Direct Cosmic Ray Measurements:

Status and Perspectives

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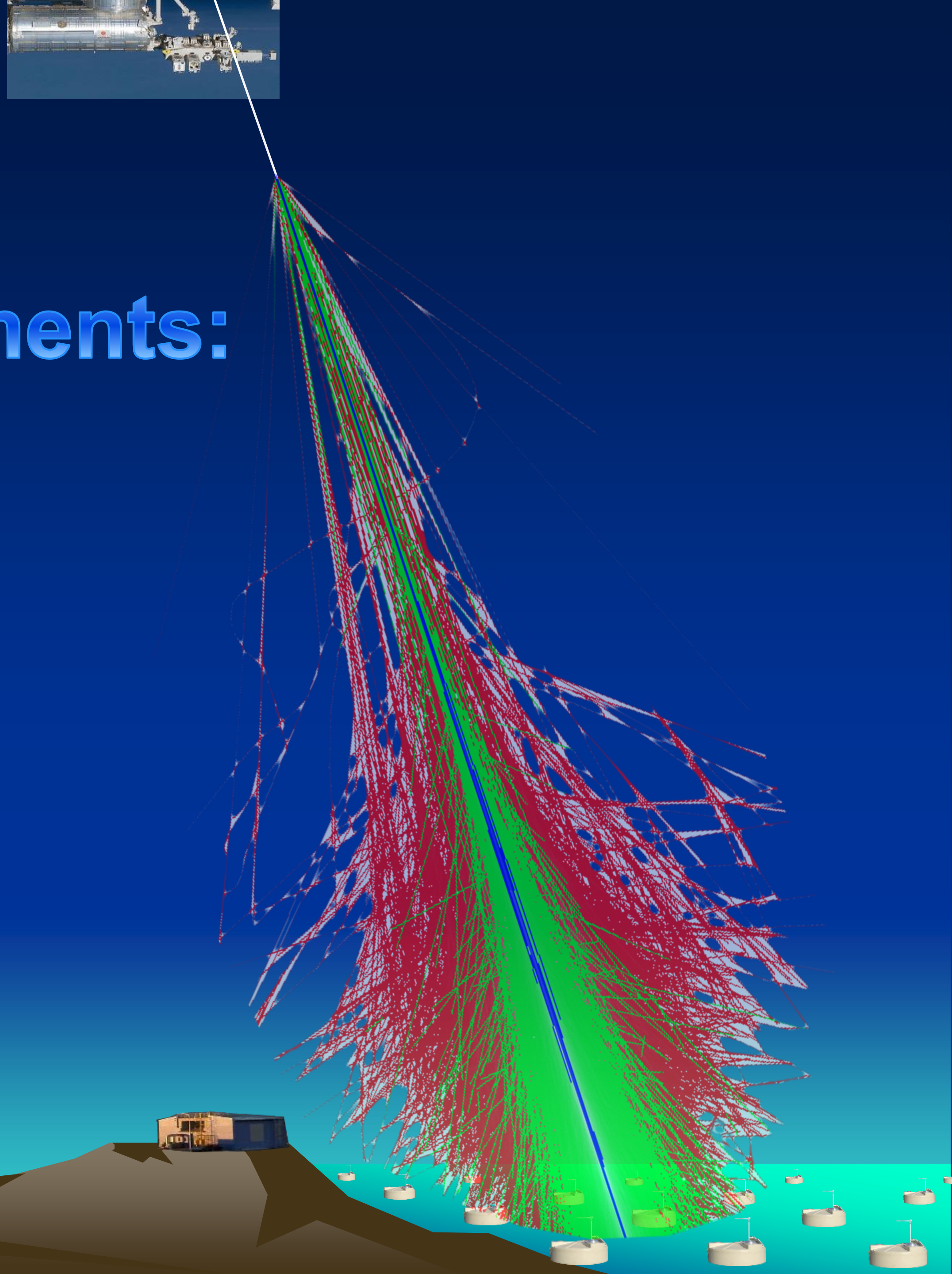
Denver
13 April, 2019



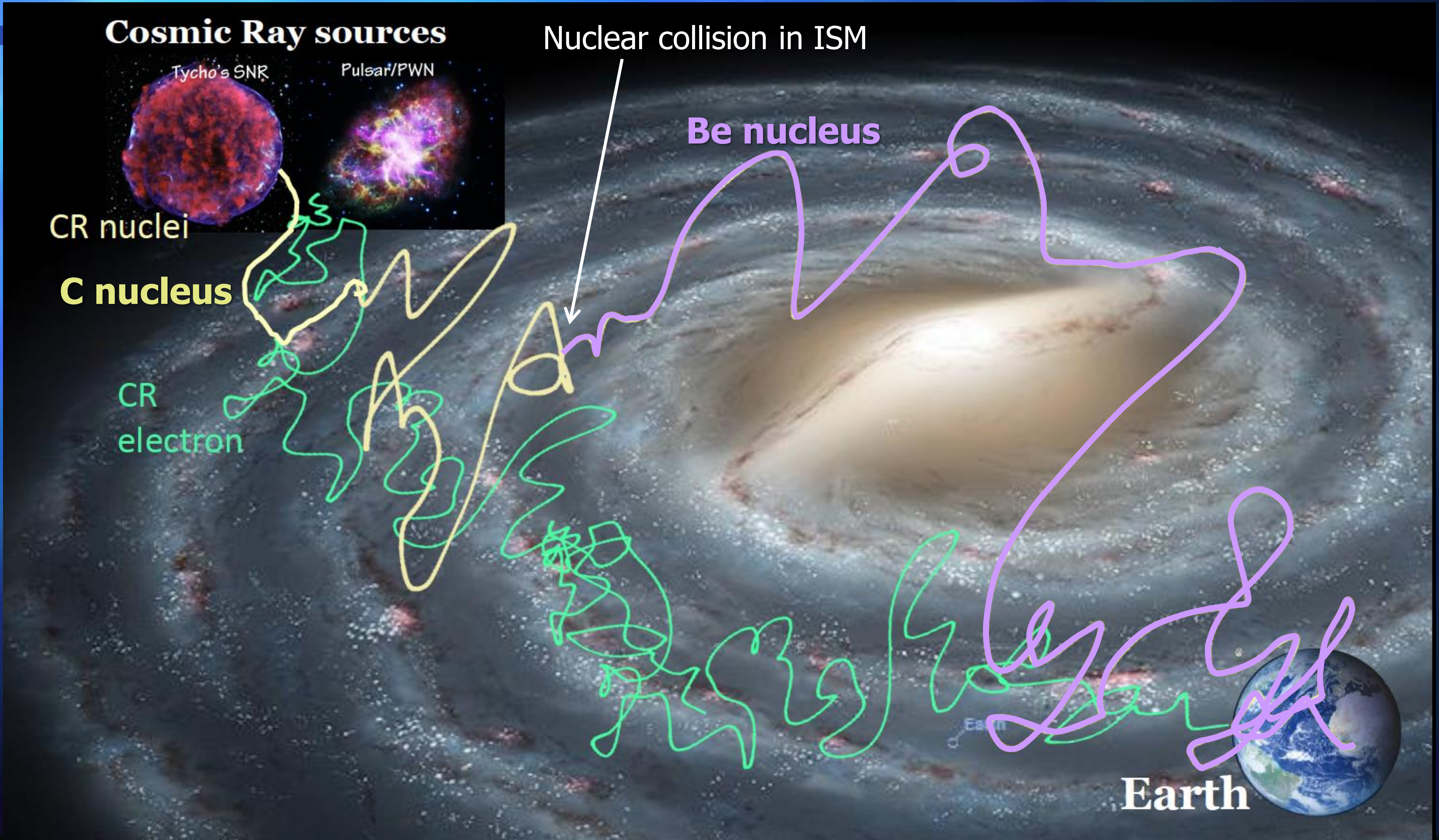
Outline

- Cosmic rays: messengers from the Cosmos
- Direct measurements:
  - Space (AMS, CALET, DAMPE, ISS-CREAM)
  - Balloons (CREAM, HELIX)
- Link to higher energies, multimessengers

CR production, Galactic propagation

Secondary production

Secondary nuclei track propagation **effects:**
B/C ratio,
^{10}Be vs ^{9}Be isotopes
(also antimatter production)



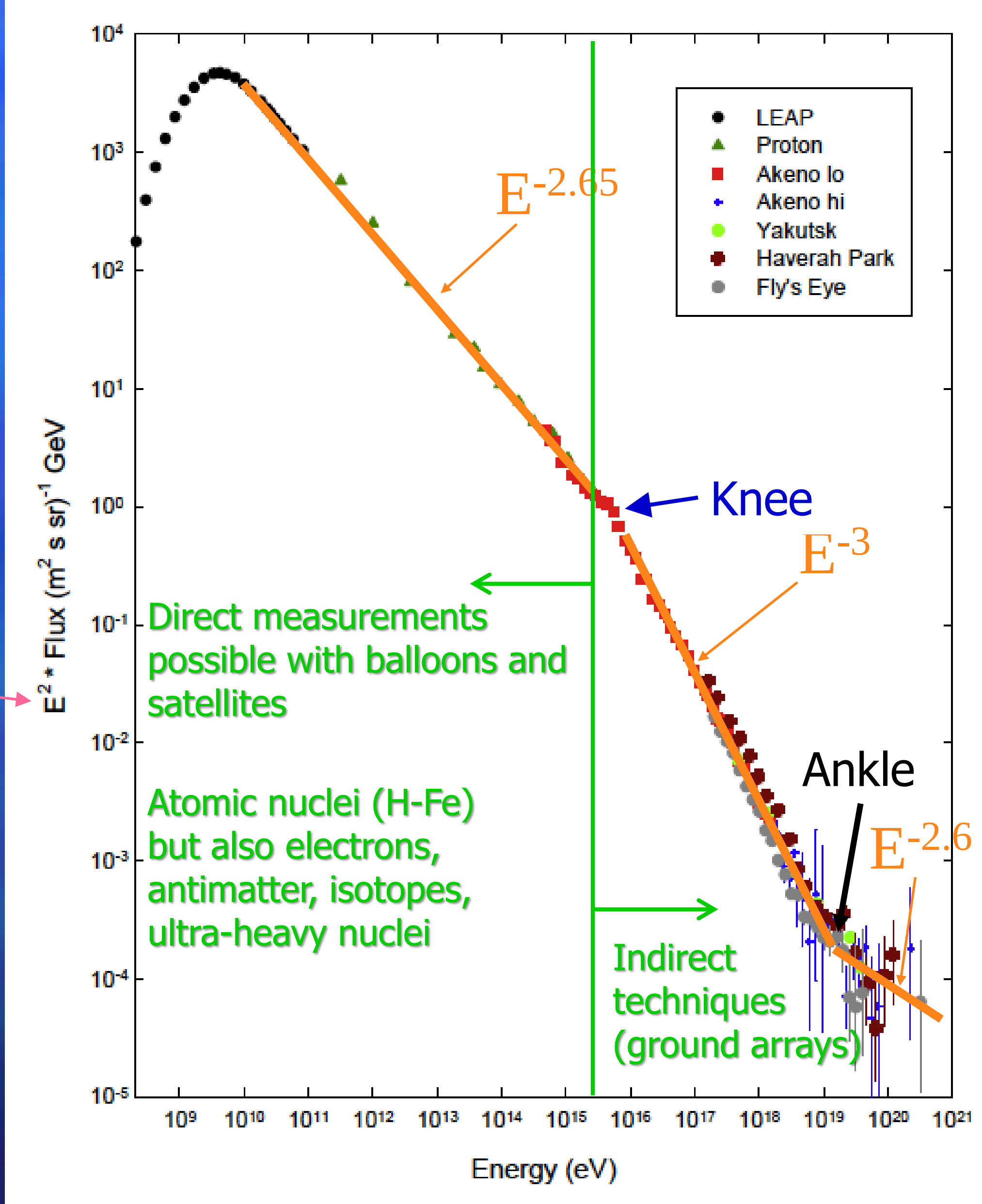
CR all particle spectrum

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

Trick:
Fluxes rescaled by E^2

The knee:
Limit to supernova acceleration in the Milky Way?

The ankle:
Transition to extragalactic sources?



Direct measurements possible with balloons and satellites

Atomic nuclei (H-Fe) but also electrons, antimatter, isotopes, ultra-heavy nuclei

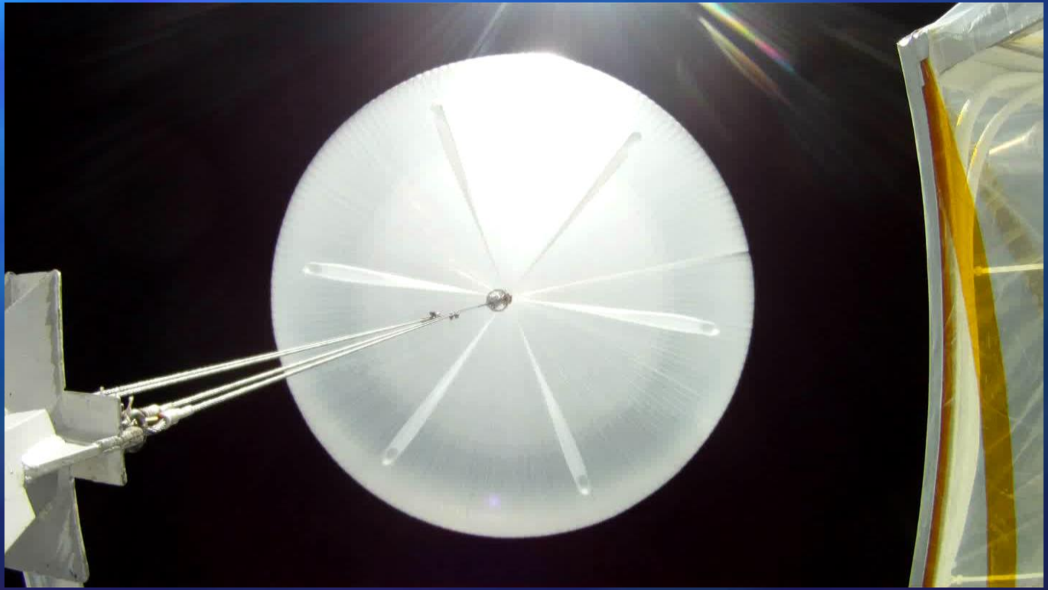
Indirect techniques (ground arrays)

Direct measurements: balloons

(2004 CREAM LDB flight)

NASA/Columbia Scientific Balloon Facility (CSBF)

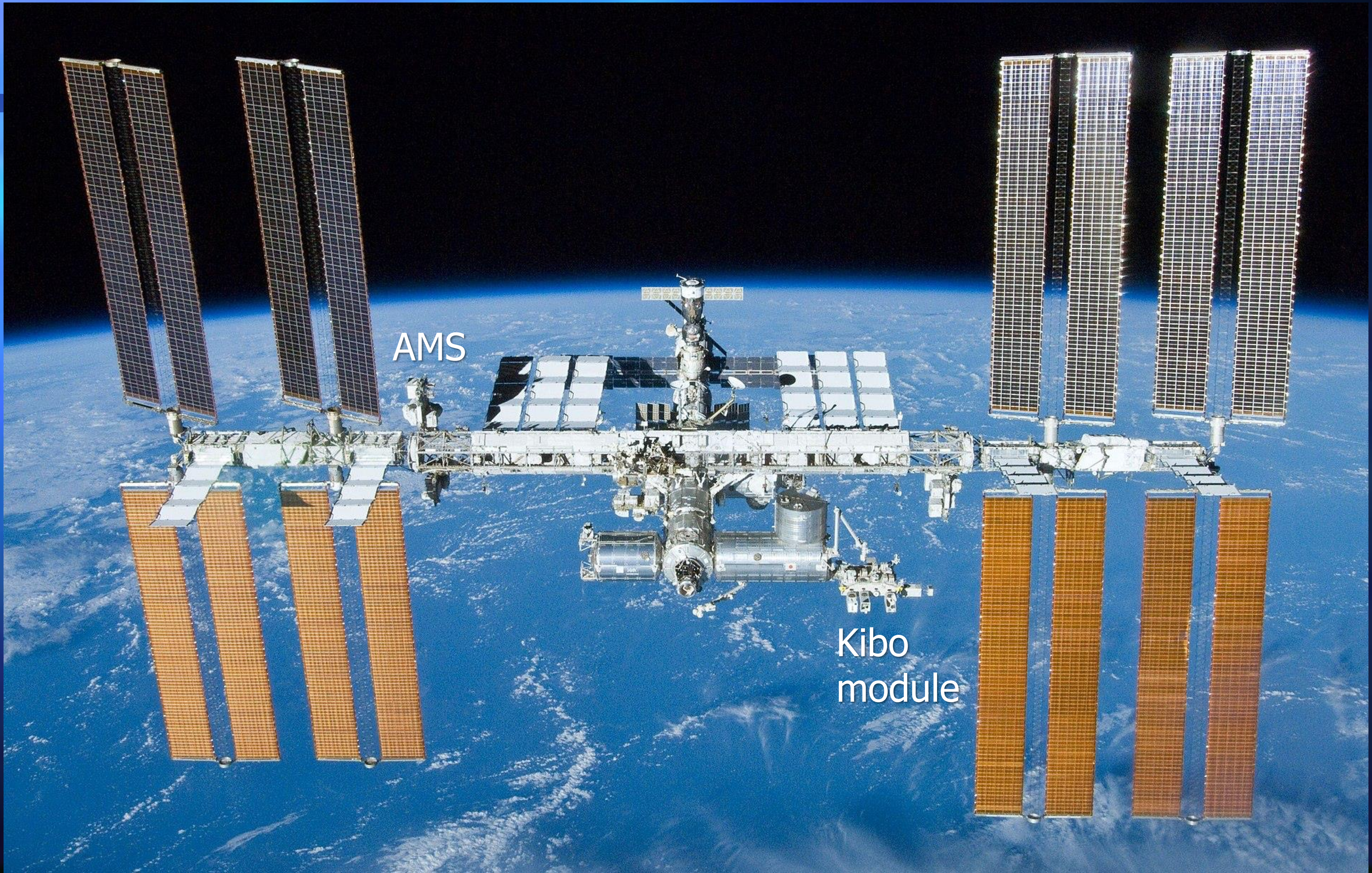
multi-week exposure possible in Antarctica since 1987 (up to 56 days!)



Direct measurements: rockets

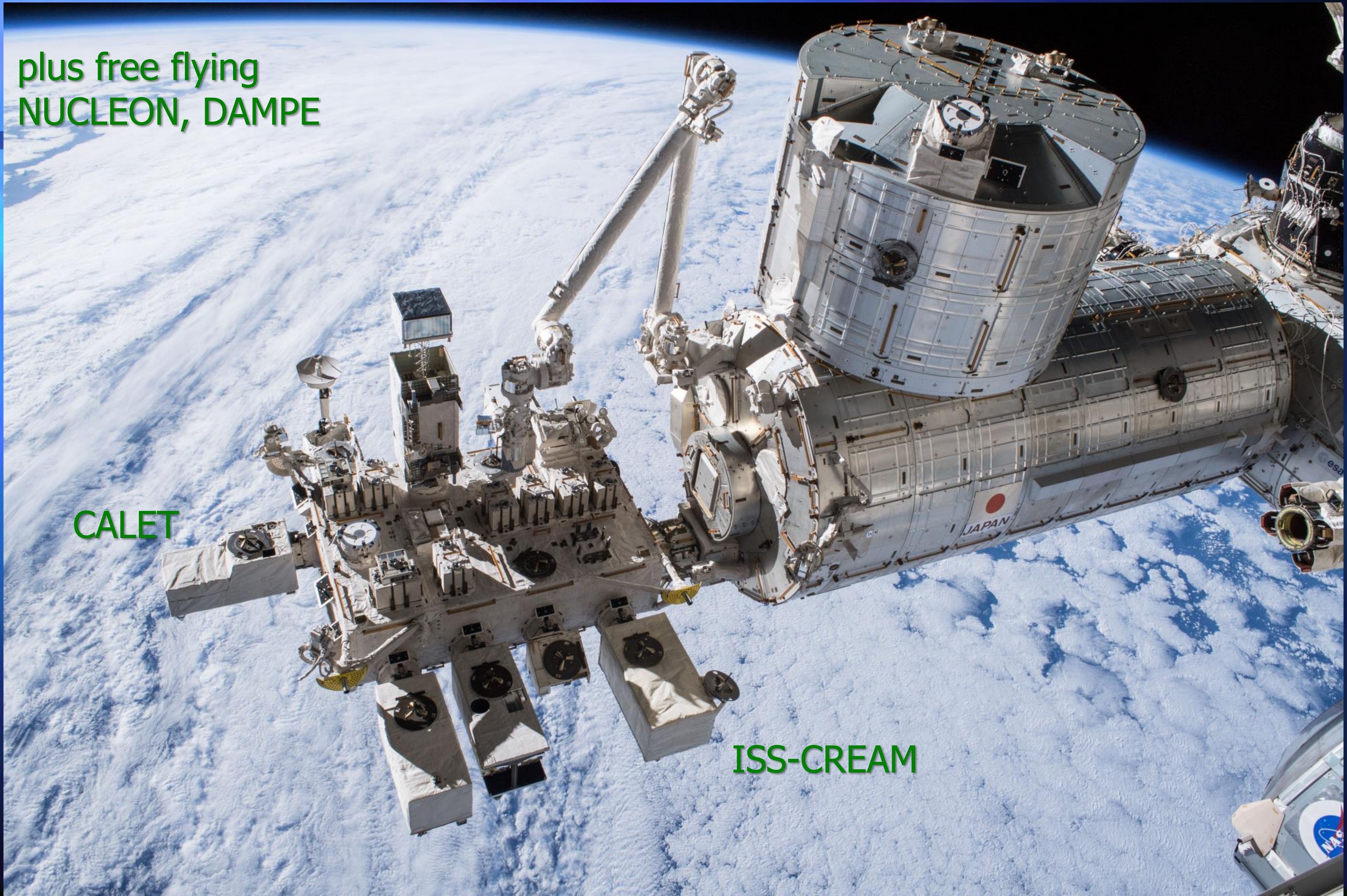
(2017 SpaceX 12 launch of ISS-CREAM)

ISS as a science platform



ISS as a science platform

AMS →



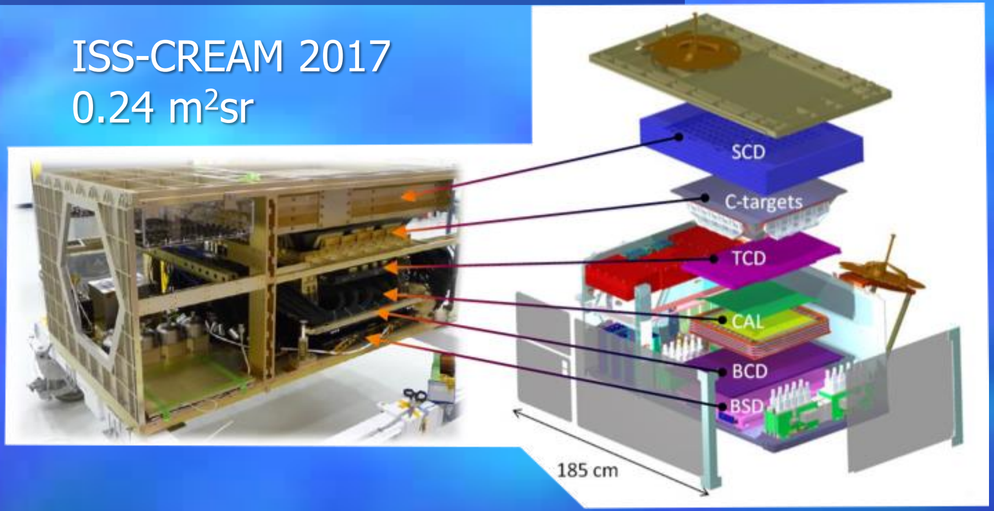
plus free flying
NUCLEON, DAMPE

CALET

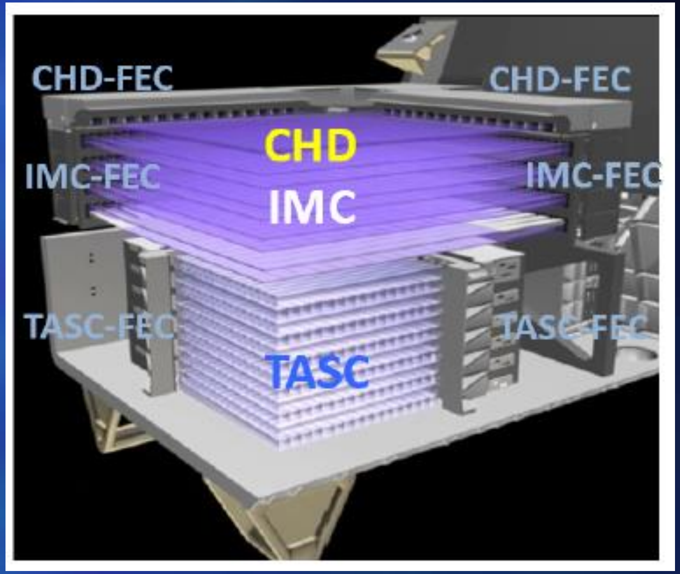
ISS-CREAM

Complex instruments!

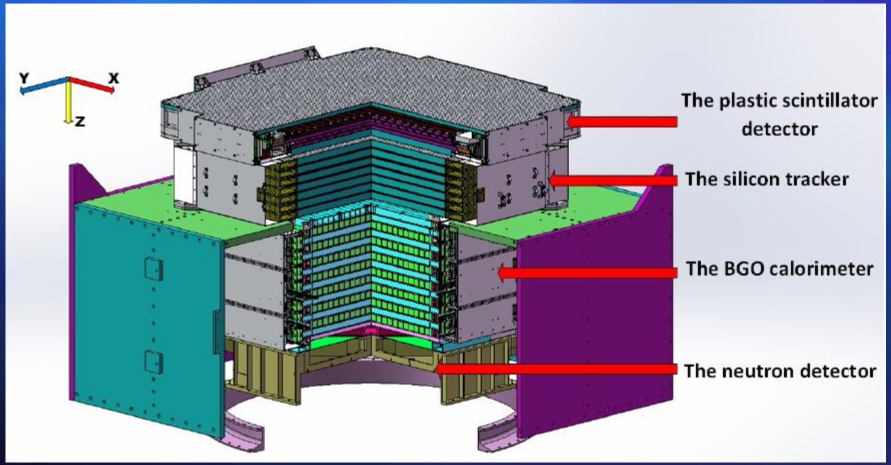
ISS-CREAM 2017
0.24 m^2sr



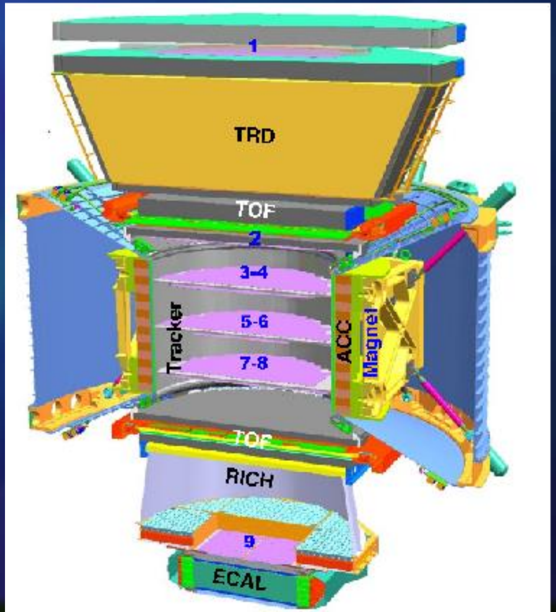
CALET 2015
0.12 m^2sr



DAMPE 2015
0.3 m^2sr



AMS 2011
0.82 m^2sr



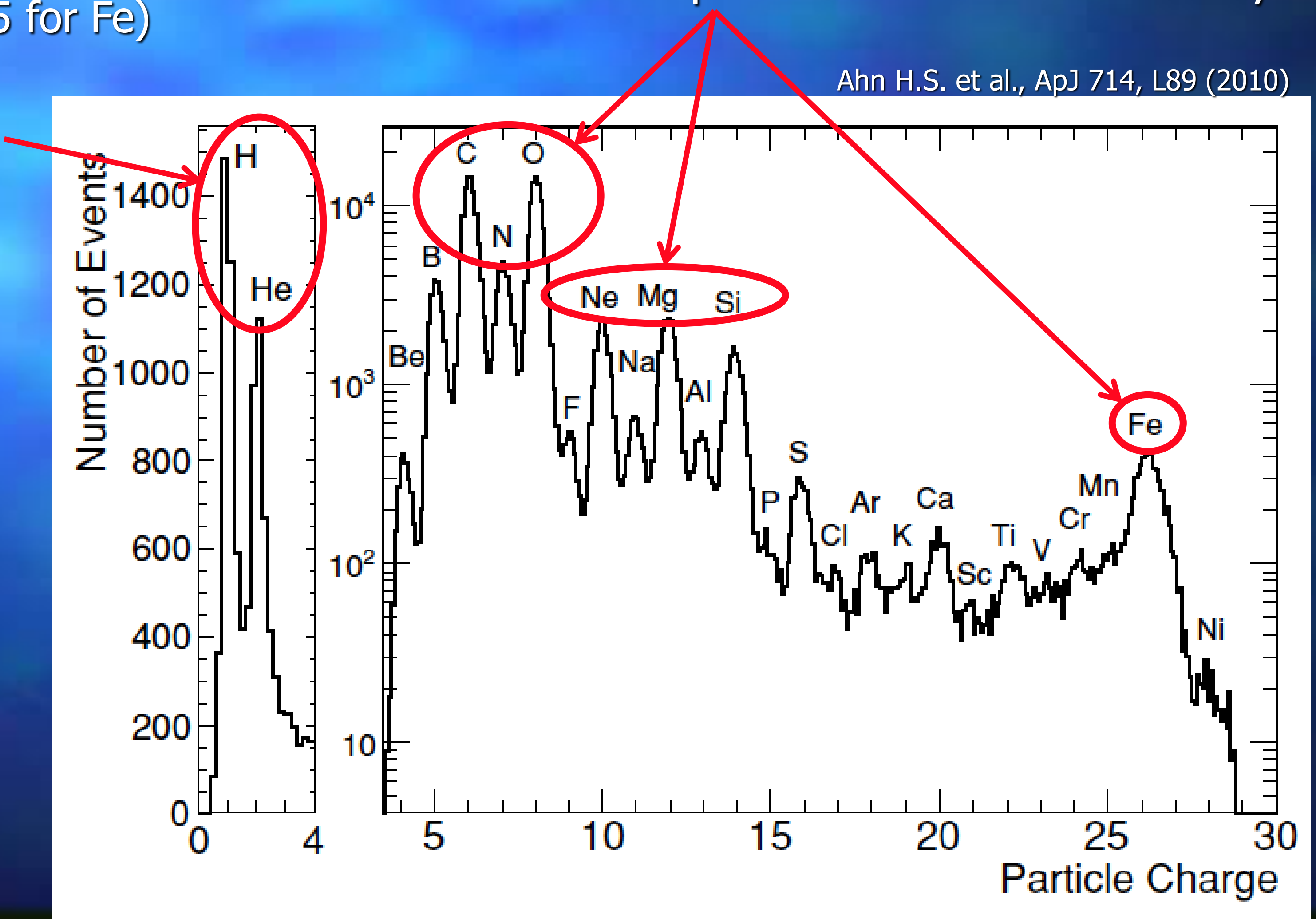
Elemental abundances

Charge resolution ~0.2e (0.35 for Fe)

H and He most abundant (primordial)

Stable nuclei produced in stellar nucleosynthesis

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



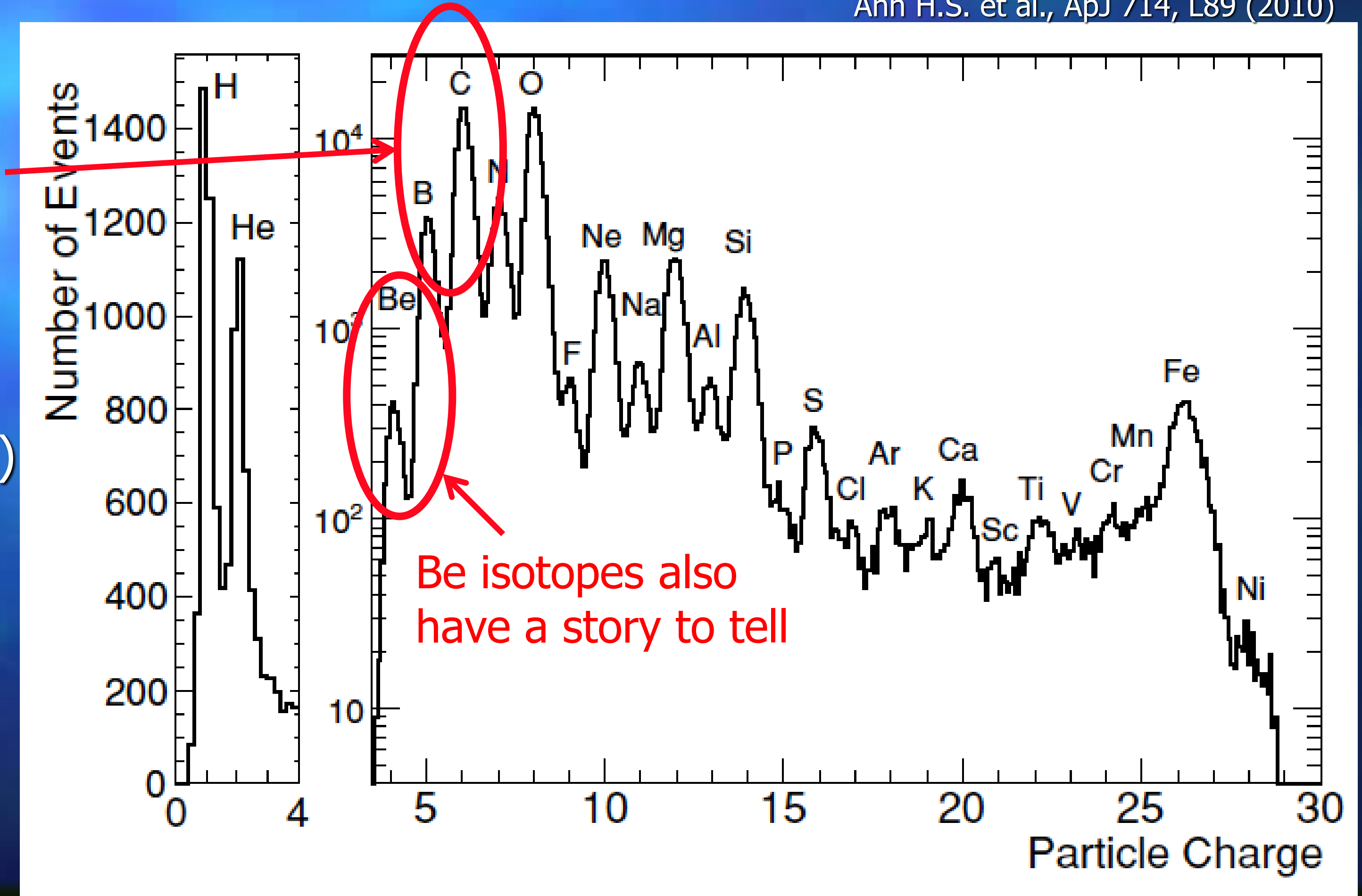
Elemental abundances

Charge resolution ~0.2e (0.35 for Fe)

C comes from the primary acceleration sites, but B is from spallation reactions…

B/C (3 – 30%) tracks the history of Galactic propagation (over ~15 Myrs)

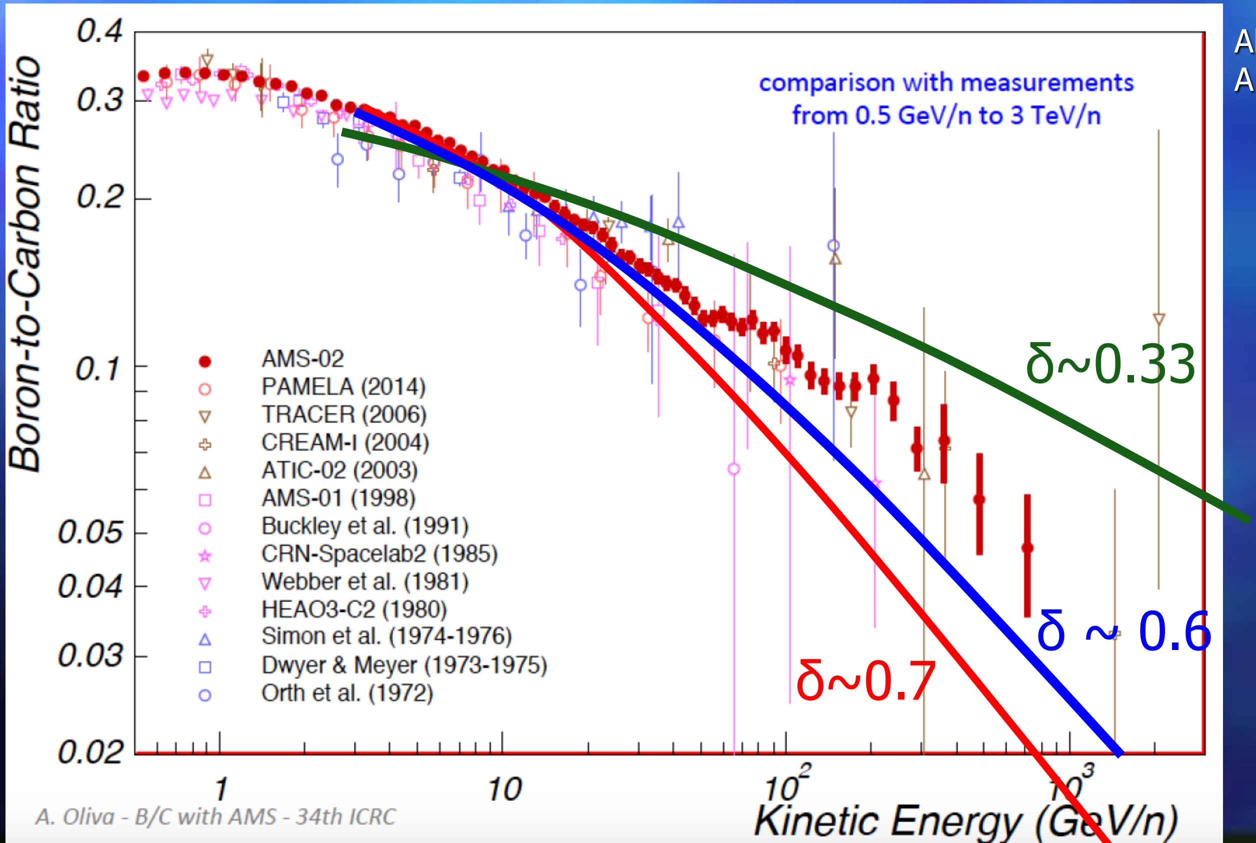
Ahn H.S. et al., ApJ 714, L89 (2010)



Be isotopes also have a story to tell

B/C ratio

B/C energy dependence has sensitivity to Galactic diffusion parameter δ; also explains shape of the observed cosmic ray spectrum at source vs Earth.

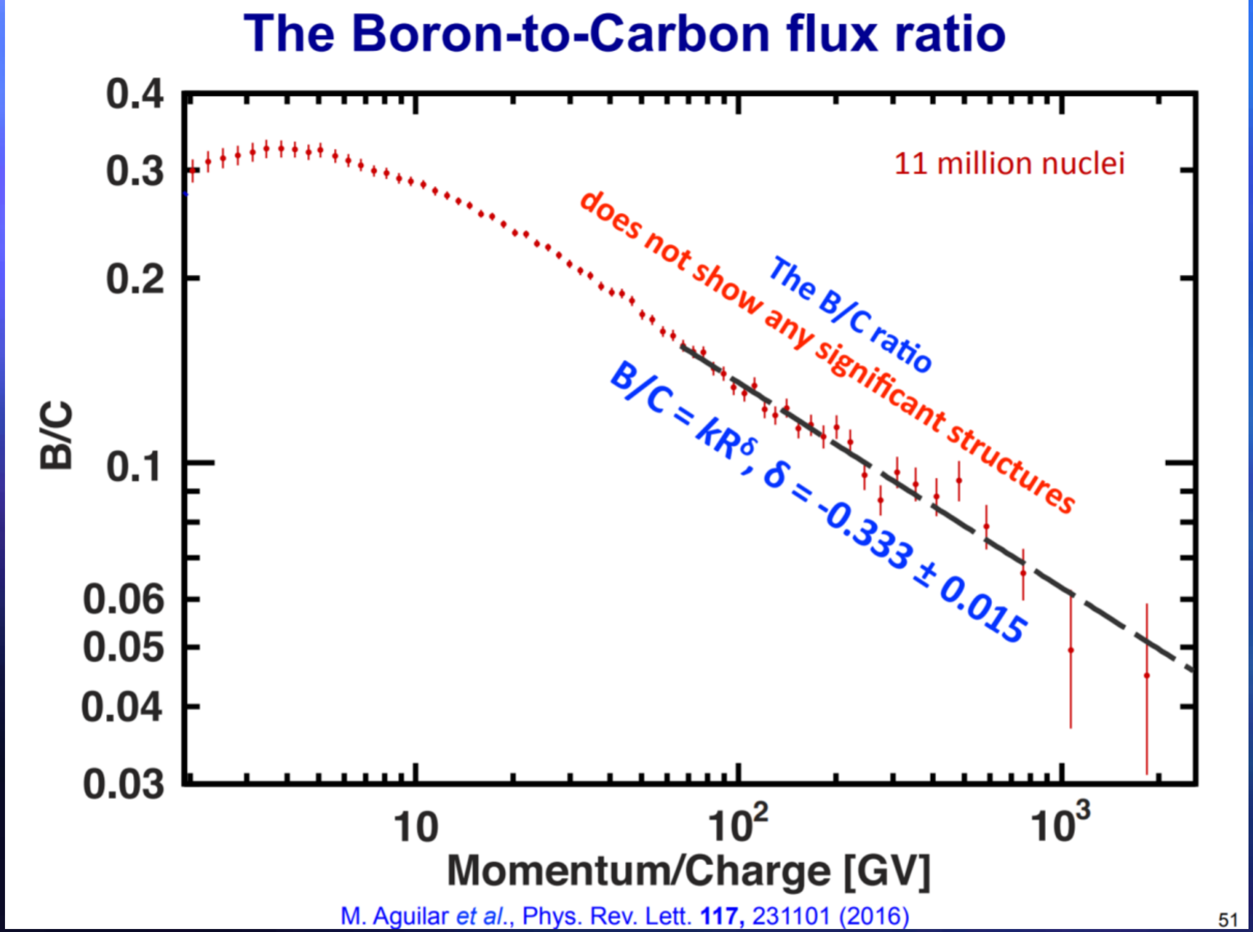


A. Oliva - B/C with AMS - 34th ICRC

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

$E^{-2.65}$ observed at Earth might have been E^{-2} at the source, with steepening by $E^{-\delta}$ due to diffusion.

B/C ratio – AMS late 2016



The Boron-to-Carbon flux ratio

11 million nuclei

The B/C ratio does not show any significant structures

$B/C = kR^{\delta}$, $\delta = -0.333 \pm 0.015$

M. Aguilar *et al.*, Phys. Rev. Lett. **117,** 231101 (2016)

High precision achieved in the measurements now;

awaiting results from CALET, DAMPE, ISS-CREAM, NUCLEON;

- could push to higher energies;
- but shape well constrained by AMS.

Elemental spectra

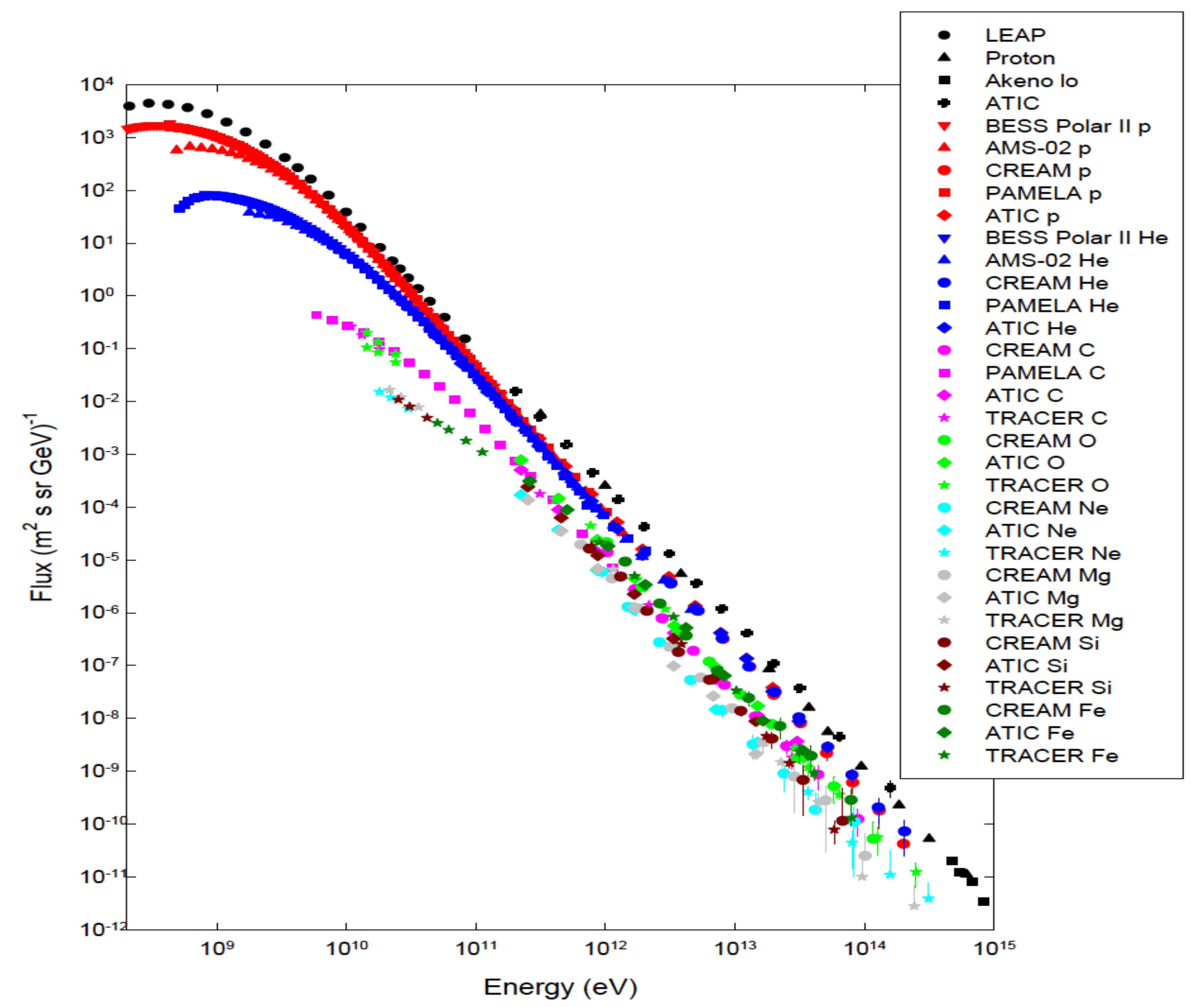
Measurements getting close to the knee;

Very high statistics at low energies (hundreds of GeV) from magnet spectrometers: BESS, PAMELA, AMS (CALET, DAMPE, ISS-CREAM coming);

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

Hard to see the details...

Warning! Plot vs E, E/n, R, with or without rescaling by E^3, $R^{2.75}$, $(E/n)^{2.6}$, with or without rescaling by 10^{-8} or something...

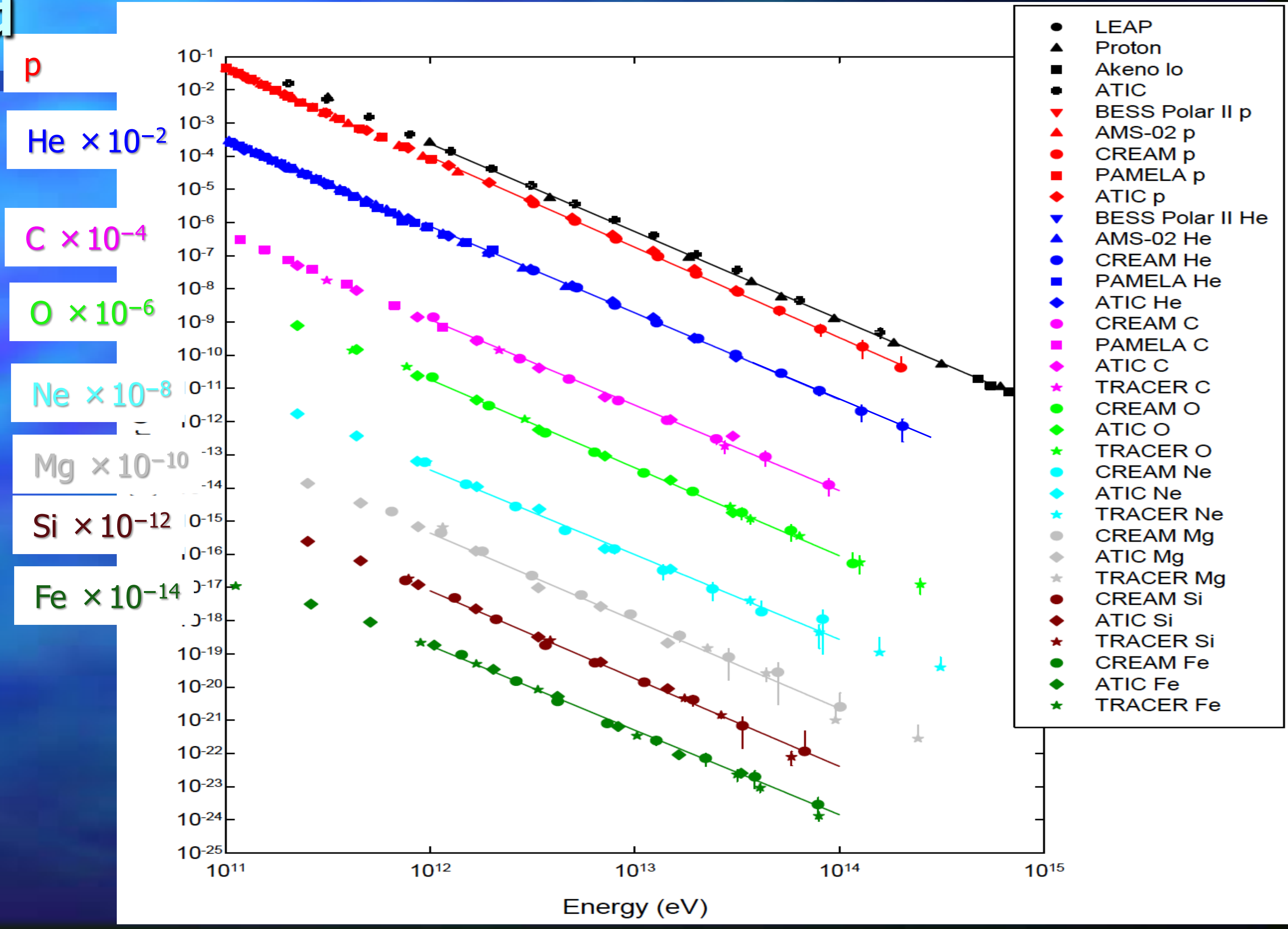


Ahn et al., ApJ 707, 593 (2009),
Ahn et al., ApJ 715, 1400 (2010),
Yoon et al., ApJ 728, 122 (2011)

Elemental spectra

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!

p vs He

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))

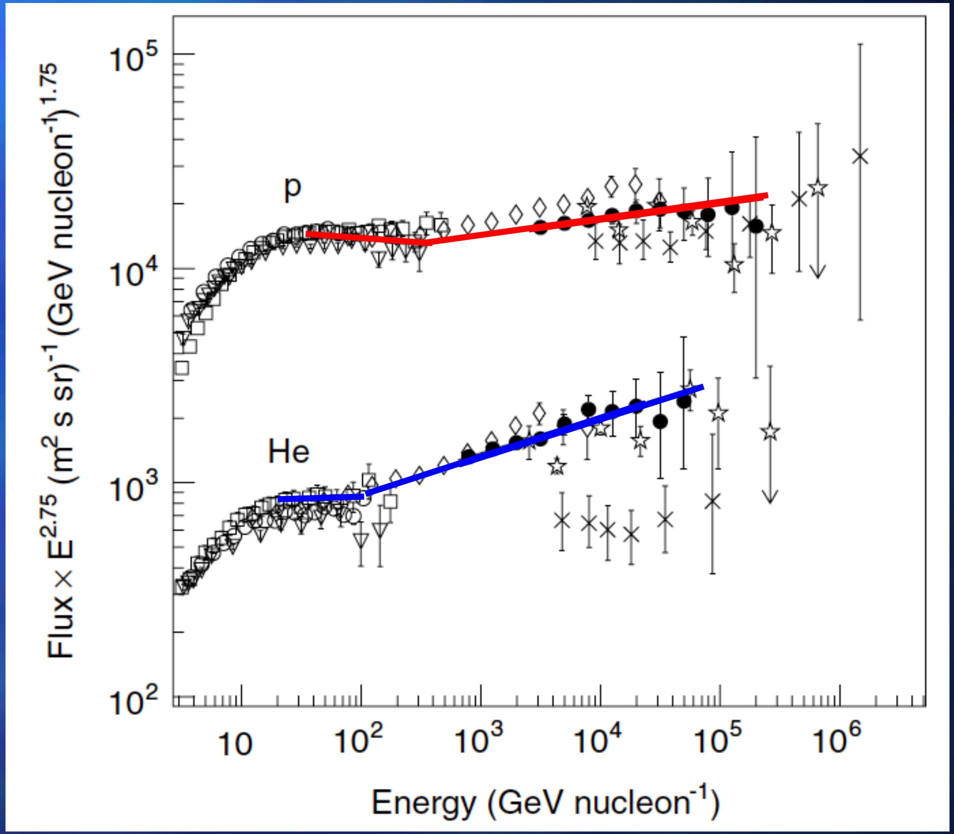
Could be due to non-linear effects in CR transport through the Galaxy;

(Aloisio et al., arXiv:1507.00594)

Could be due to young nearby sources;

(Thoudam & Hörandel, MNRAS 435, 2532 (2013))

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

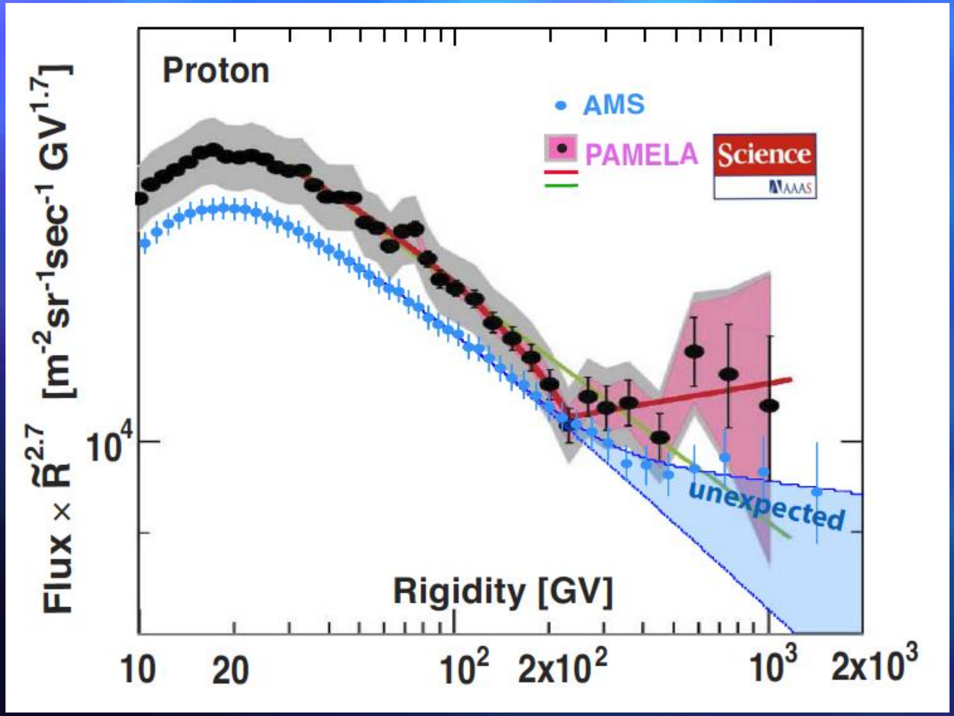


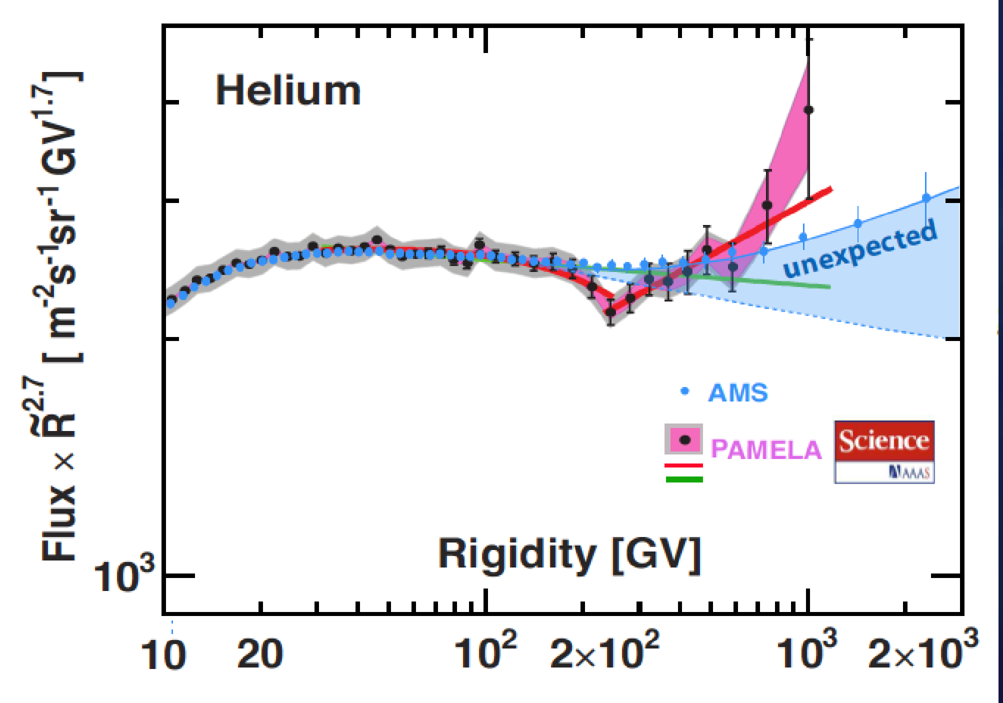
Spectral hardening at 100 – 200 GeV/n

p vs He – PAMELA + AMS updates

2011 PAMELA and 2015 AMS results do see p and He hardenings, but shape still to be understood

Kounine et al. 2017: 35th ICRC, Busan, South Korea





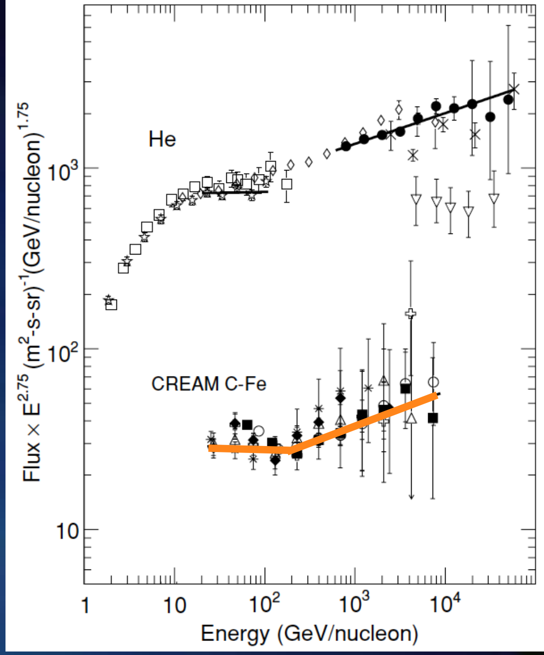
Hardening spectra

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);

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



Hardening spectra

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

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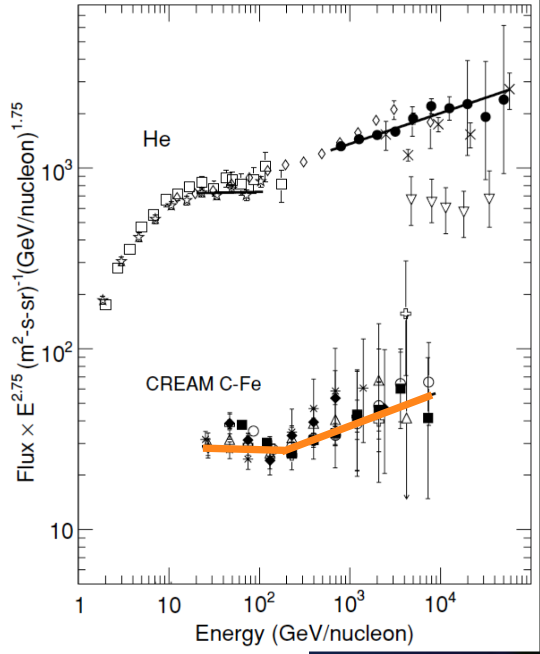
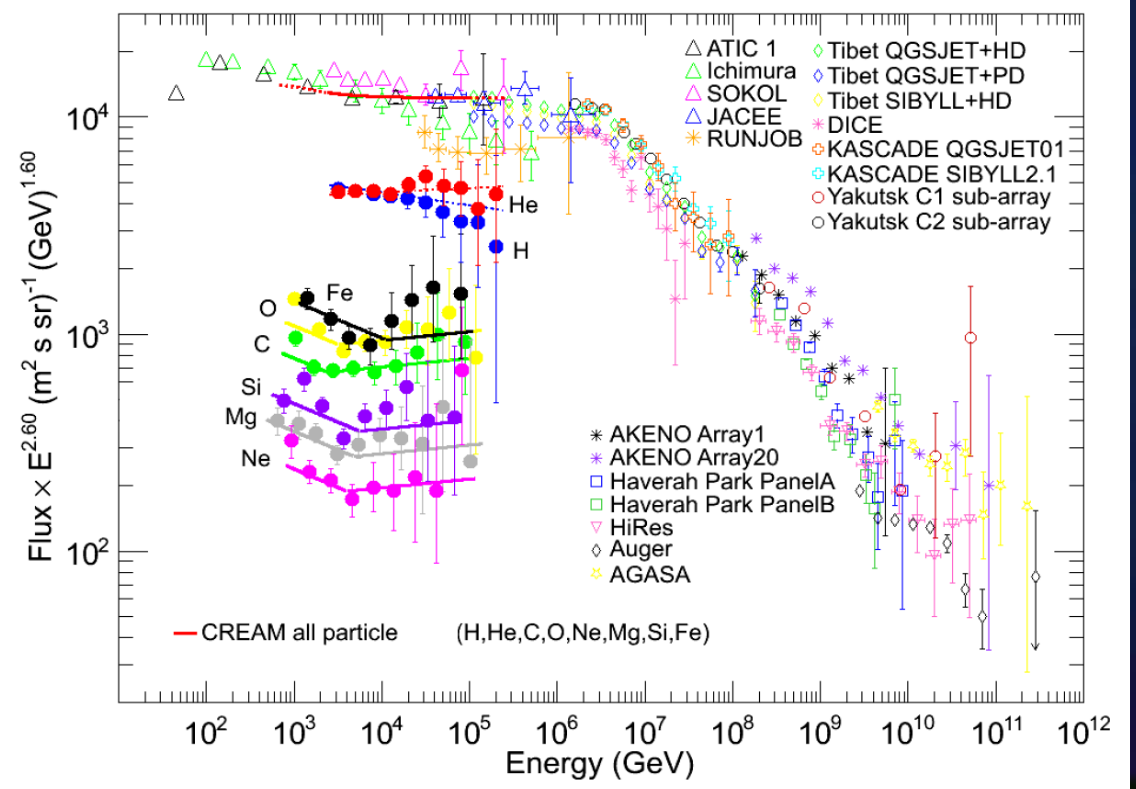
- Probably from the same source and acceleration mechanism.

- 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);

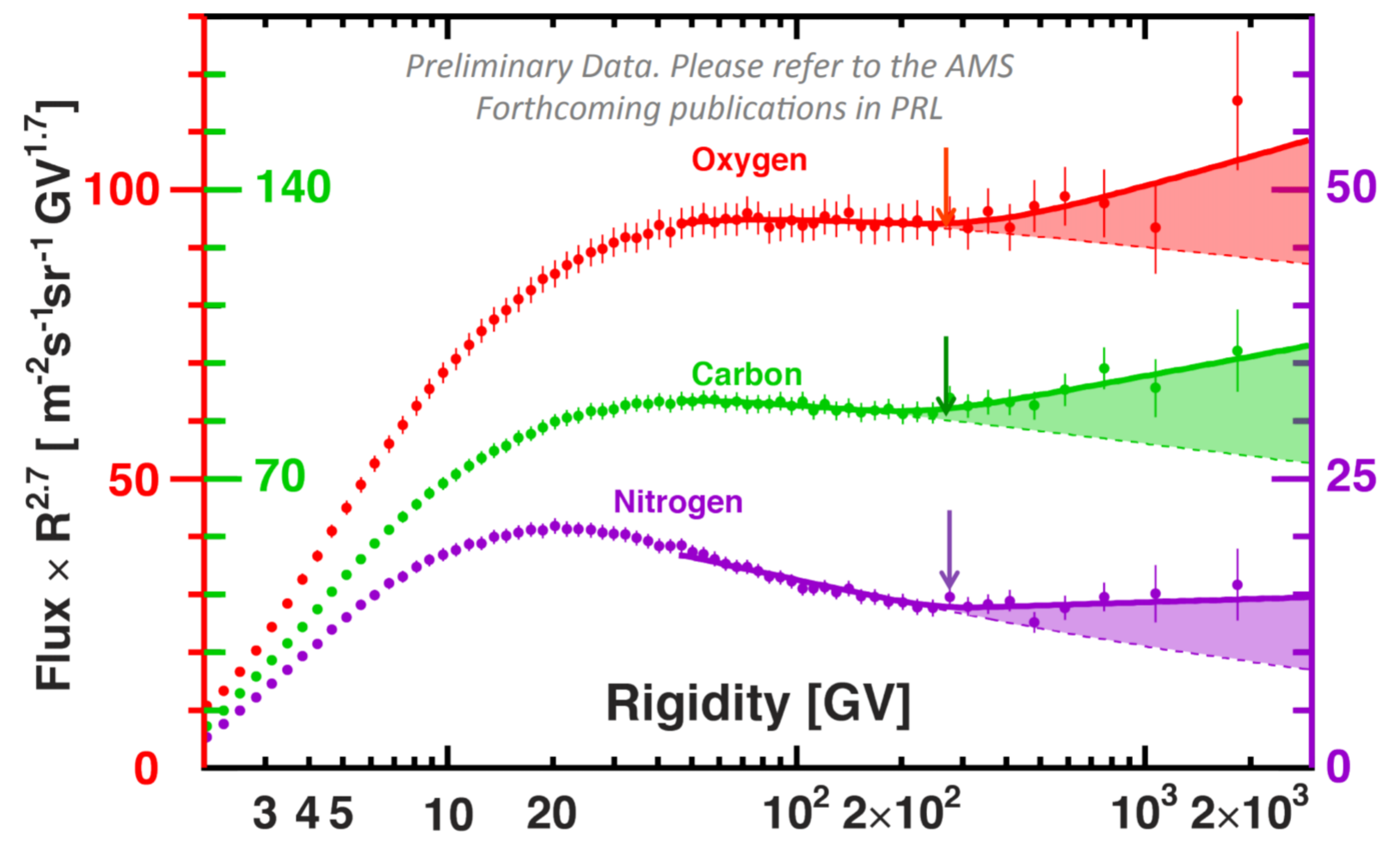
- Detailed source modeling needs to address this, but individual spectra do add up to that measured by air shower arrays.



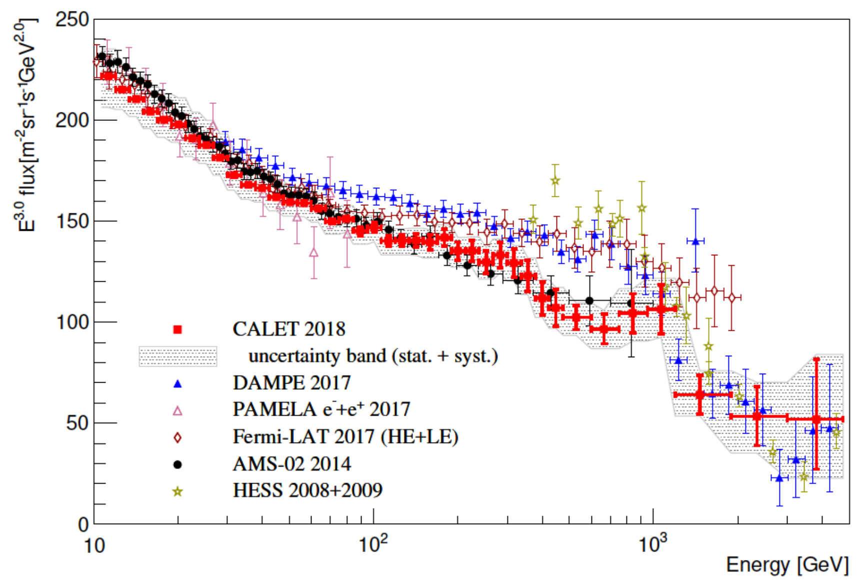


Hardening spectra – AMS update

AMS preliminary 2017: 35th ICRC, Busan, South Korea



First results from CALET and DAMPE

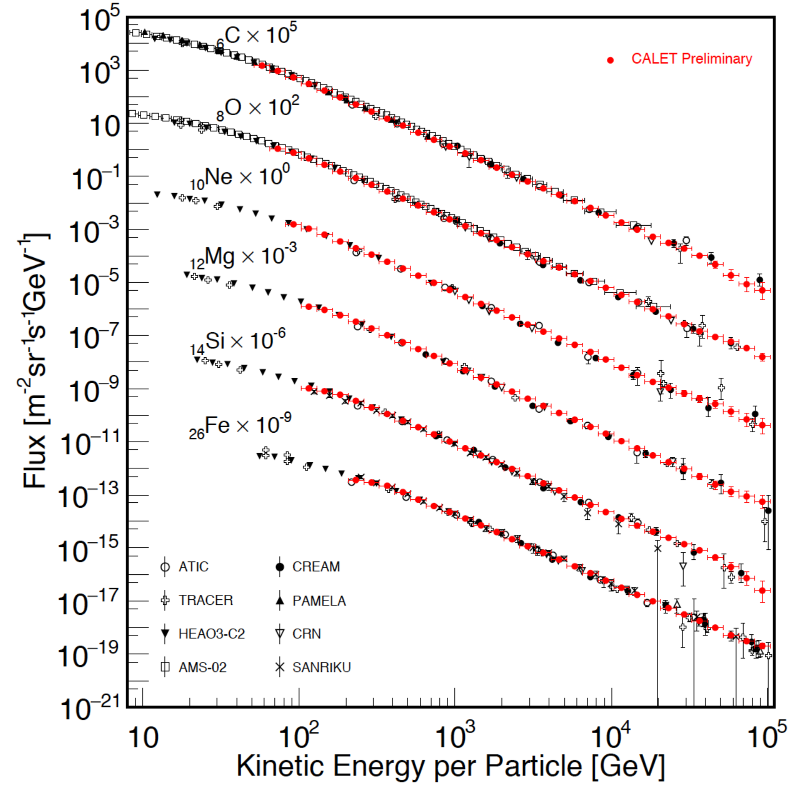


DAMPE + CALET Electrons arXiv:1903.0727

apparent tension… but E^3 rescaling can do funny things…

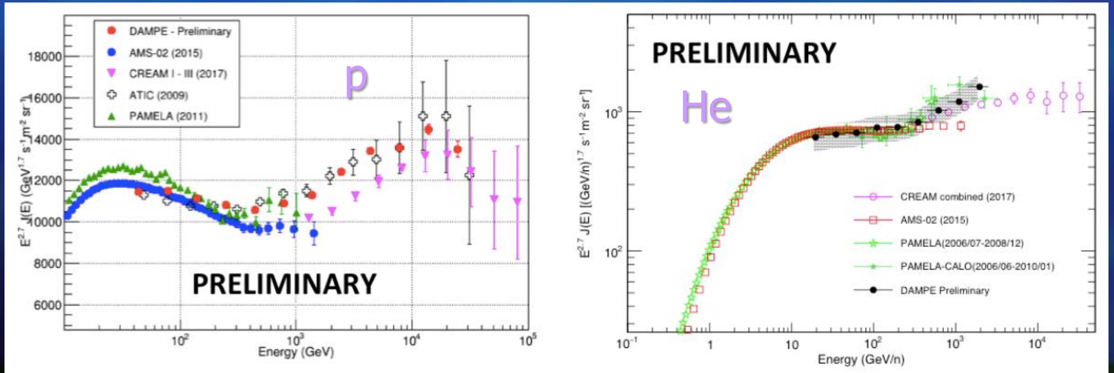
CALET Nuclei C – Fe

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



DAMPE p – He

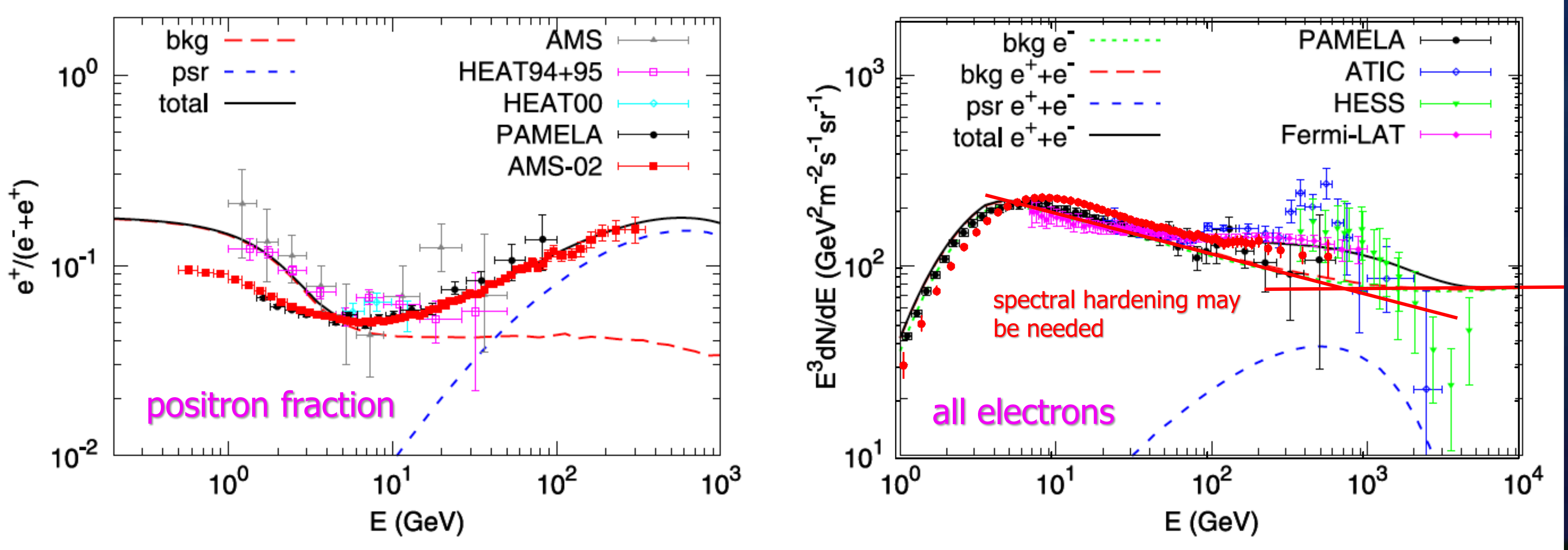
P. Bernardini et al., 2019 J. Phys.: Conf. Ser. 1181, 012043



An aside: electrons and positrons

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

- How well are the secondary (bkg) $e^{+}+e^{-}$ understood? Can DM annihilations explain the excess positrons?

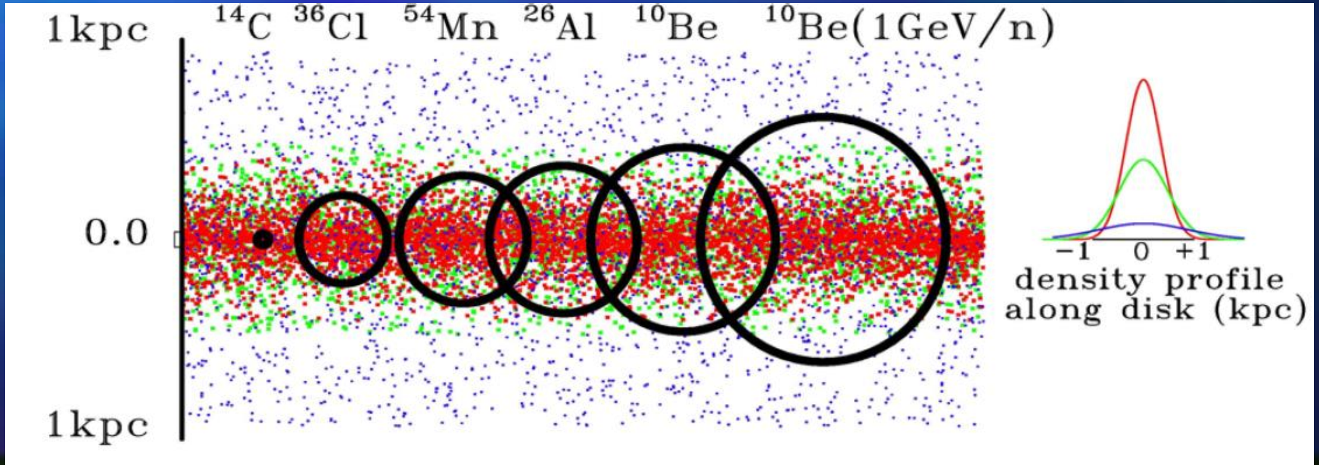


Yuan, Bi, Phys. Lett. B 727, 1 (2013)

Isotopes – the science case

- Be is rare, made in cosmic ray spallation reactions;
- ^{9}Be is stable, but ^{10}Be β decays with a half-life of λ ~ 1.39 Myr, so a cosmic clock with the right tick length for the ~15 Myr propagation history of cosmic rays;
- Energy evolution of ^{10}Be/^{9}Be ratio traces increasing regions of the Galaxy (Lorentz time dilation).

Z/A dependence of Galactic region sampled by 0.3 GeV/n clock isotopes; Be is ideal.



Isotopes – present status

- Isotope measurements are *hard.* So far the data are very limited and do not constrain the propagation models;
- Measure Z, R, β to find m:

$$R = \frac{pc}{Ze} = \frac{\gamma mvc}{Ze} = \frac{\gamma\beta mc^2}{Ze} = \frac{\beta mc^2}{Ze\sqrt{1-\beta^2}}$$

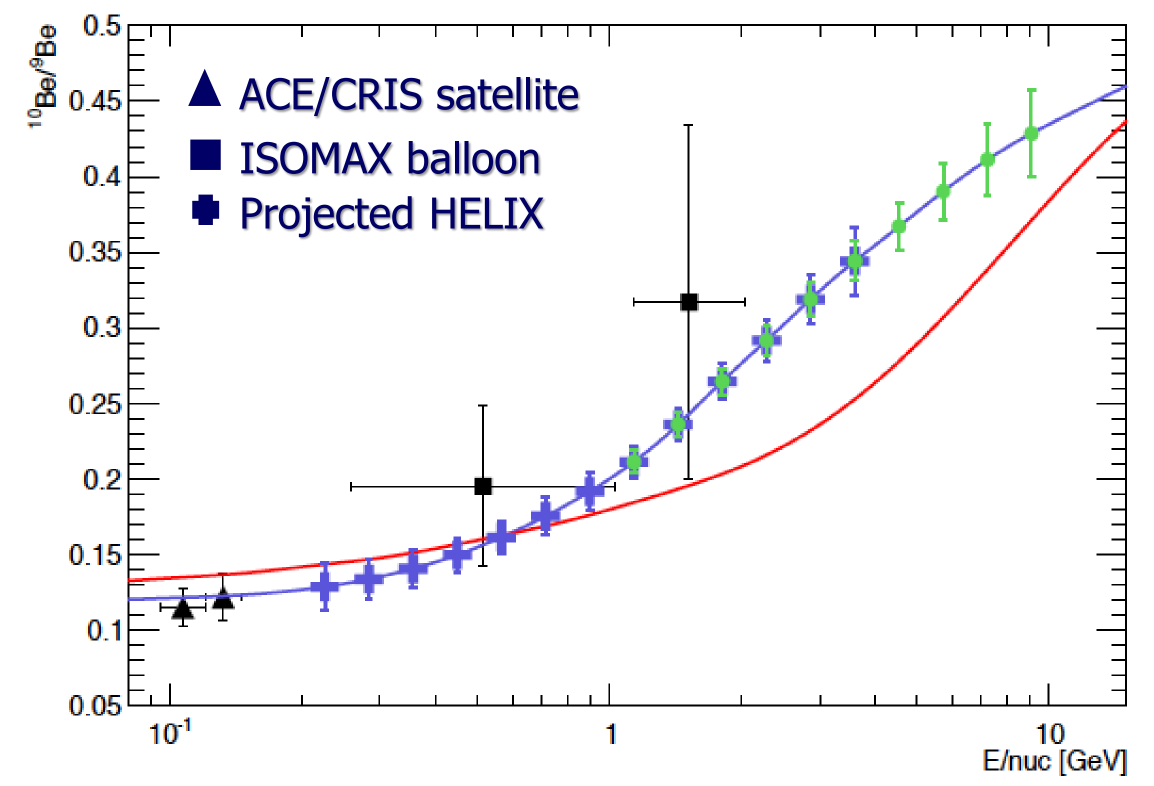
The problem:

$$\left(\frac{\Delta m}{m}\right)^2 = \left(\frac{\Delta R}{R}\right)^2 + \gamma^4\left(\frac{\Delta\beta}{\beta}\right)^2$$

For $\Delta m/m = 2.5\%$, need:

$\Delta R/R \sim$ 1-2% (AMS: 10-20%)
$\Delta\beta/\beta \sim$ 0.015% (0.1% up to 3 GeV/n)

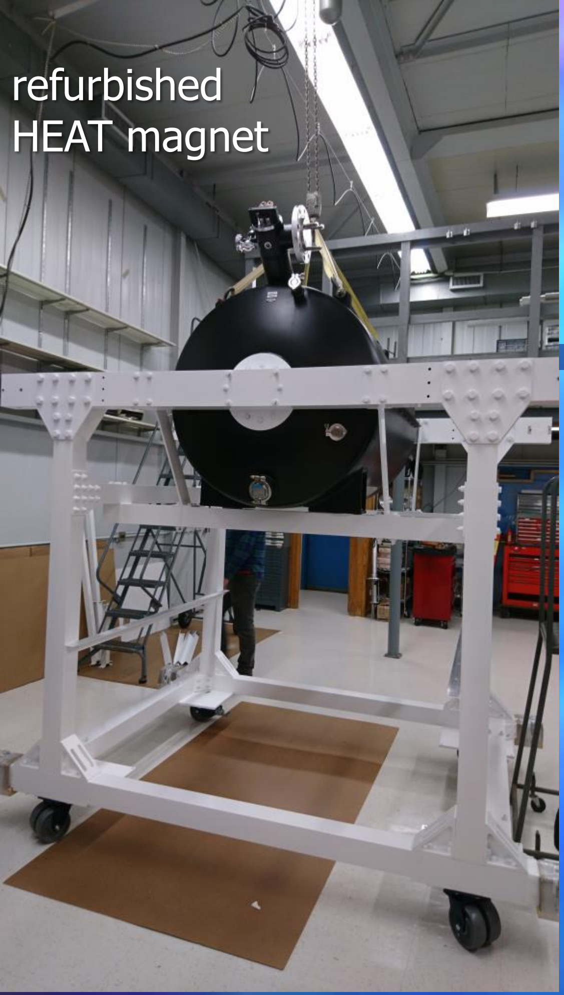
HELIX: 7-14 day exposure, 0.1 m^2sr acceptance



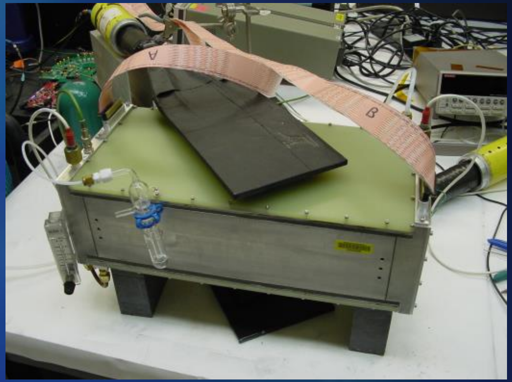
HELIX

High Energy Light Isotope eXperiment
anticipate Antarctic flight 2020

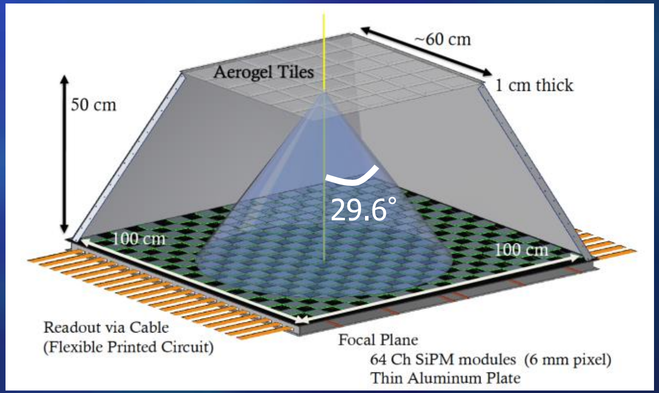
UNDER CONSTRUCTION
COMING SOON


refurbished
HEAT magnet

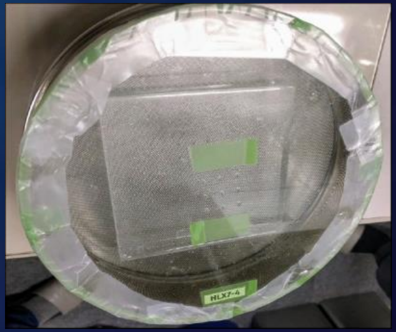
prototype DCT



RICH



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

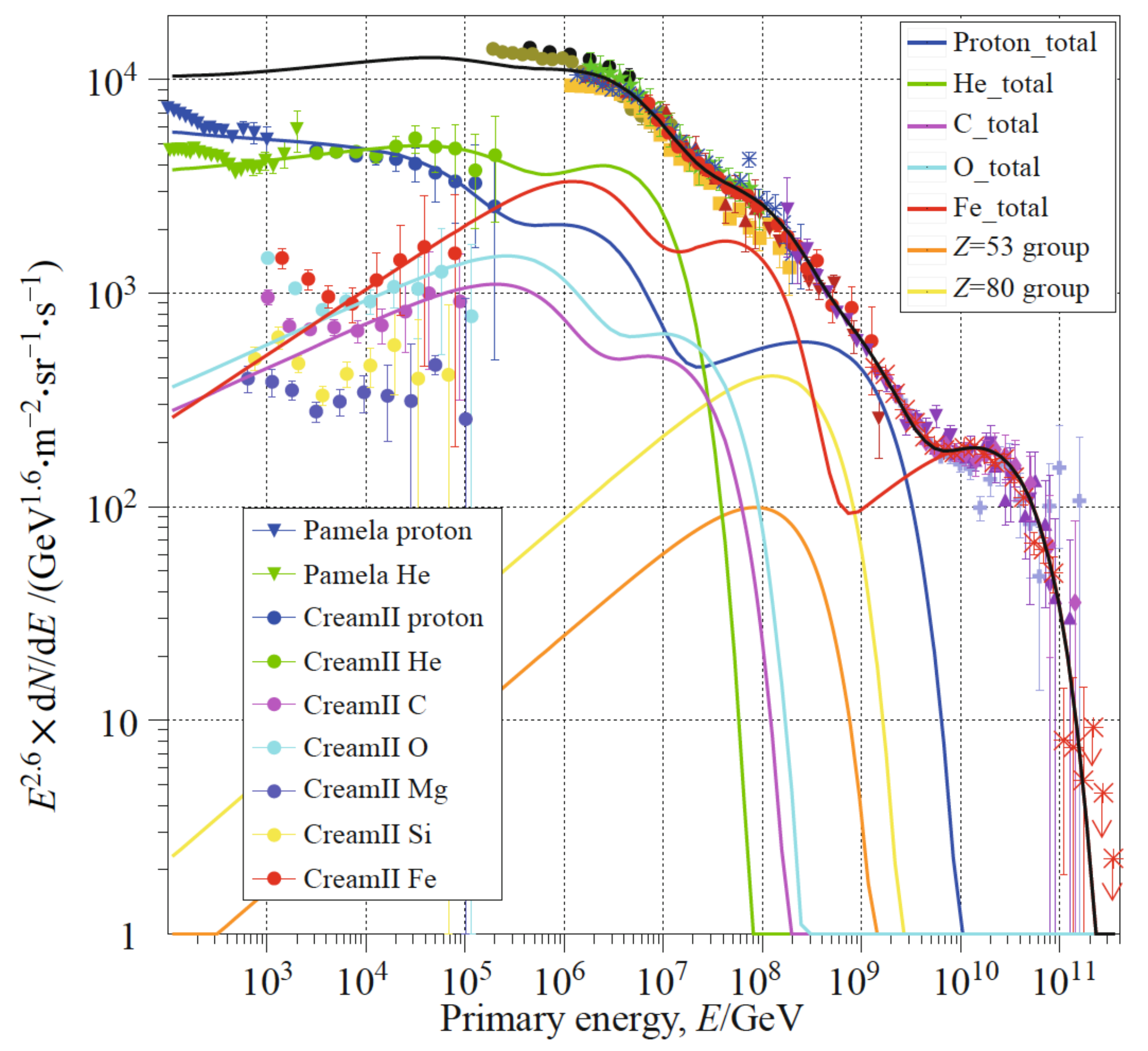


prototype
ToF

Beyond the knee

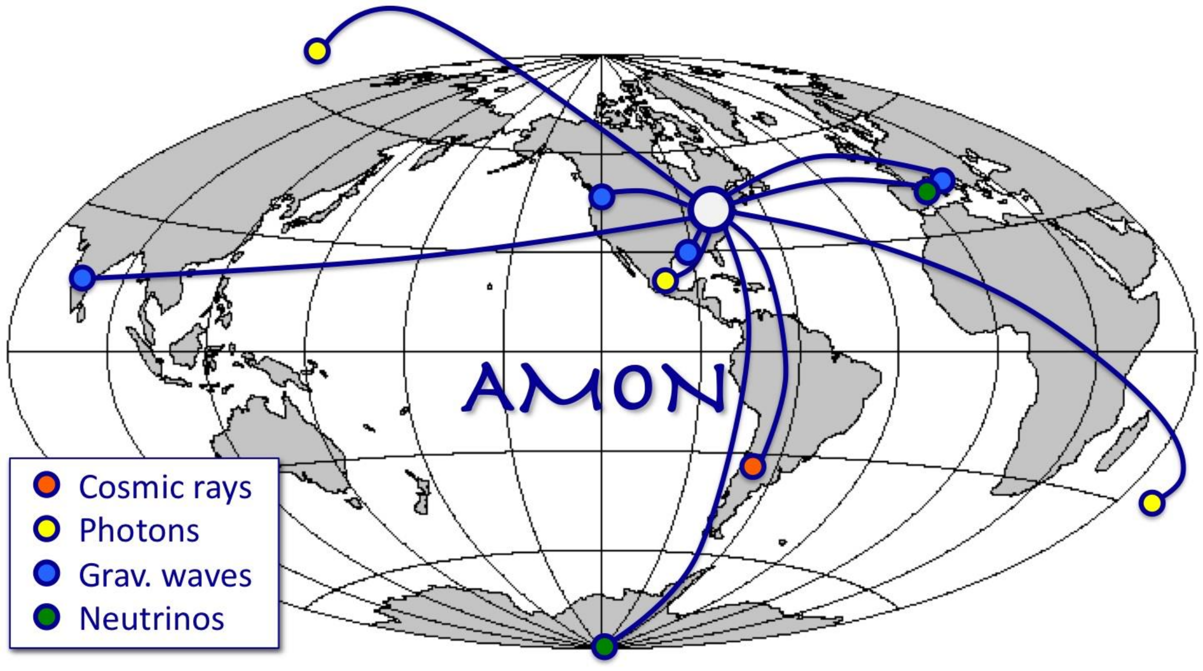
Direct measurements anchor models for composition interpretation of air shower measurements beyond the knee.

Rich phenomenology!



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

http://amon.gravity.psu.edu



- PSU initiative
- Coordinate subthreshold signals from multiple signatory observatories;
- similar to previous efforts to coordinate neutrino (SNEWS), gamma-ray burst (GCN), or gravitational wave detections;

but now with *all* messengers!

Why not add CALET, DAMPE, AMS, ISS-CREAM?

- Triggering observatories [Swift, Fermi, LIGO, IceCube, Auger, HAWC, Antares]
- Follow up observatories [HAT (Hungary), IUCAA (India), PTF, VERITAS, ROTSE]
- New members actively solicited!
- Data sharing begun, first archival searches completing now, first science:

Multiwavelength follow-up of a rare IceCube neutrino multiplet

IceCube: M. G. Aartsen[2], M. Ackermann[116], J. Adams[28], J. A. Aguilar[16], M. Ahlers[67], M. Ahrens[101], I. Al Samarai[43], D. Altmann[40], K. Andeen[69],

The Astrophysical Multimessenger Observatory Network: D. B. Fox[109,111,112], J. J. DeLaunay[110,111], C. F. Turley[110,111], S. D. Barthelmy[47], A. Y. Lien[47], P. Mészáros[110,109,111,112], K. Murase[110,109,111,112]

A&A 607, A115 (2017)
IceCube + ASAS-SN, AMON, Fermi, HAWC, LCO, MASTER, Swift, VERITAS

Thanks to

Conclusions

Direct studies of cosmic-ray nuclei now yield high precision:

- New generation of complex instruments;
- Multiple redundant particle identification techniques;
- Beam test calibrations to reduce instrumental systematics;
- Long exposures on Antarctic balloons, space platforms.

Elemental spectra now show hardening at ~200 GeV/n, and p spectrum has a softer spectrum (spectral index 2.66) than Helium and heavier nuclei (2.58):

- 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.

Elemental spectra add up to the all-particle spectrum from ground arrays.

Secondary elements are starting to constrain propagation. Needs additional information from isotope measurements. Impact on secondary production, including antimatter.

Next-gen instruments are expanding and refining these measurements, which anchor composition models for studies at higher energies with air-shower arrays.