Data-driven model of the cosmic ray flux and mass composition: Global Spline Fit 2024

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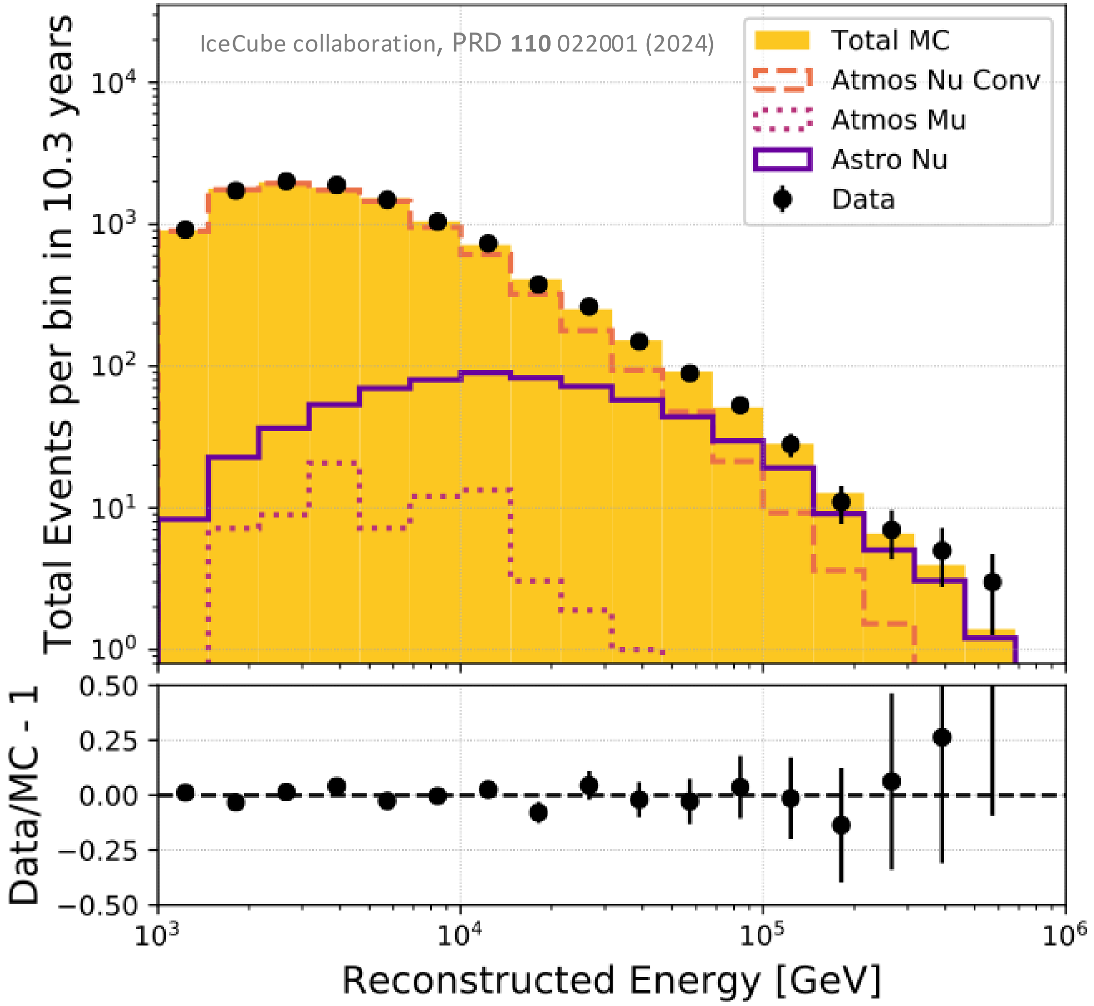
Motivation of modeling cosmic ray flux and composition

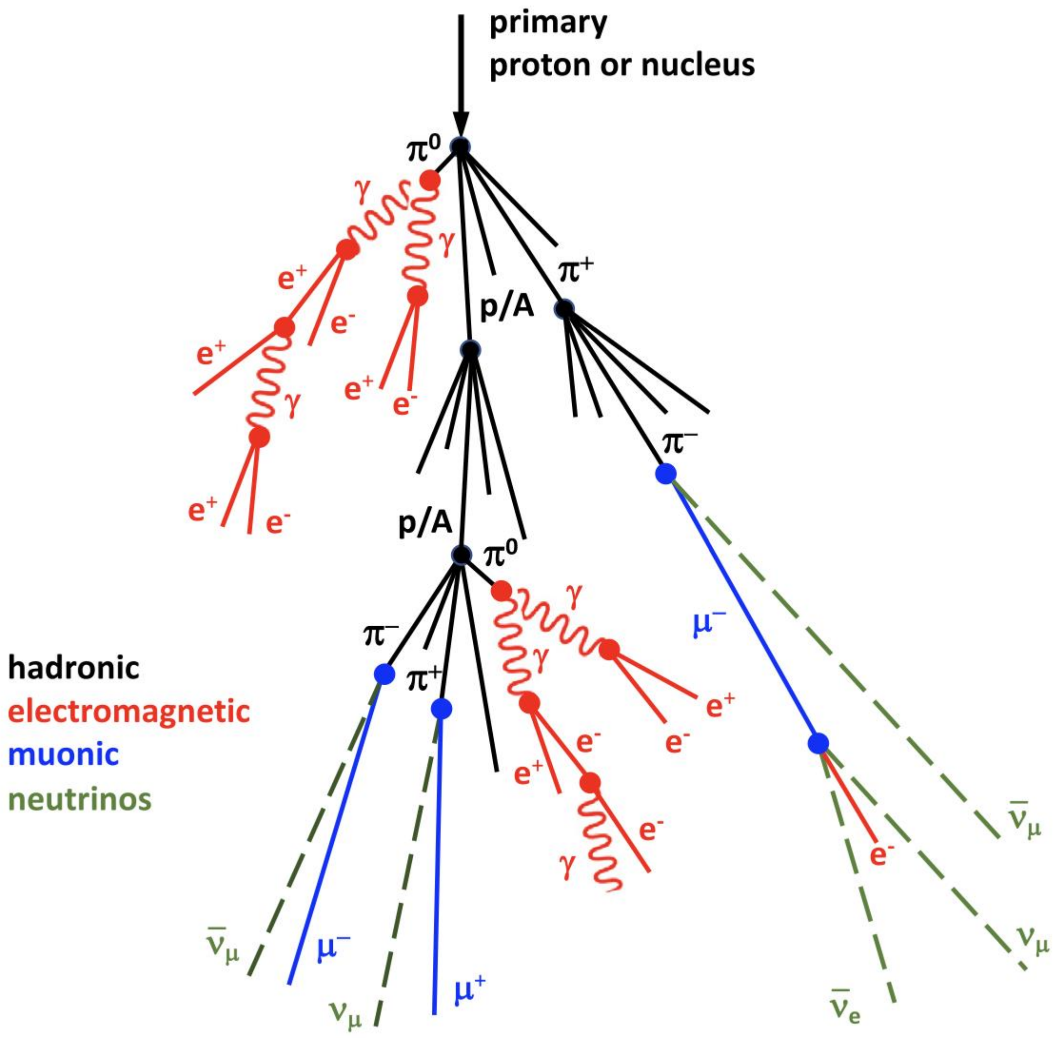
Modeling atmospheric lepton flux



- Atmospheric neutrino is background in astrophysical neutrino observation

Motivation of modeling cosmic ray flux and composition

Modeling atmospheric lepton flux

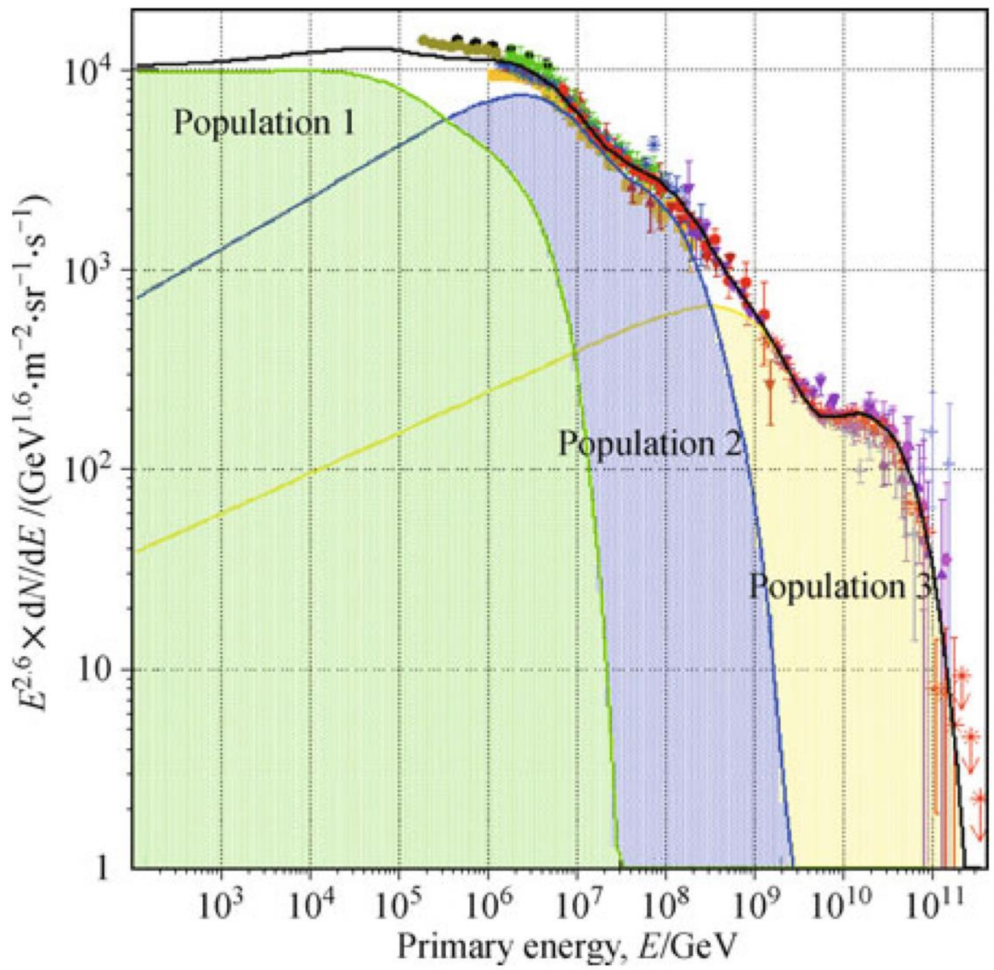


- Atmospheric neutrino is background in astrophysical neutrino observation
- Cosmic-ray nucleon flux is one of the large uncertainties in atmospheric lepton flux estimation
    - Nucleon flux is depending on **cosmic ray flux** and **mass composition**

A typical model of CR flux & mass composition

T. Gaisser, T. Stanev and S. Tilav, Front. Phys. (Beijing) **8** 748-758 (2013)

Assuming three populations, acceleration mechanism (such as rigidity-dependent cutoff), etc.



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

- Derived results (atm. lepton flux, etc.) are dependent on theoretical assumptions
- Experiments usually estimates model uncertainties by bracketing some models (It is overestimating)

A data-driven model: Global Spline Fit (GSF)

Better way to model cosmic-ray flux and mass composition
- Data driven (less dependent on theoretical assumptions)
- Use experimental uncertainties properly

→ **Global Spline Fit (GSF)**

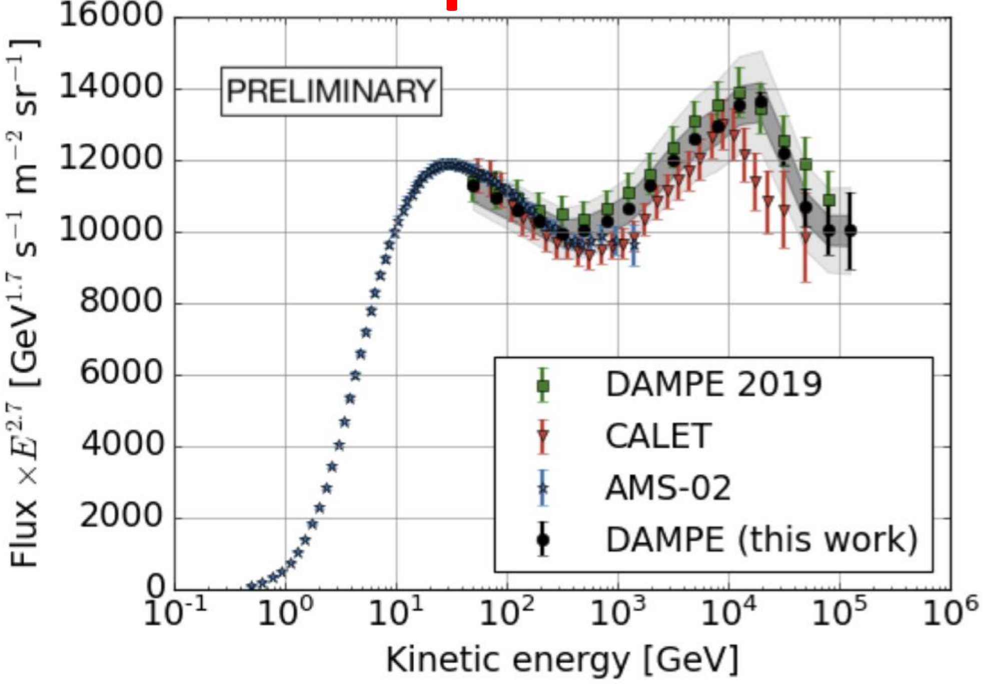
- Original work: PoS(ICRC**2017**)533
  by H. Dembinski, R. Engel, A. Fedynitch, T. Gaisser and T. Stanev

- Since the original work in 2017 (and updates in 2018-2019), many new observational results have been published

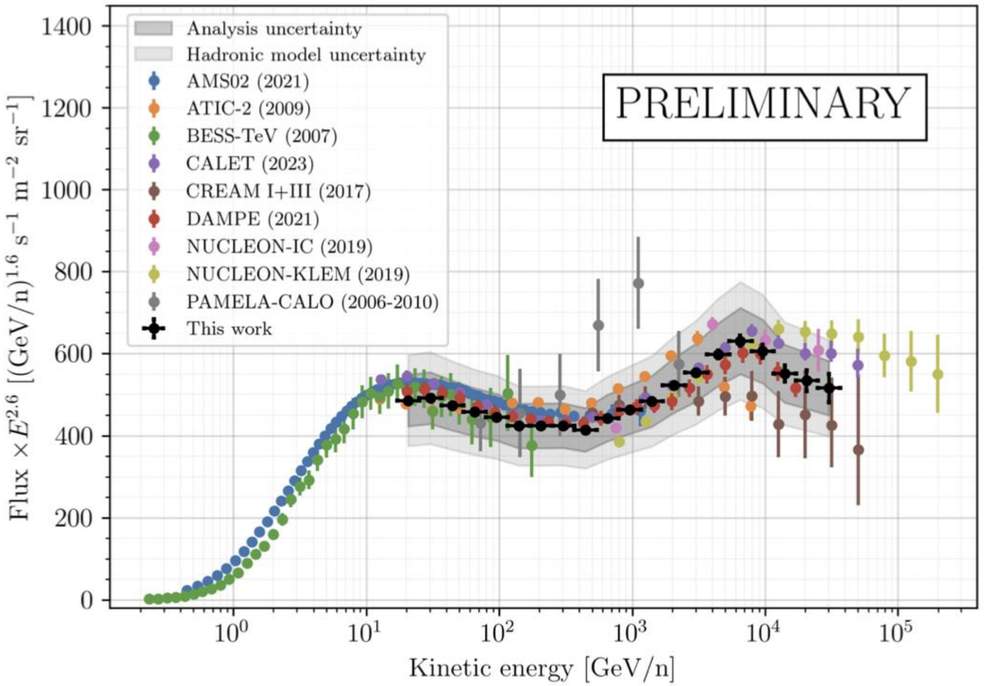
  → <u>This work: updates GSF with the latest data set</u>

Data updates: direct measurements

proton



helium

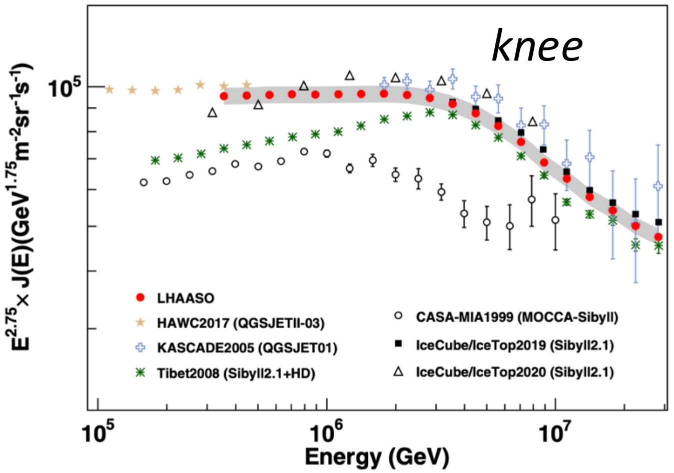


DAMPE collaboration, *PoS*(**ICRC2023**) (2023) 444

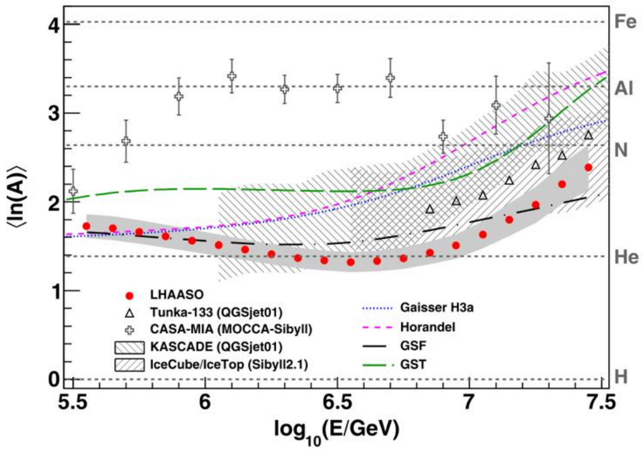
- New experiments (extends to hundreds of TeV): CALET, DAMPE, ISS-CREAM, NUCLEON-KLEM, …
- New spectral features:
  - Spectral hardening at ~ 10-20 TV for proton and helium
- New AMS-02 data (e.g. Iron AMS collaboration, PRL 126, 041104 (2021))

Data updates: indirect measurements

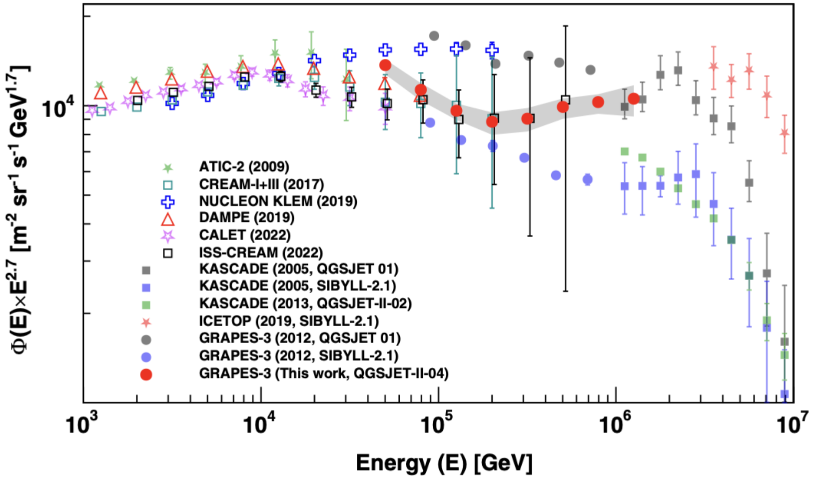
all-particle



<lnA>



proton

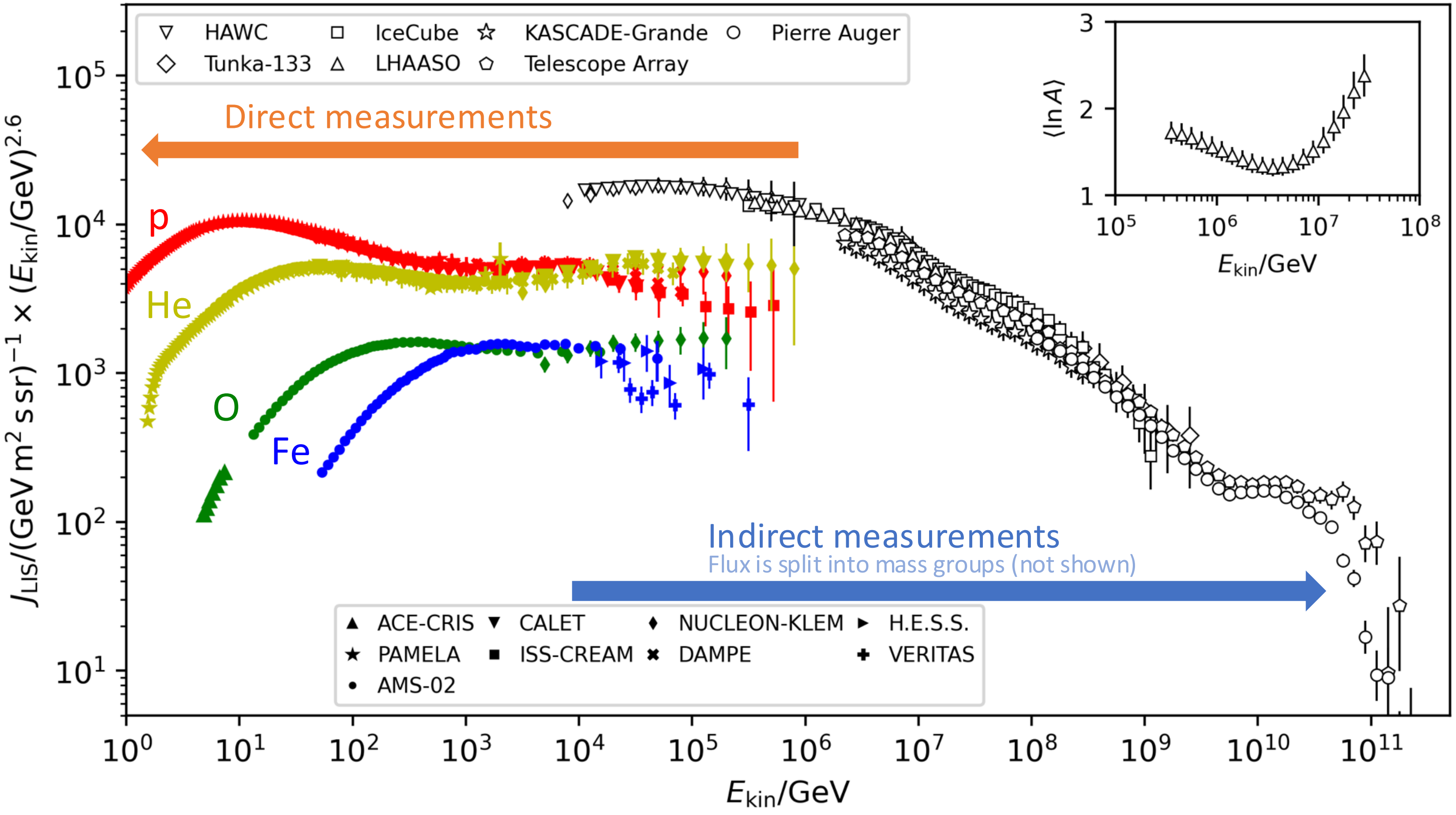


LHAASO Collab., PRL 132 (2024) 131002

GRAPES-3 Collab., PRL 132 (2024) 051002

- LHAASO: all-particle flux and mean logarithmic mass (lnA) at the *knee*
- GRAPES-3: proton break at 100–200 TeV
- New Auger data, IceCube(+IceTop) data, …

Combining cosmic-ray data



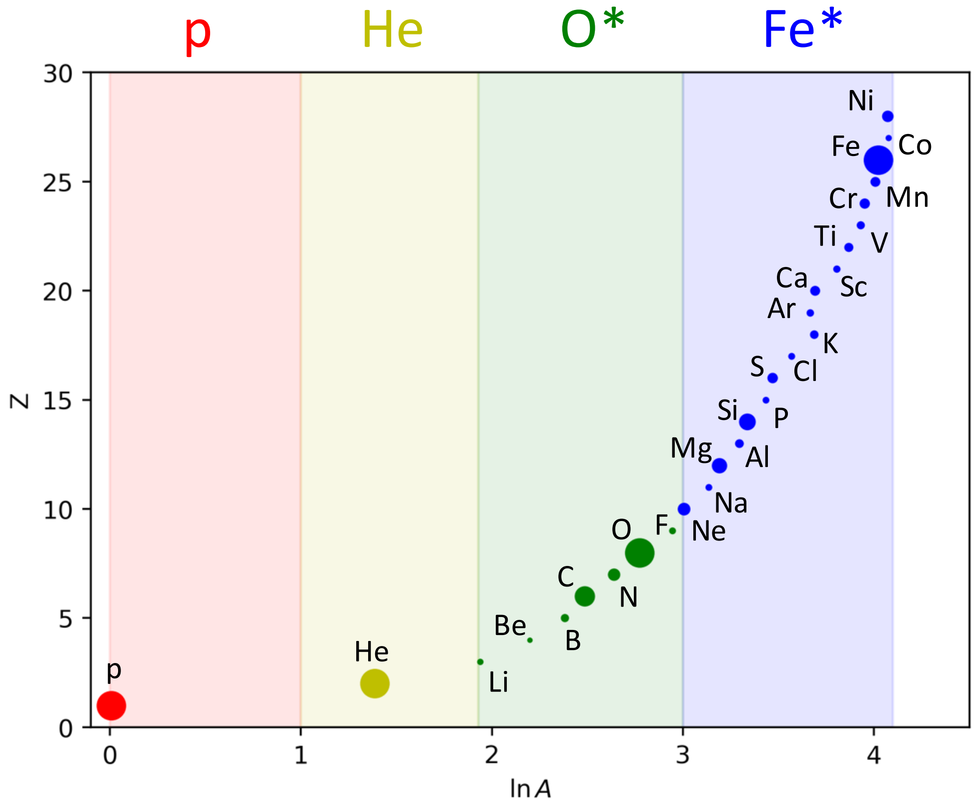
- Direct measurements (flux in each element)
  - Small systematic uncertainties
- Indirect measurements (total flux and flux in **mass groups**)
  - Large systematic uncertainties

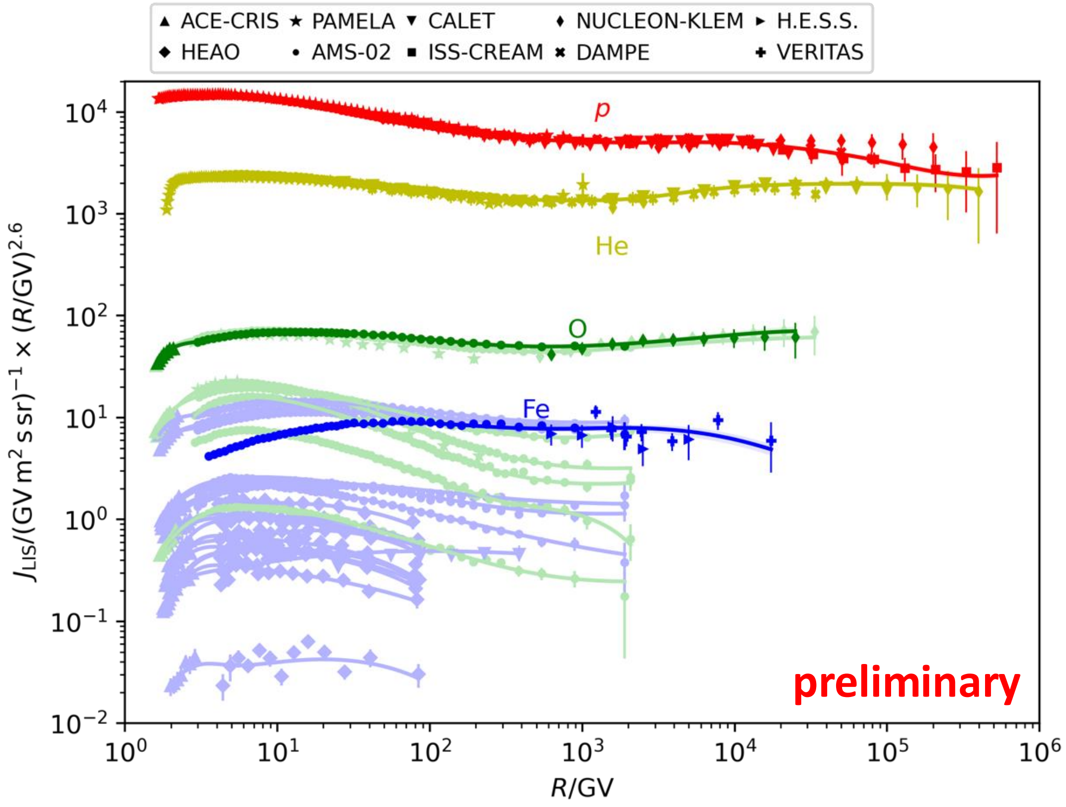
Goal:
modeling cosmic-ray flux and mass composition covering $\mathbf{10^0}$ **-** $\mathbf{10^{11}}$ **GeV**, combining both direct and indirect measurements

Combining cosmic-ray data

- Fit **four** mass groups which covers equal range in lnA:
  proton (p), helium (He), oxygen group (O*), iron group (Fe*)

- At low energies, each individual element flux is described by a smooth spline curve
- At high energies, one leading element L per group is described by a smooth spline curve
  - Other elements i in a group kept in constant ratio: $J_i(R)\ /\ J_L(R)$ = const.





Handling energy-scale uncertainties of experiments

- Energy-scale uncertainty of experiments are handled by introducing energy-scale offset z_E

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

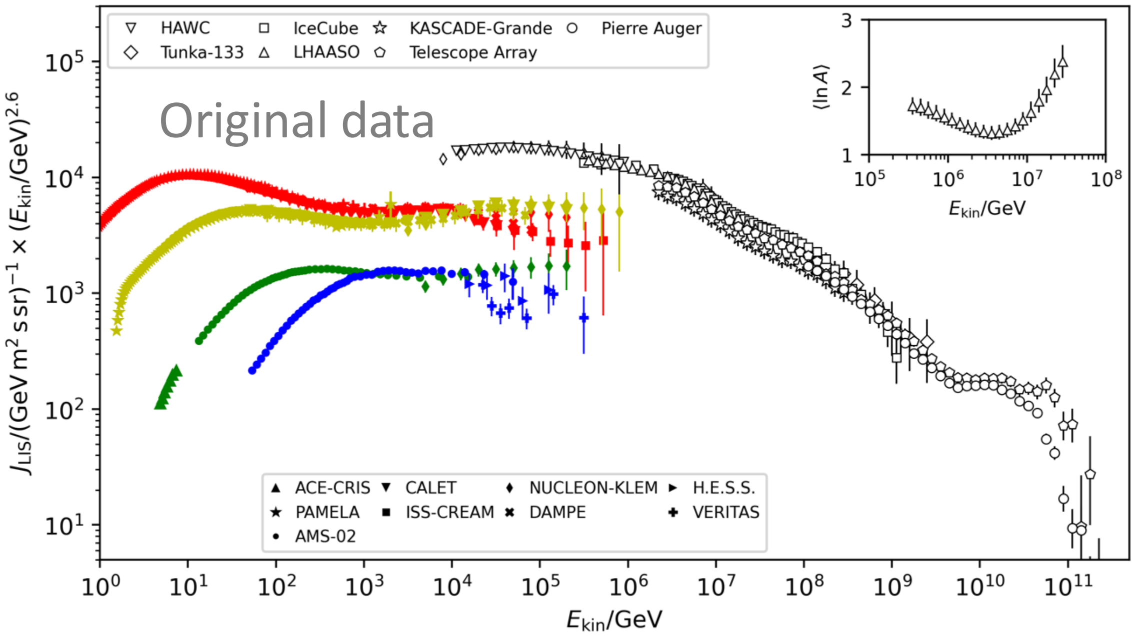
Flux distortion by energy-scale offset z_E

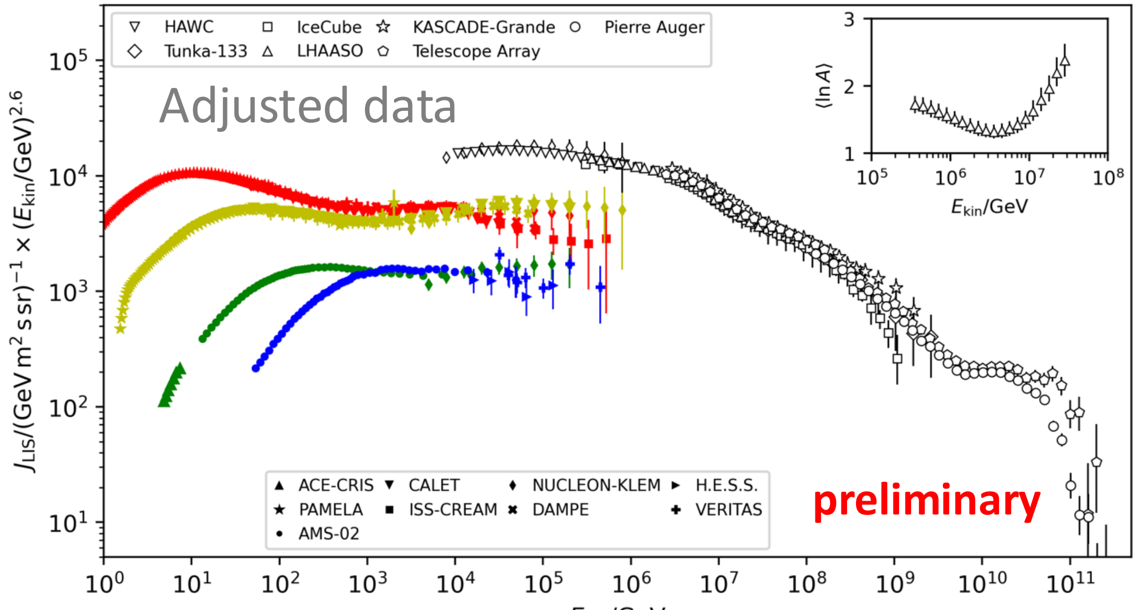
- Fit adjusts energy scales within systematic uncertainties of the experiment

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

Flux & <lnA> residuals

Energy-scale offset residuals





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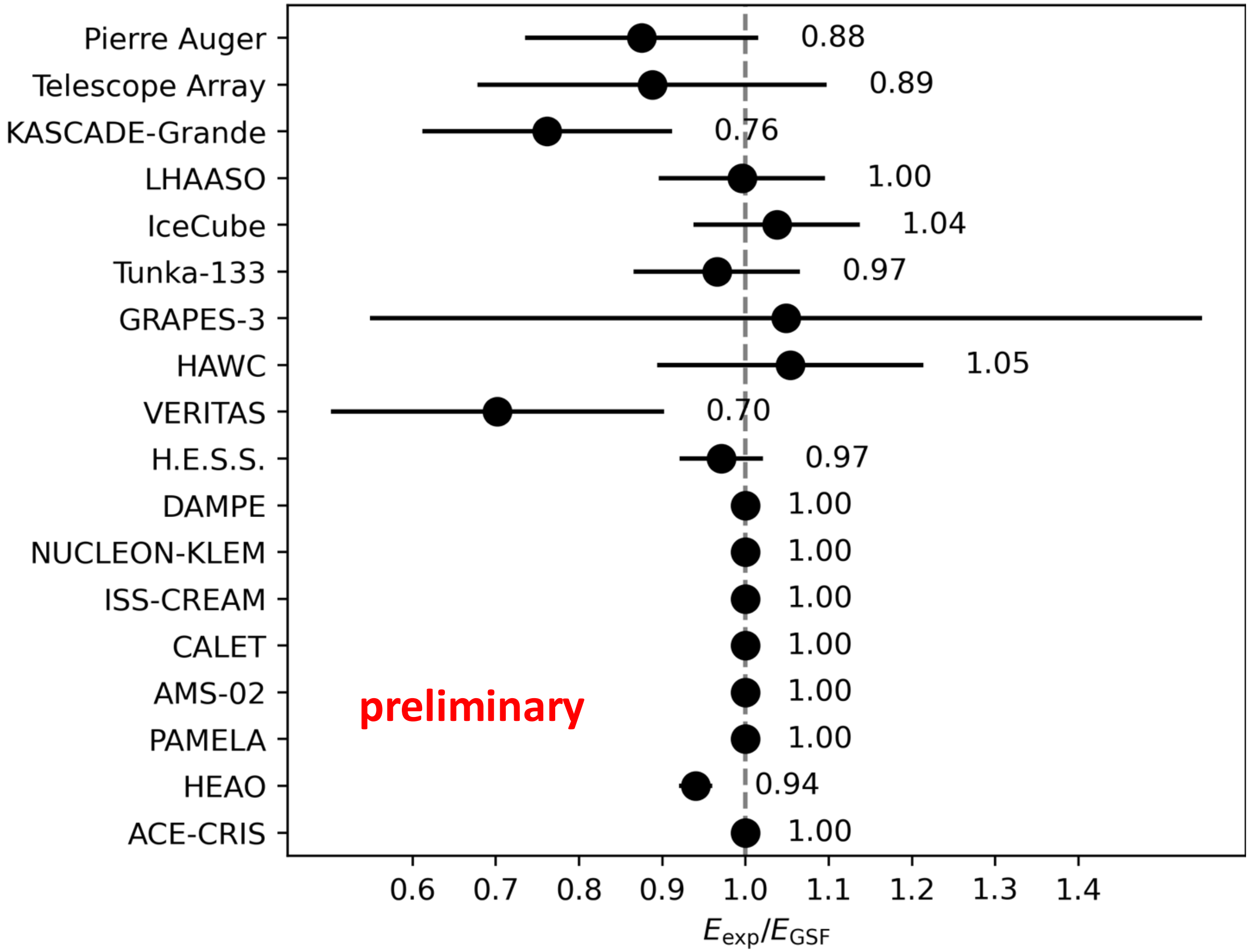
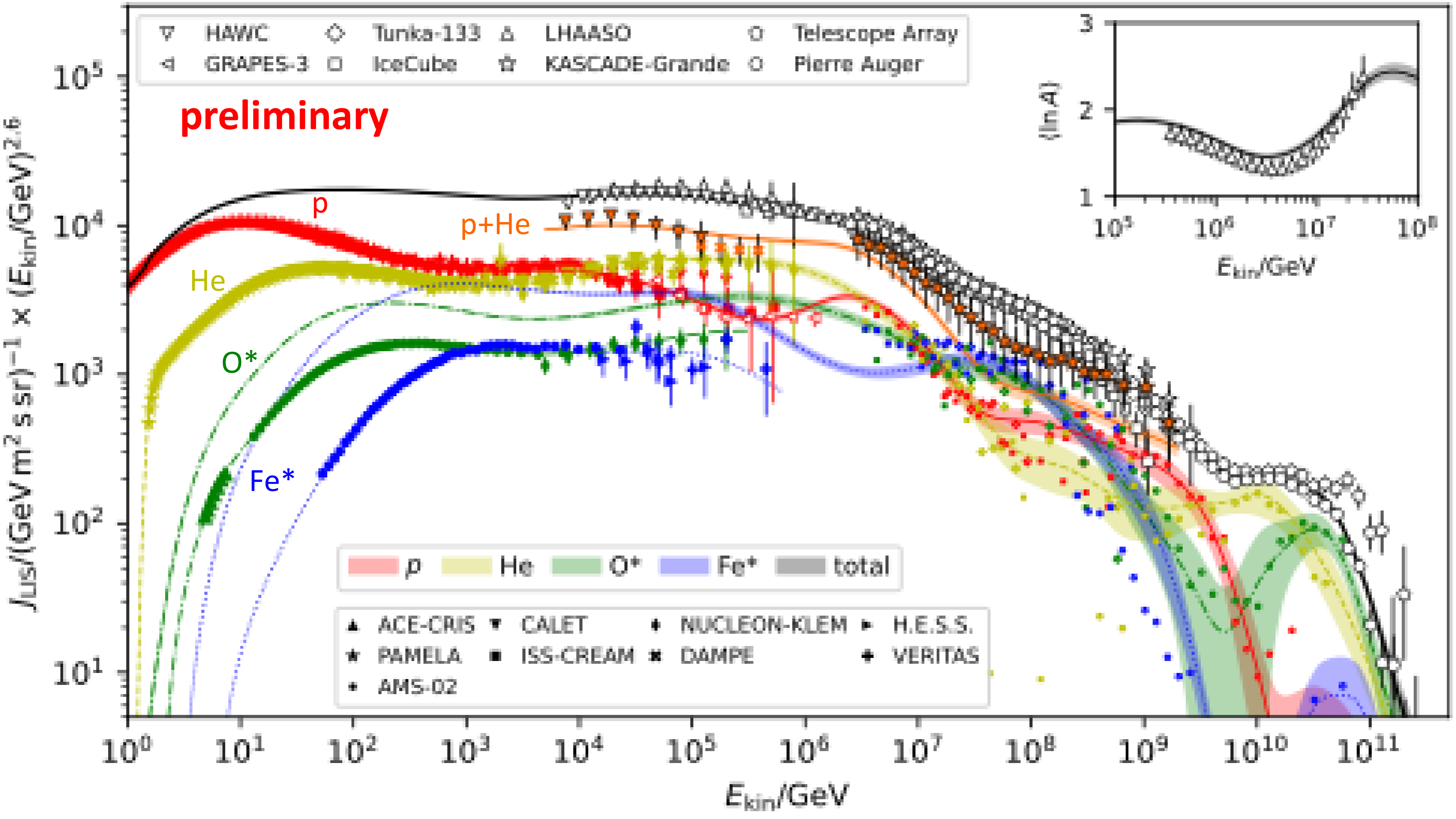


GSF energy scale fixed by direct measurements

The updated Global Spline Fit

χ^2/ ndf = 1034 / 1072 = 0.96



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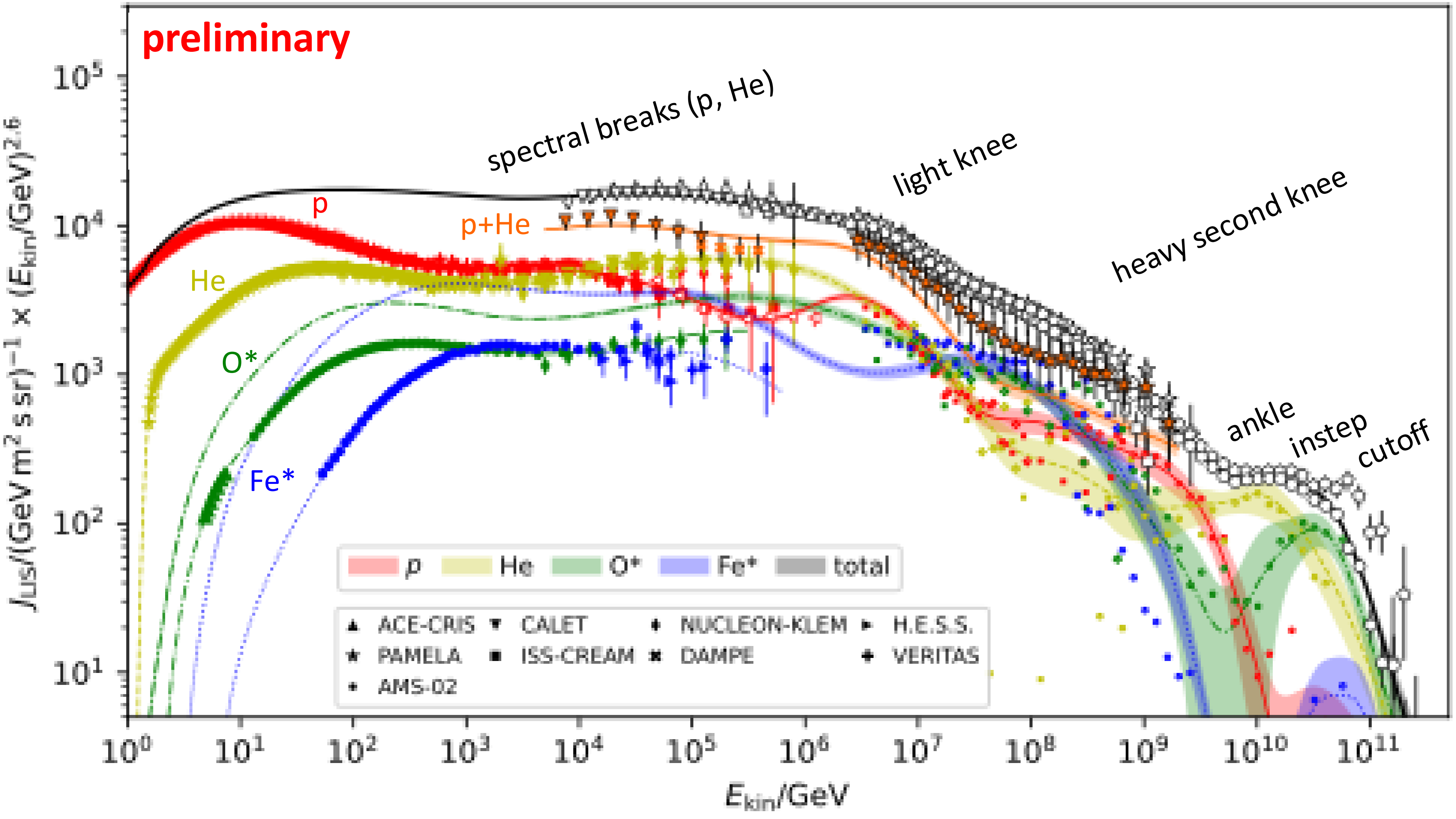

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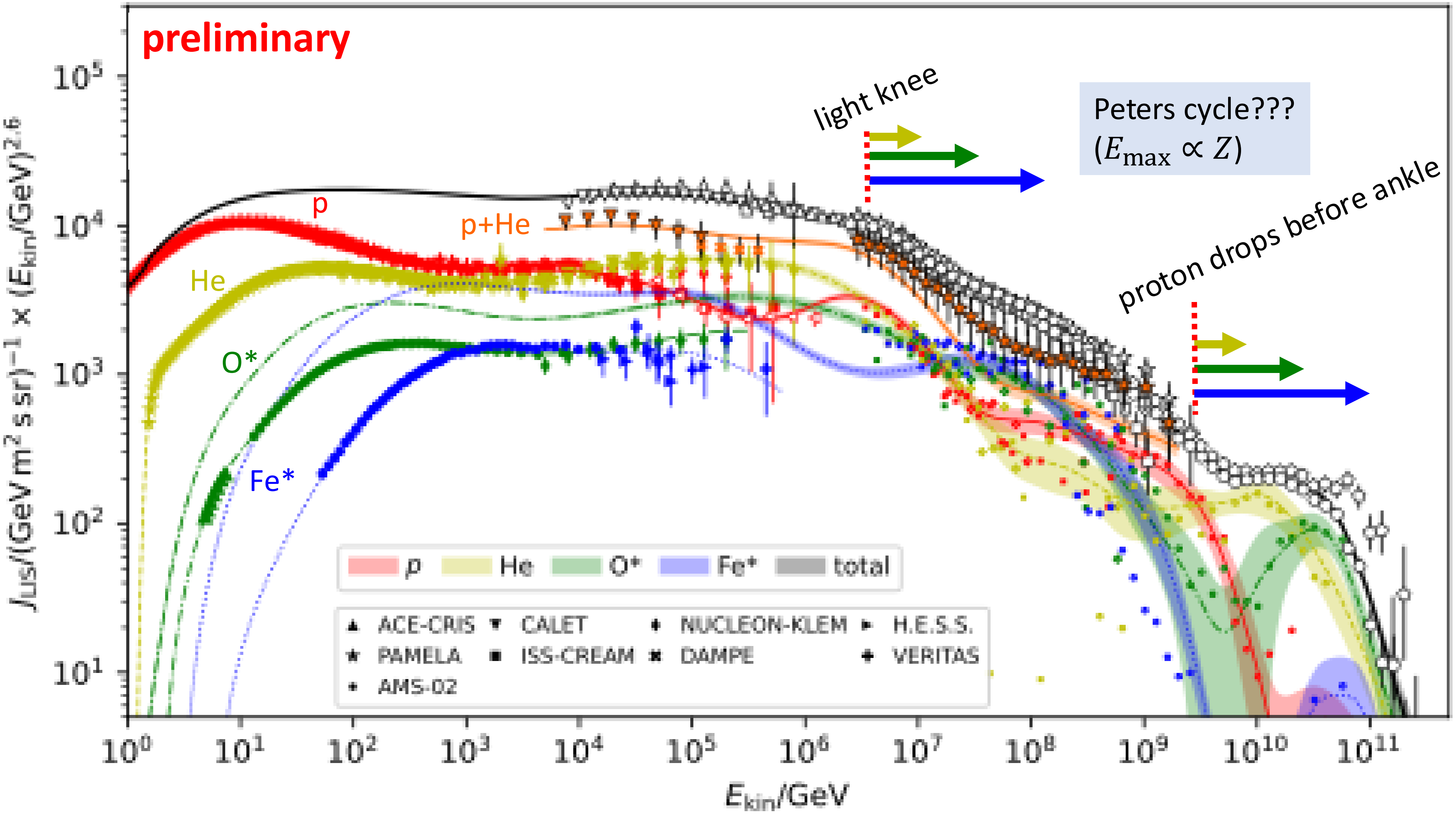
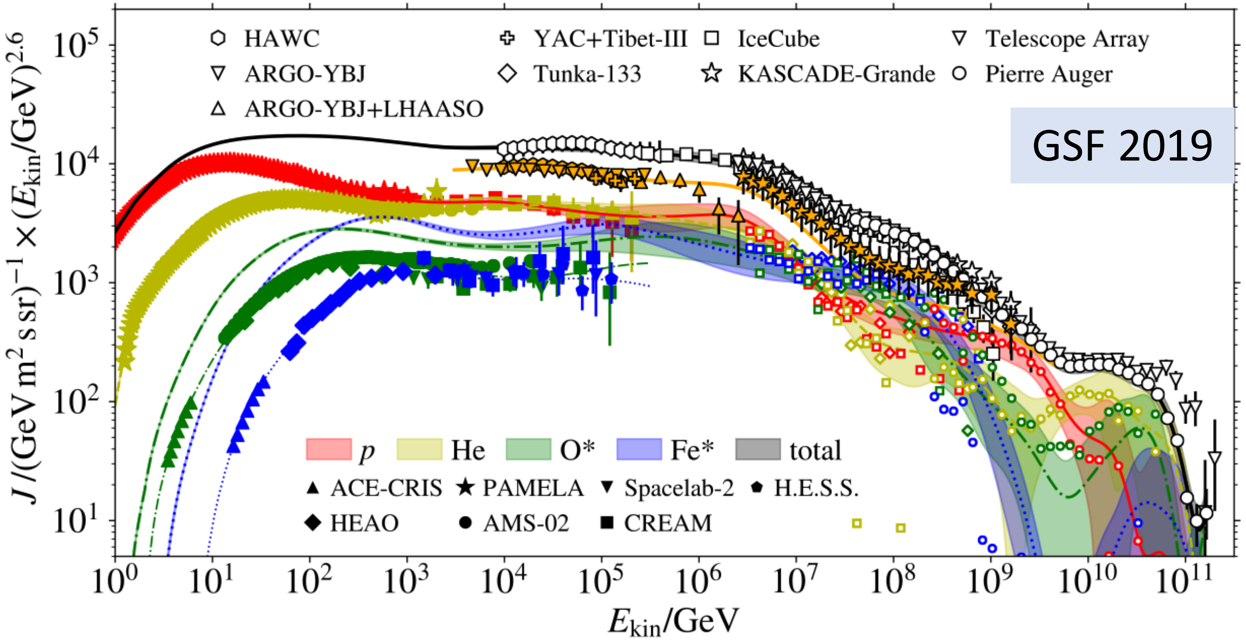
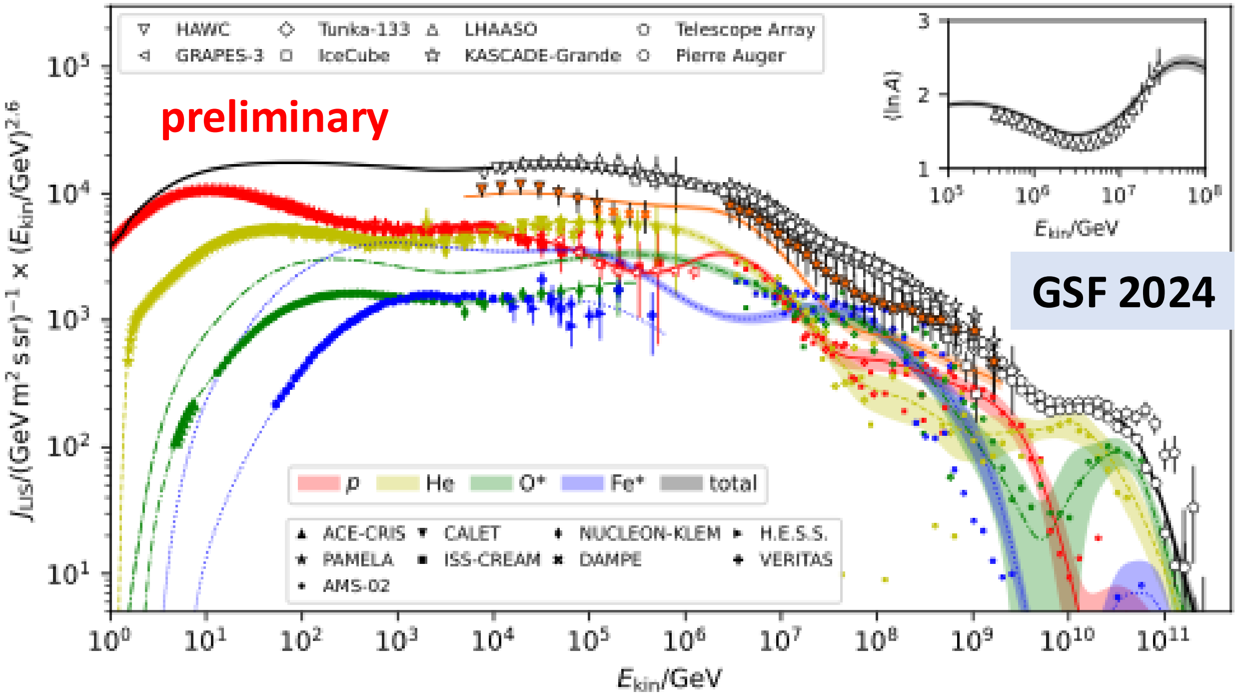


Model comparison

- Smaller errors with updated data
- Spectral breaks of proton and helium at ~10 TV

H. Dembinski, the figure is taken from F. Schröder, arXiv:1910.03721





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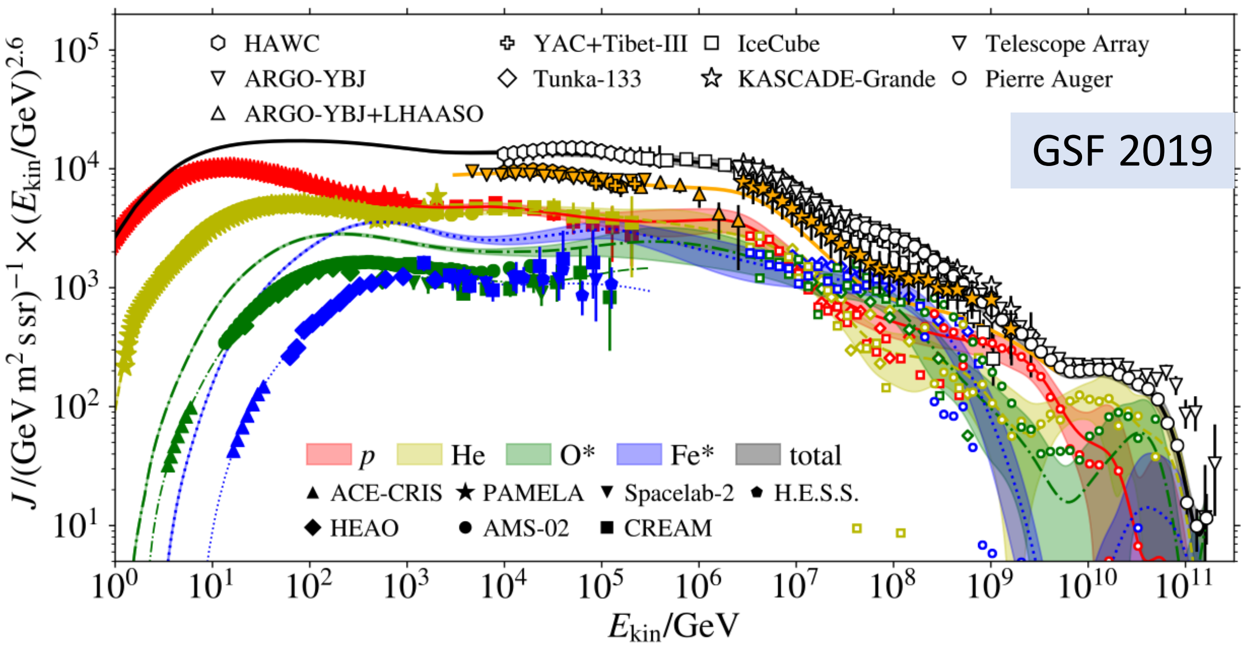
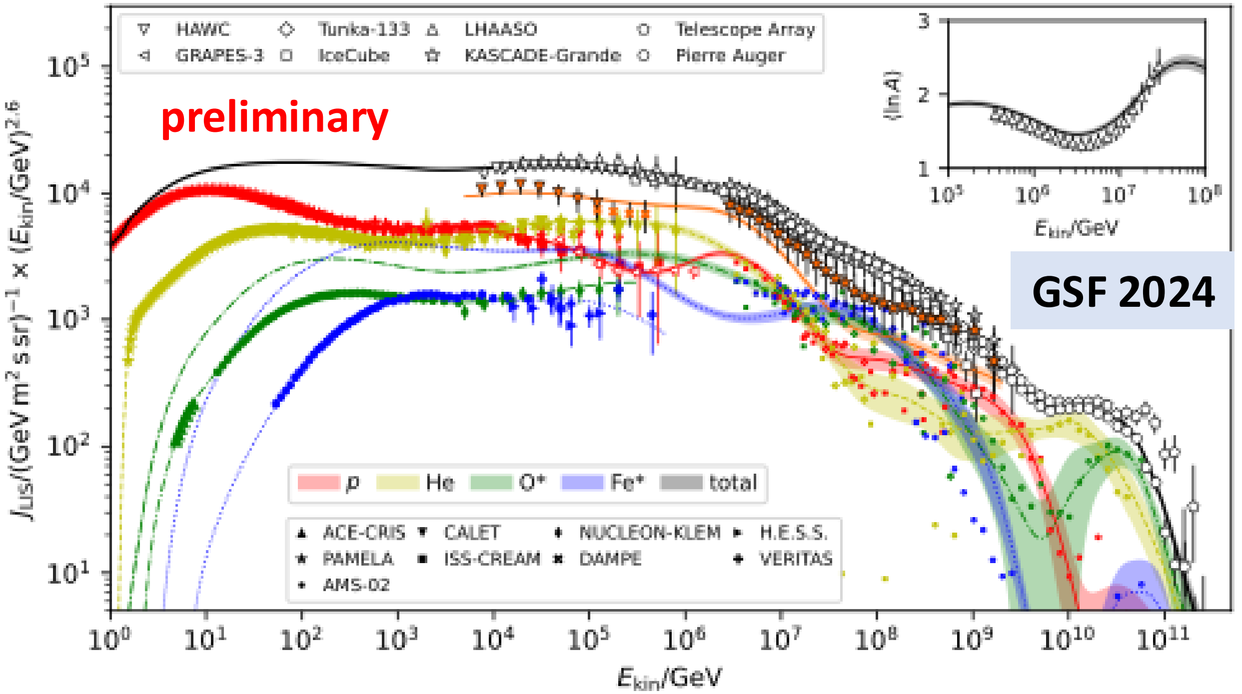
  - Data set 1: baseline model





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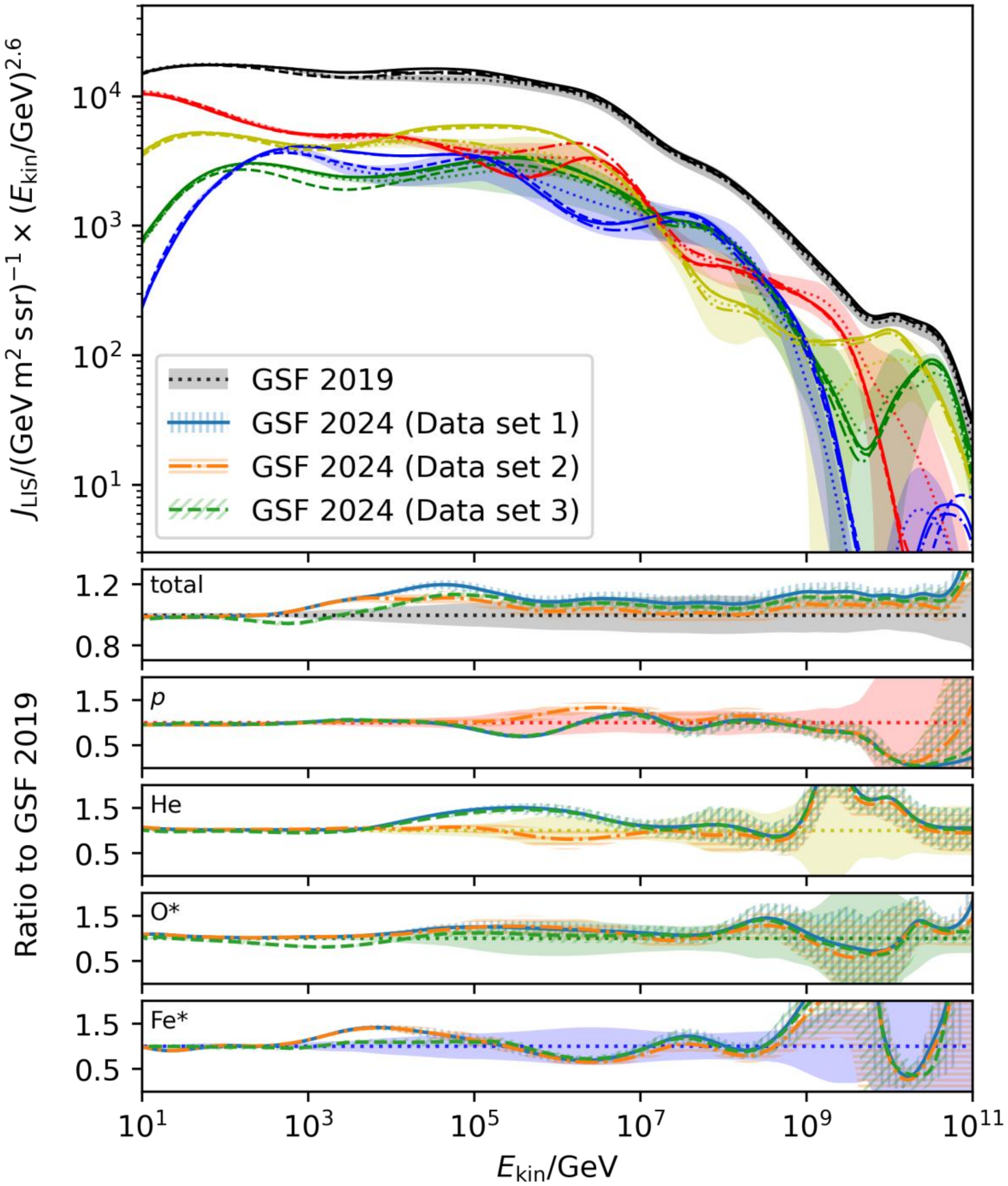
    (+) CREAM I+III
  - Data set 3: (–) AMS-02
    (+) direct data in tension with AMS-02

Direct



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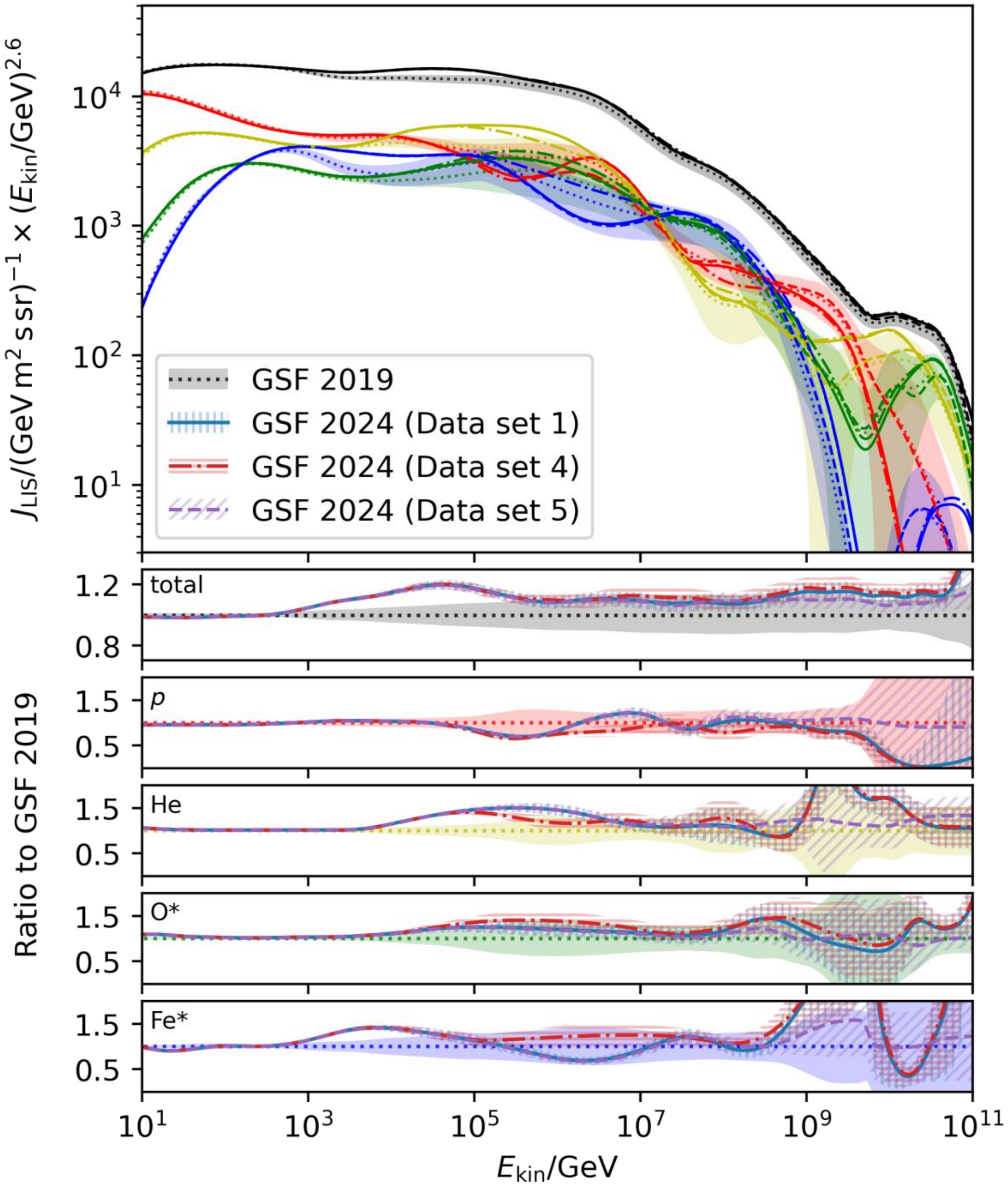
Indirect

  - Data set 4: (–) LHAASO
  - Data set 5: (–) Auger
    (+) Auger previously used in GSF2019



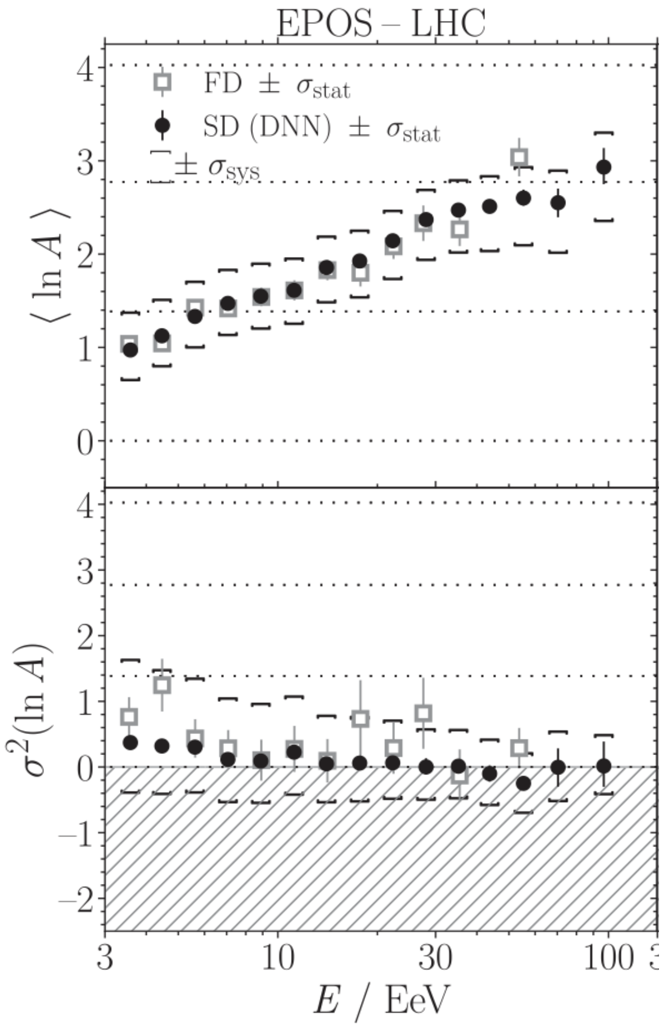
Summary

- The Global Spline Fit (**GSF**) is a **data-driven cosmic-ray flux and mass composition model**:
  - covering 11 decades in energy by unifying **direct and indirect** measurements
  - correction of **energy-scale offsets** in a global fit
  - **experimental uncertainties are propagated to the model uncertainties**
    (e.g.) atmospheric neutrino flux, where nucleon flux is an input to estimate the flux

- This work: updates with recent measurements;
  - The well-established spectral features seen in the previous model are confirmed with smaller uncertainties with **updates datasets**.
  - We illustrate the impact of new observational data.
  - Nucleon flux shows some new features reflecting spectral breaks in proton and helium flux.

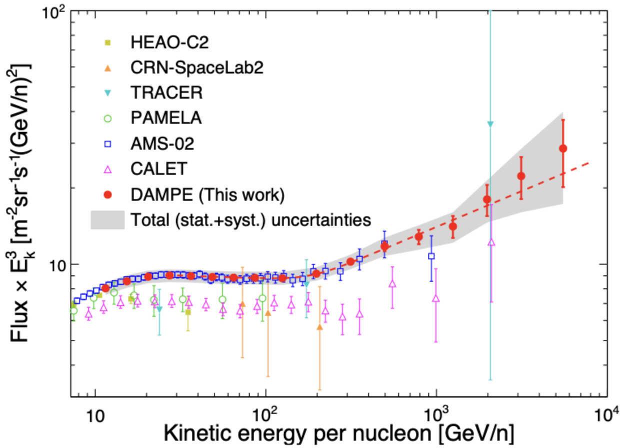
Prospects

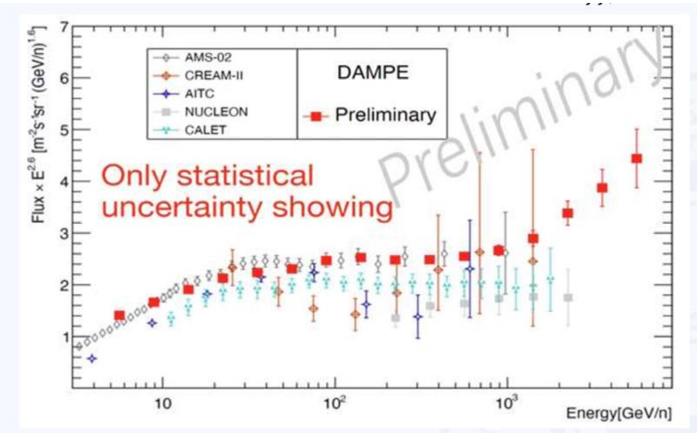
- Dataset updates and including σ(lnA) data



Pierre Auger Collab., PRL 134 (2025) 021001

Auger SD
mass composition





DAMPE boron flux, iron flux

DAMPE Collab., arXiv:2412.11460

https://indico.ihep.ac.cn/event/21331/contributions/161665/attachments/80804/101384/Iron%20spectrum.pdf

…

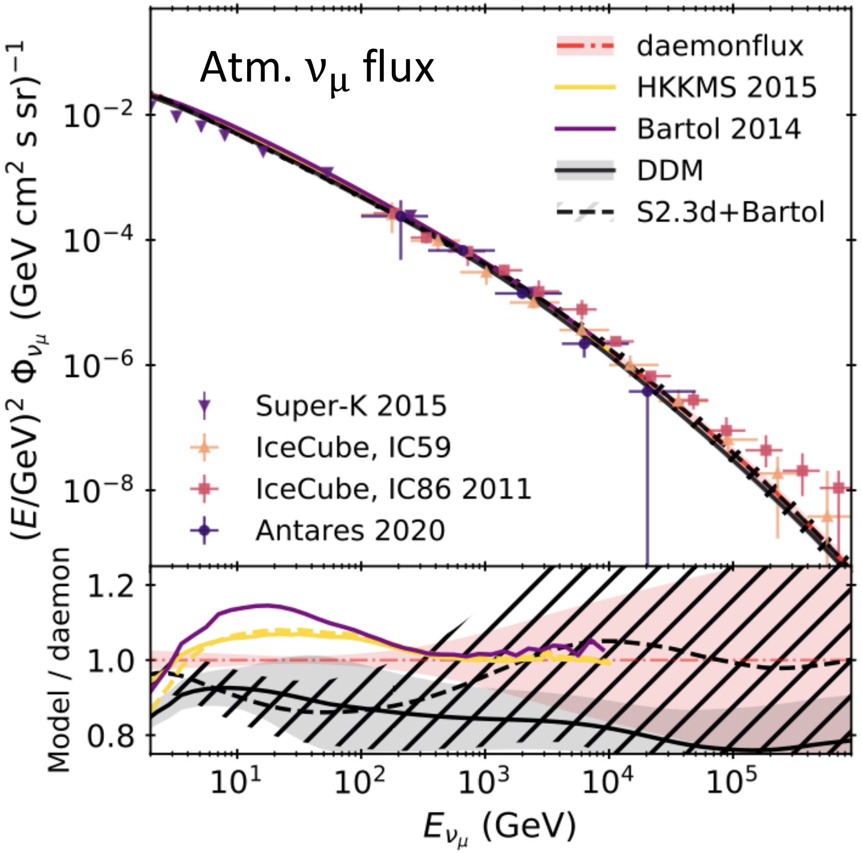
LHAASO

…

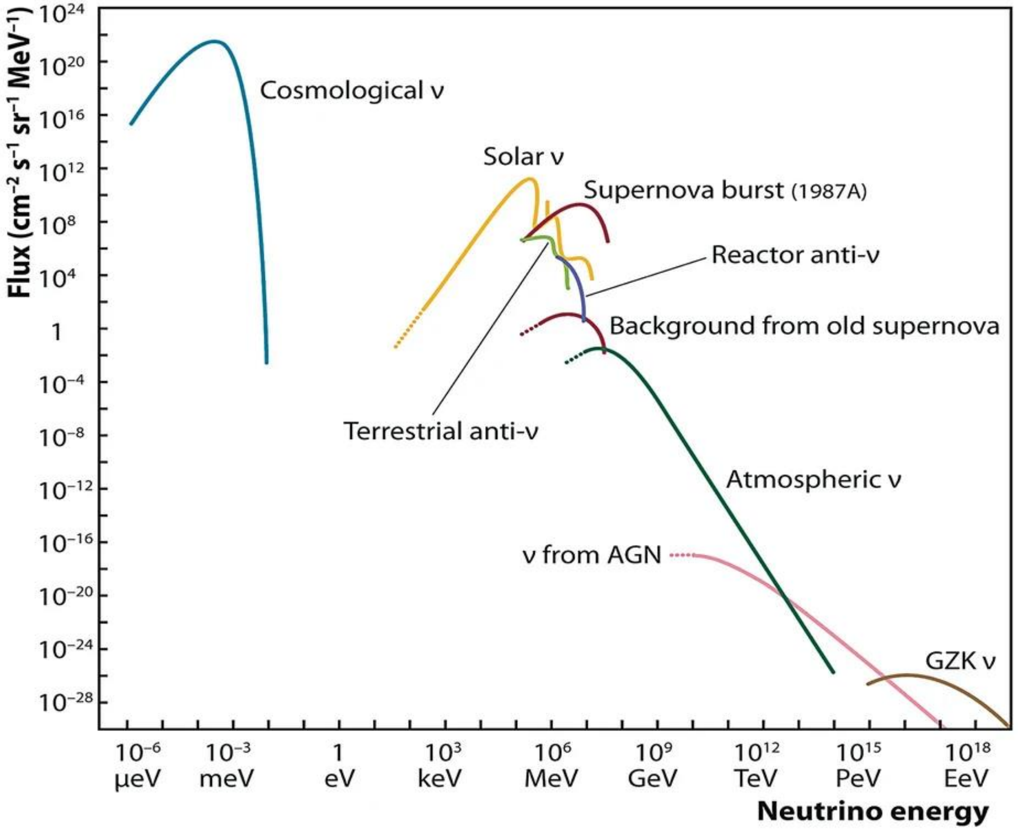
TA (TALE, TALE-infill, TAx4)

Prospects

- Dataset updates and including σ(lnA) data
- Atmospheric lepton flux calculation and comparison with observational data



J. P. Yañez and A. Fedynitch, PRD 107 (2023) 123037



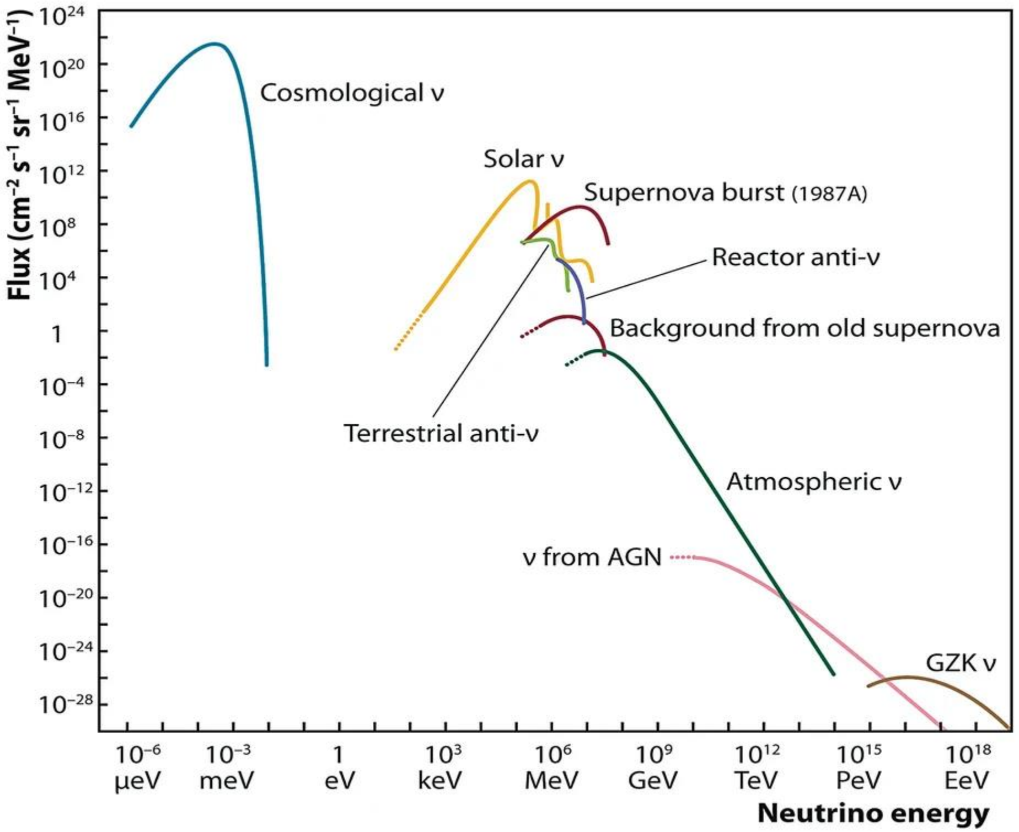
C. Spiering, Eur. Phys. J. H37, 515–565 (2012)

Prospects

- Dataset updates and including σ(lnA) data
- Atmospheric lepton flux calculation and comparison with observational data
- Publish the updated GSF model and provide code for download

  - Atm. lepton flux background
  - CR background (against gamma ray)
  - Aperture & detector response for CR obs.
  - Phenomenological analyses
  - …

with model uncertainties which reflect experimental uncertainties!



C. Spiering, Eur. Phys. J. H37, 515–565 (2012)

Backup

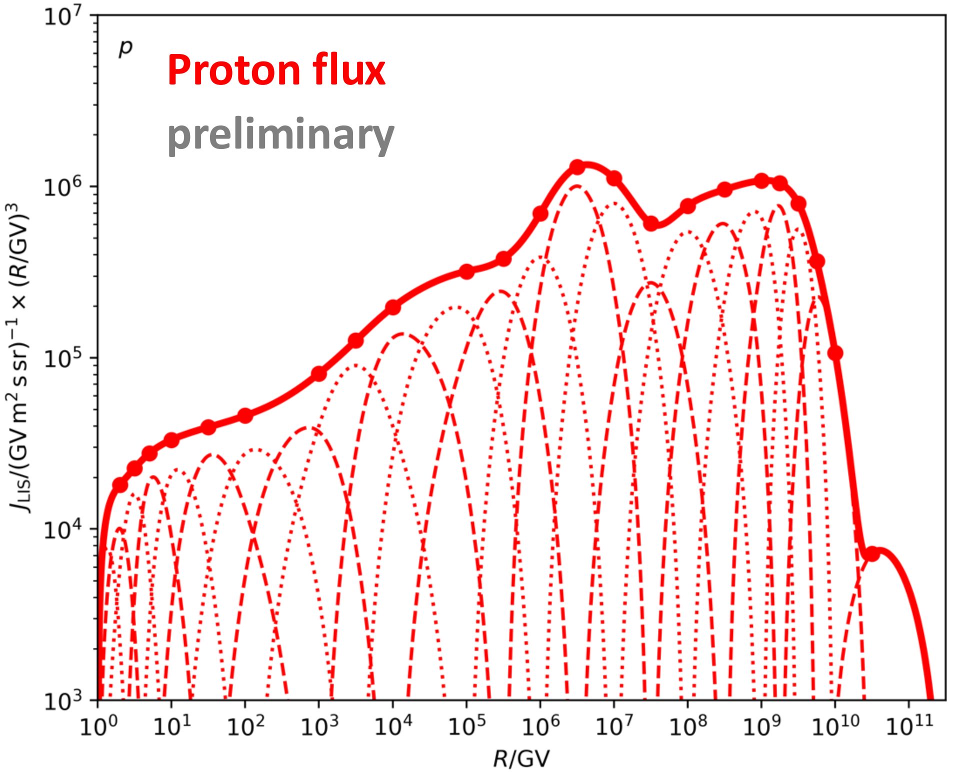
Flux model

Flux of leading element L

$$J_L(R) = (R/\mathrm{GV})^{-3} \sum_k \underbrace{a_{Lk}}_{\text{amplitude}} \underbrace{b_k\big(\ln(R/\mathrm{GV})\big)}_{\text{B-spline}}$$

Total flux

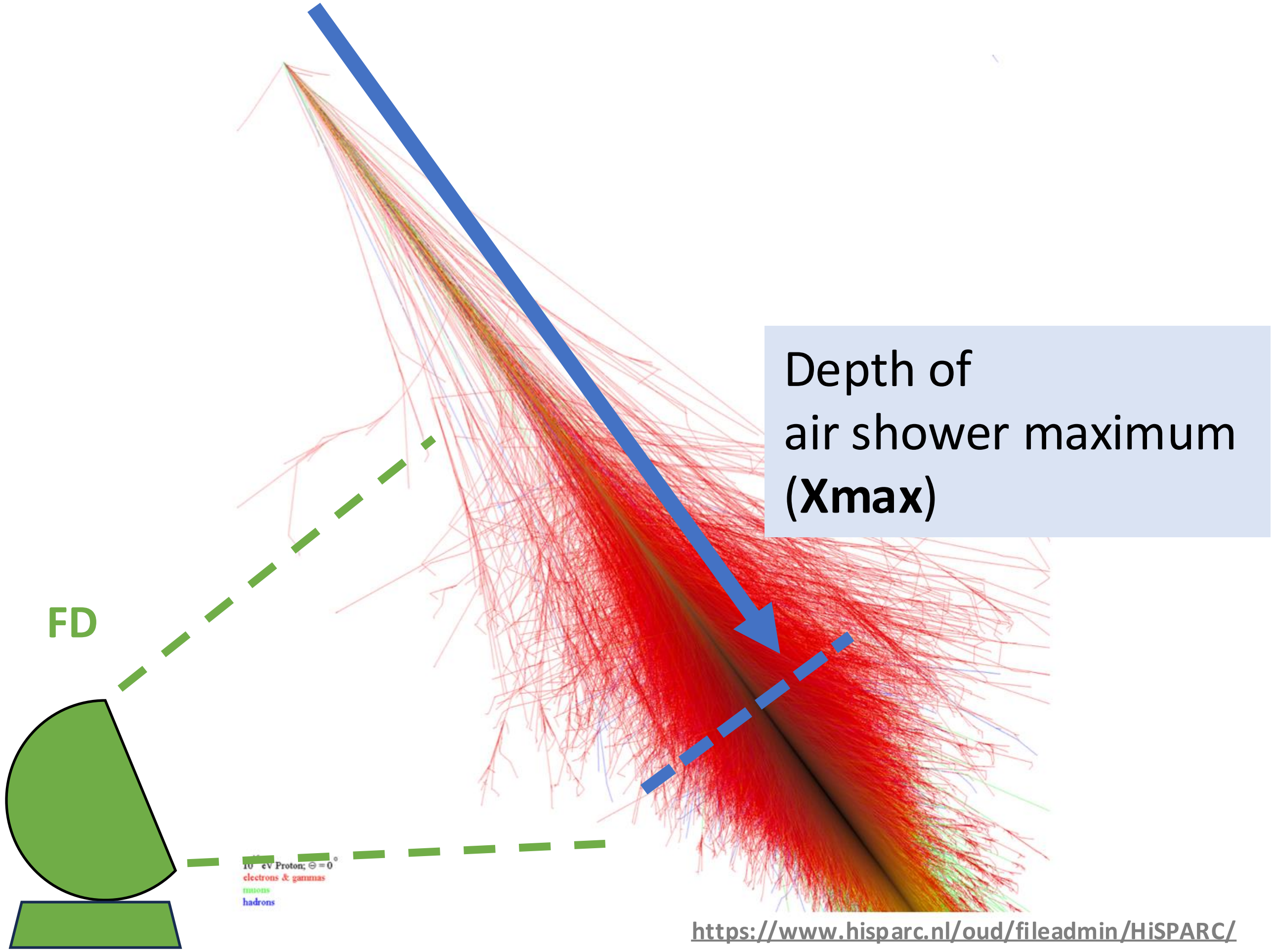
$$J(E) = \sum_L \sum_j \underbrace{w_{Lj}}_{\text{flux ratio}} J_L(R_j(E)) \left(\frac{\mathrm{d}R}{\mathrm{d}E}\right)_j$$



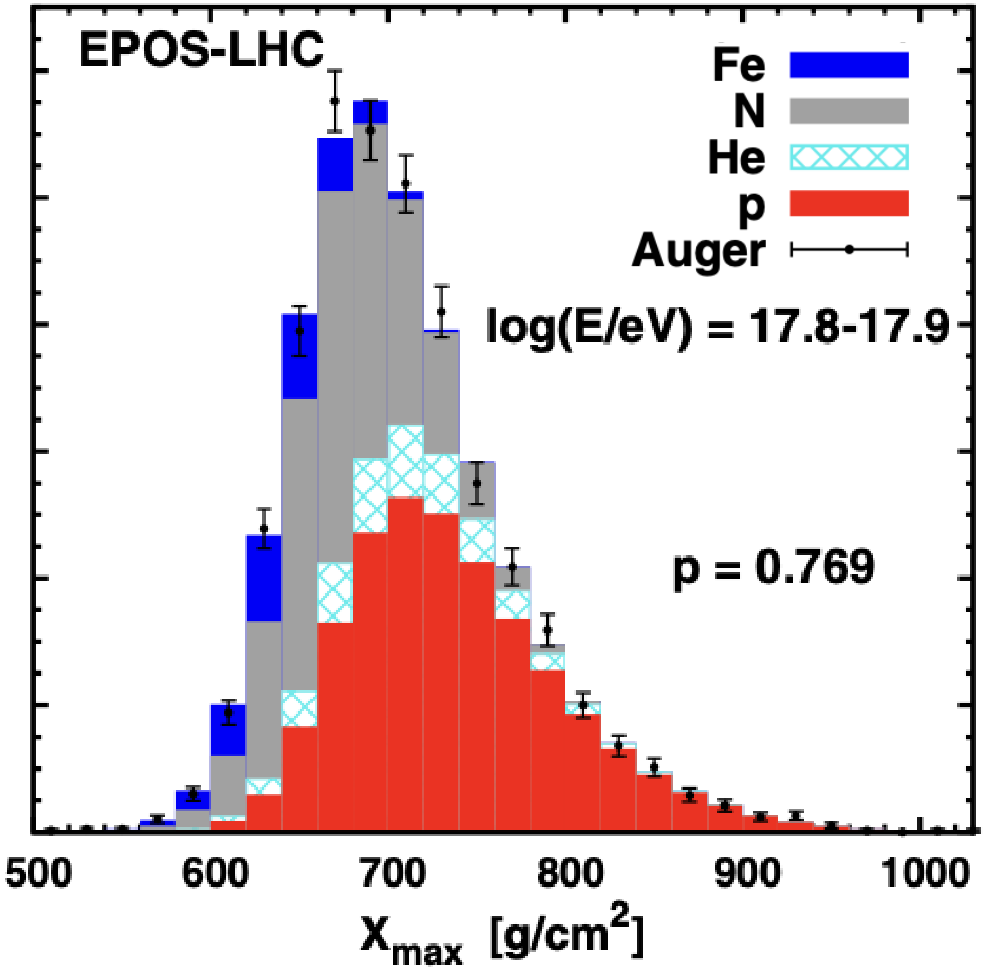
Less theoretical assumptions

- no assumption of source population,
  rigidity cut off,
  propagation calculation, …

Mass group estimation by Fluorescence detector (FD)



https://www.hisparc.nl/oud/fileadmin/HiSPARC/werk_van_studenten/UHECRs-thesis-JDHaverhoek.pdf



Pierre Auger Collab., PRD 90 (2024) 122006

- Air shower observations usually measure flux fractions of **mass groups.**
- Mass sensitivity of air shower measurements: ~**lnA**

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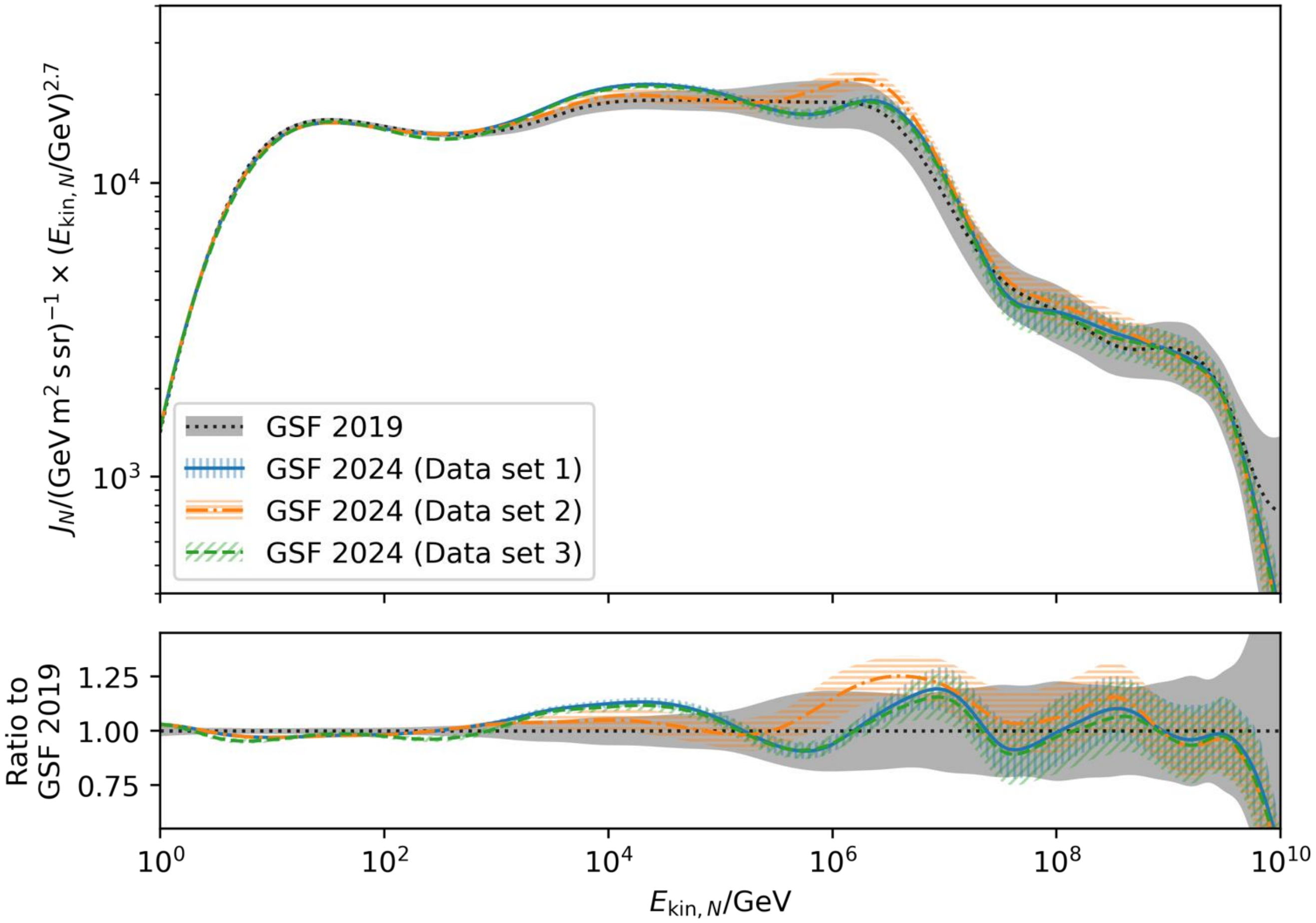
Direct (Data sets 2–3)

Indirect (Data sets 4–5)



- Nucleon flux: input for atm. neutrino flux calculation.
  - Breaks in nucleon flux reflecting new proton and helium features.

Table 1: Datasets used for the GSF 2024 model. A circle (∘) indicates that an experiment's measurements are included in a given dataset, while labels (a), (b), (c), (d), and (e) denote specific dataset variations. **ACE-CRIS:** Li, B, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, and Ni; datasets marked with (a) exclude Fe data. **HEAO:** Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, and Ni; datasets marked with (b) exclude Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, S, and Fe data. **PAMELA:** H and He, plus B and C. **AMS-02:** H, He, Li, Be, B, C, N, O, F, Ne, Na, Mg, Al, Si, S, and Fe. **CALET:** H, He, B, C, O, Fe, and Ni; datasets marked with (c) exclude B, C, O, and Fe. **DAMPE:** H, He, and a combined H + He flux at high energies (where separate proton and helium data are unavailable). **CREAM I+III:** H and He. **ISS-CREAM:** H. **NUCLEON-KLEM:** H, He, C, O, Ne, Mg, Si, Fe, and the all-particle flux; datasets marked with (d) exclude Ne, Mg, Si, and Fe. **GRAPES-3:** p. **H.E.S.S.:** Fe. **VERITAS:** Fe. **HAWC:** H + He and the all-particle flux. **LHAASO:** All-particle flux and $\langle \ln A \rangle$. **IceCube:** All-particle flux and flux of each mass group (listed twice to indicate multiple data samples). **KASCADE-Grande:** Flux of a light-mass group (treated as H + He) and a heavy-mass group (treated as O and Fe). **TA:** All-particle flux. **Auger:** All-particle flux and flux of each mass group. Datasets marked with (e) use the same configuration as the previous GSF model [43].

Experiment	Data set 1	Data set 2	Data set 3	Data set 4	Data set 5
ACE-CRIS [4, 5]	(a)	(a)	∘	(a)	(a)
HEAO [6]	(b)	(b)	∘	(b)	(b)
PAMELA [7, 8]	∘	∘	∘	∘	∘
AMS-02 [9–12]	∘	∘		∘	∘
CALET [13–18]	(c)		∘	(c)	(c)
DAMPE [19–21]	∘		∘	∘	∘
CREAM I+III [22]		∘			
ISS-CREAM [23]	∘		∘	∘	∘
NUCLEON-KLEM [24]	(d)		∘	(d)	(d)
GRAPES-3 [25]	∘		∘	∘	∘
H.E.S.S. [26]	∘	∘	∘	∘	∘
VERITAS [27]	∘	∘	∘	∘	∘
HAWC [28, 29]	∘	∘	∘	∘	∘
LHAASO [30]	∘	∘	∘		∘
IceCube [31, 32]	∘	∘	∘	∘	∘
Tunka [33, 34]	∘	∘	∘	∘	∘
KASCADE-Grande [35]	∘	∘	∘	∘	∘
TA [36, 37]	∘	∘	∘	∘	∘
Auger [38–42]	∘	∘	∘	∘	(e)

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