# Measurement of the all-particle energy spectrum with the DAMPE mission

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on behalf of the DAMPE collaboration
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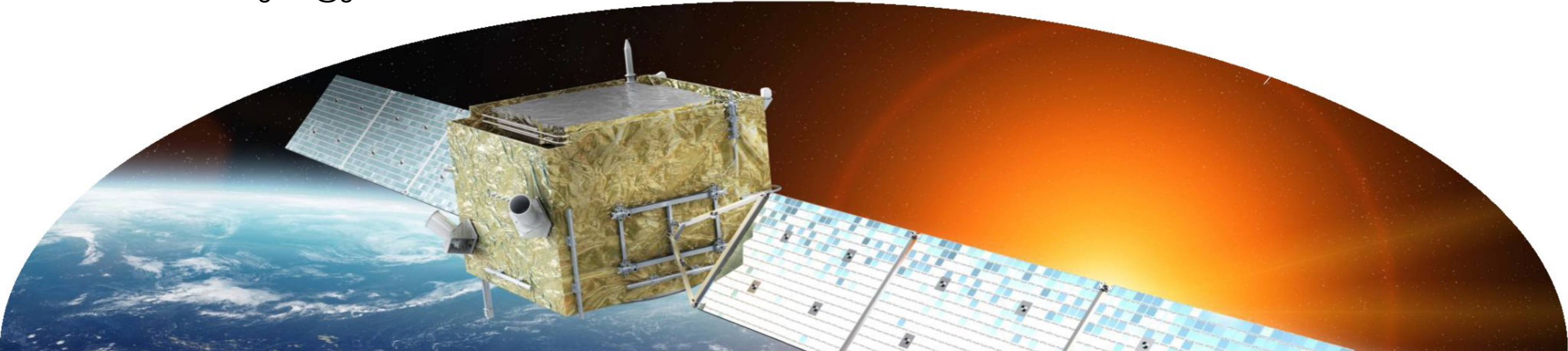
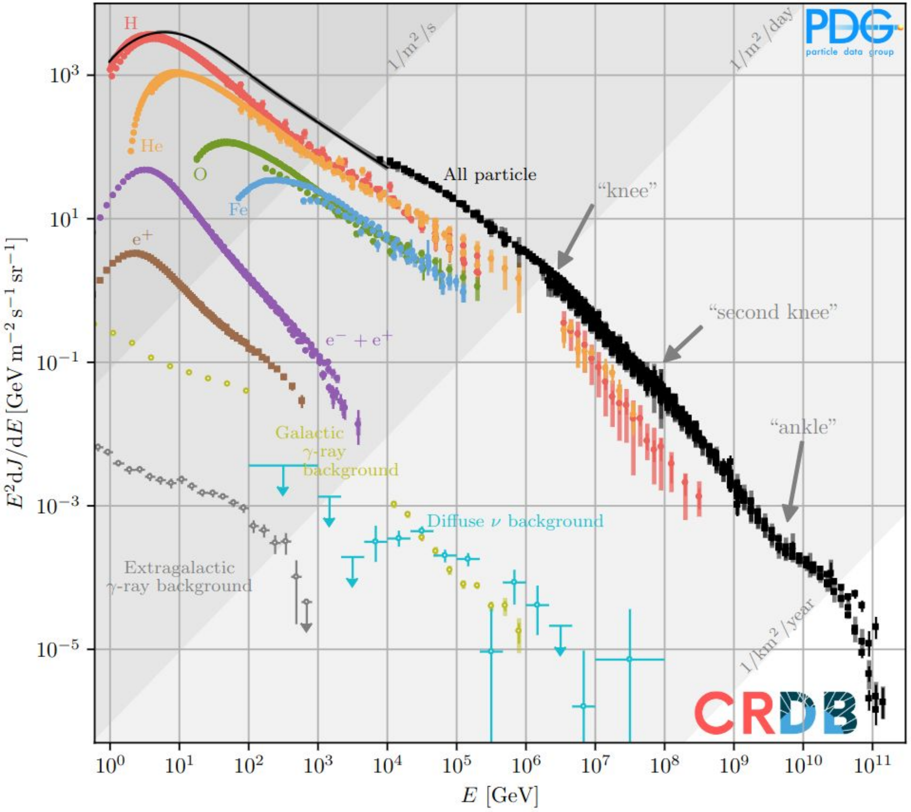


# The all-particle spectrum towards the knee




Scientific motivations for measuring the all-particle spectrum up to ~1 PeV

- Combine all particle species using a **loose charge cut selection**
  - to **minimize cross-contamination** among individual element spectra
  - to **increase the statistics and reach higher energies** than when analysing individual particles species
- Establish a **link between direct and indirect CRs experiments**: facilitate a unified understanding of CR properties across different energy ranges
- **Cross-calibration** with ground-based measurements (hadronic interaction models and other systematics)

# The DAMPE space mission

- Collaboration of Chinese, Italian and Swiss scientific institutions
- Launched on 17 December 2015
- The primary **scientific goals**:
    - Study of ($e^-$ + $e^+$), CR protons and nuclei spectra
    - High energy gamma ray astronomy
    - Indirect search for dark matter signatures in lepton spectra
- The main features

| | |
|---|---|
| Acceptance | >0.1 $m^2sr$ |
| Energy resolution | 1.2% at 100 GeV (e/γ)<br>< 40% at 800 GeV (nuclei) |
| e/γ angular resolution | 0.2° at 100 GeV |
| Detection | 10 GeV - 10 TeV (e/γ)<br>50 GeV - 200 TeV (nuclei) |

# The DAMPE detector

Plastic Scintillator Detector (PSD)

- **Charge** measurement + **anti-coincidence** for γ ID
- 2 planes (X/Y) of plastic scintillator bars

Silicon TracKer (STK)

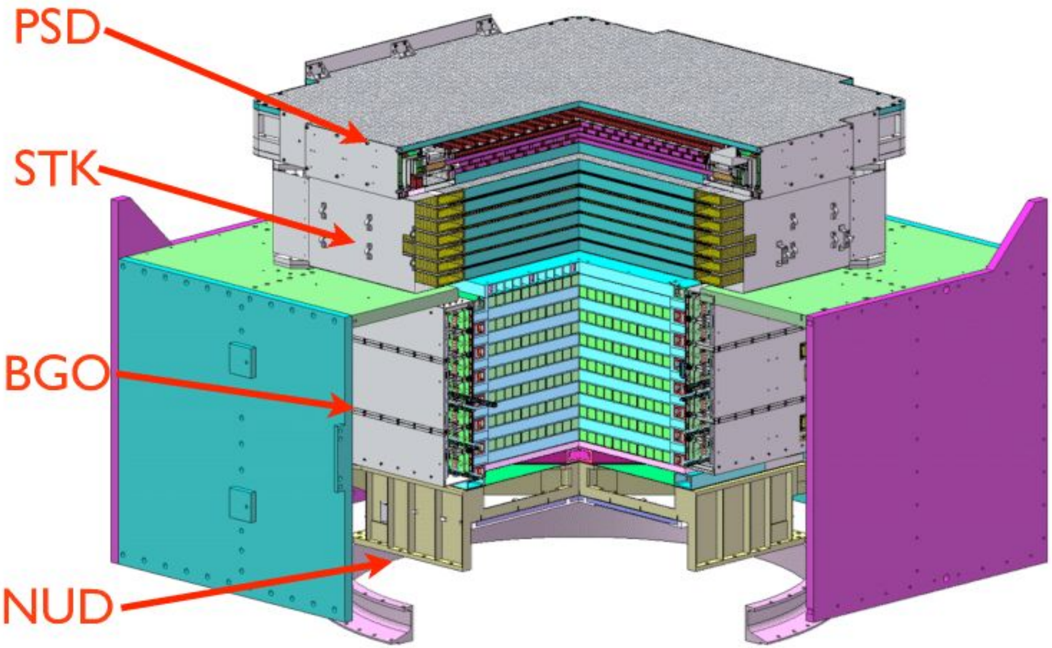
- **Track** reconstruction + additional **charge** measurement
- 6 planes of Si microstrip detectors + 3 W layers

BGO calorimeter (BGO)

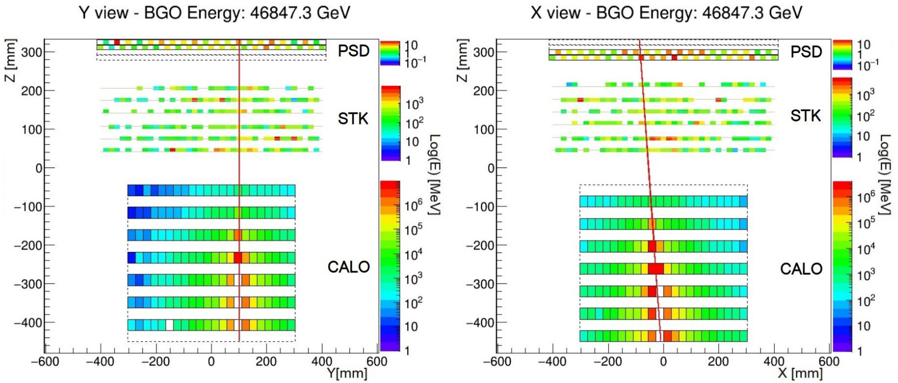
- **Energy** measurement + **em/had showers** discrimination
- 14 layers of BGO crystal bars
- 32 $X_0$ and 1.6 $\lambda_I$

NeUtron Detector (NUD)

- Further em/had showers separation
- 4 boron-doped scintillator tiles



# Analysis selection & procedure

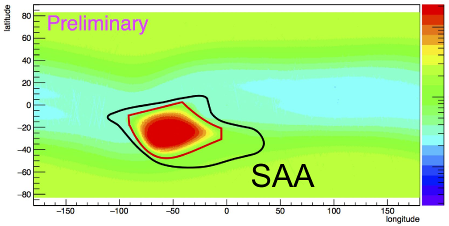



## Experimental data

- 96 months of flight data (January 2016 - December 2023)
- Total live time ~1.9 $10^8$ s

## Monte-Carlo simulations

- p, He, C, O, Ne, Mg, Si, Fe
  - [100 GeV - 500 TeV] range
  - GEANT4v4.10.5 with FTFP_BERT and EPOS-LHC
- Assumed a mass composition model
  - To build the weighted mean acceptance and response matrix
  - Different models considered to evaluate the model dependence of the output spectra

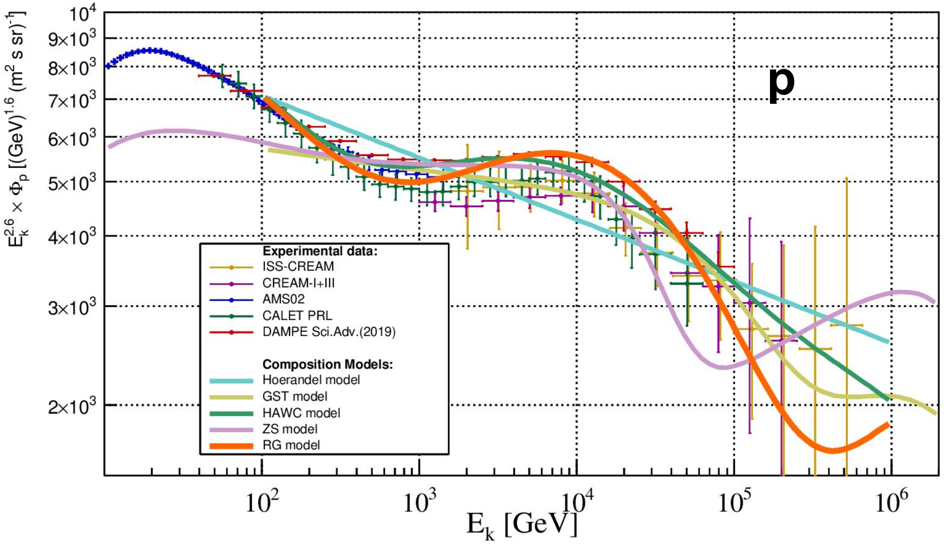


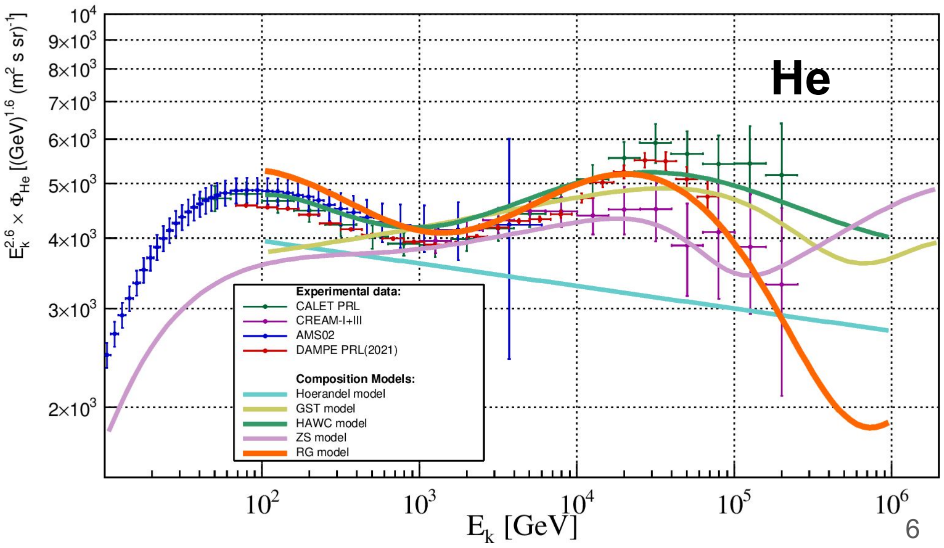

## Selection cuts

- SAA exclusion
- $E_{depo}$ in each BGO layer < 35% $E_{BGO}$
- HET trigger ON
- $E_{BGO}$ > 100 GeV
- BGO fiducial cuts
  - Reconstructed shower axis inside the fiducial volume
  - ∀ layer: max $E_{depo}$ inside the fiducial volume
- No charge/track selection cuts

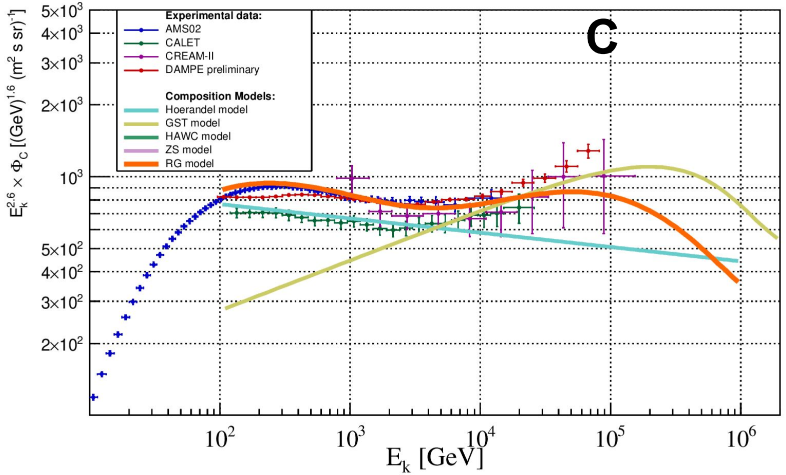
# Composition models

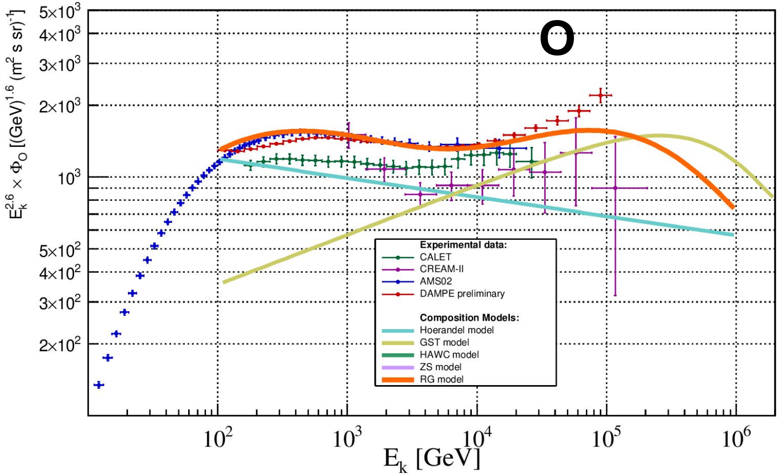
| Model | Application E range | Reference |
| --- | --- | --- |
| **Hoerandel (poly-gonato) model** | [10 GeV - $10^9$ GeV] | *J. R. Hörandel, Astropart.Phys. 19 (2003) 193-220* |
| **HAWC model** | [$10^2$ GeV - $10^6$ GeV] | *HAWC, PoS ICRC (2023) 299* |
| **Recchia-Gabici (RG) model** | [~GeV - multi PeV] | *S. Recchia, S. Gabici (2023) arXiv:2312.11397* |
| **Zatsepin-Sokolskaya (ZS) model** | [10 GeV - $10^8$ GeV] | *V. I. Zatsepin, N. V. Sokolskaya, A&A 458 (2006) 1* |
| **GST model** | [$10^5$ GeV - $10^{11}$ GeV] | *T. K. Gaisser, T. Stanev, S. Tilav, Front. Phys. 8 (2013) 748–758* |

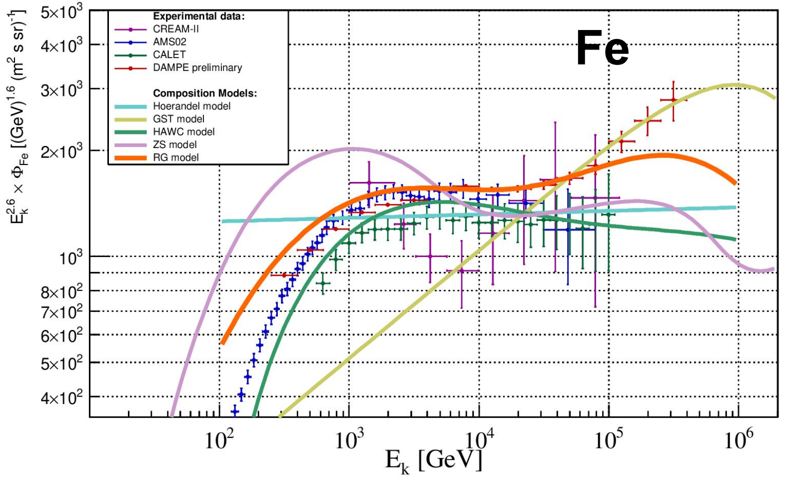


# Composition models



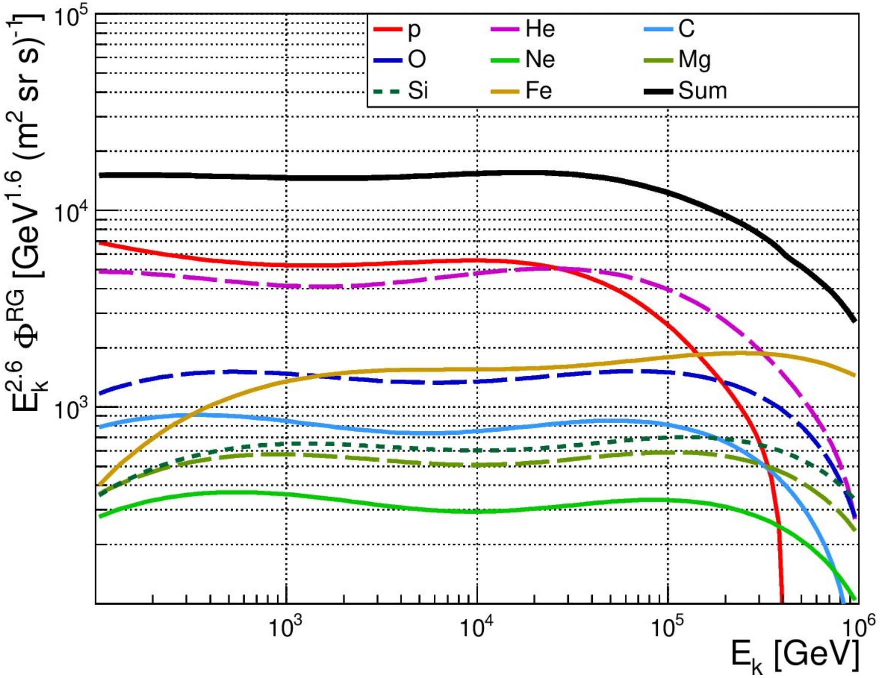



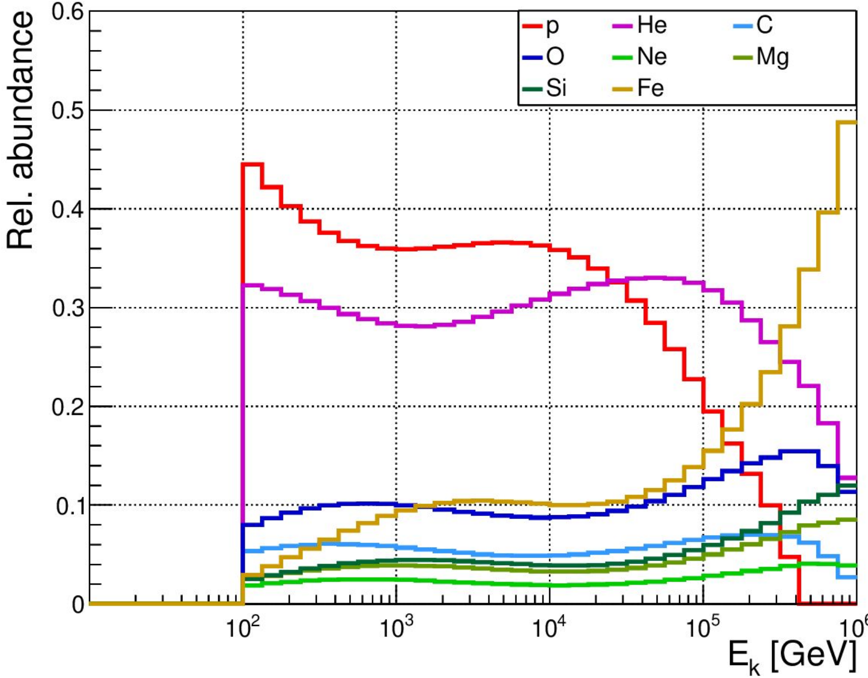

The **RG model** accurately reproduces the single nuclei spectra: **assumed as the composition model for the analysis**

# Implementation of the Recchia-Gabici model

RG flux for each element




Relative abundances




∀ element $X$

- its flux is described by the RG model
- its rel. abundance is computed and used as a weight to compute the mean acceptance & response matrix

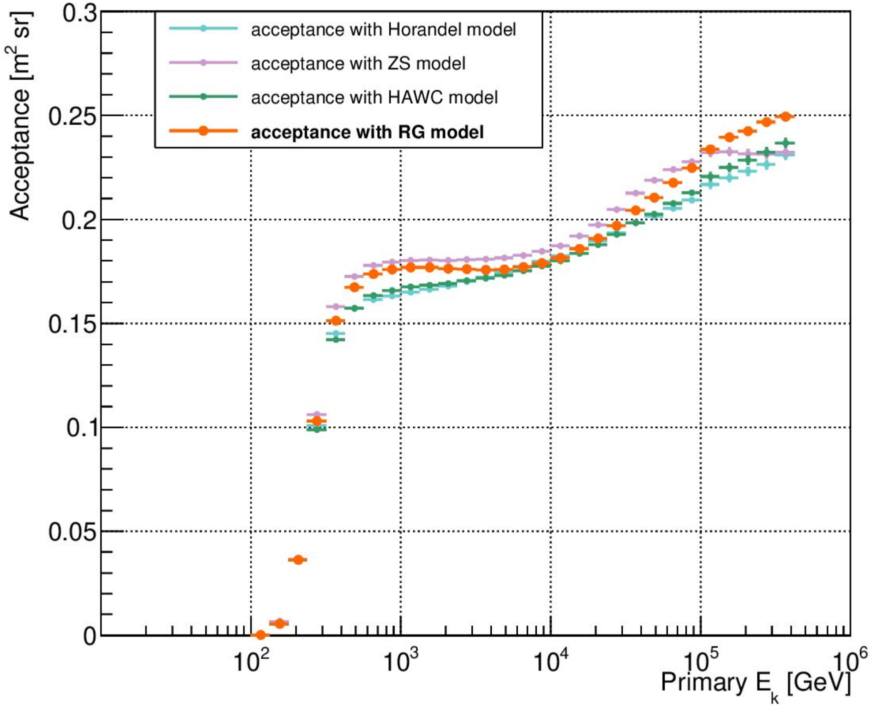
$$w_i^X = \frac{\int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^X(E)dE}{\sum_{el} \int_{E_i^{min}}^{E_i^{max}} \Phi_{RG}^{el}(E)dE}$$

$el = \mathrm{p, He, C, O, Ne, Mg, Si, Fe}$

# Acceptance and unfolding

## Weighted mean acceptance

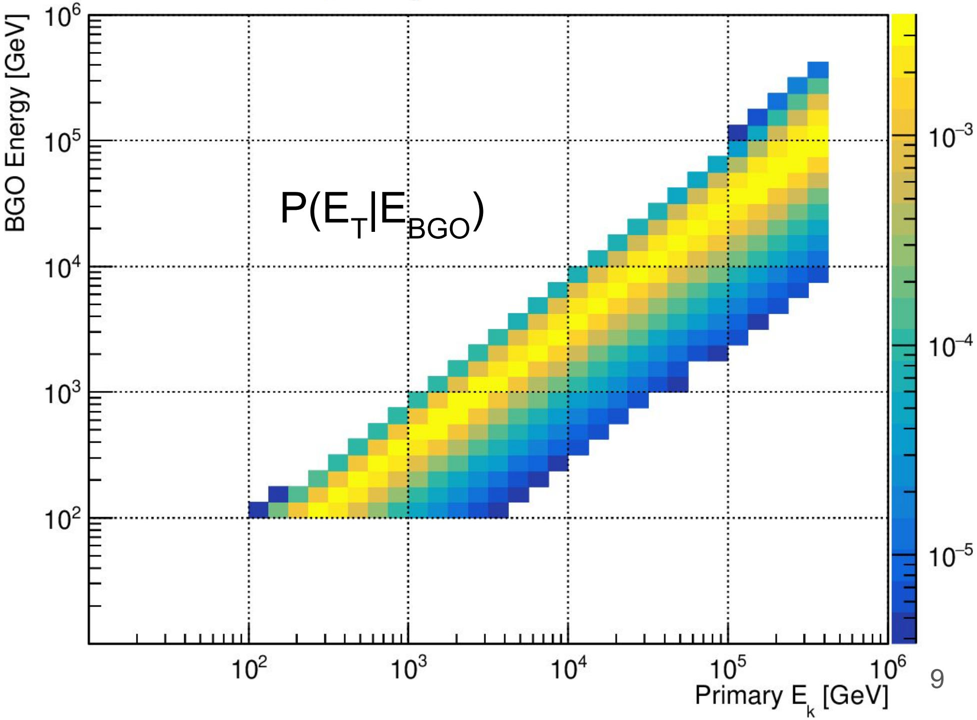
$$A_i = \sum_{el} w^{el} \; G^{el}_{gen} \; \frac{N^{el}_{sel}(E^i_T)}{N^{el}_{gen}(E^i_T)}$$



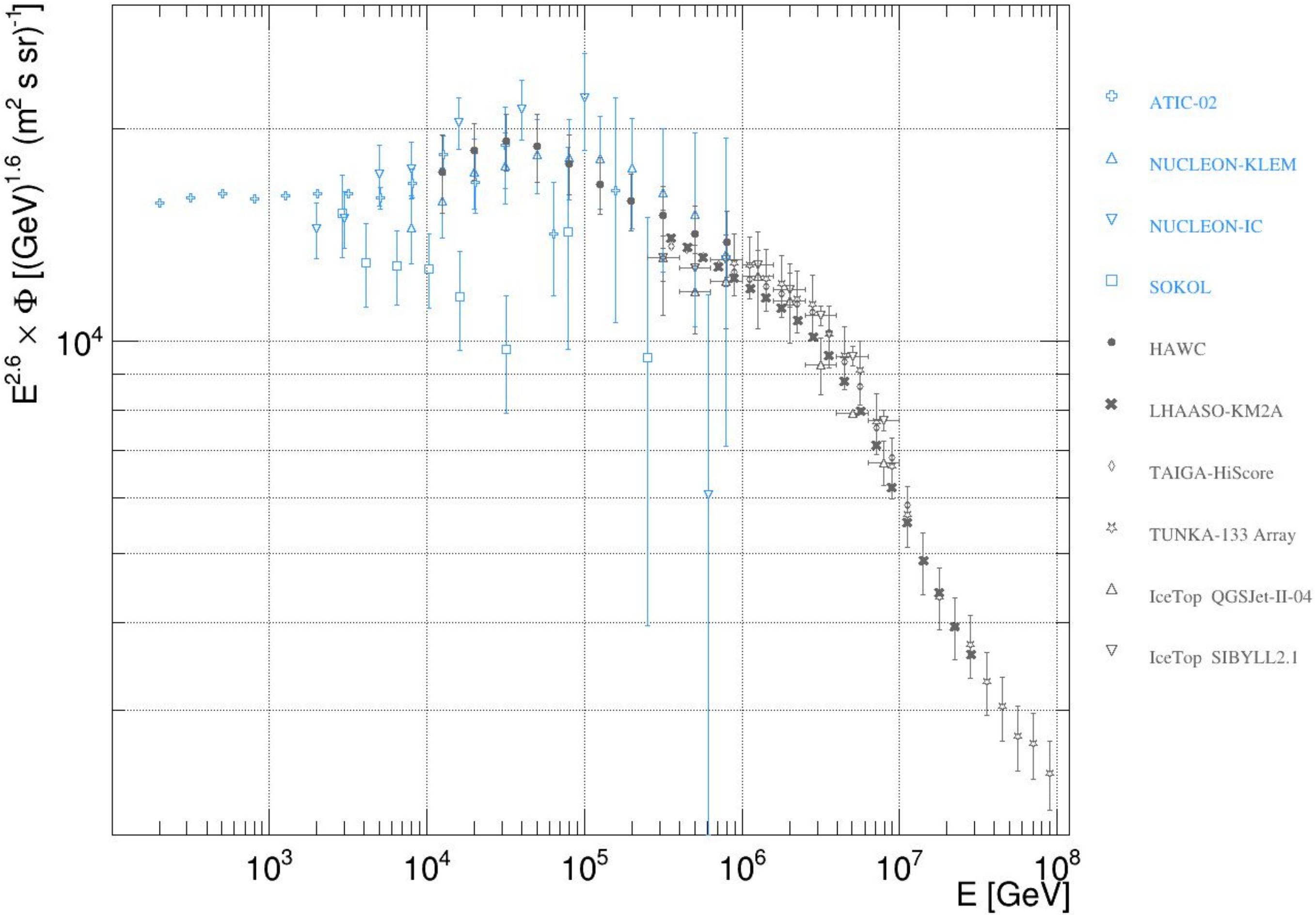

## Weighted mean response matrix

for the unfolding: iterative Bayesian procedure is adopted to reconstruct the primary energy of the events

$$N_i = \sum_{el} w^{el} \sum_{j=1}^{n} P^{el}(E^i_T|E^j_{BGO}) \; N^{el}(E^j_{BGO})$$



# All-particle flux




- Differential flux:

$$\Phi_i = \frac{N_i}{\Delta T \times A_i \times \Delta E_i}$$

- Evaluated systematics
  - Unfolding
  - Composition model
- Contribution from hadronic model is under evaluation
- In agreement with indirect experiments results
- Structure at tens TeV (convolution of the softening of different nuclei?)
- Work in progress to extend the measurement up to 0.7/0.8 PeV

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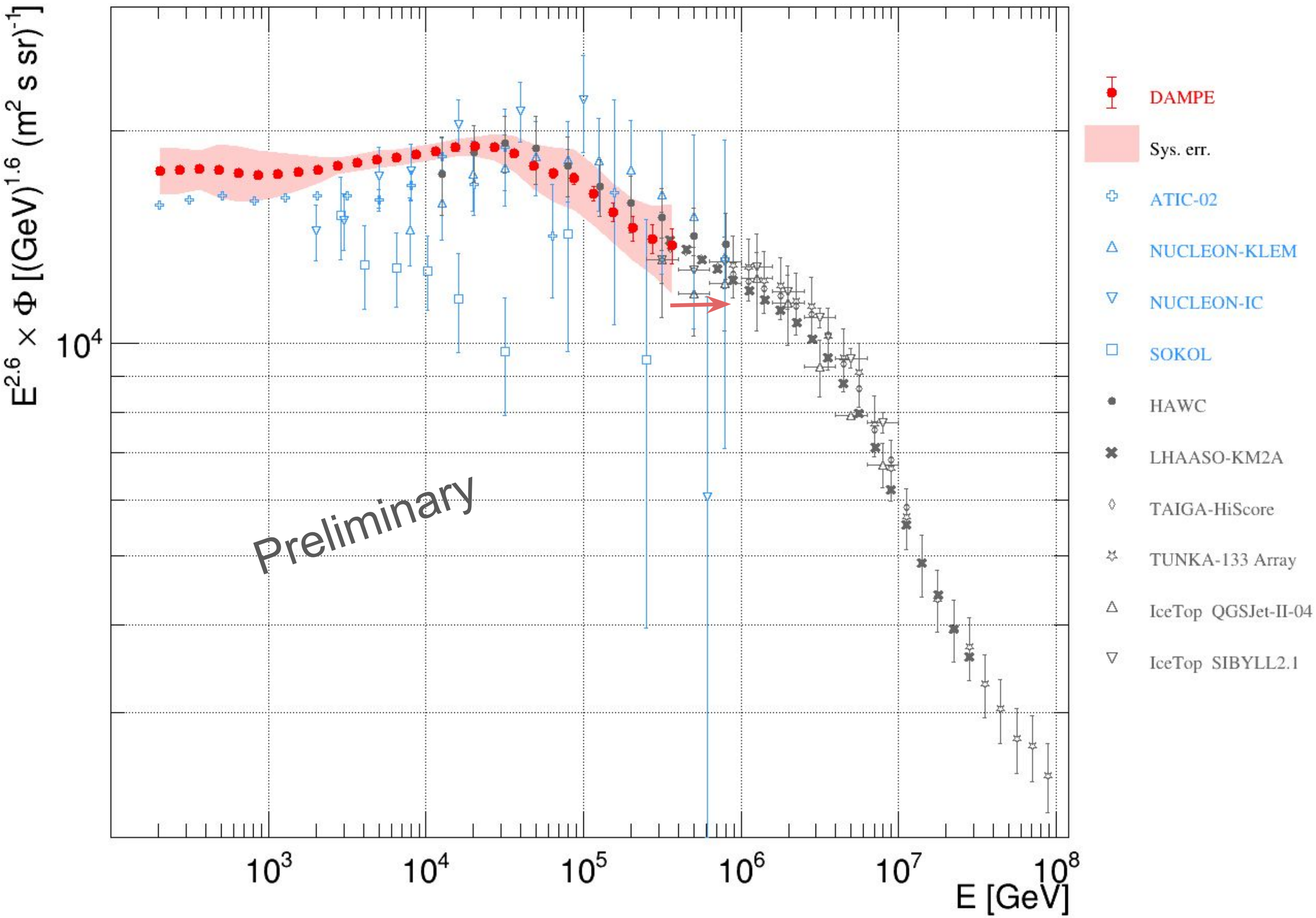


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# Conclusions

Preliminary result of the all-particle spectrum in the 200 GeV - 0.4 PeV energy range

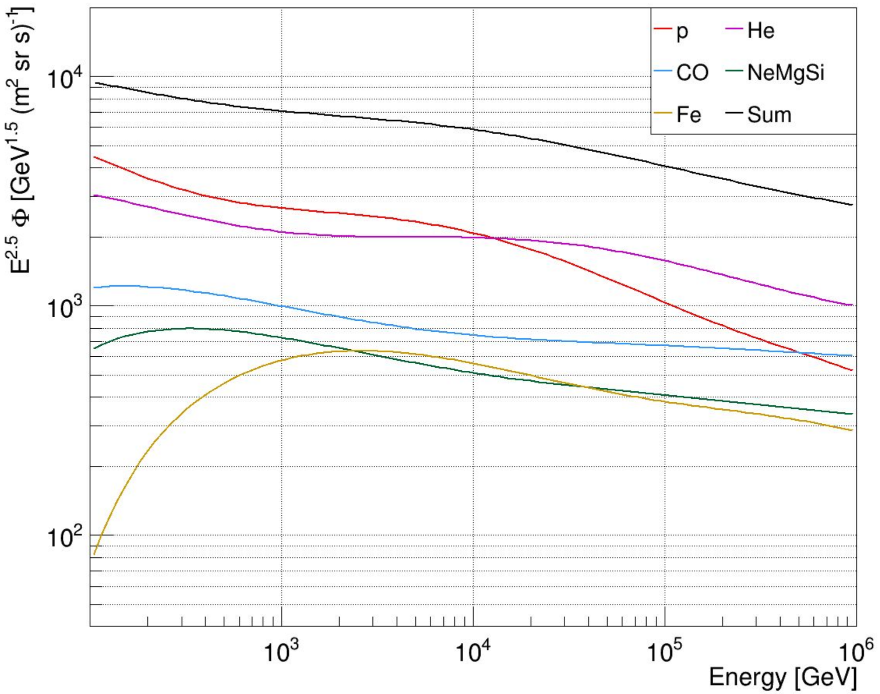
- Loose charge cut selection -> increase the statistics -> reach the PeV energies
- Results clearly show a change of slope around tens of TeV, most probably due to the softening of different components
- Full Systematics evaluation still ongoing
- Completely filling the gap between direct and indirect measurements.

# Backup

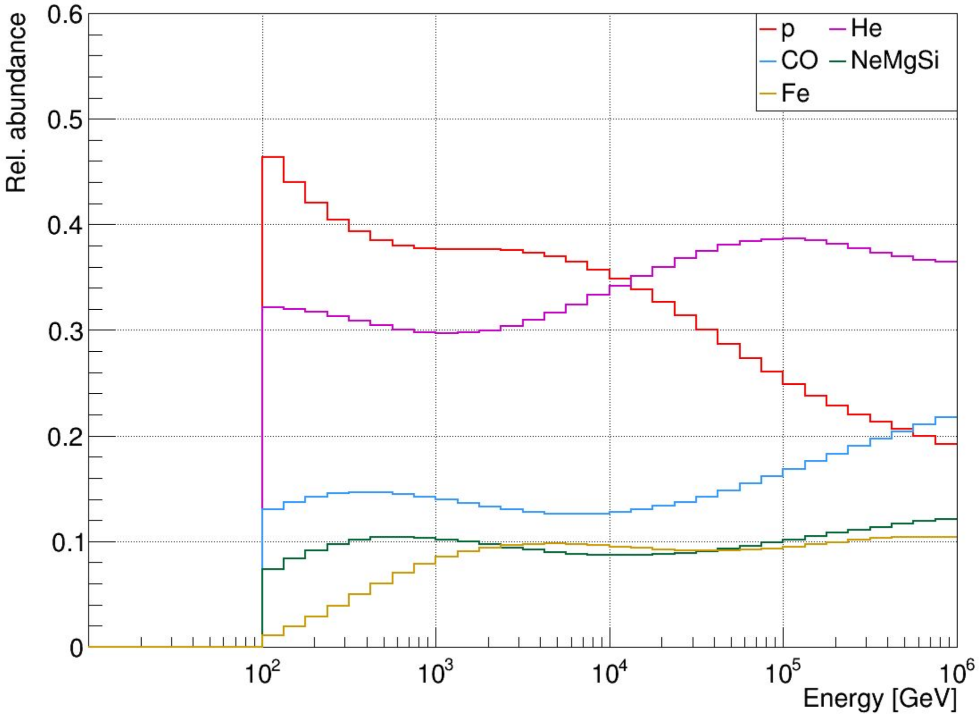
# HAWC composition model

- Derived by fitting BPL functions to data from ATIC-2, CREAM, PAMELA, AMS-2, NUCLEON, CALET, DAMPE, KASCADE

HAWC flux for each element



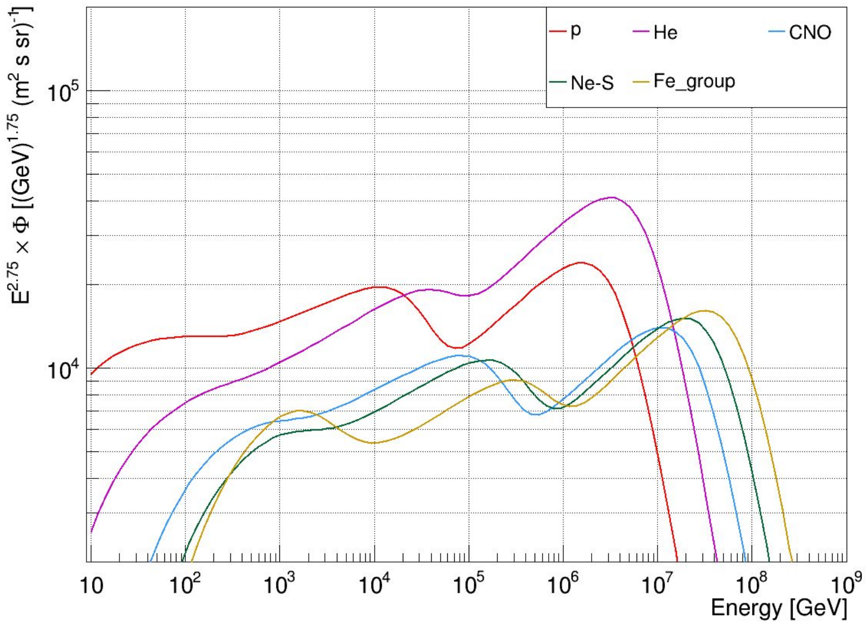

Relative abundances



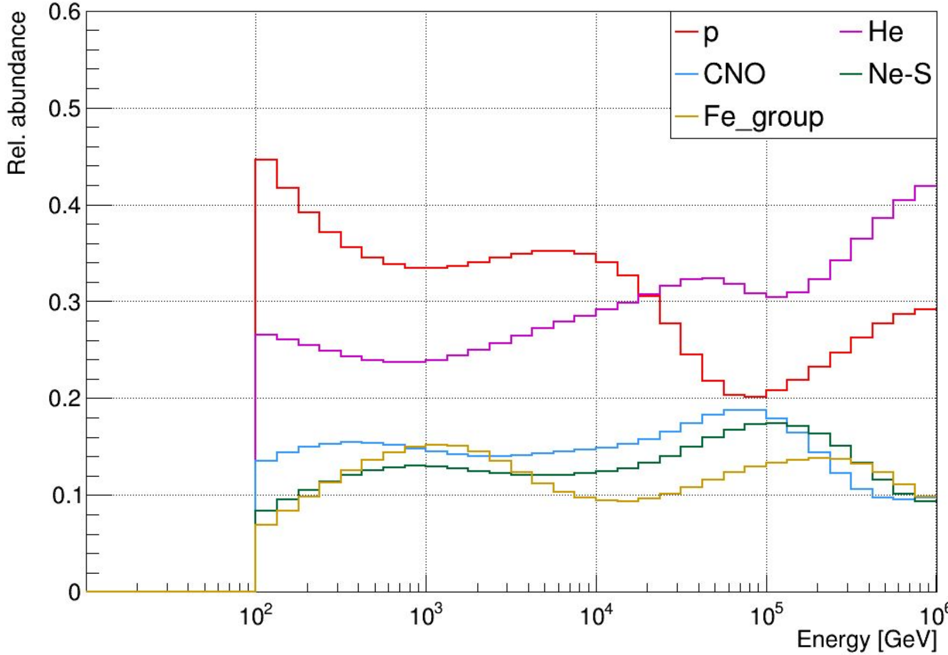
# ZS composition model

- 3 different classes of sources: each class prod. a spectrum for 5 nuclear group that
  - is simple power-law after termination of effective acceleration
  - with specific spectral-index $\gamma_k$ & Rmax
- Nuclear groups: p, He, CNO, Ne-S, Fe-group(Z>17)
- Solar modulation is taken into account
- Model fitted on experimental direct & EAS data

ZS flux for each element

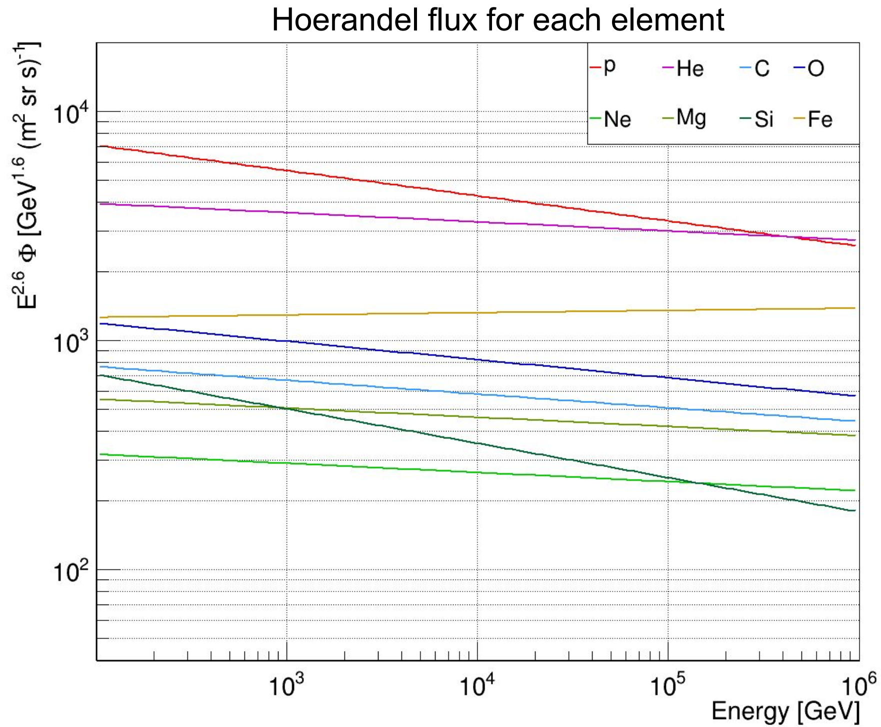


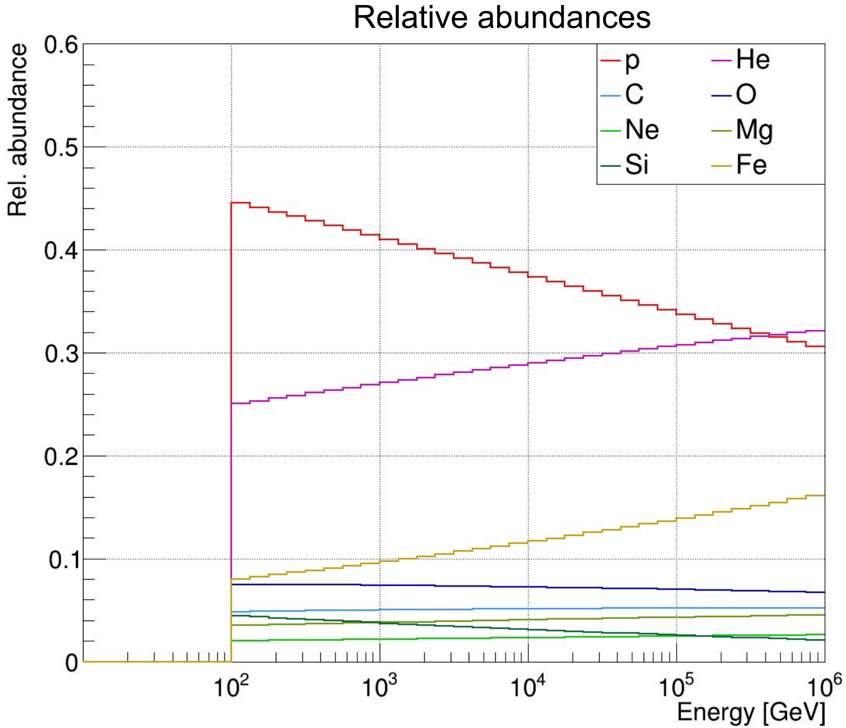

Relative abundances



# Hoerandel composition model

- Spectra of individual elements obtained from direct observations and extrapolated to high energies
- Direct experiments data fitted with SPL function $\Phi(E) = \Phi^0 \left(\frac{E}{1TeV}\right)^\gamma$



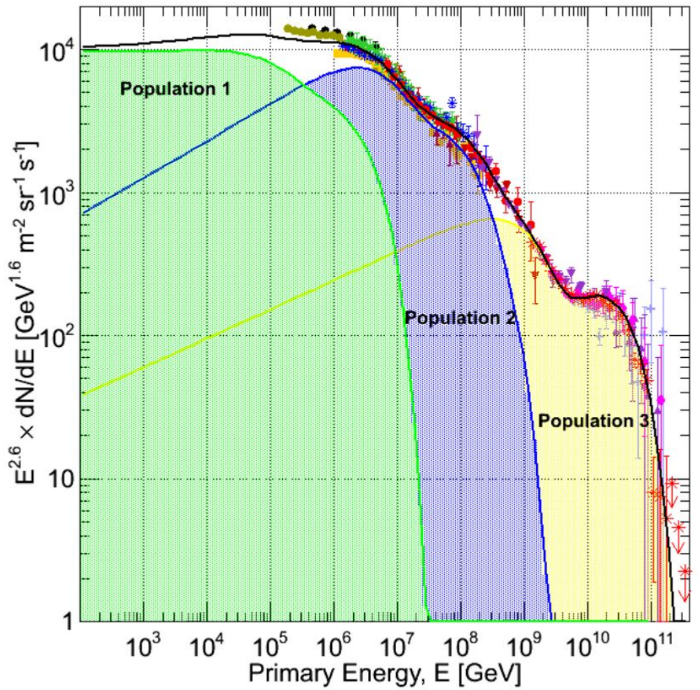



# GST composition model

- Performed 2 different fits to experimental data
  - each assuming 3 populations of particles
  - different assumptions for the rigidity cut off for each population
  - 3 populations: pop. 1 & 2 of galactic origin, pop. 3 is extragalactic
  - Each population (j) is contains 5 groups of nuclei (i)

$$\phi_i(E) = \Sigma_{j=1}^{3} a_{i,j} E^{-\gamma_{i,j}} \times \exp\left[-\frac{E}{Z_i R_{c,j}}\right]$$

| | p | He | C | O | Fe |
|---|---|---|---|---|---|
| Pop. 1: | 7000 | 3200 | 100 | 130 | 60 |
| $R_c = 120$ TV | 1.66 1 | 1.58 | 1.4 | 1.4 | 1.3 |
| Pop. 2: | 150 | 65 | 6 | 7 | 2.3 |
| $R_c = 4$ PV | 1.4 | 1.3 | 1.3 | 1.3 | 1.2 |
| Pop. 3: | 14 | | | | 0.025 |
| $R_c = 1.3$ EV | 1.4 | | | | 1.2 |



# GST composition model