HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

NSF

CONACYT

COORDINACIÓN
DE LA INVESTIGACIÓN
CIENTÍFICA

UNIVERSIDAD MICHOACANA DE SAN NICOLAS DE HIDALGO

HAWC measurements of the energy spectra of cosmic ray protons, helium and heavy nuclei in the TeV range

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Content

1. Cosmic rays
2. The HAWC γ-ray observatory
3. Analysis procedure
4. Results
5. Conclusions

XIX Mexican School of
Particles and Fields
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1) Cosmic rays

- One of the most energetic and enigmatic form of radiation from outer space

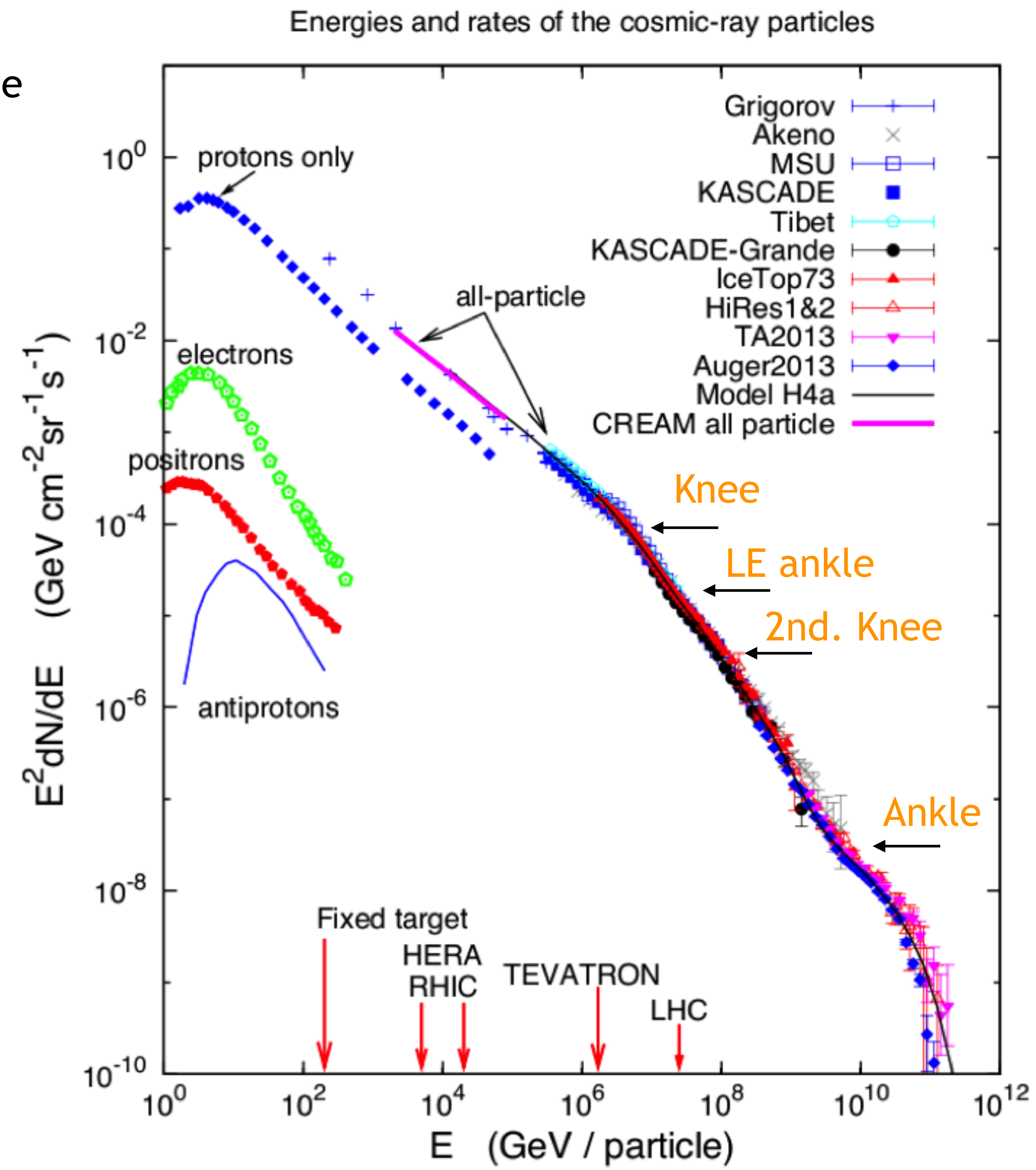
- **Composed** by atomic nuclei:
  - Atomic nuclei (99 %) :
    H (85%), He (3%), Z ≥3 (3%)
  - Electrons (1 %)
  - Traces of antiparticles

- **Energy** ranges from 100 MeV to 10^{20} eV and spectrum follows roughly a power law $F(E) = E^{-\gamma}$.

- **Origin** in cataclysmic galactic ($E < 10^{17}$ eV) and extragalactic ($E > 10^{17} - 10^{18}$ eV) events.

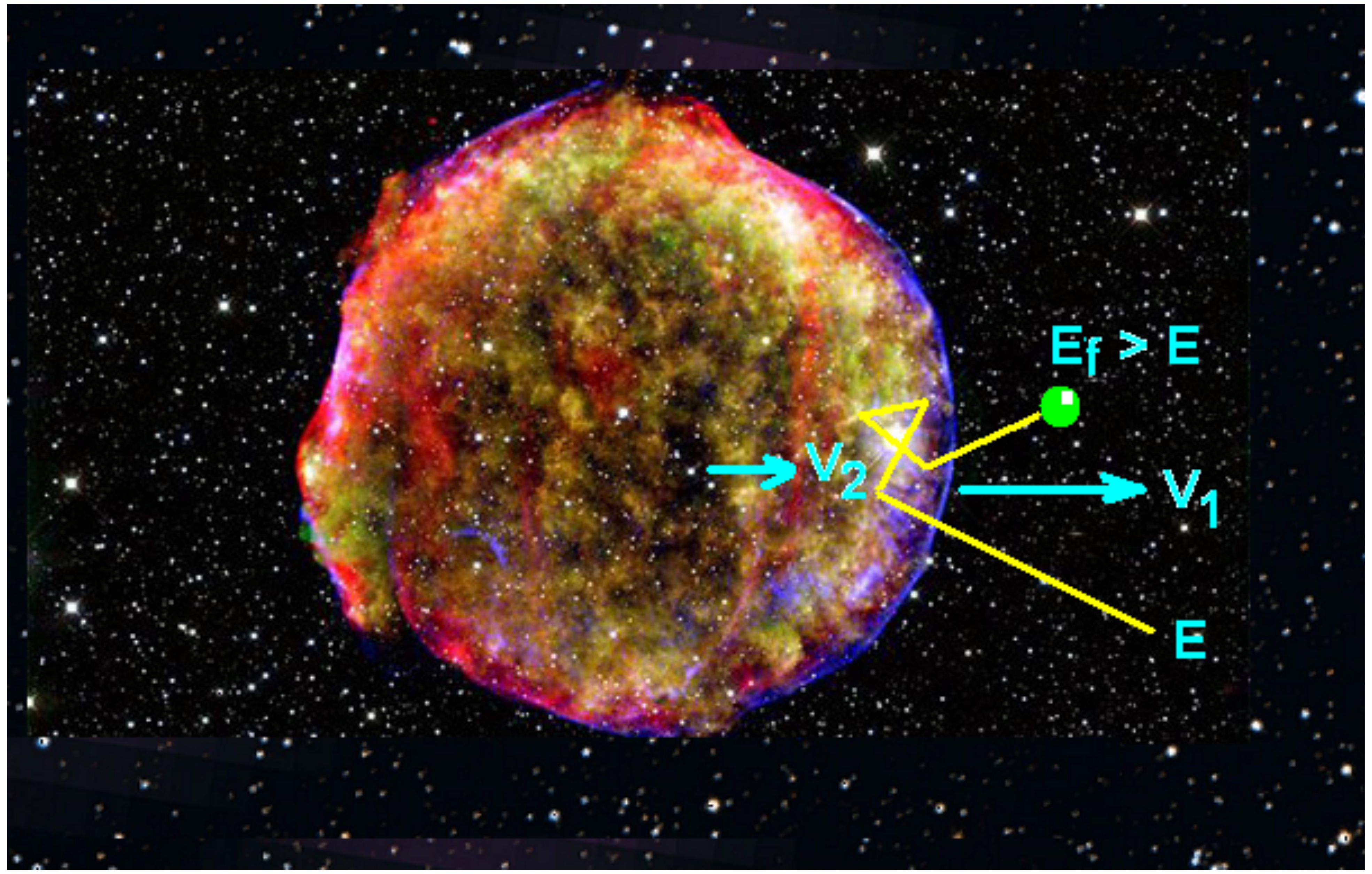
- **Unknown** questions:
  - Origin of the features of spectrum
  - Sources.
  - Propagation.
  - Acceleration mechanism.

Data:
- Spectrum.
- Composition.
- Arrival times.
- Multimessenger / multiwavelength.


Energies and rates of the cosmic-ray particles

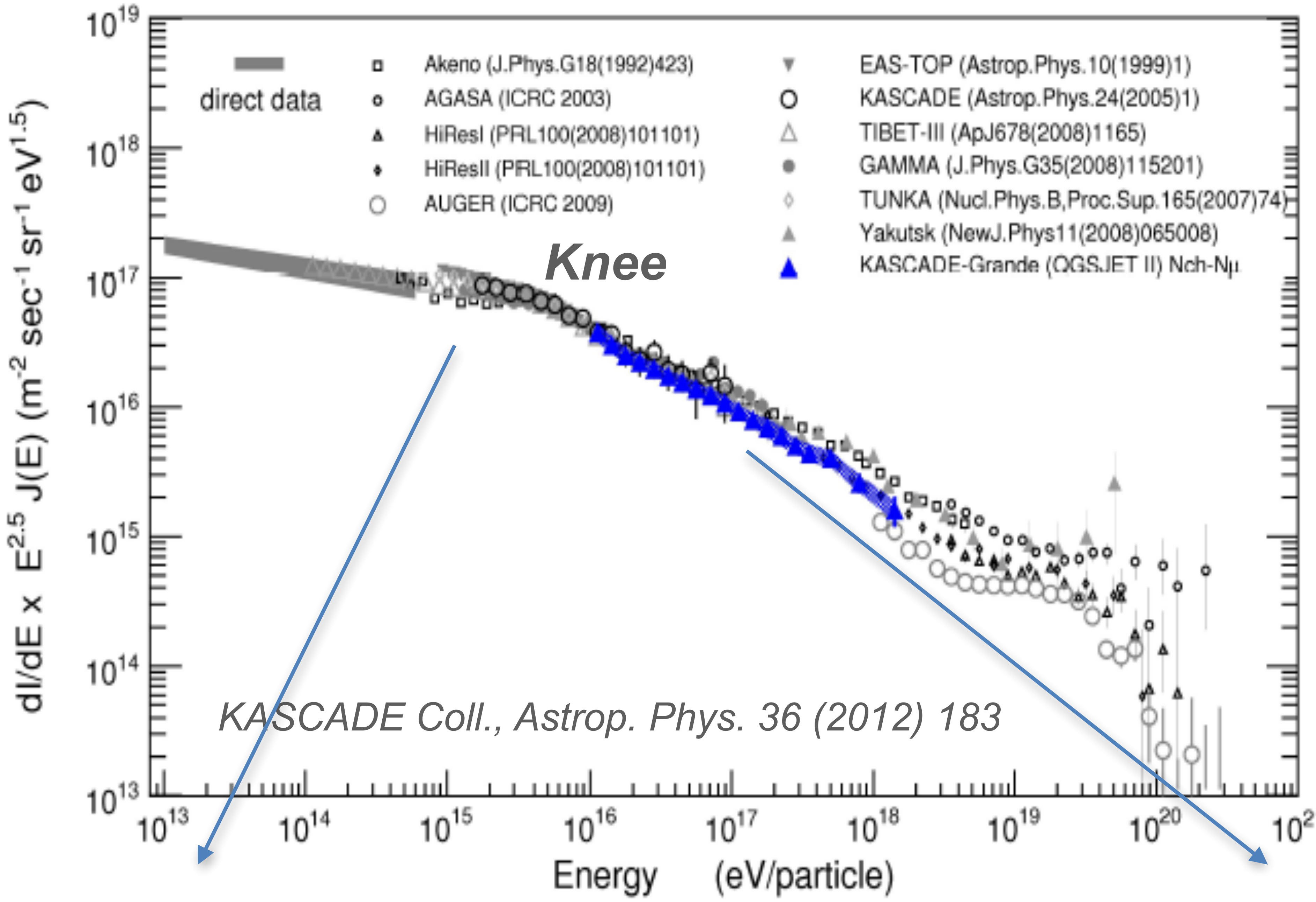
1) Cosmic rays

Galactic cosmic ray paradigm

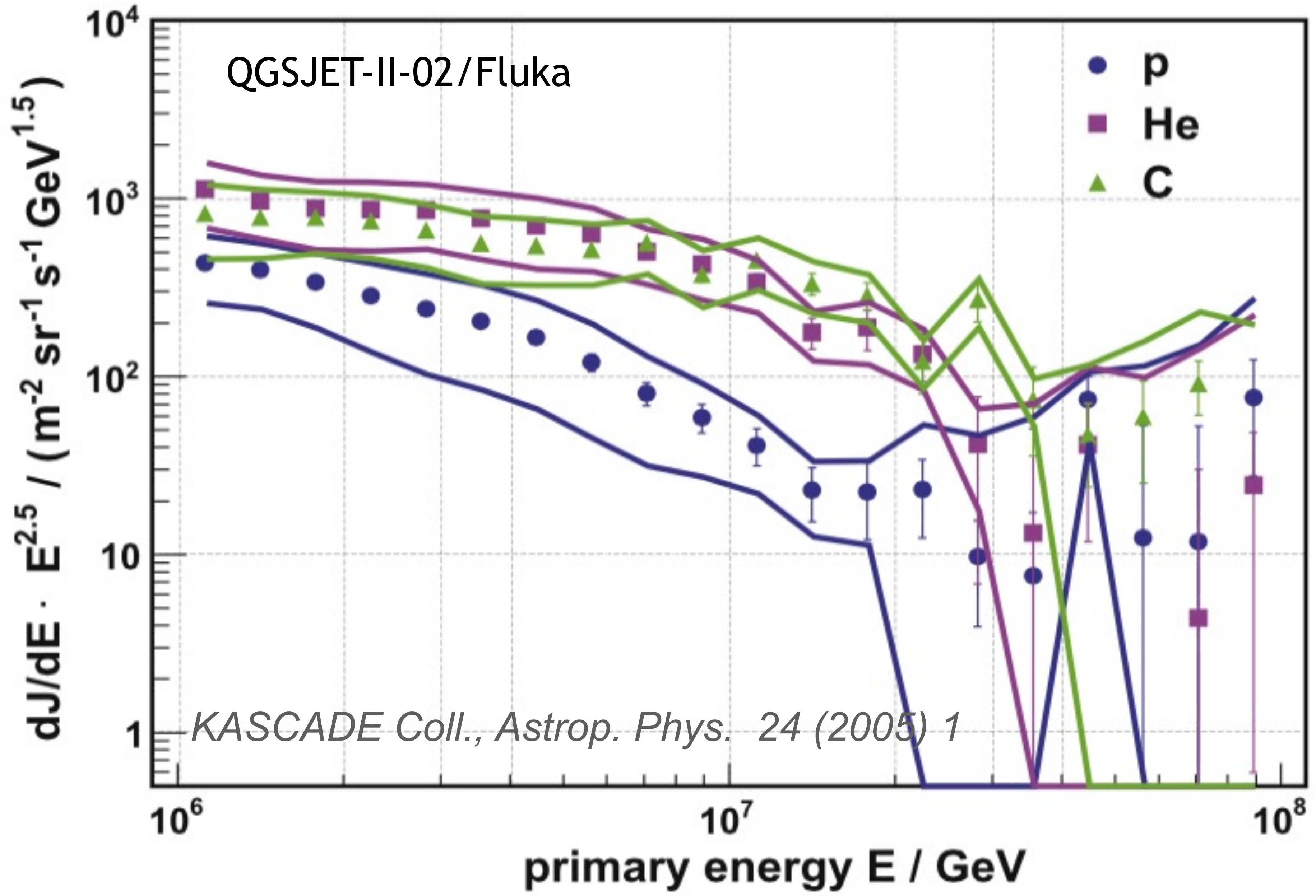


X-ray: NASA/CXC/SAO; Infrared: NASA/JPL-Caltech; Optical: MPIA, Calar Alto, O. Krause et al.

- Acceleration up to 10^{17} eV is thought to occur through Fermi's 1st order mechanism in supernova remnants.
- Spectrum has a power-law form.
- Rigidity dependent cuts at $E_Z = Z E_H$



KASCADE Coll., Astrop. Phys. 36 (2012) 183

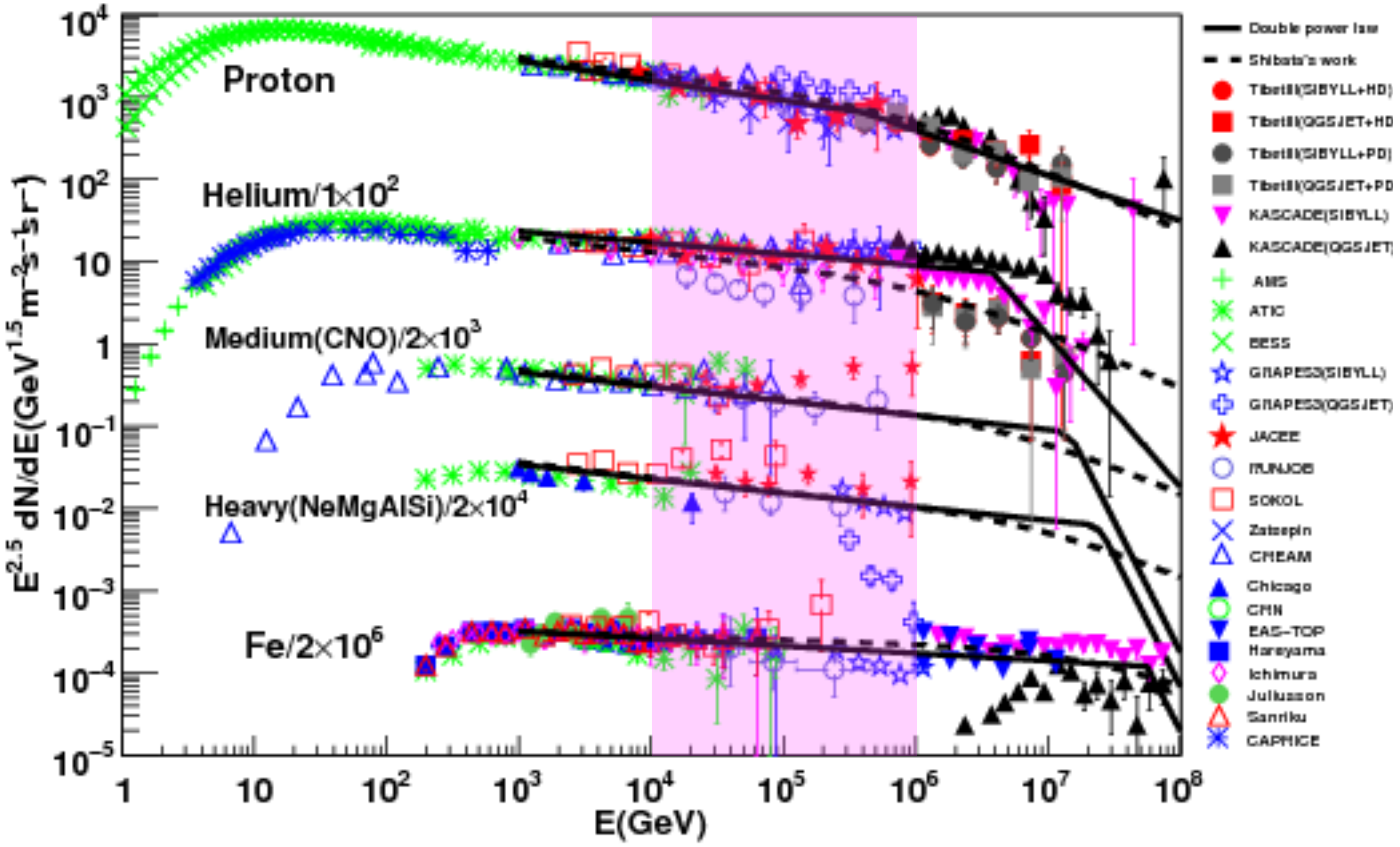


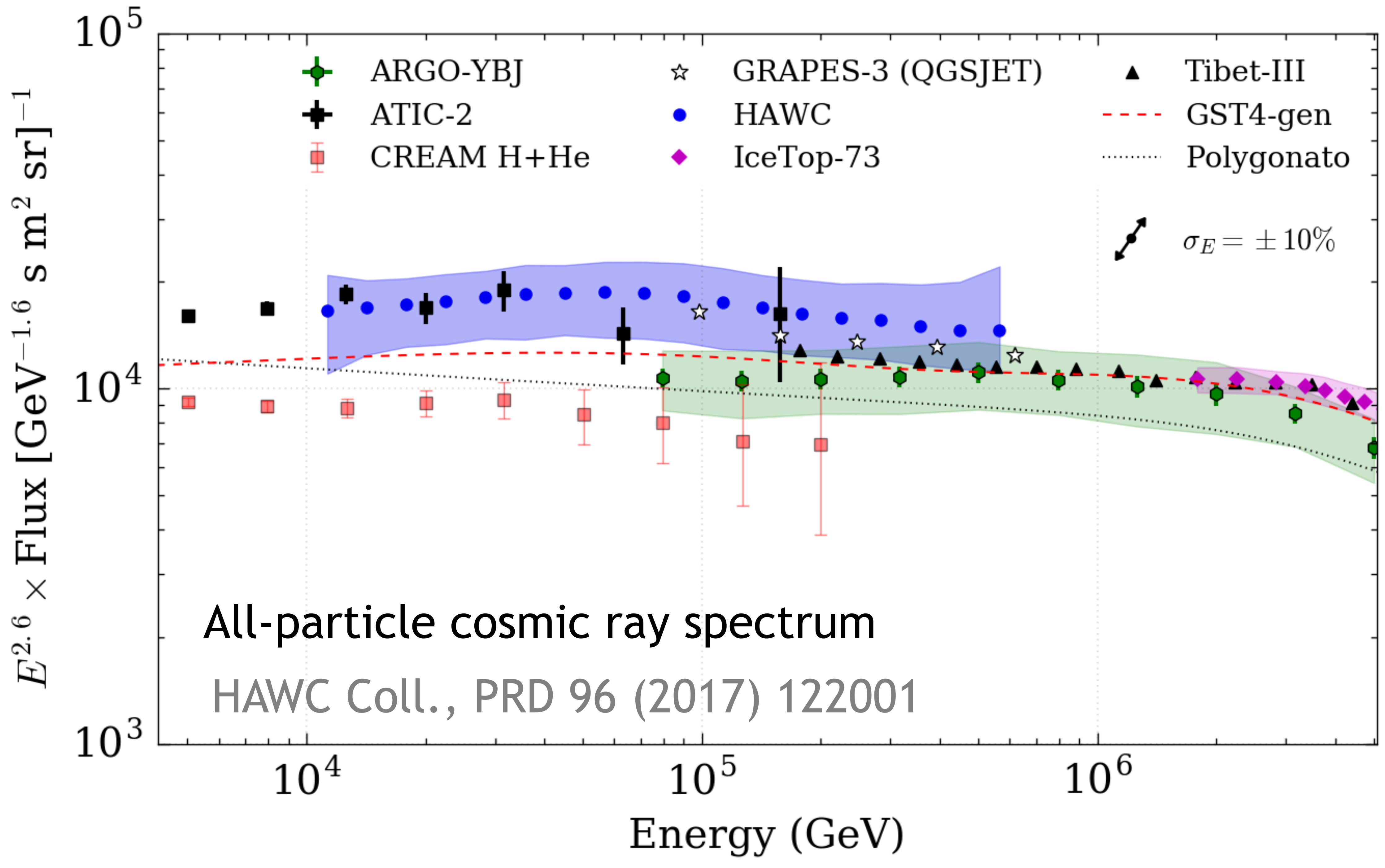
KASCADE Coll., Astrop. Phys. 24 (2005) 1

1) Cosmic rays

E = 10 TeV - 1 PeV

H. Hu, arXiv:0911.3034 **[astro-ph.HE]**





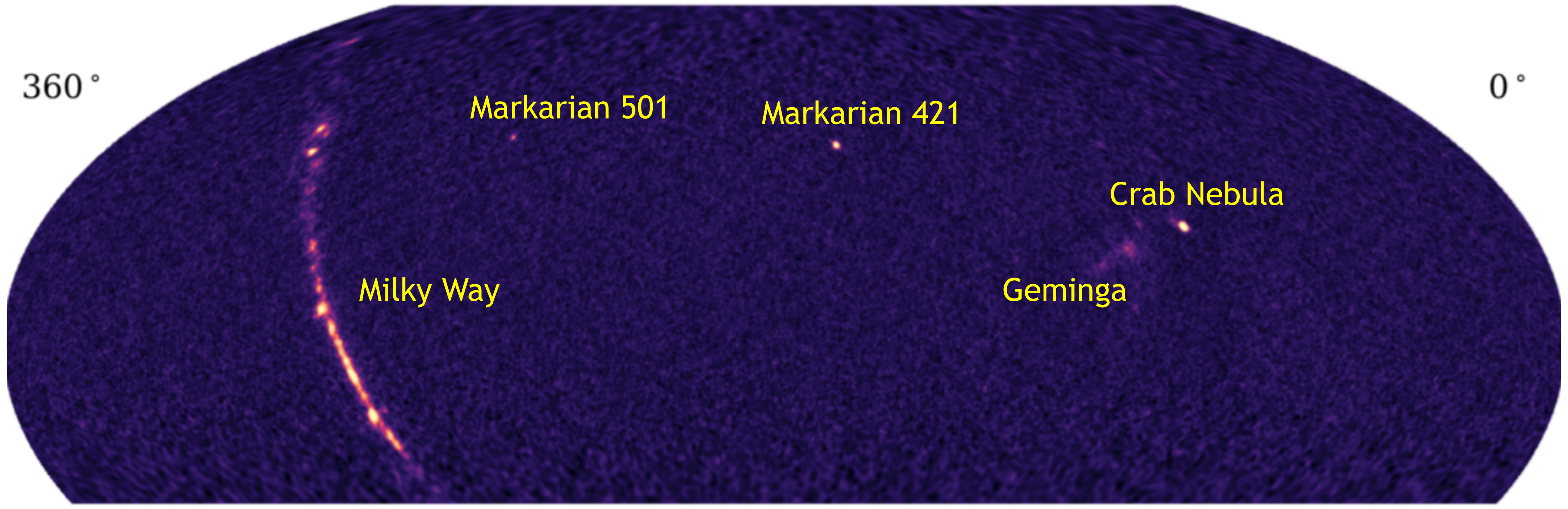
All-particle cosmic ray spectrum

HAWC Coll., PRD 96 (2017) 122001

- Region at the limit between direct/indirect detection
- Barely studied
- Detailed exploration has just started

Breaks in the total spectrum and the proton and helium spectra of cosmic rays have been found recently by direct (CREAM, NUCLEON, DAMPE, CALET) and indirect experiments (HAWC).

2) The HAWC γ-ray observatory



[HAWC Collab., APJ 905 (2020) 76]

γ- and cosmic-ray detector:

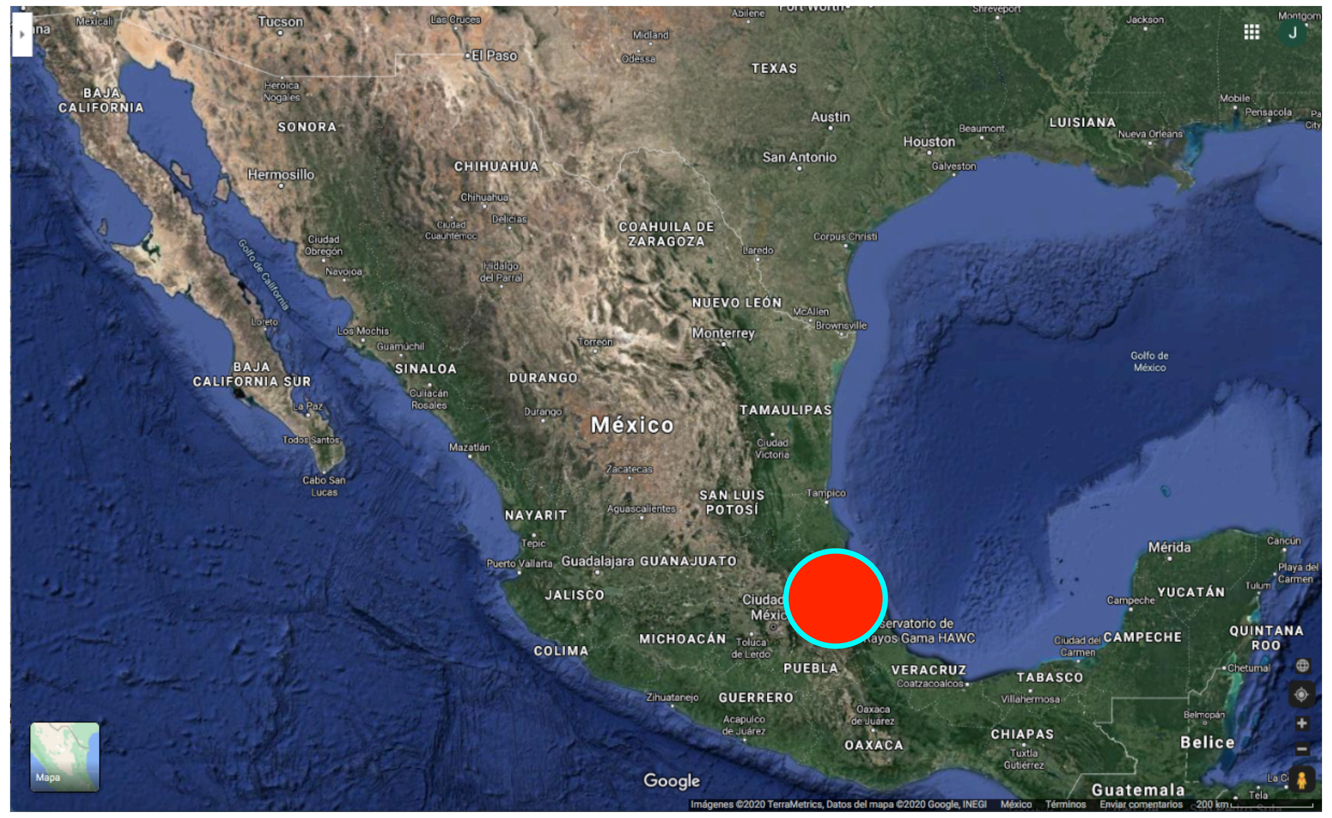
- Air-shower observatory
- Ground-based Cherenkov array
  E = 100 GeV - 100 TeV

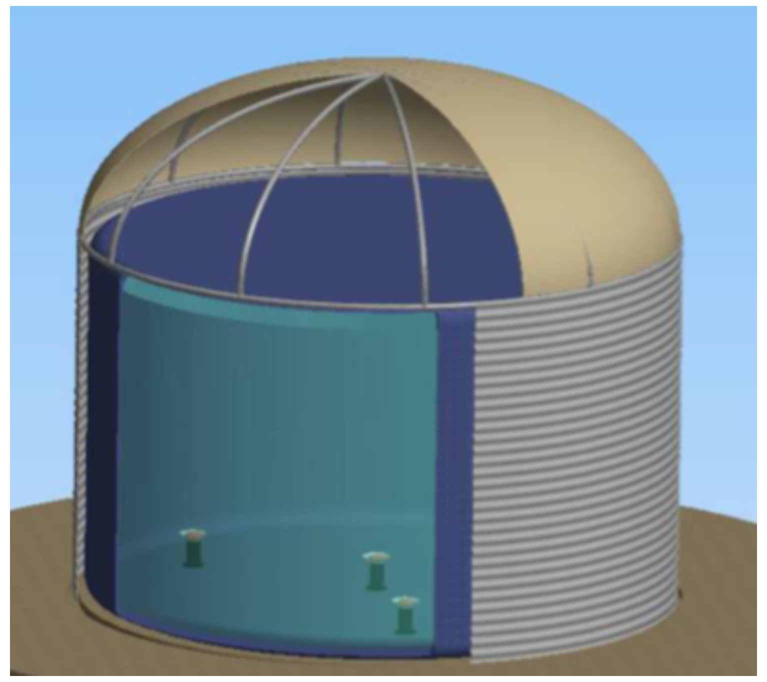
Set-up of central detector:

- 22 000 m^2 surface
- 300 densely packed water Cherenkov detectors (200,000 ℓ of water + 4 PMTs)

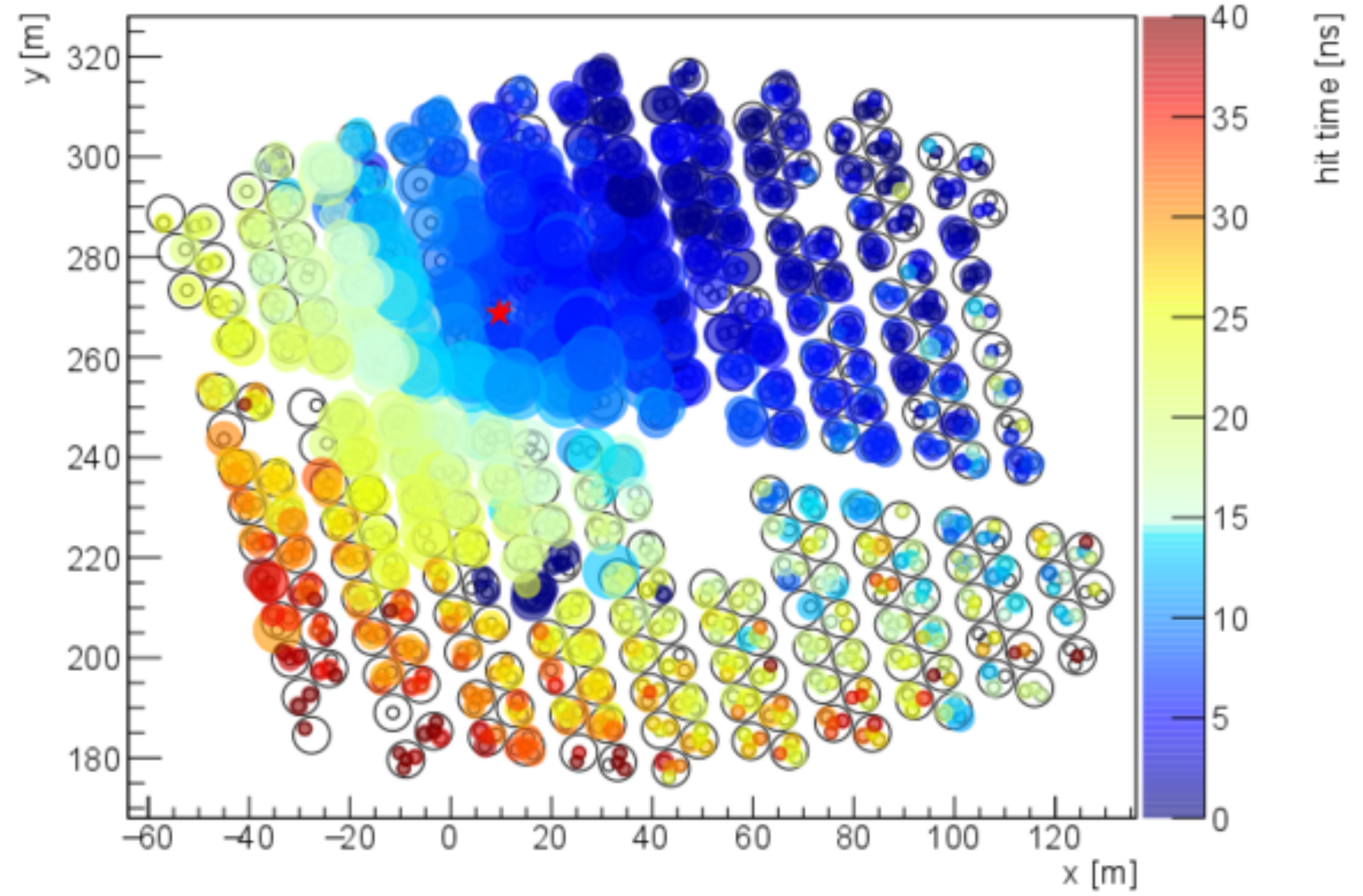
Location:

- Sierra Negra Volcano, Puebla, Mexico
- 19° N and 97° W
- 4100 m a.s.l. (640 g/cm^2)





2) The HAWC γ-ray observatory



EAS reconstruction from hit times, effective charge, number of PMT's with signal:

- Core location, (X_c, Y_c),
- Arrival direction, θ,
- Primary energy, E,
- Lateral charge profile, Qeff(r), …

Lateral age parameter (*s*):

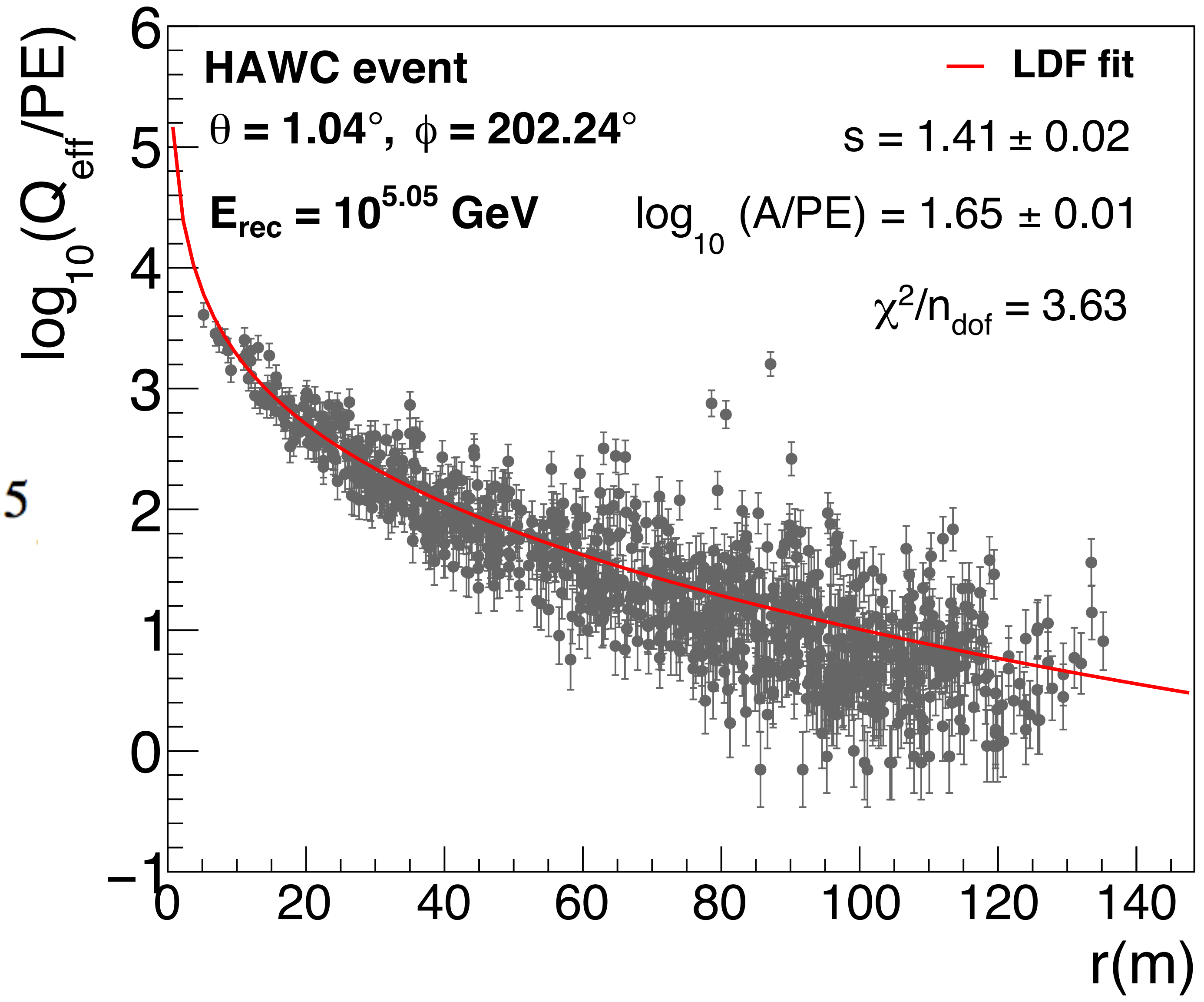
- Sensitive to composition
- Fit Qeff(r), event-by-event, with a NKG-like function:

$$f_{ch}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}$$

with r_0 = 124.21 m.

A, ***s*** are free parameters

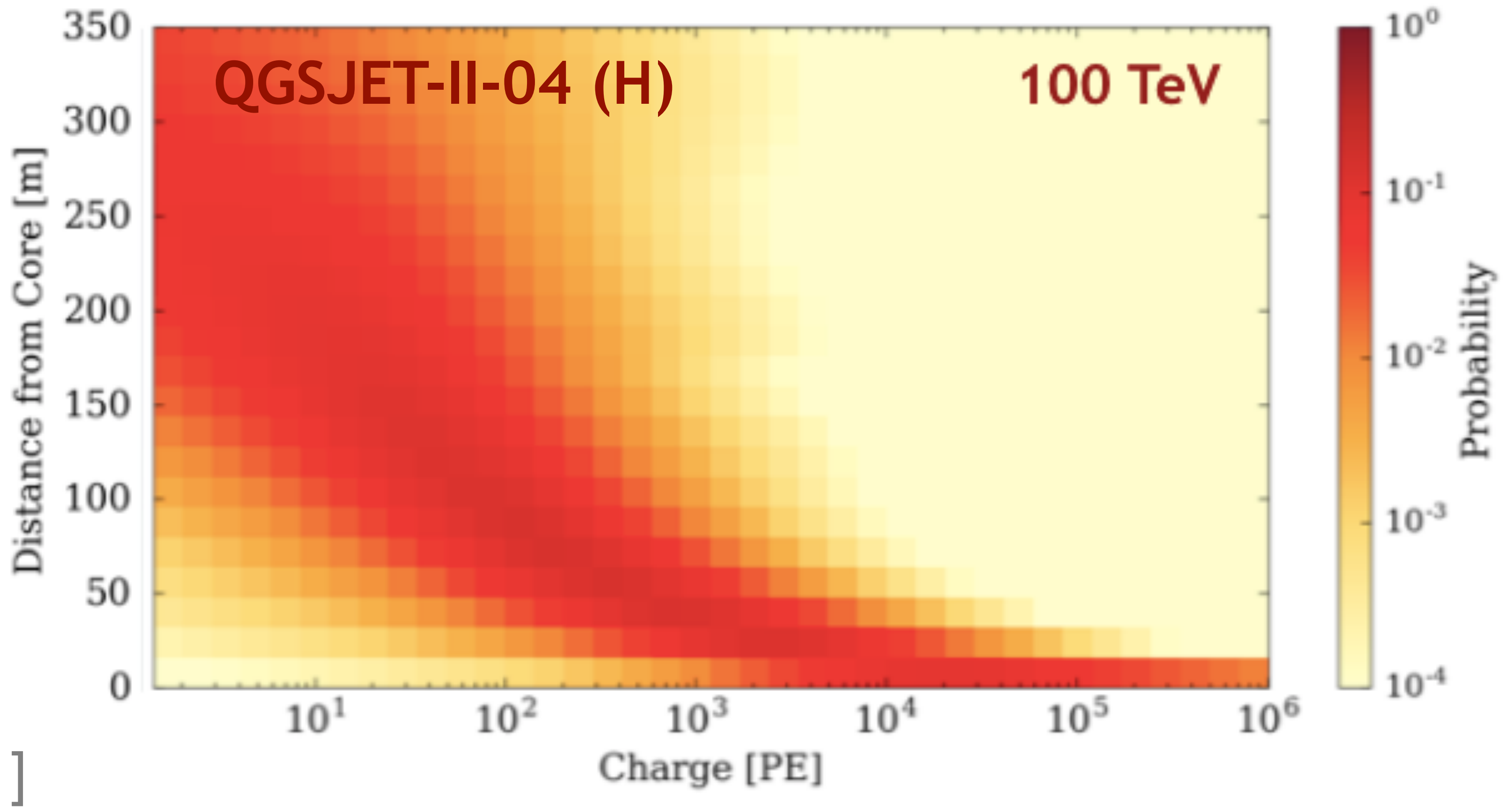
[HAWC Collab., APJ 881 (2019) 134]



Primary energy:

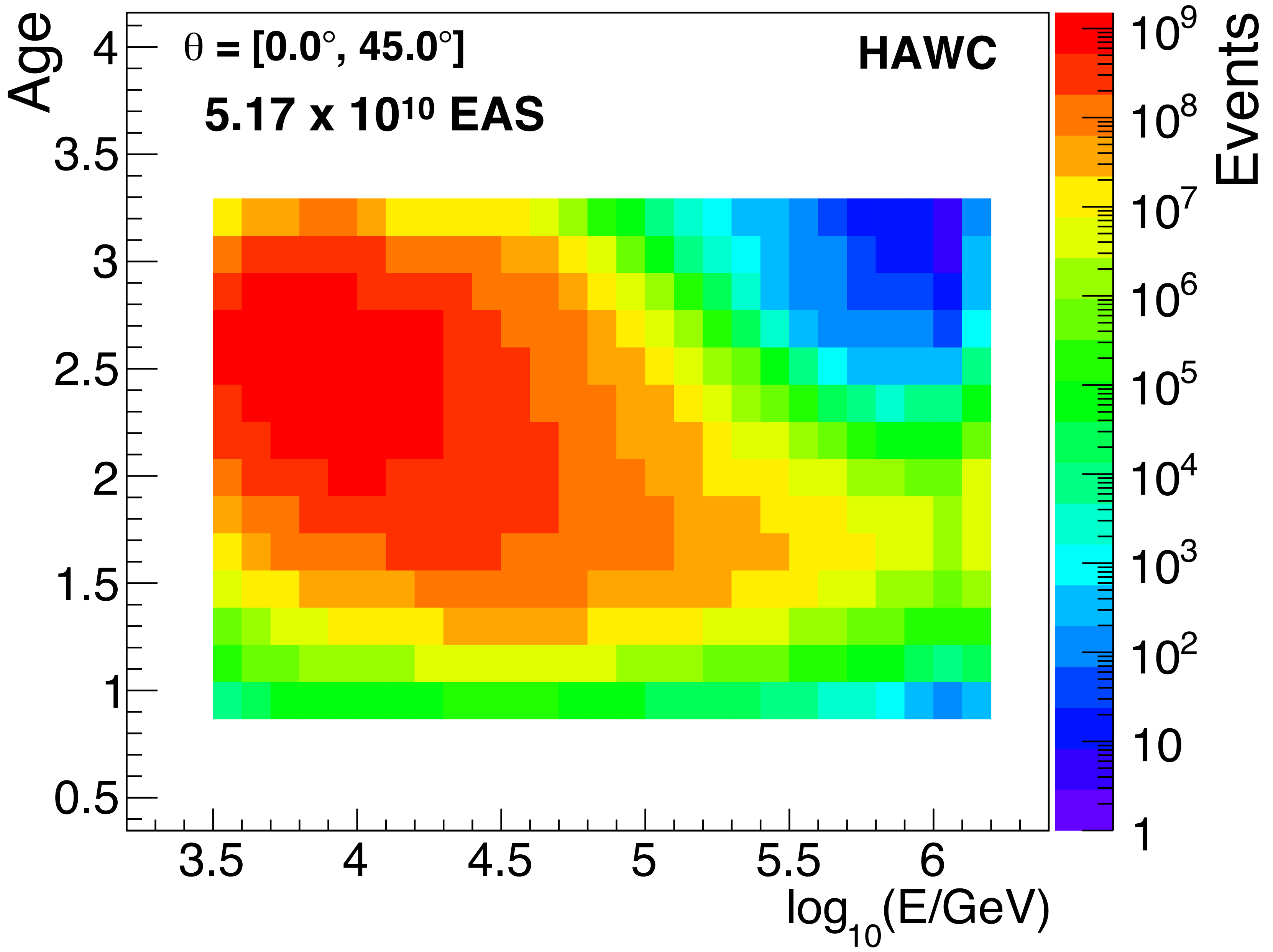
- Calibration with a maximum likelihood procedure.
- Comparison of Qeff(r) data with MC predictions for H.
- Binning in r, Qeff, θ and E.

[HAWC Collab., PRD 96 (2017) 122001]



3) Analysis procedure

- Unfold **shower age vs $\log_{10}$(E)** data to find the **elemental spectra for H, He and heavy nuclei** (Z > 2).



$$n(s, \log_{10} E) = T_{\mathrm{eff}}\,\Delta\Omega \sum_{j=1} \sum_{E_T} P_j(s, \log_{10} E \,|\, \log_{10} E_T)\, A_{\mathrm{eff},j}(E_T)\, \Phi_j(E_T)\, \Delta E_T$$

$n(s, \log_{10} E)$: # events per (s, $\log_{10} E$) bin.

$P_j(s, \log_{10} E|\, \log_{10} E_T)$: response matrix for EAS from mass group j (reconstruction and fluctuations).

A_{eff} : effective area = $A_{\mathrm{thrown}}\,\varepsilon_{\mathrm{eff}}$.

$\Phi_j(E_T)$: spectrum for mass group j.

HAWC data

- January/01/16 - June/03/19
- T_{eff} = 3.21 years
- $\Theta < 45^{\circ}$
- Successfully reconstructed
- $f_{\mathrm{hit}} \geq 0.2$

- Hit PMT's within radius of 40 m > 40
- s = [1, 3.2]
- $\log_{10}$ (E/GeV) = [3.5, 6.2]

Apply Gold's unfolding algorithm

[R.Gold, Report ANL-6984, 1964]

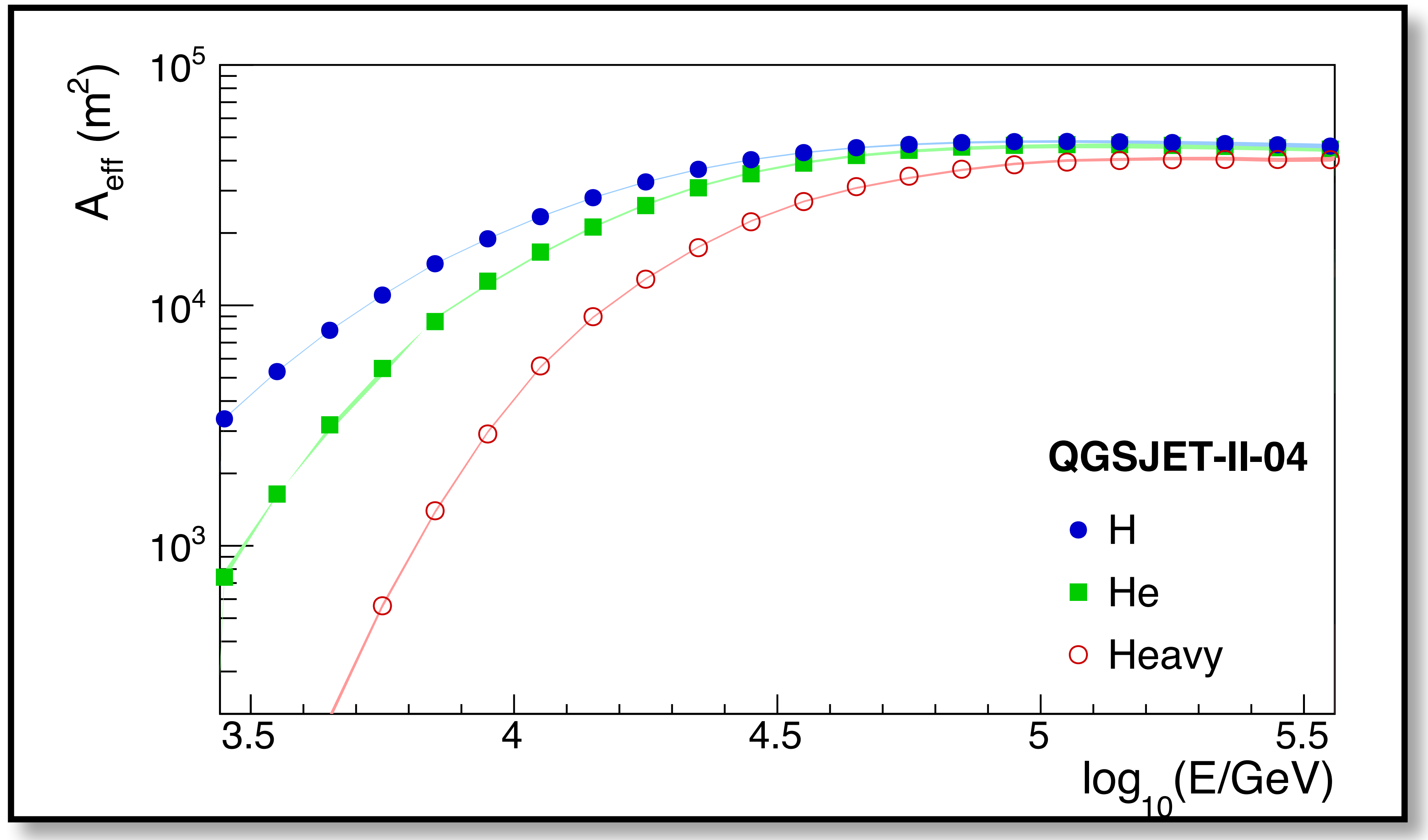
[KASCADE Collab., App 24 (2005) 1]

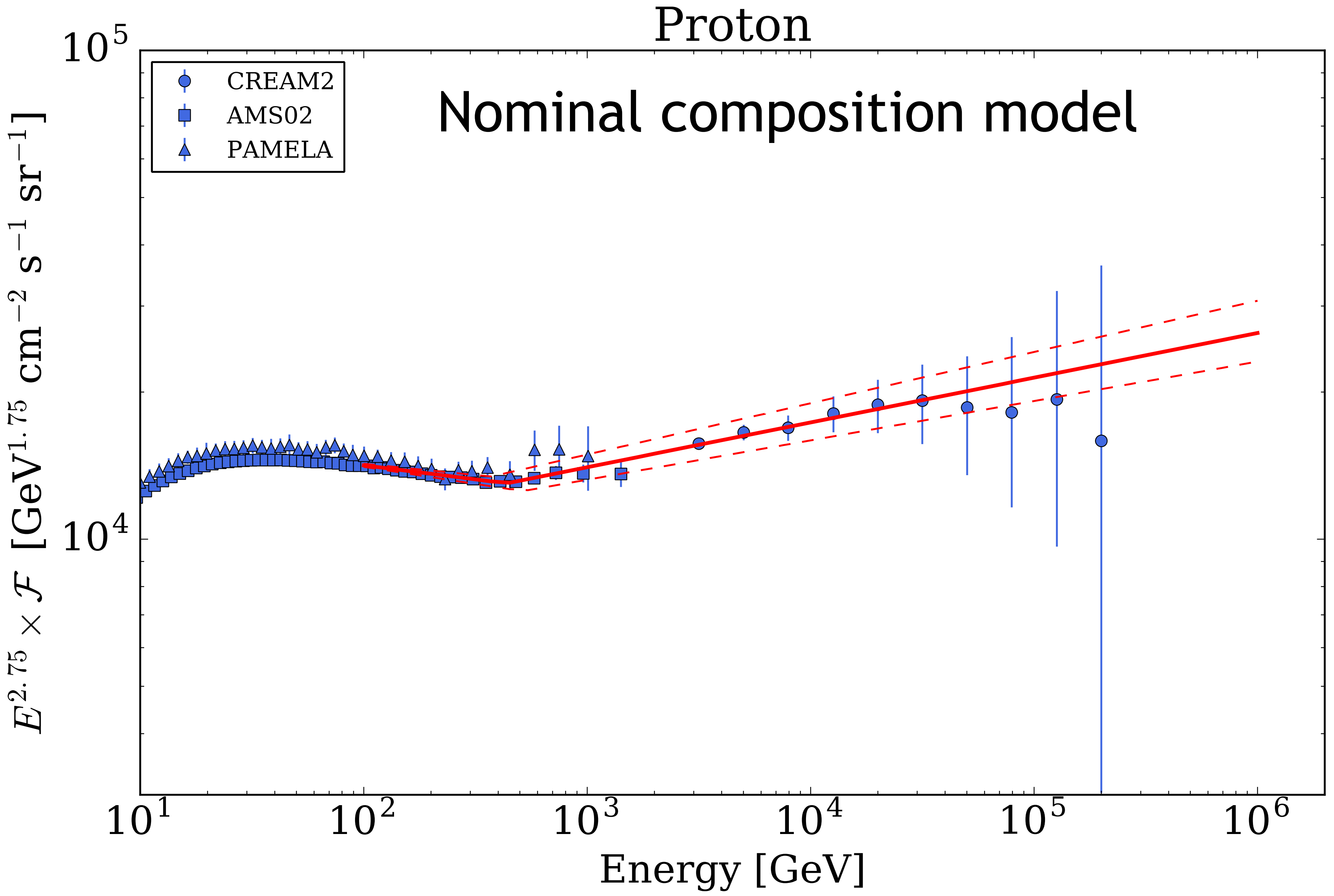
Bins:
$\Delta \log_{10}$ (E/GeV) = 0.1
$\Delta\, s = 0.17$

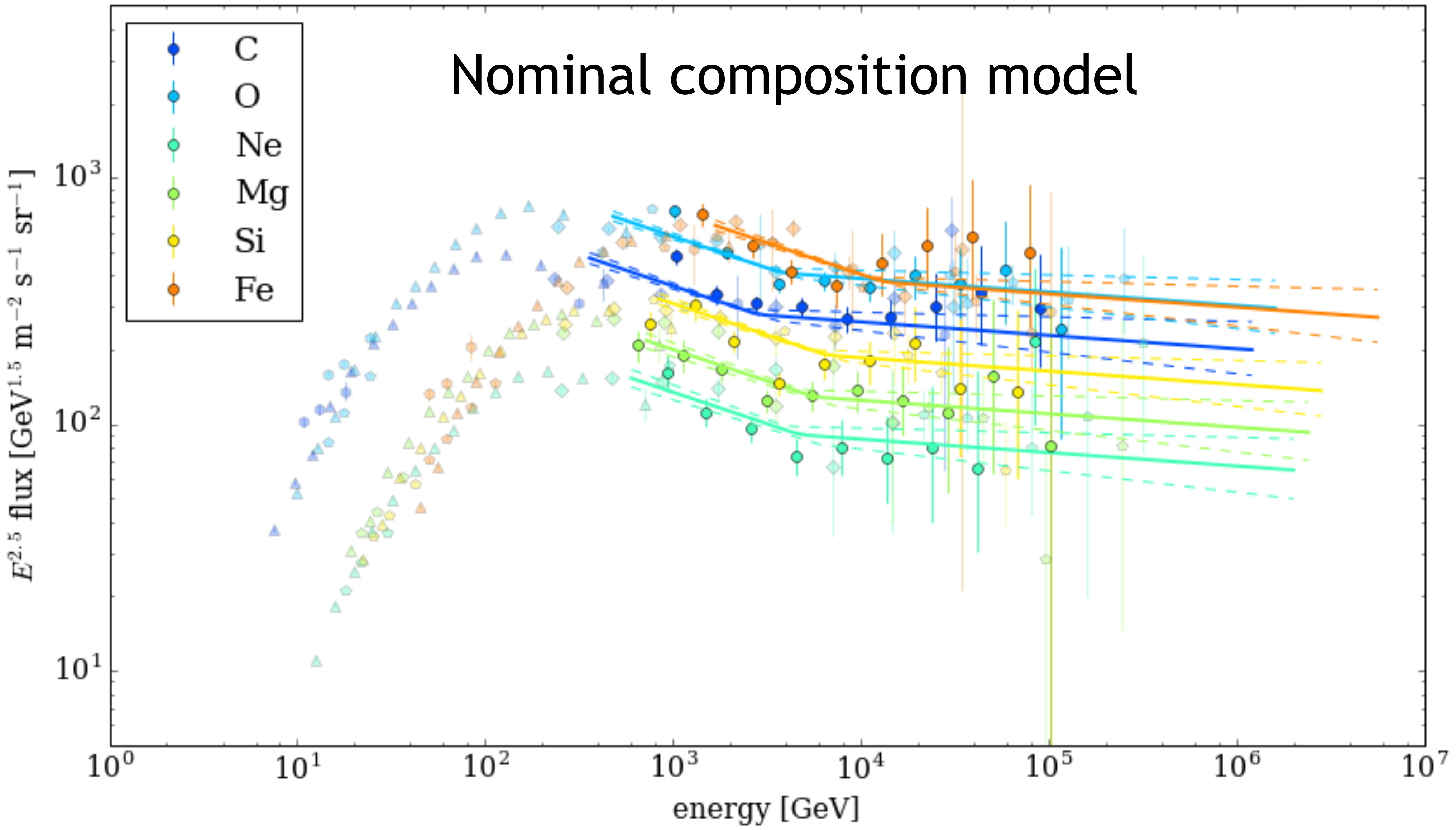
3) Analysis procedure

MC data is used to build the response matrix and effective area

- CORSIKA v7.4 (Fluka/QGSJET-II-04)
- E = 5 GeV - 2 PeV.
- θ < 70º
- Cosmic ray species: H, He, C, O, Ne, Mg, Si, Fe.
- E^{-2} spectra weighted to follow double power-laws derived from fits to **AMS-2** (2015), **CREAM-II** (2009 & 2011) and **PAMELA** (2011) data.







3) Analysis procedure

Gold's unfolding procedure

- Use **matrix formalism**:

$$N_{data} = P\, N_{unfold}$$

- **Introduce statistical errors** using new response matrix

$$P' = (C\,P)^T\,(CP),$$

and new unfolded vector

$$N'_{data} = (C\,P)^T\,C\,N_{data}$$

where

$$C_{ij} = \delta_{ij}/\sigma_i\,; \quad (\sigma_i = 1/\sqrt{n_i})$$

- N_{unfold} is found **iteratively** using the set of equations:

$$N^{k+1}_{unfold,\,i} = \frac{N^k_{unfold,\,i}\,N'_{data,\,i}}{\Sigma_j\,P'_{ij}\,N^k_{unfold,\,j}},$$

- Priors given by nominal composition model.

- **Smoothing** intermediate spectra with ROOT-CERN libraries (353HQ-twice algorithm).

- **Stopping criterium**: Minimum of Weighted Mean Square Error:

$$WMSE = \frac{1}{m}\sum_j^m \frac{\sigma^2_{stat,\,j} + \delta^2_{bias,\,j}}{N_{unfold,\,j}}$$

[R.Gold, Report ANL-6984, 1964]

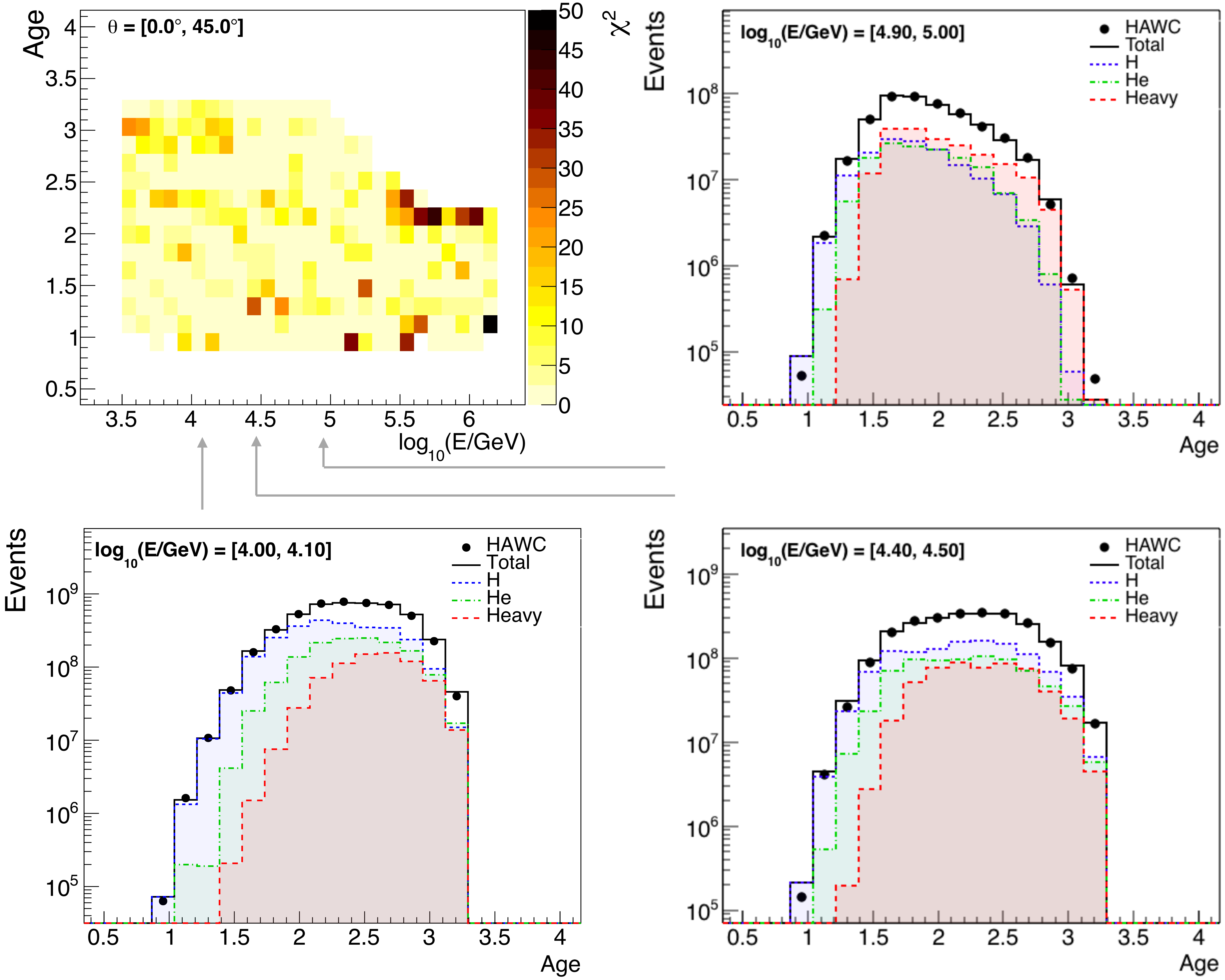
[KASCADE Collab., App 24 (2005) 1]

4) Results

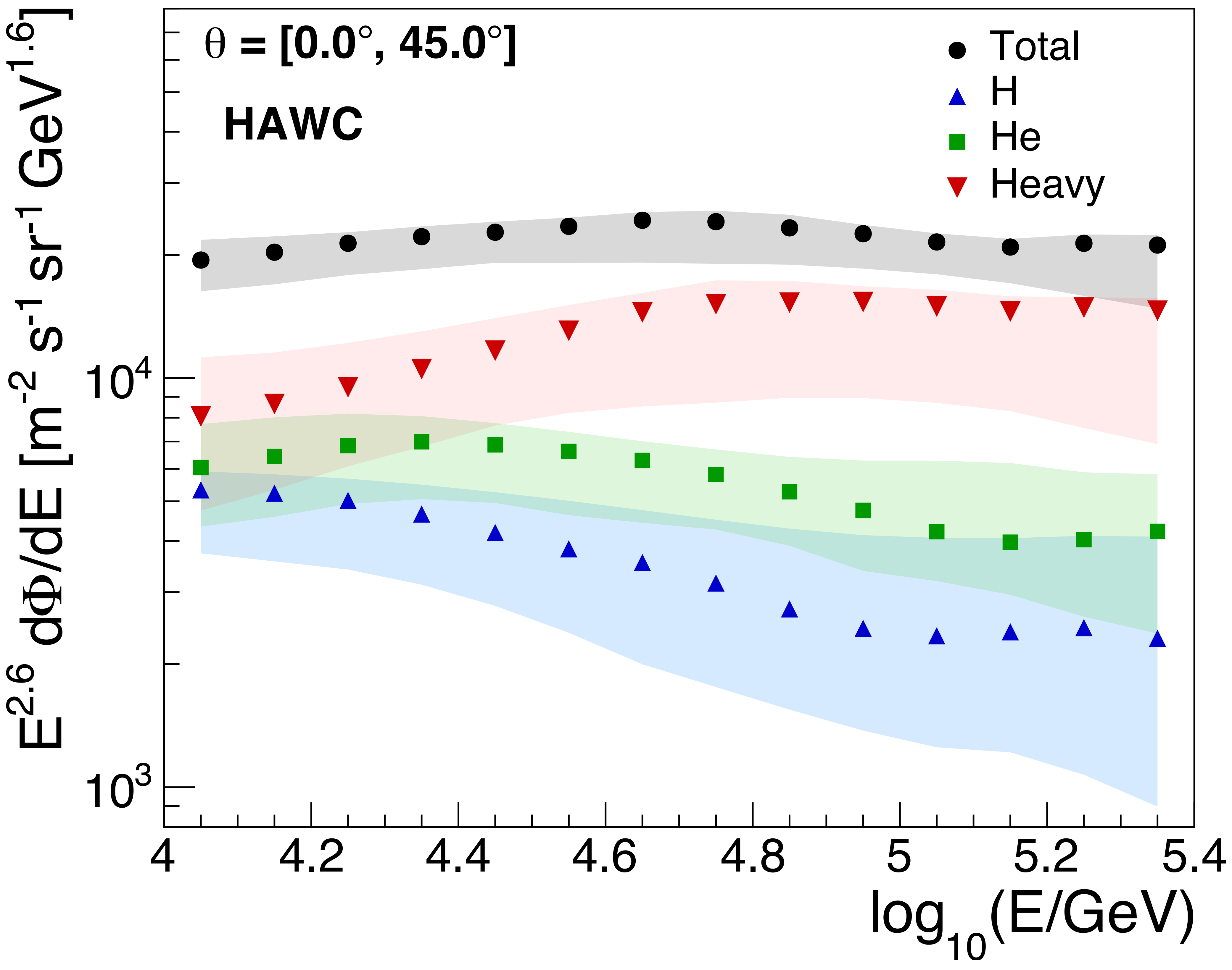
- $\chi^2/\text{n.d.f} = 5.02$

$$\chi^2 = \Sigma_j \frac{(N_{\text{data, j}} - N_{\text{forward, j}})^2}{\sigma^2_{\text{stat, j}} + \sigma^2_{\text{MC, j}}}$$

- Good description of data except for old EAS at low and high energies.



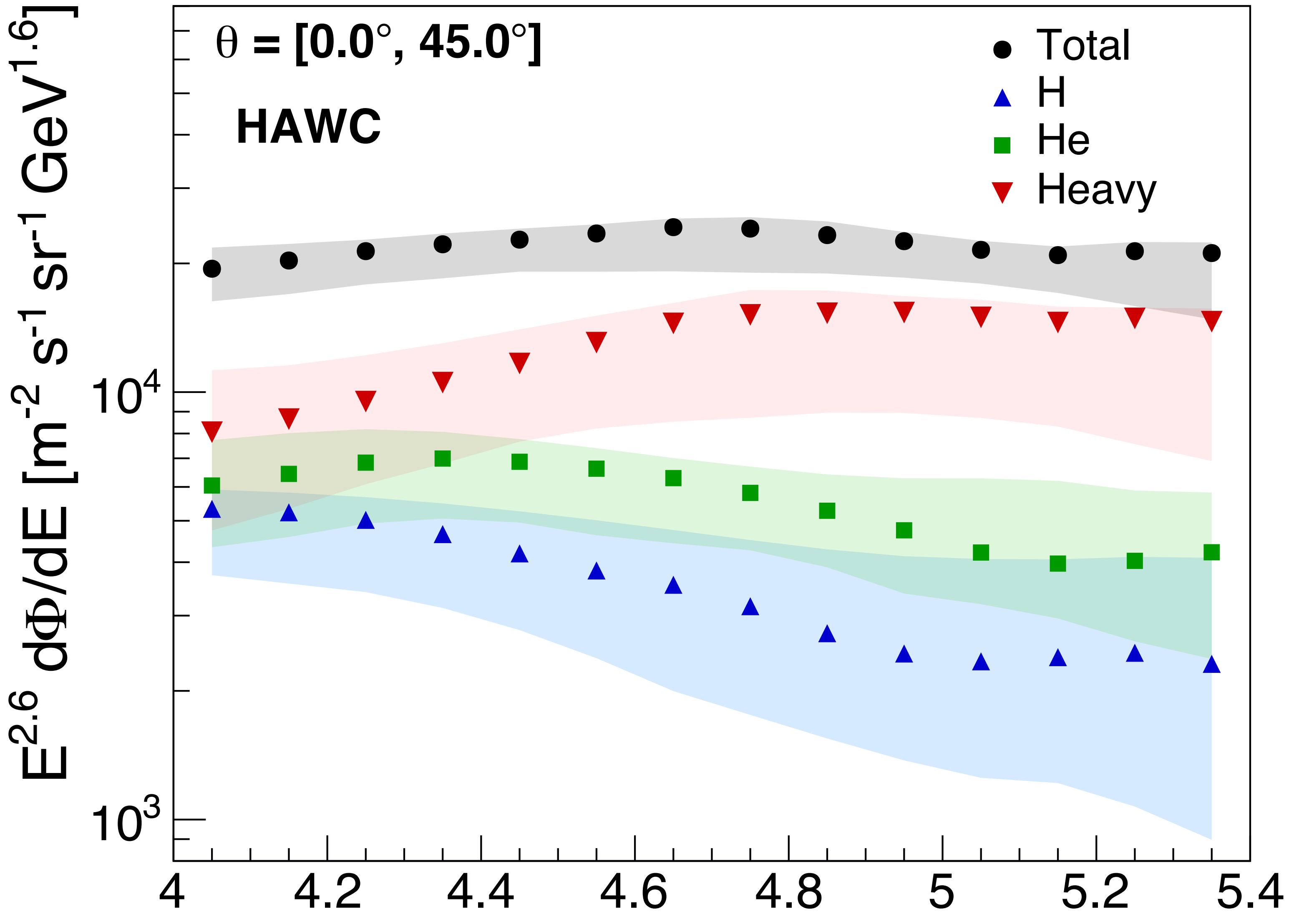
4) Results

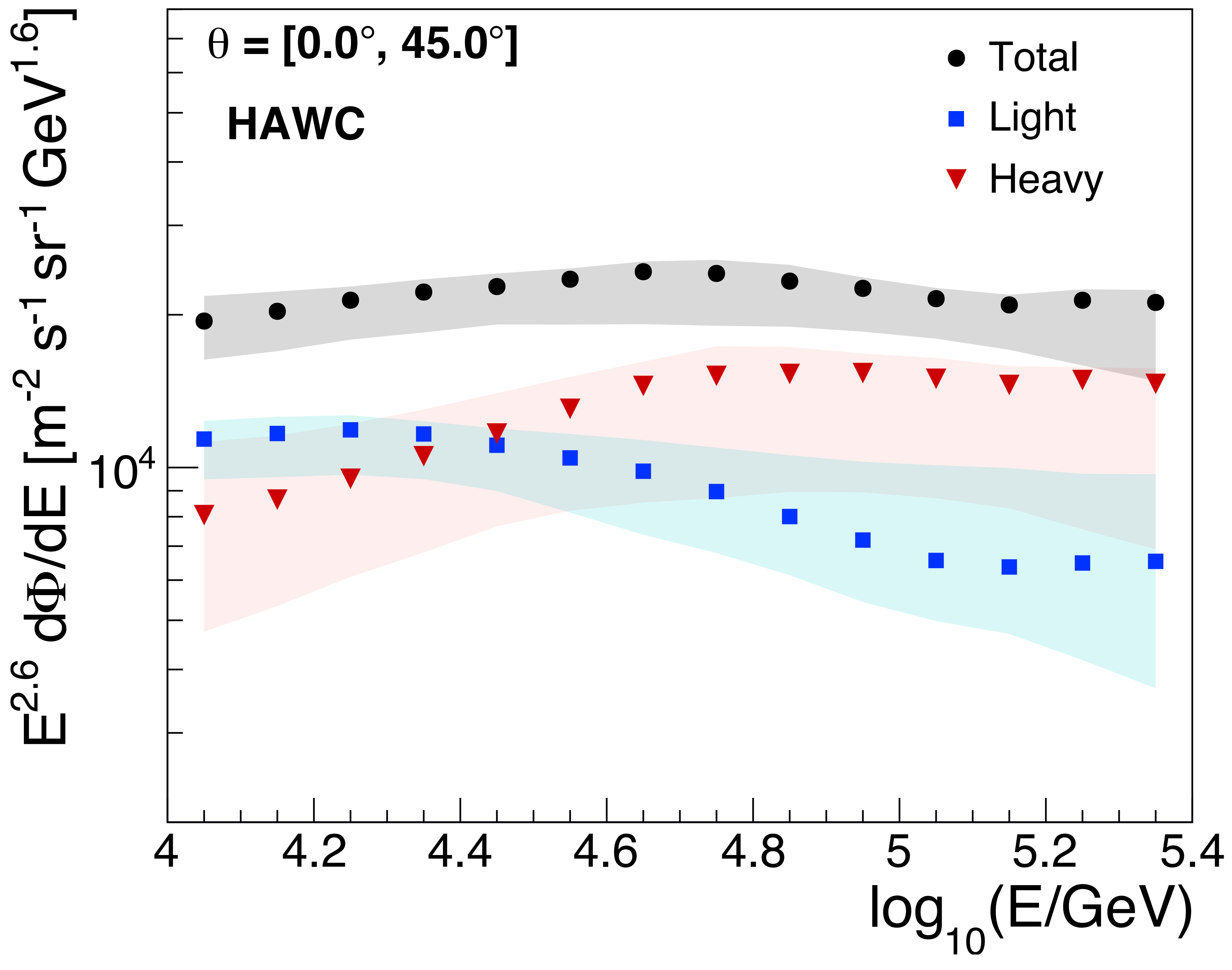


- **Statistical errors** < 0.05%.

- **Systematic errors** < 78%
  - Statistics of the MC data set + Effective area (< 7%).
  - Uncertainties in parameters of the PMTs (< 55%).
  - Hadronic interaction model: EPOS-LHC (< 30%).
  - Unfolding procedure: bias, seed, reduced cross entropy technique (< 14%) .
  - Bias in shower age (< 20%).
  - Cosmic ray composition model: GSF, poligonato, JACEE, ATIC-02 (< 19%).

4) Results





- The elemental spectra do not follow a power-law function.
- HAWC data show fine structure ($> 5\sigma$) between 10 TeV and 251 TeV:
  - **Softenings** at $\mathcal{O}$(10 TeV) for H, He and $Z > 2$.
  - Hints for **hardenings** close to 100 TeV for H and He.
- $\Phi_{H}(E)/\Phi_{He}(E) < 1$ for E = [10 TeV, 100 TeV].
- Composition becomes heavier from 10 TeV to 100 TeV.
- Bump in the the all-particle spectrum at ∼ 46 TeV reported by HAWC in 2017 is due to the superposition of individual softenings in the spectra of light and heavy mass groups.

  [HAWC Collab., PRD 96 (2017) 122001]
- Knee-like feature at ∼ 32 TeV in spectra of H+He observed by HAWC in 2019 comes from individual cuts in spectra for H and He.

  [HAWC Collab., PoS(ICRC2019) 176]

4) Results

Fits

$$\Phi(E) = \Phi_0 E^{\gamma_1}\left[1+\left(\frac{E}{E_0}\right)^{\varepsilon_0}\right]^{(\gamma_2-\gamma_1)/\varepsilon_0}\left[1+\left(\frac{E}{E_1}\right)^{\varepsilon_1}\right]^{(\gamma_3-\gamma_2)/\varepsilon_1}$$

	E_0(TeV)	E_1(TeV)	γ_1	γ_2
H	14.1 +2.2/-0.4	103 +1/-4	-2.6 +0.2/-0.5	-3.1 ± 0.3
He	25.3 +1.1/-0.8	152 +11/-9	-2.2 +0.1/-0.3	-3.1 +0.4/-0.1
Z > 2	51 ± 1	__	-2.1 ± 0.3	-2.6 +0.04/-0.2

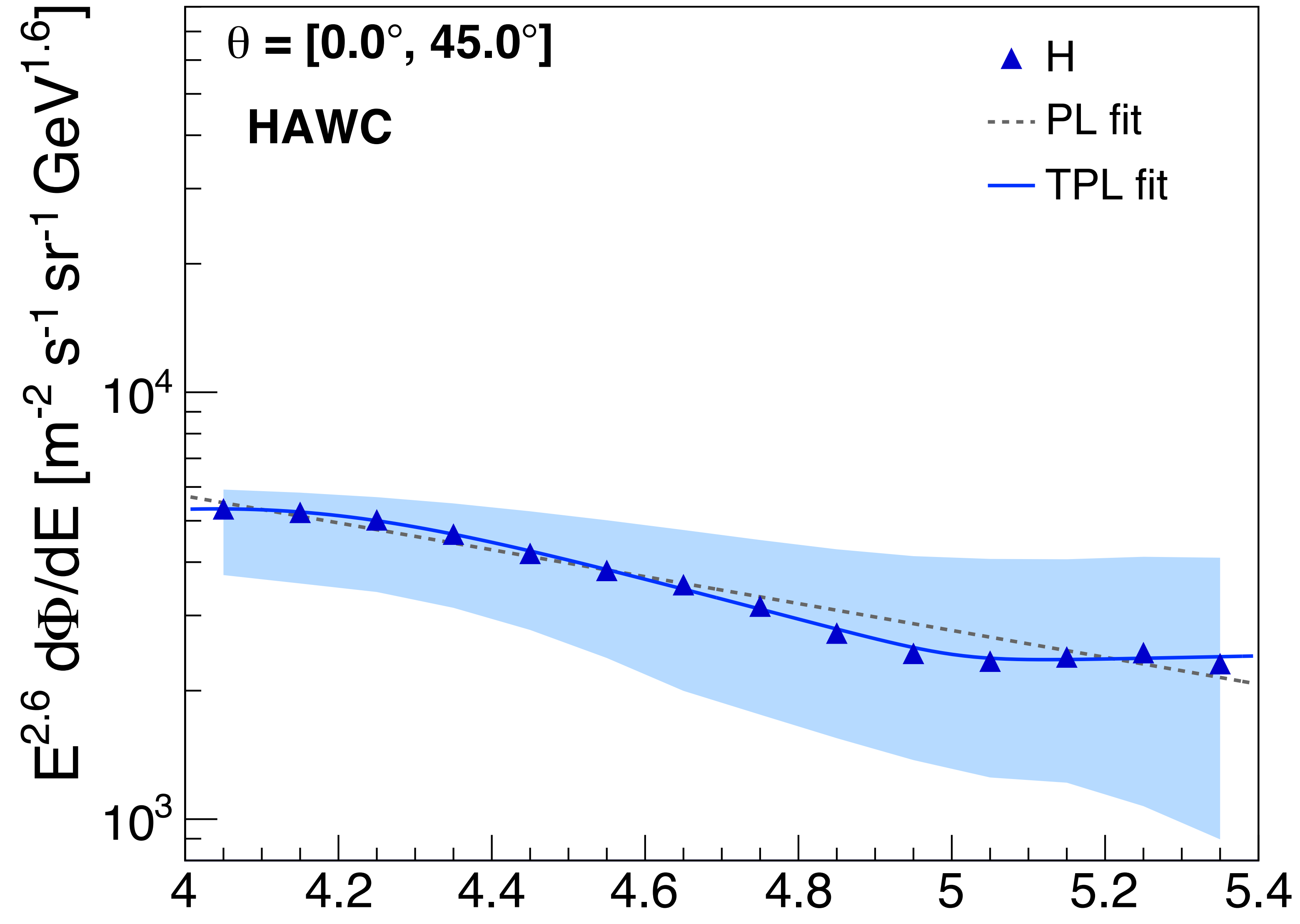
In the table, total errors are shown

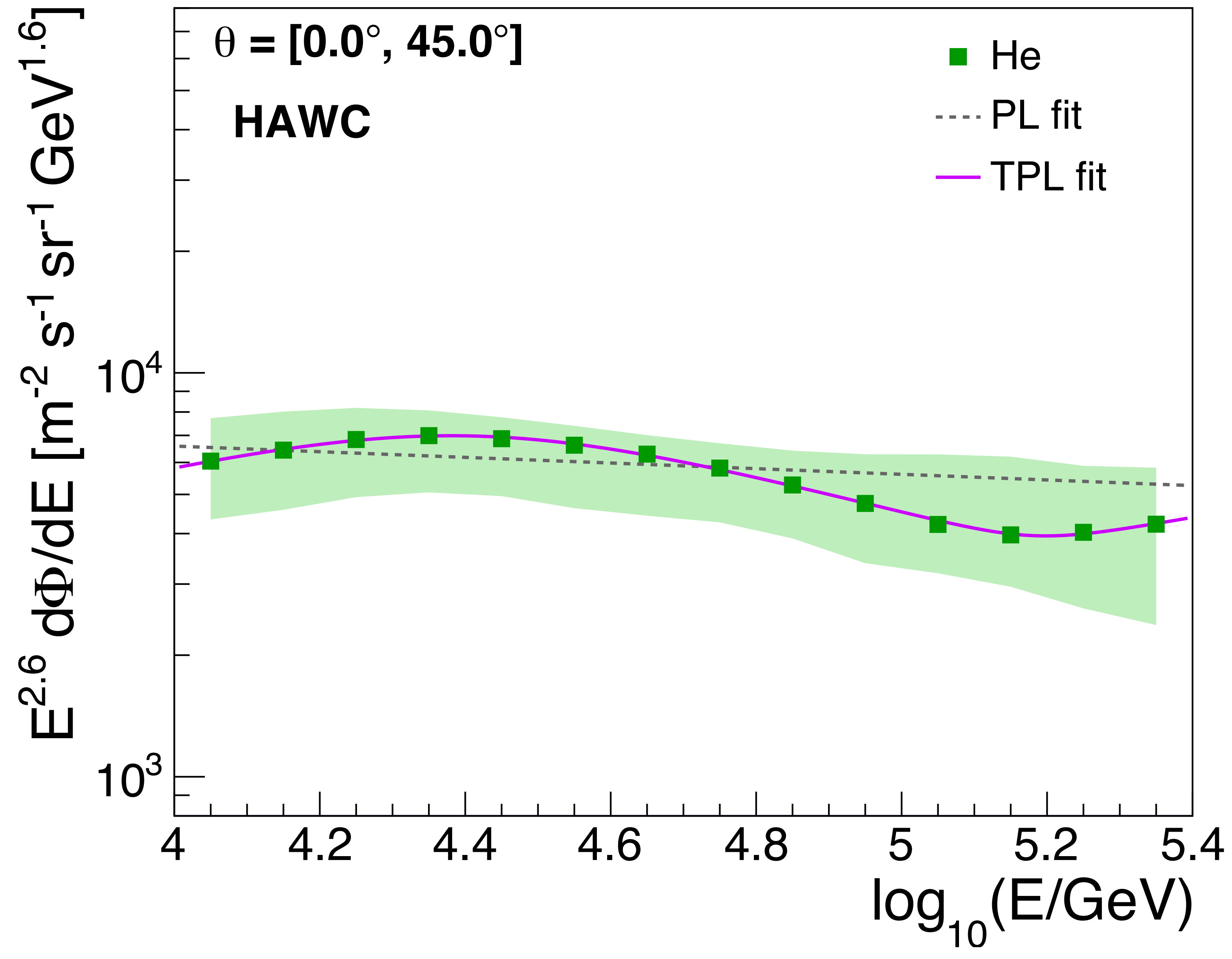
E_0: Energy 1st break.

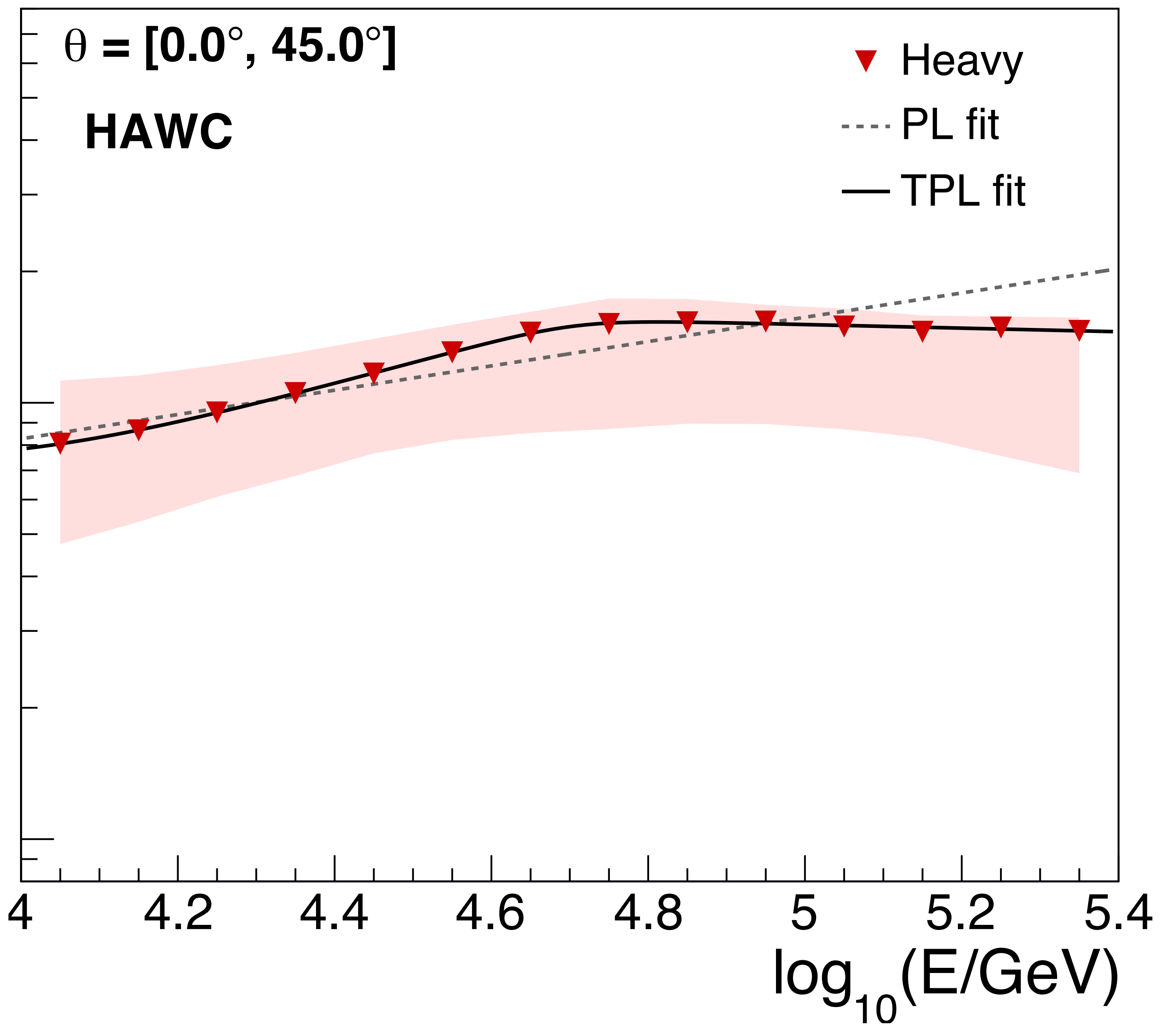
E_1: Energy 2nd break.

γ_1: spectral index before E_0.

γ_2: spectral index after E_0.







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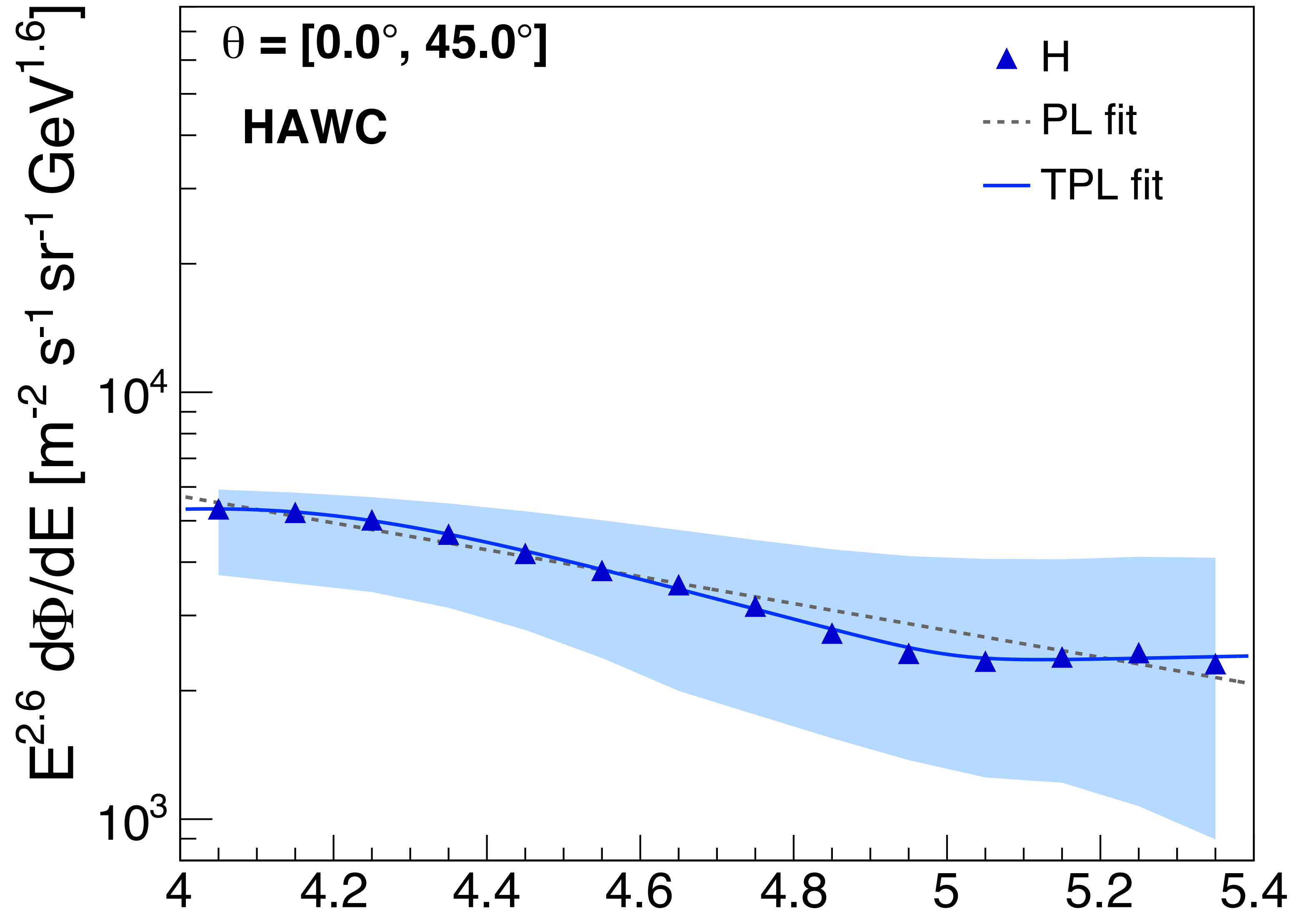
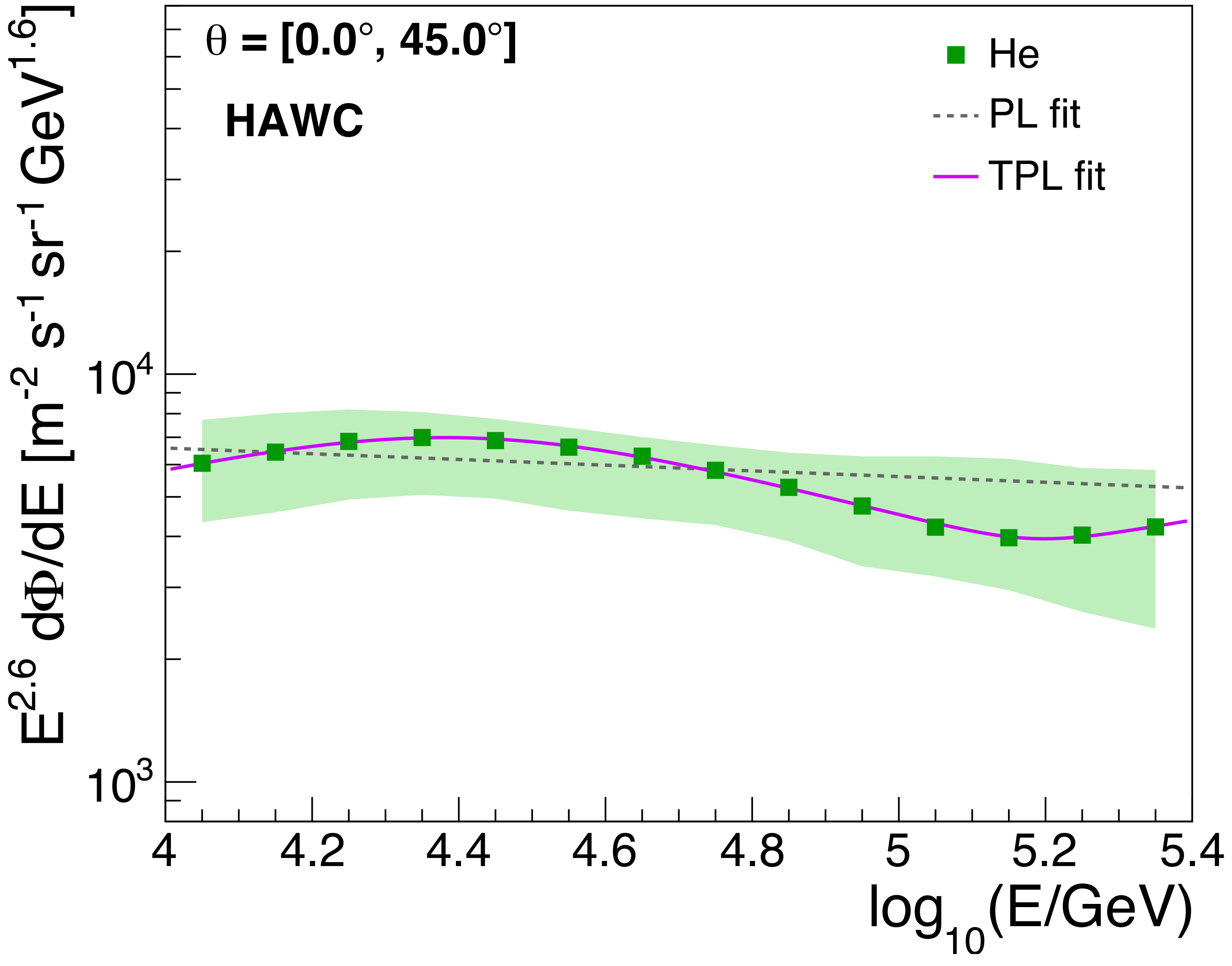
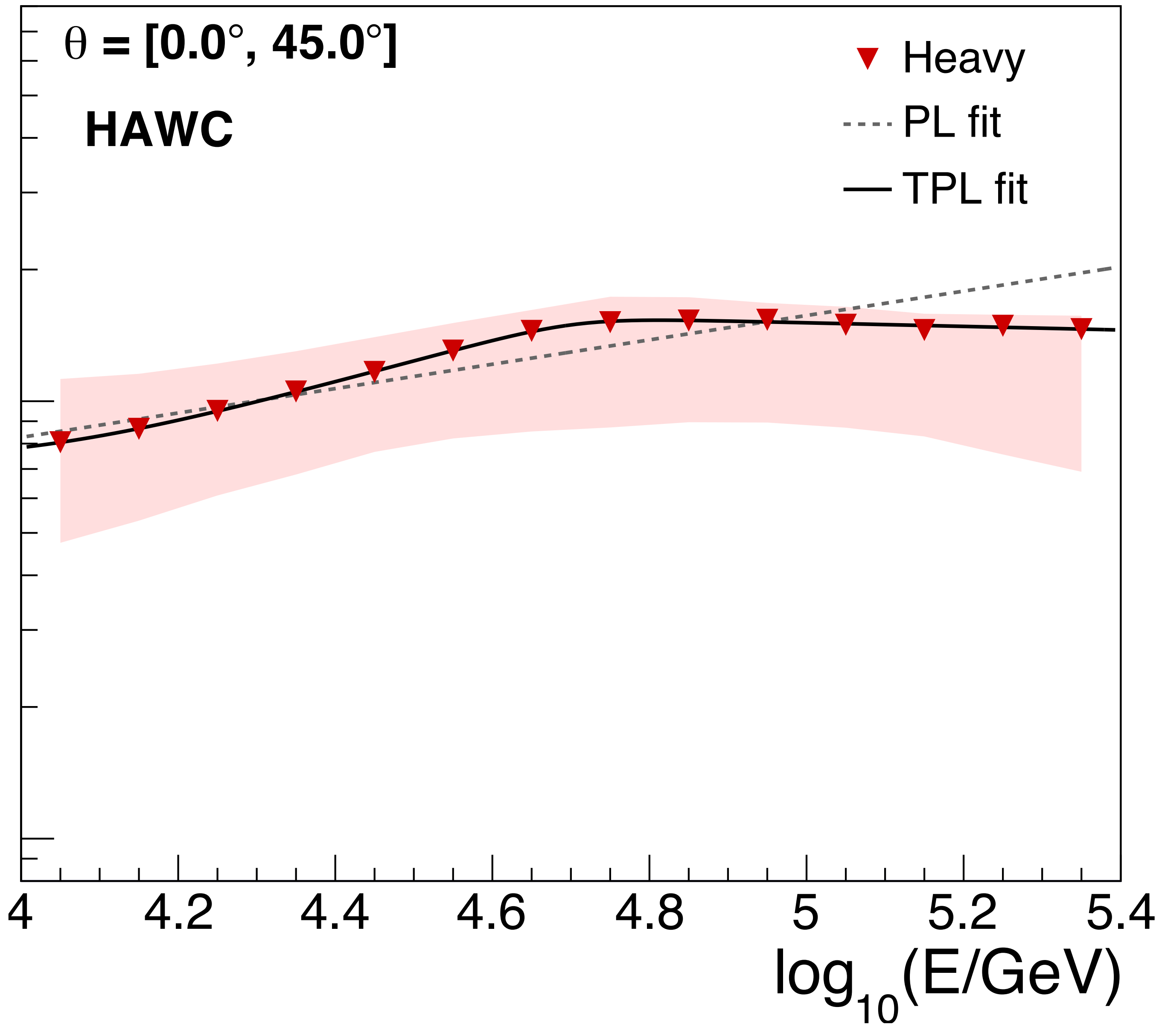


Position of the softenings seems to increase with the primary mass.

$$E_{0,\,He}/E_{0,\,H} = 1.8\,^{+0.3}_{-0.1}$$





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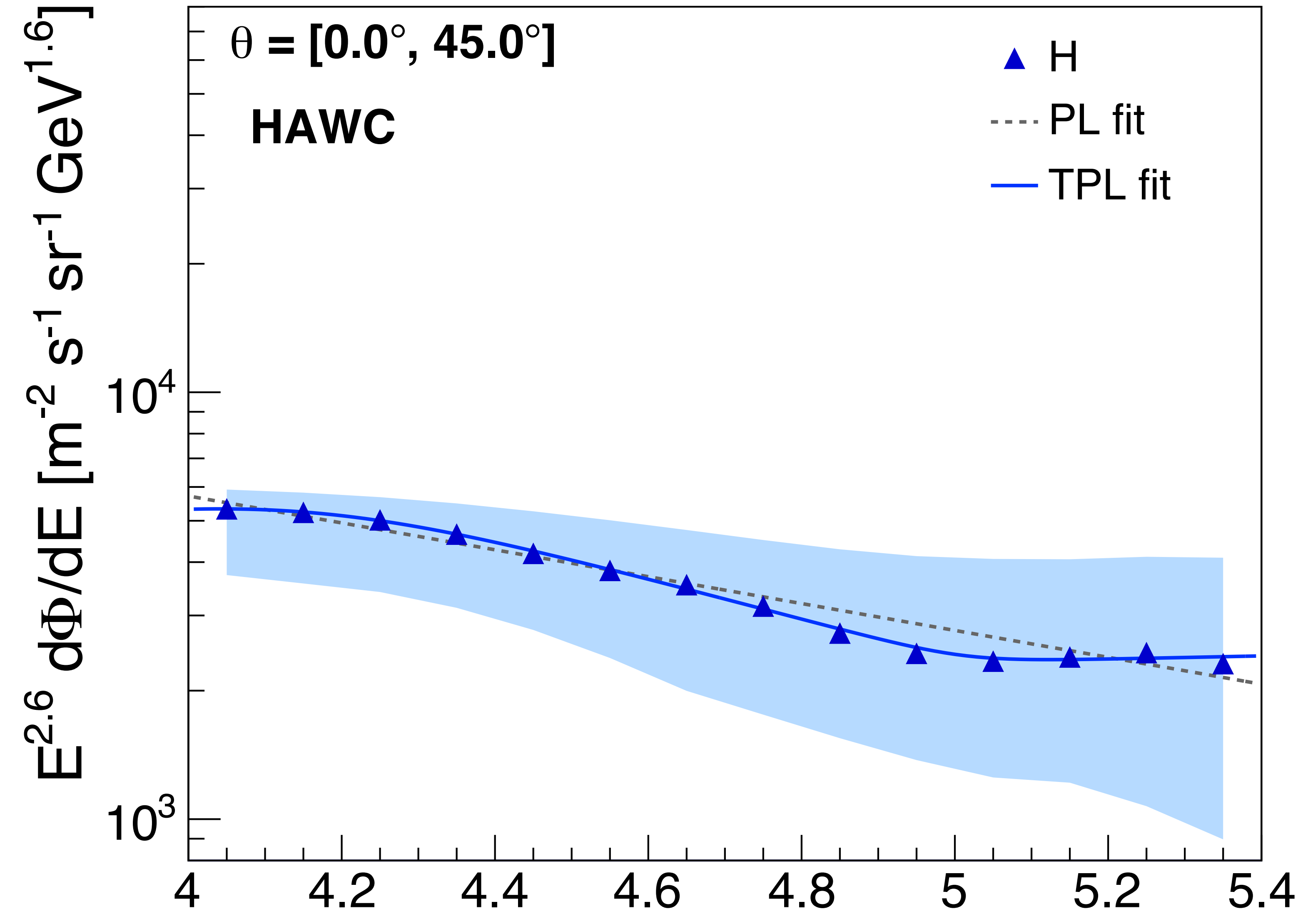
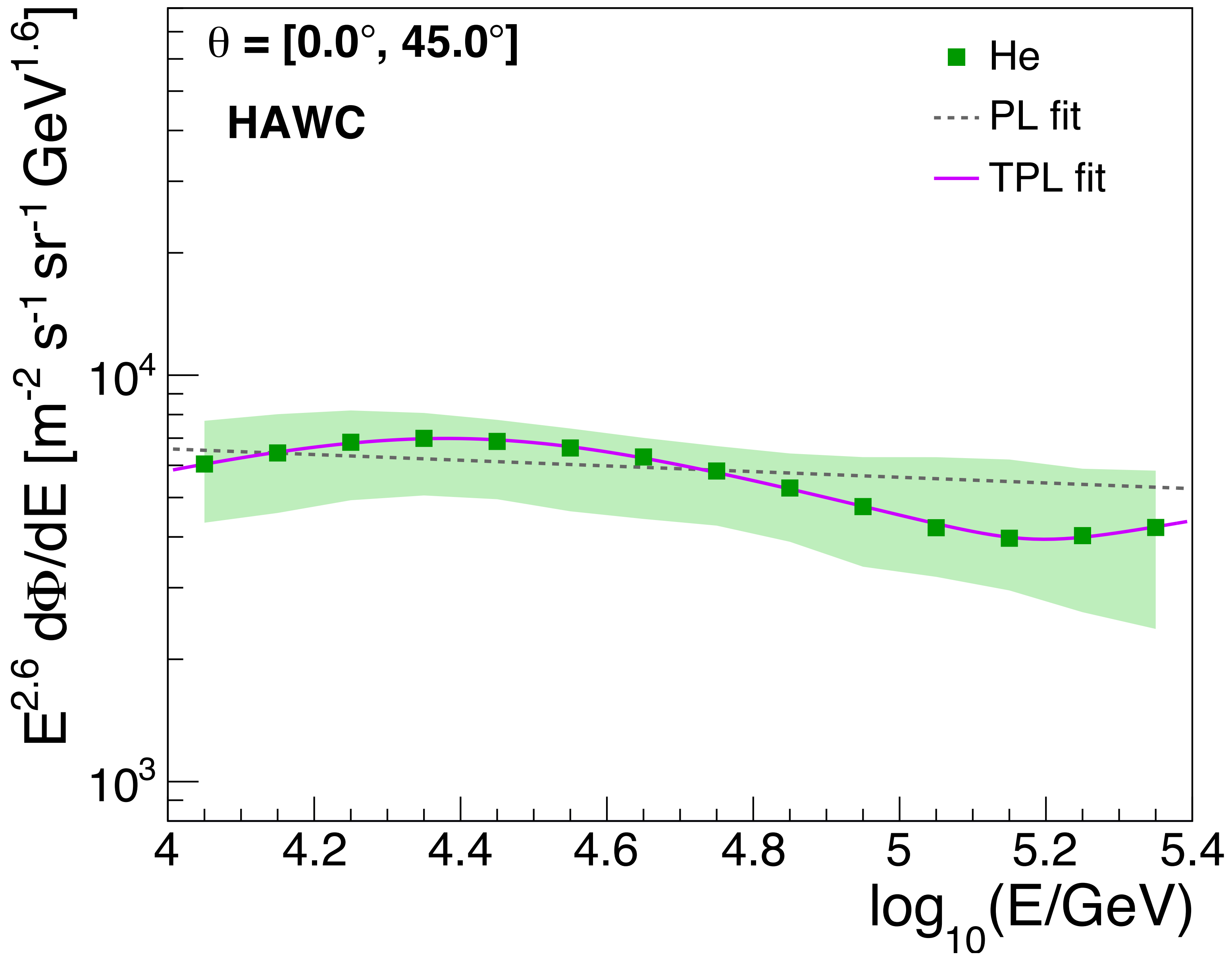
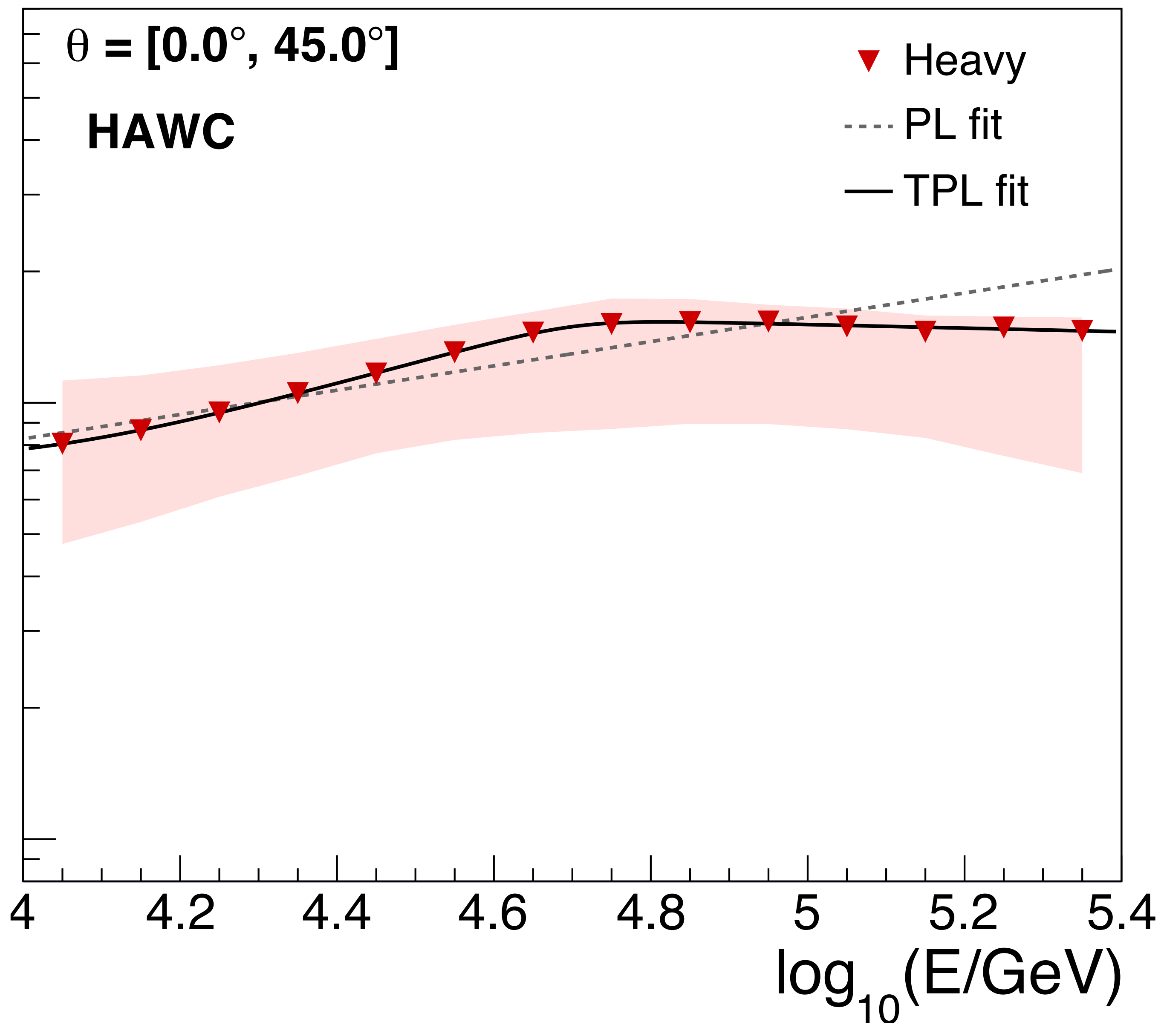


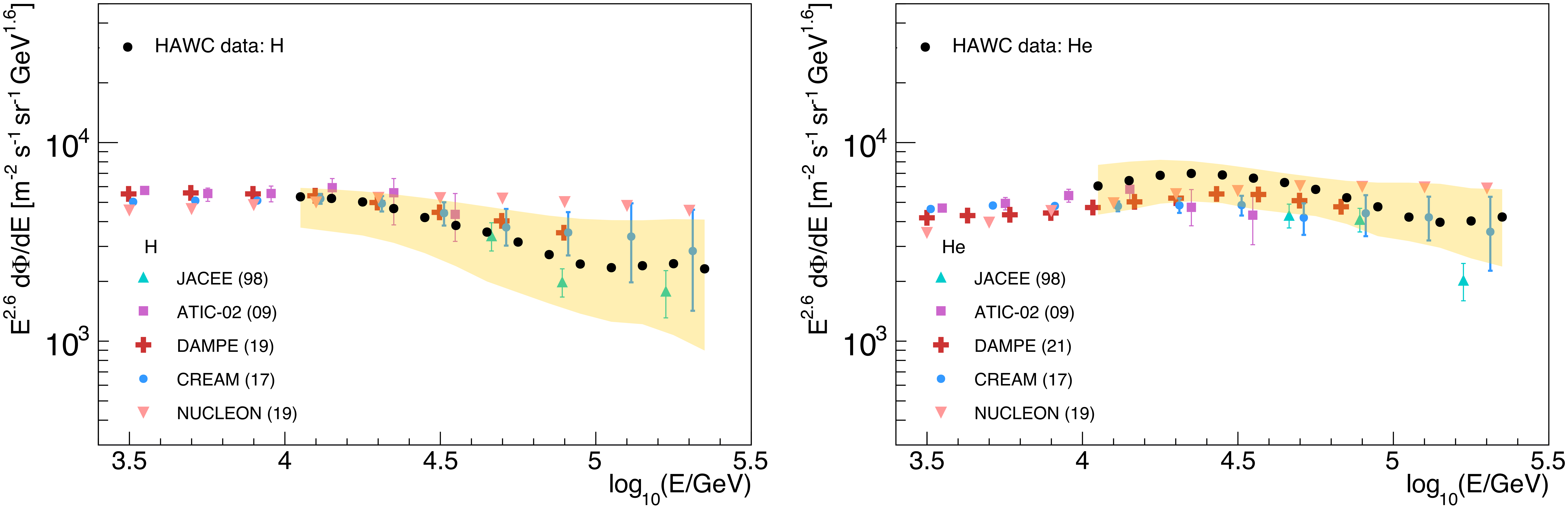
- Spectra for He and Heavy nuclei seem to be harder than that for protons, before E_0.
- Spectra for H and He seem to have a similar γ_2.
- Spectral index just above E_0 for spectrum of heavy nuclei seems to be harder than those for H and He primaries.





4) Results

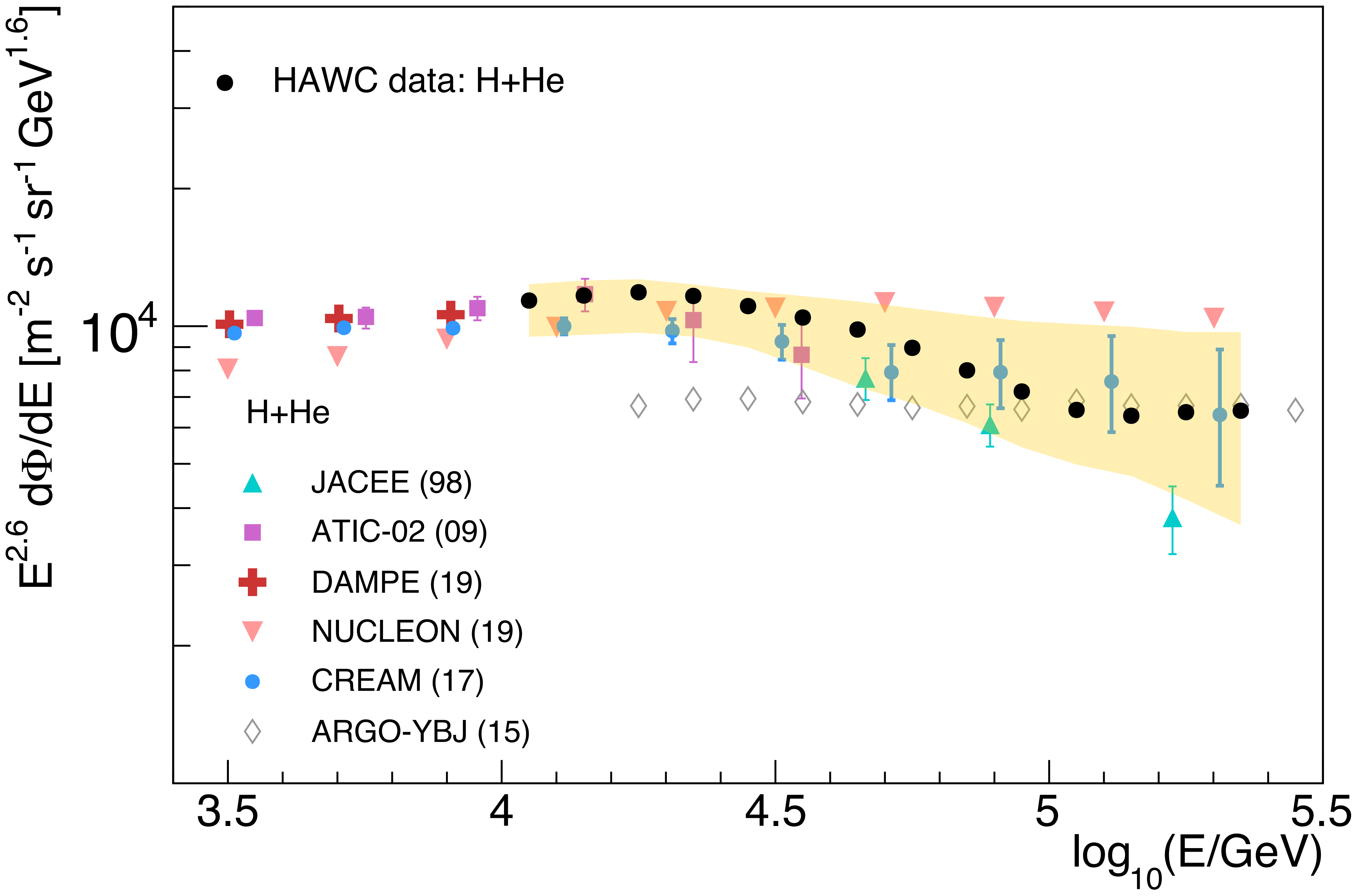
H and He spectra: Comparison with other experiments

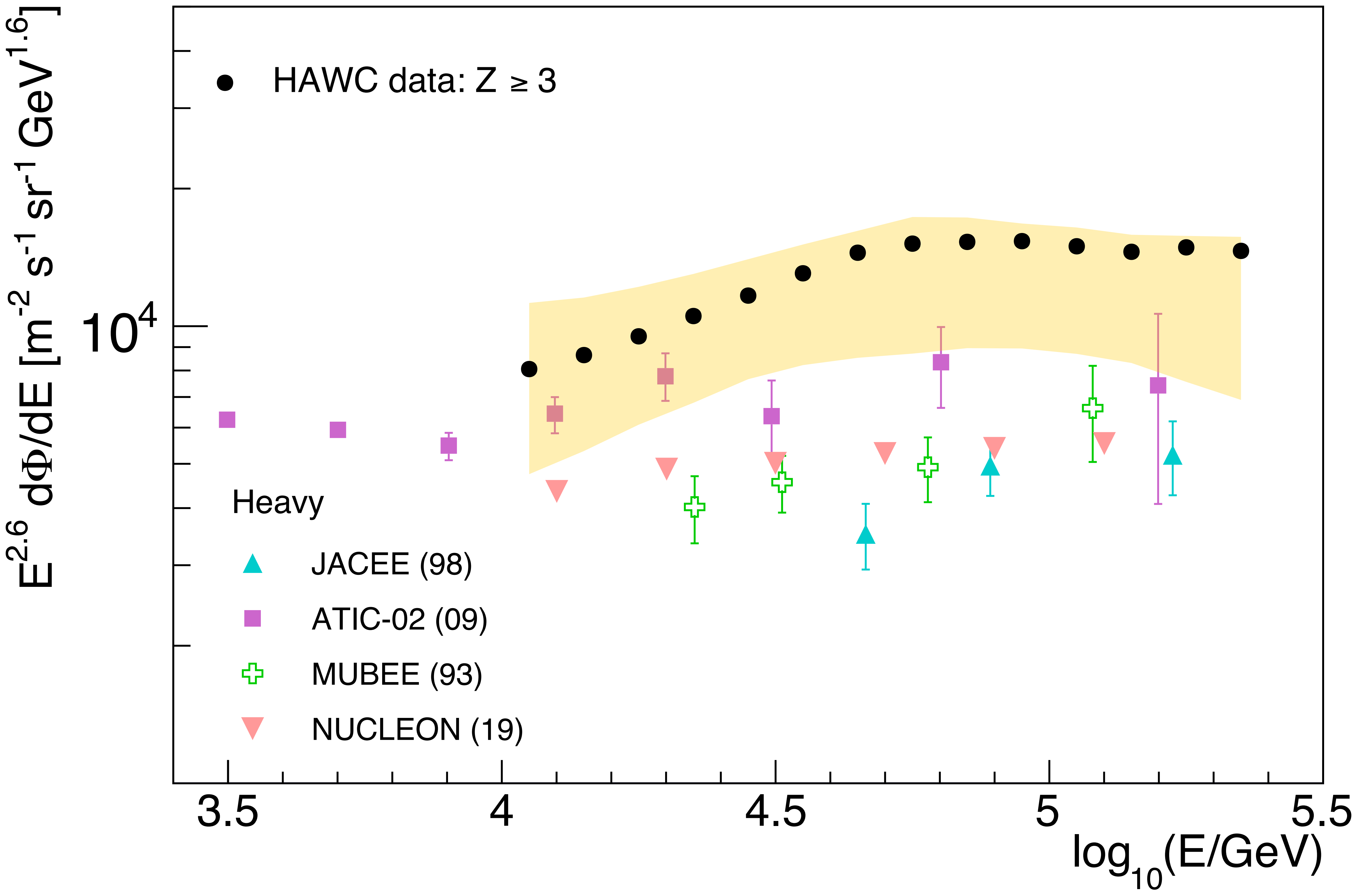


- Good agreement of **HAWC** with direct data from **DAMPE**, **ATIC-02** and **CREAM I-III** within systematic errors.
- **HAWC** confirms softenings at tens of TeV observed by **DAMPE**, first hinted by **ATIC-02**, **CREAM** and **NUCLEON**.

4) Results

Light (H + He) and Heavy (Z > 2) spectra: Comparison with other experiments



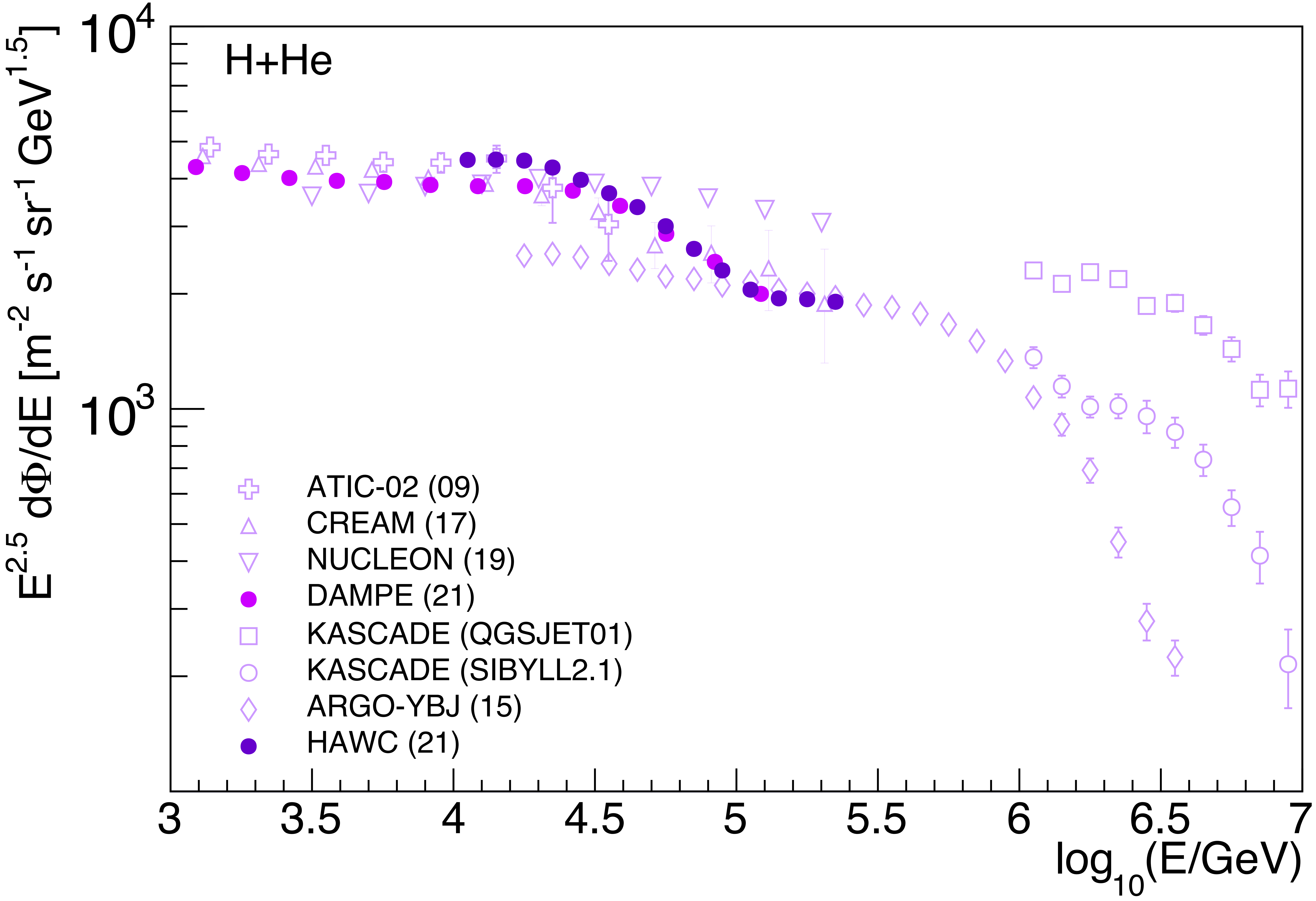


- Good agreement of **HAWC** with **ATIC-02, CREAM** and **JACEE** within systematic errors.
- **ARGO-YBJ** disagrees with **HAWC** data for E < 50 TeV.

- Agreement of **HAWC** with **ATIC-02** within systematic errors.
- **HAWC** data is above **NUCLEON**, **MUBEE** and **JACEE** observations.

4) Results

Light (H + He) spectrum: Comparison with other experiments (updated from ICRC 2021)



5) Conclusions

- We have estimated the elemental energy spectra for H, He and heavy nuclei (Z >2) with HAWC for E = [10, 251] TeV.

- HAWC results reveal individual softenings at tens of TeV, whose positions seem to move to higher energies for heavy primaries. ($E_{0,\,He}/E_{0,\,H} = 1.8^{+0.3}_{-0.1}$, agreement with *Z*-dependent scenario).

- HAWC confirms the TeV knee-like features observed recently by DAMPE (2019&2021) for the spectra of H and He.

  —> First time that high-statistics data on cosmic ray composition from direct and EAS experiments are compared.

  —> There is potential in observatories like HAWC to perform TeV composition research on cosmic rays.

- Cosmic ray composition becomes heavier at high energies within the range 10 - 100 TeV.

- HAWC hints to possible hardenings close to 100 TeV in the spectra of H and He.

HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Thank you