Recent developments and results obtained with the USINE code

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CRISM, Grenoble
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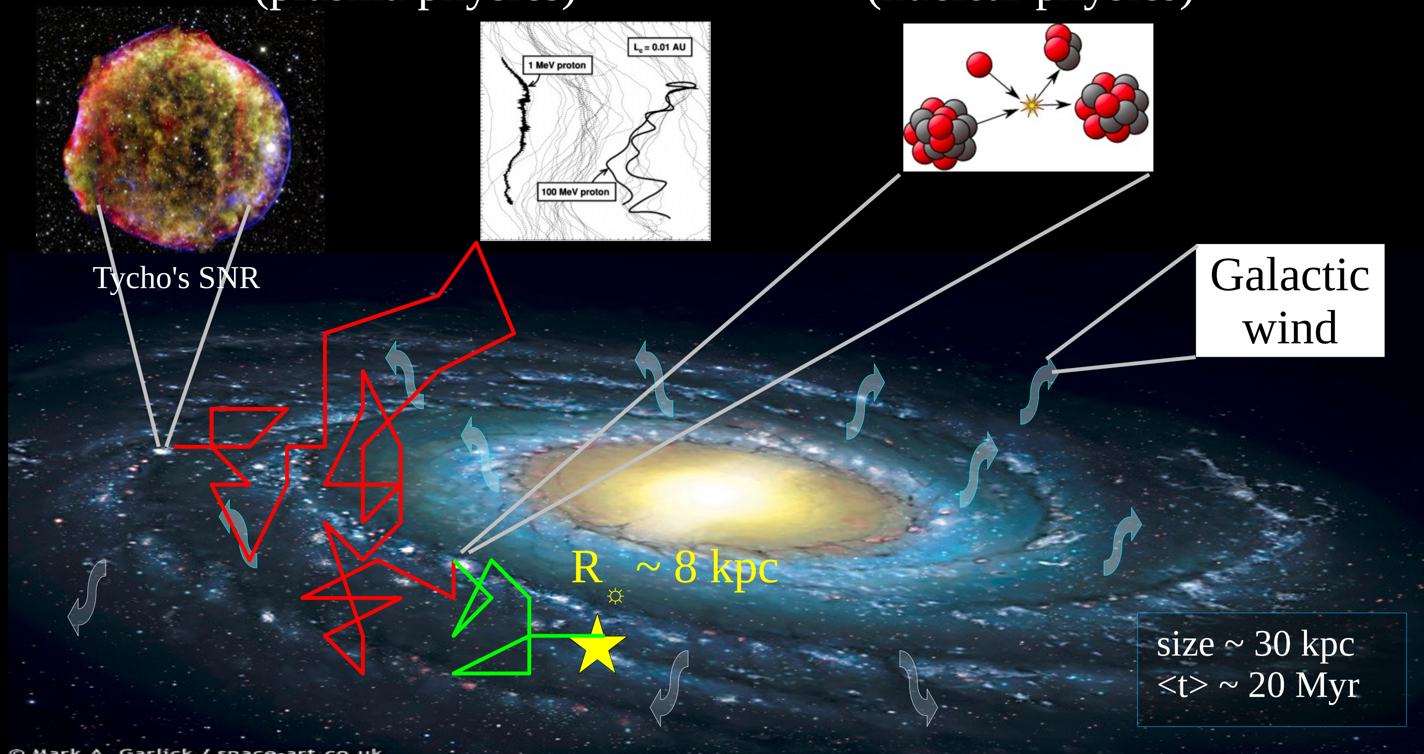
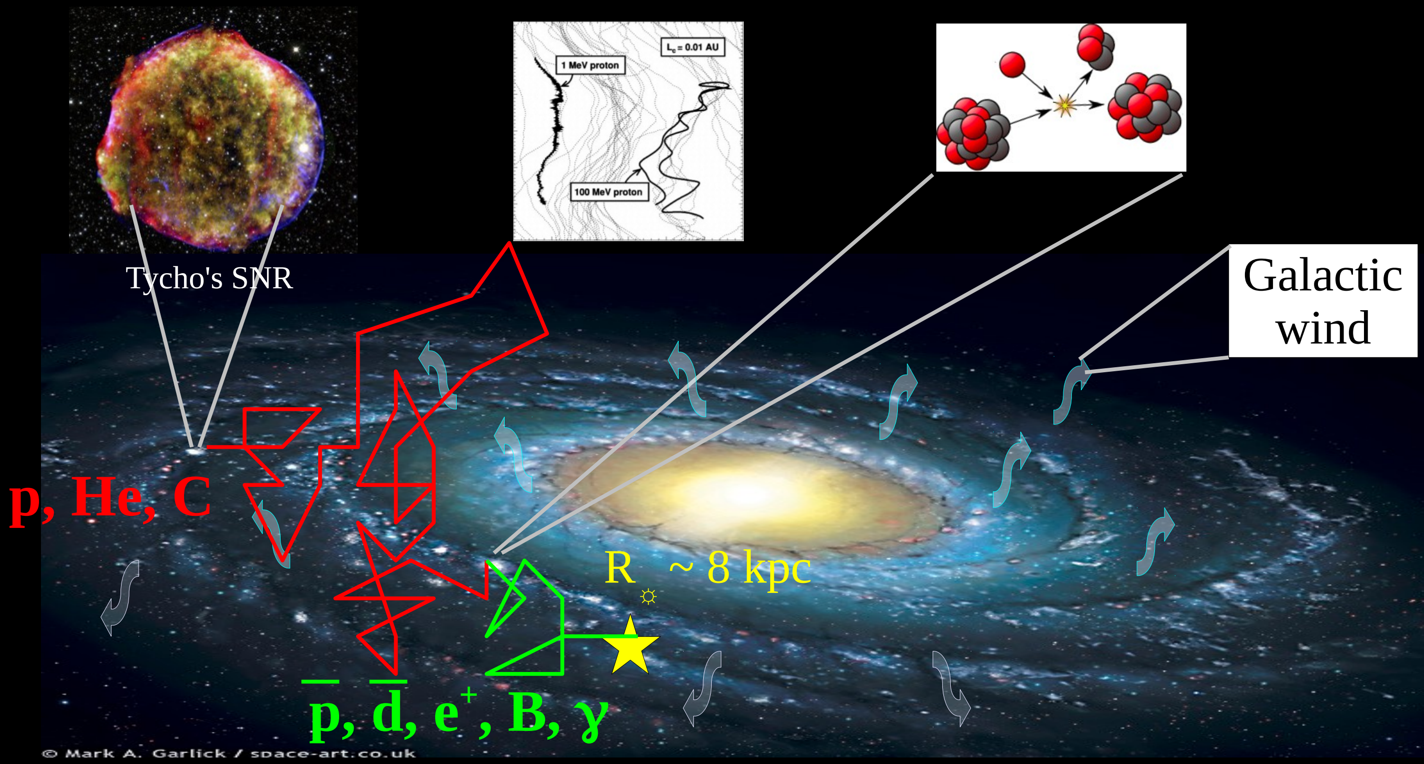
1. Introduction: GCR journey

(plasma physics) (nuclear physics)

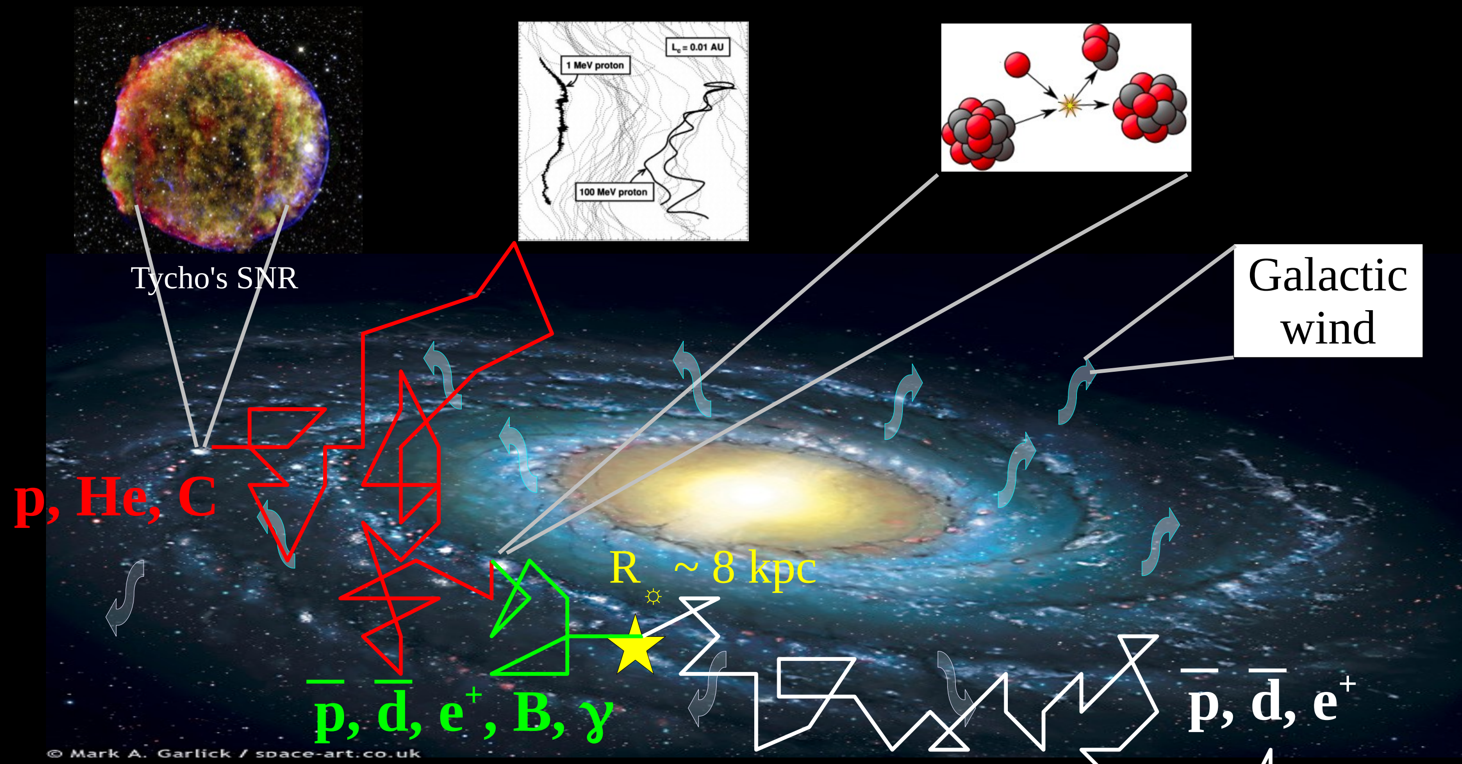


(astrophysics + particle physics)

1. Introduction: dark matter indirect detection



1. Introduction: dark matter indirect detection



→ Same transport but different origin
(from DM halo)

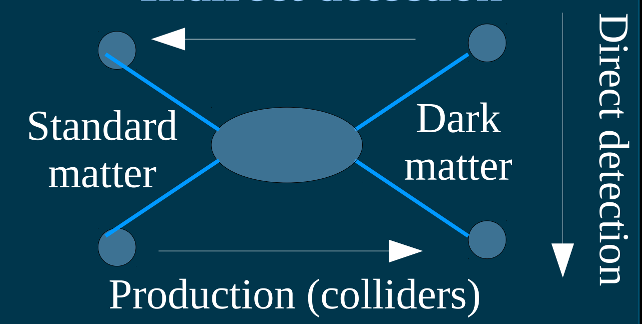
Universe (after Planck)
- 68.3 % dark energy
- 26.8 % dark matter
- 4.9 % ordinary matter

→

Milky-Way dark matter halo
- ~ spherical halo
- radius ~300 kpc

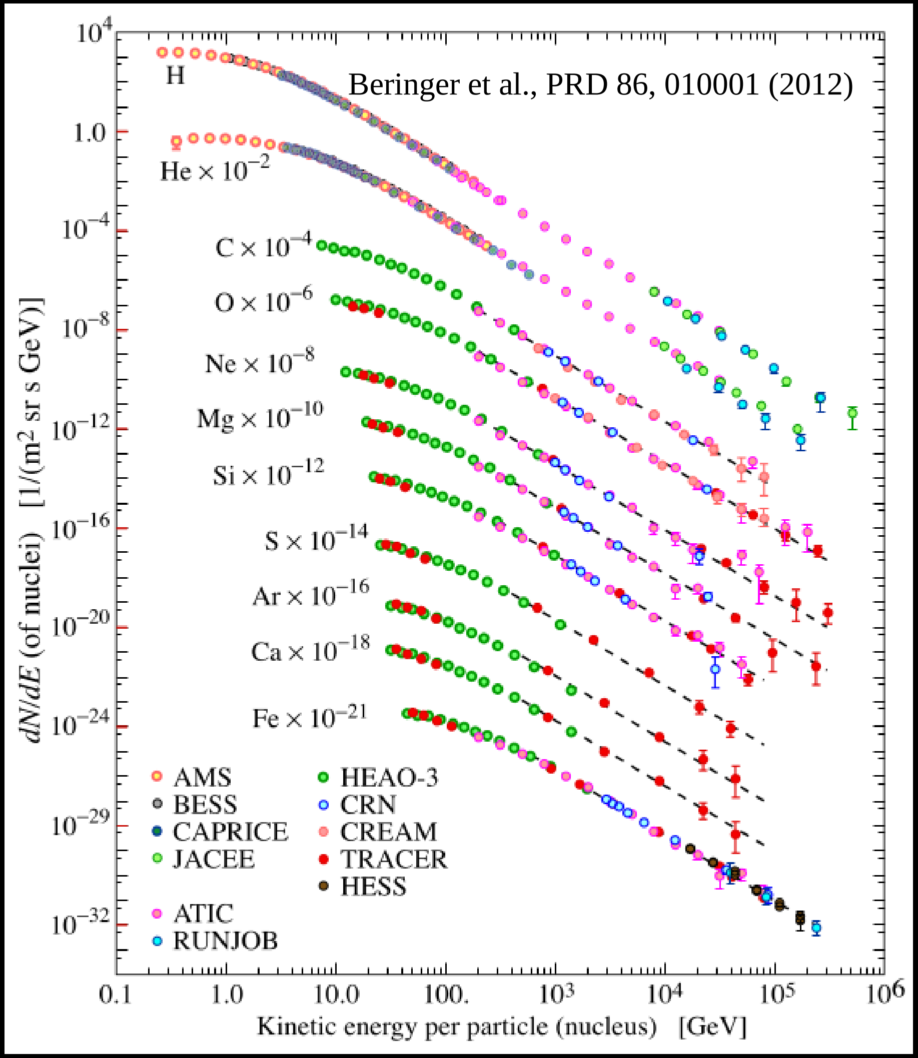
→

Indirect detection



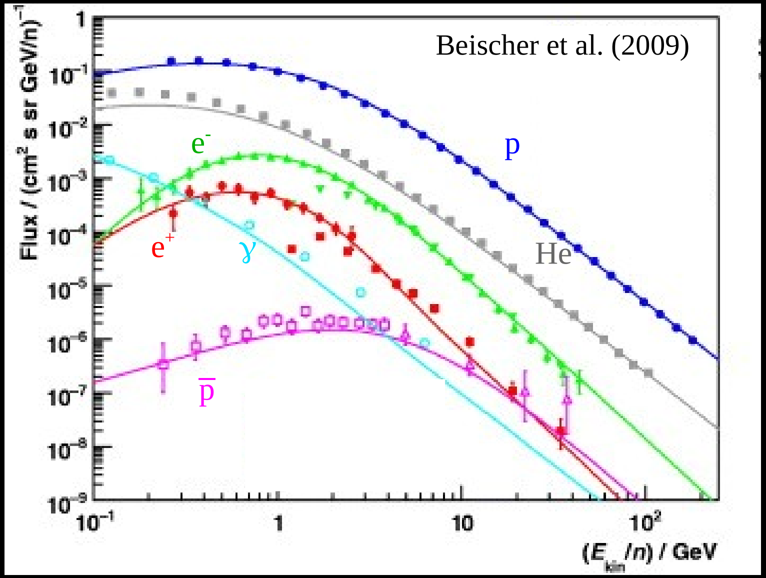
1. Introduction: GCR data (~10^{8}-10^{15} eV)

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?

2. Transport equations: techniques and codes

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

	Weighted-slab/LB
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$
Tools	• 1D numerical integr.
Pros	• Simple
cons	• Leakage approx. fails (leptons and decay)
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)

0D

2. Transport equations: techniques and codes

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

	Weighted-slab/LB	*(Semi-)analytical*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)
cons	• Leakage approx. fails (leptons and decay)	• "Effective" models • New eq. per model
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)

↓ 0D ↓ 1D, 2D

2. Transport equations: techniques and codes

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

	Weighted-slab/LB	*(Semi-)analytical*	*Finite difference scheme*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry	Discretize equation: • Numerical scheme (e.g., Crank-Nicholson) → Matrix inversion
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations	• Num. recipes/solvers (NAG, GSL libraries)
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)	• Simple algebra • Universal (any model)
cons	• Leakage approx. fails (leptons and decay)	• “Effective” models • New eq. per model	• Slower / instabilities • RAM for high.res.
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong *et al.*, 1998) DRAGON (Evoli *et al.*, 2008) PICARD (Kissmann *et al.*, 2013)
	↓ 0D	↓ 1D, 2D	↓ 3D, 3D+1

2. Transport equations: techniques and codes

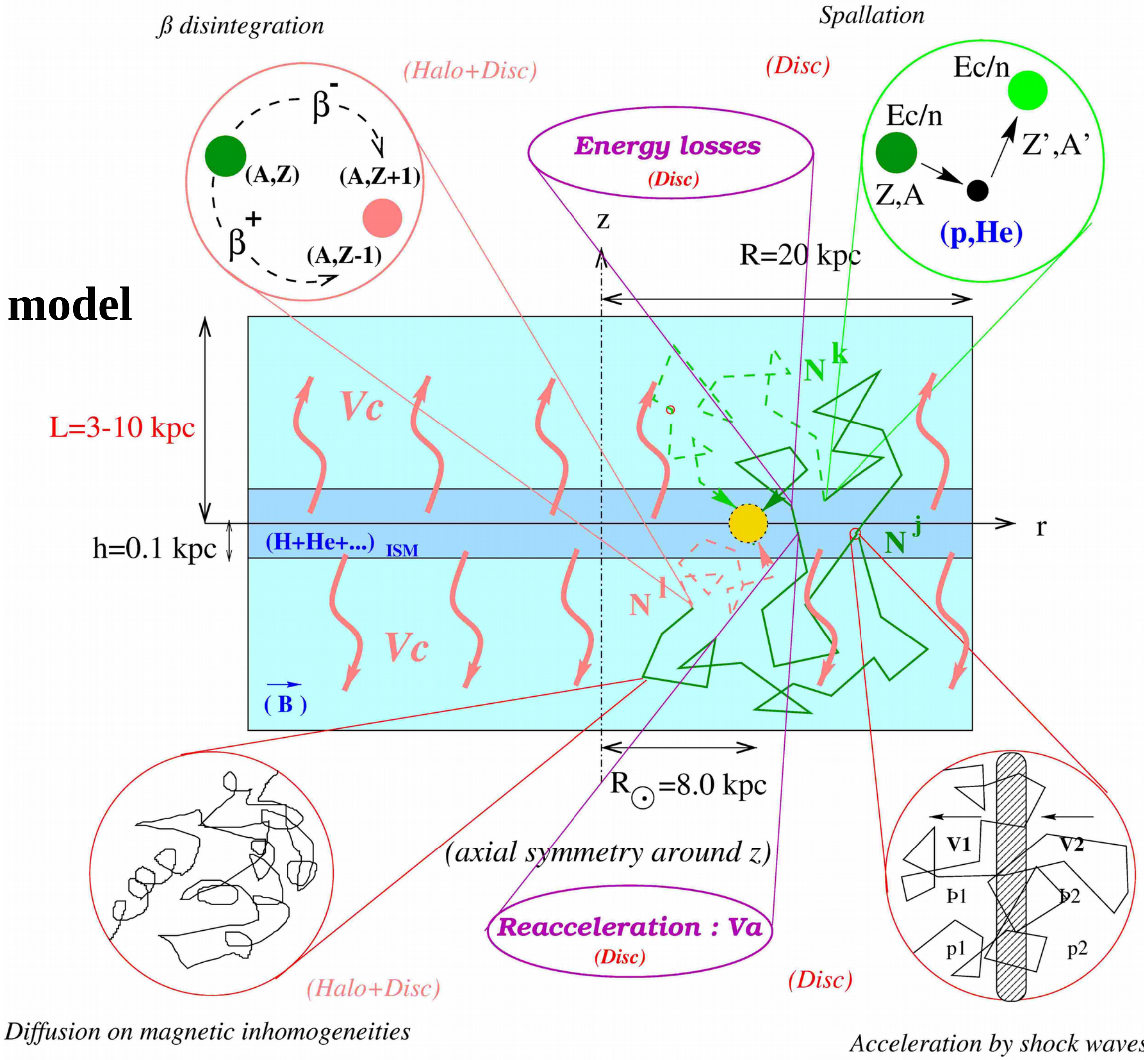
$$\overbrace{\frac{\partial N^j}{\partial t}}^{\text{Variation}} + \overbrace{\left(-\vec{\nabla}\cdot\left(K(E,\vec{r})\vec{\nabla}\right)+\vec{\nabla}\cdot\vec{V}(\vec{r})\right)}^{\text{Spatial transport: diffusion+convection}} N^j + \overbrace{\left(\Gamma_{\rm rad}+\Gamma_{\rm inel}\right)}^{\text{Catastrophic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

	Weighted-slab/LB	*(Semi-)analytical*	*Finite difference scheme*	*Monte Carlo*
Approach	Separate fragmentation: • Grammage dist. (PLD) • Integrate on grammage LB → PLD(X) = $e^{(-X/\lambda esc)}$	Simplify problem: • dominant effects • simple geometry	Discretize equation: • Numerical scheme (e.g., Crank-Nicholson) → Matrix inversion	Follow each particle: • N particles at t=0 • evolve each @ t+1 $1D: \Delta z = \pm\sqrt{2D\Delta t}$
Tools	• 1D numerical integr.	• Green functions • Fourier/Bessel • Diff. equations	• Num. recipes/solvers (NAG, GSL libraries)	• Stochastic diff. equations Markov process + MPI
Pros	• Simple	• Direct dep. in sol. • Fast (e.g. w/ MCMC)	• Simple algebra • Universal (any model)	• Stat. properties (along path) • t step (for/back)-ward
cons	• Leakage approx. fails (leptons and decay)	• "Effective" models • New eq. per model	• Slower / instabilities • RAM for high.res.	• N large (statistical errors) • Massively parallel
Codes and/or references	Davis (1960) – Leaky box Ginzburg & Syrovatskii (1969) Jones/Ptuskin/Webber (70-01) Jones *et al.* (2001)	Ptuskin (1980+) Schlickeiser (1990+) USINE (2000+)	GALPROP (Strong *et al.*, 1998) DRAGON (Evoli *et al.*, 2008) PICARD (Kissmann *et al.*, 2013)	Webber & Rockstroh (1997) Farahat *et al.* (2008) Kopp, Büshing *et al.* (2012) CRPROPA3.1 (Merten *et al.*, 2017)
	↓ 0D	↓ 1D, 2D	↓ 3D, 3D+1	↓ 3D, 3D+1

3. USINE code: models (LB, 1D, and 2D)

LBM: Putze *et al.*, A&A 497, 991 (2009)
1D: Putze *et al.*, A&A 516, A66 (2010)
2D: Maurin *et al.*, ApJ 555, 585 (2001)

2D model



Any energy dependence (e.g. break)

Any spectrum/abundances

Model limitation

- Steady-state
- Homogeneous diffusion
- Isotropic diffusion
- Constant V_c along z
- Gas and sources in thin disc
- Reacceleration in disc only

N.B.: 1D version with $R \to \infty$

For (anti-)nuclei

- Pedagogical value
- Testbed for high precision data
- Does it still match the data?

3. USINE code (in a nutshell)

Code technicalities

- C++ (with classes) + cmake + gitlab + CI + online documentation

USINE

Search docs

1. General information
2. Installation and tests
3. Inside USINE (c++)
4. USINE input files
5. Parameter value syntax (init. file)
6. Tutorial: `./bin/usine`
7. Licenses

Home » USINE documentation   Edit on GitLab

USINE documentation

Welcome to USINE, a library with several semi-analytical Galactic cosmic-ray (GCR) propagation models.

We hope you will enjoy using USINE whether you want to:

- **learn and know more about CR propagation phenomenology**, taking advantage of the simple command-line interface and graphical pop-ups to quickly see and compare the importance of various ingredients on the resulting fluxes;
- **perform state-of-the art analyses of new CR data**, taking advantage of the very flexible ASCII parameter file to select your model, configuration, etc., to fit your data with any number of free parameter (transport, source, geometry...) and nuisance parameters (cross sections, data systematic uncertainties...);
- **develop and use you own semi-analytical model** without having to spend years setting all inputs and outputs right, taking advantage of the modularity and flexibility of the USINE C++ library.

USINE: semi-analytical models for Galactic cosmic-ray propagation

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Abstract

I present the first public release (v3.4) of the USINE code for cosmic-ray propagation in the Galaxy. It contains several semi-analytical propagation models previously used in the literature (leaky-box model, 2-zone 1D and 2D diffusion models) for the calculation of nuclei ($Z = 1 - 30$), anti-protons, and anti-deuterons. With a single ASCII initialisation file to configure runs, its many displays, and the speed associated to semi-analytical approaches, USINE should be a useful tool for beginners, but also for experts to perform statistical analyses of high-precision cosmic-ray data. Any geometry, transport, and source parameters can be enabled as free parameters, whereas nuisance parameters are enabled on solar modulation levels, cross sections (inelastic and production), and systematics of the CR data. The next release, in preparation, will include leptons, dark matter contributions in 2D model, interface with MCMC engine, etc.

Contents

Run features

- Intitialisation from ASCII files (list of CRs, E-range, CR and XS data…)
- Run configuration (models, free params in minimization) from ASCII file
- Simple command-line + pop-up graphics

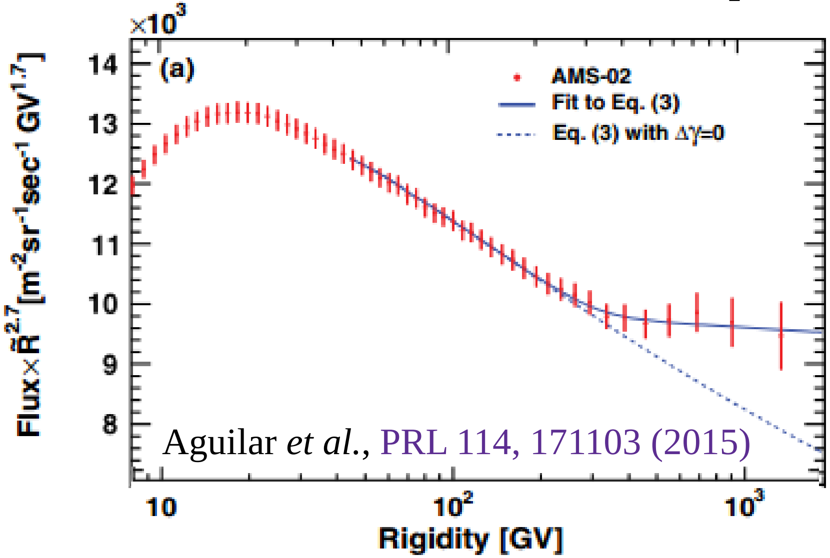
→ **on arXiv before the end of CRISM**

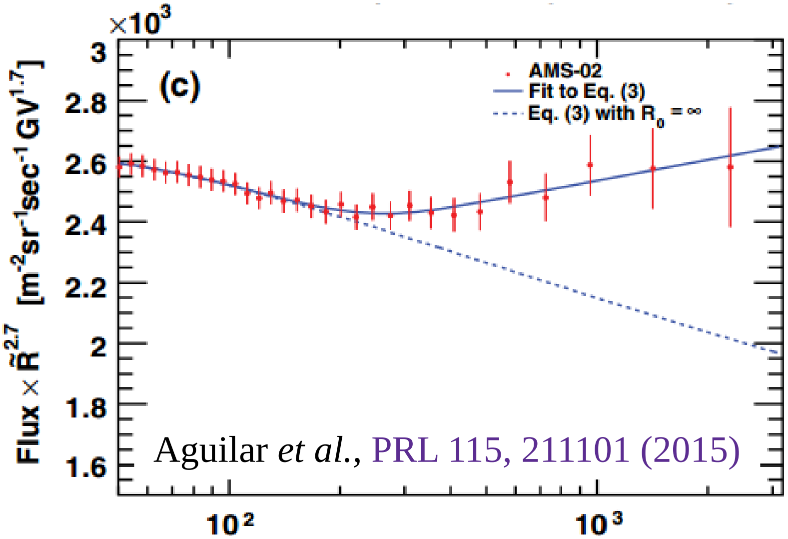
Génolini, Serpico, *et al.*,
PRL 119, 241101 (2017)

4. Break: source or diffusion?

H and He

→ spectral break at ~ 300 GV





→ what is the origin of the break?

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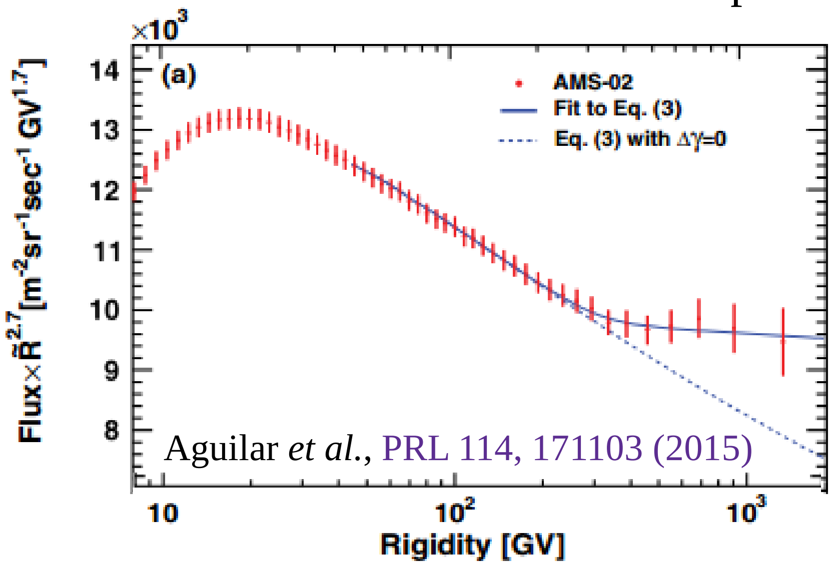

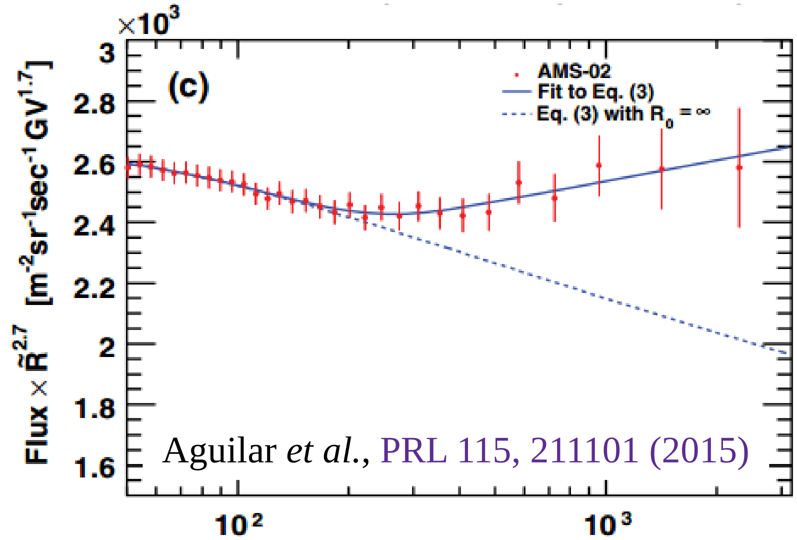

B/C

→ what is the origin of the break?

	No break	Break in source	Break in diffusion
Primary species $\propto$ Src/Diff	$\propto R^{-(\alpha+\delta)}$	$\propto R^{-(\alpha+\Delta\alpha+\delta)}$	$\propto R^{-(\alpha+\delta+\Delta\delta)}$
Secondary species $\propto$ Primary/Diff	$\propto R^{-(\alpha+2\delta)}$	$\propto R^{-(\alpha+\Delta\alpha+2\delta)}$	$\propto R^{-(\alpha+2\delta+2\Delta\delta)}$
B/C	$\propto R^{-\delta}$	$\propto R^{-\delta}$	$\propto R^{-\delta+\Delta\delta}$

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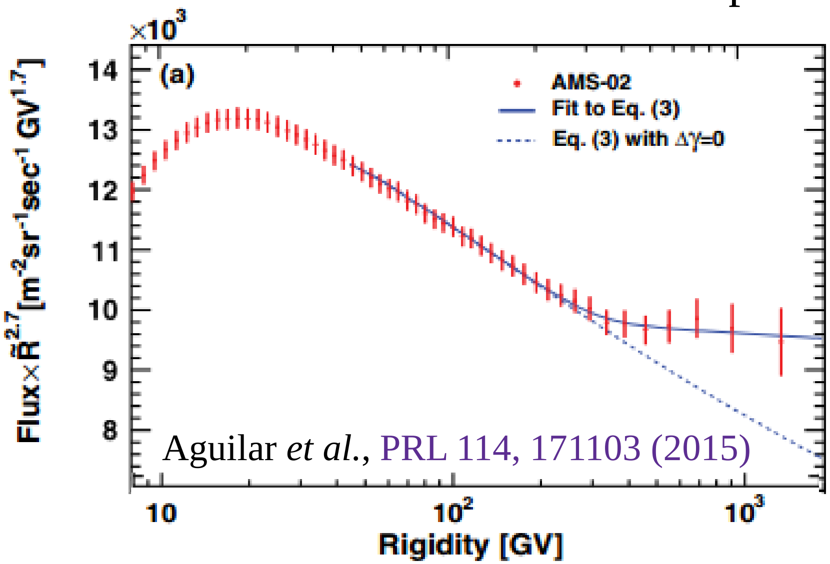

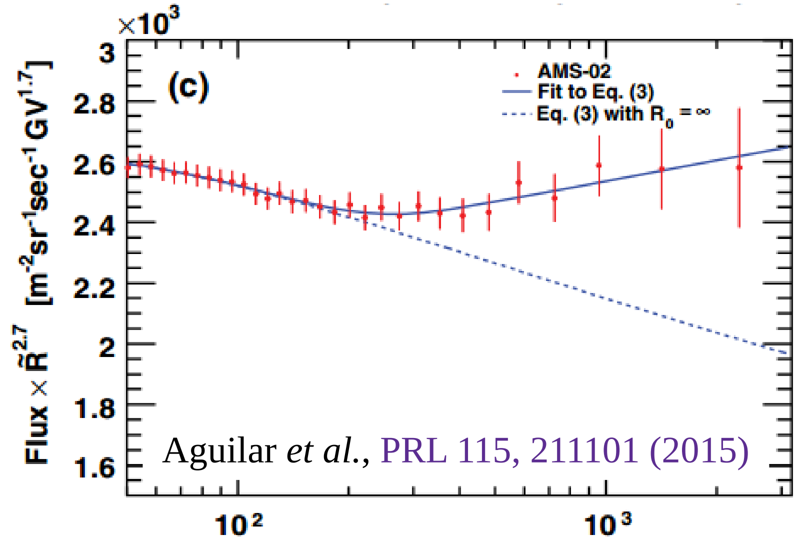

B/C

→ what is the origin of the break?

[see, e.g., P. Blasi talk]

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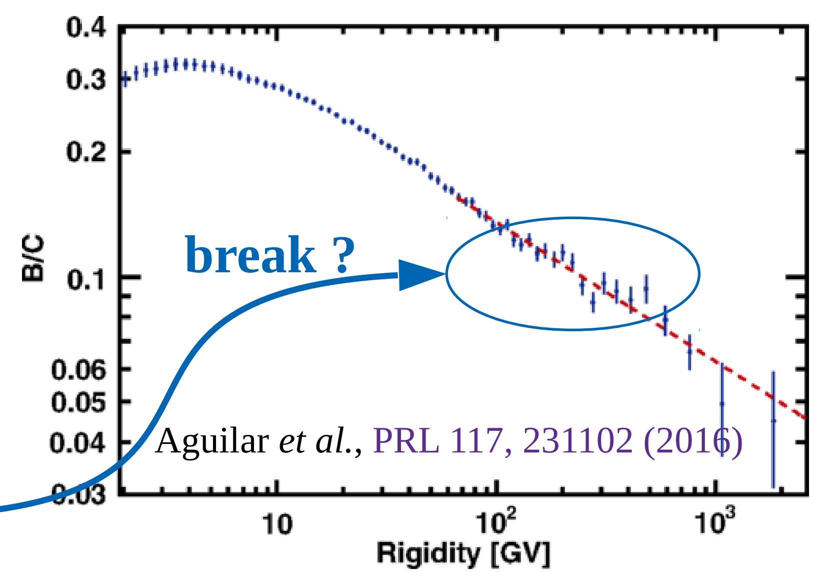


4. Break in the diffusion coefficient?

Génolini, Serpico *et al.*, PRL 119, 241101 (2017)

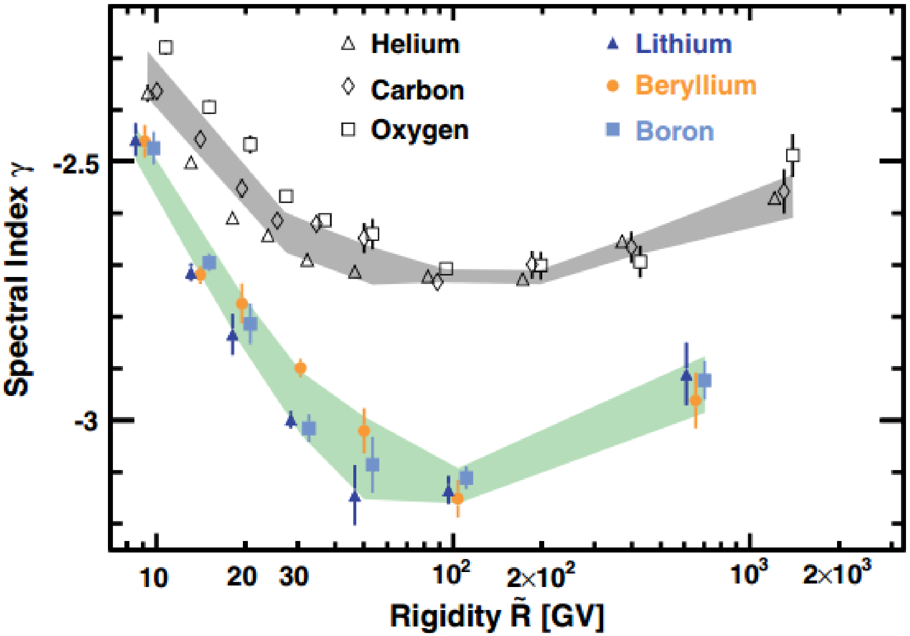
Indications for a High-Rigidity Break in the Cosmic-Ray Diffusion Coefficient

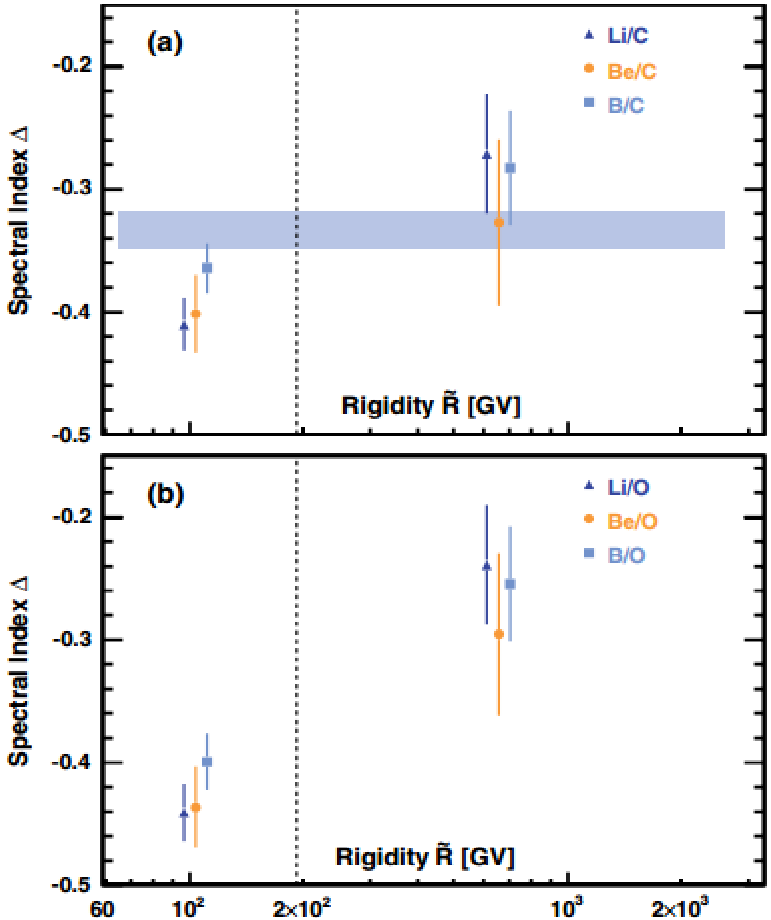
Using cosmic-ray boron to carbon ratio (B/C) data recently released by the AMS-02 experiment, we find indications (*decisive evidence*, in Bayesian terms) in favor of a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He). The result is robust with respect to

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

→ Break in all secondary/primary ratios

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





"XSCRC2017: Cross sections for Cosmic Rays" at CERN
(organised by F. Donato & P. Serpico)

Génolini, D.M., Moskalenko, and Unger, arXiv:1803.04686

5. Ranking XS: motivation (1)

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

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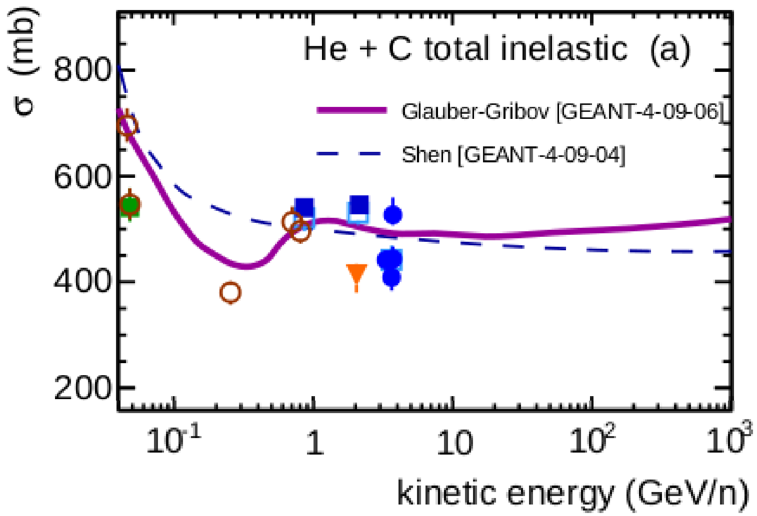
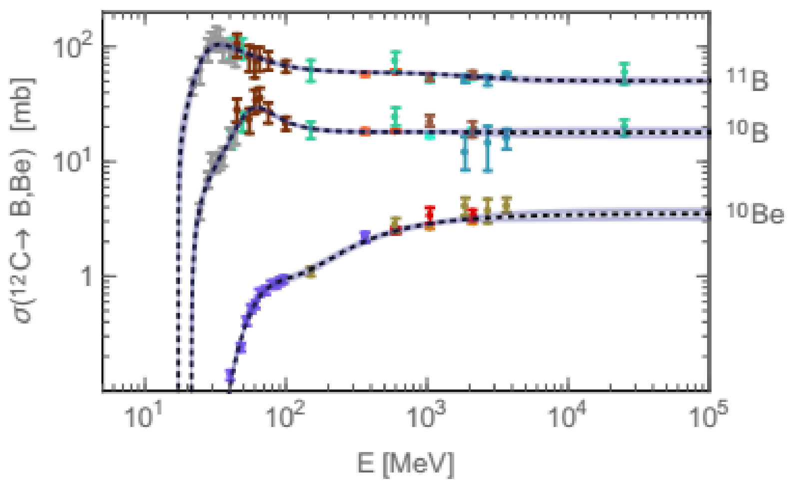
Tomassetti, PRD 93, 3005 (2017)



Reinert & Winkler, JCAP 01, 055 (2018)



→ No data above a few GeV/n

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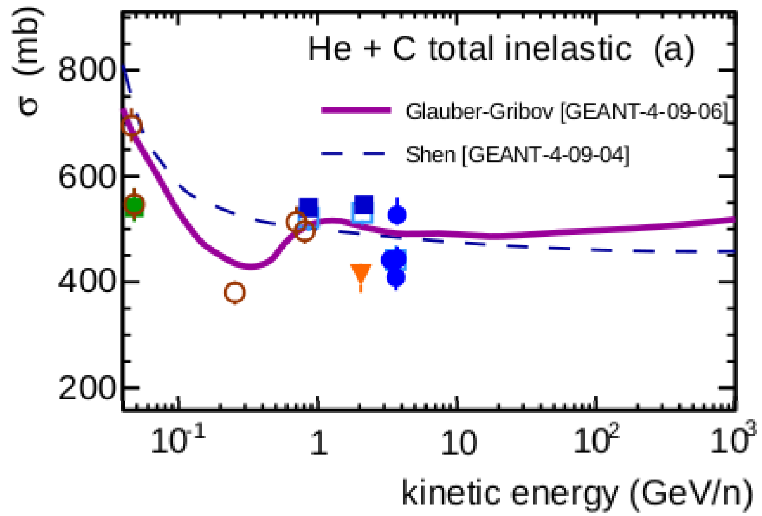

Various approaches
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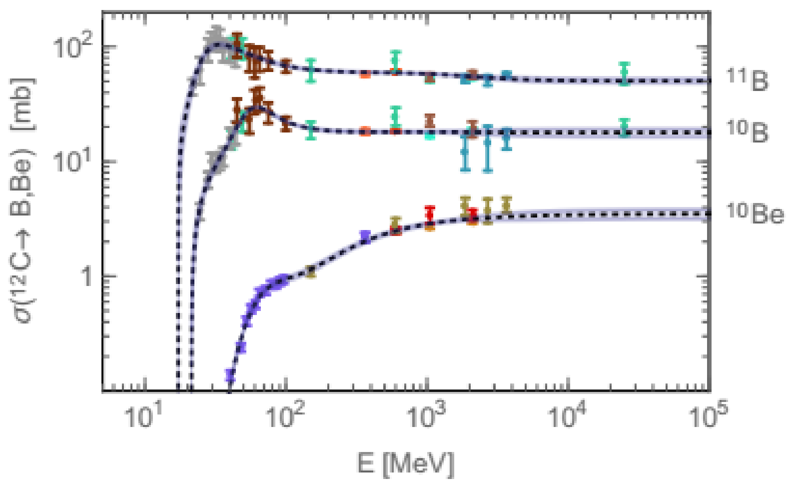
Reinert & Winkler, JCAP 01, 055 (2018)



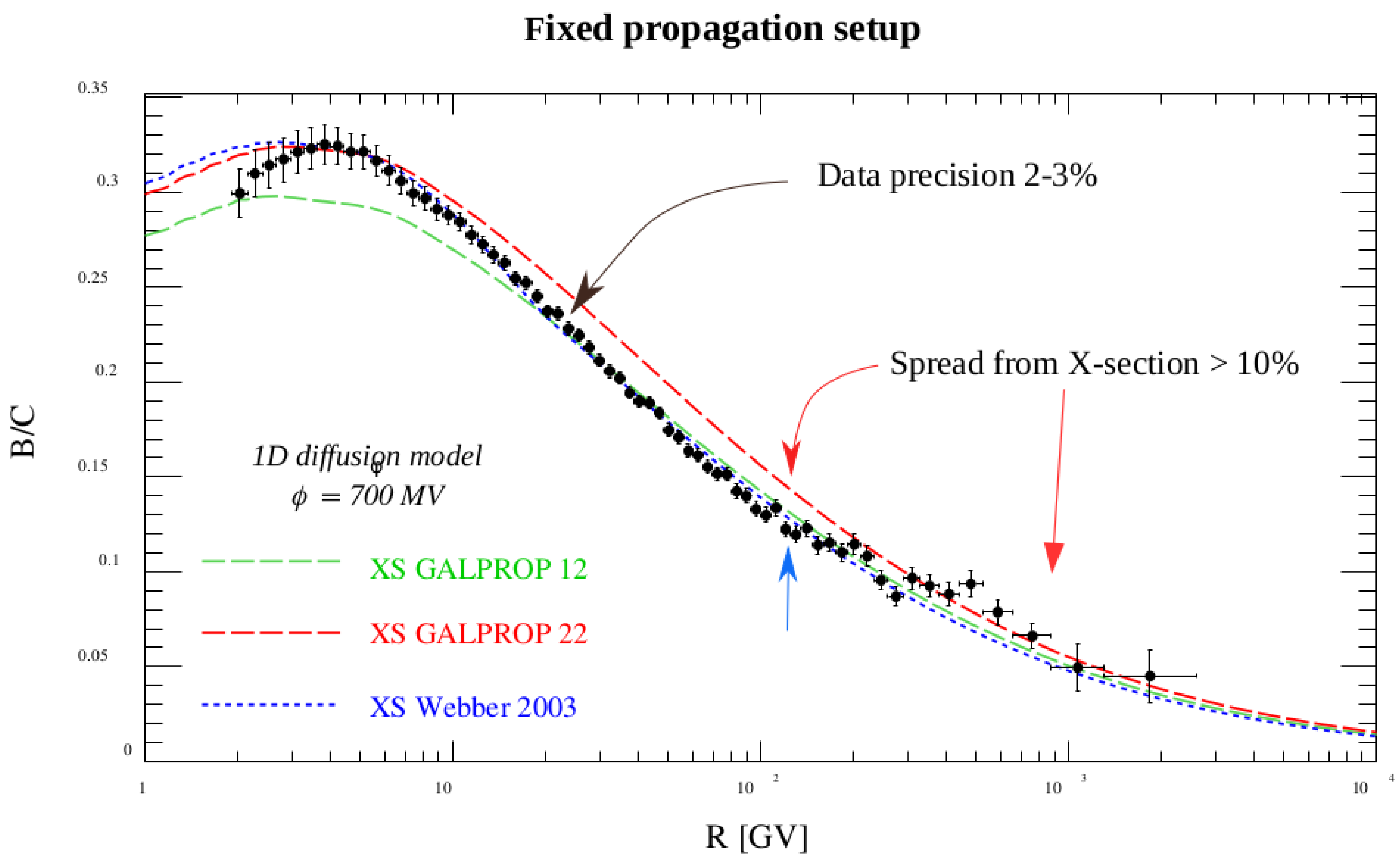
→ Systematics from XS dominate over data CR uncertainties

Maurin, Putze, and Derome, A&A 516, 67 (2010)

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

→ No data above a few GeV/n

5. Ranking XS: motivation (2)



New XS data required!
→ Which reactions are the most important, how many matter?
→ How to have a proper error budget (from XS to fluxes)

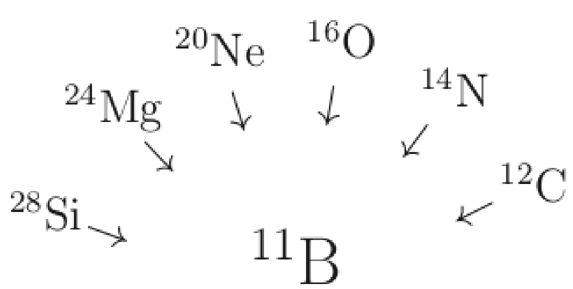
5. Ranking XS: most important channels for B (1)

Illustration with Boron

$$B = {}^{10}B + {}^{11}B$$

(~30%) (~70%)

Reactions contributing to ^{11}B



1-step channels

5. Ranking XS: most important channels for B (2)

Illustration with Boron

$$B = {}^{10}B + {}^{11}B$$

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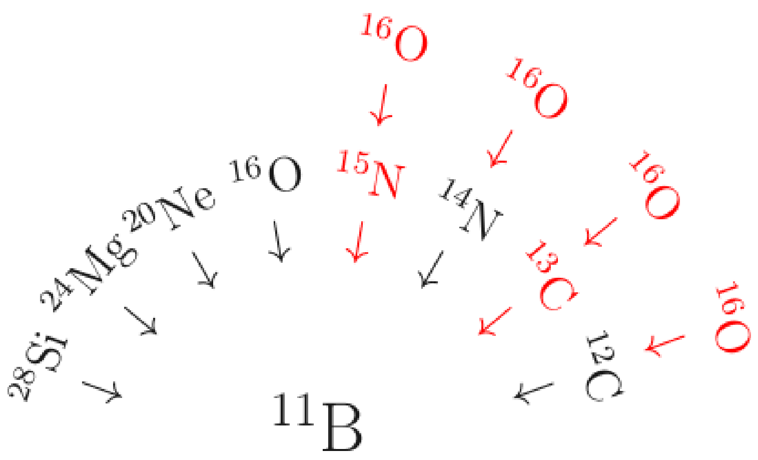
Reactions contributing to ^{11}B



2-step channels

5. Ranking XS: most important reactions for B (1)

Reactions to consider

a (CRs) + b (H, He) → c (CRs + ghost nuclei)

Ghost nuclei to account for

- Exemple

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

- 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%)

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Calculate f_{abc}

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

5. Ranking XS: most important reactions for B (1)

Reactions to consider

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Ghost nuclei to account for

- Exemple

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

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^{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%)

Calculate f_{abs}… et voilà!

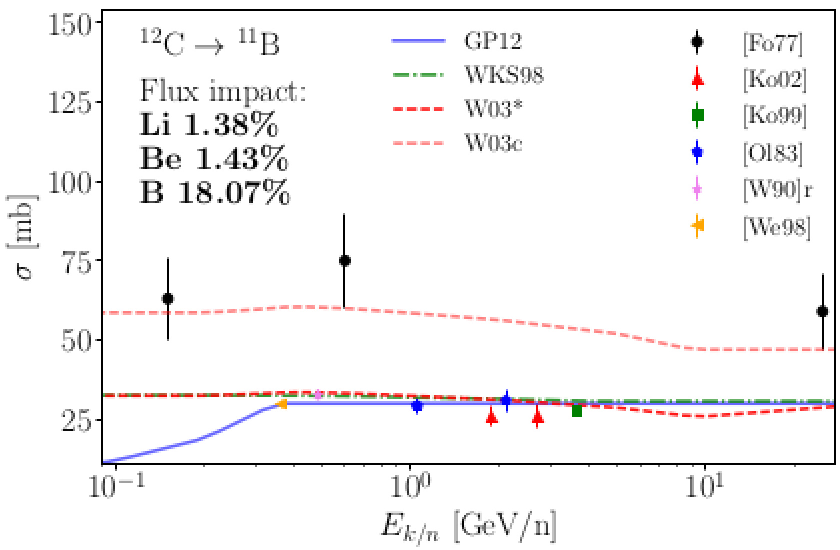
$$f_{abc} = \frac{\psi^{\rm sec}({\rm ref}) - \psi^{\rm sec}(\sigma^{a+b\to c}=0)}{\psi^{\rm sec}({\rm ref})}$$

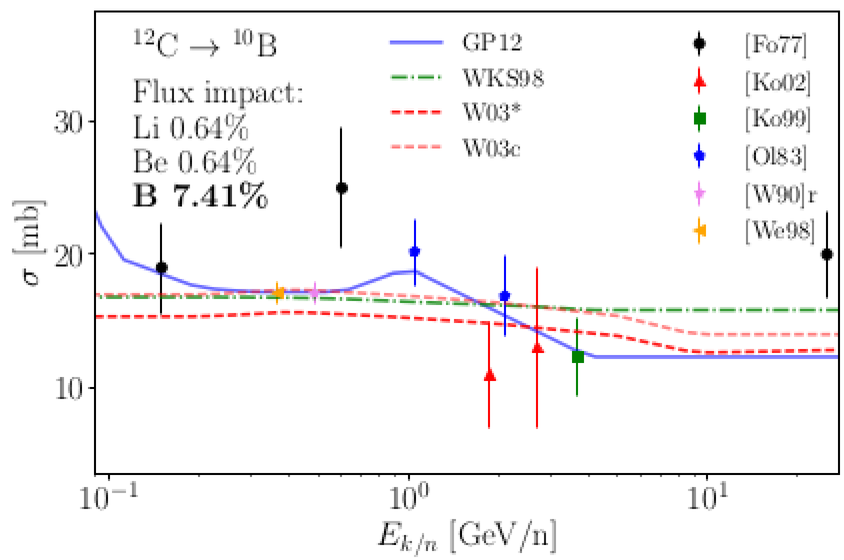
Reaction $a+b\to c$	Flux impact f_{abc} [%]			σ [mb]
	min	**mean**	max	range
$\sigma(^{12}C+H\to{}^{11}B)$	18.0	**18.1**	19.0	30.0
$\boldsymbol{\sigma(^{12}C+H\to{}^{11}C)}$	16.0	**16.2**	17.0	26.9
$\sigma(^{16}O+H\to{}^{11}B)$	11.3	**11.8**	12.0	18.2
$\sigma(^{12}C+H\to{}^{10}B)$	7.20	**7.41**	7.60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

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

5. Ranking XS: most important reactions for B (2)

This is what it looks like...





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

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

5. Ranking XS: error propagation

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

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

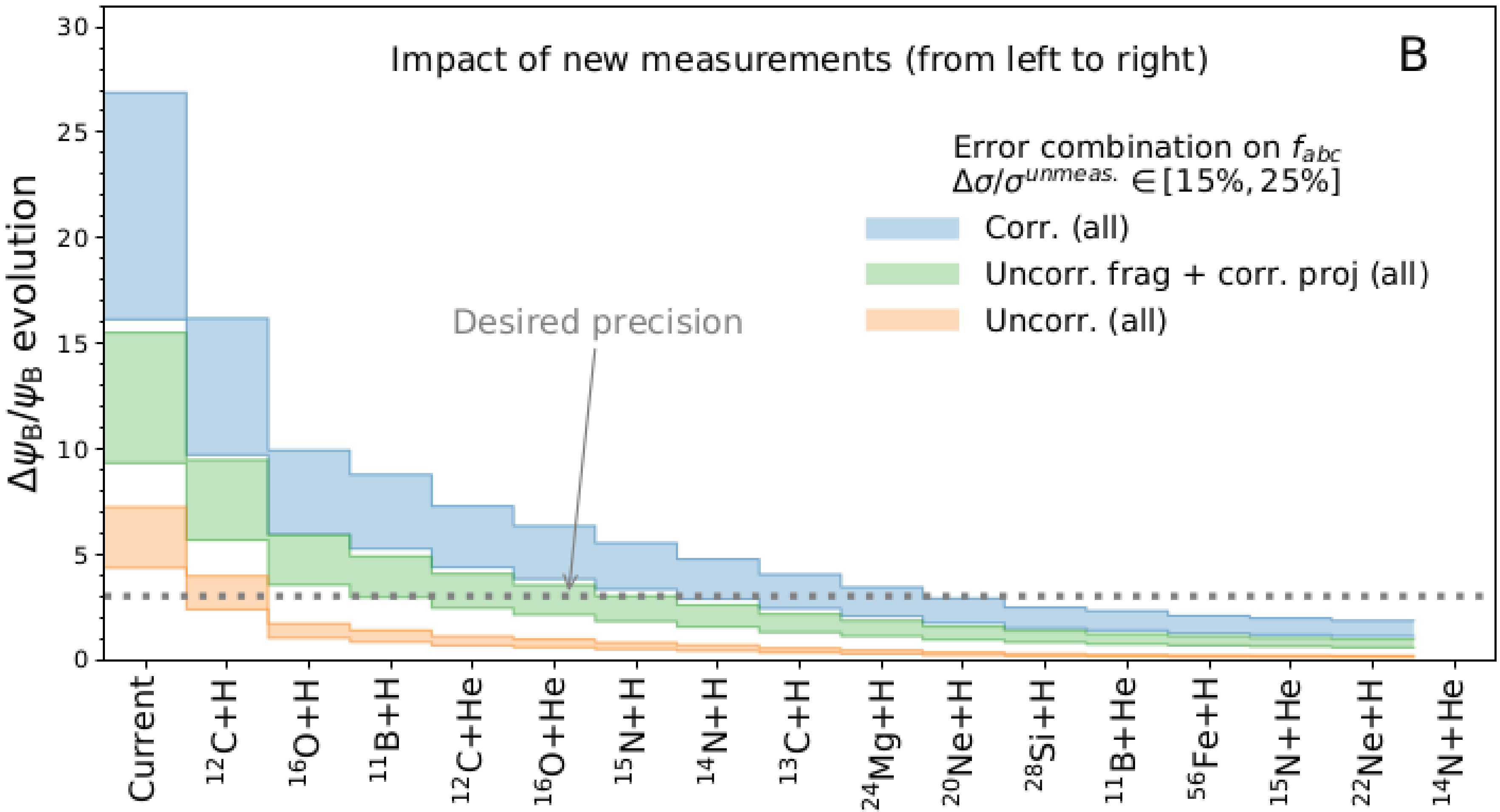
Looking at the data/parameterizations

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

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

5. Ranking XS: error propagation

(projectile + target) to measure with high priority



→ Ordering insensitive on error assumption
→ Calculated for Li, Be, B, N, and C

New measurements at NA61 soon!

6. Conclusions

USINE code

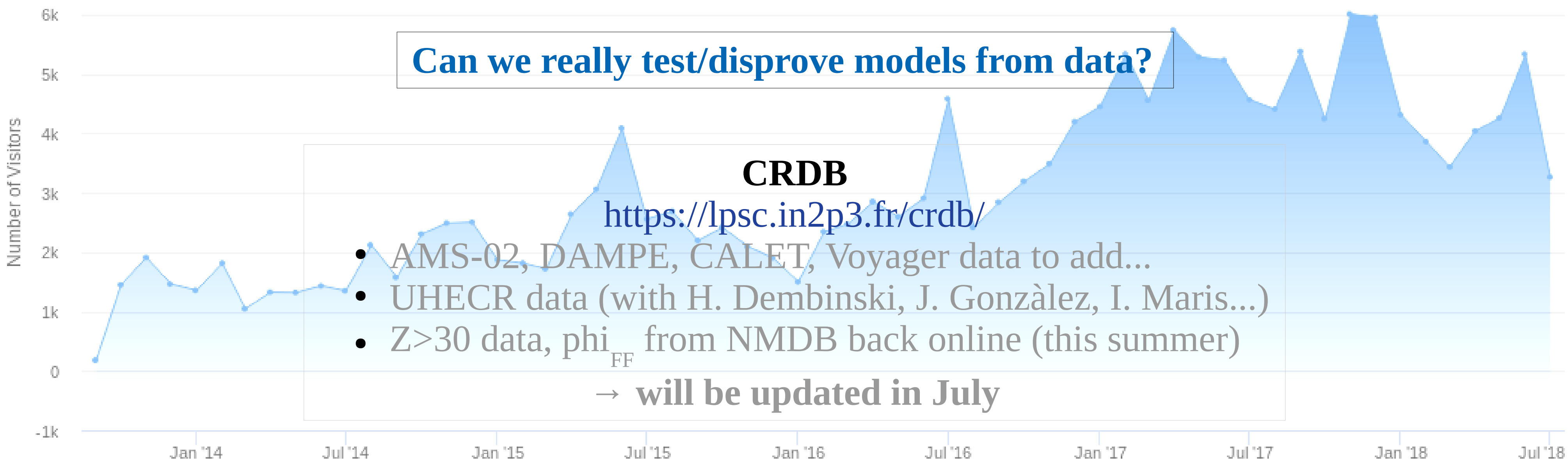
- C++/ROOT + gitlab + tests + documentation
- Semi-analytical models (LBM, 1D/2D 2-zones) + dbar, pbar, ^{1}H to ^{70}Zn
- Input ASCII files (CR data, XS, …) + pop-up plots

Ranking of cross sections

- Extend to other elements/isotopes (Li,Be,B,C,N in Génolini *et al.*)
- Advertise in nuclear/particle physics communities for measurements
  → forthcoming runs with NA61 (lead by M. Unger)

In progress… analysis of AMS-02 fluxes and (Li,Be,B)/C data

- Account for systematics in data (correlation or nuisance?)
- Realistically account for XS uncertainties



Can we really test/disprove models from data?

CRDB

https://lpsc.in2p3.fr/crdb/

- AMS-02, DAMPE, CALET, Voyager data to add...
- UHECR data (with H. Dembinski, J. Gonzàlez, I. Maris...)
- Z>30 data, phi_{FF} from NMDB back online (this summer)

→ **will be updated in July**

4. Break in the diffusion coefficient?

Génolini, Serpico *et al.*, PRL 119, 241101 (2017)

Indications for a High-Rigidity Break in the Cosmic-Ray Diffusion Coefficient

Using cosmic-ray boron to carbon ratio (B/C) data recently released by the AMS-02 experiment, we find indications (*decisive evidence*, in Bayesian terms) in favor of a diffusive propagation origin for the broken power-law spectra found in protons (p) and helium nuclei (He). The result is robust with respect to

Test hypotheses

- Break in source: $K(R) = K_0 \beta (R/\mathrm{GV})^{\delta}$
- Break in diffusion: $K(R) = K_0 \beta \frac{(R/\mathrm{GV})^{\delta}}{\{1 + (R/R_b)^{\Delta\delta/s}\}^{s}}$

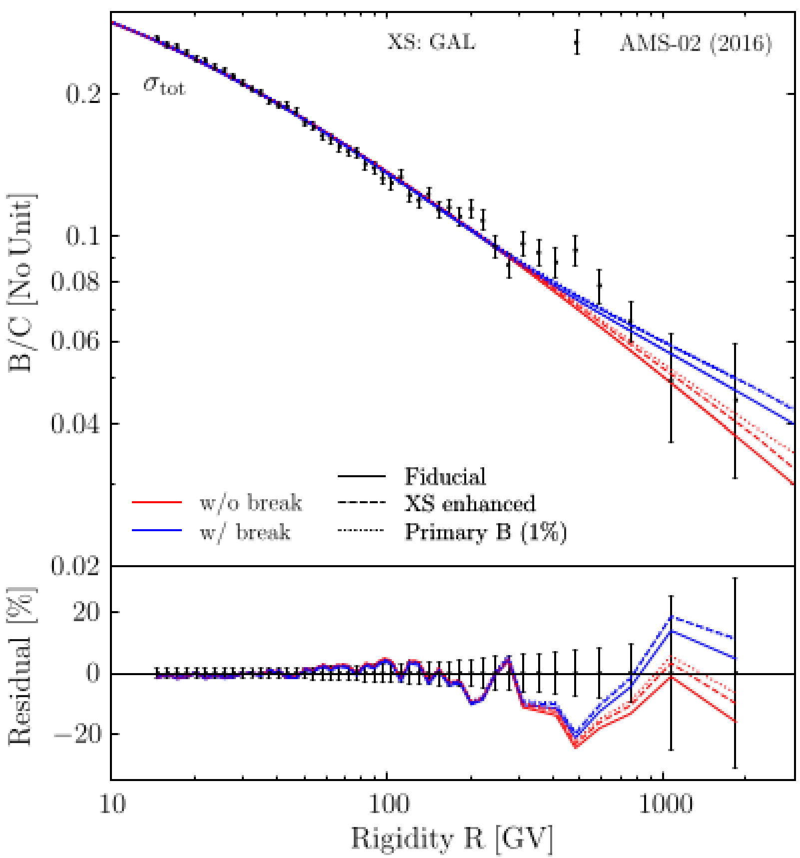
→ same number of free parameters (K_0, δ, V_c)

→ no extra parameters:

- R_s, Δδ, and s from AMS-02 p and He break
- Correlations accounted for

Robustness against

- Energy dependence of inelastic cross sections ($\propto \ln^2 E$)
- primary B fraction as high as 4.5% of the C (would already overshoot antiprotons)



N.B.: difference not compelling by eye… but that what statistics is for!

5. Ranking XS: error propagation

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

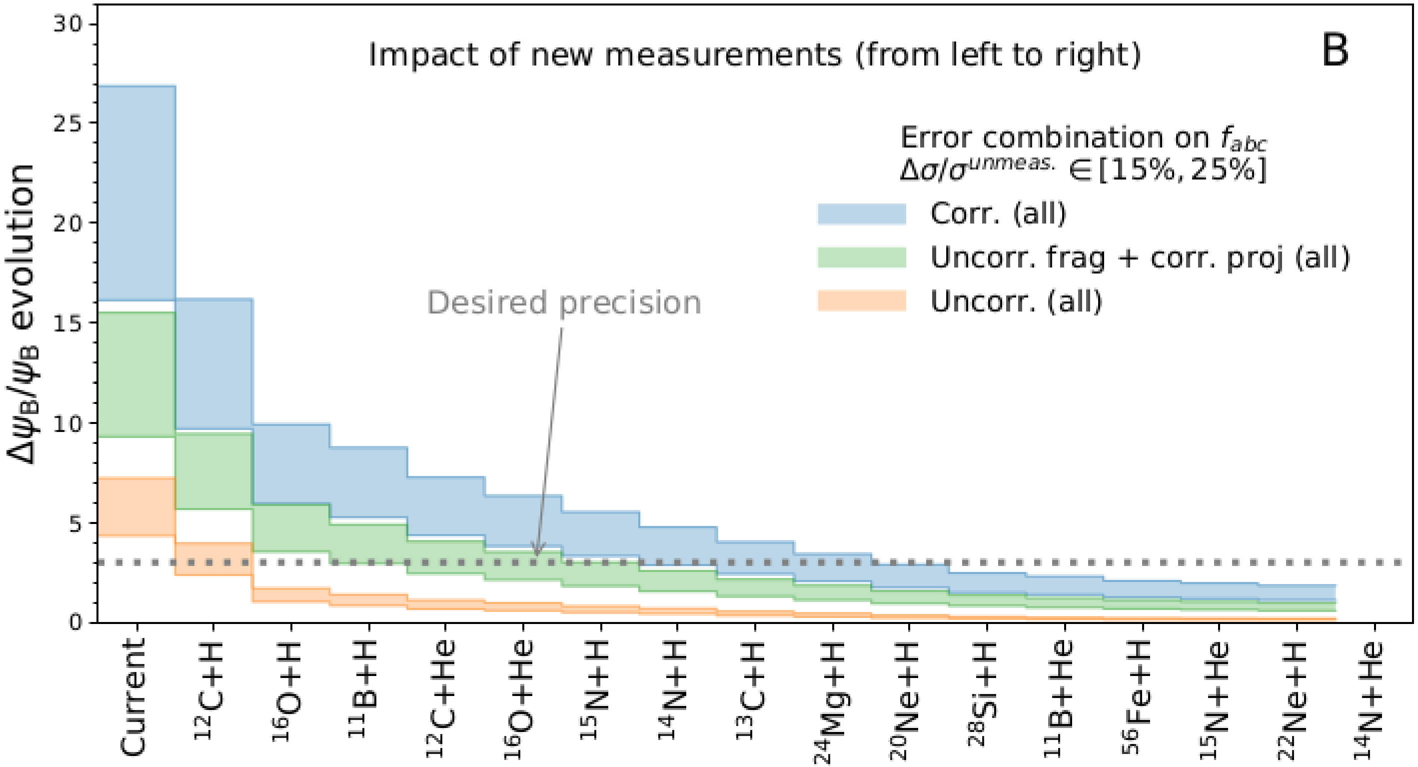
$$\left(\frac{\Delta\psi^{\rm tot}}{\psi^{\rm tot}}\right)^{\rm uncorr} \approx f^{\rm sec}\sqrt{\sum_{a,b,c}\left(f_{abc}\frac{\Delta\sigma^{abc}}{\sigma^{abc}}\right)^2}$$

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

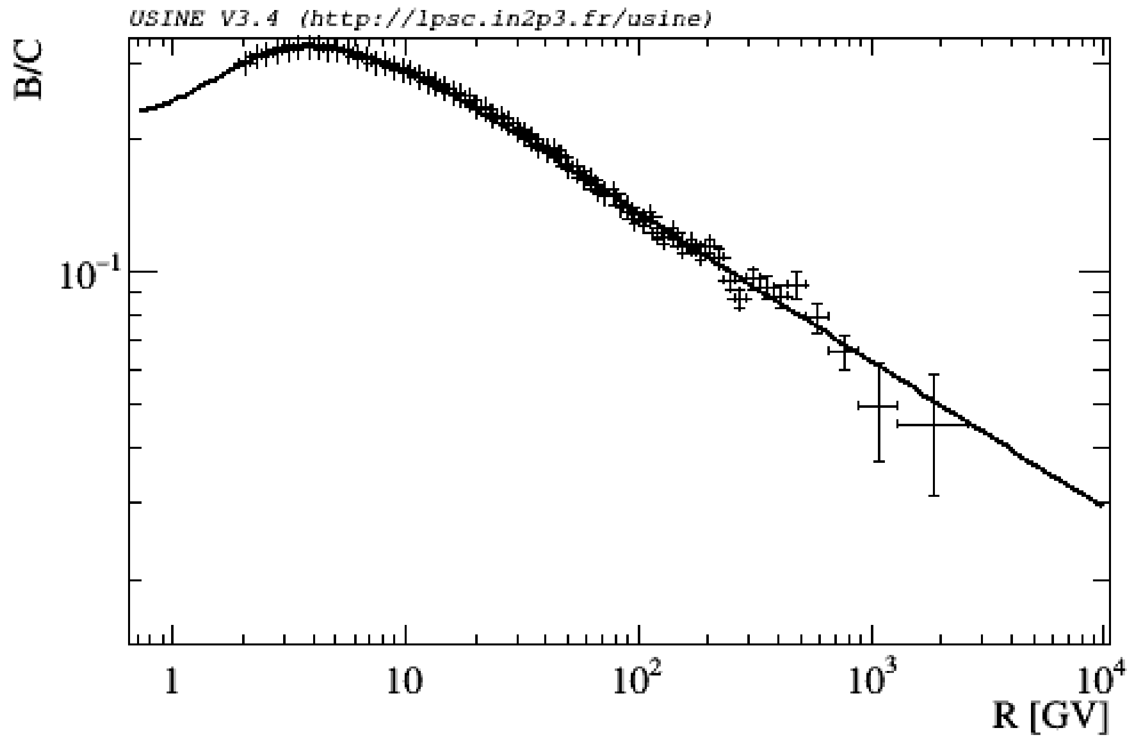


→ Ordering insensitive on error assumption

→ Calculated for Li, Be, B, N, and C

New measurements at NA61 soon!

B/C from $D \propto R^{-1/3}$

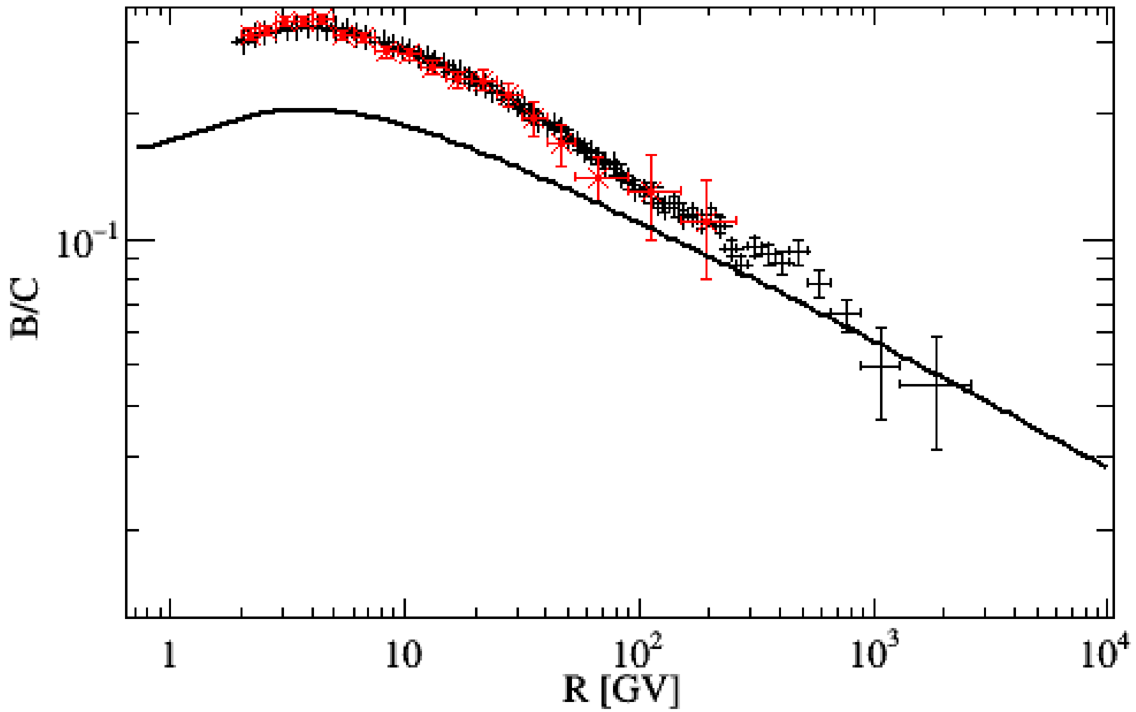


Pure diffusion model (1D)

looks great!

… but no B and C destruction

BUT



Unavoidable B and C destruction
→ flattening (not power law)

N.B.: pure diffusive regime for which slope(data)=slope(diffusion) Is at very high rigidity!