From the AMS-02 isotope fluxes to their production cross sections

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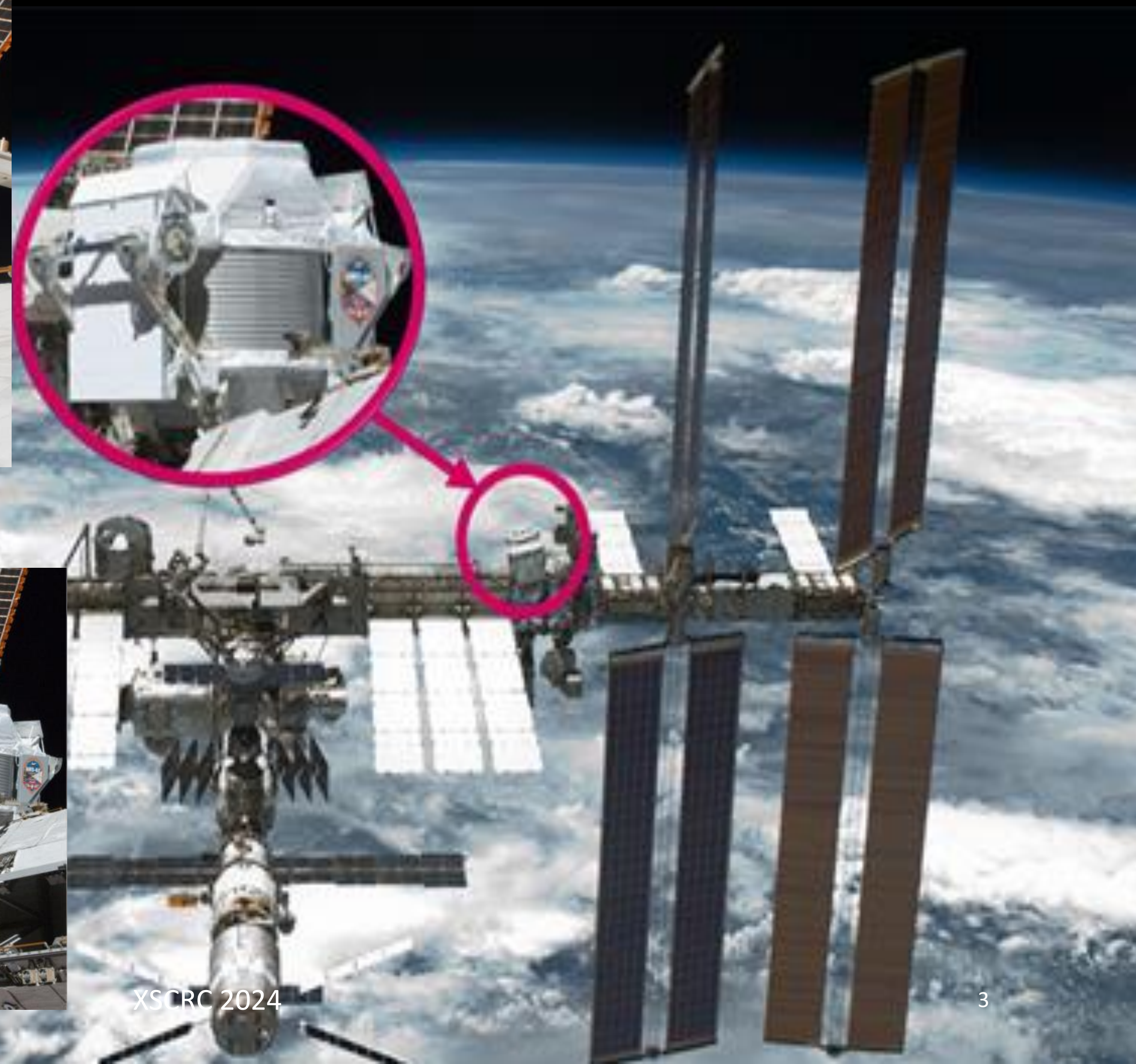
Outline

- Motivation
- Method
- Results
- HIAF in China

Based on:
Phys.Rev. D 109 (2024) 8, 083036

Preliminary Beryllium and Lithium isotope fluxes



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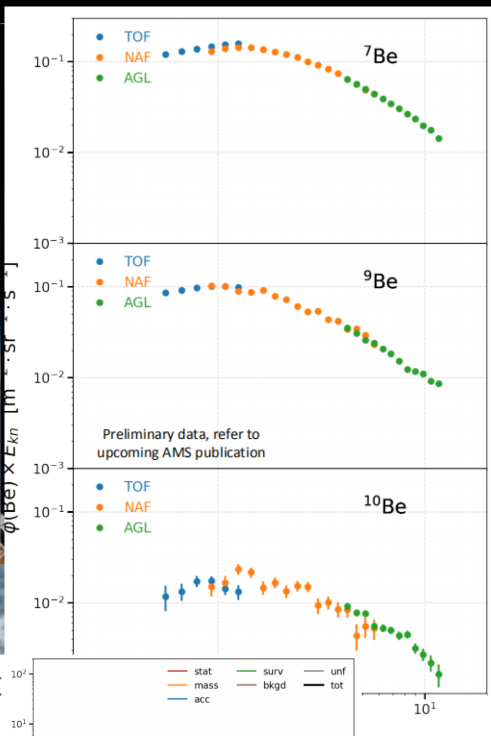
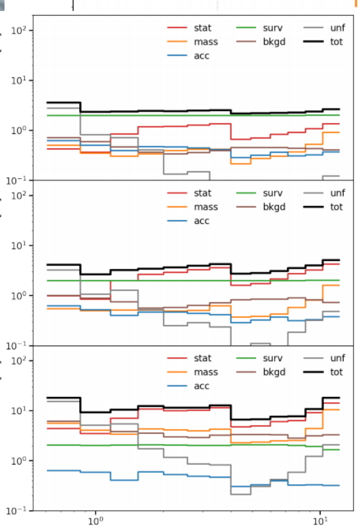
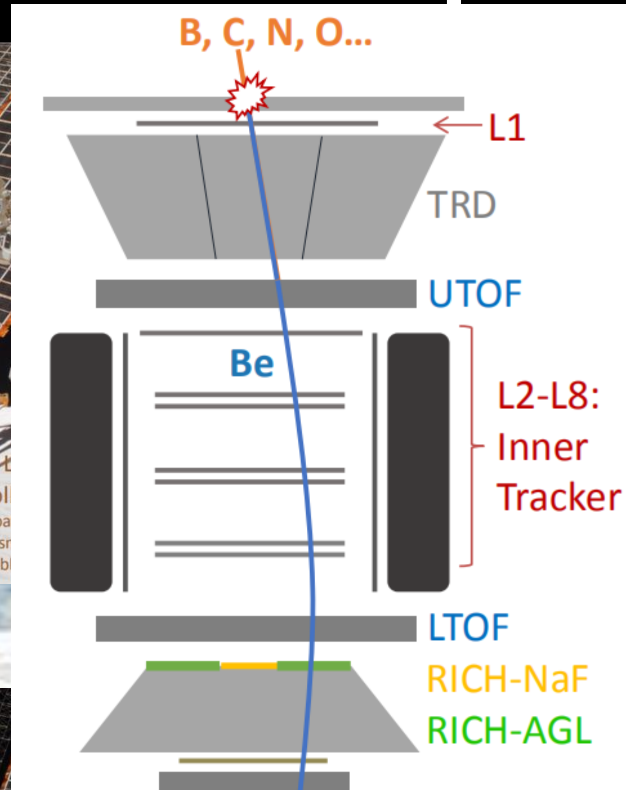
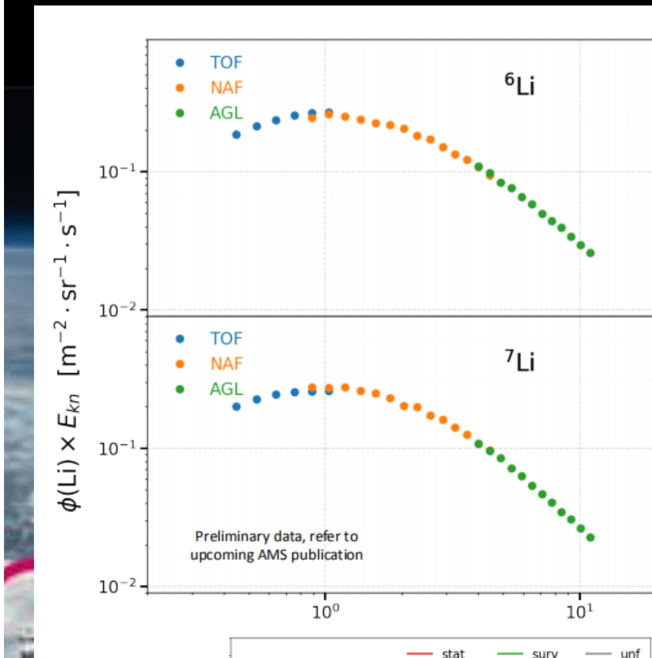
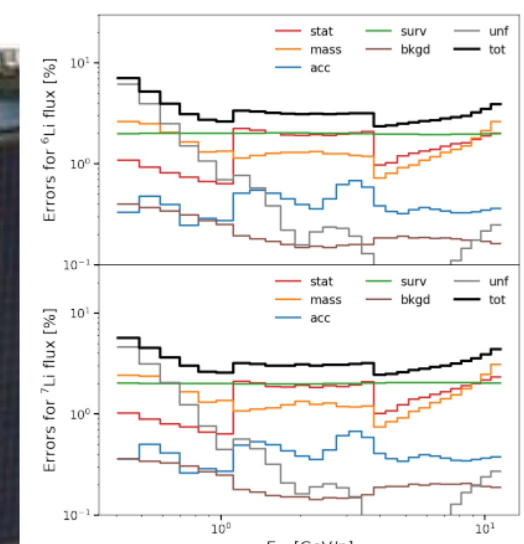






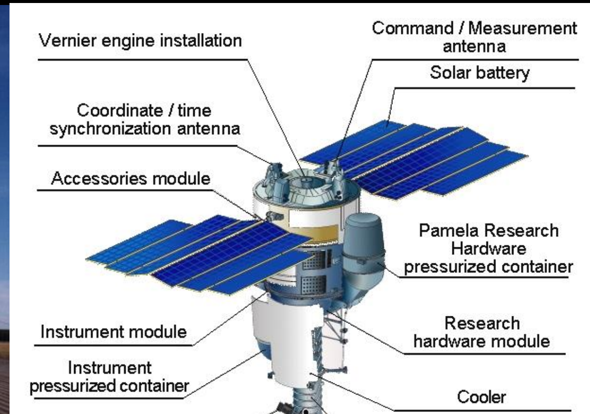


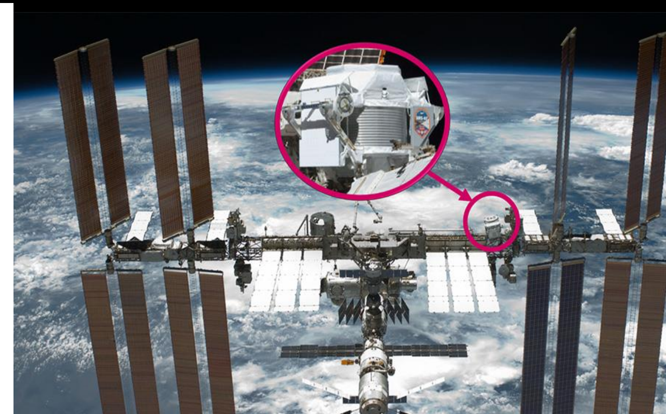


Energy range from 0.5 GeV/n to 12 GeV/n

Err(6Li), Err(7Li), Err(7Be) ≤4%
Err(9Be) ≤5%
Err(10Be) =10% - 20%

The development of XS models

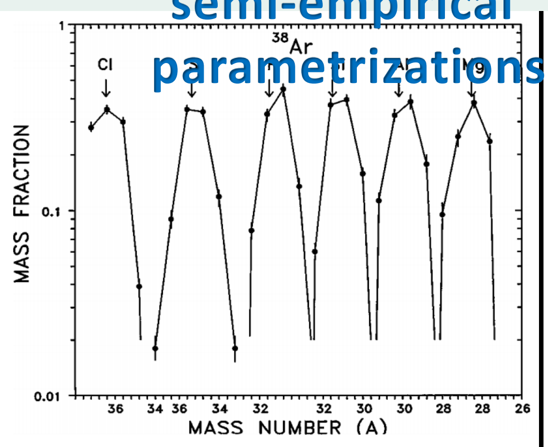


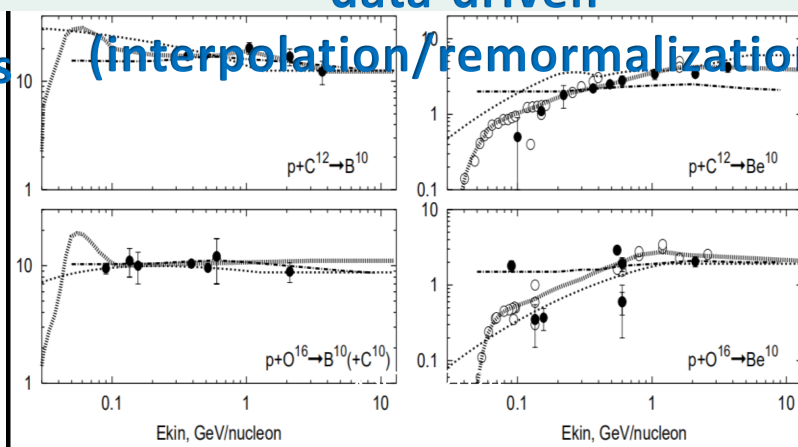


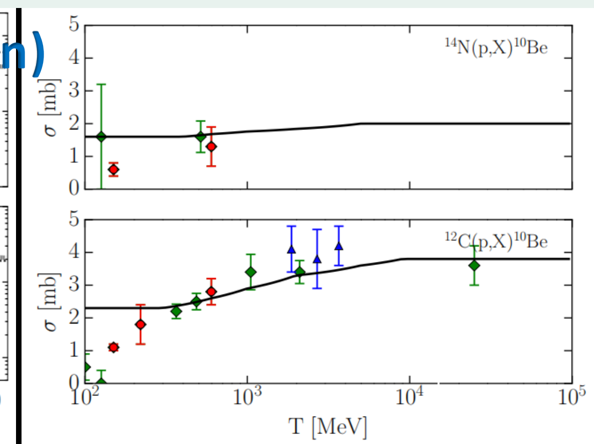
Year	1990s	2000 - 2010	2010 – Now
Direct CR measurements	Balloons, HEAO3 (20%)	ATIC, CREAM, PAMELA (≤10%)	DAMPE, AMS-02, CALET (5%)
Production XS models	WNEW, YIELDX (15% - 25%)	GALPROP, DRAGON (≤10% - 20%)	? (5%)

semi-empirical parametrizations

data-driven (interpolation/remormalization)

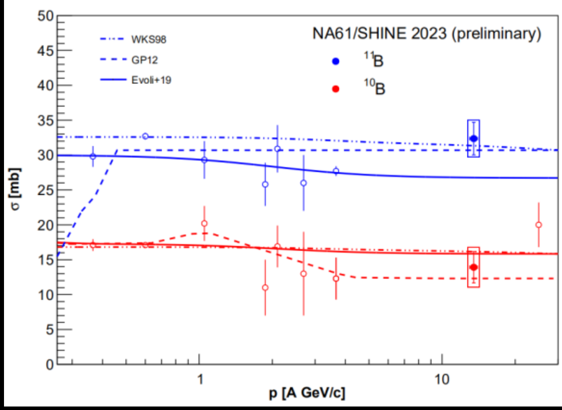




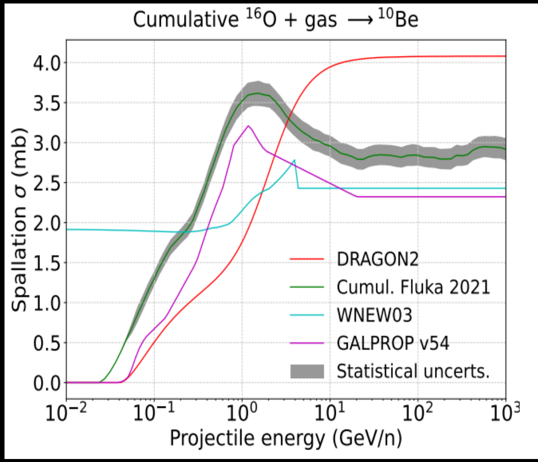


How to improve/constrain the XS

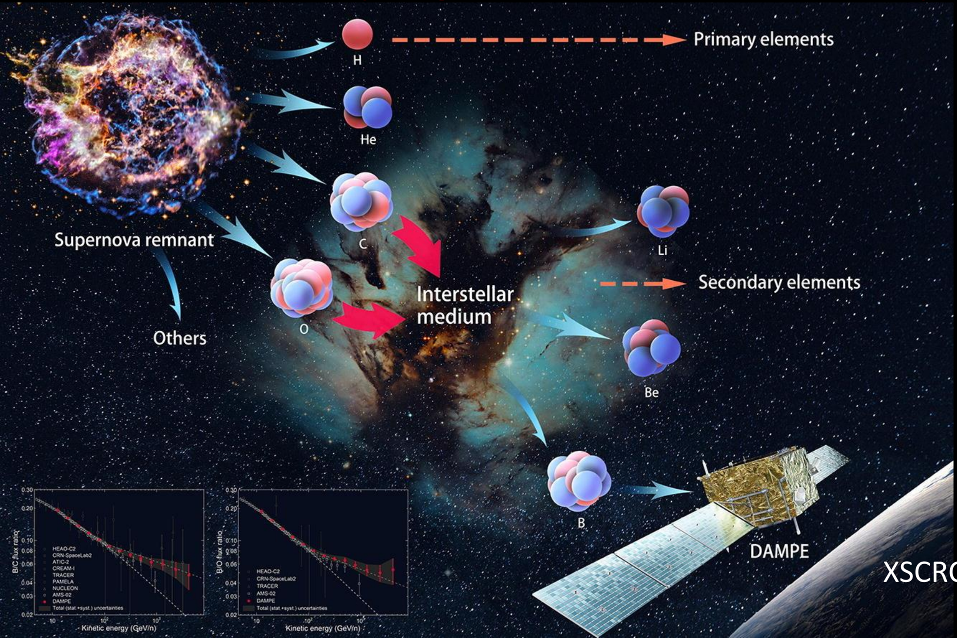
1. more measurements
   - EXFOR, NA61/SHINE …
2. formulae expectation
   - data-driven + parametrization
   - n-n interaction (FLUKA, Geant4 …)
   - machine learning
3. CR propagation consistency



N. Amin PoS ICRC2023



De La Torre Luqu et al. JCAP 07 (2022)



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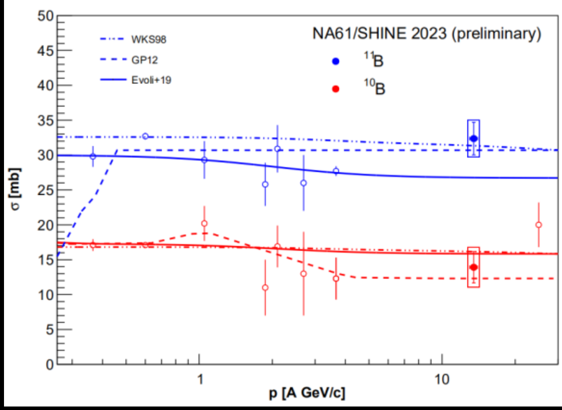

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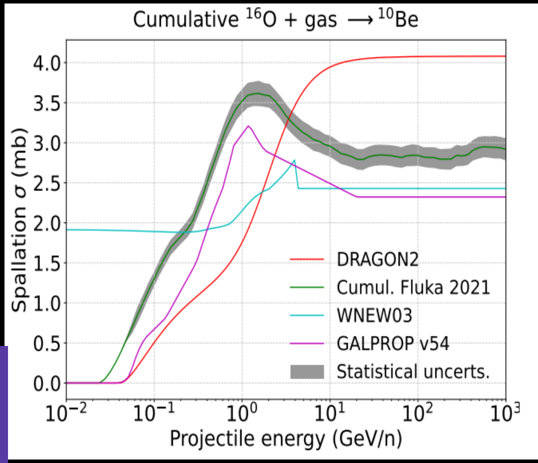

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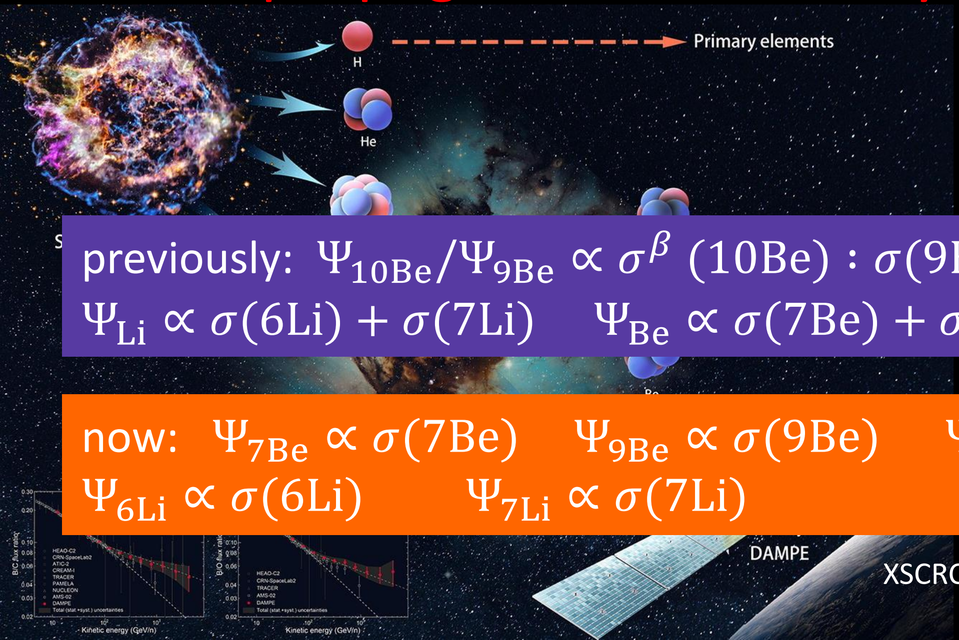


previously: $\Psi_{10\mathrm{Be}}/\Psi_{9\mathrm{Be}} \propto \sigma^{\beta}(10\mathrm{Be}) : \sigma(9\mathrm{Be})$

$\Psi_{\mathrm{Li}} \propto \sigma(6\mathrm{Li}) + \sigma(7\mathrm{Li})$ $\quad \Psi_{\mathrm{Be}} \propto \sigma(7\mathrm{Be}) + \sigma(9\mathrm{Be}) + \sigma^{\beta}(10\mathrm{Be})$

now: $\Psi_{7\mathrm{Be}} \propto \sigma(7\mathrm{Be})$ $\quad \Psi_{9\mathrm{Be}} \propto \sigma(9\mathrm{Be})$ $\quad \Psi_{10\mathrm{Be}} \propto \sigma^{\beta}(10\mathrm{Be})$

$\Psi_{6\mathrm{Li}} \propto \sigma(6\mathrm{Li})$ $\quad \Psi_{7\mathrm{Li}} \propto \sigma(7\mathrm{Li})$

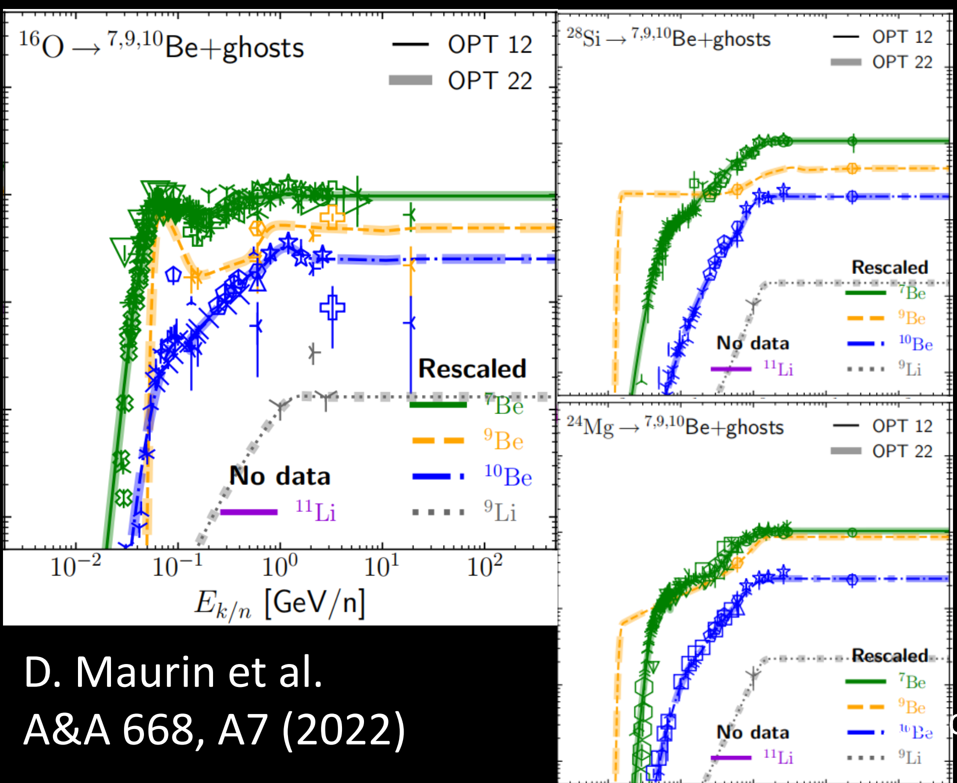
7Be in place of 9Be

Challenges

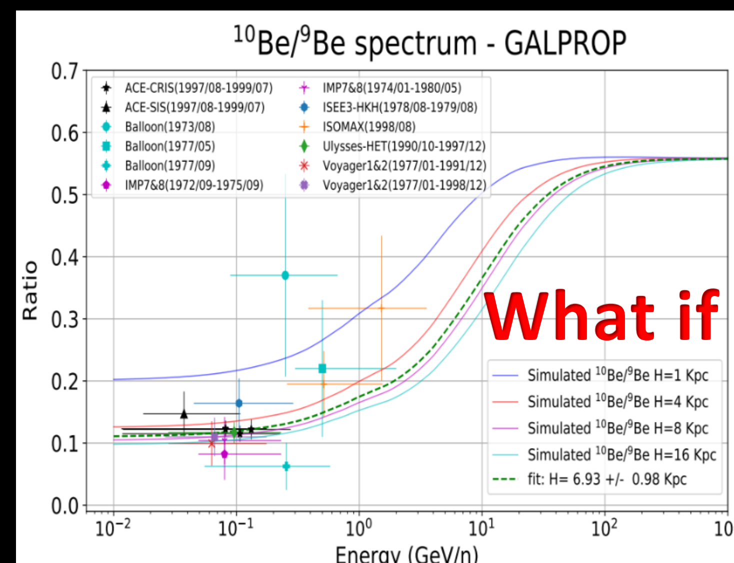
- ☐ Single CR species can be consist of many isotopes, contributed from multiple channels.
- ☐ Some channels are less-constrained.
- ☐ High-energy XS are less-constrained.

Luckily

- ✓ The isotope fluxes can precisely be measured now. A few channels dominate the result.
- ✓ Some channels are well-constrained.
- ✓ Low-energy XS are usually well-constrained.



D. Maurin et al.
A&A 668, A7 (2022)



De La Torre Luqu et al.
JCAP 03(2021)099

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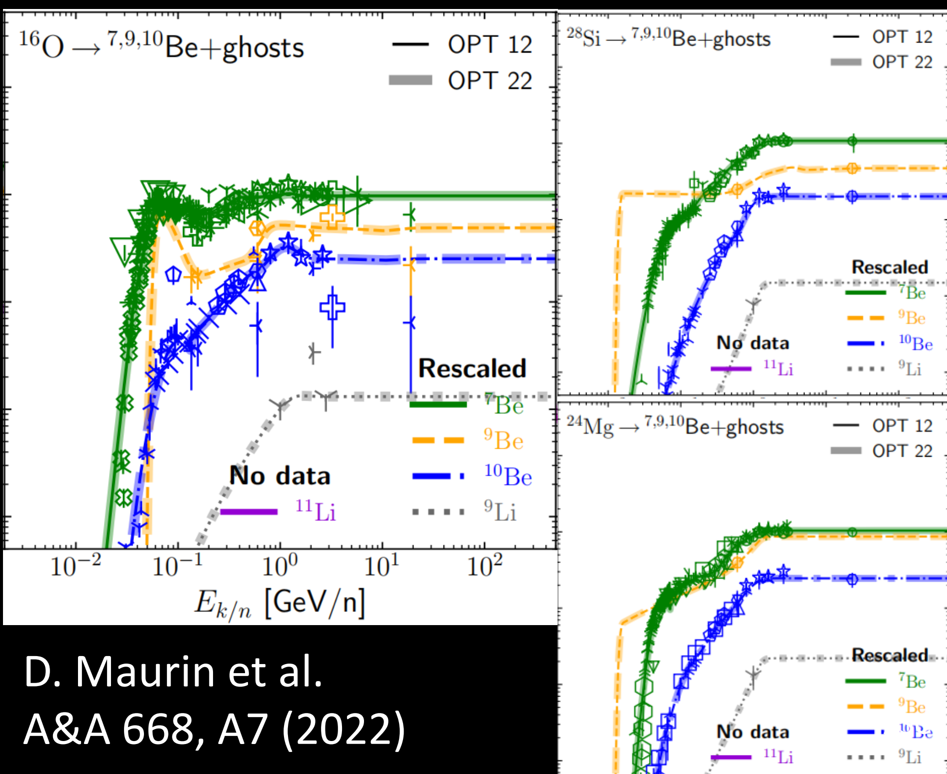

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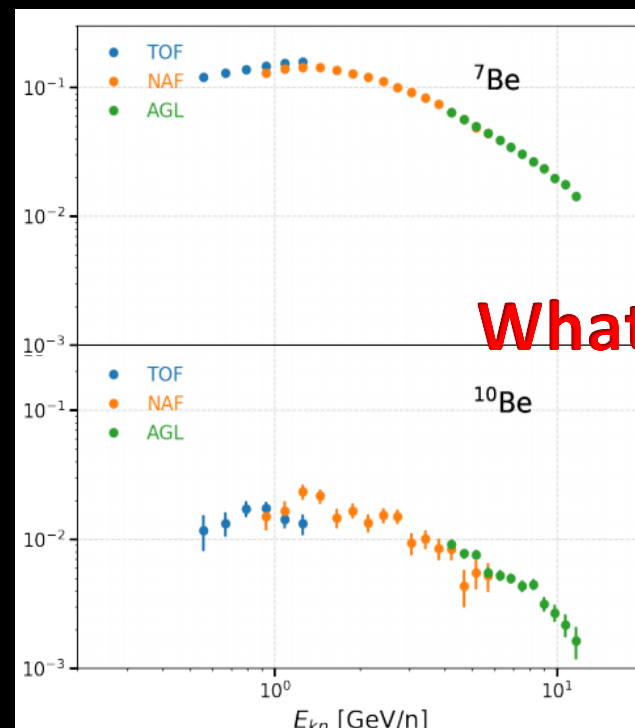
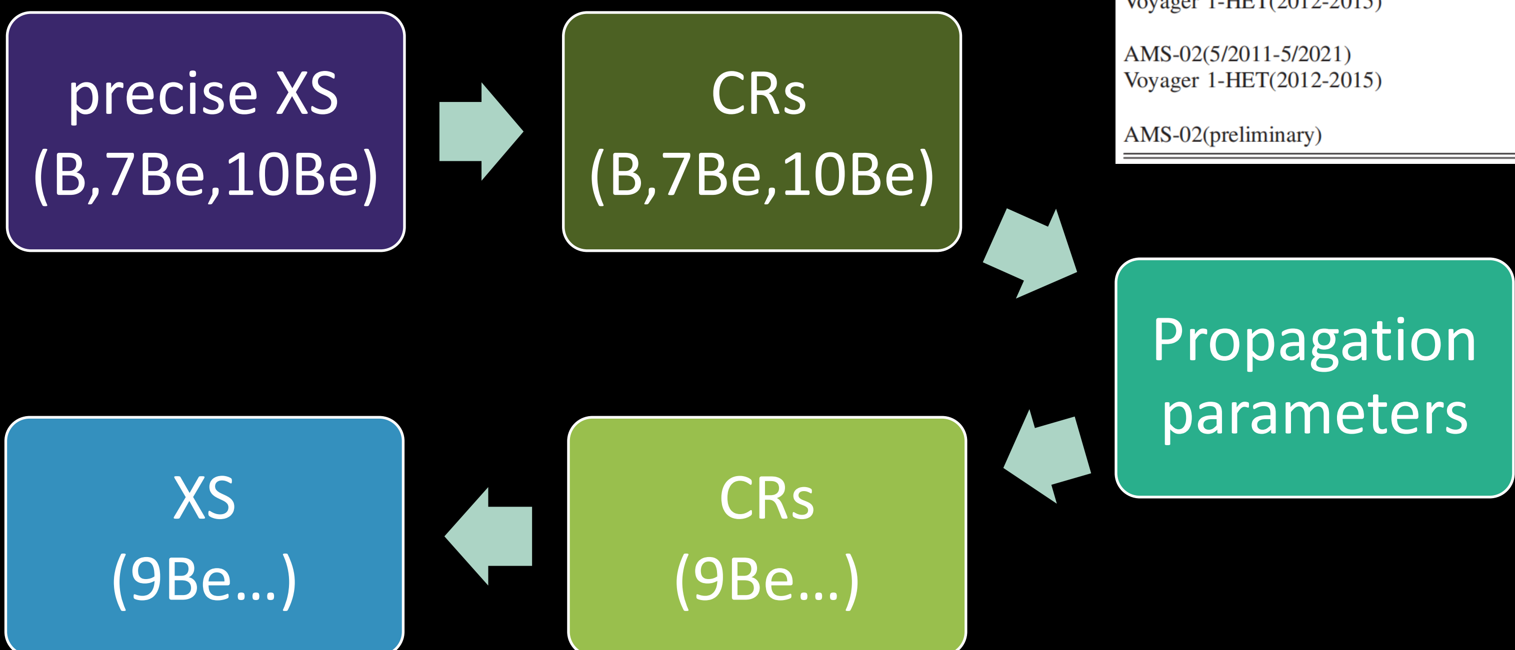


What if ...

Routine of the work

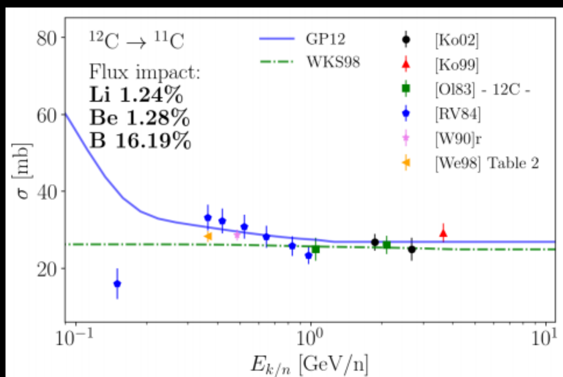
TABLE I. Data used in this analysis.

Experiment	Energy Range
	C
NUCLEON(7/2015-6/2017)	250–17000 GeV/n
CREAM-II(12/2005-1/2006)	85–7500 GeV/n
CALET(10/2015-10/2019) × 1.27[a]	10–1700 GeV/n
AMS-02(5/2011-5/2021)	2–2000 GV
Voyager 1-HET(2012-2015)	0.02–0.13 GeV/n
	O
NUCLEON(7/2015-6/2017)	300–13000 GeV/n
CREAM-II(12/2005-1/2006)	64–7500 GeV/n
CALET(10/2015-10/2019) × 1.27	10–1700 GeV/n
AMS-02(5/2011-5/2021)	2–2000 GV
Voyager 1-HET(2012-2015)	0.02–0.15 GeV/n
	B
AMS-02(5/2011-5/2021)	2–2000 GV
Voyager 1-HET(2012-2015)	0.02–0.11 GeV/n
	^{7}Be, ^{10}Be
AMS-02(preliminary)	0.7–11 GeV/n

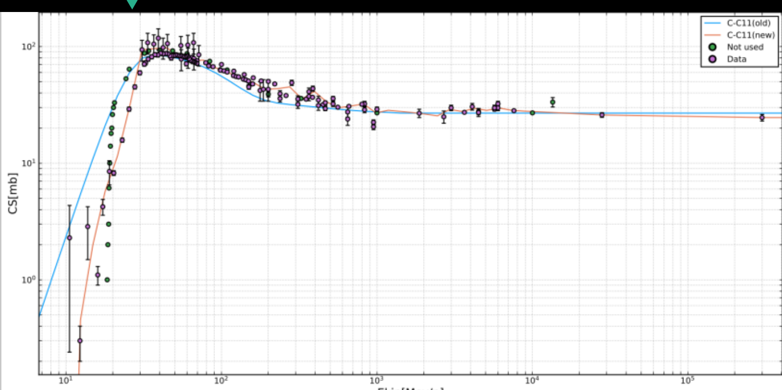


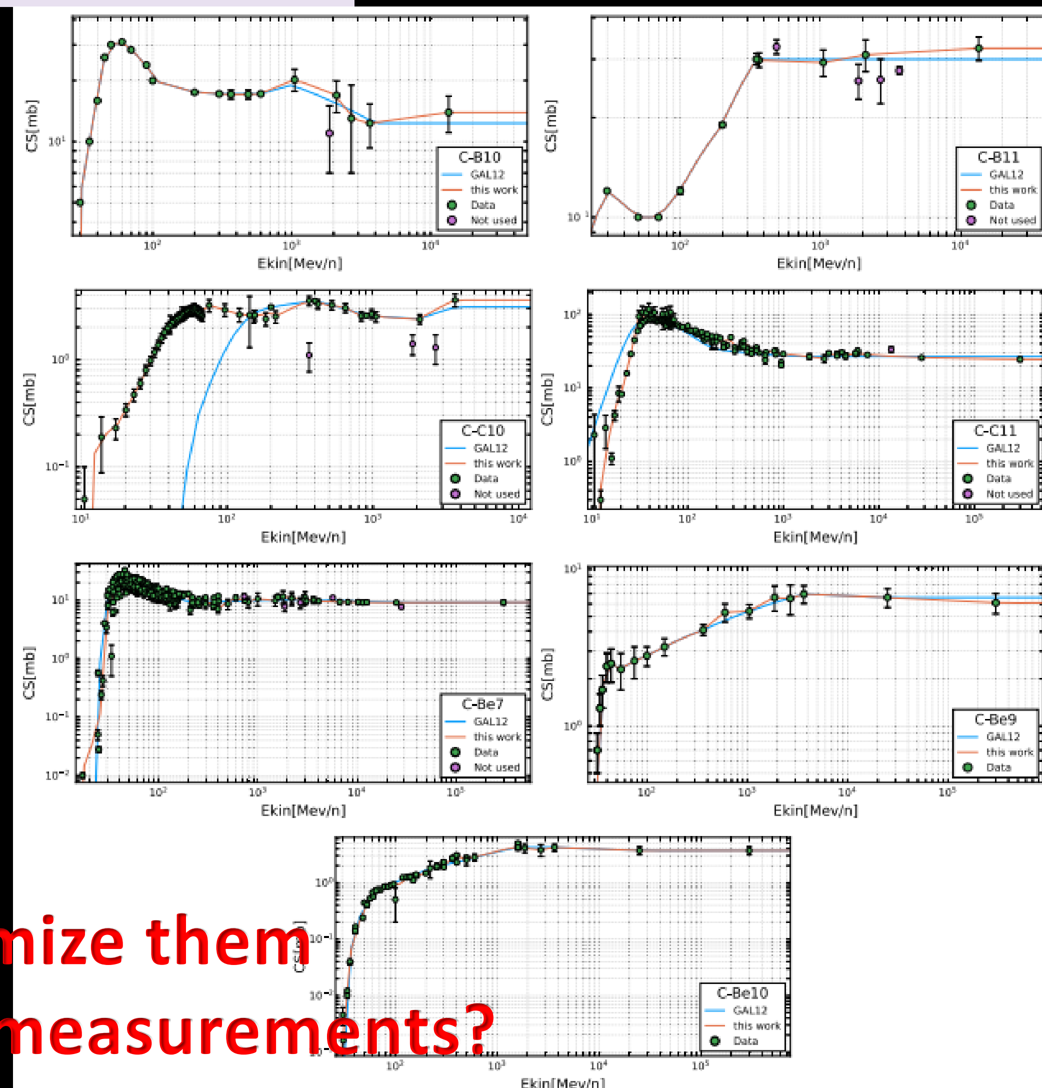
Updating the XS database

Experimental Nuclear Reaction Data (EXFOR)
Database Version of 2023-11-13



Adding more measurements!





What if we optimize them with all the available measurements?

Another work

Based on: arxiv 2409.07139

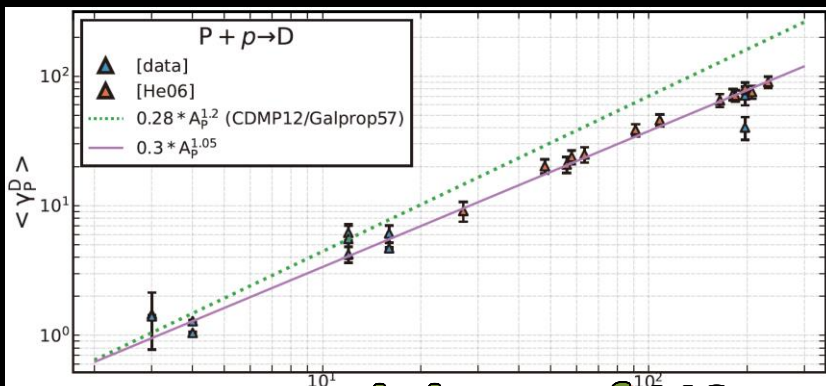
"Cosmic-ray deuteron excess from a primary component"

$p + p \rightarrow \pi^{+} + D$

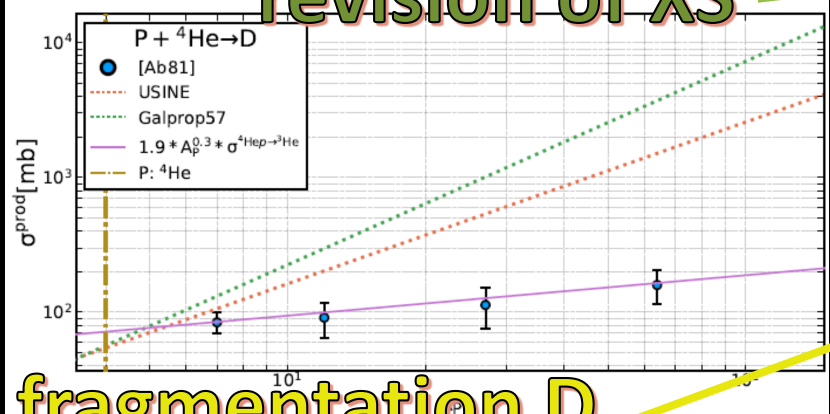
fusion D from source

+acceleration

$$\Phi^{\rm LIS}_{\rm primary\ B} \times \frac{\Phi^{\rm LIS}_{p}\sigma^{pp\to \rm D}}{\Phi^{\rm LIS}_{\rm C}\sigma^{{\rm C}p\to \rm B} + \Phi^{\rm LIS}_{\rm O}\sigma^{{\rm O}p\to \rm B}}$$



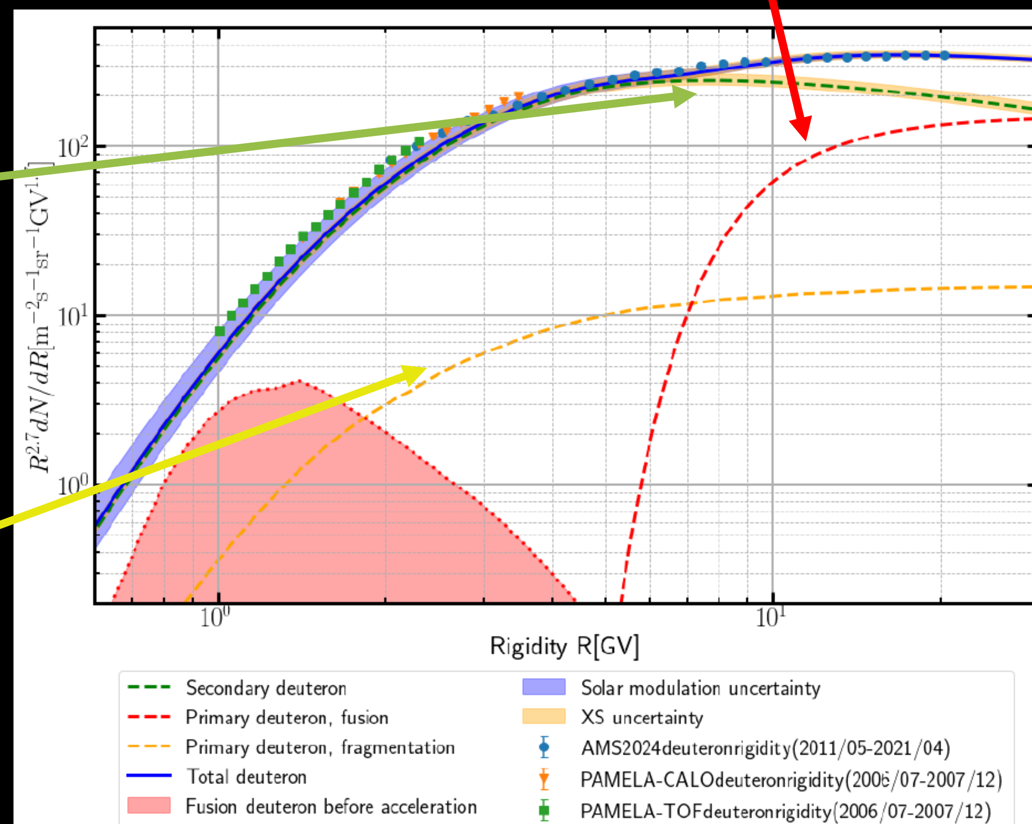
revision of XS



fragmentation D

from source

$$\Phi^{\rm LIS}_{\rm primary\ B} \times \frac{\Phi^{\rm LIS}_{^4\rm He}\sigma^{^4{\rm He}p\to \rm D}}{\Phi^{\rm LIS}_{\rm C}\sigma^{{\rm C}p\to \rm B} + \Phi^{\rm LIS}_{\rm O}\sigma^{{\rm O}p\to \rm B}}$$



Calculating tools

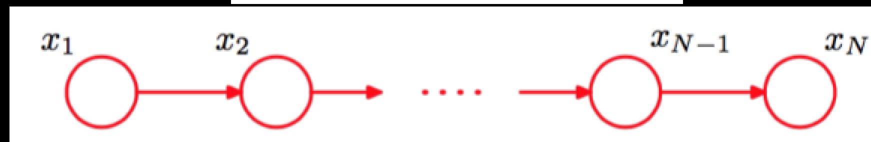
with updated XS database

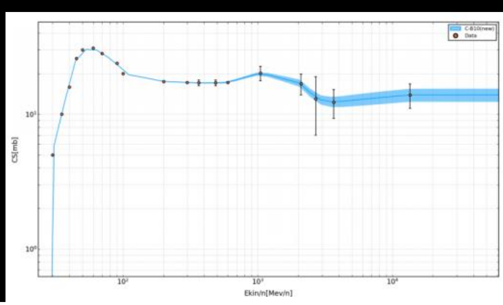
$$\boldsymbol{\theta} = \{D_0, \delta, L, V_a, \eta, \nu_0, \nu_1, R_{br}, A_C, A_O, \phi, \mu_{C-B_{10}}, \mu_{C-B_{11}}, \mu_{C-C_{11}}, \cdots\},$$

\+

Cosmological MonteCarlo

$$P(\boldsymbol{\theta}|\mathrm{D}) = \frac{P(\mathrm{D}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{P(\mathrm{D})}$$





$$\sigma = \sigma^0\left[1 + \frac{\mu}{1+(E_{th}/E_{kin/n})^2} + \frac{\mu\omega_0/\omega_1}{1+(E_{kin/n}/E_{th})^2}\right]$$

Extra modifications for different XS channels are allowed in the fitting.

$$\chi^2 = \sum \chi^2_{\mathrm{cr},q} + \chi^2_{\mathrm{cs}},$$

$$\chi^2_{\mathrm{cr}} = \sum_{i=1}^{\mathrm{bin}} \left(\frac{y_i^{\mathrm{data}} - y_i^{\mathrm{model}}}{\sigma_i^{\mathrm{data}}}\right)^2,$$

$$\chi^2_{\mathrm{cs}} = \sum_{i=1}^{n_{\mathrm{cs}}} \left(\frac{\mu_i}{\omega_{1i}}\right)^2,$$

estimated XS error

Result: Consistency

TABLE III. The prior range, best-fit values, and posterior 95% range of all parameters in the combined fitting.

Parameter	Prior range	Best-fit values	Posterior 95% range
$D_0 (10^{28}\ \mathrm{cm^2\ s^{-1}})$	[0,15.0]	5.197	[4.176,6.396]
δ	[0.2,1.0]	0.433	[0.424,0.456]
L(kpc)	[1.0,20.0]	5.674	[4.384,7.443]
V_a(km/s)	[0,50]	15.409	[12.333,18.068]
η	[−5, 5]	−0.484	[−0.732, −0.161]
ν_0	[0.5,2.4]	1.249	[1.003,1.446]
ν_1	[2.2,2.5]	2.390	[2.372,2.400]
R_{br}(GV)	[0.1,15]	2.088	[1.743,2.551]
$A_c(10^3)$[a]	[2.5,4.5]	3.304	[3.257,3.328]
$A_o(10^3)$	[3.5,5.5]	4.114	[4.062,4.185]
ϕ(GV)	[0.4,1.0]	0.645	[0.619,0.697]
μ_{C-B10}	[−0.5, 0.5]	0.099	[−0.085, 0.316]
μ_{C-B11}	[−0.5, 0.5]	0.075	[−0.007, 0.211]
μ_{C-C11}	[−0.5, 0.5]	−0.001	[−0.018, 0.025]
μ_{O-B10}	[−0.5, 0.5]	0.010	[−0.062, 0.081]
μ_{O-B11}	[−0.5, 0.5]	0.026	[−0.058, 0.071]
μ_{O-C11}	[−0.5, 0.5]	0.026	[−0.095, 0.134]
μ_{C-Be7}	[−0.5, 0.5]	−0.001	[−0.037, 0.049]
μ_{C-Be10}	[−0.5, 0.5]	−0.039	[−0.159, 0.122]
μ_{O-Be7}	[−0.5, 0.5]	0.001	[−0.036, 0.045]
μ_{O-Be10}	[−0.5, 0.5]	0.031	[−0.154, 0.128]
$\chi^2_{\mathrm{min}}/n_{\mathrm{dof}}$	...	232.6/320	...
$\chi^2_{\mathrm{cs}}/n_{\mathrm{cs}}$	...	3.2/10	...

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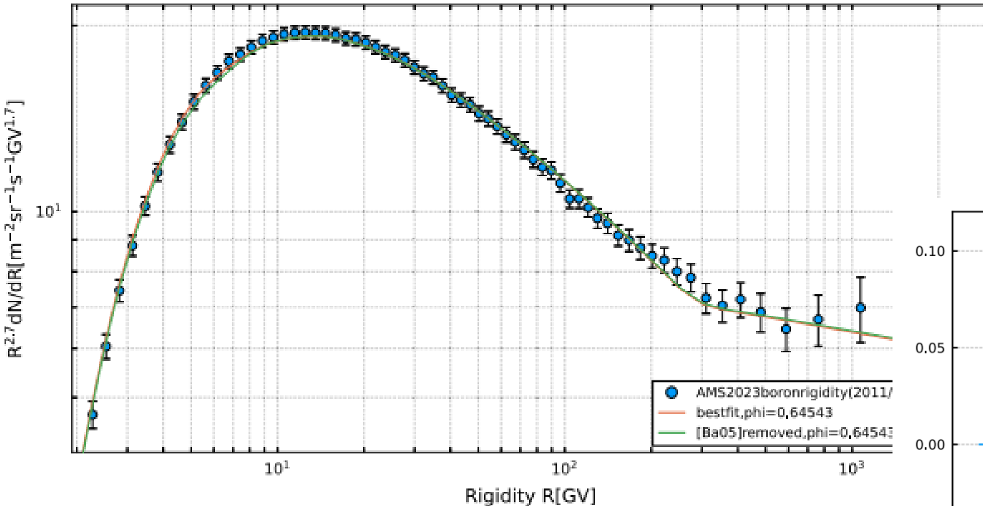

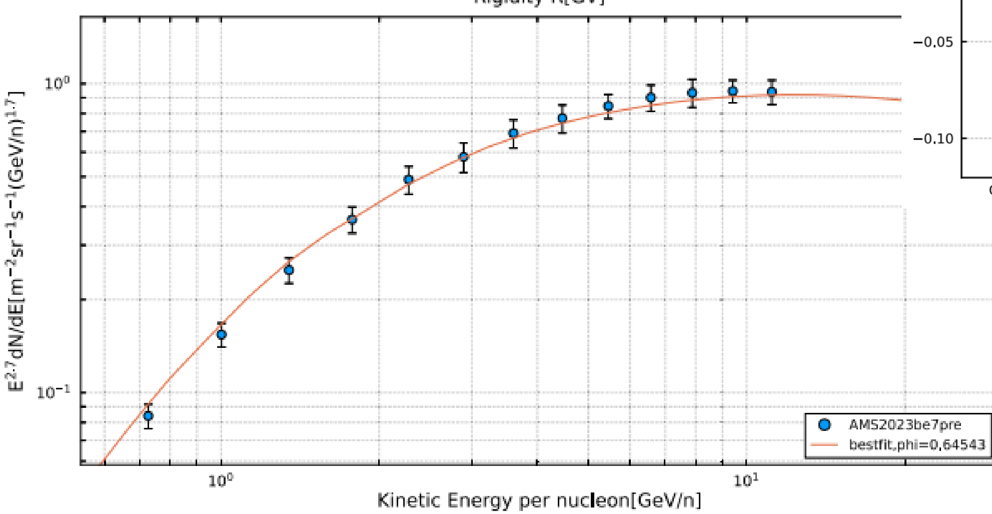

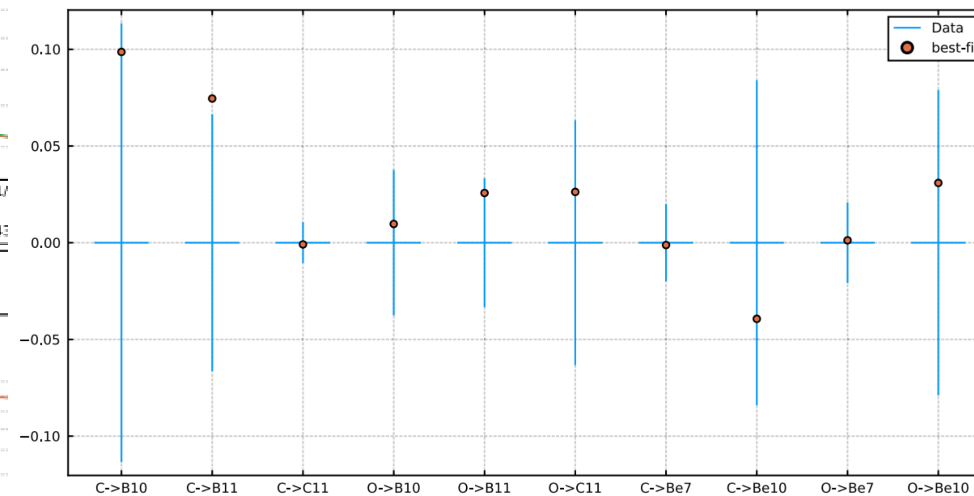

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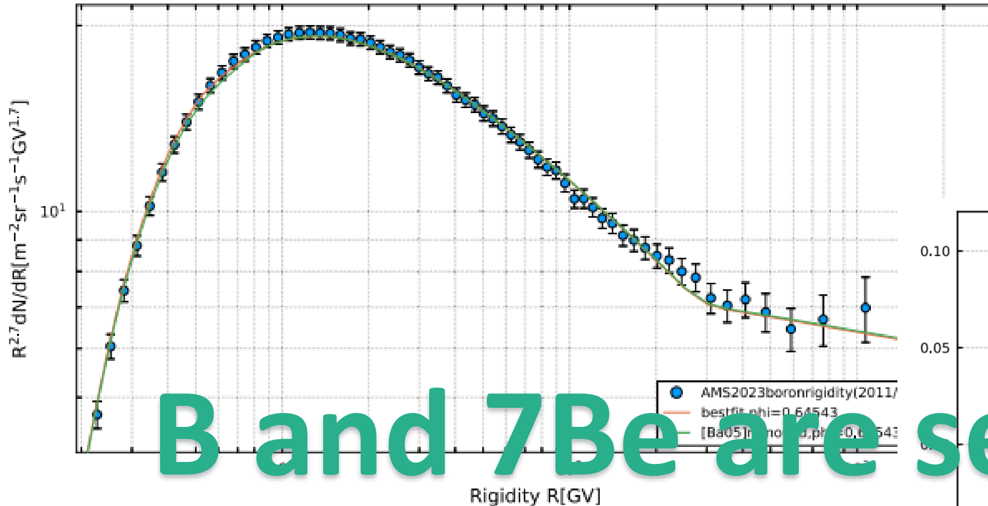

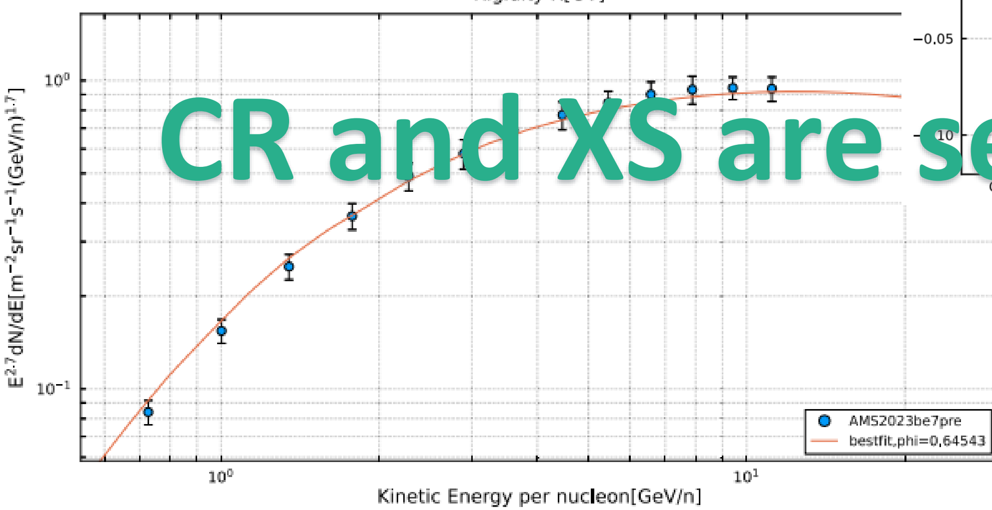

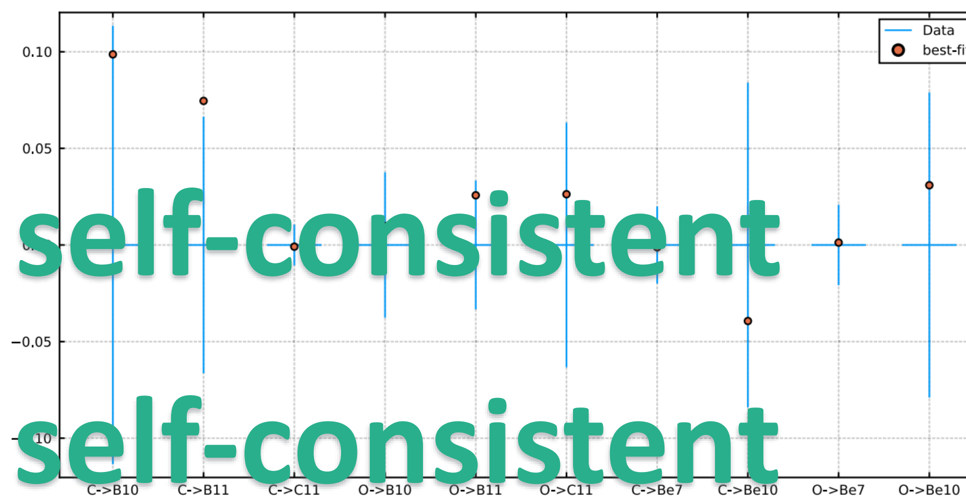

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0.031	[−0.154, 0.128]
232.6/320	...
3.2/10	...

B and 7Be are self-consistent

CR and XS are self-consistent

Reaction ranking (Isotope ver.)

Contribution(%) are taken at 10 GeV/n, those less than 1% are ignored.
errs:
I - adequate data
A[x] - need higher energy (>xGeV/n) data
B - need mid energy (>=1GeV/n) data
C - only 1~2 points at low energies
D - without any measurements

Fluorine_19
(pri)
20Ne → 19Ne 21.260 C
20Ne → 19F 18.094 B
24Mg → 19F 11.237 C
28Si → 19F 9.412 C
22Ne → 19F 6.527 B
26Mg → 19F 3.266 C
28Si → 19Ne 3.244 C
24Mg → 19Ne 3.201 C
25Mg → 19F 2.822 C
23Na → 19F 2.732 C
27Al → 19F 2.011 C
56Fe → 19F 1.821~3.5 A[1.5]
32S → 19F 1.547 B
22Ne → 19O 1.139 B

Lithium_6
(pri)
16O → 6Li 28.557 B
12C → 6Li 26.349 I
56Fe → 6Li 4.056 A[1.2]
28Si → 6Li 2.992 D
24Mg → 6Li 2.888 D
14N → 6Li 2.508 B
20Ne → 6Li 2.092 D
16O → 6He 1.304 B
14N → 6He 1.245 C
12C → 6He 1.078 I
22Ne → 6Li 0.907 D

Lithium_7
(pri)
12C → 7Li 26.661 I
16O → 7Li 23.919 A[3.2]
56Fe → 7Li 4.810 A[1.2]
28Si → 7Li 4.055 D
24Mg → 7Li 3.914 D
20Ne → 7Li 2.835 D
14N → 7Li 2.692 B
22Ne → 7Li 1.860 D

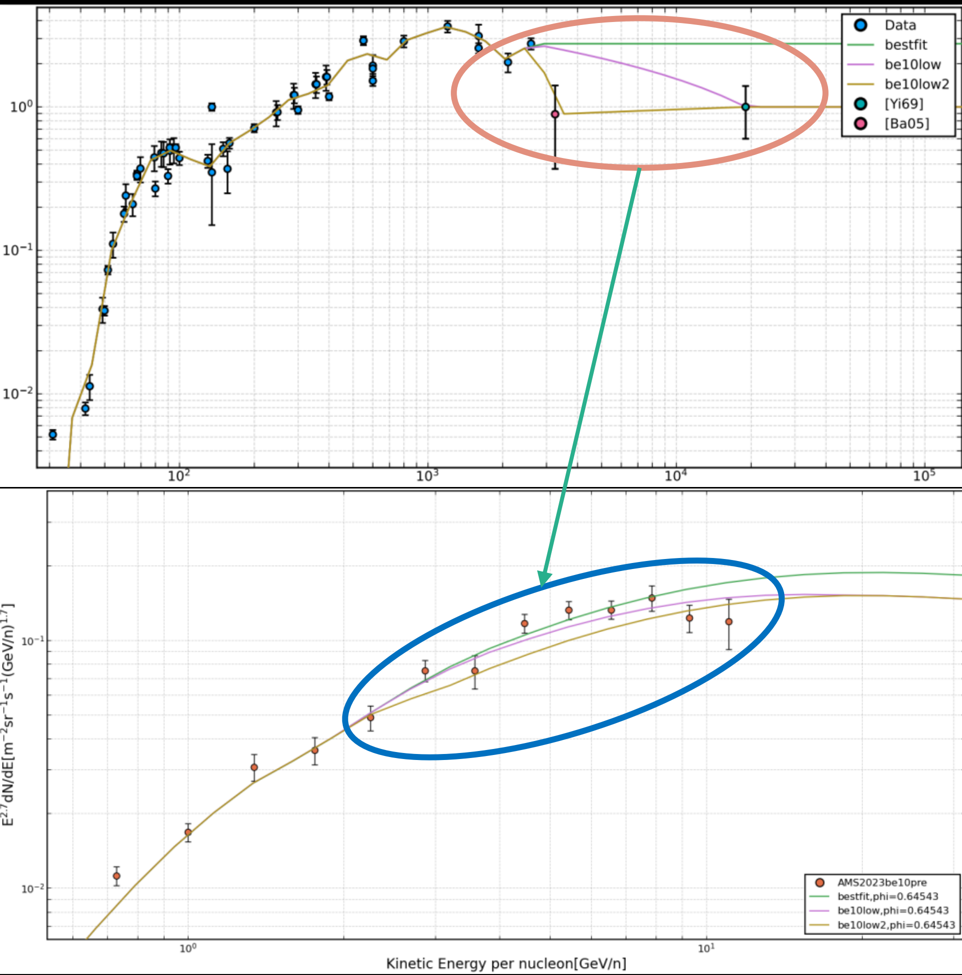
Beryllium_10
(pri)
12C → 10Be 36.270 I
16O → 10Be 26.959 A[2.5]
24Mg → 10Be 3.973 A[2.6]
56Fe → 10Be 3.600 A[2.6]
28Si → 10Be 3.363 A[2.6]
14N → 10Be 3.262 A[1.6]
20Ne → 10Be 2.068 D
22Ne → 10Be 1.191 D

Beryllium_7
(pri)
16O → 7Be 34.203 I
12C → 7Be 28.983 I
28Si → 7Be 5.599 I
14N → 7Be 5.287 I
24Mg → 7Be 5.072 I
56Fe → 7Be 4.225 A[2.9]
20Ne → 7Be 2.725 D
23Na → 7Be 1.117 B

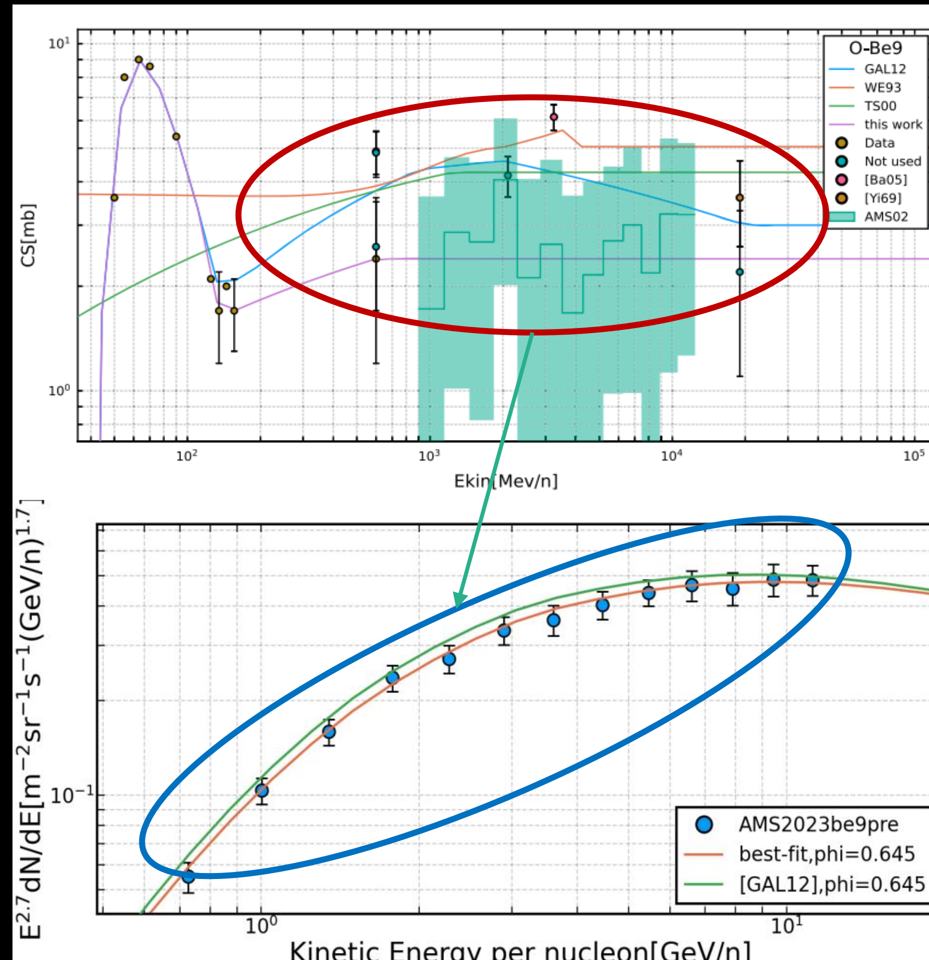
Beryllium_9
(pri)
12C → 9Be 36.213 I
16O → 9Be 29.038 B
24Mg → 9Be 5.416 C
28Si → 9Be 4.144 B
56Fe → 9Be 3.804 A[1.2]
20Ne → 9Be 2.735 D
14N → 9Be 1.582 C
22Ne → 9Be 1.188 D

Result: constraint on the XS

$^{16}O + p \rightarrow {}^{10}Be$



$^{16}O + p \rightarrow {}^{9}Be$



Result: XS measurements deviate from expectation

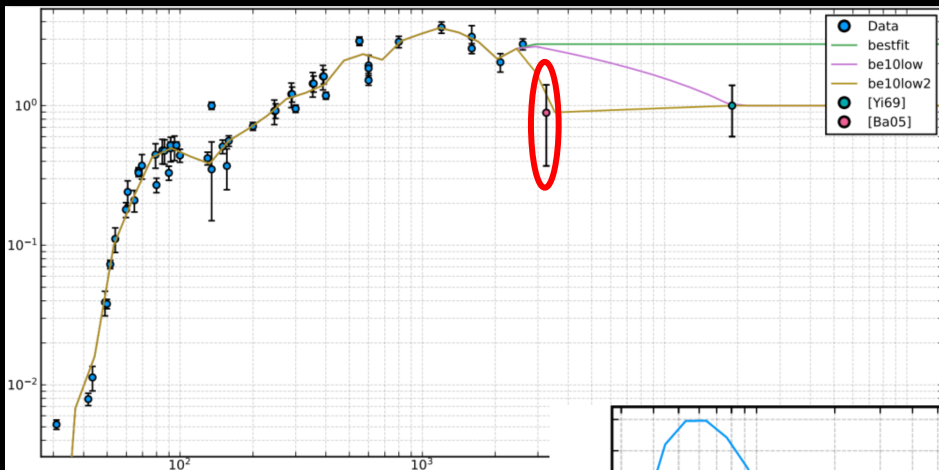
Cross Sections for the Production of Stable and Unstable Isotopes with Charge Numbers from One to Eight in ^{16}Op Collisions at 3.25 A GeV/c

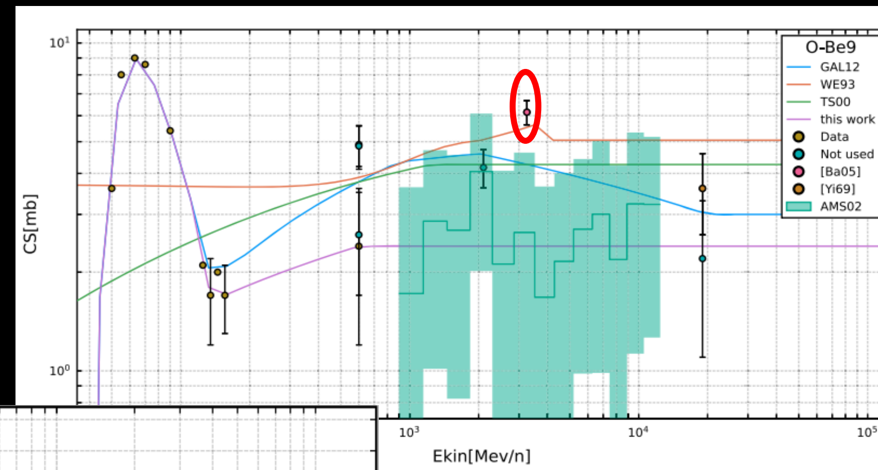
É. Kh. Bazarov[1], V. V. Glagolev[2], V. V. Lugovoy[1], S. L. Lutpullaev[1], K. Olimov[1], V. I. Petrov[1], A. A. Yuldashev[1], and B. S. Yuldashev[3]

Z	A	$\sigma \pm \Delta\sigma$, mb	Z	A	$\sigma \pm \Delta\sigma$, mb
1	$^{1}H_1$	509.0 ± 5.7	5	$^{9}B_5^*$	5.70 ± 0.29
	$^{2}H_1$	116.9 ± 1.3		$^{10}B_5$	10.6 ± 0.4
	$^{3}H_1$	41.8 ± 0.4		$^{11}B_5$	10.9 ± 0.4
2	$^{3}He_2$	40.7 ± 1.9	6	$^{12}B_5$	0.51 ± 0.42
	$^{4}He_2$	164.0 ± 1.9		$^{10}C_6$	1.77 ± 0.8
	$^{5}He_2^*$	8.40 ± 0.50		$^{11}C_6$	9.18 ± 0.76
	$^{6}He_2$	1.03 ± 0.23		$^{12}C_6$	26.3 ± 0.8
3	$^{5}Li_3^*$	8.40 ± 0.50		$^{12}C_6^*$	9.80 ± 0.80
	$^{6}Li_3$	19.0 ± 0.8		$^{13}C_6$	9.48 ± 0.76
	$^{7}Li_3$	10.6 ± 0.8		$^{14}C_6$	3.68 ± 0.76
	$^{8}Li_3$	4.80 ± 0.76	7	$^{13}N_7$	9.40 ± 0.79
4	$^{7}Be_4$	10.3 ± 0.5		$^{14}N_7$	26.1 ± 0.8
	$^{8}Be_4^*$	7.63 ± 0.37		$^{15}N_7$	30.3 ± 0.8
	$^{9}Be_4$	6.15 ± 0.52	8	$^{14}O_8$	2.85 ± 0.7
	$^{10}Be_4$	0.89 ± 0.52		$^{15}O_8$	31.1 ± 0.7
				$^{16}O_8$	13.0 ± 0.7

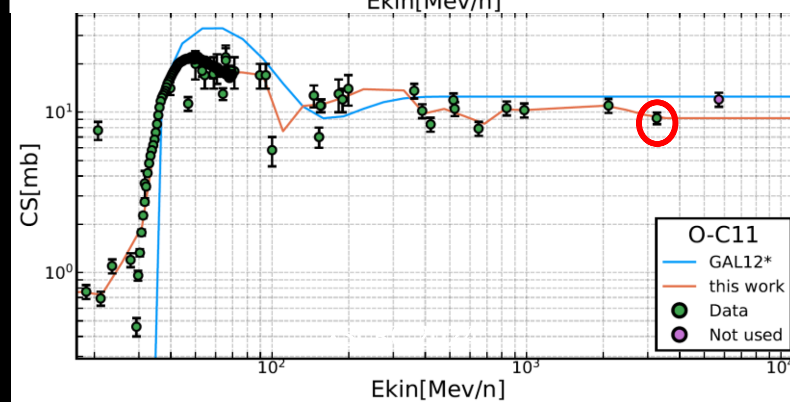
* Unstable or excited states.

Result: XS measurements deviate from expectation





How much should we believe in specific measurements, where there are no other data?



Conclusion

- Silly ideas:
  - Use 7Be instead of 9Be to constrain the transport parameters
  - Use as many XS measurements as possible to determine the parametrization
- Results: **Based on preliminary measurement**
  - The production XS of 7Be and B are well-constrained, and their CR measurements and XS measurements are self-consistent.
  - The high-energy extrapolation of 10Be energy spectrum disfavors a fast-decreasing XS of the 16O ⟶ 10Be channel.
  - We discovered a significant overestimation of the 9Be CR fluxes in comparison with the AMS-02 measurement. A constraint on the XS of the 16O ⟶ 9Be channel is given.
  - Some XS measurements significantly deviate from our expectation (considered less credible ?)
- More to learn:
  - Lithium isotopes, F, P, sub-Fe …

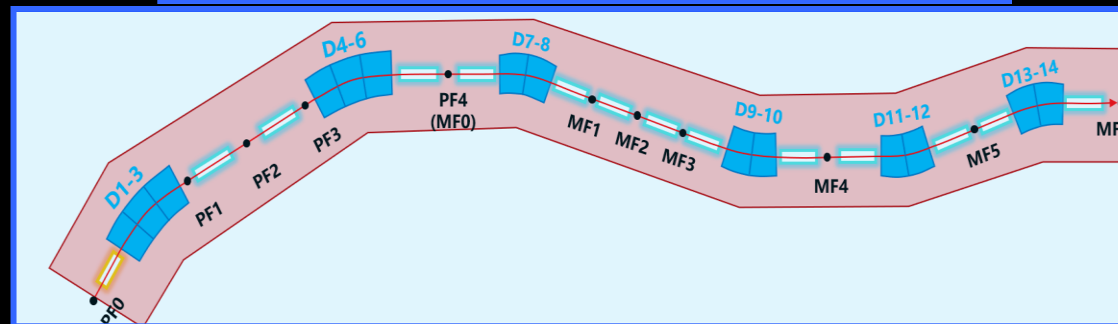
Next page: HIAF in China

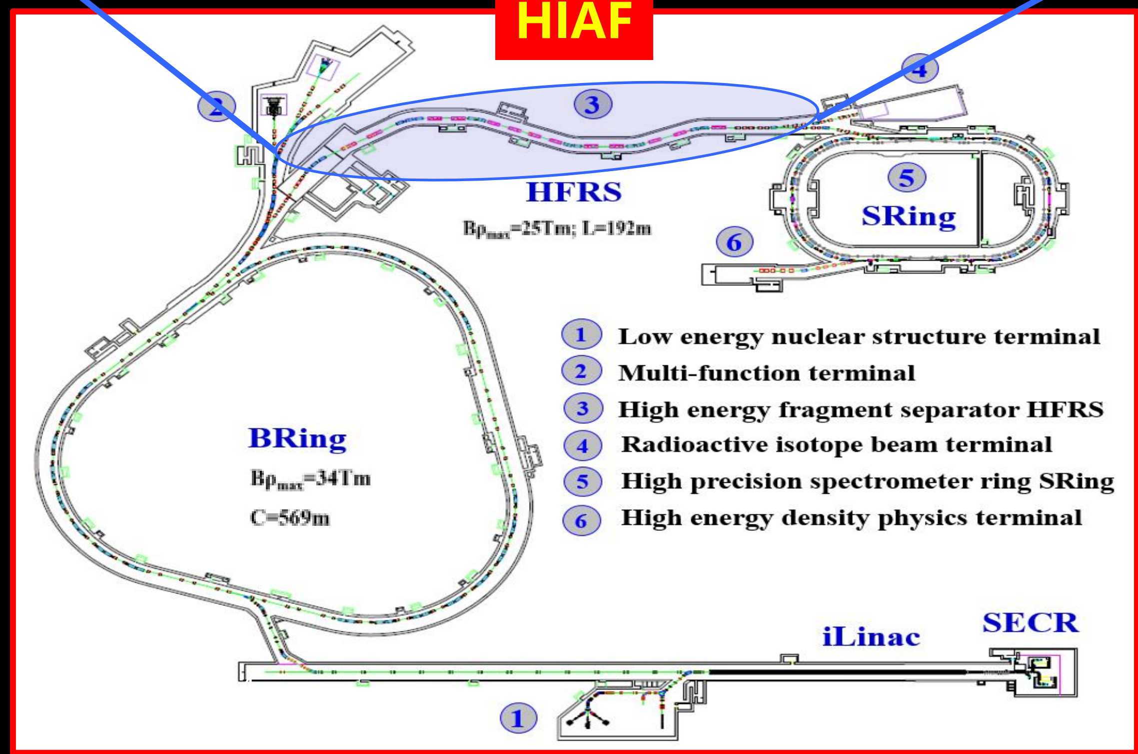
High Intensity heavy-ion Accelerator Facility

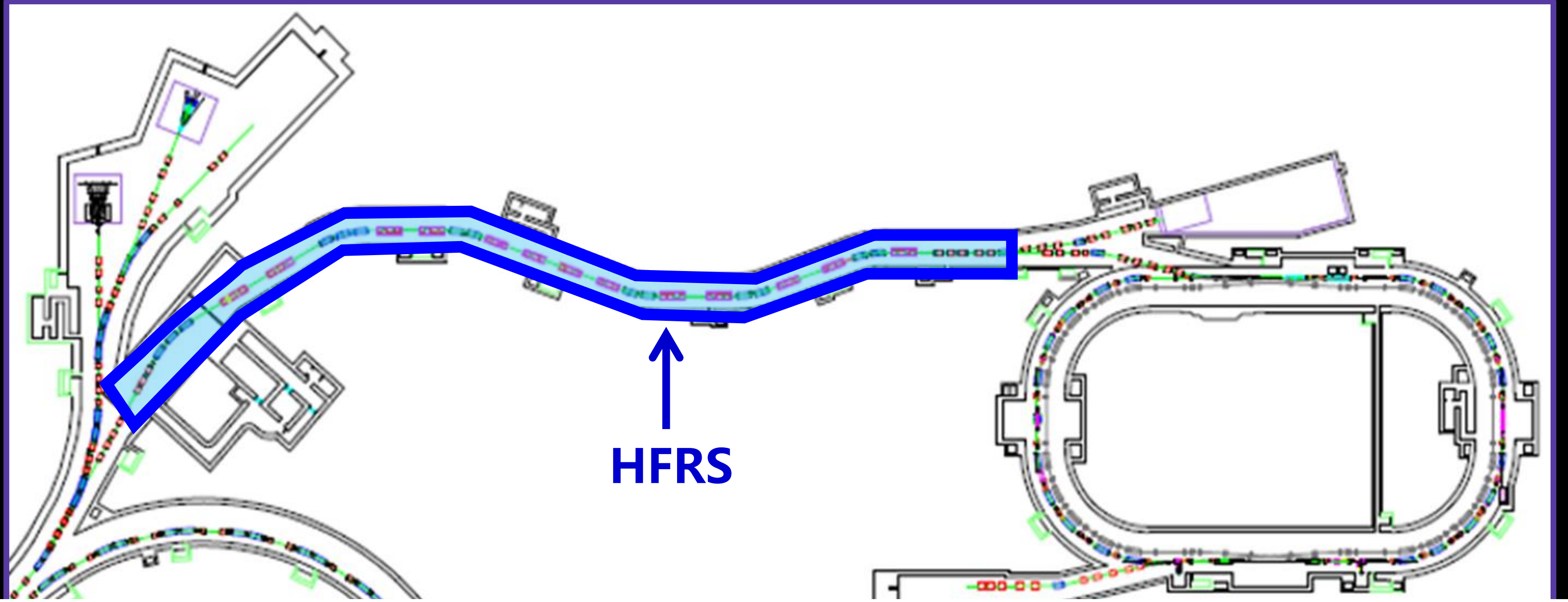
中国科学院
CHINESE ACADEMY OF SCIENCES
Institute of Modern Physics
Chinese Academy of Sciences

Photo Augest 2024

High energy FRagment Separator





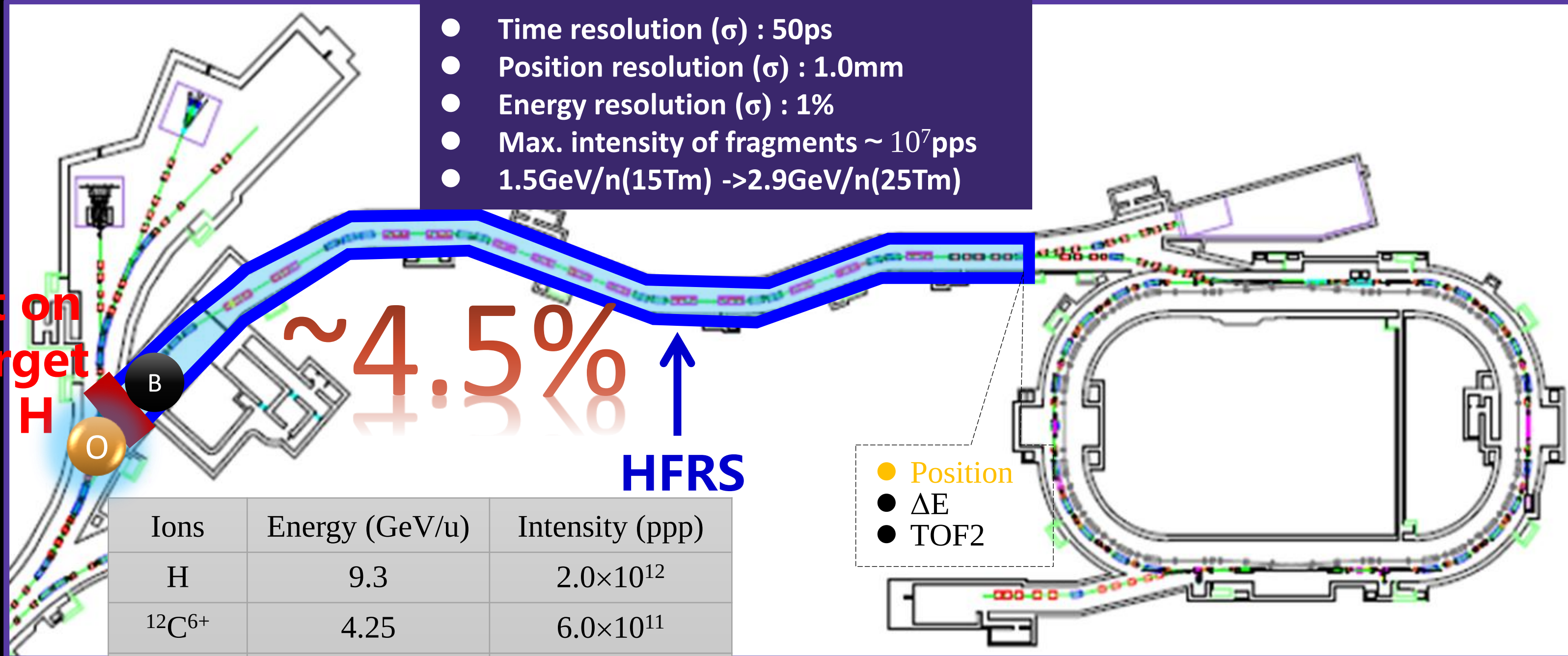


- **RIB production mechanism (fragmentation cross section / two-step reaction / …)**
- **Discovery of new isotope**
- **Mass measurement of extremely short-lived nuclei**
- **……**

Parameters of HFRS compared with others

	Length (m)	Beam size at target (mm)	Angular acceptance(mrad)	Momentum acceptance (%)	Resolving power	Max. Bρ (Tm)
HFRS NIM.B 547(2024),165214	191.38	±1/±1.5	±30 (X); ±25 (Y)	±2.0	850/1100 (ΔX=±1mm)	15->25
SuperFRS NIM.B 204(2003),71	182.2	±1/±2	±40 (X); ±20 (Y)	±2.5	750/1500 (ΔX=±1mm)	20
BigRIPS Prog.Theor.EXP.Phys.2012,03 C003	78.2	±0.5/±0.5	±40 (X); ±50 (Y)	±3	1260/3420 (ΔX=±0.5mm)	9.5
ARIS NIM.B 317(2013), 349	86.8	±0.5/±0.5	±40 (X); ±40 (Y)	±5	1720/3000 (ΔX=±0.5mm)	8

- Time resolution (σ) : 50ps
- Position resolution (σ) : 1.0mm
- Energy resolution (σ) : 1%
- Max. intensity of fragments ~ 10^7pps
- 1.5GeV/n(15Tm) ->2.9GeV/n(25Tm)



Ions	Energy (GeV/u)	Intensity (ppp)
H	9.3	2.0×10^{12}
$^{12}C^{6+}$	4.25	6.0×10^{11}
$^{16}O^{6+}$	3.0	4.0×10^{11}
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$^{58}Ni^{18+}$	2.37	1.4×10^{11}
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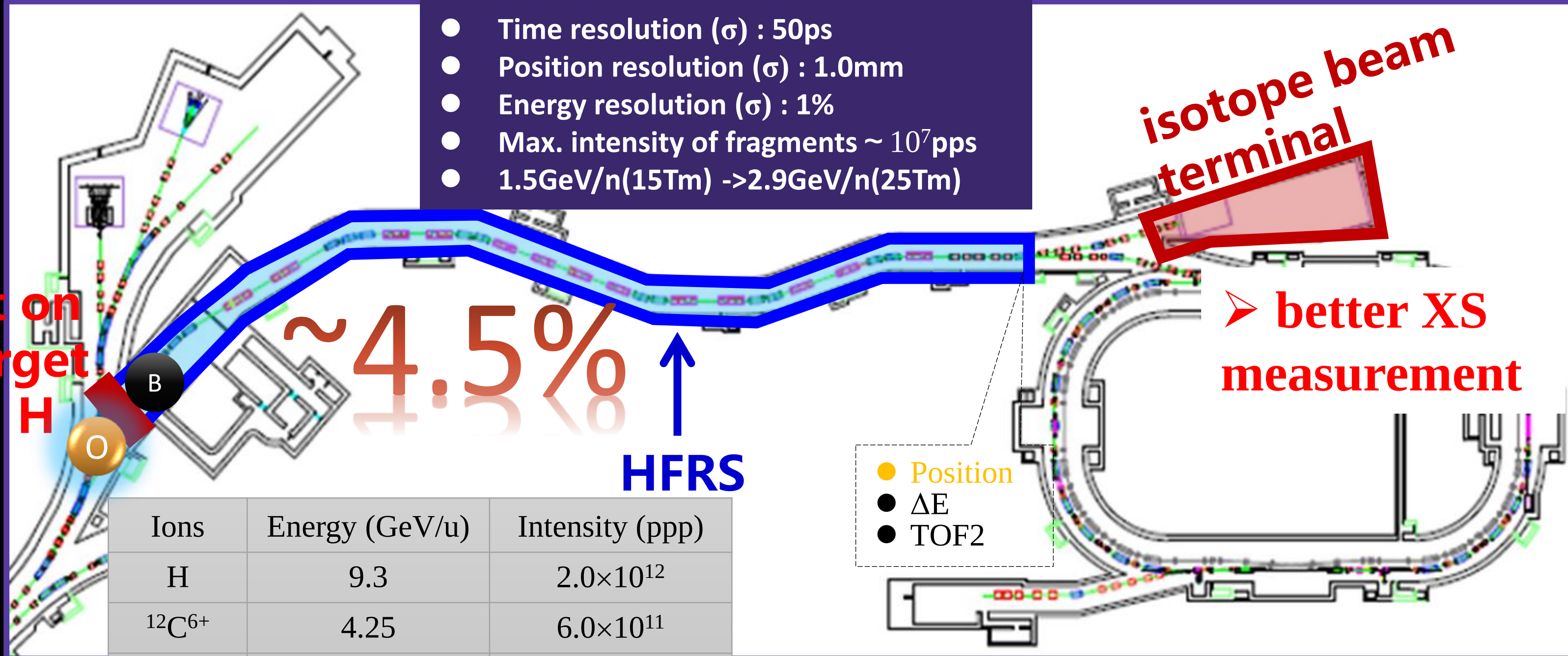

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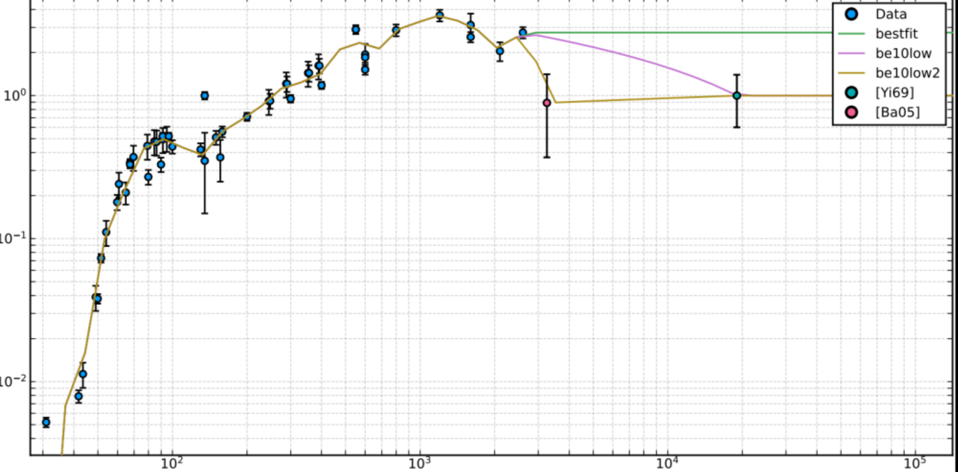
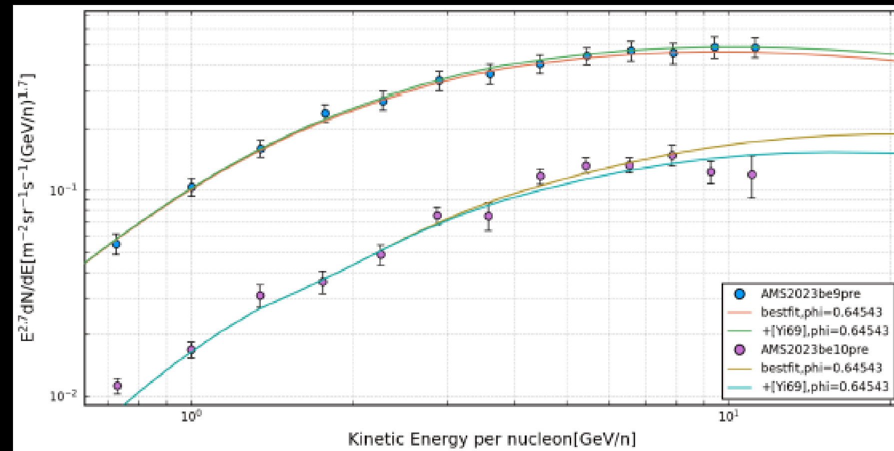
Thanks for your attention!


Data
bestfit
be10low
be10low2
[Yi69]
[Ba05]


Kinetic Energy per nucleon[GeV/n]
AMS2023be9pre
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AMS2023be10pre
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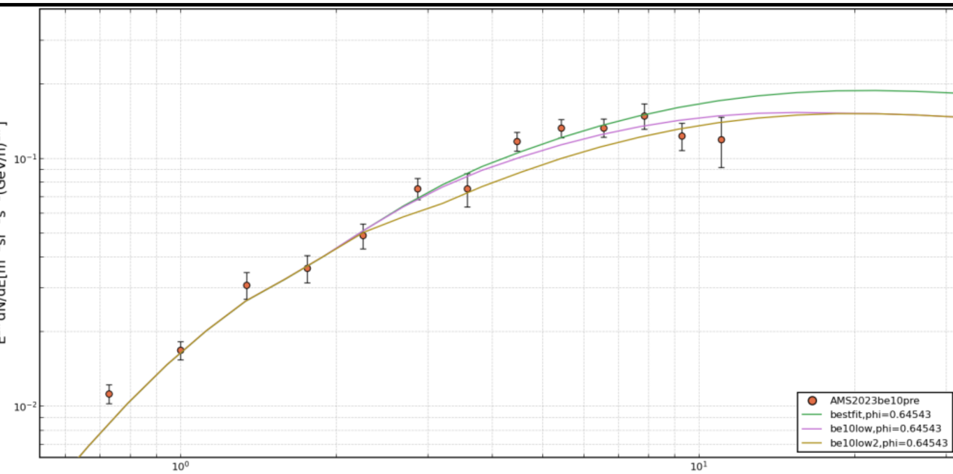
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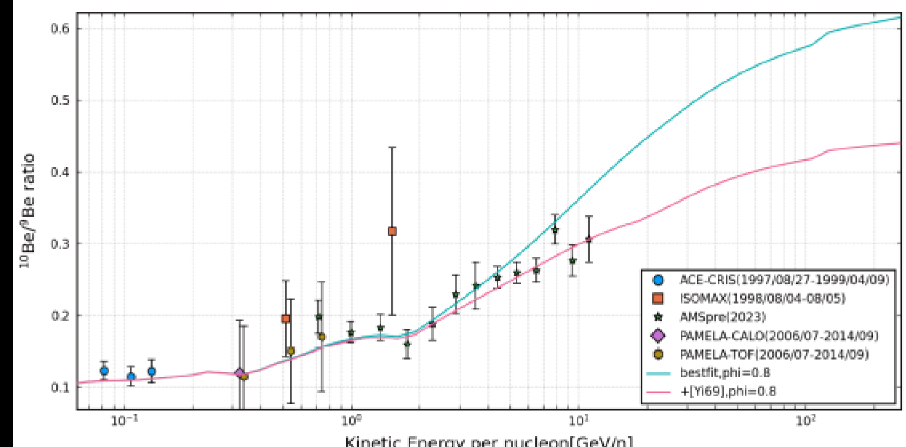
be10low2,phi=0.64543


^{10}Be/^{9}Be ratio
Kinetic Energy per nucleon[GeV/n]
ACE-CRIS(1997/08/27-1999/04/09)
ISOMAX(1998/08/04-08/05)
AMSpre(2023)
PAMELA-CALO(2006/07-2014/09)
PAMELA-TOF(2006/07-2014/09)
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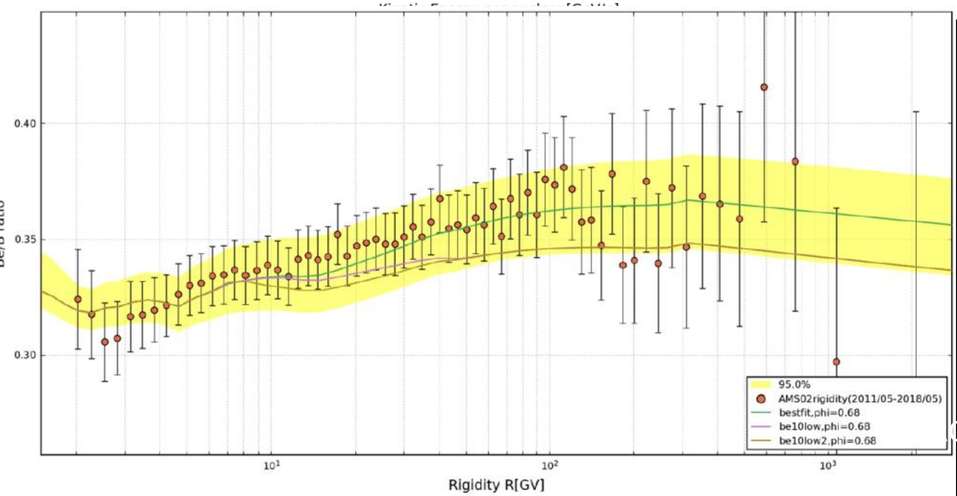
Rigidity R[GV]
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AMS02rigidity(2011/05-2018/05)
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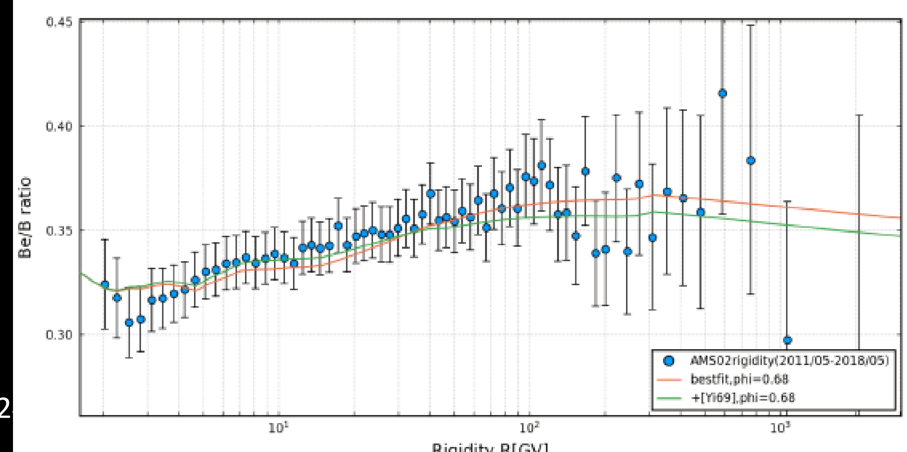
be10low2,phi=0.68

C 202


Be/B ratio
Rigidity R[GV]
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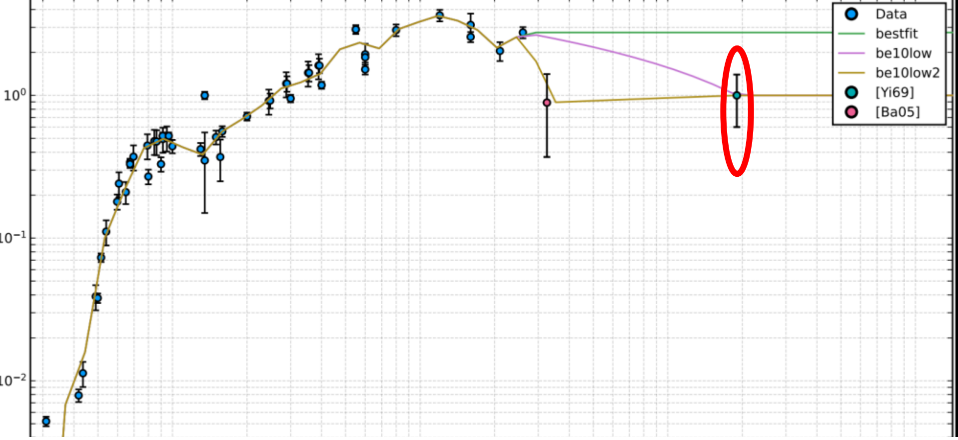
+[Yi69],phi=0.68


Data
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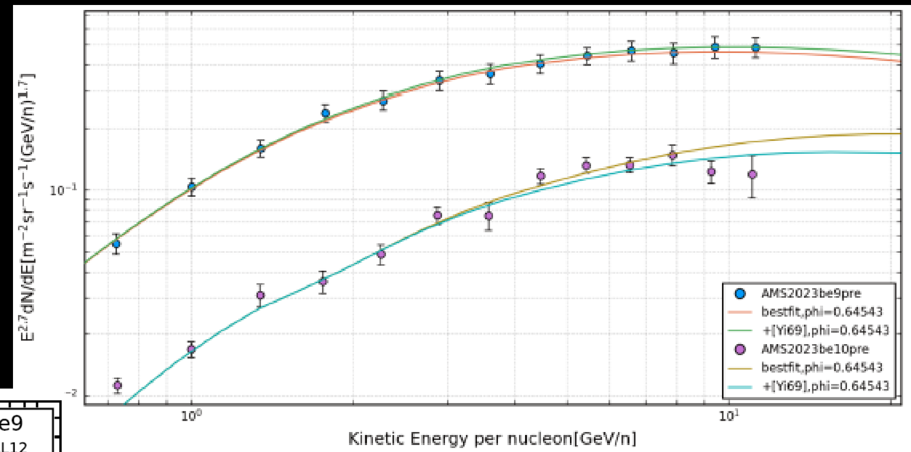
be10low
be10low2
[Yi69]
[Ba05]


$E^{2.7}dN/dE[m^{-2}sr^{-1}s^{-1}(GeV/n)^{1.7}]$
Kinetic Energy per nucleon[GeV/n]
AMS2023be9pre
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+[Yi69],phi=0.64543
AMS2023be10pre
bestfit,phi=0.64543
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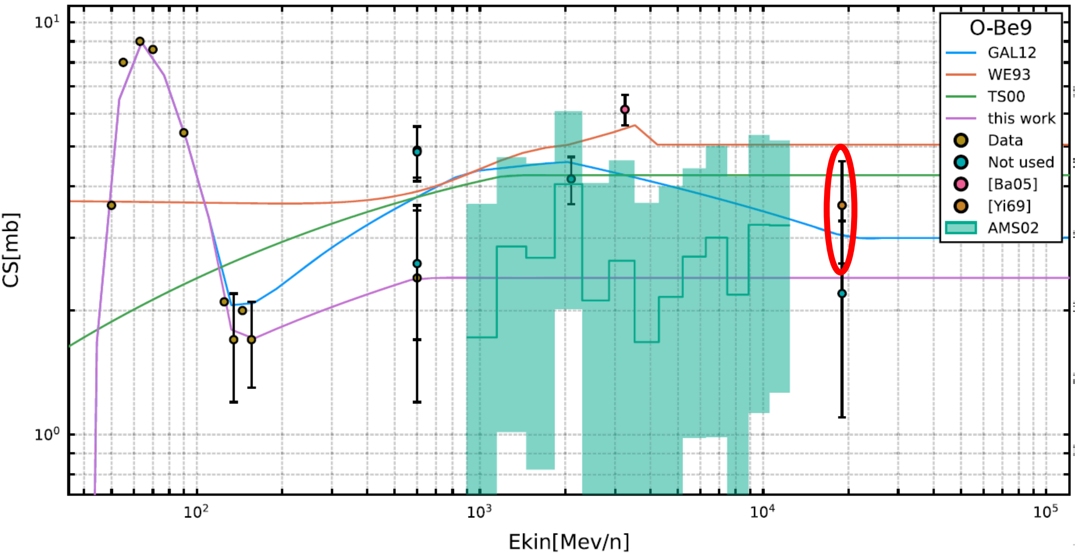
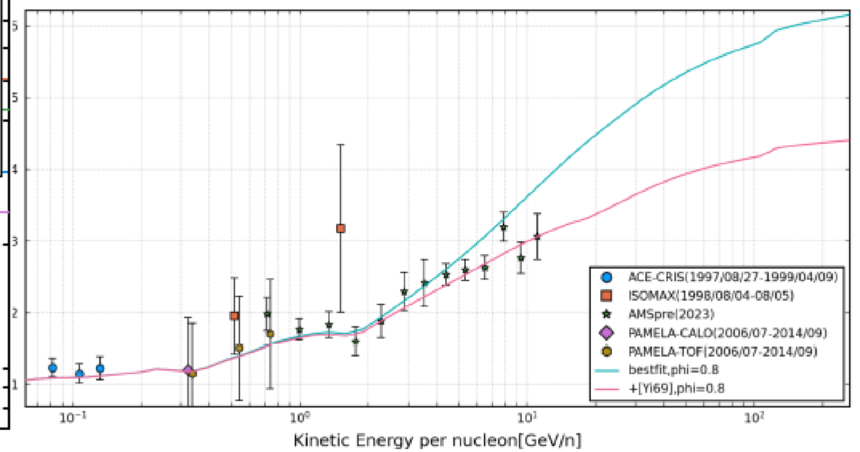

O-Be9
GAL12
WE93
TS00
this work
Data
Not used
[Ba05]
[Yi69]
AMS02
CS[mb]
Ekin[Mev/n]


Kinetic Energy per nucleon[GeV/n]
ACE-CRIS(1997/08/27-1999/04/09)
ISOMAX(1998/08/04-08/05)
AMSpre(2023)
PAMELA-CALO(2006/07-2014/09)
PAMELA-TOF(2006/07-2014/09)
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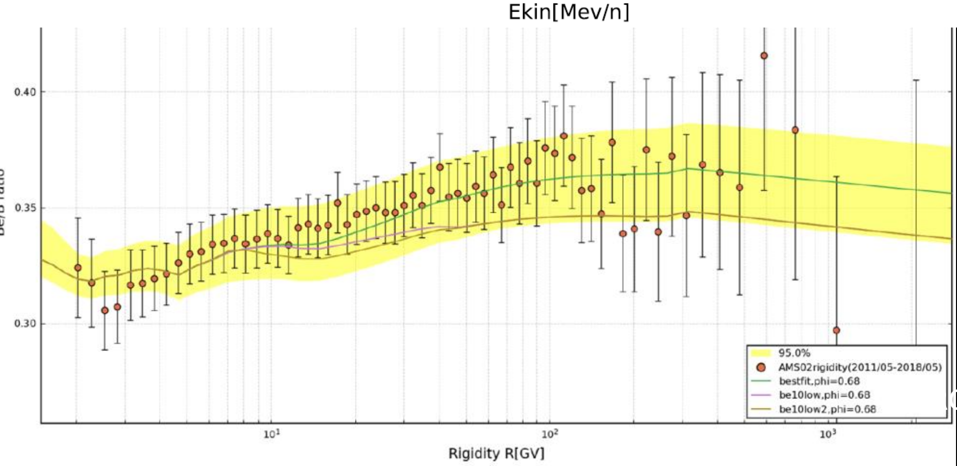
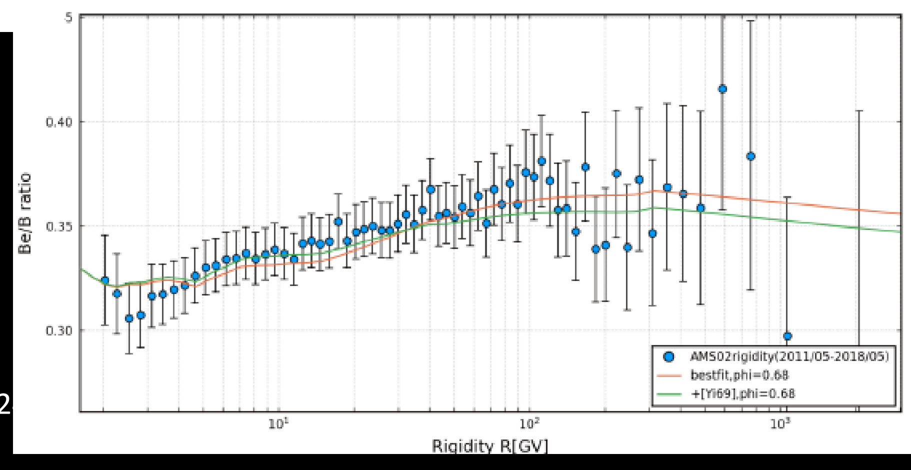
+[Yi69],phi=0.8


95.0%
AMS02rigidity(2011/05-2018/05)
bestfit,phi=0.68
be10low,phi=0.68
be10low2,phi=0.68
Rigidity R[GV]

C 202


Be/B ratio
Rigidity R[GV]
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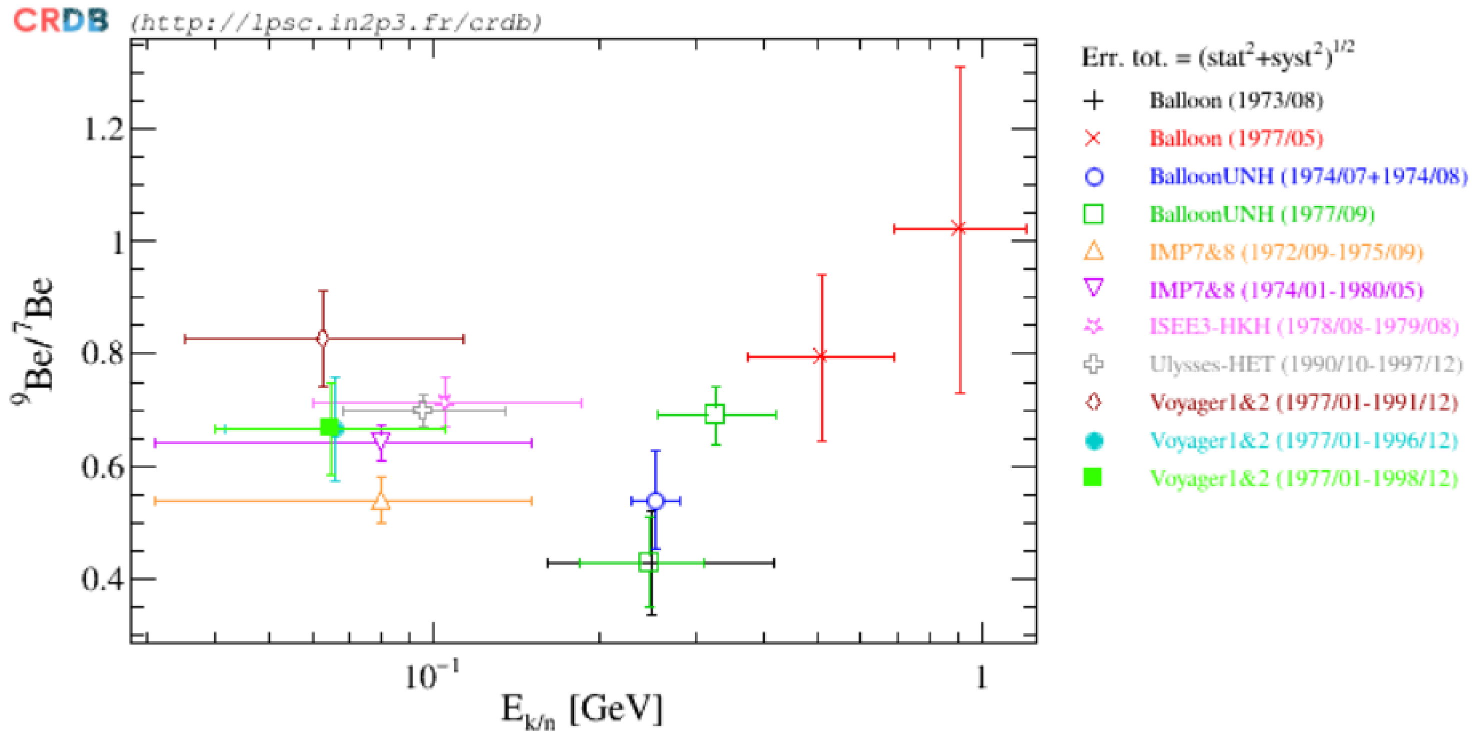
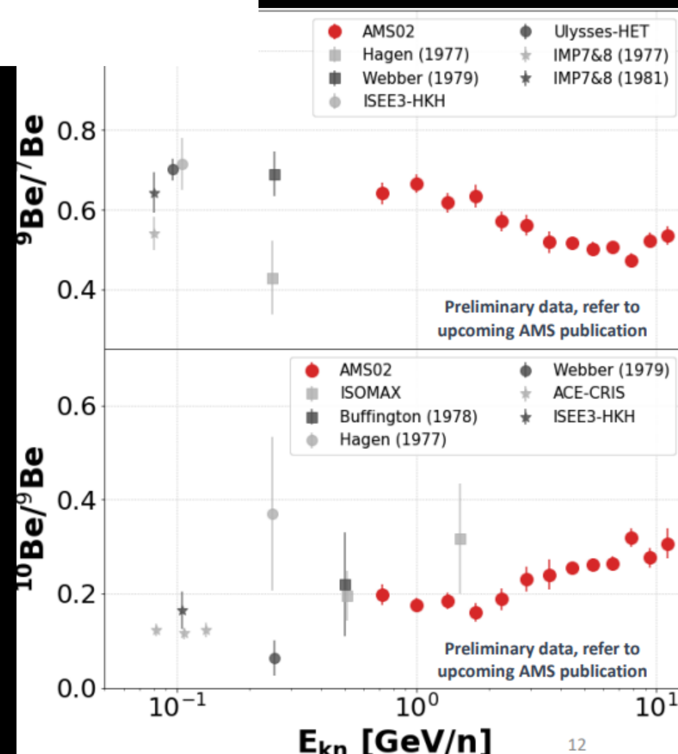

CRDB (http://lpsc.in2p3.fr/crdb)
Err. tot. = (stat²+syst²)^1/2
Balloon (1973/08)
Balloon (1977/05)
BalloonUNH (1974/07+1974/08)
BalloonUNH (1977/09)
IMP7&8 (1972/09-1975/09)
IMP7&8 (1974/01-1980/05)
ISEE3-HKH (1978/08-1979/08)
Ulysses-HET (1990/10-1997/12)
Voyager1&2 (1977/01-1991/12)
Voyager1&2 (1977/01-1996/12)
Voyager1&2 (1977/01-1998/12)
⁹Be/⁷Be
E_k/n [GeV]


AMS02
Hagen (1977)
Webber (1979)
ISEE3-HKH
Ulysses-HET
IMP7&8 (1977)
IMP7&8 (1981)
⁹Be/⁷Be
Preliminary data, refer to
upcoming AMS publication
AMS02
ISOMAX
Buffington (1978)
Hagen (1977)
Webber (1979)
ACE-CRIS
ISEE3-HKH
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Preliminary data, refer to
upcoming AMS publication
E_kn [GeV/n]