Cosmic ray spectrum and mass composition from IceTop and IceCube

TeVPA 2018, Berlin

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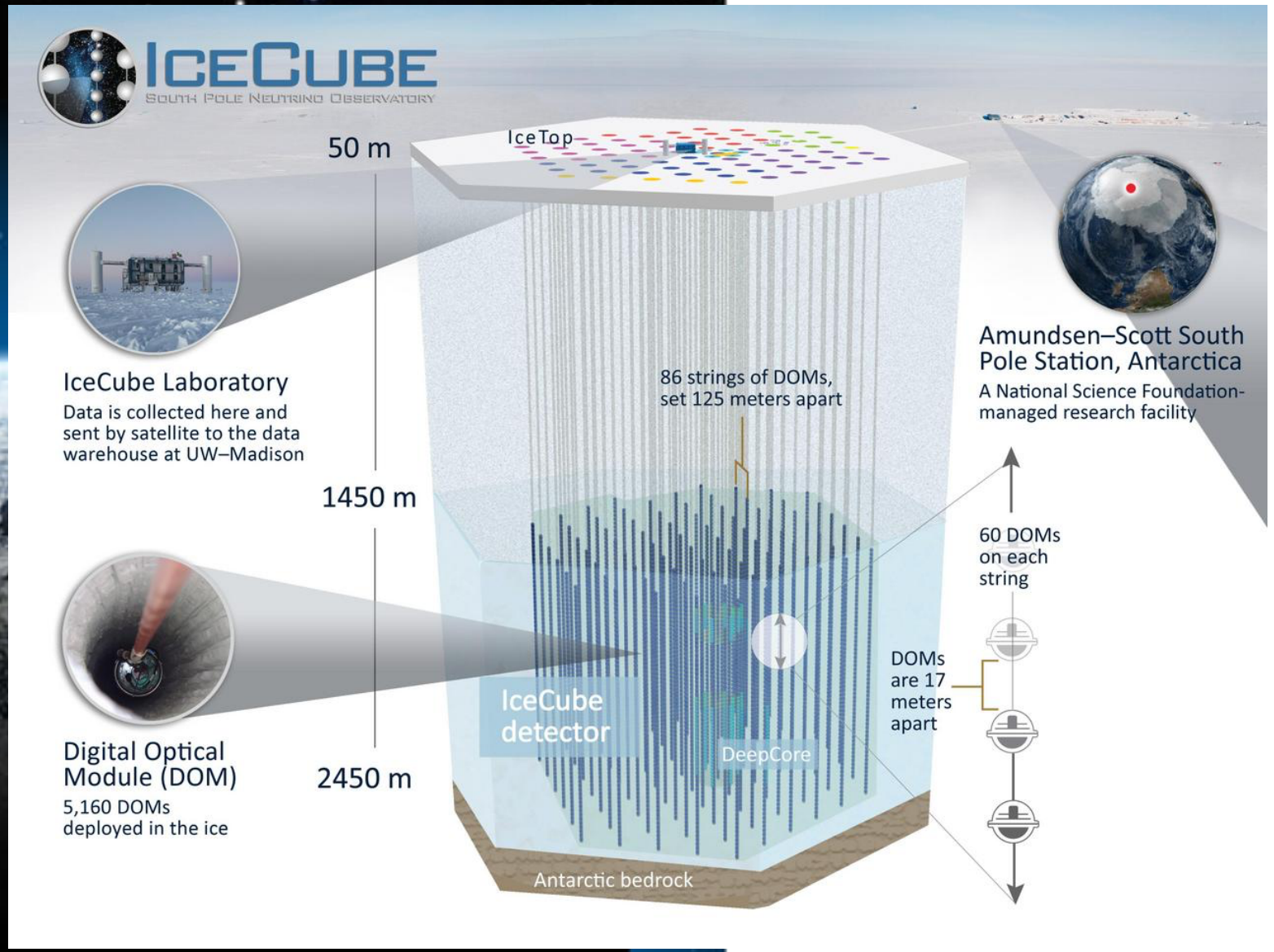
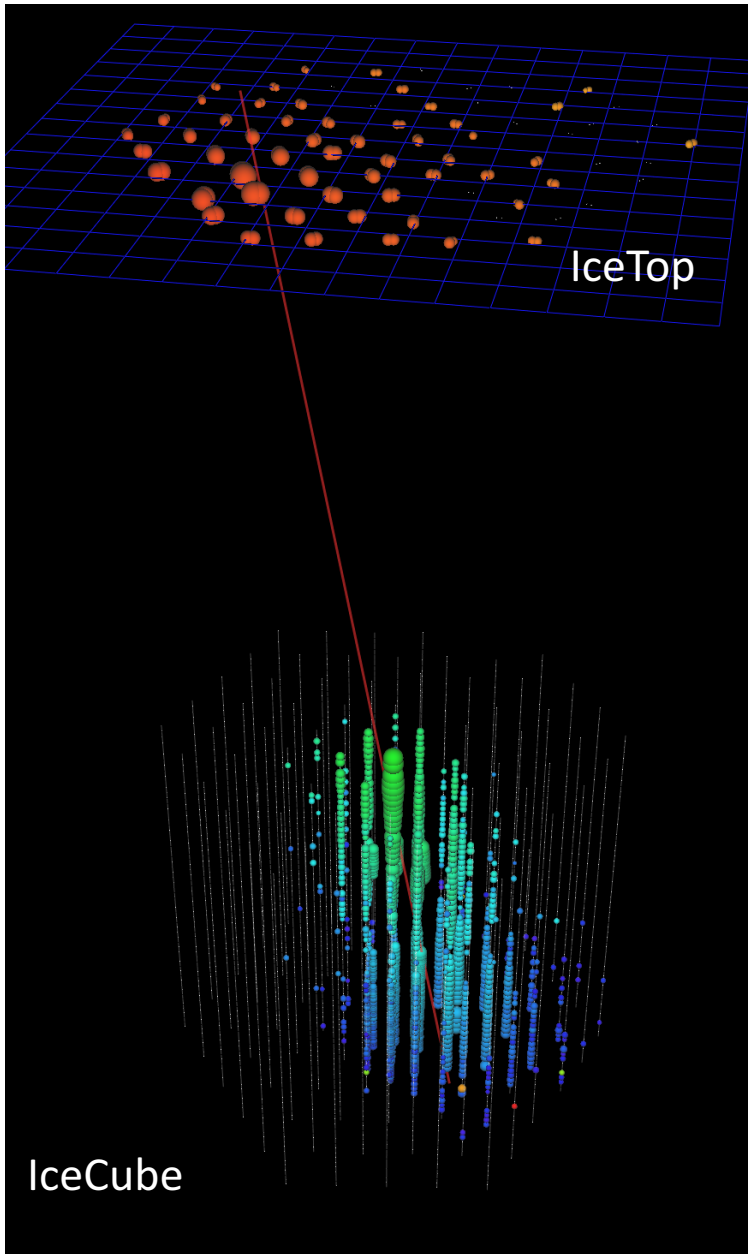
Outline

- Introduction
- Energy spectrum & Composition
  - IceTop Analysis
  - IceTop/IceCube Coincidence Analysis
- Summary

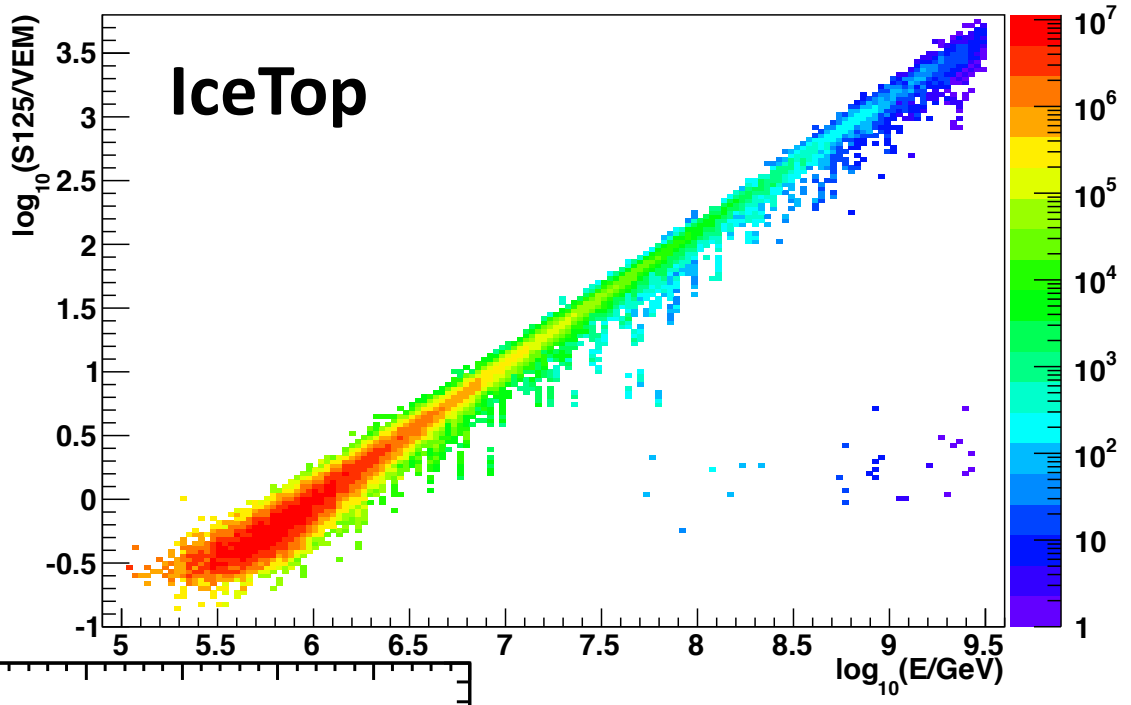
IceCube Neutrino Observatory

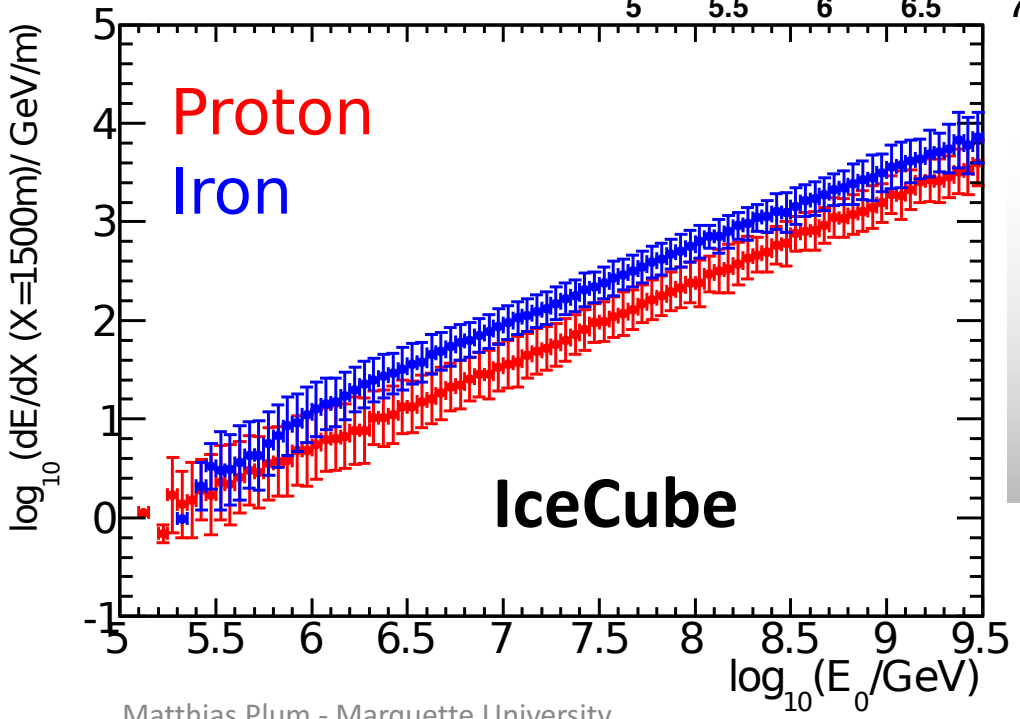


Reconstruction



- 'Shower size' S_{125} is signal strength measured in vertical equivalent muons (VEM) at 125m
- Only small composition sensitivity

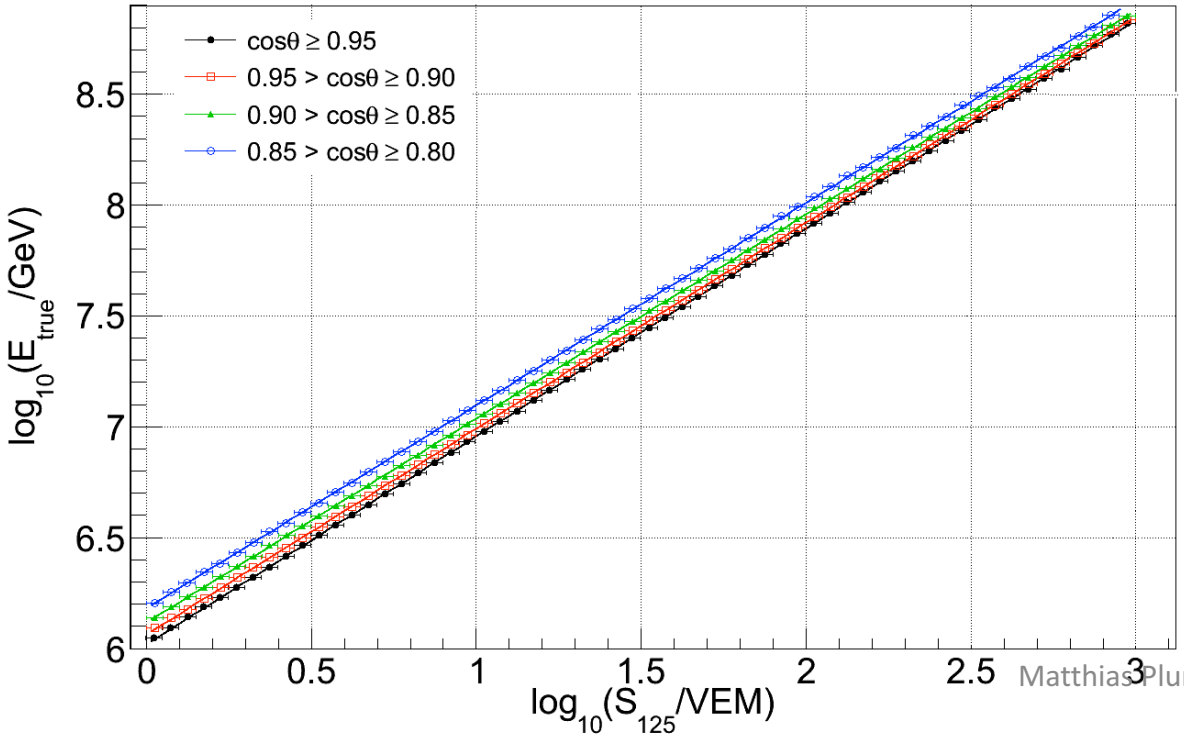




- Energy loss dE/dX at a fixed slant depth of X=1500 m in the glacial ice
- Good composition sensitivity

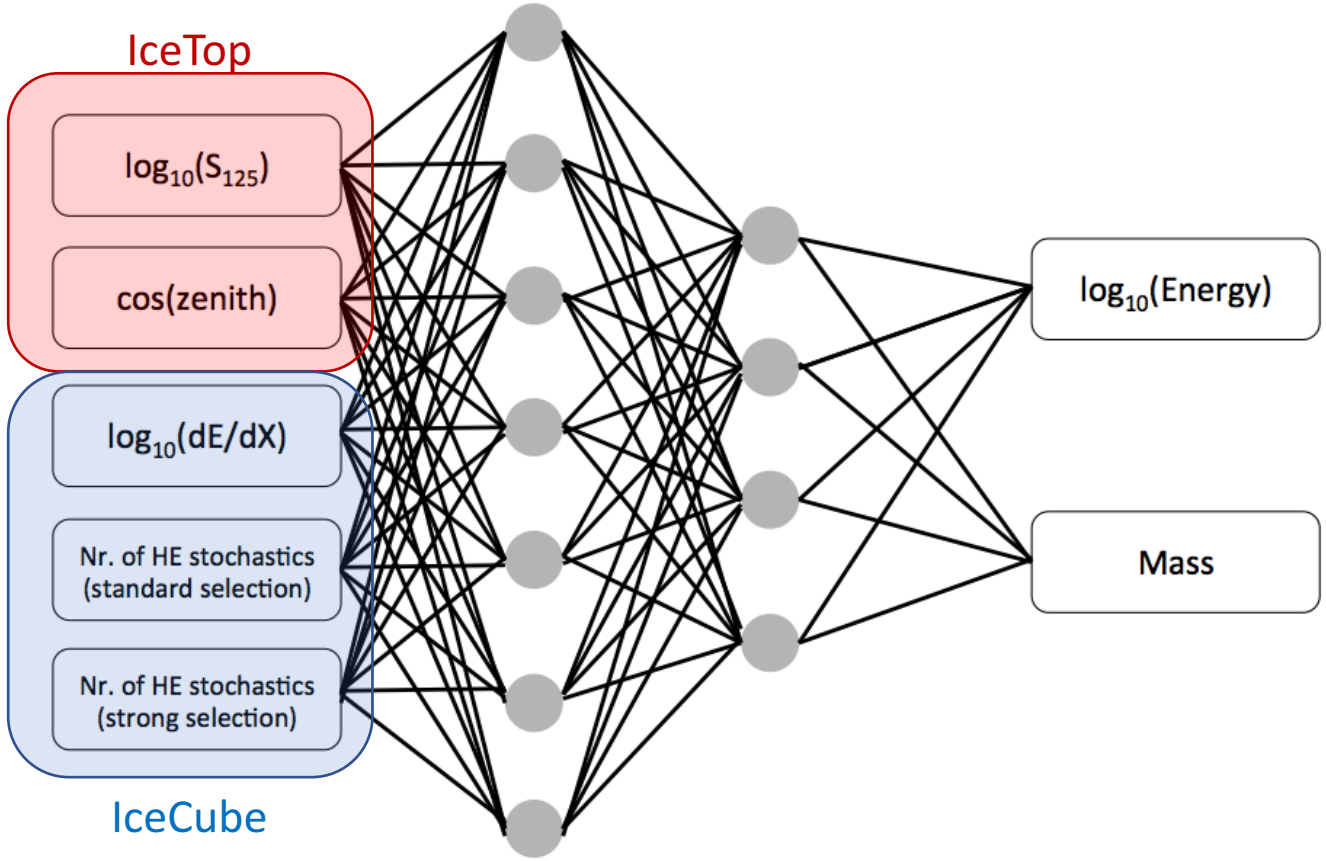
IceTop Only

- Energy reconstruction using maximum-likelihood procedure
- Reconstruct core position, direction and shape/normalization of LDF from the deposited charge
- Includes effects snow coverage by assuming an ‘effective attenuation length’ λ (range 2.10 – 2.25m)

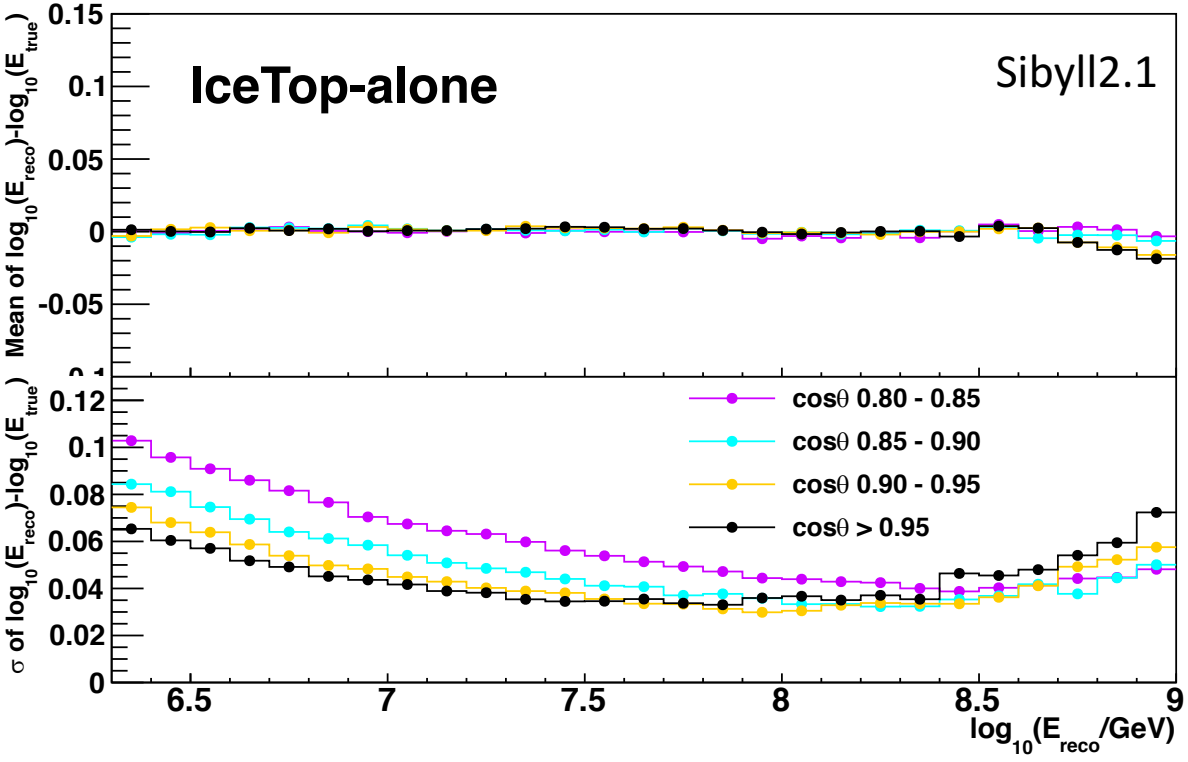


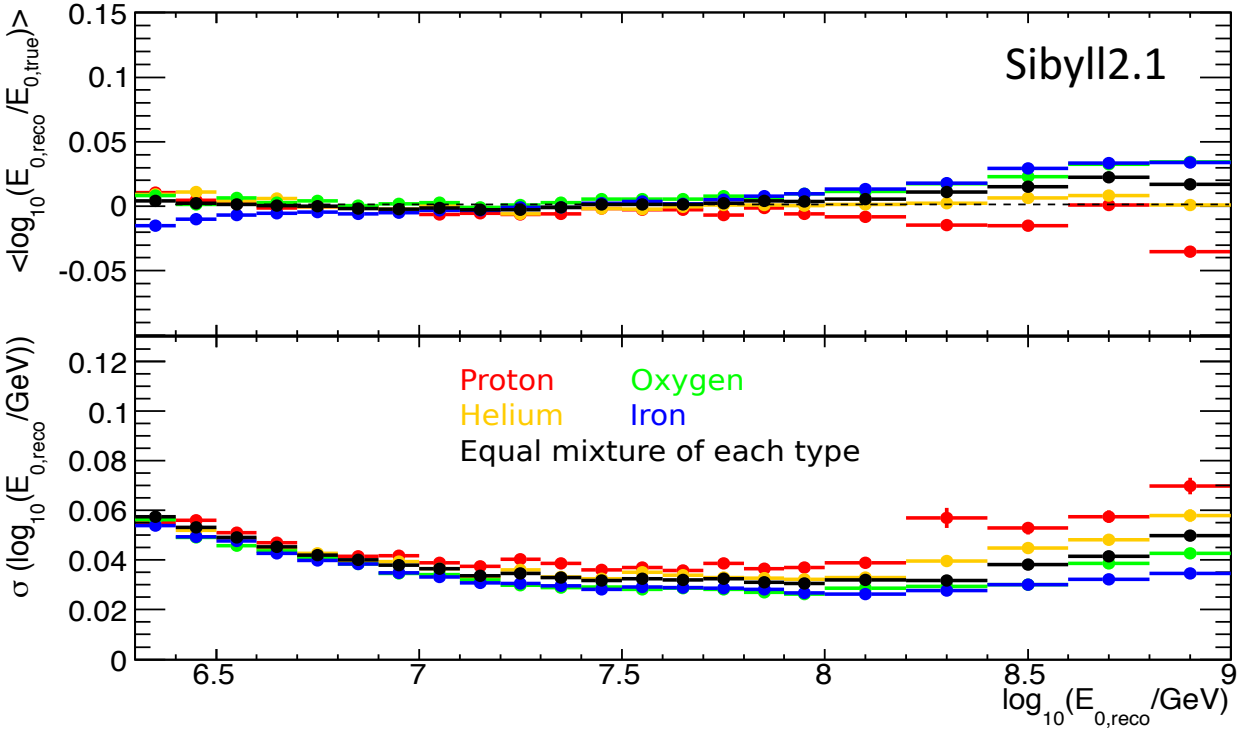
IceTop/IceCube Coincidence

- Energy & Mass reconstructed with neural network
- Use best available detector simulation including snow coverage



Energy Reconstruction & Resolution



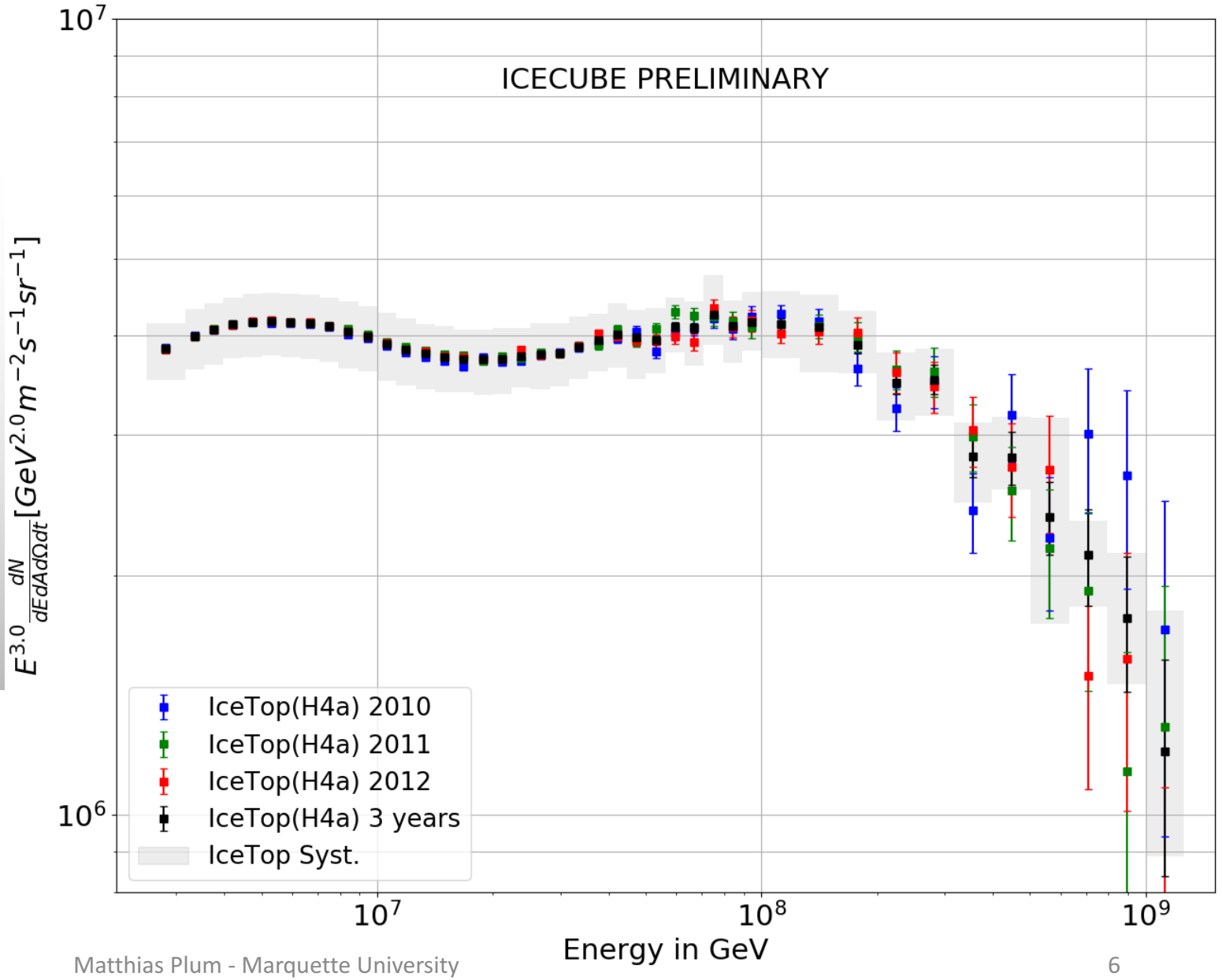


Both analyzes have a small energy bias and and a tight resolution

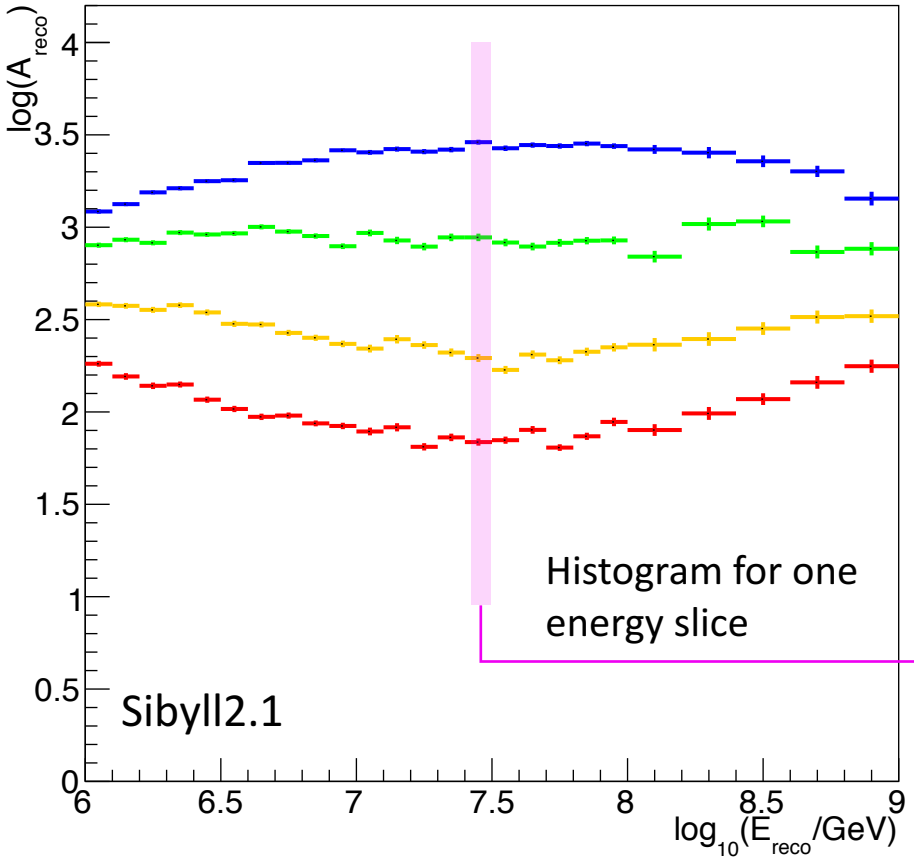
Energy Spectrum IceTop Only

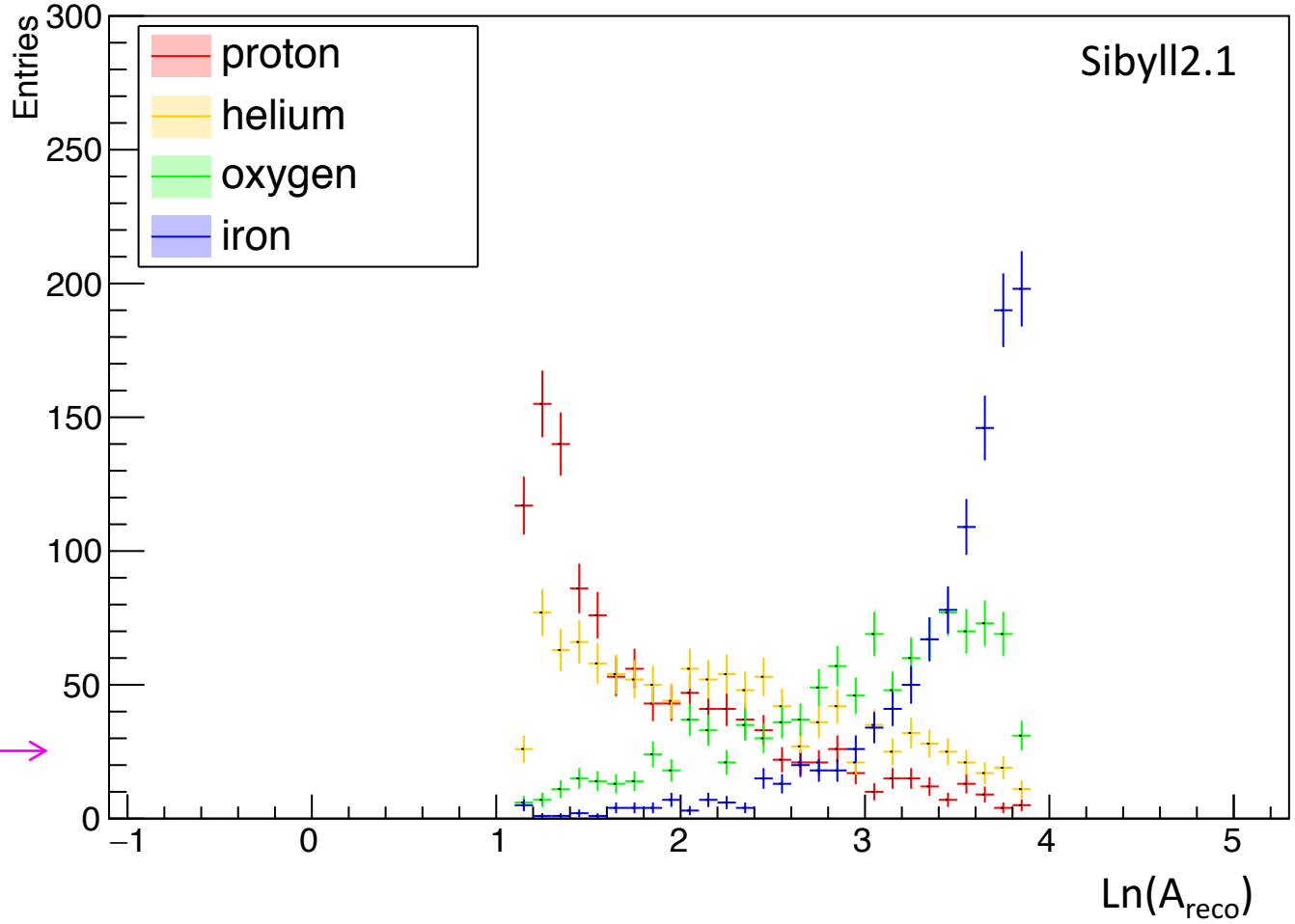
- Total uptime from June 2010 to May 2013 - 977.6 days
- Composition assumption from H4a model

➢ Divided data set into individual years show good agreement with each other



Mass Reconstruction



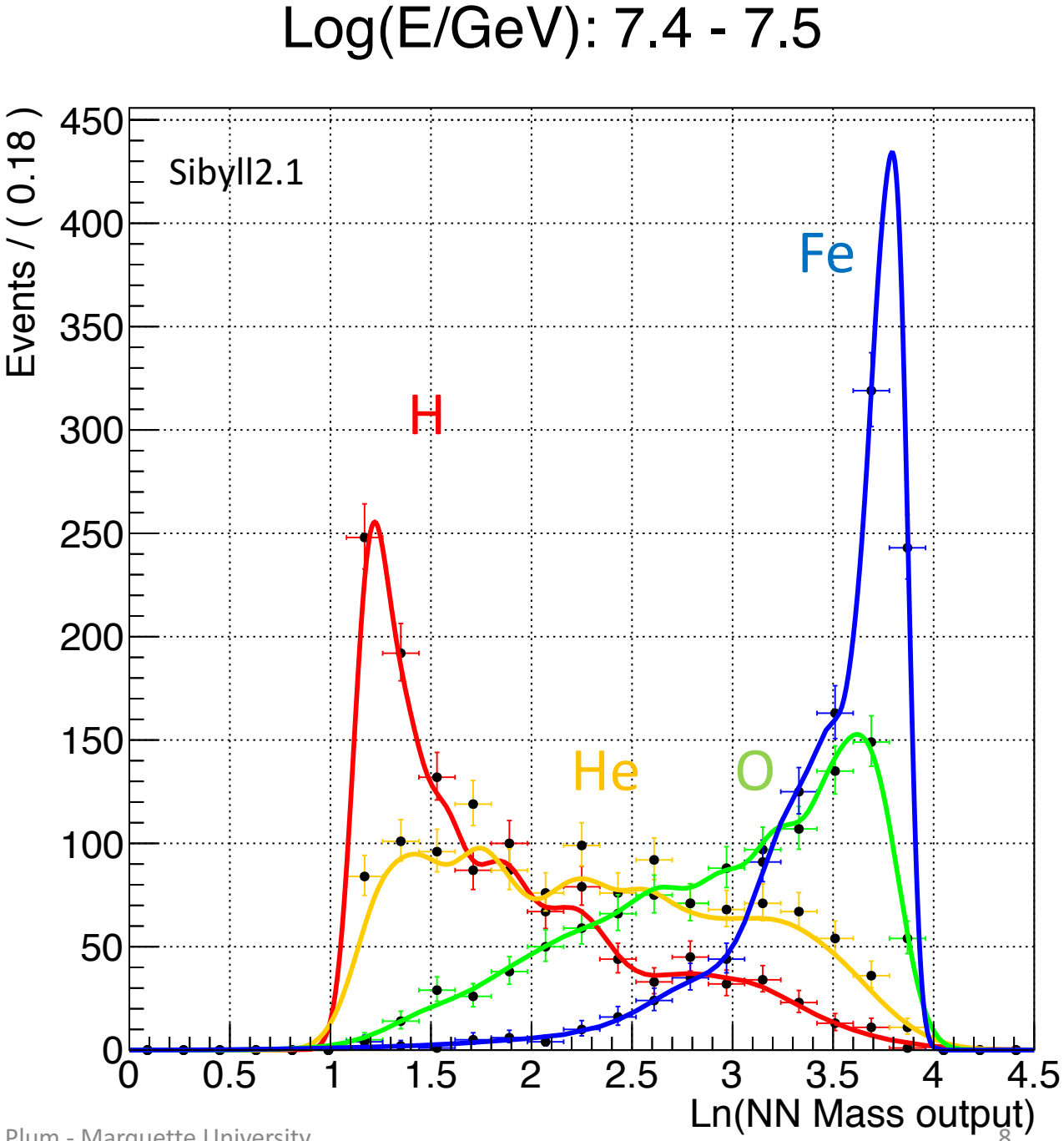


- Mass types reconstruction needs an extra step
  - ➢ Event-by-event classification not possible

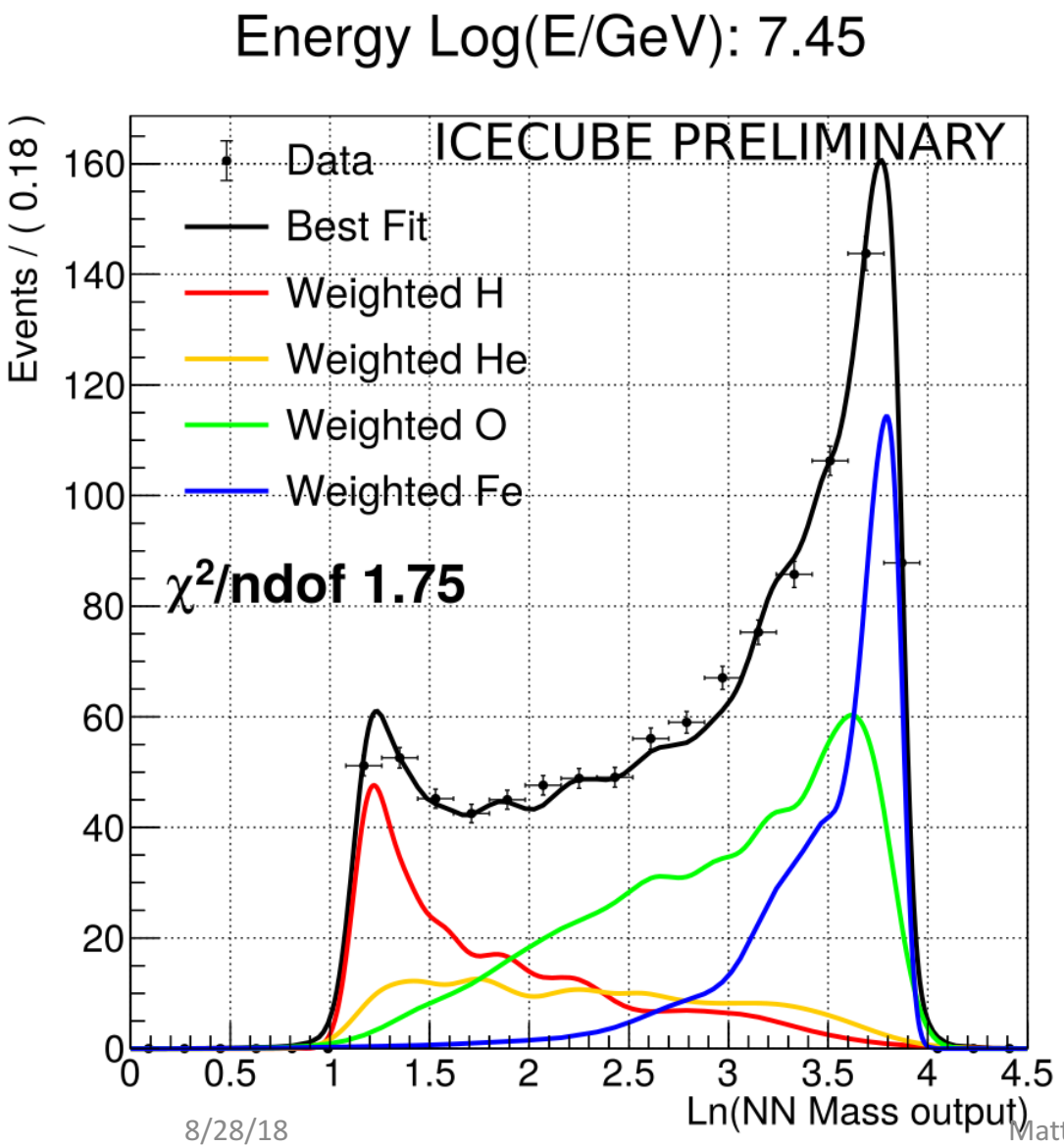
→ Analyze mass as a function of energy on statistical bases

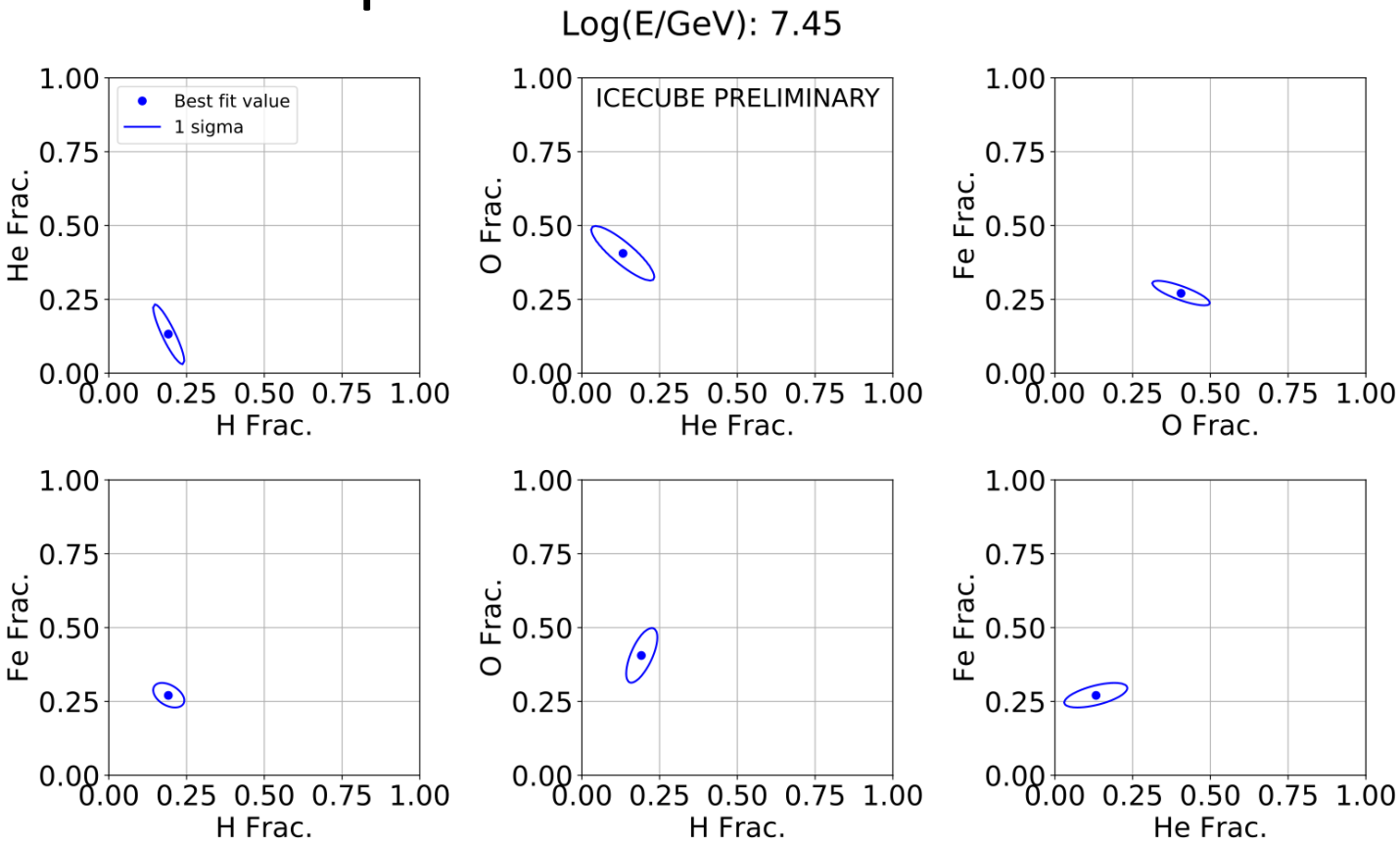
KDE templates

- Monte Carlo data converted into template 'probability density functions' (PDF) for each primary in each energy bin
- Used adaptive Gaussian kernel width to preserve characteristic features of neural net output
- PDFs used in extended Likelihood analysis



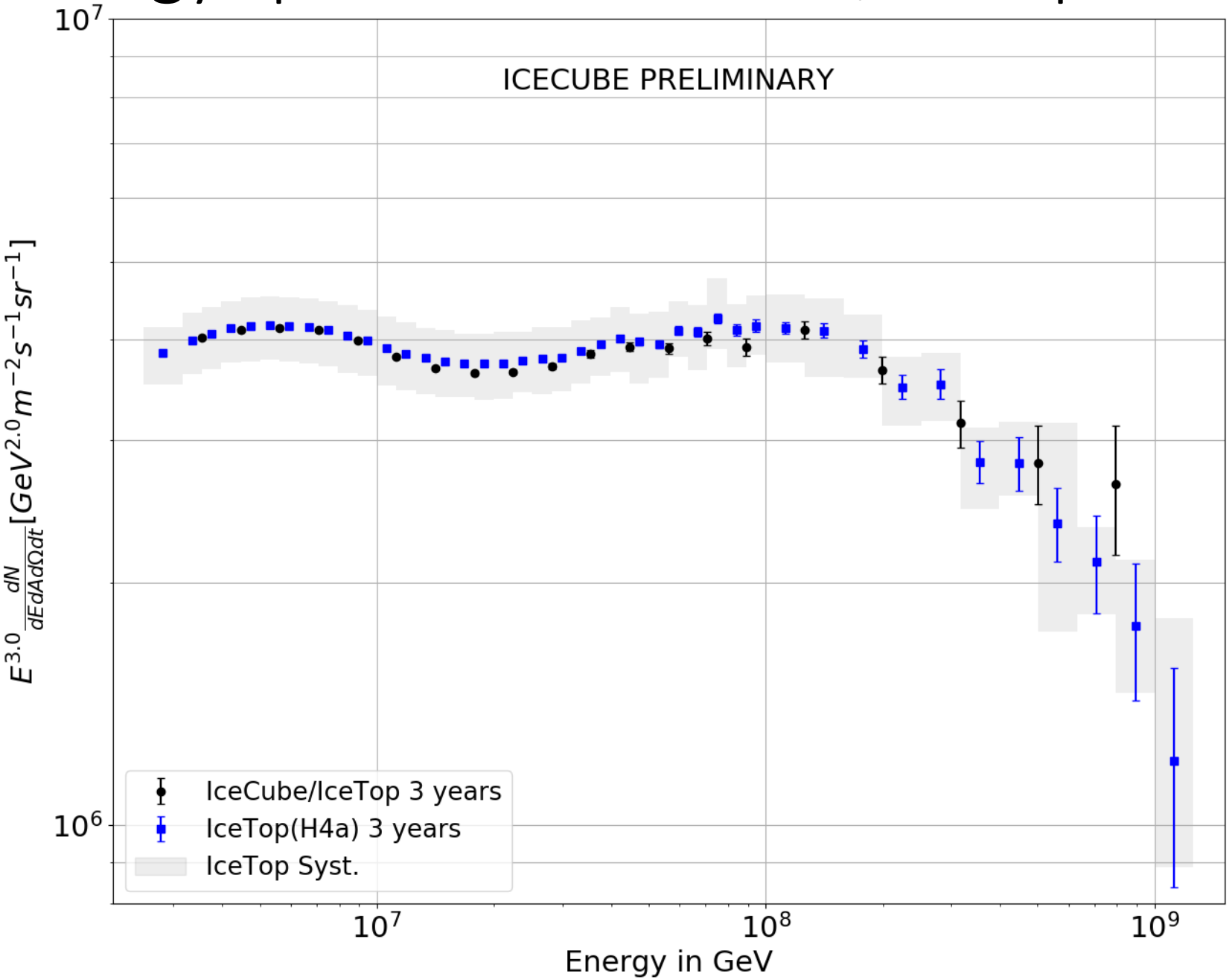
Application to Data – Example Bin





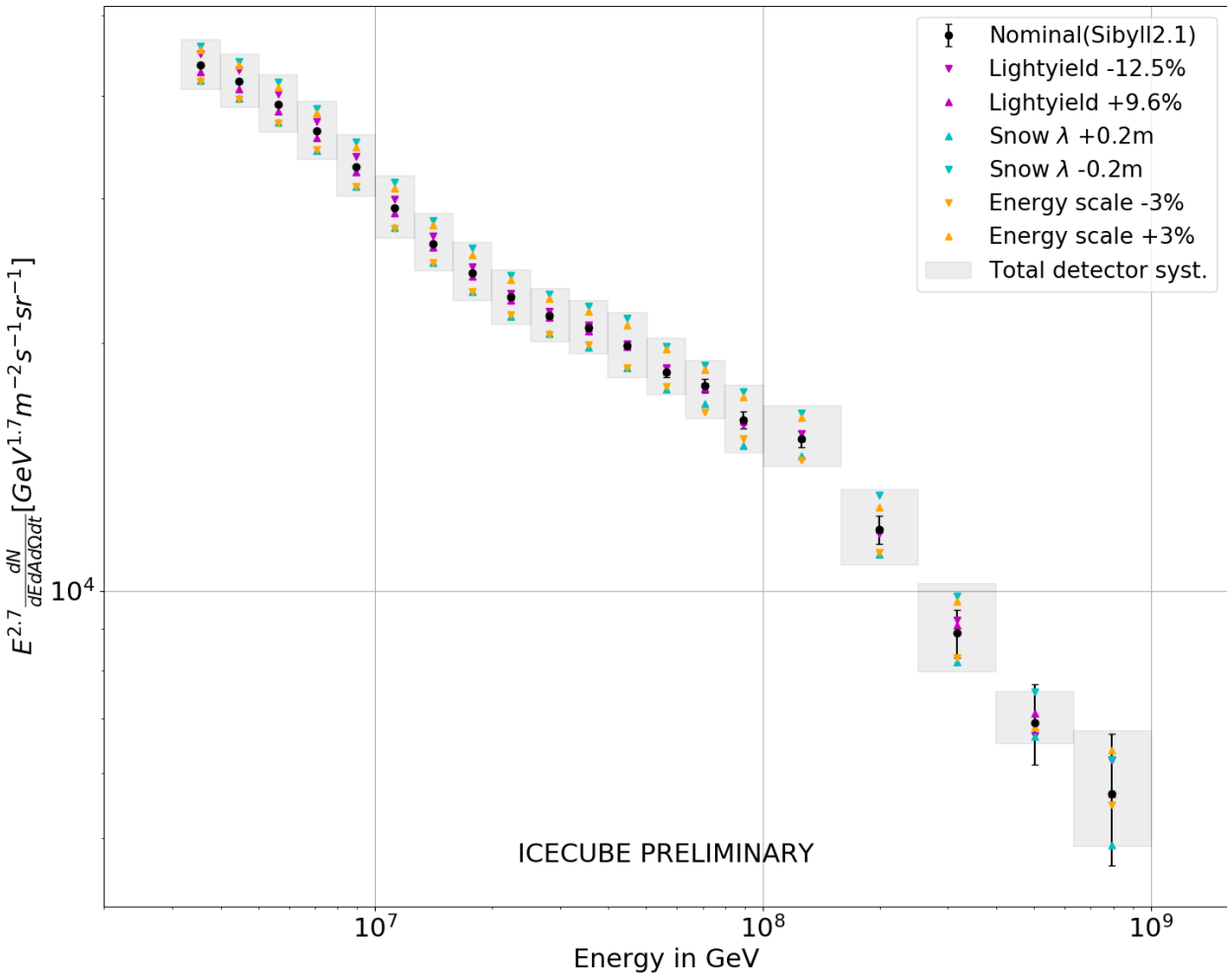
- Data in each energy bin are weighted with corresponding sets of templates
- Weights correspond to a mass fraction
- Strong correlation between neighboring primaries

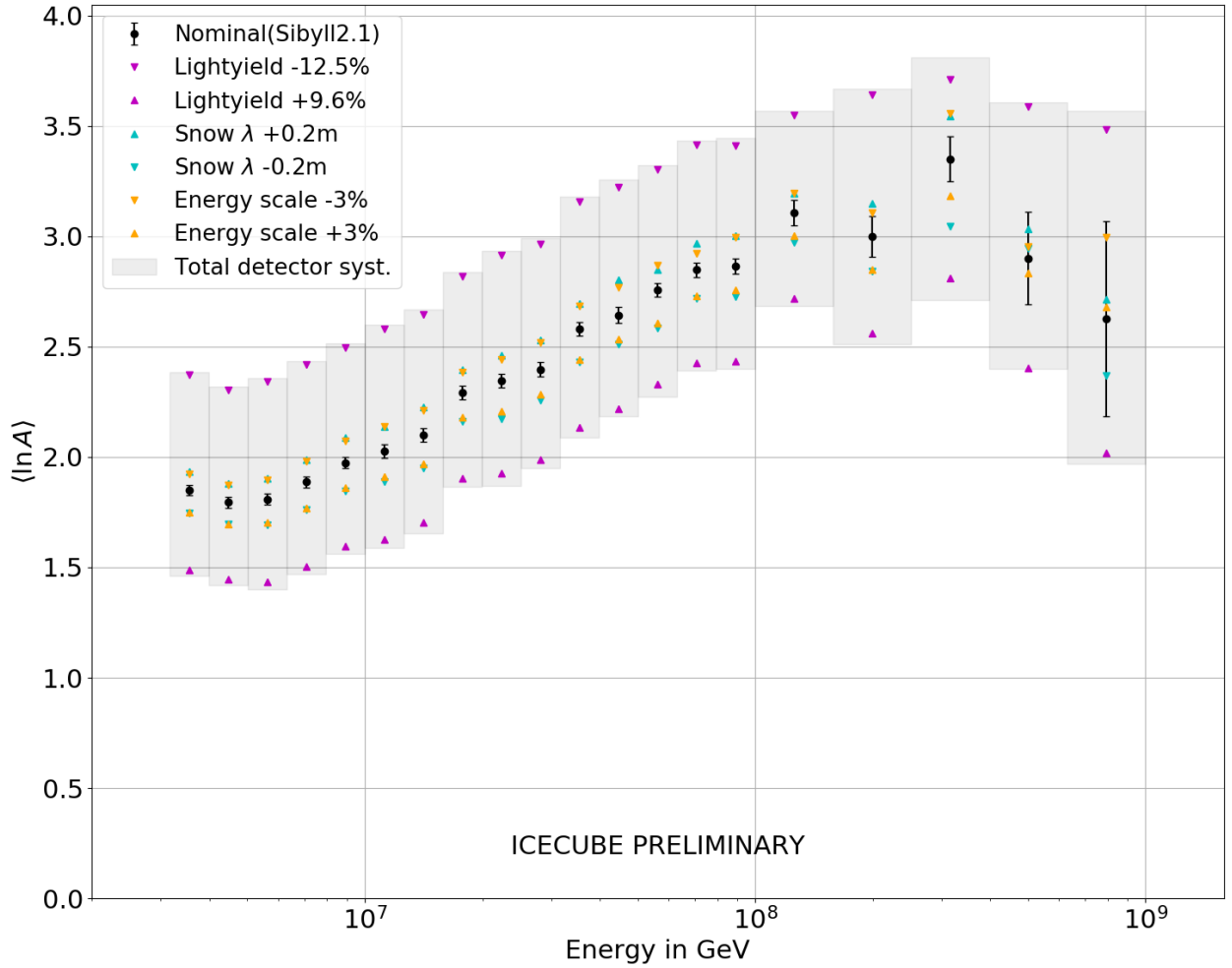
Energy spectrum - IceCube/IceTop vs. IceTop Only



- Due to constrains for the coincidence analysis smaller energy range than IceTop Only
- Good agreement between the energy spectra of both analyses methods

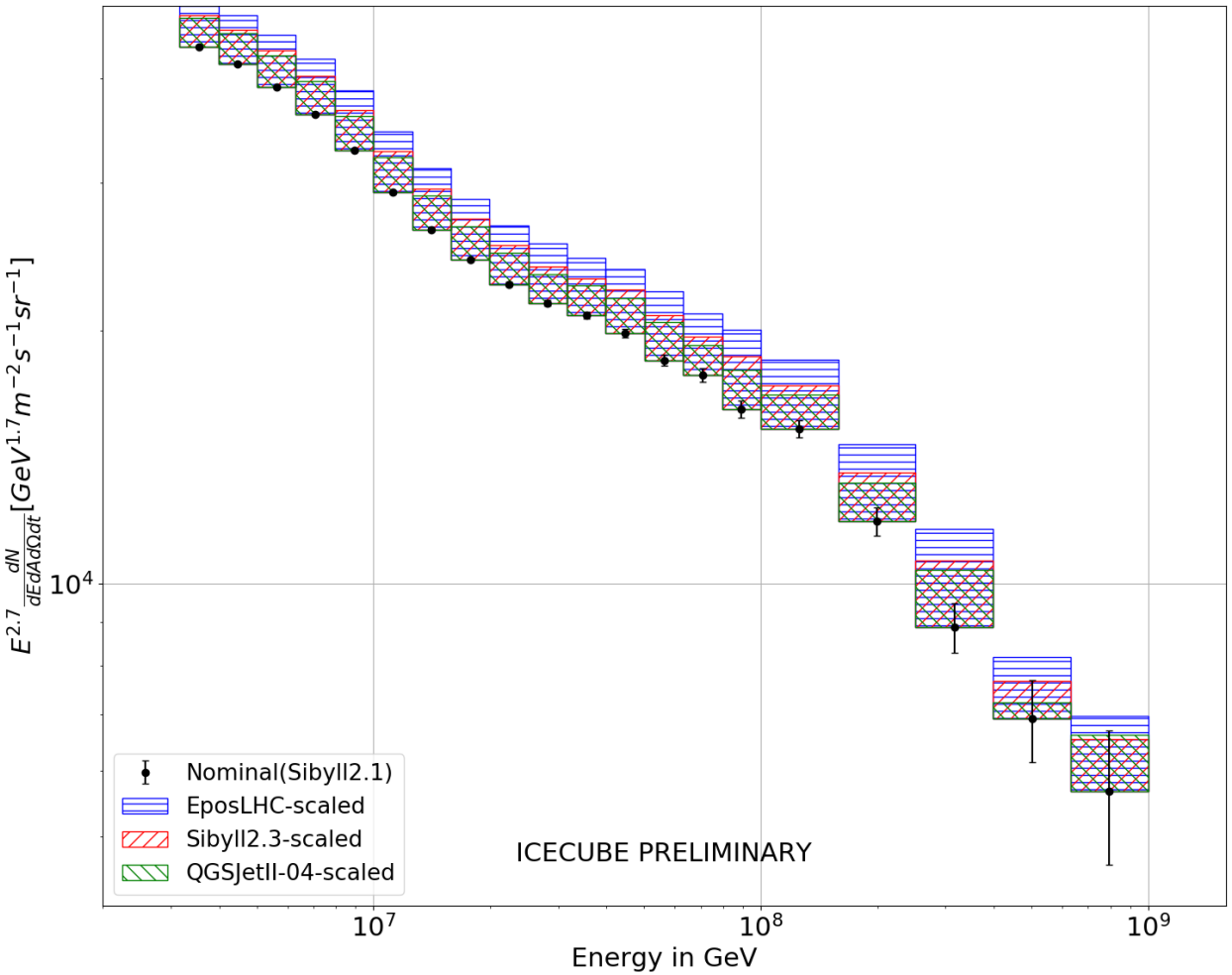
Detector Systematic Uncertainty

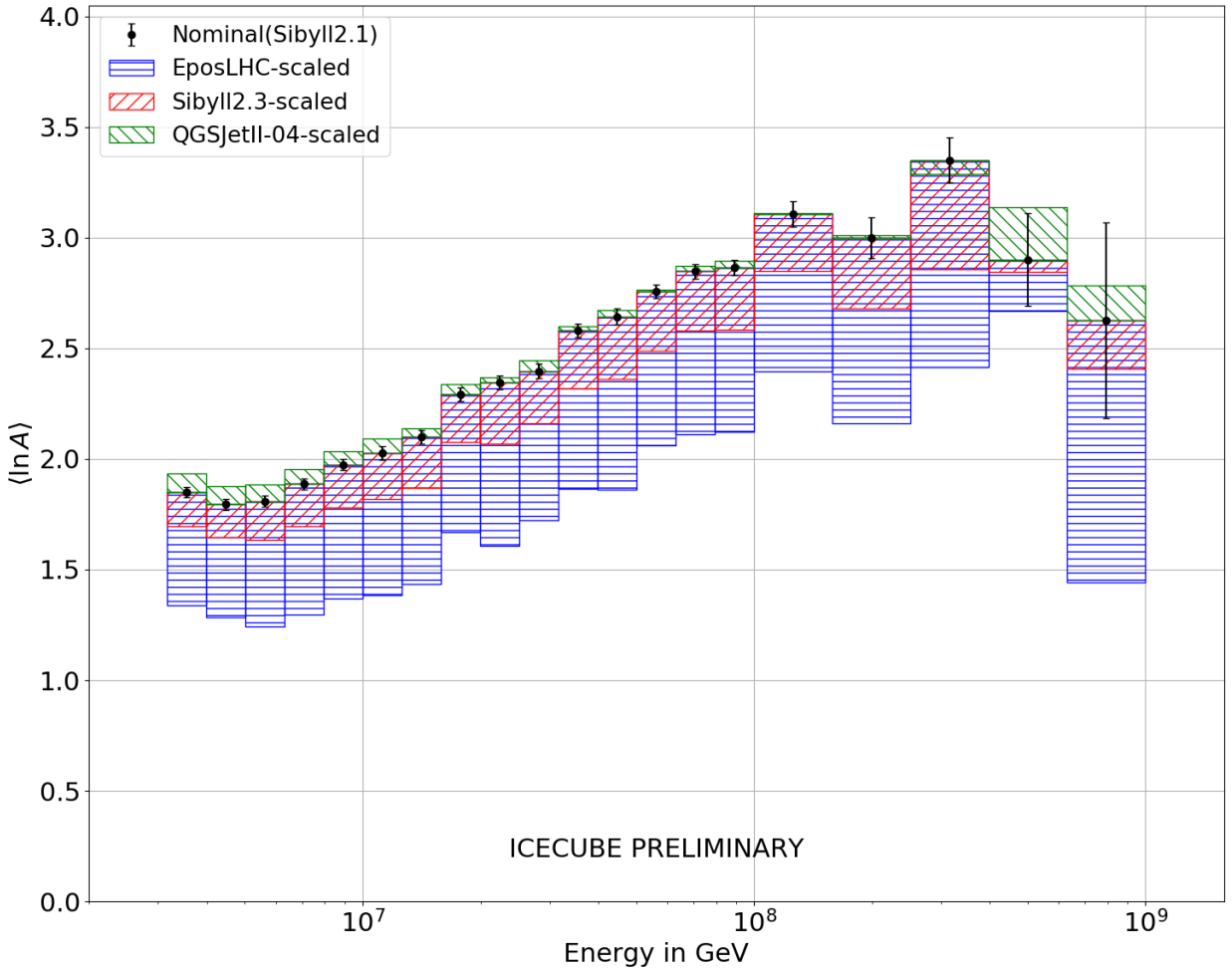




- Snow, light yield and energy scale uncertainty result in systematic offsets on flux and <ln(A)>

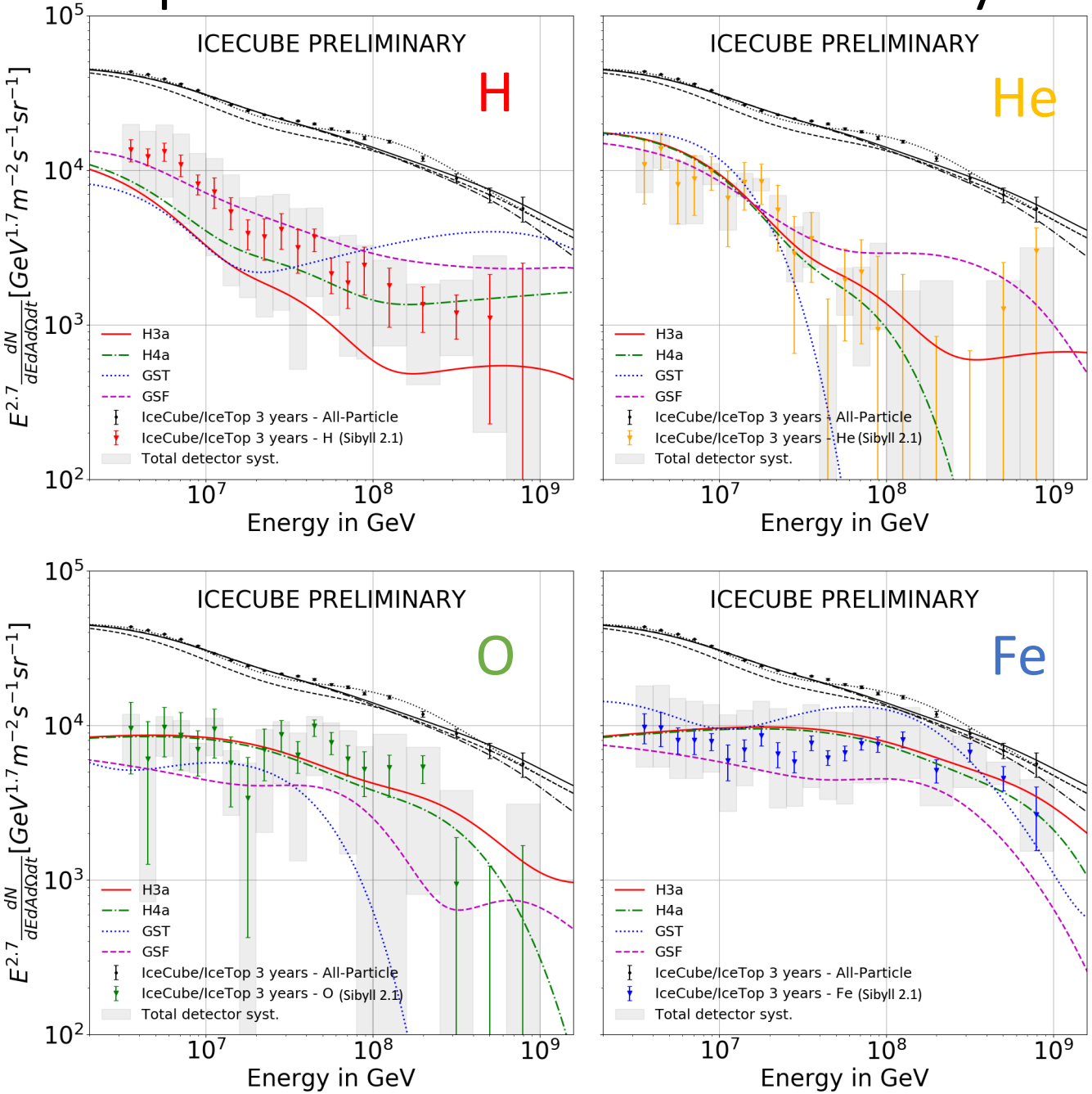
Hadronic Systematic Uncertainty





- Scaling data according to differences in detector response due to interaction models result in uncertainty region in the flux and the <ln(A)>

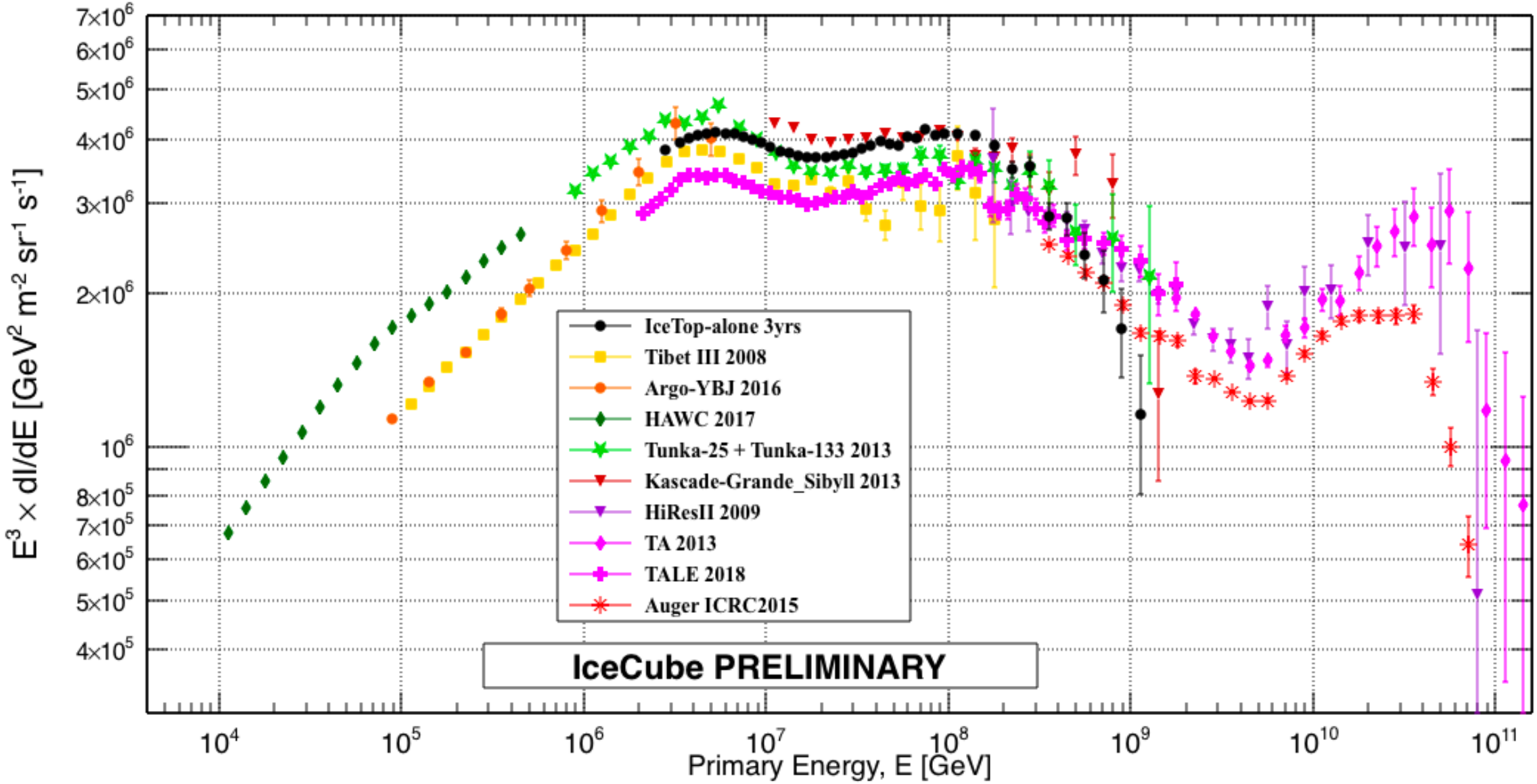
Comparison with Cosmic Ray Composition Model & Fits



- Models:
  - H3a and H4a
- Fits:
  - GST [T. Gaisser, T. Stanev & S. Tilav 2013]
  - GSF (Global spline fit) [H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser, F. Riehn, T. Stanev 2017]

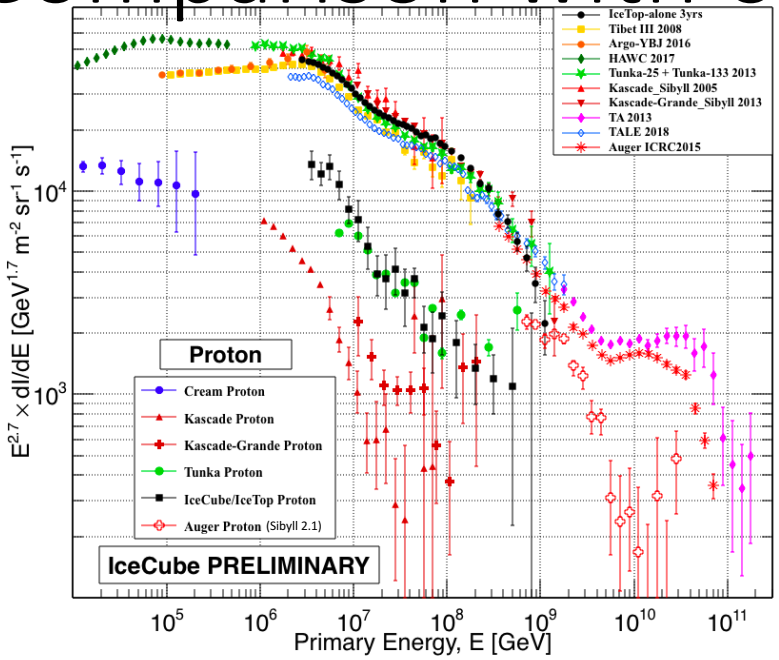
➢Inside statistical and systematic uncertainties good agreement with the predicted models

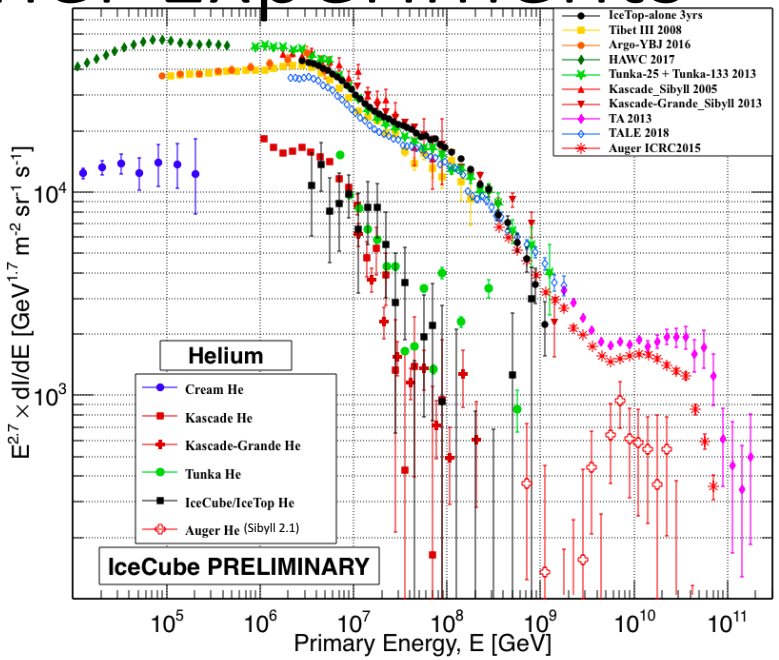
Comparison with other Experiments

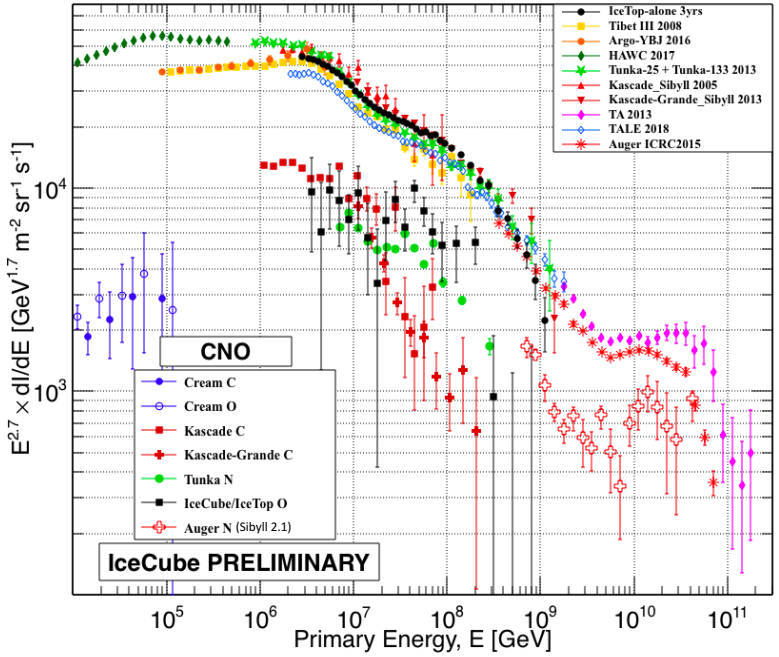


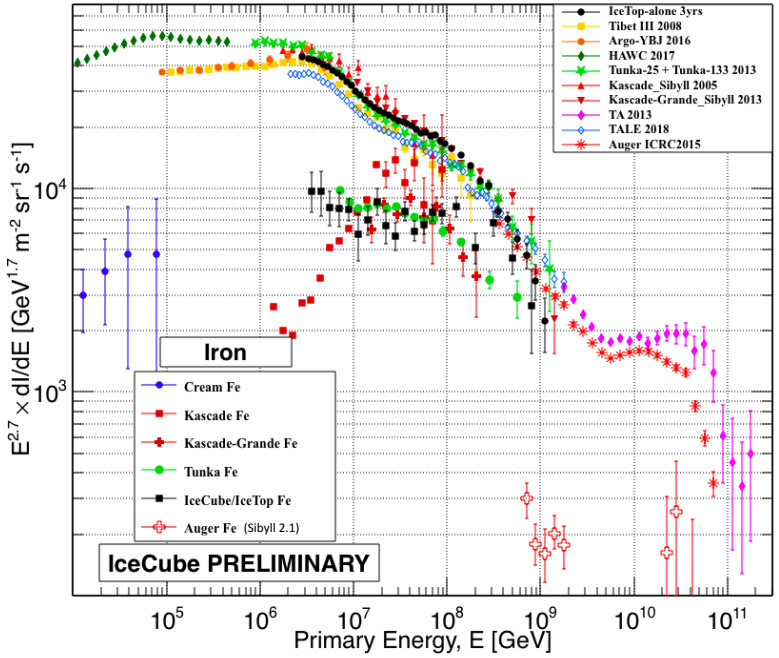
Overall good agreement of with results from other experiments

Comparison with other Experiments









- Composition seems to get heavier with increasing energy up to 10^8 GeV
- Overall good agreement with the composition results from most other experiments

Summary

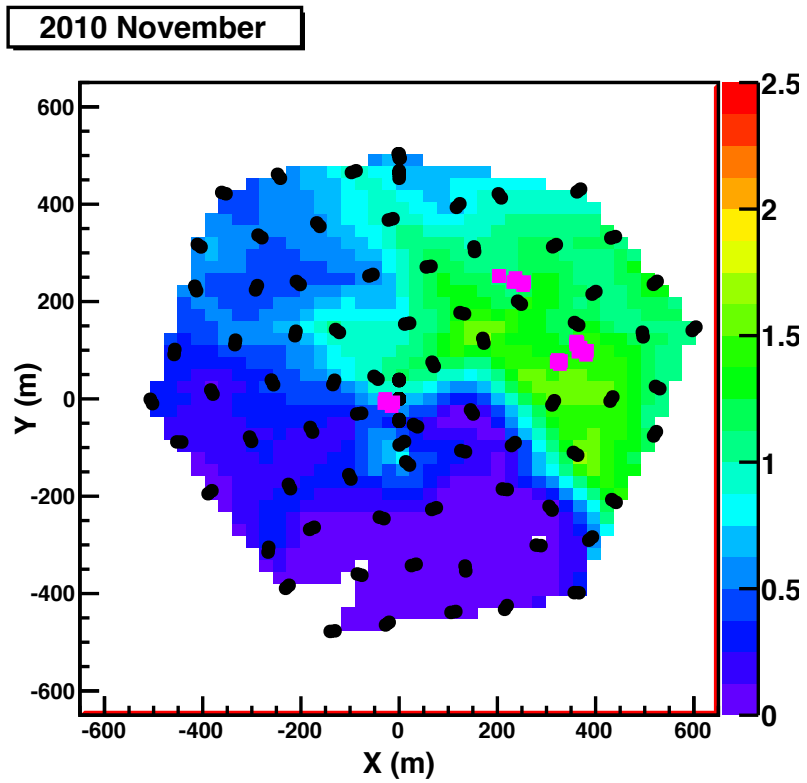
- Evolution of CR energy spectrum and mass composition is studied
  - Composition is getting heavier with increasing energy up to 10^8 GeV
  - Individual spectra shown in the energy range from $10^{6.5}$ – 10^9 GeV
- Good agreement with cosmic ray composition models and fits
- Good agreement with results of other experiments

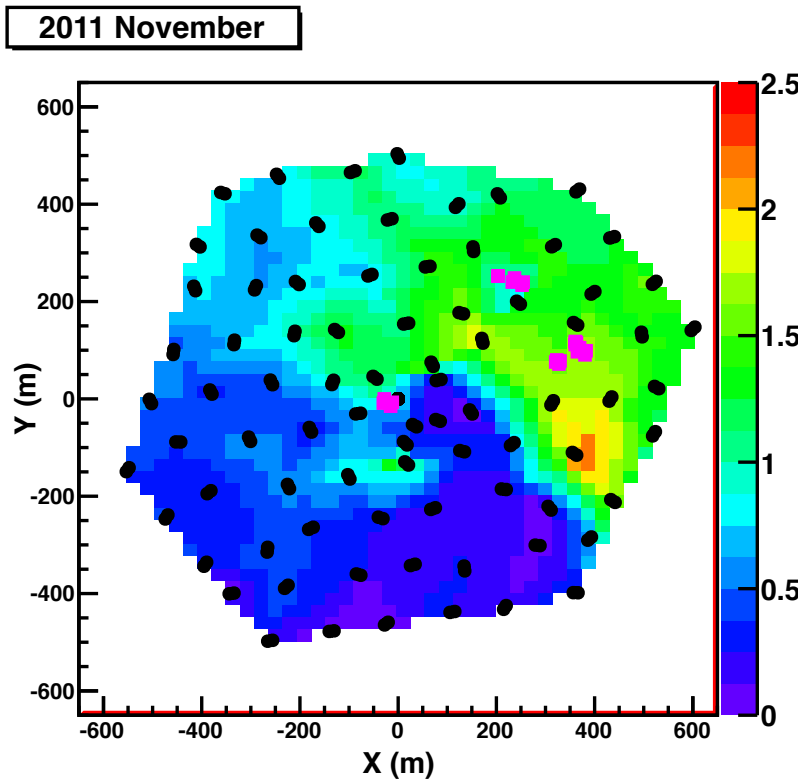
Future Prospects

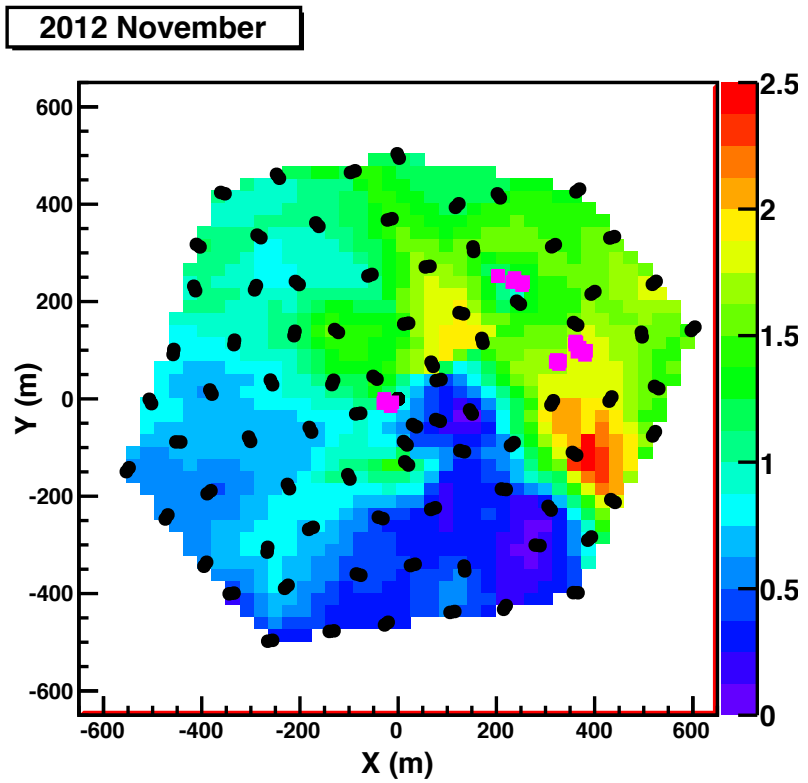
- Systematical uncertainties will be reduced by:
  - Improved detector systematics
  - Improved simulations and reconstruction
  - Improvements to hadronic interaction models in air shower simulation

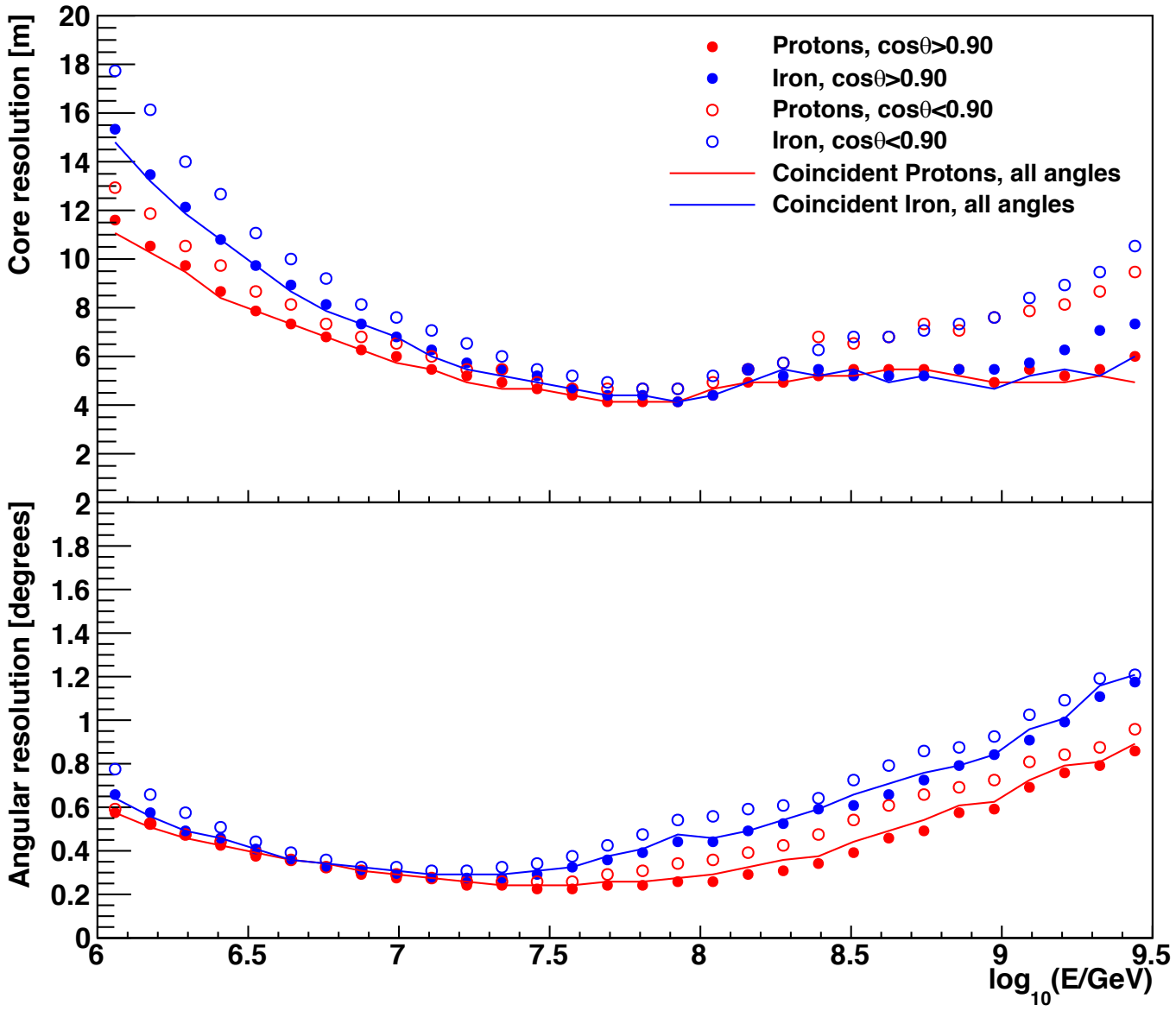
Backup

Snow accumulation








Core resolution [m]
Angular resolution [degrees]
log10(E/GeV)
Protons, cosθ>0.90
Iron, cosθ>0.90
Protons, cosθ<0.90
Iron, cosθ<0.90
Coincident Protons, all angles
Coincident Iron, all angles

Superposition Model of Mass Composition PDFs

Total PDF for all nuclear mass cosmic rays is given by
(our model only use 4 typical components (H,He,O,Fe))

$$f(x;\theta) = \sum_{i=1}^{m} \theta_i f_i(x),$$

Due to the constraint, one fraction parameter can be substituted

$$\theta_m, \text{ by } 1 - \sum_{i=1}^{m-1} \theta_i$$

With Extended LogLikelihood:

- Poisson fluctuations included
- Advantage of extended LL is to have a more symmetrical fit problem (easier fitting and error calculation)
  - 4 free fit parameter

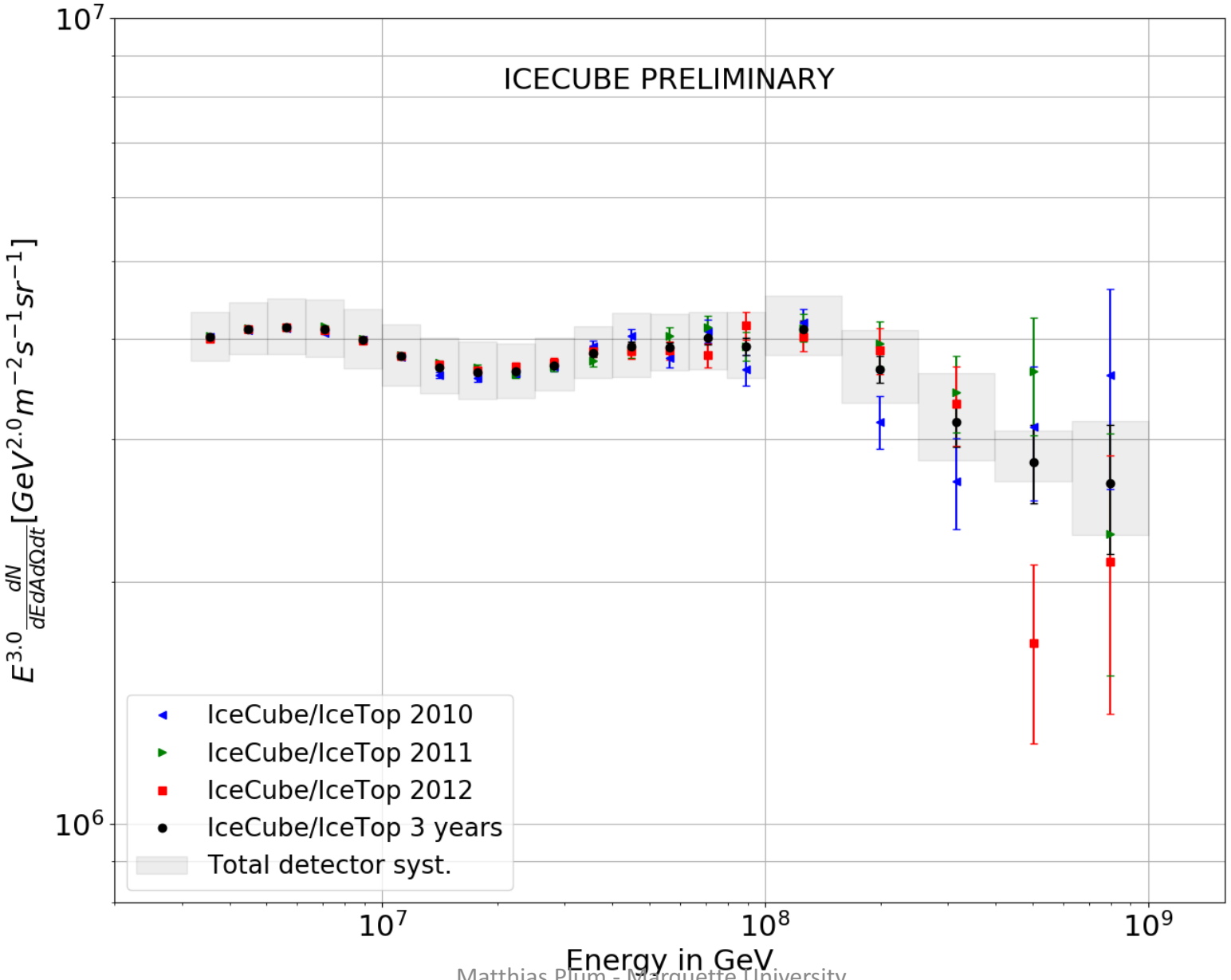
$$\log L(\nu, \boldsymbol{\theta}) = -\nu + \sum_{i=1}^{n} \log \left(\sum_{j=1}^{m} \nu \theta_j f_j(x_i) \right)$$

- By using $\mu_i = \theta_i \nu$ follows

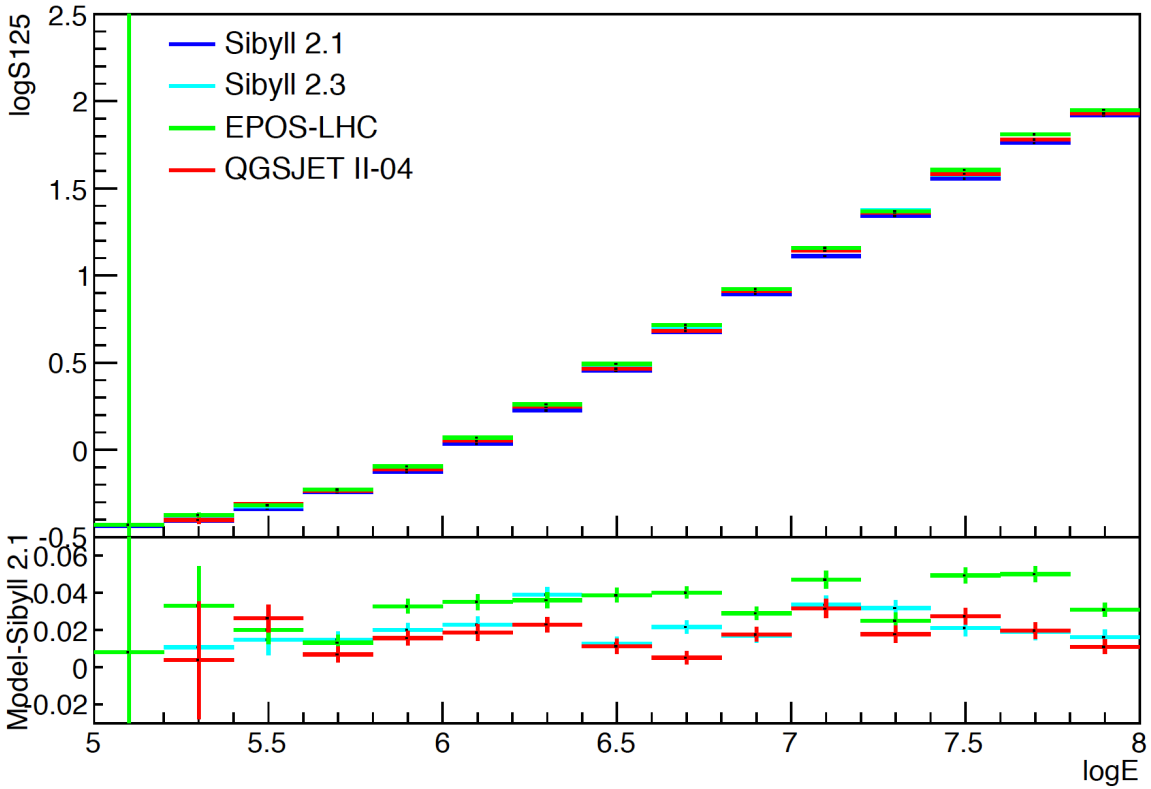
$$\log L(\boldsymbol{\mu}) = -\sum_{j=1}^{m} \mu_j + \sum_{i=1}^{n} \log \left(\sum_{j=1}^{m} \mu_j f_j(x_i) \right)$$

Fit result gives now the number of events per mass species, which we need for the energy spectrum

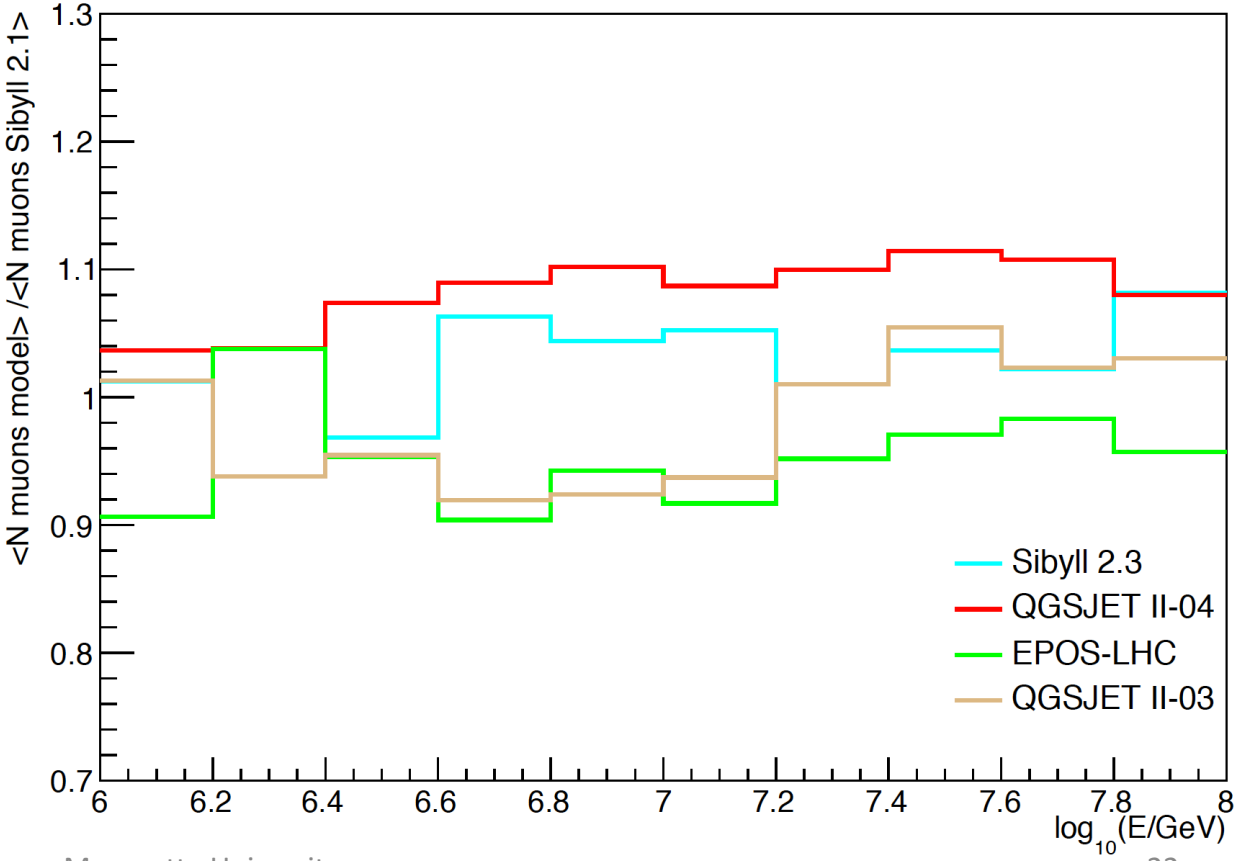
Energy Spectrum IceTop/IceCube

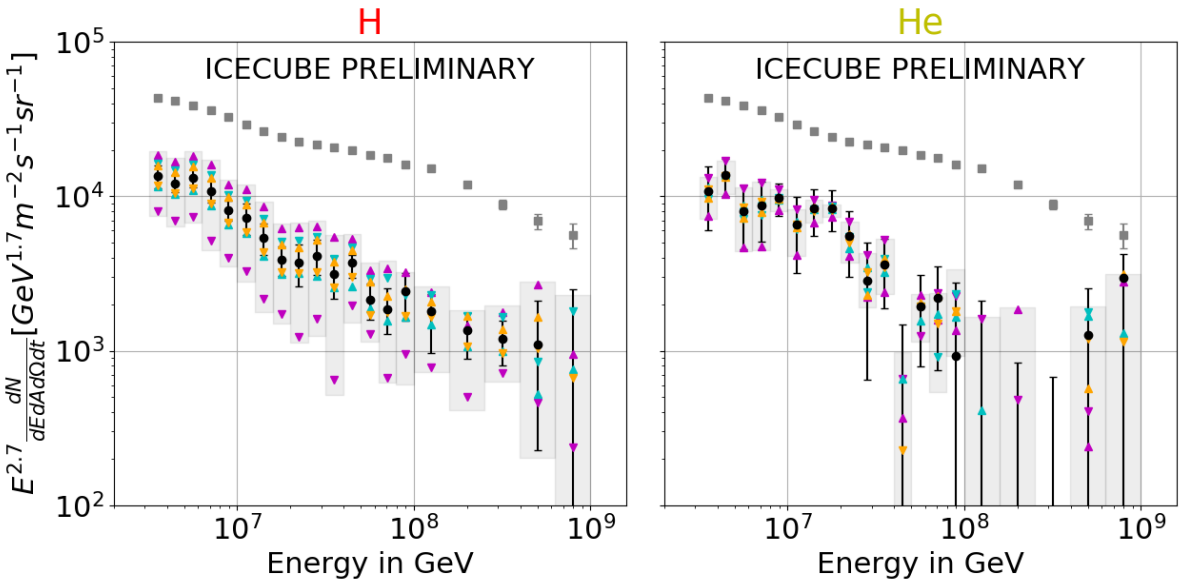


S_{125} shift

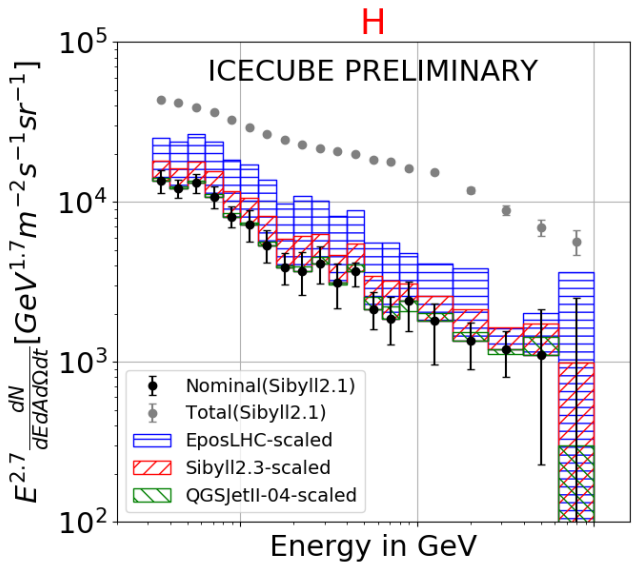


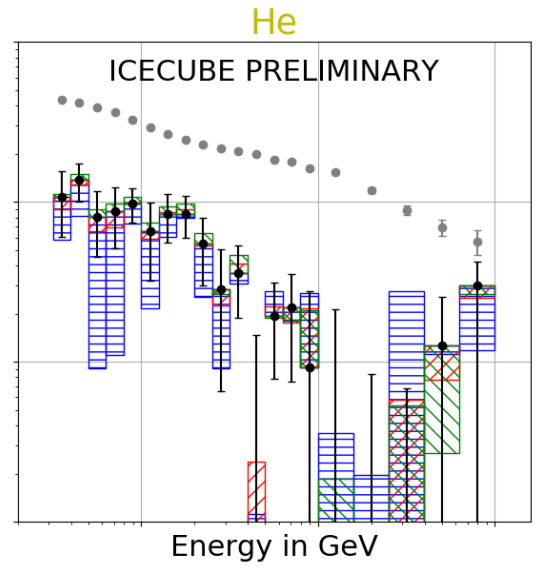
dEdX shift

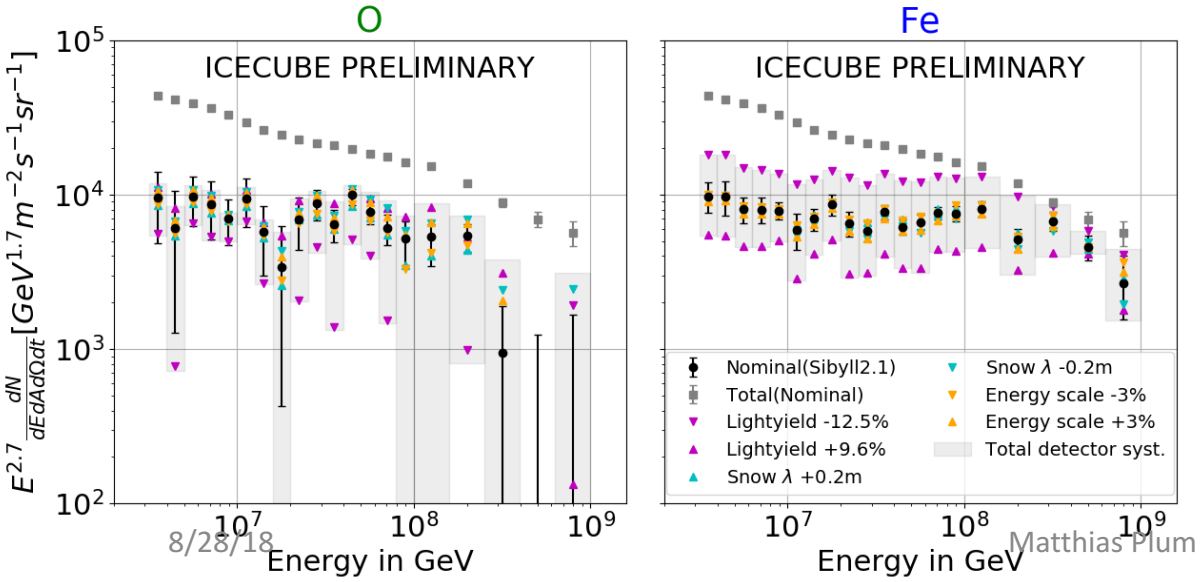



H
ICECUBE PRELIMINARY
$E^{2.7}\frac{dN}{dEdAd\Omega dt}[GeV^{1.7}m^{-2}s^{-1}sr^{-1}]$
Energy in GeV

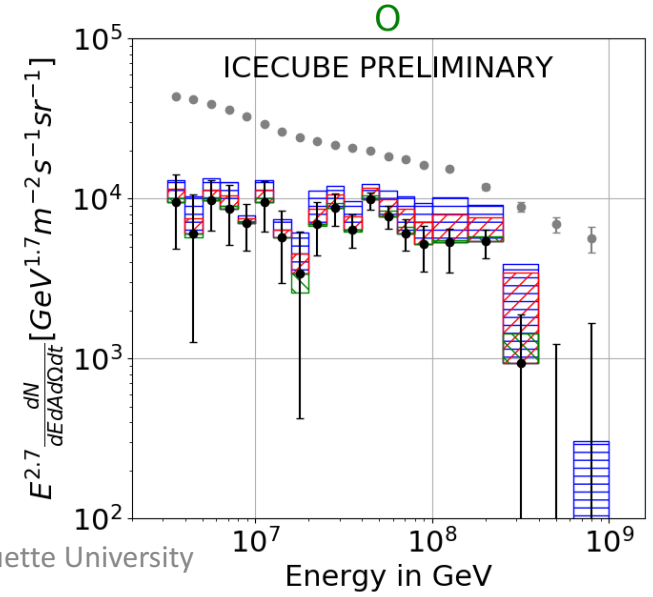
He
ICECUBE PRELIMINARY
Energy in GeV

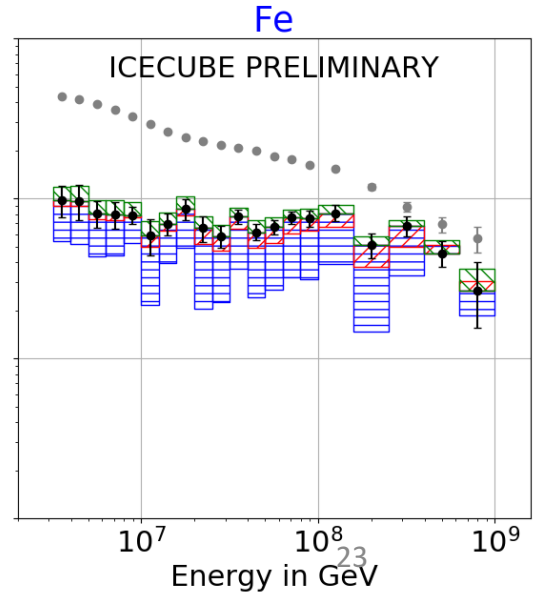

H
ICECUBE PRELIMINARY
$E^{2.7}\frac{dN}{dEdAd\Omega dt}[GeV^{1.7}m^{-2}s^{-1}sr^{-1}]$
Nominal(Sibyll2.1)
Total(Sibyll2.1)
EposLHC-scaled
Sibyll2.3-scaled
QGSJetII-04-scaled
Energy in GeV

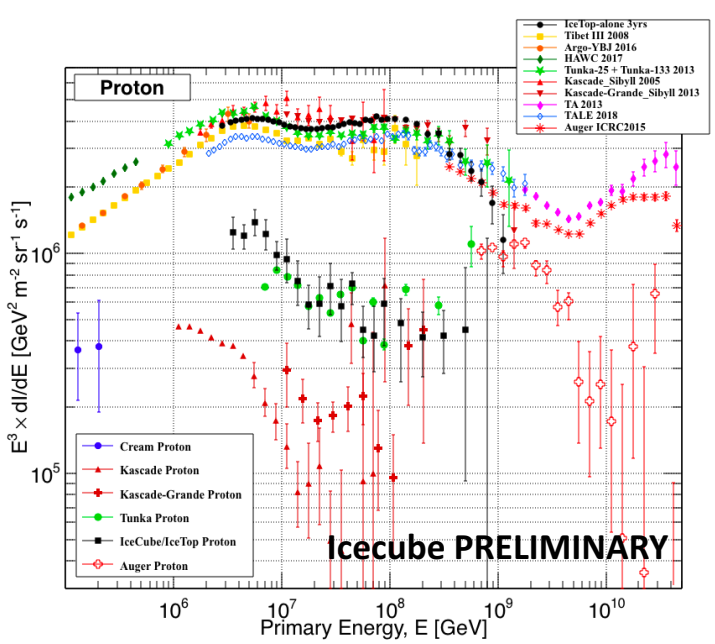

He
ICECUBE PRELIMINARY
Energy in GeV

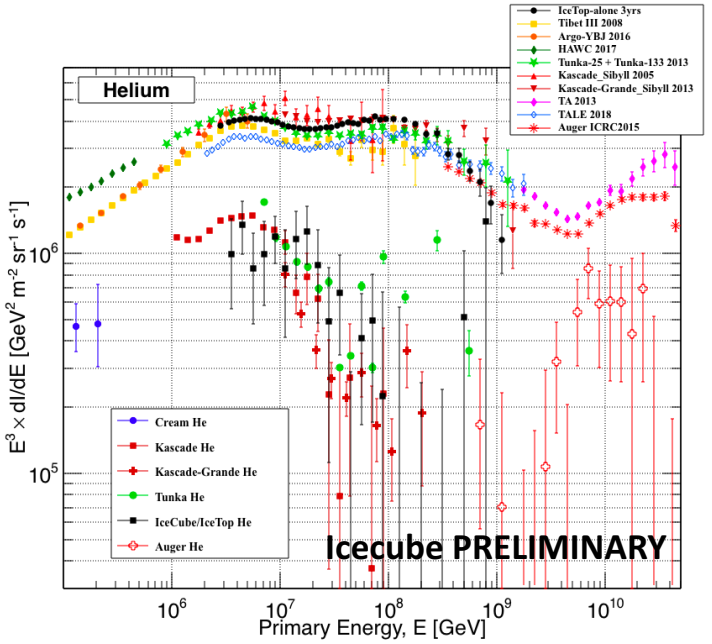

O
ICECUBE PRELIMINARY
$E^{2.7}\frac{dN}{dEdAd\Omega dt}[GeV^{1.7}m^{-2}s^{-1}sr^{-1}]$
Energy in GeV

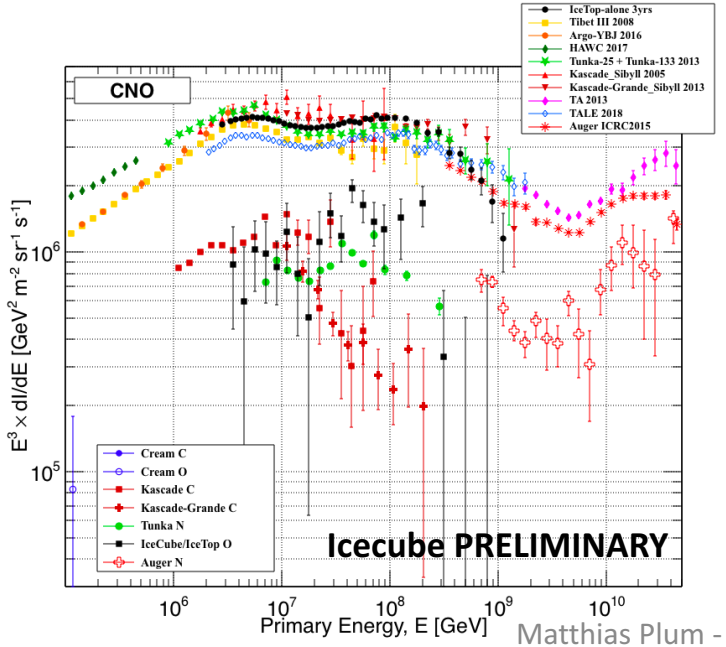
Fe
ICECUBE PRELIMINARY
Nominal(Sibyll2.1)
Total(Nominal)
Lightyield -12.5%
Lightyield +9.6%
Snow λ +0.2m
Snow λ -0.2m
Energy scale -3%
Energy scale +3%
Total detector syst.
Energy in GeV

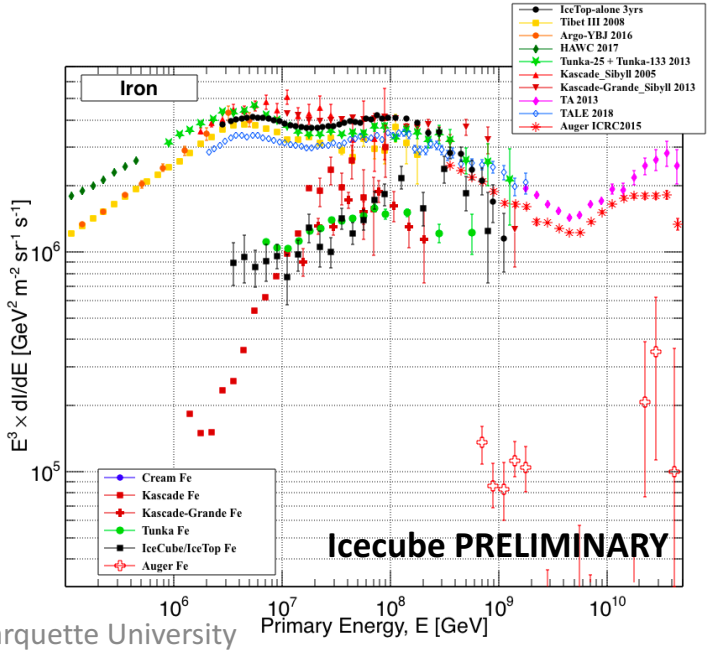

O
ICECUBE PRELIMINARY
$E^{2.7}\frac{dN}{dEdAd\Omega dt}[GeV^{1.7}m^{-2}s^{-1}sr^{-1}]$
Energy in GeV


Fe
ICECUBE PRELIMINARY
Energy in GeV


Proton
IceTop-alone 3yrs
Tibet III 2008
Argo-YBJ 2016
HAWC 2017
Tunka-25 + Tunka-133 2013
Kascade_Sibyll 2005
Kascade-Grande_Sibyll 2013
TA 2013
TALE 2018
Auger ICRC2015
Cream Proton
Kascade Proton
Kascade-Grande Proton
Tunka Proton
IceCube/IceTop Proton
Auger Proton
Icecube PRELIMINARY
$E^3 \times dI/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]


Helium
IceTop-alone 3yrs
Tibet III 2008
Argo-YBJ 2016
HAWC 2017
Tunka-25 + Tunka-133 2013
Kascade_Sibyll 2005
Kascade-Grande_Sibyll 2013
TA 2013
TALE 2018
Auger ICRC2015
Cream He
Kascade He
Kascade-Grande He
Tunka He
IceCube/IceTop He
Auger He
Icecube PRELIMINARY
$E^3 \times dI/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]


CNO
IceTop-alone 3yrs
Tibet III 2008
Argo-YBJ 2016
HAWC 2017
Tunka-25 + Tunka-133 2013
Kascade_Sibyll 2005
Kascade-Grande_Sibyll 2013
TA 2013
TALE 2018
Auger ICRC2015
Cream C
Cream O
Kascade C
Kascade-Grande C
Tunka N
IceCube/IceTop O
Auger N
Icecube PRELIMINARY
$E^3 \times dI/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]


Iron
IceTop-alone 3yrs
Tibet III 2008
Argo-YBJ 2016
HAWC 2017
Tunka-25 + Tunka-133 2013
Kascade_Sibyll 2005
Kascade-Grande_Sibyll 2013
TA 2013
TALE 2018
Auger ICRC2015
Cream Fe
Kascade Fe
Kascade-Grande Fe
Tunka Fe
IceCube/IceTop Fe
Auger Fe
Icecube PRELIMINARY
$E^3 \times dI/dE$ [GeV^2 m^{-2} sr^{-1} s^{-1}]
Primary Energy, E [GeV]