Ground Observations of the Spectrum and Composition of Cosmic Rays Below the Knee

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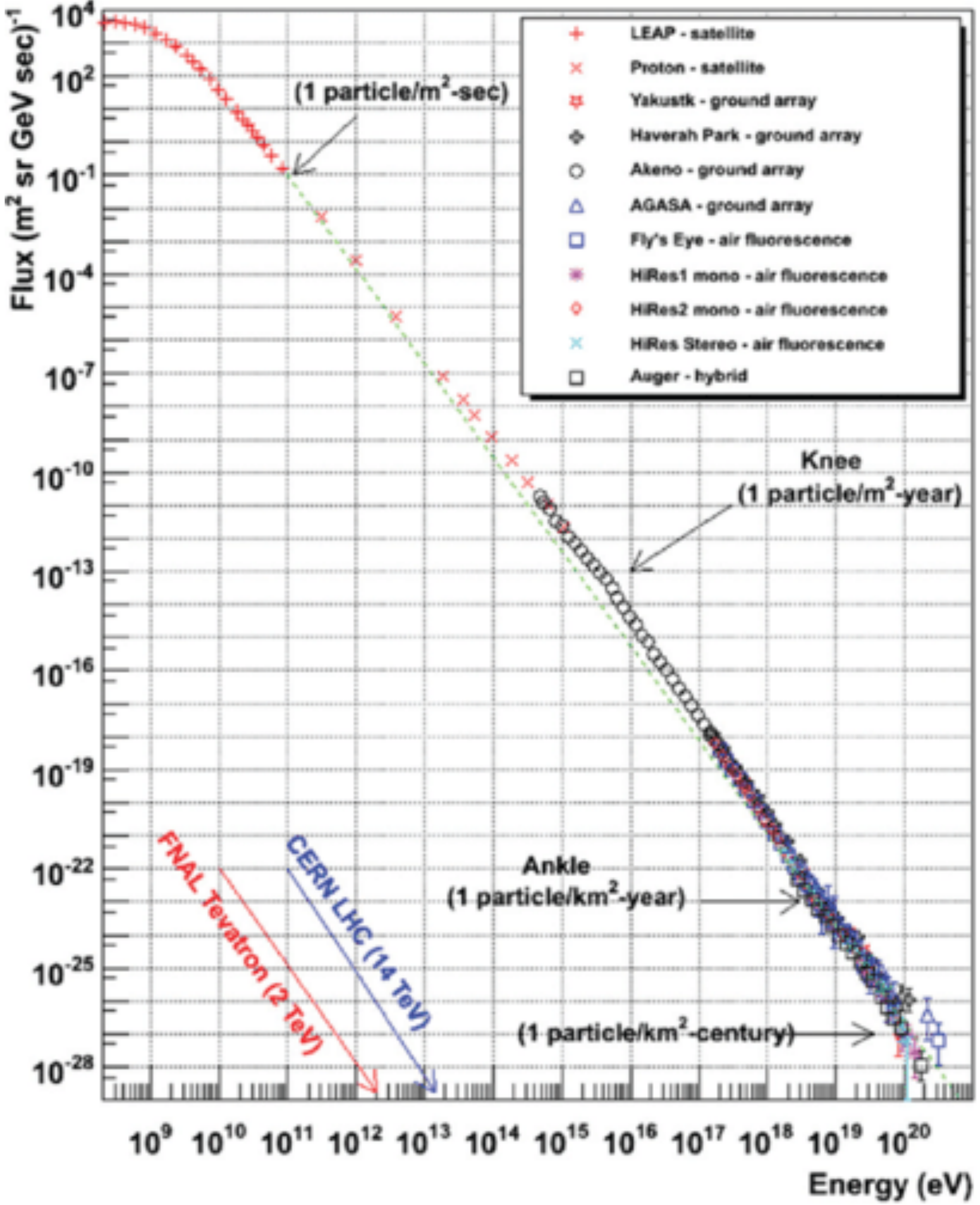
Universidad de Guadalajara
on behalf of the HAWC Collaboration

5 Dic. 2022
Cosmic Rays in the Multi-Messenger Era
APC Laboratory (Paris)

Image: tecreview.tec.mx

The Cosmic-Ray Spectrum

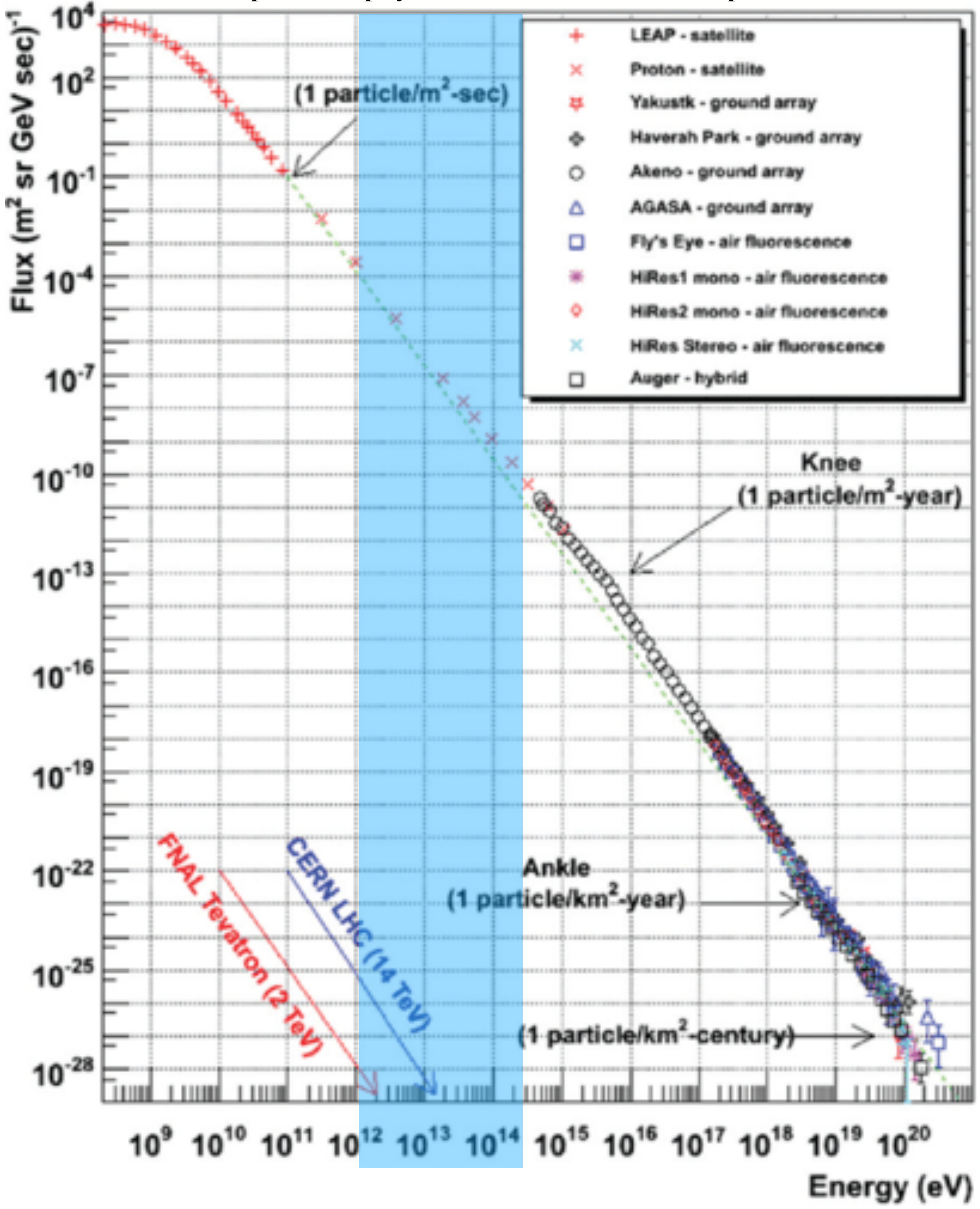
- **Spectral characteristics** from acceleration and propagation mechanism effects
- **Mass composition** reveals information about local source environment and of cosmic ray propagation in the Galaxy.
- In general, it is thought that cosmic rays with energies **below PeV are of galactic origin** and that their acceleration and transport in the Galaxy occur through diffusive processes driven by B-fields.
- Energies up to PeV assumed from 1st order Fermi acceleration in shocked plasmas of SNRs with propagation through scattering on random fluctuations in the ISMF.
- CR of **extra-galactic** origin above 10^9 GeV



https://web.physics.utah.edu/~whanlon/spectrum.html

The Cosmic-Ray Spectrum

https://web.physics.utah.edu/~whanlon/spectrum.html



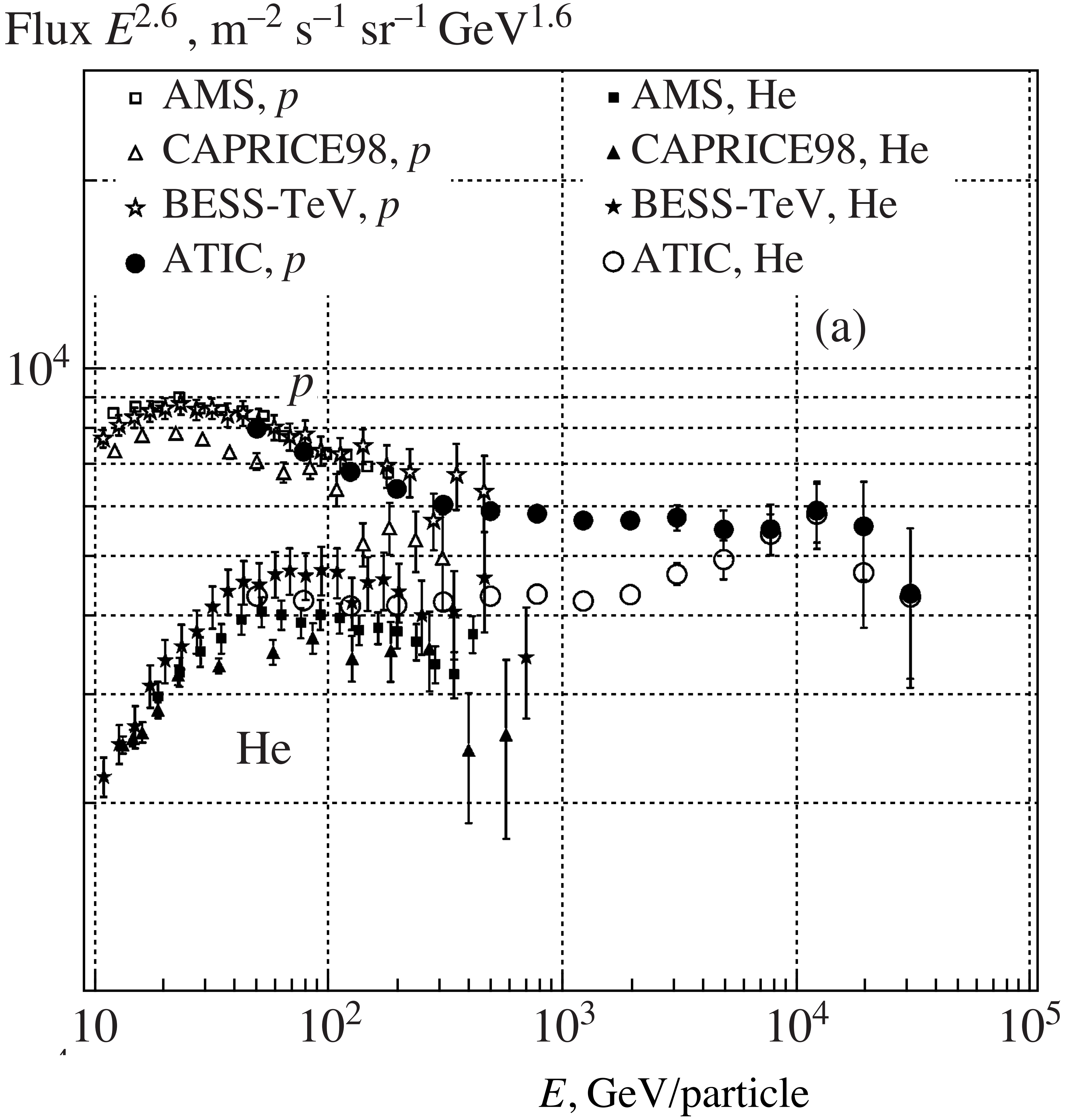
- Previously: little data in 10 TeV - 100 TeV region
  - Recent direct measurements have been extended to higher energies
  - Ground-based experiments to lower energies
  - Overlap allows for cross-calibration

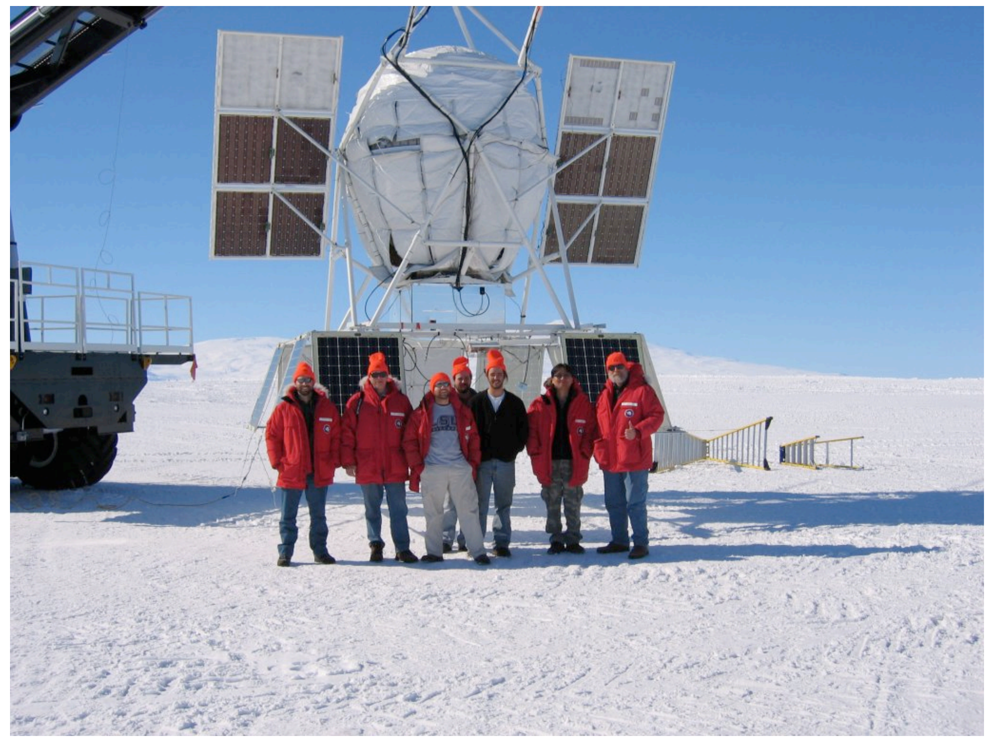
Direct measurements

10 GeV - 100 TeV

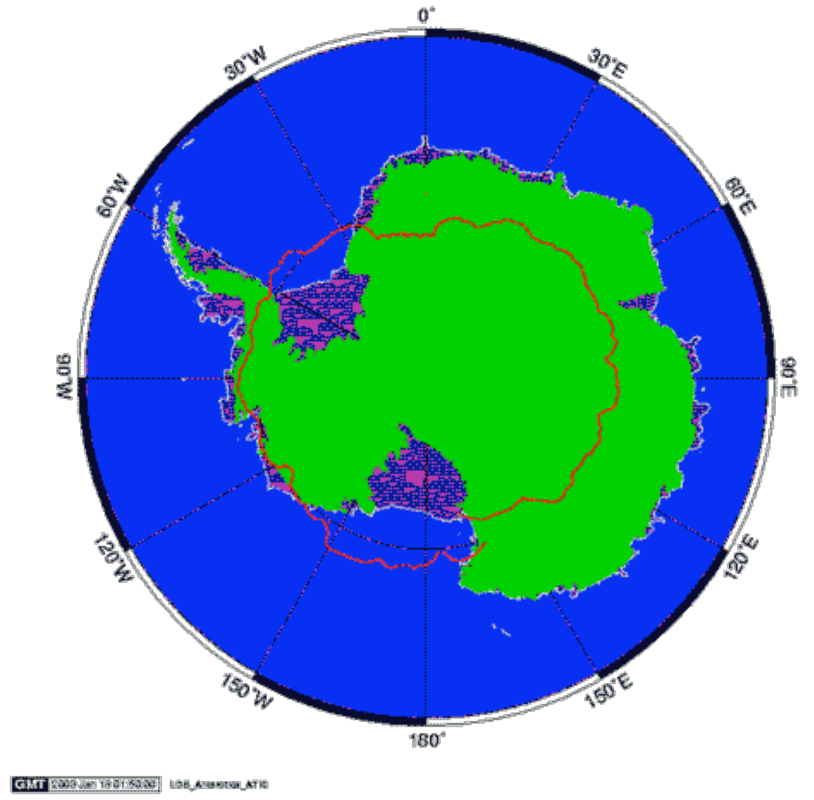
- ATIC-2
  - Energy spectra of protons and He, C, O, Ne, Mg, Si, and Fe nuclei
  - Complex structure of the energy dependence of the mean logarithm of atomic weight. (i. e. softening at ~ 10 TV)

Panov, A.D., *et al. Bull. Russ. Acad. Sci. Phys.* **73**, 564–567 (2009).





http://science.nasa.gov



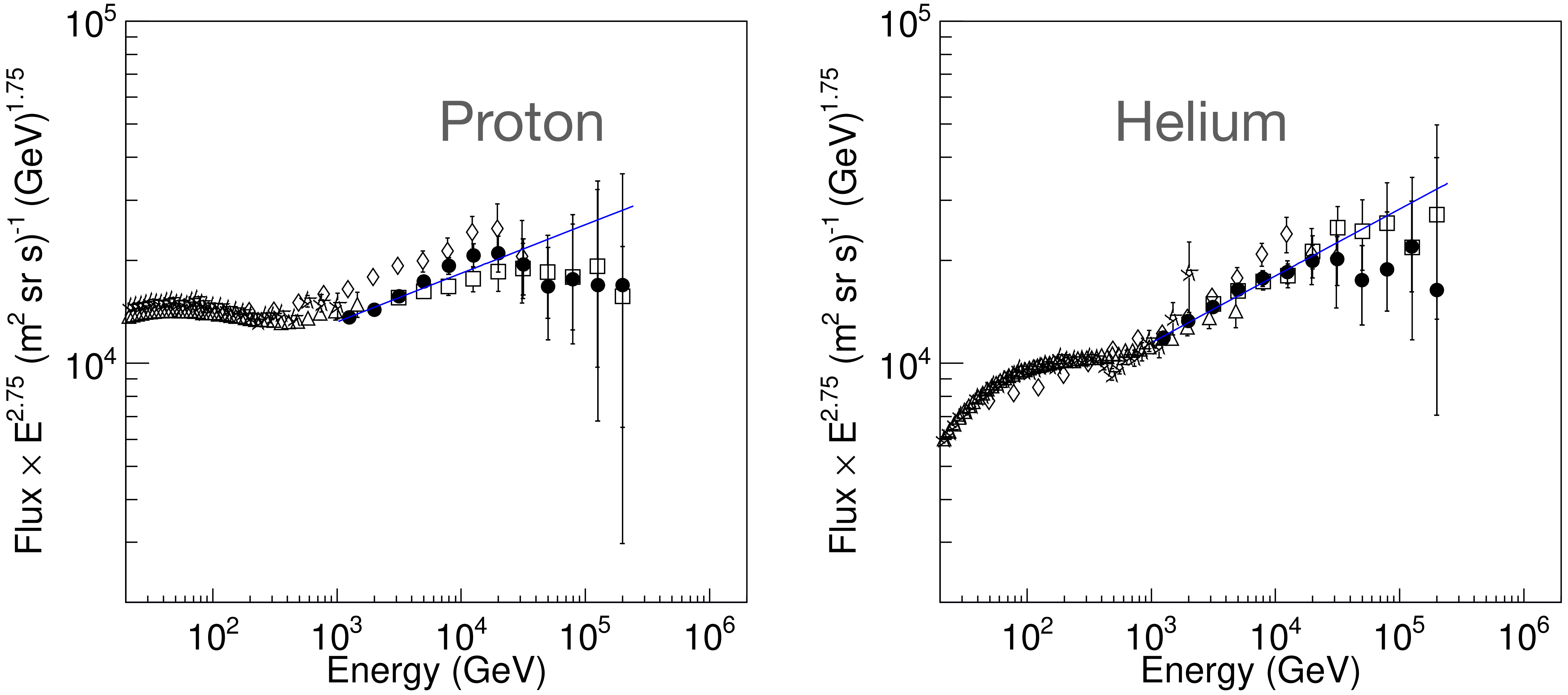
http://stratocat.com.ar

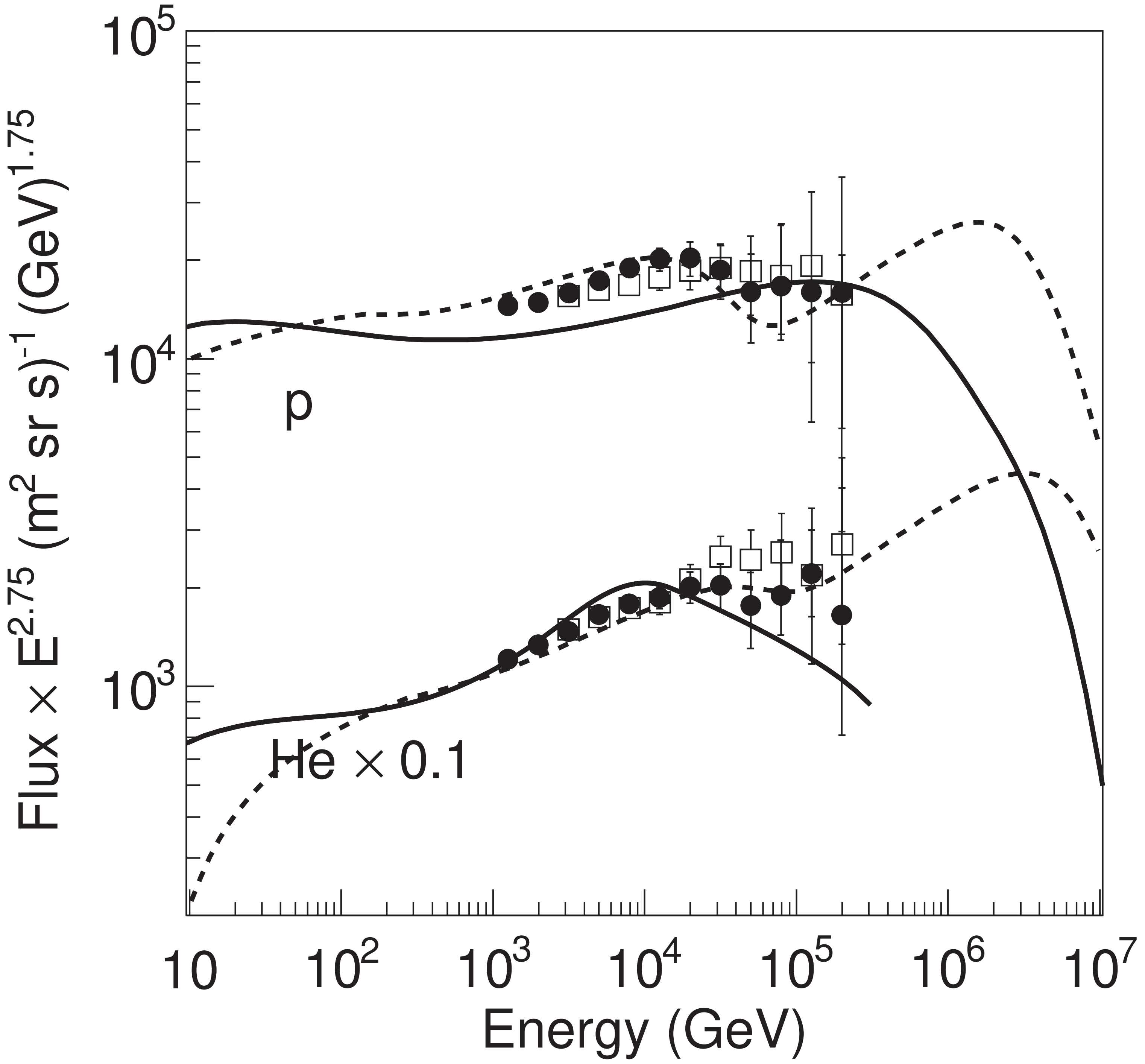
Direct measurements

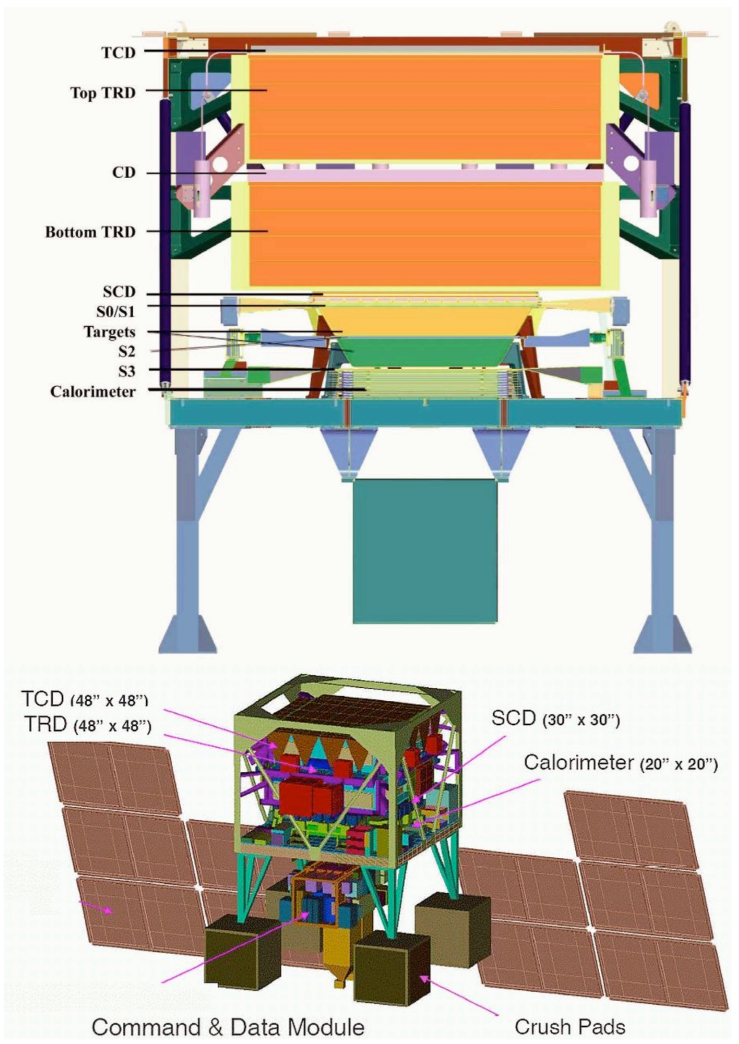
10 GeV - 100 TeV

- CREAM I-III:
  - apparent suppression beyond 20TeV in the spectra of H
  - Statistical uncertainties are large and suggest additional data needed.

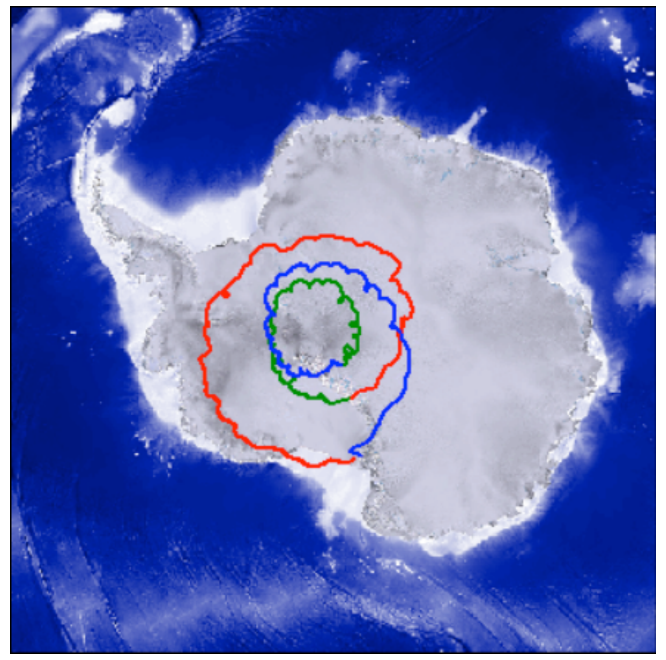
Y. S. Yoon *et al* 2017 *ApJ* **839** 5







http://stratocat.com.ar



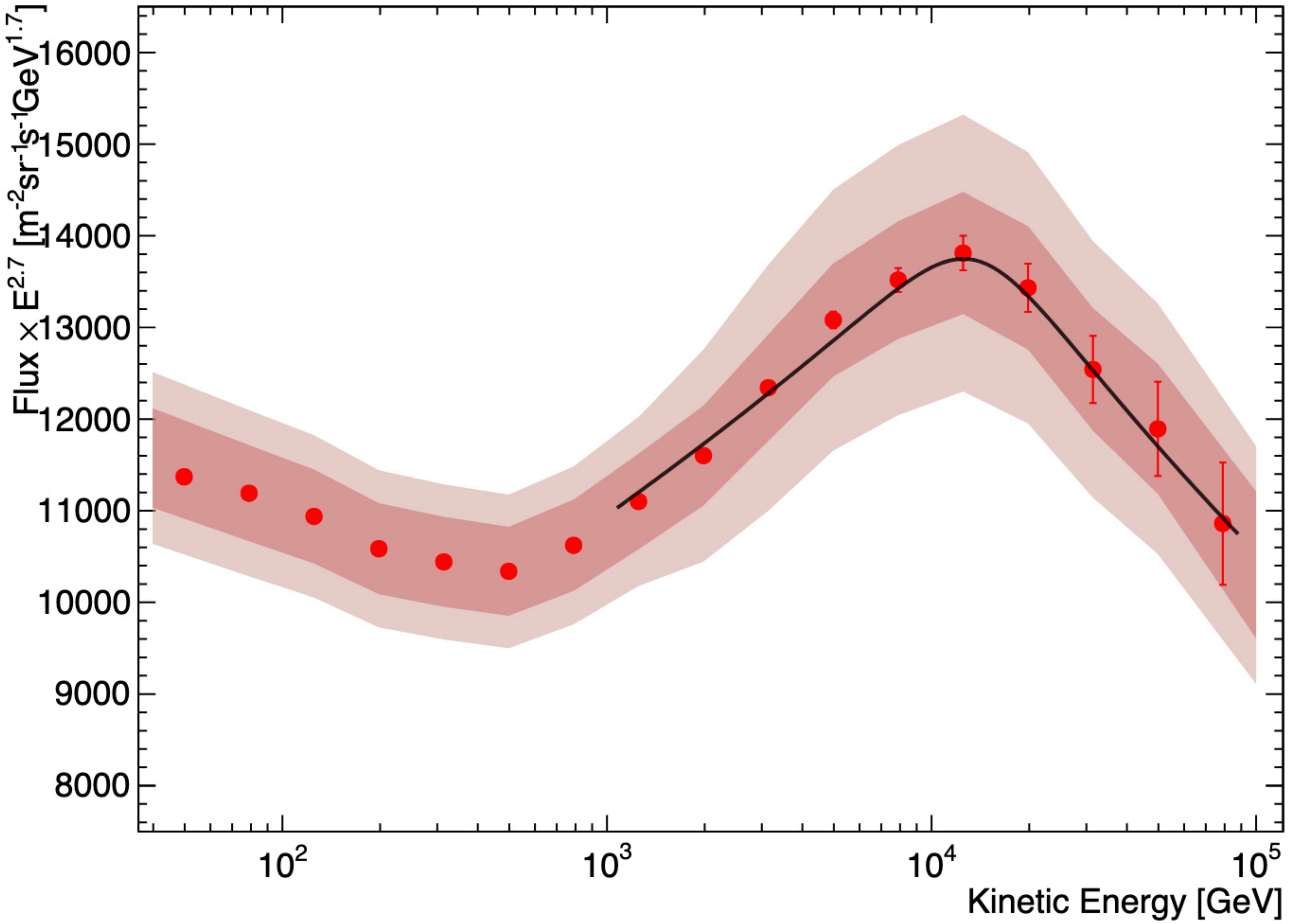
https://cosmicray.umd.edu/cream

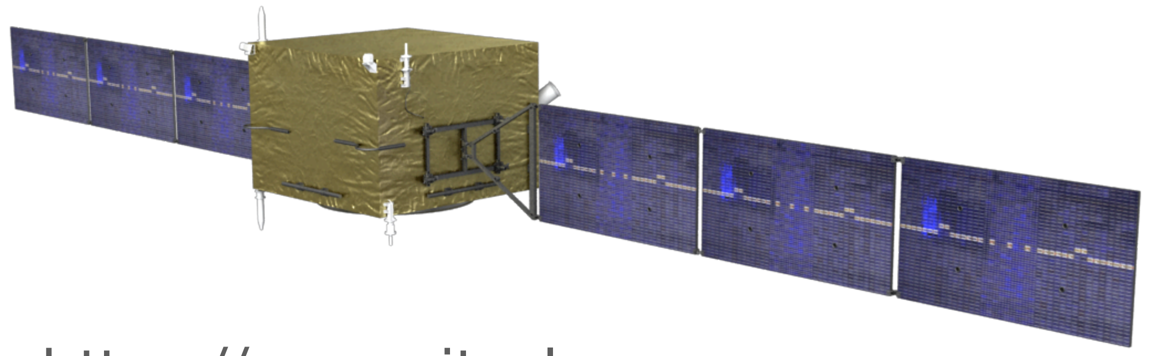
Direct measurements

10 GeV - 100 TeV

- DAMPE:
  - Measurements of the spectrum of protons (Q. An et al., 2019) between 40 GeV and 100 TeV;

Q. An et al., Science Adv. (2019)





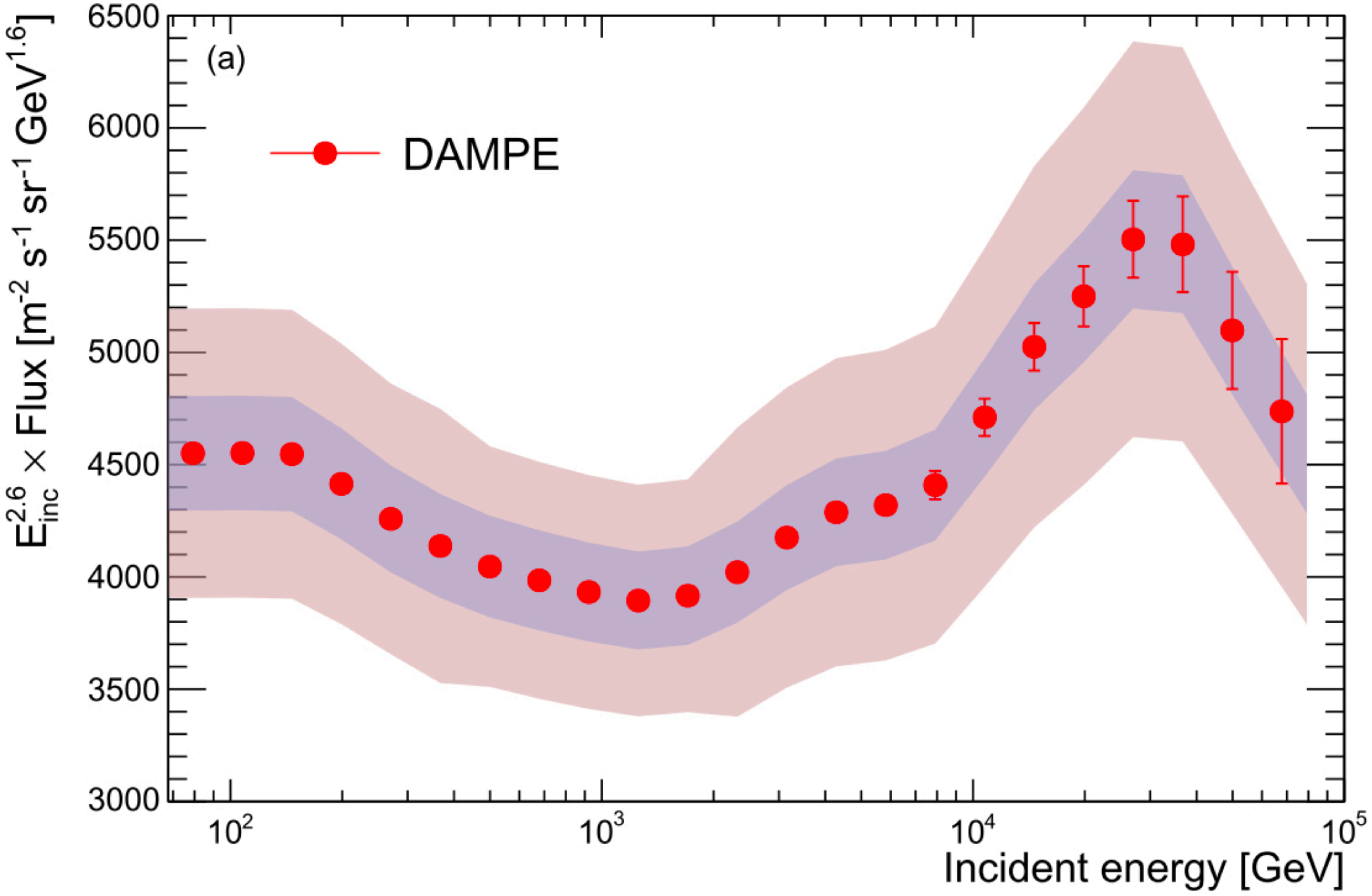
https://www.sitael.com

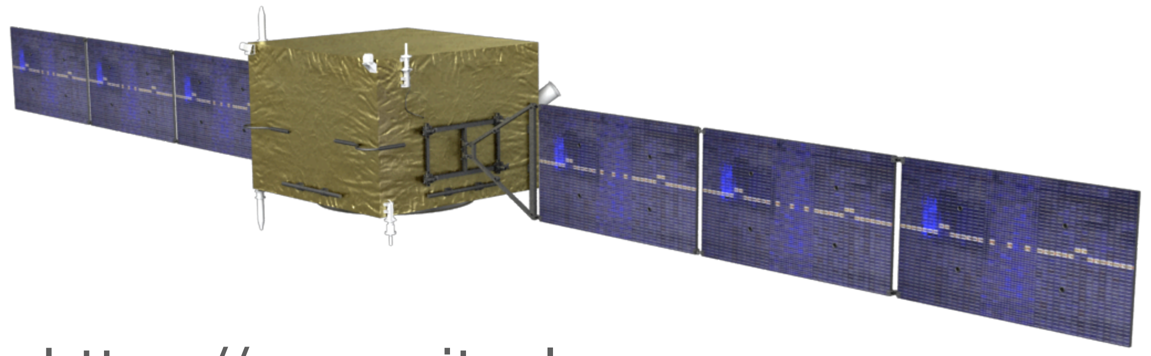
Direct measurements

10 GeV - 100 TeV

- DAMPE:
  - Measurements of the spectrum of protons (Q. An et al., 2019) between 40 GeV and 100 TeV;
  - He for E = 70 GeV - 80 TeV (F. Alemanno *et al.*, 2021).

F. Alemanno *et al.*, *Phys. Rev. Lett.* (2021)



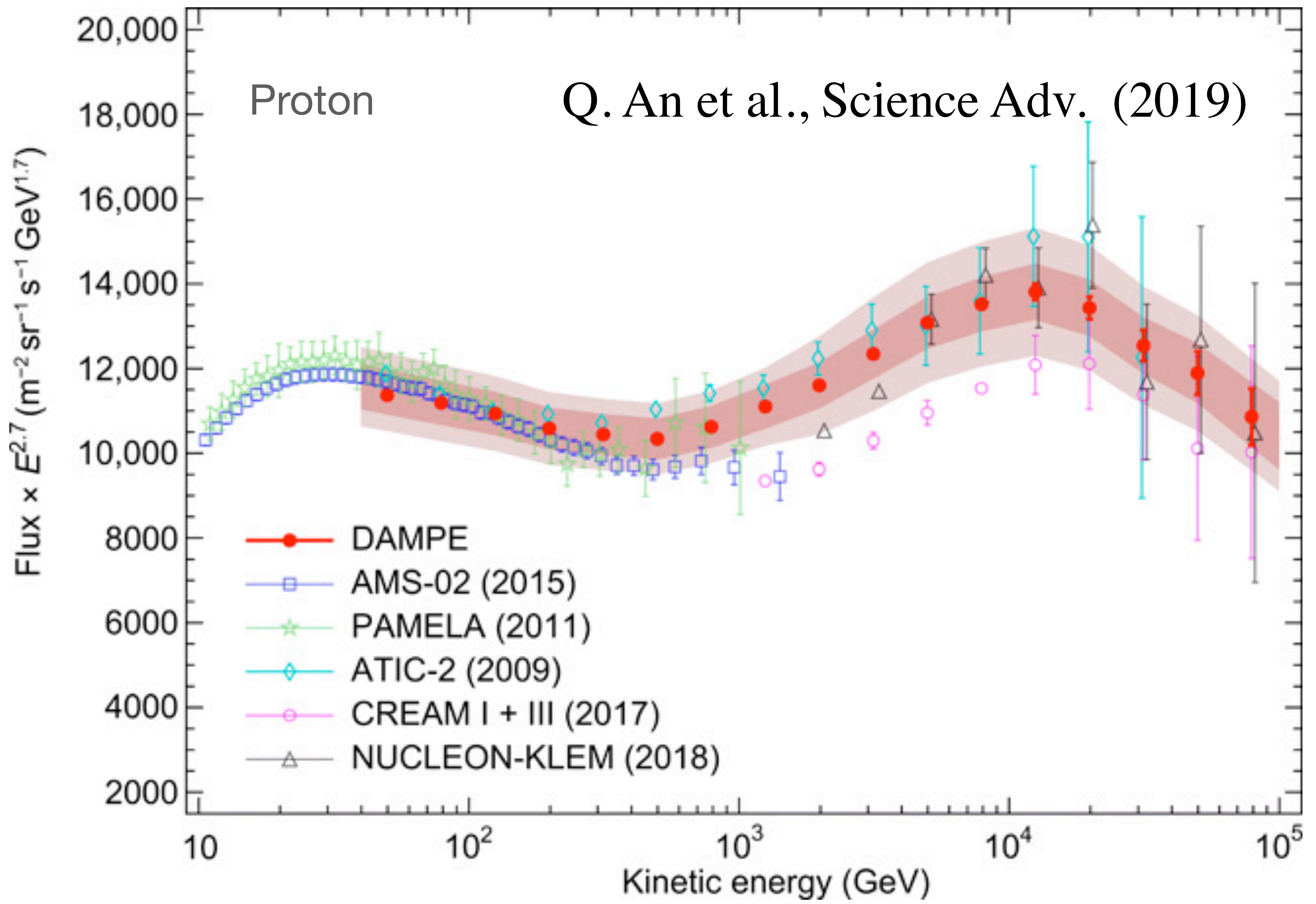


https://www.sitael.com

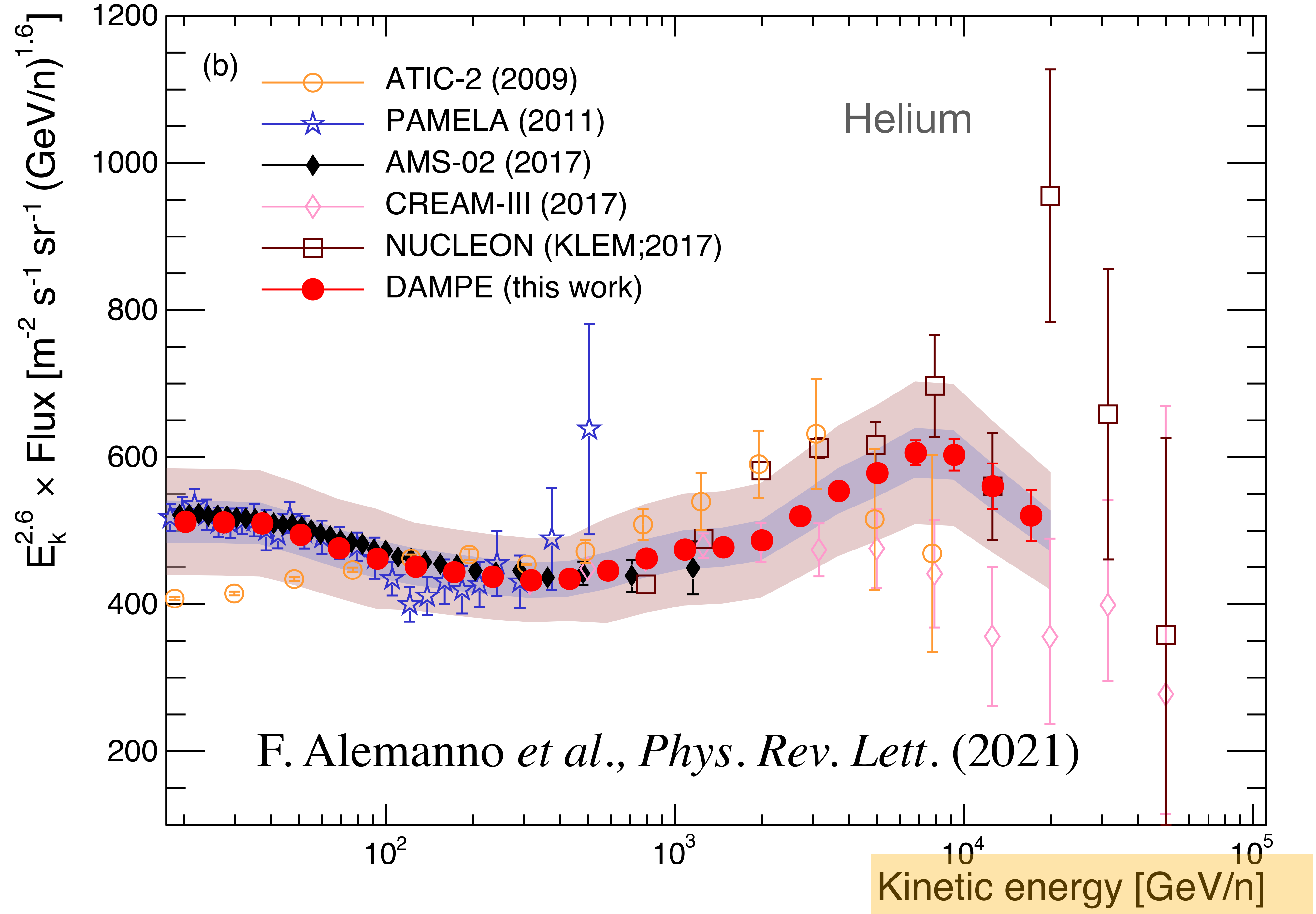
Direct measurements

10 GeV - 100 TeV

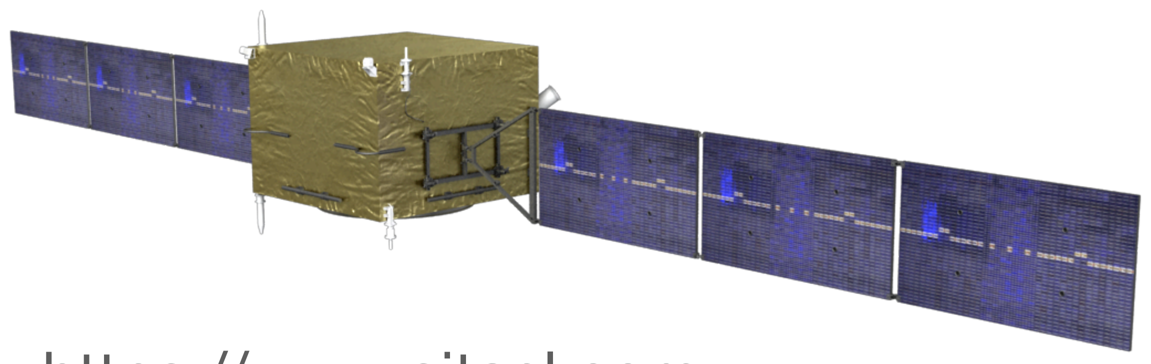
- DAMPE:
  - Measurements of the spectrum of protons (Q. An et al., 2019) between 40 GeV and 100 TeV;
  - He for E = 70 GeV - 80 TeV (F. Alemanno *et al*., 2021).
  - First confirmation of TeVs cutoffs in H and He spectra reported by ATIC-2 AND CREAM I-III.



Q. An et al., Science Adv. (2019)



F. Alemanno *et al*., *Phys. Rev. Lett*. (2021)

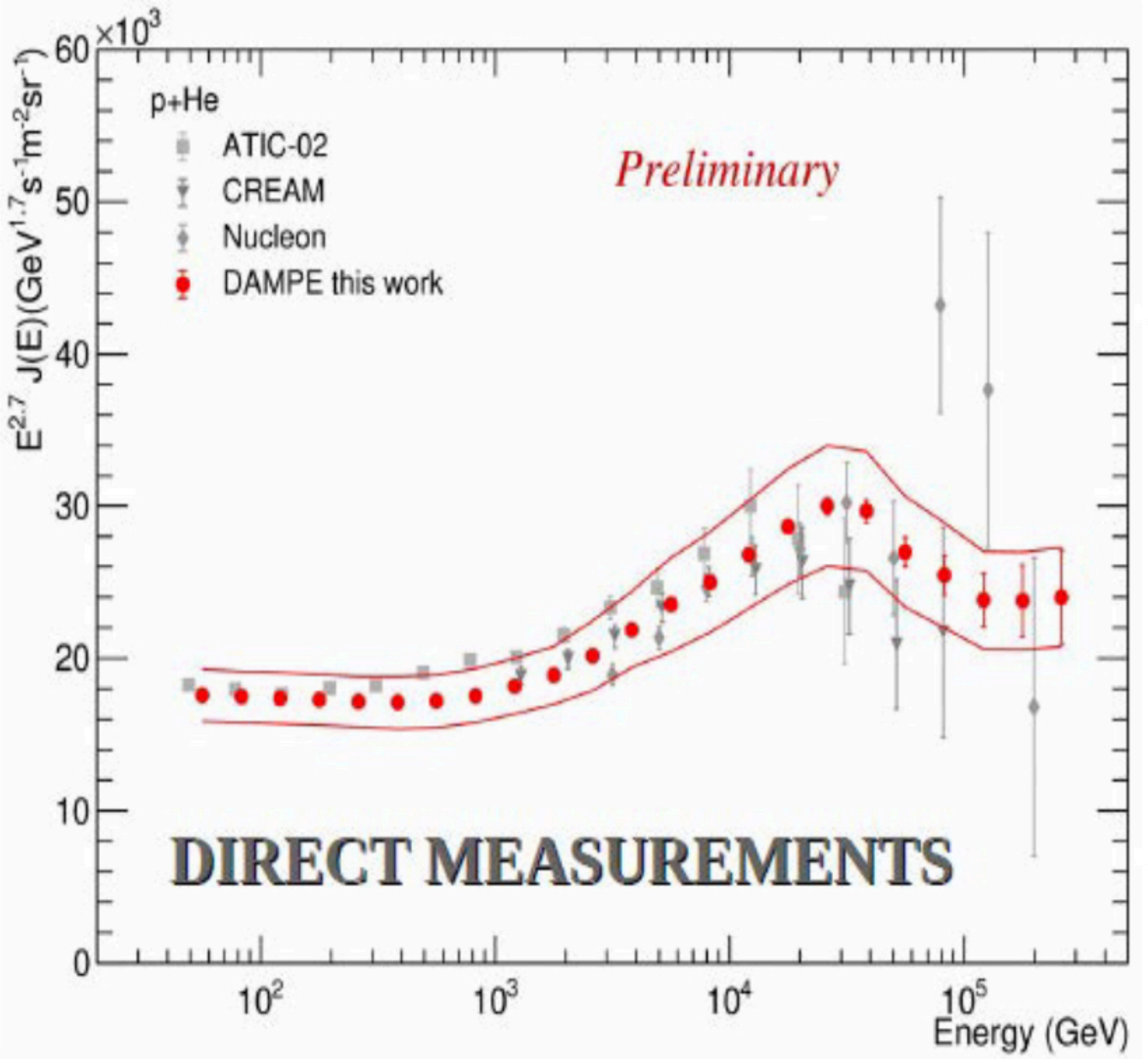


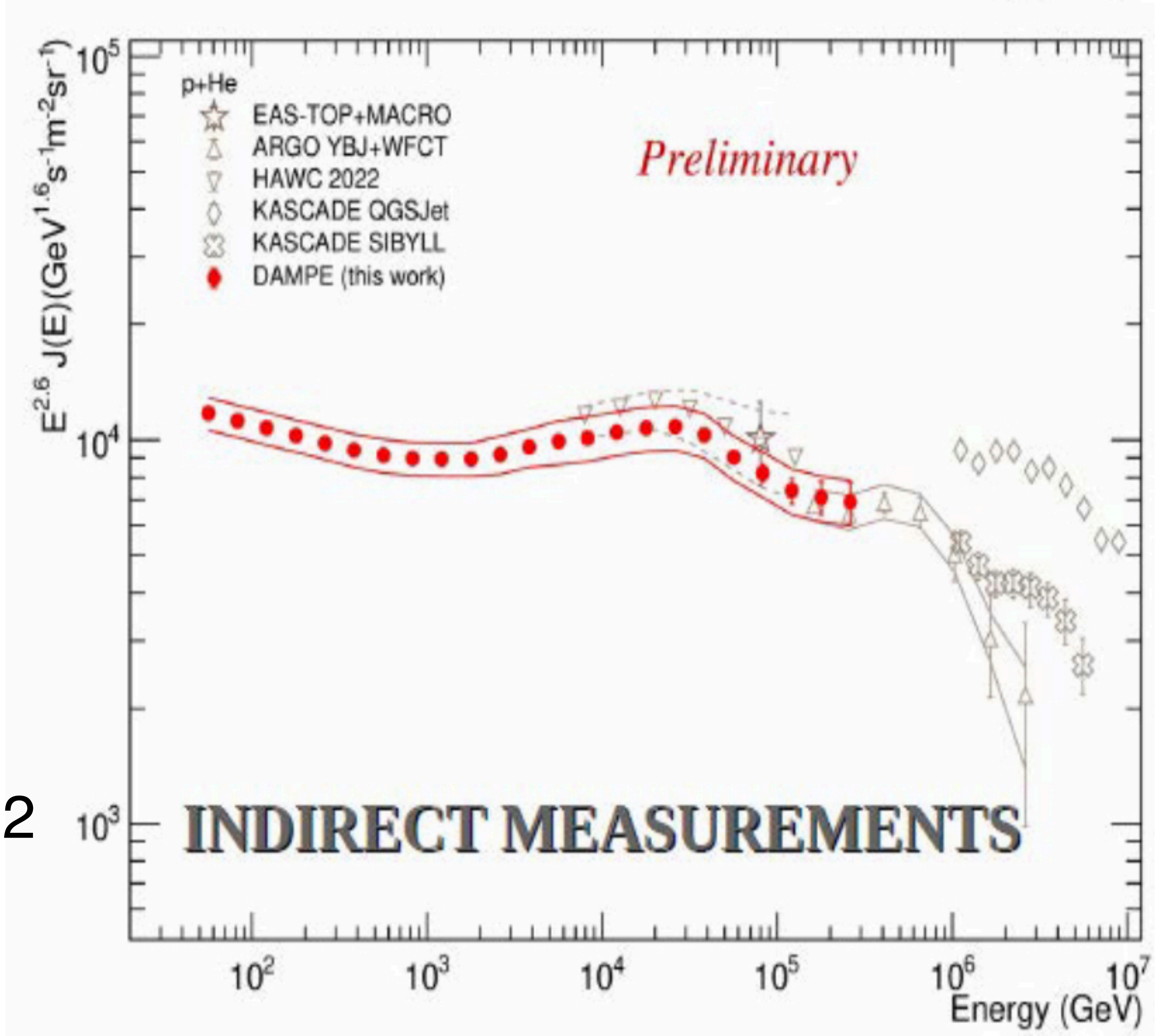
https://www.sitael.com

Direct measurements

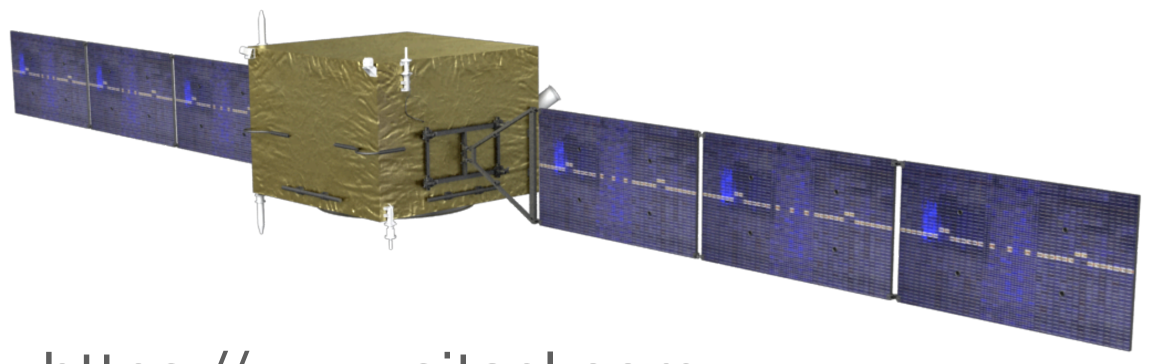
10 GeV - 100 TeV

- DAMPE:
  - Confirmation of the softening at ~ 25 TeV for combination of p and He spectra
  - Extension to 300 TeV
  - Overlapping with indirect measurements





I. de Mitri, ECRS 2022

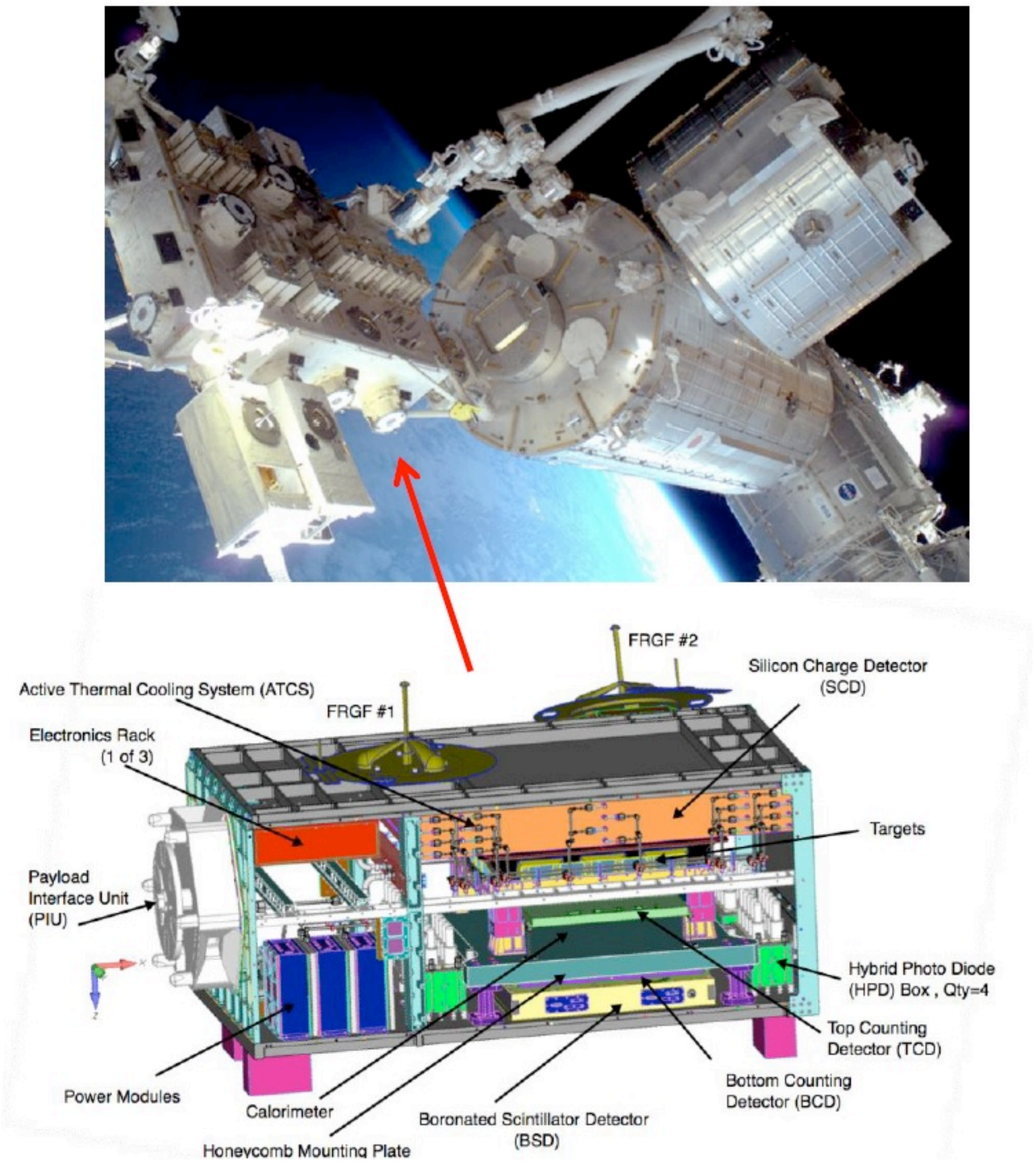


https://www.sitael.com

Direct measurements

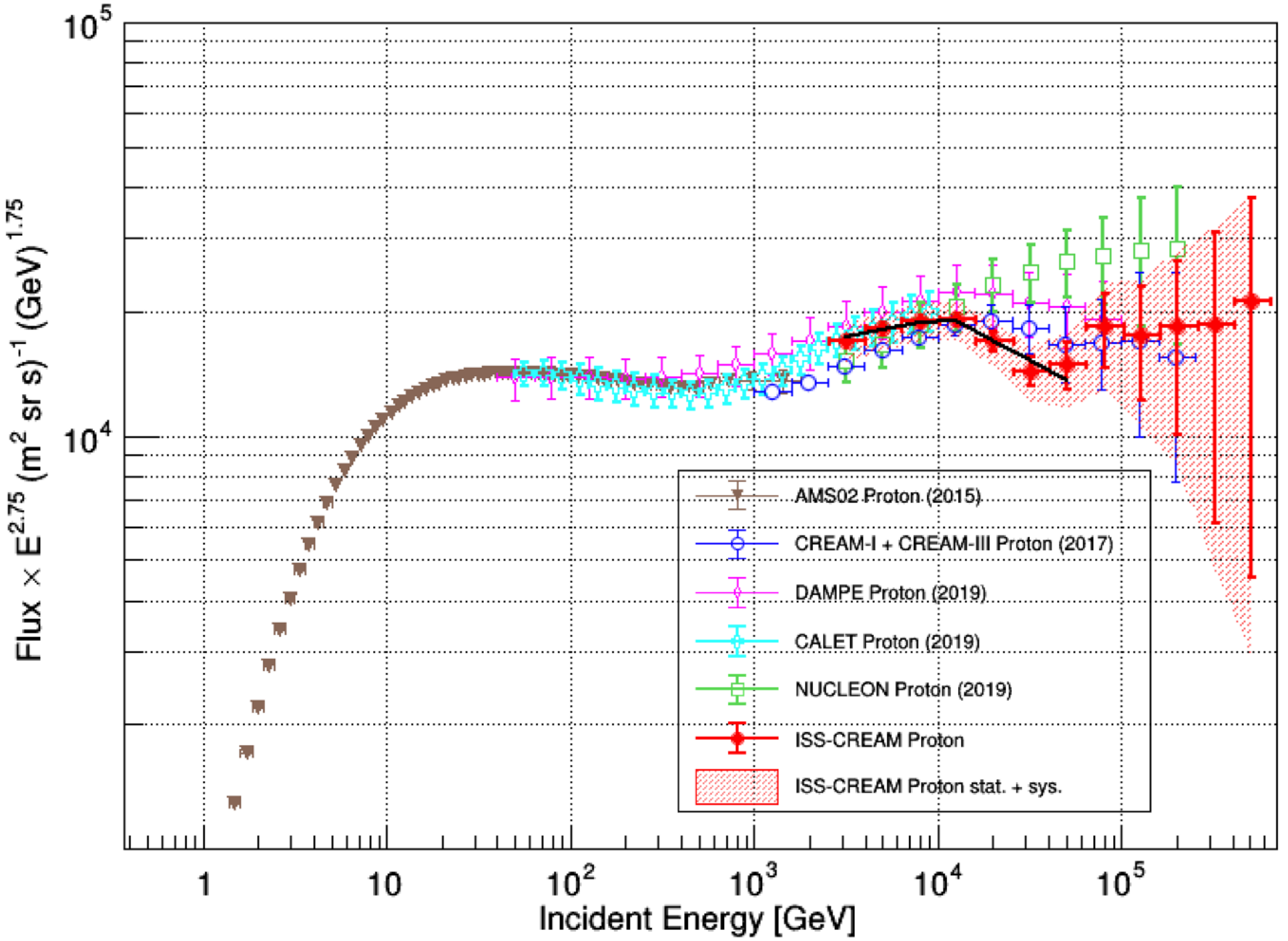
10 GeV - 100 TeV

- ISS-CREAM: showed preliminary results at ICRC2021 that seem to support HAWC observations on the recovery of light cosmic ray spectra around 100 TeV



ISS-CREAM; NASA; UMd

G. H. Choi, PoS(ICRC2021)094

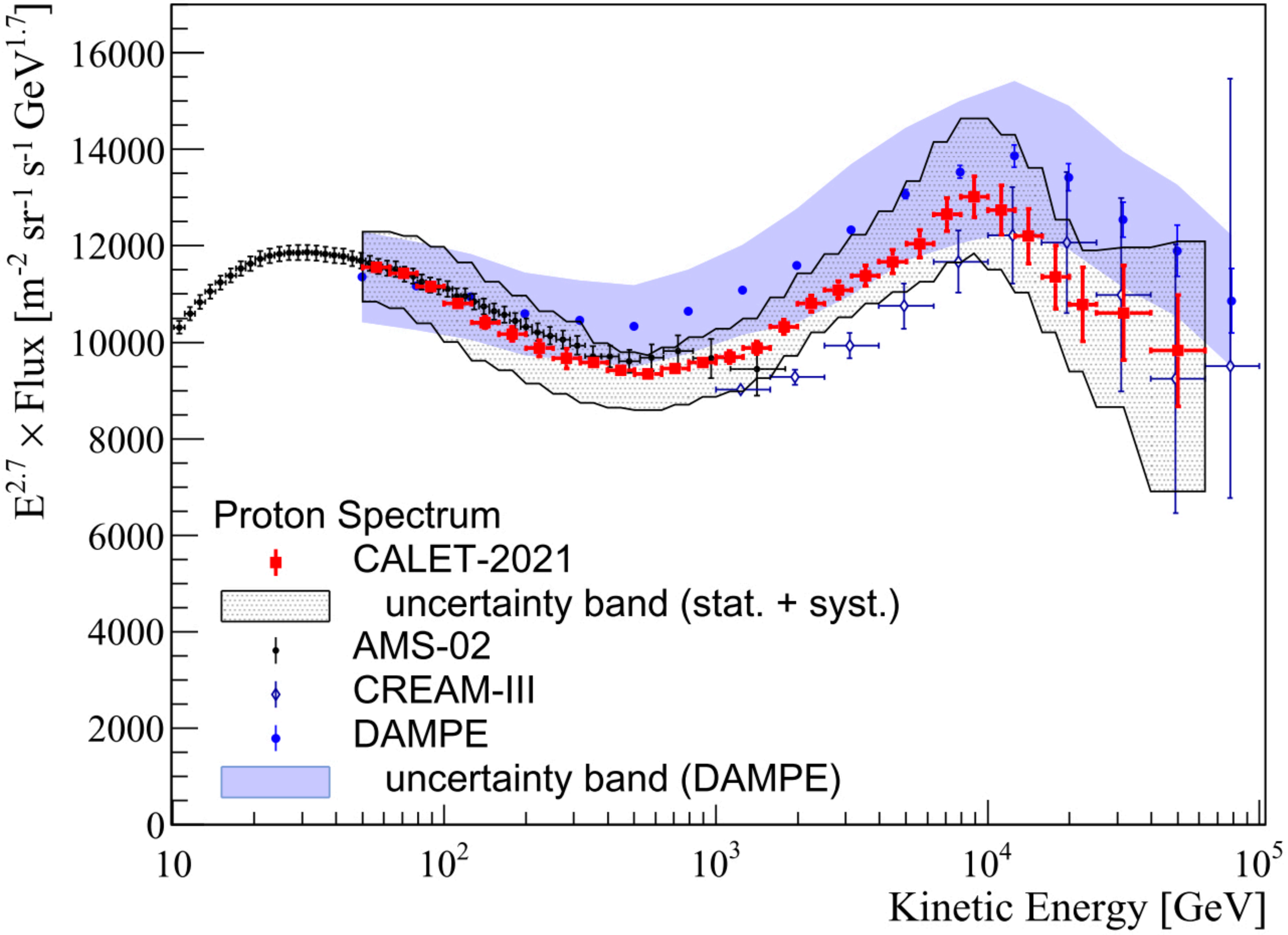


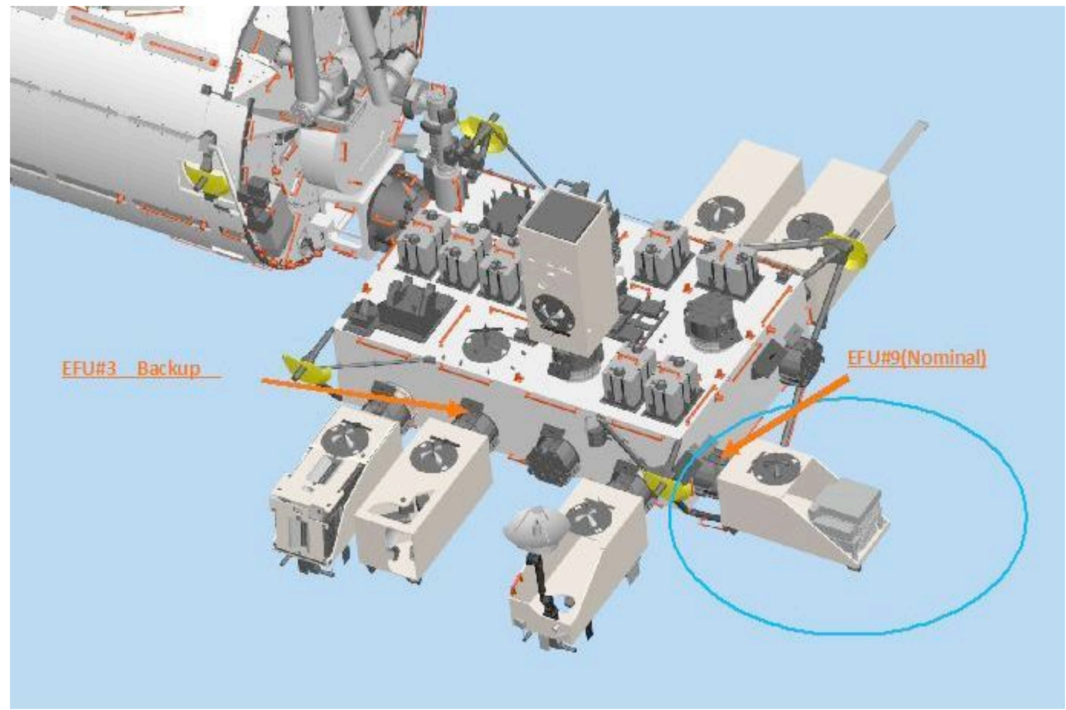
Direct measurements

10 GeV - 100 TeV

- CALET: Measurements of the p and He spectrum confirm the cutoffs in the p spectrum between 50 GeV and 60 TeV.

O. Adriani et al. Phys. Rev. Lett. (2022)





NASA

Indirect Detection Methods

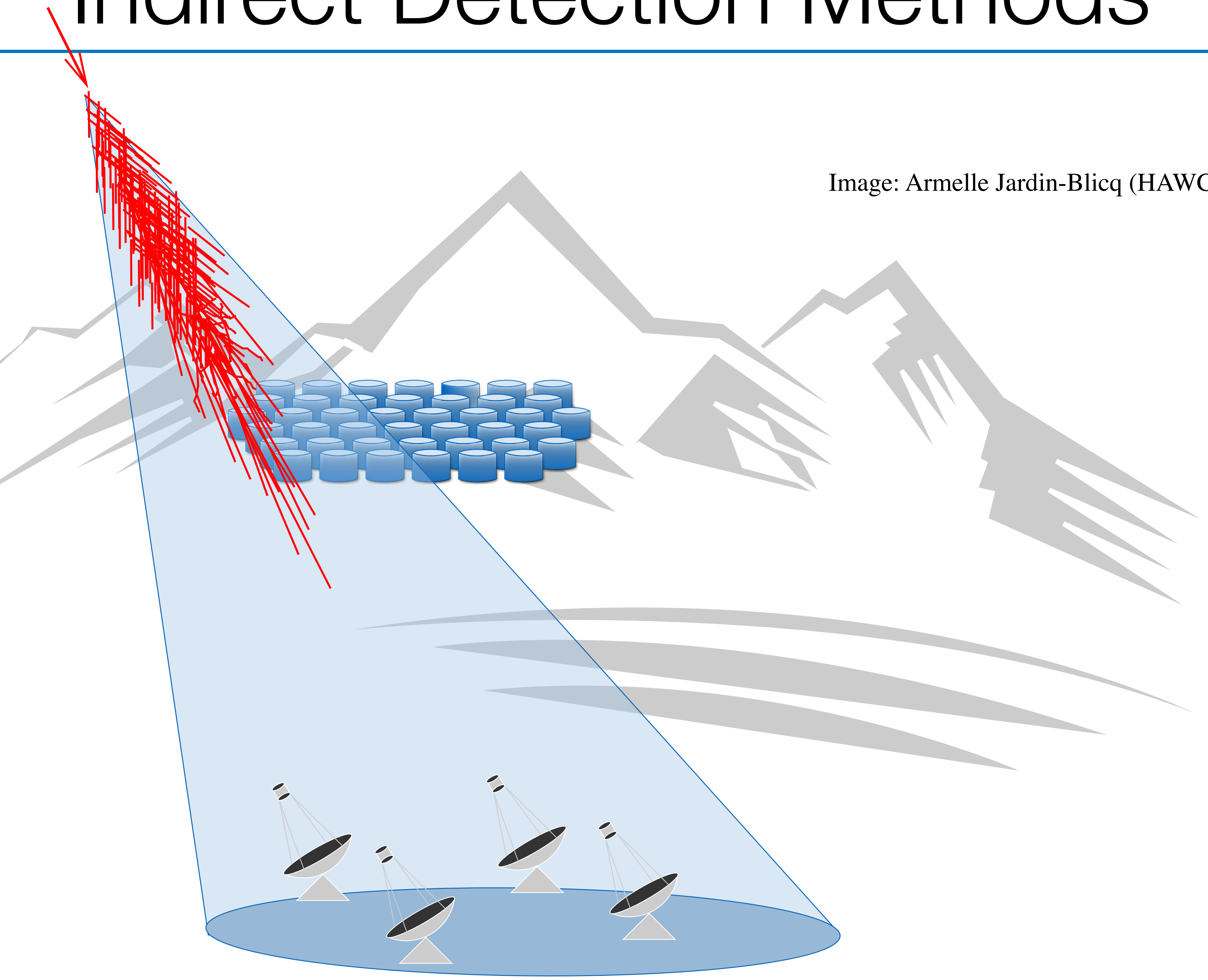
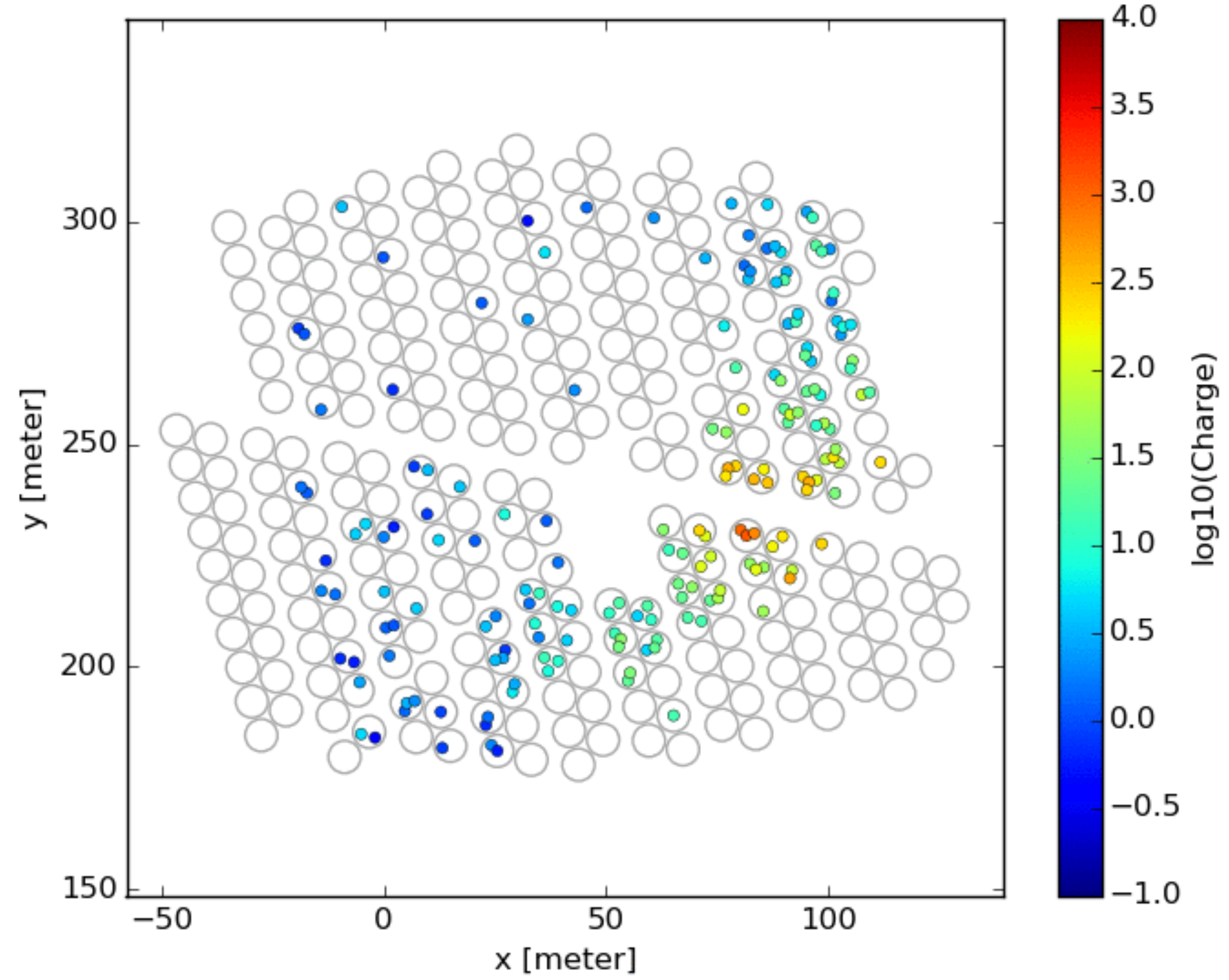


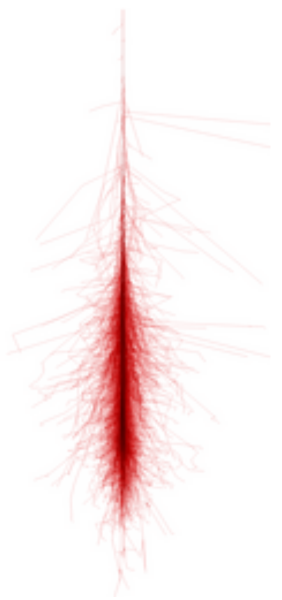
Image: Armelle Jardin-Blicq (HAWC Collaboration)

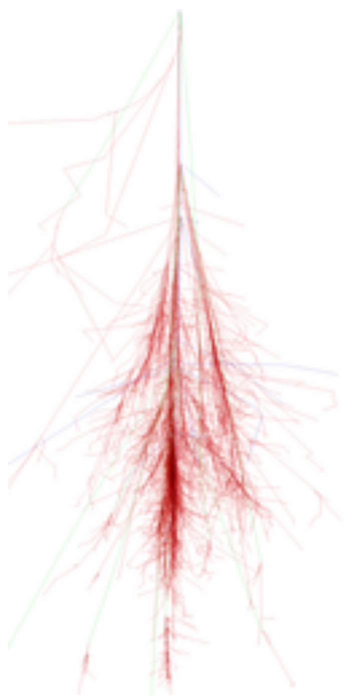
Imaging Atmospheric Cherenkov Telescope (IACT)

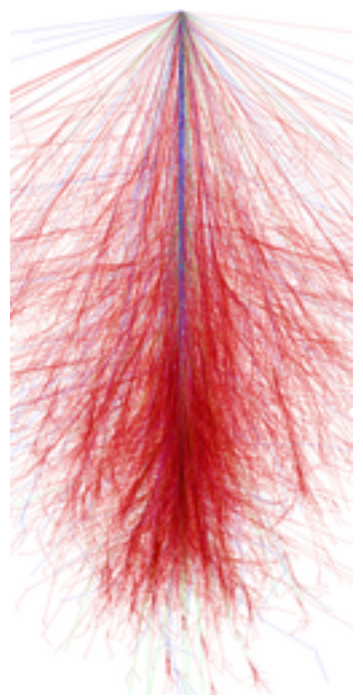
HAWC Collaboration



Extensive Air Shower Array (EAS)

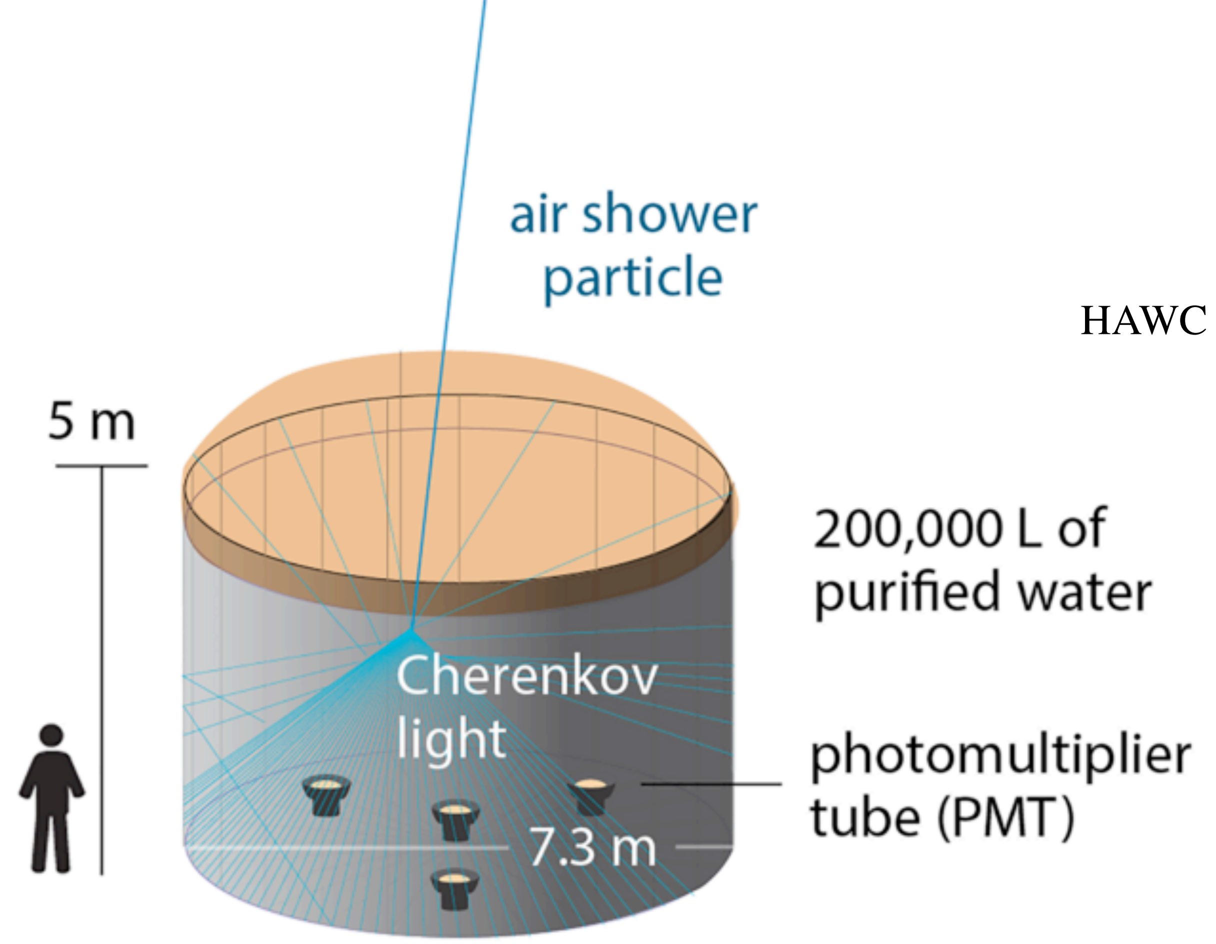

gamma shower


Proton shower

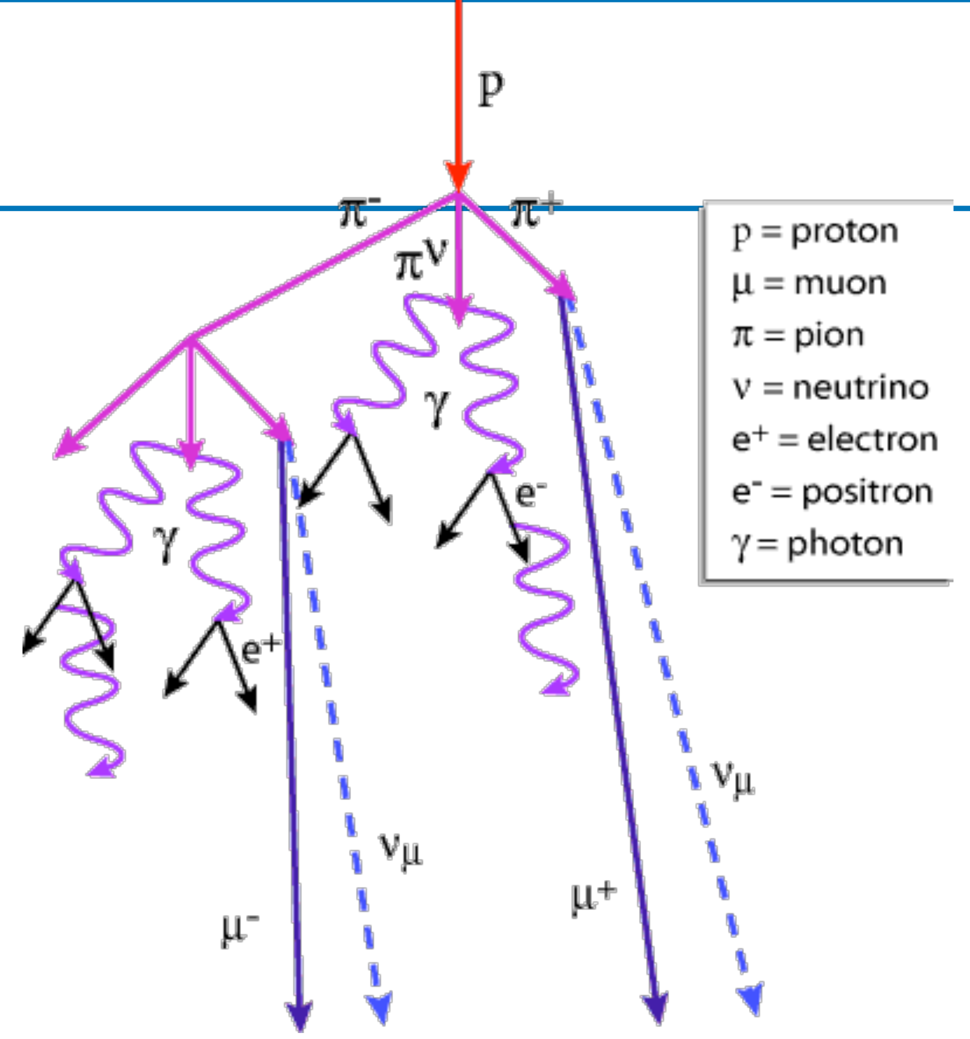

Iron shower

Images: Fabian Schmidt, University of Leeds, UK (https://www.iap.kit.edu/corsika/)

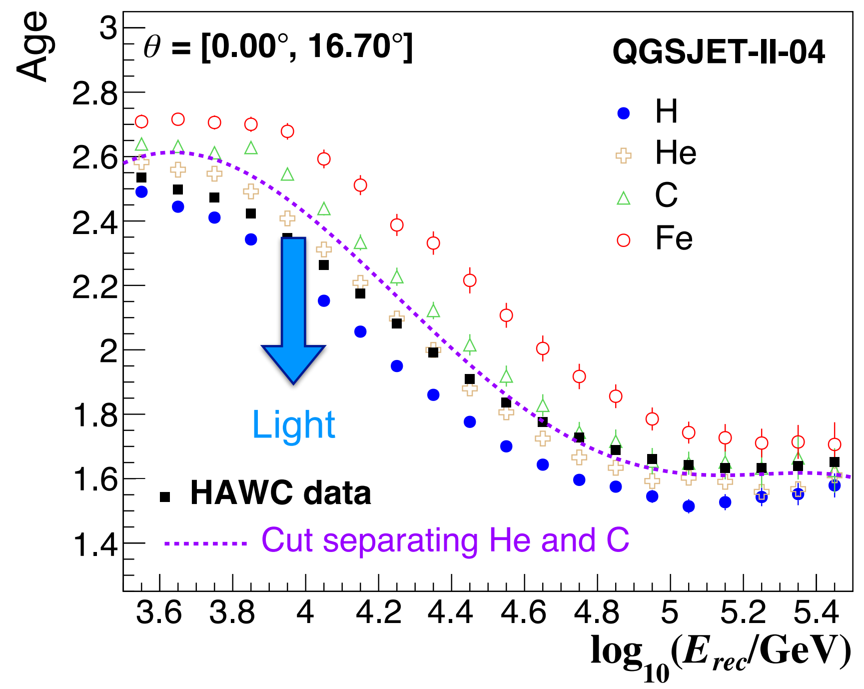
HAWC Collaboration



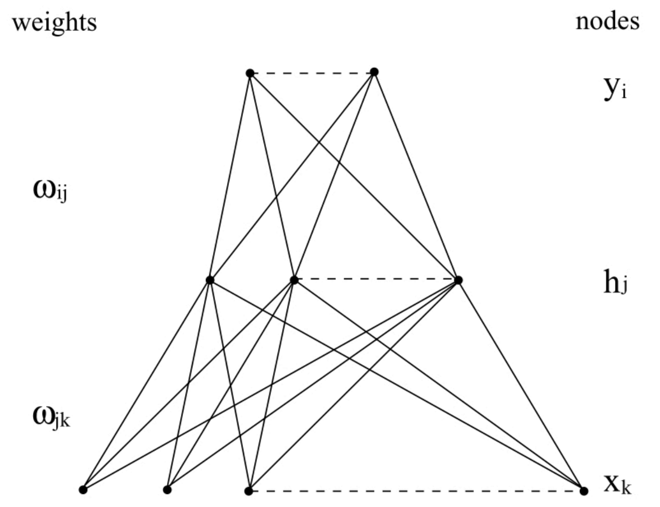
Indirect Detection Methods



- Detection of secondary air shower particles
- Large variance in shower development
- Method:
  - Limited observables: deposited charge, lateral charge distribution, core location, arrival direction, etc.
  - Use Monte Carlo simulations to statistically separate different mass species based on observables:
    - Direct cuts
    - ML methods
  - (typically) use an unfolding method to derive physical spectrum from observed spectrum, accounting for effective area, efficiency.



J. C. Arteaga-Velázquez (ISVHE-CRI 2022)



Amenomori, M. *et al*, Phys. Rev. D (2000)

$$N(E_{\rm reco}) = \frac{1}{\Omega}\int A_{\rm eff}(E, E_{\rm reco})N(E)dE,$$

$$P(E|E_{\rm reco}) = \frac{P(E_{\rm reco}|E)P(E)}{\epsilon(E)\sum_{E'}P(E_{\rm reco}|E')P(E')} \qquad N(E) = \sum_{E_{\rm reco}} N(E_{\rm reco})P(E|E_{\rm reco})$$

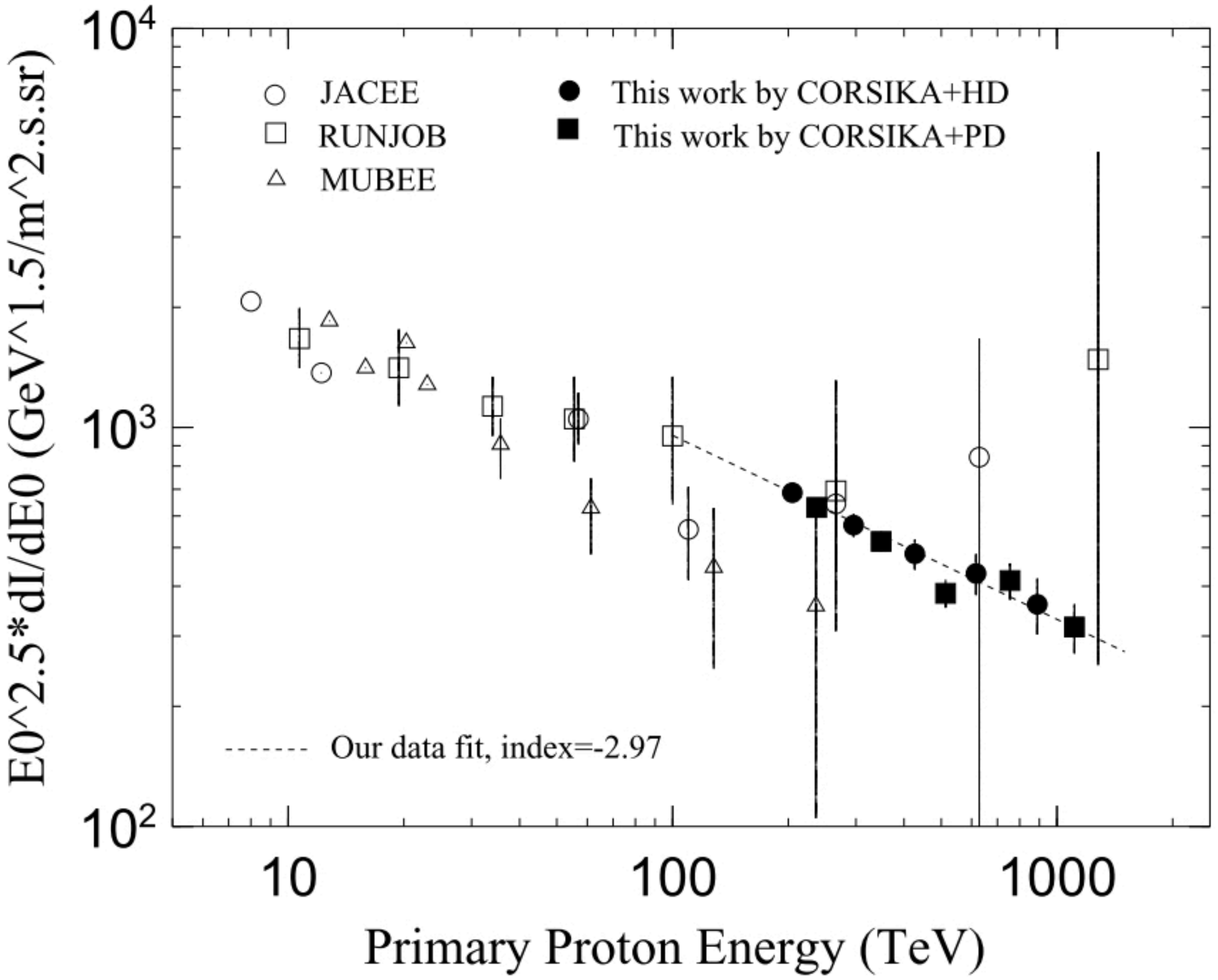
G. D'Agostini, Nucl. Inst. Meth. Phys. Res., **362** (1995).

Early Ground-based Measurements

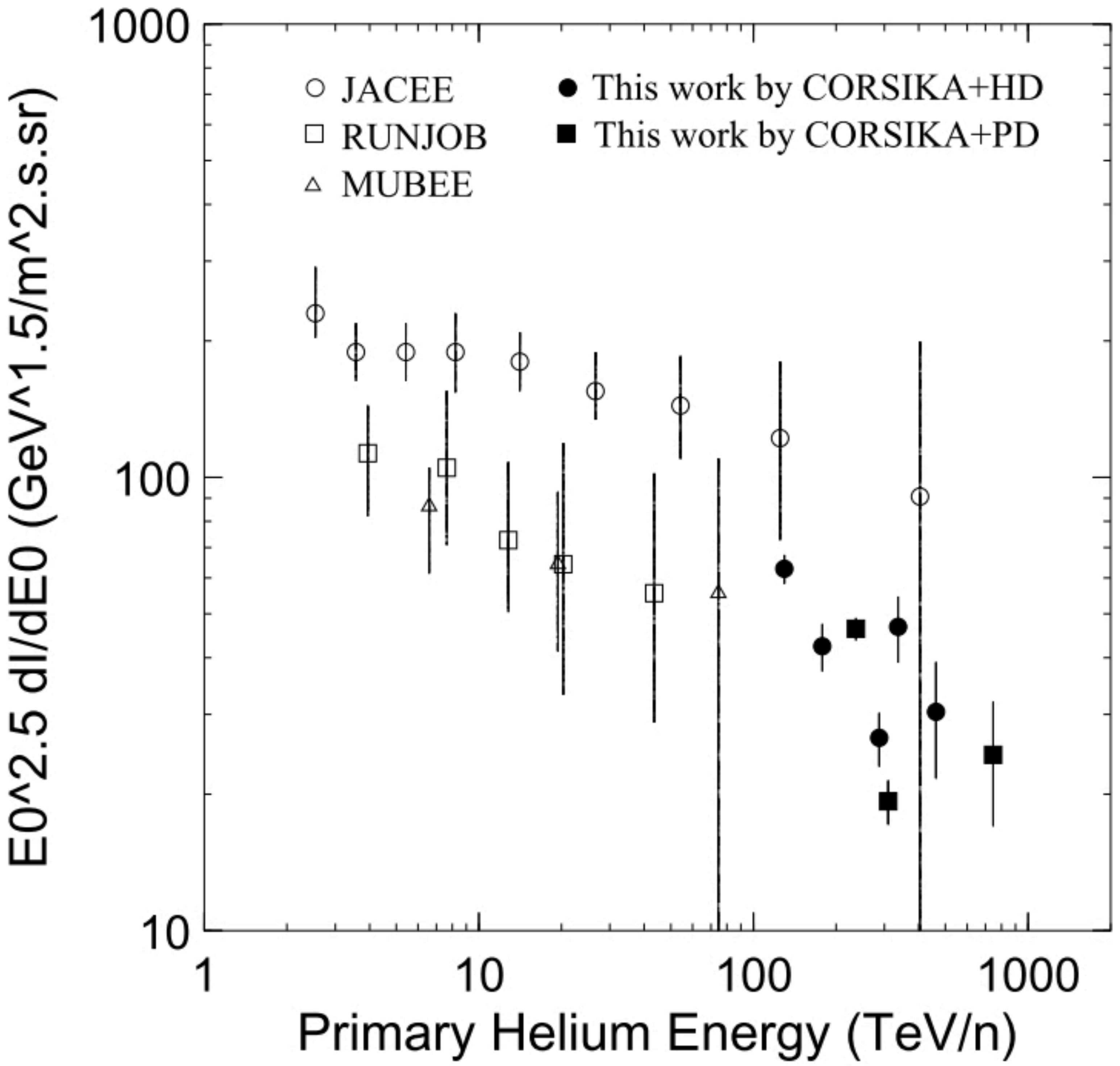
Sciascio, Giuseppe, Sciences. 12. 705. (2022).

EAS Experiments 10 TeV - 1 PeV

- **TIBET** measured the energy spectrum of H and He for E = 200 TeV - 1 PeV.
- **EAS-TOP** with **MACRO**, on the intensity of H, He and CNO primaries.
- **KASCADE**, on the flux of p primaries [6].
- **ARGO-YBJ** performed measurements on the spectrum of the H+He mass group.

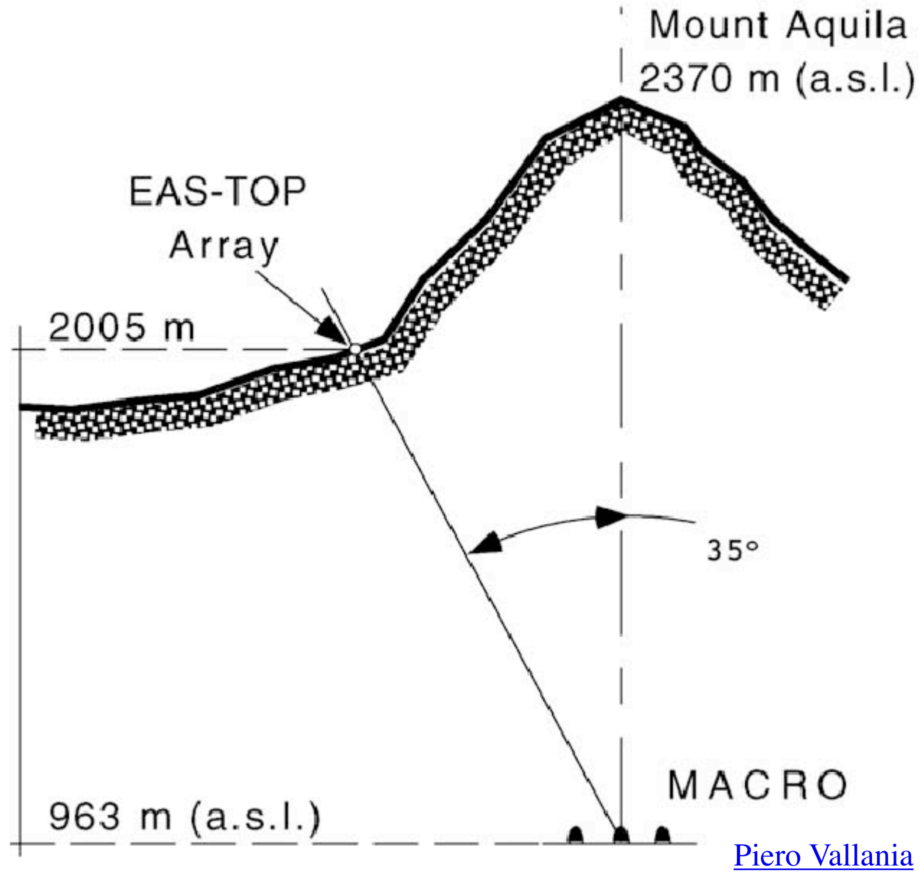


Amenomori, M. *et al*, Phys. Rev. D (2000)



Early Ground-based Measurements

EAS Array+Deep Underground μ-detector



Piero Vallania

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Aglietta, M. *et al,* Astro. Phys. **21** (2004)

Table 5
Comparison (a) of the present results alone and (b) combined with the direct p-flux measurements, with the JACEE and RUNJOB data

Quantity(*)	EAS–TOP and MACRO	JACEE	RUNJOB
(a) $J_{\mathrm{p+He}}$(80 TeV)	18 ± 4	12 ± 3	8 ± 2
(b) J_{He}(80 TeV)	12.7 ± 4.4	6.4 ± 1.4	3.1 ± 0.7
(b) $\frac{J_{\mathrm{p}}}{J_{\mathrm{p+He}}}$(80 TeV)	0.29 ± 0.09	0.45 ± 0.12	0.63 ± 0.20
(a) $J_{\mathrm{p+He+CNO}}$(250 TeV)	1.1 ± 0.3	0.7 ± 0.2	0.5 ± 0.1
(a) $\frac{J_{\mathrm{p+He}}}{J_{\mathrm{p+He+CNO}}}$(250 TeV)	0.78 ± 0.17	0.70 ± 0.20	0.76 ± 0.25

CNO data and all errors of JACEE and RUNJOB are interpreted by ourselves from plots. (*)Intensity units are 10^{-7} $\mathrm{m^{-2}\,s^{-1}\,sr^{-1}\,TeV^{-1}}$.

Aglietta, M. *et al*, Astro. Phys. **10** (1999)

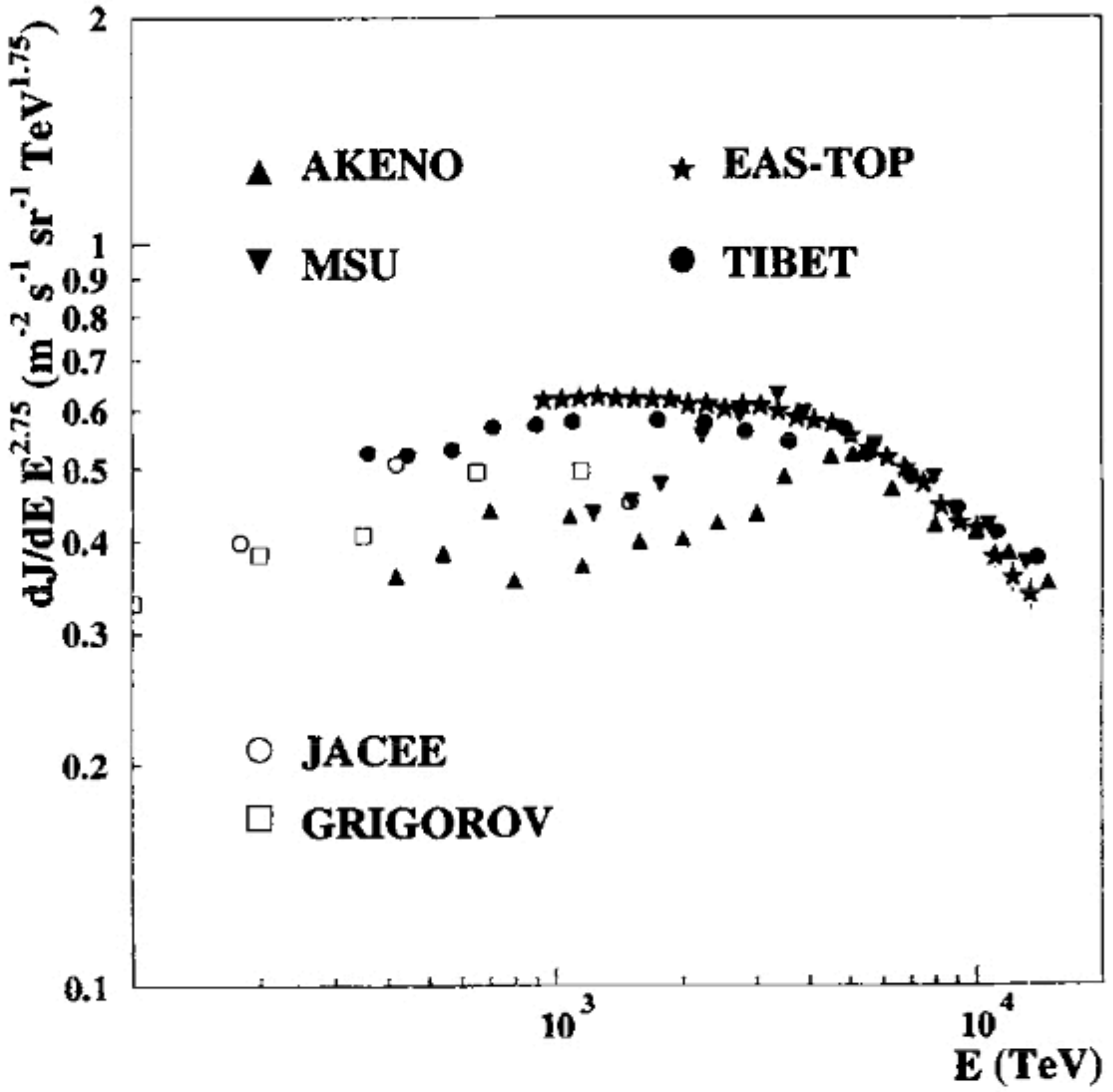

Fig. 7. The all particle spectrum obtained from the EAS-TOP shower size data, compared with the results of other experiments operating outside the atmosphere or at ground level (see text for references).

Early Ground-based Measurements

https://www.iap.kit.edu/kascade

EAS Experiments 10 TeV - 1 PeV

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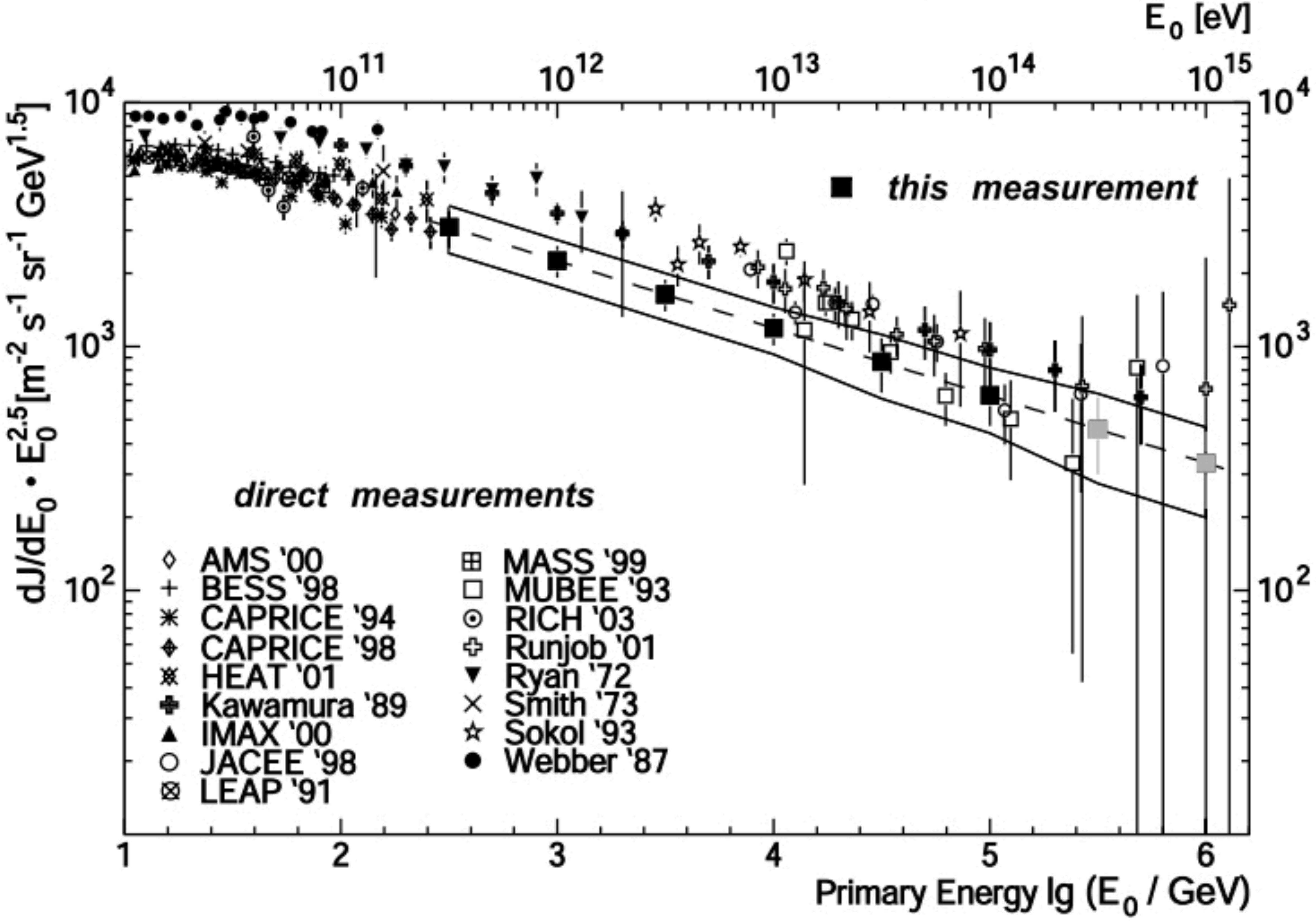
T. Antoni, et al. Astro. Phys J. 612, 2004



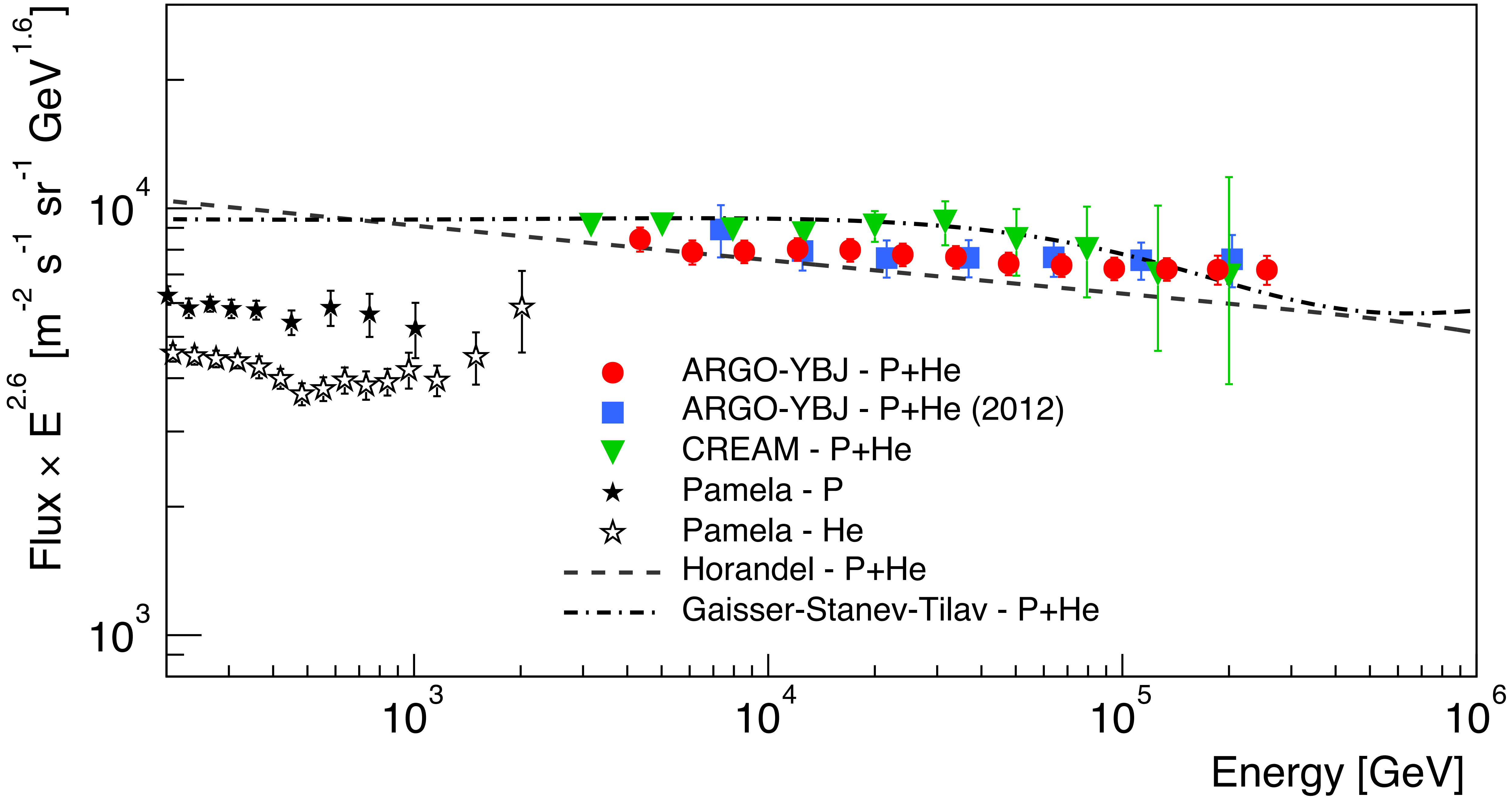
Early Ground-based Measurements

Cao, Zhen. Universe. 7. 339. (2021)

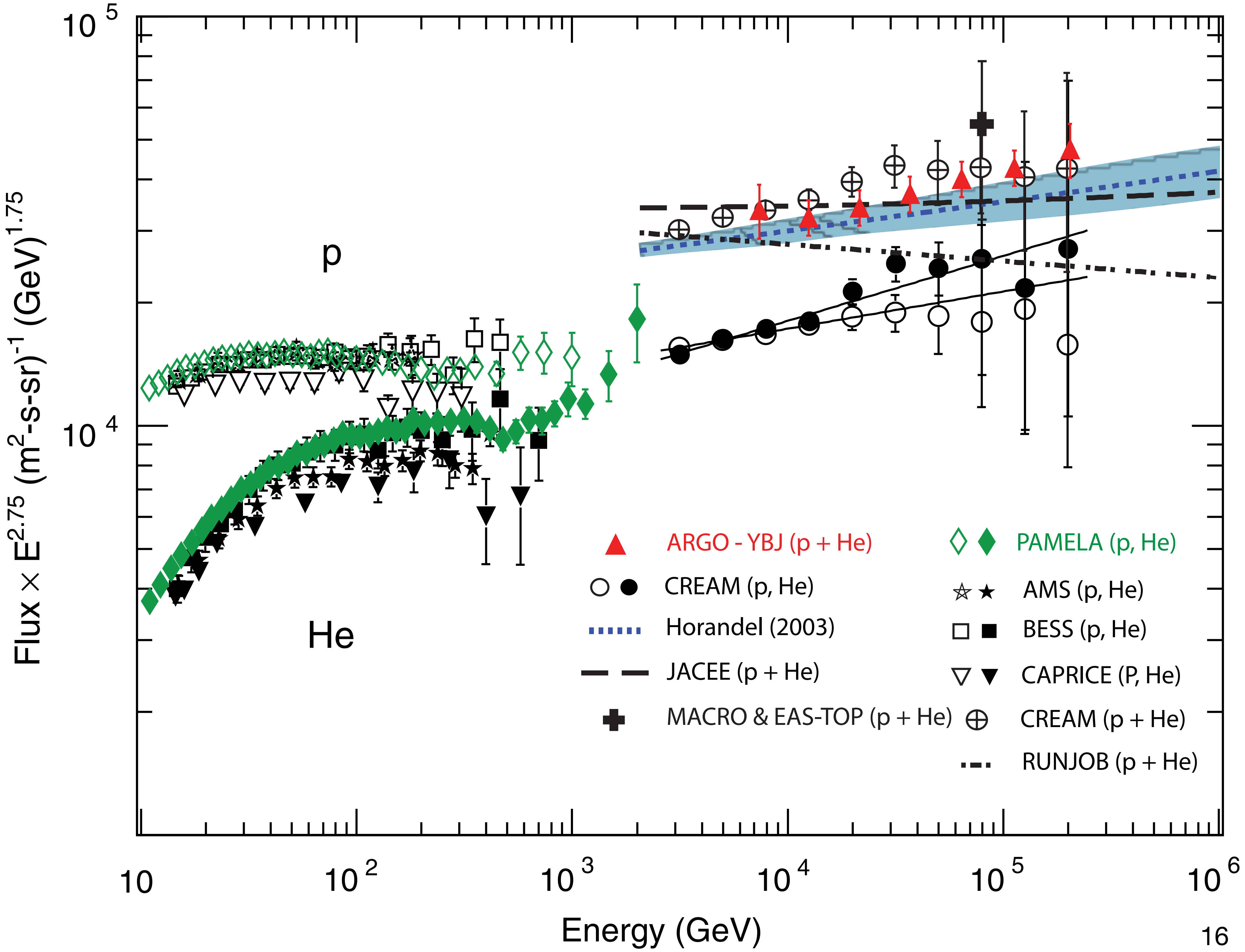
EAS Experiments 10 TeV - 1 PeV

- **TIBET** measured the energy spectrum of H and He for E = 200 TeV - 1 PeV.
- **EAS-TOP** with **MACRO**, on the intensity of H, He and CNO primaries .
- **KASCADE**, on the flux of p primaries .
- **ARGO-YBJ** performed measurements on the spectrum of the H+He mass group.
    - Consistent with single power law with γ = −2.64±0.01

B. Bartoli, et al. Phys. Rev. D (2015)



B. Bartoli, et al. Phys. Rev. D (2012)



Other Recent Ground-based Measurements

https://namibian.org

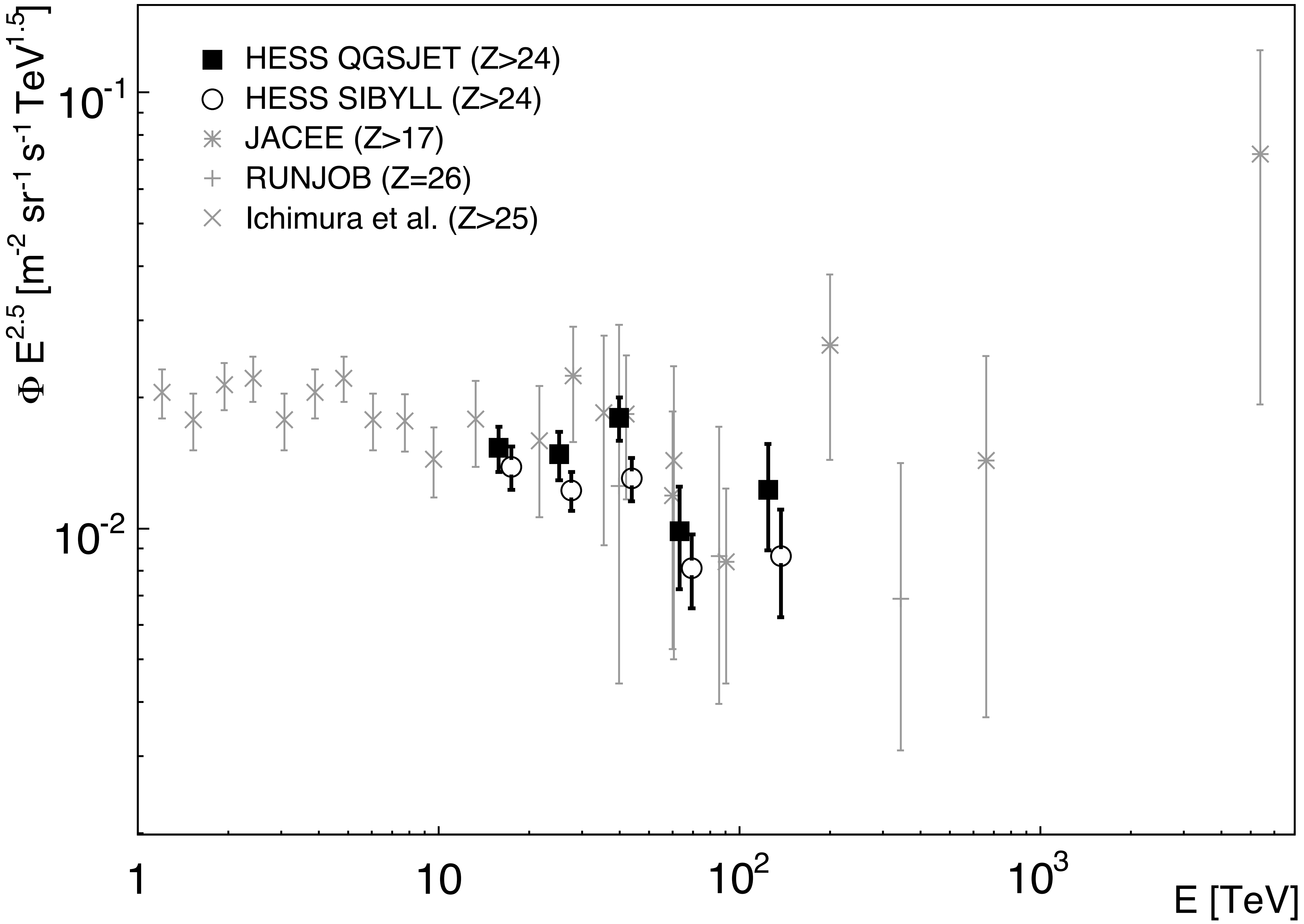
IACT Experiments 10 TeV - 1 PeV

- HESS, on the spectrum of Fe nuclei.

  Consistent with single power law: $\gamma = 2.62 \pm 0.17$

- One of the first indirect observations in agreement with direct measurements of Fe component.

F. Aharonian, et al, Physical Review D (2007)



Other Recent Ground-based Measurements

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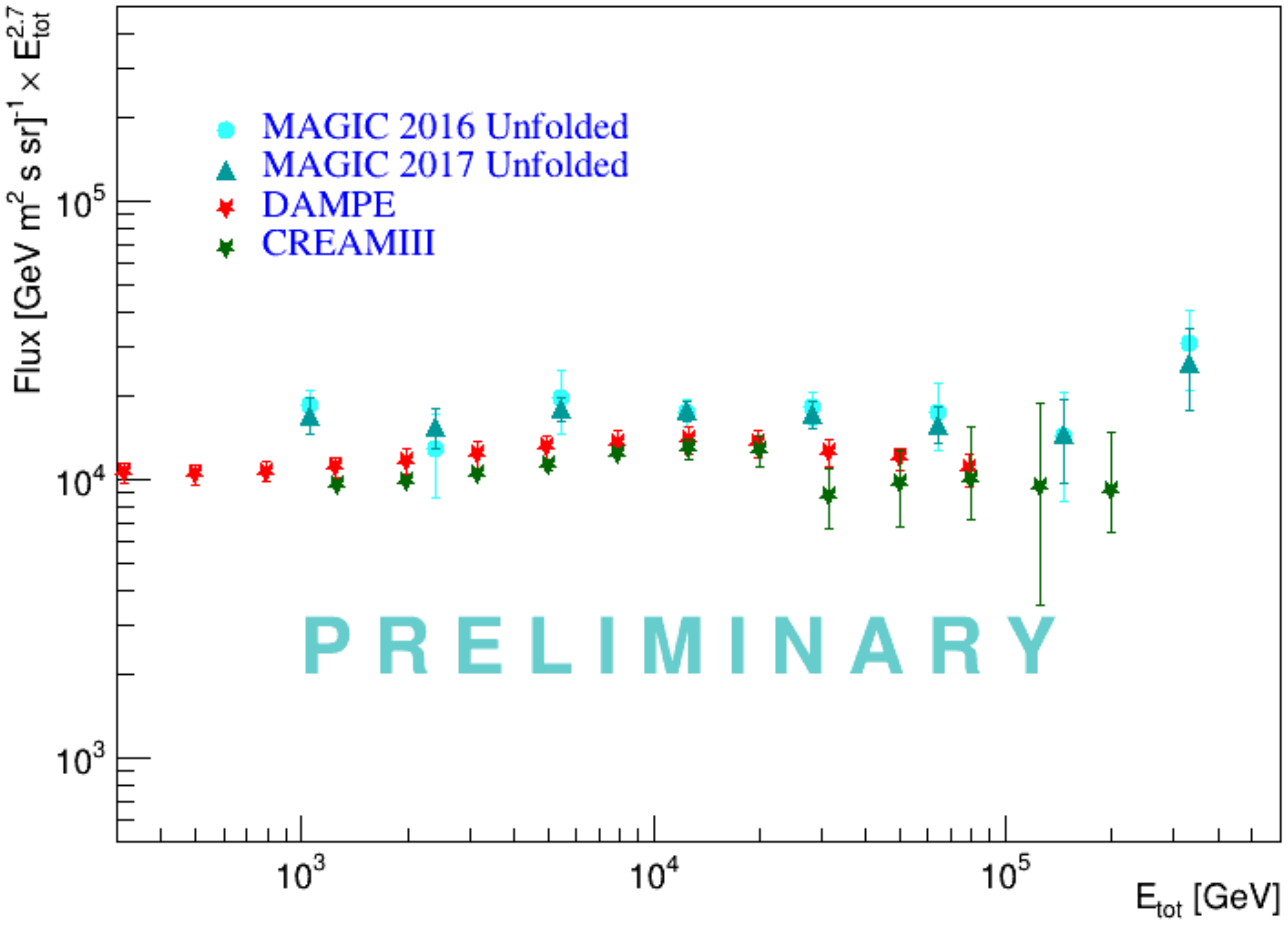
IACT Experiments 10 TeV - 1 PeV

- HESS, on the spectrum of Fe nuclei.
- MAGIC, on the intensity of protons

P. Temnikov, et al. ICRC (2021)



- Preliminary results shown at ICRC2021 (not included in proceedings).
- Protons discriminated from other nuclei through ML

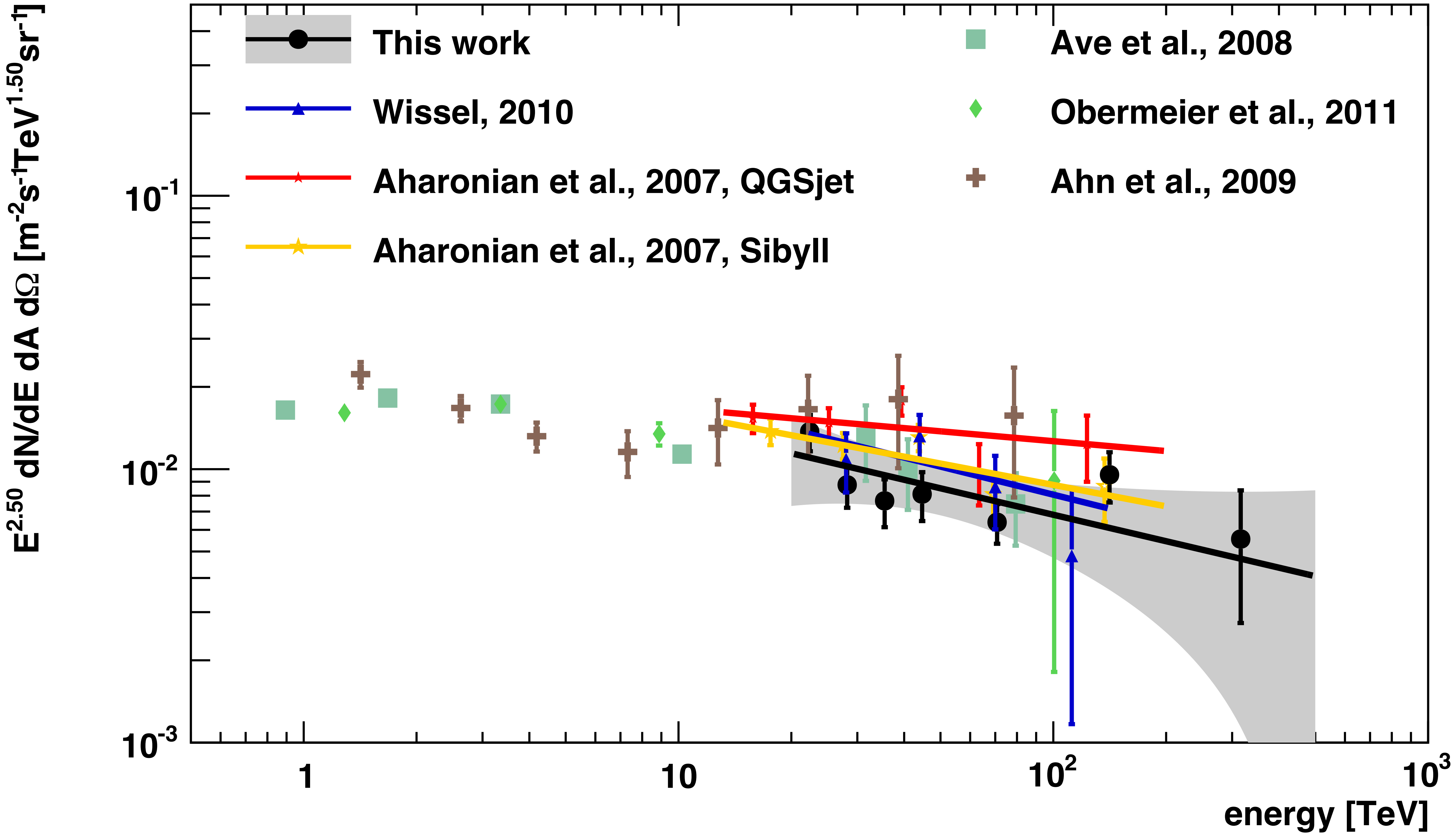
Other Recent Ground-based Measurements

IACT Experiments 10 TeV - 1 PeV

http://www.nsf.gov

- HESS, on the spectrum of Fe nuclei.
- MAGIC, on the intensity of protons
- VERITAS, on the spectrum of Fe nuclei.

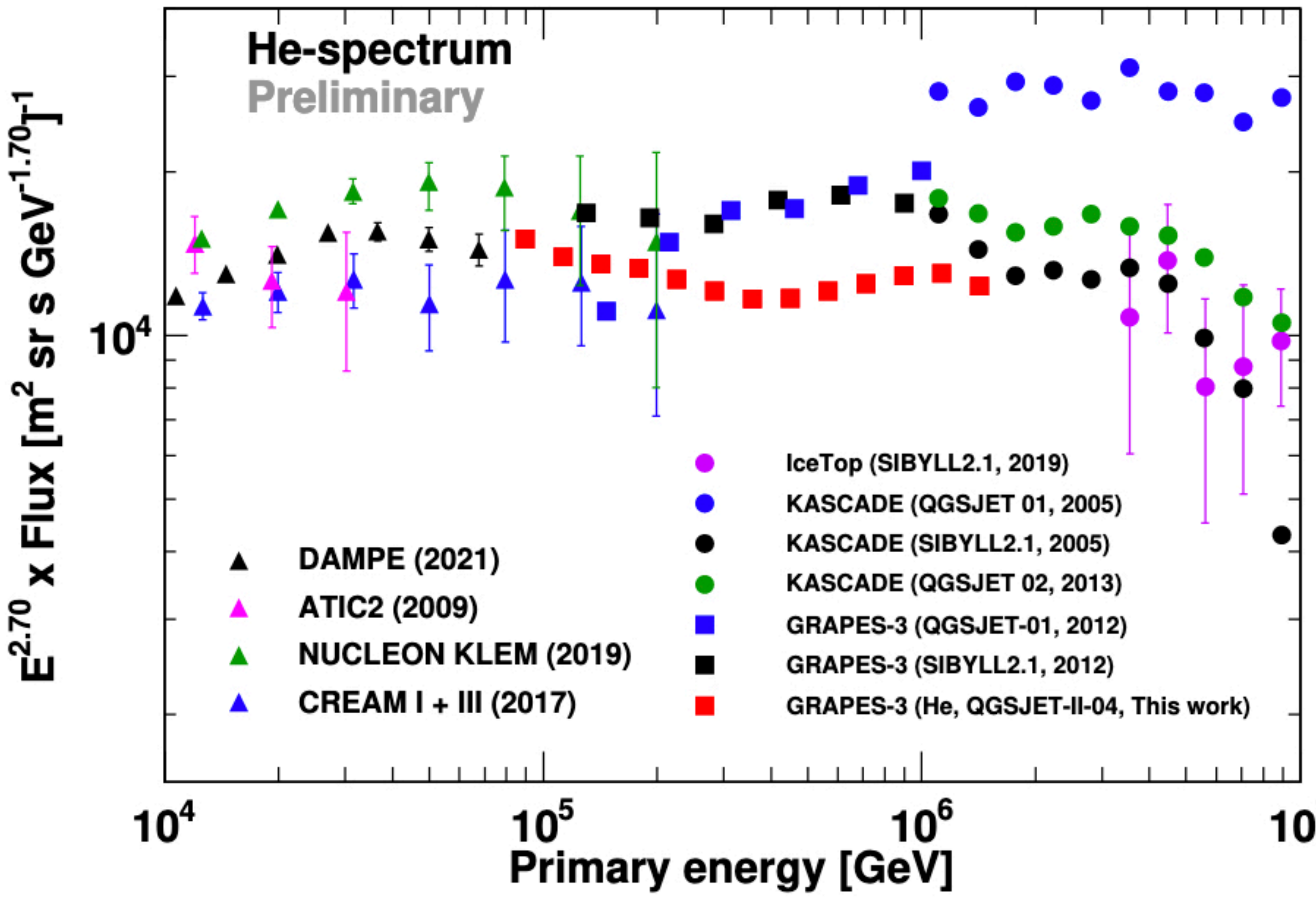
A. Archer, et al. Physical Review D **98** (2018)



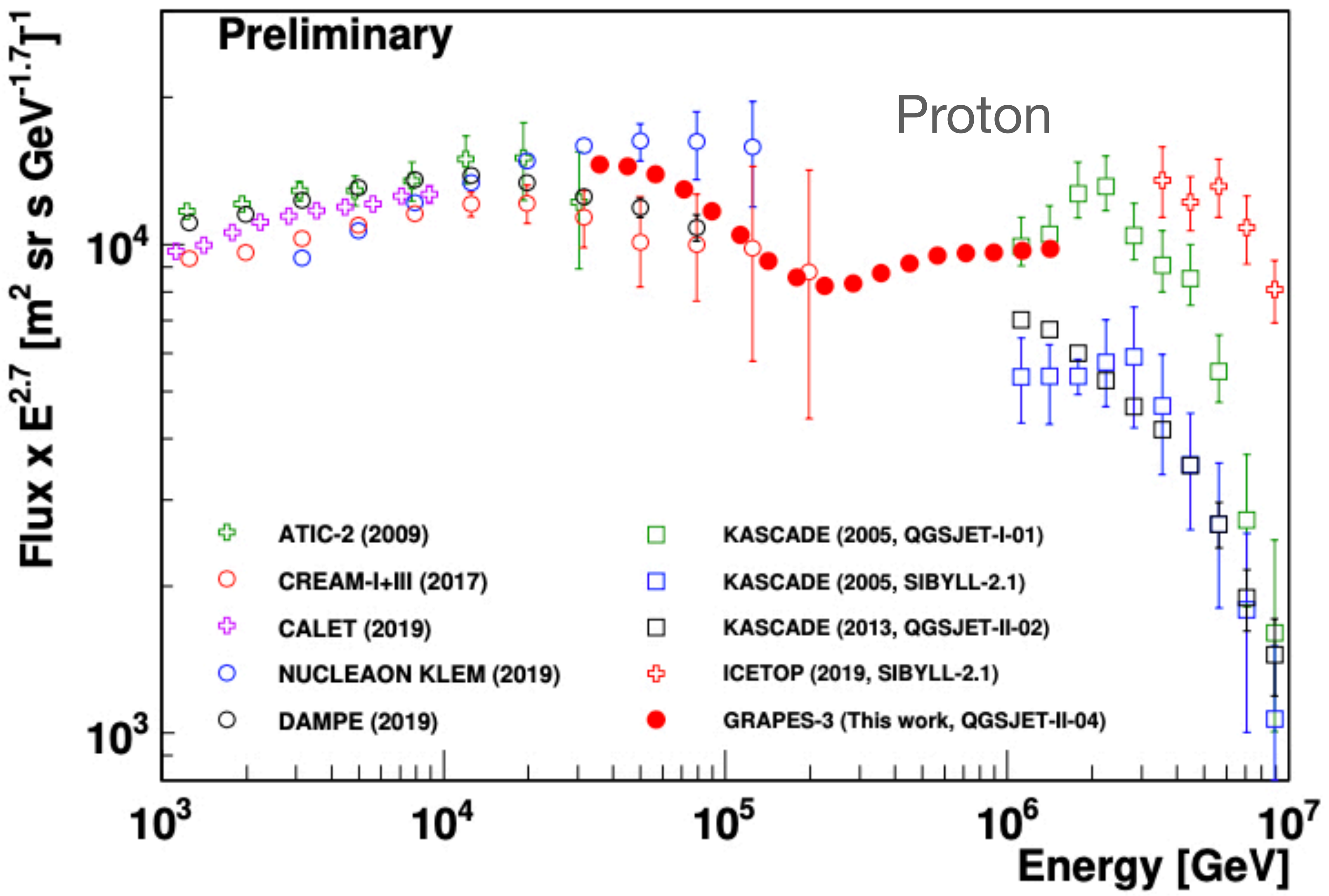
Other Recent Ground-based Measurements

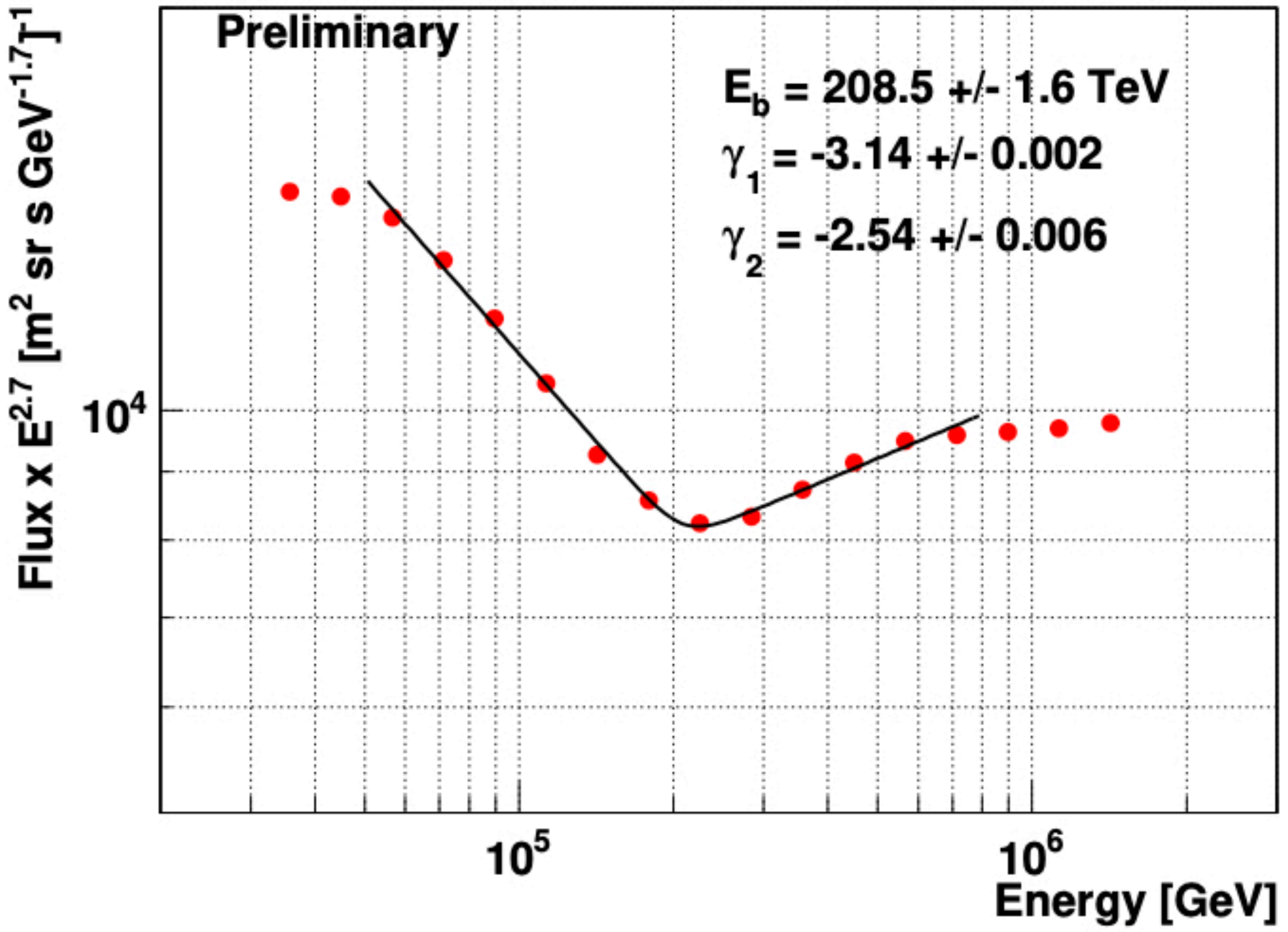
- GRAPES-3 (EAS):
  - proton spectrum indicates a spectral break at ~208TeV
  - both H and He have reasonably good overlap with other measurements

P.K. Mohanty, et a. PoS(ICRC2021)003



F. Varsi, et al. (ISVHECRI 2022)



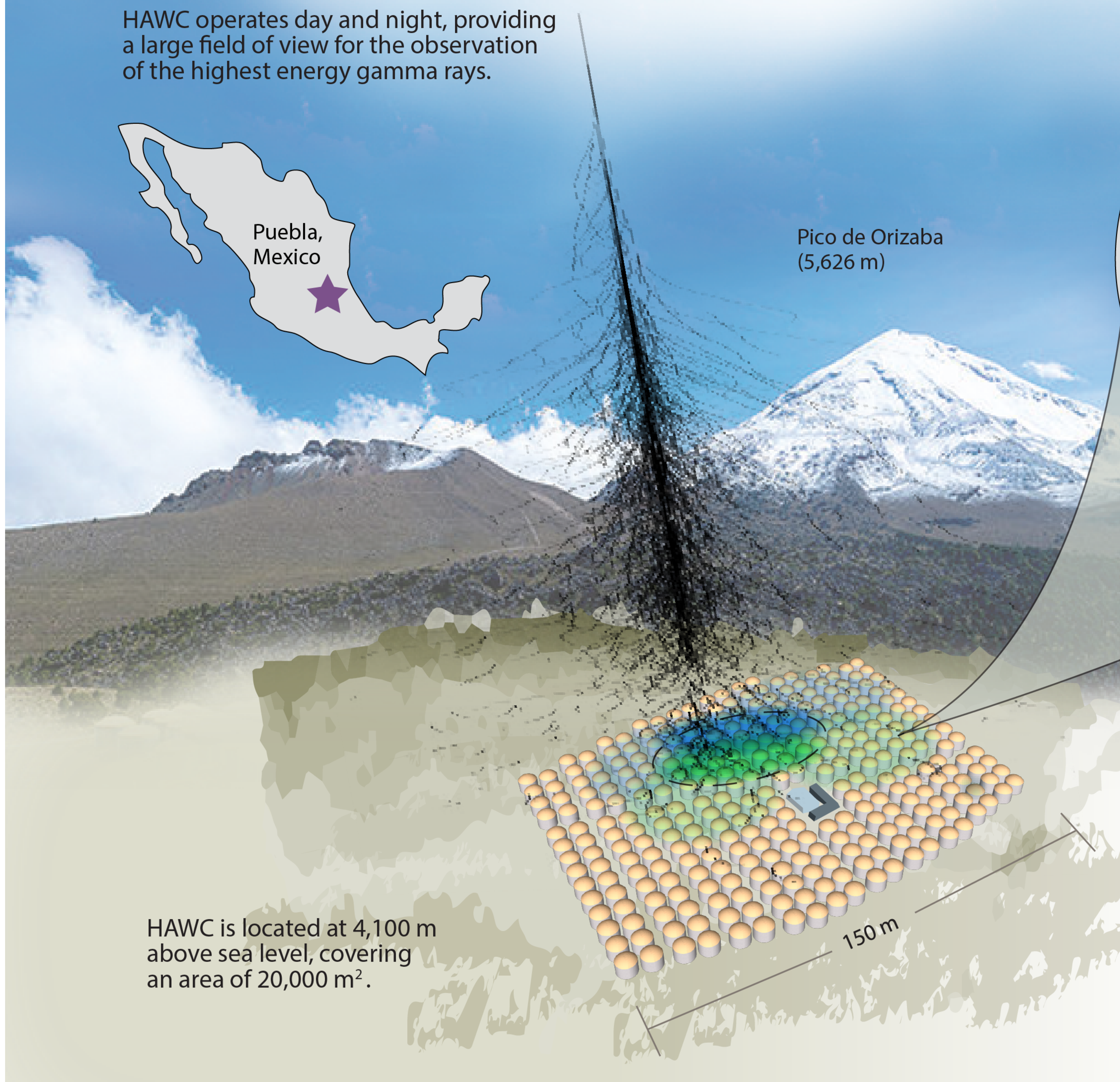


HAWC
High Altitude Water Cherenkov
Gamma-Ray Observatory

Mapping the Northern Sky in High-Energy Gamma Rays

HAWC Observatory

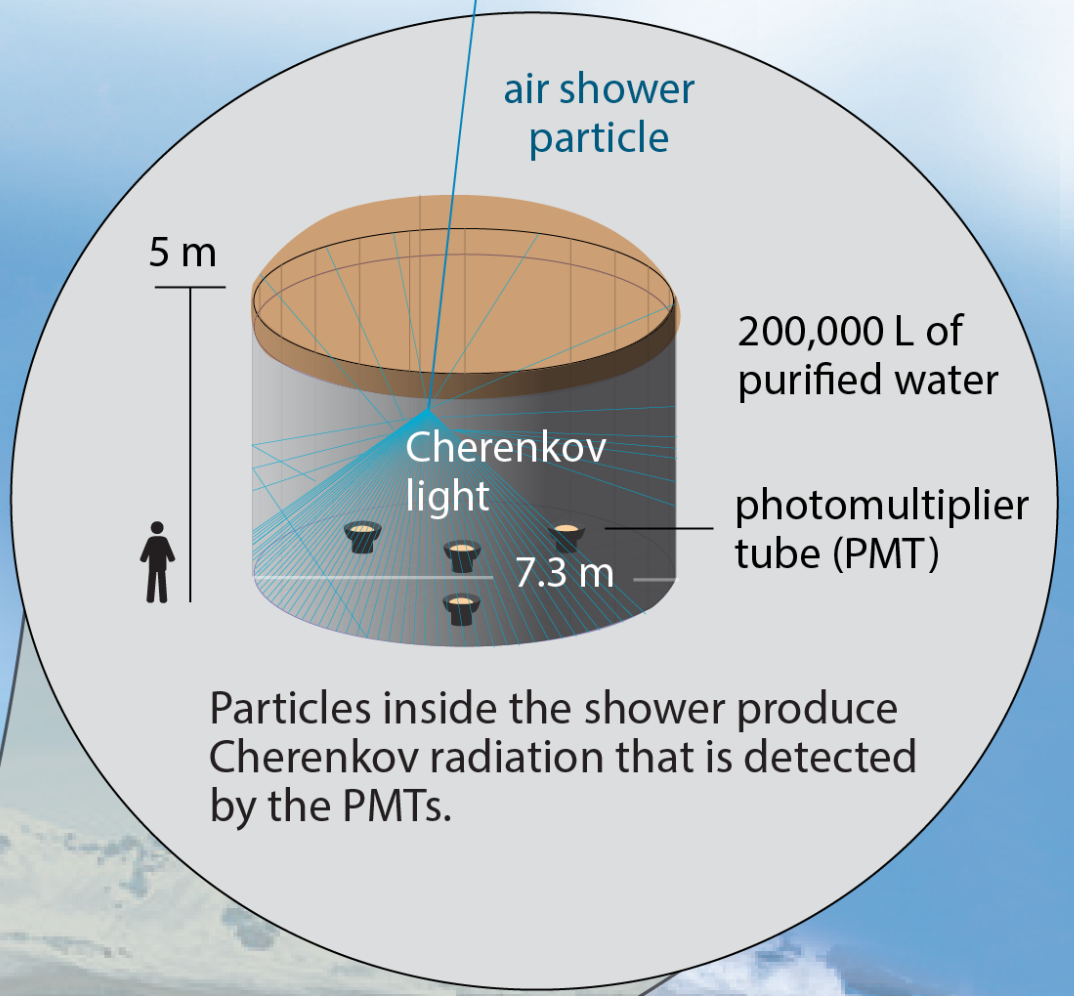
HAWC operates day and night, providing a large field of view for the observation of the highest energy gamma rays.



HAWC is located at 4,100 m above sea level, covering an area of 20,000 m^2.

Water Cherenkov tank

HAWC comprises an array of 300 tanks that record the particles created in gamma-ray and cosmic-ray showers.

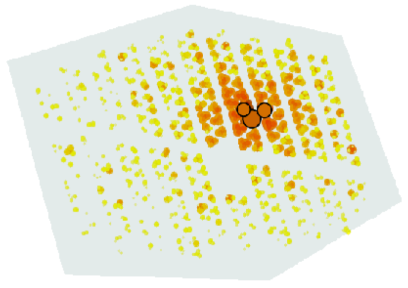


Particles inside the shower produce Cherenkov radiation that is detected by the PMTs.

Gamma rays vs cosmic rays

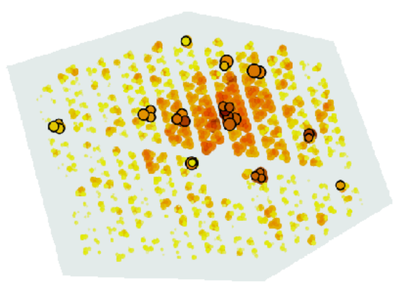
HAWC selects gamma rays from among a much more abundant background of cosmic rays.

gamma-ray shower



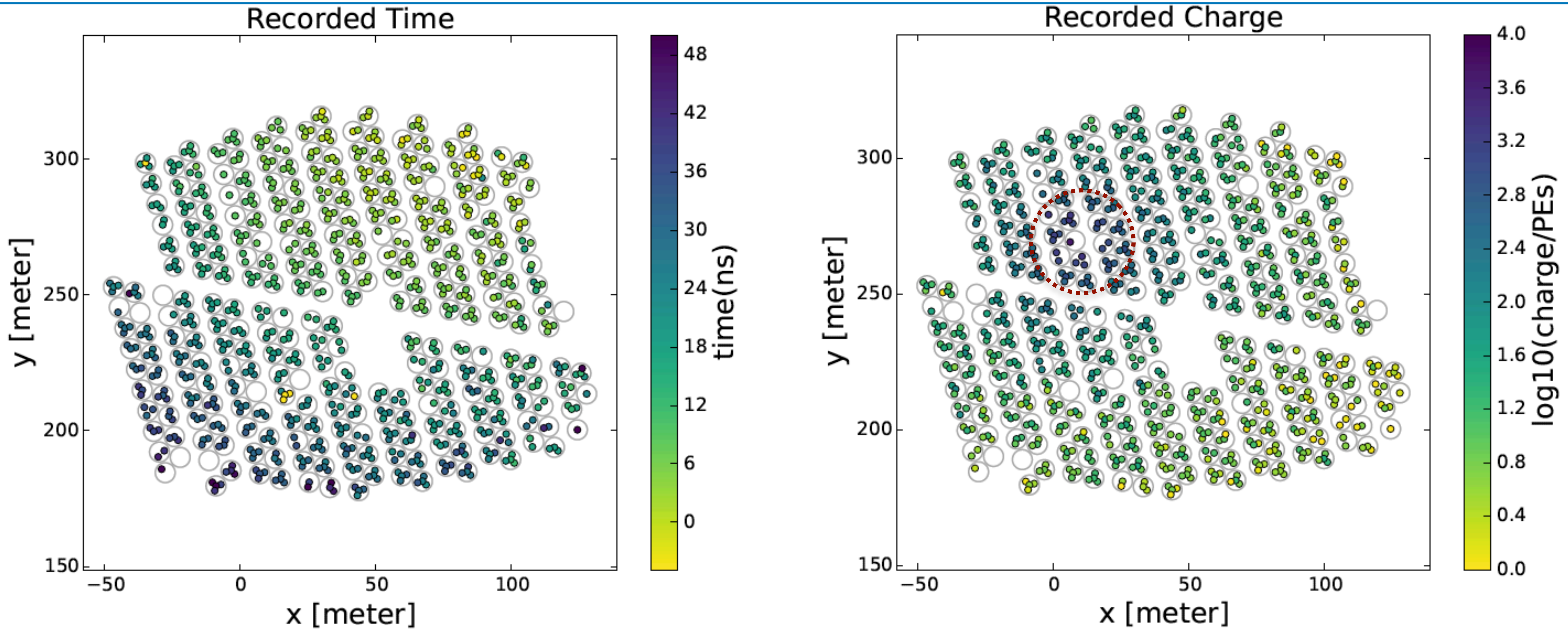
“hot” spots concentrate around the core

cosmic-ray shower



“hot” spots are more dispersed

The HAWC γ-ray observatory



- From hit times at PMTs, deposited charged, number of PMT's with signal:
  - Core location, (X_c, Y_c)
  - Arrival direction, θ
  - Fraction of hit PMT's, f_{hit}
  - Lateral charge profile, Qeff(r)
  - …

[HAWC Coll., ApJ 843 (2017) 39]

HAWC All-particle cosmic ray energy spectrum

All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV

R. Alfaro, et al. Phys. Rev. D **96** (2017)

Bayesian Unfolding

G. D’Agostini, Nucl. Inst. Meth. Phys. Res., **362** (1995).

The number of events observed in time T, within the solid angle Ω, and with reconstructed energy E_{reco}, $N(E_{reco})$ is related to the true energy distribution $N(E)$ by

$$N(E_{\text{reco}}) = \frac{1}{\Omega}\int A_{\text{eff}}(E, E_{\text{reco}})N(E)dE,$$

$$P(E|E_{\text{reco}}) = \frac{P(E_{\text{reco}}|E)P(E)}{\epsilon(E)\sum_{E'}P(E_{\text{reco}}|E')P(E')}$$

defines the probability of a shower with reconstructed energy E_{reco} to have been produced by a primary particle with energy E. $\epsilon(E)$ is the efficiency to observe an event with energy E.

The unfolded energy distribution is given by convolving the unfolding matrix with the reconstructed energy distribution iteratively via

$$N(E) = \sum_{E_{\text{reco}}} N(E_{\text{reco}})P(E|E_{\text{reco}})$$

HAWC All-particle cosmic ray energy spectrum

All-particle cosmic ray energy spectrum measured by the HAWC experiment from 10 to 500 TeV

All-particle spectrum consistent with a broken power law

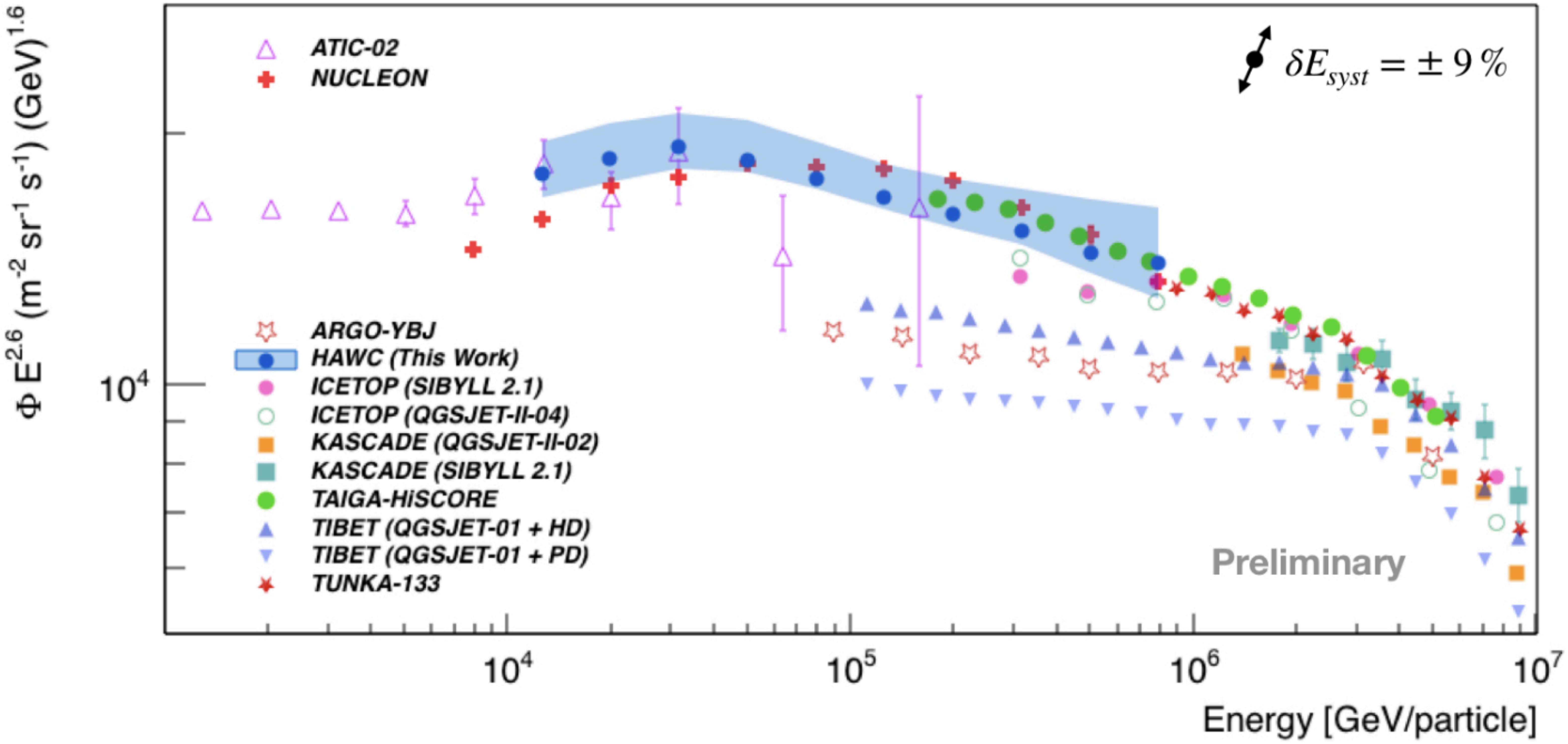
$$\Phi(E) = \Phi_0 E^{\gamma_1}\left[1+\left(\frac{E}{E_0}\right)^{\epsilon}\right]^{(\gamma_2-\gamma_1)/\epsilon}$$

with an index of $\gamma_1 = -2.5 \pm 0.009$

with a break at $E_0 = 30.84^{+1.83}_{-1.72}$ TeV,

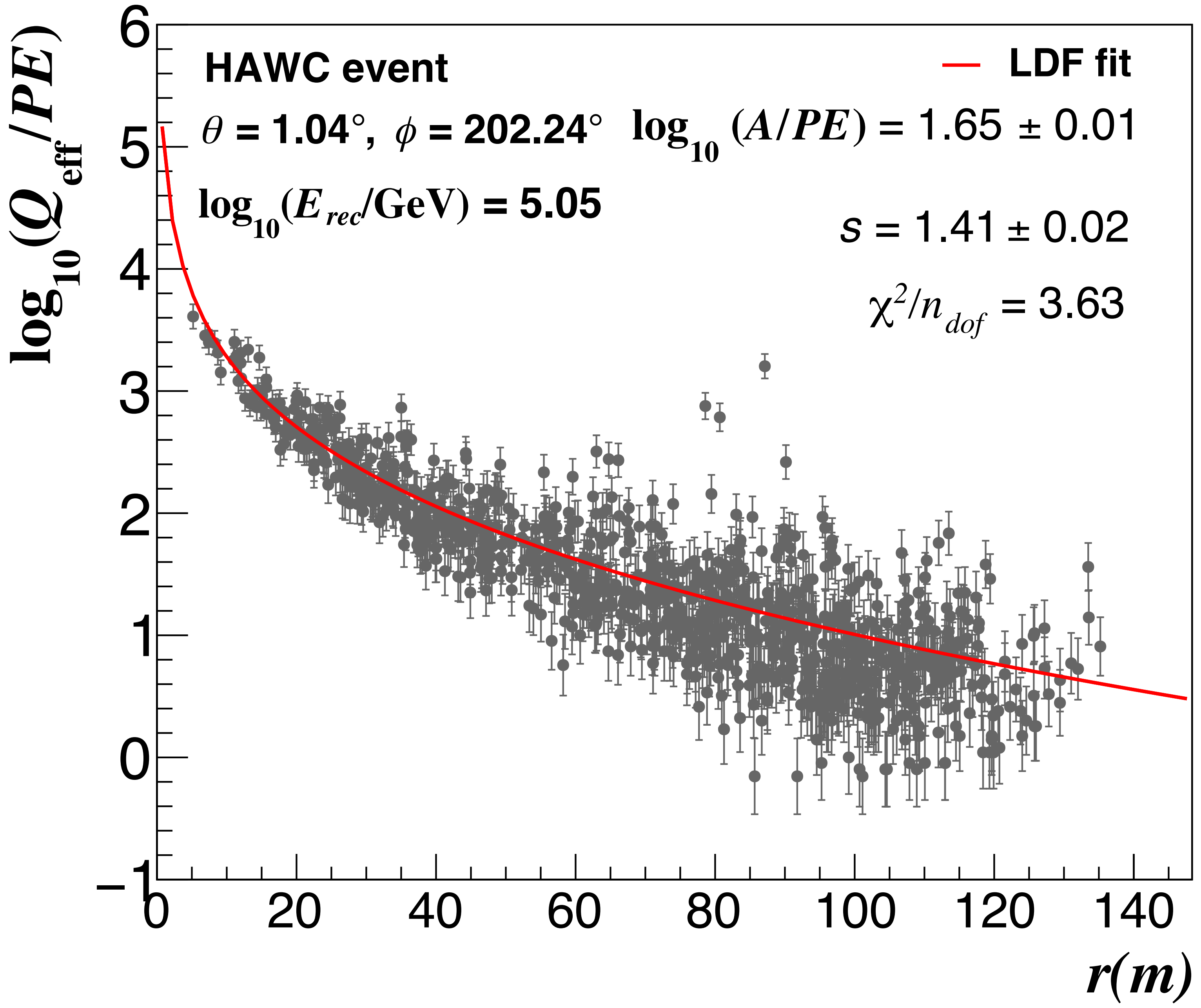
followed by an index of $\gamma_2 = -2.7 \pm 0.004$

$\varepsilon = 9.9 \pm 1.8$.



J. A. Morales-Soto & J. C. Arteaga-Velázquez ECRS 2022

HAWC H+He Energy Spectrum



[HAWC Collab., PRD 105 (2022)]

Lateral age parameter (*s*)

- Obtained event-by-event
- Fit of Qeff(r) with a NKG-like function:

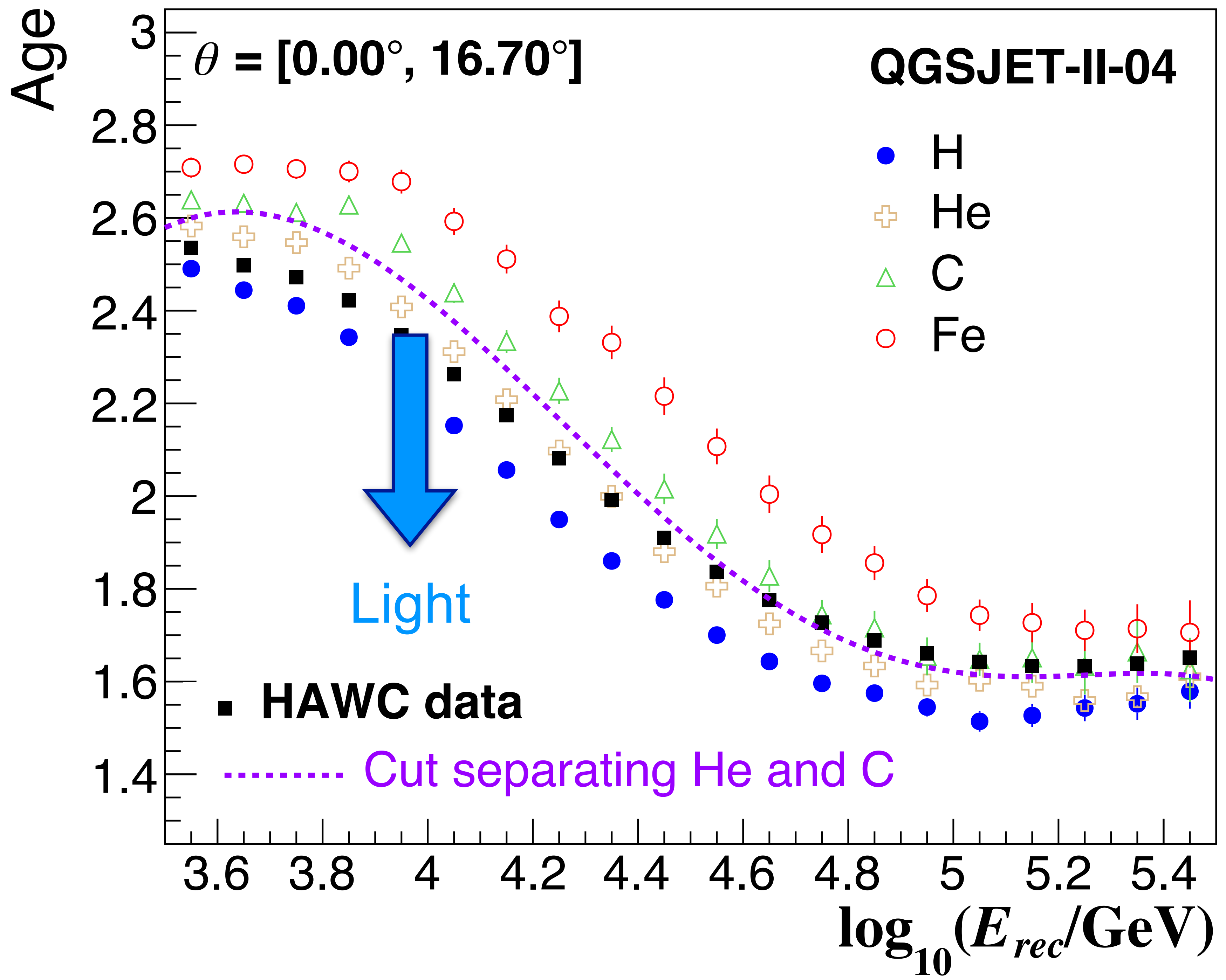
$$f_{ch}(r) = A \cdot (r/r_0)^{s-3} \cdot (1 + r/r_0)^{s-4.5}$$

with r_0 = 124.21 m.

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

[HAWC Collab., APJ 881 (2017); J.A. Morales Soto et al., PoS(ICRC2019 359 (2019)]

Select a sample enriched with light nuclei



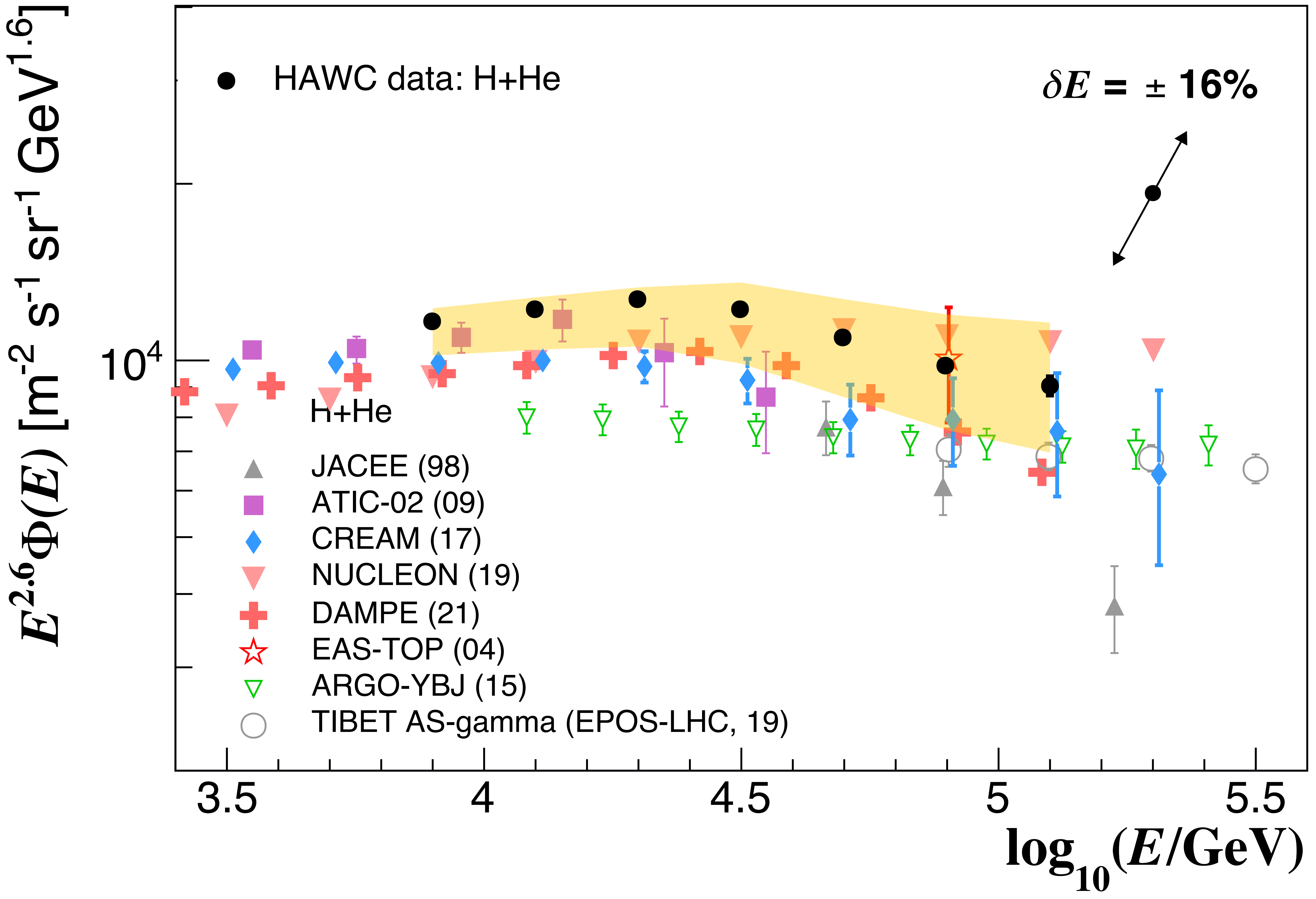
- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must have a large relative abundance of H and He.

HAWC H+He Energy Spectrum

Comparison with measurements from other experiments

H+He

[HAWC Collab., PRD 105 (2022)]



- **HAWC** data confirm previous hints from ATIC-2, CREAM I-III and NUCLEON about the existence of a break in the spectrum of the light component of cosmic rays in the 10^4 - 10^5 GeV range.

- **HAWC** result is strengthened by recent DAMPE data.

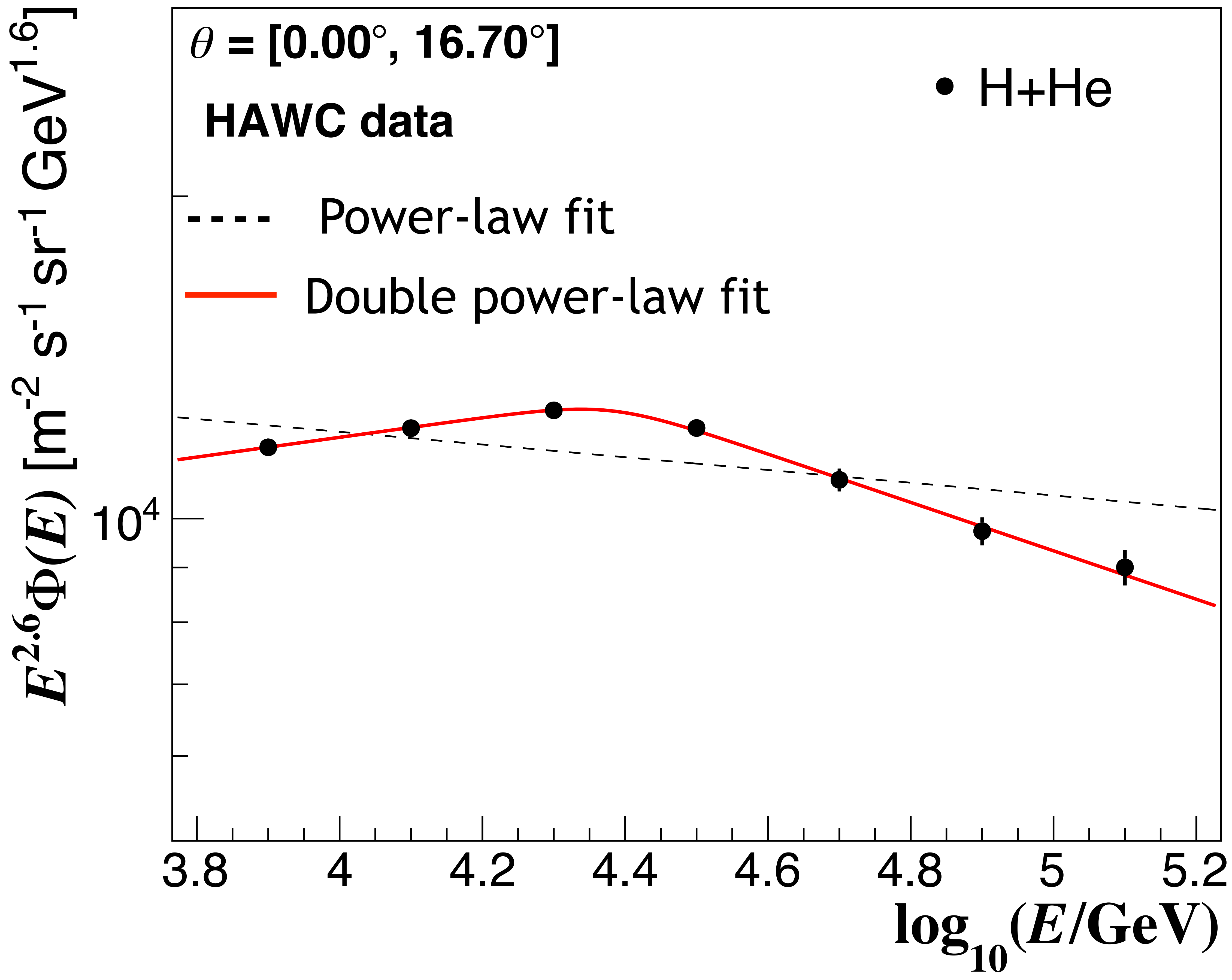
- **HAWC** data is in agreement with ATIC-2 close to 10^4 GeV.

HAWC H+He Energy Spectrum

Fit of spectrum

H+He

[HAWC Collab., PRD 105 (2022)]



- **Test Statistics:**

$TS = -\Delta\chi^2 = 177.25$

p-value = 2×10^{-5}

-> 4.1σ deviation from scenario with single power-law.

- Results for the double power-law fit:

$\gamma_1 = -2.51 \pm 0.02$

$\gamma_2 = -2.83 \pm 0.02$

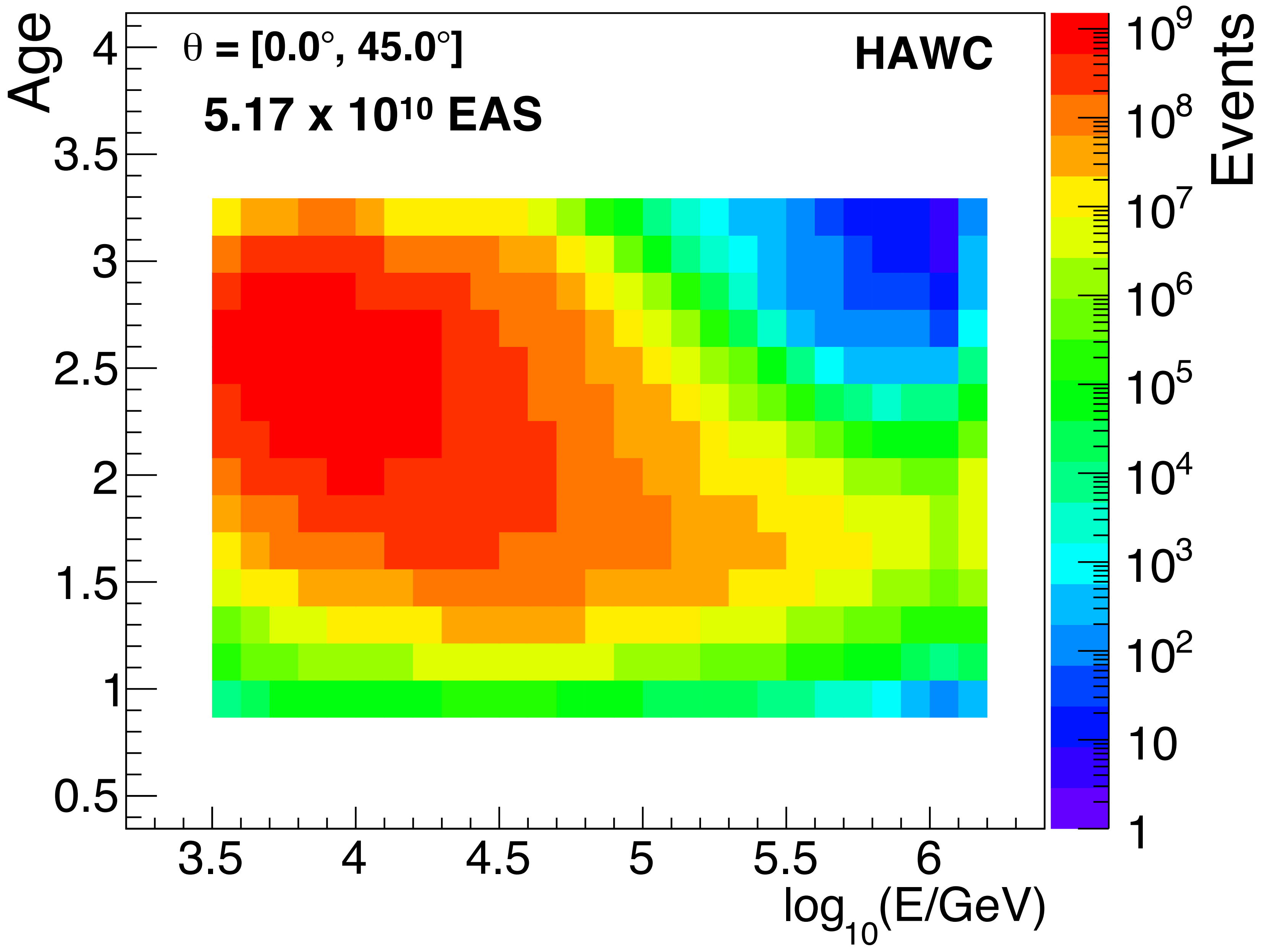
$\Delta\gamma = -0.32 \pm 0.03$

$\log_{10}(E_0/\mathrm{GeV}) = 4.38 \pm 0.06$

- **$E_0 = 24.0^{+3.6}_{-3.1}$ TeV**

HAWC p, He, Z>=3

- 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]

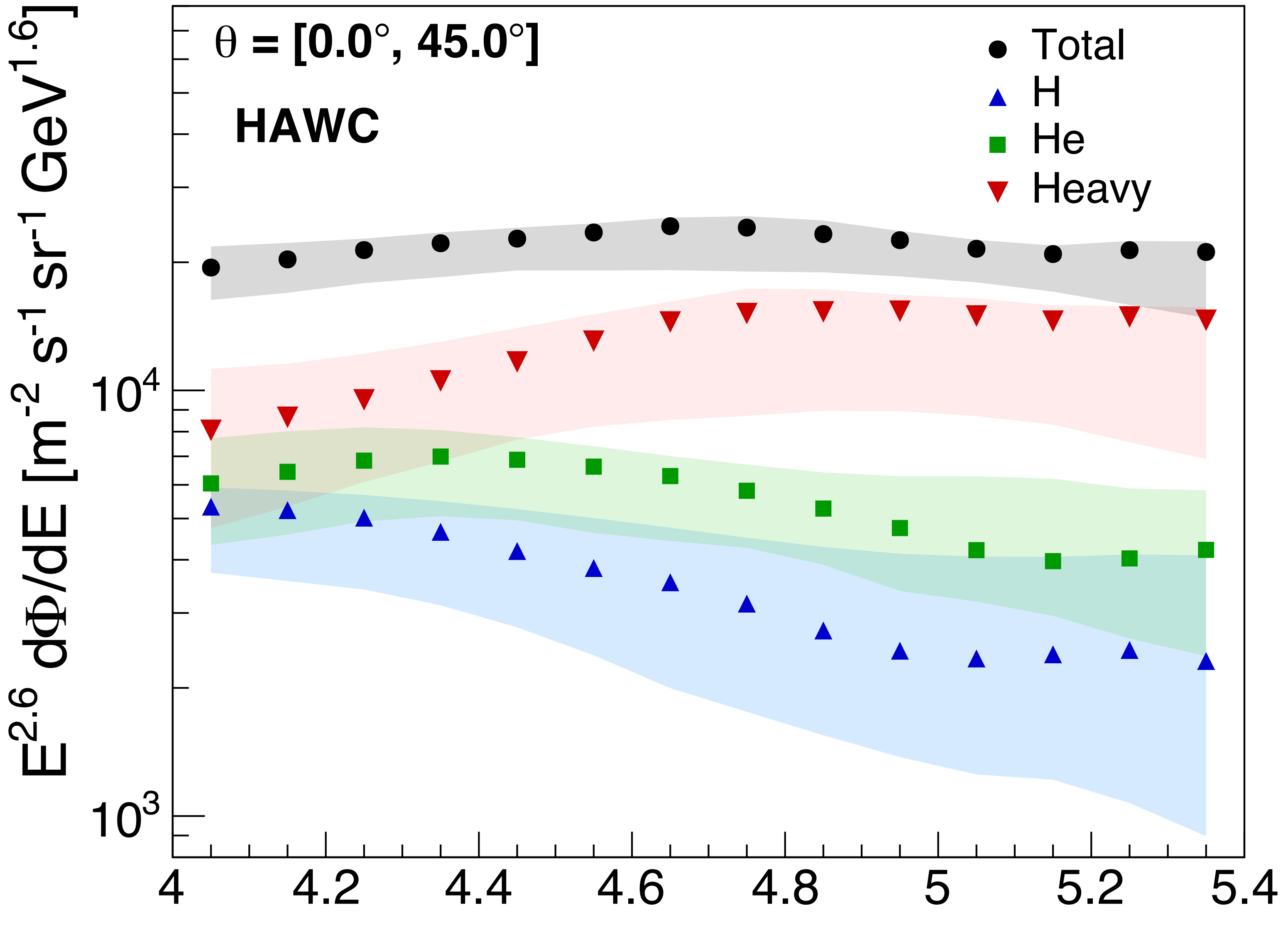
Apply Gold's unfolding algorithm

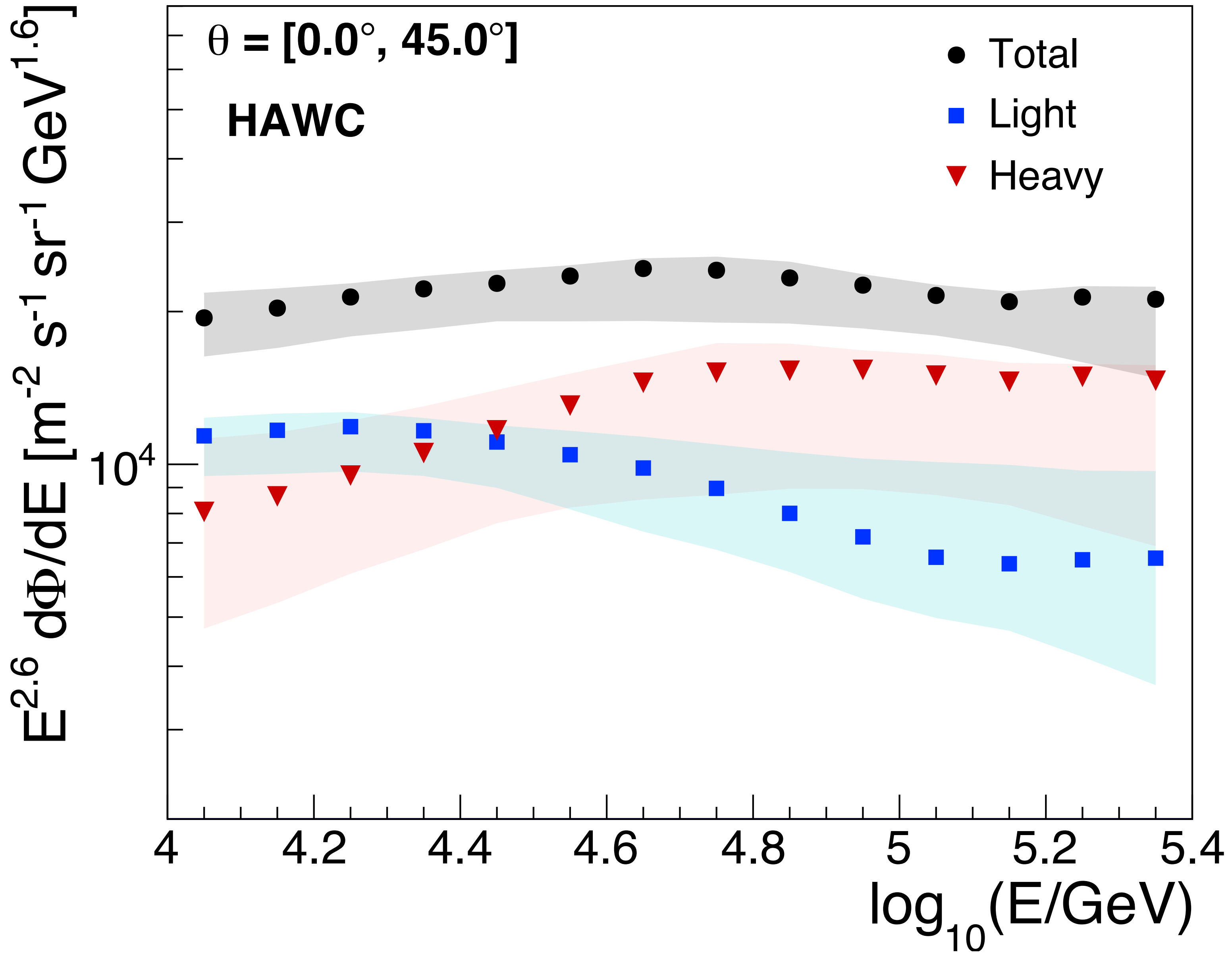
[R.Gold, Report ANL-6984, 1964]

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

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

HAWC p, He, Z>=3





- The elemental spectra do not follow a power-law function.

  HAWC data show fine structure (> 5σ) between 10 TeV and 251 TeV:

  ΦH(E)/ΦHe(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]

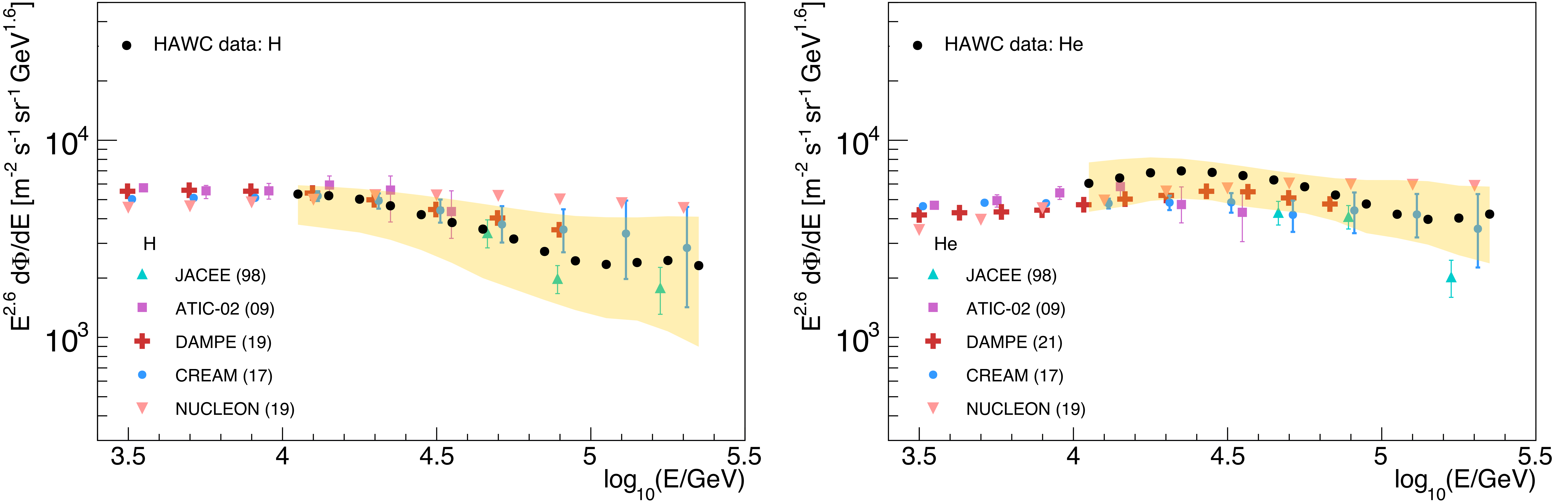
$$\Phi(E) = \Phi_0 E^{\gamma_1}\left[1+\left(\frac{E}{E_0}\right)^{\varepsilon_0}\right]^{(\gamma_2-\gamma_1)/\varepsilon_0}\left[1+\left(\frac{E}{E_1}\right)^{\varepsilon_1}\right]^{(\gamma_3-\gamma_2)/\varepsilon_1}$$

	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

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

HAWC p, He, Z>=3

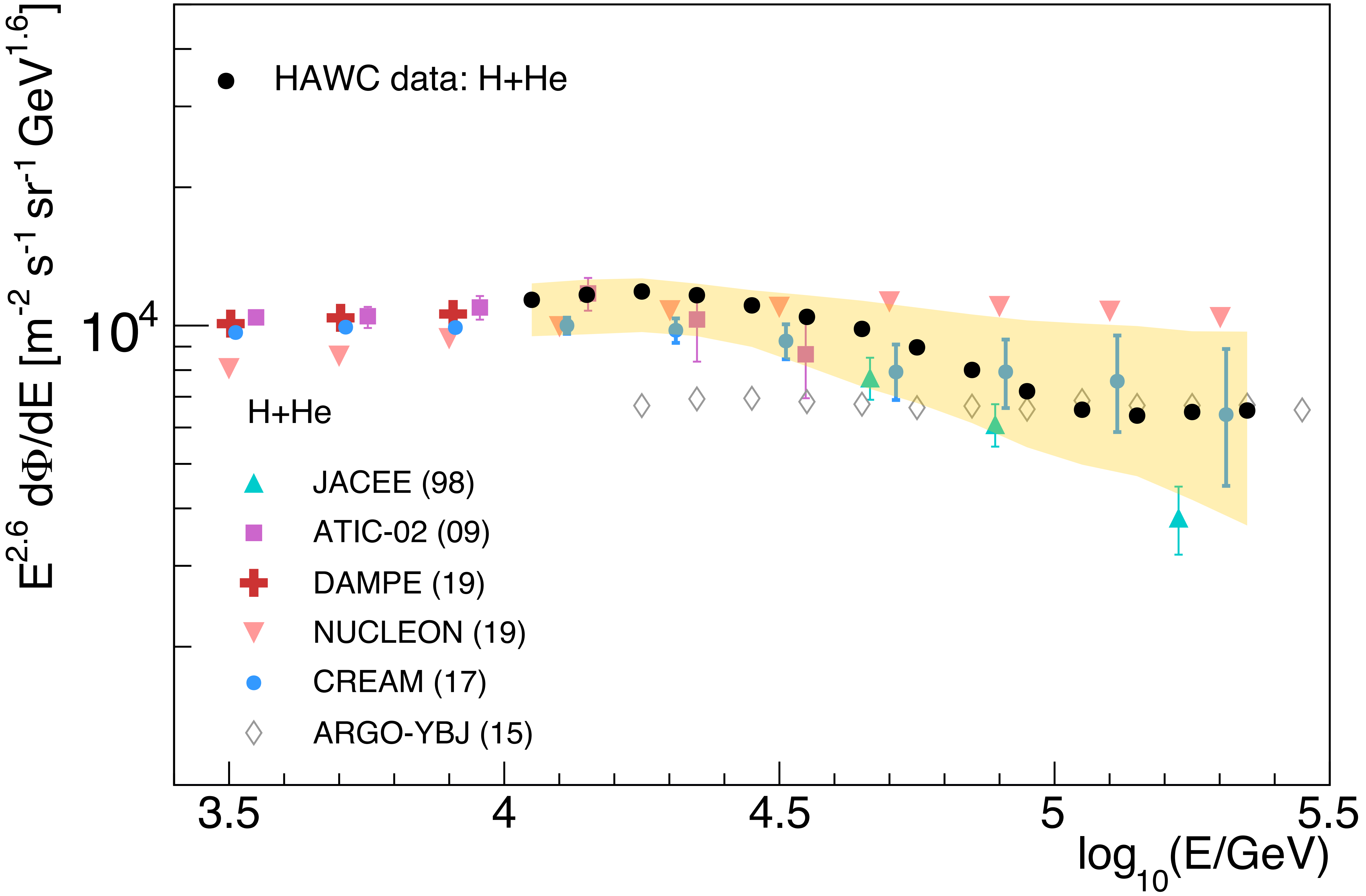
H and He spectra: Comparison with other experiments

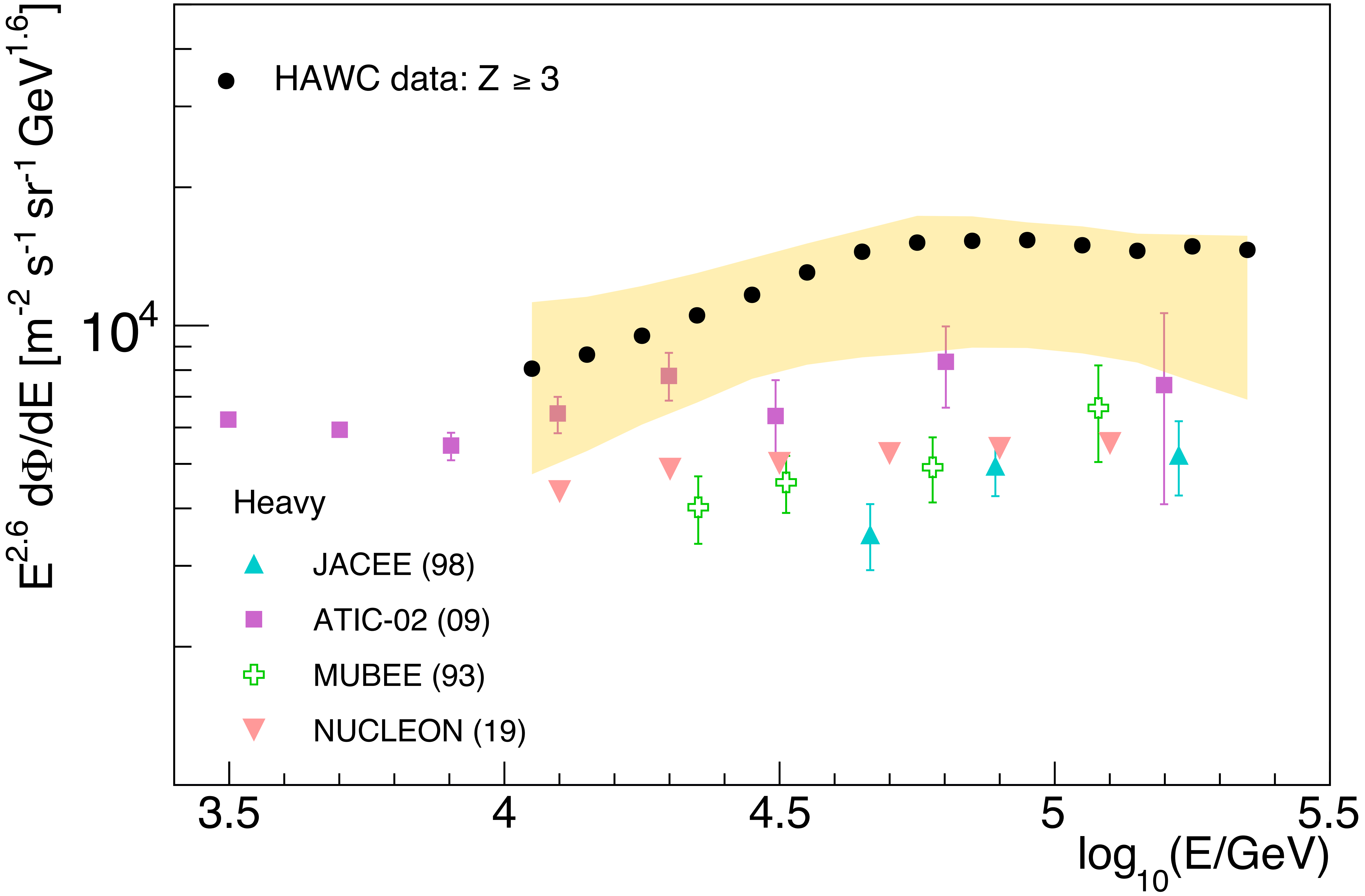


- Good agreement of **HAWC** with direct data from **DAMPE**, **ATIC-02** and **CREAM I-III** within systematic errors.
- **HAWC** confirms softenings at tens of TeV observed by **DAMPE**, first hinted by **ATIC-02**, **CREAM** and **NUCLEON**.

HAWC Composition

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





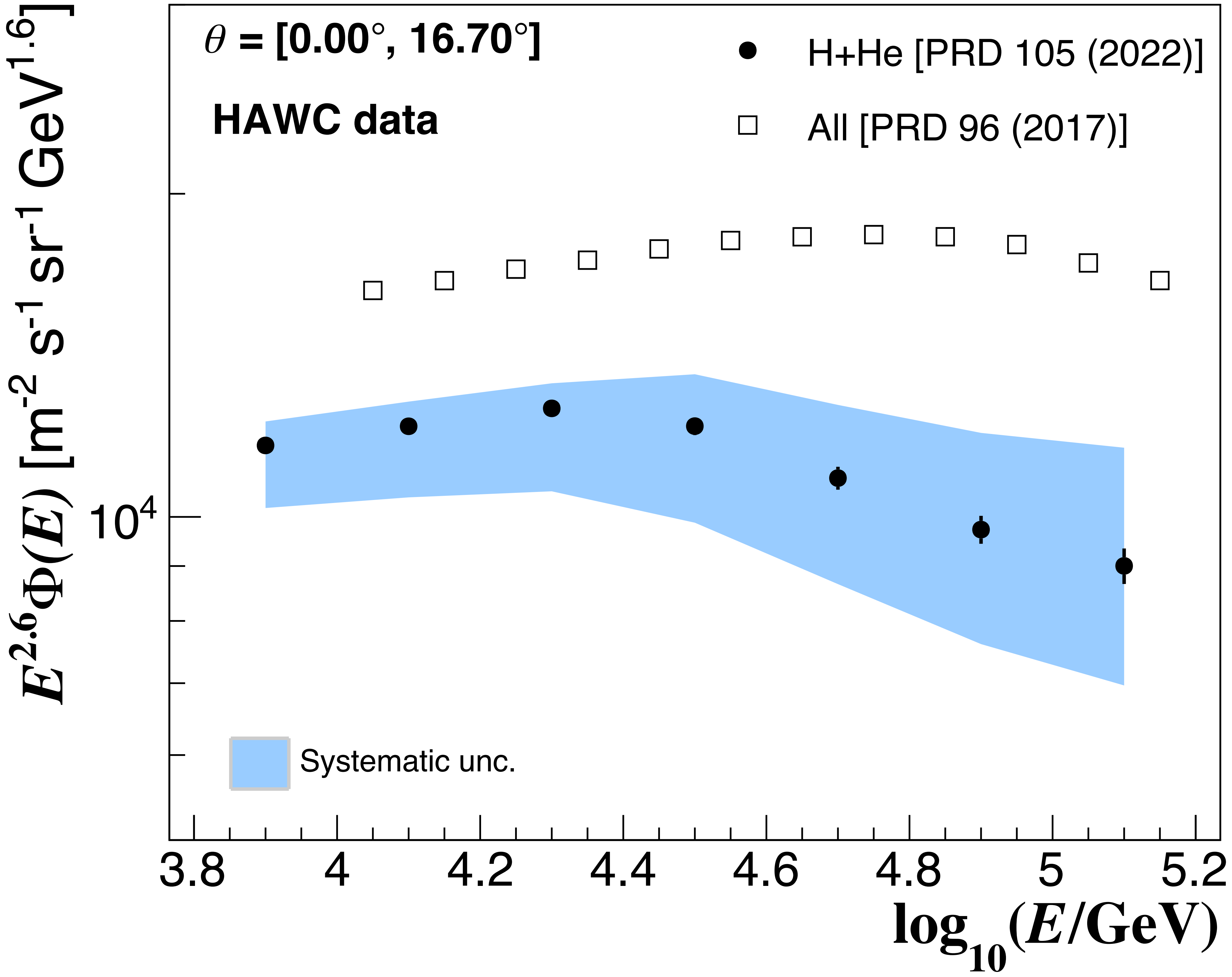
- Good agreement of **HAWC** with **ATIC-02, CREAM** and **JACEE** within systematic errors.
- **ARGO-YBJ** disagrees with **HAWC** data for E < 50 TeV.

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

Discussion

- TeV softening in p+He spectrum could contribute to the softening observed at TeV energies in all-particle spectrum.
- All-particle spectrum feature: wider and shifted to higher energies possibly from increasing influence of Z > 2 close to 100 TeV, consistent with heavy element data from NUCLEON, the mean shower age from HAWC and analysis of the efficiency of the age cut.
- Decrease in Φ_{H+He}/Φ_{Tot} ratio from 10 to 158TeV suggests relative increase in contribution of heavy nuclei in the total spectrum.
- Diffusive shock acceleration predicts a power-law spectrum of nuclei from TeV to PeV.
- Max. confinement energy by B-fields either at source or in Galaxy: rigidity dependent cuts at ~PeV
- Measurements in tension with standard scenario.
- Some nonconventional models predict features in the ~TeV spectra of different nuclei and invoke new kinds of accelerators, nearby sources, or modified mechanism of acceleration in astrophysical shocks
- Further studies needed at energy spectra of heavier nuclei in 10 TeV – 1 PeV range.

A. Albert *et al*. Phys. Rev. D 105 (2022)



Summary

- Earlier indirect measurements lacked statistics and were consistent with a single power law due to limited statistics.
- Direct measurements suggest the existence of a rigidity-dependent cutoff in the energy spectrum at around 10 TV
- Dedicated measurements of cosmic ray composition have allowed to reconstruct the spectrum of the light component (H+He) and individual nuclei for cosmic rays in the range E = [10 TeV, 100 TeV].
- First indirect observations by HAWC of a break at ~24.0 TeV in the cosmic-ray spectrum of H+He
- Measurements confirm previous hints from ATIC-2, CREAM I-III and NUCLEON (and later confirmed by DAMPE) that the H+He spectrum of cosmic rays deviates from a power-law behavior in the 10-100 TeV range.
- HAWC and GRAPES-3 measurements suggest possible hardening in the intensities of H and He above 100TeV.
- Further studies needed for energy spectra of heavier nuclei in 10 TeV − 1 PeV range.

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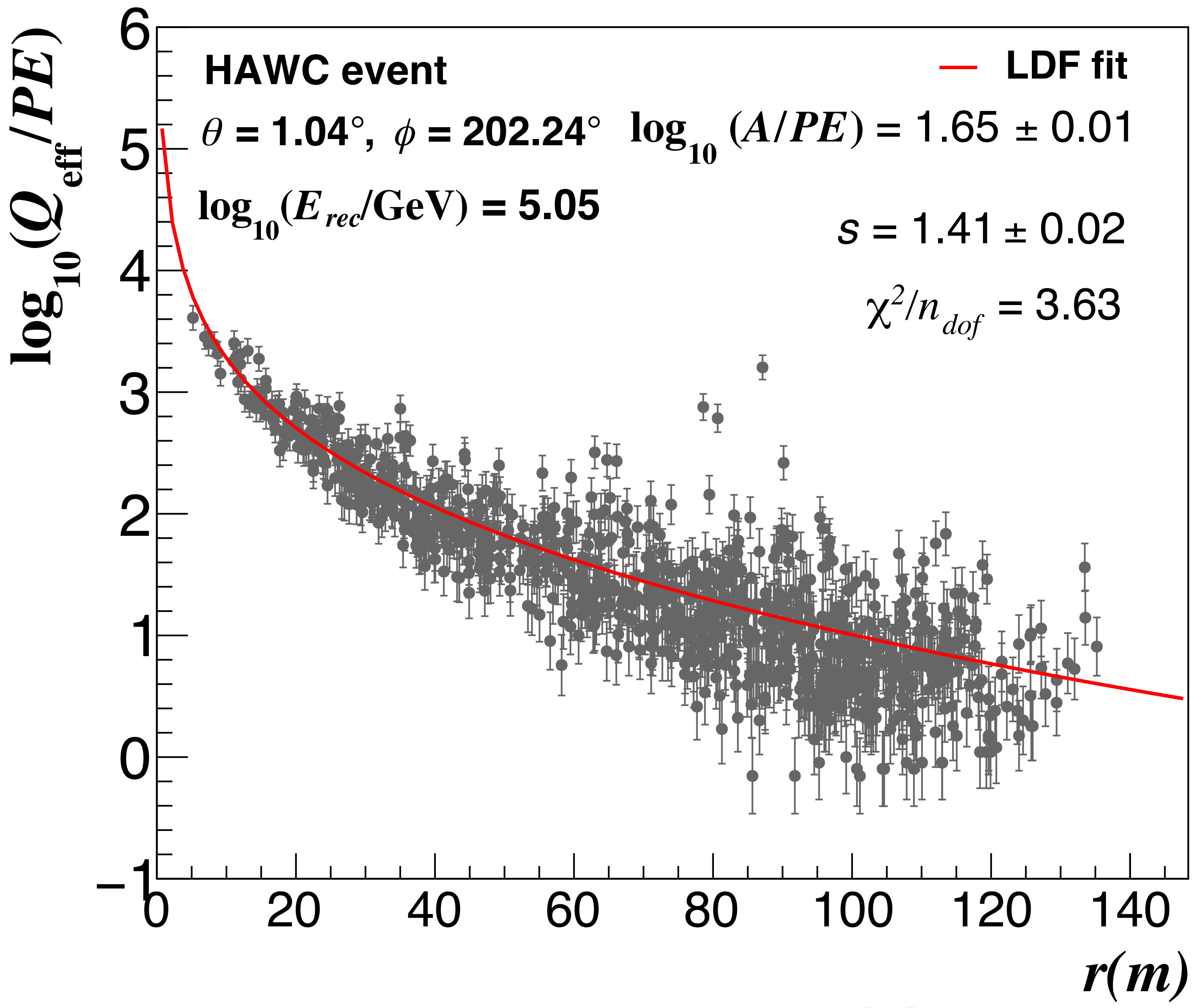
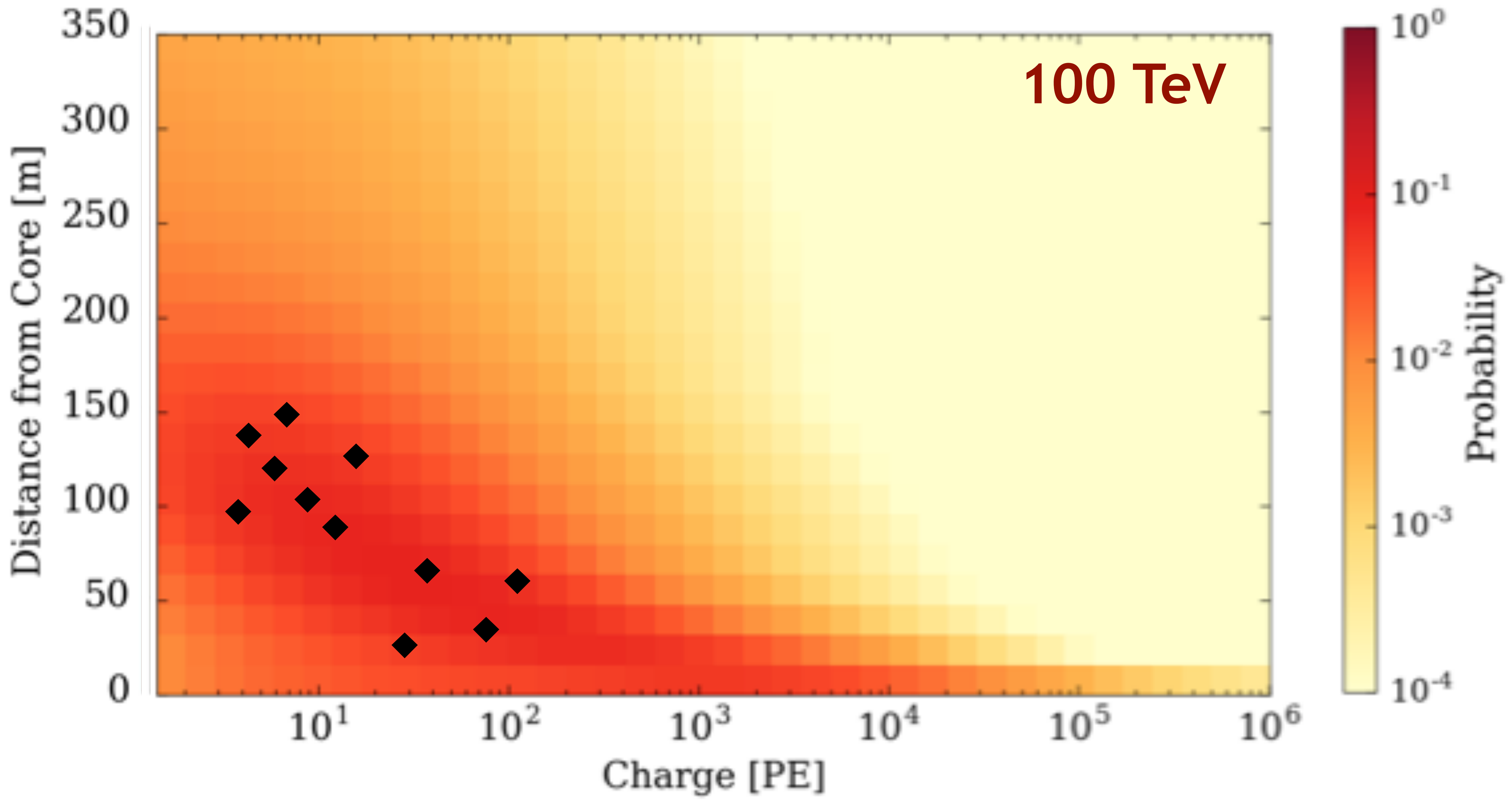
Backup

EAS Age and Energy Estimation



[HAWC Collab., PRD 105 (2022)]



Lateral age parameter (*s*)

- Obtained event-by-event
- Fit of Qeff(r) 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 (2017); J.A. Morales Soto et al., PoS(ICRC2019 359 (2019)]

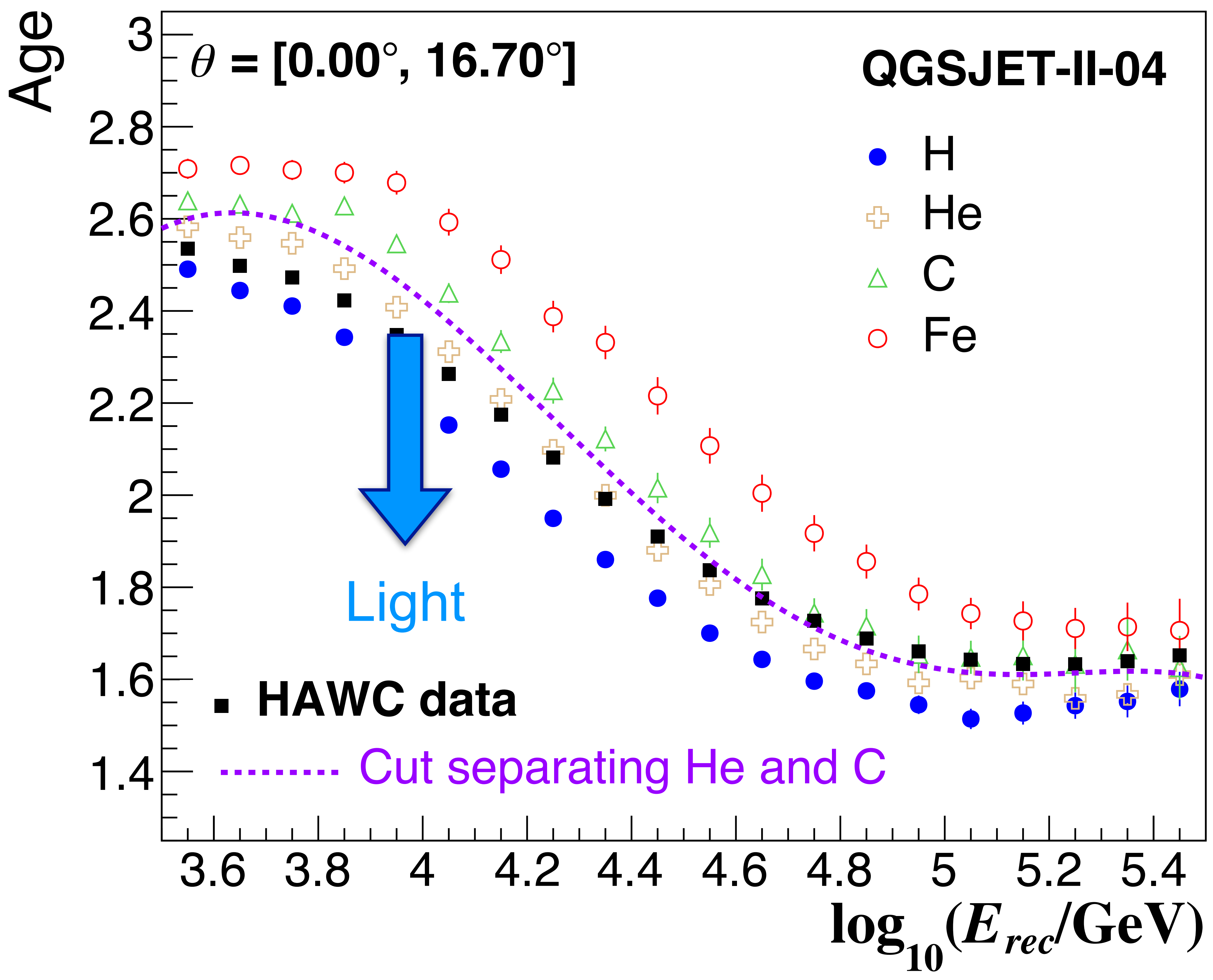
EAS primary energy:

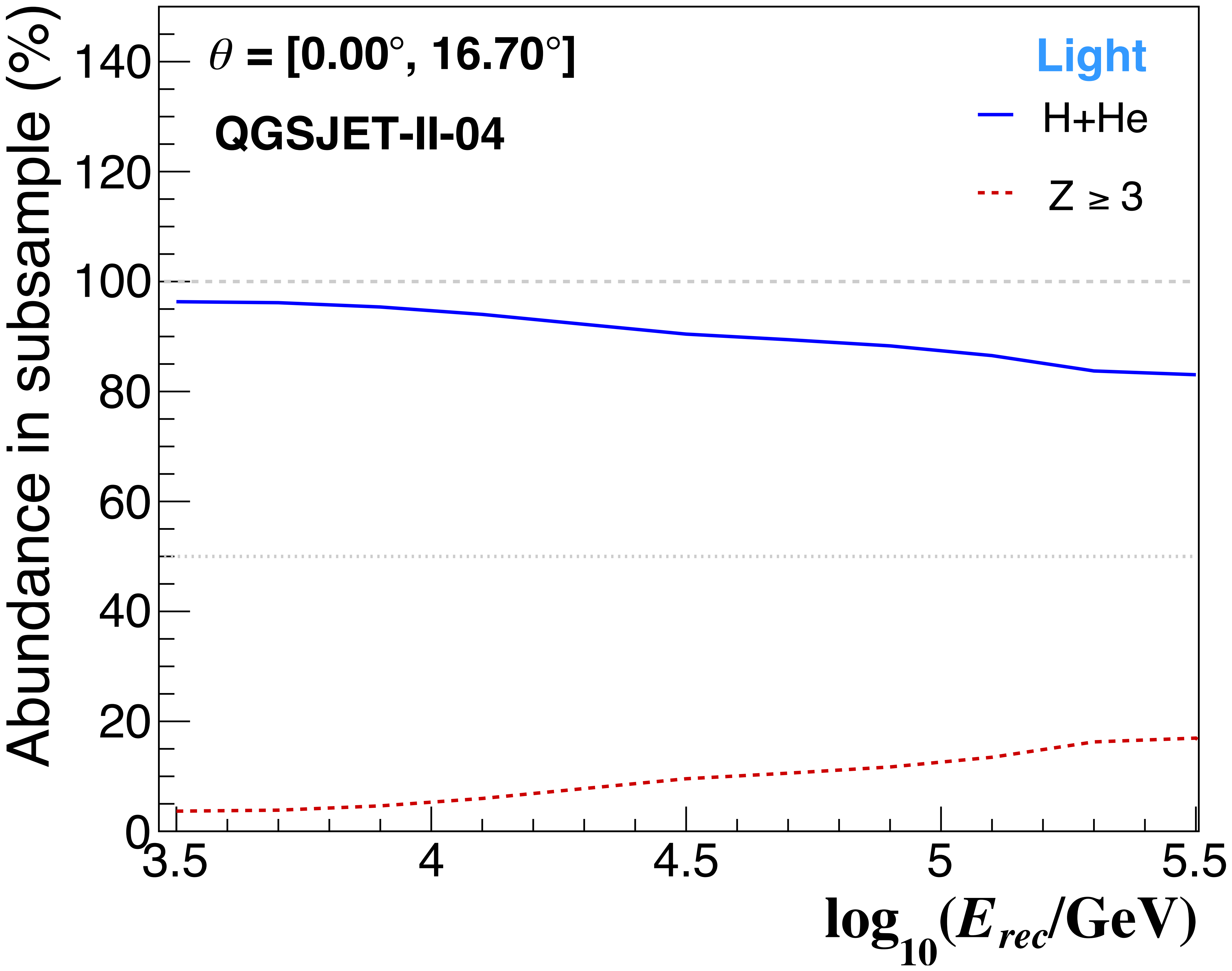
- Produce LDF tables of MC protons:
  Binning in r, Qeff, θ and E
- Maximum likelihood to find table that best fits the Qeff(r) distribution of the event, from which **E** is obtained.

[HAWC Collab., PRD 96 (2017); Z. Hampel-Arias' PhD thesis, 2017]

Analysis

Select a sample enriched with light nuclei



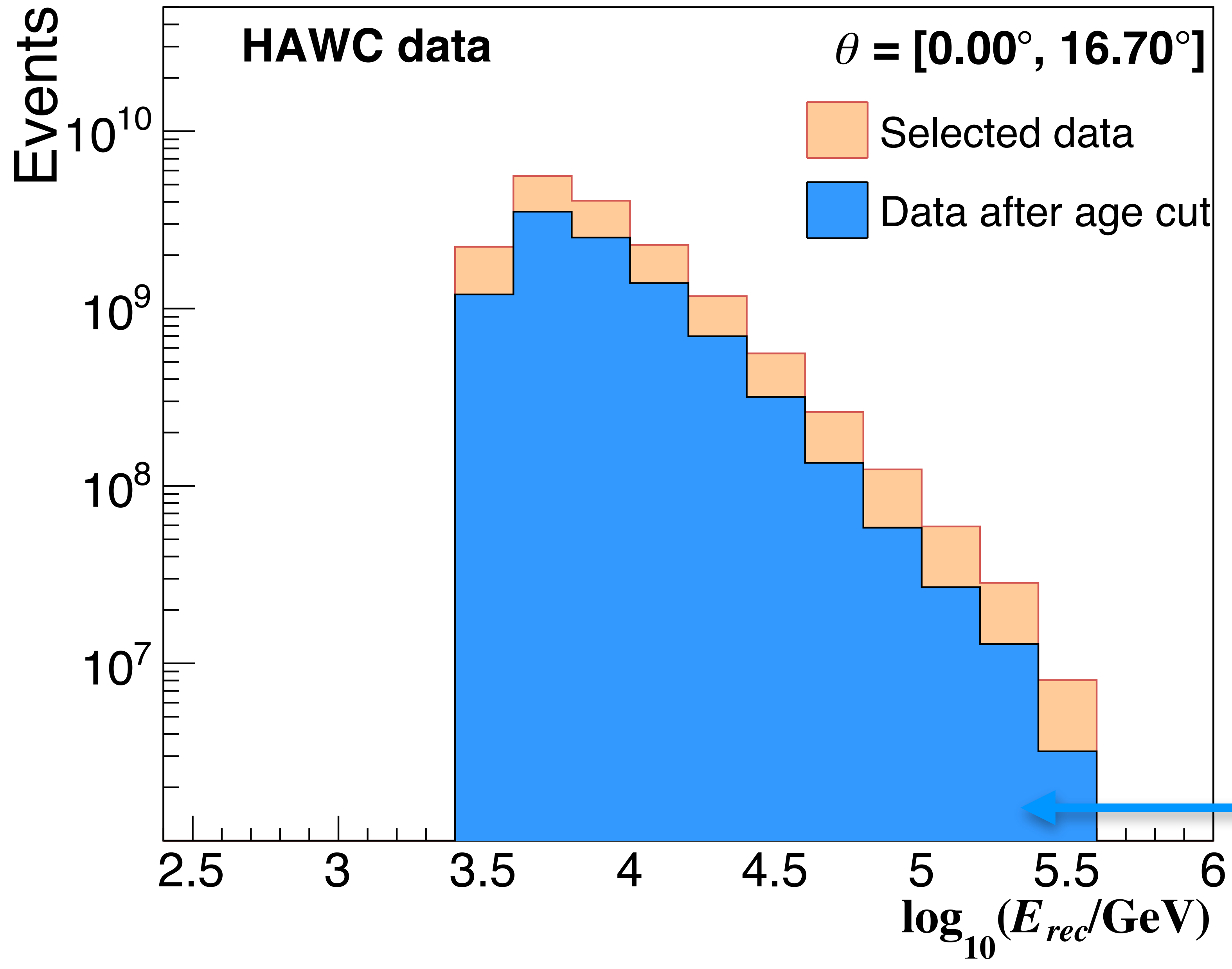


- Age parameter is sensitive to composition
- Select a subsample using a cut on the age
  - Subsample must have a large relative abundance of H and He.

- Content of H + He in subsample
  - More than 82% of H and He in subsample

Analysis

Build raw energy spectrum of subsample: $N_{raw}(E_{rec})$



- Experimental data used for analysis:

HAWC-300

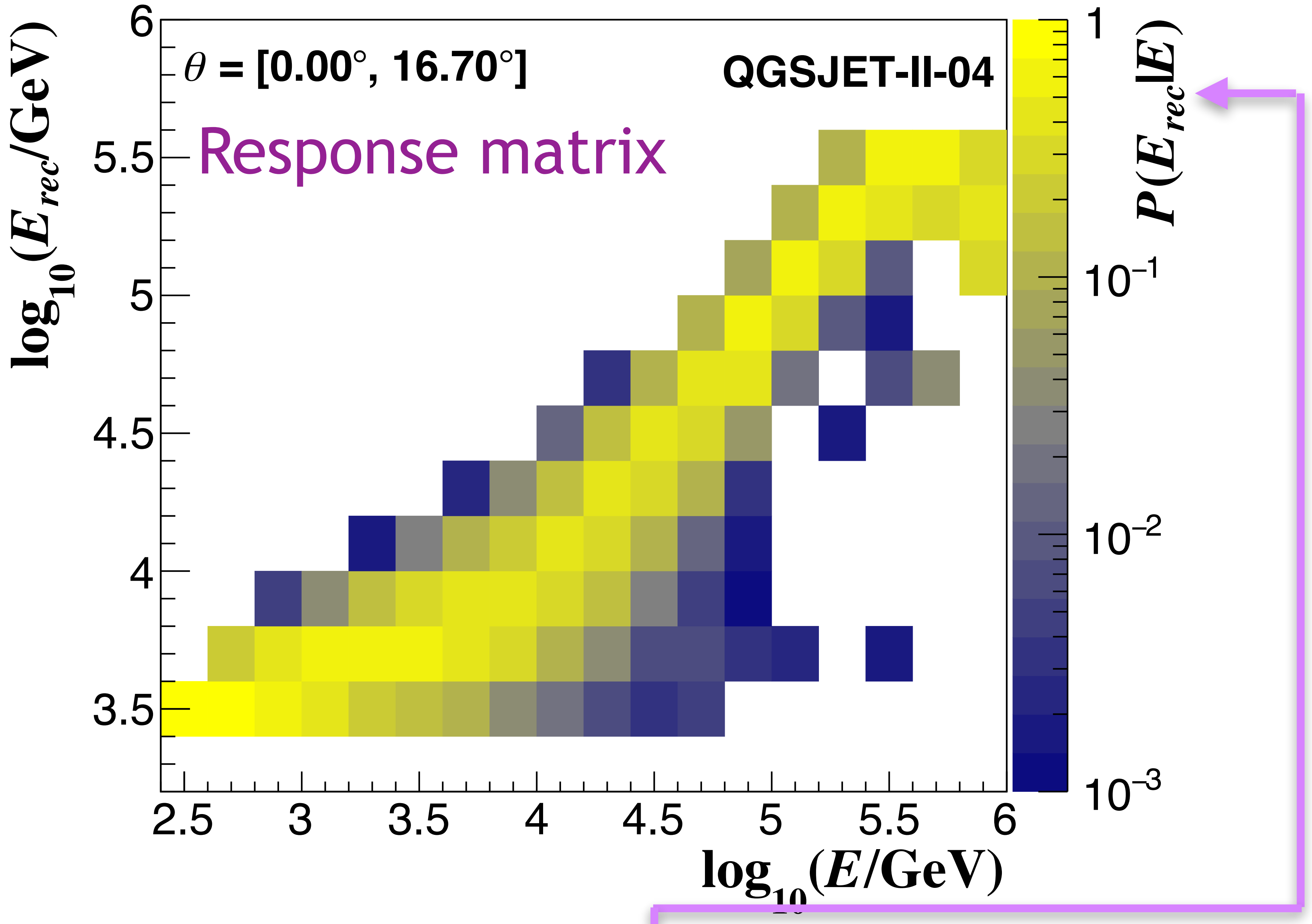
Δt_{eff} = 3.74 years (94% livetime)

(June/11/15-June/03/19)

$\Delta\ \Omega$ = 0.27 sr

Total events : 2.9 x 10^{12} EAS
+ selection cuts: 1.6 x 10^{10} EAS
+ age cut: 9.9 x 10^{9} EAS

Correct $N_{raw}(E_{rec})$ for migration effects



$$N^{Raw}(E_{rec,\,j}) = \sum_i P(E_{rec,\,j} \mid E_i)\, N^{Unf}(E_i)$$

- Solve for $N^{Unf}(E_i)$ using Bayesian unfolding

[G. D' Agostini, DESY 94-099]

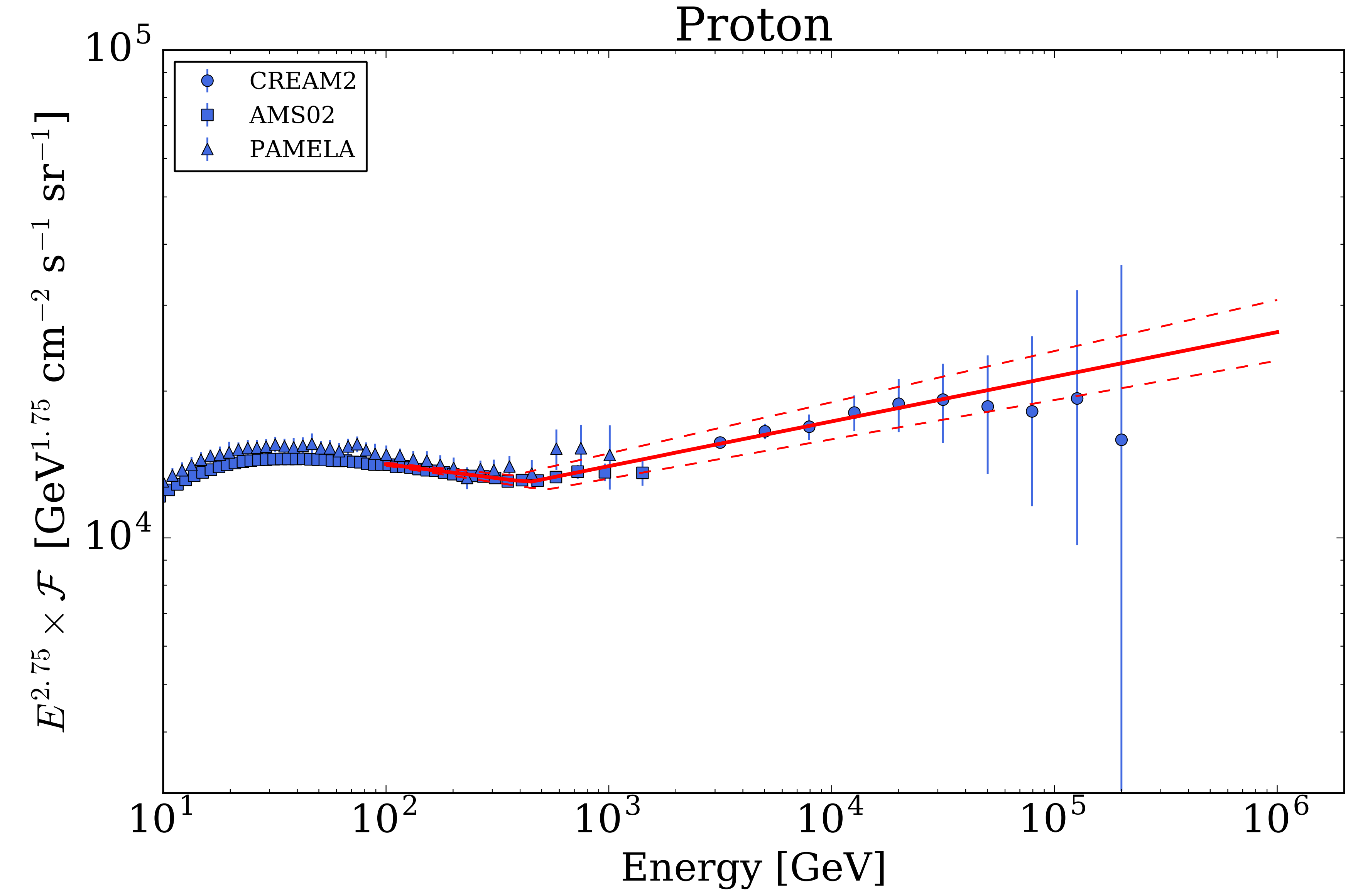
- Stopping criterium: Minimum of weighted mean squared error

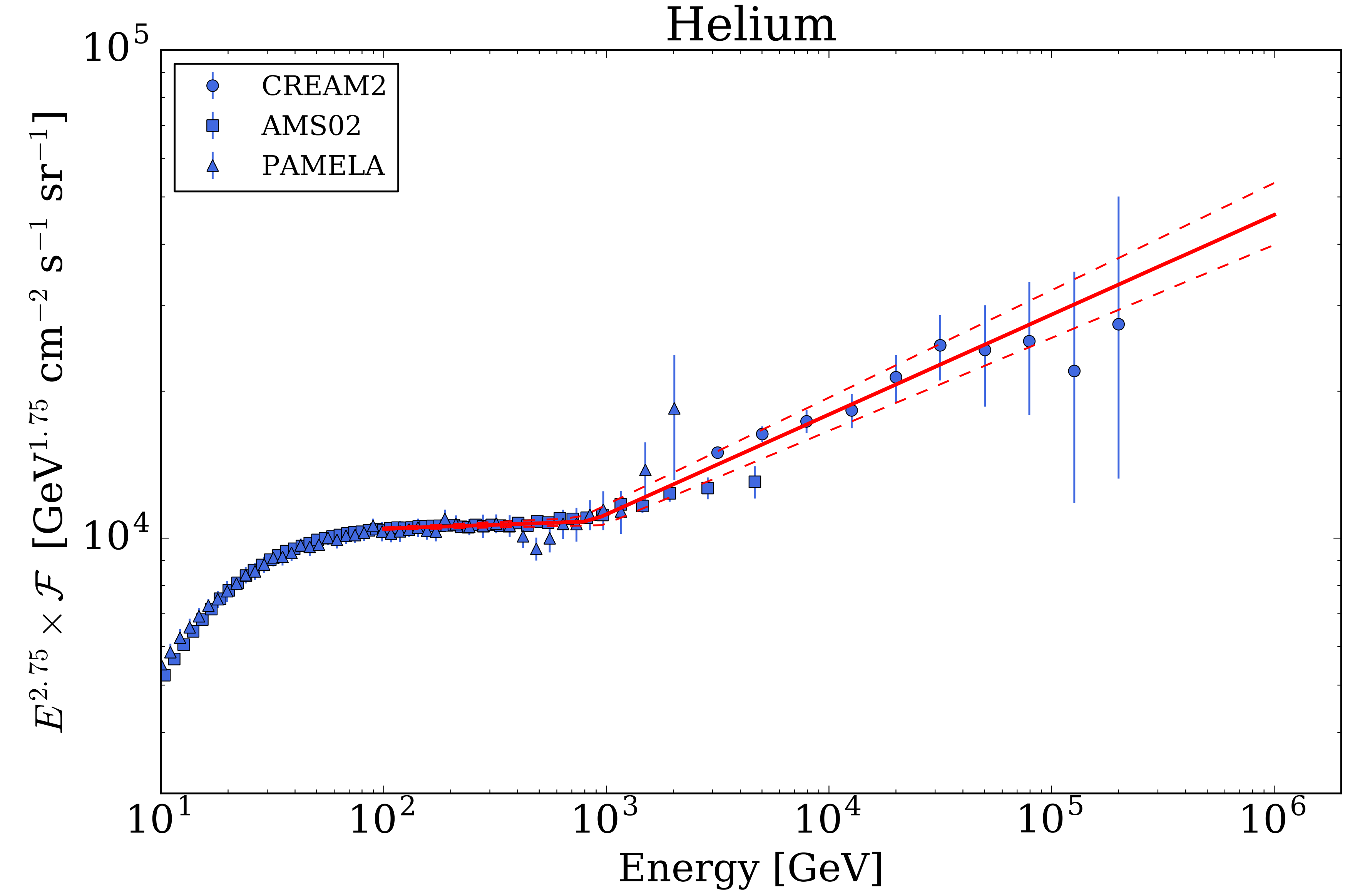
[G. Cowan, Stat. Data analysis, Oxford Press. 1998]

$$\mathrm{WMSE} = \frac{1}{N_{points}} \sum_{i}^{N_{points}} \frac{stat_i^2 + sys_i^2}{n_i}$$

Monte Carlo Simulation

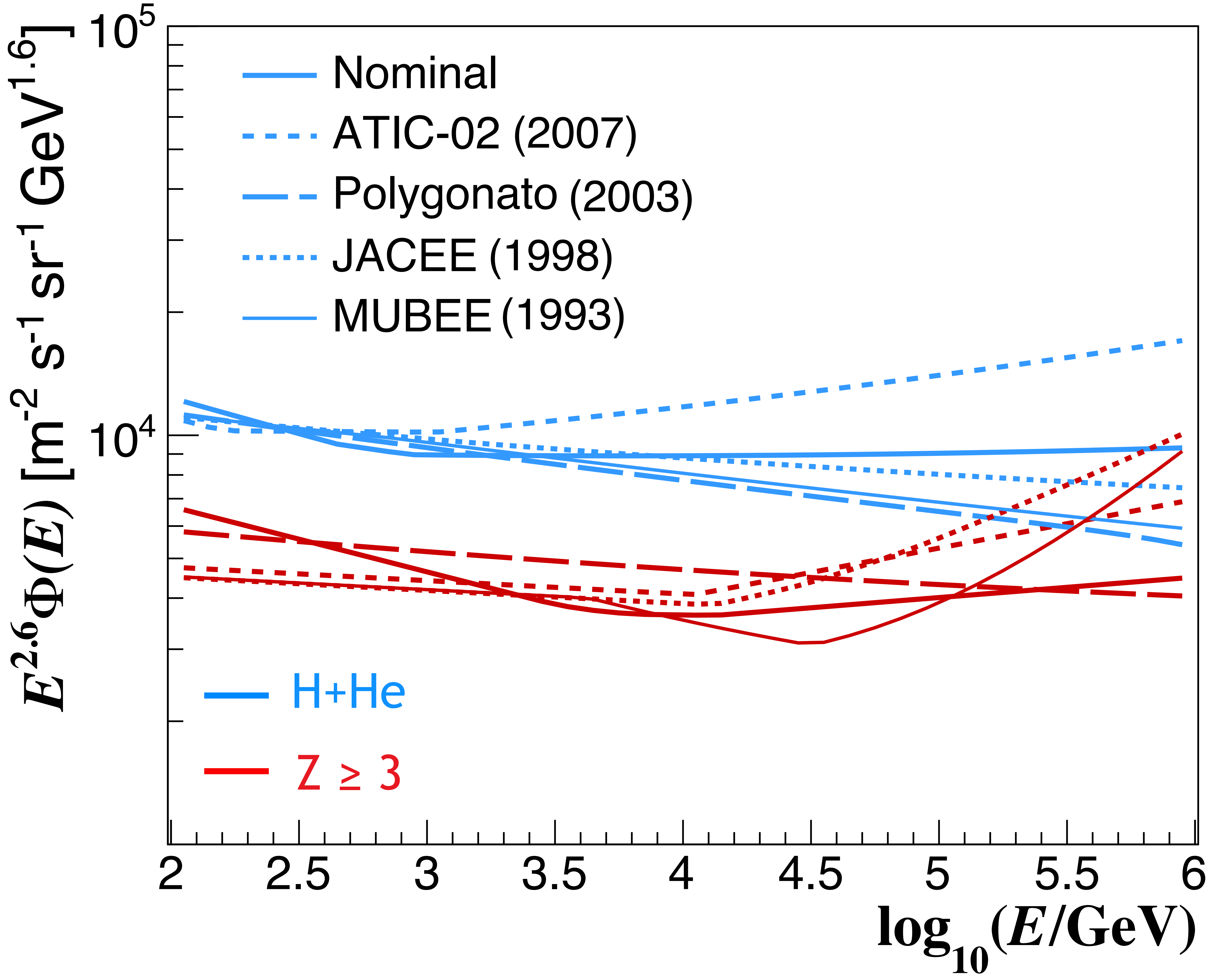
- CORSIKA v 7.40 for EAS simulation.
- **Fluka/QGSJET-II-04** as low(E_{lab} < 80 GeV)/high-energy interaction models for the main analysis.
- Fluka/EPOS-LHC simulations to study effect of hadronic interaction model.
- Full simulation of detector response with GEANT 4.
- $\theta < 70^o$; A_{thrown}~3×10^6 m^2
- Primary nuclei:
  - H, He, C, O, Ne, Mg, Si, Fe
  - E = 5 GeV – 3 PeV
  - E^{-2} spectra weighted to follow broken power-laws derived from fits to **AMS02** (2015), **CREAM-II** (2009 & 2011) and **PAMELA** (2011) data. **[HAWC Collab., PRD 96 (2017)]**

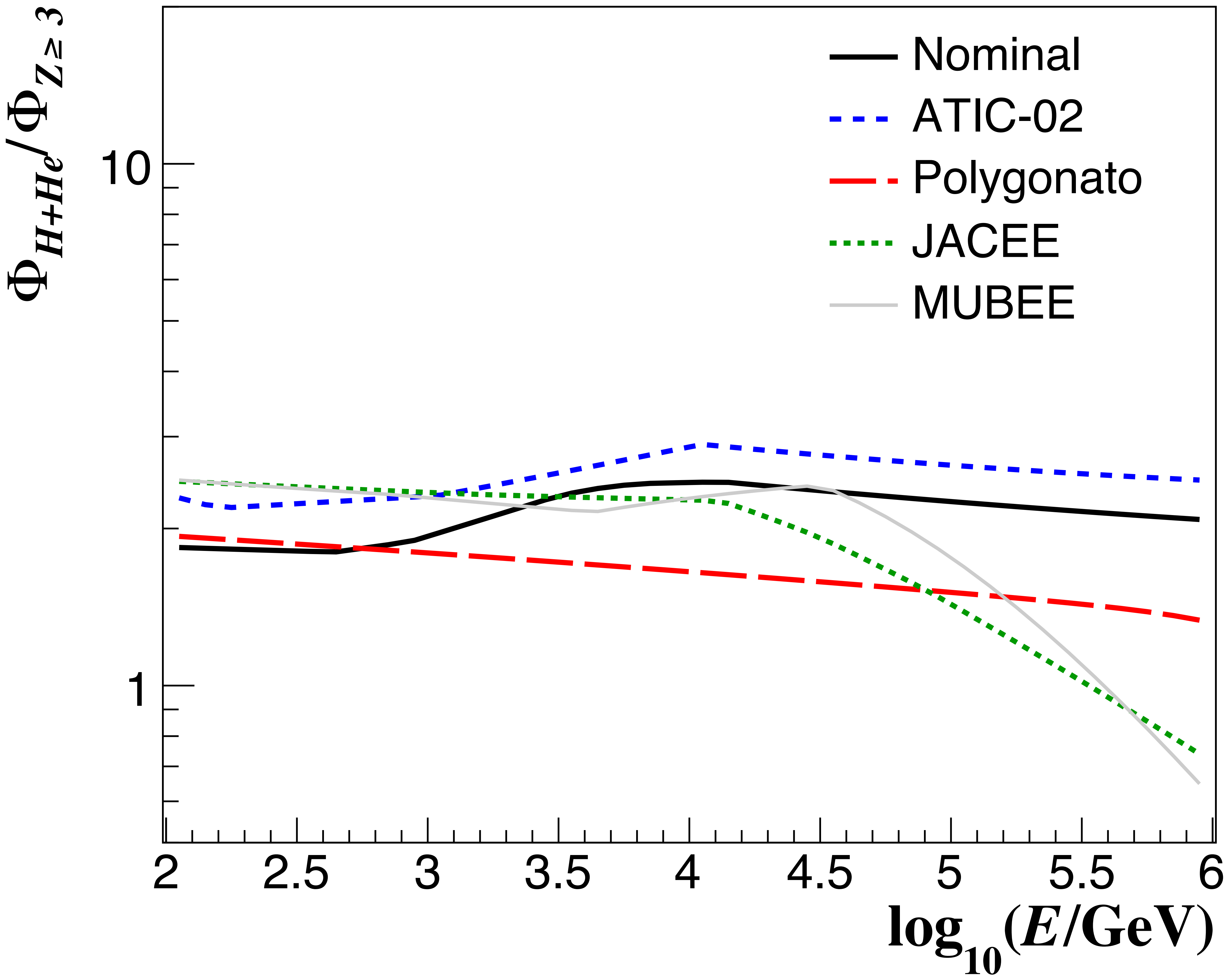




Monte Carlo Simulation

Composition models



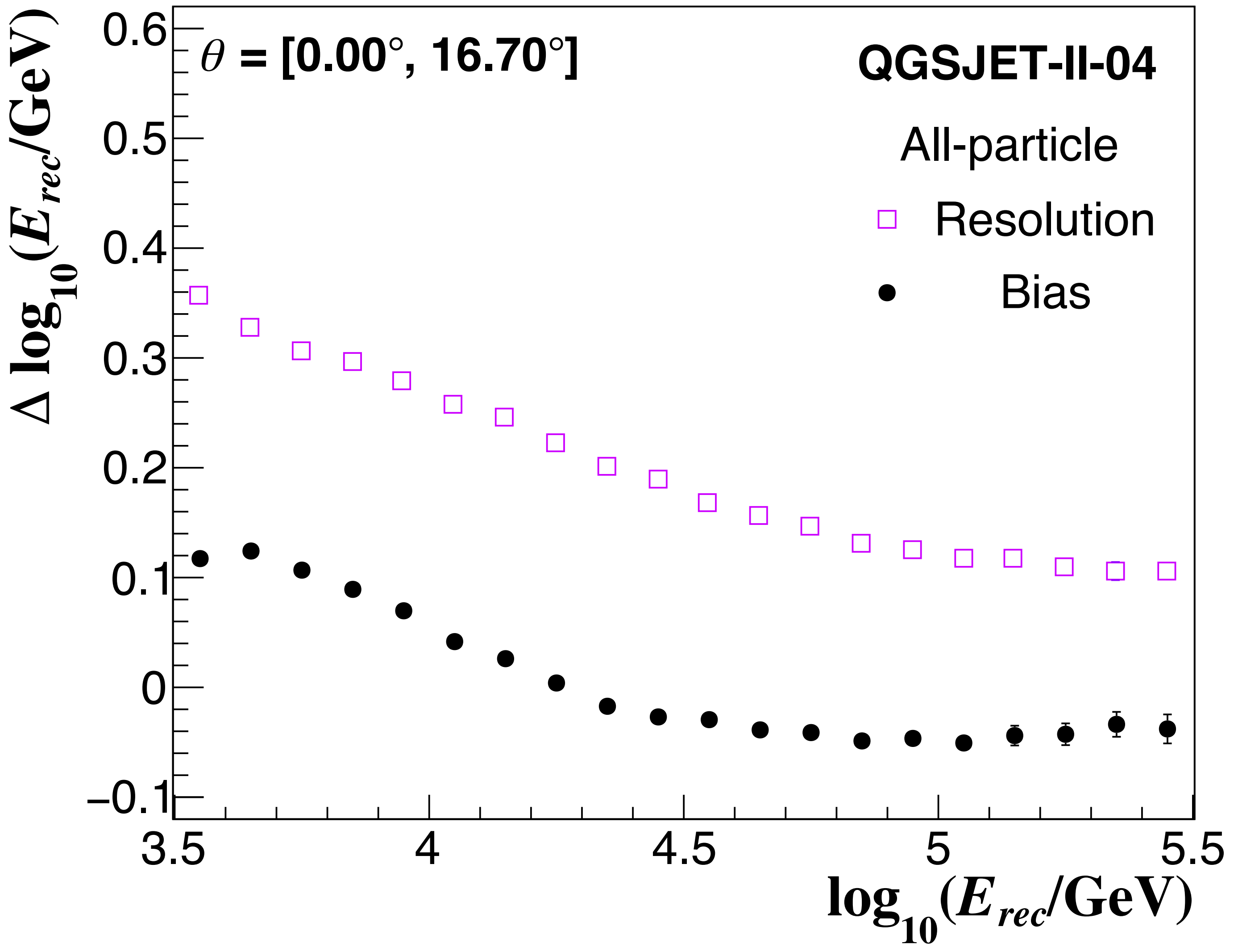


- But also use different composition models for studies of systematics

Data Selection

Selection cuts

- Important to reduce systematic effects on results:
  - $\theta < 16.7^\circ$
  - Successful core and arrival direction reconstruction
  - Activate at least 40 PMTs within 40 m from core
  - Fraction hit (# of hit PMT's/# available channels) ≥ 0.2
  - $\log_{10}(E/\mathrm{GeV}) = [\,3.5, 5.5]$



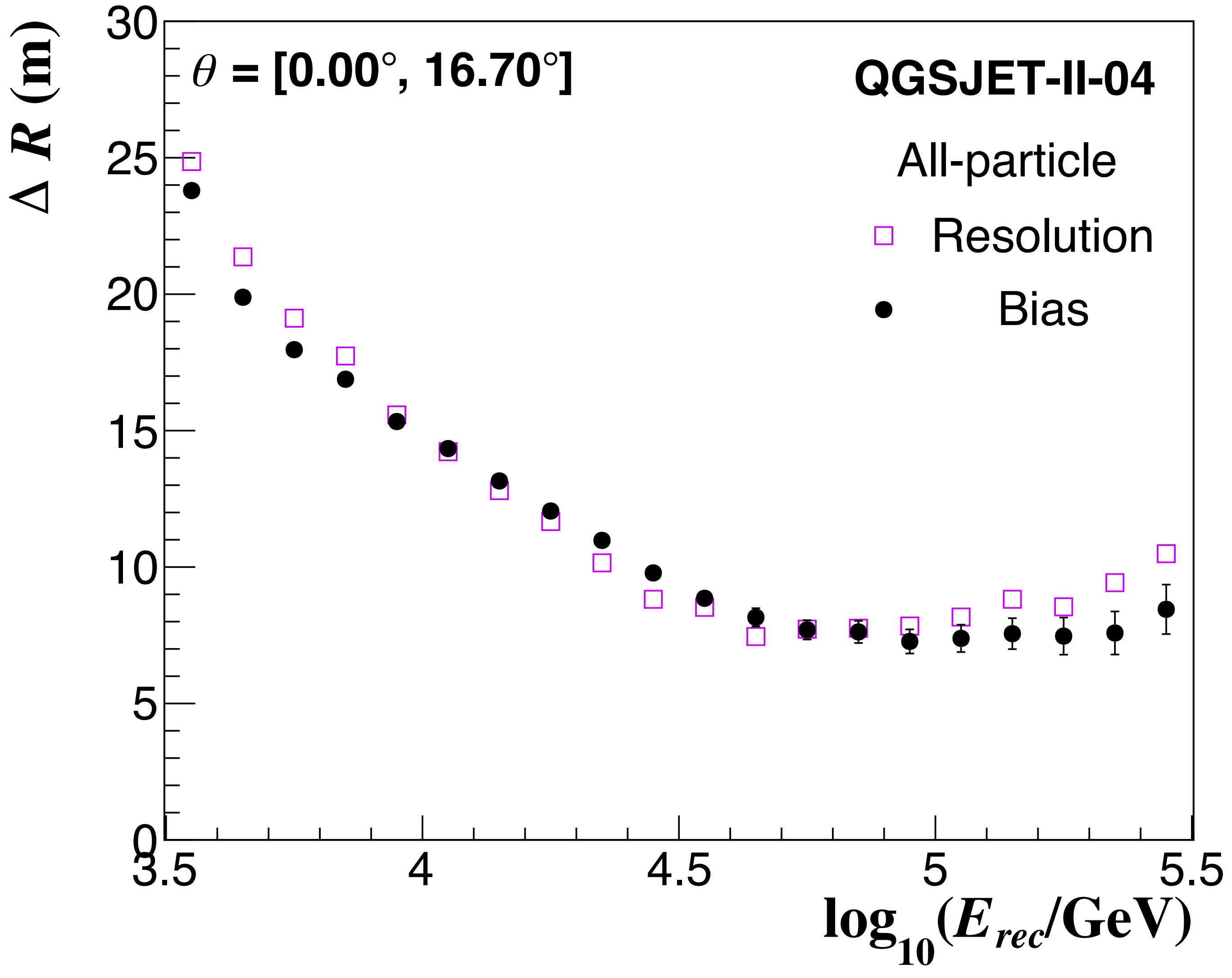
- Resolution:

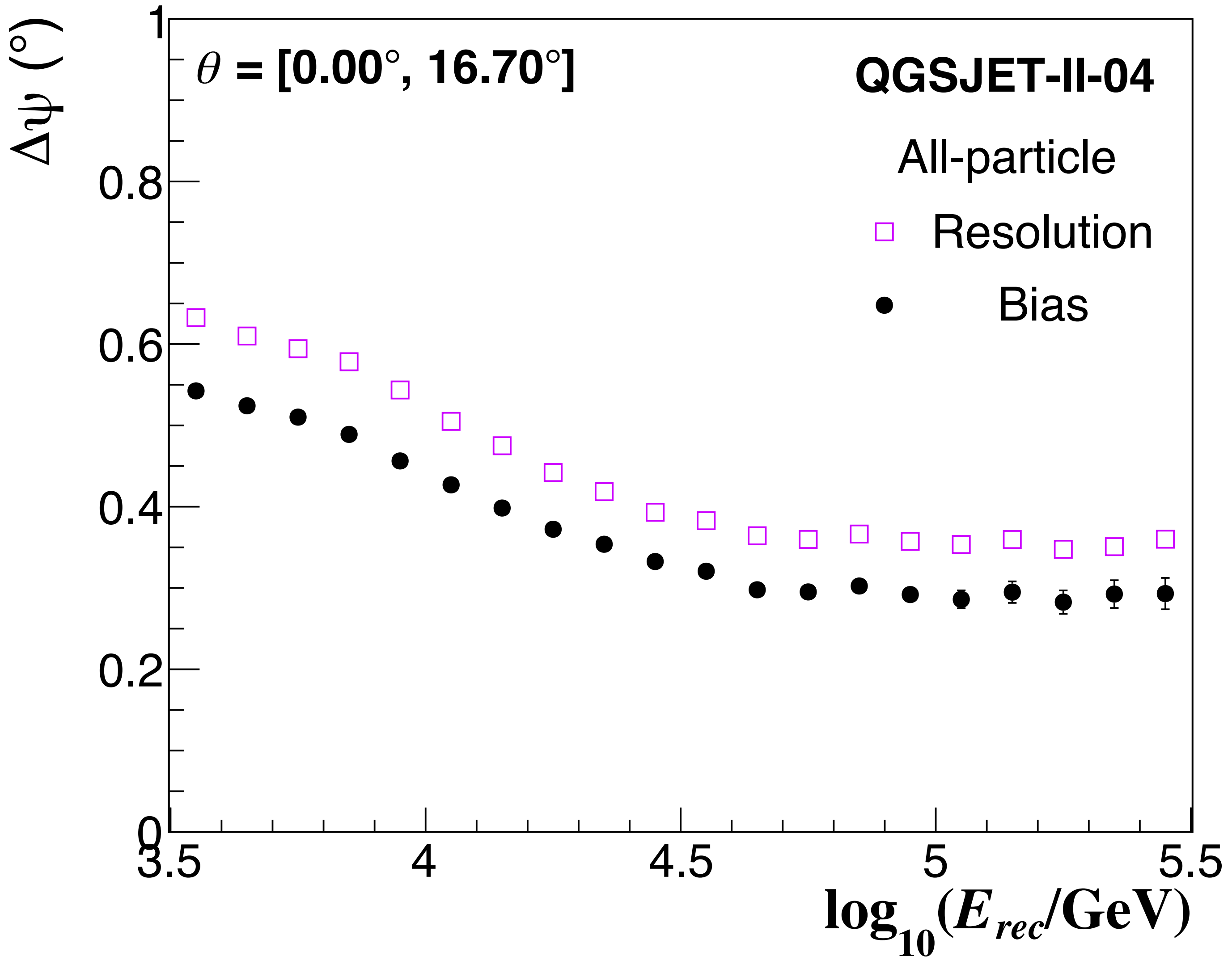
E ≥ 10 TeV:

Δcore ≤ 15 m

$|\Delta\log_{10}(E/\mathrm{GeV})| \leq 0.26$

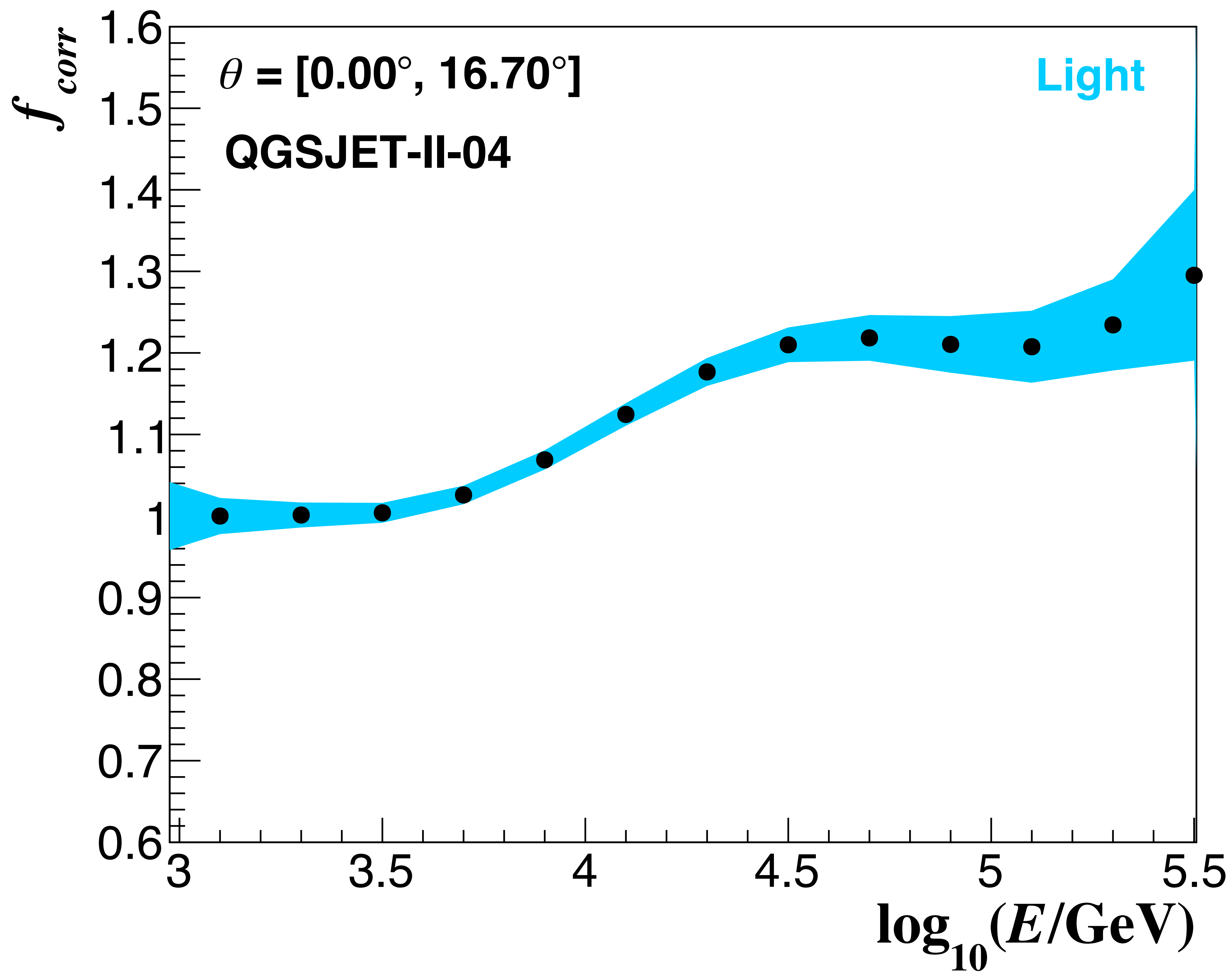
$\Delta\Psi \leq 0.55^\circ$





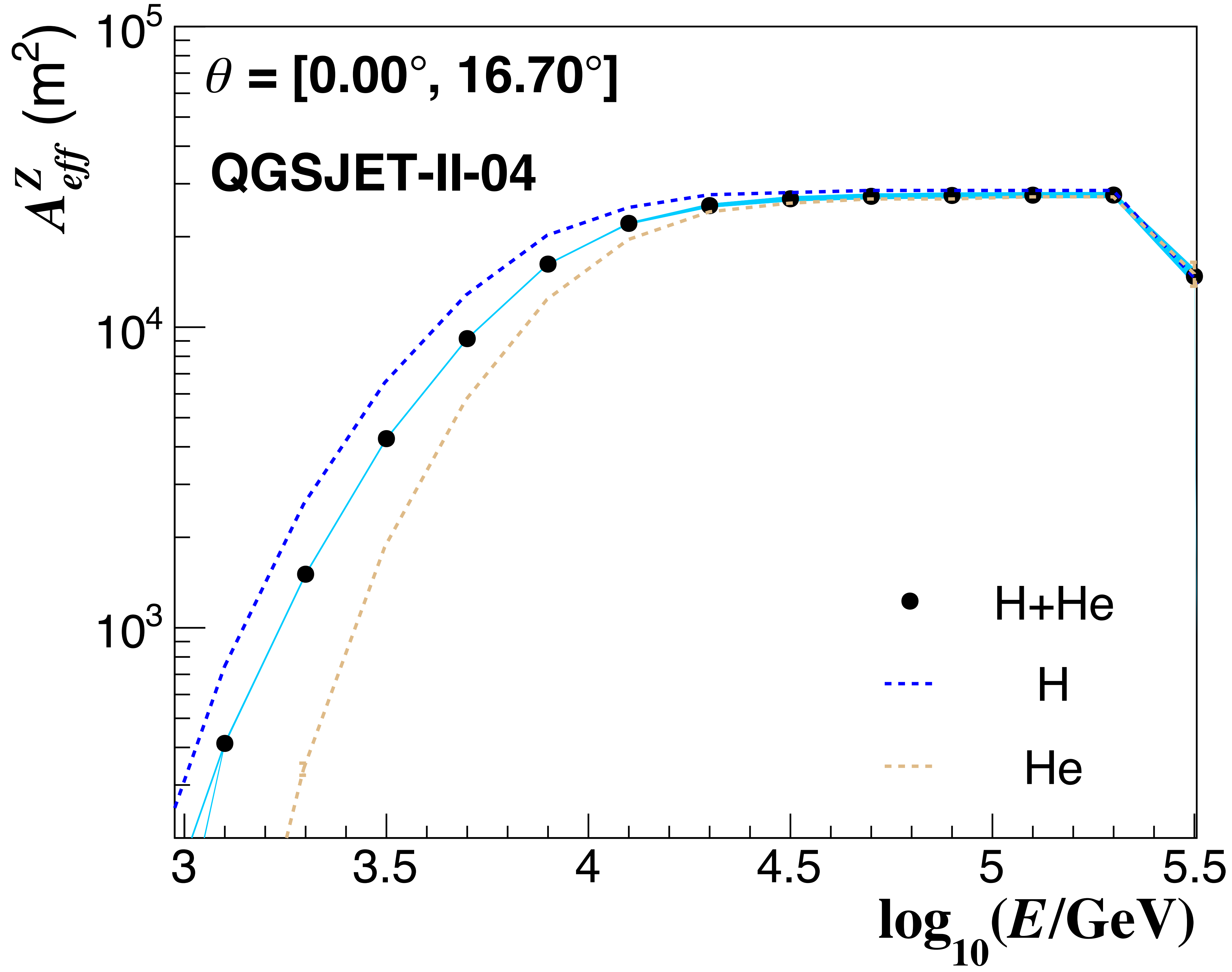
Analysis

Obtain effective area from MC simulations



- Correction factor due to contamination of heavy events

$$f_{corr} = (N_{light} / N_{light}^{H+He})$$

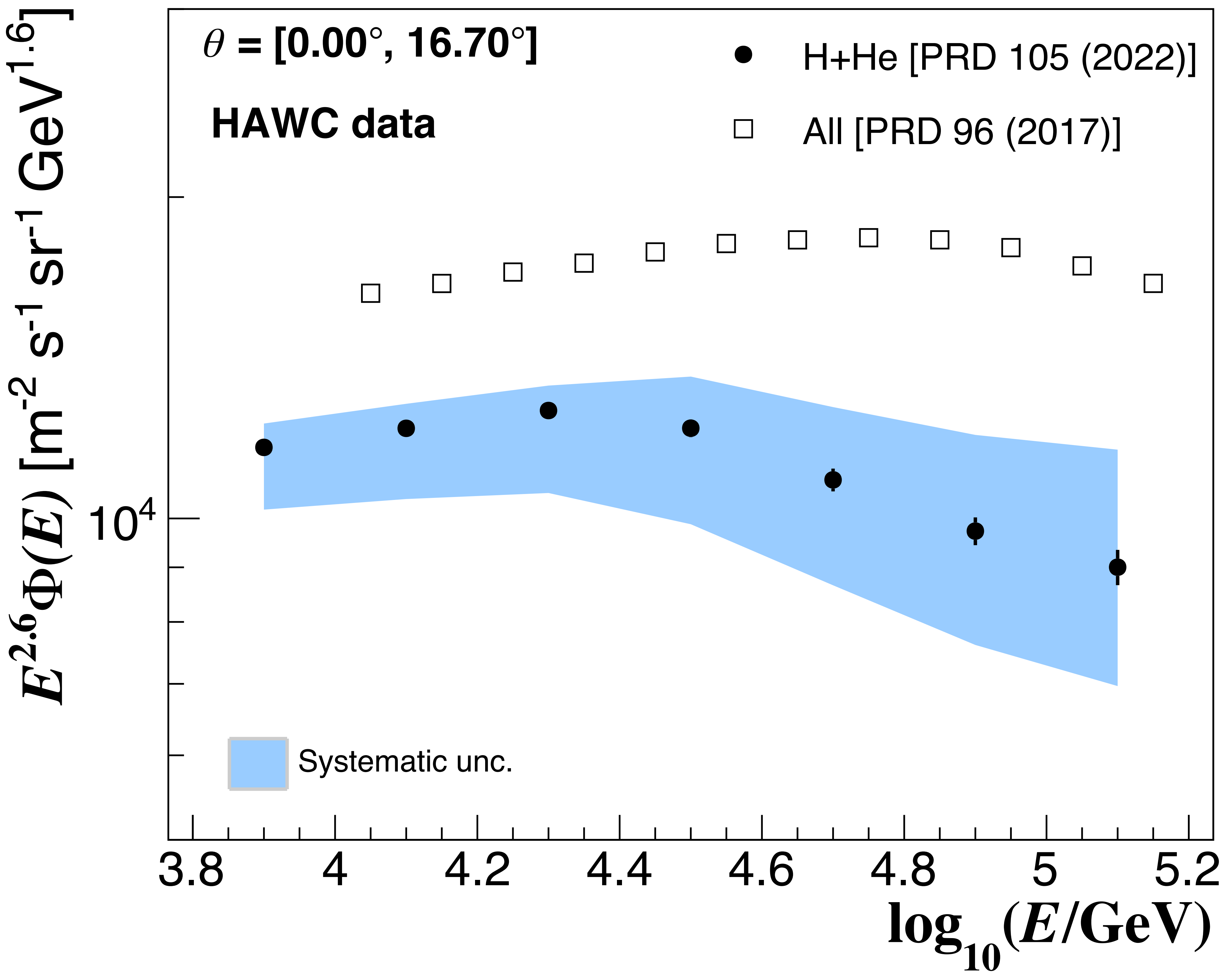


- Effective area of H+He in subsample

$$A_{eff}^{H+He}(E_i) = A_{thrown}\, \varepsilon^{H+He}(E_i)\, \frac{\cos\theta_{max} + \cos\theta_{min}}{2}$$

HAWC H+He Energy Spectrum

Get energy spectrum from N^{Unf} and effective area



- Energy spectrum was calculated as:

$$\Phi = N^{Unf}(E)/[\Delta E^{T} \cdot \Delta t_{eff} \cdot \Delta\Omega \cdot f_{corr}(E) \cdot A_{eff}^{H+He}(E)]$$

Statistical and systematic uncertainties

H+He

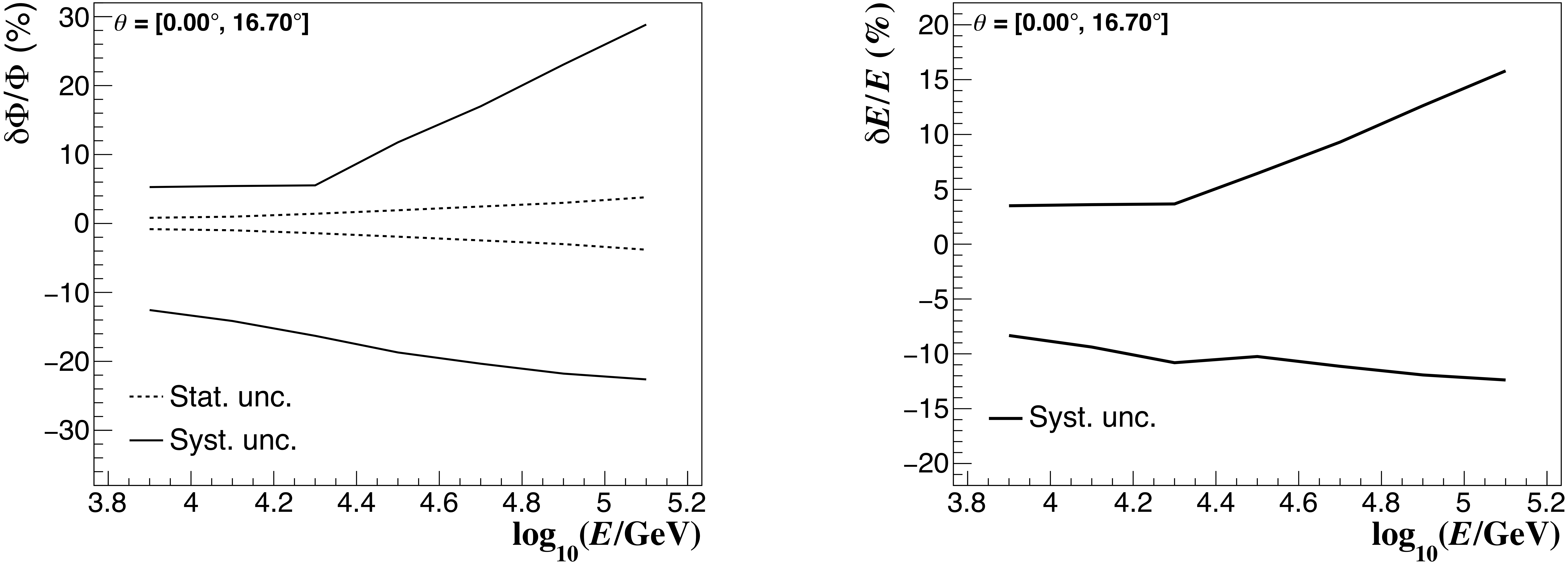
$\log_{10}(E/\mathrm{GeV}) = 4.5$ (32 TeV)

	Relative error Φ (%)
Statistical	**+/- 1.92**
Exp. Data	+/- 0.01
Response matrix	+/- 1.92
Systematic	**+11.77/-18.71**
Composition	+0.86/-17.25
Aeff	+1.85/-2.04
Cut at He or C	+2.87/-0.75
Gold unfolding	+1.23
Seed unfolding	-1.42
Smoothing unfold.	+3.73/-1.32
PMT efficiency	+5.00
PMT threshold	+2.33/-1.53
PMT charge	+1.83
PMT late light	+8.77/-0.14
Hadronic model	-6.47
Total	**+11.93/-18.81**

H+He Energy Spectrum

Statistical and systematic uncertainties

H+He



From $N(E^R)$ we get the unfolded energy distribution $N(E)$

How? Iterative procedure, Bayesian Unfolding [11-13]

1) $P(E_j^R \mid E_i)$ …………………… Response Matrix (calculated from MC data)

2) $$P(E_i \mid E_j^R) = \frac{P(E_j^R \mid E_i)P_0(E_i)}{\sum_l^{n_c} P(E_j^R \mid E_l)P_0(E_l)}\,.$$ …………………… Bayes formula

3) $$N(E_i) = \sum_{j=1}^{n_E} P(E_i \mid E_j^R)N(E_j^R) = \sum_{j=1}^{n_E} M_{ij}N(E_j^R)\,.$$ …………………… True event distribution

4) $$P(E_i) \equiv \frac{N(E_i)}{\sum_{i=1}^{n_c} N(E_i)} = \frac{N(E_i)}{N_{true}}\,.$$ …………………… Final probability

5) $$WMSE = \frac{1}{n}\sum_{i=1}^{n} \frac{\bar{\sigma}_{stat,i}^2 + \bar{\delta}_{bias,i}^2}{N(E_i)}$$ …………………… Weighted mean squared error (The minimum is employed as a stopping criteria for the iteration depth)

Gold's Unfolding

Use **matrix formalism**:

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

Introduce statistical errors using new response matrix

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

and new unfolded vector

$$N'_{\text{data}} = (CP)^T C N_{\text{data}}$$

where

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

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

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

Priors given by nominal composition model.

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

Stopping criterium: Minimum of Weighted Mean Square

Error:

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

[R.Gold, Report ANL-6984, 1964]
[KASCADE Collab., App 24 (2005) 1]

H+He Energy Spectrum

Fit of spectrum

H+He

1. Use following functions:

—> Single power law:

$$d\Phi(E)/dE = \Phi_0 \, E^{\gamma 1}$$

—> Broken power law:

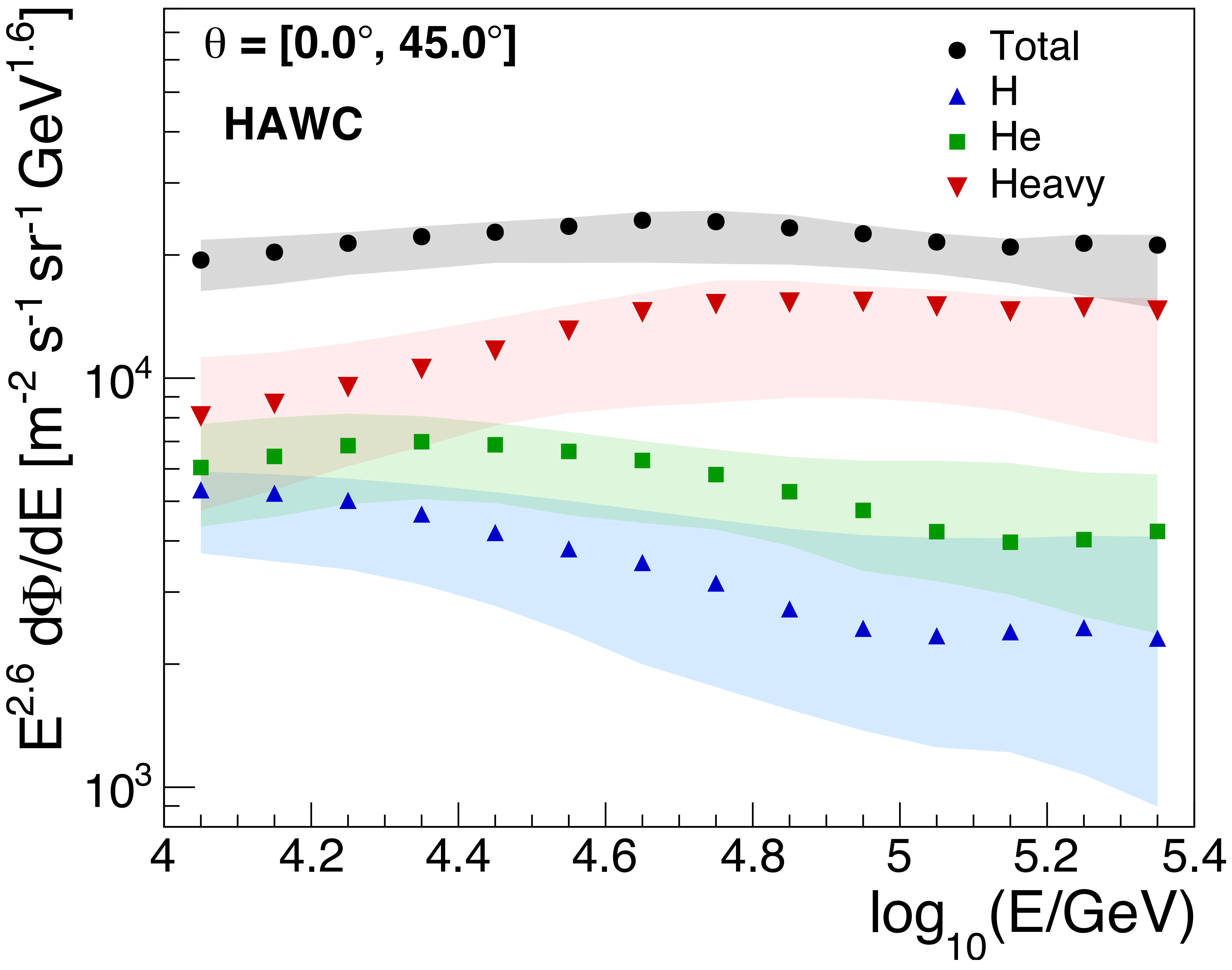
$$d\Phi(E)/dE = \Phi_0 \, E^{\gamma 1}[\, 1 + (E/E_0)^{\varepsilon} \,]^{(\gamma 2 - \gamma 1)/\varepsilon}$$

2. Minimize χ^2 with MINUIT and take into account correlation between points:

$$\chi^2 = \sum_{i,j} [\Phi_i^{data} - \Phi^{fit}(E_i)] \, [V_{stat}^{Tot}]^{-1}_{ij} \, [\Phi_j^{data} - \Phi^{fit}(E_j)]$$

[C. Patrignani et al. (PDG), Chin. Phys. C, 40 (2016) and (2017) update]

HAWC p, He, Z>=3



- **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%).

HAWC Composition

- Results show that the spectra of these mass groups have fine structures, in particular, individual softenings, whose energy positions increase with the primary mass.
- Observation of softening in the spectra of H and He at ~ 14 TeV and ~25TeV respectively.
- Confirms recent detections by DAMPE of similar features in p and He spectra.
- Agreement between both techniques confirms potential of high-altitude EAS for studying TeV cosmic rays.
- Additional feature in spectrum of the heavy CR component in TeV region and indications in HAWC data of possible hardening in the intensities of H and He near 100TeV in agreement with GRAPES-3.

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