Is the B/C slope in AMS-02 data actually telling us something about the diffusion coefficient slope ?

ICRC2019
Madison, WI, USA

P.-I. Batista, M. Vecchi, D. Maurin, L. Derome, M. Boudaud, Y. Génolini, J.Lavalle, V. Poulin, P. Salati, P. D. Serpico

rijksuniversiteit groningen

IFSC UNIVERSIDADE DE SÃO PAULO
Instituto de Física de São Carlos

Scientific motivations and goals

There is a common misconception about the fact that high-energy B/C data directly provides the slope of the diffusion coefficient, implying that additional effects at play (convection, reacceleration, and destruction) can be neglected.

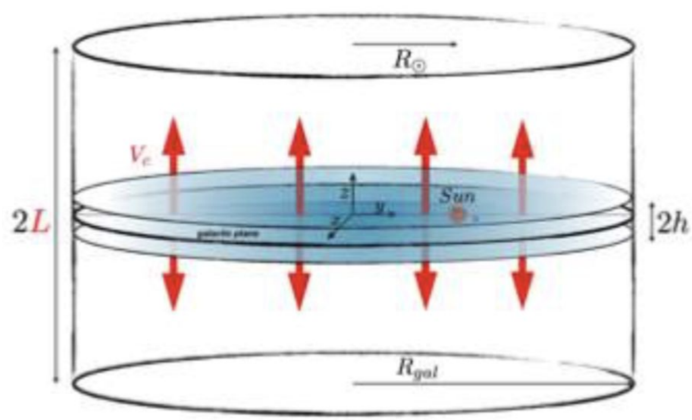
Using the code USINE for CR propagation and taking into account all relevant processes, we study:

- the slope of the B/C in different propagation scenarios, and compare to the B/C data from AMS-02.
- the flux slope for different CR species.

Cosmic ray transport in the galaxy

$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_c\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = \; q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\right\}\,\psi_\beta$$

A two break diffusion coefficient is used to reproduce the B/C, following first hint of diffusive origin reported in PRL 119, 241101 (2017)



1D model and semi-analytic approach with the USINE code [arxiv:1807.02968]

Benchmarks for galactic propagation

Phys.Rev. D99 (2019) no.12, 123028

The best fit parameters:



Parameters	BIG	SLIM	QUAINT
χ^2/dof	$61.7/61 = 1.01$	$61.8/63 = 0.98$	$62.1/62 = 1.00$
	Intermediate-rigidity parameters		
K_{10} [kpc^2 Myr^{-1}]	$0.30^{+0.03}_{-0.04}$	$0.28^{+0.02}_{-0.02}$	$0.33^{+0.03}_{-0.06}$
δ	$0.48^{+0.04}_{-0.03}$	$0.51^{+0.02}_{-0.02}$	$0.45^{+0.05}_{-0.02}$
	Low-rigidity parameters		
V_c [km s^{-1}]	$0^{+7.4}$	N/A	0.0^{+8}
V_A [km s^{-1}]	67^{+24}_{-67}	N/A	101^{+14}_{-15}
η	1 (fixed)	1 (fixed)	$-0.09^{+0.35}_{-0.57}$
δ_l	$-0.69^{+0.61}_{-1.26}$	$-0.87^{+0.33}_{-0.31}$	N/A
R_l [GV]	$3.4^{+1.1}_{-0.9}$	$4.4^{+0.2}_{-0.2}$	N/A
	High-rigidity break parameters (nuisance parameters)		
Δ_h	0.18	0.19	0.17
R_h [GV]	247	237	270
s_h	0.04	0.04	0.04

Slide from Y. Genolini

Analysis strategy

- Compute B/C flux ratio as a function of rigidity (R=pc/Ze).
- Compute the observed spectral index: $\boxed{\gamma_{Obs} = \mathrm{d}\left[\log \phi\right] / \mathrm{d}\left[\log R\right]}$
- Compute the difference wrt theoretical expectations
  $\boxed{\Delta_{slope} = \left|\gamma_{Th}\right| - \left|\gamma_{Obs}\right|}$
- Extend the work to other CR species, from H to Fe

Purely diffusive scenario

Convection, reacceleration and destruction are neglected.

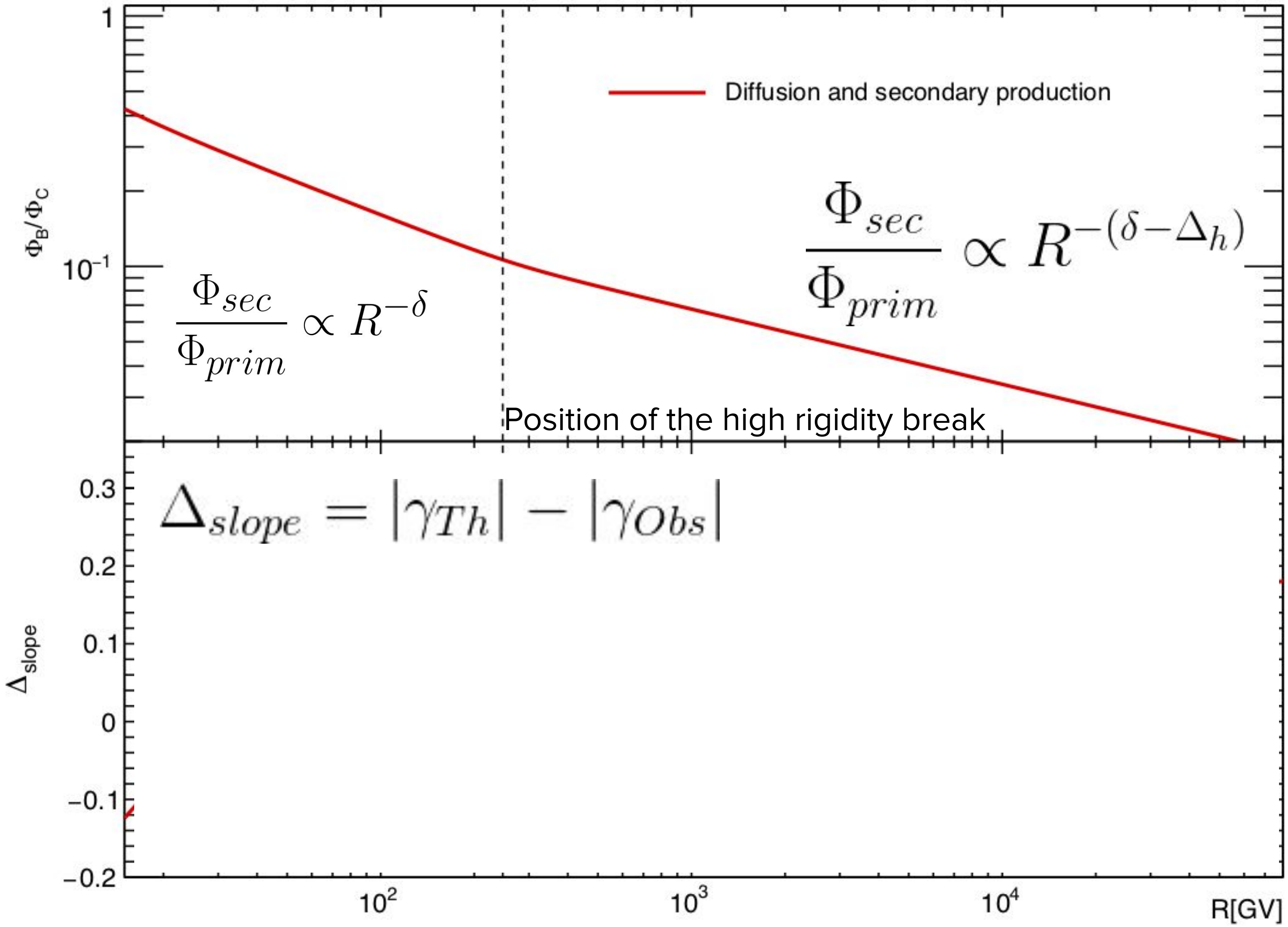
$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \cancel{V_c\psi_\alpha}\right\} + \frac{\partial}{\partial E}\left\{\cancel{b_{\mathrm{tot}}(E)}\,\psi_\alpha - \cancel{\beta^2 K_{pp}}\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\cancel{\sigma_\alpha v_\alpha n}_{\mathrm{ism}}\,\psi_\alpha + \cancel{\Gamma_\alpha}\psi_\alpha = q_\alpha + \sum_\beta \left\{\sigma_{\beta\to\alpha} v_\beta n_{\mathrm{ism}} + \cancel{\Gamma_{\beta\to\alpha}}\right\}\psi_\beta$$

Free parameters / Models	BIG	BIG Pure diff
$K_{10}[kpc^2]$	0.30	0.30
δ	0.48	0.48
η	1 or	1
δ_l	-0.69	-0.69
s_l	0.05	0.05
R_l [GV]	247	247
V_A [km/s]	0	N/A
V_c [km/s]	67	N/A
Δ_h	0.18	0.18

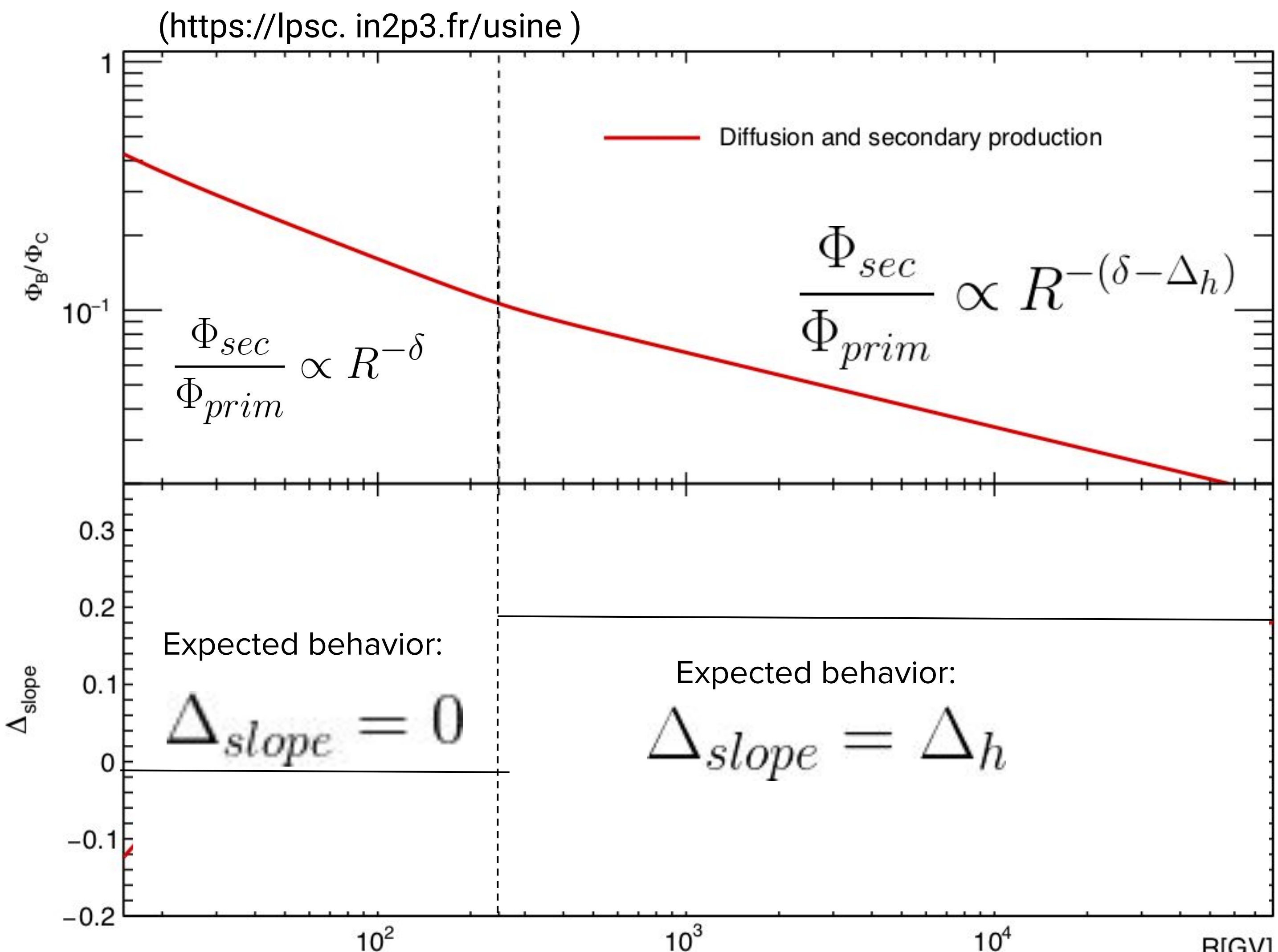
B/C on a pure diffusion scenario

Goal: simulate the B/C for a given set of propagation parameters, and study its slope with respect to the diffusion coefficient slope

(https://lpsc. in2p3.fr/usine)

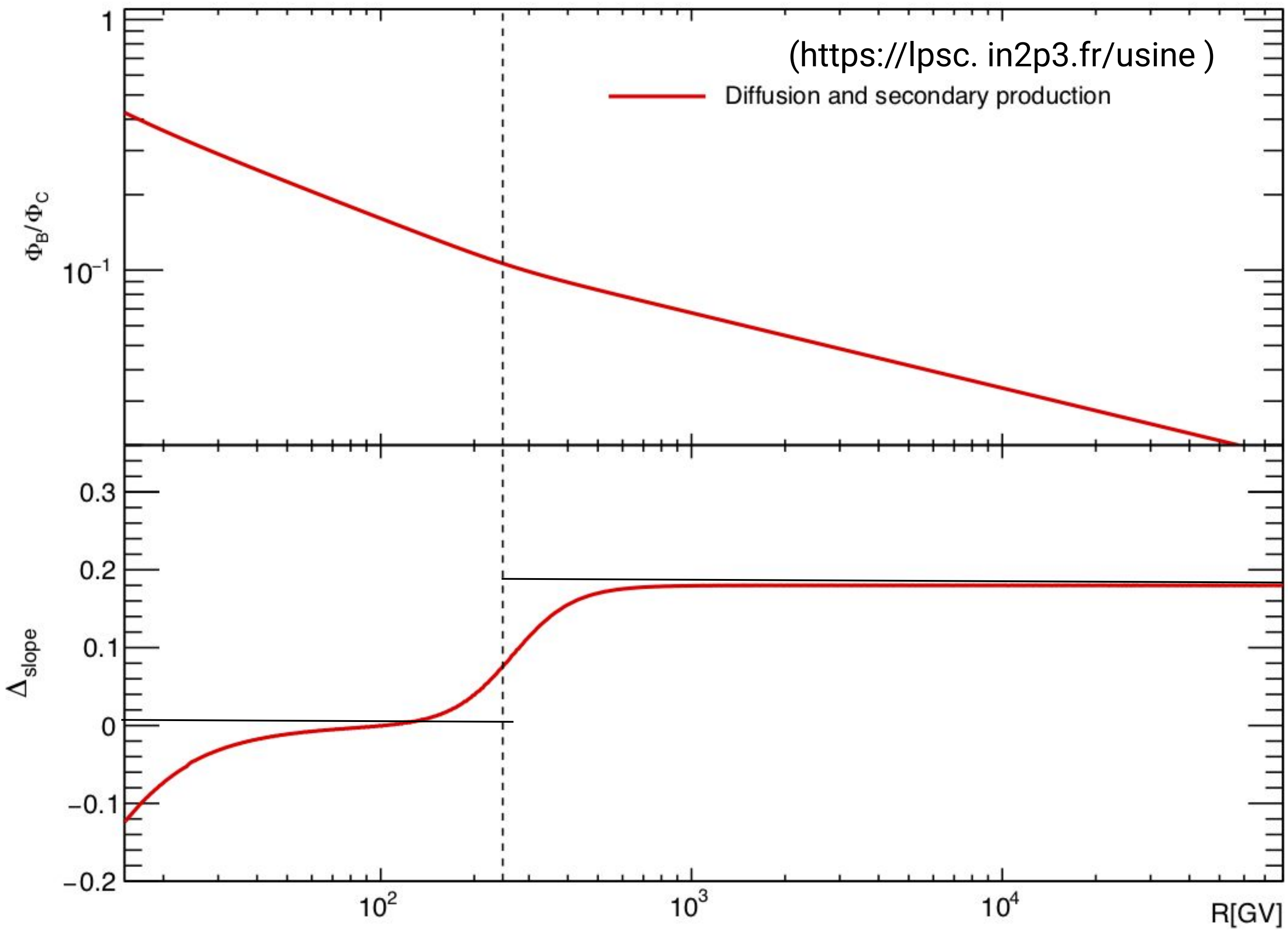


B/C on a pure diffusion scenario



B/C on a pure diffusion scenario

Our result is in agreement with the expected behaviour above 50 GV. Below 50 GV, even for the purely diffusive regime, departure from expectations is due to secondary production.



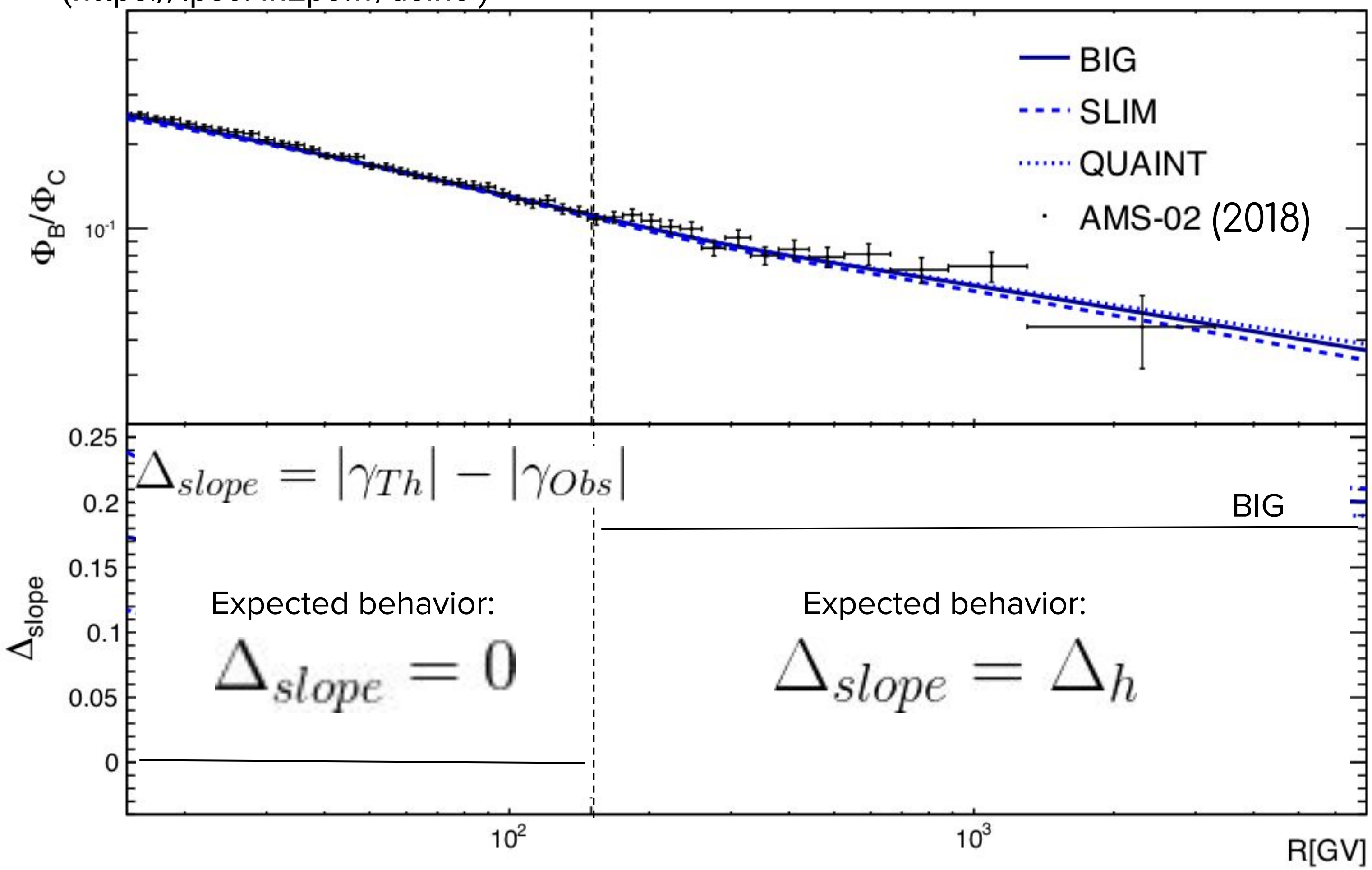
Full transport scenario

Destruction, convection and reacceleration are taken into account.

$$
\begin{aligned}
&- \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \vec{V}_c \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{\mathrm{tot}}(E)\, \psi_\alpha - \beta^2 K_{pp} \frac{\partial \psi_\alpha}{\partial E} \right\} \\
&\qquad + \sigma_\alpha\, v_\alpha\, n_{\mathrm{ism}}\, \psi_\alpha + \Gamma_\alpha\, \psi_\alpha = q_\alpha + \sum_\beta \left\{ \sigma_{\beta\to\alpha} v_\beta n_{\mathrm{ism}} + \Gamma_{\beta\to\alpha} \right\} \psi_\beta
\end{aligned}
$$

B/C on a Full transport model

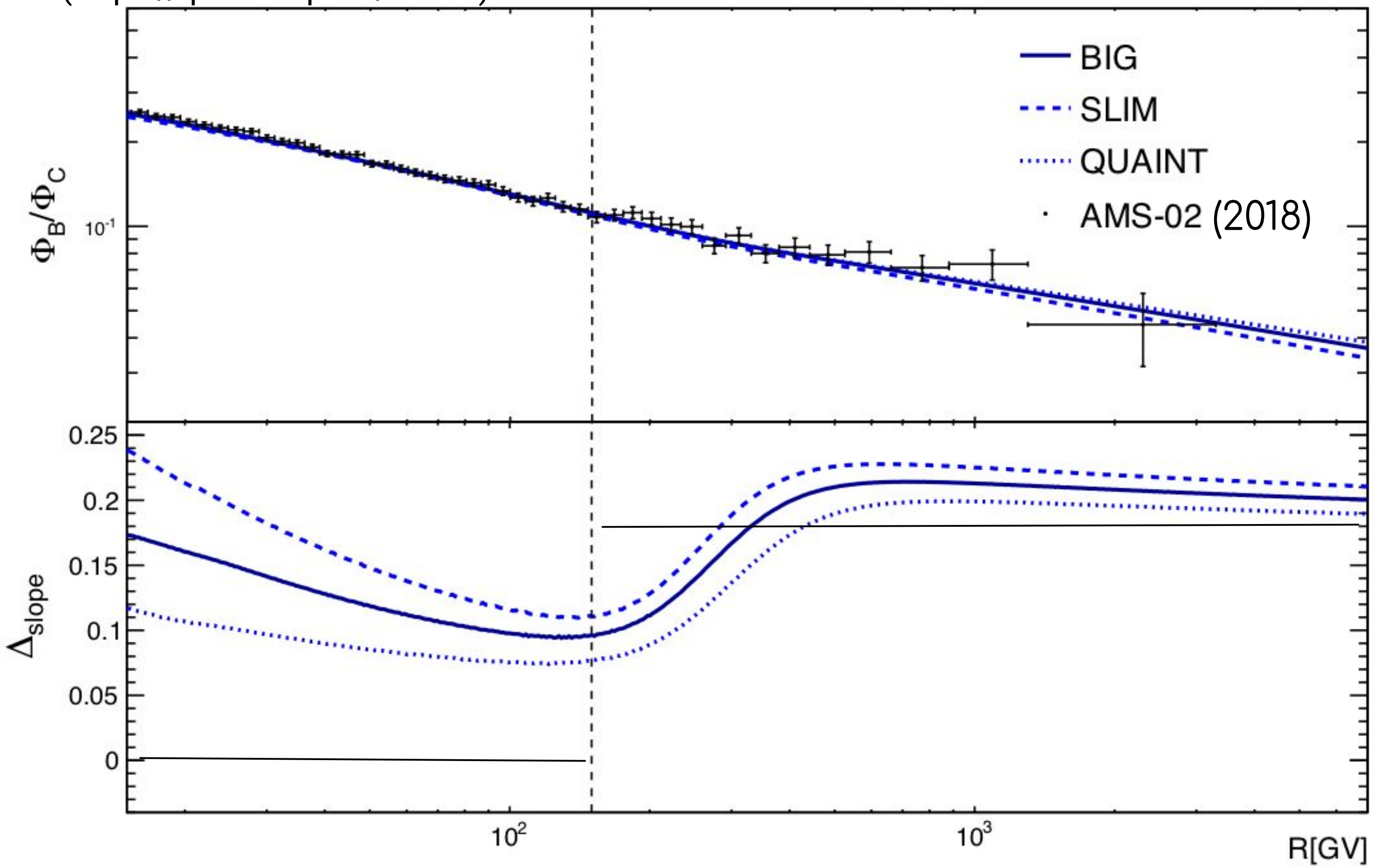
(https://lpsc. in2p3.fr/usine)



B/C on a full transport model

The B/C slope rigidity dependence is shaped in particular by inelastic interactions up to TeV energies.

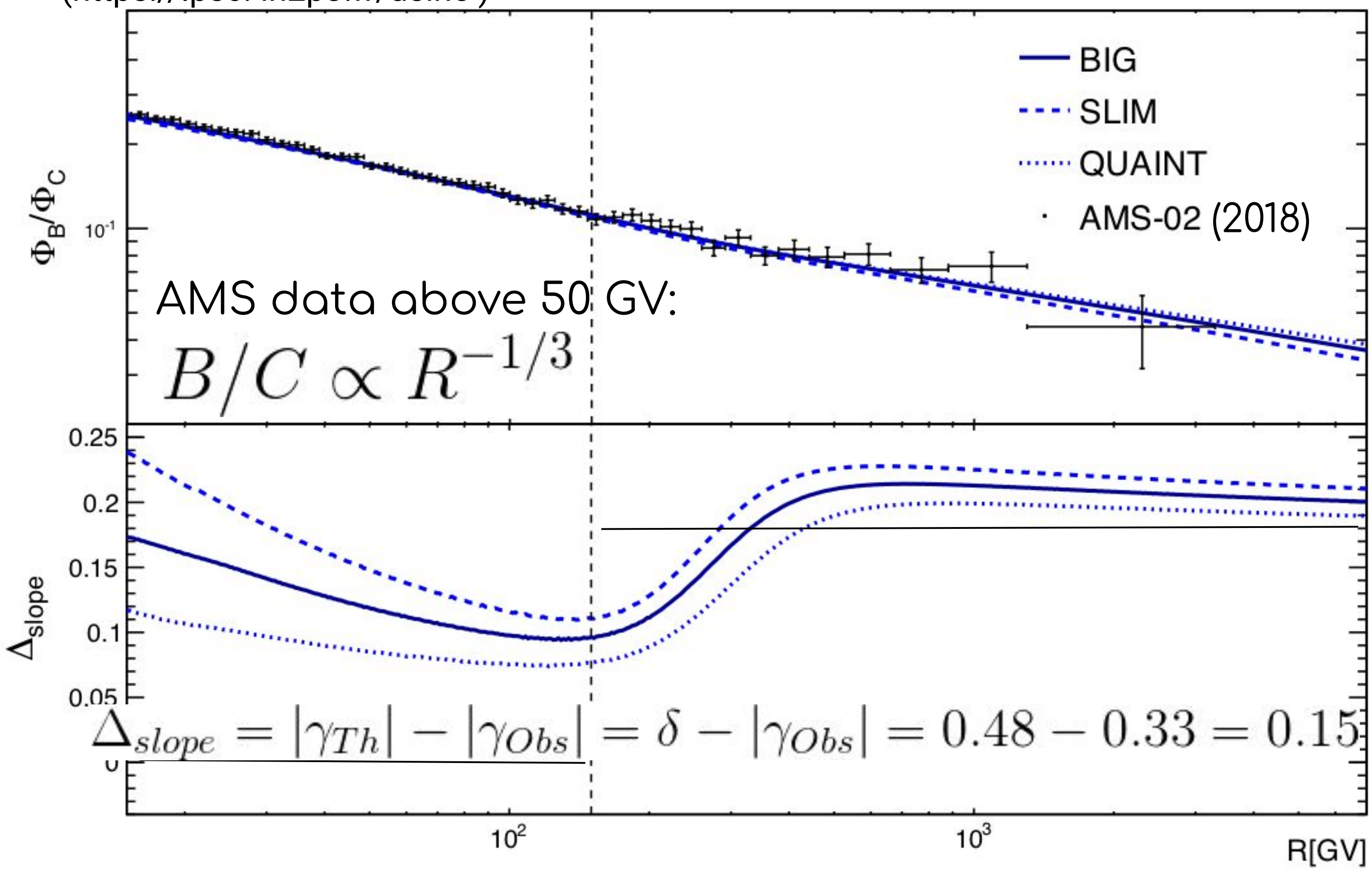
(https://lpsc. in2p3.fr/usine)



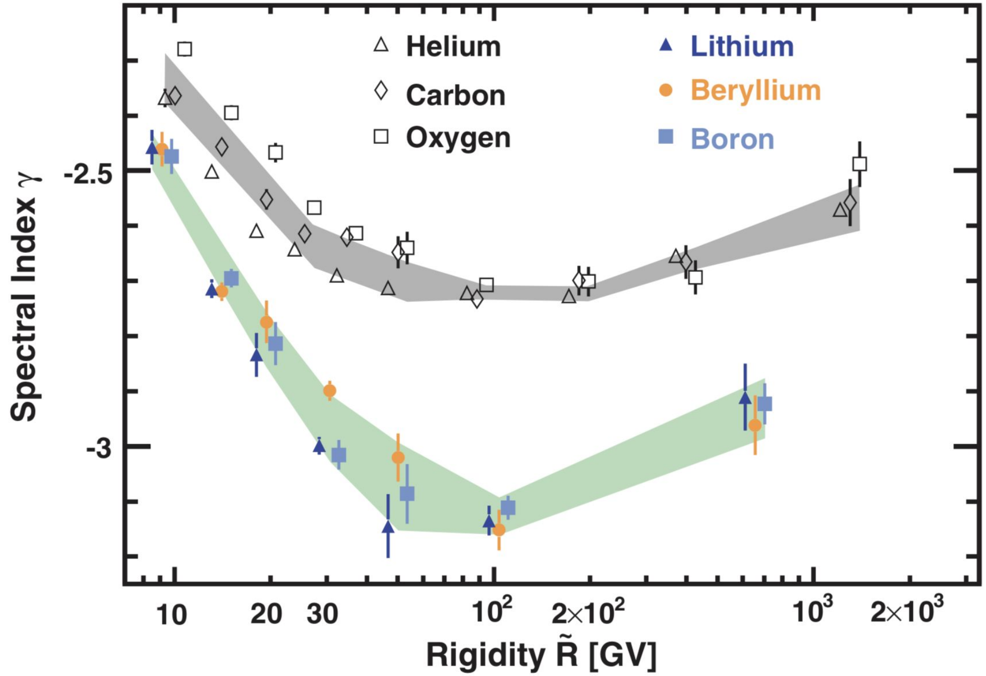
B/C on a full transport model

The B/C slope rigidity dependence is shaped in particular by inelastic interactions up to TeV energies.

(https://lpsc. in2p3.fr/usine)



Take home message



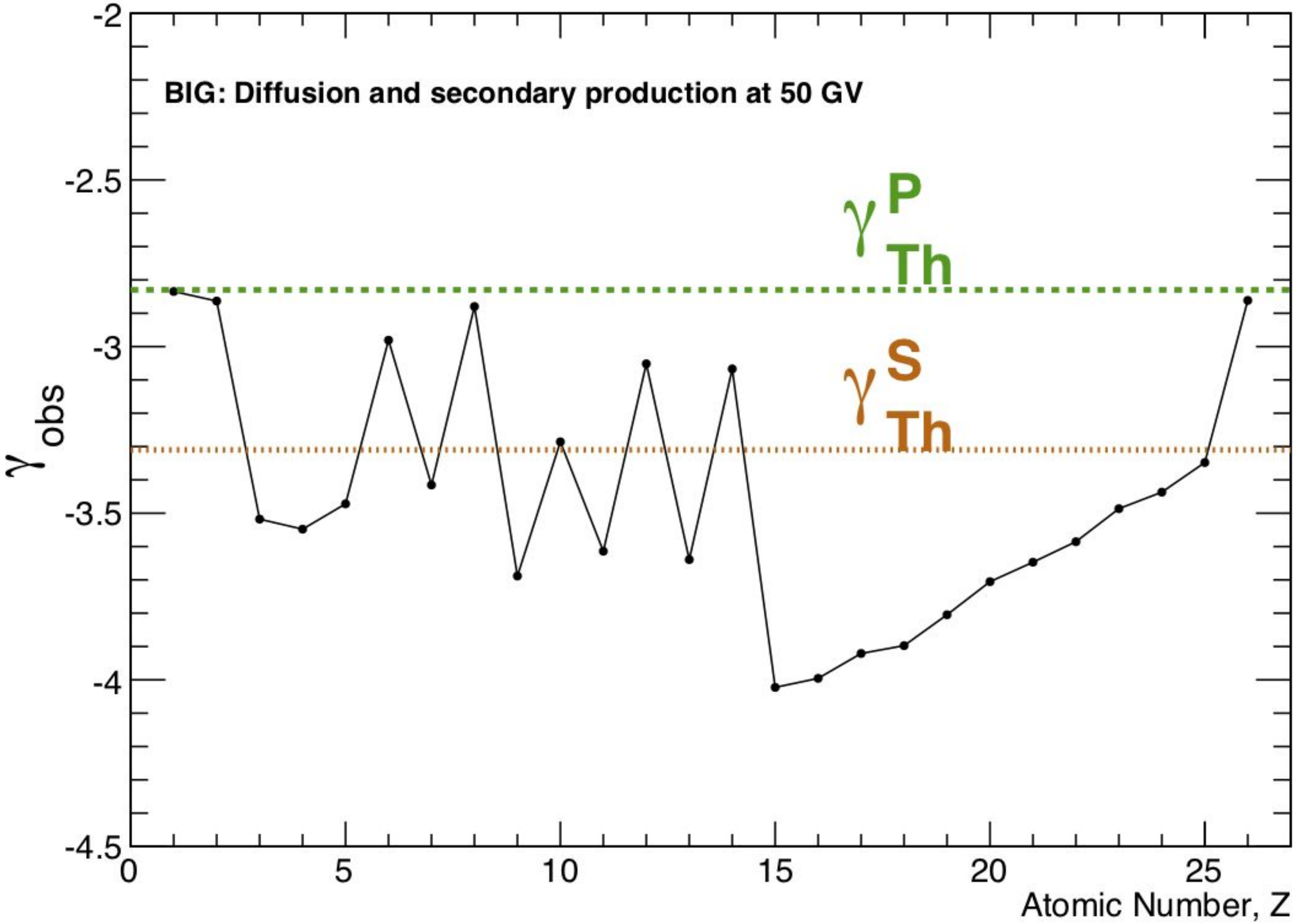
- The slope of the B/C should be disregarded as a direct indicator of the diffusion coefficient, because additional physical processes, in particular inelastic interactions, play a major role up the TV region.

Is this universal or species dependent?

- Dominant effect is destruction, and X-section depends on A: consequences on data slopes?

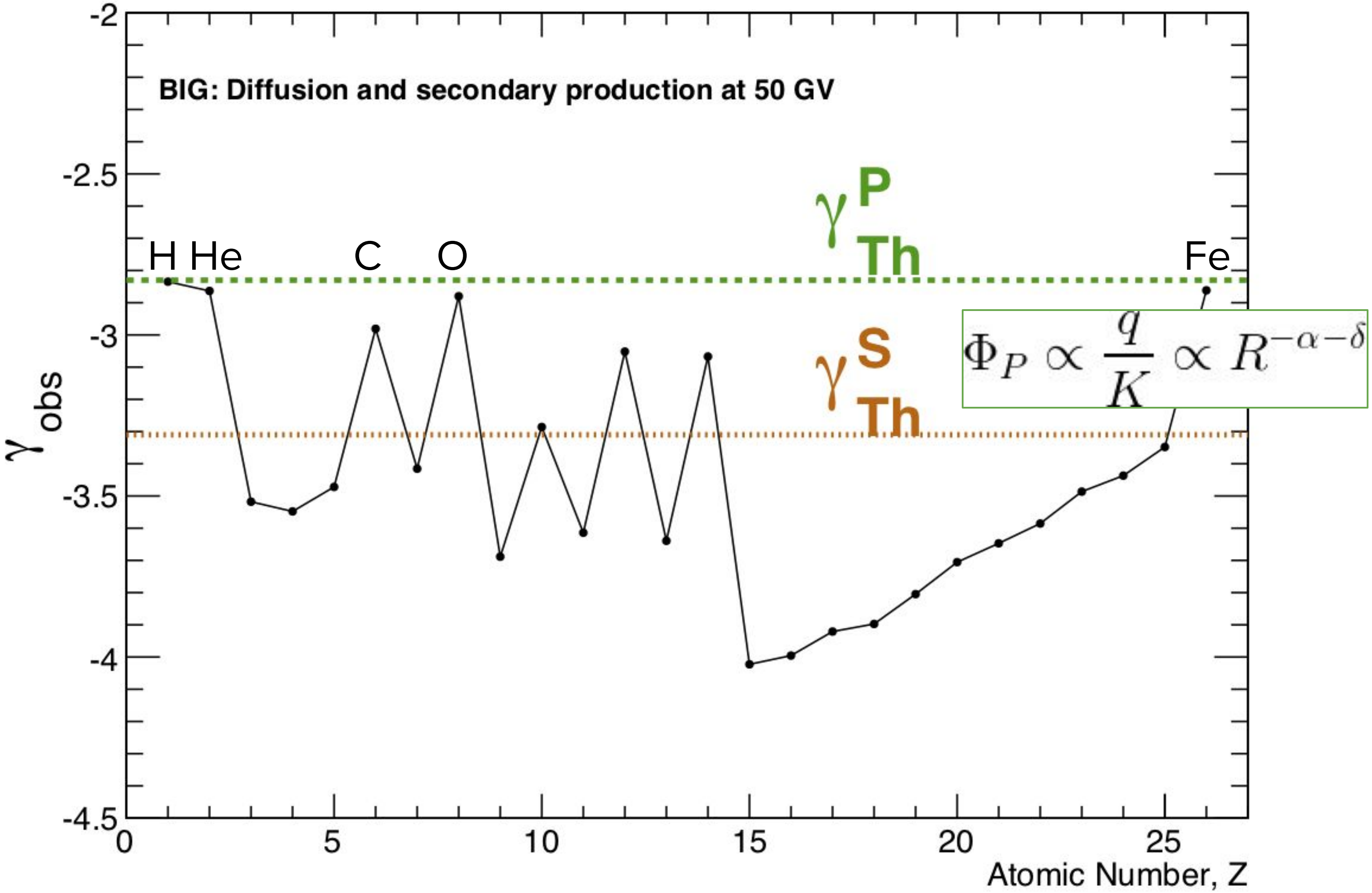
Flux slope dependence on Z: diffusion-only scenario

(https://lpsc. in2p3.fr/usine)



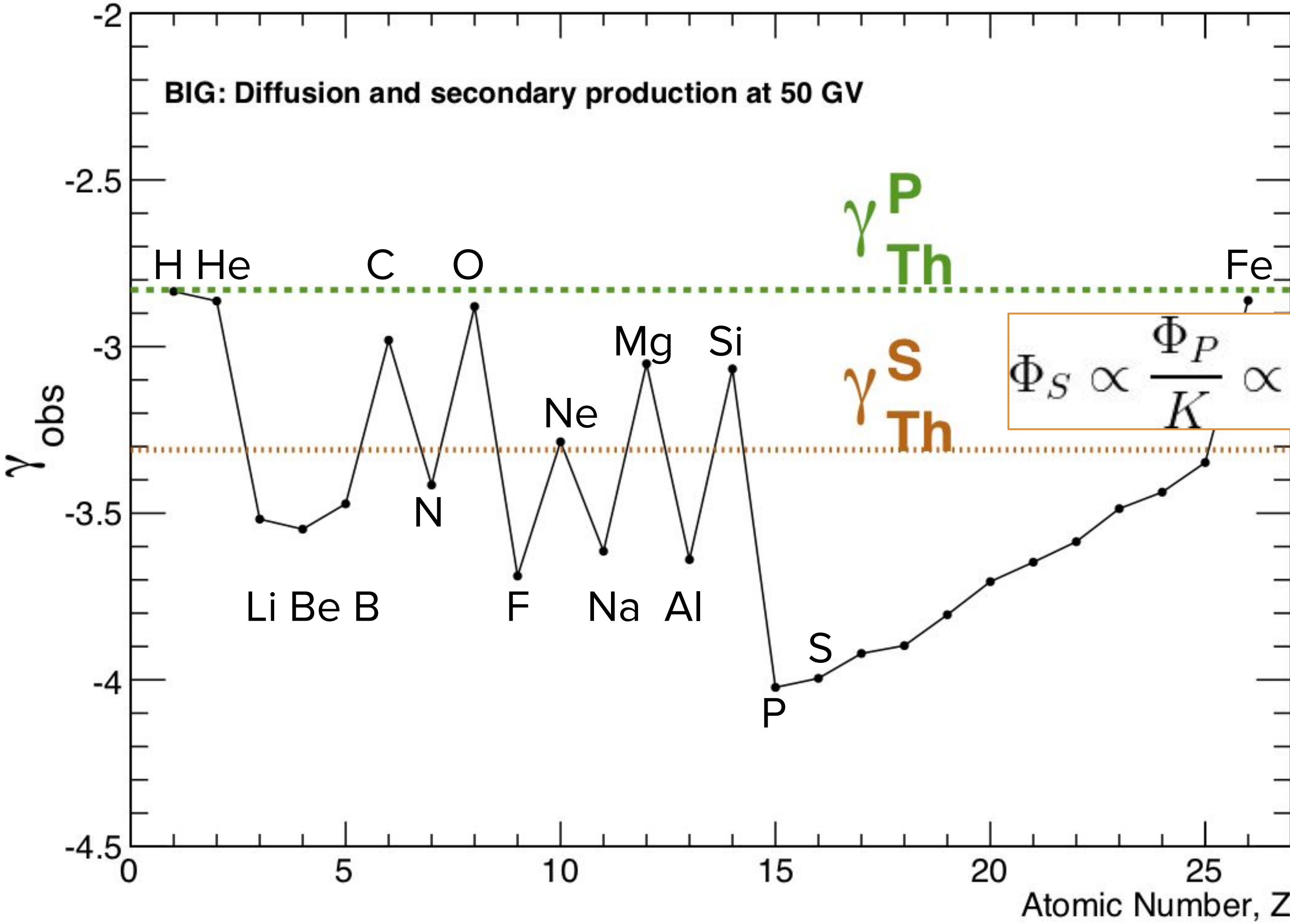
Flux slope dependence on Z: diffusion-only scenario

(https://lpsc. in2p3.fr/usine)



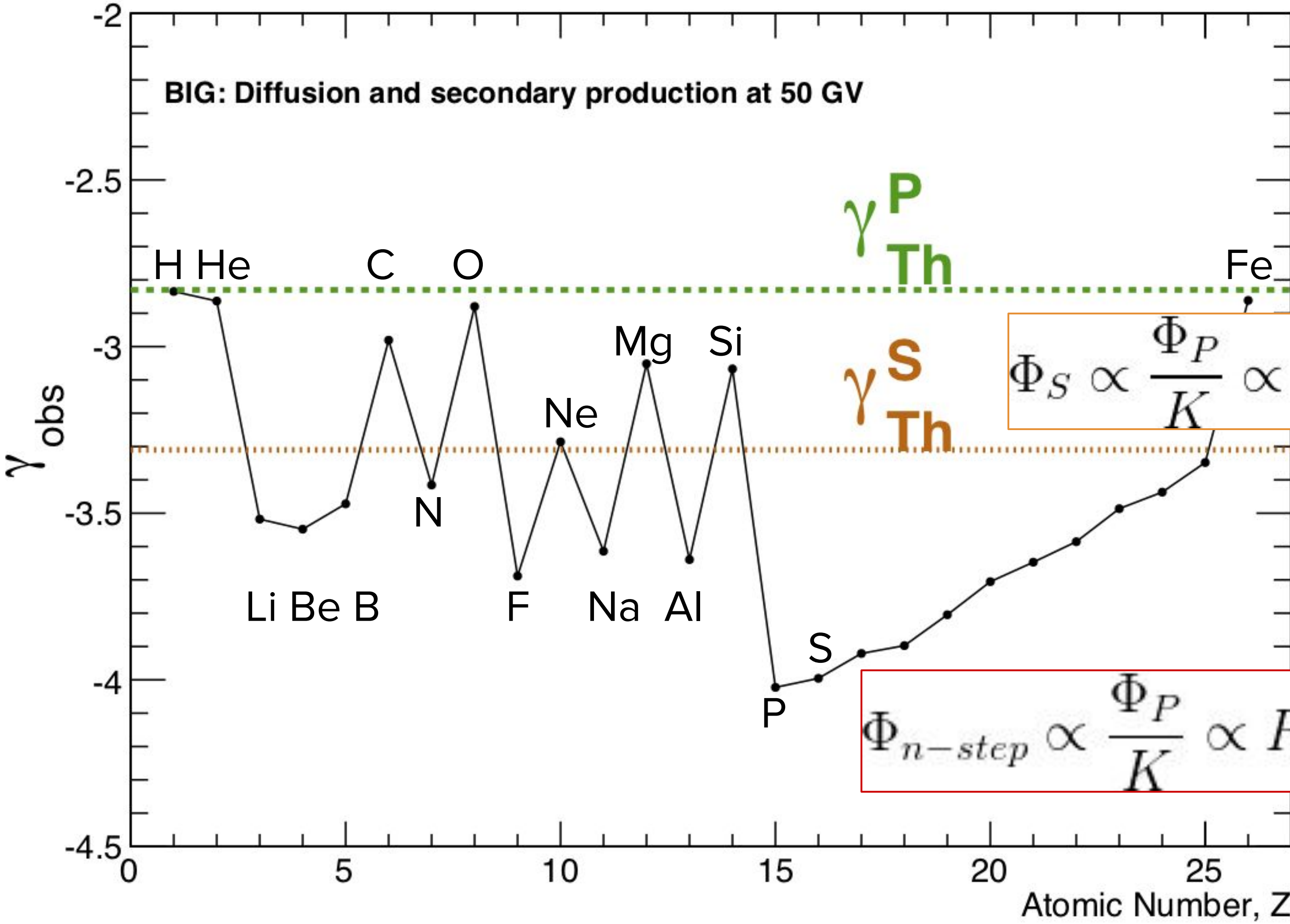
Flux slope dependence on Z: diffusion-only scenario

(https://lpsc. in2p3.fr/usine)



$$\Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta}$$

Flux slope dependence on Z: diffusion-only scenario

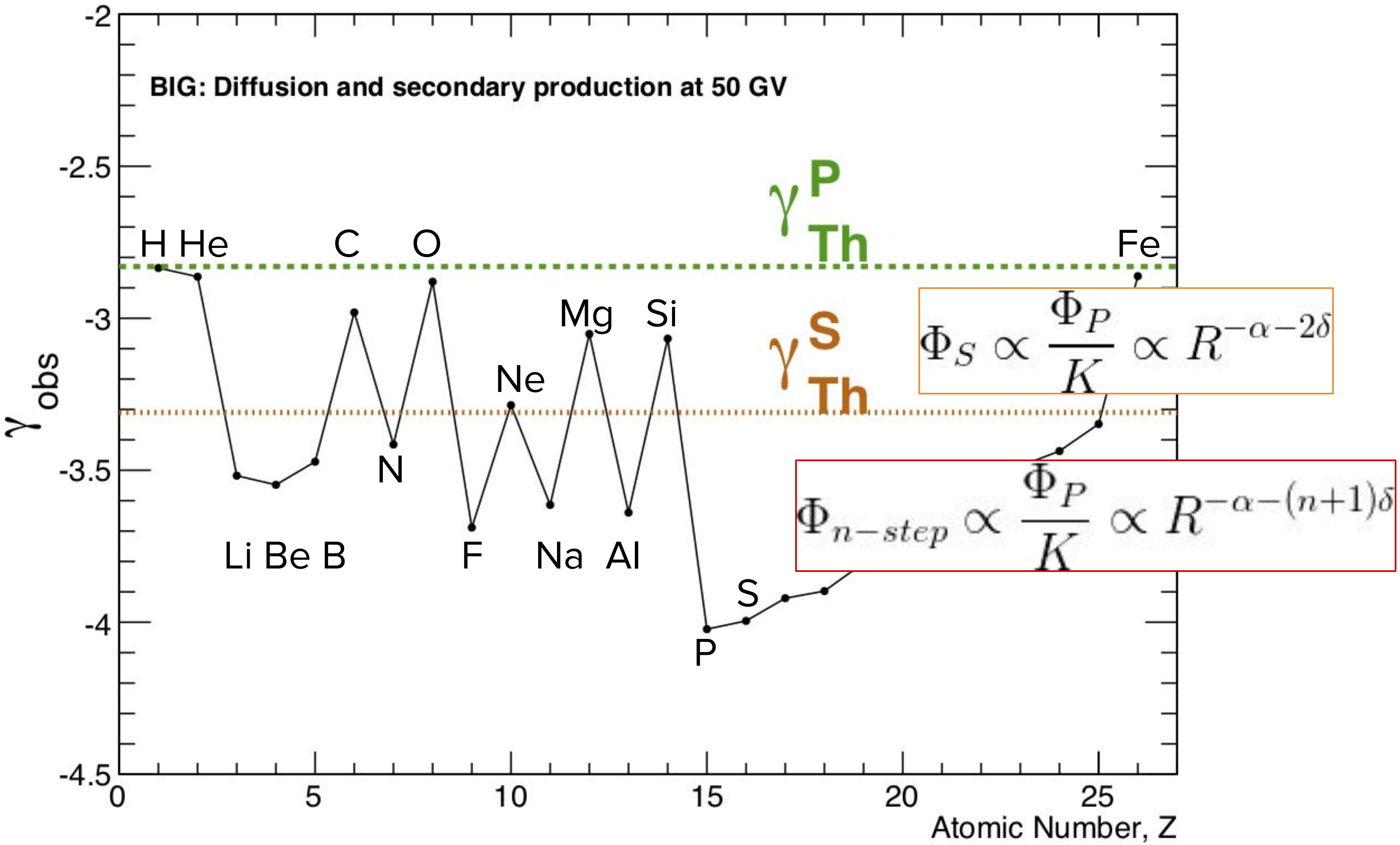


$$\Phi_S \propto \frac{\Phi_P}{K} \propto R^{-\alpha-2\delta}$$

$$\Phi_{n-step} \propto \frac{\Phi_P}{K} \propto R^{-\alpha-(n+1)\delta}$$

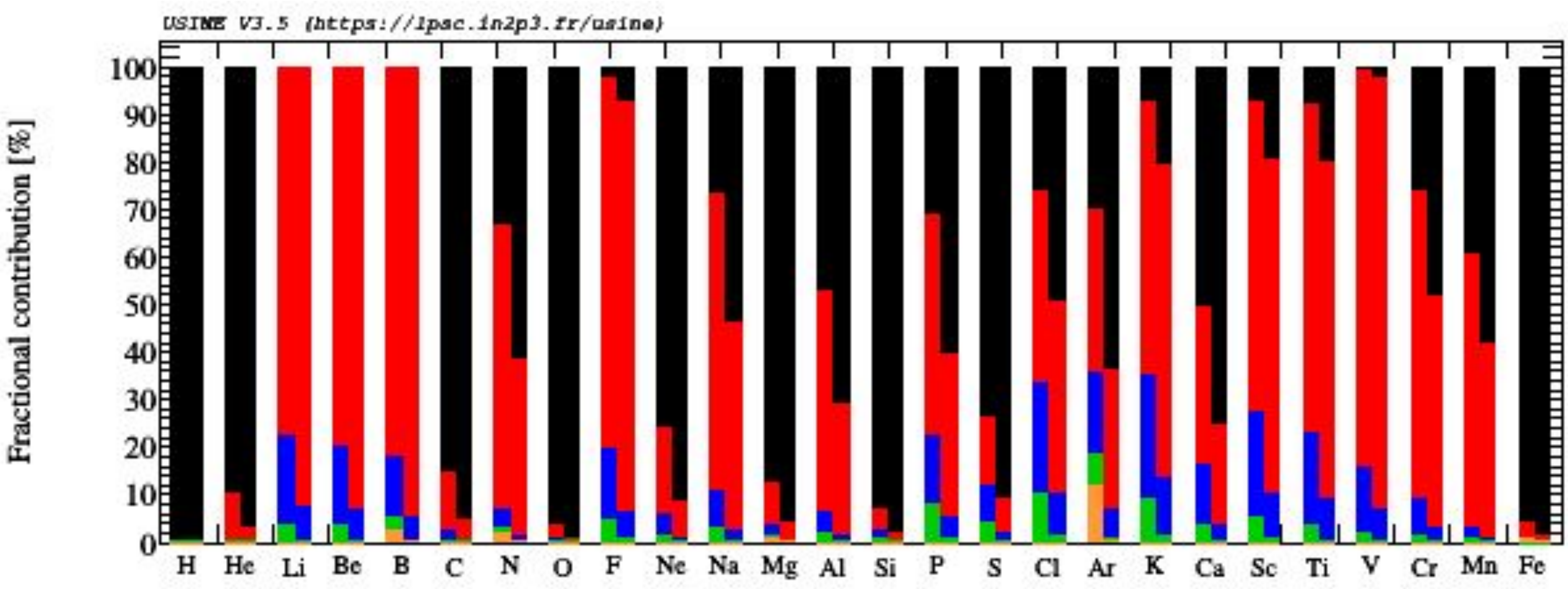
Flux slope dependence on Z: diffusion-only scenario

Even in diffusion-only scenario, departure from naive expectation due to multi-step production



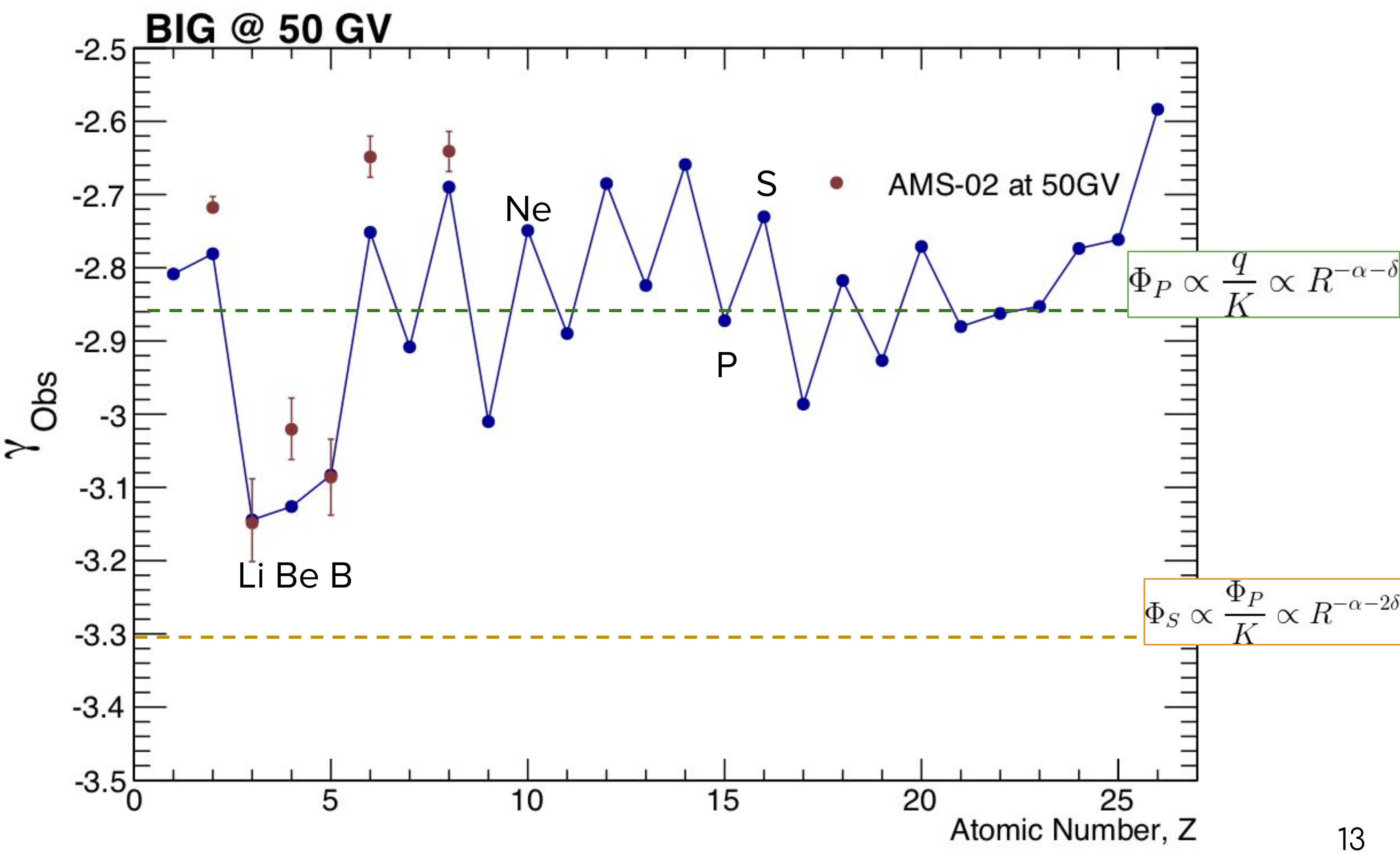
Secondary CR production

Relative contributions per production process for elemental fluxes (at 50 and 2 TV).



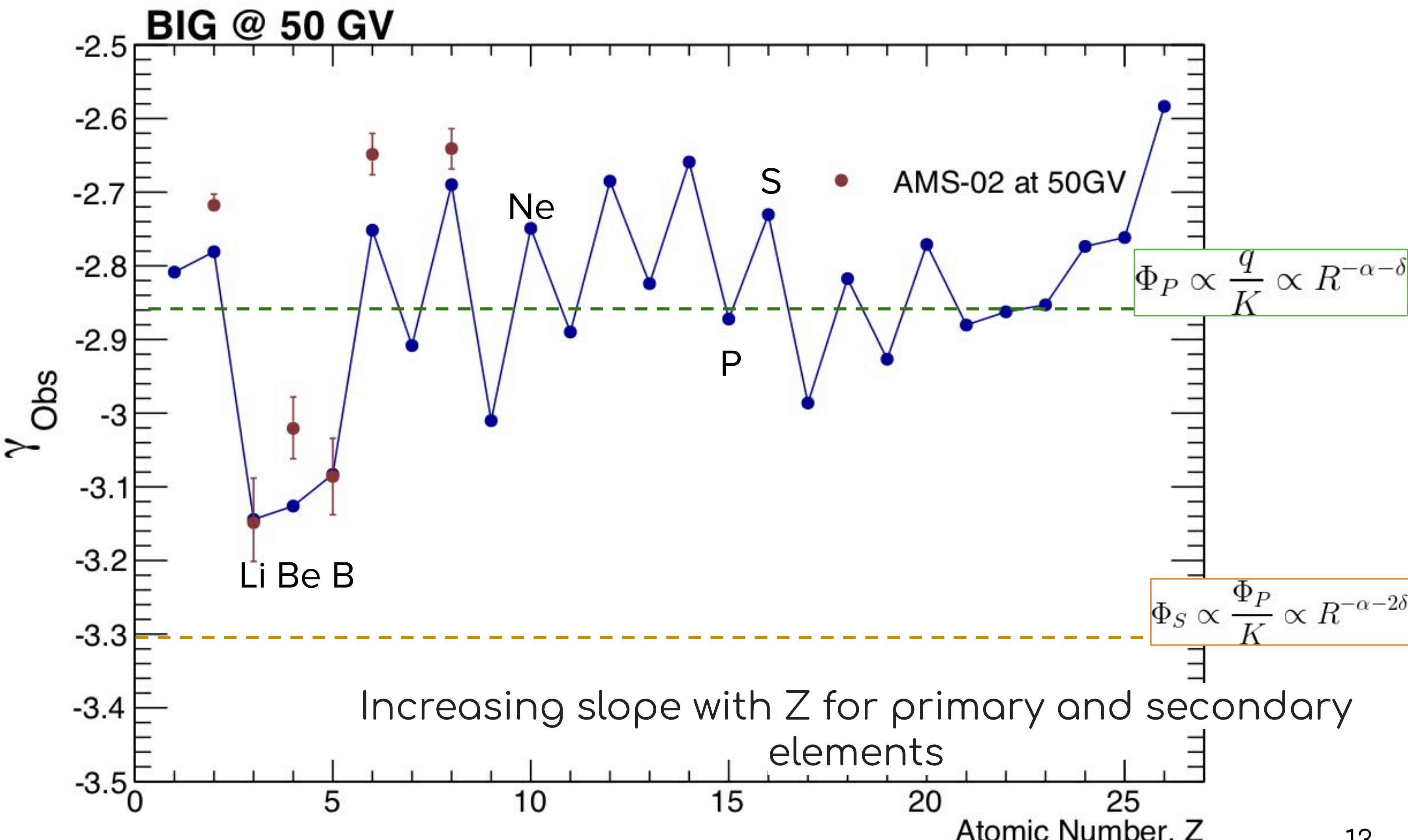
The species with the highest primary content are H, O, Si, and Fe (black), while Li, Be, B, F, and Cl to V have the highest secondary component from both single (red) and multi-step production (blue and green).

Full propagation model



Full propagation model

Result: Neither primary nor secondary data slope provide direct indication of “source + diffusion” coefficient.



Summary

- The B/C slope should not be interpreted as the diffusion coefficient spectral index, since additional physical processes, especially inelastic collisions play an important role.
- Up to TV rigidities, the measured flux spectral index as a function Z differs significantly from the values expected in diffusion-only scenario.
- We expect a slope difference between light and heavy nuclei at ~ 50GV, this difference decreasing with rigidity. AMS-02, CALET, DAMPE should see this effect in their data.