PennState

Direct Composition Measurements: Status and Prospects

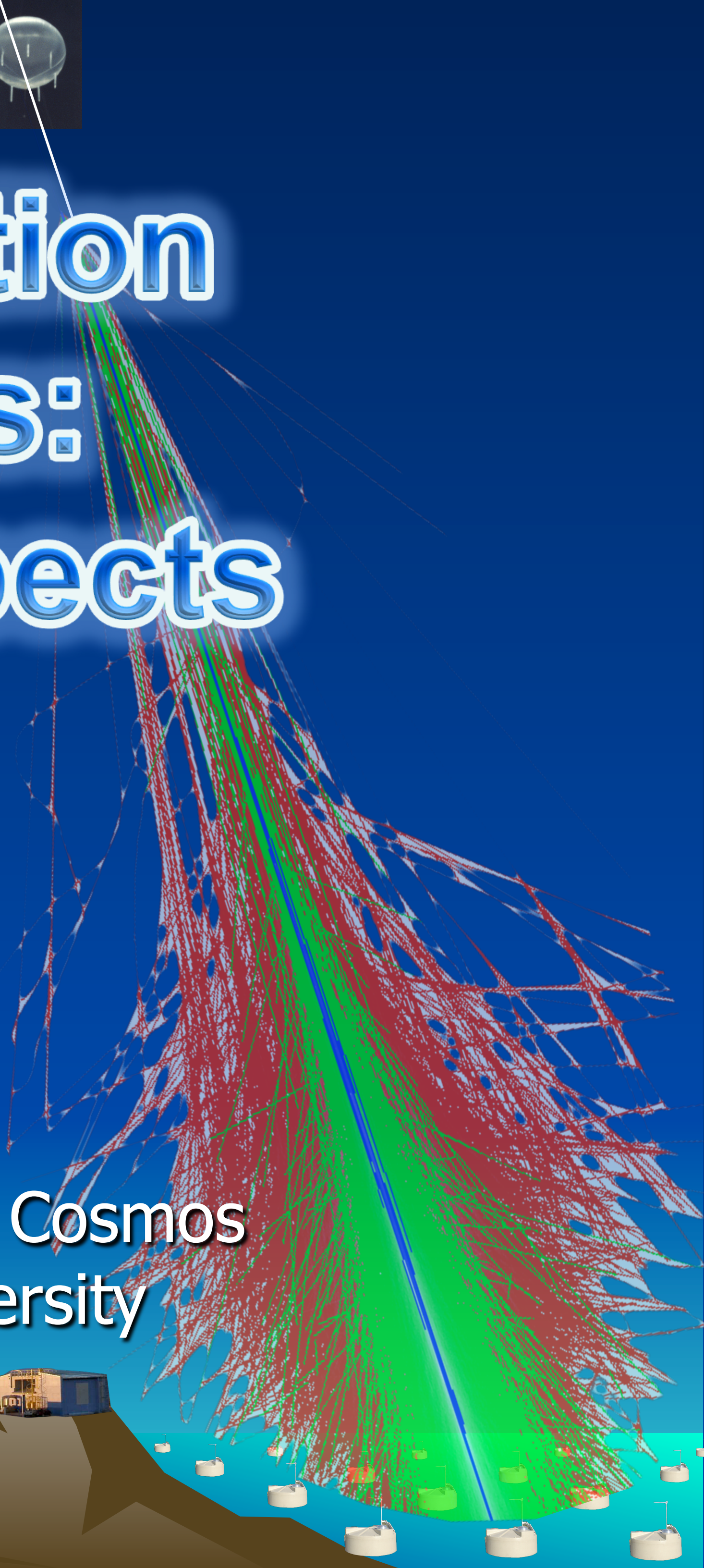
HAP Workshop 2015

COMPOSITION in the galactic to extragalactic transition range

KIT

September 21-23, 2015

Stéphane Coutu
Institute for Gravitation and the Cosmos
The Pennsylvania State University

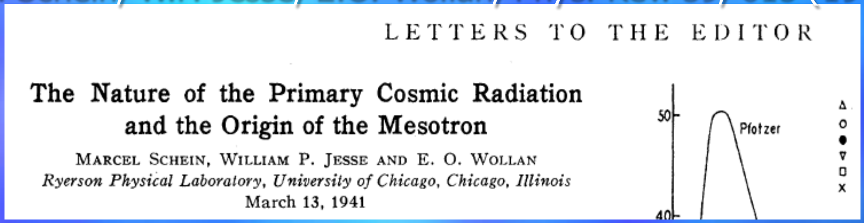


The Pioneers

Advent of balloons: *direct* measurements

- 85% protons (Schein, 1940s);

M. Schein, W.P. Jesse, E.O. Wollan, Phys. Rev. 59, 615 (1941)



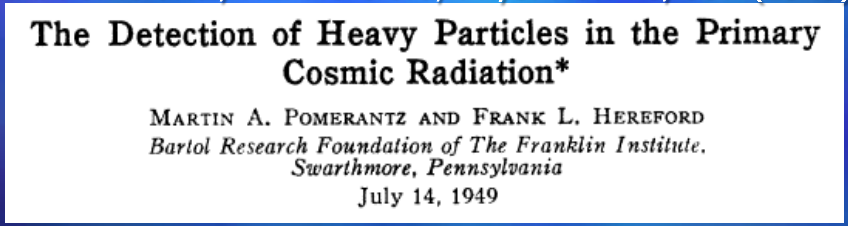
LETTERS TO THE EDITOR

The Nature of the Primary Cosmic Radiation and the Origin of the Mesotron

MARCEL SCHEIN, WILLIAM P. JESSE AND E. O. WOLLAN
Ryerson Physical Laboratory, University of Chicago, Chicago, Illinois
March 13, 1941

- 12% helium (Pomerantz, Hereford 1947);

M.A. Pomerantz, F.L. Hereford, Phys. Rev. 76, 997 (1949)

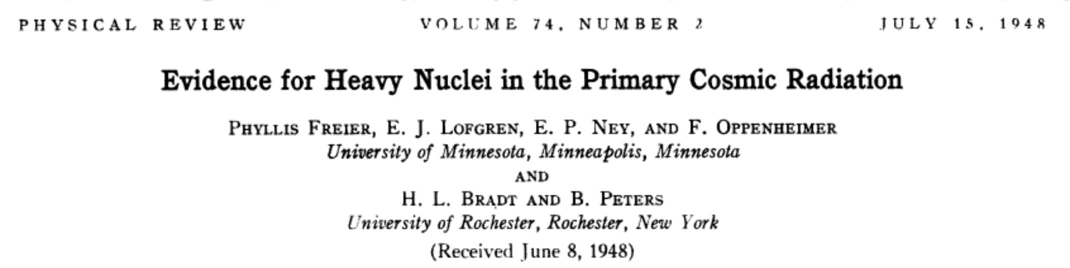


The Detection of Heavy Particles in the Primary Cosmic Radiation*

MARTIN A. POMERANTZ AND FRANK L. HEREFORD
Bartol Research Foundation of The Franklin Institute, Swarthmore, Pennsylvania
July 14, 1949

- 2% Li-Fe (Freier et al. 1948);

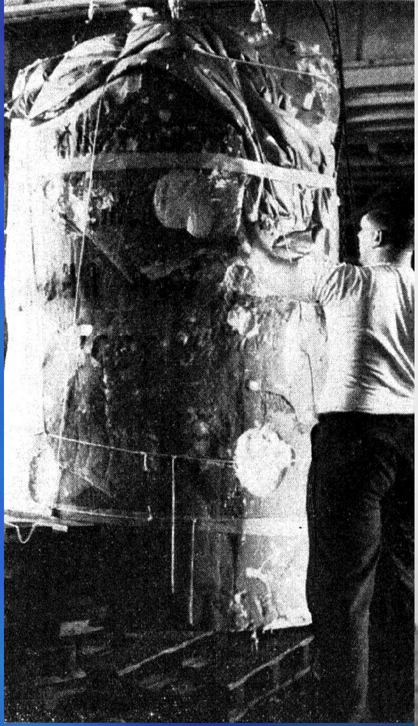
P. Freier, E.J. Lofgren, E.P. Ney, F. Oppenheimer, H.L. Bradt, B. Peters, Phys. Rev. 74, 213 (1948)

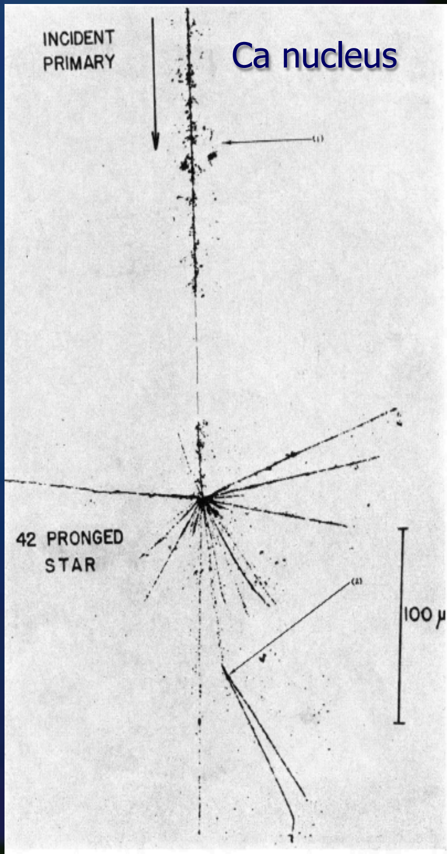


PHYSICAL REVIEW VOLUME 74, NUMBER 2 JULY 15, 1948

Evidence for Heavy Nuclei in the Primary Cosmic Radiation

PHYLLIS FREIER, E. J. LOFGREN, E. P. NEY, AND F. OPPENHEIMER
University of Minnesota, Minneapolis, Minnesota
AND
H. L. BRADT AND B. PETERS
University of Rochester, Rochester, New York
(Received June 8, 1948)



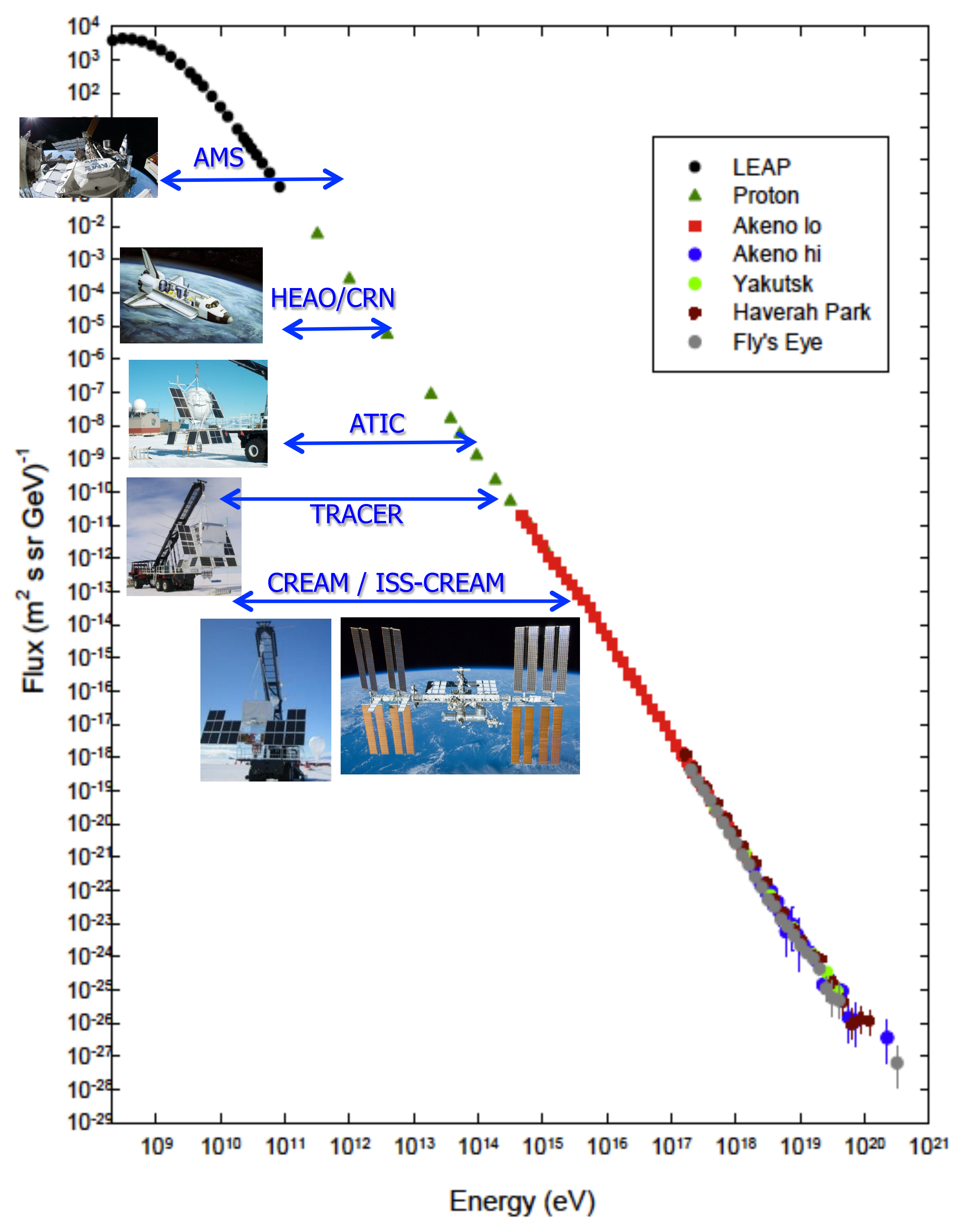


The spectrum

Direct measurements are hampered by steep power-law fall off…

11 orders of magnitude in energy;
31 orders of magnitude in intensity…

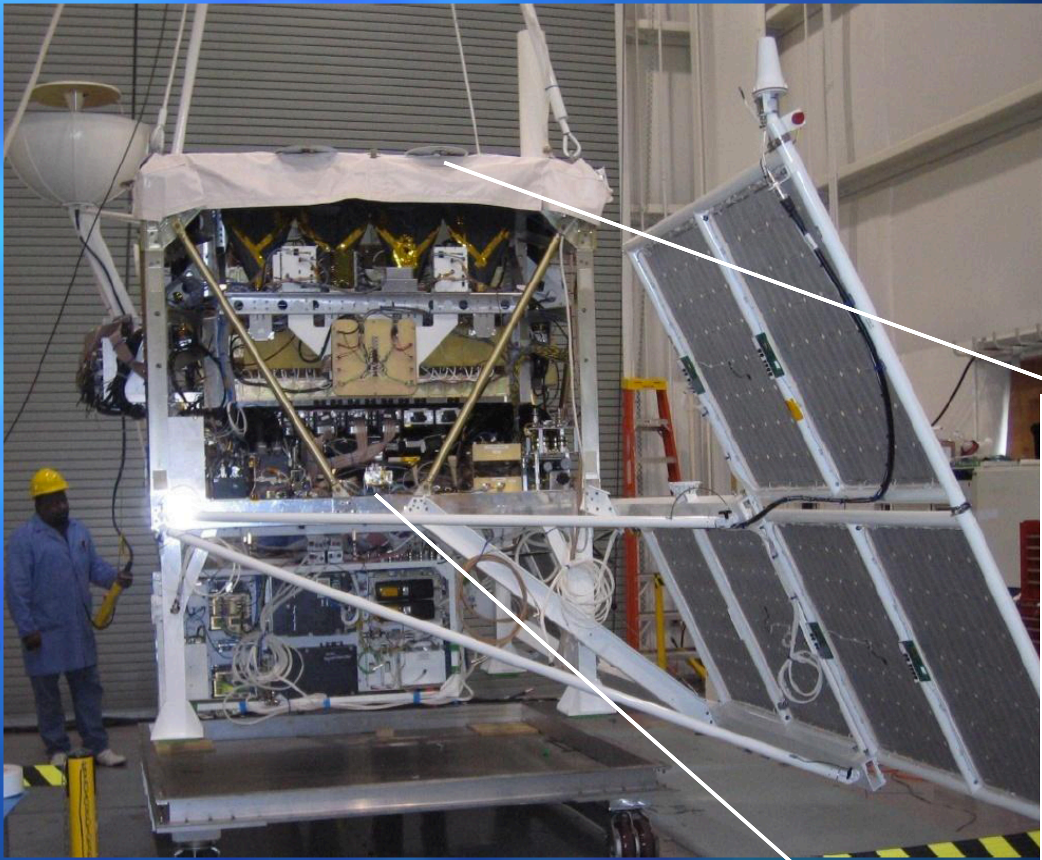
Direct elemental spectra can be measured up to the knee, but not beyond.

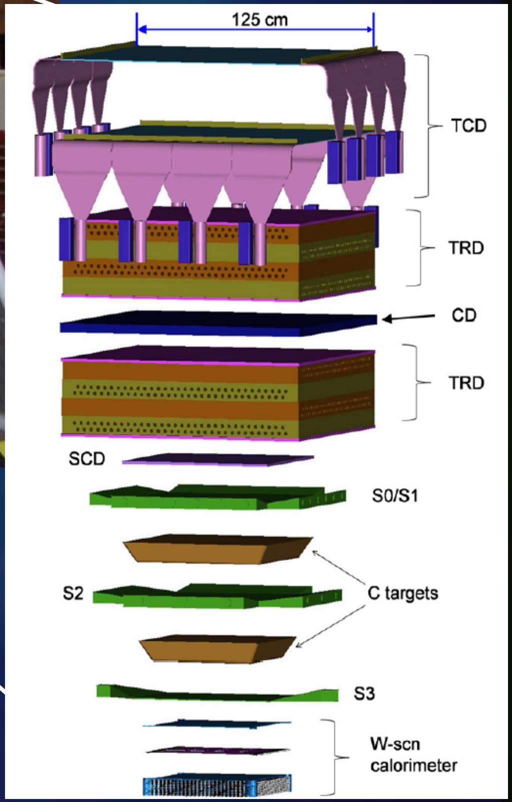


CREAM
(Cosmic Ray Energetics And Mass)

Since the 1960s, ever larger, more complex instruments flown for longer durations;
e.g.: JACEE, RUNJOB, BESS, TRACER, ATIC, HEAT, (Super) TIGER, CREAM:

- 2004-2011,
- 6 Antarctic flights,
- 166 days of exposure.





Measure elemental primary spectra from H to Fe, from 100 GeV to >100 TeV/nucleus.

Mass 1,300 kg, power 400 W; 2.2 m^2 sr aperture;
CAL: 20X_0; 0.46λ_{int} C target; $\delta E \sim 5\%$ energy scale;
Charge: $\delta Z \sim 0.2e$ (0.35e for Fe);

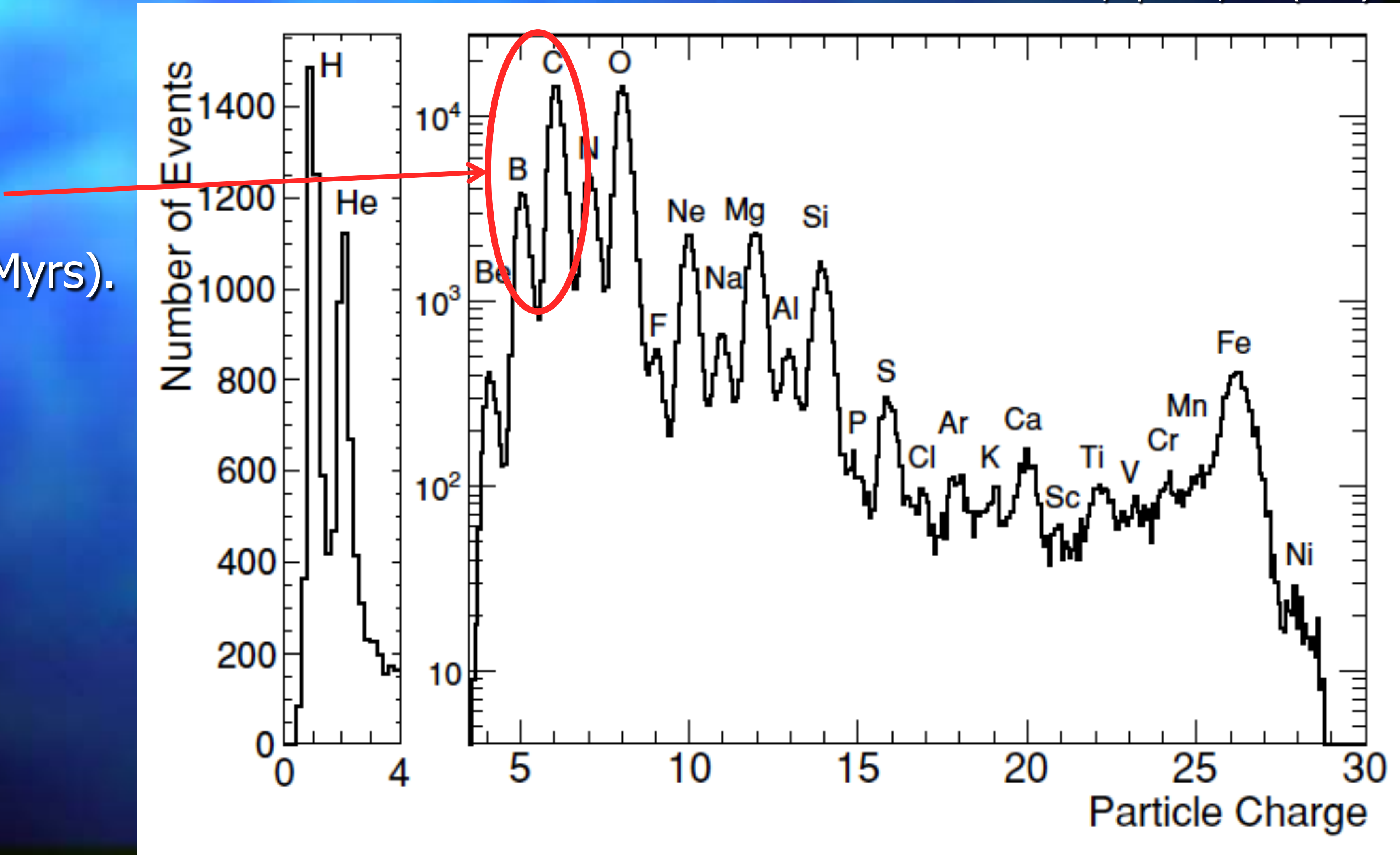
Overall flux systematics ~10%.

Elemental abundances

Charge resolution ~0.2e (0.35 for Fe)

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

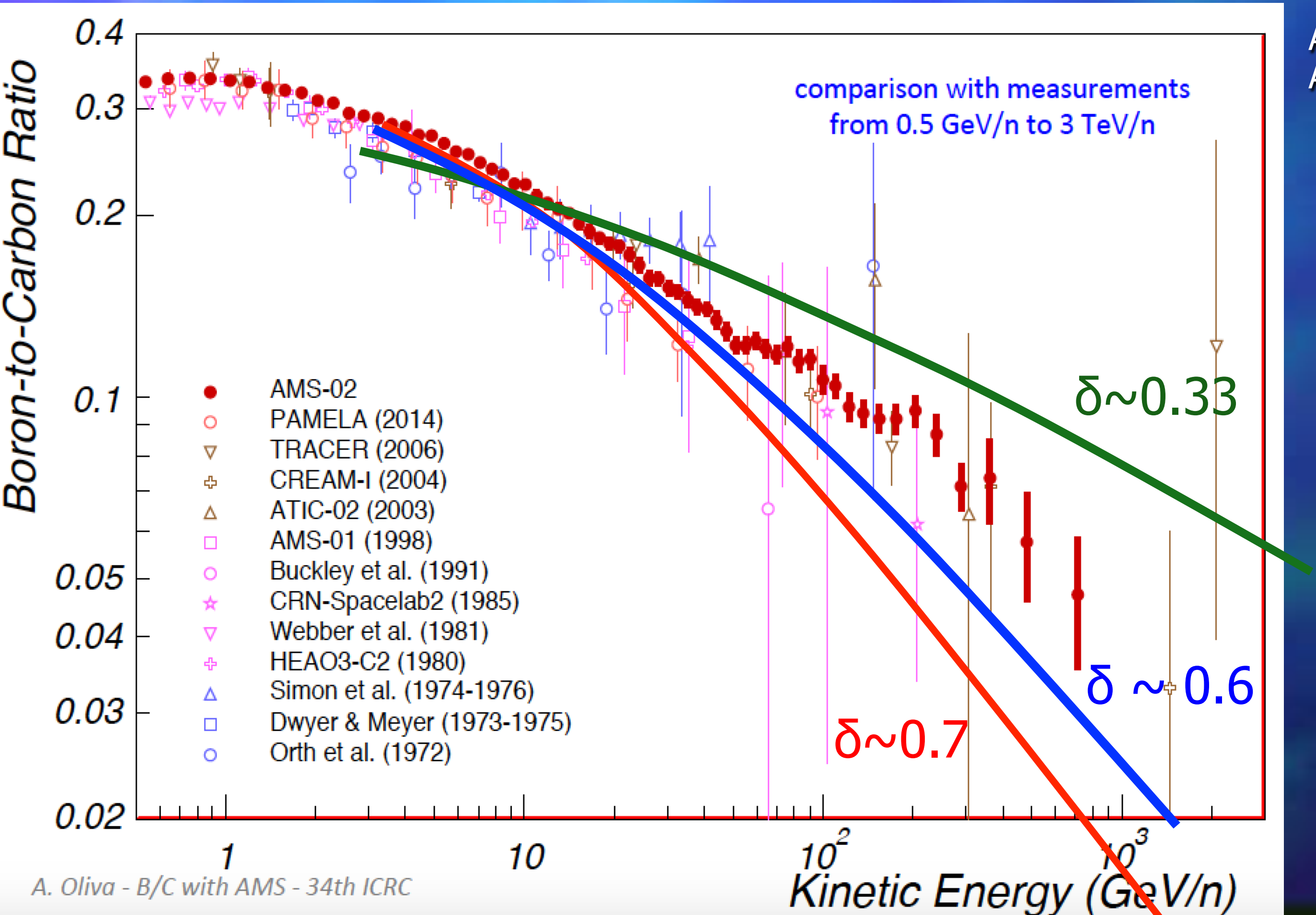
B/C sensitive to the CR propagation history (over Myrs).



B/C ratio

B/C has sensitivity to Galactic diffusion δ;

DSA theory predicts E^{-2} spectrum, observed $E^{-2.65}$, expect $E^{-(2+\delta)}$.



A. Oliva - B/C with AMS - 34th ICRC

Ahn H.S. et al., Astropart. Phys. 30, 133 (2008)
A. Oliva et al., 34th ICRC (2015)

Technique limited to a few TeV/n at balloon altitudes because of local B production.

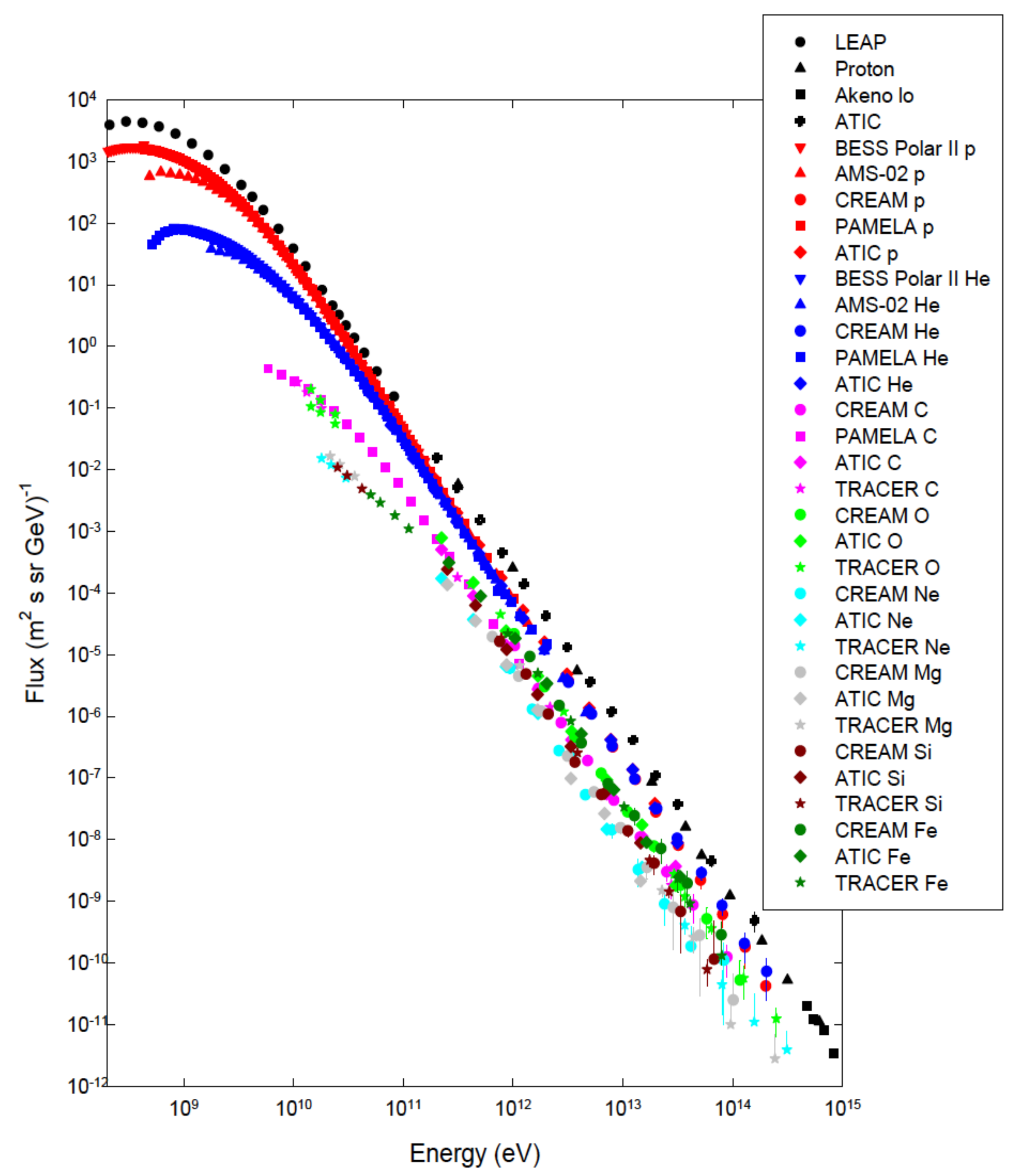
Elemental spectra

Measurements getting close to the knee;

Very high statistics at low energies (hundreds of GeV) from magnet spectrometers: BESS, PAMELA, AMS;

Balloon experiments agree at hundreds of GeV to ~100 TeV (ATIC, TRACER, CREAM);

Hard to see the details...

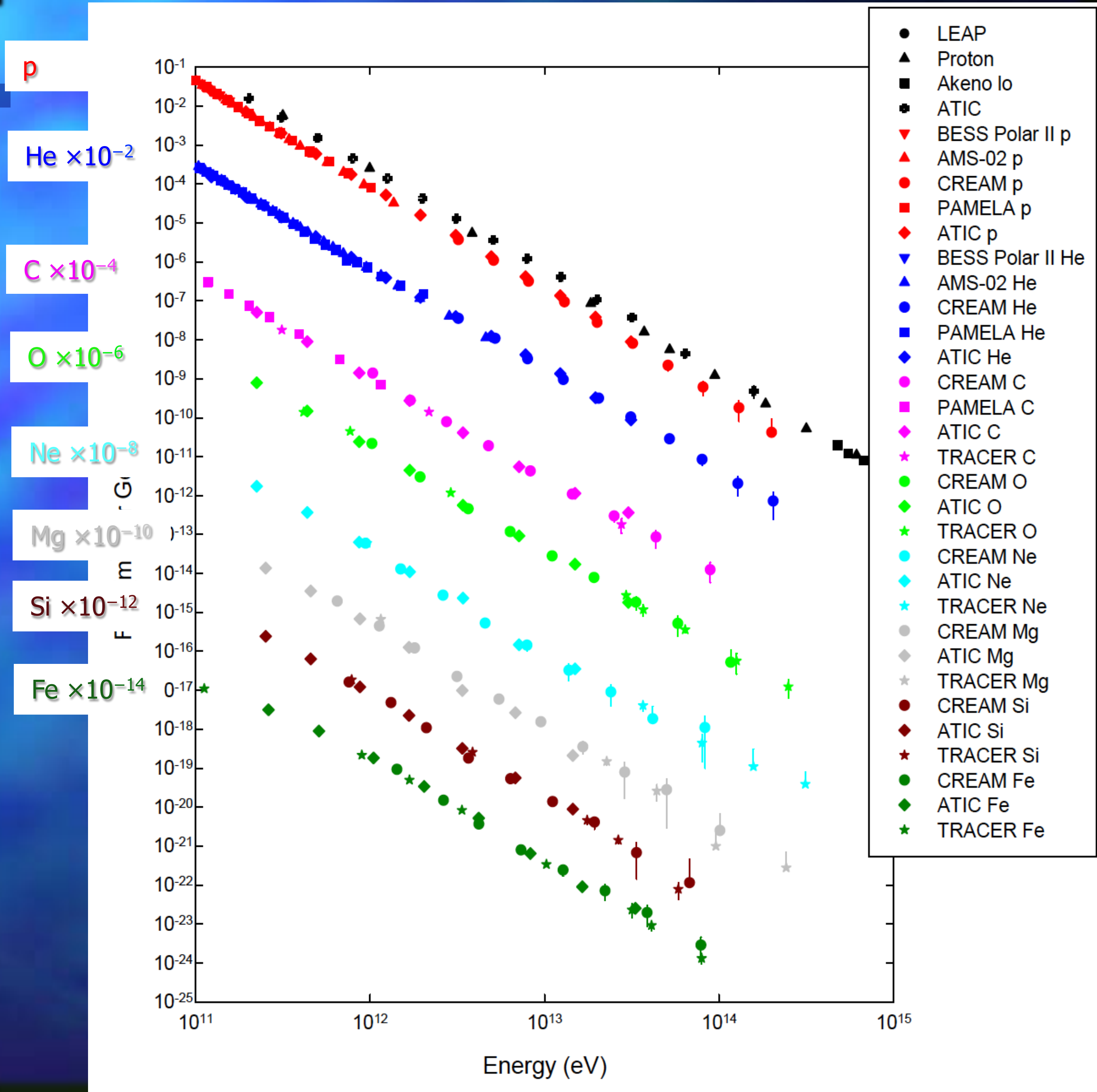


Elemental spectra

Zoomed in view above range of solar modulation effects (>100 GeV);

Separate things out with rescaling;

Better, but log scales can hide some “sins”…

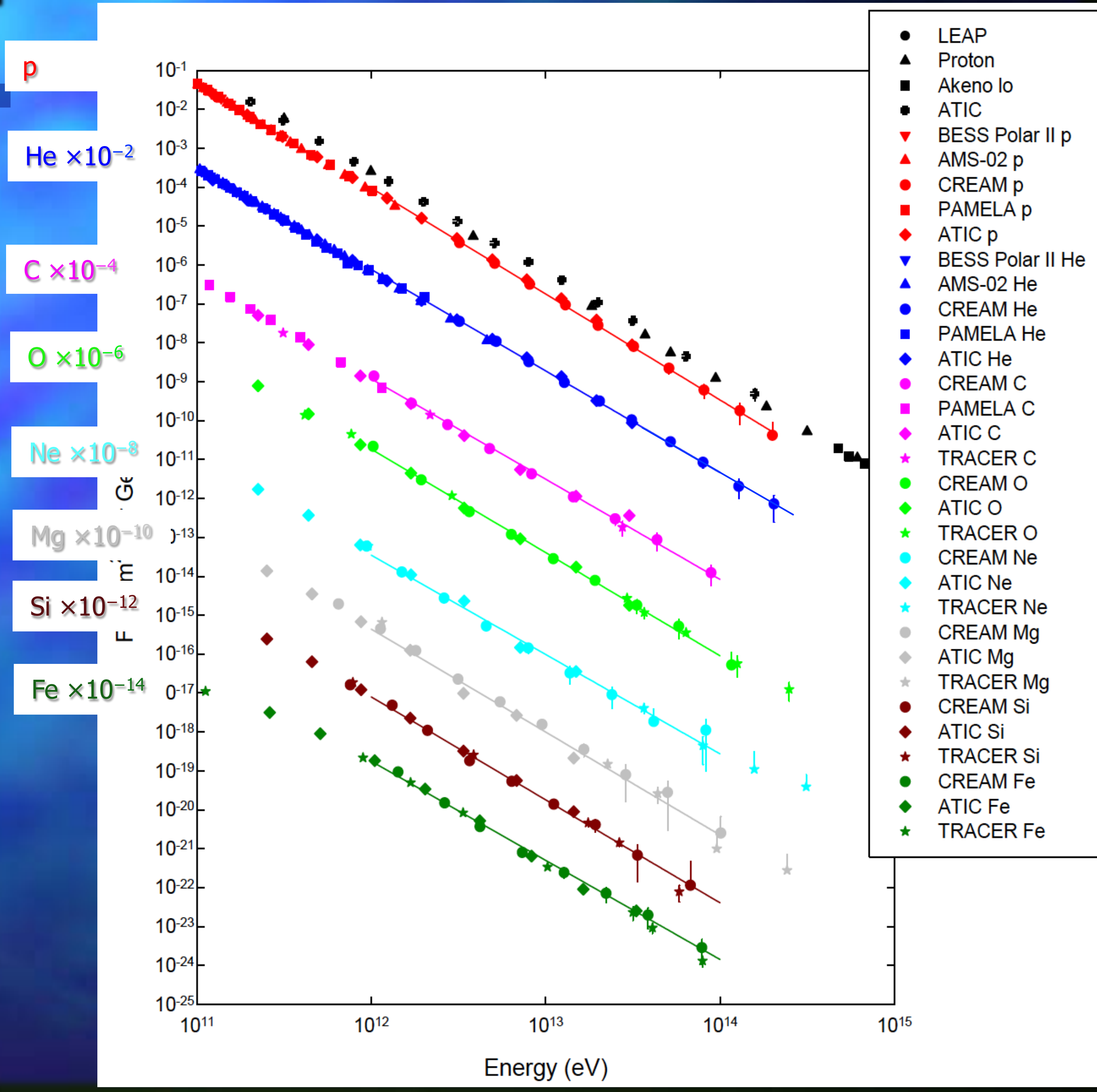


Elemental spectra

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: $dN/dE \sim E^{-2.63\pm0.11}$



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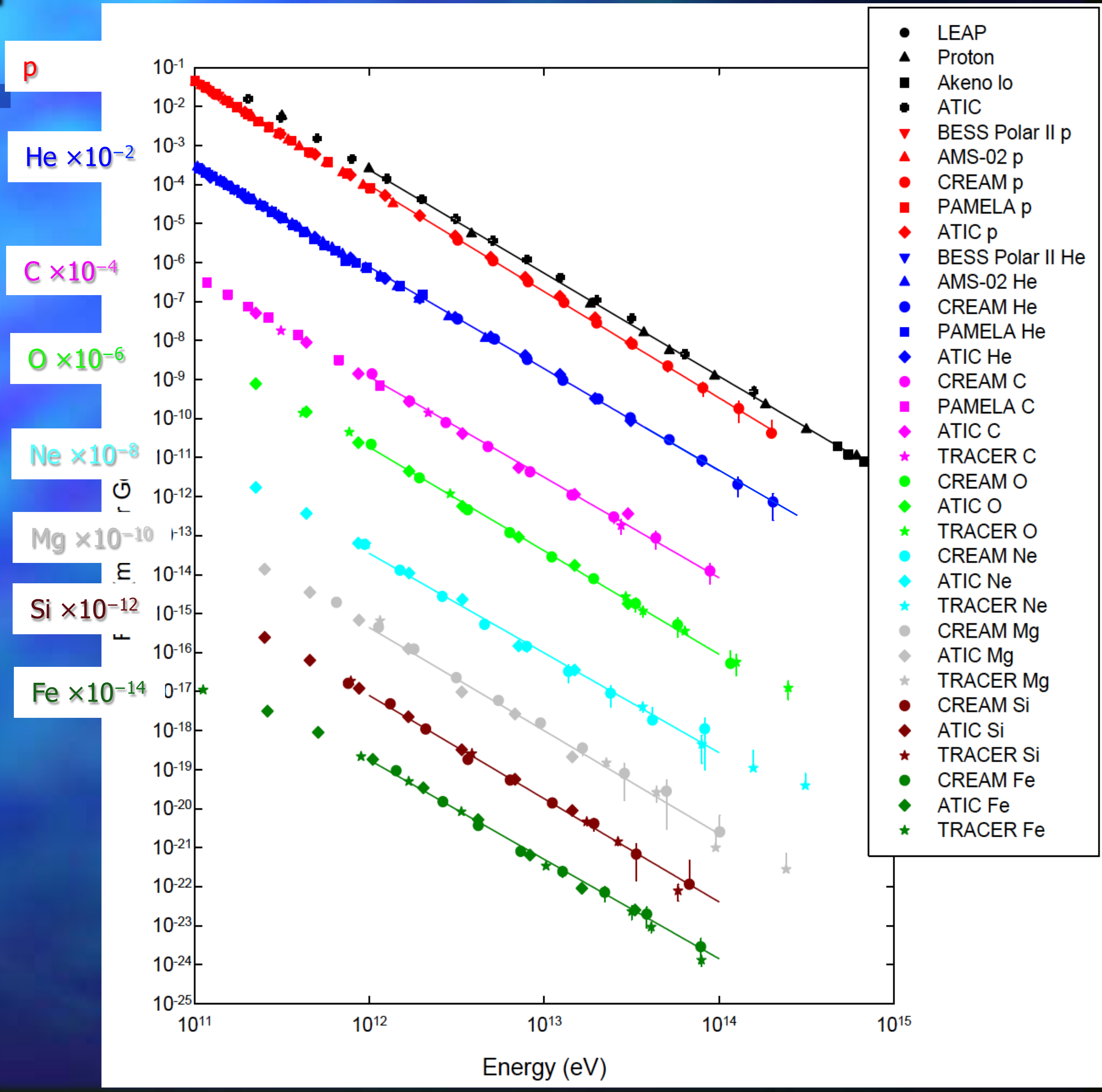
- Fe: $dN/dE \sim E^{-2.63\pm0.11}$

The components do add up to the all-particle spectrum!



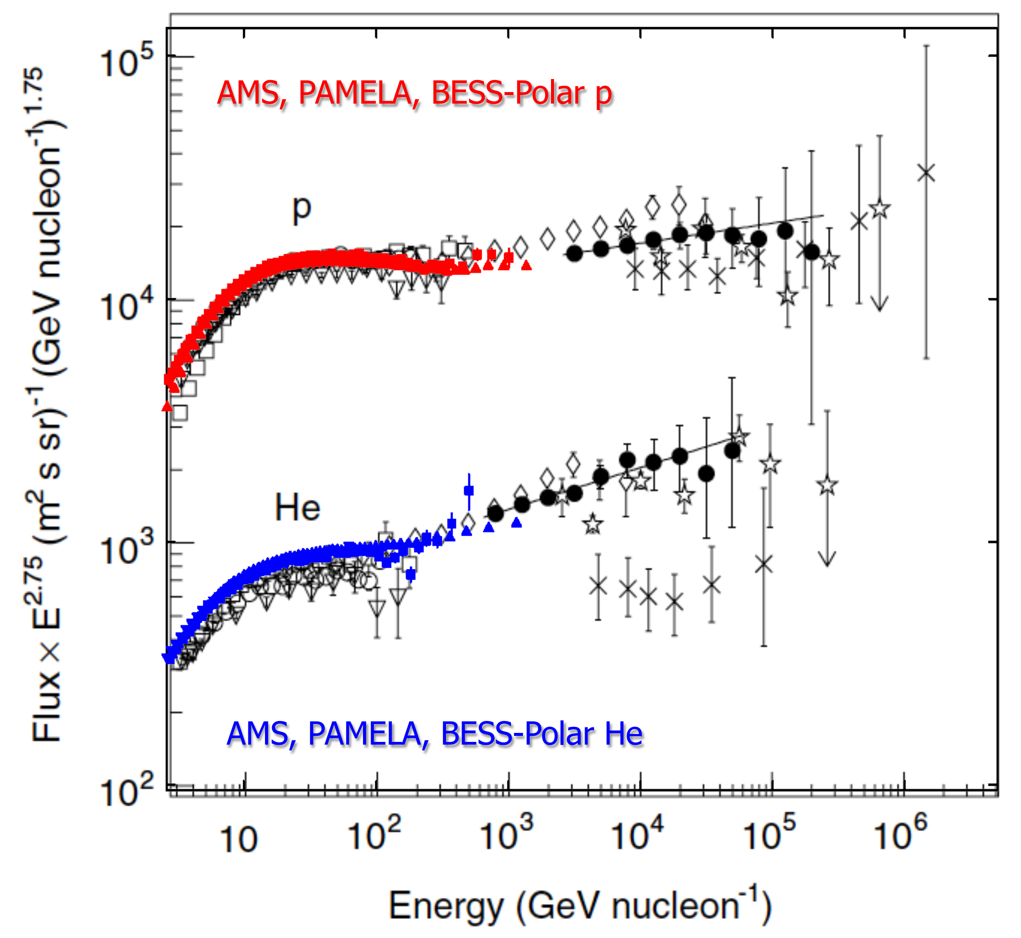
p vs He

Aguilar et al., PRL 114, 171103 (2015)
Adriani et al., Science 332, 69 (2011)
Abe et al., arXiv: 1506.01267 (2015)

Yoon et al., ApJ 728, 122 (2011)

CREAM measures a statistically different energy spectral index for the first time beyond a few TeV/nucleus:

- H: $dN/dE \sim E^{-2.66\pm0.02}$
- He: $dN/dE \sim E^{-2.58\pm0.02}$



Origin could be 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))

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))

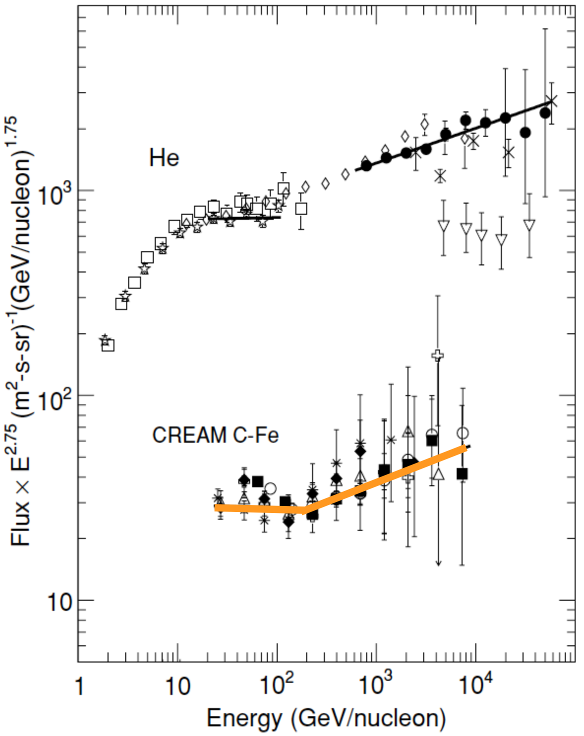
Hardening spectra

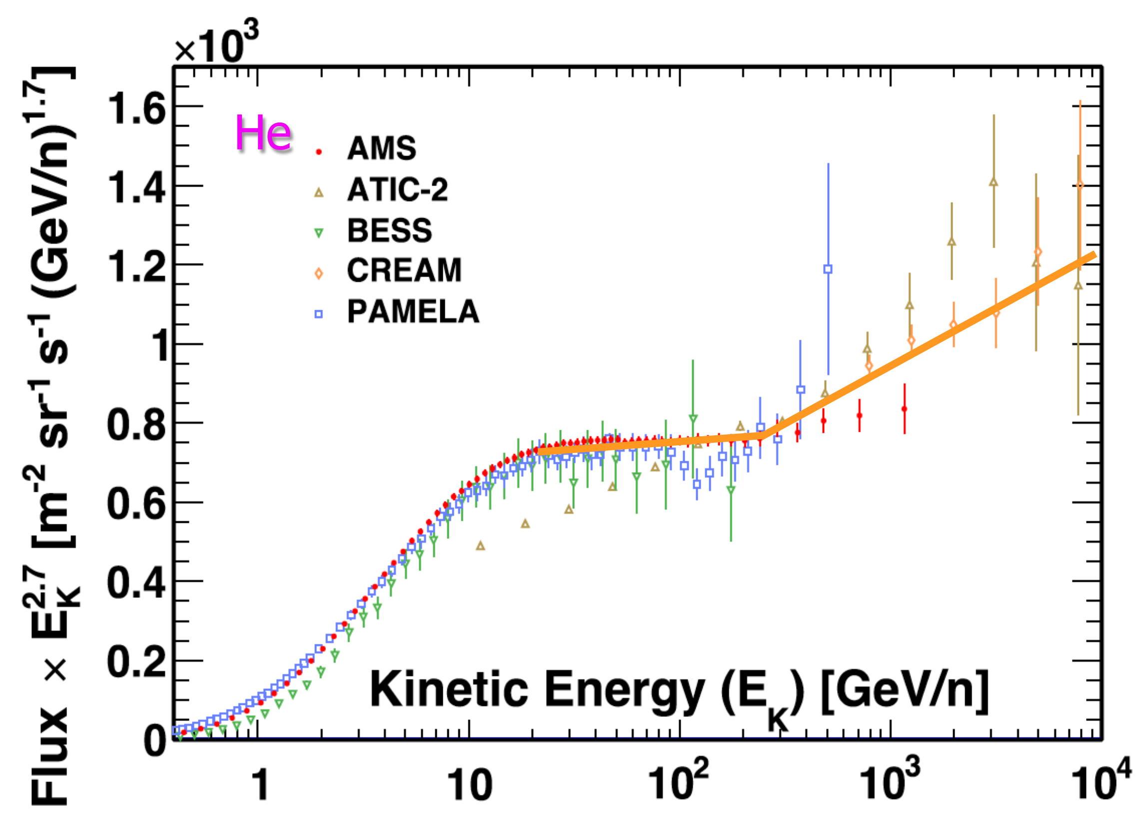
CREAM heavy element spectra (2010):
- He to Fe all seem to have similar spectra, same index as He (−2.58±0.02);
- Probably from the same source and acceleration mechanism.

- But at the 4σ level better fit with a broken power law (index change at 200 GeV/n);

- AMS/PAMELA see this in He;

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





https://indico.cern.ch/event/381134/timetable/#20150415

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

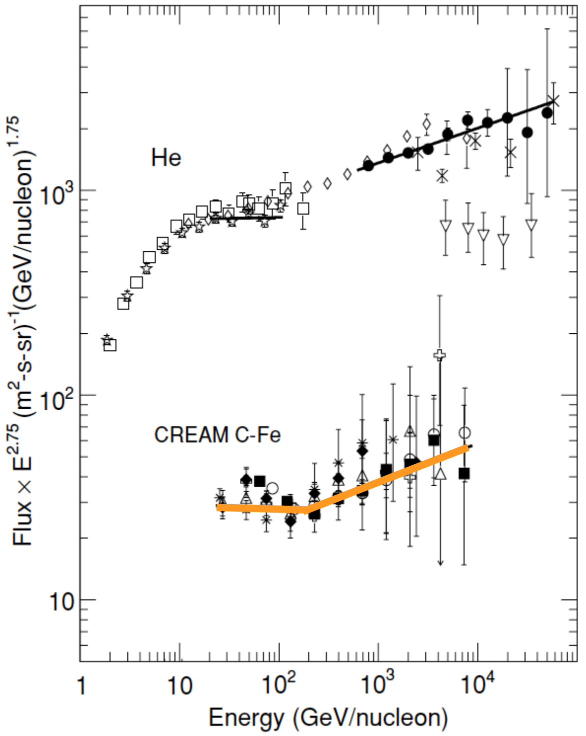
Hardening spectra

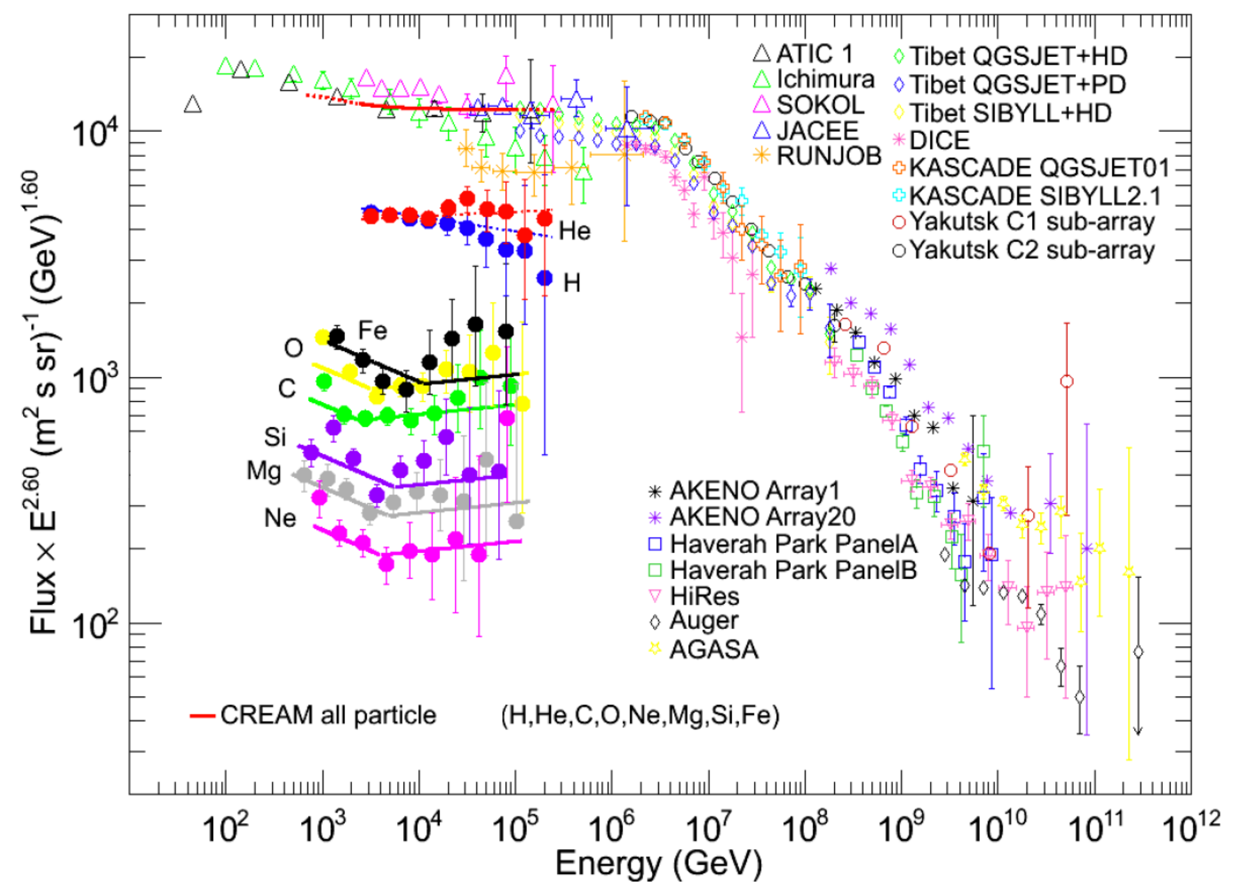
CREAM heavy element spectra (2010):
- He to Fe all seem to have similar spectra, same index as He (−2.58±0.02);
- Probably from the same source and acceleration mechanism.

- But at the 4σ level better fit with a broken power law (index change at 200 GeV/n 2.77±0.03 ➔ 2.56±0.04);

- AMS/PAMELA see this in He;

- Detailed source modeling needs to address this, but individual spectra do add up to that measured by air shower arrays.



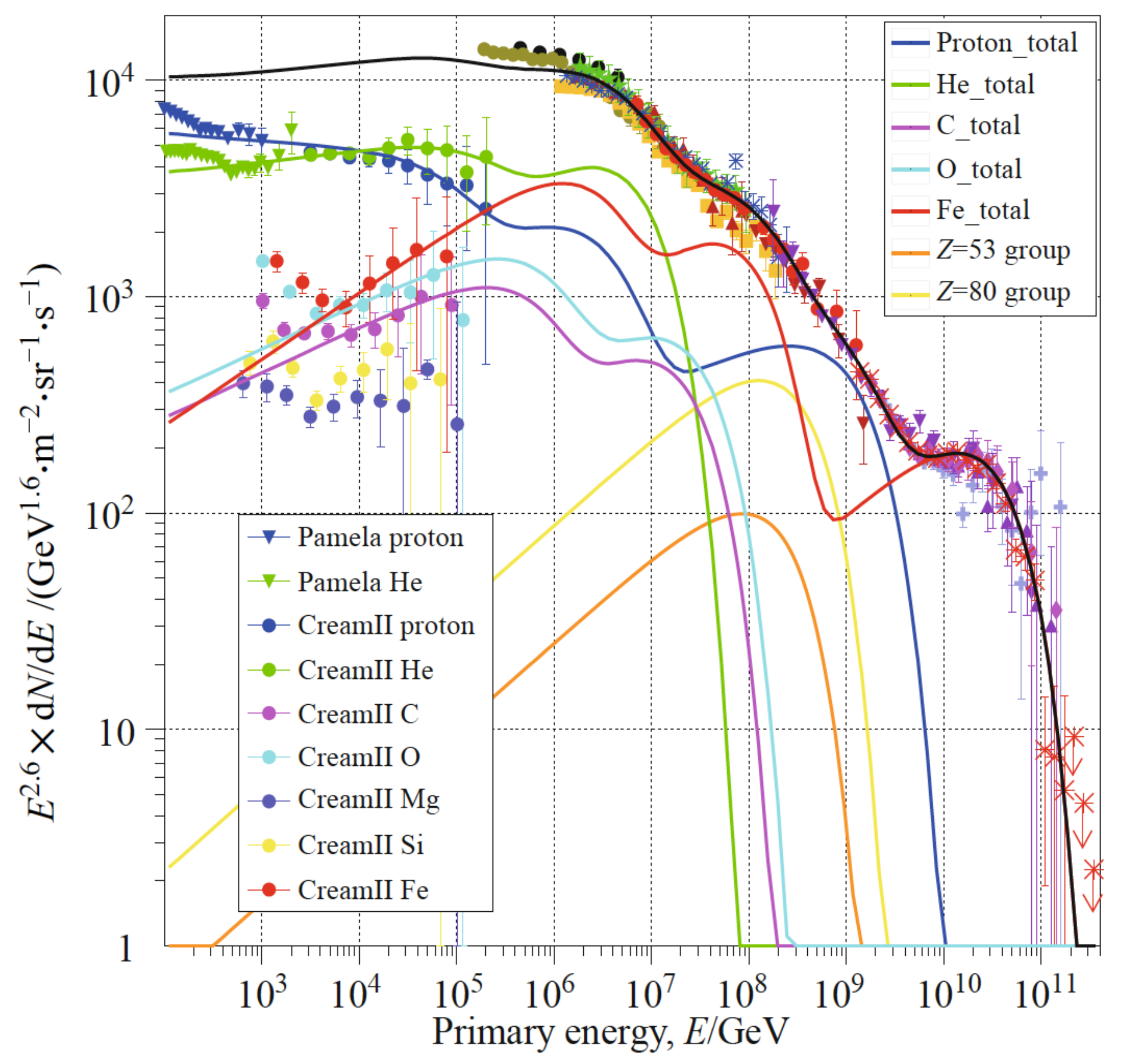


Beyond the knee

Direct measurements anchor models for composition interpretation of air shower measurements beyond the knee.

Rich phenomenology!

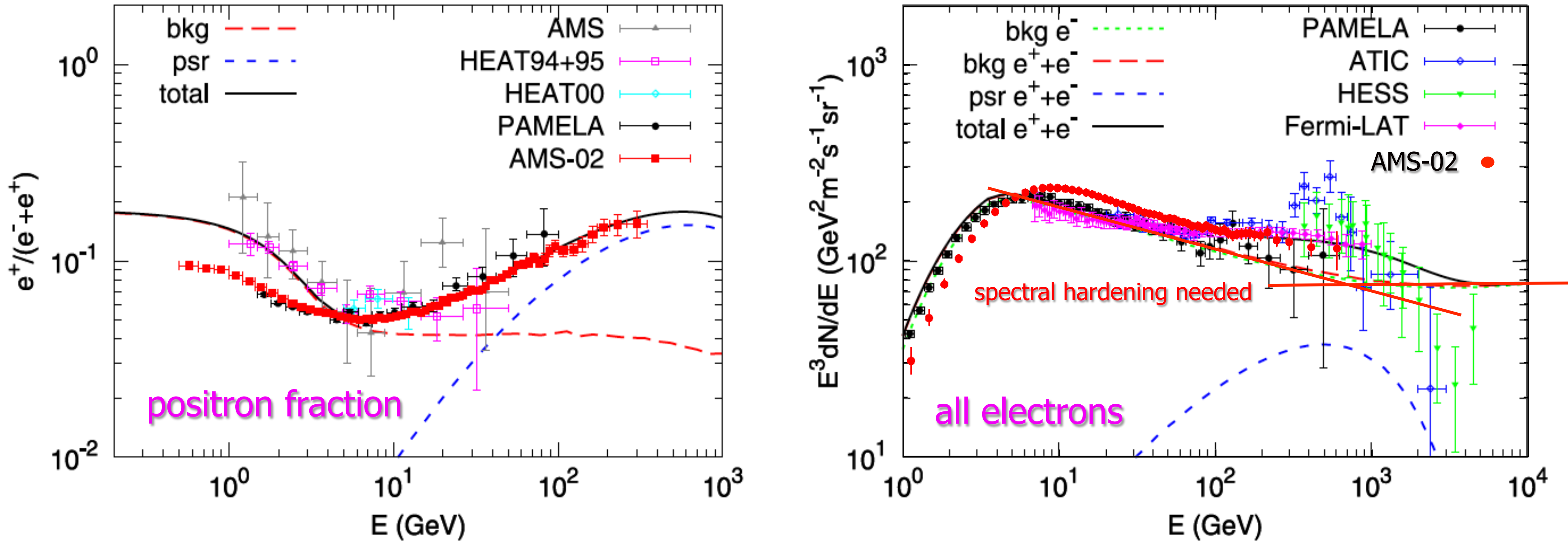
Gaisser, Stanev, Tilav, Front. Phys. 8(6), 748 (2013)



Electrons and positrons

- Electron spectra seem harder than previously thought (similar to nuclei);
- nearby pulsar contributions may be needed as well;
- needs to be updated for AMS-02 all-electron data;
- hint of similar origin for nuclei and primary electrons?

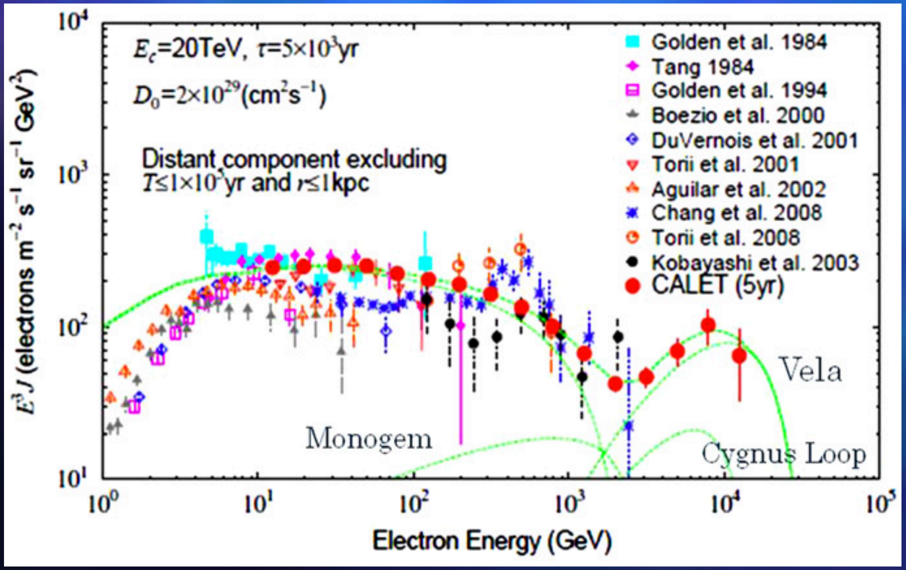
Yuan, Bi, Phys. Lett. B 727, 1 (2013)



The way forward

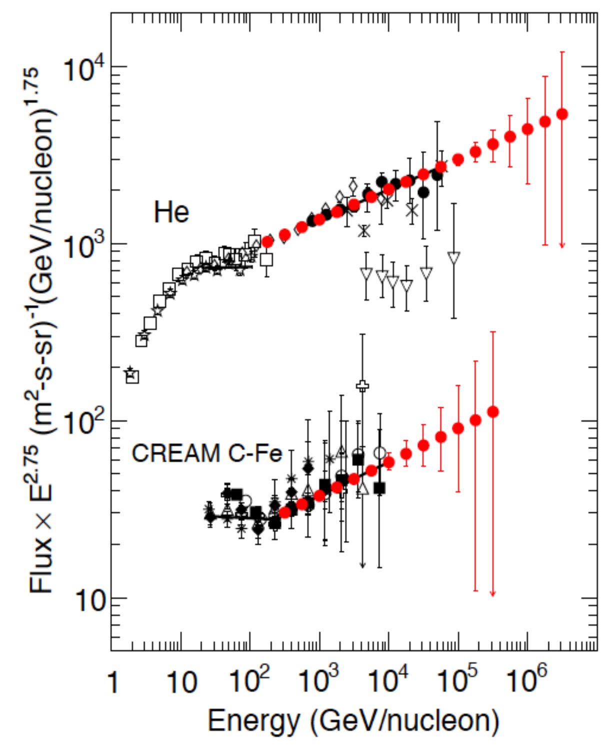
- New generation of instruments with long exposures (NUCLEON, CALET, ISS-CREAM, DAMPE, Super-TIGER);
- refined modeling, guidance from LHC results;

Expectation from 5 years of CALET electron data.



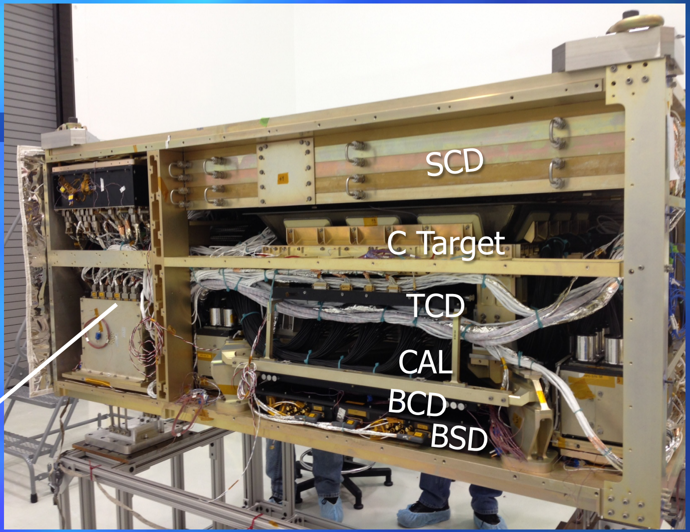
Torii et al., NIMA 630, 55 (2009)

Expectation from 3 years of ISS-CREAM data.

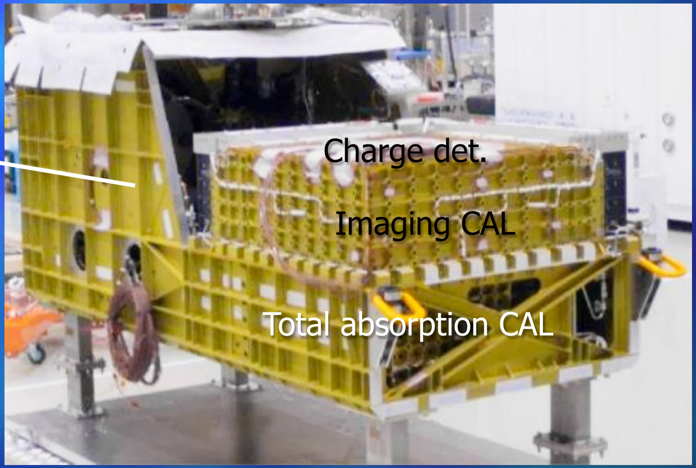


Seo et al., 33rd ICRC Rio de Janeiro (2013)

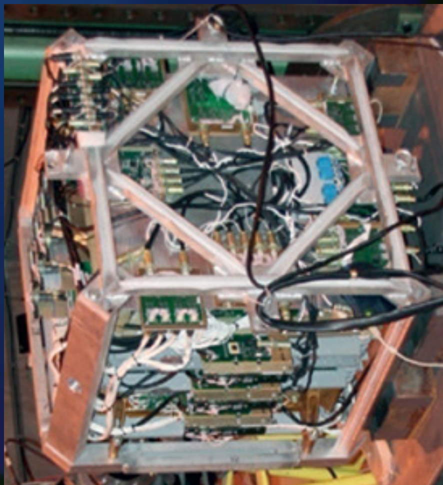
Next gen instruments



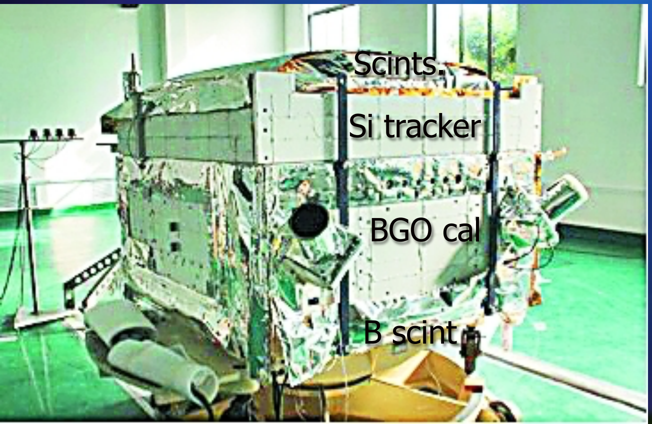
ISS-CREAM, space qualified and ready for launch; at KSC, awaiting SpaceX flight in late spring 2016; will measure nuclei up to >10^{15} eV; additional e capability.



CALET, deployed on ISS Aug 27, 2015; will study electrons > 1 TeV, with capabilities for nuclei.



NUCLEON, launched on RESURS-p satellite on Dec 26, 2014; nuclei up to 10^{15} eV; e capability.



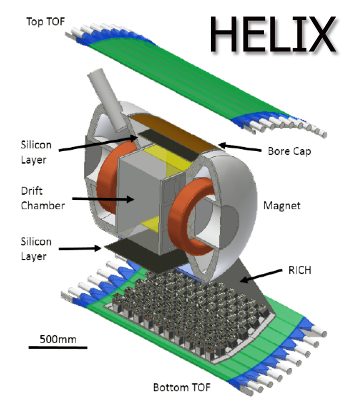
DAMPE, assembled, to launch on Chinese rocket in Dec. 2015; nuclei up to 100 TeV

Next gen instruments

Project	$e^+ + e^-$	CR	UHGCR	gamma	Type/ launch
NUCLEON	100 GeV – 3 TeV	p-Zn 100 GeV – 1 PeV			SAT 26 Dec 2014
CALET	1 GeV – 10 TeV	p-Fe 10 GeV – 1 PeV	Z=26-40 ~ GeV/n	10 GeV – 10 TeV	ISS 16 Aug 2015
ISS-CREAM	100 GeV – 10 TeV	p-Fe 1 TeV – >1 PeV			ISS May/Jun 2016
DAMPE	5 GeV – 10 TeV	p-Ca 100 GeV – 100 TeV		5 GeV – 10 TeV	SAT Dec 2015
HELIX		light isotopes <10 GeV/n			LDB ~2020
SuperTIGER redux			Z=10-40 (➔ 60) ~ GeV/n		LDB ~2019?
GAMMA-400	1 GeV – 20 TeV	p-Fe 1 TeV – 3 PeV		20 MeV – 1 TeV	SAT 2023-2025

The way forward

- New generation of instruments with long exposures (NUCLEON, CALET, ISS-CREAM, DAMPE, Super-TIGER);
- refined modeling, guidance from LHC results;
- future missions (HELIX, GAMMA-400, AMS-03);



isotopes up to 10 GeV/n, e.g., ^{10}Be/^{9}Be, ^{3}He/^{4}He

- increasing overlap with air-shower arrays;
- coordination of results from multiple instruments, multi-messenger astrophysics (cosmic rays, gamma rays, neutrinos, e.g. AMON);
- Bright prospects!

Danke !