# Data-driven model of the cosmic-ray flux and mass composition over all energies

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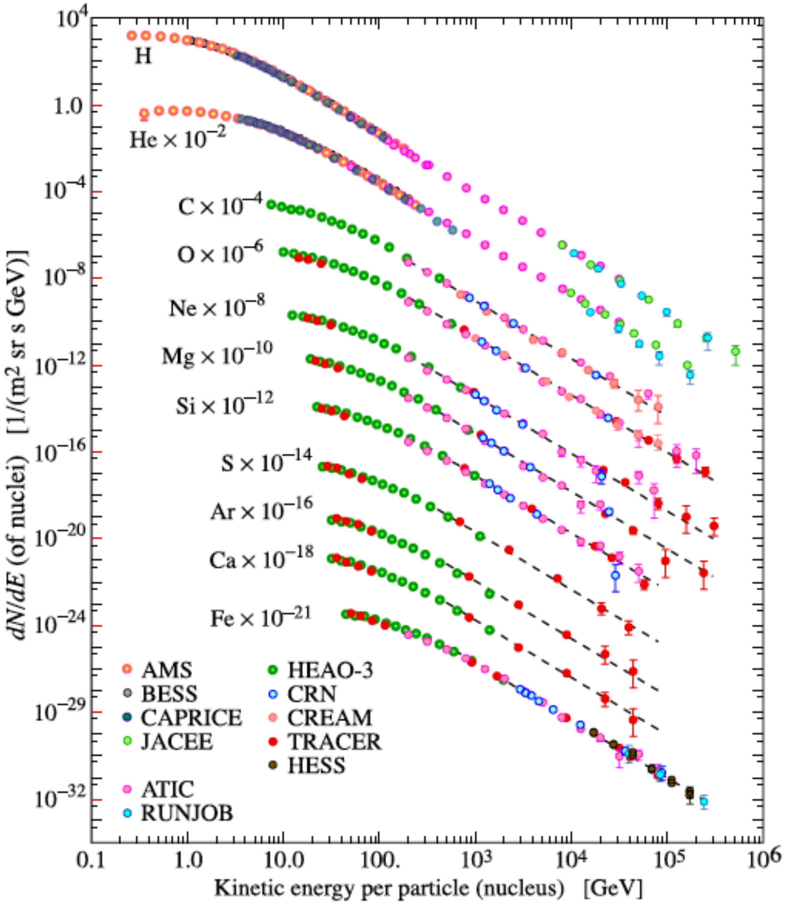
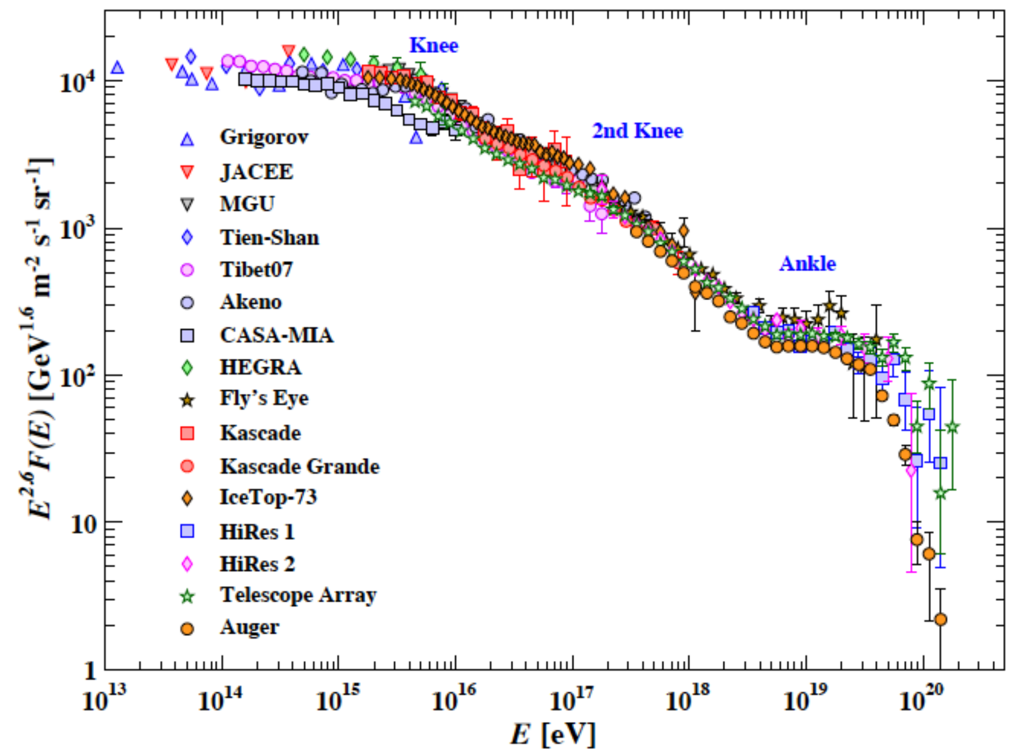
# Particle Data Group on Cosmic Rays

*Can we do better?*




"from several GeV to somewhat beyond 100 TeV"

$$I_N(E) \approx 1.8 \times 10^4 \, (E/1\,\text{GeV})^{-\alpha} \, \frac{\text{nucleons}}{\text{m}^2 \;\; \text{s} \;\; \text{sr} \;\; \text{GeV}}$$

$\alpha = 2.7$

| $Z$ | Element | $F$ | $Z$ | Element | $F$ |
|---|---|---|---|---|---|
| 1 | H | 540 | 13–14 | Al-Si | 0.19 |
| 2 | He | 26 | 15–16 | P-S | 0.03 |
| 3–5 | Li-B | 0.40 | 17–18 | Cl-Ar | 0.01 |
| 6–8 | C-O | 2.20 | 19–20 | K-Ca | 0.02 |
| 9–10 | F-Ne | 0.30 | 21–25 | Sc-Mn | 0.05 |
| 11–12 | Na-Mg | 0.22 | 26–28 | Fe-Ni | 0.12 |

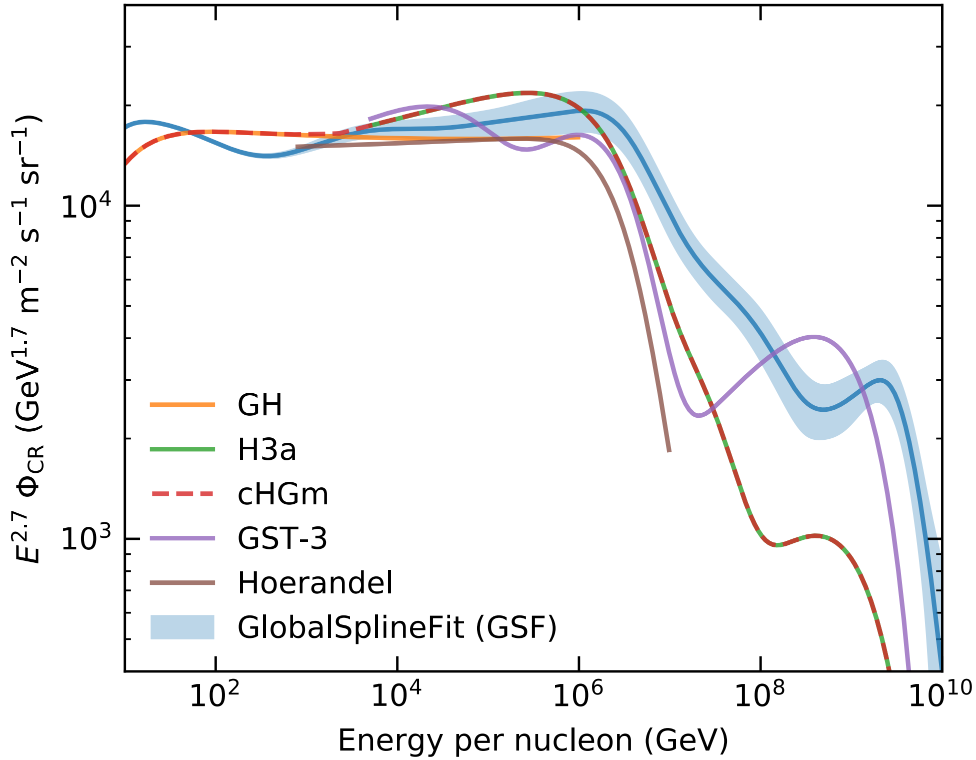
@ 10.6 GeV/nucleon

# Motivation for this work

A. Fedynitch et al., ICRC 2017 https://pos.sissa.it/301/1019
State-of-the-art calculation of atm. lepton flux

Flux calculation with **uncertainty estimate**

- Needs uncertainty of **cosmic-ray nucleon flux**
- Nucleon flux depends on **cosmic-ray flux** and **mass composition**




## How to estimate uncertainties?

**"Bracketing"**

Min/max of some flux models

- Uncertainty not based on latest experimental data
- May be dominated by differences in models

Bracketing **overestimates** uncertainty

**Global Spline Fit**

Fit current cosmic ray data with splines

- Minimal assumptions: no power-laws/ populations/cut-offs
- Covariance matrix captures data uncertainties

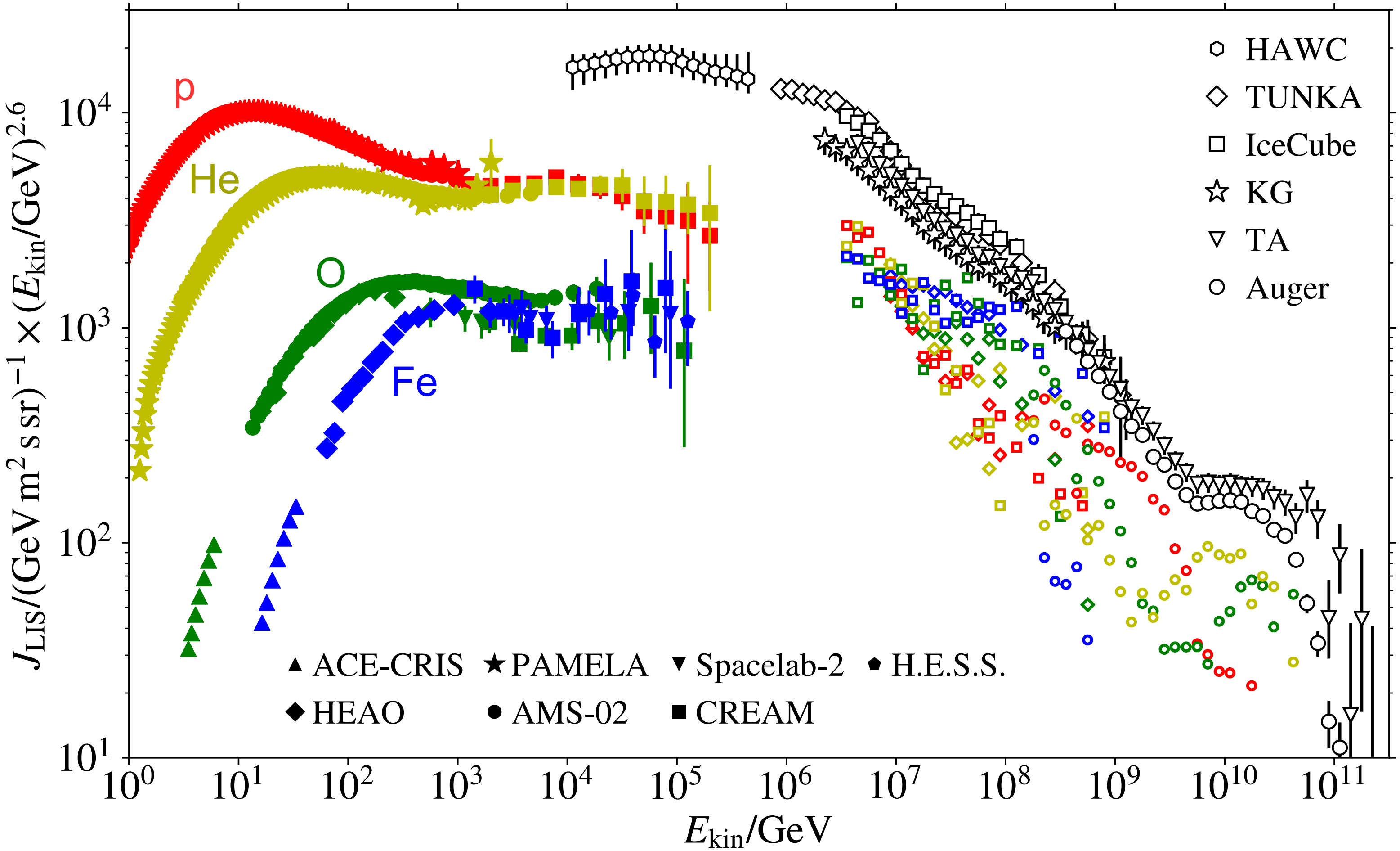
Uncertainty reflects **current state of data**

# Combining direct/indirect data

- Cover all energies: Use direct and air-shower measurements
- Solar modulation correction uses standard force-field approximation
- Approximate treatment of sub-leading elements at high energies

*Direct observation*
fluxes of **individual elements**

*Air-shower observation*
**total** flux and **mass groups**



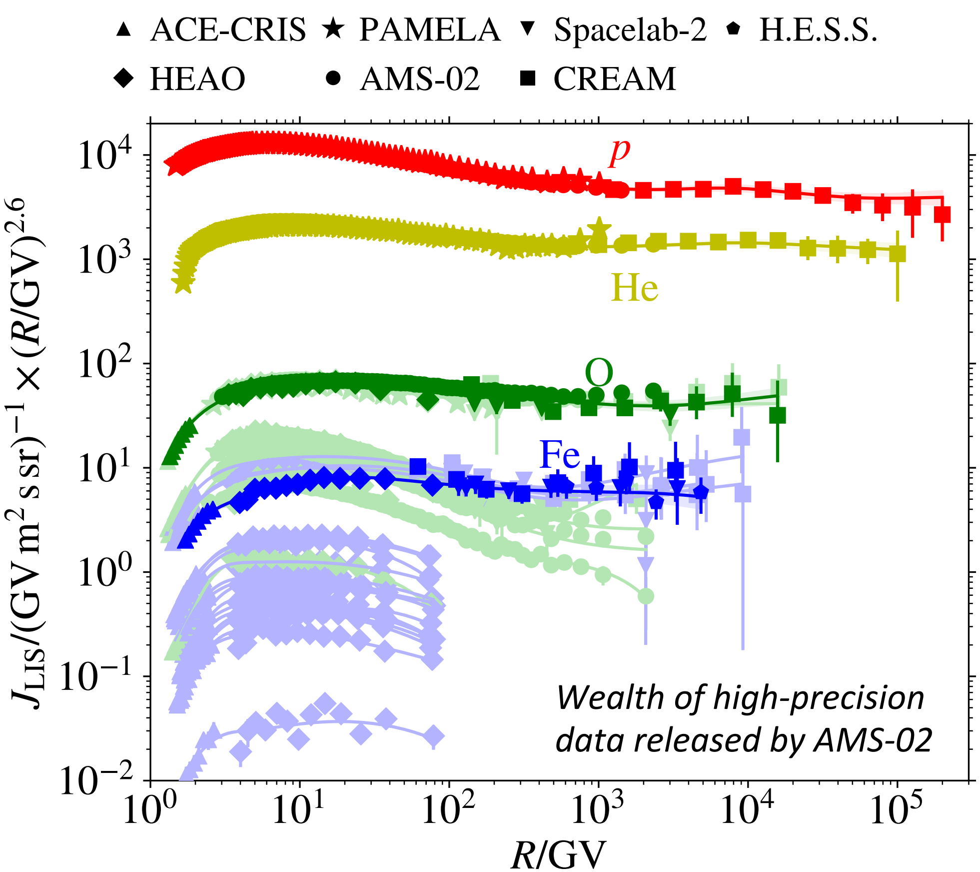
# Input data sets

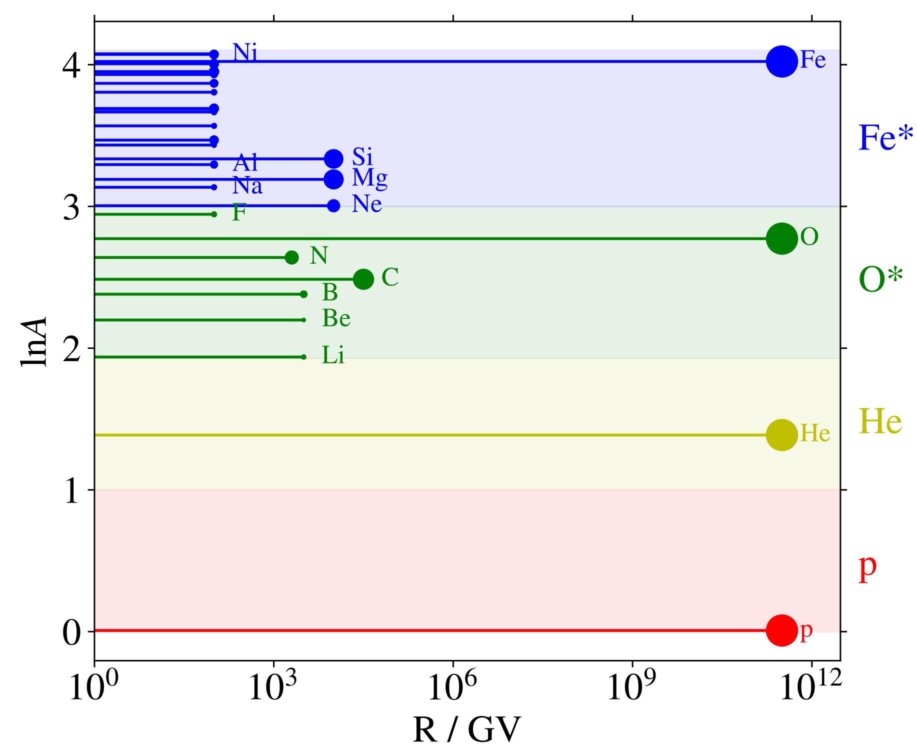
*Many thanks to the **CRDB** for making low-energy cosmic ray data easily accessible*

- **ACE-CRIS** G.A. de Nolfo et al., Adv. in Space Res. 38 (2006) 1558; K.A. Lave et al., ApJ 770 (2013) 117
- **AMS-02** M. Aguilar et al., Phys. Rev. Lett. 114 (2015) 171103; M. Aguilar et al., Phys. Rev. Lett. 119 (2017) 251101; M. Aguilar et al. Phys. Rev. Lett. 120 (2018) 021101
- **ARGO-YBJ** B. Bartoli et al., Phys.Rev. D91 (2015) no.11, 112017
- **ARGO+LHAASO** S. Zhang and Z. Cao et al., PoS(ICRC2015)261 **[Preliminary]**
- **Auger** Pierre Auger collab., Phys. Rev. D 90, 122006 (2014); F. Fenu for Pierre Auger collab., PoS(ICRC2017)486 **[Preliminary]**; J. Bellido for Pierre Auger collab., PoS(ICRC2017)506 **[Preliminary]**
- **HEAO** Engelmann et al., Astronomy and Astrophysics 233 (1990) 96
- **H.E.S.S.** F. Aharonian et al. (H.E.S.S. collaboration), Phys.Rev. D75 (2007)
- **CREAM-I,II,III** H.S. Ahn et al., ApJ 707 (2009) 593; Y.S. Yoon et al. ApJ 728 (2011) 122
- **IceCube** M. Plum for IceCube collab., TeVPA 2018 **[Preliminary]**
- **KASCADE-Grande** S. Schoo for KASCADE-Grande collab., PoS (ICRC 2015) 263 **[Preliminary]**
- **PAMELA** O. Adriani et al., Science 332 (2011) 69; O. Adriani et al., ApJ 791 (2014) 93
- **Spacelab-2** S.P. Swordy et al., ApJ 349 (1990) 625; D. Mueller et al., ApJ 374 (1991) 356
- **Telescope Array** D. Ivanov for Telescope Array collab., PoS(ICRC2015)349 **[Preliminary]**
- **TUNKA** Prosin et al., Nuclear Instruments and Methods A 756 (2014) 94-101
- **HAWC** R. Alfaro et al. (HAWC collab.), PRD 96, 122001 (2017)

# Global Spline Fit (GSF)

- Fit **four** independent mass groups, which cover equal ranges in lnA:
  proton (p), helium (He), oxygen group (O*), and iron group (Fe*)
- One leading element *L* per group described by smooth spline curve
- Other elements *j* in a group kept in constant ratio: $J_j(R) / J_L(R) = const.$



# Energy-scale adjustment

- **Energy-scale offsets** of experiments = major correlated systematic uncertainty
- Fit constrained **energy-scale adjustment factors** $z_E$ as nuisance parameters

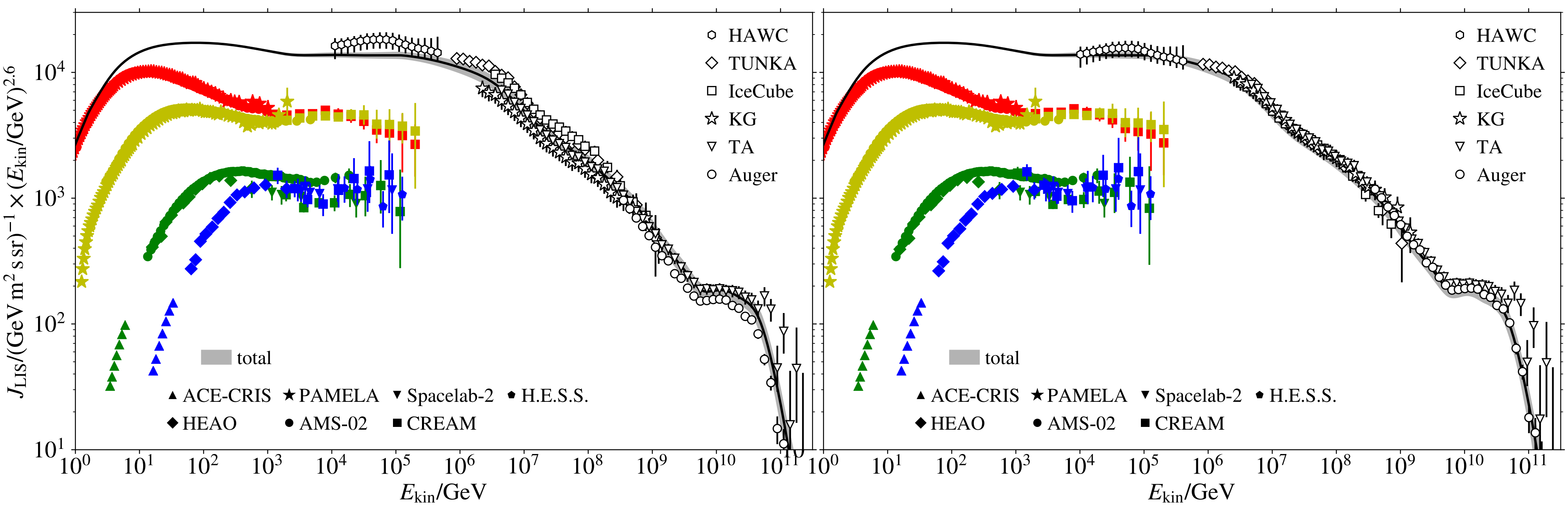
R. Barlow "Combining Experiments with Systematic Errors", arXiv:1701.03701

$$\tilde{J}(\tilde{E}) = J(E)\frac{\mathrm{d}E}{\mathrm{d}\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right)\frac{1}{1+z_E}$$

Flux distortion caused by energy-scale offset $z_E$

$$S = \sum_i z_i^2 + \sum_j \left(\frac{z_{Ej}}{(\sigma[E]/E)_j}\right)^2$$

Flux residuals    Energy-scale offset residuals



# Energy-scale adjustment

- **Energy-scale offset** assumed to be constant relative factor per experiment
- Fit constrained **energy-scale adjustment factors** $z_E$ as nuisance parameters

R. Barlow "Combining Experiments with Systematic Errors", arXiv:1701.03701

$$\tilde{J}(\tilde{E}) = J(E)\frac{\mathrm{d}E}{\mathrm{d}\tilde{E}} = J\left(\frac{\tilde{E}}{1+z_E}\right)\frac{1}{1+z_E}$$

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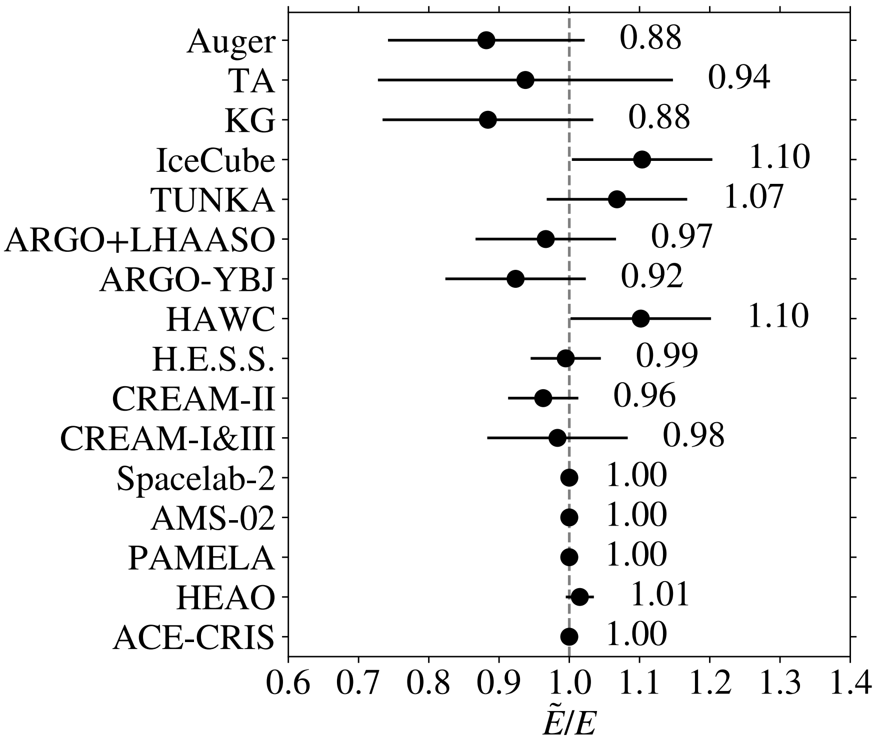
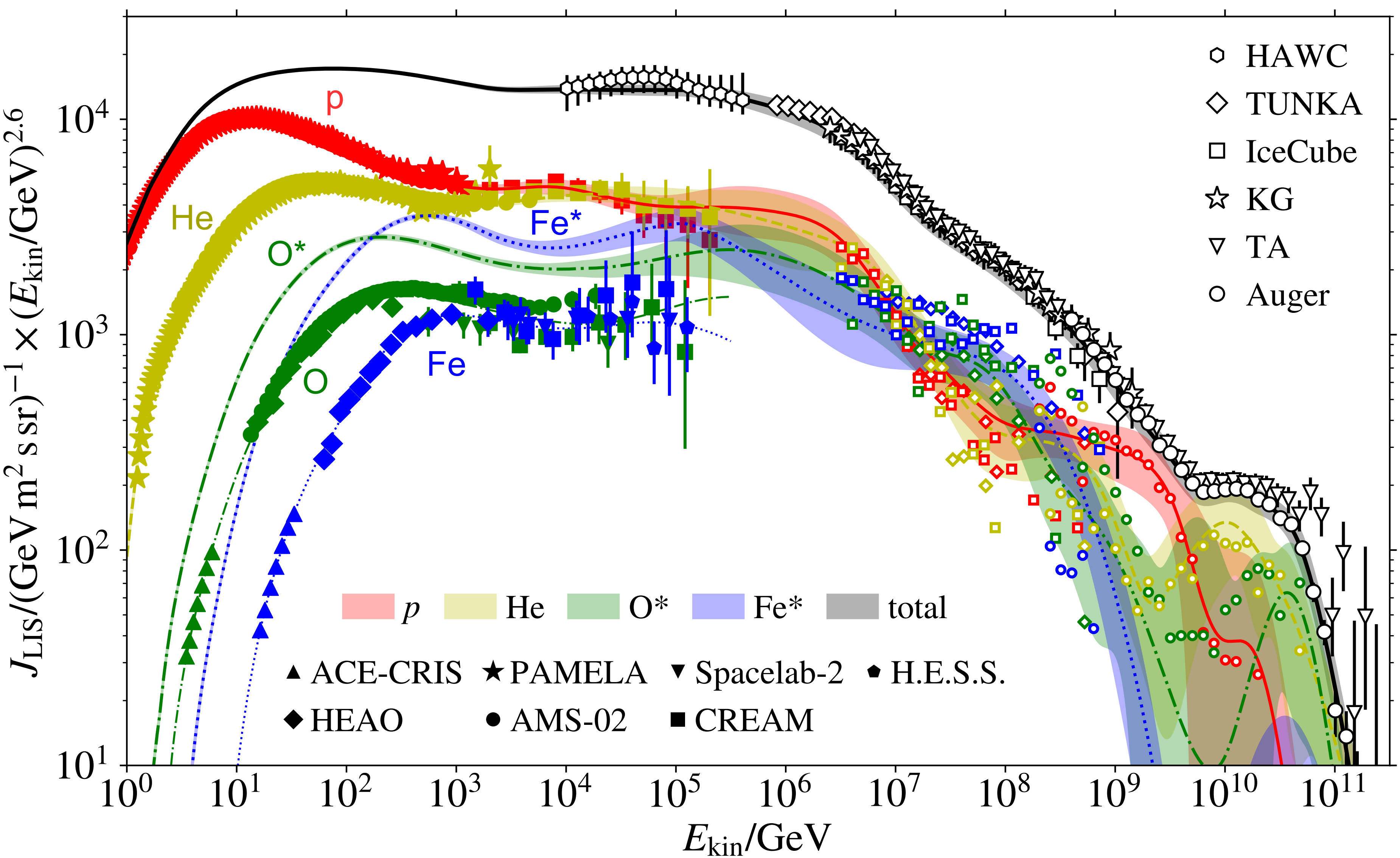



Fitted energy-scale offsets compatible with reported systematic uncertainties

**GSF energy scale** anchored by **direct measurements**

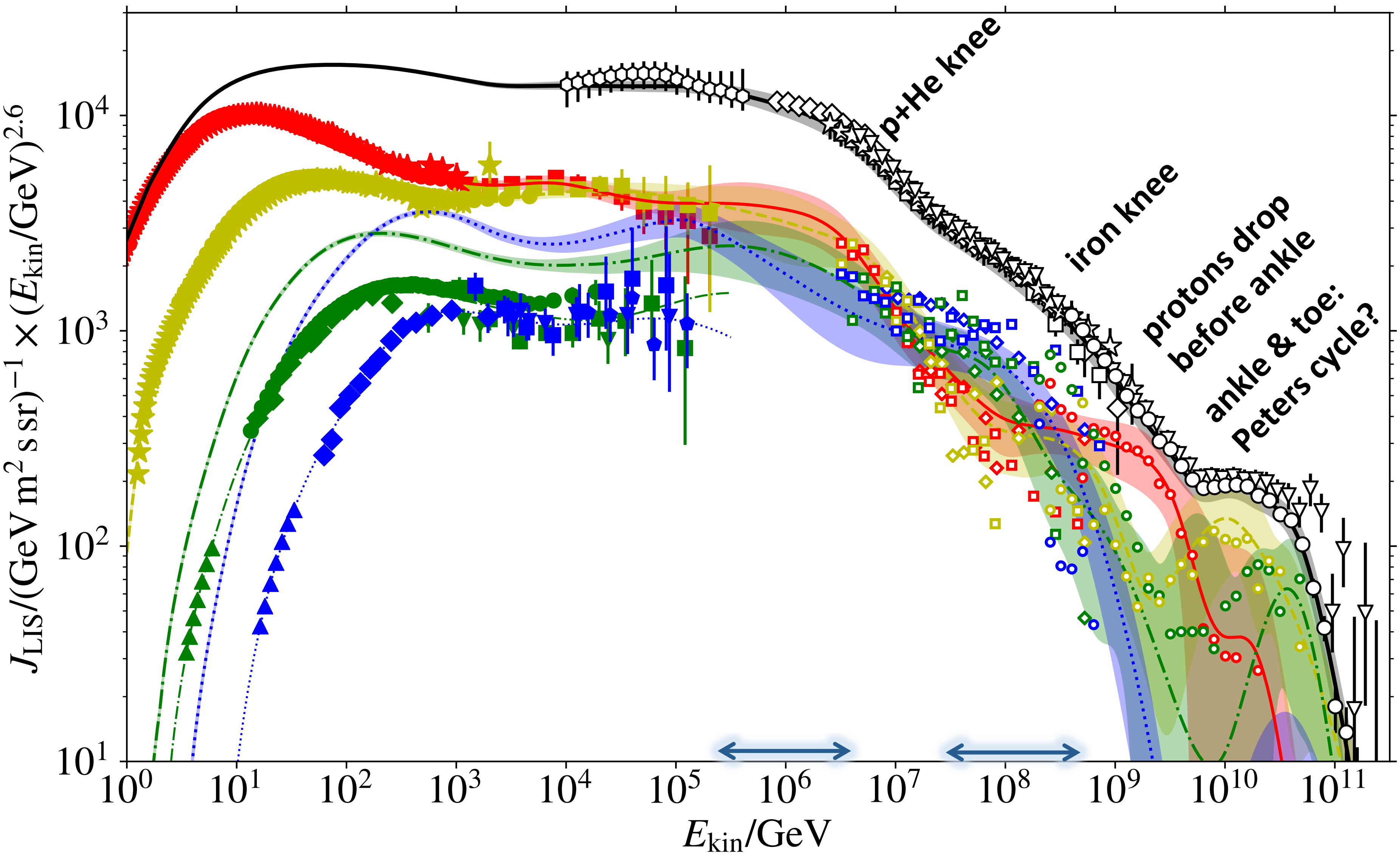
# Global Spline Fit




Flux of iron (oxygen) group **factor two higher** than elemental iron (oxygen)

# Global Spline Fit

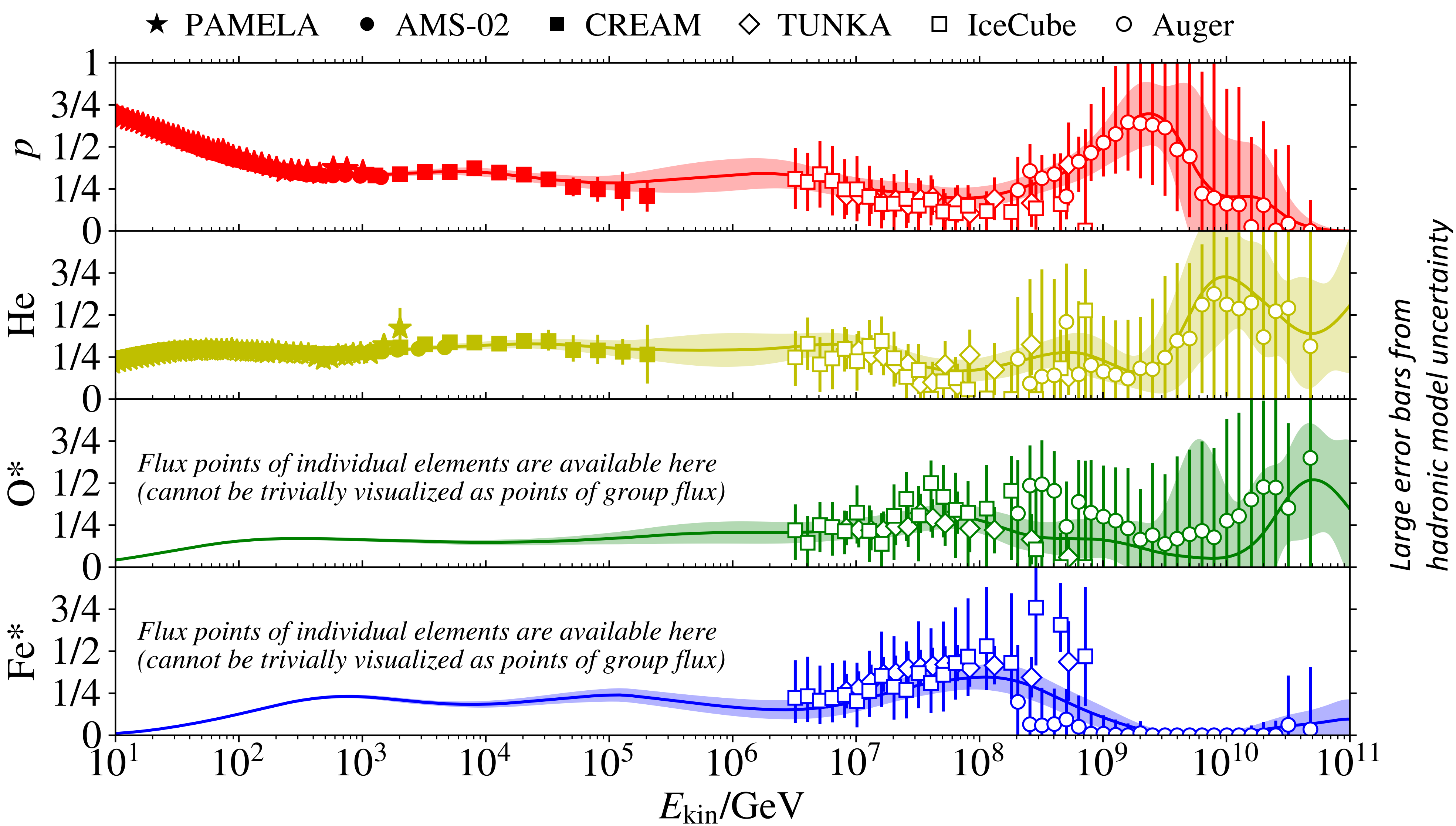
$\chi^2/n_{dof}$ = 1358.3/895
= 1.5



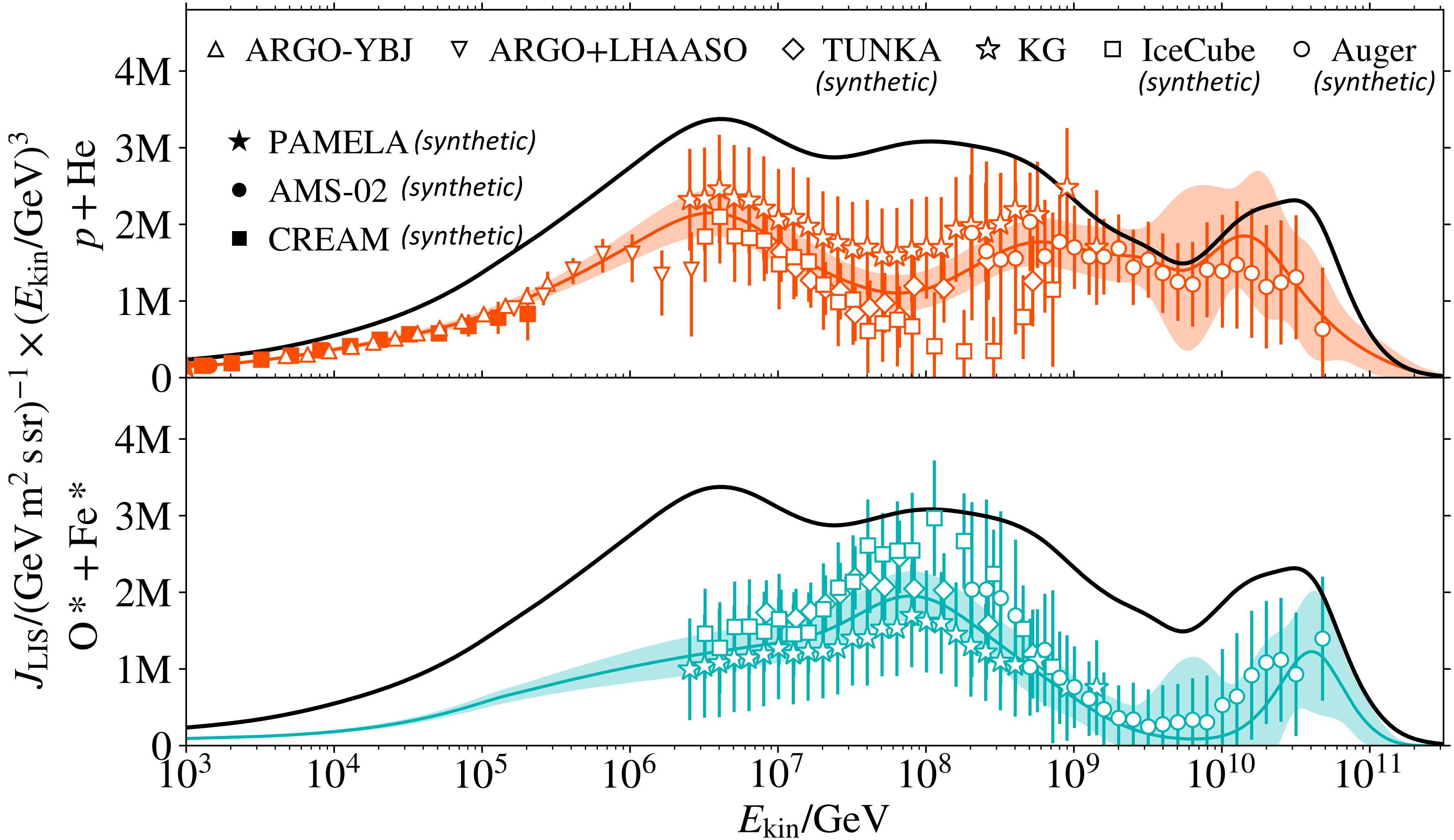

**More composition data needed**

# Composition data: 4 components

Includes latest IceCube results by Matthias Plum, TeVPA 2018



# Composition data: 2 components



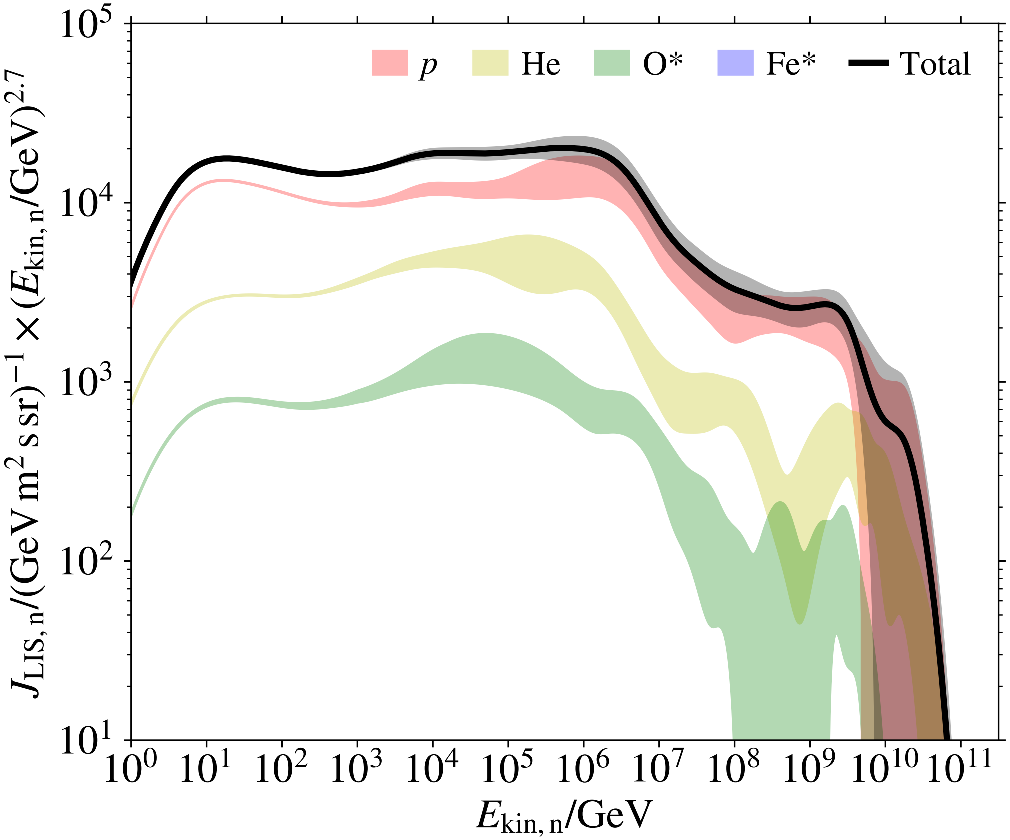

Good agreement:
Auger, KASCADE-Grande, TUNKA

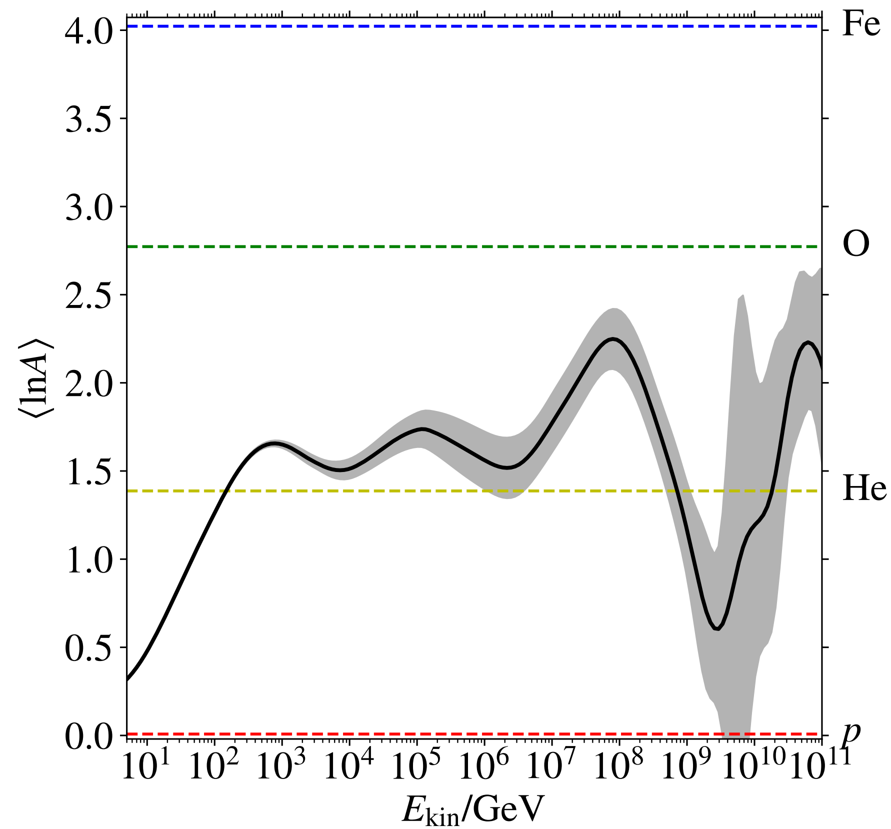
Iron knee very pronounced in IceCube data

Pre-knee drop of p+He in ARGO+LHAASO?

# Examples of derived results

Sub-leading elements approximate in GSF, but not important for many results




Nucleon flux dominated by **p and He**, sub-leading elements not important

Sub-leading elements have little impact on <lnA>

# Summary & Outlook

GSF is a smooth parameterization of cosmic-ray flux and composition data

- Combined average of direct and indirect measurements over all cosmic-ray energies
- Composition modeled with four independent components + sub-leading elements
- Detailed handling of uncertainties, including correlated systematic uncertainties
- GSF: tool to make **“world average” of cosmic ray data with error band**

GSF release

- Publication planned later this year
- Python code, parameters and covariance matrix will be open-source’d
- Interactive web page with flux and download of tables available
- Collaboration with David Maurin, CRDB http://lpsc.in2p3.fr/crdb/, to include HECR data points

# BACKUP

# Flux model

*Flux of leading element L*

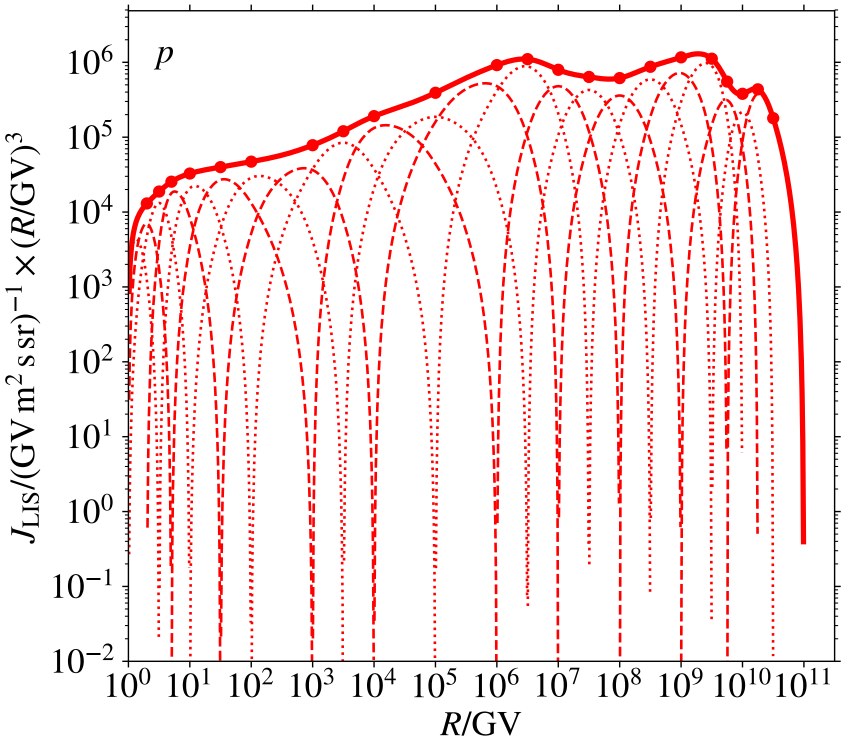
$$J_L(R) = [R/\mathrm{GV}]^{-3} \sum_k a_{Lk}\, b_k(\ln[R/\mathrm{GV}])$$

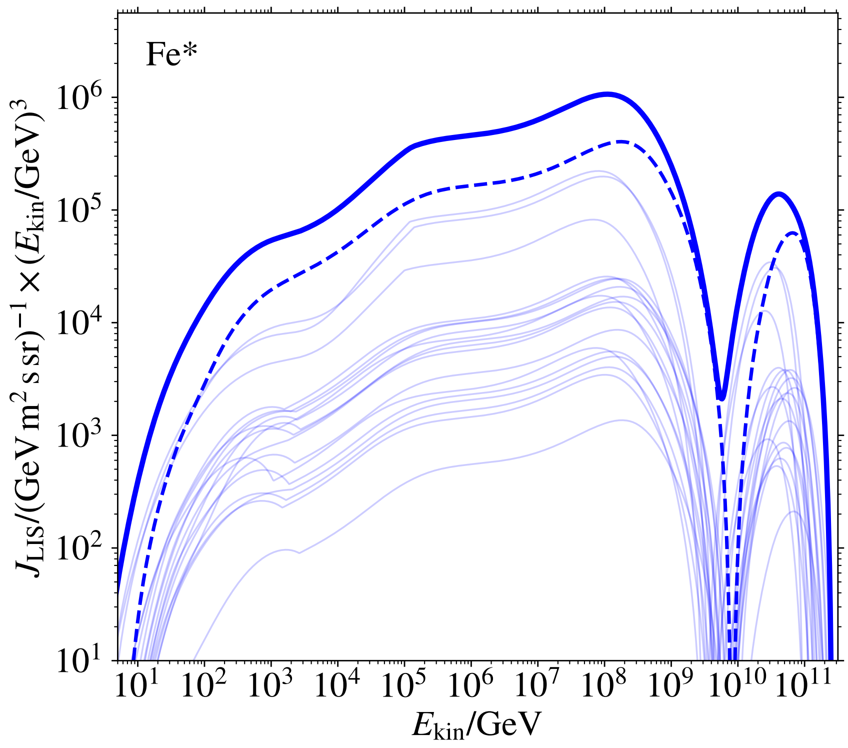
amplitudes ($a_{Lk}$), B-splines ($b_k$)

*Total flux*

$$J(E) = \sum_L \sum_j w_{Lj}\, J_L(R_j(E)) \left(\frac{\mathrm{d}R}{\mathrm{d}E}\right)_j$$

flux ratios ($w_{Lj}$)

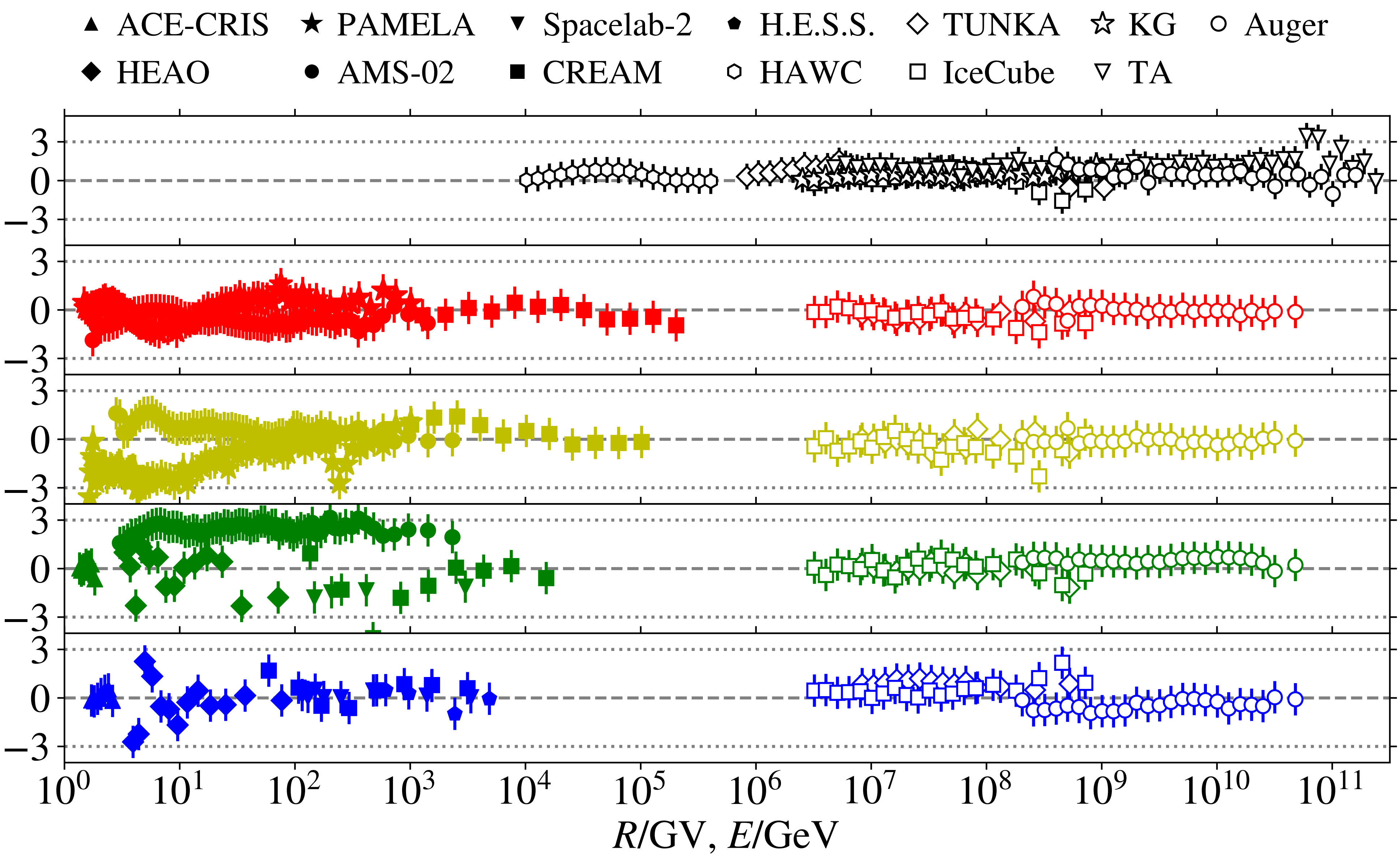


# Fit residuals

**$\chi2/n_{dof}$ = 1358.3/895 = 1.5**

*Bad chi2 mostly due to low energy helium and oxygen tension*



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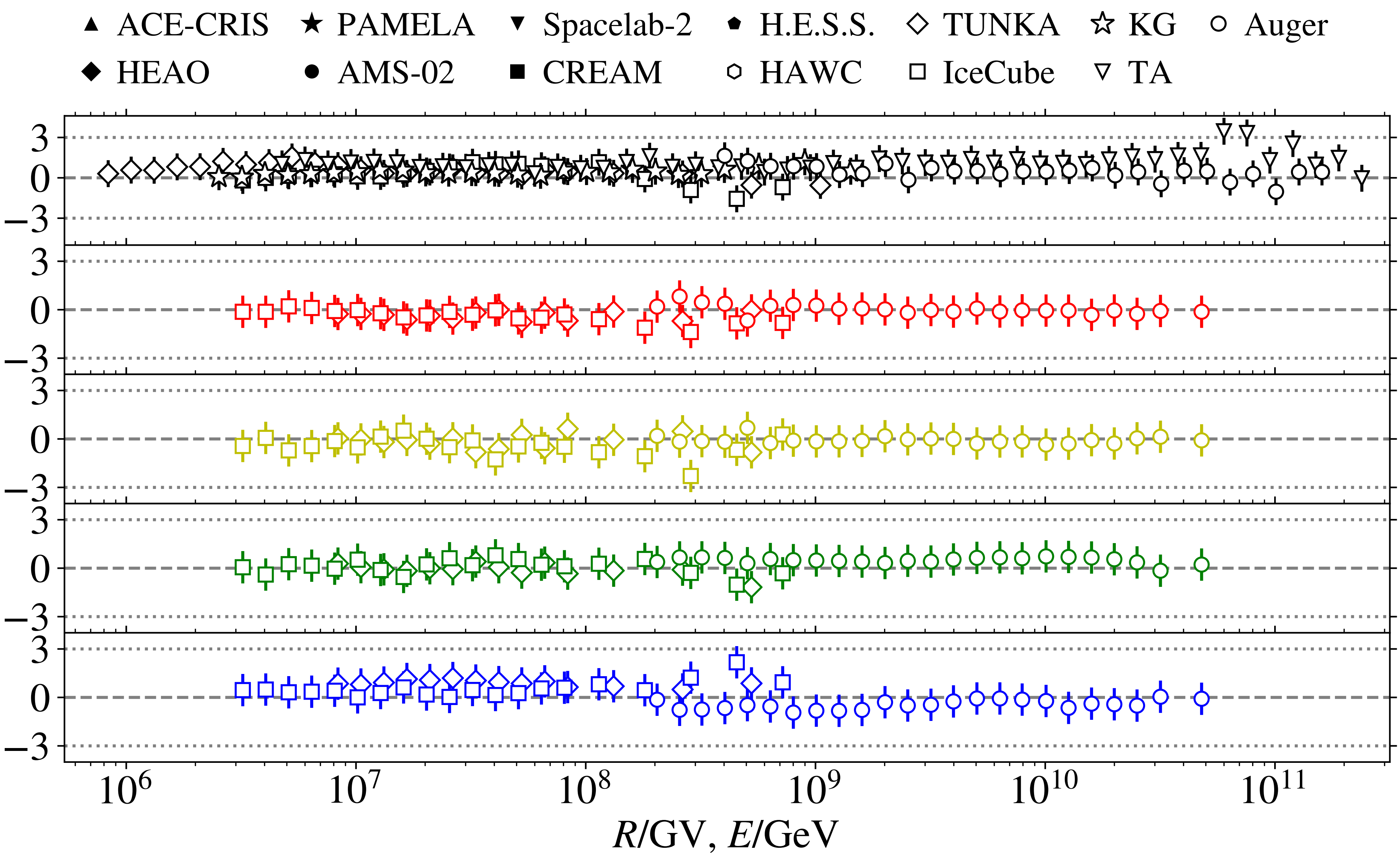


# Fitting data with correlated errors

10 points, two groups with systematic offset and correlated errors

Fit line y = a + b x

Truth: a = 1, b = 2

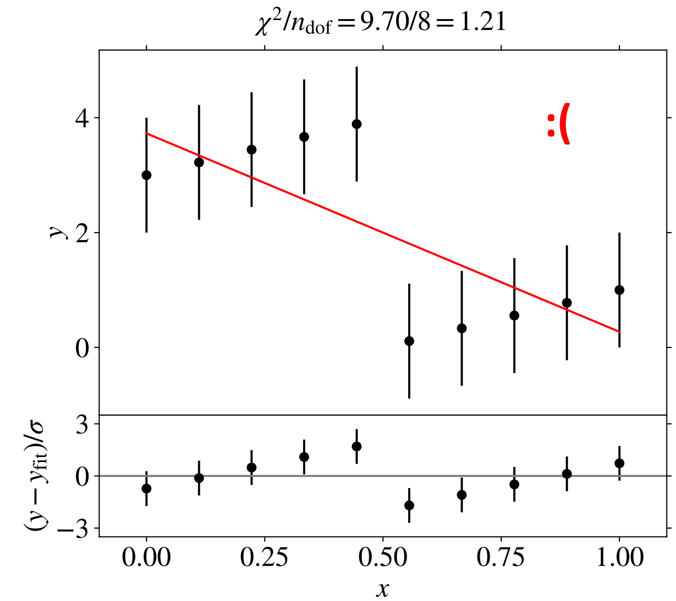
Generalized least-squares, minimize

$$Q = (\vec{y} - \vec{y}_{\mathrm{fit}})^T C^{-1} (\vec{y} - \vec{y}_{\mathrm{fit}})$$

C ... covariance matrix of data

correlation ignored

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.0 | | | | | | | | | |
| 2 | 0.0 | 1.0 | | | | | | | | |
| 3 | 0.0 | 0.0 | 1.0 | | | | | | | |
| 4 | 0.0 | 0.0 | 0.0 | 1.0 | | | | | | |
| 5 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | | | | | |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | | | | |
| 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | | | |
| 8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | | |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | |
| 10 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |




correlation correctly handled

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.0 | | | | | | | | | |
| 2 | 0.9 | 1.0 | | | | | | | | |
| 3 | 0.9 | 0.9 | 1.0 | | | | | | | |
| 4 | 0.9 | 0.9 | 0.9 | 1.0 | | | | | | |
| 5 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 | | | | | |
| 6 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 | | | | |
| 7 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 1.0 | | | |
| 8 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.9 | 1.0 | | |
| 9 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.9 | 0.9 | 1.0 | |
| 10 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.9 | 0.9 | 0.9 | 0.9 | 1.0 |