The High Energy Light Isotope eXperiment program of direct cosmic-ray studies

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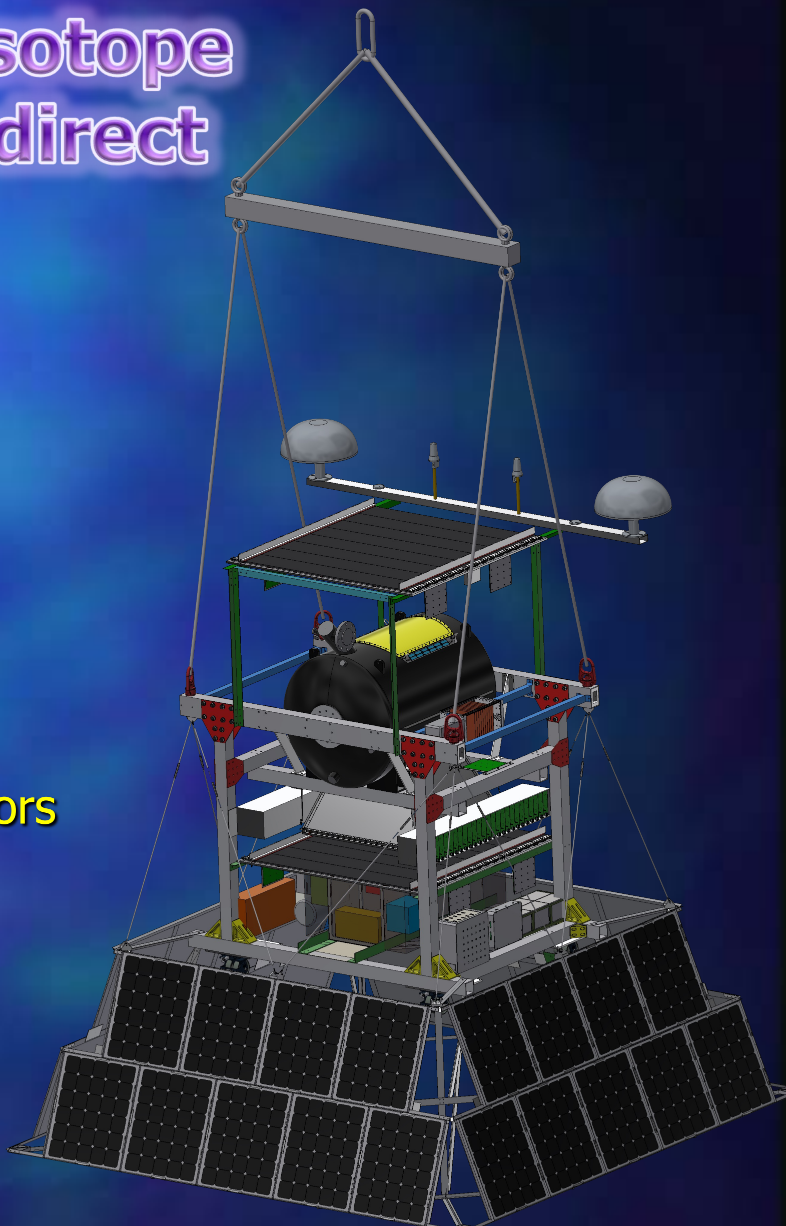
for the HELIX Collaboration

Institute for Gravitation and the Cosmos
The Pennsylvania State University

Innovative Particle and Radiation Detectors
Siena
25-29 September, 2023



HELIX collaboration

University of Chicago
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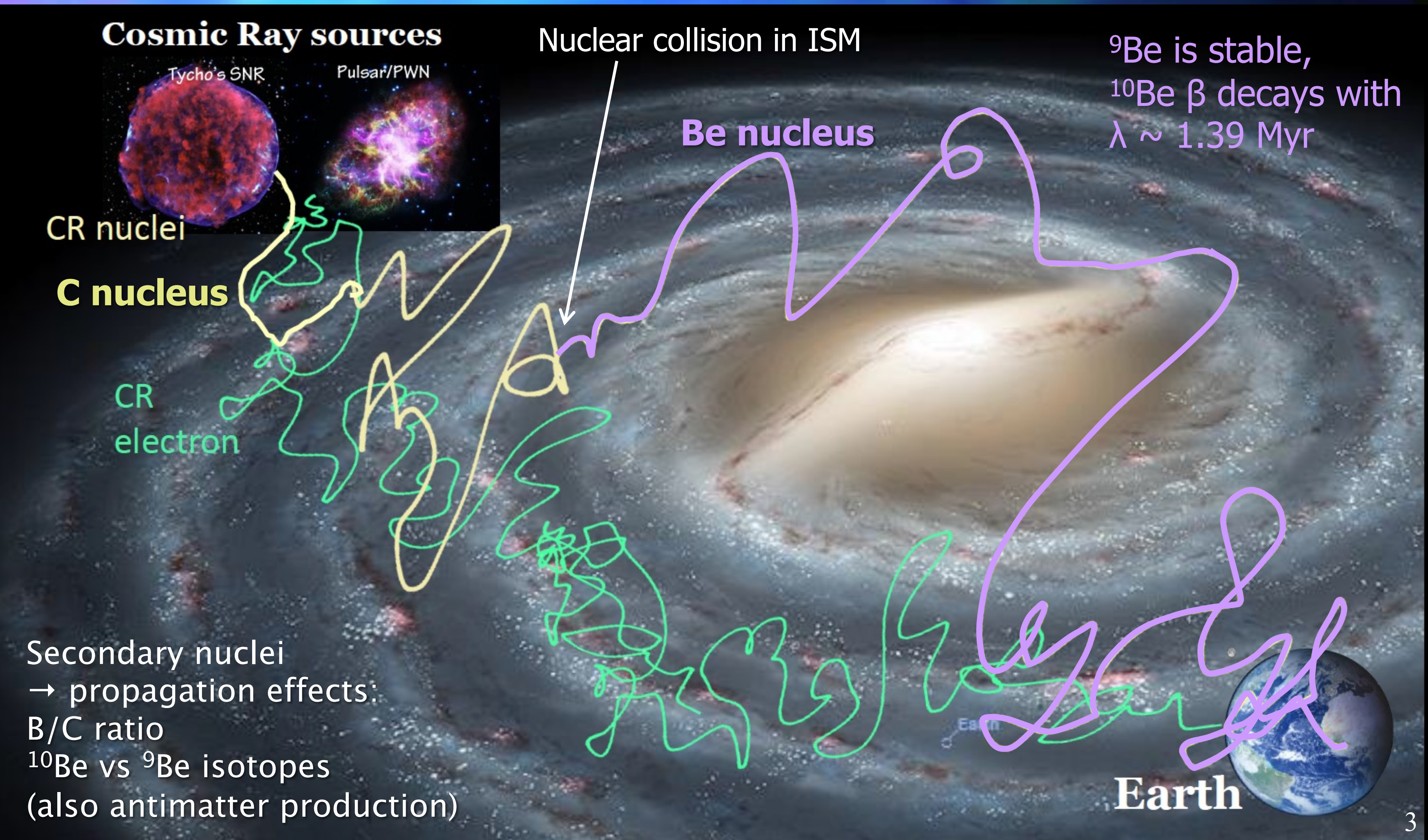
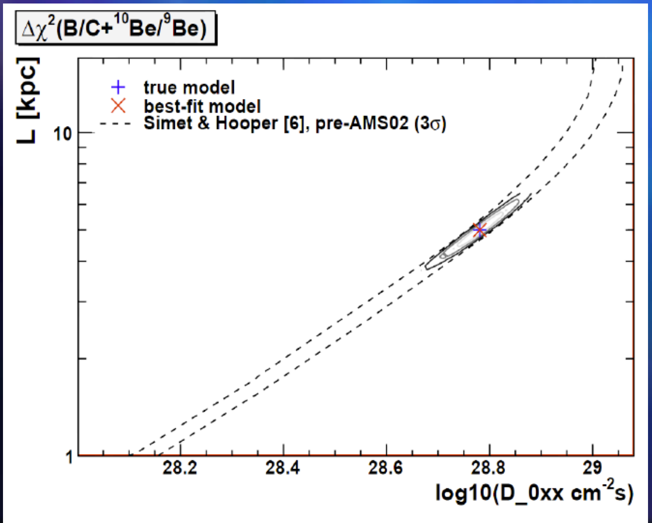
Secondary production



Isotopes

- Complementary to other secondary elements such as B/C;
- breaks 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% $\Delta\beta/\beta \sim$ 0.7%

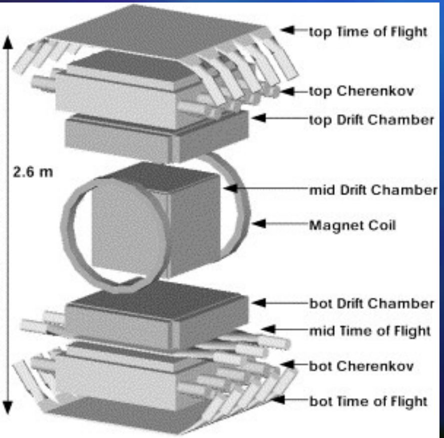
M. Pato et al., JCAP 06, 022 (2010)

Mass resolved Be isotopes

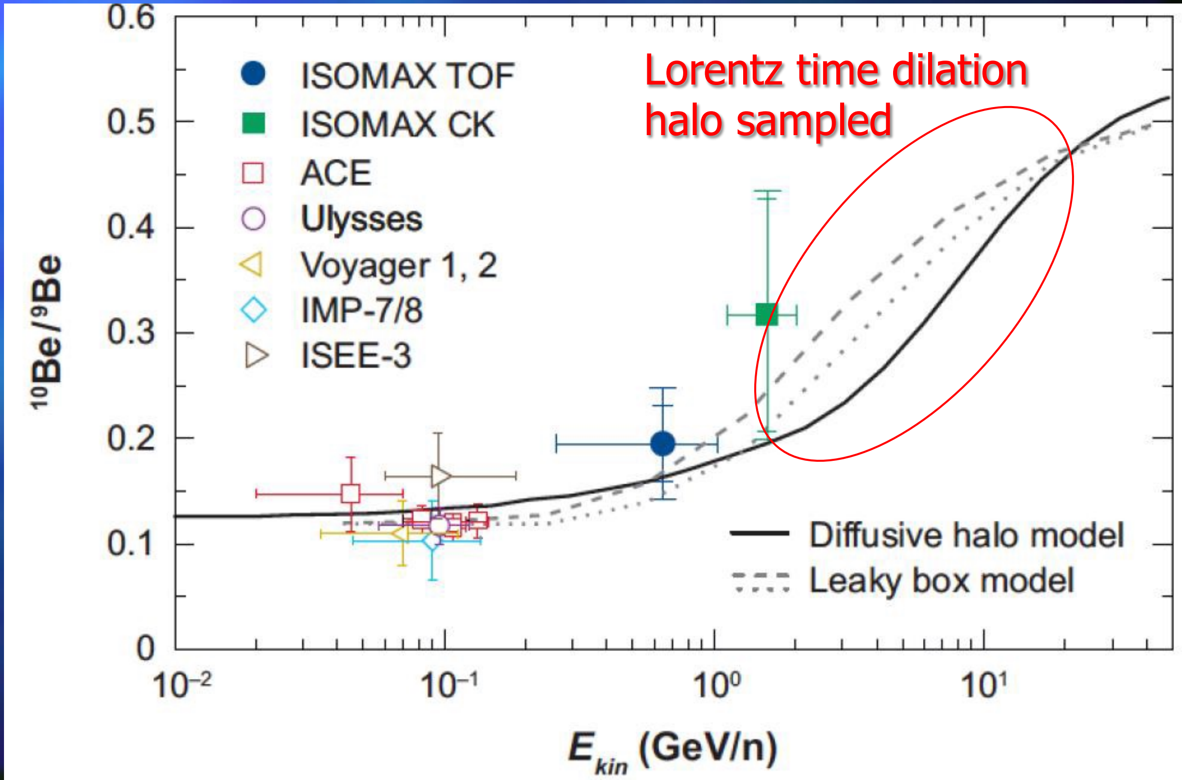
- ACE/CRIS satellite 1997 – present;
- ISOMAX 1998 (instrument destroyed after balloon flight)...

ACE

CRIS



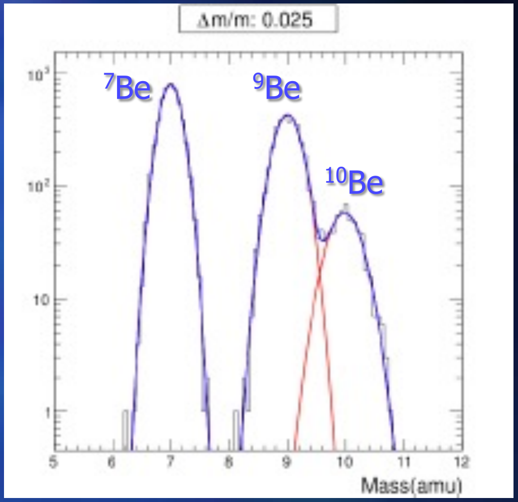
ISOMAX



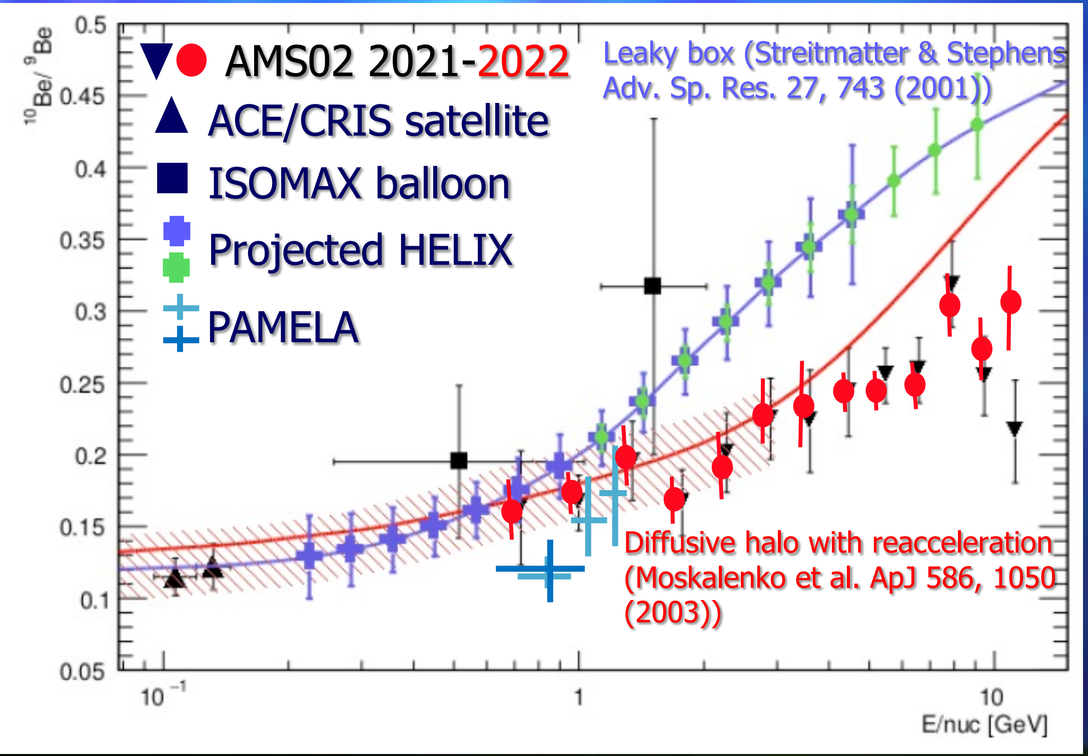
Be isotopes

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

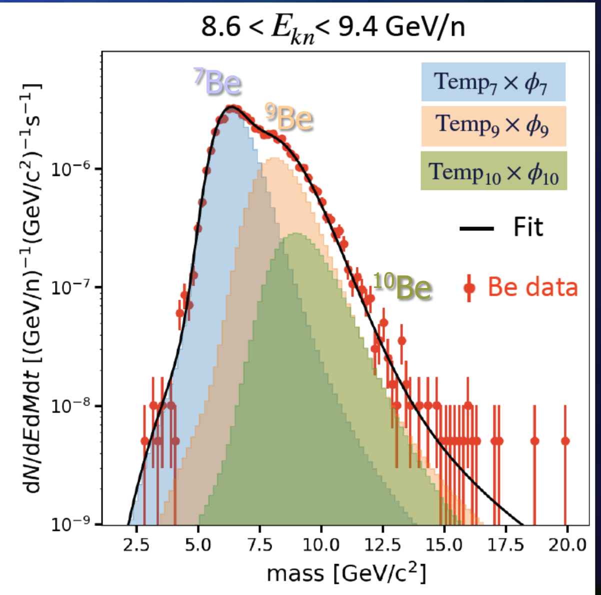
Be isotopes with $\Delta m/m = 2.5\%$, HELIX design



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



AMS Be isotopes are not mass resolved



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

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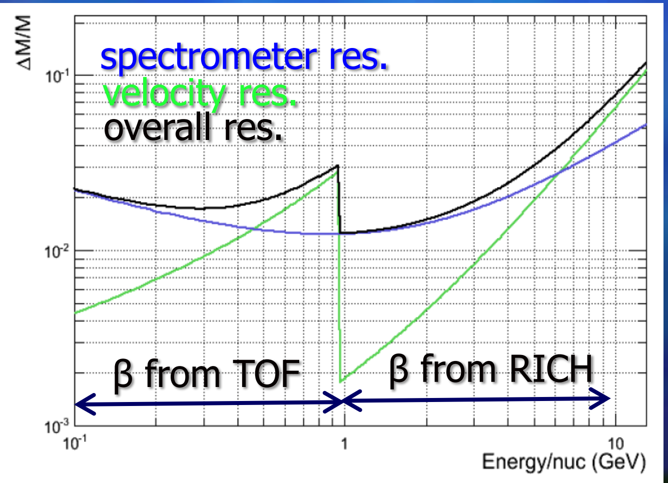
HELIX

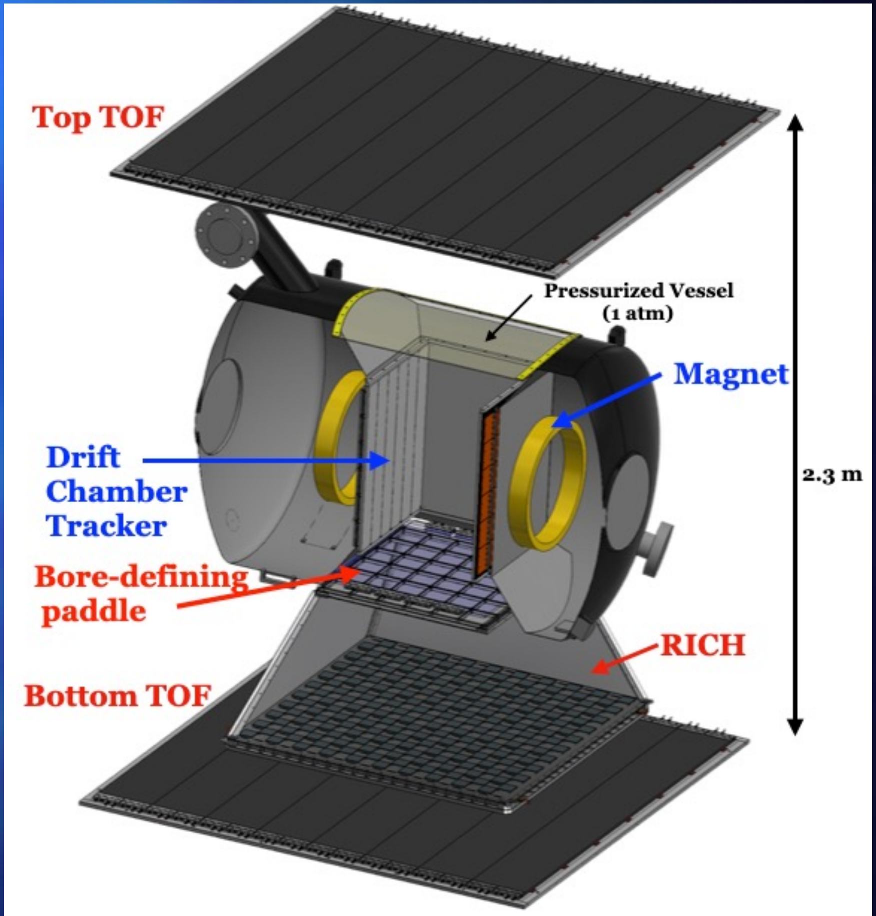
High Energy Light Isotope eXperiment
Sweden-Canada balloon flight 2024

$$m = Ze\,R\,\frac{\sqrt{1-\beta^2}}{\beta}$$

1T warm-bore superconducting magnet (HEAT) with drift-chamber tracker;

Time-of-flight scintillators for trigger, Z and β up to ~1 GeV/n
RICH for β from 0.4-1 to 10 GeV/n



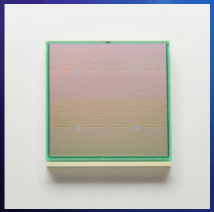


At K/A = 1 GeV/n, β=0.87

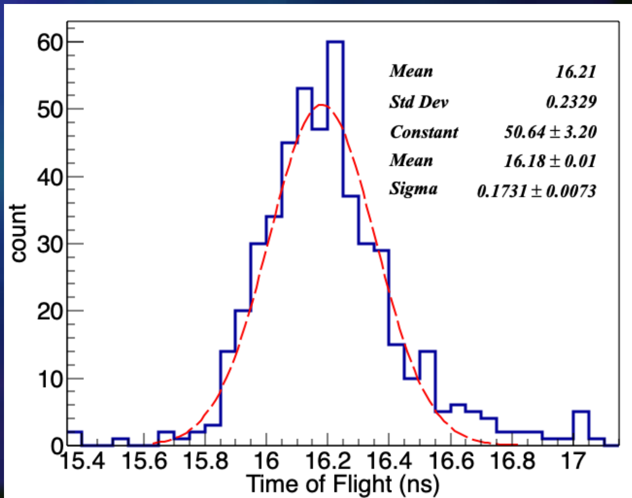
TOF system

- Below 1 GeV/n, TOF scintillators with 50 ps timing accuracy can measure the velocity to Δβ/β ~ 0.7% (2.3 m path length, 7.6 ns);
- 1.0 cm thick scintillator (20 cm x 160 cm), read out at both ends (Eljen EJ200);
- SiPM readout, insensitive to B field; only passive heat dissipation needed;
- 14 bit ADCs @40 MSPS, 25 ps timing resolution;
- scintillator dE/dx ⇒ $\sigma_Z < 0.1e$ for $Z > 3$;
- dynamic range: through Z=10 (Ne).

$\sigma_\mu = 170$ ps
⇒ $\sigma_{Be} < 50$ ps



Hamamatsu S13360-6050VE
0.6x0.6 cm^2

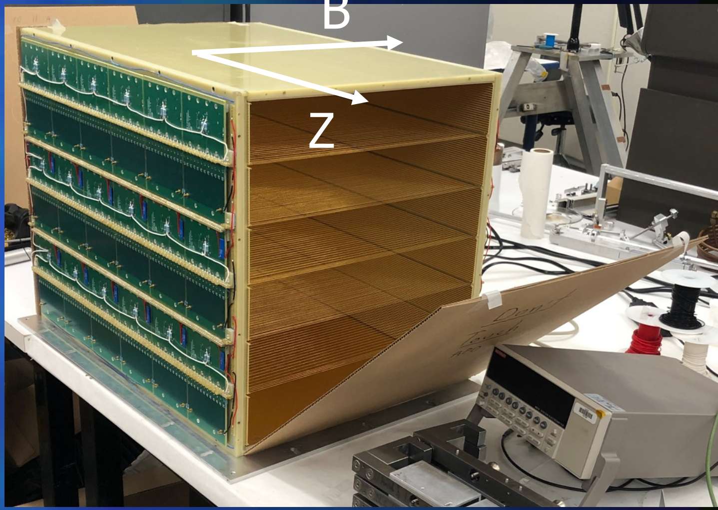


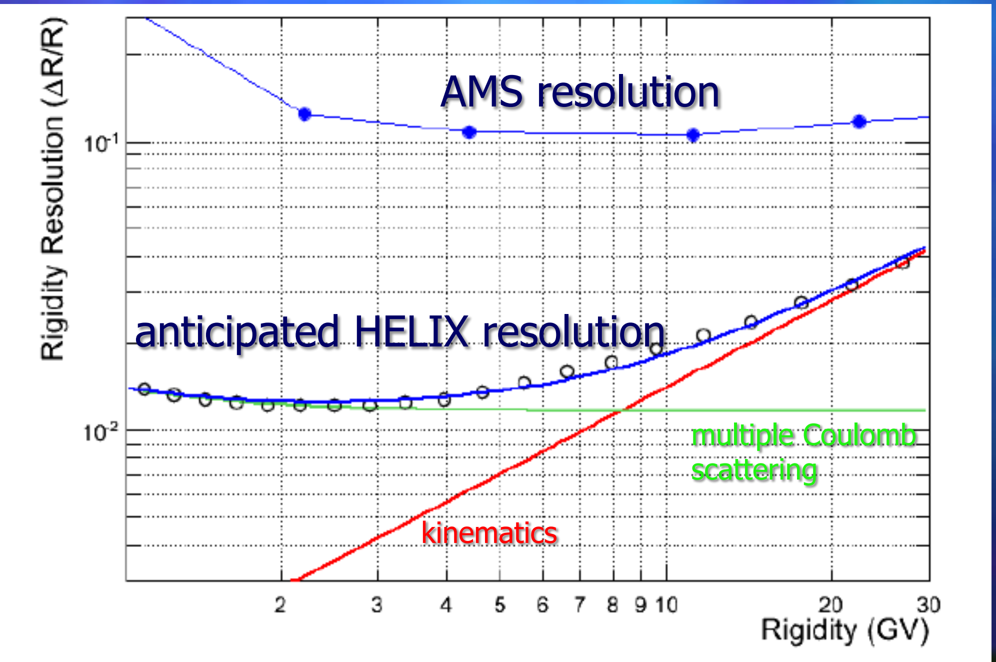
magnet

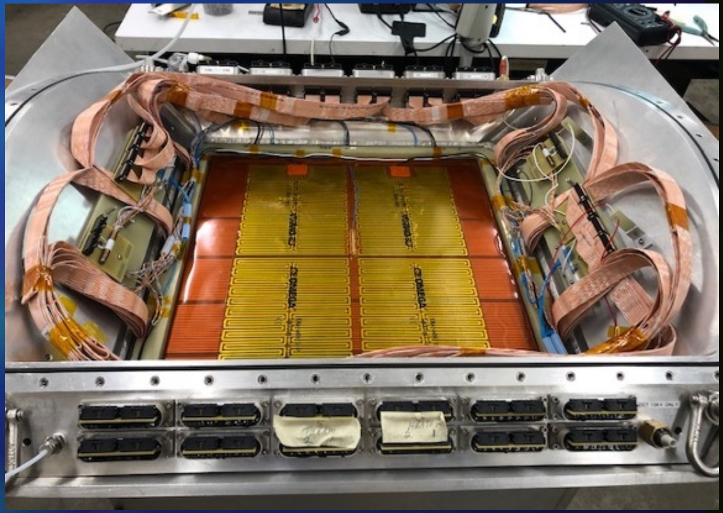
- HEAT magnet (Cryomagnetics), modified for flight without pressure gondola;
- NbTi coils, Helmholtz configuration, 91.7A, 1T central field, Al cryostat, 260L of LHe;
- successfully tested in vacuum, hold time ~6 days;
- planned upgrades for eventual Antarctic flights.

drift-chamber tracker

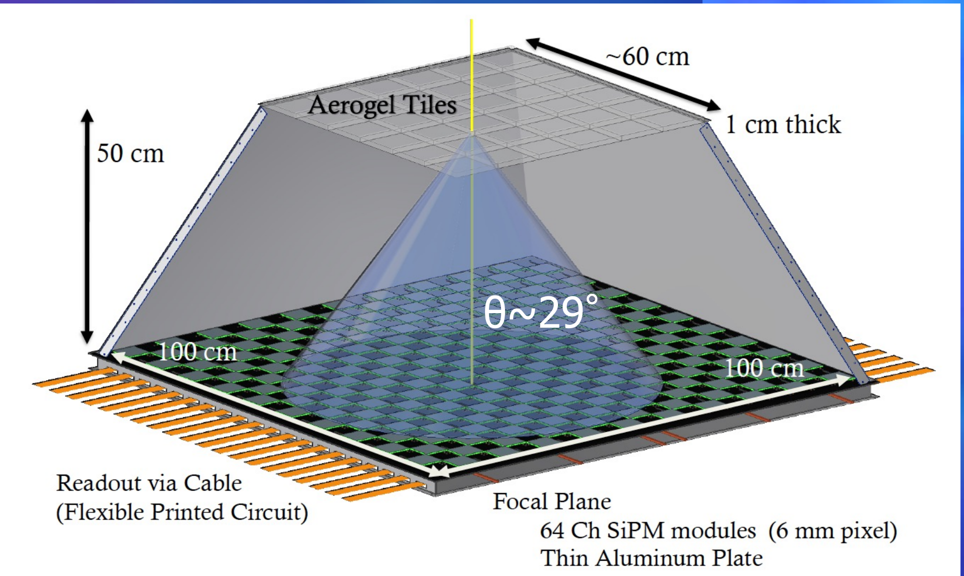
- Multi-wire (20μm moleculoy), drift gas CO_2 + Ar;
- 10 kV drift, 3 kV shaping;
- 72 sense layers, 12 bit ADCs @80 MSPS;
- spatial resolution ~65μm for Z>3;
- low-Z materials + thin pressure vessel.

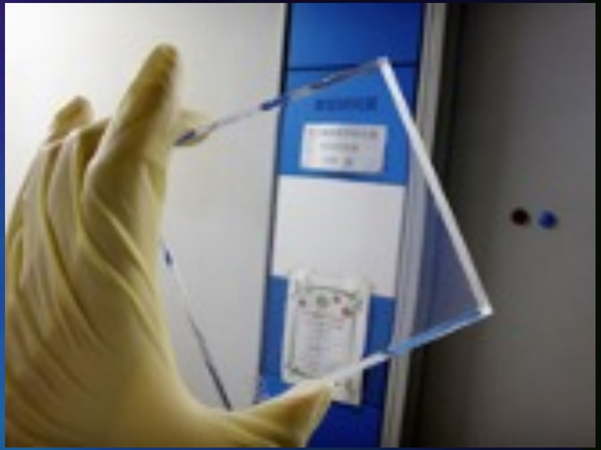




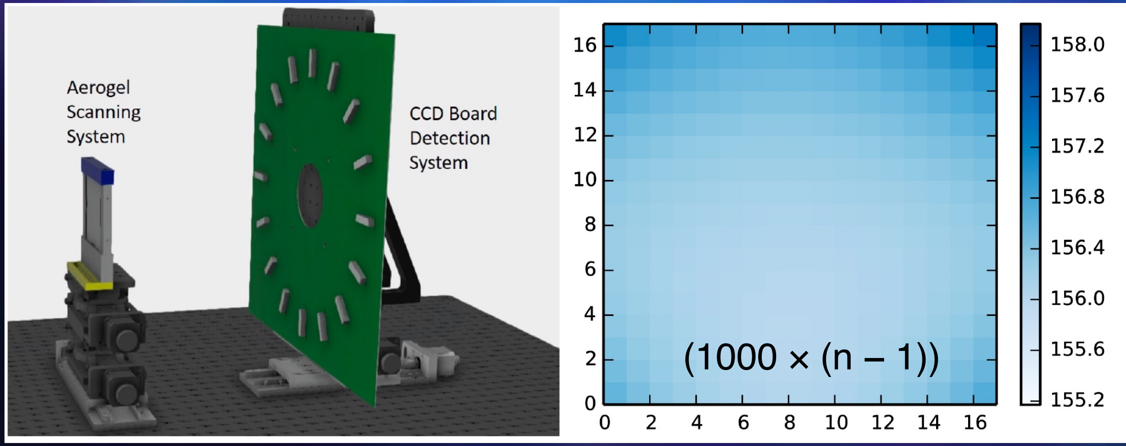


RICH radiator





$10 \times 10 \times 1\ \mathrm{cm}^3$
32 aerogel tiles
from Chiba, n=1.15
E_{th} = 1 GeV/n



Thickness meas.: CMM
n meas.: 35 MeV e^- linac
+ interferometry ⇒ $\Delta n/n \sim 1 \times 10^{-4}$

Also 4 NaF tiles, n = 1.33, θ ~ 41°
E_{th} = 0.45 GeV/n

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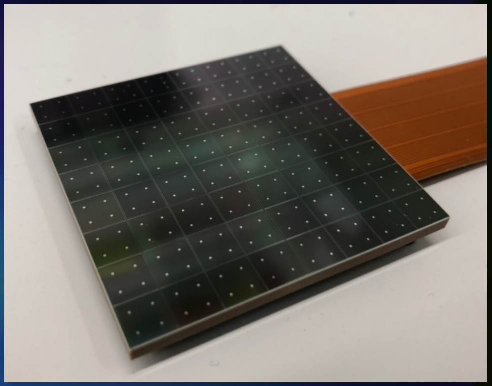
RICH SiPMs

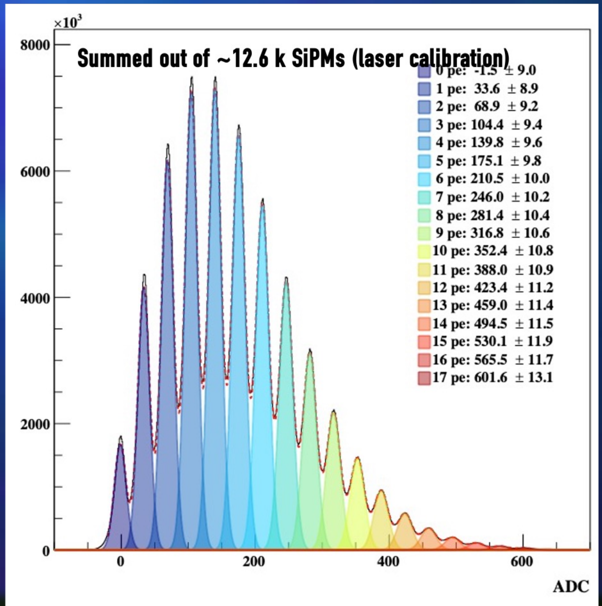
Hamamatsu
LVR2-SMP2-75um
64x(6x6 mm^2)



SiPMs:

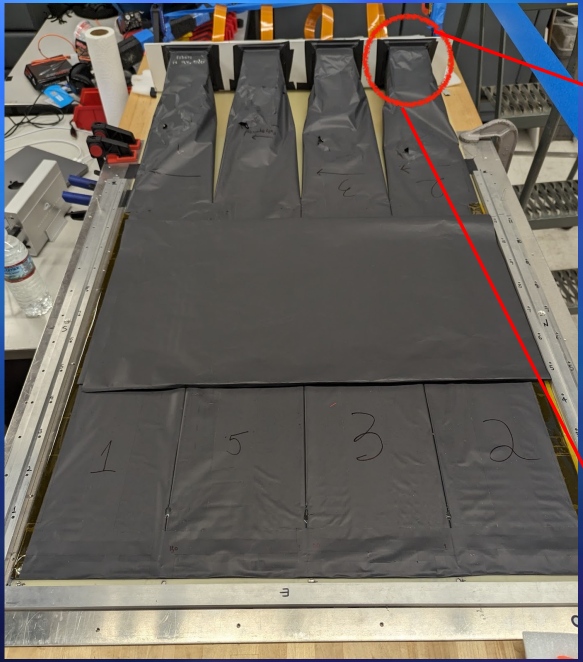
- insensitive to B field, checkerboard configuration for HELIX1 ($);
- 12,800 channels, 10 ns hit resolution, <35 mW/channel;
- CITIROC ASIC frontend + 12 bit ADCs;
- $\Delta\beta/\beta \sim 0.1\%$ for Z>3 and E>1GeV/n;
- temperature sensitivity → use heat pipes (goal < 5C).

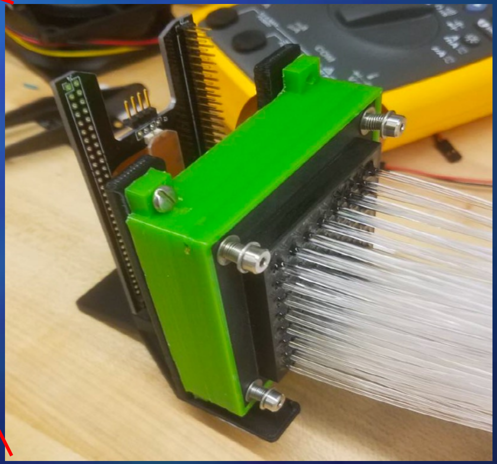
1m x 1m



hodoscope

- improve tracking in the non-bending view;
- mounted right above RICH radiator;
- 1 mm square Saint-Gobain scintillating fibers;
- same SiPM readout as the RICH;
- optical weaving to minimize readout channel count.





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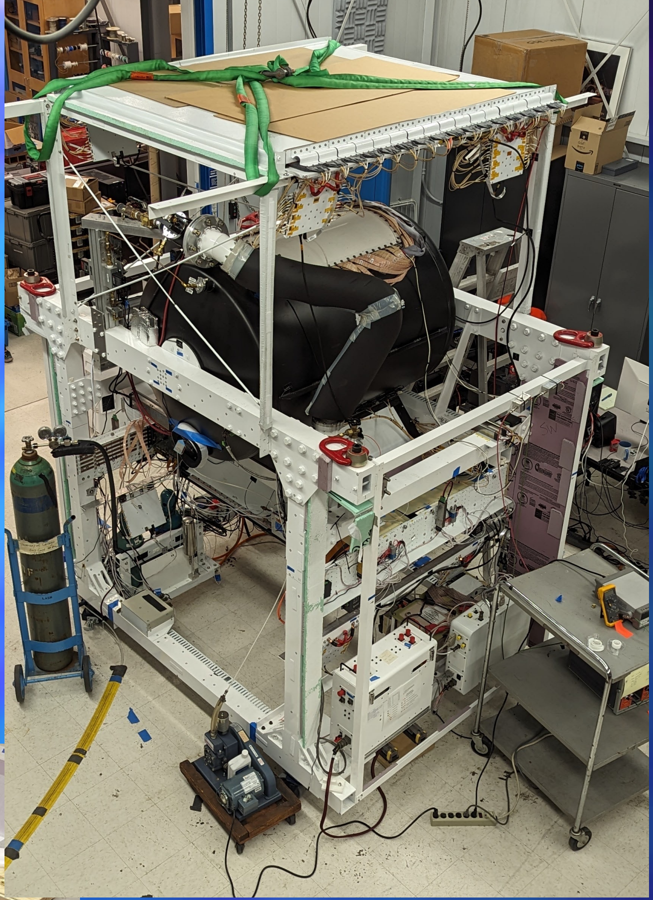
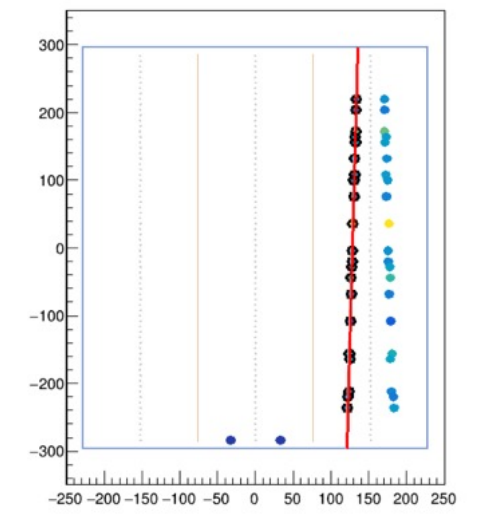
Integration

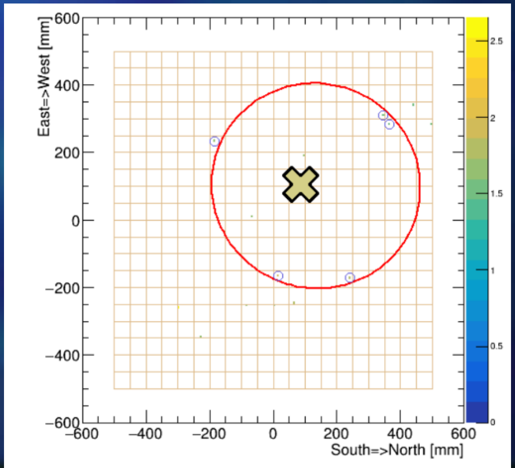
U. Chicago
muon runs to test functionality and optimize settings



DCT bending-view track left/right ambiguity Hough transform



RICH ellipse ring is a track projection, not a fit!

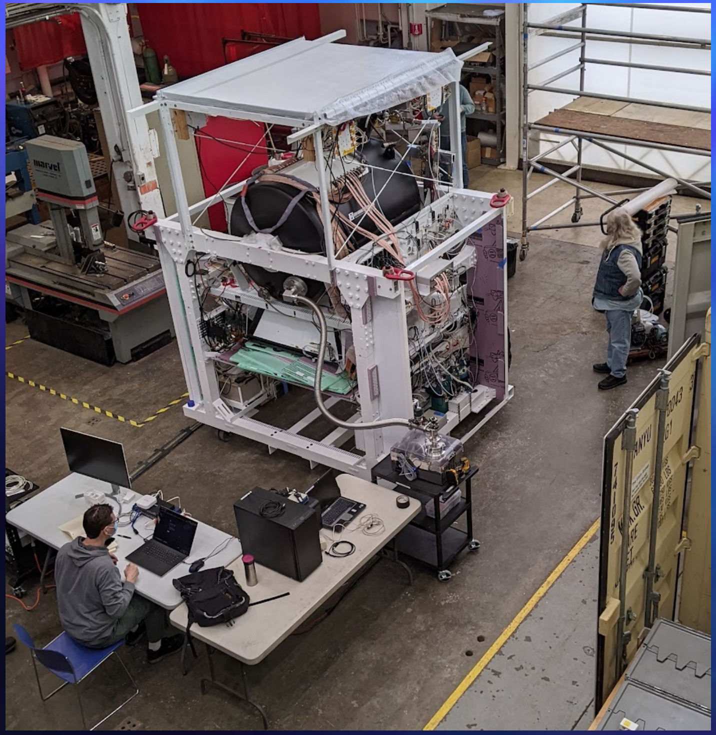


T/V test, 2022

NASA Neil A. Armstrong Test Facility
Sandusky, Ohio

Successful, although got as cold as −44C (SiPMs ok!)

used as baseline to refine thermal mitigation scheme (e.g., foam envelope)



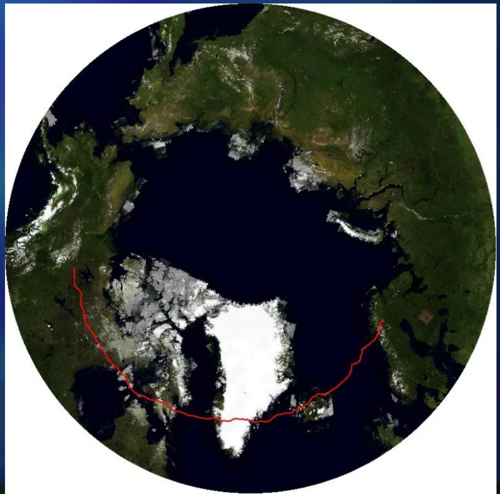
Thanks to

Conclusions

Direct studies of cosmic-ray nuclei now yield high precision and new spectral features.

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

HELIX on track to fly from Kiruna, Sweden to Canada in 2024. Optimized to measure ^{10}Be, ^{9}Be between 0.2 and 3 GeV/n, ultimately 10 GeV/n, with a mass resolution of 2-3%; will also be sensitive to other isotopes up to Ne (Z=10).



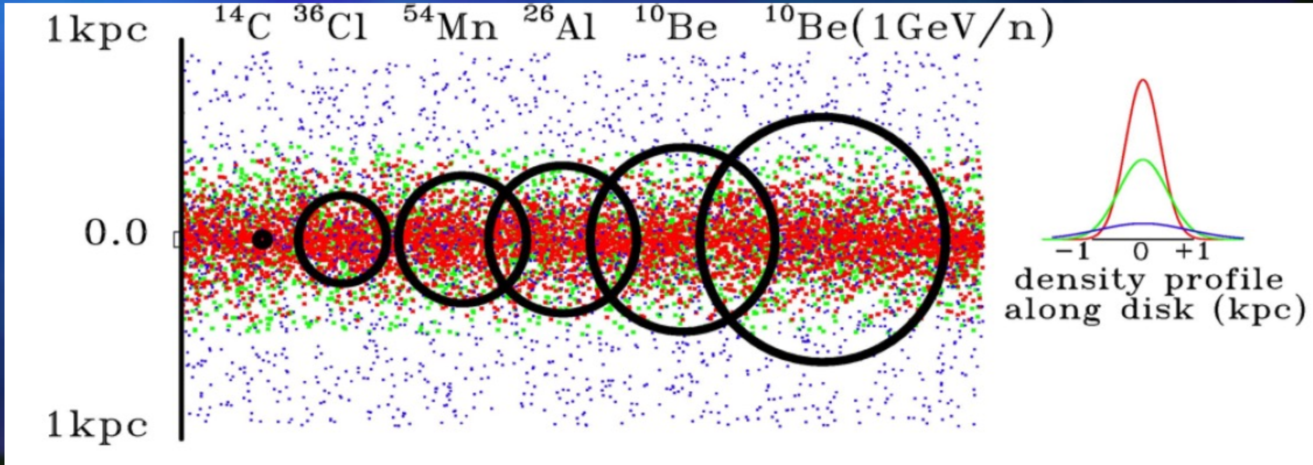

Grazie !

BACKUP

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.

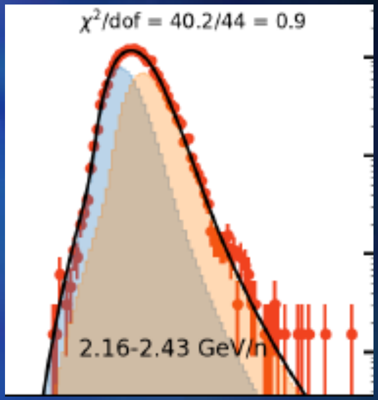
Z/A dependence of Galactic region sampled by 0.3 GeV/n clock isotopes; Be is ideal.



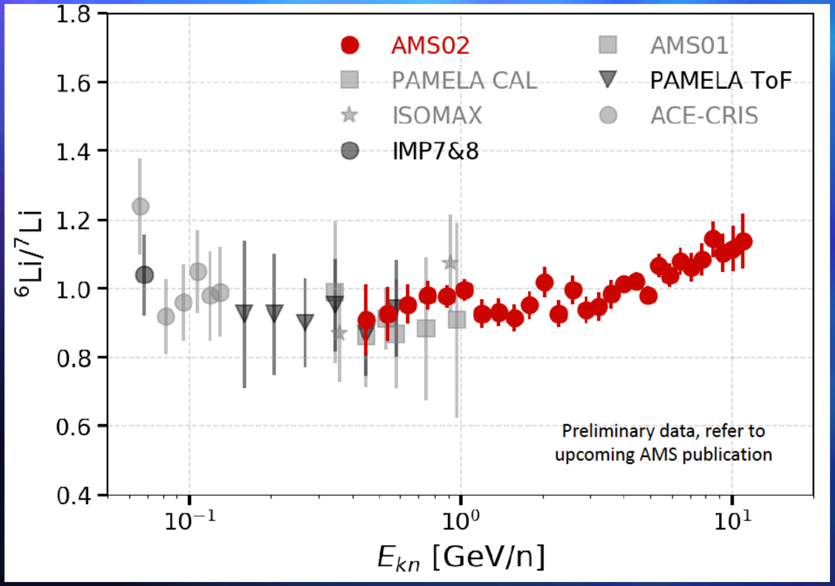
Other light isotopes

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

^{6}Li vs ^{7}Li

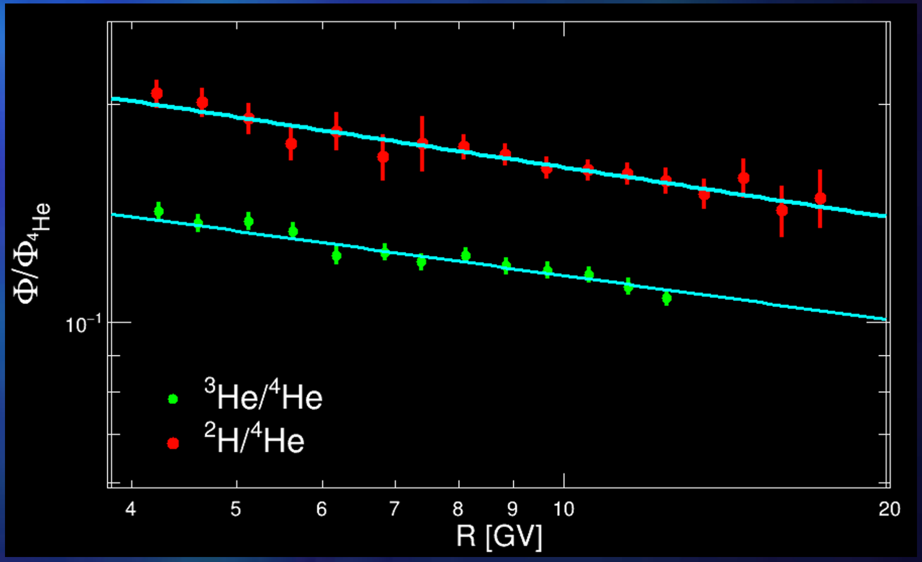


^{6}Li / ^{7}Li



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

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



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

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

NA61/SHINE

CERN SPS, e.g., C beam on p target (13.5 A GeV/c);

Madison ICRC 2019 (no update at Berlin 2021)

New Results from the Cosmic-Ray Program of the NA61/SHINE facility at the CERN SPS

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Pb beam on Be target, 3 days of running;

Little ^{10}Be produced

Measurements of Be production cross section is an explicit goal