Galactic cosmic-ray (GCR) propagation and nuclear production cross sections

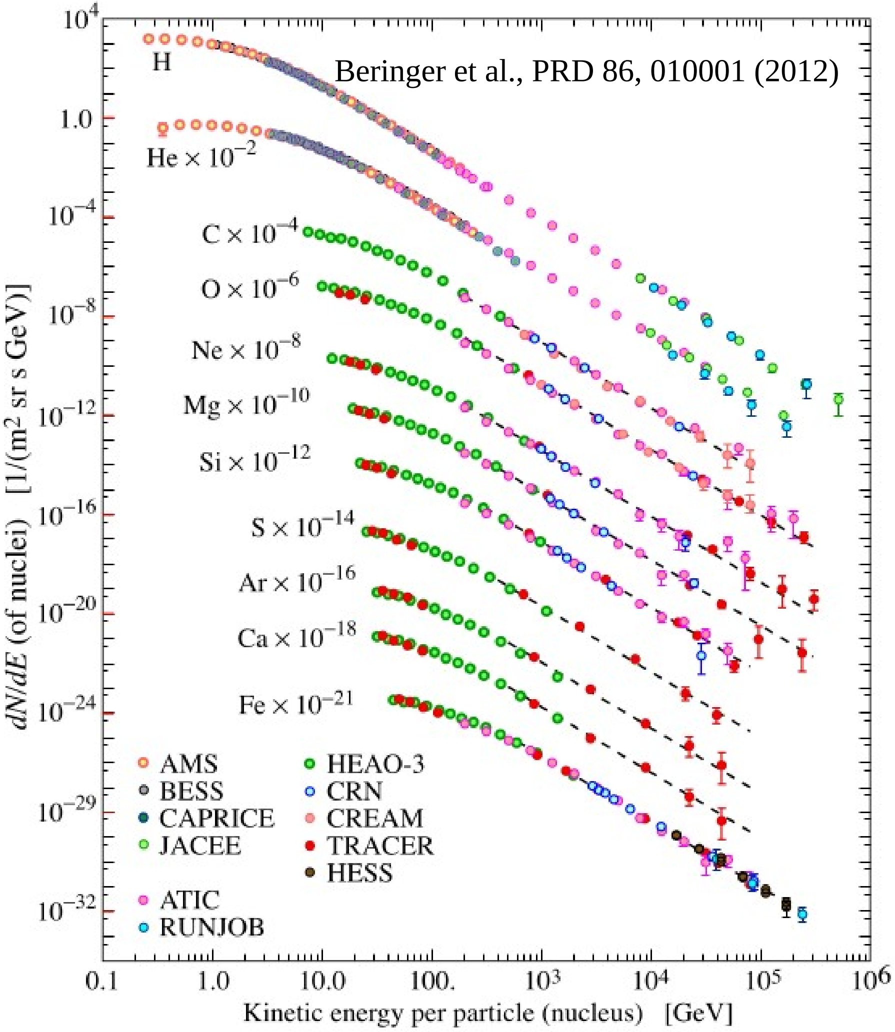
1) GCR propagation in brief
2) Production XS in the AMS02 era
3) GCR perspective for NA61/SHINE

David Maurin
(LPSC)
dmaurin@lpsc.in2p3.fr

NA61++/Shine @ CERN
16 December 2022

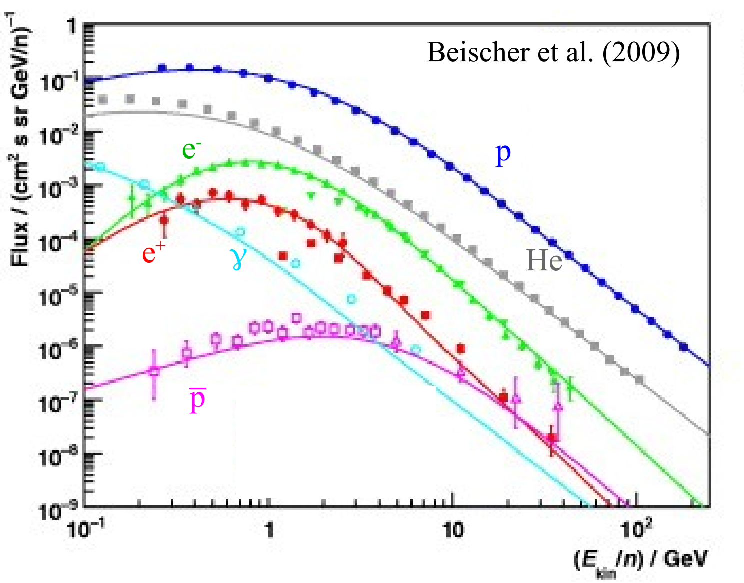
1) Introduction: Galactic CR data ($E \sim 10^8 - 10^{15}$ eV)

Elemental spectra



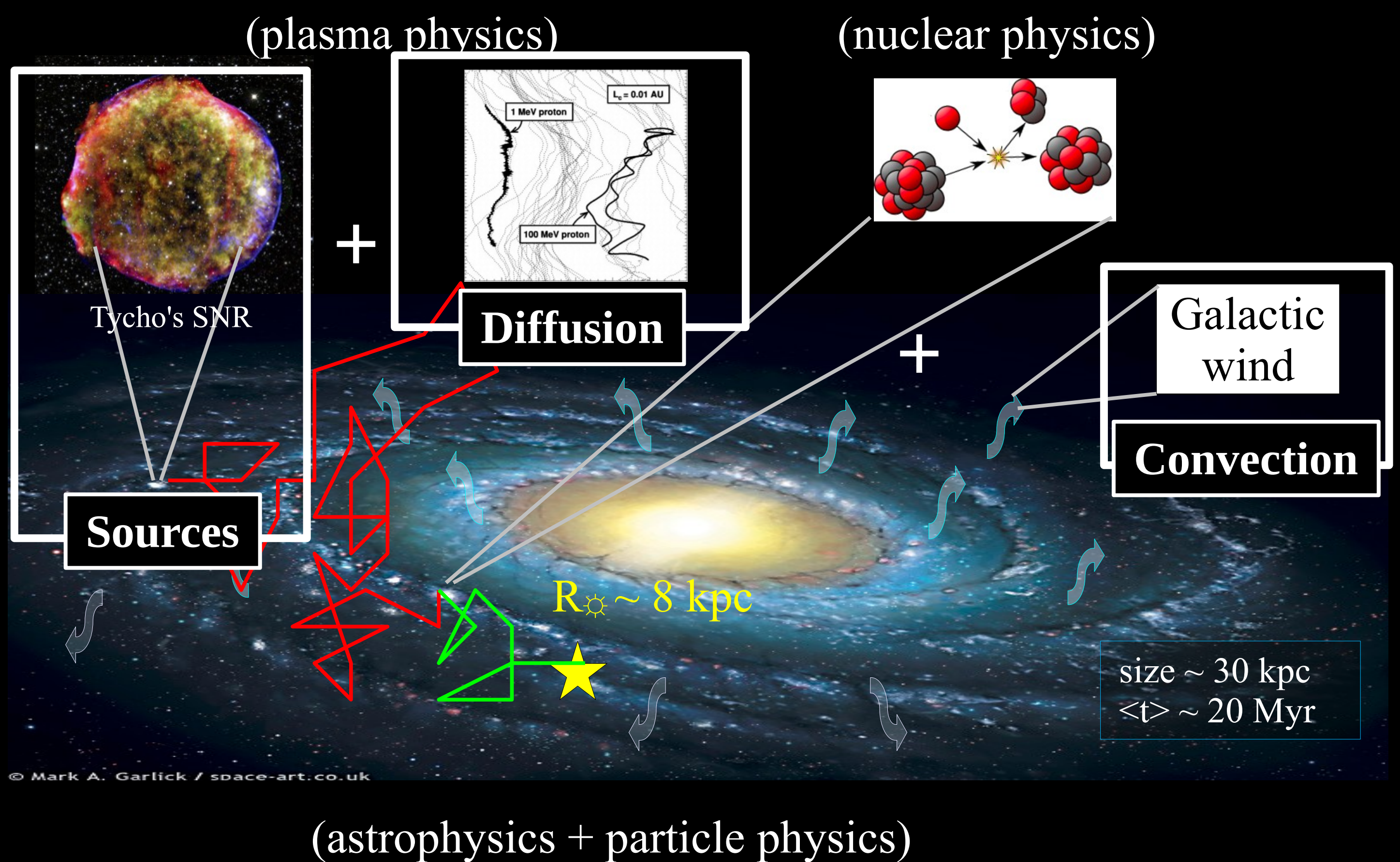
→ Origin of quasi-universal power law ($E^{-2.8}$)?
→ Maximum energy of Galactic sources?
→ Abundances of elements and isotopes?
→ Patterns in small-scale anisotropies ($\delta < 10^{-3}$)

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



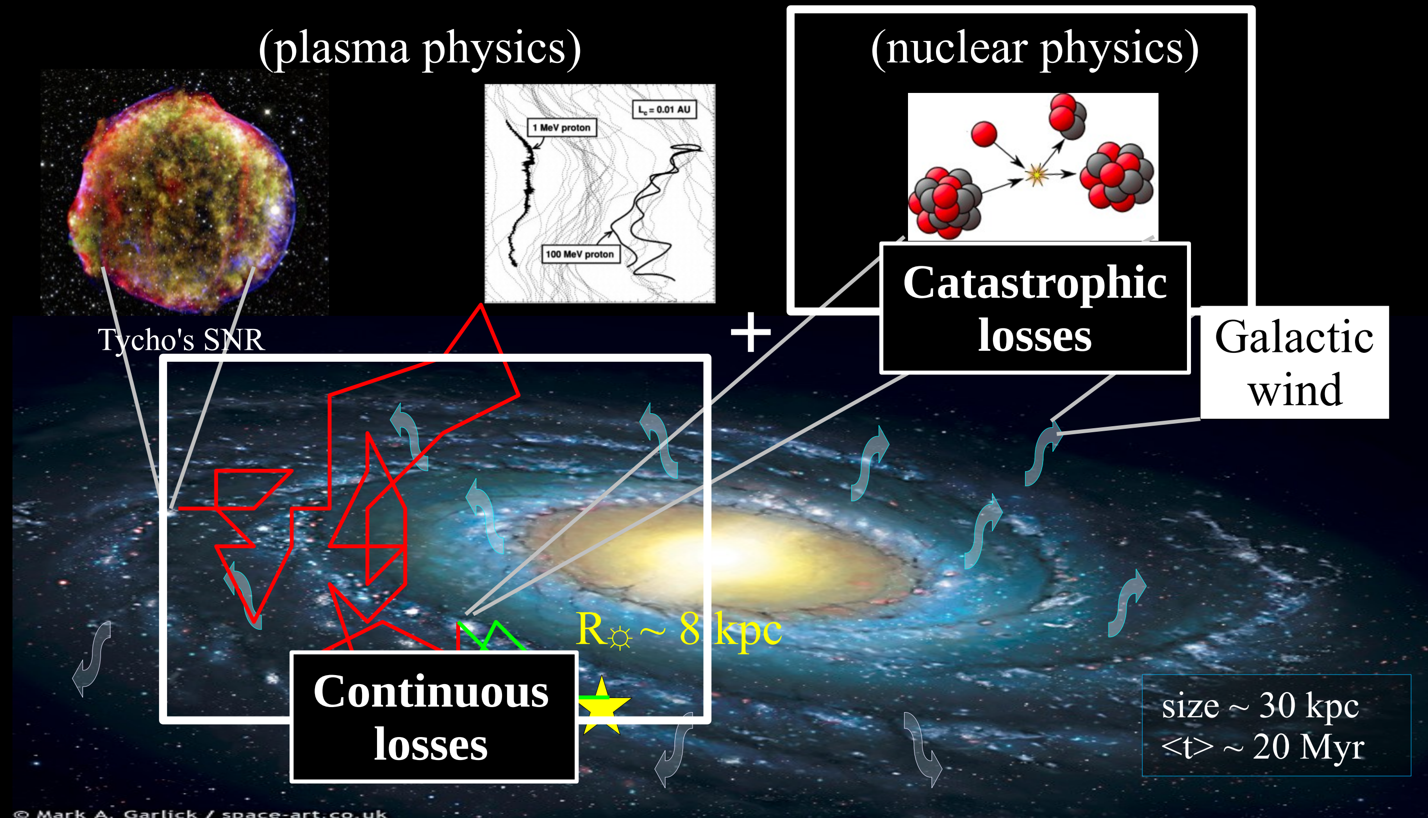
N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Are there primary sources?
→ Is it a good place to look for dark matter?

1) Introduction: transport parameters



Source term and transport parameters (diffusion, convection, reacceleration)
→ "Free" parameters to determine from GCR data

1) Introduction: input ingredients

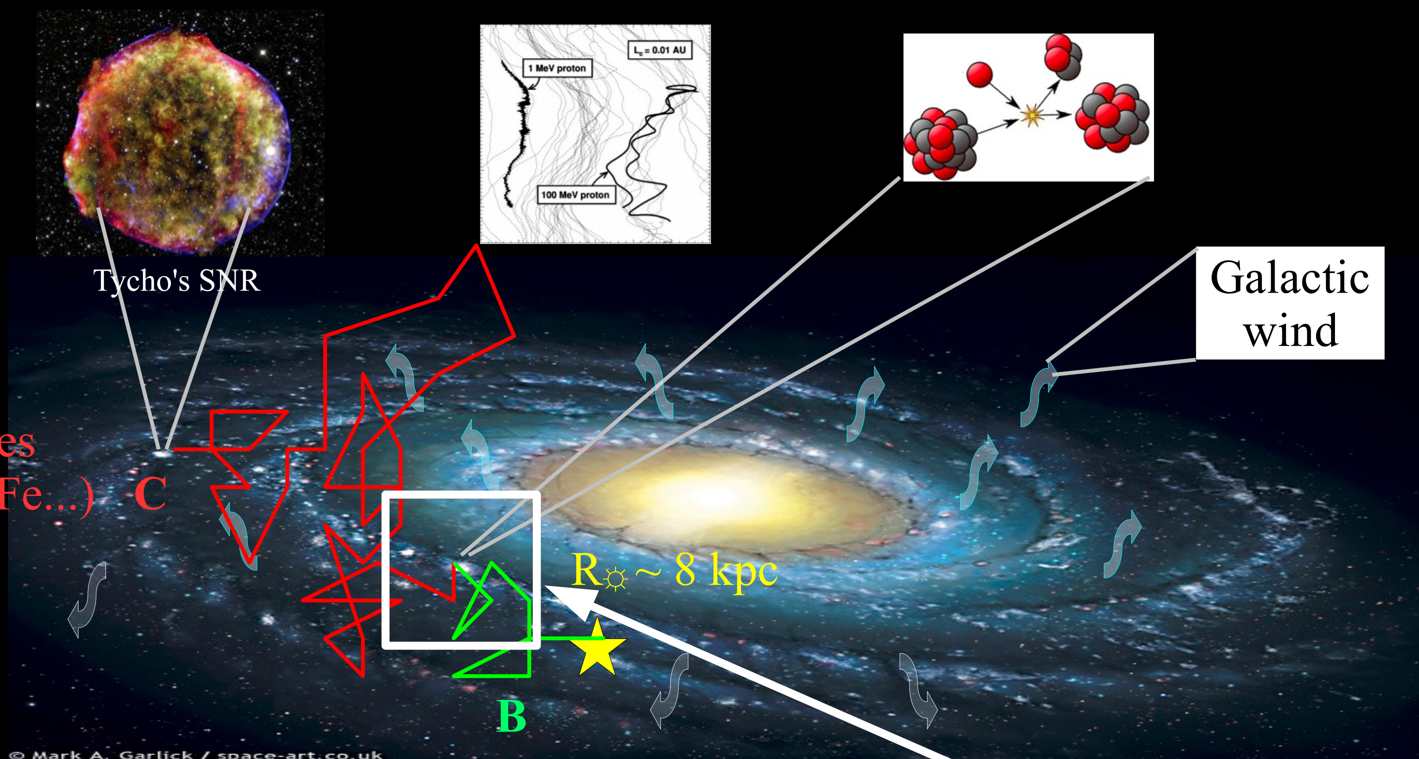


(astrophysics + particle physics)

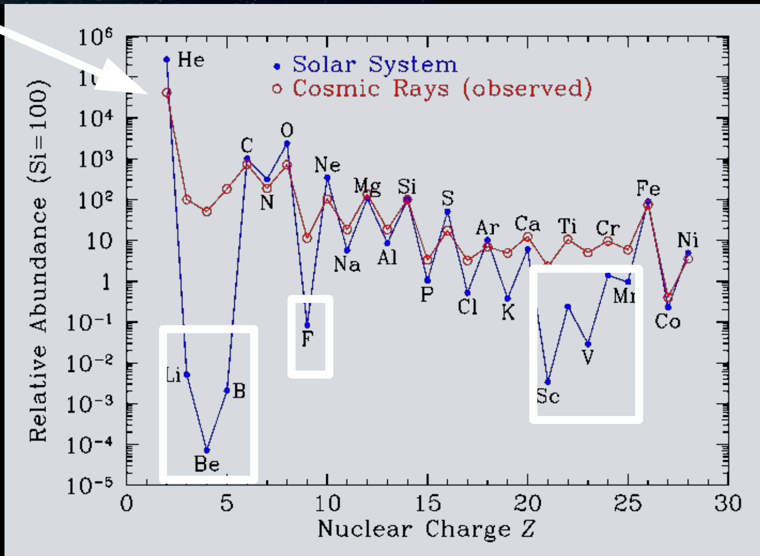
Continuous and catastrophic losses
→ “Input” ingredients of the GCR calculation
N.B.: large uncertainties on production cross sections

1) Introduction: secondary species from production XS

Primary species
(p, He, C, O, Si, Fe...)

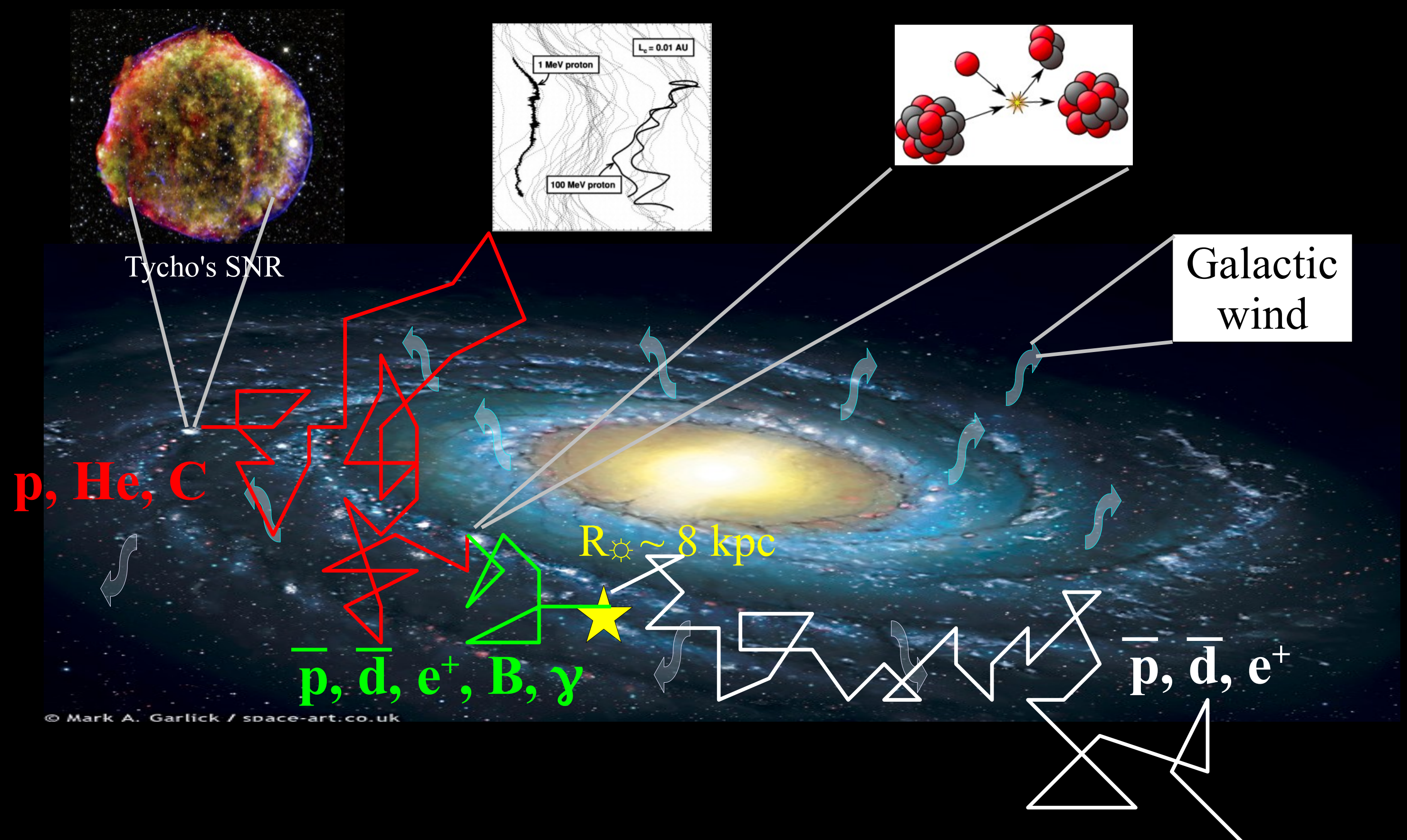


Secondary species
(^{2}H^{3}He, LiBeB, F, sub-Fe)



→ Secondary-to-primary ratios constrain the transport parameters
→ **Production XS required (to calculate secondary species)**

1) Introduction: XS key ingredient for many studies...



Dark-matter induced
(from dark matter halo, ~300 kpc)

Production XS for nuclei needed for:
→ Astrophysical interpretation of GCRs
→ Astrophysical background calculation for anti-nuclei, positrons, gamma-rays, neutrinos

Galactic

1) GCR propagation in brief

2) Production XS in the AMS02 era

3) GCR perspective for NA61/SHINE

2) AMS-02

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 200 billion events so far!

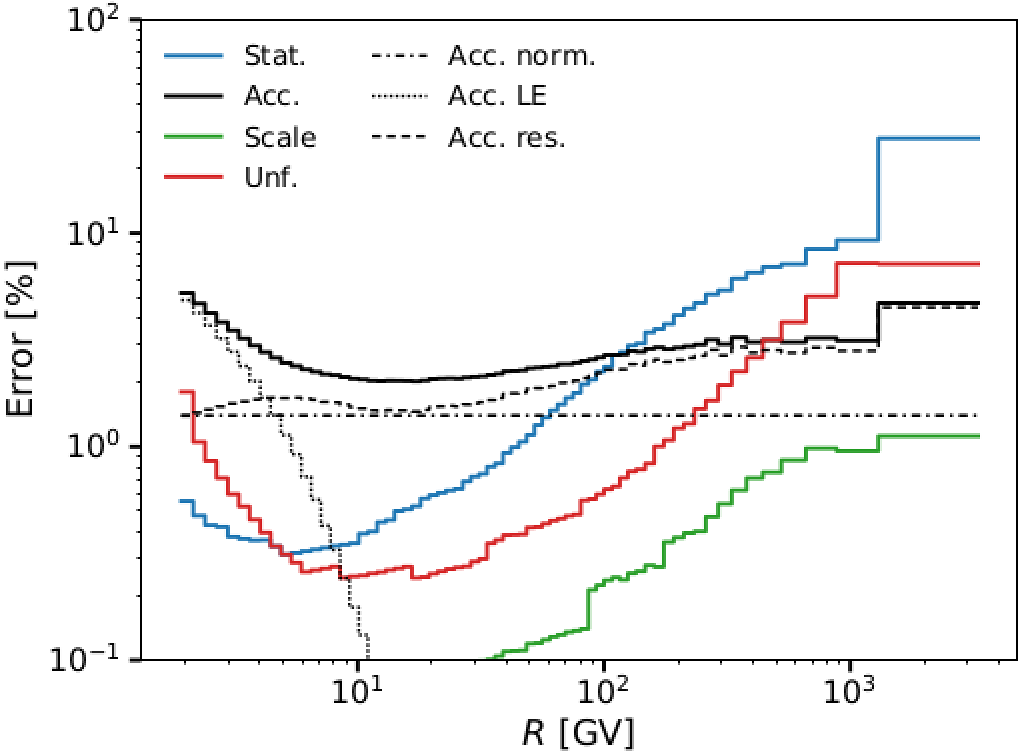
N.B.: access "all" CR data via CRDB
DM et al. (2014, 2020)
https://lpsc.in2p3.fr/crdb/

A game-changing experiment
→ high precision data
→ anomalies detected in spectra

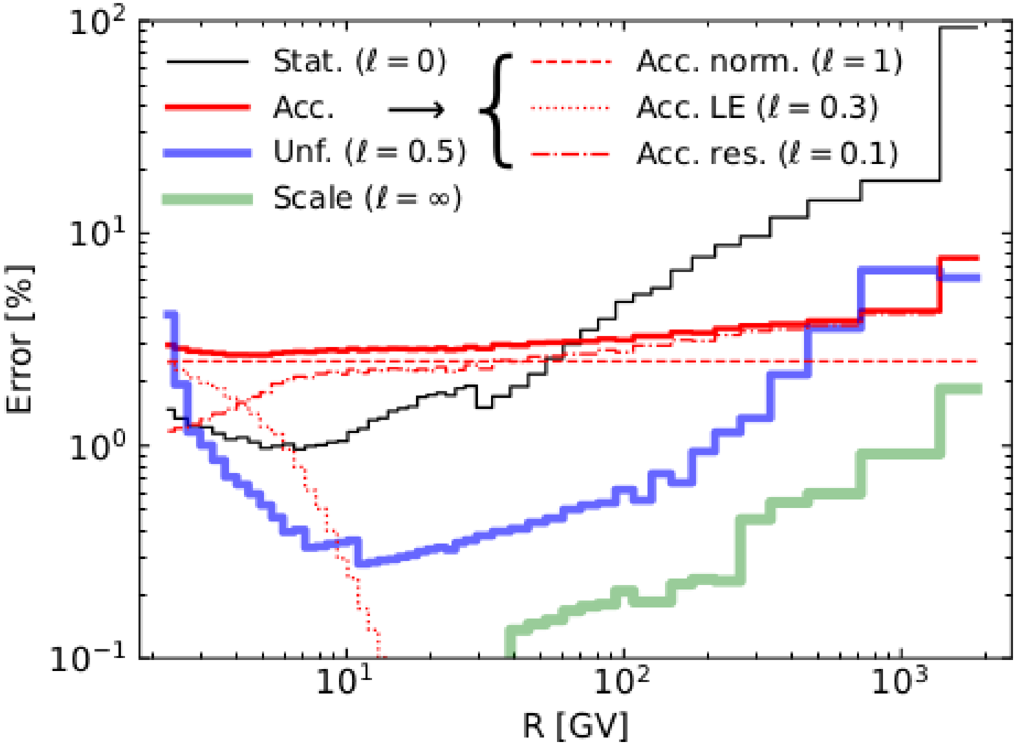
2) AMS-02 data: systematics-dominated (~ 3% at best)

AMS-02 data uncertainties
(Aguilar et al.)

B/C



F/Si



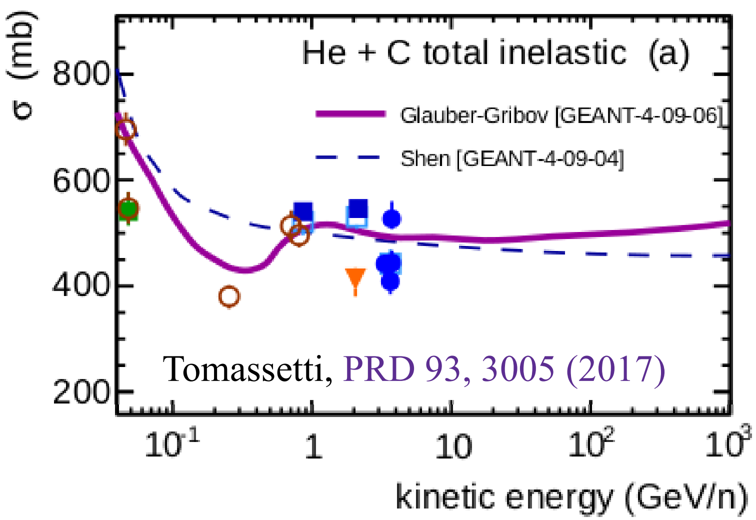
N.B.: dominated by statistical uncertainties above ~100 GV

2) Uncertainties *on* XS

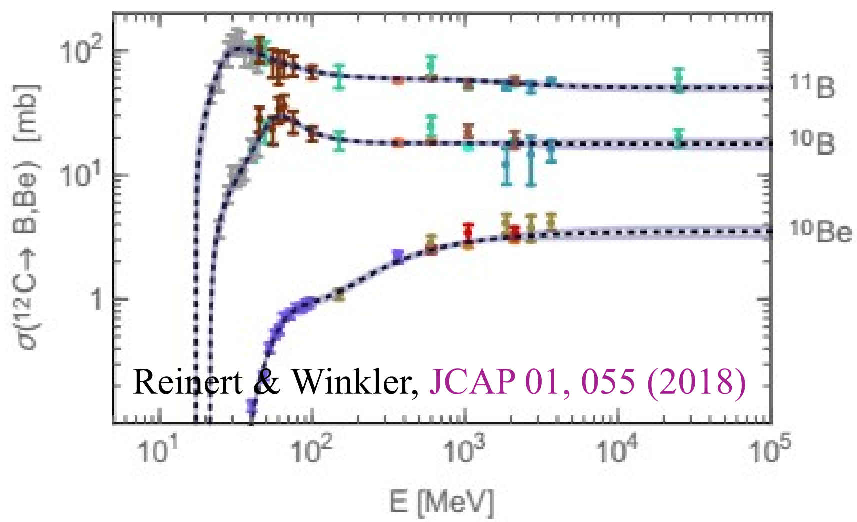
Reaction cross sections
(CR destruction)

Production cross sections
(creation of secondary species)

on targets
(ISM = 90% H+10% He)



Tomassetti, PRD 93, 3005 (2017)



Reinert & Winkler, JCAP 01, 055 (2018)

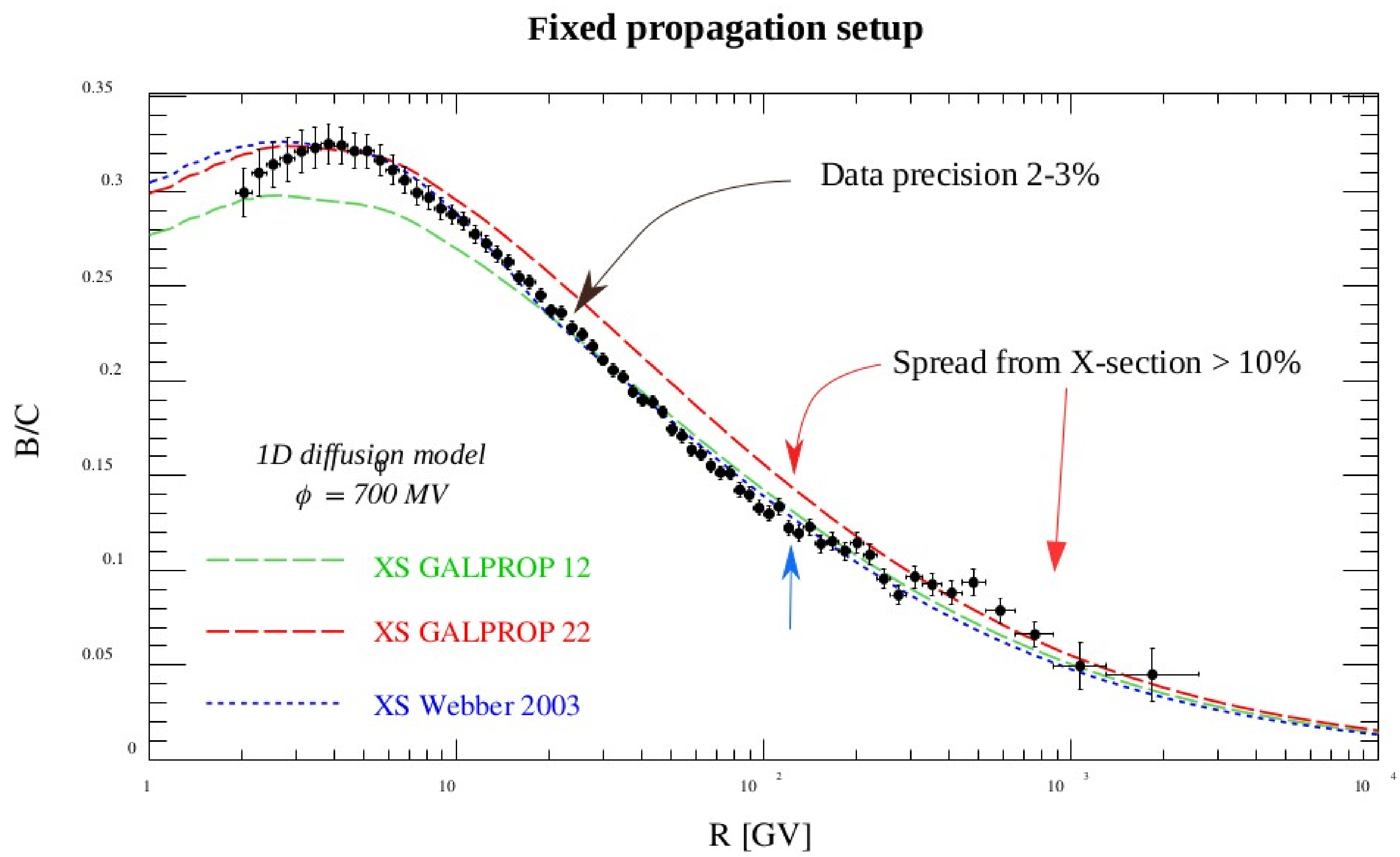
Uncertainties ~ 5-10% (on H)
→ **mostly OK in AMS02 era**

Uncertainties ~ 10-20% (on H)
→ **big issue in AMS02 era!**

2) Uncertainties *on GCRs from* production XS

Systematics from XS dominate over data CR uncertainties

(e.g., DM, Putze, and Derome, A&A 516, 67 (2010))

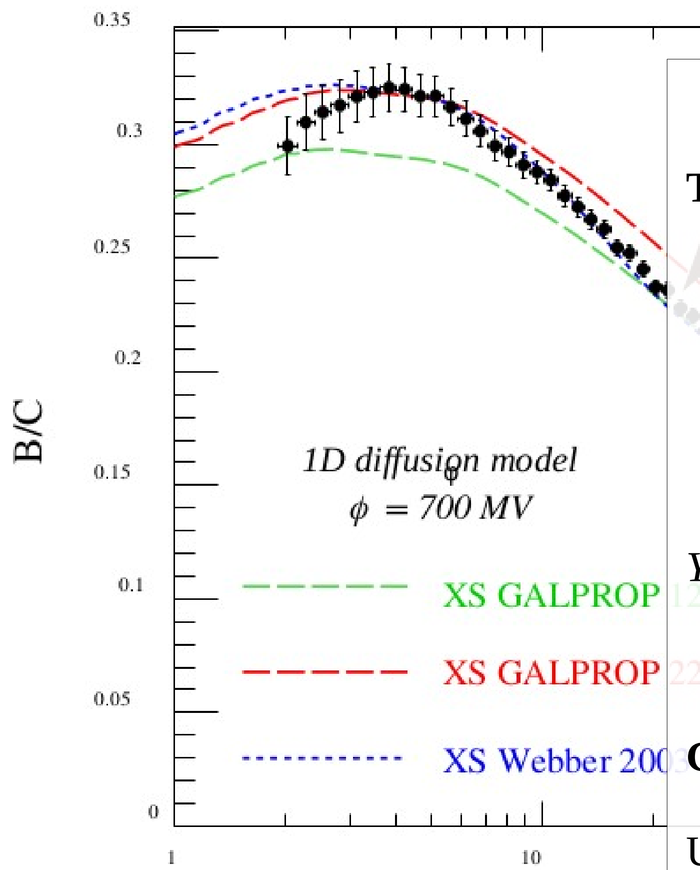


2) Uncertainties *on GCRs from* production XS

Systematics from XS dominate over data CR uncertainties

(e.g., DM, Putze, and Derome, A&A 516, 67 (2010))

Fixed propagation setup



XS Parametrisations

Two "historical" groups/codes

- <u>WNEW</u> (Webber et al., up to 2003): semi-empirical formula based on "regularities" observed in data
- <u>YIELDX</u> (Tsao & Silberberg, up to 2000): semi-analytical formula "driven" by theory

Model parameters = global fit on all data
YIELDX better than WNEW for XS reaction with "no data"

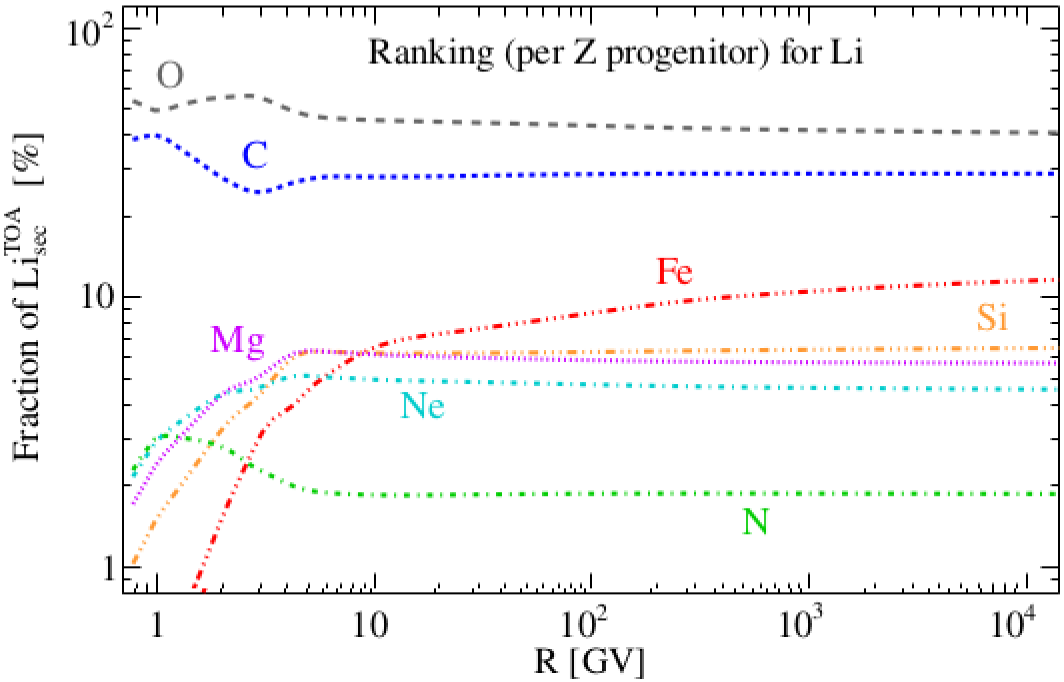
GALPROP implementation

Use of WNEW and YIELDX + rescaling on existing data (Moskalenko & Mashnick, 2003):

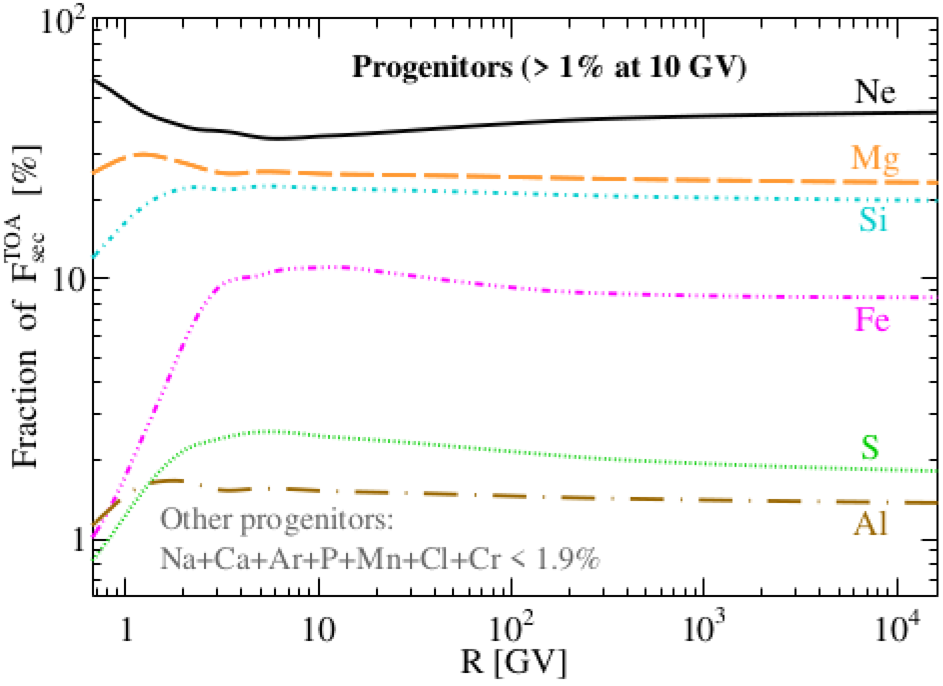
- Galp-opt12: starts from WNEW
- Galp-opt22: starts from YIELDX

2) Which GCR progenitors (projectiles)?

Lithium
DM et al. (2022)



Fluorine
Ferronato Bueno et al. (2022)



→ Main projectiles (for LiBeB and F): C, N, O, Ne, Mg, Si, Fe

but

Network of ~1000 reactions:
- Top 10 reactions make ~80% of flux
- Next 100 reactions makes ~15% of flux
- The rest makes up to ~5% of flux

Nuclear data coverage
- Most important reactions have data (but some only 1 point!)
- Most reactions have no data

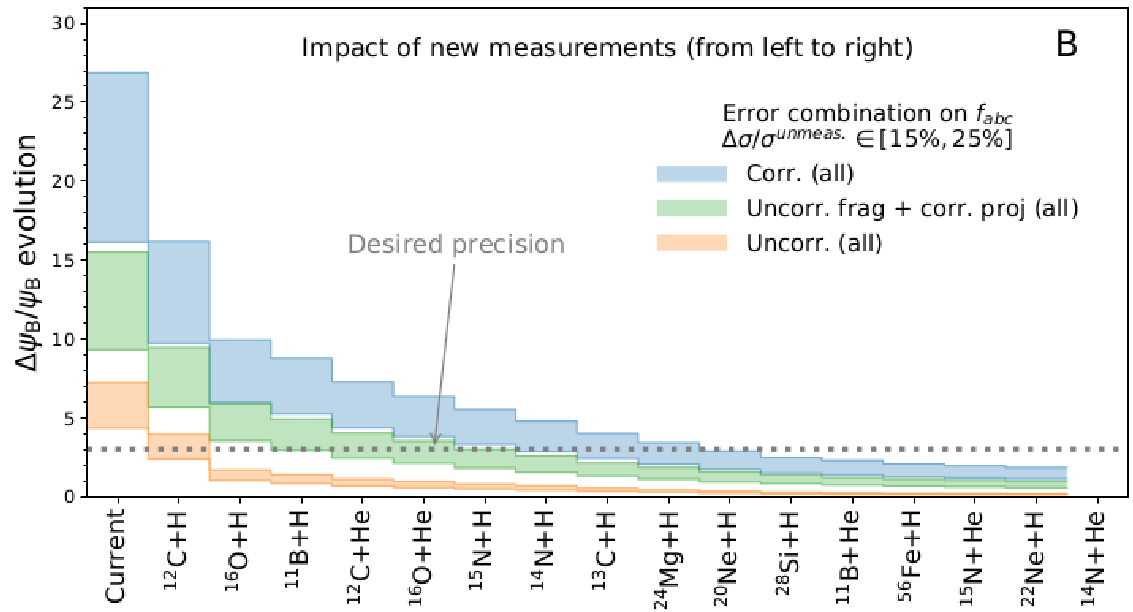
2) Which production XS

Génolini, DM, Moskalenko & Unger, PRC 98, 034611 (2019)

Ranking of XS (for B here)

Reaction $a+b\to c$	Flux impact f_{abc} [%] min	mean	max	σ [mb] range	Data
$\sigma(^{12}C+H\to^{11}B)$	18.0	**18.1**	19.0	30.0	✓
$\sigma(^{12}C+H\to^{11}C)$	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	✓
$\sigma(^{16}O+H\to^{11}C)$	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	
$\sigma(^{12}C+He\to^{11}C)$	2.10	**2.14**	2.20	32.0	
$\sigma(^{15}N+H\to^{11}B)$	2.00	**2.03**	2.10	26.1	✓
$\sigma(^{12}C+H\to^{10}C)$	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	
$\sigma(^{14}N+H\to^{11}C)$	0.90	**0.92**	0.94	11.9	
$\sigma(^{20}Ne+H\to^{11}B)$	0.87	**0.90**	0.93	12.0	
$\sigma(^{16}O+He\to^{11}C)$	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	
$\sigma(^{13}C+H\to^{11}C)$	0.54	**0.56**	0.59	8.2	
$\sigma(^{20}Ne+H\to^{11}C)$	0.52	**0.54**	0.56	7.2	✓
$\sigma(^{24}Mg+H\to^{11}C)$	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]	
$\sigma(^{28}Si+H\to^{11}C)$	0.42	**0.44**	0.46	[4.3, 5.0]	
$\sigma(^{15}N+H\to^{11}C)$	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	✓
$\sigma(^{12}C+He\to^{10}C)$	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	

Desired measurements to reach 3% precision on GCRs



→ Done for LiBeB in this paper
→ All nuclei up to Si (in progress) then Fe

Galactic

1) GCR propagation in brief

2) Production XS in the AMS02 era

3) GCR perspective for NA61/SHINE

3) NA61: measurement of C fragmentation

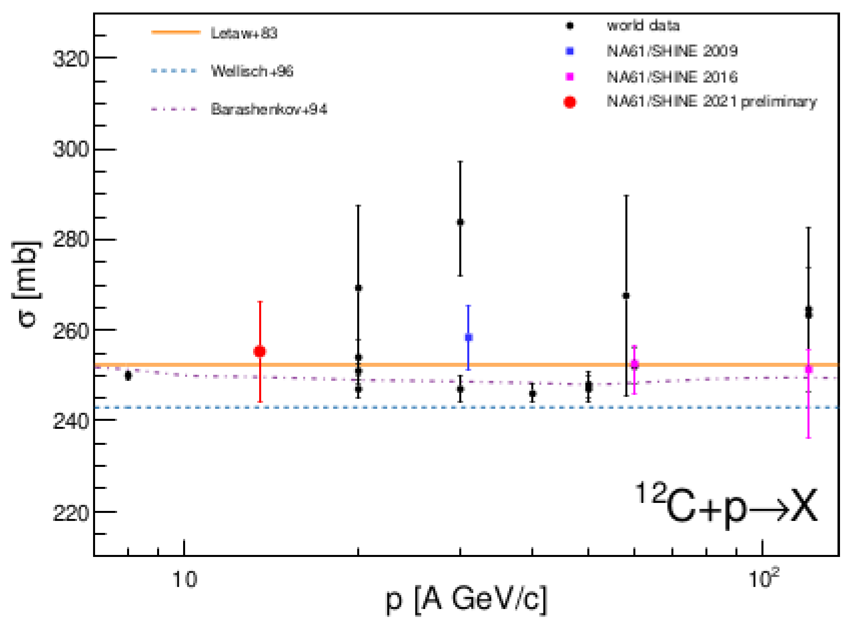
Proposal for test study (M. Unger)

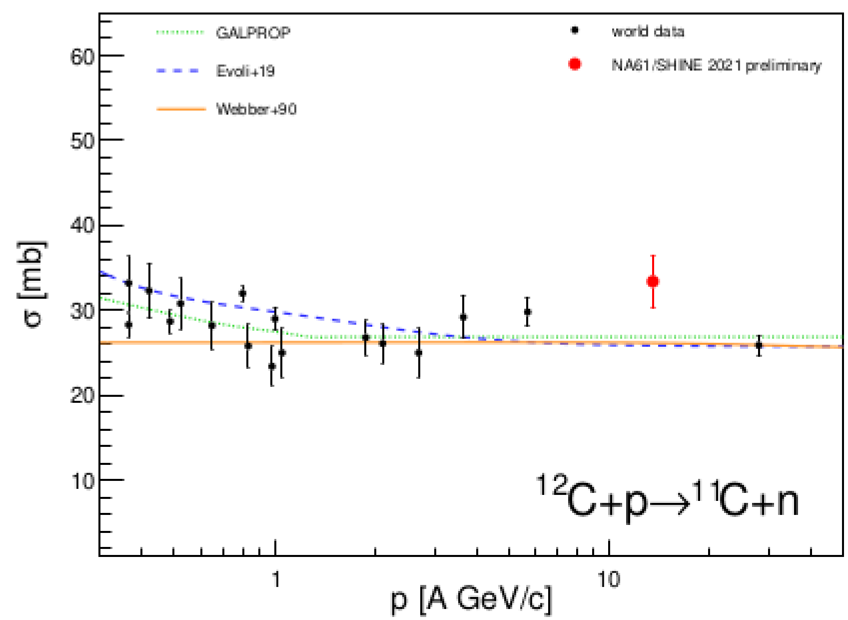
September 27, 2017

Addendum to the NA61/SHINE Proposal SPSC-P-330

Measurement of Nuclear Fragmentation Cross Sections with NA61/SHINE at the CERN SPS

Unger & NA61 collaboration (arXiv:1909.07136)
Amin & NA61 collaboration (arXiv:2107.12275)





3) NA61: measurement of C fragmentation

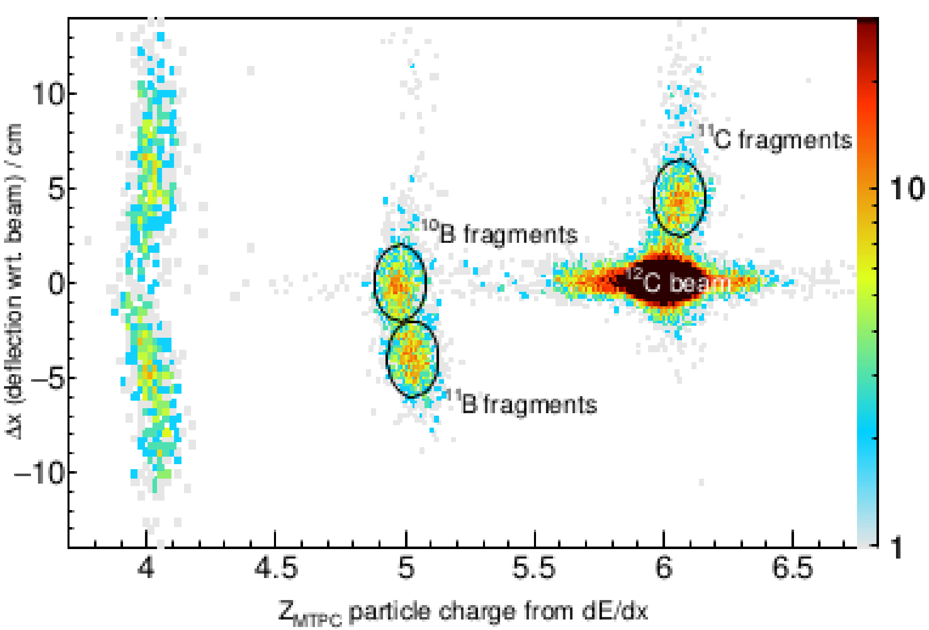
Proposal for test study (M. Unger)

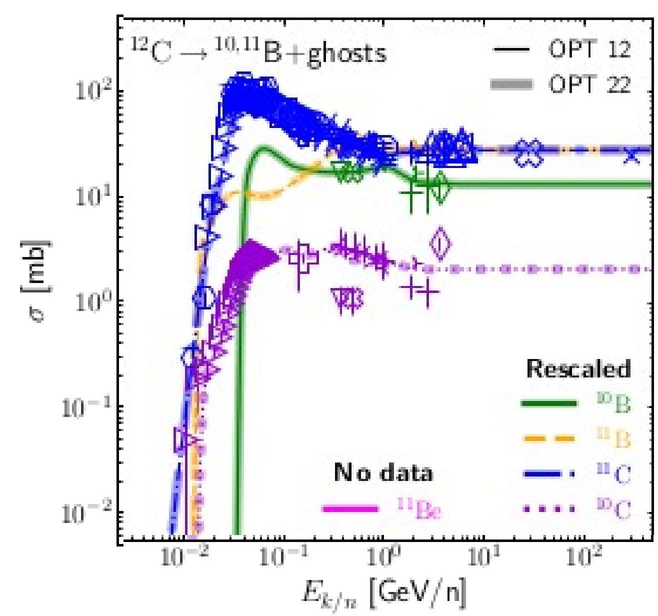
September 27, 2017

Addendum to the NA61/SHINE Proposal SPSC-P-330

Measurement of Nuclear Fragmentation Cross Sections with NA61/SHINE at the CERN SPS

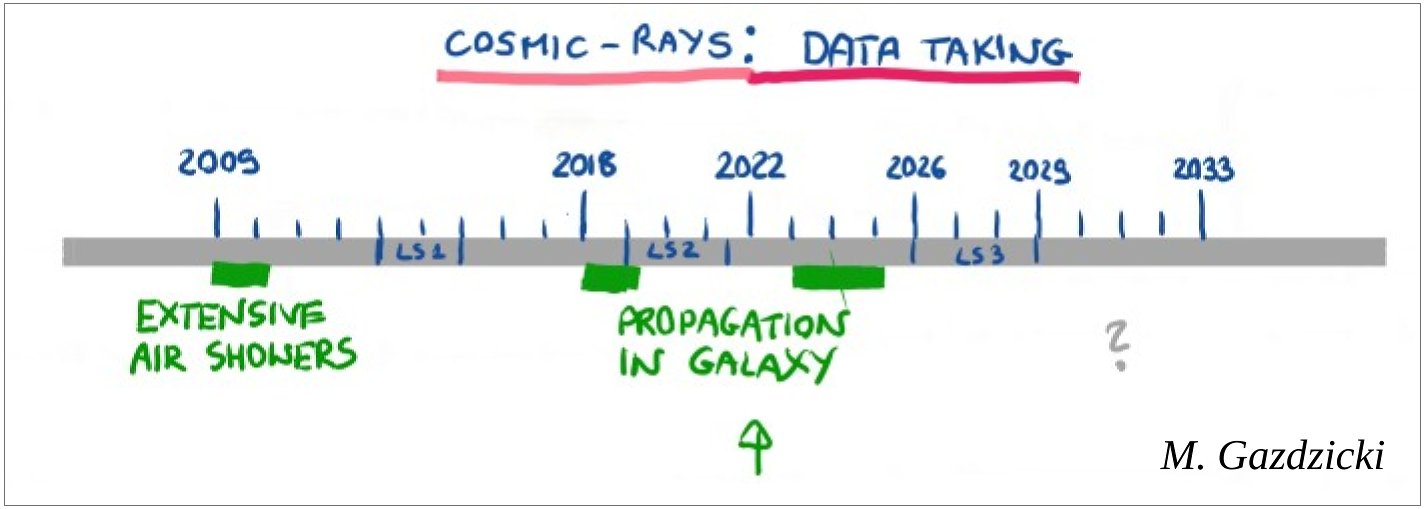
Unger & NA61 collaboration (arXiv:1909.07136)
Amin & NA61 collaboration (arXiv:2107.12275)





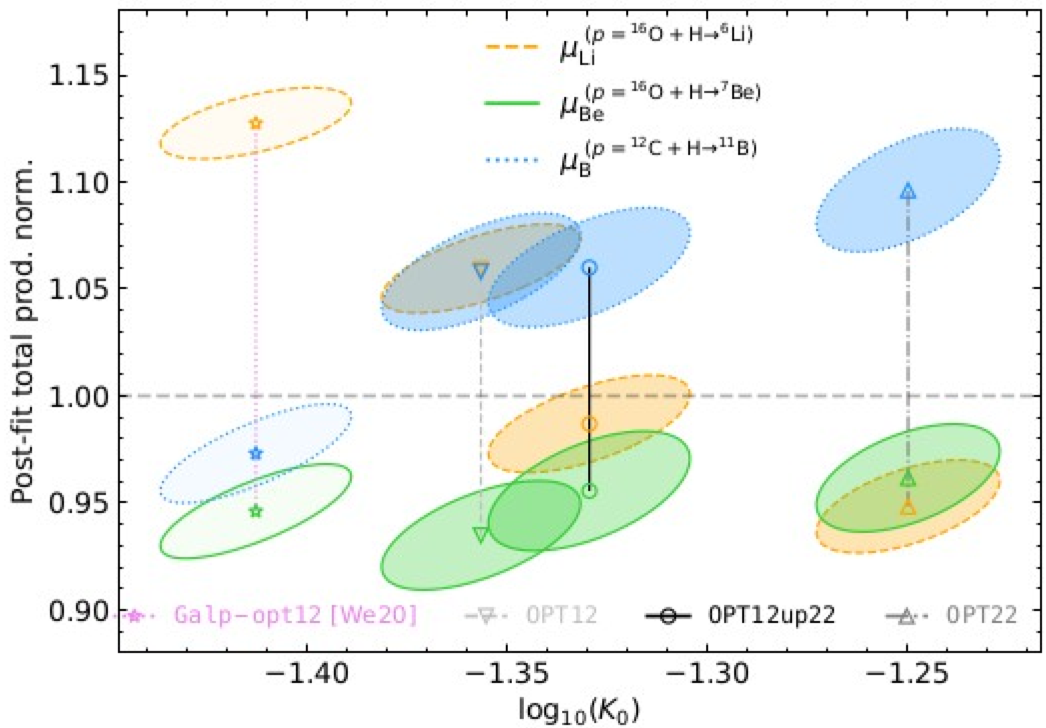
→ Also desired data for ^{10}B and ^{11}B (DM et al. 2022)

3) First (GCR) physics run at NA61 is going to be huge!

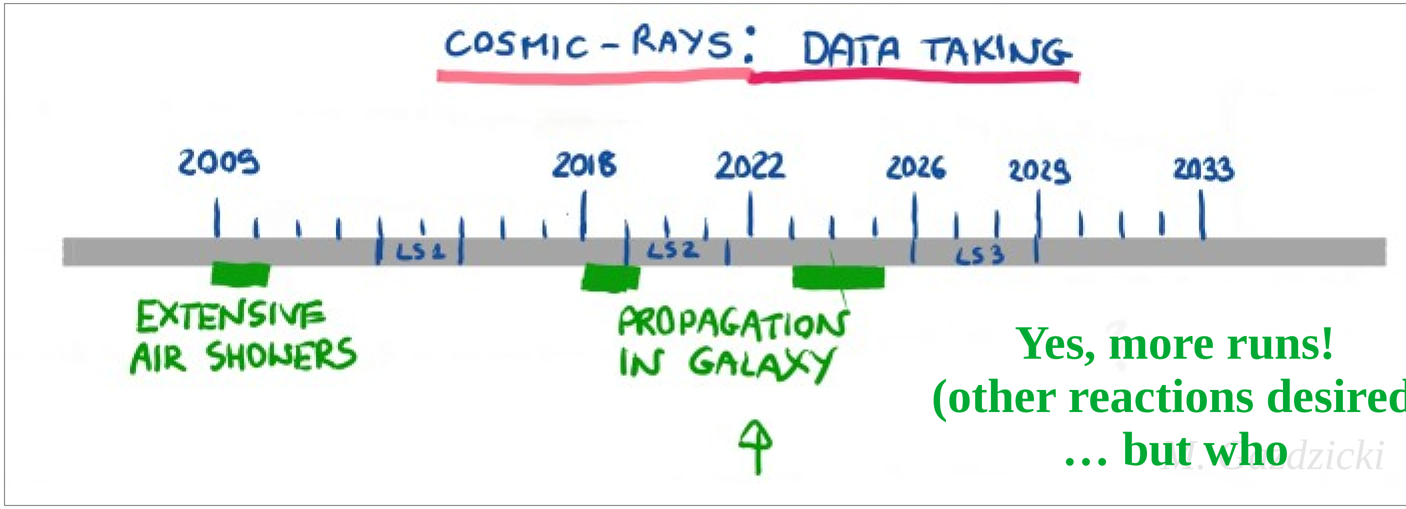


Many recent GCR papers focus on XS...
Derome et al. (2018)
Evoli et al. (2018)
Génolini et al. (2018)
Reinert & Winkler (2018)
De La Torre Luque et al. (2021a,b)
Korsmeier & Cuoco (2021)
DM et al. (2022)

Primary source of Li in GCRs or XS?
Boschini...Moskalenko et al. (2020)
DM et al. (2022)



What next?



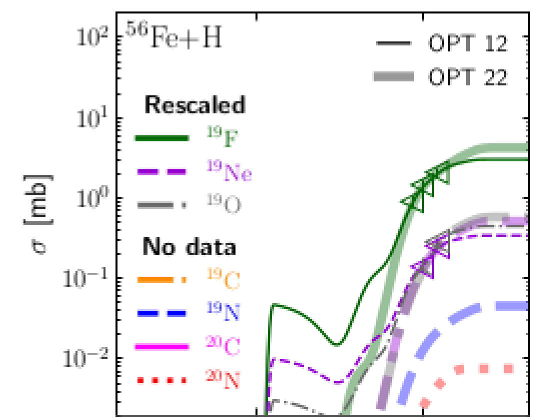
Yes, more runs!
(other reactions desired)
… but who

XS ranking
(Génolini, DM, Moskalengo, Unger)

→ Up to Si, then up to Fe (Z=17-25 AMS data not yet published)
→ Provide progenitors/targets required and estimated beam time

XS modelling
(DM, Génolini...)

→ Update our XS database (extracted from EXFOR)
→ Use machine learning to
- predict unmeasured XS
- ID key reactions (to measure) for models



XS measurement

→ (He) CNO, Ne, Mg, Si, and Fe main projectiles
→ (2H, 3He) LiBeB, F, and sub-Fe main fragments

Debate with F: primary source (Boschini et al. 2021), XS (Ferronato Bueno et al. 2022), spatial dependent diffusion (Zhao et al. 2022)