9th Symposium on Prospects in the Physics of Discrete Symmetries

DISCRETE 2024 in Ljubljana

Highlights from space astroparticle physics experiments

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Space: from spectrometers to calorimeters

Magnetic Spectrometers (PAMELA, AMS-02)

- Best precision, limited by magnetic field to ~ TV
- Cosmic ray particles and antiparticles, isotopes

Calorimetric Experiments (Fermi-LAT, CALET, DAMPE, ISS-CTREAM, HERD)

- Exploring TeV— PeV energy domain
- Less precise than magnetic spectrometers due to hadronic uncertainties

Fermi-LAT: γ-ray mission, $\sim 9X_0$ calorimeter

$\sim 21X_0$

$\sim 30X_0$

$\sim 33X_0$

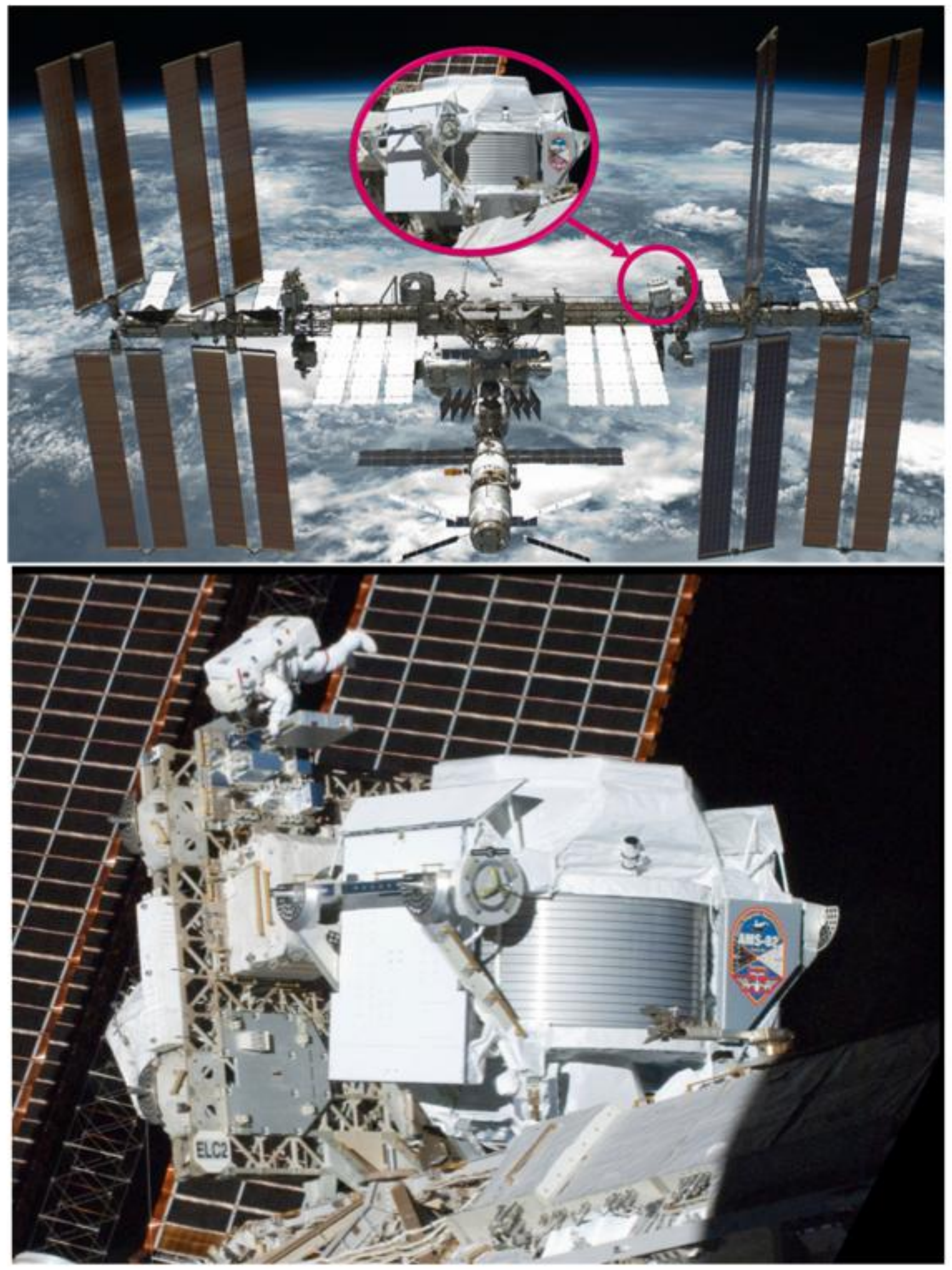
$\sim 55X_0$

2005 2010 2015 2020 2025

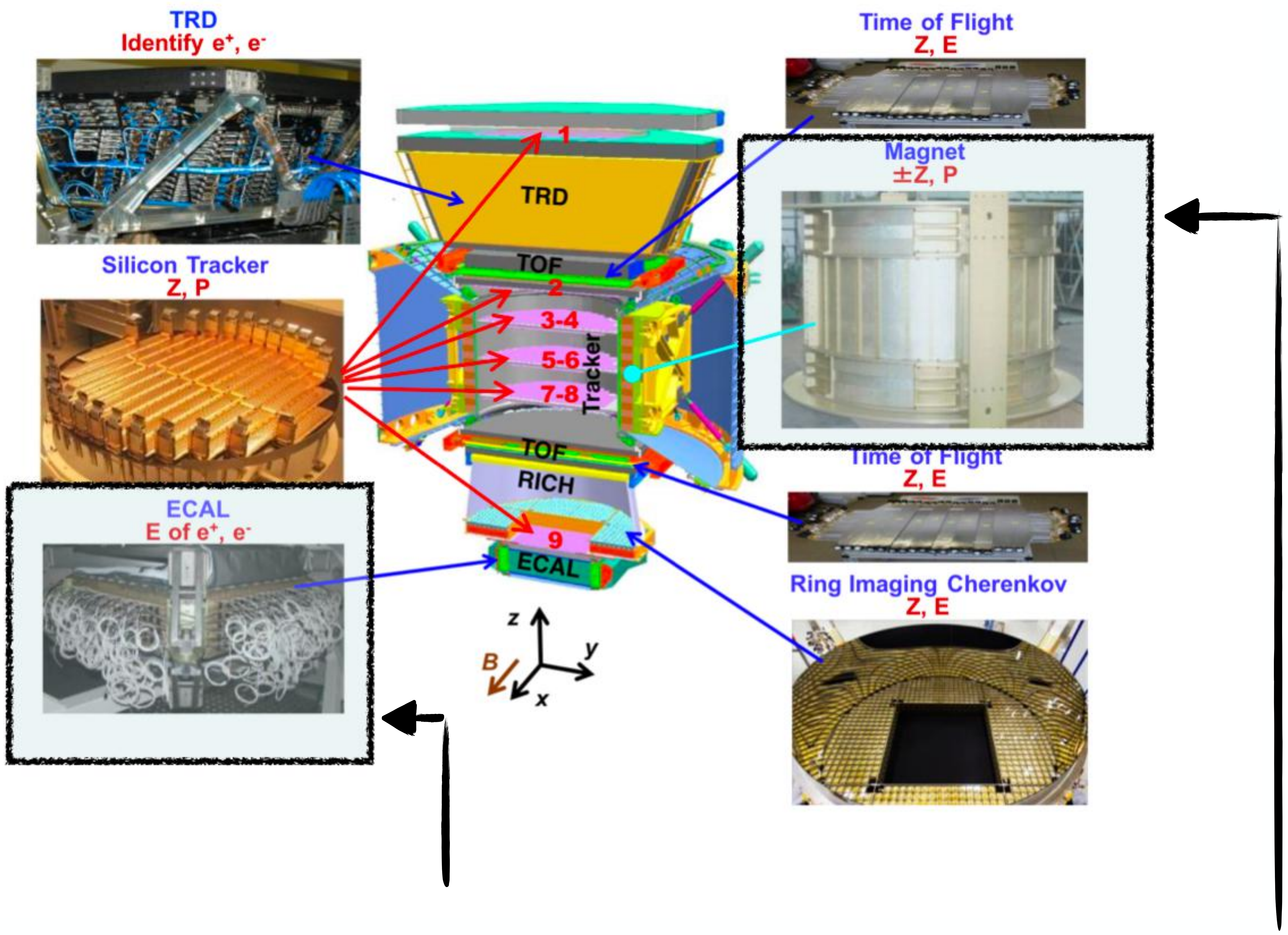
DISCLAIMER: impossible to cover all activities/experiments.
Biased (and subjective) view presented, focusing mostly on **high-energy frontier.**

Alpha Magnetic Spectrometer (AMS-02)

Largest & most complex particle detector in space



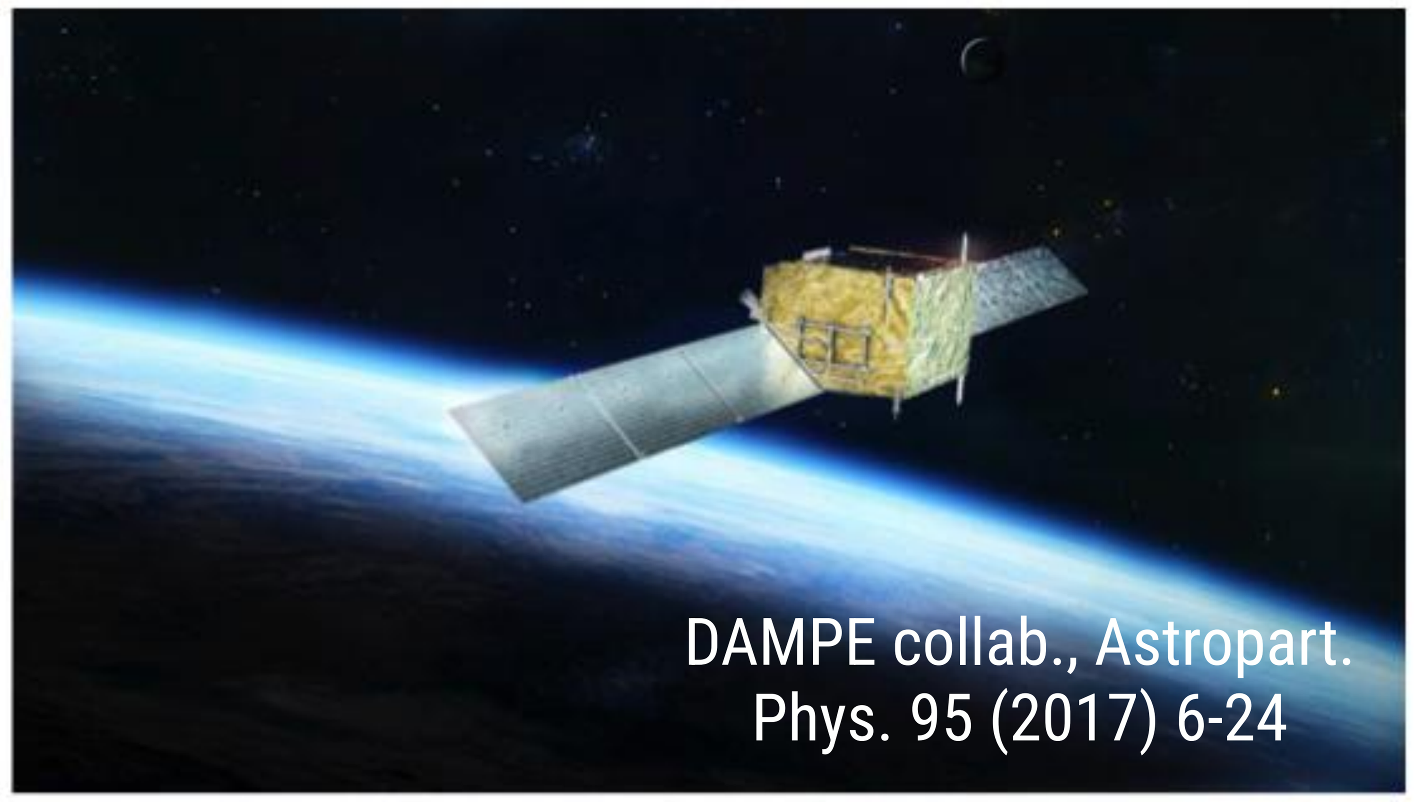
Phys. Rev. Lett. 110, 141102 (2013)

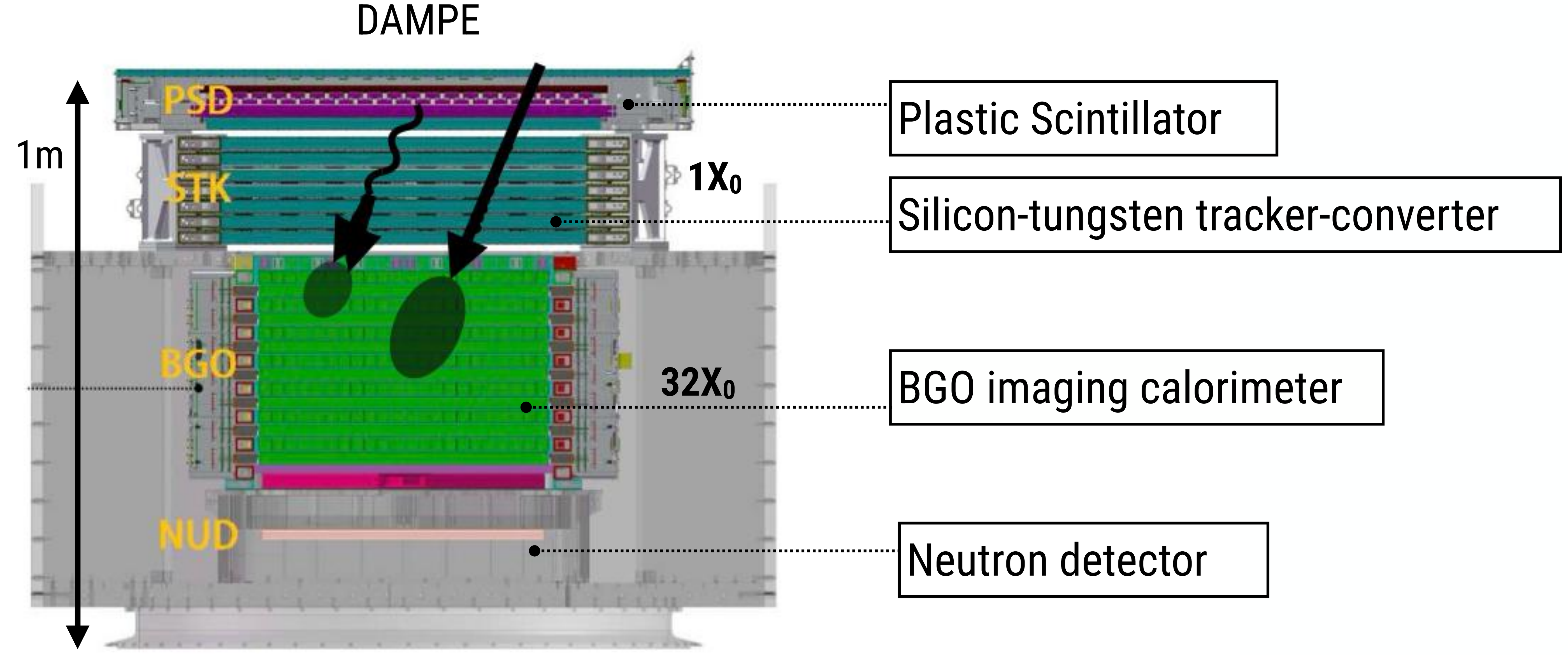


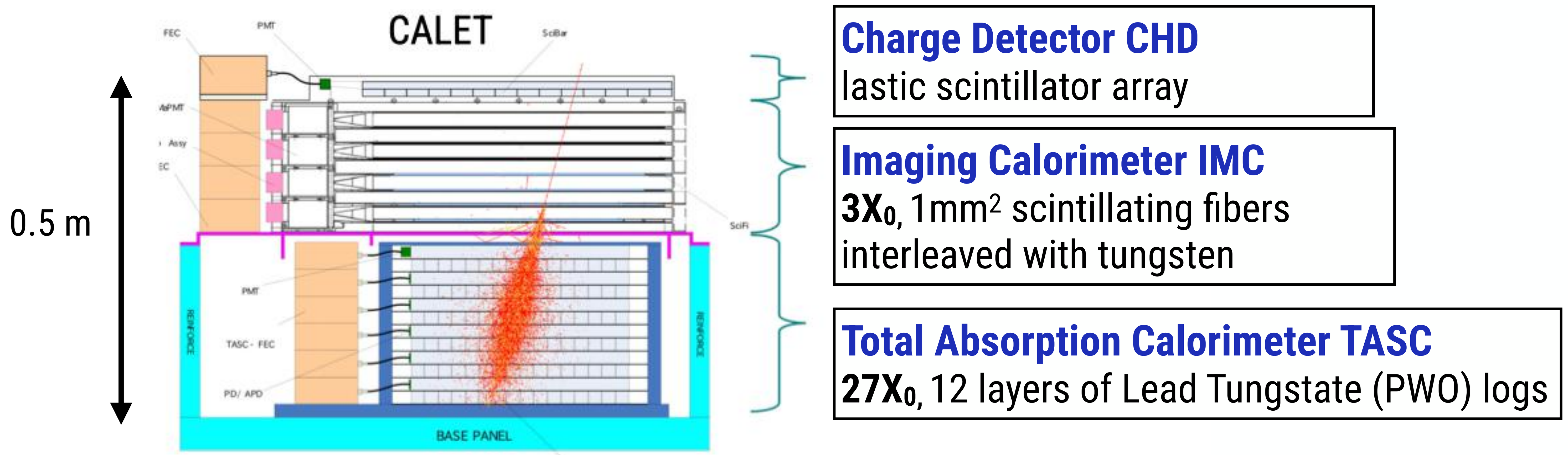
Sampling Calorimeter ~17X_0
(electrons & positrons)

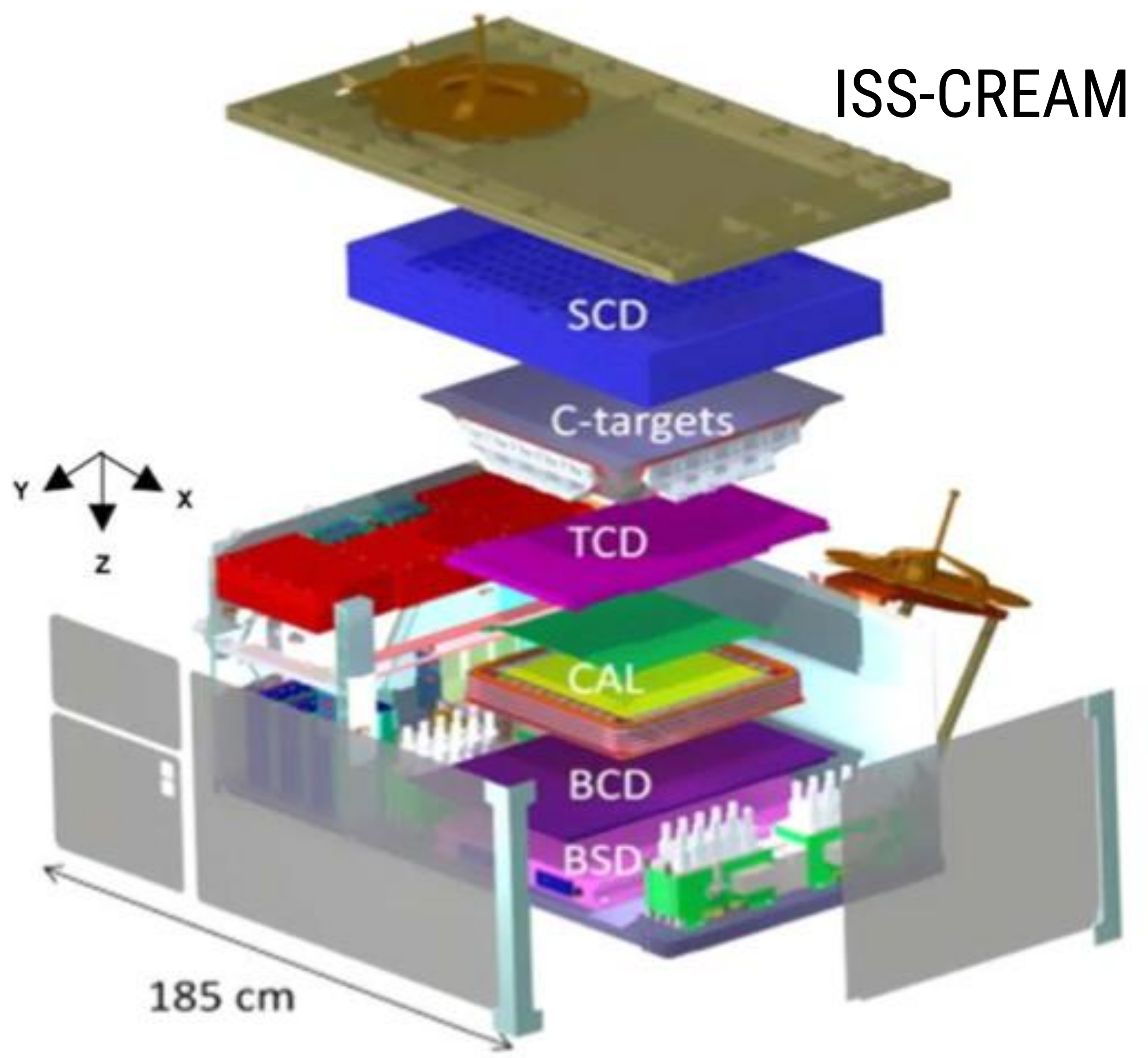
Magnetic spectromenter
(maximum detectable rigidity 2.3 TV)

Calorimeters: DAMPE, CALET, ISS-CREAM, NUCLEON









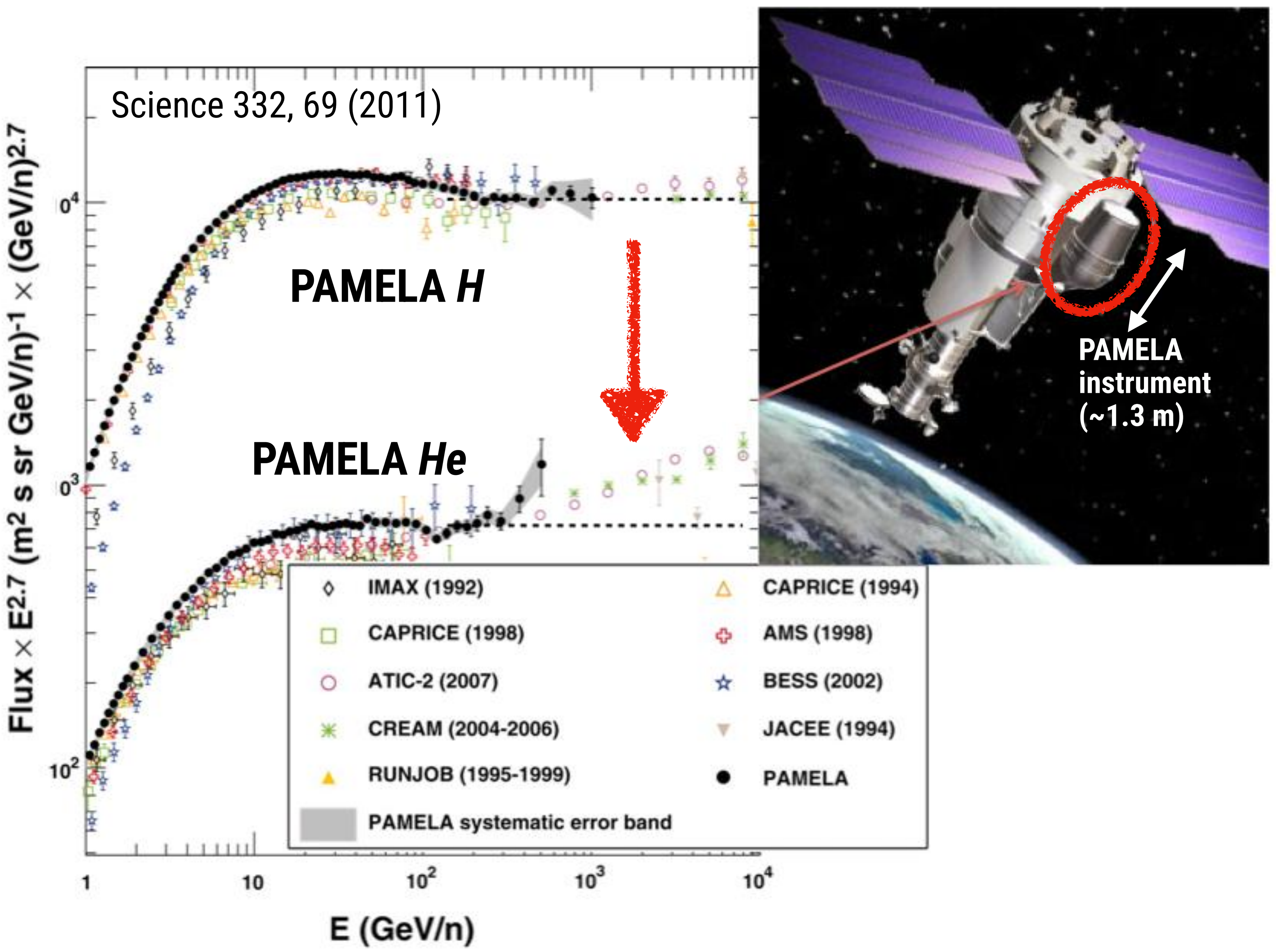
CALET & DAMPE — similar physics goals, both using total absorption calorimeters. ISS-CREAM uses sampling calorimeter, NUCLEON - small (25x25cm) sampling calorimeter (15 X_0)

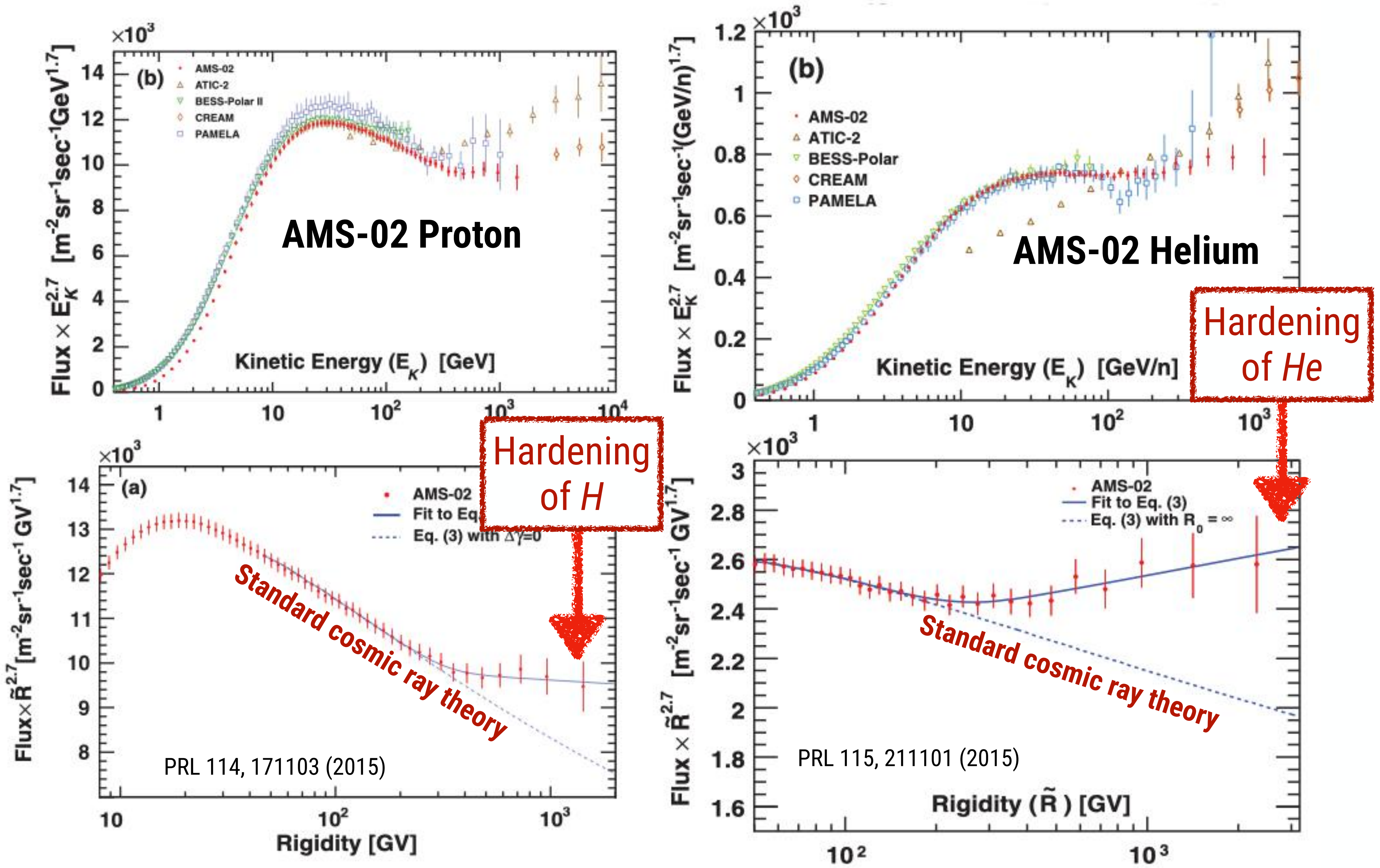
Era of precise measurements: surprises *H* and *He*

Canonical hypothesis of cosmic ray origin: Fermi 2nd order shock acceleration in Supernovae with diffusive propagation in the Galaxy (~leaky box model) — single power-law spectrum up to the *knee* …

ATIC, CREAM (balloons)**, PAMELA**: first indication of a spectral structure in the most abundant CR, hydrogen and helium

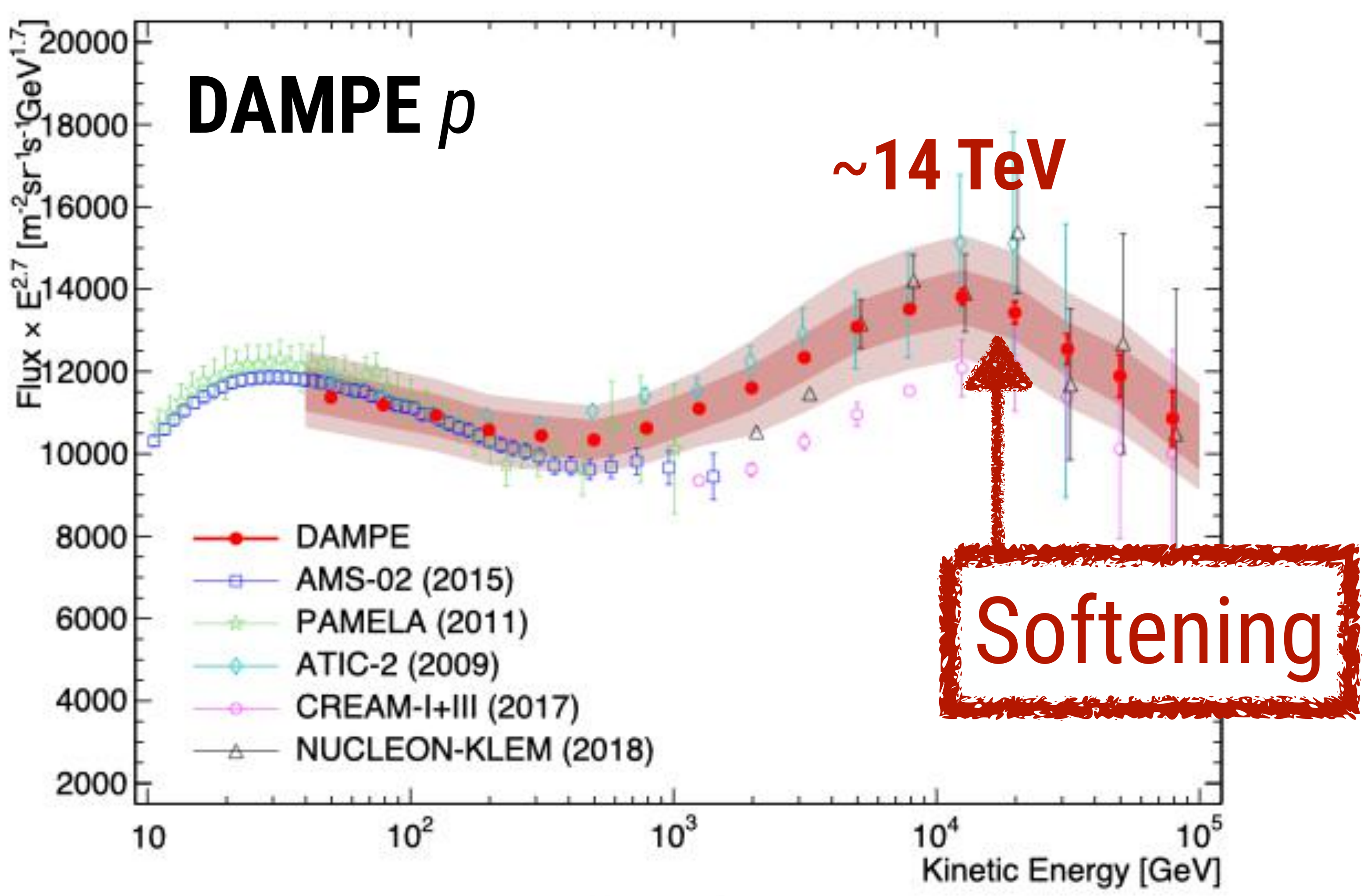
AMS-02: discovery of spectral *break (hardening)* in the spectra of both species:



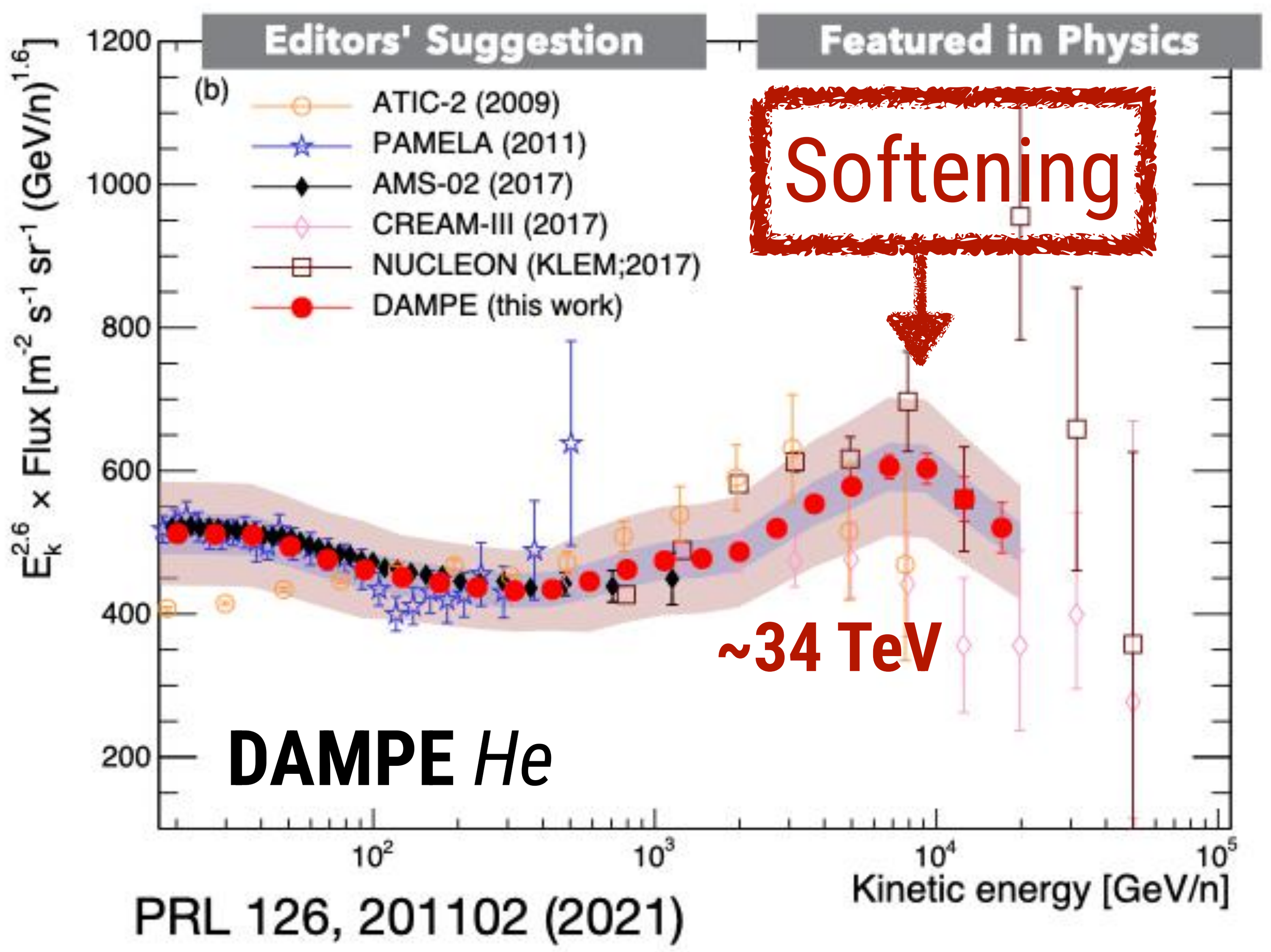


H and *He*: going beyond TeV with big calorimeters

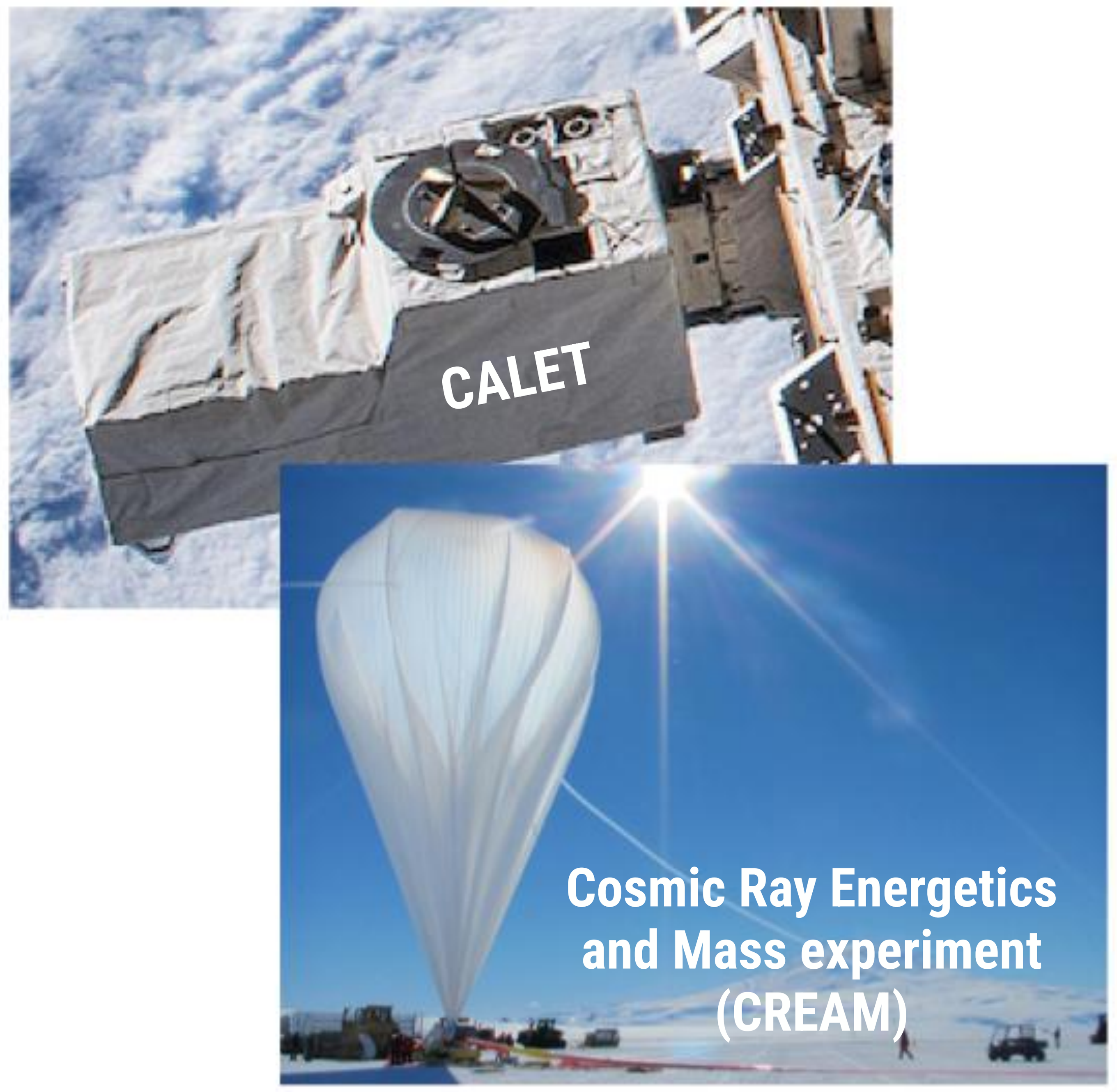
- Spectral *hardening* at ~few hundred GeV/n confirmed by calorimetric experiments (DAMPE, CALET, CREAM)
- Observation of yet another new structure – *softening* at ~10 TeV/n! Are these structures *A* or *Z* dependent?

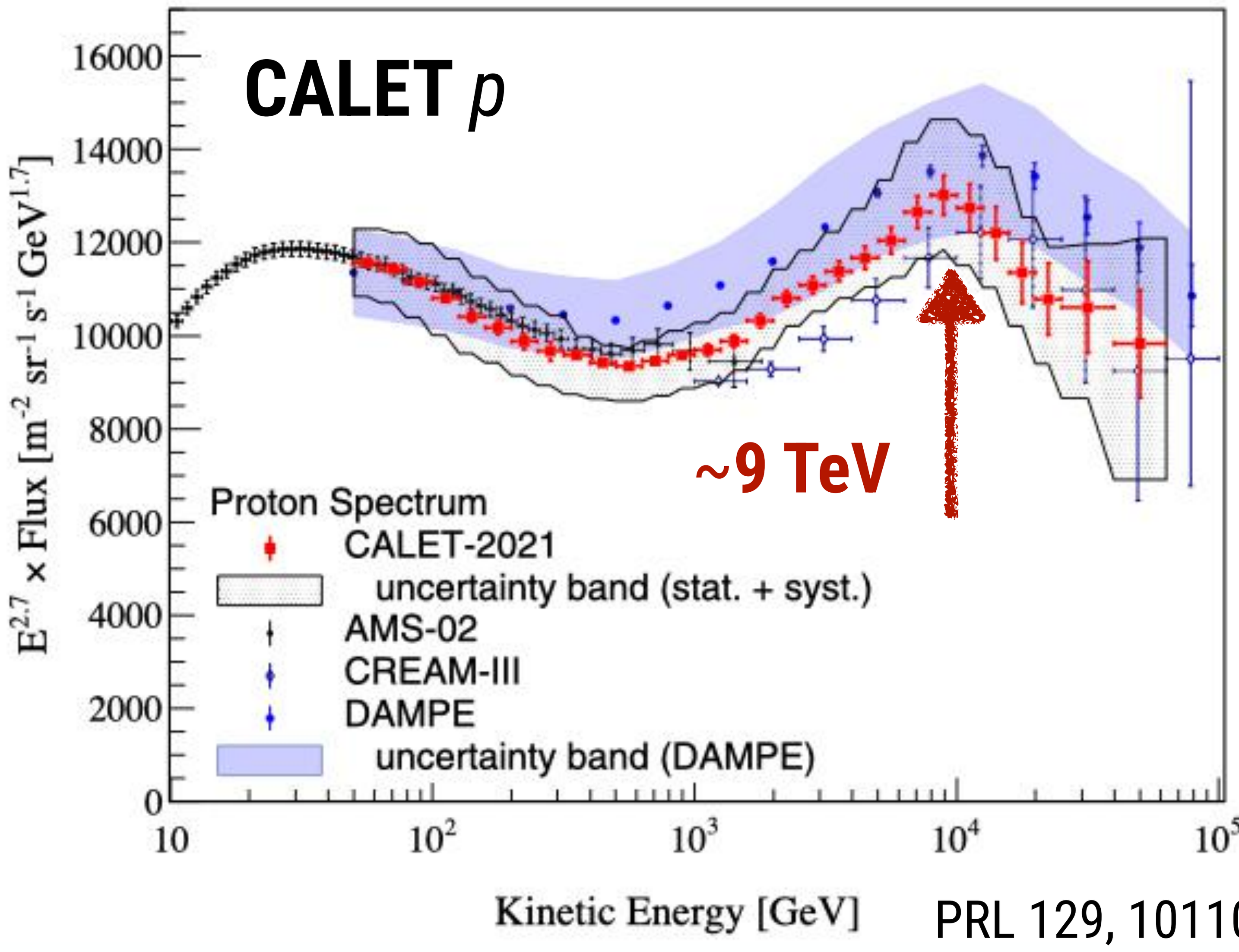


Science Adv aax3793 (2019)

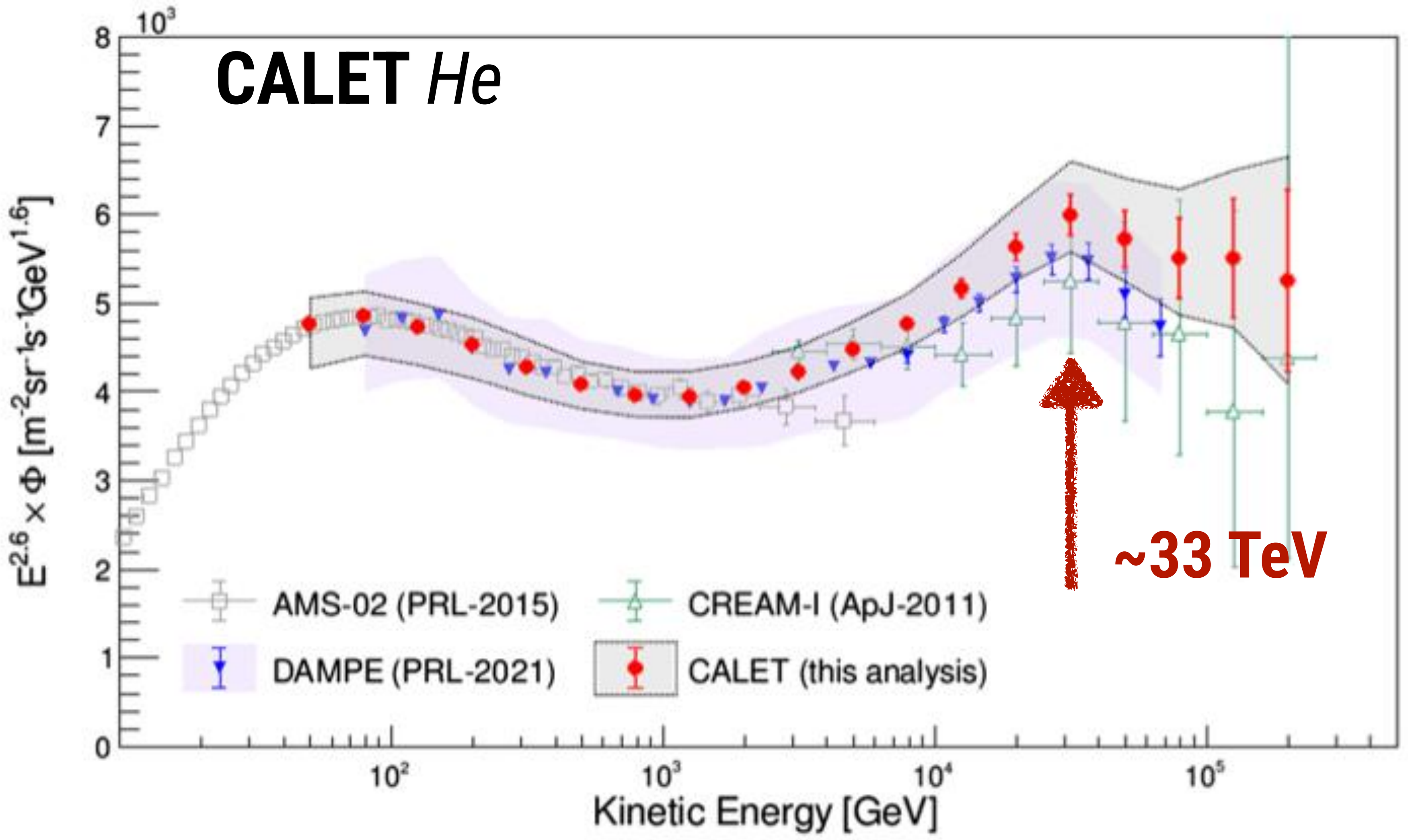


PRL 126, 201102 (2021)





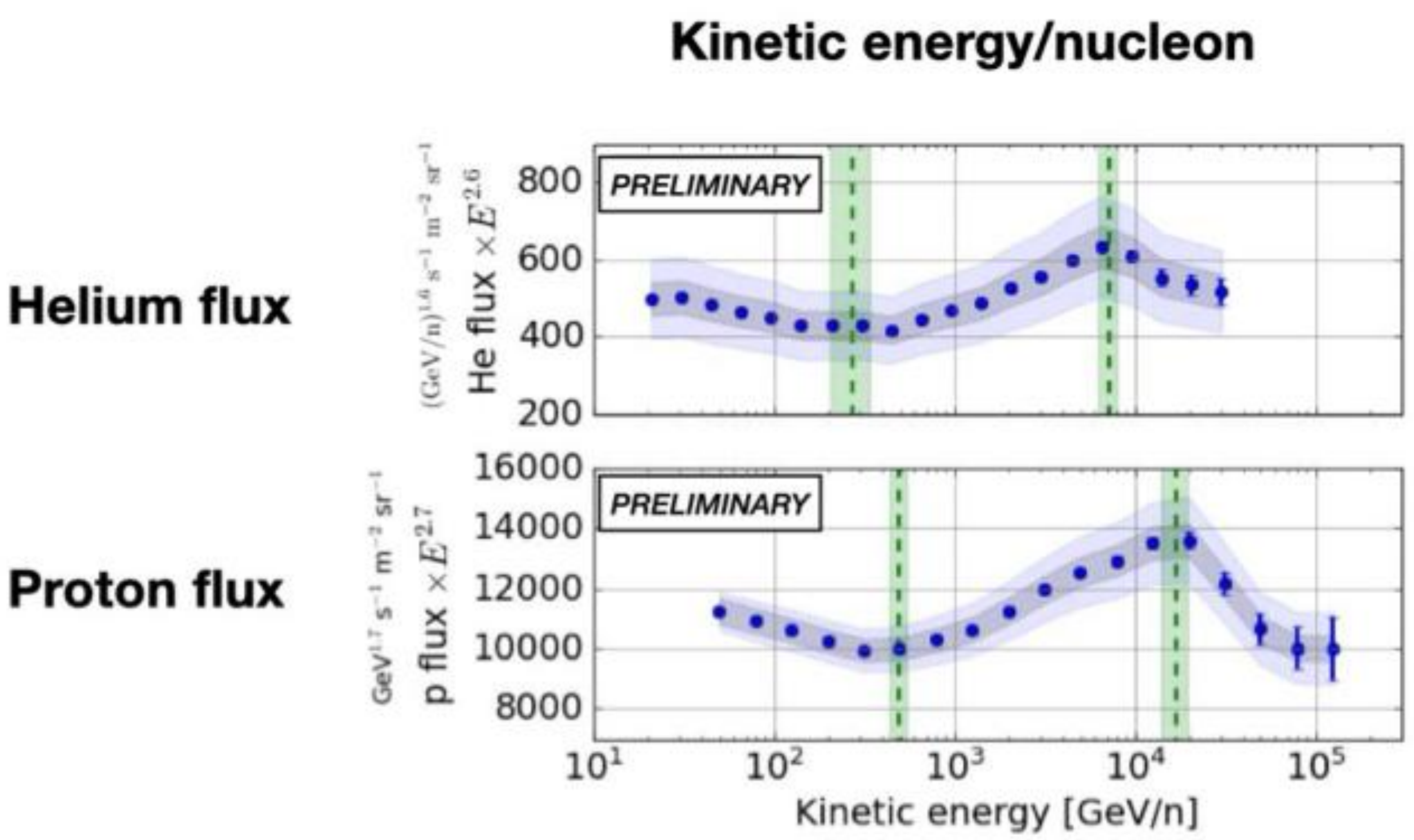
PRL 129, 101102 (2022)



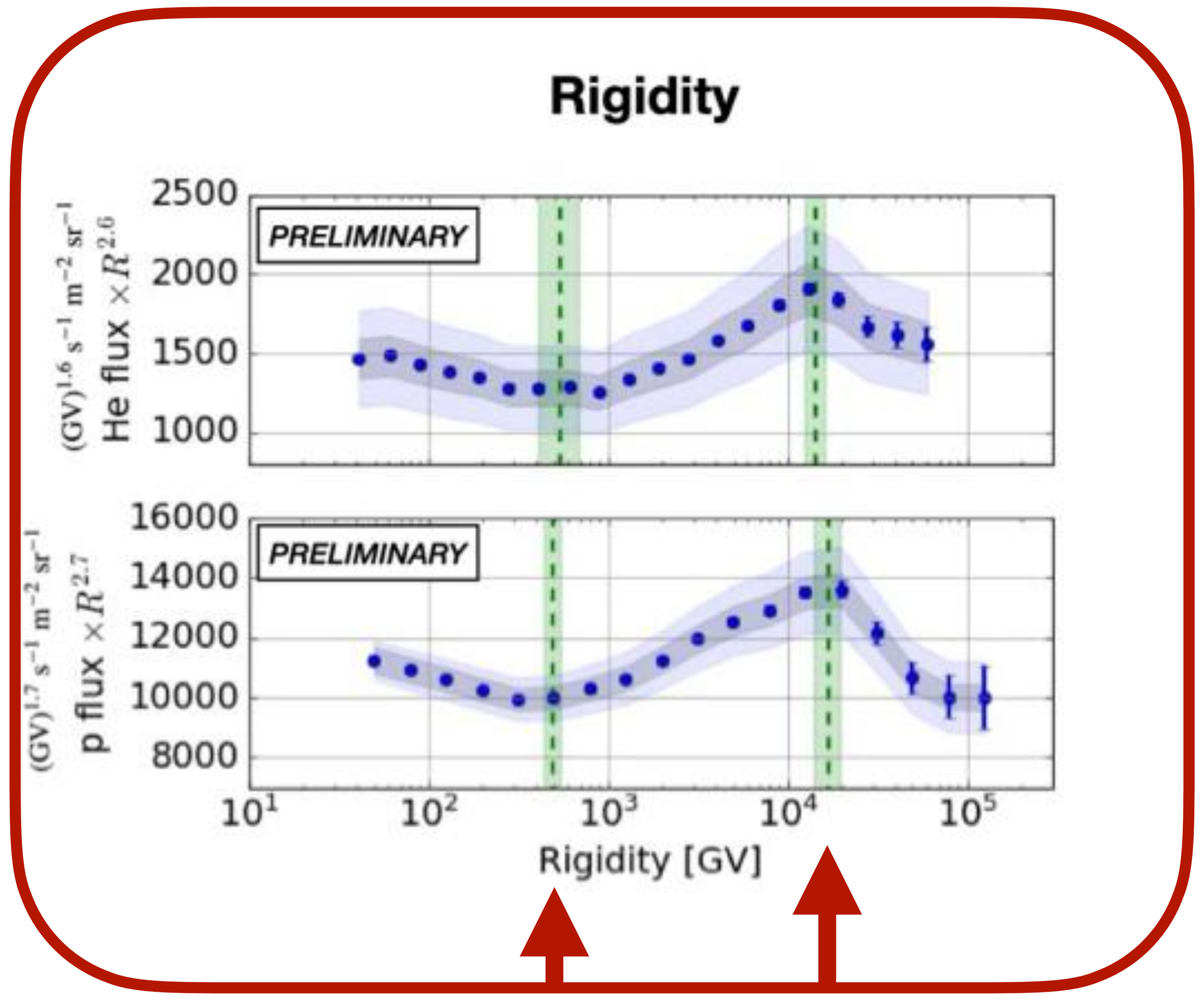
PRL 130, 171002 (2023)

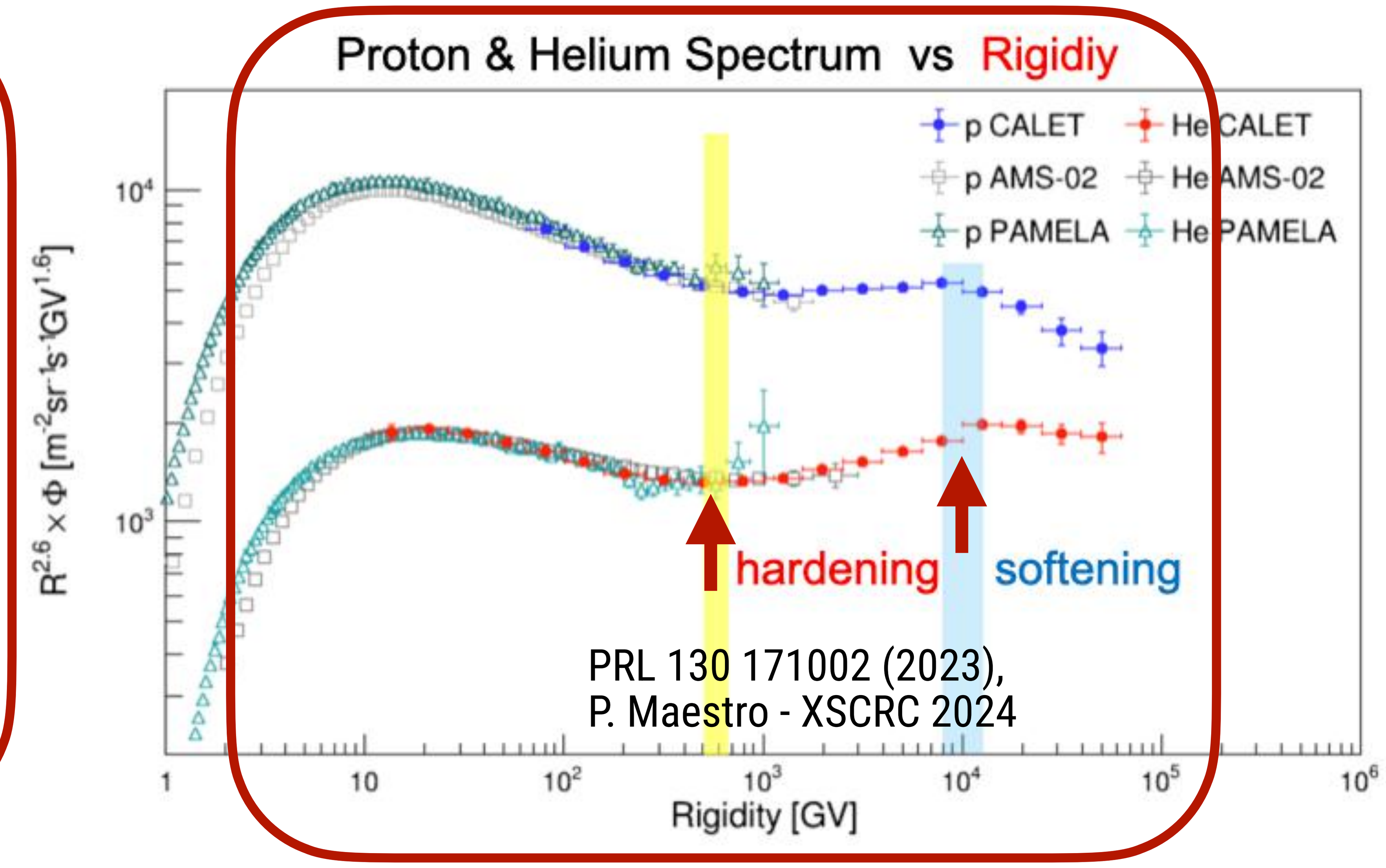
H and *He*: updated spectra, going towards PeV

DAMPE and CALET indicate that both hardening and softening are more compatible with rigidity/charge dependence rather than mass (A) dependence. *H* spectrum is consistently softer than *He* by Δγ~0.1 in the entire energy range

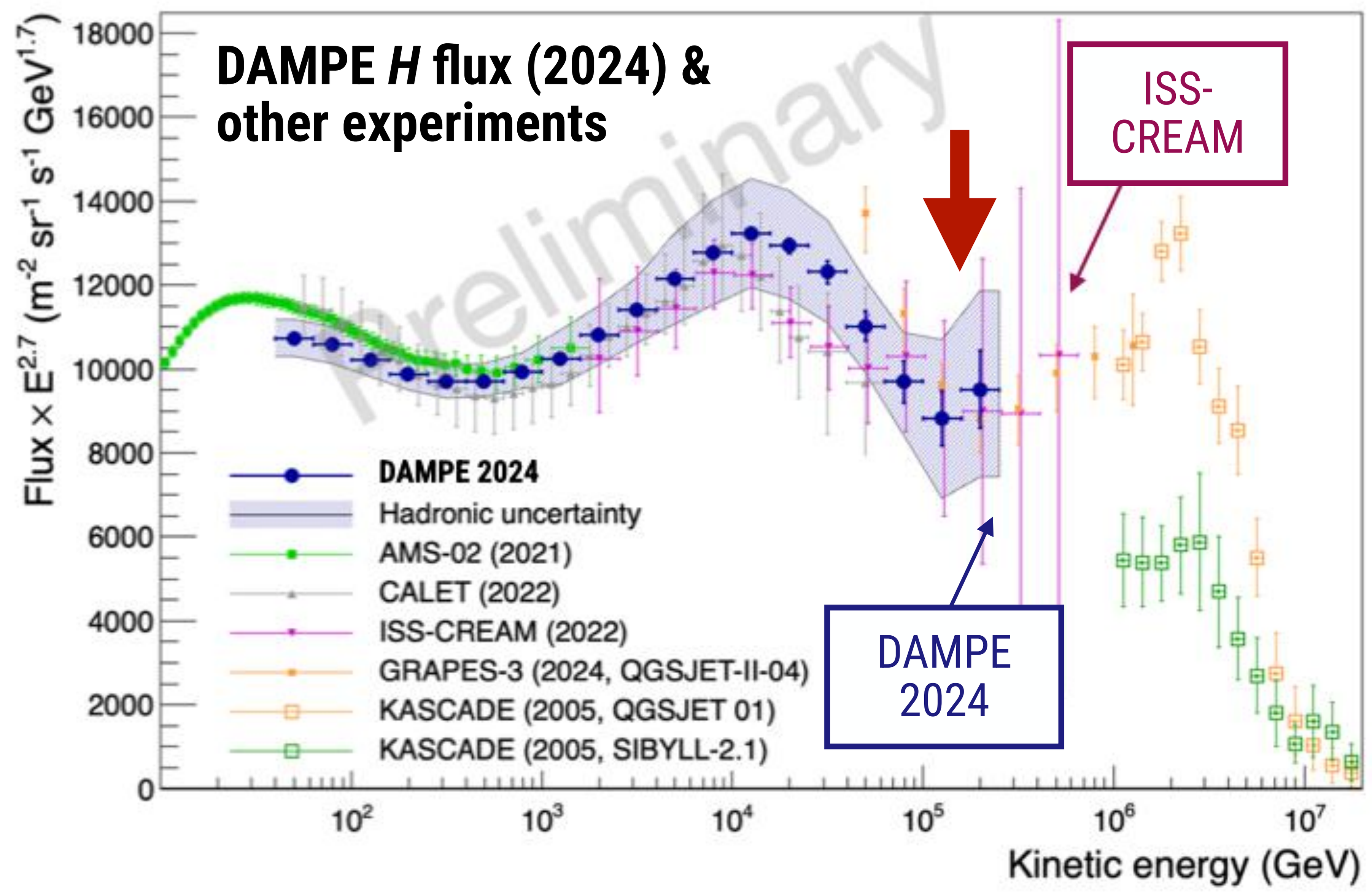


A. Ruina et al. pos.sissa.it/444/170/ (2023)

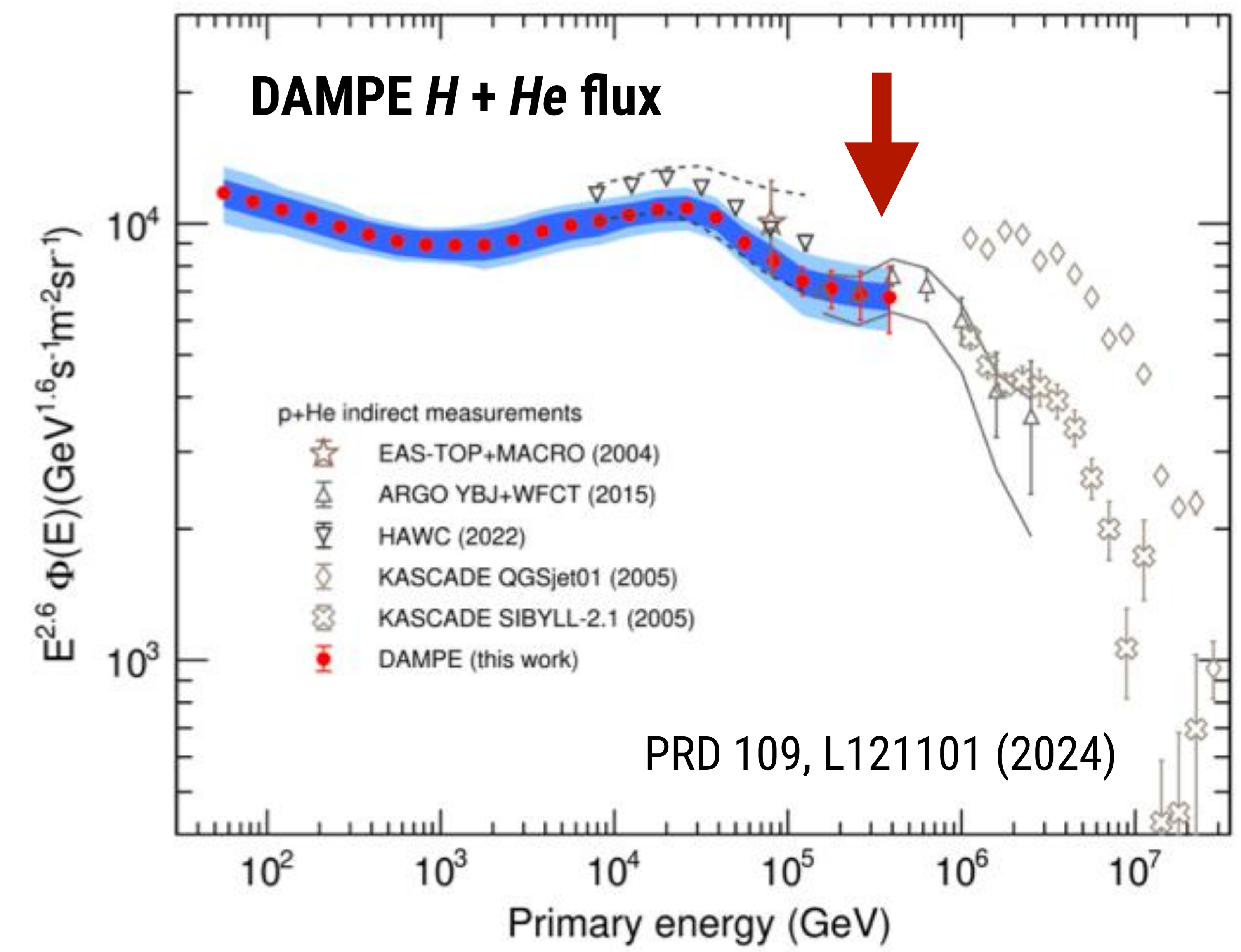




New results of DAMPE (2024) and ISS-CREAM (2022) indicate of **new hardening** in *H (and He)* at ~150 TeV:

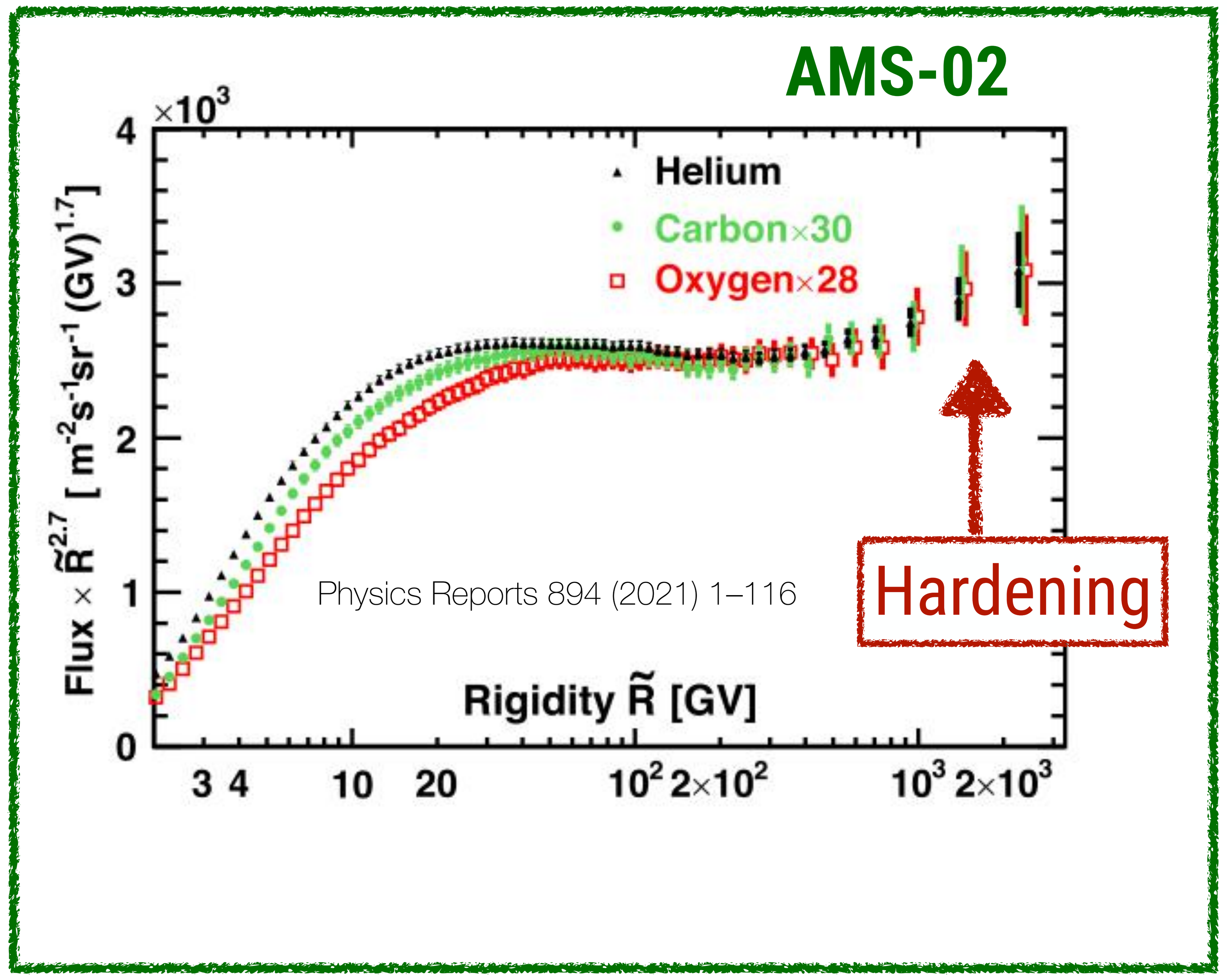


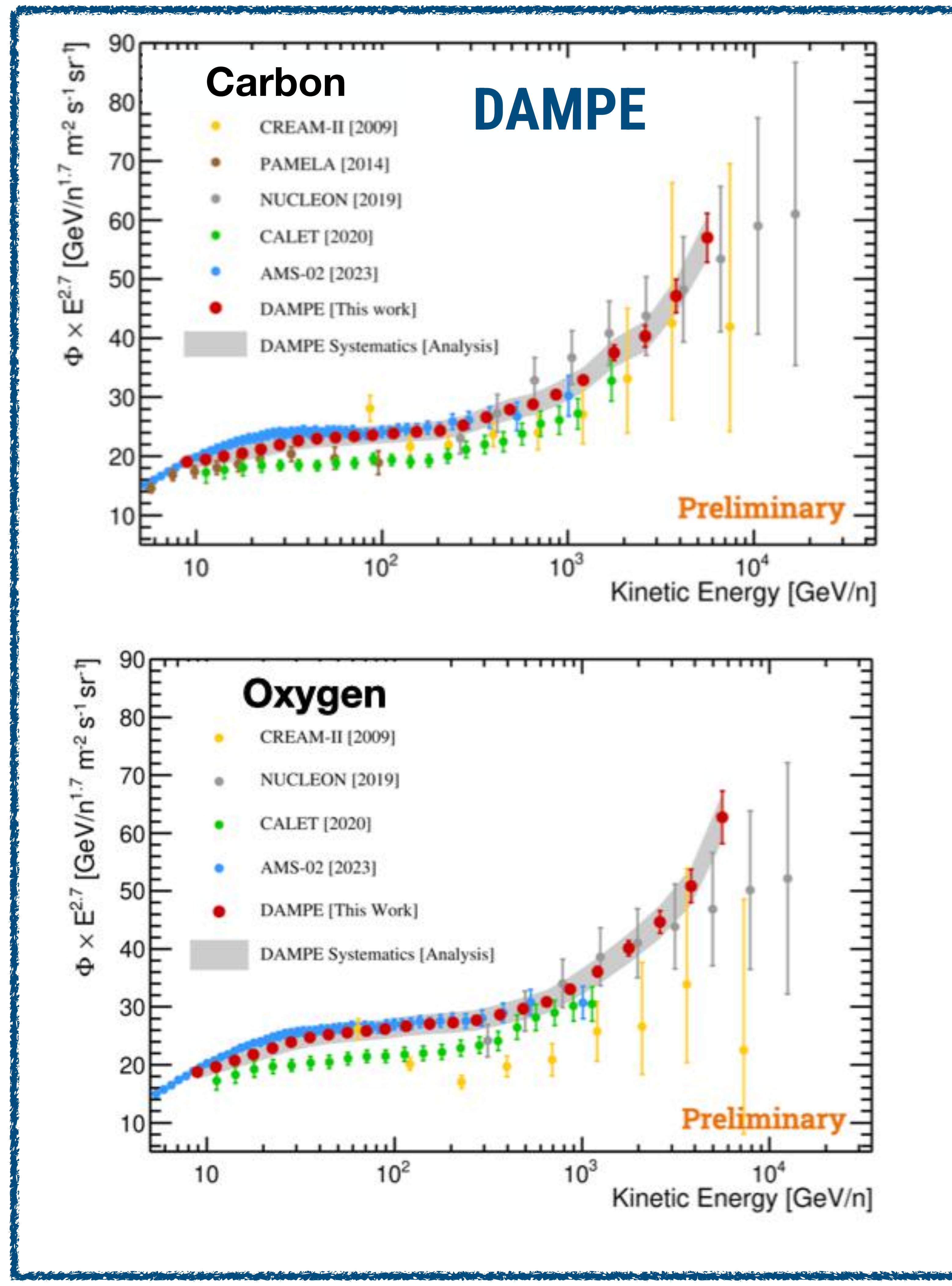
ISS-CREAM: Astrophysical Journal, 940:107 (2022)

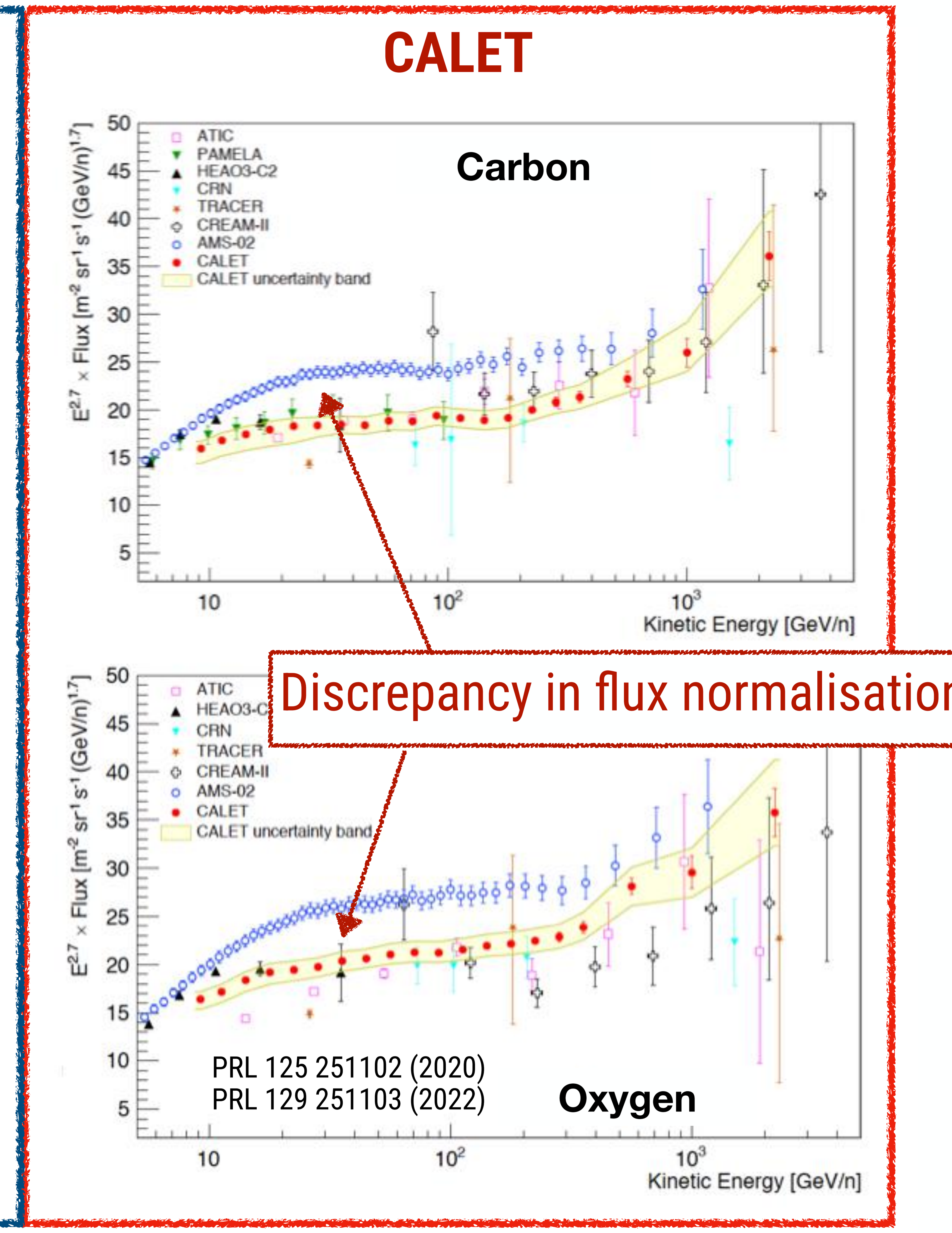


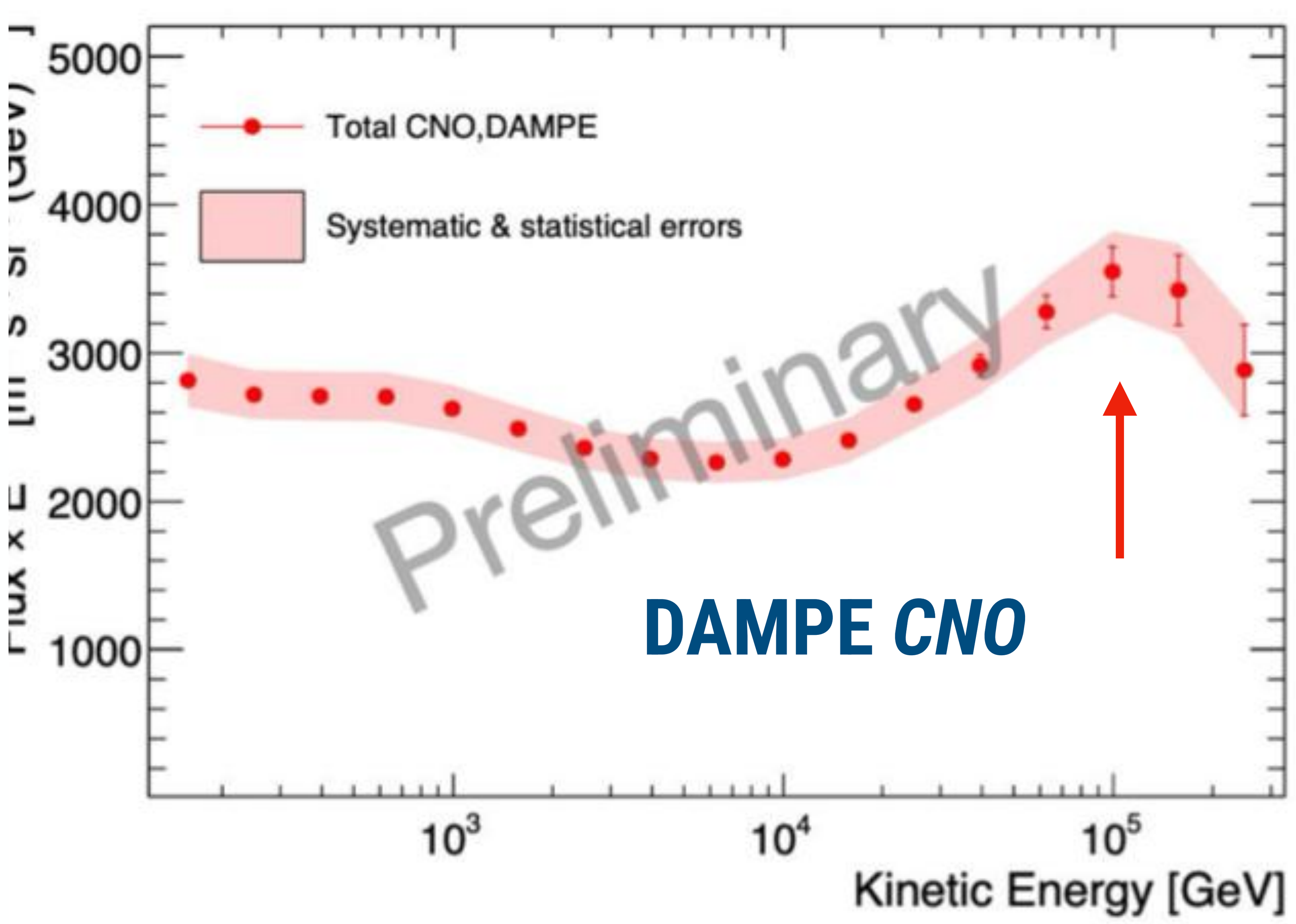
Intermediate-mass CR primaries: *Carbon, Oxygen*

Hardening at few hundred GeV/n also confirmed in Carbon and Oxygen (AMS-02, CALET, DAMPE)





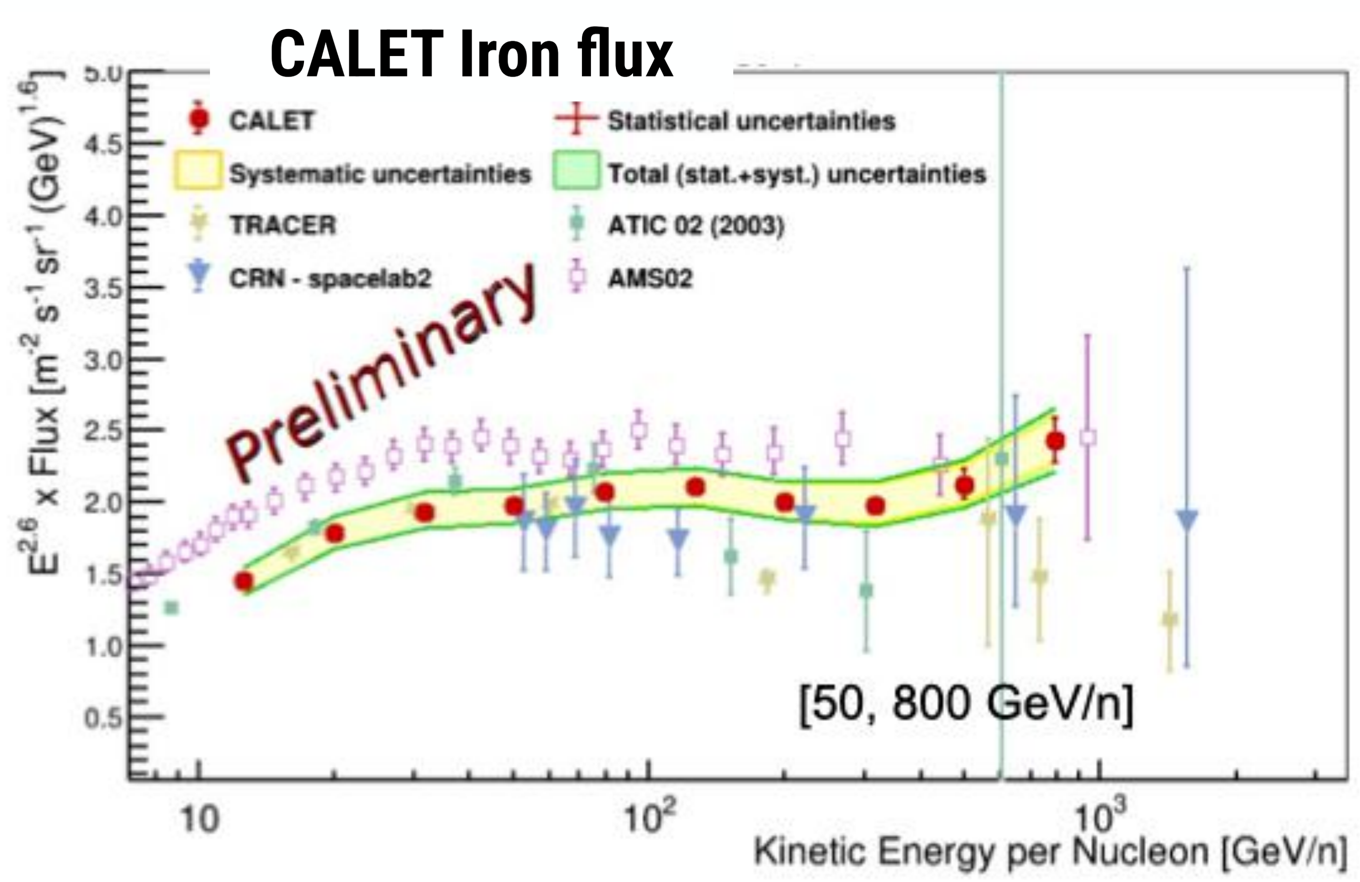


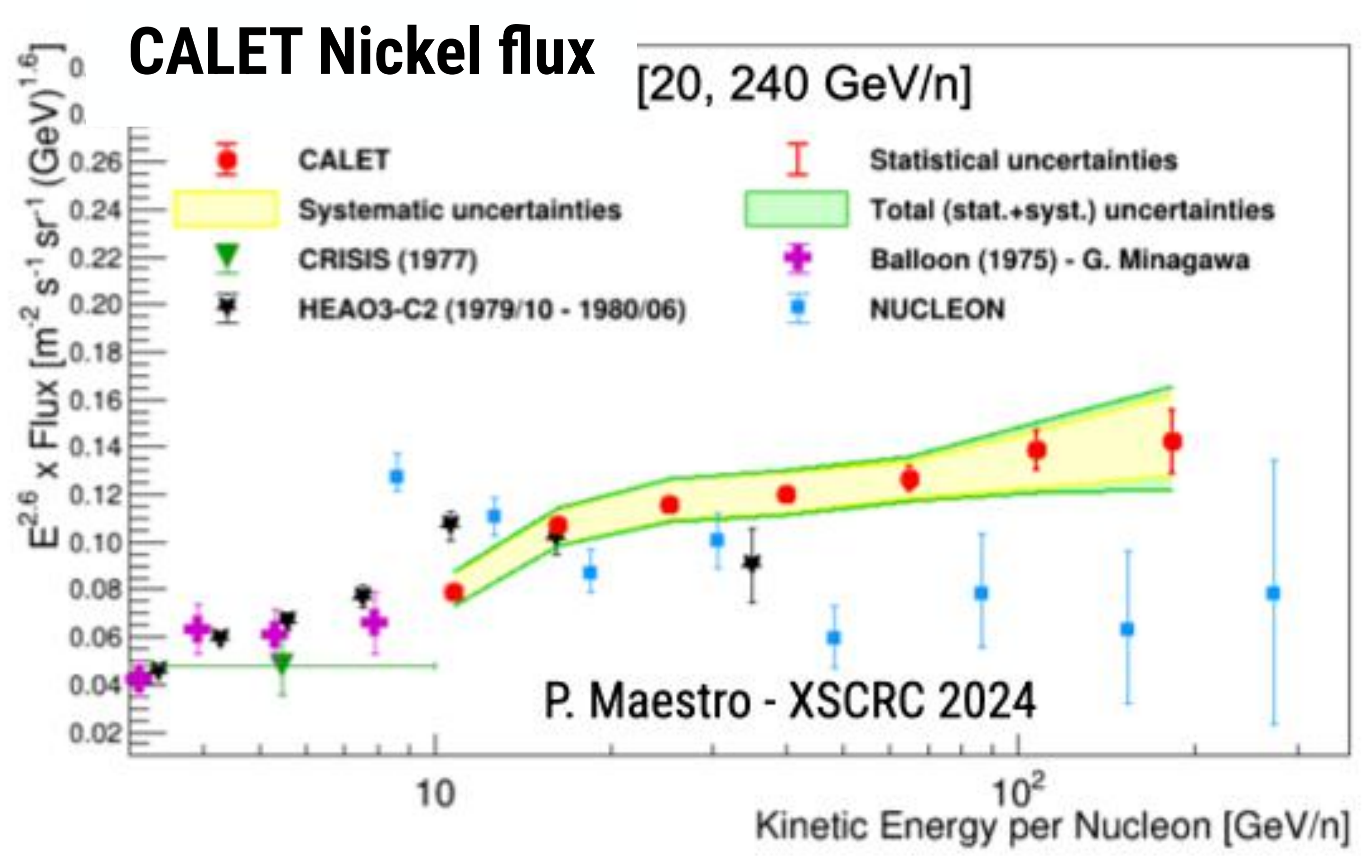


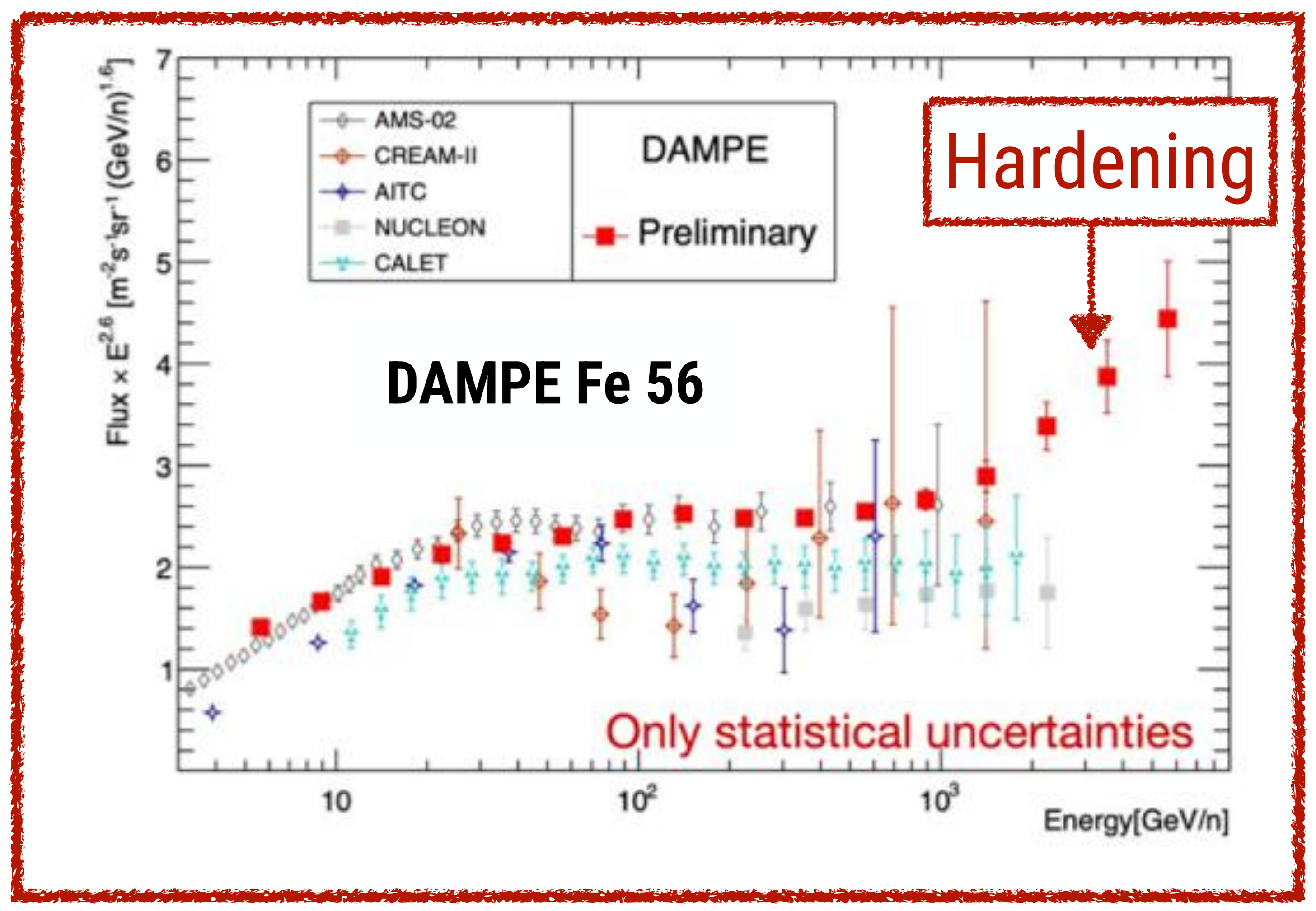
– preliminary DAMPE CNO spectrum also confirm ~10 TeV/n softening similar to the one of H and He!

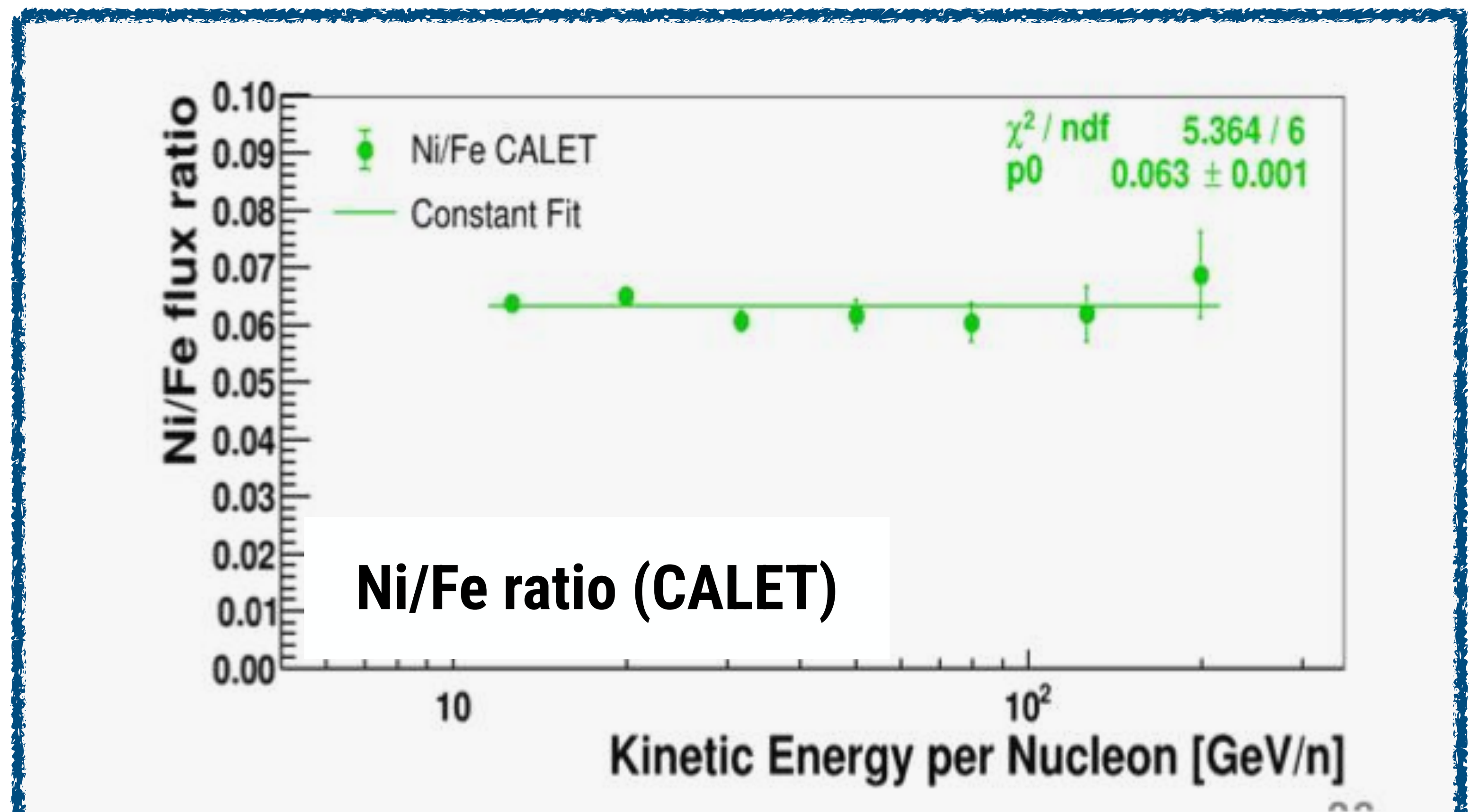
Heavy primaries (*Ne-Mg-SI, Fe-Ni*)

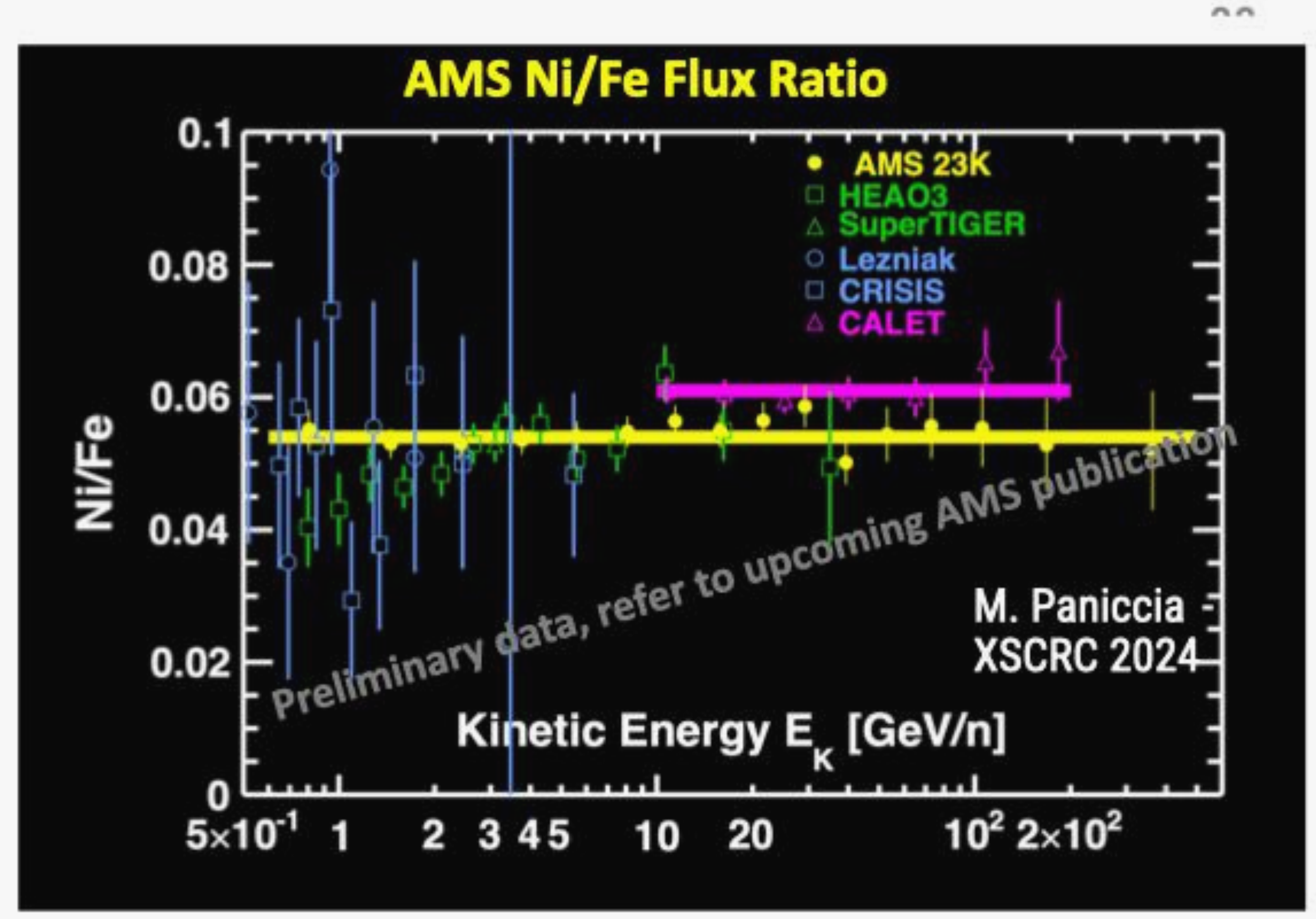
- Heavy primaries: Iron, Nickel — AMS-02 & CALET reaching hundreds GeV/n, DAMPE going to higher energies in Iron — indication of hardening!





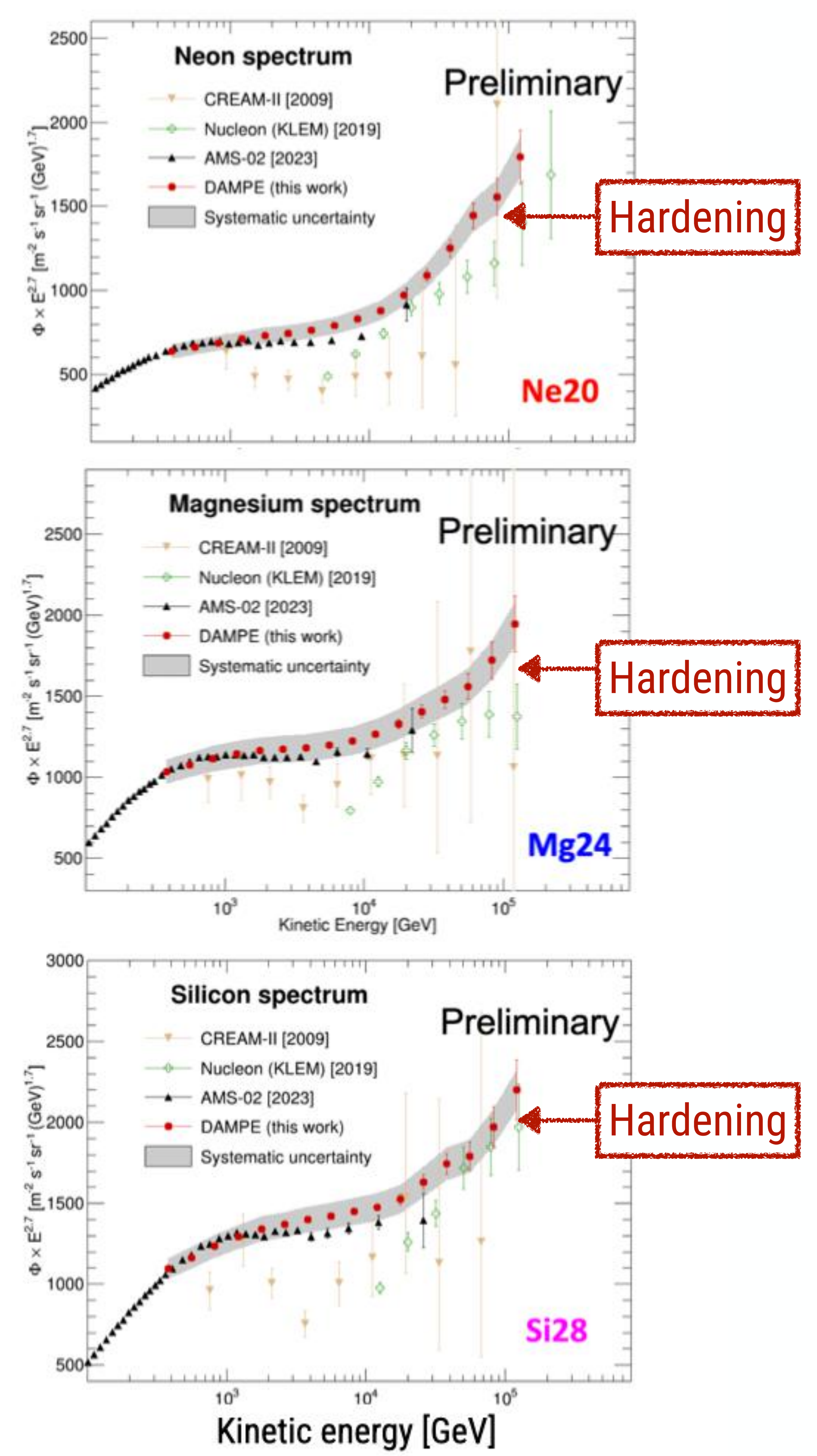






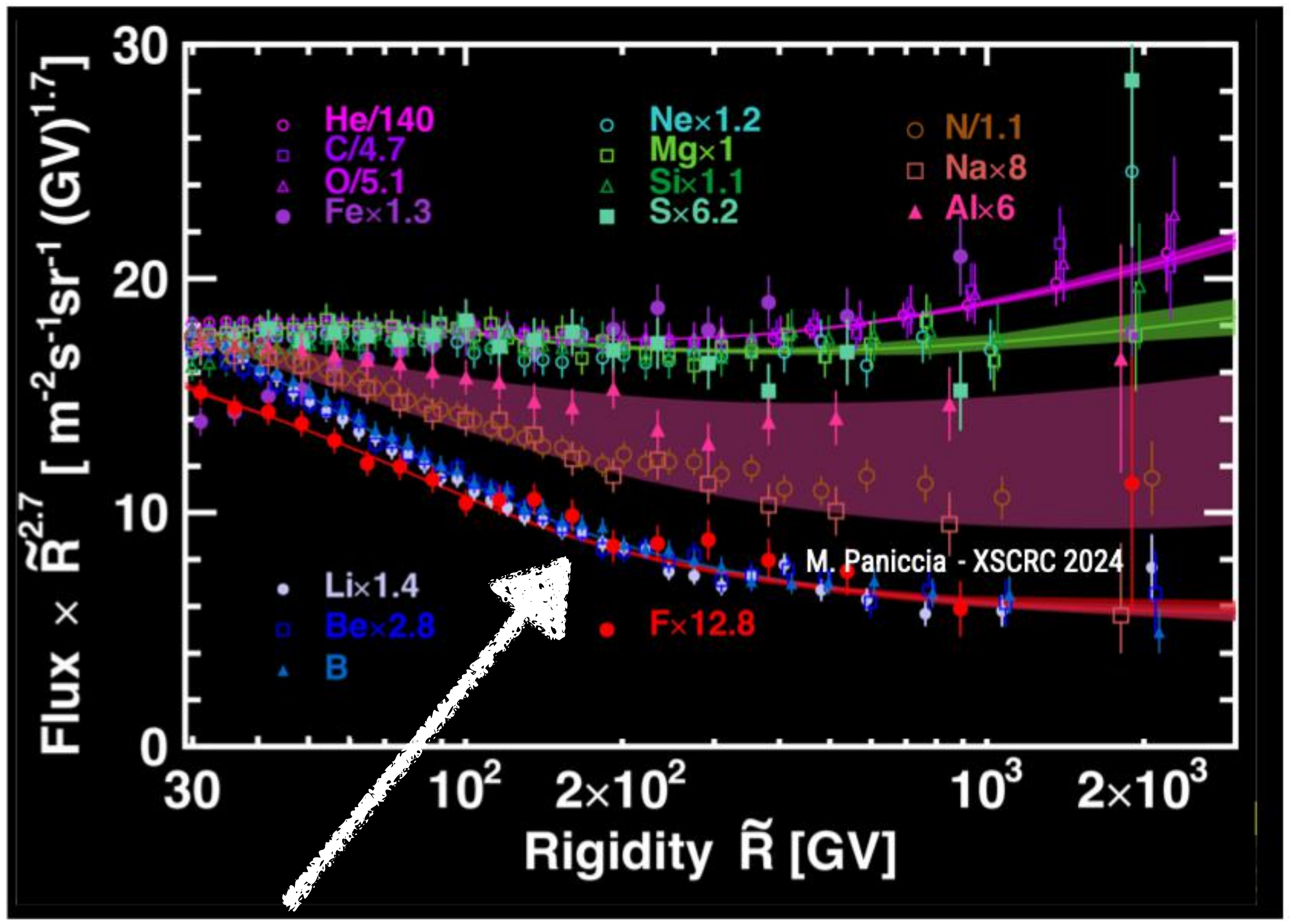
Ratio of heavy elements: Ni/Fe — nearly constant until at least few hundred GeV/n

- Preliminary DAMPE results show hardening also in *Ne-Mg-Si* group:



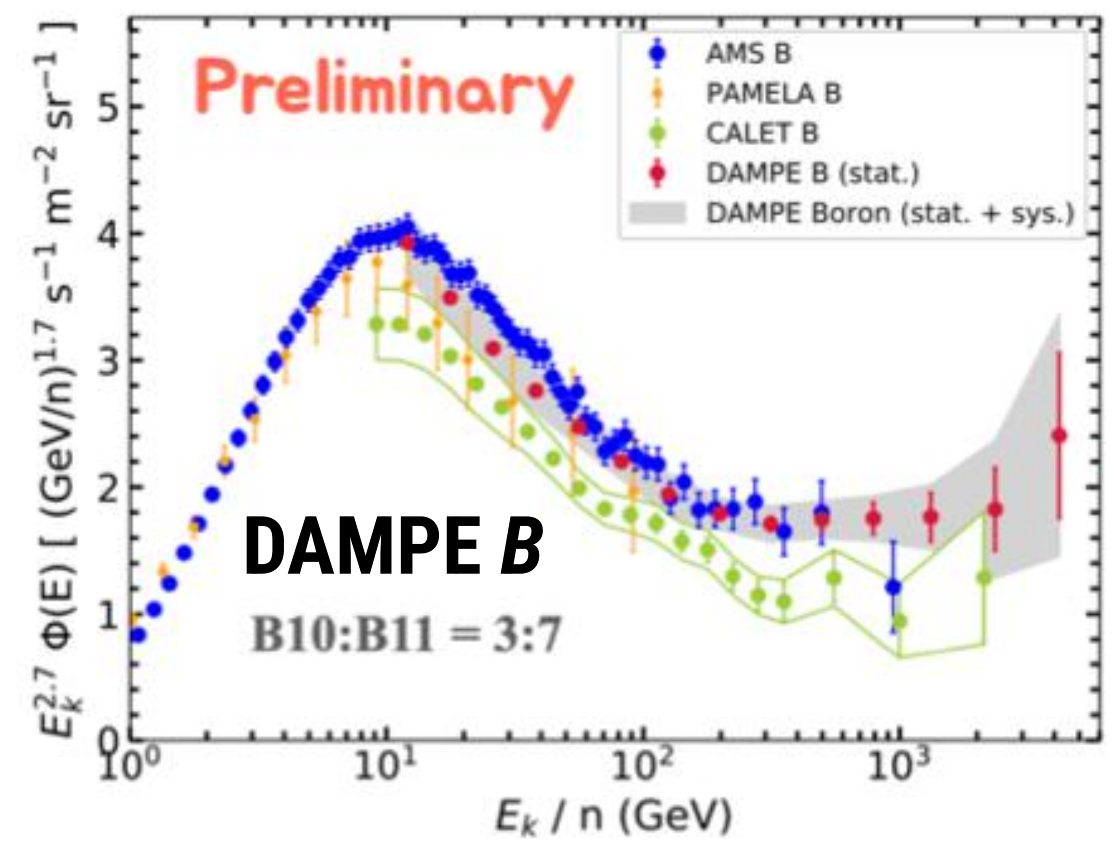
CR secondaries: *Li, Be, B, F*

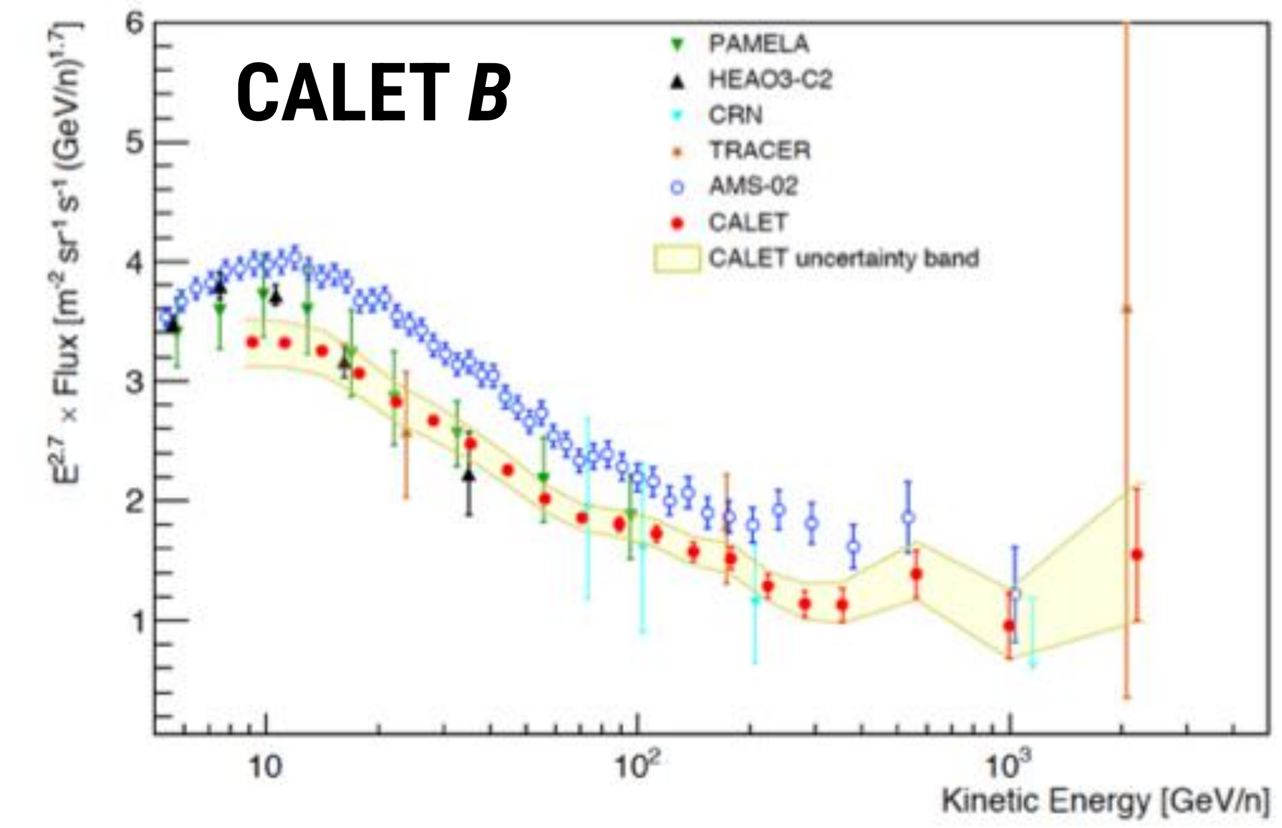
Hardening at ~200 GV observed in secondaries by AMS-02:

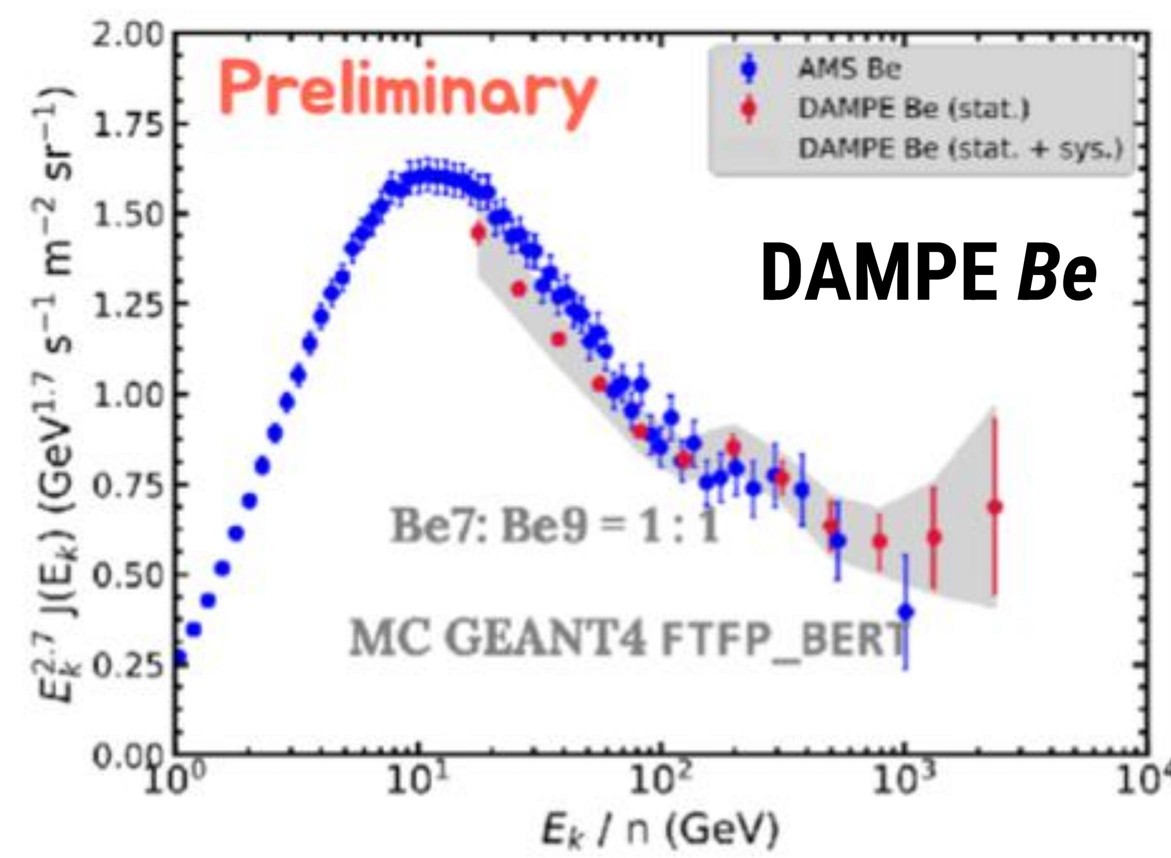


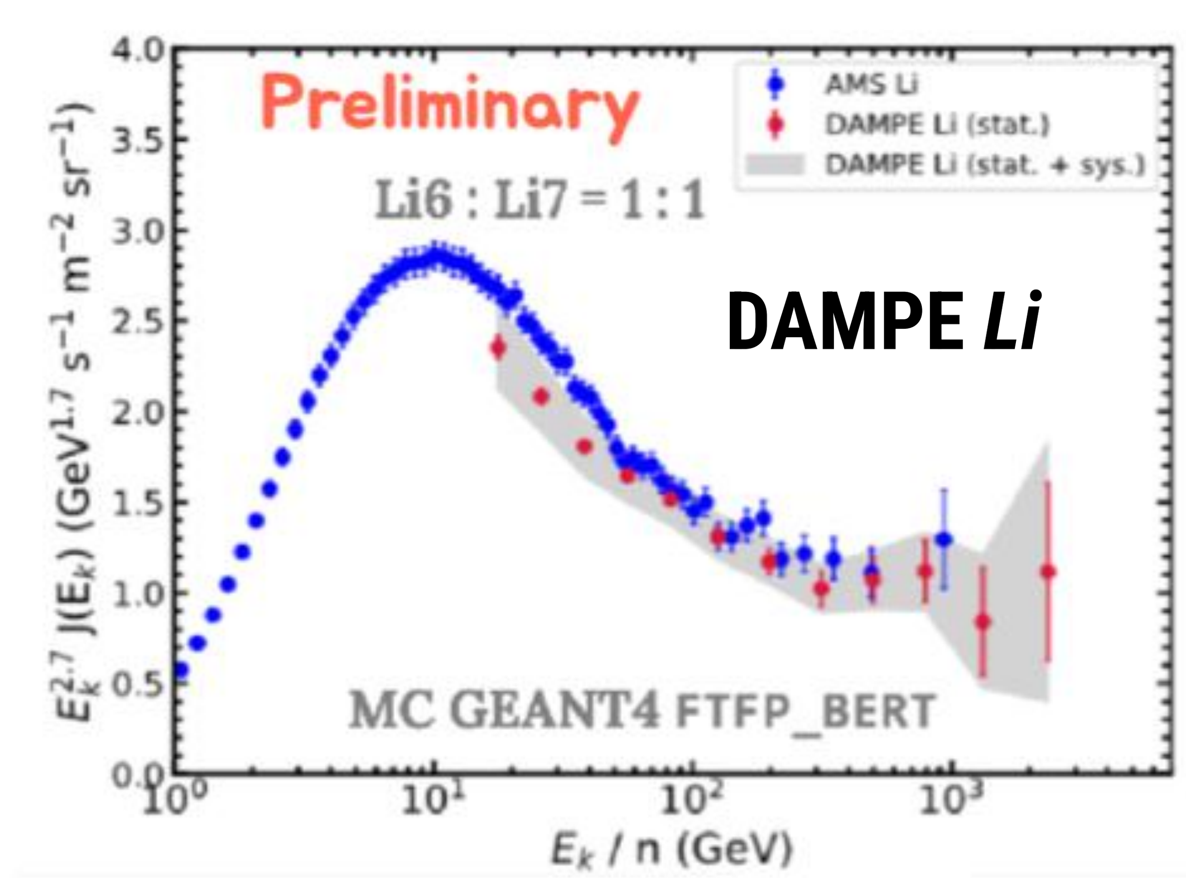
- Two primary classes: *He, C, O, Fe* and *Ne, Mg, Si, S*
- Two classes of secondaries: *Li, Be, B* and *F*

Calorimetric experiments confirm hardening of secondaries (energy reach ~8 TV in case of DAMPE







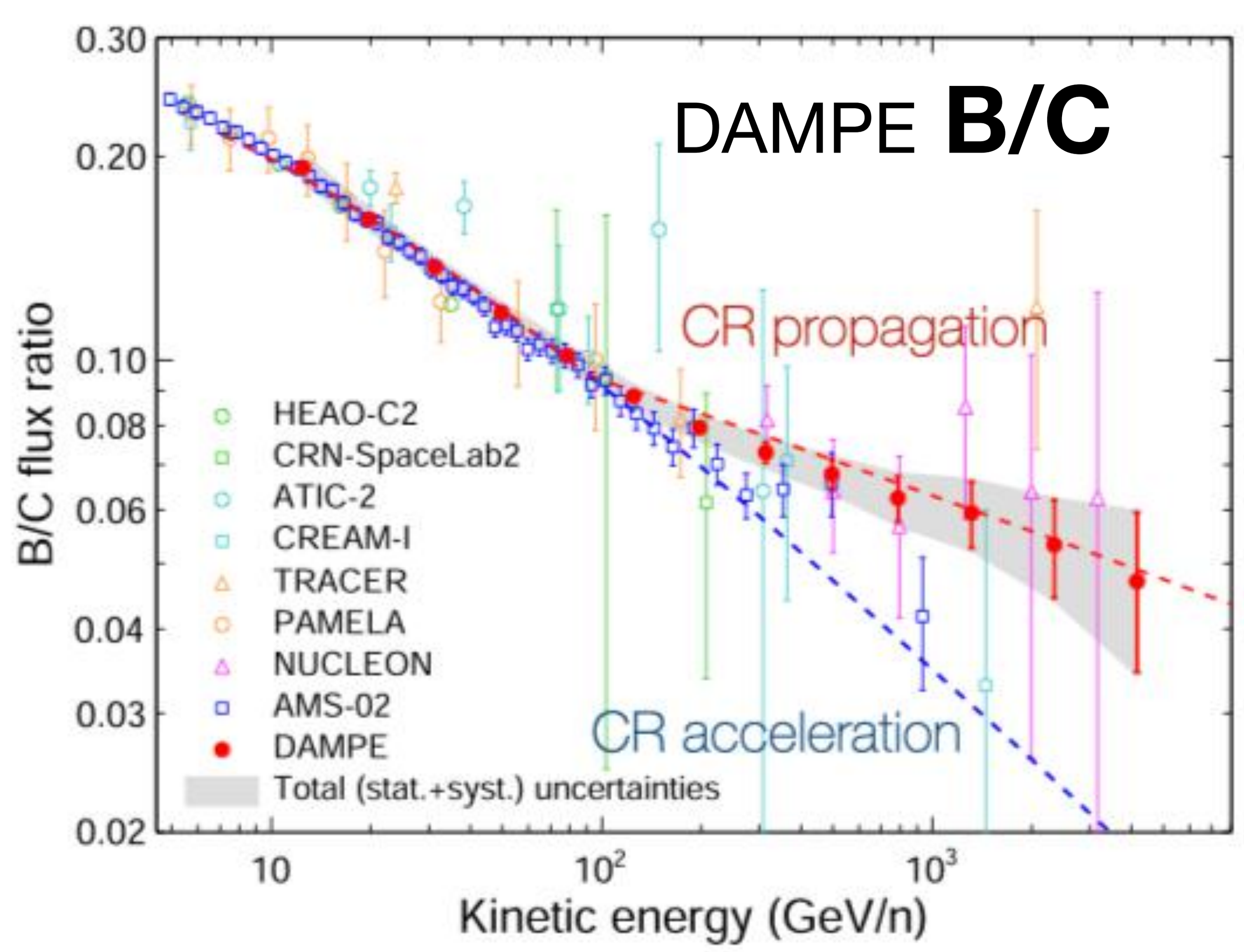


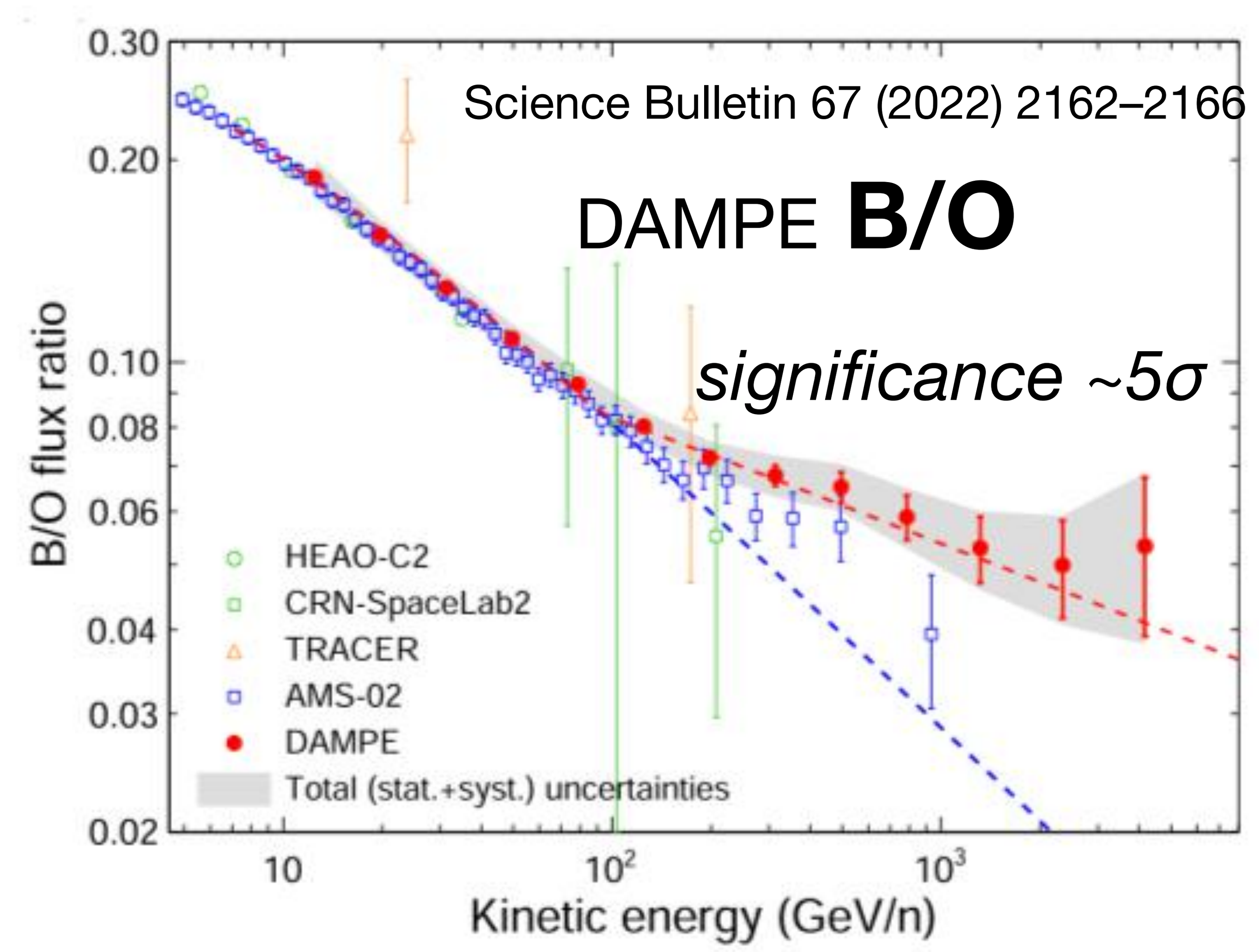
Change of spectral index in secondaries is more prominent than in primaries!

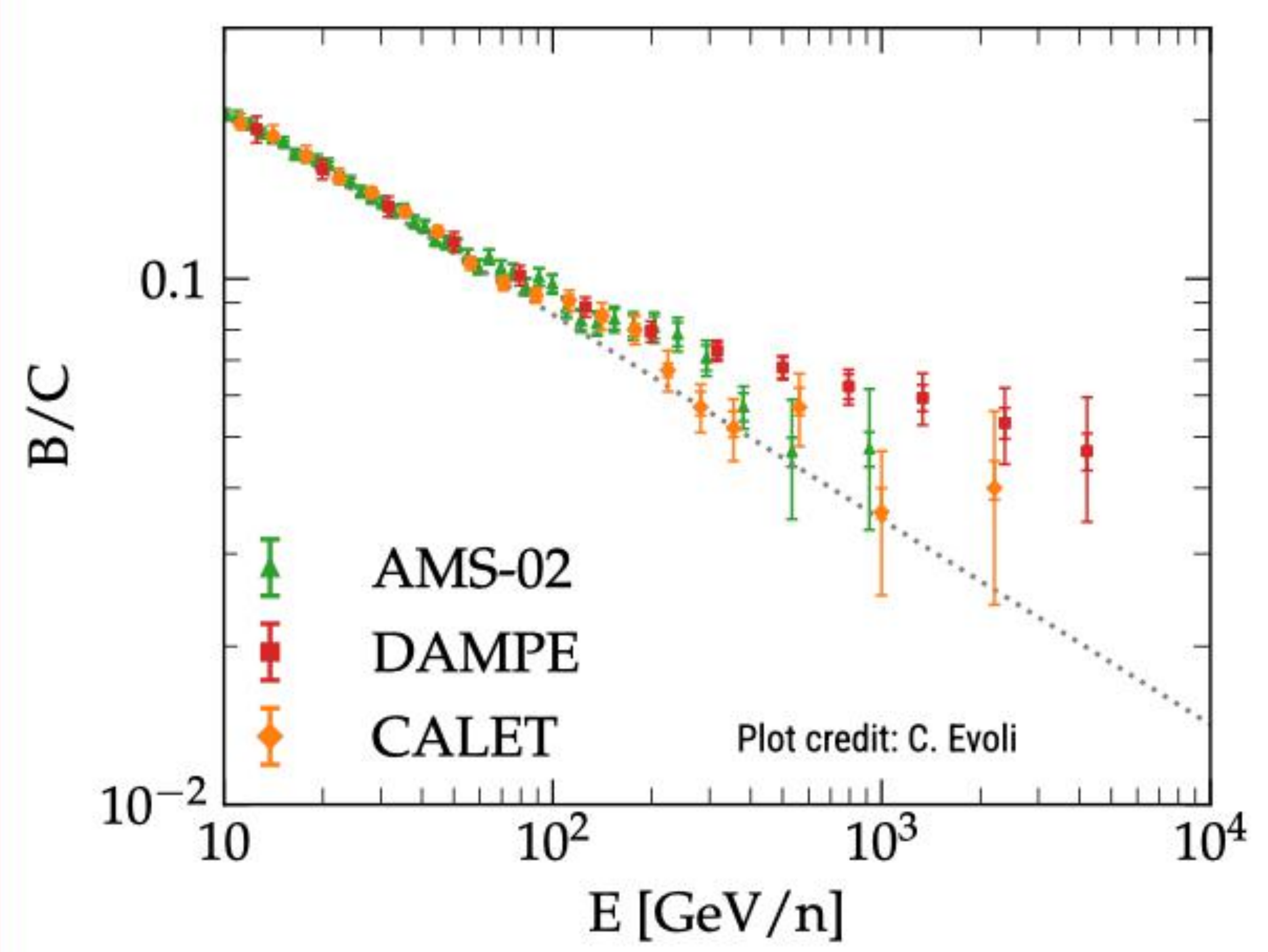
What about flux ratios?

Secondary-to-primary ratios

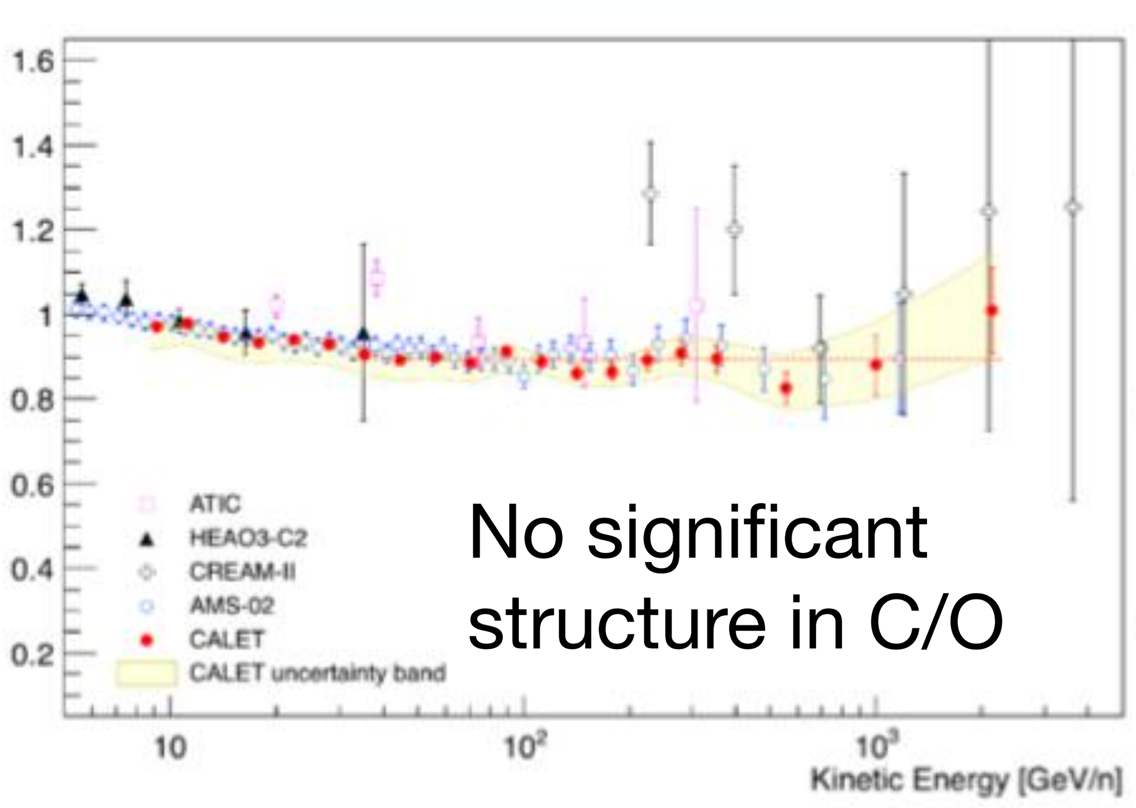
DAMPE and CALET secondary-to-primary ratios (B/C, B/O) show that secondaries are hardening ~ twice more than primaries



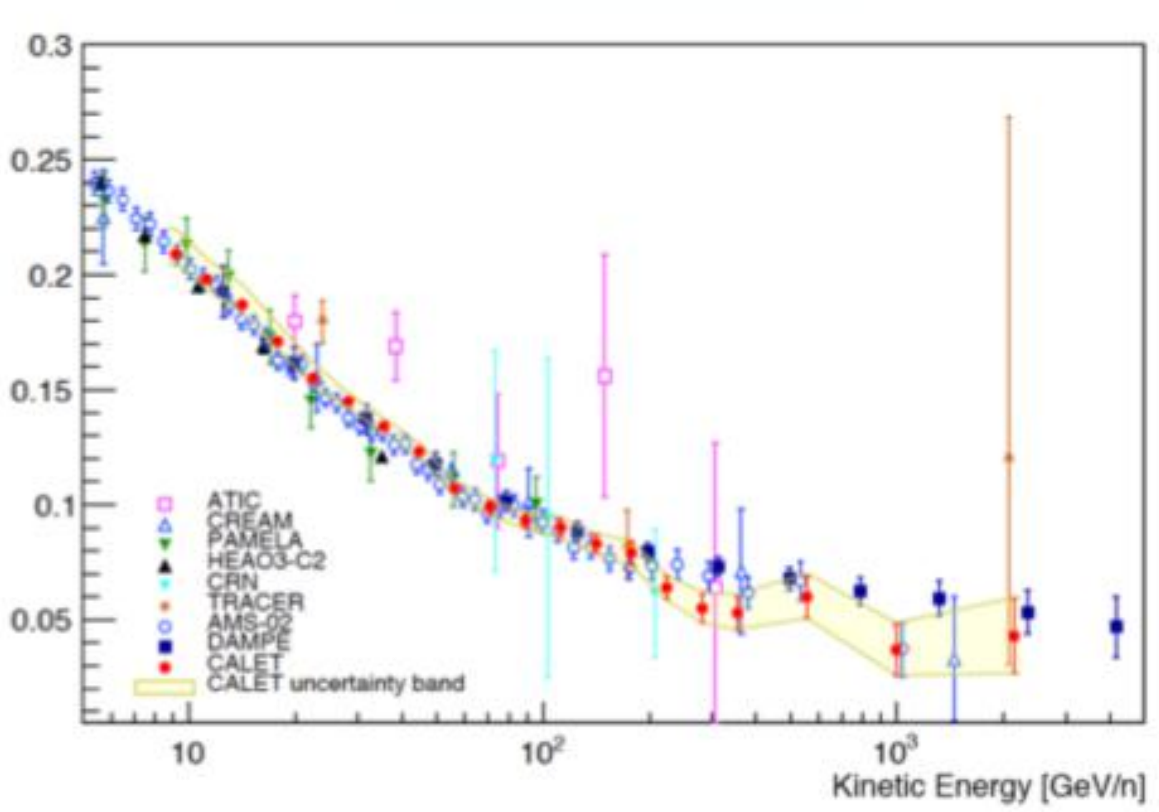




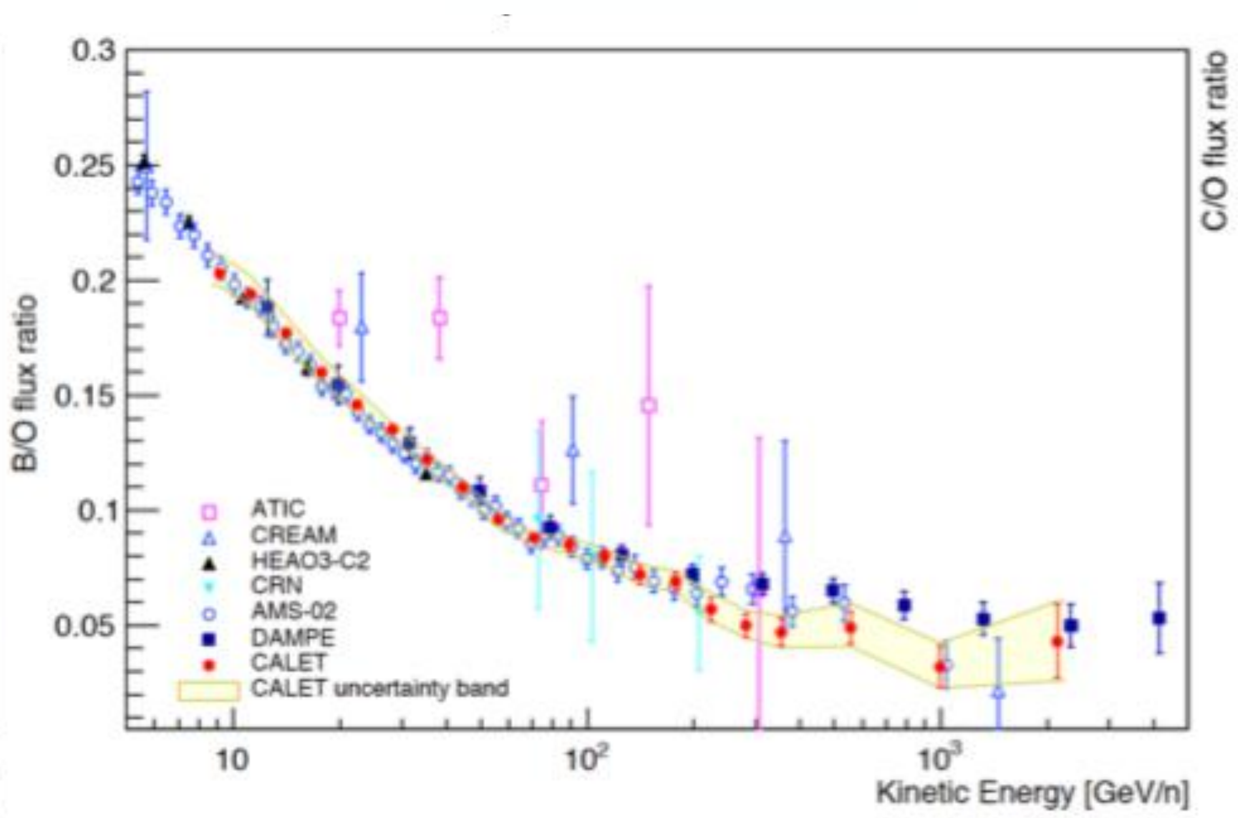
CALET **C/O**



CALET **B/C**



CALET **B/O**



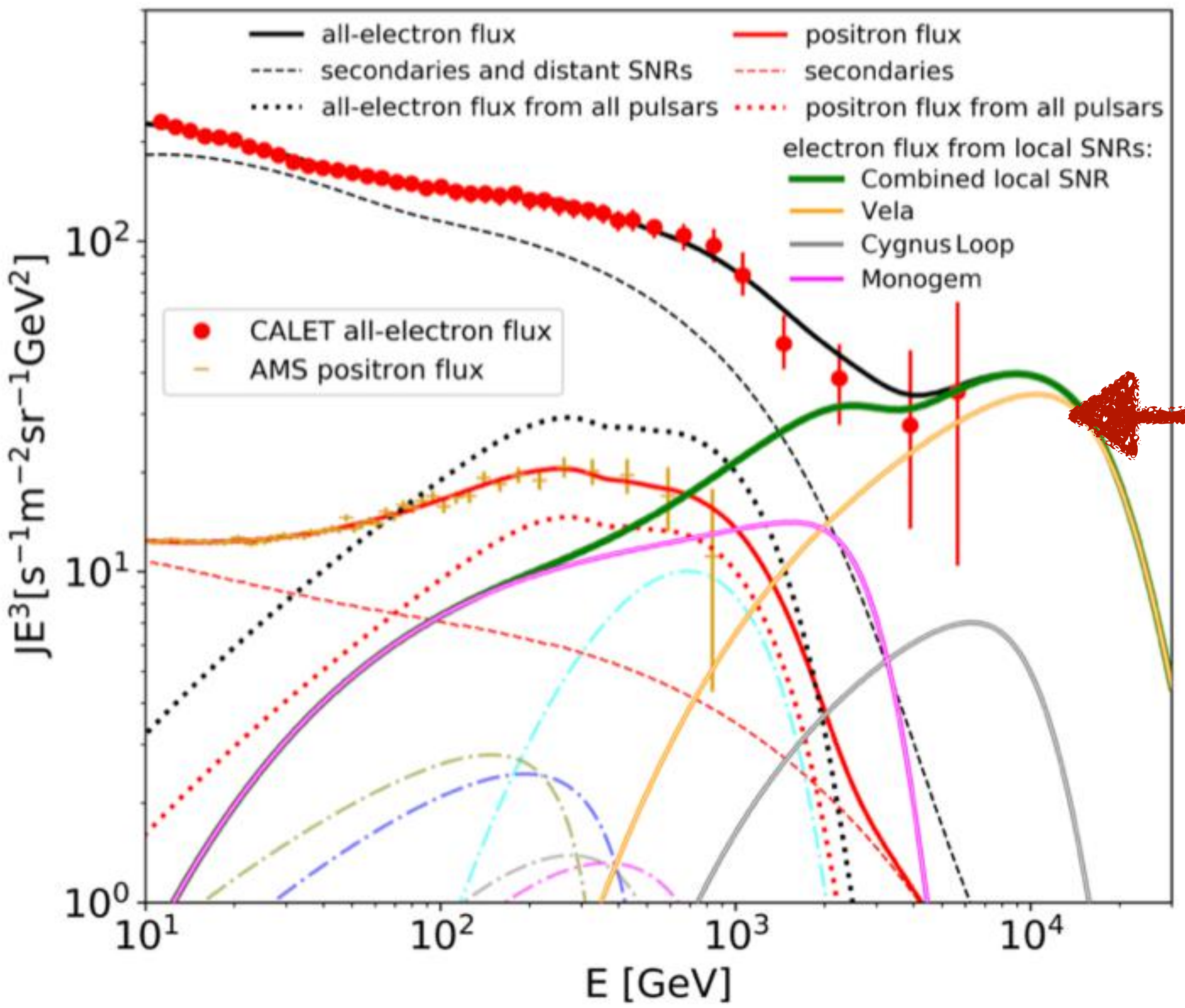
→ indication of CR propagation effect as an origin of the hardening!

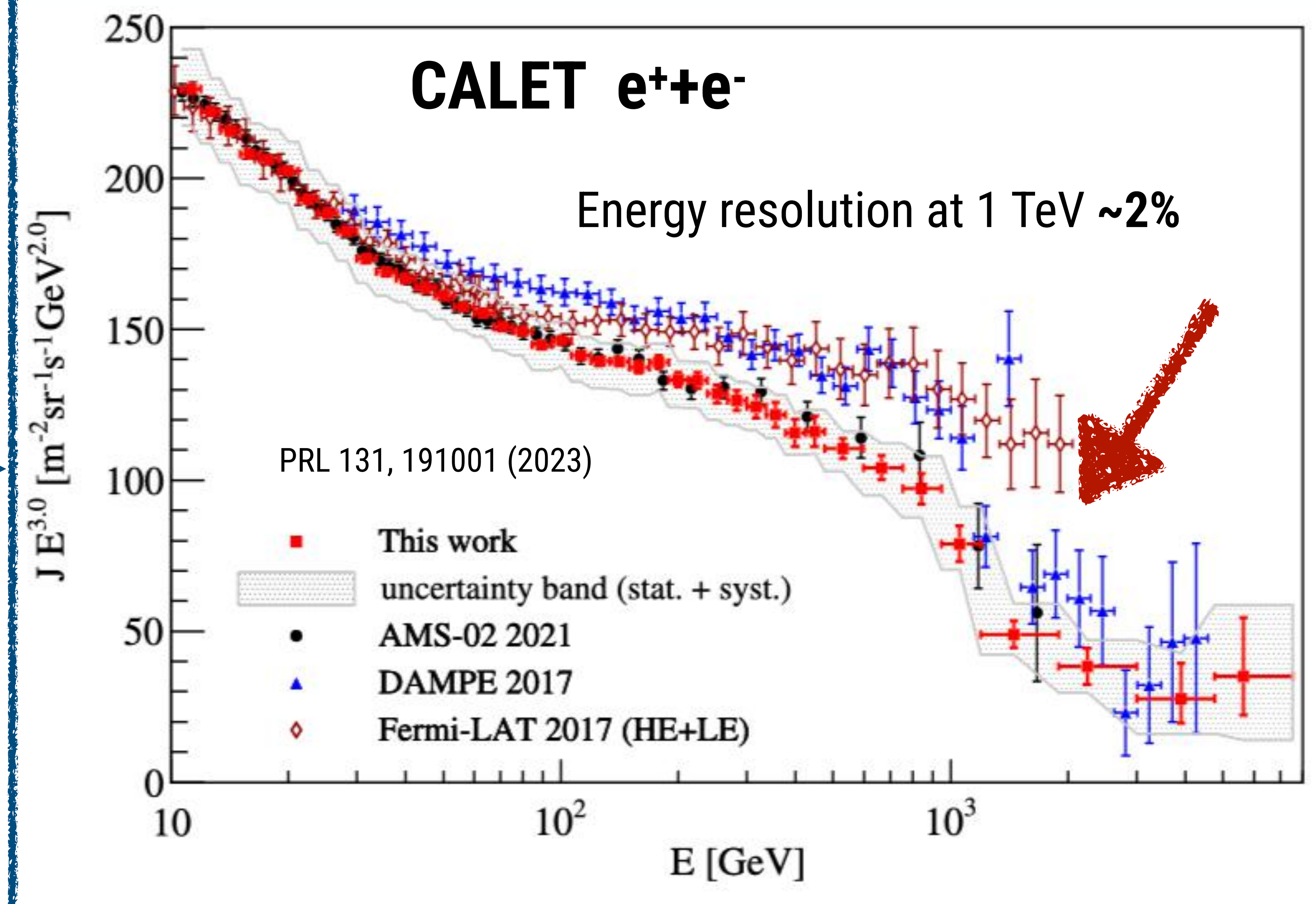
(Also possible effect of local source not fully excluded)

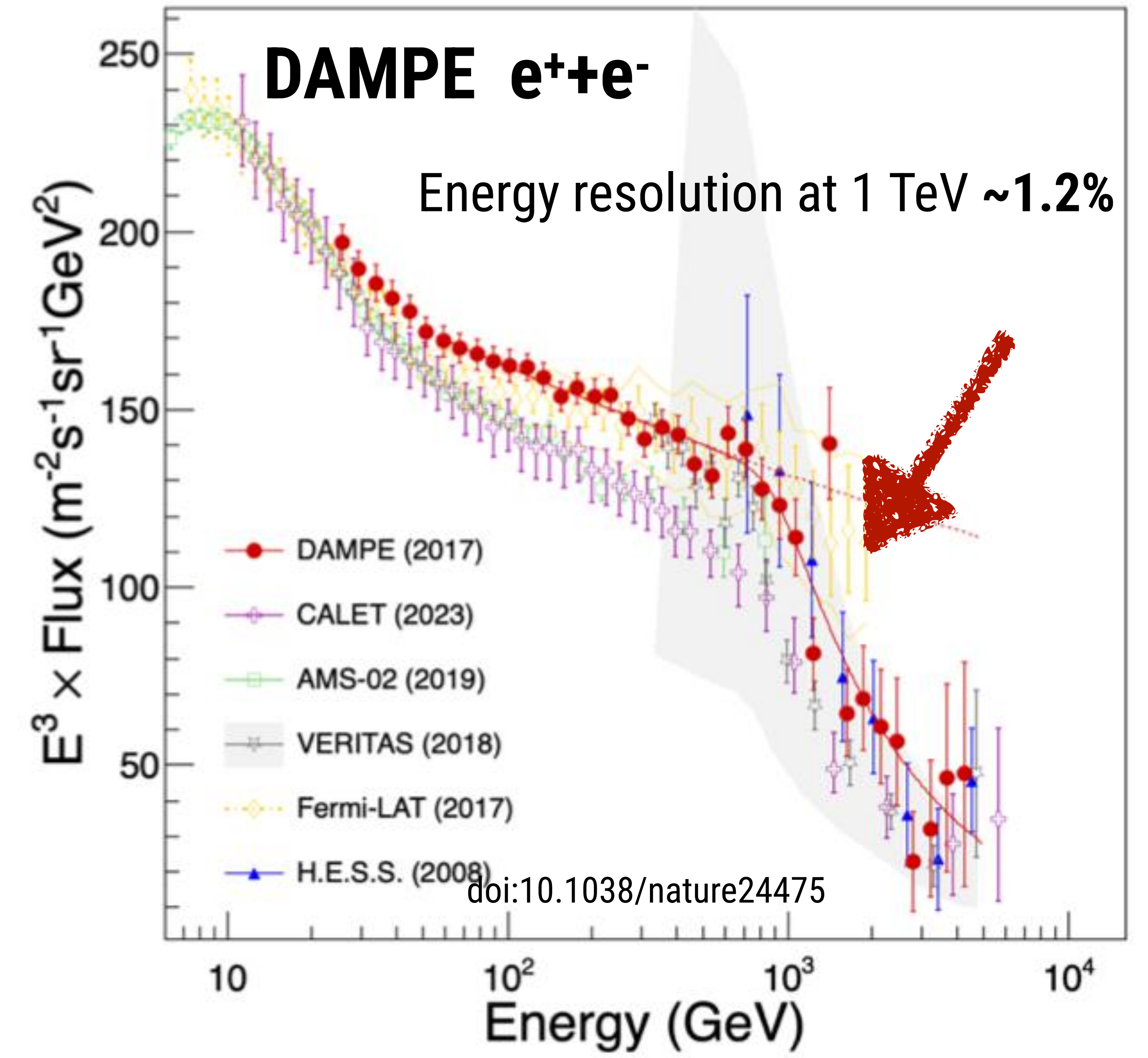
Precise measurement of cross section, including *C→B* is crucial for disentangling different theoretical possibilities (dedicated workshop Cross sections for Cosmic Rays @ CERN this year …)

Electrons

- Electrons loose energy rapidly — only contributions from local sources (<1kpc) expected at > TeV energies
- Spectral break at 1 TeV directly observed by DAMPE and CALET
- Excellent energy resolution allows to probe fine structure of the spectrum: **both experiments indicate that the TeV break is too sharp** — in a tension with multi-source prediction
- Exploring 10 TeV region is crucial to probe local source contribution



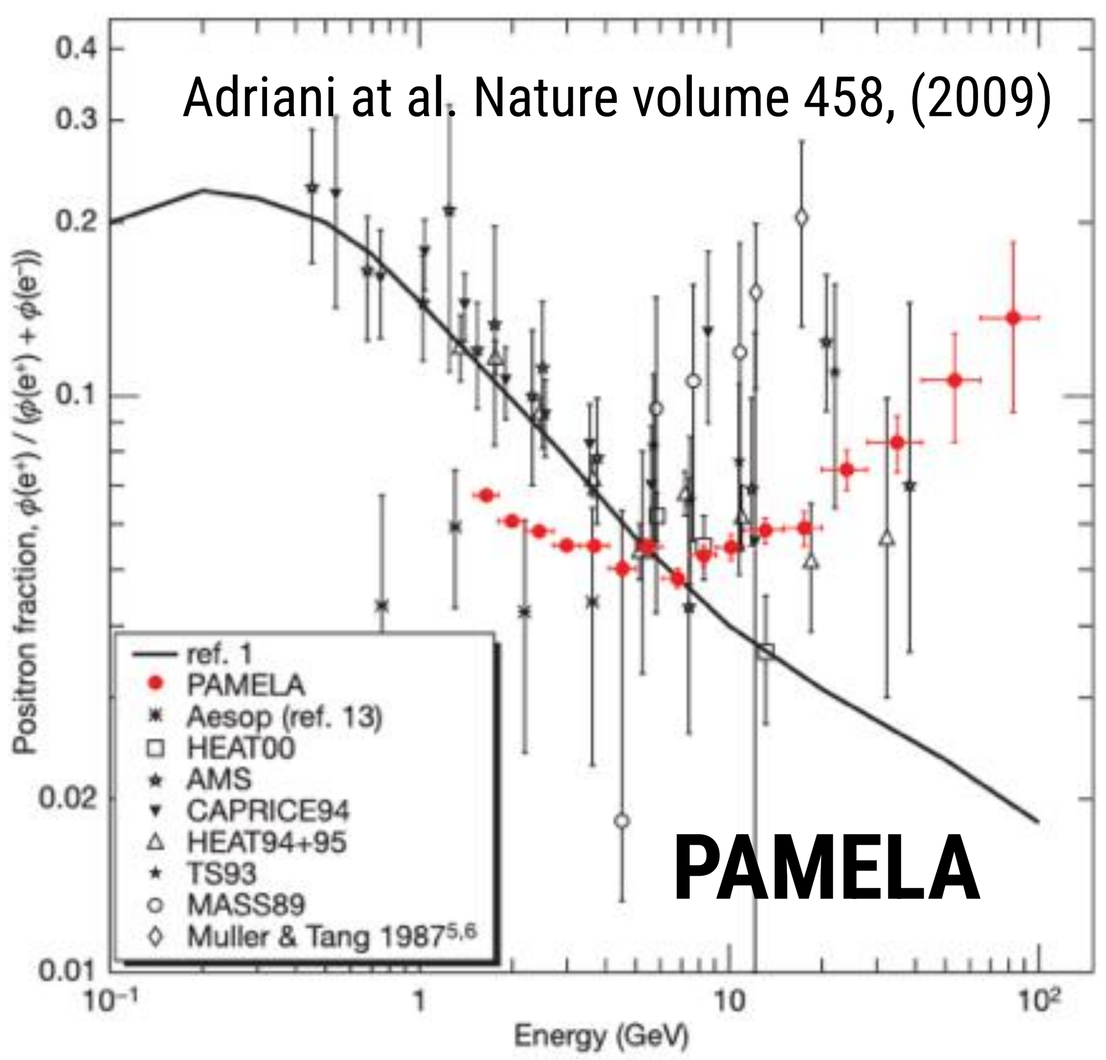


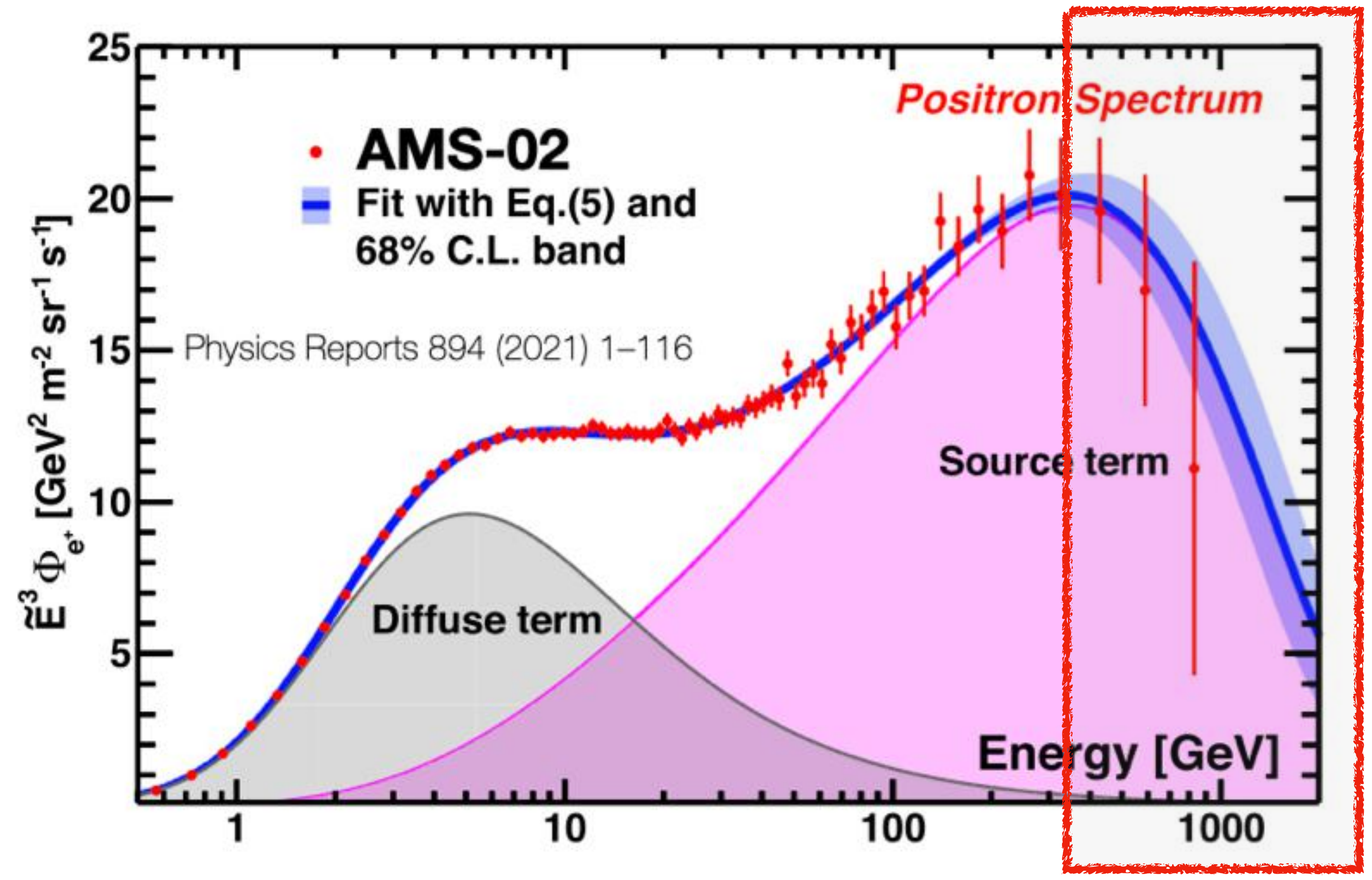


Antiparticles

- Hardening in e⁺ spectrum first observed by PAMELA, precisely measured until ~TeV by AMS-02

e⁺





pulsar

HAWC, LHASSO: γ-ray TeV around PWNs – indication of pulsar origin

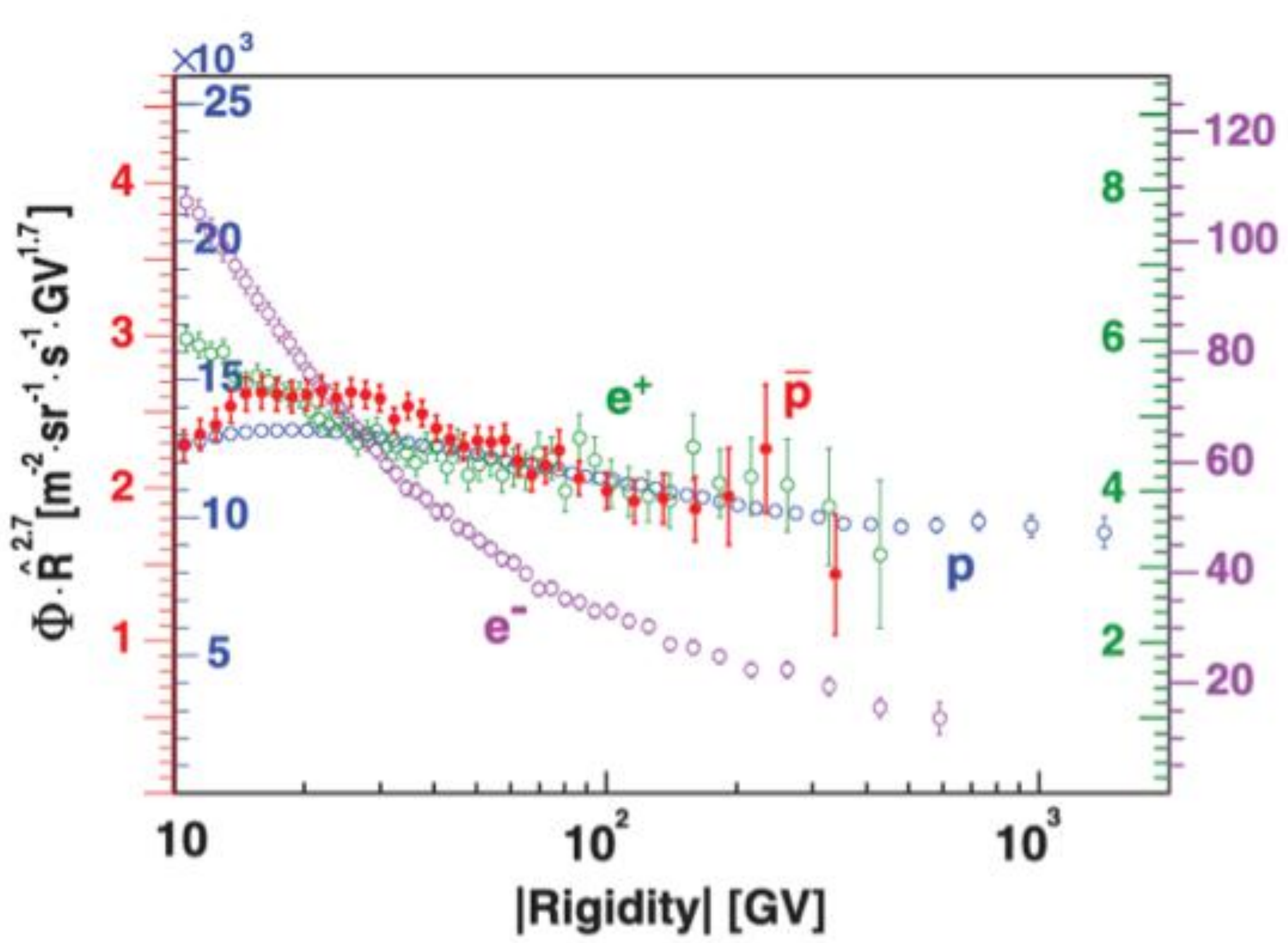
break or cutoff?

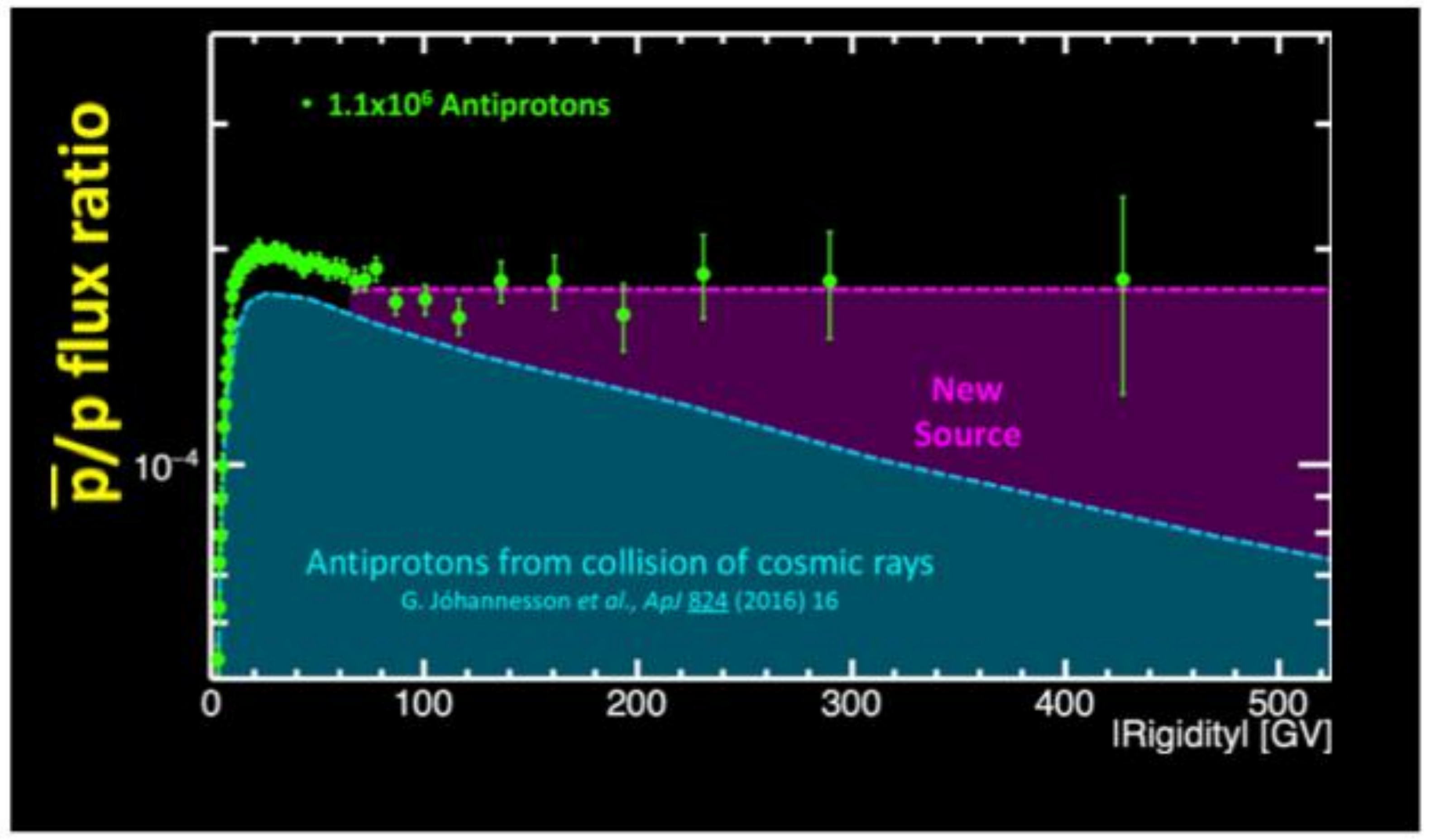
dark matter

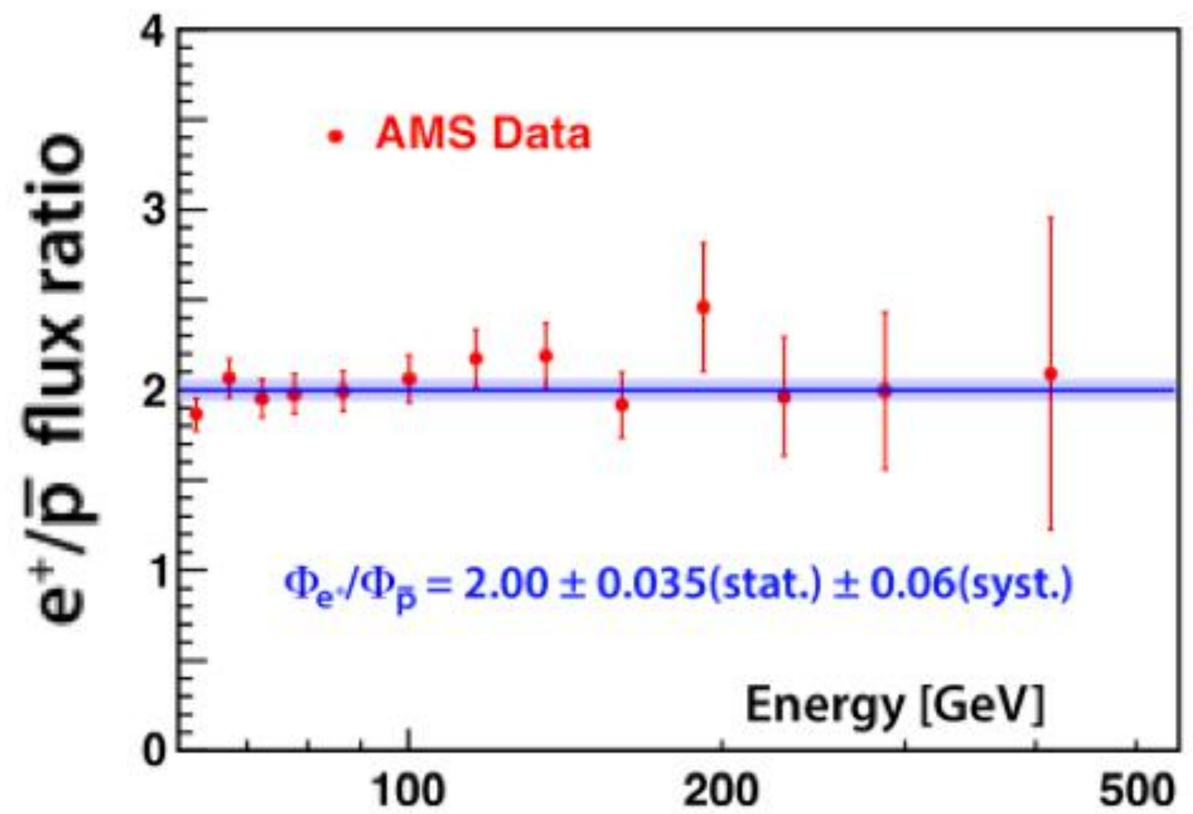
to be probed thanks to AMS0-02 L0 upgrade (x3 acceptance) with 2025–2030 data

- $\bar{p}$ spectrum remarkably similar to *p* and e⁺. While AMS-02 claims primary contribution of , purely secondary origin seems still compatible if experiment and model systematic taken into account*

$\bar{p}$



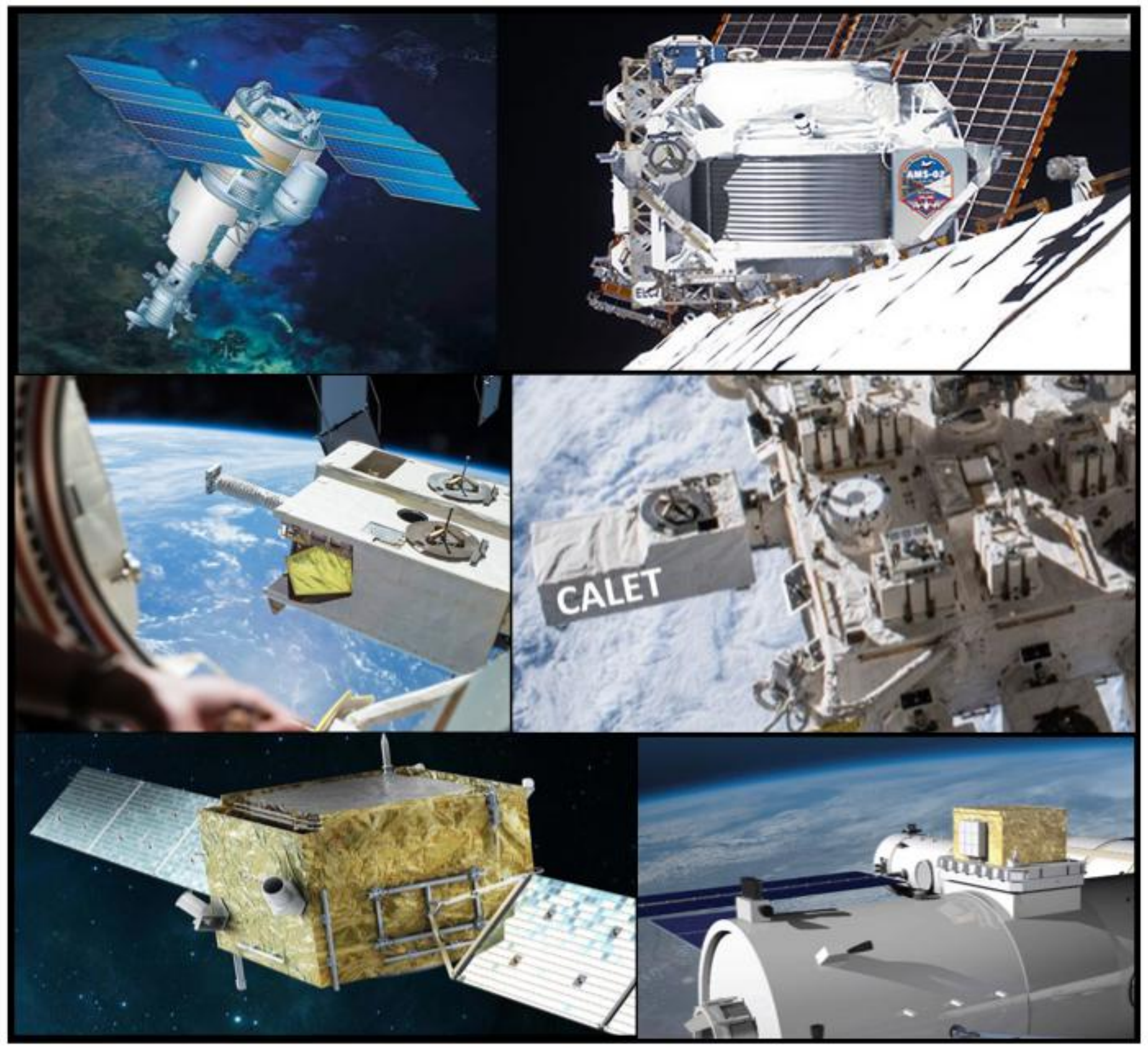




* see e.g. arxiv:2107.14606

Conclusions

- Data from space instruments challenge conventional cosmic ray theory: multiple breaks in primary and secondary CR spectra
- *Hardening at ~hundreds GeV/n*: confirmed in all major primaries up to Iron (see DAMPE), B/C & B/O ratios suggest modification of CR propagation
- *Softening at ~ 10 TeV/n:* origin not clear – crucial to get first data on secondaries
- H/He measurements toward PeV frontier – hint of another feature – *hardening at ~150 TeV*
- *Electrons ~1TeV break:* difficult to explain, remains one of the most prominent feature in cosmic rays
- Positron excess – *primary positron contribution* likely attributed to pulsars



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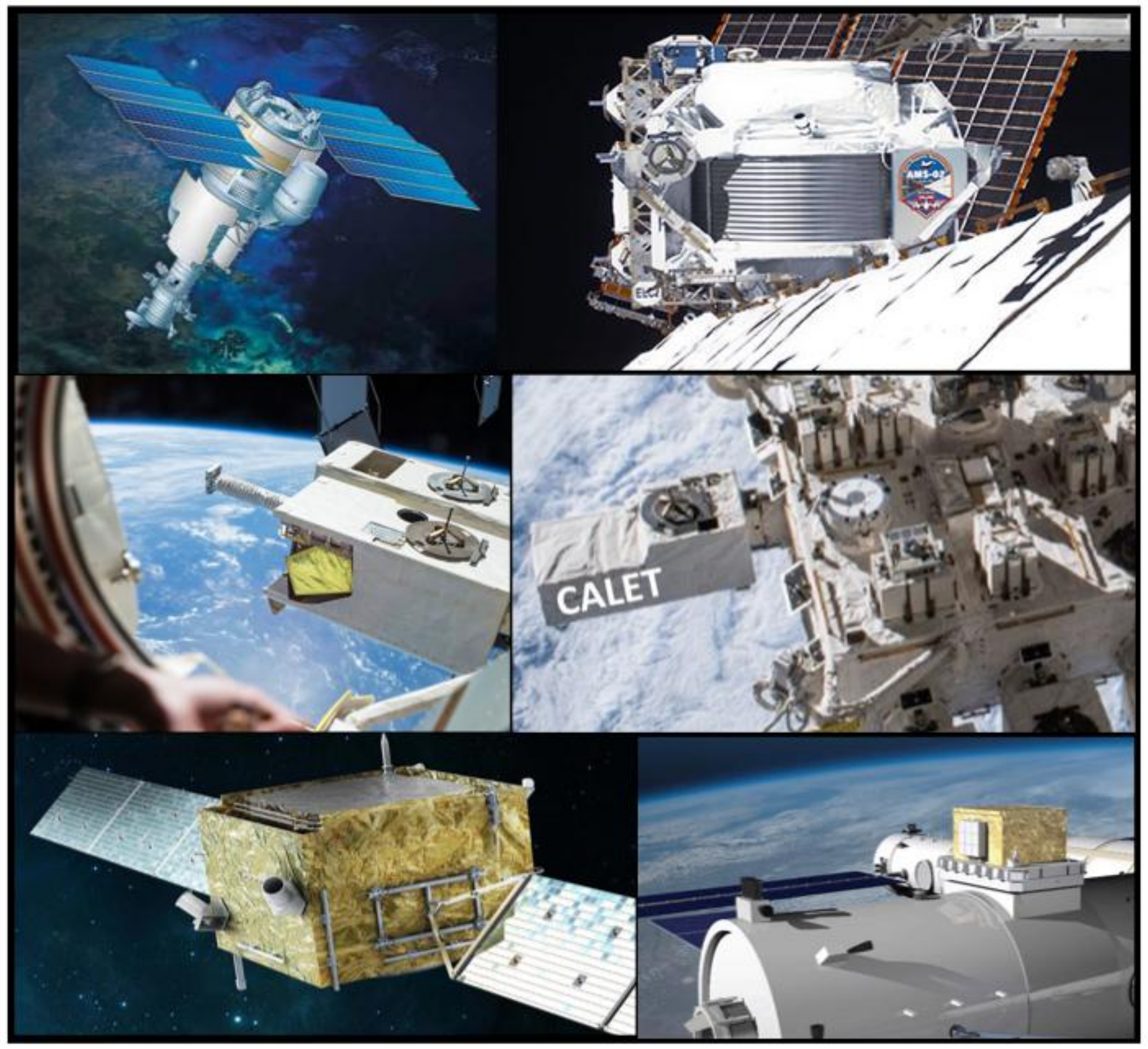


Thank You!

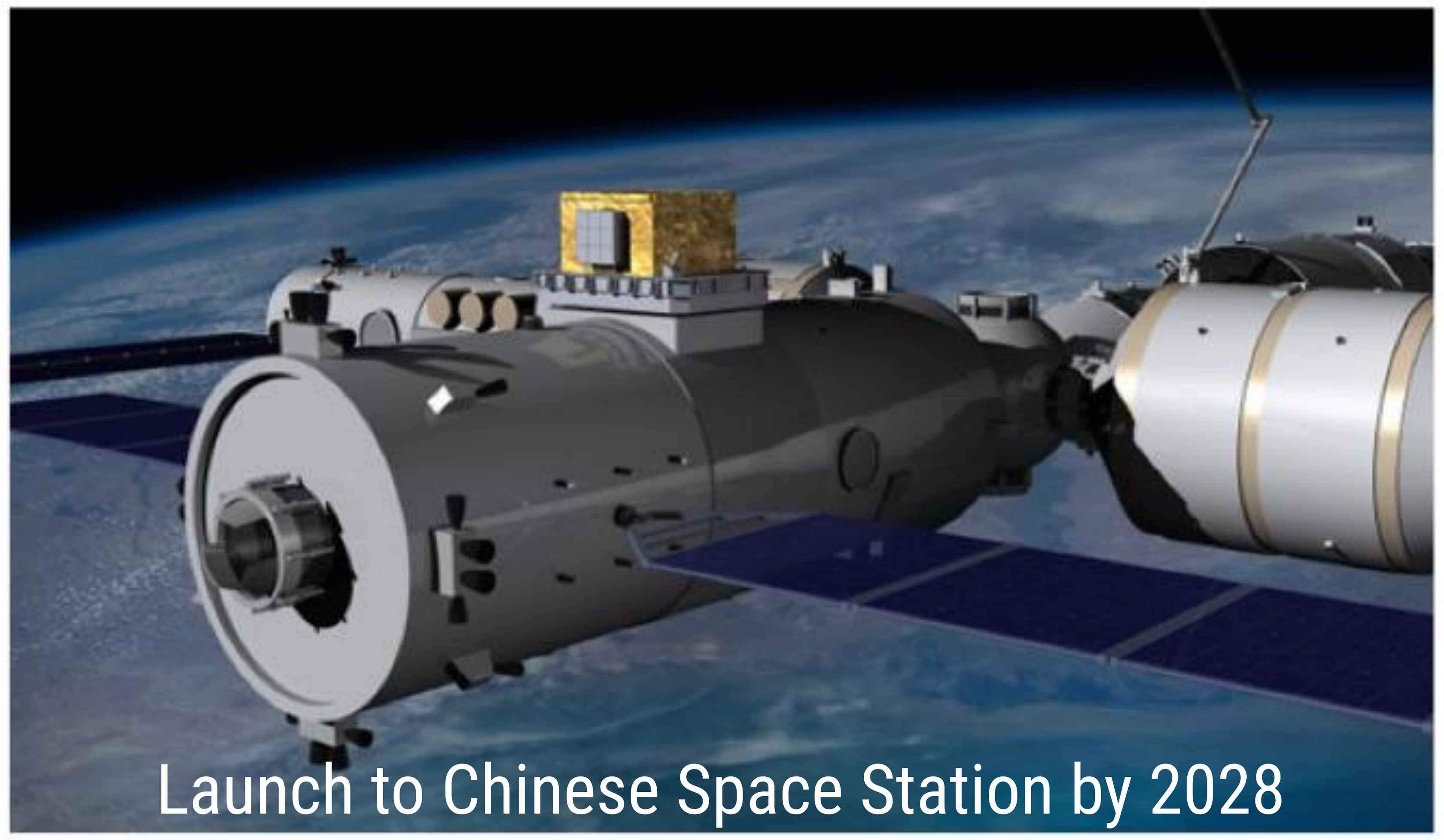
BACKUP

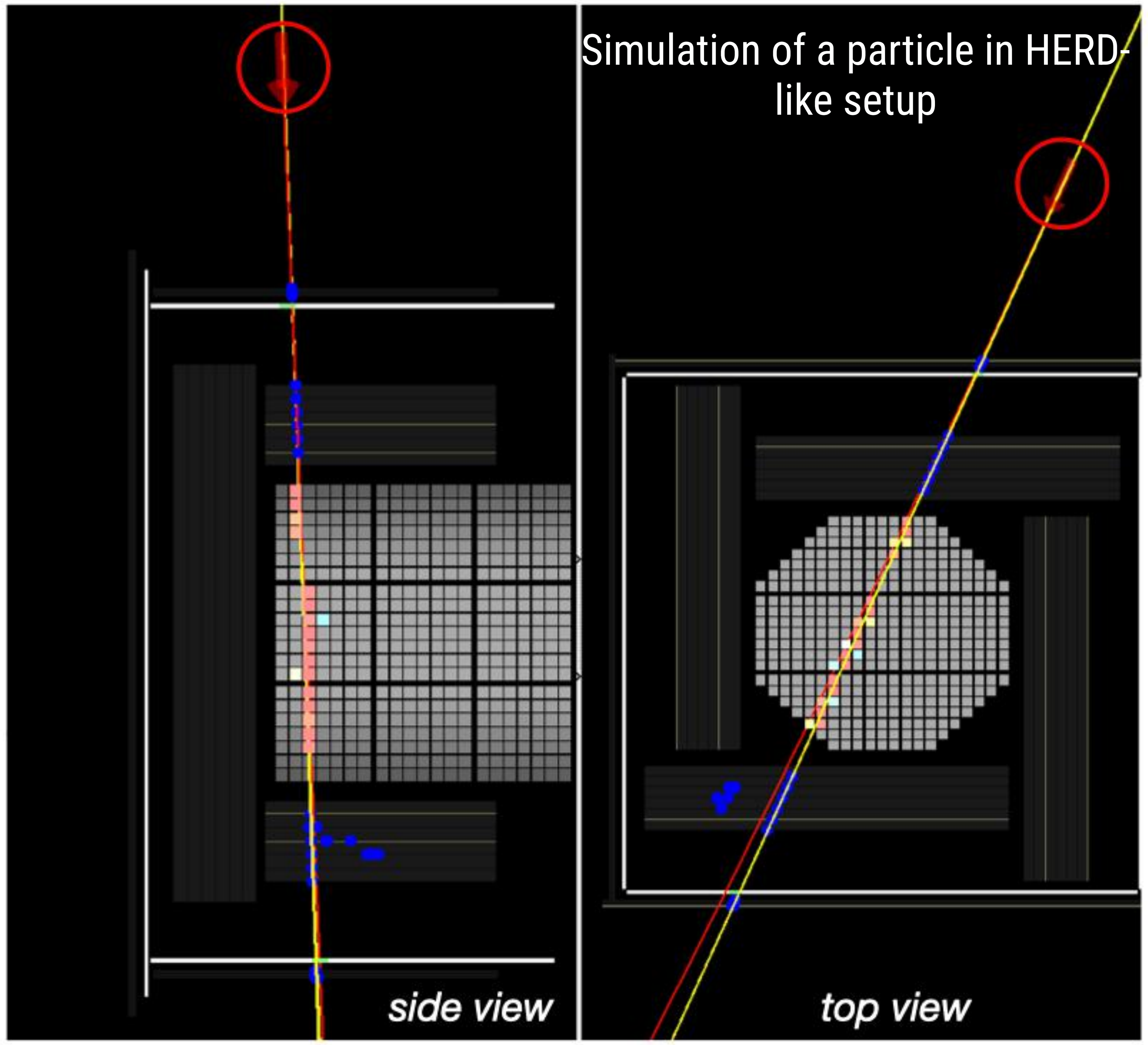
HERD

3D calorimeter of $55X_0$ (3Λ) + 5-side tracker

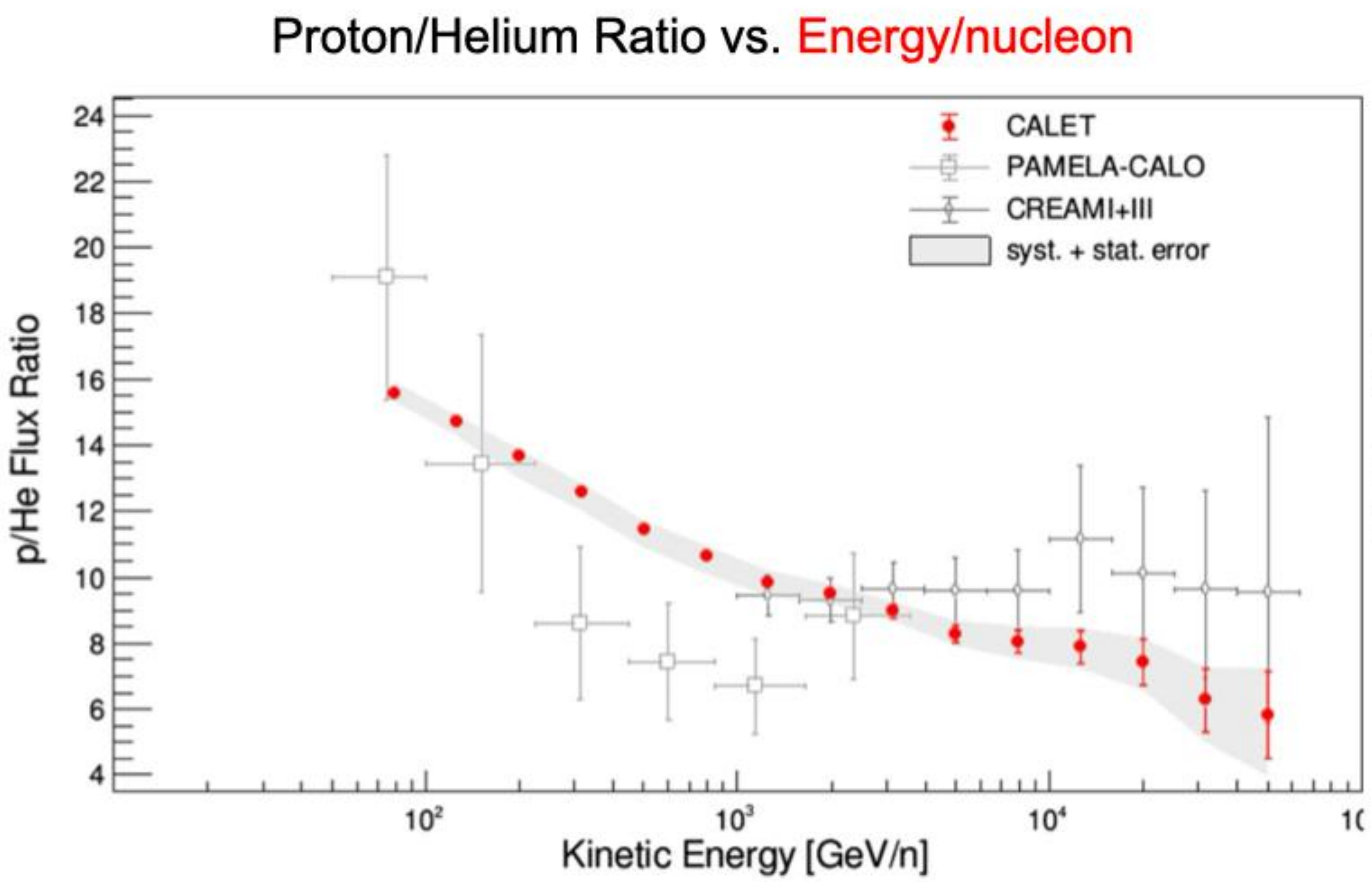
- CR electrons up to 100 TeV
- CR p/ions up to PeVs
- x 10 acceptance compared to DAMPE

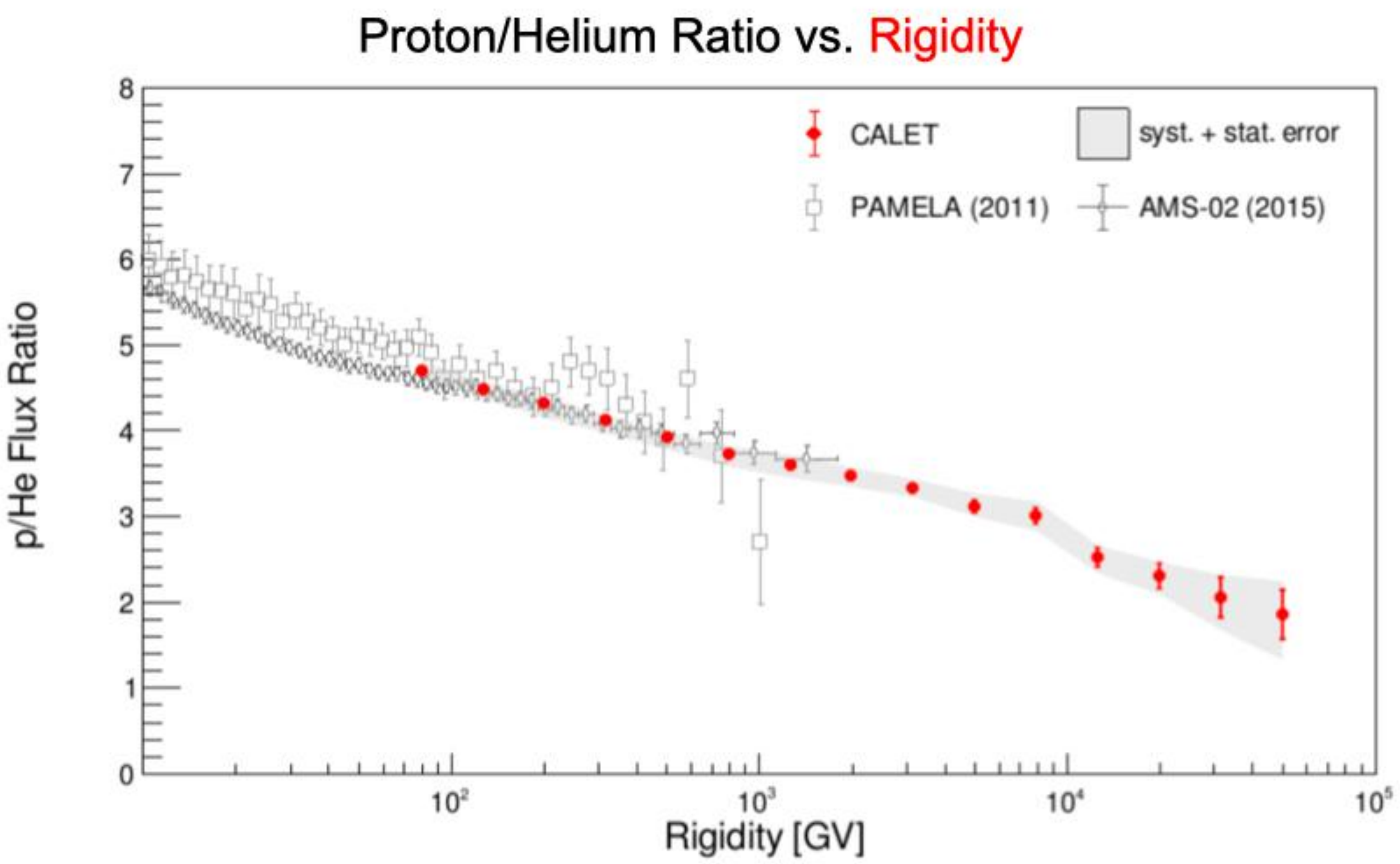
→ hundreds of PeV cosmic rays / year





H/He flux ratio (CALET)





AMS-02 L0 upgrade