Implications of AMS-02 nuclei spectra on our understanding of cosmic-ray diffusion in the Galaxy

Based on:
Korsmeier, Cuoco, PRD (2021), ArXiv:2103.09824
Korsmeier, Cuoco, PRD (2022), ArXiv:2112.08381
Di Mauro, Korsmeier, Cuoco, PRD (2023), ArXiv:2311.17150

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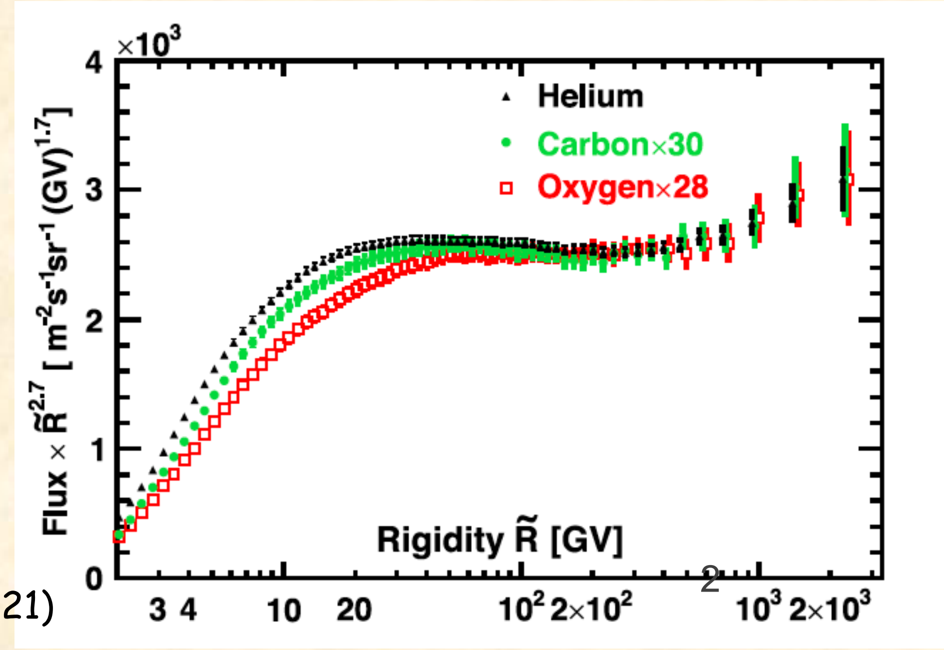
AMS-02 CR data

Golden Age for Cosmic Rays: PAMELA, CALET, DAMPE, AMS02 providing high quality data. CR precision era is starting

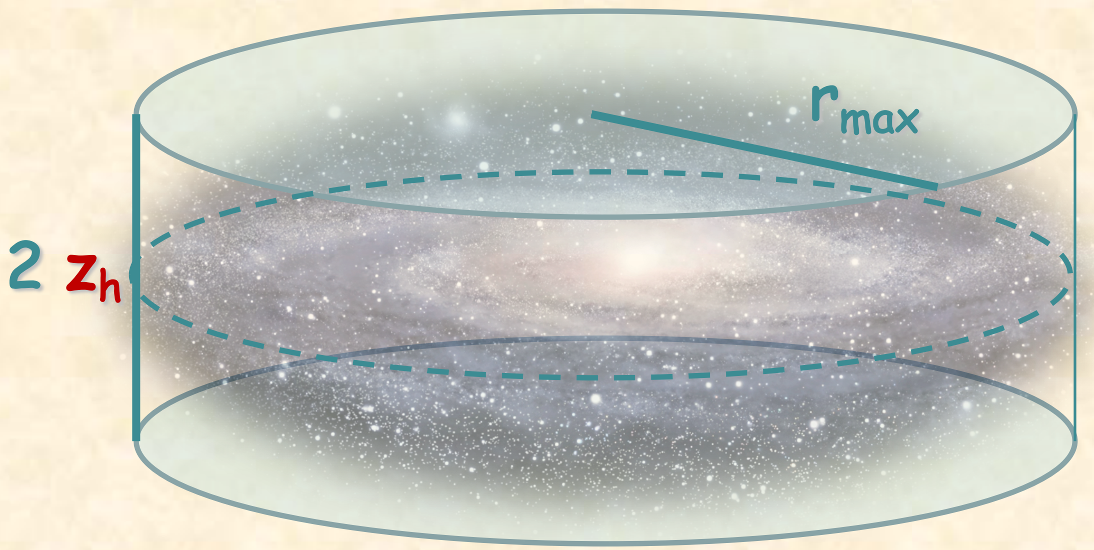
Very precise measurements from AMS02 of antiprotons, e+e-, p, He, nuclei up to Iron



AMS02 Collaboration, Phys.Rep. (2021)

Cosmic-Ray Propagation

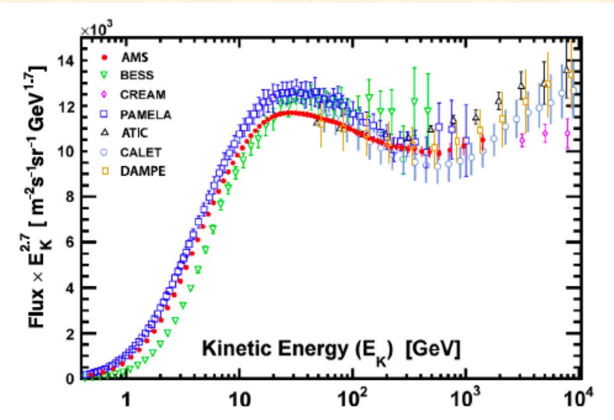
$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$
$$- \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

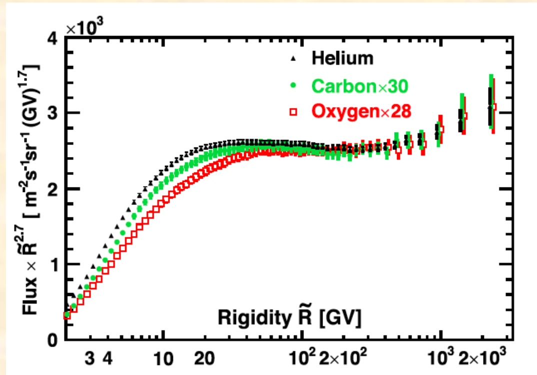


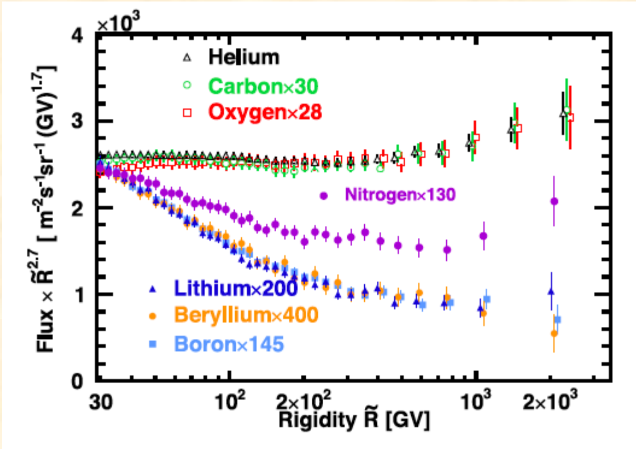
Diffusion equation is typically solved fully numerically with GALPROP or Dragon, or semi-analytically with Usine. For our analysis we used GALPROP.

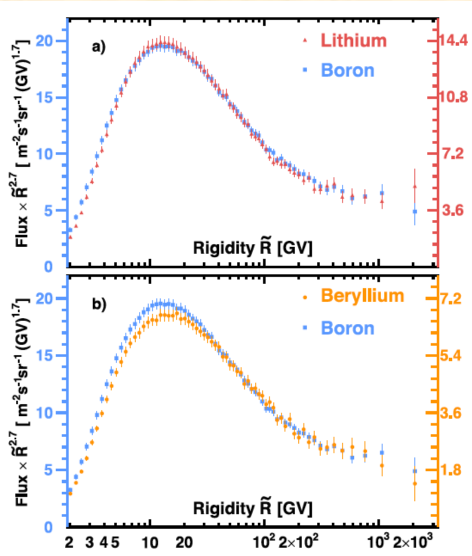
CR Data

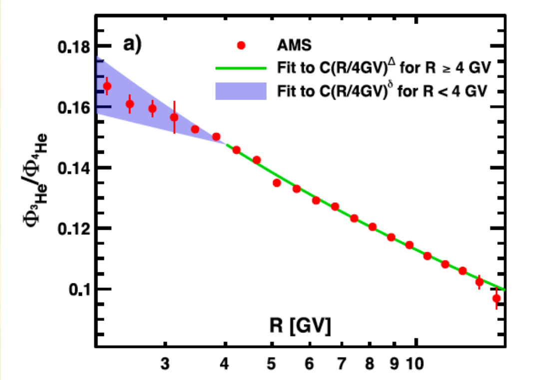
We use AMS-02 data on p, $\bar{p}$, $^3He/^4He$, He, Li, Be, B, C, N, O in a combined fit, or using specific subsets.

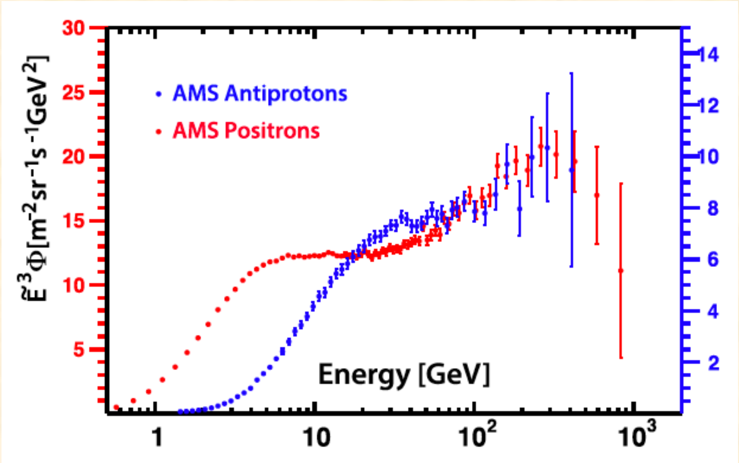












AMS02 Collaboration, Phys.Rep. (2021)

Nuclear Cross-sections nuisances

Nuclear production cross sections of secondary nuclei are still affected by large uncertainties. (See for example Genolini, Maurin, Moskalenko, Unger PRC 2018)

To take into account these uncertainties we use nuisance parameters. In particular we modify the default cross-section model with a power-law break and a normalization parameter.

$$\sigma_{k+j\to i}(T_k/A) = \sigma^{\text{default}}_{k+j\to i}(T_k/A) \cdot A_{k+j\to i} \cdot \begin{cases} (T_k/T_{\text{ref}})^{\delta_{k+j\to i}} & T_k/A < T_{\text{ref}}/A \\ 1 & \text{otherwise} \end{cases}.$$

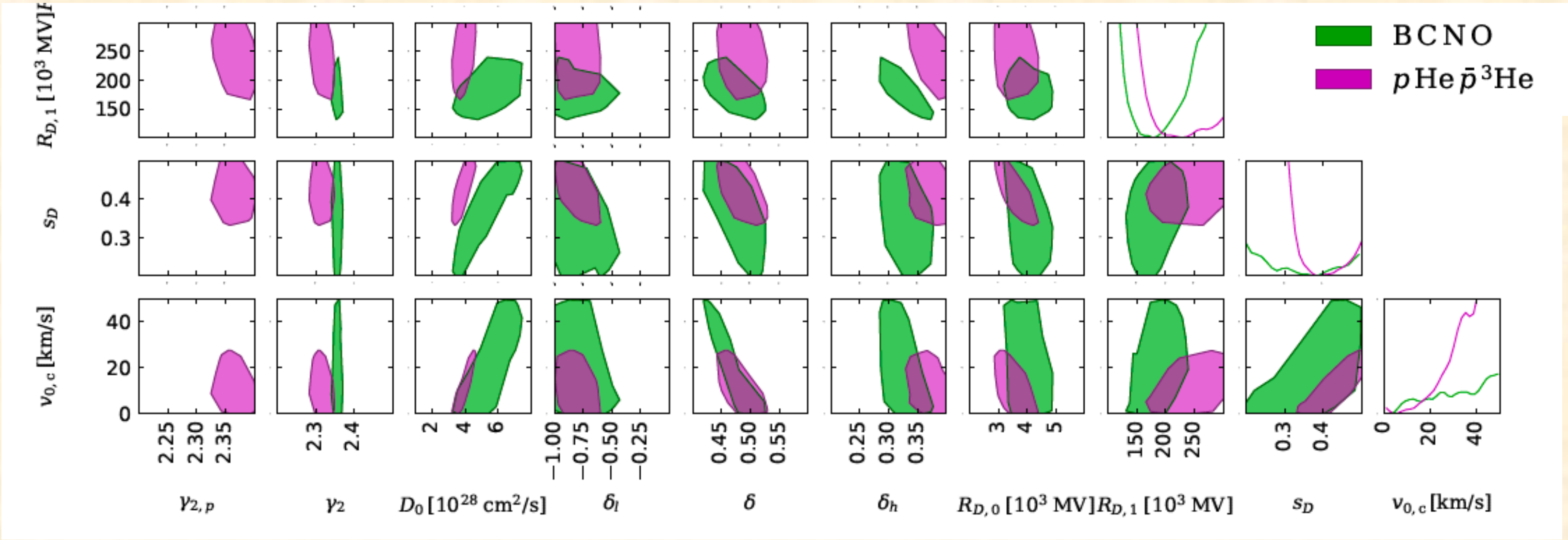
TABLE II. Cross section related nuisance parameters which are included in the CR fits.

fit parameter	nuisance parameters			
$\delta_{XS\to {}^3He}$	$\delta_{{}^4_2He\to {}^3_2He}$			
$\delta_{XS\to B}$	$\delta_{{}^{16}_8O\to {}^{10}_5B}$	$\delta_{{}^{12}_6C\to {}^{10}_5B}$	$\delta_{{}^{16}_8O\to {}^{11}_5B}$	$\delta_{{}^{12}_6C\to {}^{11}_5B}$
$\delta_{XS\to C}$		$\delta_{{}^{16}_8O\to {}^{12}_6C}$	$\delta_{{}^{16}_8O\to {}^{13}_6C}$	
$\delta_{XS\to N}$		$\delta_{{}^{16}_8O\to {}^{14}_7N}$	$\delta_{{}^{16}_8O\to {}^{15}_7N}$	
$A_{XS\to \bar{p}}$		$A_{p\to \bar{p}}$	$A_{{}^4_2He\to \bar{p}}$	
$A_{XS\to {}^3He}$	$A_{{}^4_2He\to {}^3_2He}$			
$A_{XS\to B}$	$A_{{}^{16}_8O\to {}^{10}_5B}$	$A_{{}^{12}_6C\to {}^{10}_5B}$	$A_{{}^{16}_8O\to {}^{11}_5B}$	$A_{{}^{12}_6C\to {}^{11}_5B}$
$A_{XS\to C}$		$A_{{}^{16}_8O\to {}^{12}_6C}$	$A_{{}^{16}_8O\to {}^{13}_6C}$	
$A_{XS\to N}$		$A_{{}^{16}_8O\to {}^{14}_7N}$	$A_{{}^{16}_8O\to {}^{15}_7N}$	

Results: Light vs Heavy nuclei

We tested the consistency of light vs heavy nuclei datasets.

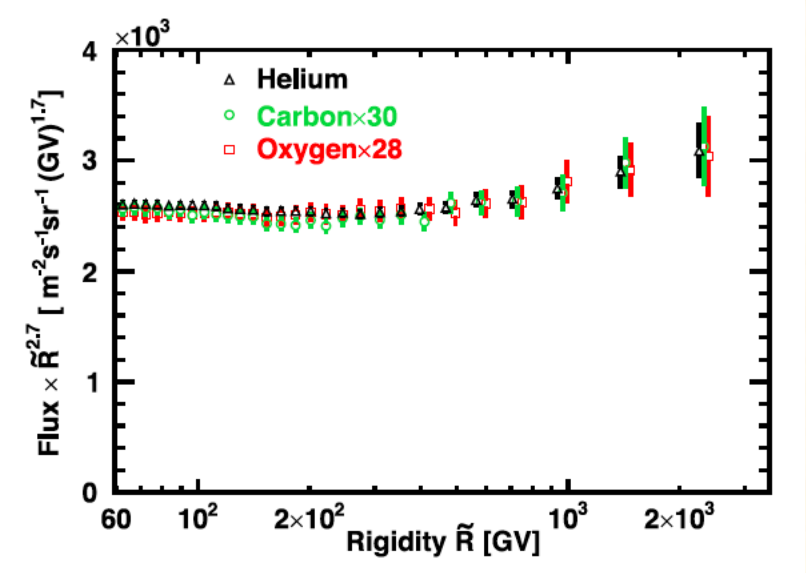
- Fit1: p, $\overline{p}/p$, ^{3}He/^{4}He, He
- Fit2: B, C, N, O



The main result is that injections slopes of He and CNO are different. Also some tensions on diffusion.

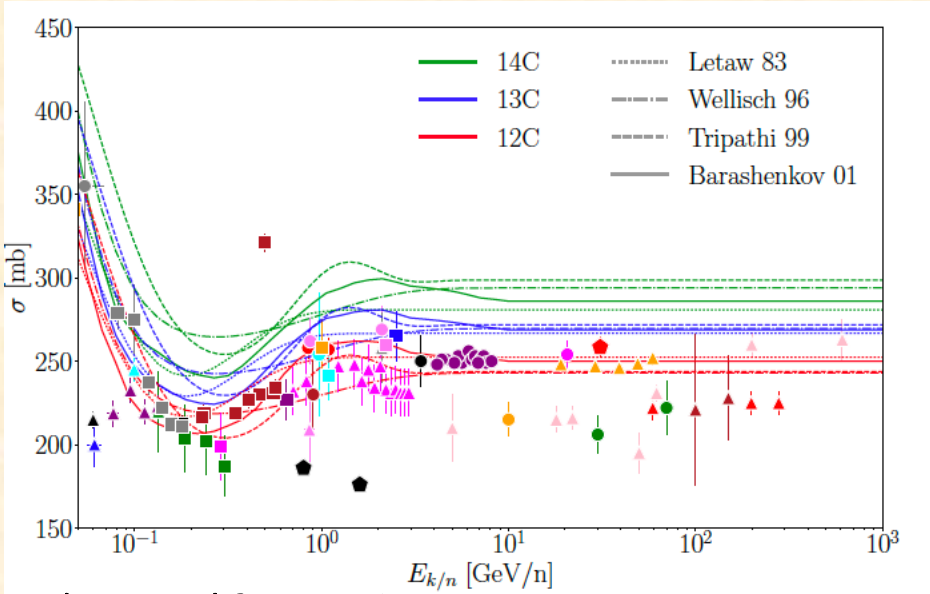
Lessons #1

Be careful in drawing conclusions looking at data only:

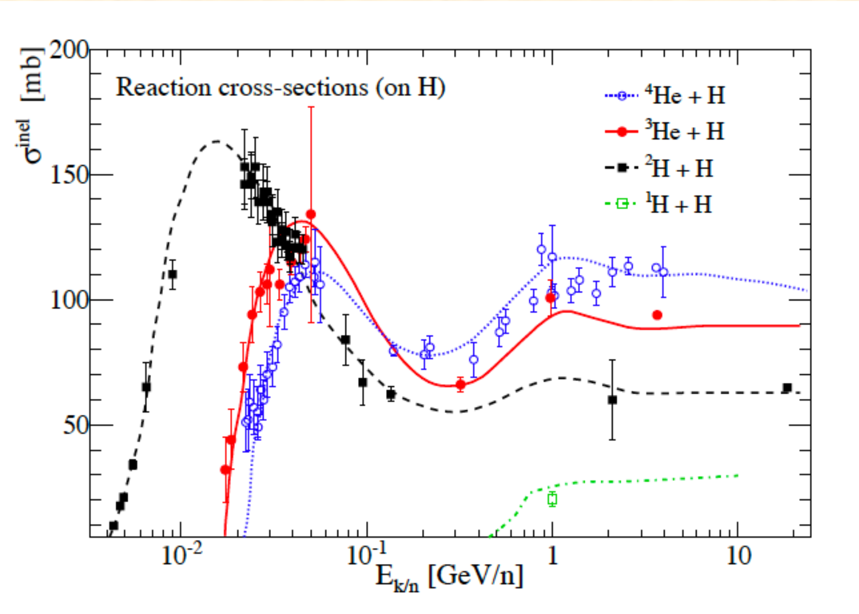


- The fact that He, C, O have the same spectral shape is at odd with model predictions.
- Energy losses are different, so with the same injection spectrum the observed ones should be different.
- Hence: either there are no energy losses (very odd…) or injection is different.

Cross sections?



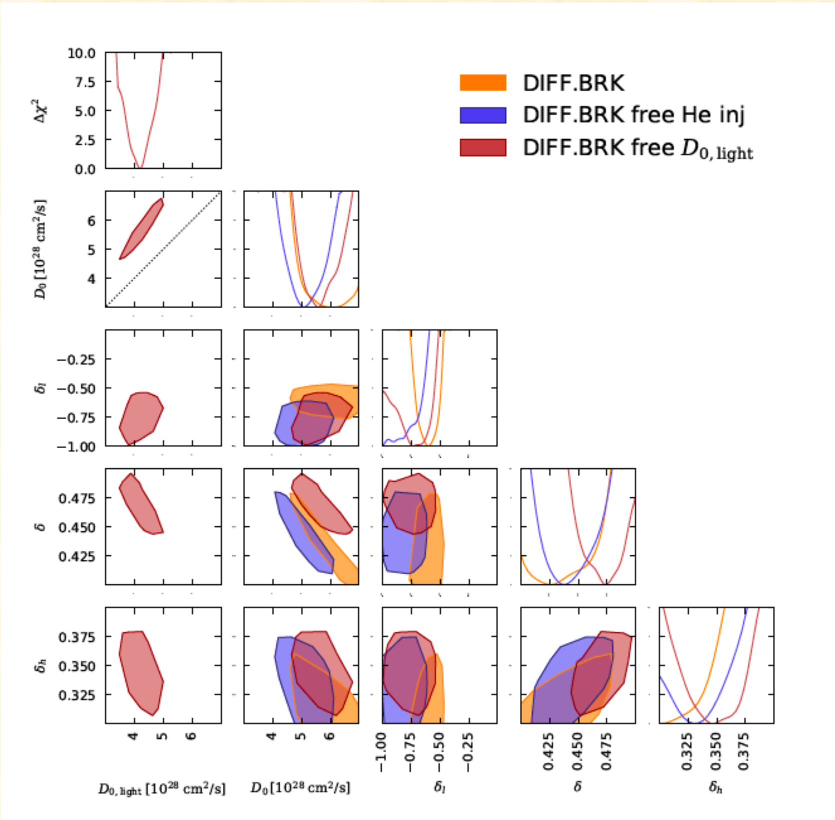
Genolini et al.PRC 2018



Coste et al. A&A 2011

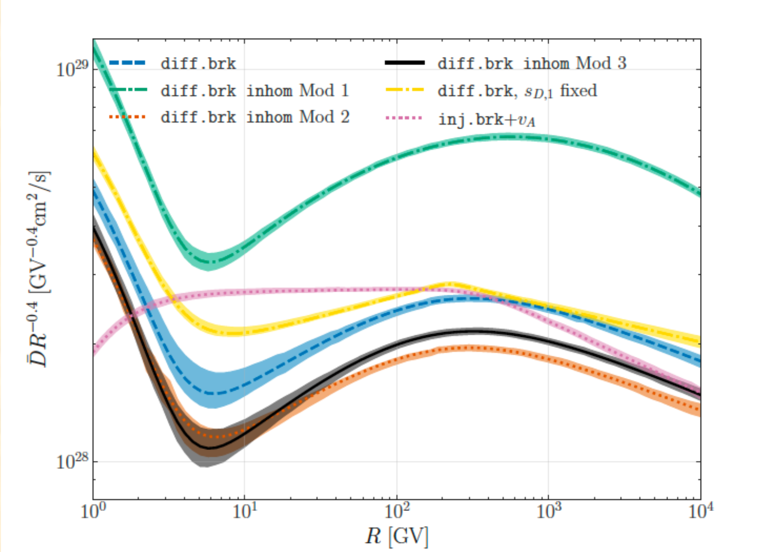
- Energy losses depend on total inelistic cross-sections with uncertainties at the 10-20% level.
- Even taking into account uncertainties seems unlikely that cross-sections can explain the He/C tension.

Results: effective non-homogeneous diffusion

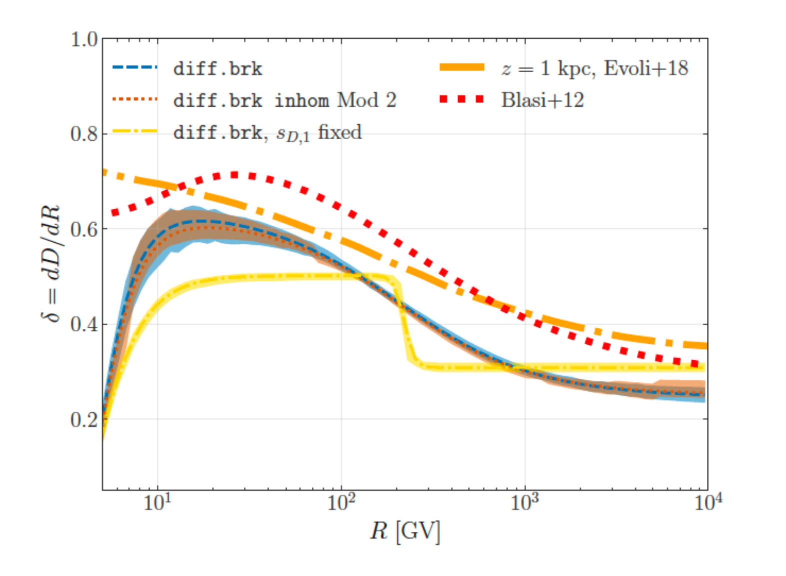


- A combined fit with all nuclei with same injection and same diffusion provides a poor fit. One needs either to use different injections or different diffusions.
- If we use the same injection for He and CNO, then indeed different values of D0 are preferred for light vs heavy nuclei, ---> evidence for non-homogenous diffusion?
- A more careful study with a proper model of non-homogenous propagation is required. Ongoing analysis.

Self-turbulence model



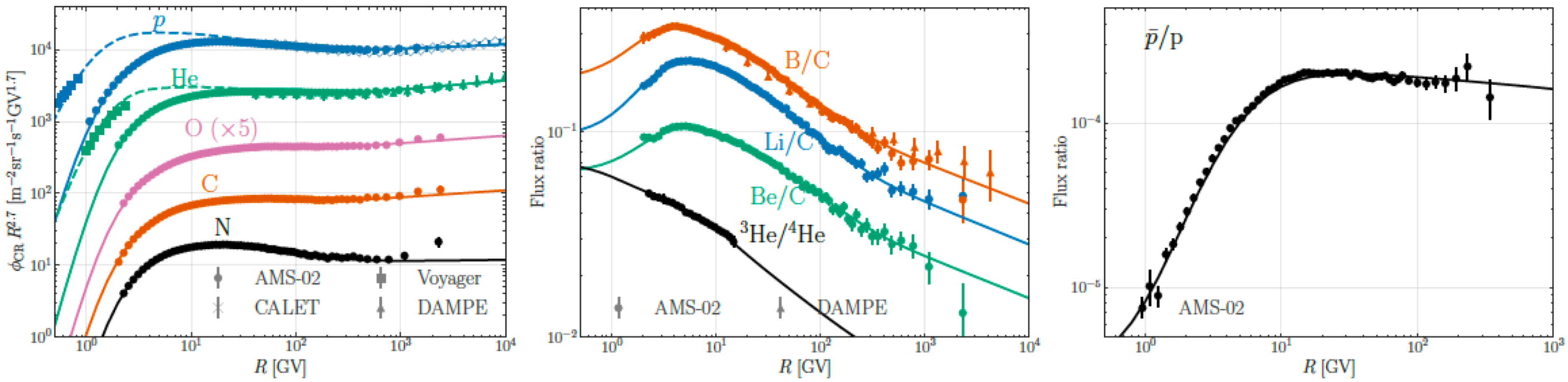
Di Mauro, Korsmeier, Cuoco, PRD2024



Models of self-generated self-turbulence predict a smooth behavior in energy of the diffusion coefficient, not a broken power law.

Indeed, we find that smooth transition decribes the data better, with χ^2 improvements of about $\Delta\chi^2 \approx 70$.

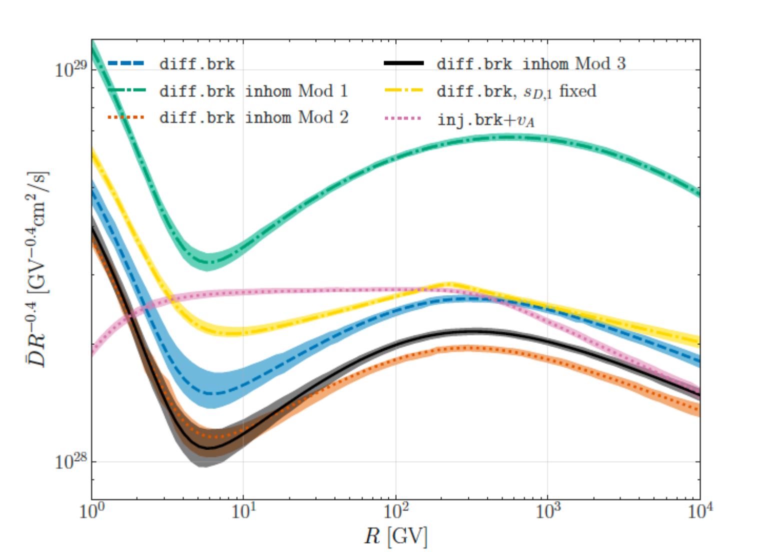
Data/Model agreement



Data-Model agreement is very good. Typically better than 10%, and generally comparable with the data error bars.

χ^2 values are about 200 for 450 data points, i.e. $\tilde{\chi}^2 \approx 0.45$

Self-turbulence vs Reacceleration

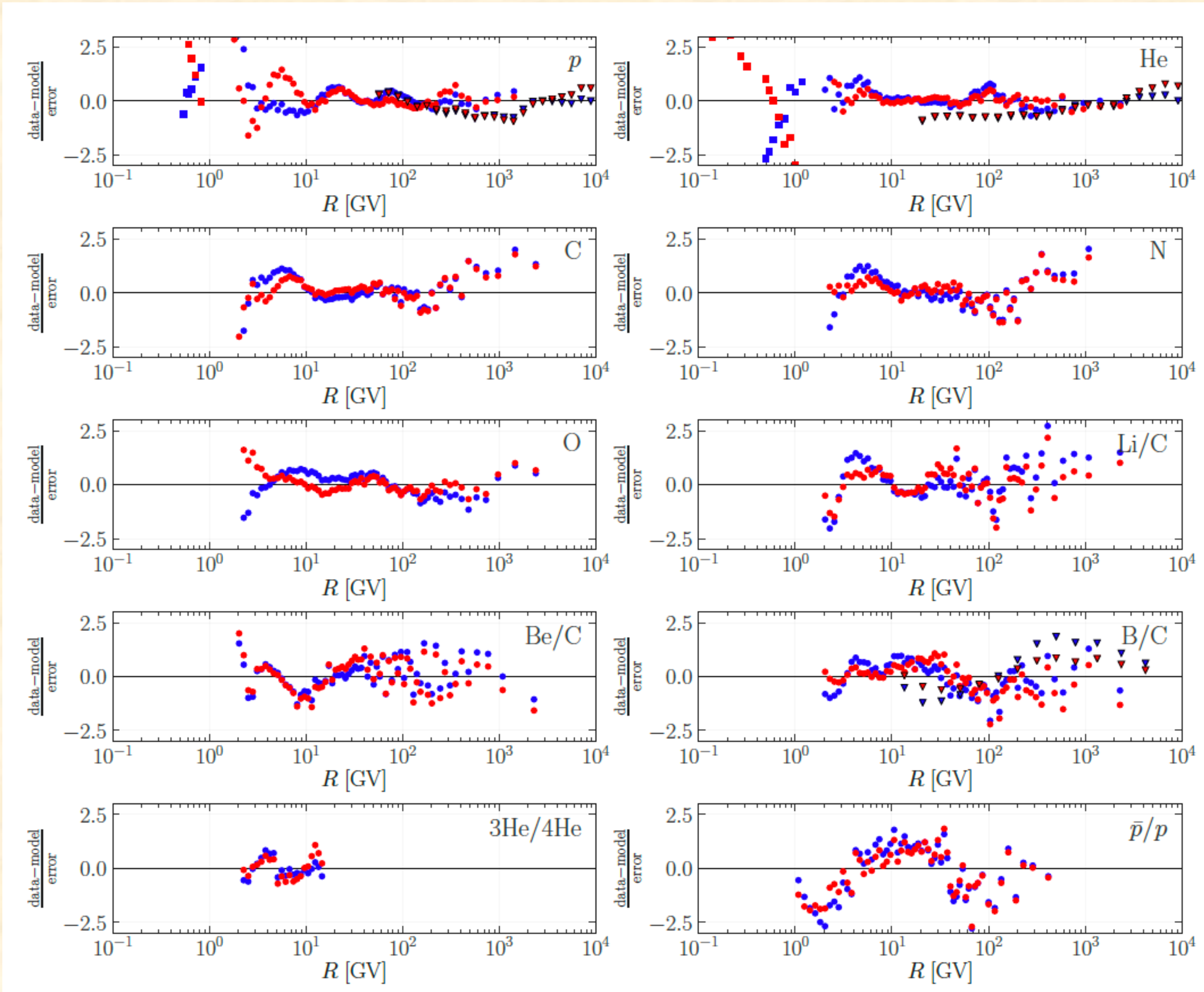


Di Mauro, Korsmeier, Cuoco, PRD2024

We consider two alternative diffusion models:

1) The self-turbulence model, with a curved diffusion coefficient and no reacceleration.
2) A 'Standard' model with reacceleration and a simple power-law for the diffusion coefficient

Self-turbulence vs Reacceleration



Both models provide a good description of the data, with similar residuals

However: Cross-sections, Again

- The fit quality is similar indicating that we cannot distinguish between the two scenarios. However, this happens only at the prize of significantly different cross sections via the cross section nuisance parameters.

- Thus, again, the lack of precise data on the cross sections (at least as precise as the CR observations) is crucially limiting our ability to understand CR physics (and new physics)!

Summary and Conclusions

- Presently available precise CR data allow to test finer details of the CR "standard" propagation model
- We perform a combined fit of AMS-02 data on p, $\overline{p}$, $^{3}He/^{4}He$, He, Li, Be, B, C, N, O.
- Possible evidence for different diffusion in light and heavy nuclei. Evidence for non-homogenous diffussion?
- Significant preference for a smooth slope change in the diffusion coefficient. Further support for self-turbulence.
- X-sections uncertainties are significantly limiting our understanding of CR physics and the search for new physics

Summary and Conclusions

- Presently available precise CR data allow to test finer details of the CR “standard” propagation model
- We perform a combined fit of AMS-02 data on p, $\overline{p}$, ^{3}He/^{4}He, He, Li, Be, B, C, N, O.
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Thanks!

Backup

Solar Modulation

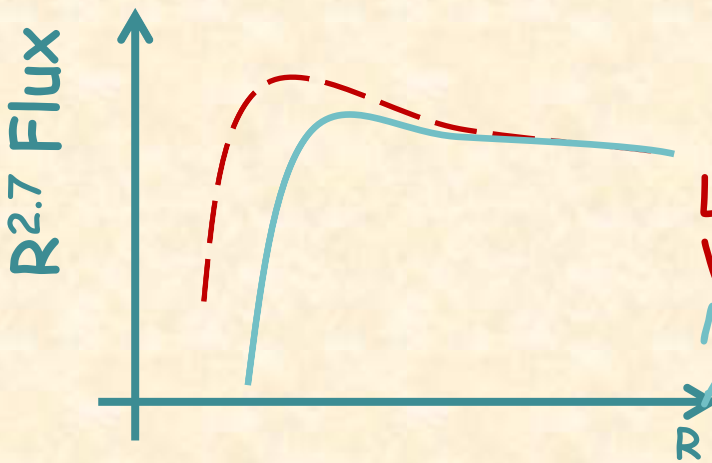
- Phenomenological description: force-field approximation

$$E = E_{\mathrm{LIS}} - |Z|e\phi,$$

$$\Phi_E(E) = \frac{E^2 - m^2}{E_{\mathrm{LIS}}^2 - m^2}\Phi_{E,\mathrm{LIS}}(E_{\mathrm{LIS}})$$

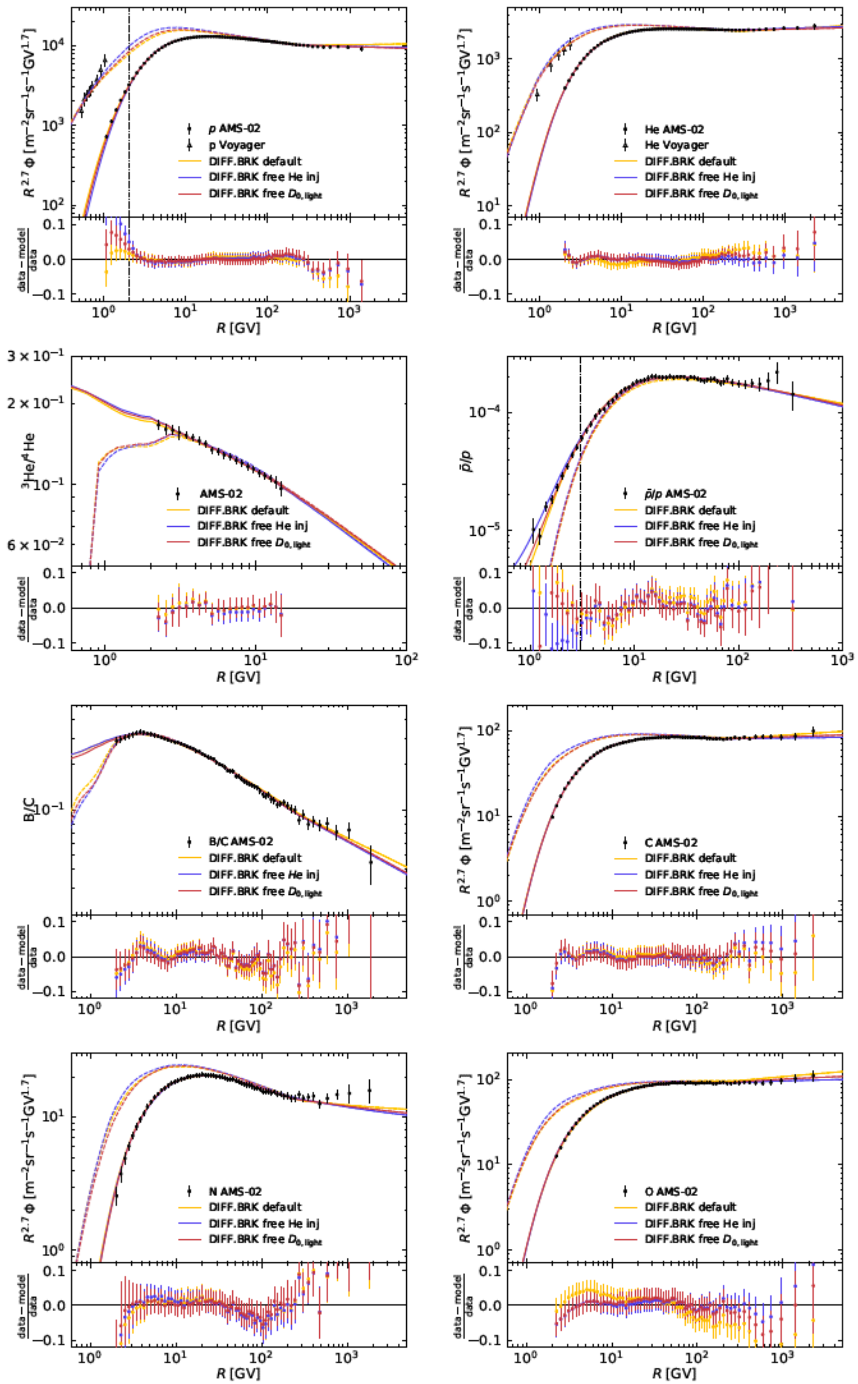
Our novel approach:

- Constrain LIS flux by VOYAGER data
- Solar modulation potential is a "linear" parameter: marginalized for each GALPROP evaluation



LIS flux fitted to VOYAGER

Modulated flux fitted to AMS


p AMS-02
p Voyager
DIFF.BRK default
DIFF.BRK free He inj
DIFF.BRK free $D_{0,\mathrm{light}}$
He AMS-02
He Voyager
AMS-02
$\bar{p}/p$ AMS-02
B/C AMS-02
C AMS-02
N AMS-02
O AMS-02
$R^{2.7}\,\Phi\,[\mathrm{m^{-2}sr^{-1}s^{-1}GV^{1.7}}]$
^{3}He/^{4}He
$\bar{p}/p$
B/C
$\frac{\mathrm{data-model}}{\mathrm{data}}$
R [GV]

Residuals