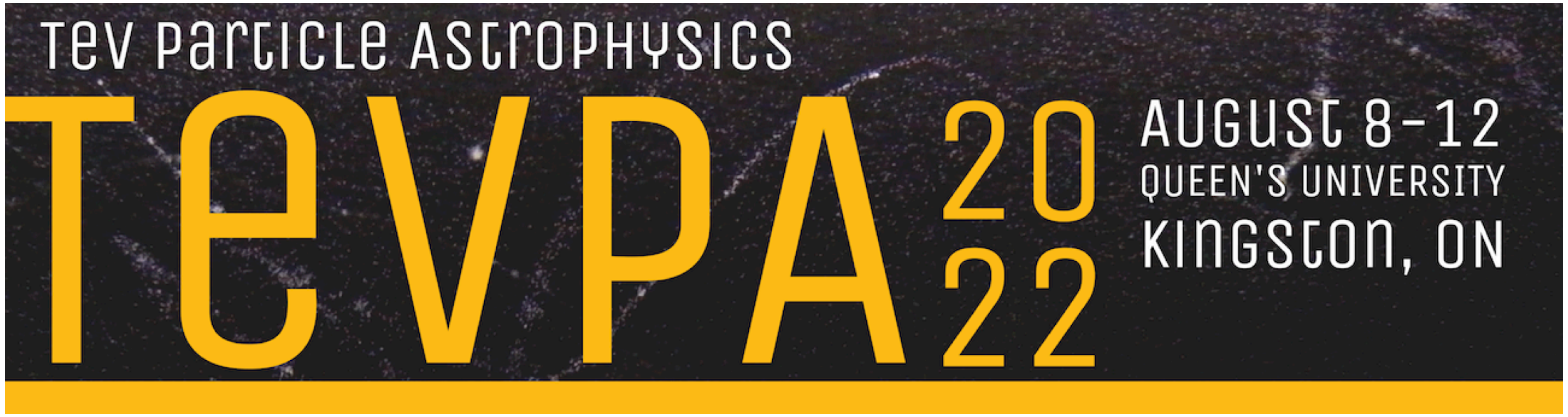
Testing the universality of cosmic-ray nuclei from protons to oxygen with AMS-02

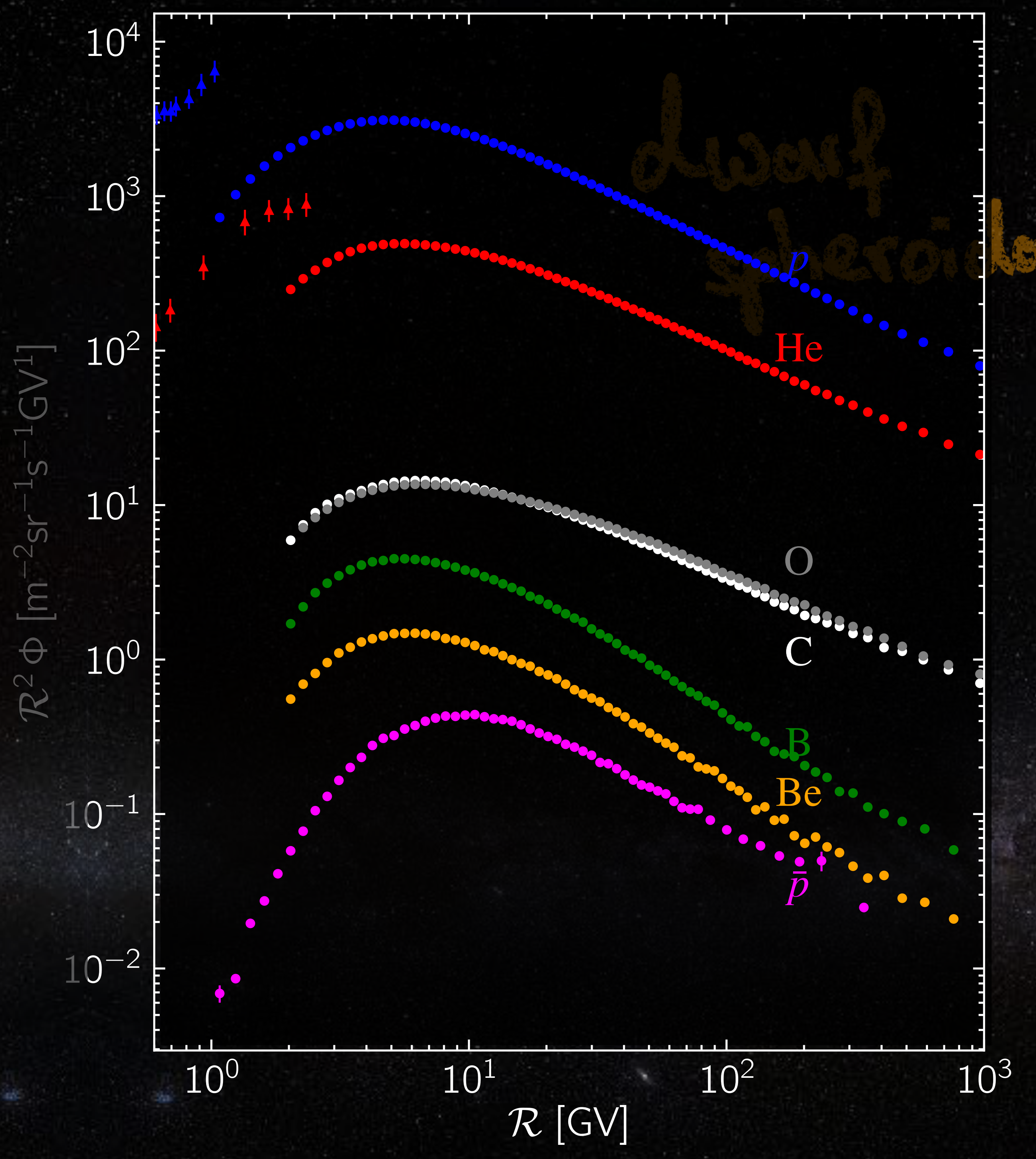
Michael Korsmeier, Alessandro Cuoco

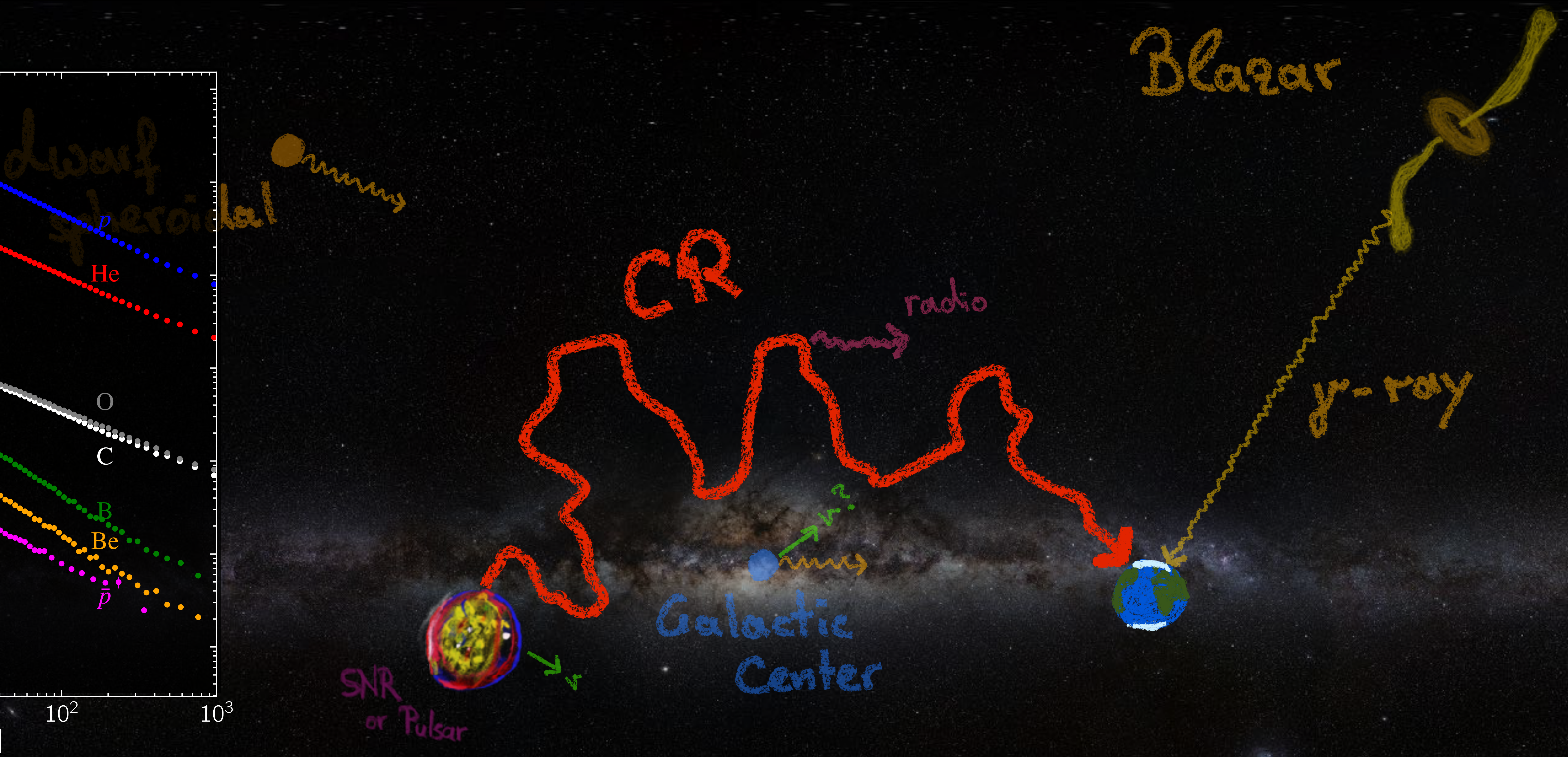
Based on ***Phys.Rev.D* 105 (2022) 10, 103033**
***Phys.Rev.D* 103 (2021) 10, 103016**

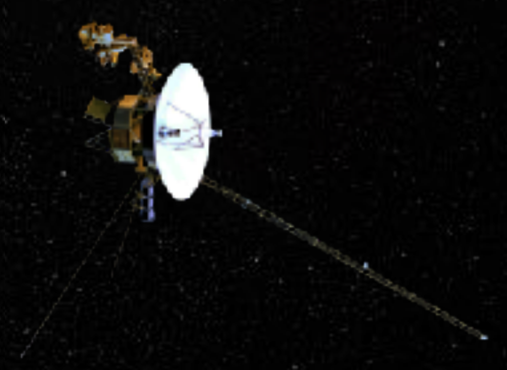


Astroparticle messenger

Astroparticle messenger







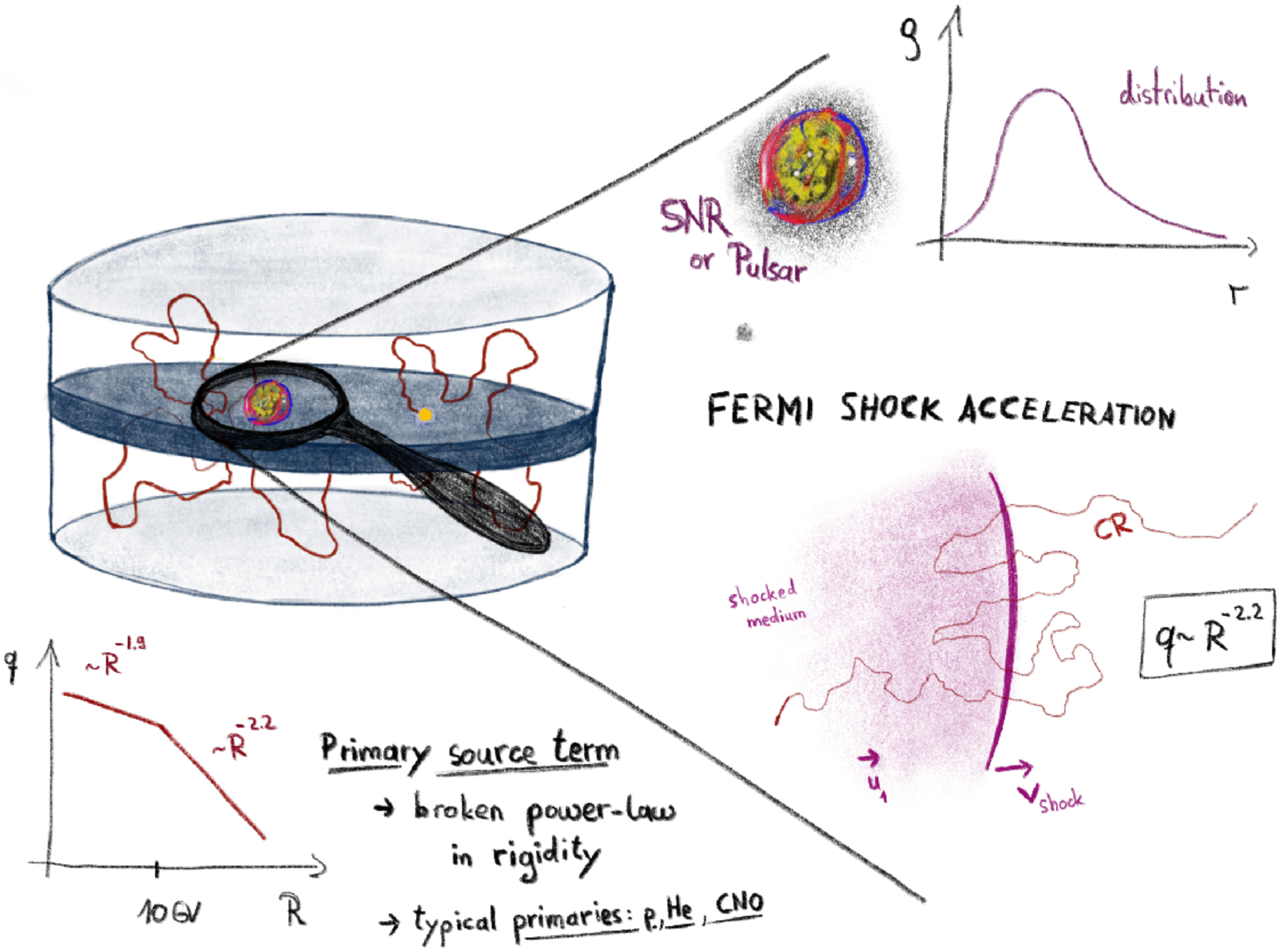
Voyager

AMS-02

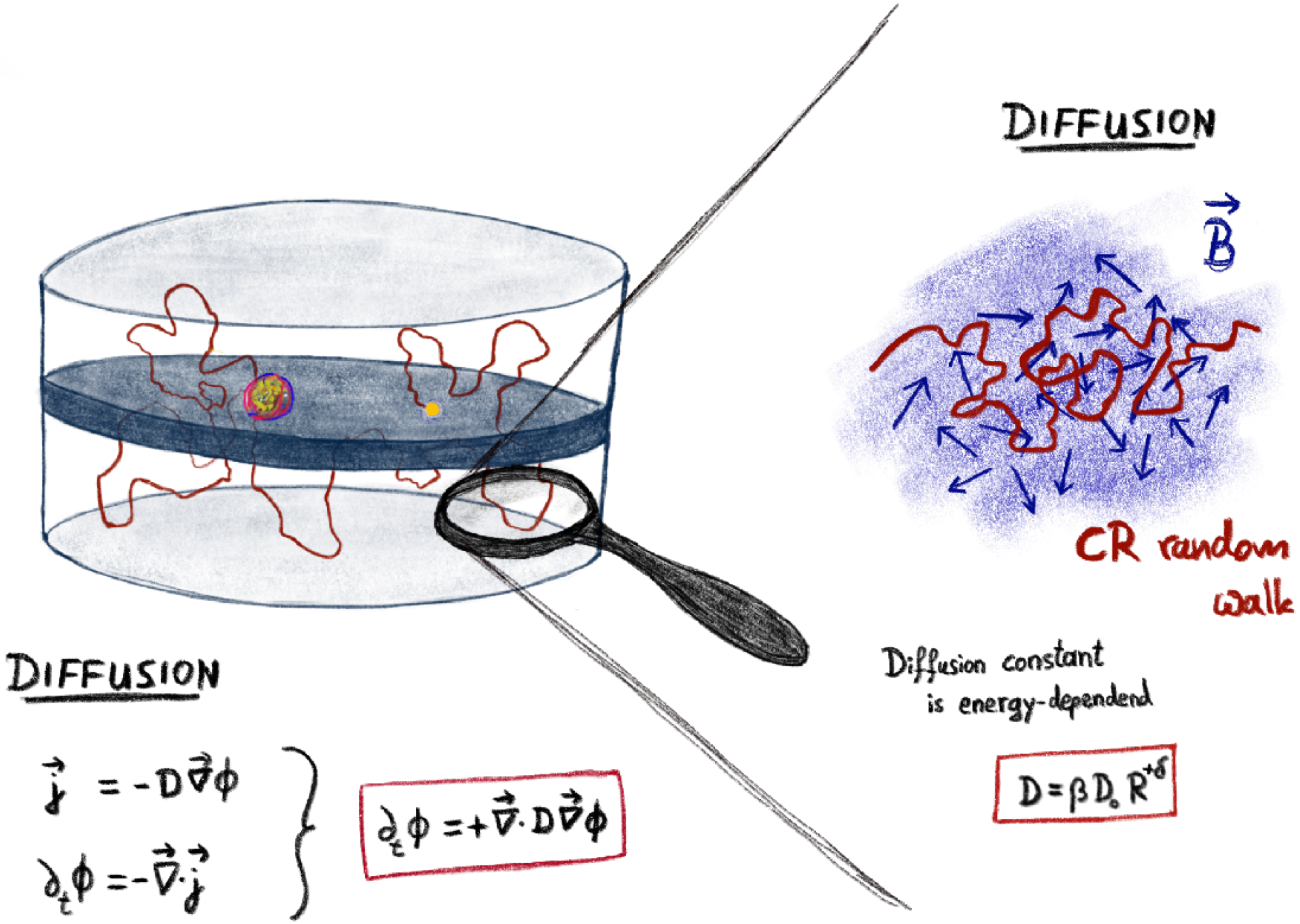
Outline

- **Introduction**
- **Modeling CR data from Li to O**
- **Testing CR universality with data from *p* to O**
- **Conclusions**

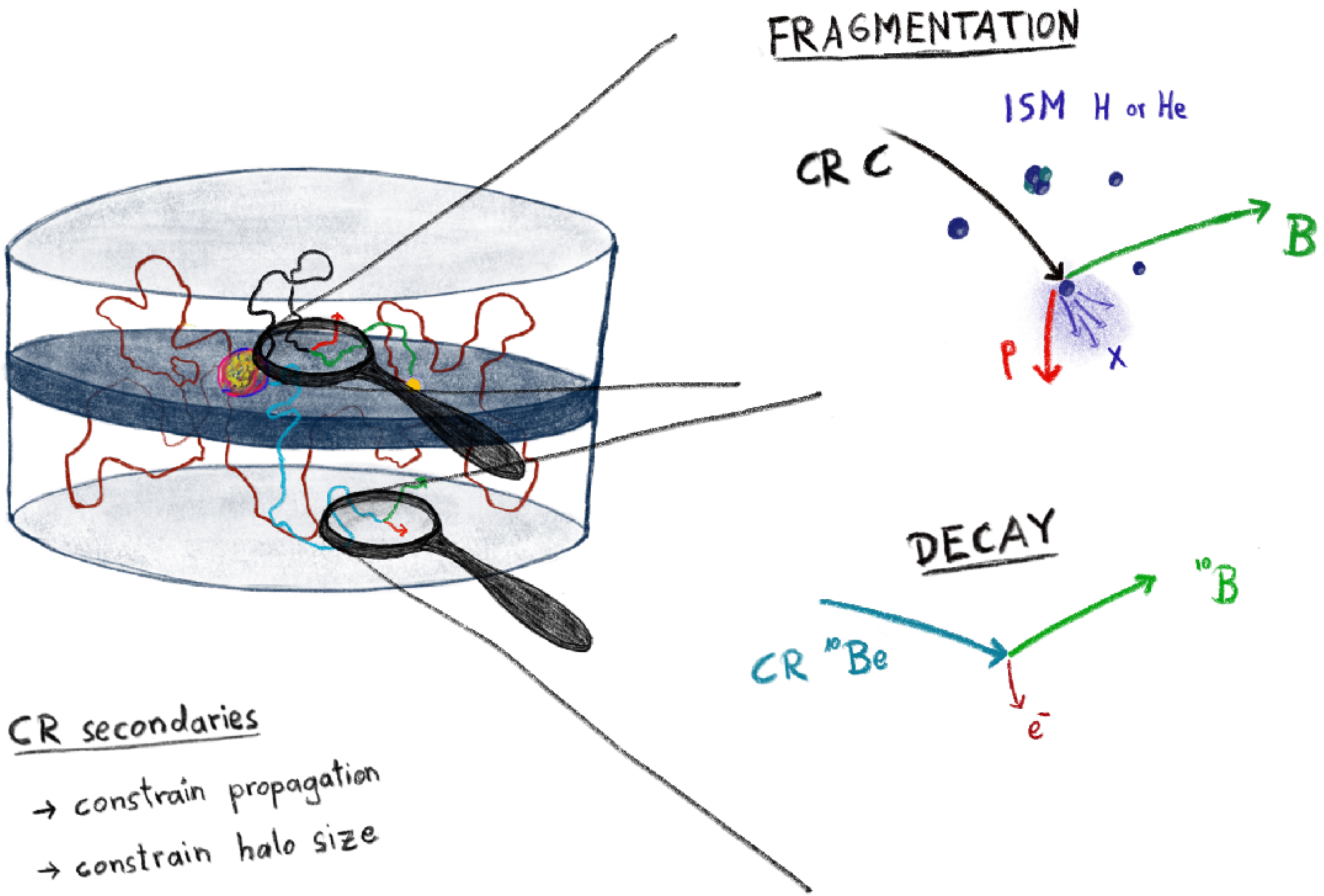
Modeling cosmic-ray propagation



Modeling cosmic-ray propagation

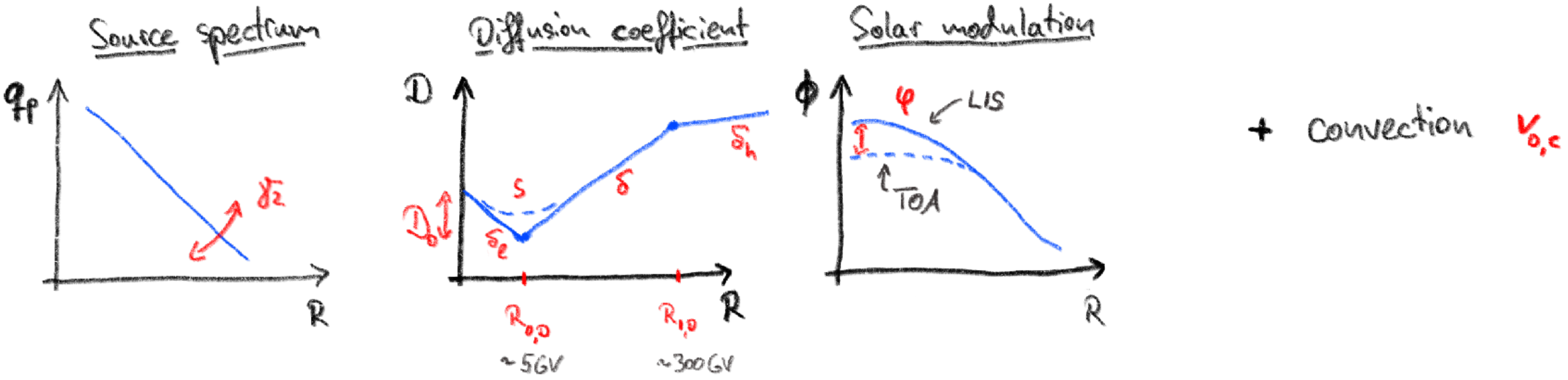


Modeling cosmic-ray propagation



We explore 2 different setups for CR propagation:

DIFF.BRK INJ.BRK+vA

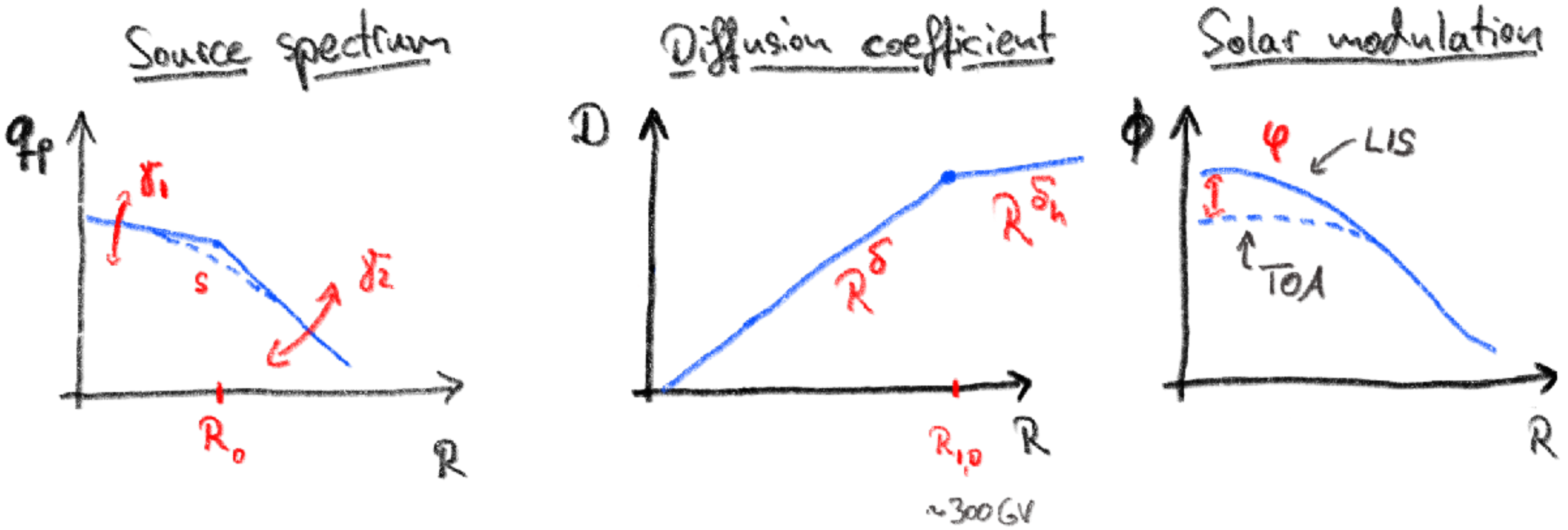


$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla}\cdot\left(D_{xx}\boldsymbol{\nabla}\psi - \boldsymbol{V}\psi\right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi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

Cosmic-ray propagation models

We explore 2 different setups for CR propagation:

DIFF.BRK **INJ.BRK+vA**



\+ convection $v_{0,c}$

\+ reacceleration v_A

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

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We explore 2 different setups for CR propagation:

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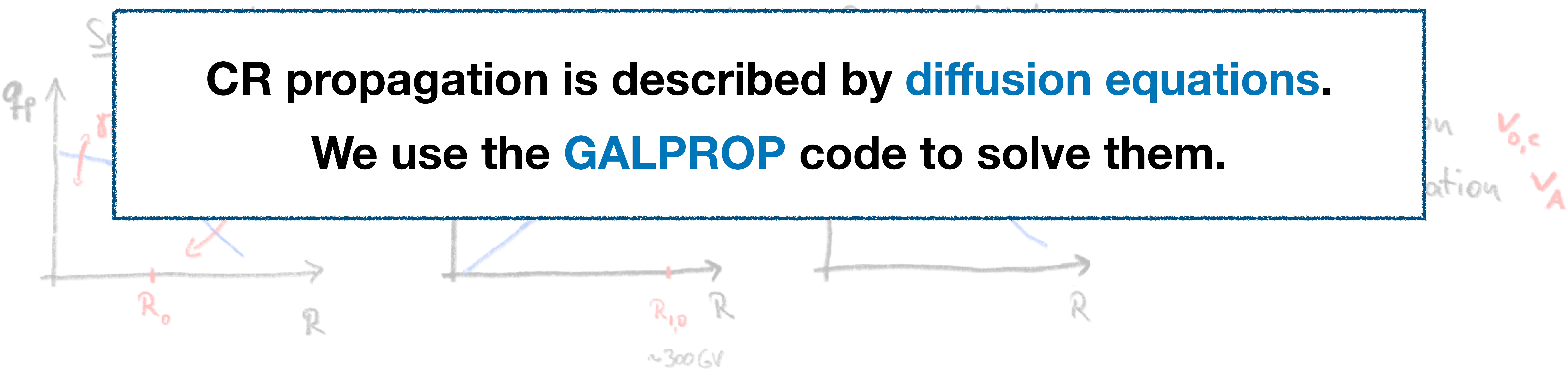


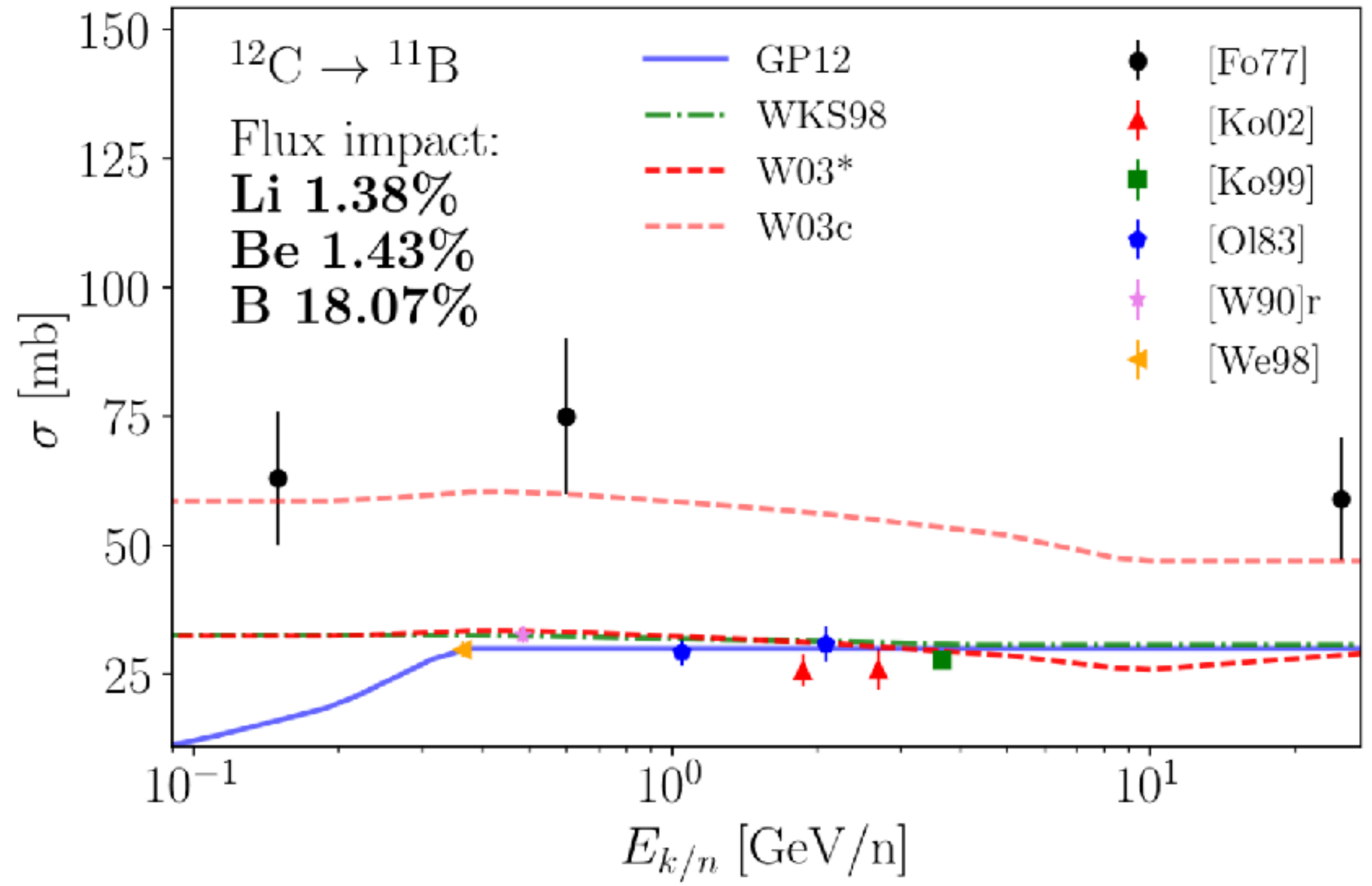
CR propagation is described by diffusion equations.

We use the GALPROP code to solve them.

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

Systematic uncertainty: fragmentation cross sections

Example: Fragmentation of ^{12}C to ^{11}B



[Genolini *et al.*, Phys.Rev.C 98 (2018) 3, 034611]

Systematic uncertainties in the fragmentation cross sections are larger than those in the measured CR spectra!

see also [Maurin+, 2022] [Talk by De la torre Luque]

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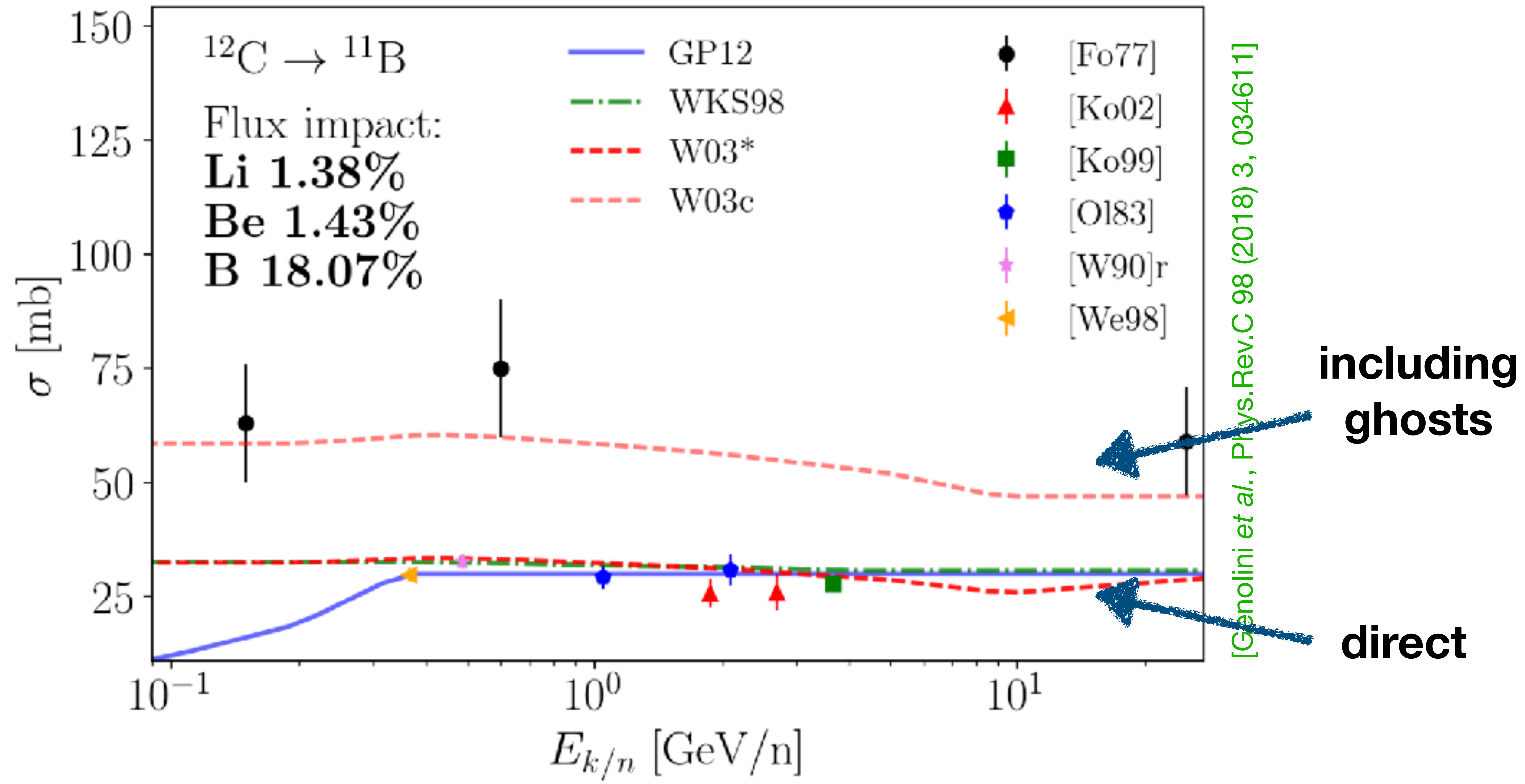

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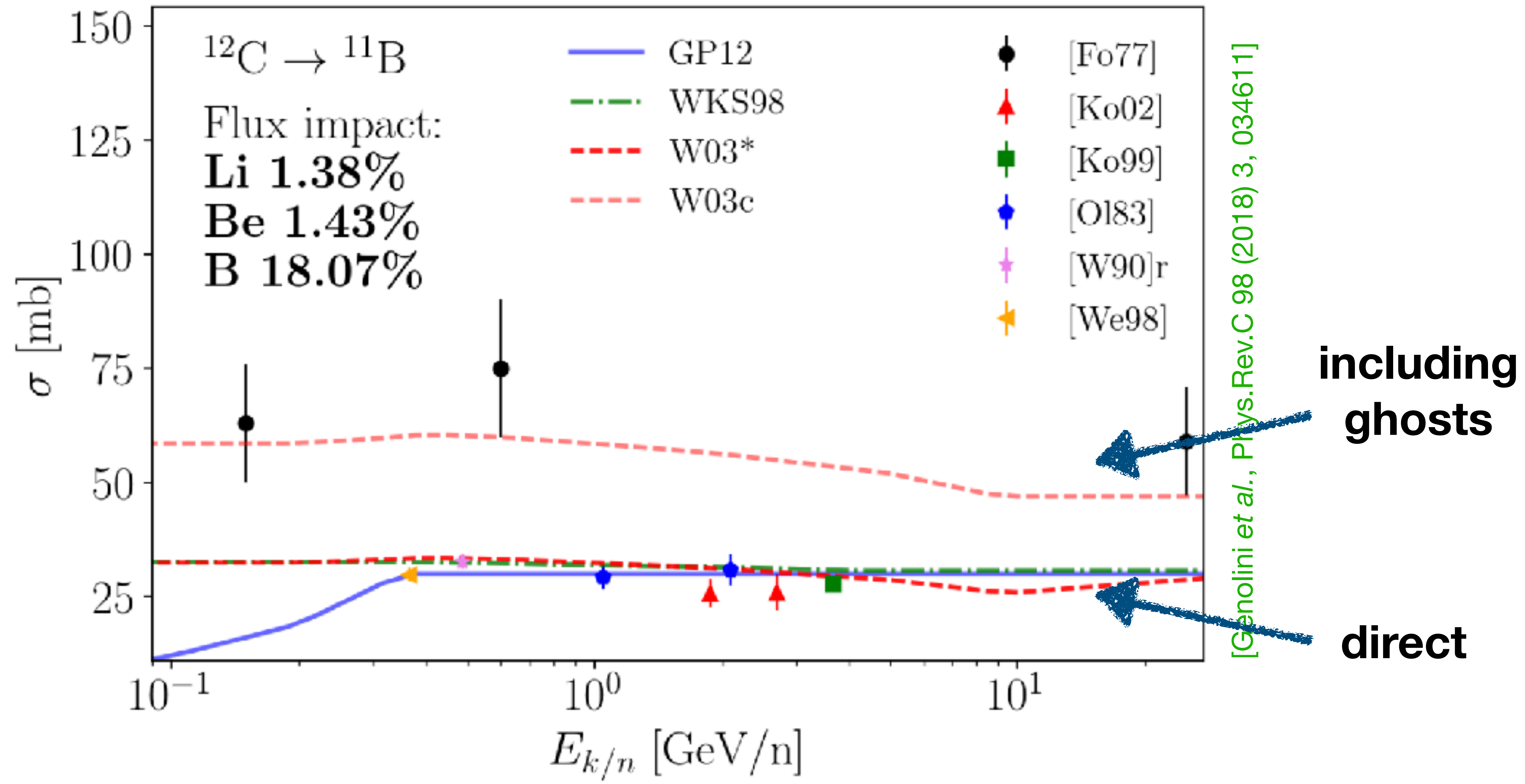

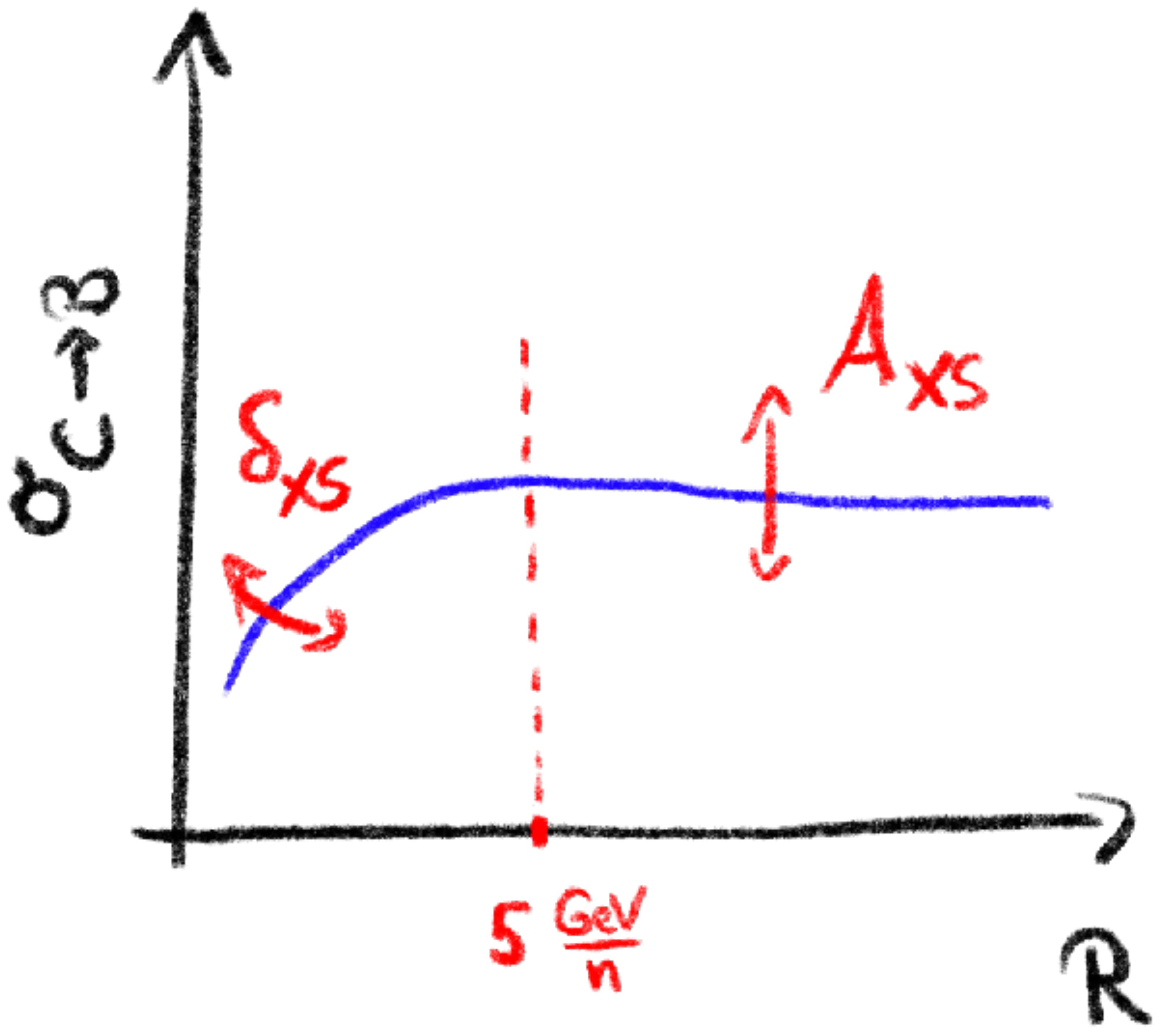

Systematic uncertainties in the fragmentation cross sections are larger than those in the measured CR spectra!

We perform a global fit and profile over nuisance parameters in the most relevant fragmentation cross sections.

see also [Maurin+, 2022] [Talk by De la torre Luque]

Systematic uncertainty: fragmentation cross sections

Example: Fragmentation of ^{12}C to ^{11}B

fit parameter	nuisance parameters			
$\delta_{XS\to B}$	$\delta\ {}^{16}_{8}O\to{}^{10}_{5}B$	$\delta\ {}^{12}_{6}C\to{}^{10}_{5}B$	$\delta\ {}^{16}_{8}O\to{}^{11}_{5}B$	$\delta\ {}^{12}_{6}C\to{}^{11}_{5}B$
$\delta_{XS\to Li}$	$\delta\ {}^{16}_{8}O\to{}^{6}_{3}Li$	$\delta\ {}^{12}_{6}C\to{}^{6}_{3}Li$	$\delta\ {}^{16}_{8}O\to{}^{7}_{3}Li$	$\delta\ {}^{12}_{6}C\to{}^{7}_{3}Li$
$\delta_{XS\to Be}$	$\delta\ {}^{16}_{8}O\to{}^{7}_{4}Be$	$\delta\ {}^{12}_{6}C\to{}^{7}_{4}Be$	$\delta\ {}^{16}_{8}O\to{}^{9}_{4}Be$	$\delta\ {}^{12}_{6}C\to{}^{9}_{4}Be$
$\delta_{XS\to C}$		$\delta\ {}^{16}_{8}O\to{}^{12}_{6}C$	$\delta\ {}^{16}_{8}O\to{}^{13}_{6}C$	
$\delta_{XS\to N}$		$\delta\ {}^{16}_{8}O\to{}^{14}_{7}N$	$\delta\ {}^{16}_{8}O\to{}^{15}_{7}N$	
$A_{XS\to B}$	$A\ {}^{16}_{8}O\to{}^{10}_{5}B$	$A\ {}^{12}_{6}C\to{}^{10}_{5}B$	$A\ {}^{16}_{8}O\to{}^{11}_{5}B$	$A\ {}^{12}_{6}C\to{}^{11}_{5}B$
$A_{XS\to Li}$	$A\ {}^{16}_{8}O\to{}^{6}_{3}Li$	$A\ {}^{12}_{6}C\to{}^{6}_{3}Li$	$A\ {}^{16}_{8}O\to{}^{7}_{3}Li$	$A\ {}^{12}_{6}C\to{}^{7}_{3}Li$
$A_{XS\to Be}$	$A\ {}^{16}_{8}O\to{}^{7}_{4}Be$	$A\ {}^{12}_{6}C\to{}^{7}_{4}Be$	$A\ {}^{16}_{8}O\to{}^{9}_{4}Be$	$A\ {}^{12}_{6}C\to{}^{9}_{4}Be$
$A_{XS\to C}$		$A\ {}^{16}_{8}O\to{}^{12}_{6}C$	$A\ {}^{16}_{8}O\to{}^{13}_{6}C$	
$A_{XS\to N}$		$A\ {}^{16}_{8}O\to{}^{14}_{7}N$	$A\ {}^{16}_{8}O\to{}^{15}_{7}N$	

Systemati... fragmentation ... than those in the measured CR spectra!

...it and profile over ...ers in the most relevant fragmentation cross sections.

see also [Maurin+, 2022] [Talk by De la torre Luque]

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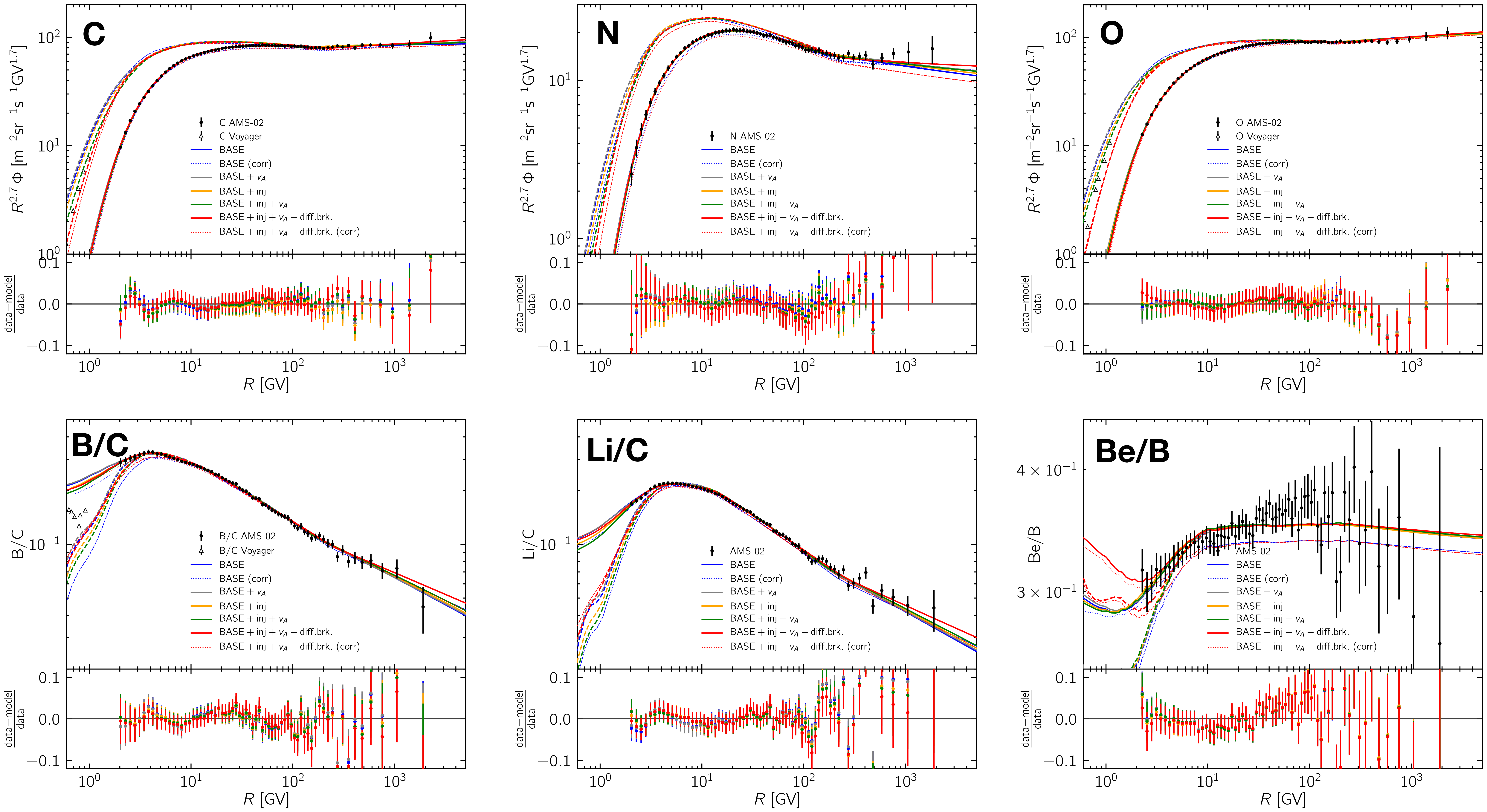
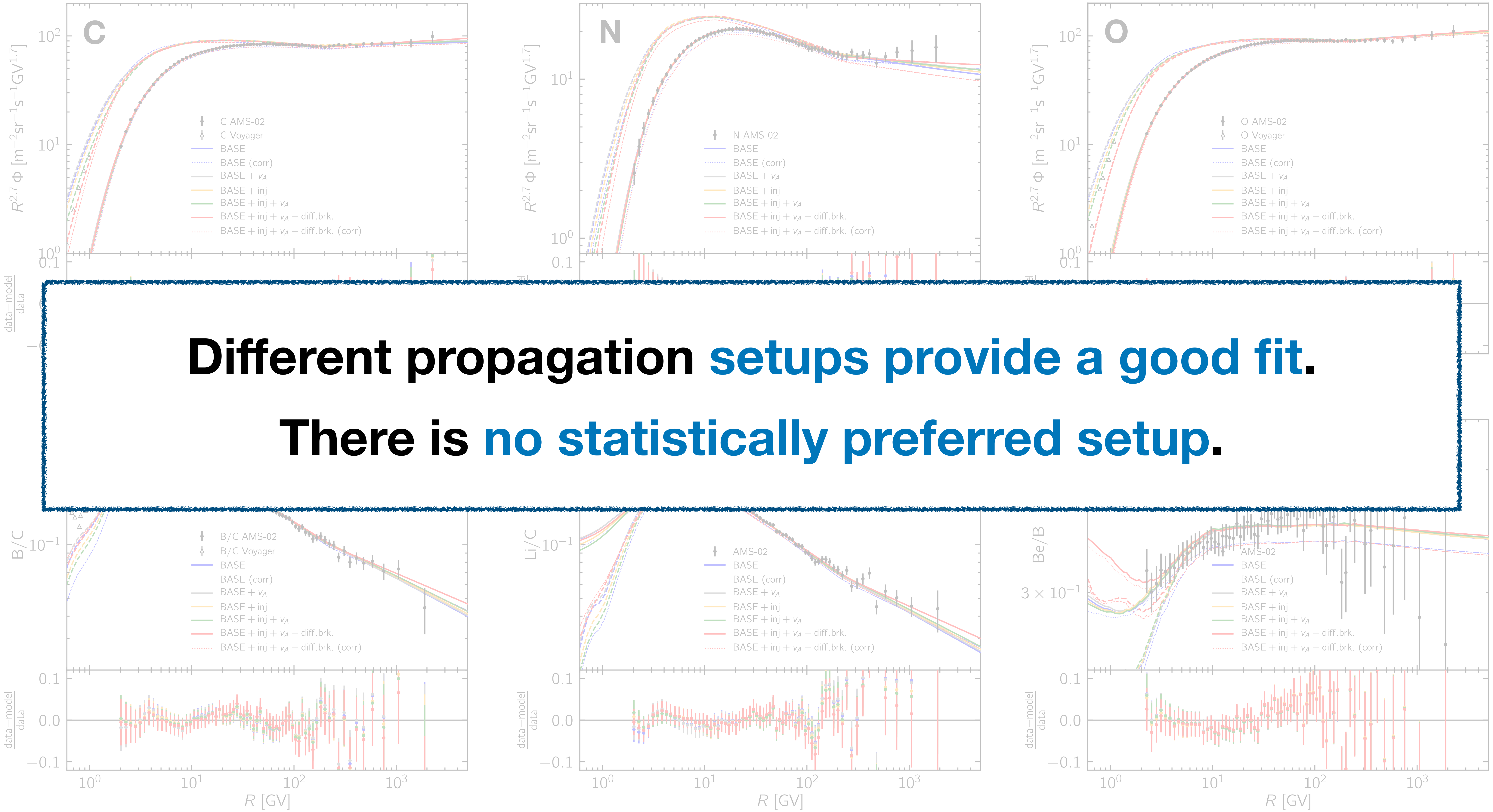
Results of the fits from Li to O



[MK, Cuoco, 2021 a]

Results of the fits from Li to O

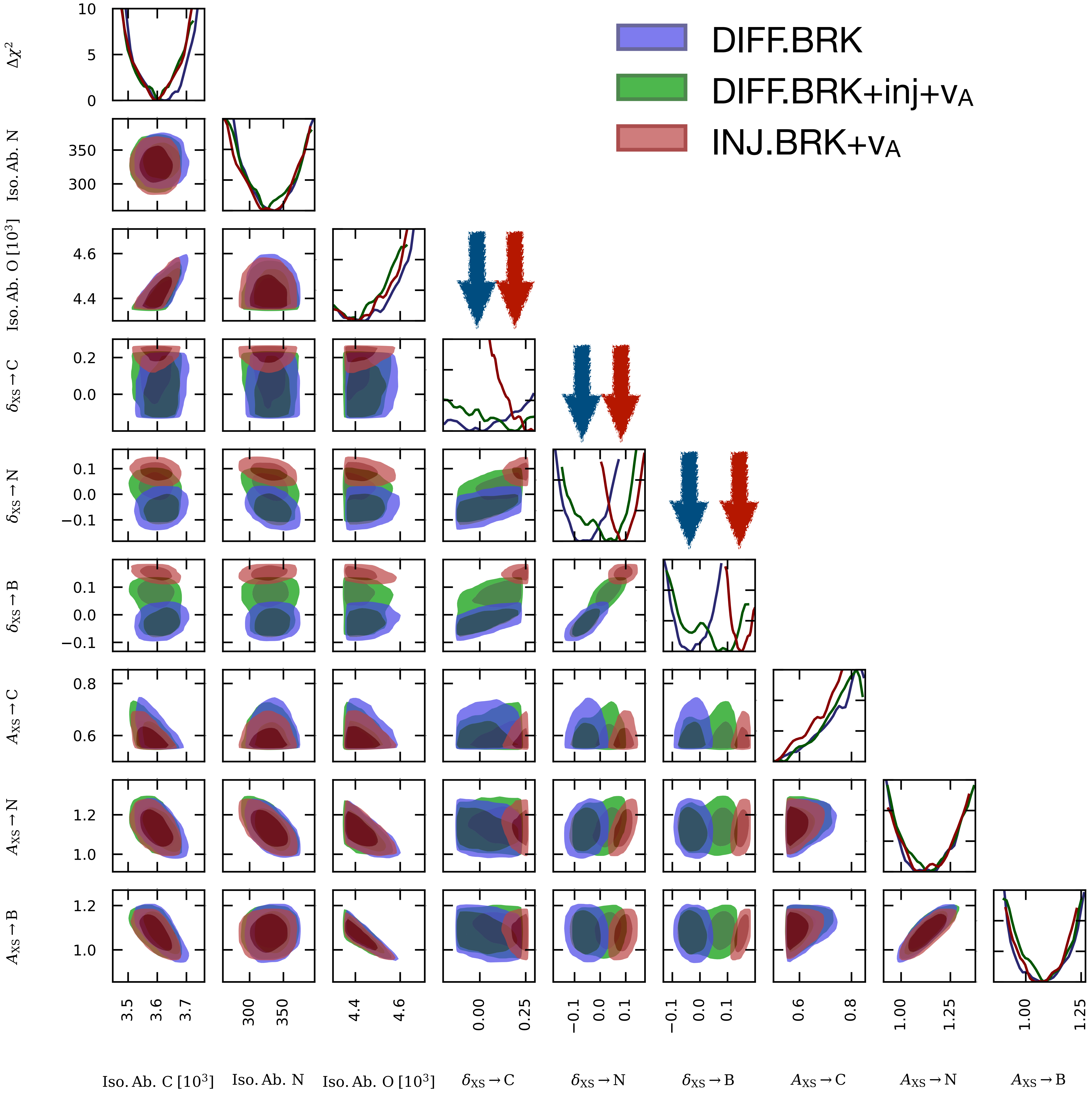


Different propagation setups provide a good fit.

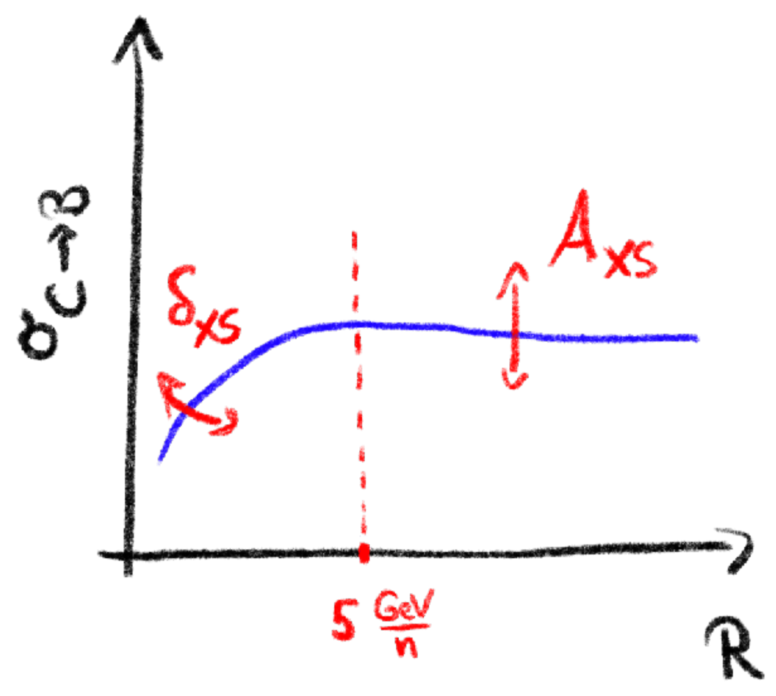
There is no statistically preferred setup.

[MK, Cuoco, 2021 a]

Cross-section nuisance parameters



[MK, Cuoco, 2021 a]



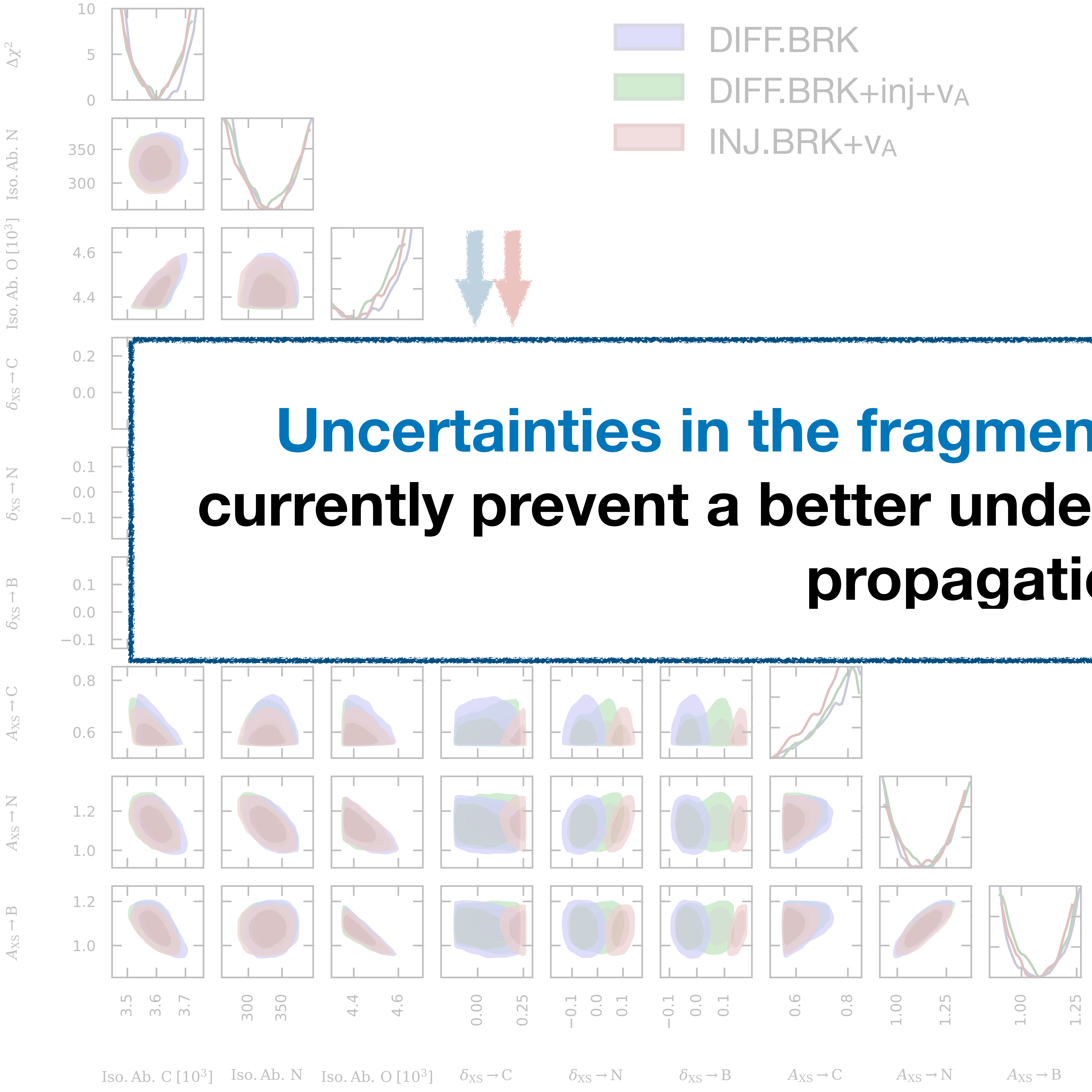
The default cross section parametrization is "GALPROP 12"

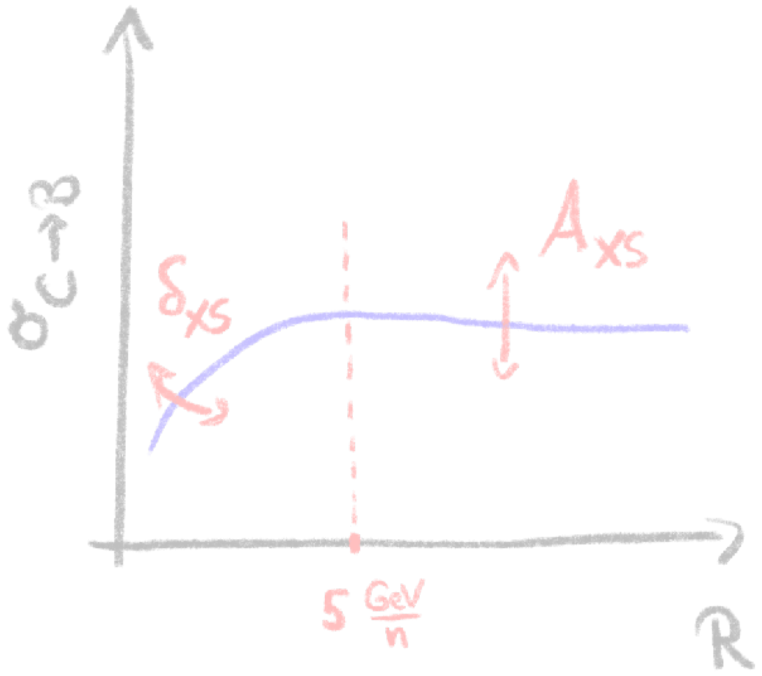
DIFF.BRK is compatible with the default cross section

INJ.BRK+vA converges at δ_{XS} ~0.1

Li cross section are increased by ~25% see also [Maurin+, 2022]

Cross-section nuisance parameters





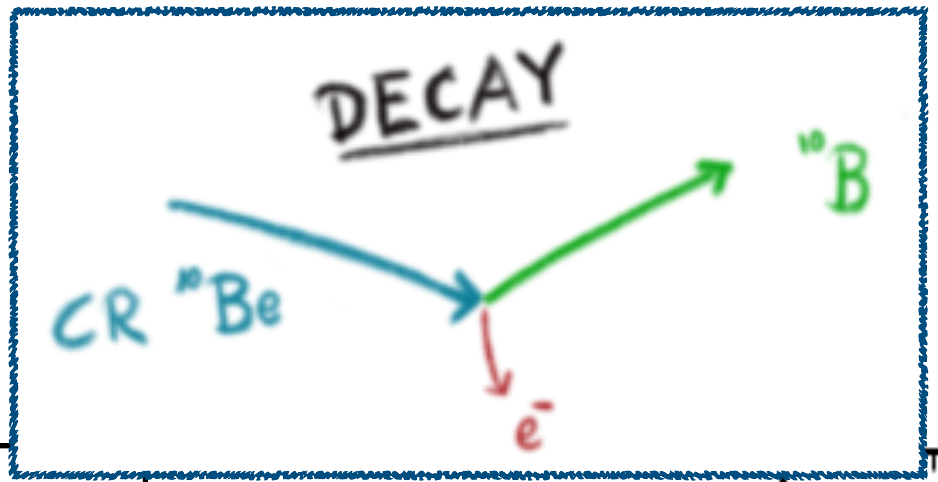
Uncertainties in the fragmentation cross sections currently prevent a better understanding of cosmic-ray propagation.

INJ.BRK+vA converges at δ_{XS} ~0.1

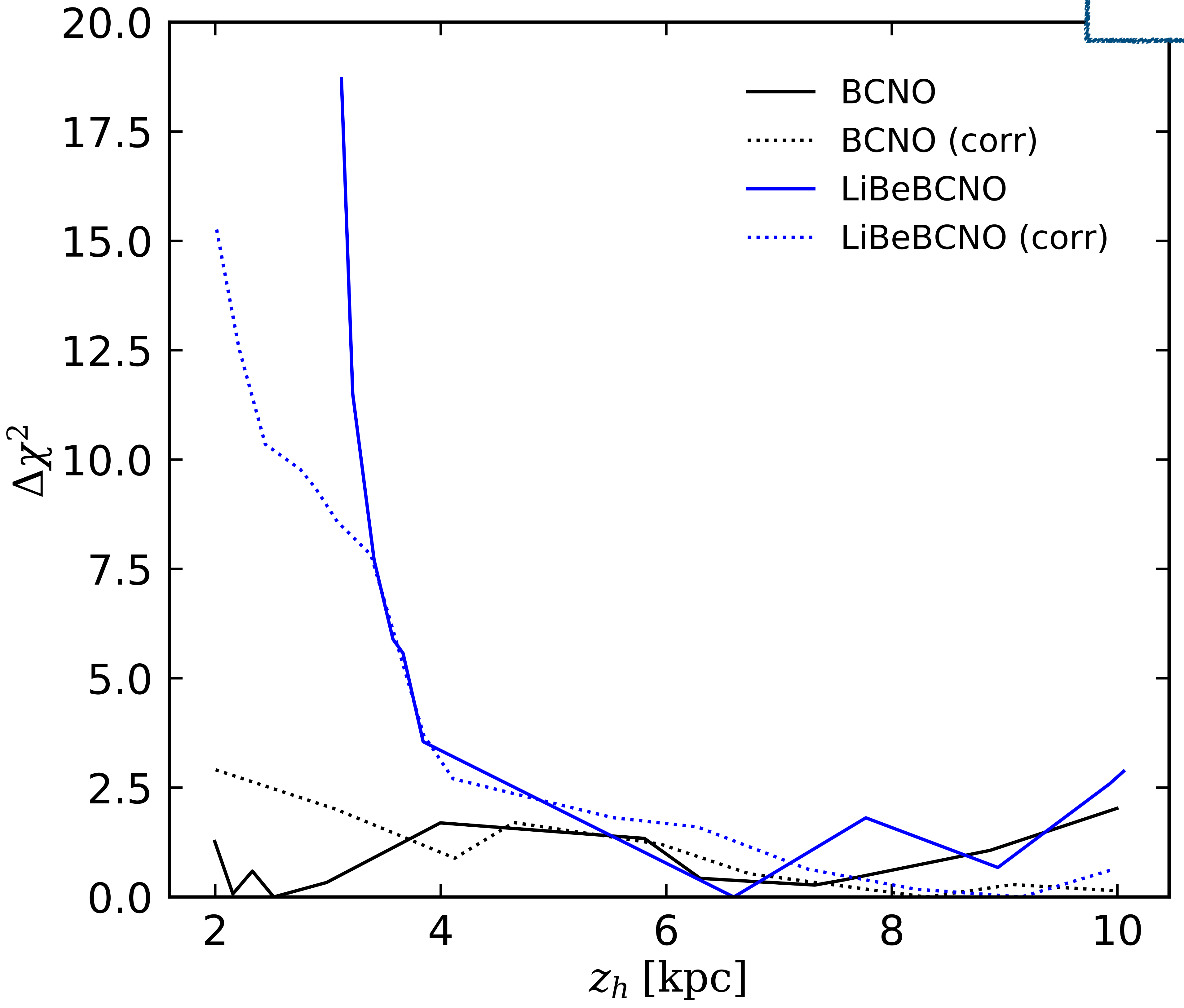
Li cross section are increased by ~25% see also [Maurin+, 2022]

[MK, Cuoco, 2021 a]

Constraints on the size of the diffusion halo



DIFF.BRK



[MK, Cuoco, 2021 a]

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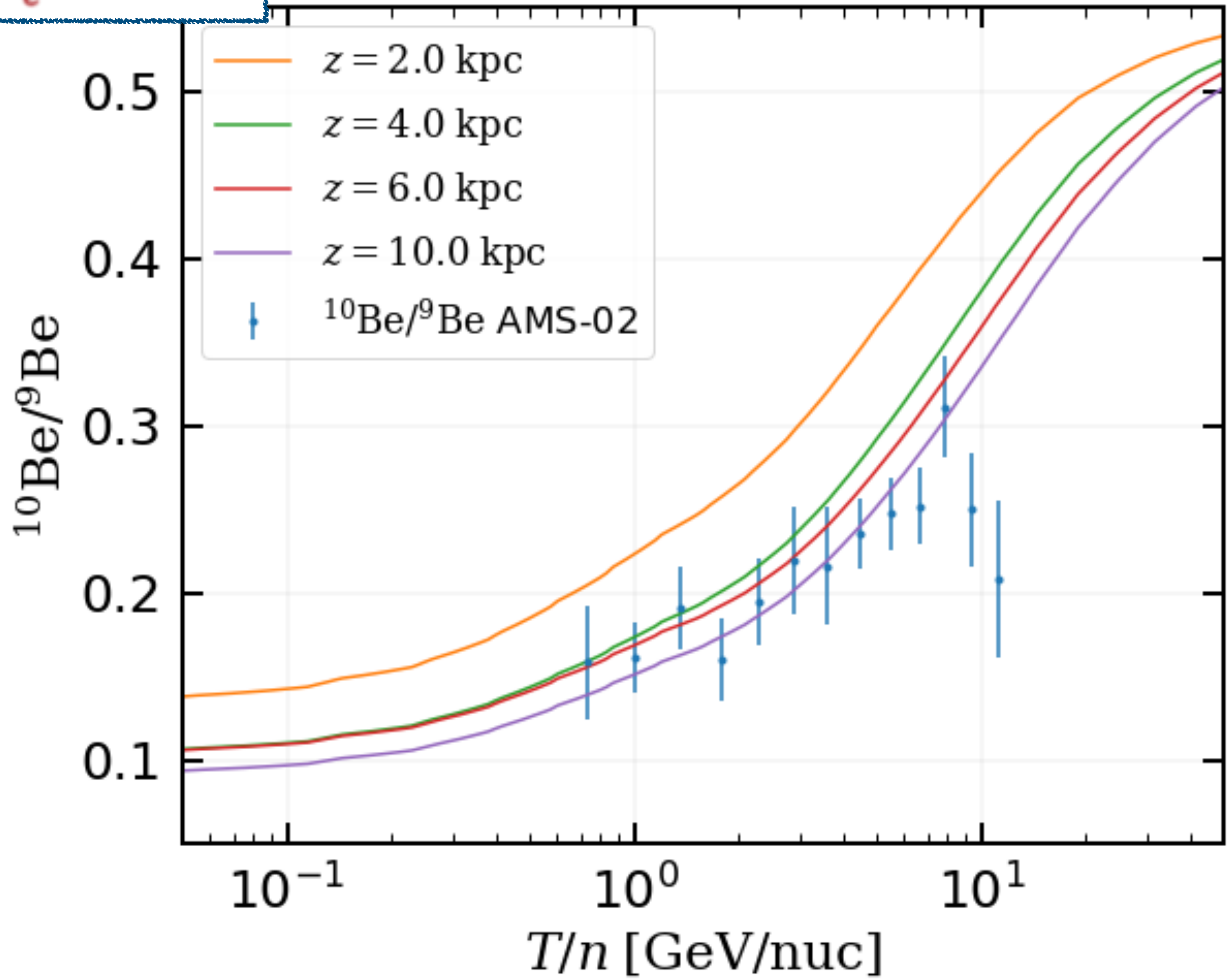

Preliminary AMS-02 data from [L.Derome; ICRC 2021]

The combination of B and Be data allows to constrain z_h

[see also talk by Jiahui Wei]

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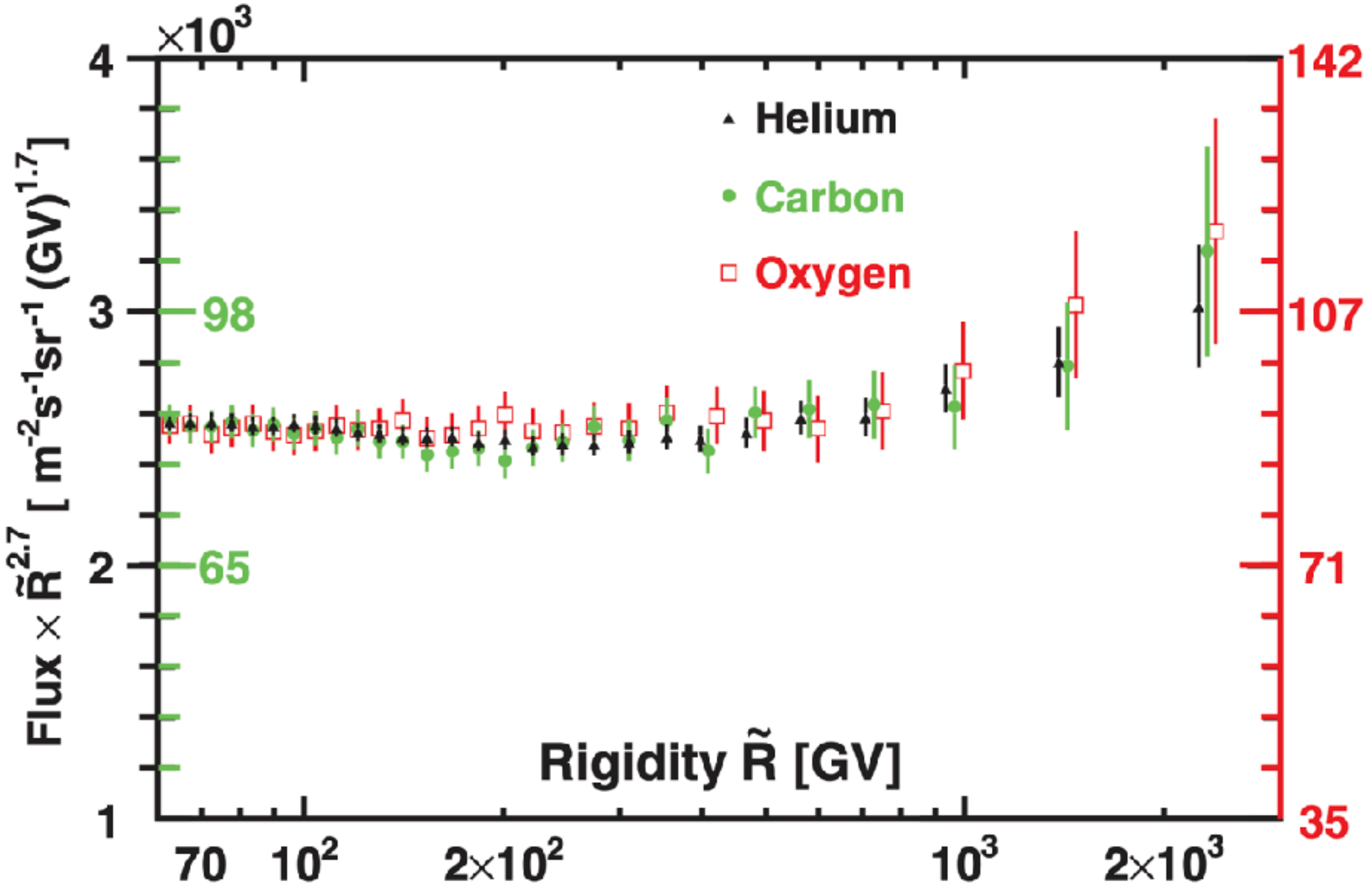
Motivation

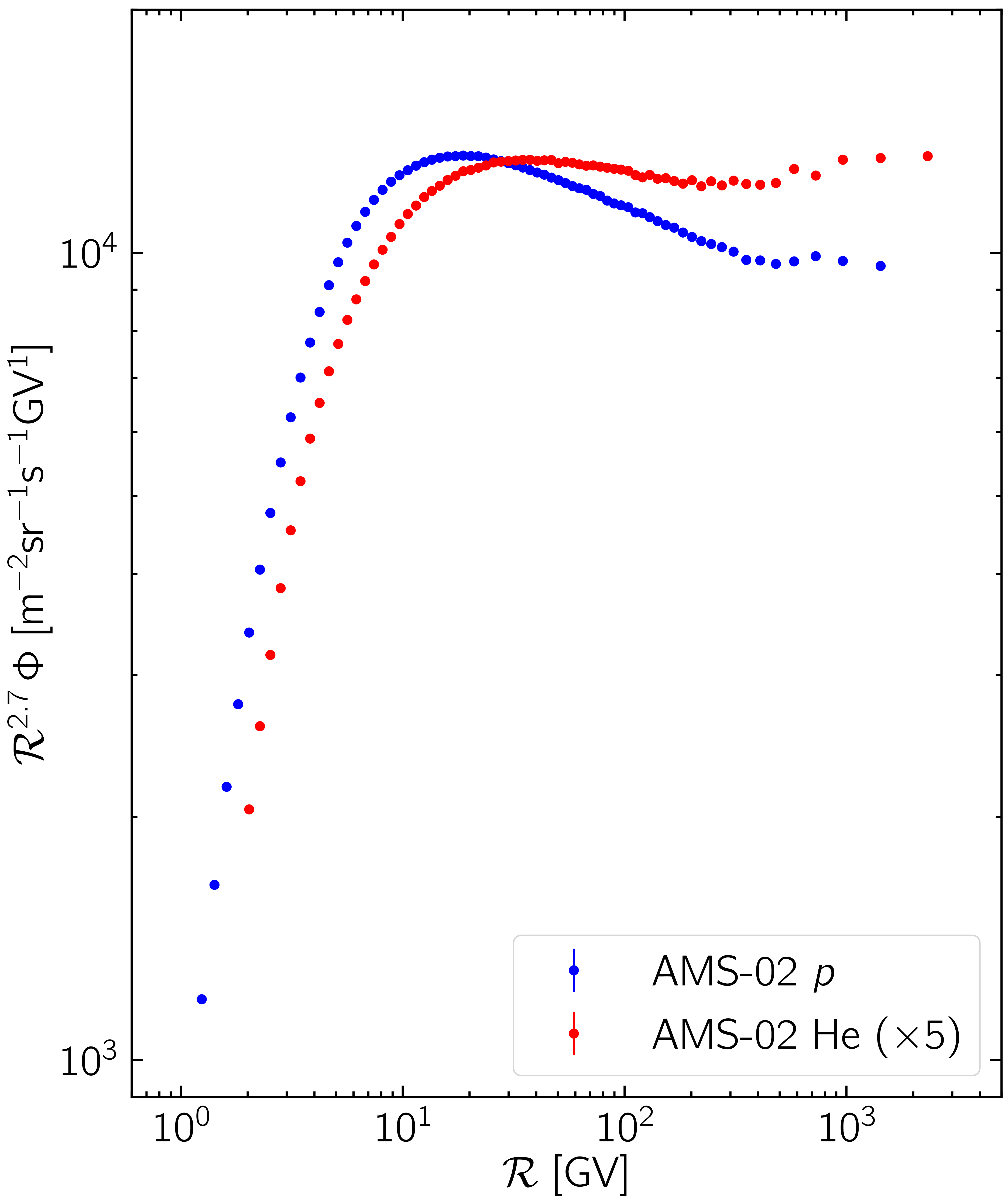
PRL **119,** 251101 (2017) PHYSICAL REVIEW LETTERS week ending 22 DECEMBER 2017

Observation of the Identical Rigidity Dependence of He, C, and O Cosmic Rays at High Rigidities by the Alpha Magnetic Spectrometer on the International Space Station



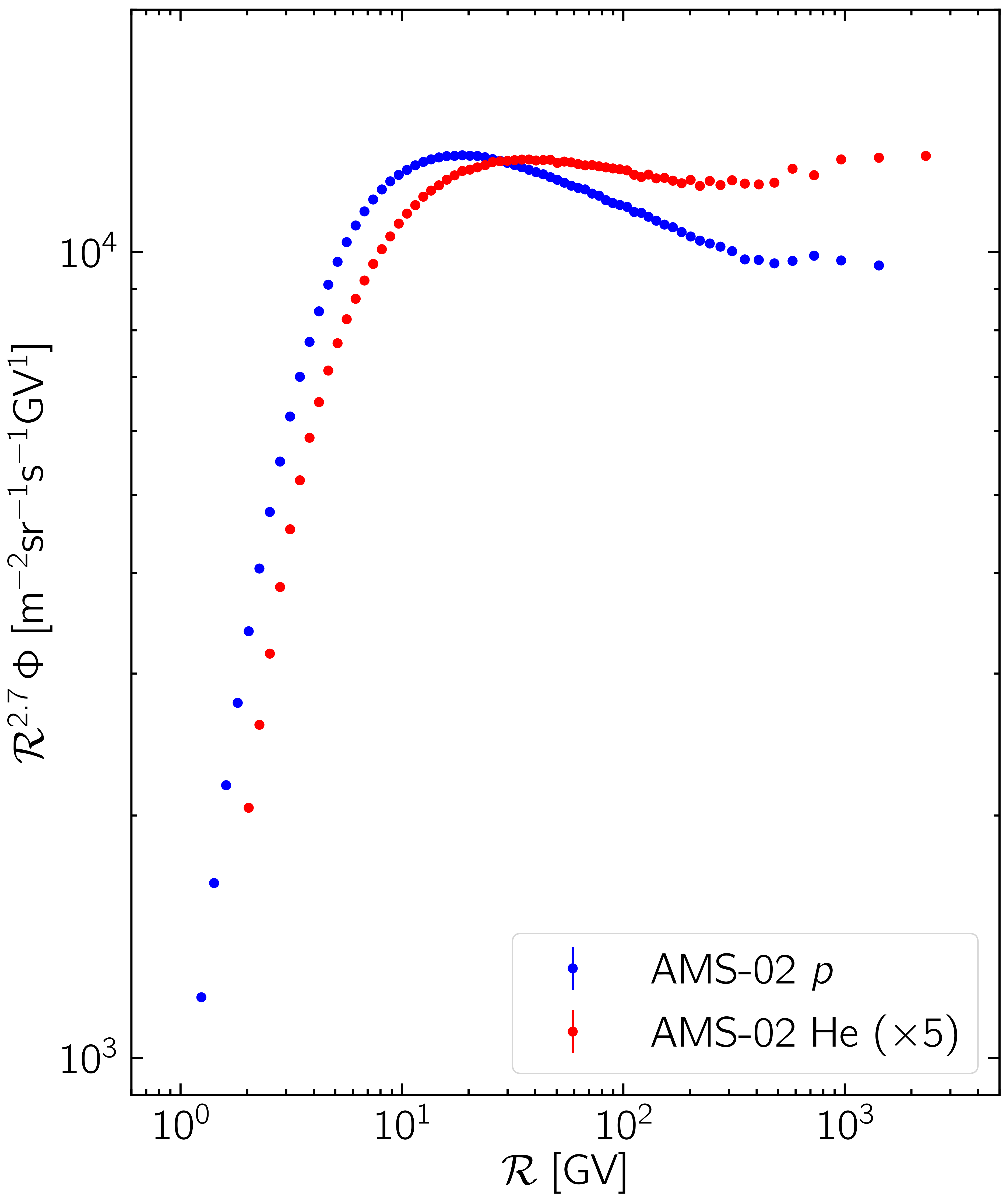
[see also talk by Yi Lia]

A separate issue: *p* and He slopes



We always allow for a different injection slope of protons and all other nuclei.

A separate issue: *p* and He slopes



We always allow for a different injection slope of protons and all other nuclei.

Suggested explanations:

- Different source populations (e.g. hydrogen rich local sources)
- Time-dependent shock evolution (can lead to Z/A dependence)
- CR spallation

Analysis strategy

- *Naive* **default** approach
- Source approach:
  free He inj
- Propagation approach
  (inhomogeneous diffusion):
  free $D_{0,light}$

Additional freedom breaks universality
between He, C and O

Analysis strategy

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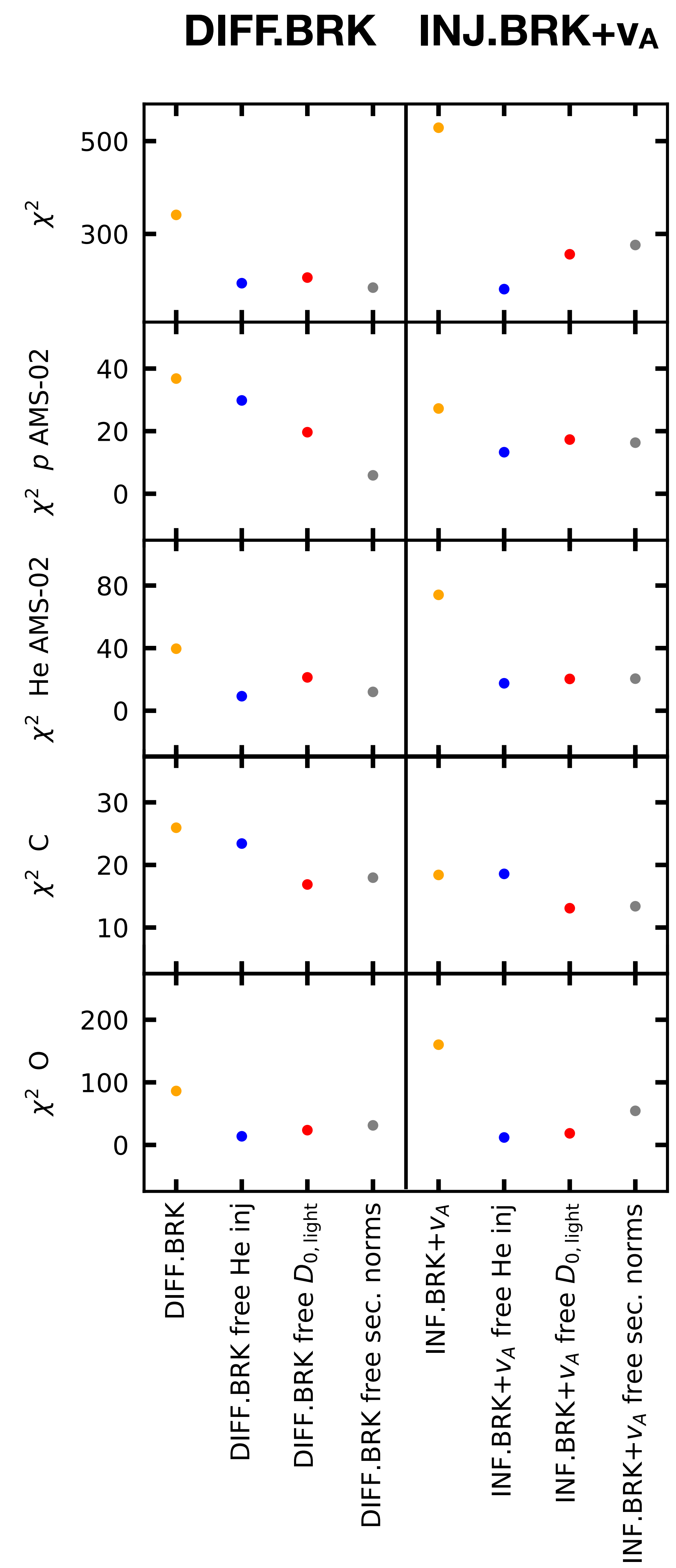
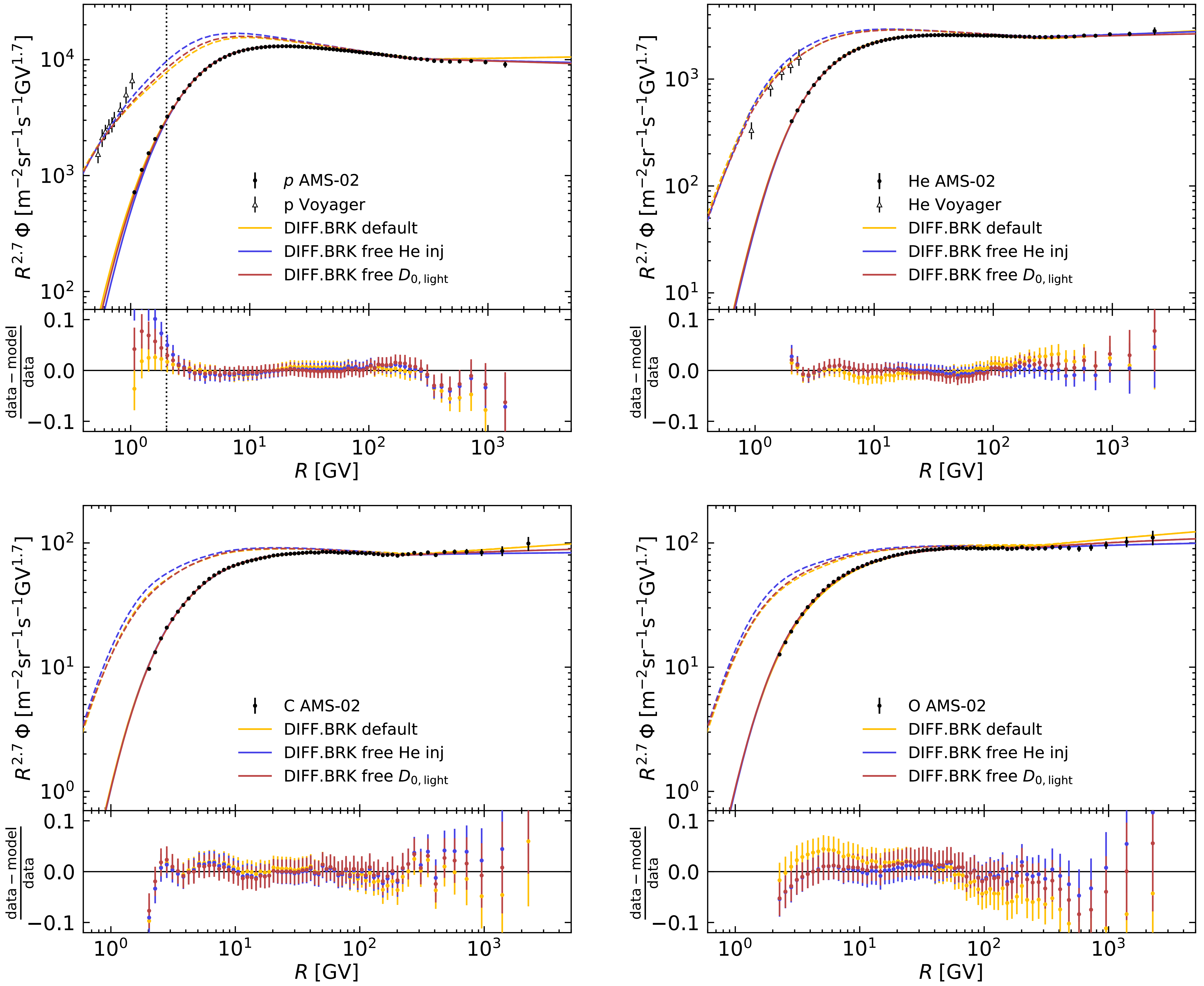


[MK, Cuoco, 2021 b]

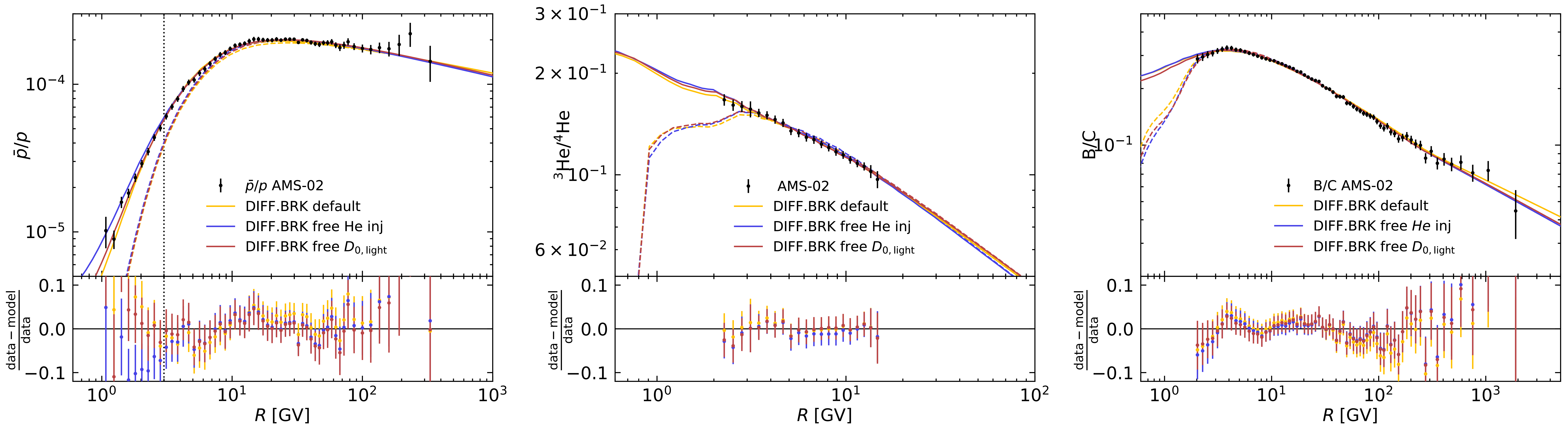
CR primary spectra - DIFF.BRK



[MK, Cuoco, 2021 b]

In the default setup the oxygen flux is not well fitted!

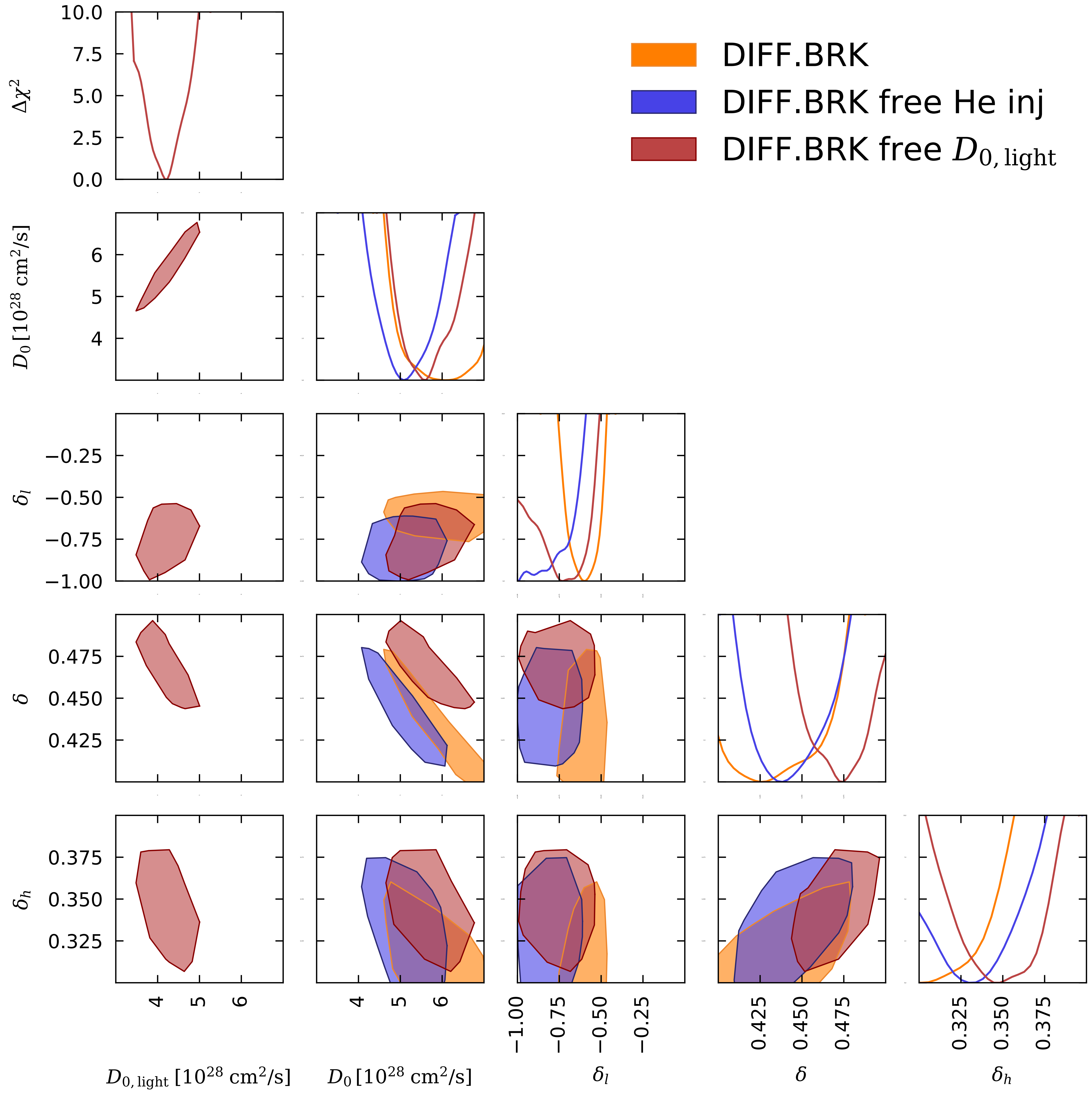
CR secondary spectra - DIFF.BRK

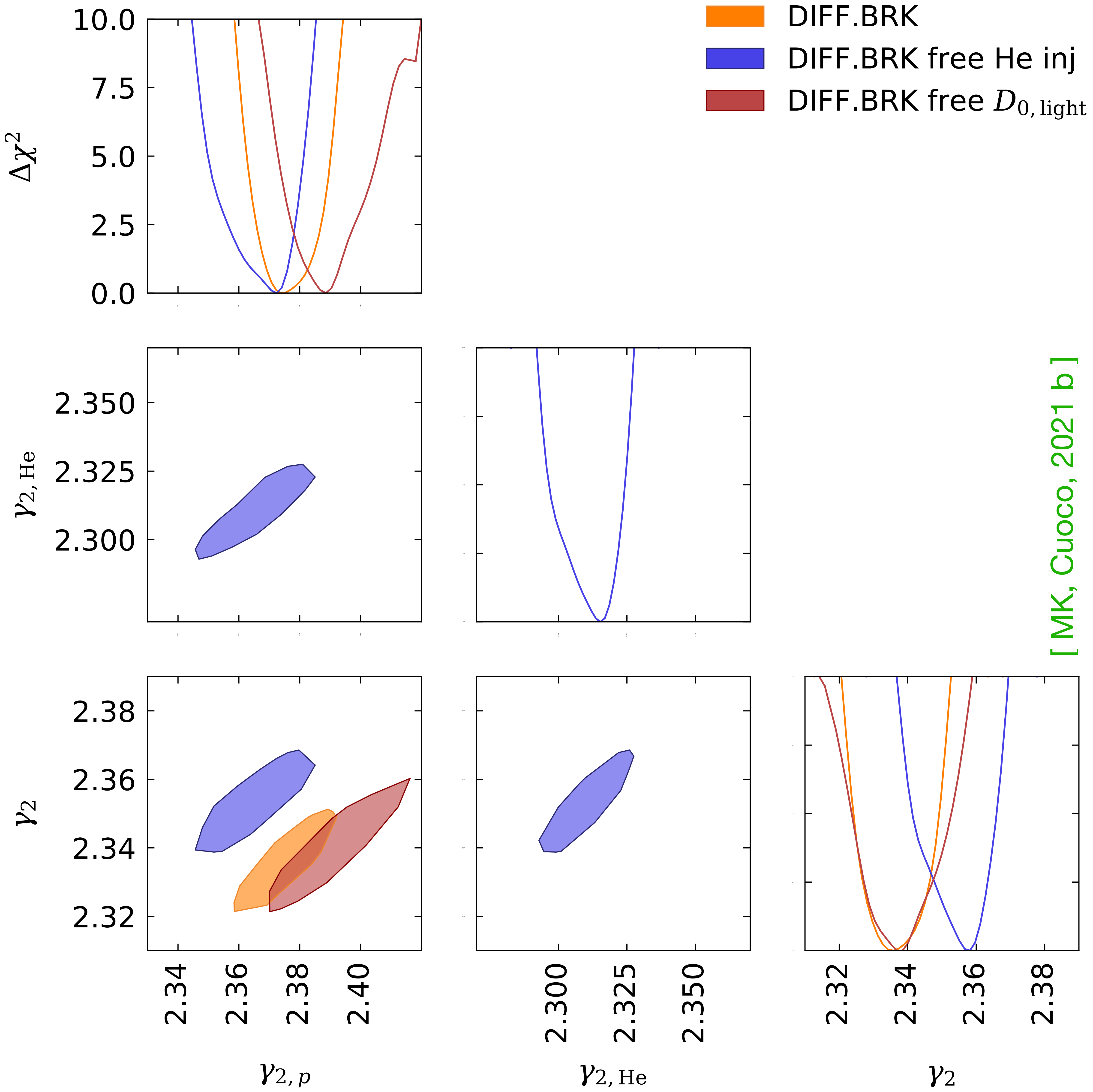


[MK, Cuoco, 2021 b]

Secondary spectra are consistent!

Results - DIFF.BRK setup





[MK, Cuoco, 2021 b]

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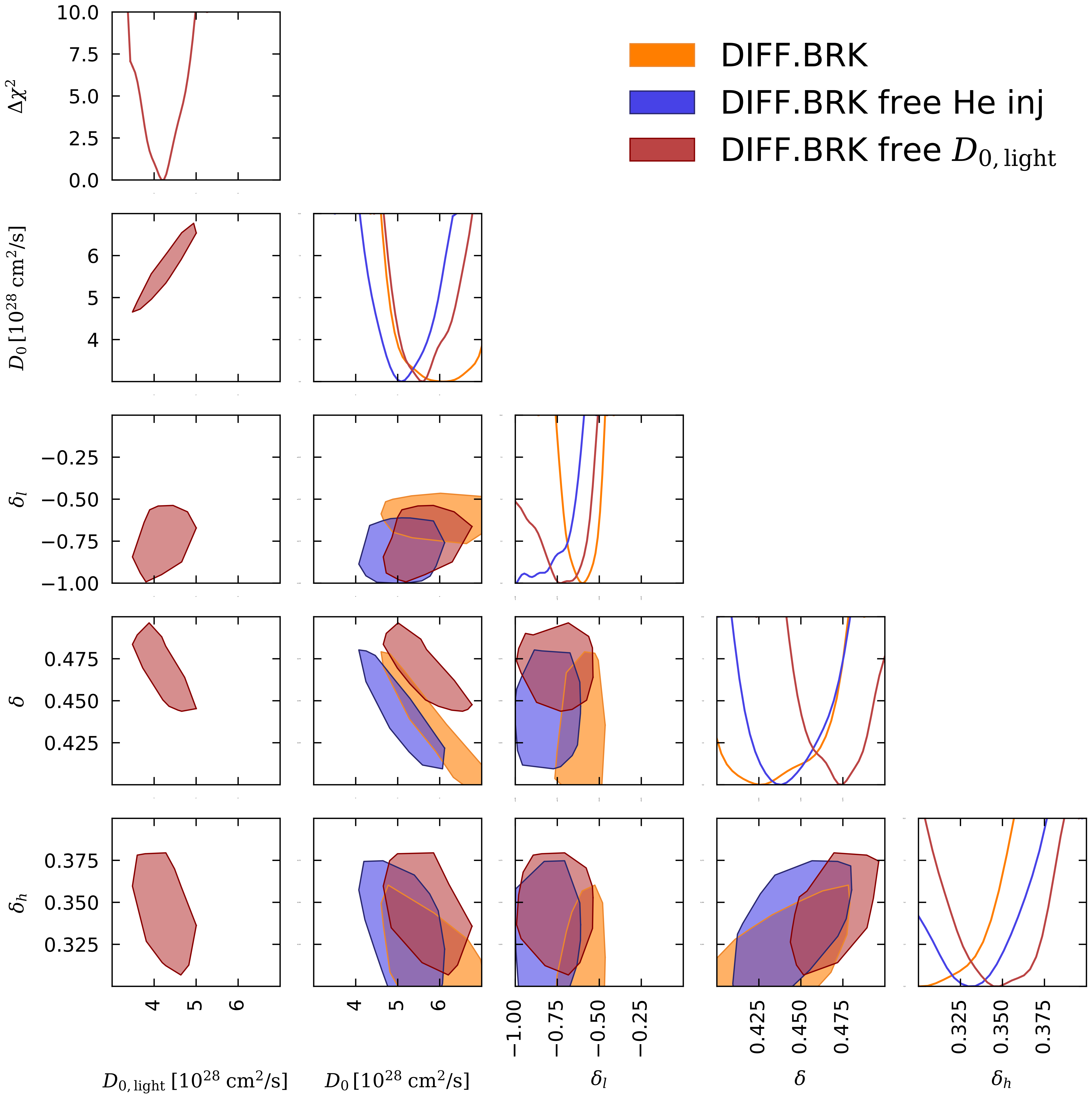

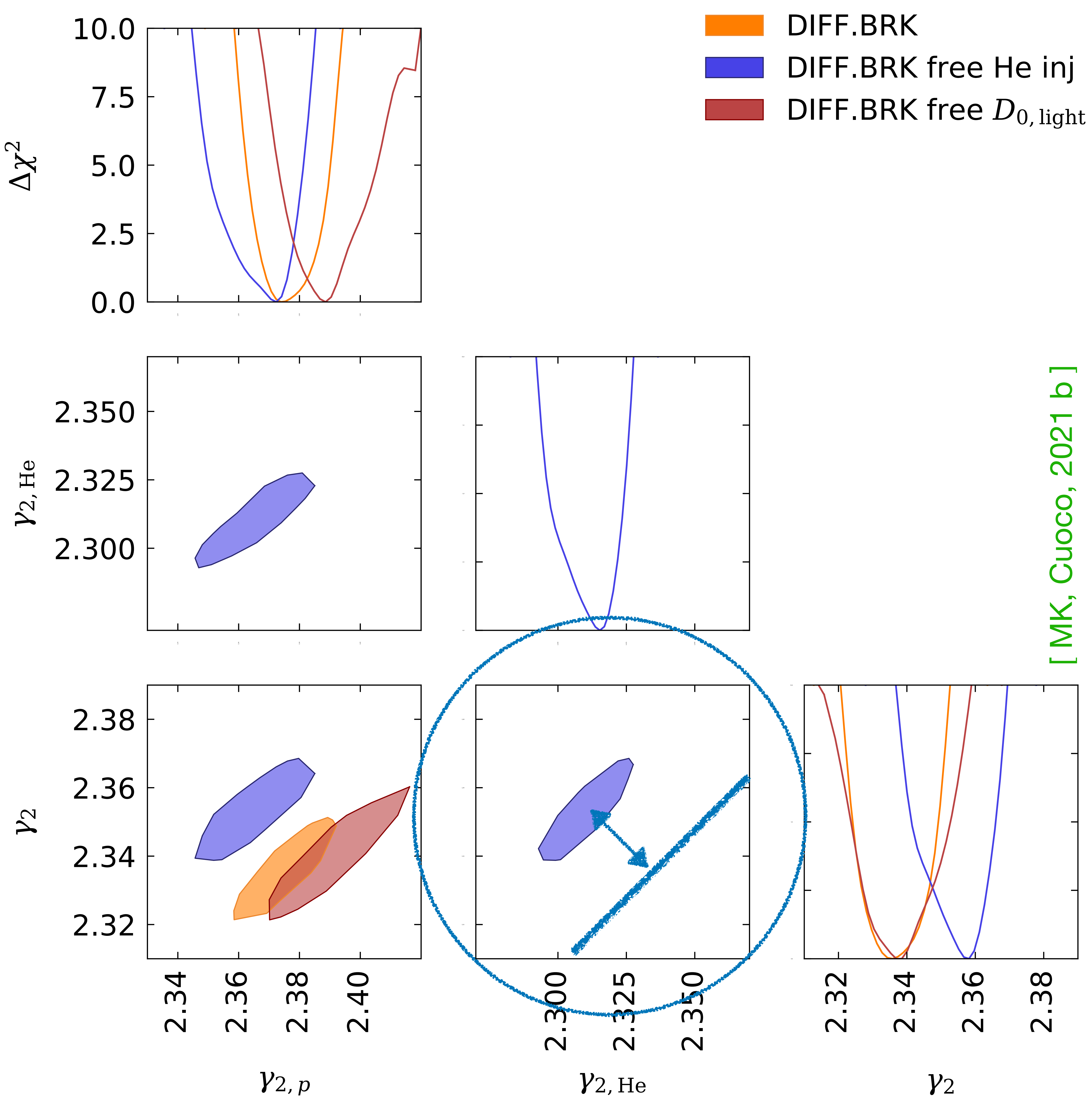

[MK, Cuoco, 2021 b]

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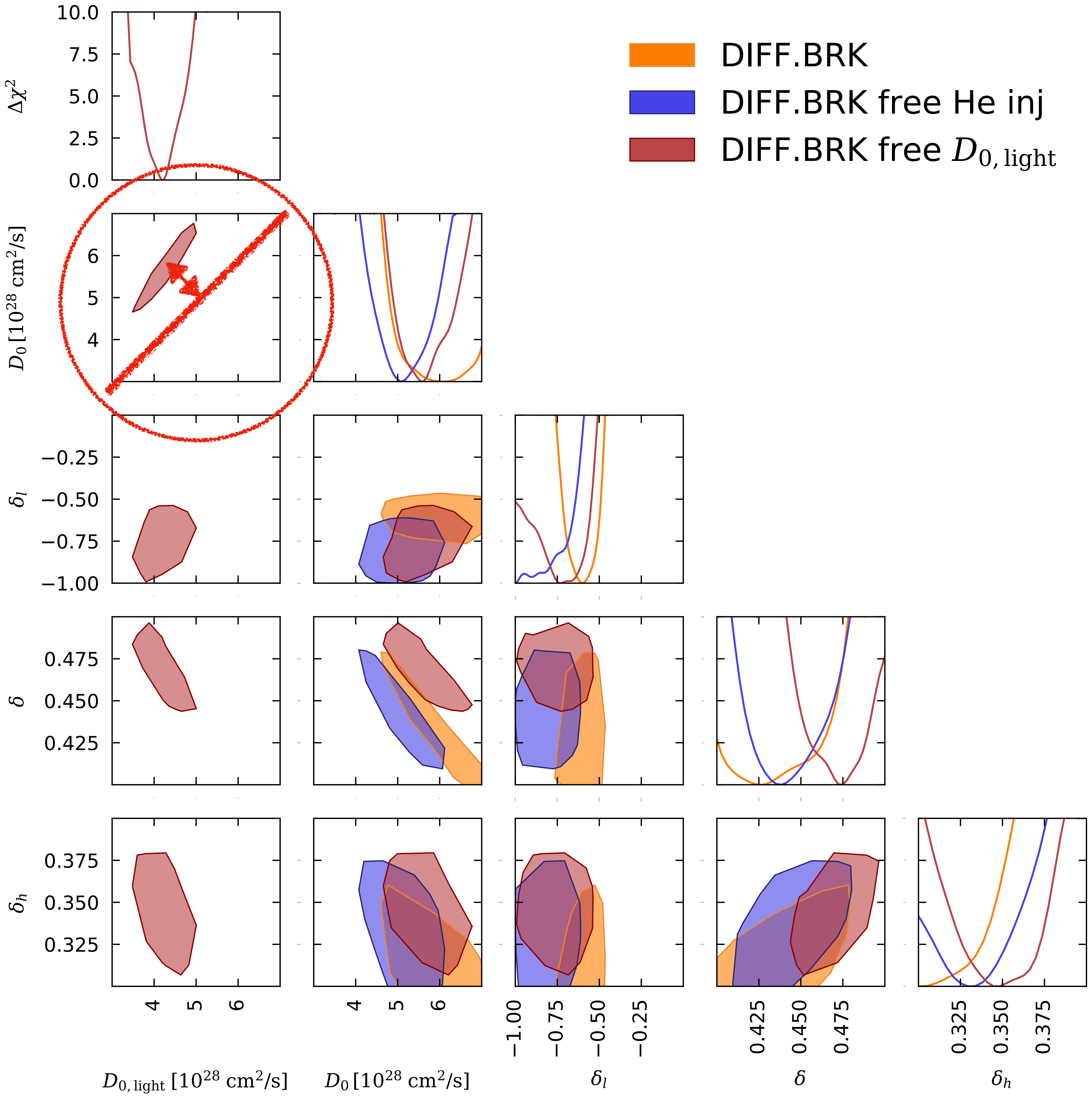

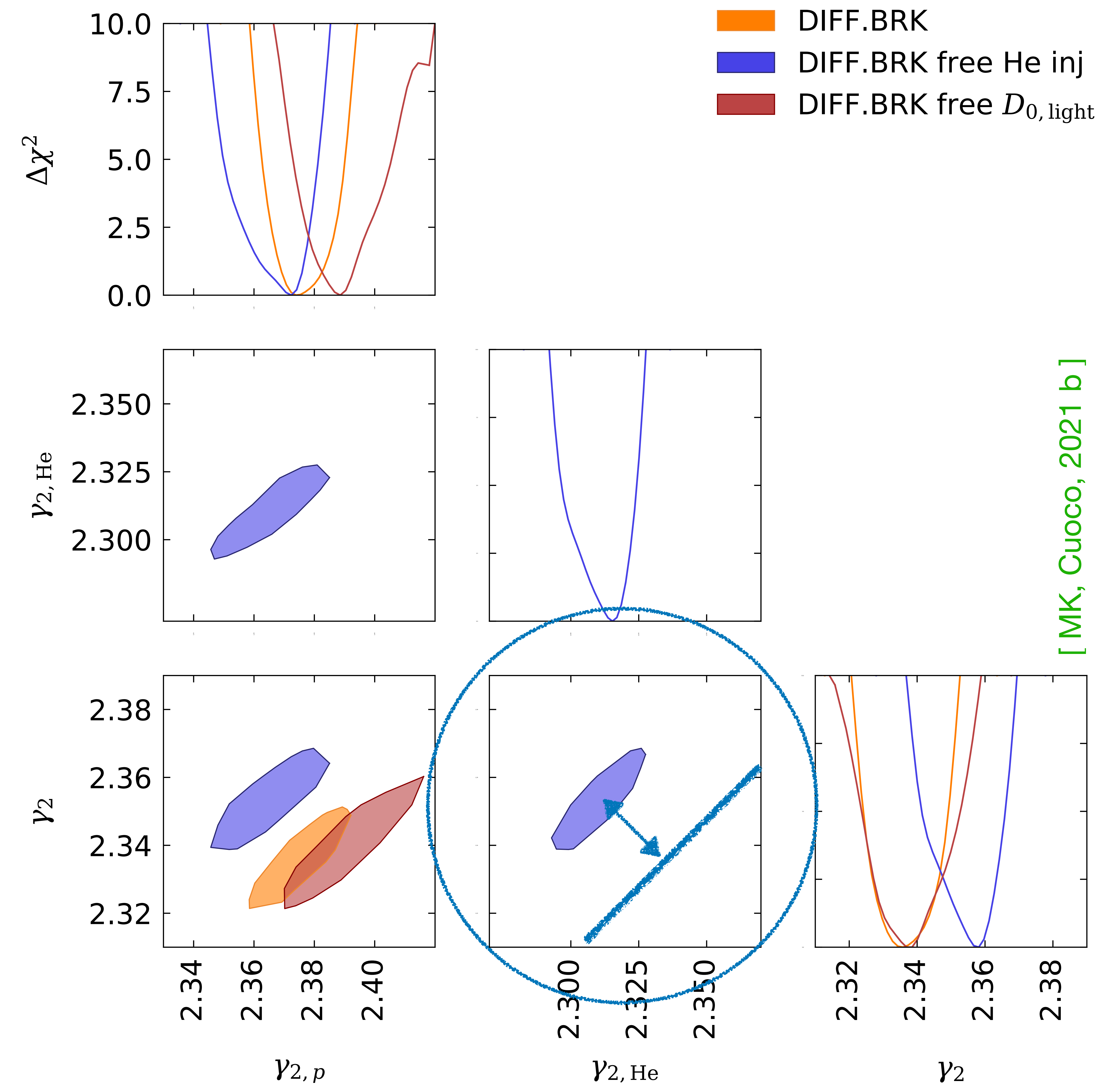

[MK, Cuoco, 2021 b]

Take-home message

Propagation effects (spallation, energy losses, and contributions from secondary components) are different for helium, carbon and oxygen.

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Propagation effects (spallation, energy losses, and contributions from secondary components) are different for helium, carbon and oxygen.

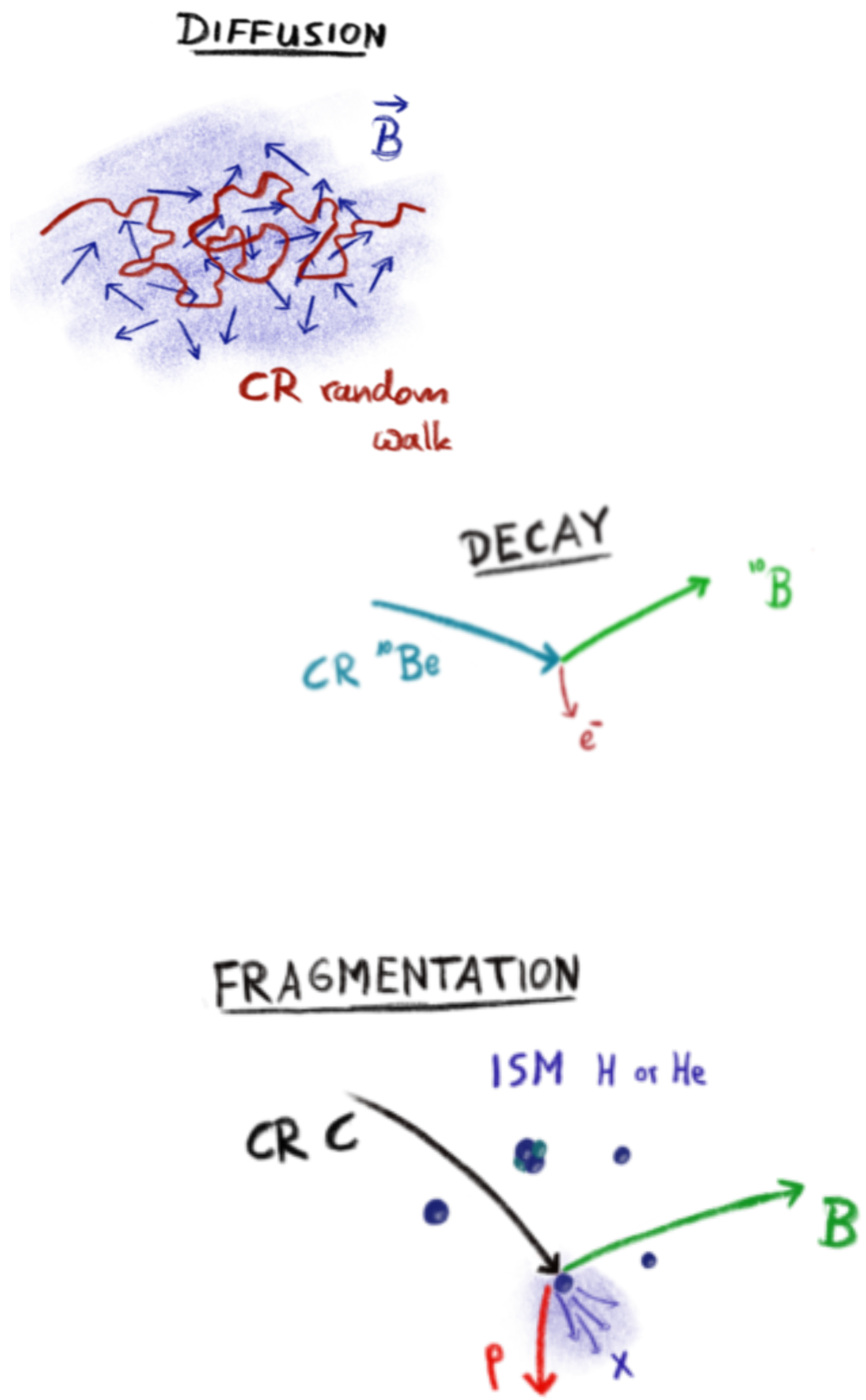
↓

In order to measure the same spectral slope at the level of the fluxes, the injection slopes have to be different!

Secondary CR nuclei are consistent with the traditional CR diffusion models

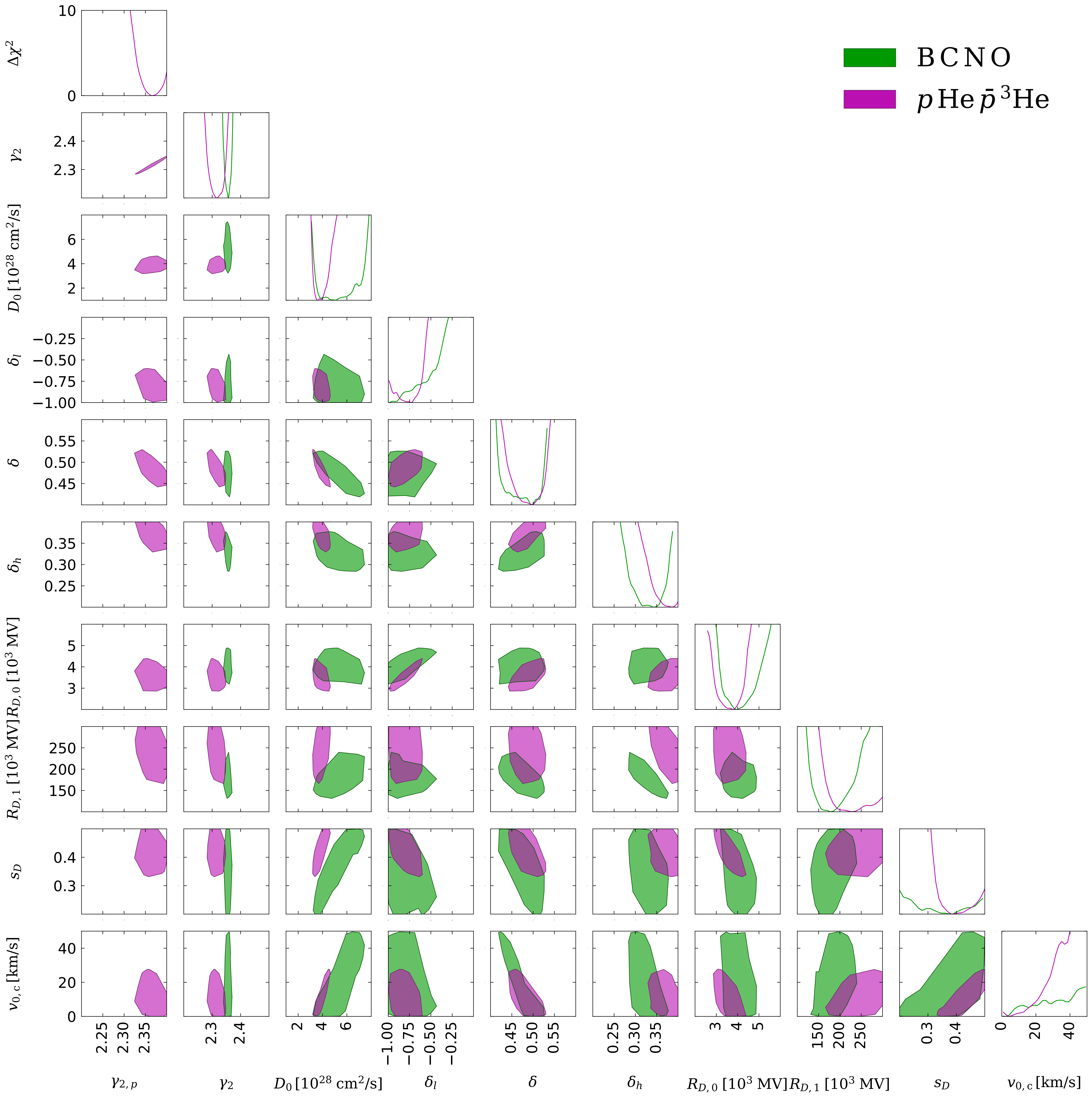
Combination of nuclei from *p* to O reveal a violation of universality
Option 1: Different injection slopes for He and C, O
Option 2: Inhomogeneous diffusion

Small halo heights of $z_\mathrm{h} < 3\ \mathrm{kpc}$ are disfavored and the diffusion coefficient is well constrained above 10 GeV



Thank you for your attention!

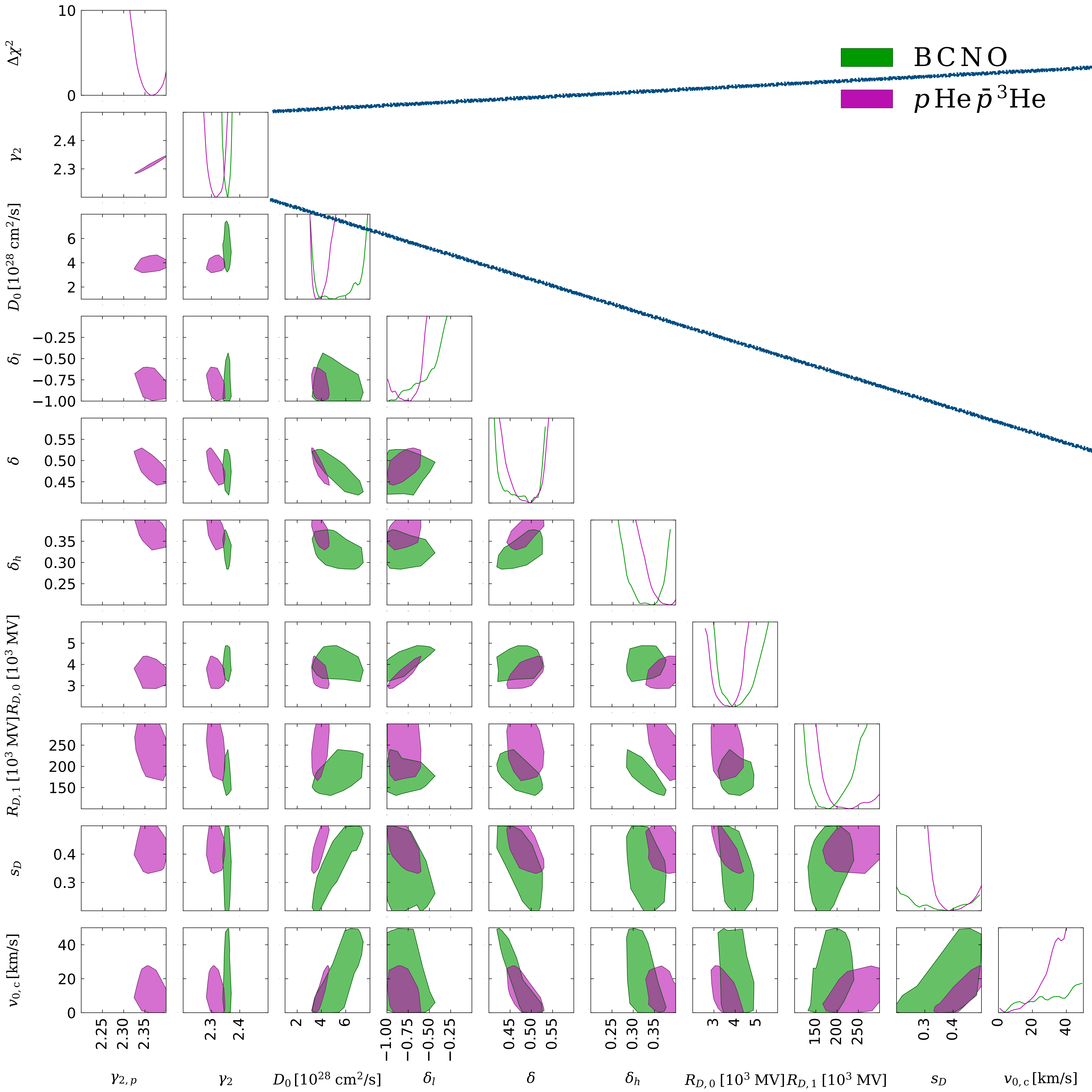
Light vs. heavier cosmic rays



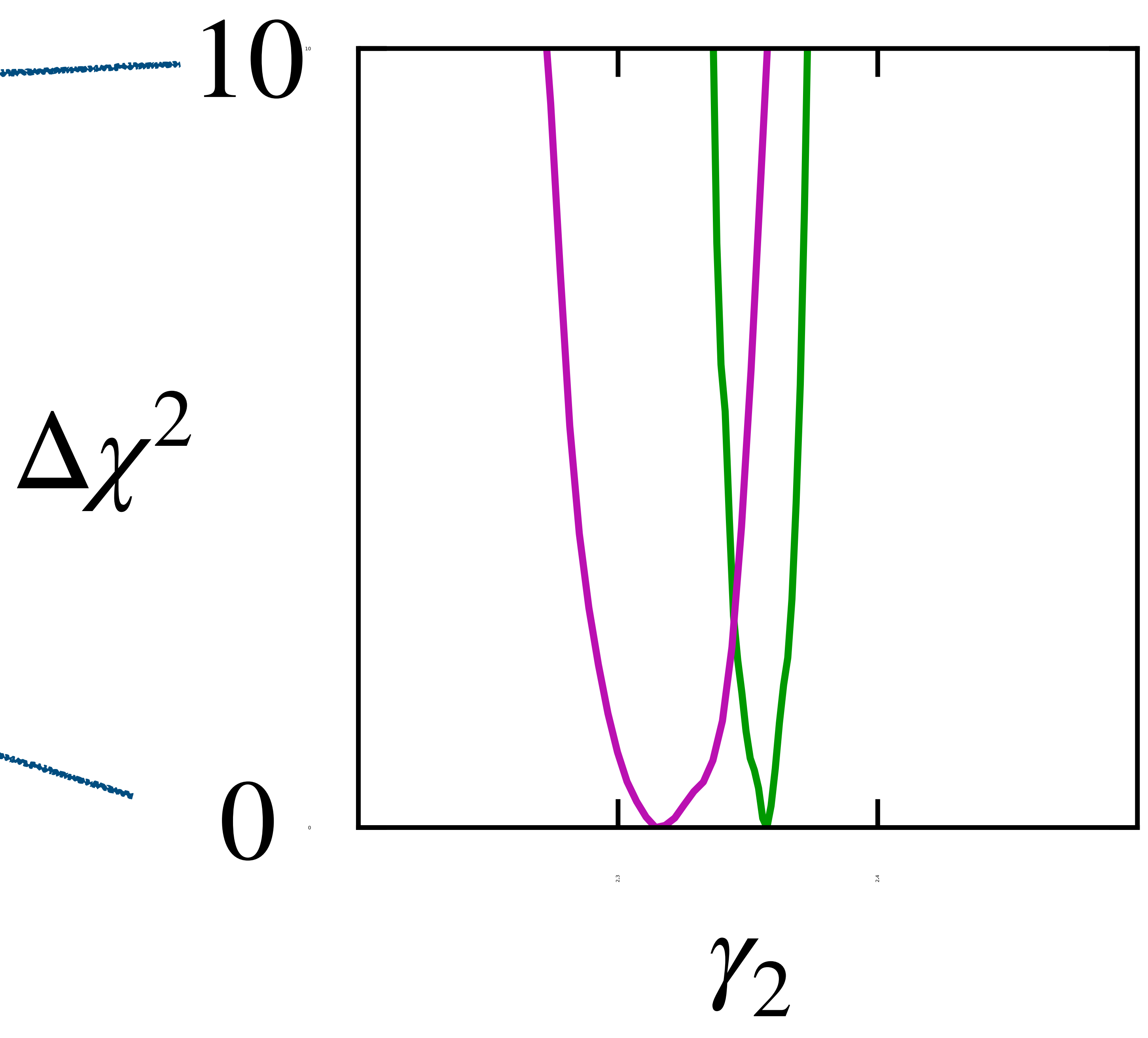
[MK, Cuoco, 2021 b]

see also [Johannesson+, 2016]

Light vs. heavier cosmic rays



[MK, Cuoco, 2021 b]



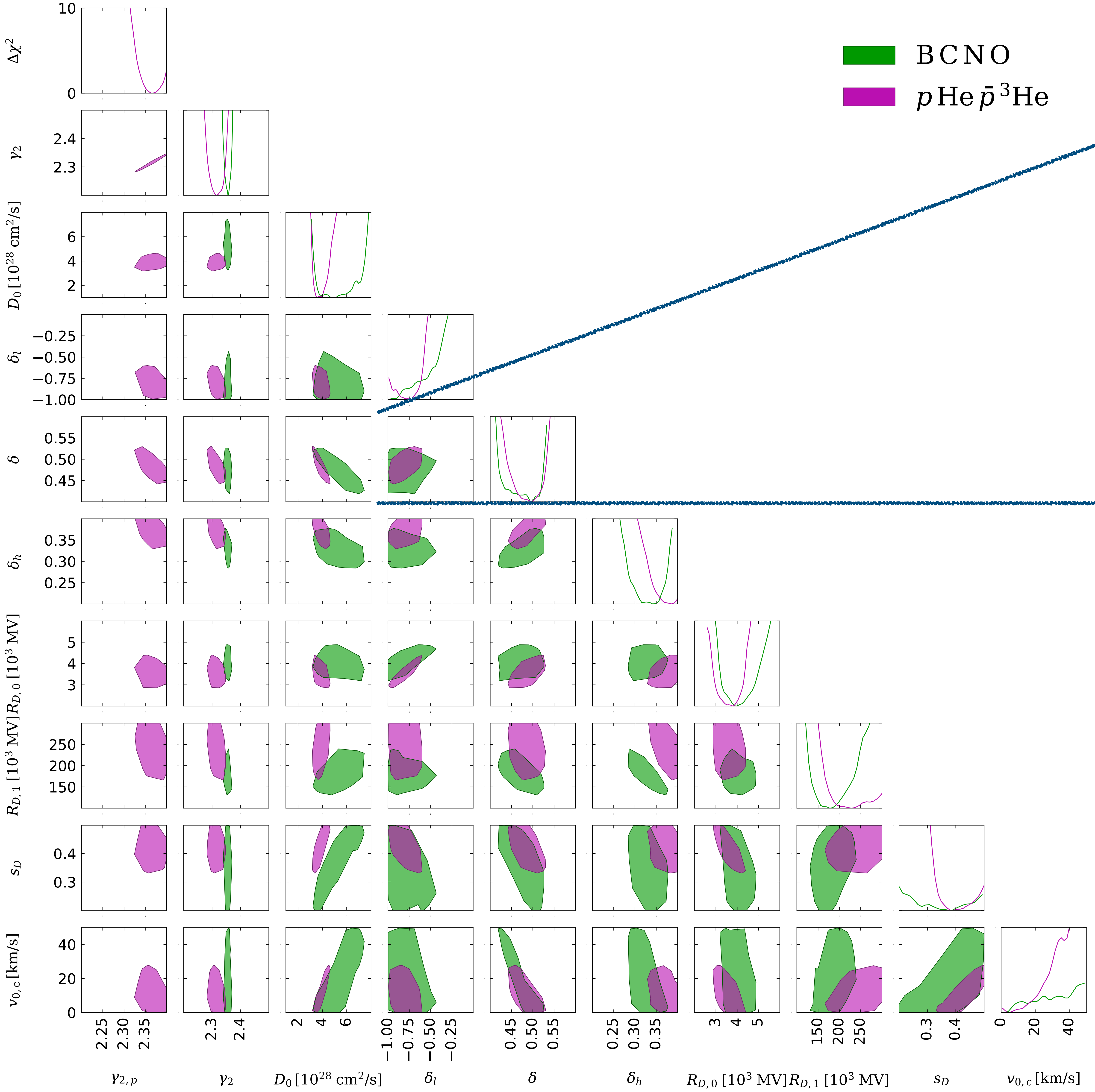
Light nuclei:
p He $\bar{p}$ ^{3}He

Heavier nuclei:
B C N O

Obvious tension for the injections slopes

see also [Johannesson+, 2016]

Light vs. heavier cosmic rays



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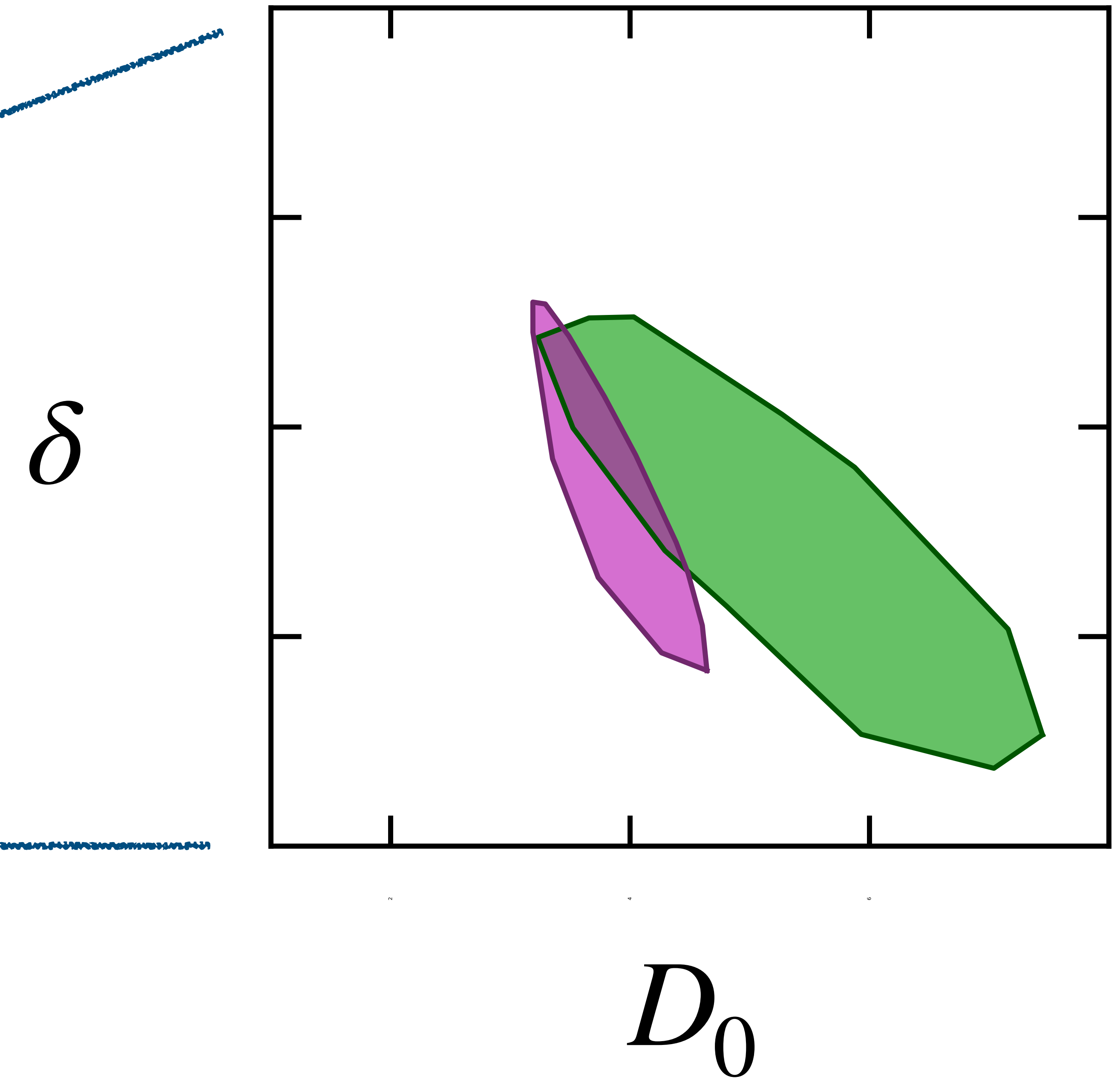


Light nuclei:
p He $\bar{p}$ ^{3}He

Heavier nuclei:
B C N O

Obvious tension for the injections slopes

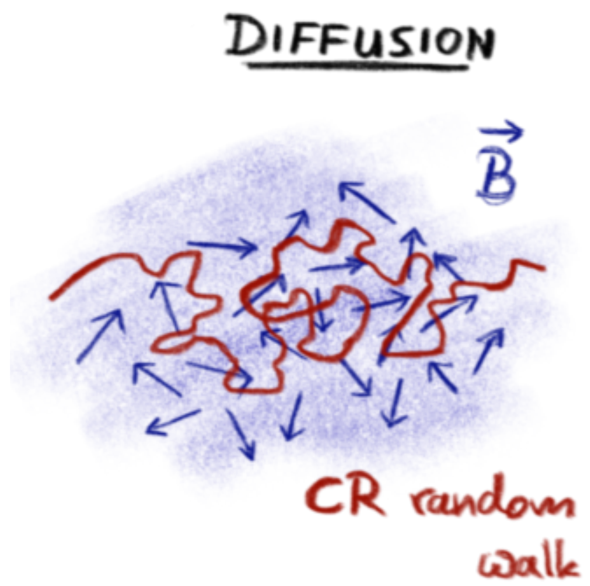
Smaller tension for the normalization of D_0

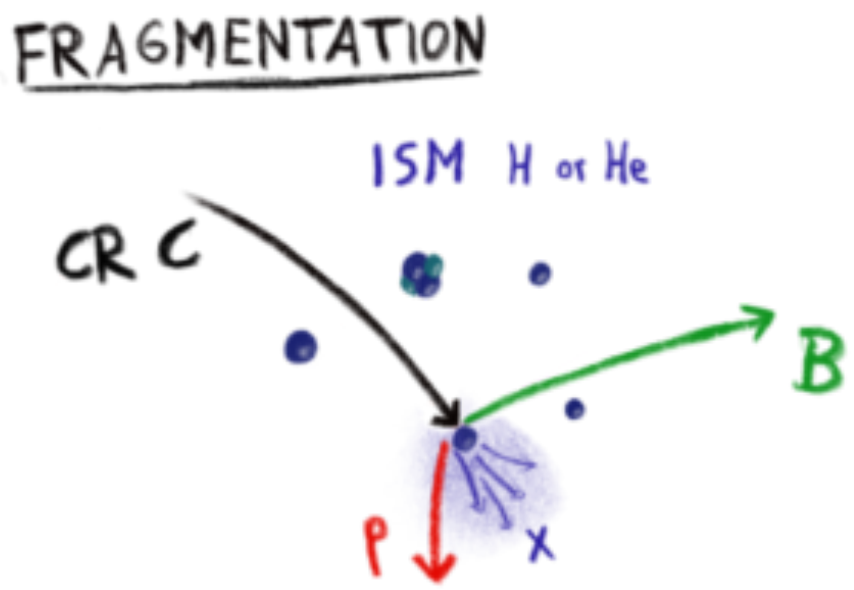
see also [Johannesson+, 2016]

Further scenarios

We found that the following scenarios do not allow to restore universality:

- Free secondary normalizations
- Free inelastic cross sections
- Free gas density





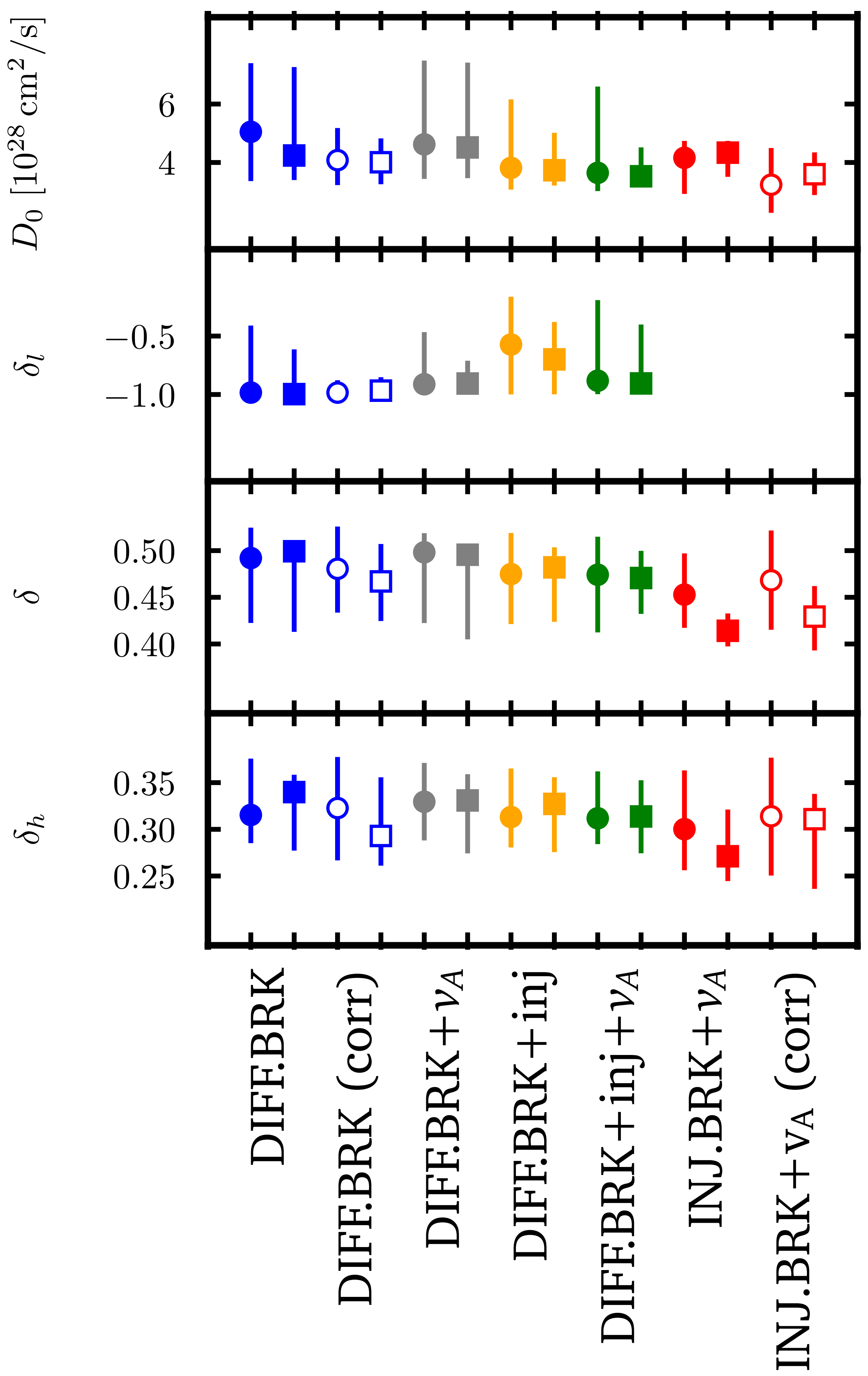
CR propagation models

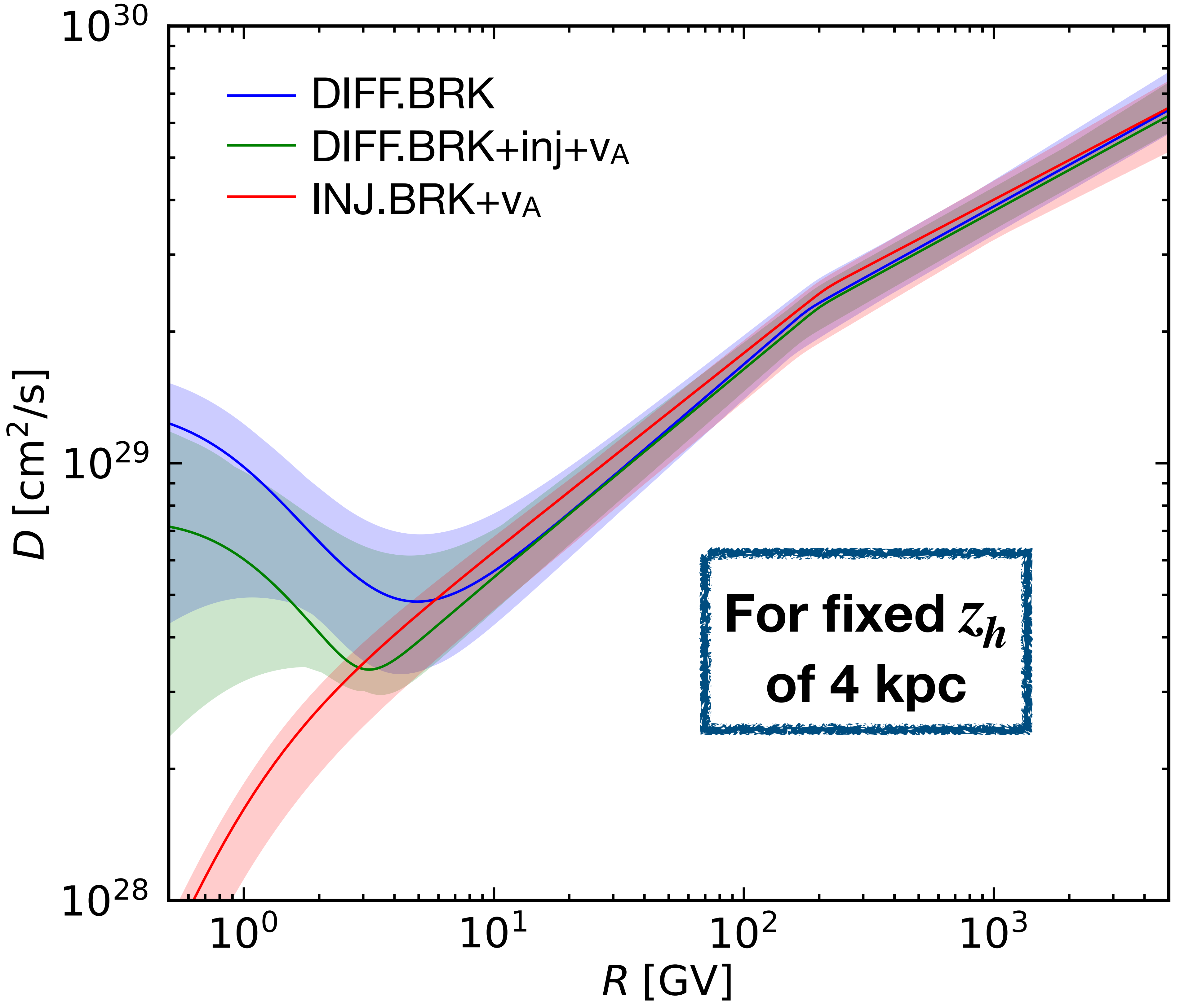
THIS WORK GALPROP	DIFF.BRK	INJ.BRK+vA
analytic [Evoli+; 2019] [Schroer+; 2021]	●	
USINE (semi-analytic) [Génolini+; 2019] [Weinrich+; 2020] [Maurin+; 2022] [Vecchi+; 2022]	~SLIM	~QUAINT
DRAGON [De la Torre Luque+; 2021] [De la Torre Luque+; 2022]		●
GALPROP [Boschini+;2018] [Boschini+;2019] [Boschini+;2020] [Boschini+;2022]		●

Comparison with other works

THIS WORK GALPROP	Universality between He and C, O is broken
[Evoli+; 2019] [Schroer+; 2021]	Focus on CRs above 10 GV
[Génolini+; 2019] [Weinrich+; 2020] [Maurin+; 2022] [Vecchi+; 2022]	Focus on CR secondaries Hint for different injection
[De la Torre Luque+; 2021] [De la Torre Luque+; 2022]	Focus on CR secondaries Hint for different injection
[Boschini+;2018] [Boschini+;2019] [Boschini+;2020] [Boschini+;2022]	Enormous freedom for CR primaries.

Parameter constraints



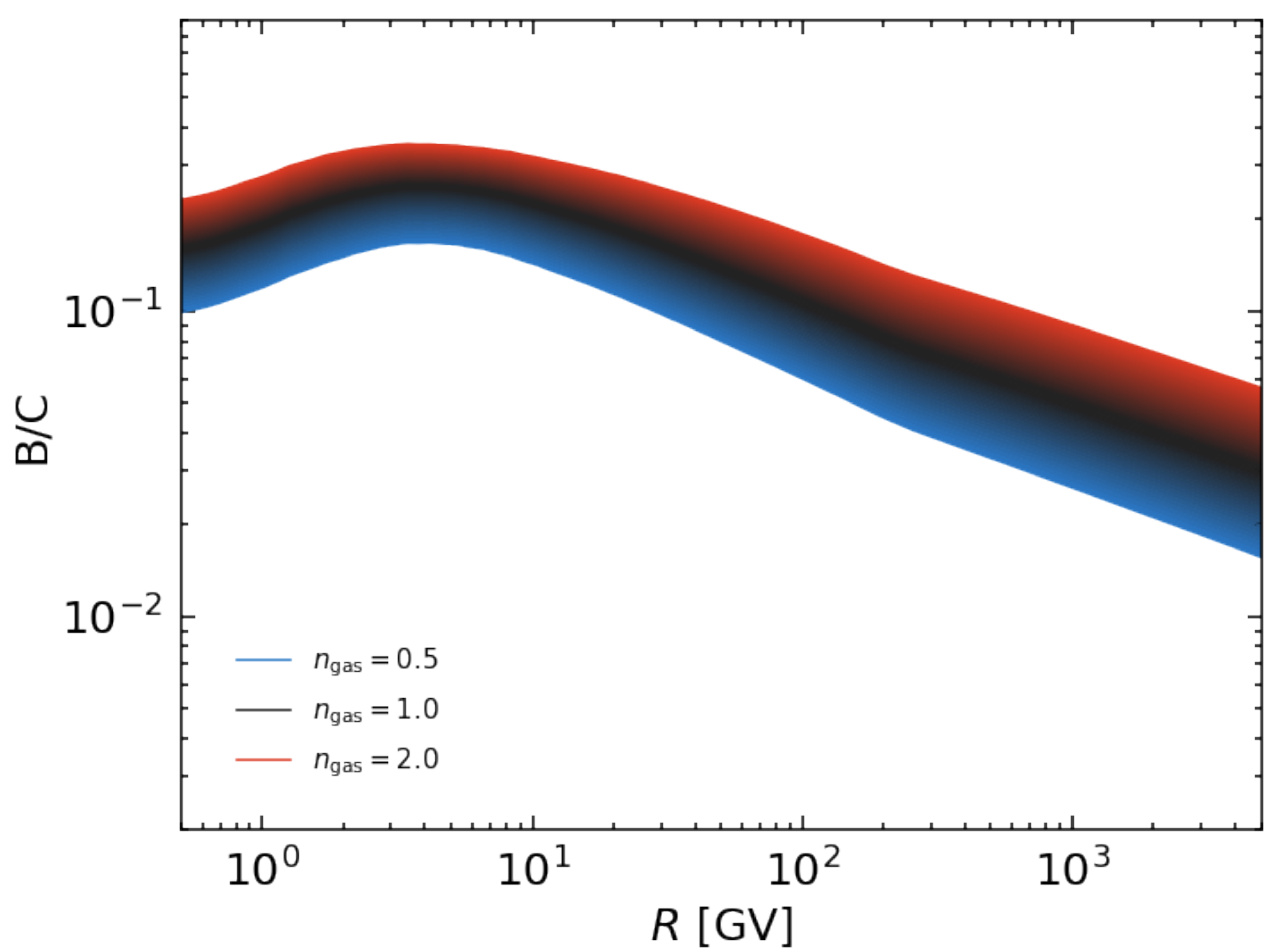


[MK, Cuoco, 2021 a]

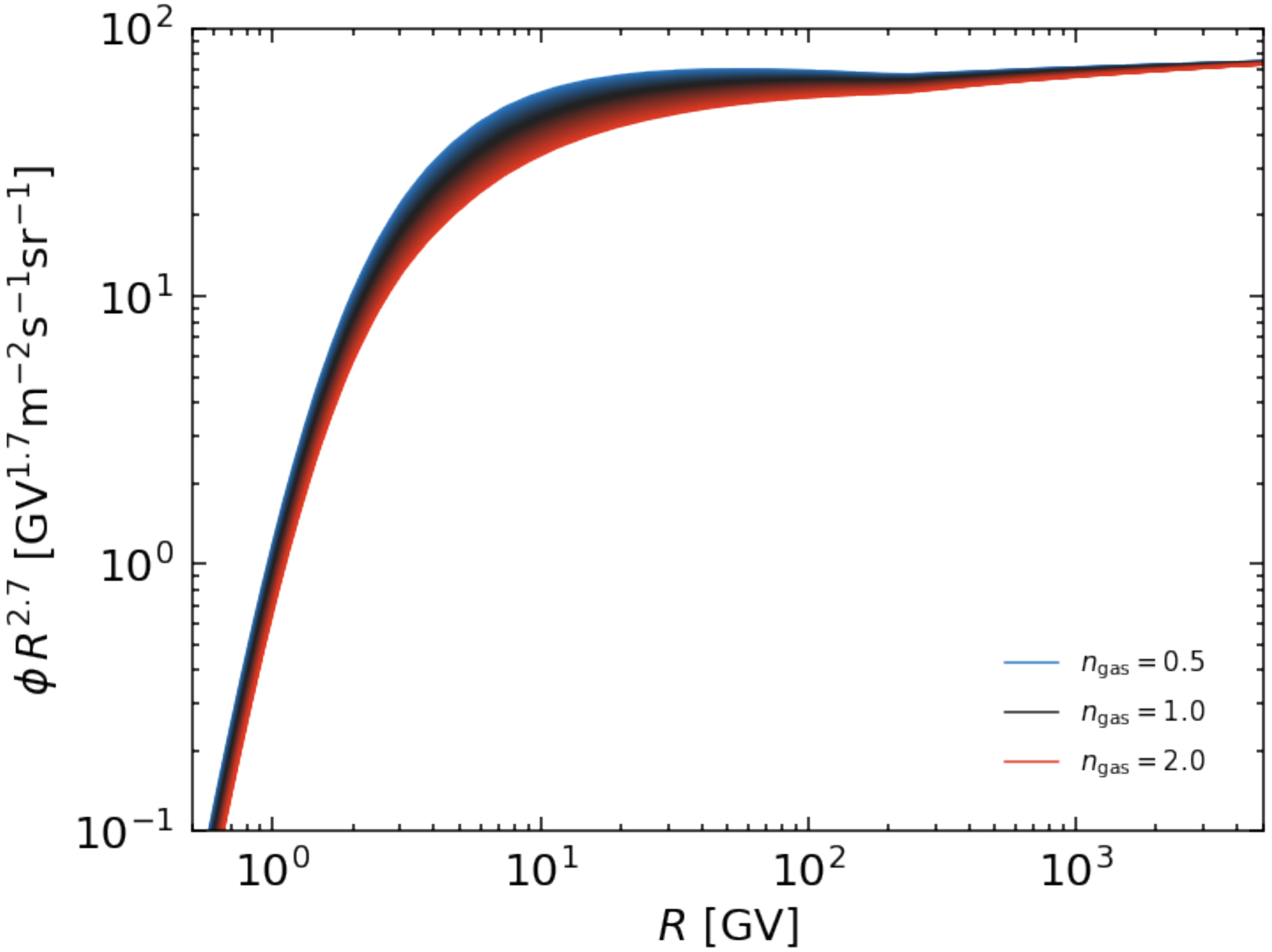
The diffusion coefficient is well constrained above 10 GV

Example: gas density

Secondary over primary: B/C



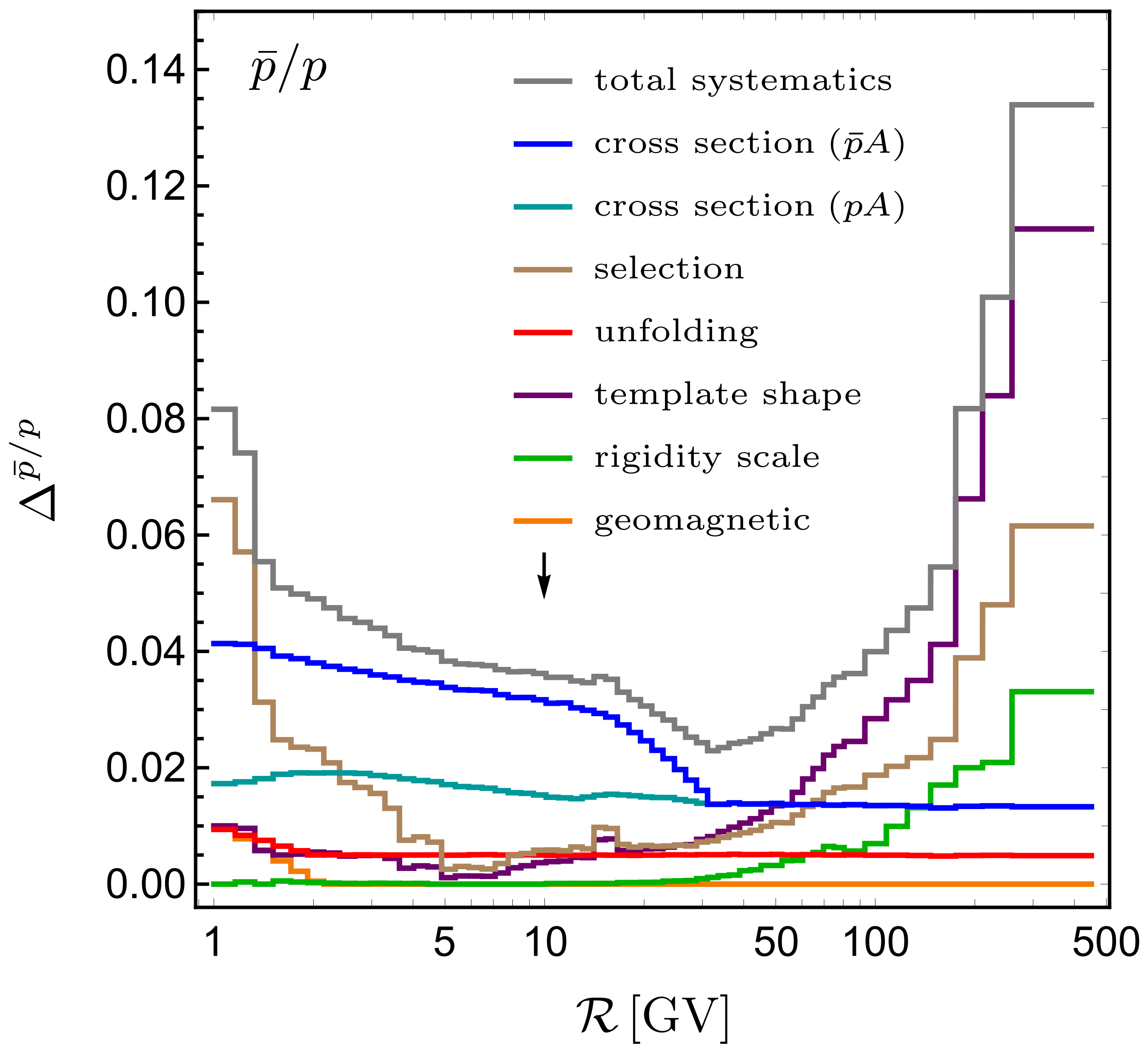
Pure primary: Oxygen

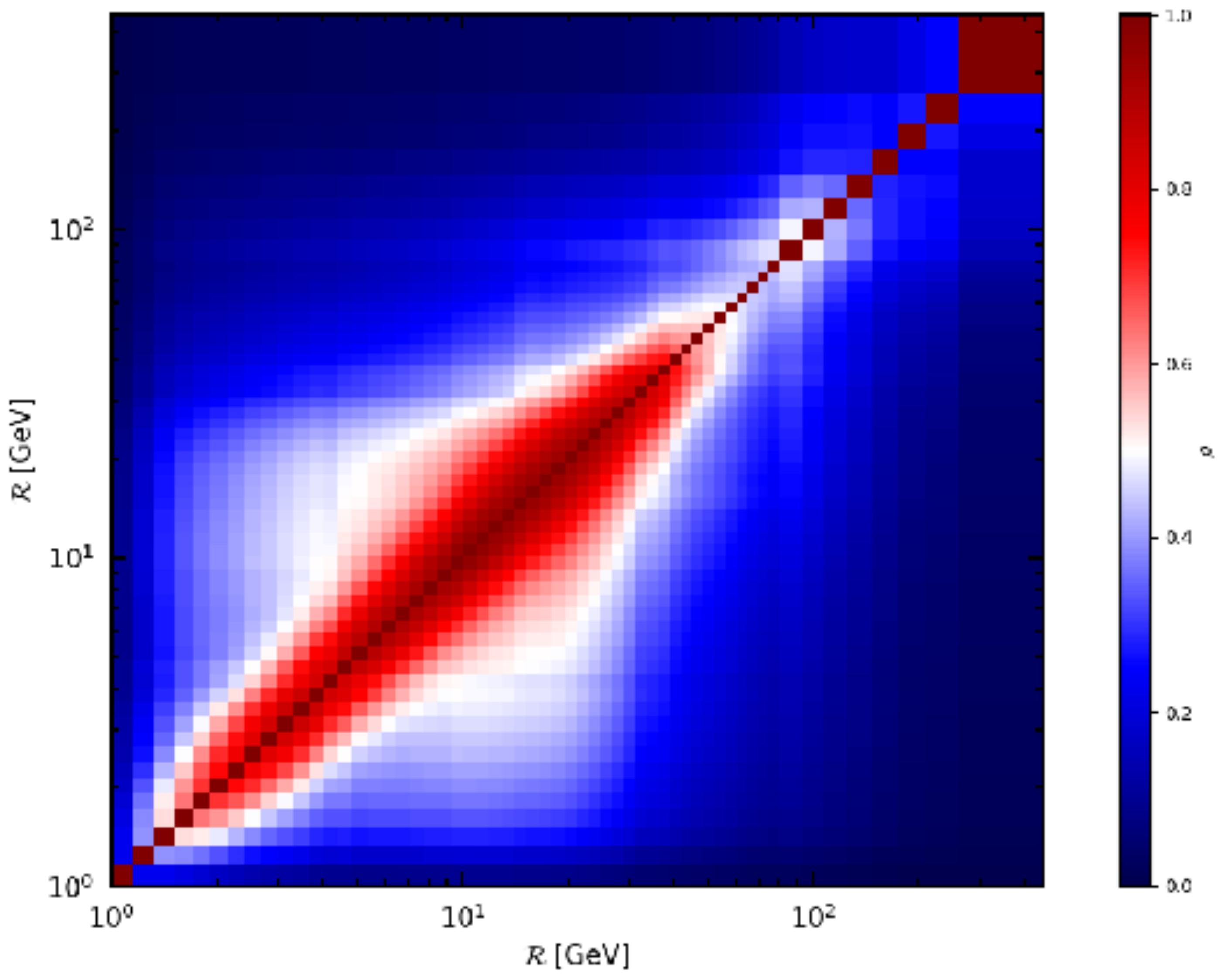


Impact on B/C is a normalization while for oxygen it changes the slope

Correlation in the cosmic-ray data of AMS-02

[Heisig, MK, Winkler; PRR; 2020]





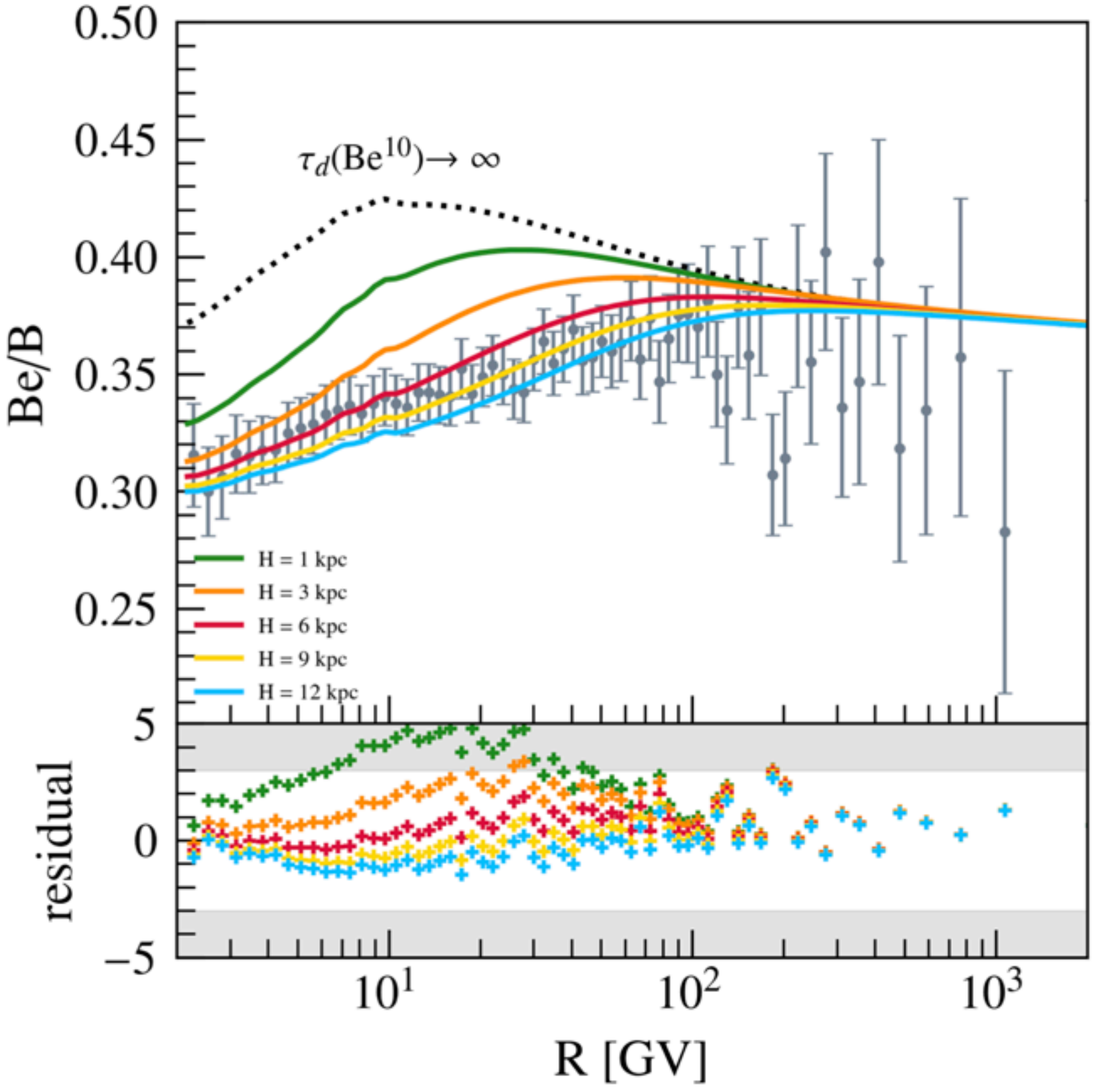
The AMS-02 collaboration does not provide the correlation of the flux data points

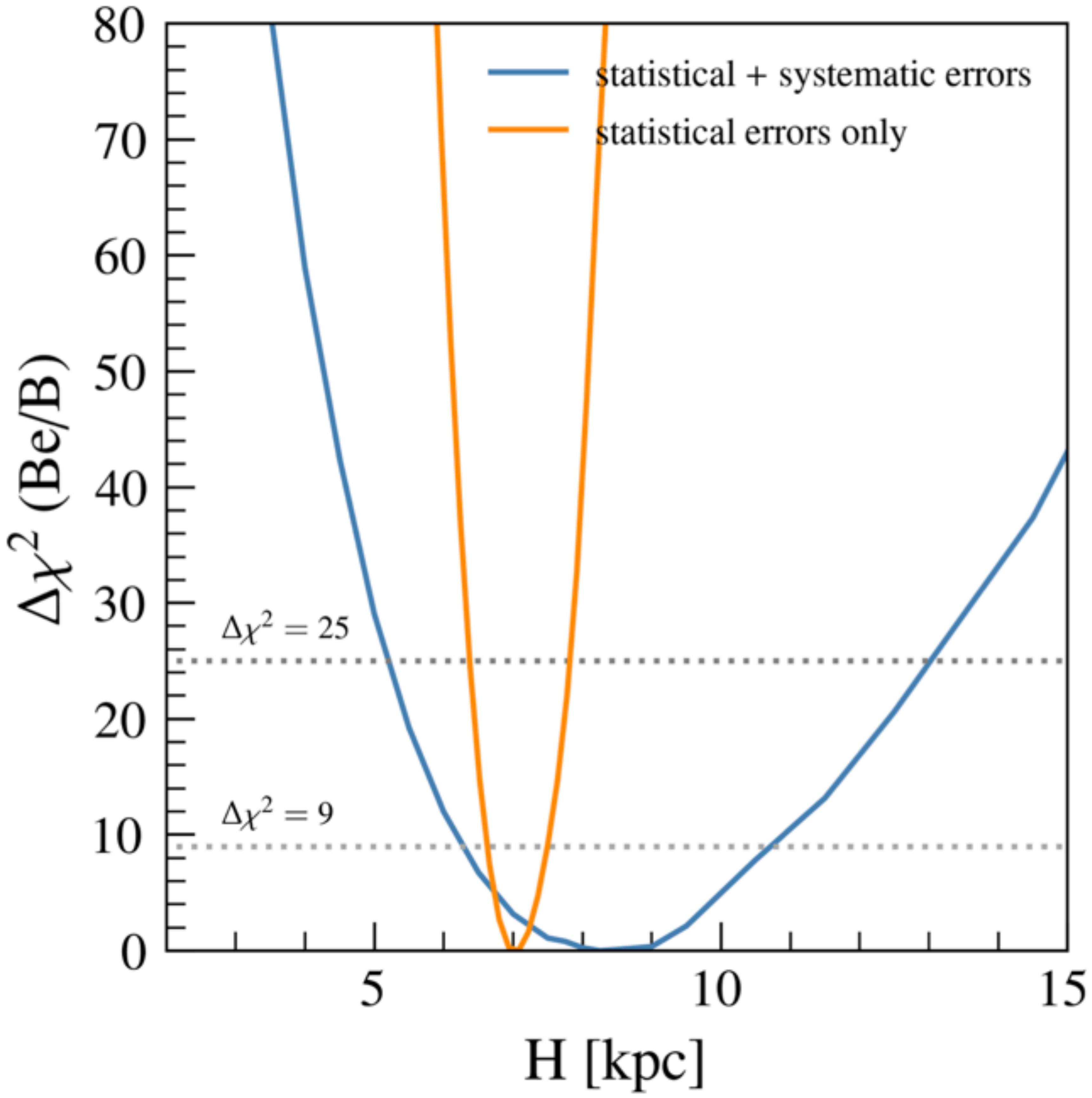
We model the covariance matrix by splitting the systematic uncertainties into separate contributions and attributing a correlation length to each contribution

The inclusion of correlation does not change our conclusions!

$$\mathcal{V}_{ij} = \sigma_i \sigma_j \exp\left(-\frac{1}{2} \left(\frac{R_i - R_j}{\ell_{\mathrm{corr}}} \right)^2 \right)$$

Comparison: Constraints on the diffusion halo

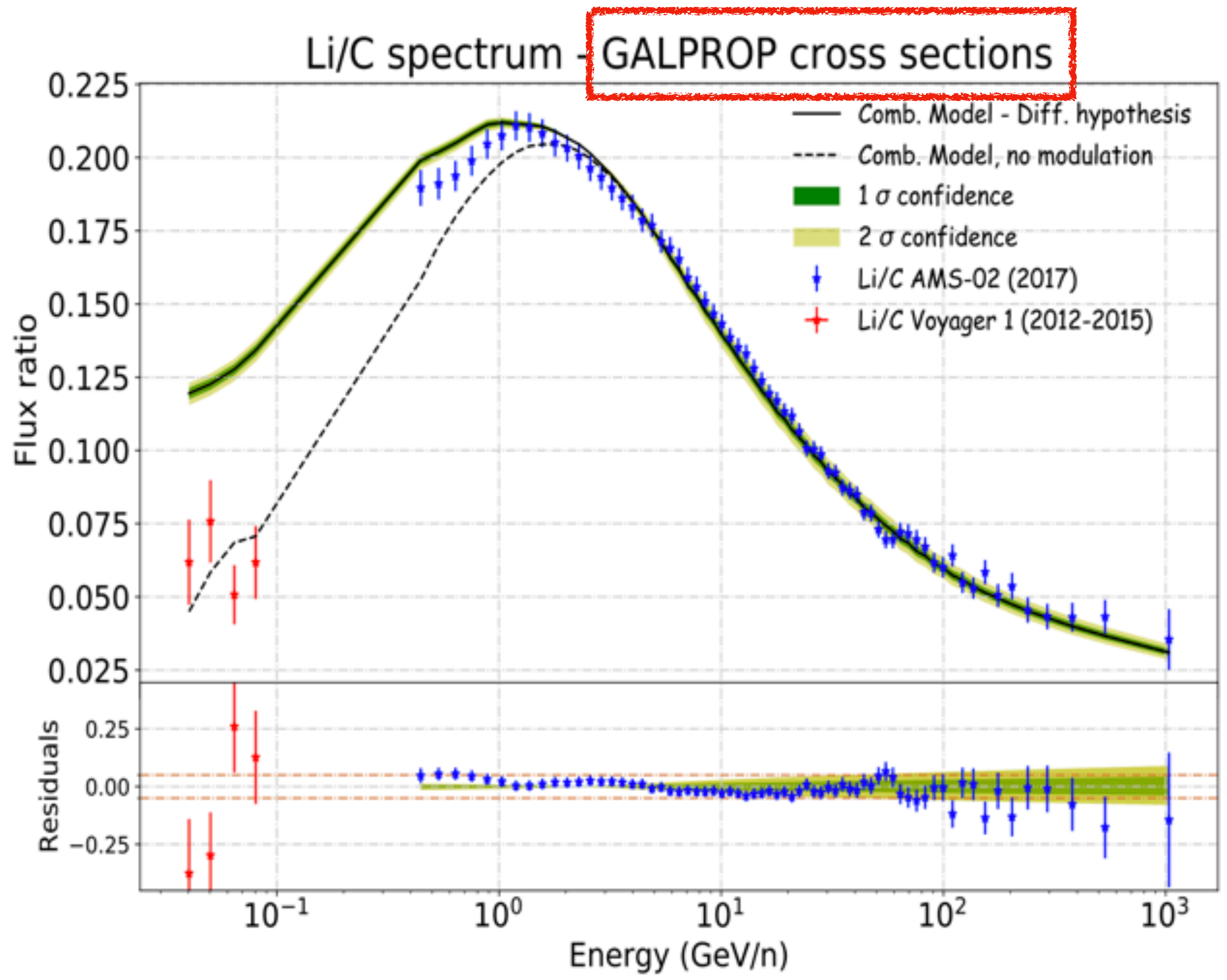


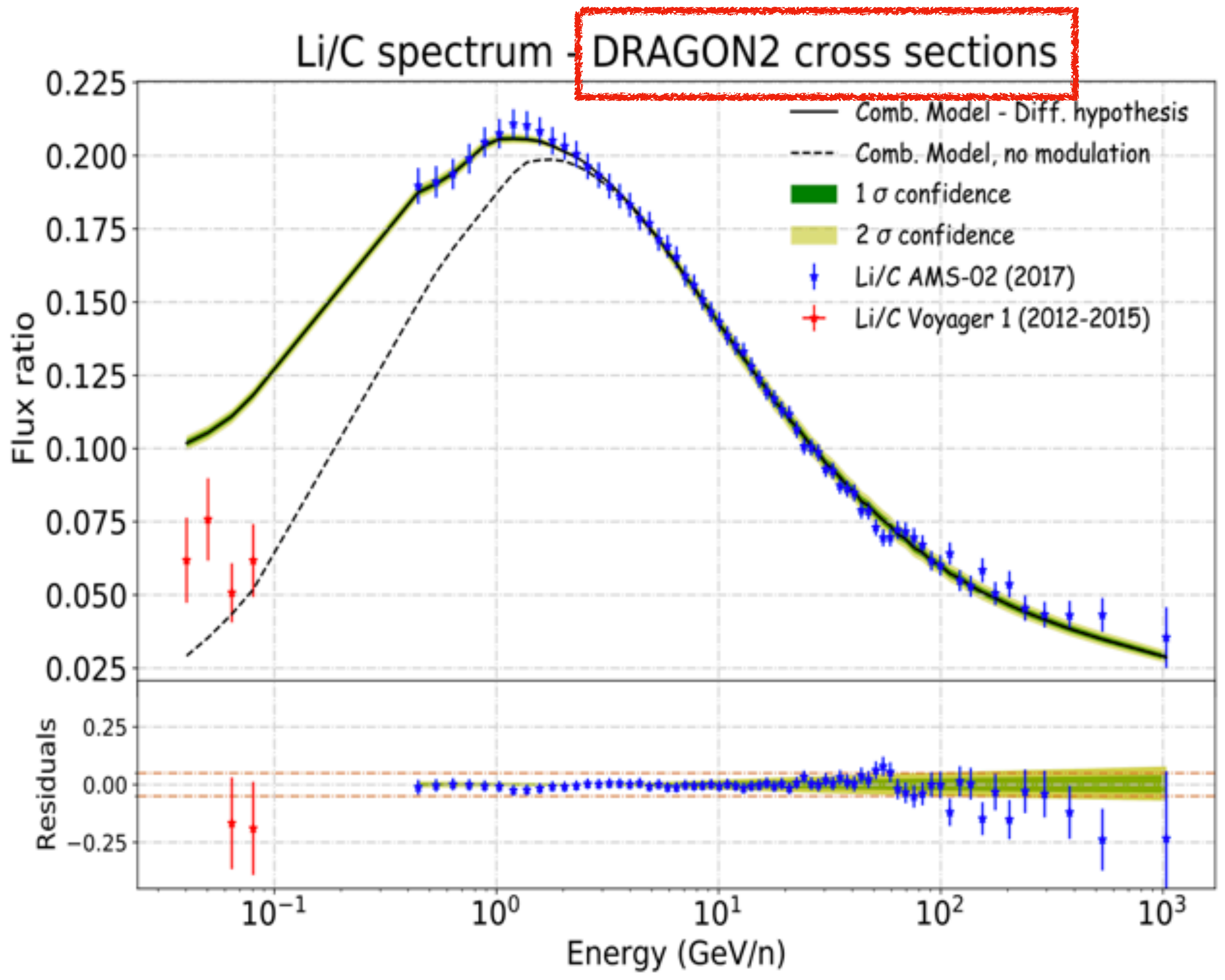


[Evoli+ 2019]

See also: [Weinrich+ 2020]

Comparison: Li production cross sections





[De la Torre Luque+ 2021]

GALPROP cross sections:
Li is rescaled by 1.26

DRAGON2 cross sections:
Li is rescaled by 0.97

See also: [Weinrich+ 2019; Boschini+ 2020]