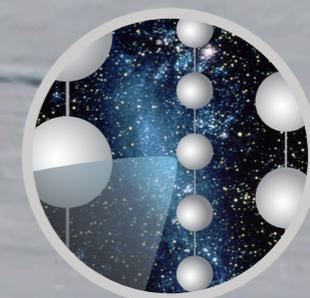
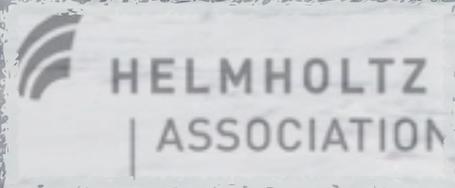


Measurement of the Cosmic Ray Energy Spectrum and Composition with IceCube.



Timo Karg
for the IceCube Collaboration

RICAP 16
22 June 2016 in Frascati, IT

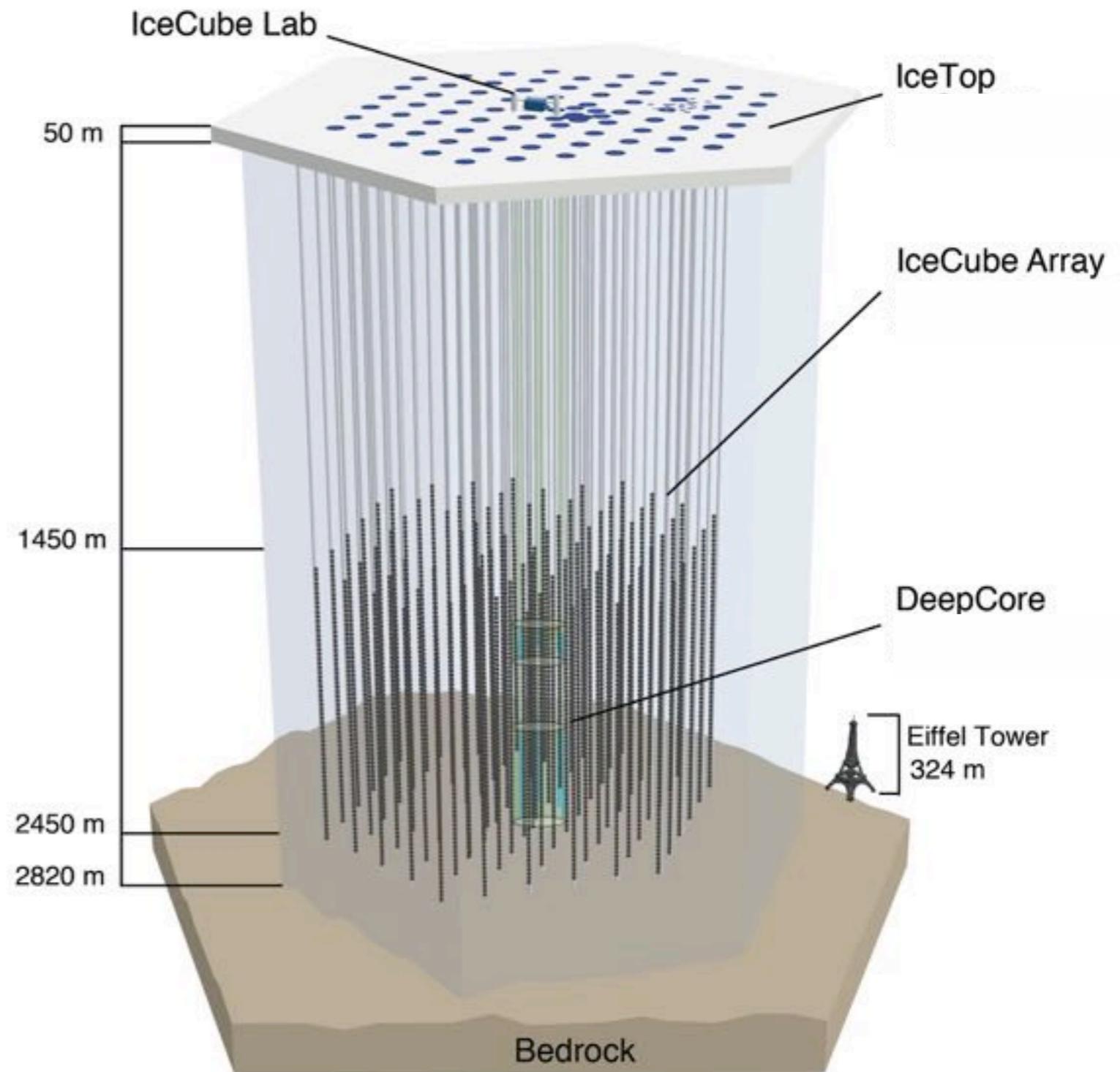


ICECUBE

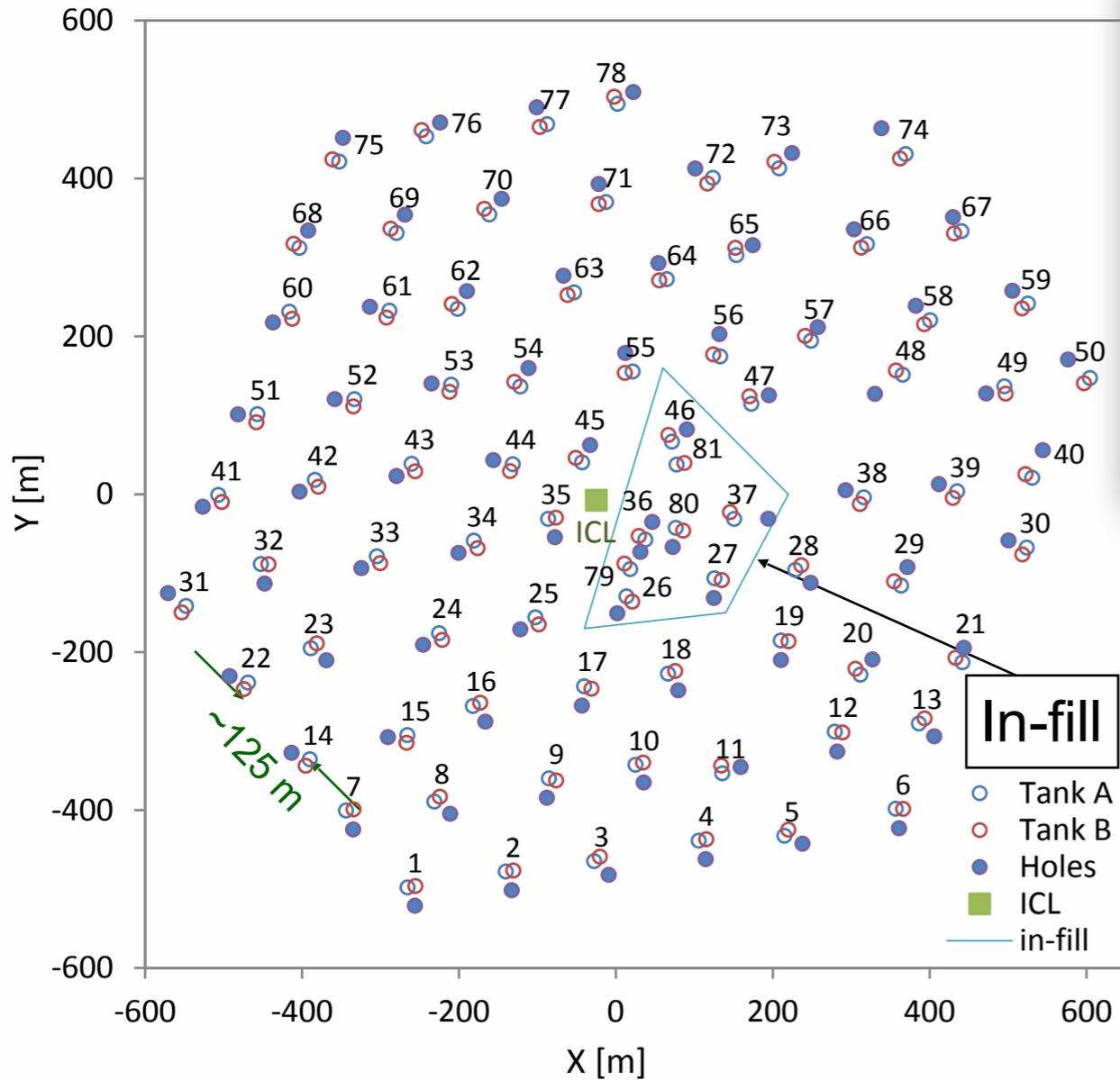


The IceCube Observatory

- Depth: 1450 to 2450 m
- 86 strings
(60 optical modules each)
- 17 m vertical distance
btw. optical modules
- 125 m distance btw. strings
- Volume: 1 km³
- More dense instrumentation
in center (DeepCore)
- **1 km² surface array (IceTop)**
- Completed: 18 Dec. 2010



The IceTop Detector Array (~ 1 km²)

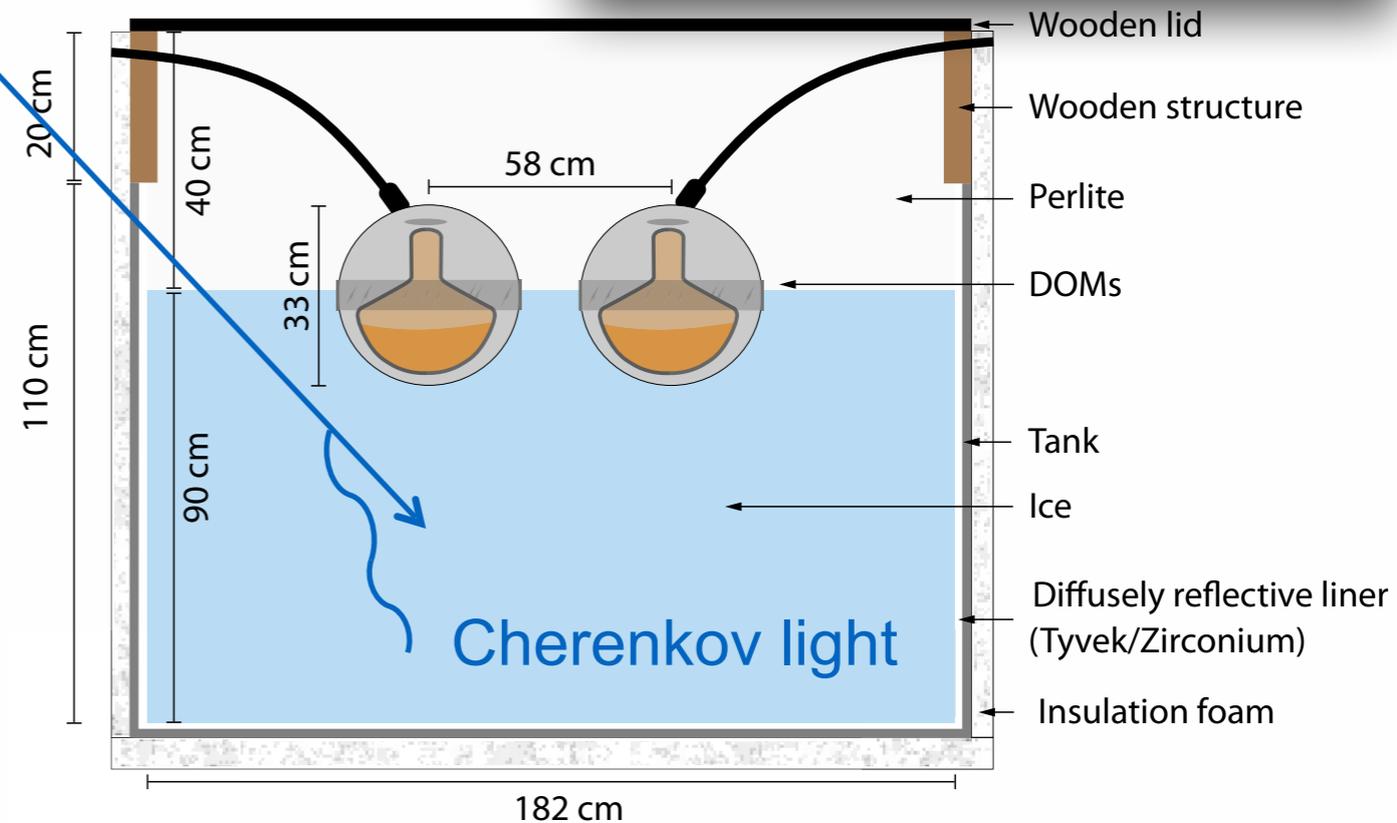
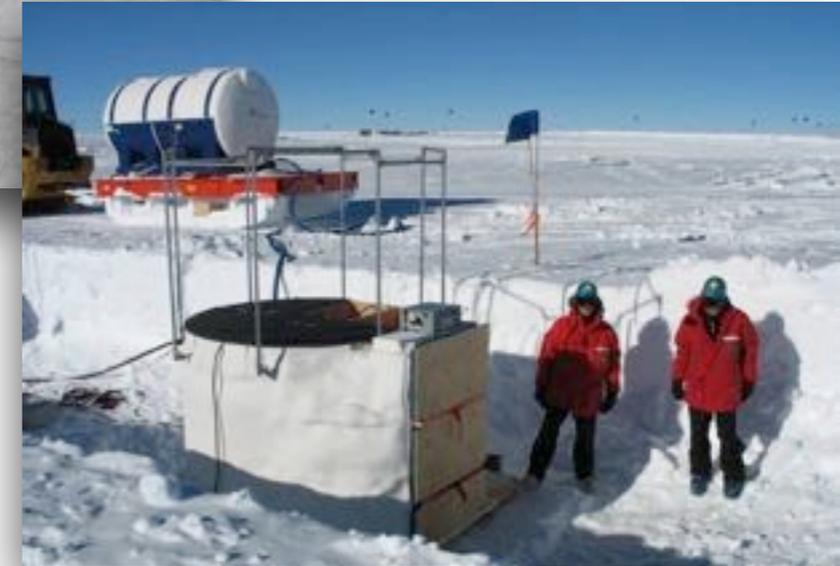


81 stations (162 tanks)

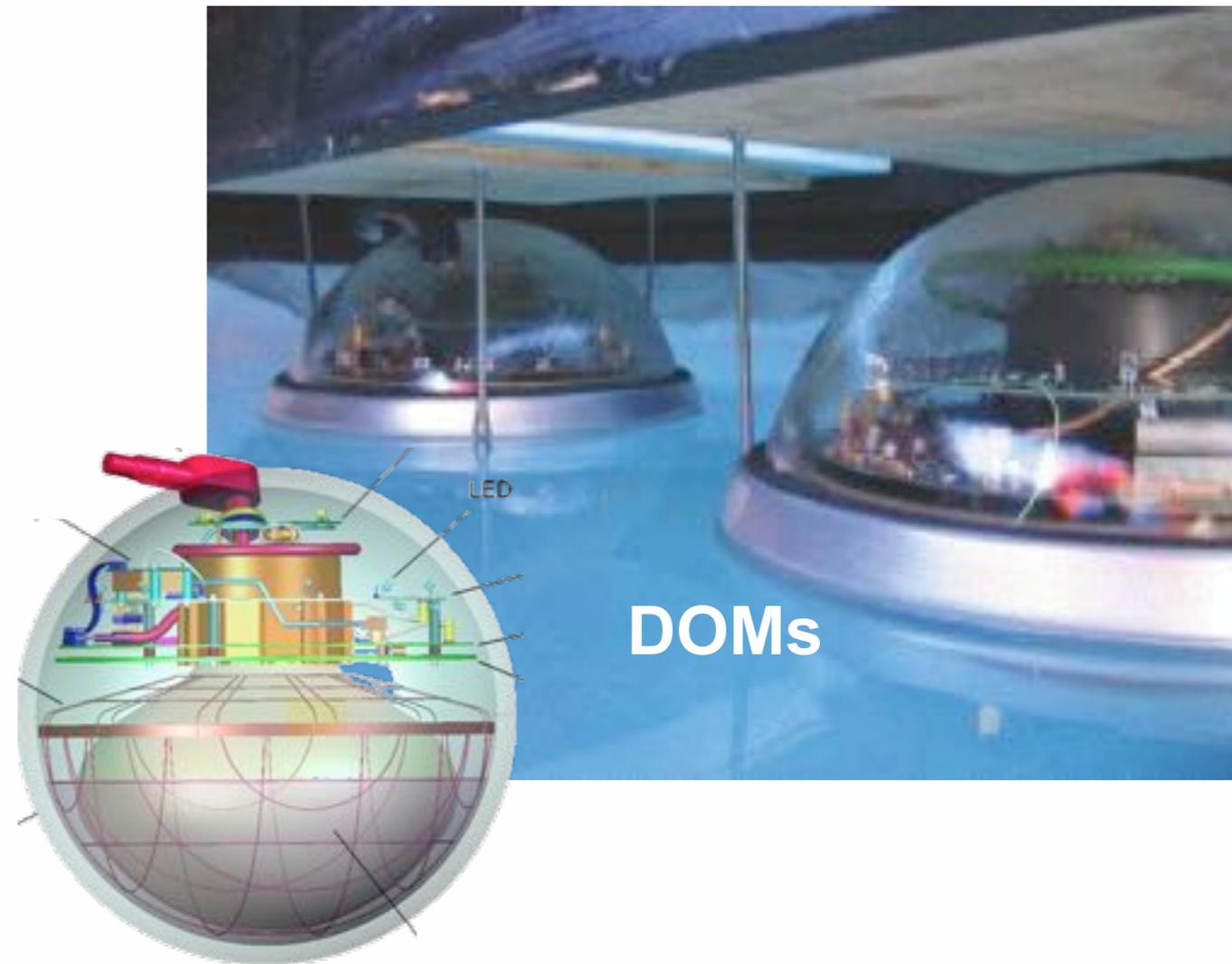
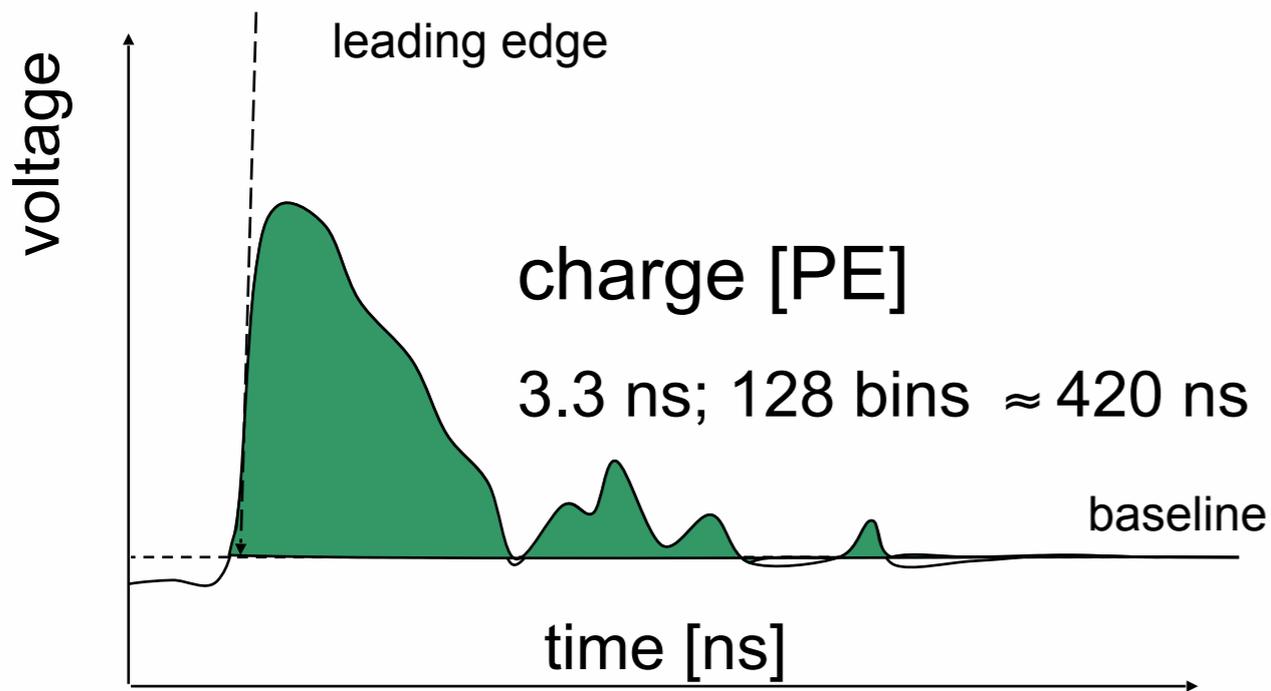
typical spacing: 125 m

fill ratio $\sim 4 \times 10^{-4}$

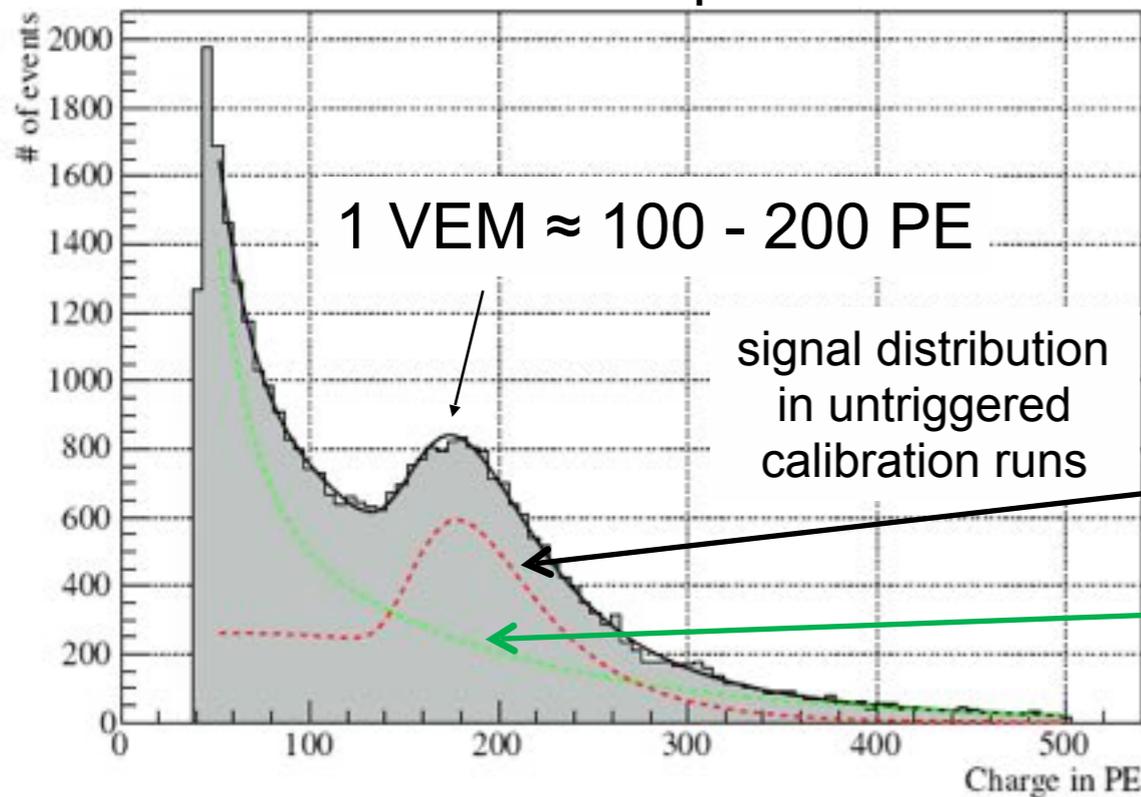
altitude: 2835 m ($X = 680 \text{ g cm}^{-2}$)



IceTop Data Acquisition



Calibration: Vertical Equivalent Muons



muon signal

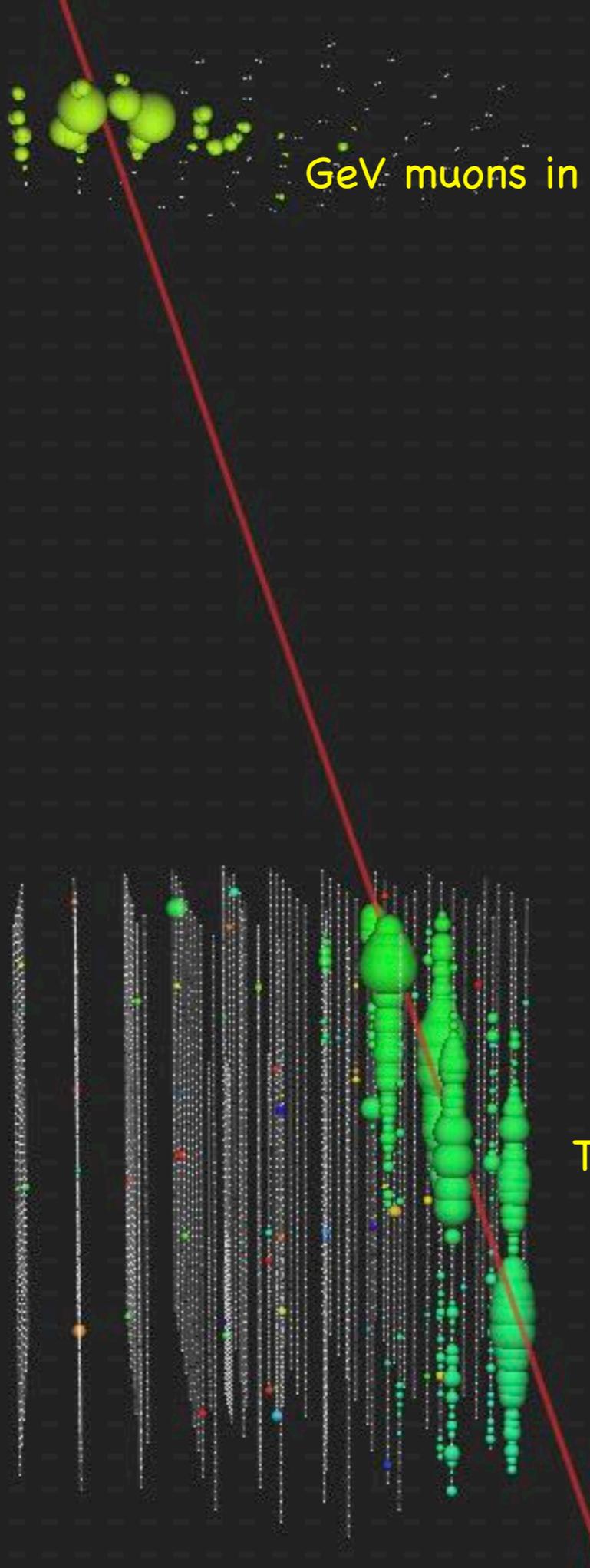
e.m. background

EM particles

GeV muons in the shower periphery

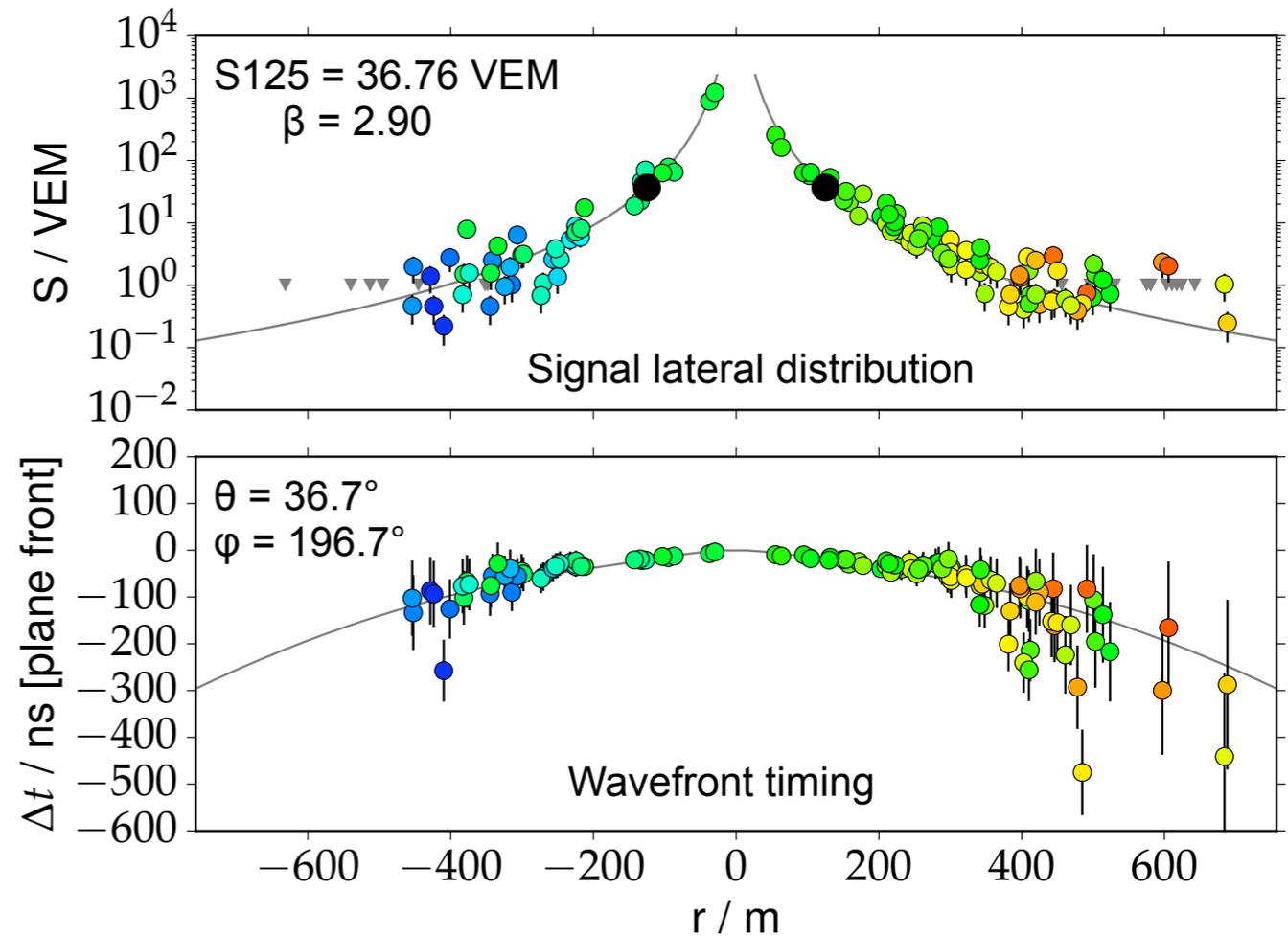
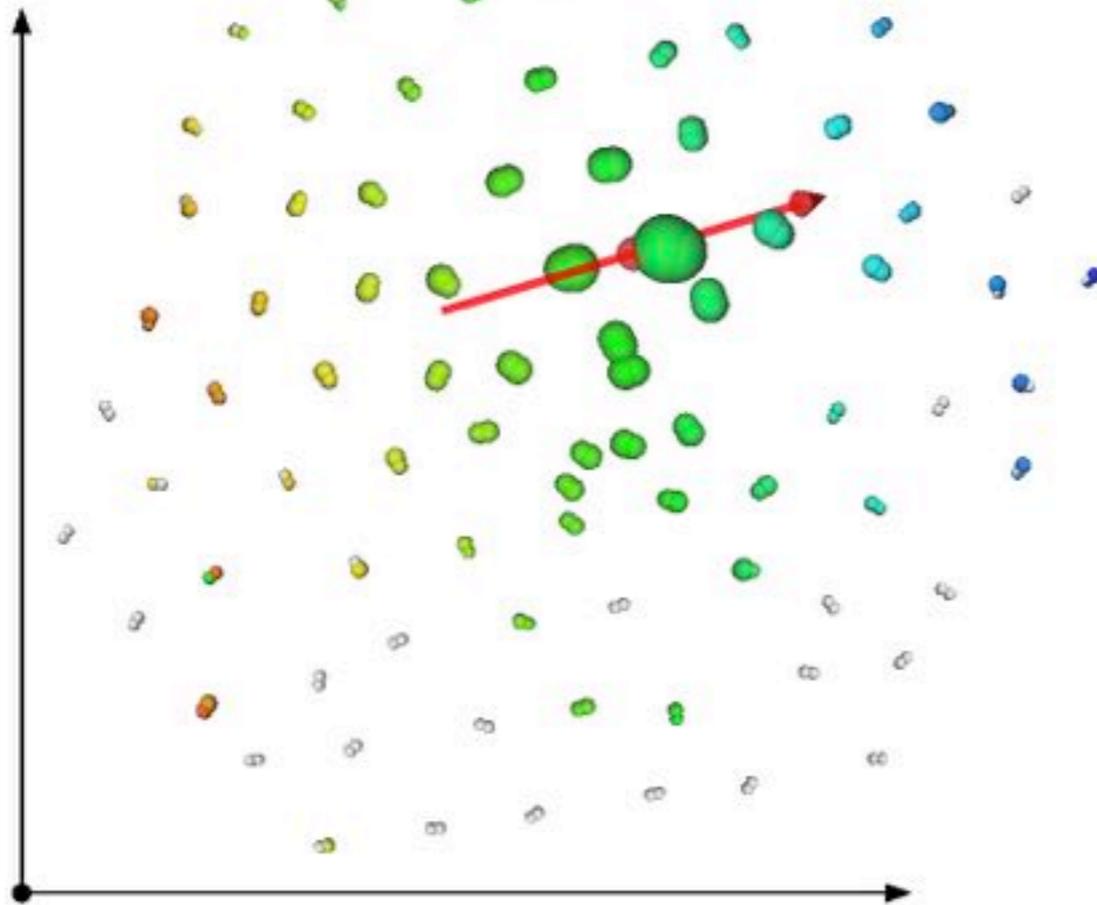
TeV muon bundle

Data,
 $E_{\text{prim}}: o(10 \text{ PeV})$



Air Shower Reconstruction

Event 120401/2498463-0
 Time 2012-07-01 03:43:27 UTC
 Duration 30819.2 ns



Signal lateral distribution:

$$S(r) = S_{125} e^{-\frac{d \sec \theta}{\lambda}} \left(\frac{r}{125 \text{ m}} \right)^{-\beta - \kappa \log\left(\frac{r}{125 \text{ m}}\right)}$$

Correction for attenuation in snow

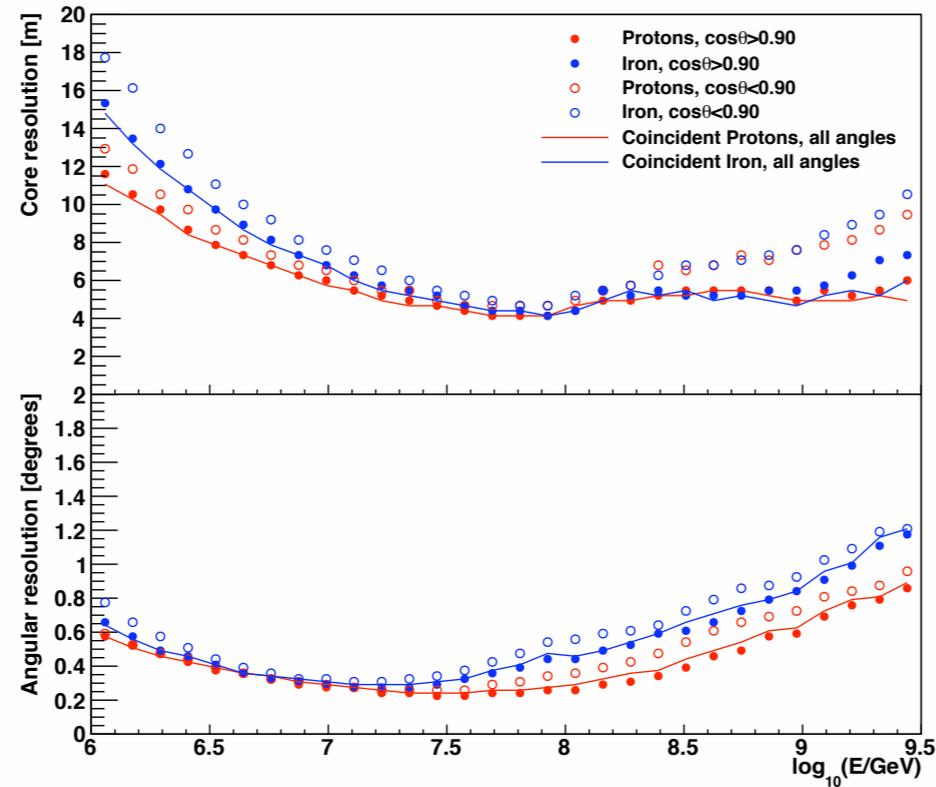
Wavefront timing:

$$t(\vec{x}) = t_0 + \frac{1}{c} (\vec{x} - \vec{x}_c) \cdot \vec{n} + \Delta t(r)$$

$$\Delta t(r) = ar^2 + b \left(1 - \exp\left(-\frac{r^2}{2\sigma^2}\right) \right)$$

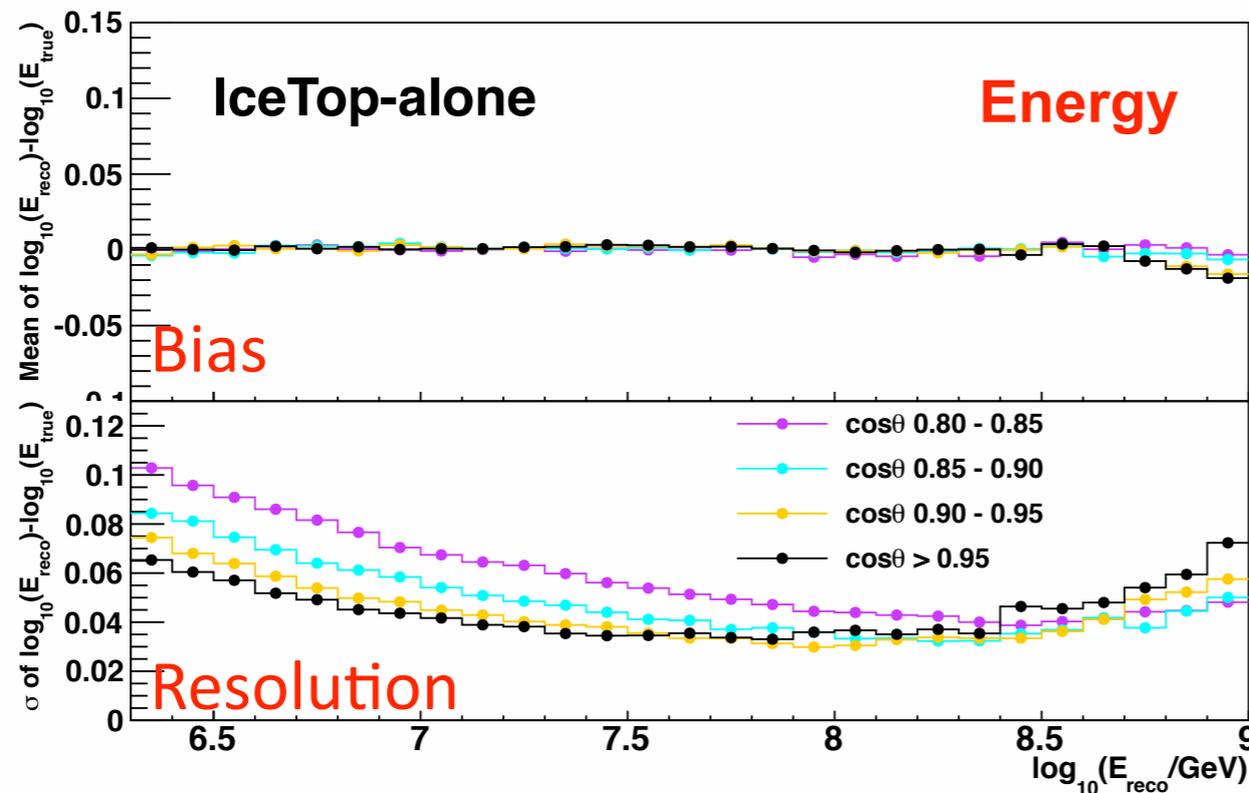
Reconstruction Performance

Typical resolutions; might differ slightly between analyses / event selections



Core position:
between 5 and 10 m

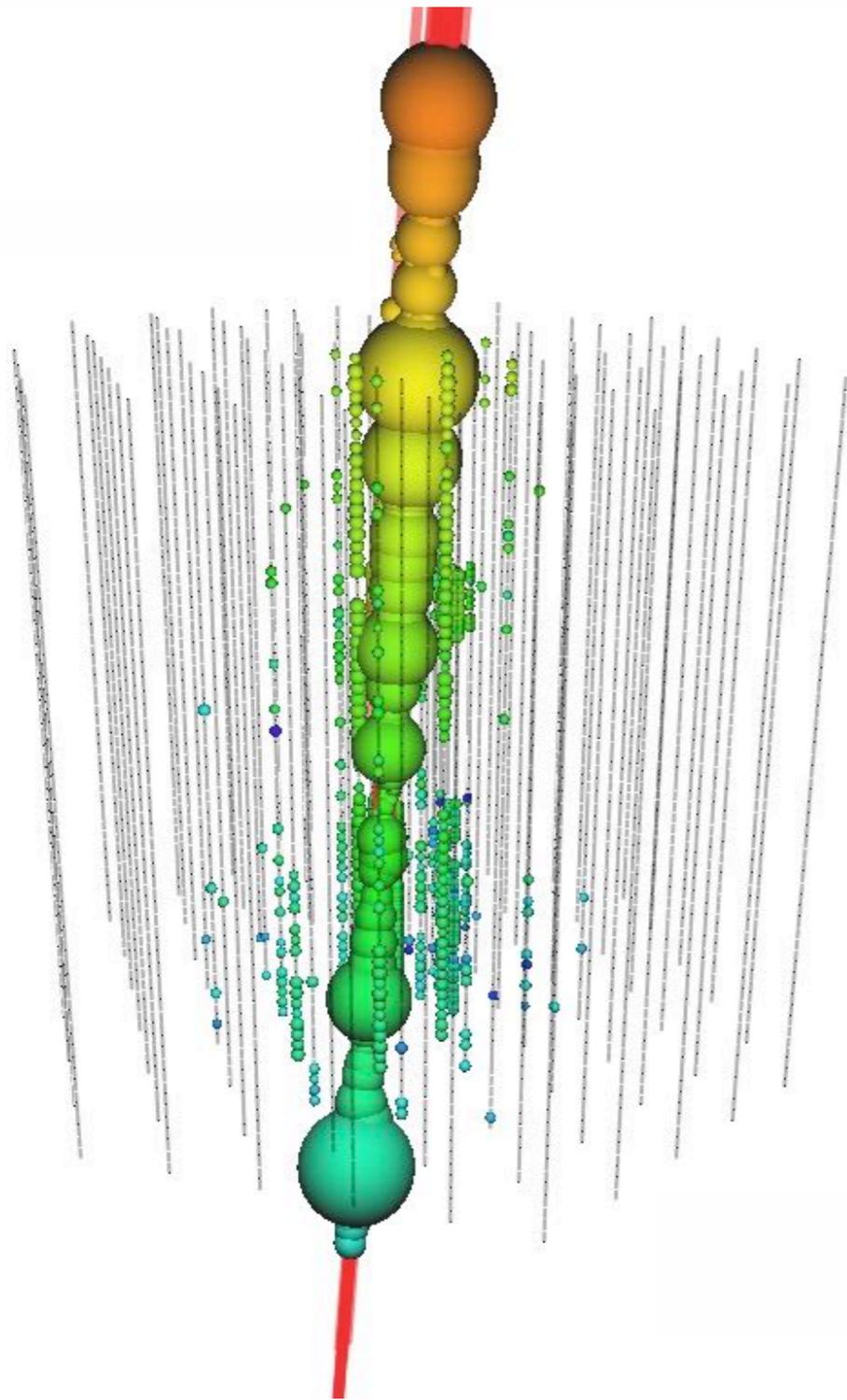
Direction:
better than 1°



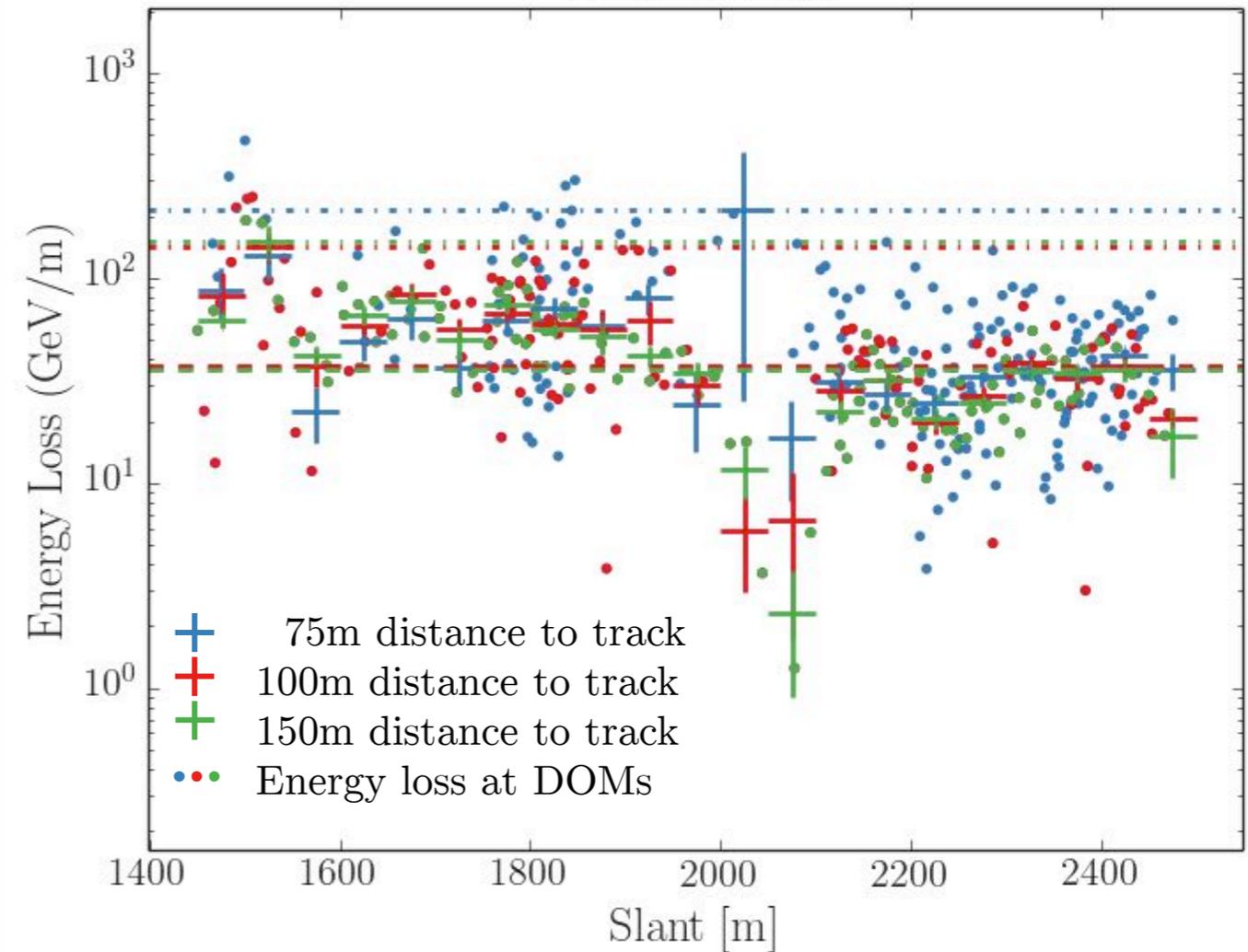
Bias near zero

Resolution best
between 10
and 300 PeV

Muon Bundle Reconstruction



Energy Loss Profile



- Reconstruct energy loss as function of slant depth
- Measure for the number of muons in bundle

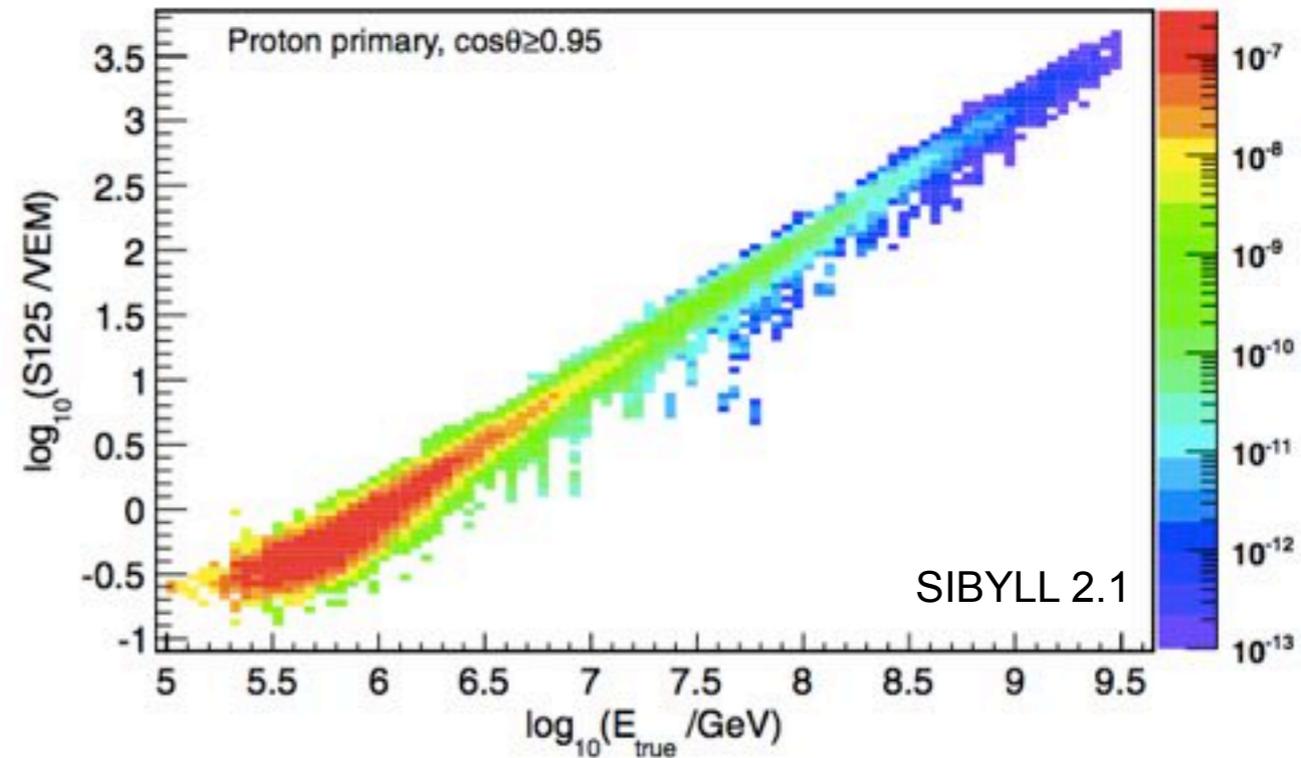
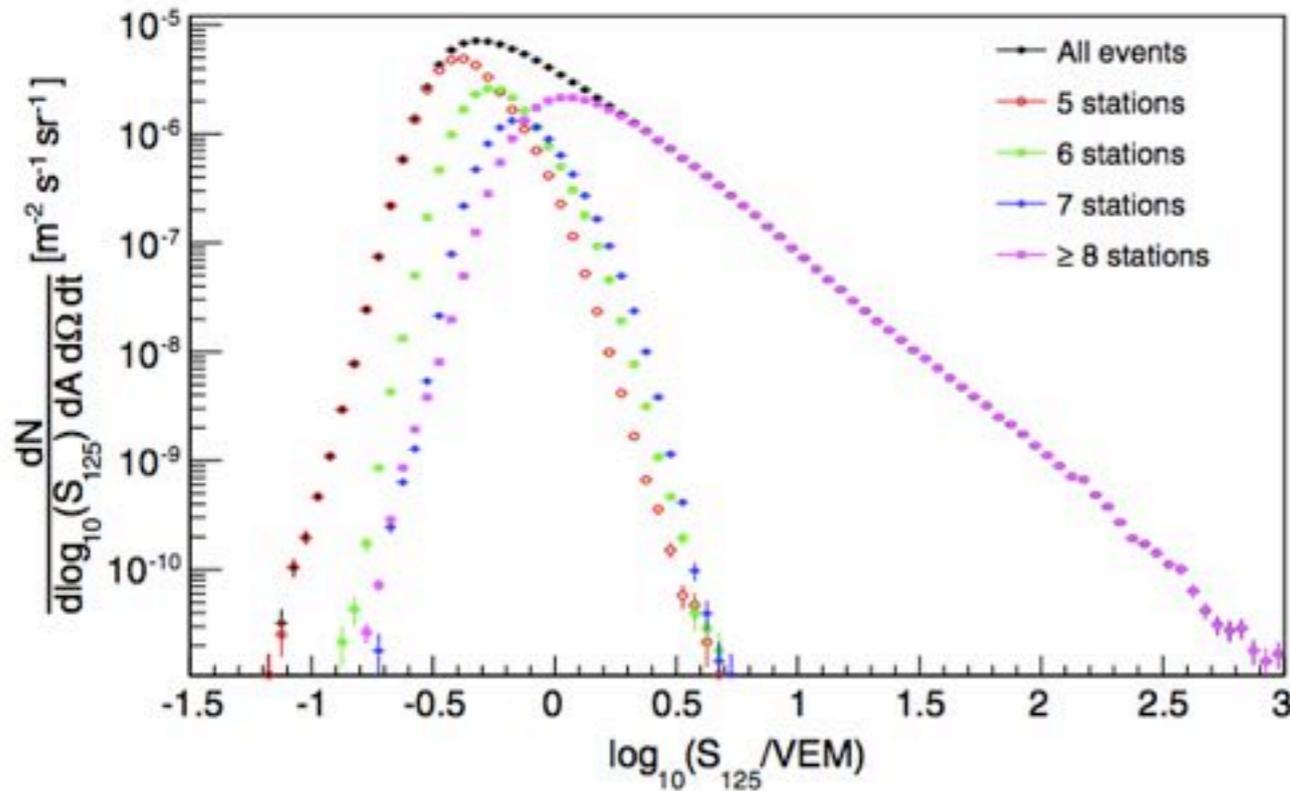
Results



Cosmic Ray Energy Spectrum

IceTop only: primary energy from shower size (number of particles) at ground level

Phys. Rev. D 88 (2013) 042004

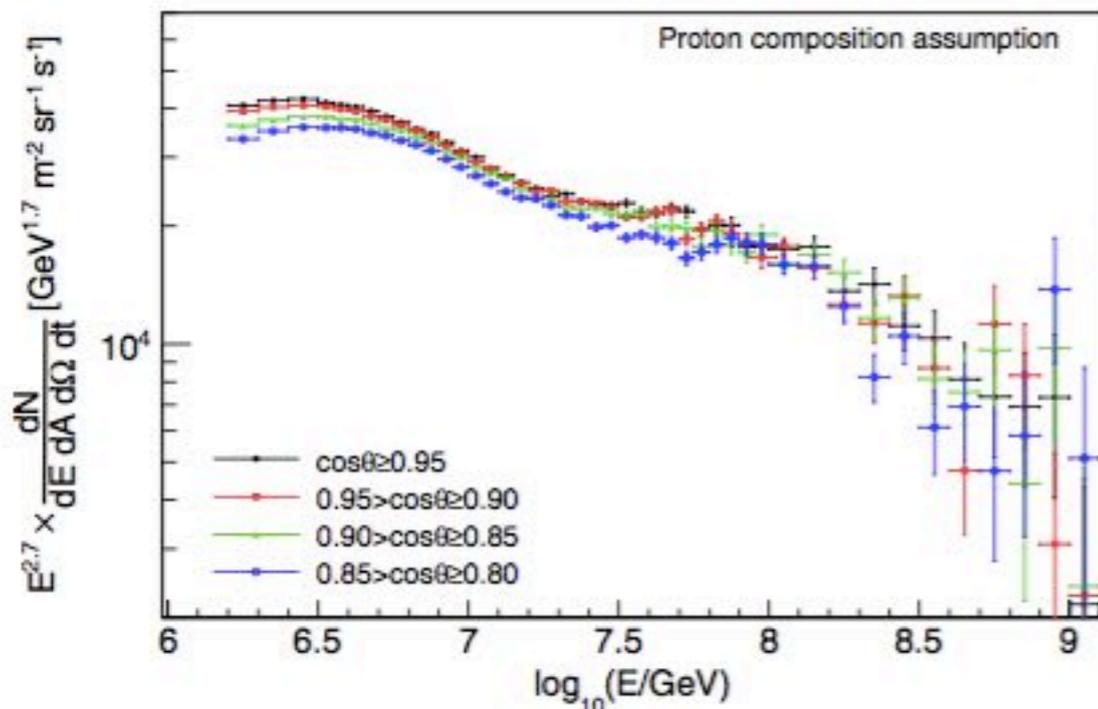


- Conversion from shower size to primary energy depends on zenith angle and composition assumption
- Zenith dependence can be used as cross check for composition assumption

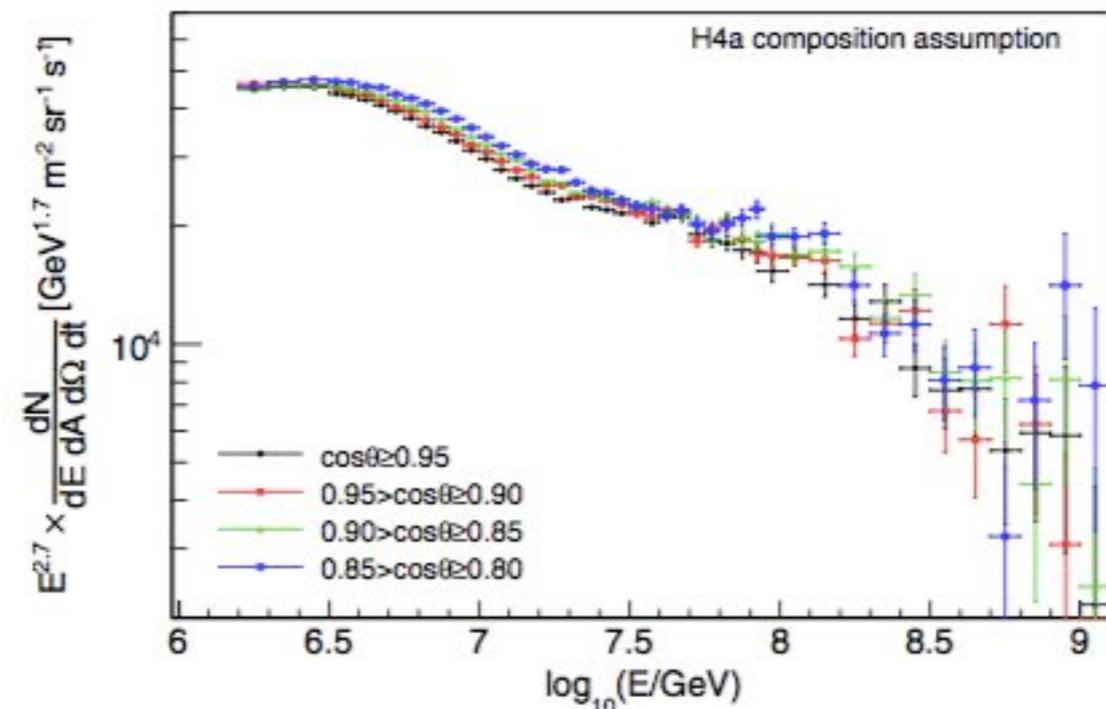


Zenith Dependence as Cross Check for Composition

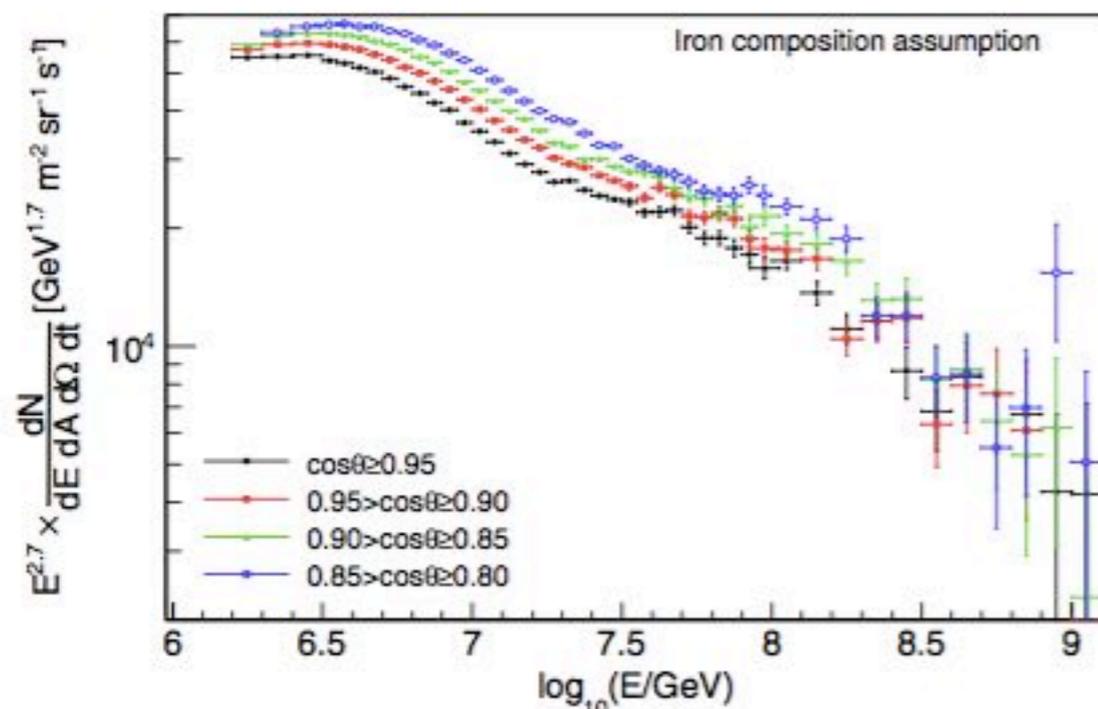
Phys. Rev. D 88 (2013) 042004



Pure Proton



H4a



Pure Iron

- > Energy spectrum expected to be the same for all zenith ranges
- > H4a^(*) model gives best agreement (of tested models)

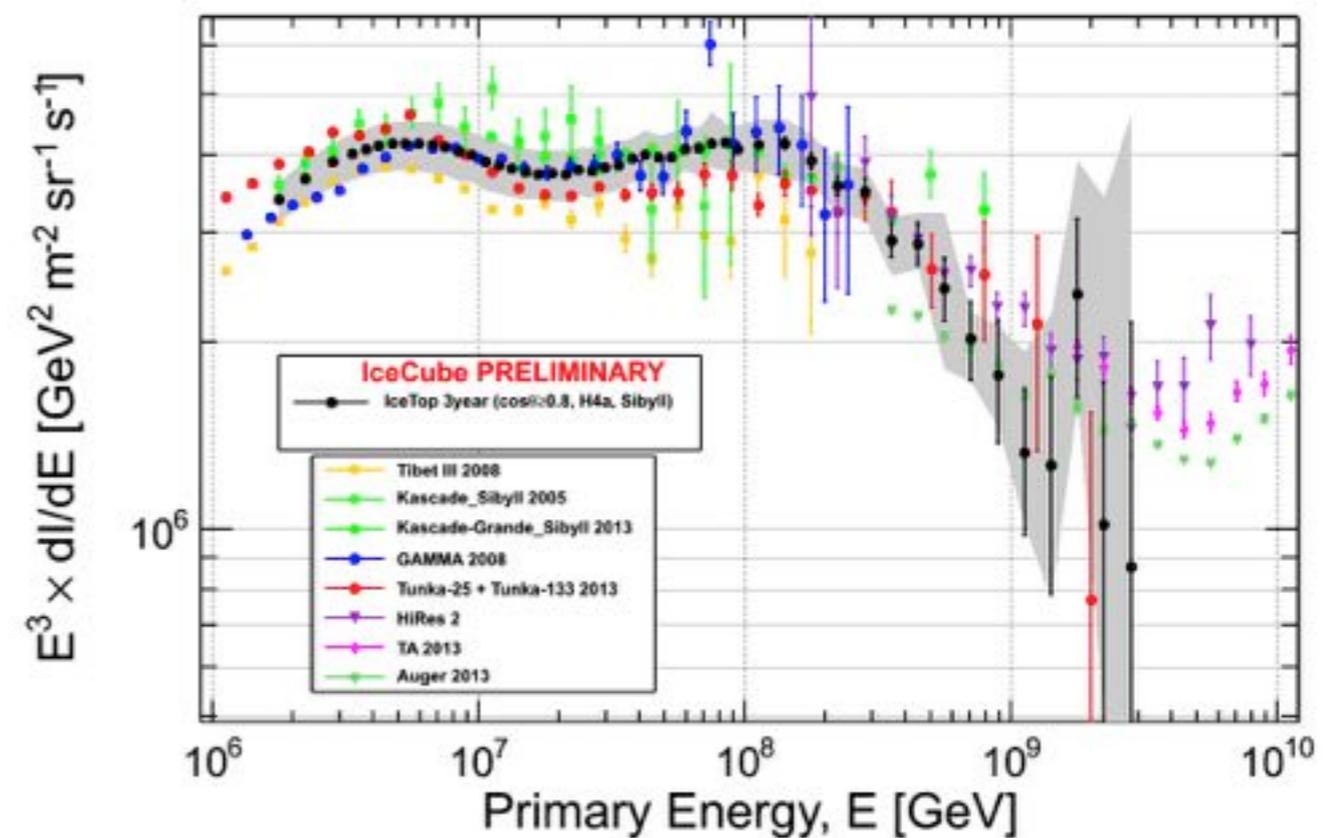
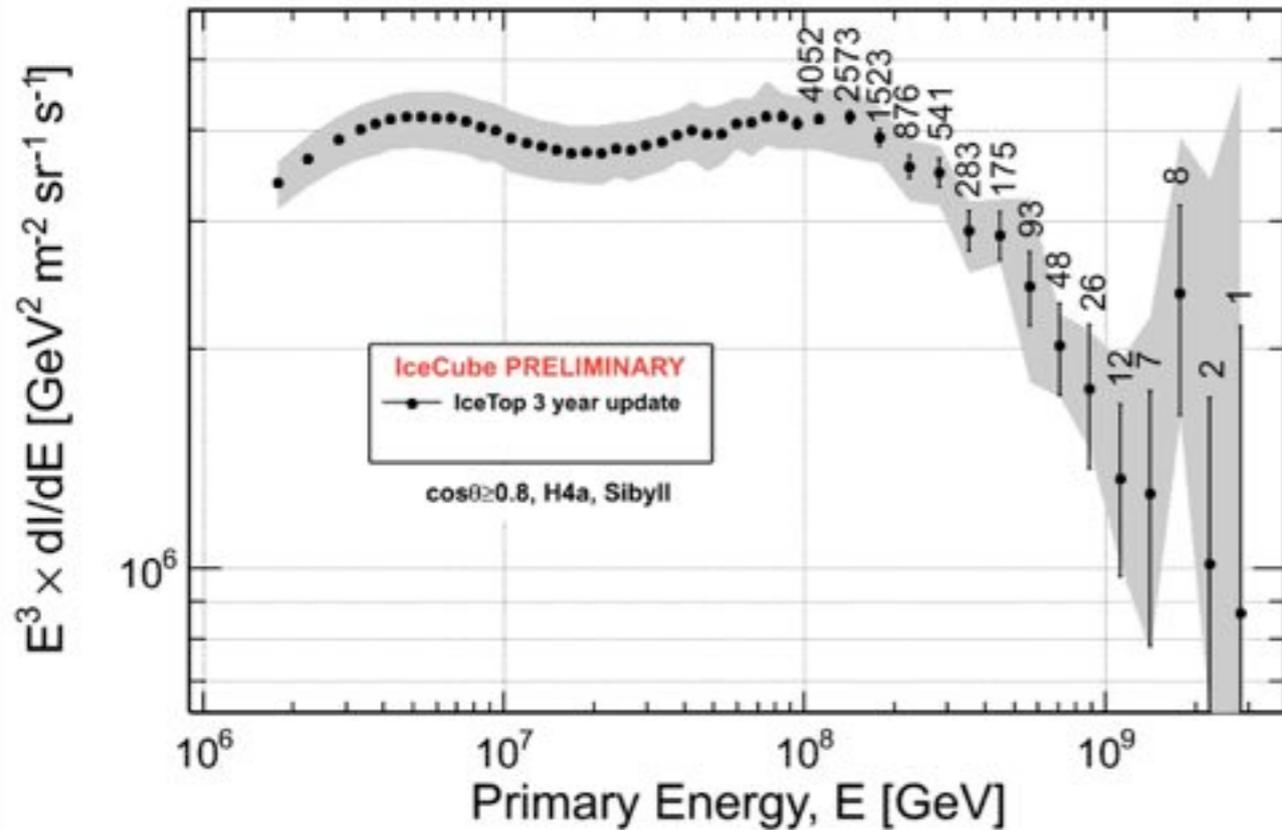
(*) Gaisser: *Astropart. Phys.* 35 (2012) 801



IceTop-only Energy Spectrum

Three years of data (2010 — 2012)

PoS(ICRC2015)334



Systematic uncertainties:

	3 PeV	30 PeV
VEM calibration	+4.0% - 4.2%	+5.3% - 5.3%
Snow	+4.6% - 3.6%	+6.3% - 4.9%
Interaction models	-4.4%	-2.0%
Composition ^a	±7.0%	±7.0%
Ground pressure	+2.3% - 2.0%	+0.4% - 1.0%

^aComposition uncertainty is not constant with energy but the largest value was chosen as a fixed, conservative estimate.

➤ CR energy spectrum does not follow a single power law

- Hardening at around 20 PeV, softening past 100 PeV
- Contribution of different source populations?

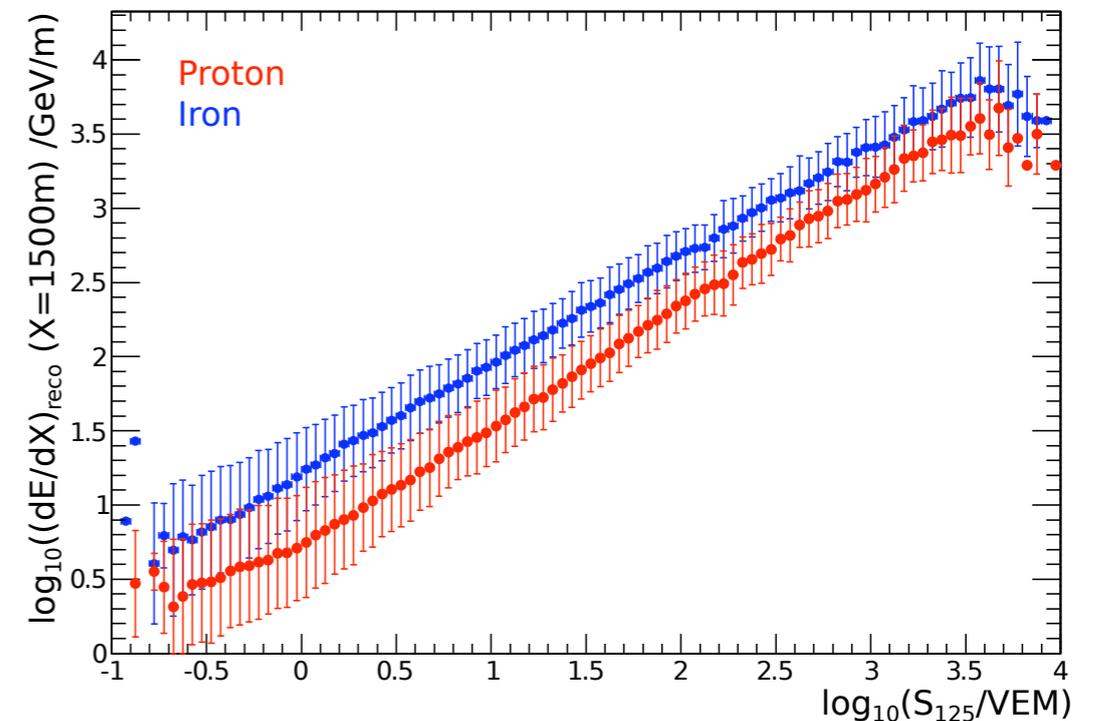
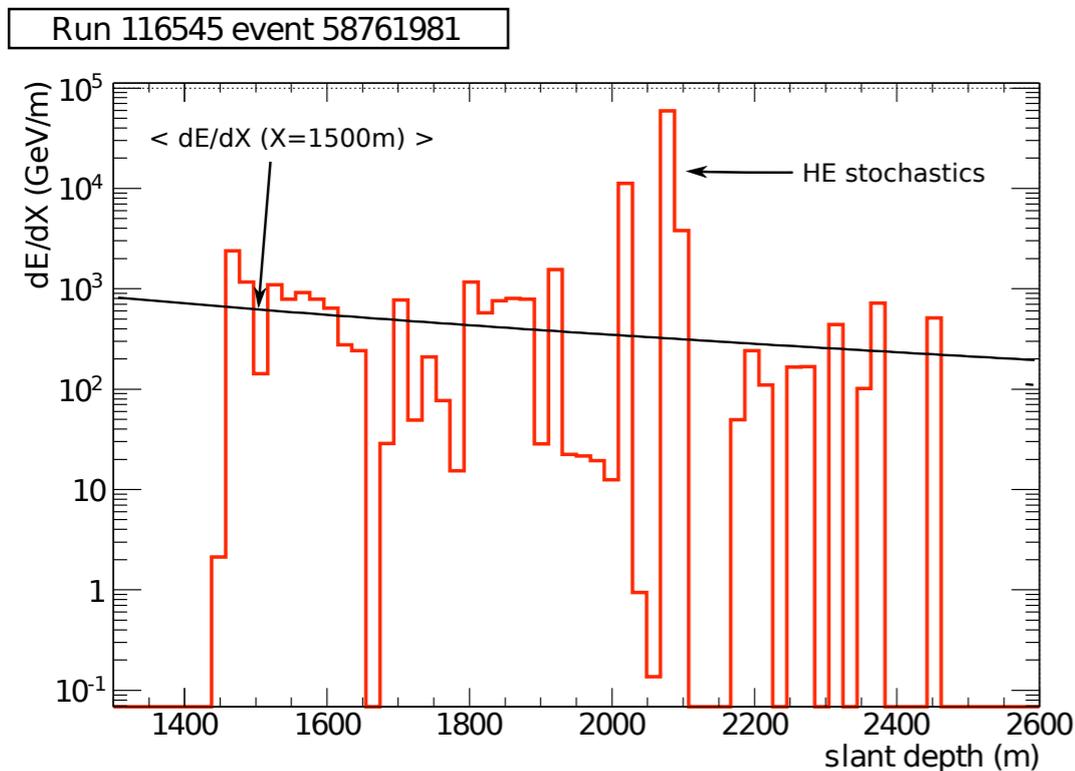
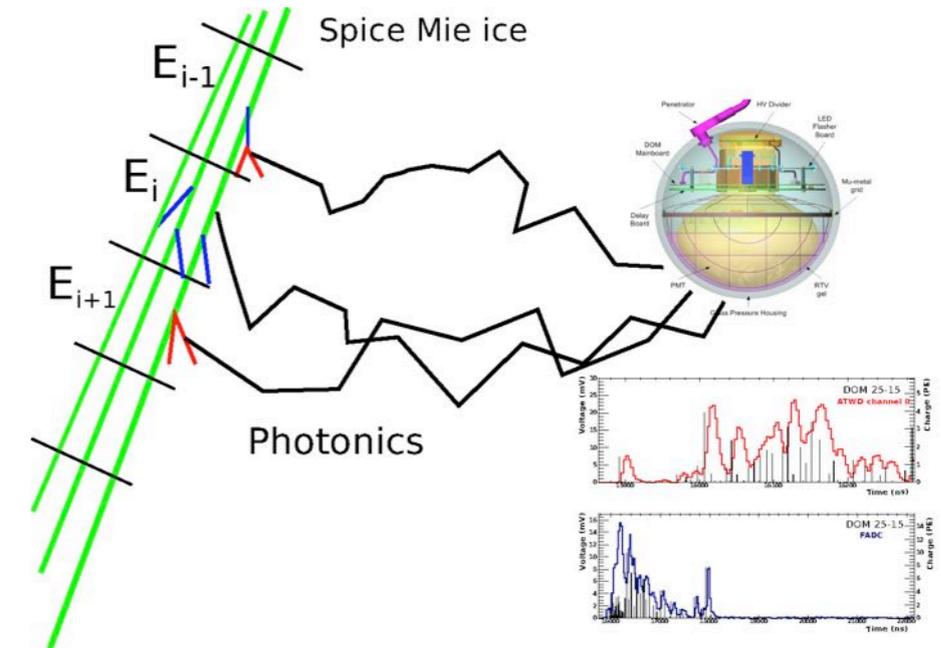


Cosmic Ray Composition

Coincident analysis with deep-ice detector: number of high energy muons as measure for mass number A

> Unfolding the energy loss pattern

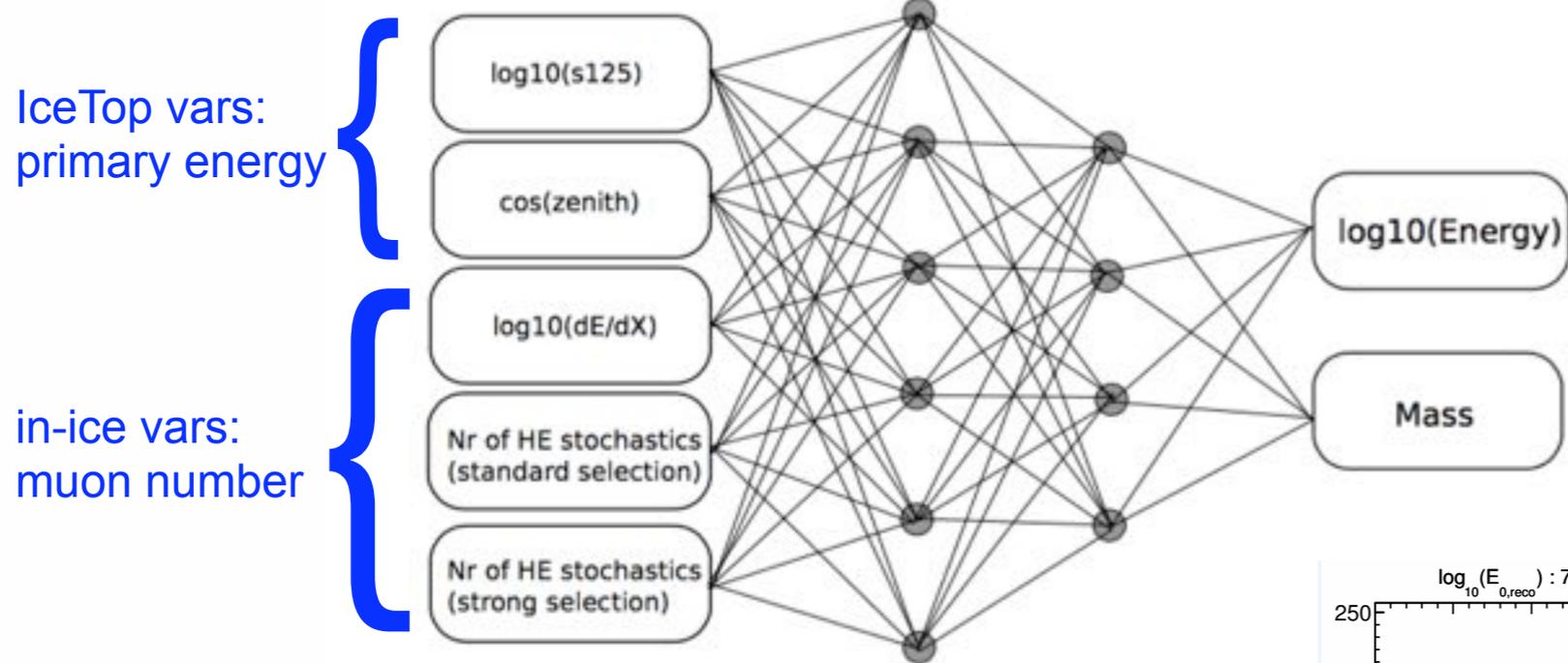
- Muon bundle energy loss depends on number of muons
- Stochastic behavior: count number of peaks above some threshold (2 selection procedures)



Composition sensitive variable: dE/dx at 1500 m slant depth

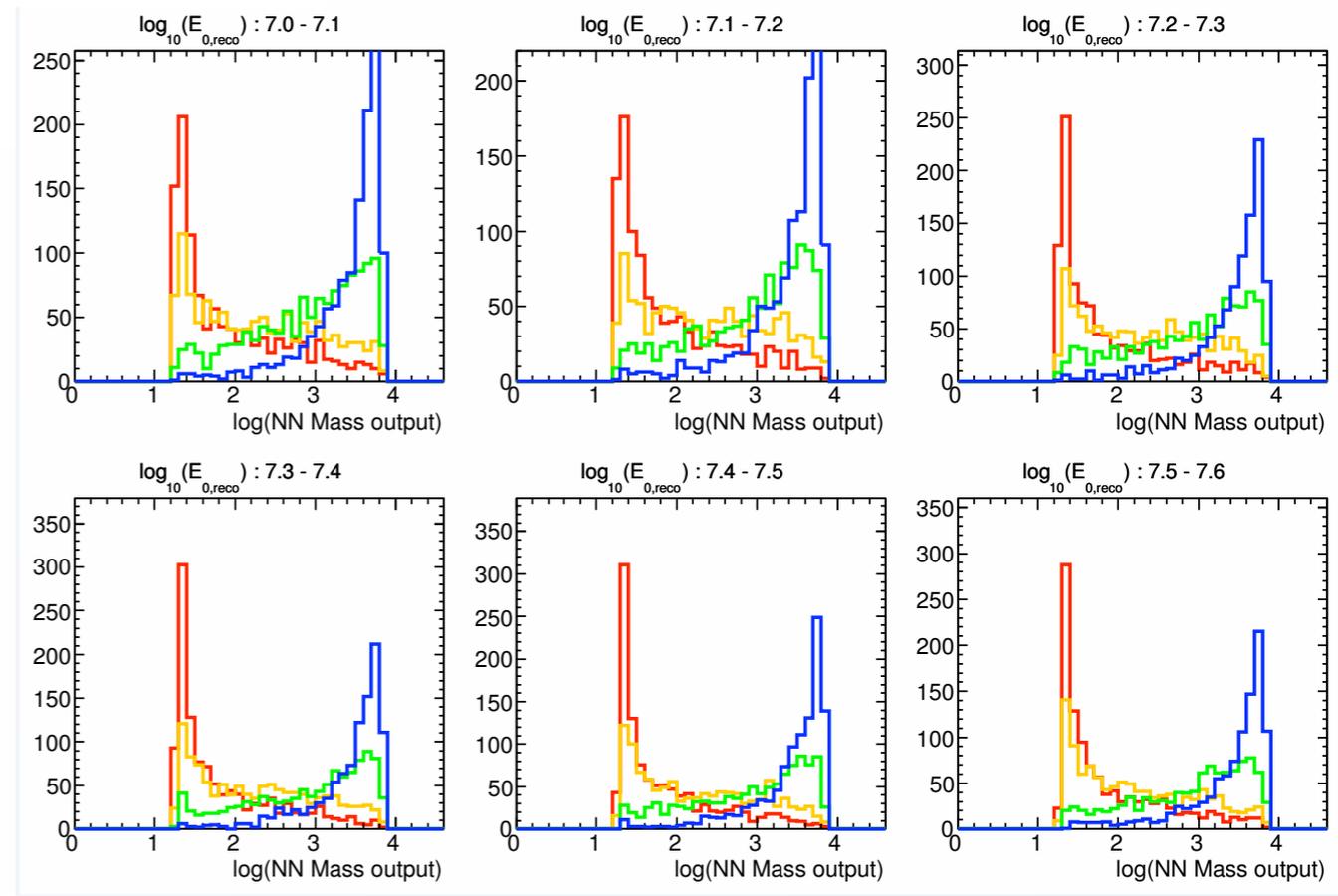


Analysis Using a Neural Network



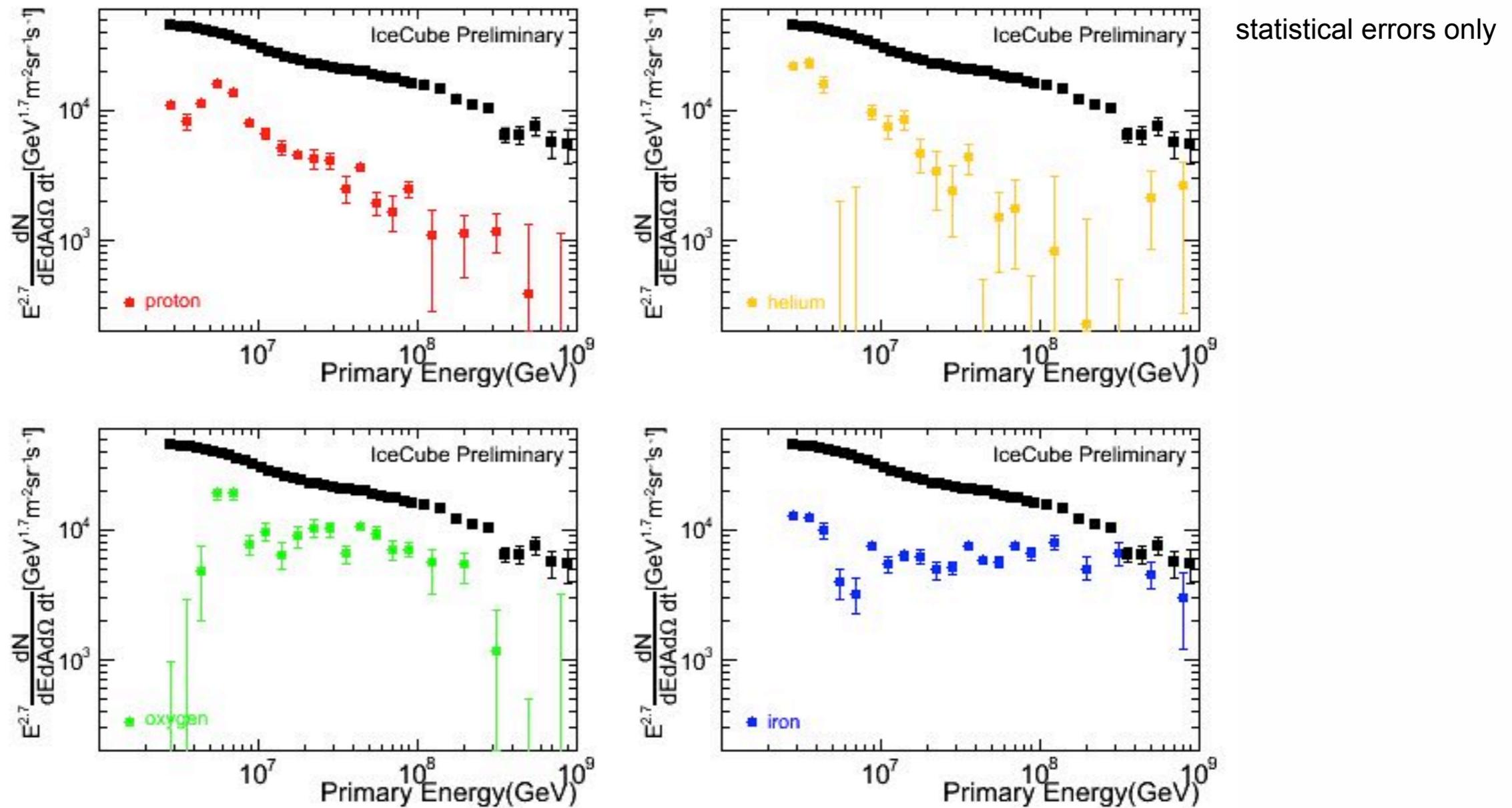
- > Train neural network on Monte Carlo data (four mass groups: p, He, O, Fe)
- > Derive MC templates for mass groups in each energy bin
- > Process data with same NN and fit templates to data output

Templates:



Spectra for Individual Mass Groups (p, He, O, Fe)

Three years of data (2010 — 2012)



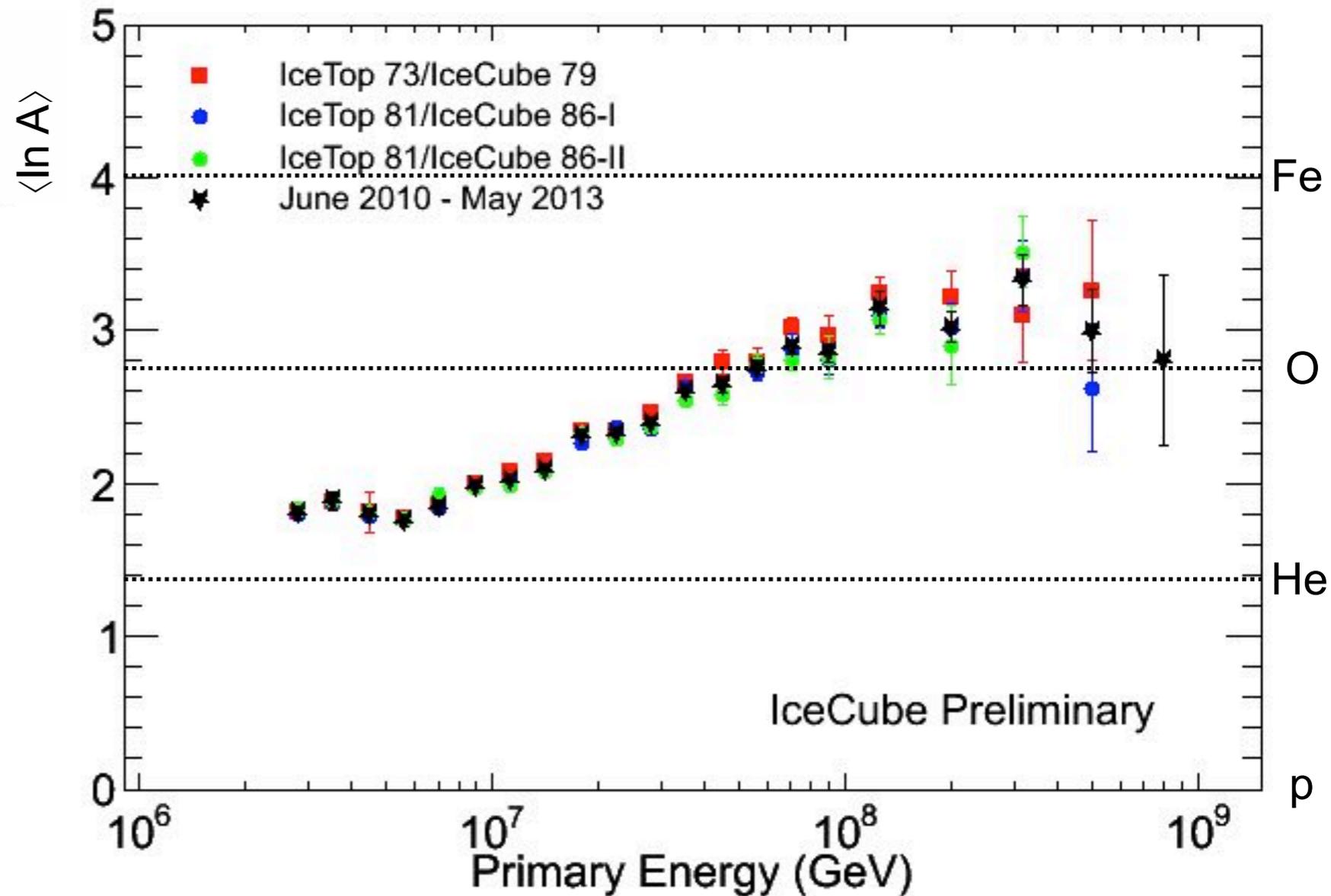
- Proton and helium turning down steeply at lower energies
- Oxygen and iron maintain harder spectrum up to higher energies



Mean Mass and Systematic Uncertainties

Three years of data (2010 — 2012)

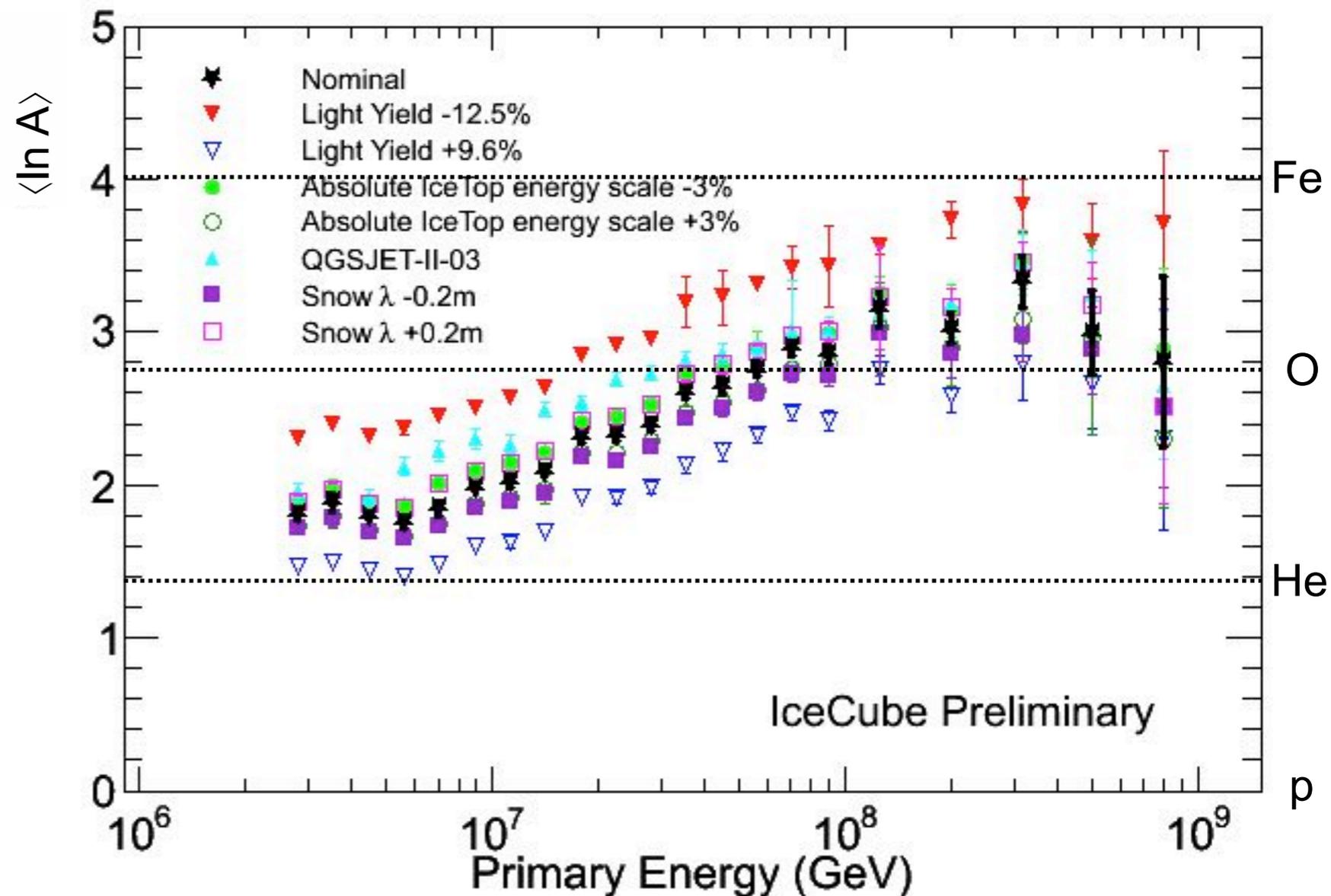
> Consistent results in each year



Mean Mass and Systematic Uncertainties

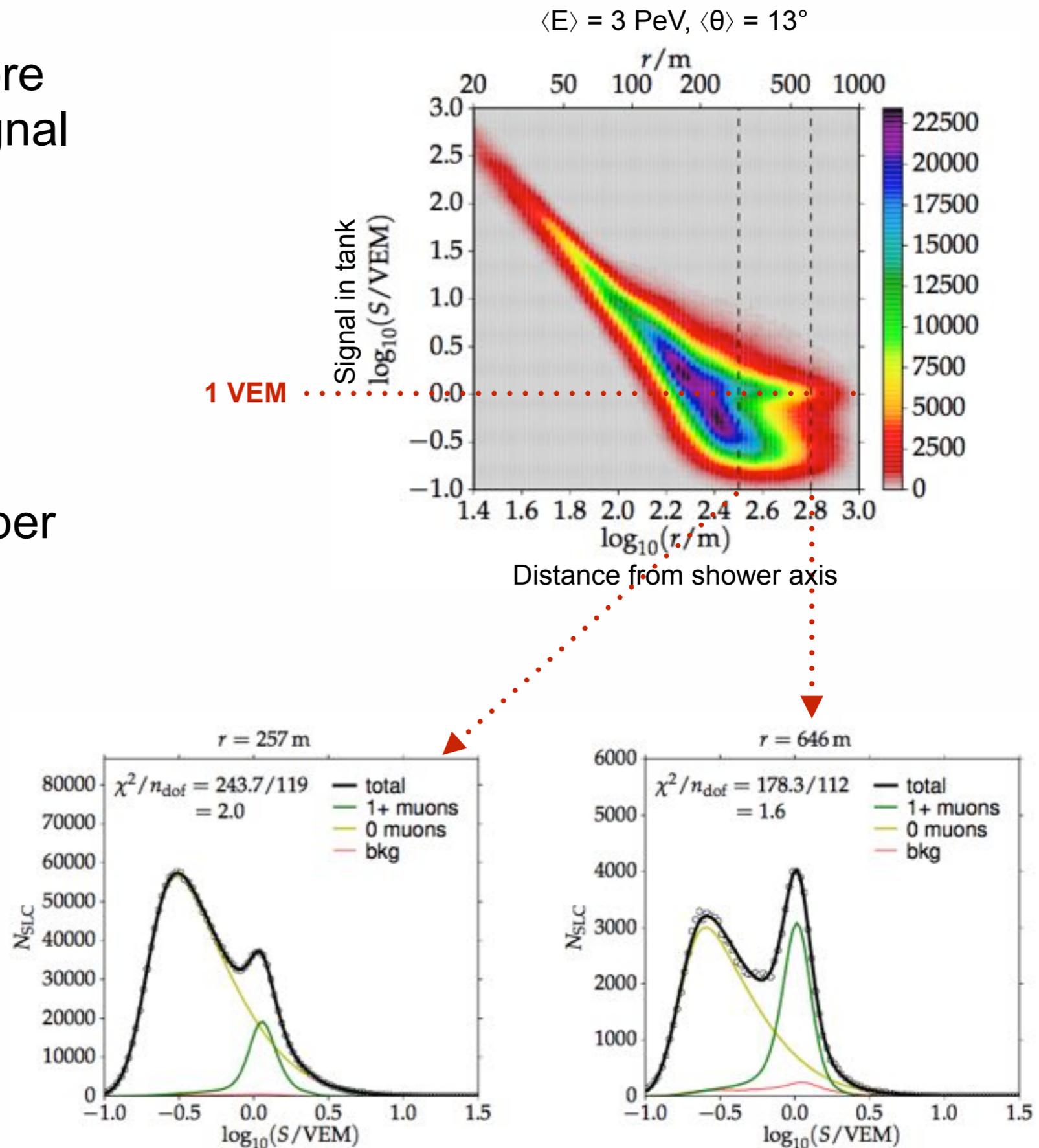
Three years of data (2010 — 2012)

- Consistent results in each year
- Dominant systematic uncertainties:
 - Light yield: optical properties (scattering, absorption) of the Antarctic ice
 - Hadronic interaction model

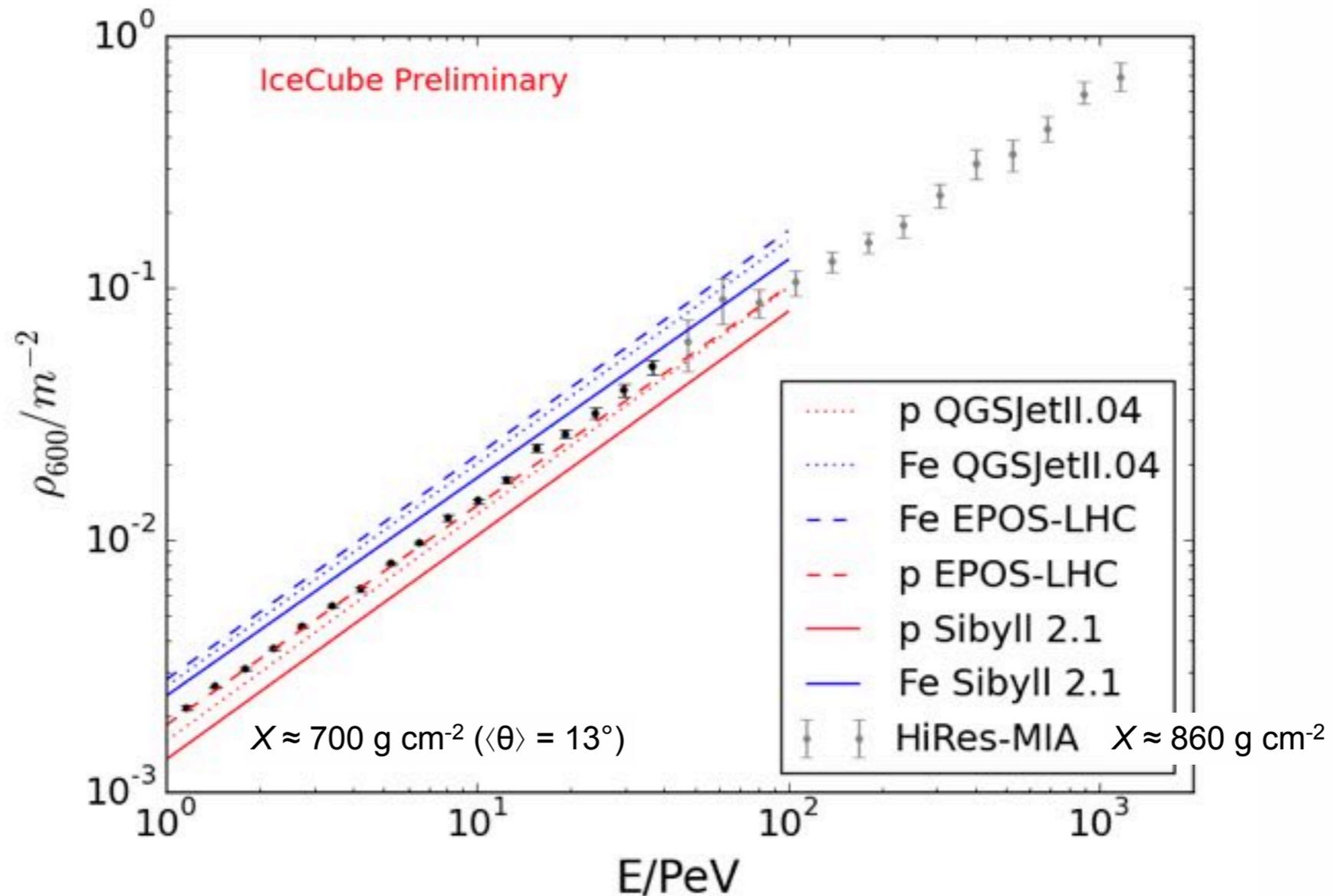


GeV Muons on the Surface

- At large distance from the core muons dominate the tank signal
- Trigger threshold of tanks:
~ 1/6 VEM
- Determine mean muon number from fit to charge distribution (fixed radius, E_{CR} , θ)
- Measurement independent of air shower simulation!

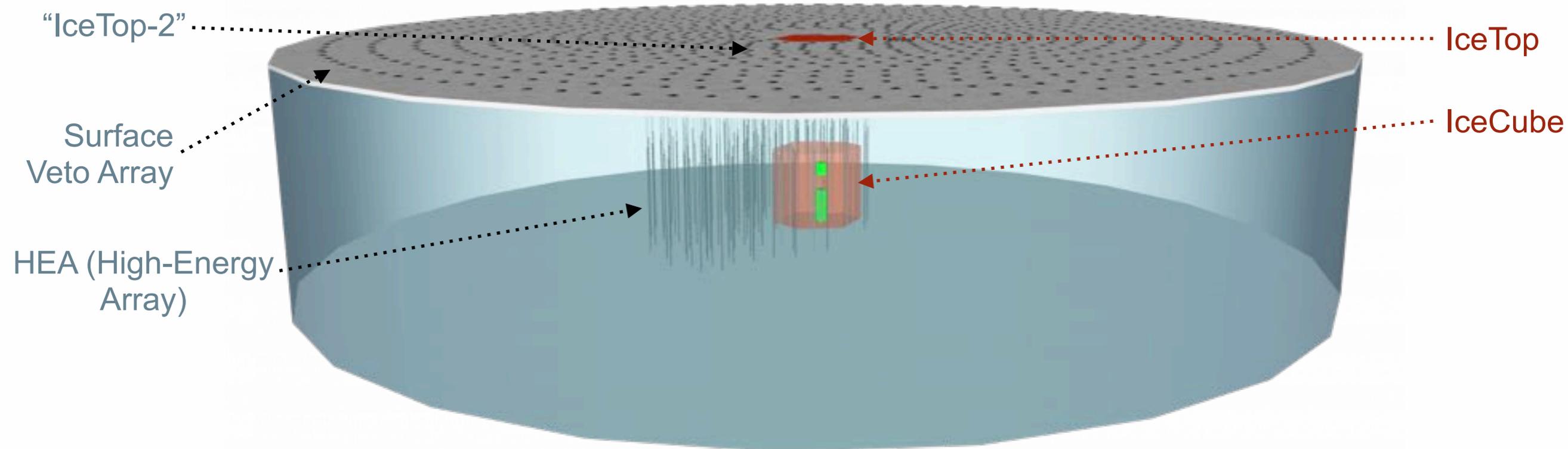


GeV Muons on the Surface



- Muon density 600 m from shower core
- Air shower simulations for reference
- Will improve composition measurements in the future

Cosmic Ray Physics with IceCube-Gen2



- > 10 km³ in-ice array with 10 km² "IceTop-2" cosmic-ray array on top
 - Increase accessible cosmic-ray energy range by factor 3
 - Increase coincident events by factor 50 (due to increased zenith range)
- > Surrounded by ≈ 75 km² veto (less sophisticated air shower detectors)
 - Enable lateral muon distribution measurements for every event

Summary and Conclusions

- > The IceCube Observatory can simultaneously measure EM component, GeV surface muons, and TeV muon bundle
 - Will help to test cosmic-ray composition **and** hadronic interaction models
- > All particle spectrum and composition from the knee to 1 EeV
 - Changes of spectral index at 20 PeV and ~ 100 PeV
 - Heavy composition at high energies observed
- > Muon density at 600 m measured between up to 40 PeV
 - Independent test of composition / hadronic interaction models





The IceCube Collaboration



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)

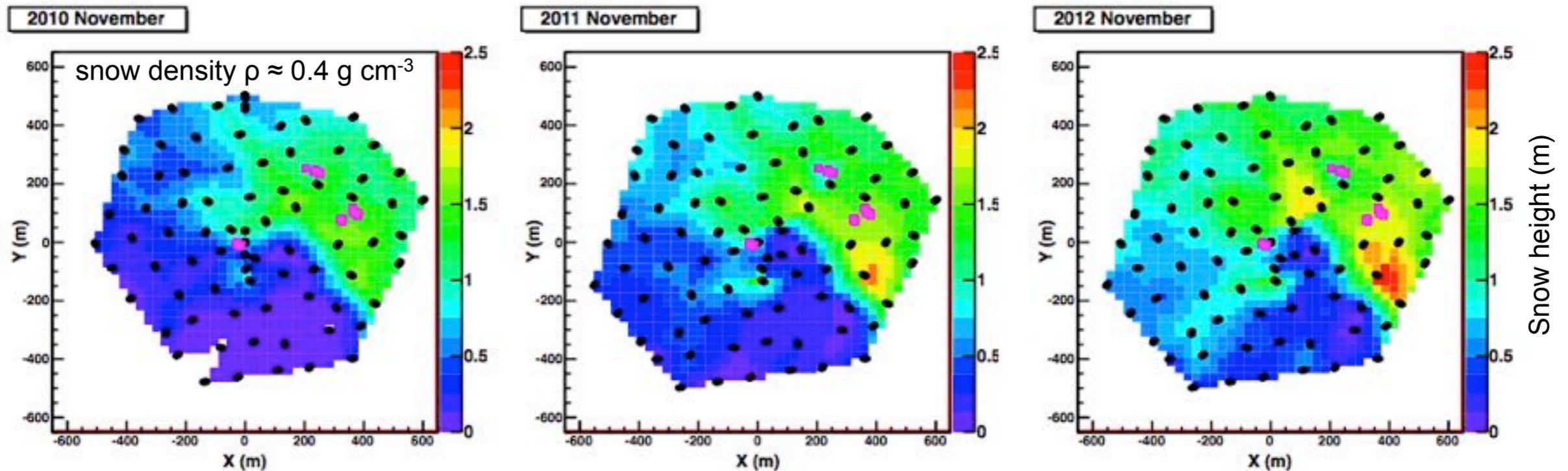
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

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

Backup Slides

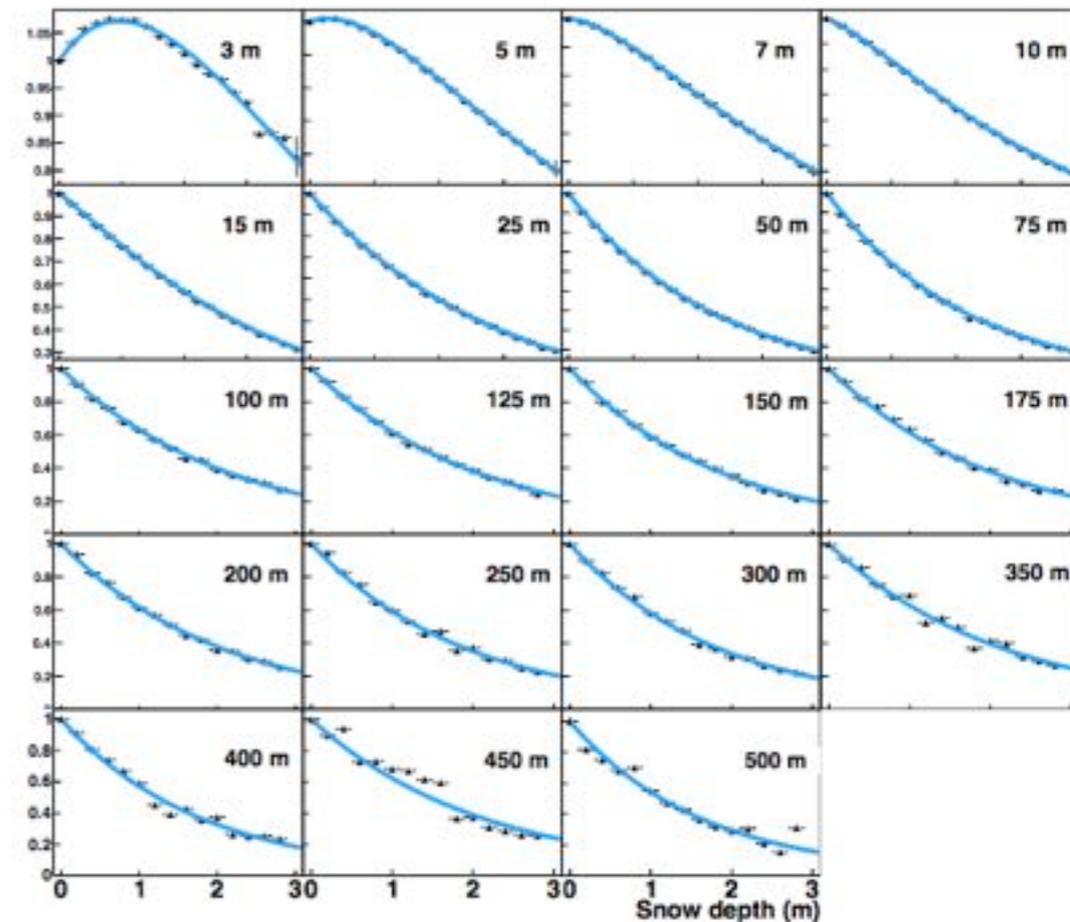


IceTop and the Snow



- Snow is largest detector-related systematic uncertainty in IceTop
- Snow height on each tank measured twice per year
- Signal attenuation different for muons and e.m. particles
 - Signal becomes more muon dominated
 - ➔ Simple exponential snow correction not sufficient

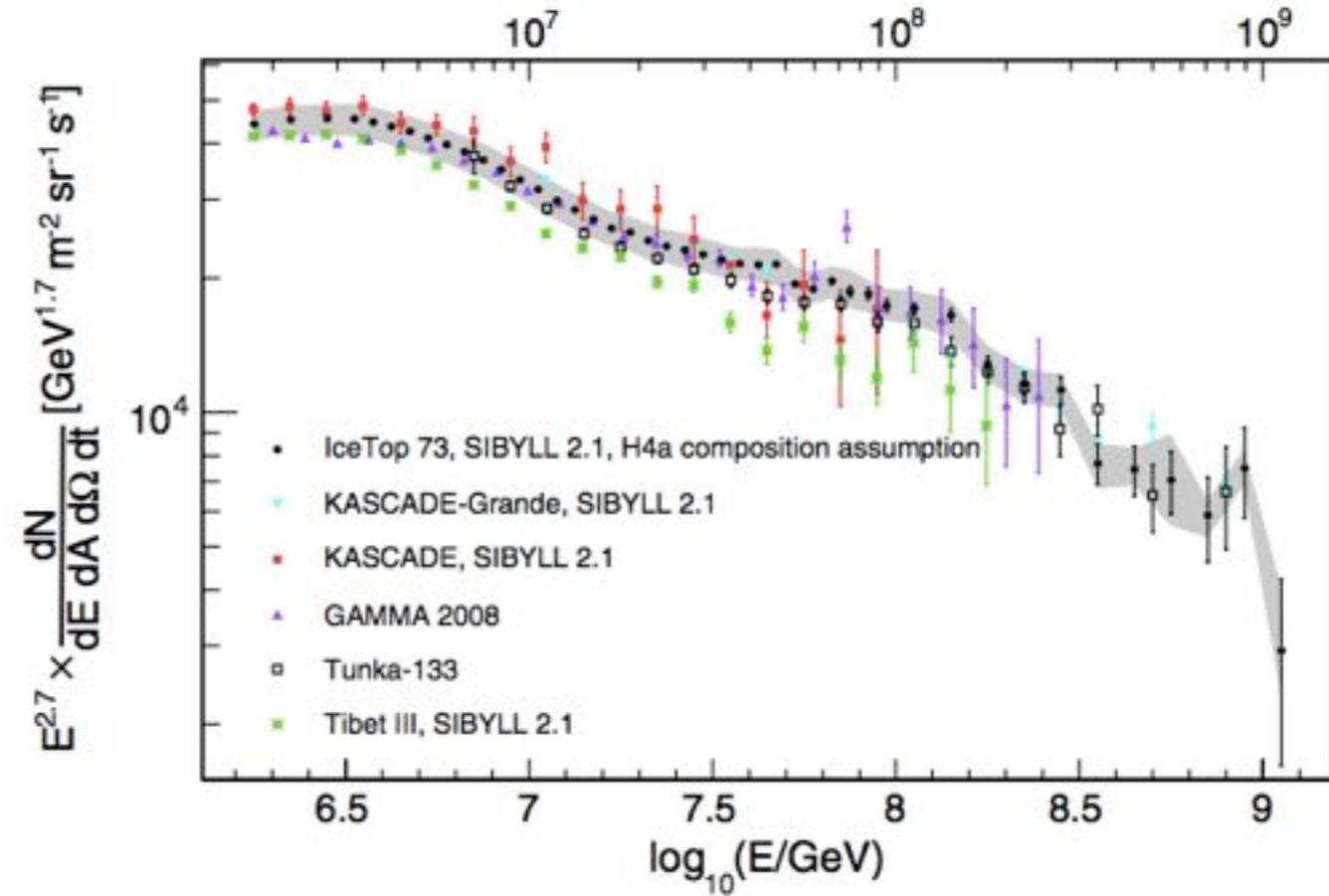
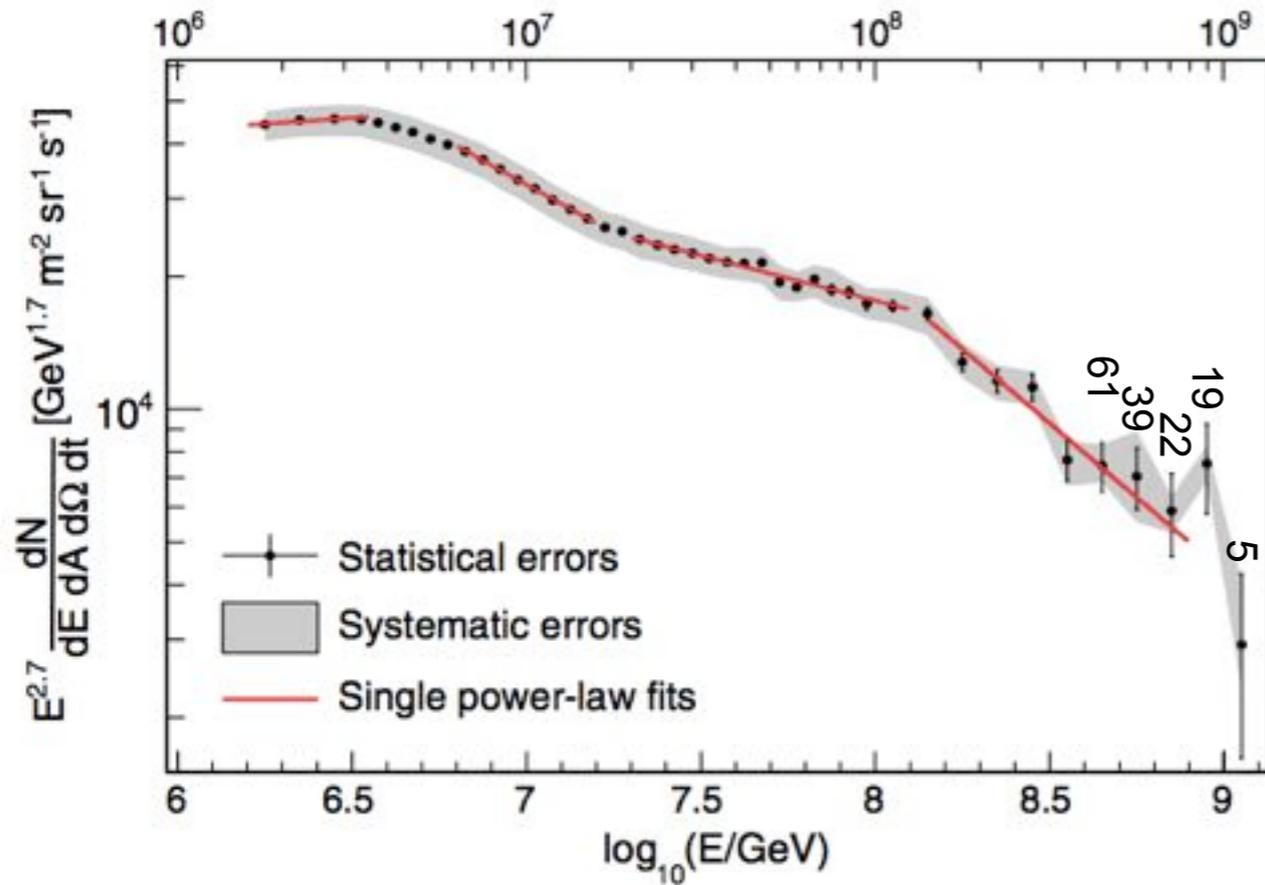
Approach: Parameterize MC simulations



IceTop-only Energy Spectrum

One year of data (IT-73)

Phys. Rev. D 88 (2013) 042004



Systematic uncertainties:

	3 PeV	30 PeV
VEM calibration	+4.0% - 4.2%	+5.3% - 5.3%
Snow	+4.6% - 3.6%	+6.3% - 4.9%
Interaction models	-4.4%	-2.0%
Composition ^a	±7.0%	±7.0%
Ground pressure	+2.3% - 2.0%	+0.4% - 1.0%

^aComposition uncertainty is not constant with energy but the largest value was chosen as a fixed, conservative estimate.

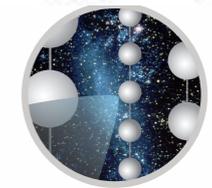
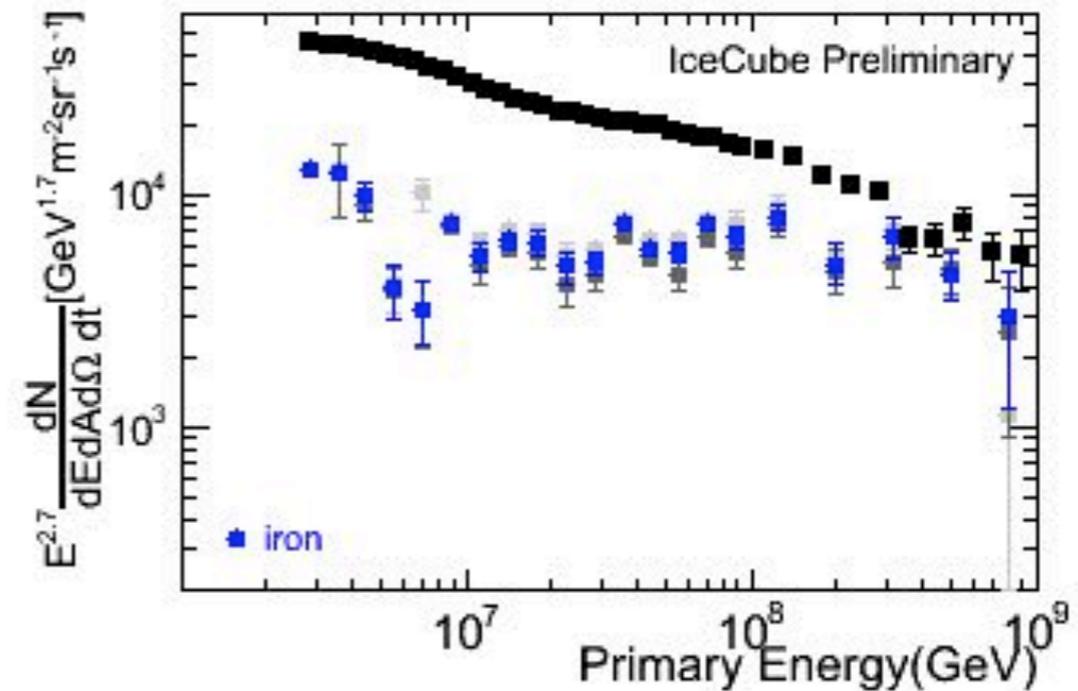
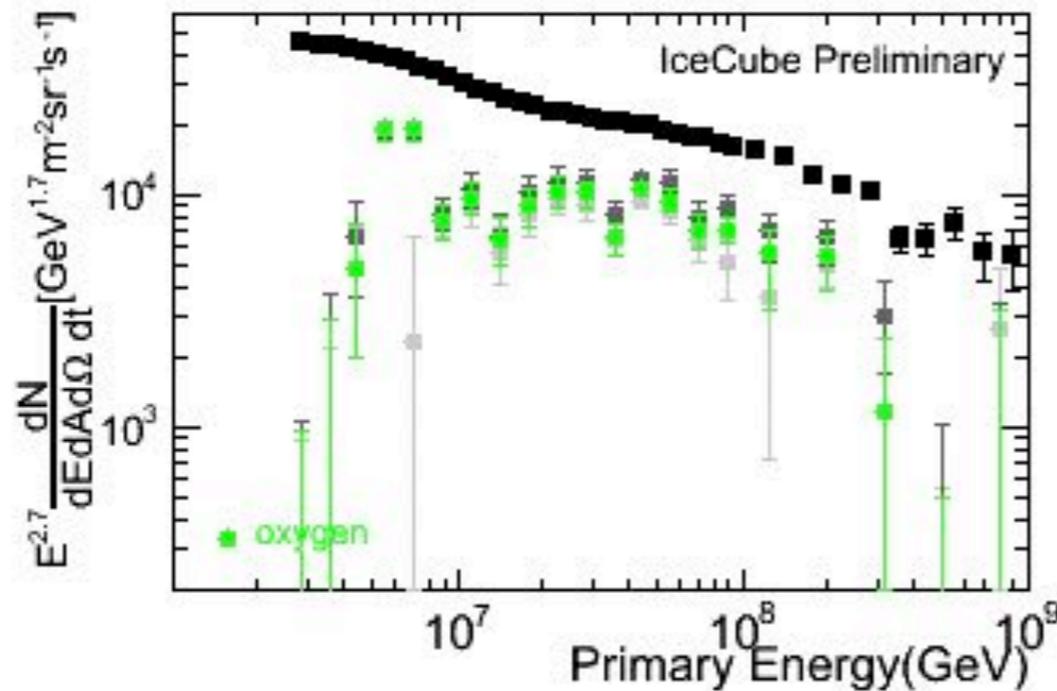
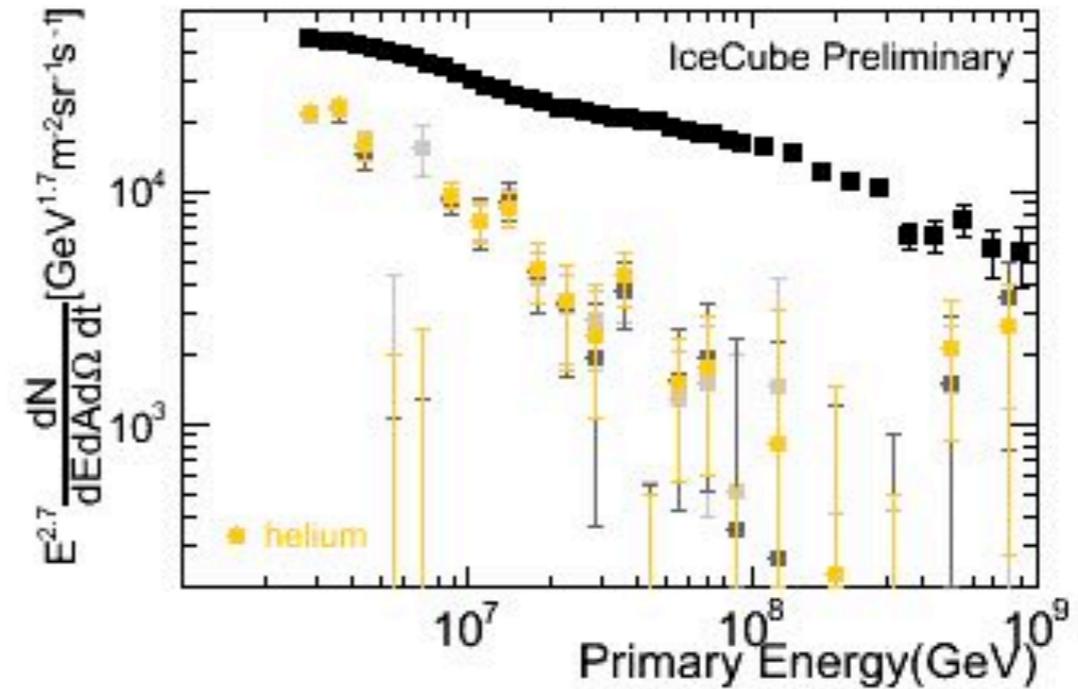
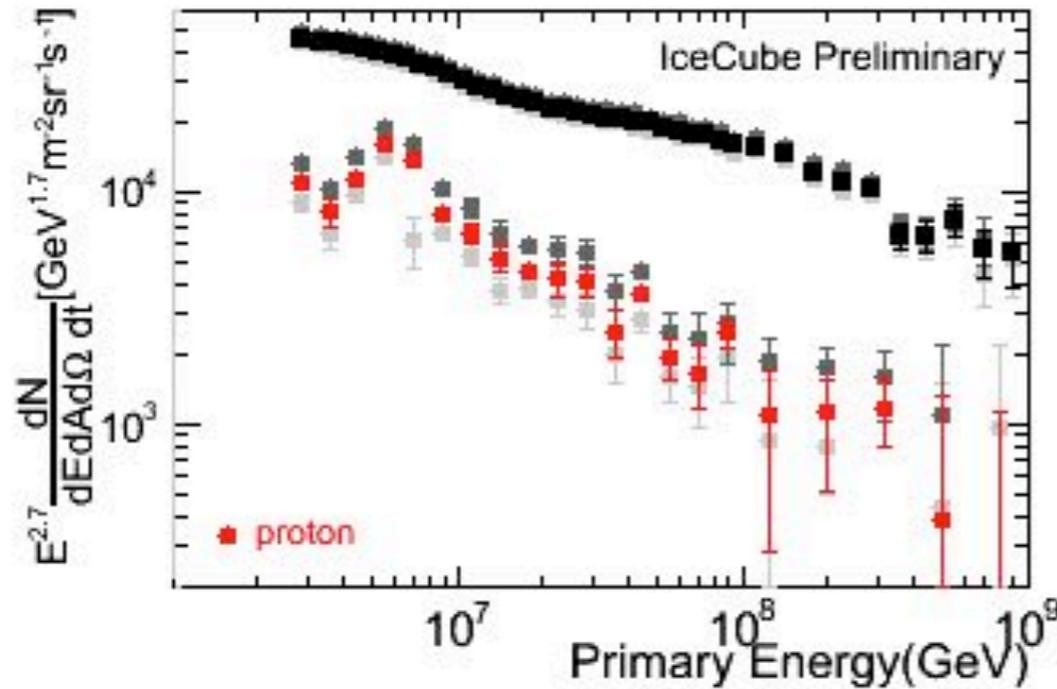
➤ CR energy spectrum does not follow a single power law

- Hardening at around 20 PeV, softening past 100 PeV
- Contribution of different source populations?



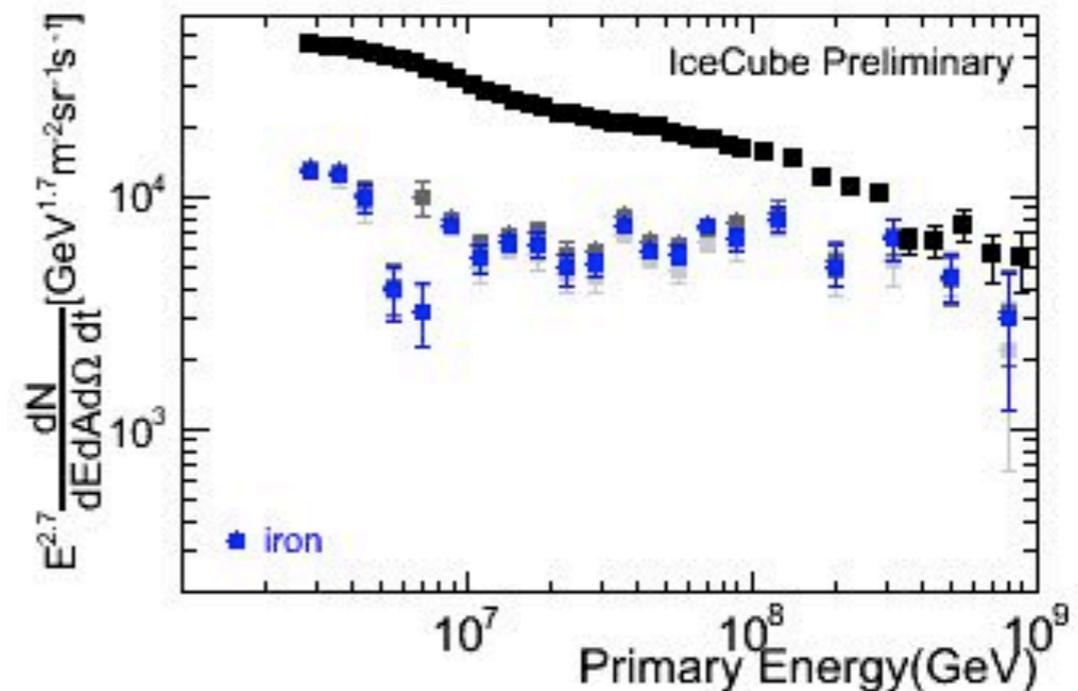
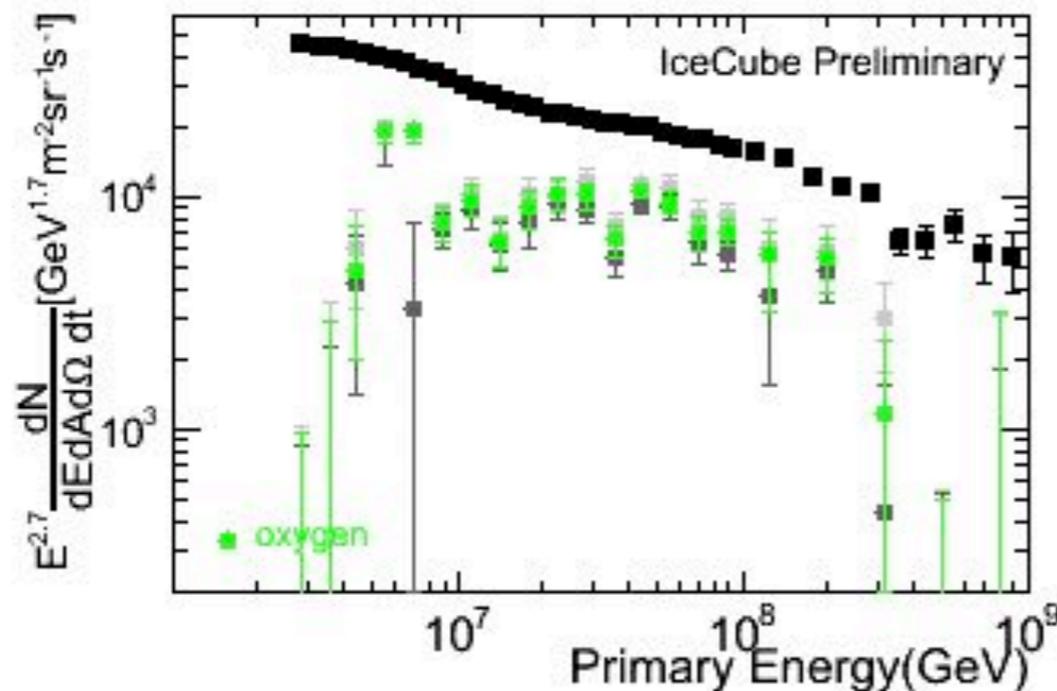
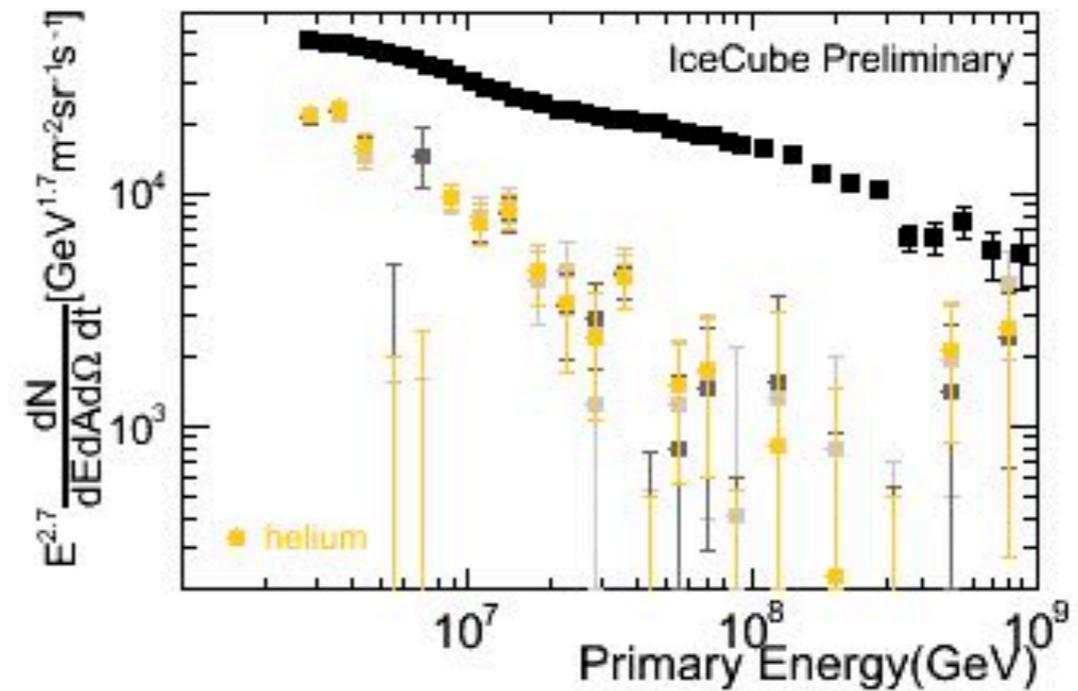
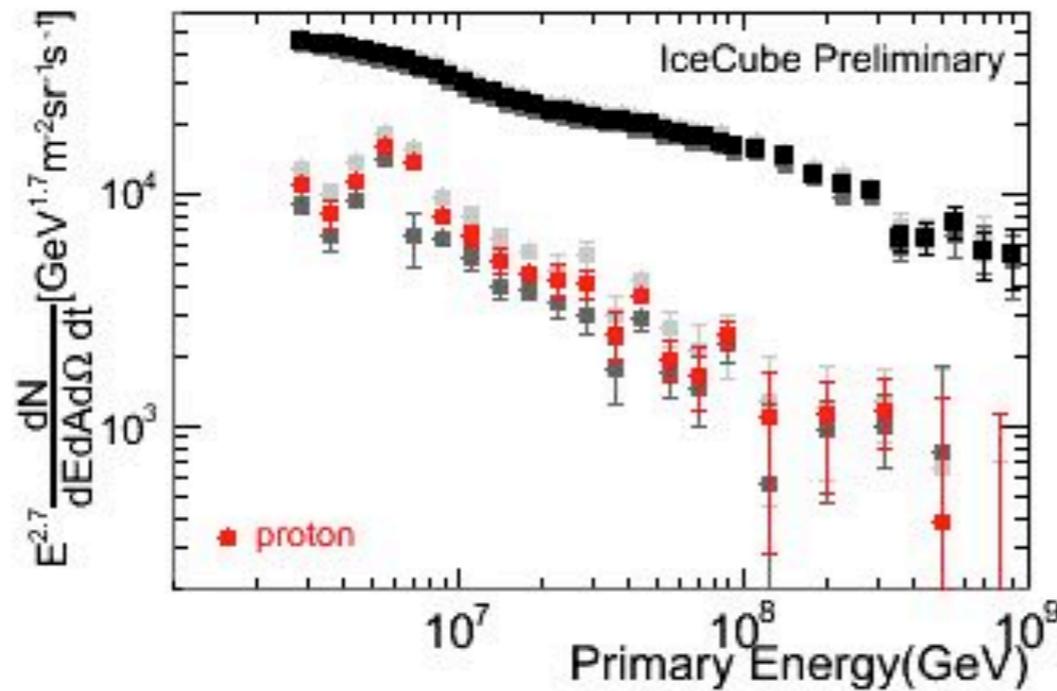
Elemental Spectra: Snow Correction Uncertainty

dark gray: -0.2 m, light gray: +0.2 m



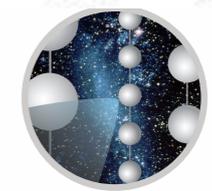
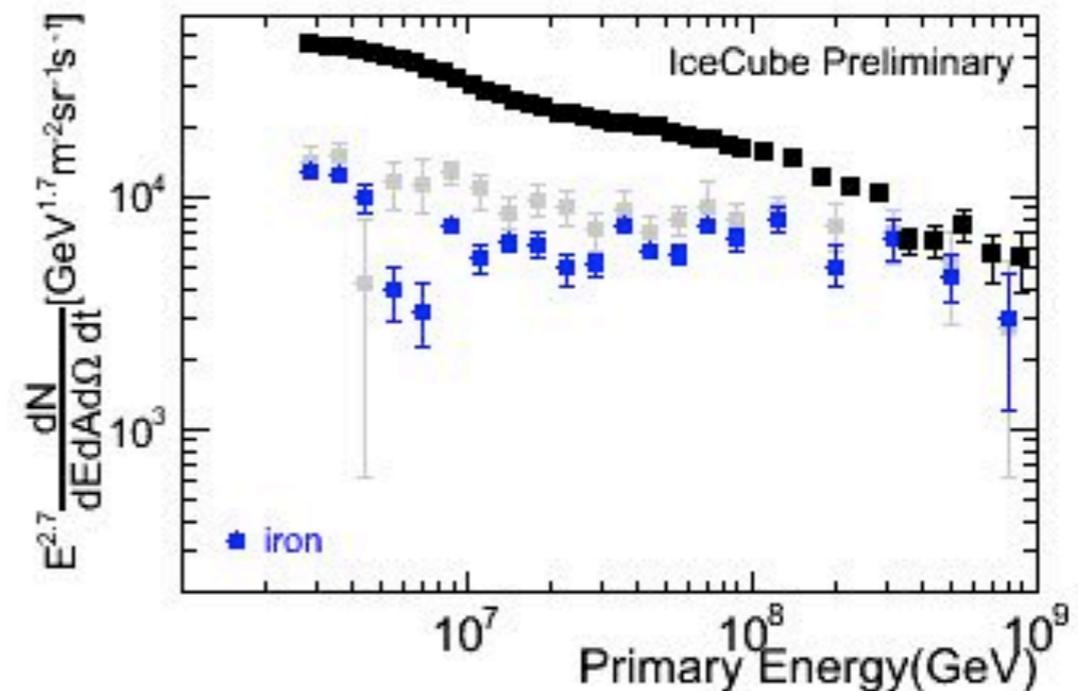
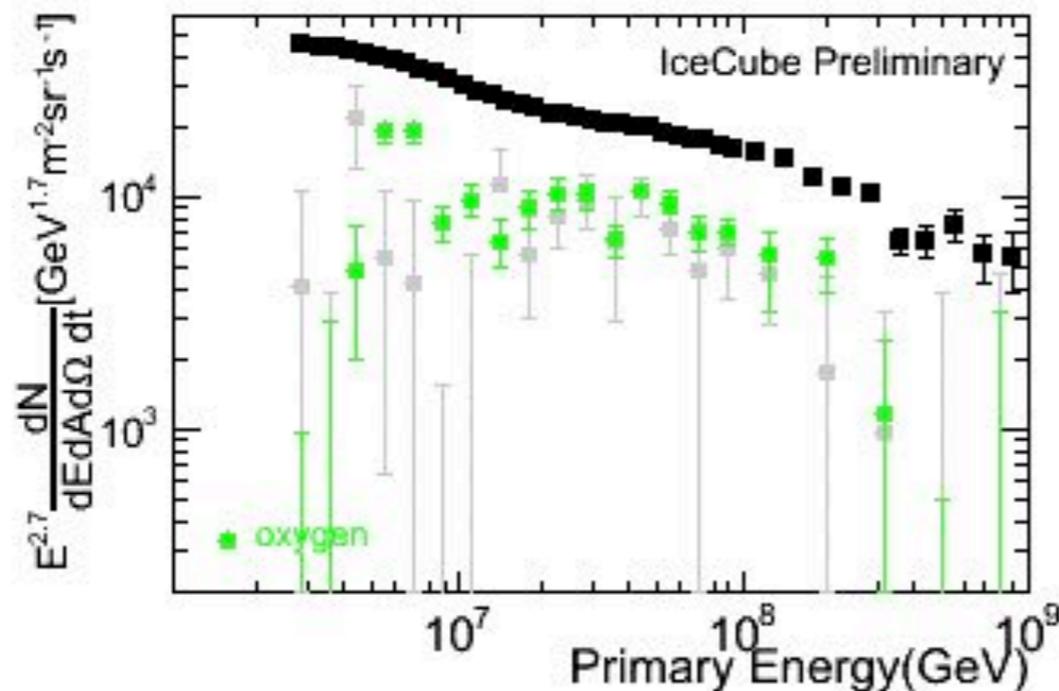
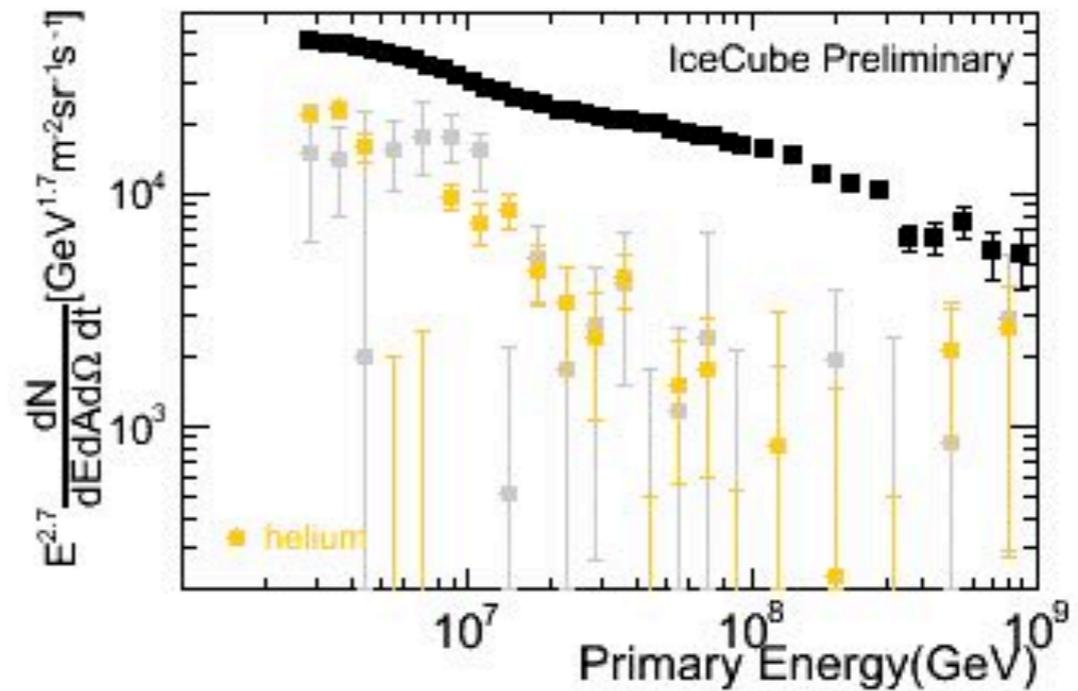
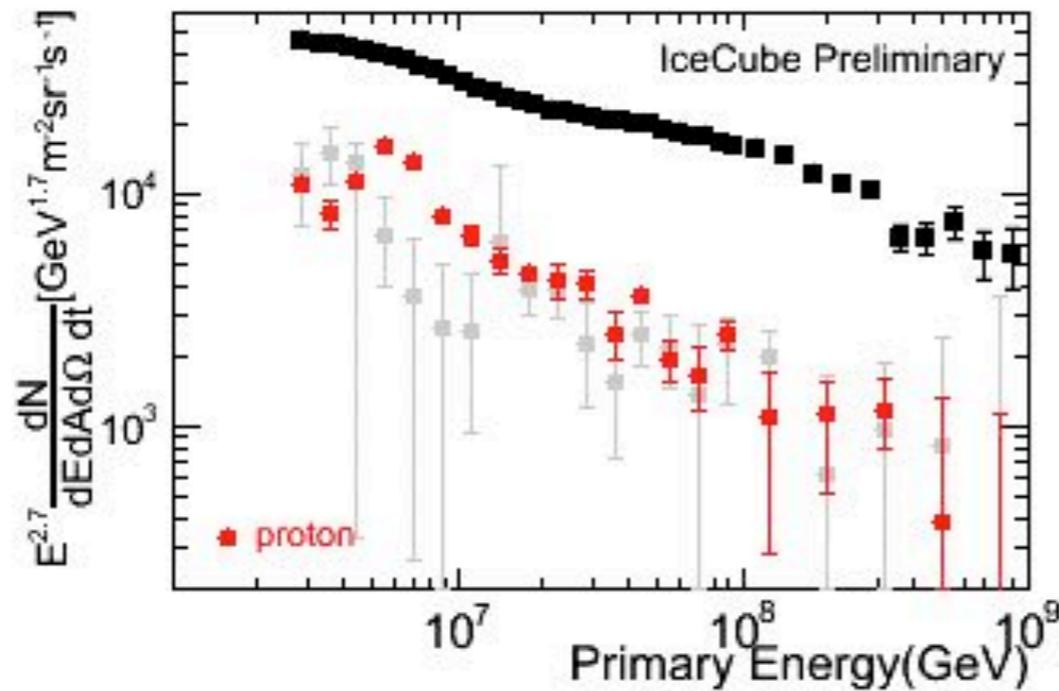
Elemental Spectra: IceTop Energy Scale Uncertainty

dark gray: -3%, light gray: +3%



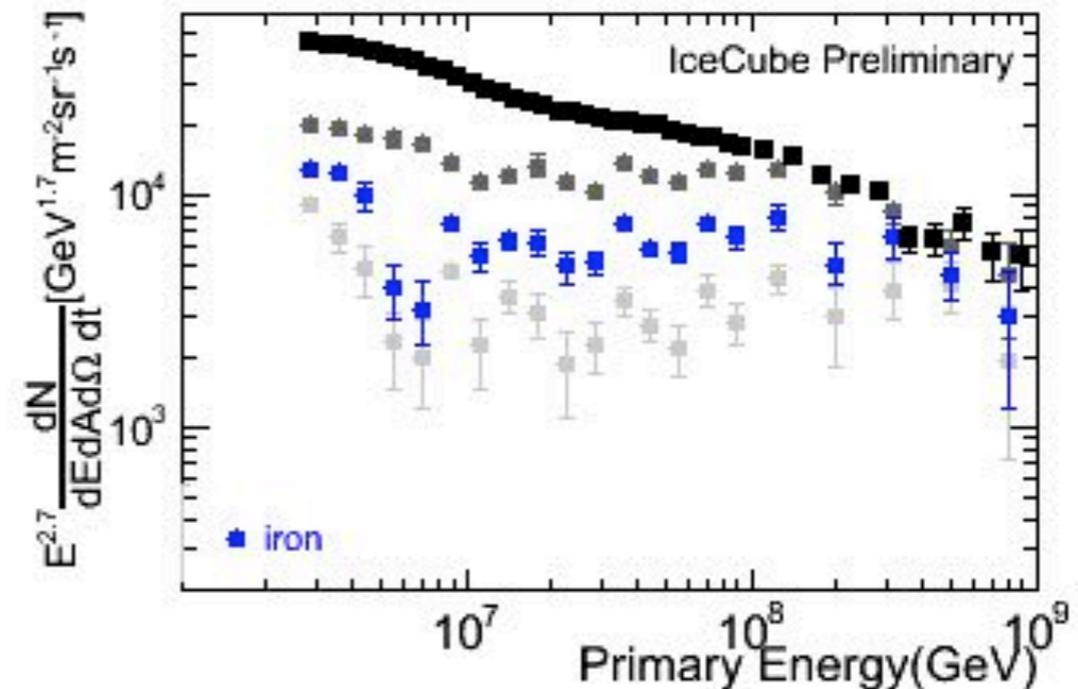
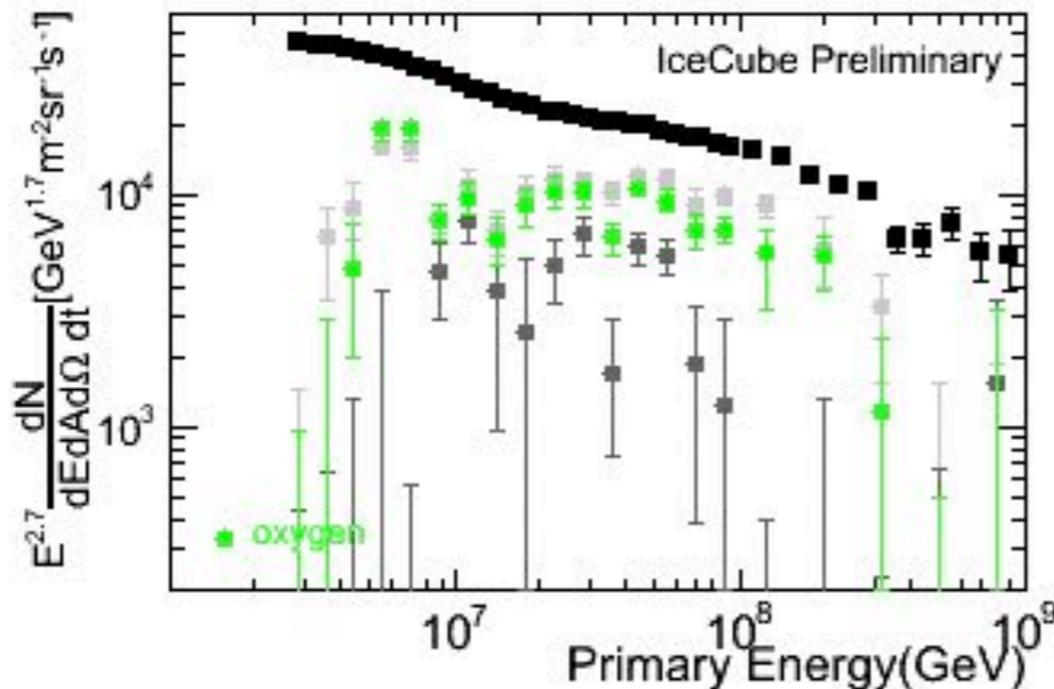
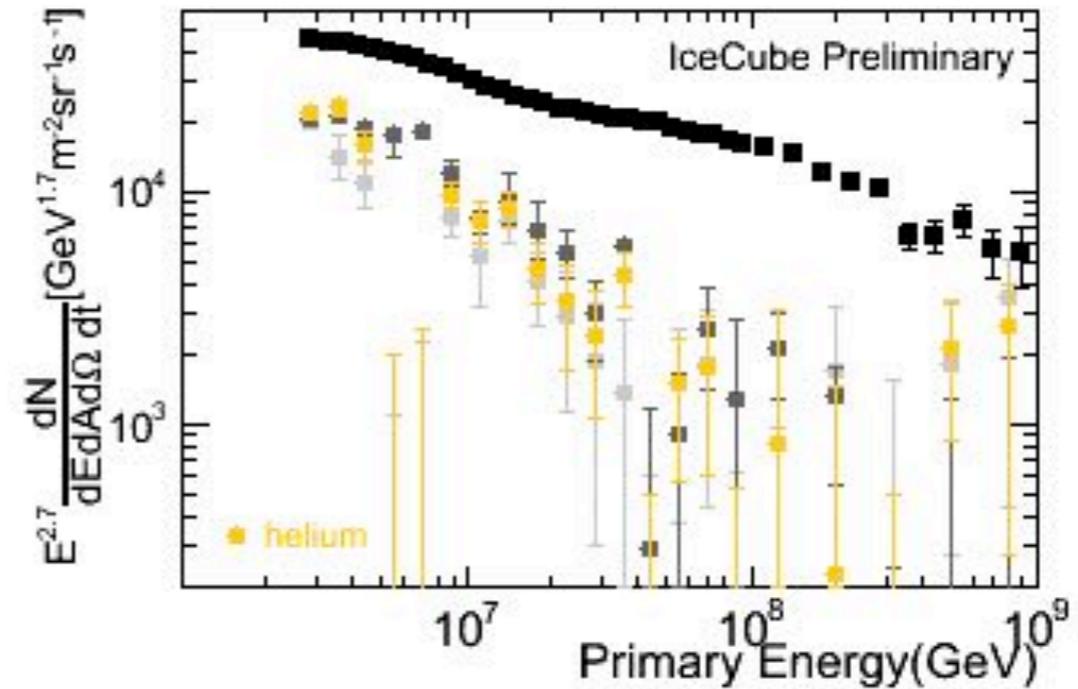
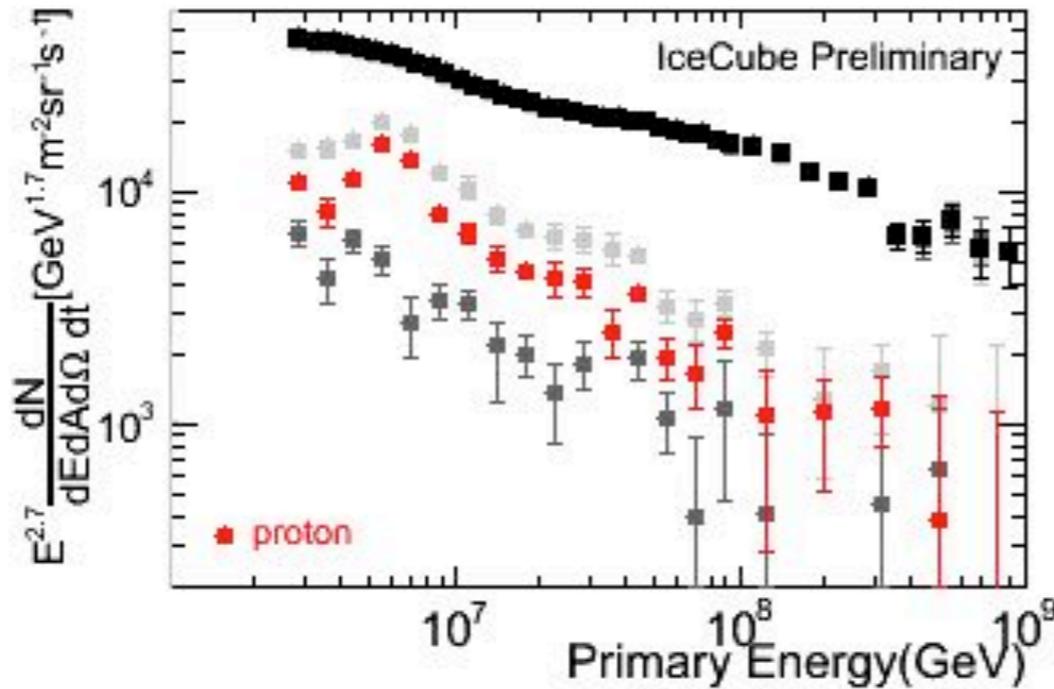
Elemental Spectra: Hadronic Model Uncertainty

light gray: QGSJet-II.03

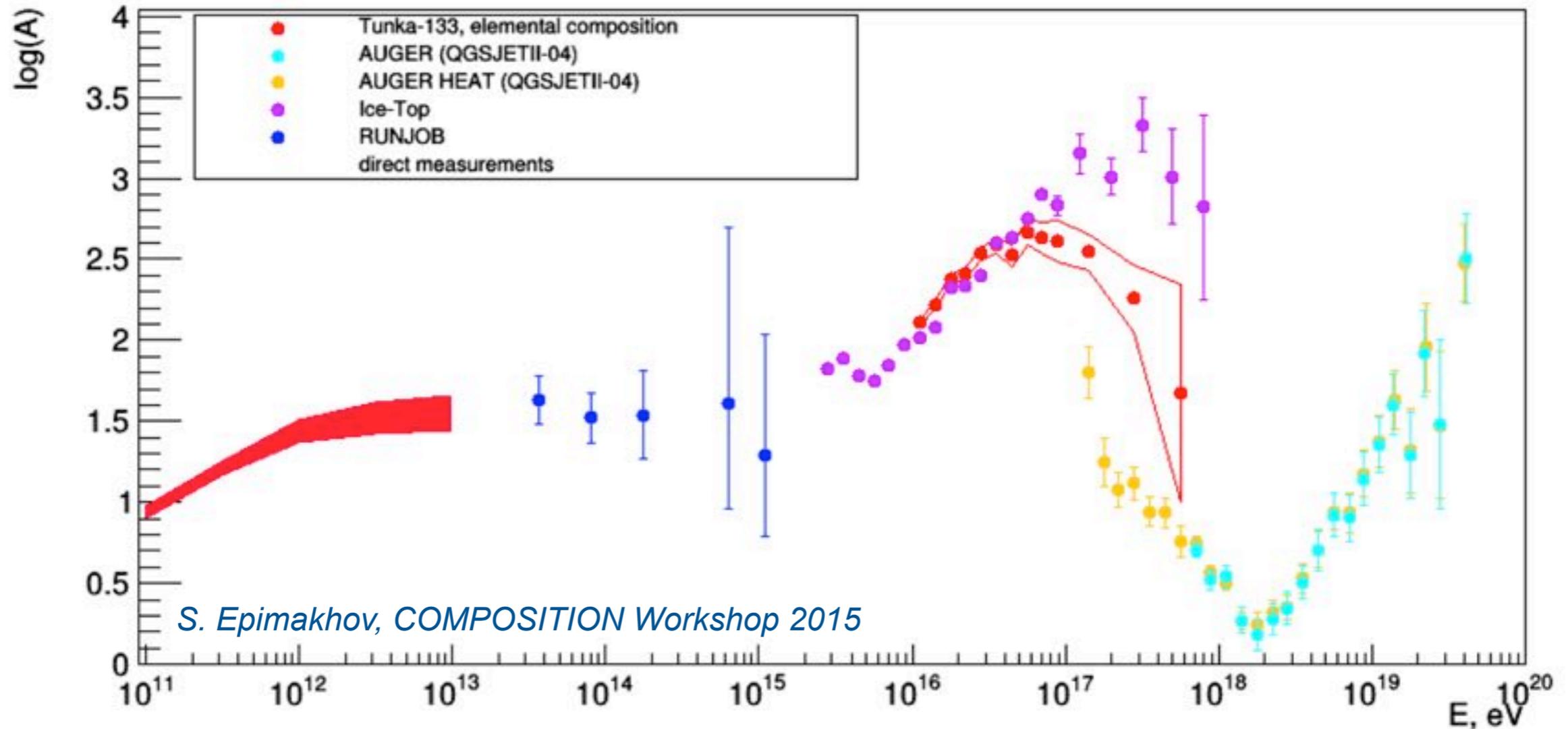


Elemental Spectra: In-ice Light Yield Uncertainty

dark gray: -12.5%, light gray: +9.6%



Comparison to Other Experiments

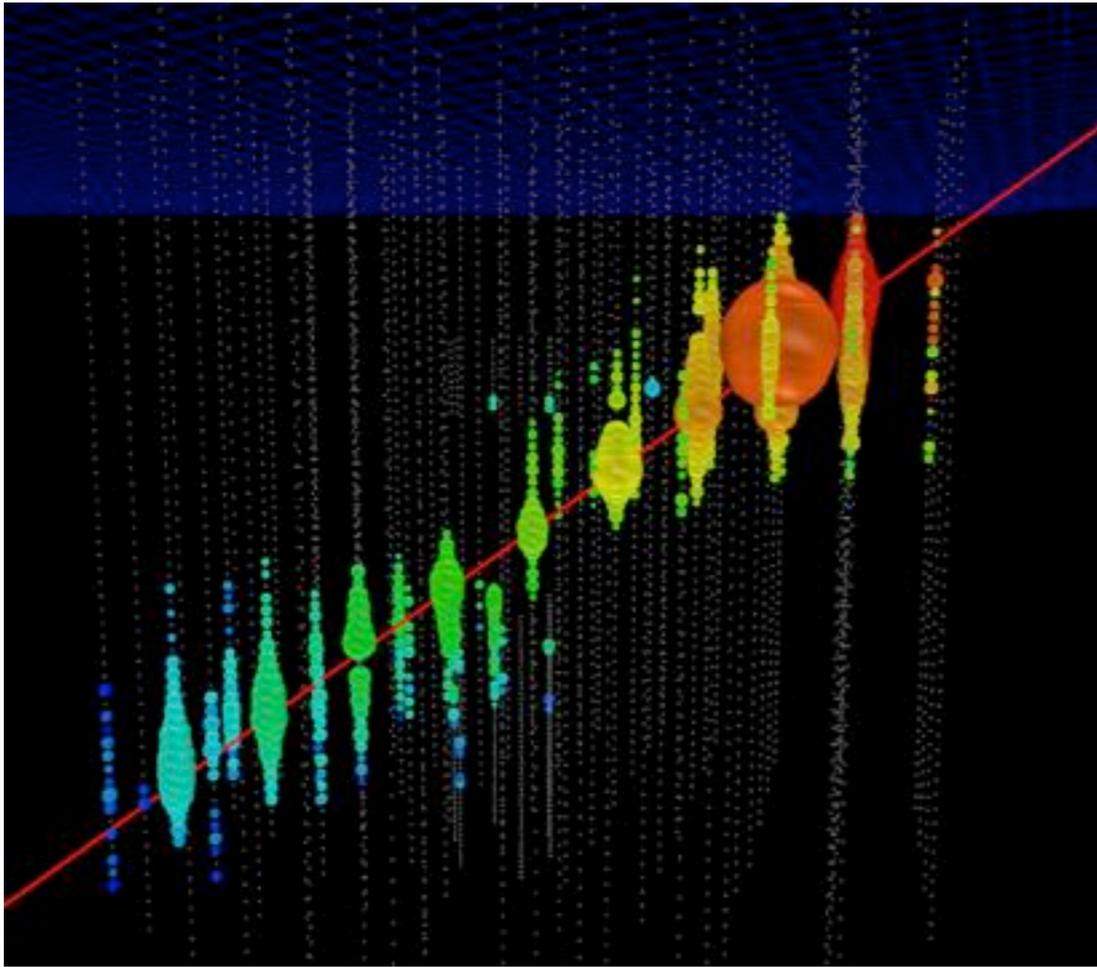


> Tension between different experiments

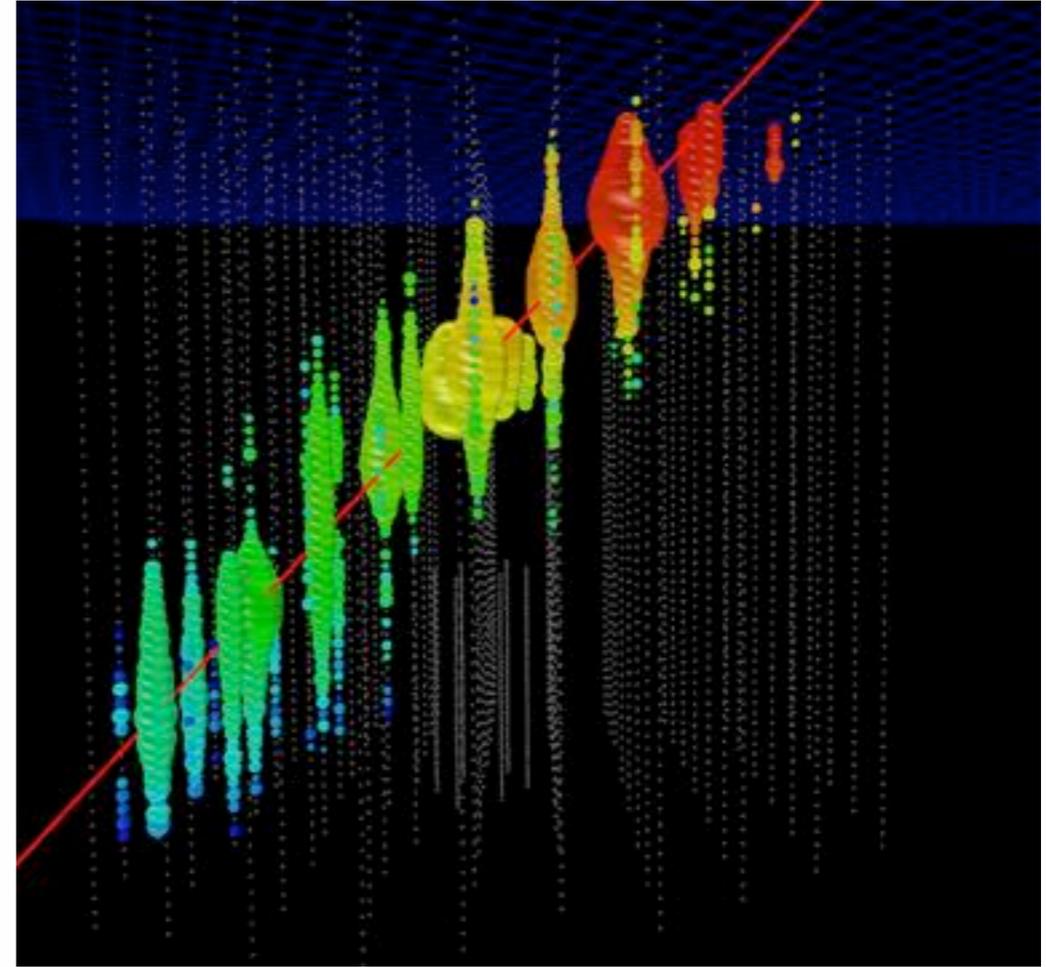
- Different experimental techniques — measurement of:
depth of shower maximum (air fluorescence), non-imaging air-Cherenkov, TeV muon bundles
probe different components of the air shower
- Different hadronic interaction models used to describe the data
Models evolve rapidly thanks to LHC data



Atmospheric Muon Bundles



High-energy muon



Muon bundle

- > Bundle multiplicity proportional to number of nucleons A
- > Select events w/o large stochastic losses to suppress high-energy muons
- > Energy deposition in deep-ice detector proportional to muon number

$$E_{\text{mult}} := E_{\text{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}} = g_{\text{scale}}(\cos \theta) \cdot N_{\mu, \text{det}}^{1/\alpha}$$

- > Unfold E_{mult} spectrum from measured muon bundles



Interpretation of E_{mult} Spectrum

- Comparison to cosmic-ray models converted to E_{mult} via

$$E_{\text{mult}} := E_{\text{prim}} \cdot (A/56)^{\frac{1-\alpha}{\alpha}}$$

- Conversion of E_{mult} spectrum to all-particle flux assuming a composition model

IC-79, 1.2×10^7 muon bundle events

Astropart. Phys. **78** (2016) 1

