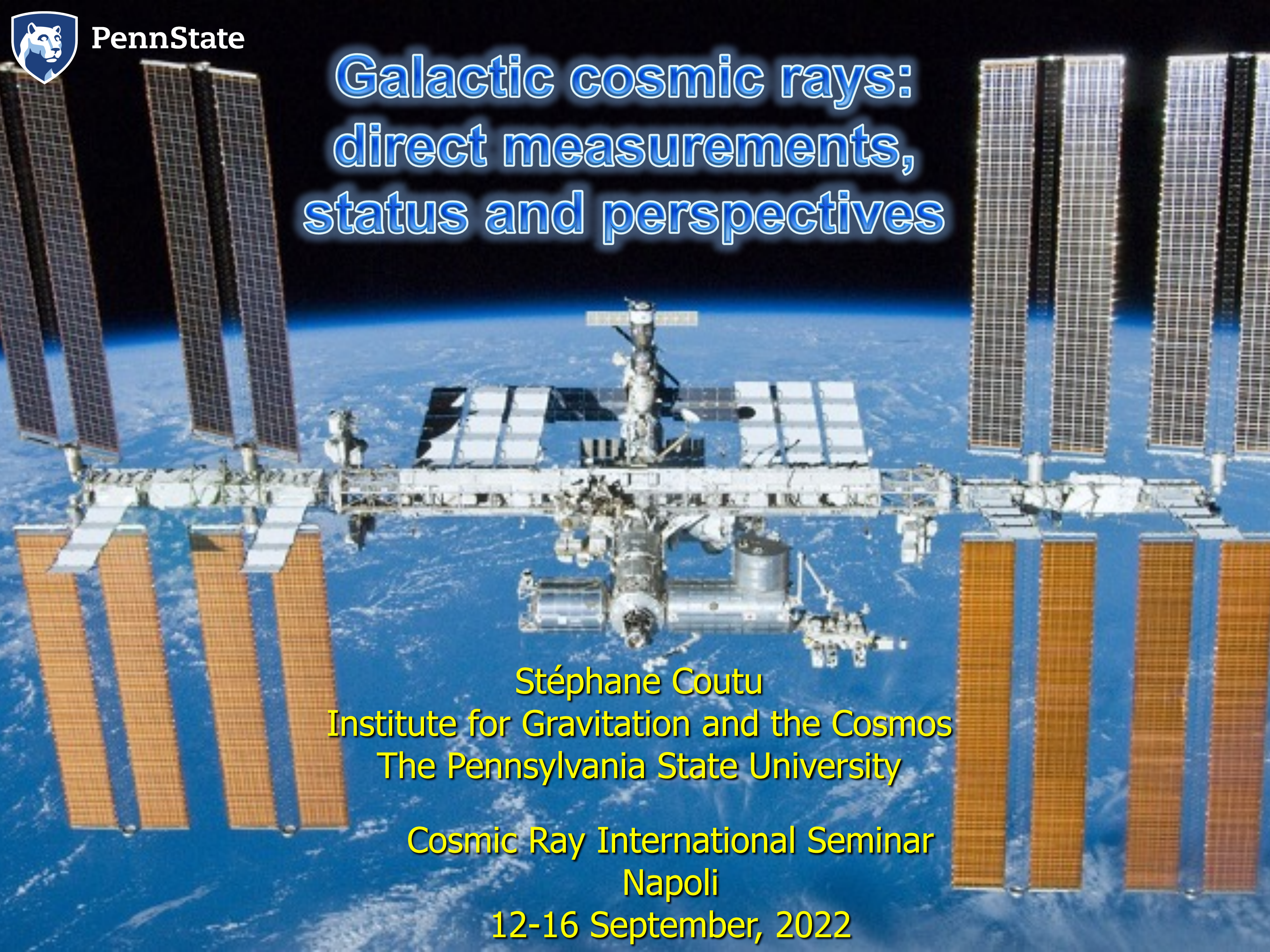


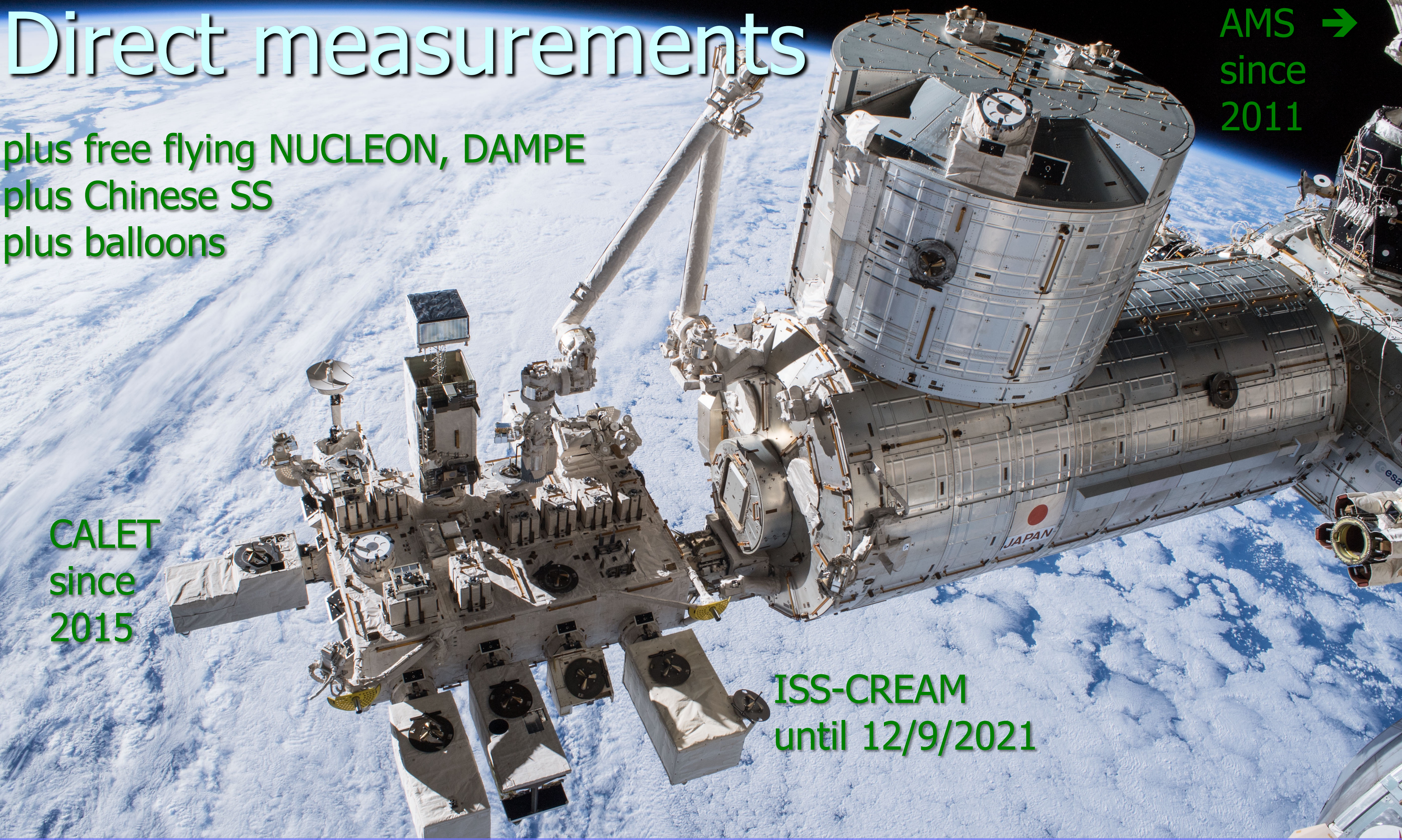
PennState

Galactic cosmic rays: direct measurements, status and perspectives

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

Cosmic Ray International Seminar
Napoli
12-16 September, 2022

Direct measurements



plus free flying NUCLEON, DAMPE
plus Chinese SS
plus balloons

AMS → since 2011

CALET since 2015

ISS-CREAM until 12/9/2021

Charged messengers: nuclei (primary, secondary, isotopes, superheavy), electrons, antimatter; see also Paolo Zuccon

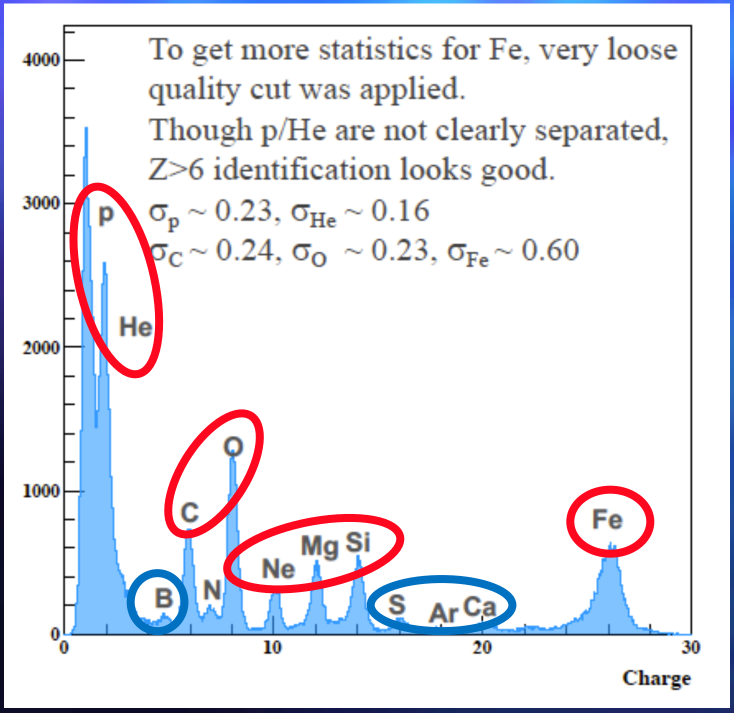
Space (AMS, CALET, DAMPE, ISS-CREAM, NUCLEON, …) Balloons (CREAM, HELIX, SuperTIGER, GAPS, …)

Link to higher energies, the future

Nuclei: elemental abundances

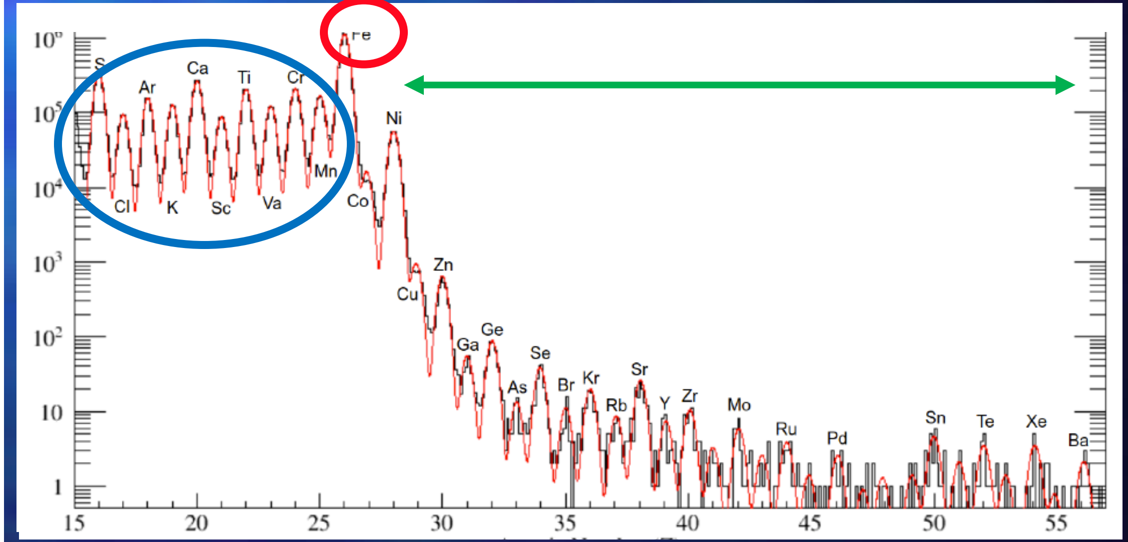
Primary nuclei produced in stellar nucleosynthesis, directly from the sources
Secondary nuclei produced spallation reactions during Galactic propagation
Ultraheavy nuclei from r-process in mergers of compact objects / supernovae

ISS-CREAM above ~2 TeV



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

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



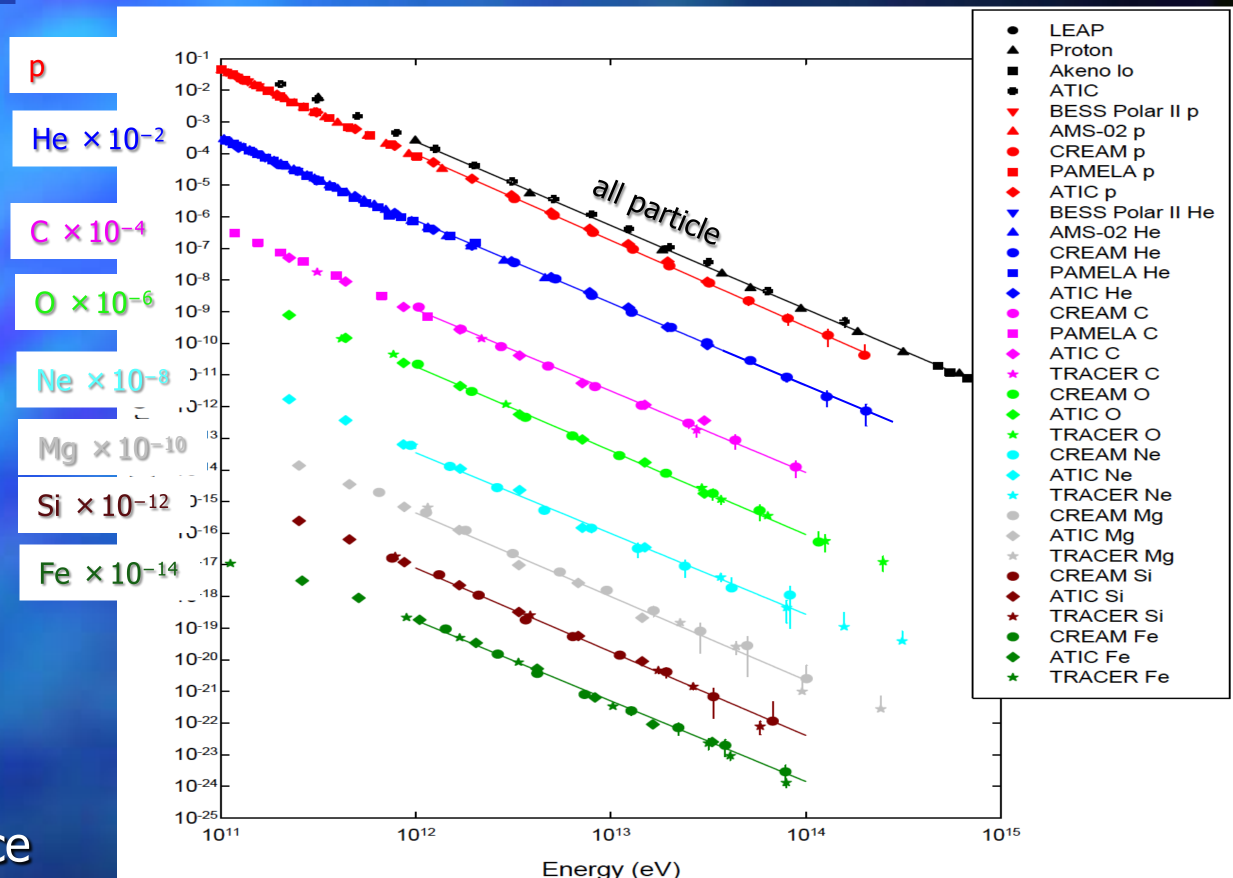
N.E. Walsh et al., PoS(ICRC2021)118

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!

Elemental spectra

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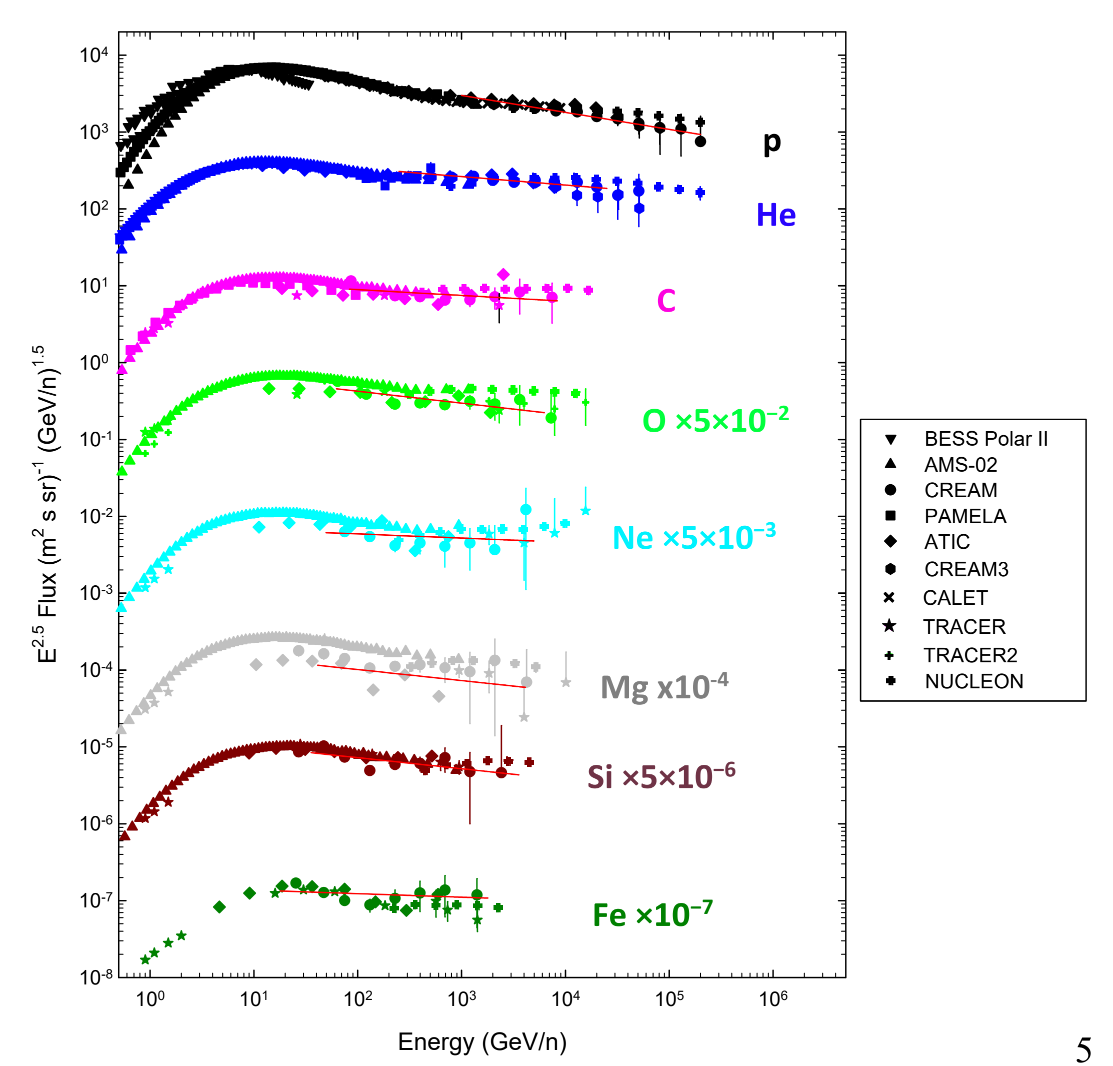
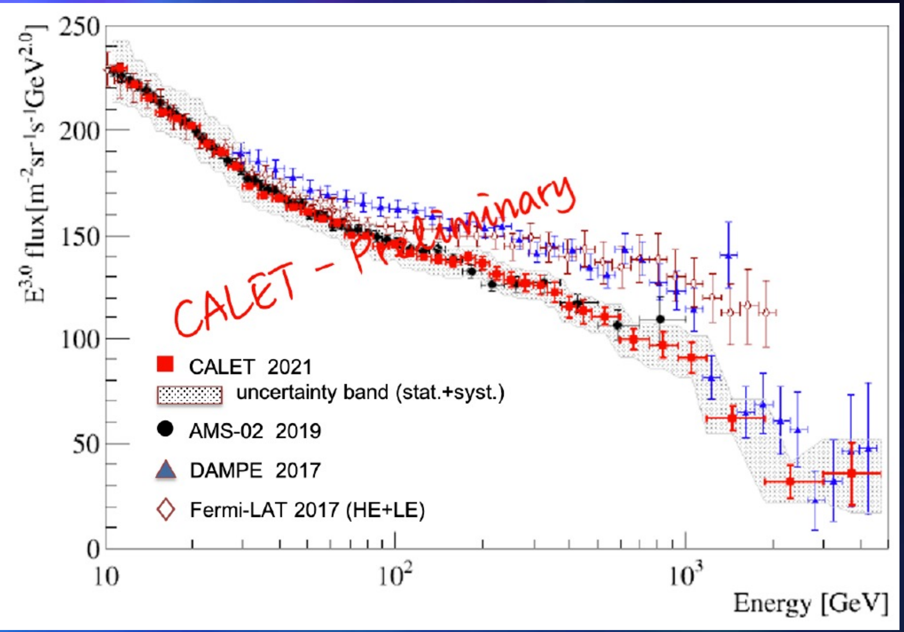


S. Torii et al. (CALET) PoS(ICRC2021)105

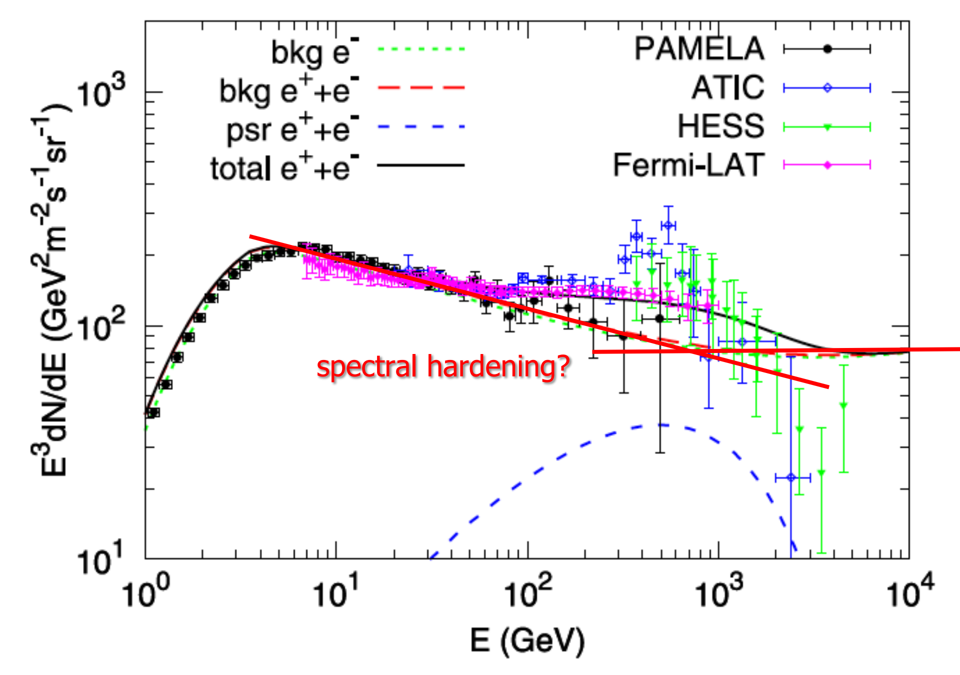
Electrons



Guaranteed Galactic origin due to dE/dx ~ E^2 during propagation

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

Electrons



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

Guaranteed Galactic origin due to $dE/dx \sim E^2$ during propagation

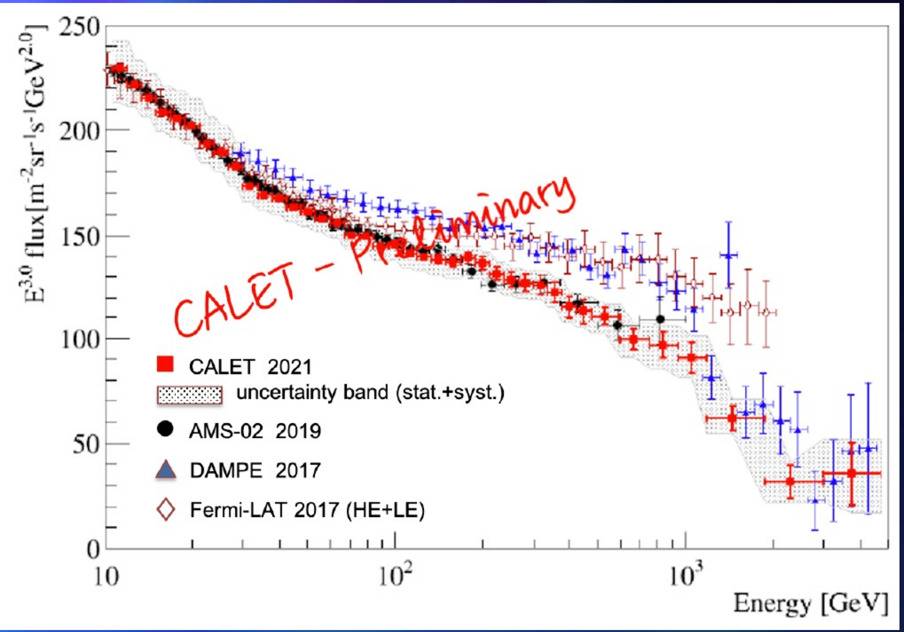
(CALET+AMS02) vs (DAMPE+Fermi-LAT)
Apparent tension... but E^3 rescaling can do funny things and control of systematics needs improvement

- Interpretation requires understanding distributed Galactic source contributions + perhaps some nearby pulsars;

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

Electrons

Guaranteed Galactic origin due to dE/dx ~ E^2 during propagation

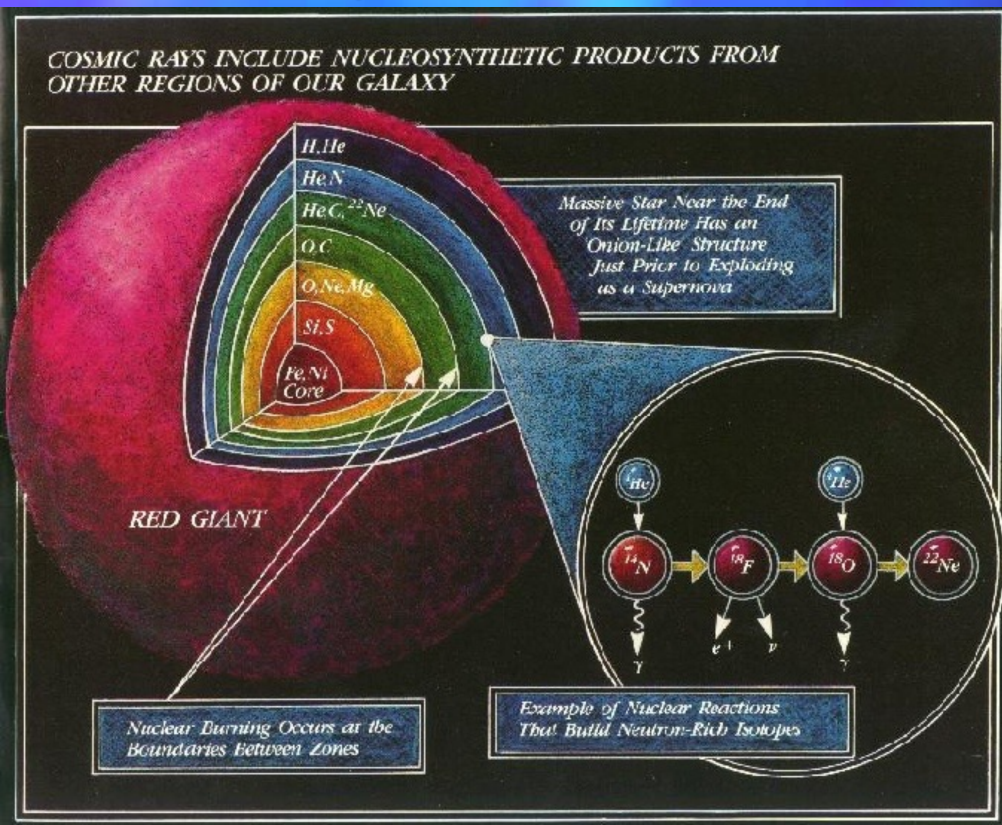


(CALET+AMS02) vs (DAMPE+Fermi-LAT)
Apparent tension... but E^3 rescaling can do funny things and control of systematics needs improvement

- 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.

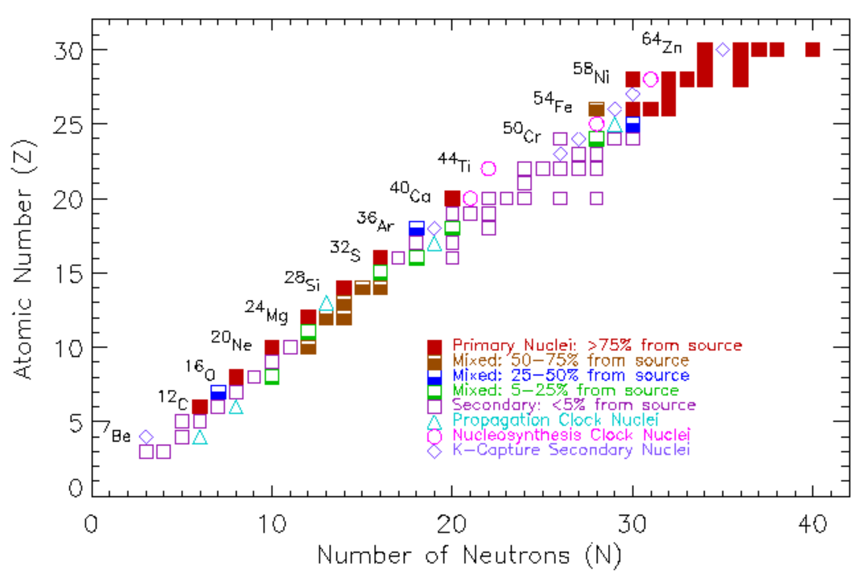
Nucleosynthesis + isotopes

Stellar nucleosynthesis + release in SN



Isotopes can have different origins:

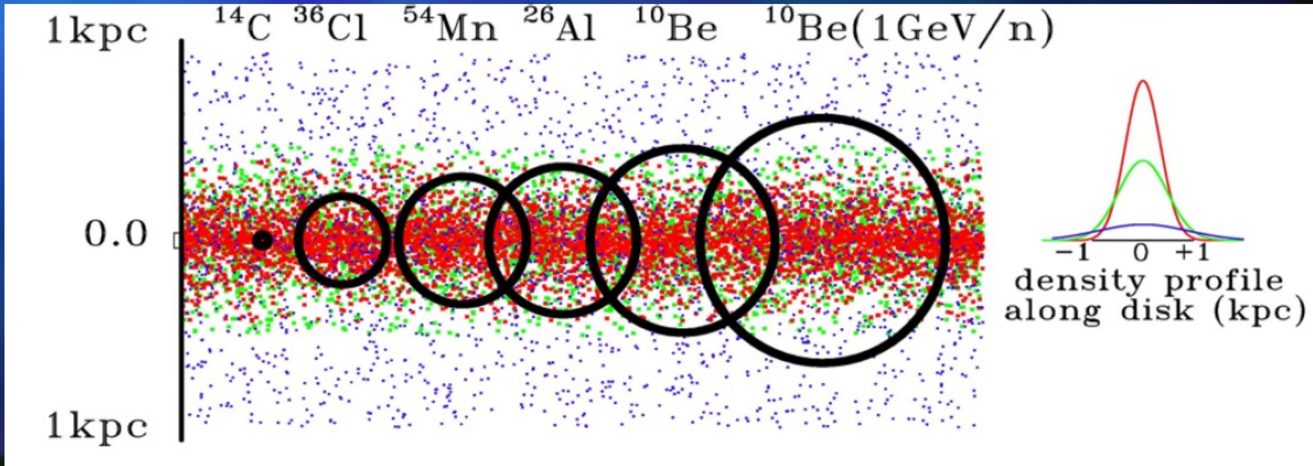
- stable, from primary SNR site;
- unstable, from primary SNR site (nucleosynthesis clock isotope);
- spallation products of nuclear breakup in the ISM;
- some stable, some unstable (propagation clock isotope).



Isotopes – the science case

- Be entirely secondary;
- ^{9}Be is stable, but ^{10}Be β decays with a half-life of λ ~ 1.39 Myr (vs 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): disk at 0.3 GeV/n, halo at 10 GeV/n.

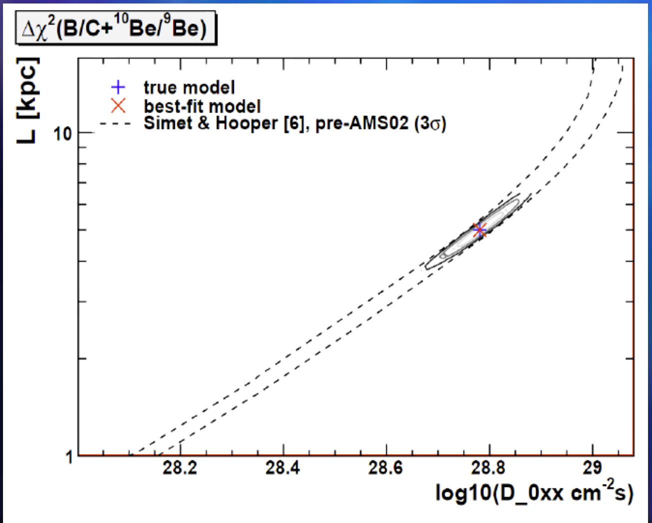
Z/A dependence of Galactic region sampled by 0.3 GeV/n clock isotopes; Be is ideal.



Isotopes, e.g., Be

- Complementary to other secondary elements such as B/C;
- Helps to break a degeneracy in Galactic diffusion effects.

χ^2 map for GALPROP
L: halo height
D_{0xx}: diffusion coefficient



But isotope measurements are *hard;* 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:

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

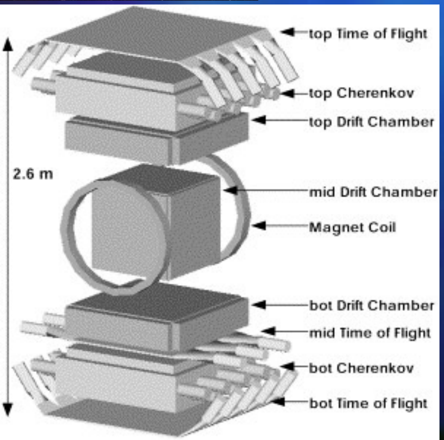
For $\Delta m/m$ = 2.5%, need:
$\Delta R/R \sim$ 1-2% $\Delta\beta/\beta \sim$ 0.1%

M. Pato et al., JCAP 06, 022 (2010)

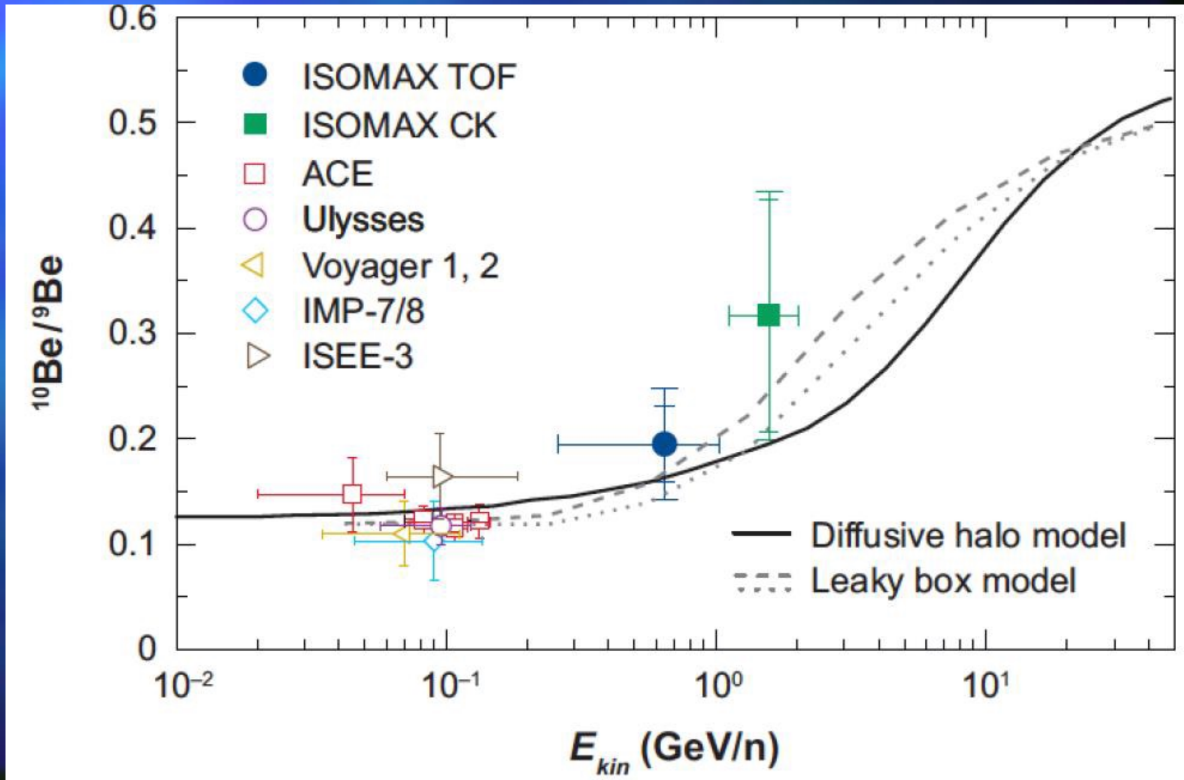
Mass resolved Be isotopes

- ACE/CRIS satellite 1997 – present;
- Isomax 1998 (instrument destroyed after balloon flight)...

CRIS



ISOMAX

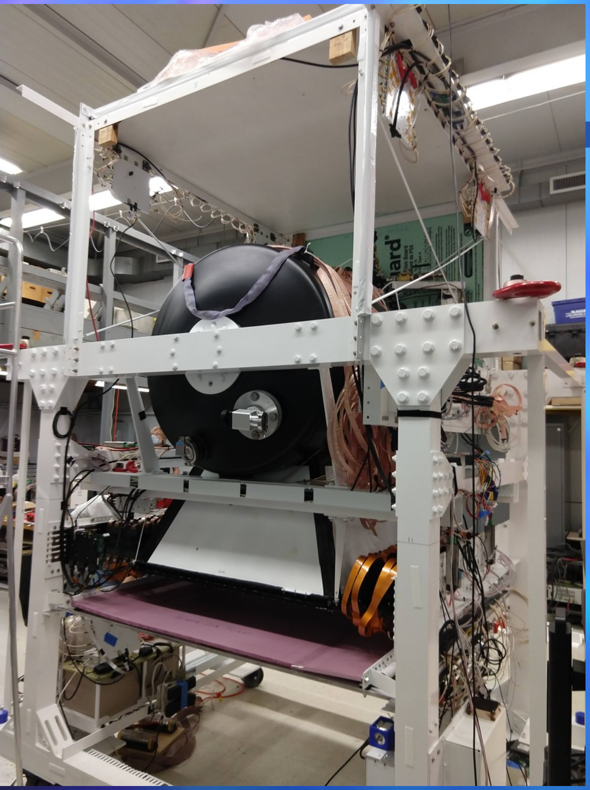


S. Coutu

HELIX

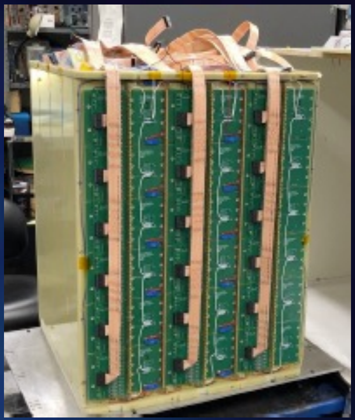
High Energy Light Isotope eXperiment
Sweden or Antarctic flight 2023-24

refurbished
HEAT magnet



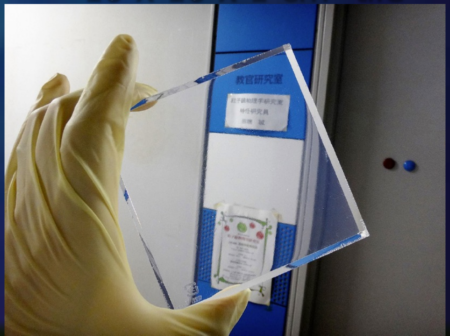
ToF plane

DCT



RICH

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



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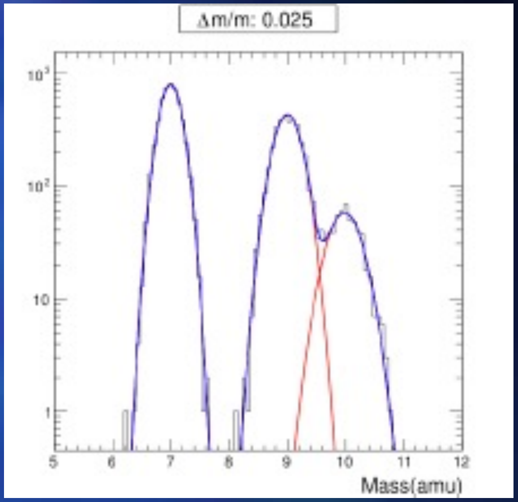
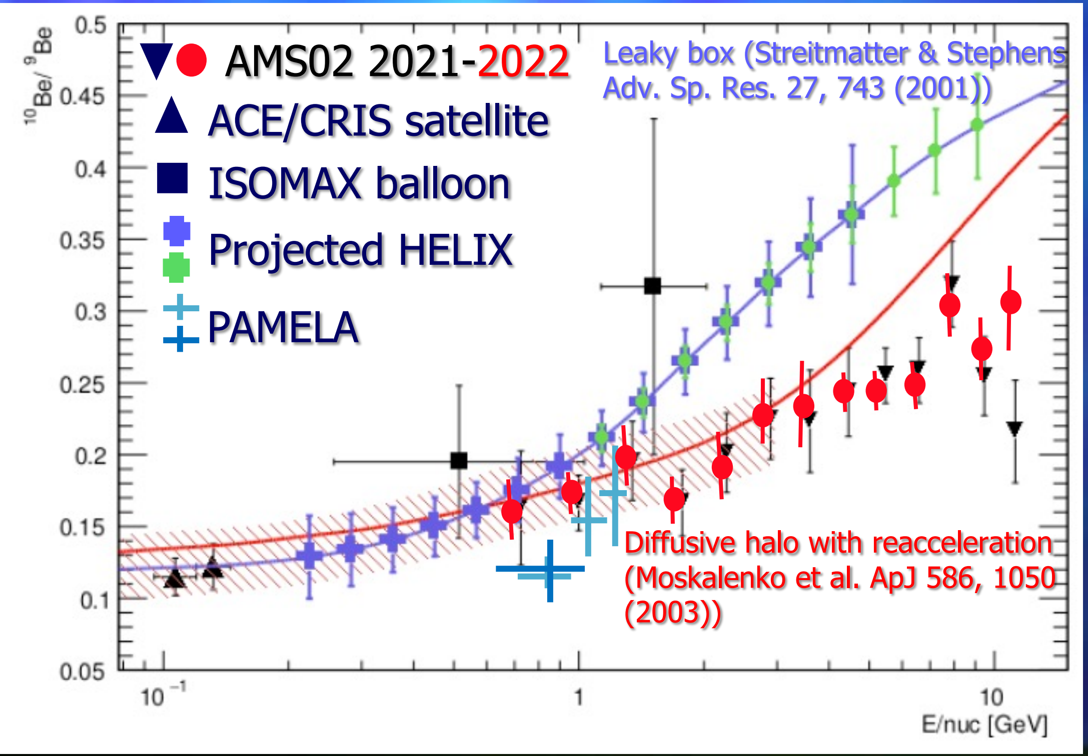
Be isotopes

- 2021 surprise: AMS results – not mass resolved (Berlin ICRC);
- Also a 2021 result from PAMELA data.

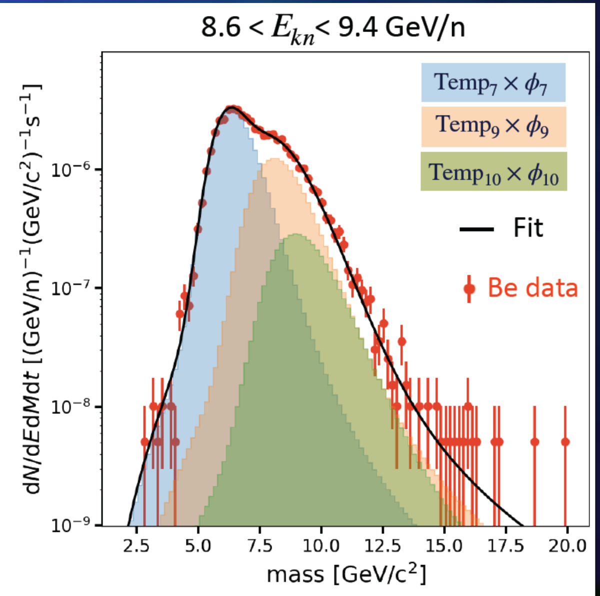
Be isotopes with $\Delta m/m = 2.5\%$, HELIX design



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



AMS Be isotopes are not mass resolved



L. Derome et al., Berlin ICRC (2021)

Be interpretation tricky

Y. Génolini, D. Maurin, I. Moskalenko, M. Unger, Phys. Rev. C 98, 034611 (2018)

TABLE XI. Reactions and associated cross sections important for calculations of Be flux at 10 GeV/nucleon, sorted according to the flux impact f_{abc}, Eq. (4), until the cumulative of the flux impact $>0.8 \times f_{\rm sec} \times \sum f_{abc}$, with $f_{\rm sec} = 100\%$ and $\sum f_{abc} = 1.14$ (see Sec. IV B). Reactions in **bold** highlight short-lived fragments (see Sec. IV A), whose properties are gathered in Table XV.

Reaction $a + b \to c$	Flux impact f_{abc} [%]			σ [mb]	Data	$\sigma\%\sigma$
	Min	Mean	Max	range		
$\sigma(^{16}O + H \to {}^{7}Be)$	17.0	**17.6**	19.0	10.0	✓	
$\sigma(^{12}C + H \to {}^{7}Be)$	15.0	**15.9**	17.0	9.7	✓	
$\sigma(^{12}C + H \to {}^{9}Be)$	8.80	**9.27**	9.80	6.8	✓	
$\sigma(^{16}O + H \to {}^{9}Be)$	5.00	**5.34**	5.60	3.7	✓	
$\sigma(^{16}O + He \to {}^{7}Be)$	2.70	**2.87**	3.00	14.7		
$\sigma(^{28}Si + H \to {}^{7}Be)$	2.60	**2.77**	2.90	10.8		
$\sigma(^{24}Mg + H \to {}^{7}Be)$	2.50	**2.65**	2.80	10.0		
$\sigma(^{12}C + He \to {}^{7}Be)$	2.30	**2.48**	2.60	13.7		
$\sigma(^{11}B + H \to {}^{9}Be)$	2.30	**2.36**	2.50	10.0	✓	
$\sigma(^{12}C + H \to {}^{10}Be)$	2.00	**2.16**	2.30	4.0	✓	
$\sigma(^{14}N + H \to {}^{7}Be)$	2.00	**2.12**	2.20	10.1	✓	
$\sigma(^{20}Ne + H \to {}^{7}Be)$	1.60	**1.73**	1.90	[7.4, 9.7]		
$\sigma(^{10}B + H \to {}^{9}Be)$	1.60	**1.62**	1.70	13.9		
$\sigma(^{12}C + He \to {}^{9}Be)$	1.40	**1.45**	1.50	9.6		
$\sigma(^{12}C + H \to {}^{11}B)$	1.30	**1.43**	1.60	30.0	✓	1.8
$\sigma(^{15}N + H \to {}^{9}Be)$	1.20	**1.29**	1.40	7.3	✓	
$\boldsymbol{\sigma(^{12}C + H \to {}^{11}C)}$	1.20	**1.28**	1.40	26.9	✓	**n/a**
$\sigma(^{16}O + H \to {}^{10}Be)$	1.20	**1.27**	1.40	2.2	✓	
$\sigma(^{11}B + H \to {}^{10}Be)$	1.10	**1.21**	1.30	12.9	✓	
$\sigma(^{11}B + H \to {}^{7}Be)$	0.99	**1.16**	1.30	[3.6, 4.5]	✓	
$\sigma(^{15}N + H \to {}^{7}Be)$	1.10	**1.15**	1.20	5.4	✓	

Many reactions to take into account.

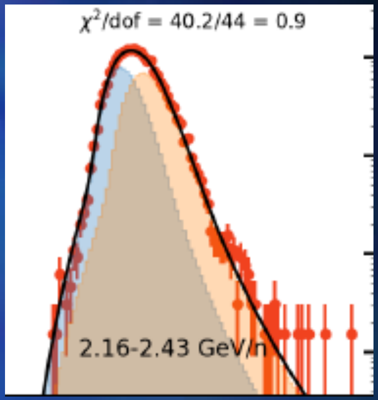
17 channels → 71.5% Be
46 channels → 13.4% Be
207 channels → 6.1% Be
532 channels → 1.8% Be
+ 879 + 3624 channels…

Then fold in all Galactic propagation effects

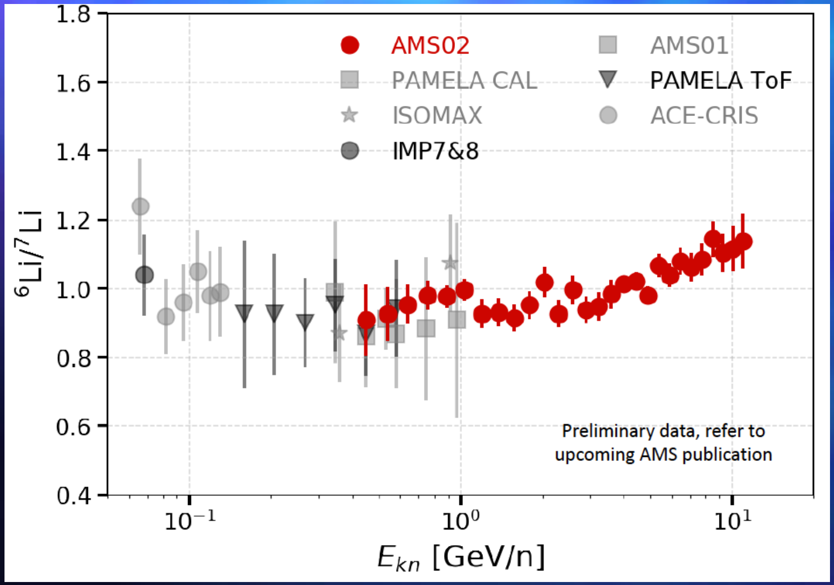
Other light isotopes

- Several new AMS02 results, also requiring template fits;
- good for model tuning (GALPROP, USINE).

^{6}Li vs ^{7}Li

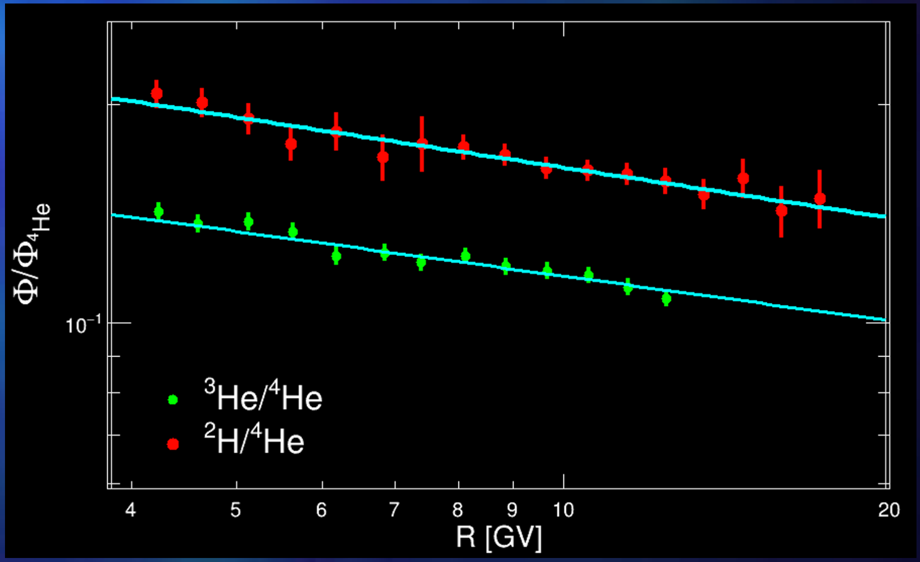


^{6}Li / ^{7}Li



L. Derome et al., Berlin ICRC (2021)

^{3}He / ^{4}He ^{2}H / ^{4}He



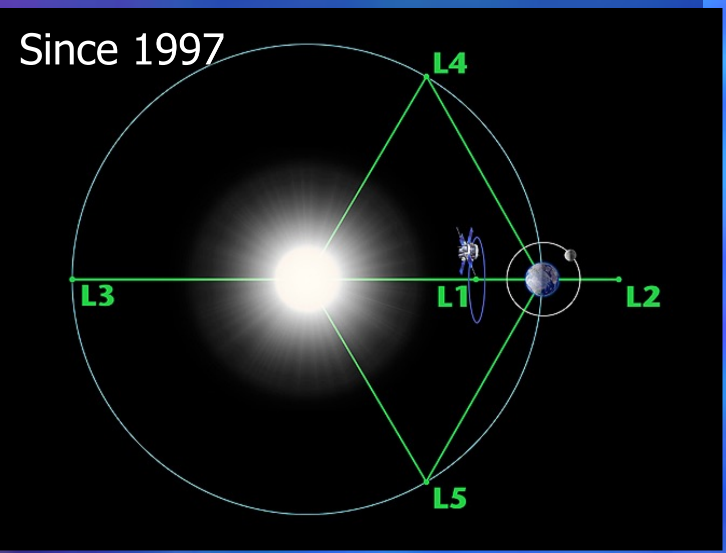
J. Wei et al., Kingston TeVPA (2022)

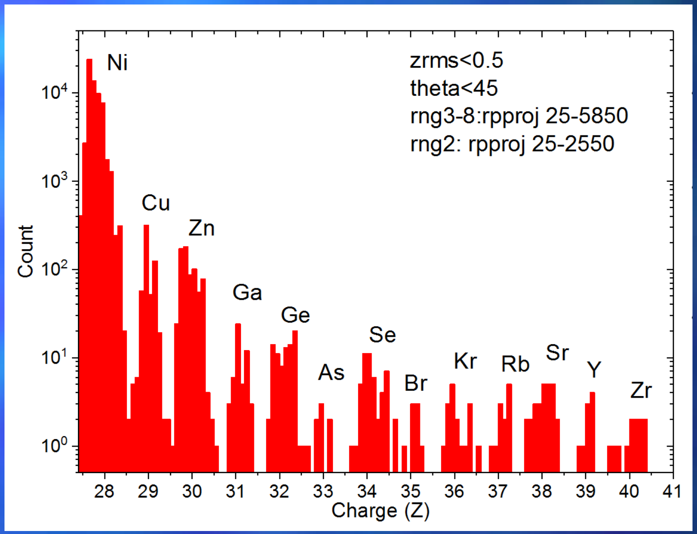
ACE/CRIS

Elements divided into:

- volatiles (not strongly bound in rocks, say);
- refractories (strongly bound);

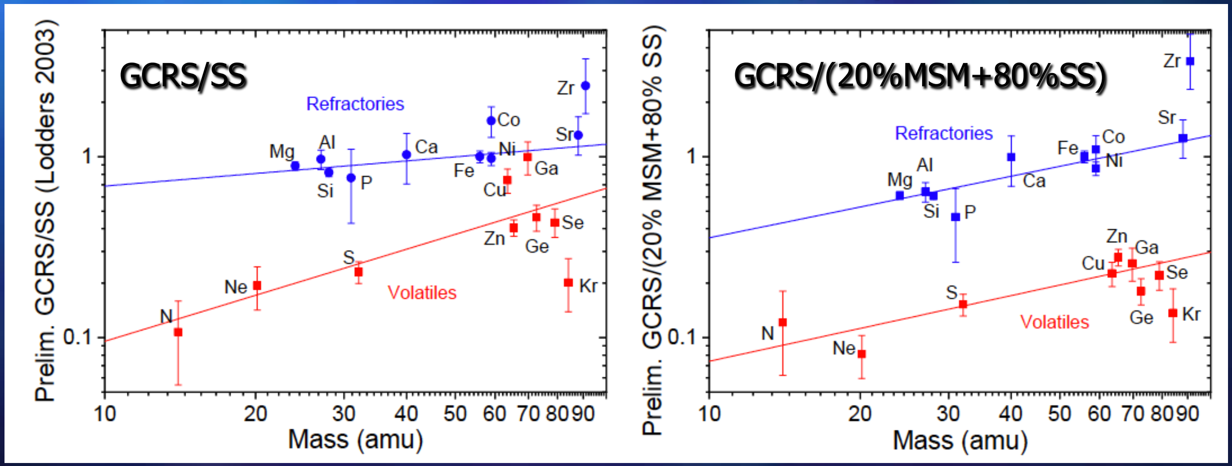
- models of their origin of massive star material (MSM) and interstellar material (ISM);
- interesting structure, not fully understood...



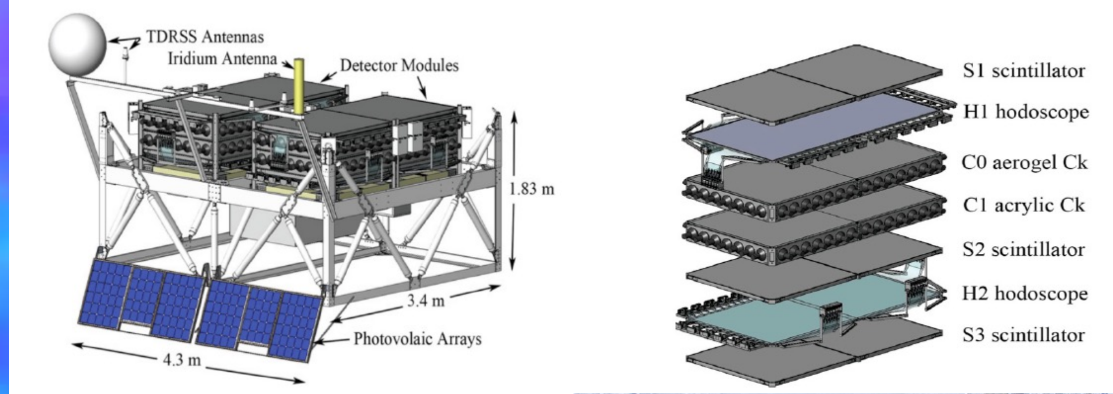


Small instrument operating for a long time, under an extended period of solar minimum ➔ remarkable populations of ultraheavy cosmic rays!

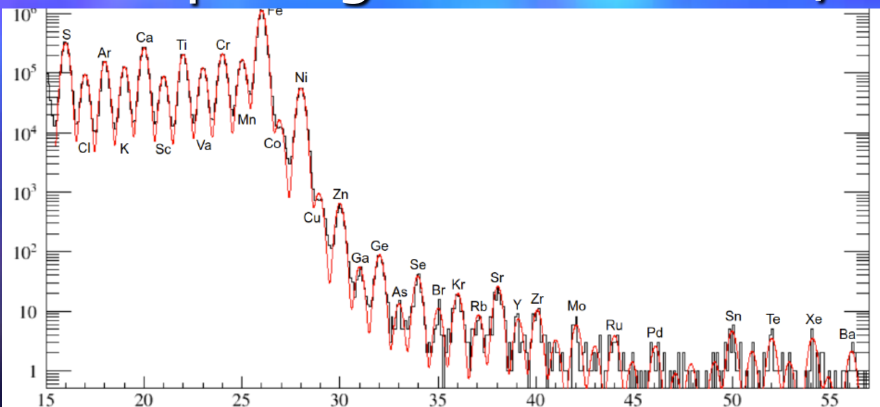
R. Binns et al., Madison ICRC (2019)

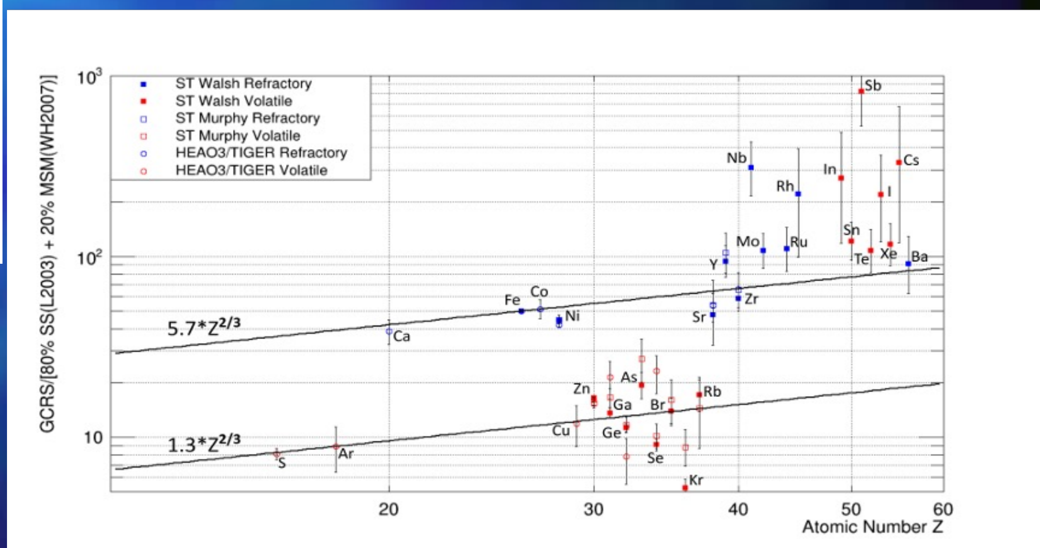


SuperTiger



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





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.

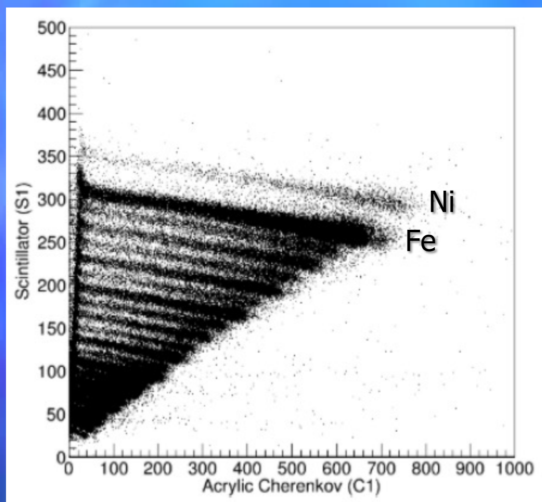
N.E. Walsh et al., PoS(ICRC2021)118

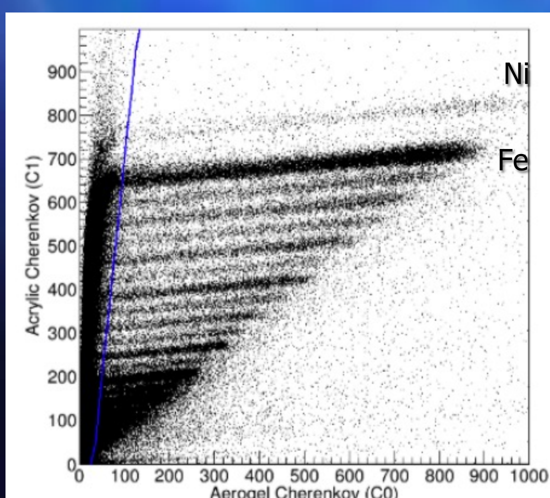
S. Coutu

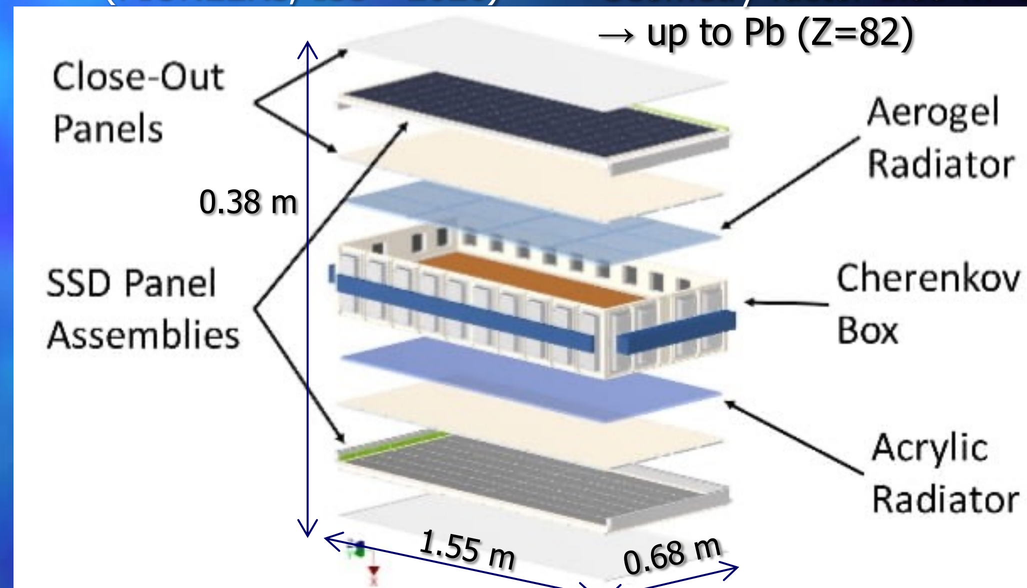
Trans-Iron Galactic Element Recorder on the ISS

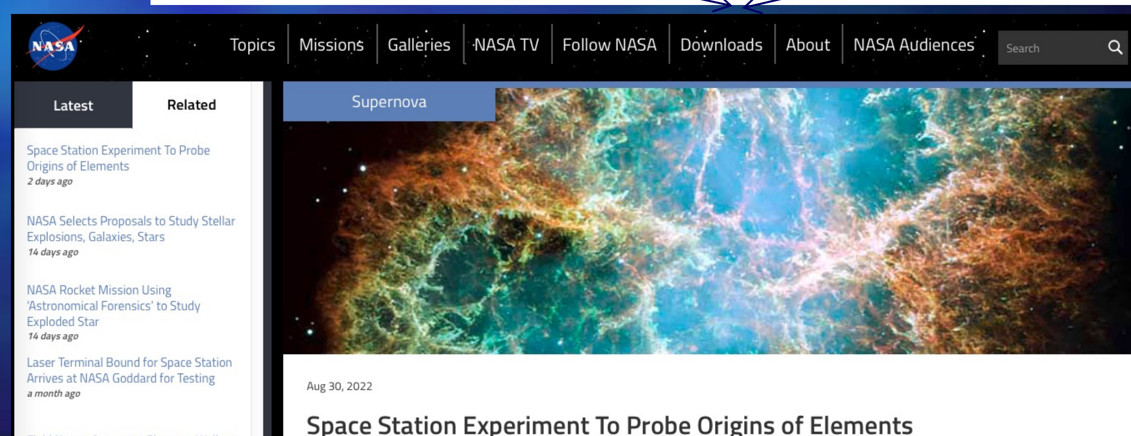
TIGERISS for ultraheavies (PIONEERS, ISS ~2026)

Geometry factor 1.53 m^2 sr → up to Pb (Z=82)





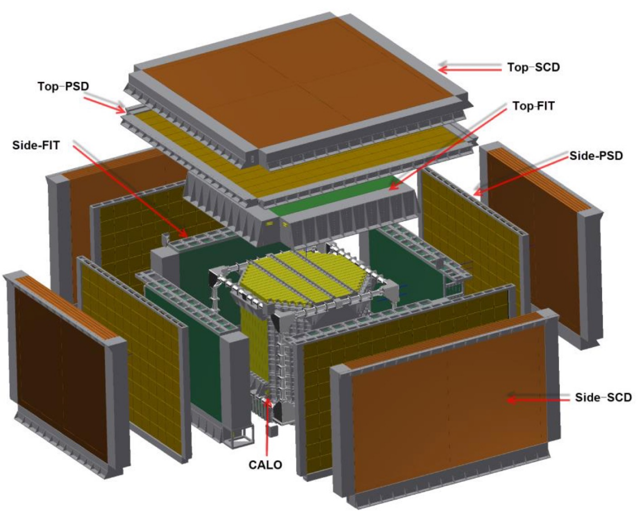




S. Coutu

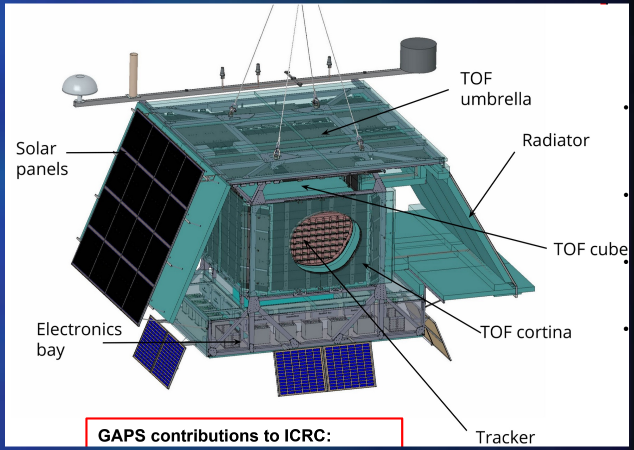
Future missions

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



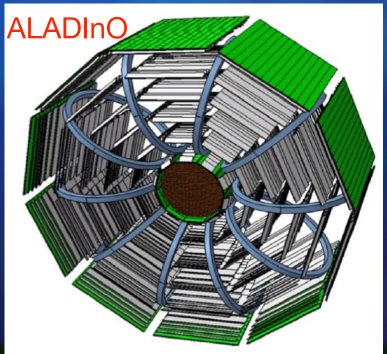
Plus PUEO, POEMMA, EUSO, APT, HEPD02, GAMMA-400, …

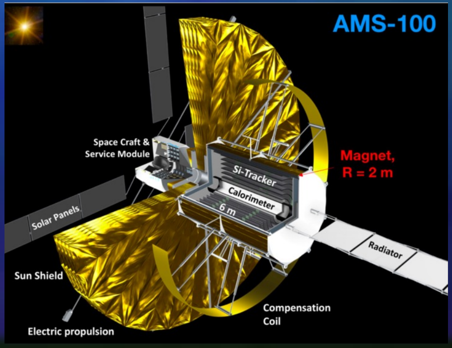
GAPS for antideuterons (balloon 2023?)



ALADInO and AMS-100 for antimatter (concepts)

AMS-02 tracking upgrades planned





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.


Grazie !