Current status and desired accuracy of the isotopic production cross sections relevant to astrophysics of cosmic rays: 1. Li, Be, B, C, N

Génolini, Maurin, Moskalenko & Unger
https://arxiv.org/abs/1803.04686
Phys. Rev. C 98, 034611
(as an *Editors' Suggestion*)

1. GCR: brief introduction
2. XS uncertainties ≫ GCR data uncertainties
3. Which reactions matter? Ranking for GCRs
4. Conclusions

GCR = Galactic cosmic rays
XS = cross sections

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GdR RESANET,
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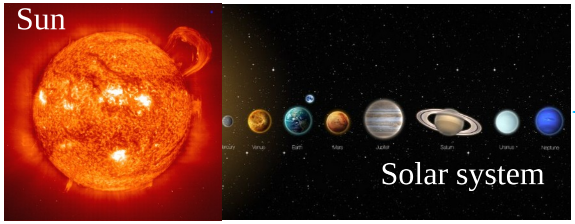
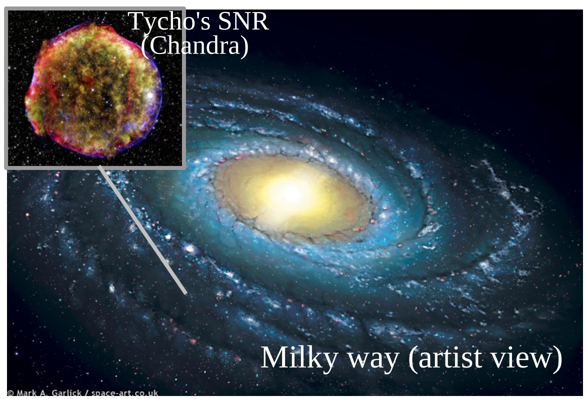
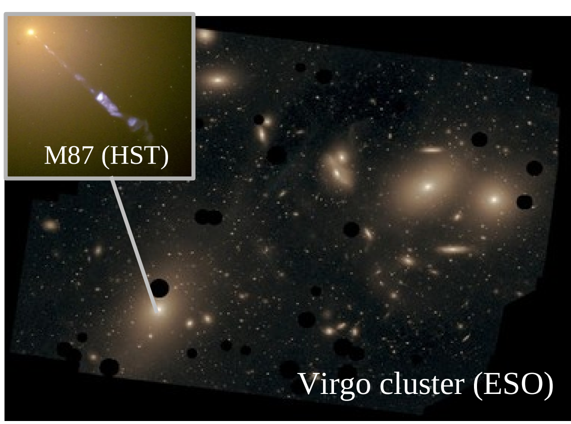
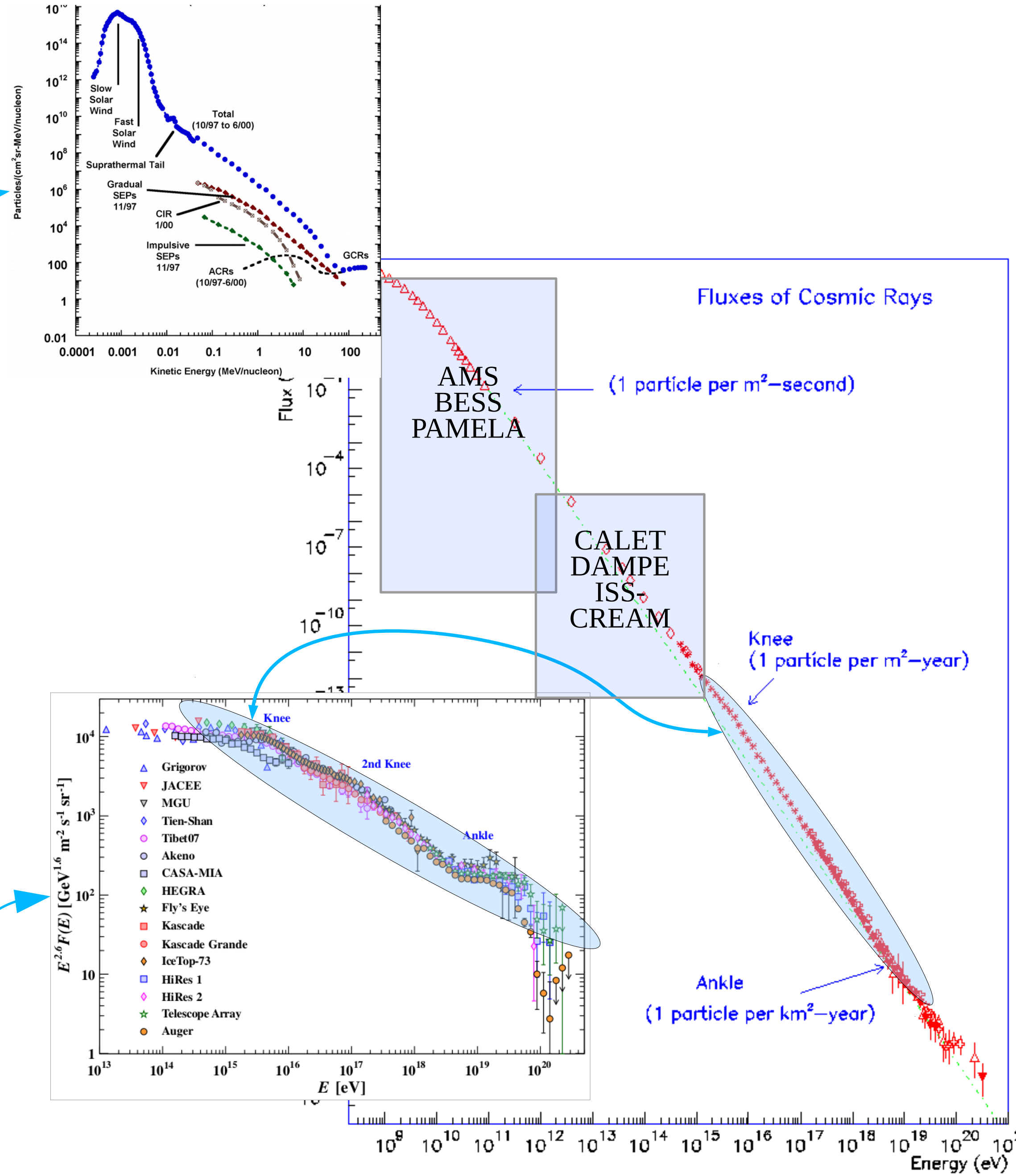
24 September 2018

Cosmic ray spectrum and sources









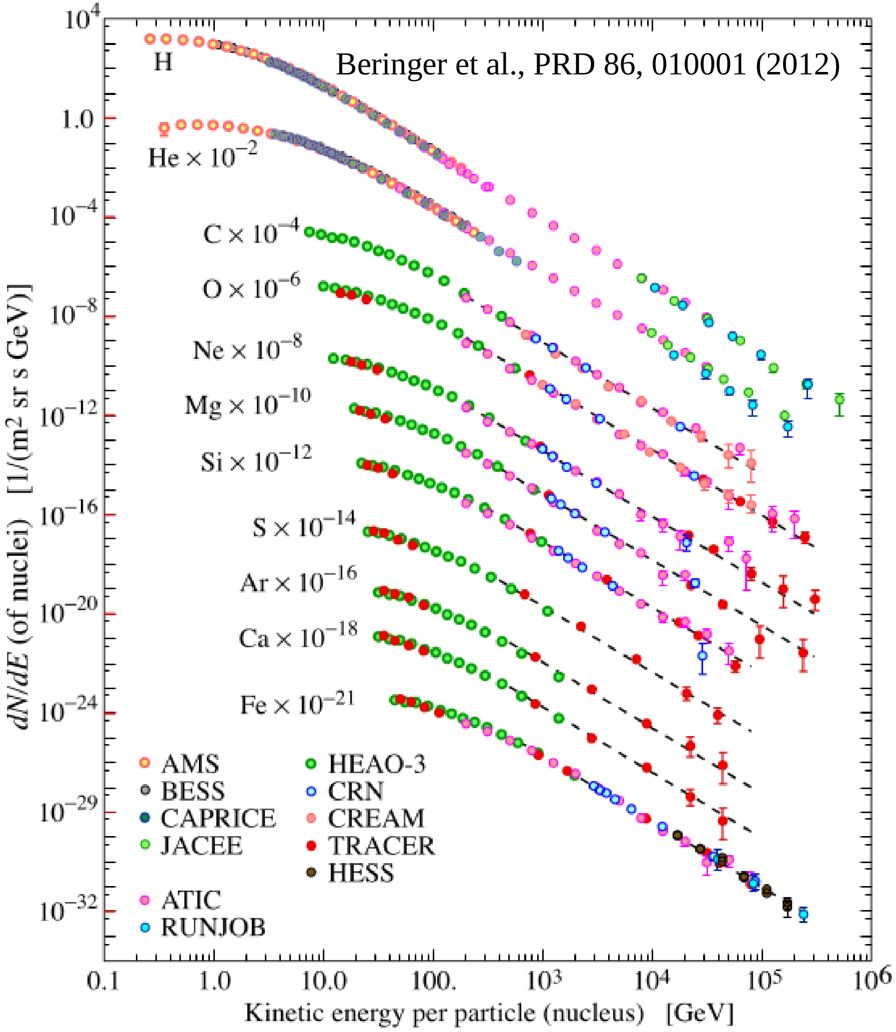
Transition galactic vs extragalactic

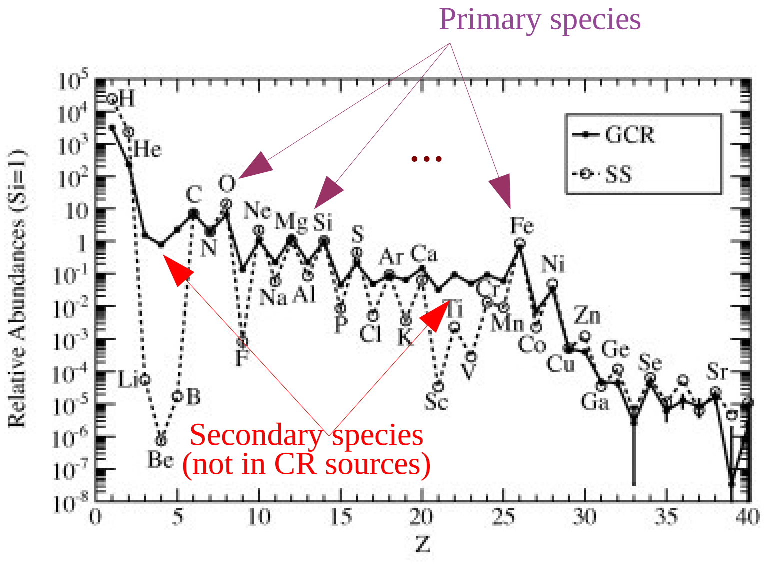
→ CR sources and transport?

→ Origin of spectral features, composition, anisotropy?

GCR data: abundances

Elemental spectra



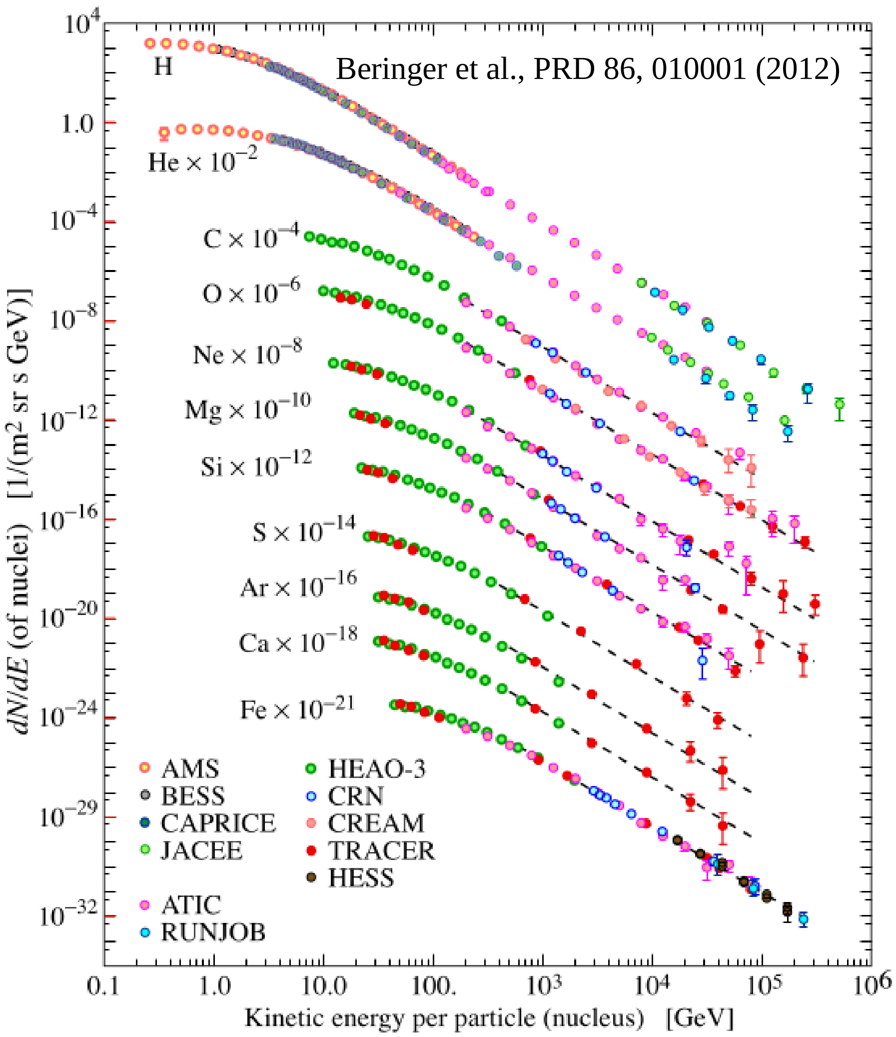


Bauch et al., AdSR 53 (2014)

→ Origin of 'universal' power law ($E^{-2.8}$)?
→ Abundances of elements/isotopes?
→ CR anisotropy ($\delta<10^{-3}$)

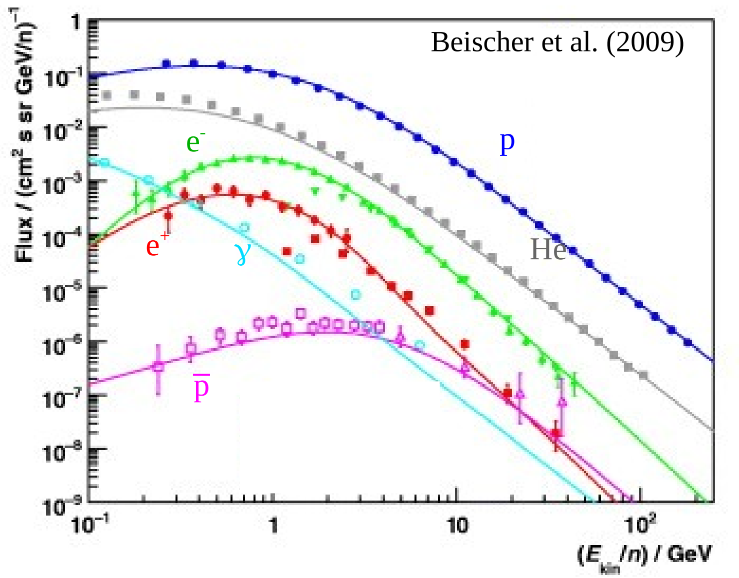
GCR data: rare production

Elemental spectra



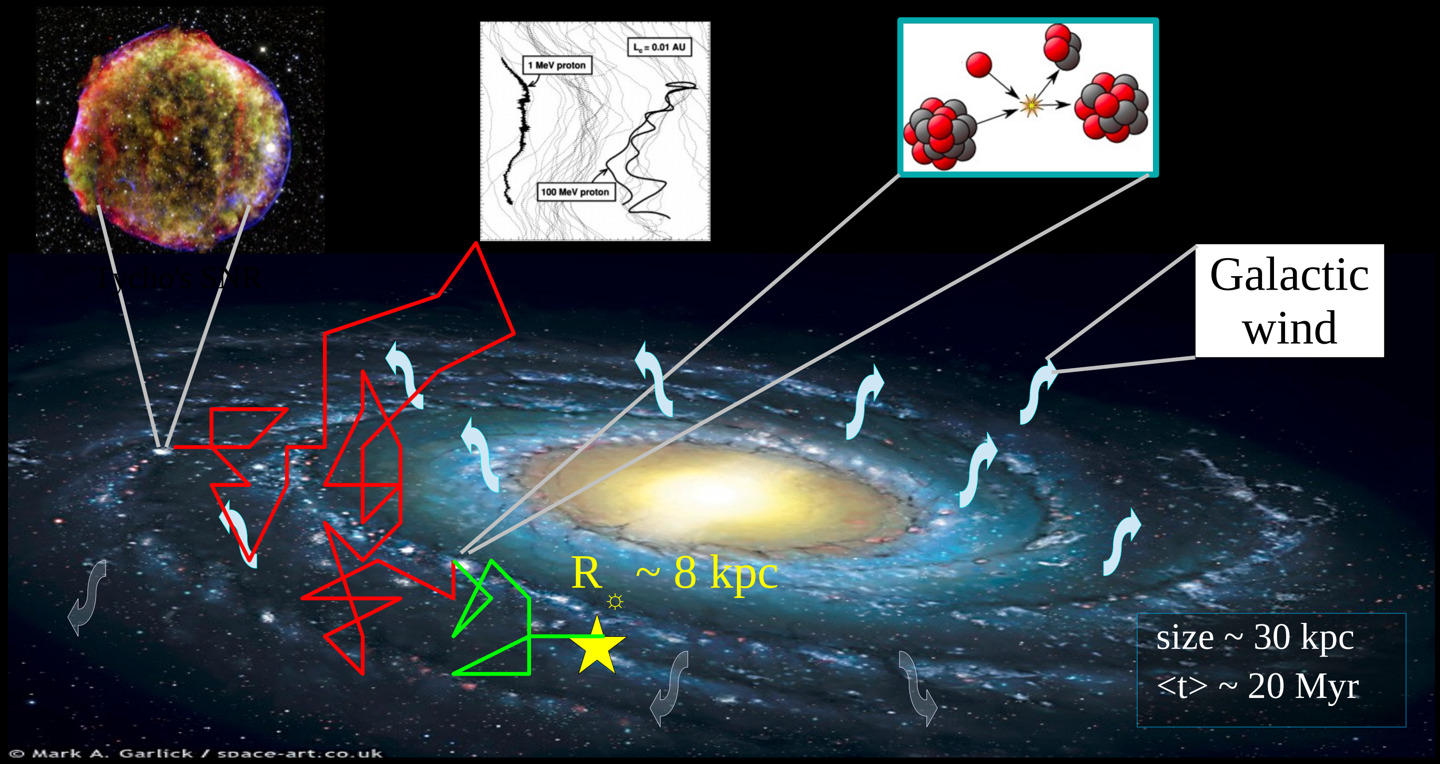
→ Origin of 'universal' power law ($E^{-2.8}$)?
→ Abundances of elements/isotopes?
→ CR anisotropy ($\delta<10^{-3}$)

Protons and He
vs
diffuse γ-rays, pbar, e^- and e^+



N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Is it a good place to look for dark matter?

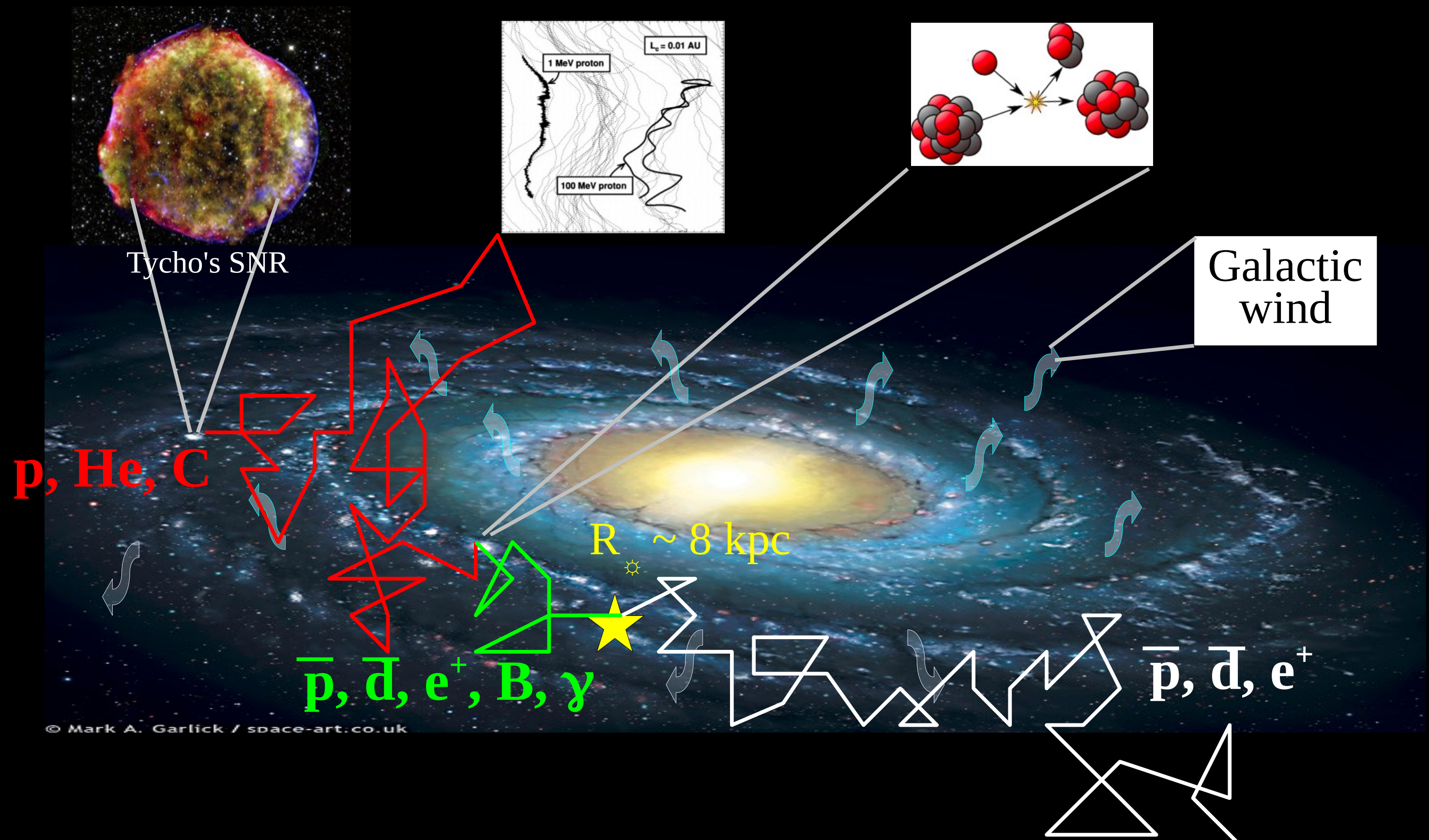
GCR journey



Nuclear reactions
(ISM ~ 90%H + 10% He)

- Inelastic XS (e.g., ^{12}C+H $\rightarrow$ X)
- Production XS (e.g., ^{12}C+H $\rightarrow$ ^{11}B+X)

GCR journey



Milky-Way dark matter halo

- ~ spherical halo
- radius ~300 kpc

AMS experiment

Installed on ISS in May 2011

→ Circular orbit, 400 km, 51.6°

→ Continuous operation 24/7

→ Average rate ~700 Hz (60 millions particles/day)

More than 100 billion events so far!

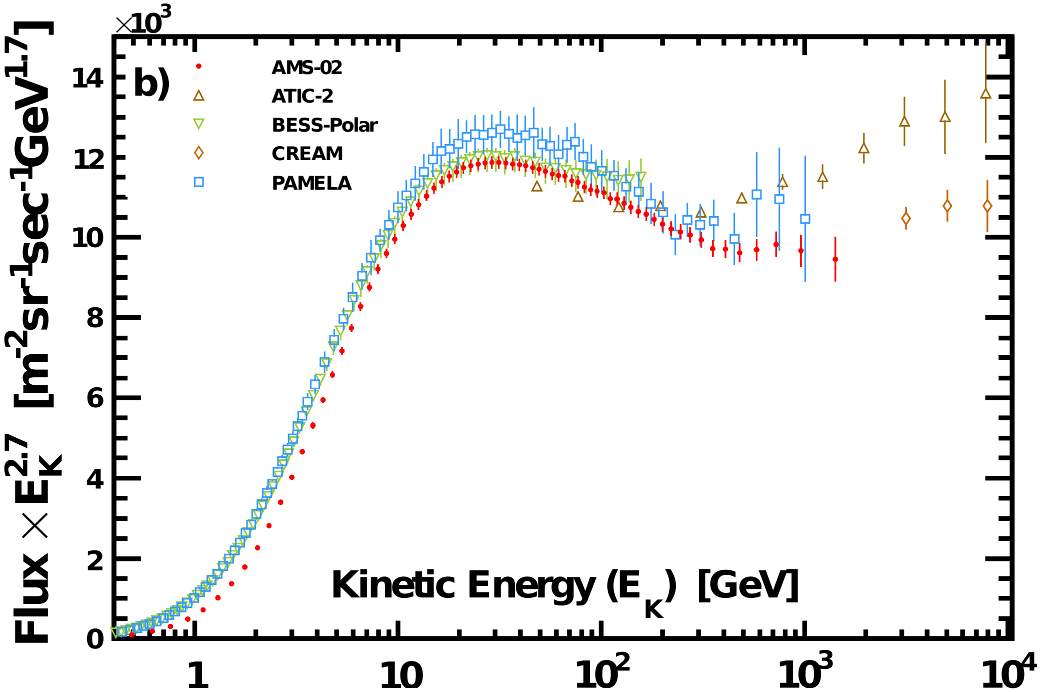
A game-changing experiment

→ high precision data

→ anomalies detected in spectra

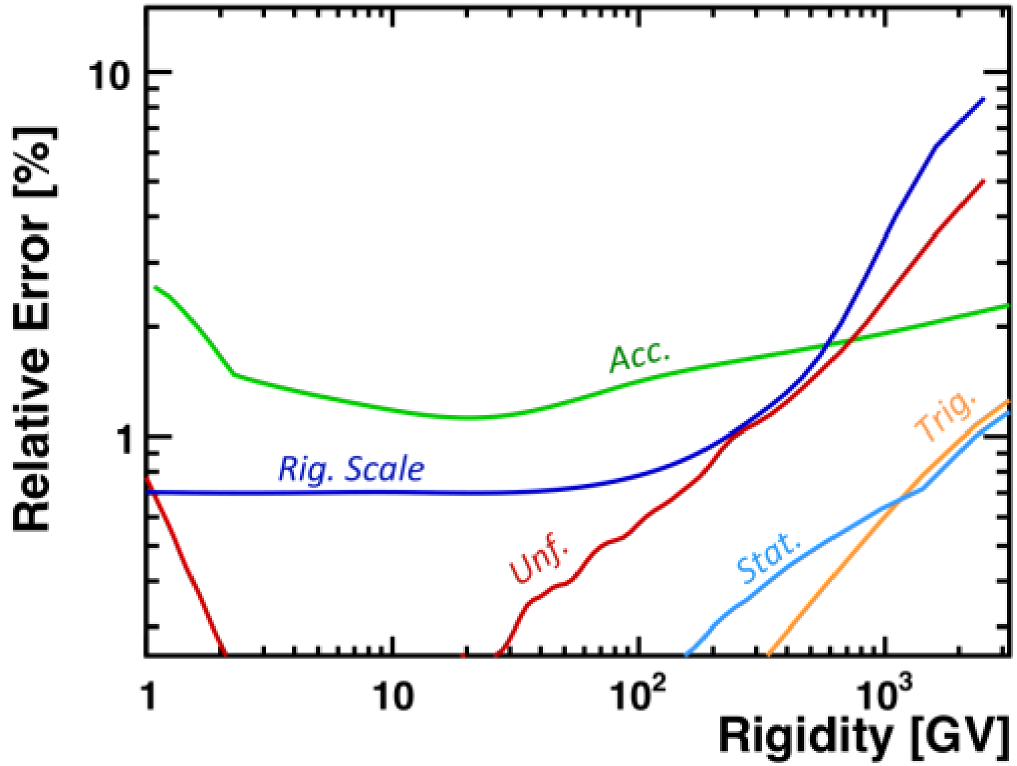
AMS results: ~3% uncertainties!

AMS-02 proton flux
Aguilar et al., PRL 114 (2015)
→ *based on 300 million events*



… and uncertainties

→ most difficult part of the analysis
→ stat. uncertainties sub-dominant



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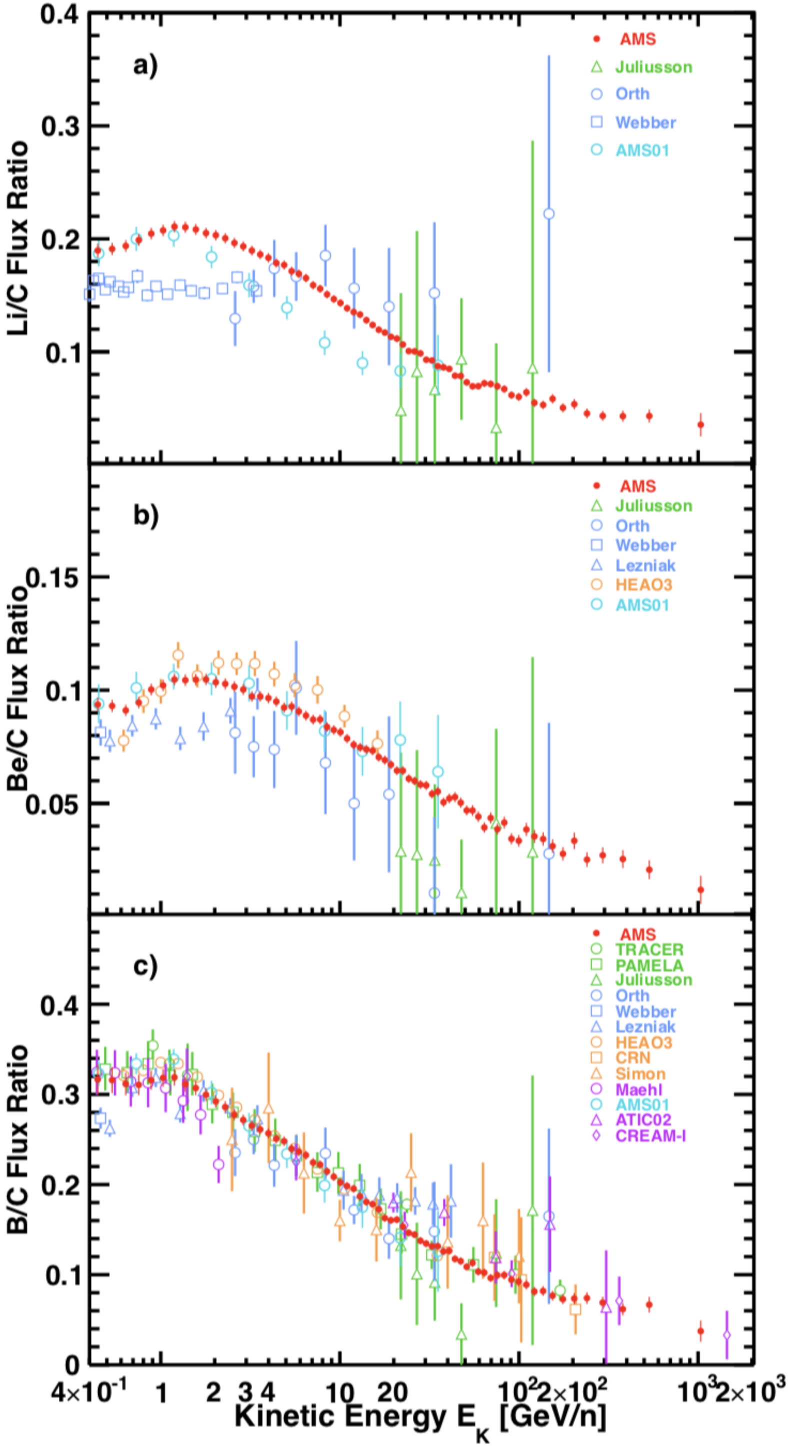
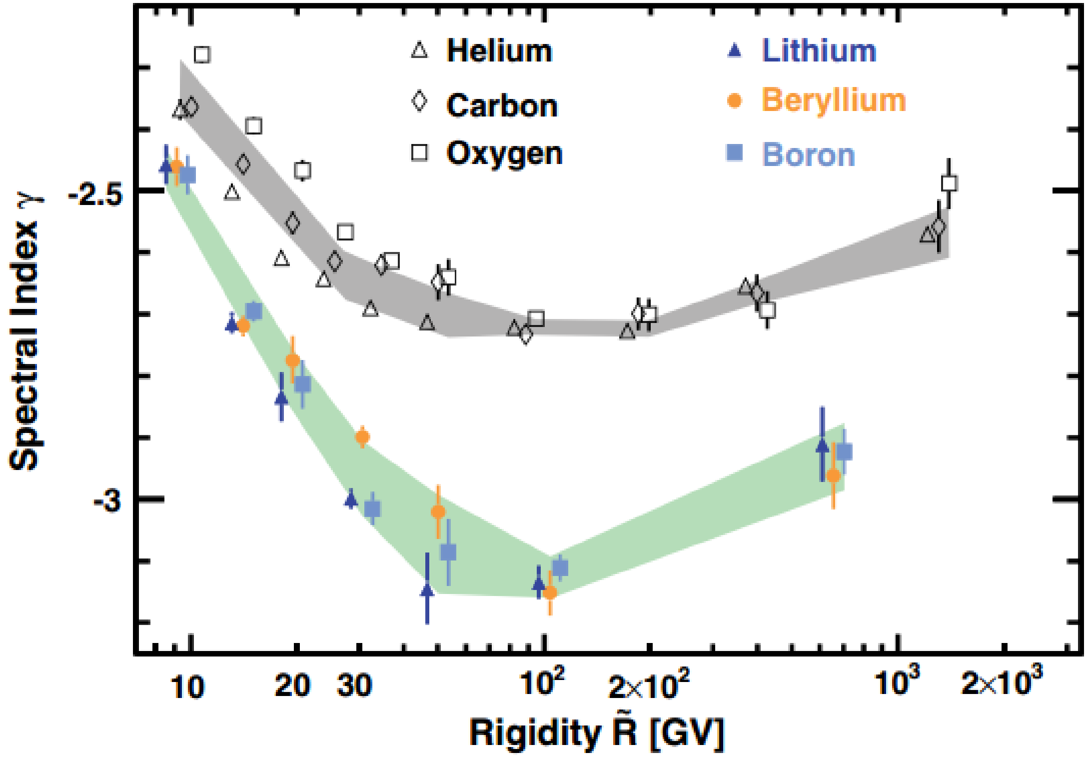
AMS results: spectral break in all nuclei!



→ Break seen in all data
(primary and seconday species)

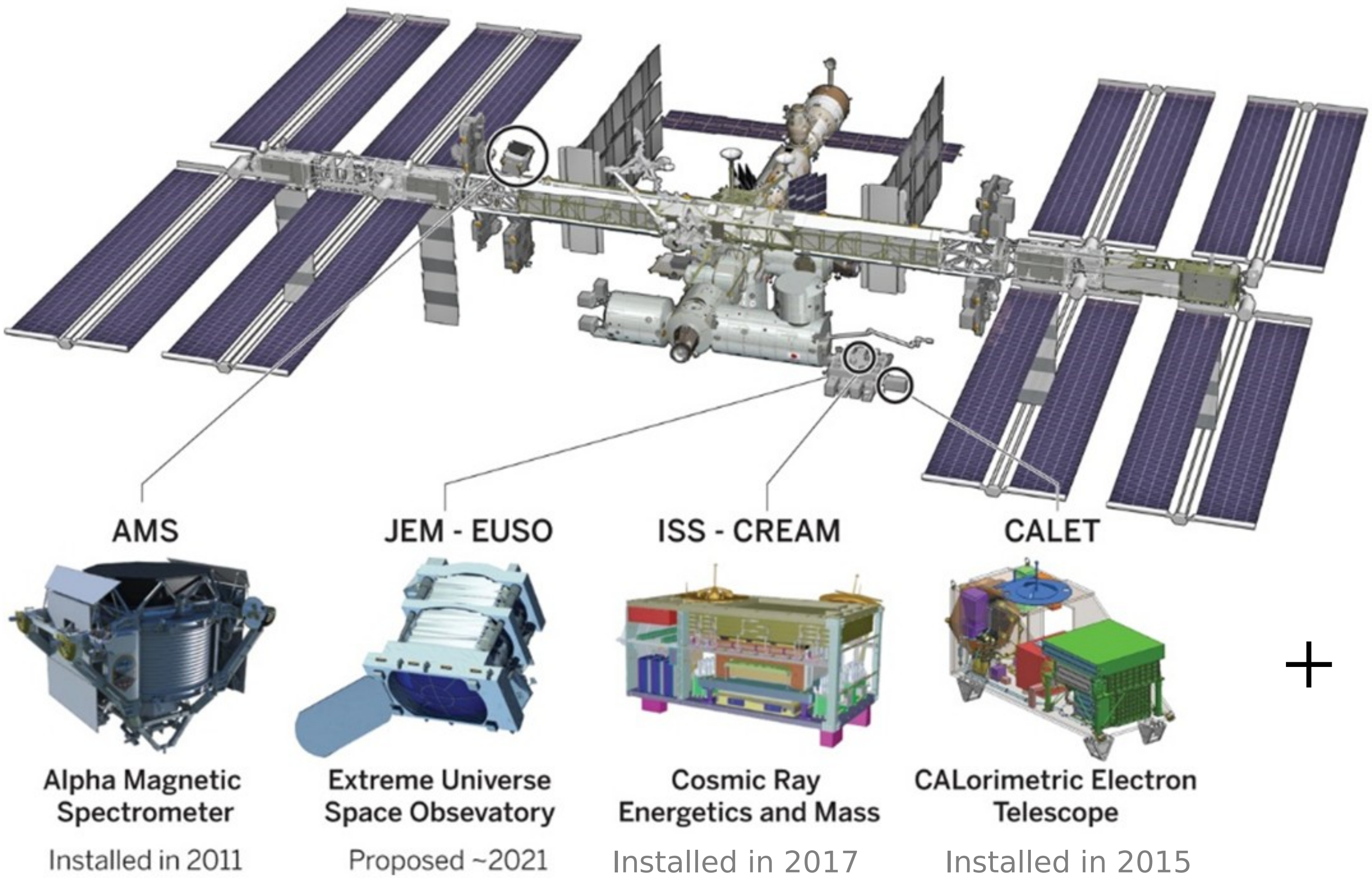
Aguilar *et al.*, PRL 120, 021101 (2018)



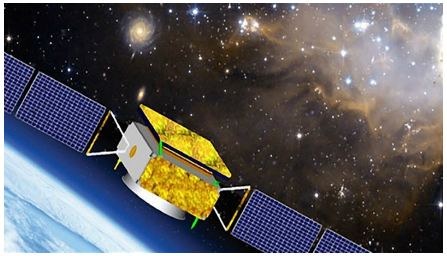
→ most likely transport (not source spectrum)
[coupling CR/B/gas via MHD]

Other experiments taking data

→ A bright present (and near future)
for high-energy cosmic-rays



+



DAMPE satellite

Launched in 2015

… but data interpretation limited by XS uncertainties!

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“*Nuclear physics for GCRs in the AMS-02 era*”
LPSC (2012)
https://indico.in2p3.fr/event/7012/

“*XSCRC2017: Cross sections for Cosmic Rays*”
CERN (2017)
https://indico.cern.ch/event/563277/

XS data: inelastic and production

$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right) + \vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\text{rad}} + \Gamma_{\text{inel}}\right)}^{\text{Catastrophic losses}} N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j \frac{\partial N^j}{\partial E}\right)}^{\text{E gains/losses}} = \overbrace{Q^j(E,\vec{r}) \quad + \sum_{m_i>m_j} \Gamma^{i\to j} N^i}^{\text{Source term: prim.+sec.}}$$

CR modelling requires

- Reaction cross-section (CR destruction)
- Production cross sections (secondary species)

on ISM
(~ 90% H, 10% He)

Various approaches
→ Microscopic
→ Semi-empirical
→ Parametric

XS data: illustration with B and C

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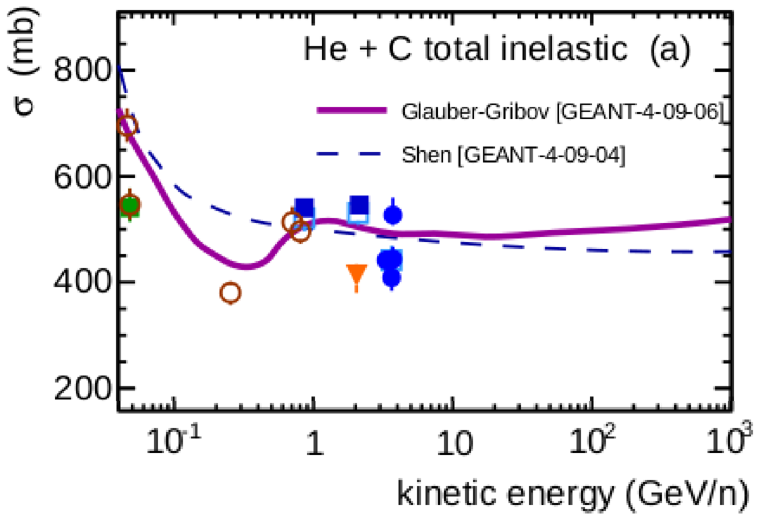
- Reaction cross-section (CR destruction)
- Production cross sections (secondary species)

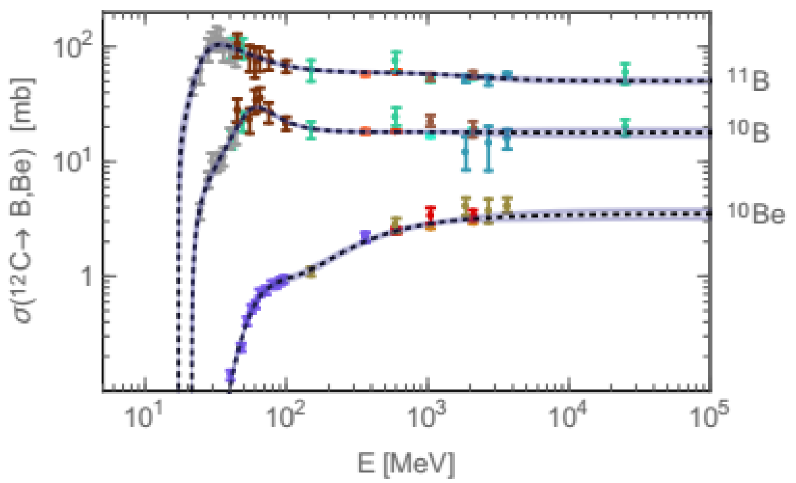
on ISM
(~ 90% H, 10% He)

Tomassetti, PRD 93, 3005 (2017)



Various approaches
→ Microscopic
→ Semi-empirical
→ Parametric

Reinert & Winkler, JCAP 01, 055 (2018)



→ No data above a few GeV/n

XS data: impact on GCRs

CR modelling requires

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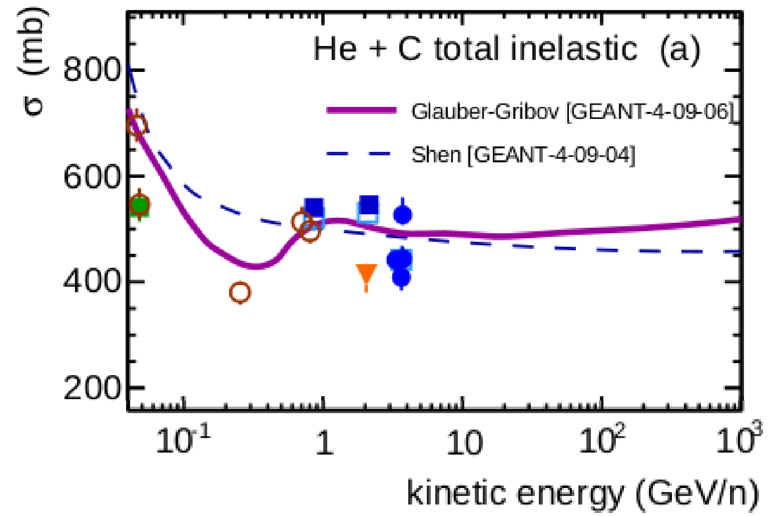

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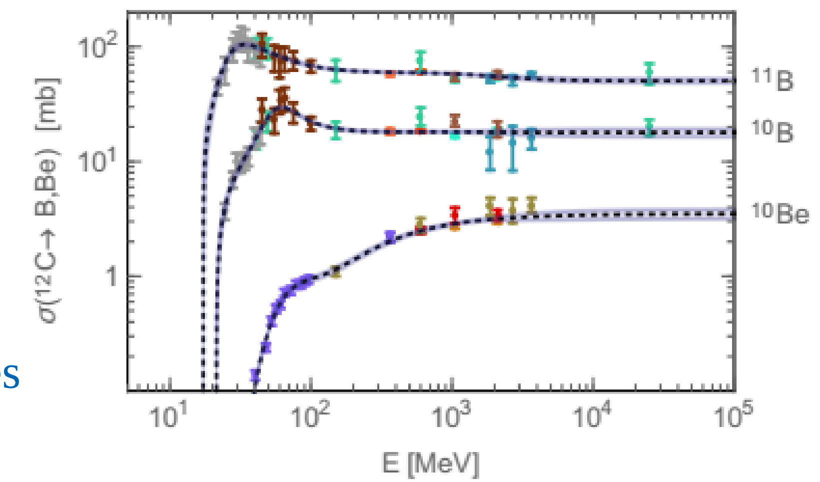
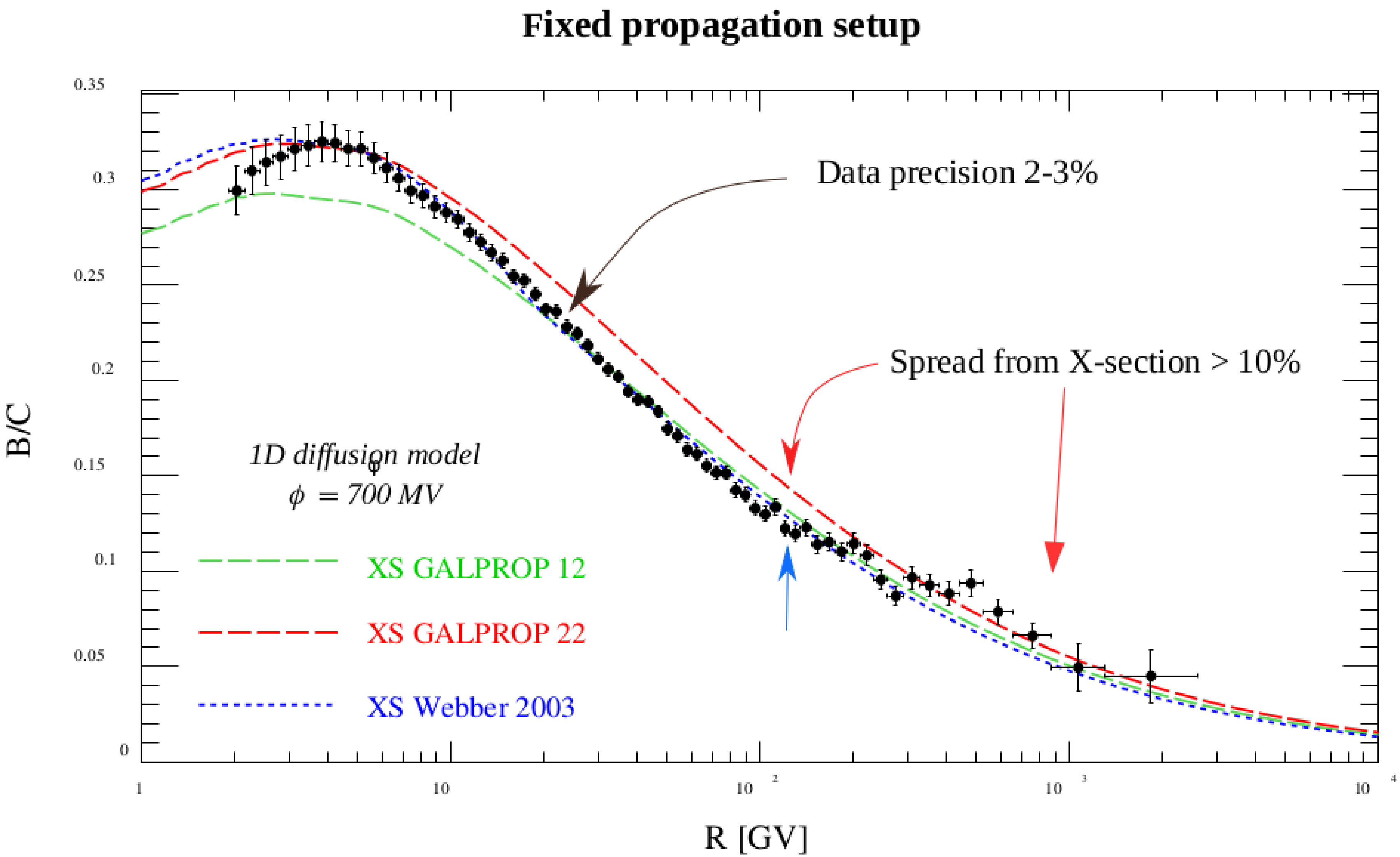


→ Systematics from XS dominate over data CR uncertainties
Maurin, Putze, and Derome, A&A 516, 67 (2010)

→ XS uncertainties ~ 10-15 %
→ AMS-02 uncertainties ~ 3%

→ No data above a few GeV/n

XS data: impact on GCRs



New XS data required!

→ Which reactions are the most important, how many matter?

→ How to have a proper error budget (from XS to fluxes)

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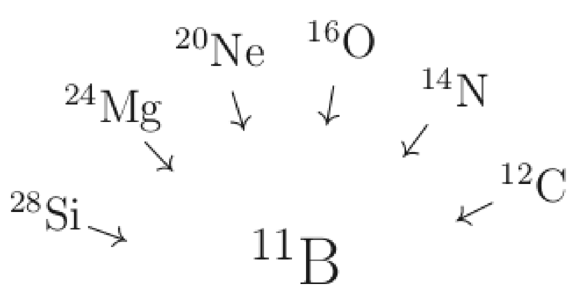
(as an *Editors' Suggestion*)

Reactions involved: 1-step reactions

Illustration with GCR Boron

$$\mathrm{B} = \underset{(\sim 30\%)}{{}^{10}\mathrm{B}} + \underset{(\sim 70\%)}{{}^{11}\mathrm{B}}$$

Reactions contributing to ^{11}B



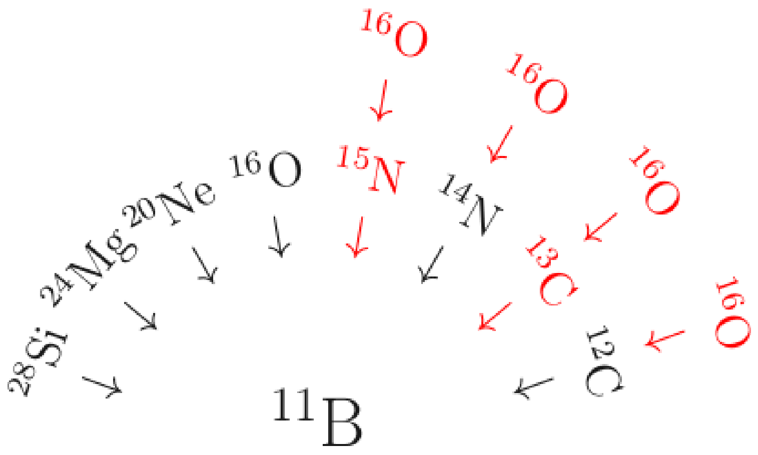
1-step channels

Reactions involved: 2-step reactions

Illustration with GCR Boron

$$B = \underset{(\sim30\%)}{{}^{10}B} + \underset{(\sim70\%)}{{}^{11}B}$$

Reactions contributing to ^{11}B



2-step channels

Reactions involved: short-lived nuclei

Reactions to consider

a (CRs) + b (H, He) $\rightarrow$ c (CRs + ghost nuclei)

Ghost nuclei to account for

- Exemple

$$\sigma^{\rm c}_{{\rm X}\to{}^{10}{\rm B}} = \sigma_{{\rm X}\to{}^{10}{\rm B}} + \sigma_{{\rm X}\to{}^{10}{\rm C}} \times \mathcal{B}r({}^{10}{\rm C} \to {}^{10}{\rm B})$$

- Relevant list for Li, Be, B fluxes

Nucleus	$T_{1/2}$	Daughter (decay mode)
^{6}He	806.92 ms	^{6}Li (β^-, 100%)
^{9}Li	178.3 ms	^{9}Be (β^-, 49.2%, ^{4}He ($\beta^- n$, 50.8%)
^{10}C	19.3009 s	^{10}B (β^+, 100%)
^{11}C	20.364 m	^{11}B (β^+, 100%)
^{12}B	20.20 ms	^{12}C (β^-, 98.4%), ^{4}He ($\beta^- 3\alpha$, 1.6%)
^{13}N	9.965 m	^{13}C (β^+, 100%)
^{13}O	8.58 ms	^{13}C (β^+, 89.1%), ^{12}C ($\beta^+ p$, 10.9%)
^{14}O	70.620 s	^{14}N (β^+, 100%)
^{15}O	122.24 s	^{15}N (β^+, 100%)

Flux impact: f_{abc} coefficients

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Calculate f_{abc}

$$f_{abc} = \frac{\psi^{\rm sec}(\rm ref) - \psi^{\rm sec}(\sigma^{a+b\to c} = 0)}{\psi^{\rm sec}(\rm ref)}$$

Flux impact: ranking XS

Reactions to consider

a (CRs) + b (H, He) $\rightarrow$ c (CRs + ghost nuclei)

Ghost nuclei to account for

- Exemple

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^{14}O	70.620 s	^{14}N (β^+, 100%)
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Calculate f_{abs}… et voilà!

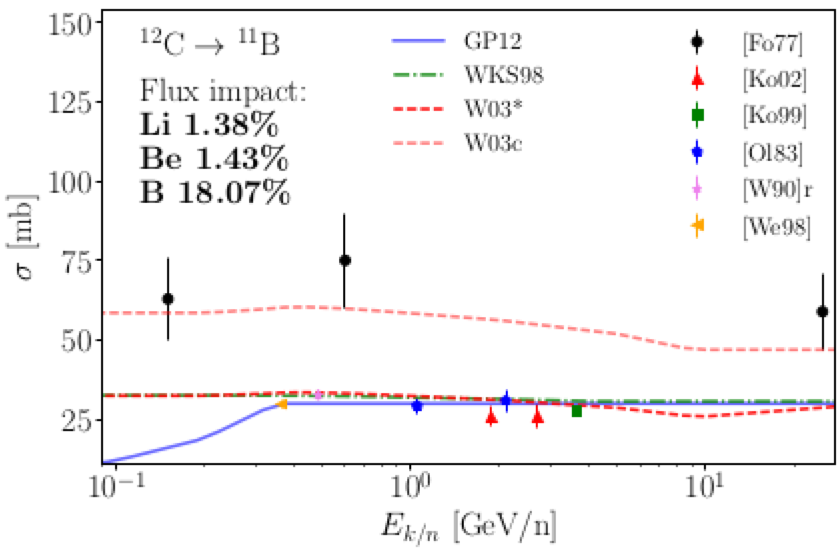
$$f_{abc} = \frac{\psi^{\rm sec}(\mathrm{ref}) - \psi^{\rm sec}(\sigma^{a+b\to c}=0)}{\psi^{\rm sec}(\mathrm{ref})}$$

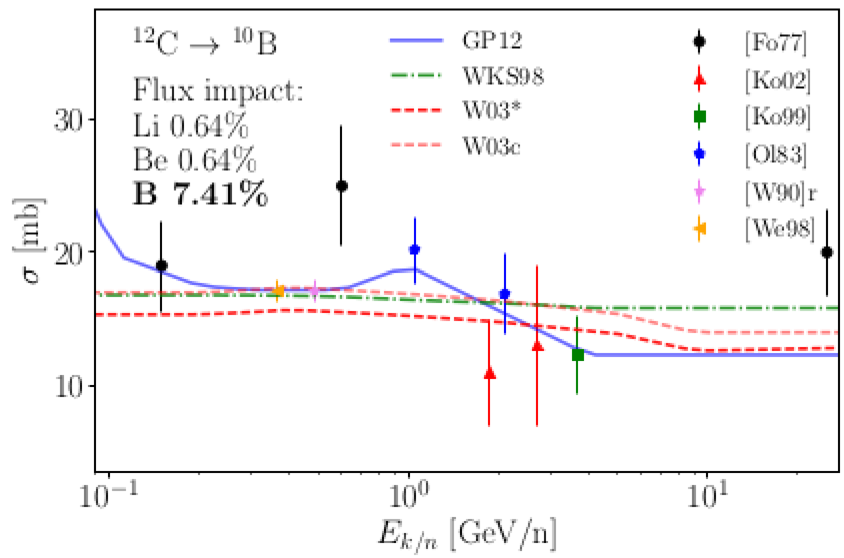
Reaction $a+b\to c$	Flux impact f_{abc} [%]			σ [mb]
	min	**mean**	max	range
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	18.0	**18.1**	19.0	30.0
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{C})}$	16.0	**16.2**	17.0	26.9
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{B})$	11.3	**11.8**	12.0	18.2
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	7.20	**7.41**	7.60	12.3
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{B})$	6.82	**7.03**	7.21	10.9
$\boldsymbol{\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{C})}$	5.67	**5.89**	6.00	9.1
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{B})$	4.00	**4.07**	4.20	38.9
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{B})$	2.50	**2.59**	2.70	38.6
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{C})}$	2.10	**2.14**	2.20	32.0
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	2.00	**2.03**	2.10	26.1
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{C})}$	1.80	**1.87**	1.90	3.1
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{B})$	1.67	**1.75**	1.80	24.4
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.50	**1.53**	1.60	22.2
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	1.40	**1.48**	1.50	4.0
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.30	**1.34**	1.36	17.3
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{B})$	1.00	**1.06**	1.10	15.8
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.99	**1.05**	1.09	14.6
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.98	**1.01**	1.00	10.4
$\boldsymbol{\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.90	**0.92**	0.94	11.9
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.87	**0.90**	0.93	12.0
$\boldsymbol{\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{C})}$	0.83	**0.88**	0.90	12.2
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.84	**0.87**	0.91	2.2
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.81	**0.83**	0.85	12.9
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.77	**0.79**	0.82	10.3
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.72	**0.74**	0.77	9.6
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.39	**0.63**	0.87	[4.0, 9.5]
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.59	**0.62**	0.65	9.0
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.58	**0.60**	0.62	6.2
$\sigma(^{11}\mathrm{B}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.57	**0.58**	0.59	50.0
$\boldsymbol{\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.54	**0.56**	0.59	8.2
$\boldsymbol{\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.52	**0.54**	0.56	7.2
$\boldsymbol{\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.51	**0.53**	0.56	[5.1, 5.9]
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.49	**0.51**	0.52	[6.4, 7.1]
$\boldsymbol{\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.42	**0.44**	0.46	[4.3, 5.0]
$\boldsymbol{\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{C})}$	0.40	**0.41**	0.43	5.3
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.27	**0.39**	0.52	[2.8, 5.7]
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.03	**0.35**	0.67	[0.4, 11.0]
$\sigma(^{15}\mathrm{N}+\mathrm{He}\to{}^{11}\mathrm{B})$	0.29	**0.29**	0.30	34.1
$\sigma(^{22}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.27	**0.28**	0.30	[16.0, 18.0]
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.24	**0.25**	0.26	5.9
$\boldsymbol{\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{C})}$	0.24	**0.25**	0.25	3.7
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.01	**0.24**	0.47	[0.2, 7.8]
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{Be})$	0.22	**0.23**	0.24	5.6

N.B.: ranking robust against transport/source parameters

Flux impact: ranking XS

This is what it looks like...





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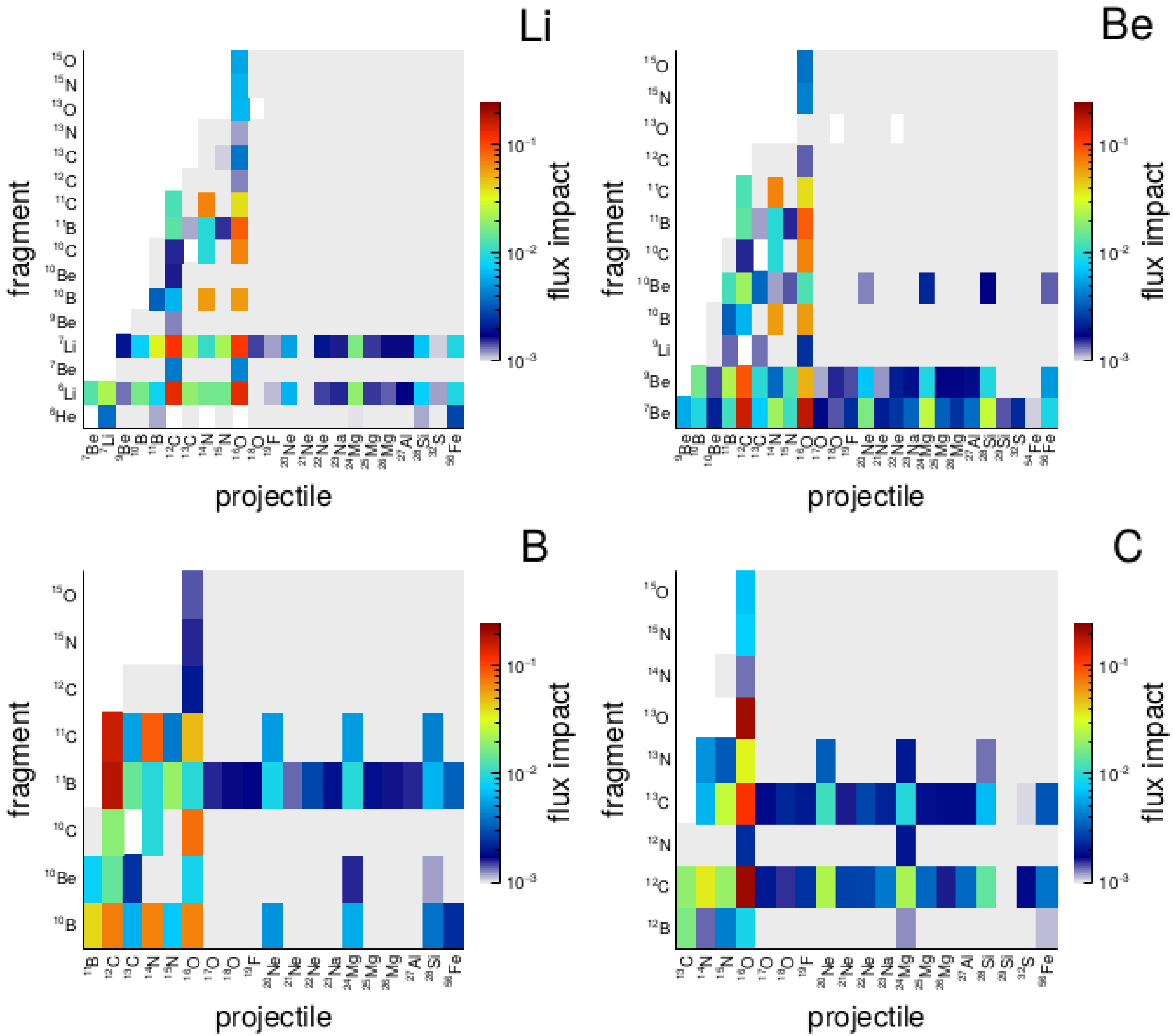
	min	**mean**	max	range		
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	18.0	**18.1**	19.0	30.0	✓	1.8
$\sigma(\mathbf{^{12}C+H\to{}^{11}C})$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{11}\mathrm{B})$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{B})$	6.82	**7.03**	7.21	10.9	✓	
$\sigma(\mathbf{^{16}O+H\to{}^{11}C})$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{B})$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{11}\mathrm{B})$	2.50	**2.59**	2.70	38.6		1.8
$\sigma(\mathbf{^{12}C+He\to{}^{11}C})$	2.10	**2.14**	2.20	32.0		**n/a**
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	2.00	**2.03**	2.10	26.1	✓	1.2
$\sigma(\mathbf{^{12}C+H\to{}^{10}C})$	1.80	**1.87**	1.90	3.1	✓	**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{11}\mathrm{B})$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{11}\mathrm{B})$	1.30	**1.34**	1.36	17.3	✓	1.7
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{B})$	1.00	**1.06**	1.10	15.8		1.1
$\sigma(^{16}\mathrm{O}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.98	**1.01**	1.00	10.4		1.6
$\sigma(\mathbf{^{14}N+H\to{}^{11}C})$	0.90	**0.92**	0.94	11.9		**n/a**
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.87	**0.90**	0.93	12.0		1.7
$\sigma(\mathbf{^{16}O+He\to{}^{11}C})$	0.83	**0.88**	0.90	12.2		**n/a**
$\sigma(^{16}\mathrm{O}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.84	**0.87**	0.91	2.2	✓	
$\sigma(^{11}\mathrm{B}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.81	**0.83**	0.85	12.9	✓	
$\sigma(^{14}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.77	**0.79**	0.82	10.3	✓	
$\sigma(^{15}\mathrm{N}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.72	**0.74**	0.77	9.6	✓	
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.39	**0.63**	0.87	[4.0, 9.5]		2.1
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.59	**0.62**	0.65	9.0		1.6
$\sigma(^{24}\mathrm{Mg}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.58	**0.60**	0.62	6.2		
$\sigma(^{11}\mathrm{B}+\mathrm{He}\to{}^{10}\mathrm{B})$	0.57	**0.58**	0.59	50.0		
$\sigma(\mathbf{^{13}C+H\to{}^{11}C})$	0.54	**0.56**	0.59	8.2		**n/a**
$\sigma(\mathbf{^{20}Ne+H\to{}^{11}C})$	0.52	**0.54**	0.56	7.2	✓	**n/a**
$\sigma(\mathbf{^{24}Mg+H\to{}^{11}C})$	0.51	**0.53**	0.56	[5.1, 5.9]		**n/a**
$\sigma(^{20}\mathrm{Ne}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.49	**0.51**	0.52	[6.4, 7.1]		
$\sigma(\mathbf{^{28}Si+H\to{}^{11}C})$	0.42	**0.44**	0.46	[4.3, 5.0]		**n/a**
$\sigma(\mathbf{^{15}N+H\to{}^{11}C})$	0.40	**0.41**	0.43	5.3	✓	**n/a**
$\sigma(^{28}\mathrm{Si}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.27	**0.39**	0.52	[2.8, 5.7]		
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.03	**0.35**	0.67	[0.4, 11.0]		3.3
$\sigma(^{15}\mathrm{N}+\mathrm{He}\to{}^{11}\mathrm{B})$	0.29	**0.29**	0.30	34.1		1.2
$\sigma(^{22}\mathrm{Ne}+\mathrm{H}\to{}^{11}\mathrm{B})$	0.27	**0.28**	0.30	[16.0, 18.0]	✓	1.2
$\sigma(^{13}\mathrm{C}+\mathrm{H}\to{}^{10}\mathrm{Be})$	0.24	**0.25**	0.26	5.9	✓	
$\sigma(\mathbf{^{12}C+He\to{}^{10}C})$	0.24	**0.25**	0.25	3.7		**n/a**
$\sigma(^{56}\mathrm{Fe}+\mathrm{H}\to{}^{10}\mathrm{B})$	0.01	**0.24**	0.47	[0.2, 7.8]		1.1
$\sigma(^{12}\mathrm{C}+\mathrm{He}\to{}^{10}\mathrm{Be})$	0.22	**0.23**	0.24	5.6		

N.B.: ranking robust against transport/source parameters

Flux impact: repeated for Li to N



XS improvement → flux prediction improvement

Correlated uncertainties?

→ measurements from same experimental setup
→ parametrizations induce systematics

Uncorrelated uncertainties?

→ data from different experimental setups

Looking at the data/parameterizations

- correlated for all fragments of a given projectile
- Uncorrelated between different projectile

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm corr} \approx f^{\rm sec} \sum_{a,b,c} f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}$$

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm uncorr} \approx f^{\rm sec} \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm mix} \approx f^{\rm sec} \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2},$$

XS improvement → flux prediction improvement

Correlated uncertainties?
→ measurements from same experimental setup
→ parametrizations induce systematics

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm corr} \approx f^{\rm sec} \sum_{a,b,c} f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}$$

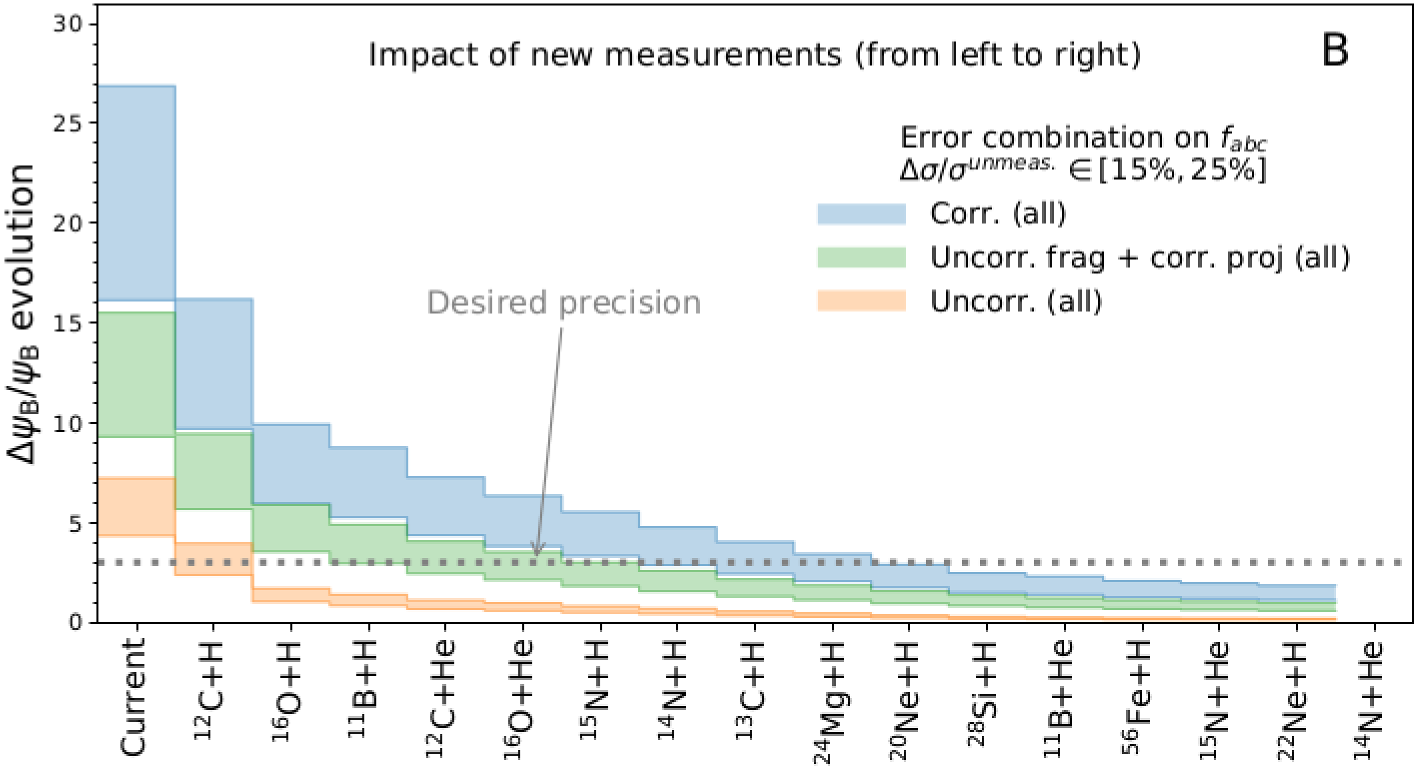
Uncorrelated uncertainties?
→ data from different experimental setups

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm uncorr} \approx f^{\rm sec} \sqrt{\sum_{a,b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

Looking at the data/parameterizations
- correlated for all fragments of a given projectile
- Uncorrelated between different projectile

$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm mix} \approx f^{\rm sec} \sum_{a} \sqrt{\sum_{b,c} \left(f_{abc} \frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2},$$

(projectile + target) to measure with high priority



→ Ordering insensitive on error assumption

→ Calculated for Li, Be, B, N, and C

1. GCR: brief introduction
2. XS uncertainties $\gg$ GCR data uncertainties
3. Which reactions matter? Ranking for GCRs
4. Conclusions

XS improvement → flux prediction improvement

Wealth of high precision GCR data
but
interpretation limited by insufficient quality of XS data/models

→ **Need support** for nuclear physics and high energy physics communities

- ~few % accuracy required on key channels (100 MeV/n to multi-GeV/n)
- improve models if possible...

In **Génolini et al.** (1803.04686), we provide:

- Motivation for XS community to propose new experiments
- Key reactions for which we need better data (for Li to N GCR fluxes)
- C_{ab} coeff. to calculate # of interactions required (to plan an experiment)
- XS data and models (in hundreds of plots) and references

→ the **GCR community**, as a whole, would be extremely grateful for your help!

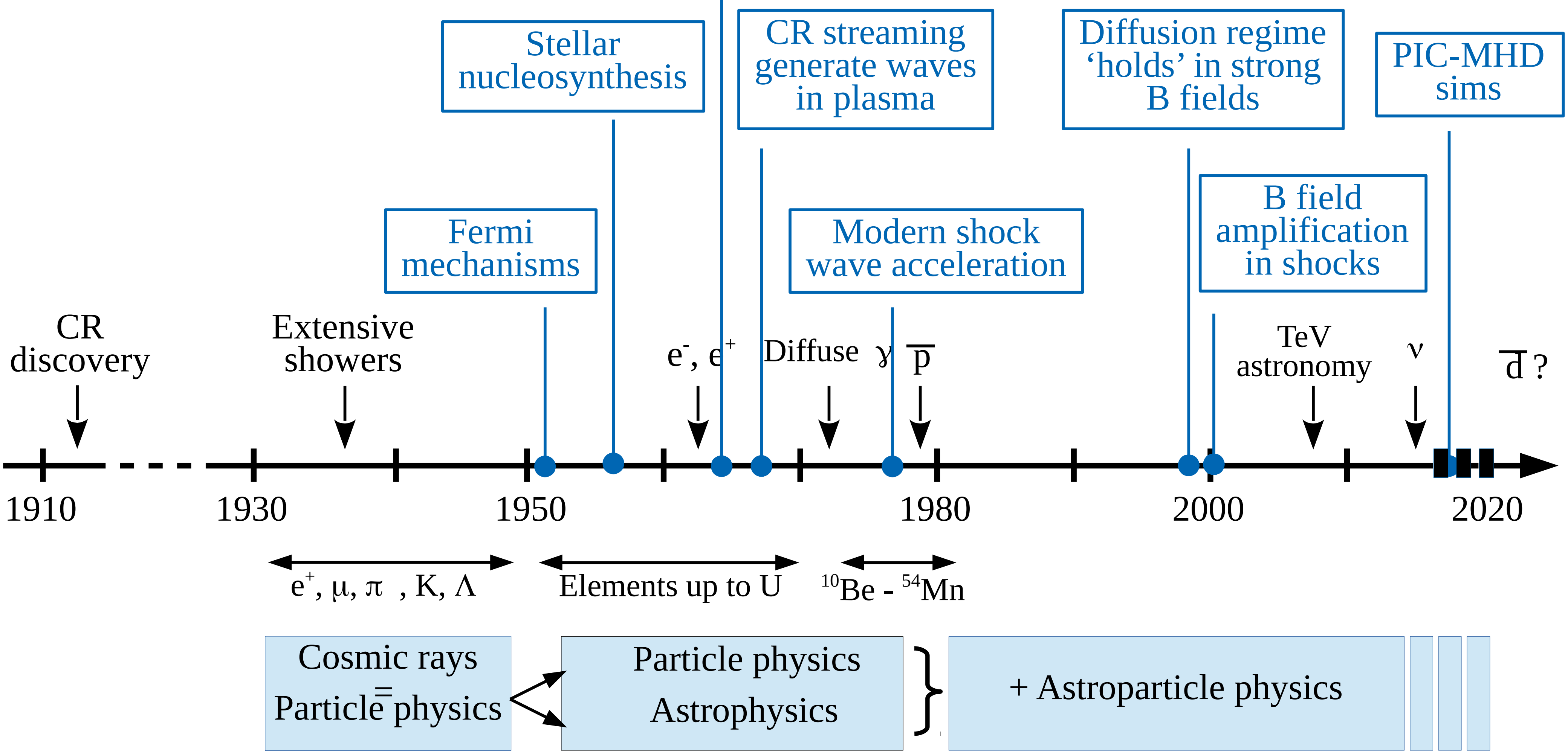
- NA61/SHINE proposal SPSC-P-330 at 10 GeV/n (M. Unger)
- Other candidates?

Public ressources for GCRs

USINE propagation code	*Cosmic-ray data base (CRDB)*
https://arxiv.org/abs/1807.02968	A&A 569, A32 (2014)
https://lpsc.in2p3.fr/usine	https://lpsc.in2p3.fr/crdb

Theoretical milestones

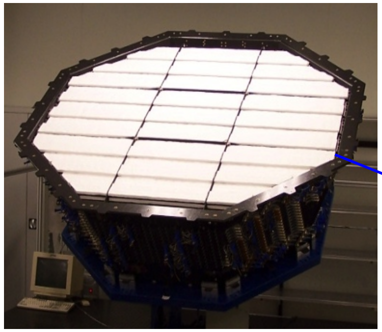
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Transport (diff+conv)}} N^j + \overbrace{(\Gamma_{\rm rad}+\Gamma_{\rm inel})}^{\text{catastrophic losses}}\; N^j + \overbrace{\frac{\partial}{\partial E}\left(b^j N^j - c^j\frac{\partial N^j}{\partial E}\right)}^{\text{E gain/losses}} = \overbrace{Q^j(E,\vec{r}) + \sum_{m_i>m_j}\Gamma^{i\to j}N^i}^{\text{Sources (prim+sec)}}$$



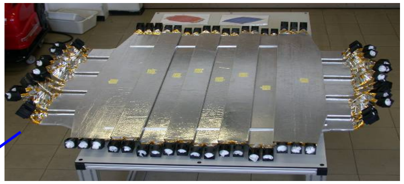
A(lpha) M(agnetic) S(pectrometer)

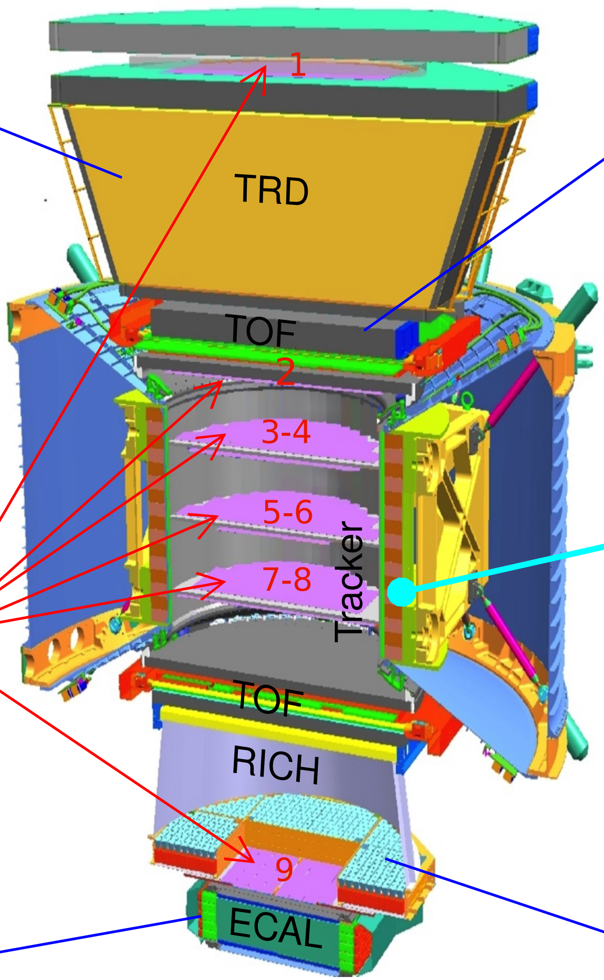
A TeV precision, multipurpose spectrometer in space.

TRD
Identify e^+, e^-

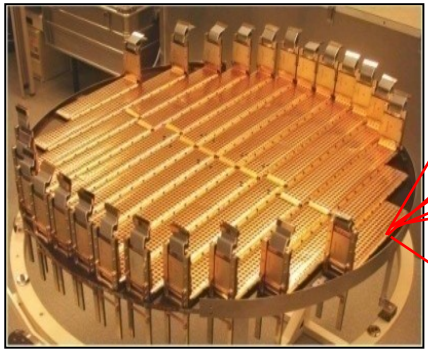


TOF
Z, β





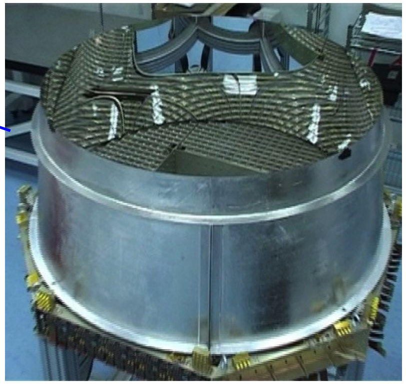
Silicon Tracker
Z, p



Magnet
R, $\pm Z$

ECAL
Identify e^+,e^-
E of e^+, e^-, γ

RICH
Z, β



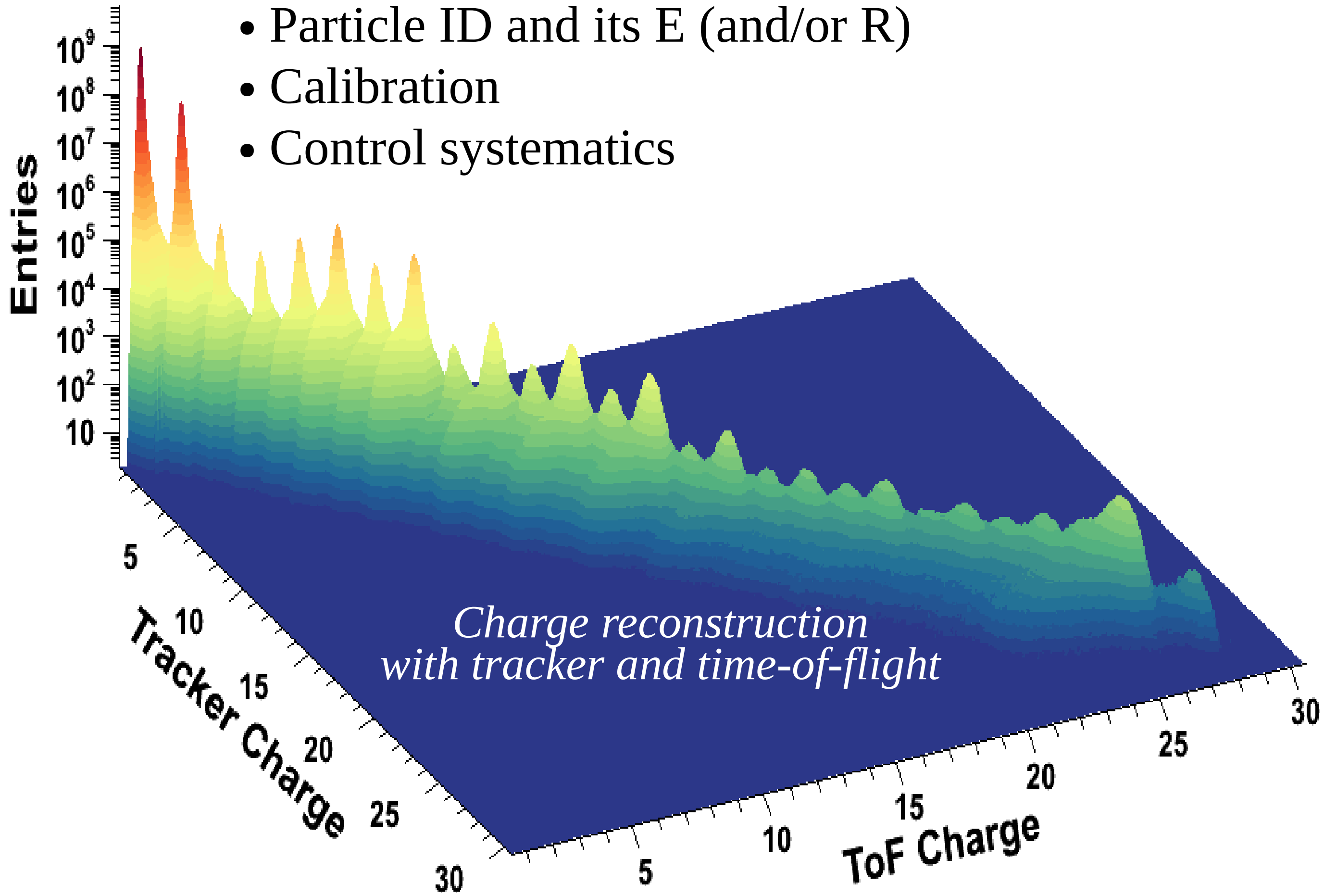
5m x 4m x 3m

7.5 tons

A(lpha) M(agnetic) S(pectrometer)

Sub-detector redundancy

- Particle ID and its E (and/or R)
- Calibration
- Control systematics



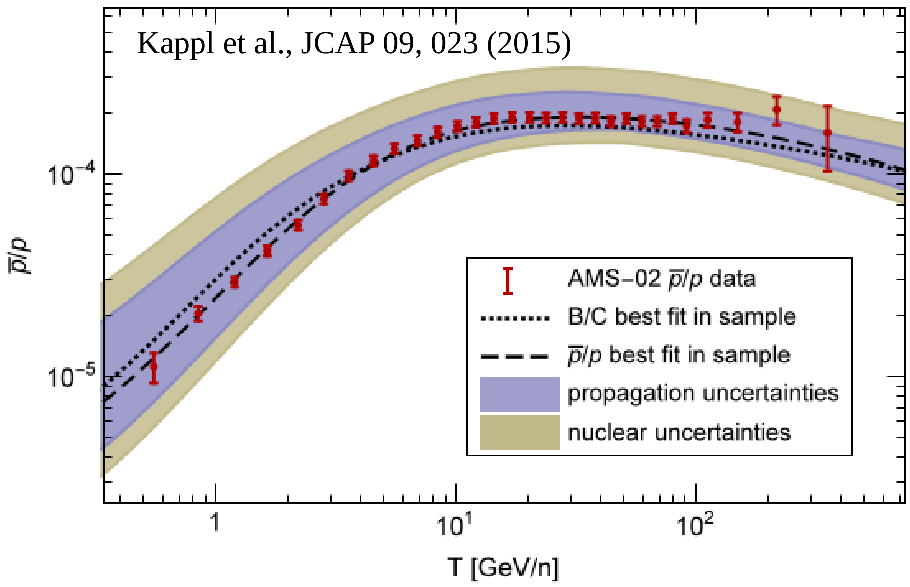
Each analysis specific (flux/ratio, leptons/nuclei)

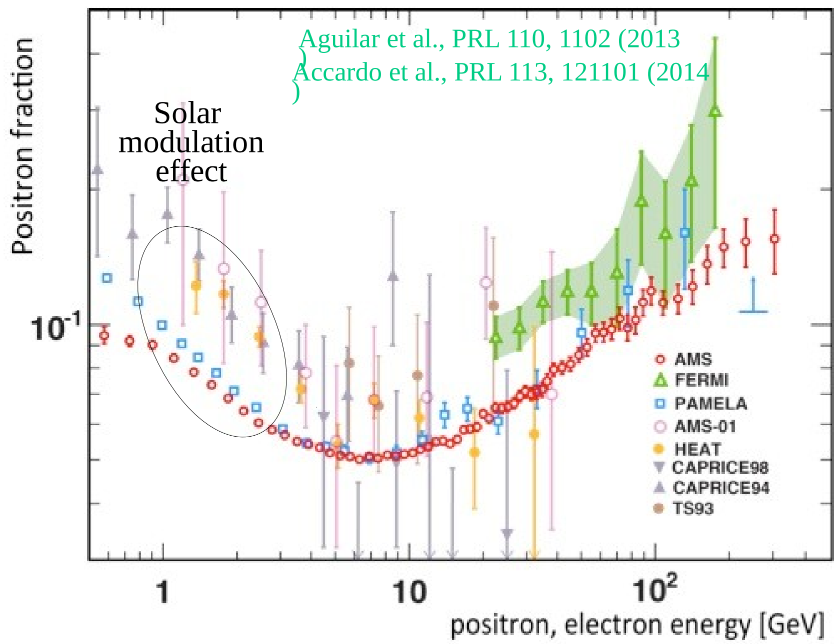
- ID and E (or R) measurement
- Background from other particles
- Background from interaction in detector

+ rely on

- Beam test
- In-flight data
- Monte Carlo sims

Dark matter detection with AMS-02?





Antiprotons

→ Seems consistent with astrophysics only

Positron fraction, e^-, e^+ and e^-+e^+ spectra used to test astrophysical and/or dark matter hypothesis

- Contribution from local SNRs/pulsars?
  → e.g., Delahaye et al., A&A 524, A51 (2010)
- Dark matter hypothesis?
  → e.g., Boudaud et al., A&A 575, 67 (2015)
  [N.B.: no boost, Lavalle et al., A&A 479, 427 (2008)]

N.B.: see also e- and e+ in Aguilar et al., PRL 113, 121102 (2014)

‘Origin’ of Li to N fluxes

Contributions (relative and absolute) at 10 GeV/n

CR	% isotope		% of total flux: prim.	frag.	rad.	% of multi-step secondaries: 1	2	>2
Li			0	100	0	66	25	9
	(56%)	^{6}Li	0	100	0	66	25	9
	(44%)	^{7}Li	0	100	0	66	26	8
Be			0	100	0	73	20	7
	(63%)	^{7}Be	0	100	0	78	17	6
	(30%)	^{9}Be	0	100	0	65	26	9
	(6%)	^{10}Be	0	100	0	66	26	7
B			0	95	5	79	17	5
	(33%)	^{10}B	0	85	15	70	24	6
	(67%)	^{11}B	0	100	0	82	14	4
C			79	21	0	77	17	5
	(90%)	^{12}C	88	12	0	72	21	6
	(10%)	^{13}C	7	93	0	83	13	4
	(0.02%)	^{14}C	0	100	0	56	35	9
N			27	72	2	87	9	4
	(54%)	^{14}N	49	48	3	83	13	4
	(46%)	^{15}N	0	100	0	89	7	3

→ Which reactions are the most important, how many matter?

→ How to have a proper error budget (from XS to fluxes)

Ranking of channels (sum over all targets + ghosts)

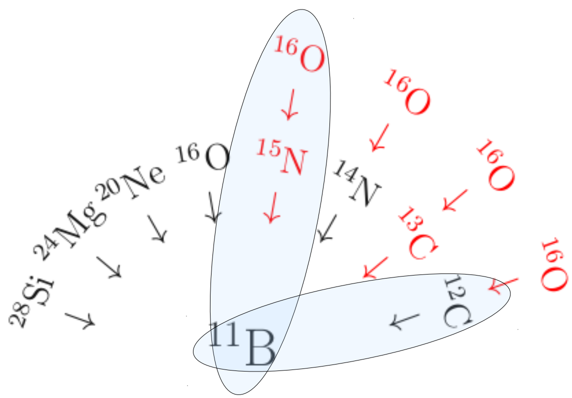
→ **Many channels contribute!**

1-step and 2-step only (>2 steps~5%)

# of channels	in range	contribution [%]
13	[1%,100%]	82.2
25	[0.1%,1%]	7.7
110	[0.01%,0.1%]	3.8
346	[0.001%,0.01%]	1.3
526	[0.0001%,0.001%]	0.2
2340	[0.0%,0.0001%]	0.0

Channel	min	**mean**	max
$^{12}C \to {}^{11}B$	30.8	**32.7**	35.3
$^{16}O \to {}^{11}B$	16.2	**17.7**	18.8
$^{12}C \to {}^{10}B$	9.04	**9.95**	10.9
$^{16}O \to {}^{10}B$	7.64	**8.17**	8.68
$^{12}C \to {}^{11}B \to {}^{10}B$	2.07	**2.16**	2.26
$^{16}O \to {}^{12}C \to {}^{11}B$	1.60	**1.96**	2.34
$^{16}O \to {}^{15}N \to {}^{11}B$	1.29	**1.69**	2.04
$^{24}Mg \to {}^{11}B$	1.51	**1.59**	1.69
$^{20}Ne \to {}^{11}B$	1.26	**1.32**	1.39
$^{14}N \to {}^{11}B$	1.00	**1.32**	1.66
$^{28}Si \to {}^{11}B$	0.85	**1.29**	1.66
$^{16}O \to {}^{11}B \to {}^{10}B$	1.03	**1.17**	1.26
$^{16}O \to {}^{13}C \to {}^{11}B$	0.54	**1.15**	1.62
$^{16}O \to {}^{14}N \to {}^{11}B$	0.68	**0.83**	0.92
$^{24}Mg \to {}^{10}B$	0.66	**0.75**	0.84
$^{16}O \to {}^{12}C \to {}^{10}B$	0.51	**0.59**	0.69
$^{16}O \to {}^{15}N \to {}^{10}B$	0.50	**0.59**	0.68
$^{20}Ne \to {}^{10}B$	0.47	**0.54**	0.63
$^{28}Si \to {}^{10}B$	0.32	**0.53**	0.67
$^{14}N \to {}^{10}B$	0.39	**0.50**	0.65
$^{56}Fe \to {}^{11}B$	0.11	**0.49**	1.10
$^{16}O \to {}^{13}C \to {}^{10}B$	0.12	**0.32**	0.50
$^{16}O \to {}^{14}N \to {}^{10}B$	0.26	**0.31**	0.36
$^{24}Mg \to {}^{12}C \to {}^{11}B$	0.21	**0.22**	0.25
$^{56}Fe \to {}^{10}B$	0.00	**0.21**	0.71
$^{20}Ne \to {}^{12}C \to {}^{11}B$	0.19	**0.20**	0.22
$^{14}N \to {}^{12}C \to {}^{11}B$	0.14	**0.20**	0.25
$^{13}C \to {}^{11}B$	0.15	**0.18**	0.24
$^{28}Si \to {}^{12}C \to {}^{11}B$	0.10	**0.18**	0.21
$^{25}Mg \to {}^{11}B$	0.14	**0.17**	0.19

→ **Known result:**
dominant channels ~ most abundant CRs
[secondaries ∝ Source abund * σ]



Element	C	N	O	Ne	Na	Mg	Al	Si	S	Ca	Fe
Abund.	986	219	1000	152	26	197	31	163	30	18	110

HEAO-3 abundances at ~10 GeV/n

Few reactions to measure to get Li, Be, and B

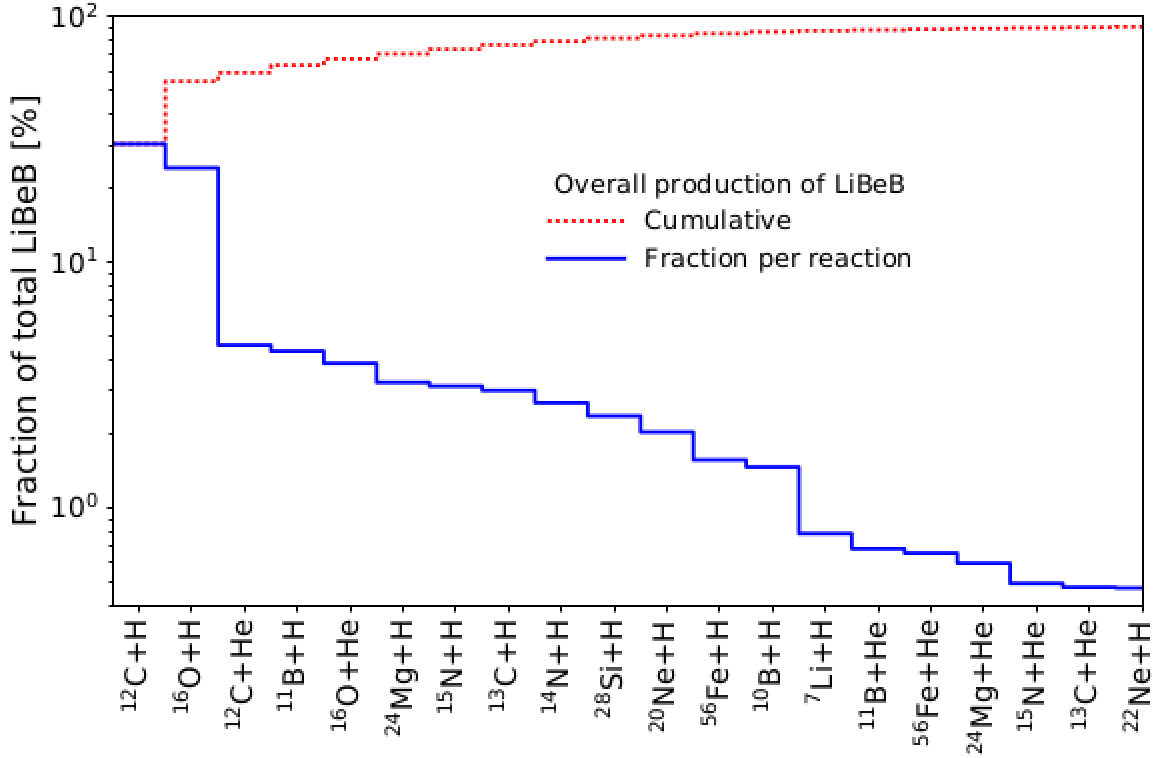


FIG. 2. Contributive and cumulative fractions of reactions for the overall production of secondary LiBeB in GCRs at 10 GeV/nucleon. The labels on the abscissa give the projectile+target combination considered.

Planning an experiment: Cab and # of interactions

N = number of interactions (poissonian distribution)
V = covariance of the measured number of fragments

$$p_c = \frac{\sigma^{abc}}{\sigma_{ab}}, \qquad n_i = p_i N,$$

$$V_{ij}^n \equiv V(n_{c_i}, n_{c_j}) = \begin{cases} N\, p_i(1-p_i), & i = j \\ -N\, p_i p_j, & i \neq j. \end{cases}$$

$$\mathcal{C}_{ab} \equiv \left[\left(\sum_{i=1}^{m} f_{abc_i} \right)^2 + \sum_{i=1}^{m} f_{abc_i}^2 \left(\frac{\sigma^{ab}}{\sigma^{abc_i}} - 1 \right) - 2 \sum_{i=1}^{m} \sum_{j=i+1}^{m} f_{abc_i} f_{abc_j} \right]^{\frac{1}{2}},$$

$$\left(\frac{\Delta\psi^{\mathrm{sec}}}{\psi^{\mathrm{sec}}} \right)_{ab} = \frac{1}{\sqrt{N}}\, \mathcal{C}_{ab}.$$

B

$(\sum C_{ab} = 3.96)$

Reaction $(a+b)$	C_{ab}
^{12}C + H	0.808
^{16}O + H	0.656
^{16}O + He	0.609
^{14}N + H	0.574
^{14}N + He	0.202
^{12}C + He	0.148
^{11}B + H	0.108
^{24}Mg + H	0.094
^{15}N + H	0.088
^{28}Si + H	0.080
^{13}C + H	0.074
^{20}Ne + H	0.073
^{56}Fe + H	0.058