FACULTEIT WETENSCHAPPEN

Dept. of Physics and Astronomy

Alessio Porcelli

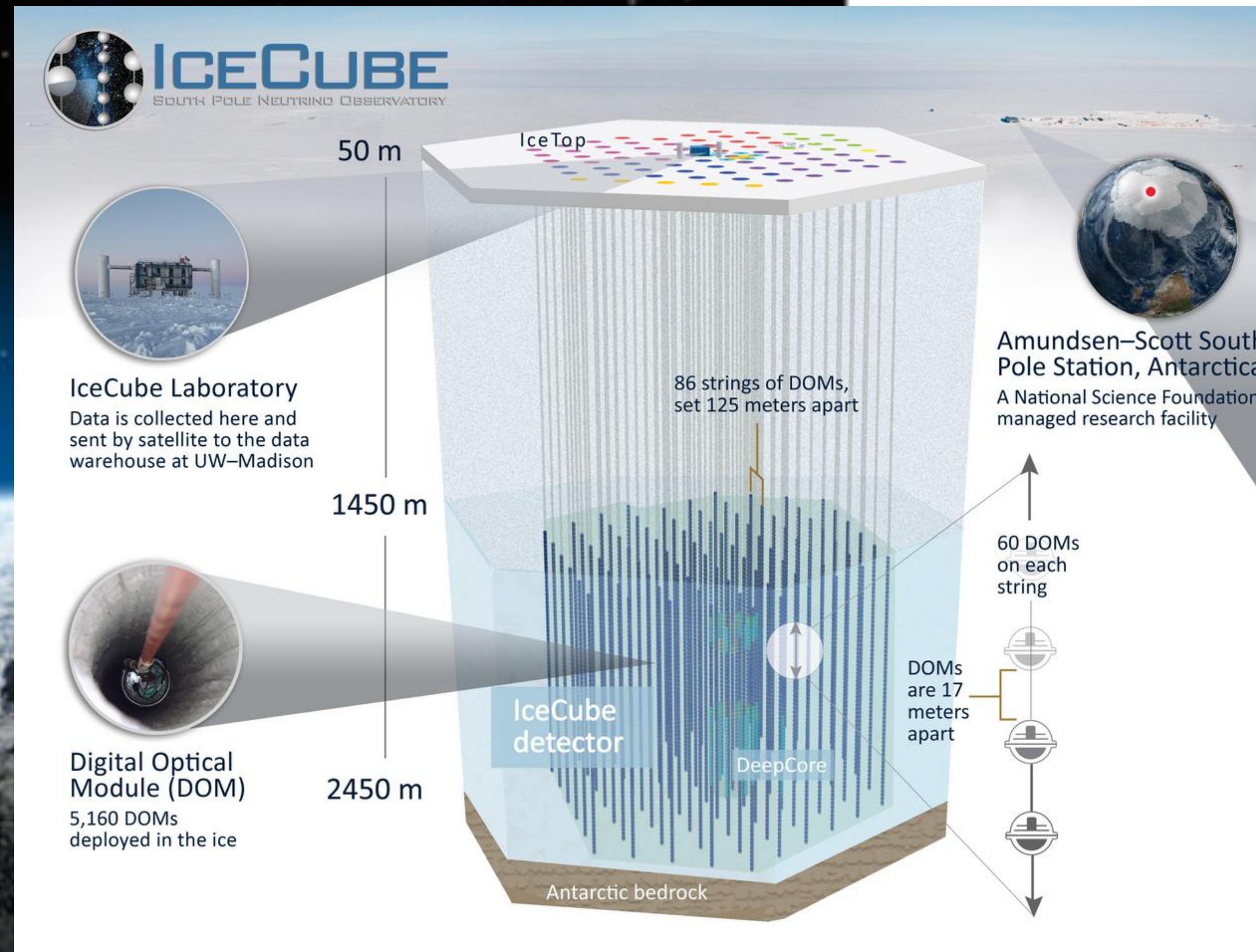
4th October 2019

Latest results from IceTop

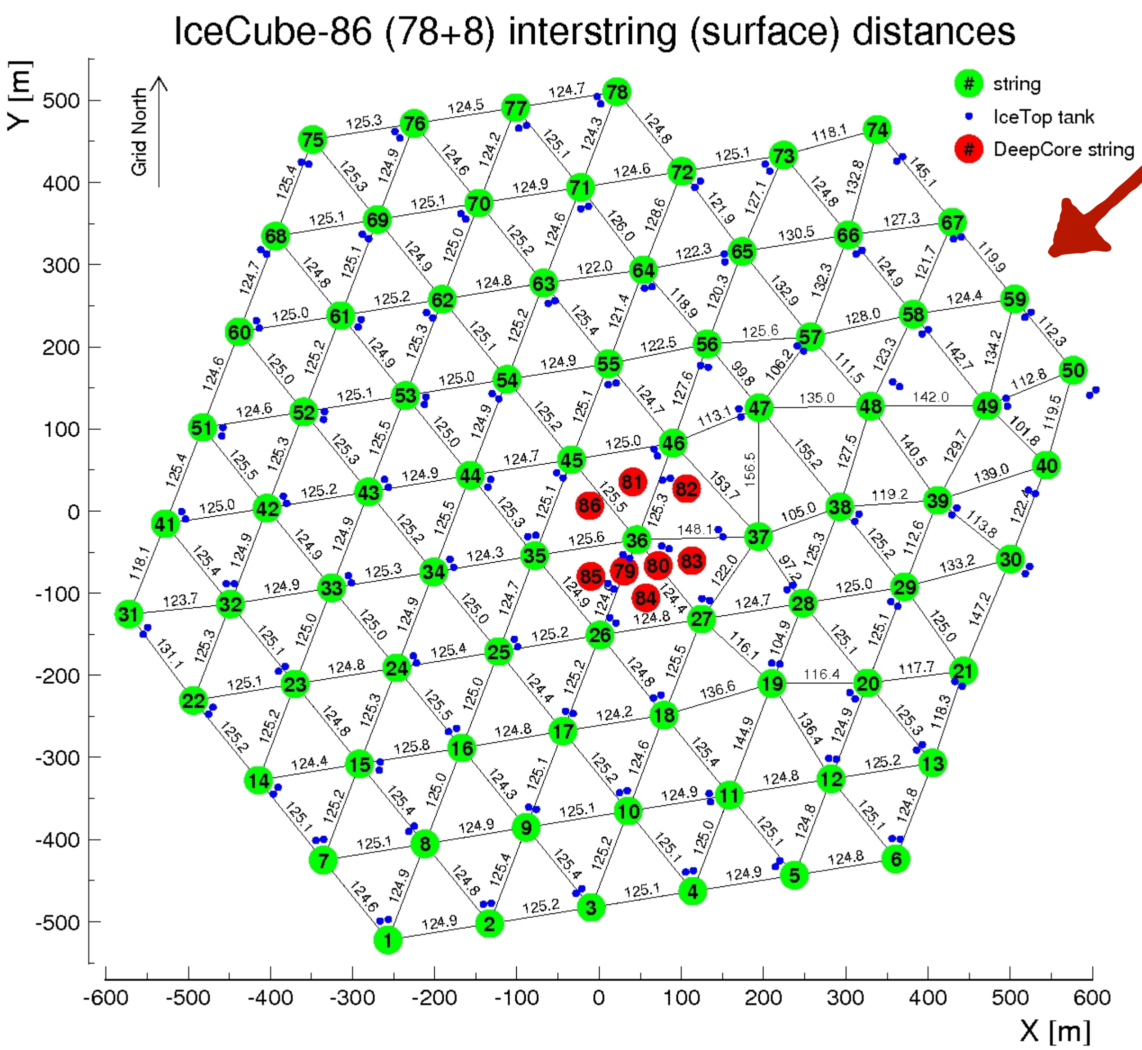
UNIVERSITEIT GENT

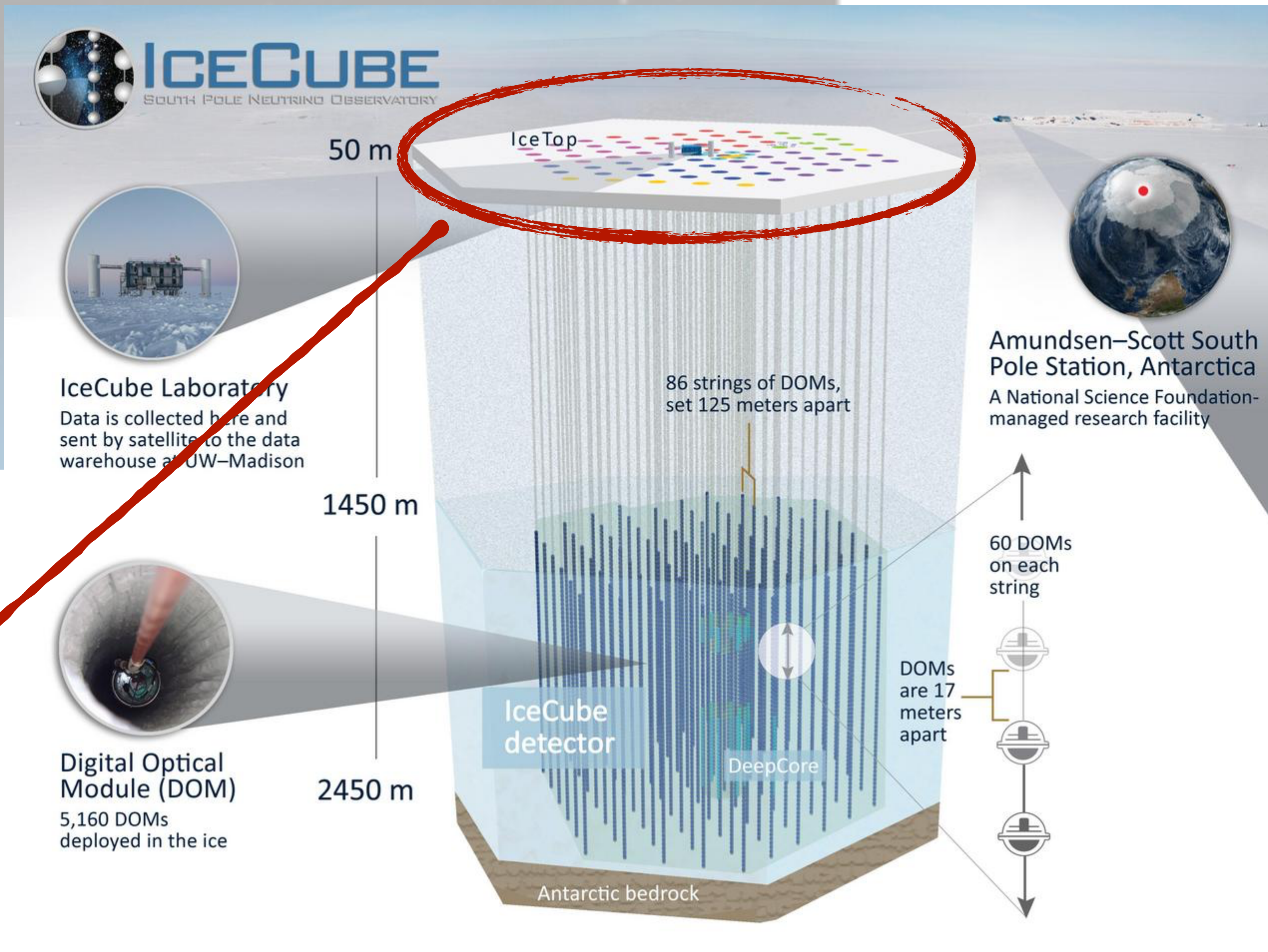
ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

IceCube


ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY
IceTop
50 m
1450 m
2450 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Antarctic bedrock

IceCube: IceTop





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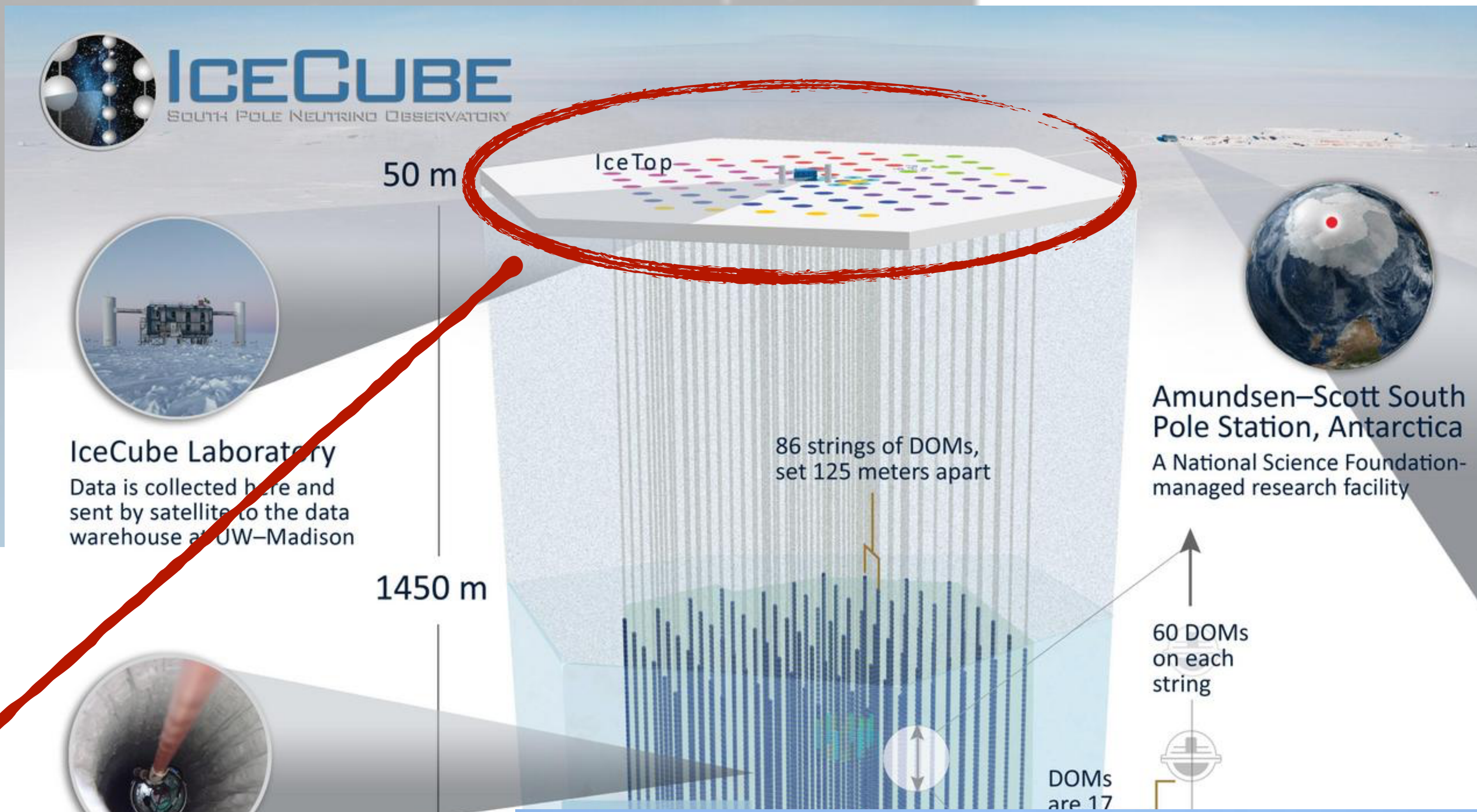
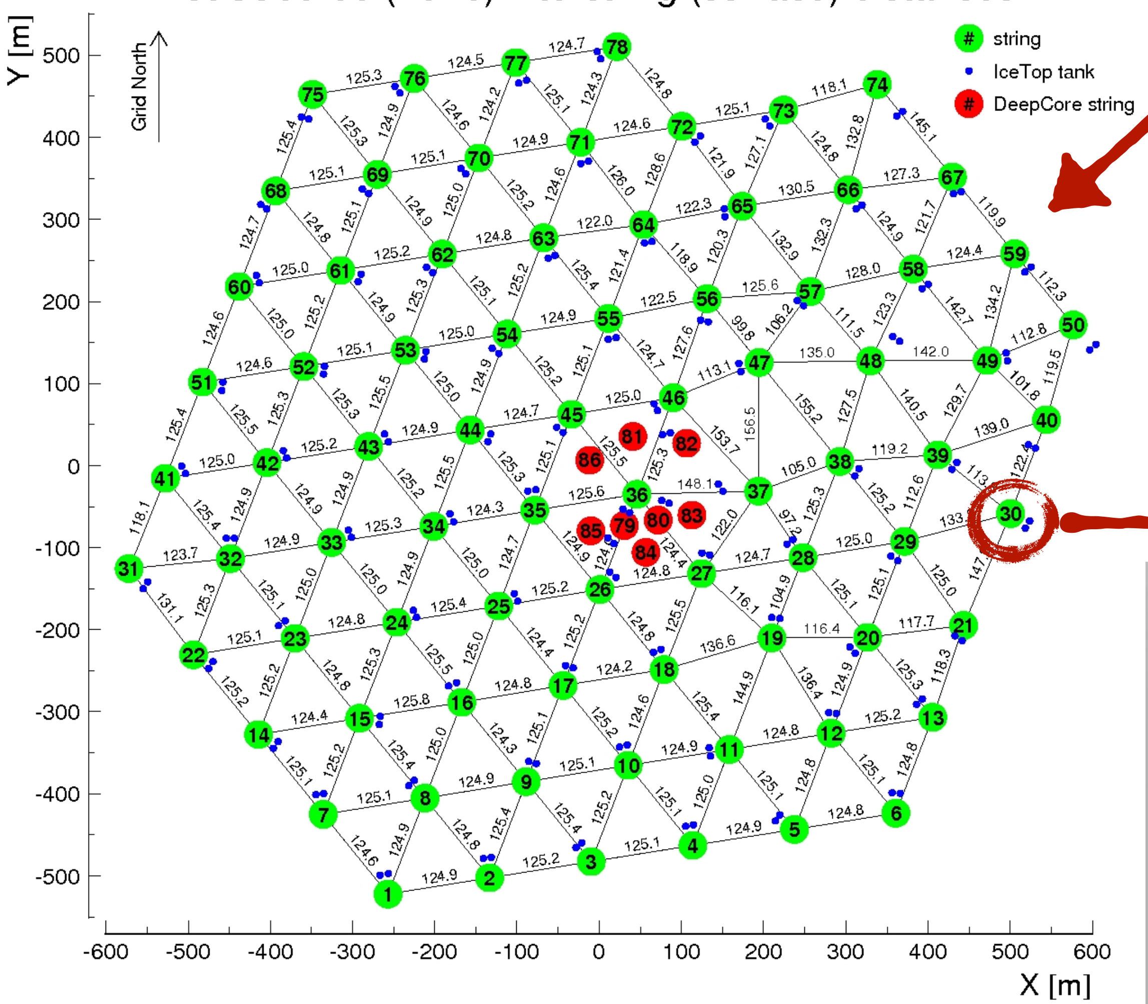
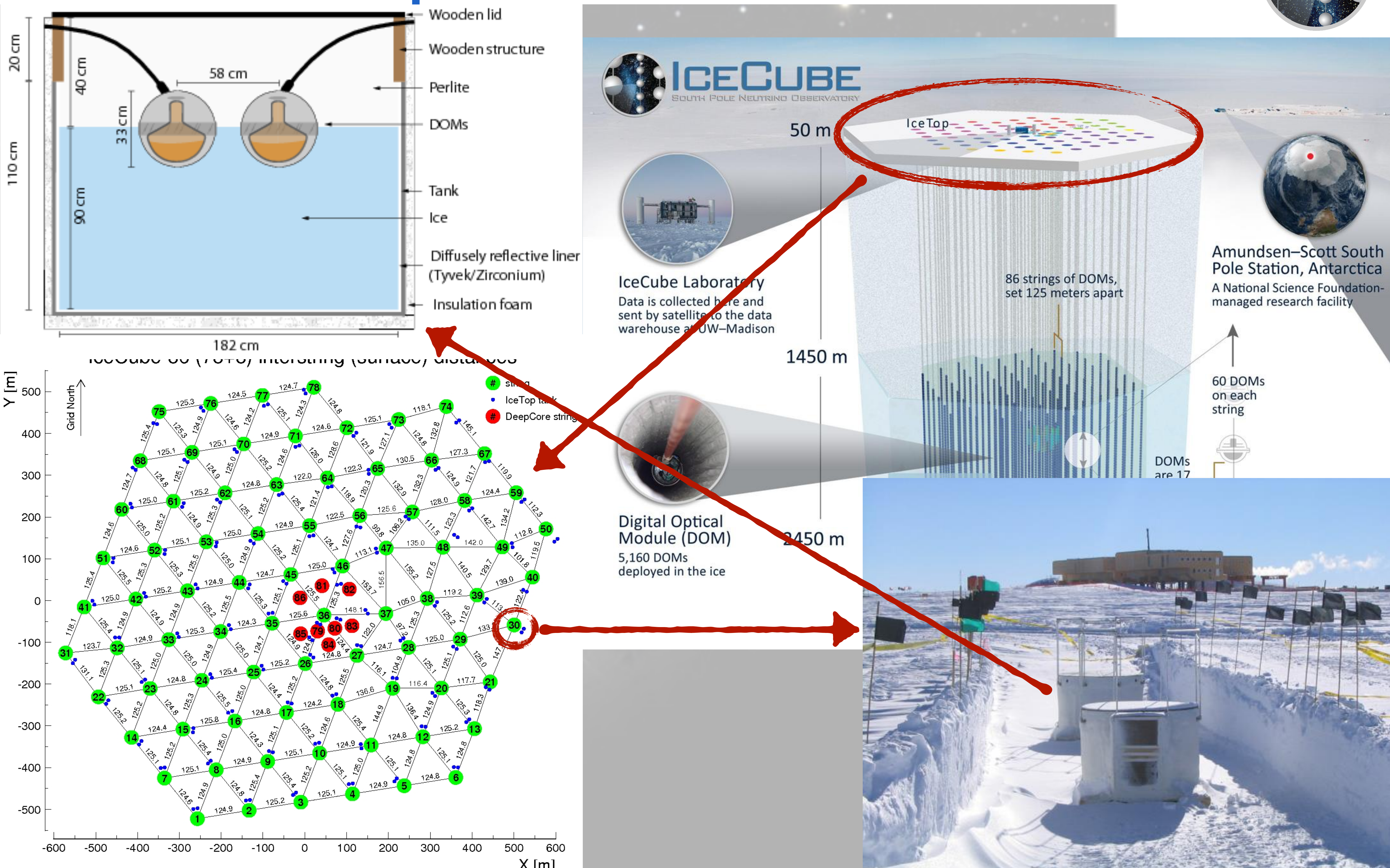


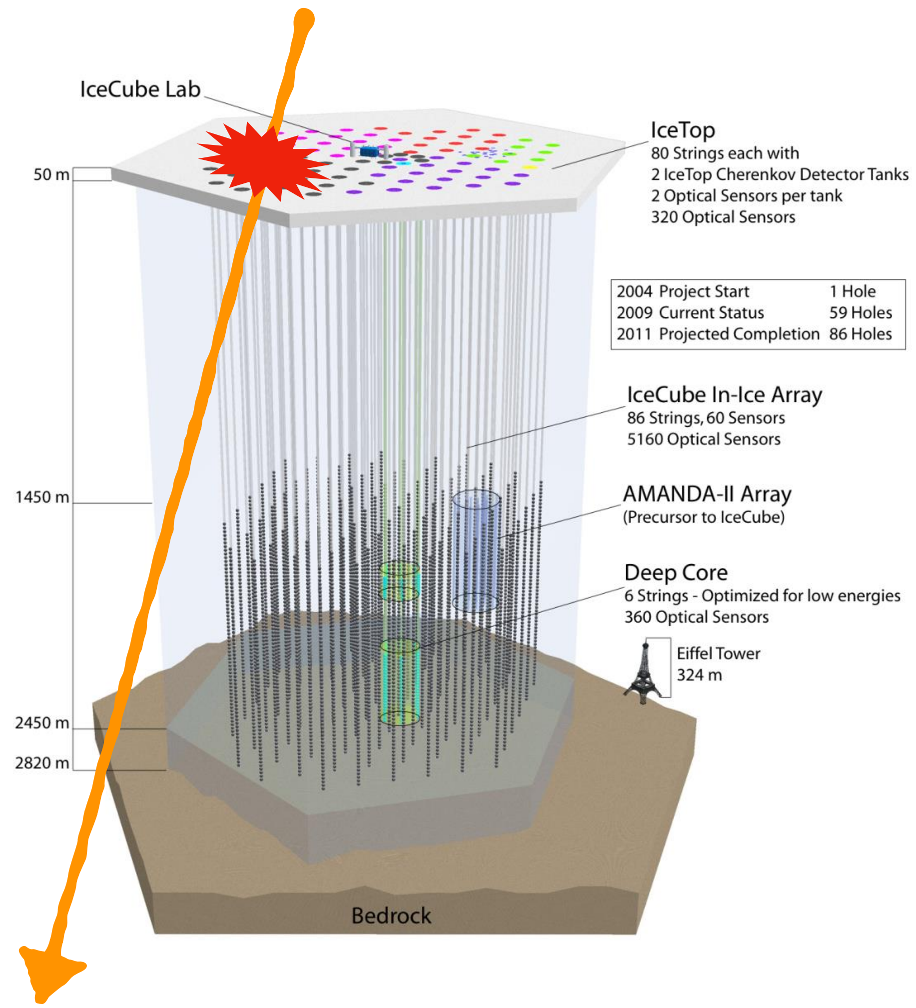
IceCube-86 (78+8) interstring (surface) distances

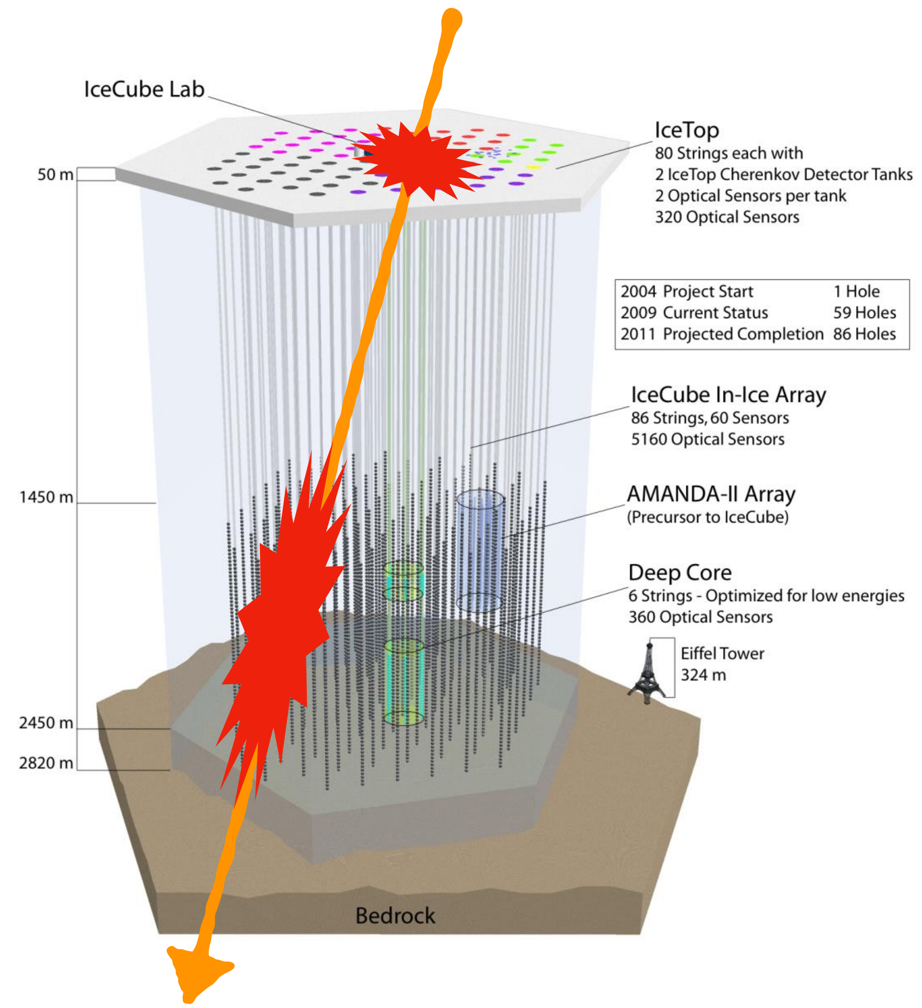


IceCube: IceTop



Two styles of detections





IceTop

- Greater Acceptance (more events)
- Energy sensitivity from shower size (model assumed)
- Uses low energy muons (<300 GeV)

IceTop+InIce in coincidence

- Energy loss profile (high-energy, >300 GeV, muons penetrating deep inside the ice)
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  - …but less events

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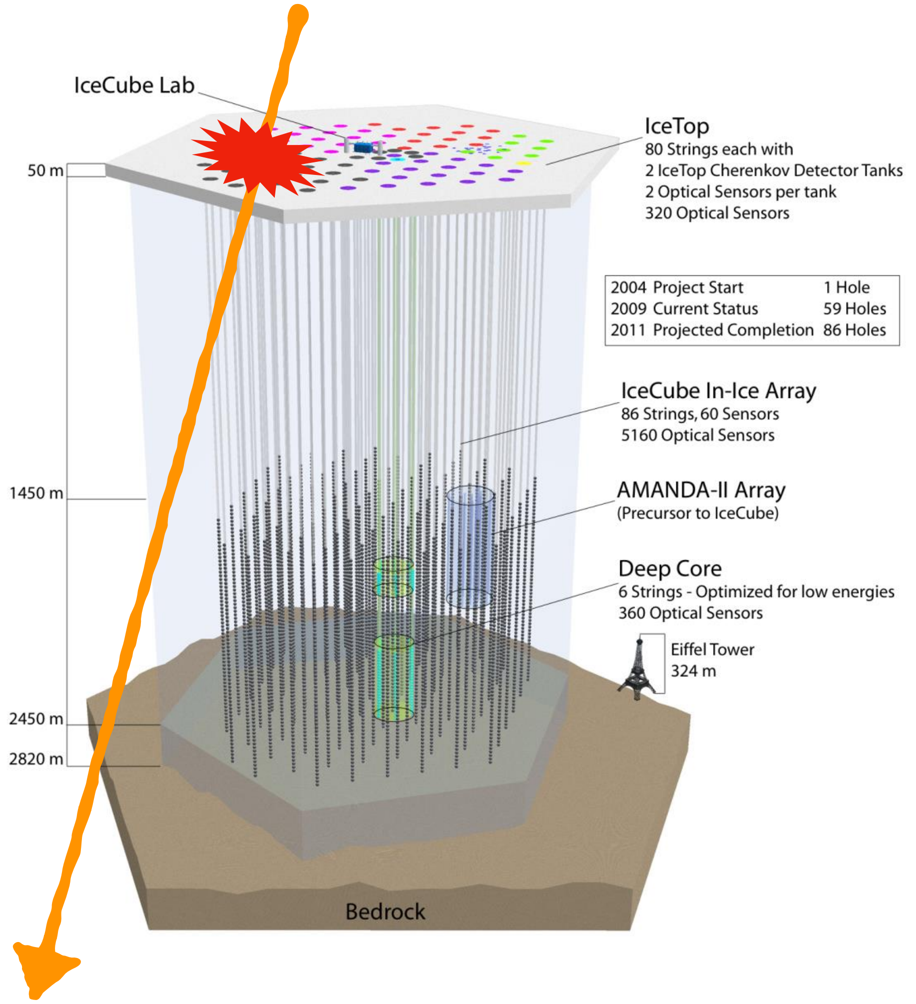

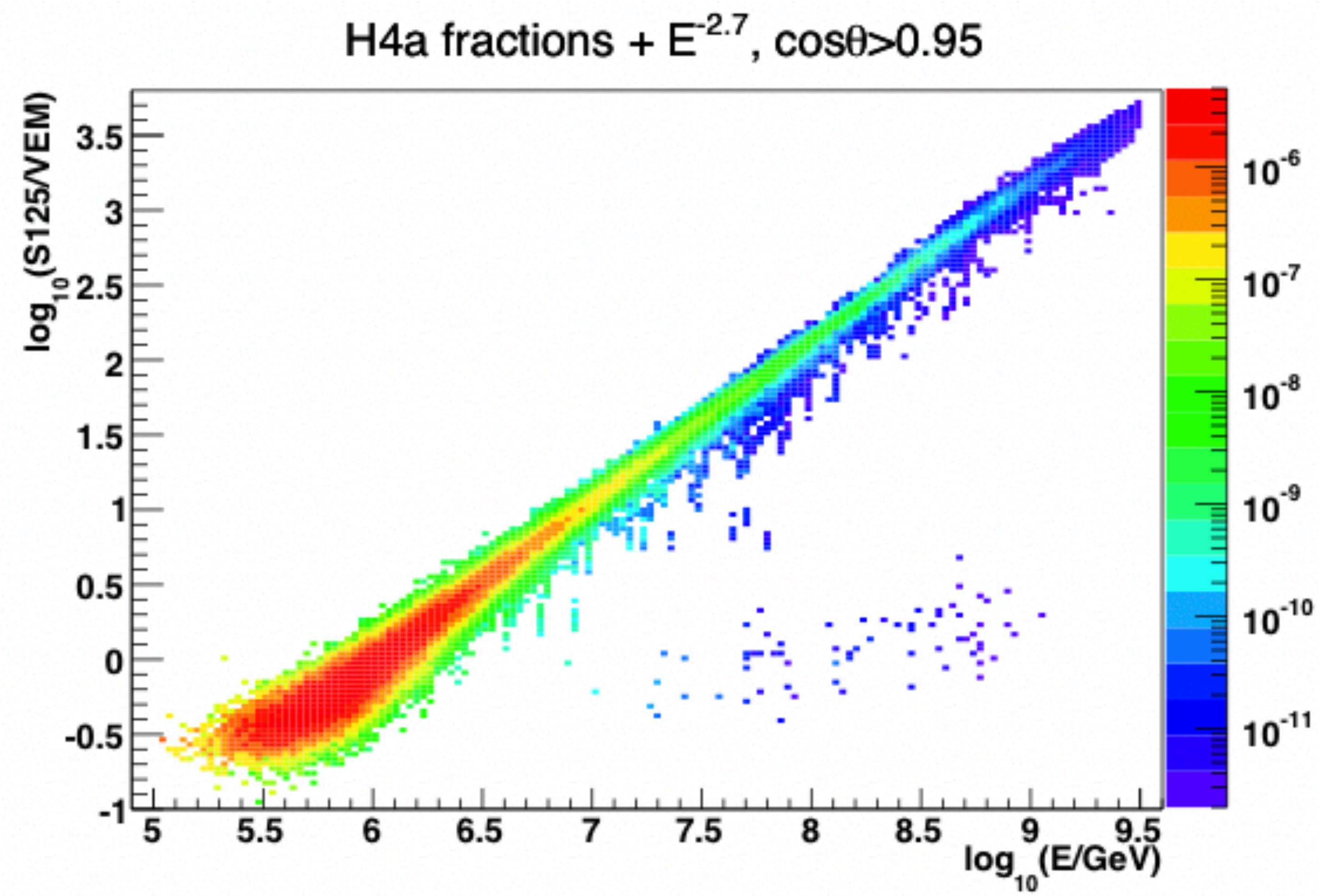

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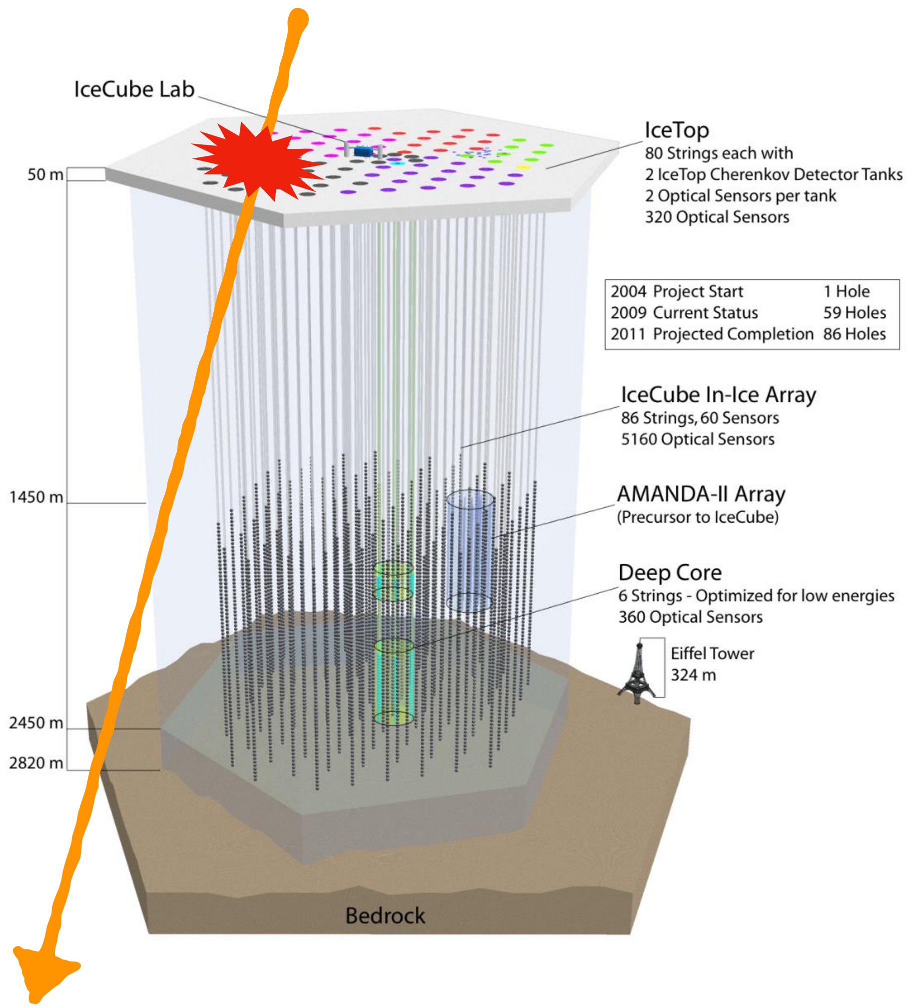
Energy conversion functions:

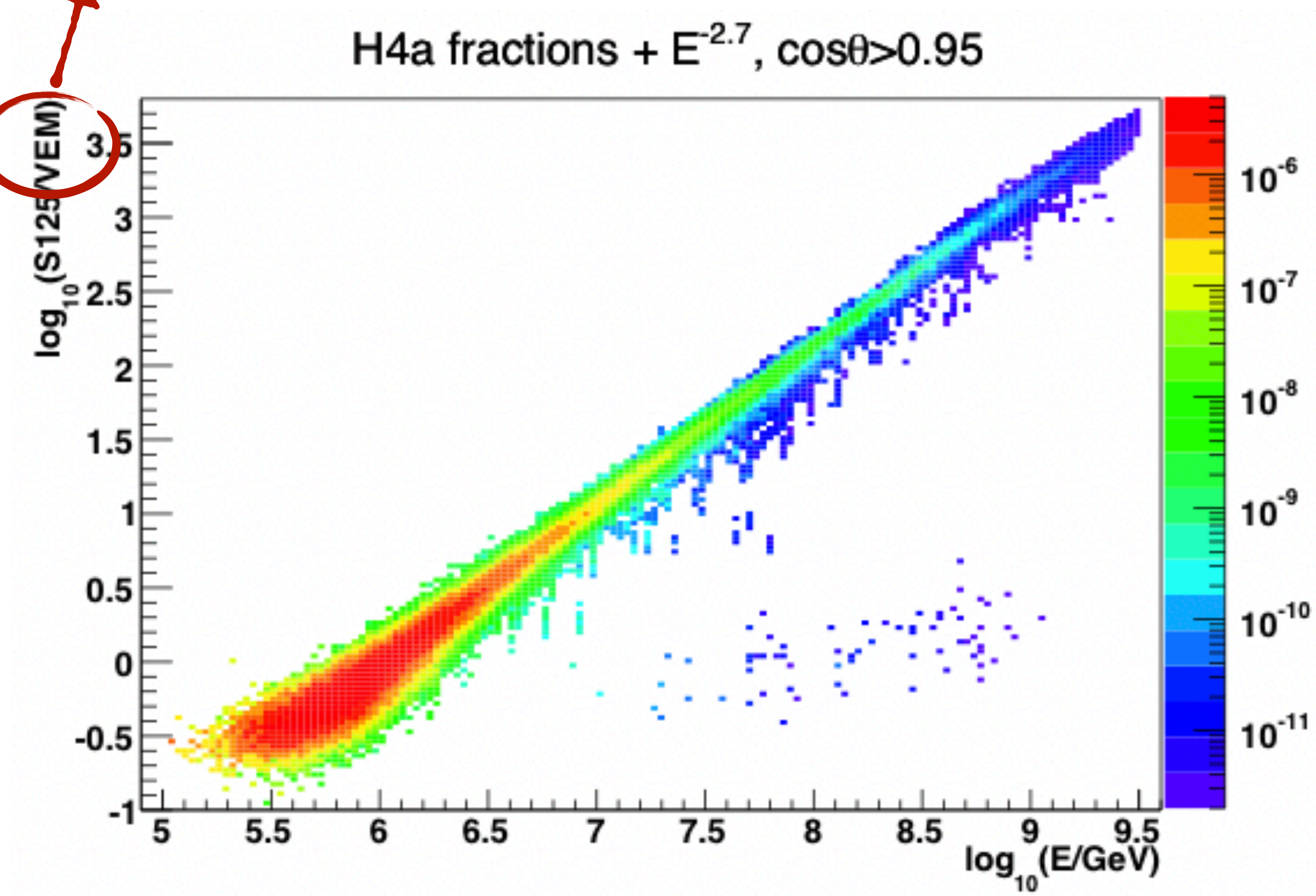
Using Monte Carlo simulations (and assuming a composition model)

- Find most likely energy within each slice of **S125** (signal @ 125 m from shower core)
- Do separately for 4 zenith angle ranges

IceTop

1 "VEM" = "Vertical Equivalent Muon"
the amount of charge deposited by a single muon going straight down through a tank.





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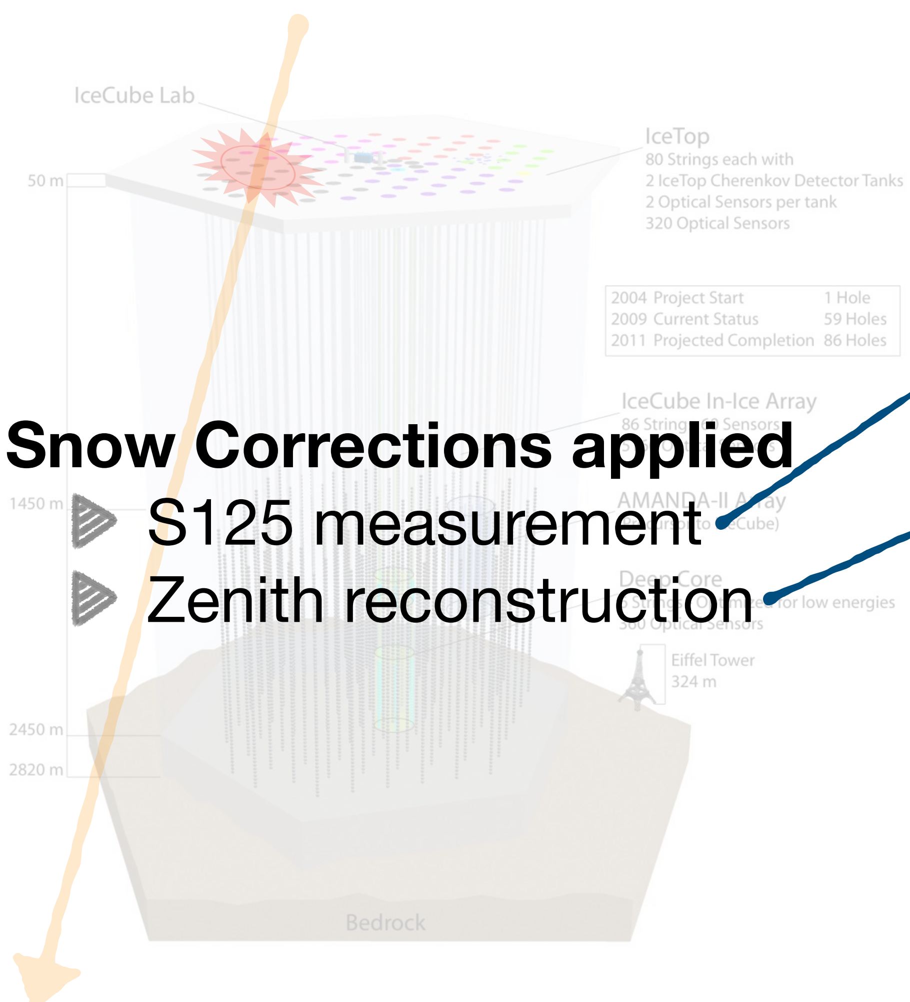
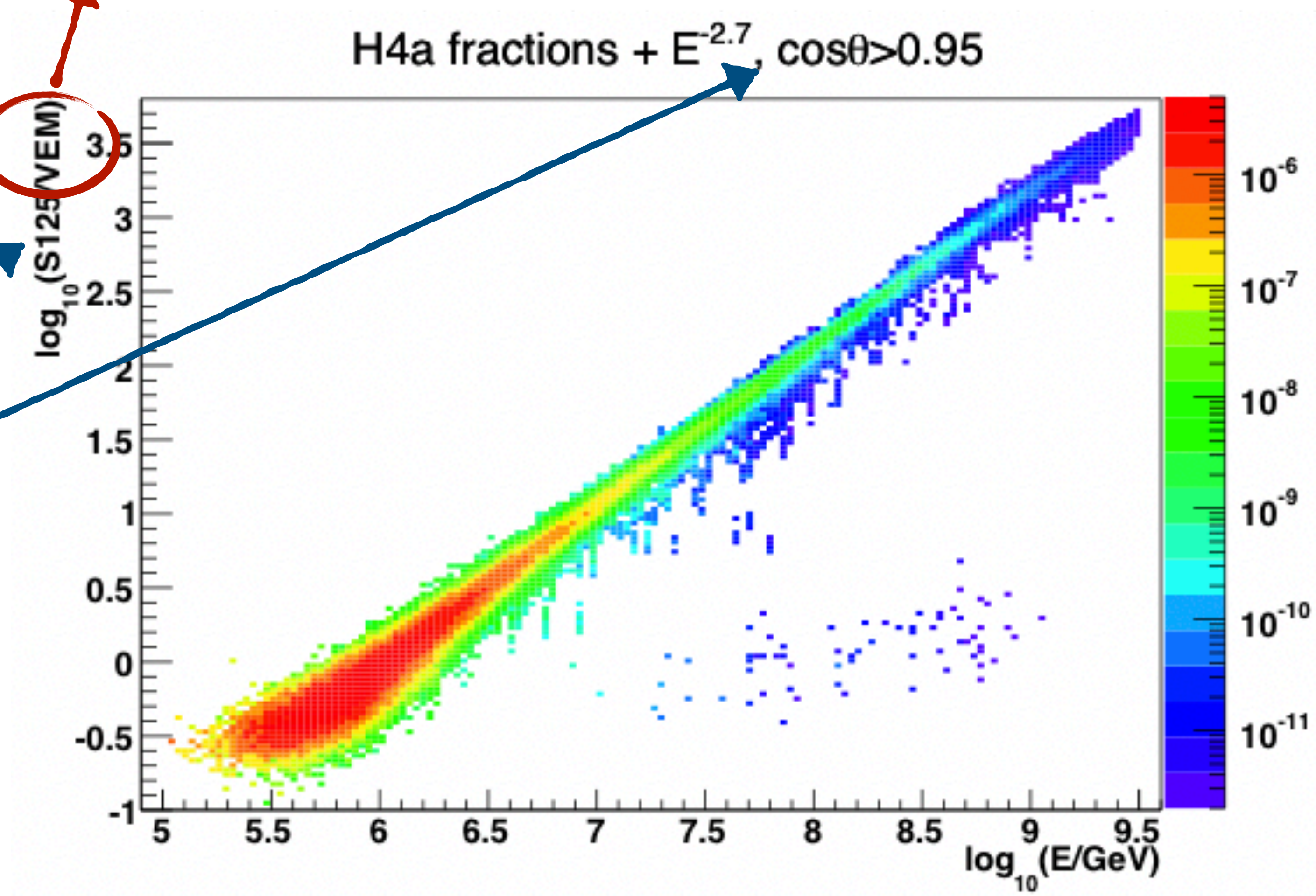
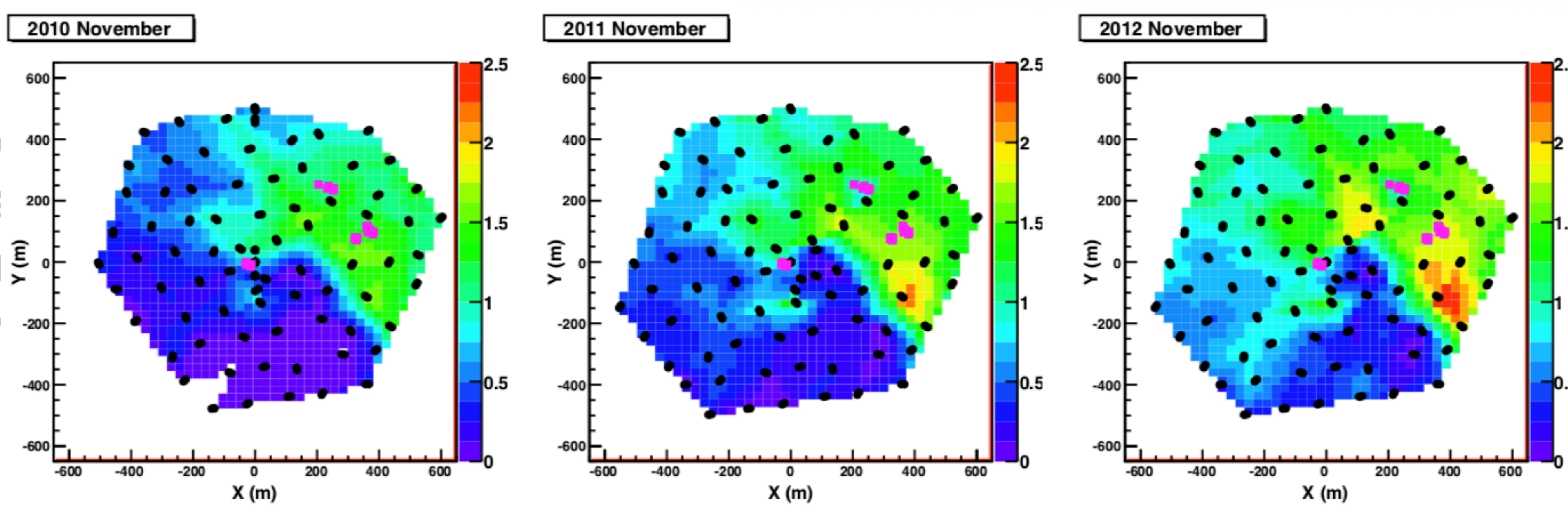


Snow Corrections applied

- S125 measurement
- Zenith reconstruction





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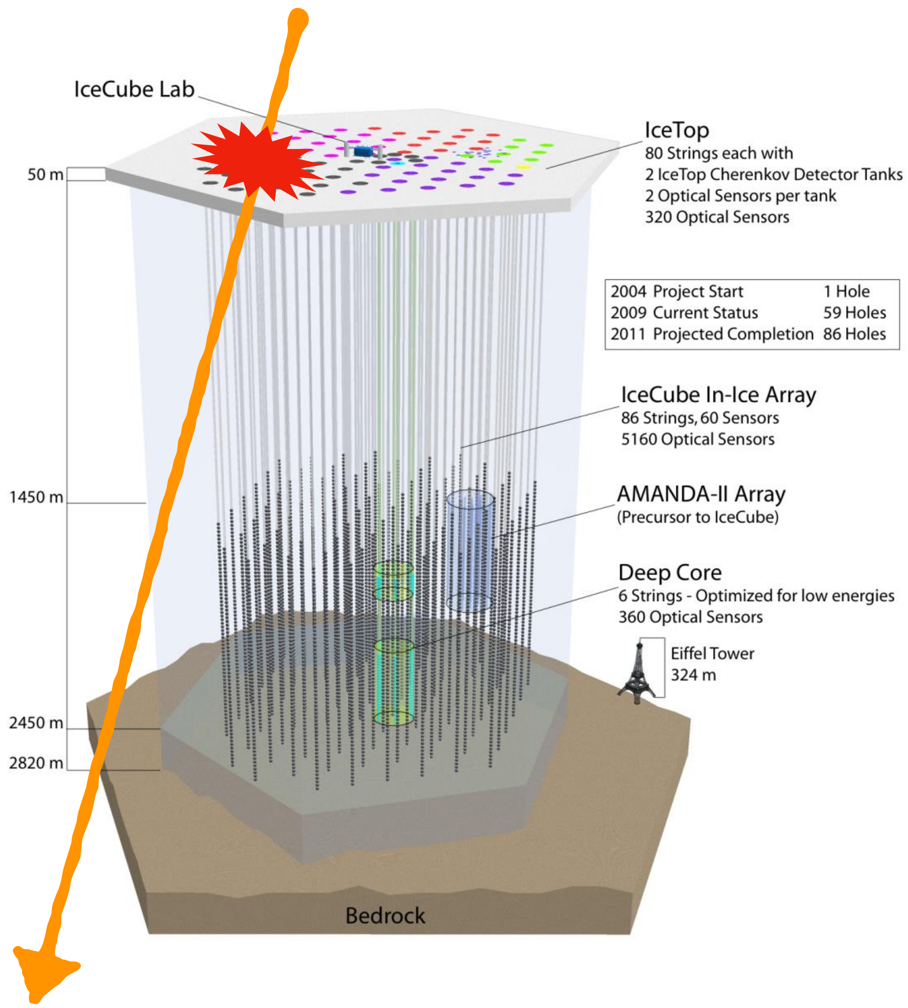
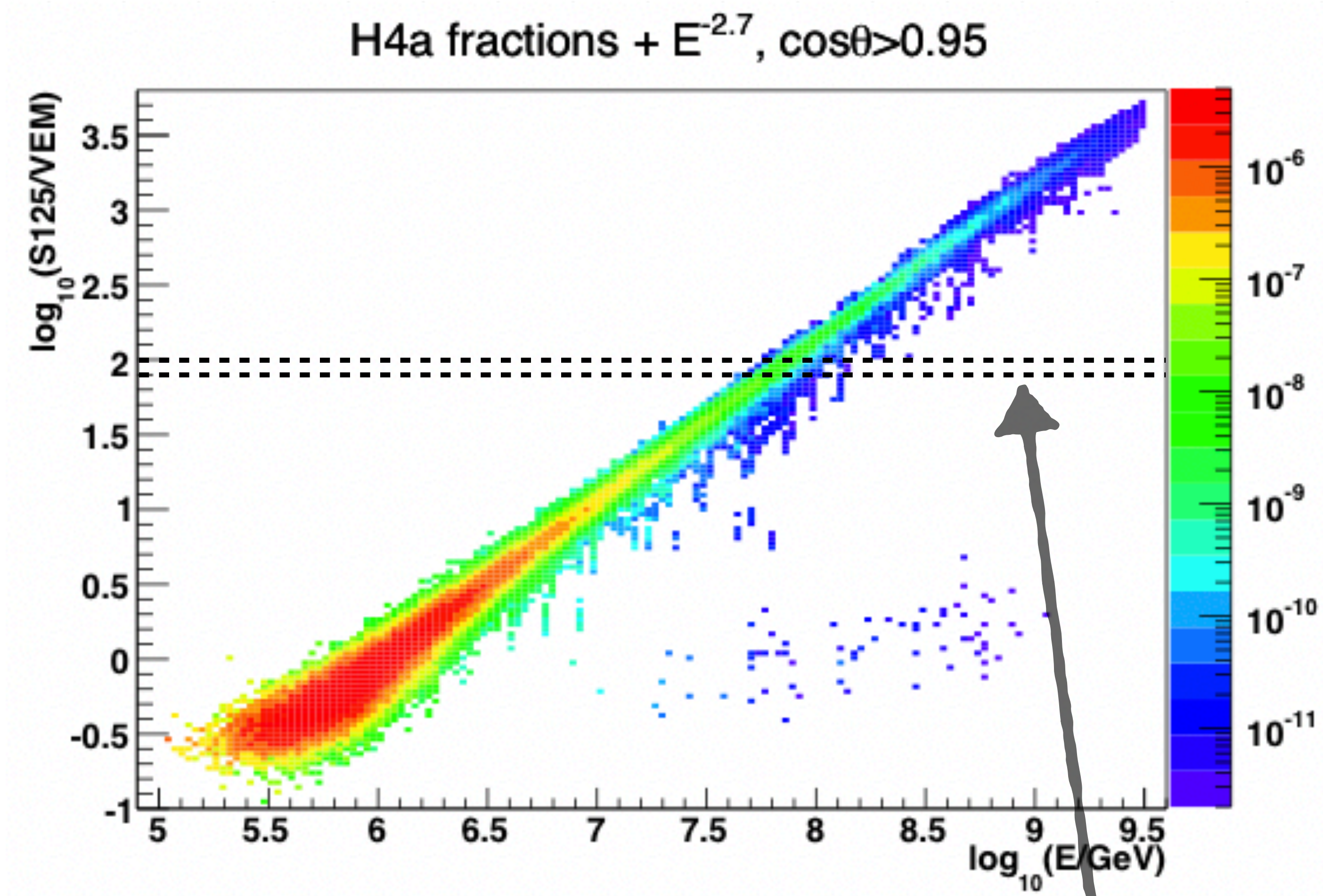
IceTop





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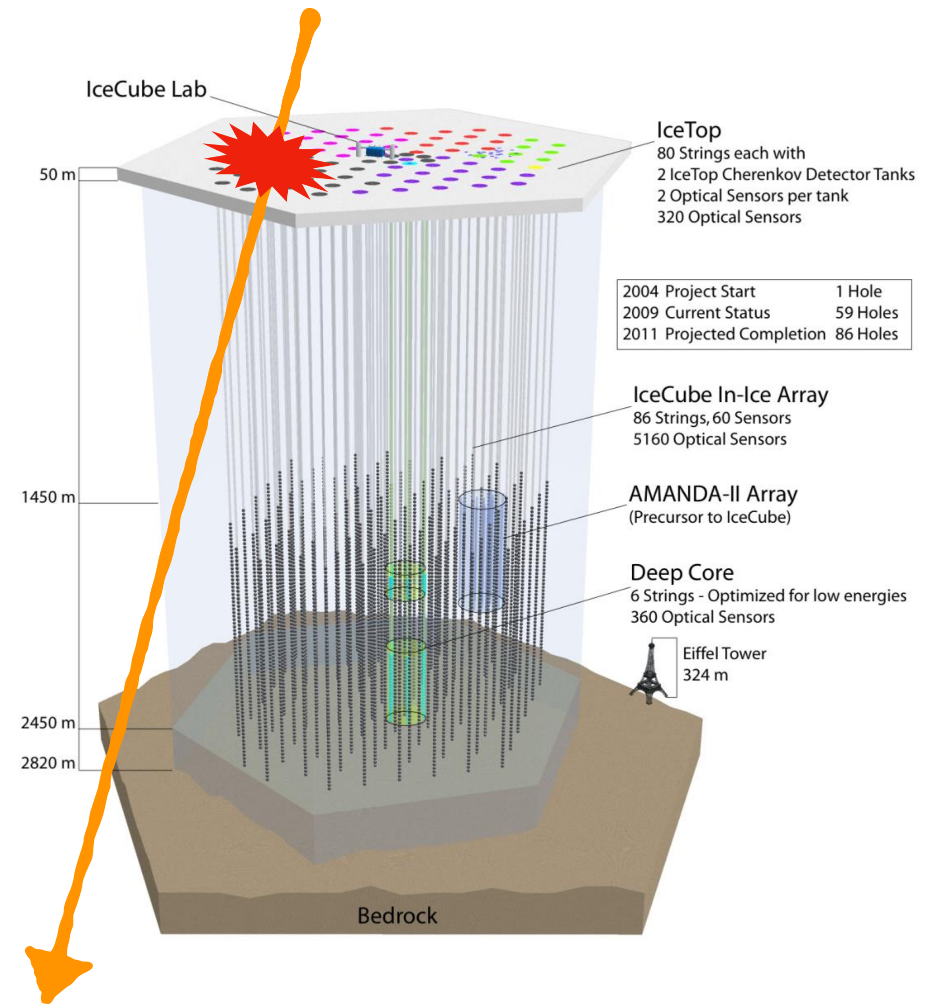

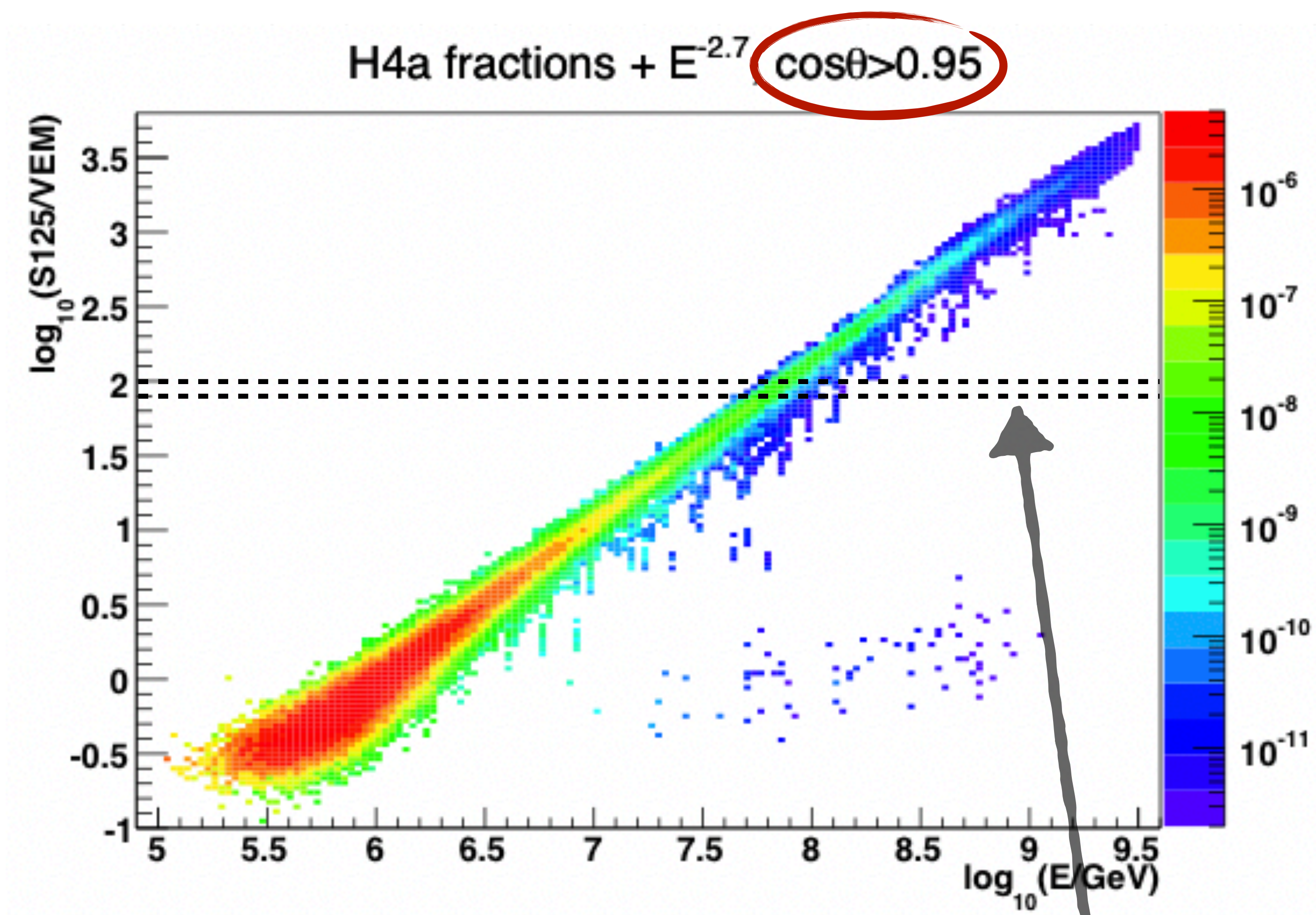

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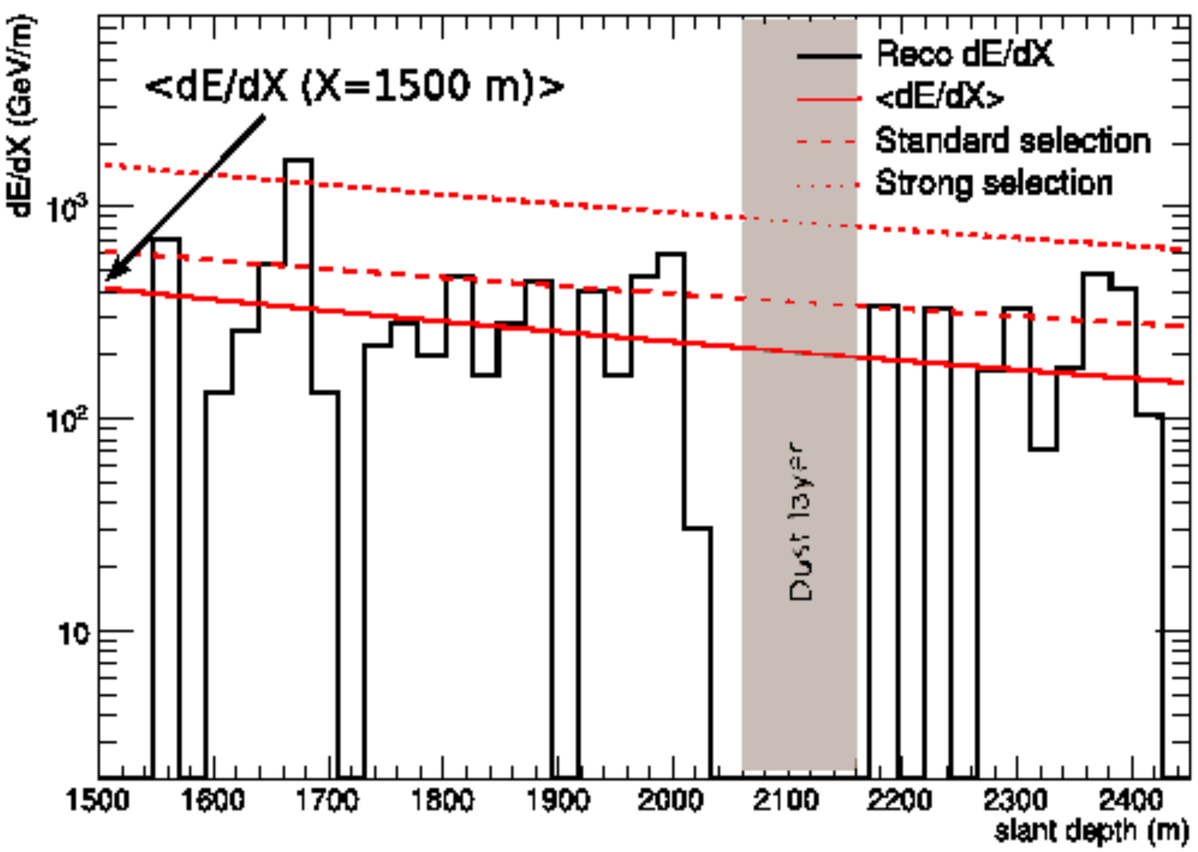
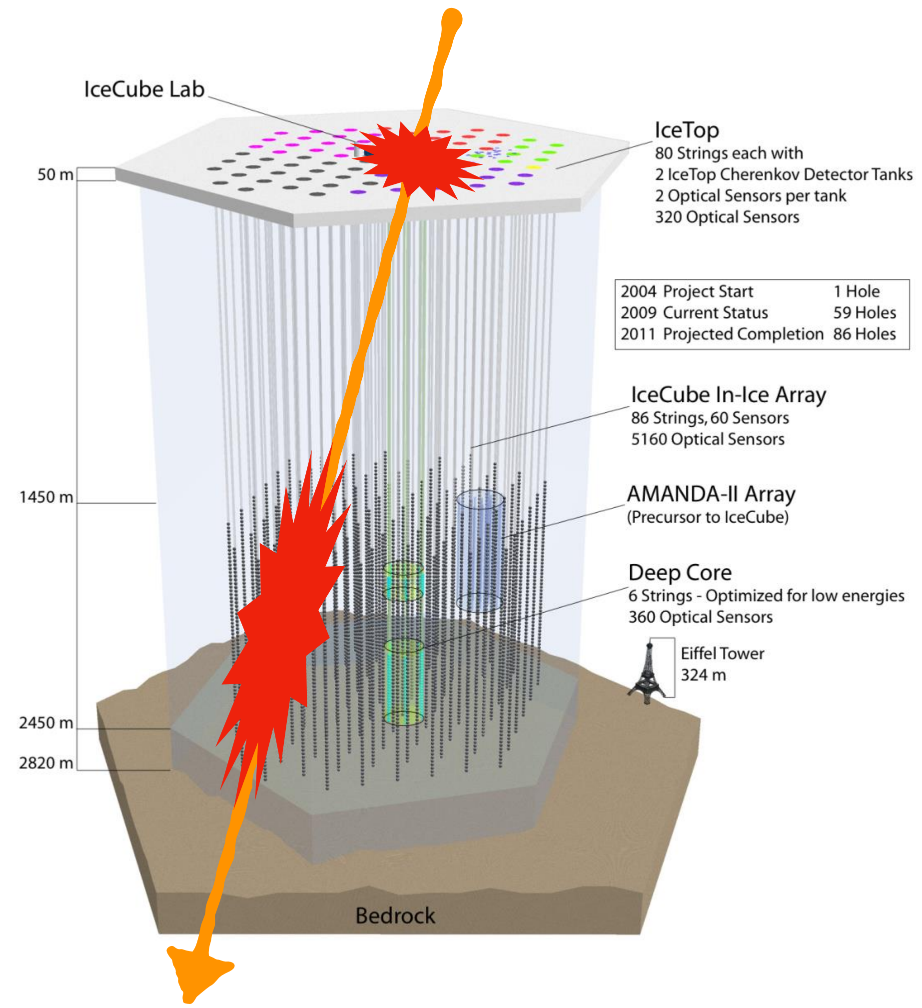
IceTop + InIce





Muon energy loss at 1500 m into the ice

Number of large stochastic losses: peaks above 2 different thresholds (standard and weak)

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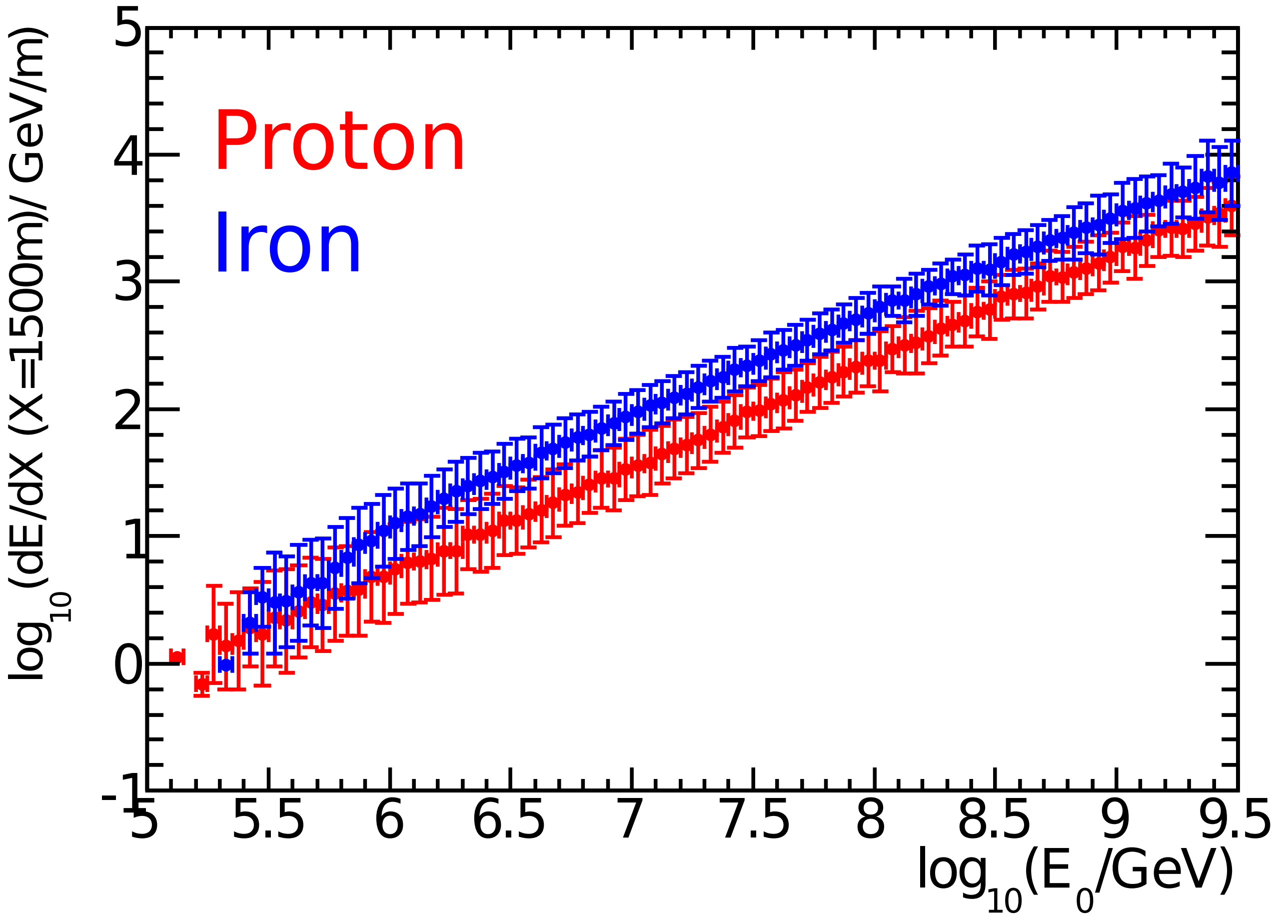

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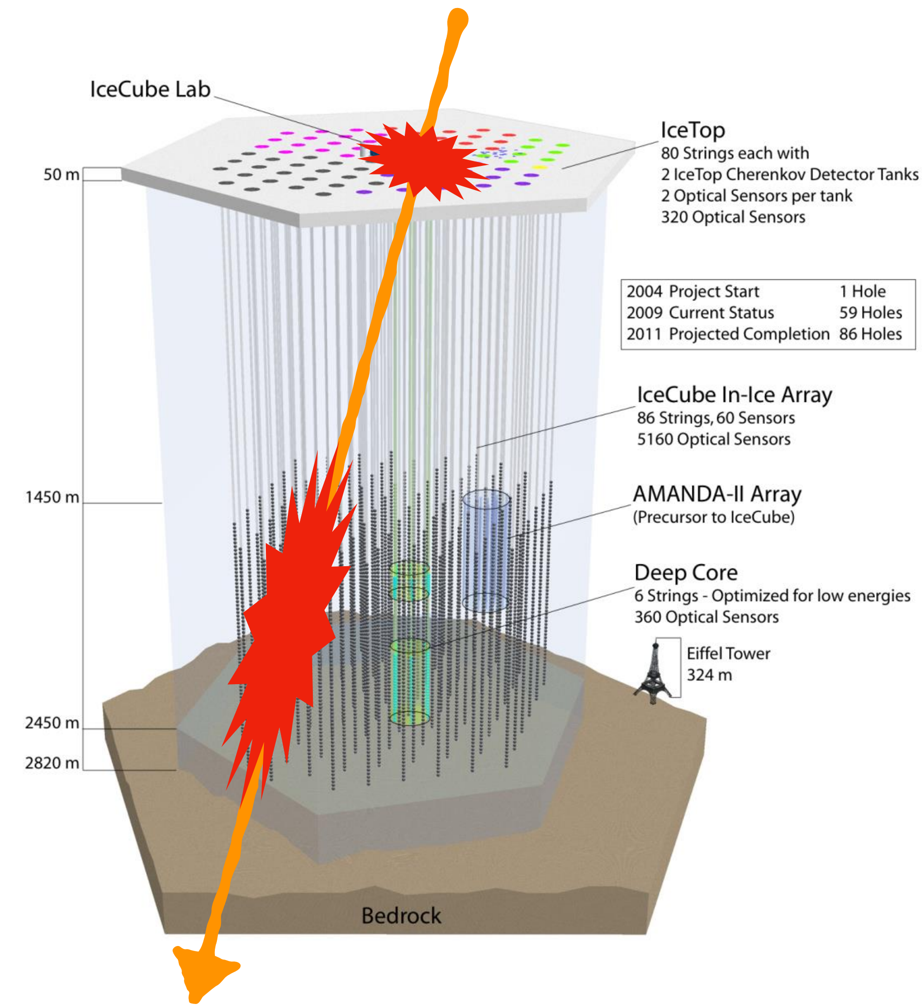
Number of large stochastic losses: peaks above 2 different thresholds (standard and weak)

Composition-sensitive observable



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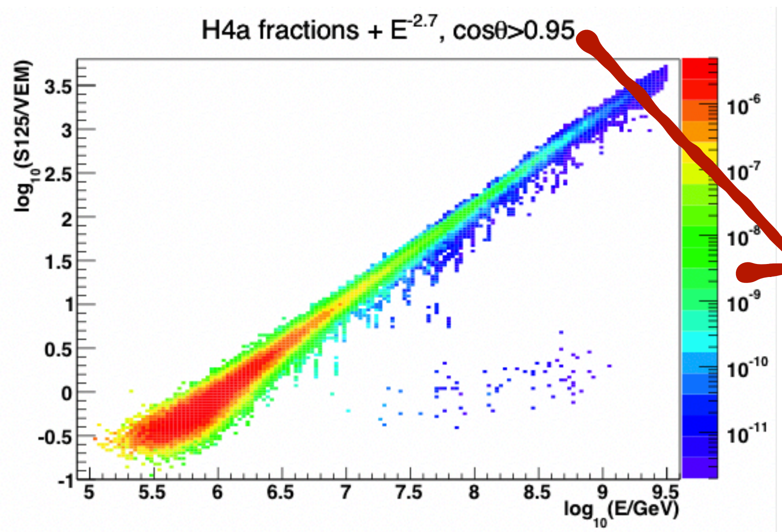
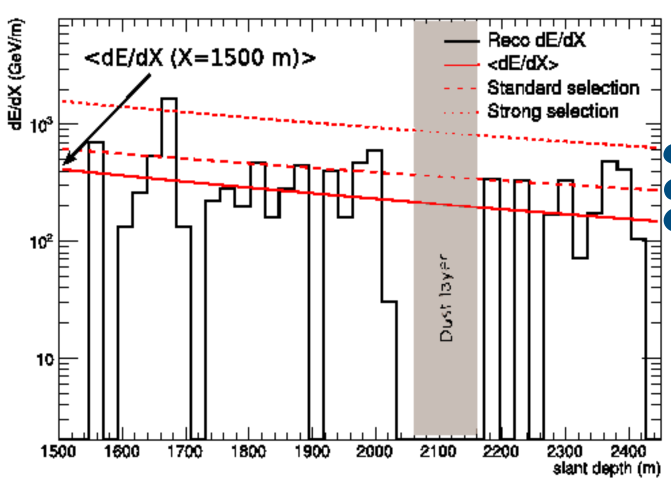
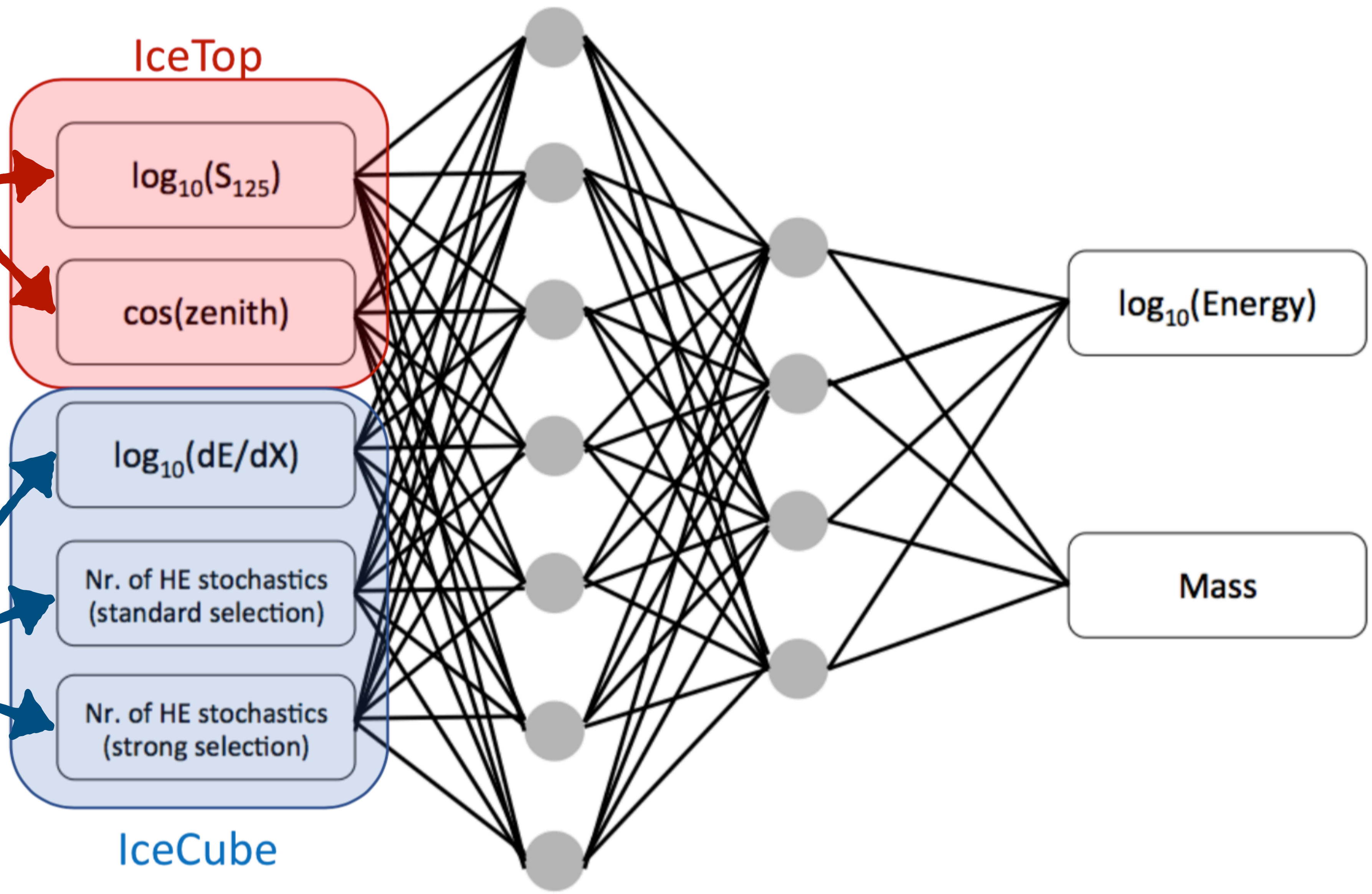
Analysis

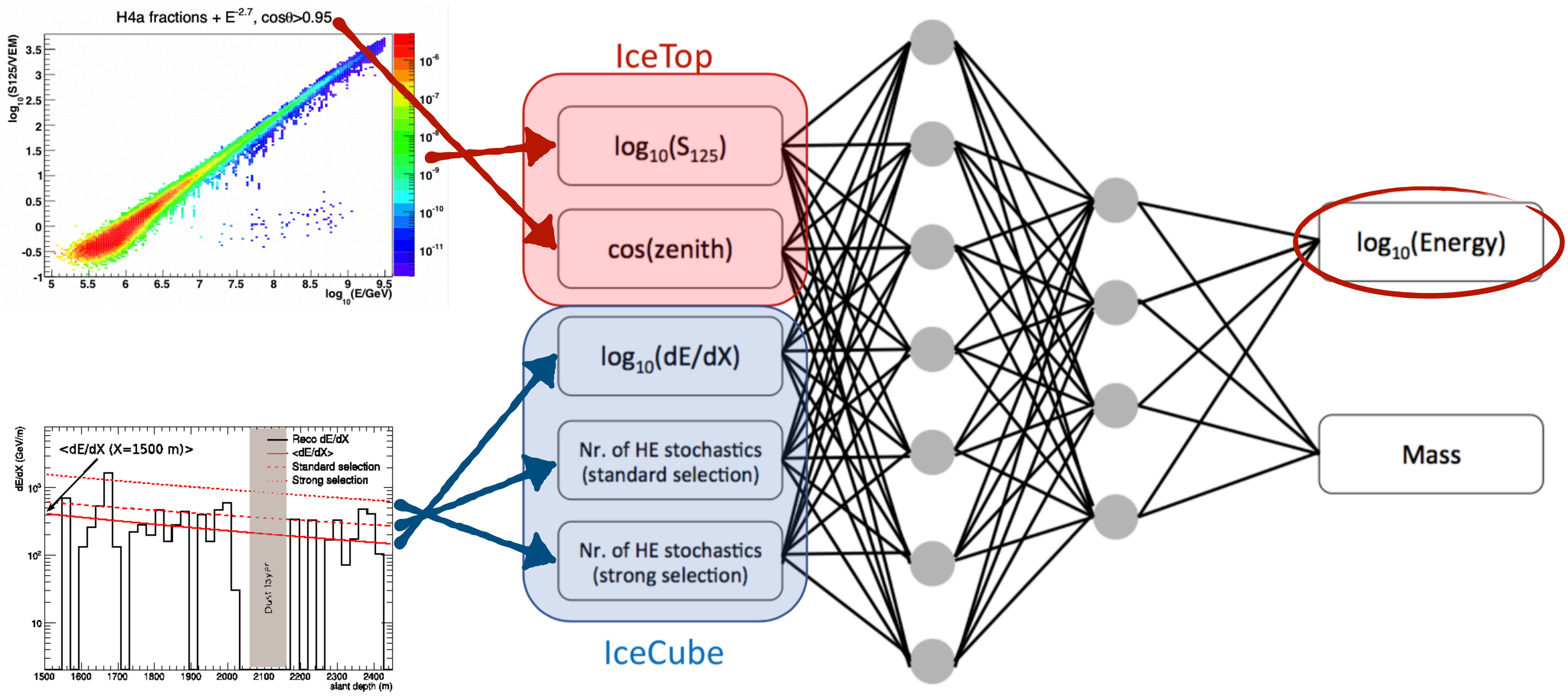
- Trained with Monte Carlo
- Applied event by event
- Energy and Mass to be considered only as distributions



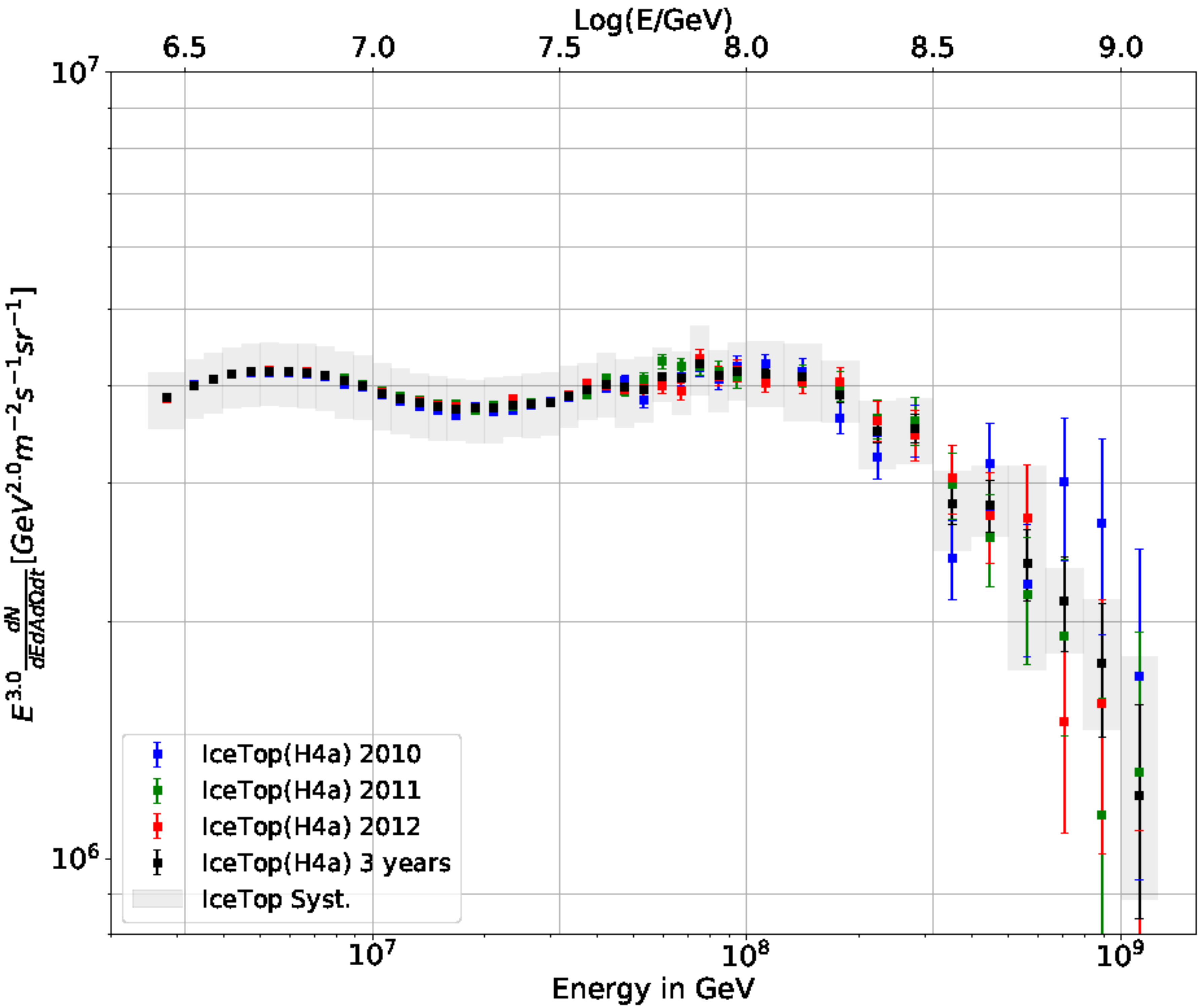




Energy...


H4a fractions + $E^{-2.7}$, cosθ>0.95
$\log_{10}(S125/VEM)$
$\log_{10}(E/GeV)$
IceTop
$\log_{10}(S_{125})$
cos(zenith)
$\log_{10}(dE/dX)$
Nr. of HE stochastics (standard selection)
Nr. of HE stochastics (strong selection)
IceCube
$\log_{10}$(Energy)
Mass
<dE/dX (X=1500 m)>
Reco dE/dX
<dE/dX>
Standard selection
Strong selection
Dust layer
dE/dX (GeV/m)
slant depth (m)

Energy Spectrum from IceTop (alone)

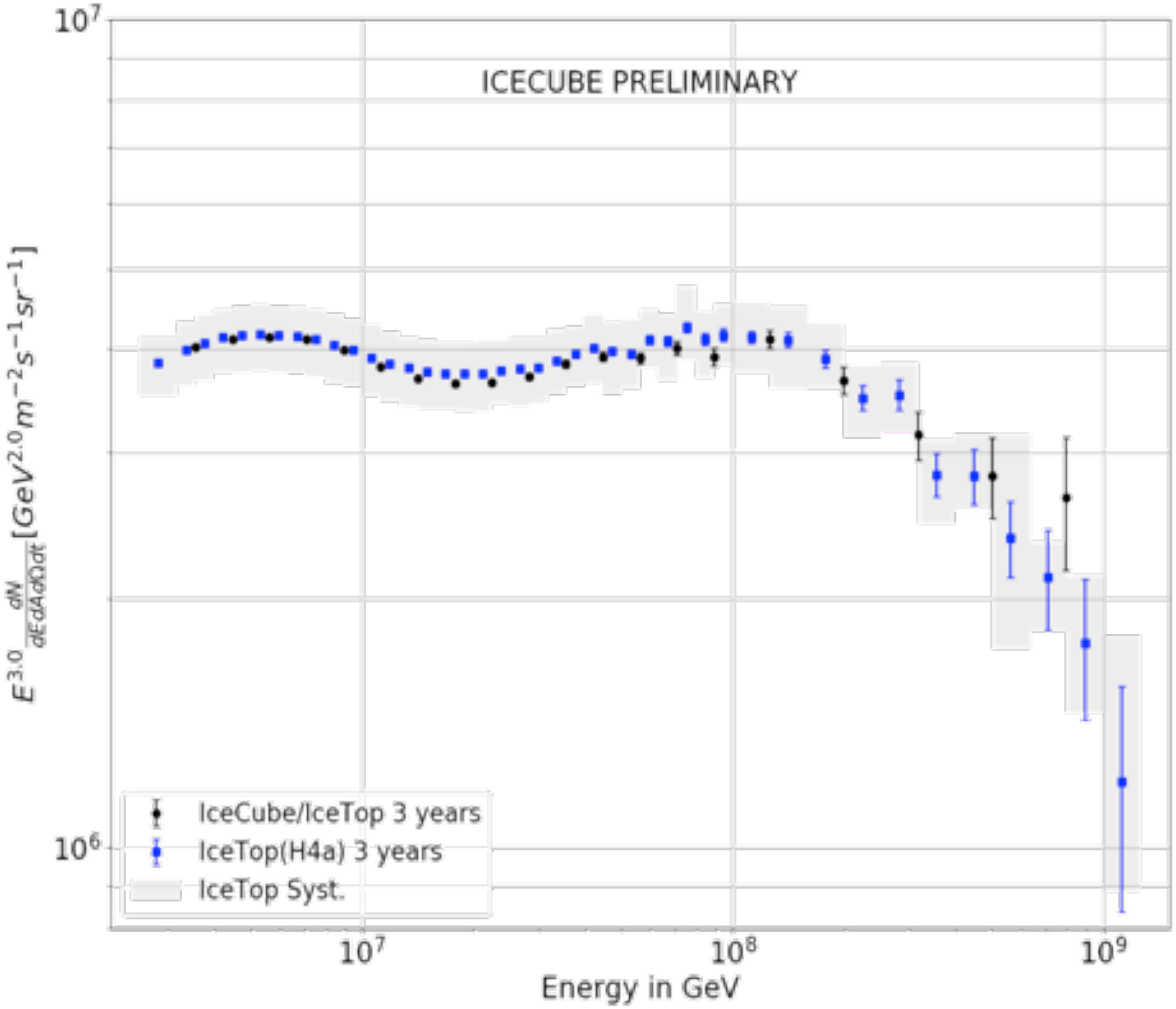


Results from 3 individual years consistent with each other (This assumes fractions of nuclei – p, He, O, Fe – drawn from the H4a composition model)

Main systematic effects:

- Snow attenuation effects
- Absolute scale of IceTop energy

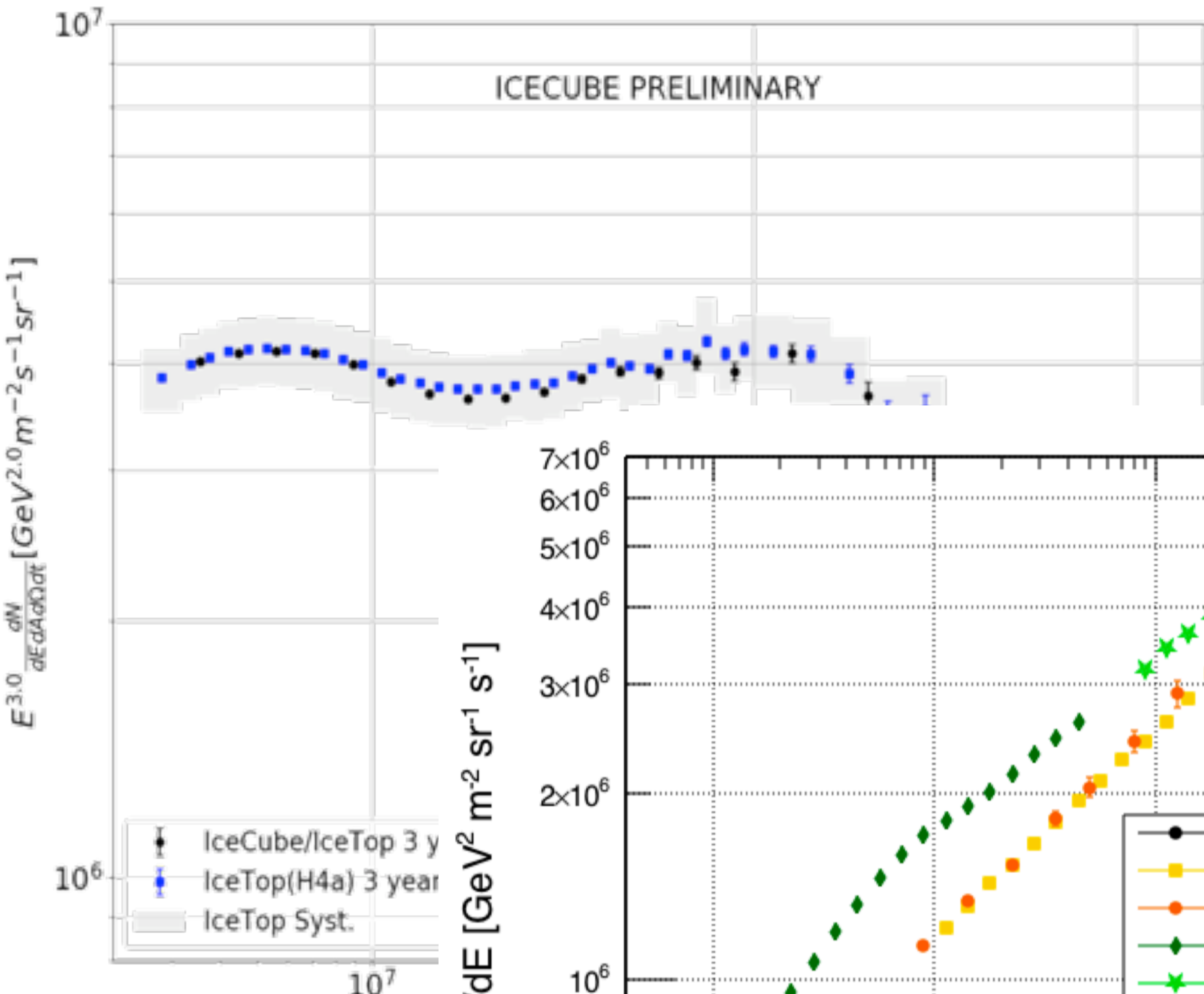
Energy Spectrum IceTop VS IceTop+InIce



Good agreement between the energy spectra of both analyses methods

Smaller energy range than IceTop alone due to constrains for the coincidence analysis, i.e. smaller statistics

Energy Spectrum IceTop VS others



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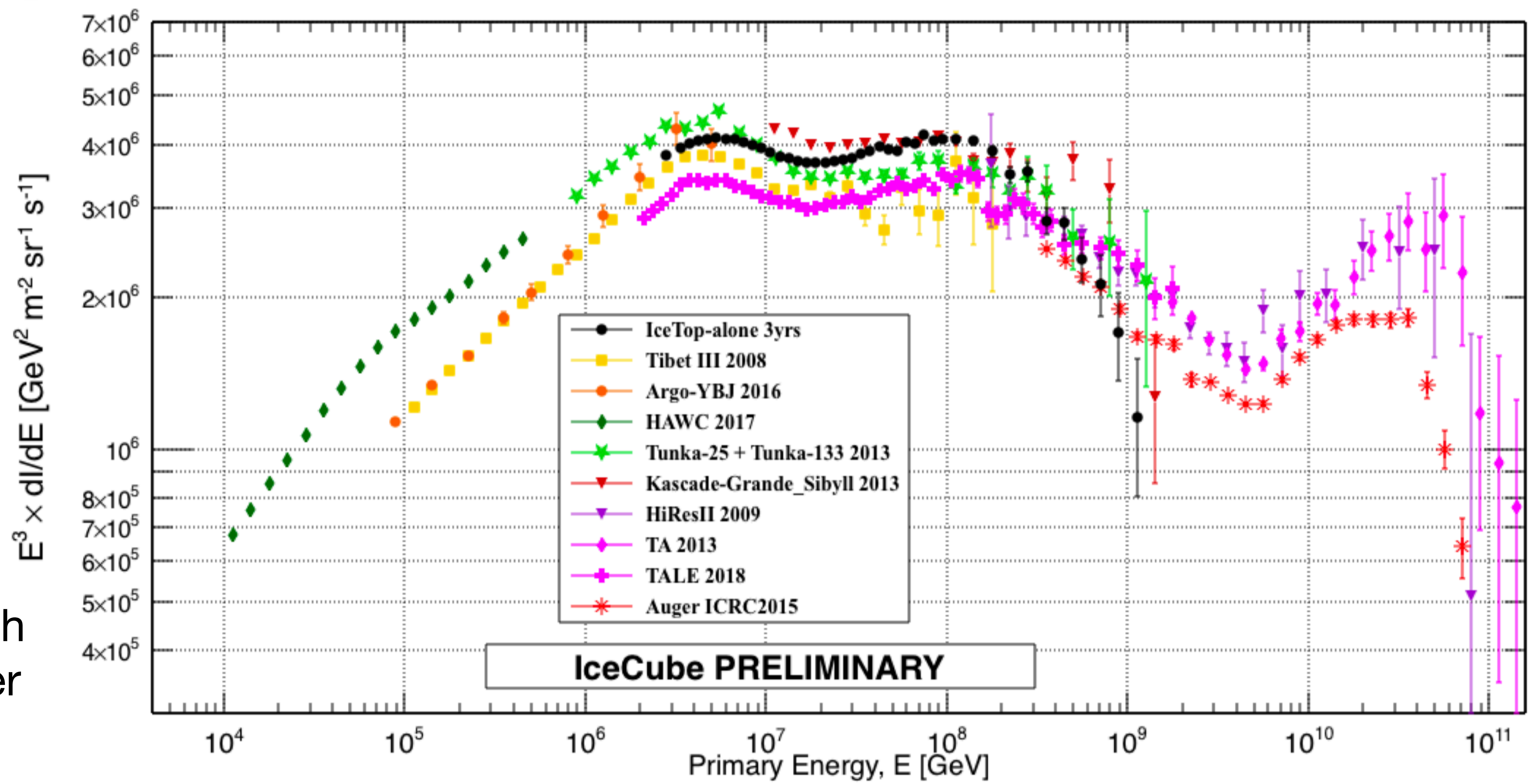
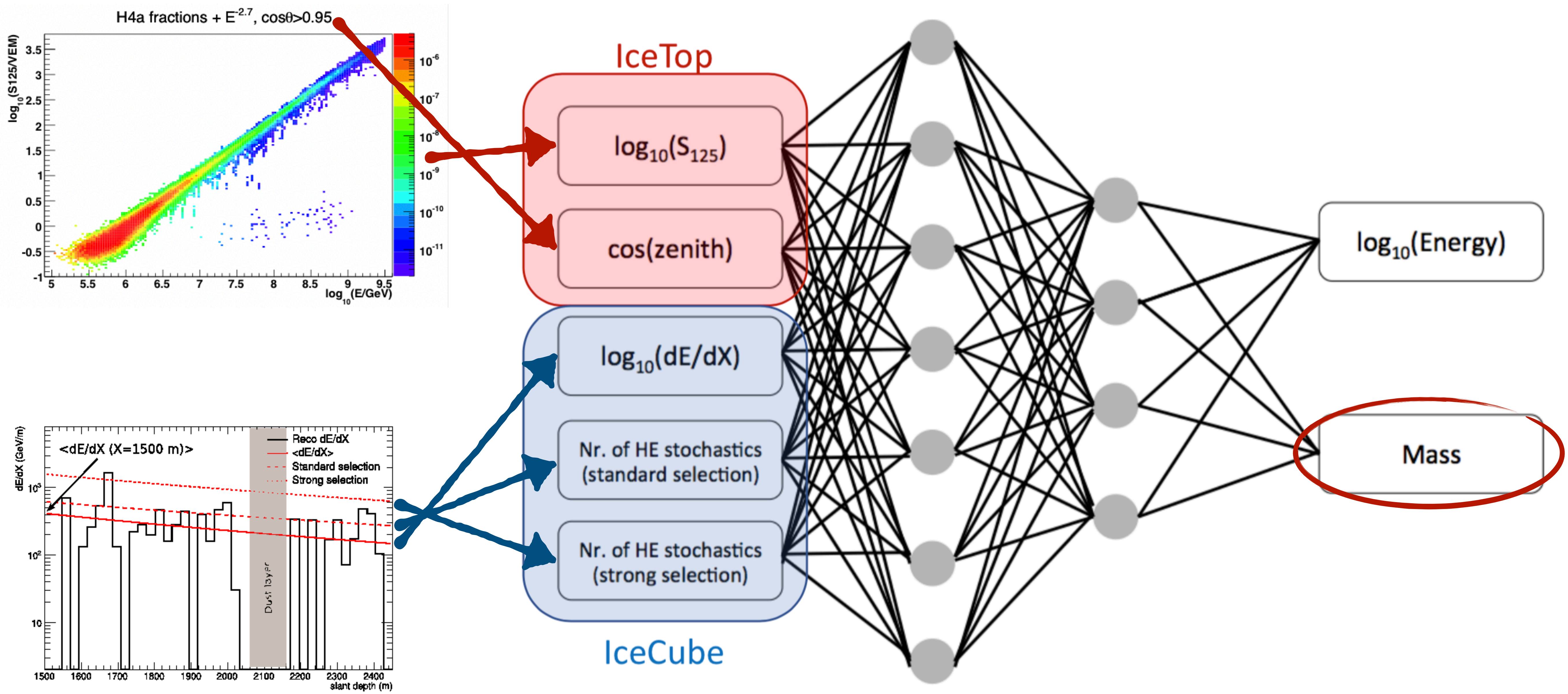


Overall good agreement of with results from other experiments

...and mass



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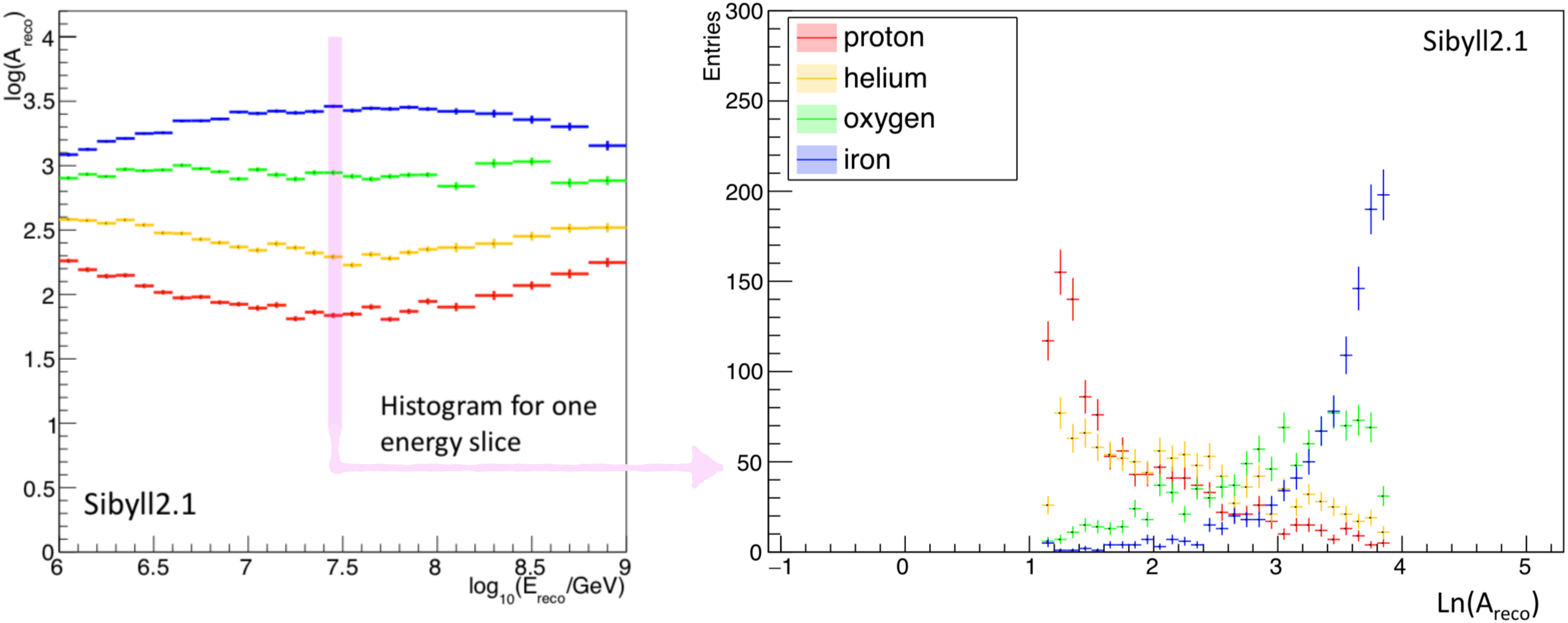
slant depth (m)

Mass reconstruction

Event-by-event classification of mass types is not possible

Analyse mass as a function of energy on statistical bases



KDE templates:

- Monte Carlo data converted into template of **P**robability **D**ensity **F**unctions' (PDF) for each primary in each energy bin
- Used adaptive Gaussian kernel width to preserve characteristic features of neural net output

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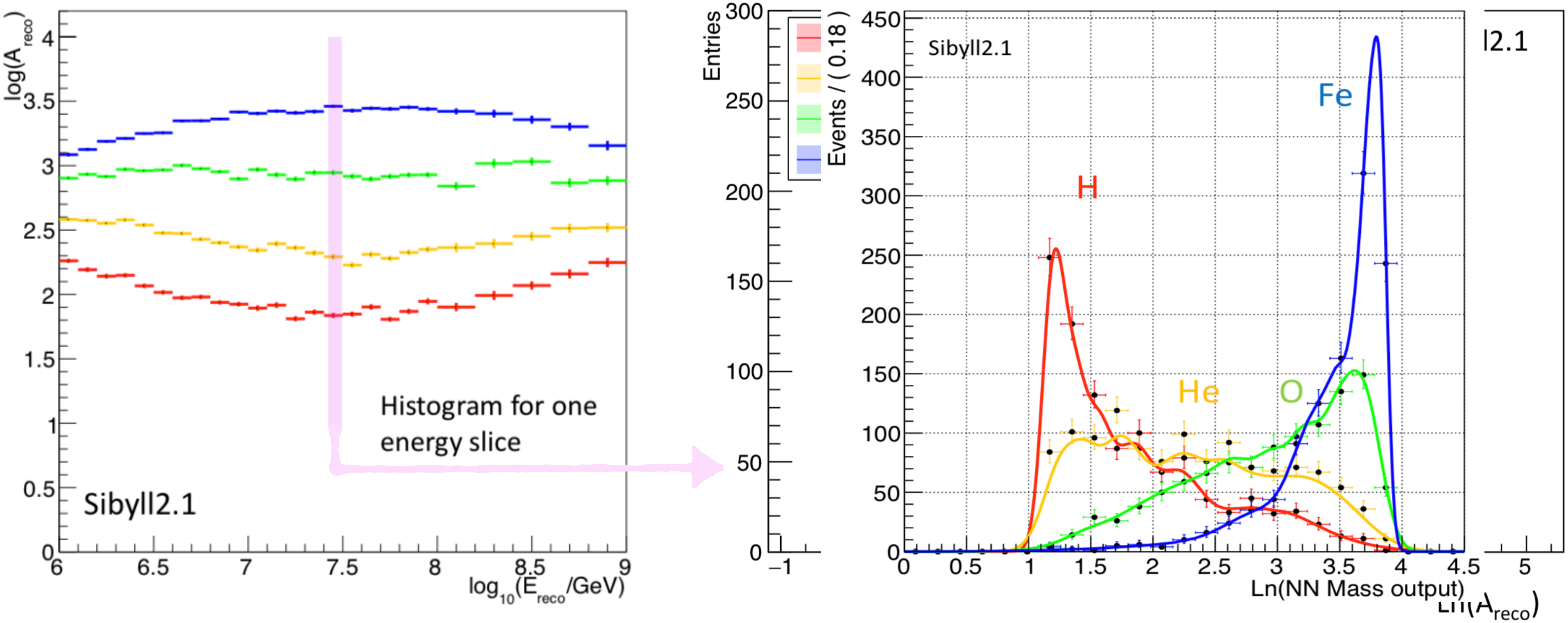

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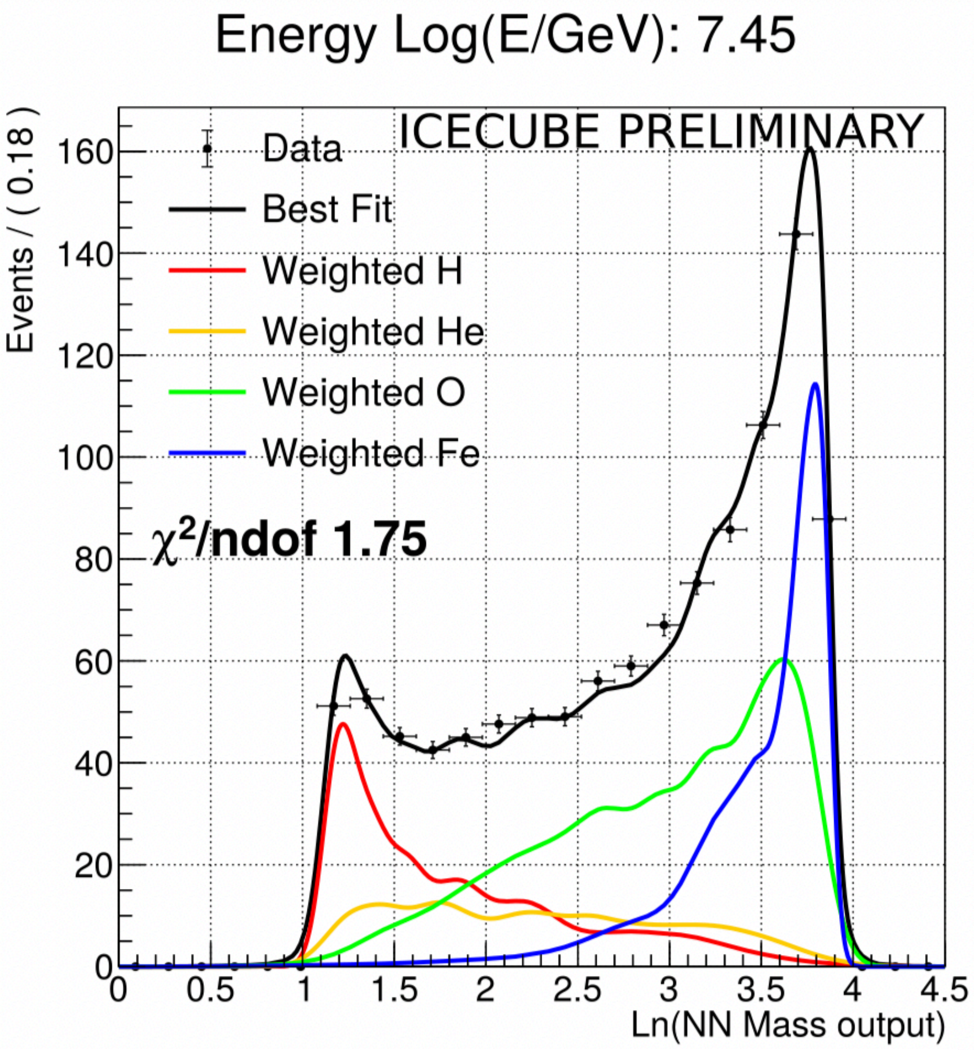
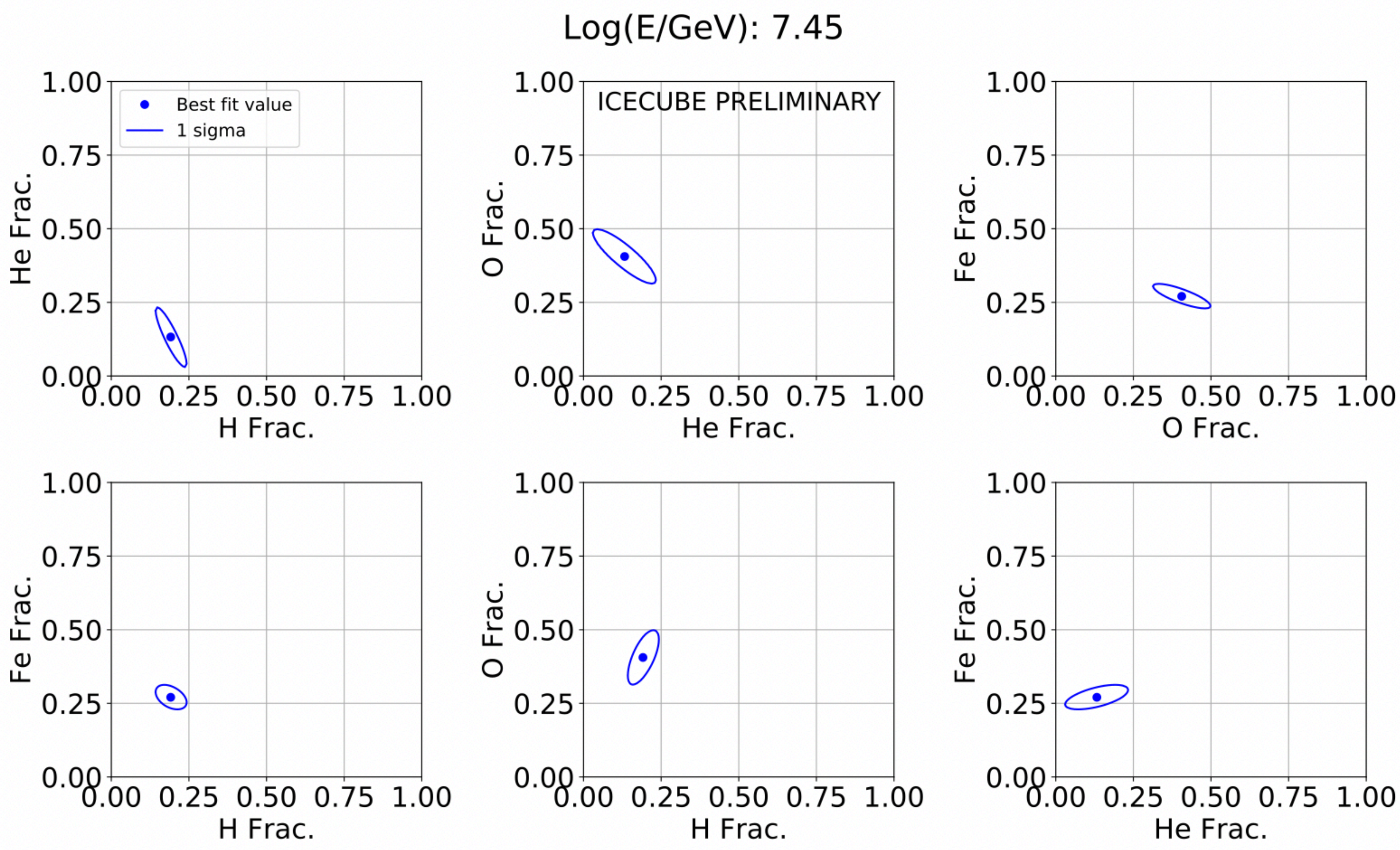
Mass reconstruction: example on Data

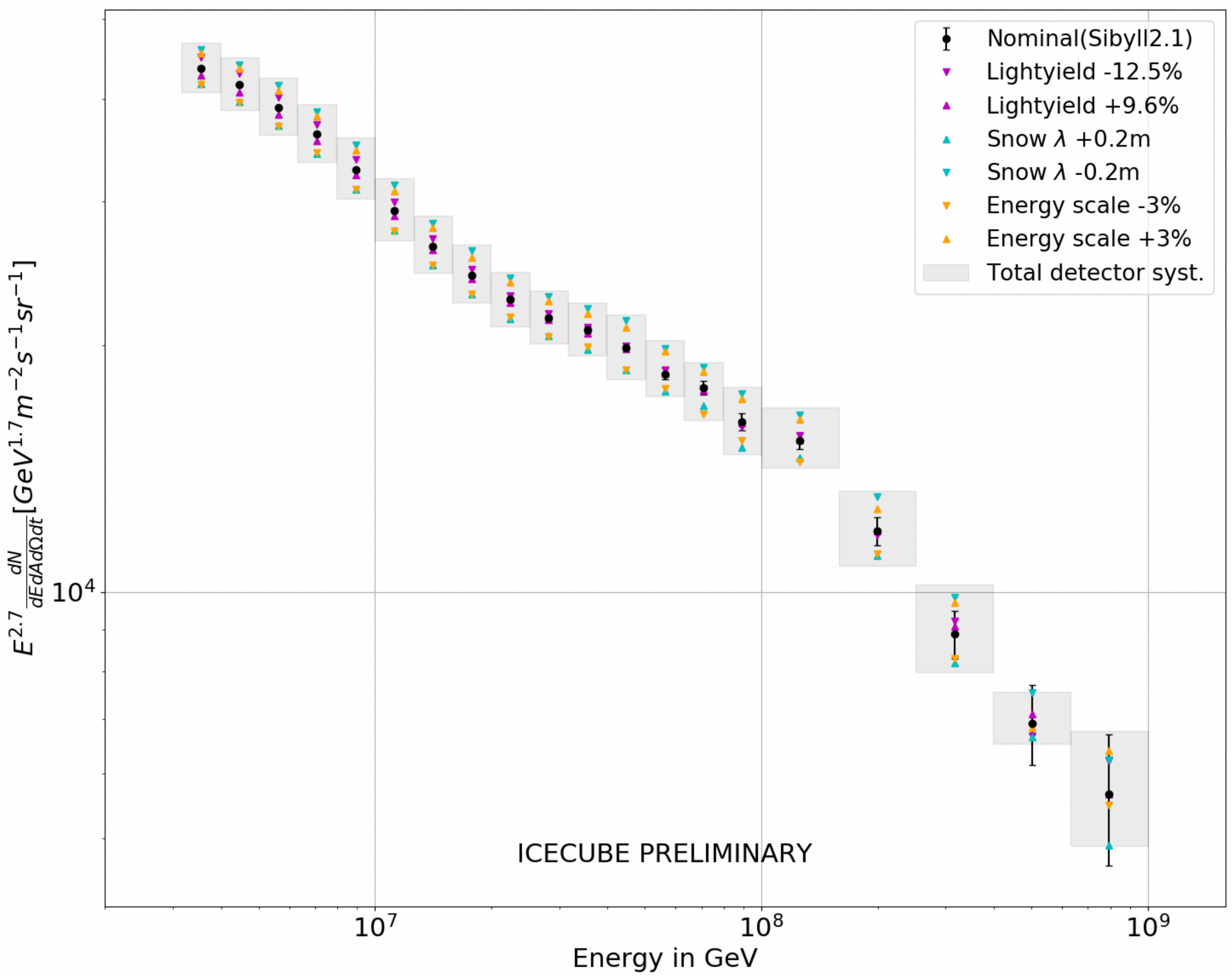


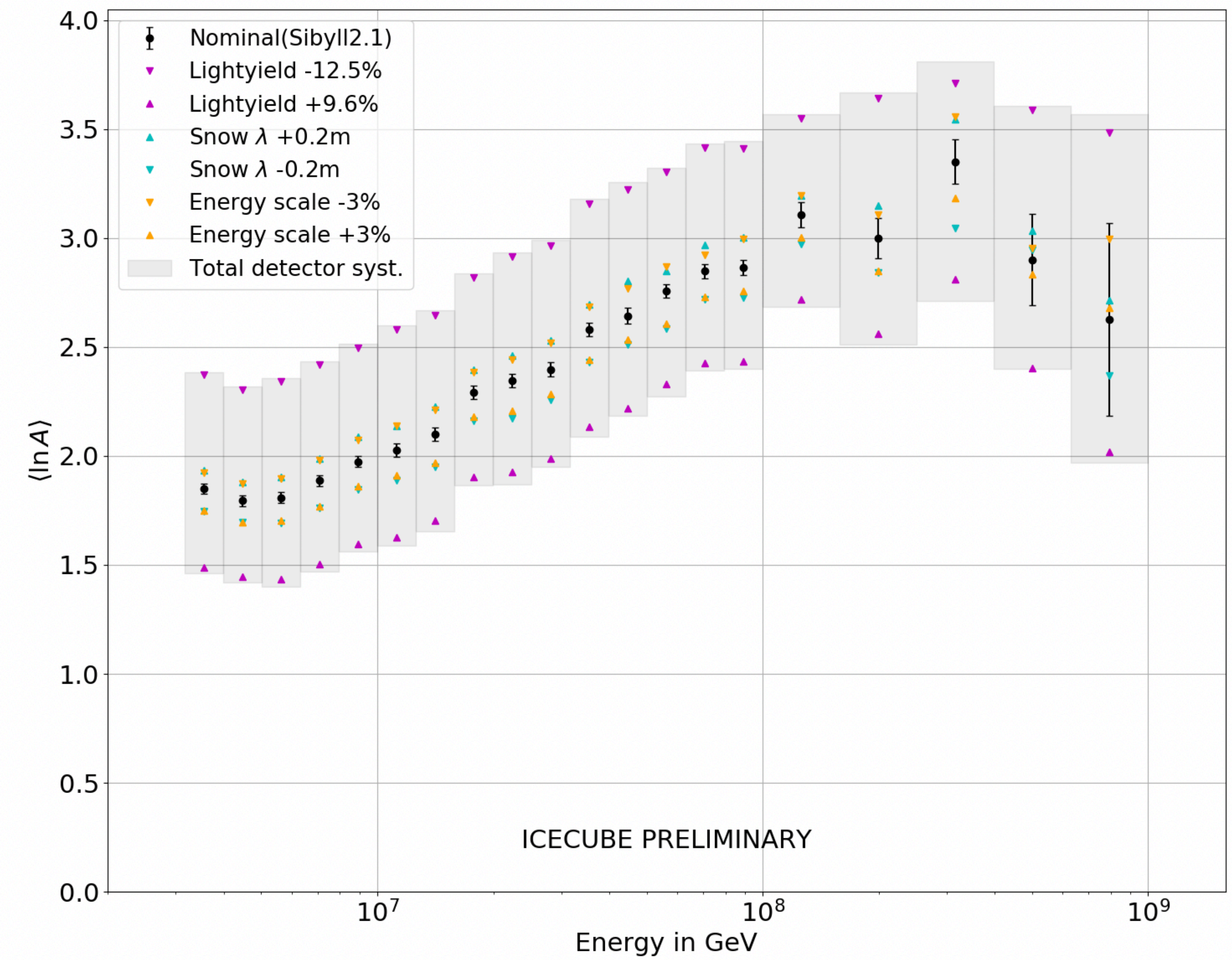


PDFs from KDE templates used in extended Likelihood analysis:

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

Detector Systematic Uncertainties

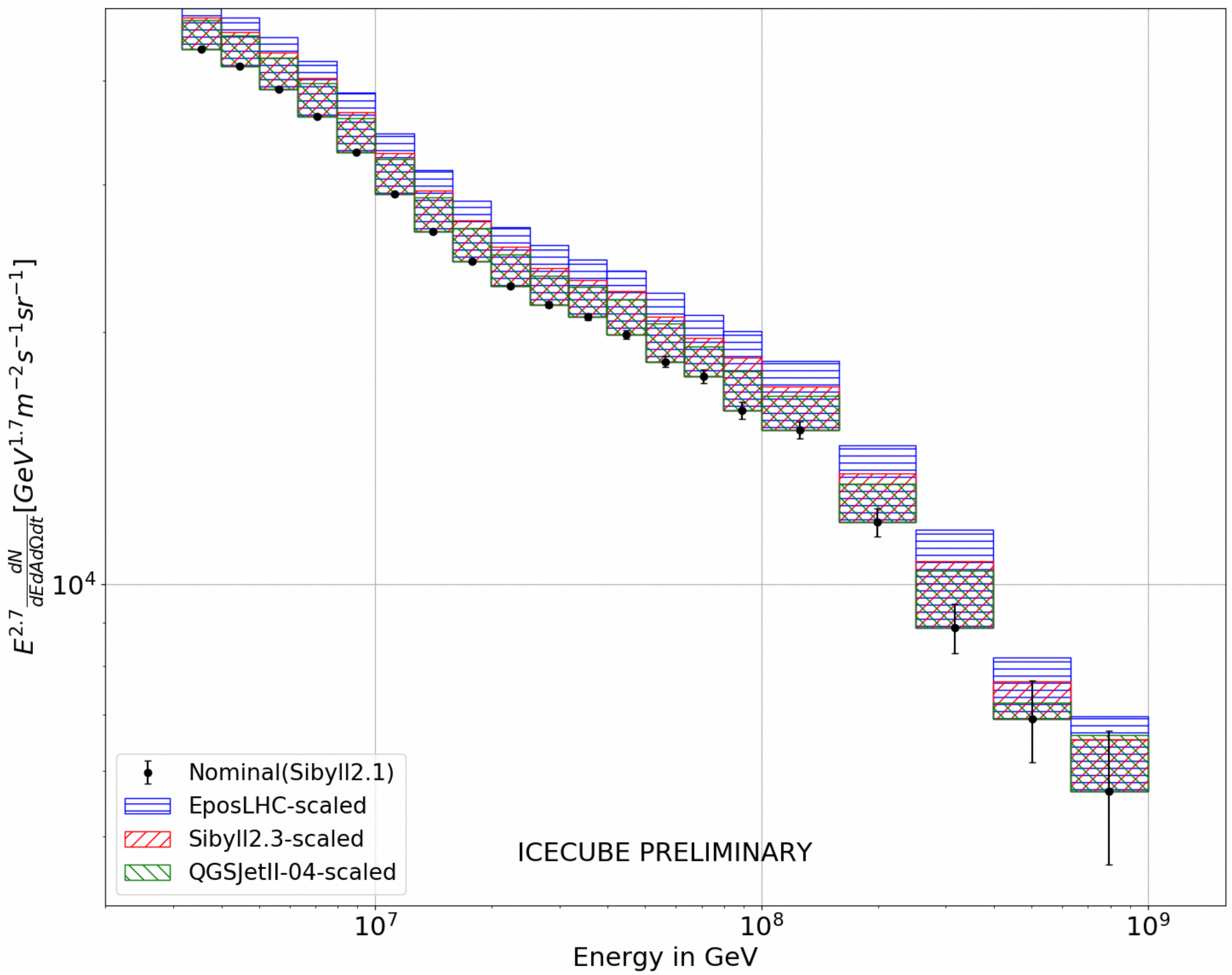


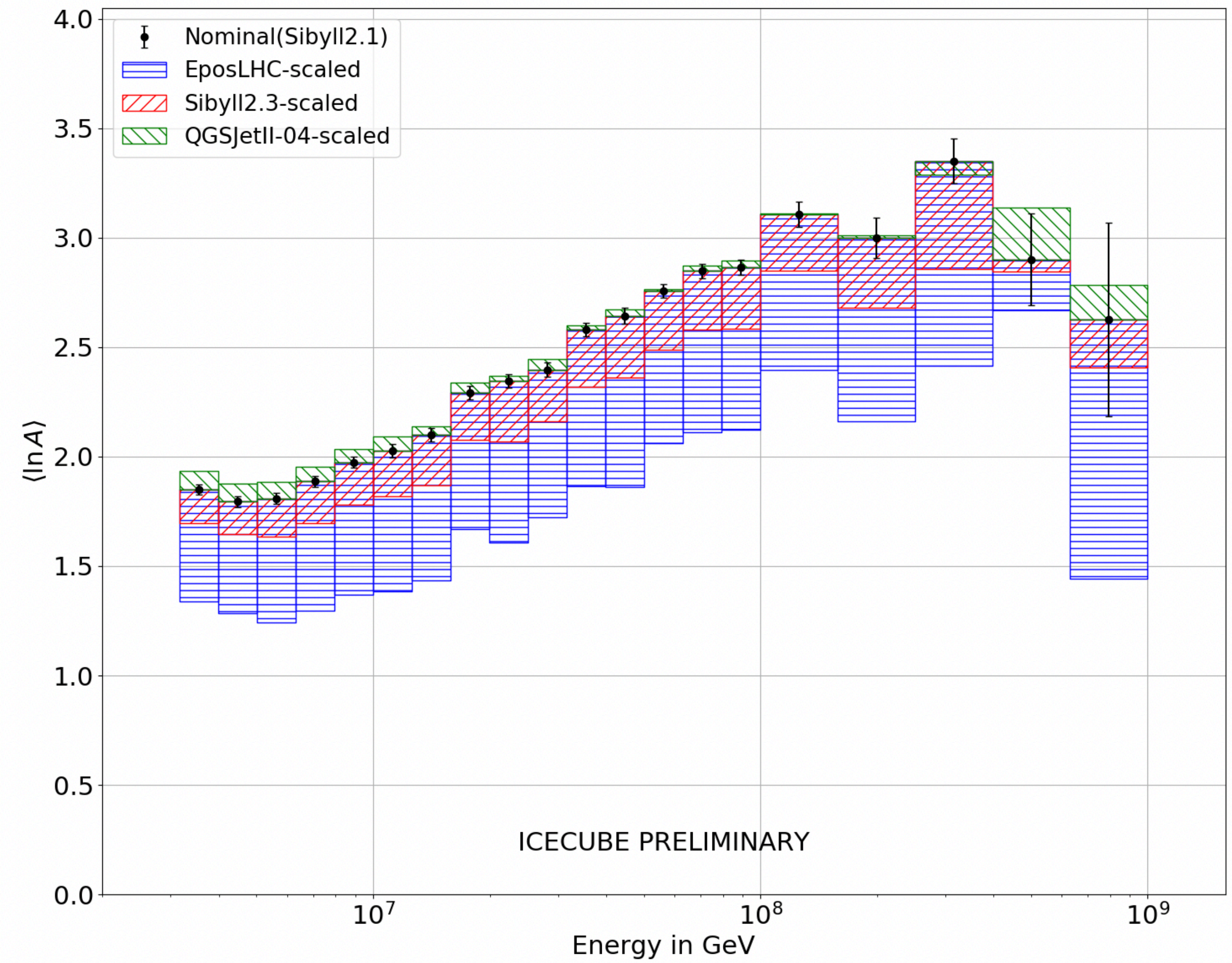


Considered for in systematic offsets on flux and ⟨ln *A*⟩

Snow, **InIce light yield** and **energy scale uncertainty**

Hadronic Systematic Uncertainties

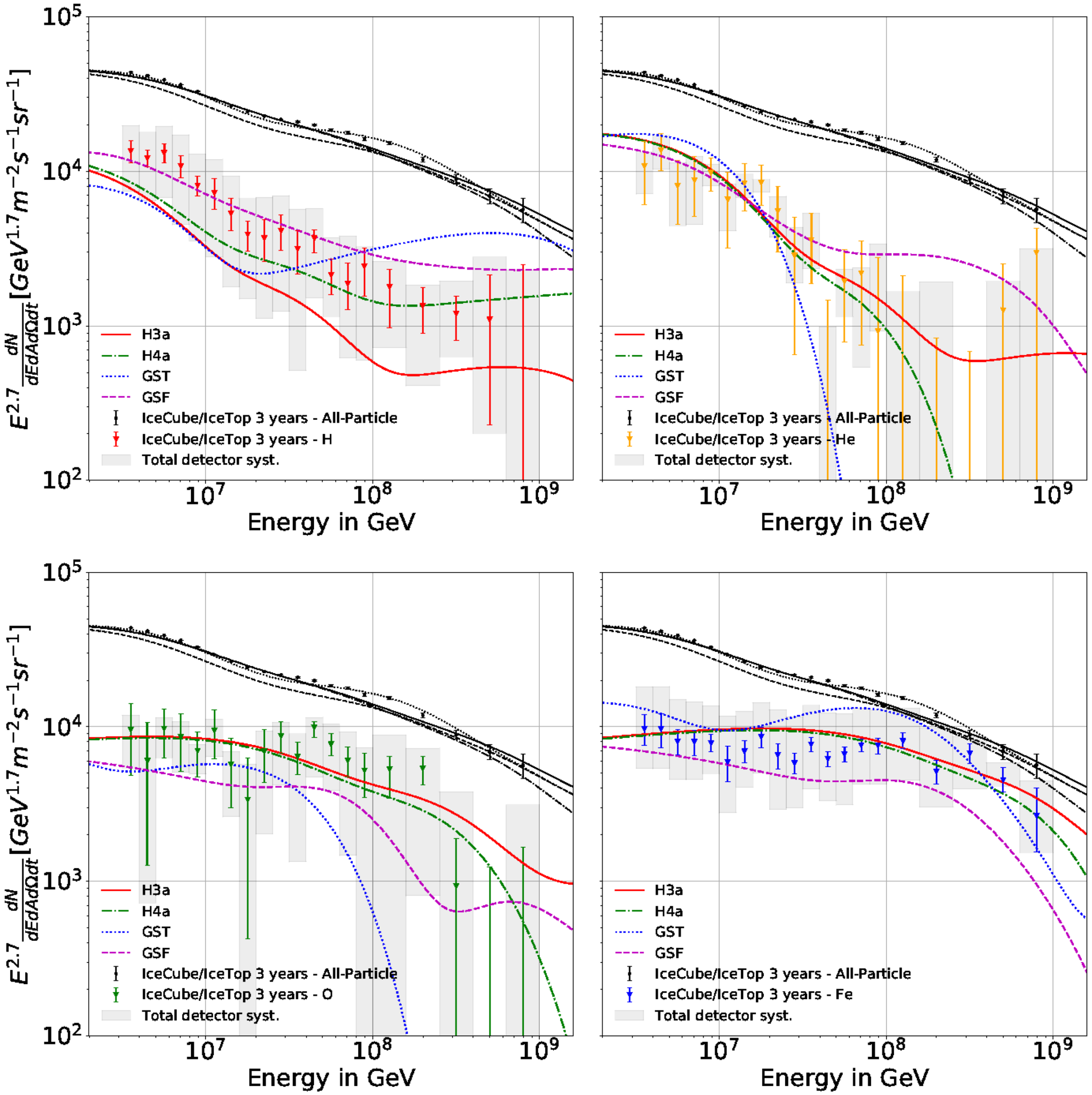




Scaling data according to differences in detector response due to interaction models result in uncertainty region in the flux and the $\langle \ln A \rangle$

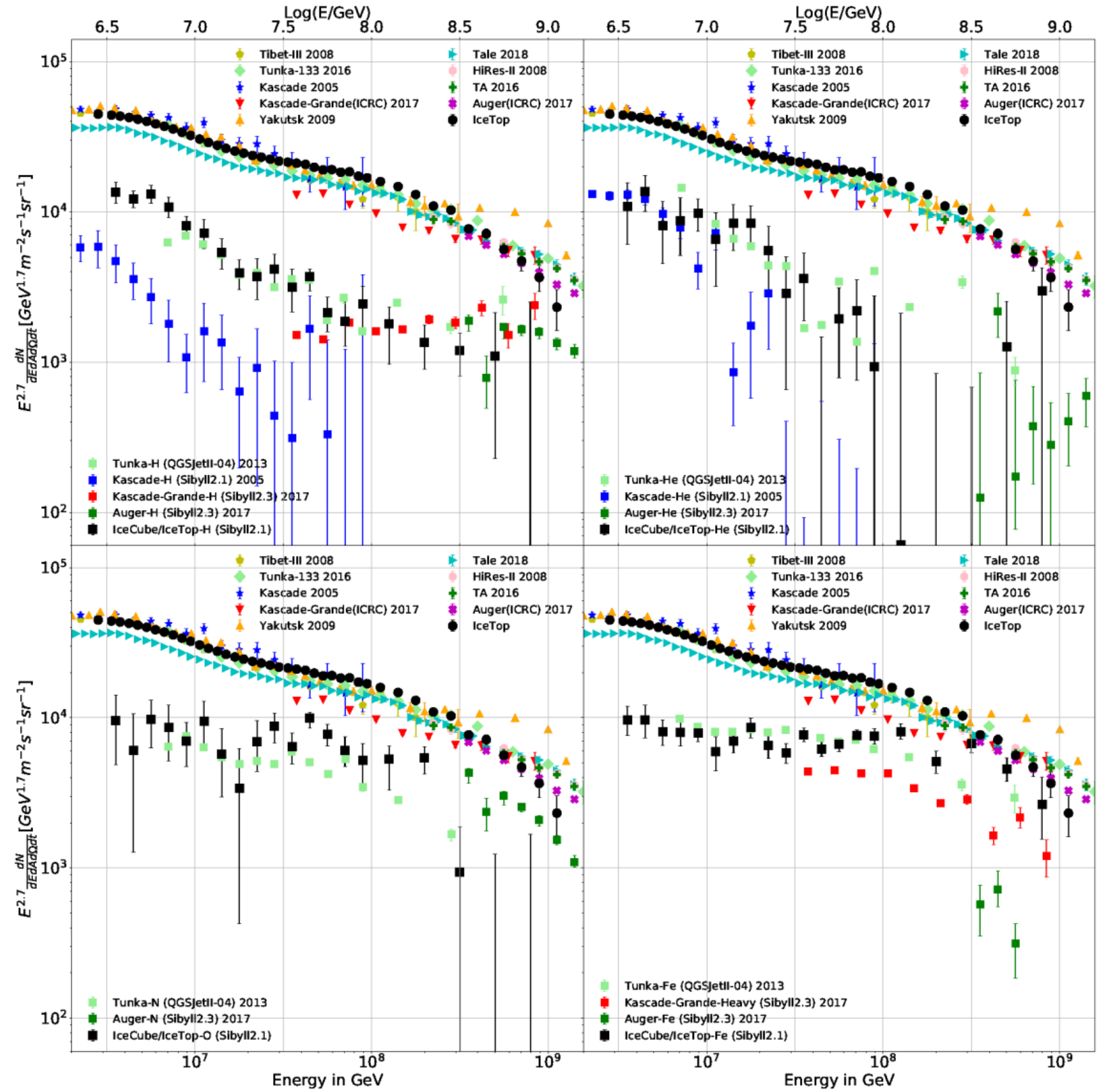
Mass Composition of the flux

IceCube results



Inside statistical and systematic uncertainties good agreement with models

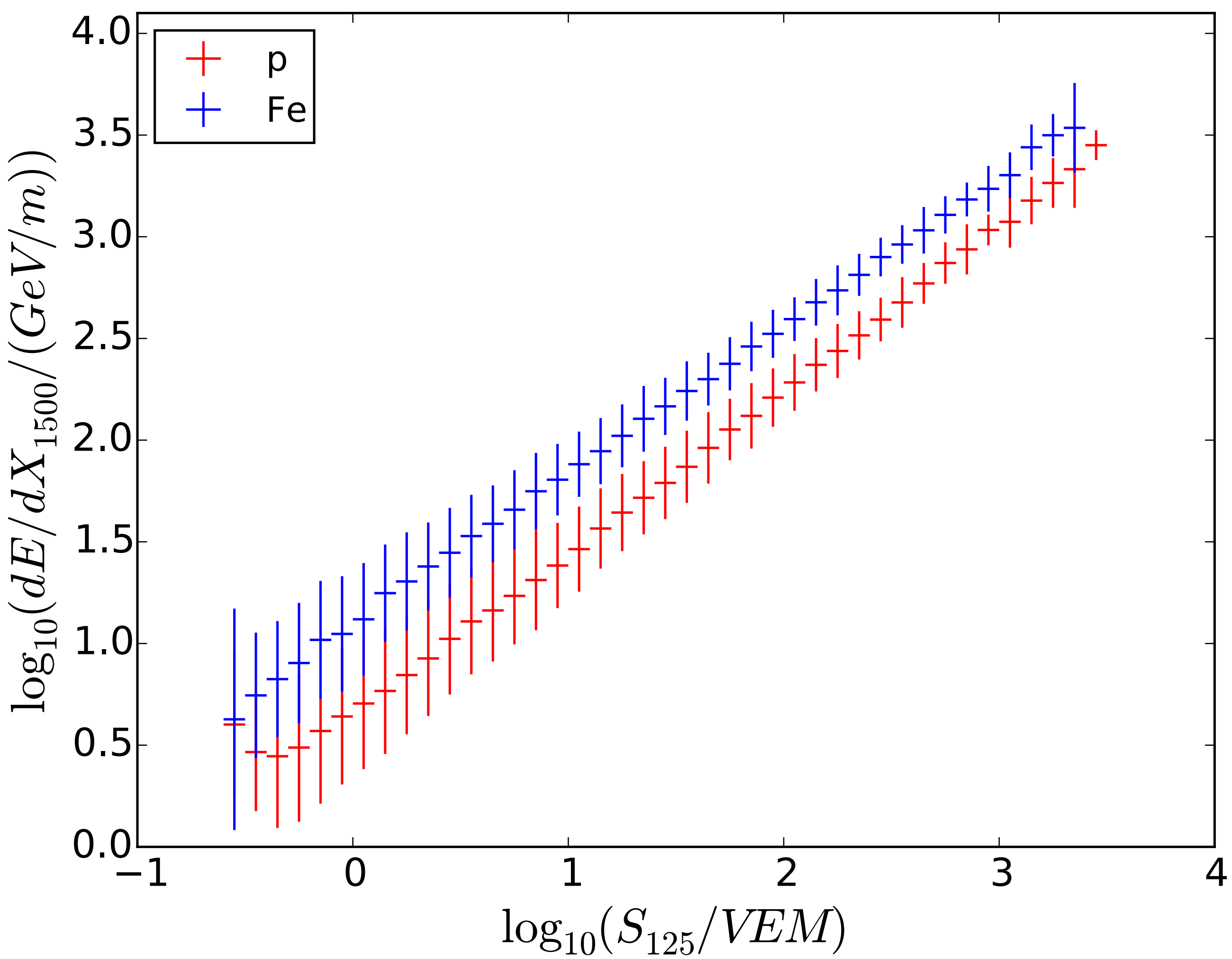
IceCube VS others



Overall good agreement up to 100 PeV with the composition results from most other experiments

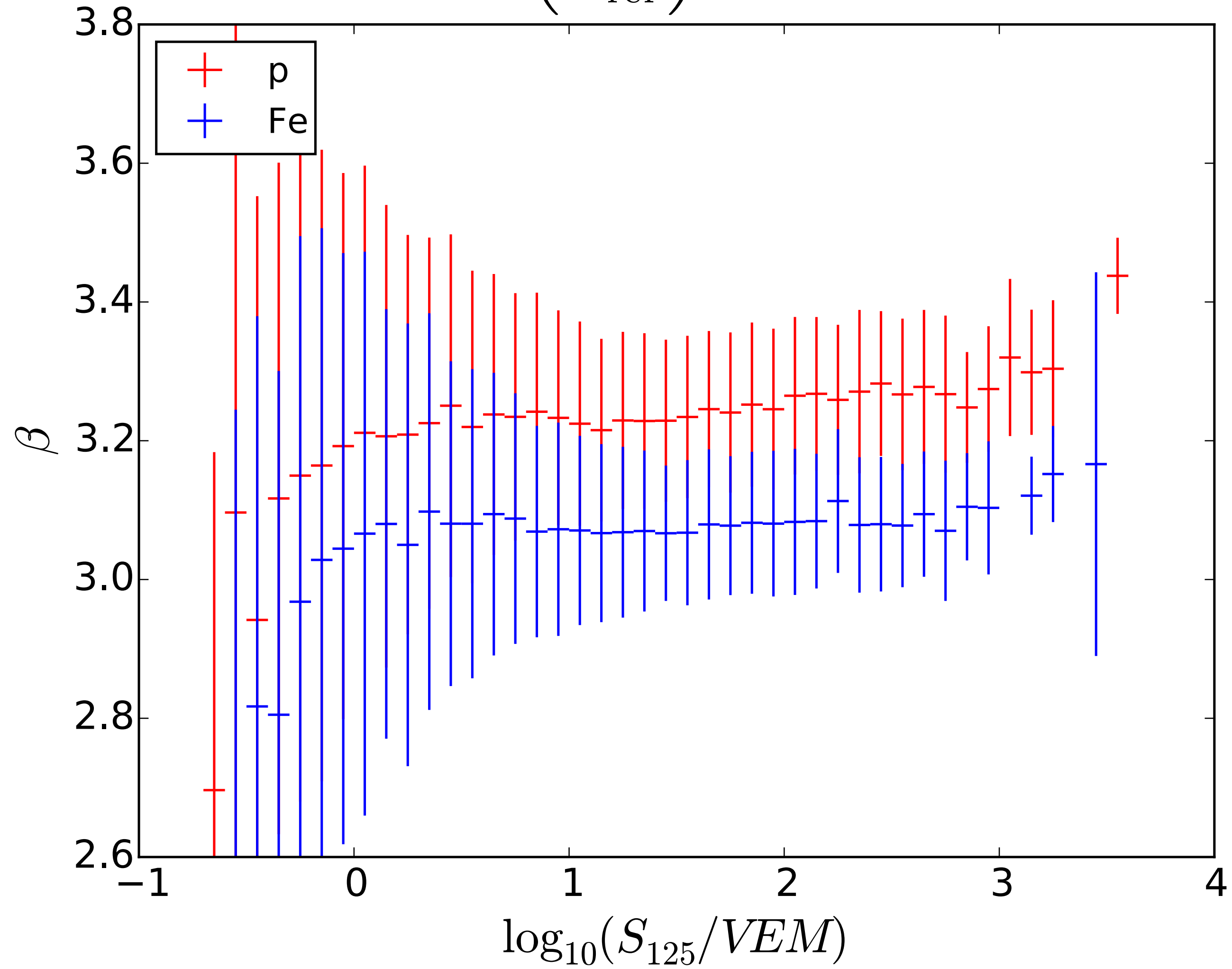
But... the models?

Energy loss of HE muon bundle in IceCube at slant depth of 1500 m (previously seen: here with larger binning)



Slope of LDF at 125 m from shower axis

$$S_{\mathrm{exp}}(R) = S_{\mathrm{ref}} \left(\frac{R}{R_{\mathrm{ref}}}\right)^{-\beta-\kappa\,\log_{10}\left(\frac{R}{R_{\mathrm{ref}}}\right)}$$



- dE/dX_{1500} sensitive to #HE muons reaching InIce detector
- Iron showers more muon rich than proton showers

- β sensitive to shower age and muons far from shower axis
- Iron showers develop faster and are more muon rich than proton showers

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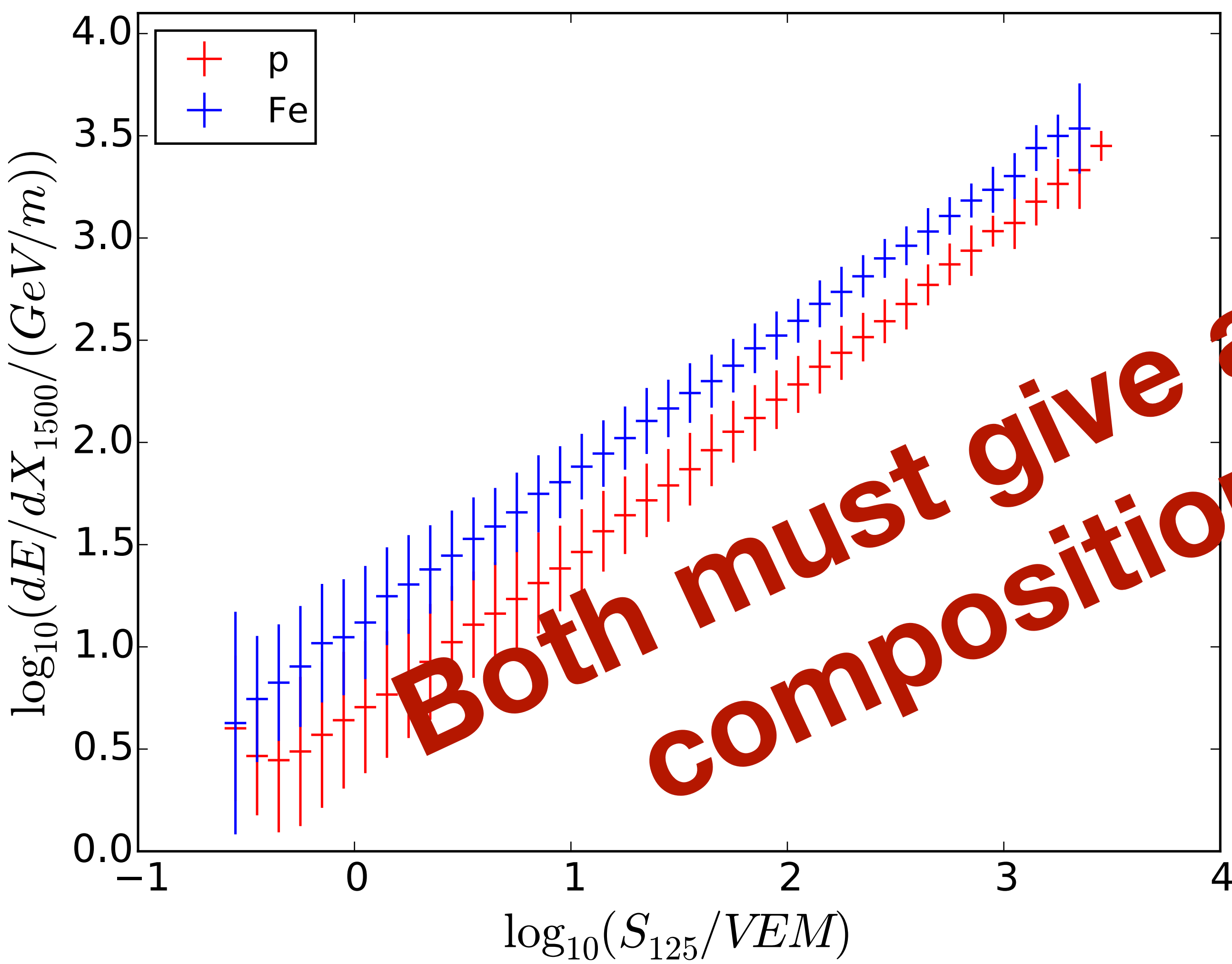

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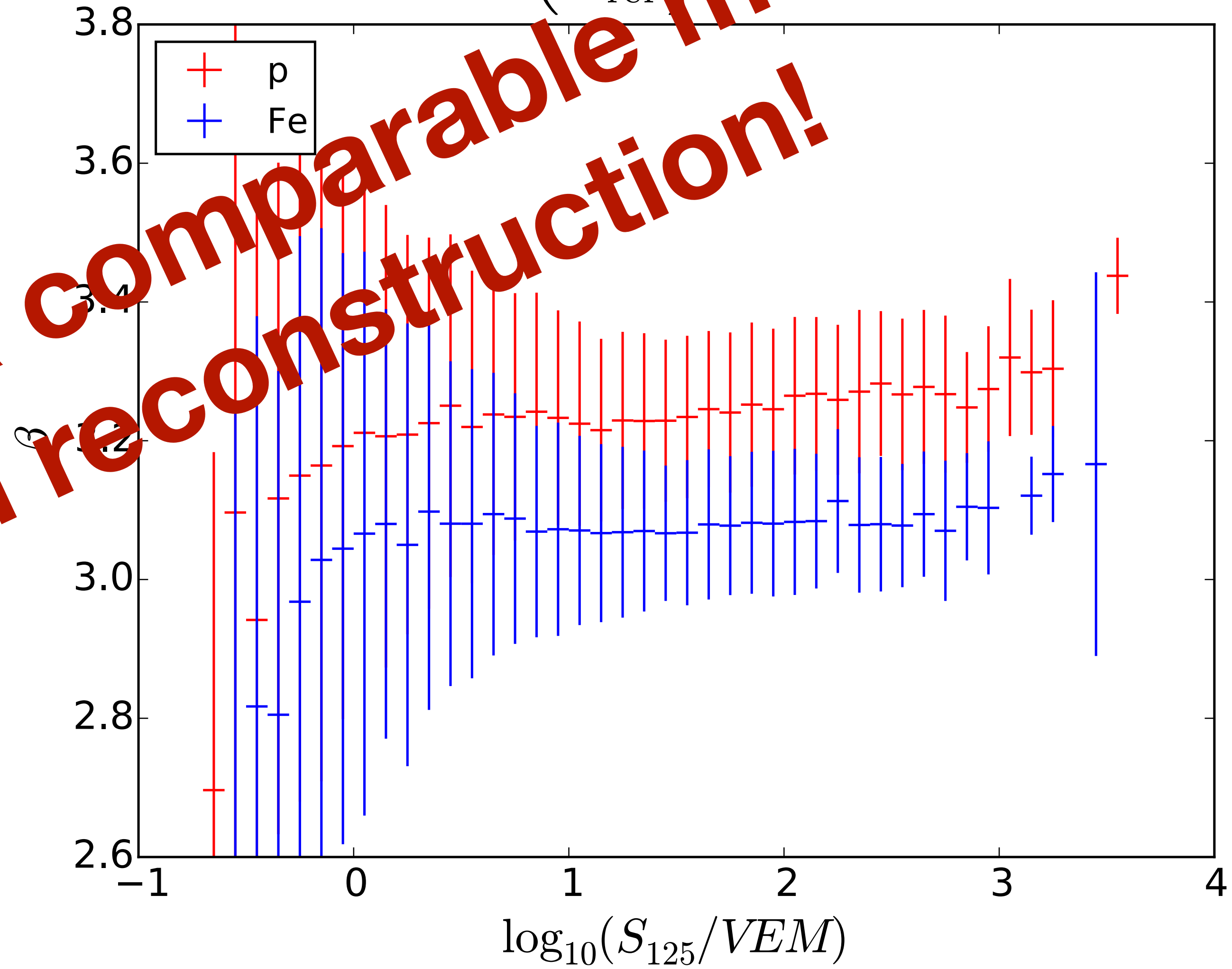

Both must give a comparable mass composition reconstruction!

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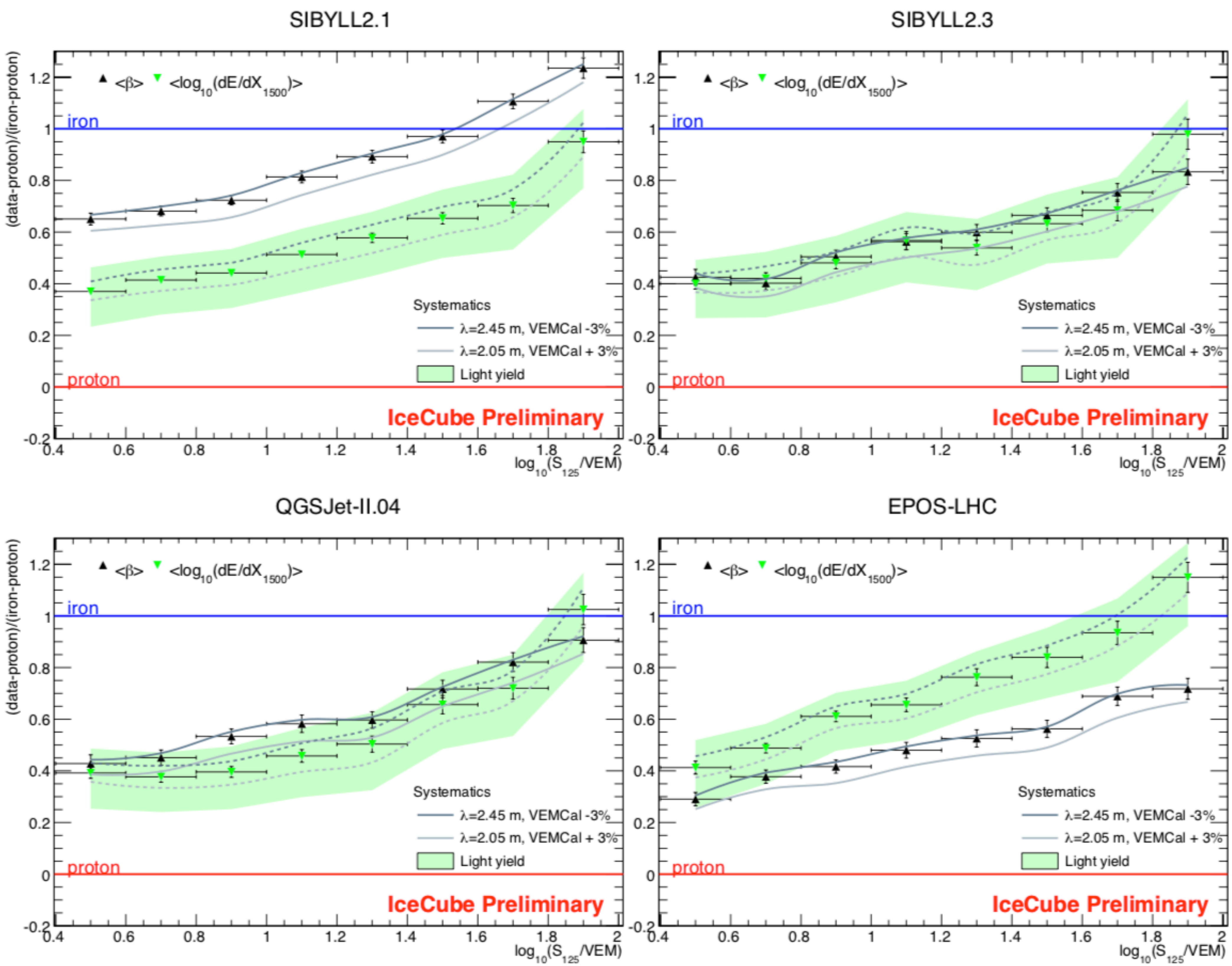


Using dE/dX_{1500} or β in the analysis with everything else unchanged, their

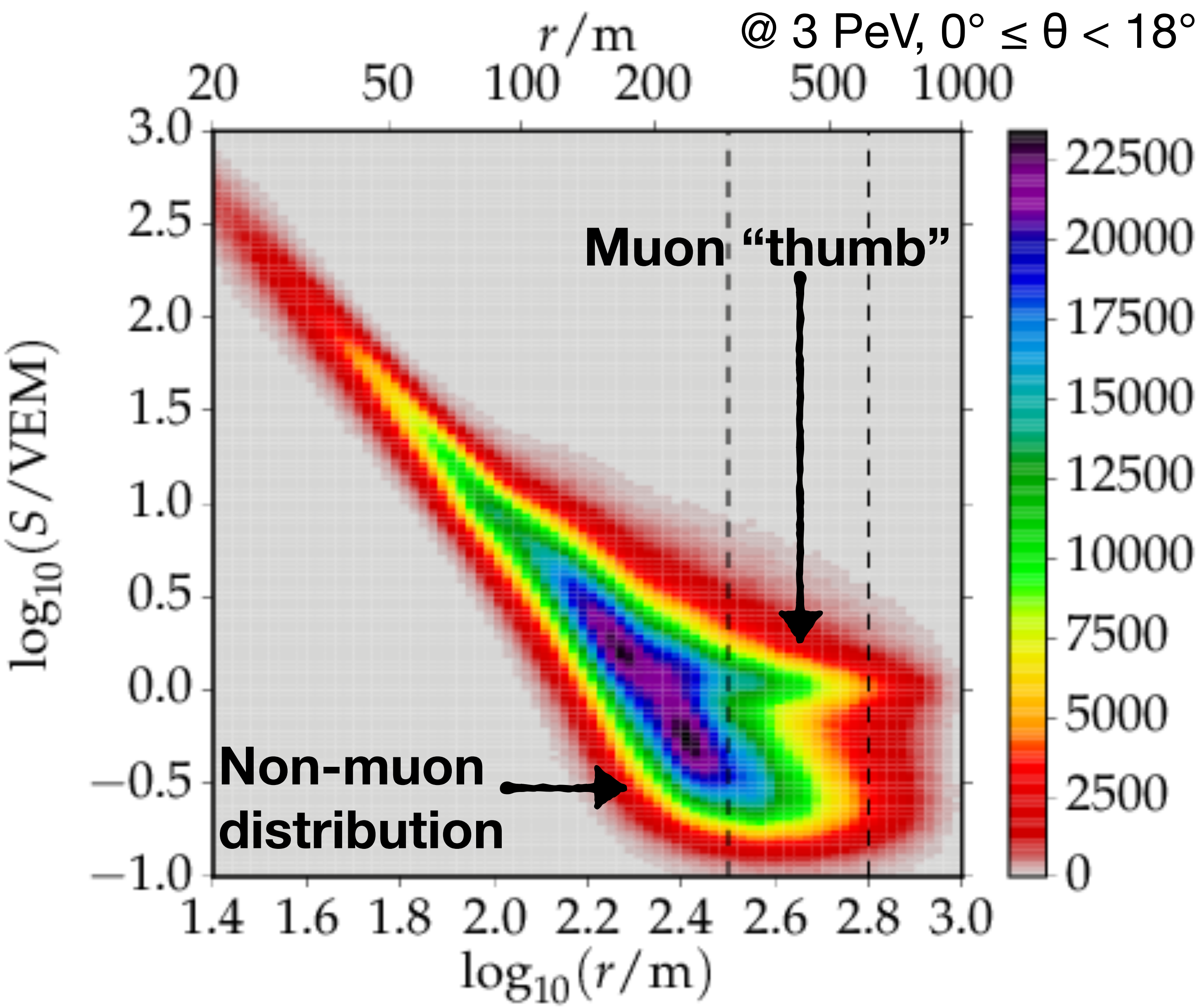
$$\frac{\mathrm{data} - \mathrm{p}}{\mathrm{Fe} - \mathrm{p}}$$

must be compatible!

- QGSJet-II.04, Sibyll2.3 are in good agreement
- EPOS-LHC in 2σ (at low S_{125})
- Sybill2.1 not much

Sibyll2.3 and QGSJet-II.04 have better internal consistency

Lateral Signal Distribution



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- At larger distances, the EM component weakens, and signals from single muons become visible

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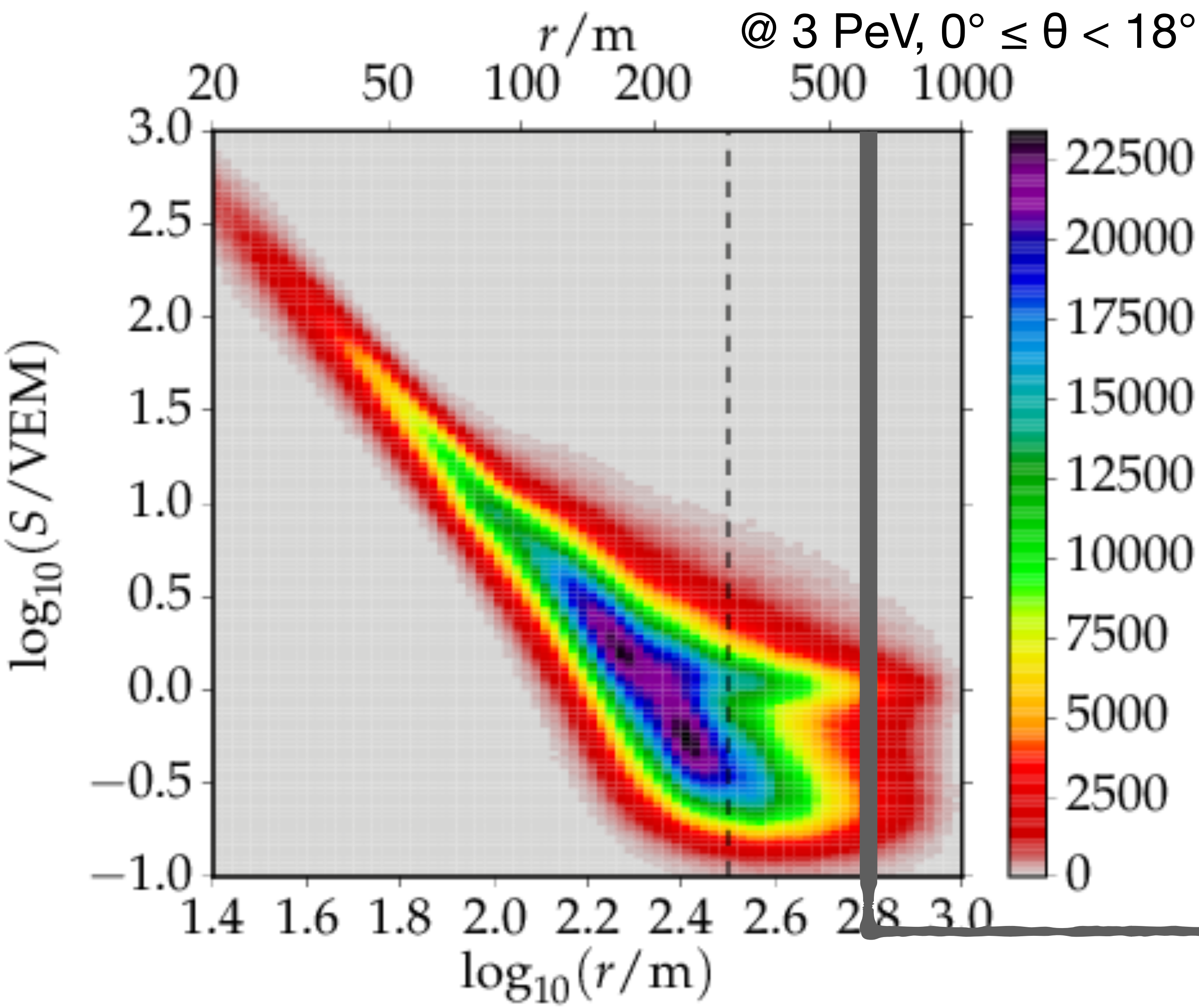

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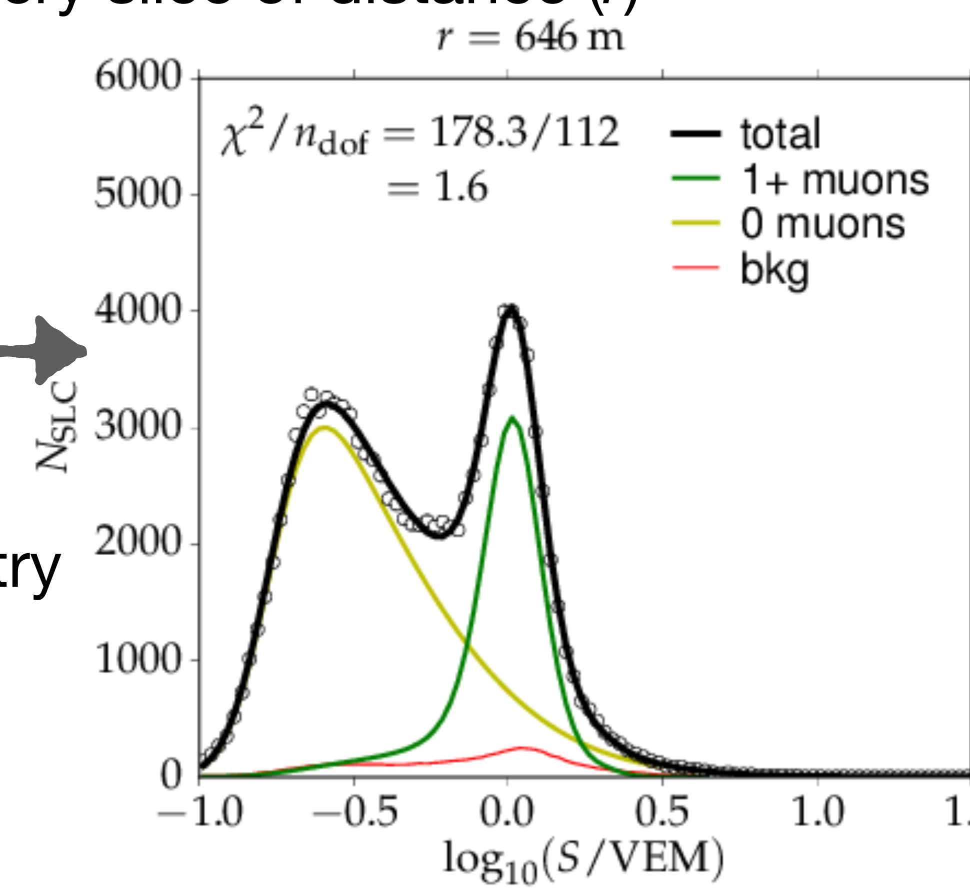
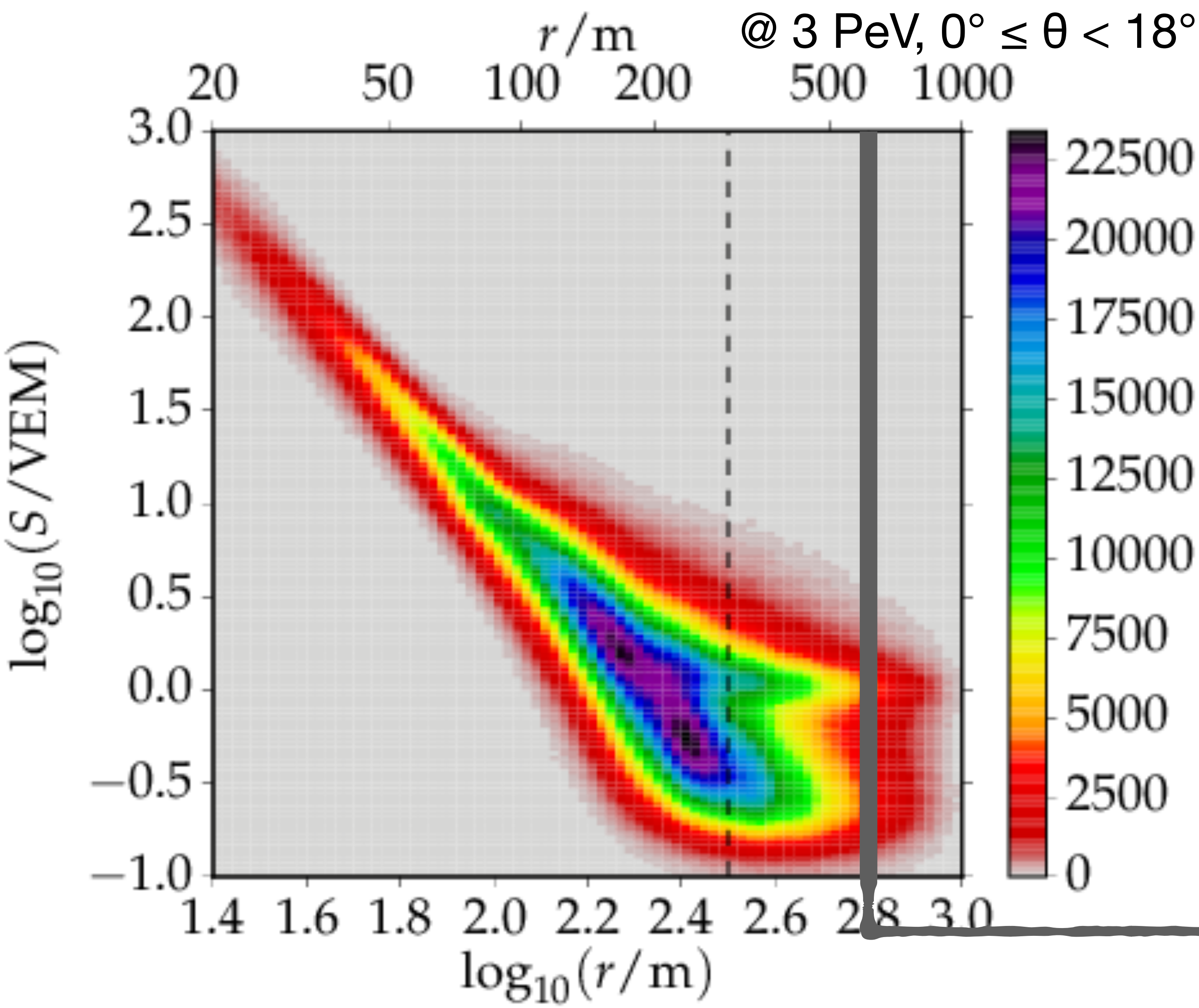
- Histogram (*S*/VEM distribution) for every slice of distance (*r*)



- **Muon component** (single VEM's, modulated by geometry
- **~EM component** (power law + threshold behaviour)
- **Background** from accidental coincidence hits

Lateral Signal Distribution



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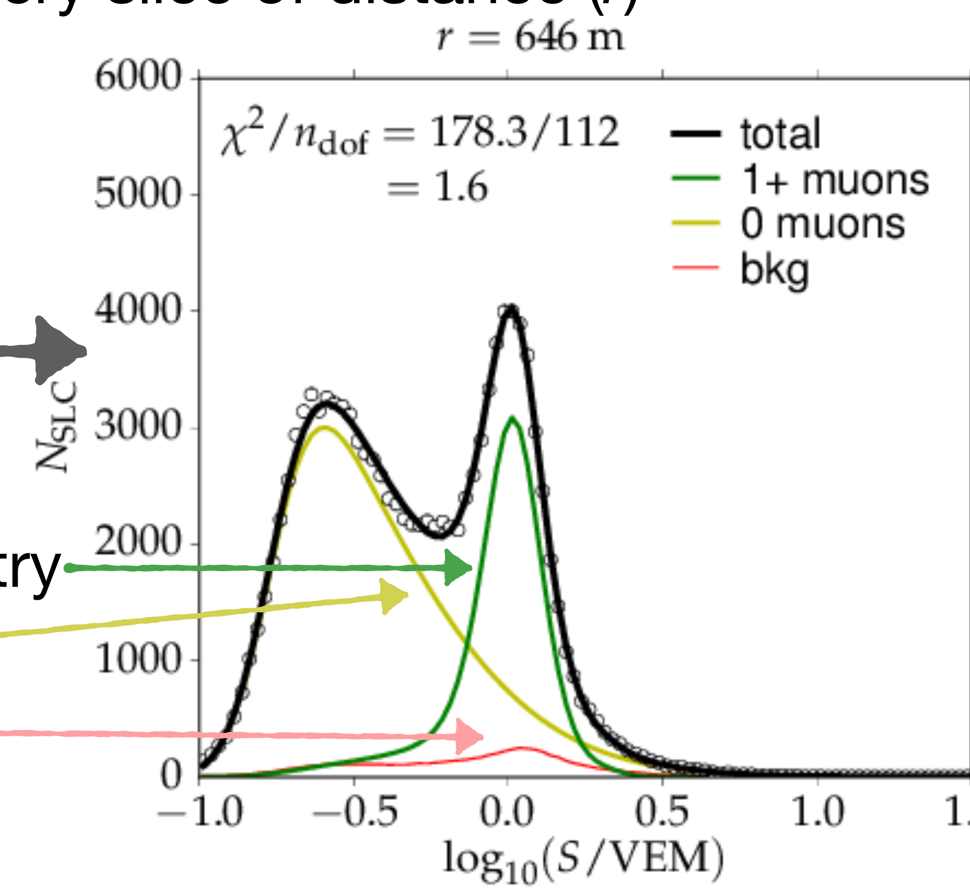

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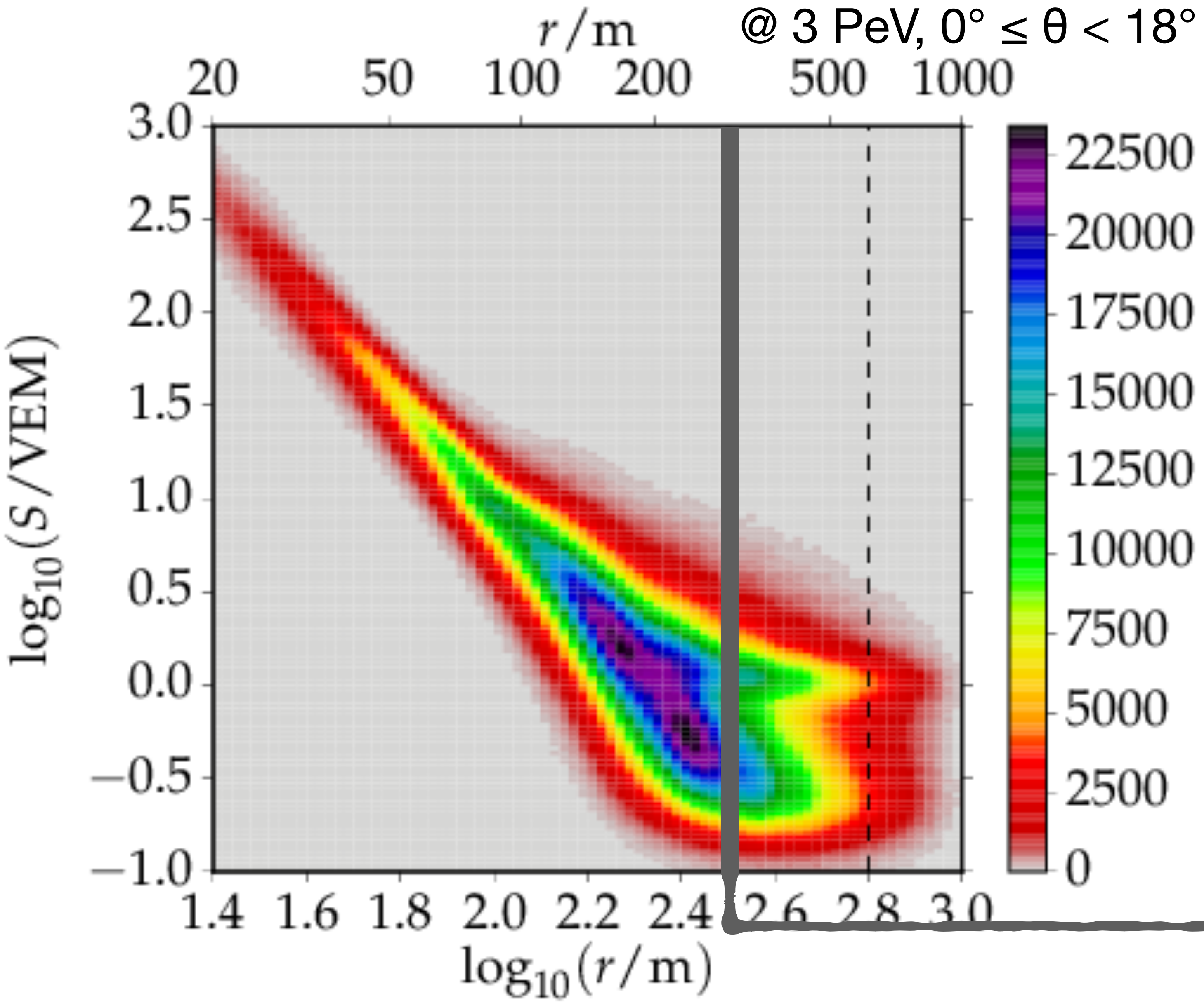
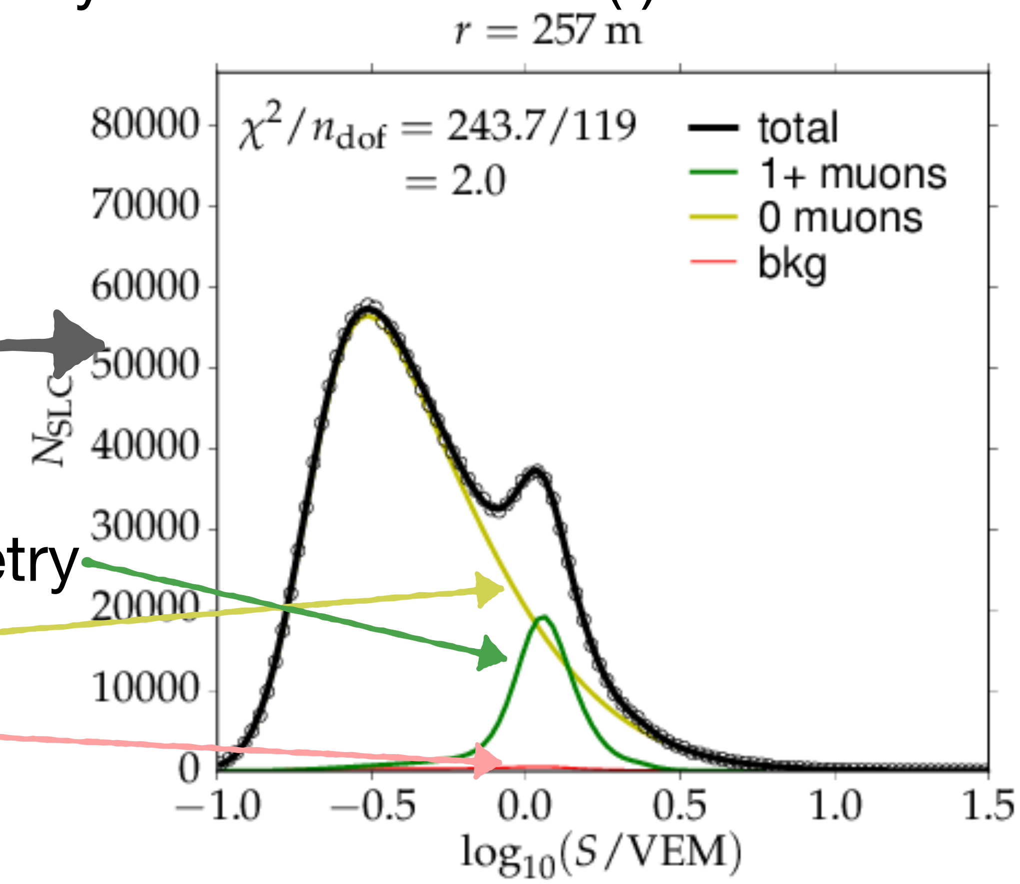
- **Background** from accidental coincidence hits

Lateral Signal Distribution



- EM signals dominate near the core of the shower.
- At larger distances, the EM component weakens, and signals from single muons become visible
- One distribution for every energy bin
- Histogram (*S*/VEM distribution) for every slice of distance (*r*)



- **Muon component** (single VEM's, modulated by geometry)
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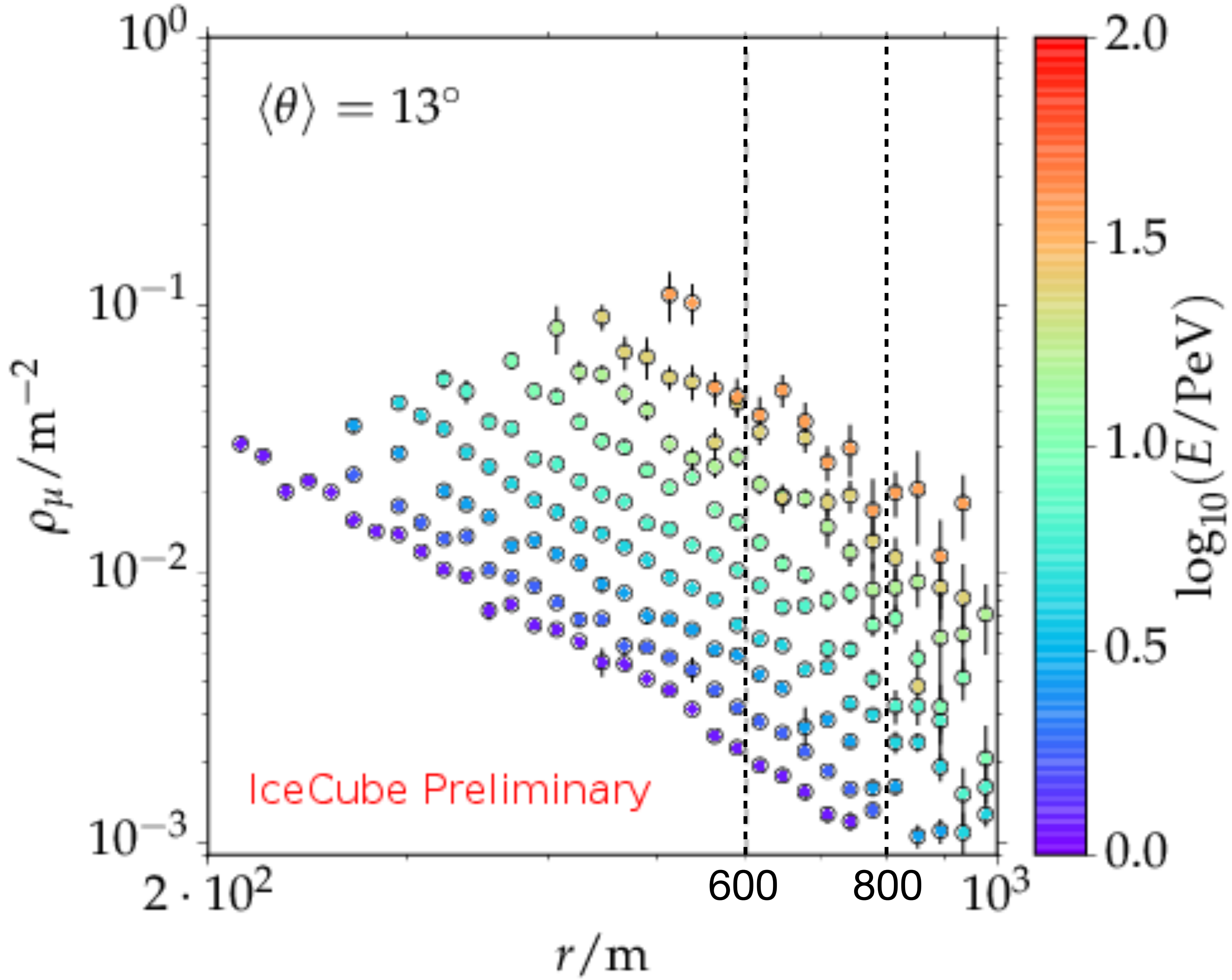
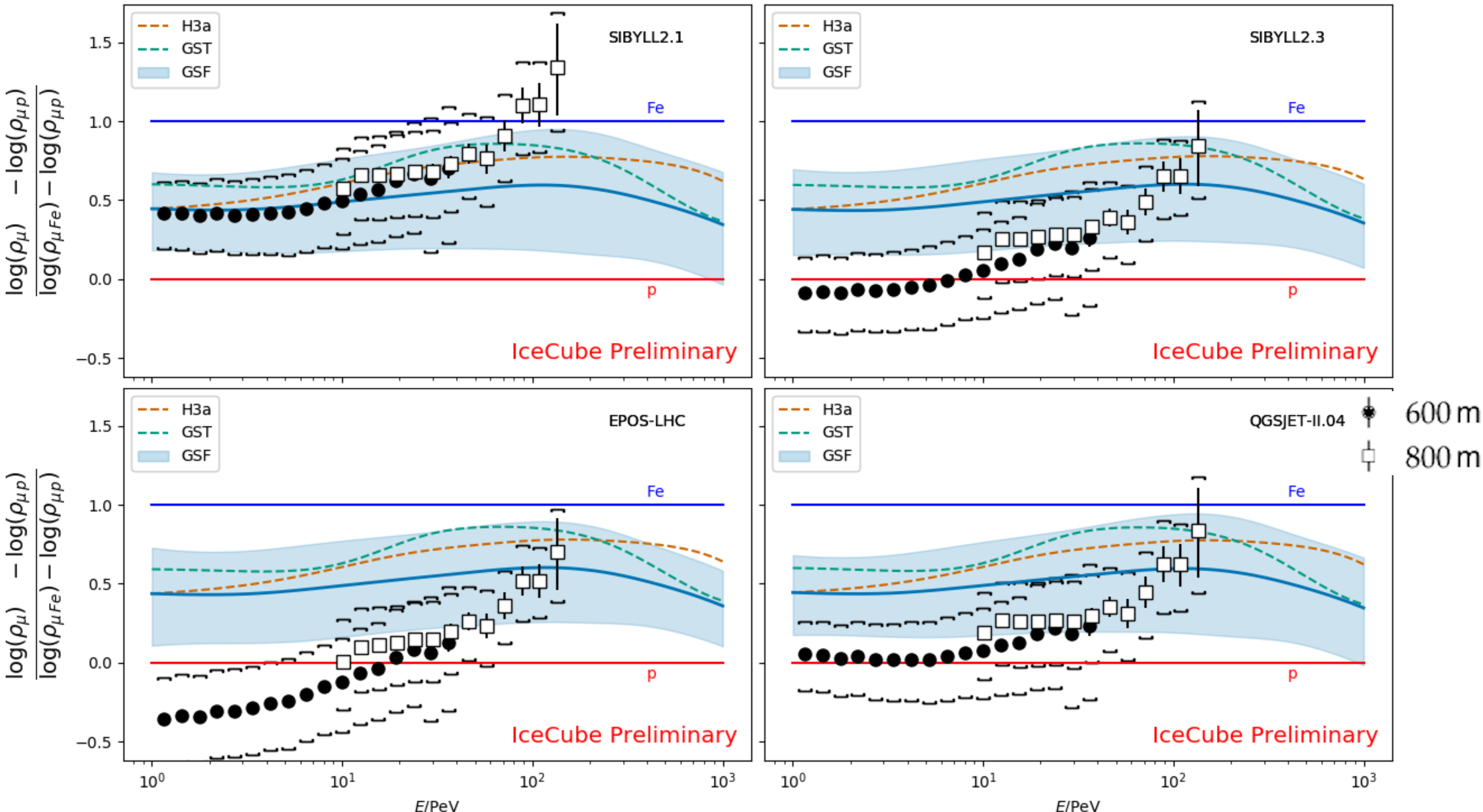
Lateral Distribution Function



Each dot is a the result of a vertical slice histogram

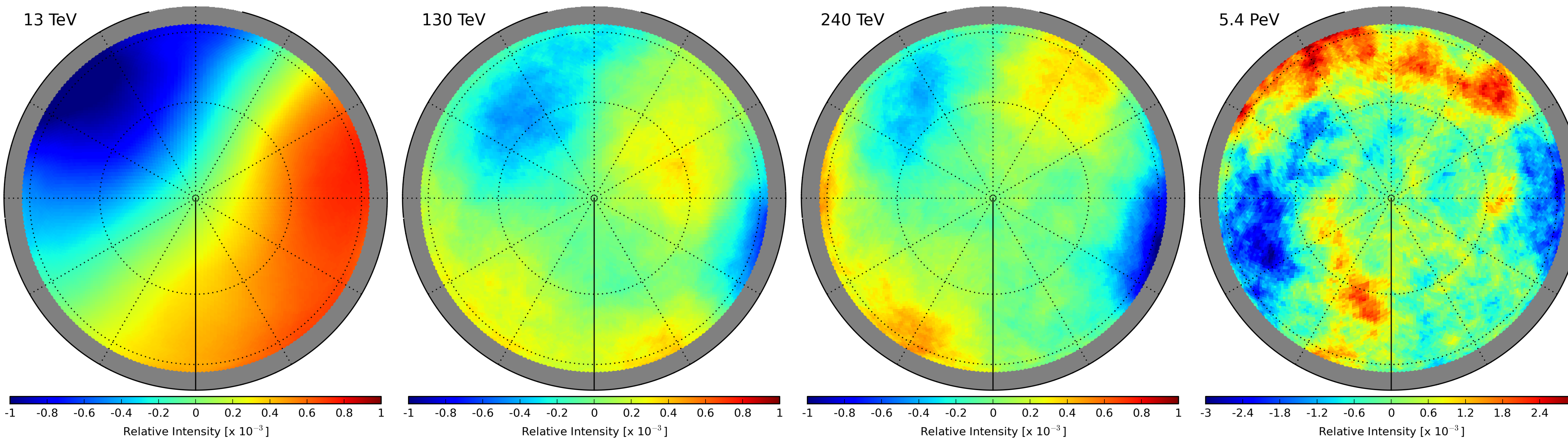
Find the muon density ρ_μ at two reference distances: 600m and 800m

Comparison with models



Results with systematic uncertainties (squared caps)
in comparison with for three composition models commonly used of the primary flux
Sibyll2.1 seems the most consistent, while EPOS-LHC the most off.

Cosmic Rays anisotropy



There is an evolution of the anisotropy with the energy

- **Large Scale**:
  - Flip between 130 and 240 TeV: not fully understood
    - density gradient of cosmic rays due to stochastically distributed sources?
  - Change in the phase of the anisotropy between TeV and PeV energies could indicate a shift of the sources from the Orion arm to the Galactic center
- **Small Scale:**
  - Isotropically turbulent interstellar magnetic field

IceCube-Gen2 on the surface (Cosmic Rays)

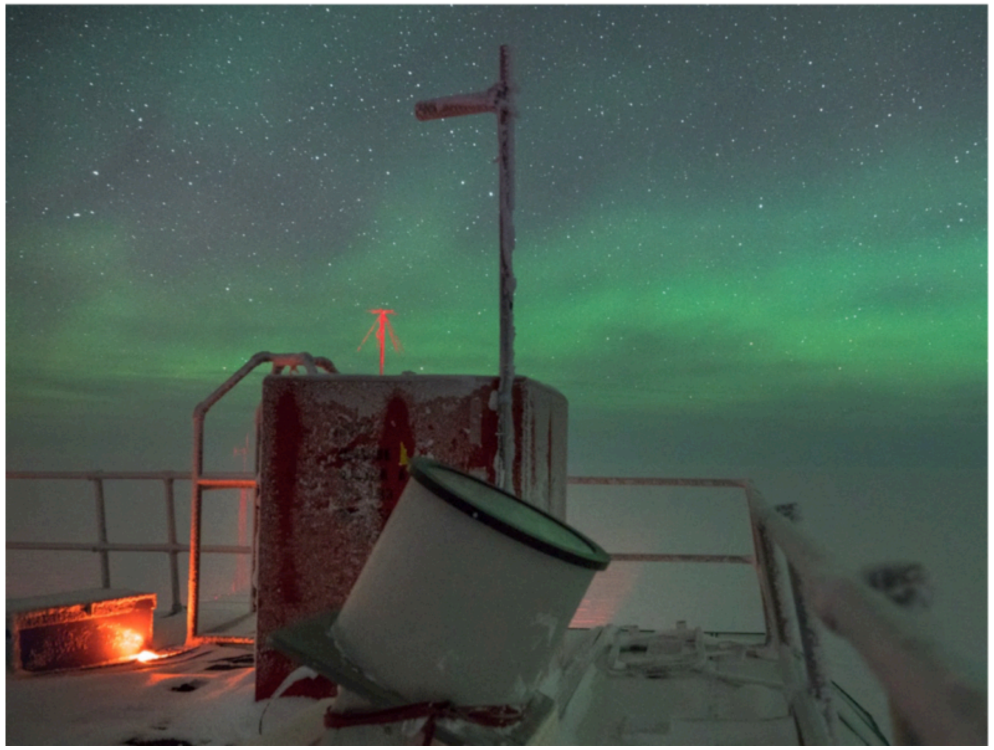
(In the IC86 area)

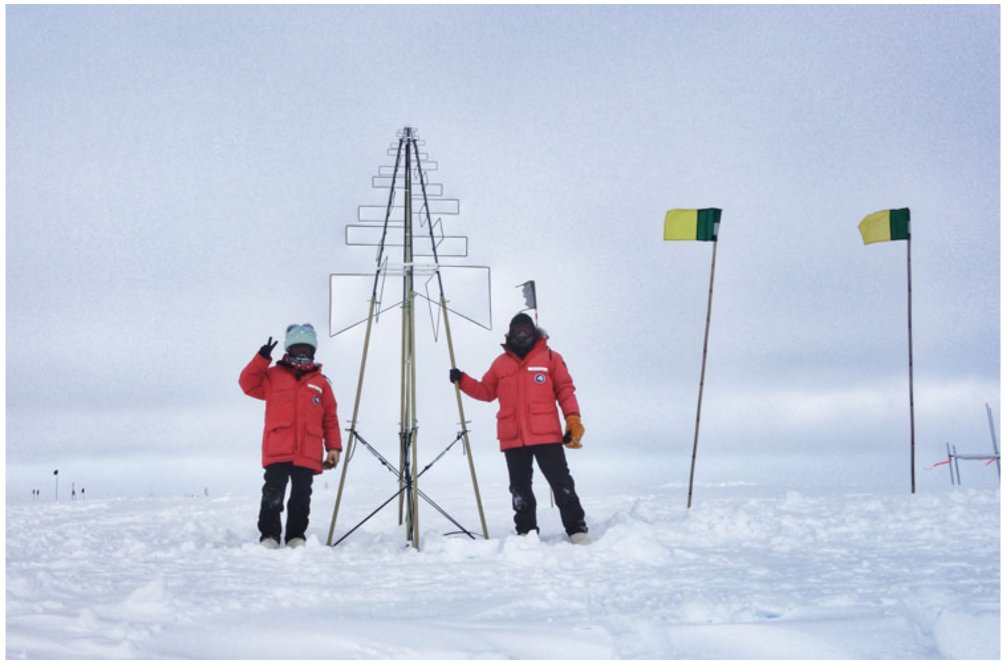
Scintillator above IceTop (IceTAXI/μDAQ)

- particle counting(/veto) above IceTop
- better snow absorption studies

IceACT

- IACT detector
- direct Cherenkov light: mass/ direction observables

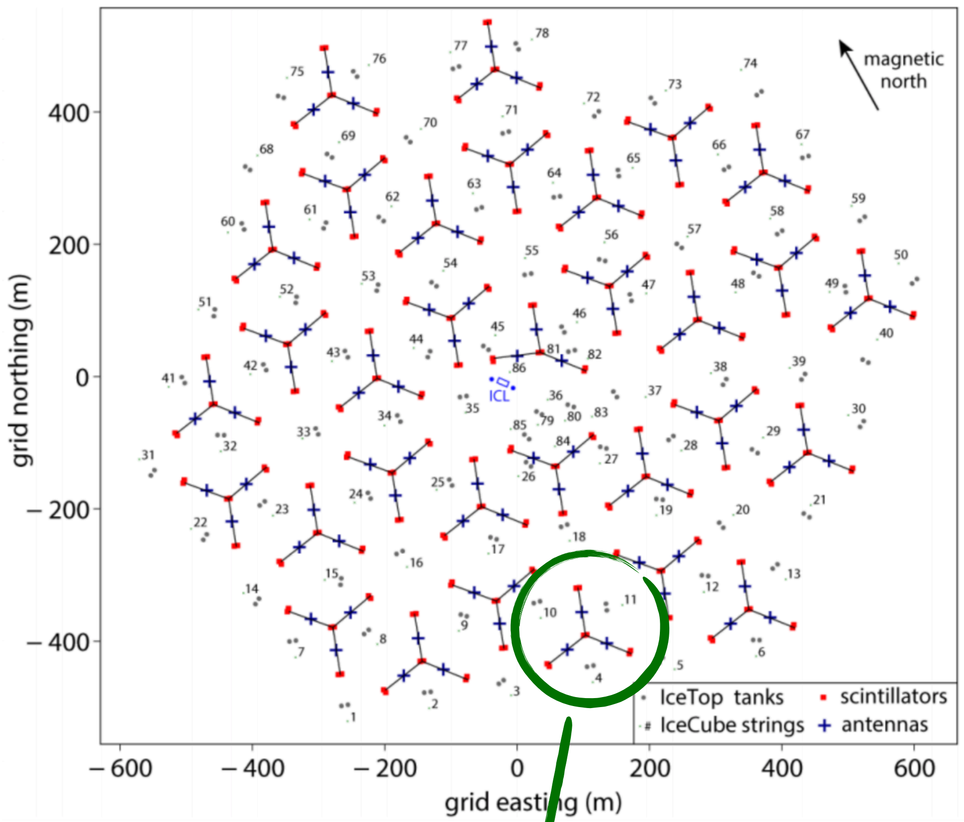


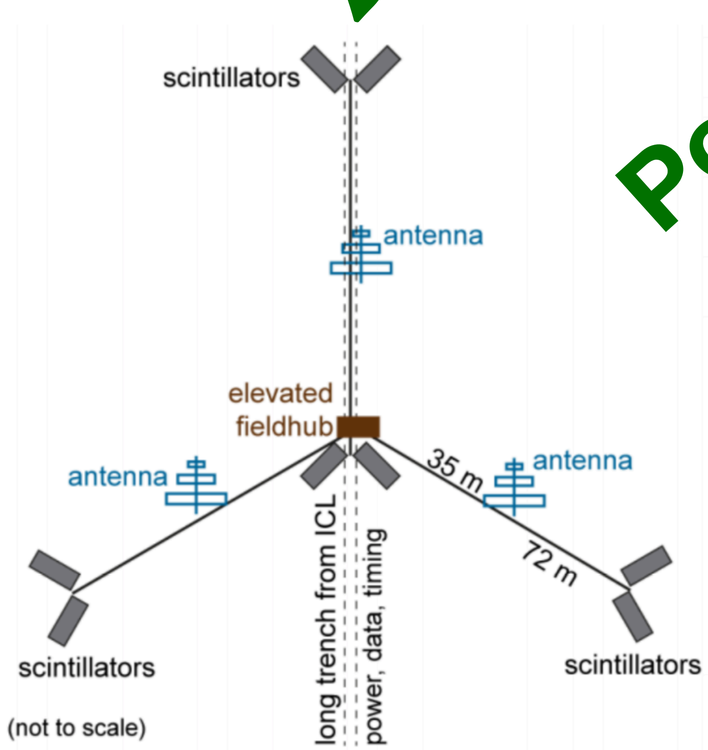


Radio Antenna array

- longitudinal profile of the EAS
- direct energy/mass related observables

IceCube-Gen2 on the surface (Cosmic Rays)





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Scintillator above IceTop (IceTAXI/μDAQ)

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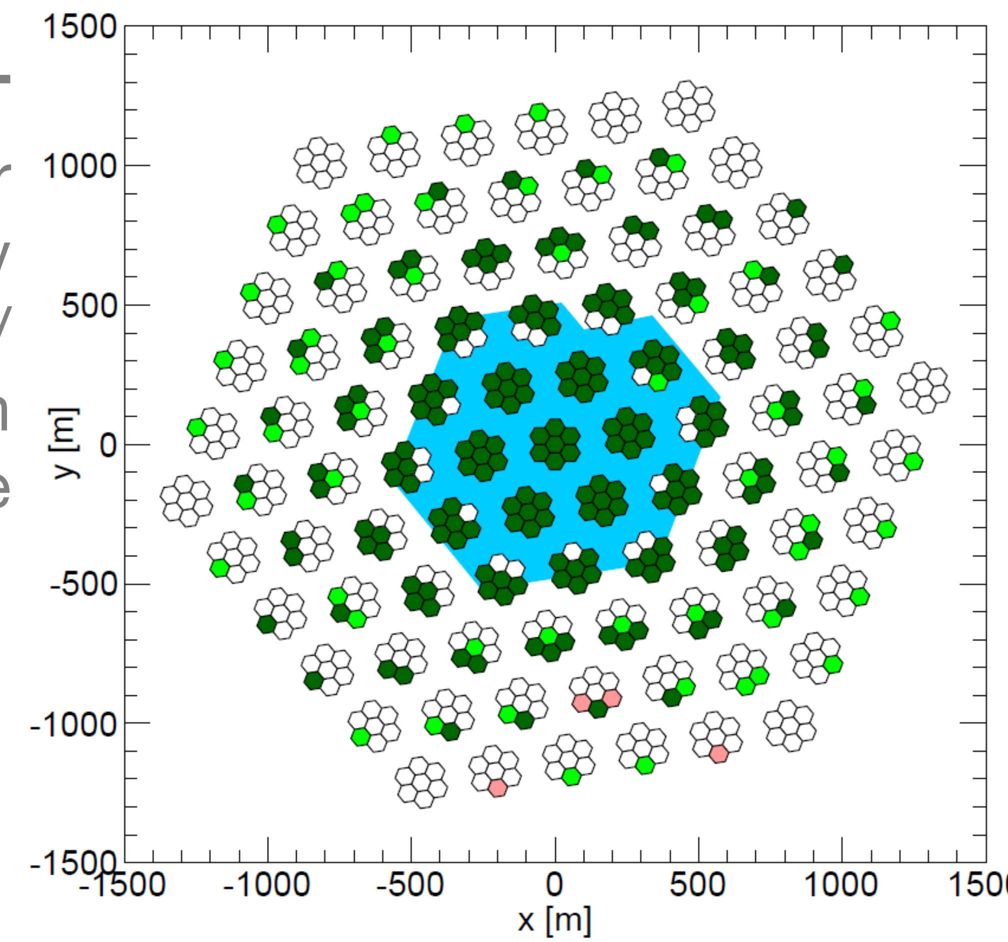
Possible configurations

IceACT

- IACT detector
- direct Cherenkov light: mass/ direction observable



Radio Antenna array

- longitudinal profile of the EAS
- direct energy/mass related observable

Outlook

- 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
- Agreement with cosmic ray composition models and fits
  - …but not yet a clear depiction of the hadronic interaction models
- Good agreement with results of other experiments up to 10^8 GeV

What's next

- Improve the analysis and systematic uncertainties
  - Improved detector systematics
  - Improved simulations, reconstruction, hadronic interaction models
  - New observables such as arrival time resolution or the snow absorption
- IceCube-Gen2: arrays of scintillators, IACTs, Radio Antennas

THANK YOU

THE ICECUBE COLLABORATION

AUSTRALIA
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Universiteit Gent
Vrije Universiteit Brussel

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DENMARK
University of Copenhagen

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University of Wisconsin–River Falls
Yale University

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US National Science Foundation (NSF)

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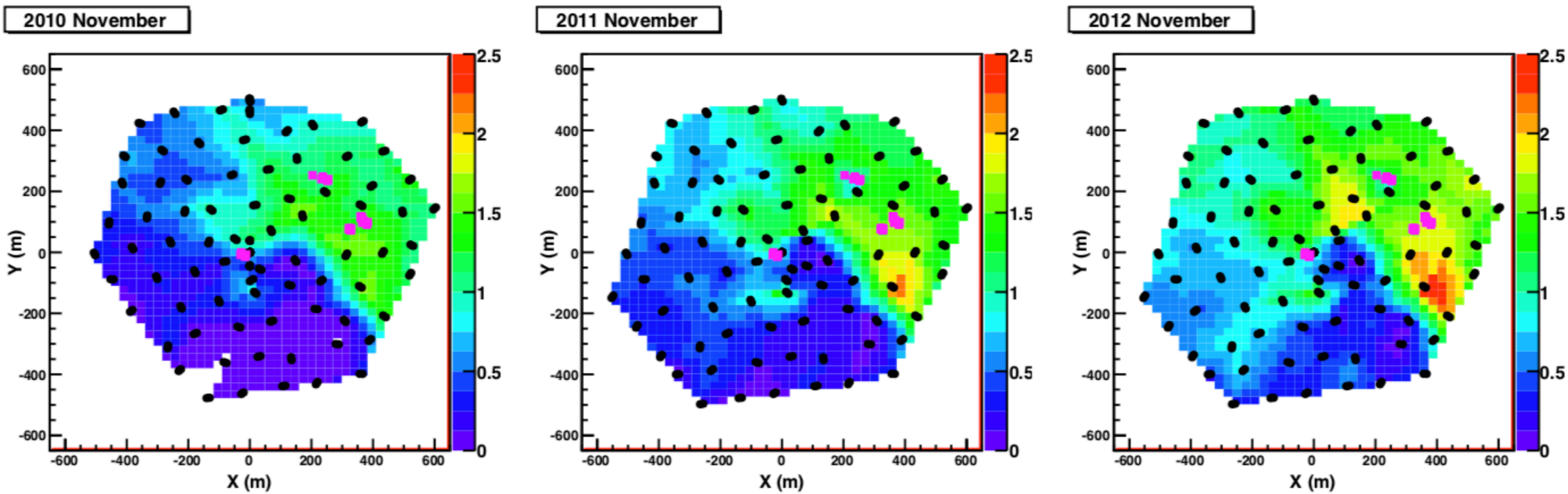
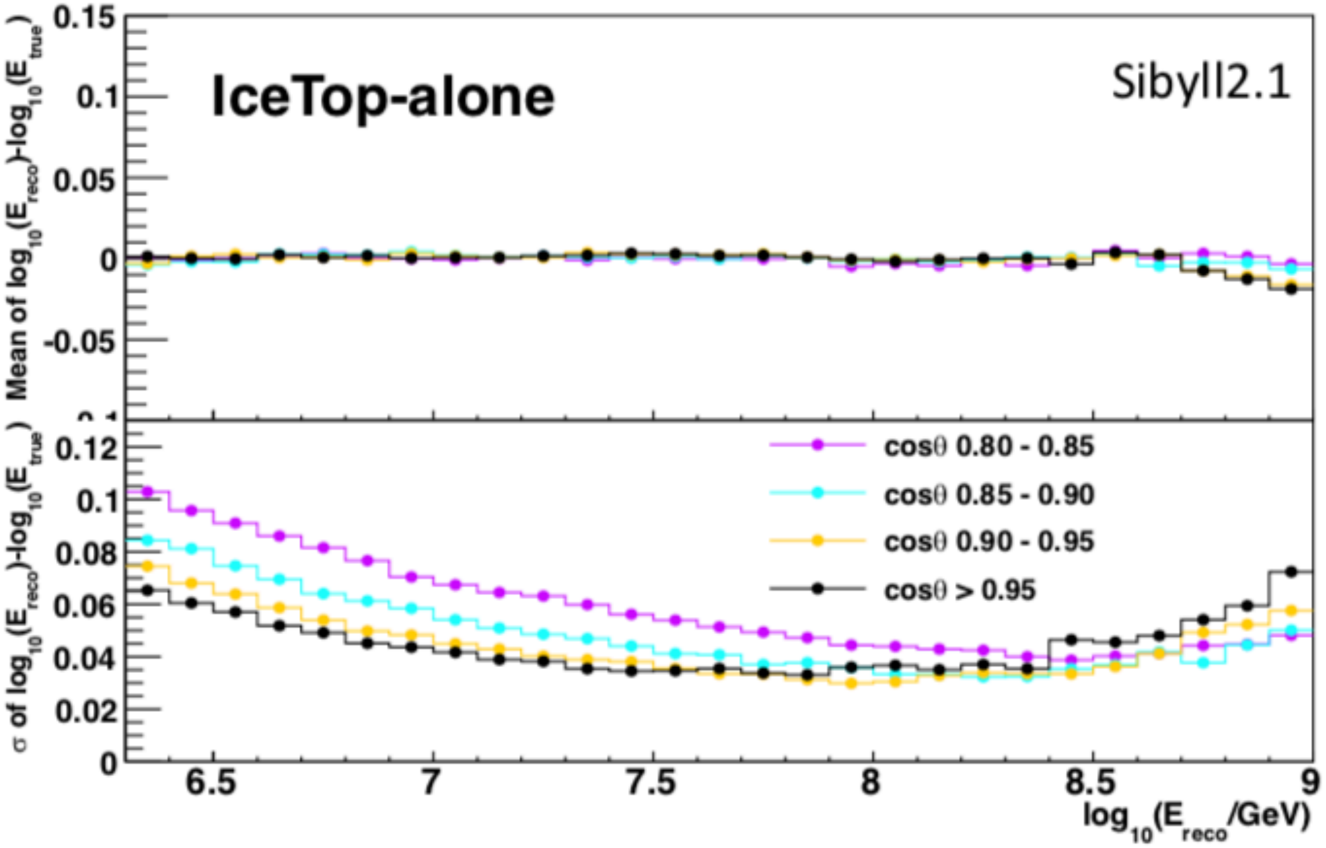
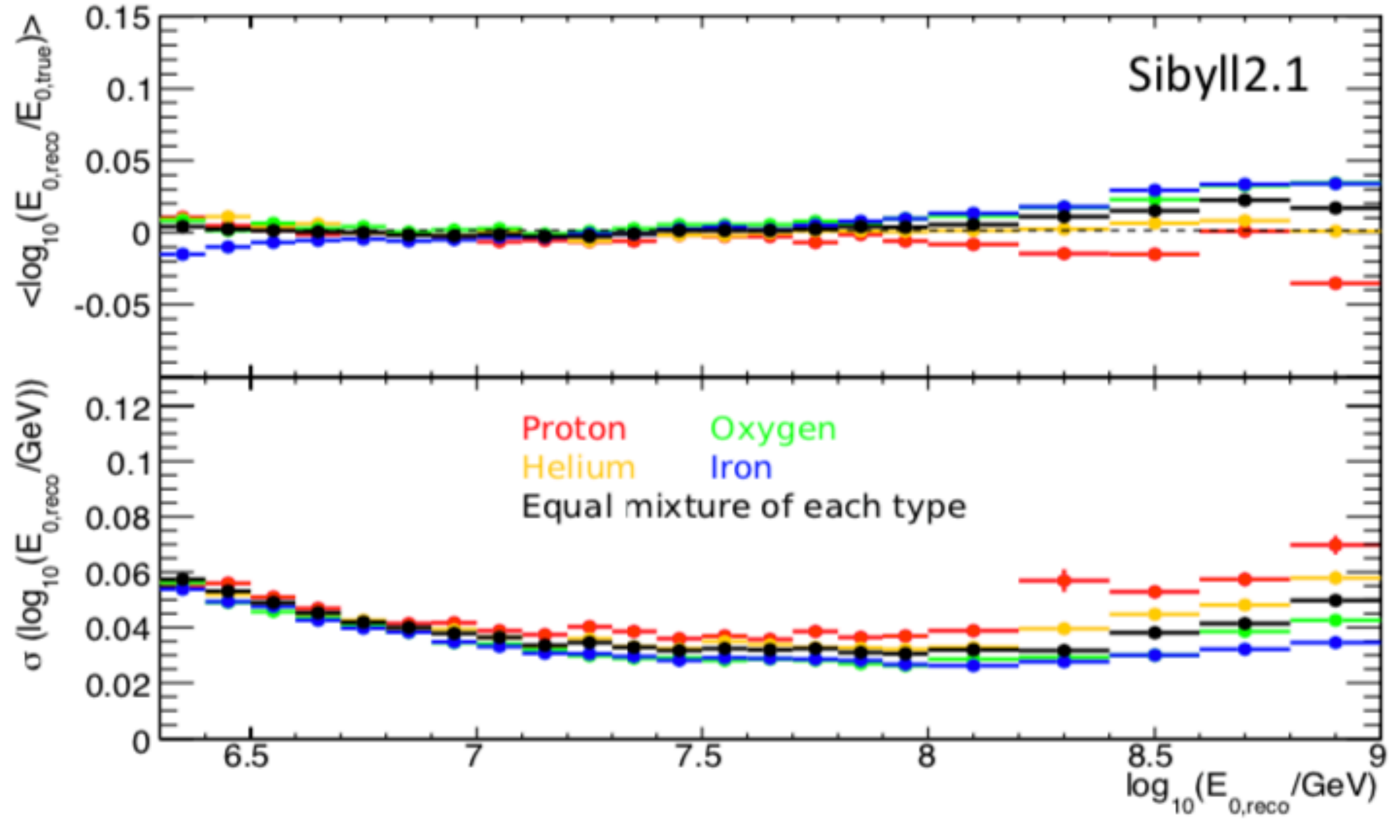
BACKUPS

Snow Accumulation



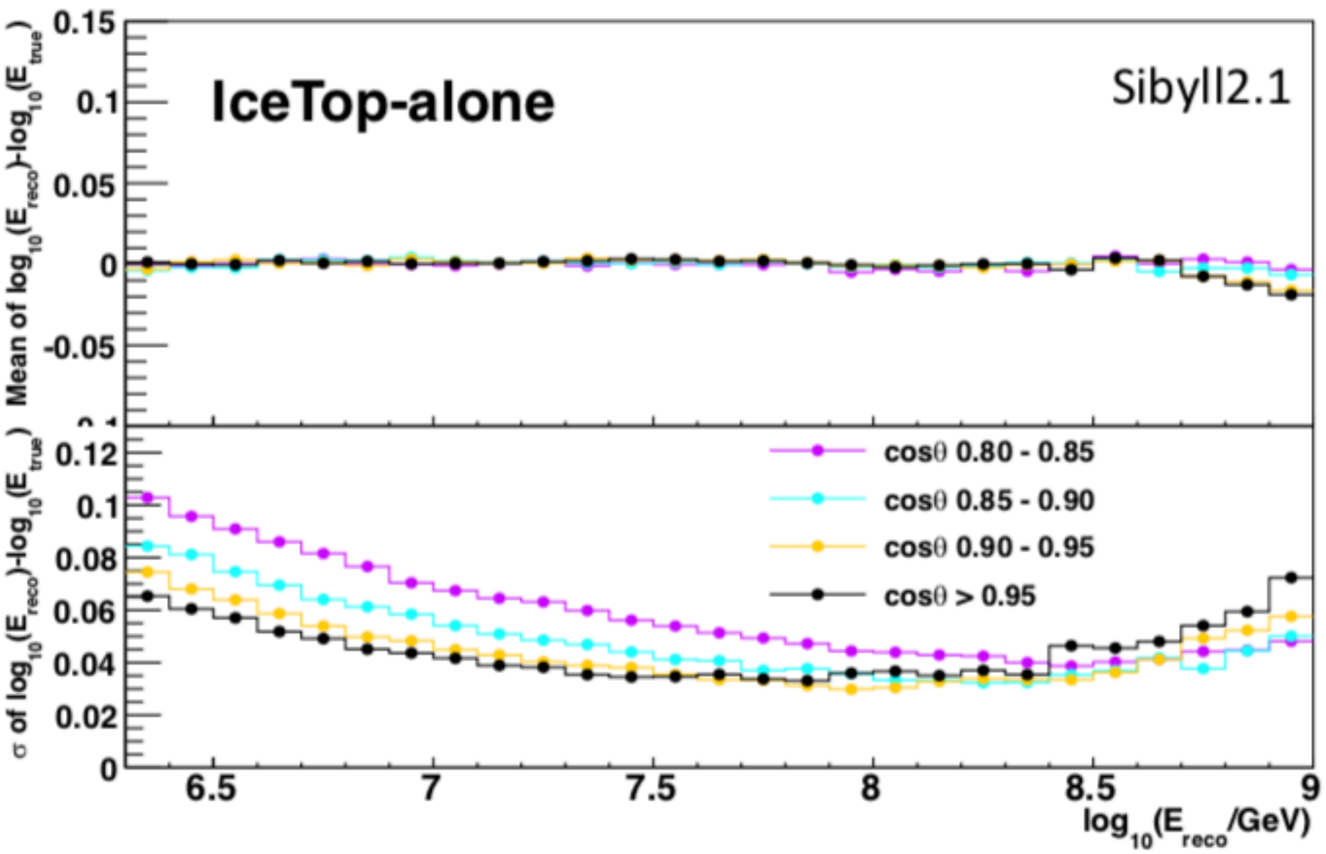
Energy resolution

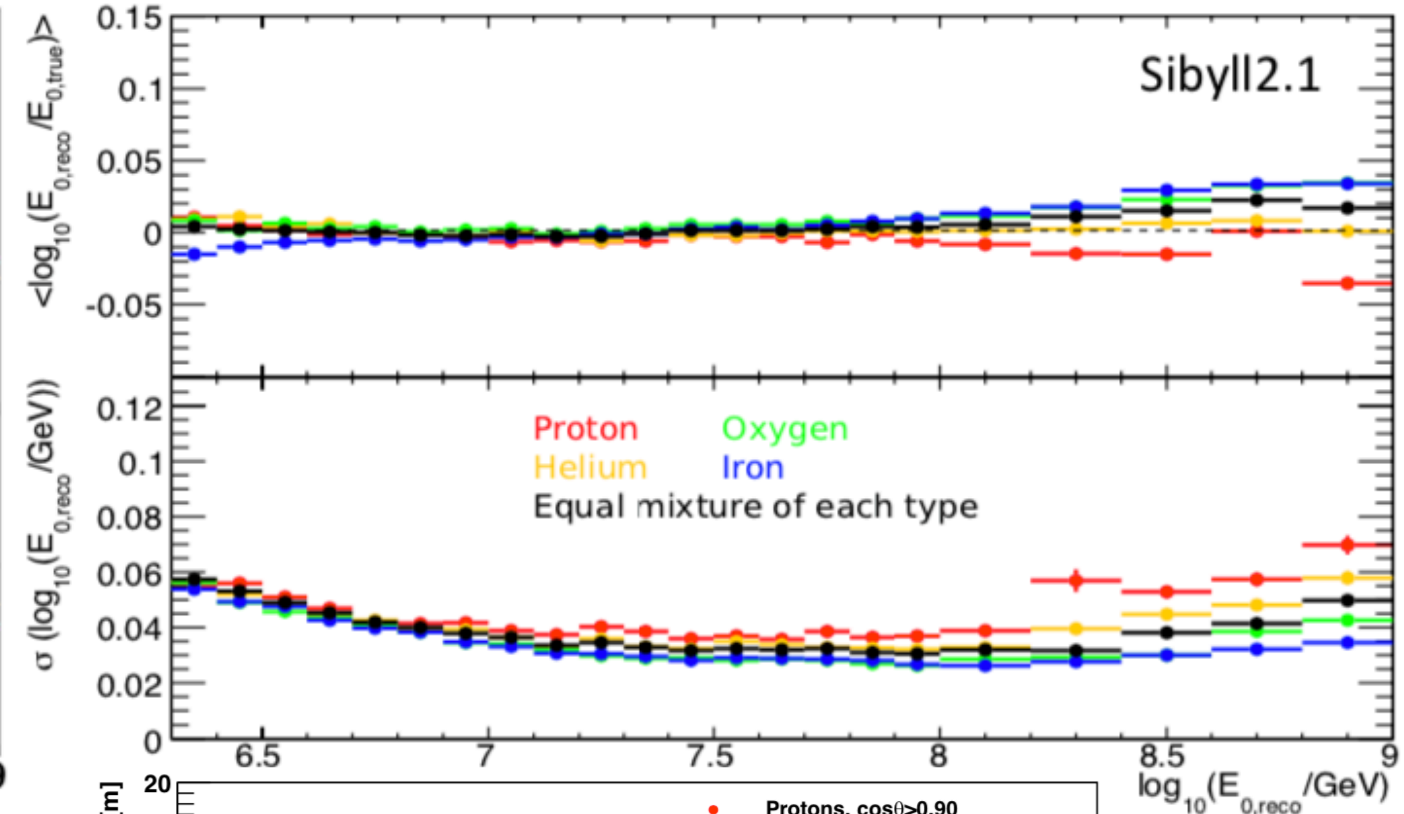


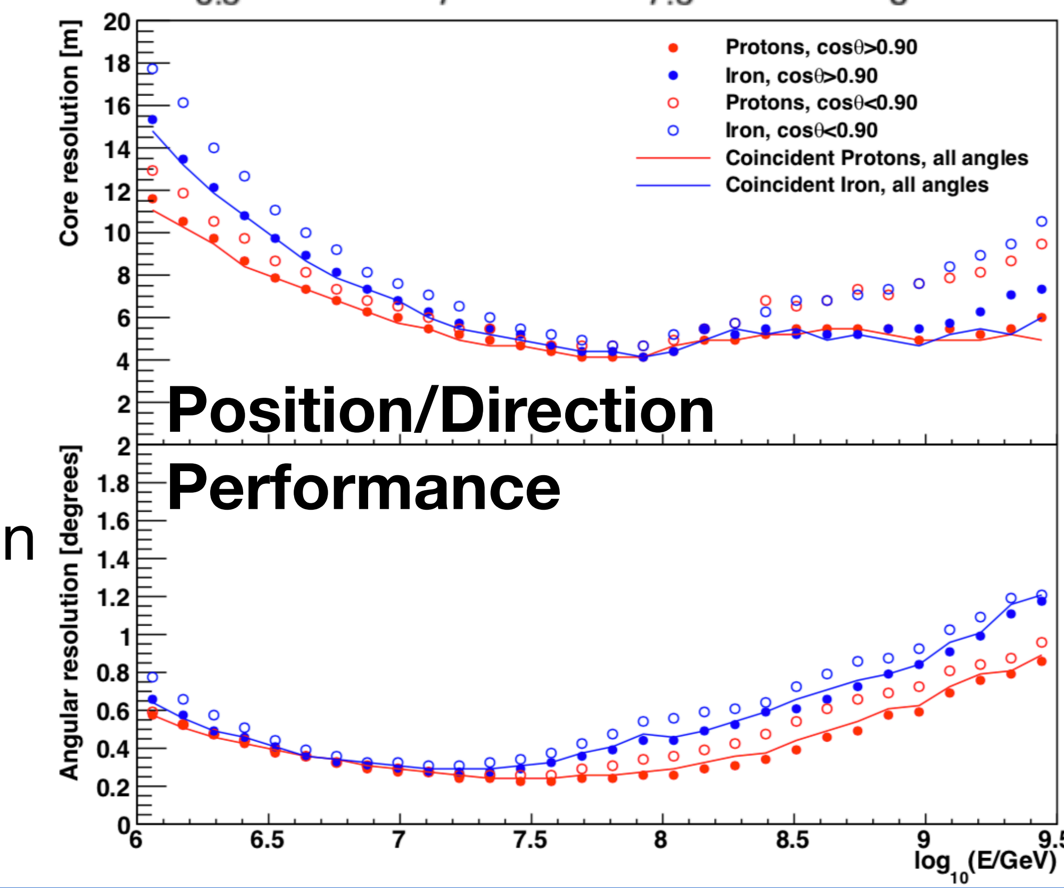


- **Bias**: ~0
- **Resolution**: best between 10 and 300 PeV

Energy resolution

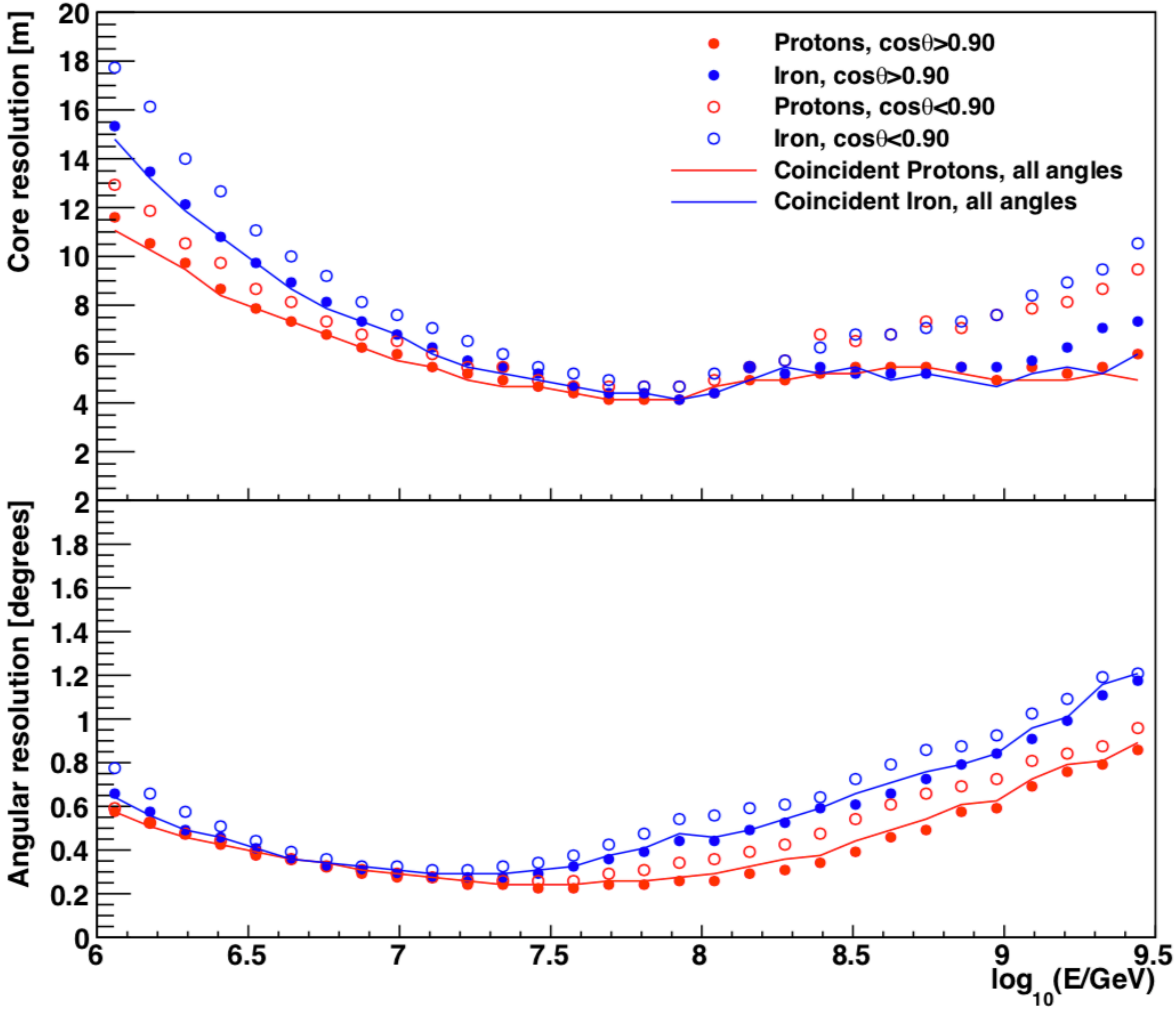




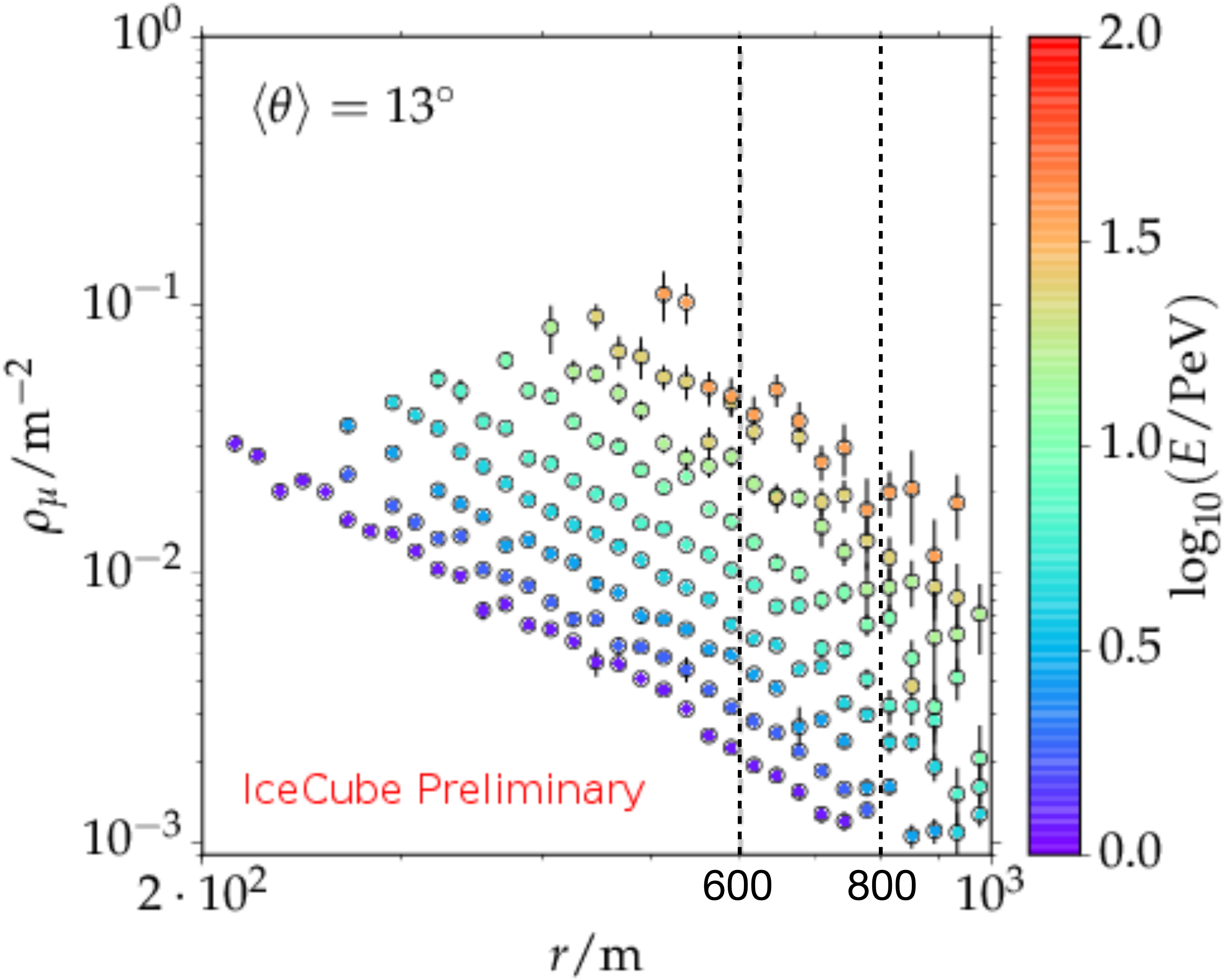


- **Bias**: ~0
- **Resolution**: best between 10 and 300 PeV worsening in regions where position/direction resolution suffers (misreconstructions)

Position/Direction Performance



Lateral Distribution Function



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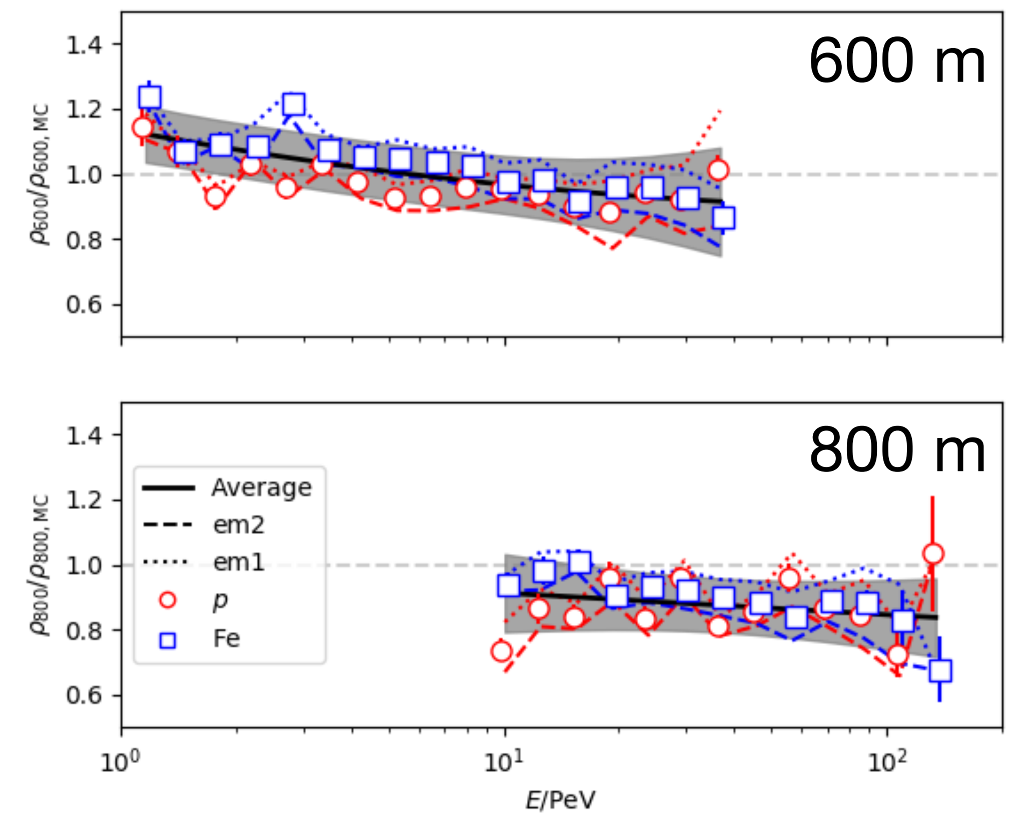
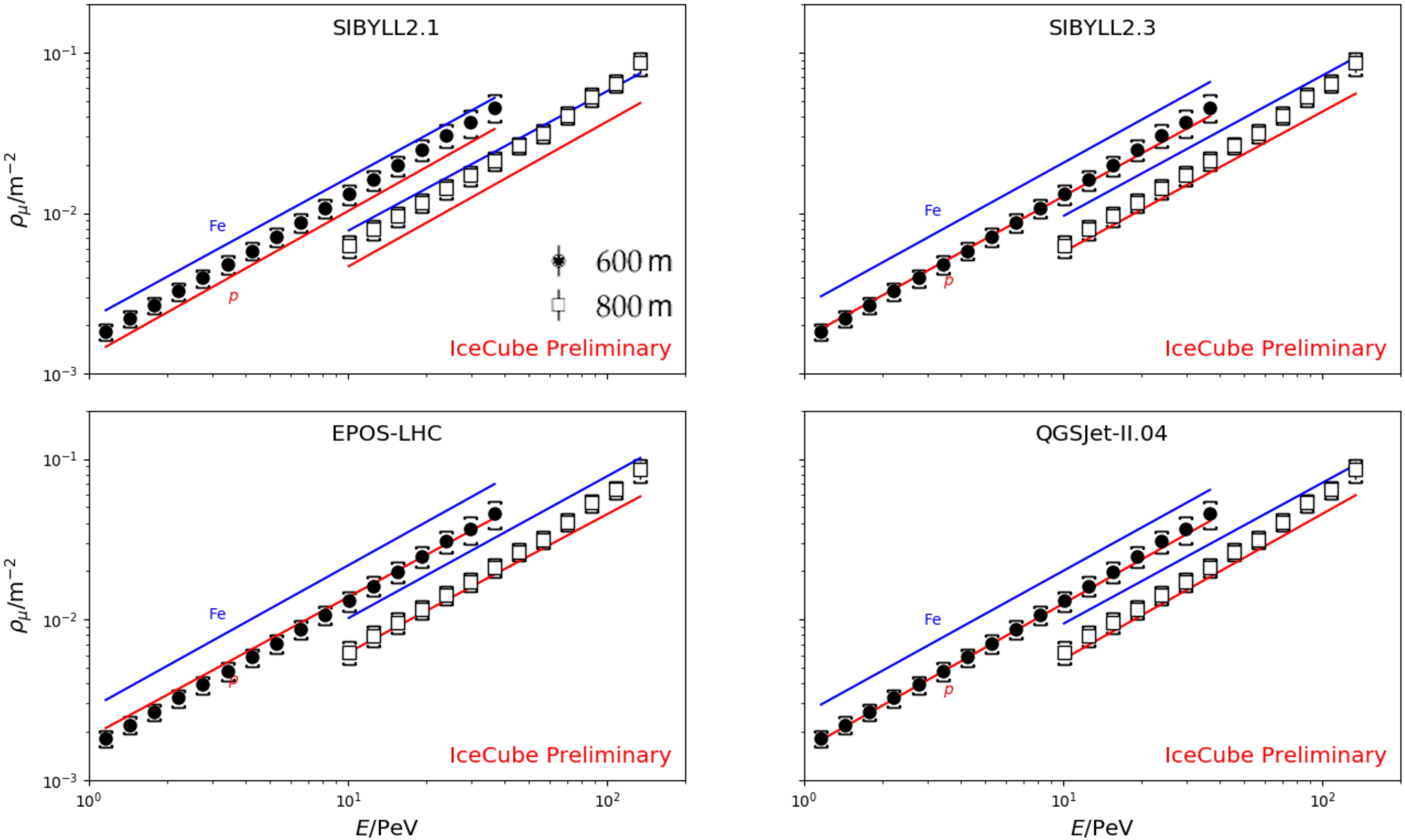


Correction factors

$\rho/\rho_{\mathrm{TRUE}}$ using Sibyll2.1 (em1/2 are max/min changes varying the models; realistic CR flux using weighted with H4a model)

Error bands include statistical, composition and EM model uncertainties

Resulting Muon density



ρ_μ should range between p and Fe. EPOS-LHC seems off