MEASUREMENTS OF COSMIC RAY MASS COMPOSITION WITH THE ICECUBE NEUTRINO OBSERVATORY

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South Dakota School of Mines & Technology

UHECR 2022 - L'Aquila
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Outline

- Detector IceCube & IceTop
- Mass Composition Analysis Results
- Future Detector Enhancements

Supported by U.S. National Science Foundation-EPSCoR (RII Track-2 FEC, award #2019597)

ICECUBE NEUTRINO OBSERVATORY

Unique astroparticle detector at the South Pole for high energy particles

IceTop

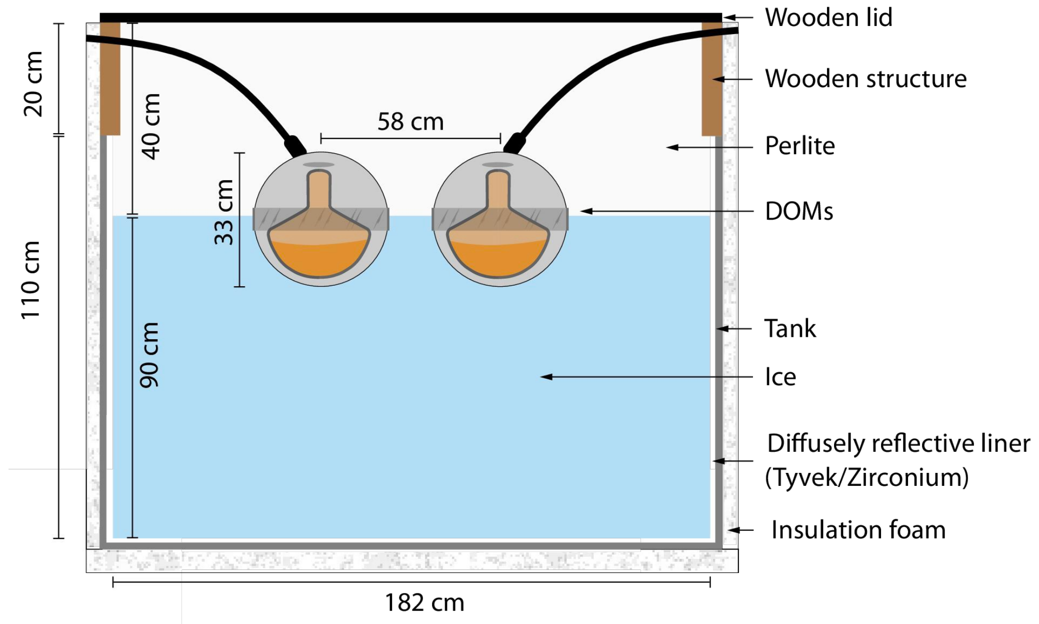
- 1 km^2 air shower array
- 81 x 2 Ice Cherenkov Tanks with 2 DOMs each
- Mostly electromagnetic component and mainly GeV muons
- PeV – EeV energy range

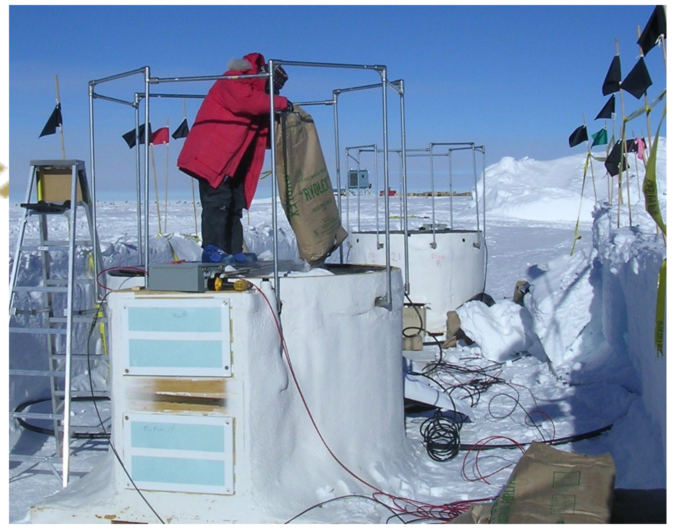
IceCube

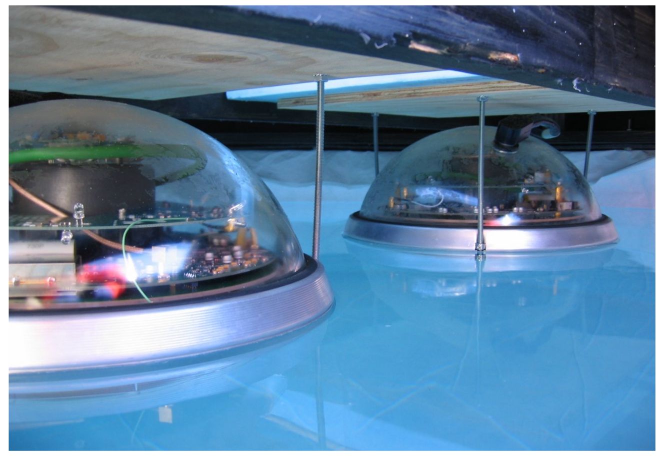
- 1 km^3 instrumented volume
- 86 strings with ~5000 DOMs

- TeV muons
- Neutrinos (indirect)

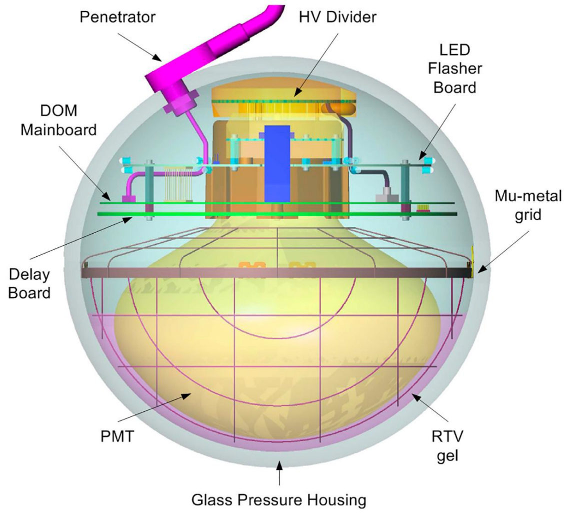
IceTop Tank

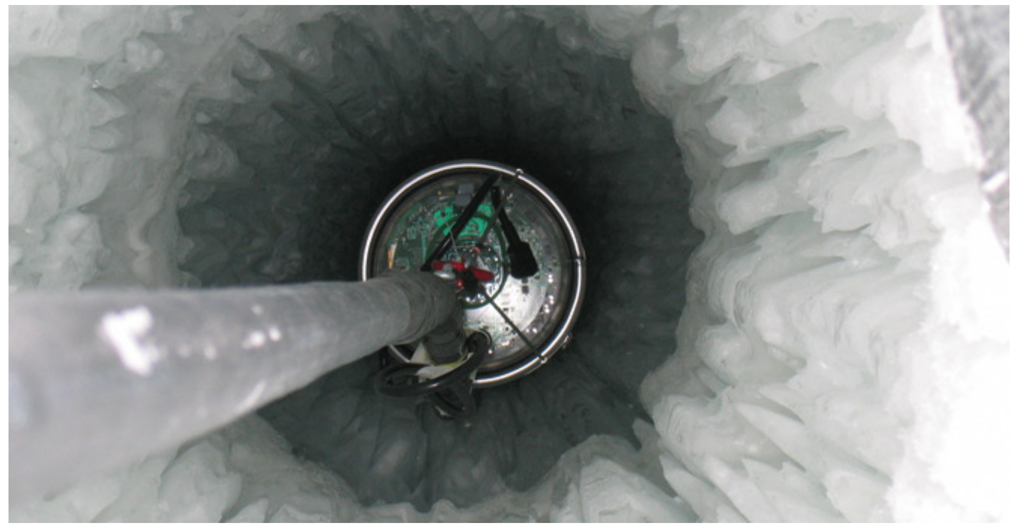


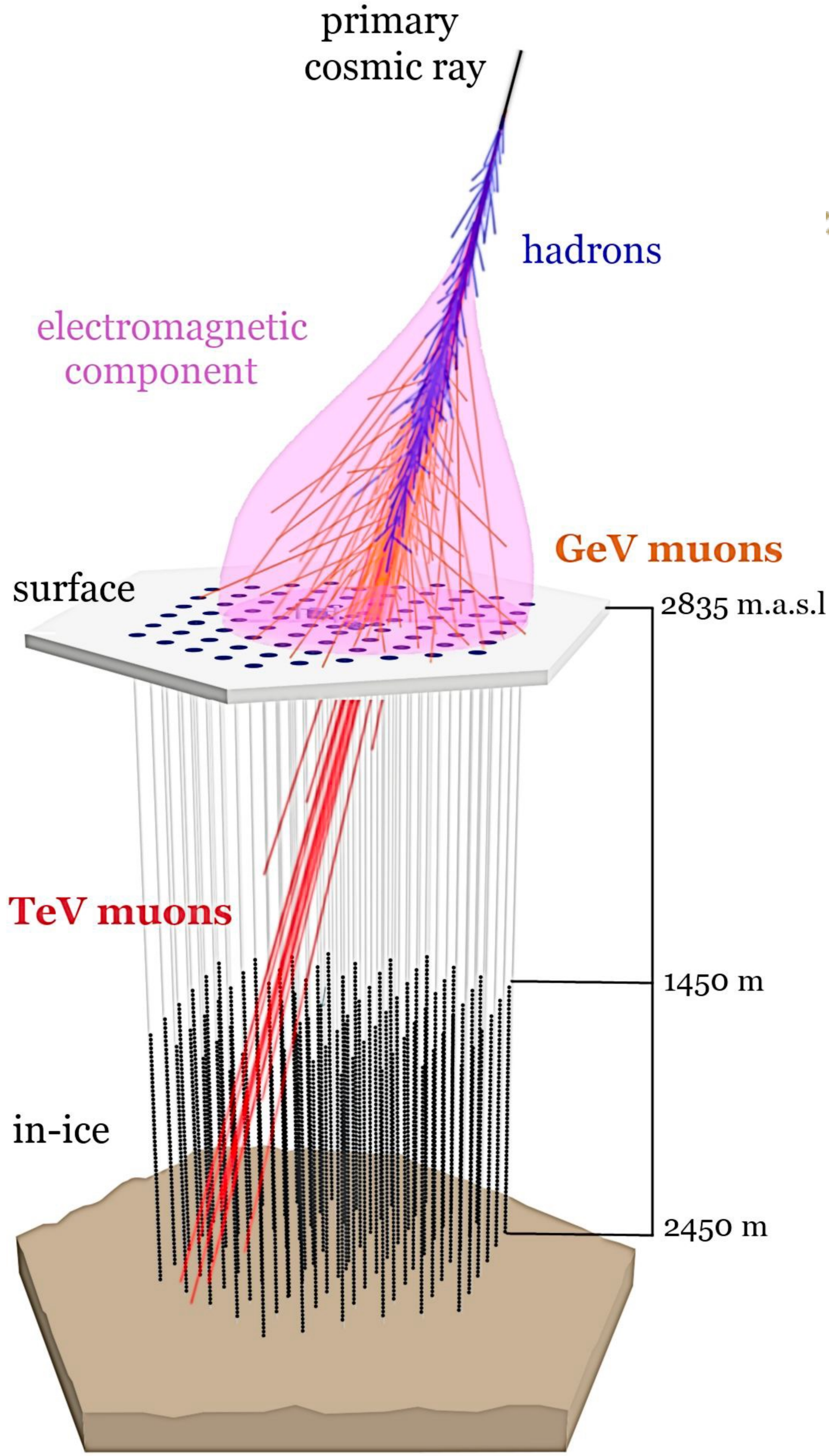




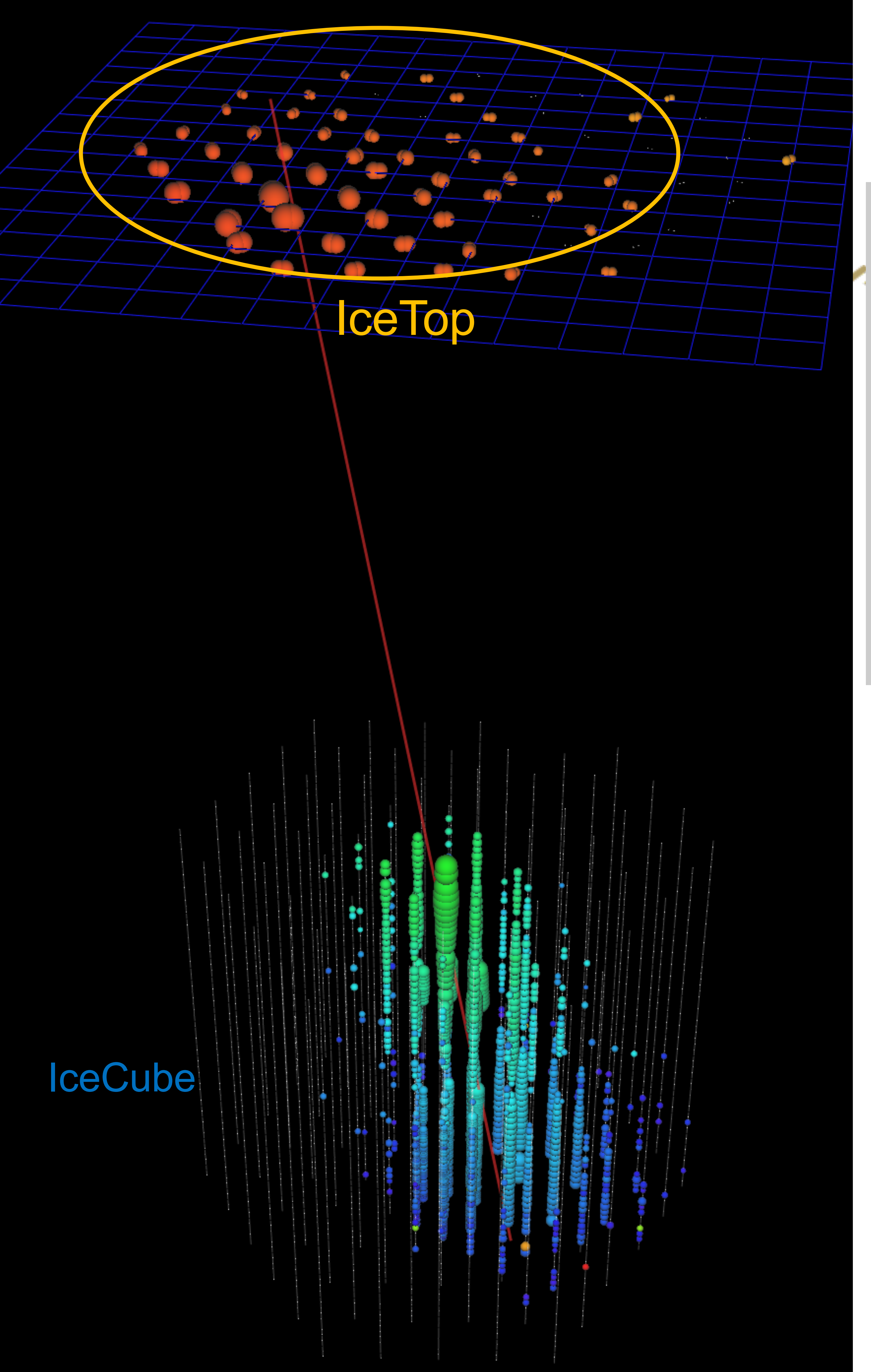
Digital Optical Module

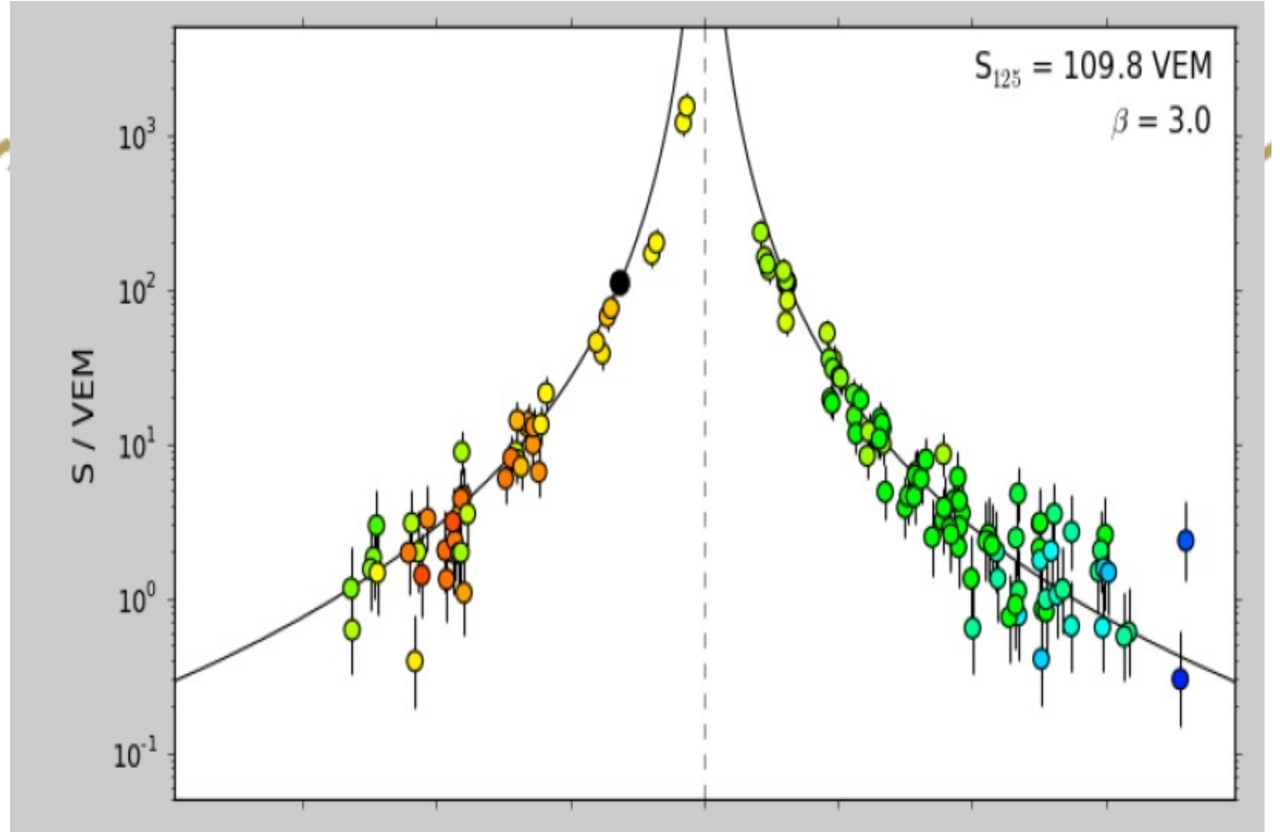


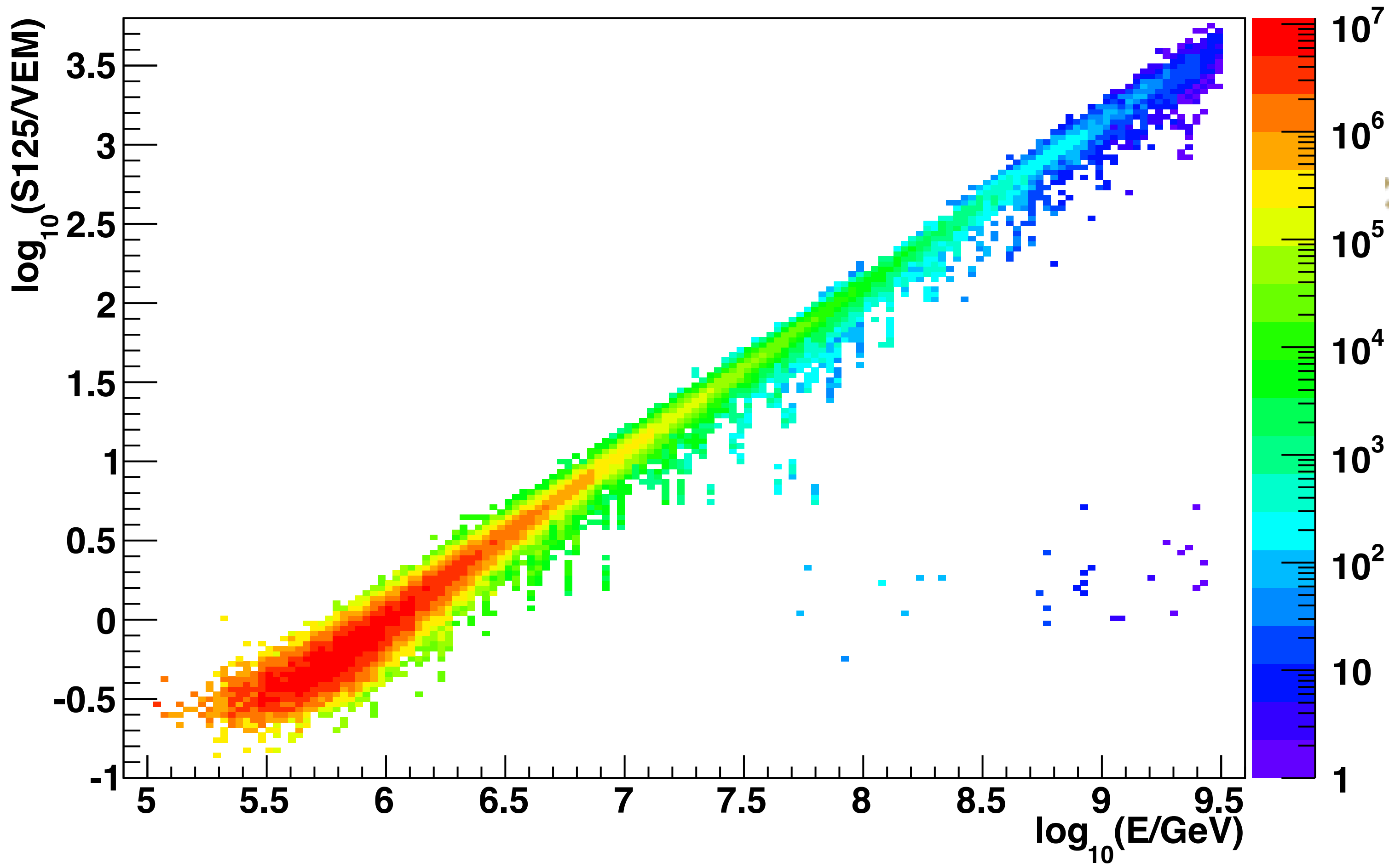




ICETOP-ONLY RECONSTRUCTION







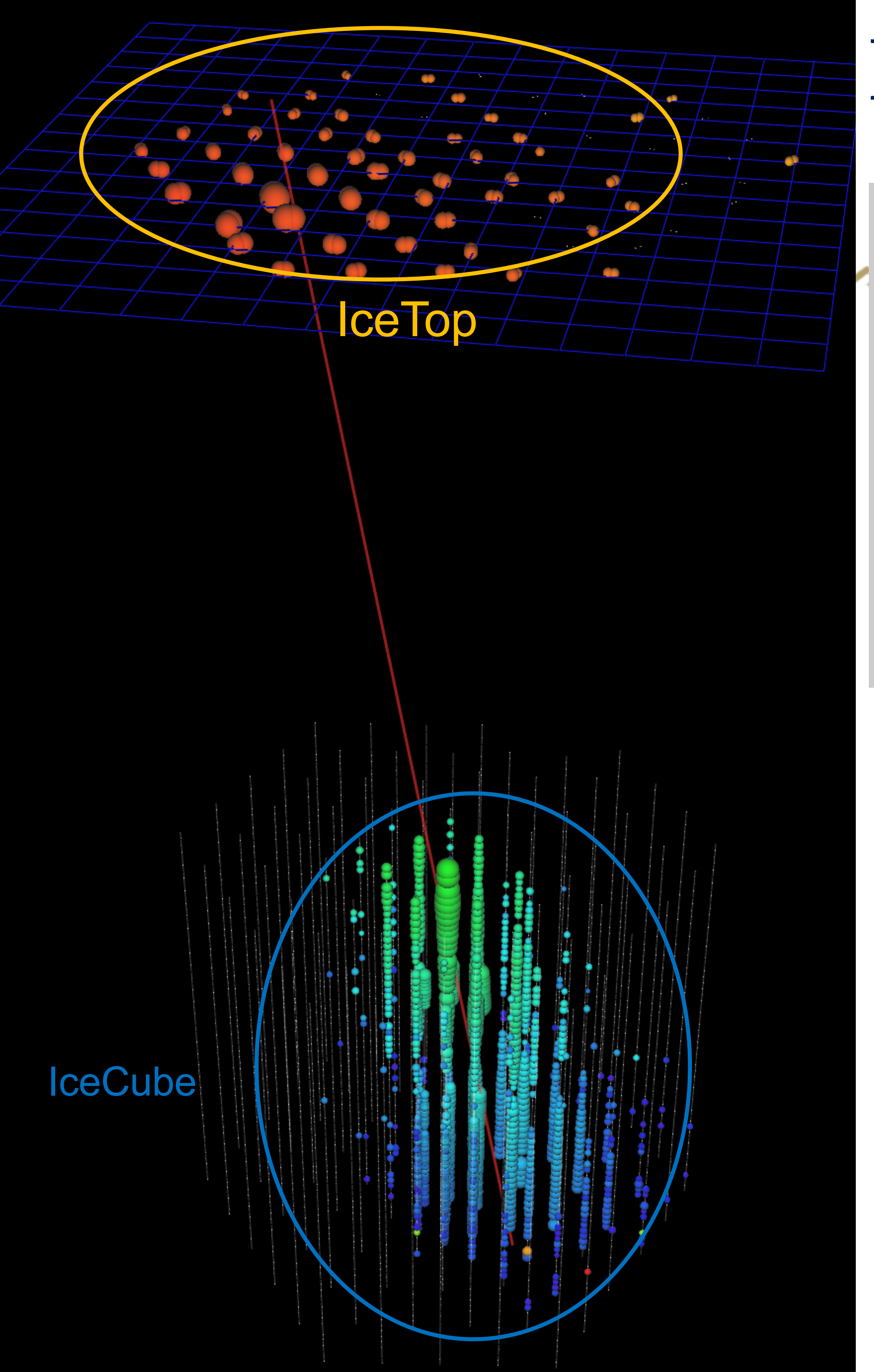
Lateral signal distribution in VEM:

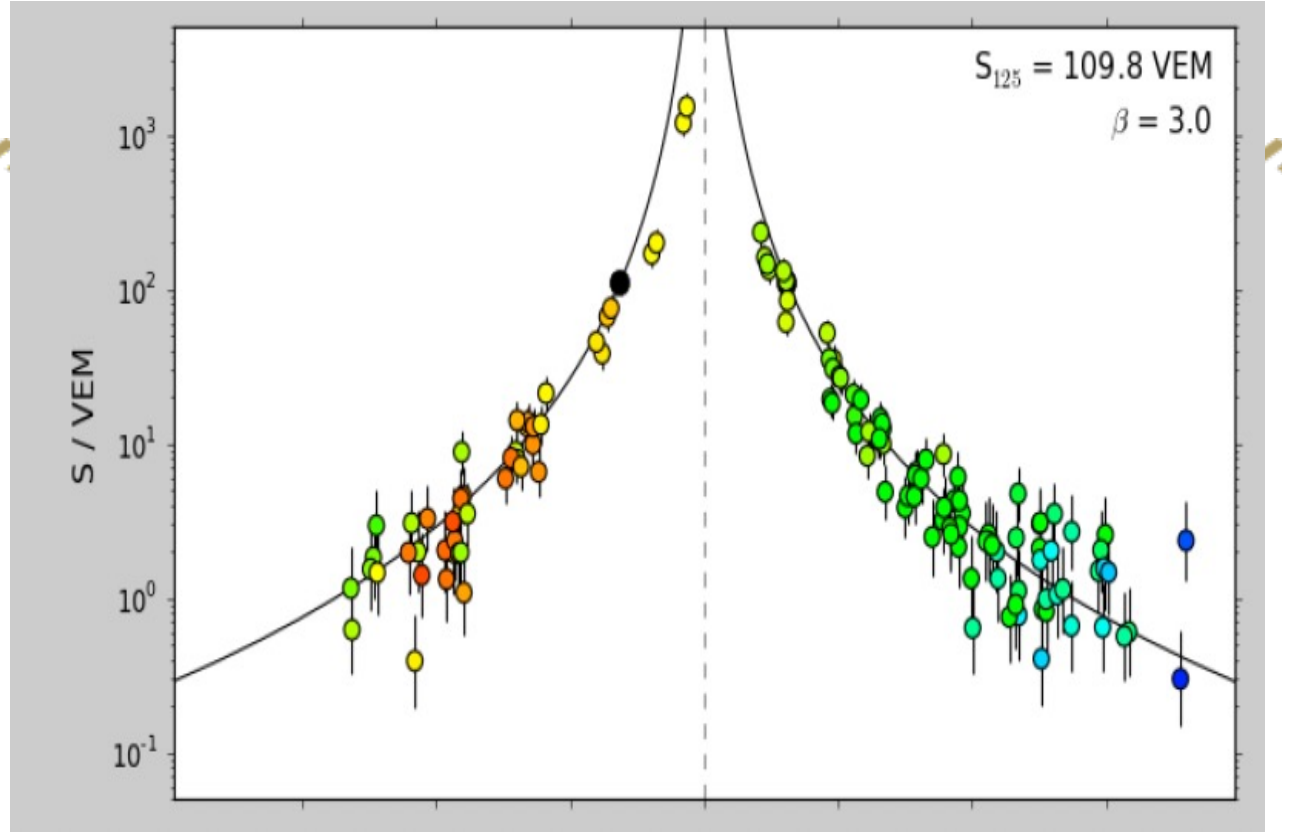
$$S(R) = S(R_0)\left(\frac{R}{R_0}\right)^{-\beta-\kappa\log_{10}\left(\frac{R}{R_0}\right)}$$

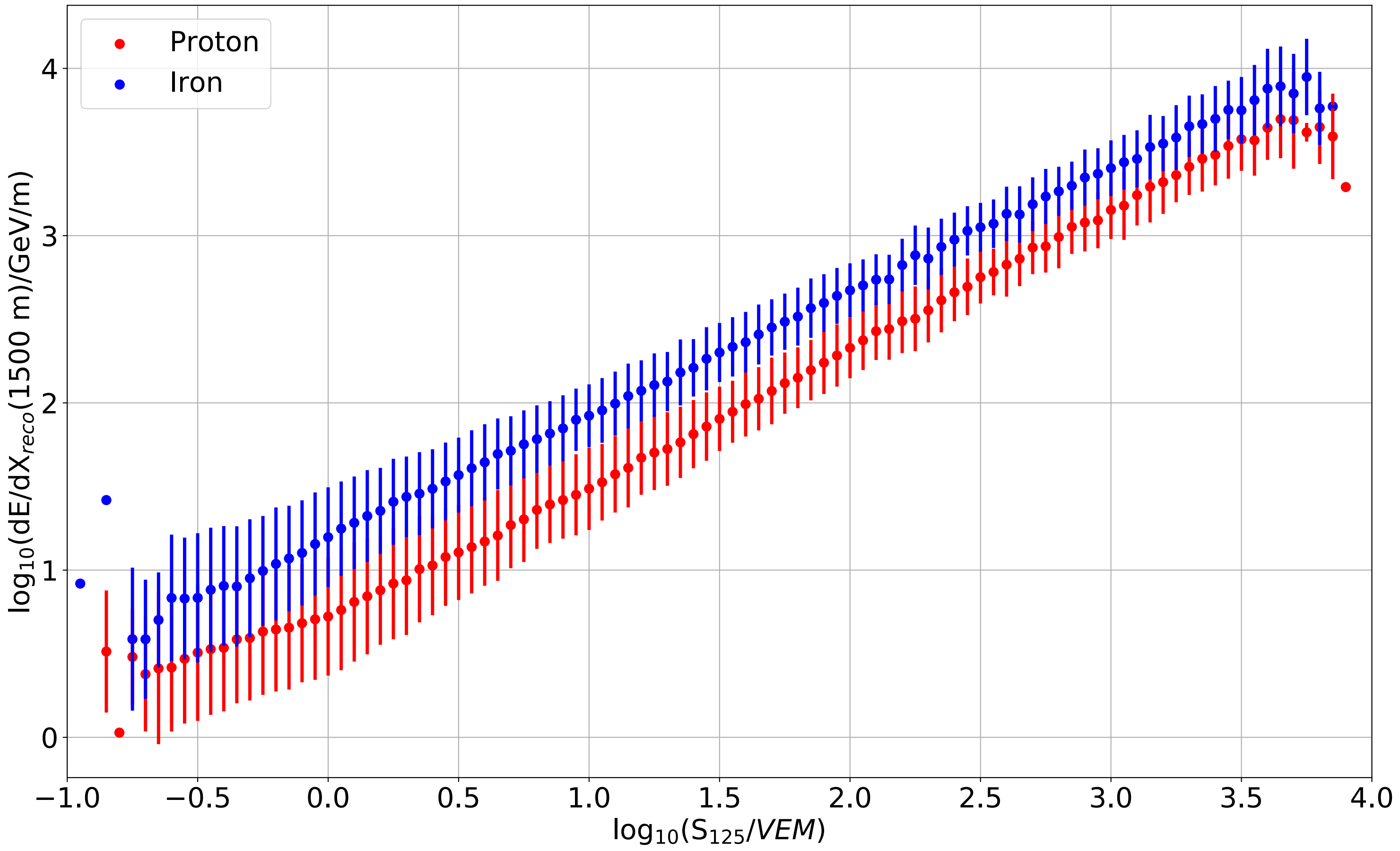
(Double Logarithmic Parabola)

- 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)

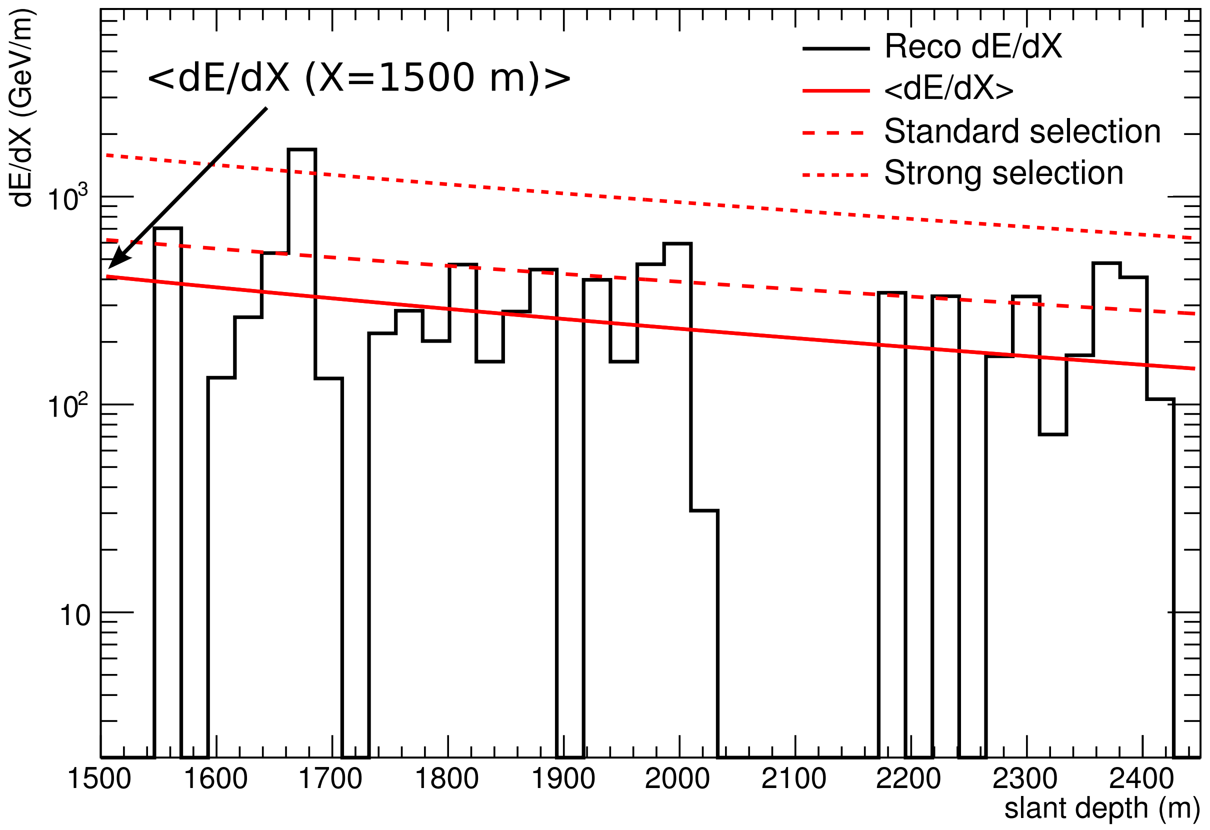
ICETOP/ICECUBE RECONSTRUCTION







High energy muons (>500 GeV)



- Energy and mass proxy reconstruction with neural network technique
- Use best available detector simulation including snow coverage

https://arxiv.org/abs/1906.04317

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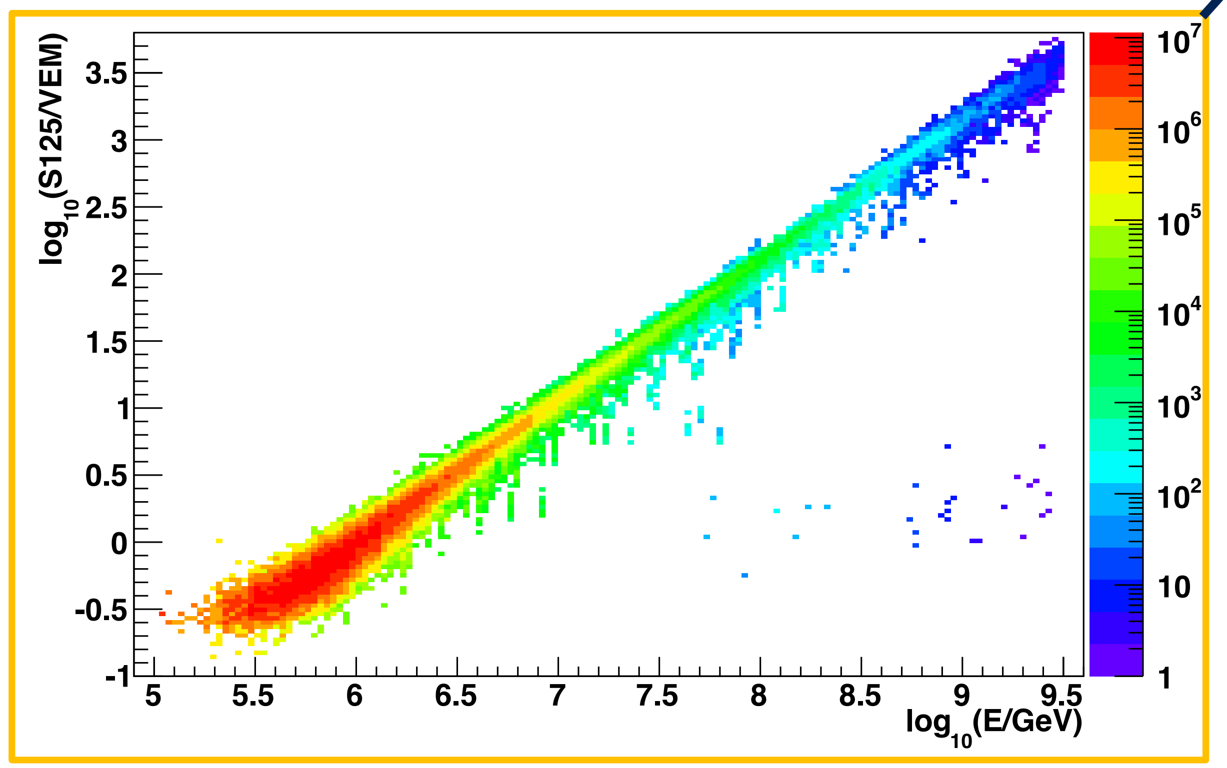
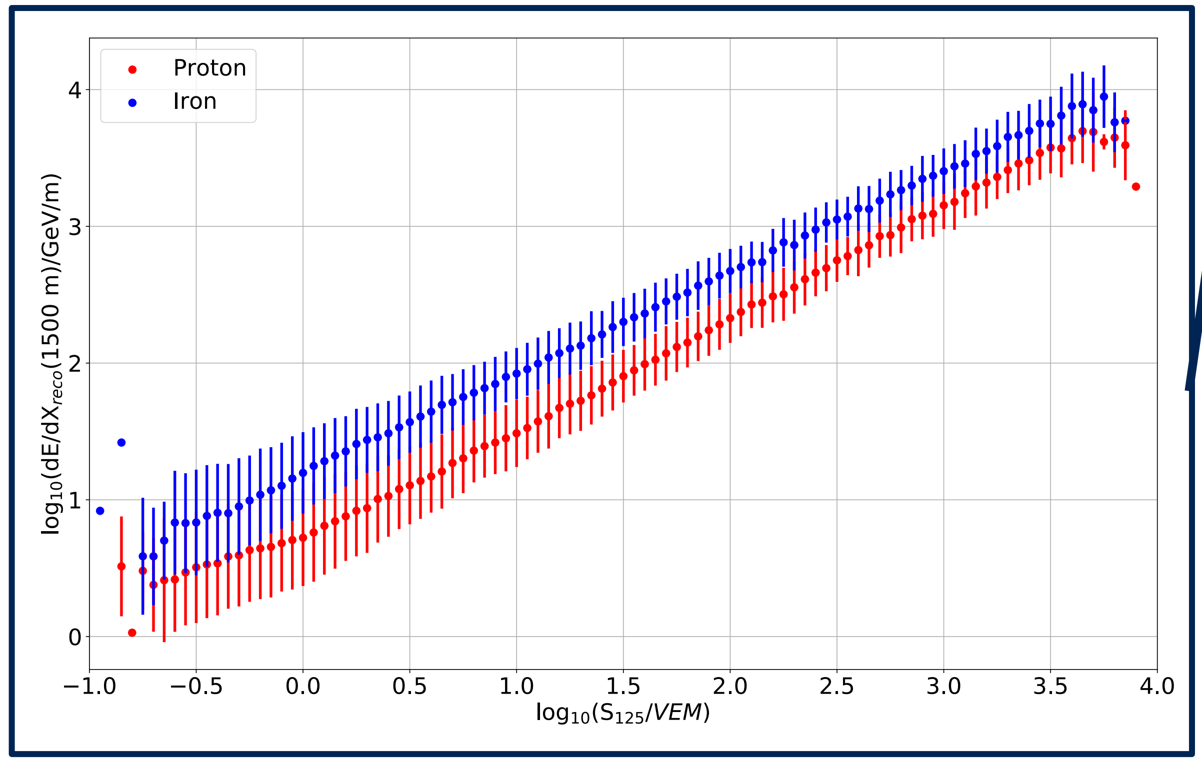
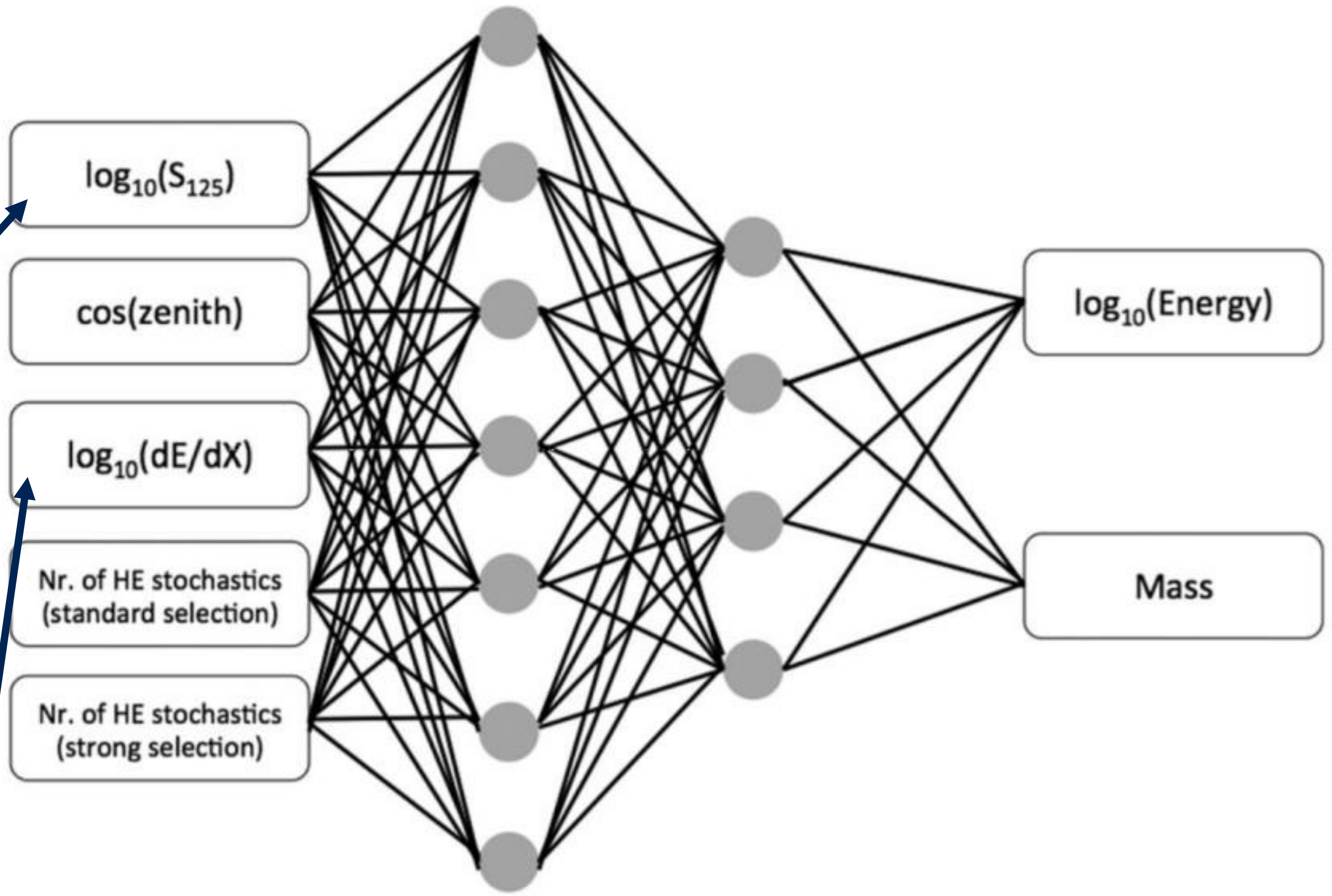
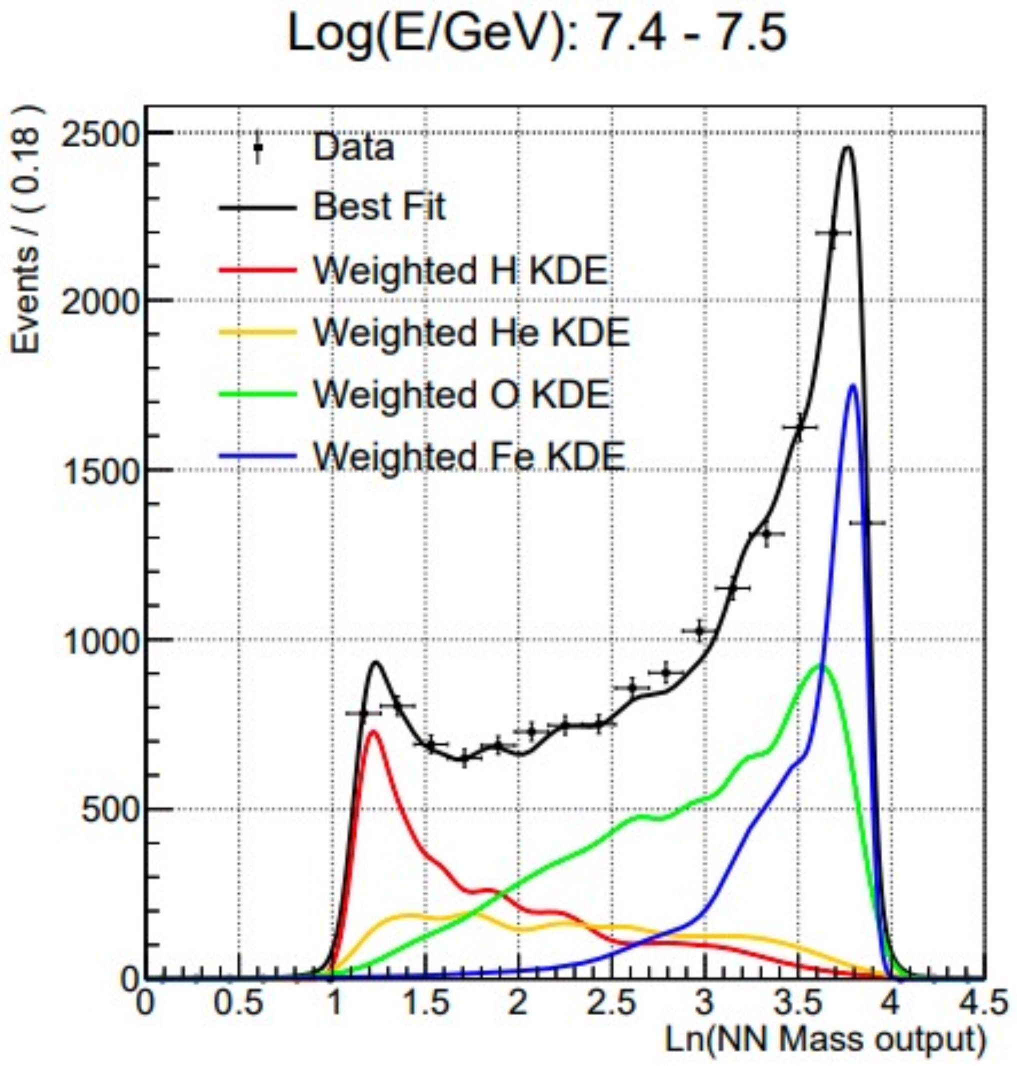
ICETOP-ICECUBE MASSCOMPOSITION

- Data 2011-2013
- Log(E/GeV) = 6.5 … 9.0
- Primary elementary groups
  - H, He, CNO, Fe
- Input variables
  - IceTop
    - S125 (Energy estimator)
    - Zenith
  - IceCube
    - dEdx at 1500m slant depth
    - Number of HE stochastic losses









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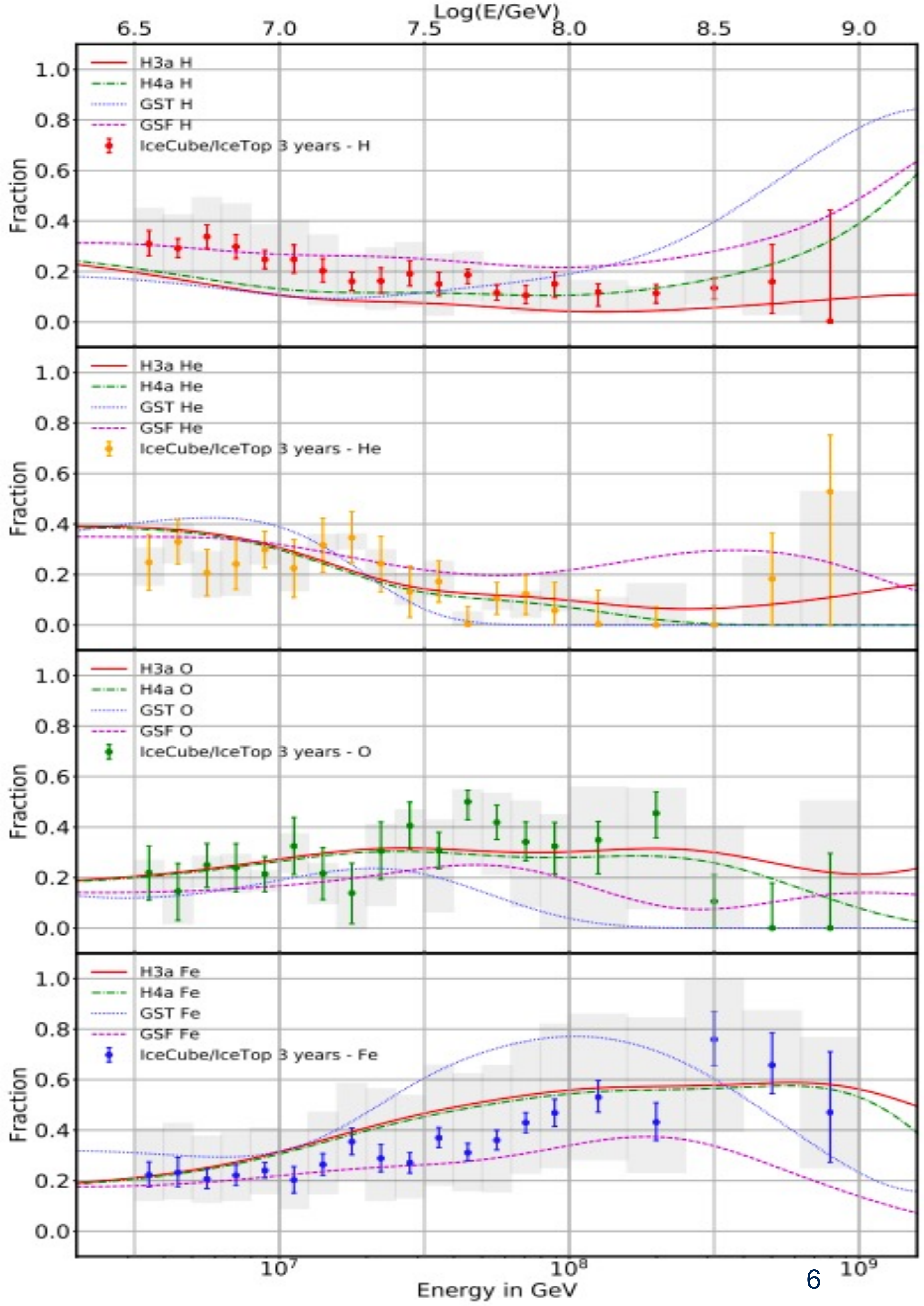
ICETOP-ICECUBE MASSCOMPOSITION

- Mass spectrum divided in ln(A)
- A = mass number

- Results are analyzed in mass groups corresponding to similar nuclei
  - H
  - He
  - O
  - Iron

- These results are highly correlated with each other

- Sum of all elementary groups must be conserved



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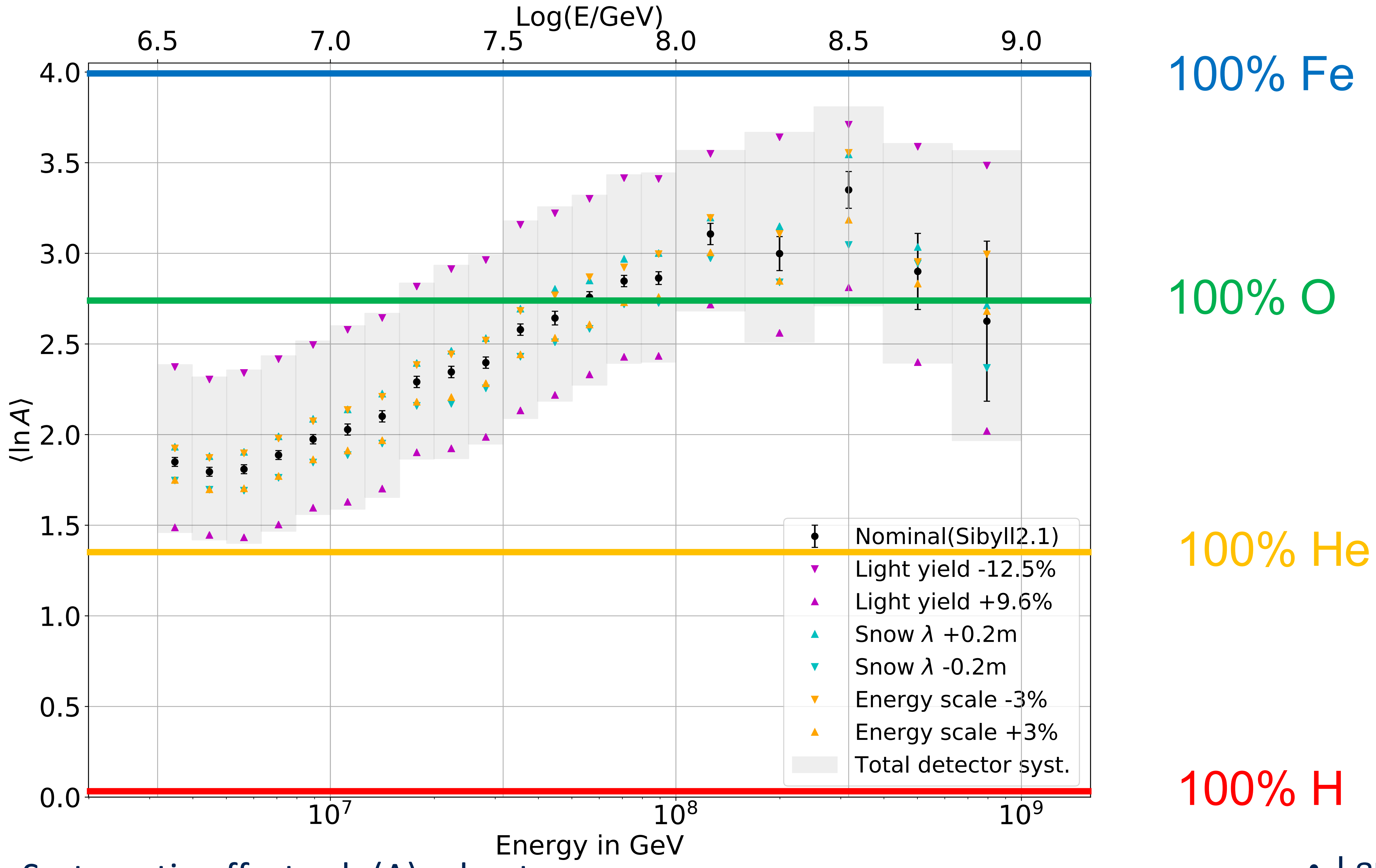
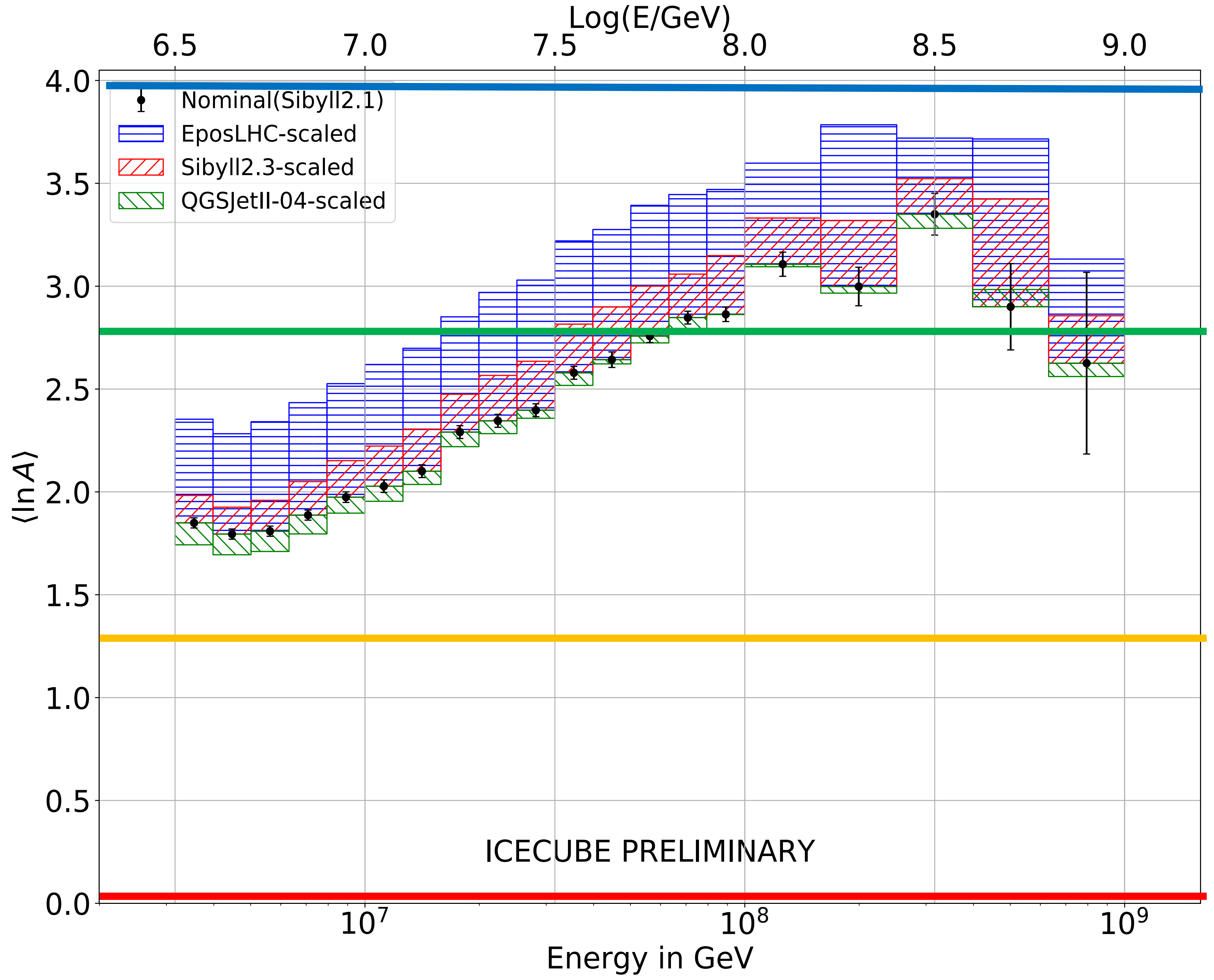
SYSTEMATIC UNCERTAINTY





Systematic offsets <ln(A)> due to:

- Snow (±0.2 m)
- Light yield (-12.5% , +9.6%)
- Energy scale (±3%)

- Large systematic uncertainties hadronic interaction model
- Epos LHC
- Sibyll2.3
- QGSJetII-04

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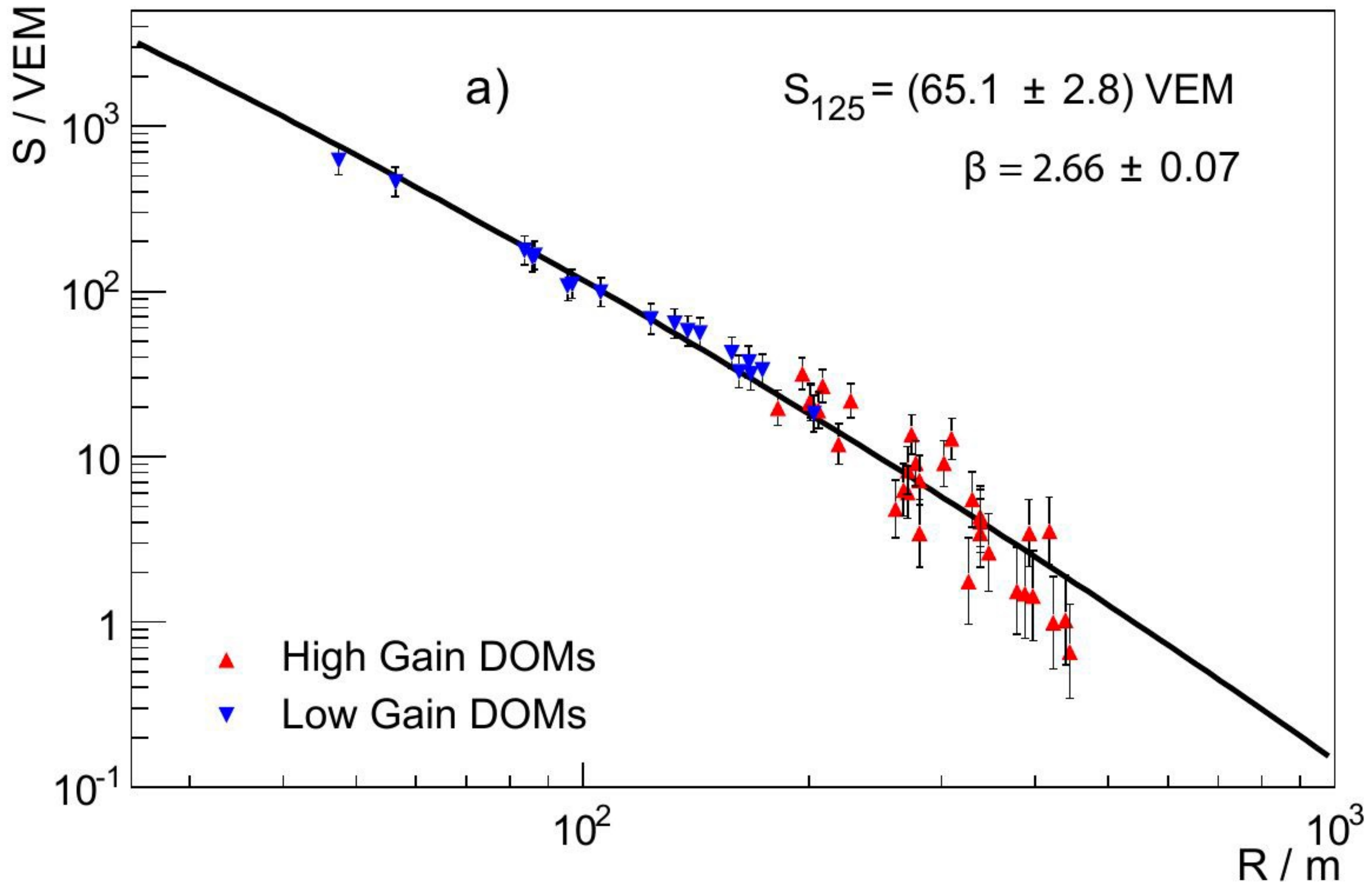
MEASURING HIGH ENERGY MUON MULTIPLICITY

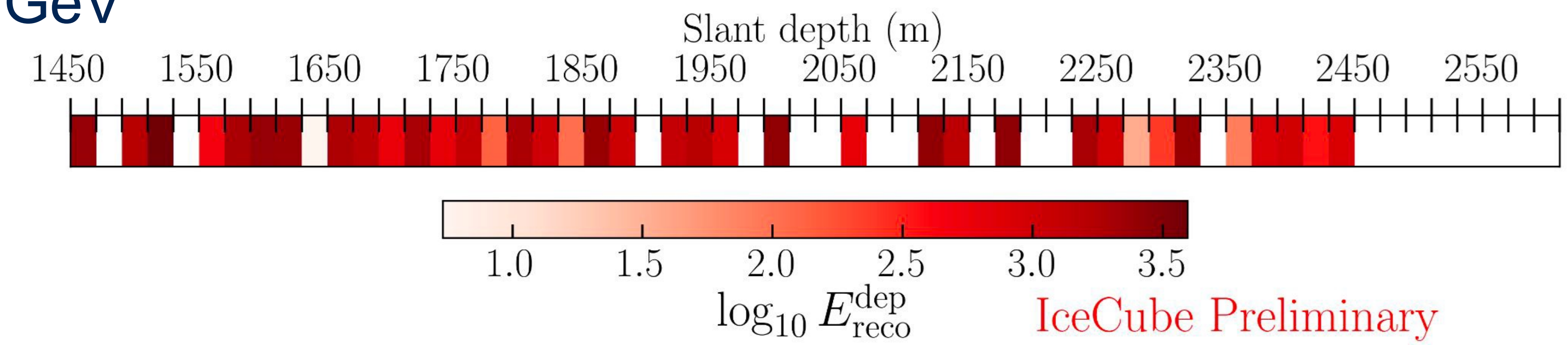
Neural network reconstruction

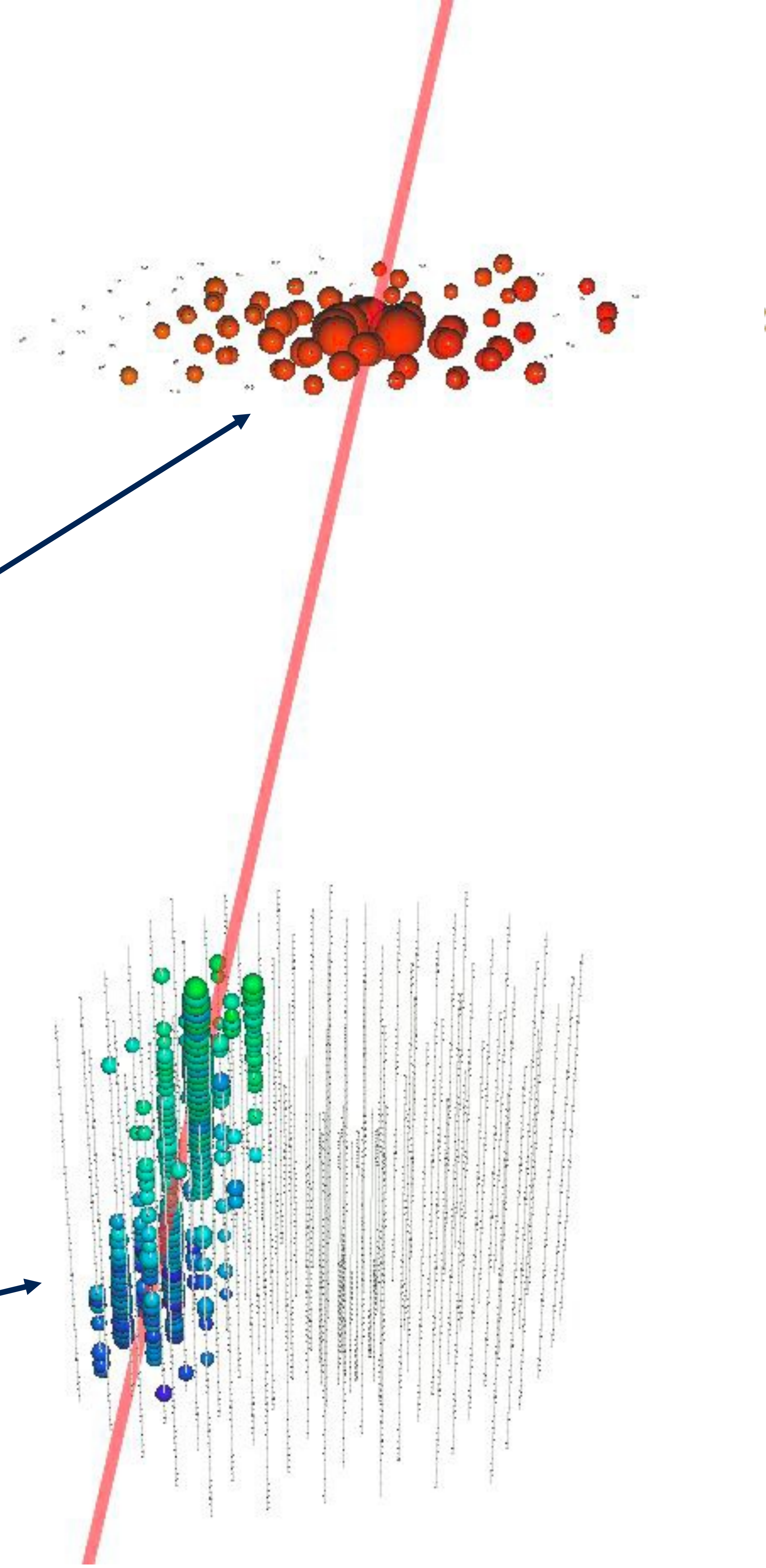
Using
- RNN + Dense layers

- Inputs
  - Shower size S_{125}
  - Zenith θ
  - Energy loss vector

- Outputs
  - Primary energy E_0
  - Number of muons > 500 GeV in shower at surface N_μ







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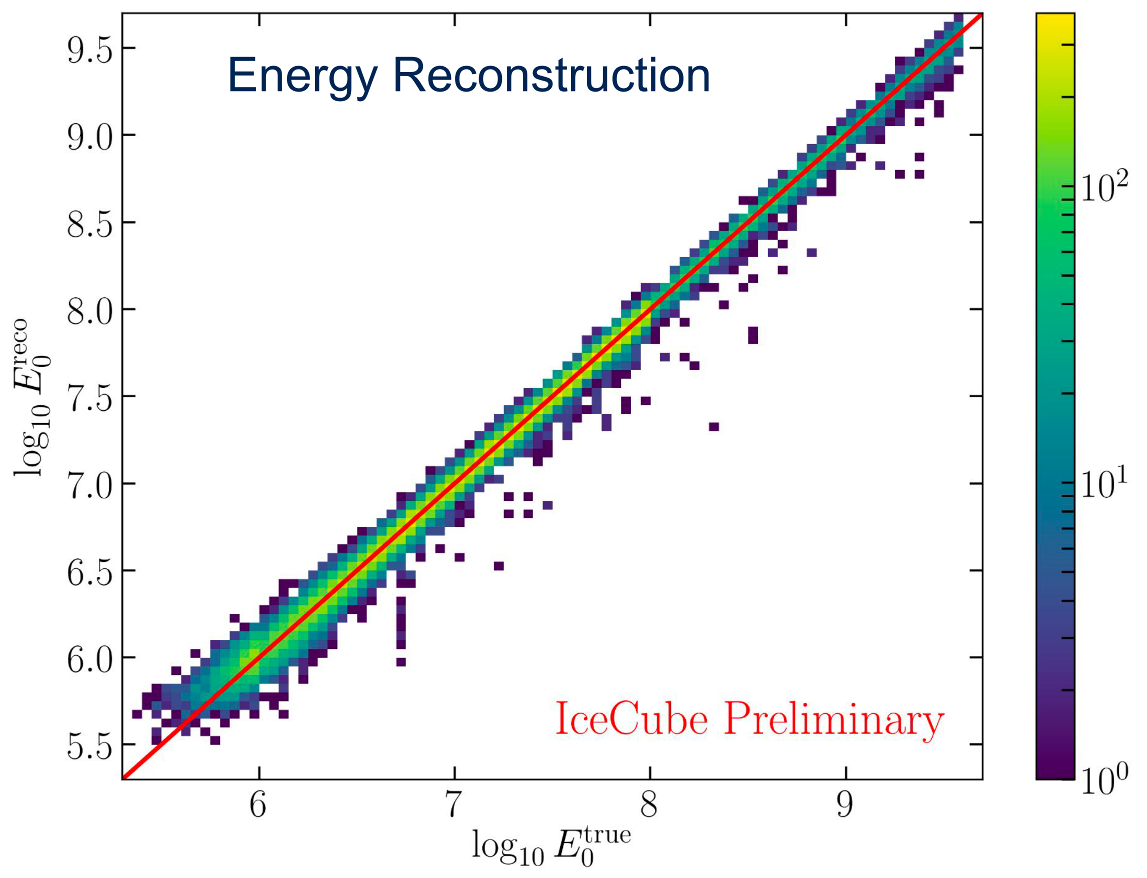
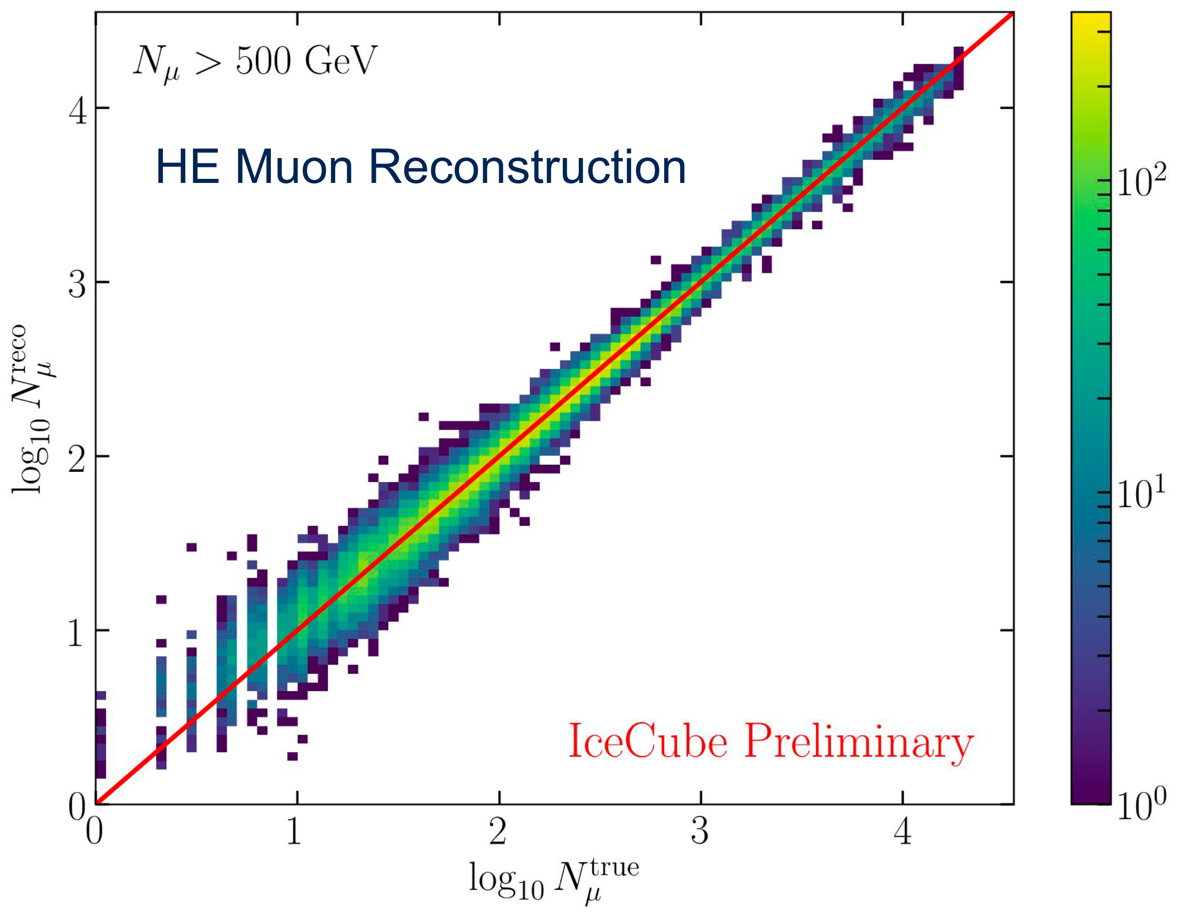
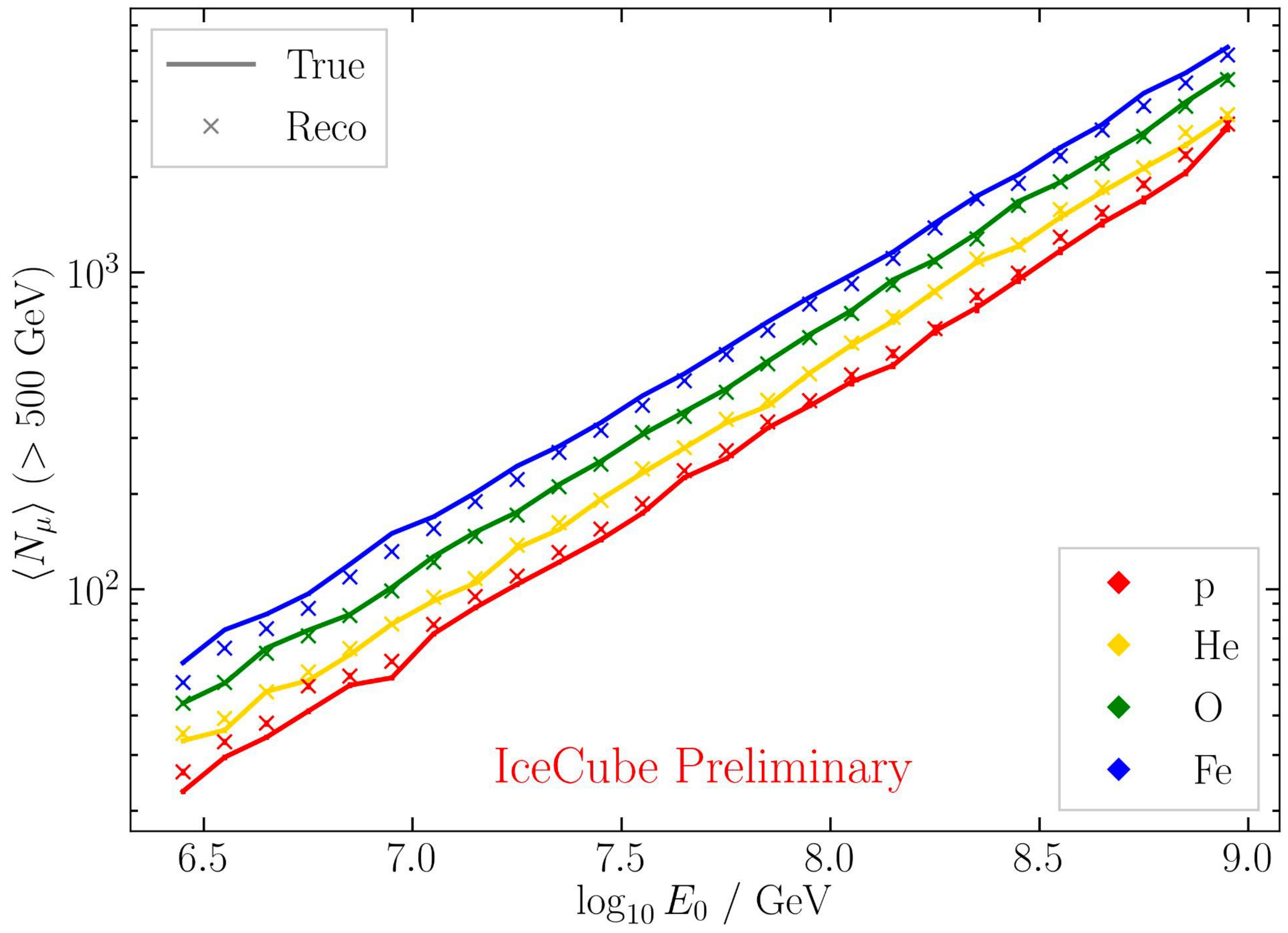
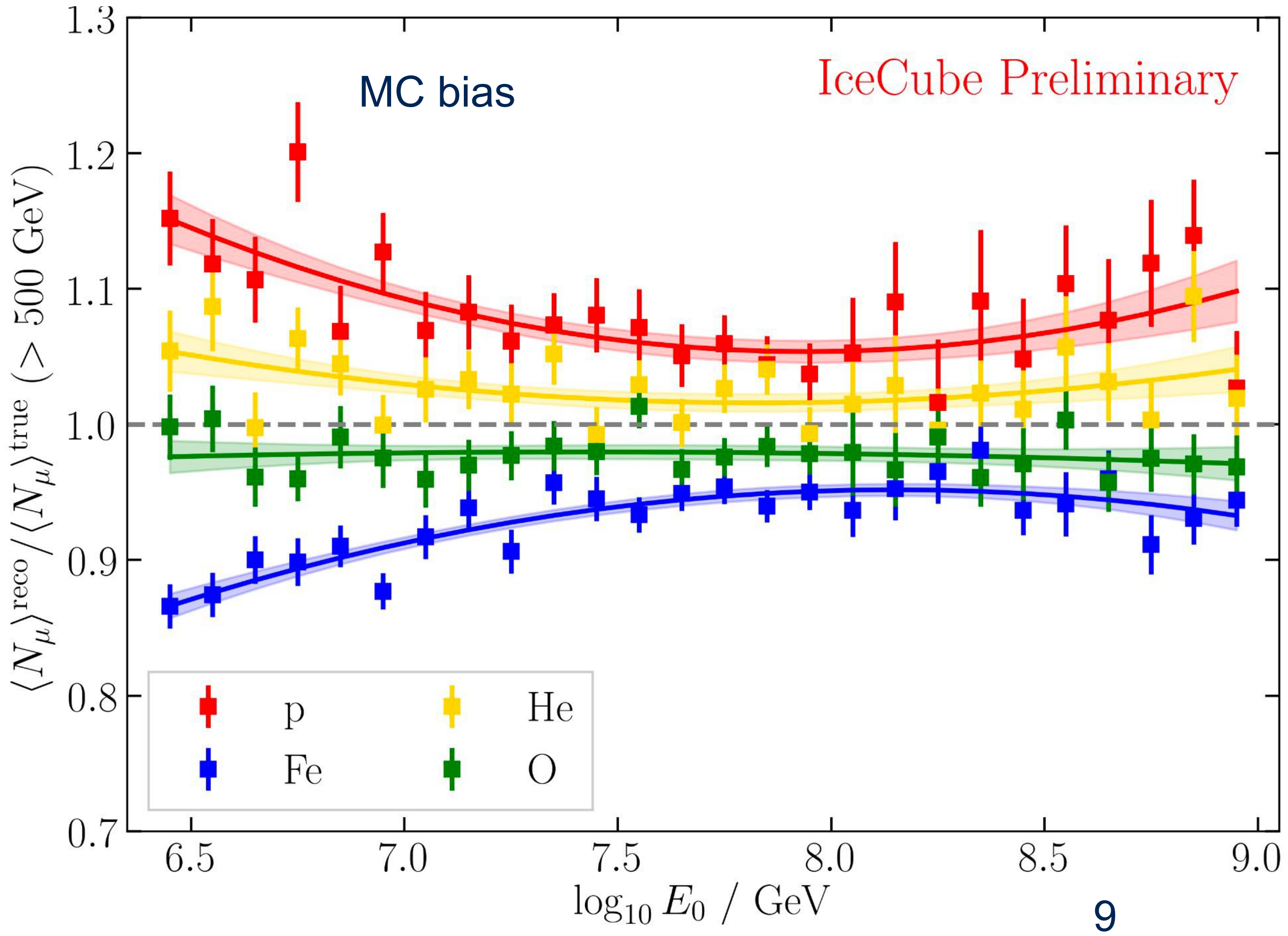
MEASURING HE MUON MULTIPLICITY









Simultaneous energy and muon number reconstruction

- Good linearity
- Small composition bias on muon number

Correction factor

- Composition dependent over/underestimation
- Ratios fitted with quadratic function
- Used to correct bias

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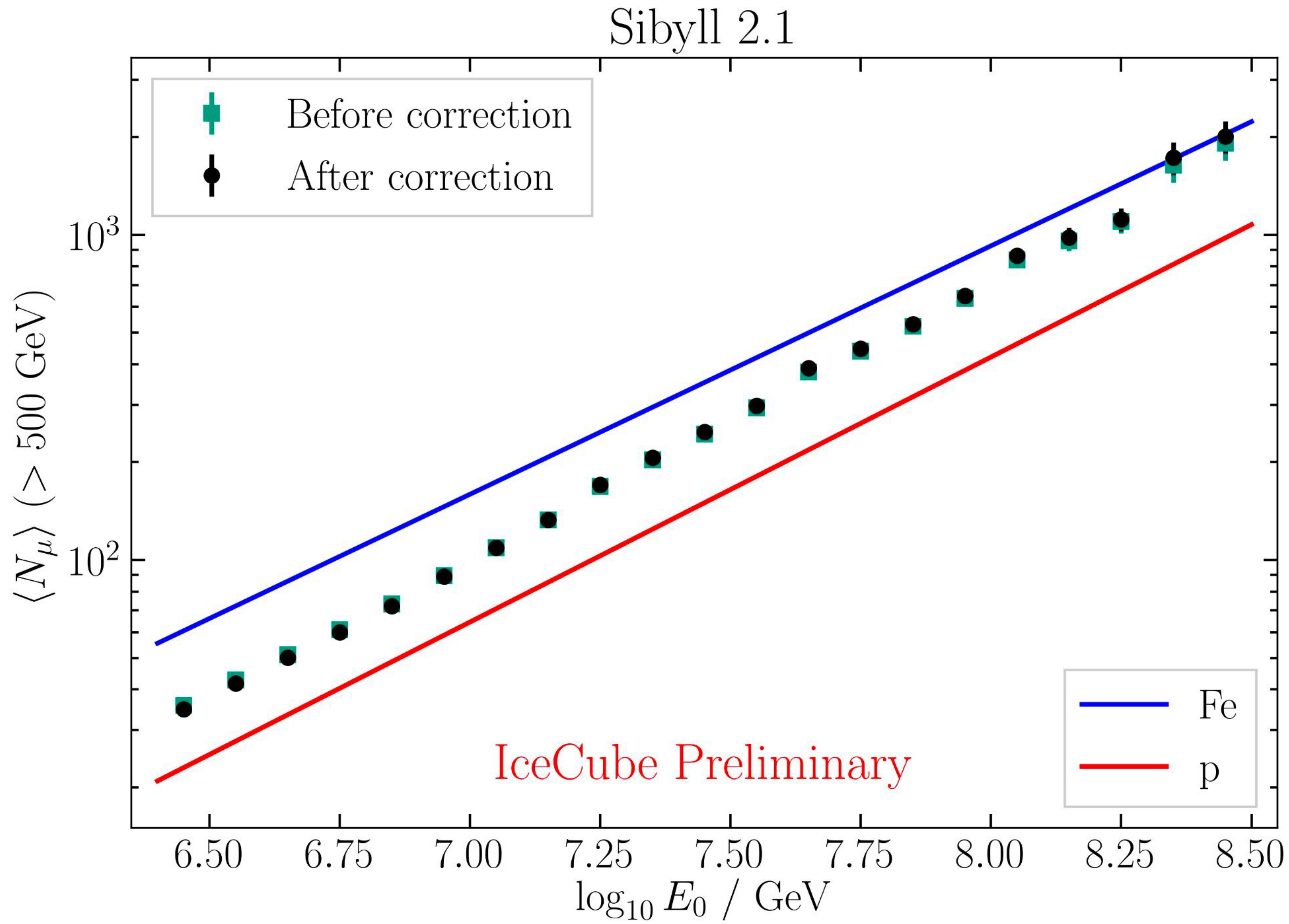
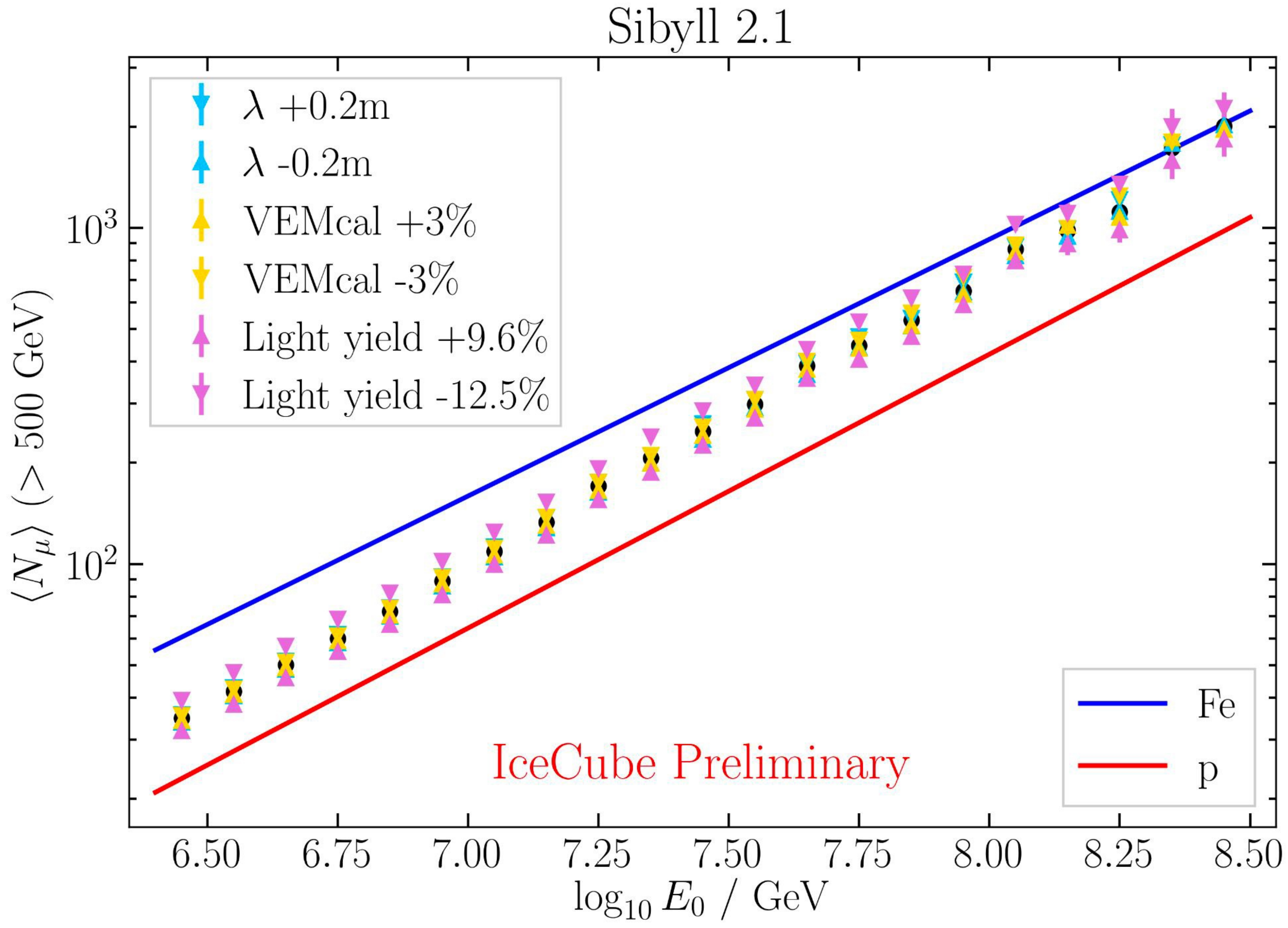
AVERAGE HE MUON NUMBER





Application to experimental data
- 10% of 1 year (05/2012 - 05/2013)
- Compared to expectations from Sibyll 2.1

Systematic uncertainties

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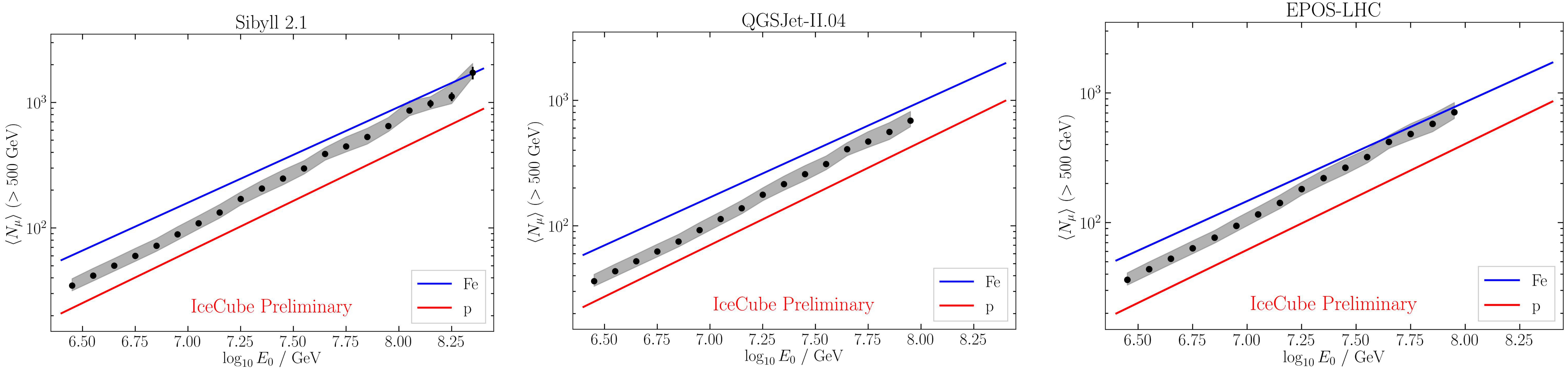
HADRONIC INTERACTION MODELS

Average muon multiplicity > 500 GeV
- Hadronic model dependent
- Compared to corresponding MC predictions
- Shaded area: total systematic uncertainty



ICETOP- SURFACE ENHANCEMENT ARRAY

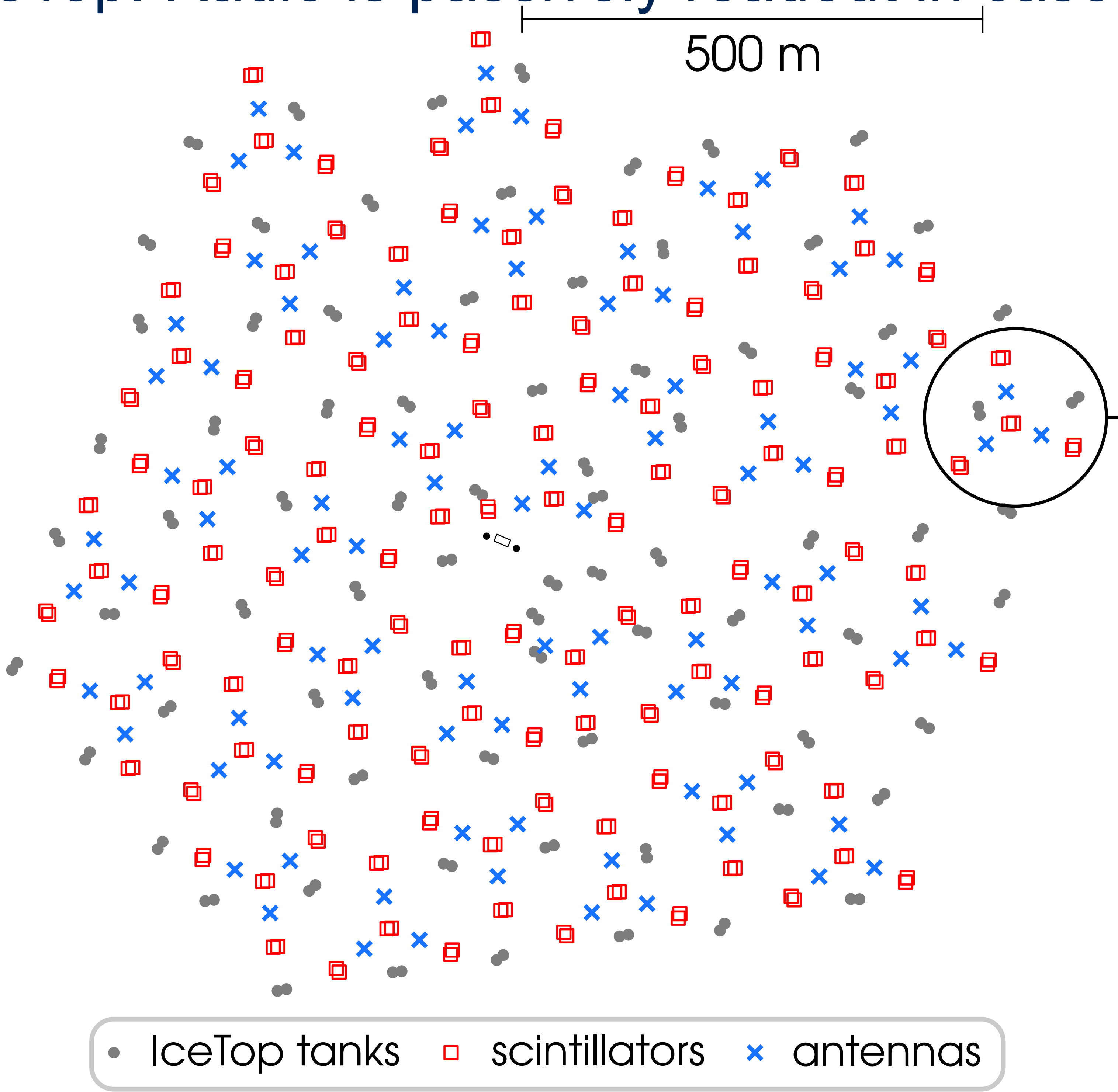
- Additional scintillator + radio station planned to mitigate increasing snow coverage + add composition sensitivity

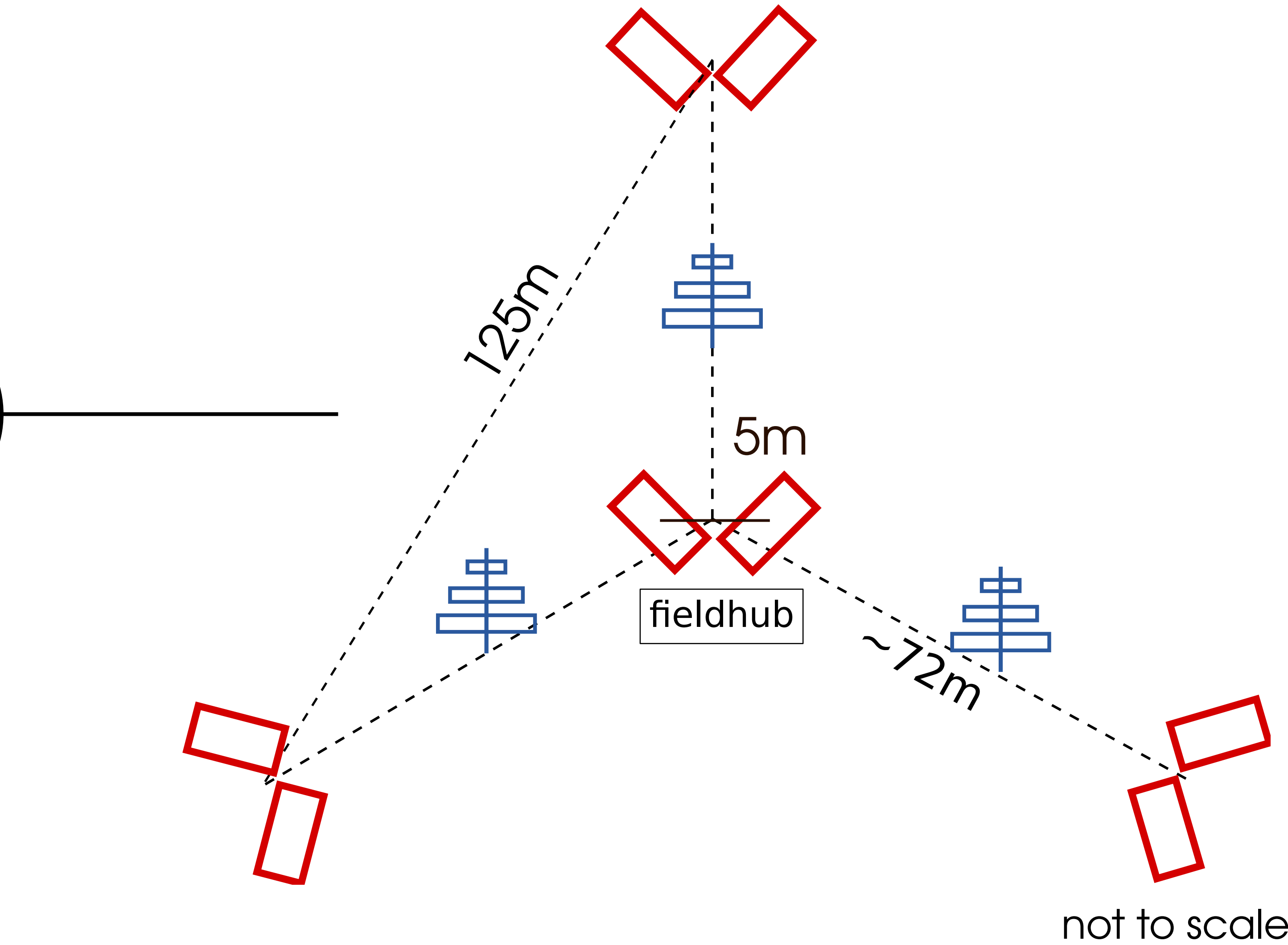
- Scintillator triggers similarly IceTop. Radio is passively readout in case of a surface trigger

Radio antenna

First production level R&D station deployed in Jan.2020

Scintillator panel



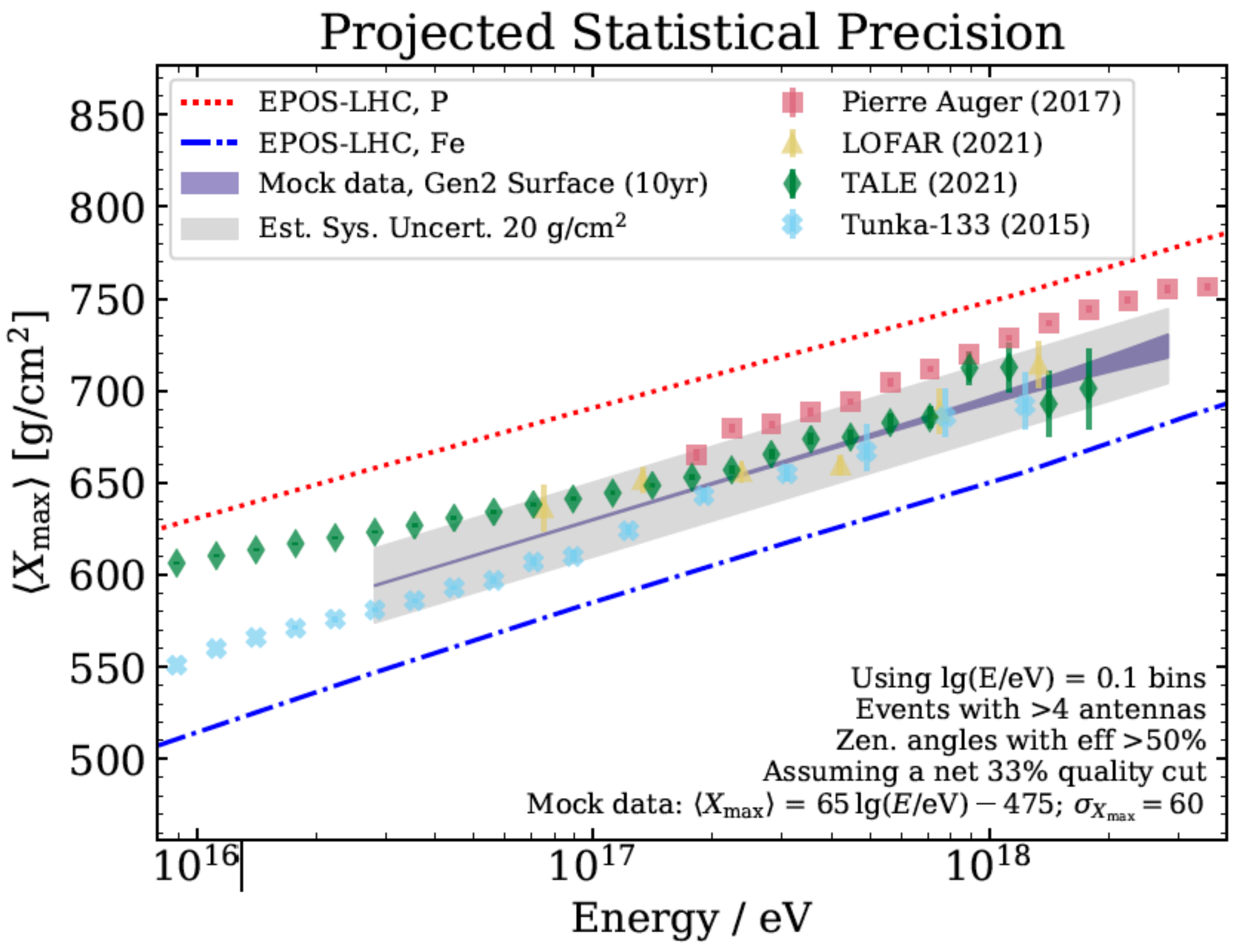


1 station =
8 scintillator modules + 3 antennas

ICETOP- SURFACE ENHANCEMENT ARRAY

Radio :

- Direct X_{max} measurement for inclined high energy shower

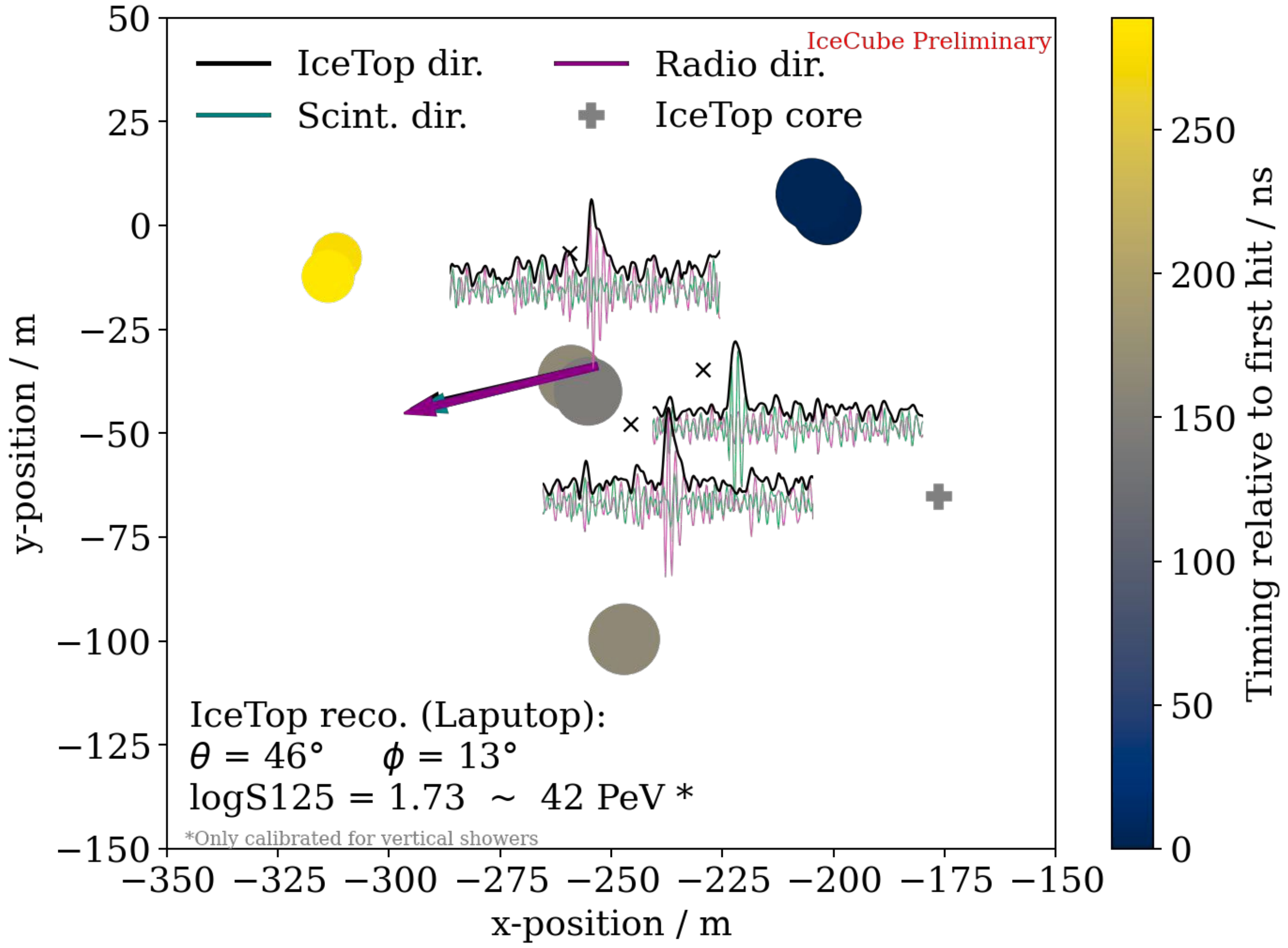


https://arxiv.org/abs/2205.05845

Scintillator:

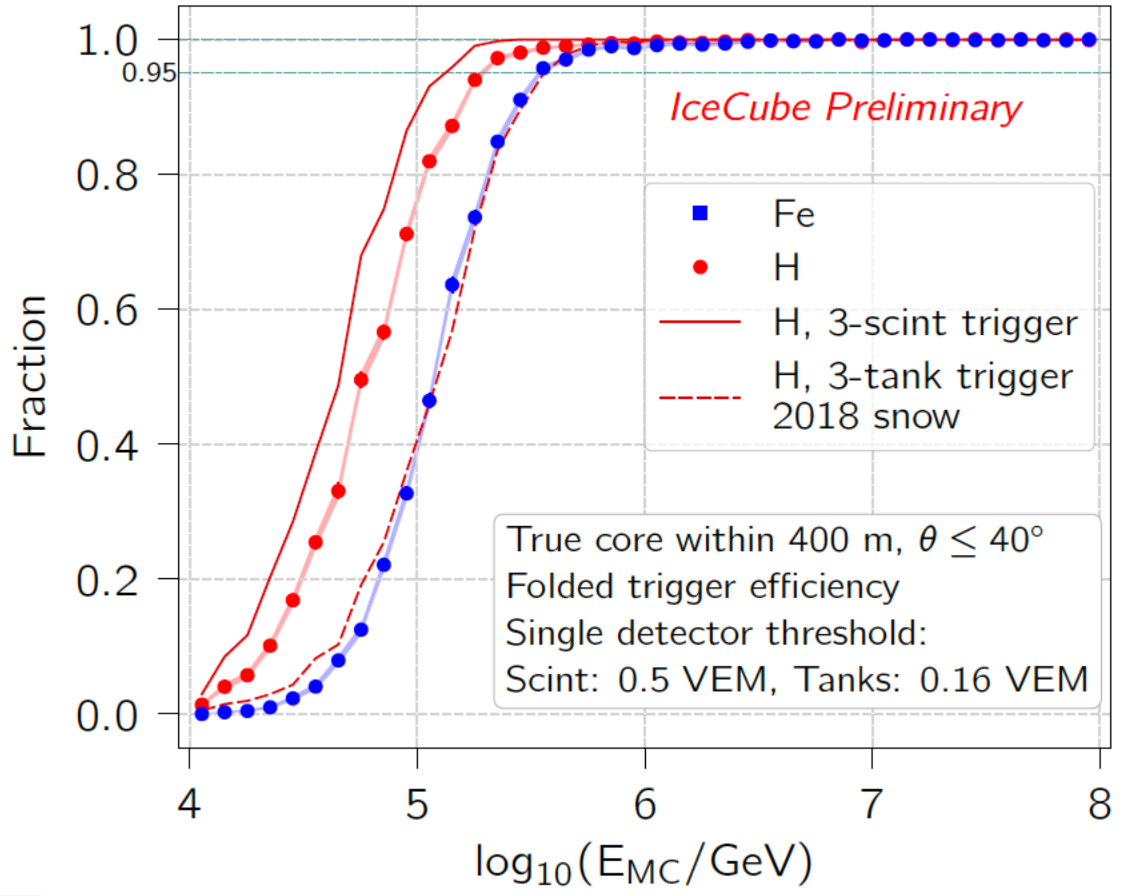
- Lower trigger probability
- Improved muon density measurements at surface level

First coincident measurement



Hrvoje Dujmovic, ARENA2022

Improved trigger probability



DOI: 10.22323/1.358.0332

IMAGING AIR CHERENKOV TELESCOPES ICEACT

Low energy (10 TeV - 200 TeV) air shower particle barely reach the ground making ‘classic’ surface reconstruction challenging

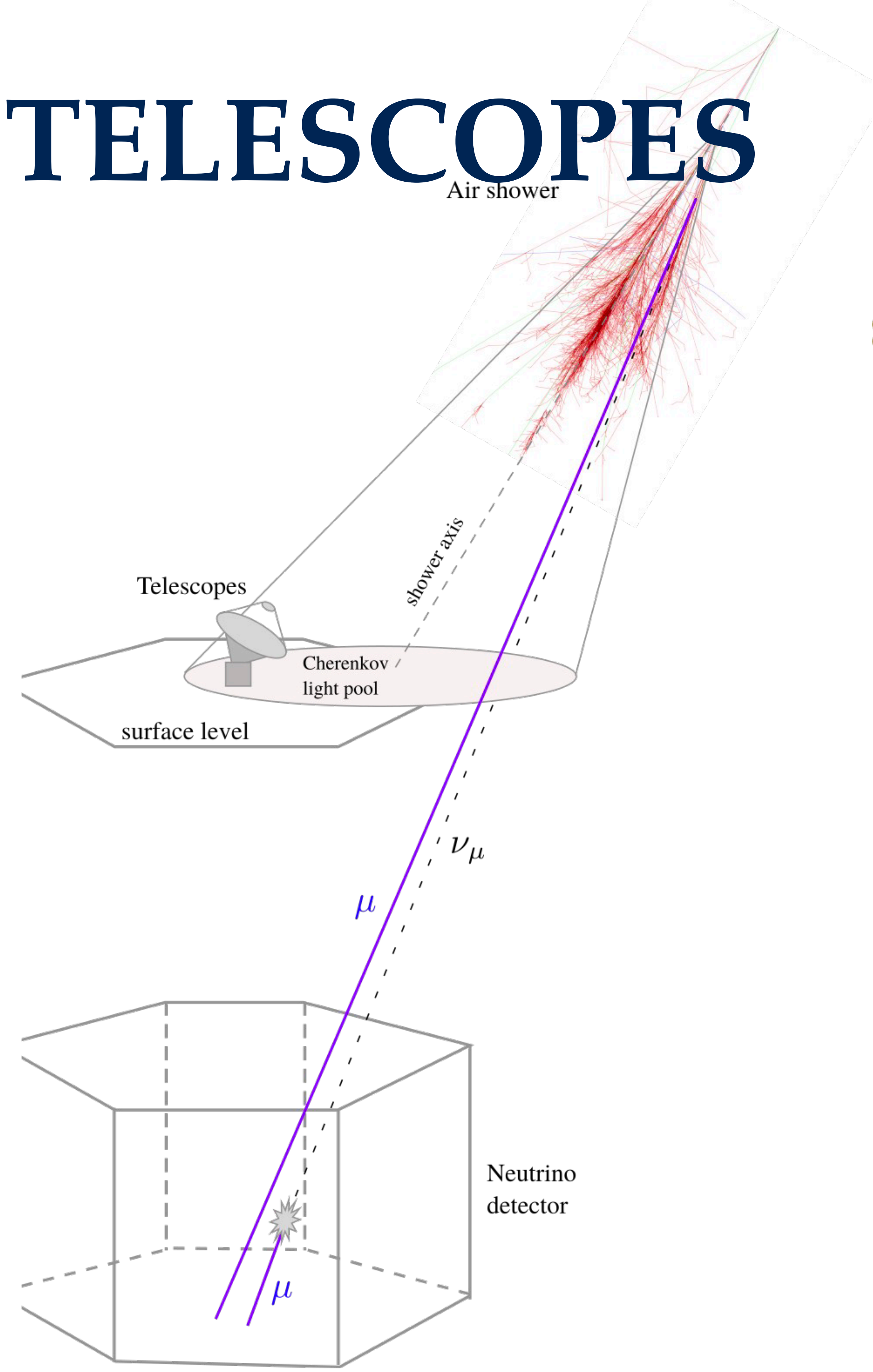
IceAct

- measure the el.-mag. shower component inside the atmosphere
- combine with particle footprint on ground level and in-ice muon reconstruction:
    - calibration of geometry and energy
    - hybrid composition studies
    - possible veto capability

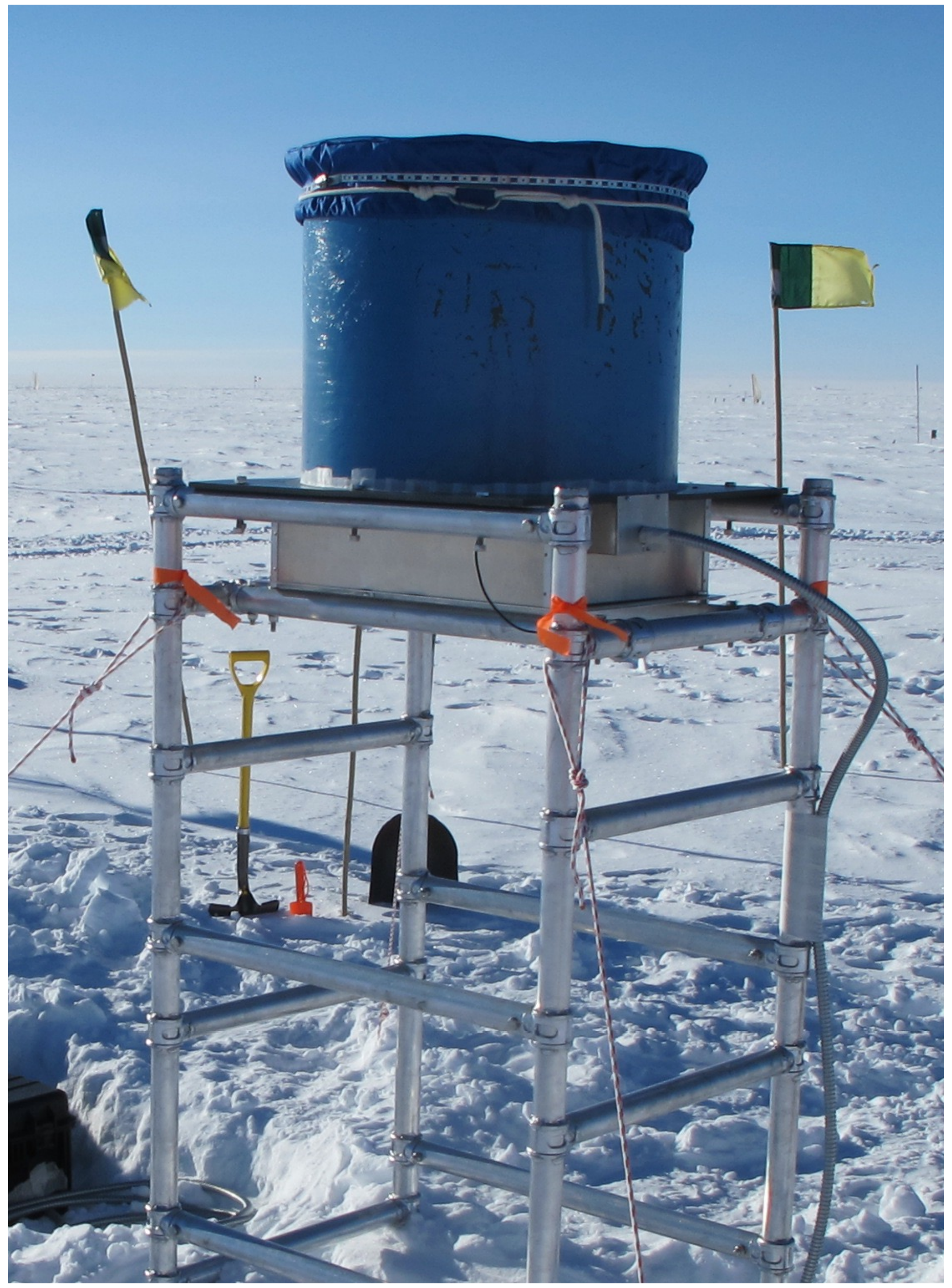
- Since 2019 two R&D telescopes are deployed at South Pole and taking data

The telescopes can only operate during the Antarctic night (roughly 4.5 month non-stop) and good atmospheric conditions

- Duty cycle ~ 20%

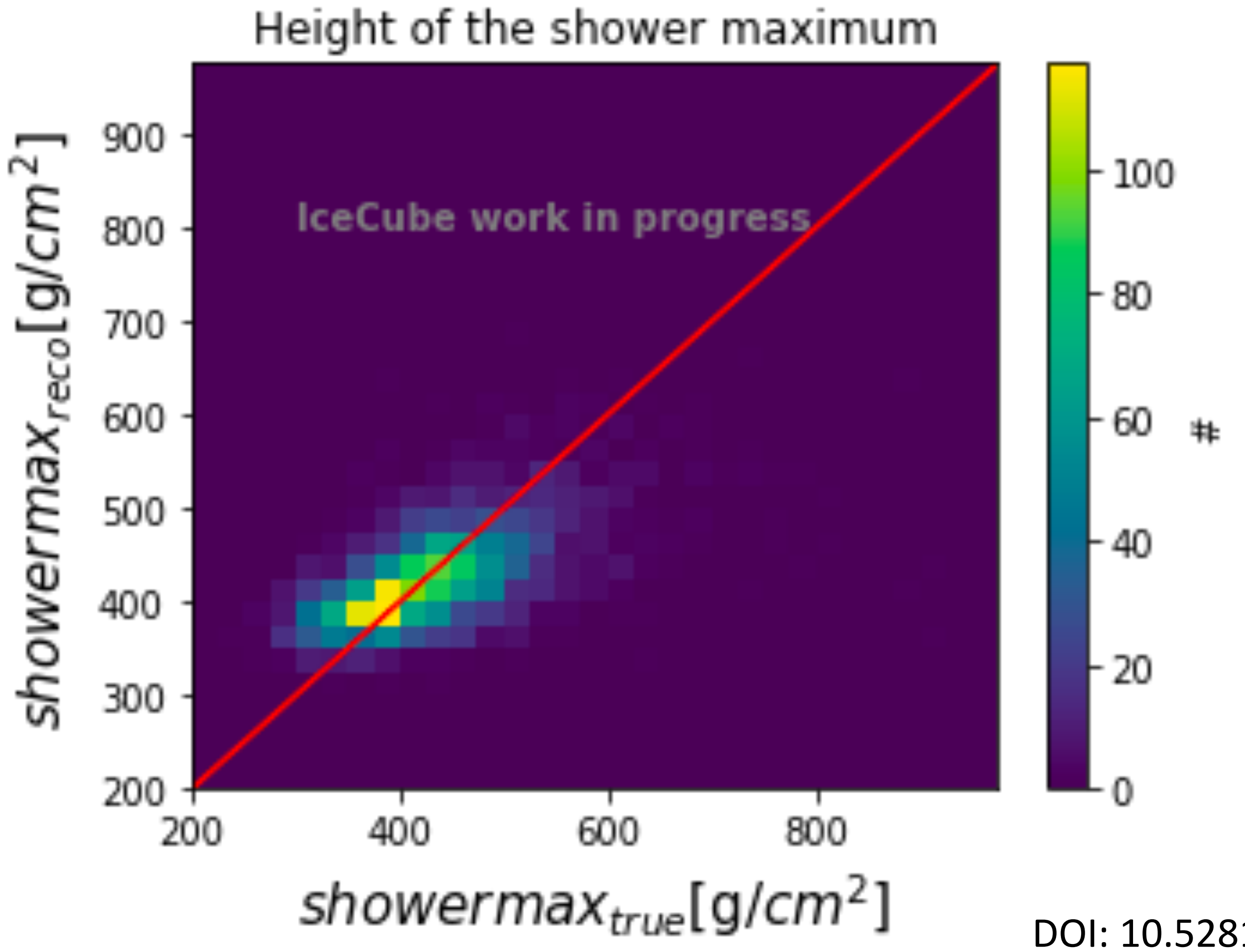


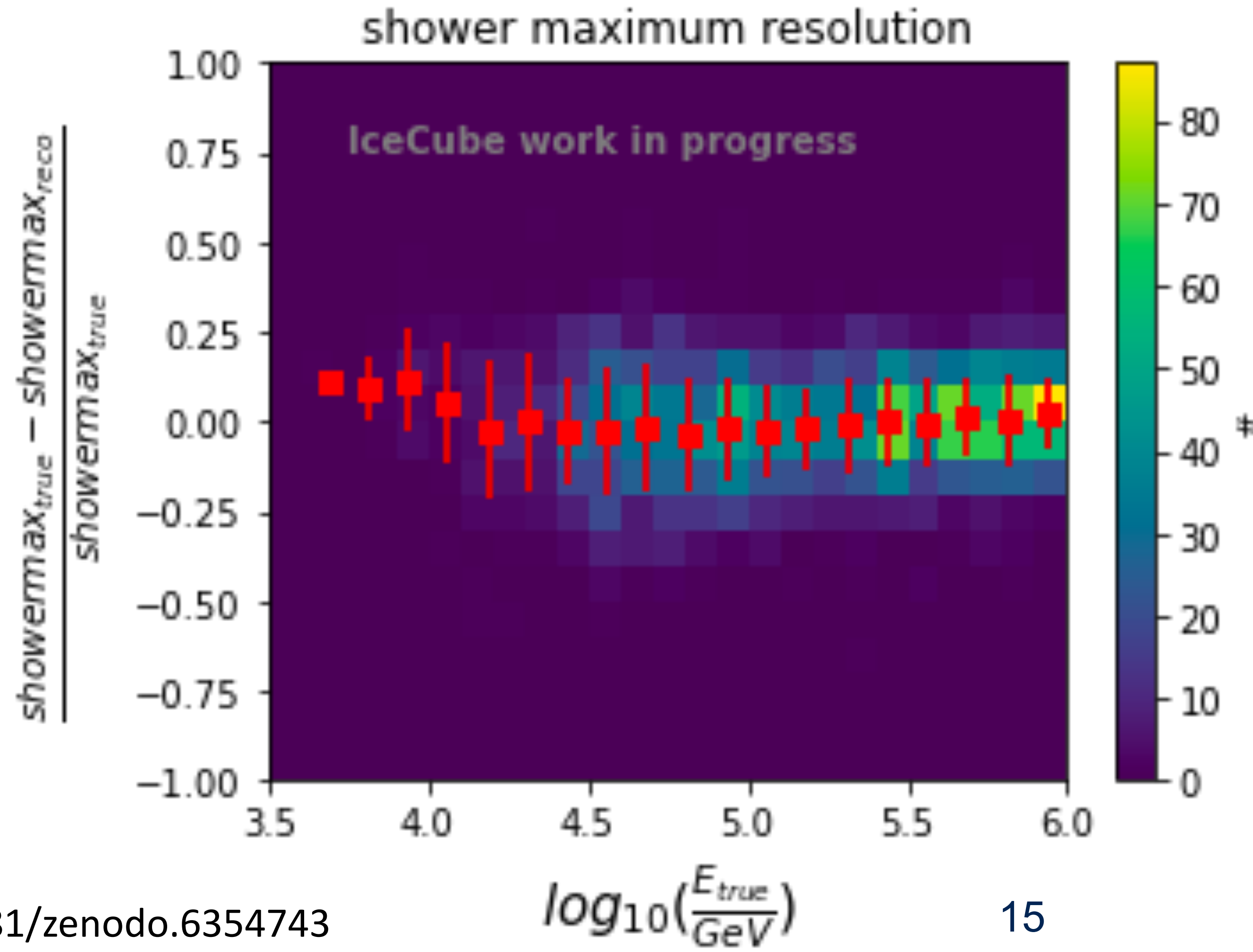
IMAGING AIR CHERENKOV TELESCOPES ICEACT



- First approach of single telescope Graph Neural Networks reconstruction
- Simultaneously determines:
  - Air shower geometry
  - Energy
  - X_{max}

for vertical low energy air shower





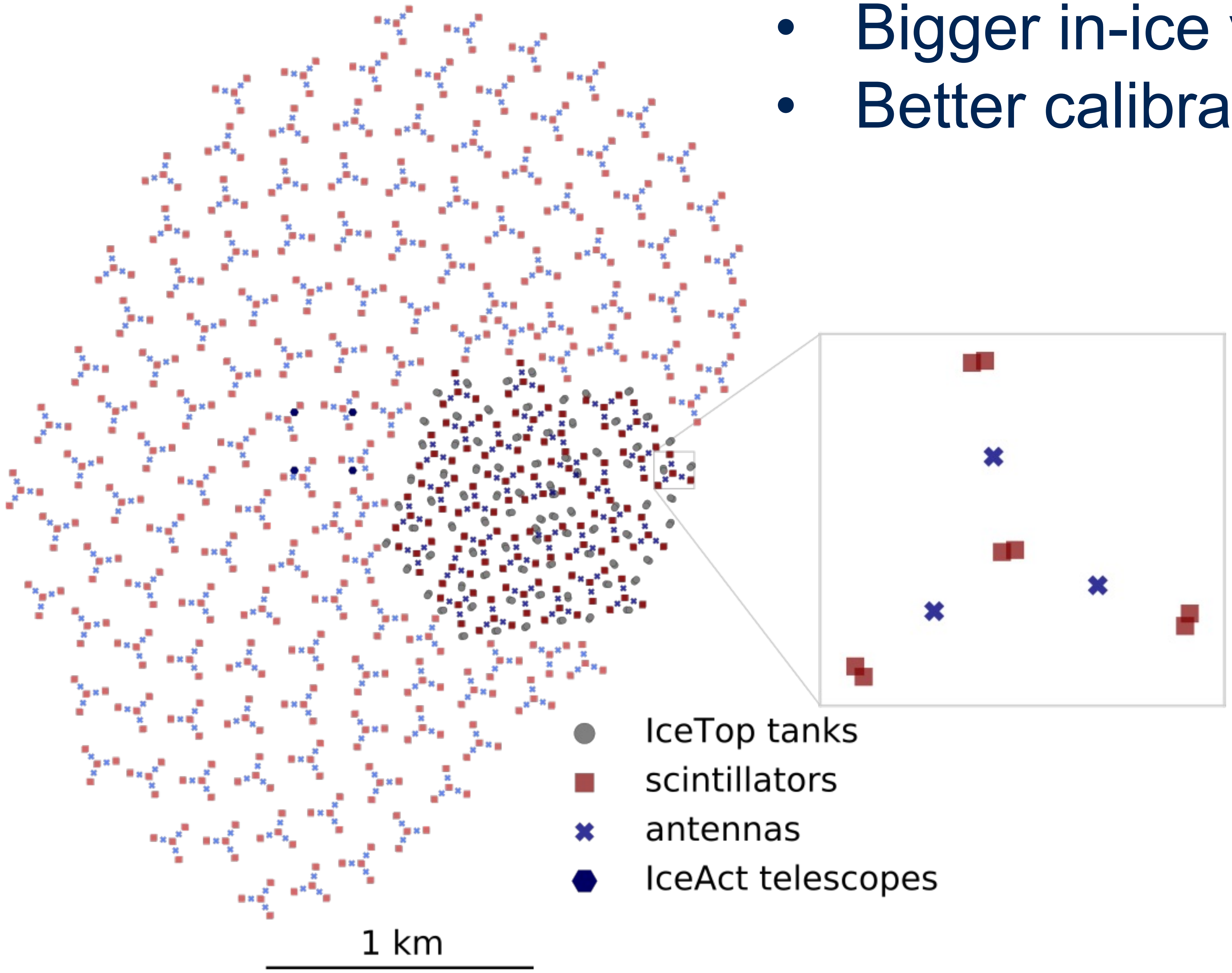
- 50 cm Fresnel lens
- 50 cm focal length
- 61 hexagonal pixel

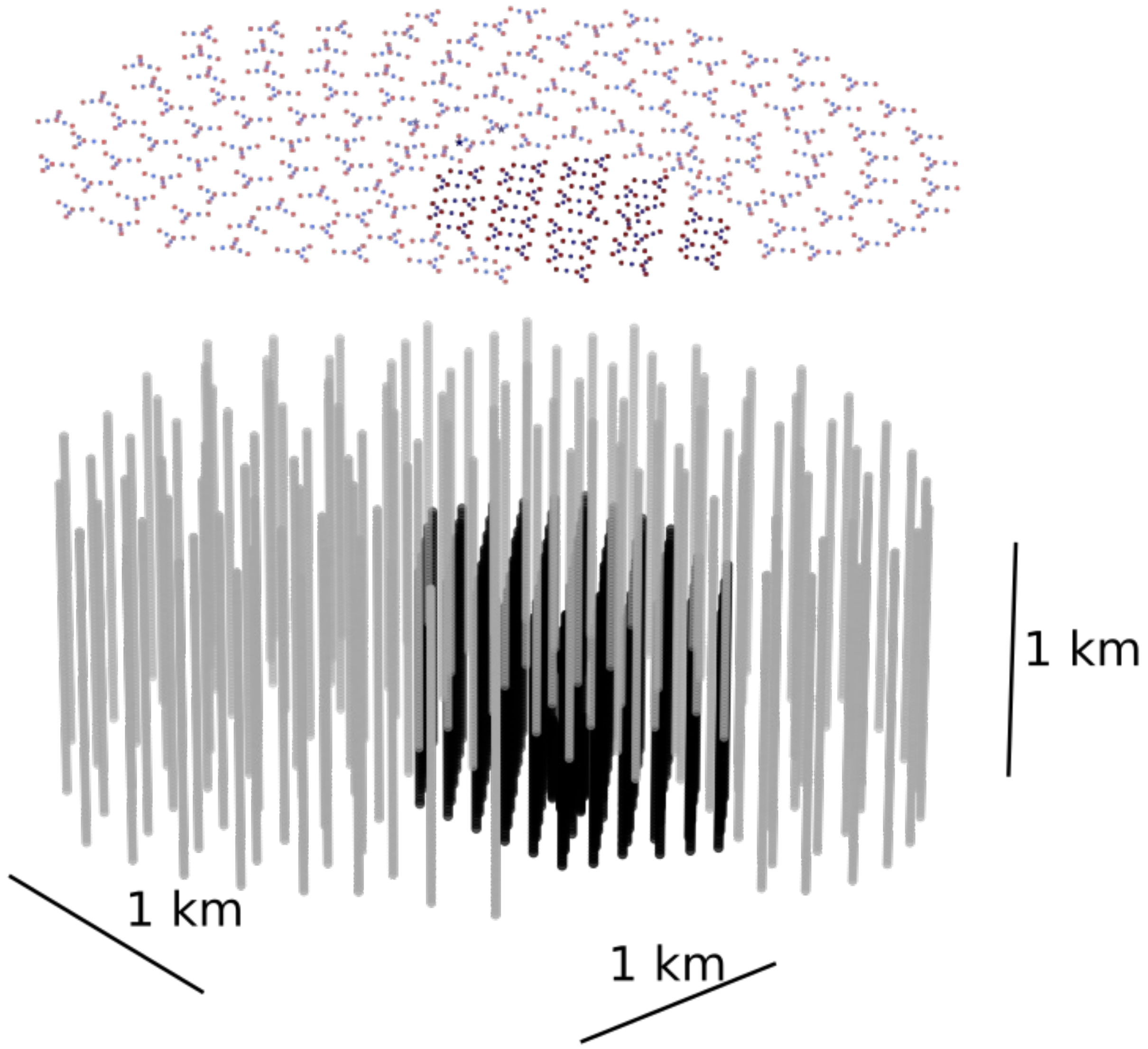
DOI: 10.5281/zenodo.6354743

FUTURE DETECTOR

IceCube Gen2

- Larger surface area
- Bigger in-ice volume
- Better calibration





SUMMARY & OUTLOOK

- IceCube Neutrino observatory is a unique cosmic ray detector
  - Mass composition is measured from PeV to EeV
  - Change in mass composition as a function of energy visible
  - Measurement of high energy muon multiplicity allows to study seasonal variations and hadronic interaction models
- Future
  - Surface enhancement with scintillation detectors, radio antennas and imaging air-Cherenkov telescopes will enable a better analysis in the future

BACKUP

https://arxiv.org/abs/1906.04317

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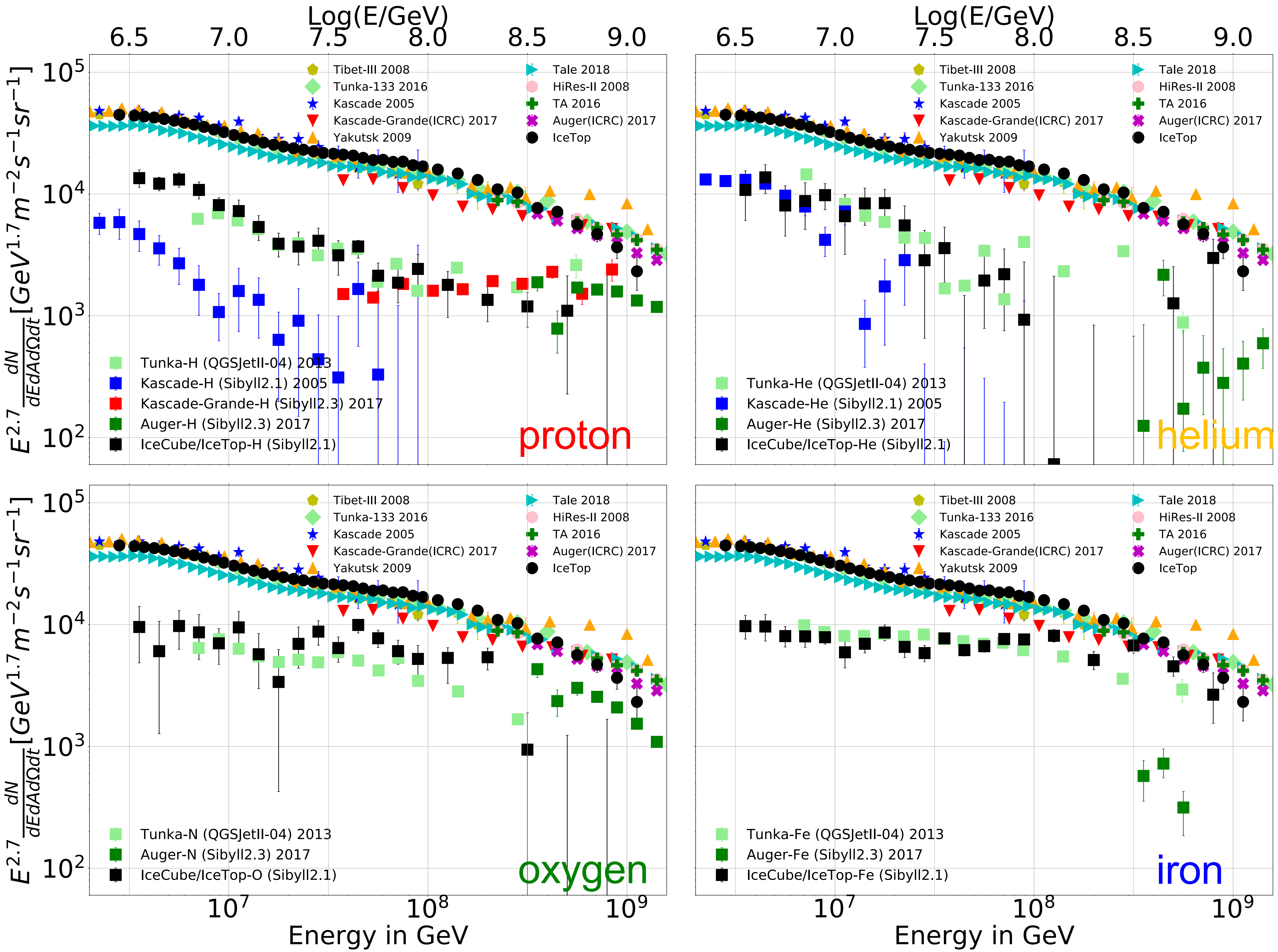
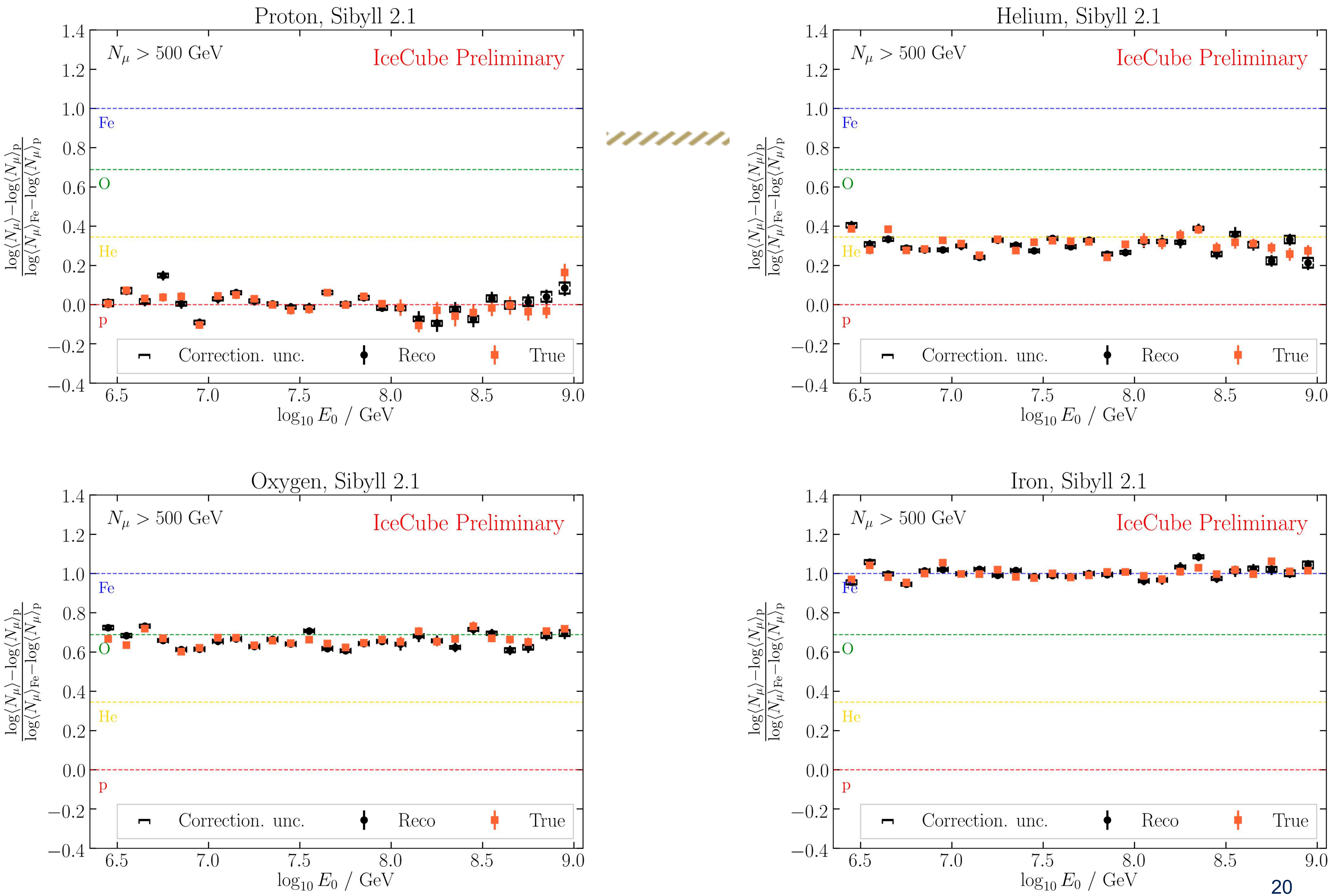
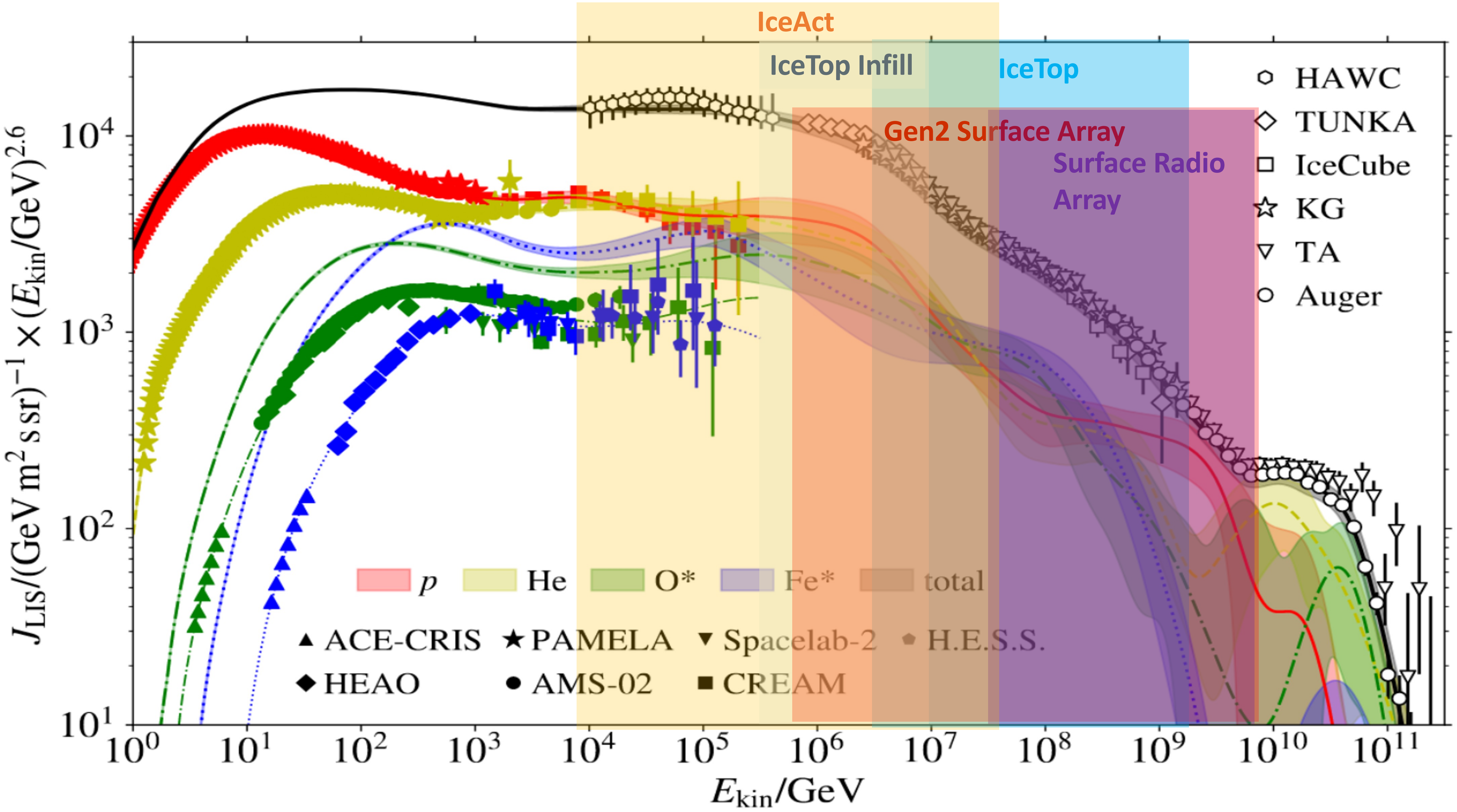
ENERGYSPECTRUM




Proton, Sibyll 2.1
Helium, Sibyll 2.1
Oxygen, Sibyll 2.1
Iron, Sibyll 2.1
$N_\mu > 500$ GeV
IceCube Preliminary
Fe
O
He
p
Correction. unc.
Reco
True
$\frac{\log\langle N_\mu\rangle - \log\langle N_\mu\rangle_p}{\log\langle N_\mu\rangle_{Fe} - \log\langle N_\mu\rangle_p}$
$\log_{10} E_0$ / GeV

ENERGY RANGE



https://arxiv.org/pdf/1902.08124.pdf

SCINTILLATOR ONLY MASSCOMPOSITION

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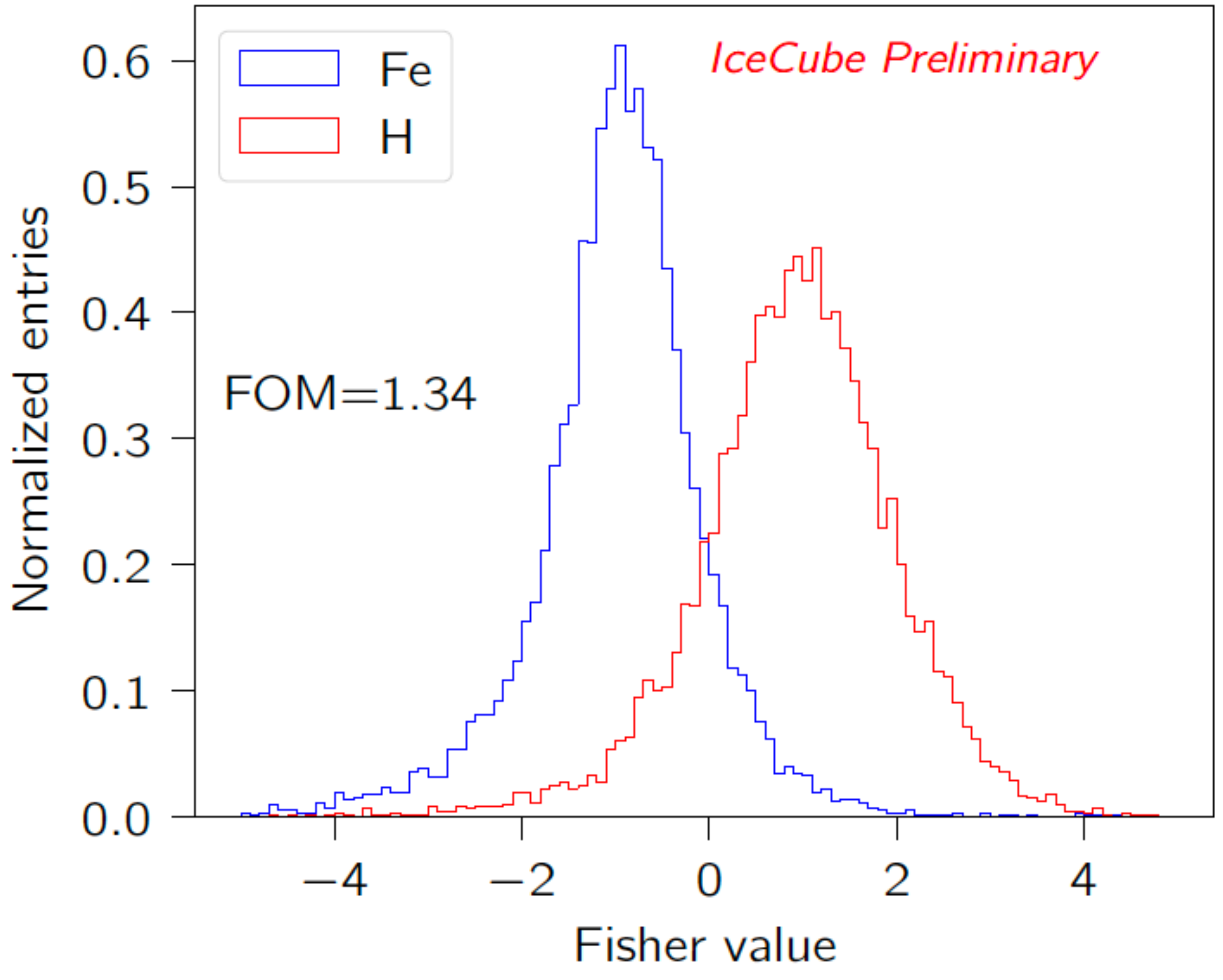
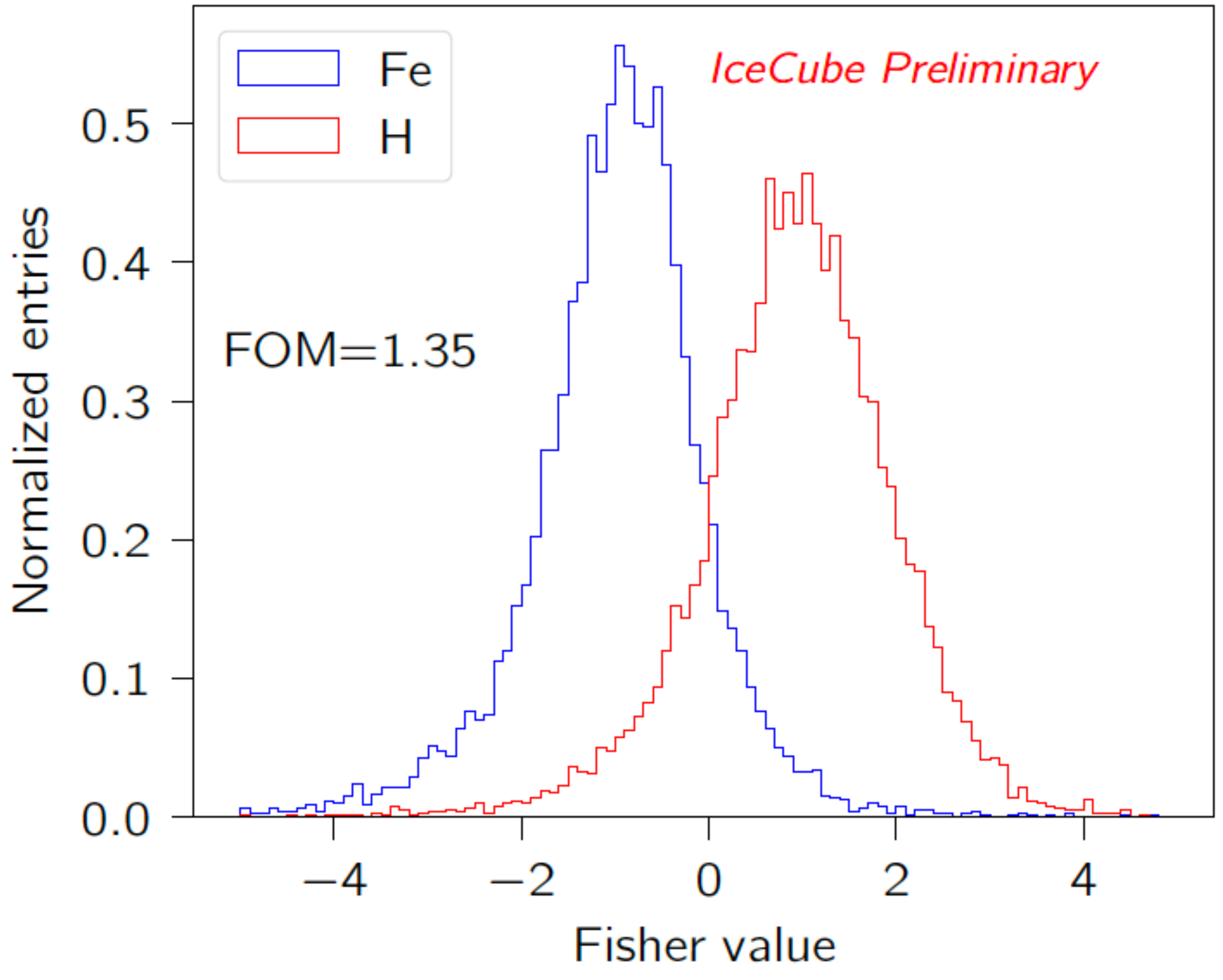


(a) Zenith angular range: 0–27°



(b) Zenith angular range: 27–40°

DOI: 10.5281/zenodo.6354743

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ICEACT MASSCOMPOSITION

- Use Graph Neural Networks to reconstruct
  - Geometry
  - Energy
  - X_{max}

for vertical low energy air shower