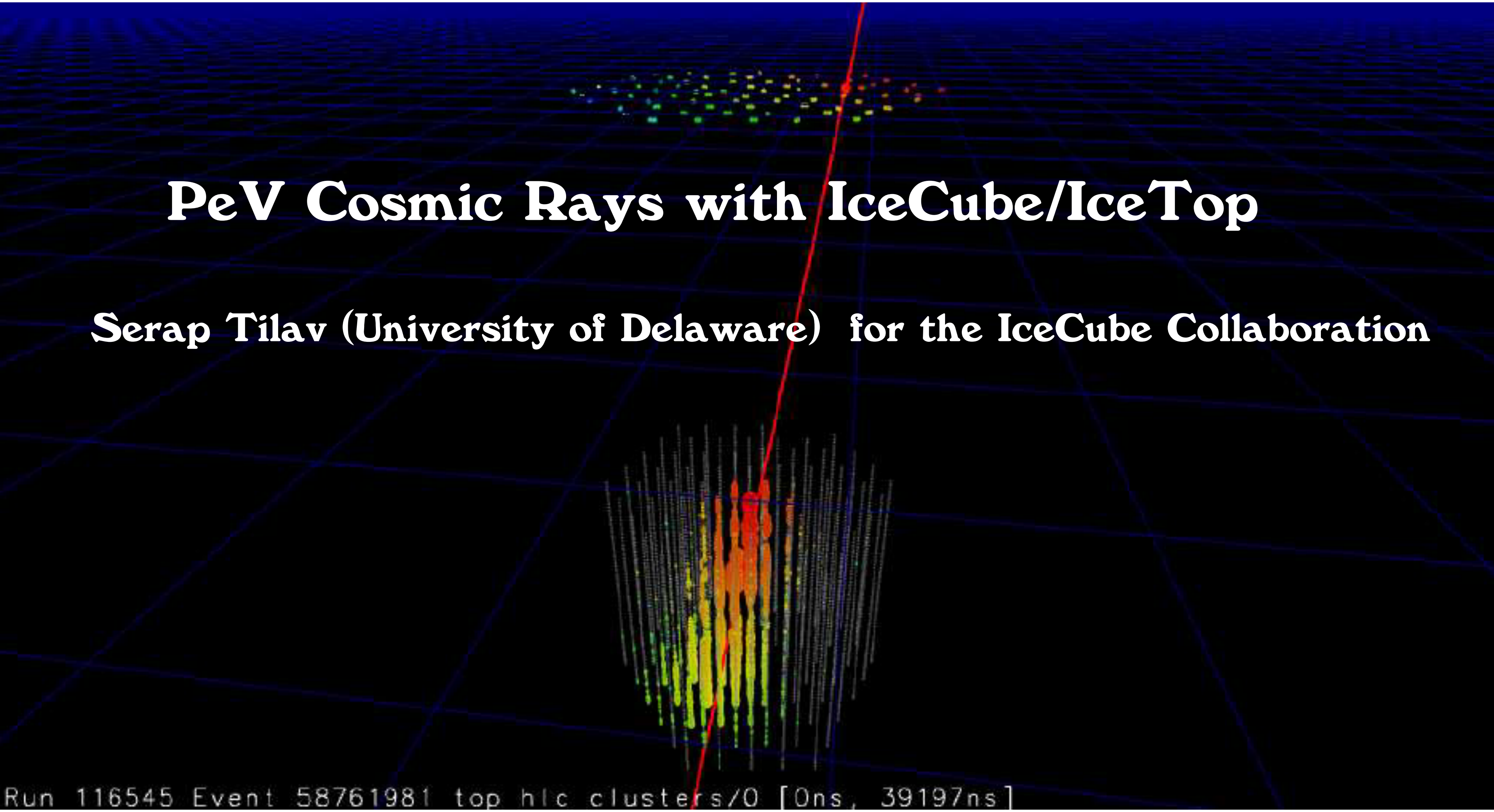
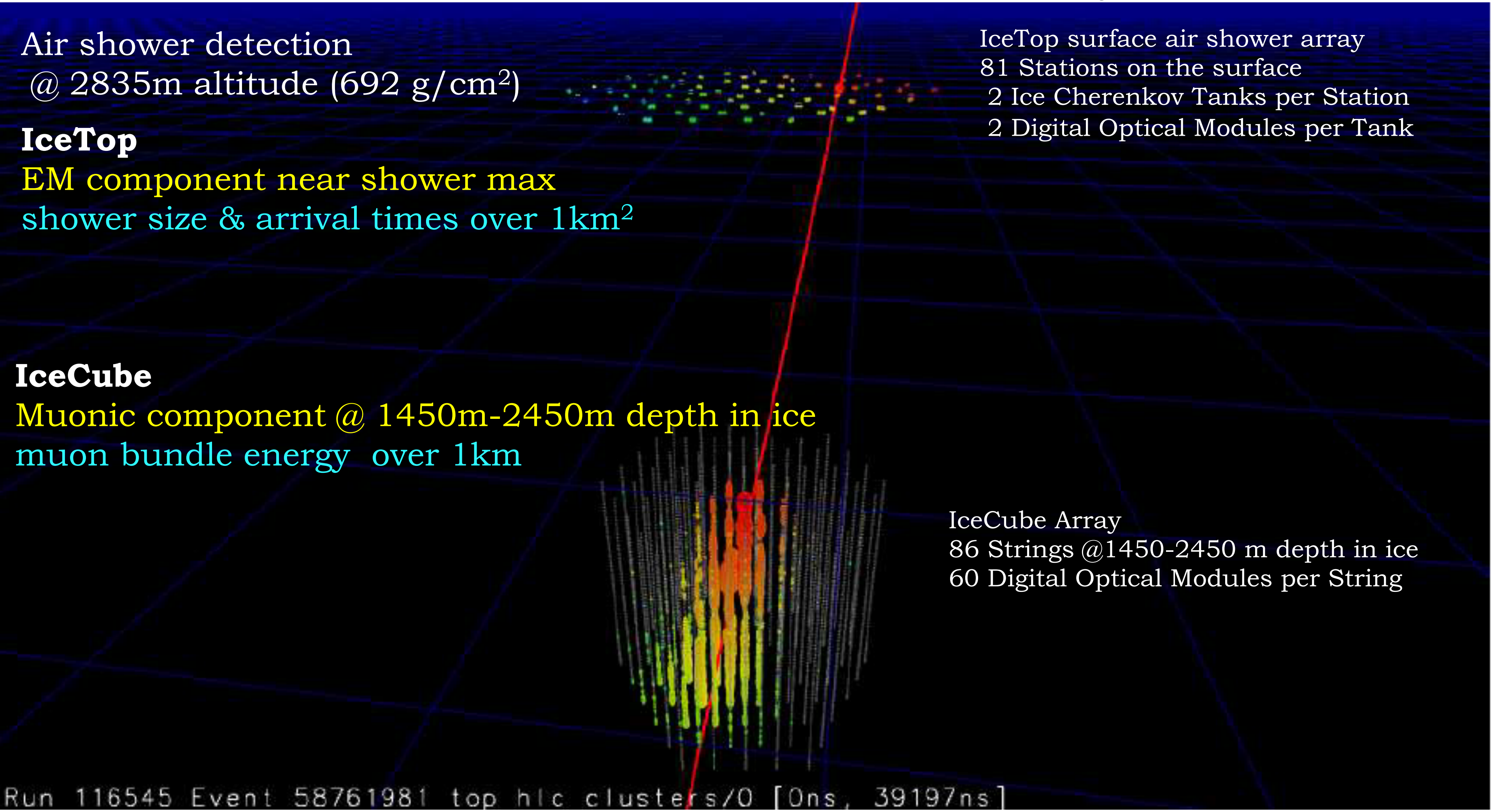
PeV Cosmic Rays with IceCube/IceTop

Serap Tilav (University of Delaware) for the IceCube Collaboration



CASPAR Workshop, 10-19 September 2013, DESY-Hamburg

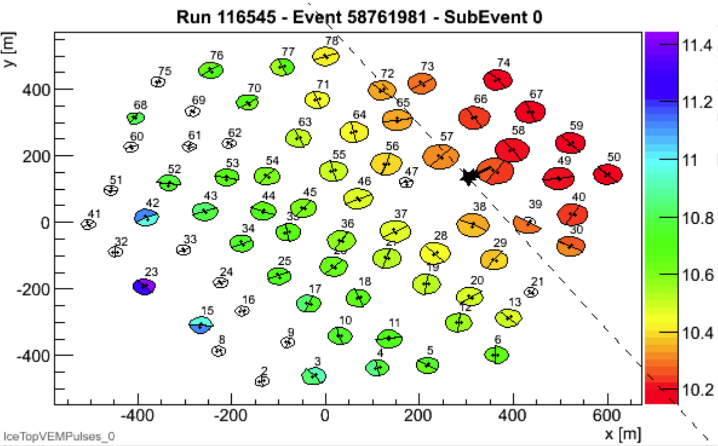
IceCube
Neutrino Telescope & 3D Cosmic Ray Detector

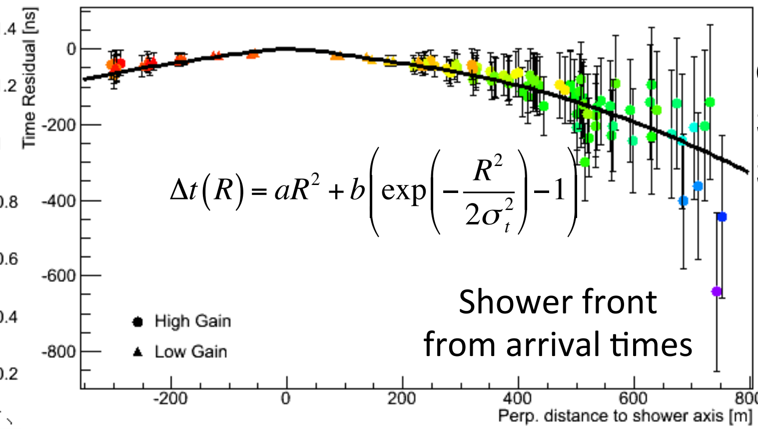


IceTop: Calibration device for IceCube

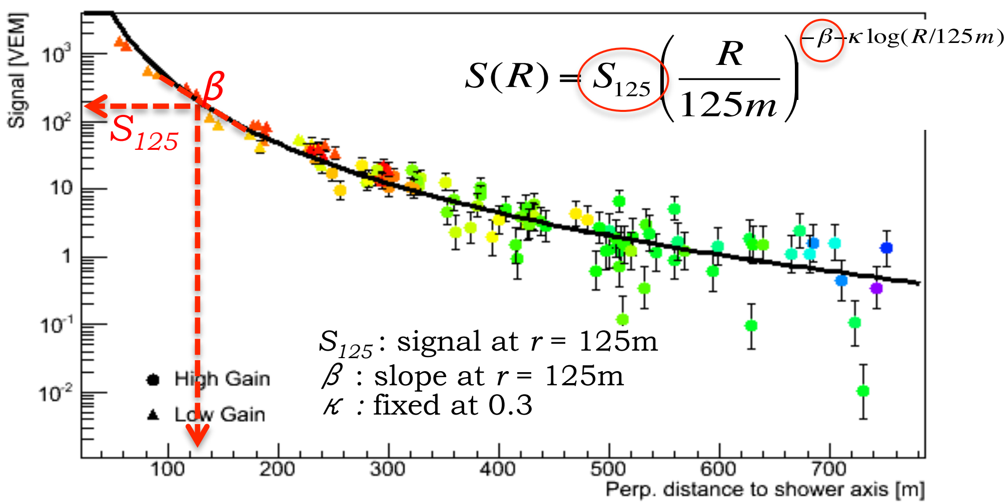
➔ measure cosmic ray spectrum and composition as input to neutrino calculations

Air Shower Reconstruction

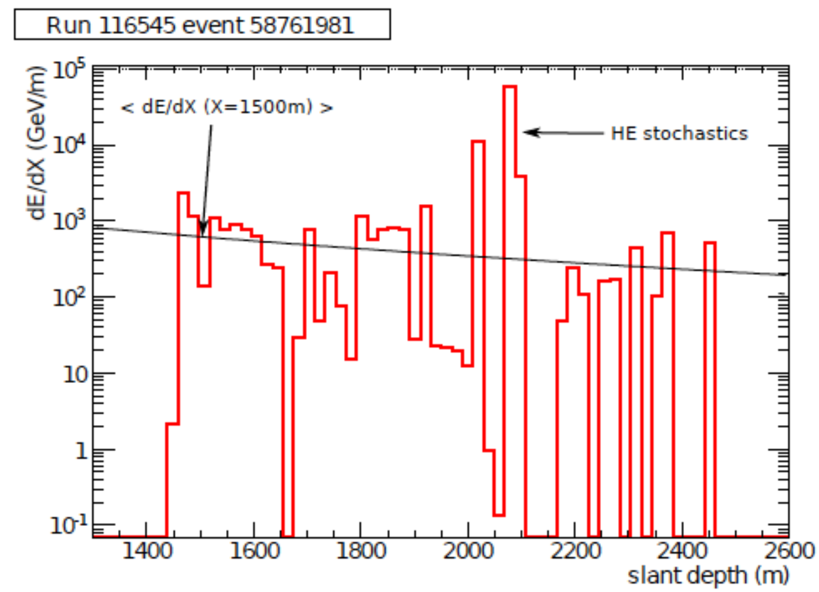




On the surface:
Shower core: x,y,z
Shower direction: θ,φ



On the surface:
IceTop shower size S_{125} and β



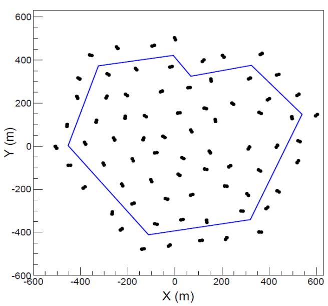
In deep ice:
Muon bundle energy loss
dE/dX (GeV/m) and stochastic
behavior

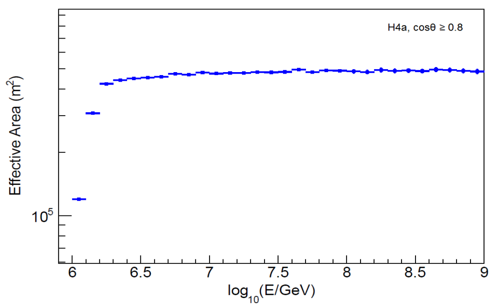
IceCube-79 / IceTop-73 Analysis

June 2010 – May 2011

Surface Only: IT73

327 days of live time
12M events after quality cuts





Effective area=Geometric area=5.7710^5 m^2 above ~ 1.28 PeV

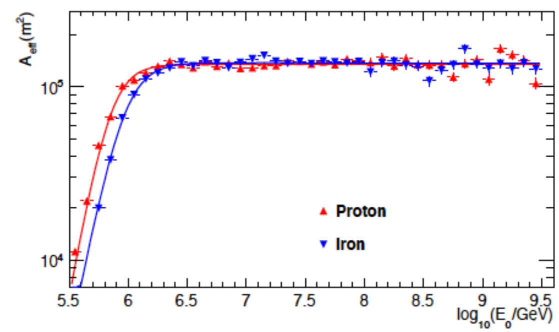
- Assumes composition to derive energy spectrum

Default model: H4a from
T.K. Gaisser, Astropart.Phys. 35 (2012) 801-806

- Tests composition by analyzing spectrum in different zenith ranges

Surface and In Ice: IC79/IT73

310 days of live time
1.56M events after quality cuts



Effective area=1.3610^5 m^2 above ~ 2.5 PeV

- Multivariate Neural Network Analysis
- Measures Composition
- Measures composition independent energy spectrum

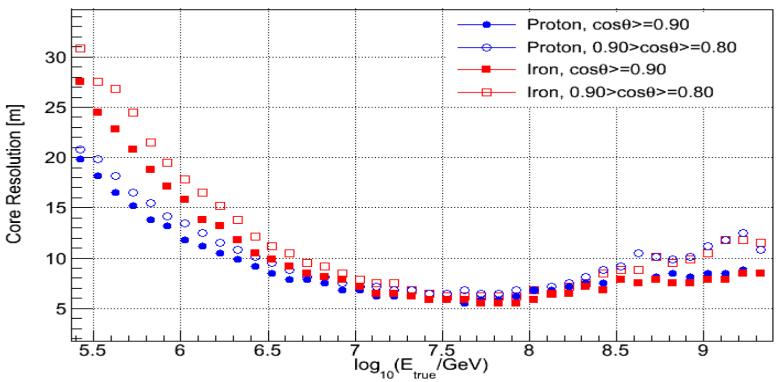
IceCube-79 / IceTop-73 Analysis

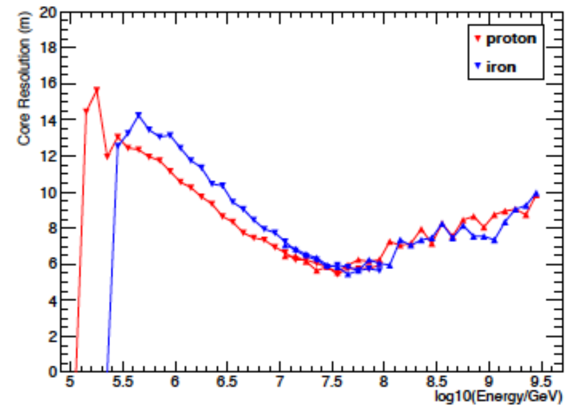
June 2010 – May 2011

Surface Only: IT73

Surface and In Ice: IC79/IT73

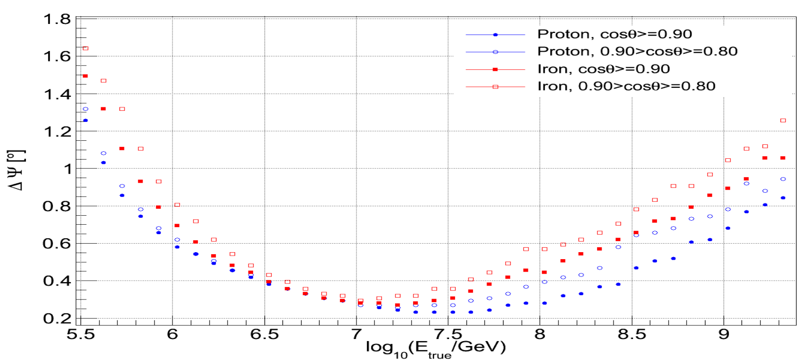
Performance

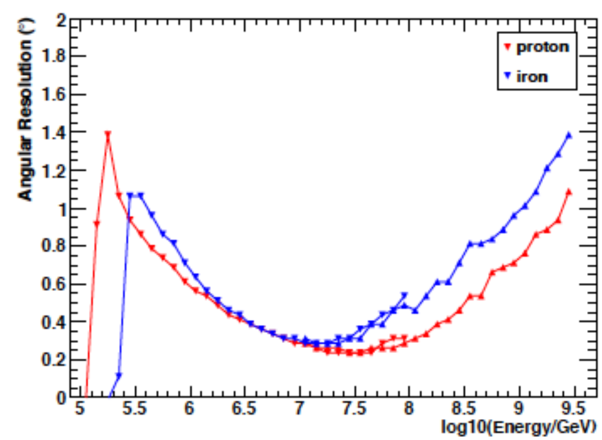




Core resolution : 6-13 m

Core resolution : 6-10 m





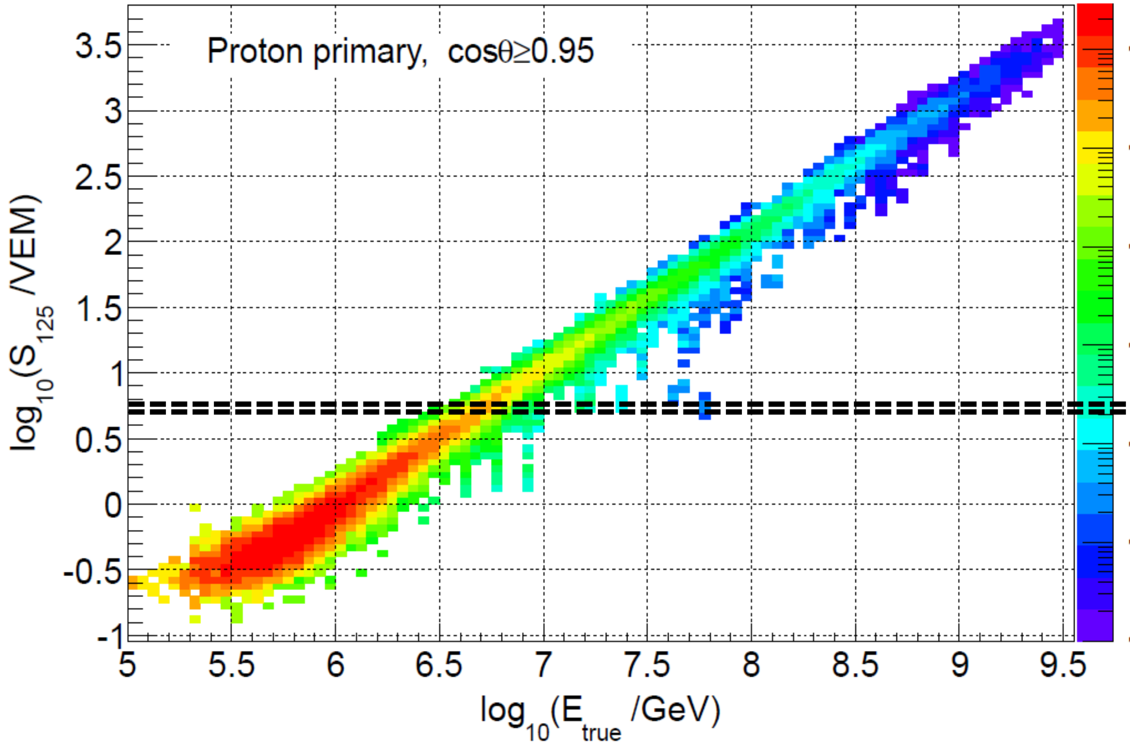
Angular resolution: 0.2° – 0.8°

Angular resolution: 0.4° – 1.0°

IceTop-73 Analysis

S_{125} - Energy Conversion

CORSIKA Sibyll 2.1 – FLUKA   Primaries: H, He, O, Fe   South Pole July atmosphere.
E^{-1} spectrum: 100 TeV - 3 EeV   Zenith: 0-40°   42000 showers per primary



weighted by $dN/dE \approx E^{-2.7}$

Mean energy as function of measured S_{125} in

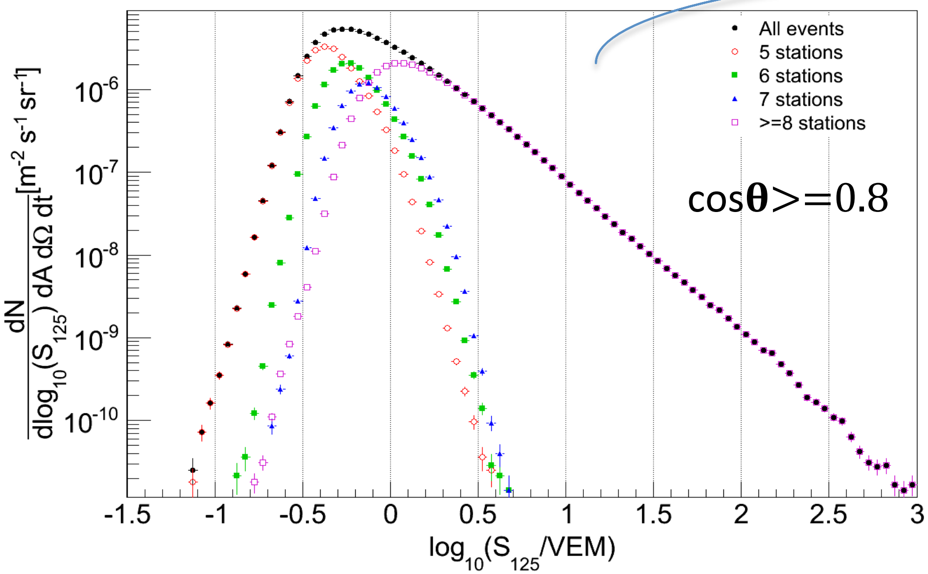
$$\Delta \log(S_{125} / VEM) = 0.05$$

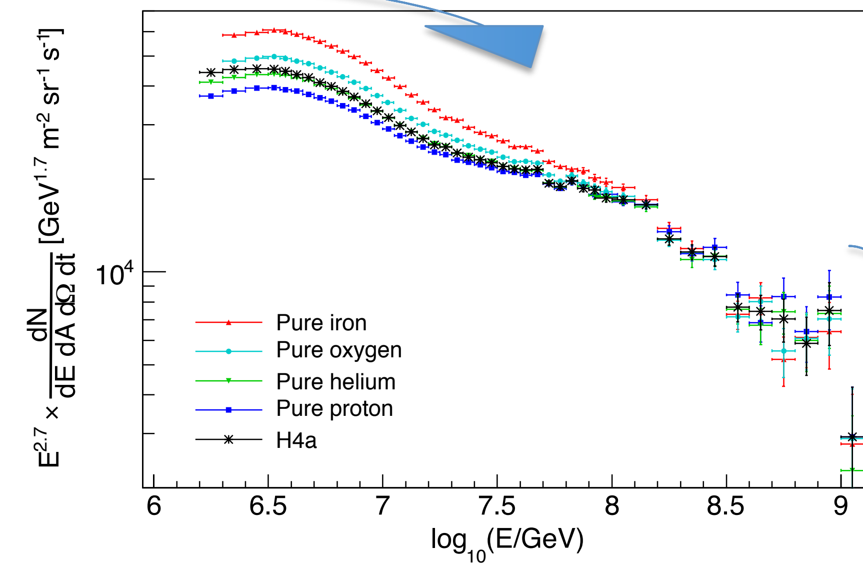
Fit performed in four cos**θ** bins between 1.0 and 0.8

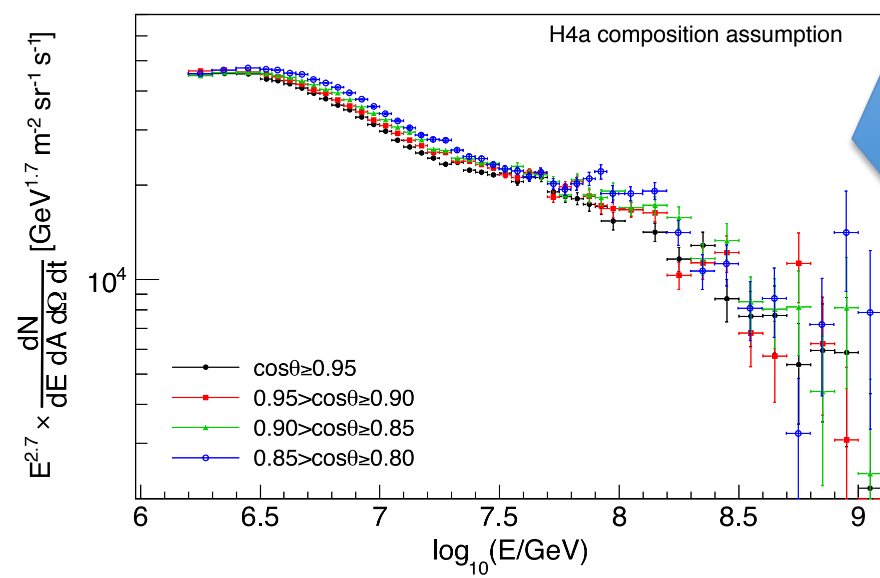
$$\log_{10}(E) = p_1 \log_{10}(S125) + p_0$$

IceTop-73 Analysis

S_{125} - Energy Conversion



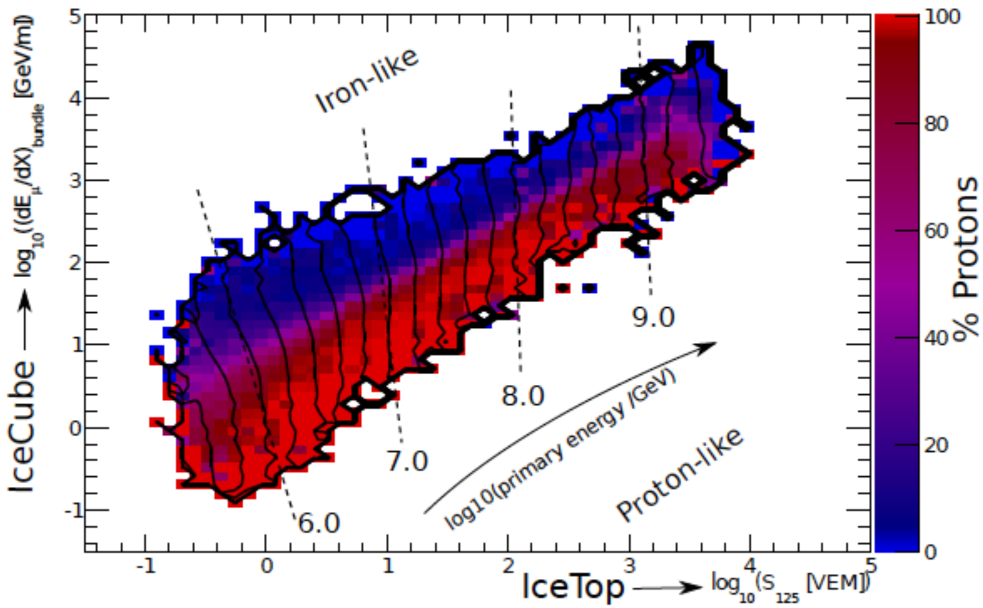




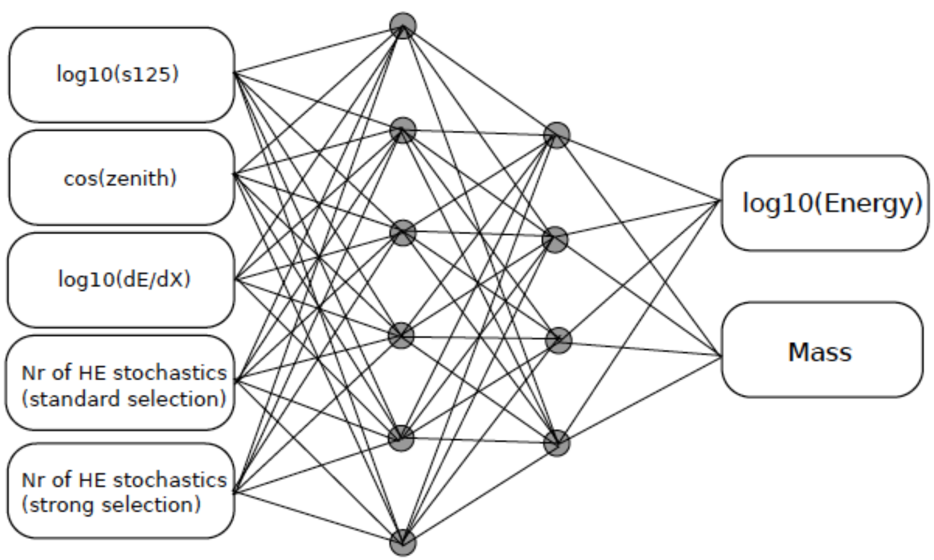
Systematic Uncertainties

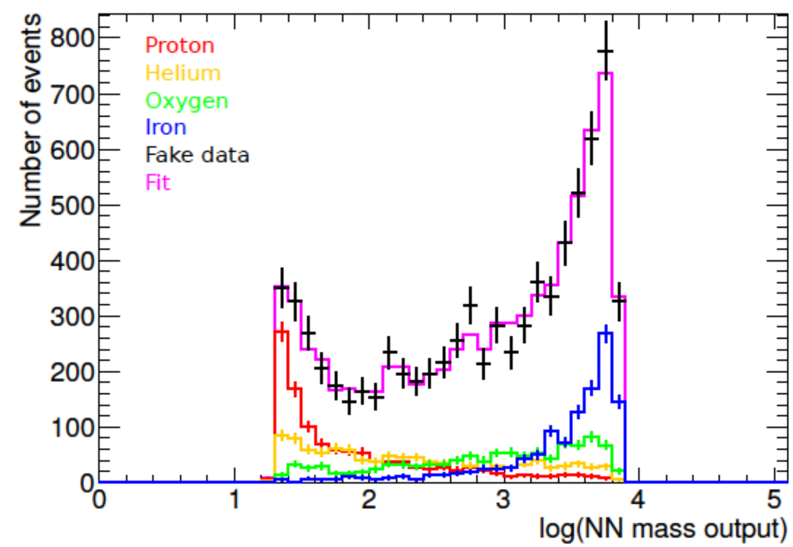
	3 PeV	30 PeV
Energy scale (VEM calibration)	±4%	±5%
Snow Correction	±5%	±6%
Interaction models QGSJet-II-03 and SYBILL 2.1	-2%	-4%
Composition	±7%	±7%
Ground pressure (690 hPa/670 hPa)	±2%	±0.5%

IceCube-79 / IceTop-73 Coincidence Analysis



- 5-6-4-2 Neural Network to map 5 observables to Primary Energy and Mass
- Energy spectrum directly from NN output
- Composition from fitting data in E_{reco} bins to template histograms (H,He,0,Fe) from NN mass output





e.g. Template histograms for 4 mass groups in one energy bin for a fake dataset scrambled from MC

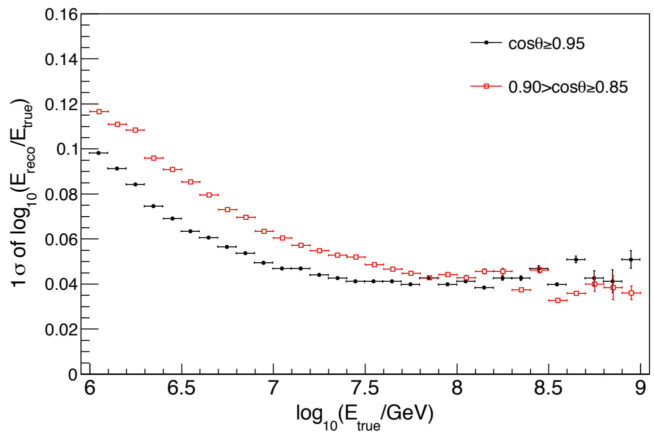
IceCube-79 / IceTop-73 Analysis

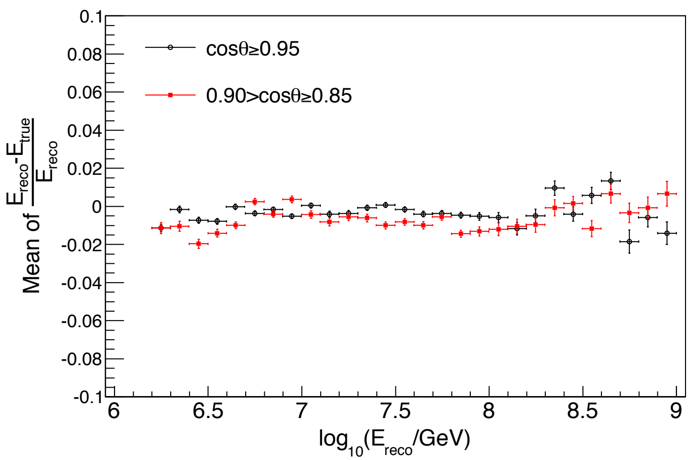
June 2010 – May 2011

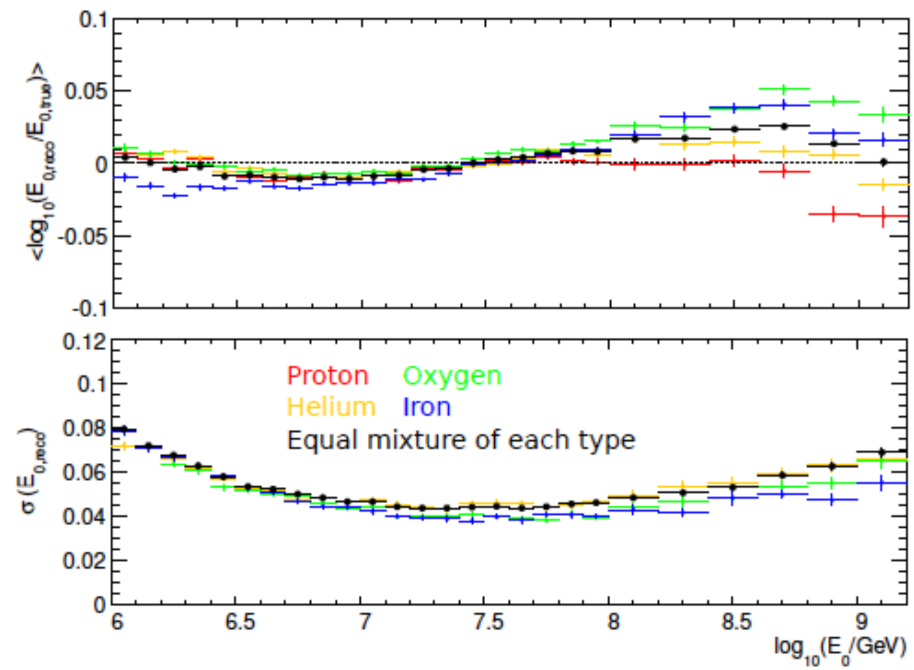
Surface Only: IT73

Surface and In Ice: IC79/IT73

Energy Resolution





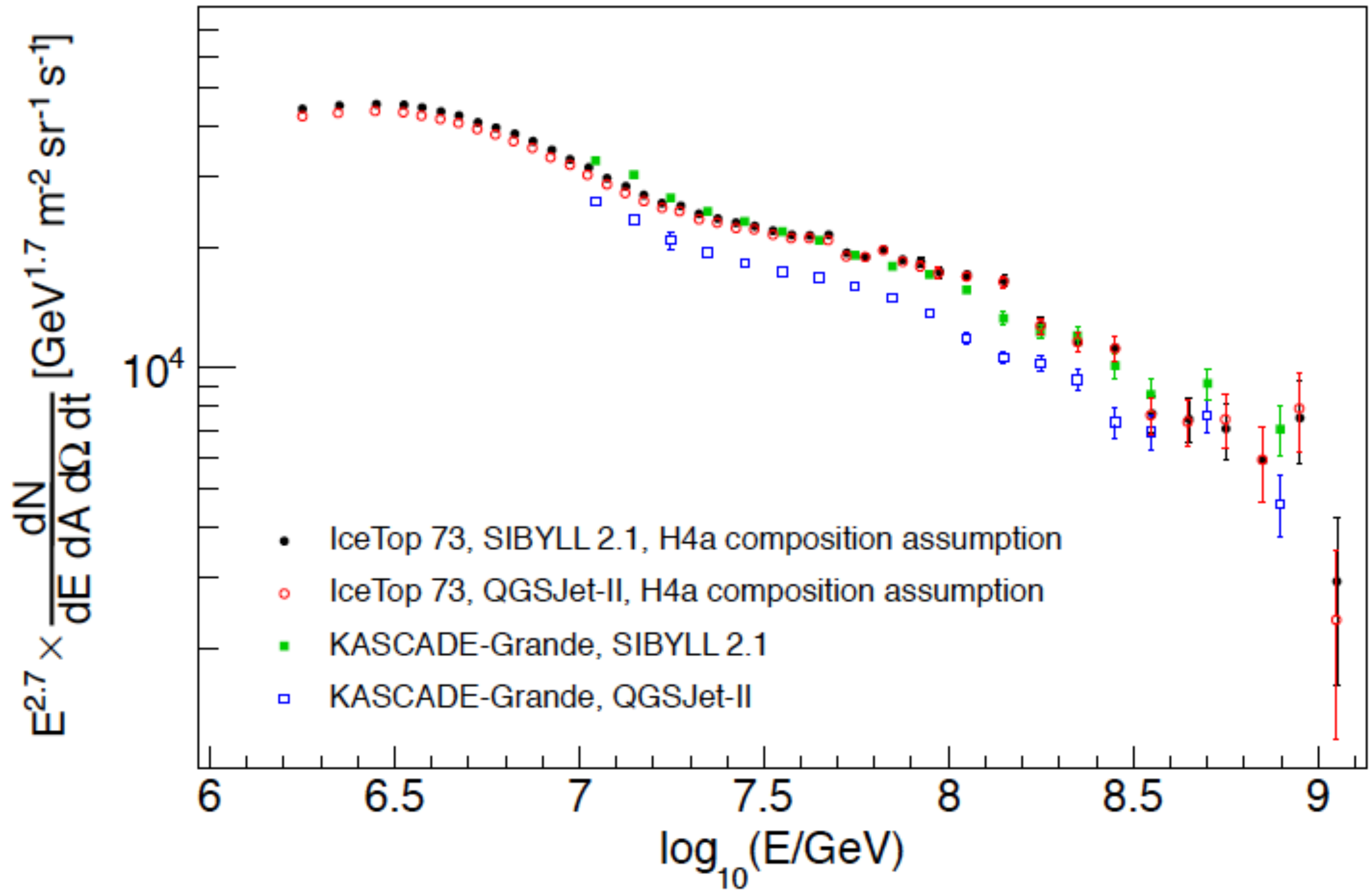


use variable bin sizes: $\Delta \log_{10}(E) = 0.05$ for $6.5 < \log_{10}(E/GeV) < 8$

$\Delta \log_{10}(E) = 0.1$ for $6.2 < \log_{10}(E/GeV) < 6.5$ and $8 < \log_{10}(E/GeV) < 9$

IceTop-73 Analysis

Energy Spectrum -- Interaction Model Sensitivity

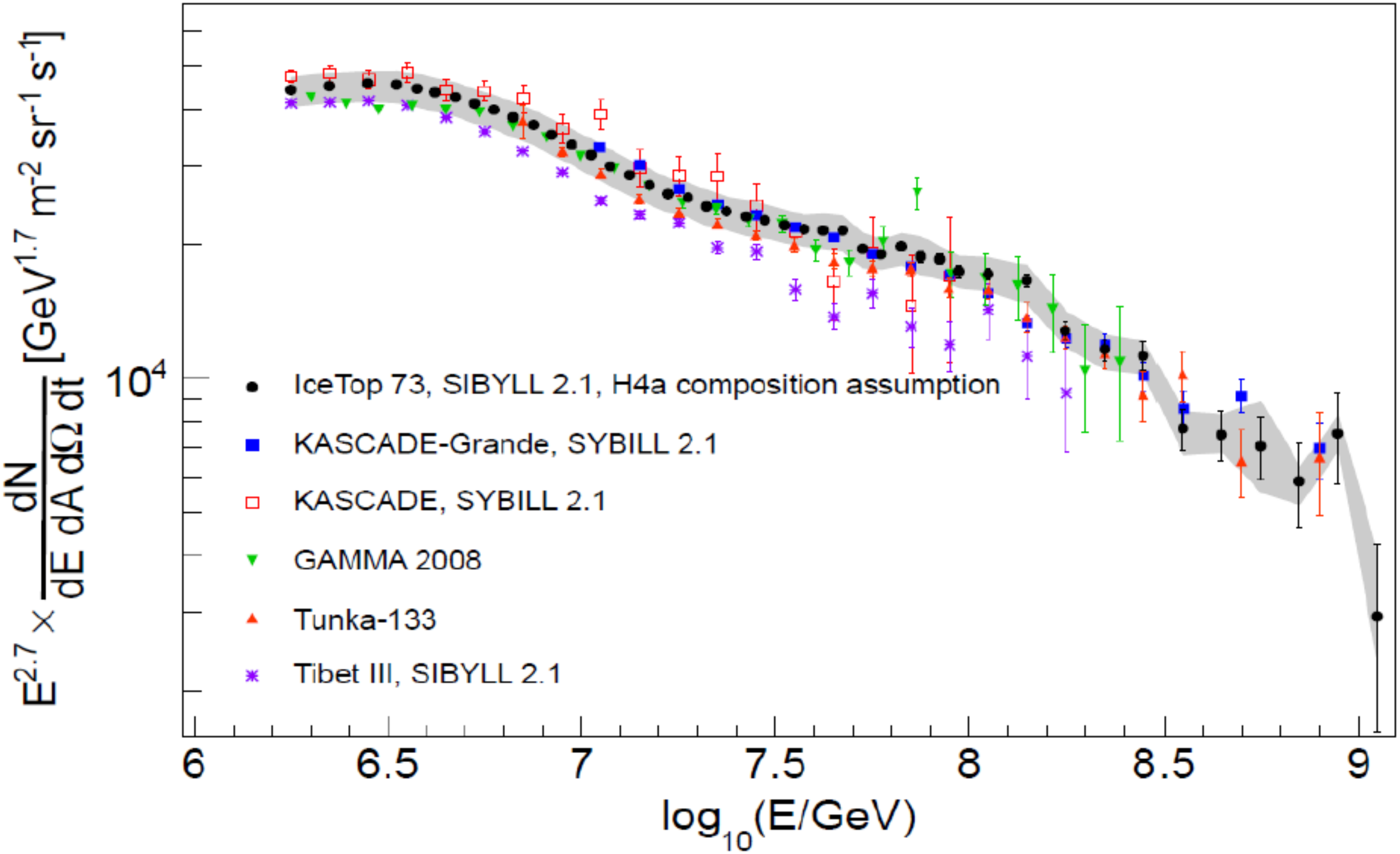


- IceTop: high altitute, near Xmax
  dominated by EM
- KASCADE-Grande: sea level
  EM + GeV muons

→ sea level is better probe
to see interaction model differences

IceTop-73 Analysis

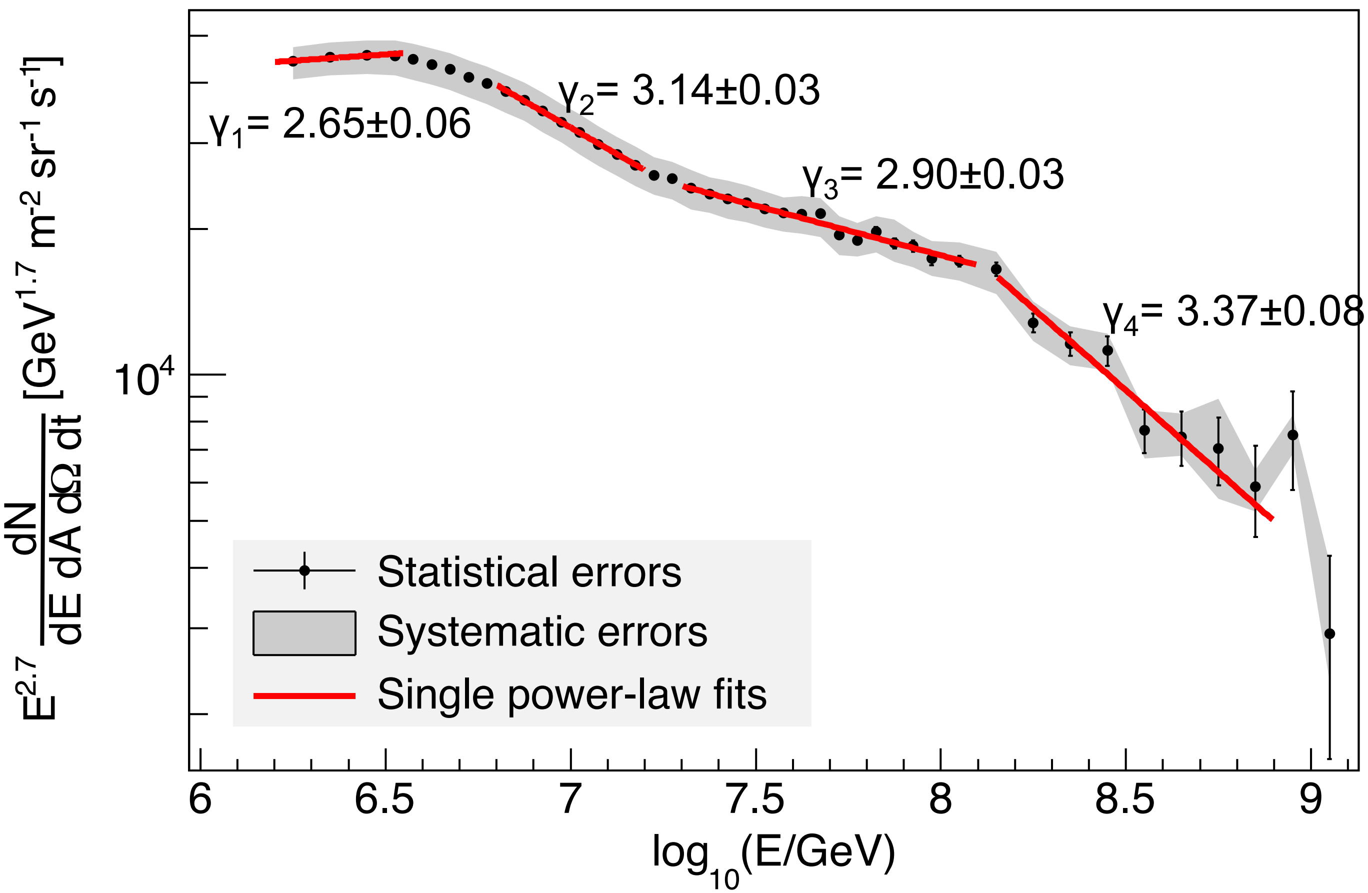
Energy Spectrum -- Comparison with other experiments



Excellent agreement with GAMMA, Tunka & KASCADE-Grande SIBYLL version

IceTop-73 Analysis

Energy spectrum 1.58 PeV to 1.26 EeV



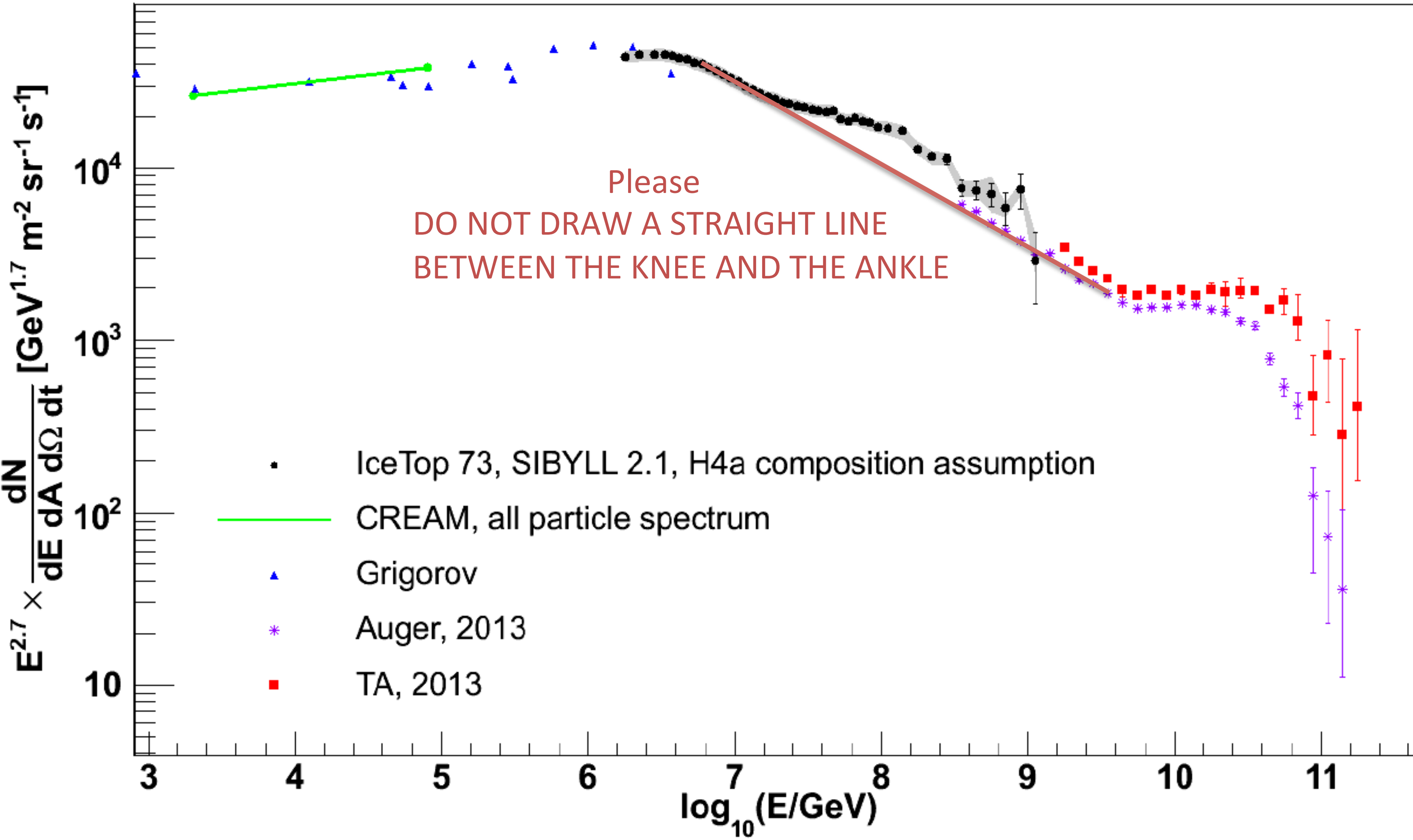
Large scale structure in spectrum

- Spectrum does not follow a simple power law above the knee up to 1 EeV.
- Spectral hardening at 18±2 PeV (124800 events expected, 139880 observed)
- Spectrum steepens at 130±30 PeV (4213 events expected, 3673 observed)

IceCube, Phys. Rev. D 88, 042004 (2013)

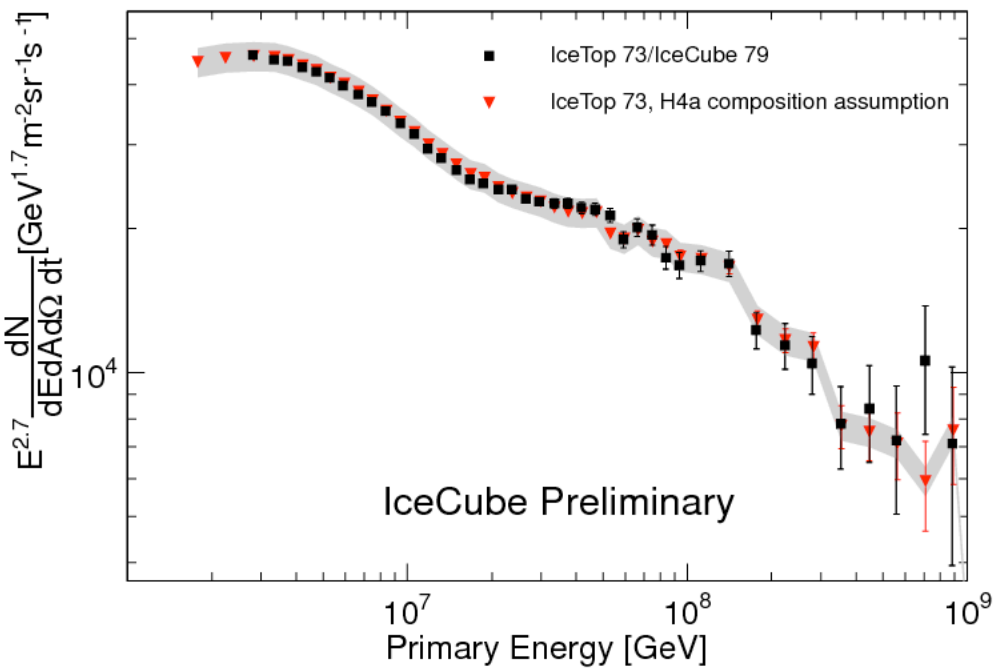
IceTop-73 Analysis

Energy spectrum --- Big Picture

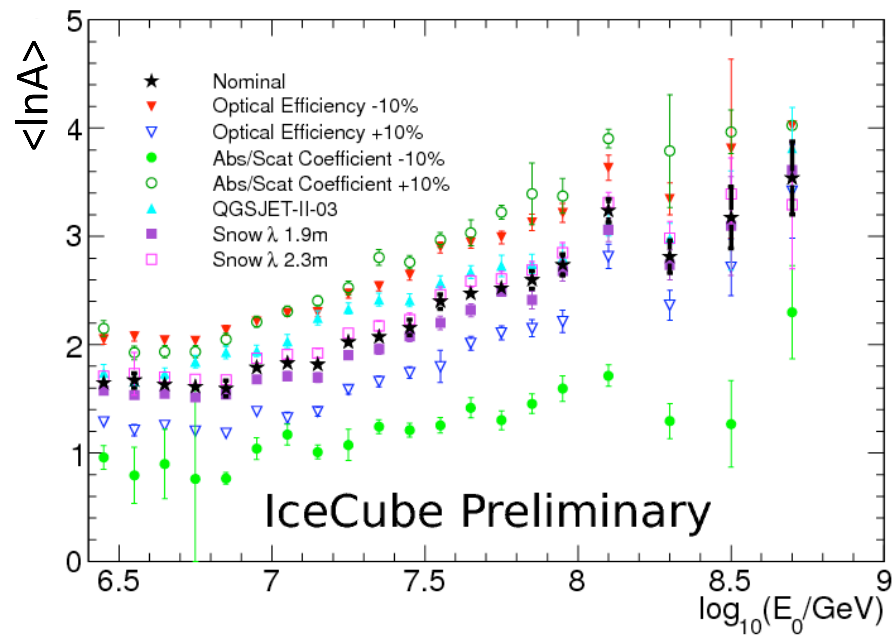


IceCube-79 / IceTop-73 Coincidence Analysis

Systematics under study – will finalize soon



gray band is ±7 composition systematics of IceTop-73 analysis



Excellent agreement between two independent analyses

clear trend towards heavier composition up to ~100 PeV

Large Scale Anisotropy with IceCube / IceTop

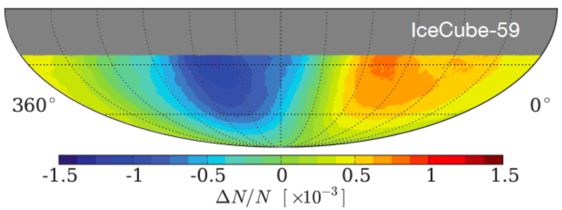
IceCube
muon bundles > 1 TeV

IceTop
CR showers > 100 TeV

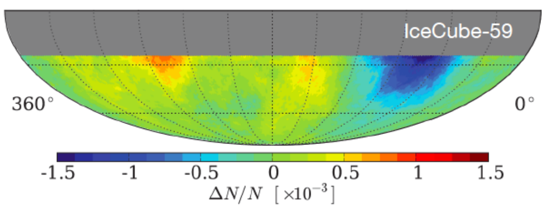
IceCube, ApJ 746, 33 (2012)

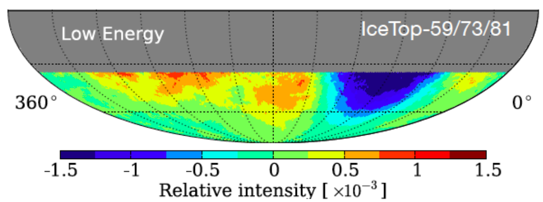
IceCube, ApJ 765, 55 (2013)

20 TeV



400 TeV

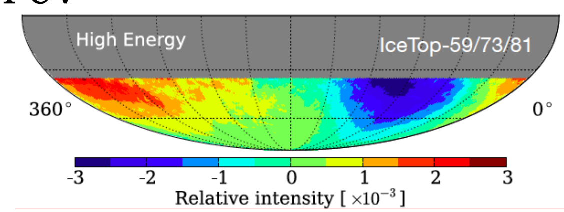




topology changes
between 20 - 400 TeV

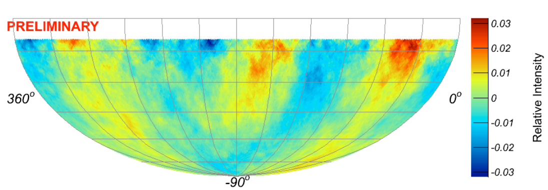
anisotropy is not dipole

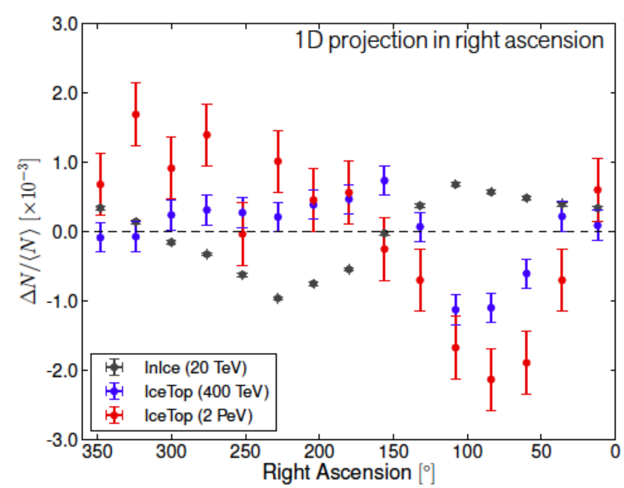
2 PeV



amplitude increases
with energy

10 PeV





PeV Gamma Astronomy with IceCube / IceTop

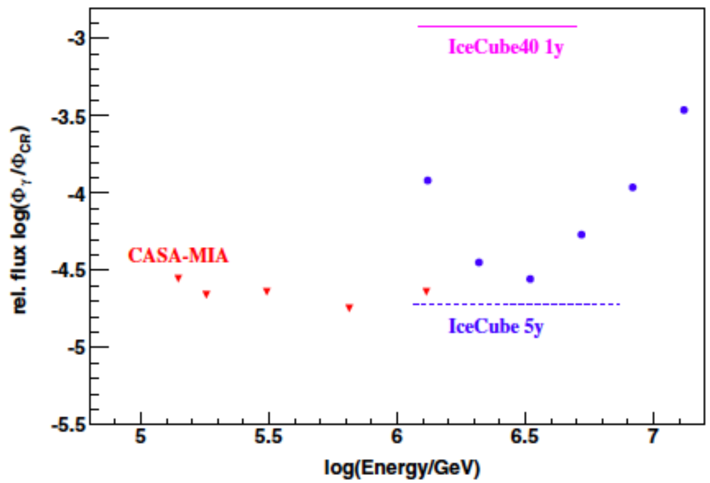
Look for muon poor showers:

- Select IceTop showers with cores going through IceCube
- No activity in IceCube around the shower axis

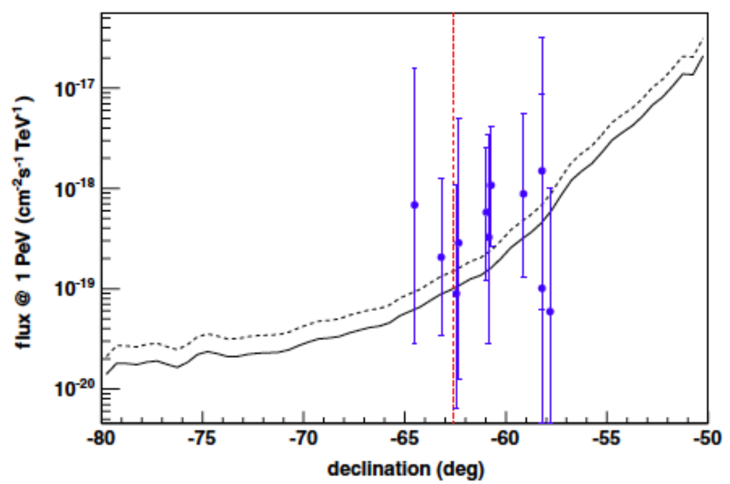
➔ threshold ~ 1 PeV

➔ event topology restricts field of view to declination range -60° to -90°

268 candidate events found in IceCube-40/IceTop-40 detector configuration (2008/2009)
Seach for correlation with the Galactic plane and scan for point sources performed
IceCube, Phys. Rev. D87, 062002 (2013)



- 90% C.L. sensitivity to a diffuse flux from the Galactic plane.
- 5yr sensitivity of IceCube-86 is compatible to existing limits from different regions of the plane.



- 5yr sensitivity of IceCube-86 to point sources near the Galactic plane.
  Assume sources do cut off between TeV and PeV
- Several hard gamma-ray sources are in FOV
- IceCube will study these systems

Summary

- High resolution measurement of cosmic ray all particle spectrum and composition in 1.58 PeV – 1.26 EeV region with one year of data from 2010-2011
- Good agreement between recent measurements of other experiments
- Overlap with UHE measurements around EeV
- Spectrum shows large structures hinting to a different mechanism above the knee
- Composition gets heavier up to at least 100 PeV
- Anisotropy changes topology between 20 - 400 TeV, its amplitude increases between 400 TeV and 2 PeV

➔ CR modelers of acceleration/propagation need to reproduce these features

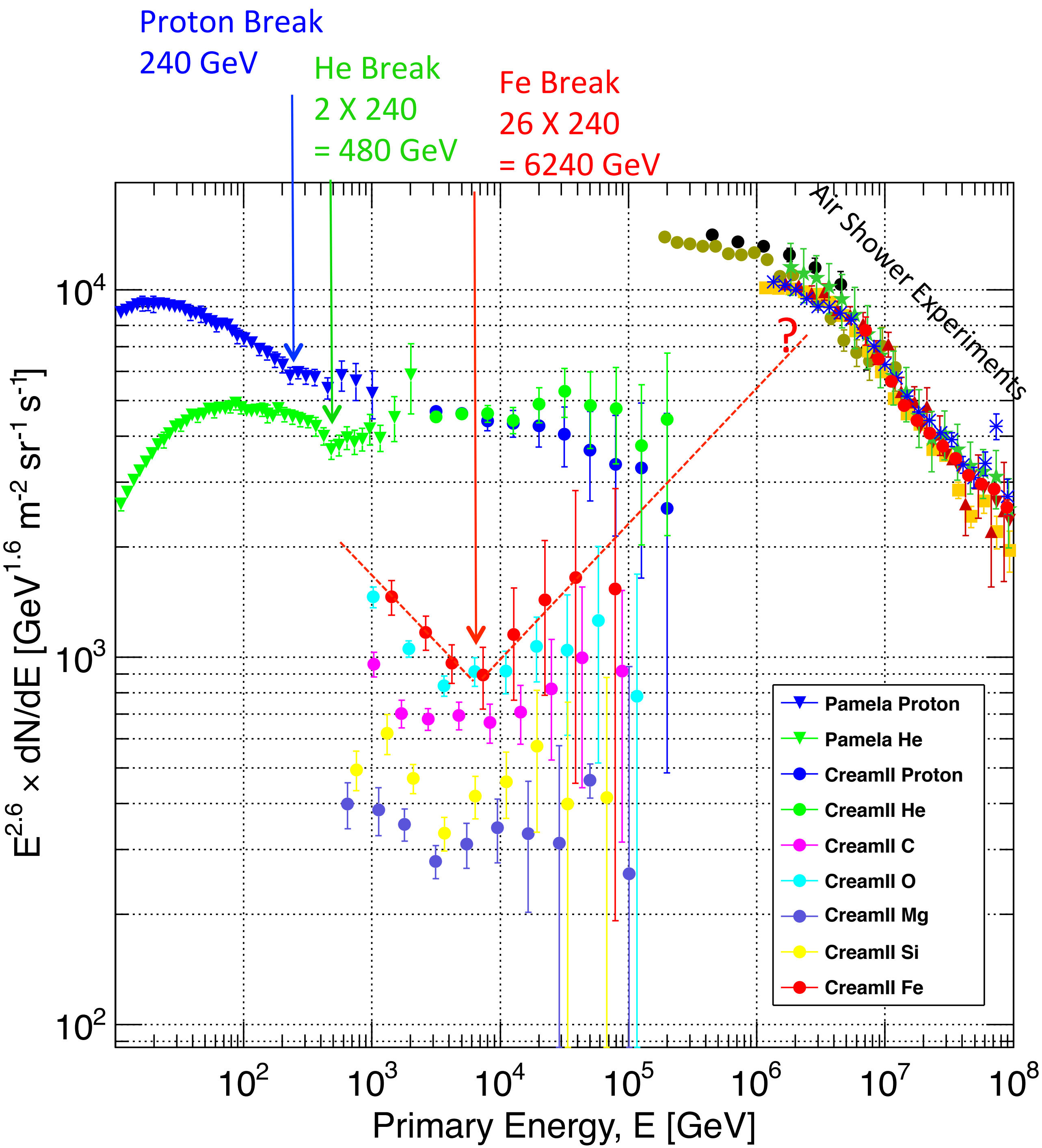
- Interesting prospect to search for PeV gamma-rays in correlation with PeV neutrinos

One Century Later

Triumph of the High Resolution Measurements

Spectral breaks observed in CR spectrum solves the puzzle with the knee and beyond

Serap Tilav

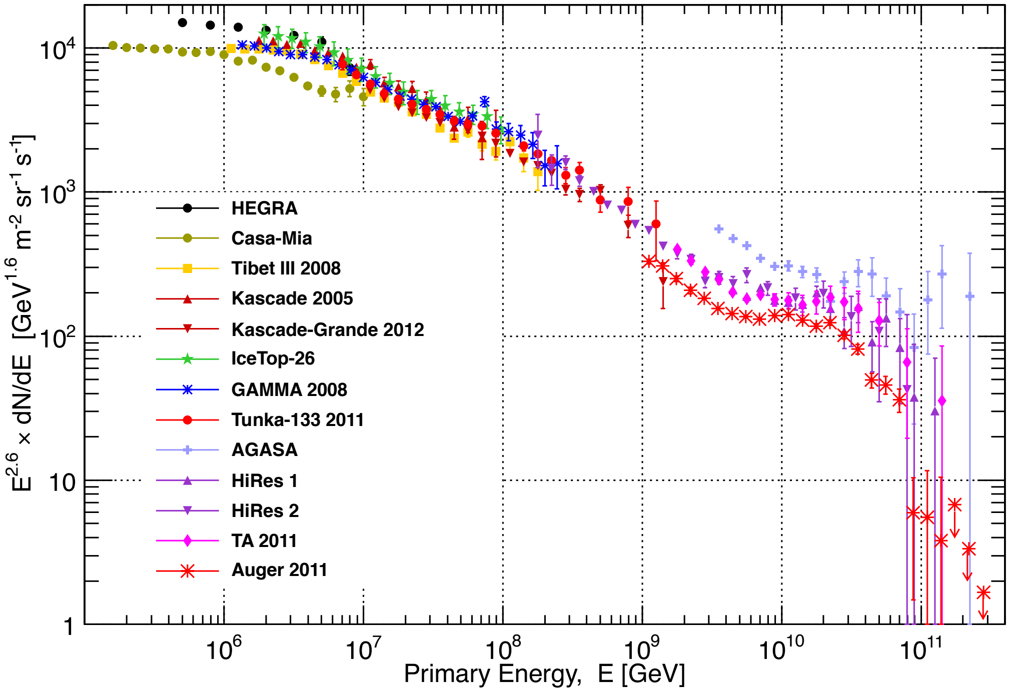


PAMELA /ATIC/ CREAM II
reveal
rigidity dependent
spectral breaks
and
remarkable hardening
after the breaks

Perfect demonstration
of Peters cycle:

When protons accelerated to E^{p}_{max} a nucleus with Ze will be accelerated up to
$E^{z}_{max} = Ze \times R = Z \times E^{p}_{max}$

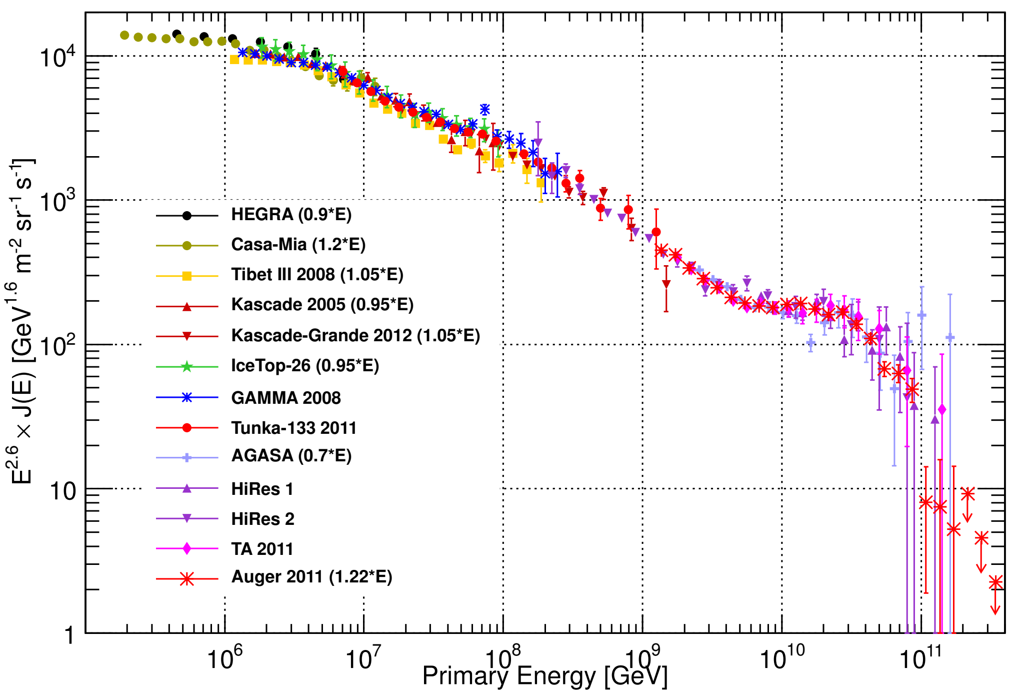
where magnetic rigidity
$R = Pc/Ze$



All Particle Spectrum
from Air Shower Experiments

selection based on variety of techniques:

- cherenkov
- fluorescence
- scintillators
- muon counters

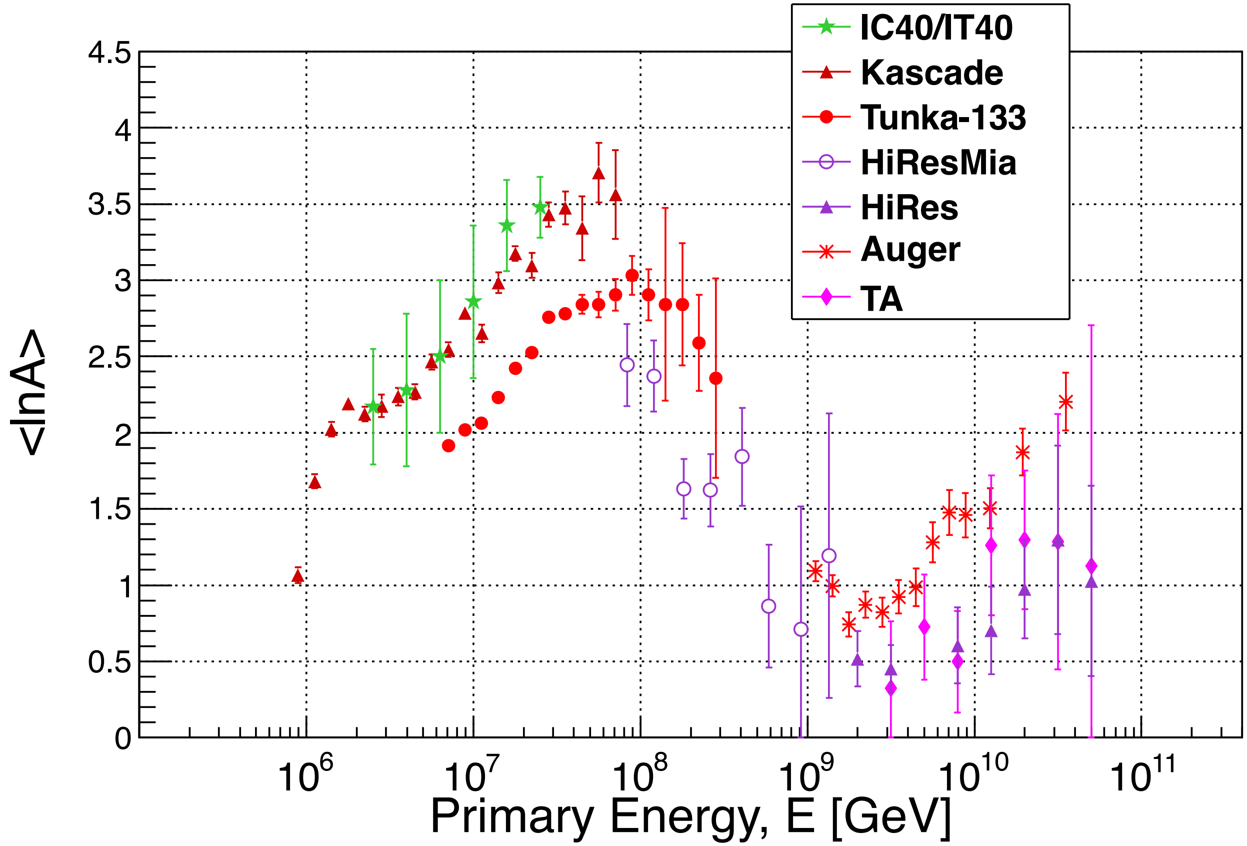


Gaisser's cross-calibrated spectrum:

5-20% energy shift to align features in the spectrum

arXiv:1303.3565 [astro-ph.HE] 14 Mar 2013
Gaisser , Stanev ,Tilav

The mean logarithmic mass <lnA> from Air Shower Experiments

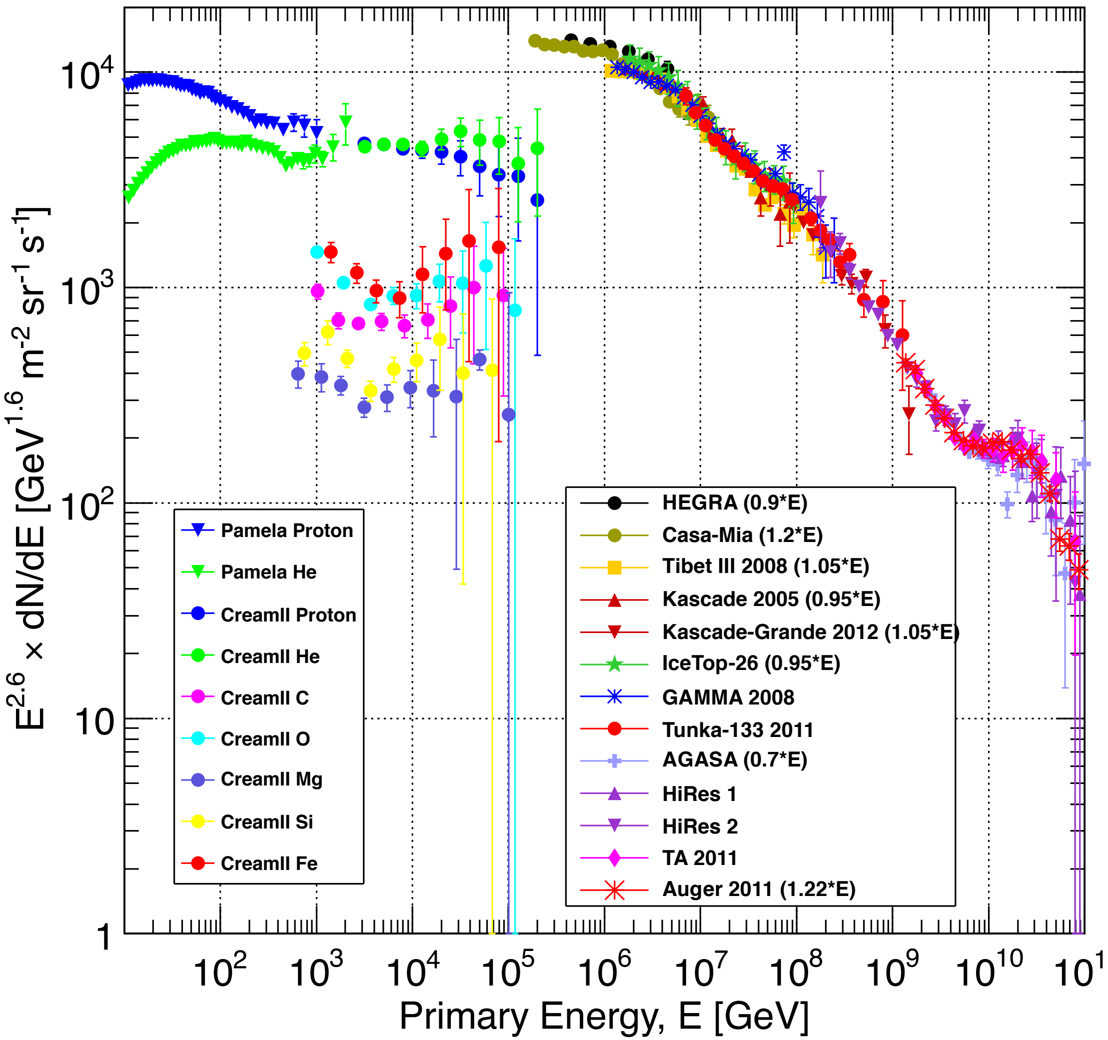


IC40/IT40 and Tunka-133 are published by the experiments

Kascade/HiRes/Auger/TA do not provide <lnA>

Use derived data by Kampert and Unger analysis

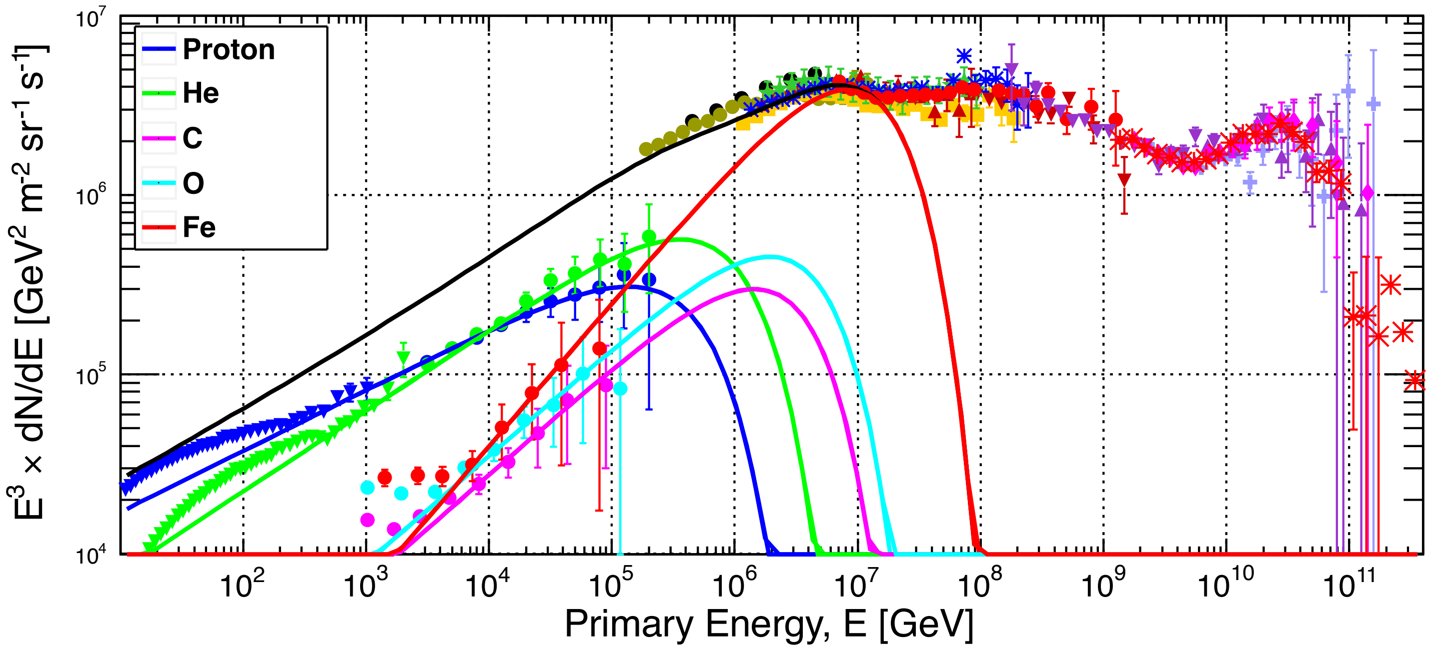
K. H. Kampert and M. Unger, Astropart. Phys., 2012, 35(10): 660



Fit the combined spectrum with Gaisser's formulation of Peters cycle

$$E\frac{dN}{dE} = \sum_{i}^{elements} A_i E^{-\gamma_i} e^{-\frac{E}{Z_i E_{cutoff}}}$$

A	Amplitude
γ	spectral index
$Z * E_{cutoff}(PeV)$	Z dependent cutoff energy



Amplitudes and indexes of all elements are defined by the CreamII data. Only the cutoffs need to be fit.

Fe spectrum is the key to the whole puzzle.

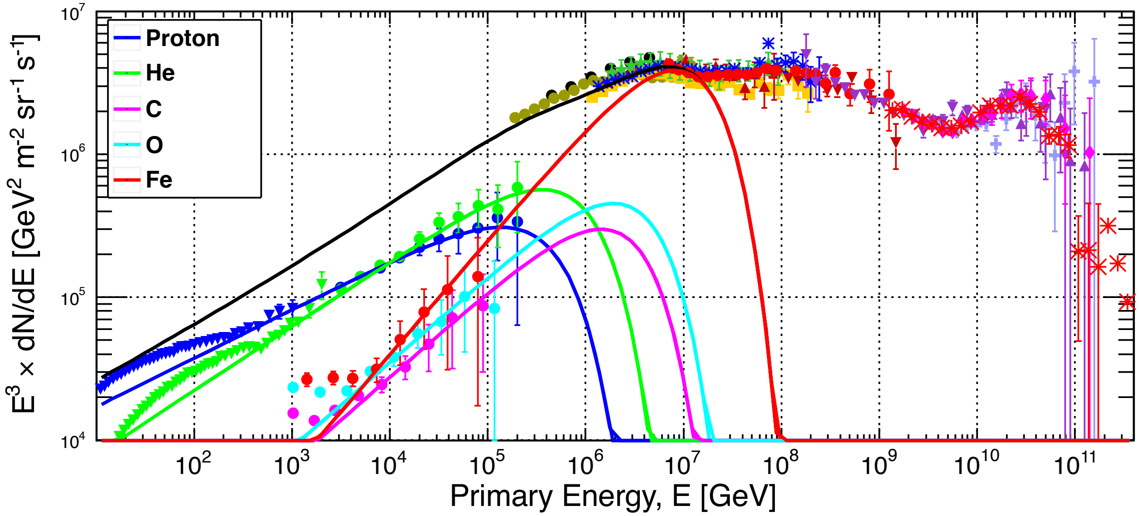
The Cream Fe data, when extended with the same index up to an energy where it makes 100% of the all particle spectrum, defines the maximum cut off energy for Fe.

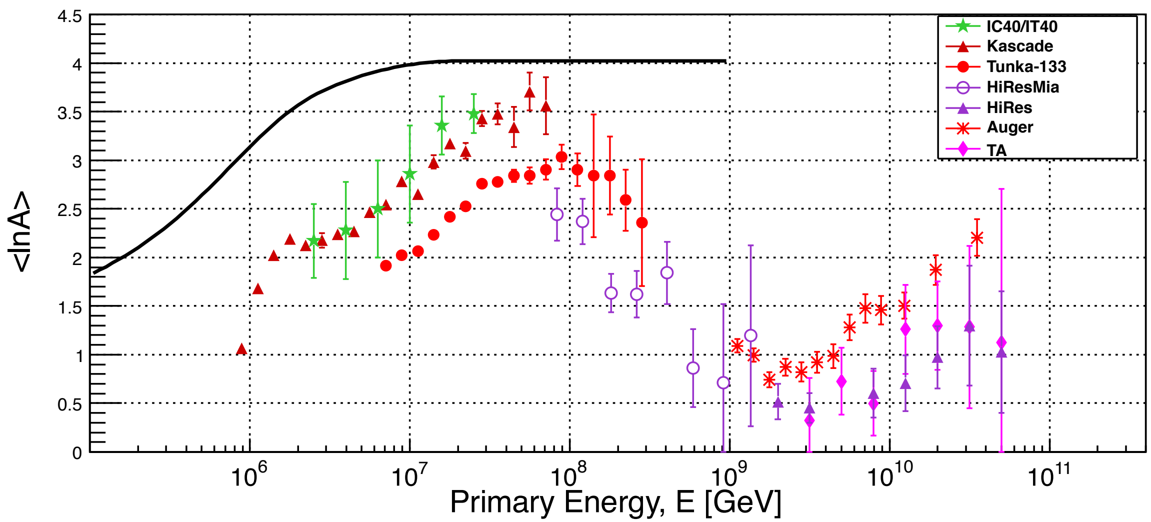
This point turns out to be 26*400 TeV = 10.4 PeV.

This means proton cuts off at 400 TeV

Amplitudes, integral indexes, cutoff energies

Proton: 7800, 1.66, 400 TeV
He : 2800, 1.58, 2x400 TeV
C : 110, 1.4, 6x400TeV
0 : 140, 1.4, 8x400 TeV
Fe : 25, 1.2, 26x400 TeV



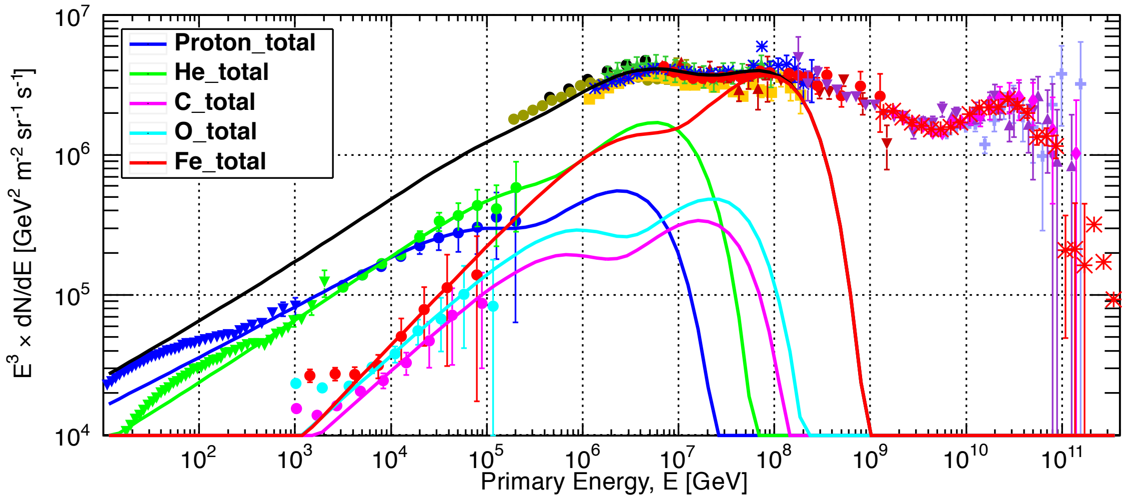


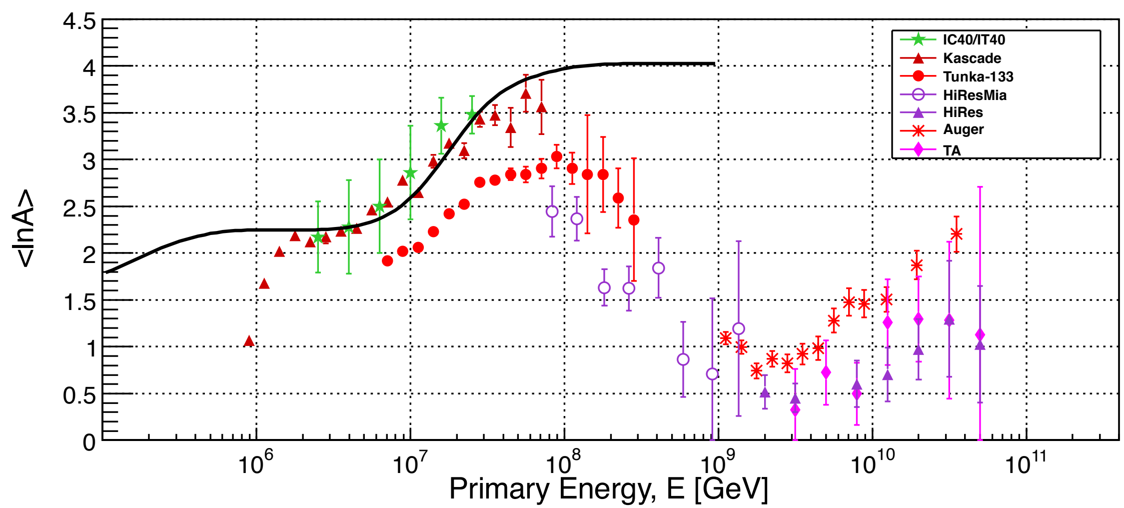
However

<lnA> data tells us
the knee is not 100% Fe.

Since the amplitudes are locked
by the Cream data,
the only way to bring it down is
to bring its cutoff down

and fill the rest with light elements
of a new Peters cycle
(a new population of particles)





== Method ==

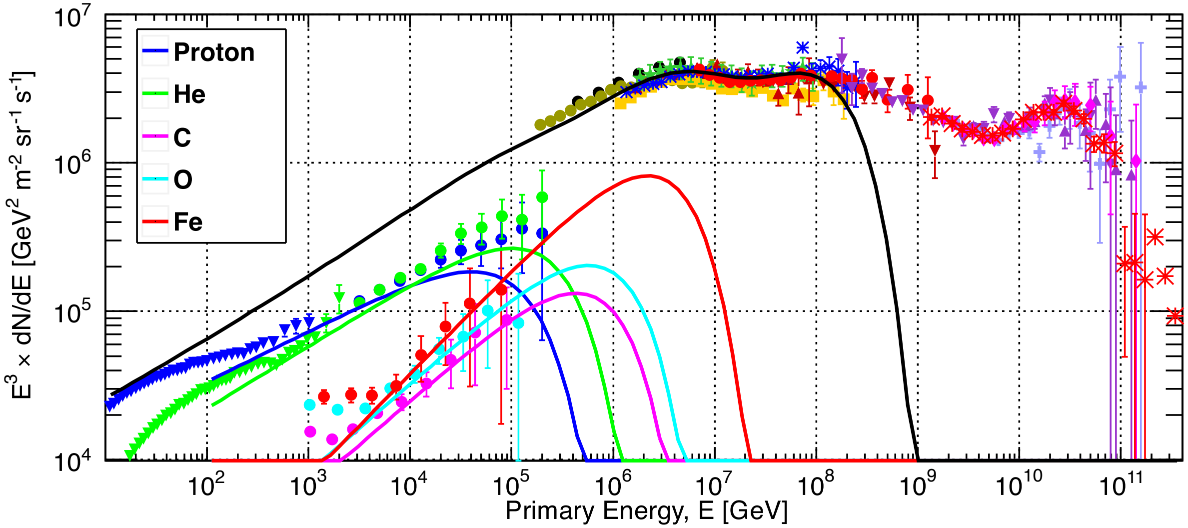
Make a template for Population 2 similar to Population 1

Scan for cutoff energy by sliding the template until best agreement with lnA is reached.

The cutoff energies defined by the proton under the first iron (according to lnA) and the second iron not to overproduce the spectrum around 100 PeV.

Initially the indexes are same as Pop1
Next, the amplitudes are adjusted by fitting Pop1+Pop2 elements to CreamII+ ShiftedSpectrum.

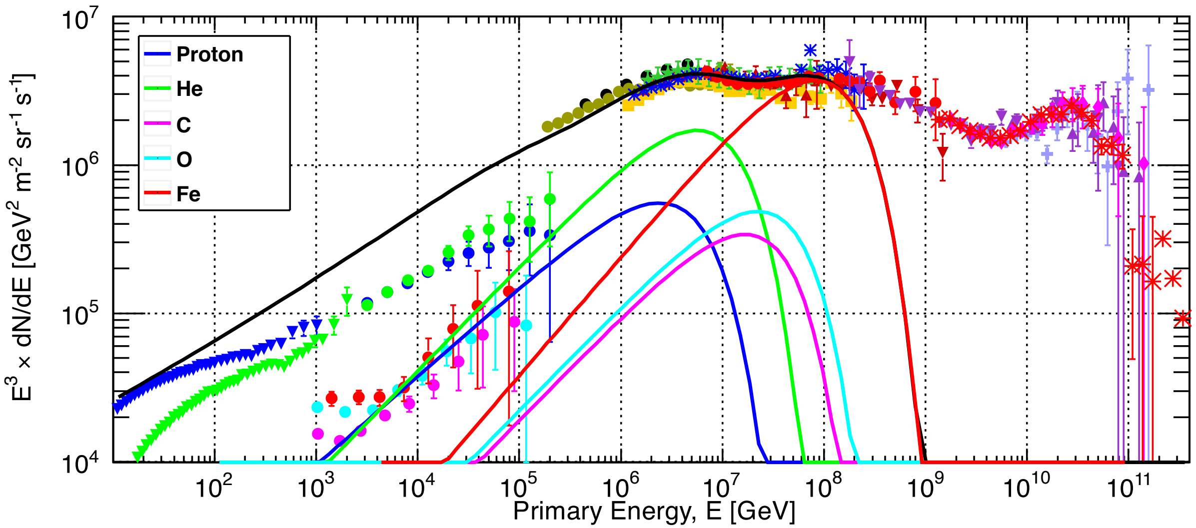
Pop1 cutoff energy comes down from 400 TeV to 120 TeV,
and Pop2 Indices are adjusted, amplitudes are fitted again.



Population 1 alone after Population 2 injected

in order to accommodate Pop2 overlapping with Pop1, the cutoff energy of Pop1 comes down to 120 TeV after the fits.

Note: there is yet another population before Pop1. When data below the breaks are fitted with another population Pop1 fit parameters change slightly. The biggest change is the spectral indexes for Proton and He and 90 TeV < E^{1}_{cutoff} < 150 TeV



Population 2 alone

Pop2 cutoff at 4 PeV gives the overall best fit. (Fe cuts off at 26*4= 104 PeV)

Note:
When Pop0 is fitted this cutoff changes along with the Pop1 cutoff.

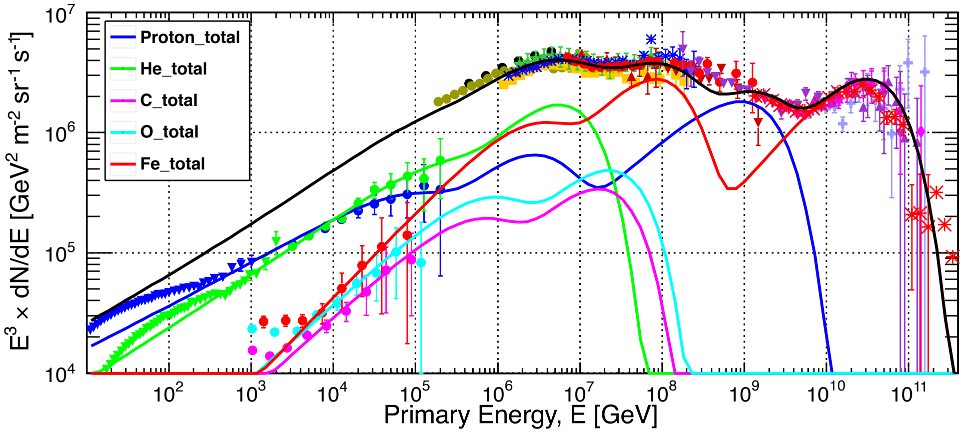
3.5 PeV < E^{2}_{cutoff} < 4.5 PeV

Proceed with the same method to inject another Peters cycle as Population 3

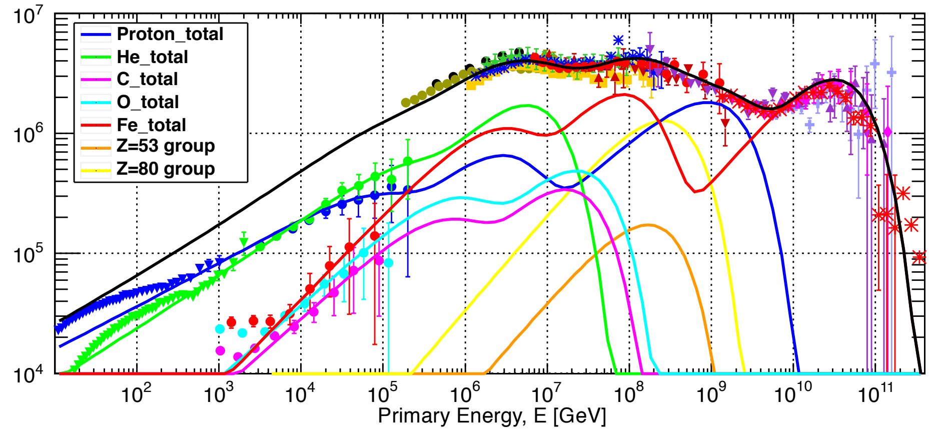
The best fit is achieved with only Proton and Iron making up the spectrum, other elements are reduced to negligible amounts.
However, a gap is left between Pop2 and Pop3 and lnA is not described well.

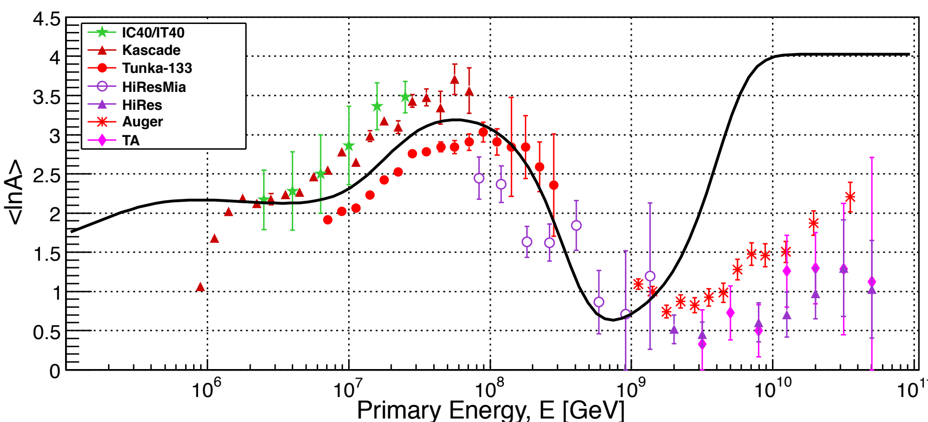
It was necessary to include the ultraheavy element groups as inspired by the lowE CR measurements

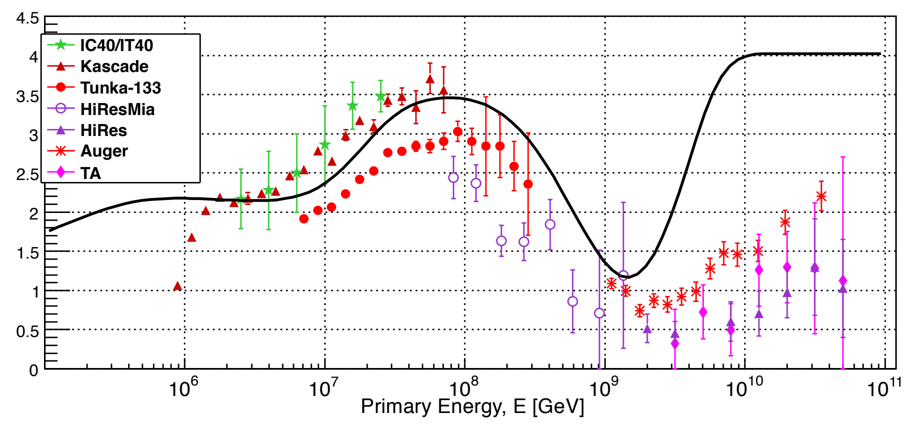
without ultraheavy nuclei



with ultraheavy nuclei



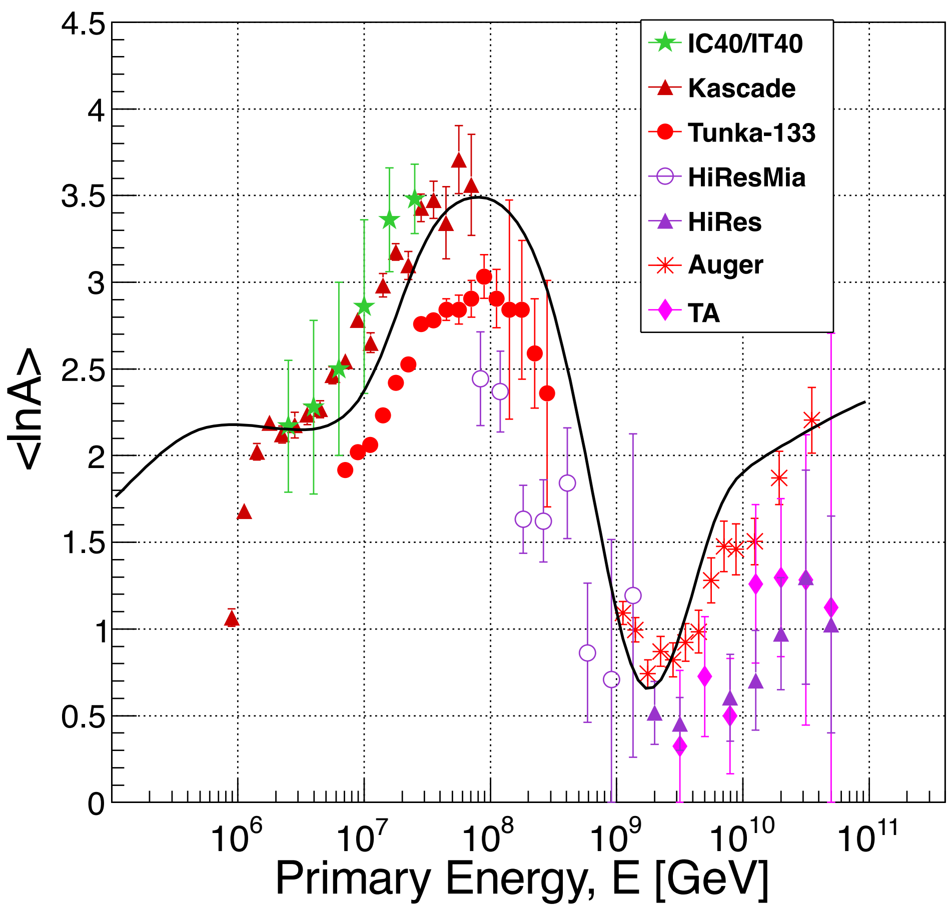


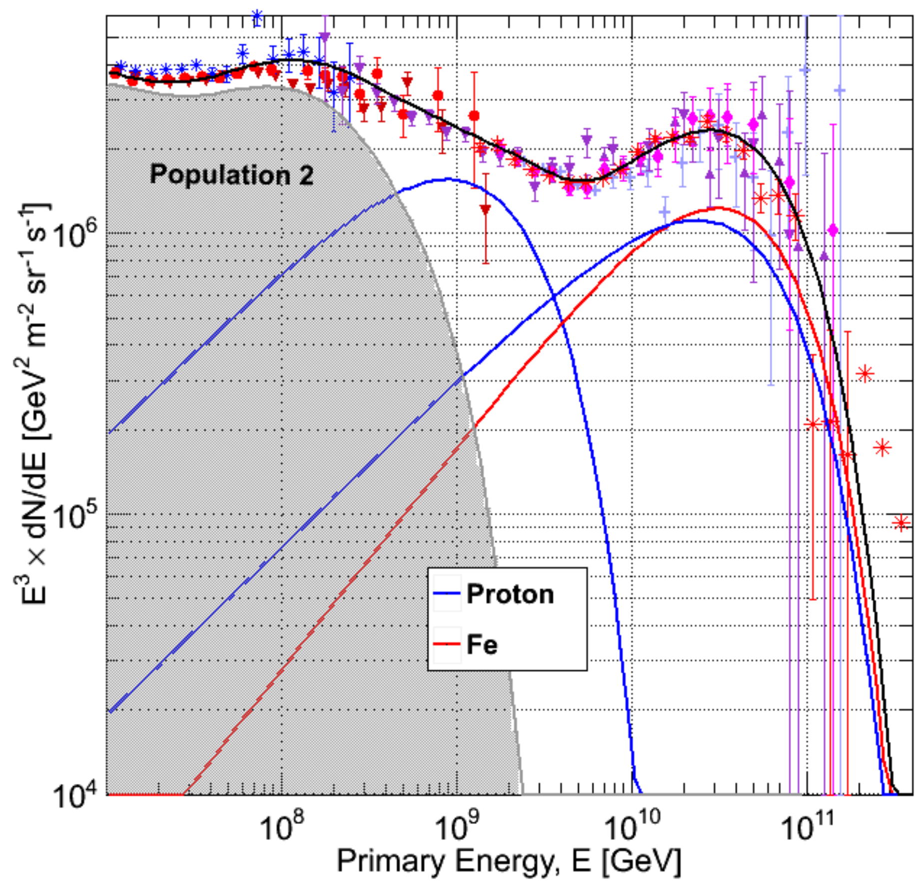


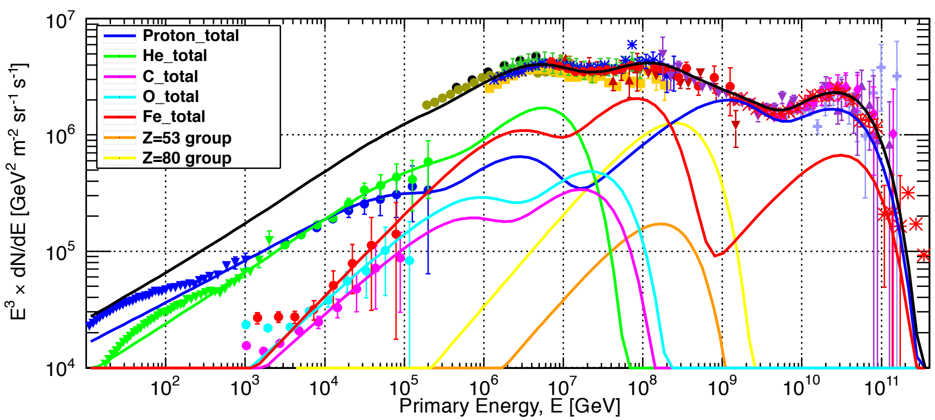
There has to be another proton under the iron bump to bring <lnA> down

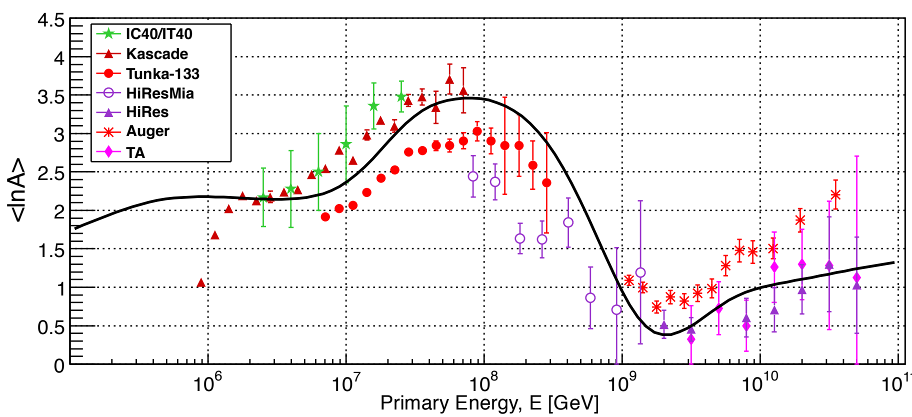
This extra proton has a much harder spectrum with $E^{-2.2}$ and cuts off around 22 EeV

➔ extra-galactic proton cutting off due to GZK?



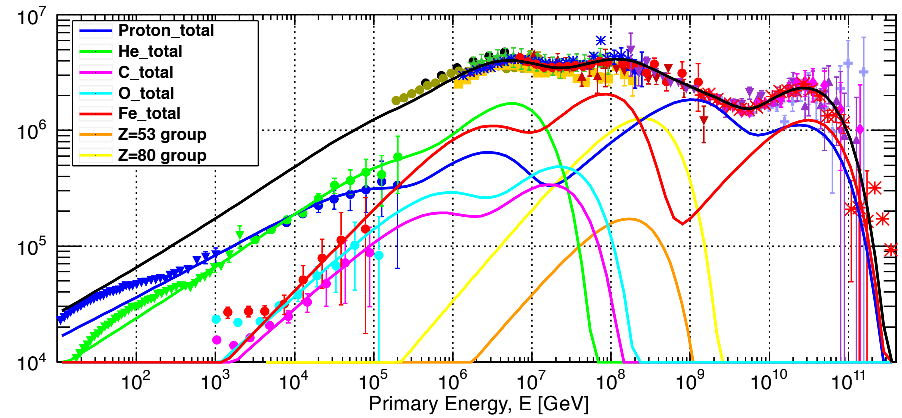


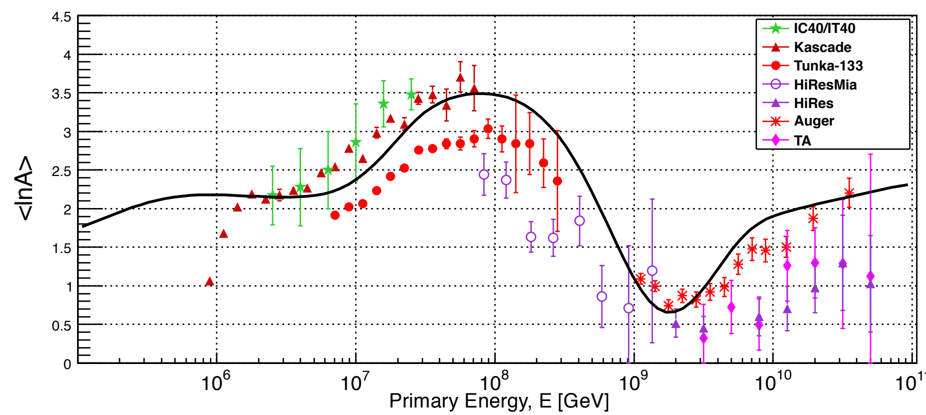




Pop3 for TA/HiRes

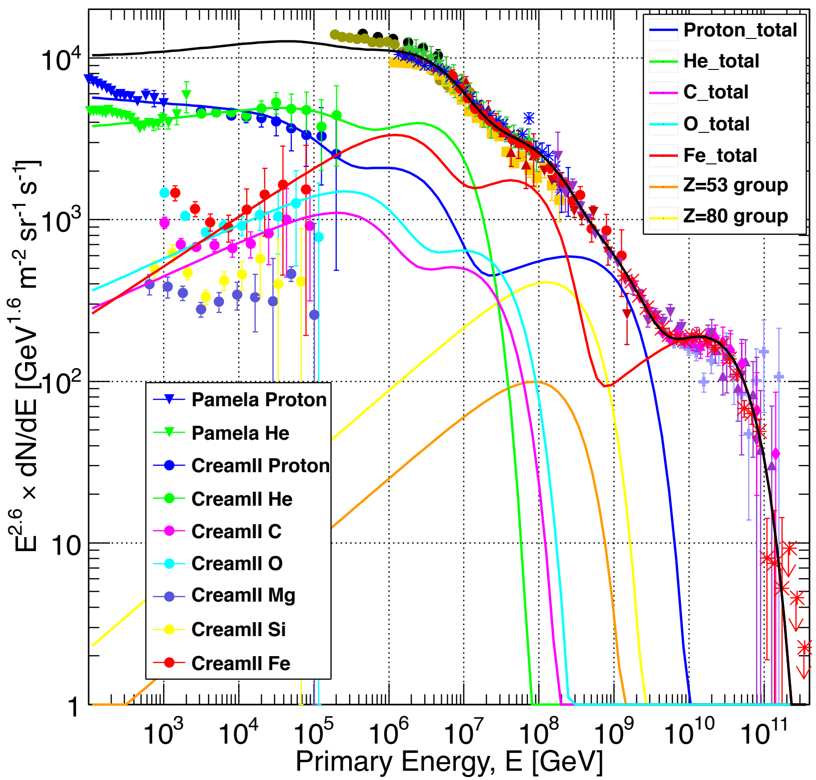
Pop4 Proton makes up most of the bump.

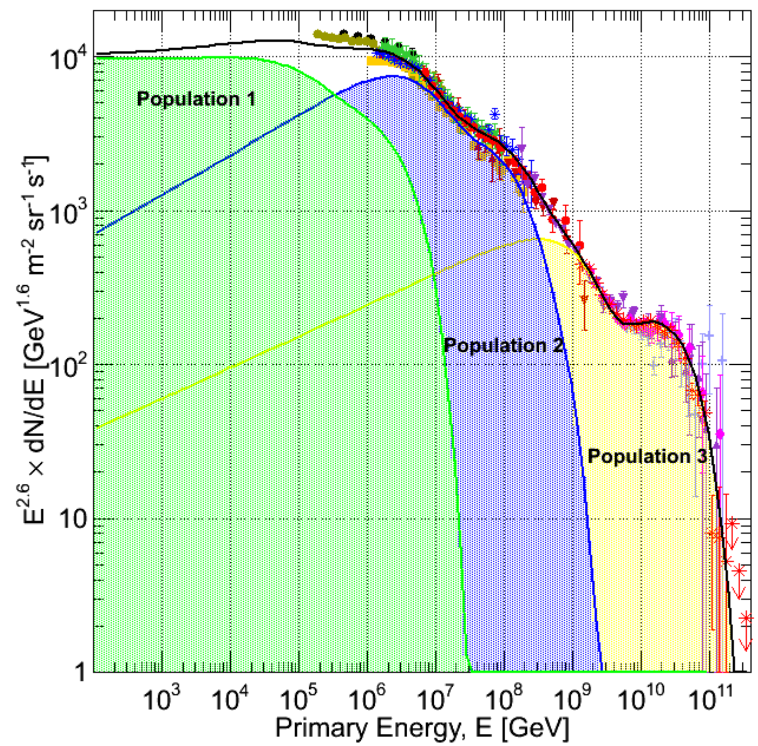




Pop3 for Auger

Pop3 Fe + Pop4 Proton make up the bump.





At least 3 Populations of Peters Cycle are needed to explain the spectrum and <lnA> from ~ 200 GeV up to 200 EeV

Population 1: The classical supernova cutting around 100 TeV
Population 2: “Galactic PeVatron” to produce the IceCube neutrinos
Population 3: Another powerful source superposed with extra-galactic protons cutting by GZK

Spectral index of 2.7 is the superposition of much harder indexes of elements