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

Hans Dembinski[1], Anatoli Fedynitch[2], Thomas Gaisser[3]

[1] Max-Planck Institute for Nuclear Physics, Heidelberg, Germany
[2] DESY Zeuthen, Germany
[3] Bartol Institute, University of Delaware, Newark DE, USA

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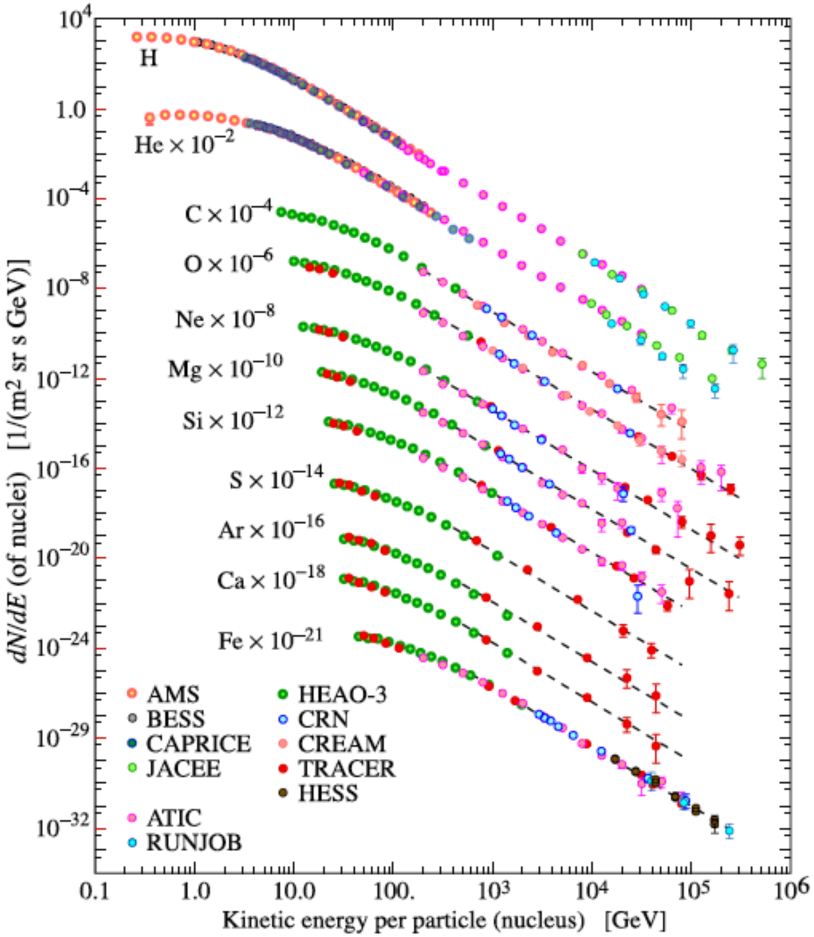
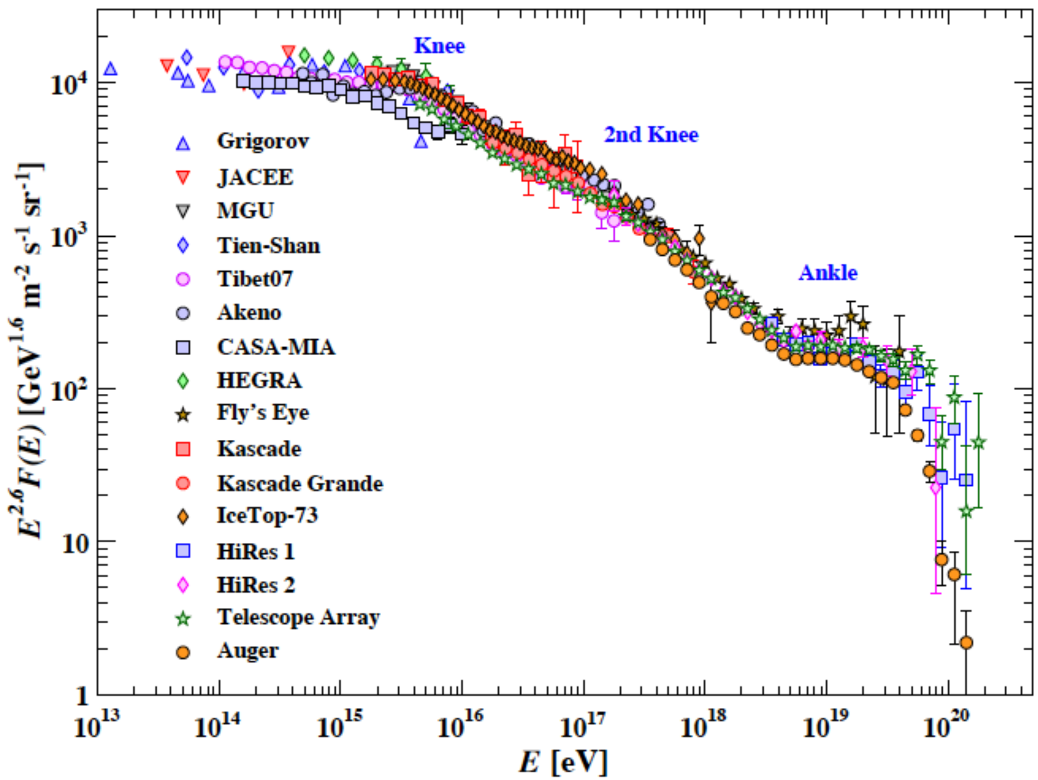
Particle Data Group on Cosmic Rays





"from several GeV to somewhat beyond 100 TeV"

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

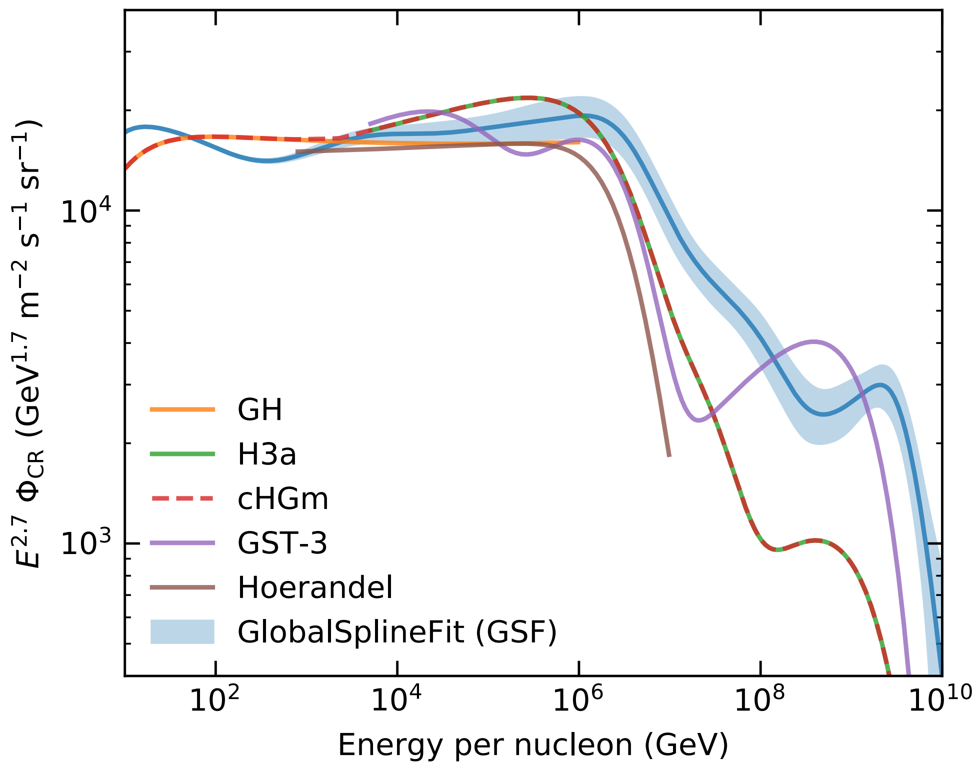
$\alpha = 2.7$

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

Global Spline Fit
Fit current cosmic ray data with splines

- "theory-free" (no power-laws/populations/cut-offs)
- Covariance matrix captures data uncertainties

Bracketing **overestimates** uncertainty

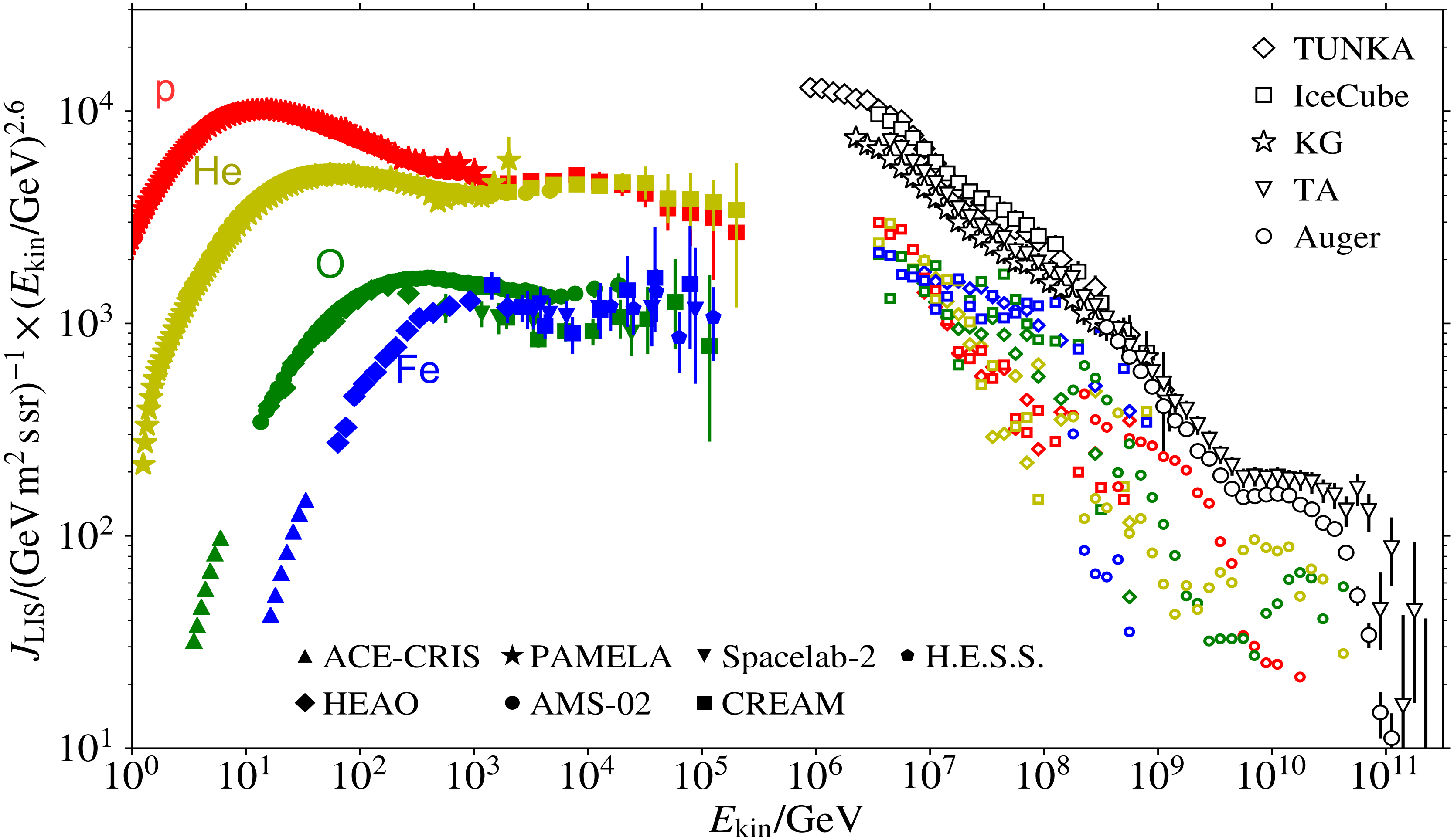
Uncertainty reflects **current state of data**

Challenge of combining two regimes

- Cover all energies: Use direct and air-shower measurements
- Correct solar modulation based on 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**



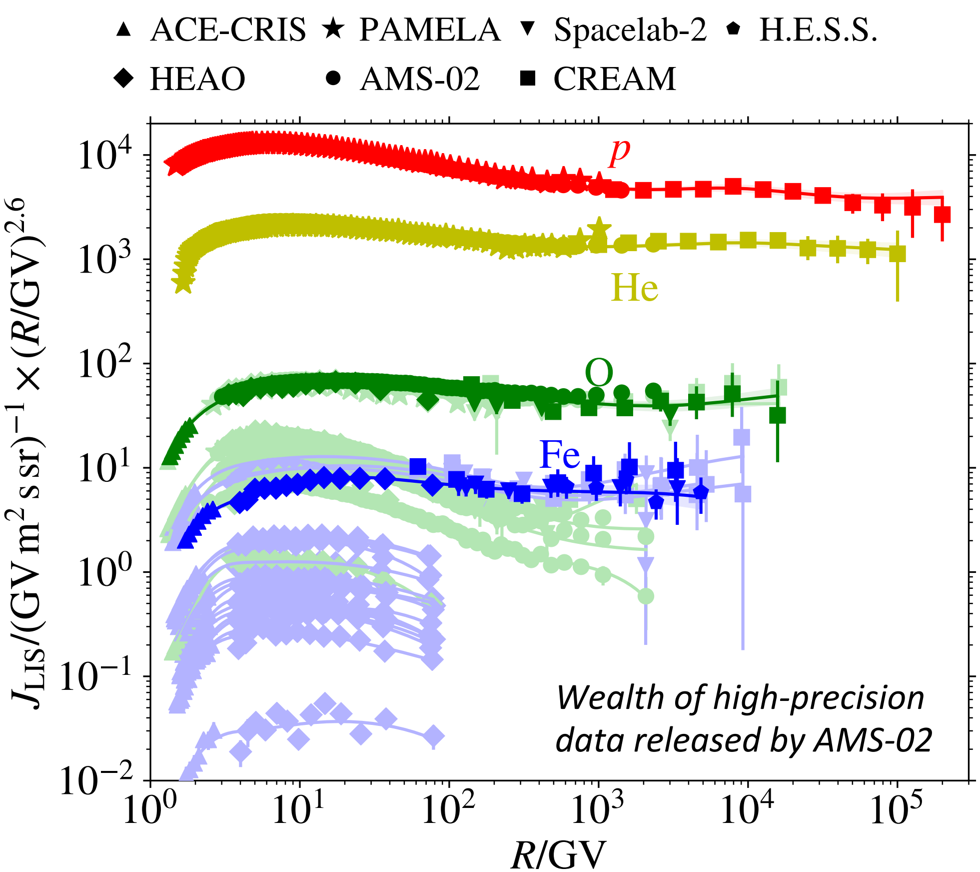
Input data sets

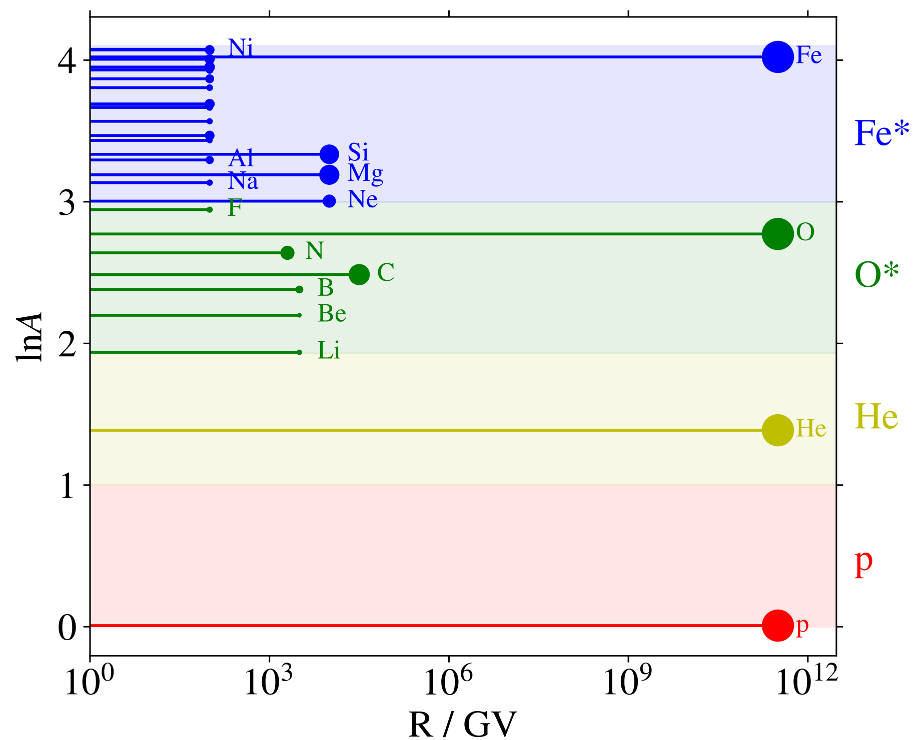
*Many thanks to the **CRDB** for making low-energy cosmic ray data easily accessible*

- **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
- **Auger** Pierre Auger collab., Phys. Rev. D 90, 122006 (2014); F. Fenu for Pierre Auger collab., PoS(ICRC2017)486; J. Bellido for Pierre Auger collab., PoS(ICRC2017)506
- **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
- **KASCADE-Grande** S. Schoo for KASCADE-Grande collab., PoS (ICRC 2015) 263
- **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
- **TUNKA** Prosin et al., Nuclear Instruments and Methods A 756 (2014) 94-101

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

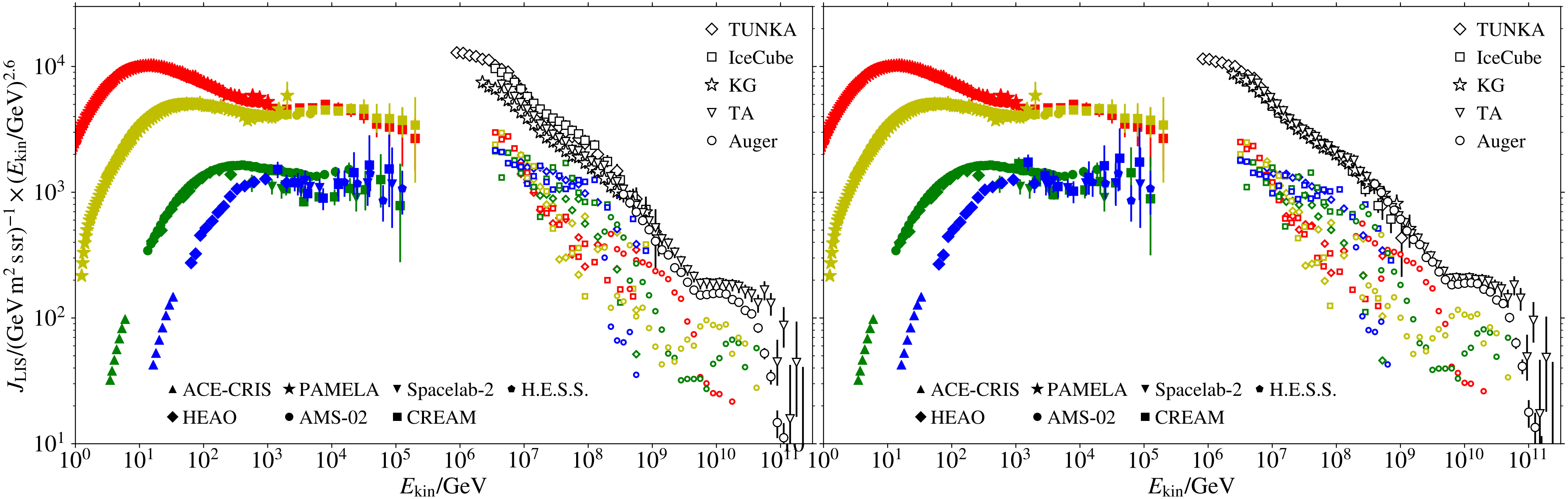
R. Barlow "Combining Experiments with Systematic Errors", arXiv:1701.03701

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

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



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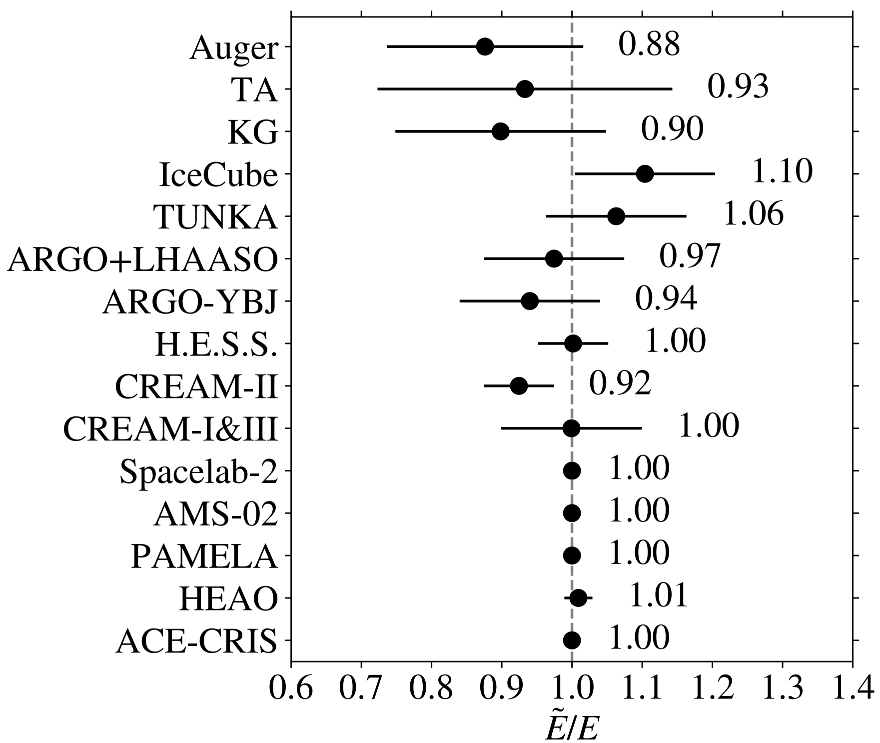
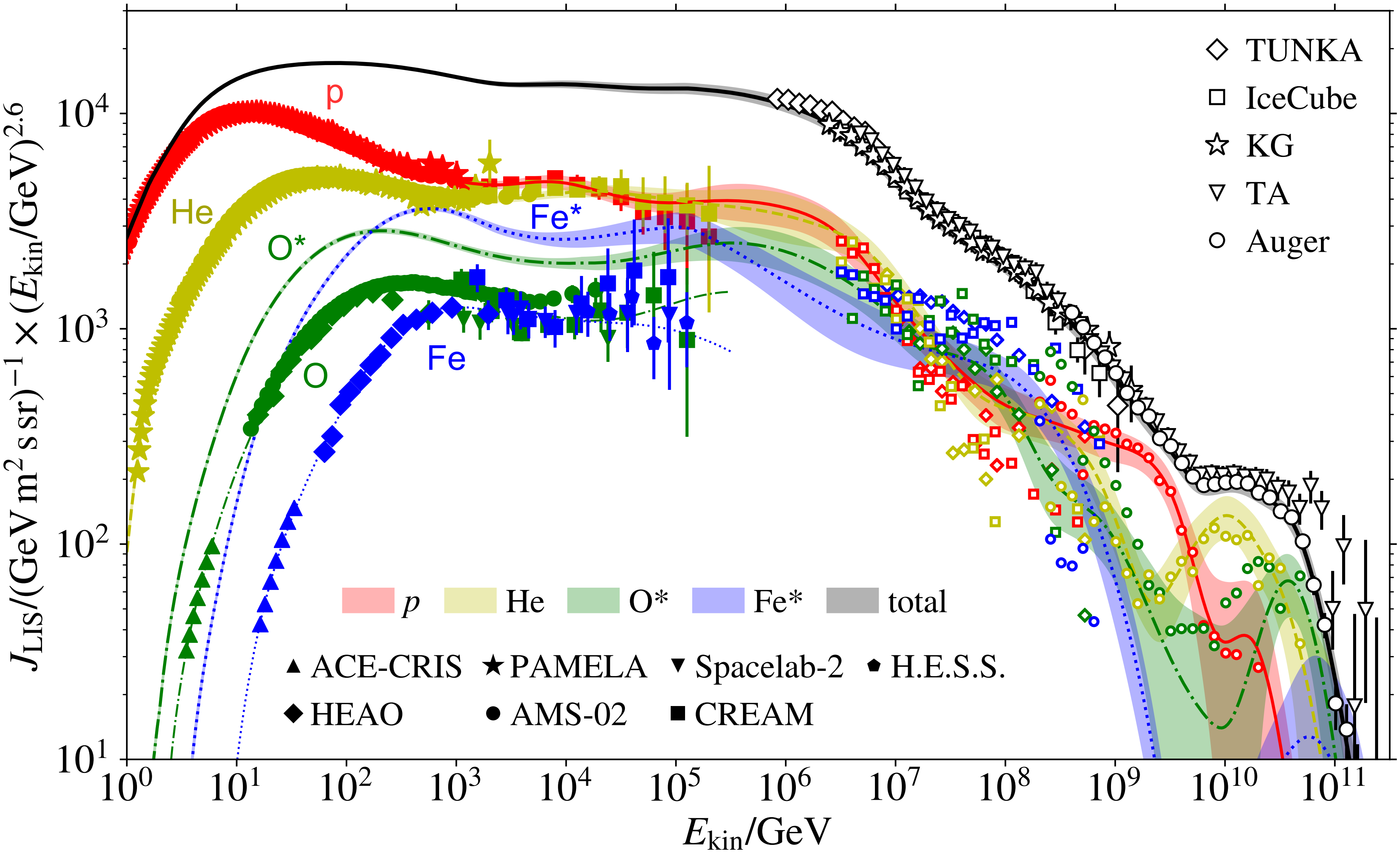


Fitted energy-scale offsets compatible with reported systematic uncertainties for almost all experiments

GSF energy scale ultimately fixed by **direct measurements**

Global Spline Fit

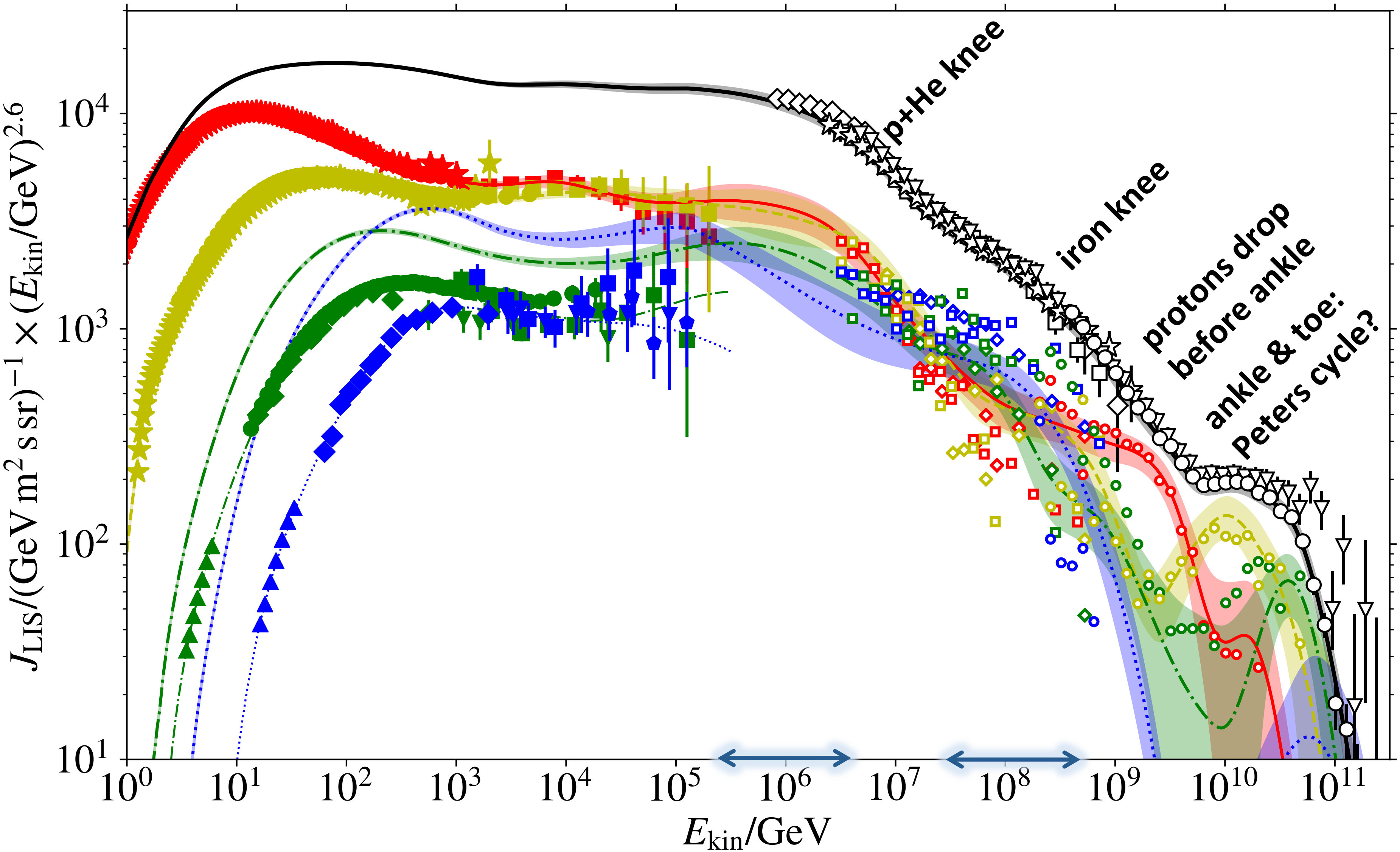
$\chi 2/n_{dof}$ = 1363.5/1160



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

Global Spline Fit

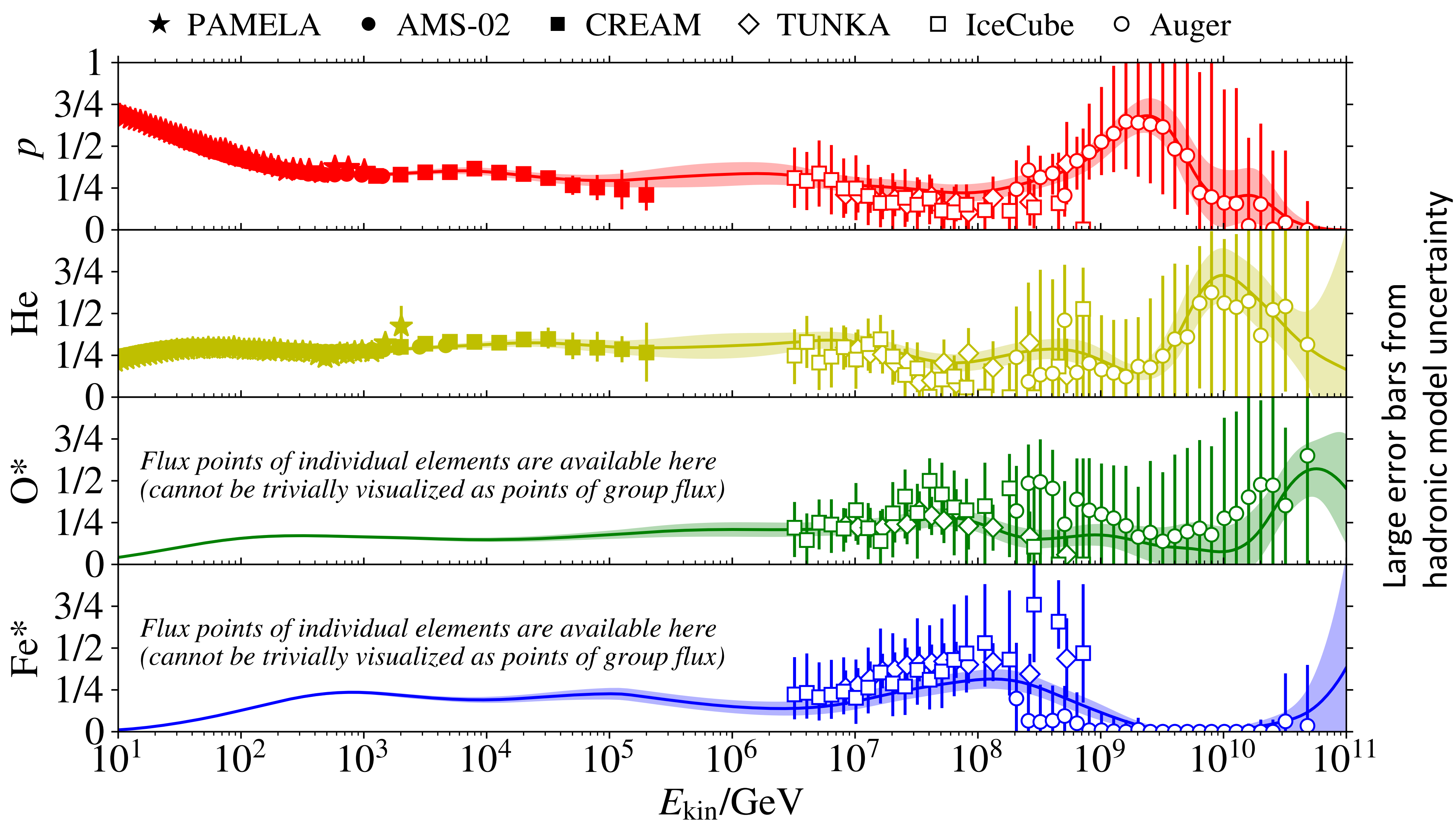
$\chi 2/n_{dof}$ = 1261/999



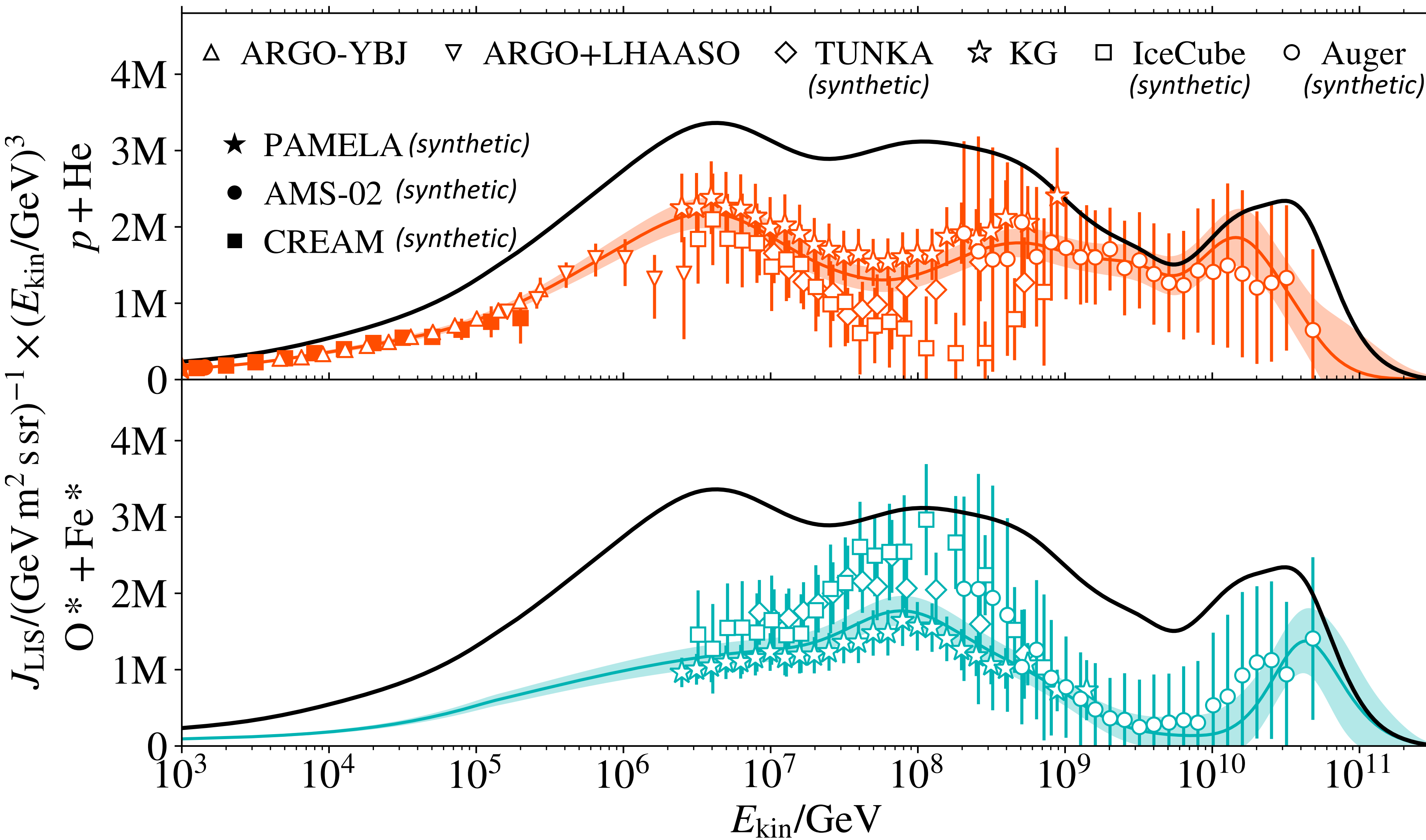
More composition data needed

Fitted composition data: 4 components

Includes latest IceCube results by Matthias Plum, TeVPA 2018



Fitted composition data: 2 components



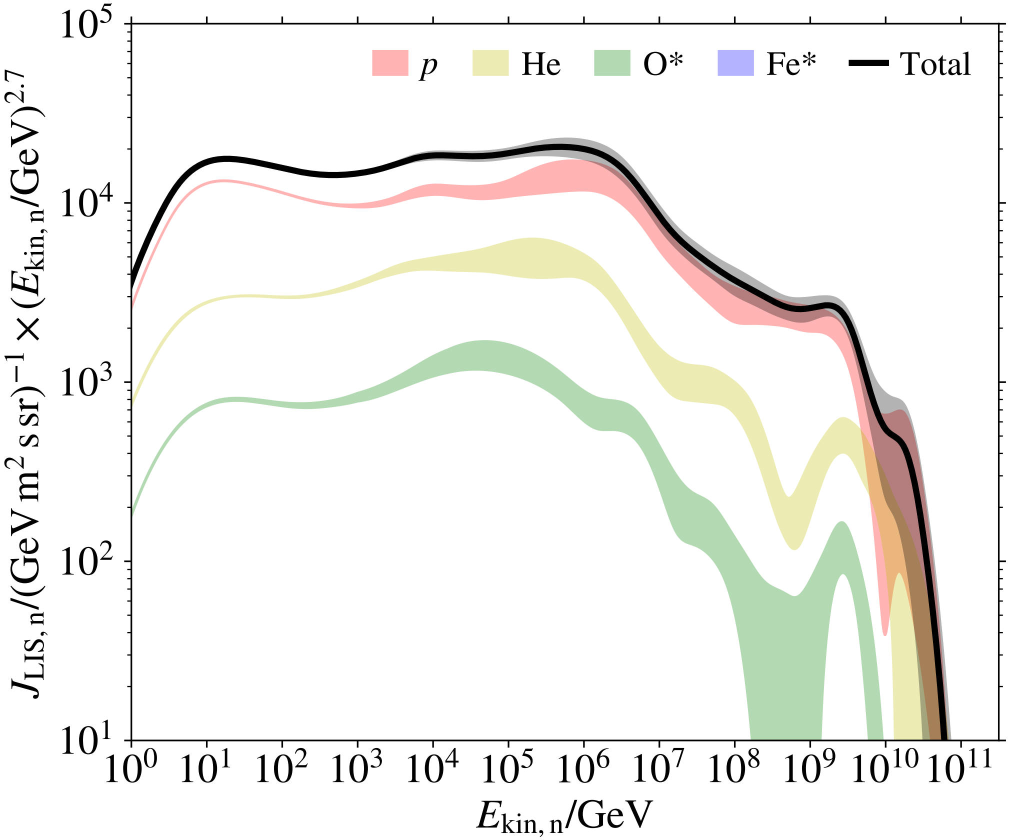
Good agreement:
Auger, KASCADE-Grande, TUNKA

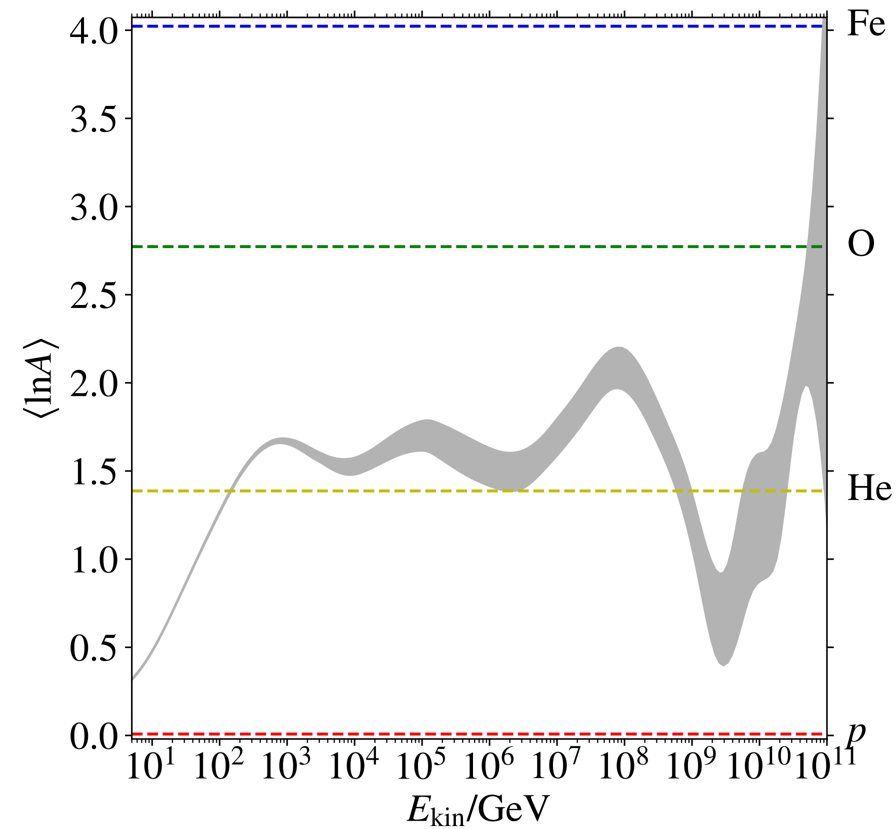
Iron knee very pronounced in IceCube data

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

- Seamless summary of direct and indirect measurements over all cosmic-ray energies
- Composition modeled with four independent components with sub-leading elements
- Energy-scale offsets of experiments are fitted as nuisance parameters
- Correlated systematic uncertainties are handled correctly
- GSF is tool to make a **"world average" of cosmic ray data with error band**

GSF release

- Publication planned later this year
  - Analysis is complete and paper draft has mostly been written
- 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

We want to include your data in GSF!

By our selection rules, we require:

- Combined flux & composition measurements
- Estimated systematic uncertainties

BACKUP

Flux model

Flux of leading element L

amplitudes

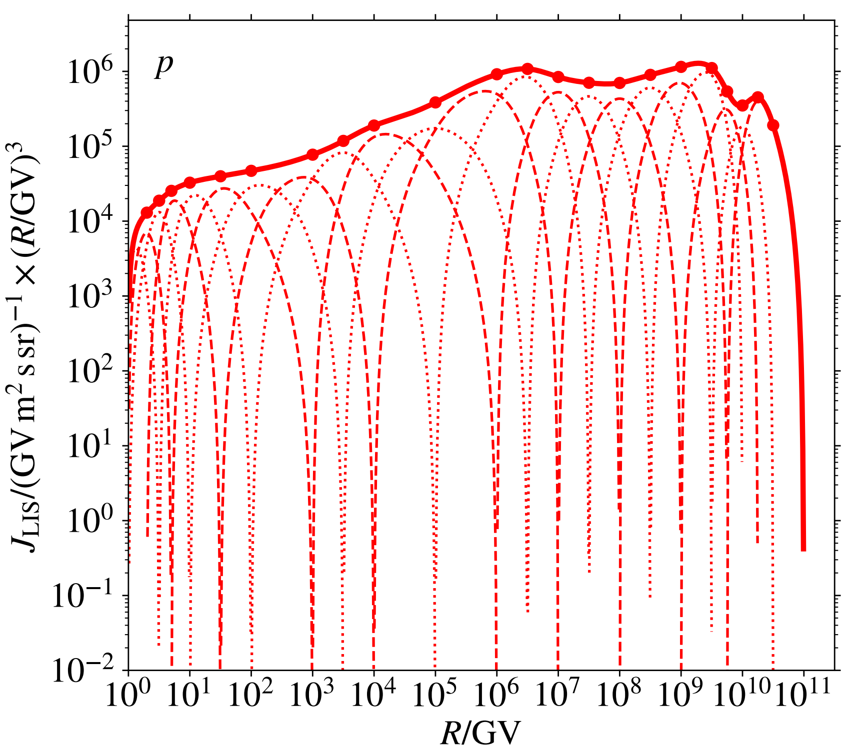
$$J_L(R) = [R/\mathrm{GV}]^{-3} \sum_k a_{Lk}\, b_k(\ln[R/\mathrm{GV}])$$

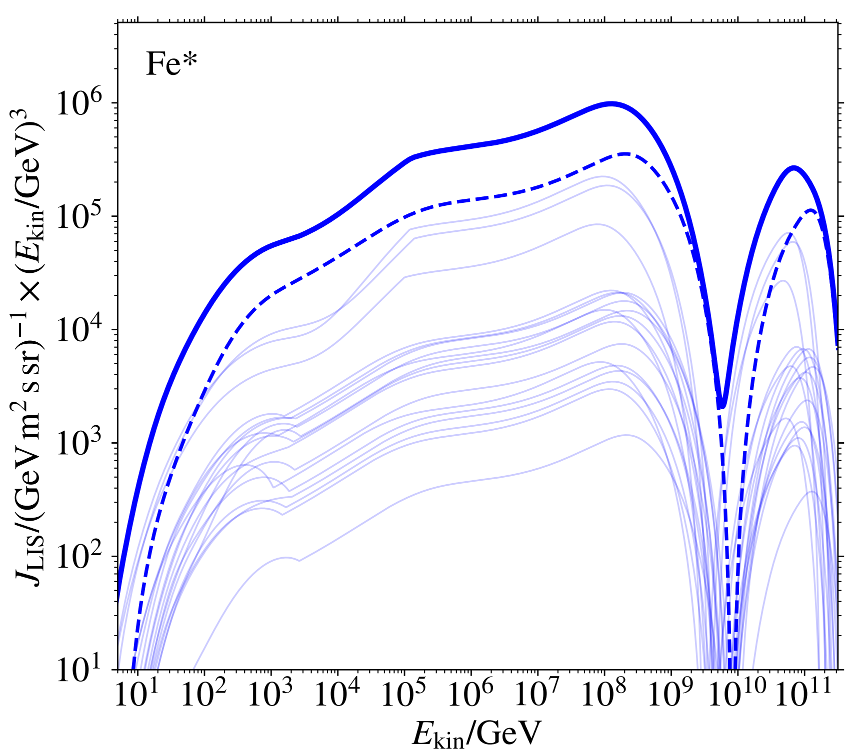
B-splines

flux ratios

Total flux

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





Fit residuals

$\chi 2/n_{dof}$ = 1360.8/1161 = 1.2

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