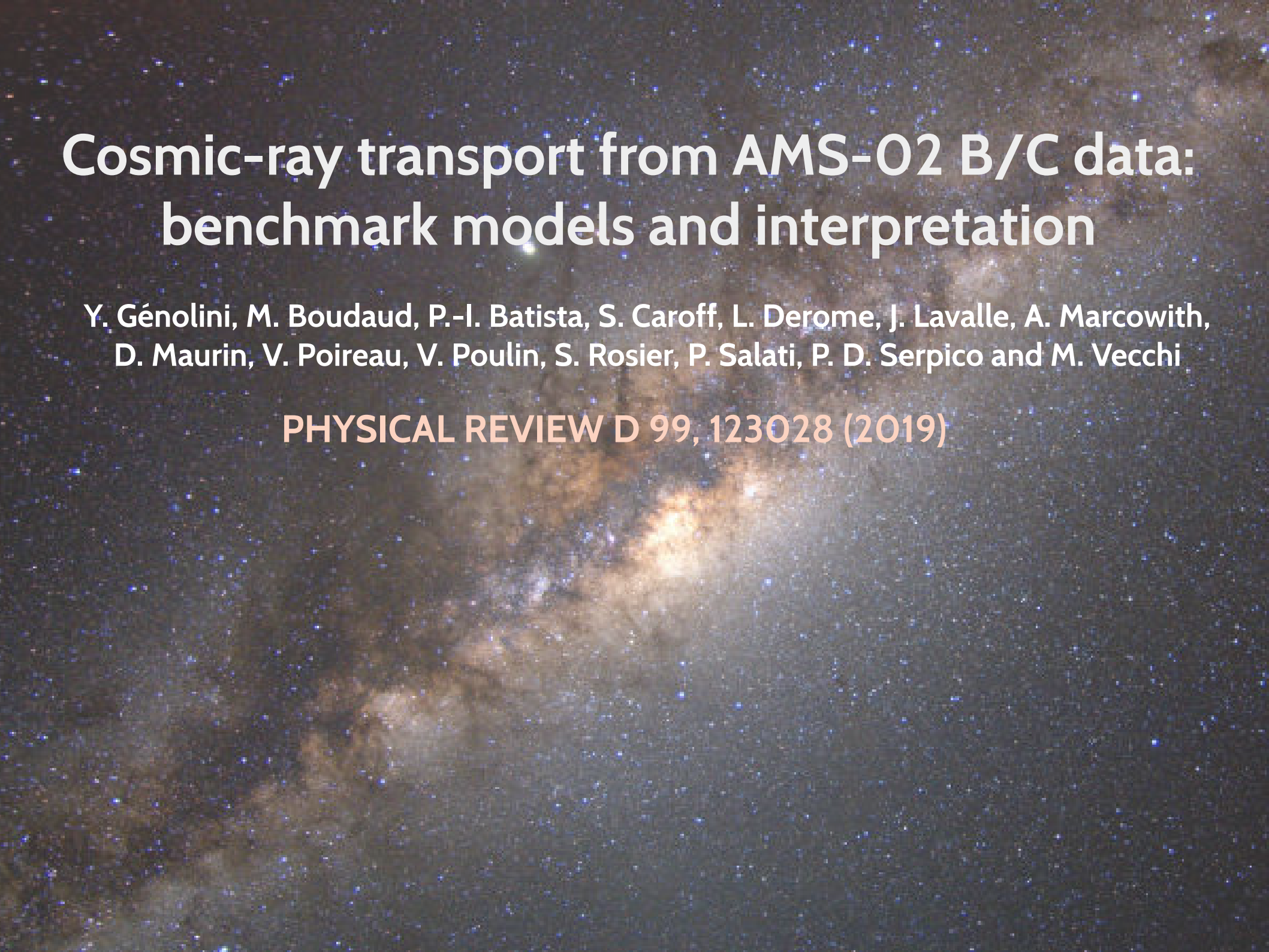

Cosmic-ray transport from AMS-02 B/C data: benchmark models and interpretation

Y. Génolini, M. Boudaud, P.-I. Batista, S. Caroff, L. Derome, J. Lavalle, A. Marcowith, D. Maurin, V. Poireau, V. Poulin, S. Rosier, P. Salati, P. D. Serpico and M. Vecchi

PHYSICAL REVIEW D 99, 123028 (2019)

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PHYSICAL REVIEW D 99, 123028 (2019)

Goal: -> To provide up-to-date transport benchmark models (and their uncertainties) in the context of AMS-02 very small uncertainties.

Method: -> No global fit.
-> New modelling ingredients.
-> New fitting procedure.

I - Novelties and benchmark models

II - Subtleties of the fitting procedure

III - Main results!

I - Novelties and benchmark models

II - Subtleties of the fitting procedure

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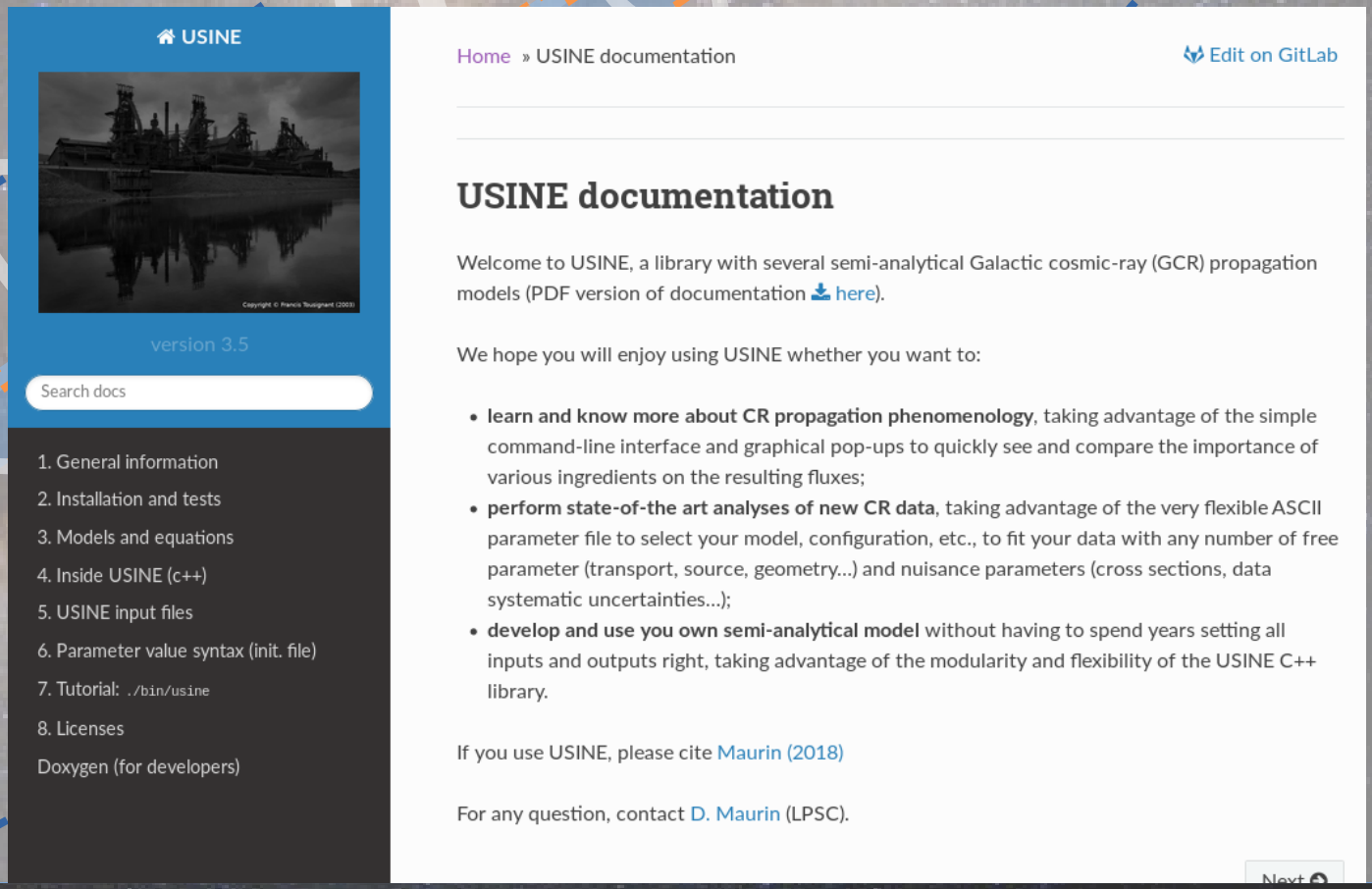
Analysis performed with USINE V-3.5 propagation code.

Arxiv : 1807.02968
-> https://dmaurin.gitlab.io/USINE/



USINE

version 3.5

Search docs

1. General information
2. Installation and tests
3. Models and equations
4. Inside USINE (c++)
5. USINE input files
6. Parameter value syntax (init. file)
7. Tutorial: `./bin/usine`
8. Licenses

Doxygen (for developers)

Home » USINE documentation

Edit on GitLab

USINE documentation

Welcome to USINE, a library with several semi-analytical Galactic cosmic-ray (GCR) propagation models (PDF version of documentation here).

We hope you will enjoy using USINE whether you want to:

- **learn and know more about CR propagation phenomenology**, taking advantage of the simple command-line interface and graphical pop-ups to quickly see and compare the importance of various ingredients on the resulting fluxes;
- **perform state-of-the art analyses of new CR data**, taking advantage of the very flexible ASCII parameter file to select your model, configuration, etc., to fit your data with any number of free parameter (transport, source, geometry...) and nuisance parameters (cross sections, data systematic uncertainties...);
- **develop and use you own semi-analytical model** without having to spend years setting all inputs and outputs right, taking advantage of the modularity and flexibility of the USINE C++ library.

If you use USINE, please cite Maurin (2018)

For any question, contact D. Maurin (LPSC).

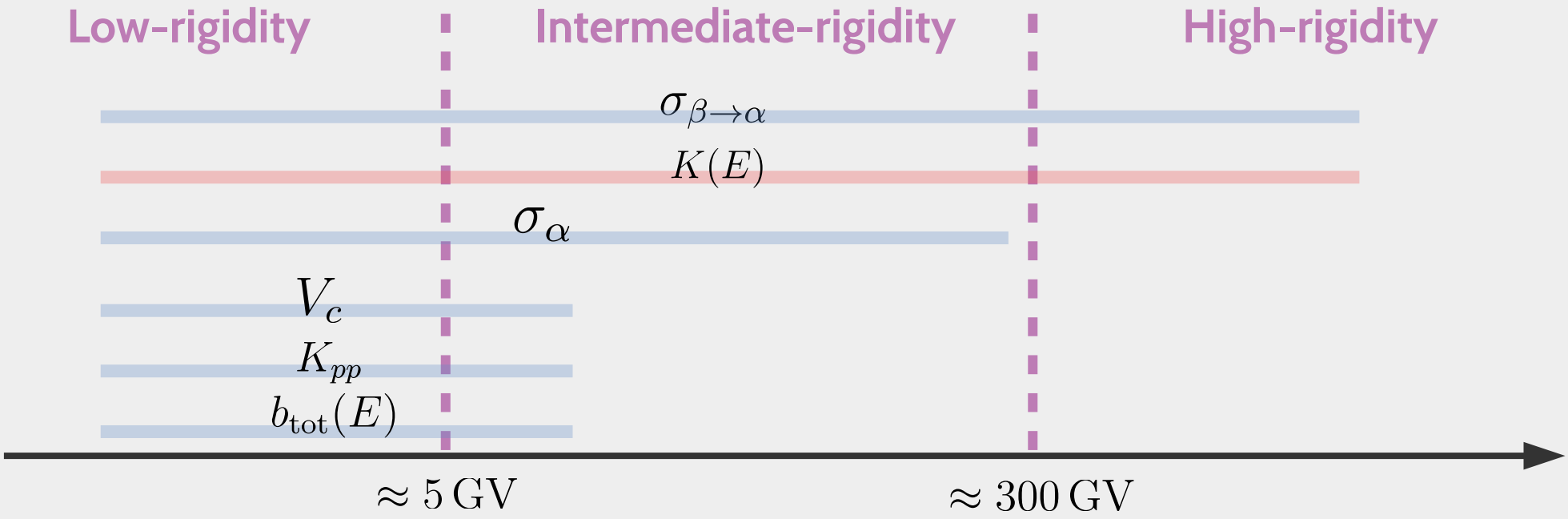
Next

I - Novelties and benchmark models

We solve semi-analytically the famous propagation equation in a 1D geometry:

$$-\vec{\nabla}_{\mathbf{x}}\left\{K(E)\,\vec{\nabla}_{\mathbf{x}}\psi_\alpha - \vec{V}_{\rm c}\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{\rm tot}(E)\,\psi_\alpha - \beta^2\,K_{pp}\,\frac{\partial\psi_\alpha}{\partial E}\right\}$$

$$+\sigma_\alpha\,v_\alpha\,n_{\rm ism}\,\psi_\alpha + \Gamma_\alpha\,\psi_\alpha = q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{\rm ism} + \Gamma_{\beta\to\alpha}\right\}\psi_\beta$$

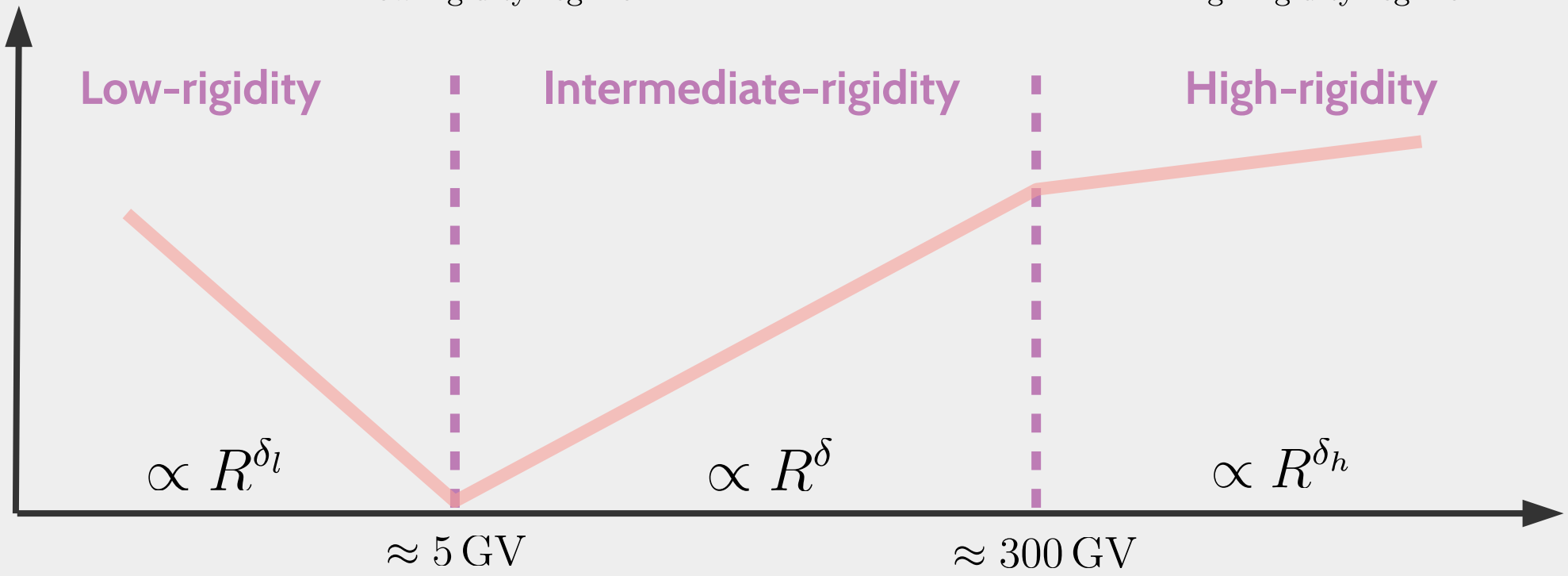


I - Novelties and benchmark models

-> Diffusion is assumed to be ***homogeneous*** and ***isotropic.***

-> We introduce several breaks in the diffusion coefficient:

$$K(R) = \beta^{\eta}\, K_{10} \underbrace{\left\{1 + \left(\frac{R}{R_{\rm l}}\right)^{\frac{\delta_{\rm l}-\delta}{s_{\rm l}}}\right\}^{s_{\rm l}}}_{\text{low-rigidity regime}} \underbrace{\left\{\frac{R}{(R_{10} \equiv 10\,\mathrm{GV})}\right\}^{\delta}}_{\text{intermediate regime}} \underbrace{\left\{1 + \left(\frac{R}{R_{\rm h}}\right)^{\frac{\delta-\delta_{\rm h}}{s_{\rm h}}}\right\}^{-s_{\rm h}}}_{\text{high-rigidity regime}} .$$



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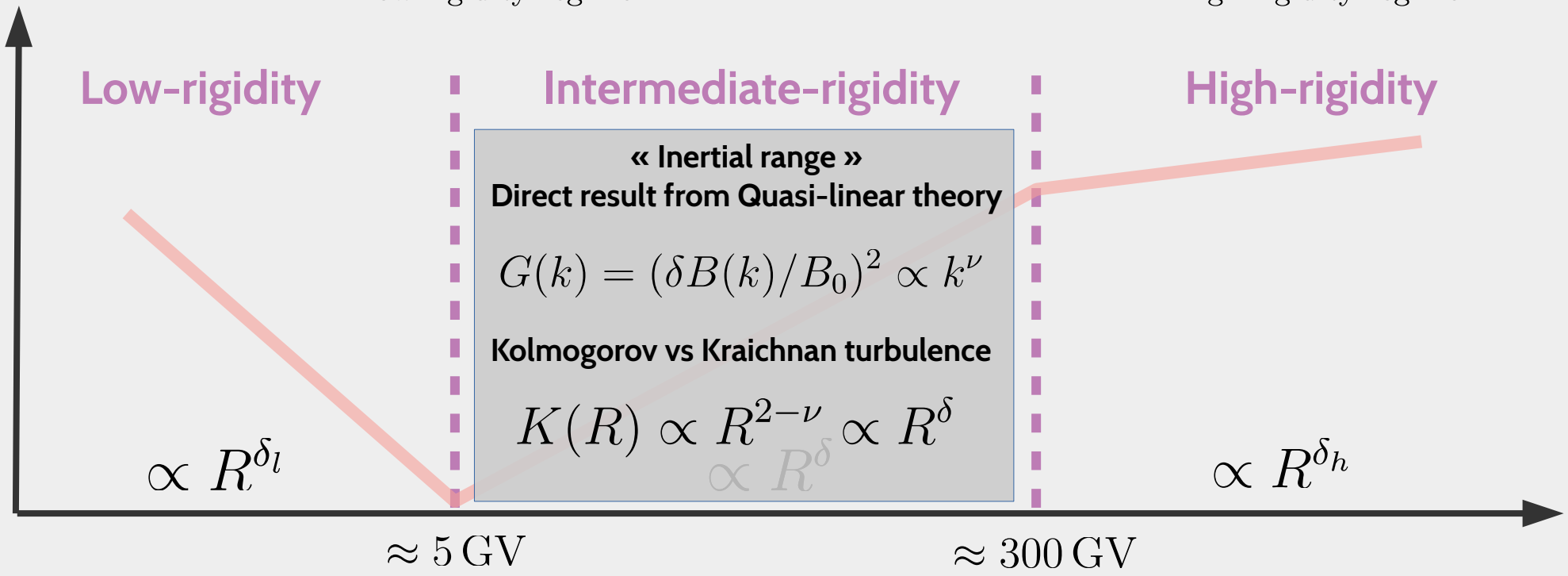

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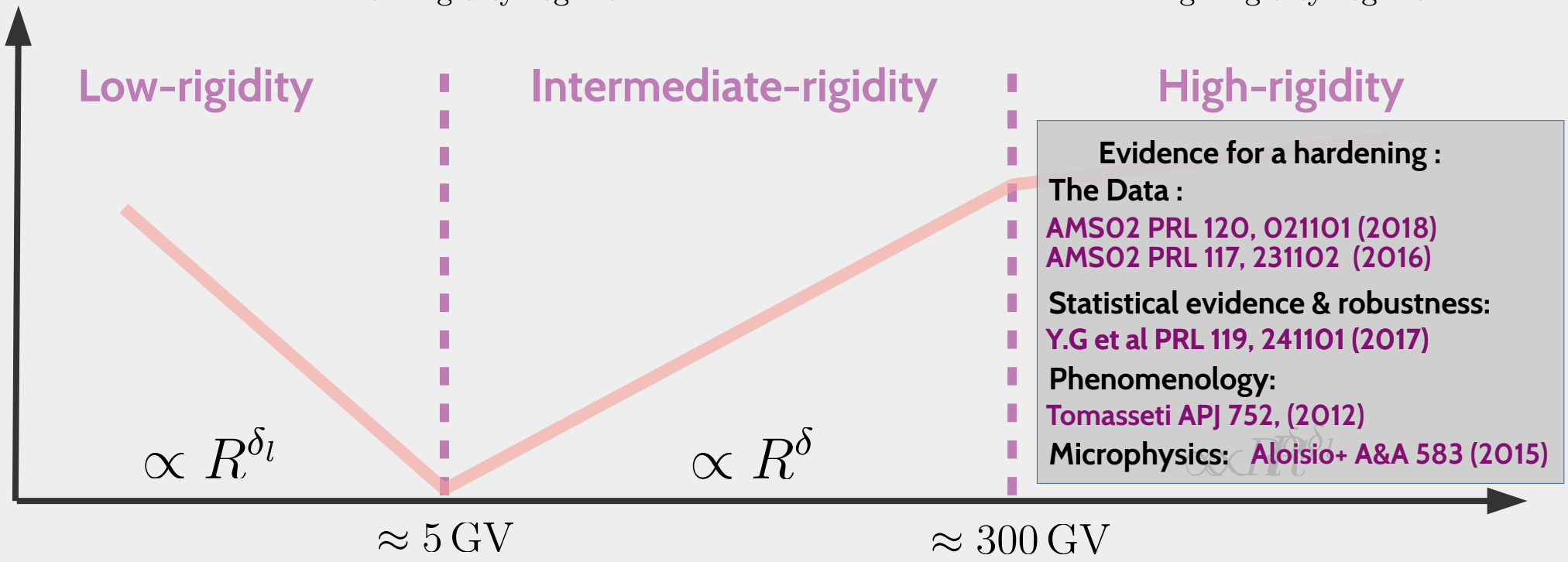

Evidence for a hardening :

The Data :

AMSO2 PRL 120, 021101 (2018)
AMSO2 PRL 117, 231102 (2016)

Statistical evidence & robustness:

Y.G et al PRL 119, 241101 (2017)

Phenomenology:

Tomasseti APJ 752, (2012)

Microphysics: Aloisio+ A&A 583 (2015)

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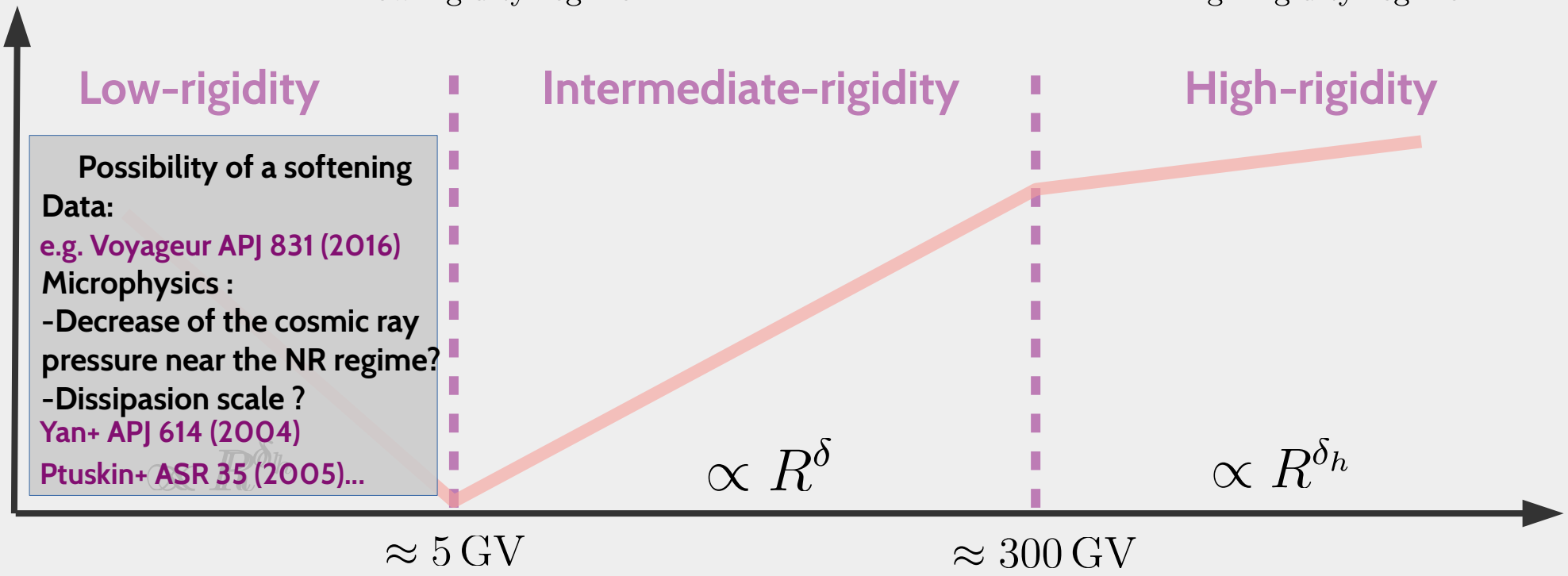

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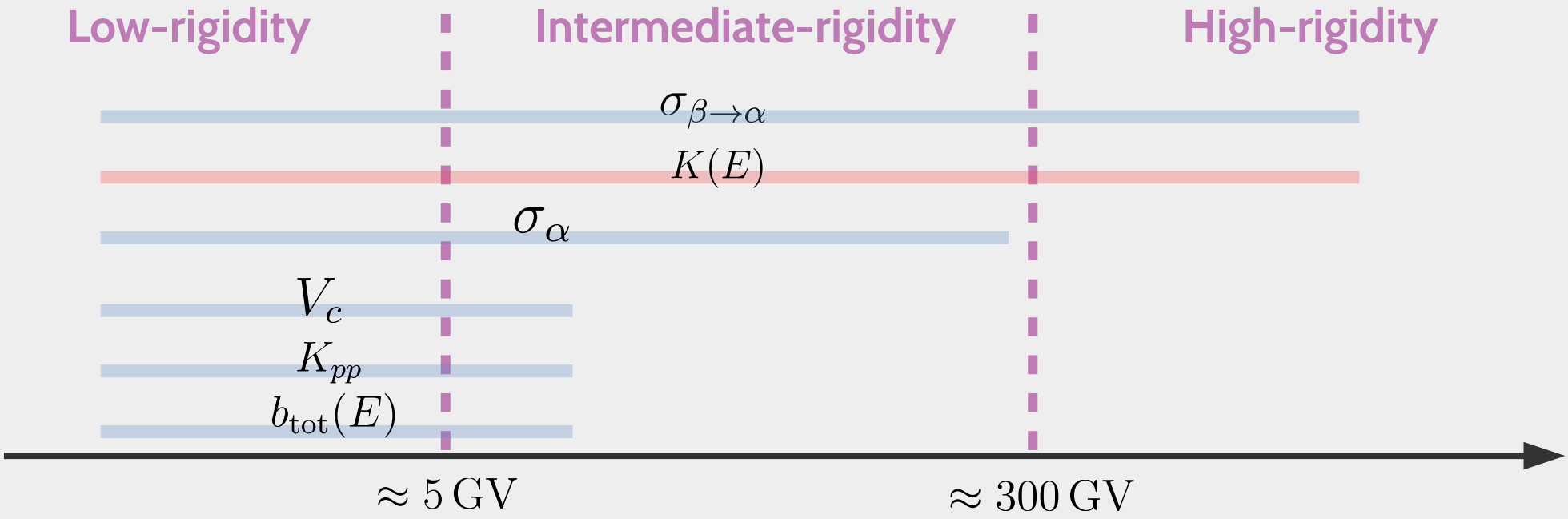
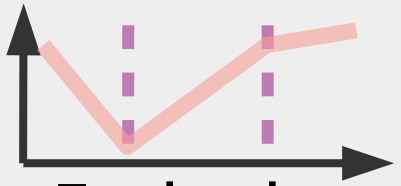


I - Novelties and benchmark models

We define three benchmark models:

BIG

V_c K_{pp} $K(E)$



6 free parameters

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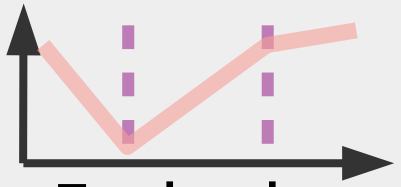
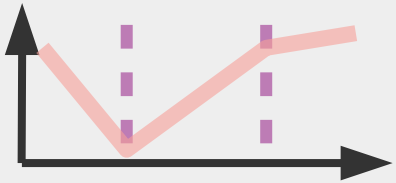


6 free parameters

SLIM $K(E)$



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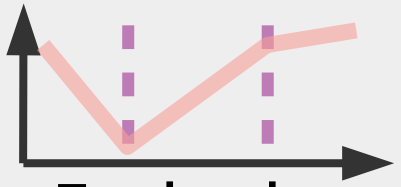

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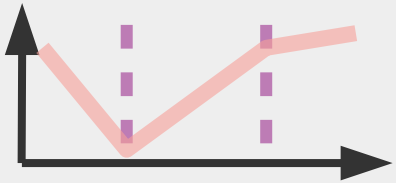
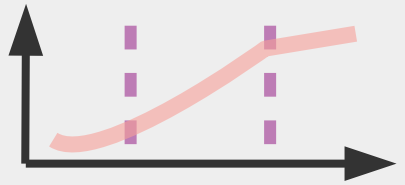


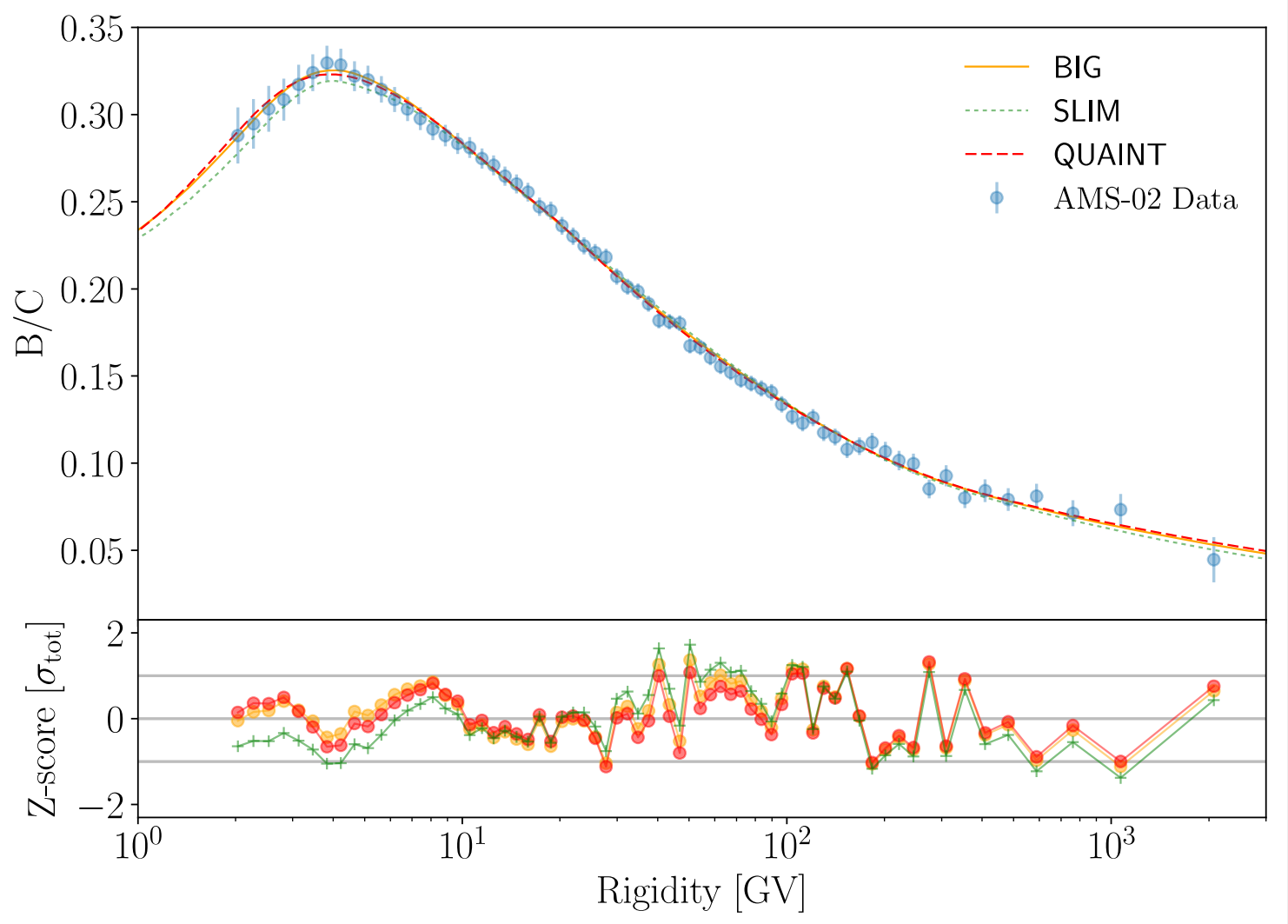
4 free parameters

QUAINT V_c K_{pp} $K(E)$



5 free parameters

I - Novelties and benchmark models



A priori no preference for one model compared to the others!

I - Novelties and benchmark models

II - Subtleties of the fitting procedure

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II - Subtleties of the fitting procedure

Methodology -> 1-Covariance matrix for data uncertainties

Errors are dominated by systematics

CRD6f : See Laurent Derome talk in a bit !

II - Subtleties of the fitting procedure

Methodology -> 1-Covariance matrix for data uncertainties

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-> 2-Theoretical errors are handled with *nuisance* parameters

Solar modulation: force field approximation

A. Ghelfi et al A&A 591, A94 (2016)

Production cross sections: NSS nuisance method only on $\sigma_{^{12}\mathrm{C}\rightarrow{}^{11}\mathrm{B}}$

Most important XS

see Y.G et al PRC 034611 (2018)

II - Subtleties of the fitting procedure

Y. Genolini, D. Maurin, I. Moskalenko and M. Unger et al PRC 034611 (2018) :
Current status and desired precision of the isotopic production cross sections relevant to astrophysics of cosmic rays. Li, Be, B, C, N

Reaction $a + b \to c$	Flux impact f_{abc} [%]			σ [mb]	Data	σ^c/σ
	min	**mean**	max	range		
$\sigma(^{12}\mathrm{C} + \mathrm{H} \to ^{11}\mathrm{B})$	18.0	**18.1**	19.0	30.0	✓	1.8
$\sigma(\mathbf{^{12}C + H \to ^{11}C})$	16.0	**16.2**	17.0	26.9	✓	**n/a**
$\sigma(^{16}\mathrm{O} + \mathrm{H} \to ^{11}\mathrm{B})$	11.3	**11.8**	12.0	18.2	✓	1.5
$\sigma(^{12}\mathrm{C} + \mathrm{H} \to ^{10}\mathrm{B})$	7.20	**7.41**	7.60	12.3	✓	1.1
$\sigma(^{16}\mathrm{O} + \mathrm{H} \to ^{10}\mathrm{B})$	6.82	**7.03**	7.21	10.9	✓	
$\sigma(\mathbf{^{16}O + H \to ^{11}C})$	5.67	**5.89**	6.00	9.1		**n/a**
$\sigma(^{11}\mathrm{B} + \mathrm{H} \to ^{10}\mathrm{B})$	4.00	**4.07**	4.20	38.9	✓	
$\sigma(^{12}\mathrm{C} + \mathrm{He} \to ^{11}\mathrm{B})$	2.50	**2.59**	2.70	38.6		1.8
$\sigma(\mathbf{^{12}C + He \to ^{11}C})$	2.10	**2.14**	2.20	32.0		**n/a**
$\sigma(^{15}\mathrm{N} + \mathrm{H} \to ^{11}\mathrm{B})$	2.00	**2.03**	2.10	26.1	✓	1.2
$\sigma(\mathbf{^{12}C + H \to ^{10}C})$	1.80	**1.87**	1.90	3.1	✓	**n/a**
$\sigma(^{16}\mathrm{O} + \mathrm{He} \to ^{11}\mathrm{B})$	1.67	**1.75**	1.80	24.4		1.5
$\sigma(^{13}\mathrm{C} + \mathrm{H} \to ^{11}\mathrm{B})$	1.50	**1.53**	1.60	22.2		1.7
$\sigma(^{12}\mathrm{C} + \mathrm{H} \to ^{10}\mathrm{Be})$	1.40	**1.48**	1.50	4.0	✓	
$\sigma(^{14}\mathrm{N} + \mathrm{H} \to ^{11}\mathrm{B})$	1.30	**1.34**	1.36	17.3	✓	1.7
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$\sigma(^{16}\mathrm{O} + \mathrm{He} \to ^{10}\mathrm{B})$	0.99	**1.05**	1.09	14.6		
$\sigma(^{24}\mathrm{Mg} + \mathrm{H} \to ^{11}\mathrm{B})$	0.98	**1.01**	1.00	10.4		1.6

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Contribution in % to the Boron flux

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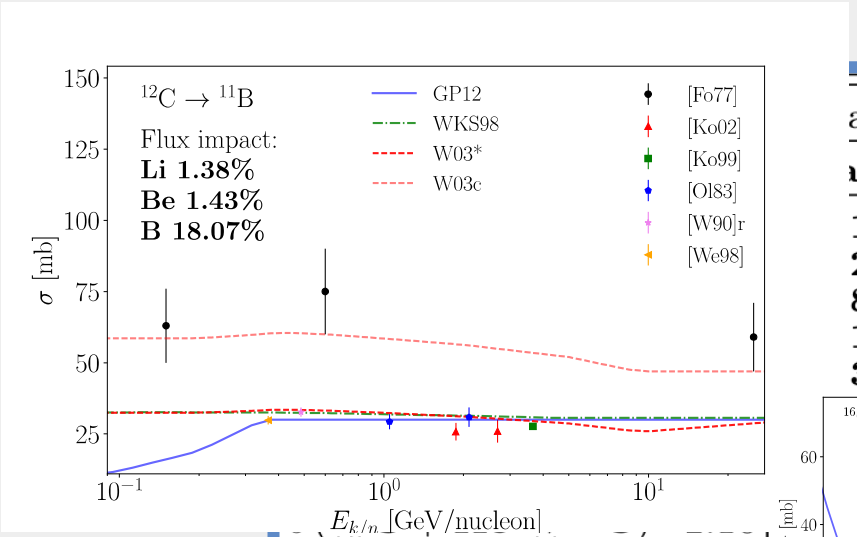

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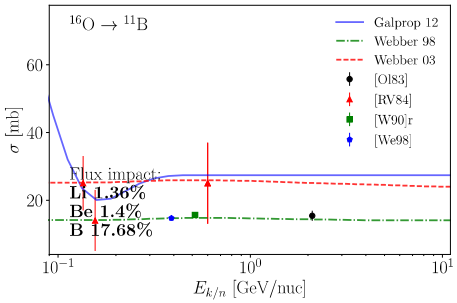
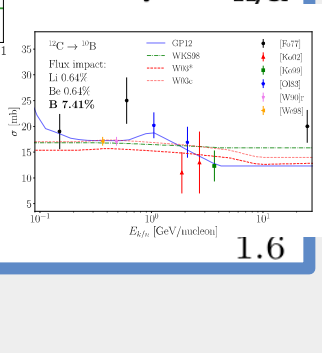
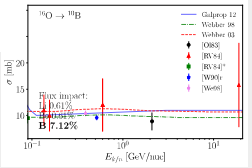
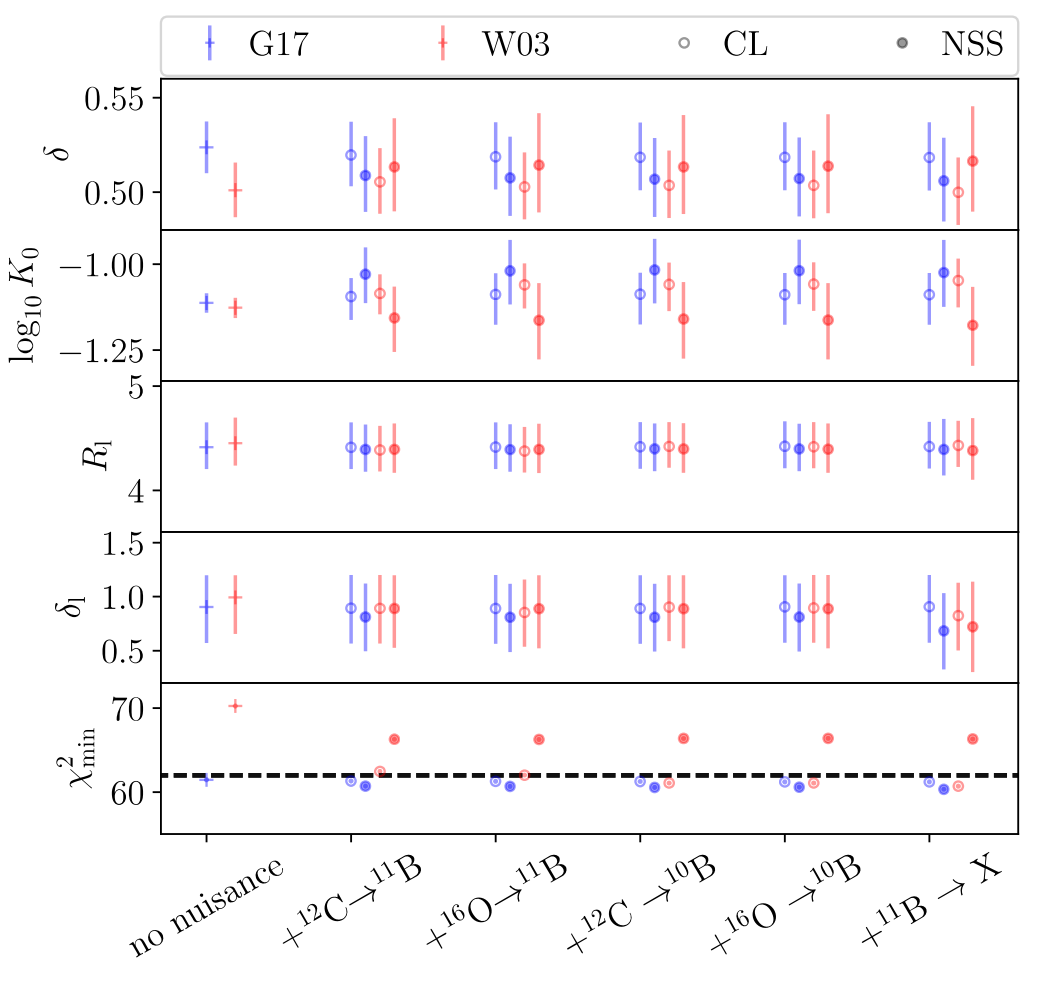






II - Subtleties of the fitting procedure



Derome et al 1904.08210

Best fit propagation parameters with uncertainties increasing the number of XS as nuisance following Y.G et al PRC 034611 (2018)

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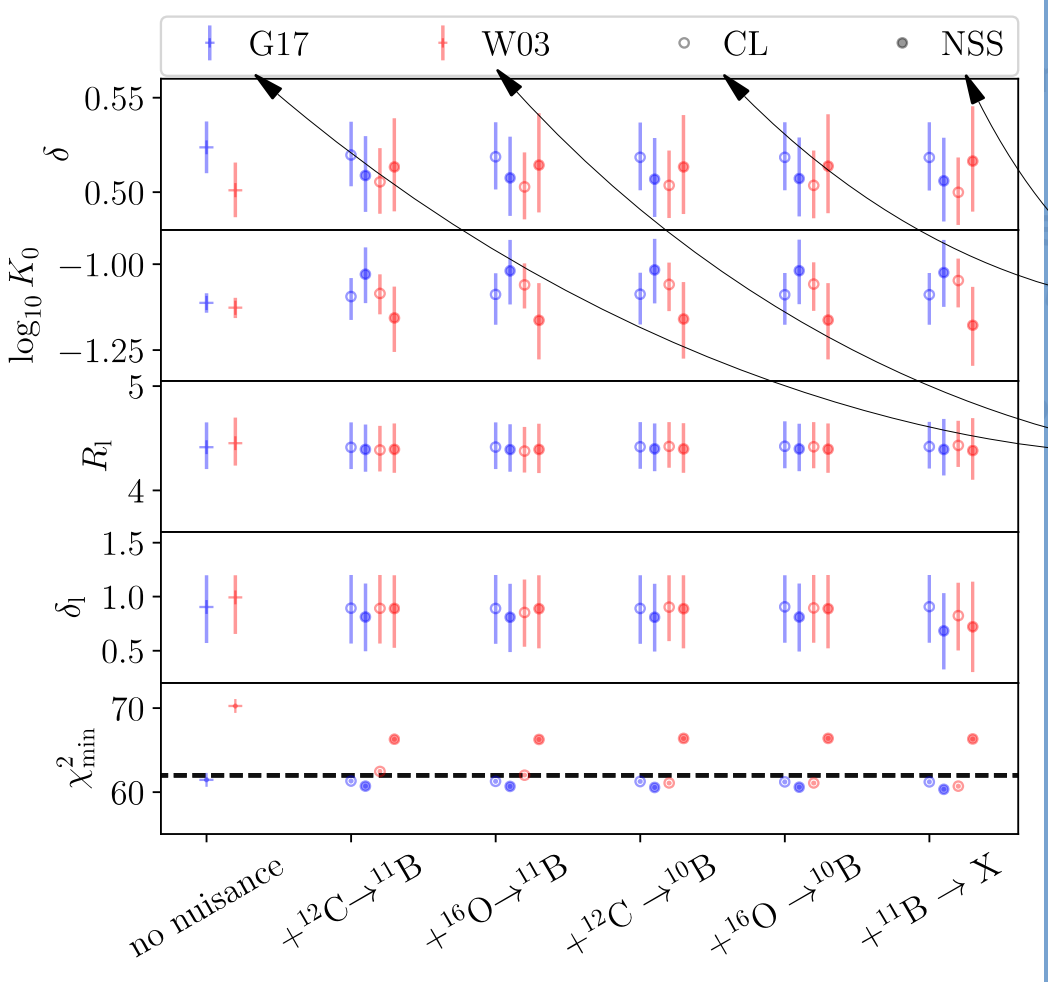


Derome et al 1904.08210

Best fit propagation parameters with uncertainties increasing the number of XS as nuisance following Y.G et al PRC 034611 (2018)

Two methods of nuisance

Using Galprop or Webber XS

Three conclusions :

1- The tension btw the two XS sets is released using a single reaction as nuisance

2- Adding more XS as nuisance does not increase further the error bars.
->Data systematics mitigate the uncertainties from XS

3- NSS method gives a little bit more freedom so we use it.

II - Subtleties of the fitting procedure

Methodology -> 1-Covariance matrix for data uncertainties

Errors are dominated by systematics

CRD6f : See Laurent Derome talk in a bit !

-> 2-Theoretical errors are handled with *nuisance* parameters

Solar modulation: force field approximation

A. Ghelfi et al A&A 591, A94 (2016)

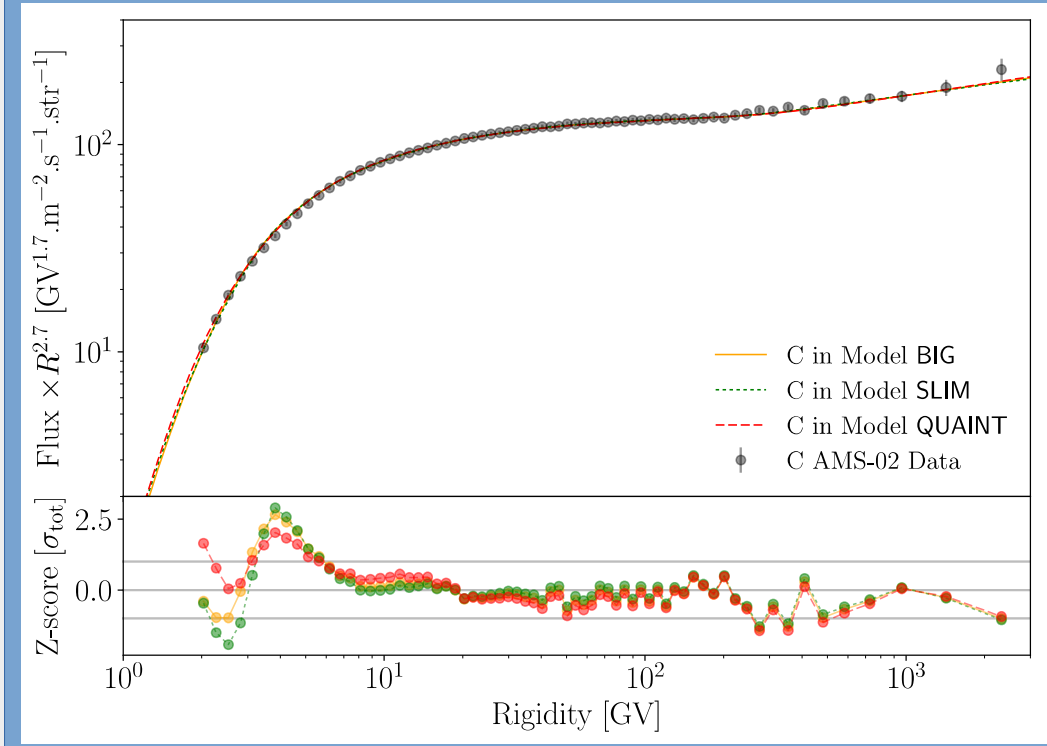
Production cross section: NSS nuisance method only on $\sigma_{^{12}\mathrm{C}\rightarrow^{11}\mathrm{B}}$

-> 3-Iterative fitting procedure using C and O AMS02 data

Two reasons : - To be consistent with primary AMS02 data

- To better constrain the high-rigidity break

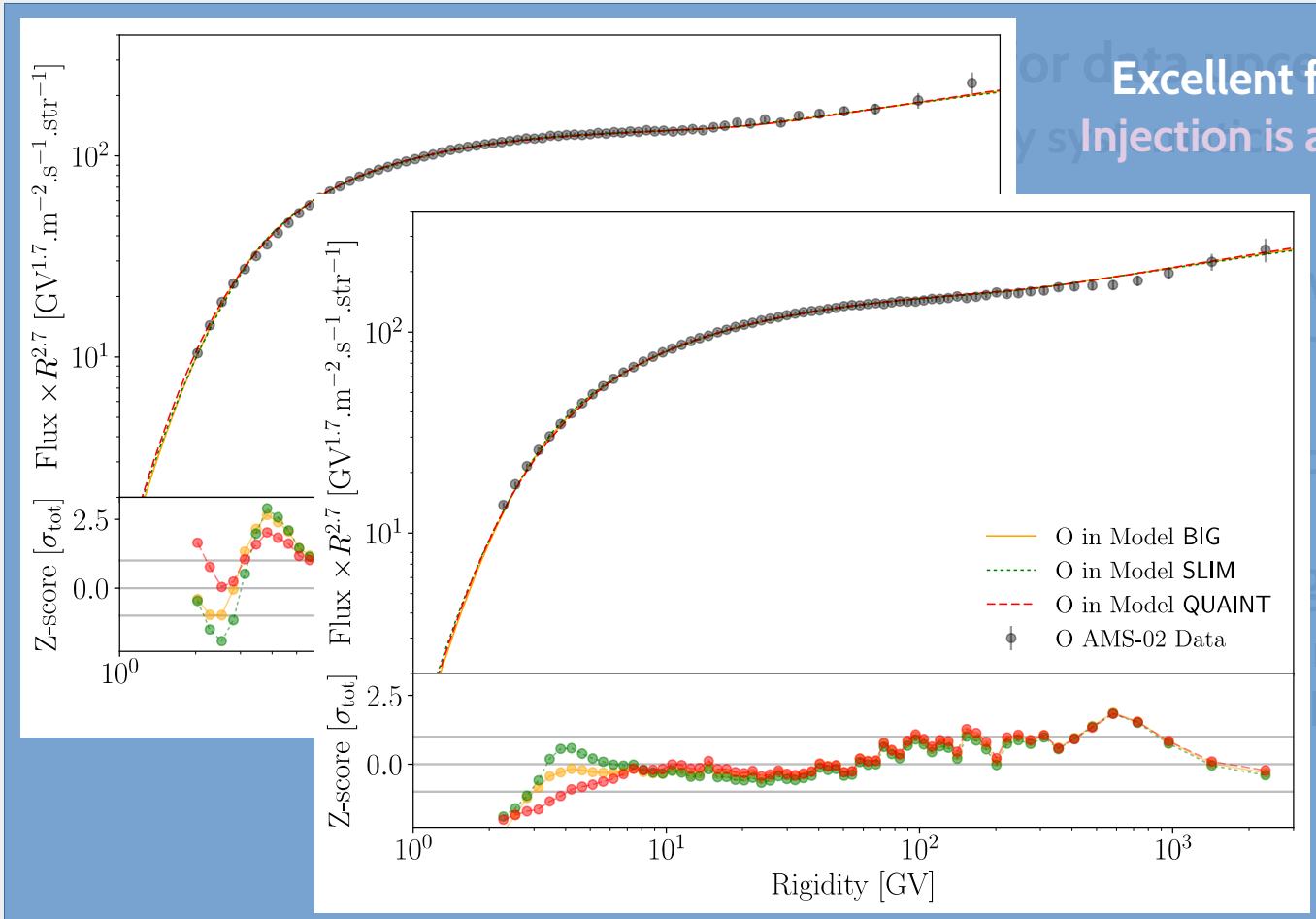
II - Subtleties of the fitting procedure



Excellent fit to C and O AMS02 data !

Injection is a pure power law of the rigidity

II - Subtleties of the fitting procedure



Excellent fit to C and O AMS02 data !
Injection is a pure power law of the rigidity

	$\chi^2_{\rm dof}$
BIG	$75.9/129 = 0.59$
SLIM	$73.2/129 = 0.57$
QUAINT	$80.3/129 = 0.62$

They are used to constrain the high-rigidity break parameters, nuisances of the B/C fit

I - Novelties and benchmark models

II - Subtleties of the fitting procedure

III - Main results!

III – Main results!

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

III – Main results!

The best fit parameters:

1 - Similar fit qualities

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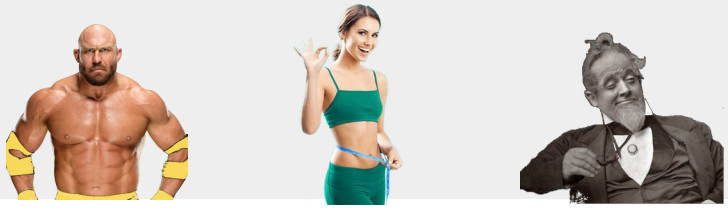

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2 – One sigma compatible parameters in the inertial regime. Closer to Kraichnan turbulence

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Y.G et al PRL 119, 241101 (2017)
with a decisive bayesian evidence of a high-rigidity break in the effective diffusion coefficient.

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Best fit parameters and covariance matrices are available on request!

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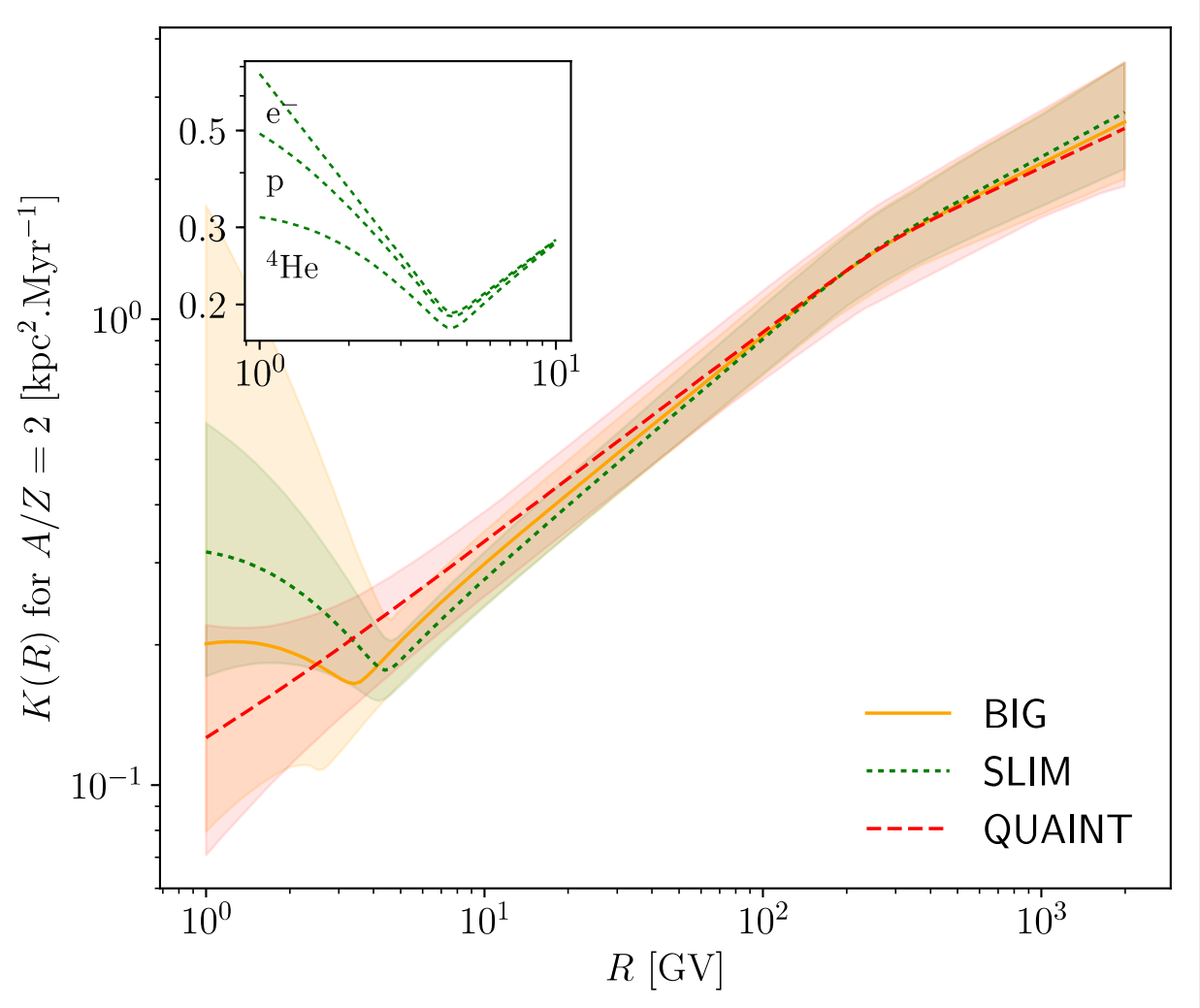
III – Main results!

Illustration : uncertainty on the diffusion coefficient.



Conclusions

RESULTS:

-> Kraichnan like delta

-> High-rigidity break confirmed in the diffusion coefficient

Y.G et al PRL 119, 241101 (2017)

-> Hint for a low-rigidty break in diffusion @~4GV

-> Primary injection is compatible with a simple rigidity power law

BIG, SLIM and, QUAINT : New up-to-date transport benchmark parameters

-> Already used for antiprotons Boudaud et al: arxiv 1906.07119

CRD1b: See Mathieu Boudaud talk last Thursday !

-> Also used to forecast expected data slopes in AMS02 data

CRD6g: See Manuela Vecchi talk in a bit !

-> Dictionary provided to go from 1D to 2D model
(useful for dark matter-related studies)

Present analysis: B/C data only.

-> Data available: Li, Be, B, C, N, O, possibly 3,4He and heavier nuclei soon.

CRD6b: See Alberto Oliva talk in a bit!

PROSPECTS:

-> Use other secondary-to-primary species to check consistency and tighten the constraints on transport parameters.

-> Use radioactive species to constrain halo size of the Galaxy (necessary for dark matter studies).

-> Forthcoming interface of USINE with Python will give us a better control to deal with more global studies.

KEY INGREDIENTS to further improve all analyses:

-> Experimental covariance from the AMS02 collaboration.

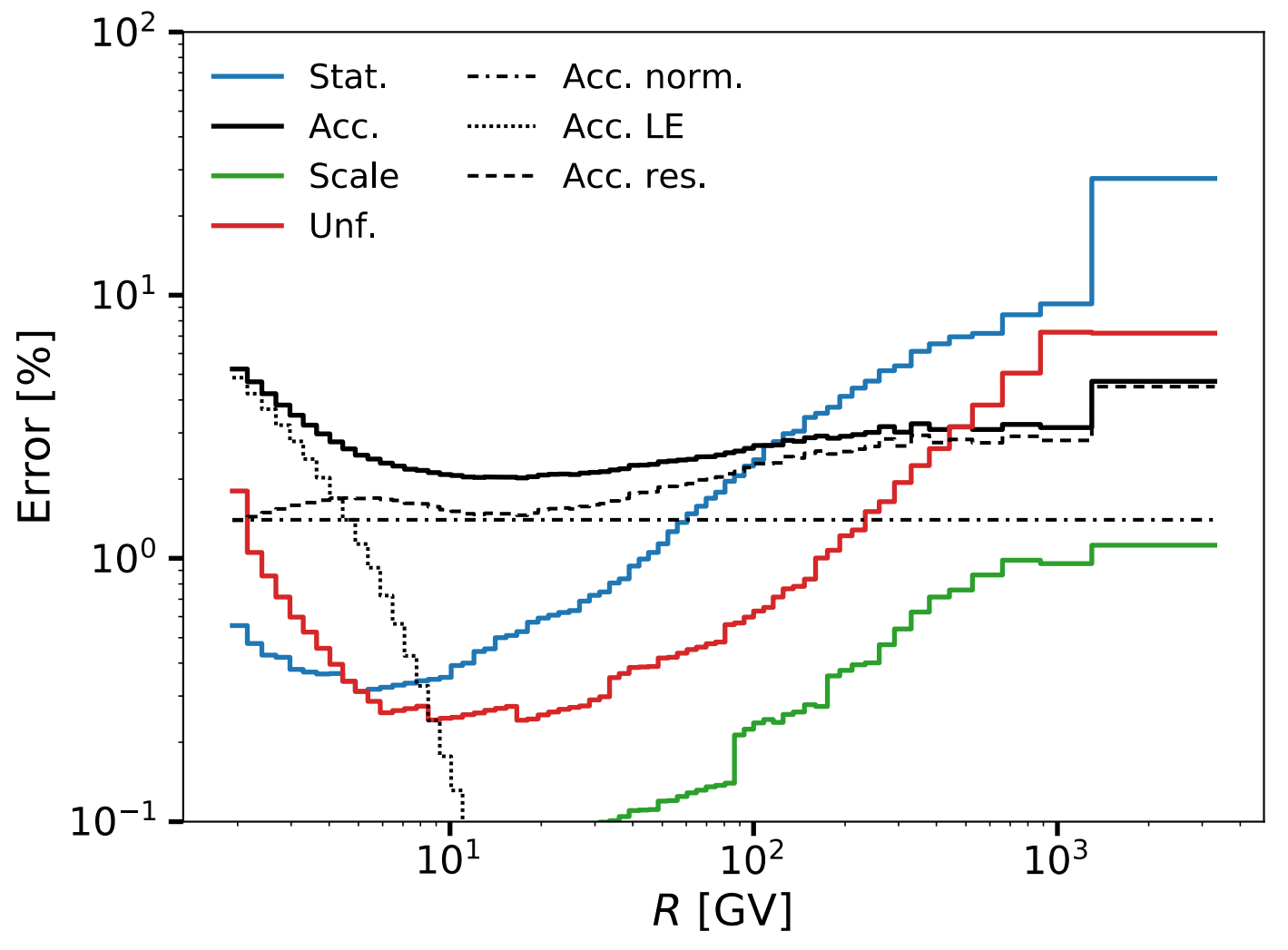
-> Reduce the uncertainties on spallation cross sections.

CRI6e: See Michael Unger talk on Saturday!

BACK UP

Parameters	BIG	SLIM	QUAINT
δ	$0.55^{+0.20}_{-0.04}$	$0.55^{+0.09}_{-0.03}$	$0.9_{-0.23}$
K_{10} [kpc^2/Myr]	$0.26^{+0.05}_{-0.2}$	$0.26^{+0.07}_{-0.01}$	$0.10^{+0.07}_{-0.01}$
V_A [km/s]	0^{+64}	NA	71^{+20}_{-7}
V_c [km/s]	0^{+16}	NA	19^{+3}_{-5}
η_t	1 (fixed)	1 (fixed)	$-0.30^{+0.54}_{-0.75}$
δ_l	$-0.84^{+0.32}_{-0.36}$	$-0.87^{+0.35}_{-0.33}$	NA
R_l [GV]	$4.4^{+0.46}_{-2.1}$	$4.4^{+0.2}_{-0.2}$	NA
Δ_h	$0.27^{+0.22}_{-0.12}$	$0.27^{+0.21}_{-0.12}$	$0.56^{+0.09}_{-0.24}$
R_h [GV]	158^{+235}_{-58}	159^{+240}_{-59}	100^{+96}
s_h	$0.10^{+0.20}_{-0.10}$	$0.11^{+0.19}_{-0.1}$	$0.26^{+0.04}_{-0.26}$
χ^2/dof	58.6/58 = 1.01	58.7/60 = 0.98	59.7/59 = 1.01

Parameters	BIG	SLIM	QUAINT
δ	$0.48^{+0.02}_{-0.02}$	$0.48^{+0.02}_{-0.02}$	$0.42^{+0.03}_{-0.02}$
K_{10} [kpc^2/Myr]	$0.29^{+0.02}_{-0.02}$	$0.29^{+0.02}_{-0.02}$	$0.36^{+0.02}_{-0.04}$
V_A [km/s]	0^{+115}	NA	113^{+7}_{-15}
V_c [km/s]	0^{+12}	NA	$0^{+4.1}$
η_t	1 (fixed)	1 (fixed)	$0.6^{+0.3}_{-0.5}$
δ_l	$-0.88^{+0.31}_{-0.30}$	$-0.88^{+0.32}_{-0.30}$	NA
R_l [GV]	$4.4^{+0.23}_{-2.4}$	$4.4^{+0.24}_{-0.21}$	NA
χ^2/dof	72.8/61 = 1.19	72.8/63 = 1.16	67.1/62 = 1.08
$\Delta\chi^2$	11.1	11.0	5.0


Stat.
Acc.
Scale
Unf.
Acc. norm.
Acc. LE
Acc. res.
Error [%]
10^2
10^1
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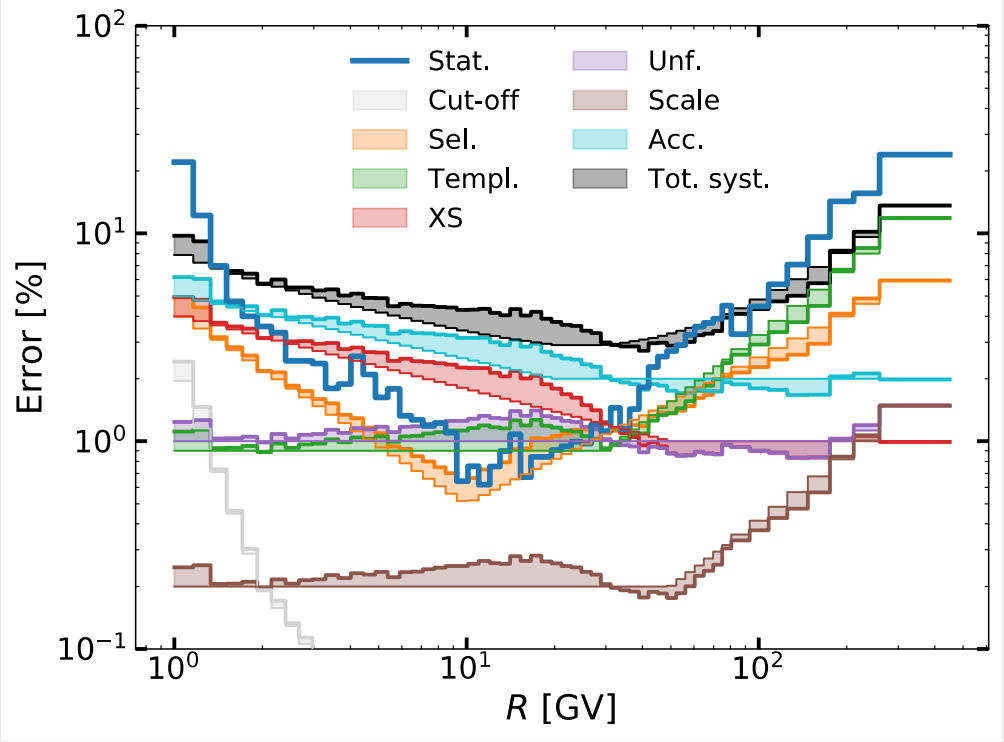
10^{-1}
10^1
10^2
10^3
R [GV]


Stat.
Cut-off
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Templ.
XS
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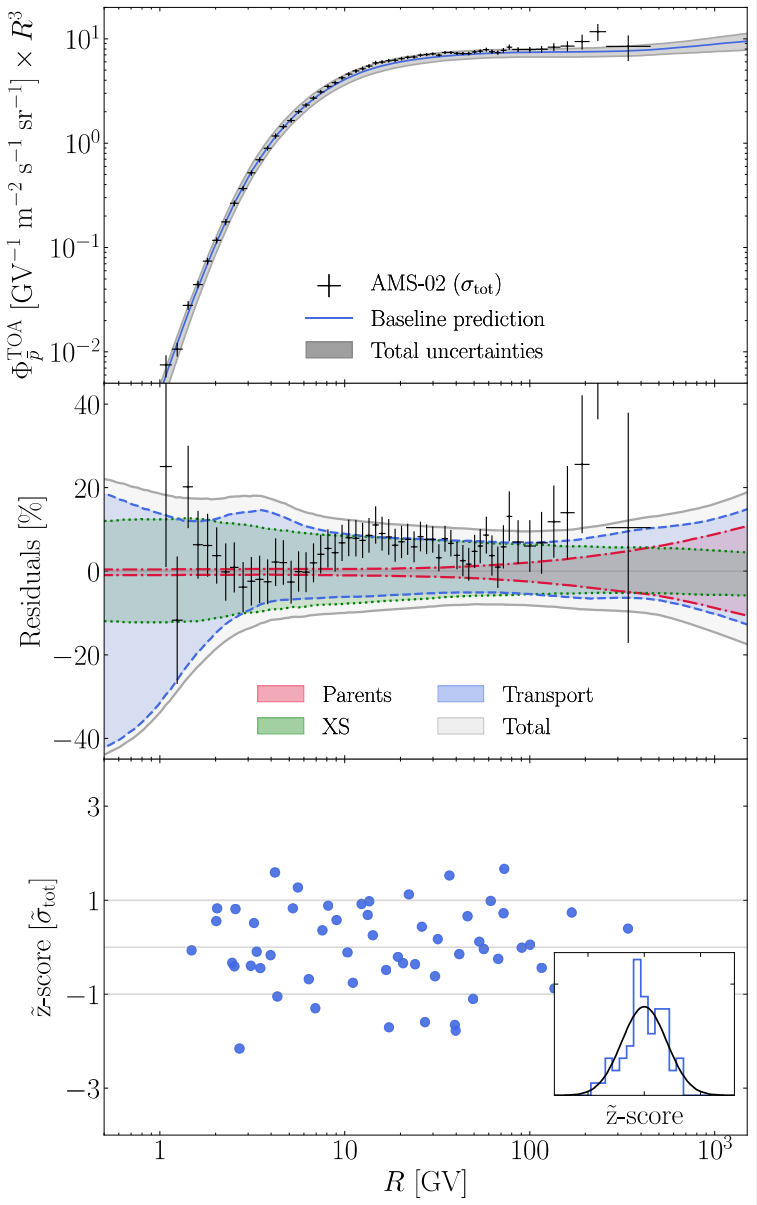
Tot. syst.
Error [%]
R [GV]


AMS-02 ($\sigma_{\rm tot}$)
Baseline prediction
Total uncertainties
$\Phi_{\bar{p}}^{\rm TOA}$ [GV^{-1} m^{-2} s^{-1} sr^{-1}] $\times R^3$
Residuals [%]
Parents
XS
Transport
Total
$\tilde{z}$-score [$\tilde{\sigma}_{\rm tot}$]
$\tilde{z}$-score
R [GV]