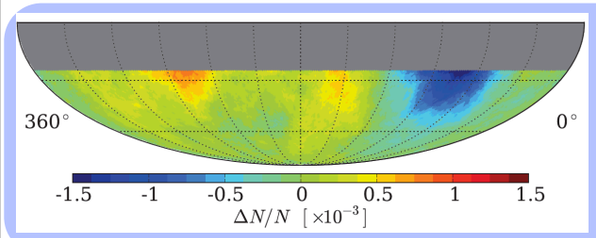
IceCube

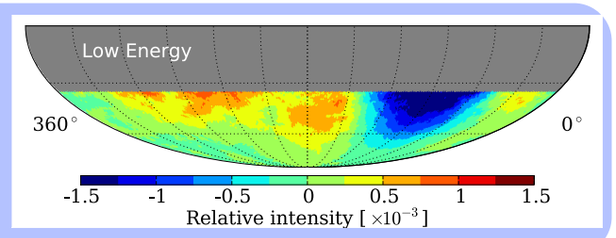
IceTop

20 TeV

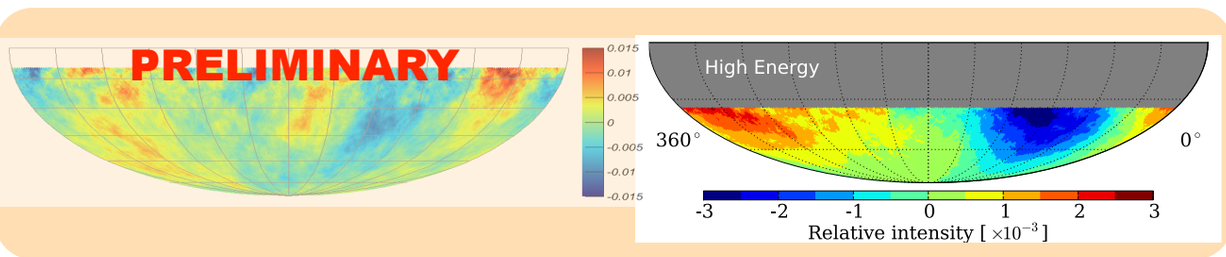


400 TeV

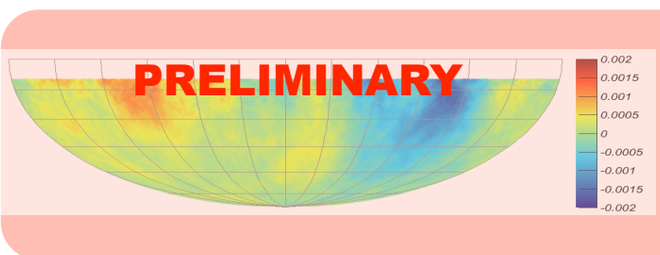


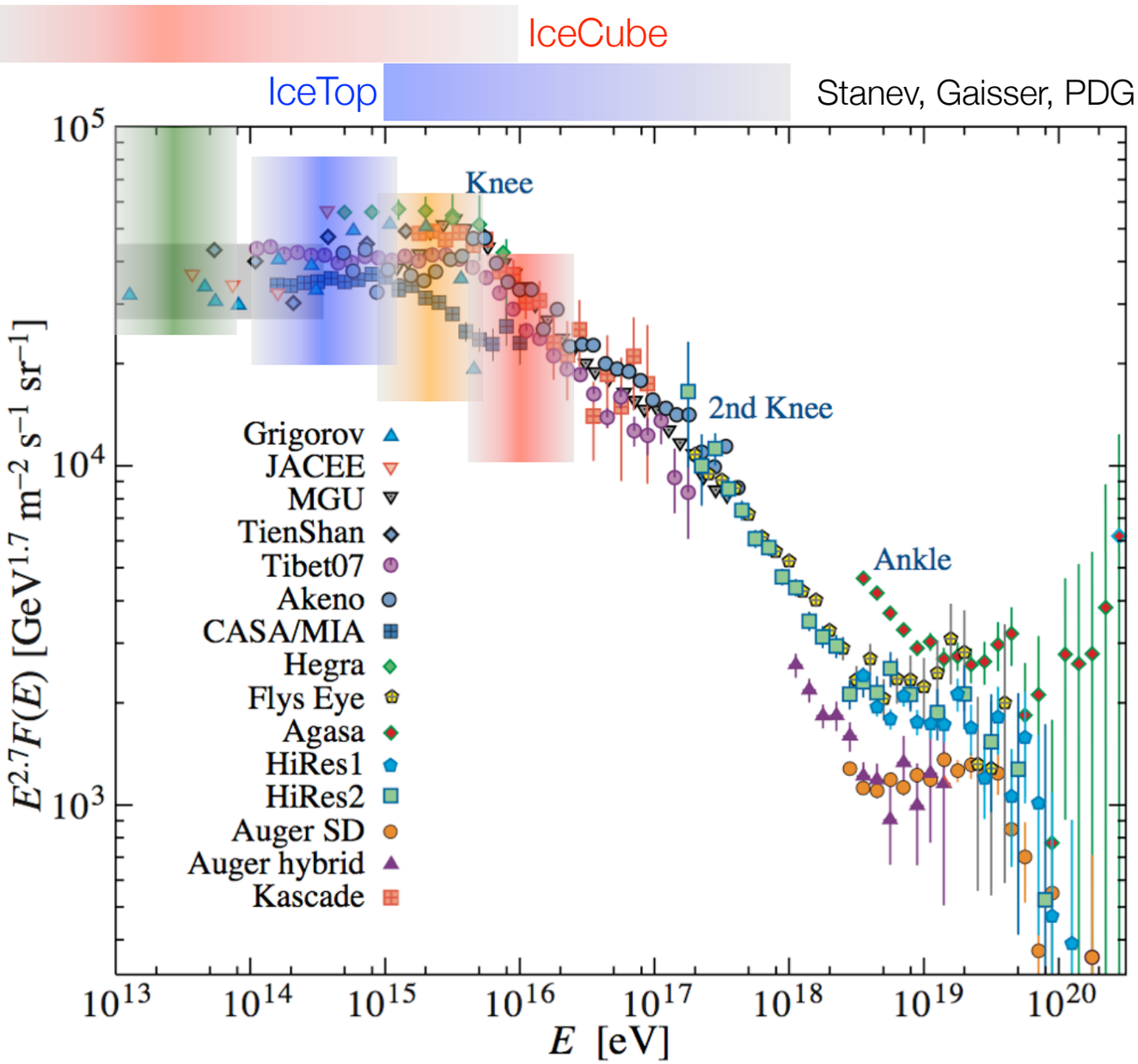


2 PeV



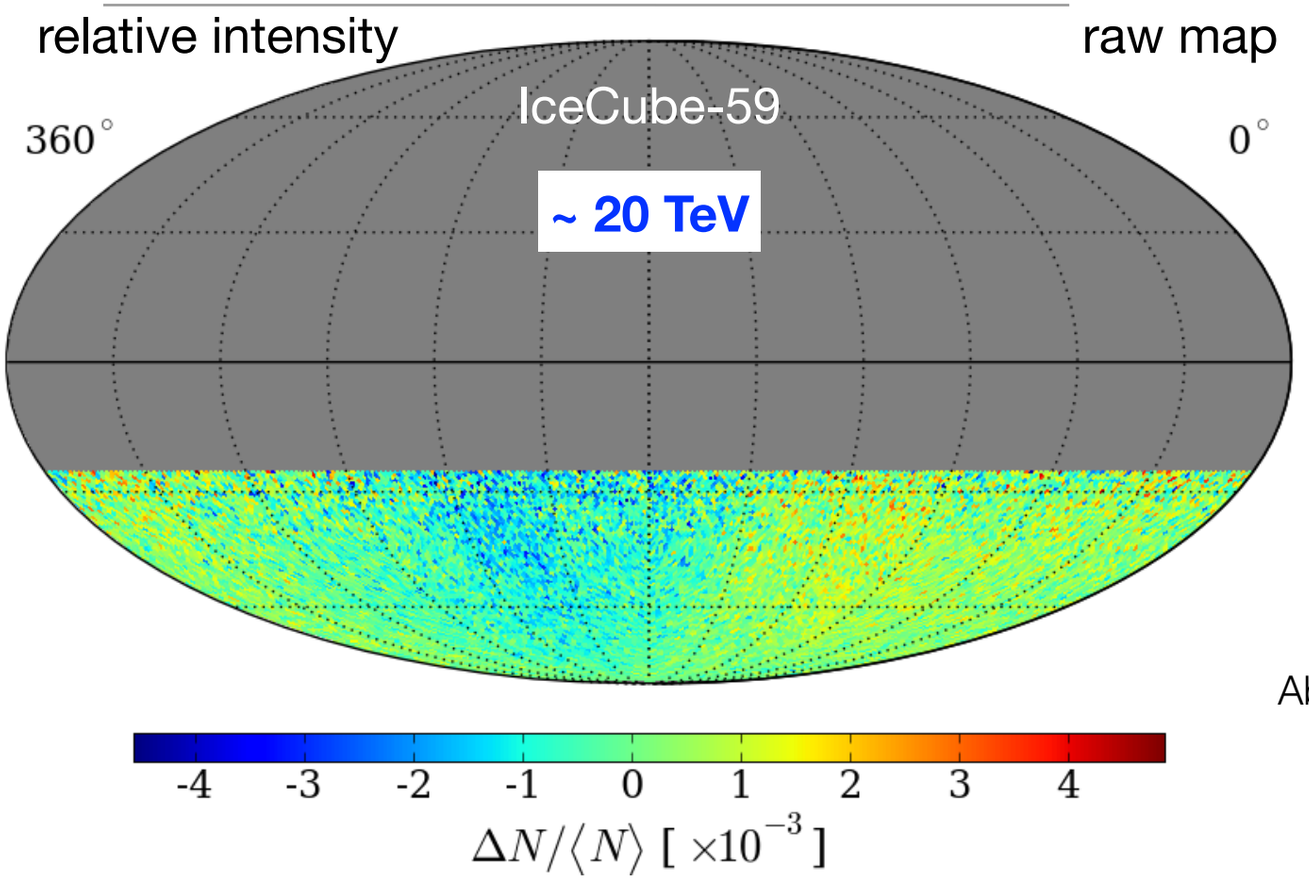
10 PeV





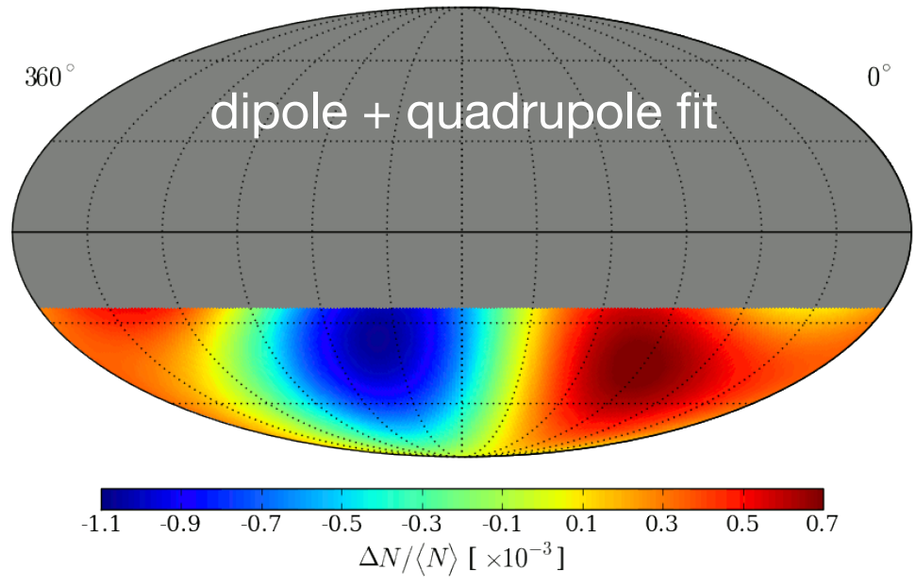
- extend observation above PeV range
- primary mass dependency
- primary spectrum at excess/deficit

cosmic ray anisotropy small scale
IceCube

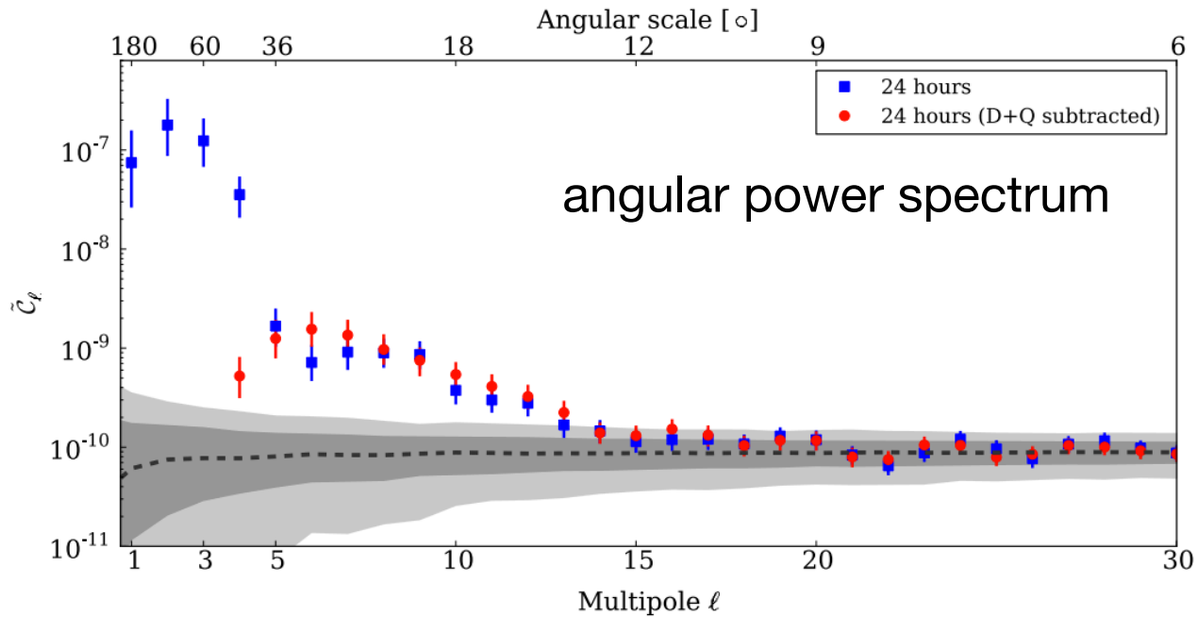


χ^2/ndf = 14743.4 / 14187

Pr(χ^2|ndf) = 0.05%



Abbasi et al., ApJ, **740**, 16, 2011



sky map contains correlations at several angular scales

in gray 60% and 95% of simulated isotropic bands

large and small scales *separated* @ ~20 TeV ?

cosmic ray anisotropy large scale

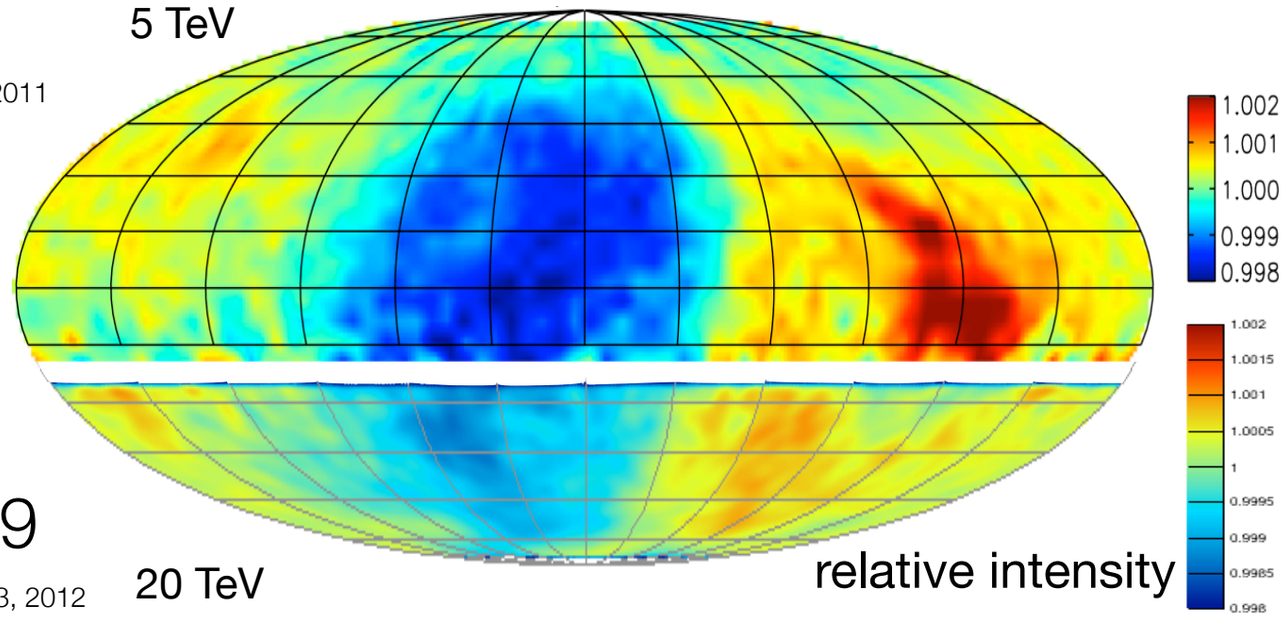
equatorial coordinates

Tibet-III

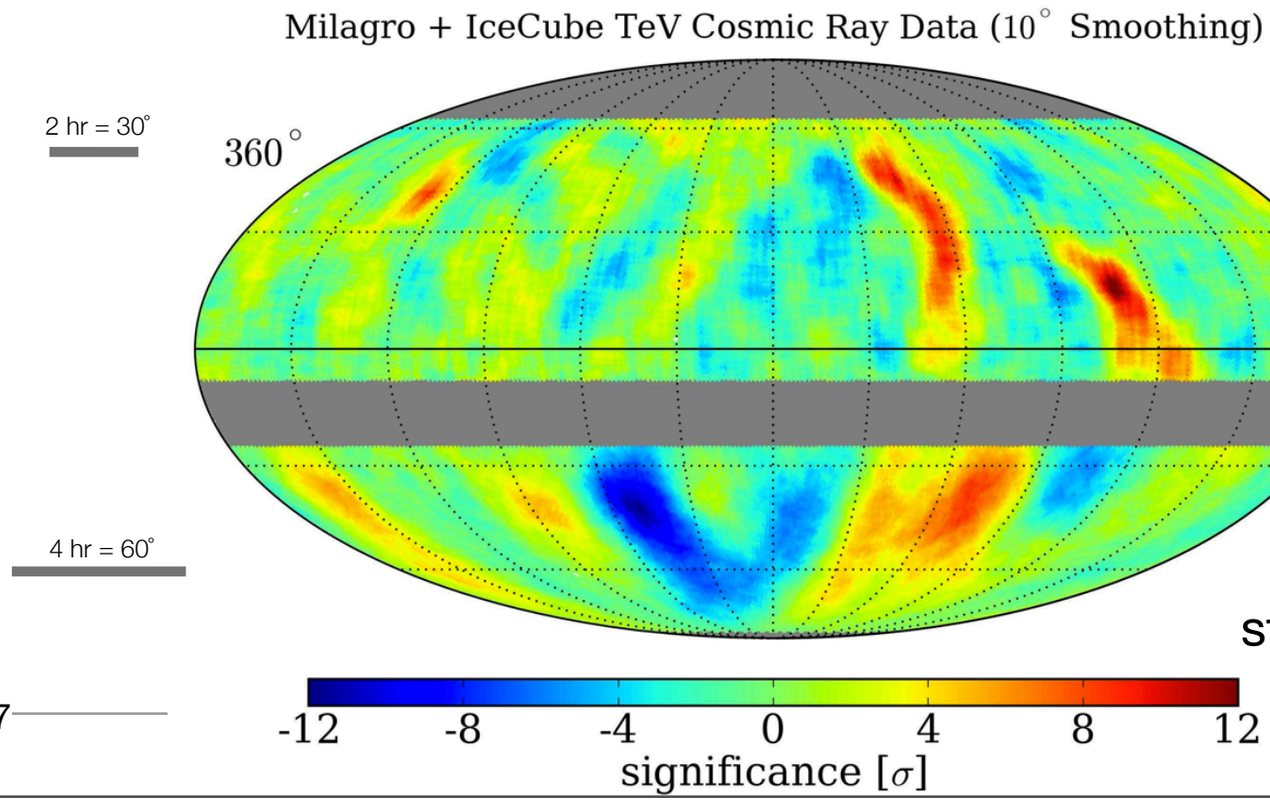
Amenomori et al., ICRC 2011

IceCube-59

Abbasi et al., ApJ, **746**, 33, 2012



- complete sky coverage at equivalent energies
- understand systematics of maps derivation



Milagro 1 TeV

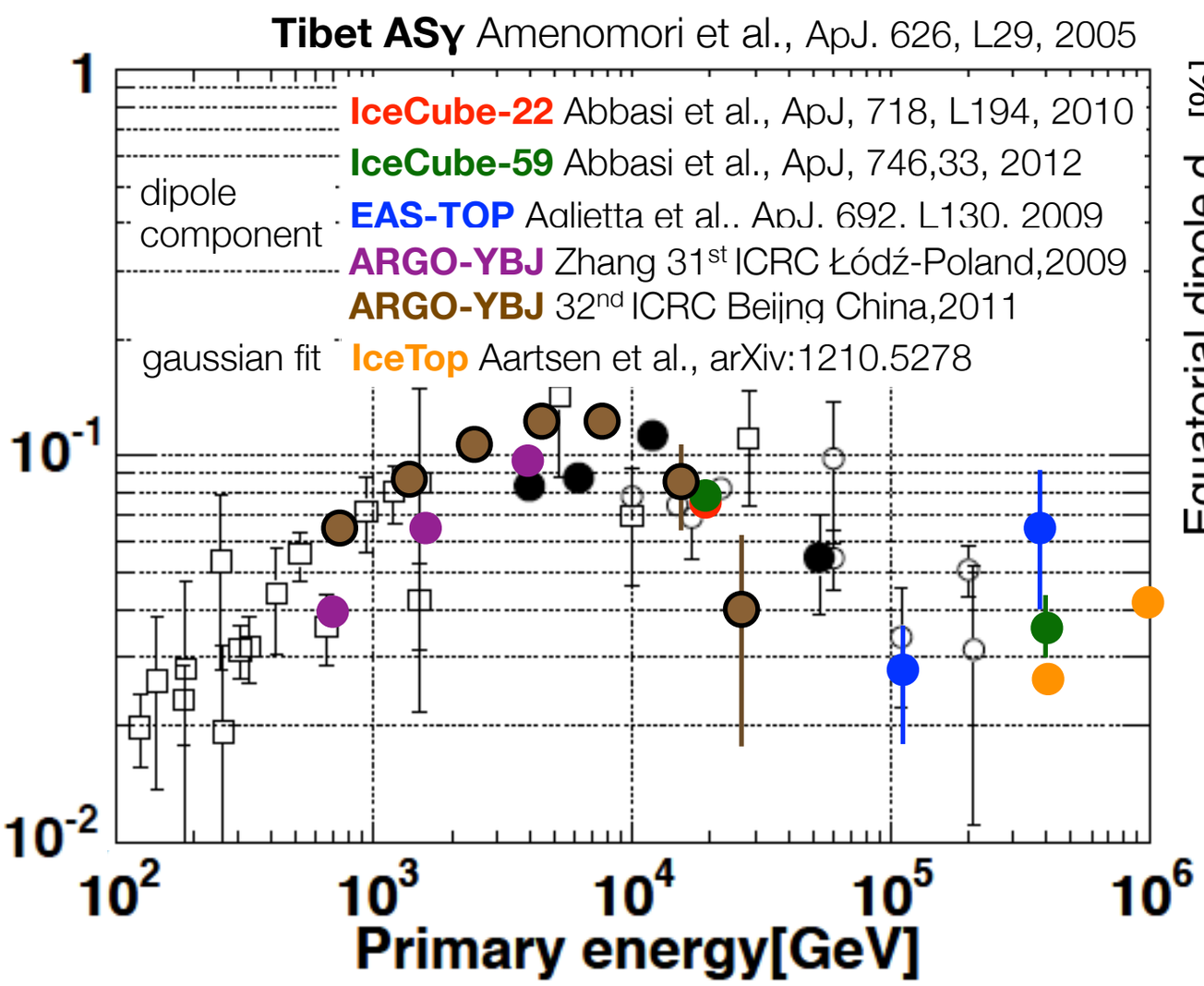
Abdo et al., PRL, **101**, 221101, 2008

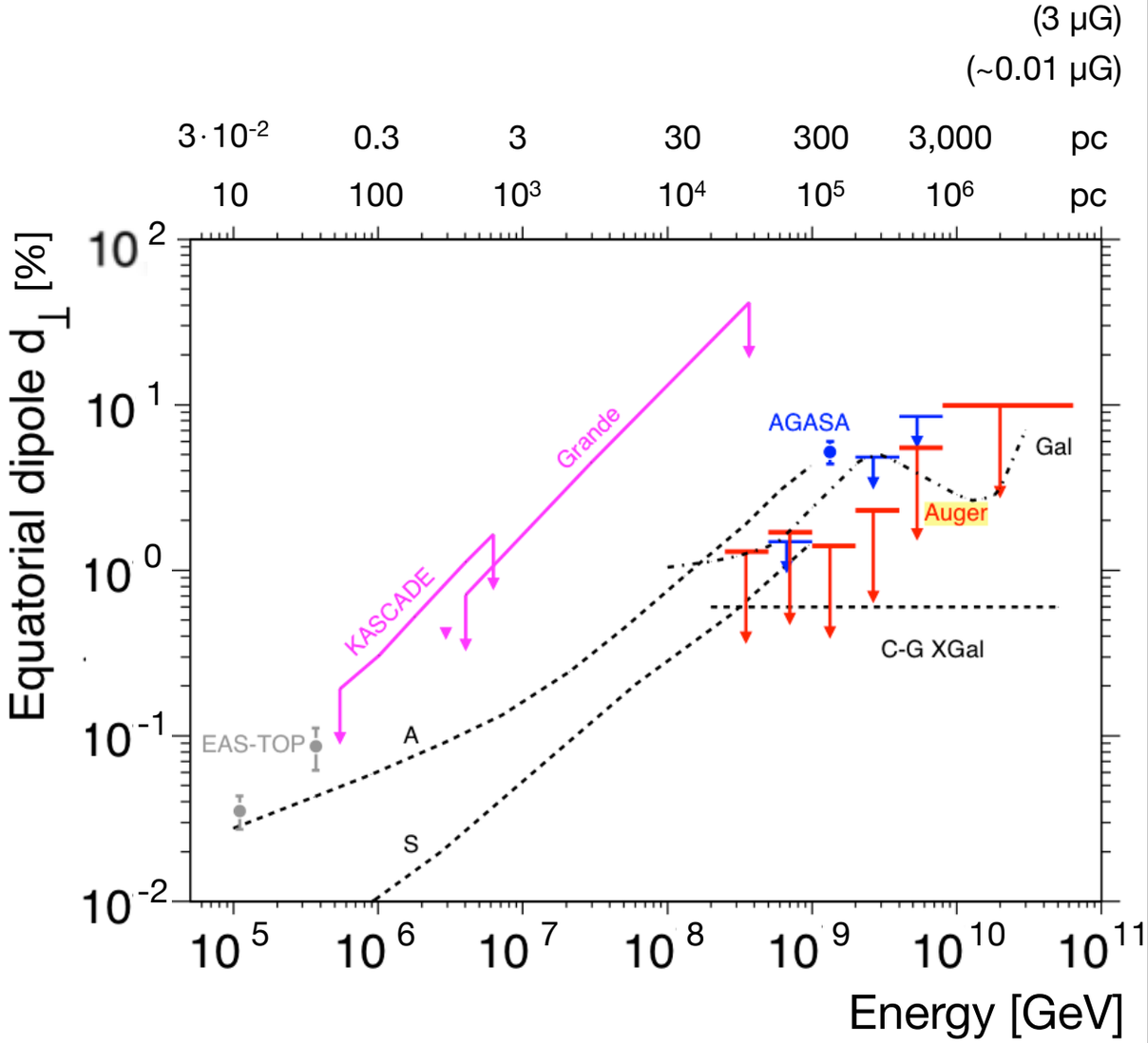
IceCube 20 TeV

Abbasi et al., ApJ, **740**, 16, 2011

statistical significance

cosmic ray anisotropy large scale energy dependency



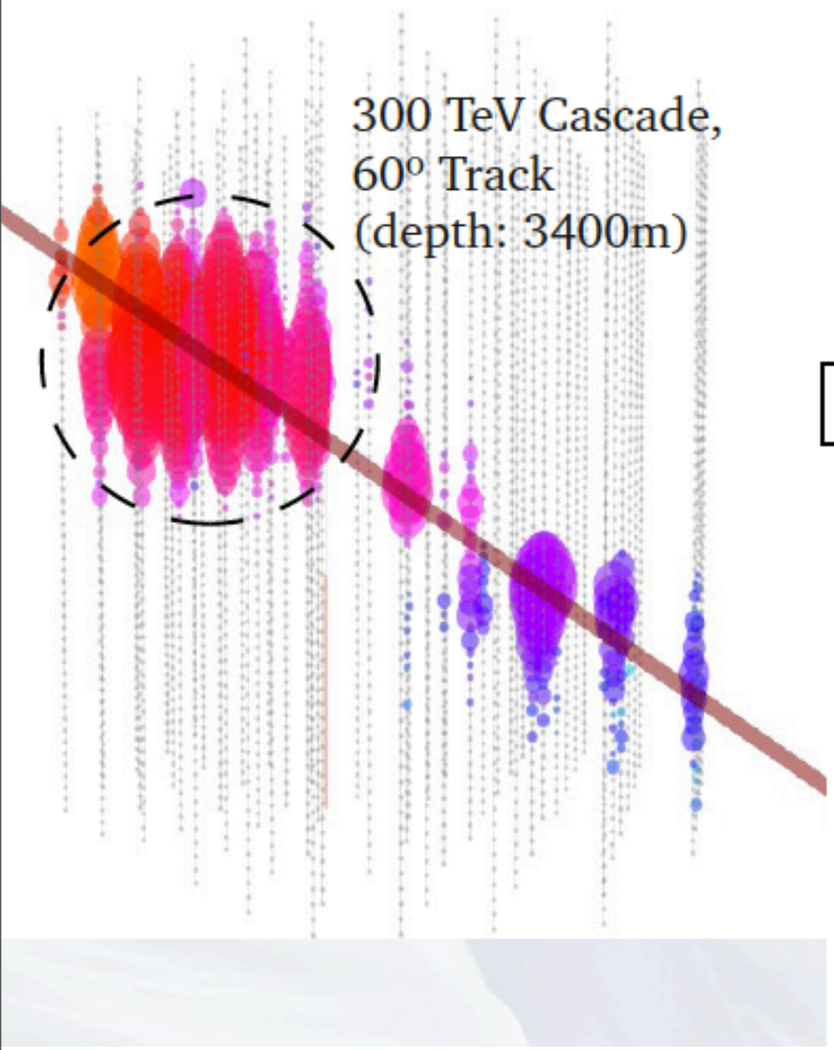


Abreu et al., Astrop. Phys., 34, 627, 2011

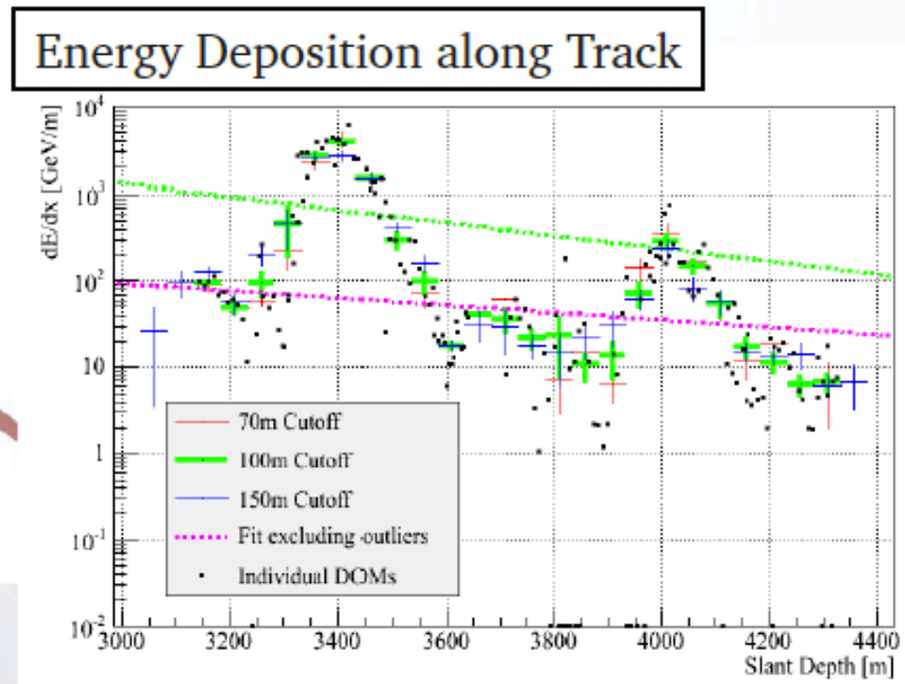
				(3 μG)	
$3\cdot10^{-5}$	$3\cdot10^{-4}$	$3\cdot10^{-3}$	$3\cdot10^{-2}$	0.3	gyro-radius (pc)
7	70	700	7,000	70,000	gyro-radius (AU)

muon inclusive spectrum

high energy muons ∝ energy/nucleon



1.07(±60%) PeV surface energy (MC-simulation estimate based on cascade energy, slant depth)



high energy muons have large stochastic energy loss processes

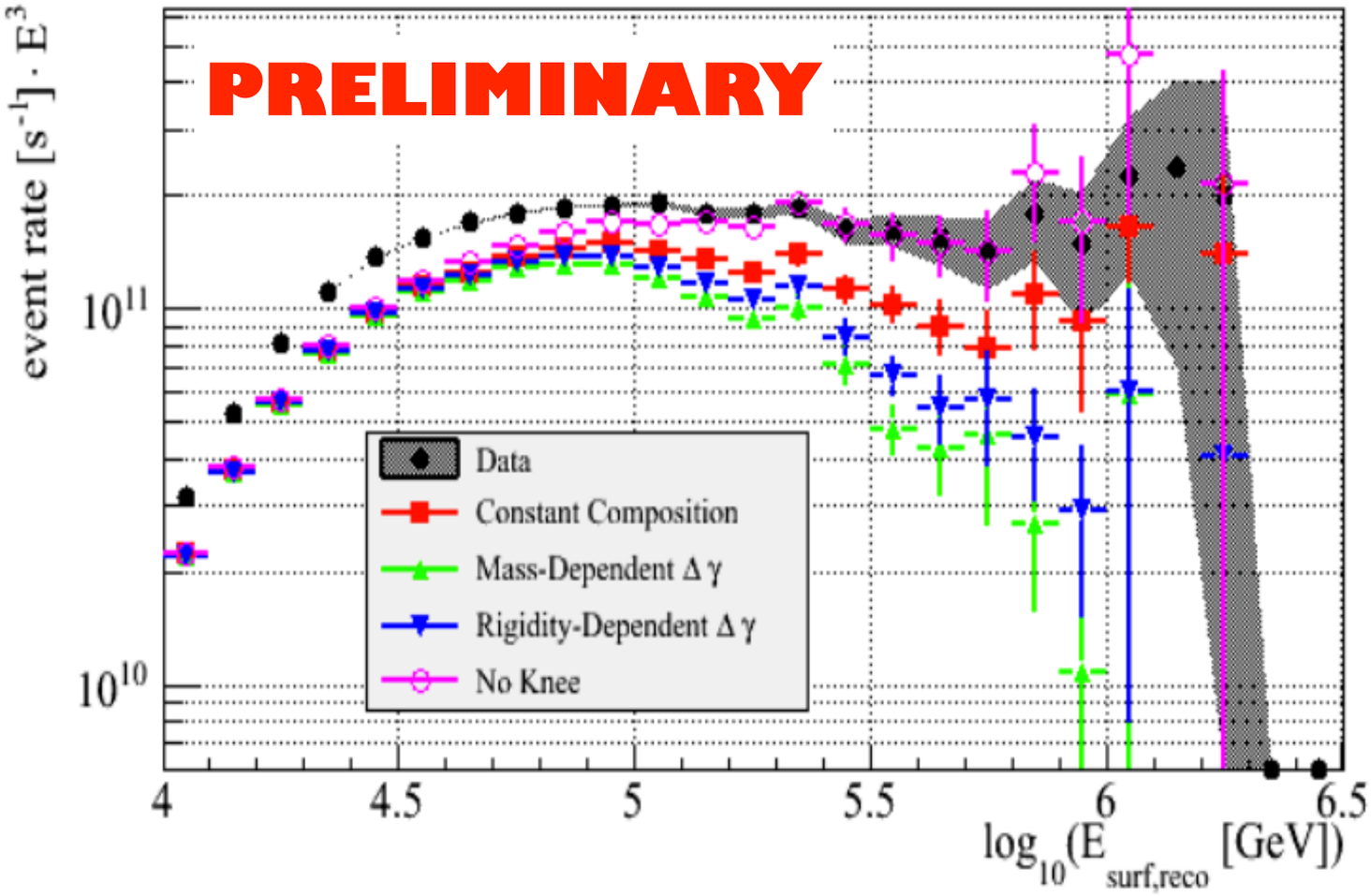
energy lost by muon bundle in the detector dominated by the highest energy muon

low multiplicity or single muon events selected

inclusive dN_μ/dE_μ can be determined

muon inclusive spectrum

high energy muons ∝ energy/nucleon



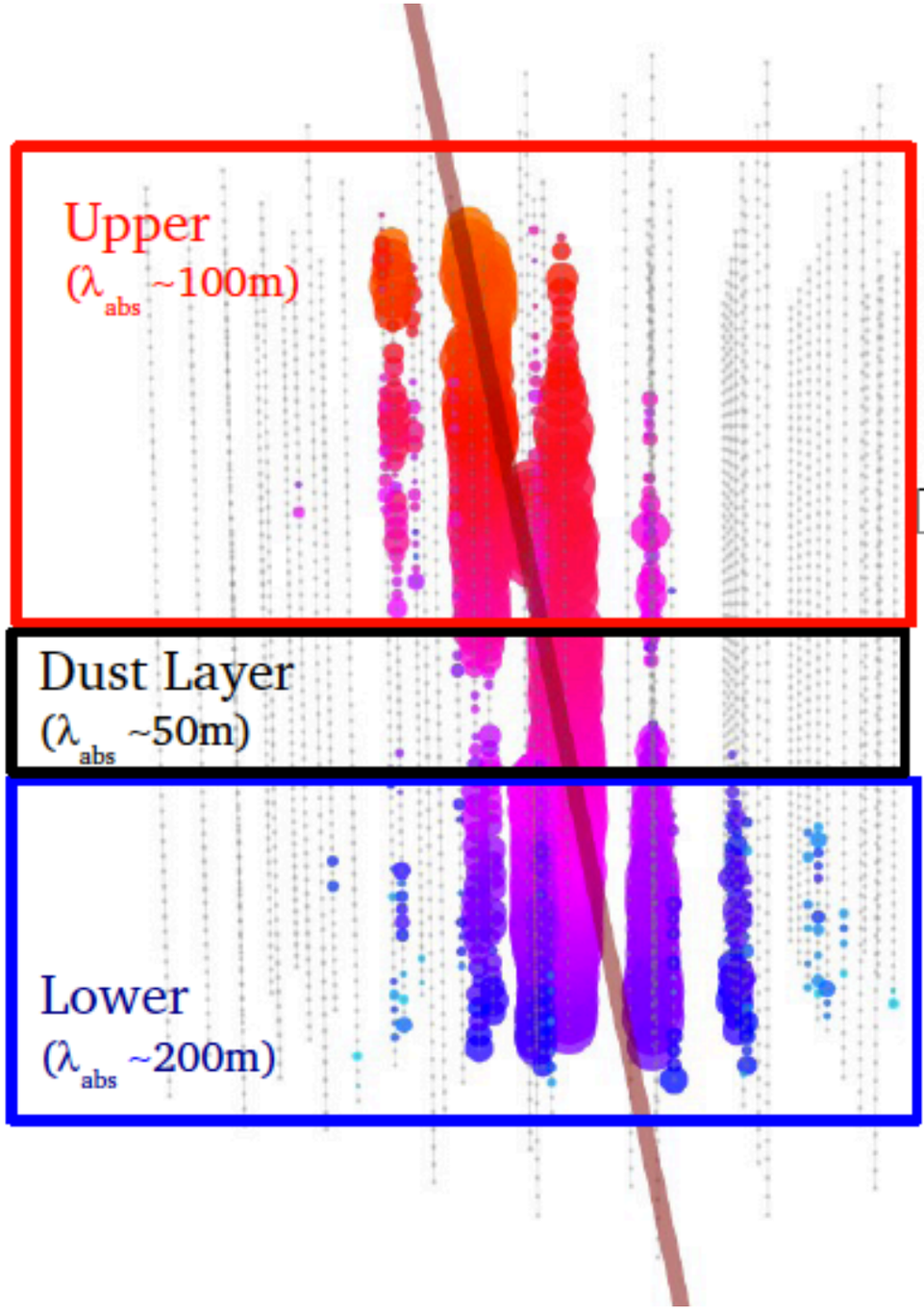
nucleon spectrum from Hörandel mixed composition models

prompt component in PeV range to be considered

analysis in progress

muon multiplicity spectrum

muon bundles ∝ energy/particle



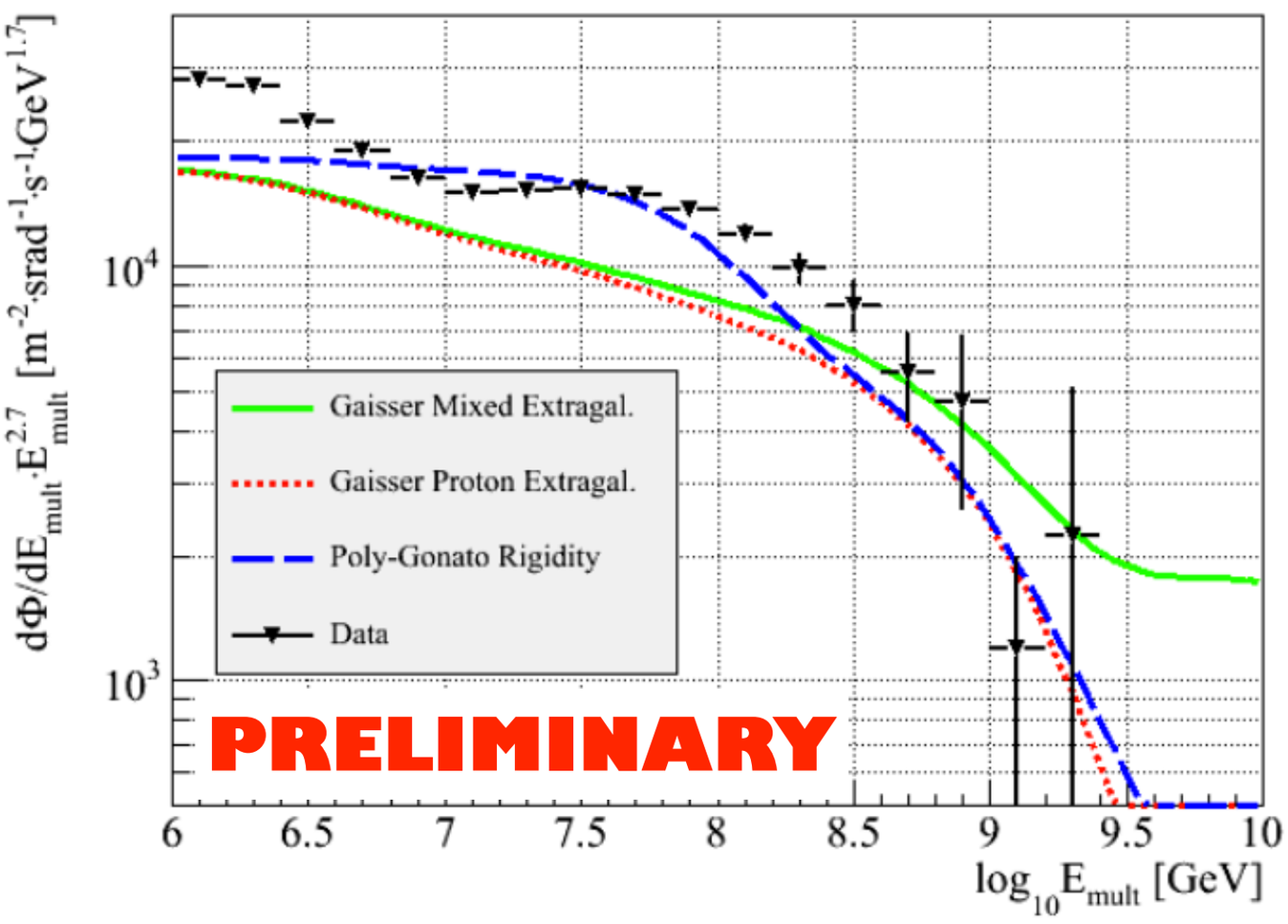
high multiplicity muons have high total energy but low energy/muon

stochastic energy losses are less important

smoother energy loss profile

muon multiplicity spectrum

muon bundles ∝ energy/particle



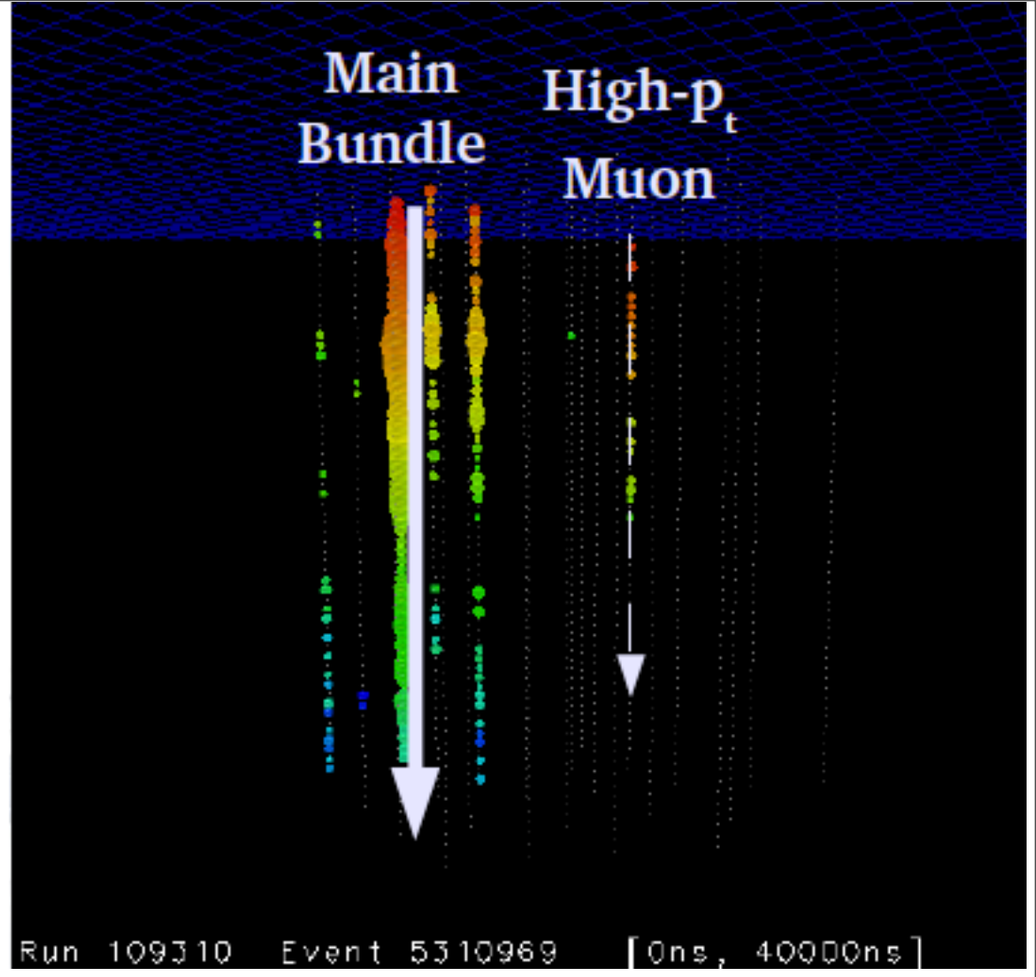
$$N_\mu \propto A^{1-\alpha}\, E_{prim}^{\alpha}$$

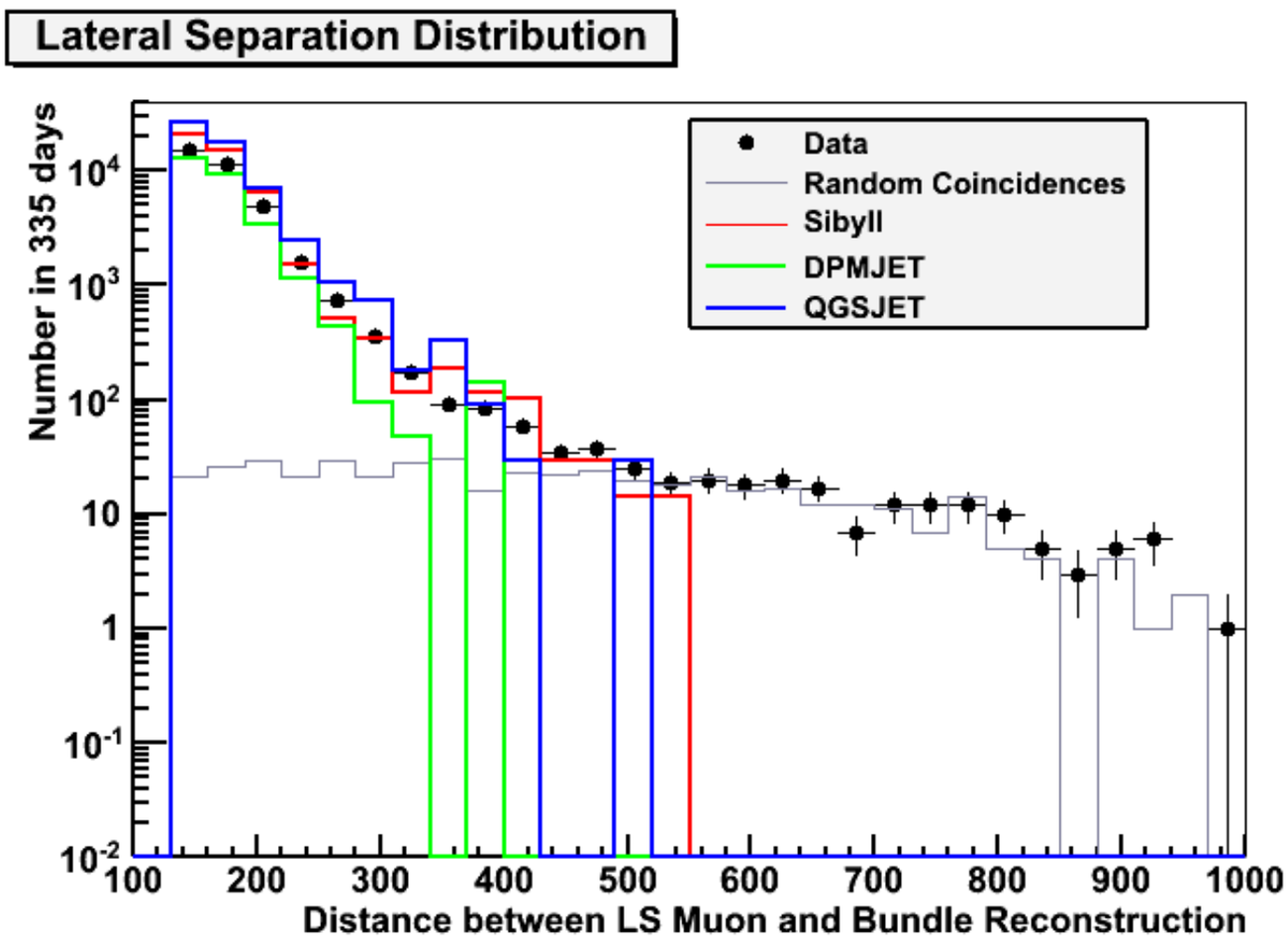
$$E_{mult} \equiv E_{prim}\,(A/56)^{\frac{1-\alpha}{\alpha}} \propto N_\mu^{1/\alpha}$$

muon energy lost in the detector ∝ muon multiplicity

E_{mult} as a measurement of primary energy with mass-dependent weight

muon bundles
evidence of high p_T muons

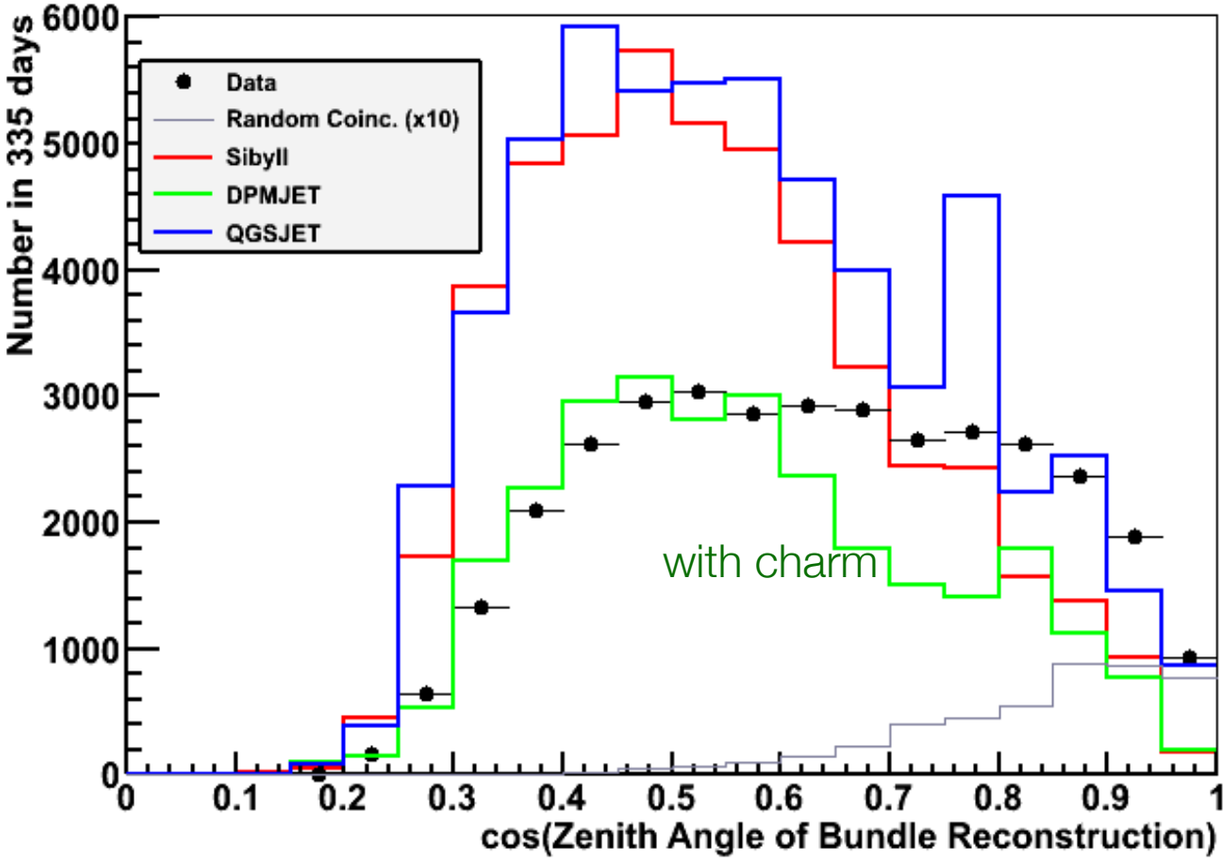




observation of parallel tracks in coincidence with muon bundles

separation distribution reasonably well reproduced by interaction models

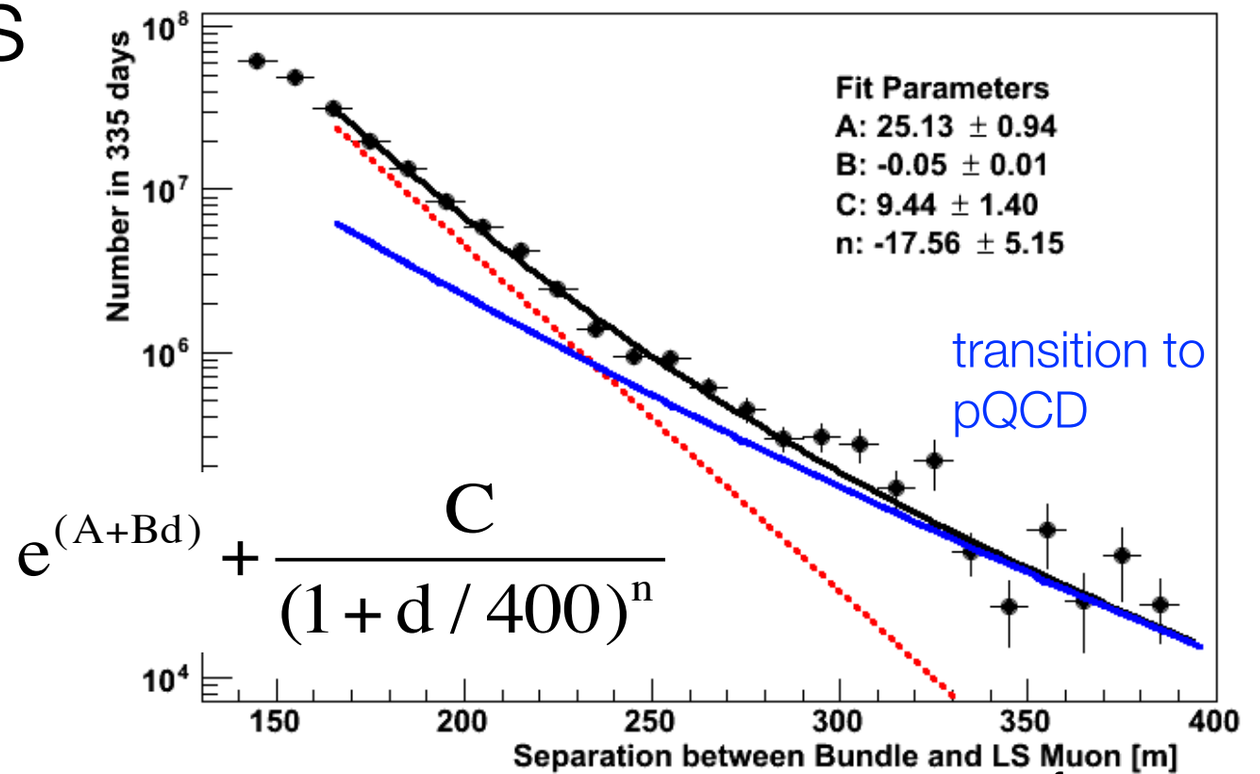
muon bundles
evidence of high p_T muons

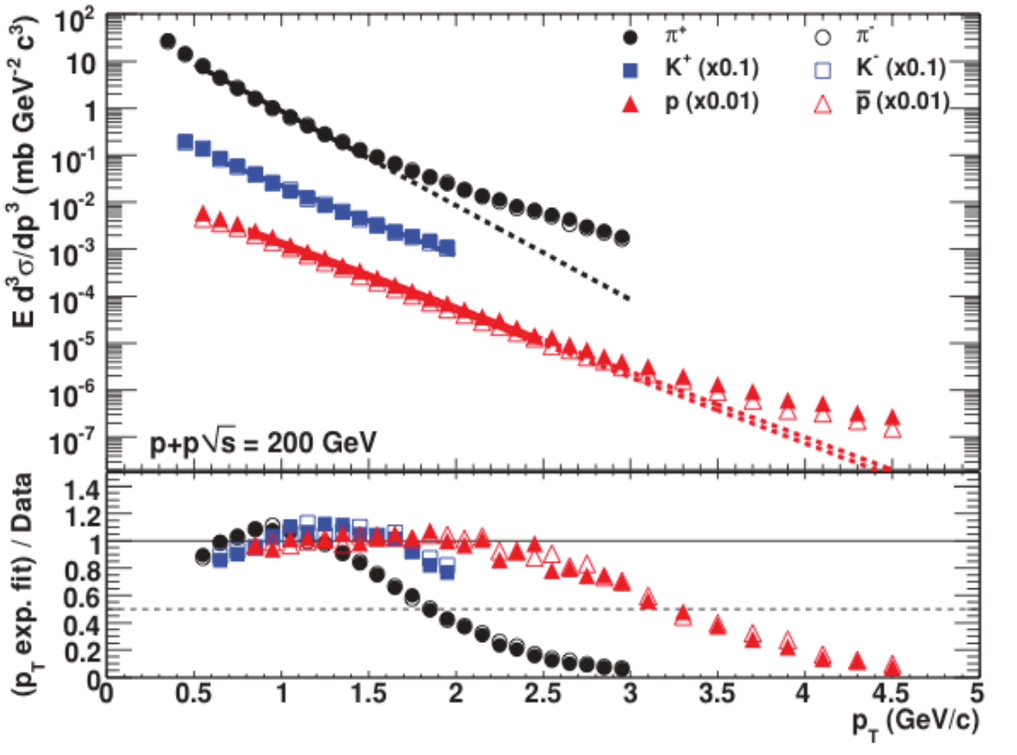


observation has flatter angular distribution

indication of heavy quark production
(that would flatten distribution @horizon) ?

effect of cosmic ray composition ?



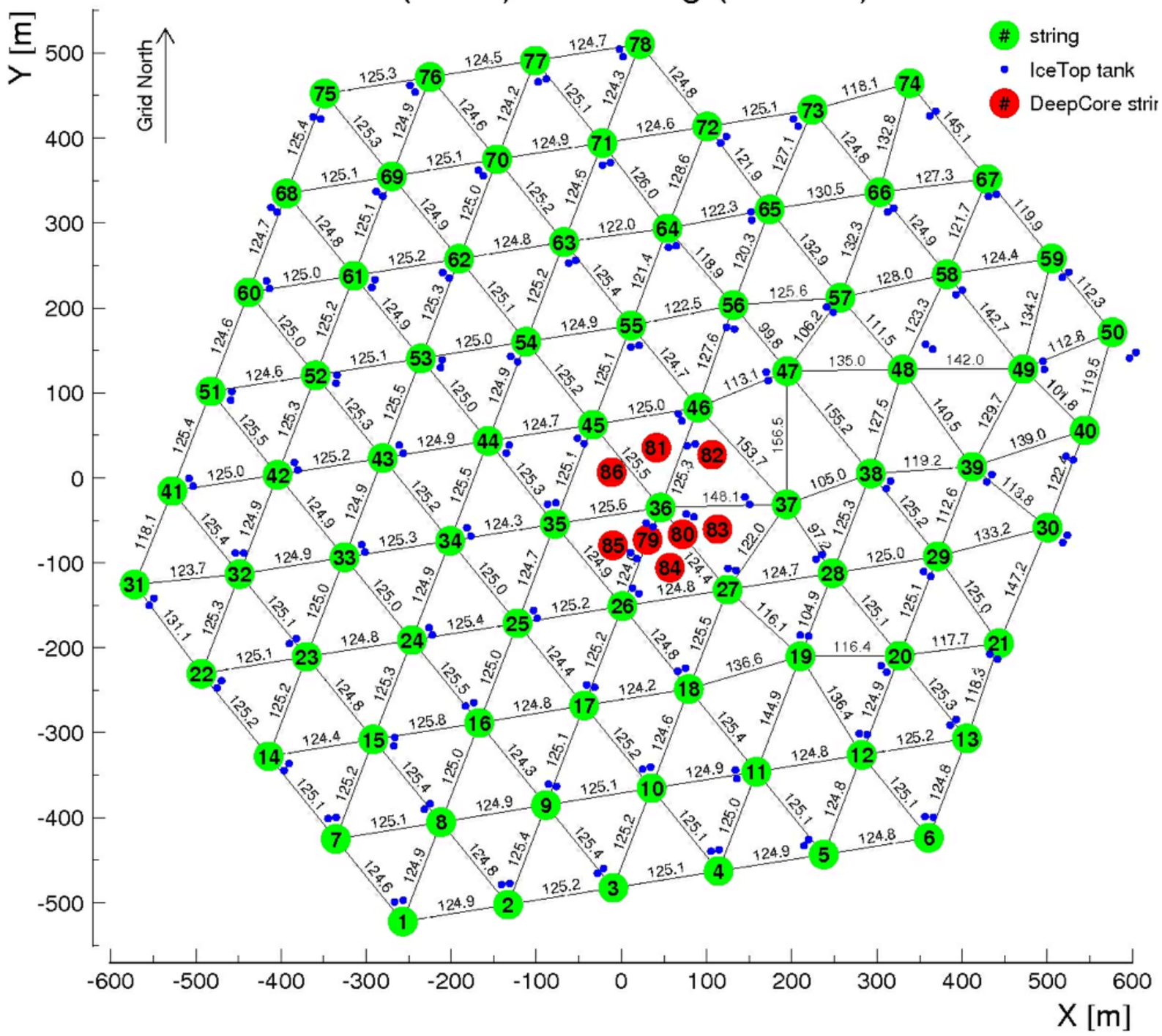


Adare et al. PRC **83**:064903 (201

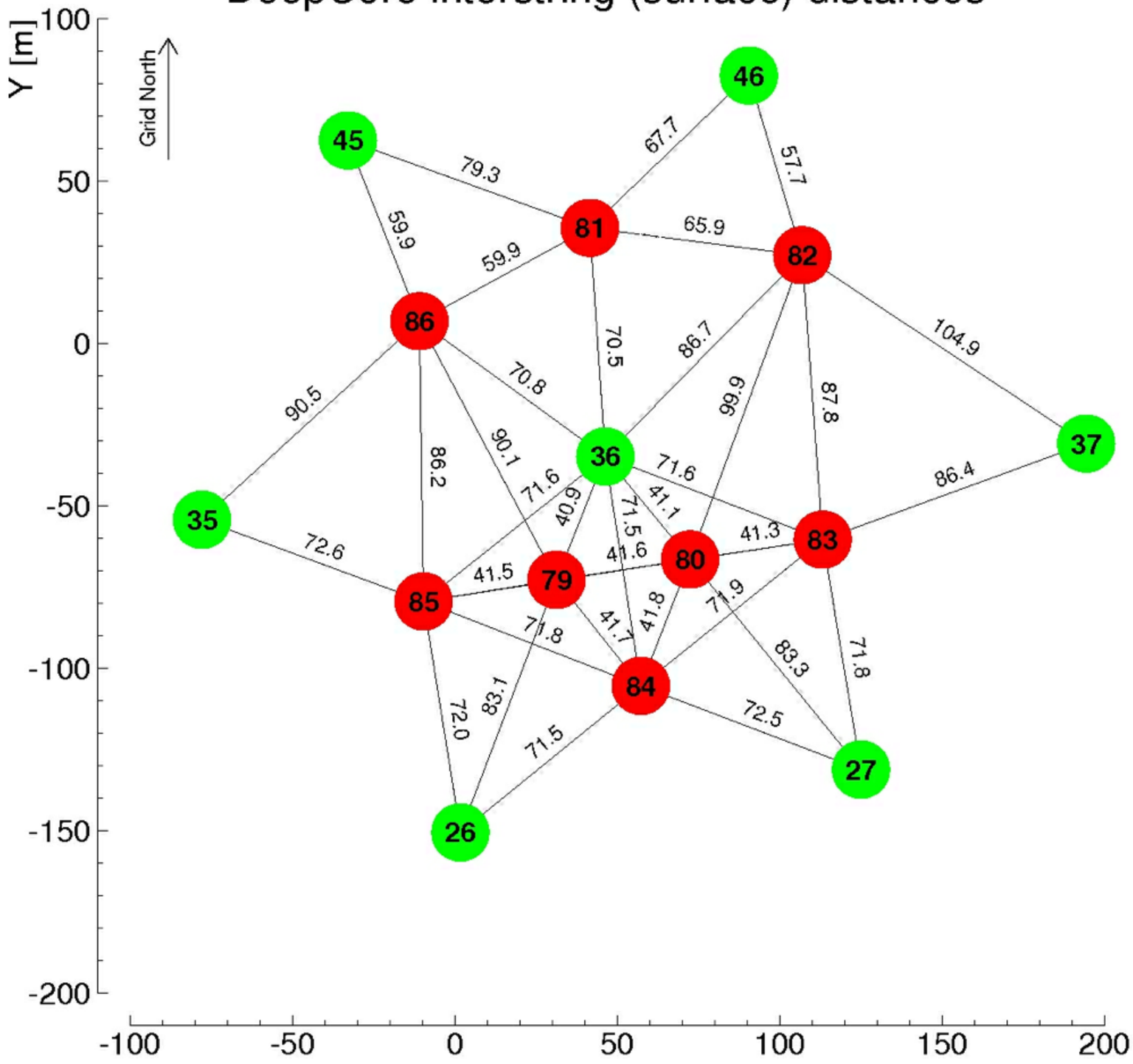
conclusions

- IceTop is providing all-particle primary spectrum with high statistical precision
- IceTop/IceCube coincidence for better energy resolution and mass sensitivity
- cosmic ray anisotropy observed at different scales, energies, with muon/e.m. components. Working on full-sky coverage with ARGO-YBJ, short/long time stability, composition-dependent observation, and to extent to higher energies
- muon multiplicity observation to provide inclusive muon spectrum, and probe primary mass and high pT muons as evidence of transition to pQCD and heavy quark production in the atmosphere
- Others: seasonal variation of muon events in correlation with stratospheric temperature. Study short/long time durations, probe heavy quark production in the atmosphere

backup slides



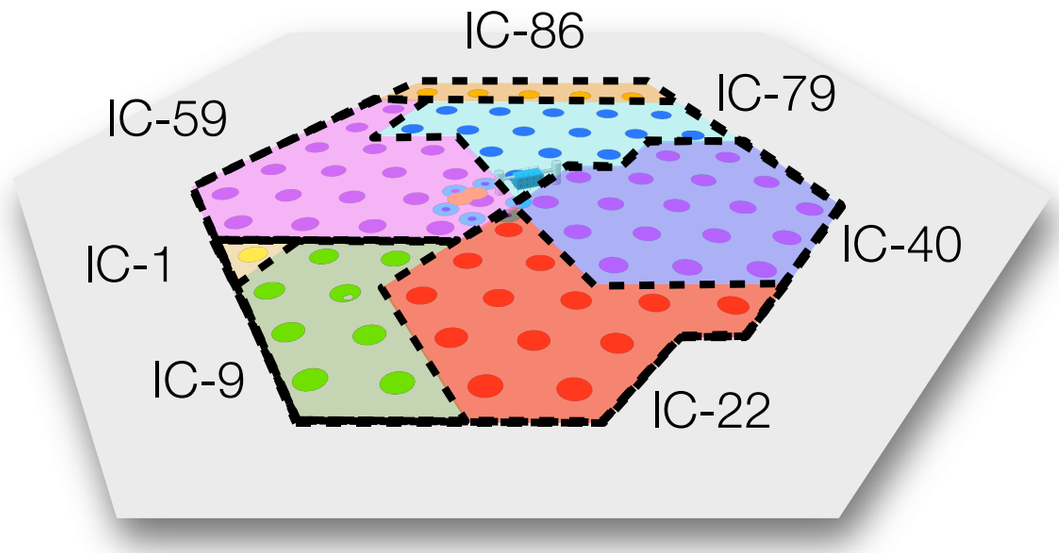
IceCube geometry

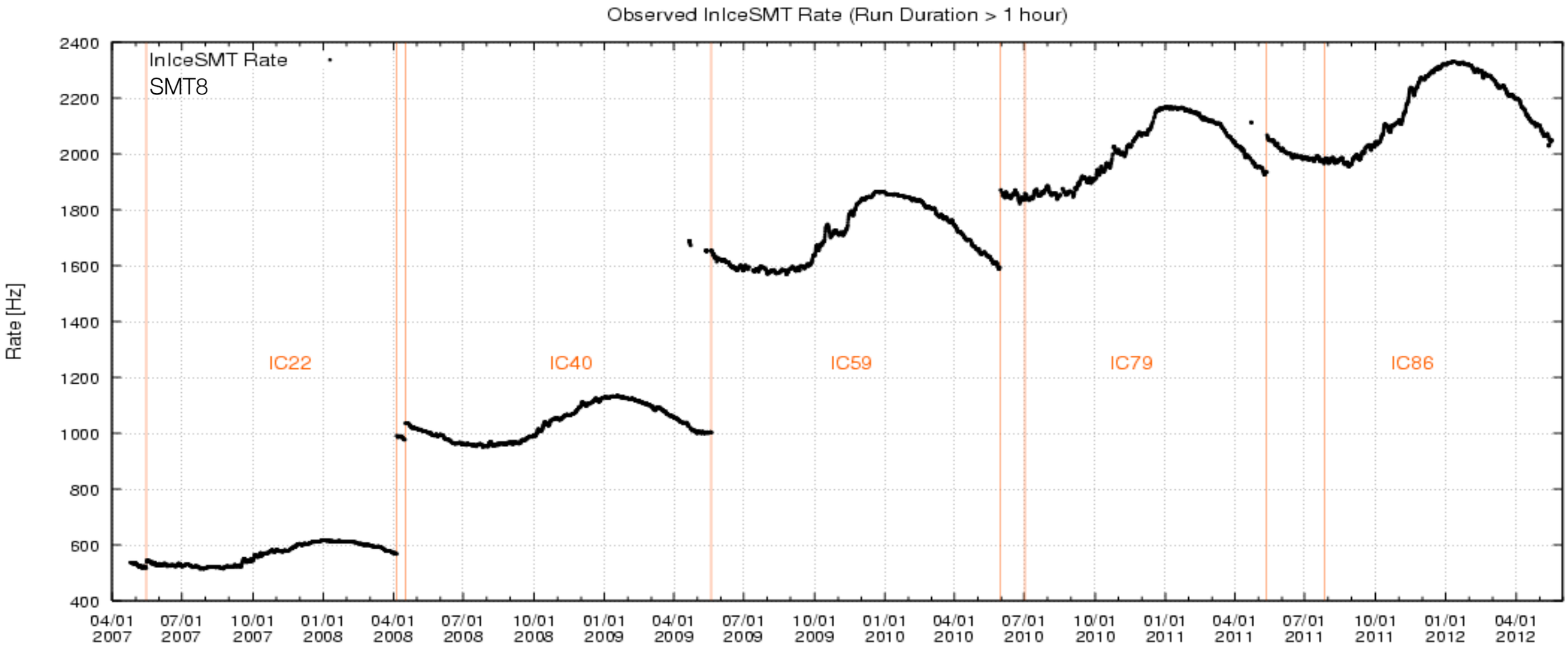


DeepCore geometry

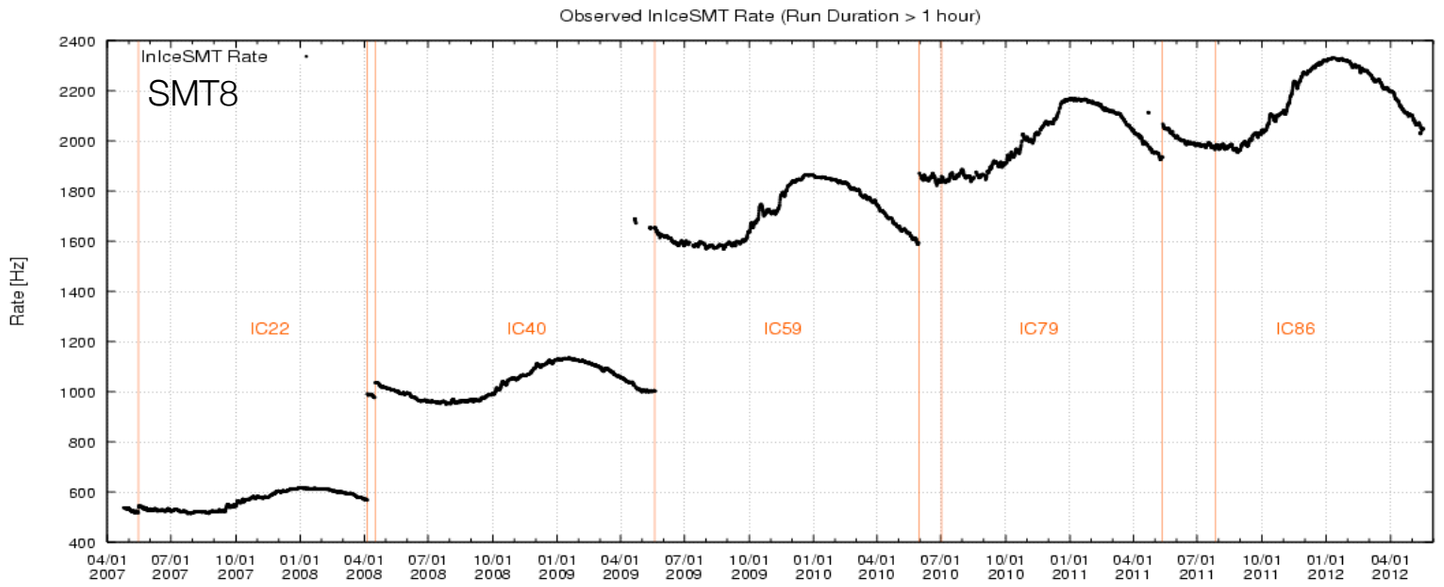
growing IceCube
& event collection

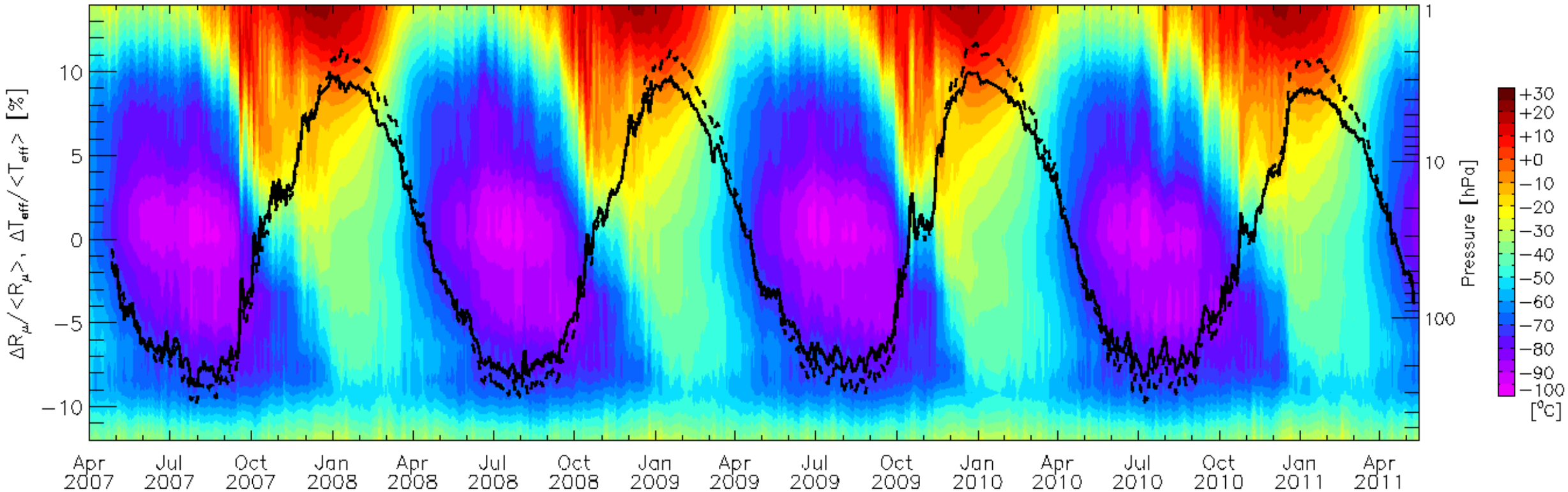
Strings	Year	μ rate
IC22	2007	500 Hz
IC40	2008	1100 Hz
IC59	2009	1700 Hz
IC79	2010	2000 Hz
IC86	2011	2100 Hz





growing IceCube
& event collection





IceTop array: triggering and calibration

single hits (1 DOM)

(muon detection & air shower veto for icecube studies)

1600 Hz

station trigger

(HG-HG or HG-LG coincidence in 1 μs)

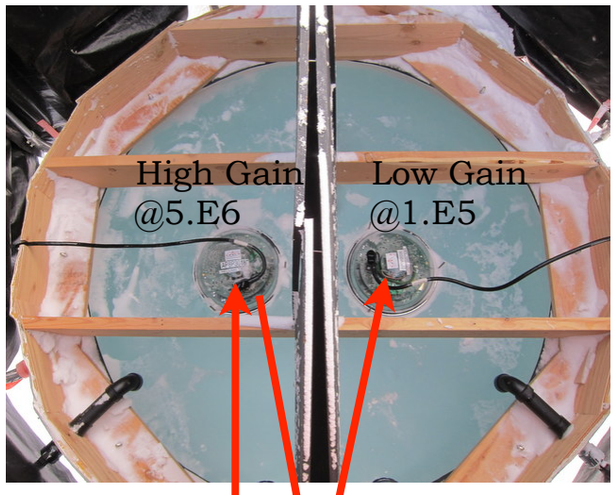
30 Hz

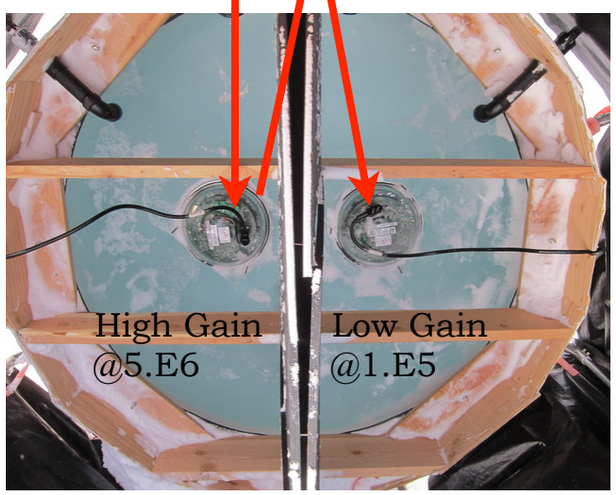
IceTop event trigger

(3+ stations in 10 μs)

35 Hz

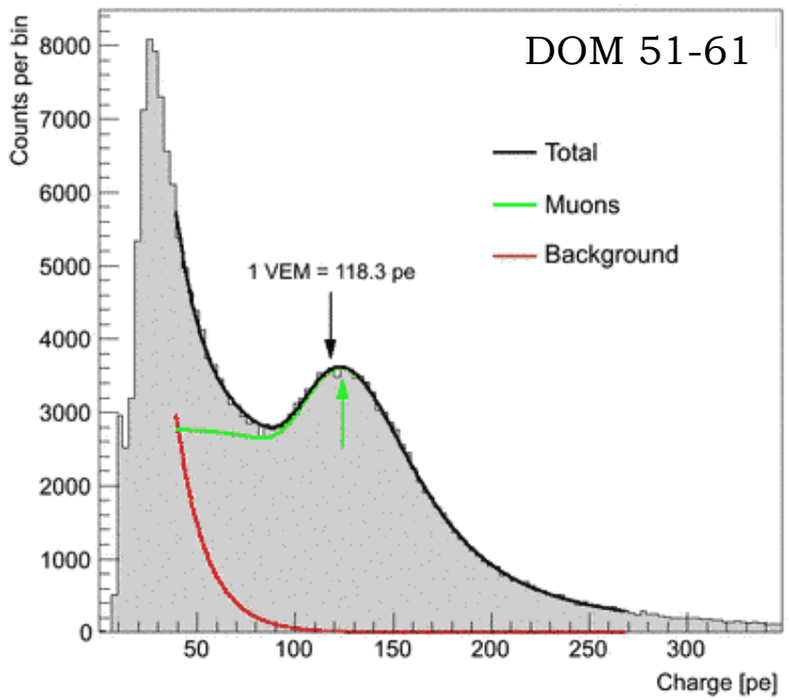
tank A





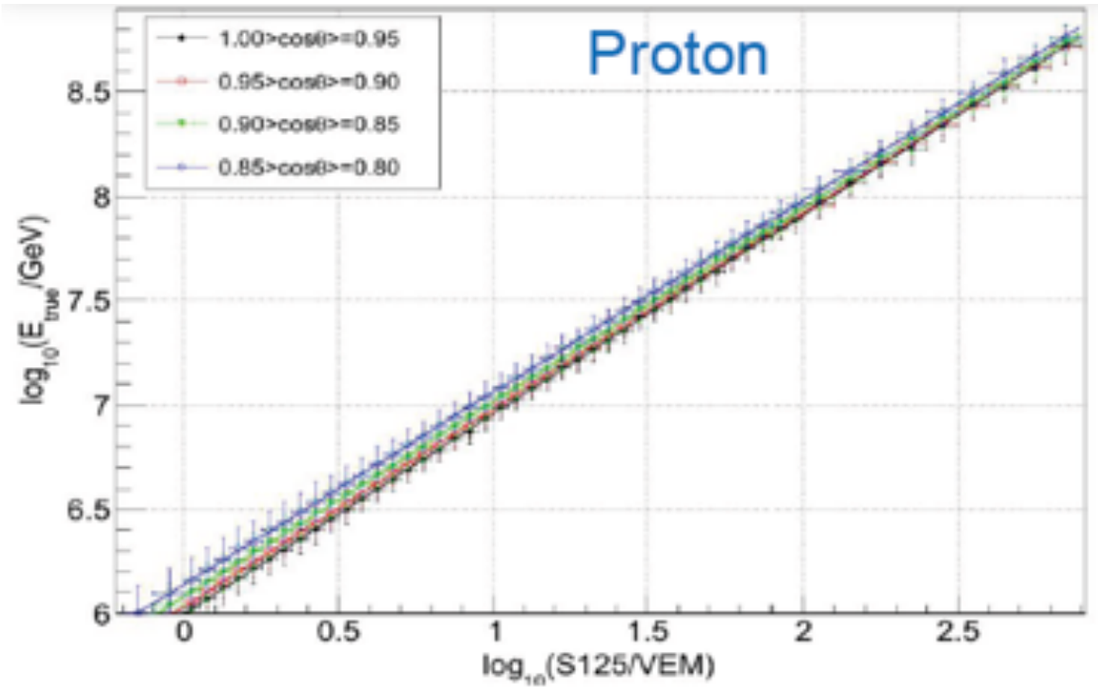
tank B

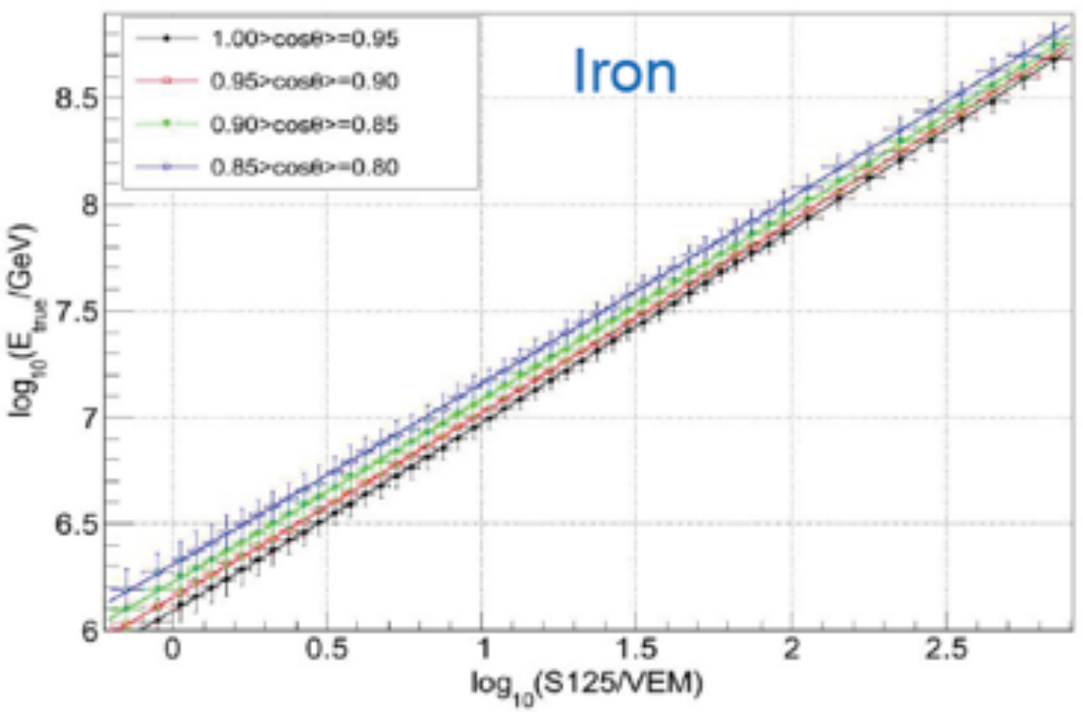
Calibration: Vertical Equivalent Muon



IceTop-only all-particle spectrum estimating primary energy

IceTop-73
326 days livetime
Jun 2010 - May 2011

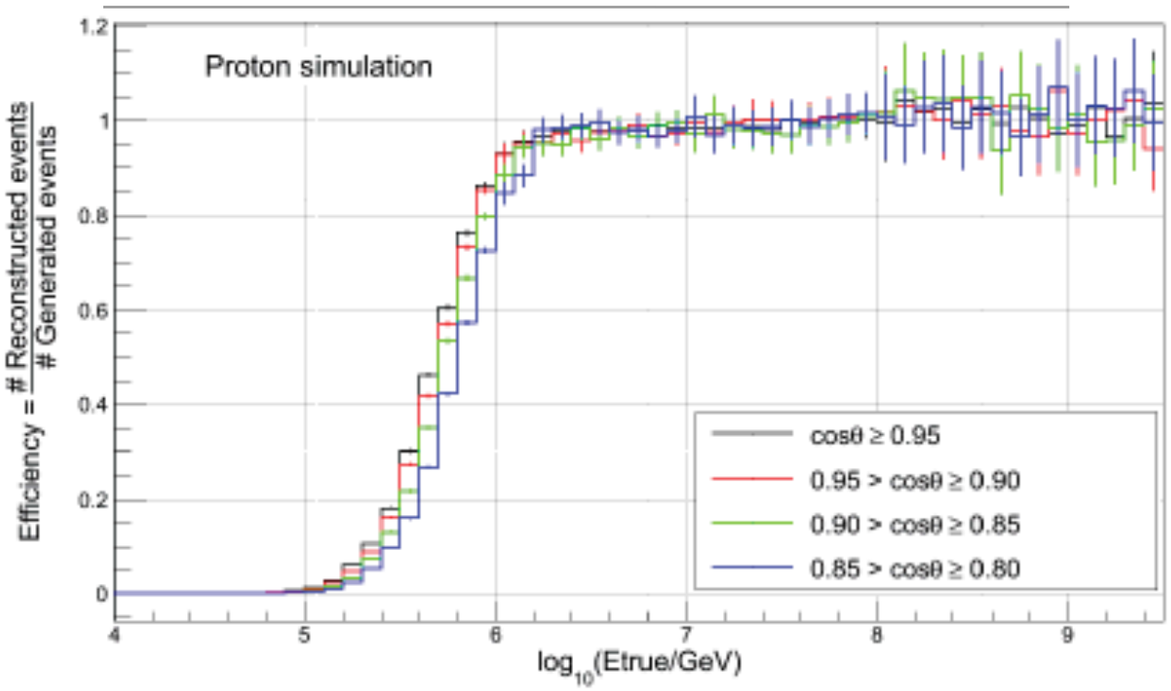




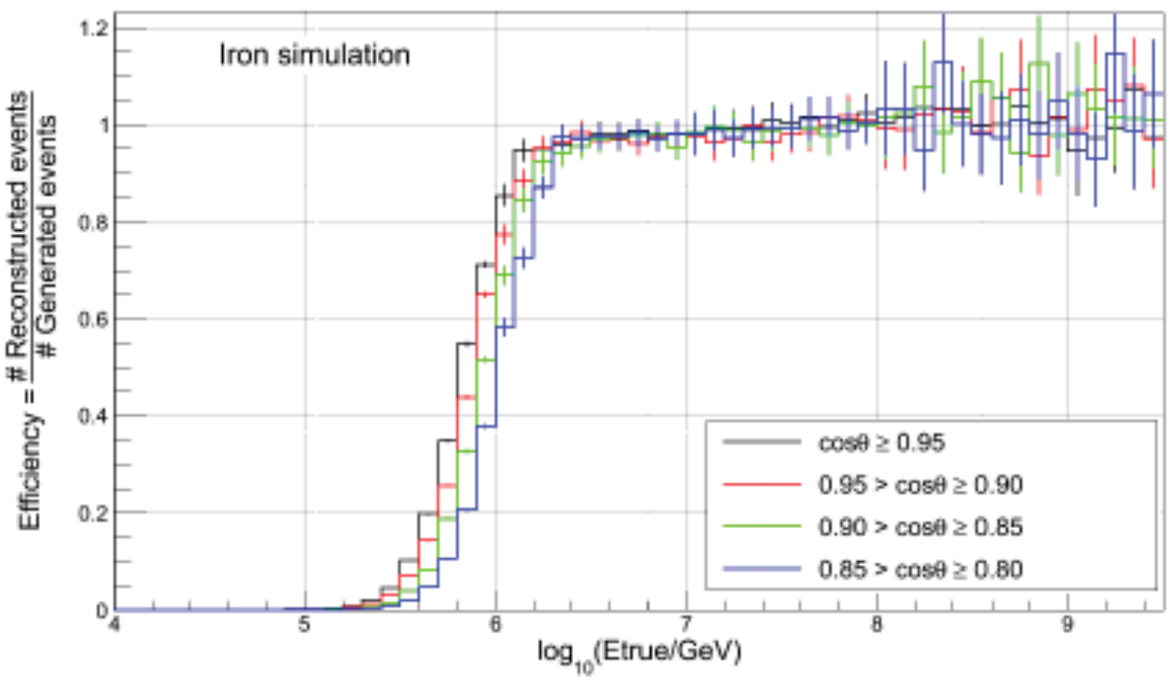
the relationship between S_{125} and primary energy depends on **mass** and **zenith angle**

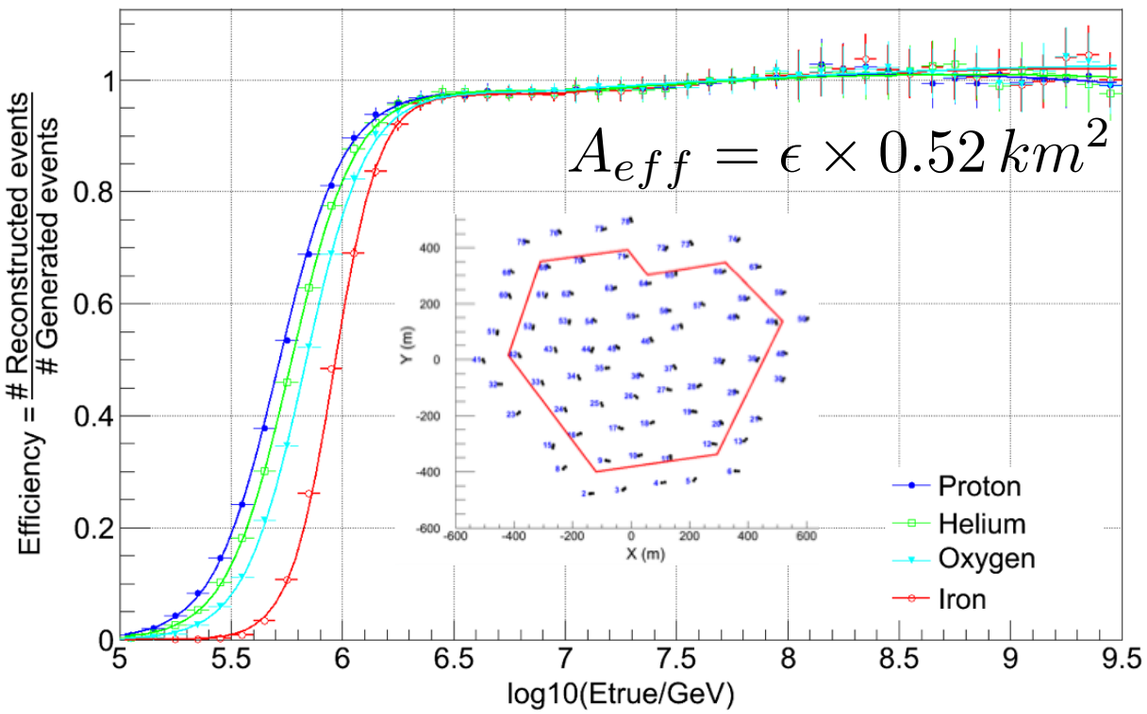
IceTop-only all-particle spectrum acceptance

IceTop-73
326 days livetime
Jun 2010 - May 2011



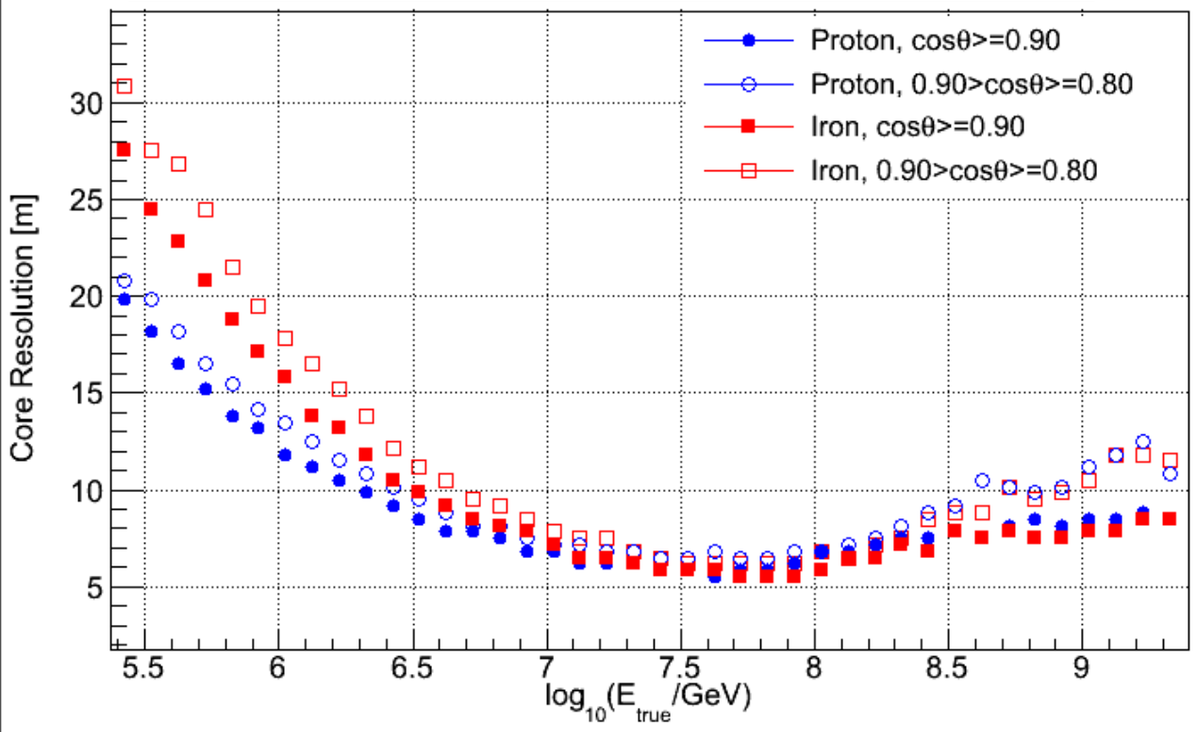
the acceptance **does not** depend on **mass** and **zenith angle** above threshold

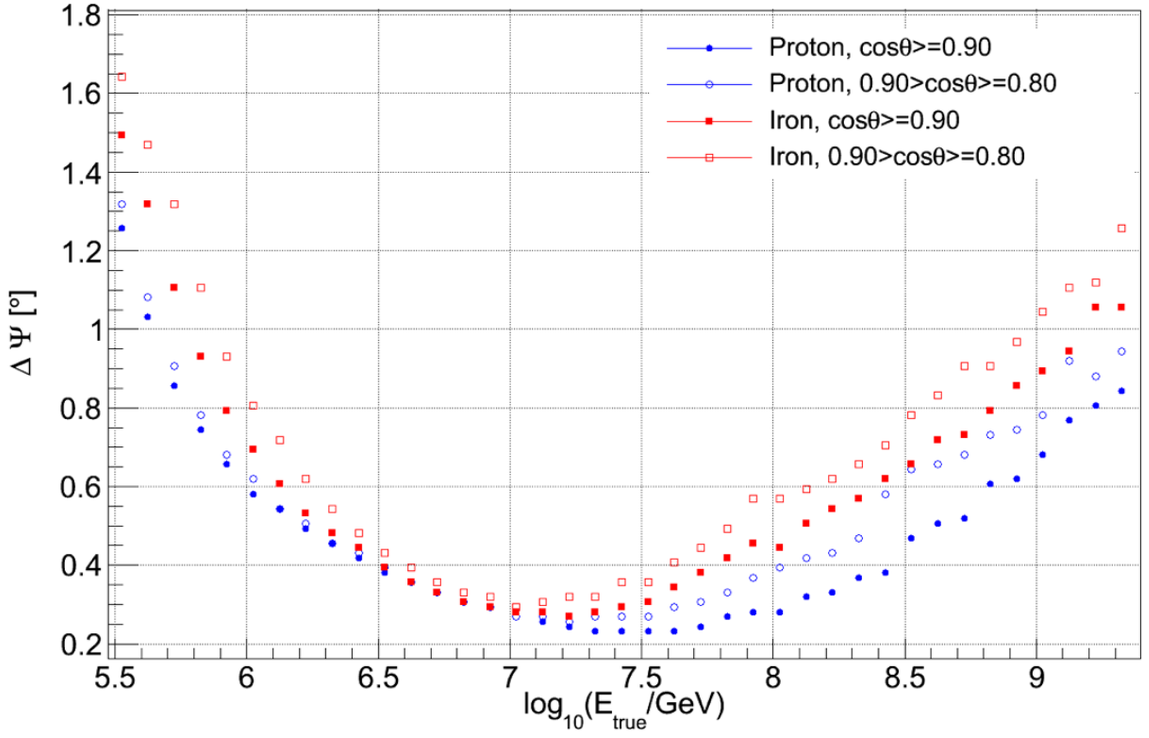


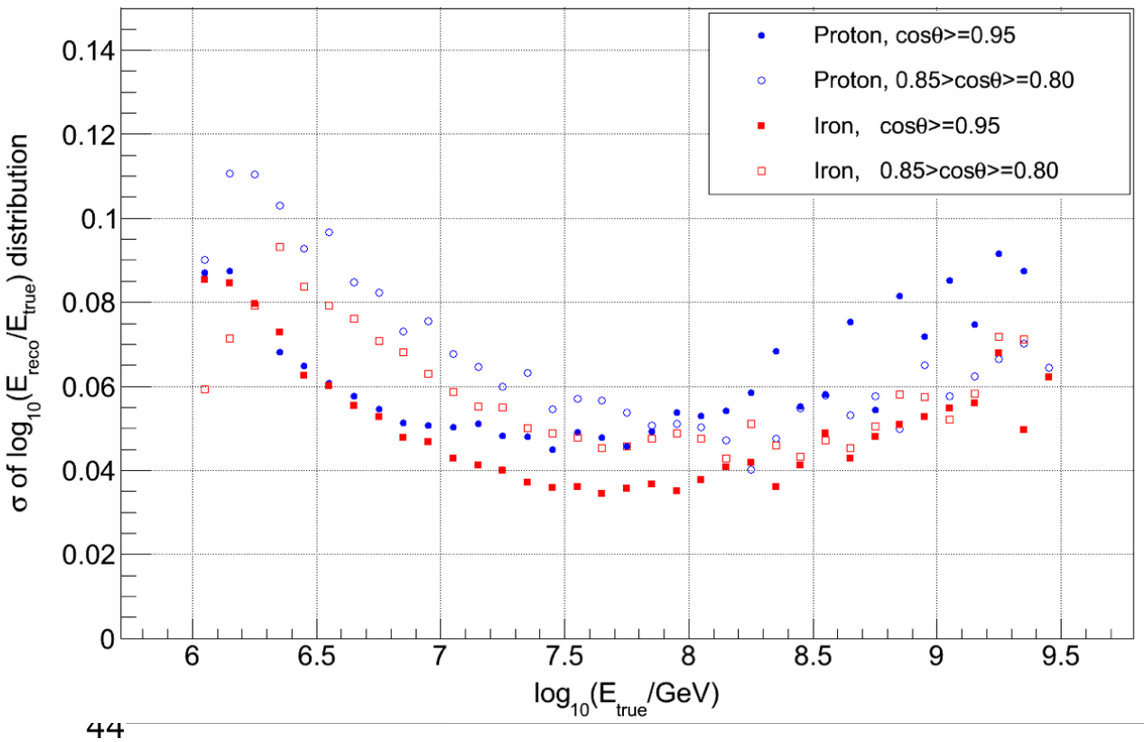


IceTop-only all-particle spectrum resolutions

IceTop-73
326 days livetime
Jun 2010 - May 2011

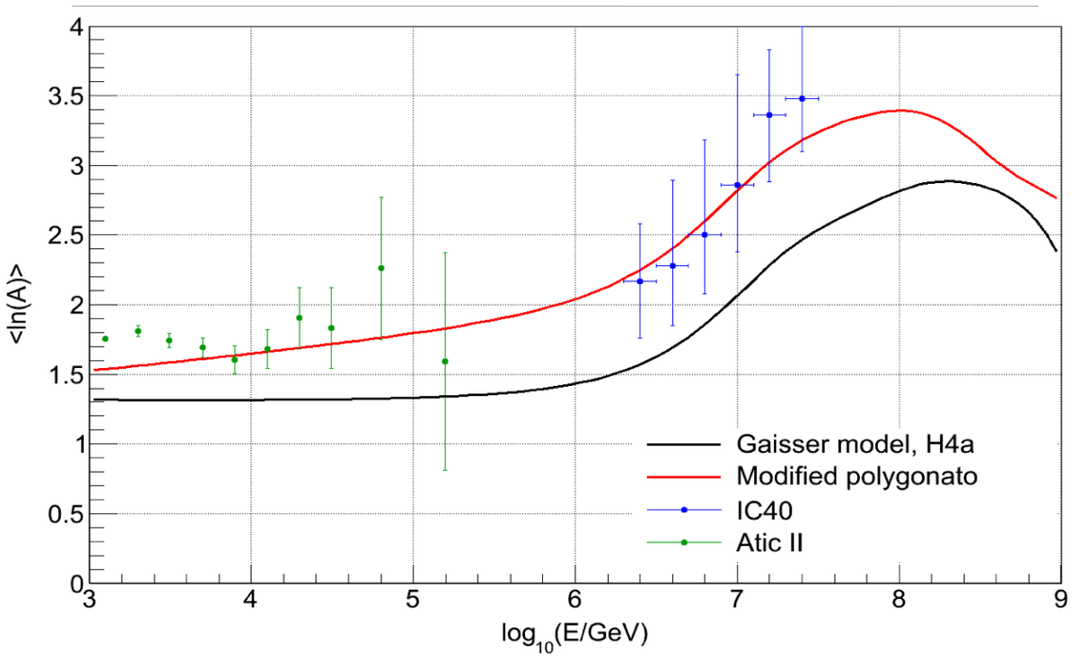


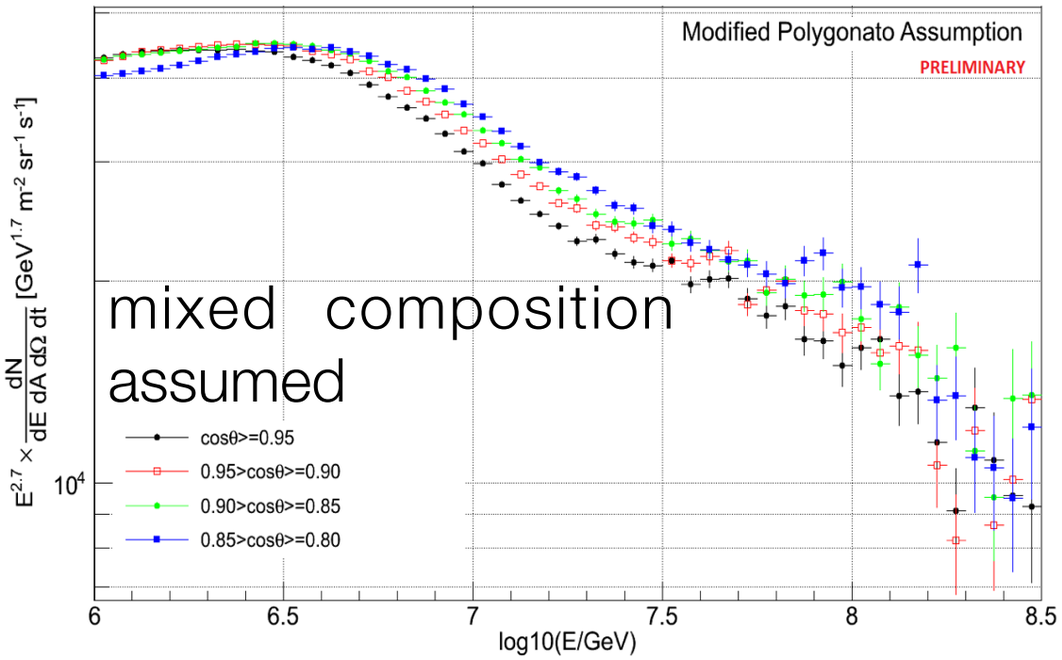


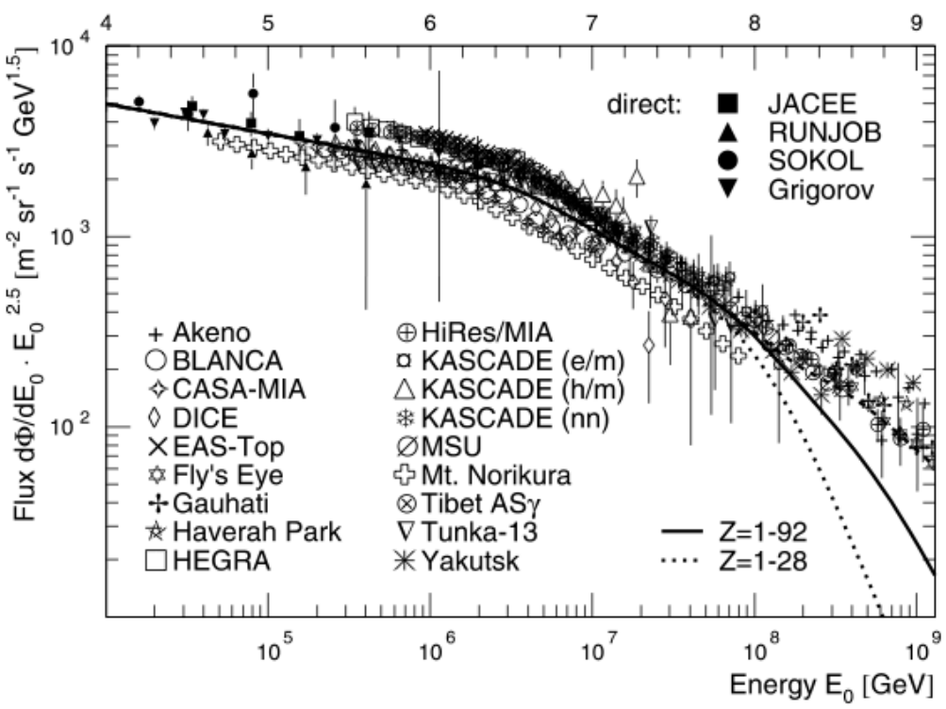


IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011







Hörandel, Astropart. Phys. 19 (2003) 193

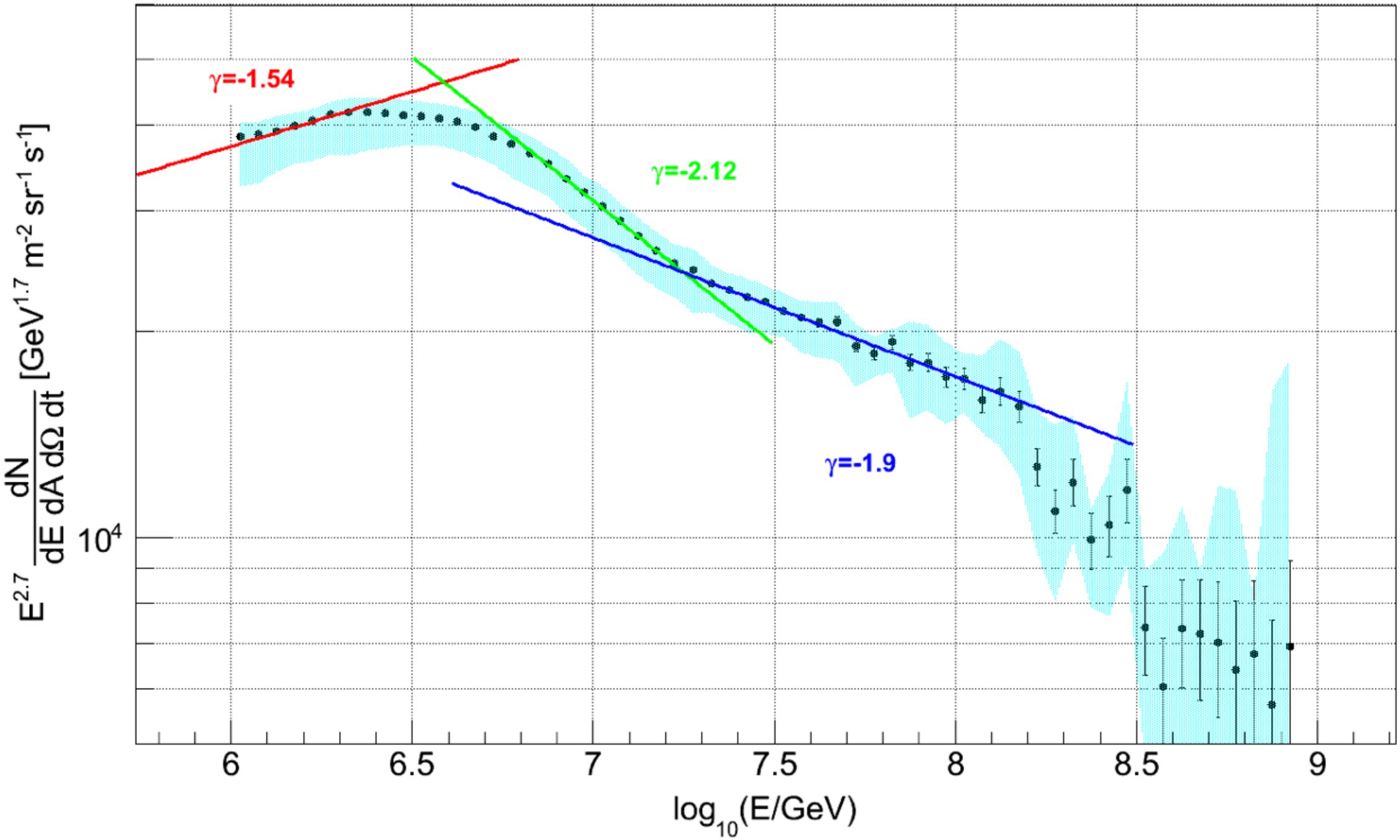
5 nuclear components

3 populations

- galactic (e.g. SNR) - CREAM
- galactic II - Hillas
- extragalactic (p or mixed)

IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011



IceTop-only all-particle spectrum

IceTop-73
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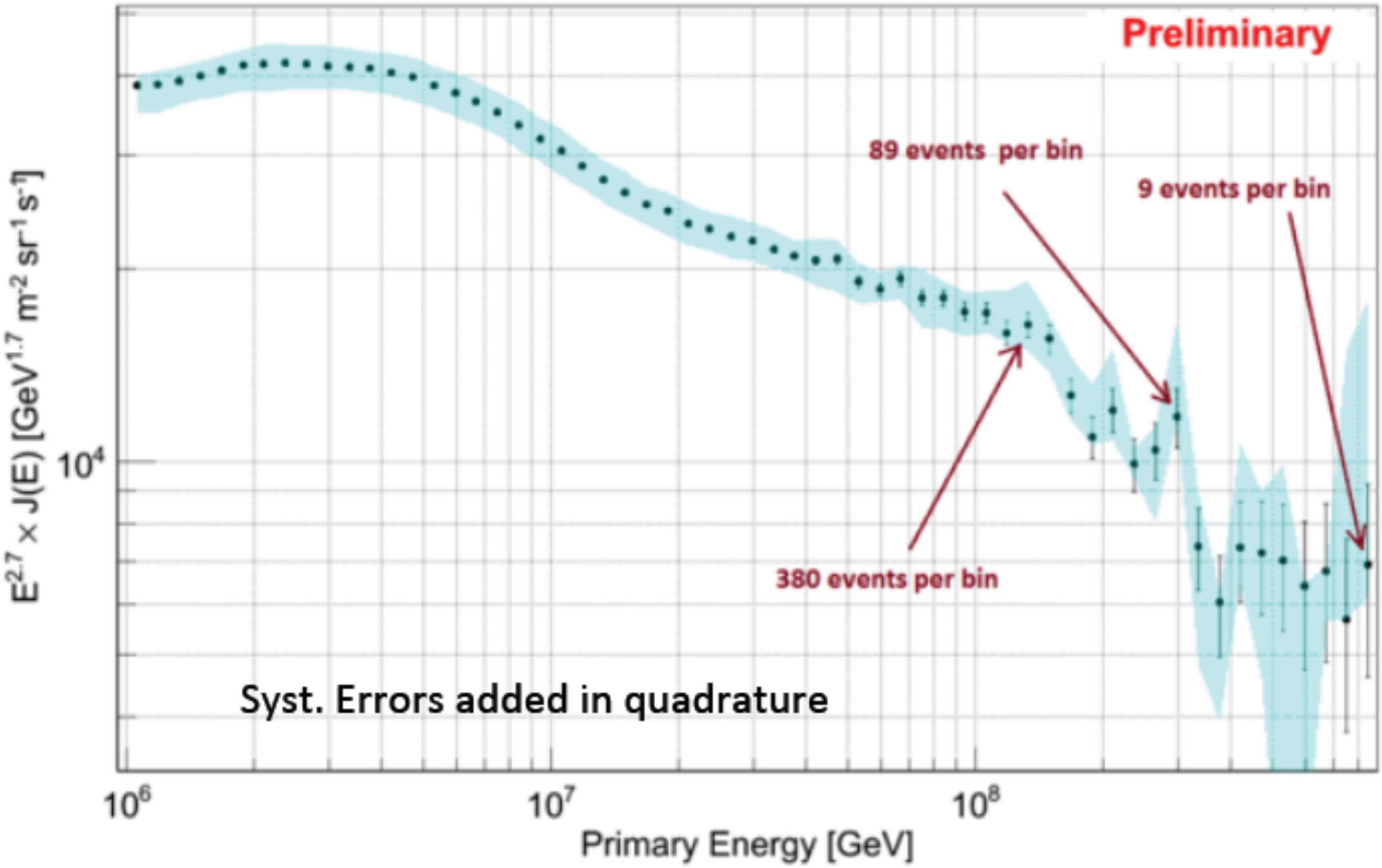
Jun 2010 - May 2011



IceTop-only all-particle spectrum

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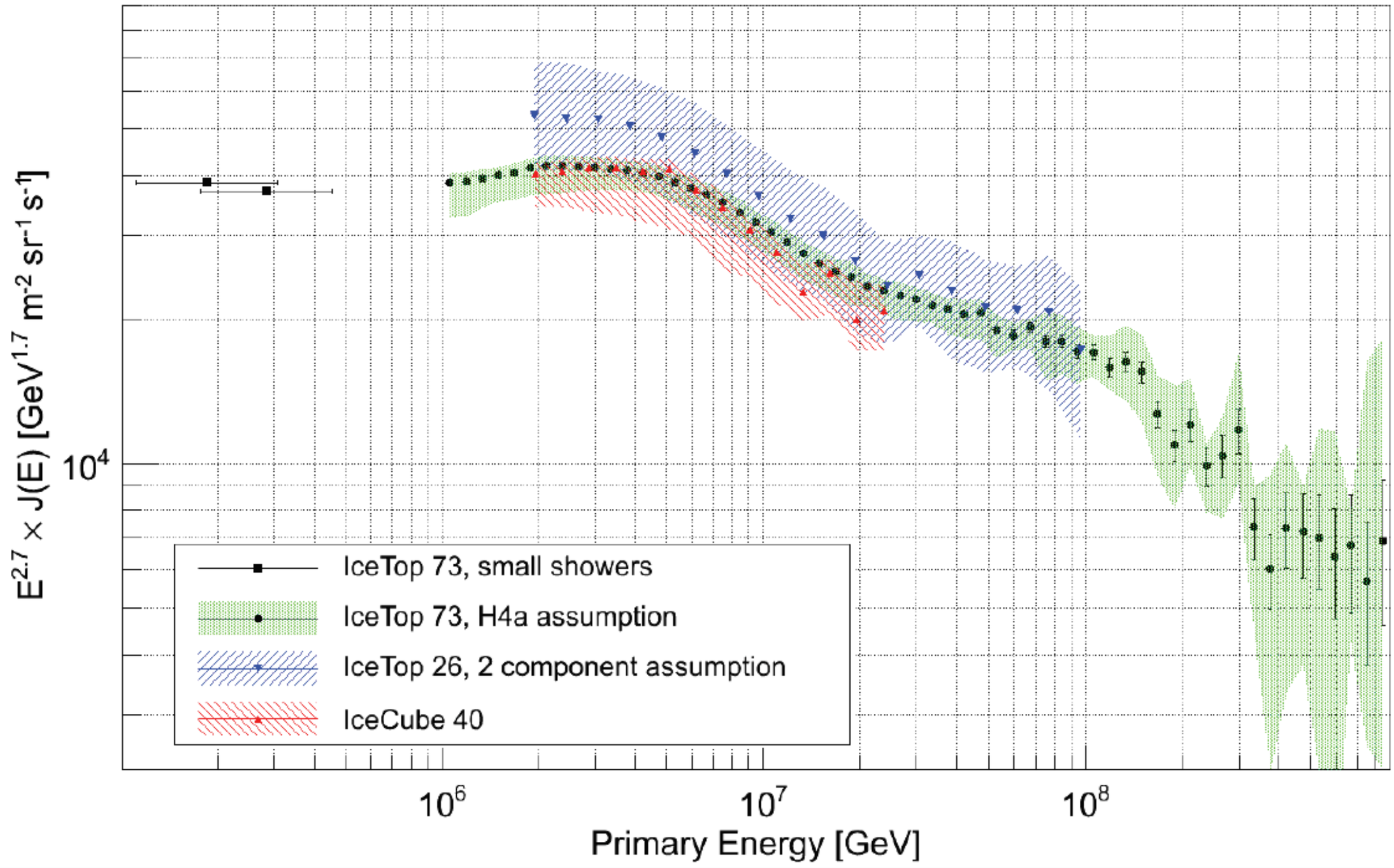
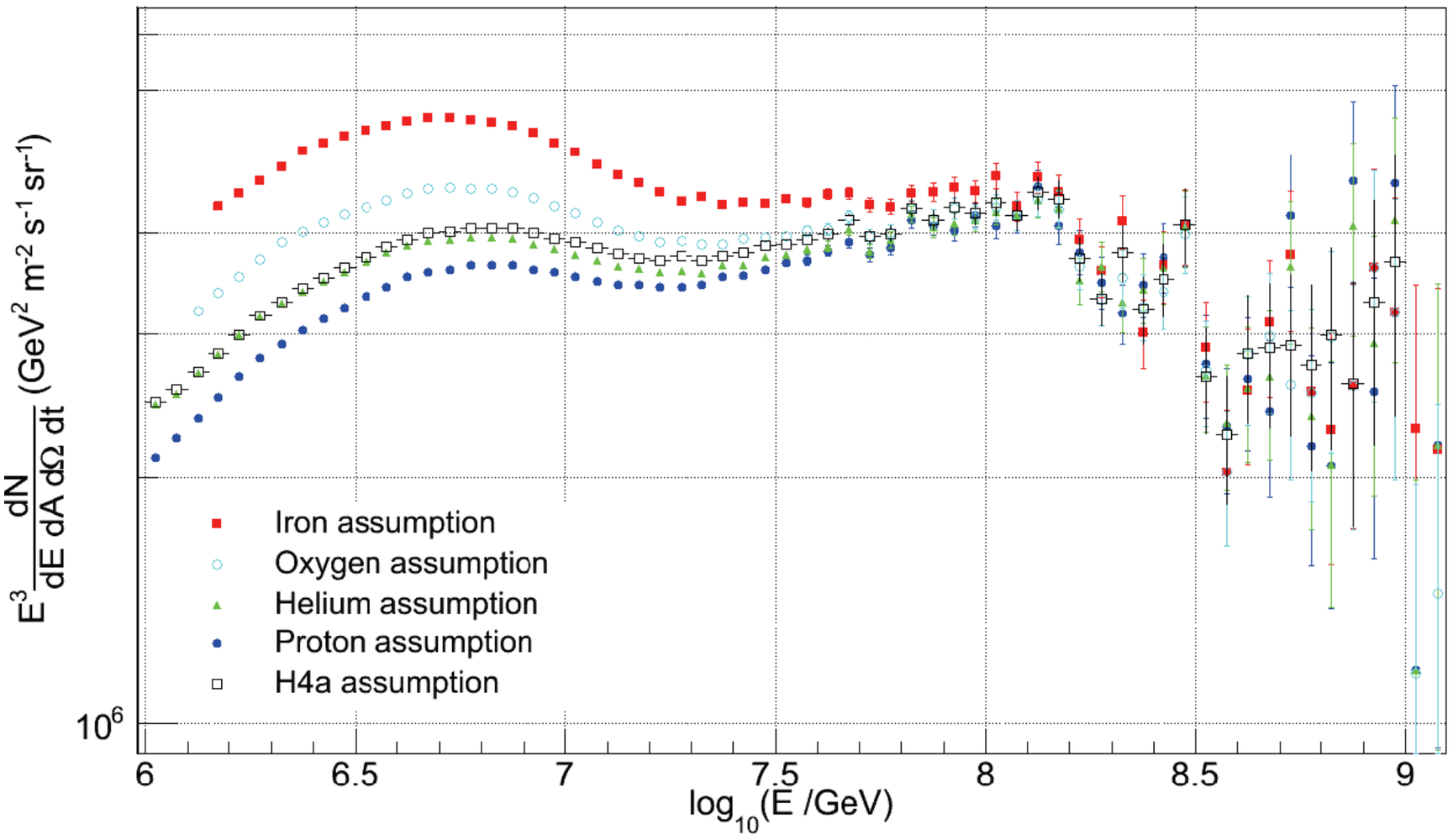
Jun 2010 - May 2011

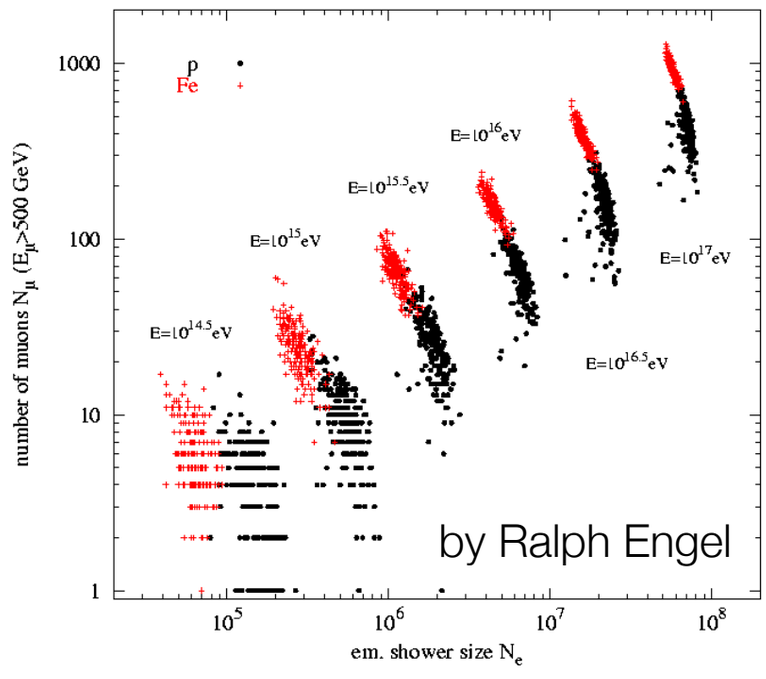


IceTop-only all-particle spectrum

IceTop-73
326 days livetime
Jun 2010 - May 2011

Data reconstructed with 5 different composition assumptions

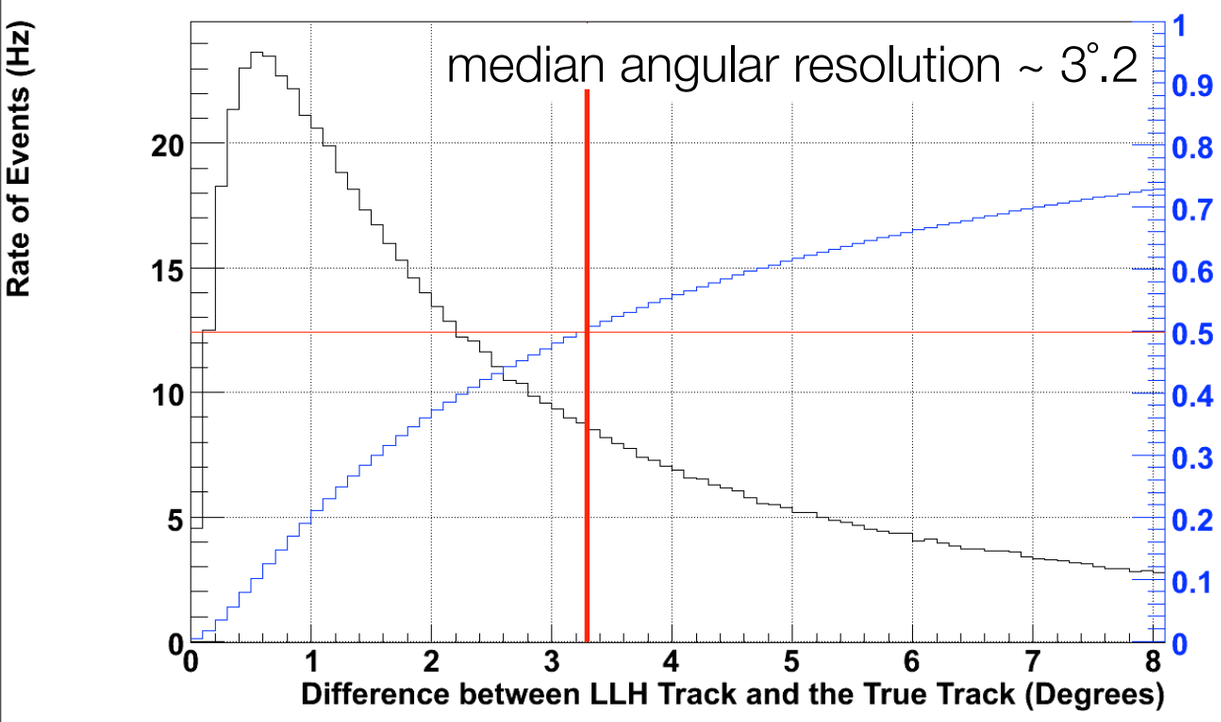


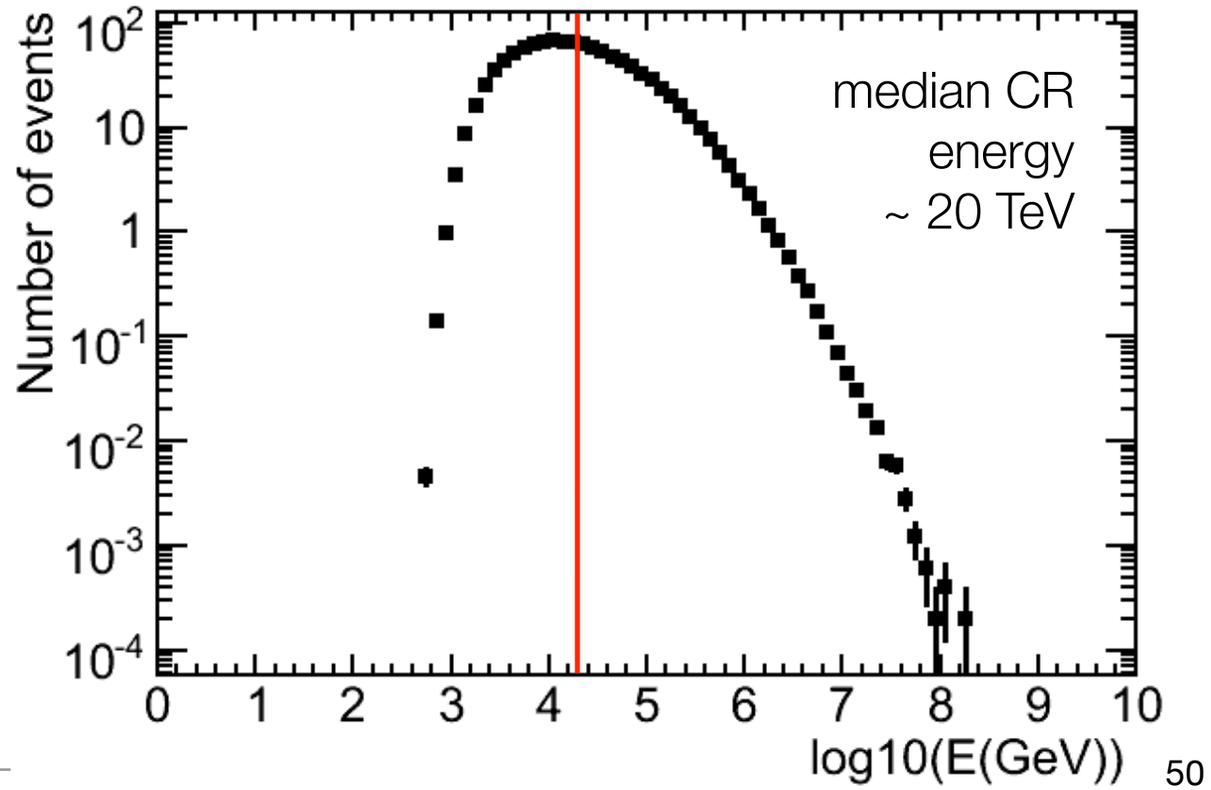


IceCube muon bundle trigger statistics

detector	trigger rate (Hz)	actual time (d)	livetime (d)	number of events (*)
IceCube-22	500	300	226	5.4×10^9
IceCube-40	1,100	358	324	19×10^9
IceCube-59	1,700	367	334.5	34×10^9
IceCube-79	2,000	365	337	40×10^9
IceCube-86	2,500	365 × 2	365 × 2	50×10^9 × 2

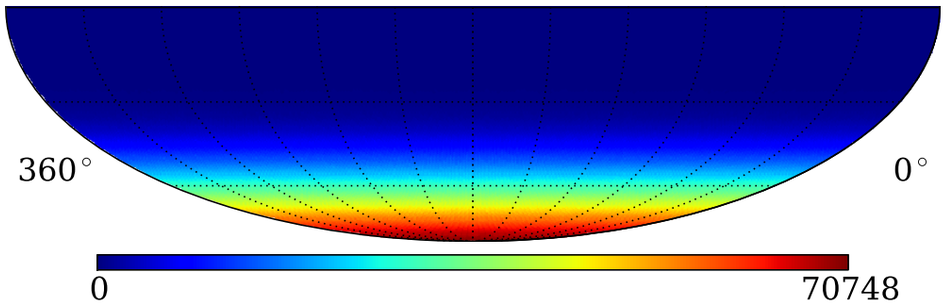
(*) number of events with LLH reconstruction from online-filter collected by DST



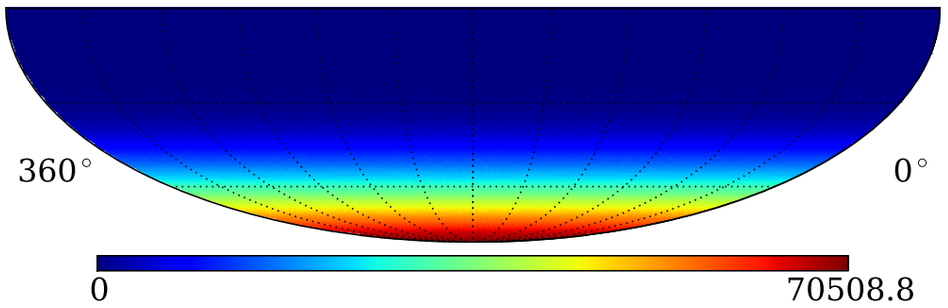


cosmic ray anisotropy analysis technique

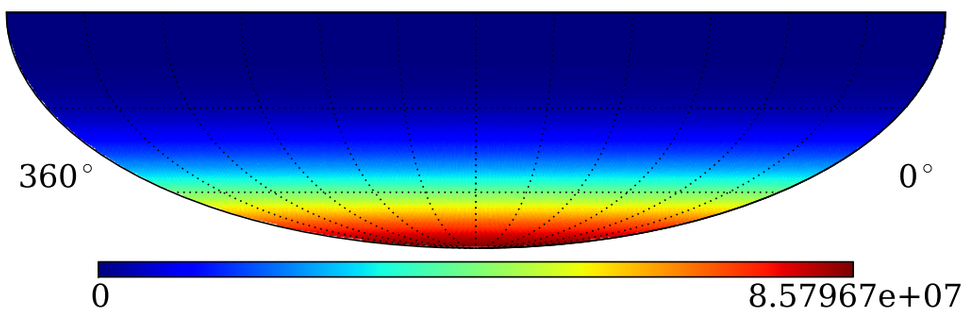
raw map of events in equatorial coordinates $(\alpha,\delta)_i$



reference map from events scrambled over 24hr in α (or time)

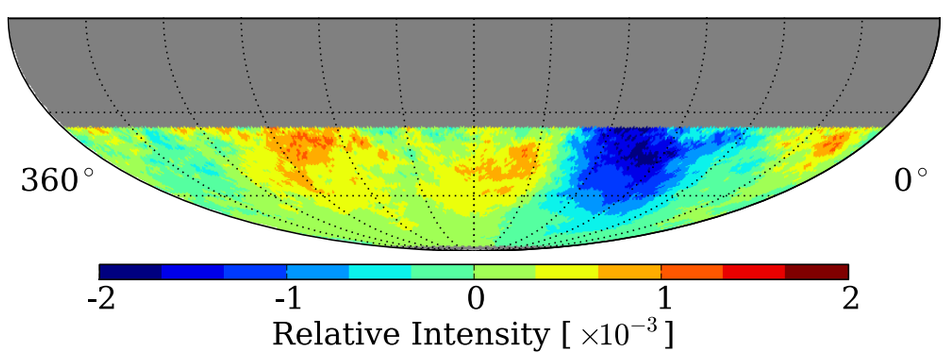


rebin raw and reference maps to enhance inter-bin correlations



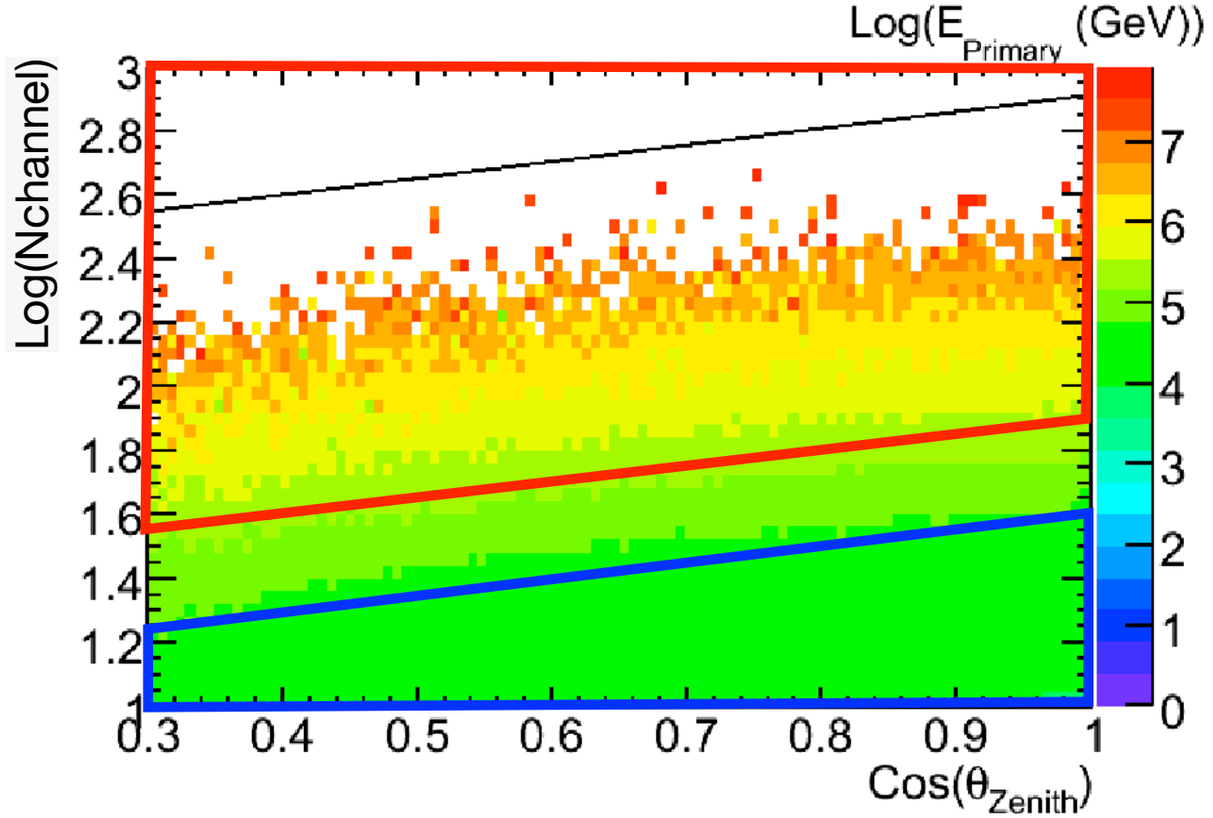
subtract reference map from raw map to determine the residual *relative intensity* map

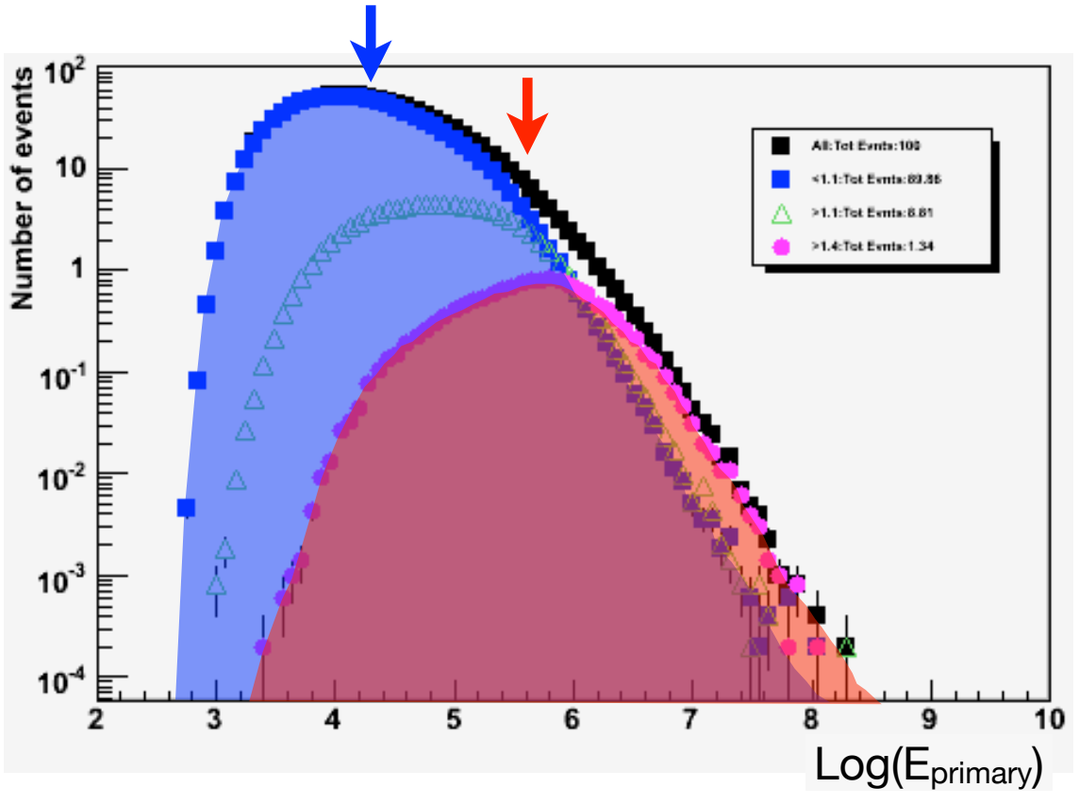
$$\frac{\Delta I}{\langle I \rangle} \equiv \frac{N_i - \langle N \rangle}{\langle N \rangle}$$

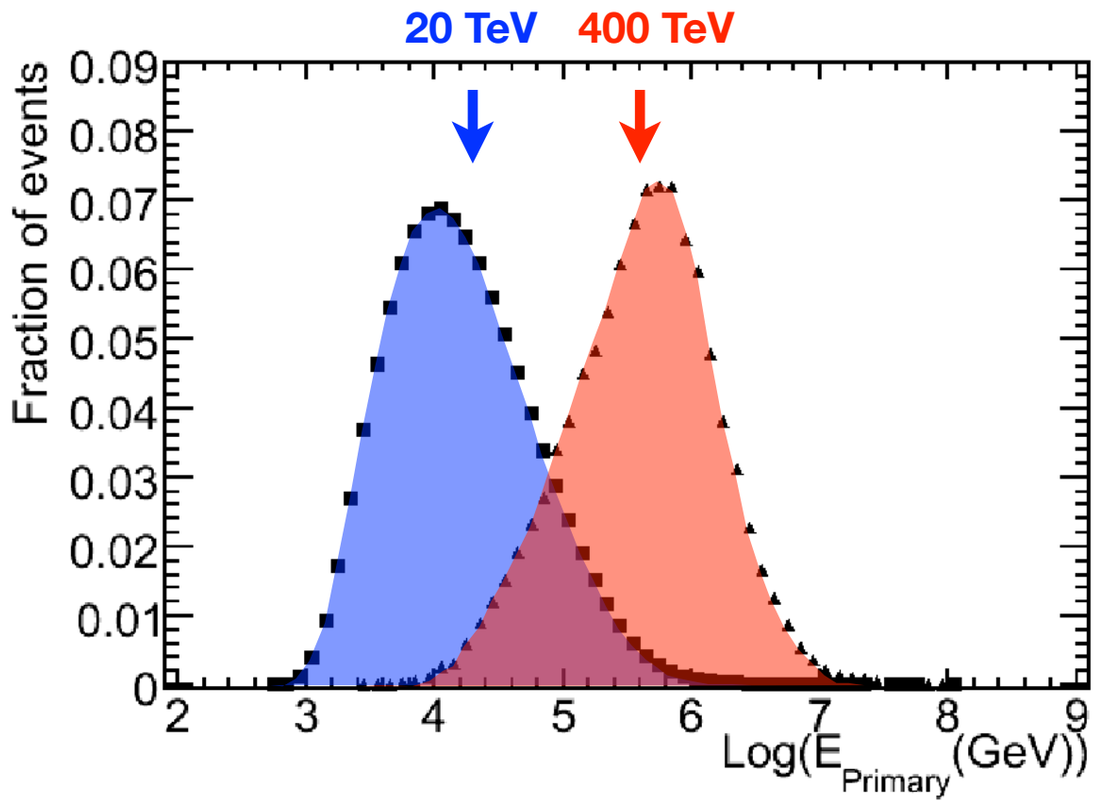


cosmic ray anisotropy energy selection

IceCube







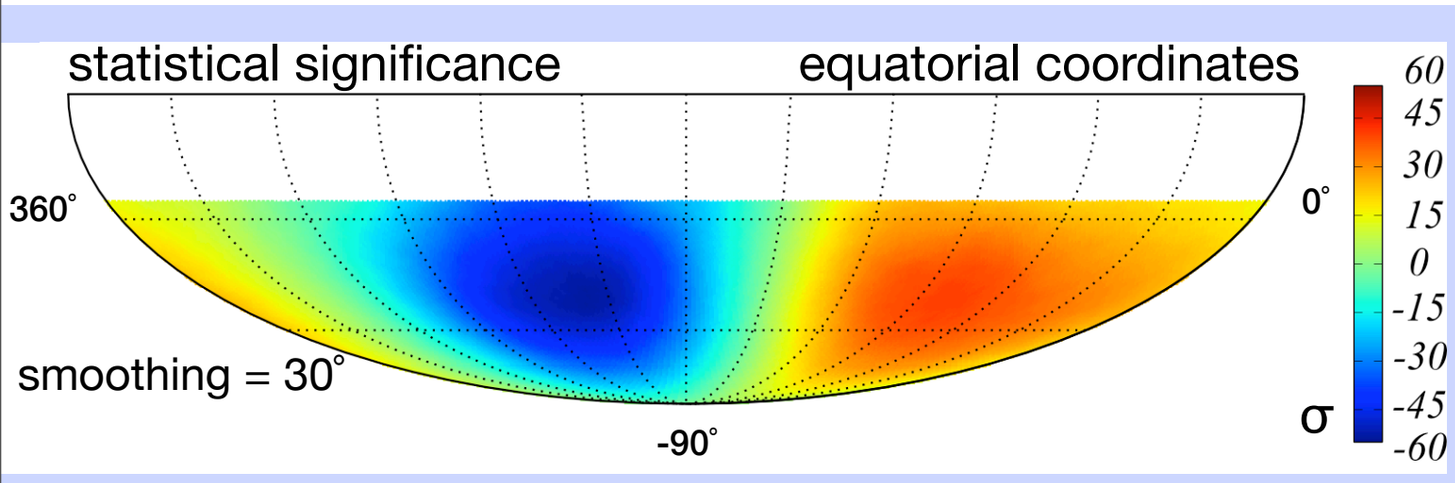
cosmic ray anisotropy vs energy in IceCube-59

energy

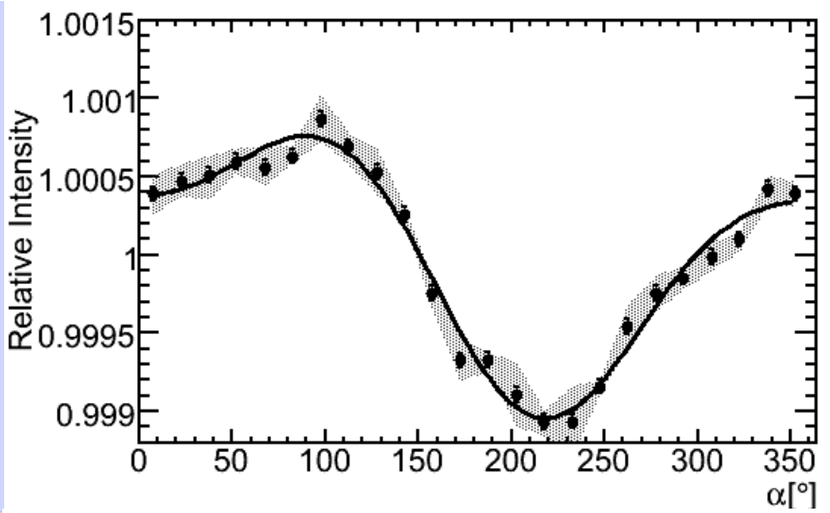
- reference map derived from data with time scrambling
- smoothing radius optimized on highest significance in excess/deficit region

$$s = \sqrt{2}\left\{ N_{\rm on} \ln\left[\frac{1+\alpha}{\alpha}\left(\frac{N_{\rm on}}{N_{\rm on}+N_{\rm off}}\right)\right] + N_{\rm off} \ln\left[(1+\alpha)\left(\frac{N_{\rm off}}{N_{\rm on}+N_{\rm off}}\right)\right]\right\}^{1/2} \qquad \alpha = 1/20$$

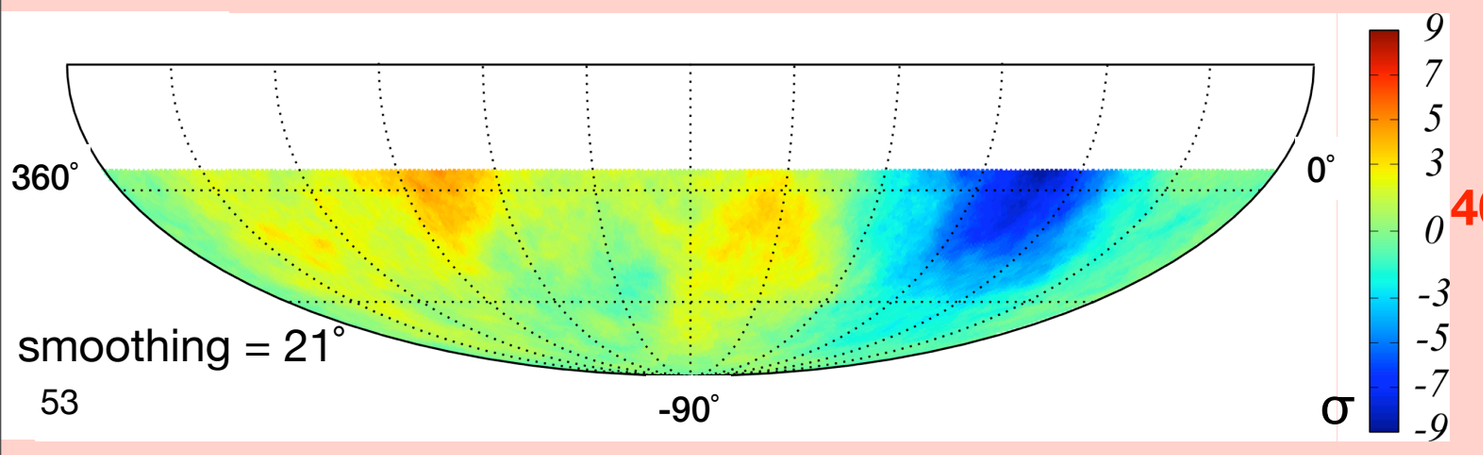
Li, T., & Ma, Y. 1983, ApJ, 272, 317



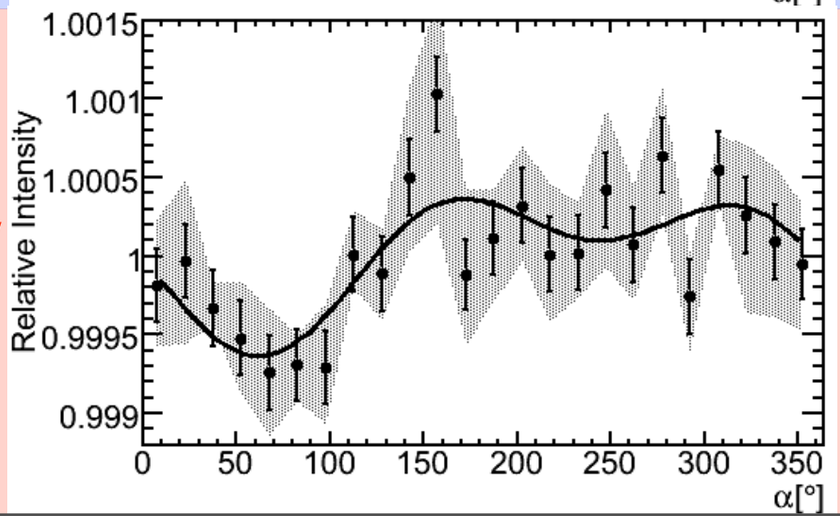
20 TeV



Abbasi et al., ApJ, **746**, 33, 2012

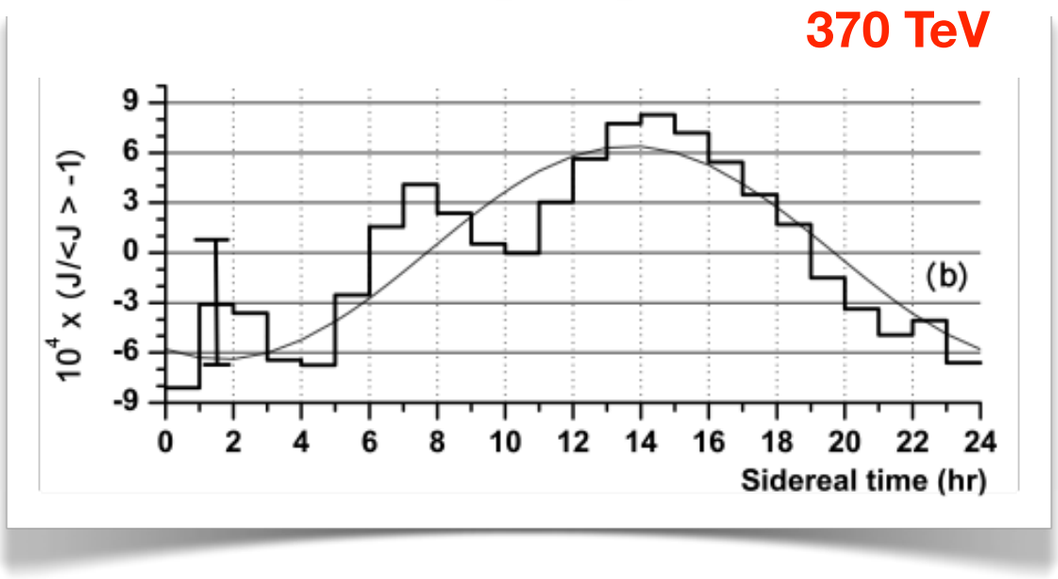


400 TeV

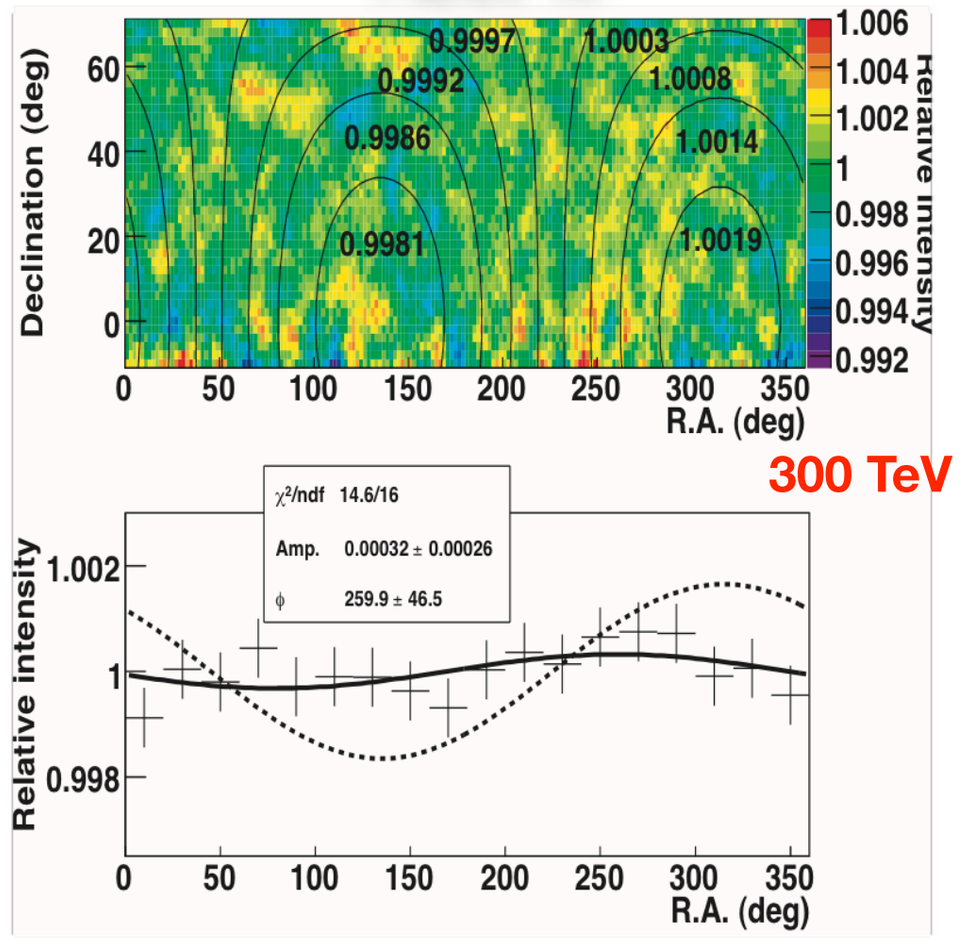


cosmic ray anisotropy vs energy in IceCube-59

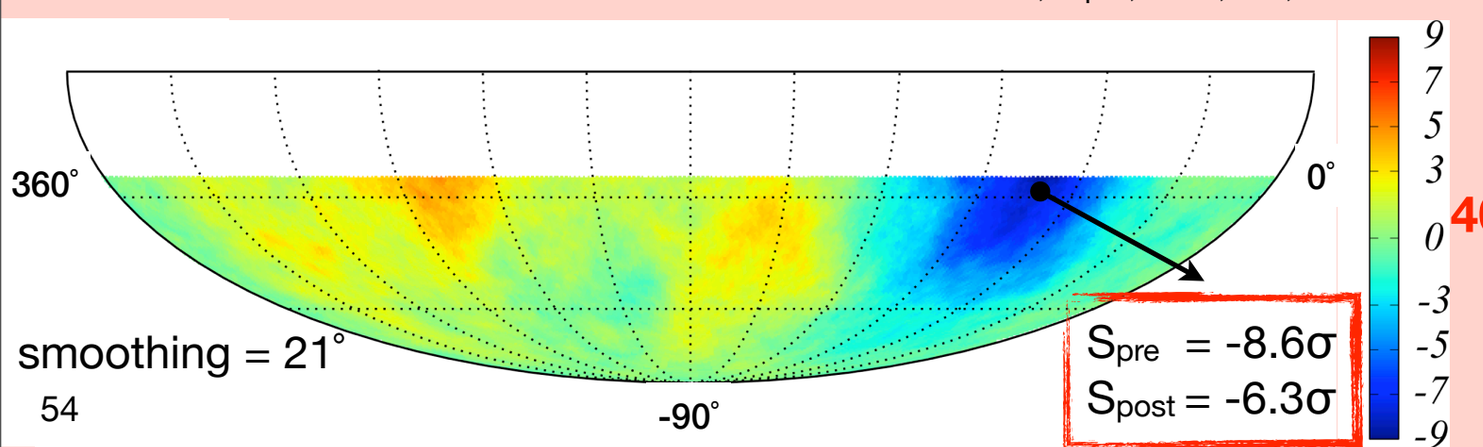
EAS-TOP

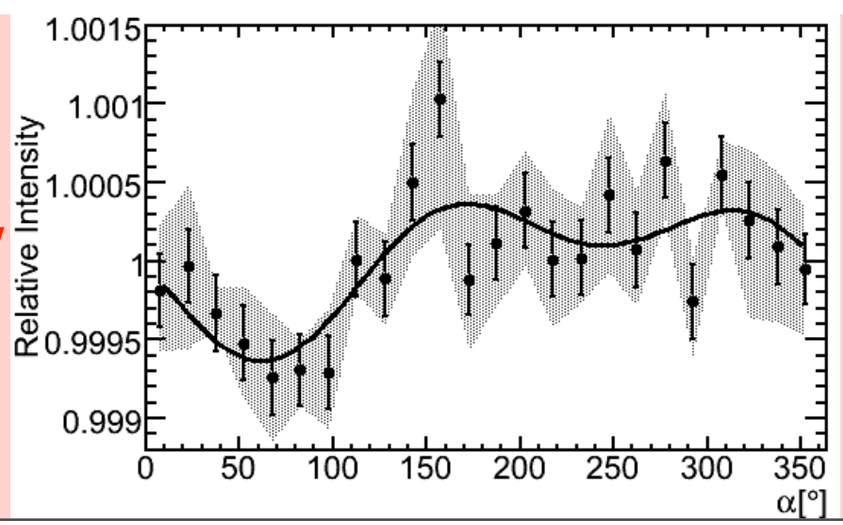


Tibet-III



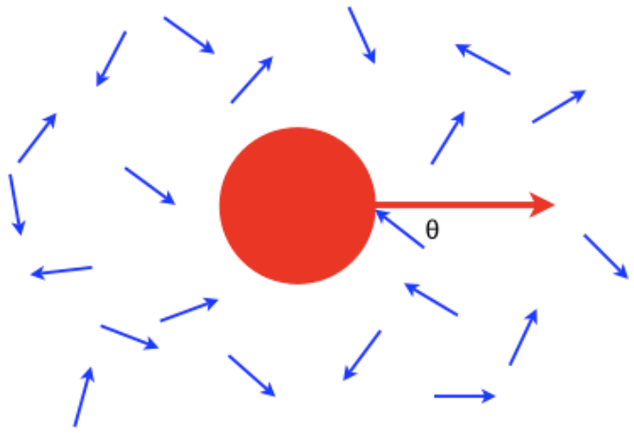
Abbasi et al., ApJ, **746**, 33, 2012





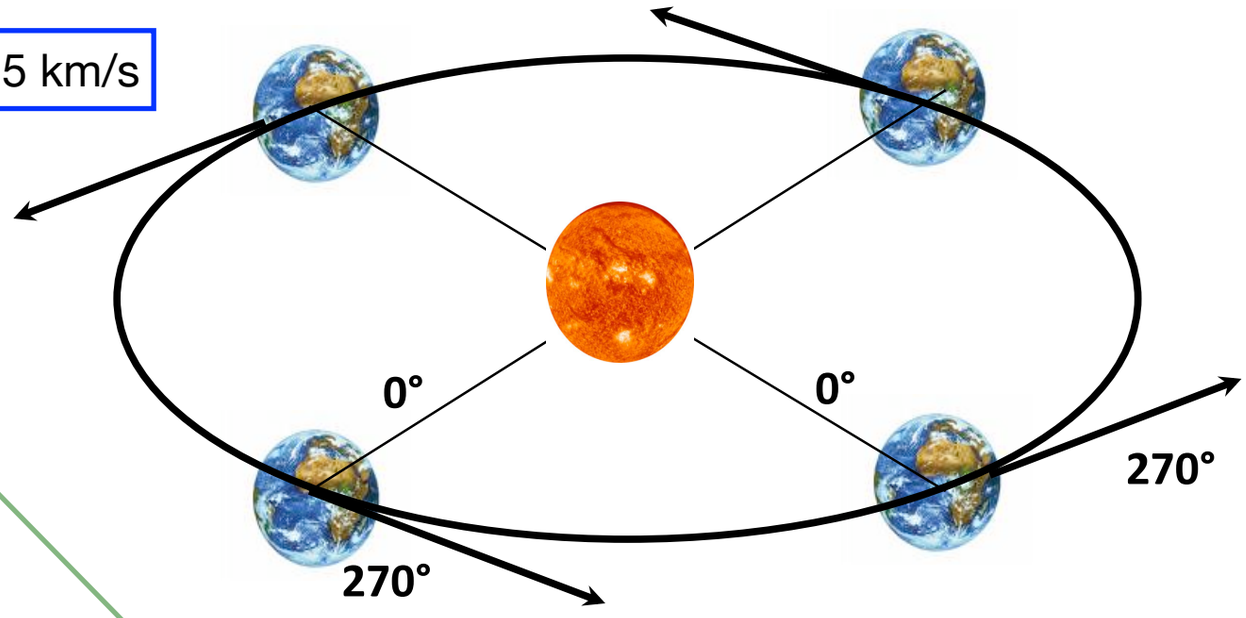
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)

Earth's motion around the Sun

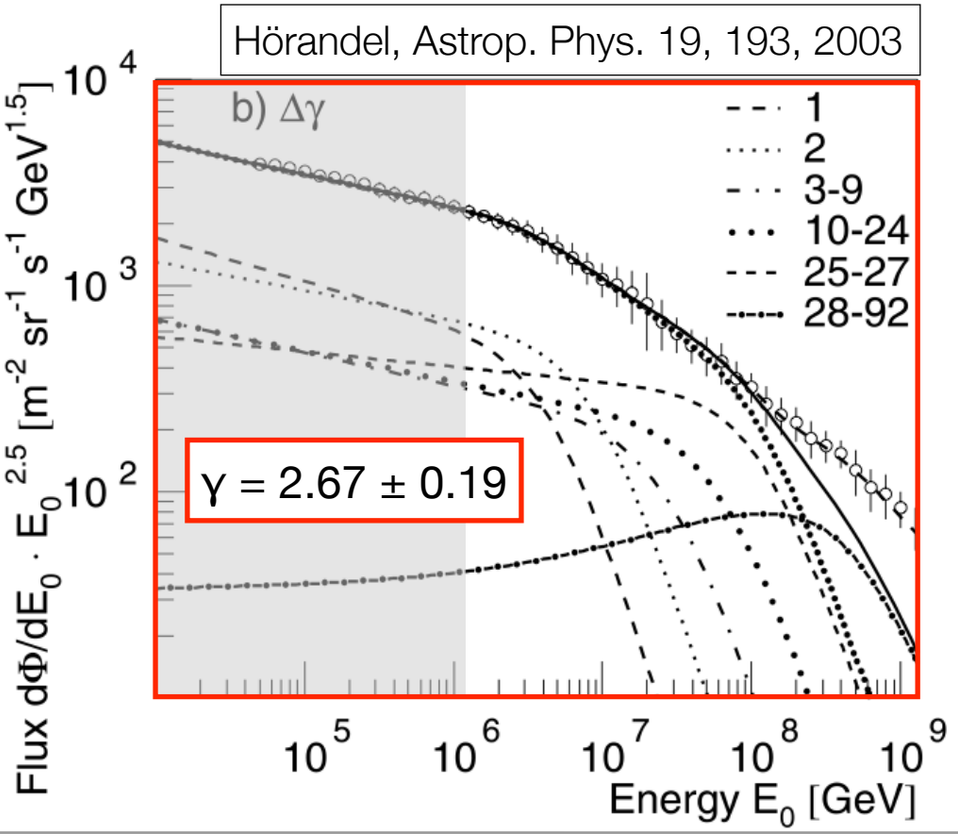


v = 29.8 ± 0.5 km/s

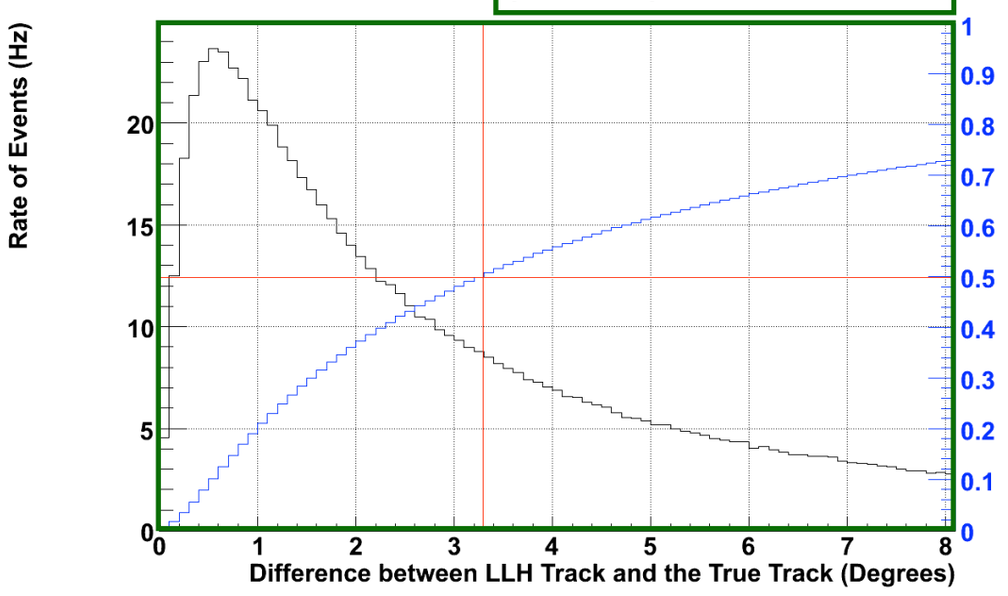
$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$



Hörandel, Astrop. Phys. 19, 193, 2003

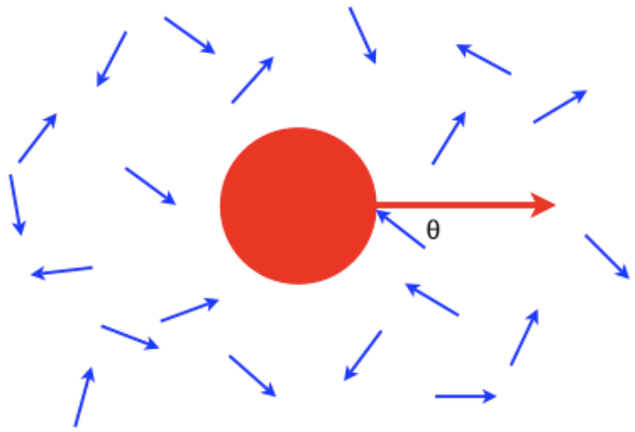


point spread function



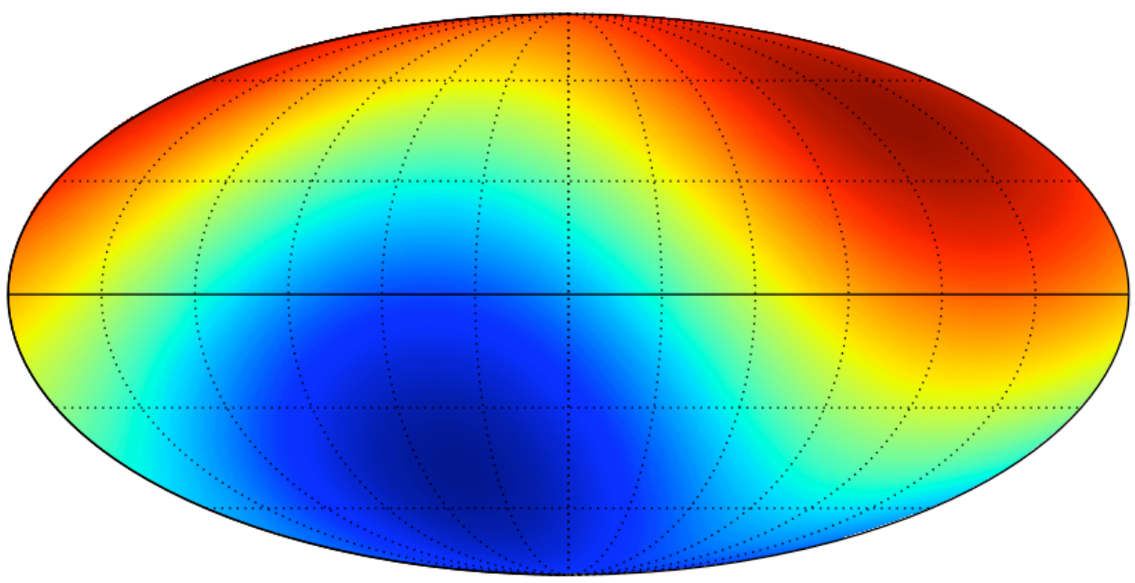
origin of large scale anisotropy : Compton-Getting Effect ?

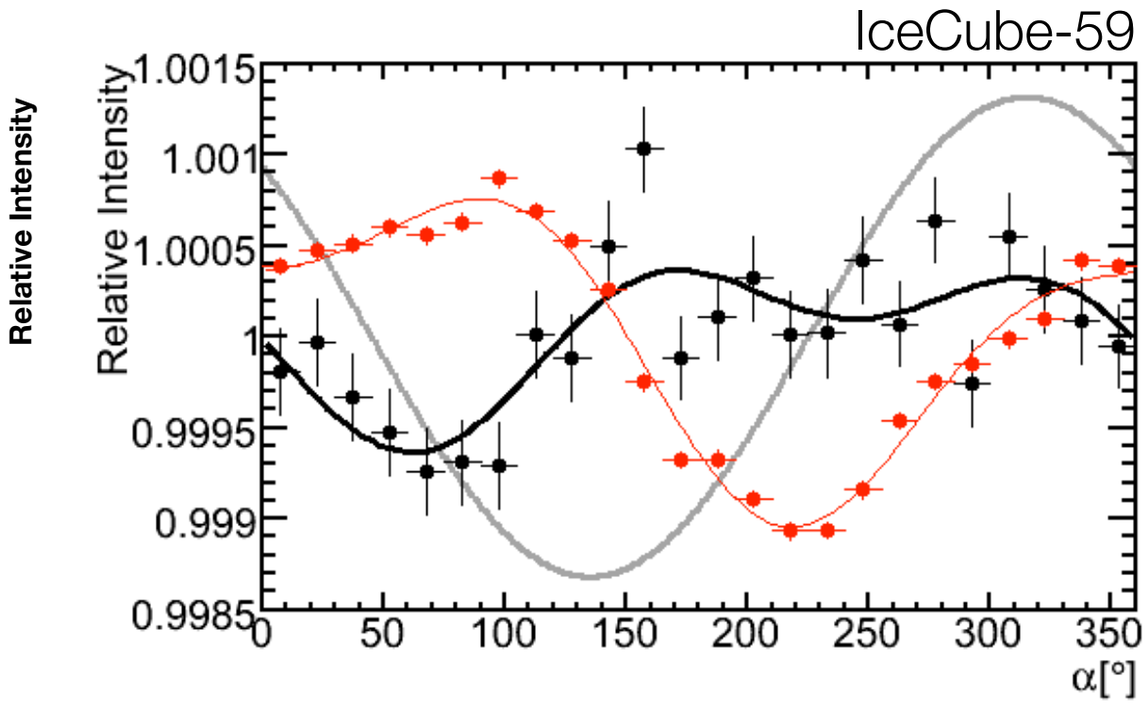
Compton & Getting, Phys. Rev. 47, 817 (1935)
Gleeson, & Axford, Ap&SS, 2, 43 (1968)



$$\frac{\Delta I}{I} = (\gamma + 2)\frac{v}{c}\cos\theta$$

- apparent energy-independent ~10^{-3} dipole anisotropy due to relative motion of solar system through ISM
- motion of solar system around galactic center ~ 220 km/s
- reference system of cosmic rays is unknown



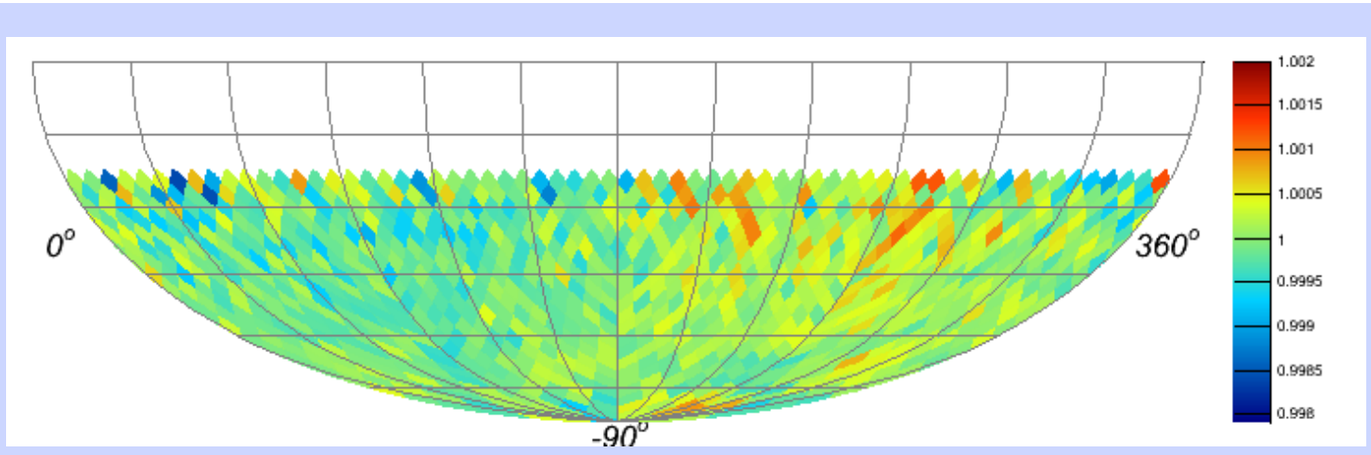


solar dipole anisotropy vs energy in IceCube-59

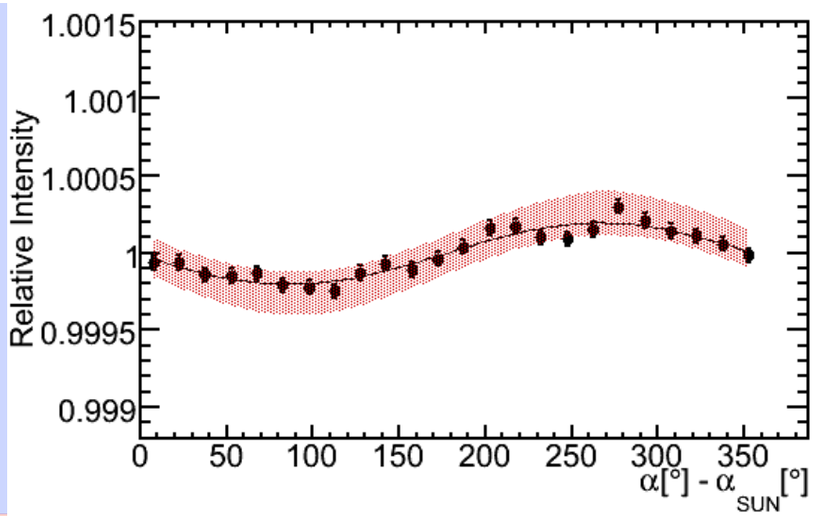
The observation of the solar dipole supports the observation of the sidereal anisotropy in cosmic ray arrival direction

relative intensity

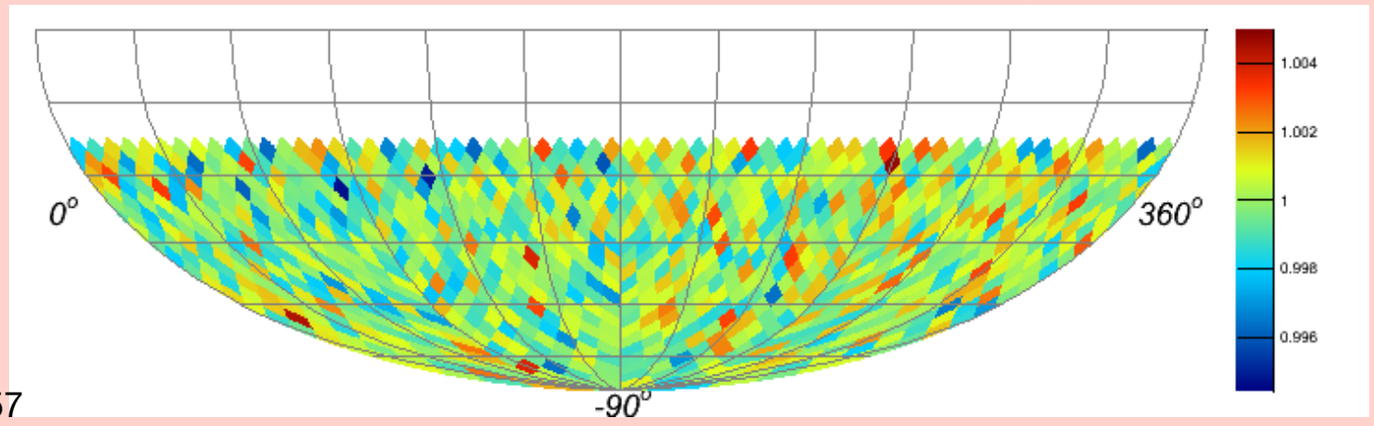
α [°] - α_{SUN} [°]



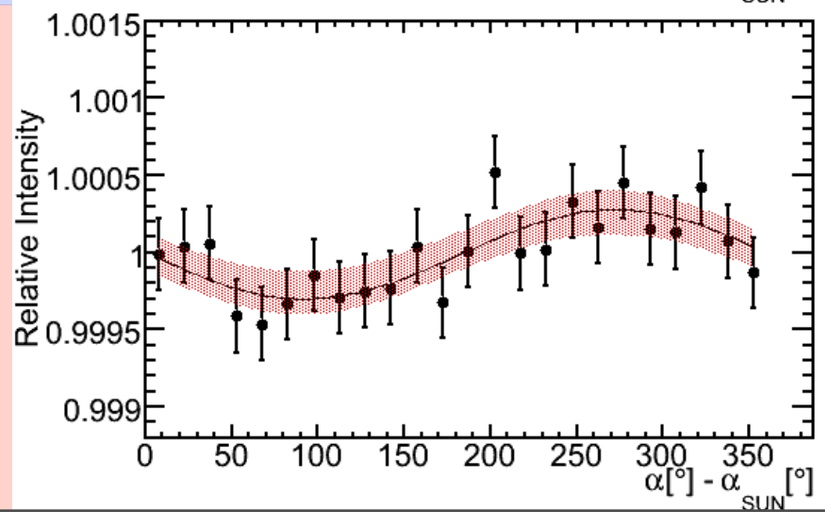
20 TeV



Abbasi et al., ApJ, **746**, 33, 2012



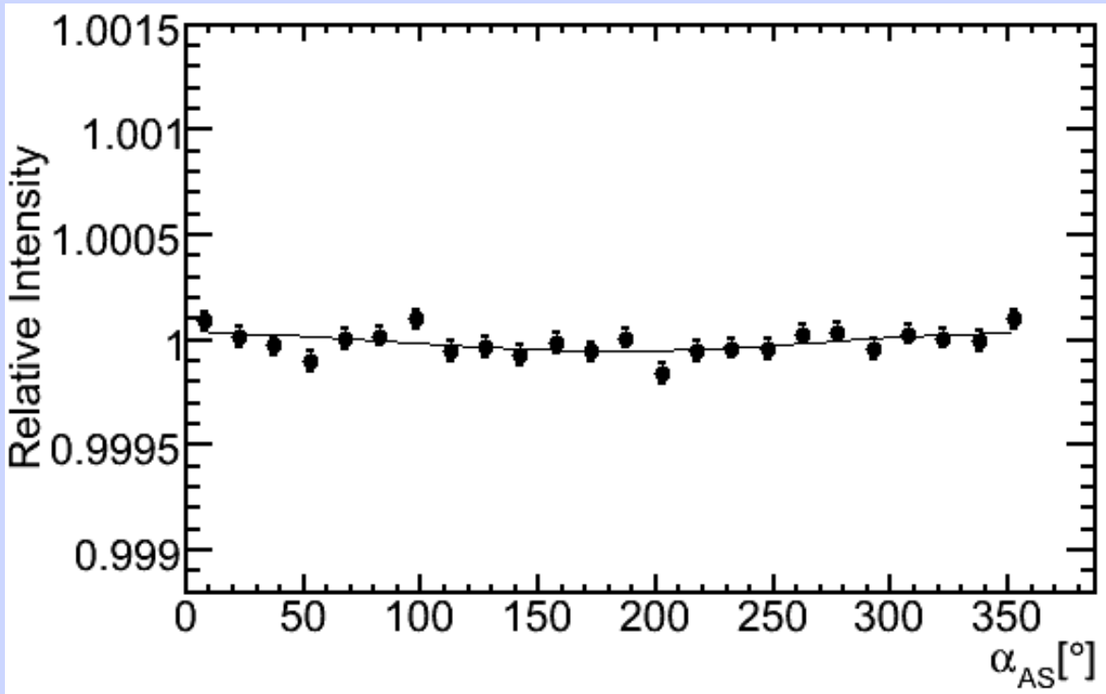
400 TeV



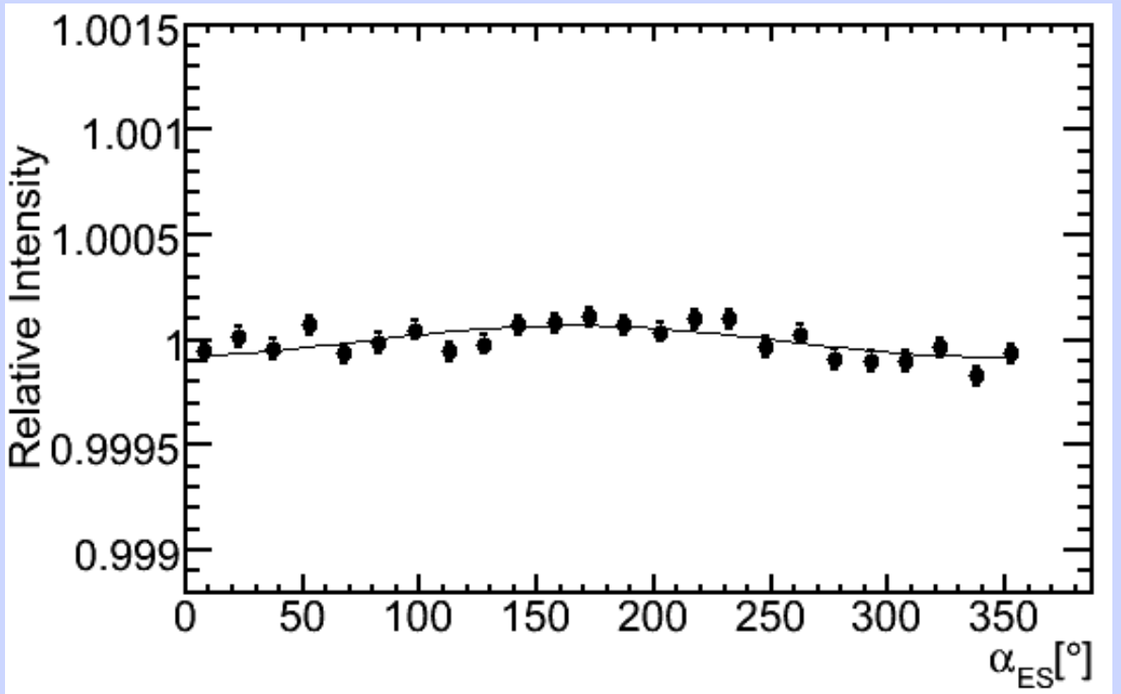
anti-/extended-sidereal distributions vs energy in IceCube-59

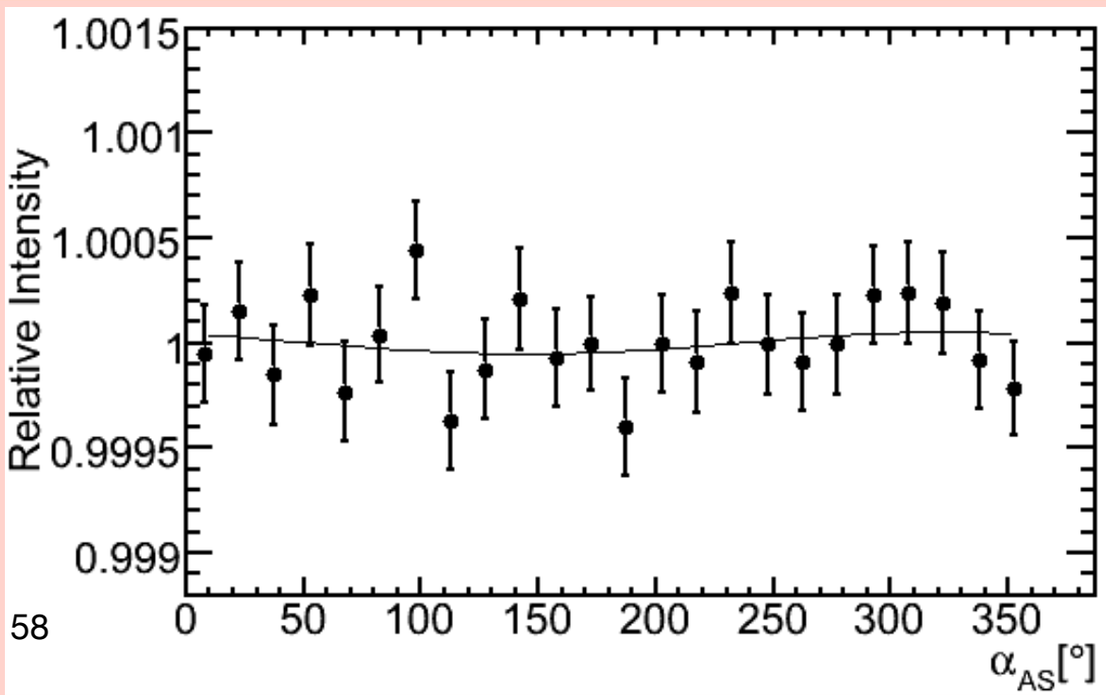
anti-sidereal distribution ~ solar dipole variability

extended-sidereal distribution ~ sid. anis. variability

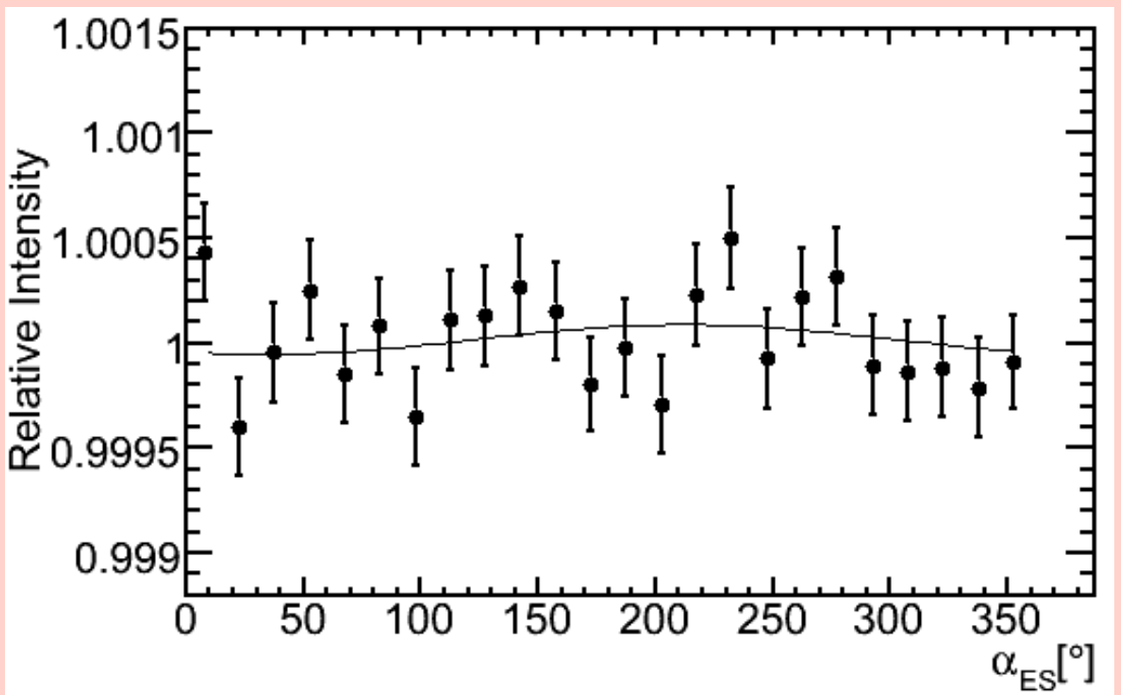


20 TeV





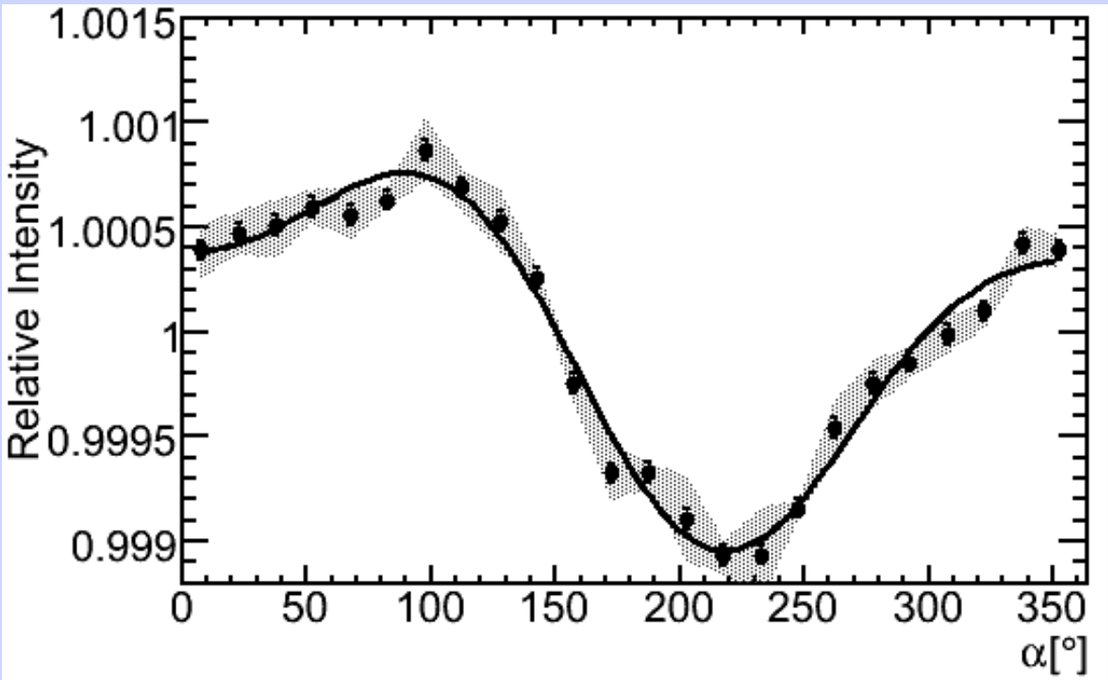
400 TeV



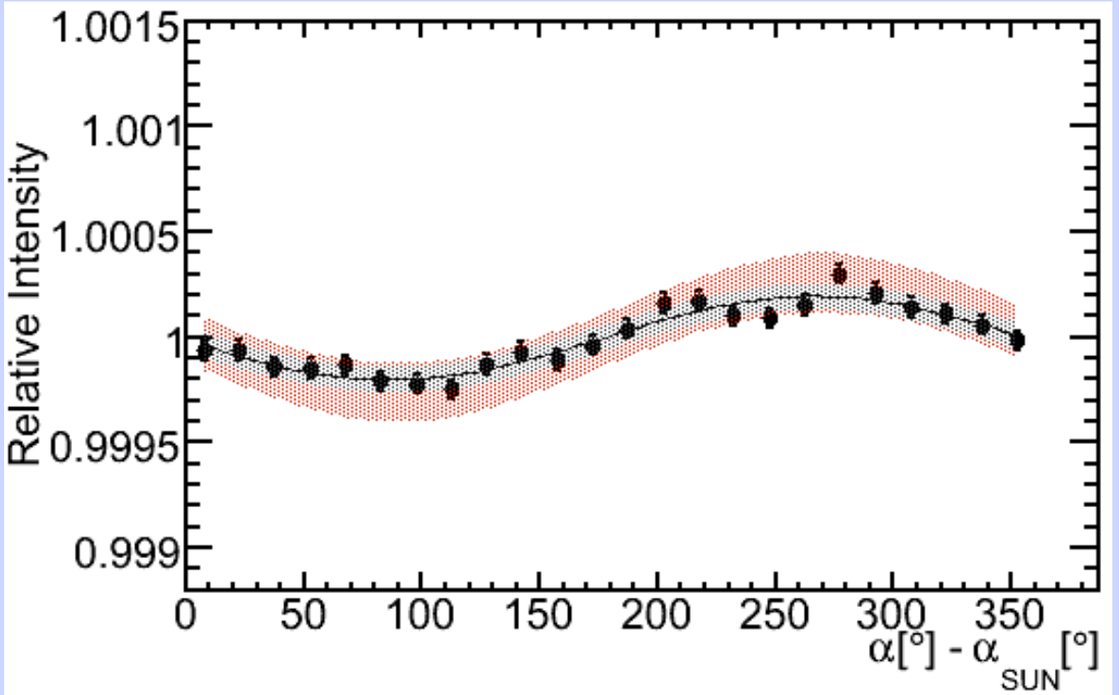
systematic uncertainties IceCube-59

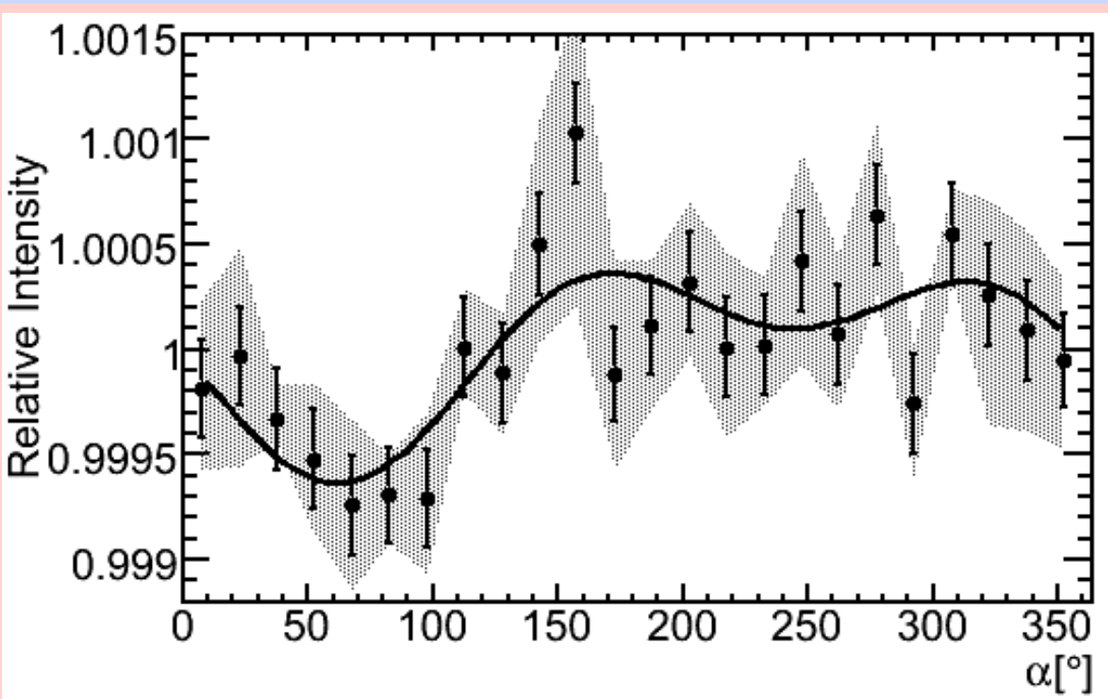
statistical stability tests + anti-sidereal effect

extended-sidereal effect

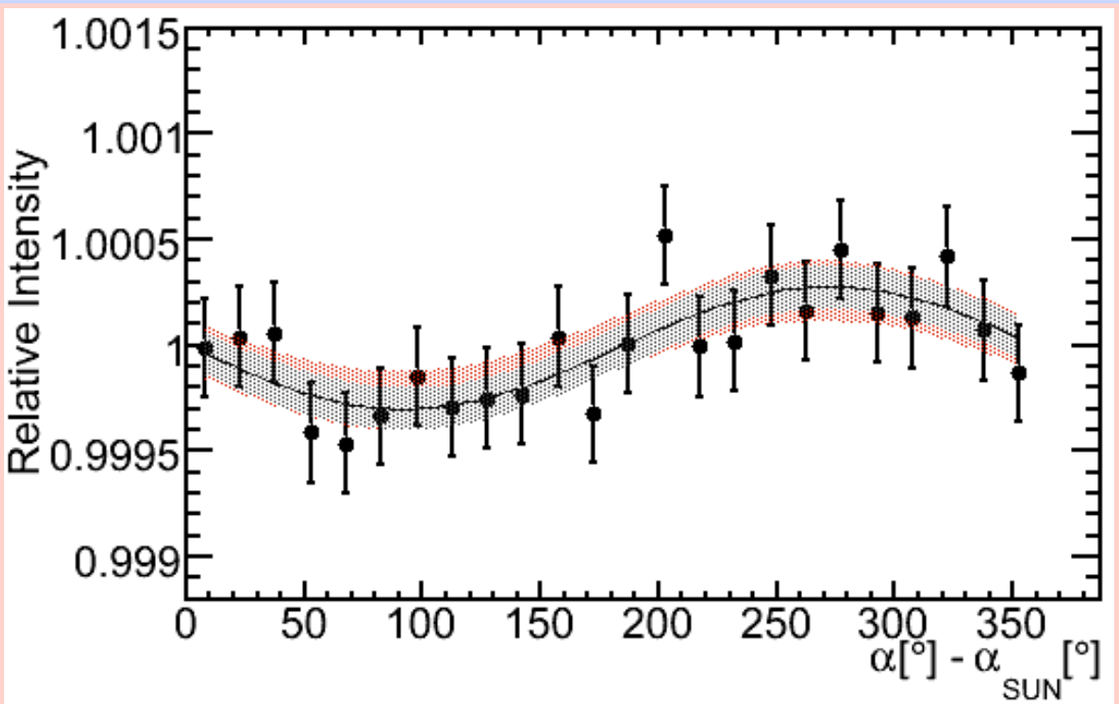


20 TeV



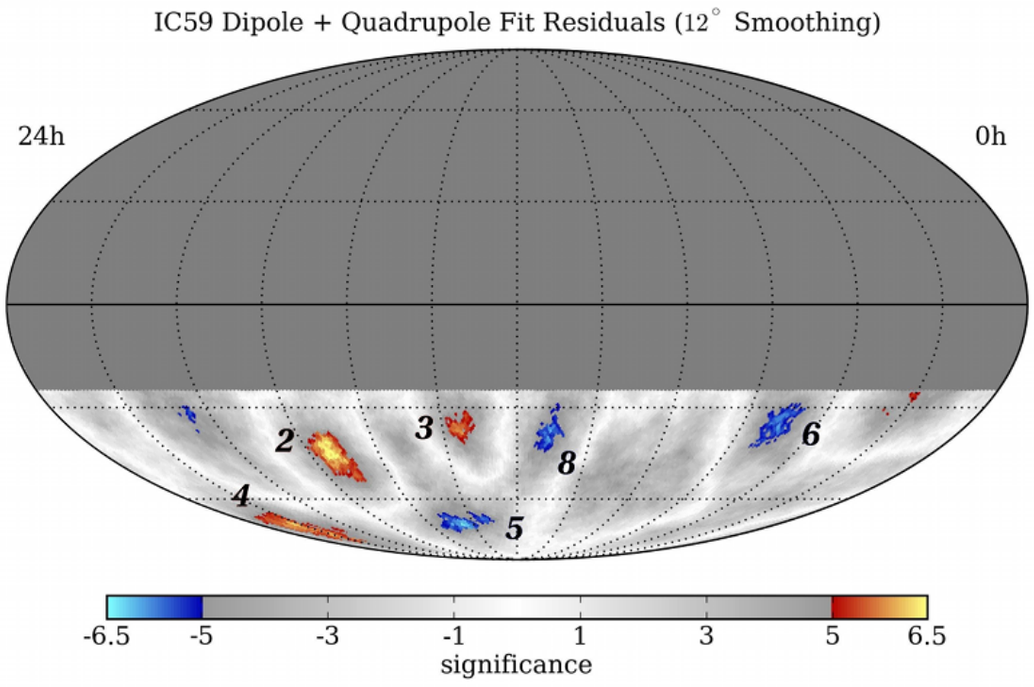


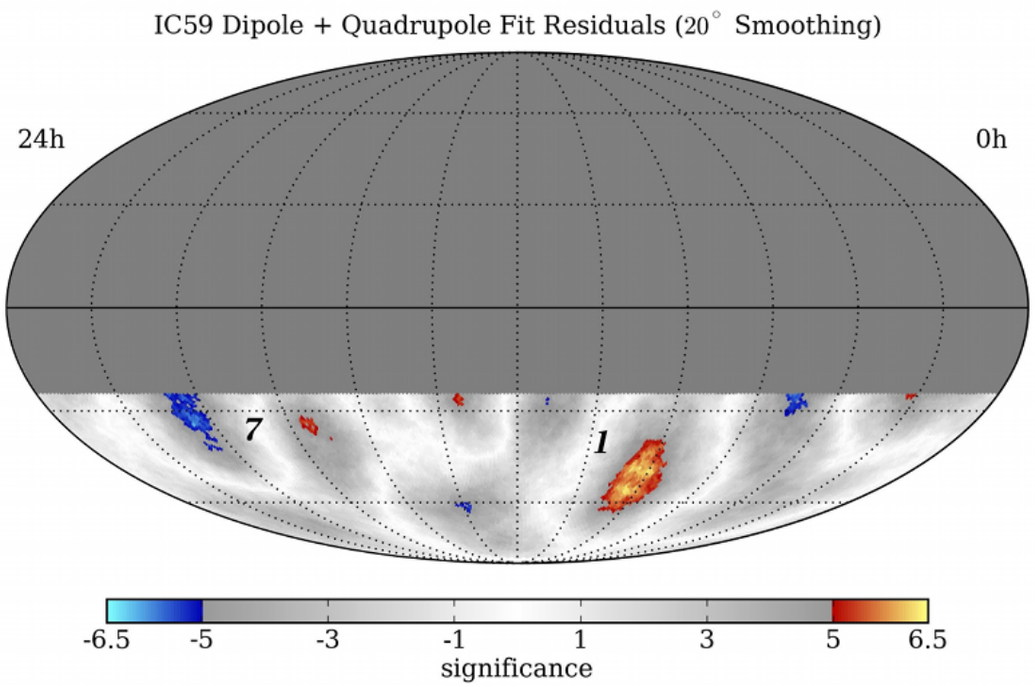
400 TeV



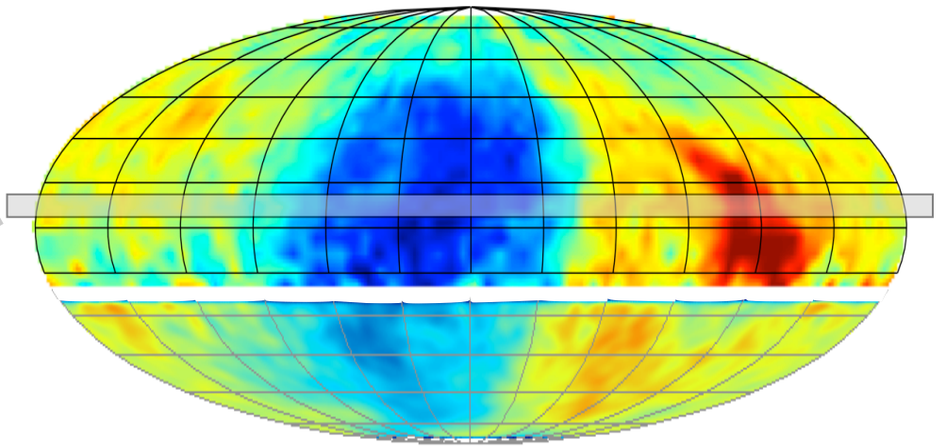
cosmic ray anisotropy small scale
IceCube

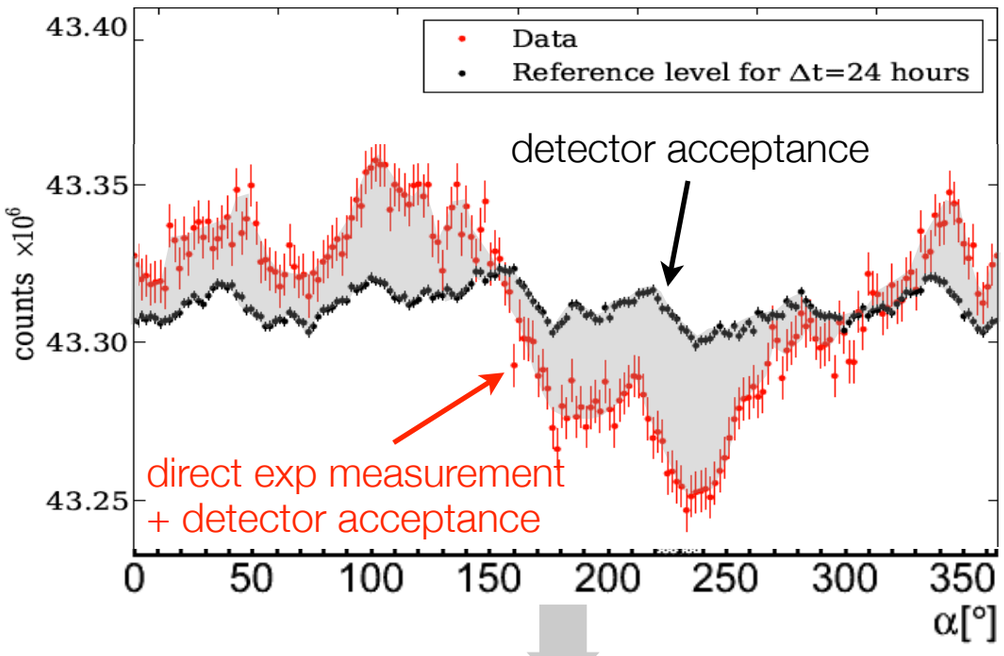
region	right ascension	declination	optimal scale	peak significance	post-trials	**IC79 (post-trials)**
1	$(122.4^{+4.1}_{-4.7})^\circ$	$(-47.4^{+7.5}_{-3.2})^\circ$	22°	7.0σ	5.3σ	6.8σ
2	$(263.0^{+3.7}_{-3.8})^\circ$	$(-44.1^{+5.3}_{-5.1})^\circ$	13°	6.7σ	4.9σ	5.4σ
3	$(201.6^{+6.0}_{-1.1})^\circ$	$(-37.0^{+2.2}_{-1.9})^\circ$	11°	6.3σ	4.4σ	6.4σ
4	$(332.4^{+9.5}_{-7.1})^\circ$	$(-70.0^{+4.2}_{-7.6})^\circ$	12°	6.2σ	4.2σ	6.1σ
5	$(217.7^{+10.2}_{-7.8})^\circ$	$(-70.0^{+3.6}_{-2.3})^\circ$	12°	-6.4σ	-4.5σ	-6.1σ
6	$(77.6^{+3.9}_{-8.4})^\circ$	$(-31.9^{+3.2}_{-8.6})^\circ$	13°	-6.1σ	-4.1σ	-4.3σ
7	$(308.2^{+4.8}_{-7.7})^\circ$	$(-34.5^{+9.6}_{-6.9})^\circ$	20°	-6.1σ	-4.1σ	-4.4σ
8	$(166.5^{+4.5}_{-5.7})^\circ$	$(-37.2^{+5.0}_{-5.7})^\circ$	12°	-6.0σ	-4.0σ	-6.4σ

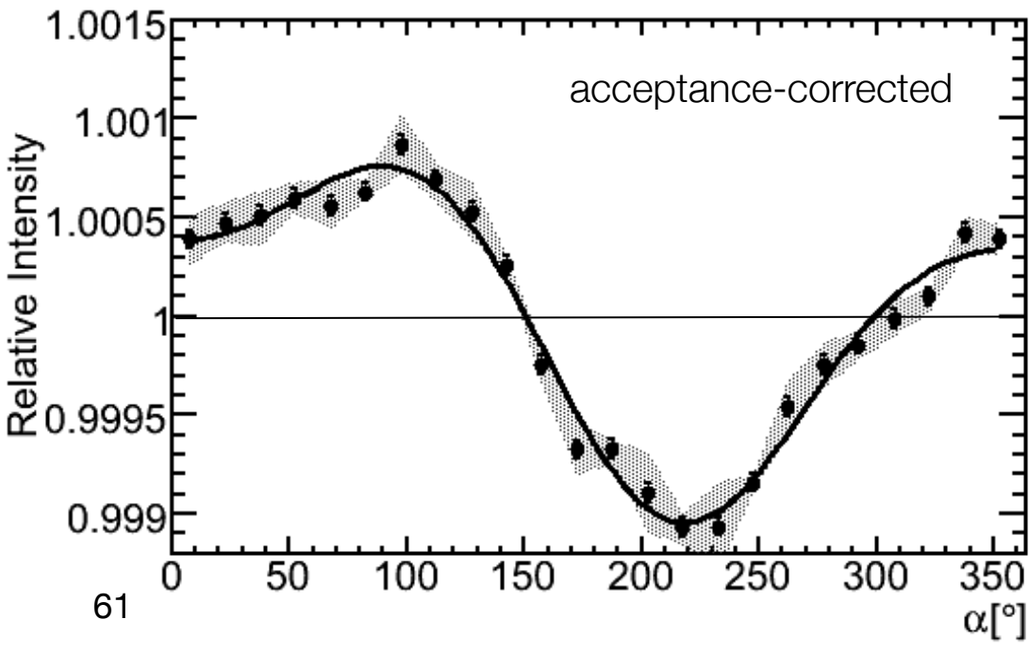




anisotropy vs. angular scale







large vs small scale anisotropy