PennState

Direct Cosmic Ray Measurements: Status and Perspectives

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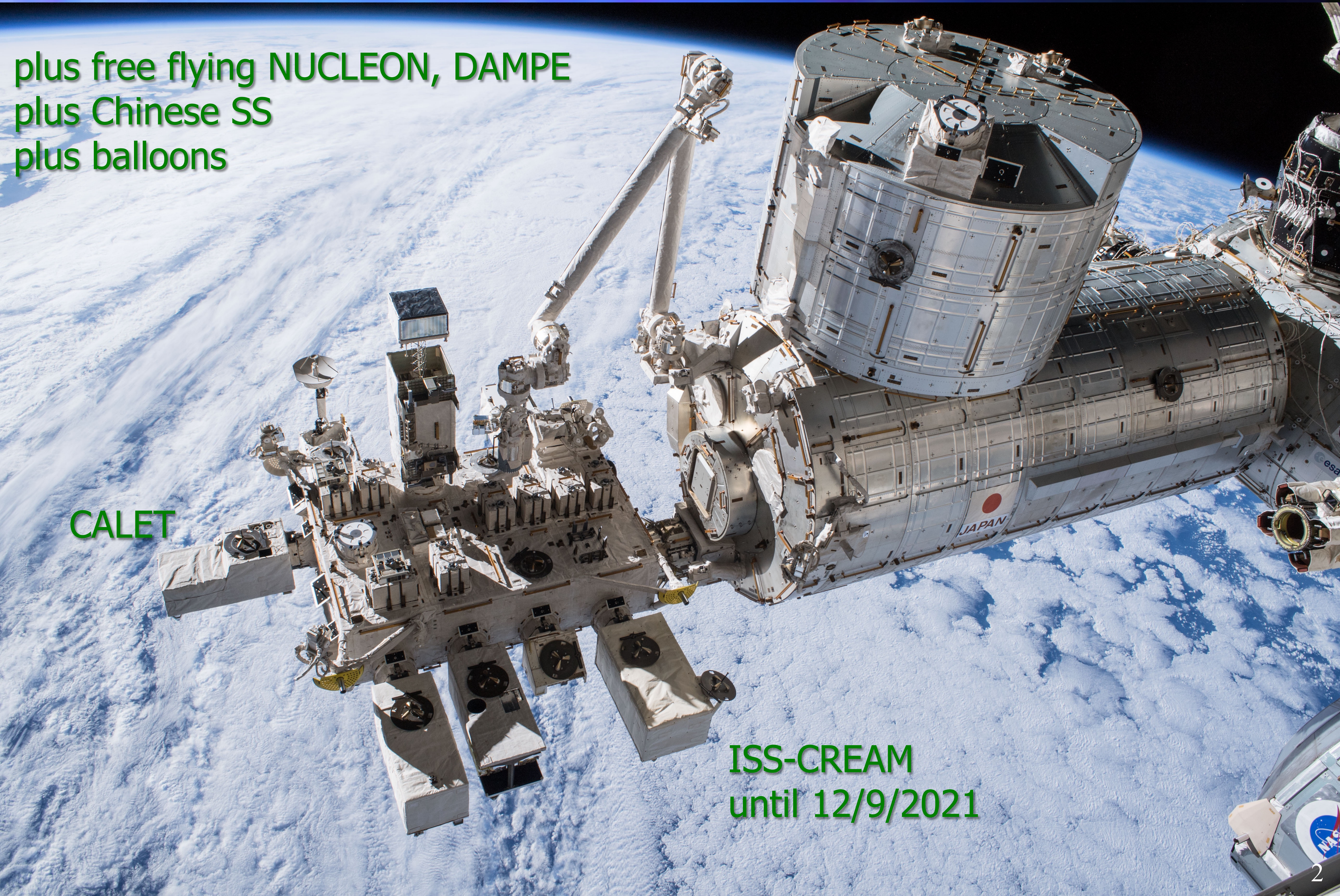
Outline

- Charged messengers: nuclei (primary, secondary, isotopes, superheavy), electrons, antimatter (e+, pbar)
- Direct measurements:
  - Space (AMS, CALET, DAMPE, ISS-CREAM, NUCLEON)
  - Balloons (CREAM, HELIX, SuperTIGER, GAPS)
- Link to higher energies, the future

Direct measurements

AMS →

plus free flying NUCLEON, DAMPE
plus Chinese SS
plus balloons



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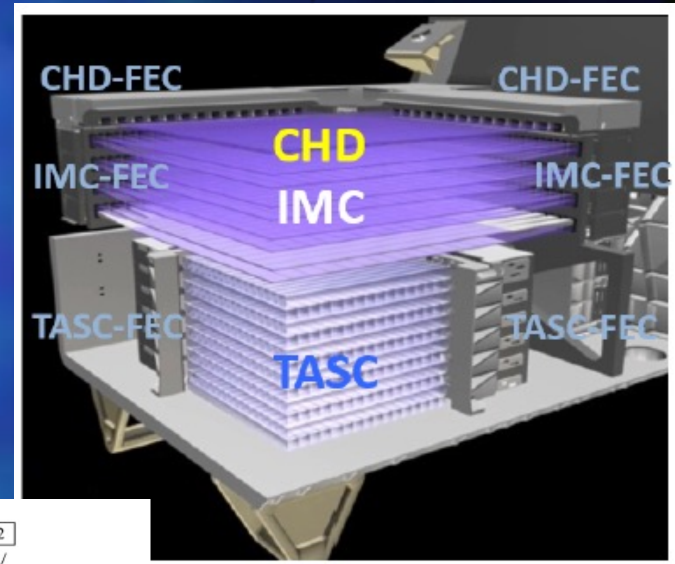
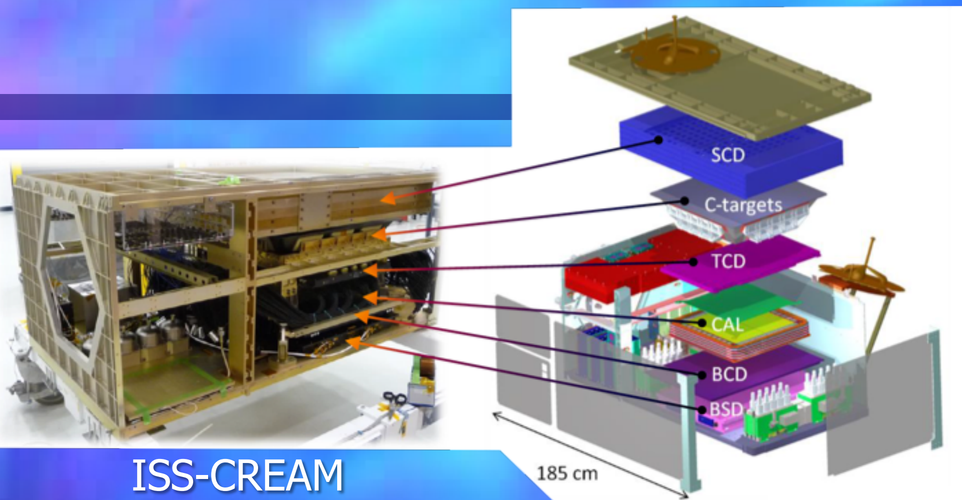
Complex instruments!

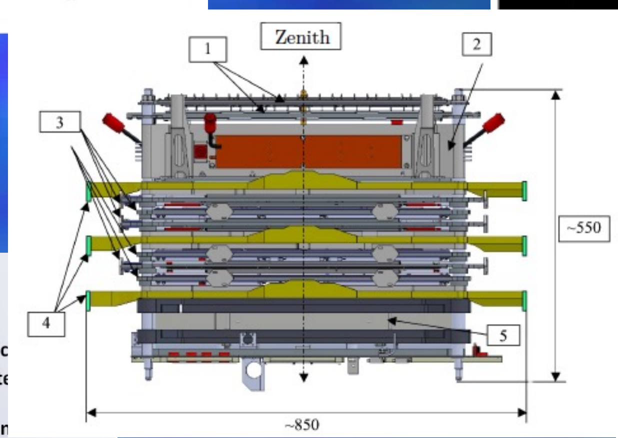
Geometric factors 0.1 - 0.8 m^2sr
nuclei up 100's TeV

CALET, 2015

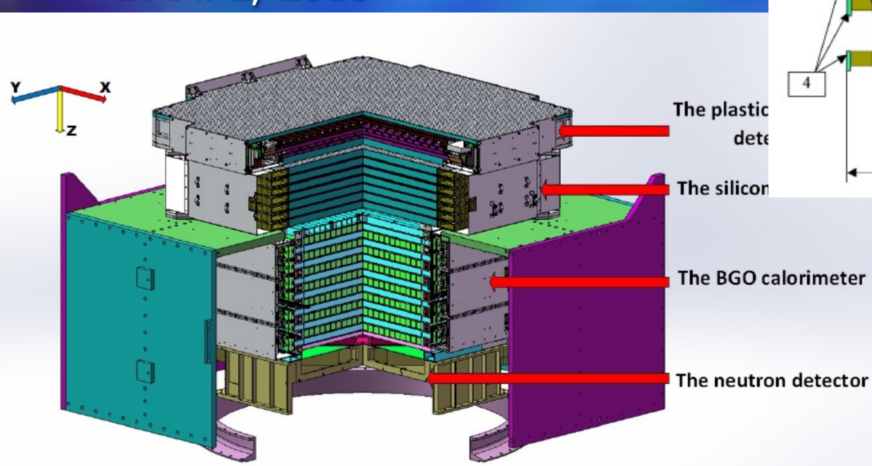




ISS-CREAM
2017-2019

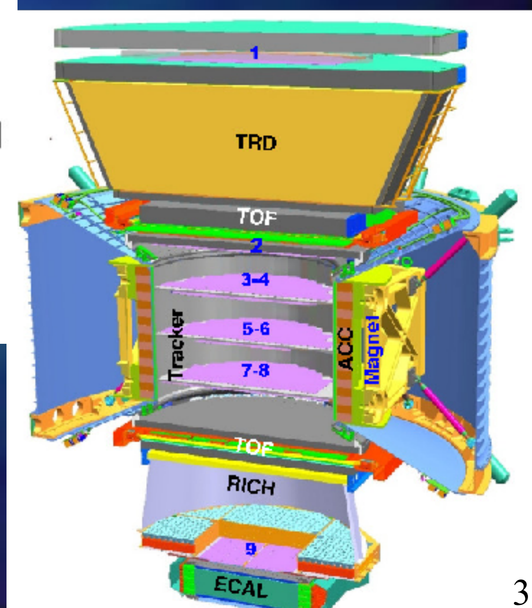


DAMPE, 2015



NUCLEON
2014

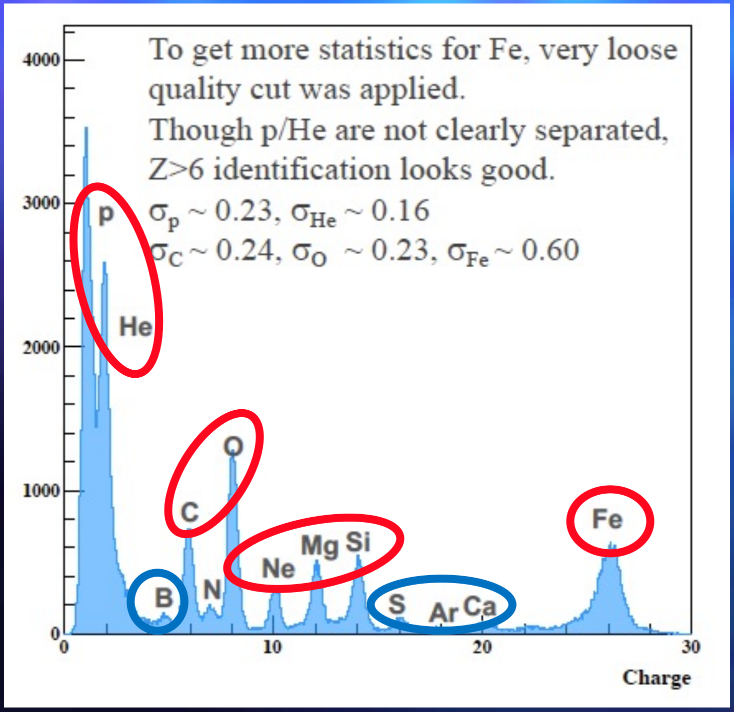
AMS
2011



Nuclei: elemental abundances

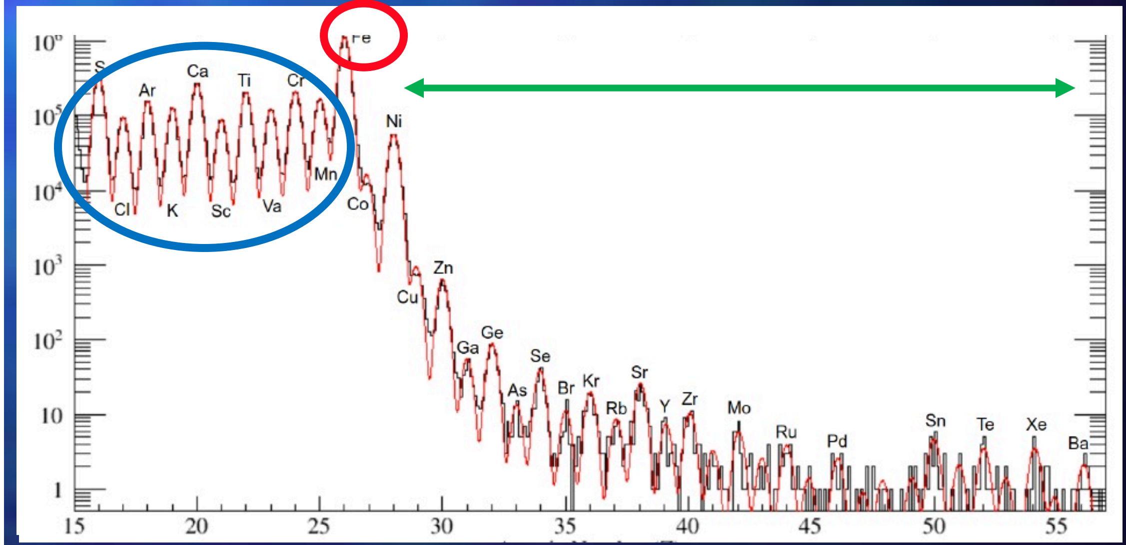
Primary nuclei produced in stellar nucleosynthesis, directly from the sources
Secondary nuclei produced spallation reactions during Galactic propagation
Ultraheavy nuclei from r-process in mergers of compact objects / supernovae

ISS-CREAM above ~2 TeV



K. Sakai et al., PoS(ICRC2021)080

SuperTiger above ~0.3 GeV/n or 2.3 GeV/n



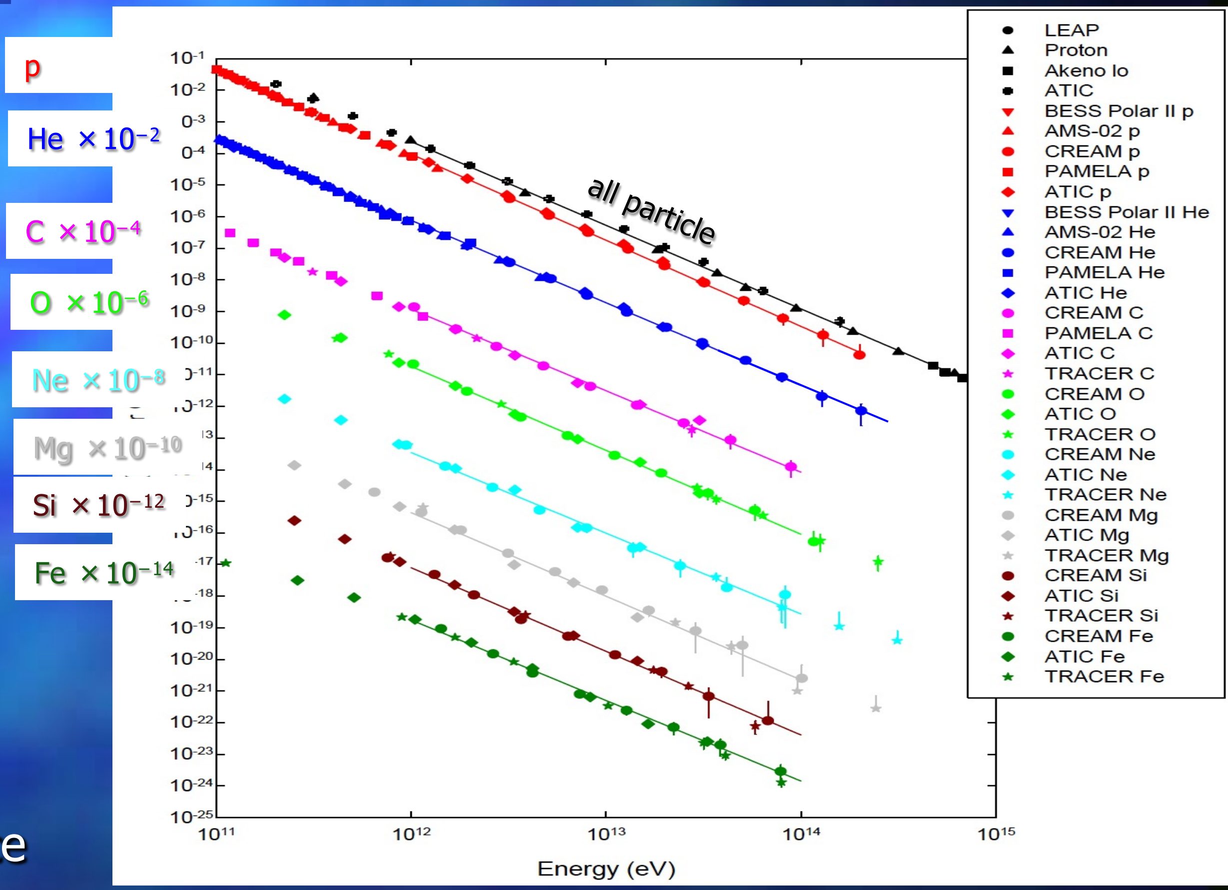
N.E. Walsh et al., PoS(ICRC2021)118

Elemental spectra

Ahn et al., ApJ 707, 593 (2009),
Ahn et al., ApJ 715, 1400 (2010),
Yoon et al., ApJ 728, 122 (2011)

Each component can be fitted to a single power law (CREAM only to avoid different systematics):

- H: $dN/dE \sim E^{-2.66\pm0.02}$
- He: $dN/dE \sim E^{-2.58\pm0.02}$
- C: $dN/dE \sim E^{-2.61\pm0.07}$
- O: $dN/dE \sim E^{-2.67\pm0.07}$
- Ne: $dN/dE \sim E^{-2.72\pm0.10}$
- Mg: $dN/dE \sim E^{-2.66\pm0.08}$
- Si: $dN/dE \sim E^{-2.67\pm0.08}$
- Fe: $dN/dE \sim E^{-2.63\pm0.11}$



Probably from the same source and acceleration mechanism. The components do add up to the all-particle spectrum!

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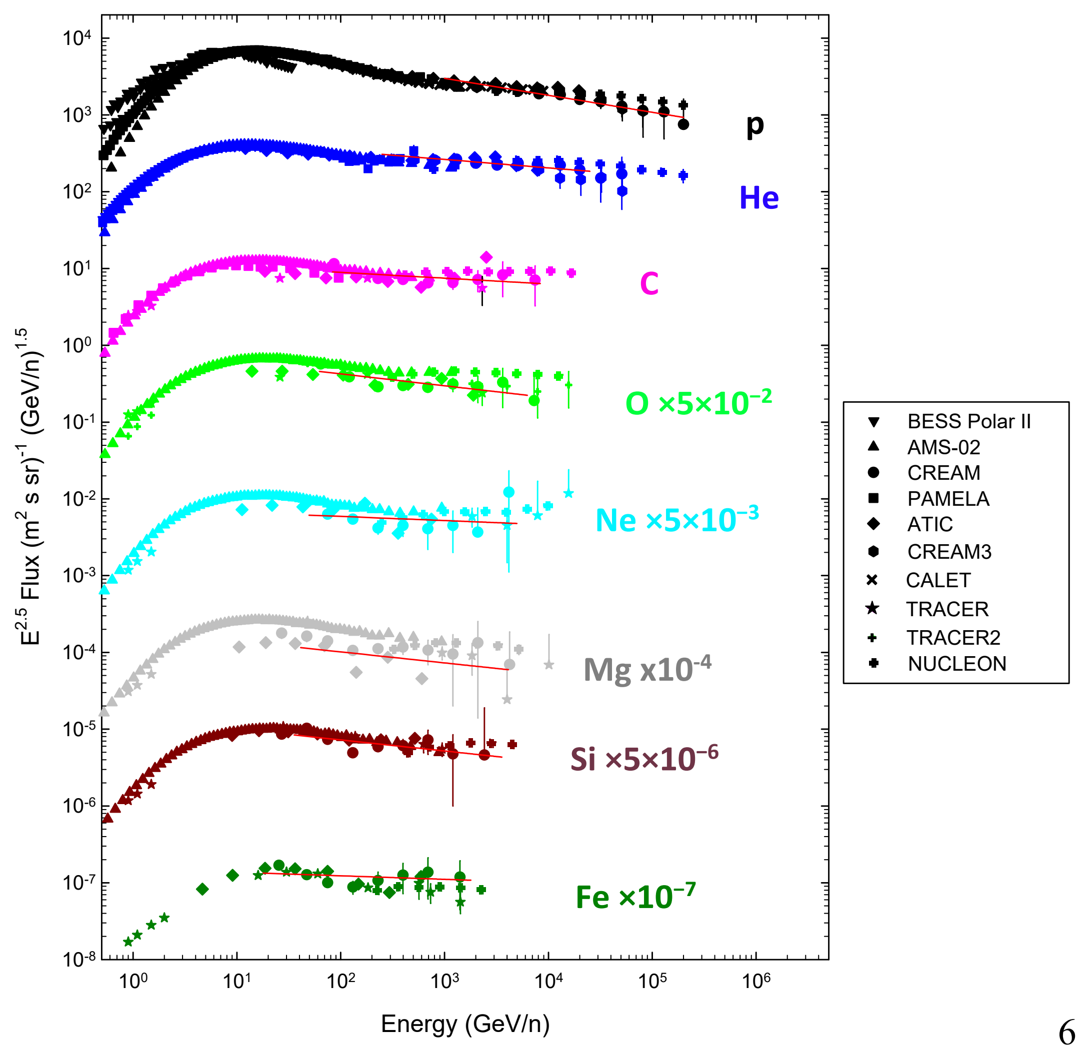
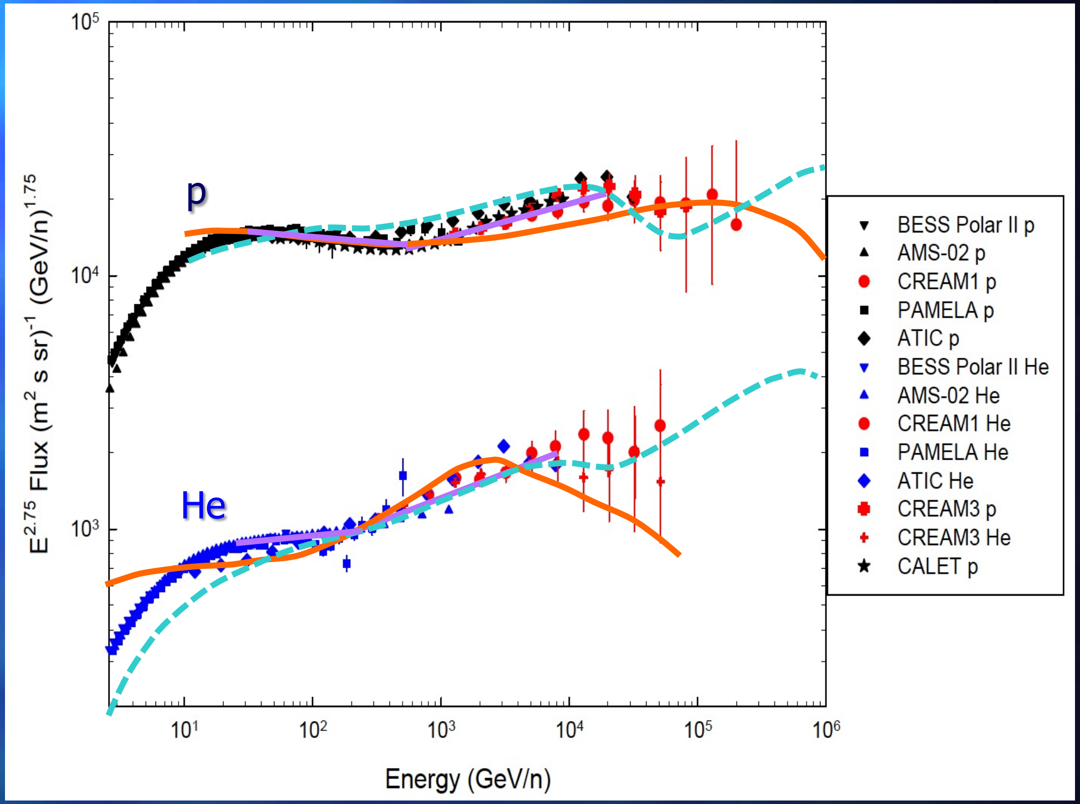


p vs He

Adriani et al., Science 332, 69 (2011)
Yoon et al., ApJ 728, 122 (2011)
Aguilar et al., PRL 114, 171103 (2015)
Abe et al., arXiv: 1506.01267 (2015)
Adriani et al., PRL 122, 181102 (2019)

Spectral hardening at few 100 GeV/n; hint of softening beyond 10 TeV/n



Complex spectra may need to account for non-linear DSA effects in the sources:

- H: reverse shocks in Type II SNRs;
- He: reverse shocks in Type I SNRs;
- both: forward shocks in all SNRs.

(Ptuskin et al., ApJ 763, 47 (2013)
Zatsepin & Sokolskaya, A&A 458, 1 (2006))

Could be due to non-linear effects in CR transport through the Galaxy;
(Aloisio et al., arXiv:1507.00594)

Could be due to young nearby sources;
(Thoudam & Hörandel, MNRAS 435, 2532 (2013))

Models can be adjusted for interesting structure...

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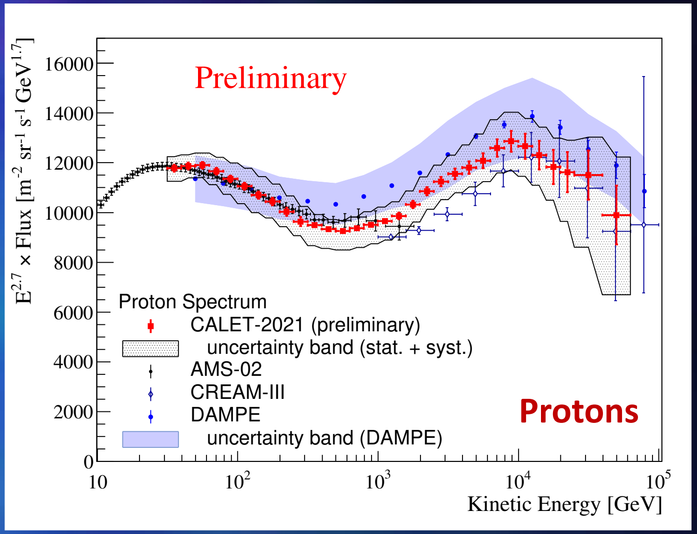
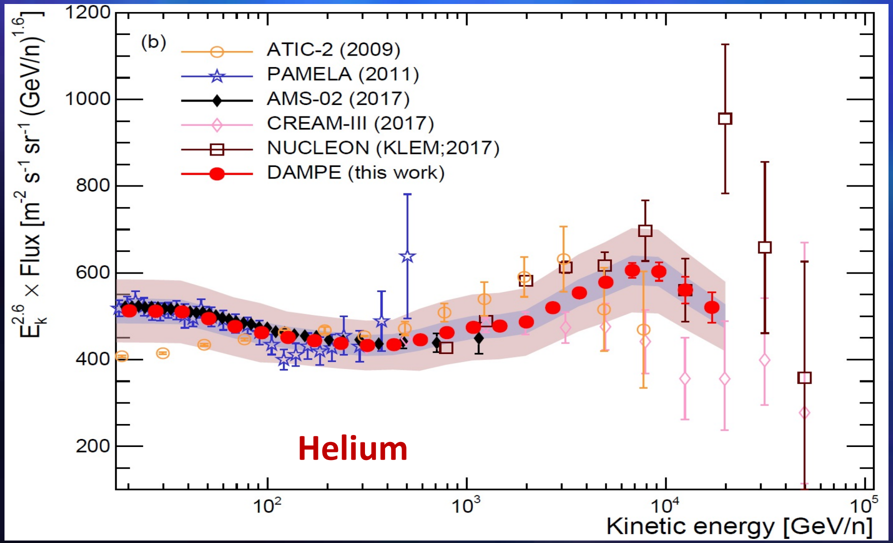
p and He updates

- Spectral hardening at a few hundred GeV/n is well established, but interpretation is not clear;
- Further structure at ~10^4 GeV/n is starting to emerge, and remains to be explained;
- Direct measurements overlap the low end of the ground-based detectors.

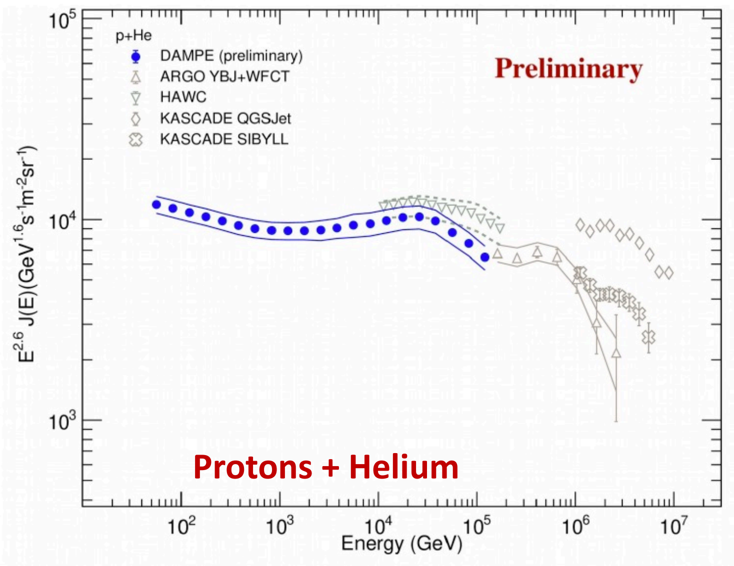
K. Kobayshi et al. (CALET) PoS(ICRC2021)098



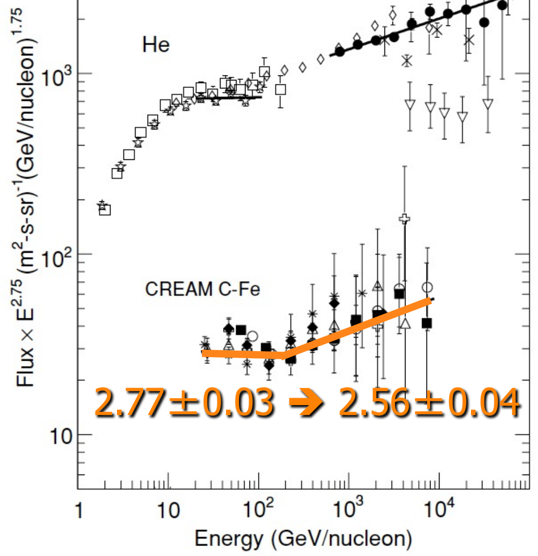
M. Di Santo et al. (DAMPE) PoS(ICRC2021)114



F. Alemanno et al. (DAMPE) PoS(ICRC2021)117



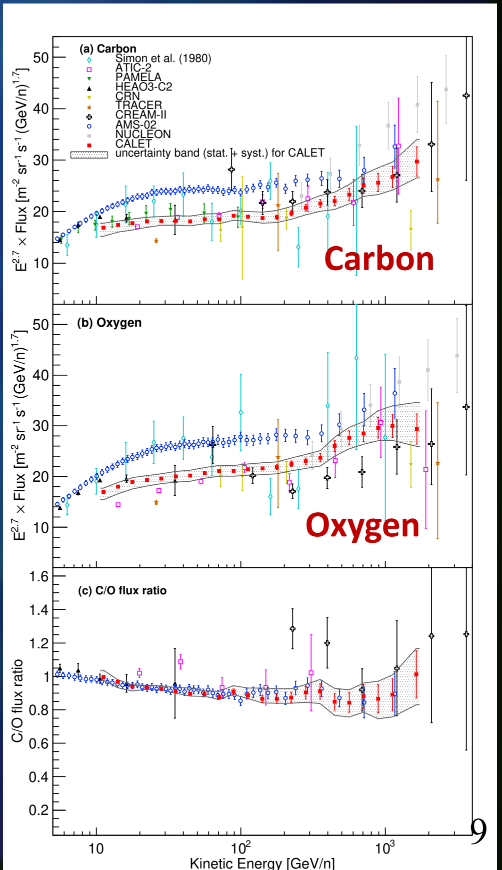
Ahn et al., ApJ 714, L89 (2010)



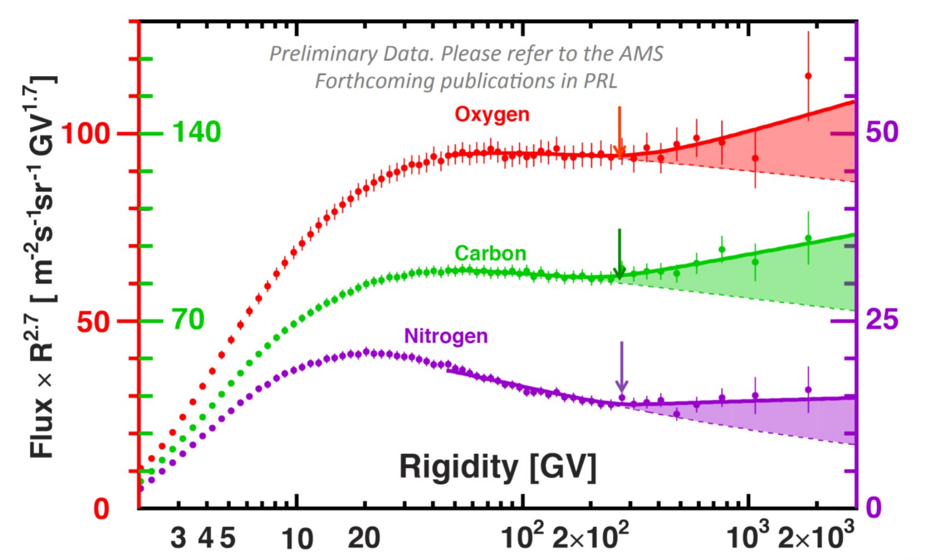
Hardening spectra

Hardening in CNO seen by AMS and CALET, at 200-300 GeV/n (but 27% difference in normalization…); spectral index changes from about 2.7 to 2.6.

P. Mastro et al. (CALET) PoS(ICRC2021)093
also
O. Adriani et al., PRL 125, 251102 (2020)

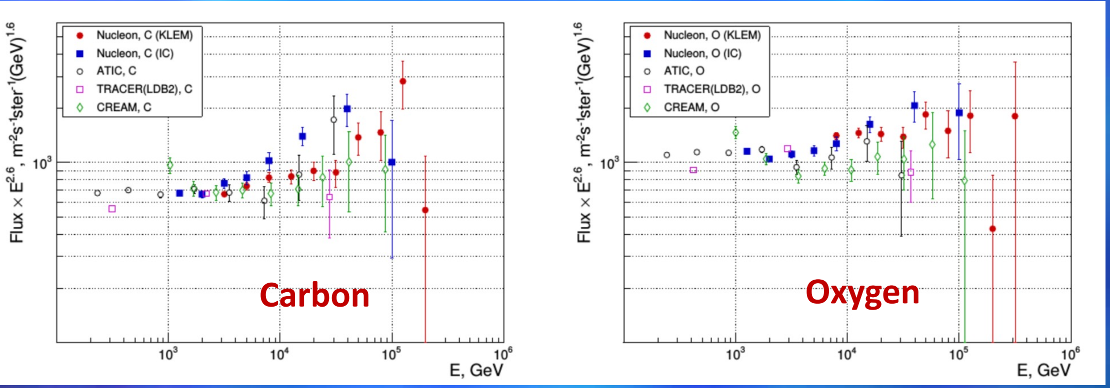


AMS 2017: 35th ICRC, Busan, South Korea
A. Kounine et al., PoS(ICRC2017)1093

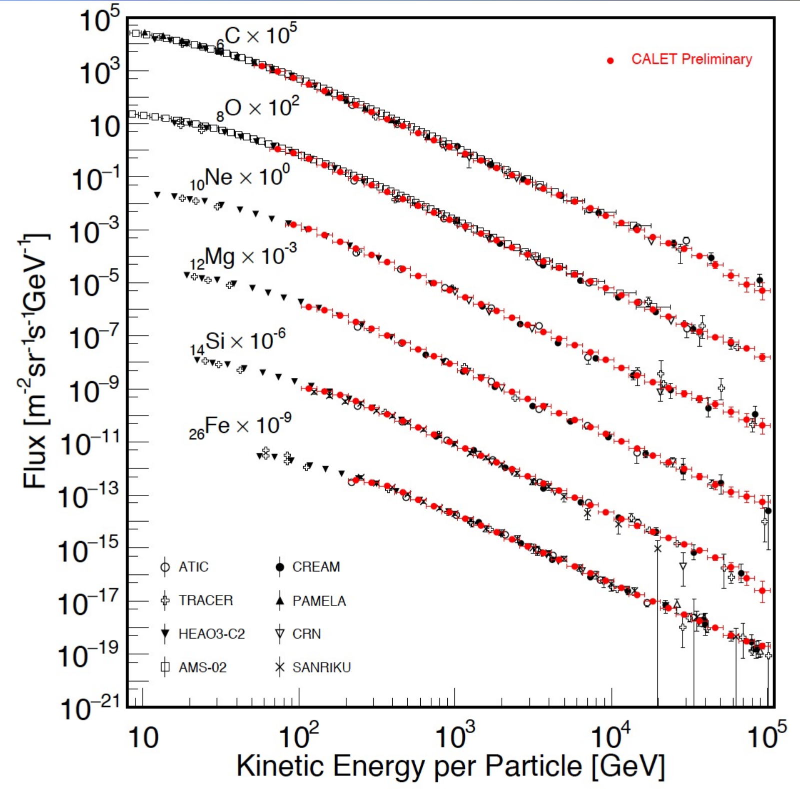


Other recent results

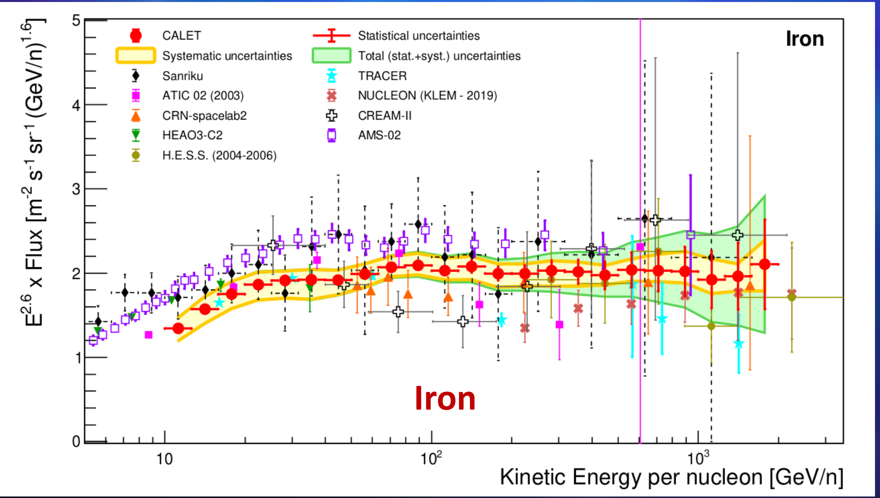
A. Panov et al. (NUCLEON) PoS(ICRC2017)1024



Y. Akaike et al. (CALET) 2019
J. Phys.: Conf. Ser. 1181, 012042

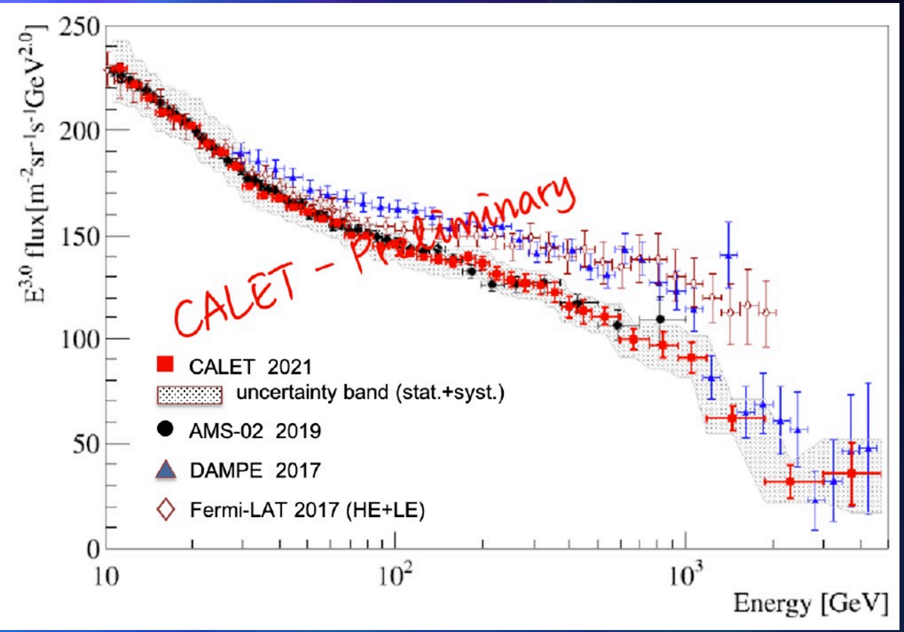


F. Stolzi et al. (CALET) PoS(ICRC2021)109



S. Torii et al. (CALET) PoS(ICRC2021)105

Electrons

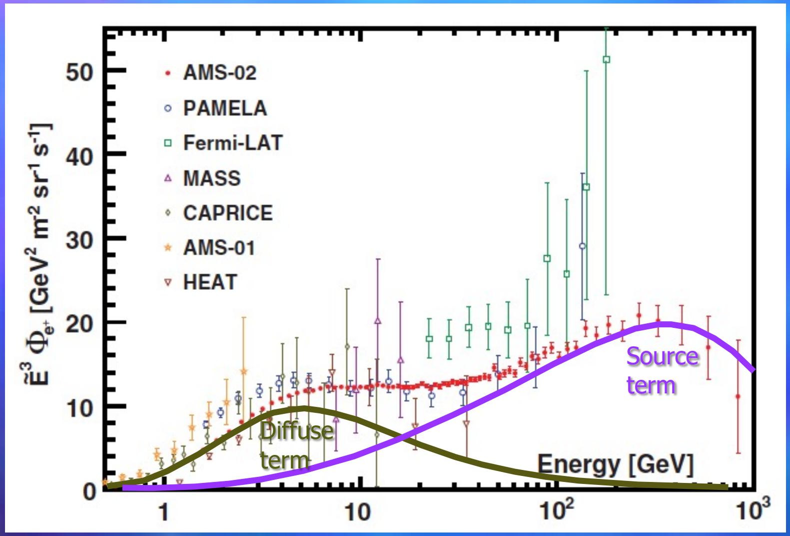


(CALET+AMS02) vs (DAMPE+Fermi-LAT)
Apparent tension... but E^3 rescaling can do funny things and control of systematics needs improvement

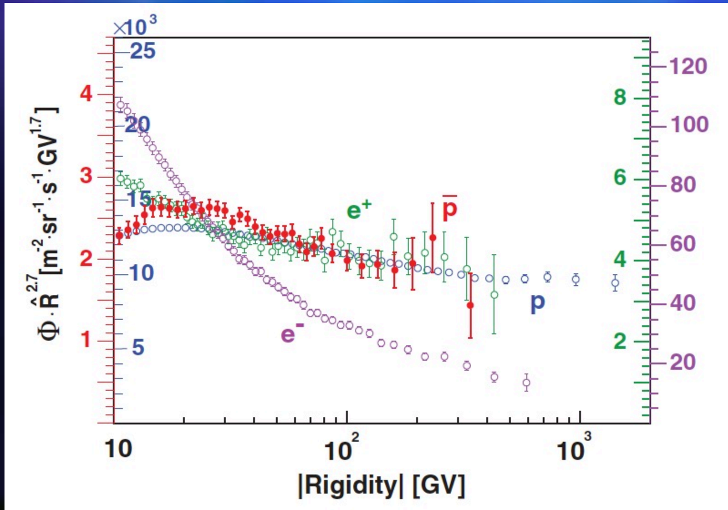
- Interpretation requires understanding distributed Galactic source contributions + perhaps some nearby pulsars;
- there seems to be a hardening in the >100 GeV region;
- TeV dropoff now confirmed;
- no strong features apparent in the multi-TeV region indicative of a dominant nearby source (maybe slight uptick at E>3TeV?);
- active theoretical investigations of shock acceleration details.

Antimatter

M. Aguilar et al., PRL 122, 041102 (2019)



- AMS-02 positrons: interpretation of the "source term" is not clear (dark matter or something less exciting?);
- secondary production needs to be better understood.



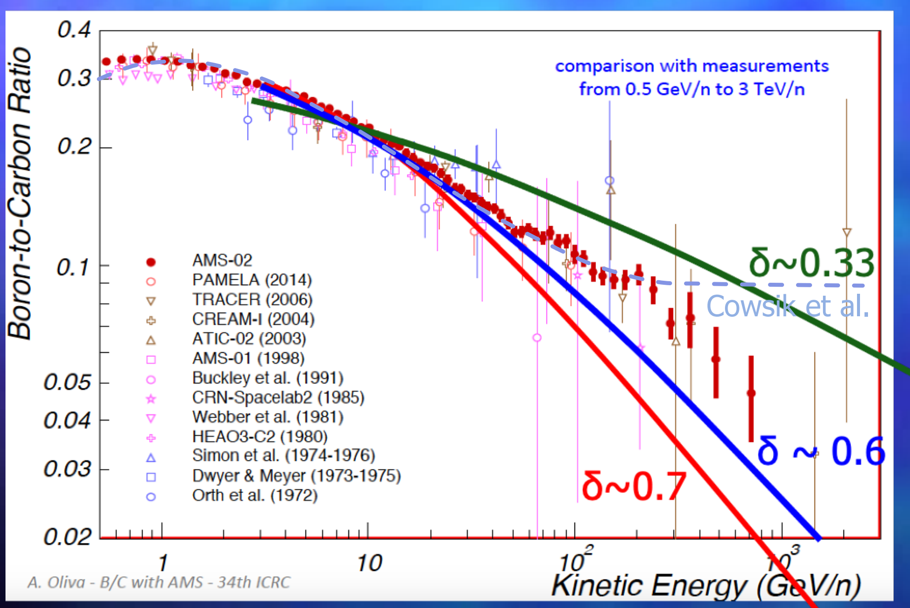
- Any meaningful pbar structure?
- Interesting similarity between positron and antiproton spectra (antiprotons cannot come from pulsars)

- New regime: antideuterons

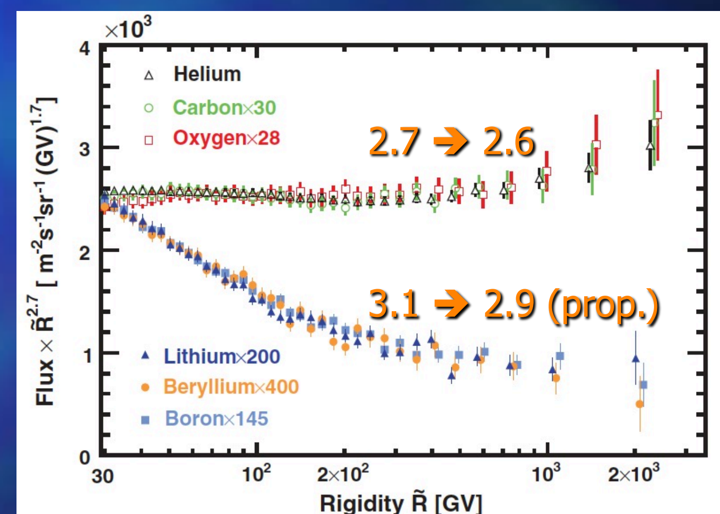
M. Aguilar et al., PRL 117, 091103 (2016)

Secondary nuclei

- B/C shape well constrained by AMS;
- interesting sec vs pri comparison;
- Be and other isotopes need better measurements (including spallation cross-sections);
- phenomenological understanding of secondary production being refined (crucial for antimatter).



H.S. Ahn et al., Astropart. Phys. 30, 133 (2008)
A. Oliva et al., 34th ICRC (2015)
M. Aguilar et al., PRL 117, 231101 (2016)

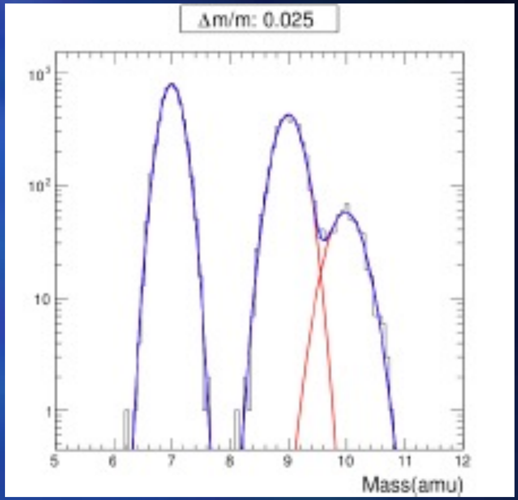


M. Aguilar et al., PRL 120, 021101 (2018)

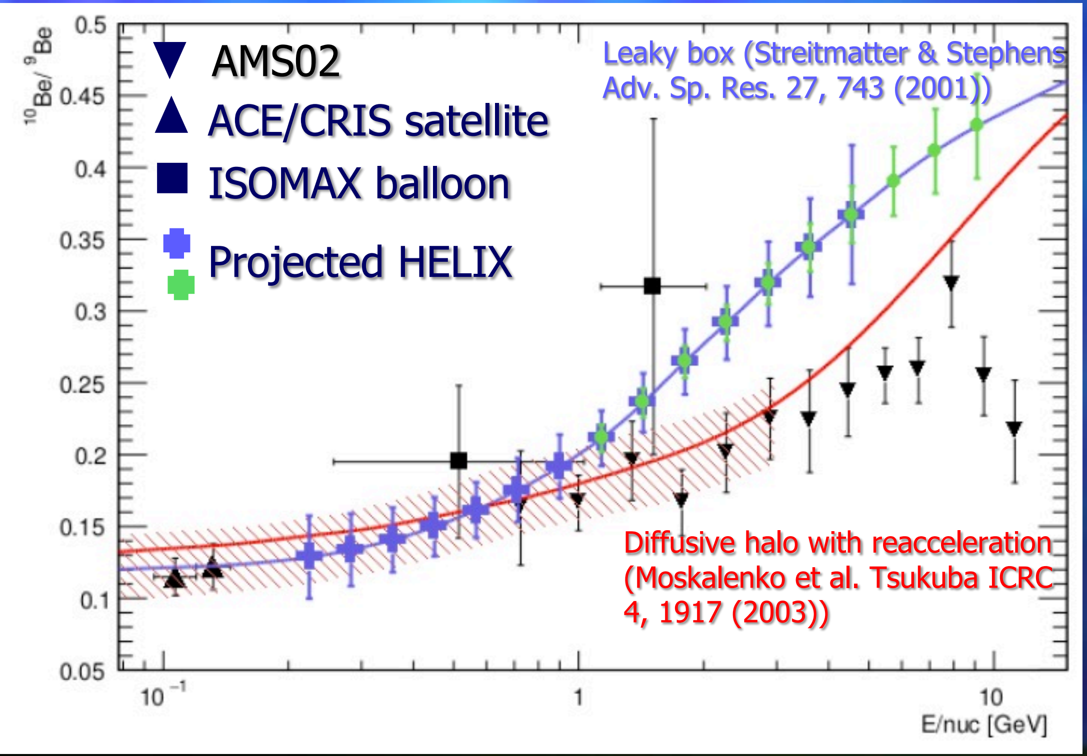
Be isotopes

- Be entirely secondary; ^{9}Be is stable, but ^{10}Be decays ($\lambda \sim 1.39$ Myr)
- Energy evolution of ^{10}Be/^{9}Be ratio traces increasing regions of the Galaxy (Lorentz time dilation): disk at 0.3 GeV/n, halo at 10 GeV/n.

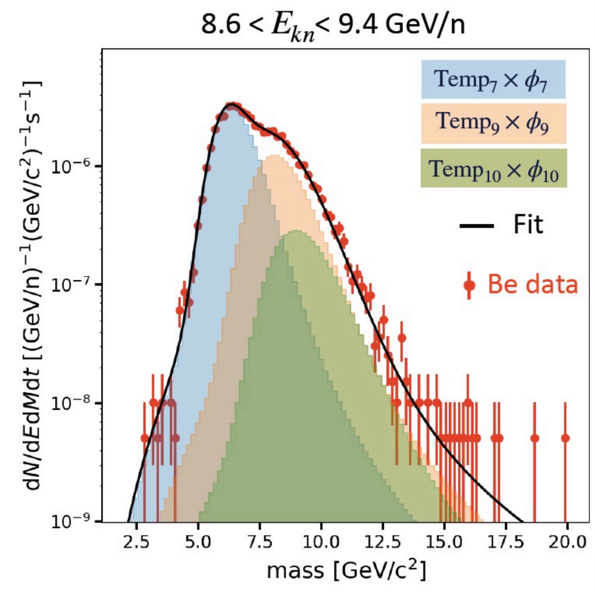
Be isotopes with $\Delta m/m = 2.5\%$, HELIX design



HELIX: 7-14 day exposure, 0.1 m^{2}sr acceptance



AMS Be isotopes are not mass resolved



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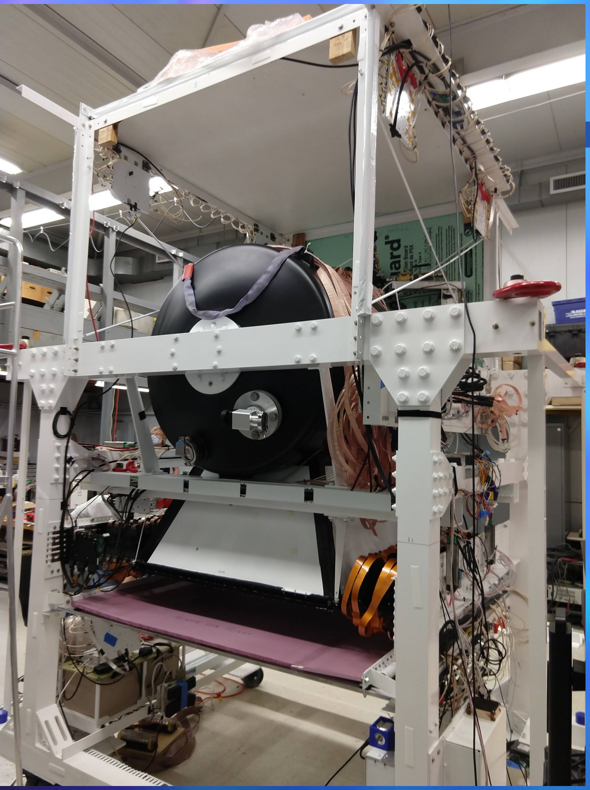
HELIX

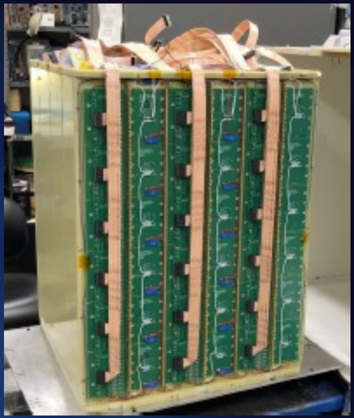
High Energy Light Isotope eXperiment
Sweden or Antarctic flight 2023

refurbished
HEAT magnet



ToF plane

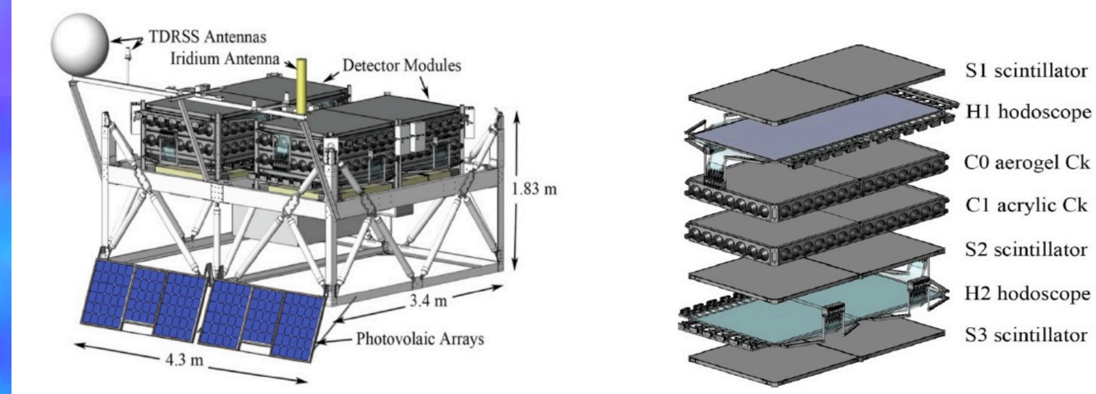
DCT



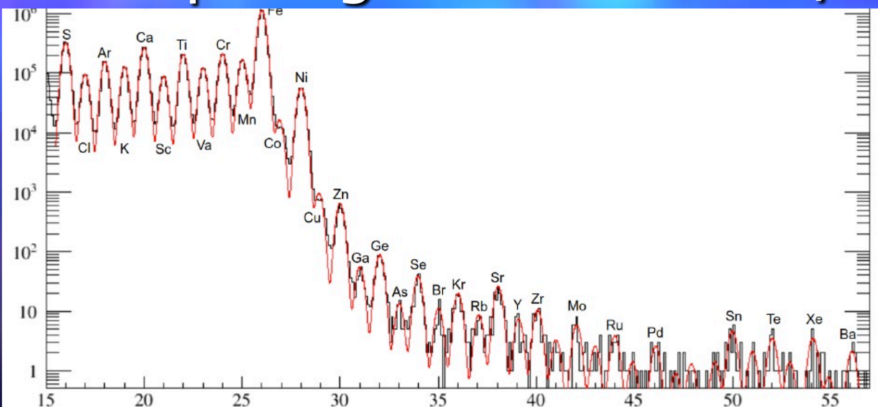
RICH

n=1.15 aerogel tiles from
Chiba University
10 x 10 x 1 cm^3 tile

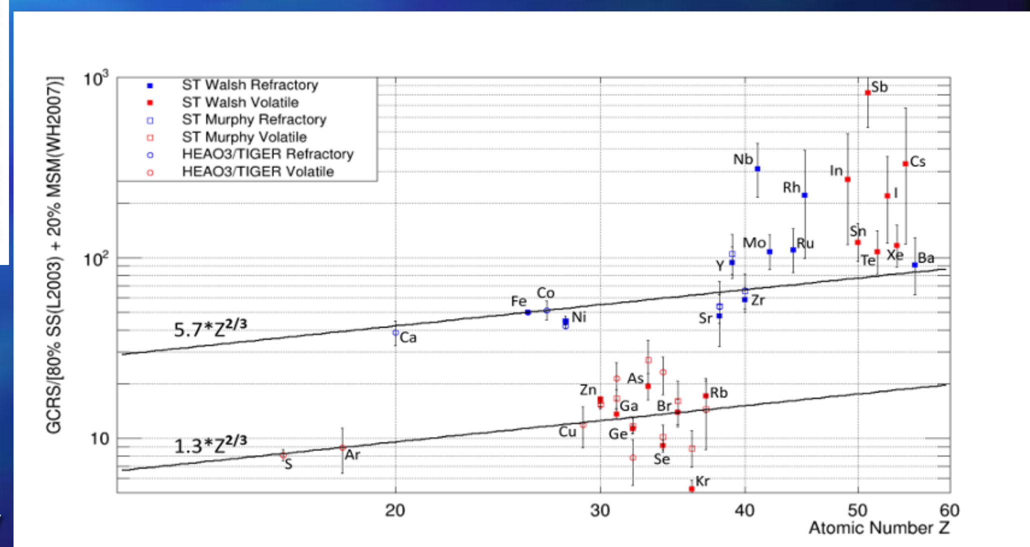
SuperTiger



- Antarctic balloon payload;
- Large acceptance for rare heavy nuclei;
- Surprising twist in volatile/refractory trends…



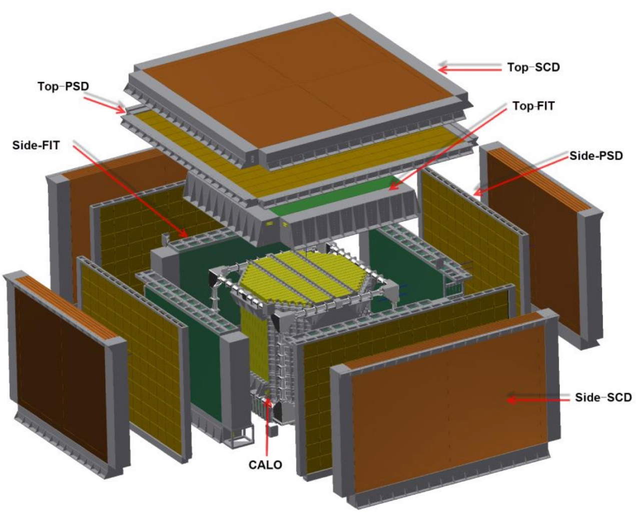
N.E. Walsh et al., PoS(ICRC2021)118



Model with 80% solar system material + 20% massive star material; refractory elements preferred over volatiles up to Z~40, but not true beyond; likely r-process origin implications.

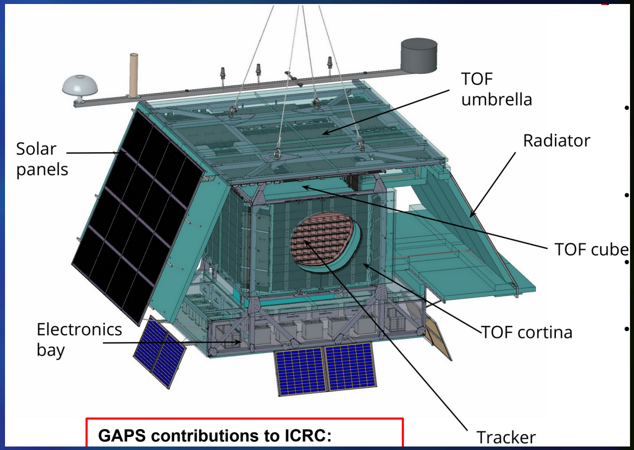
Future missions

HERD for nuclei up to 3 PeV (Chinese SS 2027)

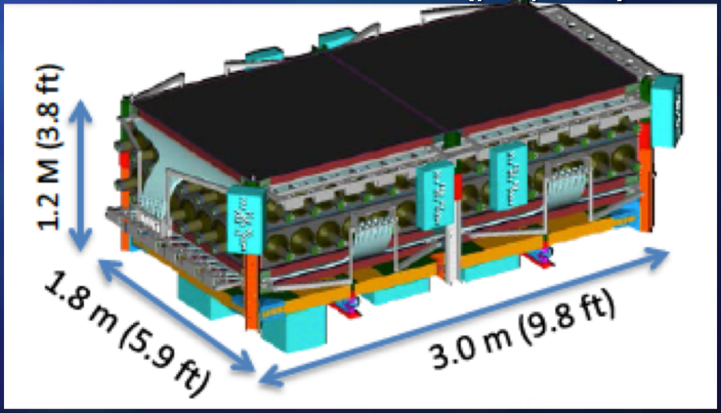


Plus PUEO, POEMMA, EUSO, APT, HEPD02, GAMMA-400, …

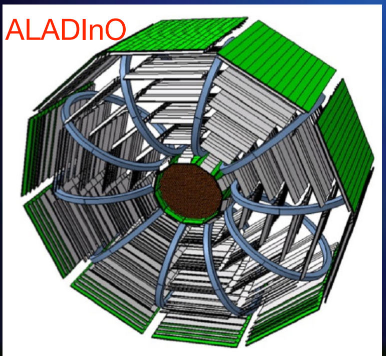
GAPS for antideuterons (balloon 2022)

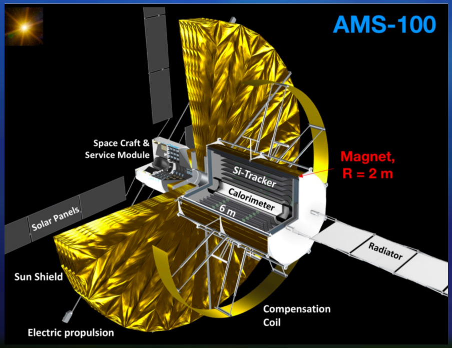


TIGERISS for ultraheavies (proposal)



ALADInO and AMS-100 for antimatter (concepts)





Thanks to

Conclusions

Direct studies of cosmic-ray nuclei now yield high precision and energy reach overlapping ground-based instruments.

Elemental spectra now show hardening at ~300-500 GeV/n; additional spectral structure at the high end (~10-14 TeV/n) for p and He;

- These observations need theoretical explanations;
- Could be a source effect and shock acceleration needs refinement;
- Could be a propagation effect;
- Could be due to the effect of nearby accelerators.

Secondary elements are starting to constrain propagation. Need refined isotope measurements, accelerator cross sections. Impact on secondary production, including antimatter.

Antimatter, electrons continue to offer fascinating alternative glimpses into the high-energy universe.

Next-gen instruments are expanding and refining these measurements, which anchor composition models for studies at higher energies with ground-based detectors. New and proposed instruments push to ever higher energies.


Dziękuję !