MCMC study of propagation diffusion parameters of cosmic rays from the ratios of B, Li and Be to C and O

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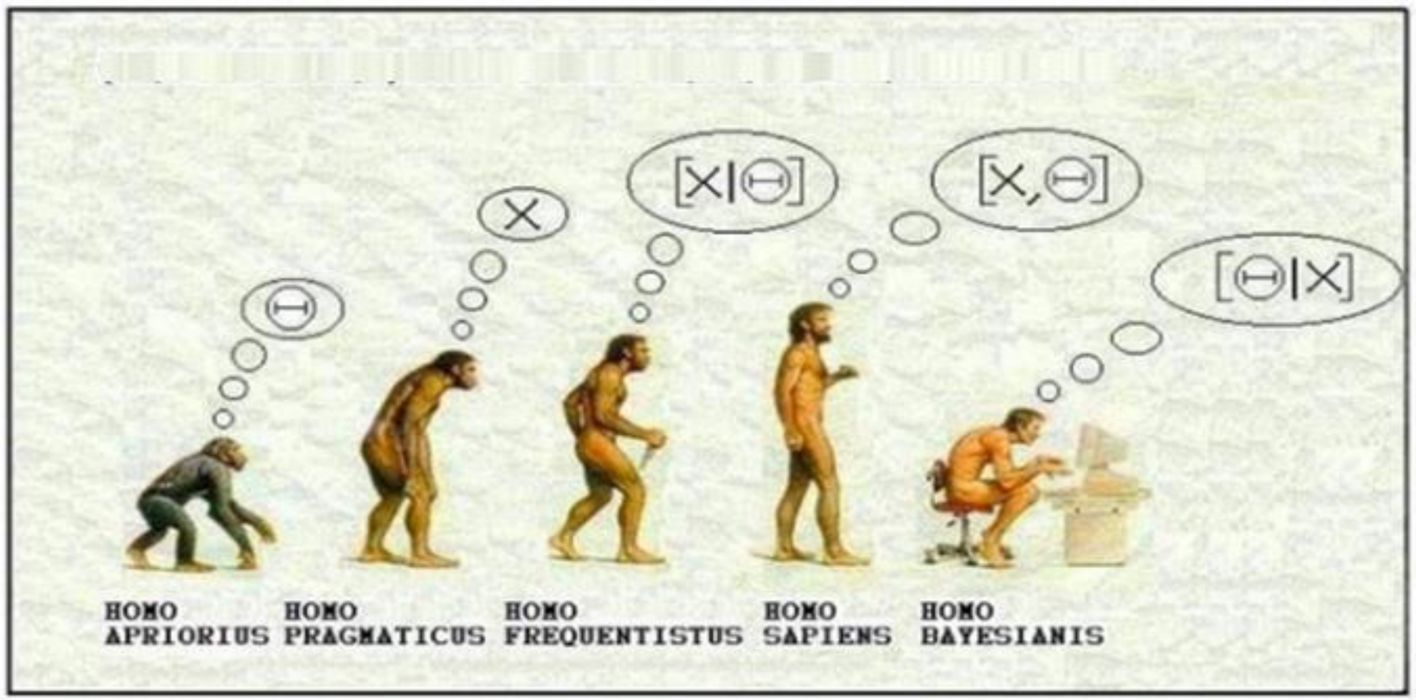
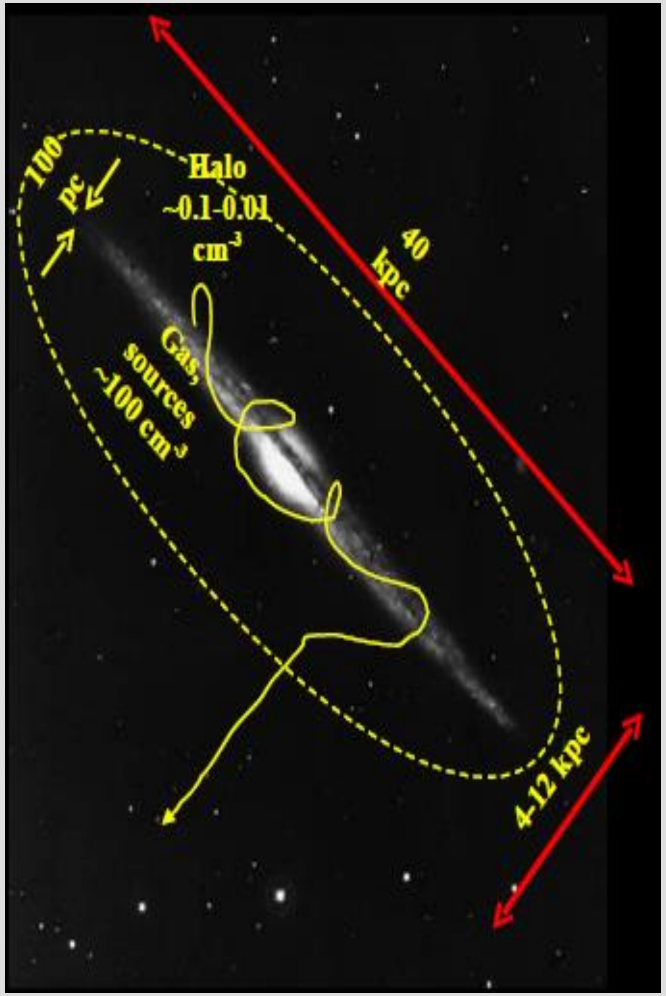
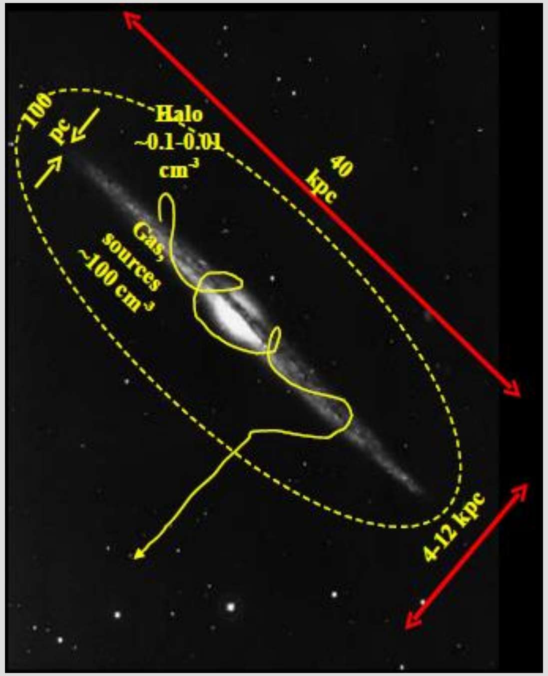
OUTLINE

- Set-up used to simulate the propagation
- Procedure → Bayesian inference

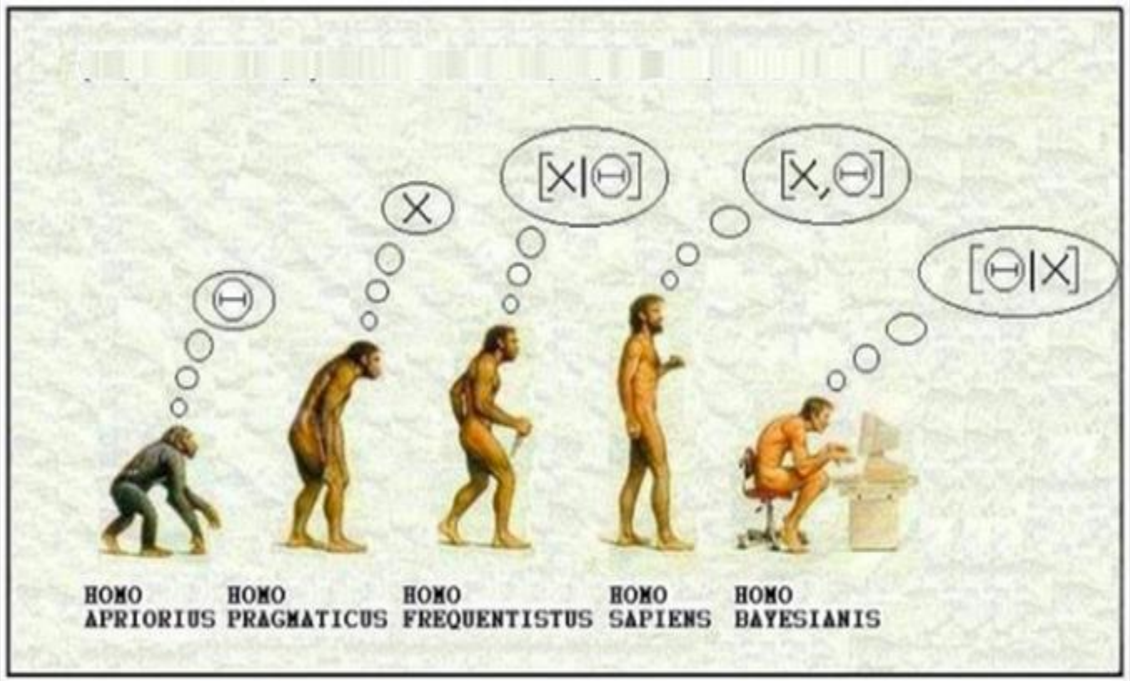




OUTLINE



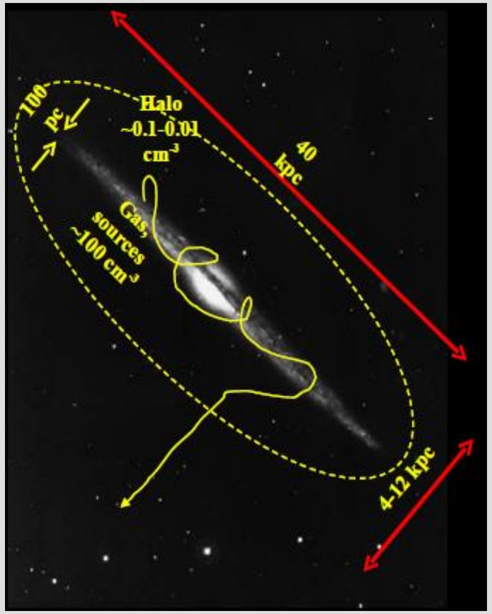
- Set-up used to simulate the propagation
- Procedure



- Results:

  Triangle plots (B/C and B/O)
  Secondary and primary spectra
  Impact of Xsecs on secondary CRs
  Electron & positron spectra
  Local γ-ray emissivity spectrum

OUTLINE



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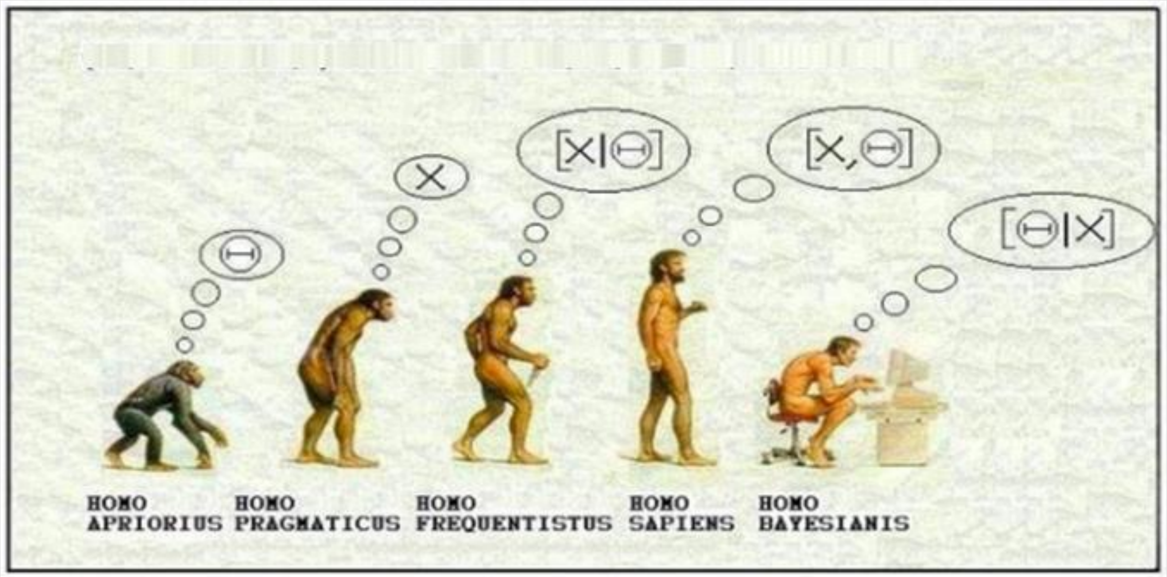
- Results:
  - Triangle plots (B/C and B/O)
  - Secondary and primary spectra
  - Impact of Xsecs on secondary CRs
  - Electron & positron spectra
  - Local γ-ray emissivity spectrum
- Conclusions



INTRODUCTION

Propagation with diffusive reacceleration and no convection is solved with a customized version of the DRAGON code in 2D and 3D (see EVOLI, Carmelo, et al. *Journal of Cosmology and Astroparticle Physics*, 2017, vol. 2017, no 02, p. 015.) :

$$\nabla \cdot (\vec{J}_i - \vec{v}_w N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] - \frac{\partial}{\partial p}\left[\dot{p} N_i - \frac{p}{3}\left(\vec{\nabla} \cdot \vec{v}_w\right) N_i\right] =$$
$$Q + \sum_{i<j}\left(c\beta n_{\rm gas}\, \sigma_{j\to i} + \frac{1}{\gamma \tau_{j\to i}}\right) N_j - \left(c\beta n_{\rm gas}\, \sigma_i + \frac{1}{\gamma \tau_i}\right) N_i$$

Spallation cross sections have been simulated using the FLUKA toolkit from 10 MeV to 10 TeV and included in the routines of the DRAGON code → See *M.N. Mazziotta et al. / Astroparticle Physics 81 (2016) 21–38*

The ISM is assumed to be H:He = 10:1.

Two different kind of diffusion models: Spatially independent (Plain model) and spatially dependent (Exponential model).

$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta e^{\frac{|z|}{z_t}}$$

R_0 = 4 GV
z_t = 4 kpc
H =16 kpc

$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta$$

H =16 kpc

MAIN GOAL → At the end, diffusion depends on four main parameters: η, δ, V_A and D_0. These ones are the parameters to be constrained in this study.

FIT PROCEDURE

An iterative procedure has been employed to find the optimal diffusion parameters that best fit the spectra of ratios of B over C and O (B/C, B/O) to AMS-02 data for both diffusion models.

Also Be/C, Be/O, Li/C, Li/O are still being studied.

$$\Phi = \begin{cases} k \times \left(\frac{R}{R_0}\right)^{\nu_1} & \text{for } R < R_{break1} \\ k \times \left(\frac{R}{R_0}\right)^{\nu_2} & \text{for } R_{break1} < R < R_{break2} \\ k \times \left(\frac{R}{R_0}\right)^{\nu_3} & \text{for } R_{break3} < R \end{cases}$$

First, the injection spectra are adjusted using a doubly-broken power law to reproduce AMS-02 and Voyager1 data.

A set of optimal propagation parameters are obtained applying a Markov Chain Monte Carlo (MCMC) based on a modified version of the Metropolis-Hasting algorithm to calculate the posterior probability for these parameters to explain real data.

The force field approximation model is used to account for the Solar modulation:

To fix ϕ, a gaussian optimization algorithm (from the python's **skopt** module, see "gp_minimize") was used in the first iteration and set to 0.58 GV for the rest of the procedure.

FIT PROCEDURE

Definition of the Likelihood:

$$\mathscr{L} = \prod_i \frac{1}{\sqrt{2\pi\sigma_i^2}} exp\left[-\frac{(\Phi_i(\vec{\theta}) - \Phi_{i,data})^2}{2\sigma_i^2}\right]$$

Flat priors are used.

Range of parameters:

Parameters range

	spatially-dependent	spatially-independent
E_b* (GeV)	[0.01, 10000]	[0.01, 10000]
D_0 $(10^{28} cm^2 s^{-1})$	[3.2 , 6.2]	[8.6 , 14.2]
v_A (km/s)	[16 , 46]	[14 , 49]
η	[-2.5 , 1]	[-2.5 , 1]
δ	[0.33, 0.6]	[0.33, 0.6]
ϕ**(GeV)	[0 , 1.2]	[0 , 1.2]

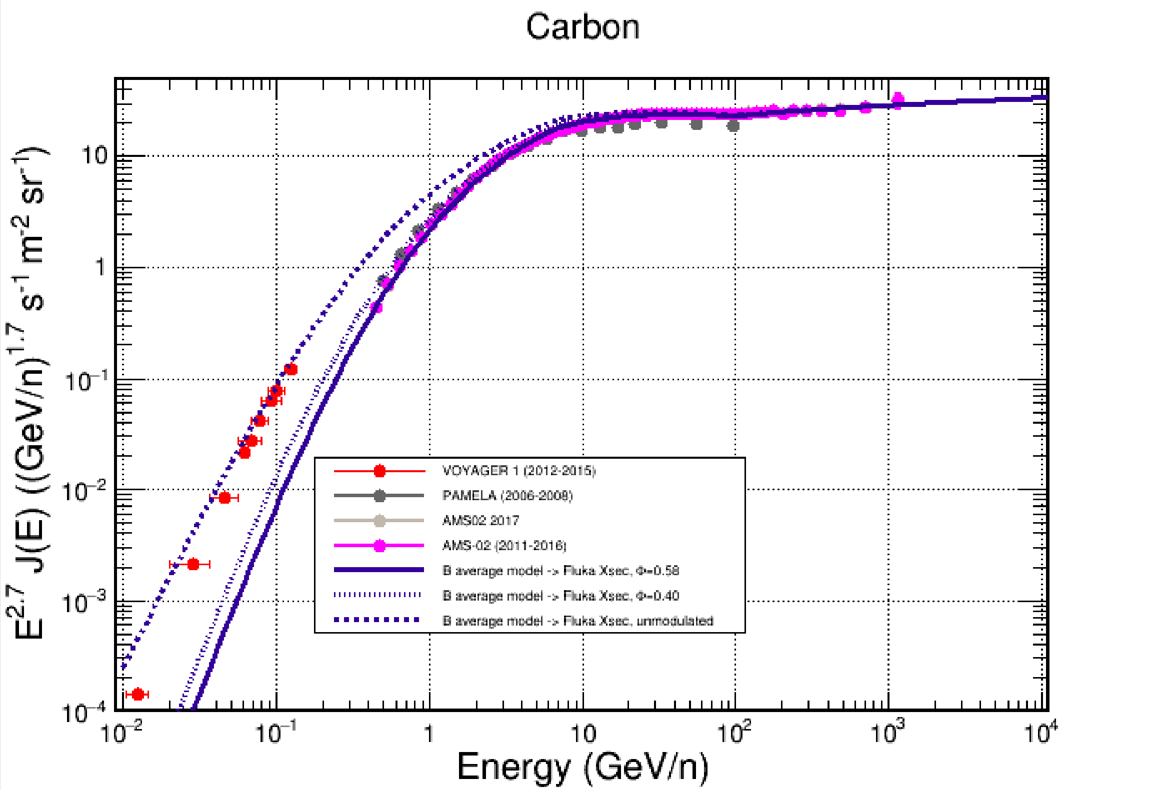
* it is the range of energies in the simulations, not a free parameter.
** ϕ is a parameter adjusted at the beginning and at the end, not in the MCMC.

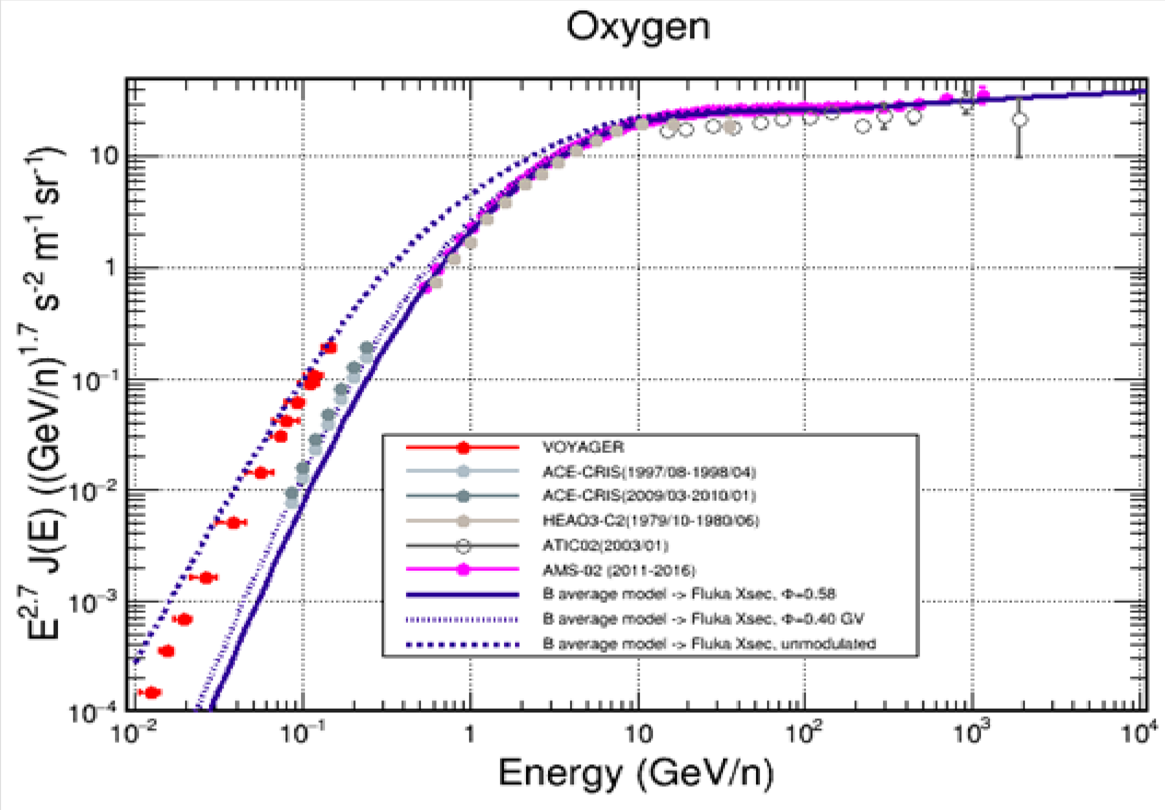
The average optimal diffusion parameters obtained are used in the next iteration and the spectra of primary CRs is fitted again with them.

Finally, when the parameters have a stable value we select those parameters as the best parameters for each of the ratios.

PRIMARY SPECTRA

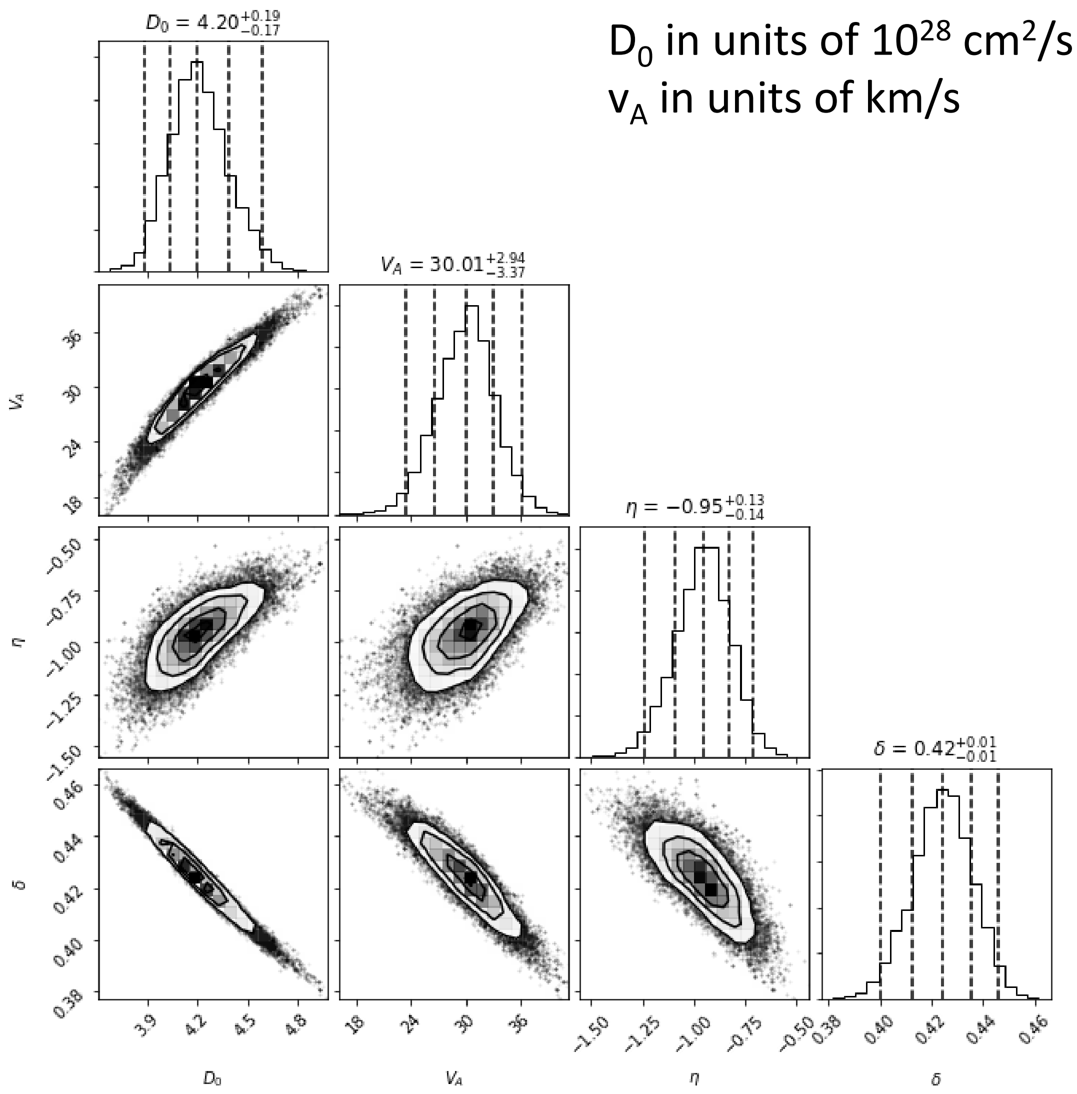
2D, Exp. Diffusion coefficient



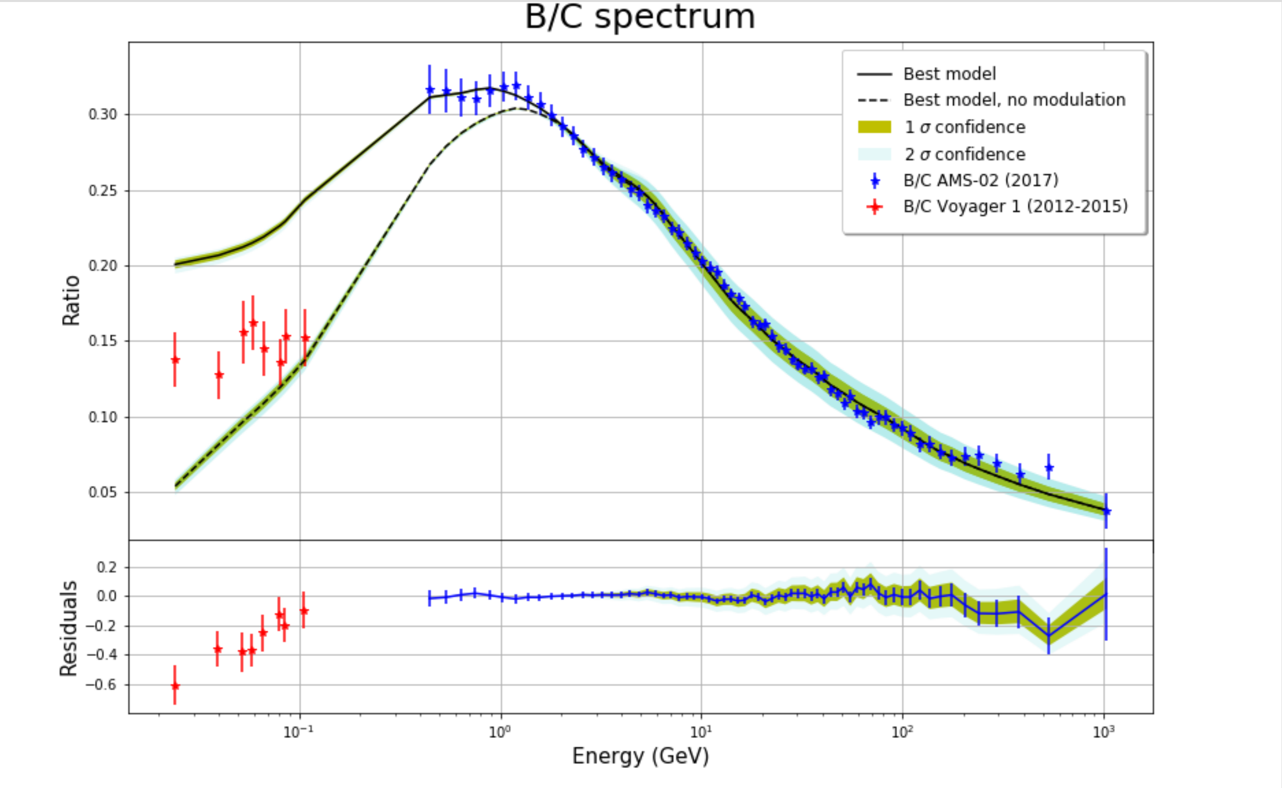


The fits of the primaries are equally good either for the 2D or the 3D simulations, using both diffusion coefficients. Also the spectra of secondaries and ratios are totally equivalent.

Boron over Carbon
(2D - Exp. Diffusion)

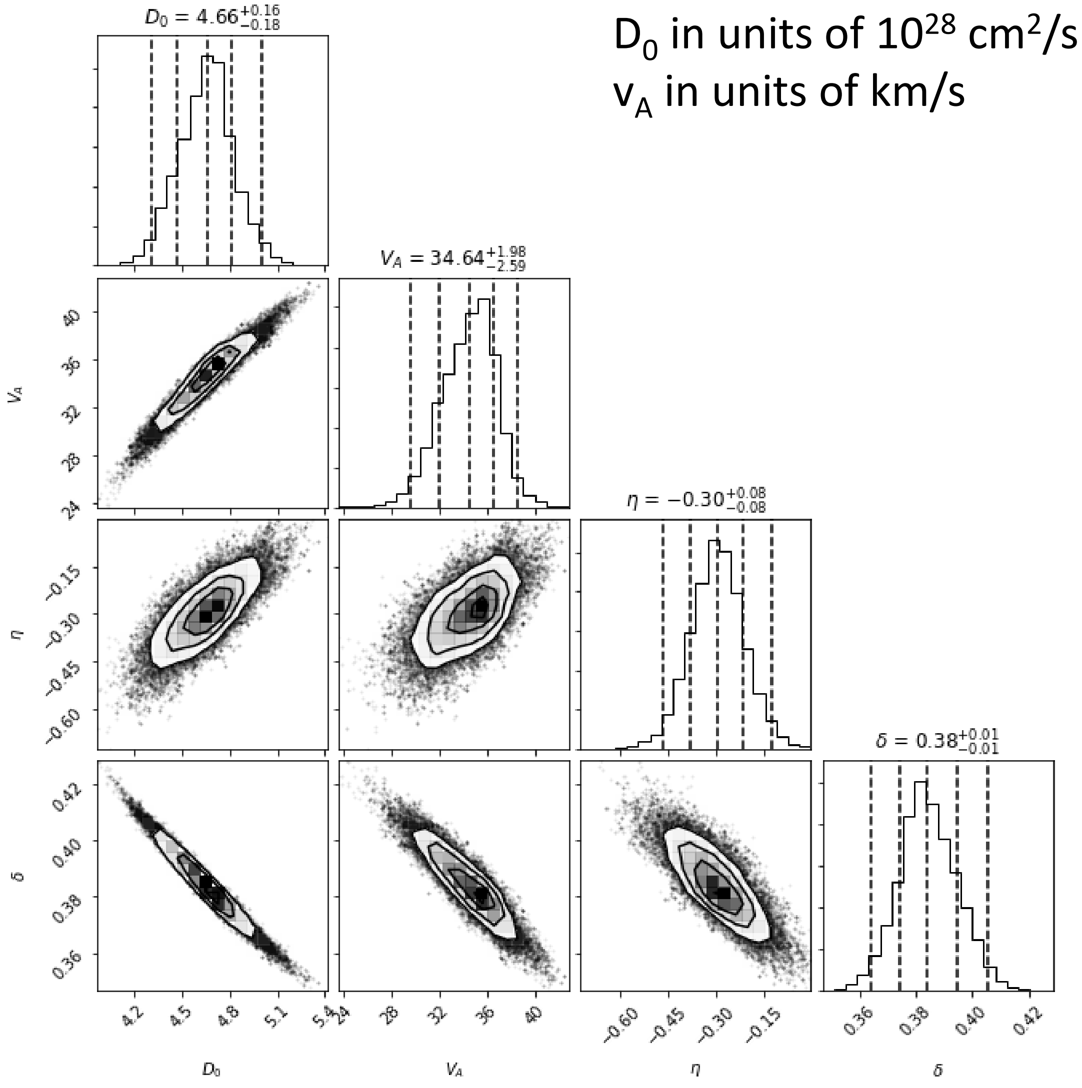


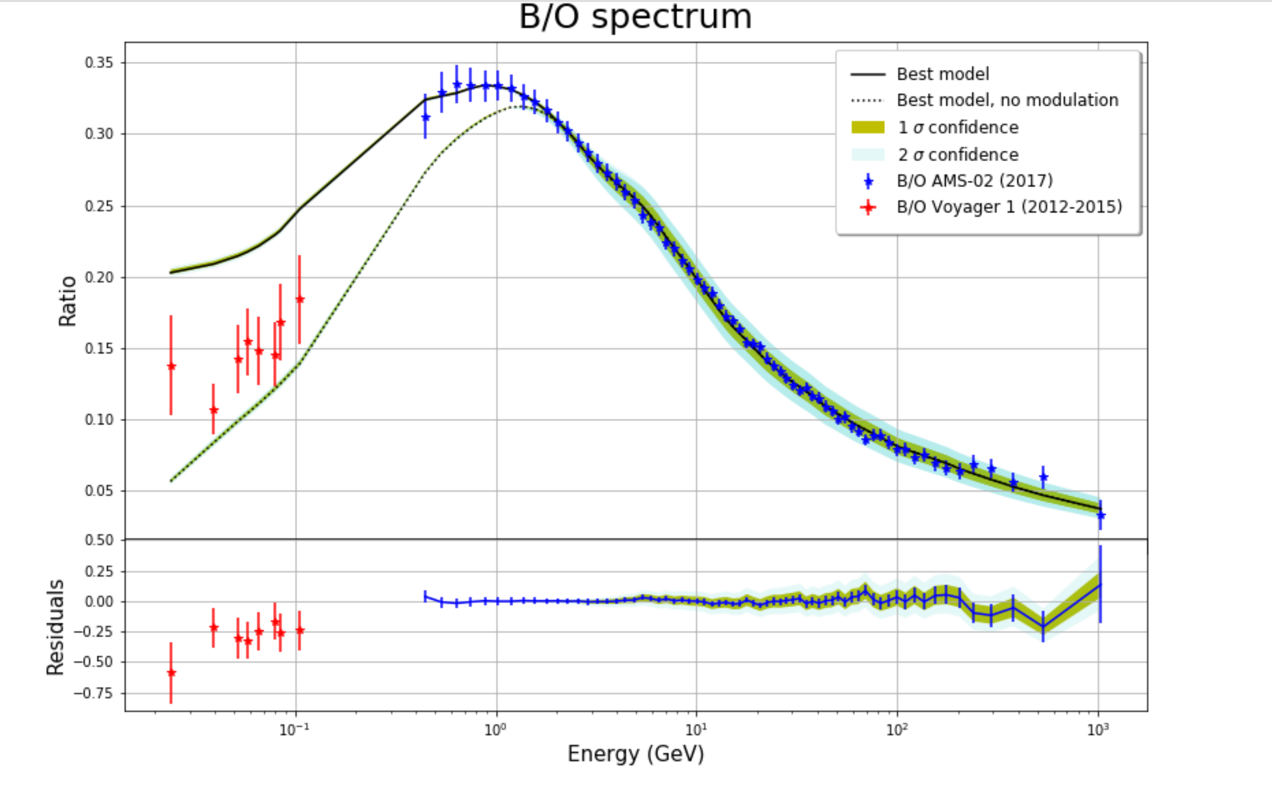
D_0 in units of 10^{28} cm^2/s
v_A in units of km/s



Boron over Oxygen
(2D - Exp. Diffusion)

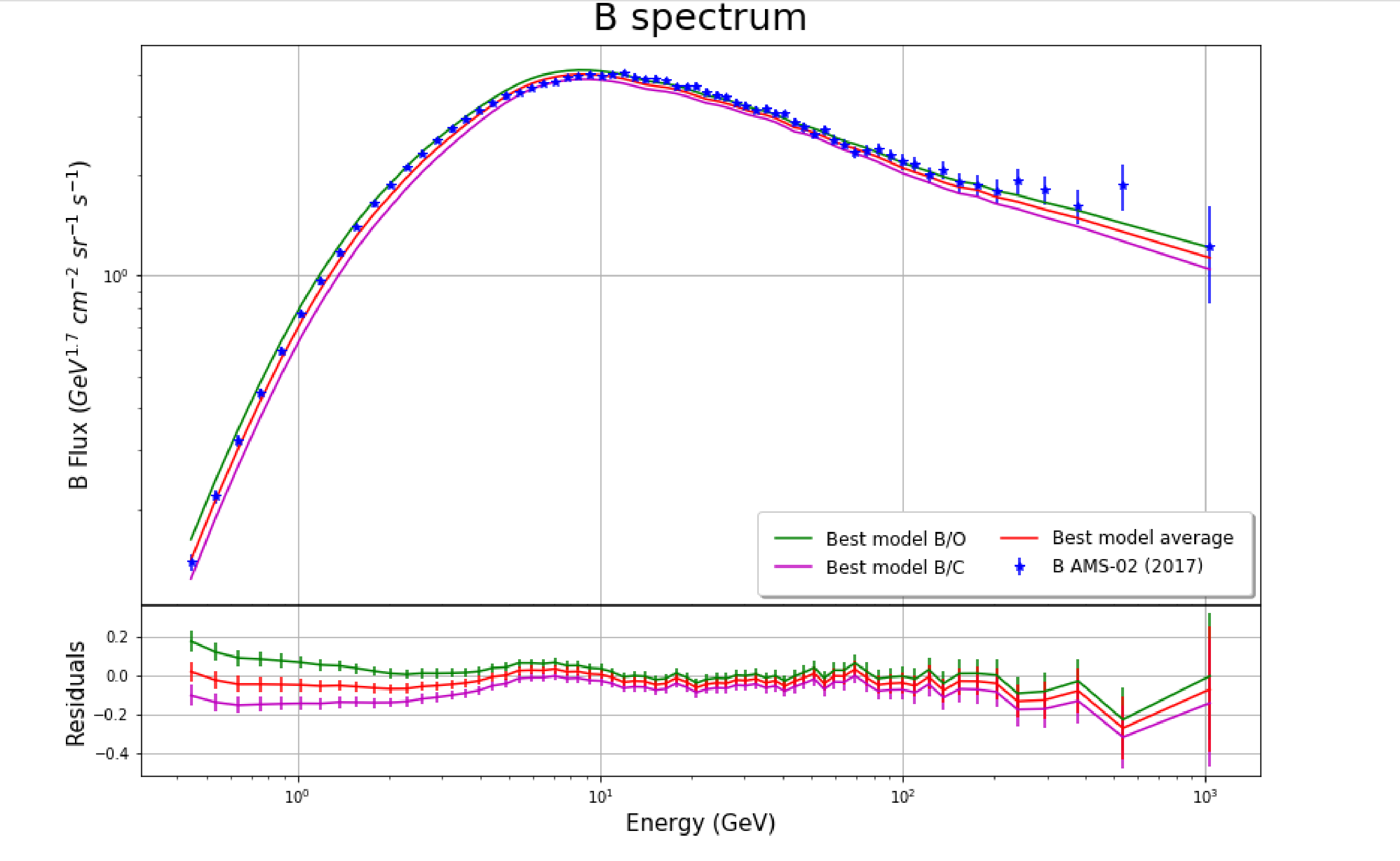
D_0 in units of 10^{28} cm^2/s
v_A in units of km/s





BORON SPECTRUM
(2D – Exp. Diffusion)

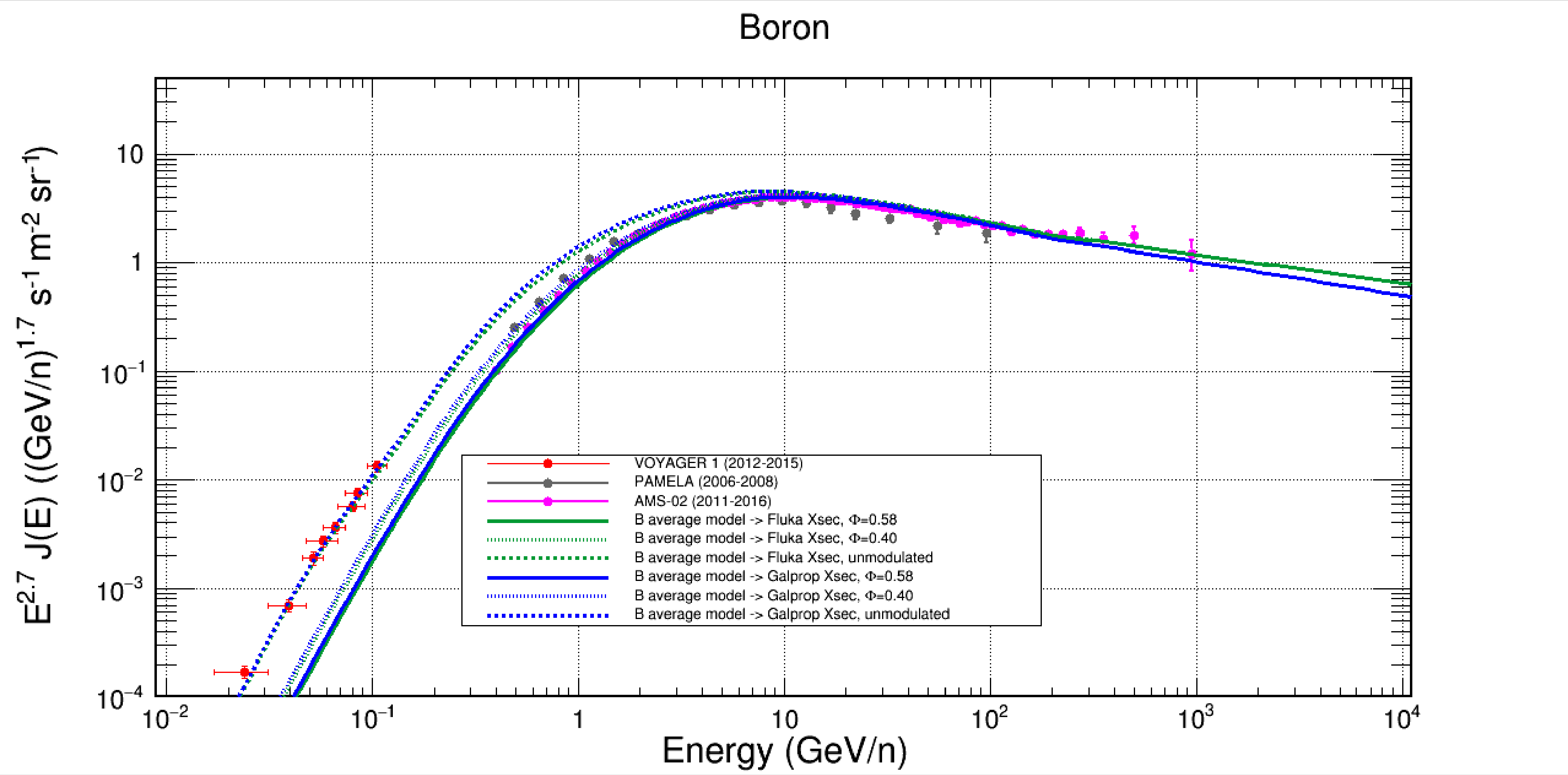
Both models reproduce the boron spectrum inside experimental errors. Taking the average of both models can help mitigating some systematics (mainly related with the Xsecs C→B, O→B and O→C).



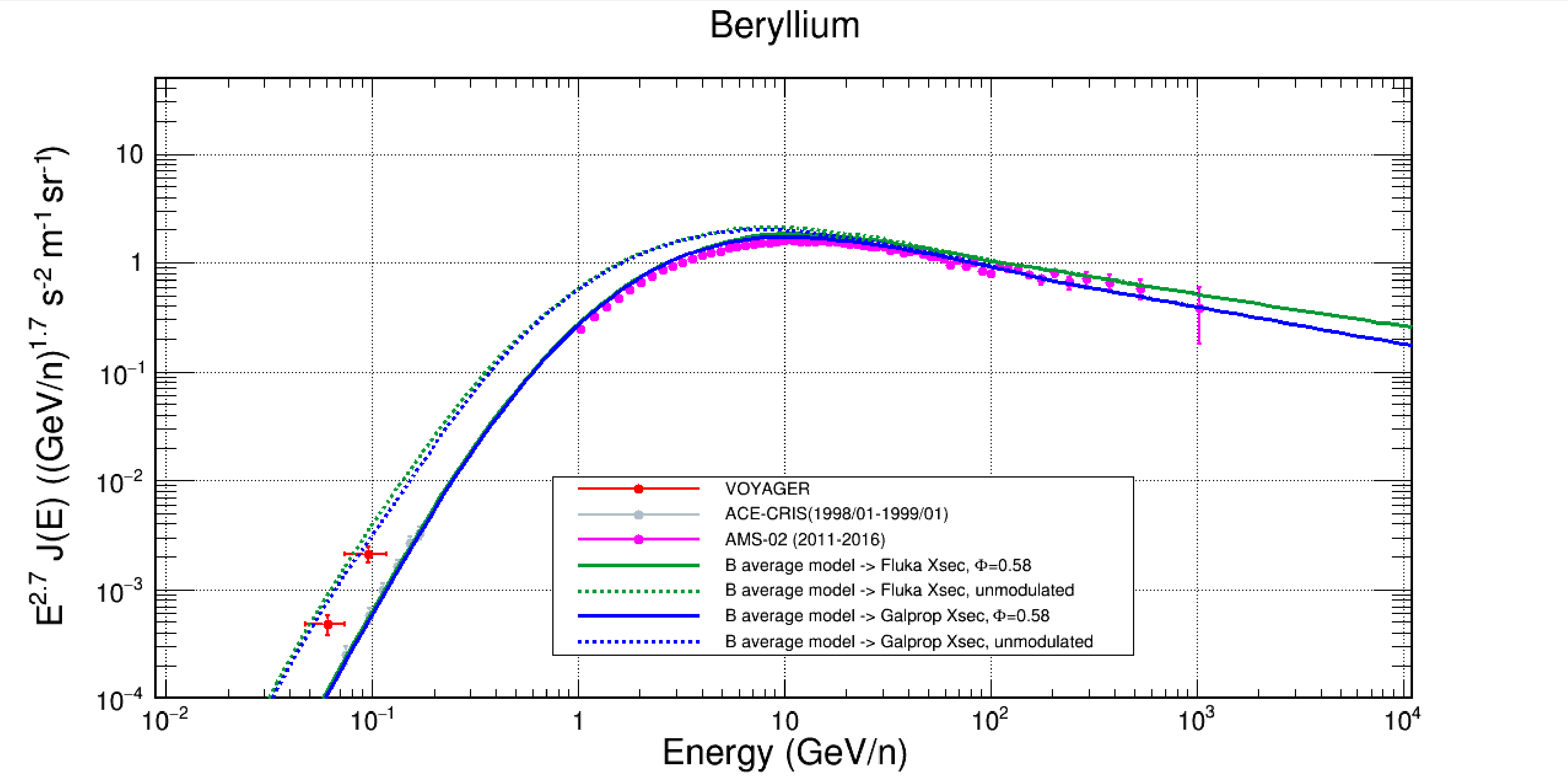
	D_0	V_A	η	δ
B/O	4.66 ± 0.17	34.64 ± 2.29	-0.30 ± 0.08	0.385 ± 0.009
B/C	4.23 ± 0.18	30.01 ± 3.22	-0.95 ± 0.14	0.42 ± 0.01

B, Li, Be – Impact of Xsecs on the spectra of Secondary CRs

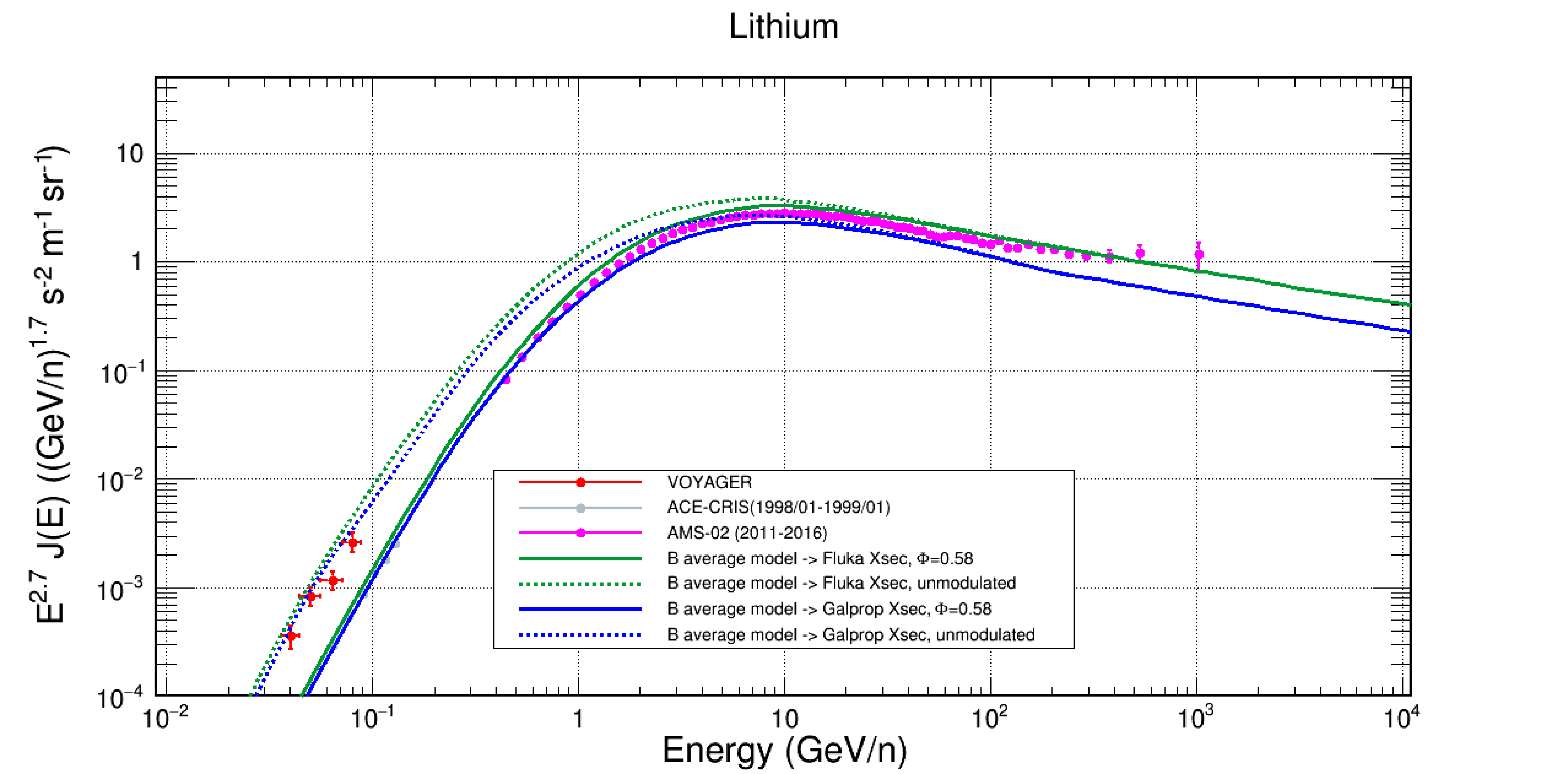
Best parameters found for FLUKA Xsecs are simulated in DRAGON using the Galprop Xsecs and are compared with the best parameters found in the MCMC for Galprop Xsecs



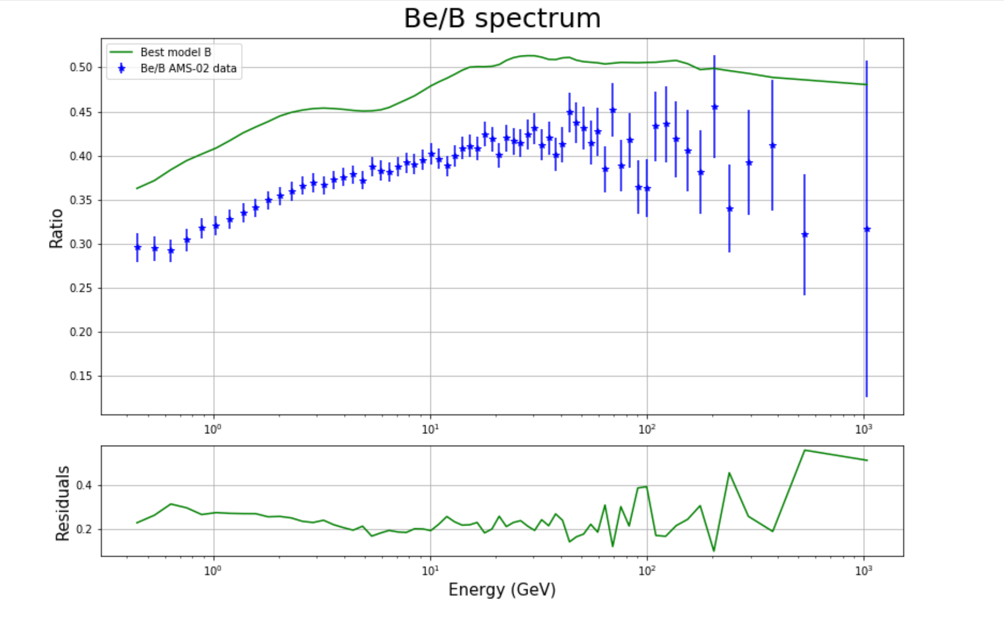
Be spectra are also very similar for both Xsecs …

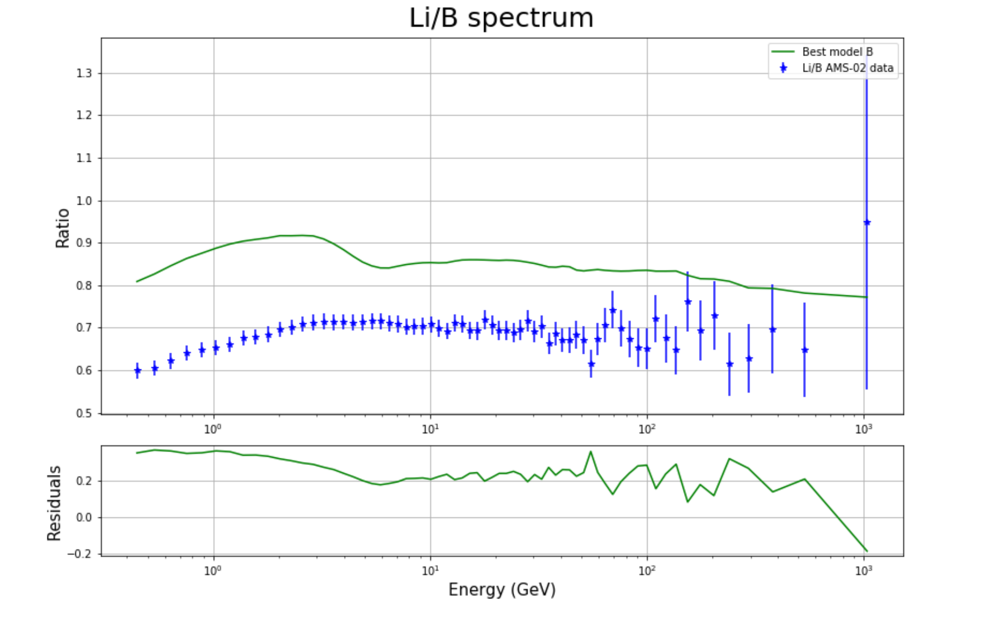


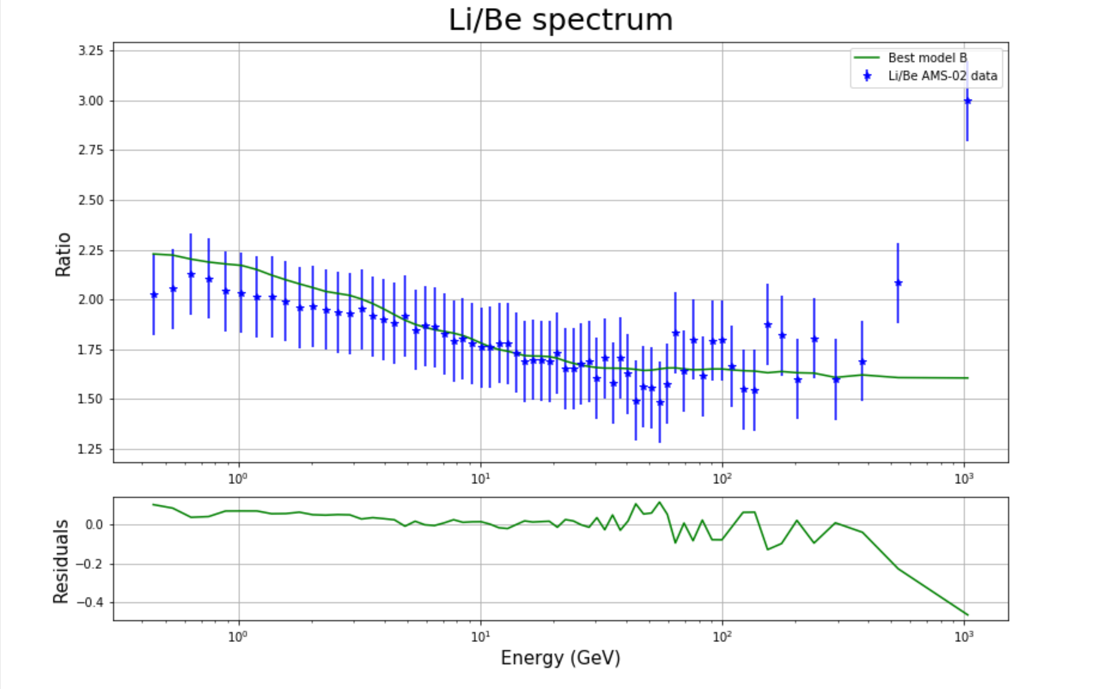
… but Li shows significant differences → ~ 33% of discrepancies at 10 GeV



XSECS PROBES: Ratios of secondary CRs using Fluka Xsecs





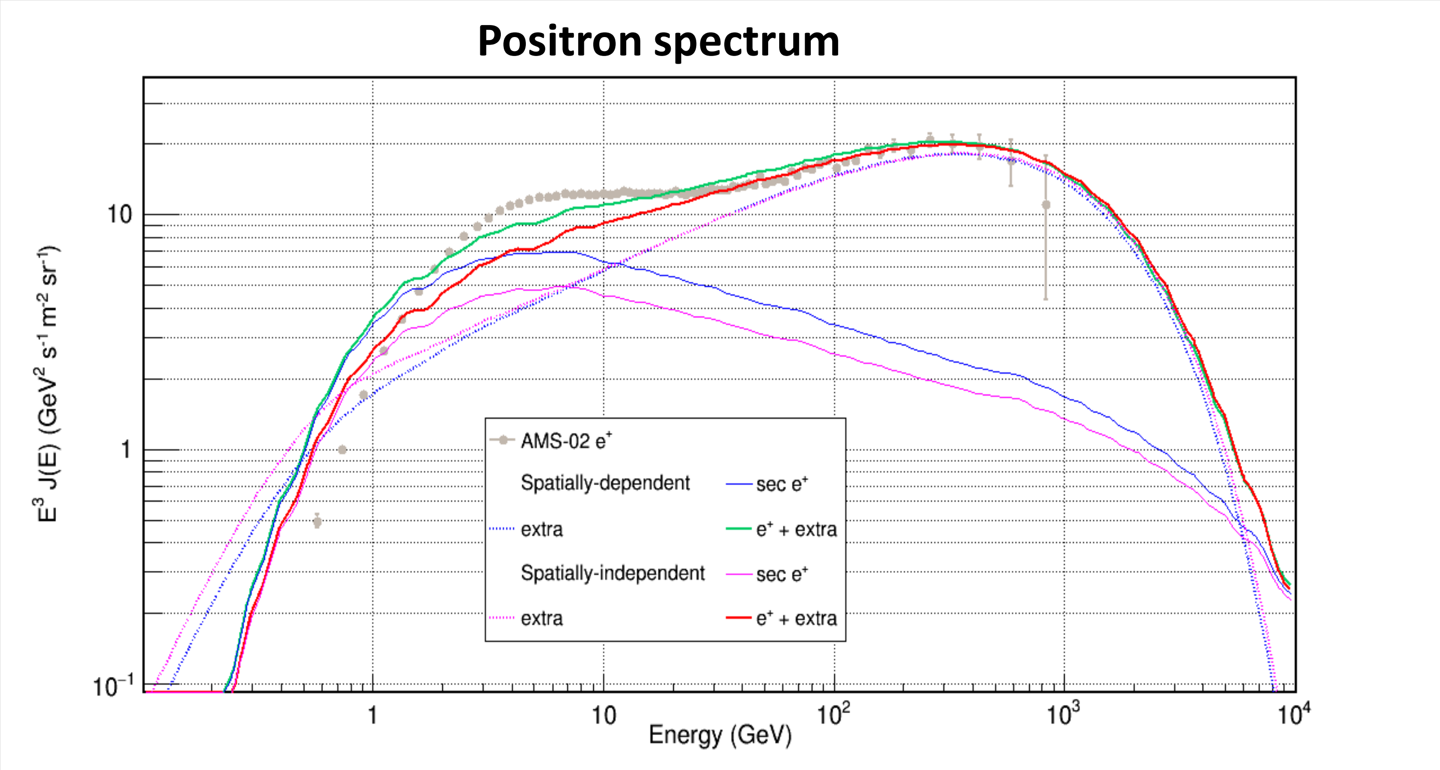


ADDITIONAL FEATURES: ELECTRONS AND γ-RAY EMISSIVITY

ELECTRONS & POSITRONS → 2D model of the Galaxy

An extra component mimicking the emission of unknown nearby sources is added in order to reproduce the high energy part of the positron spectrum.

Small difference between exponential and plain model at low energy.



ELECTRONS & POSITRONS → 2D model of the Galaxy

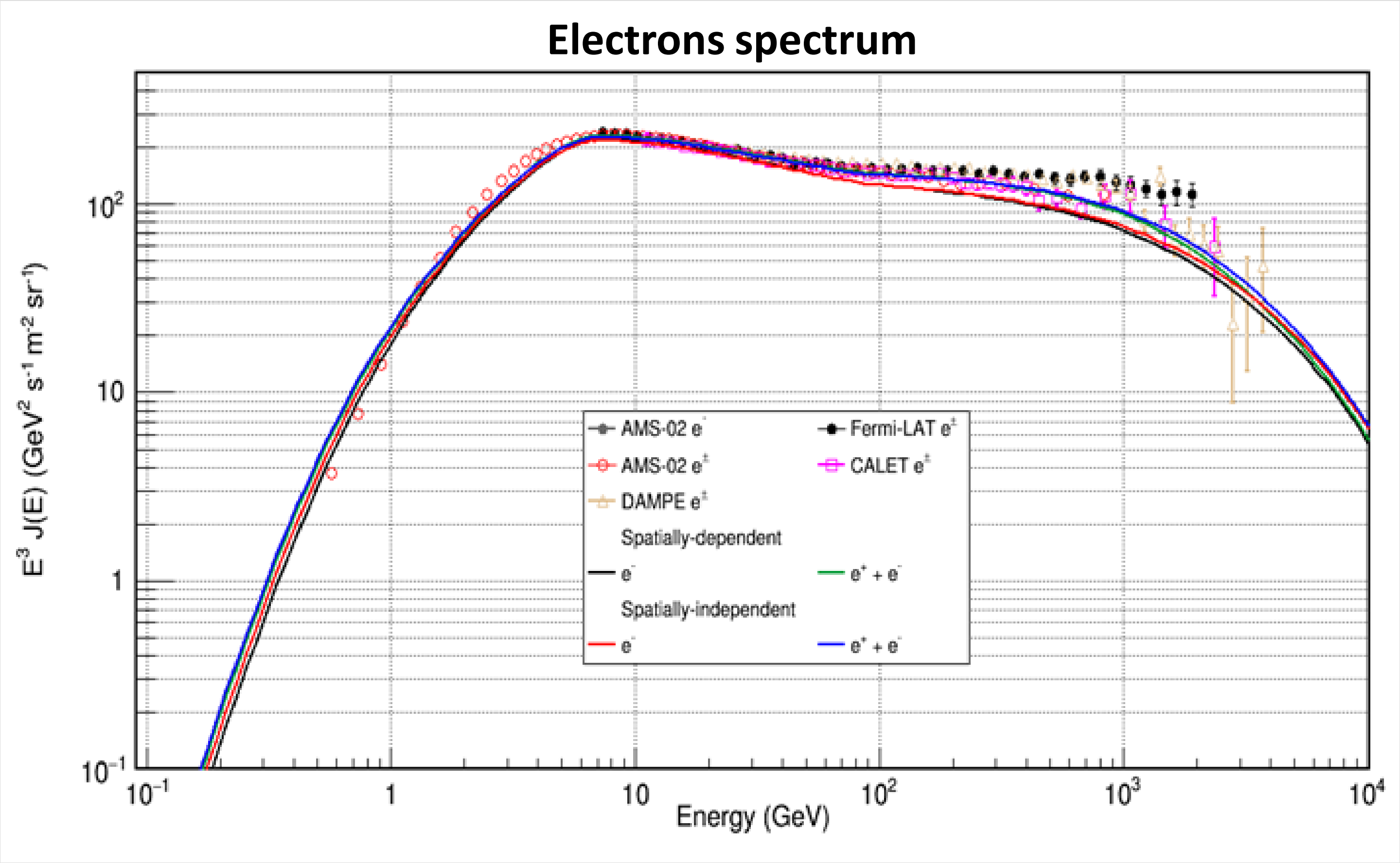
Singly-broken power law can not reproduce the high energy part of the spectrum even with the extra source.

Solutions:

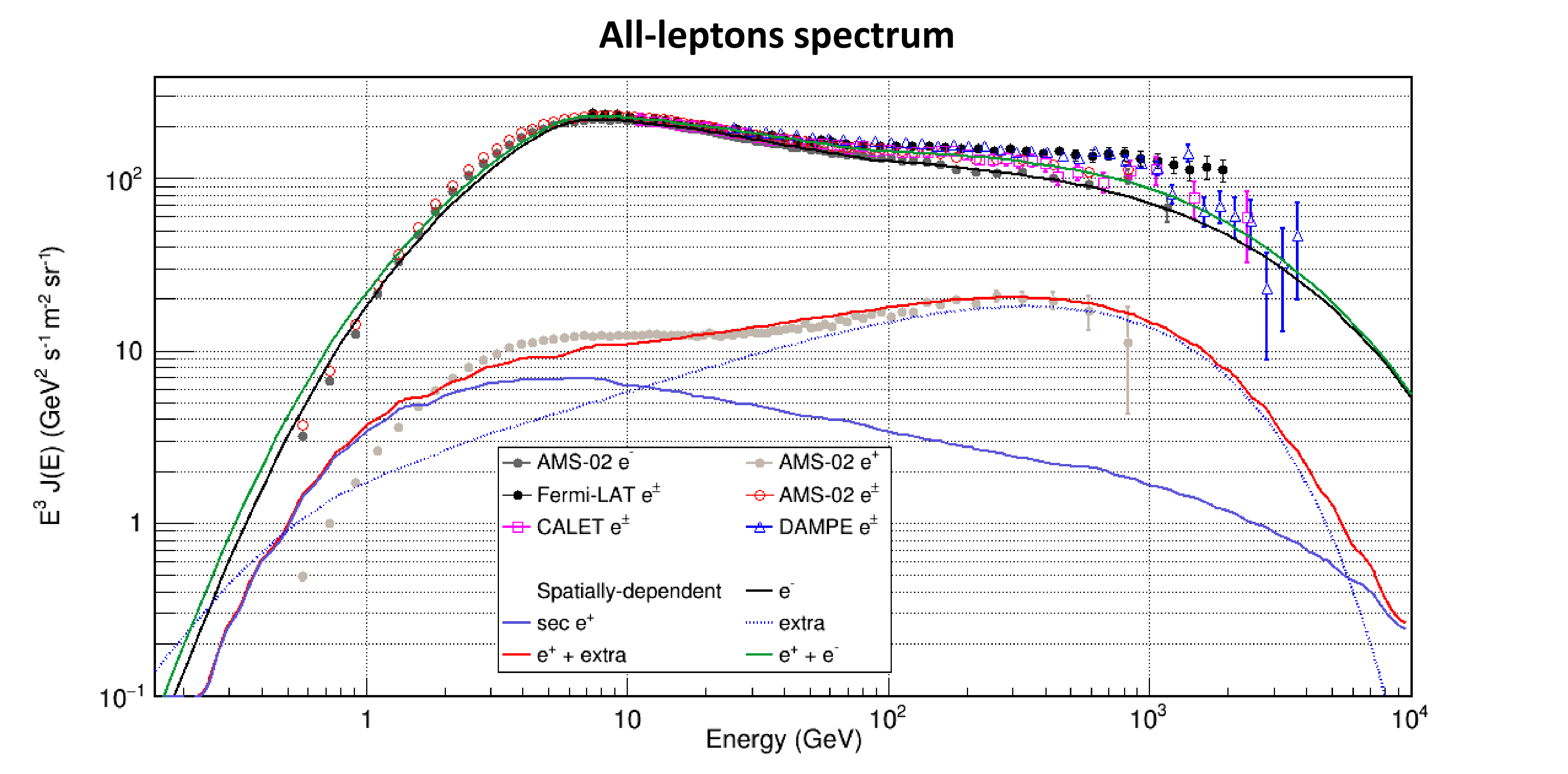
- Inclusion of another extra source which injects only e^-

(see O.Fornieri et al. arXiv:1907.03696v1)

- Use of a doubly-broken power law as for the rest of the CRs



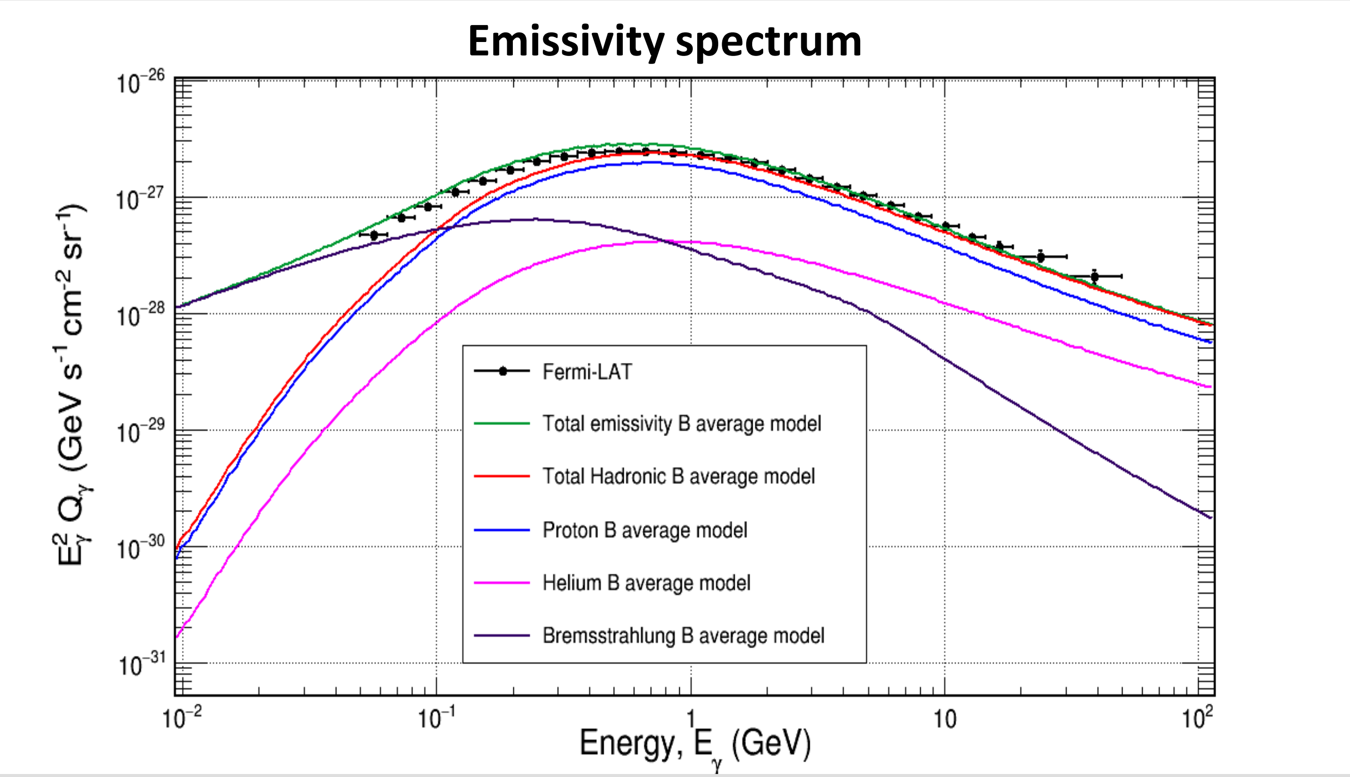
ELECTRONS & POSITRONS → 2D model of the Galaxy



More constraints from the local γ-ray emissivity

The proton, Helium and electron LIS (Local interstellar spectra) folded with the corresponding gamma-ray production cross sections from FLUKA on the ISM.

- ISM with relative abundance of *H : He : C : N : O : Ne : Mg : Si* = 1 : 0.096 : 4 .65 $\times 10^{-4}$: 8.3$\times 10^{-5}$: 8.3$\times 10^{-4}$: 1.3$\times 10^{-4}$: 3.9$\times 10^{-5}$: 3.69$\times 10^{-5}$



CONCLUSIONS

- Our customized DRAGON simulations with Fluka Xsecs demonstrate to be valid to reproduce the spectra of primary and the secondary CRs in the 2D and 3D scenarios and for both diffusion coefficients. A clear improvement is expected when using a break in the diffusion coefficient.
- The procedure followed allows to easily study a broad range of propagation parameters and the use of different secondary nuclei to mitigate some systematics inherent to individual nuclei (mainly from spallations Xsecs).
- It seems that there is no single best-fit set of values that reproduce Li, Be and B within one sigma in either set of Xsecs.
- B best parameters found with the FLUKA cross sections are also about to be the optimal parameters when using the Galprop Xsecs. Be spectra are also very similar for both Xsecs types but Li shows some differences.
- Only invoking extra sources at high energy for both positrons and electrons may allow to reproduce their spectra.
- Good agreement for the local emissivity γ-ray and more constraints can be imposed from it.
- Further investigation is being done on the isotopes of Be and the ratios of secondary species.
- New version of DRAGON is in production with the full Fluka cross sections.

BACK-UP SLIDES

DRAGON set-up

- Source term distribution type Ferriere (K.M. Ferriere, Rev. Mod. Phys. 73 (2001) 1031. [astro-ph/0106359]).

- The gas density distribution taken from the public Galprop version

- Magnetic fields model type Pshirkov

- Interstellar radiation field taken from the public Galprop version

Simulated channels in FLUKA

- Cosmic rays with ISM
- Incoming beam (projectile) nucleus:
  - Stable or very long-lived CR nuclei, e.g. p, D, T, ^{3}He, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}Be, ^{10}B, ^{11}B, ^{12}C, ^{13}C, ^{14}C, ^{14}N, ^{15}N, ^{16}O, ^{17}O, ^{18}O, ^{20}Ne, ^{24}Mg, ^{28}Si, …
- Target nucleus:
  - ISM, e.g. H:He→10:1
- Beam (primary) energy:
  - From 0.01 to $>10^{5}$ GeV/n

See *M.N. Mazziotta et al. / Astroparticle Physics 81 (2016) 21–38*

BEST PARAMETERS

D0, Va, eta, delta

- **Best B/C: 4.2, 30.01, -0.95, 0.42**
- **Best Be/C: 5.01, 26.46, -2.1, 0.44**
- **Best Li/C: 5.56, 38.22, -1.87, 0.41**

- **Best B/O: 4.66, 34.64, -0.3, 0.385**
- **Best Be/O: 4.93, 27.46, -1.3, 0.43**
- **Best Li/O: 5.37, 35.54, -1.28, 0.40**

FLUKA CROSS SECTIONS

H=16kpc, Zt=4kpc

Average used: 4.8, 32., -1., 0.41

BEST PARAMETERS

D0, Va, eta, delta

- **Best B/C: 3.87, 30.73., -0.44, 0.45**
- **Best Be/C: 4.57, 18.47, -1.4, 0.41**
- **Best Li/C: 4.07, 36.64, -0.53, 0.37**

- **Best B/O: 3.68, 31.03, -0.08, 0.45**
- **Best Be/O: 4.12, 22.13, -0.67, 0.43**
- **Best Li/O: 3.93, 34.63, -0.19, 0.38**

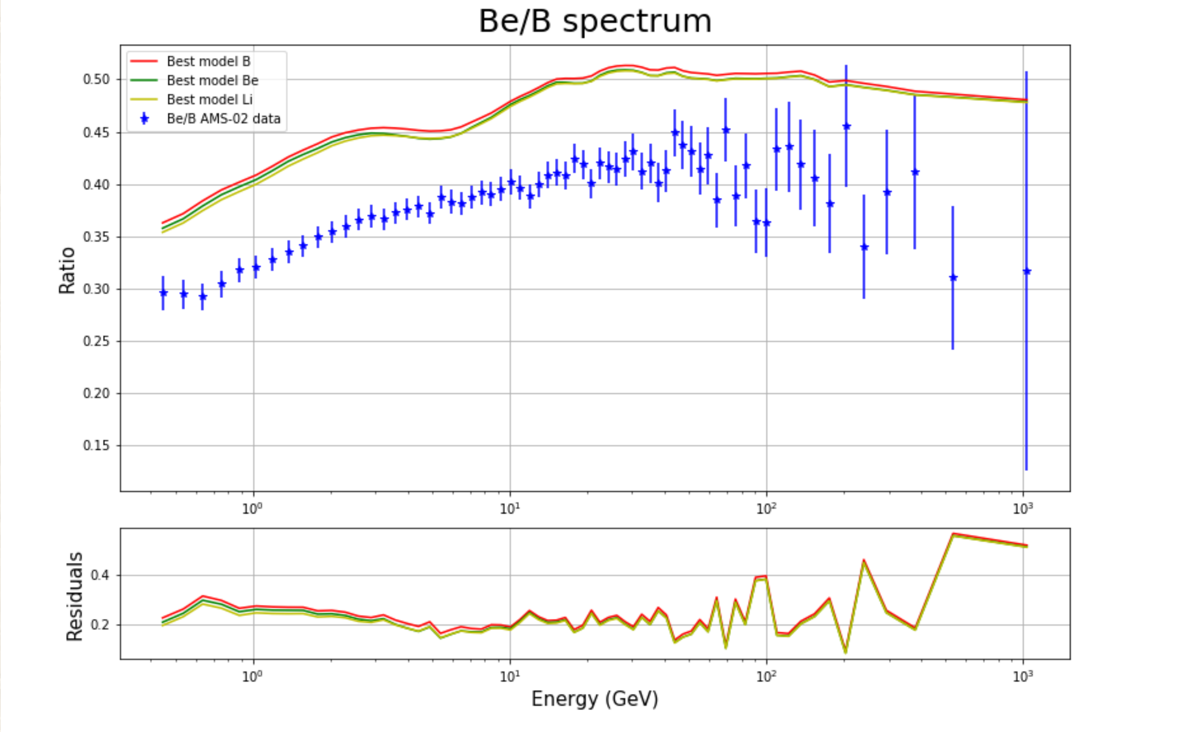
GALPROP CROSS SECTIONS

H=16kpc, Zt=4kpc

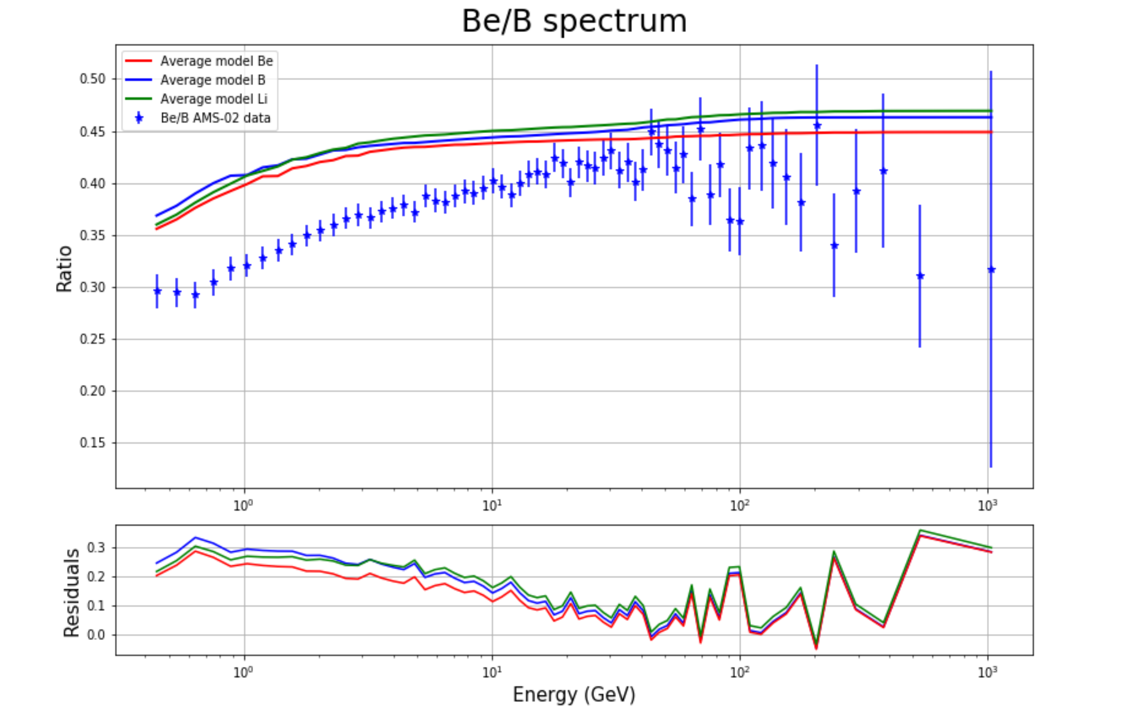
Average used: 4.17, 34., -0.3, 0.42

XSECS PROBES: Be/B

FLUKA XSECS

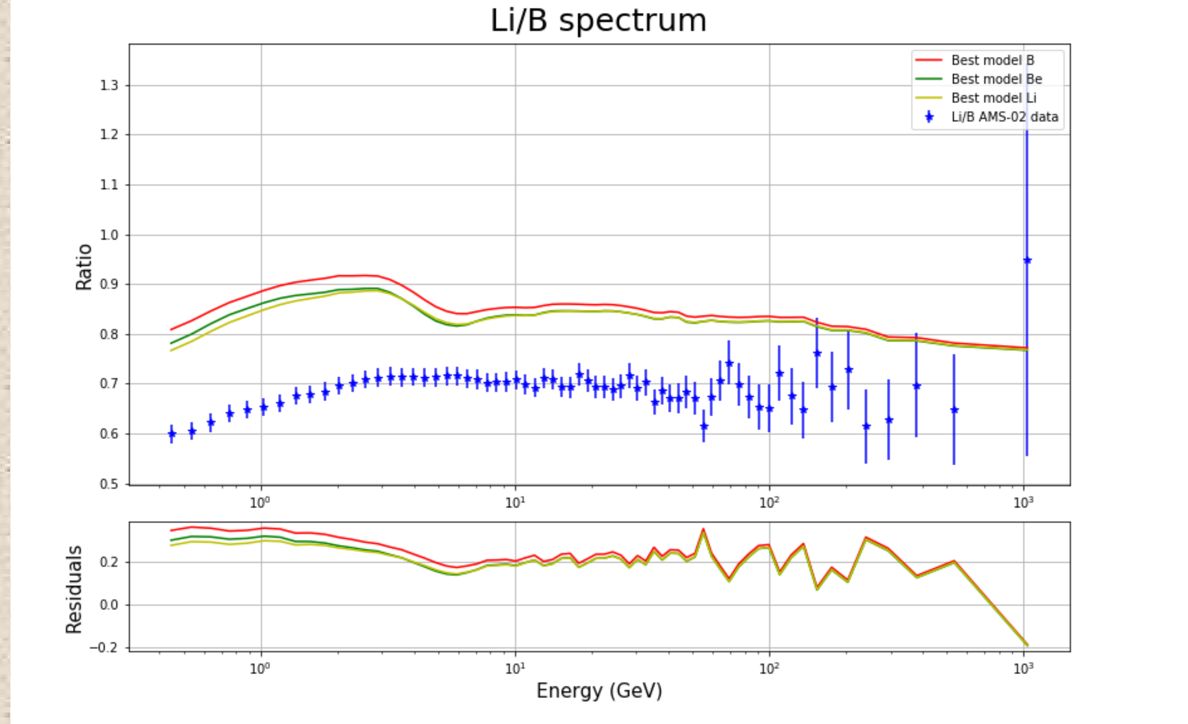


GALPROP XSECS

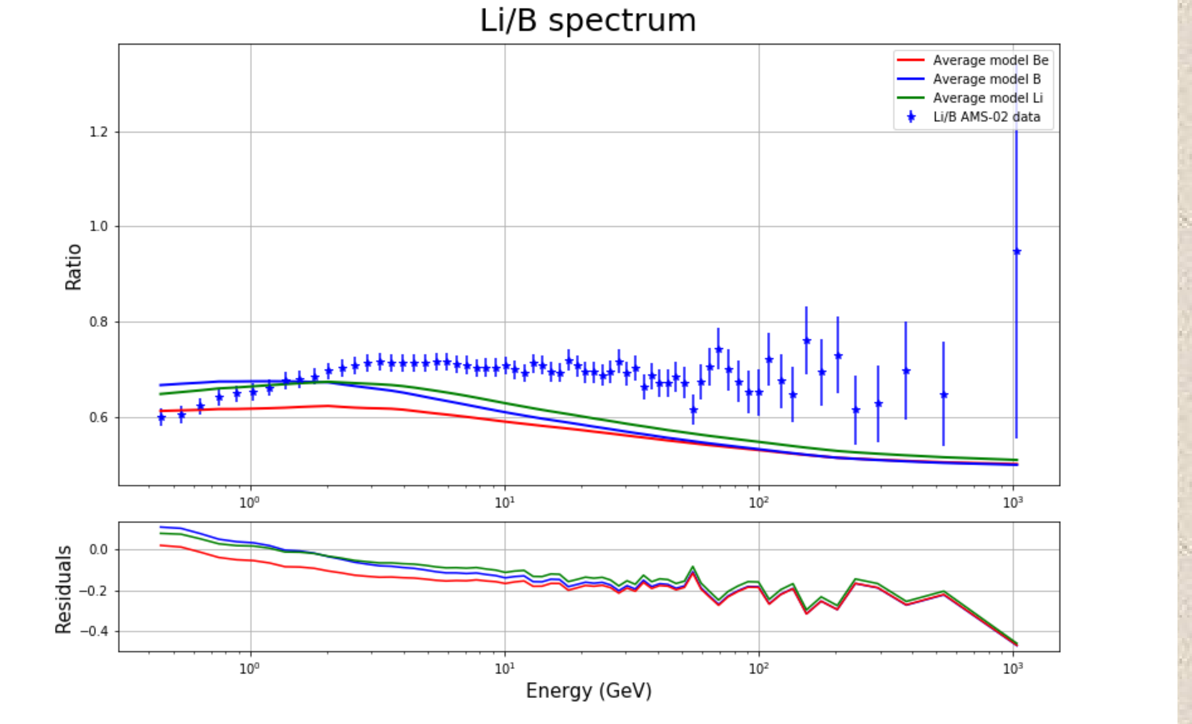


XSECS PROBES: Li/B

FLUKA XSECS

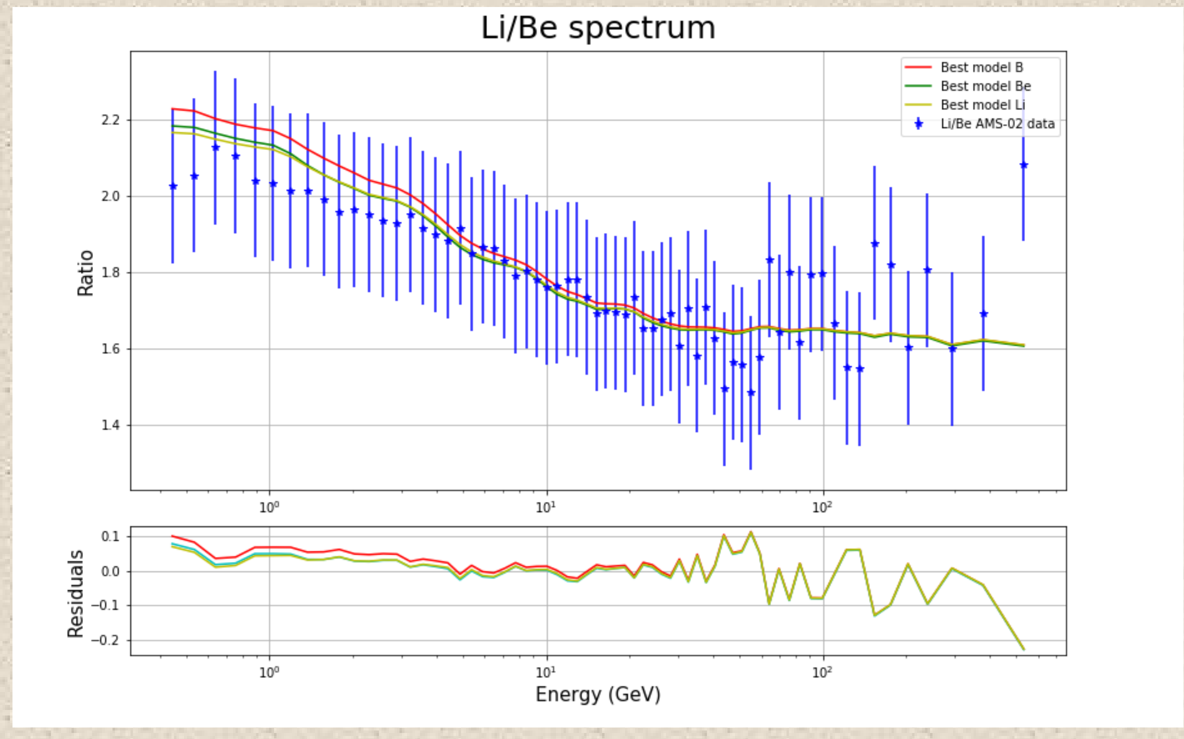


GALPROP XSECS



XSECS PROBES: Li/Be

FLUKA XSECS



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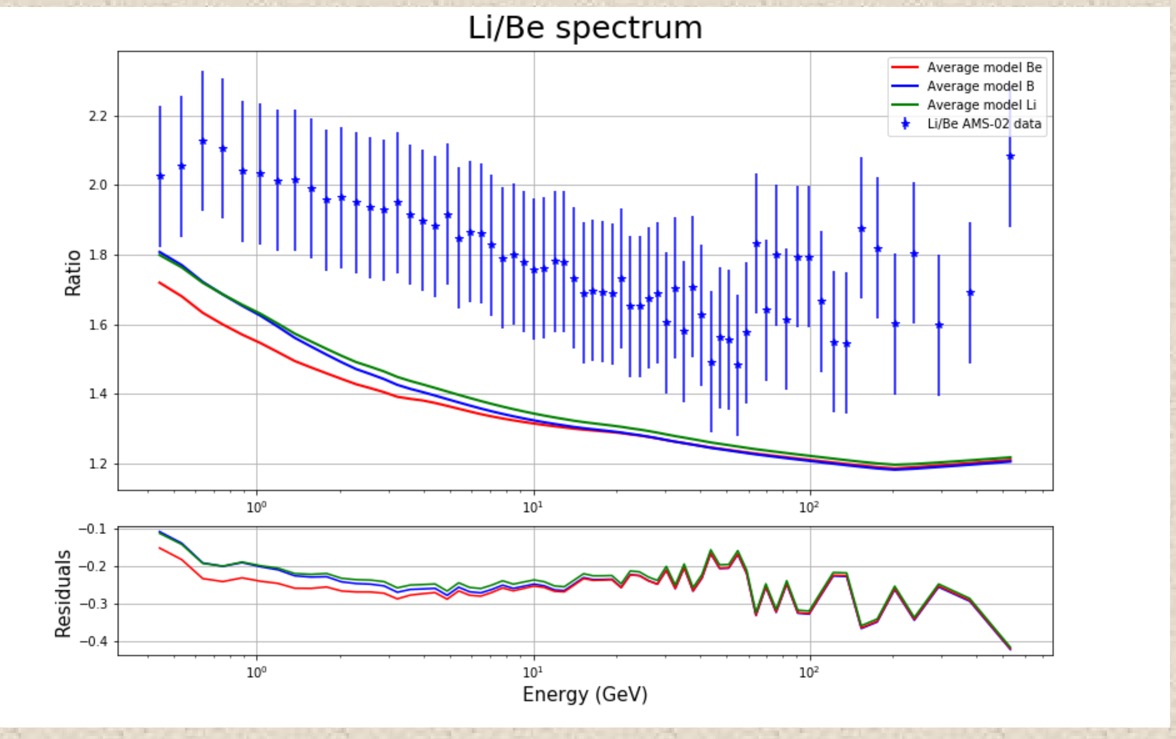

No agreement at all with Voyager for electrons even when tuning the magnetic fields components