The role of cross sections in the physics of cosmic rays

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Firenze 29.11.2022 - Brain-storming together

GALACTIC COSMIC RAYS

are charged particles (nuclei, isotopes, leptons, antiparticles)
diffusing in the galactic magnetic field
Observed at Earth with E~ 10 MeV/n – 10^3 TeV/n

1. SOURCES

PRIMARIES: directly produced in their sources
Supernova remnants (SNR), pulsars, dark matter annihilation, …

SECONDARIES: produced by spallation reactions of primaries on the interstellar medium (ISM), made of H and He

2. ACCELERATION

SNR are considered the powerhouses for CRs.
They can accelerate particles at least up to 10^2 TeV

3. PROPAGATION

CRs are diffused in the Galaxy galactic magnetic field (μG)

\+ loose/gain energy with different mechanisms (leptons)

CRs in the Galaxy

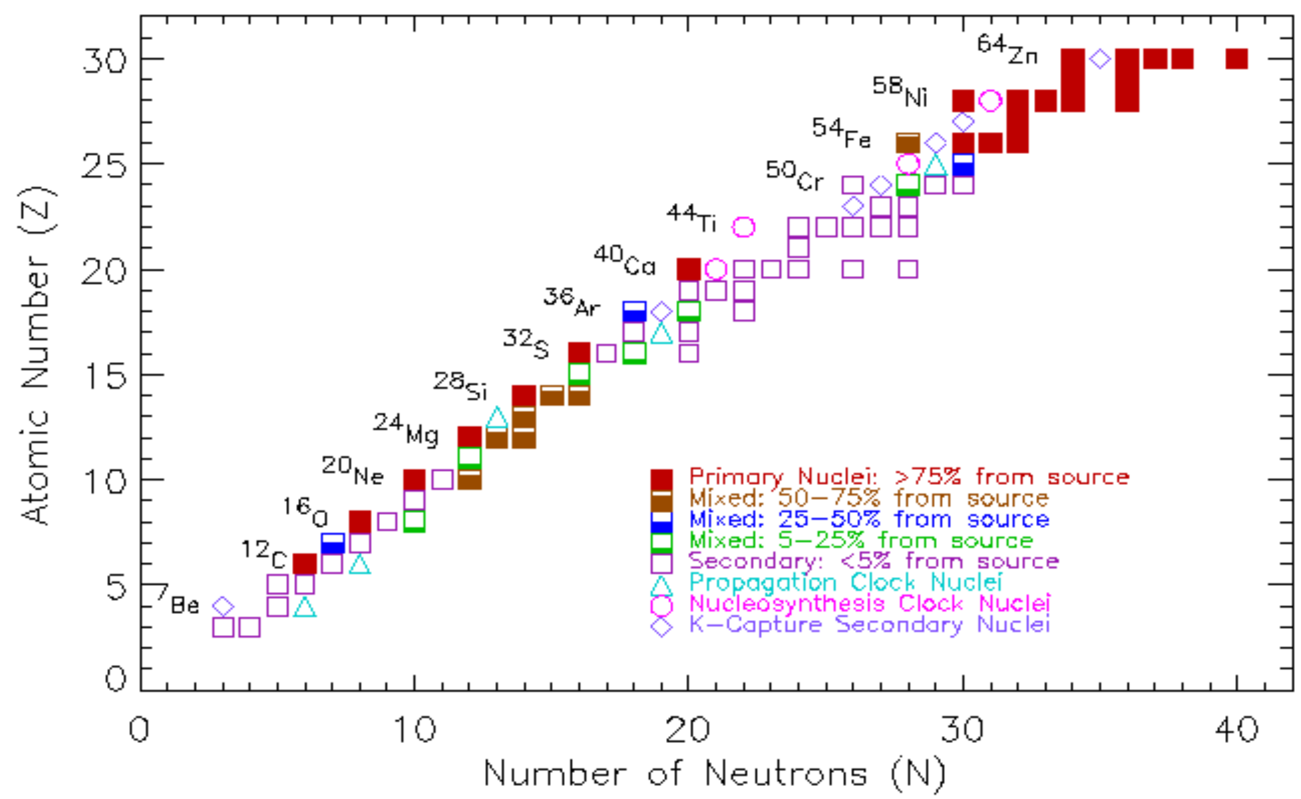
Primaries: produced in the sources (SNR and Pulsars)

H, He, CNO, Fe; e-, e+; possibly e^{+}, p^{-}, d^{-} from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e^{+}, p^{-}, d^{-}

Primaries = present in sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
e^{+}, p^{+}, d^{+} from Dark Matter annihilation

Secondaries = NOT present in sources, thus produced by
spallation of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, … ;
e^{+}, p^{+}, d^{+}; … from inelastic scatterings



Propagation equation

$$\frac{\partial \psi_i(\boldsymbol{x},p,t)}{\partial t} = q_i(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi_i - \boldsymbol{V}\psi_i) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi_i - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi_i - \frac{p}{3}(\boldsymbol{\nabla}\cdot\boldsymbol{V})\psi_i\right) - \frac{1}{\tau_{f,i}}\psi_i - \frac{1}{\tau_{r,i}}\psi_i.$$

Diffusion: D(x,R) a priori
usually assumed isotropic in the Galaxy: $D(R)=D_0R^\delta$ ($R=pc/Ze$)
D_0 and δ usually fixed by B/C (kappl+15; Genolini+15 (K15))

Energy losses: Synchrotron on the galactic B~3.6 μG
full relativistic of Compton effect (w/ Klein-Nishijna)
on photon fields (stellar, CMB, UV, IR)

Solution of the eq.: semi-analytic (Maurin+ 2001, Donato+ 2004, ...), USINE codes
or fully numerical: GALPROP, DRAGON codes

Geometry of the Galaxy: cylinder with height L ~ kpc

Solutions to the diffusion equation

The flux is $\Phi^j = N^j v/4\pi$

$$N^j(r,z) = \exp\left(\frac{V_c z}{2K}\right) \sum_{i=0}^{\infty} \frac{\bar{Q}^j}{A_i^j} \frac{\sinh\left[\frac{S_i^j(L-z)}{2}\right]}{\sinh\left[\frac{S_i^j L}{2}\right]} J_0(\zeta_i \frac{r}{R})$$

$$\bar{Q}^j \equiv q_0^j Q(E)\hat{q}_i + \sum_k^{m_k > m_j} \tilde{\Gamma}^{kj} N_i^k(0)$$

$$S_i^j \equiv \left(\frac{V_c^2}{K^2} + 4\frac{\zeta_i^2}{R^2} + 4\frac{\Gamma_{rad}^{N^j}}{K}\right)^{1/2} \qquad A_i^j \equiv 2h\tilde{\Gamma}_{N^j}^{tot} + V_c + K S_i^j \coth\left(\frac{S_i^j L}{2}\right)$$

$\Gamma = n_{ISM}\sigma(a+b \to c+X)v$

At high energy:

$\Phi_{prim} \propto Q(E)/K(E)$ $\qquad \Phi_{sec} \propto n_{ISM}\,\sigma\,\Phi_{prim}/K(E) \propto \sigma/K(E)^2$

Where cross sections matter

$$X + \{p,He\} \rightarrow Y + \text{anything}$$

Production for Y: act as a source term, very relevant

Destruction for X: a decrease in X spectrum

ps: Stable nuclei reside ij the Galaxy few tens of Myr

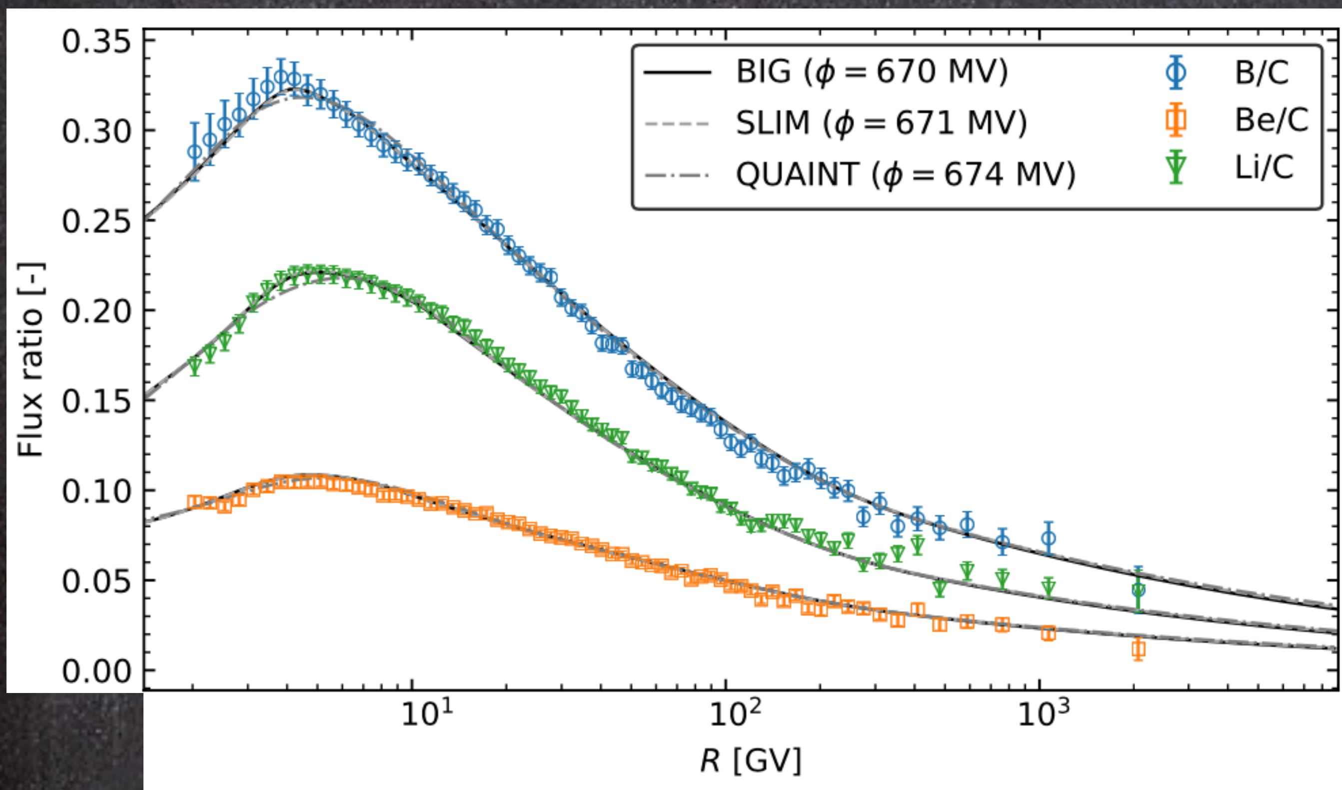
Light nuclei: primaries and secondaries

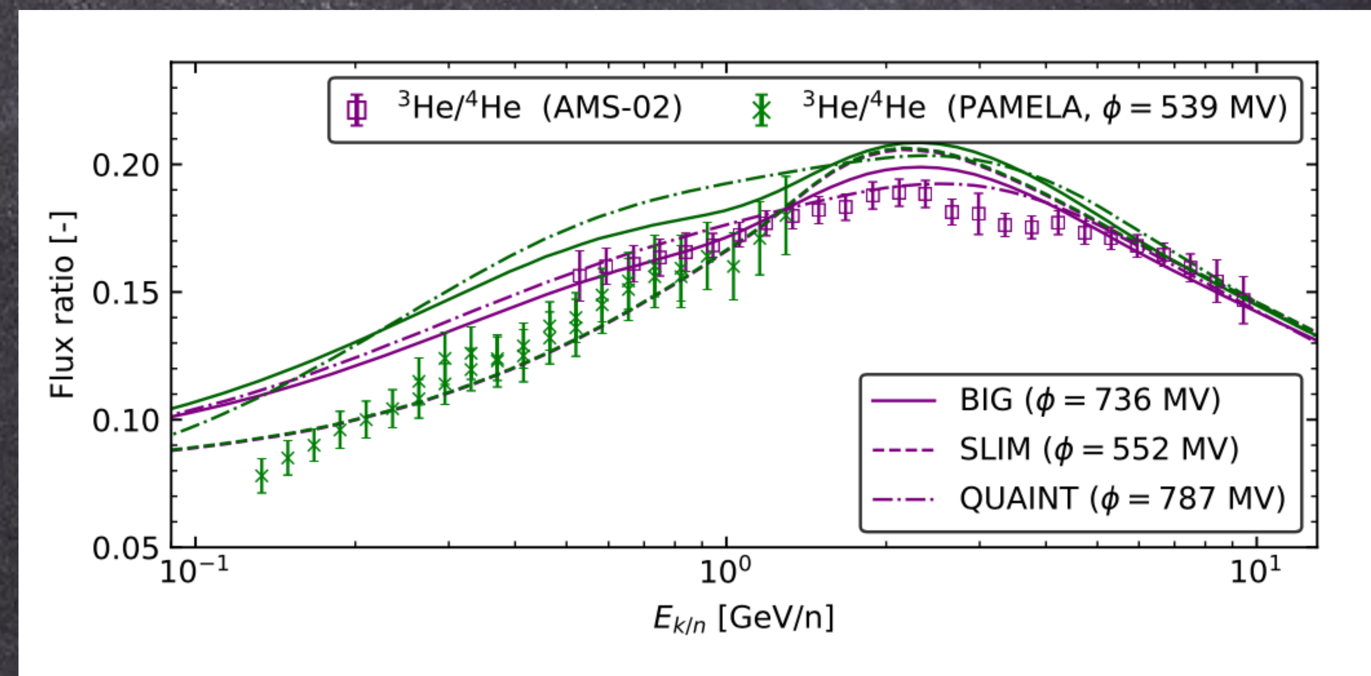
TABLE I. Fractions of primary/fragmentation/radioactive origin (w.r.t. total flux), and contributions of 1-/2-/'more-than-2' step channels (w.r.t. total secondary production) at 10 GeV/n. These numbers are independent of the propagation model if sources have the same spectral index.

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

Propagation models vs data

Weinrich+ A&A 2020





Data on secondary/primary species are well described by propagation model with diffusione coefficient power index $\delta = 0.50 \pm 0.03$.

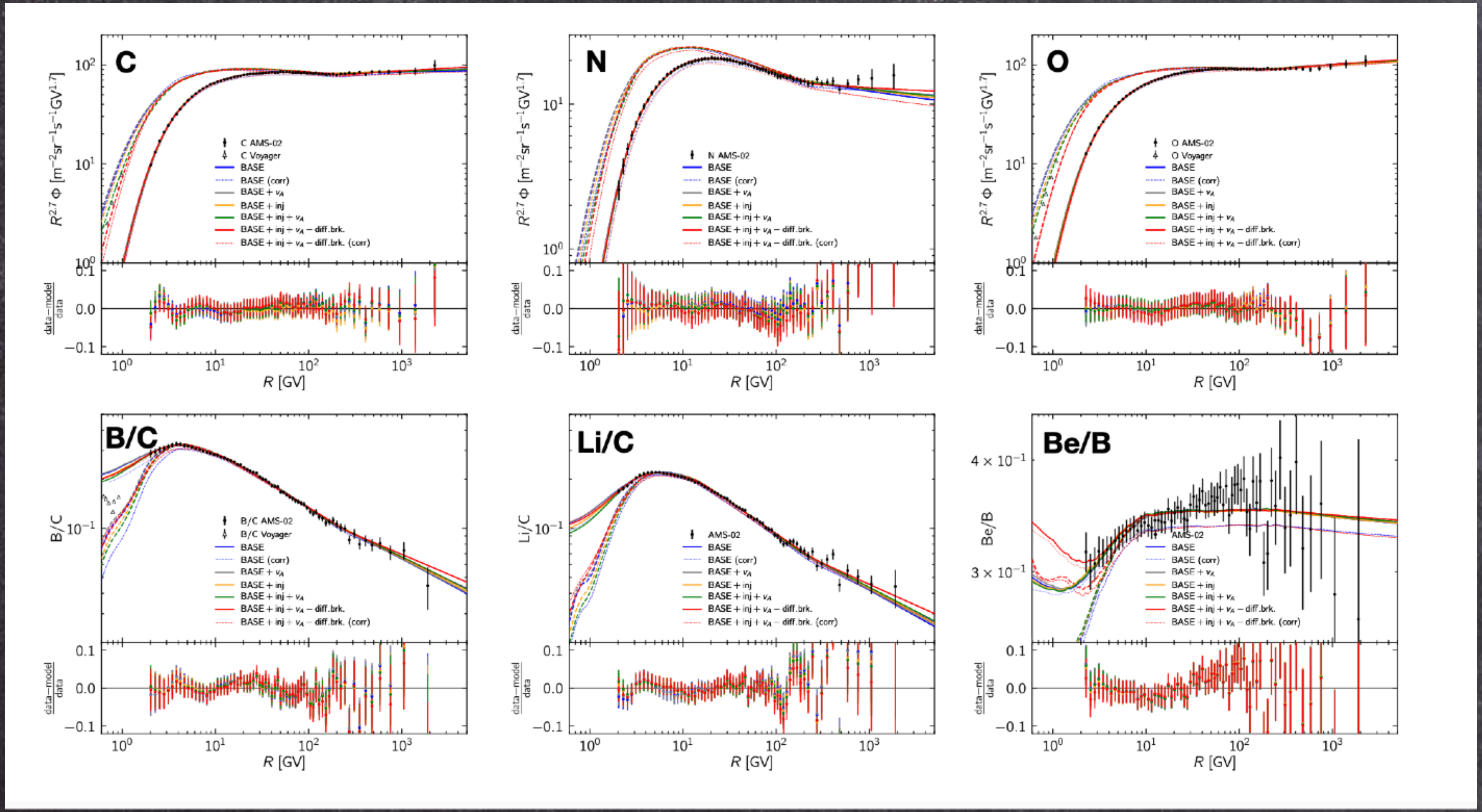
Convection + reacceleration, or pure diffusion both work.

See also Evoli+ PRD 2020; Schroer+ PRD 2021

Propagation models vs data

Korsmeier & Cuoco, PRD 2021

Several propagation models are tested

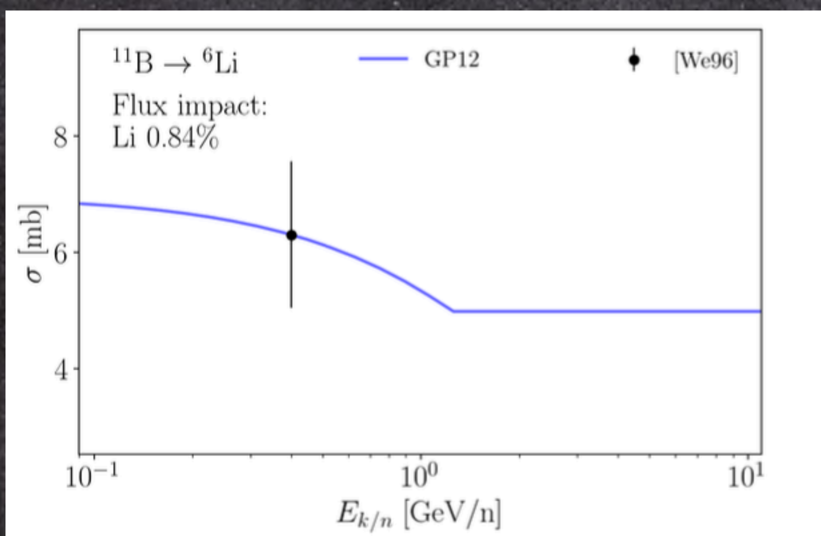


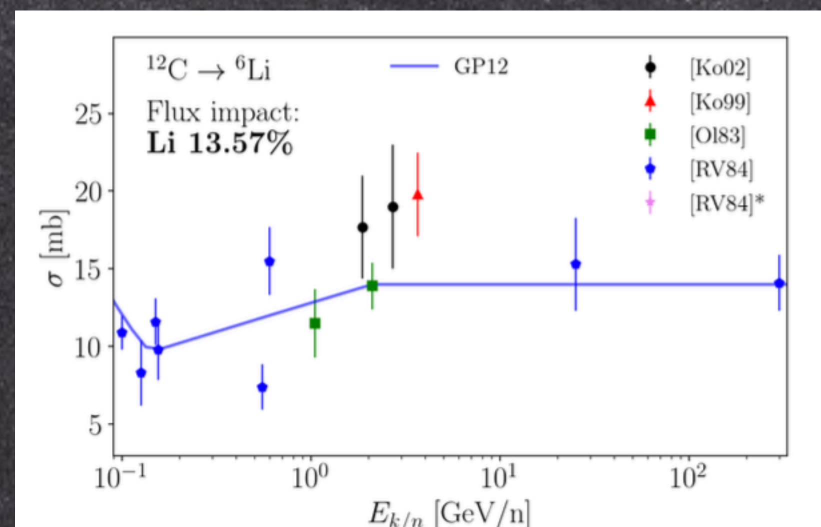
Fragmentation cross section uncertainties currently prevent a better understanding of CR propagation

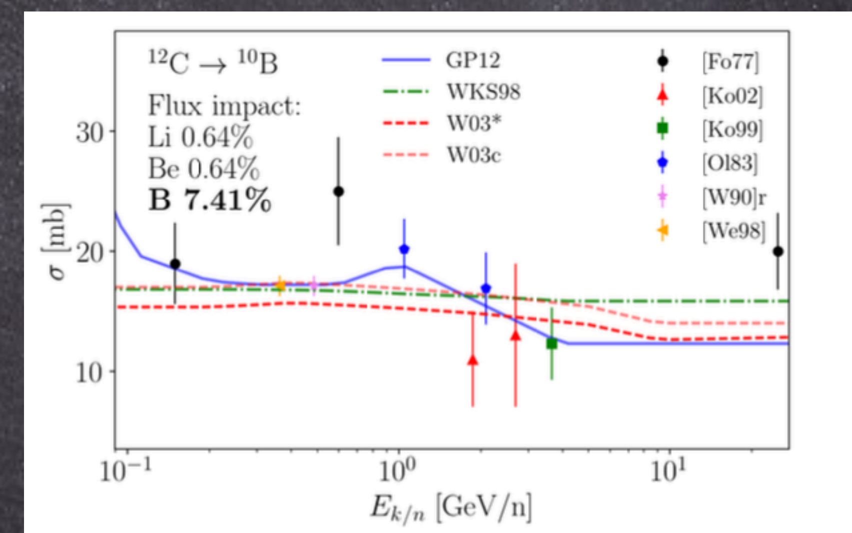
Cross sections in the predictions

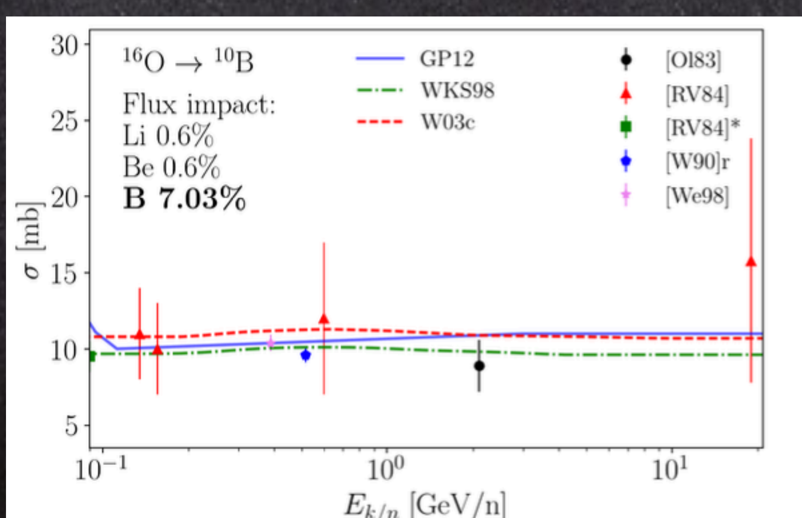
Data driven parameterizations (Silberberg&Tsao), semi-empirical formulae (Webber+), parametric formulae/direct fit to the data (Galprop), MonteCarlo (see Carmelo's talk),

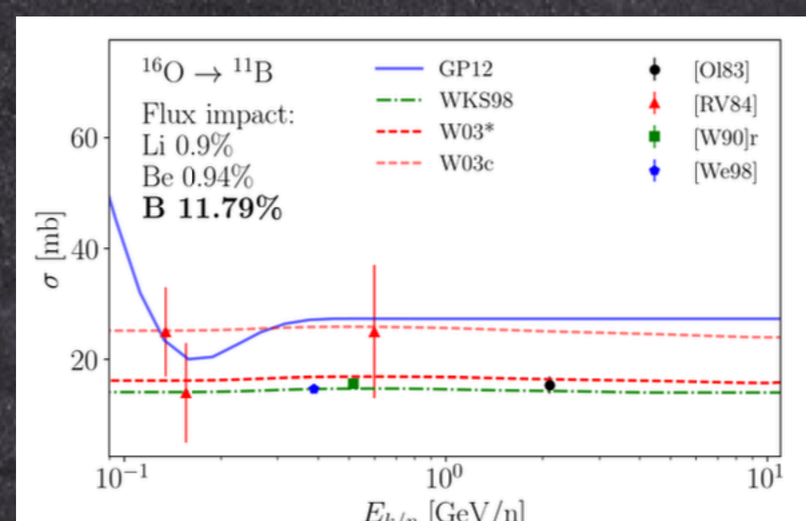
Genolini, Moskalenko, Maurin, Unger PRC 2018

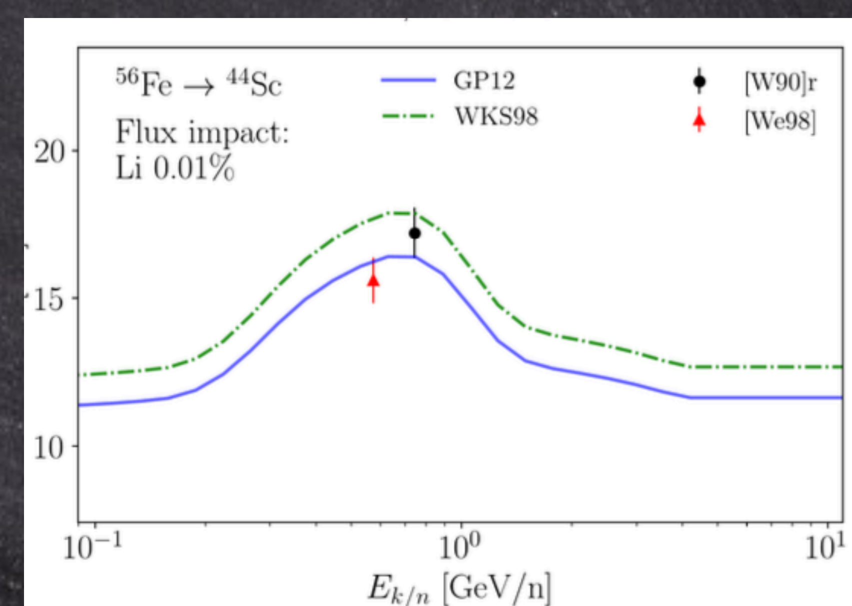








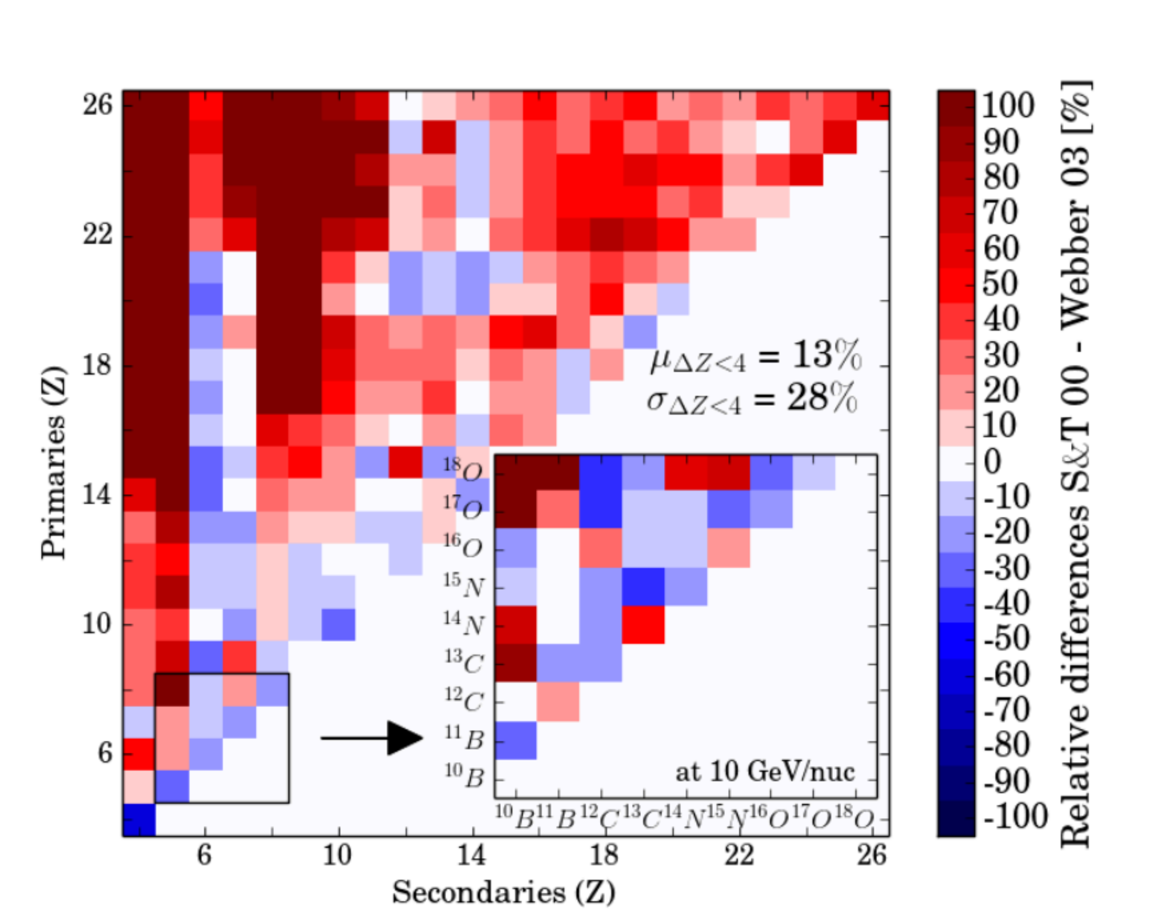


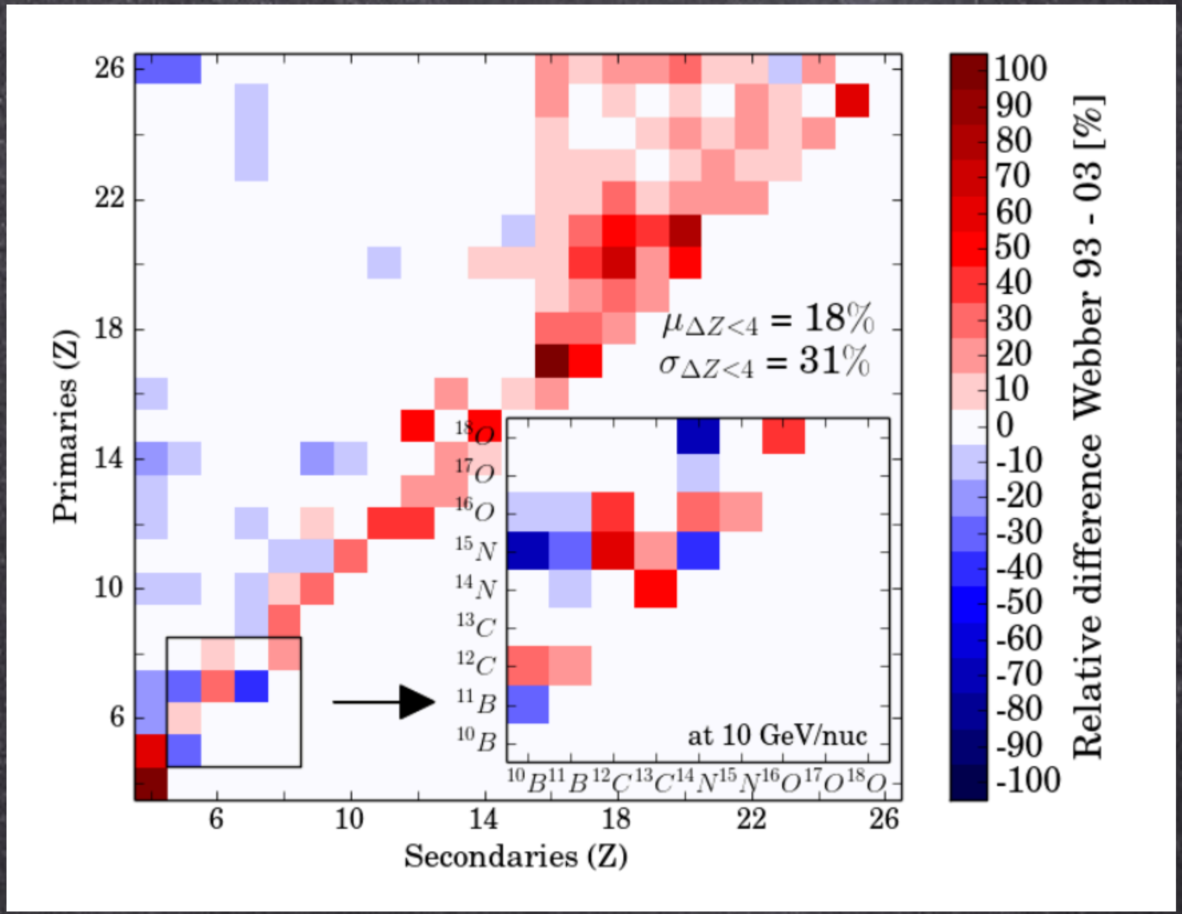


Differences in the XS parameterizations

Genolini, Putze, Salati, Serpico A&A 2015

Differences in one parameterization wrt a benchmark model



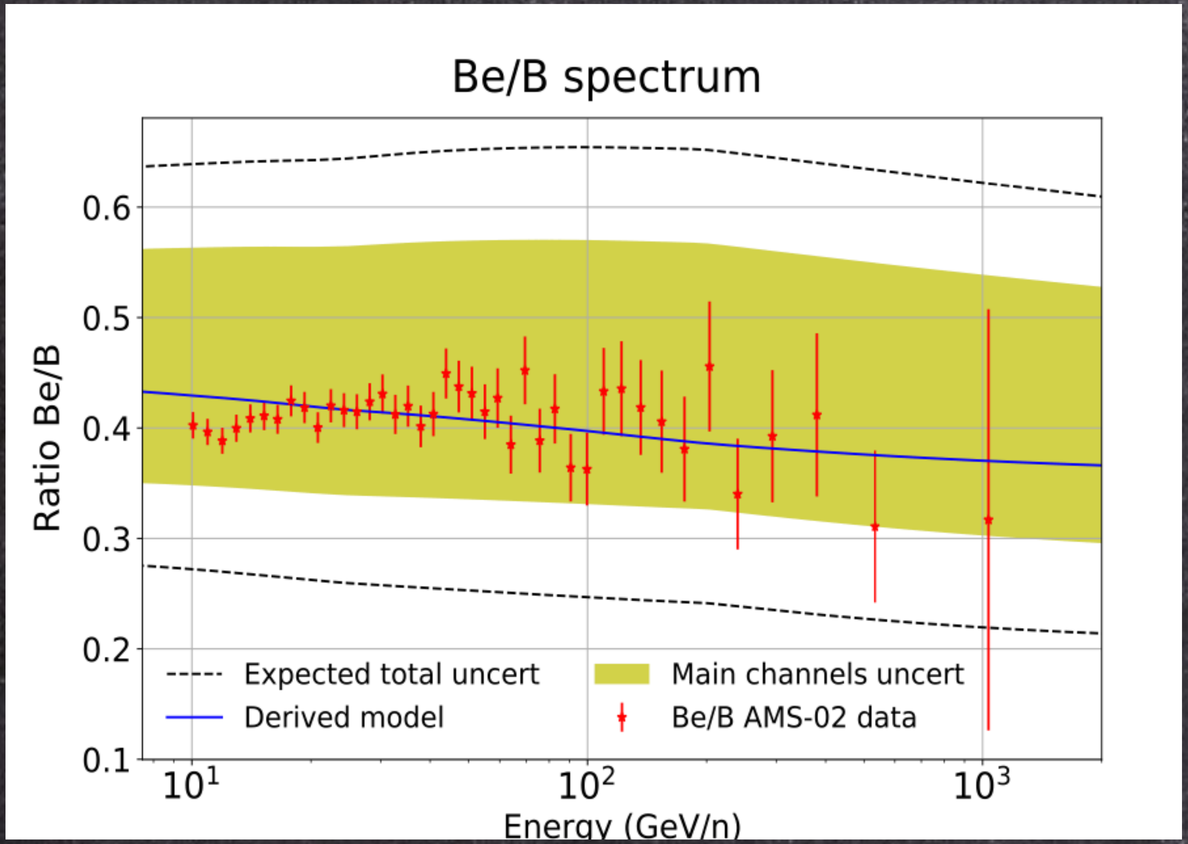


Even with the same, although scarce data, interpretation May be

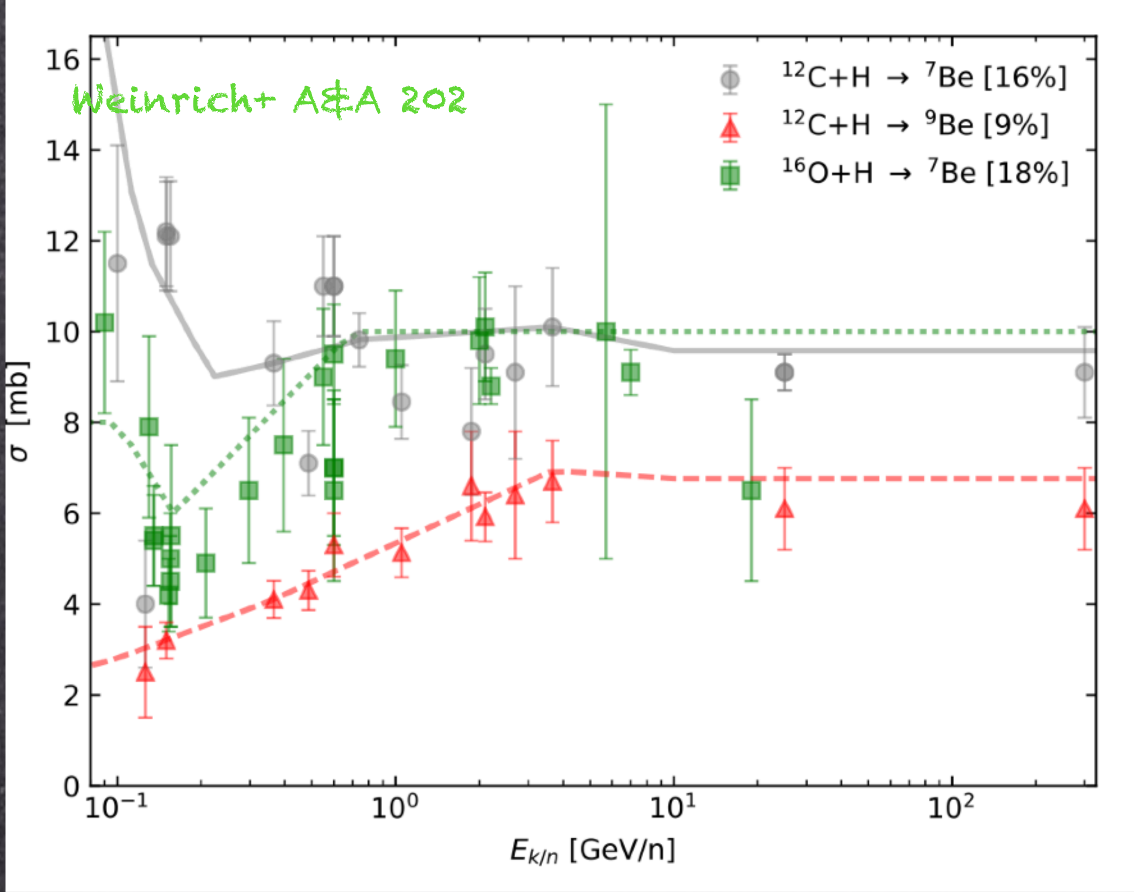
Fragmentation cross sections

They matter in both directions: as a loss term for progenitors, as a source term for daughters

De La Torre Luque+ JCAP 2021



Weinrich+ A&A 2021

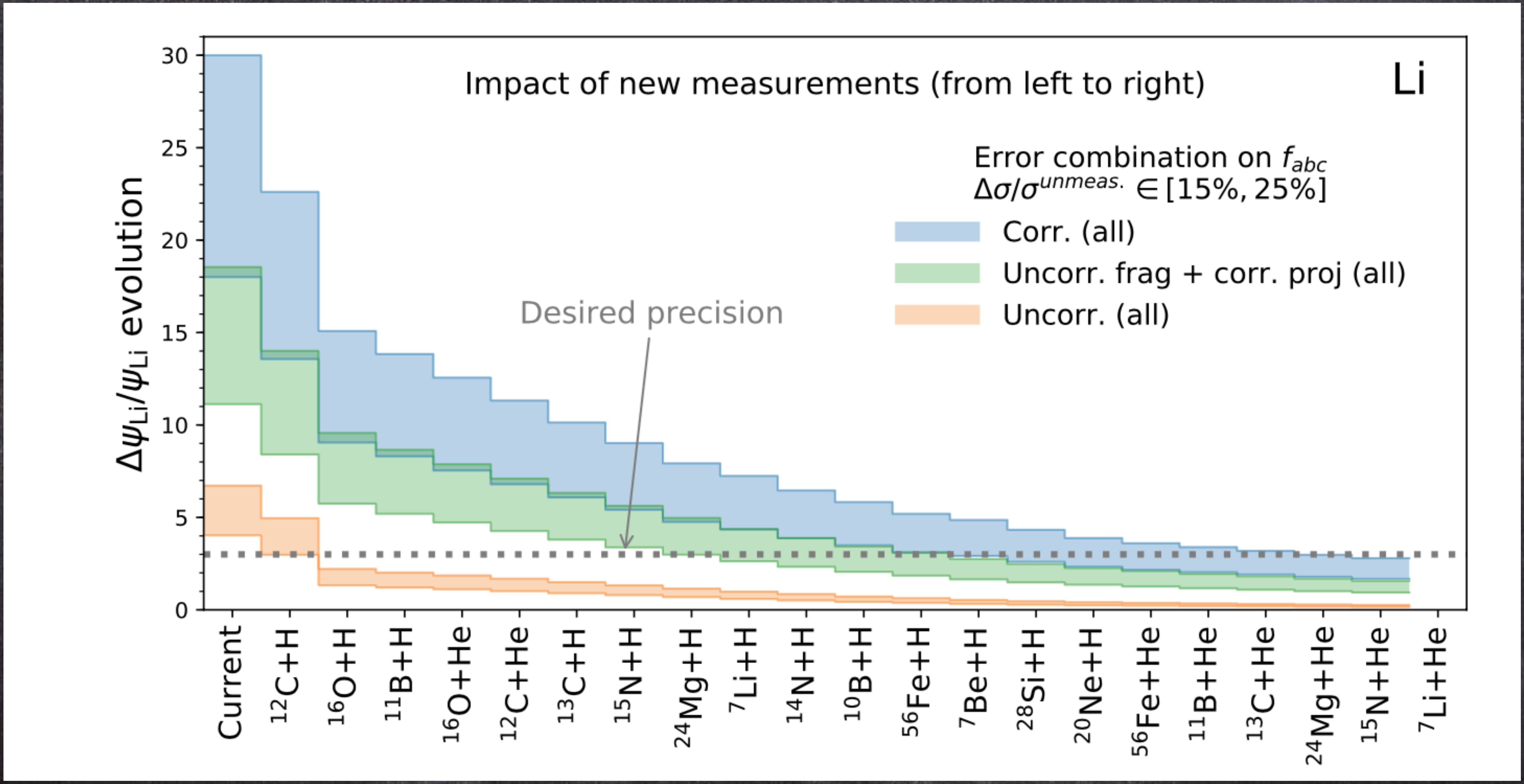


Probably the most limiting aspect now

Dedicated campaigns are needed (LHCb, NA61, Amber/Compass, ...)

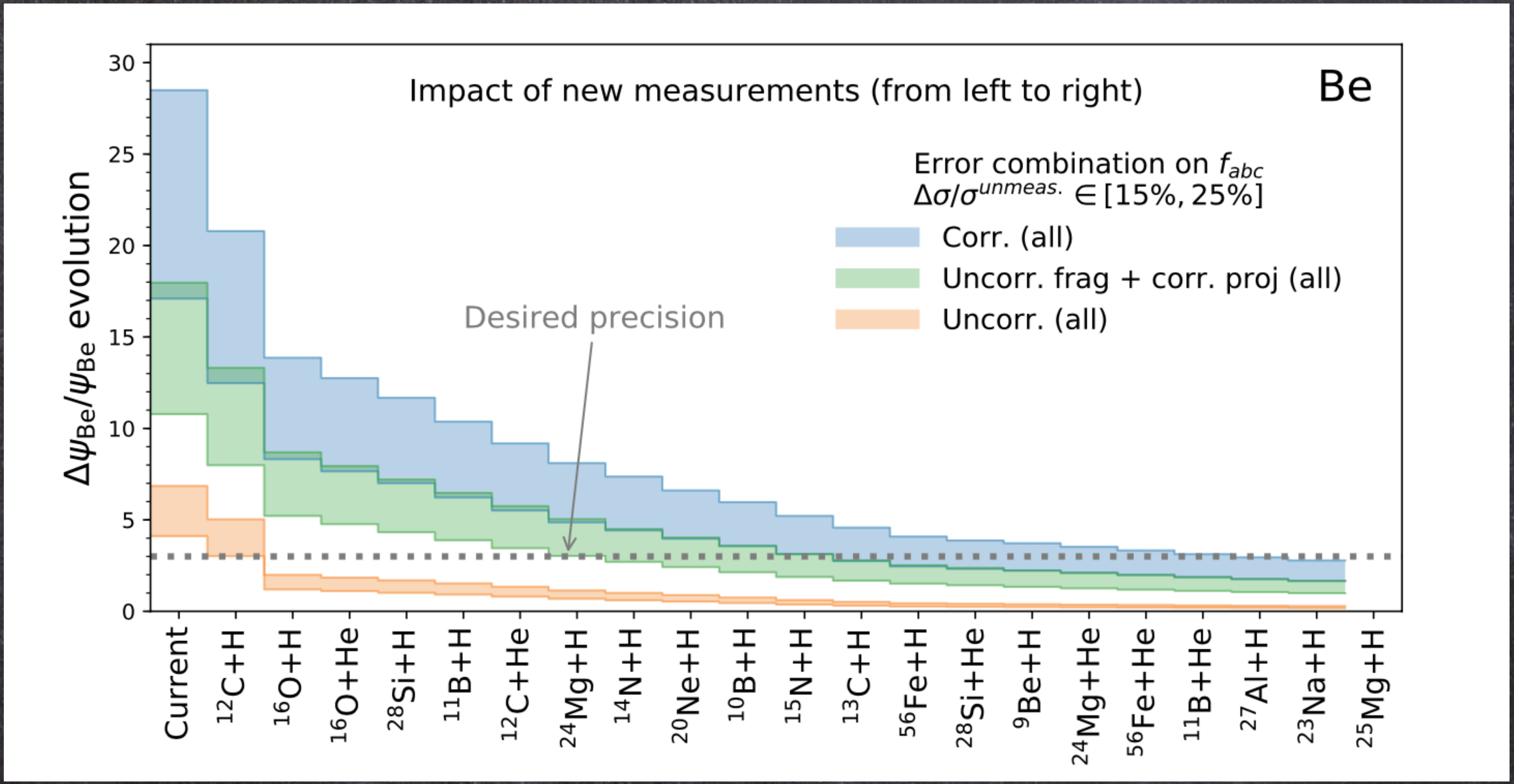
Most relevant physics cases

Improve Lithium production cross sections



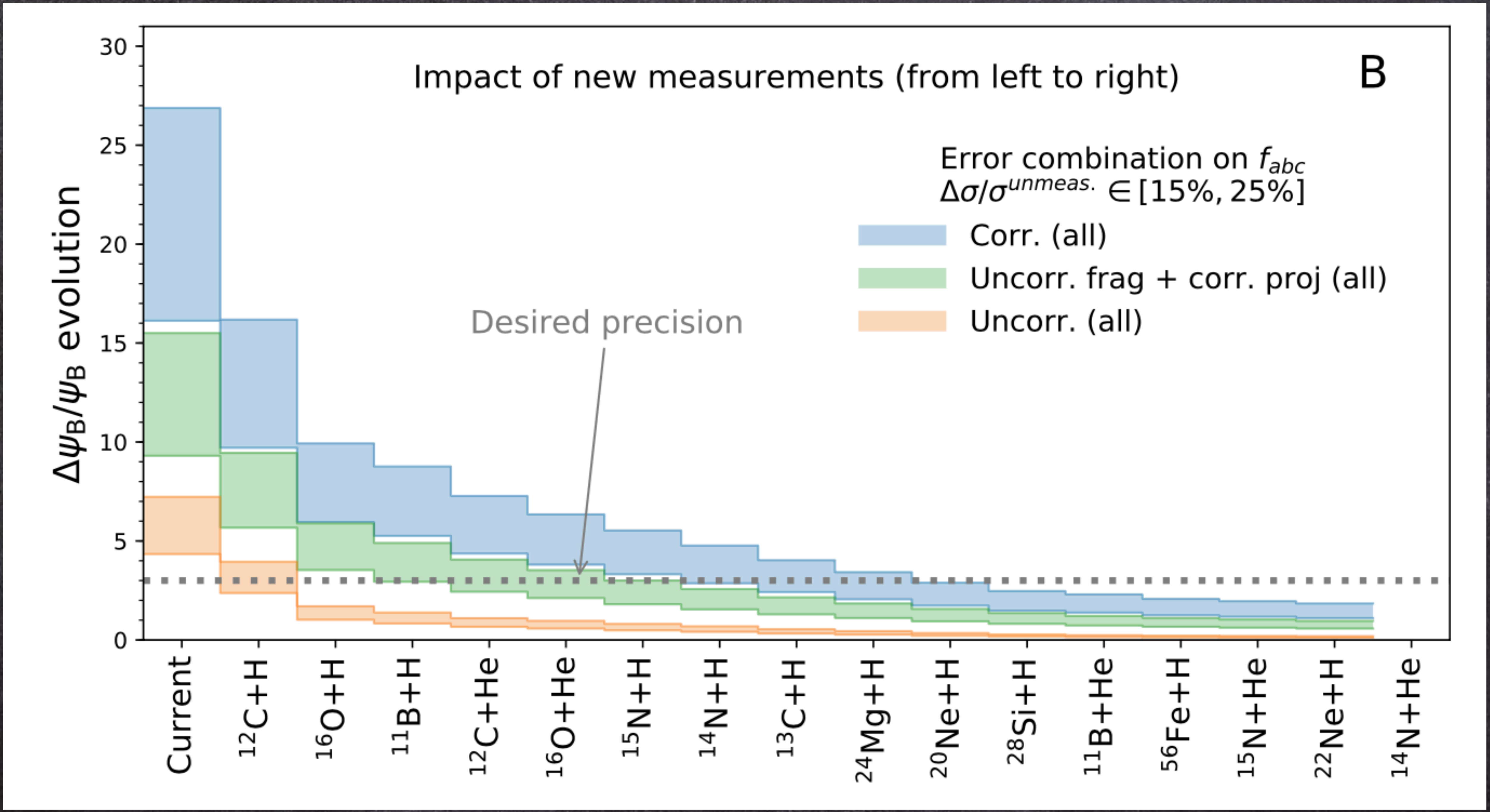
Genolini, Moskalenko, Maurin, Unger PRC 2018

Improve Beryllium production cross sections



Genolini, Moskalenko, Maurin, Unger PRC 2018

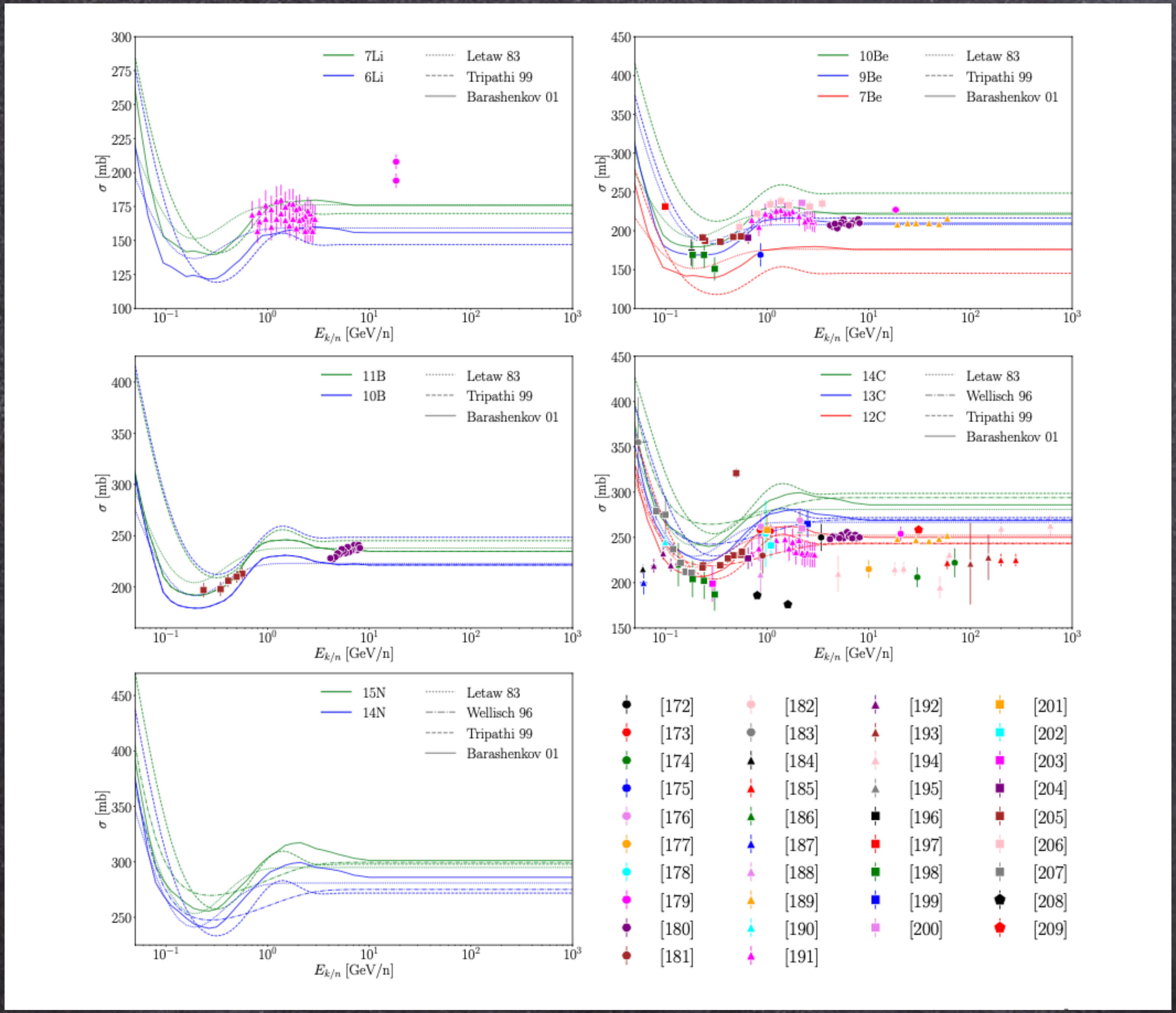
Improve Boron production cross sections



Genolini, Moskalenko, Maurin, Unger PRC 2018

Inelastic cross sections

Genolini, Moskalenko, Maurin, Unger PRC 2018



They are in general less relevant in the computations

Antimatter or γ-rays sources from DARK MATTER

Annihilation

$$Q_{\rm ann}(\vec{x},E) = \epsilon\left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Decay

$$Q_{\rm dec}(\vec{x},E) = \left(\frac{\rho(\vec{x})}{m_{DM}}\right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

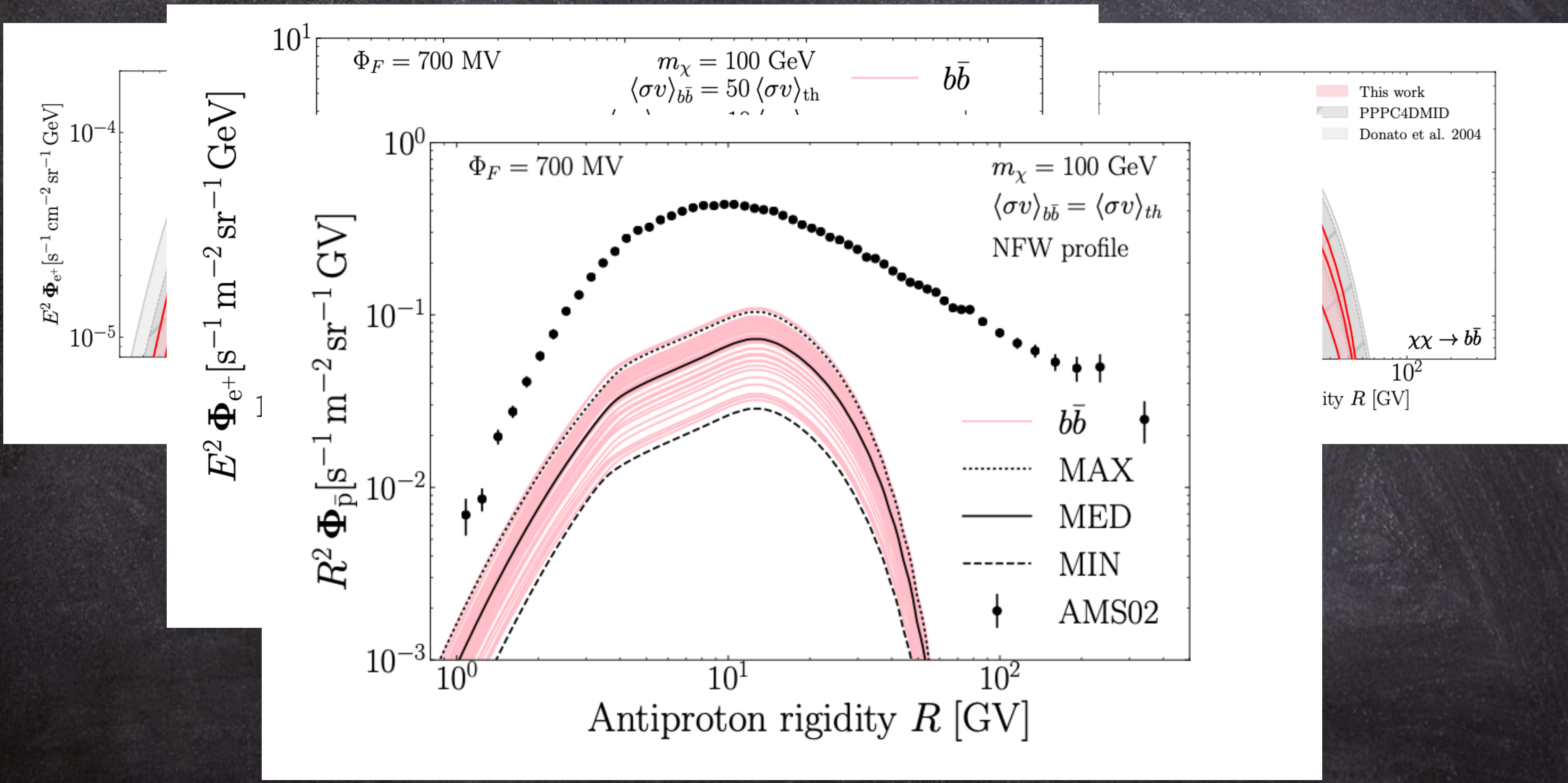
- ρ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle\sigma v\rangle$ thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Annihilations take place in the whole diffusive halo

Effect of galactic propagation

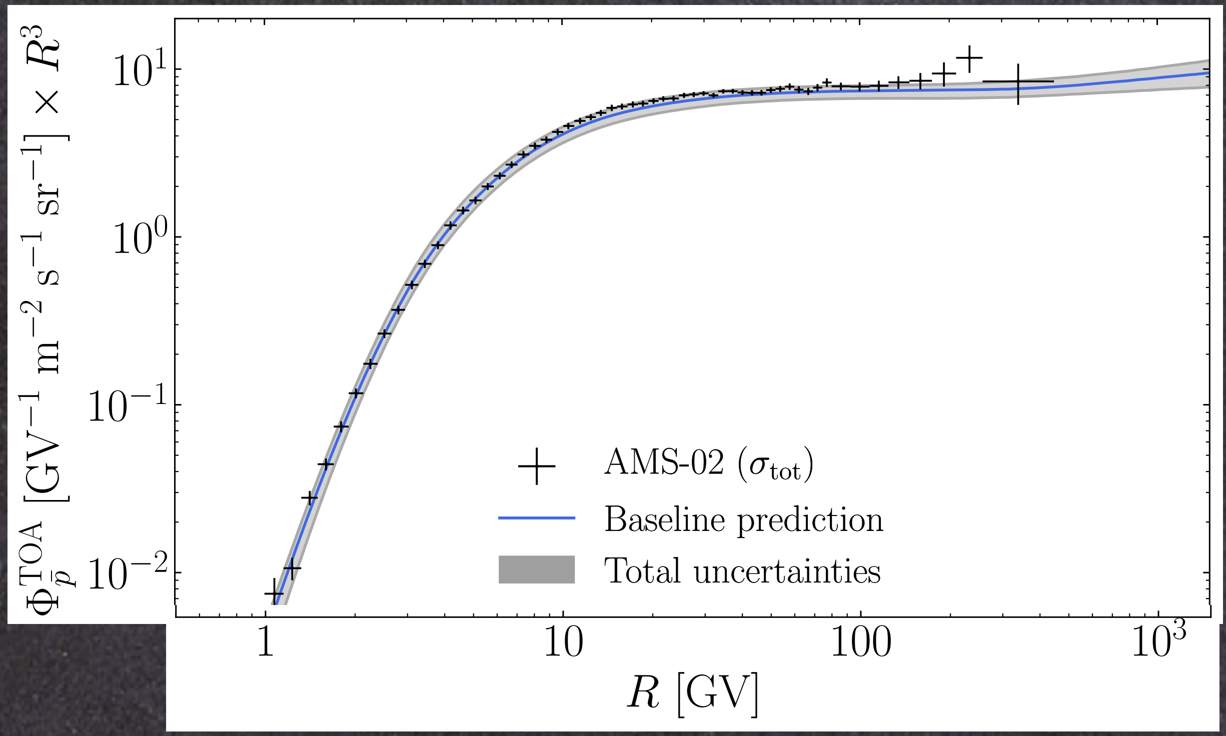
Genolini+ 2103.04108

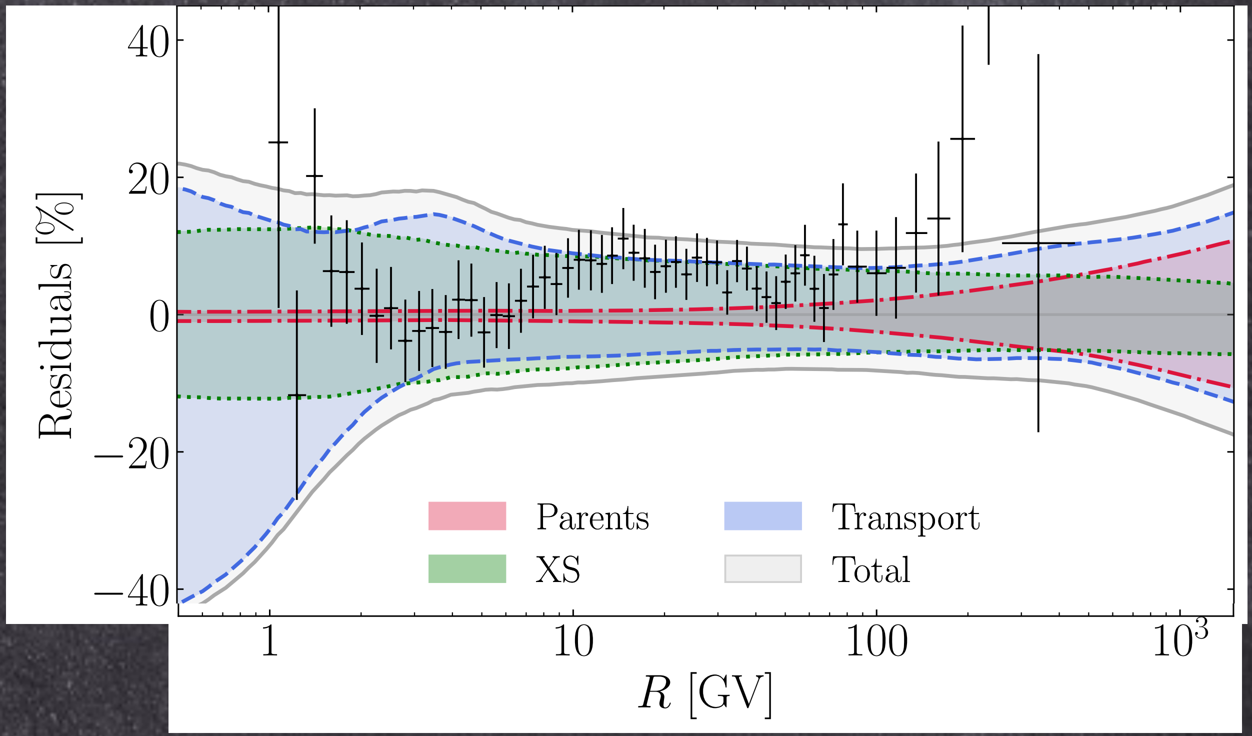
New AMS-02 sec/prim data allow reduction of propagation uncertainties



AMS-02 antiprotons are consistent with a secondary astrophysical origin

M. Boudaud, Y. Genolini, L. Derome, J.Lavalle,
D.Maurin, P. Salati, P.D. Serpico PRD 2020



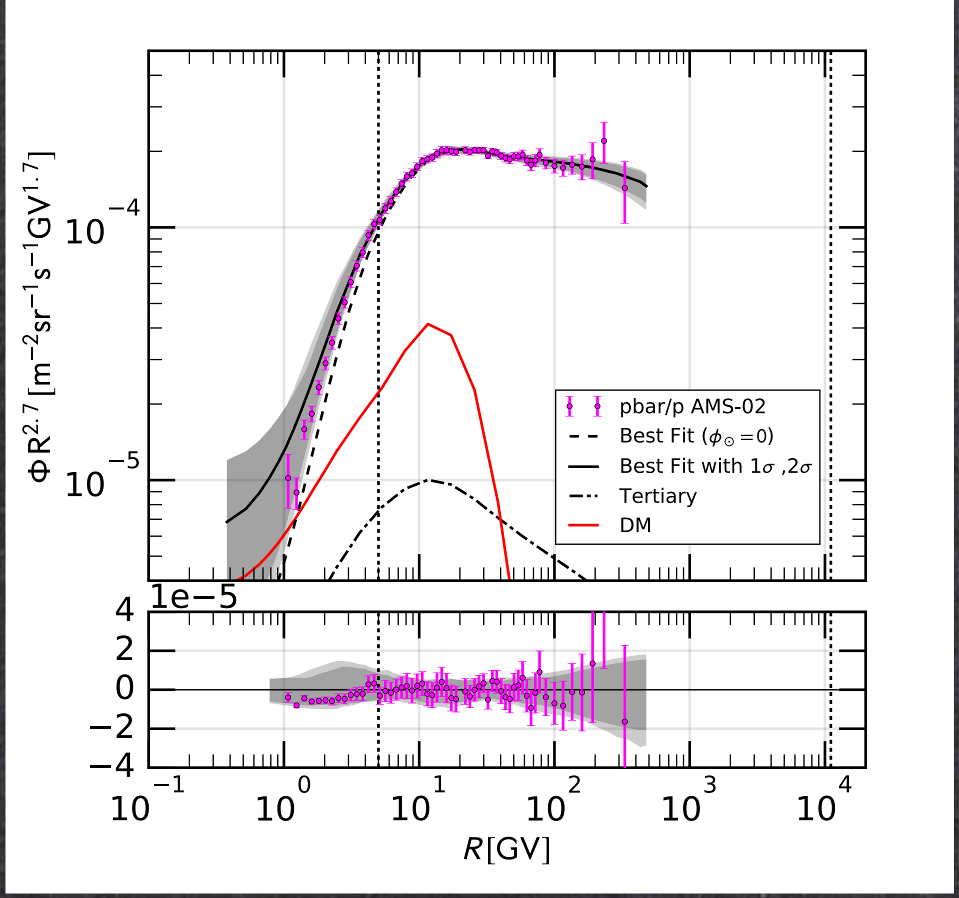


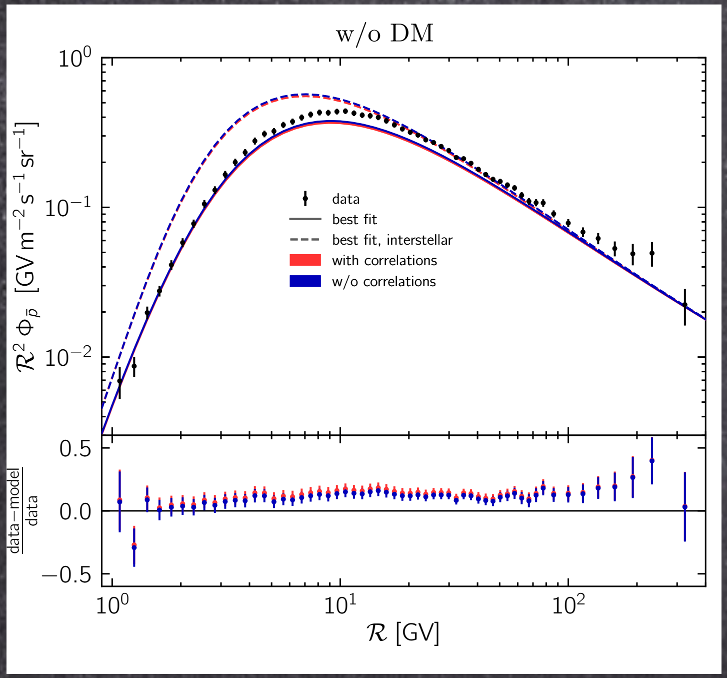
- Secondary pbar flux is predicted consistent with AMS-02 data
- Transport and cross section uncertainties are comparable
- A dark matter contribution would come as a tiny effect
- Precise predictions are mandatory

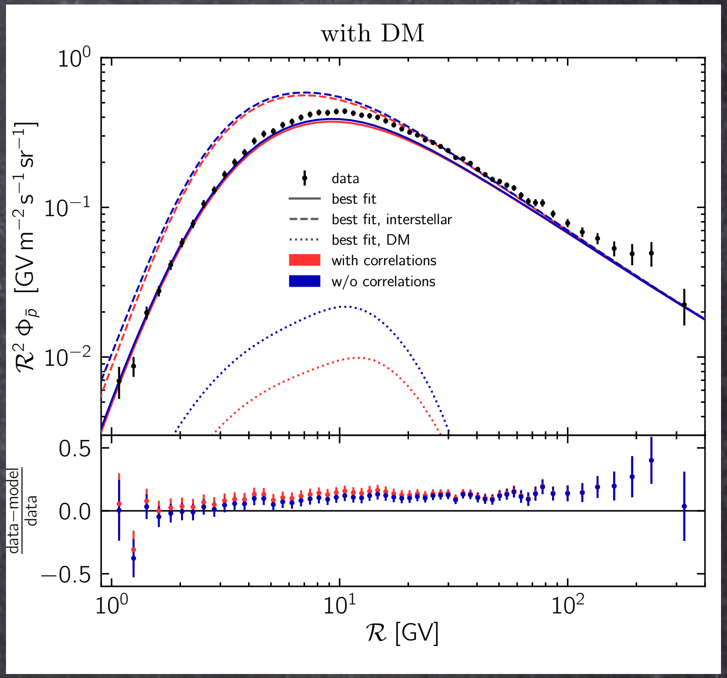
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017

Heisig, Korsmeier, Winkler PRD2020 2020







Derivation of covariance matrix for systematic errors (dominated by p(bar)C absorption cross section)
Significance drops to 1σ

GAPS will measure antiproton at E < 0.25 GeV/n

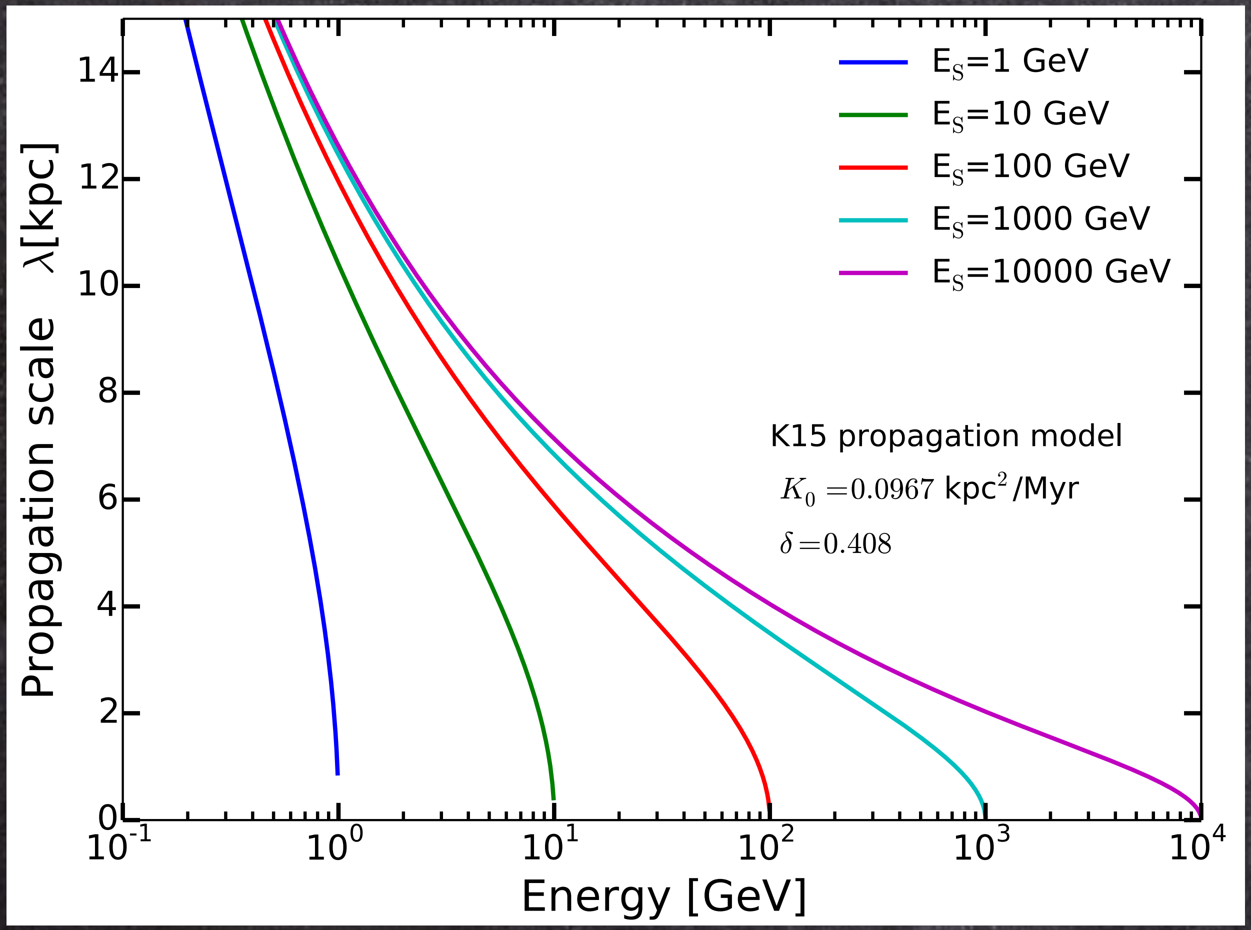
Cross section are missing in this range and they are a priority

Detected e+ and e- are local

$$\lambda^2(E, E_S) = 4\int_E^{E_S} dE' \frac{D(E')}{b_{\rm loss}(E')}$$

Typical propagation length in the Galaxy

Manconi, Di Mauro, FD JCAP 2017



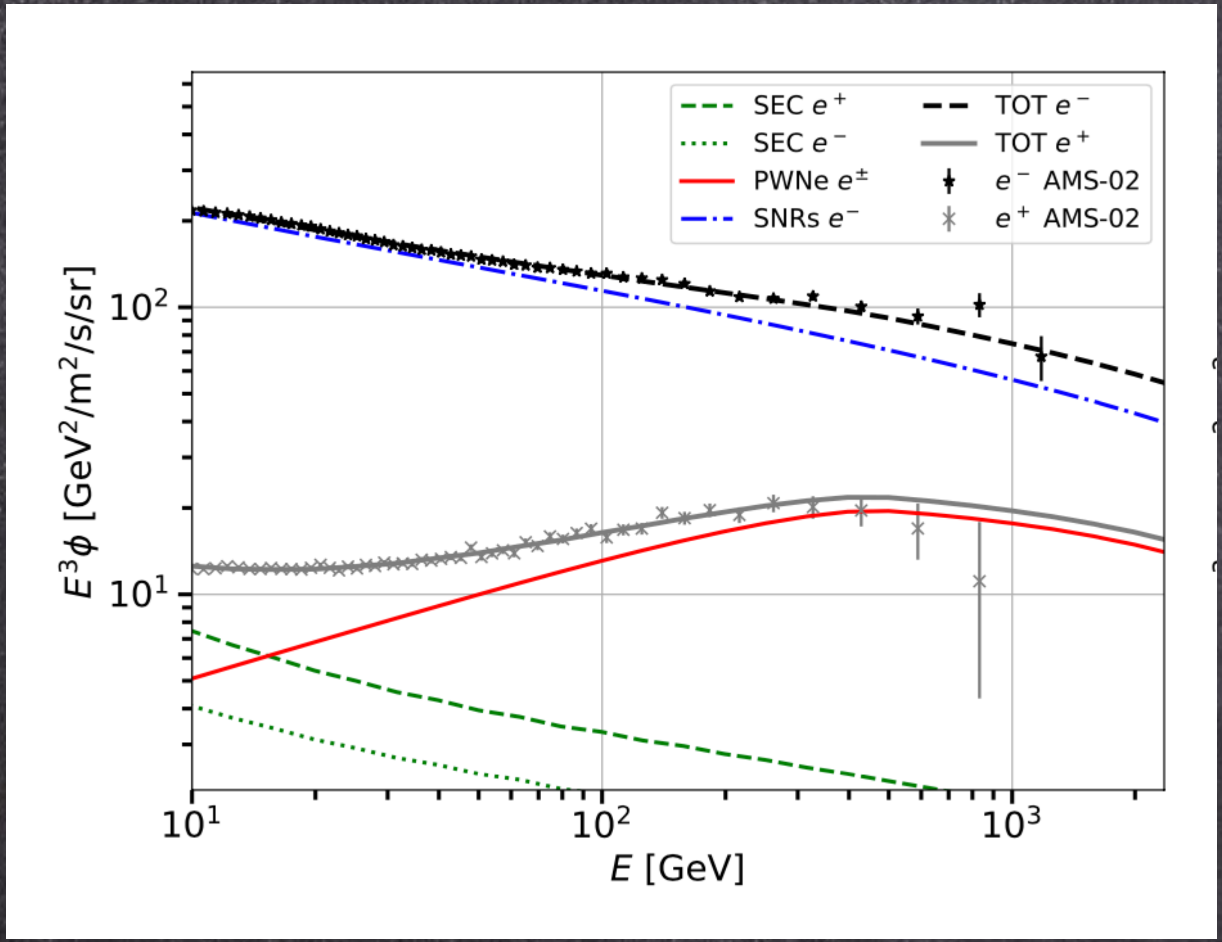
Sources of e+ & e- in the Galaxy

- Inelastic hadronic collisions (asymm.)
- Pulsar wind nebulae (PWN) (symm.)
- Supernova remnants (SNR) (only e-)
- Particle Dark Matter annihilation (e+,e-)?

e-, e+ have strong radiative cooling and arrive at Earth if produced within few kpc around it

The role of e± secondaries

M. Di Mauro, FD, S. Manconi PRD 2021



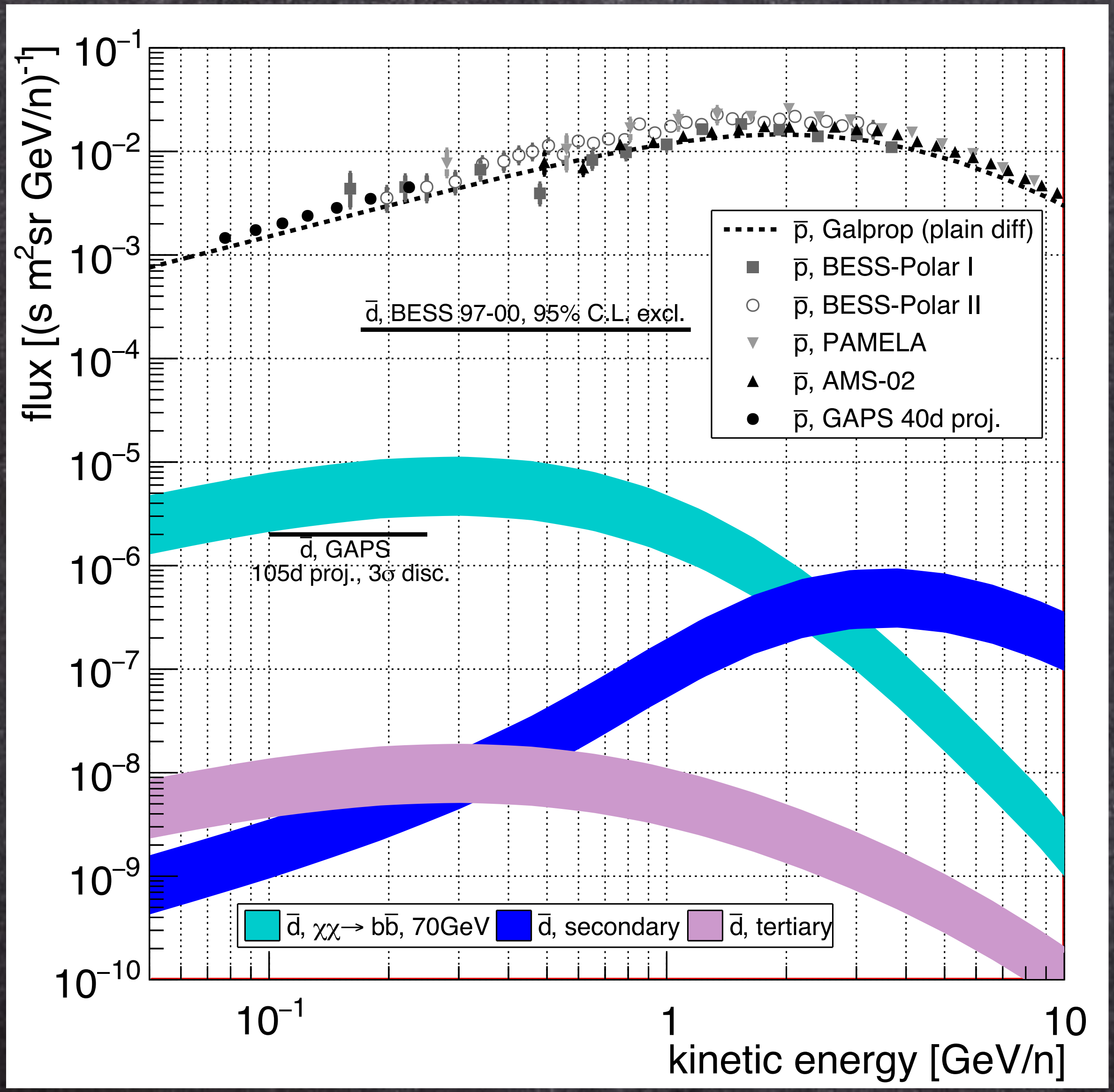
e+ secondaries contribute significantly to shape the spectrum at Earth.

The flux in the GeV region is likely dominated by secondaries

A PRIMARY component is surely there at high energies

Antideuterons persepcthves

P. Von Doetinchem et al. Phys. Rep. 2021



AMS-02 antiproton data

Antideuteron predictions for DM model indicated by pbar AMS-02 data

Bands are for coalescence uncertainty

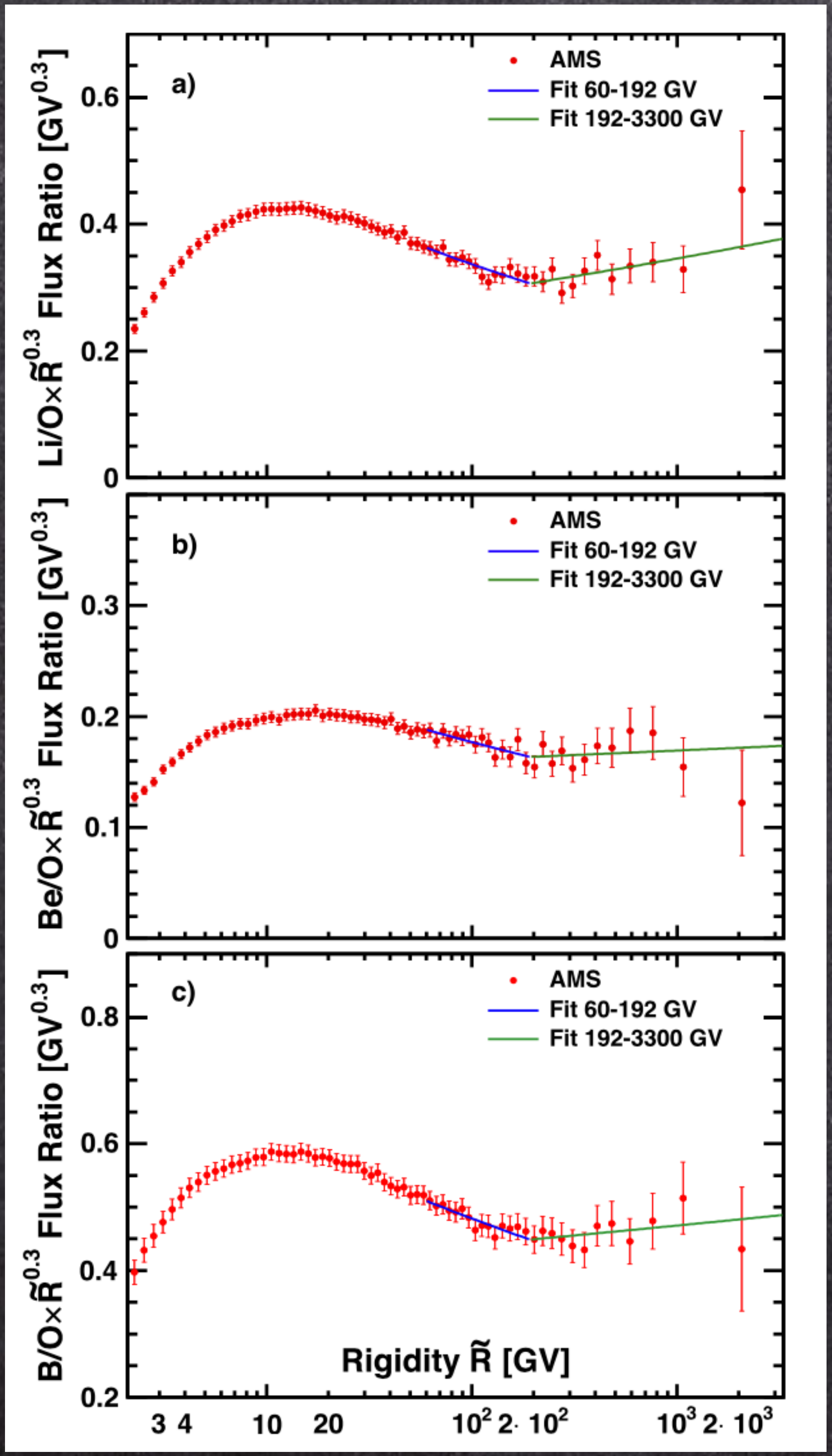
Conclusions

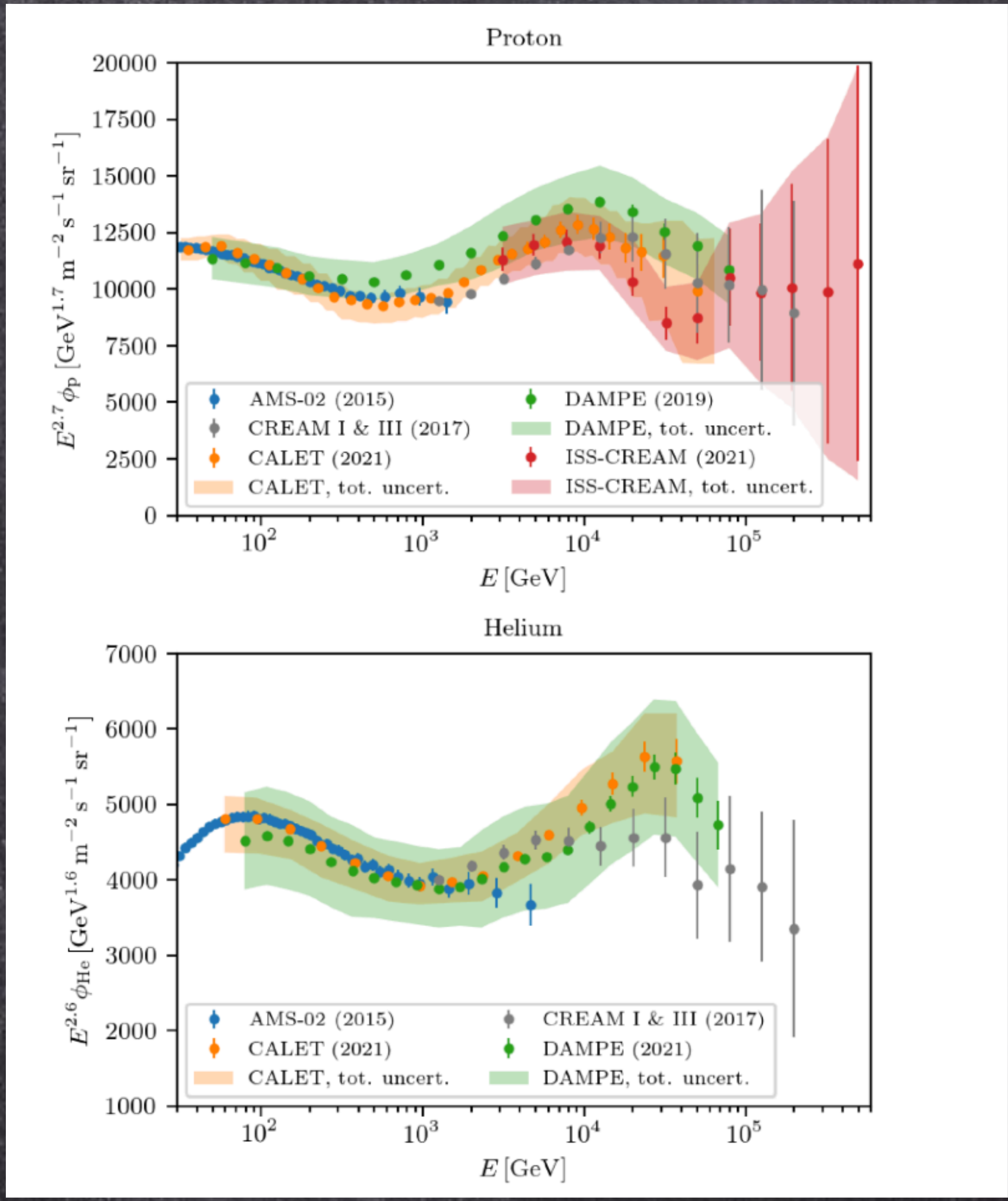
Great efforts to better understand nuclei and antinuclei in CRS: theory models, data from space, data from colliders.

Data from space are actually hampered by lack of precise (<10%) ross section: nuclei, isotopes, antimatter, γs

Data from colliders are highly desirable.
A specific receipt can be provided by the astroparticle community

Precision data from space: nuclei, electrons

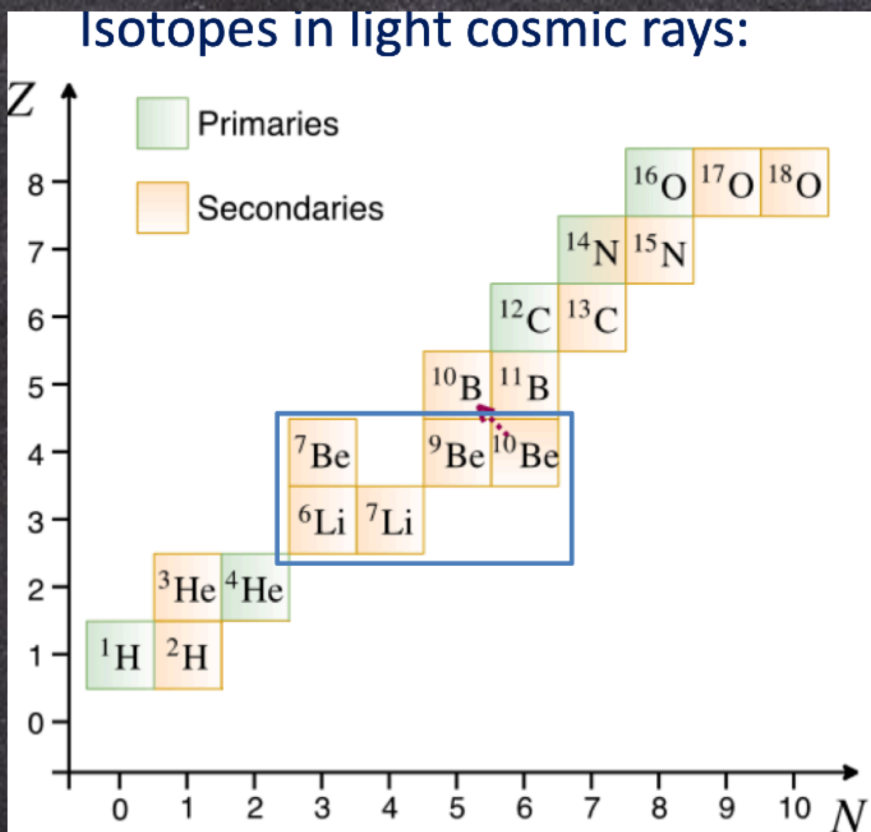




Light isotopes in cosmic rays

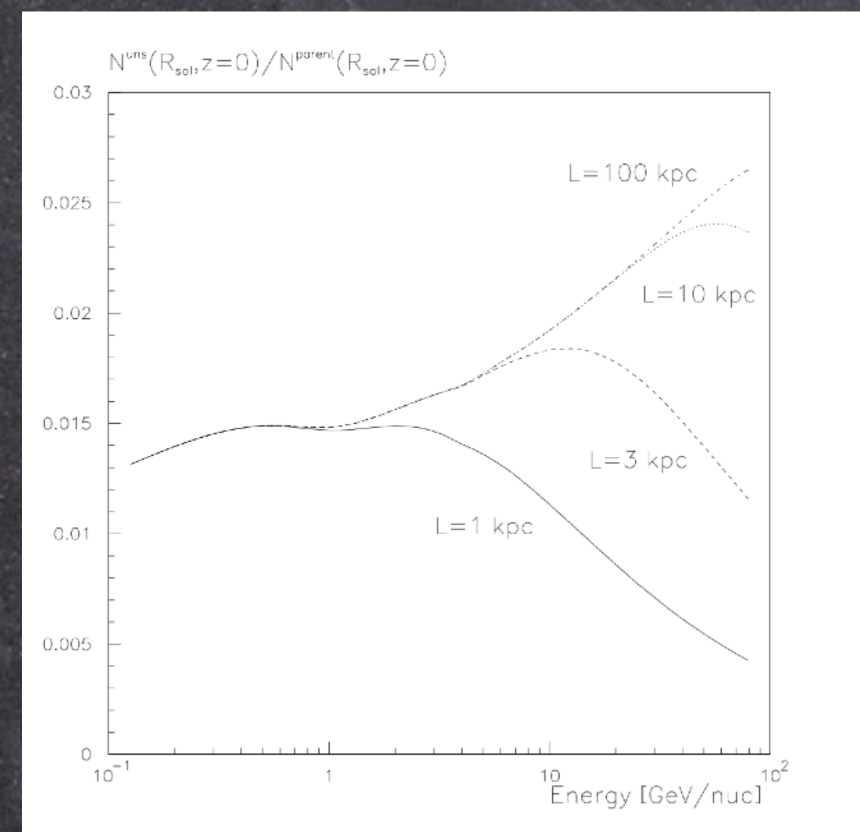
Important to test origin and propagation of CRs
Radioactive isotopes can track the diffusive halo size

Derome PoS ICRC 2021



Radioactive isotopes have different propagation history

FD, Maurin, Taillet A&A 2001



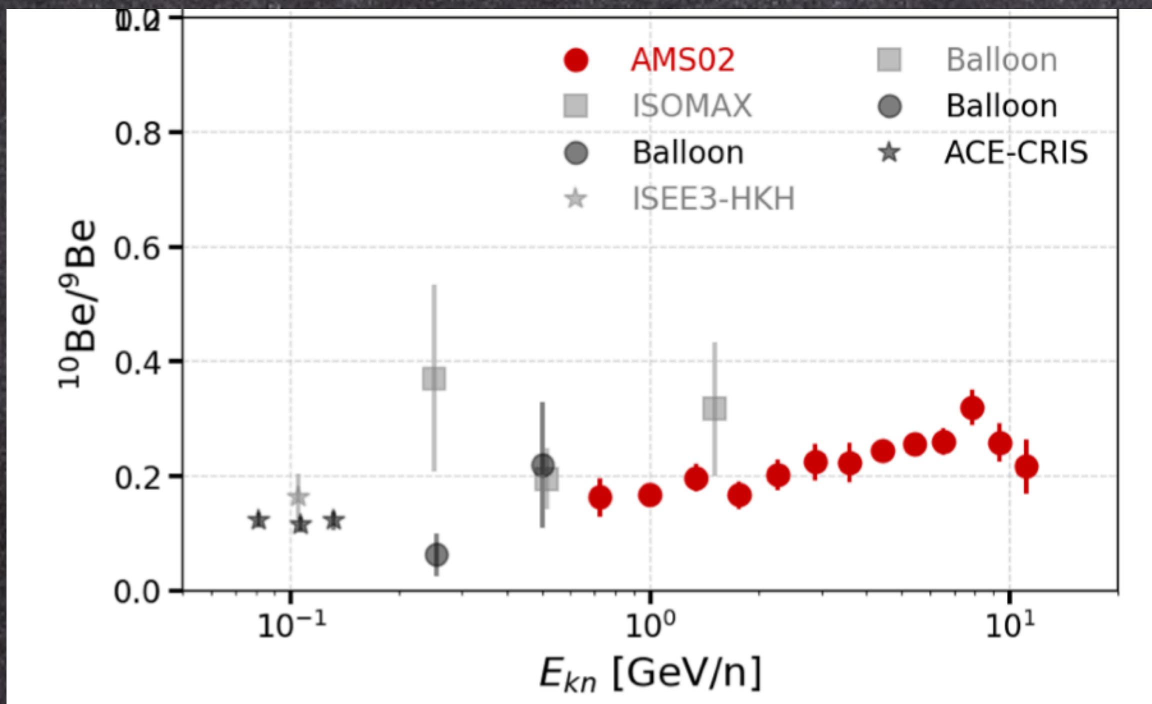
Unstable ^{26}Al to stable ^{28}Si parent ratio

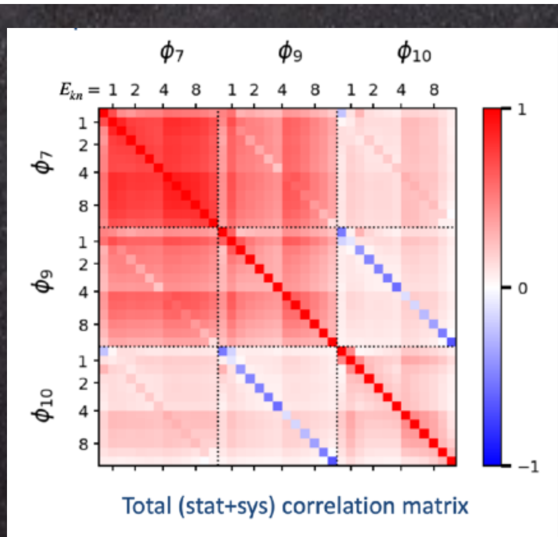
$l_{rad} = \sqrt{D(E)\gamma\tau_0} < L$: insensitive to halo size

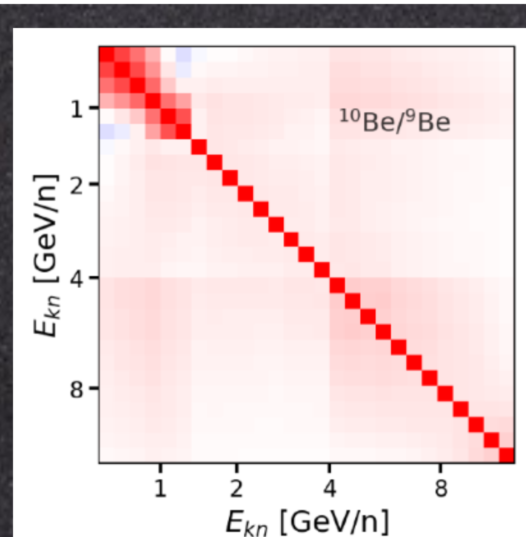
Recent results with light nuclei isotopes

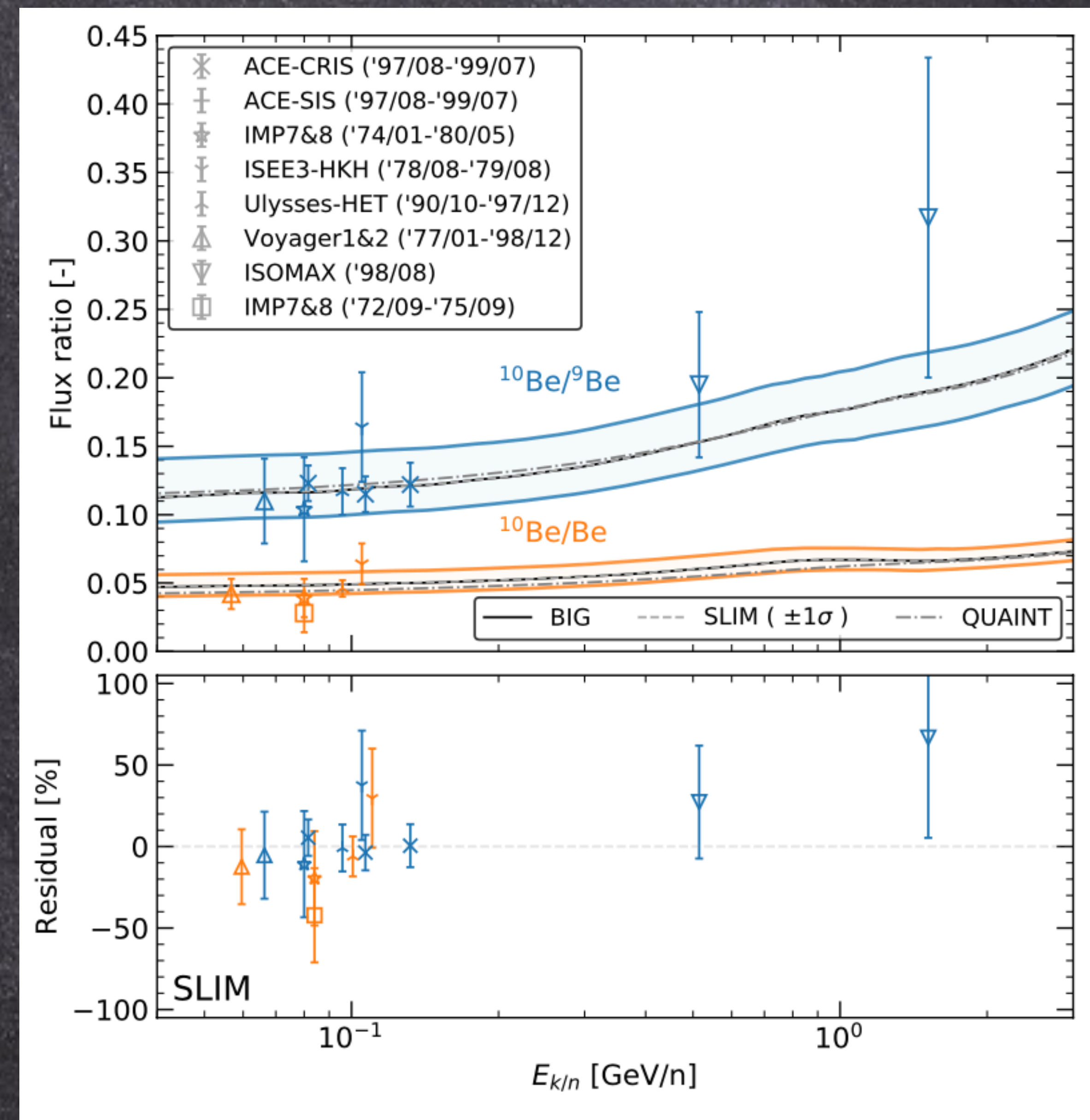
L.Derome AMS-02, ICRC 2021 PoS

Weinrich et al. A&A 2020
Maurin et al, 2203.07265









Several isotopes measured up to 10 GeV/n, with correlation matrices

Indications to rather high diffusive halo (>=5 kpc)

Paper

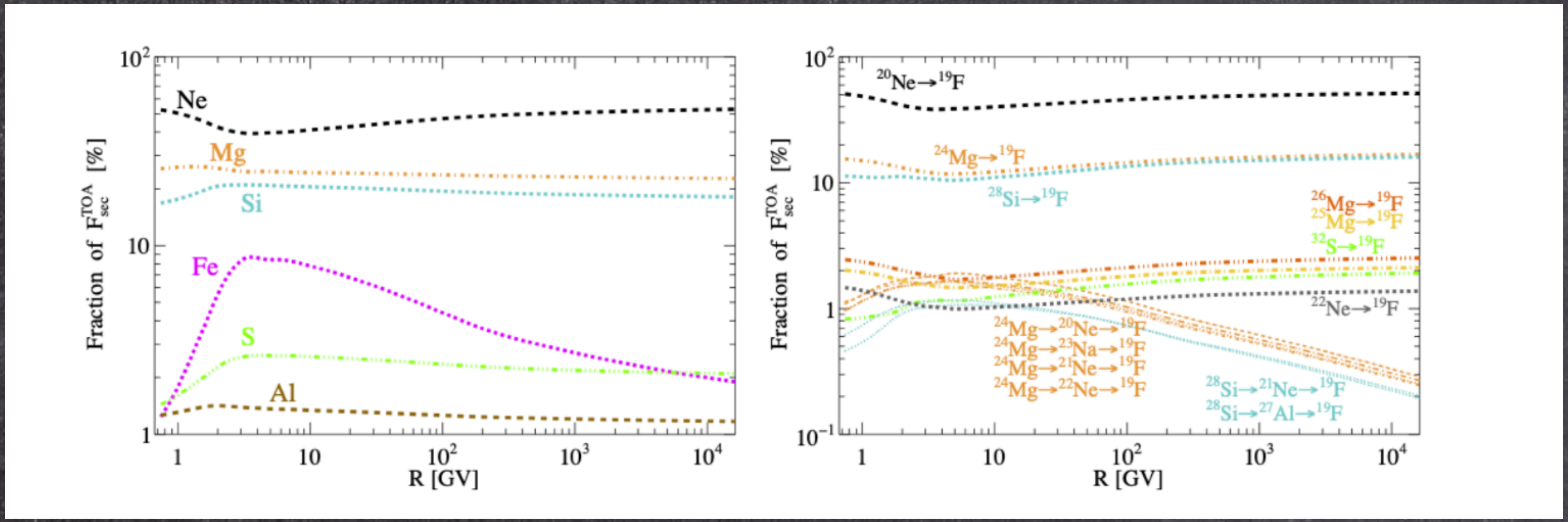
A simple determination of the halo size from $^{10}Be/^{9}Be$ data

A&A 667, A25 (2022)

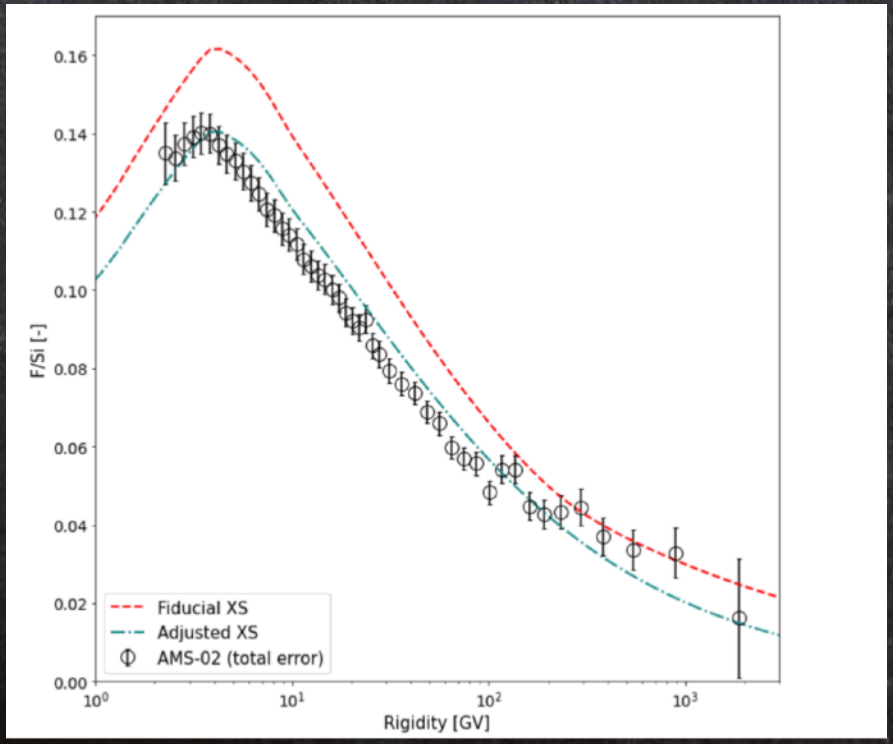
new data for the production cross-section of ^{16}O into Be isotopes above a few GeV/n are especially desired.

Spallation cross sections for nuclei: the F case

Vecchi, Bueno, Derome, Genolini, Maurin PoS ICRC 2021



Main progenitors are Ne, Mg, Si, S, Al, and other 35 channels contributing individually [0.1,2]%, 22% of the total.



Propagation parameters from lighter nuclei over-predict F/Si.
If cross sections are reduced by 15%, agreement is found for Li to F secondaries