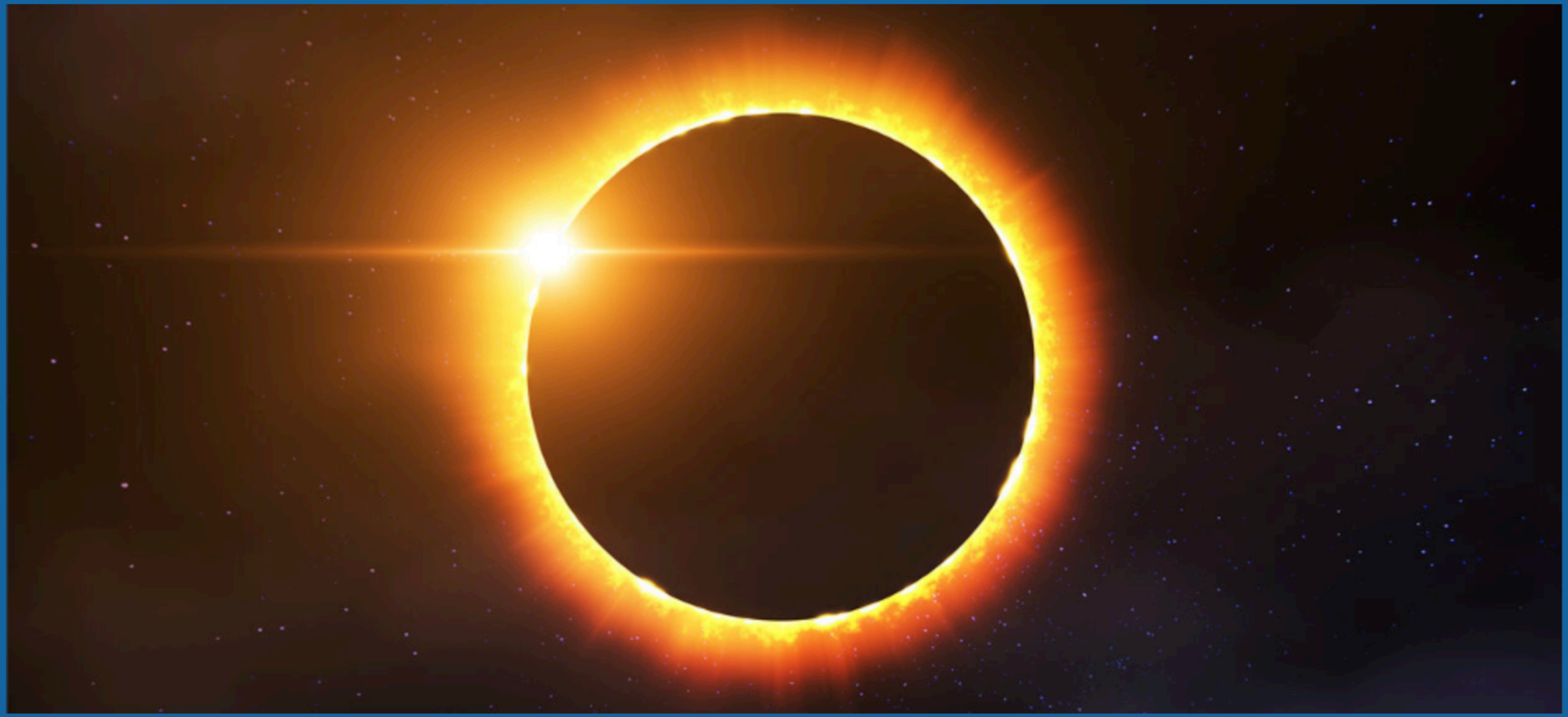
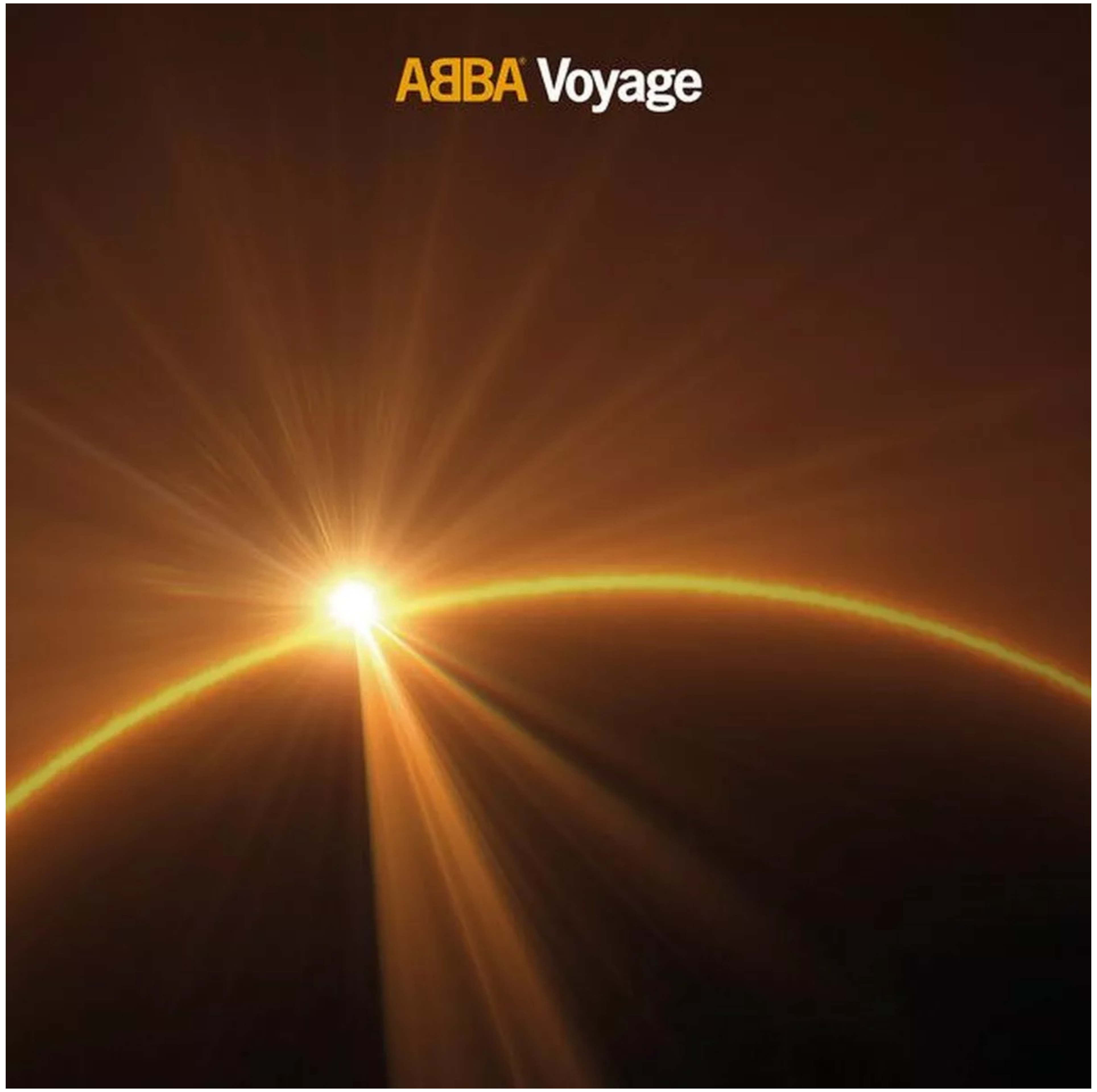
Implications of Li to O data of AMS-02 on our understanding cosmic-ray propagation



Solar Modulation and Dark Matter Workshop

Michael Korsmeier

18/11/2021

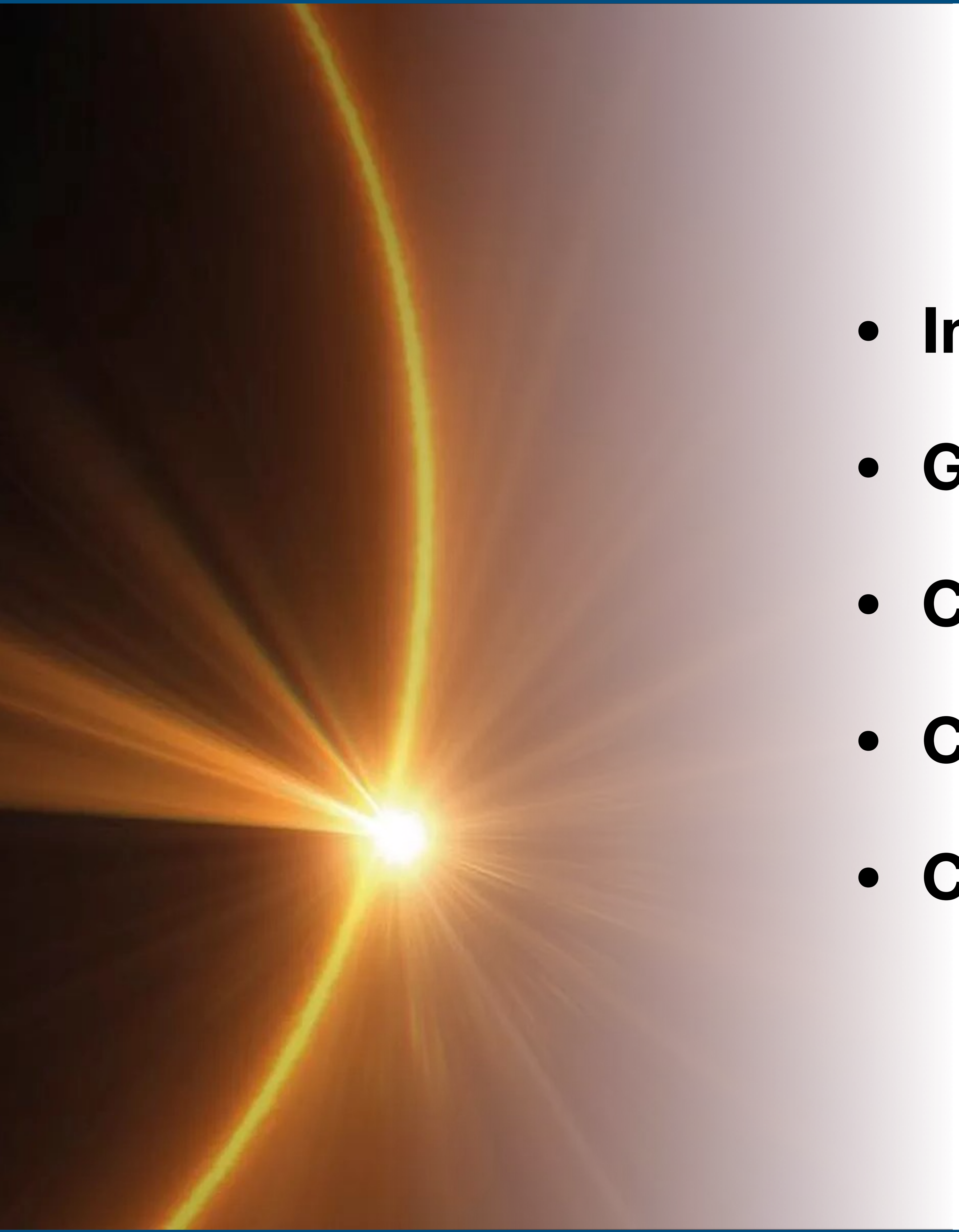


At first glance!

No Avatars → We are back in person!

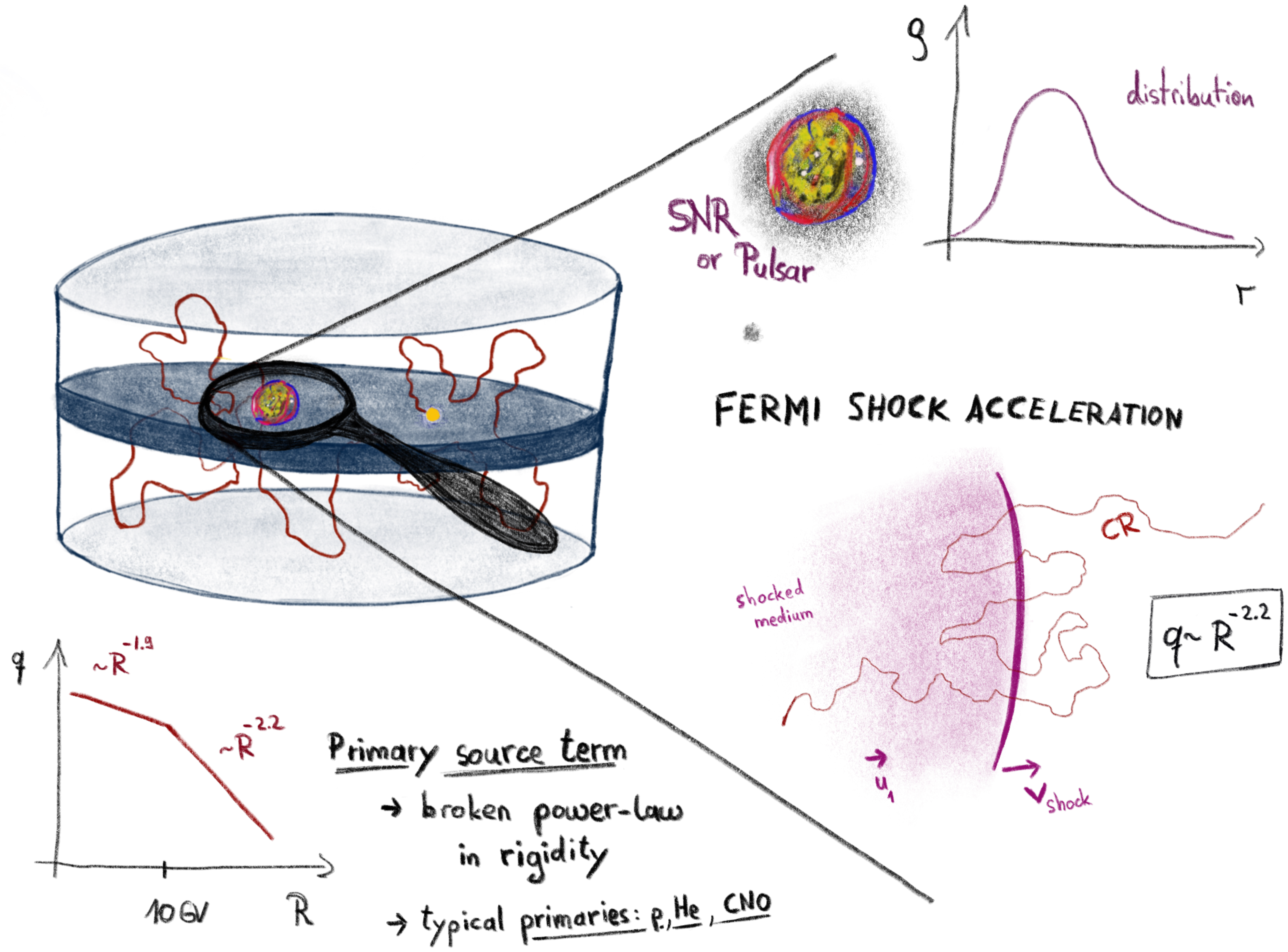
After the first talk!

Outline

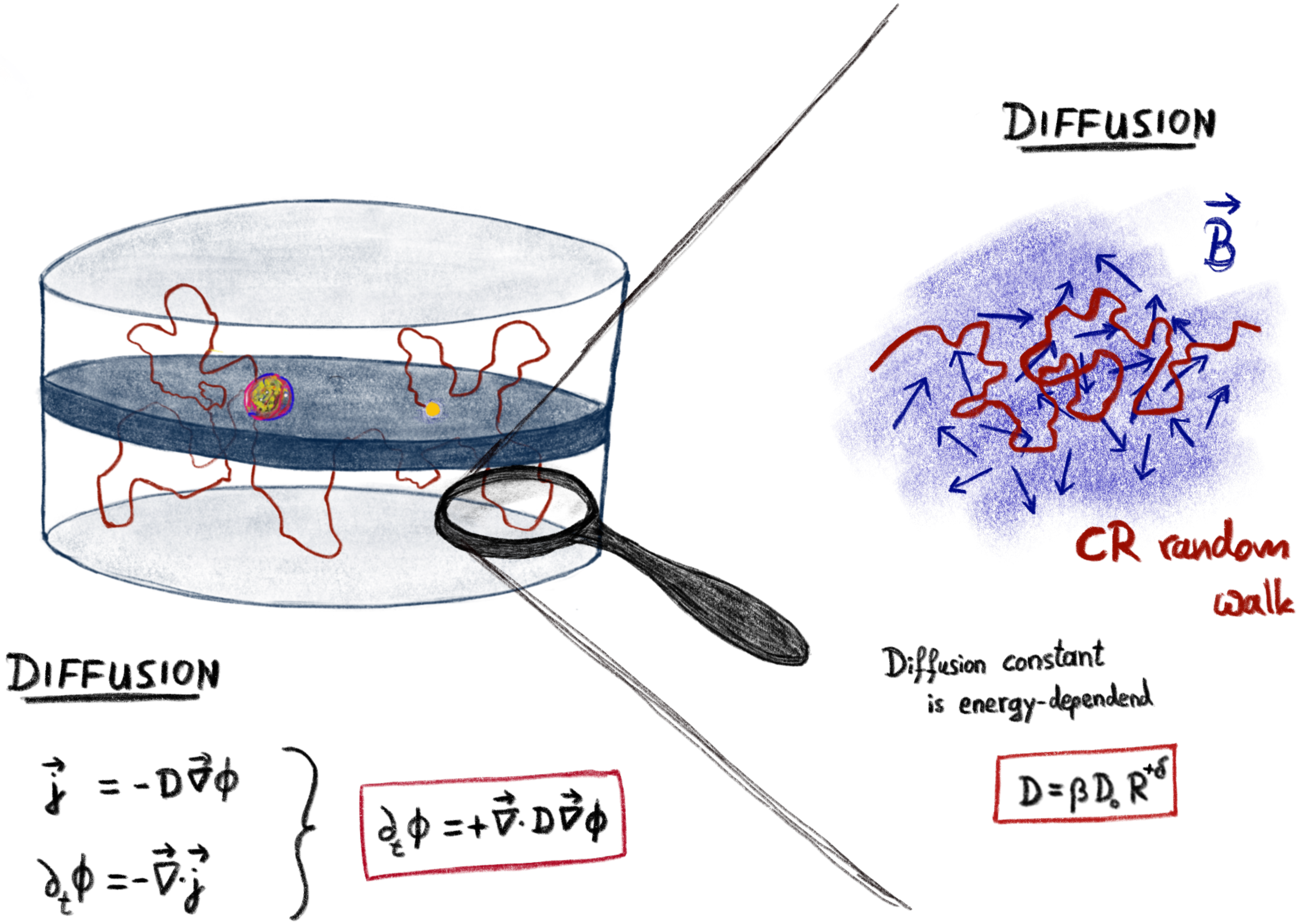


- Introduction
- Global fit of CR data from Li to O
- CR antiprotons
- CR antideuteron
- Conclusion

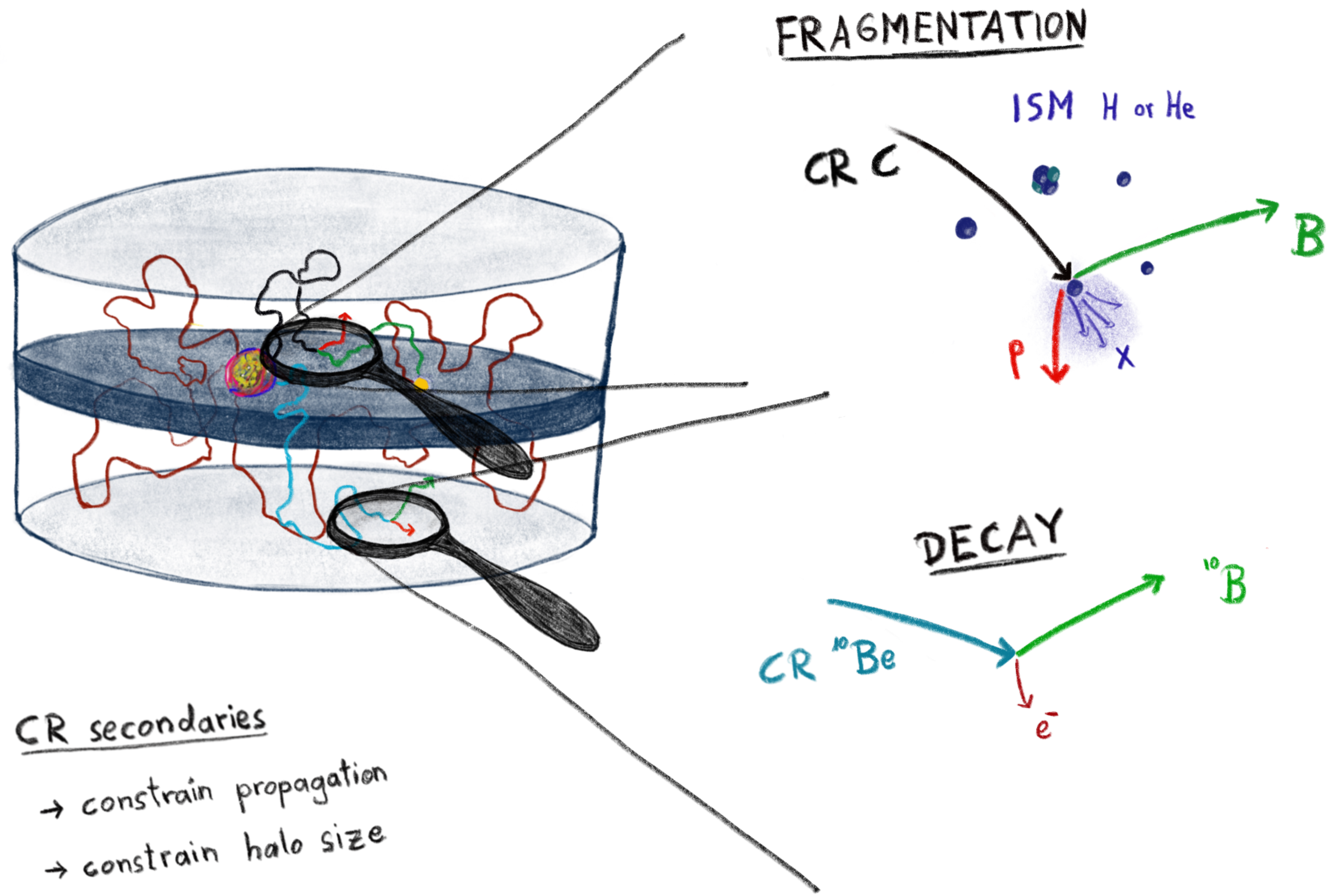
Modeling cosmic-ray propagation

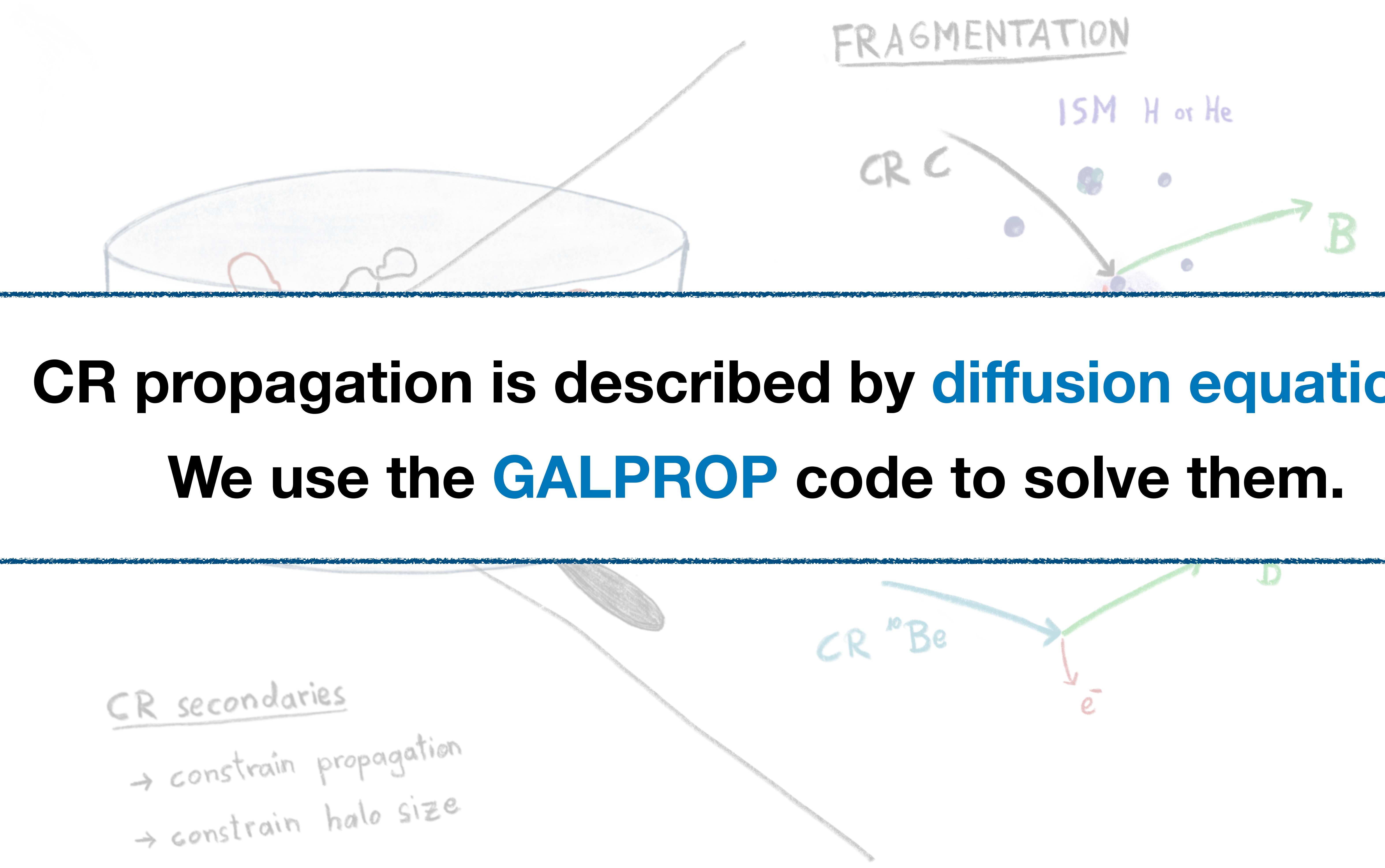


Modeling cosmic-ray propagation



Modeling cosmic-ray propagation





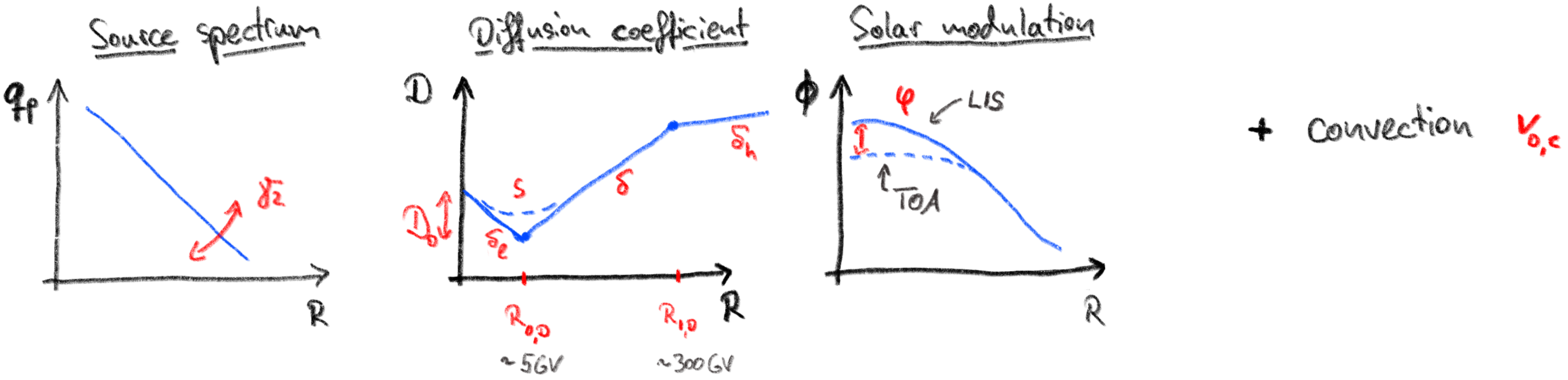
CR propagation is described by diffusion equations.

We use the GALPROP code to solve them.

CR propagation models

We explore 5 different setups for CR propagation:

BASE BASE+v$_A$ BASE+inj BASE+inj+v$_A$ BASE+inj+v$_A$-diff.brk



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

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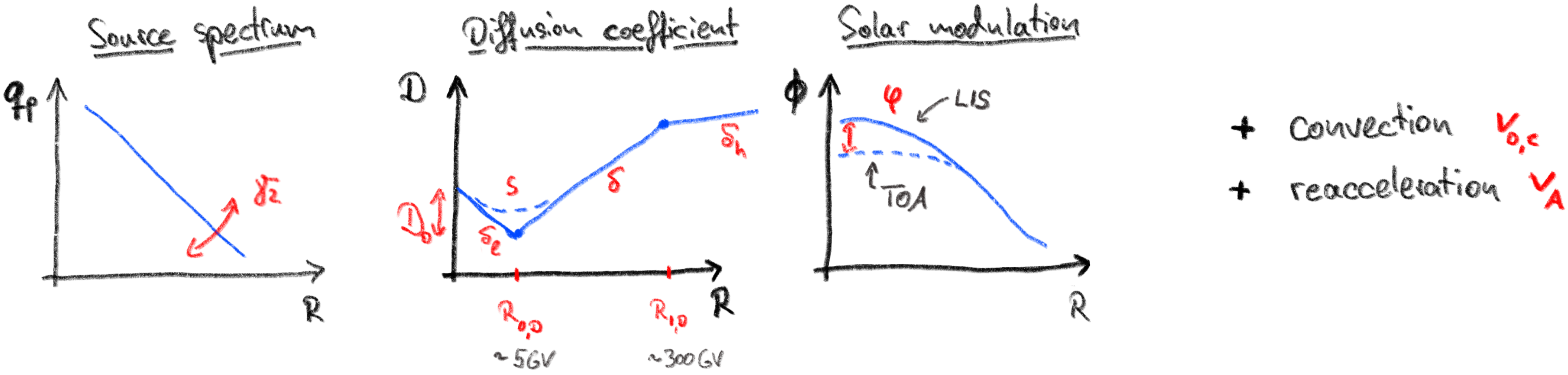

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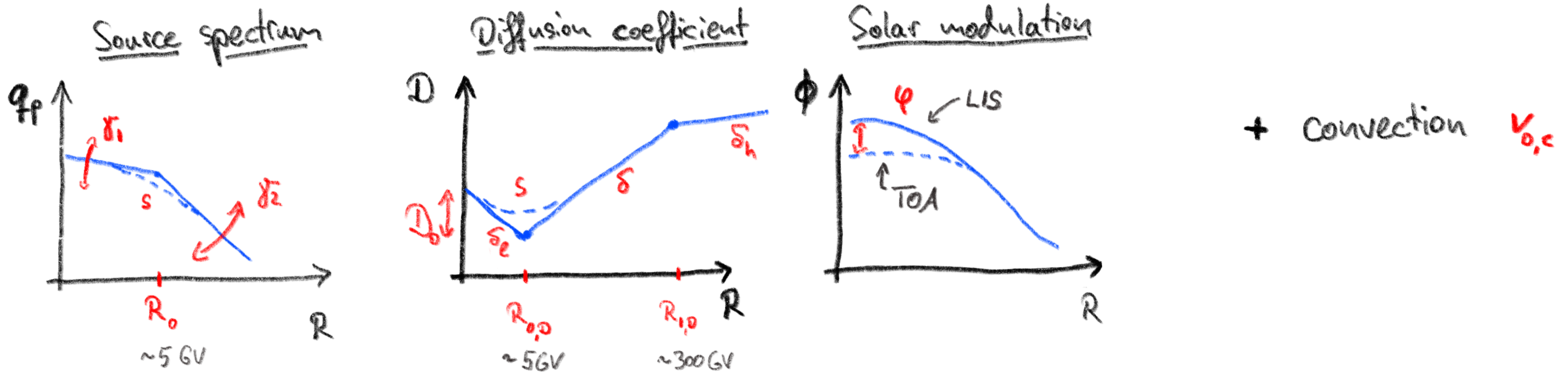

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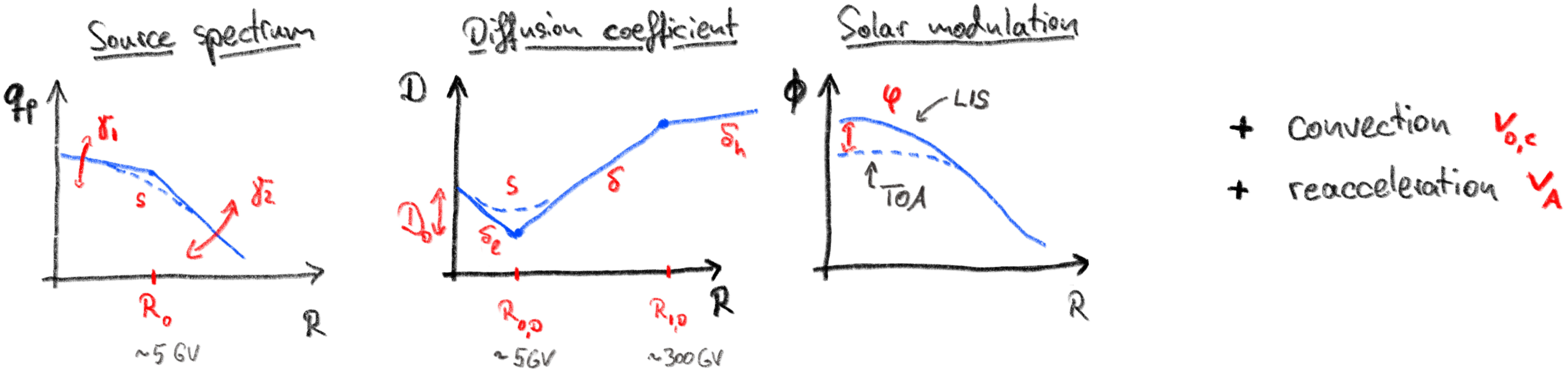

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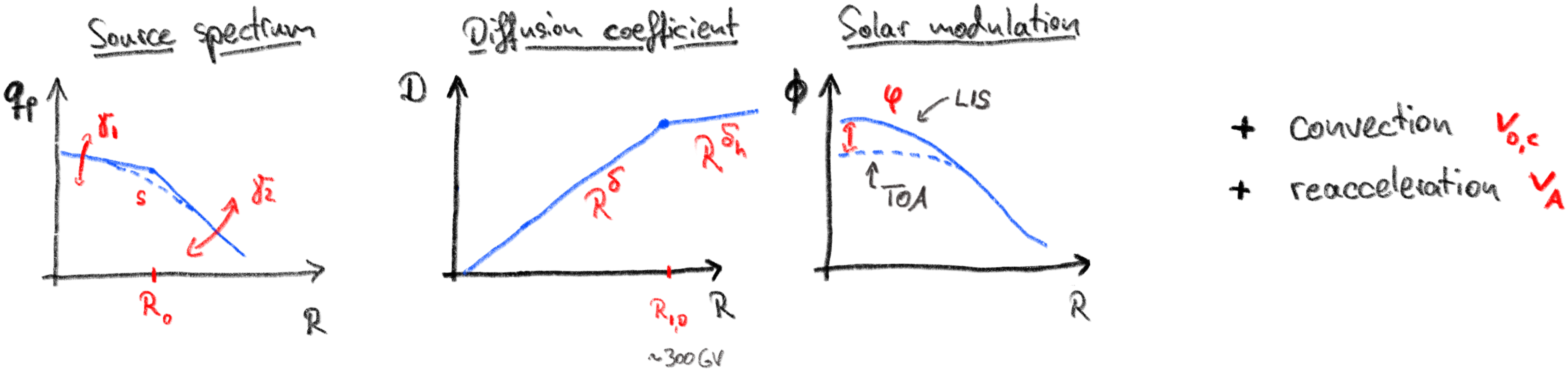

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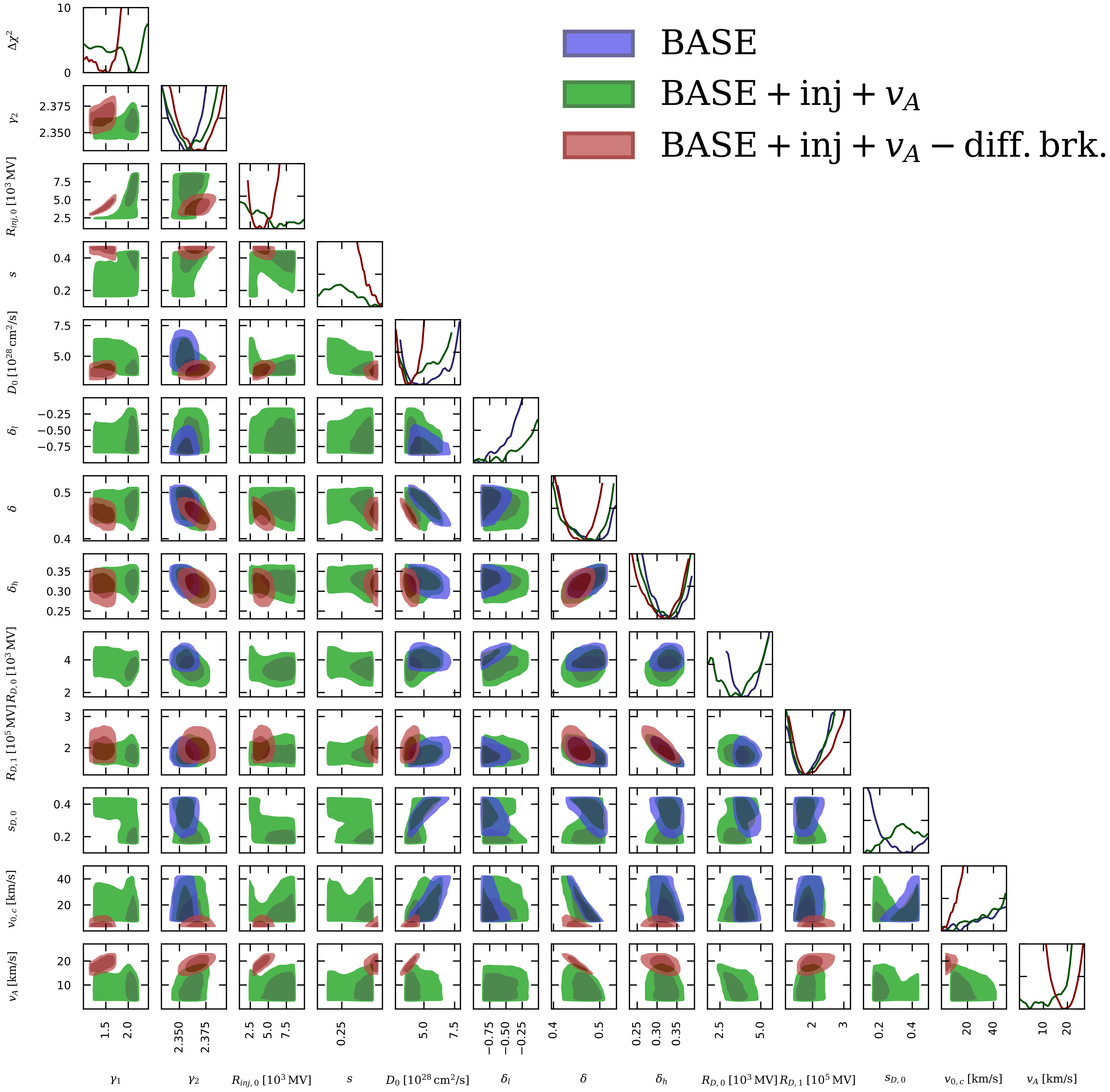
CR propagation models

THIS WORK GALPROP	BASE	BASE+v_A	BASE+inj	BASE+inj+v_A	BASE+inj+v_A-diff.brk
analytic [Evoli+; 2019] [Schroer+; 2021]	●				
USINE (semi-analytic) [Génolini+; 2019] [Weinrich+; 2020]	~SLIM			~BIG	~QUAINT
DRAGON [De la Torre+; 2021]					●
GALPROP [Boschini+;2018] [Boschini+;2019]					●

Global fit

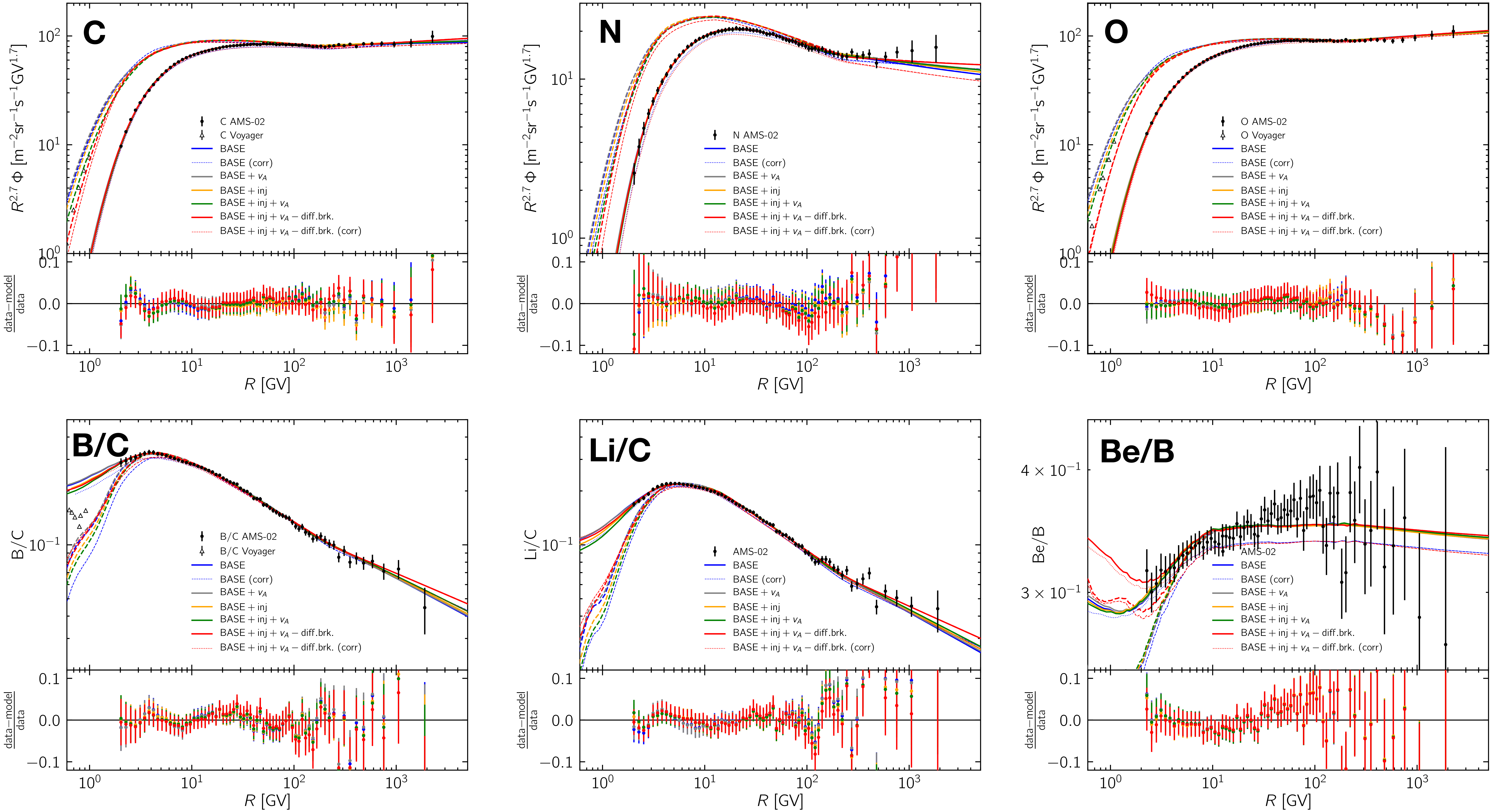


We investigate five propagation setups and perform several consistency checks

We use MultiNest to sample the large parameter space of up to 27 parameters

Parameters for CR propagation and cross section nuisance parameters are sampled at the same time

Results of the global fits



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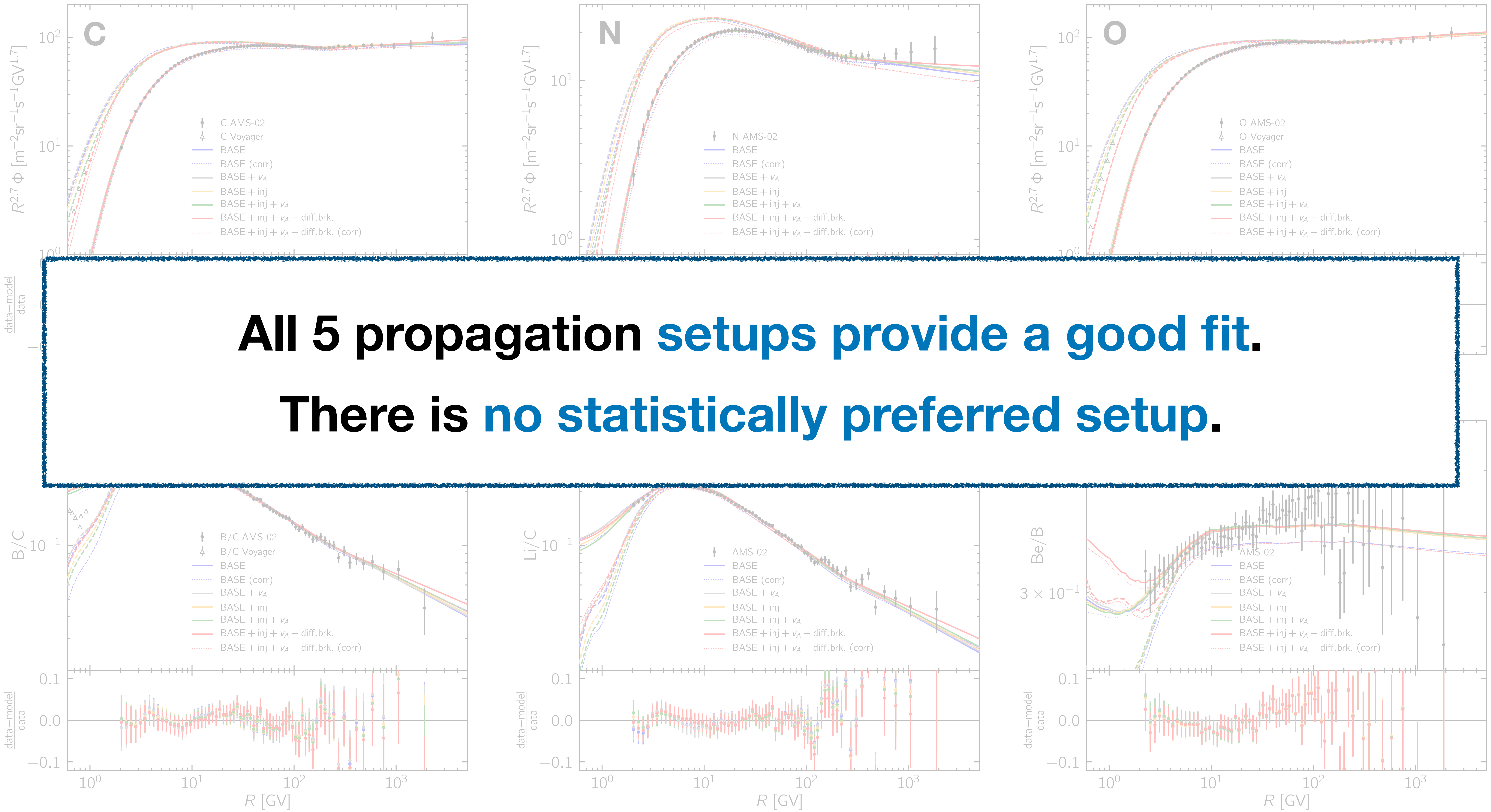
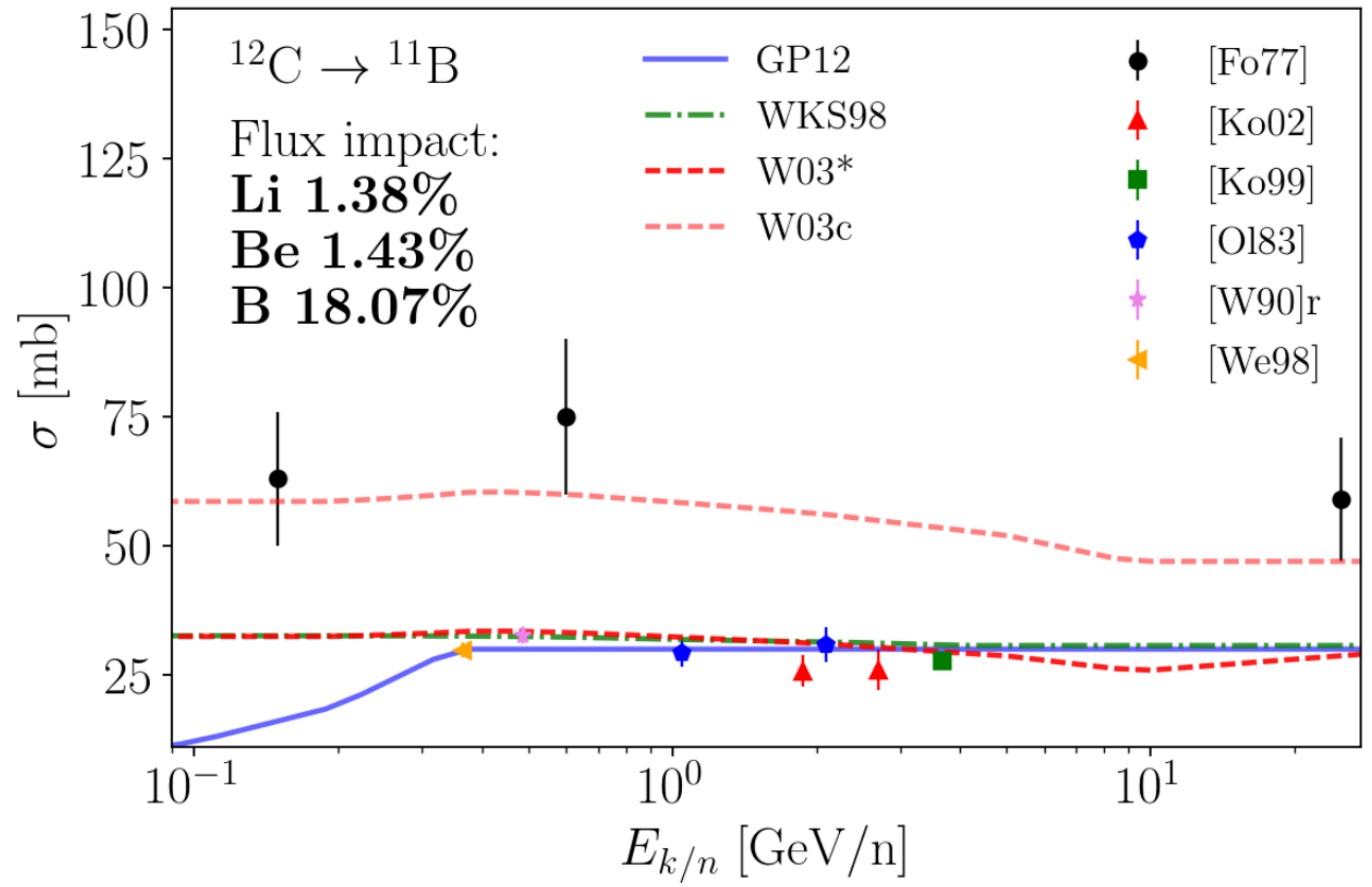


All 5 propagation setups provide a good fit.

There is no statistically preferred setup.

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!

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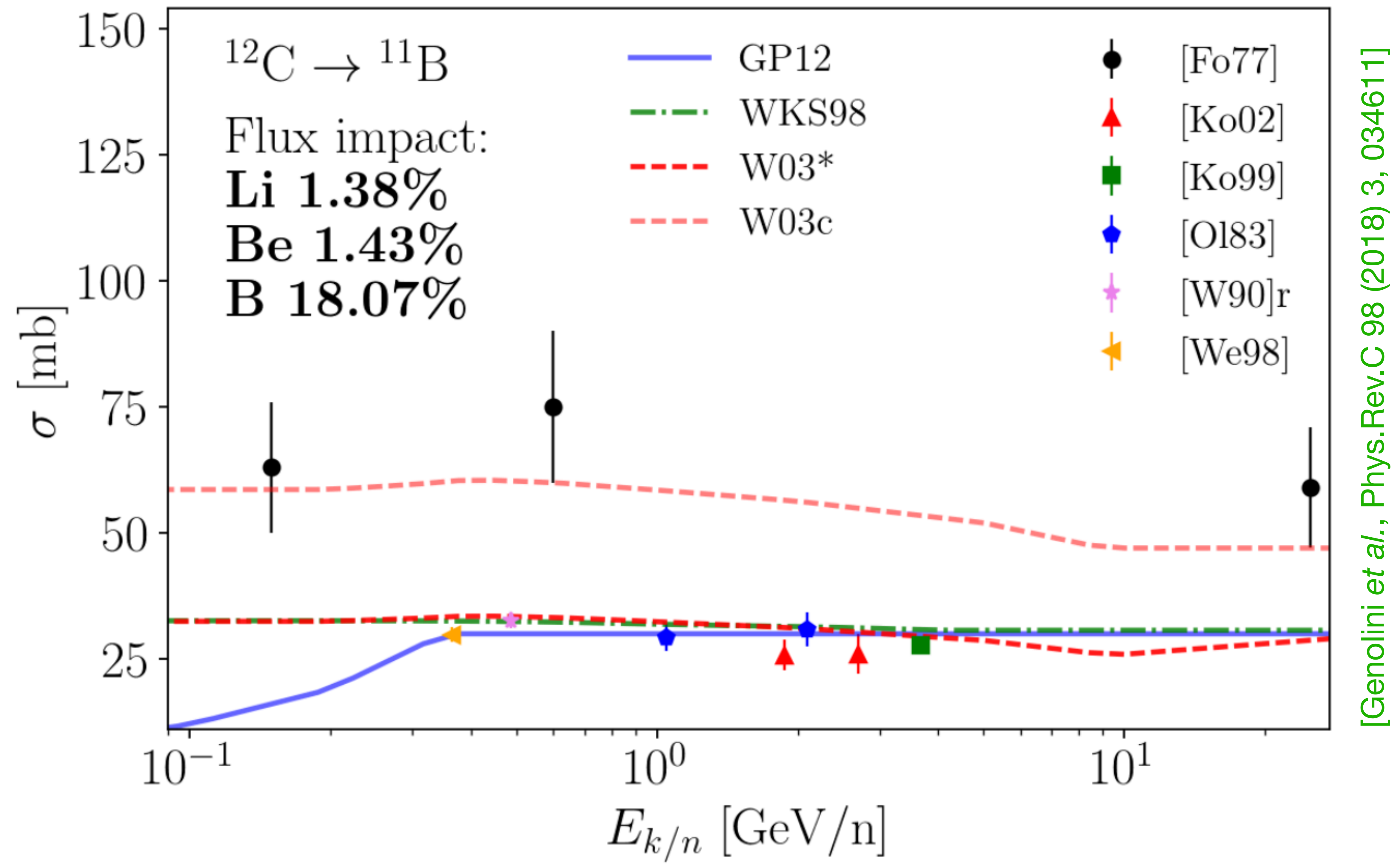

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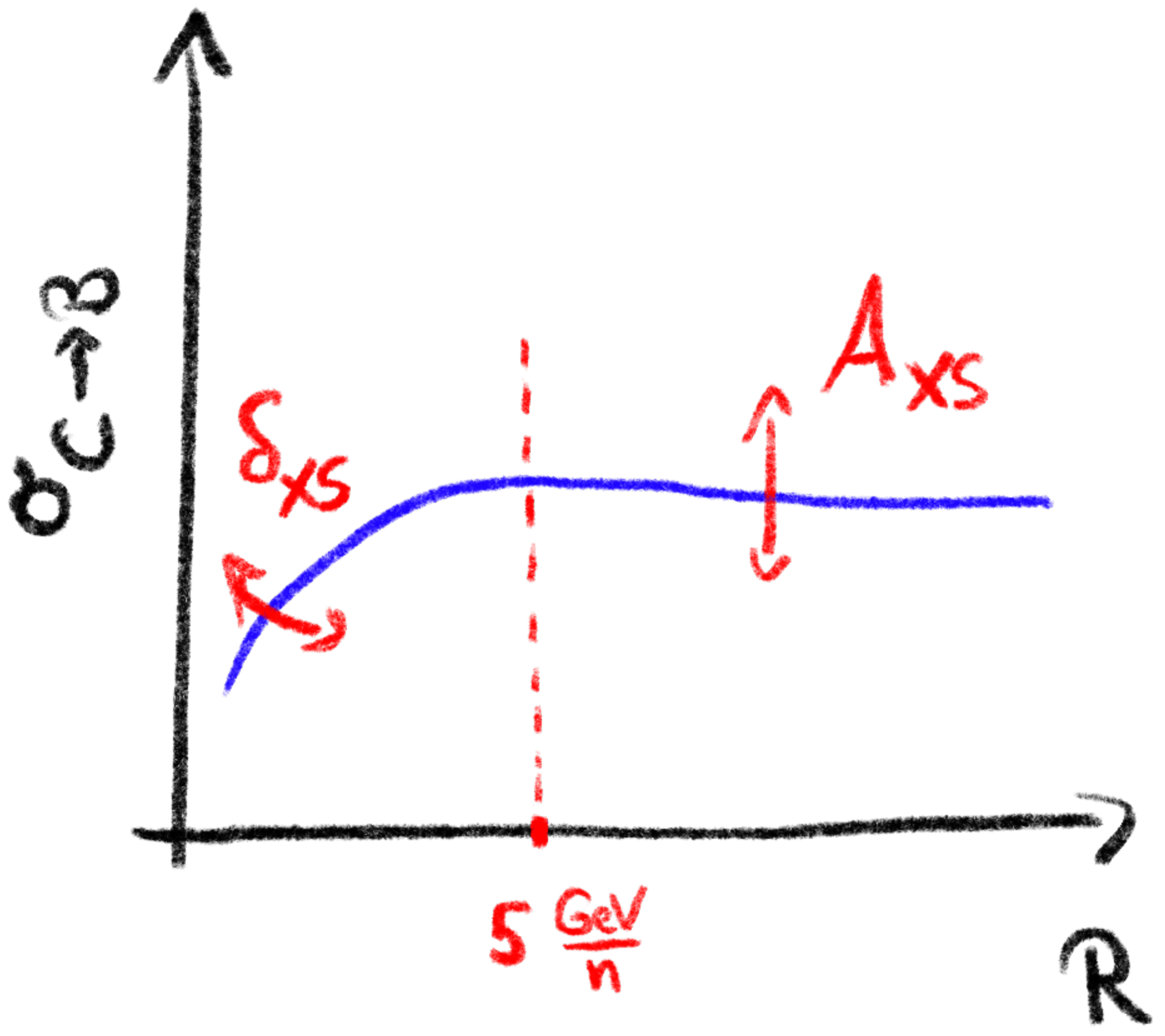


We perform a global fit and profile over nuisance parameters in the most relevant fragmentation cross sections.

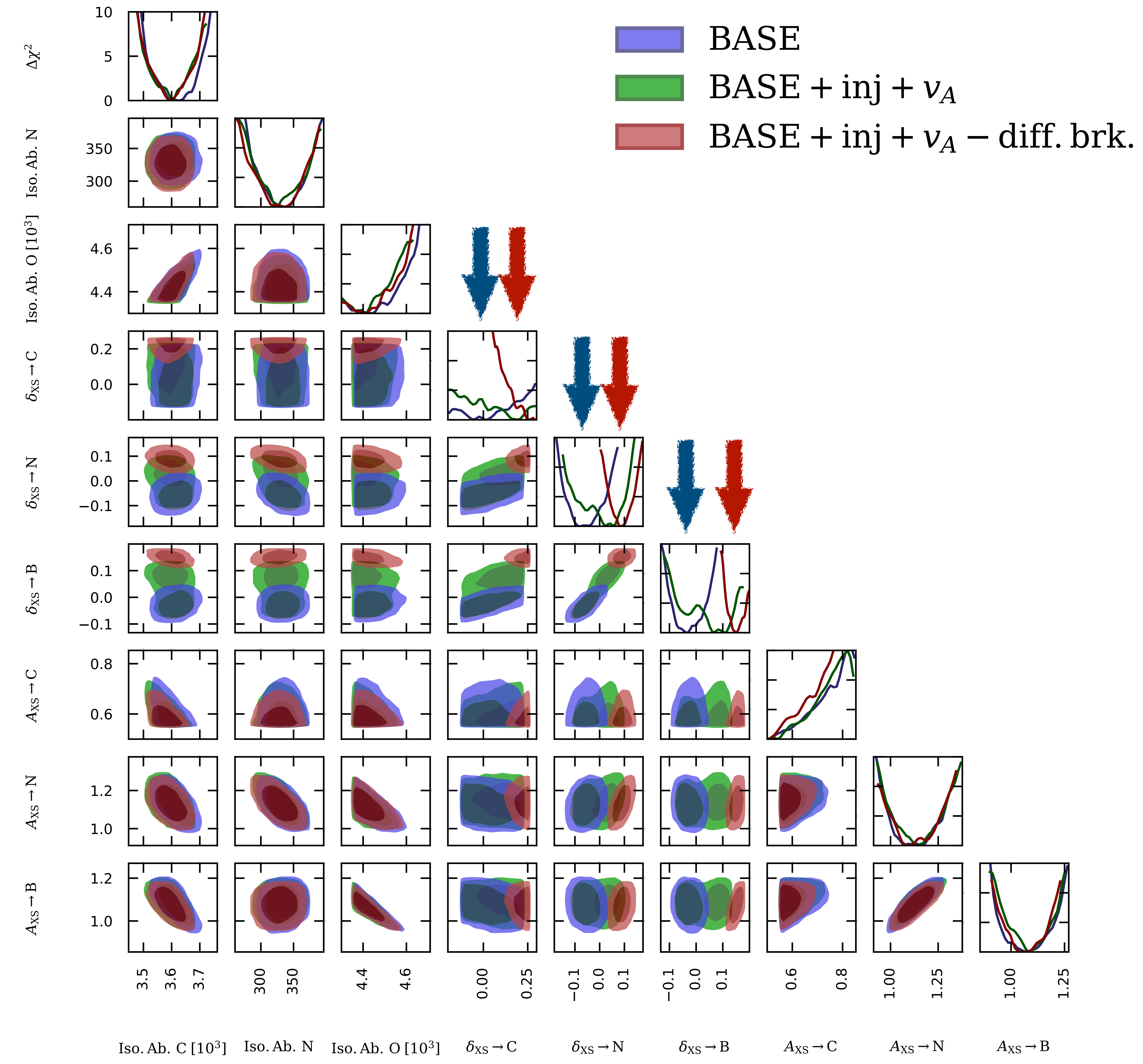
Systematic uncertainty: fragmentation cross sections

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

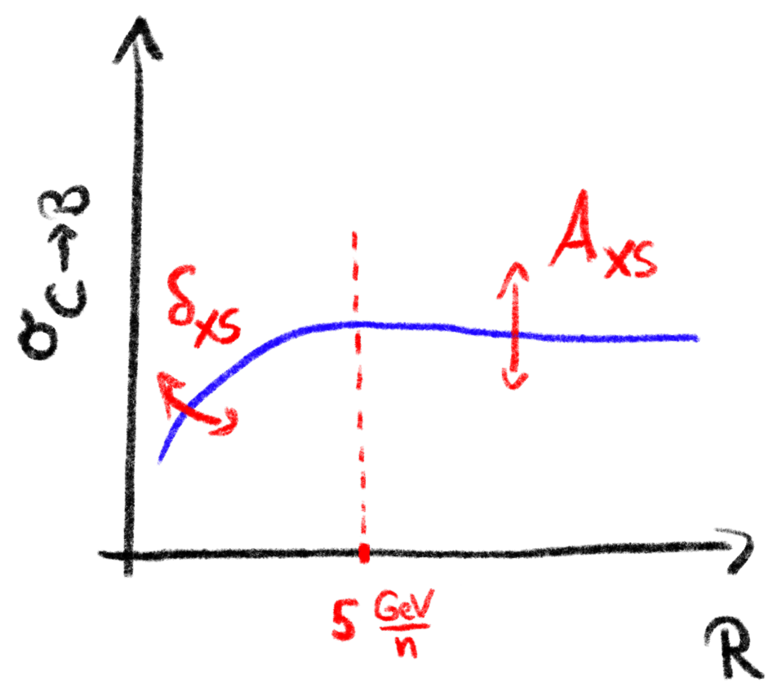
fit parameter	nuisance parameters			
$\delta_{XS\to B}$	$\delta\ {}^{16}_{8}O\to{}^{10}_{5}B$	$\delta\ {}^{12}_{6}C\to{}^{10}_{5}B$	$\delta\ {}^{16}_{8}O\to{}^{11}_{5}B$	$\delta\ {}^{12}_{6}C\to{}^{11}_{5}B$
$\delta_{XS\to Li}$	$\delta\ {}^{16}_{8}O\to{}^{6}_{3}Li$	$\delta\ {}^{12}_{6}C\to{}^{6}_{3}Li$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

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

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



[MK, Cuoco, 2021]



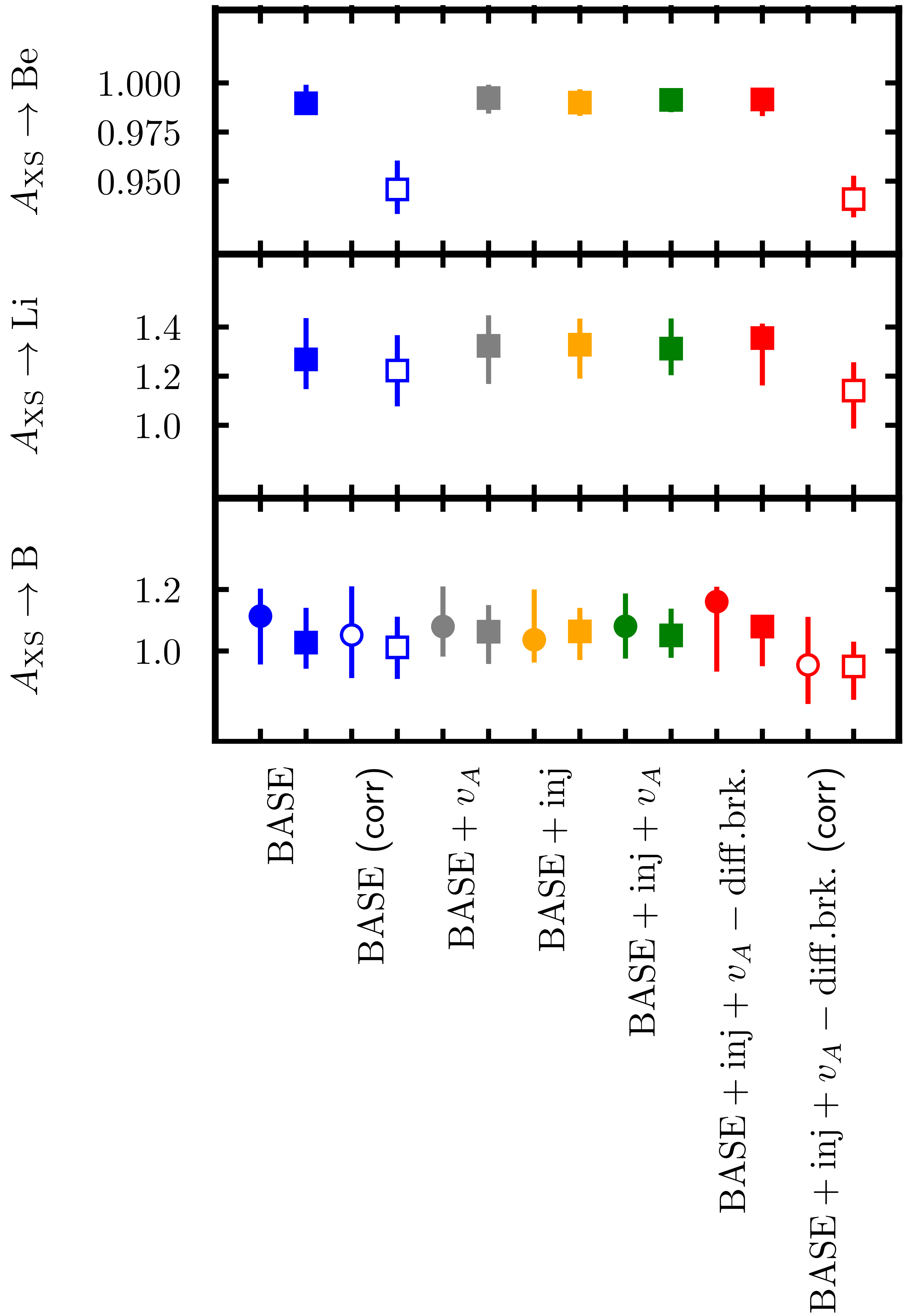
The default cross section parametrization is "GALPROP 12"

BASE is compatible with the default cross section

BASE+inj+v_A-diff.brk converges at δ_{XS} ~0.2

Li cross section are increased by ~25%

Cross section nuisance parameters



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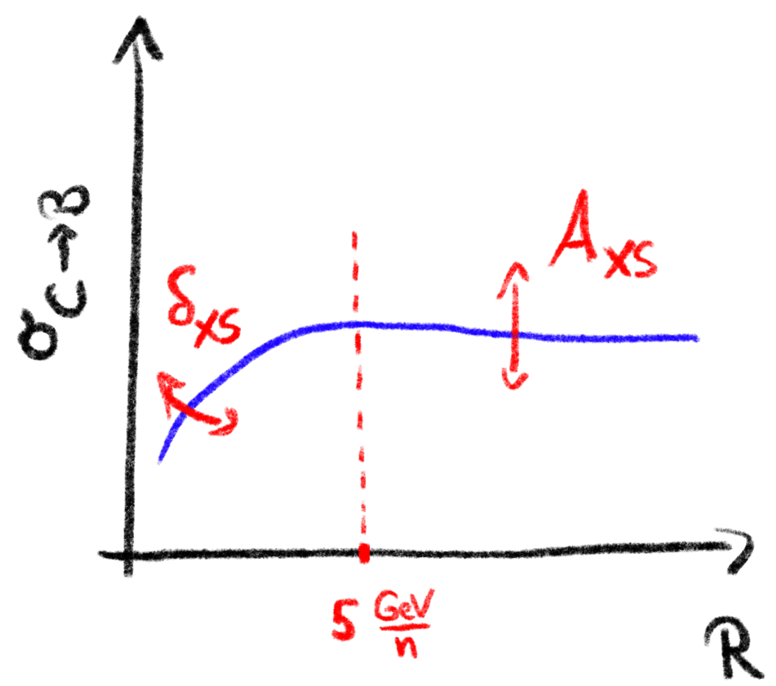

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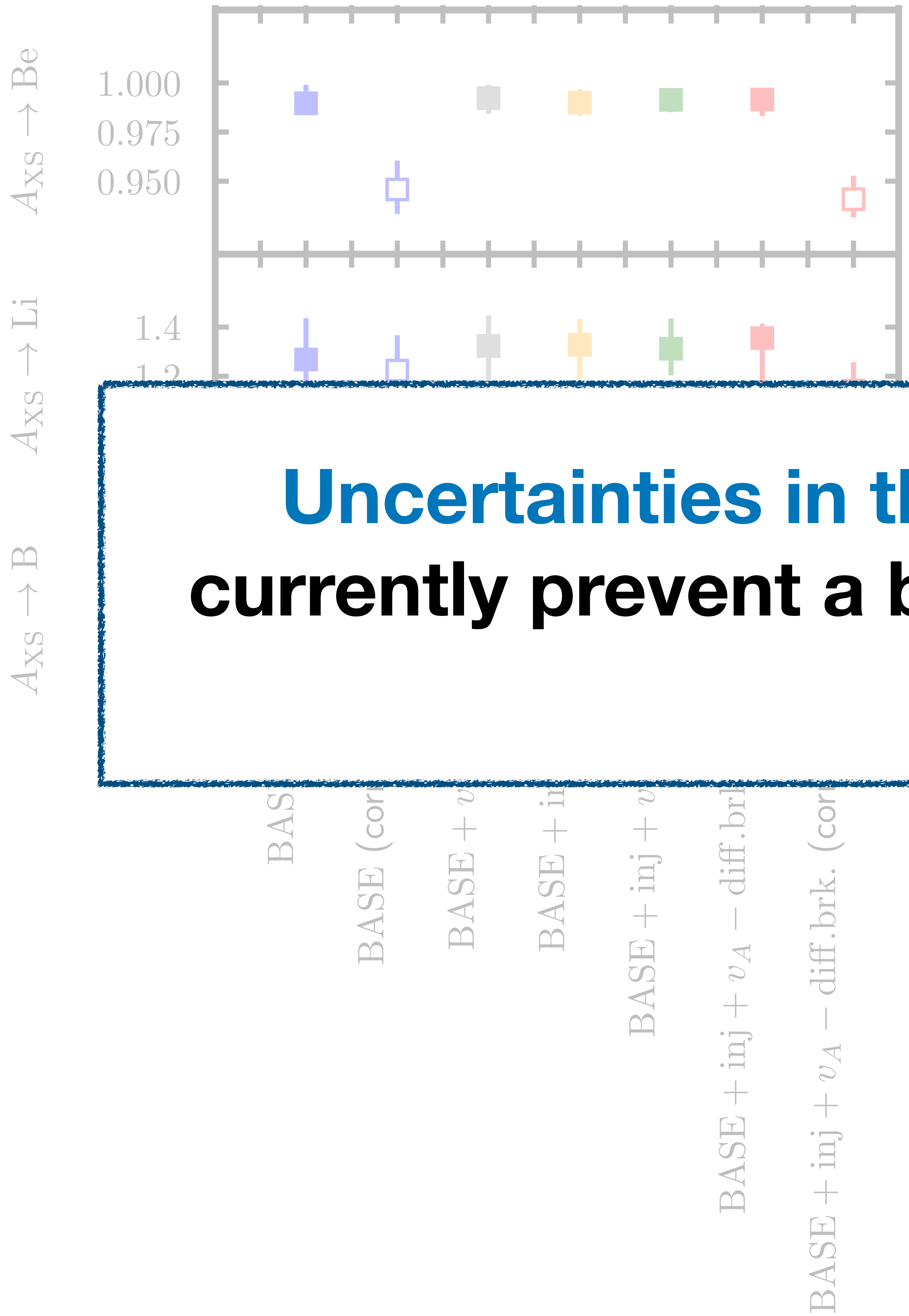

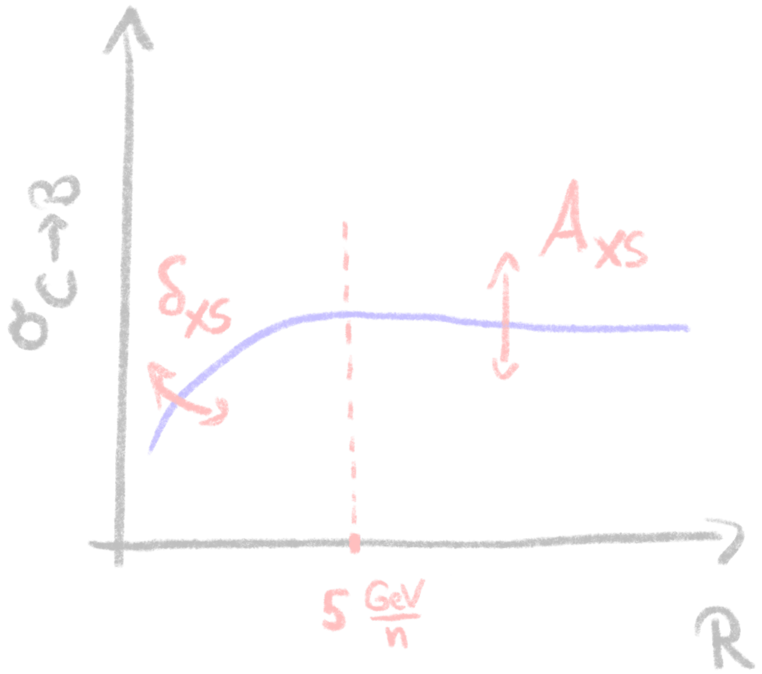

[MK, Cuoco, 2021]

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

BASE+inj+v_A-diff.brk converges at δ_{XS} ~0.2

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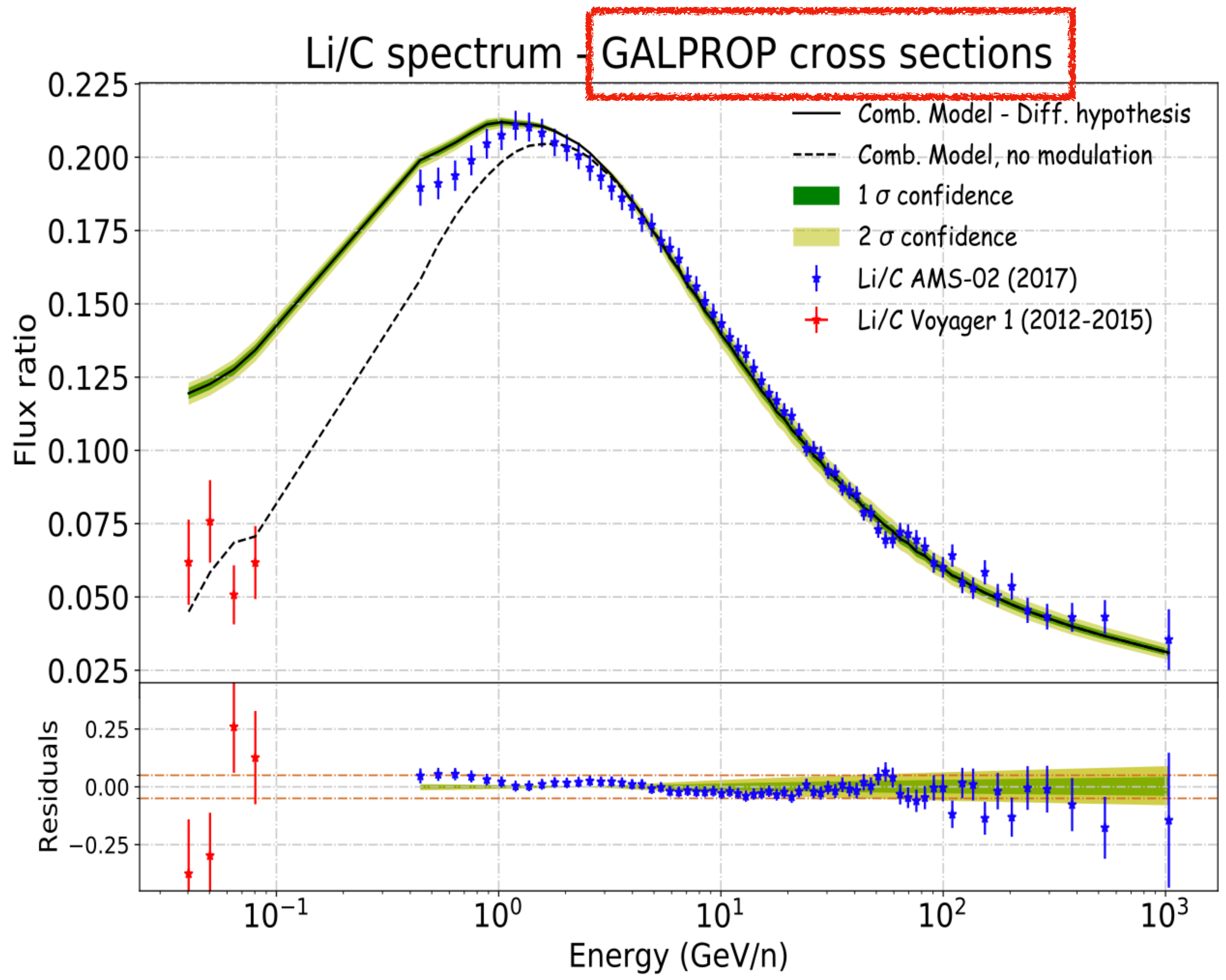
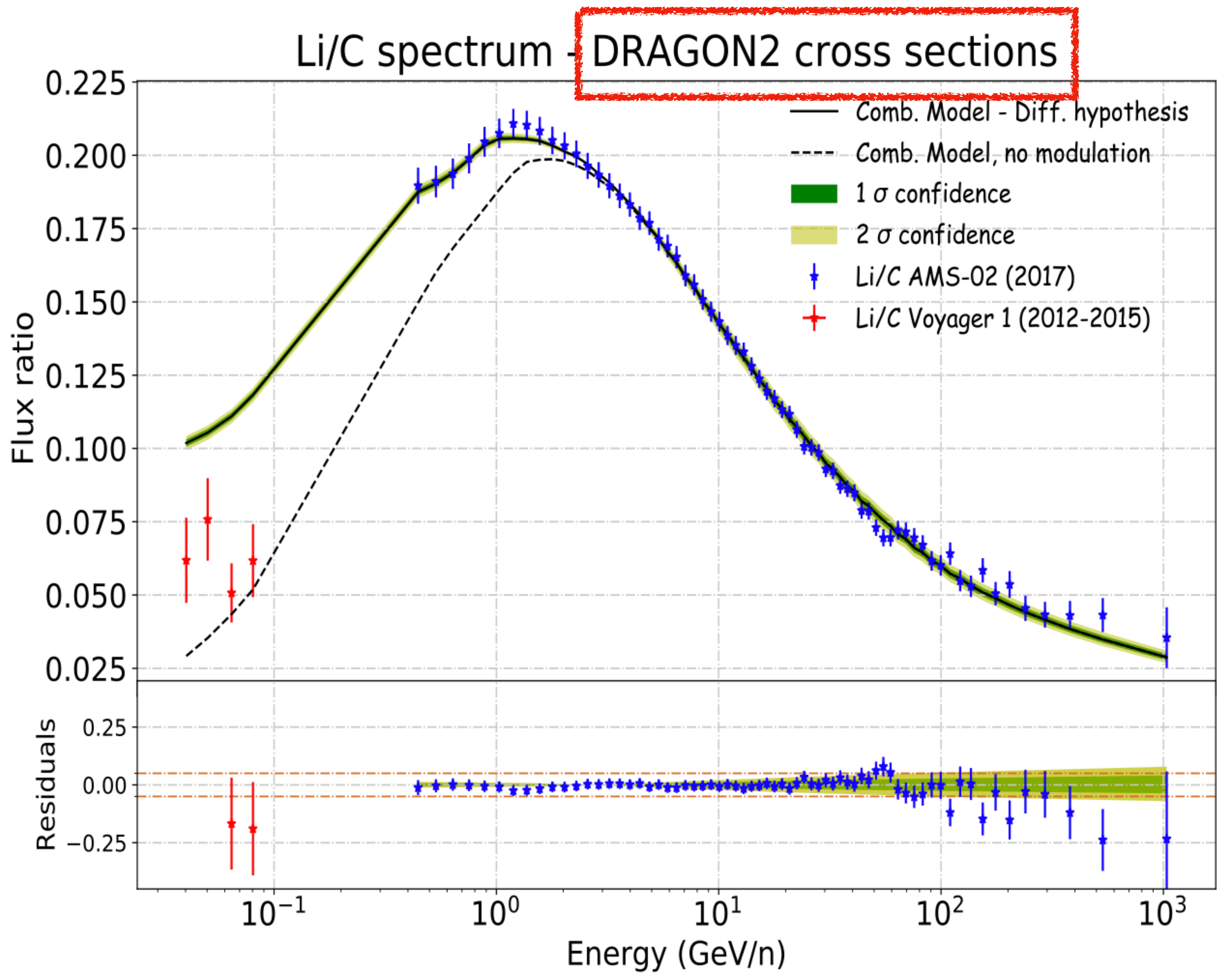
Comparison: Li production cross sections





[De la Torre Luque+ 2021]

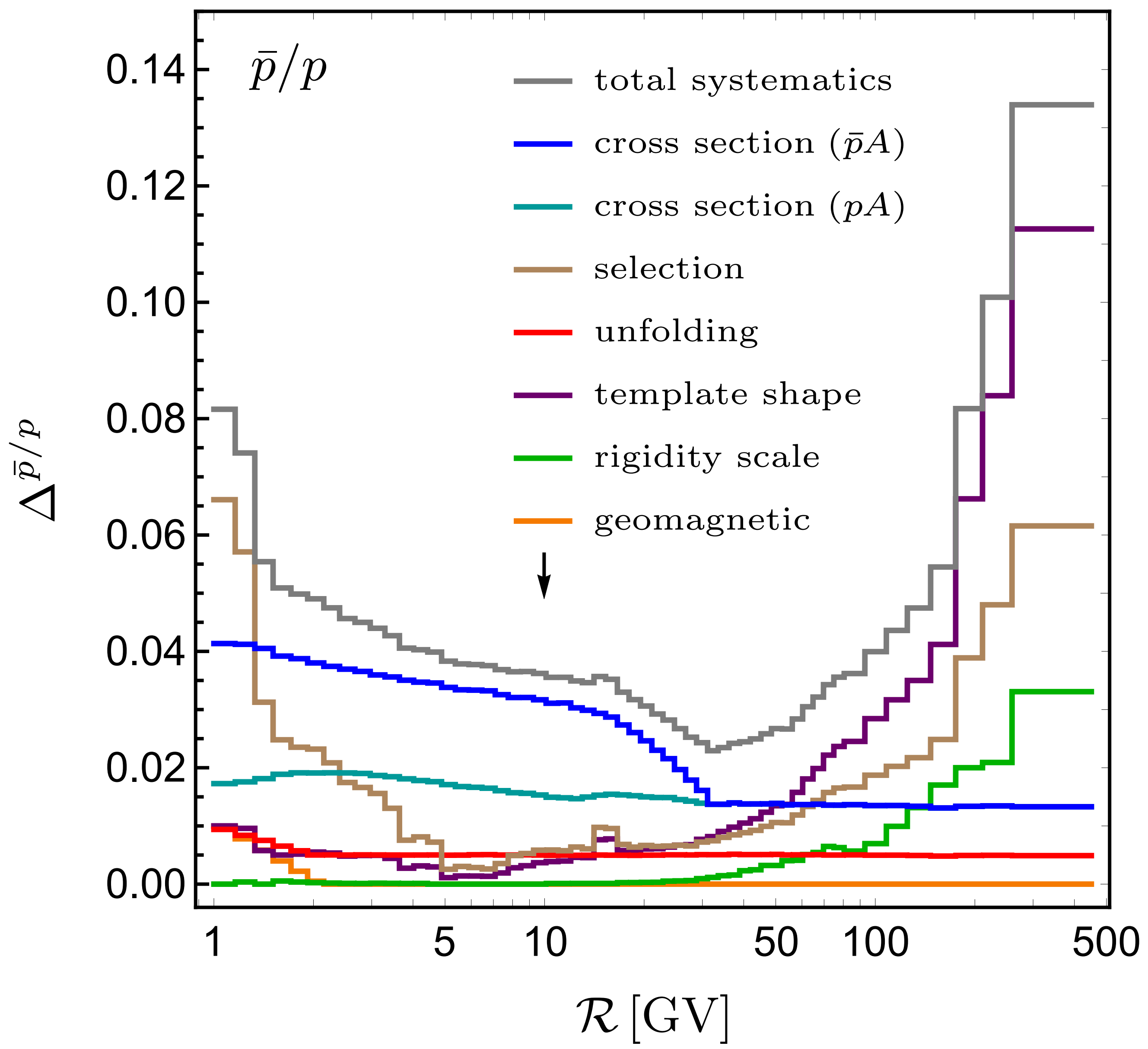
GALPROP cross sections:
Li is rescaled by 1.26

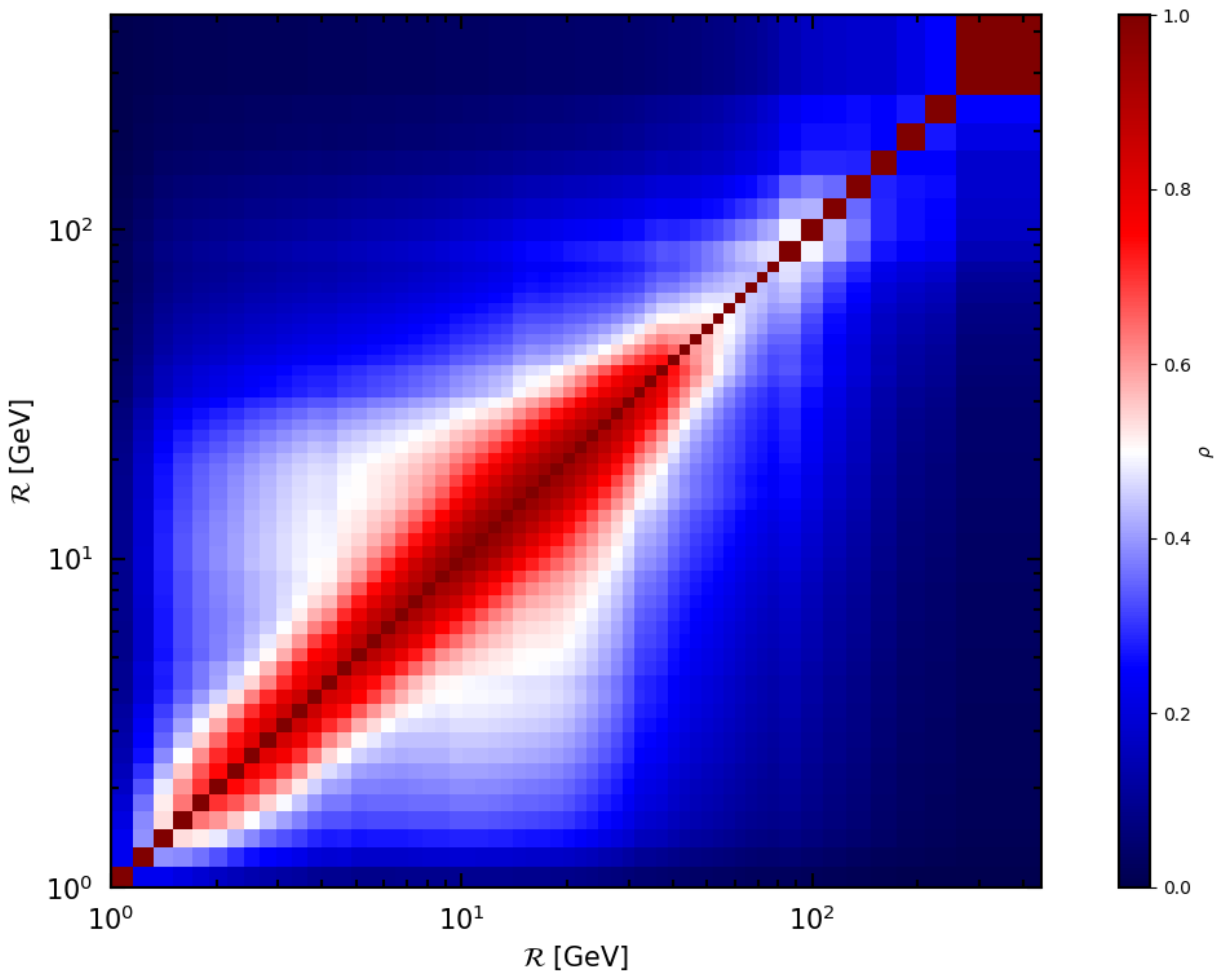
DRAGON2 cross sections:
Li is rescaled by 0.97

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

Correlation in the cosmic-ray data of AMS-02

[Heisig, MK, Winkler; PRR; 2020]





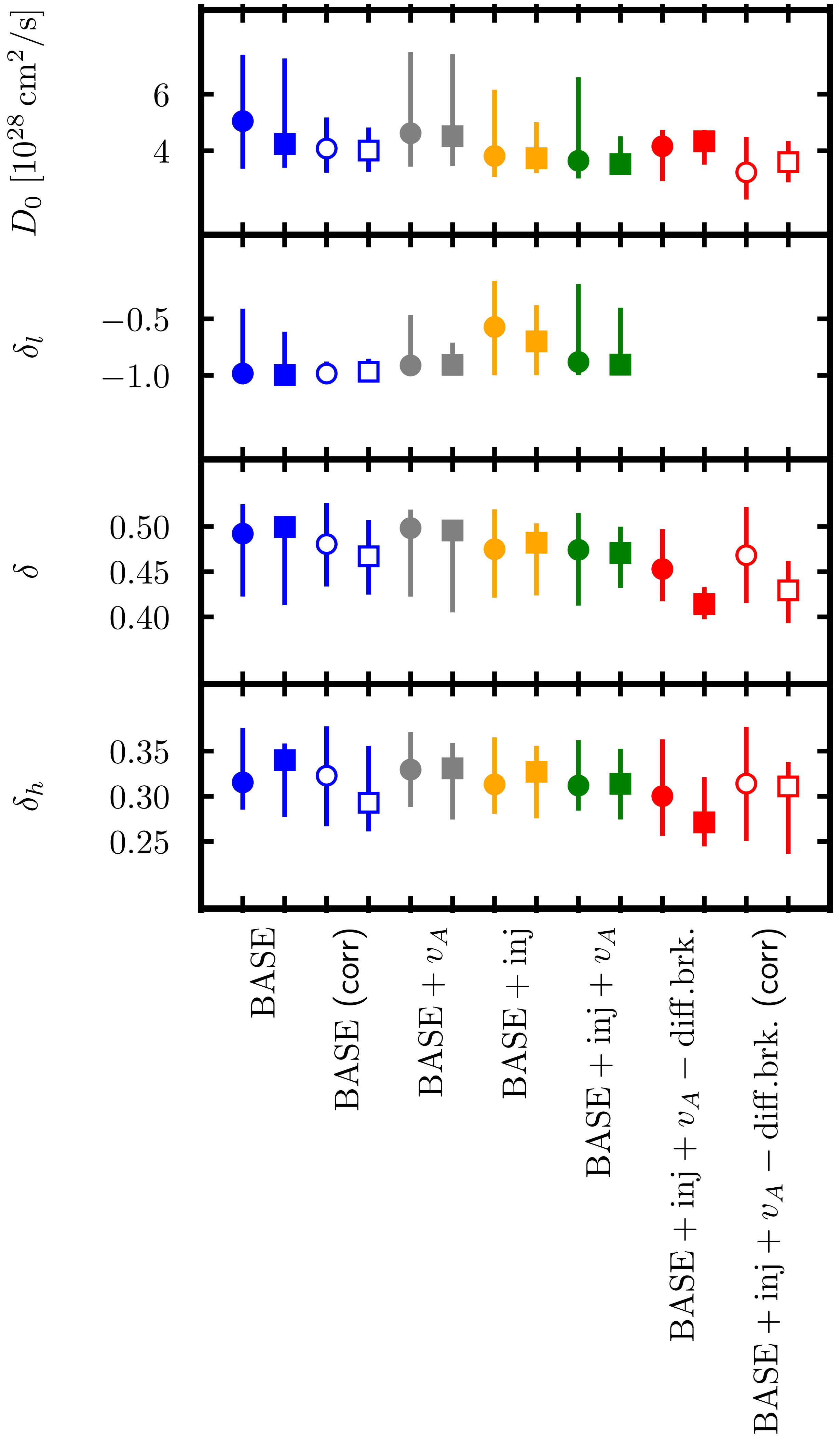
The AMS-02 collaboration does not provide the correlation of the flux data points

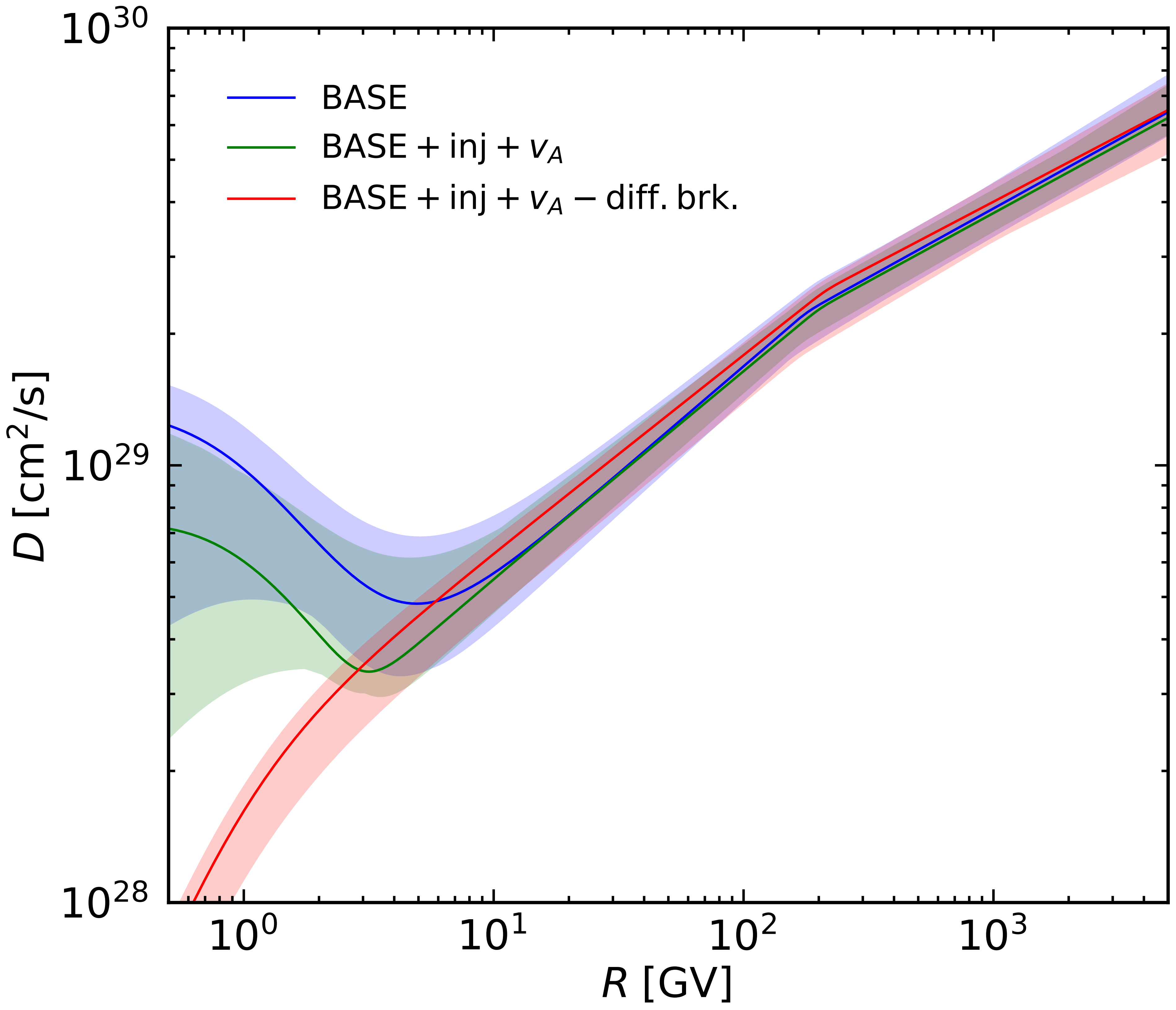
We model the covariance matrix by splitting the systematic uncertainties into separate contributions and attributing a correlation length to each contribution

The inclusion of correlation does not change our conclusions!

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

Parameter constraints

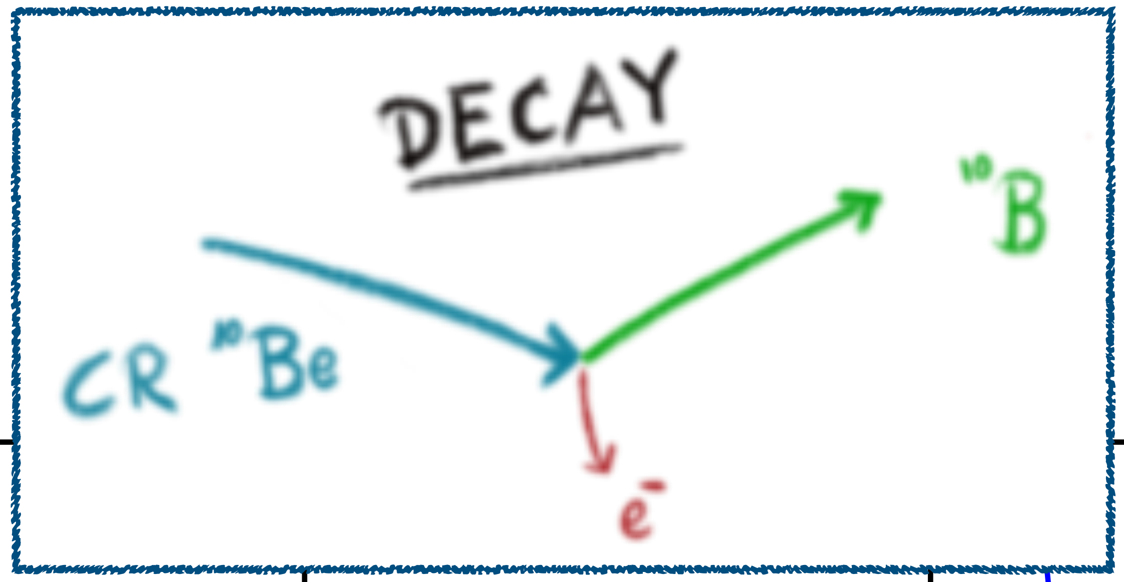




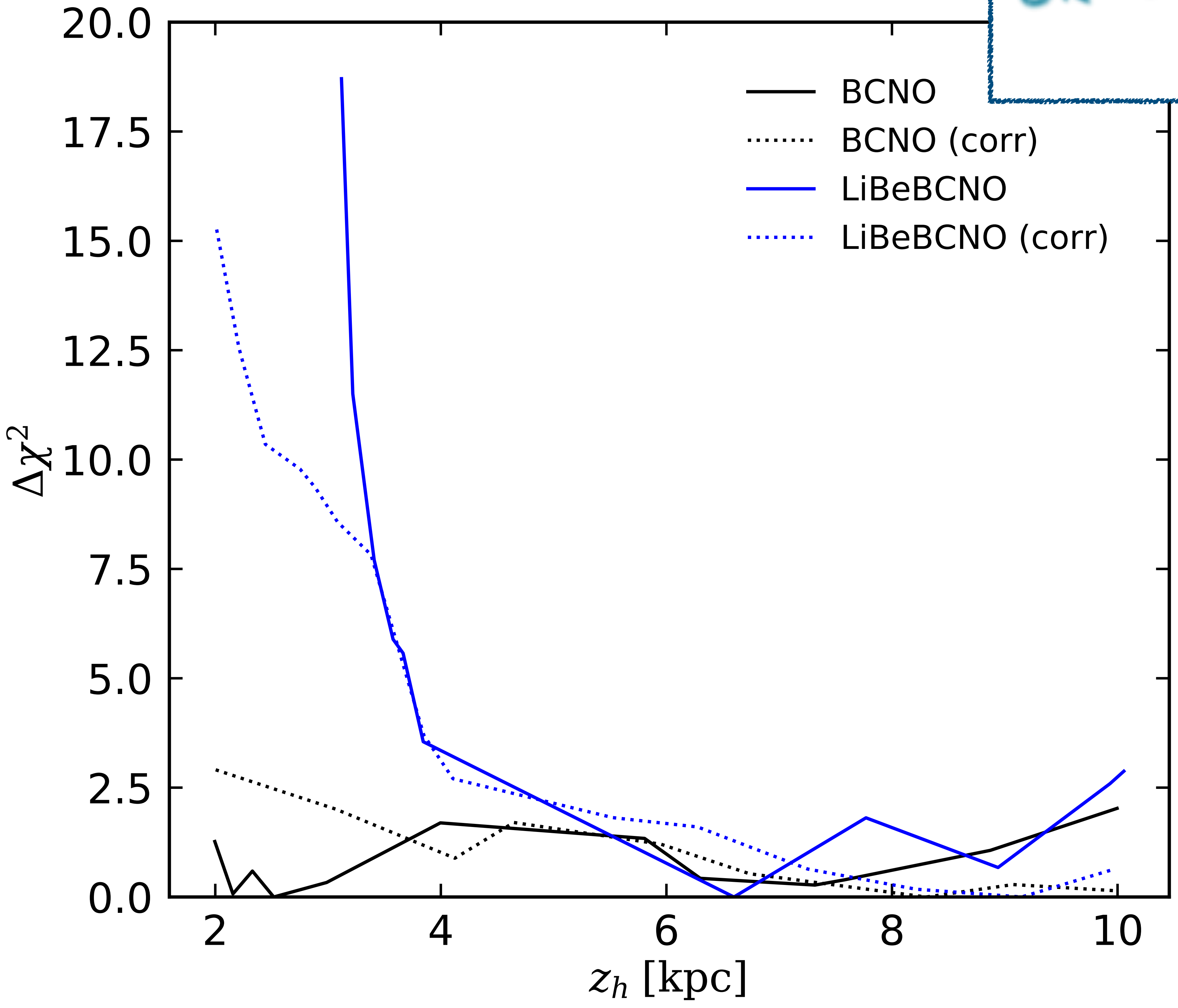
[MK, Cuoco, 2021]

The diffusion coefficient is well constrained above 10 GV

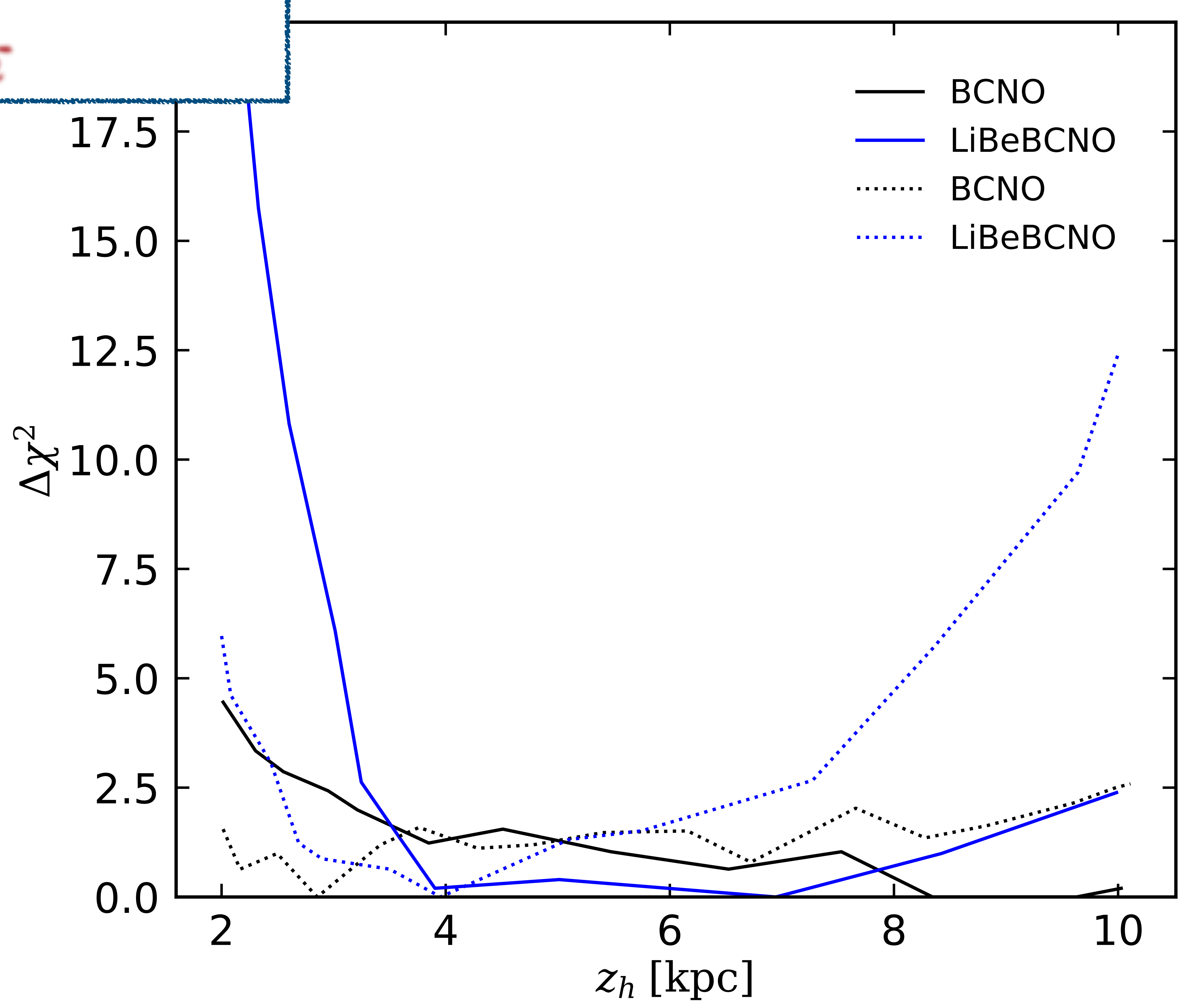
Parameter constraints



BASE



BASE+inj+vA-diff.brk

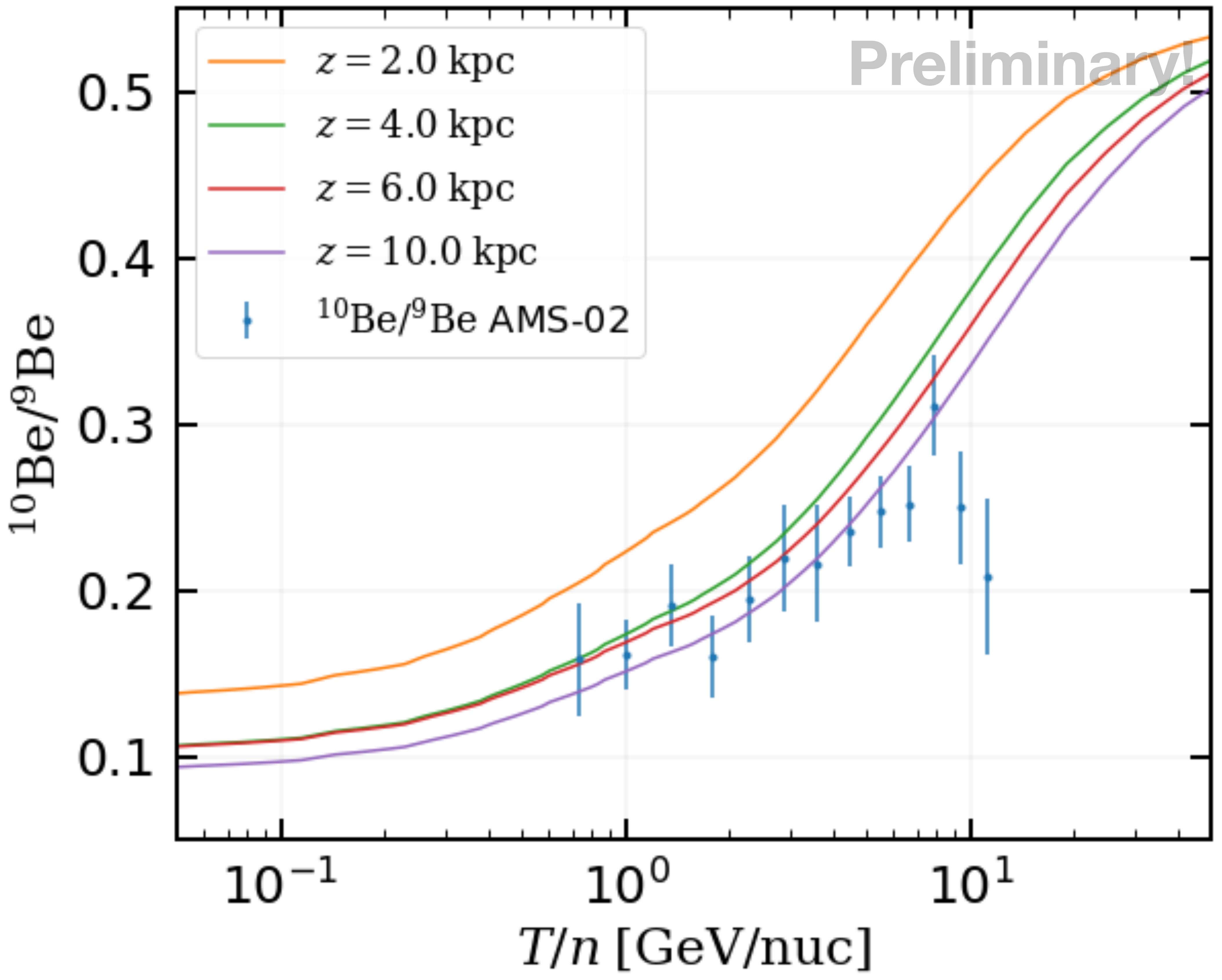


[MK, Cuoco, 2021]

The combination of B and Be data allows to constrain z_h

Recent $^{10}Be/^{9}Be$ data from AMS-02

BASE



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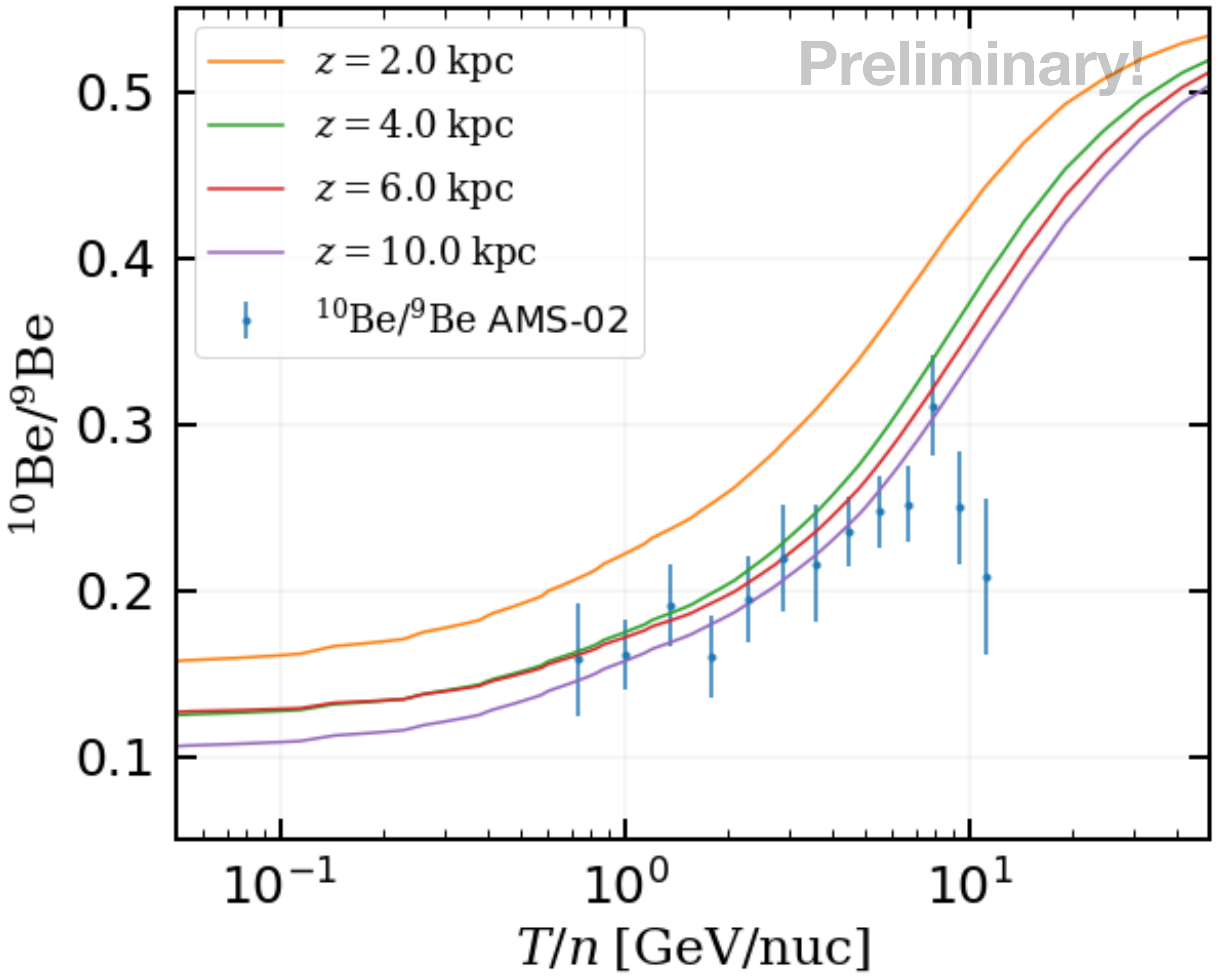
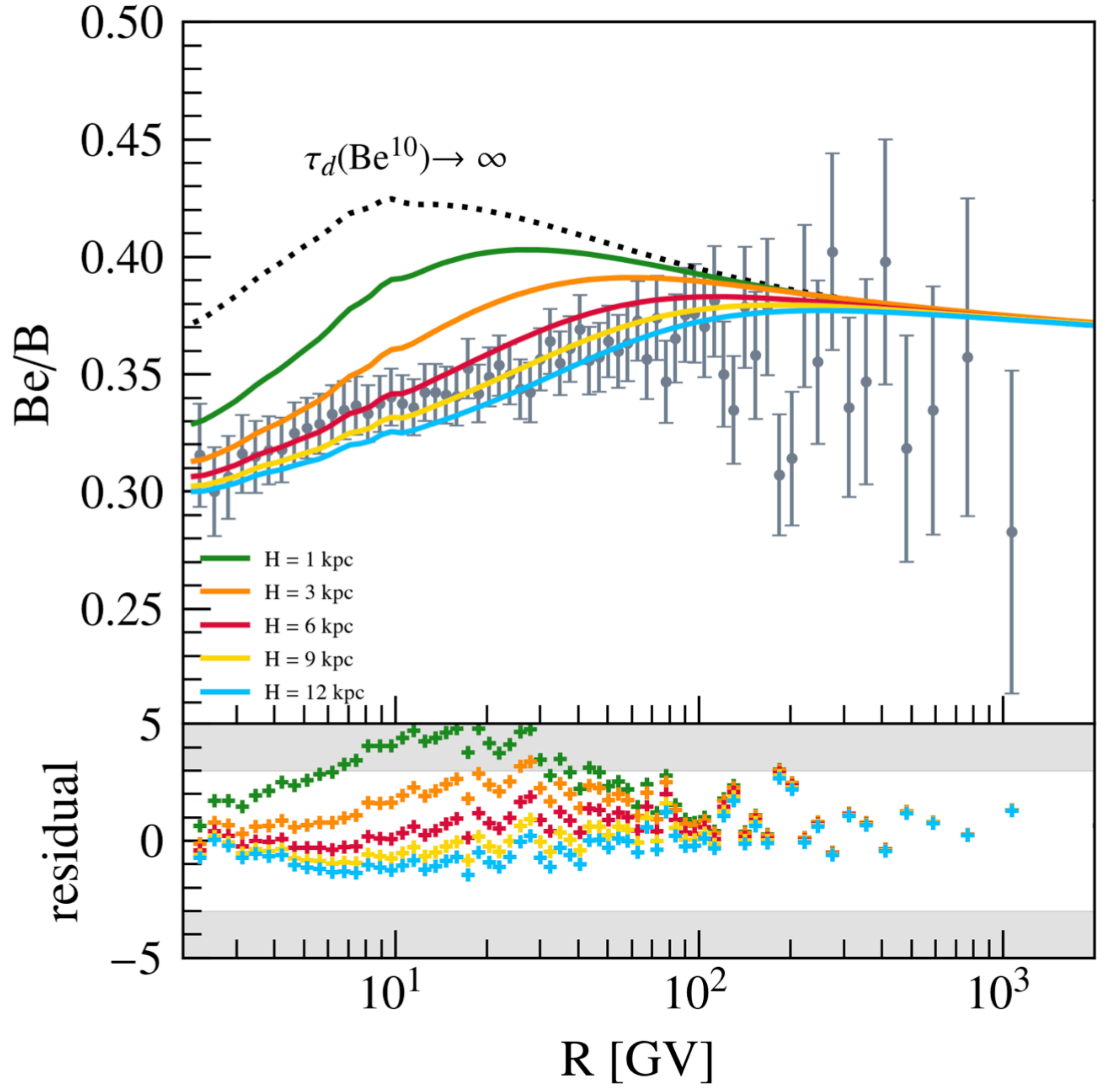
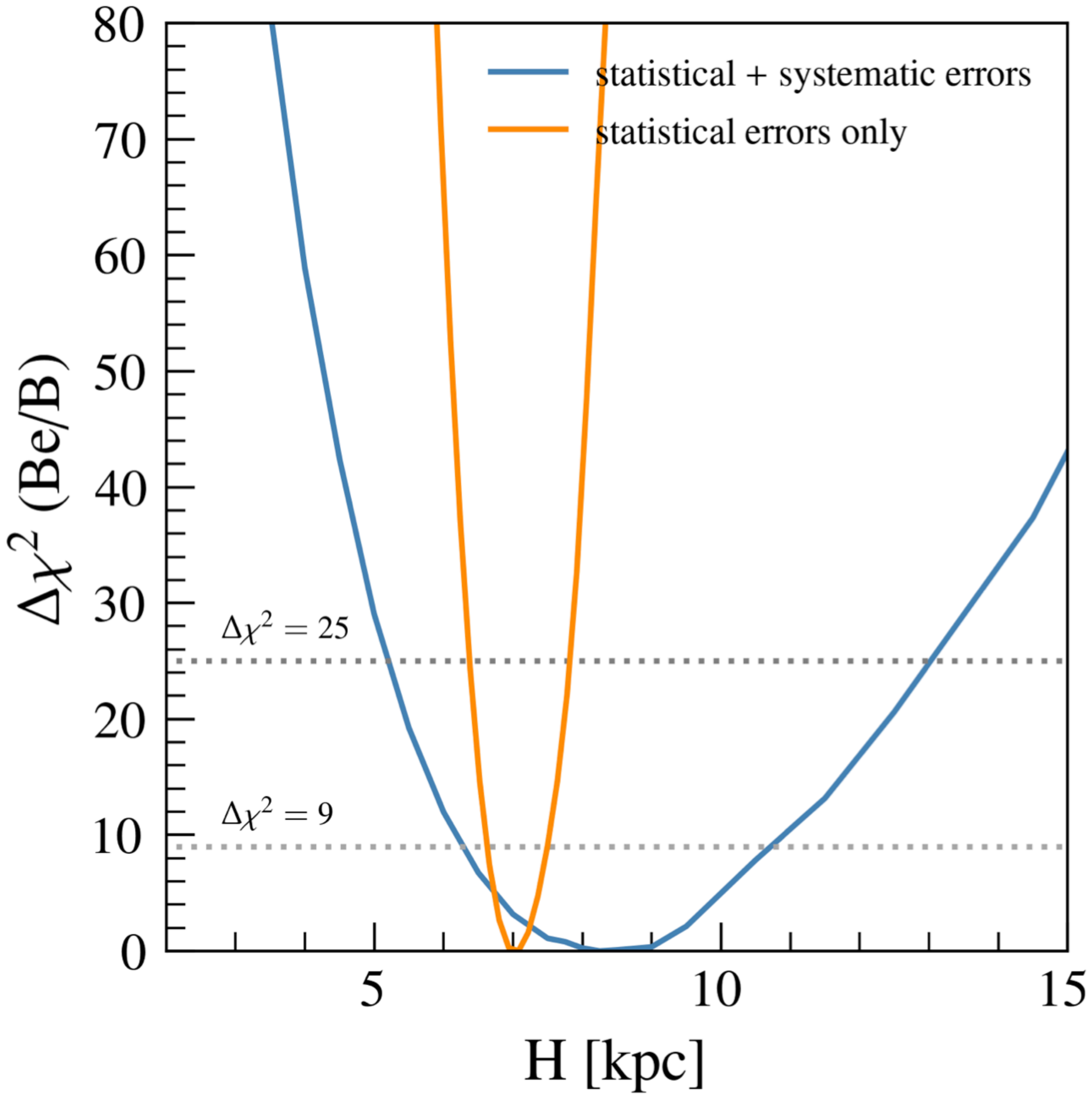


Preliminary AMS-02 data from [L.Derome; ICRC 2021]

This is a *prediction*! The data is not included in the fit!

Comparison: Constraints on the diffusion halo





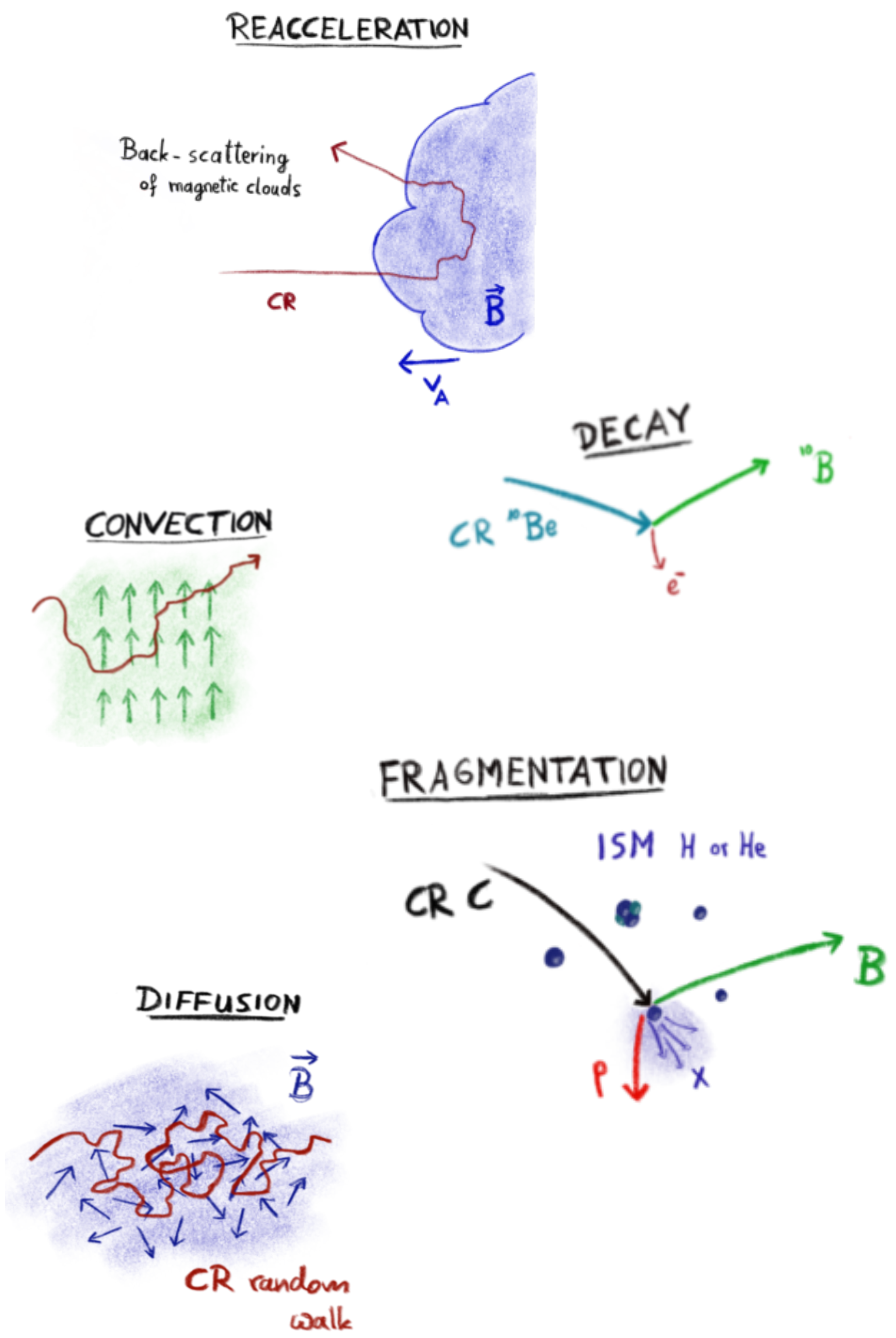
[Evoli+ 2019]

See also: [Weinrich+ 2020]

CR nuclei from Li to O are consistent with the traditional CR diffusion models

Uncertainties in the secondary fragmentation cross sections prevent better understanding of propagation

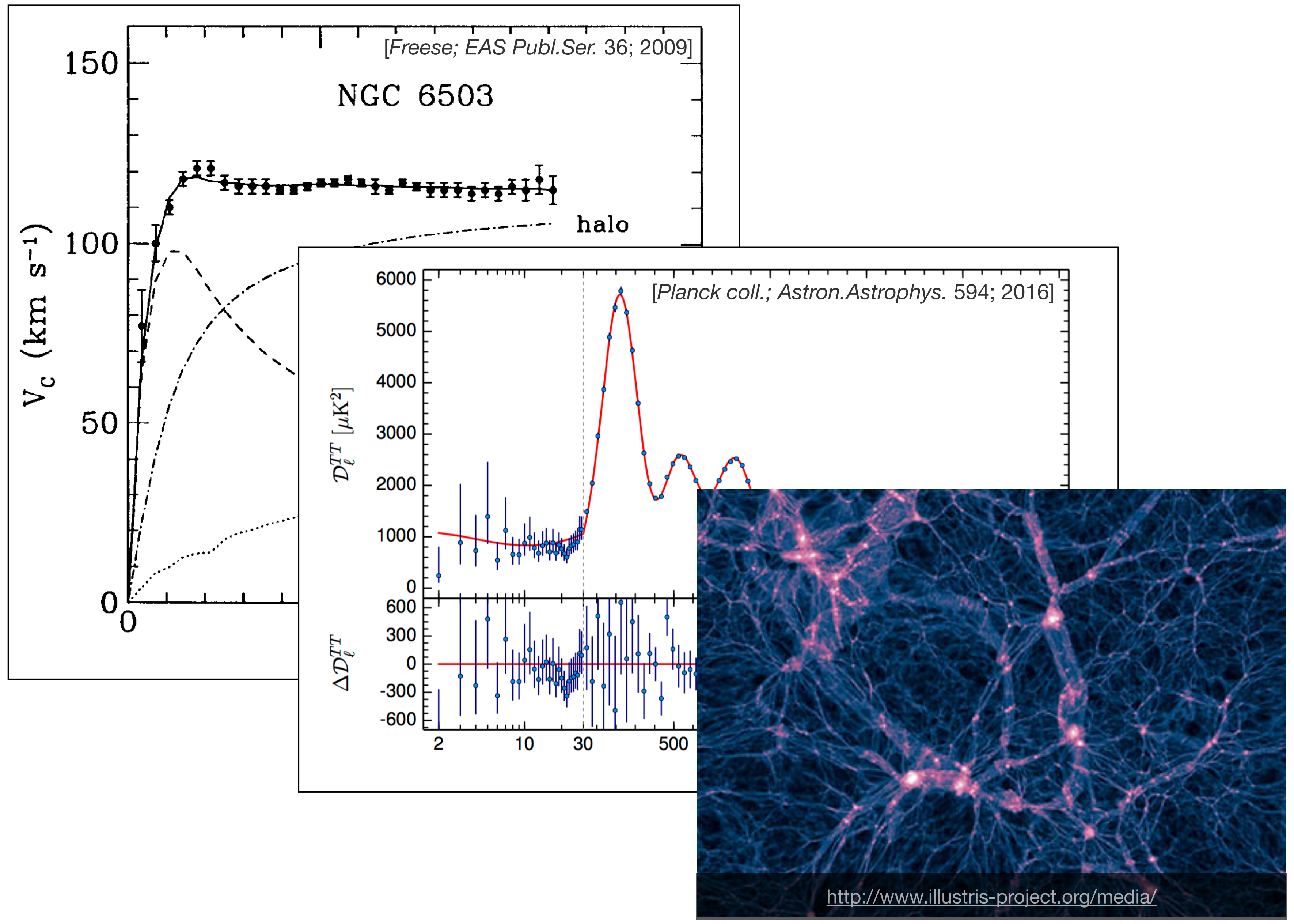
Small halo heights of $z_\mathrm{h} < 3\ \mathrm{kpc}$ are disfavored and the diffusion coefficient is well constrained above 10 GeV



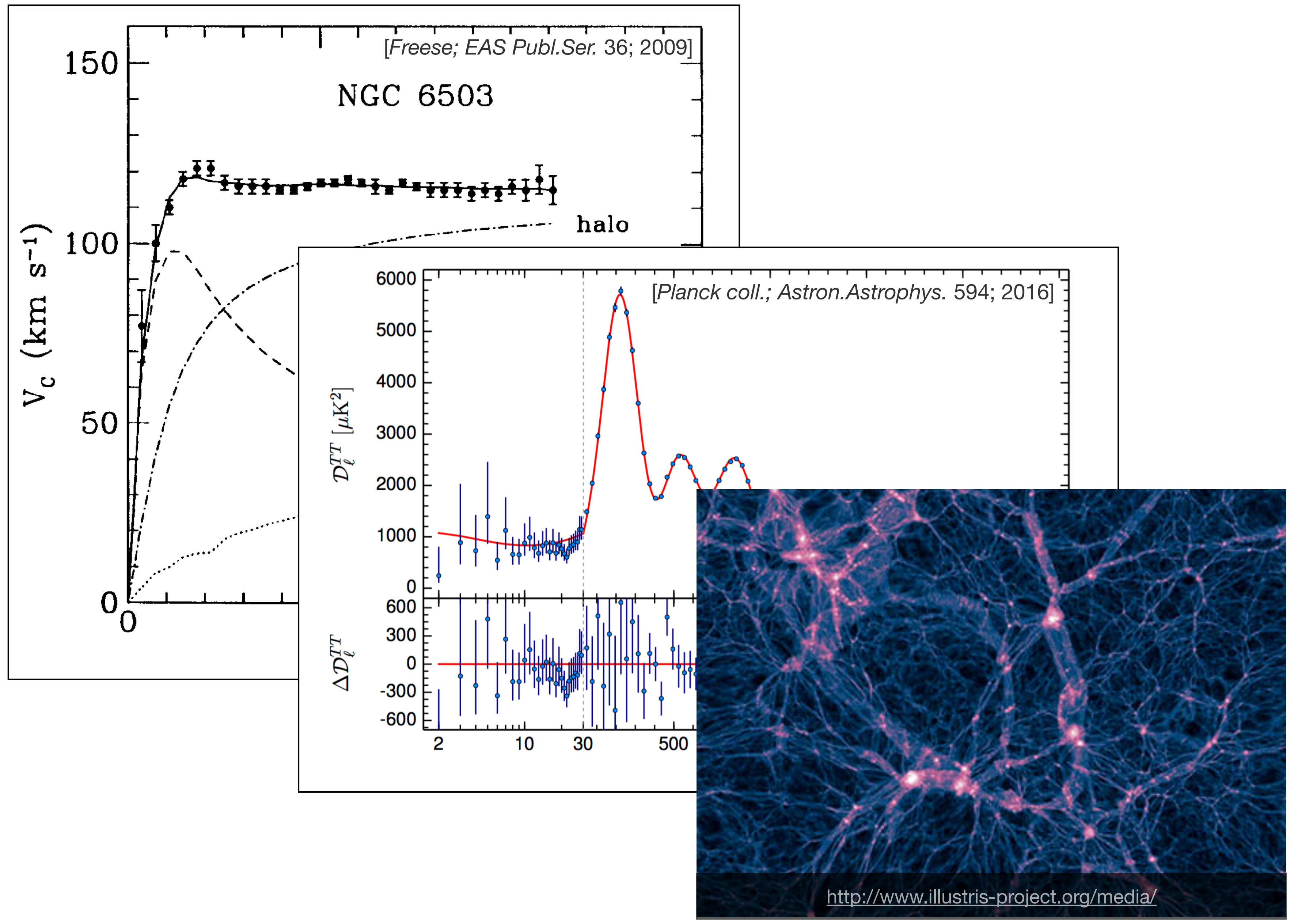
Outline

- Introduction
- Global fit of CR data from Li to O
- **CR antiprotons**
- **CR antideuteron**
- **Conclusion**

Motivation



Gravitational evidence at various scales is overwhelming.



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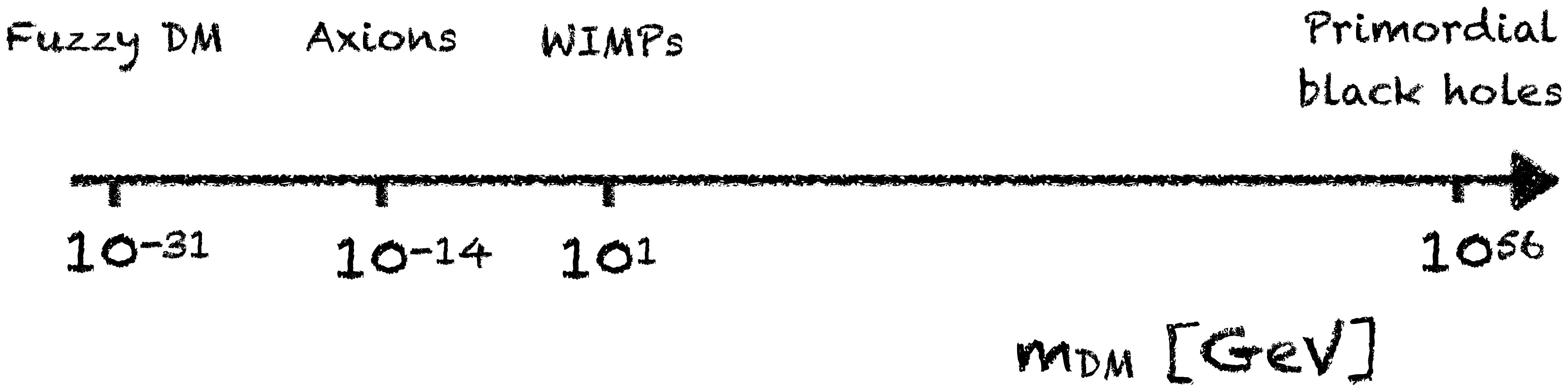
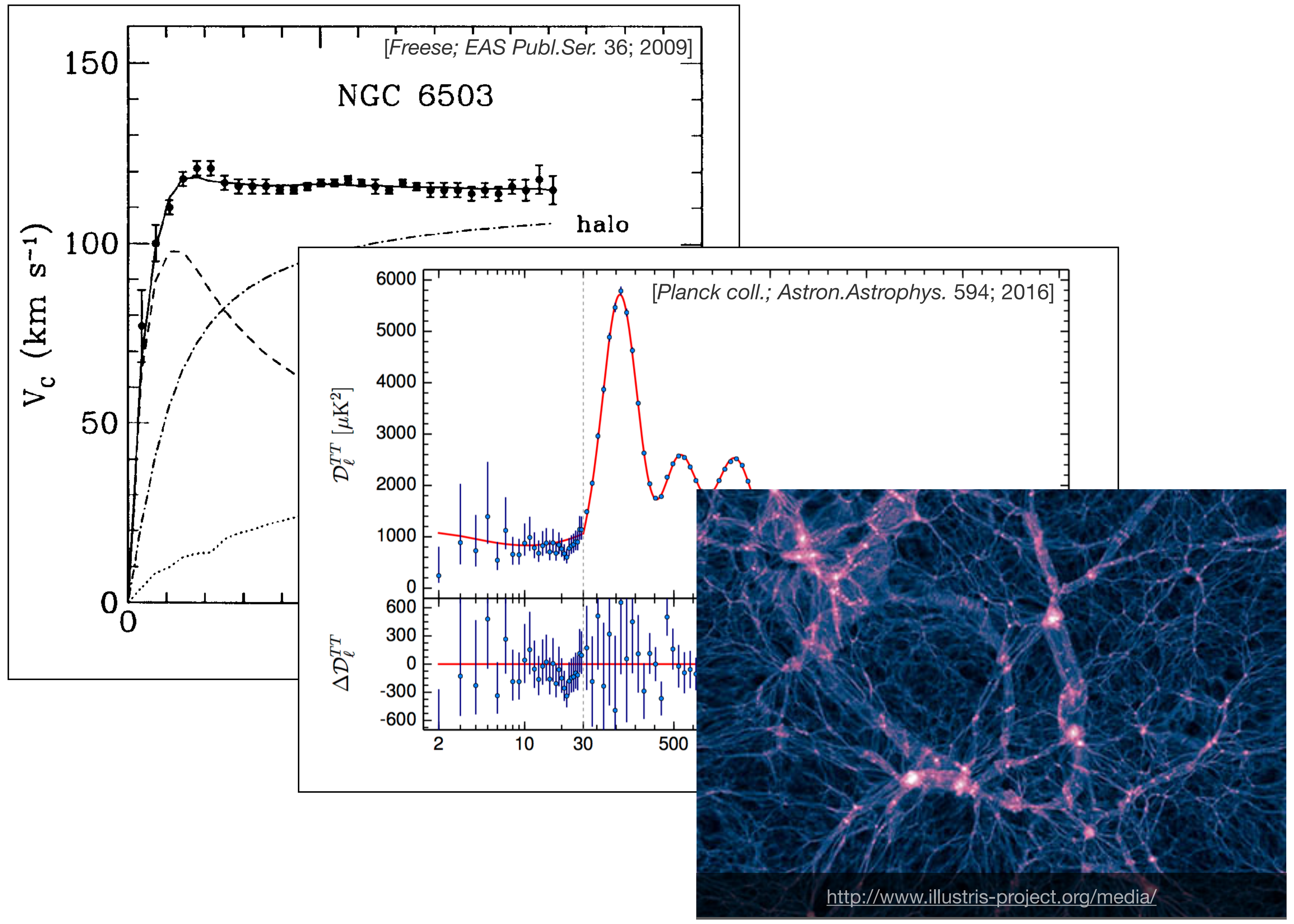


Nature of dark matter remains unknown!

Motivation



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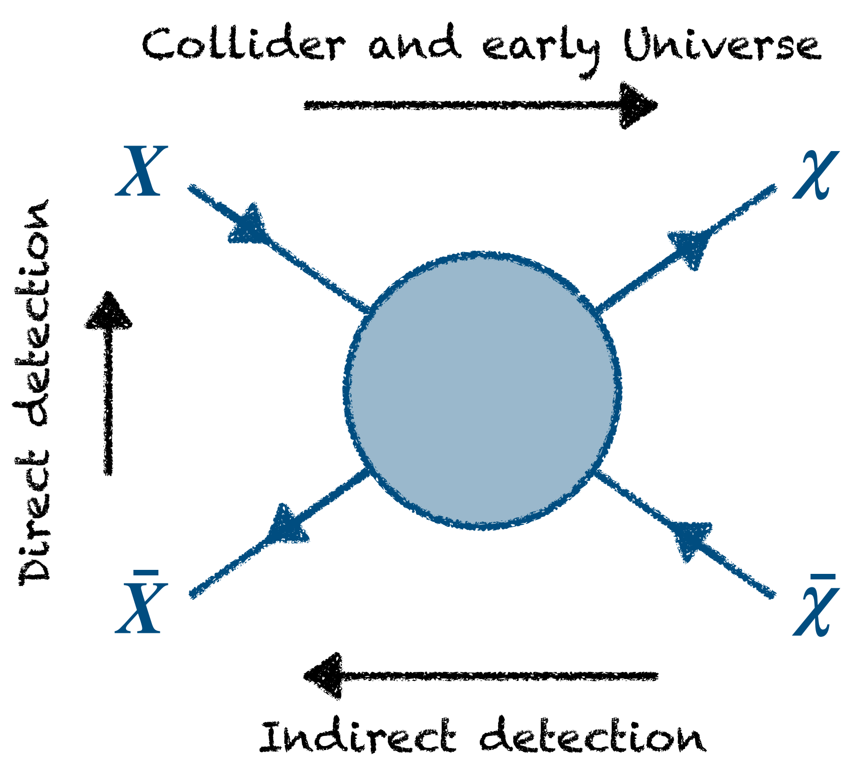
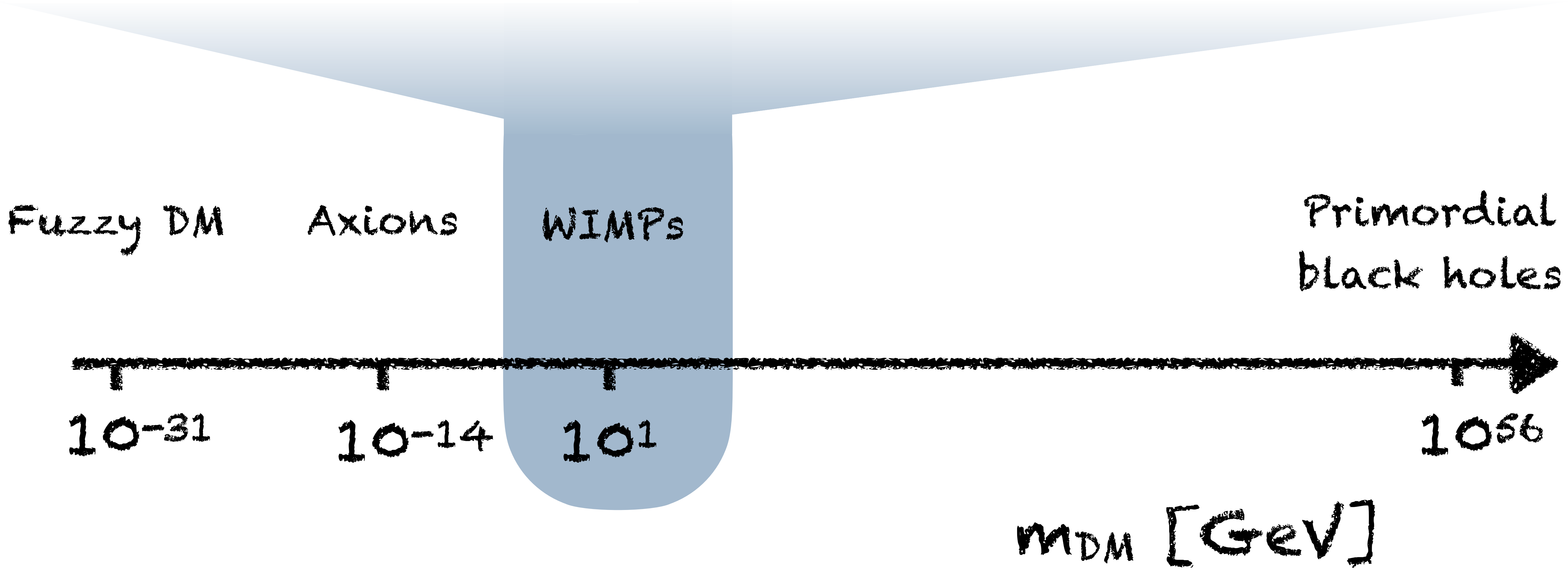


- Mass range 1 GeV to 100 TeV
- Various search strategies
- We focus on indirect detection with **cosmic rays** and γ-rays



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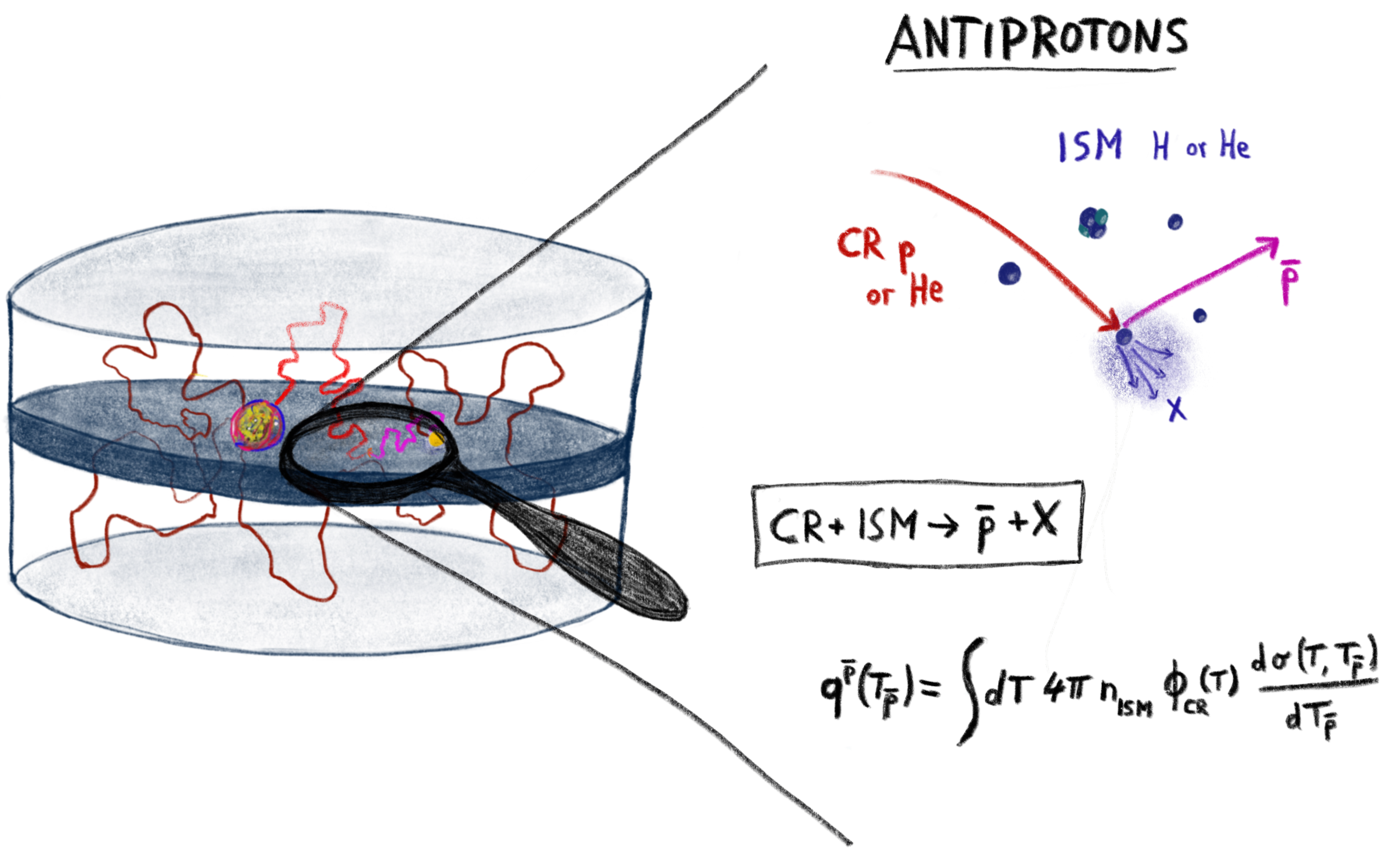
Secondary antiprotons in cosmic rays



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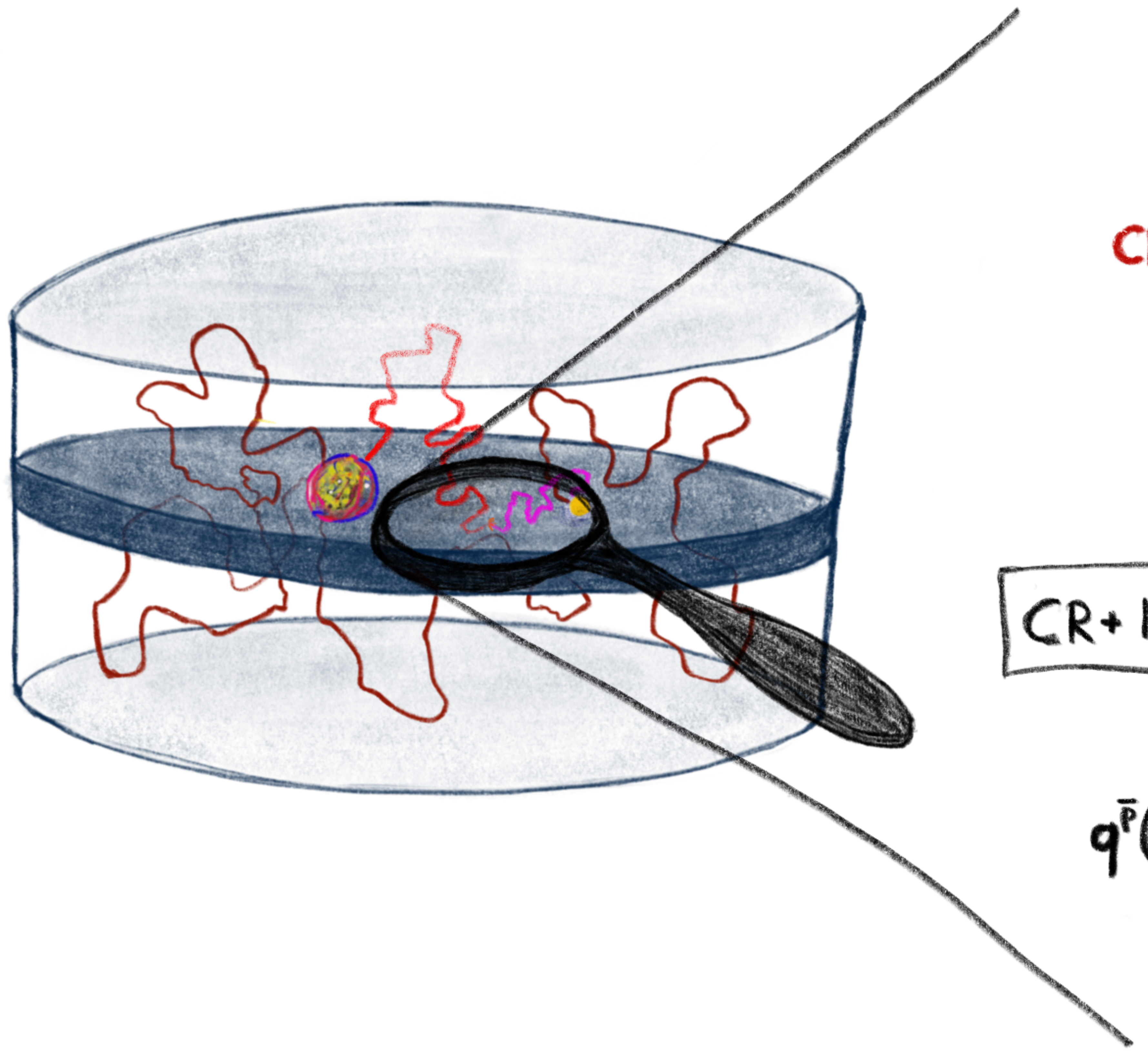
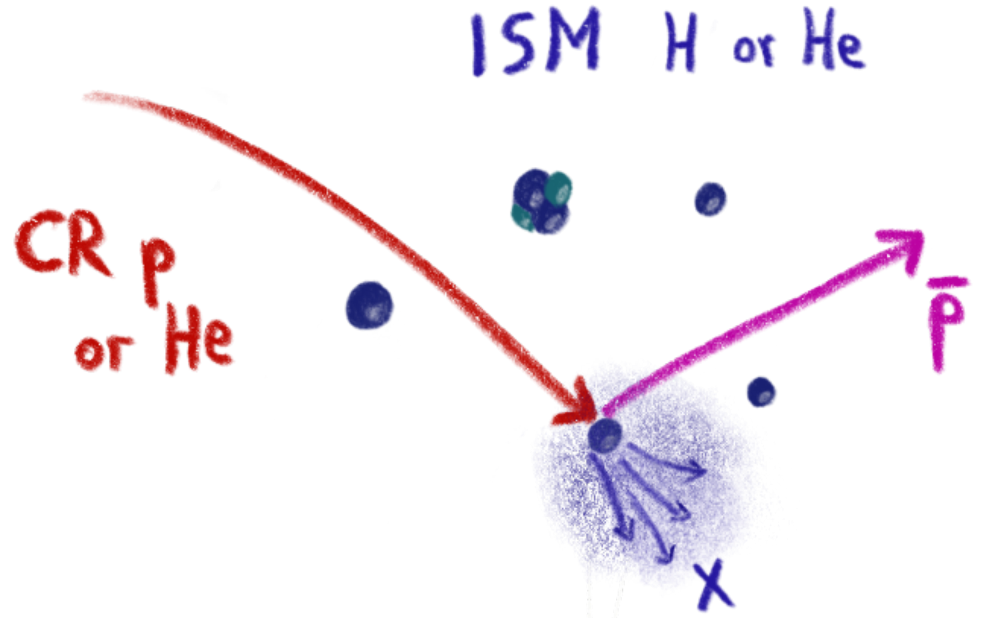
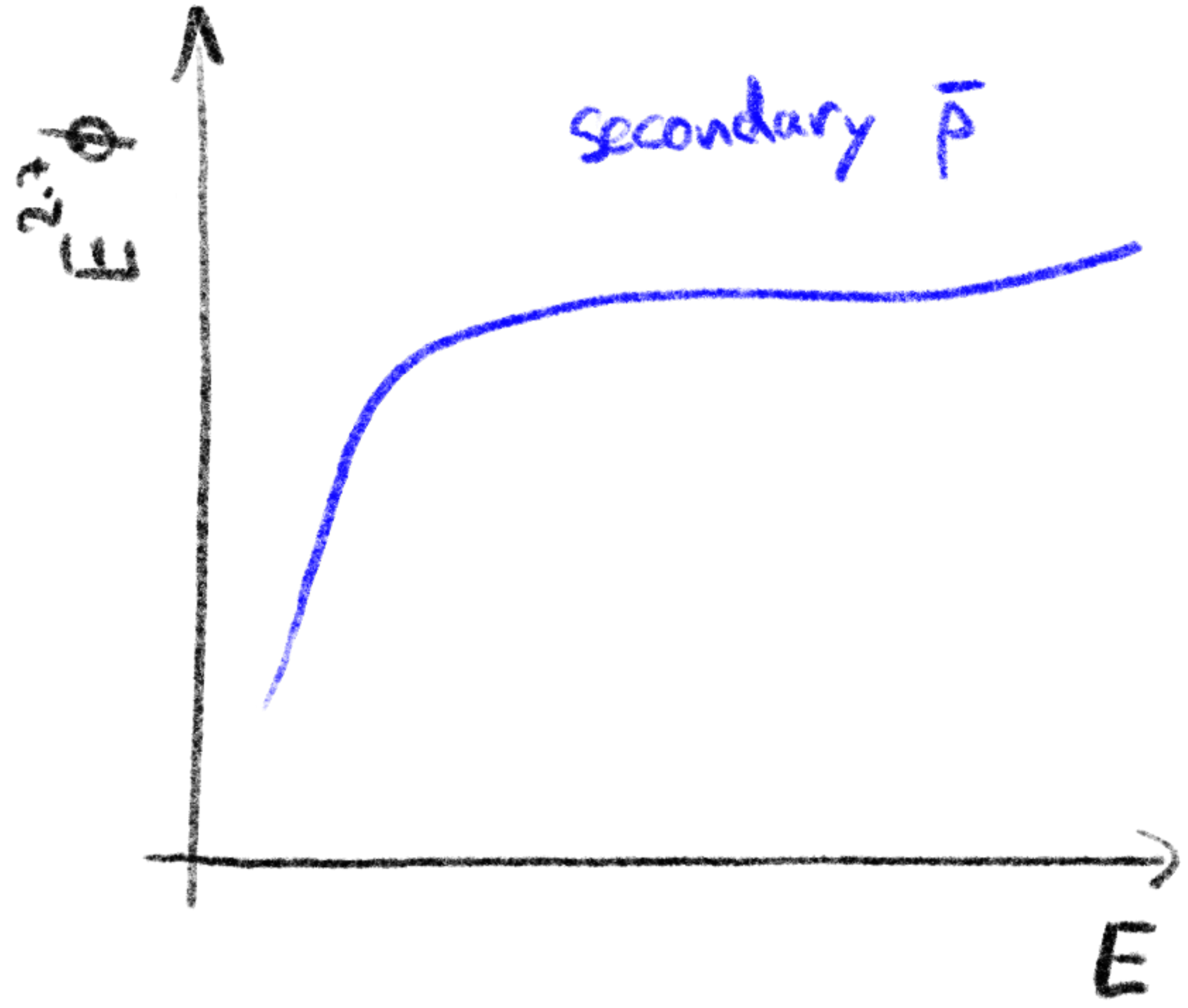


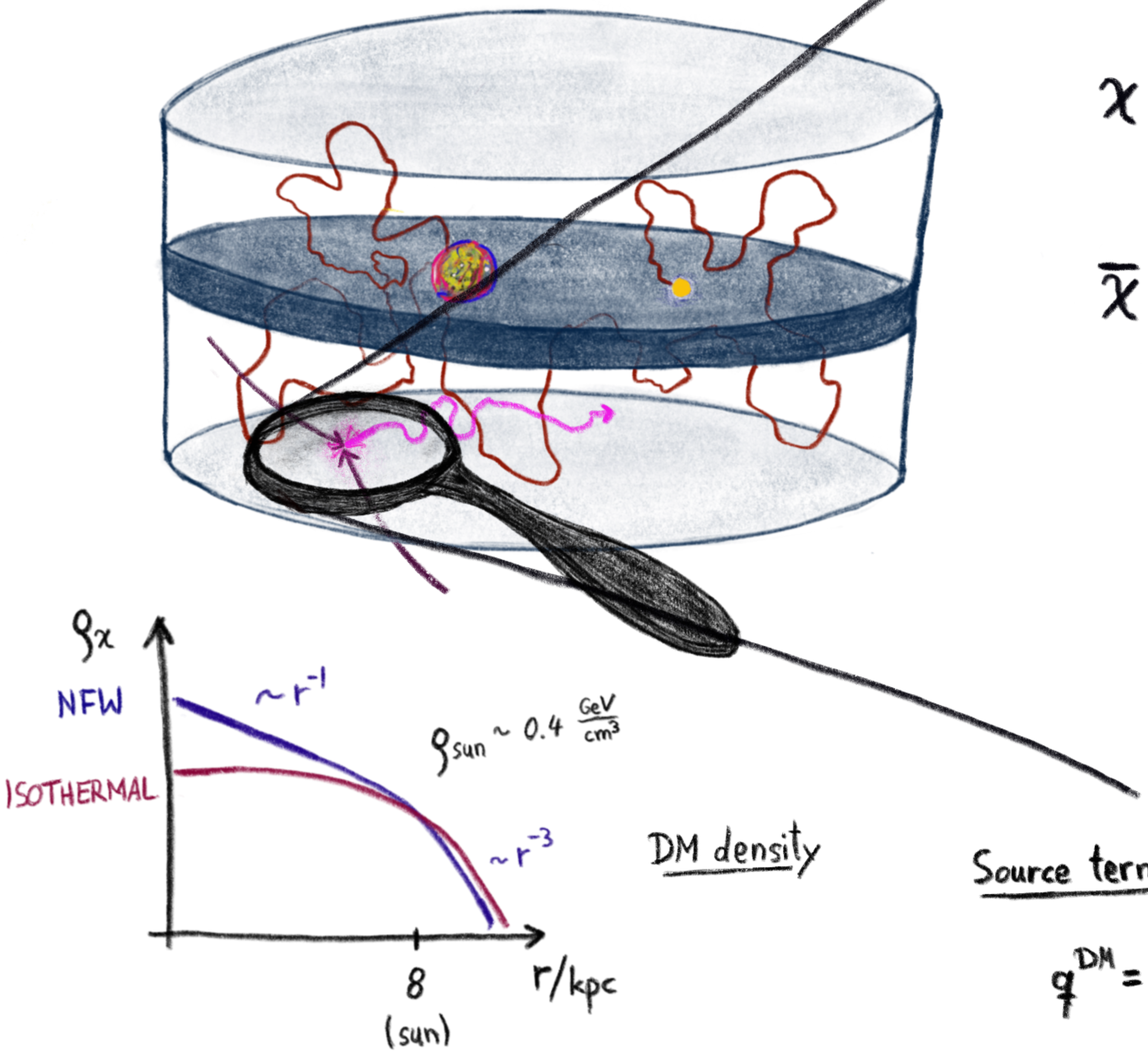
ANTIPROTONS



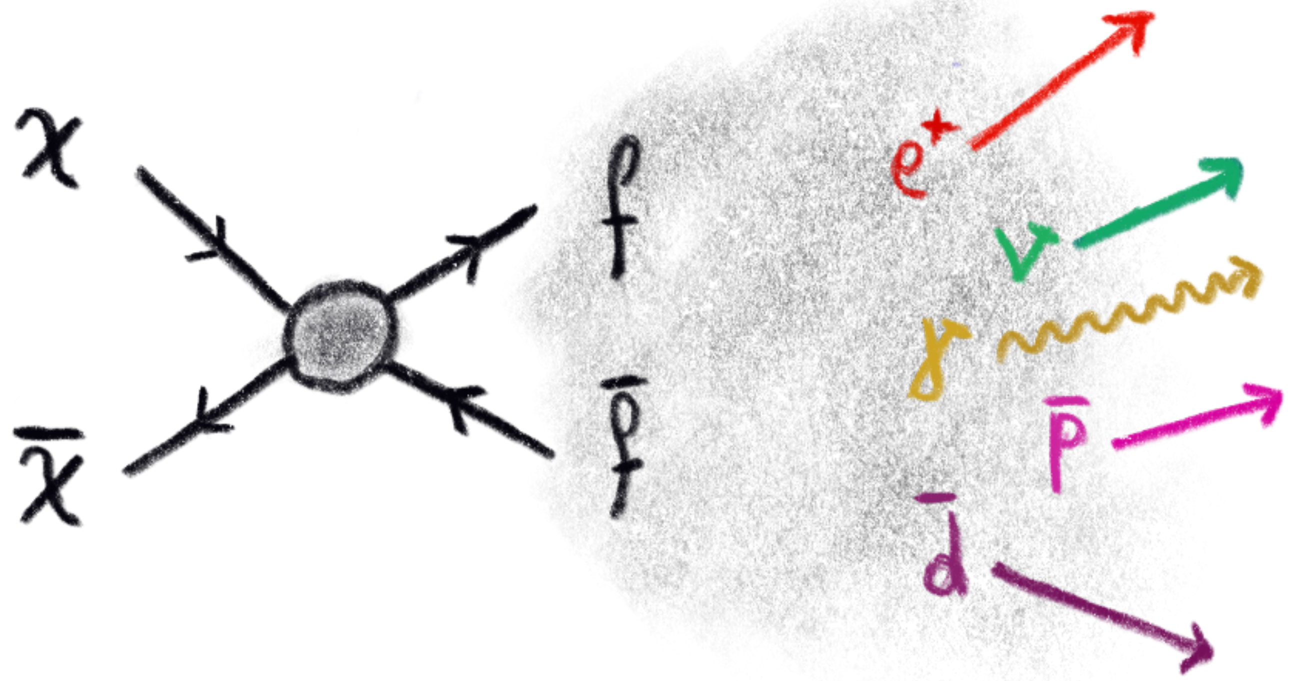
$$CR + ISM \rightarrow \bar{p} + X$$

$$q^{\bar{p}}(T_{\bar{p}}) = \int dT \, 4\pi \, n_{ISM} \, \phi_{CR}(T) \, \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$





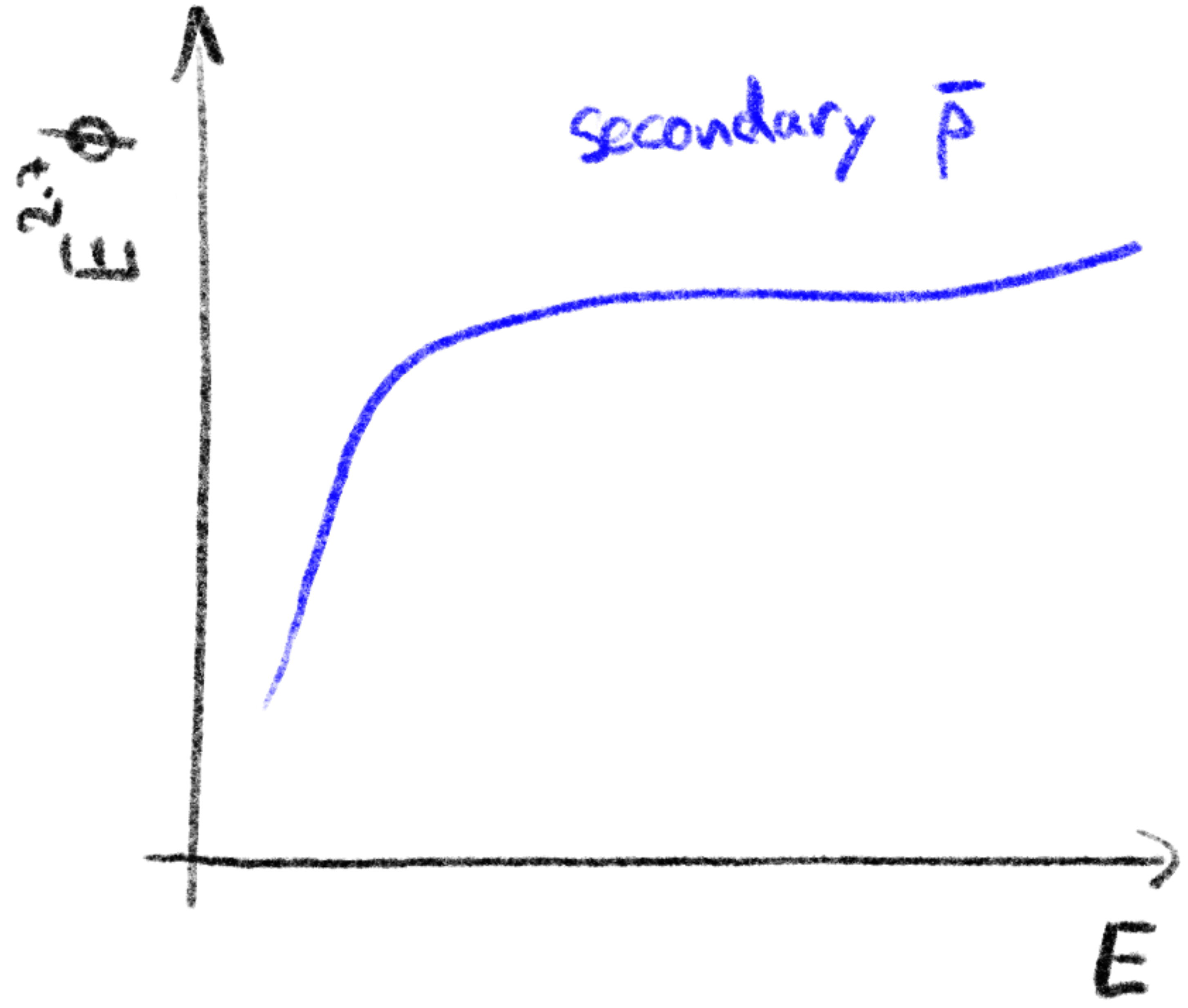
DM ANNIHILATION



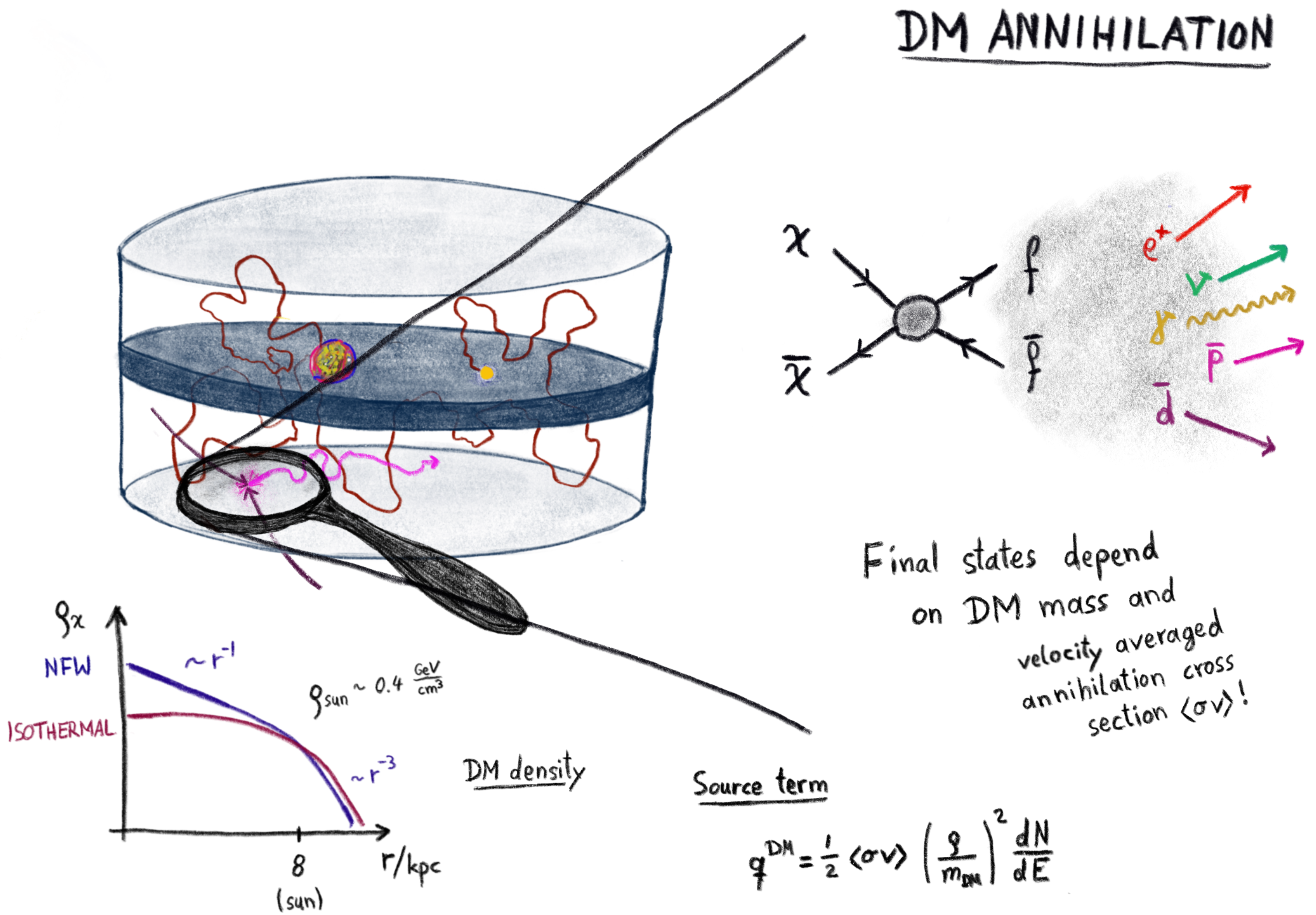
Final states depend on DM mass and velocity averaged annihilation cross section $\langle \sigma v \rangle$!

Source term

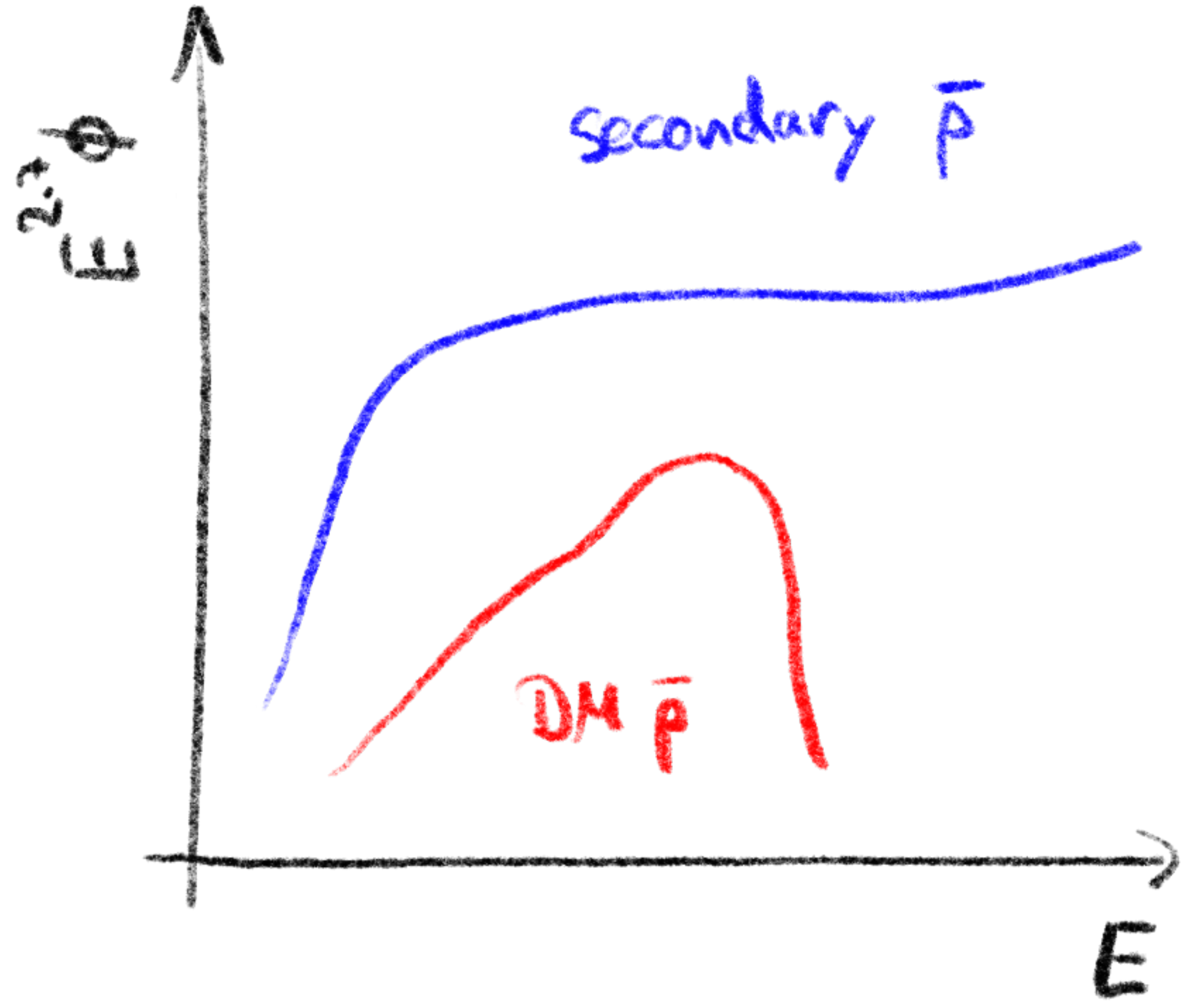
$$q^{DM} = \frac{1}{2} \langle \sigma v \rangle \left(\frac{\rho}{m_{DM}} \right)^2 \frac{dN}{dE}$$



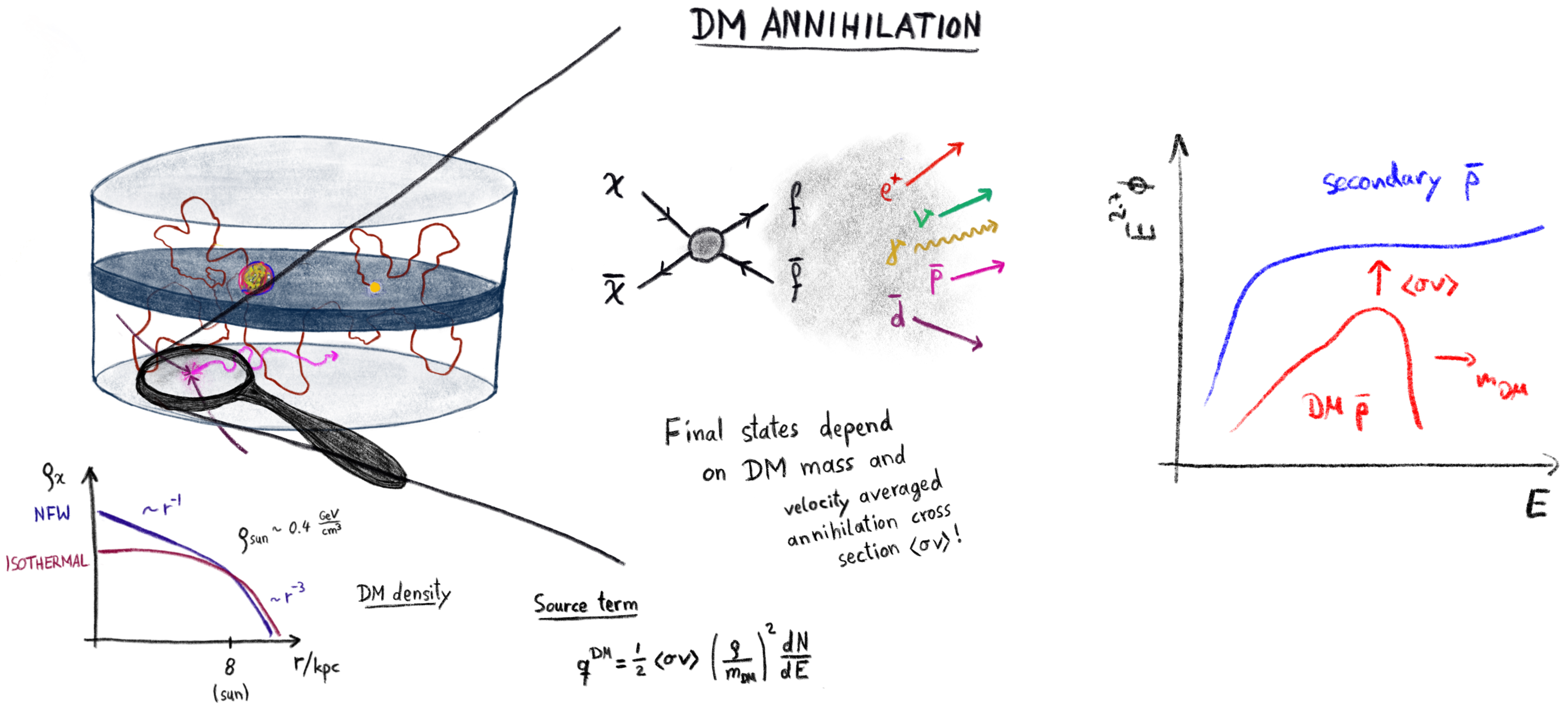
Antiprotons from DM annihilation



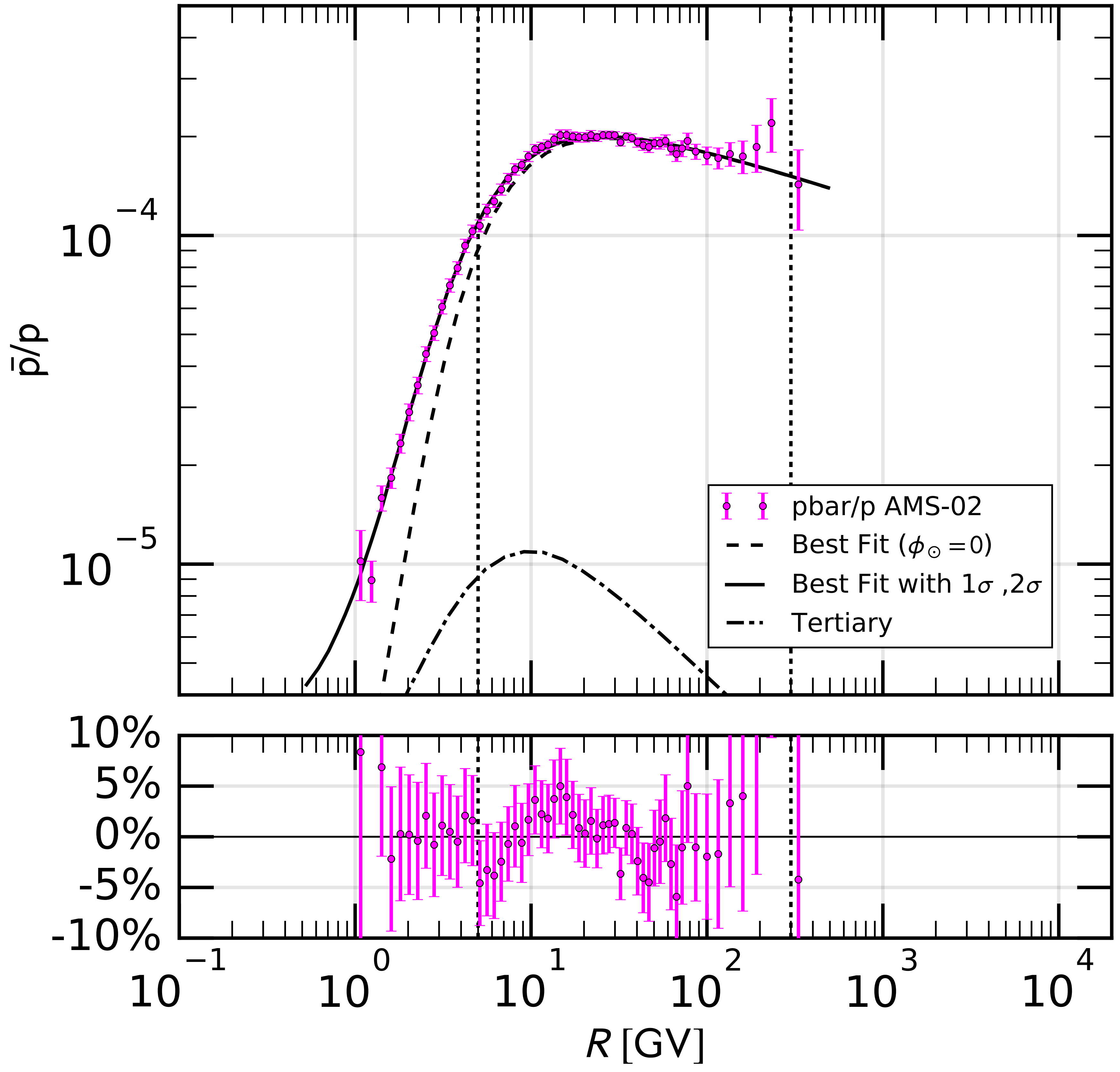
$$q^{DM} = \frac{1}{2} \langle\sigma v\rangle \left(\frac{\rho}{m_{DM}}\right)^2 \frac{dN}{dE}$$

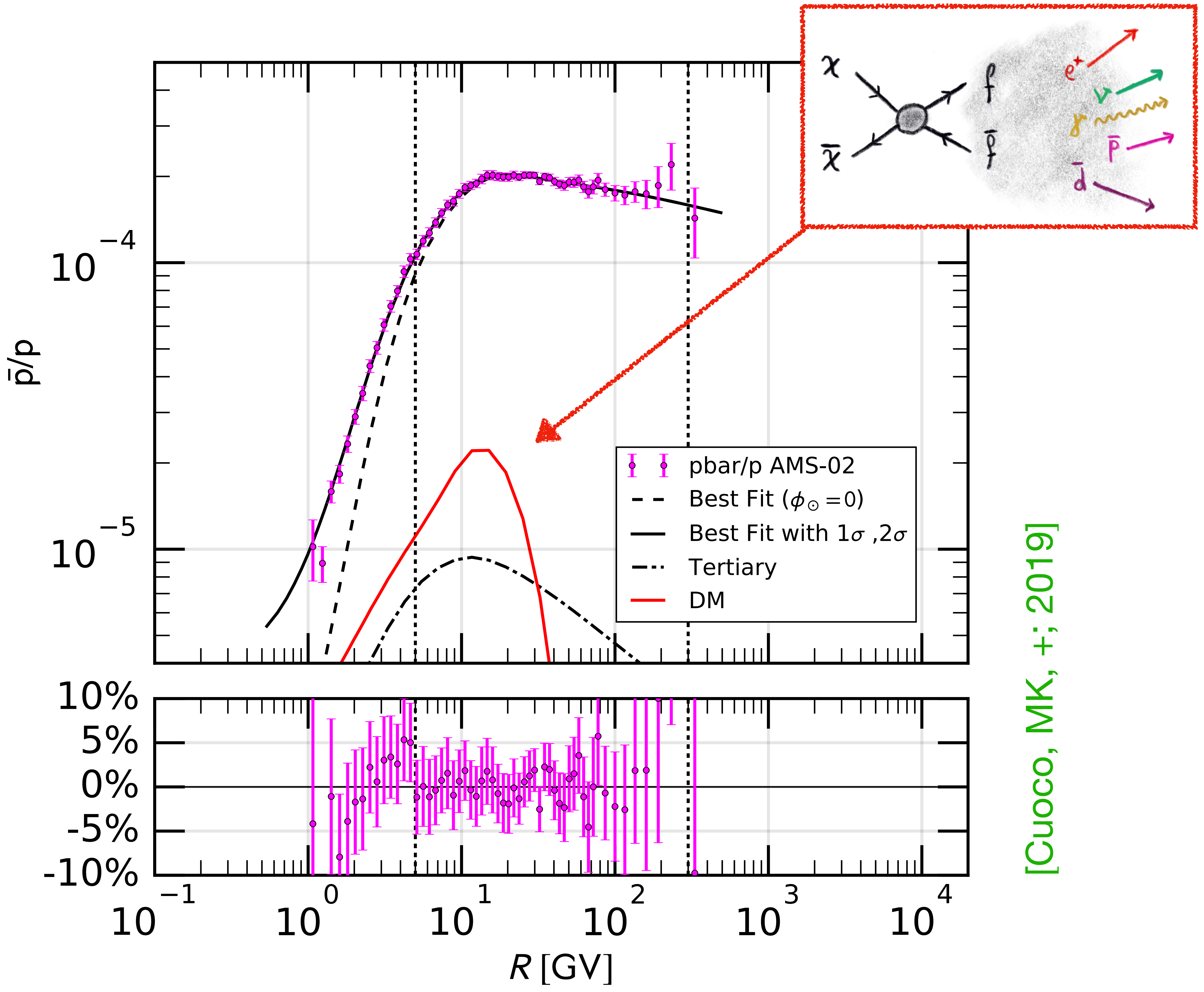


Antiprotons from DM annihilation



Fitting CR antiprotons





[Cuoco, MK, +; 2019]

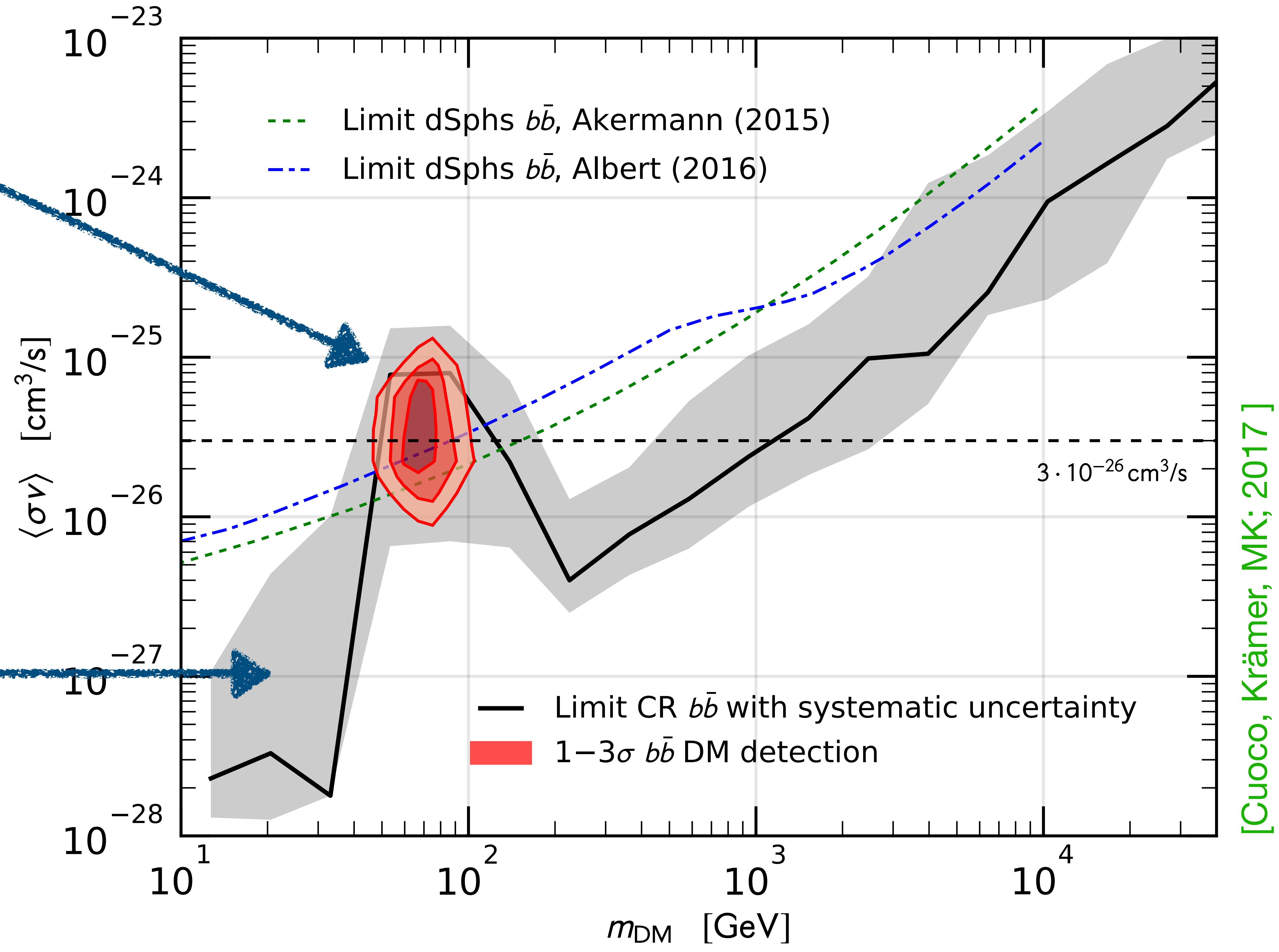
A hint for a DM signal?

Progressive interpretation:

- Hint for a potential DM signal at $m_{\mathrm{DM}} \sim 70$ GeV (for $b\bar{b}$) and a thermal annihilation cross section
- Statistical significance ($\Delta\chi^2 = 24 \;\rightarrow\; 4.5\,\sigma$)
- Systematic uncertainties are difficult to access

Conservative interpretation:

- We find strong limits on DM annihilation for $m_{\mathrm{DM}} > 200$ GeV

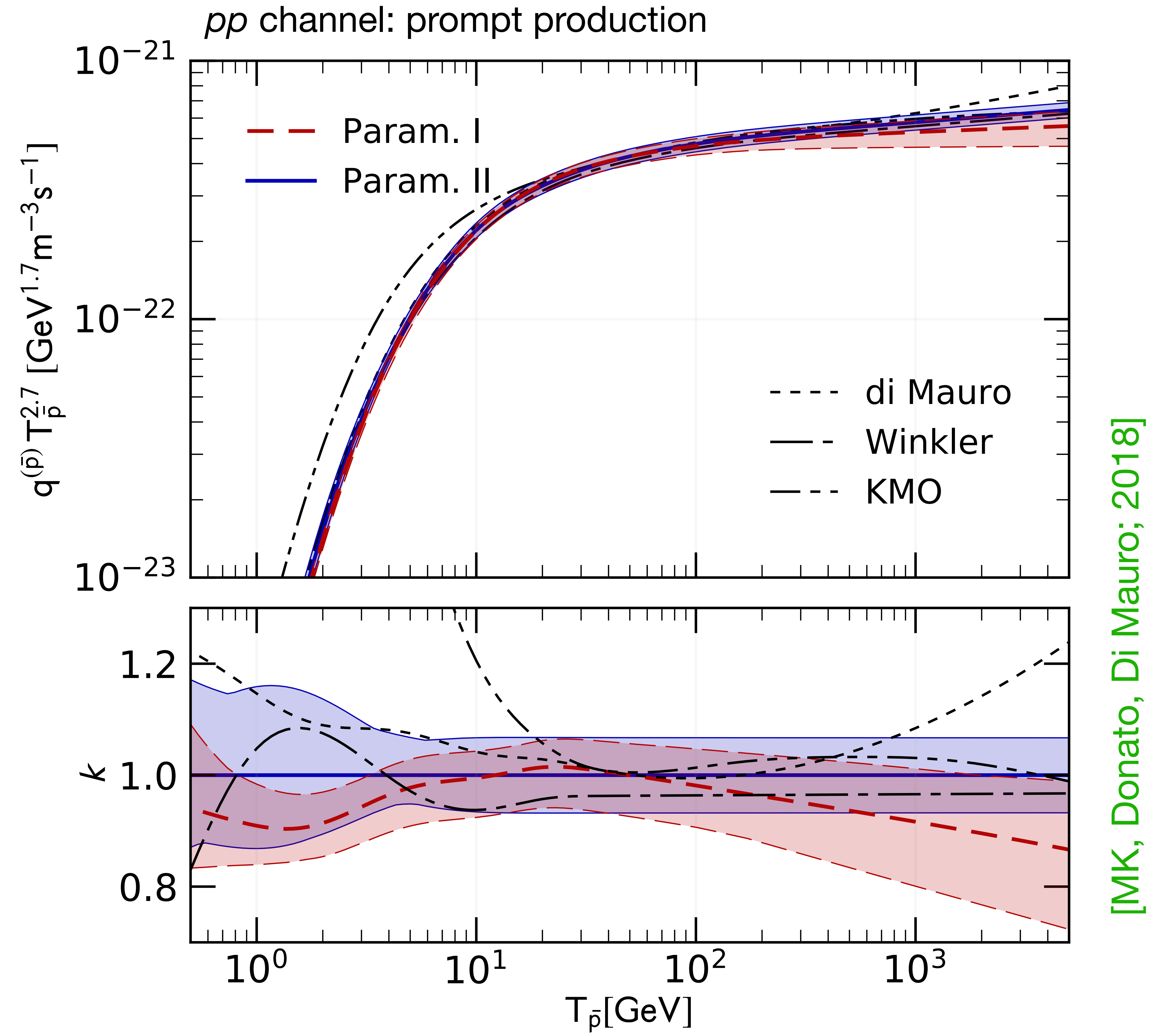


Systematic uncertainties:

- Correlation in the cosmic-ray data
- Production cross section of secondary $\bar{p}$
- Solar modulation

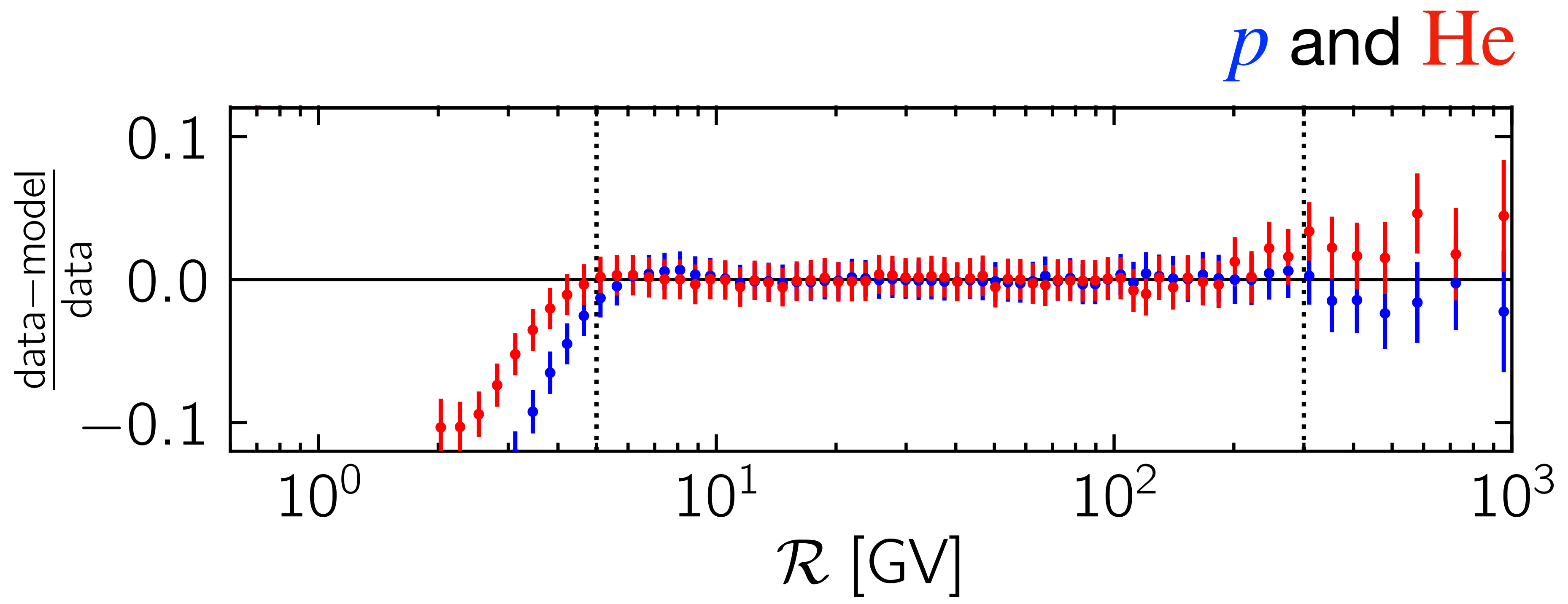
Uncertainties in the production cross section

$$q_{pp\to\bar{p}}(T_{\bar{p}}) = \int_0^\infty dT_p 4\pi n_{\mathrm{ISM,p}} \Phi_p(T_p) \frac{d\sigma_{pp\to\bar{p}}}{dT_{\bar{p}}}(T_p, T_{\bar{p}})$$



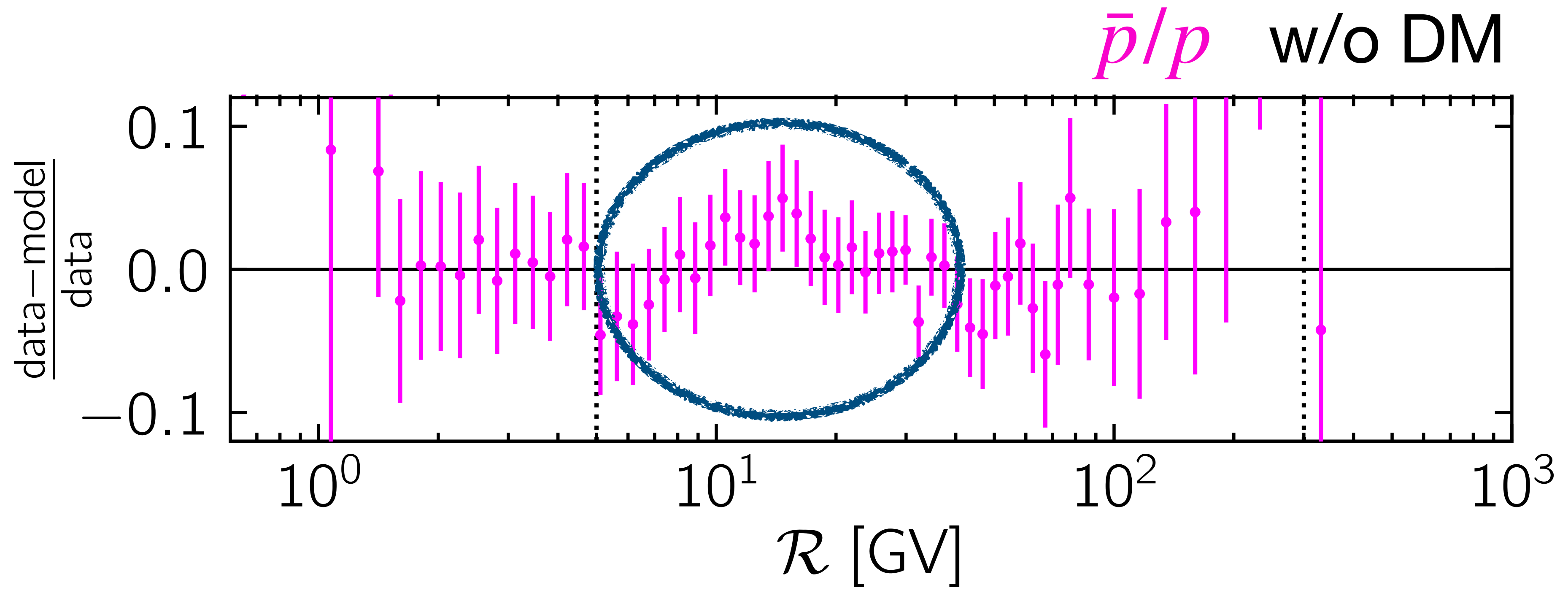
- We update the best-fit parameters of the **Winkler** and **Di Mauro** parametrization
- We derive uncertainty bands
- The **Winkler** parametrization provides best agreement with cross-section data
- Cross-section uncertainties are up to 20% at low energies (2σ C.L.)

Why correlations?



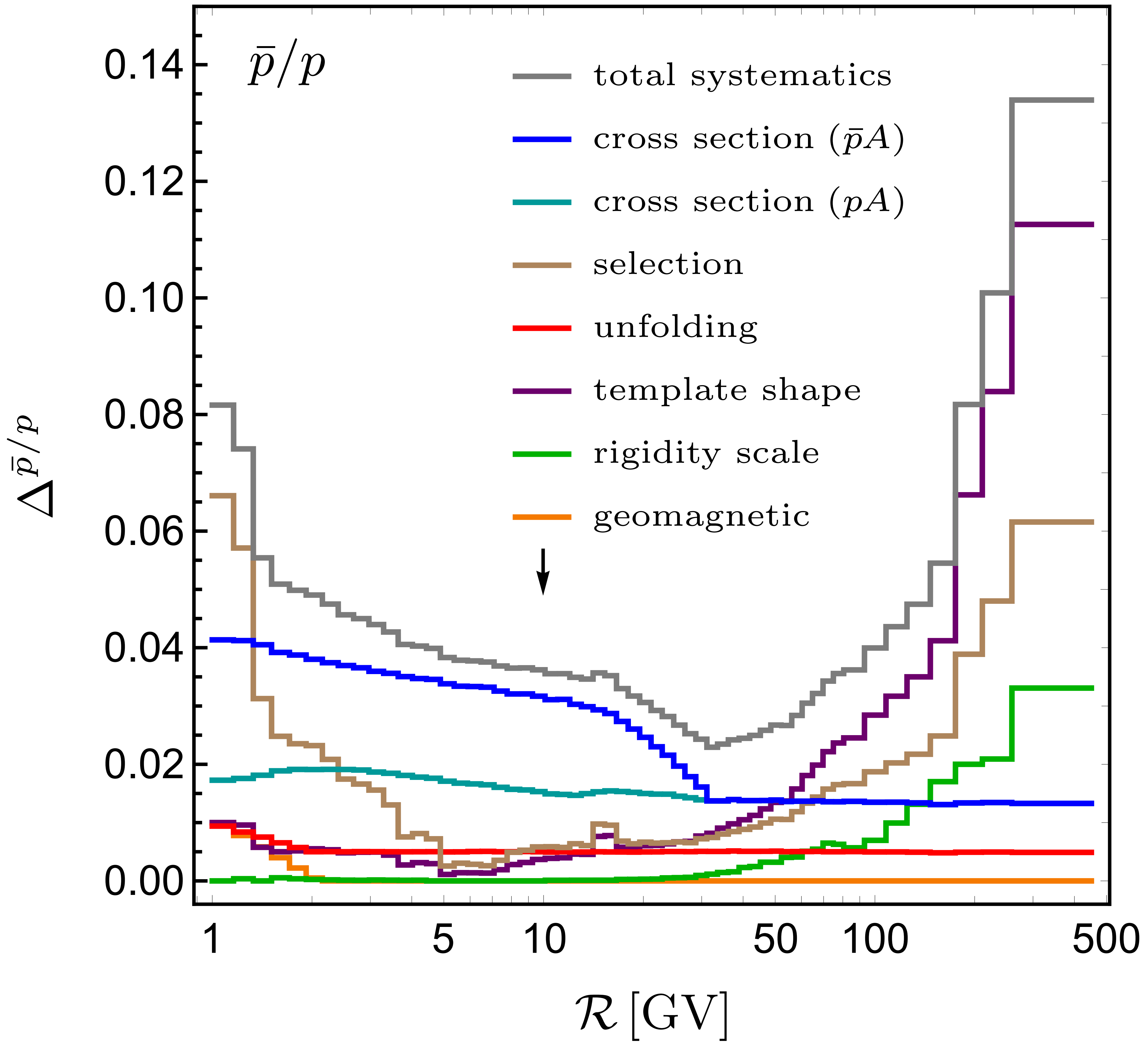
The typical χ^2 per degree of freedom is much smaller than 1

→ Hint for strong correlation among data points

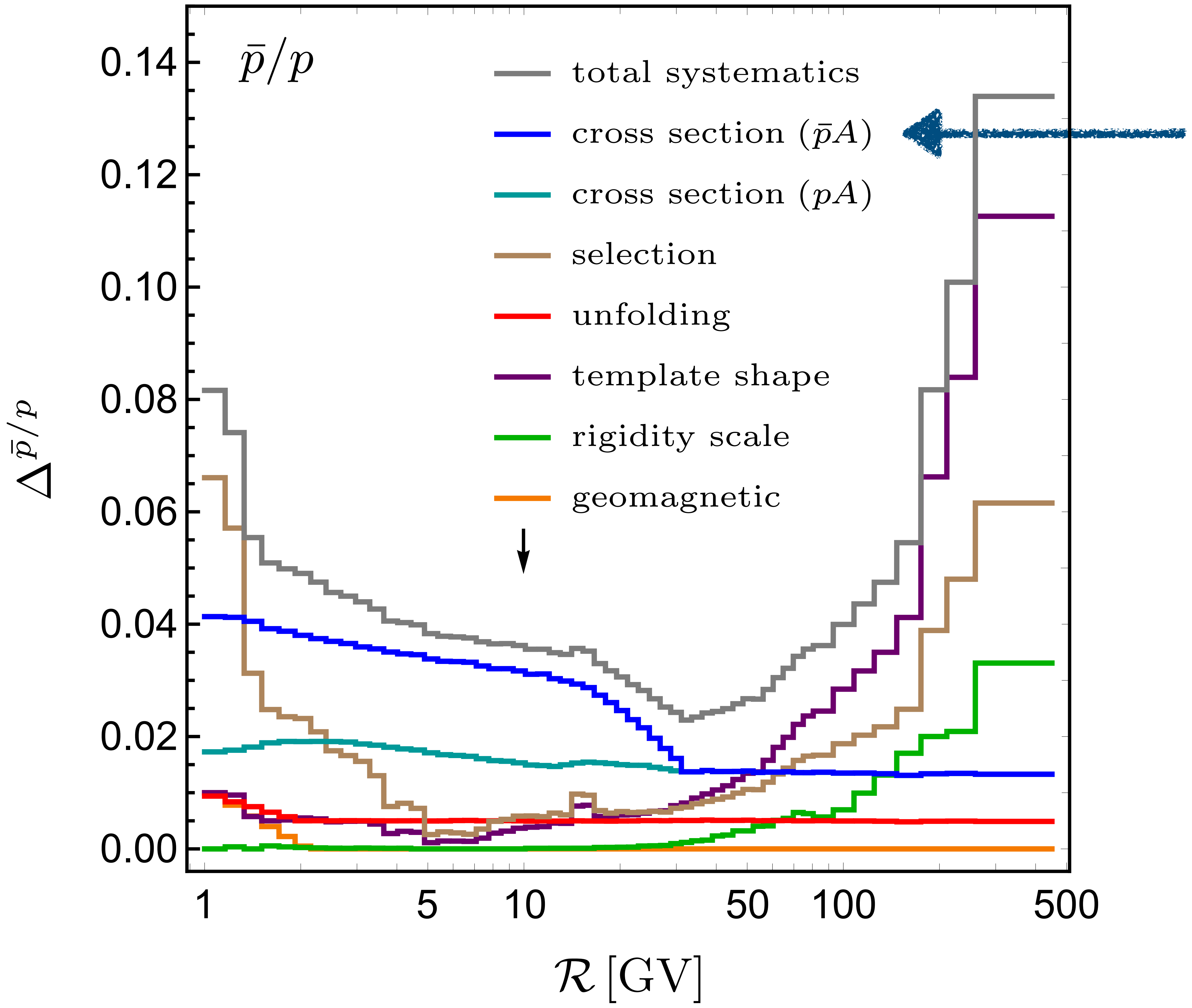


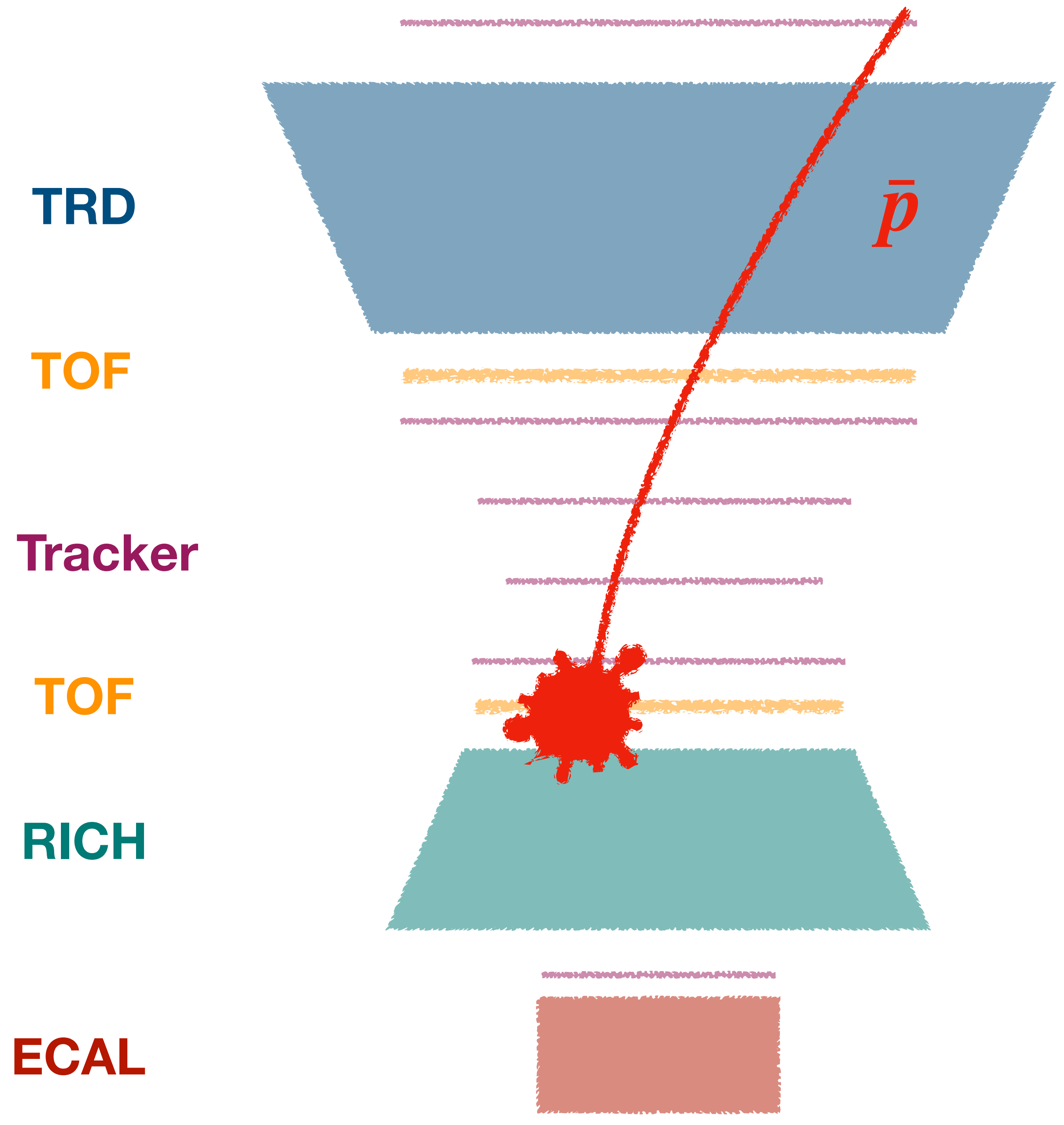
Correlations of a few neighboring data points might reduce the significance of the *feature* in the $\bar{p}/p$ ratio

Correlation in the cosmic-ray data



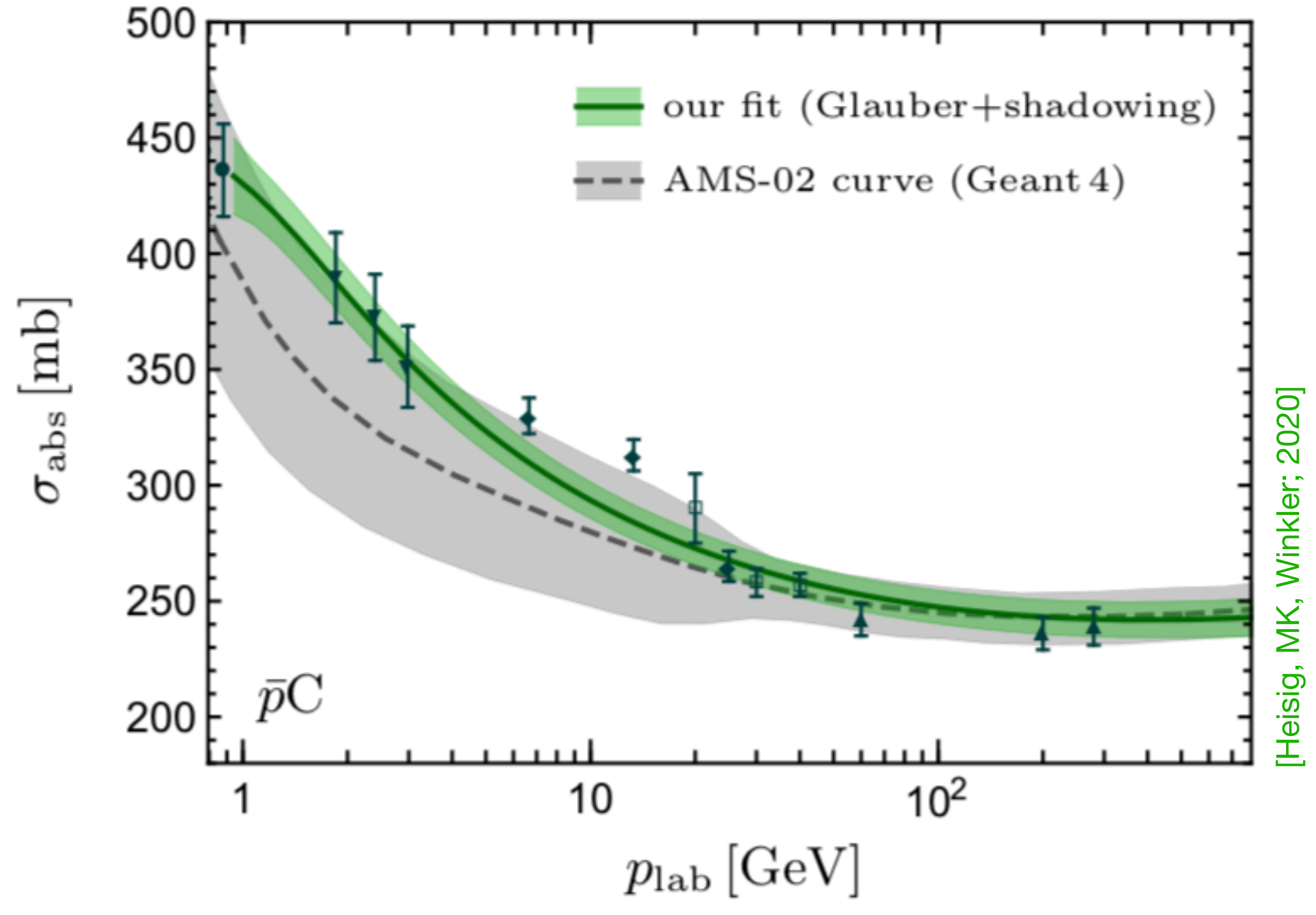
Correlation in the cosmic-ray data



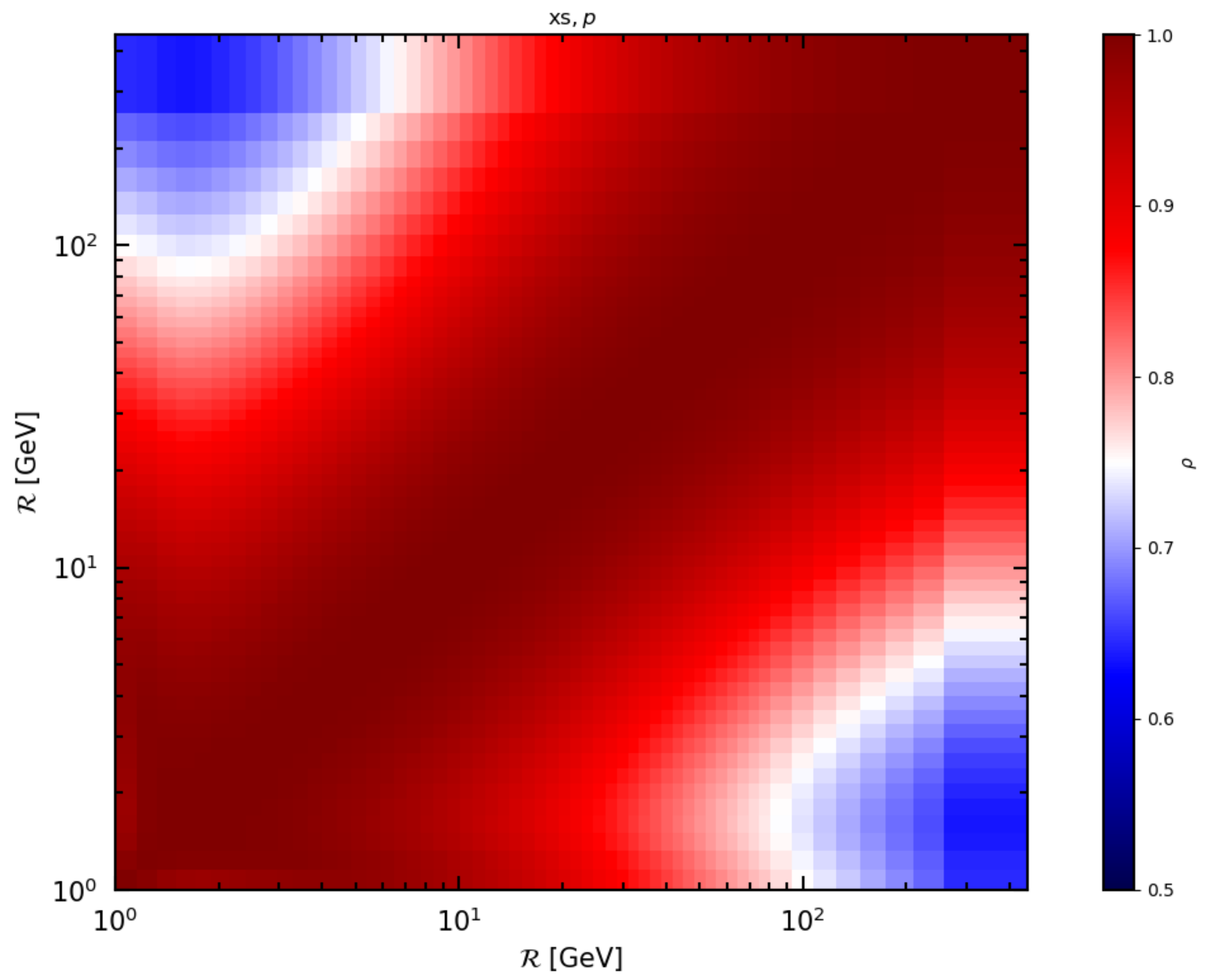


$$\Phi_{\mathrm{raw}} \sim \exp\left(-n\, z \cdot \sigma_{\mathrm{abs}}\right)\ \Phi \qquad \longrightarrow \qquad \left(\frac{\Delta\Phi}{\Phi}\right)_{\mathrm{abs.\,XS}} \approx n\, z\, \Delta\sigma_{\mathrm{abs}}$$

Correlation in the cosmic-ray data



We **modeled** the antiproton **absorption cross section** in carbon to **obtain correlated uncertainties**



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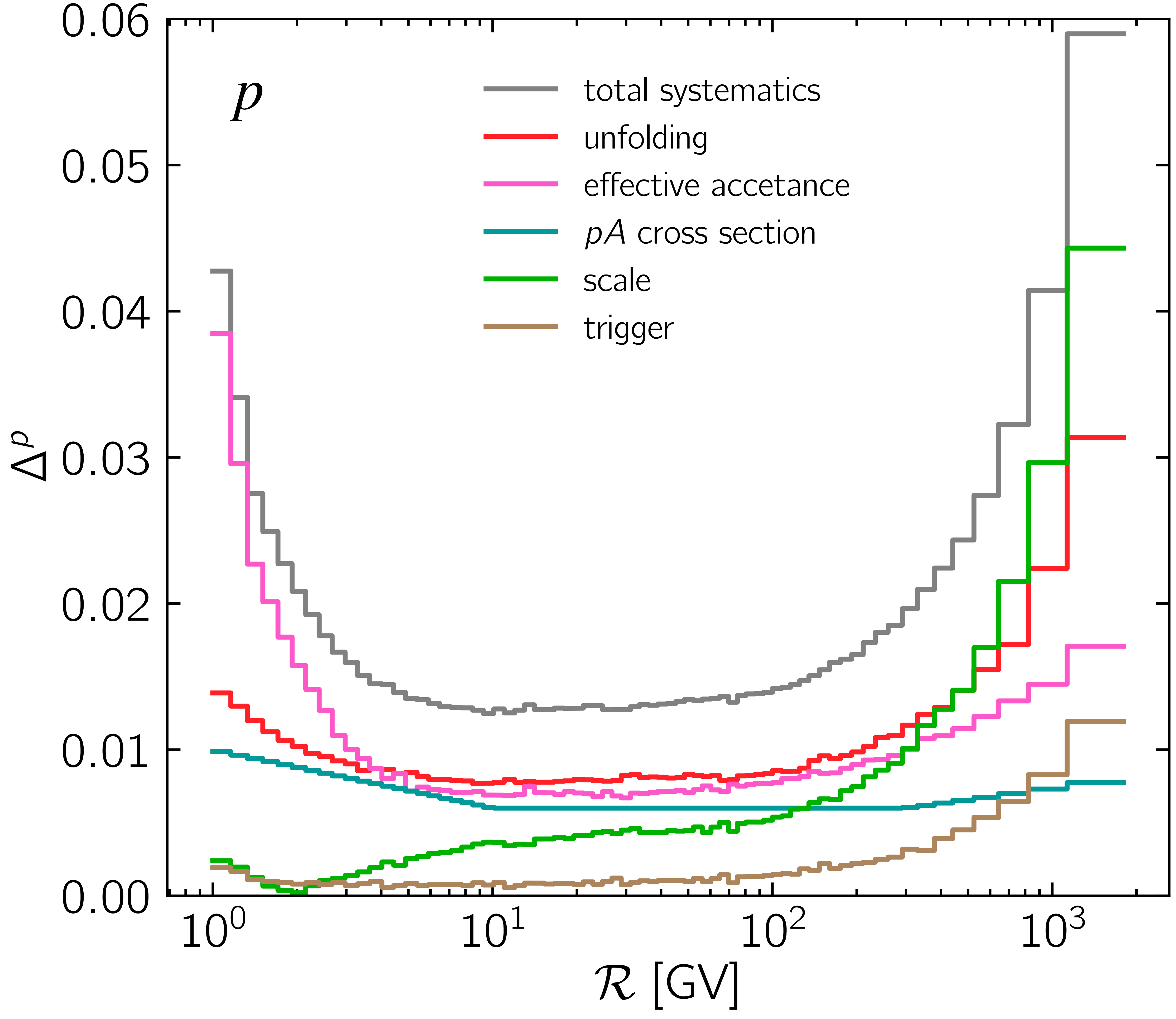
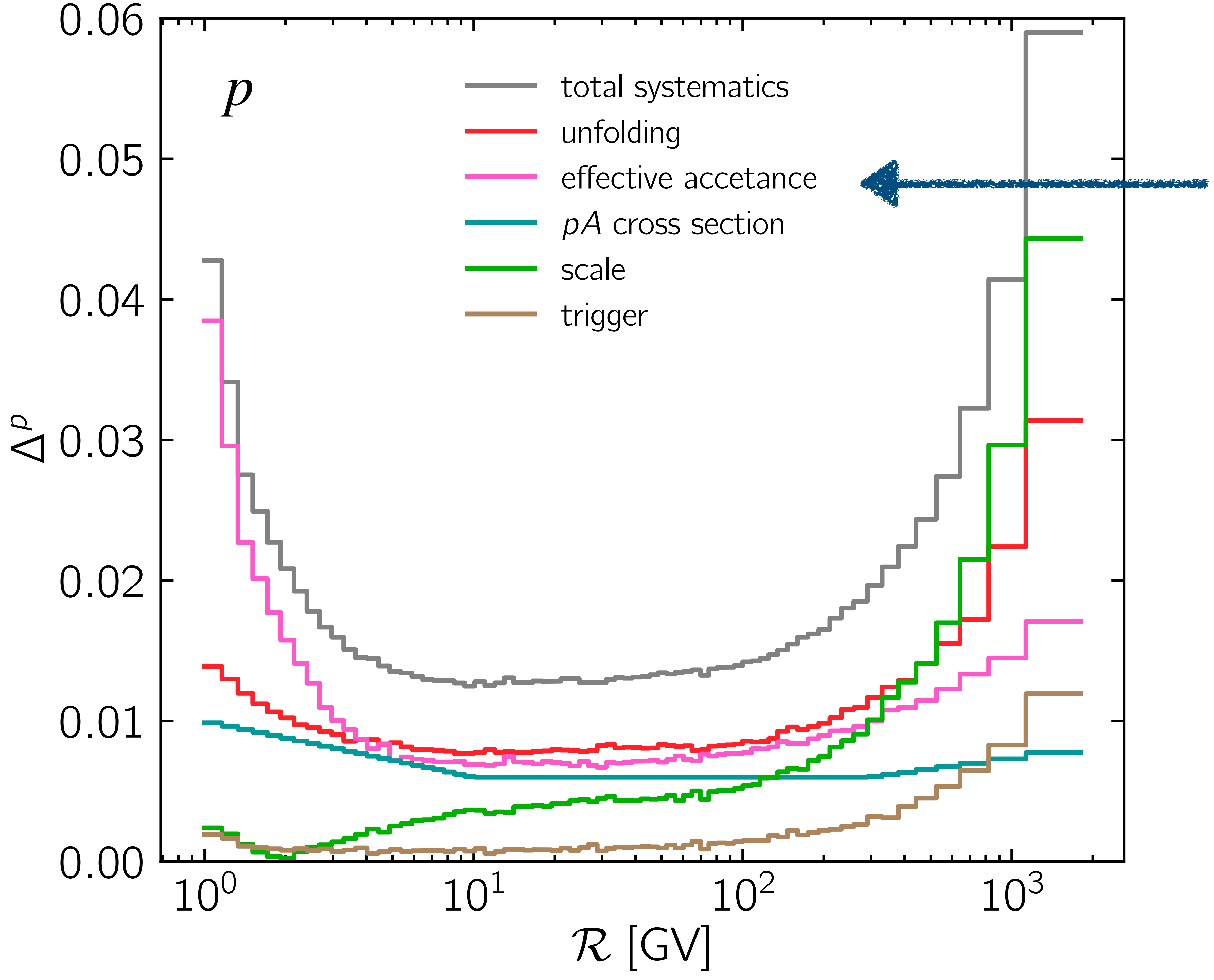
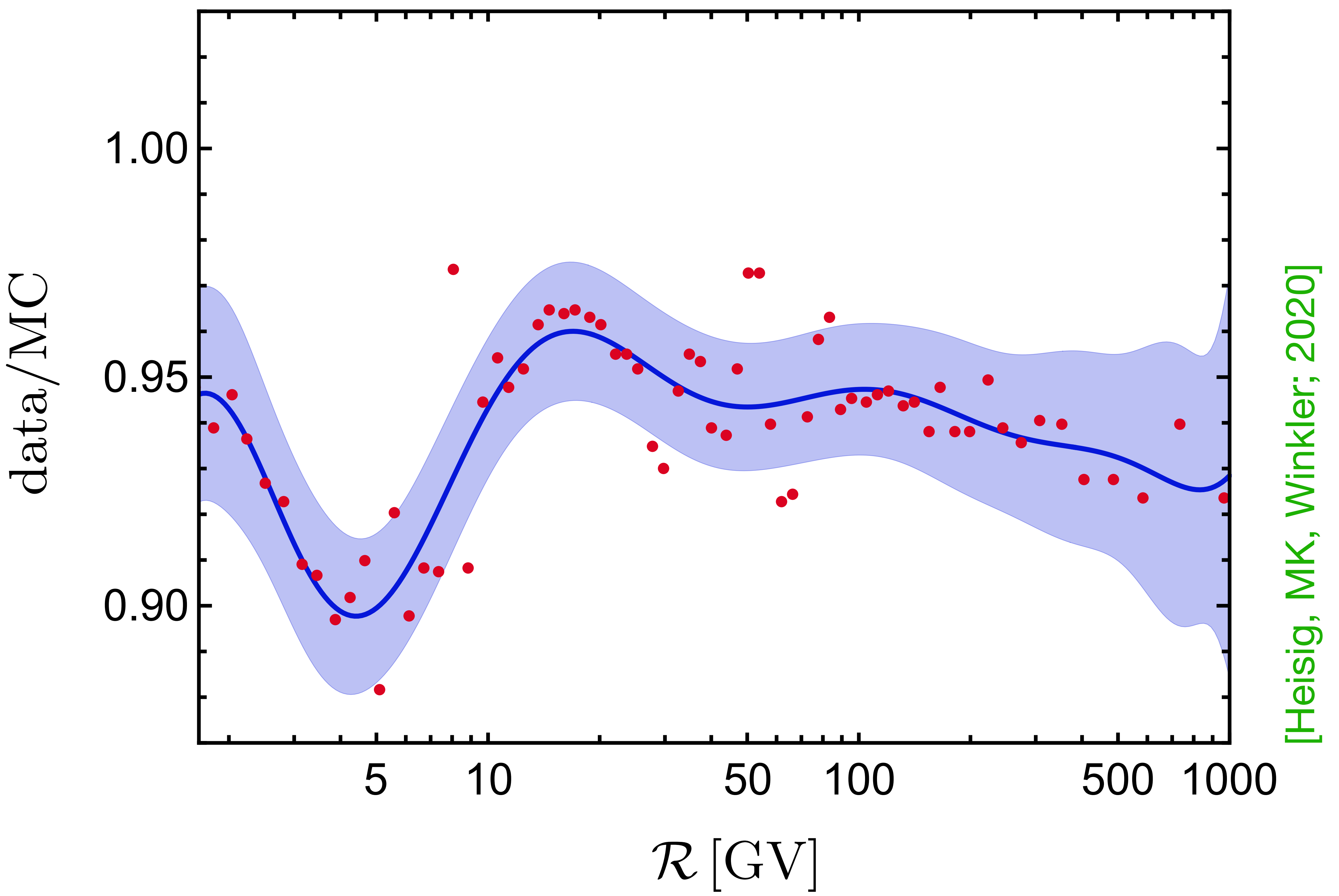
Correlation in the cosmic-ray data



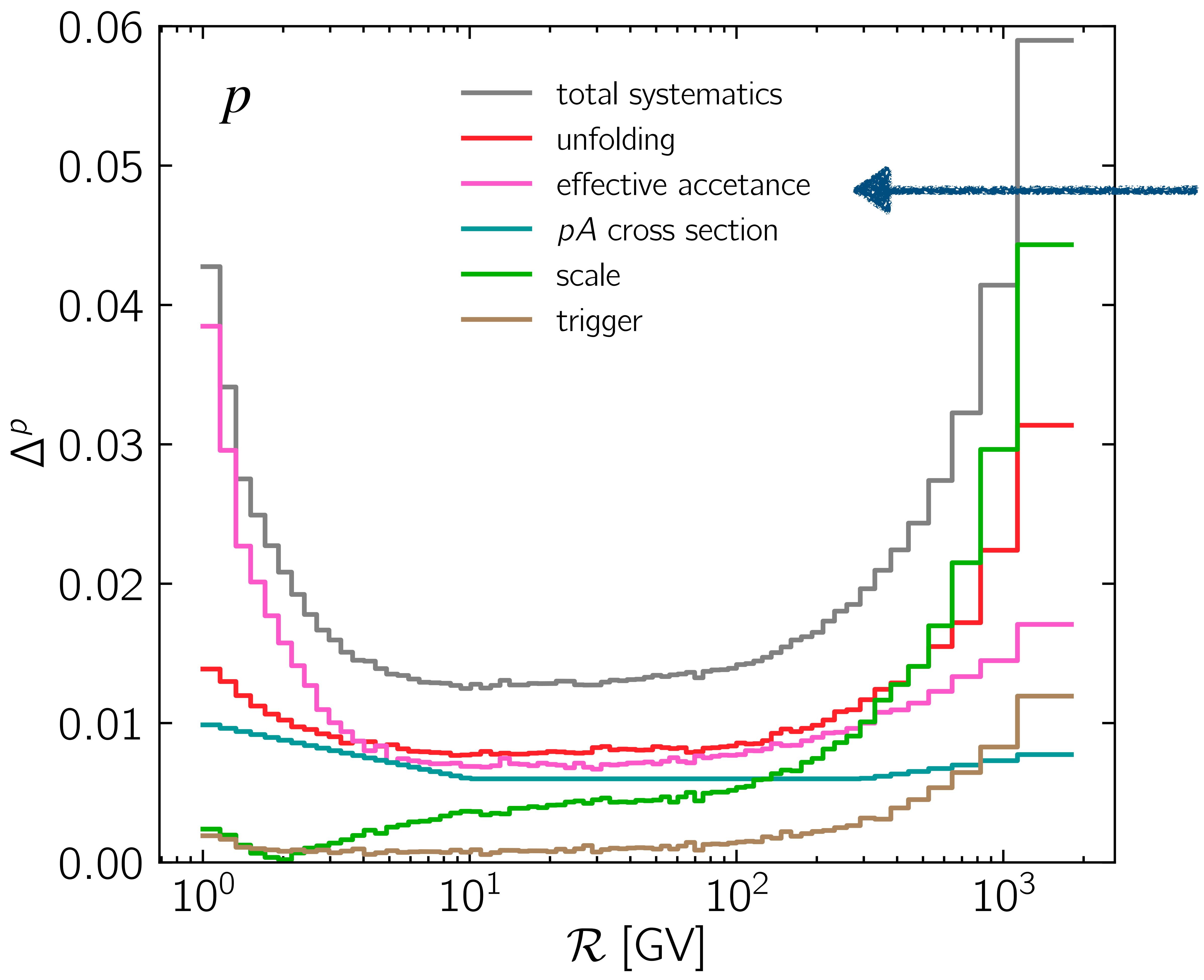
Correlation in the cosmic-ray data

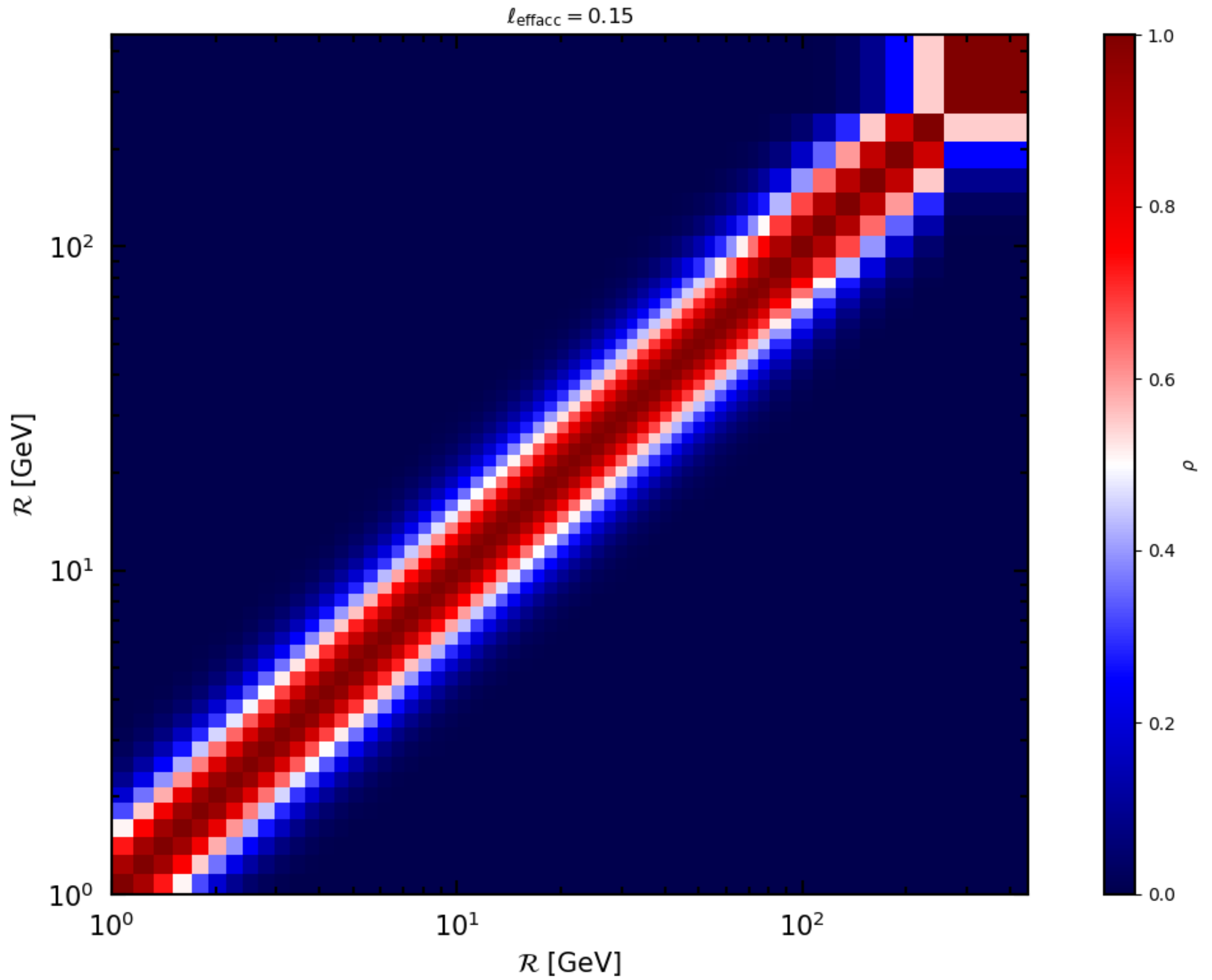




We take the "wiggliness" in the data/MC correction as a proxy for the correlation of the effective acceptance.

Correlation in the cosmic-ray data

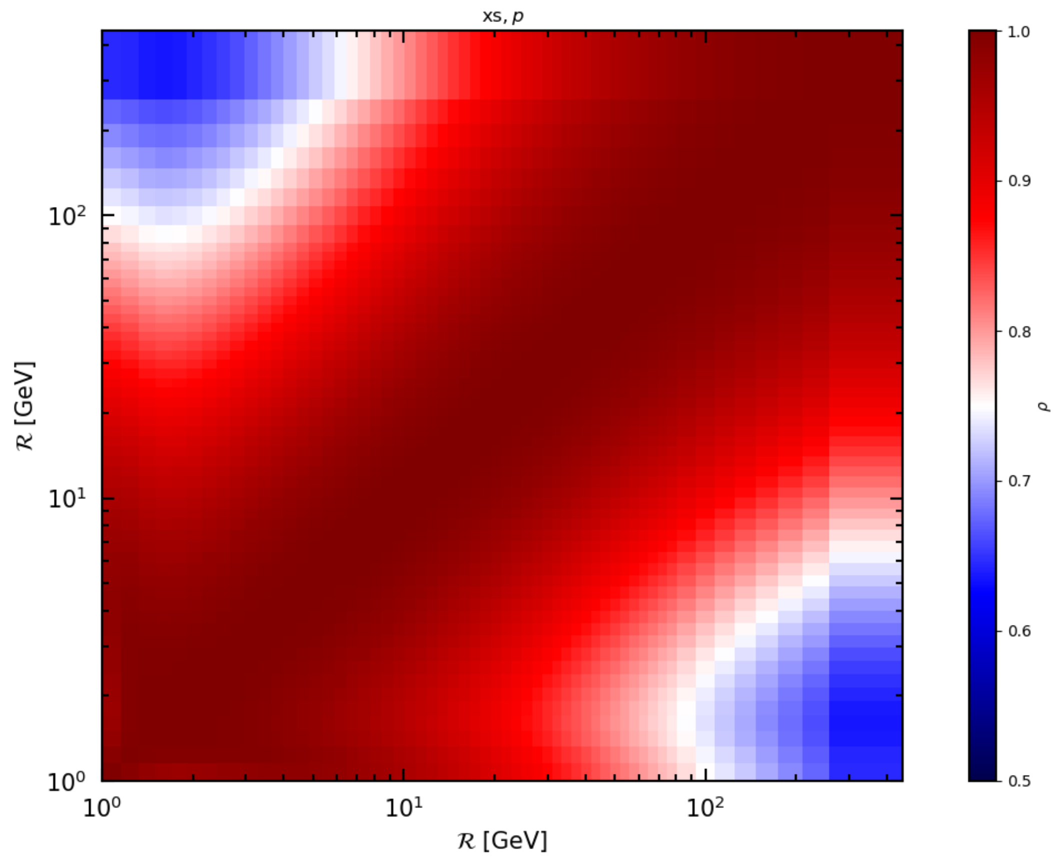




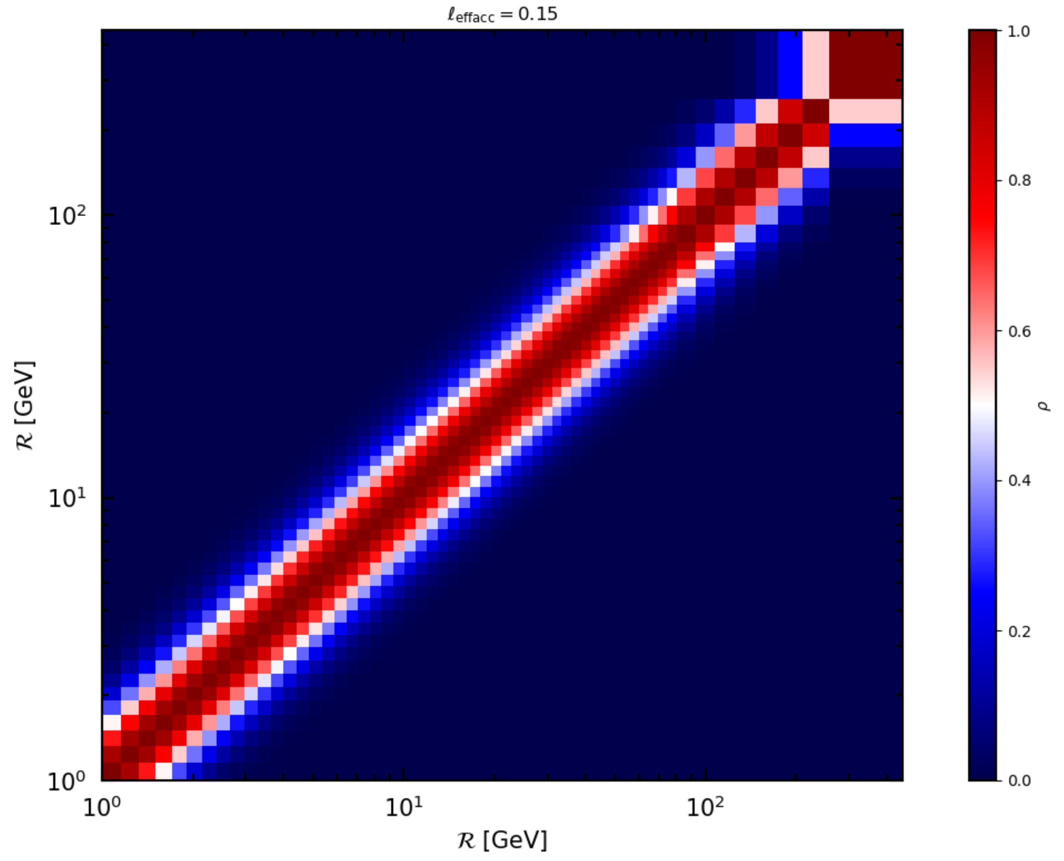
We take the "wiggliness" in the data/MC correction as a proxy for the correlation of the effective acceptance.

Correlation matrices

Absorption XS $\bar{p}C$

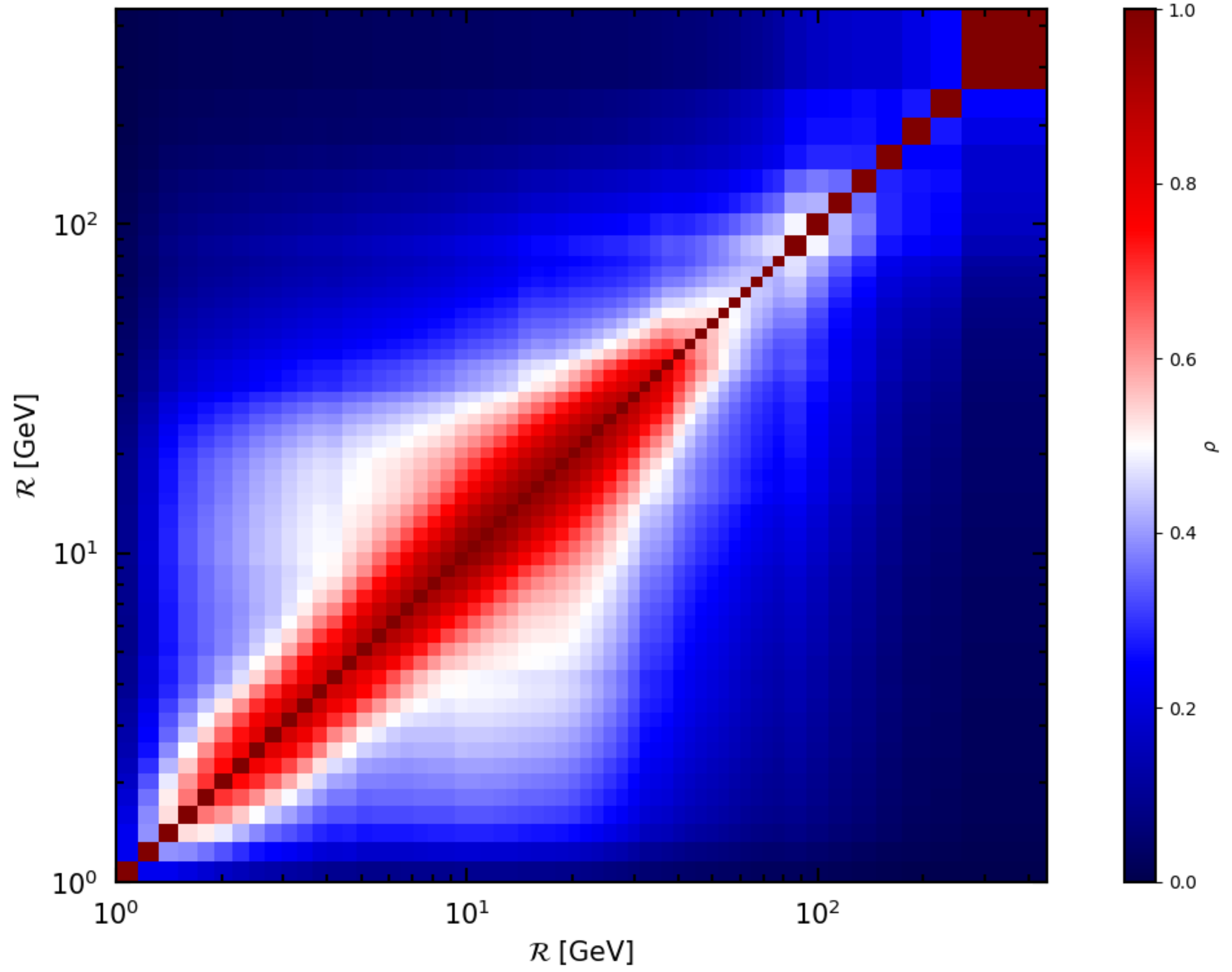


Effective acceptance



...

Correlation matrix for $\bar{p}$ data



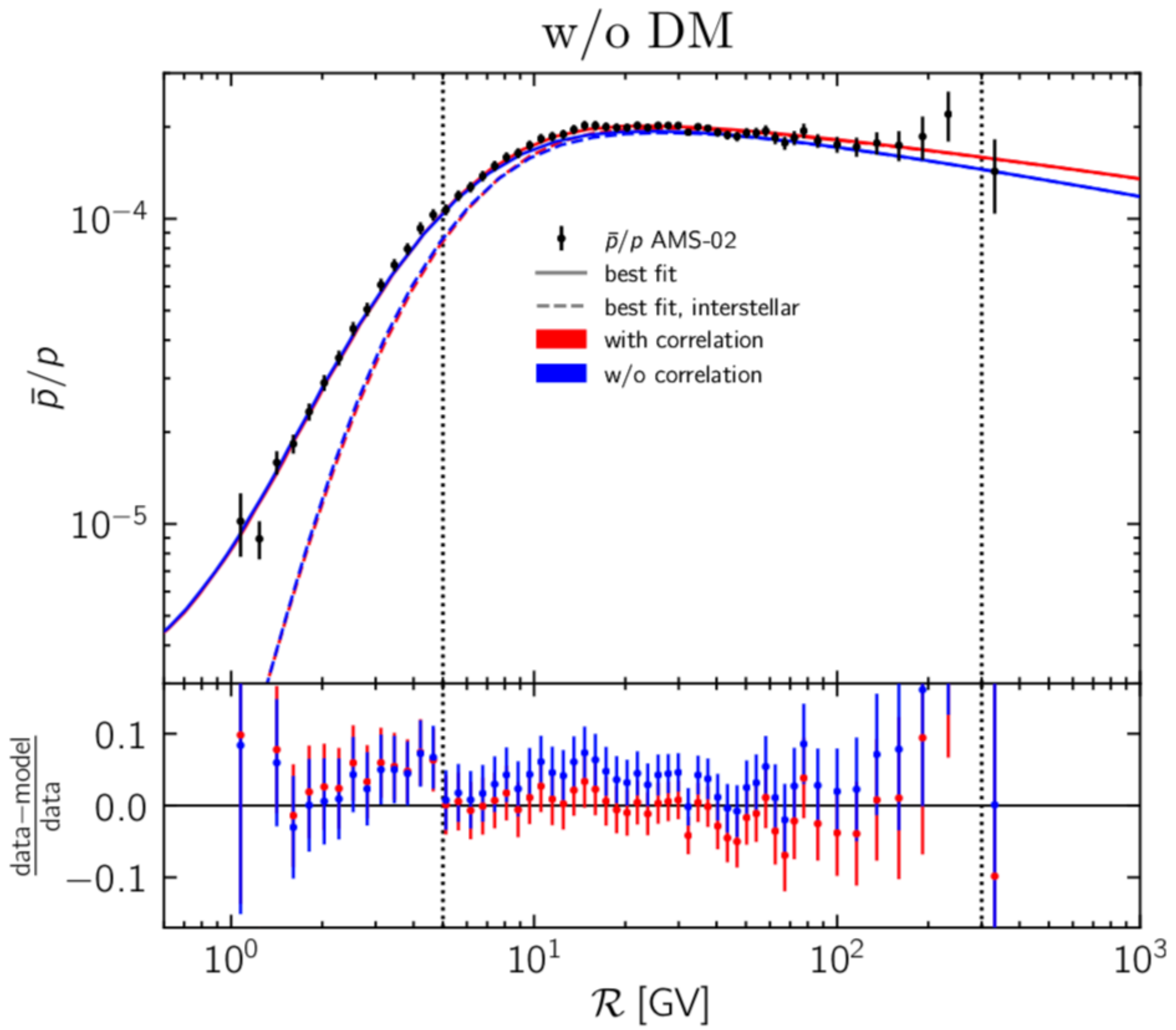
Result

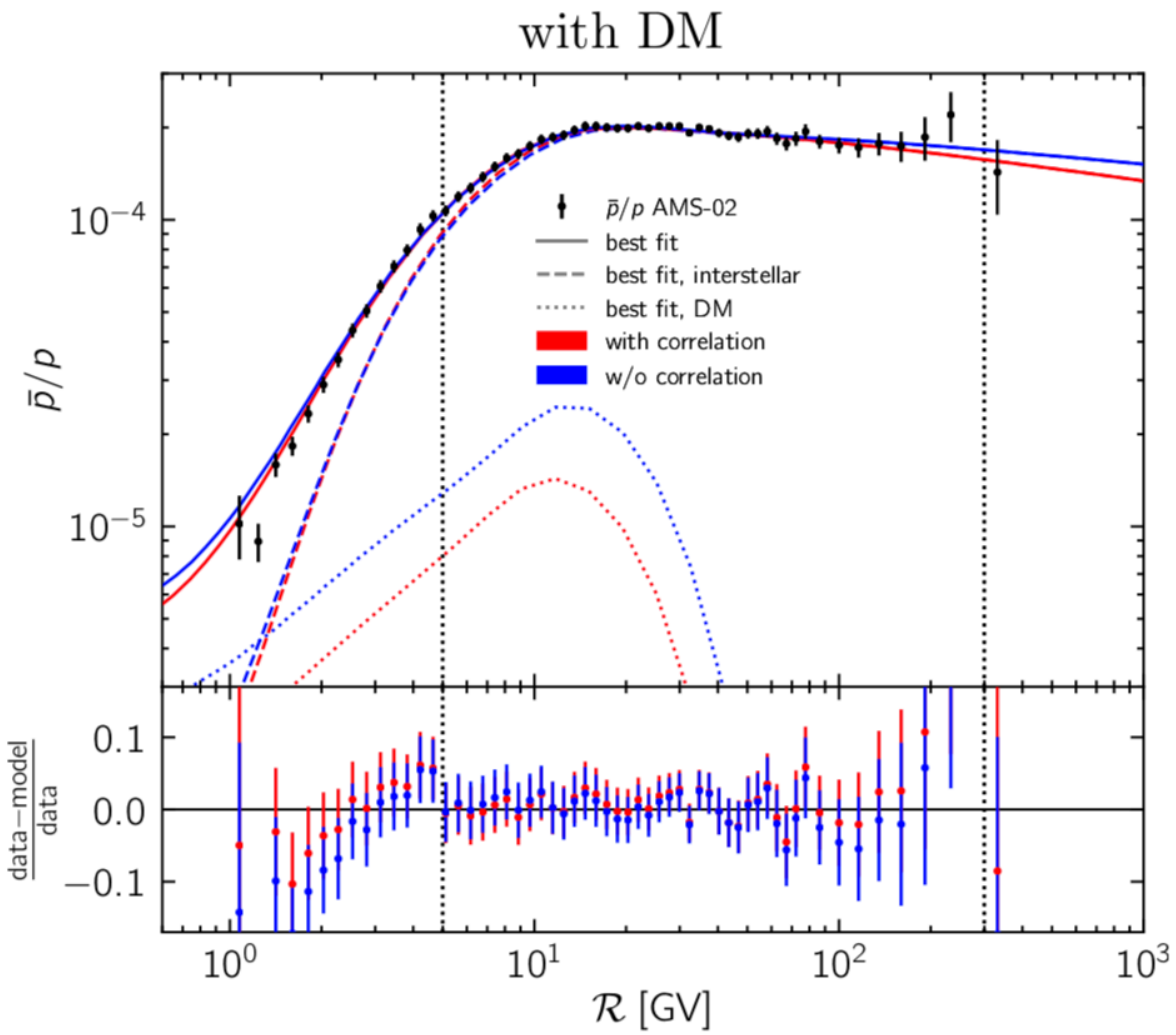
	w/o corr.	with corr.
$\chi^2_{\rm tot}$	20.3 (27.2)	233.1 (236.3)
$m_{\rm DM}$ [GeV]	76	66
$\langle \sigma v \rangle$ [10^{-26} cm^3/s]	0.91	0.74
$\Delta\chi^2_{\rm tot}$	6.9	3.2
local sig.	2.6 σ	1.8 σ
global sig.	1.8 σ	0.5 σ

1. We model correlation in the CR data (focussed on absorption cross section and *effective acceptance*)
2. We consider uncertainties in the secondary $\bar{p}$ production
3. We allow slightly more freedom in the CR propagation model

→ **No significant preference for DM**

Fit results





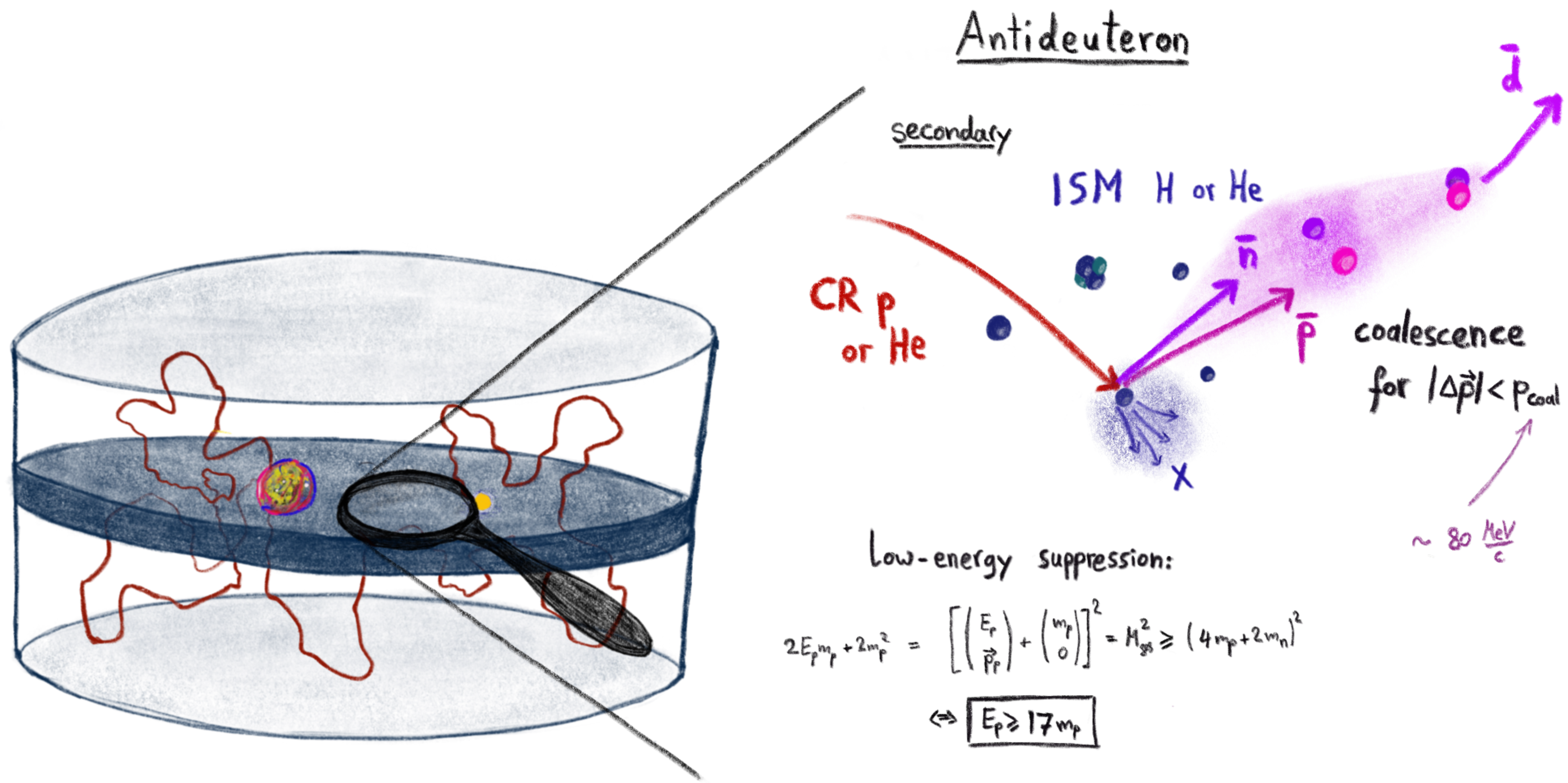
[Heisig, MK, Winkler; 2020]

→ **But the *interesting* m_{DM} - $\langle \sigma v \rangle$ region cannot be excluded**

Outline

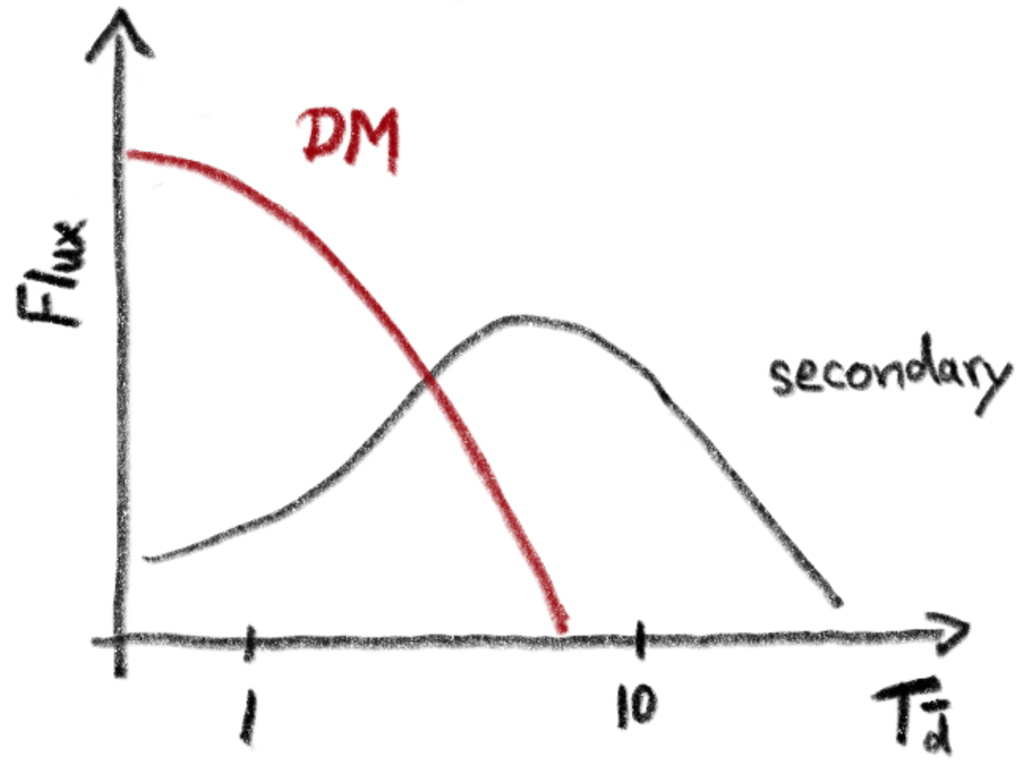
- Introduction
- Global fit of CR data from Li to O
- CR antiprotons
- **CR antideuteron**
- **Conclusion**

Antideuteron in cosmic rays

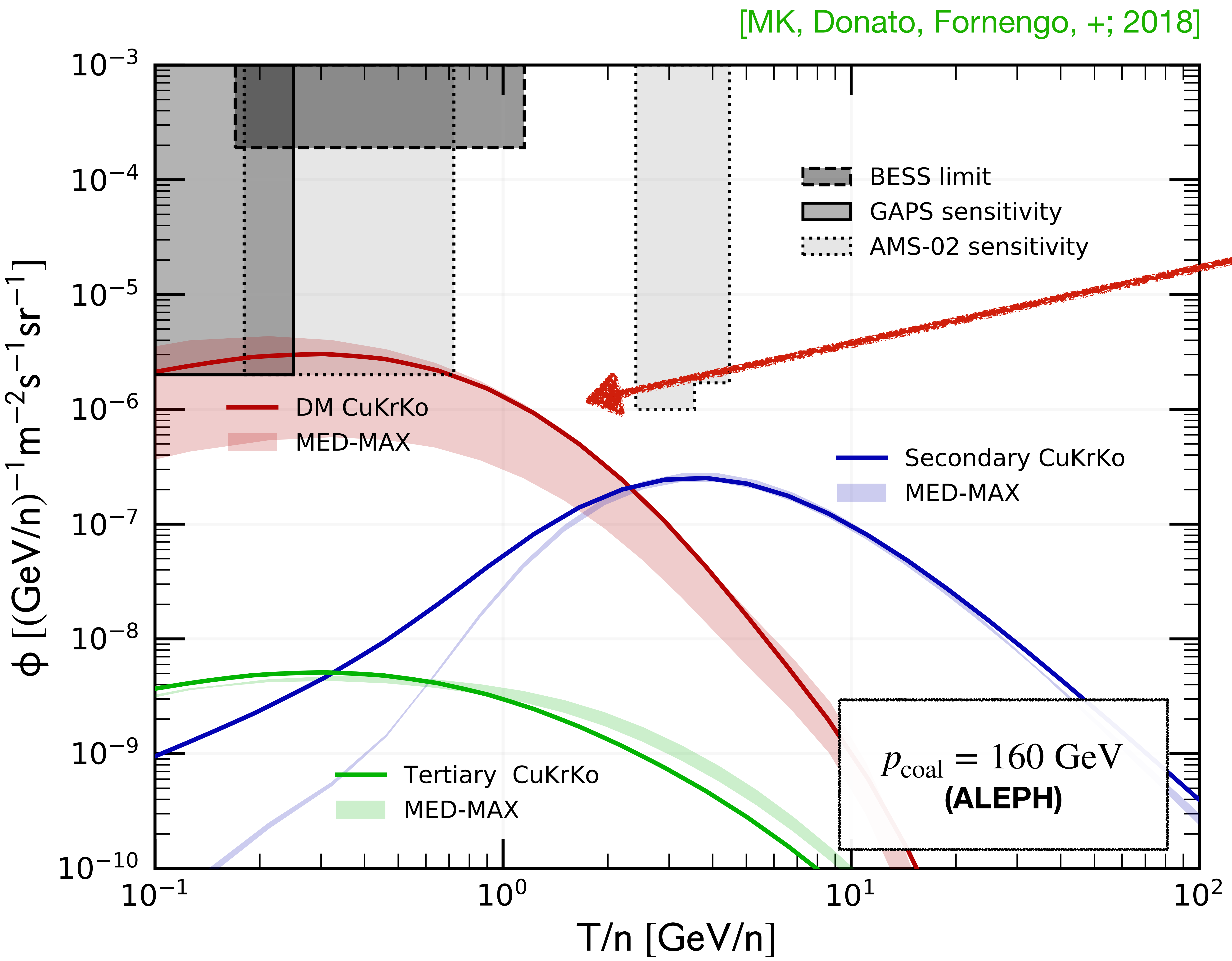


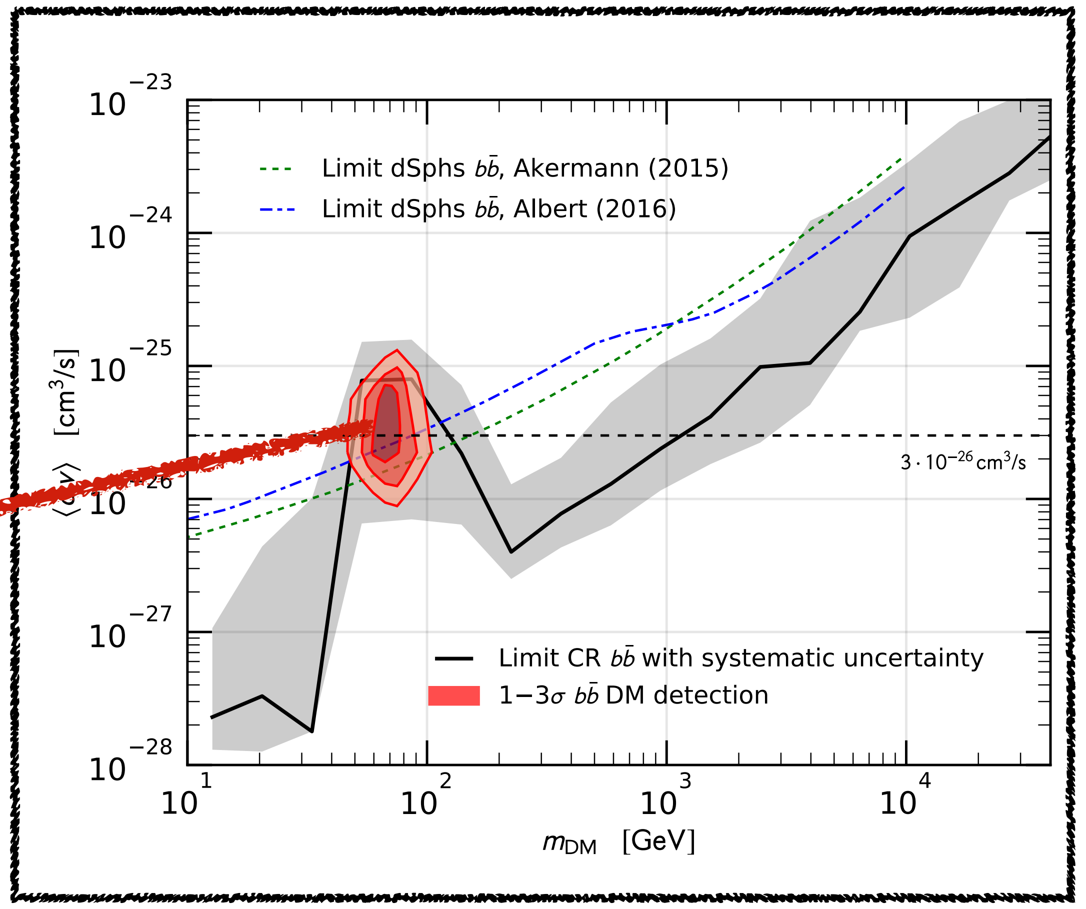
DM

- Production by coalescence
- No low-energy suppression (annihilation at rest)



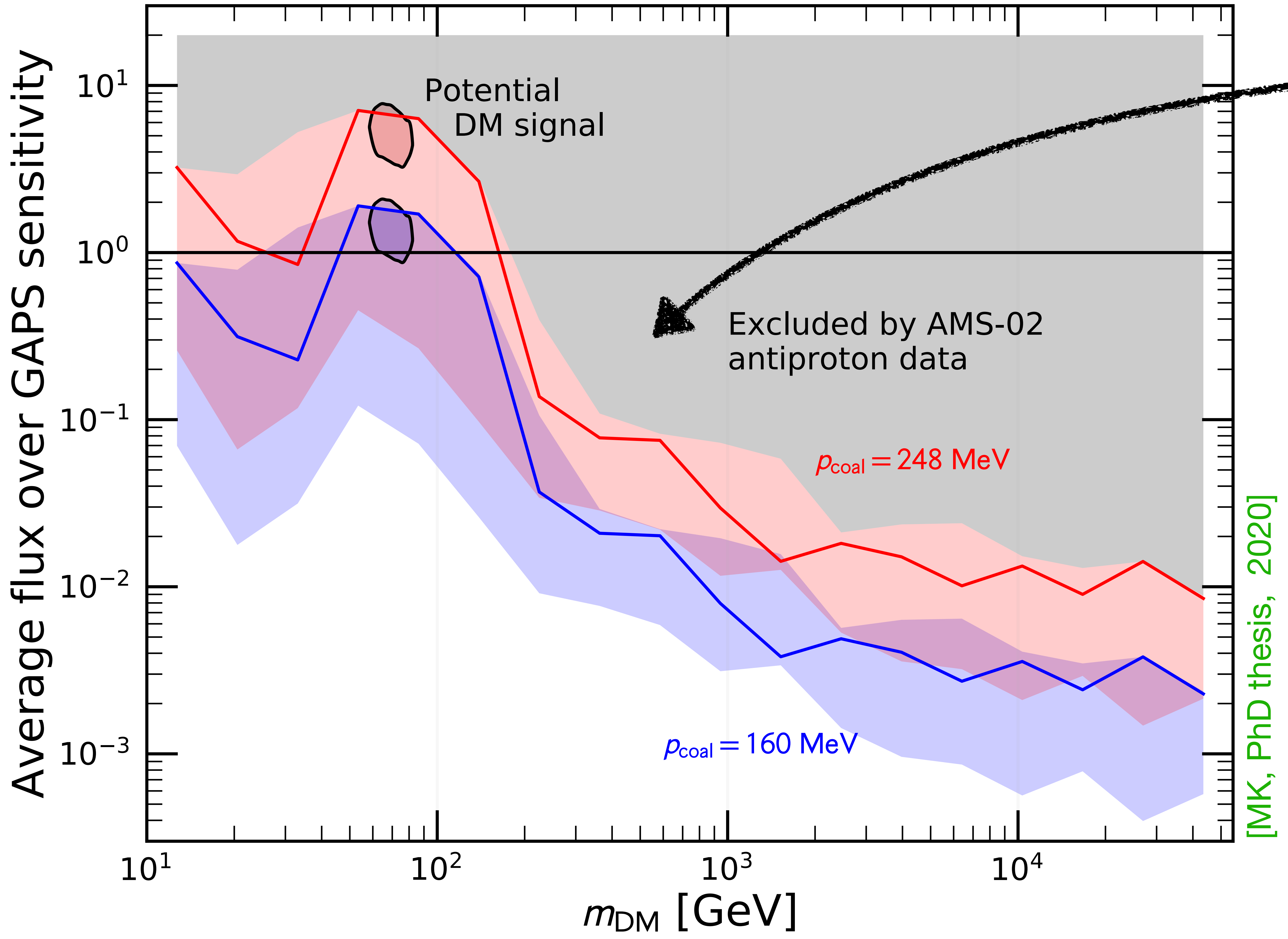
A complementary strategy: search for antideuteron

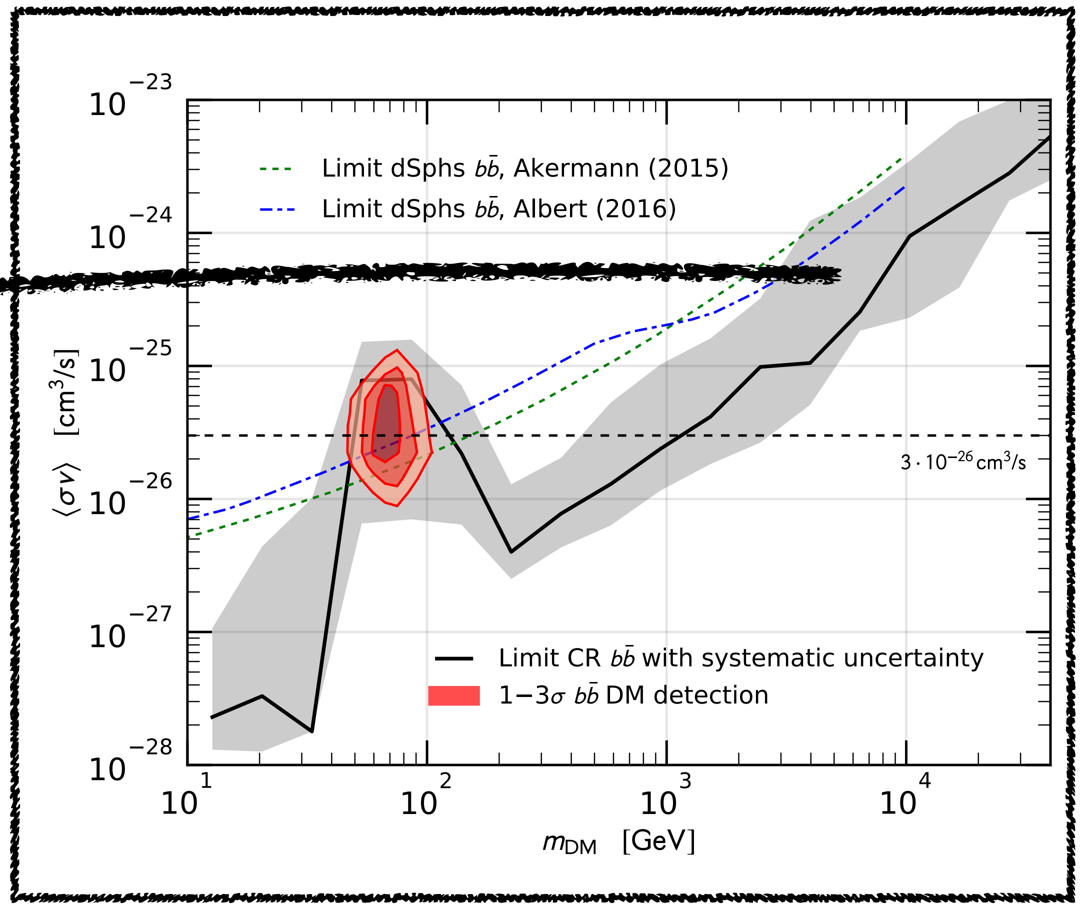




The DM hint in antiprotons might be in the sensitivity range of the (future) cosmic-ray experiments AMS-02 and GAPS.

Perspectives for the future experiment GAPS

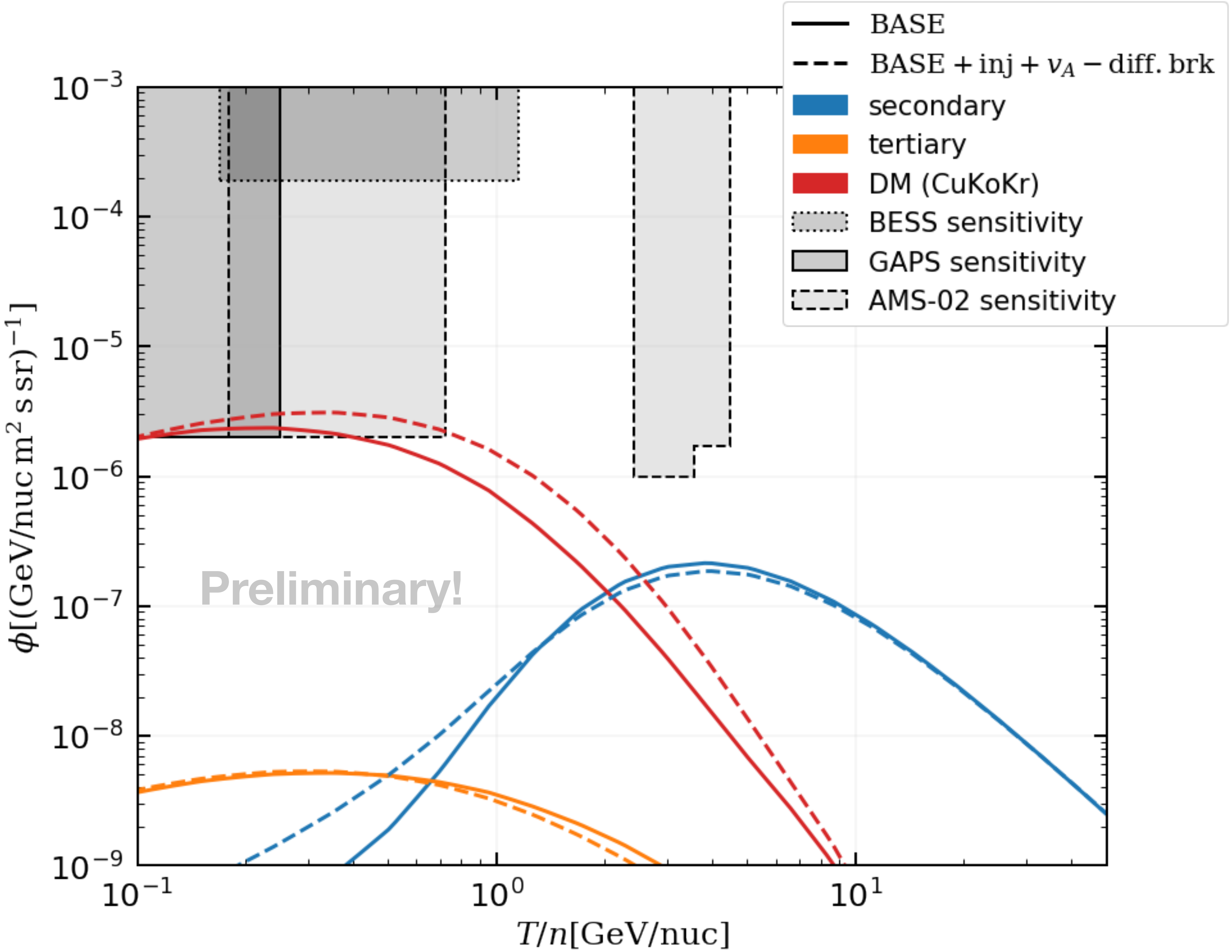




The DM limits of CR antiprotons allow an antideuteron signal by GAPS for m_{DM} smaller than a few hundred GeV.

There might be a possibility to evade the limit.
See: [Winkler, Linden 2020]

Impact of propagation on antideutrons

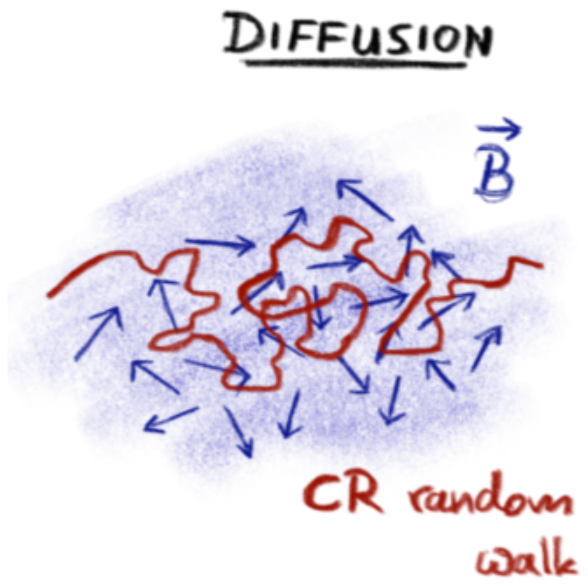


Reacceleration can slightly boost DM signal

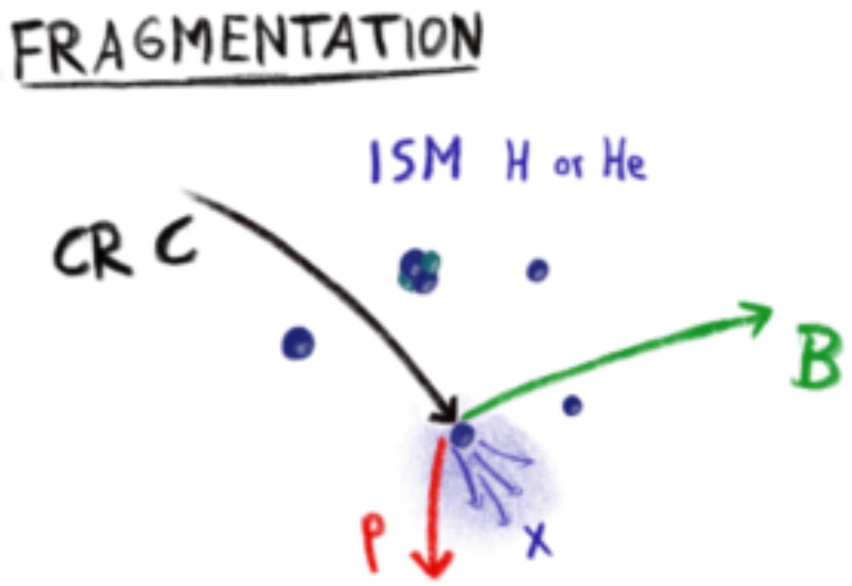
See also: [Cholis+ 2020]

Conclusions

The combination of different species constrains CR propagation

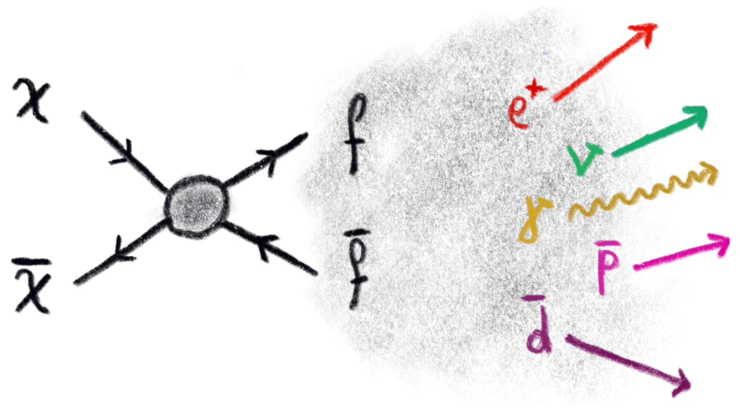


CR antiprotons and antideutrons are a sensitive probe for DM



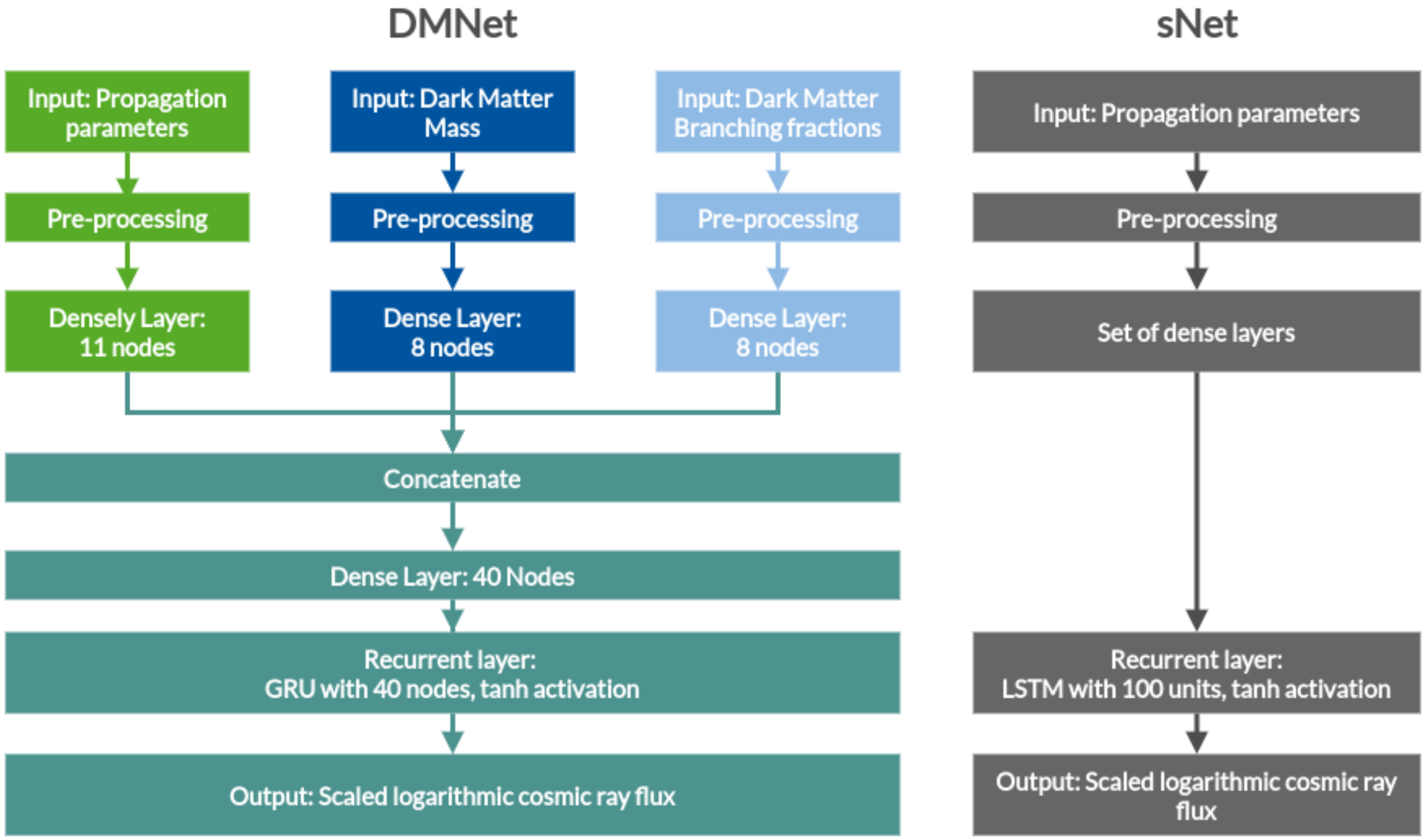
Systematic uncertainties are important and require a careful analysis:

- Fragmentation & production cross sections
- Correlations in the data
- Solar modulation



Thank you for your attention!

Accelerating the calculation of DM limits with RNNs



$$\tilde{\phi}_{\mathrm{s}}(E) = \log_{10}(E^{2.7}\phi(E)) \qquad \tilde{\phi}_{\mathrm{DM}}(x) = \log_{10}(m_{\mathrm{DM}}^{3} x \phi(E))$$

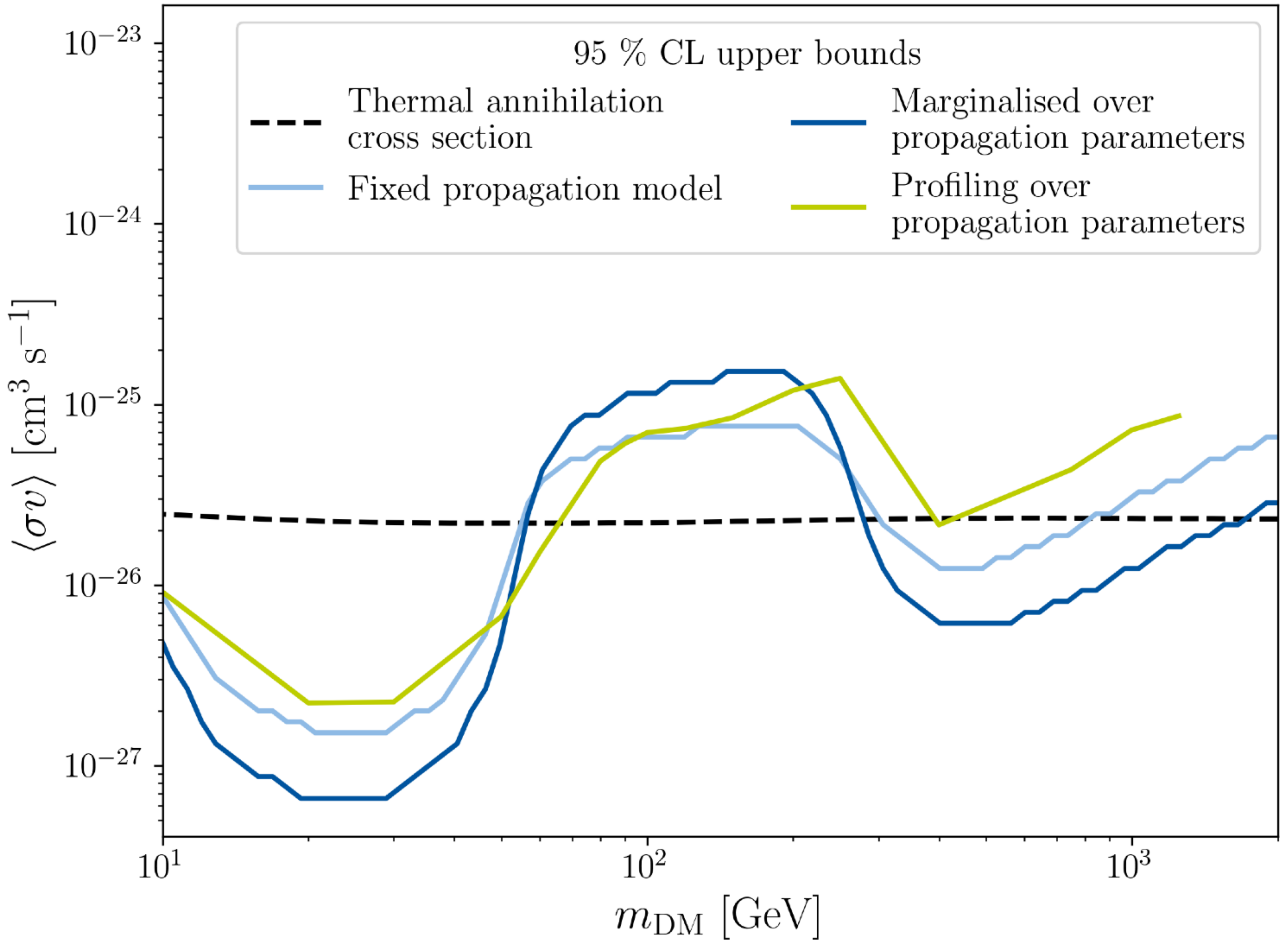
Training Data:
Chain of a MultiNest fit without DM

RNNs efficiently learn smooth spectra

Accelerating the calculation of DM limits with RNNs

DMNet

sNet

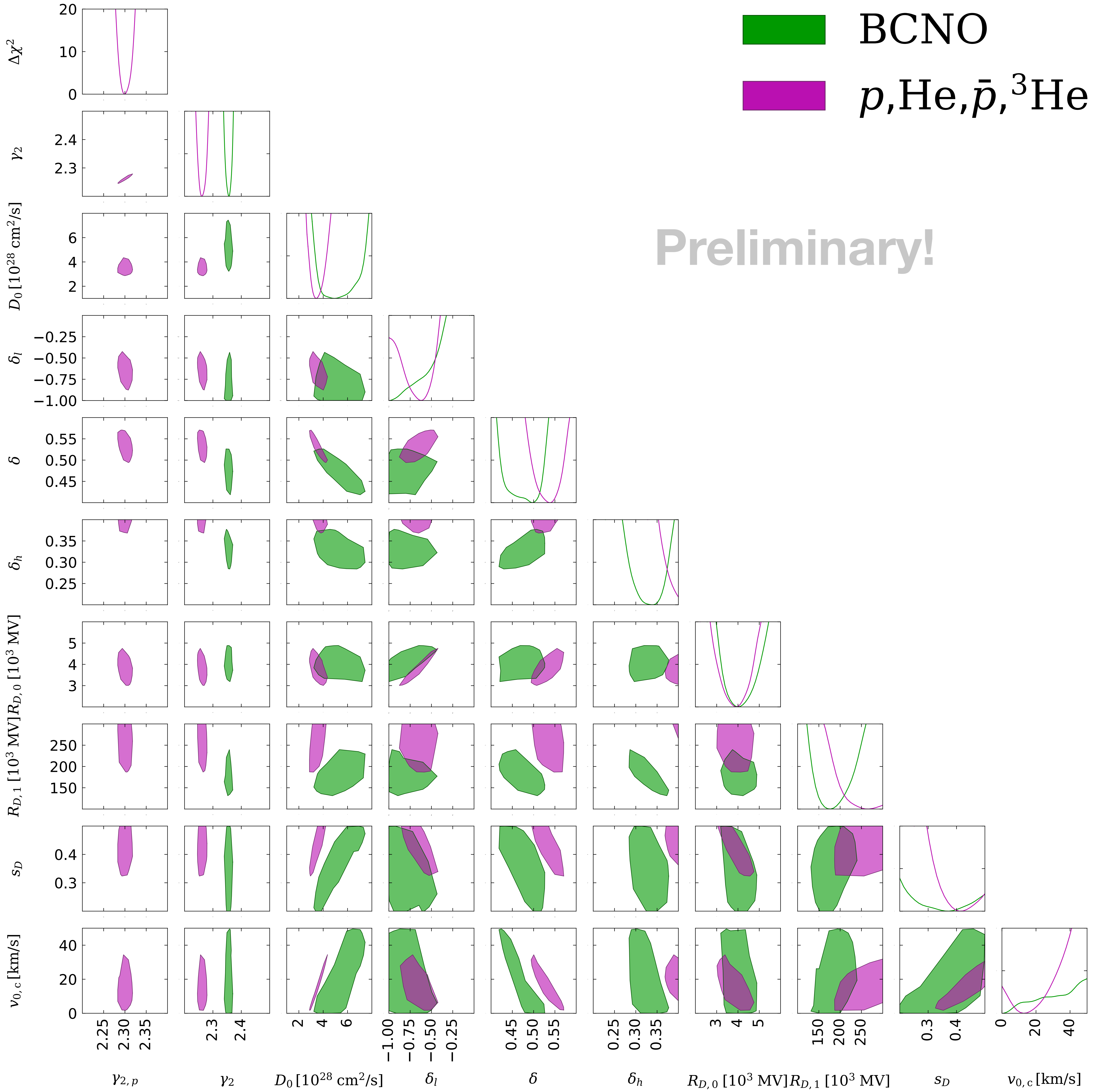


We have developed tools to quickly derive DM limits for a large number of DM models

Recurrent Neural Networks are particularly well suited to predict CR spectra both for DM and the astrophysical background

$$\tilde{\phi}_{\rm s}(E) = \log_{10}(E^{2.7}\phi(E)) \qquad \tilde{\phi}_{\rm DM}(x) = \log_{10}(m_{\rm DM}^3 x \phi(E))$$

Outlook



Light and "heavy" cosmic-ray nuclei point to slightly different propagation parameters

To combine cosmic-ray flux data from protons to oxygen we have to give up some universality

… work in progress with A. Cuoco