Interpretation of cosmic-ray data: the need for nuclear production cross sections (XS)

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NA61/SHINE Beyond 2020
University of Geneva
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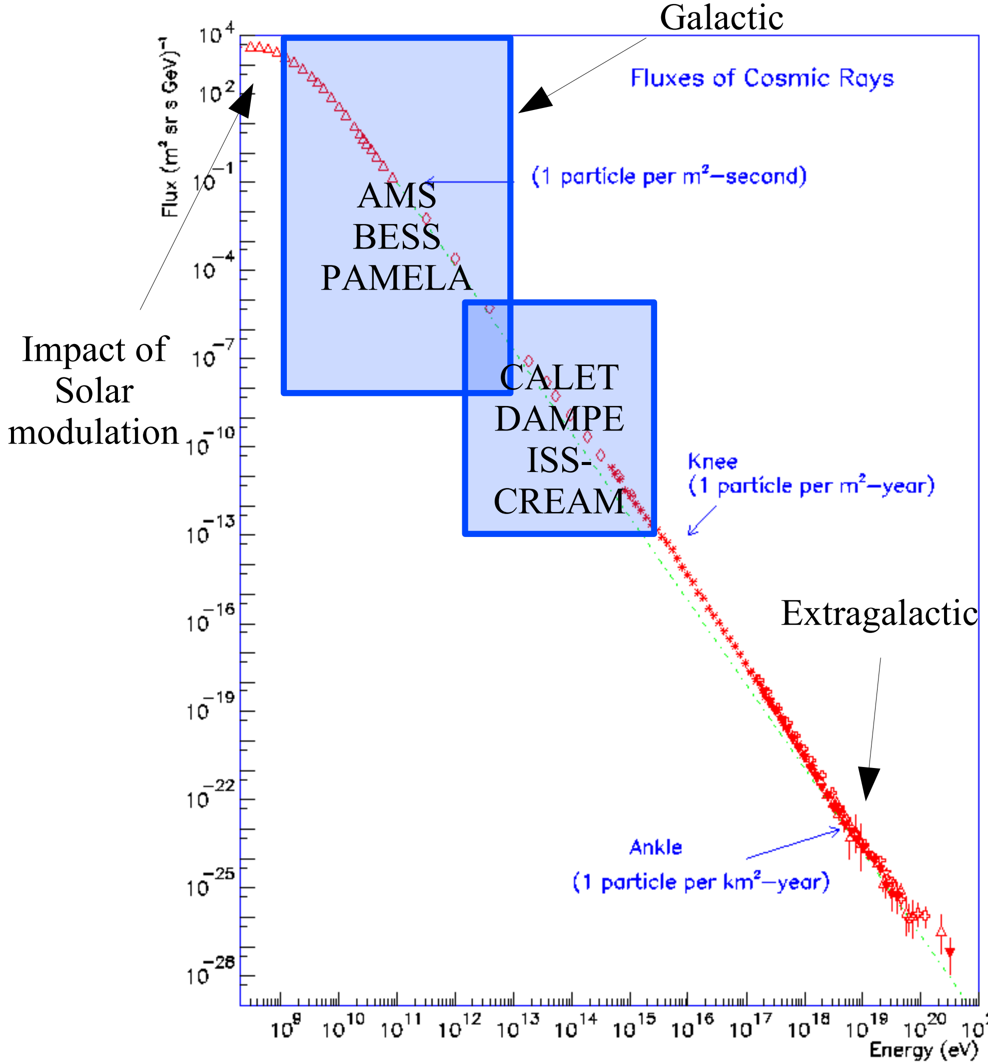
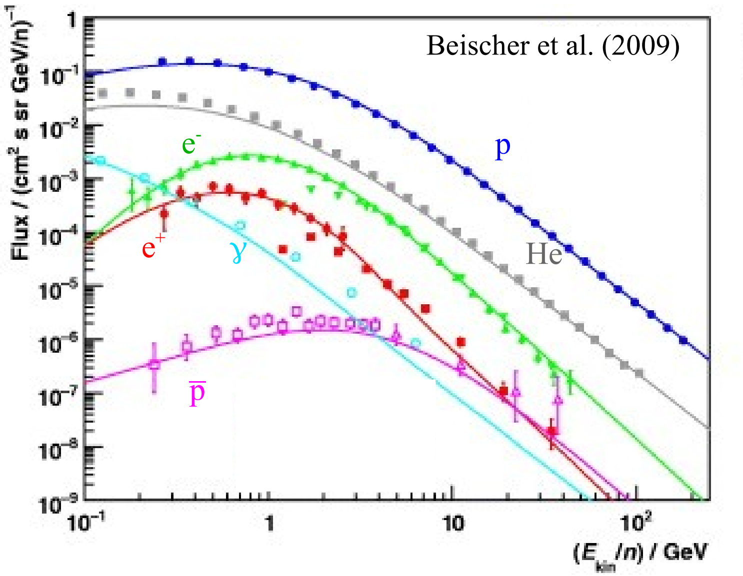
1. Introduction: GCR spectrum and composition

Spectral shape



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

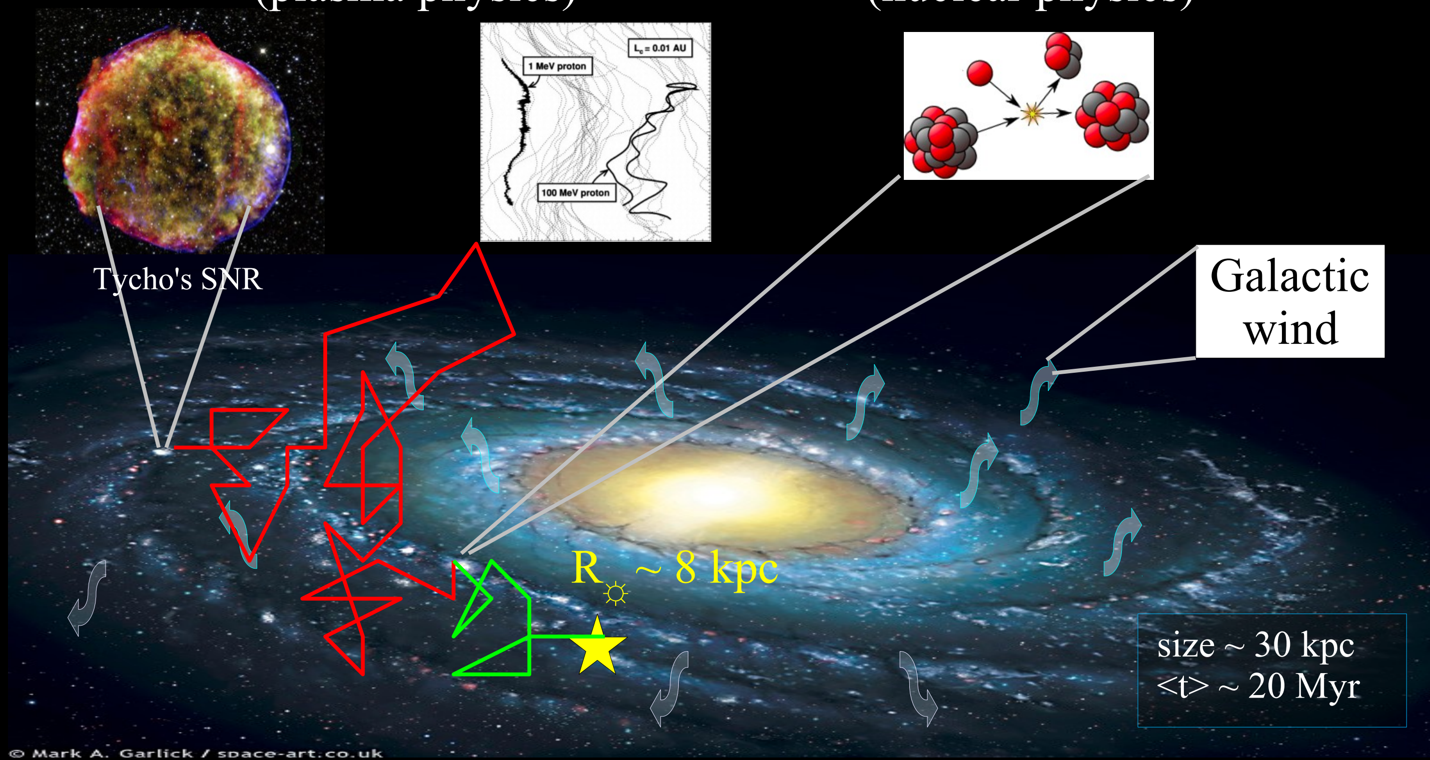


N.B.: rare CRs produced by H,He + ISM
→ How well do we know the astro. production?
→ Is it a good place to look for dark matter?

→ Acceleration mechanisms: injection, efficiency, ...
→ Transport: diffusion, convection, energy gain and losses...
→ CR anisotropy $\delta<10^{-3}$ ($\neq$ E and species)

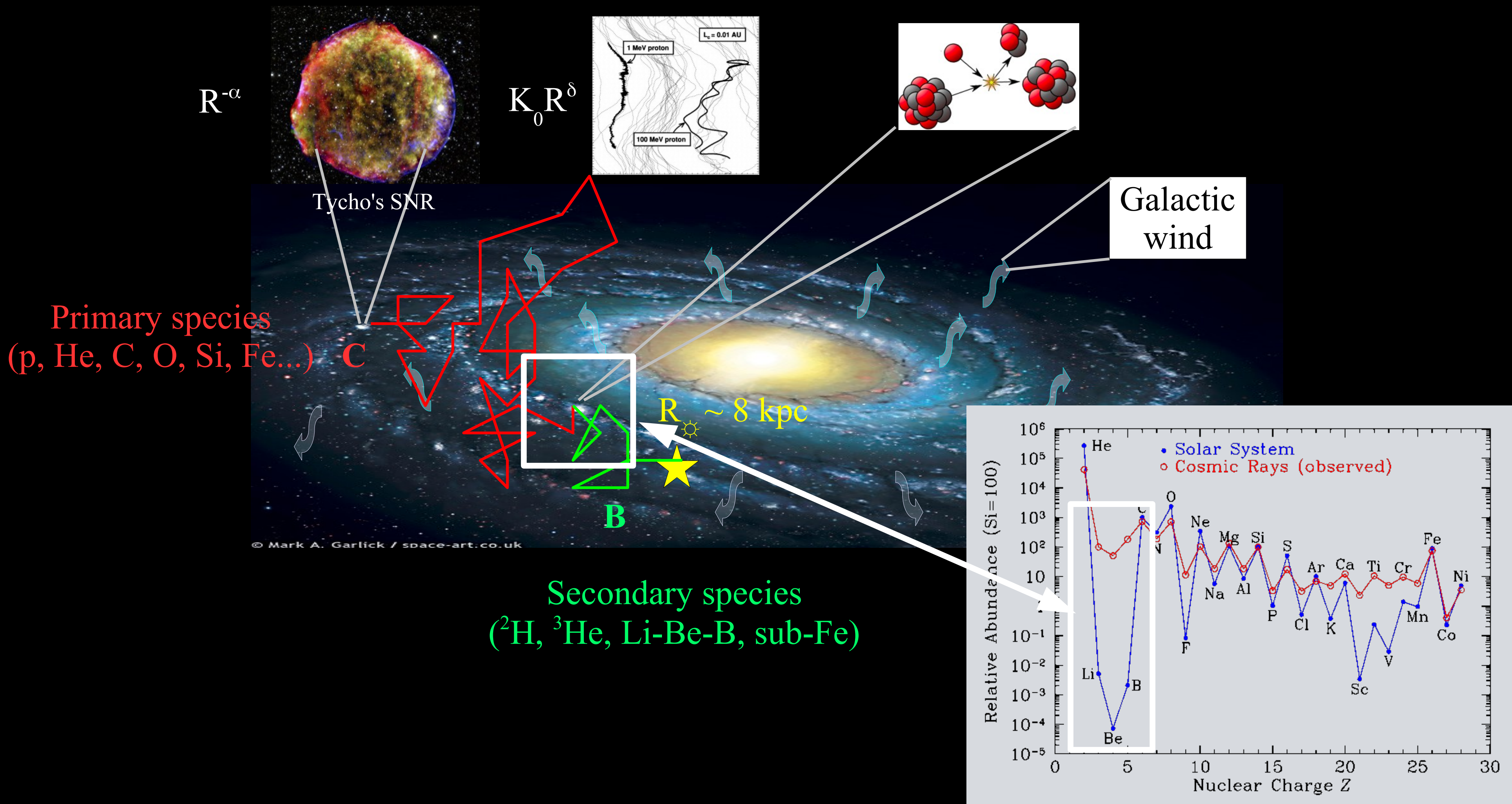
1. Introduction: GCR journey

(plasma physics) (nuclear physics)



(astrophysics + particle physics)

1. Introduction: GCR nuclear interaction

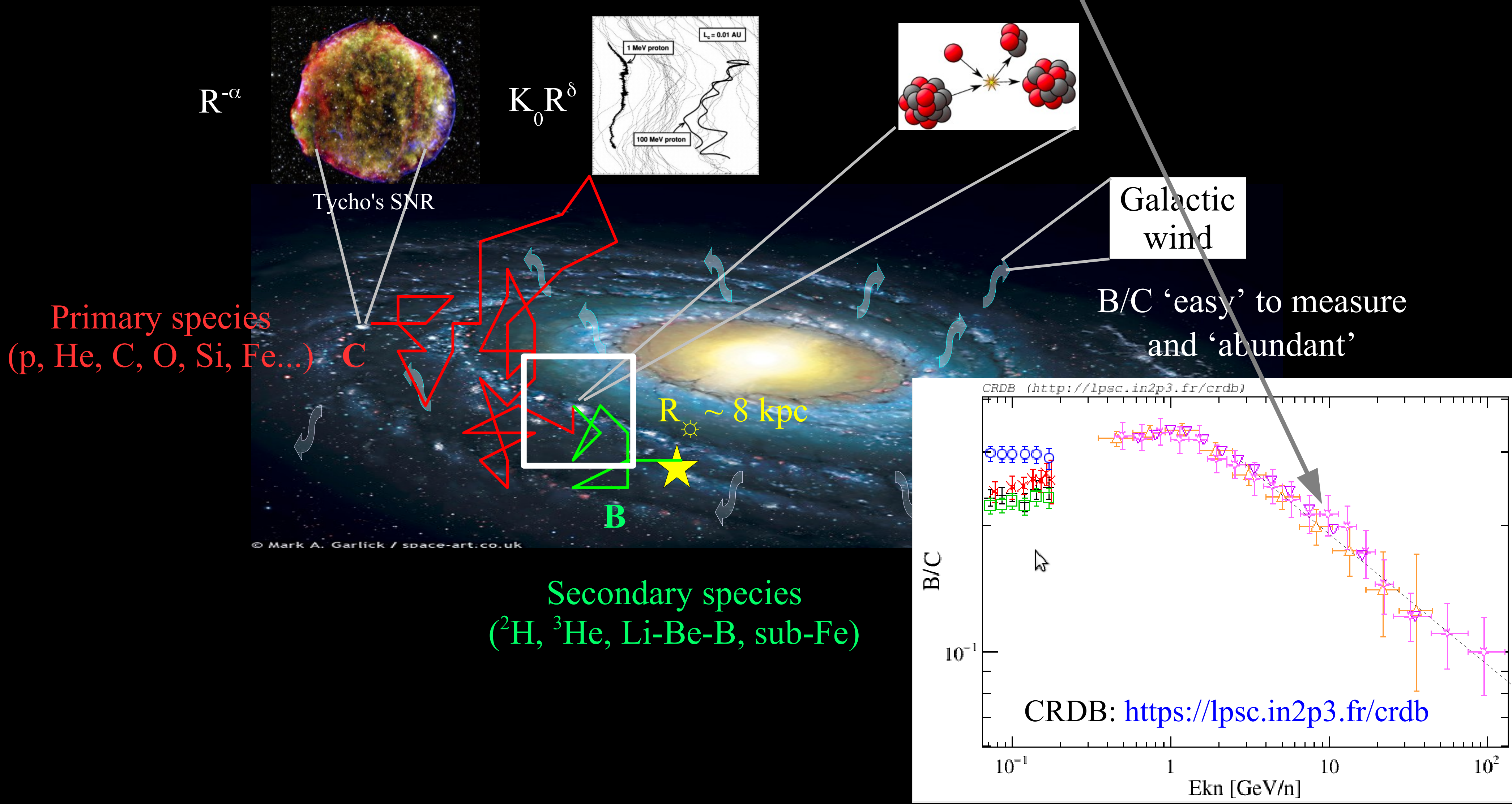


1. Introduction: secondary-to-primary ratio

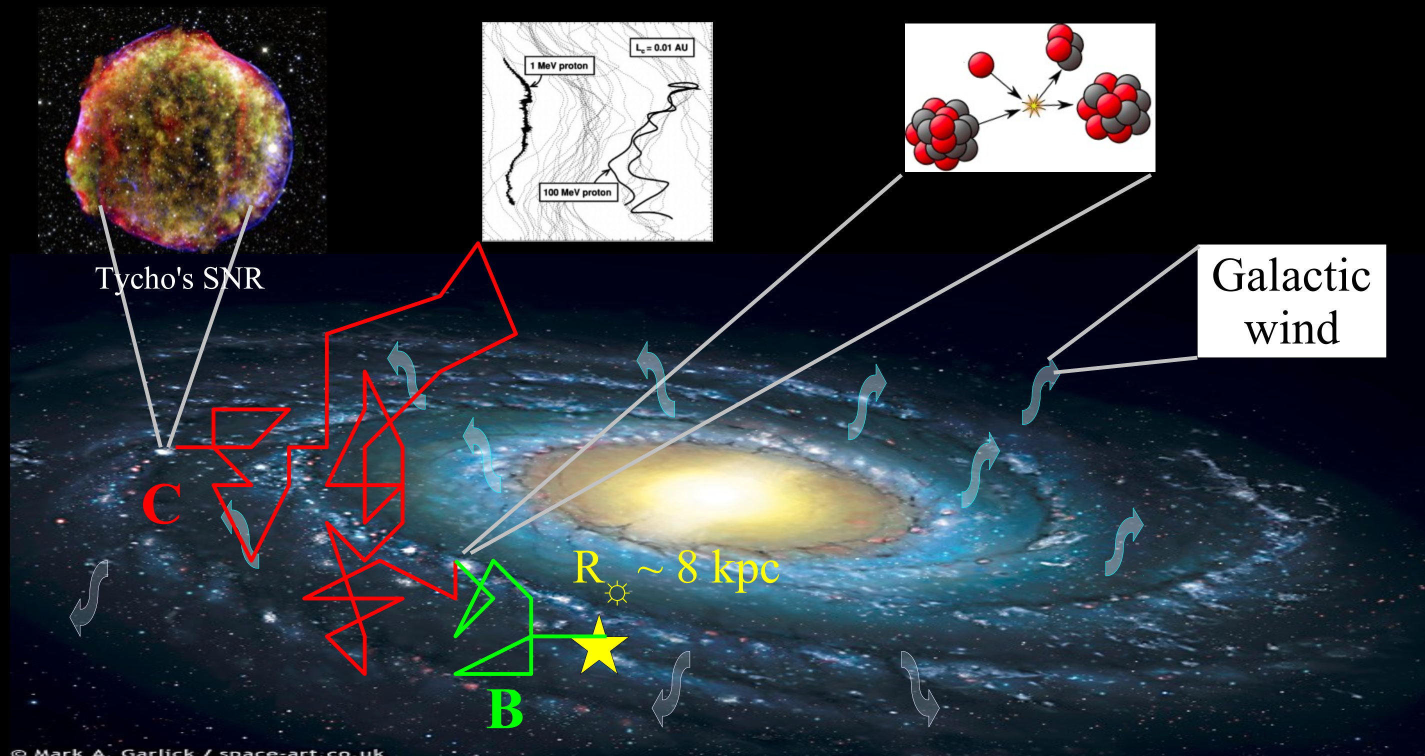
Primary species P: source/diffusion ~ $R^{-(\alpha+\delta)}$

Secondary species S: $(\sigma^{P\rightarrow S} \,.\, P)$/diffusion ~ $R^{-(\alpha+2\delta)}$

→ **Secondary to primary ratio: $\sigma^{P\rightarrow S} \,.\, R^{-\delta}$**

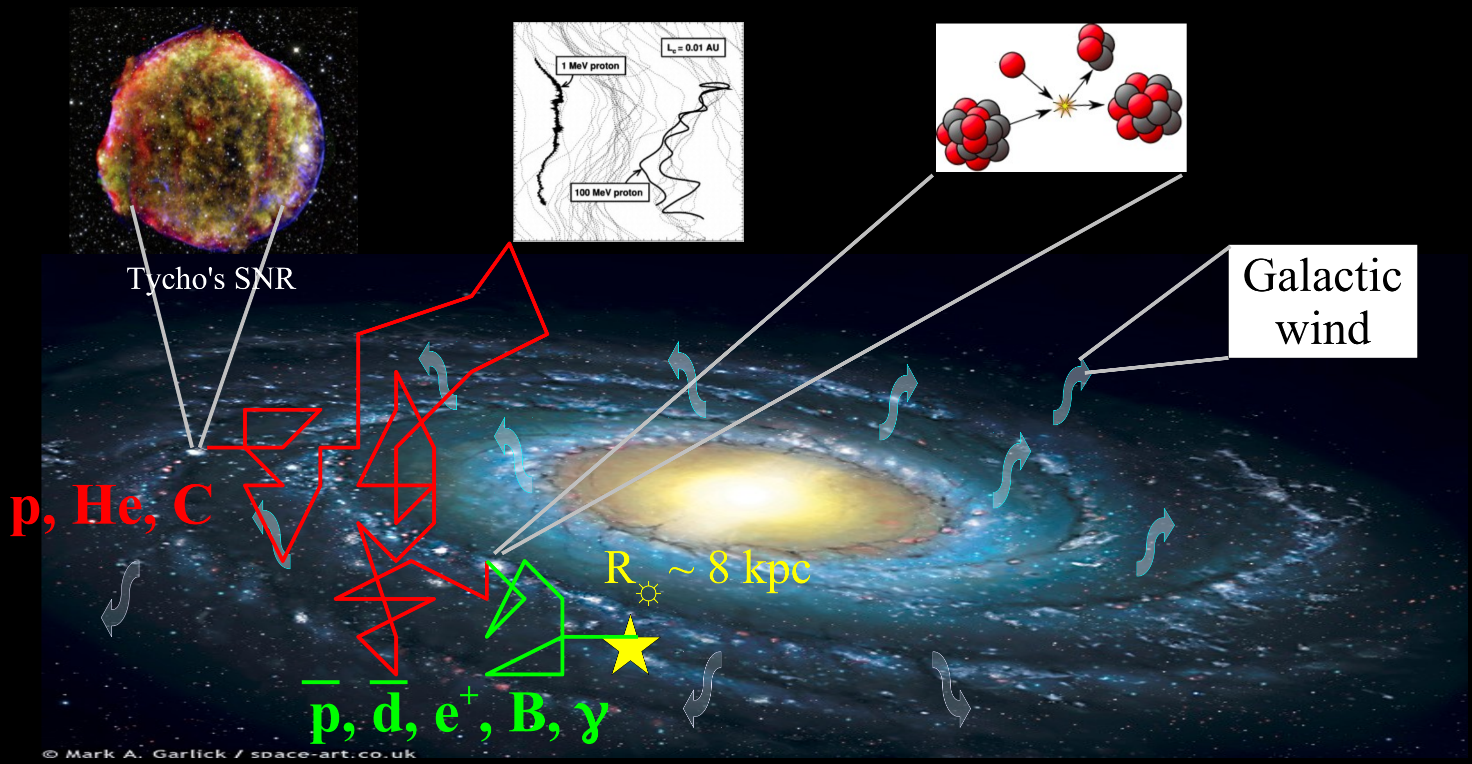


1. Introduction: B/C to calibrate transport



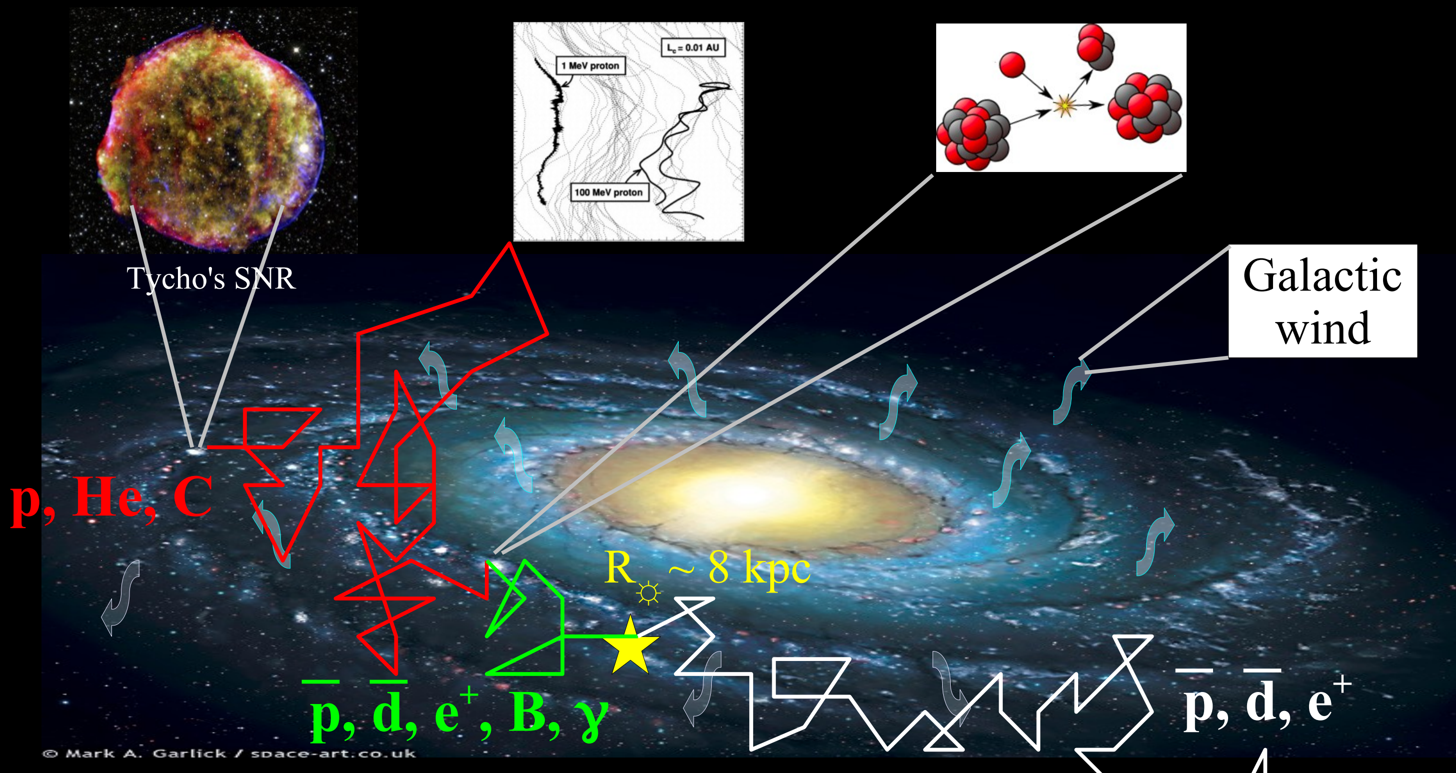
→ Transport parameters calibrated on B/C

1. Introduction: rare channel and astrophysical background



→ Same propagation history for B/C, or pbar/p
(apply previously derived parameters)

1. Introduction: rare channel and dark matter signal



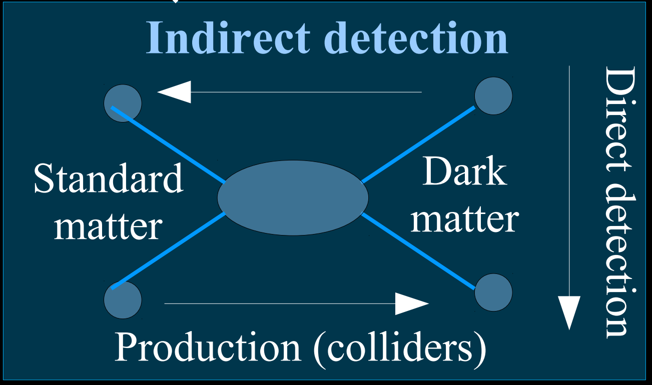
→ Same transport but different origin
(from DM halo)

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

→

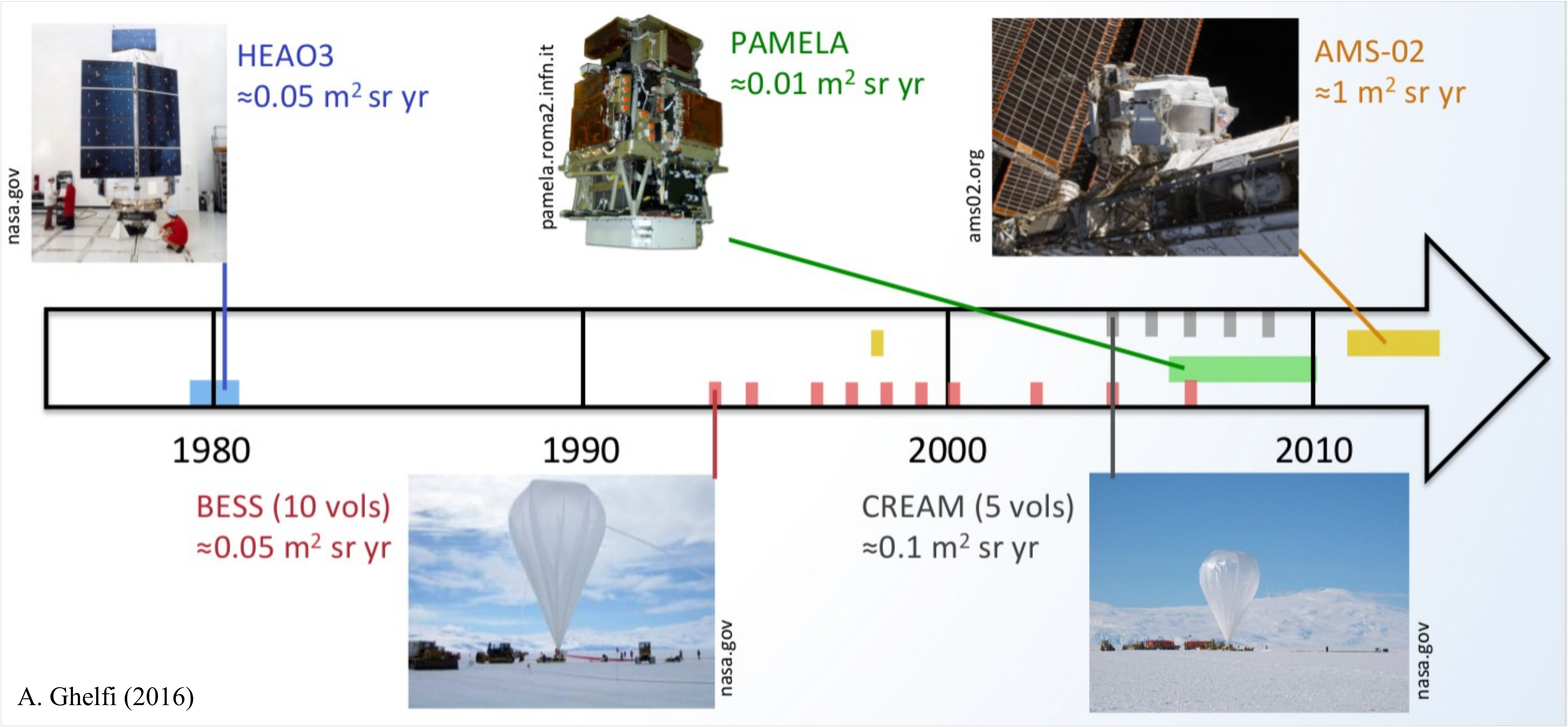


1. Introduction: Galactic cosmic-rays (GCR)
2. A quick tour of AMS-02 recent results
3. Nuclear XS: a limiting factor to go further
4. XS wanted! A roadmap for NA61
5. Conclusions

Take away message

→ AMS-02 results are changing the field of CR physics (high precision data and anomalies in spectra)

2. Recent results: high precision era with AMS-02

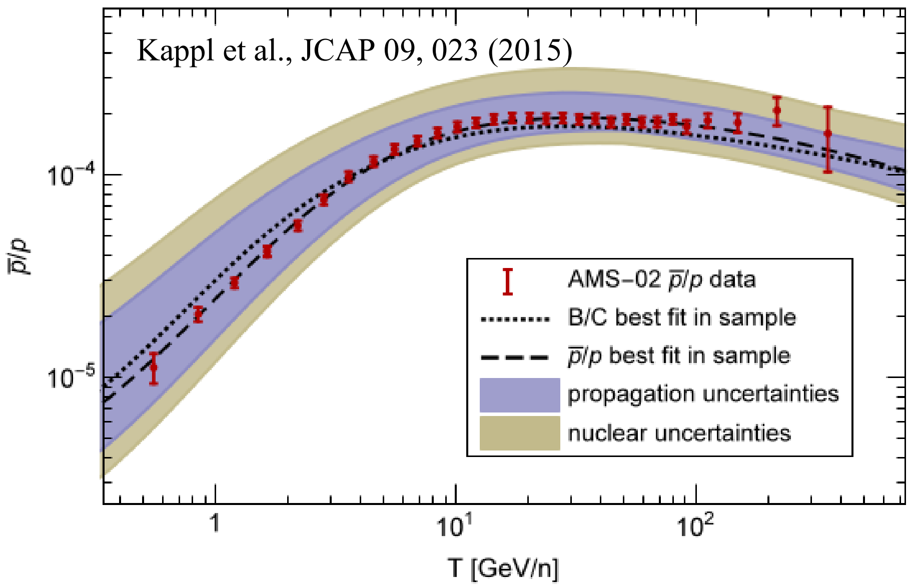


AMS-02

• Particle physics detector in space (redundancy, robust identification)
• Spectra for nuclei, antiprotons, and leptons

→ Several times the statistics of all CRs ever measured
→ Typical 1-3% accuracy from GV to TV

2. Recent results: antiprotons and positron fraction

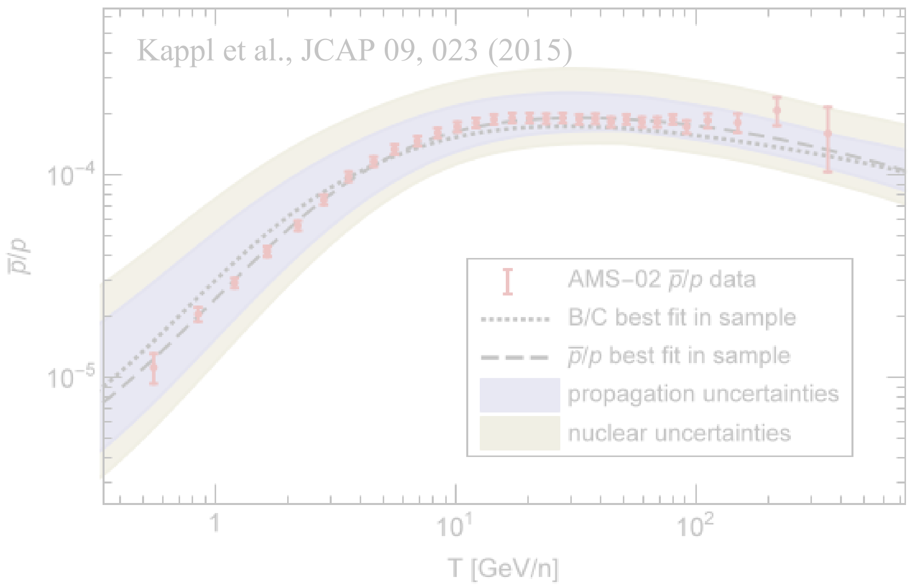


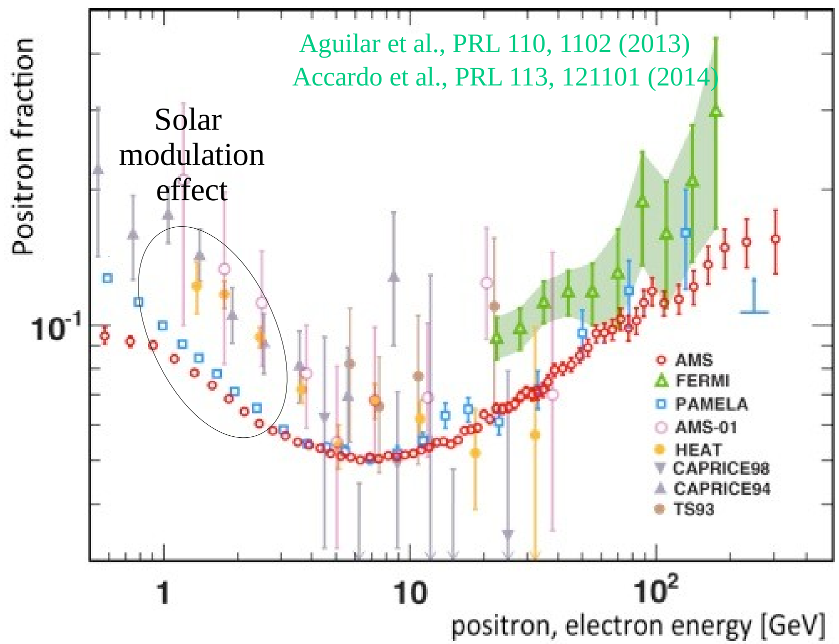
Antiprotons

→ Seems consistent with astrophysics only

See F. Donato and N. Tomassetti's talks (this afternoon)

2. Recent results: antiprotons and positron fraction





Antiprotons

→ Seems consistent with astrophysics only

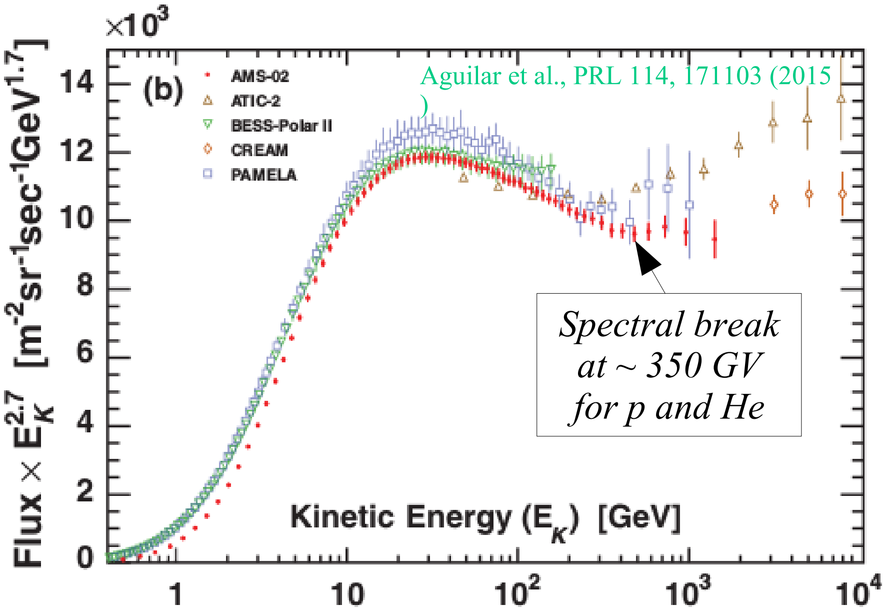
See F. Donato and N. Tomassetti's talks (this afternoon)

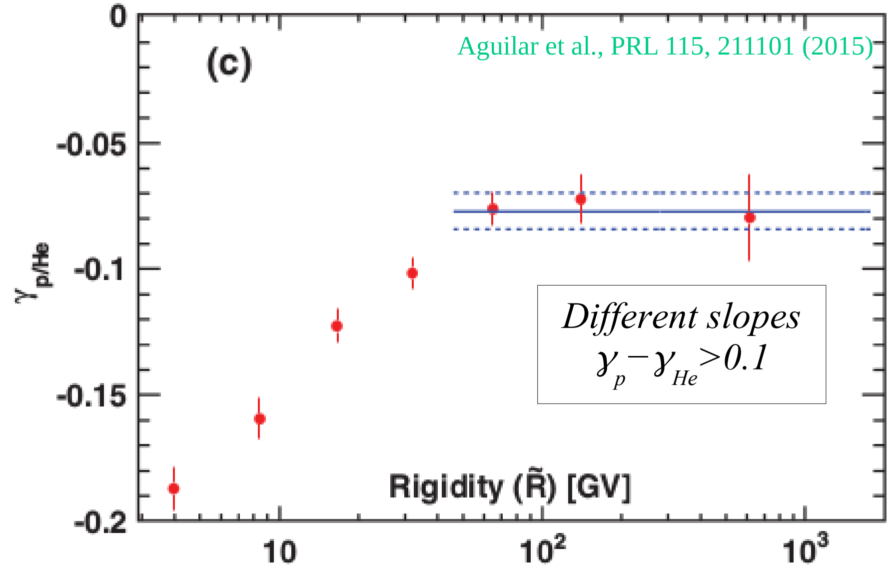
Positron fraction, e^-, e^+ and e^-+e^+ spectra used to test astrophysical and/or dark matter hypothesis

- 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)

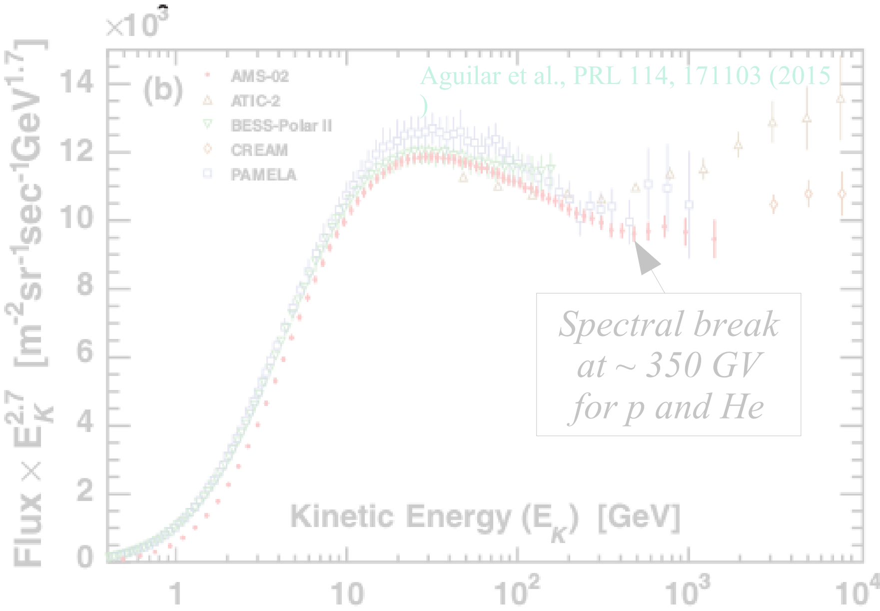
2. Recent results: p and He, B/C

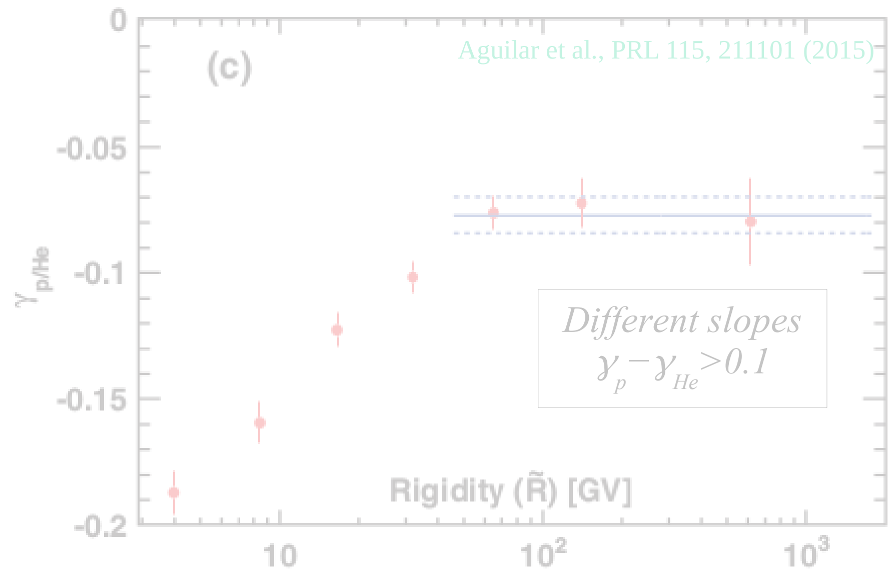


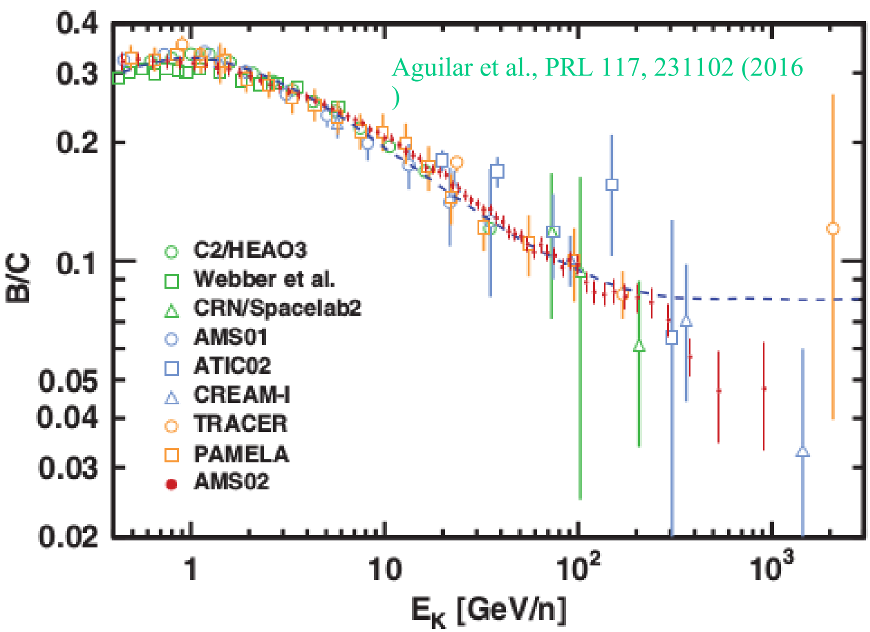


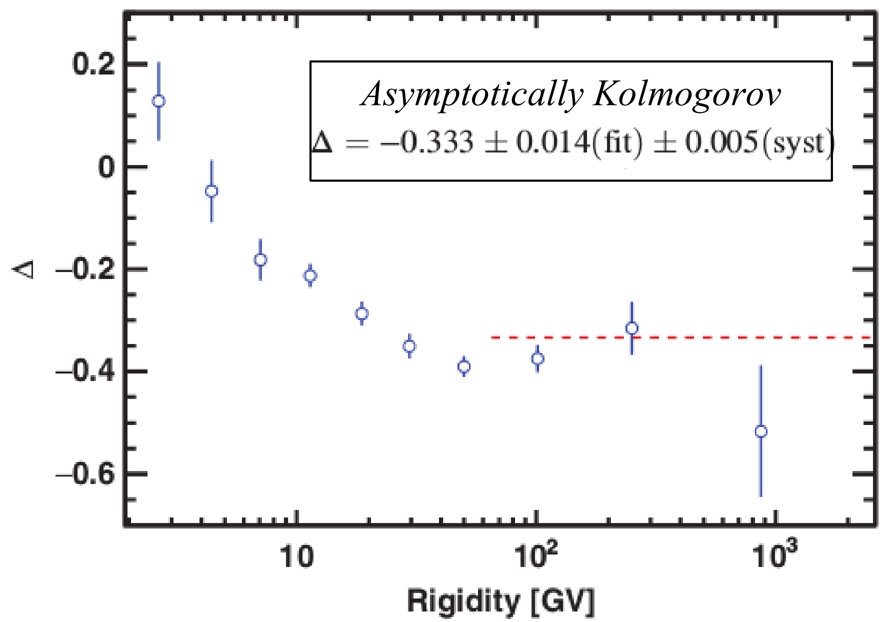
→ Spectral break @ 350 GeV (p and He)
→ Different power-law slope for H and He

2. Recent results: p and He, B/C









→ Need to explore slope for other primary (C, O) and secondary (Li, Be, B)
→ AMS-02 results (Li, Be, B, C, O) expected for this fall

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Take away message

→ 1G$ game-changing data ‘cannot be’ exploited because of GeV nuclear physics (XS uncertainties >> AMS-02 data uncertainties)

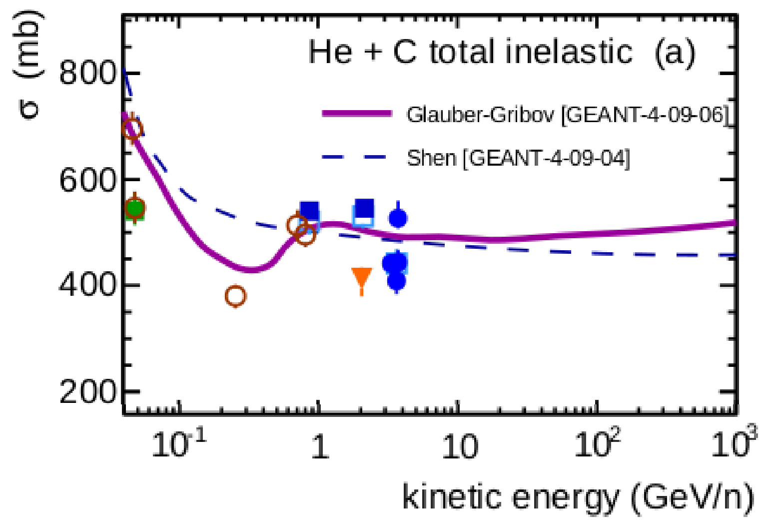
3. Nuclear XS: a limiting factor to go further

CR modelling requires

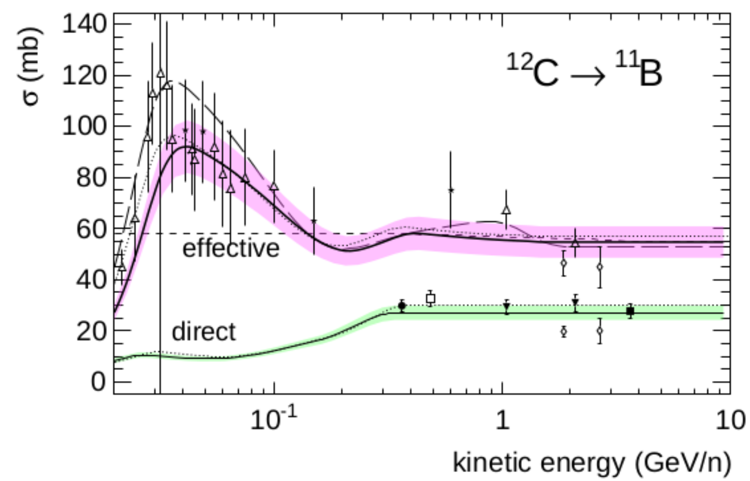
- Reaction cross-section (CR destruction)
- Production cross sections (secondary species)

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

Tomassetti: arXiv1707.06917



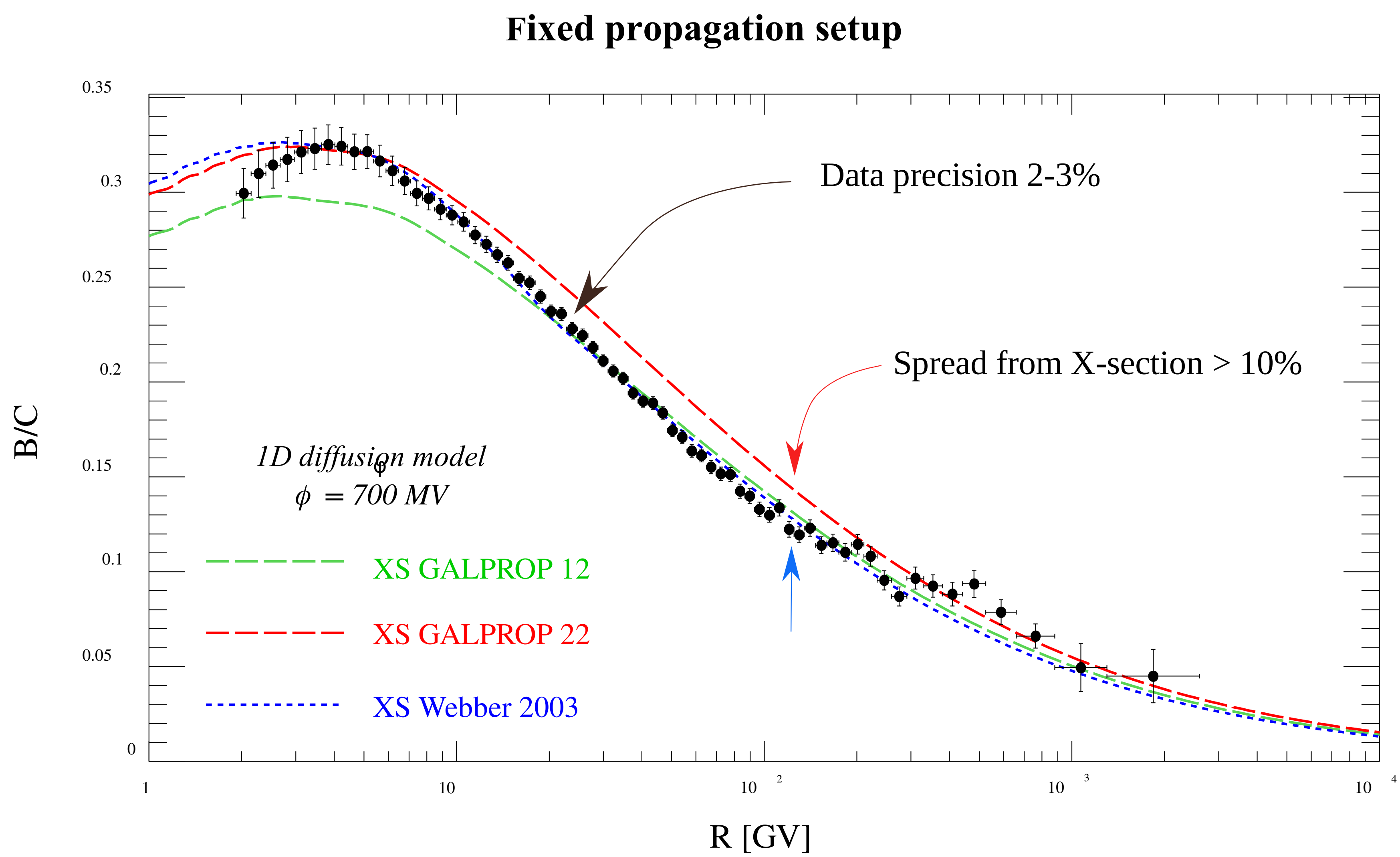
Various approaches
→ Microscopic
→ Semi-empirical
→ Parametric



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

→ No data above 5 GeV/n

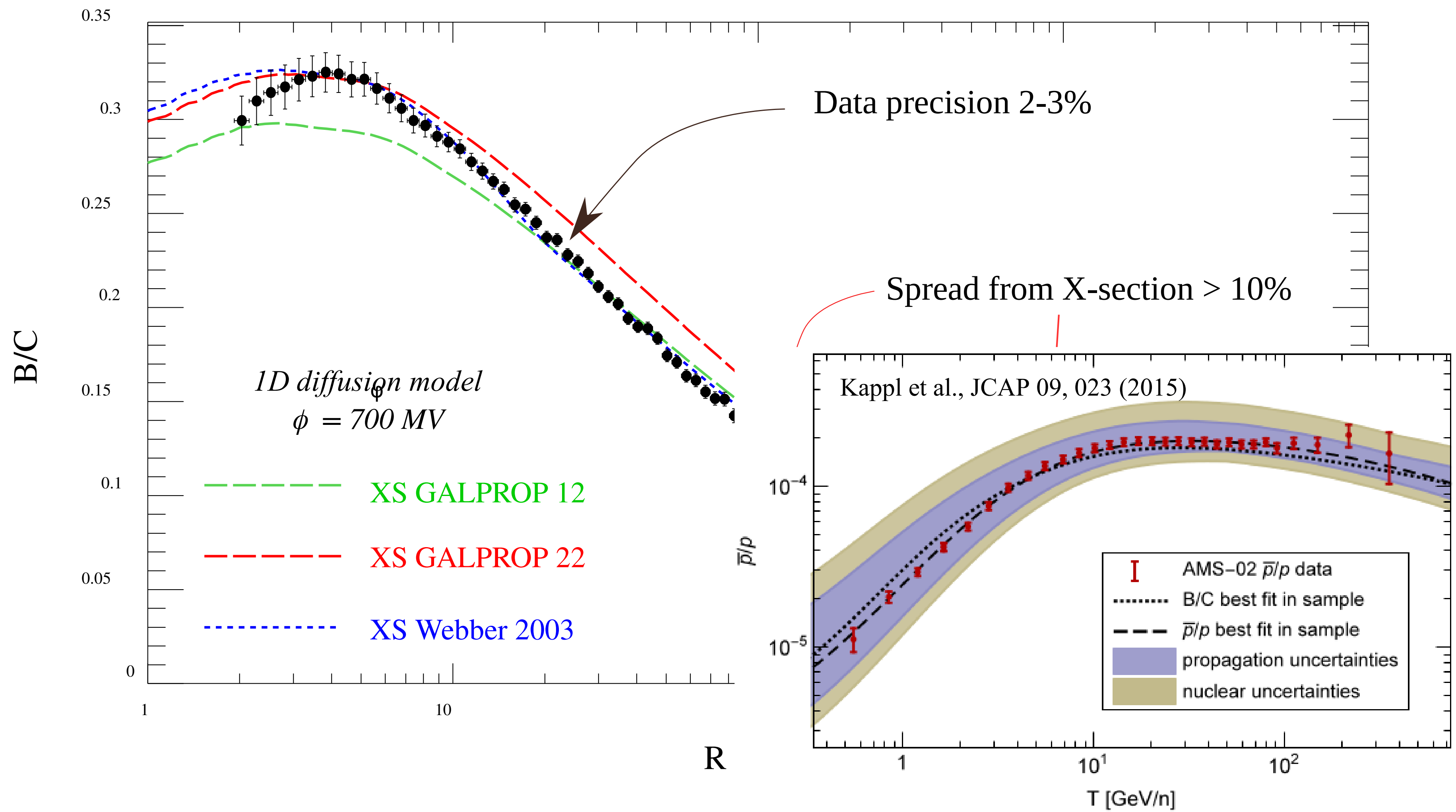
3. Nuclear XS: a limiting factor for B/C



Nuclear XS → dominant systematics on transport parameters

3. Nuclear XS: a limiting factor for pbar

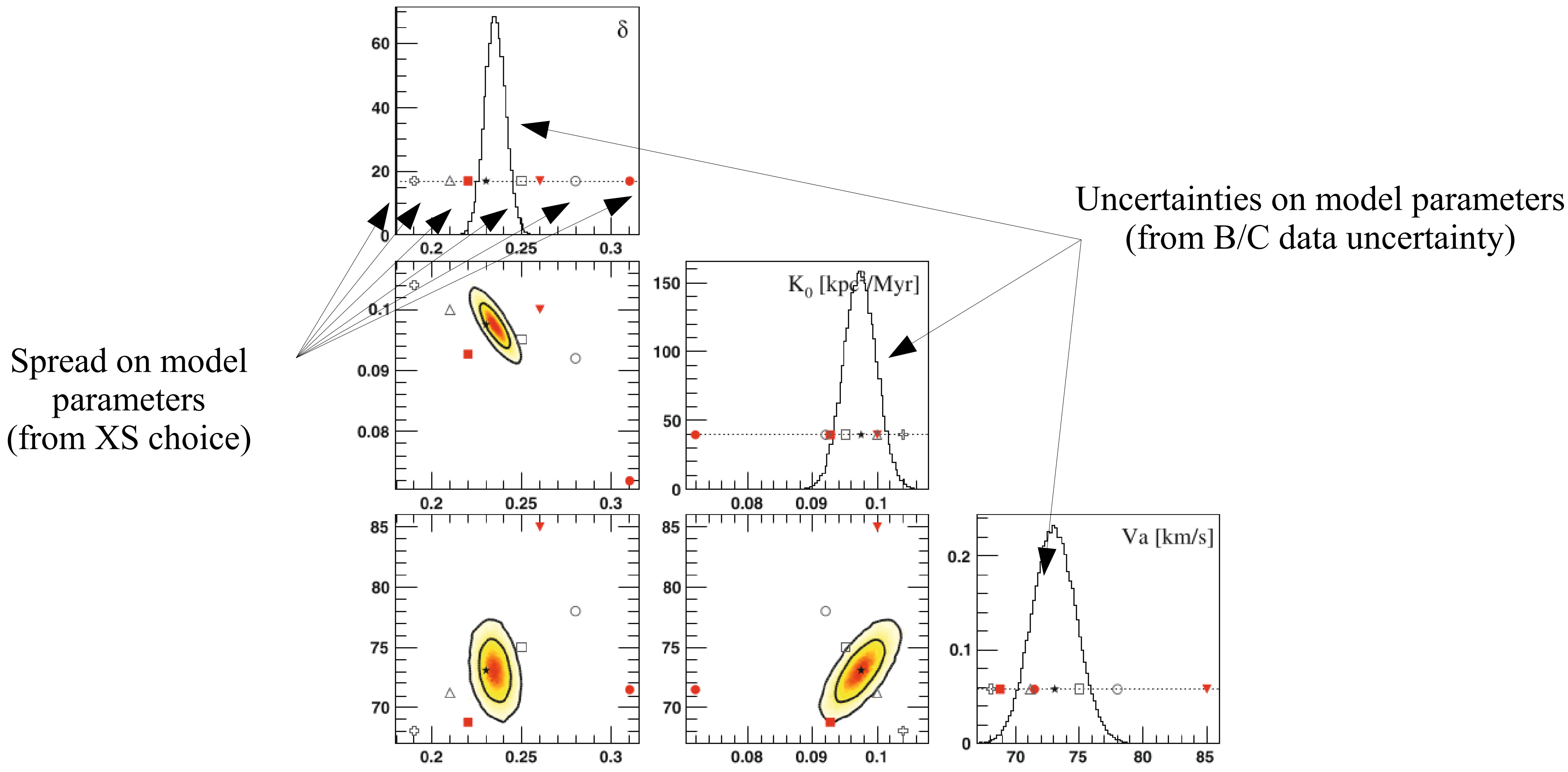
From Y. Genolini



Nuclear XS → dominant systematics on transport parameters
→ further increase uncertainties on pbar calculations

3. Nuclear XS: a limiting factor for propagation parameters

Maurin et al., A&A 516, A67 (2010)



Nuclear XS → dominant systematics on transport parameters

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Take away message

→ Timely win-win opportunity to help each other, as a united HE physics community
(ranking of the most important XS to exploit AMS-02 data,
discussion desired to ensure all necessary information available)

→ Work present in the following slides will appear soon as
Genolini, [Kirby,] Maurin, Moskalenko (in prep.)

4. XS wanted: main reaction contributing to B

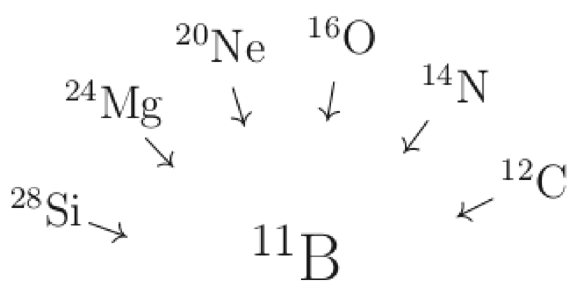
Which X-section channels should be measured with high precision?

Illustration with Boron

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

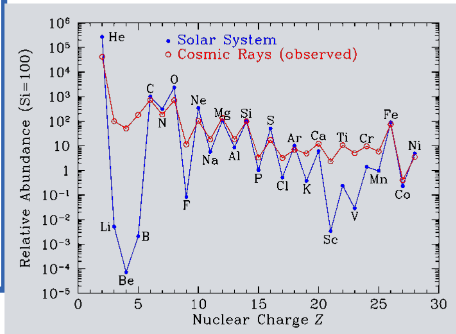
(~30%) (~70%)

Reactions contributing to ^{11}B



1-step channels

Weighted by CR abundances



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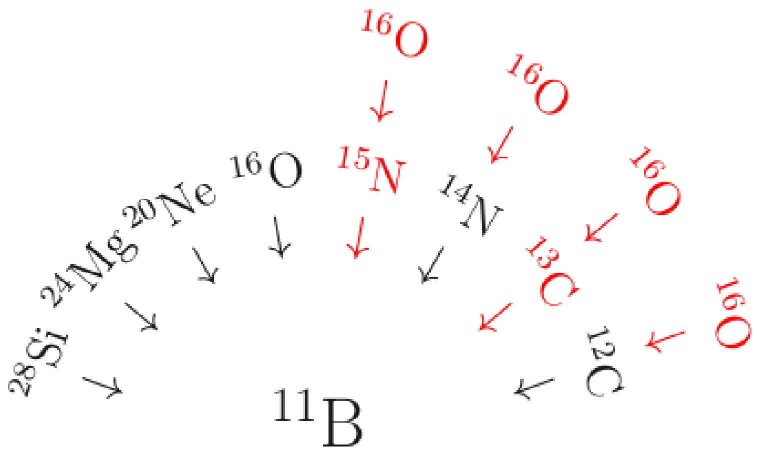
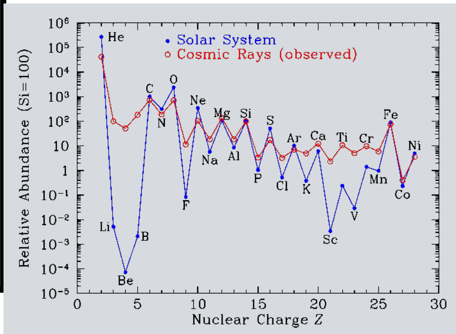


2-step channels

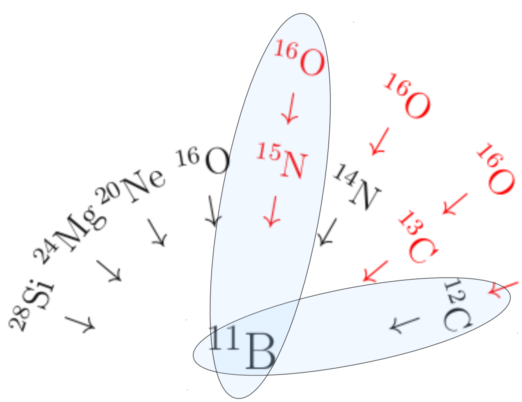
Weighted by CR abundances



4. XS wanted: ranking the channels

Ranking of 1- and 2-step channels

[Set $\sigma_{(P\rightarrow F)}$ = 0 for all XS but for reactions in channel, propagate, sort]



Energy	10 GeV/nuc	
1 step	80.6%	
2 steps	15.9%	
>2 steps	3.5%	
>1%	^{11}B $\leftarrow^{12}$ C	32.4%
	^{11}B $\leftarrow^{16}$ O	18.8%
	^{10}B $\leftarrow^{12}$ C	10.4%
	^{10}B $\leftarrow^{16}$ O	9.0%
	^{10}B $\leftarrow^{11}$ B $\leftarrow^{12}$ C	2.3%
	^{11}B $\leftarrow^{24}$ Mg	1.8%
	^{11}B $\leftarrow^{12}$ C $\leftarrow^{16}$ O	1.7%
	^{11}B $\leftarrow^{15}$ N $\leftarrow^{16}$ O	1.6%
	^{11}B $\leftarrow^{14}$ N	1.5%
	^{11}B $\leftarrow^{28}$ Si	1.4%
	^{11}B $\leftarrow^{20}$ Ne	1.4%
	^{10}B $\leftarrow^{11}$ B $\leftarrow^{16}$ O	1.3%
	^{10}Be decay	3.4%
	# of reactions	Total
[0.1%, 1%]	28	8.8%
[0.01%, 0.1%]	90	3.5%
< 0.01%	277	0.7%

(>1% channels: 87%; remaining: 13%)

To reach 3% precision on B flux @10 GeV

Need a 2% precision on ~ 10 reactions

and 10% precision on the rest

[presented @ XSCRC2017 - https://indico.cern.ch/event/563277/]

→ But does not allow to rank properly XS

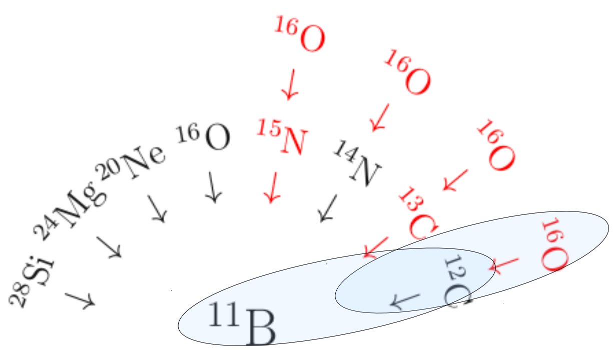
4. XS wanted: ranking the individual reactions (1)

Ranking of individual XS

[Set $\sigma_{(P+T\to F)}$ = 0 one at a time, propagate, sort]

Several targets ‘T’

ISM = 90%H + 10%He



→ But missing short-lived nuclei

N.B.: in the Galaxy, τ_{esc} ~20 Myr, ‘no’ short-lived nuclei

<u>Contributions for B at 10 GeV/n</u>

secondary	=	84.7%
primary	=	0%
radioactive	=	15.3%

Sorted XS	Involved	XS[mb]
$\sigma(^{12}C+H\to{}^{11}B)$	37.9%	56.8
$\sigma(^{16}O+H\to{}^{11}B)$	19.9%	27.3
$\sigma(^{12}C+H\to{}^{10}B)$	10.3%	15.4
$\sigma(^{16}O+H\to{}^{10}B)$	8.1%	11.0
$\sigma(^{12}C+He\to{}^{11}B)$	5.4%	73.2
$\sigma(^{11}B+H\to{}^{10}B)$	4.4%	38.9
$\sigma(^{16}O+H\to{}^{12}C)$	3.3%	35.6
$\sigma(^{16}O+He\to{}^{11}B)$	3.0%	36.6
$\sigma(^{16}O+H\to{}^{13}C)$	2.6%	49.7
$\sigma(^{14}N+H\to{}^{11}B)$	2.6%	29.2
$\sigma(^{13}C+H\to{}^{11}B)$	2.2%	31.7
$\sigma(^{20}Ne+H\to{}^{11}B)$	1.8%	19.3
$\sigma(^{12}C+He\to{}^{10}B)$	1.5%	19.8
$\sigma(^{16}O+He\to{}^{10}B)$	1.2%	14.7
$\sigma(^{24}Mg+H\to{}^{11}B)$	1.1%	10.5
…		

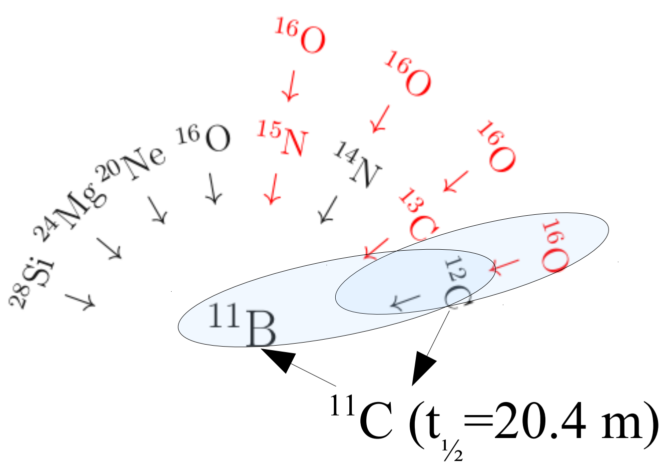
4. XS wanted: ranking the individual reactions (2)

Ranking of individual XS (with short-lived nuclei)

[Set $\sigma_{(P+T\rightarrow F)} = 0$ one at a time, propagate, sort]

Separate short-lived (ghost) nuclei

$$\sigma_{CR}^{P+T\rightarrow X} = \sigma_{Direct}^{P+T\rightarrow X} + \Sigma_i Br_i\, \sigma_{Ghost}^{P+T\rightarrow Xi(\rightarrow X)}$$



→ Exactly what we need!

N.B.: flight time between target/detector determines which XS is measured (direct or cumulative of some sort)

<u>Contributions (with ghosts) for B at 10 GeV/n</u>

secondary	=	84.7%
primary	=	0%
radioactive	=	15.3%

Sorted XS	Involved	XS[mb]
$\sigma(^{12}C+H\rightarrow ^{11}B)$	20.0%	30.0
$\sigma(^{12}C+H\rightarrow ^{11}C^{[20.4m\rightarrow 11B]}$	17.9%	26.8
$\sigma(^{16}O+H\rightarrow ^{11}B)$	19.9%	27.3
$\sigma(^{12}C+H\rightarrow ^{10}B)$	8.3%	12.3
$\sigma(^{16}O+H\rightarrow ^{10}B)$	8.1%	11.0
$\sigma(^{11}B+H\rightarrow ^{10}B)$	4.4%	38.9
$\sigma(^{16}O+H\rightarrow ^{12}C)$	3.0%	32.3
$\sigma(^{16}O+He\rightarrow ^{11}B)$	3.0%	36.6
$\sigma(^{12}C+He\rightarrow ^{11}B)$	2.9%	38.6
$\sigma(^{12}C+He\rightarrow ^{11}C^{[20.4m\rightarrow 11B]}$	2.6%	34.6
$\sigma(^{14}N+H\rightarrow ^{11}B)$	2.6%	29.2
$\sigma(^{12}C+H\rightarrow ^{10}C^{[19.3s\rightarrow 10B]}$	2.1%	3.1
$\sigma(^{13}C+H\rightarrow ^{11}B)$	1.5%	22.2
$\sigma(^{16}O+H\rightarrow ^{13}O^{[8.6ms\rightarrow 13C]}$	1.4%	30.5
$\sigma(^{16}O+He\rightarrow ^{10}B)$	1.2%	14.7
...		

4. XS wanted: content of the paper

→ Ranking lists
- for Li, Be, B, C (next AMS-02 fluxes), Z=1-30 ranking in a 2^{nd} analysis
- scatter on % and σ (XS datasets) to calculate conservative beam times

→ E-dependent XS plots for all important reactions (comparison purpose):
- parametrization used
- compilation/selection of data (I. Moskalenko)
- systematic comparison from MNCP6 prediction (L. Kerby)

→ Robustness of ranking:
- ranking depends on E (but do not change main contributors)
- using ≠ XS files
- using ≠ lists of ghosts
- using ≠ propagation parameters

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Take home message

→ AMS-02 results are changing the field of CR physics
→ 1G$ game-changing data cannot be exploited because of GeV nuclear physics
→ Timely win-win opportunity to help each other (HE physics community)

Wish list for LiBeB production

→ ^{12}C and ^{16}O projectiles provide most of the desired reactions (high priority)
→ If possible all fragments should be measured (not to miss any possible contribution, to decrease the CR overall uncertainty, to improve models)
→ H and He targets desired
→ Measurements from 100 MeV/n to TeV/n to track E dependence
→ $\sigma_{tot}^{Li,Be,B,C,O}$ required with high accuracy ($\sigma_{frag}^{P+T\to F}$ normalised to σ_{tot})

Discussion

- At what energies should we provide the ranking (10 GeV/n) ?
- What are NA61/Shine capabilities in terms of
    - beam/secondary beam (and purity) and energy
    - target, fragment isotopic ID?
- Should we provide more numbers, more detail wish-list for specific goal to reach?

→ We would be delighted to help you make it happen