Galactic cosmic rays : current status and open questions

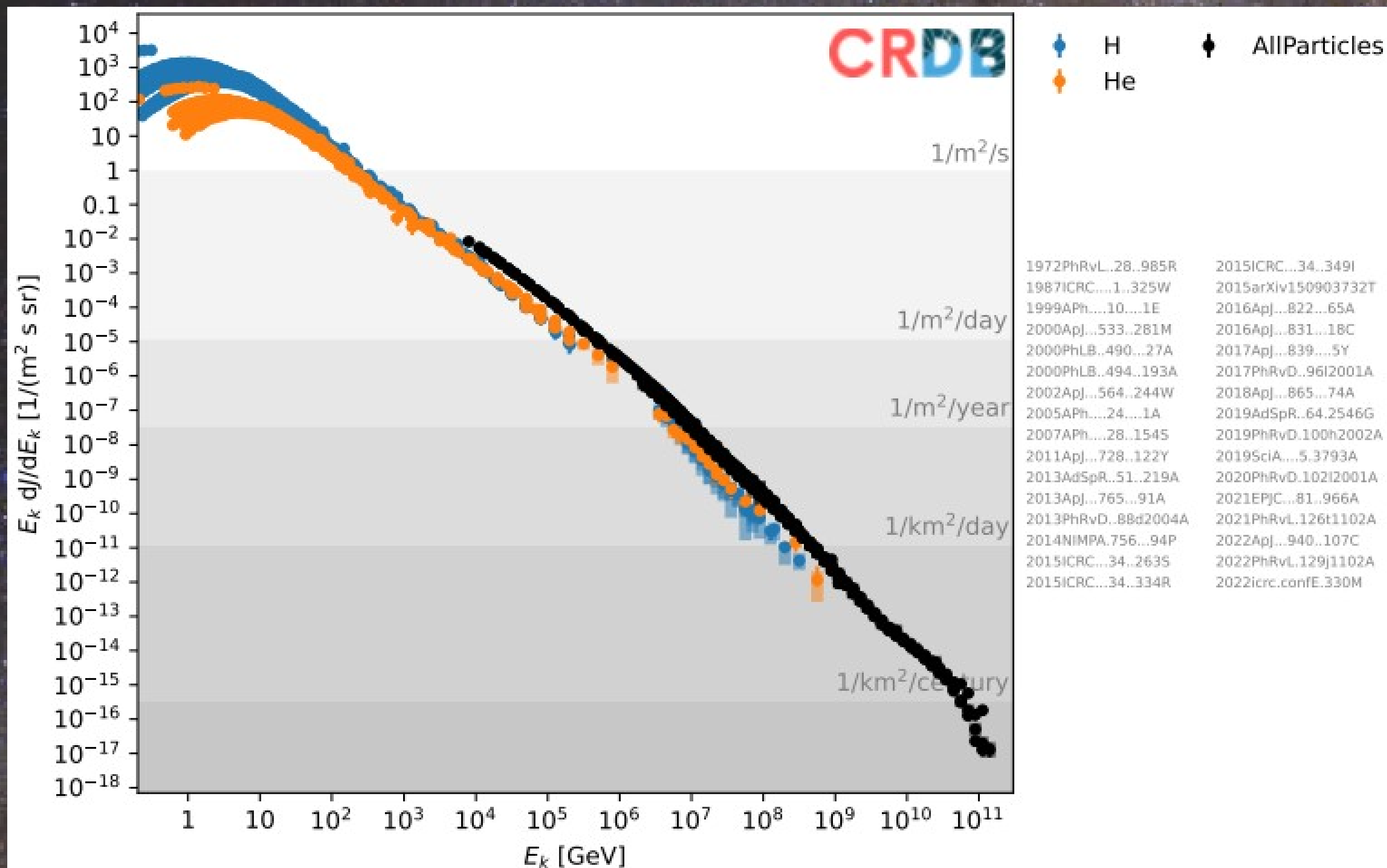
Yoann Génolini

Collaborators :

M. Boudaud, P.-I. Batista, S. Caroff,
M. Cireli, L. Derome, J. Lavalle, M. Ahlers
A. Marcowith, D. Maurin, I. Moskalenko
V.Poireau, V. Poulin, S. Rosier, P. Salati,
P. D. Serpico , M. Unger,
M. Vecchi and N. Weinrich

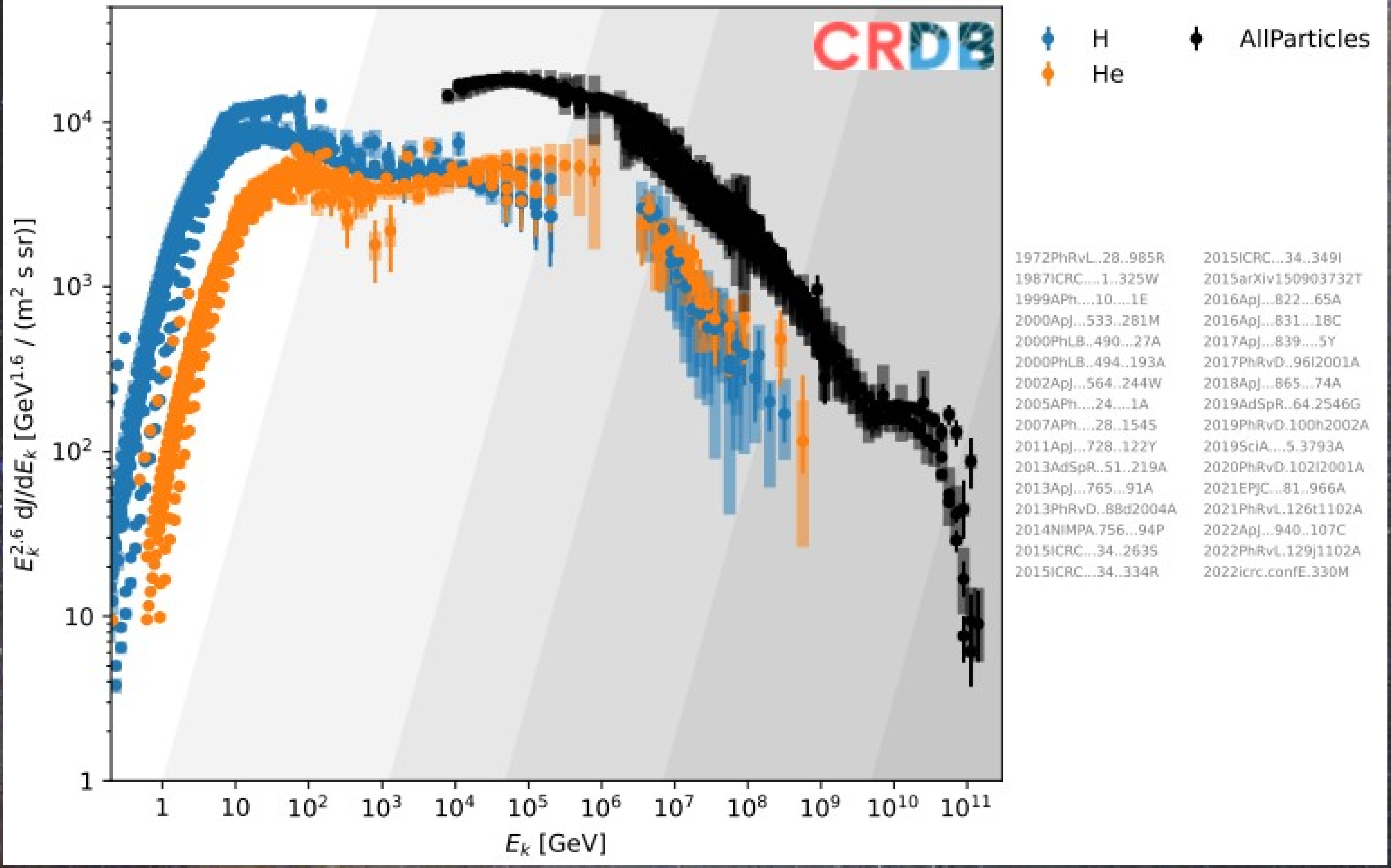
UNIVERSITÉ SAVOIE MONT BLANC
cnrs
LAPTh

TEVPA, September 11th 2023



https://github.com/crdb-project/tutorial/blob/main/gallery.ipynb

Introduction : the precision era



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Introduction : the precision era

Some pending questions of galactic CRs :

Sources

What are the sources of GCRs/acceleration mec.?
Is CR acceleration universal?
What is their respective contribution to the flux?
What is the maximum energy of GCRs?
Does the escape impact the injected flux?
What is their distribution in the galaxy?
Are there exotic (!=astrophysical) sources?
...

See also the recent review: Gabici+ (2019)

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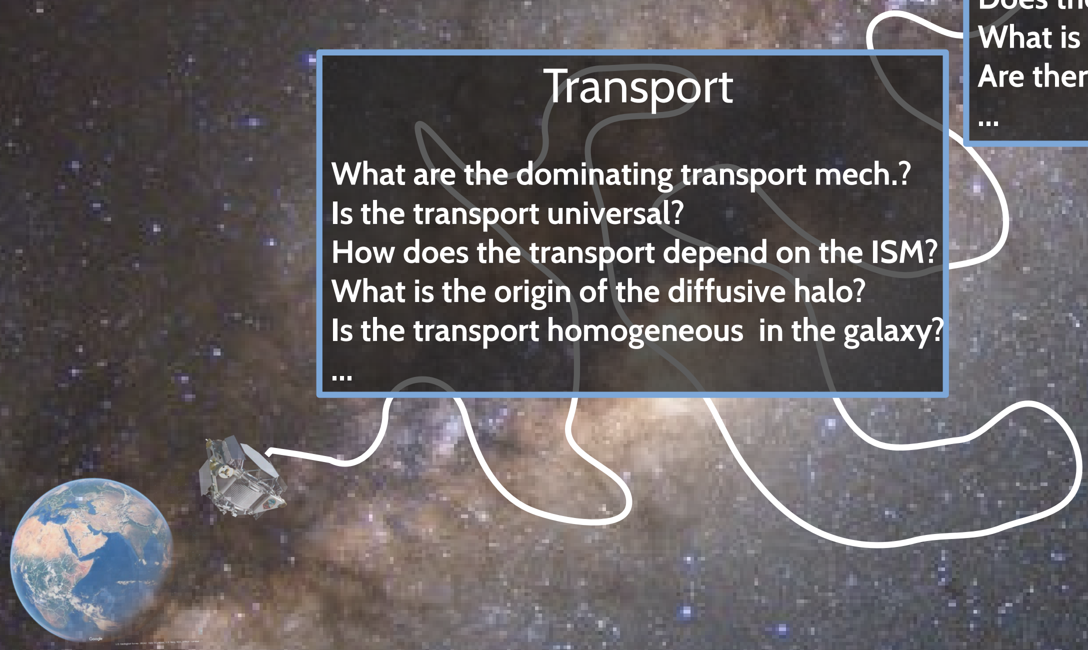

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Local environement

What is the effect of the solar wind on local fluxes?
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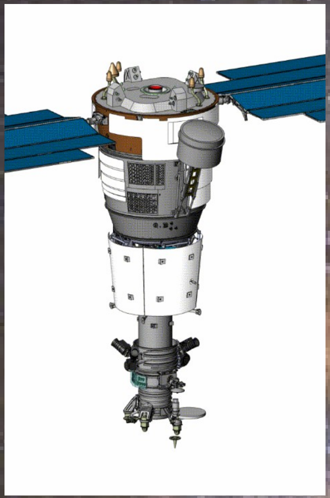
Introduction : the precision era

Game changer: high-quality data!

→ In this talk focus on direct detection experiments

AMS02

NUCLEON



CALET

DAMPE

ISS-CREAM

	AMS02	NUCLEON	CALET	DAMPE	ISS-CREAM
Op. since:	12yrs	8.5yrs	8yrs	7.5yrs	3.5yrs
Published E-range	1 GV – 1.9 TV	1 TeV – 500 TeV	10 GeV – 100TeV	10 GeV – 100 TeV	1TeV-500TeV

Spectrometer

→ Precision level % from GV to TV
→ Spectrometer : able to measure isotopes

Calorimeters

→ High-statistics up to 100TeV
→ Bridging the gap with air-shower experiments

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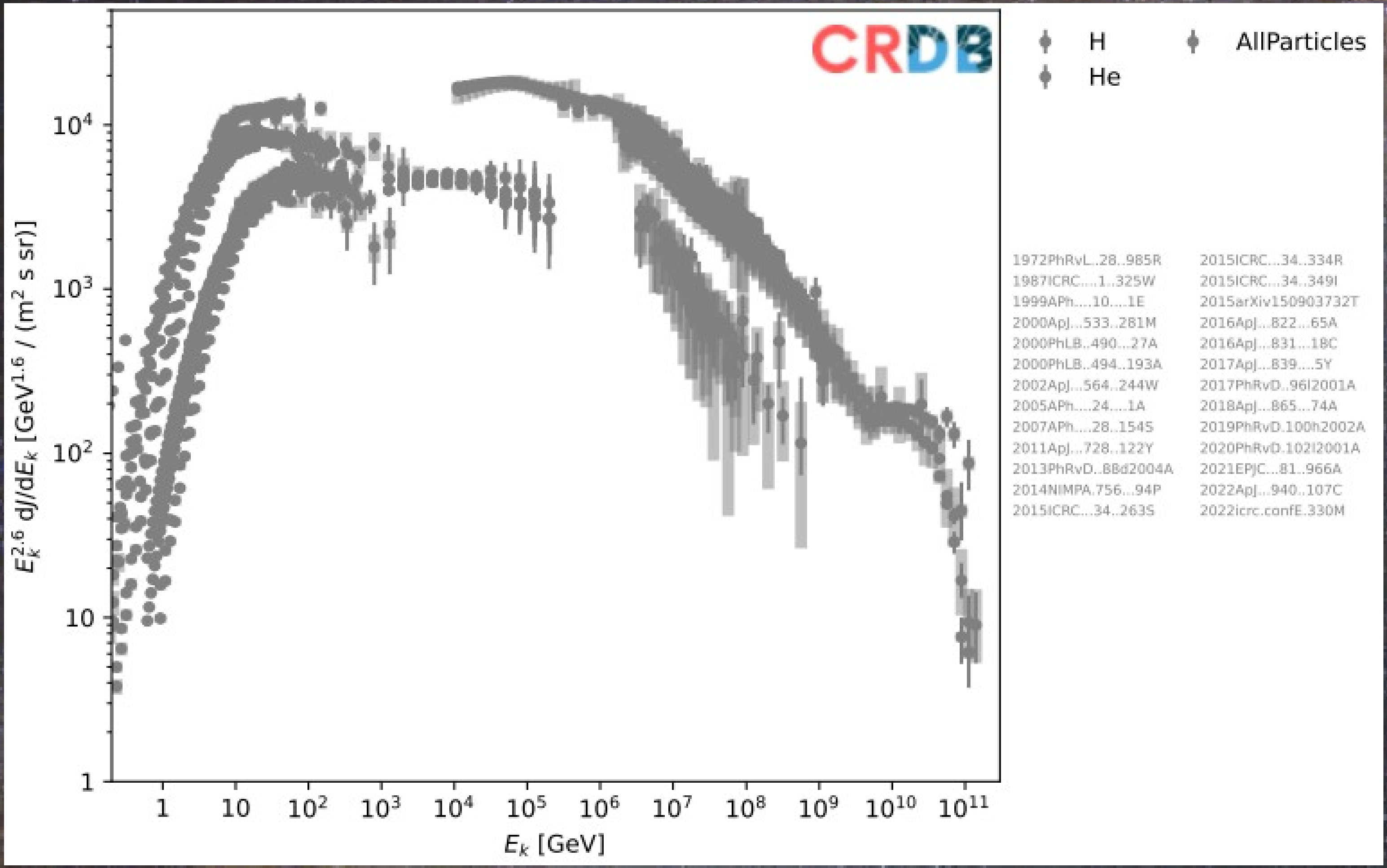
Game changer: high-quality data!



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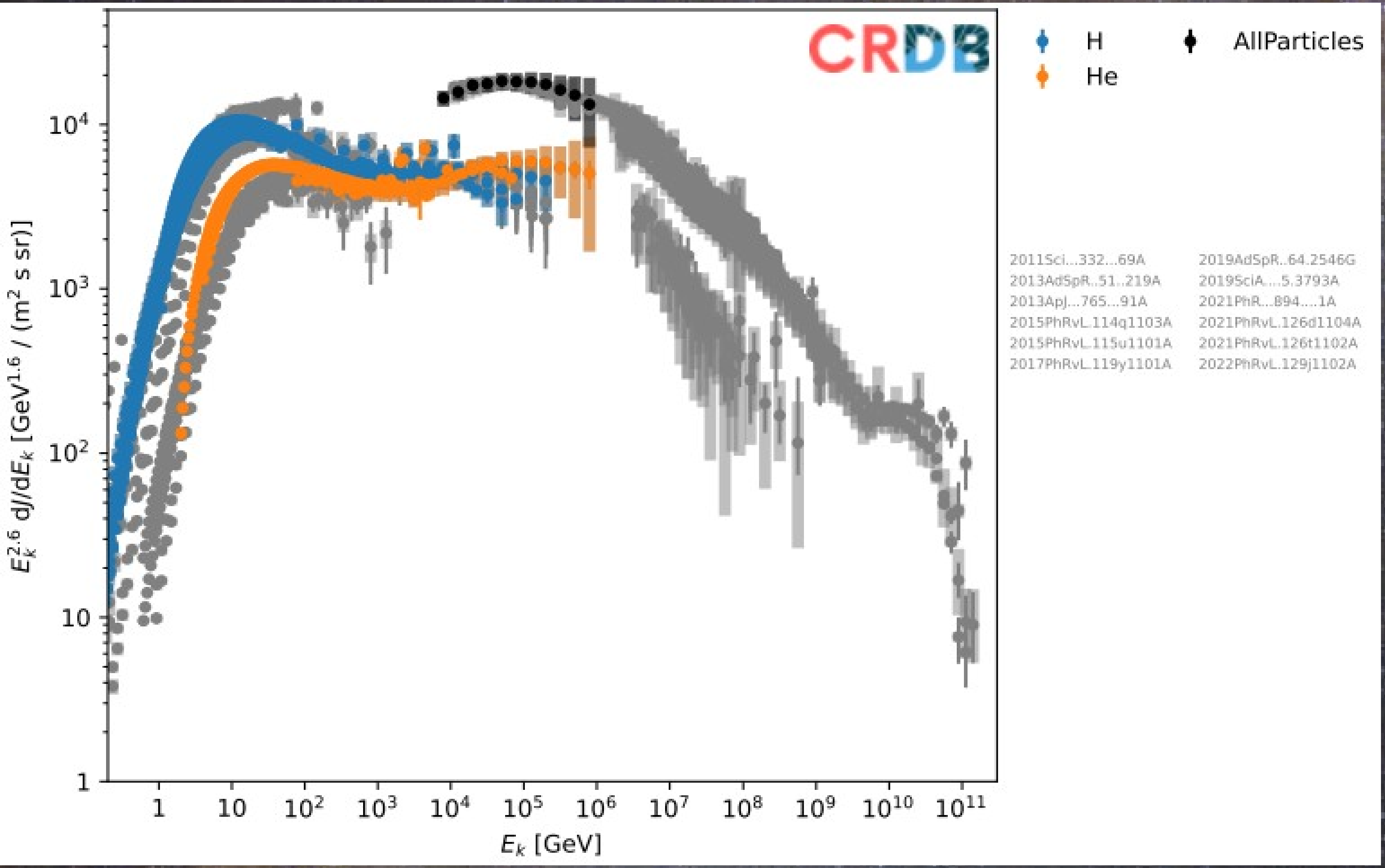
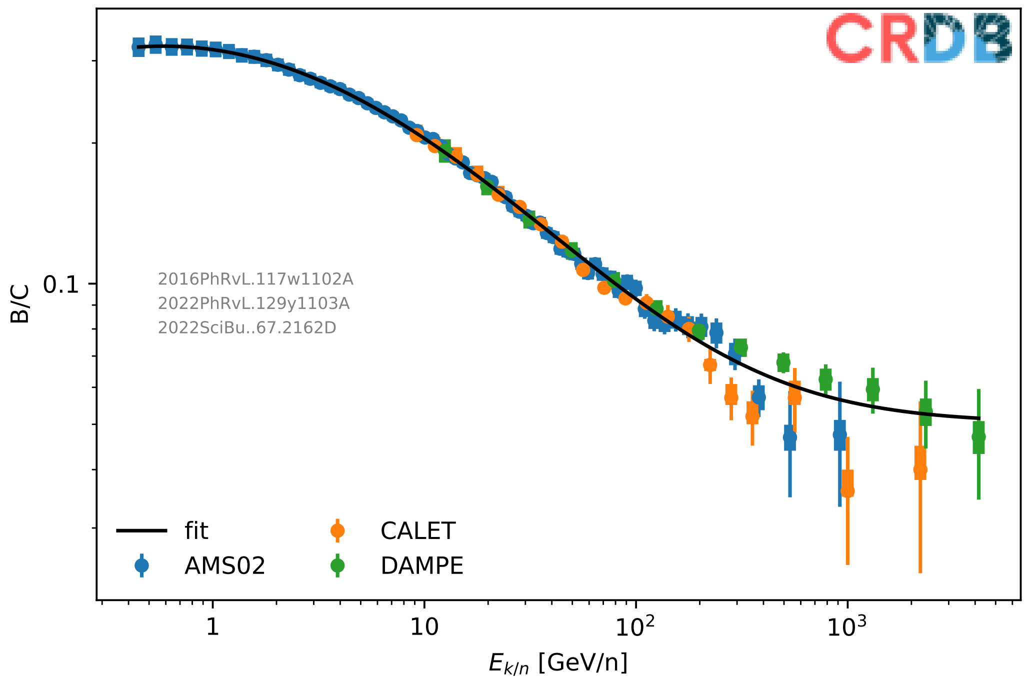


Introduction : the precision era

Game changer: high-quality data! → Disapointment : no COVARIANCE MATRICES of errors

Examples : AMS02 and DAMPE error splitting of B/C



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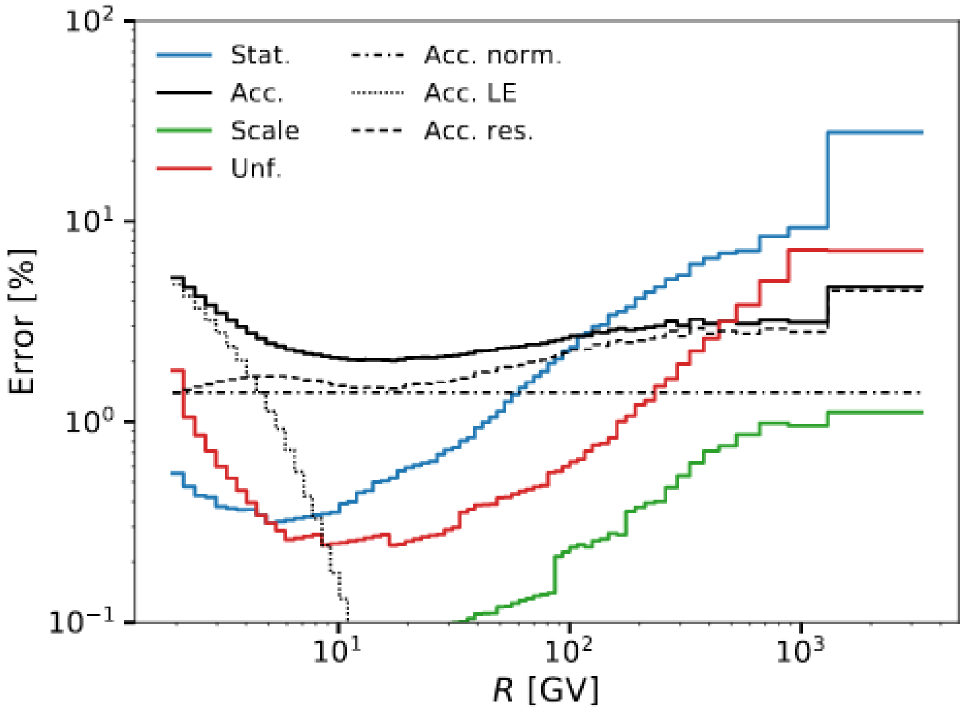
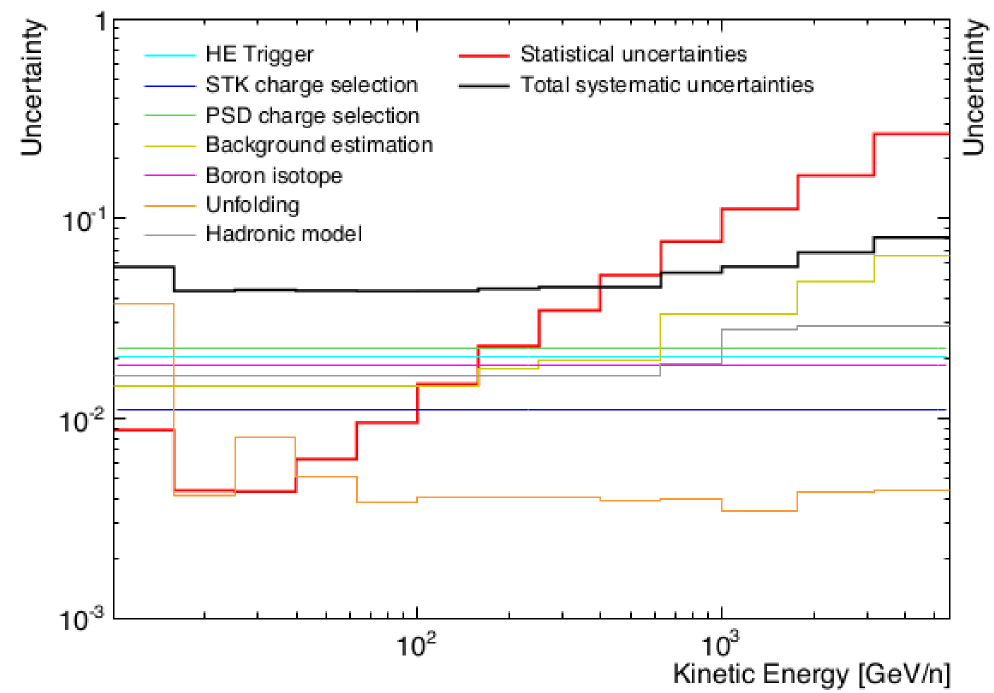


Derome,...,Y.G., A&A (2019) from AMS02 Collab., PRL (2021)



DAMPE Collab., SciBu (2022)

Systematic uncertainties dominate → Even more so for combine fits

Introduction : the precision era

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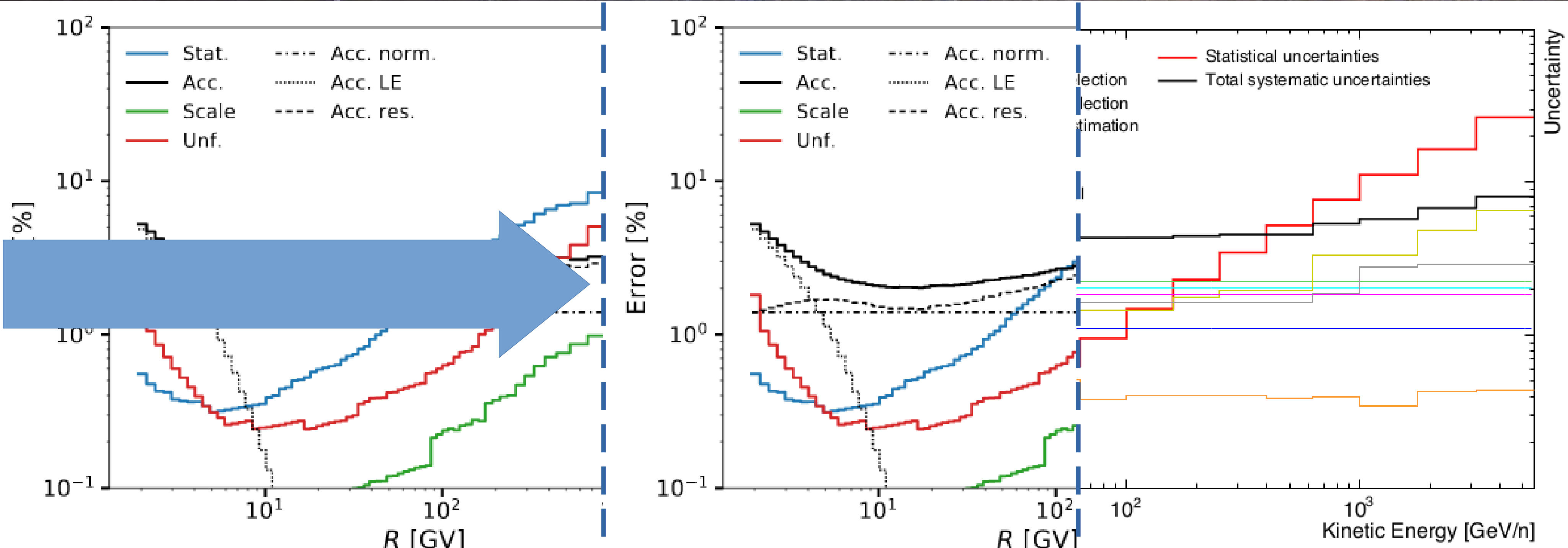

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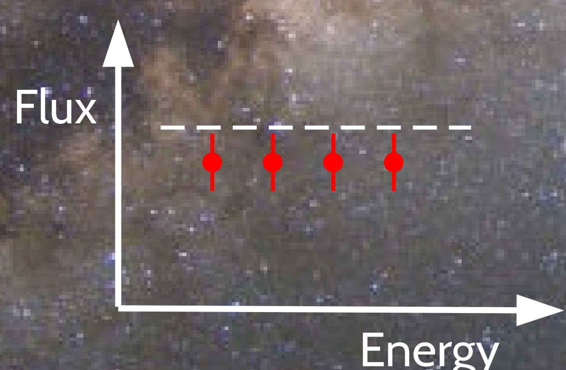
DAMPE Collab., SciBu (2022)

Systematic uncertainties dominate → Even more so for combine fits

$$\chi^2 = (\text{data}_i - \text{model}_i)\, \mathcal{C}_{ij}^{-1} (\text{data}_j - \text{model}_j)$$

Reminder :



Fully correlated errors $\rightarrow \mathcal{C} = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \rightarrow \chi^2 = 1$

Fully uncorrelated errors $\rightarrow \mathcal{C} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \rightarrow \chi^2 = 4$

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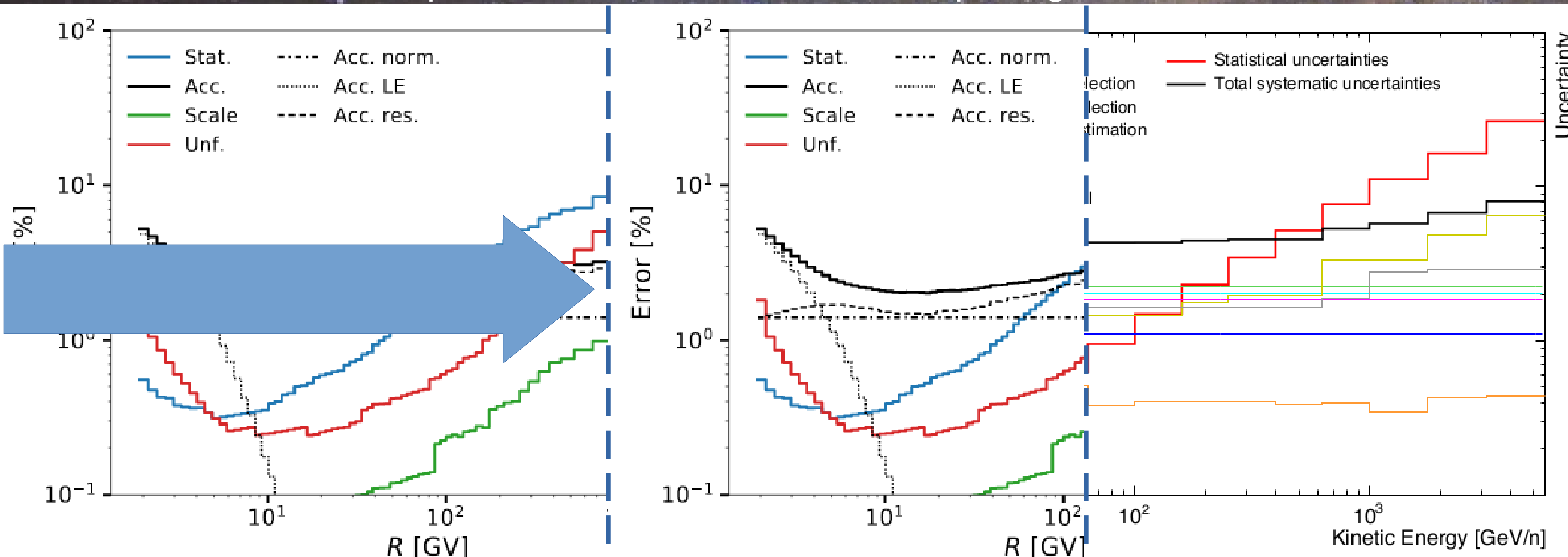
Examples : AMS02 and DAMPE error splitting of B/C



Derome,...,Y.G., A&A (2019) from AMS02 Collab., PRL (2021)

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Systematic uncertainties dominate → Even more so for combine fits

→ **Proper hypotheses testing impossible**

→ **Decrease the constraining power of the new data..**

Experimental collaborations should sytematically provide the covariance matrix of systematic errors.

→ Hopes with next AMS02 releases of isotopes?

→ First-guess covariance matrix for AMS02 data in Derome,...,Y.G., A&A (2019), Heisig et al., PRR (2020)

Introduction : the precision era

Cosmic-ray transport

Prediction of secondary (anti)particles

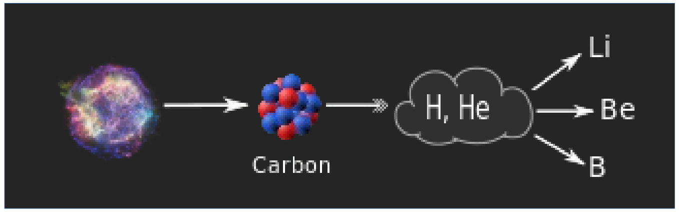
What is next?

Resolution of **CR transport equation** in steady state:

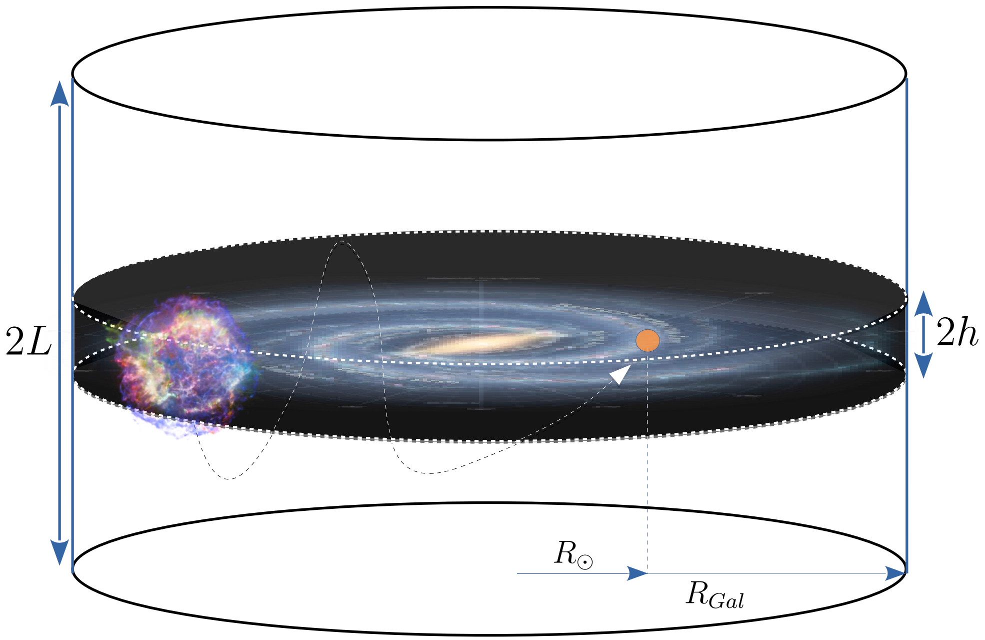
$$\frac{\partial \psi_\alpha}{\partial t} - \vec{\nabla}_{\mathbf{x}} \left\{ K(E)\, \vec{\nabla}_{\mathbf{x}} \psi_\alpha - \vec{V}_c \psi_\alpha \right\} + \frac{\partial}{\partial E} \left\{ b_{\rm tot}(E)\, \psi_\alpha - \beta^2 K_{pp} \frac{\partial \psi_\alpha}{\partial E} \right\}$$

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

Ginzburg&Syrovatskii (1964)



in a **cylindrical geometry**.



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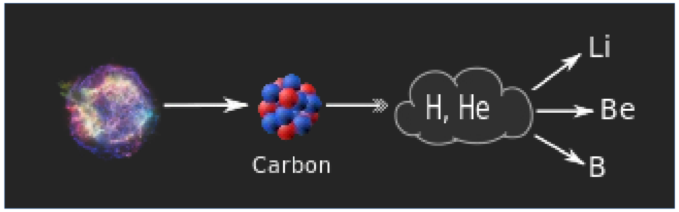

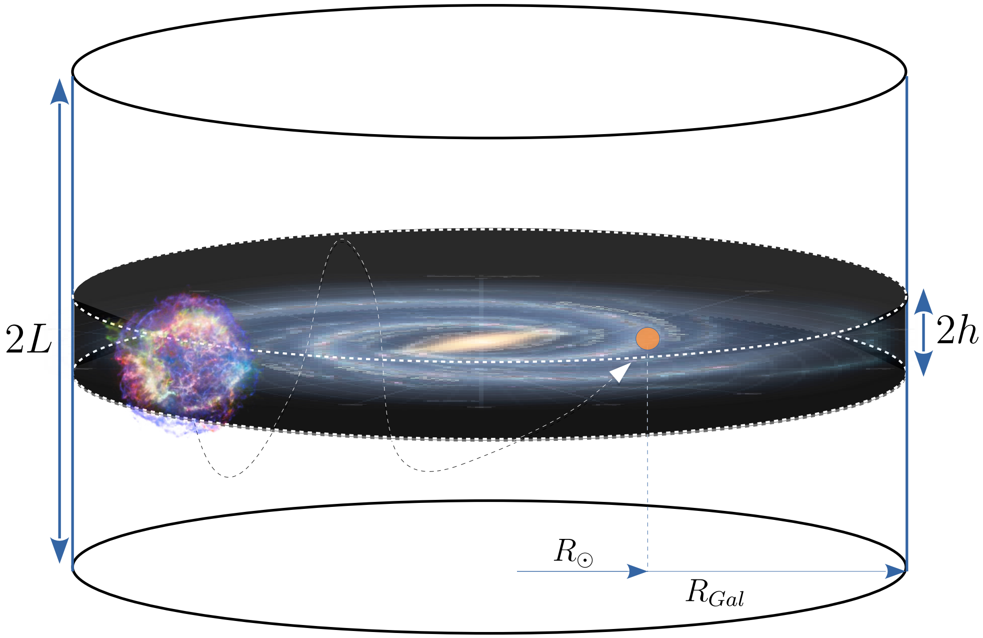

Remarks on the CR transport equation

→ Diffusion, convection, E-losses, reacceleration, spallation

→ Ingredients introduced ~60 yrs ago still satisfying

→ Non exhaustive list of fitted parameters :

$K = K_0 \beta R^\delta$ / V_c / V_A / L / ...

→ **Effective** transport param. = average over kpc scales

- pros : learn generic properties of transport/sources
- cons : several processes intricated

→ Precise determination of transport param.

- link **µ-physics**
- **prediction secondaries (antipart.)**

Resolution of **CR transport equation** in steady state:

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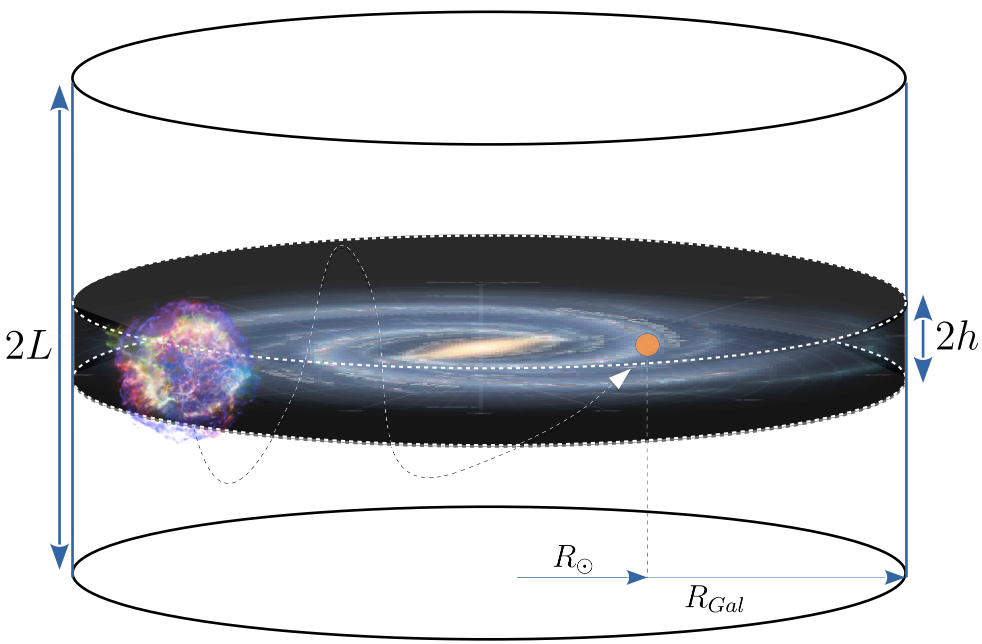

Usual assumptions of the resolution

→ Steady state is reached

→ Sources are distributed homogeneously in the galaxy

→ Injection scaling : single powerlaw $q = C \times R^{\alpha}$

→ Diffusion is homogeneous and isotropic

→ Diffusion scaling : single powerlaw $K = K_0 \beta R^{\delta}$ Jokipii (1966)

→ Injection and diffusion are universal (i.e. among species)

→ Spallation cross sections are well-known

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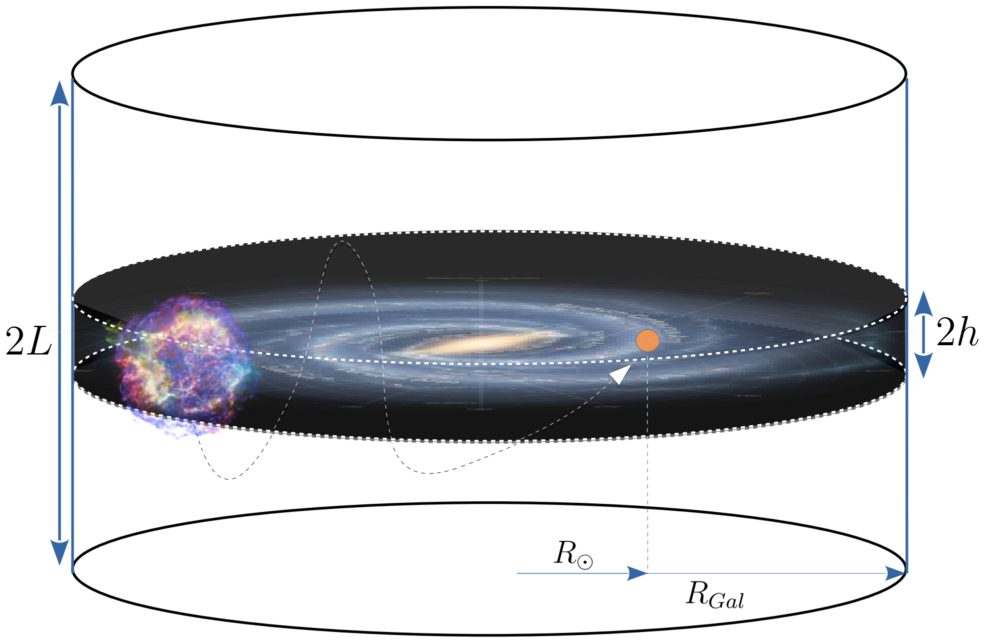
Challenged by % precise data! → **Usual assumptions** of the resolution



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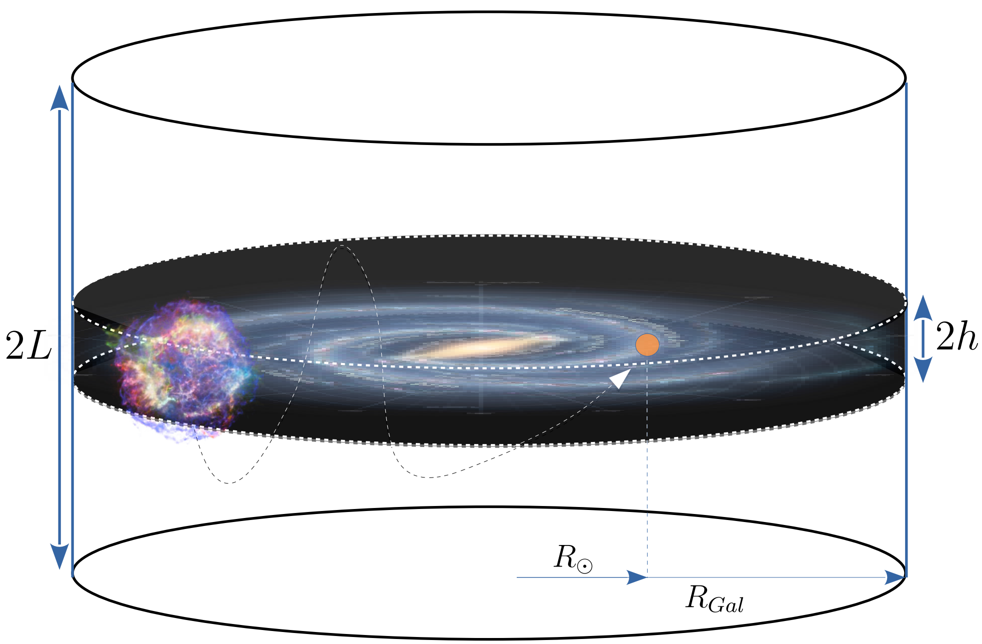


Challenged by % precise data! → **Usual assumptions** of the resolution

Rules to challenge hypothesis

→ Chose a minimal setup based on usual assumptions

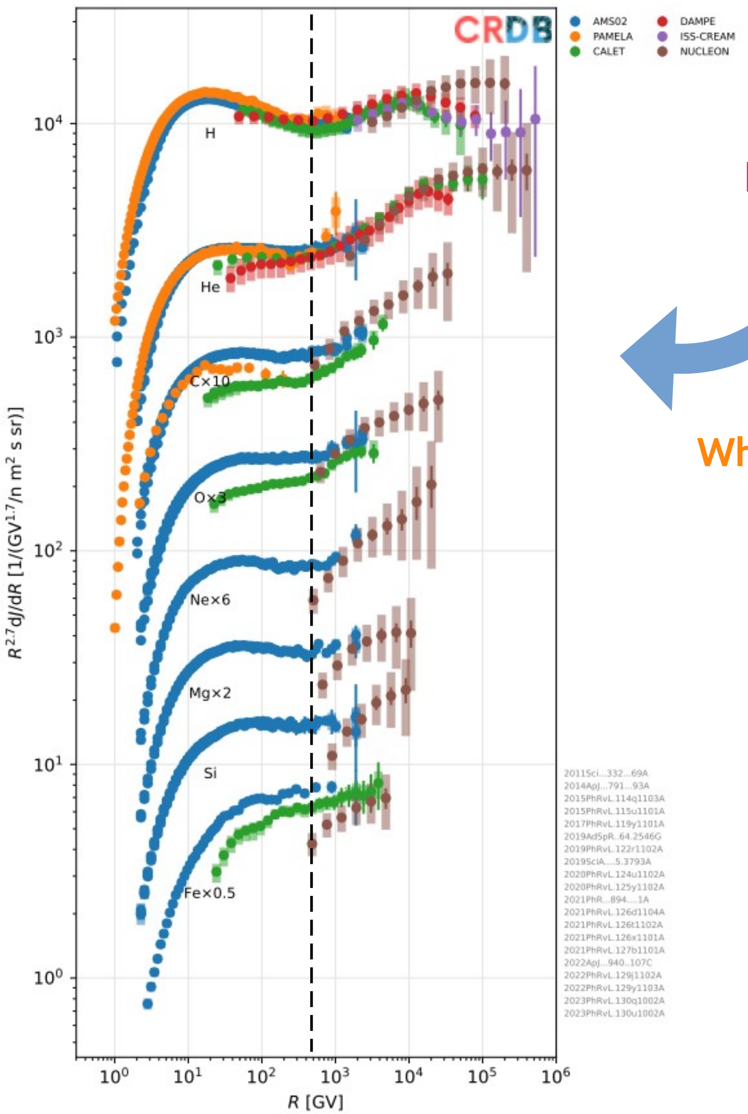
→ Add a novel ingredient

→ Check the preference of the data on a statistical basis

→ Covariance matrix required

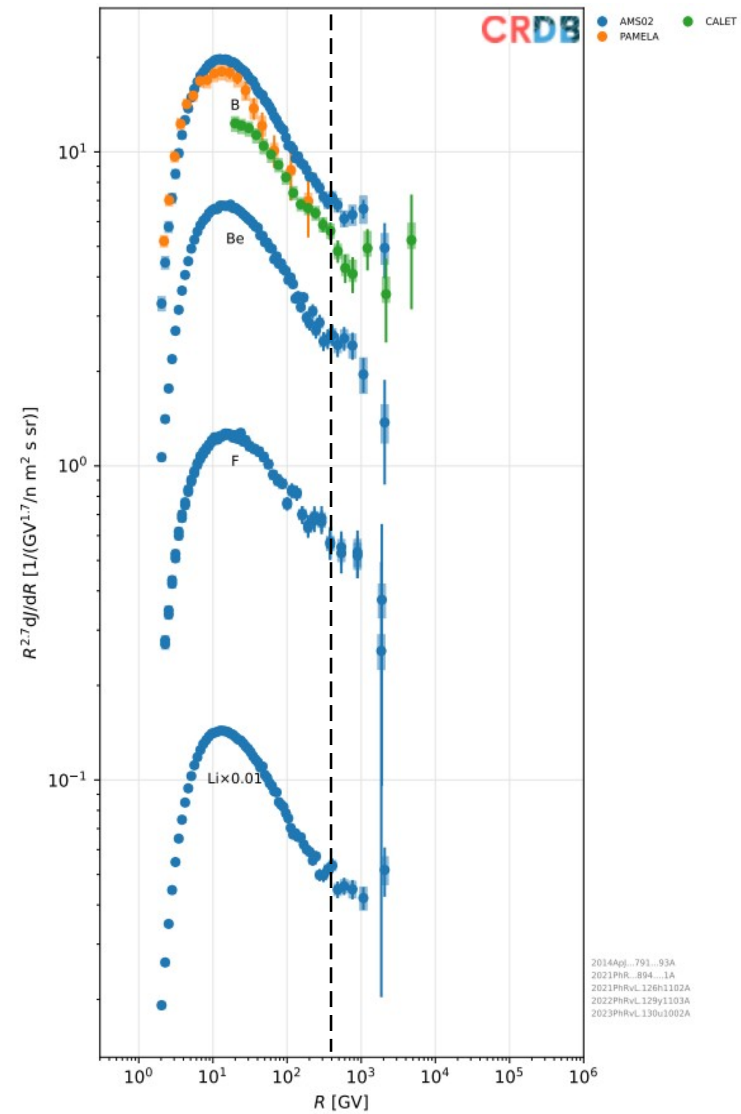
Cosmic-ray transport → Breaks?

Universal break in the spectra around 300 GV!



primaries and secondaries

What is the origin of the break?



Cosmic-ray transport → Breaks?

Universal break(s) in the spectra!

What is their origins?

Injection? **Local source?** **Diffusion?**

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Solution of CR transport equation : pure diffusive case

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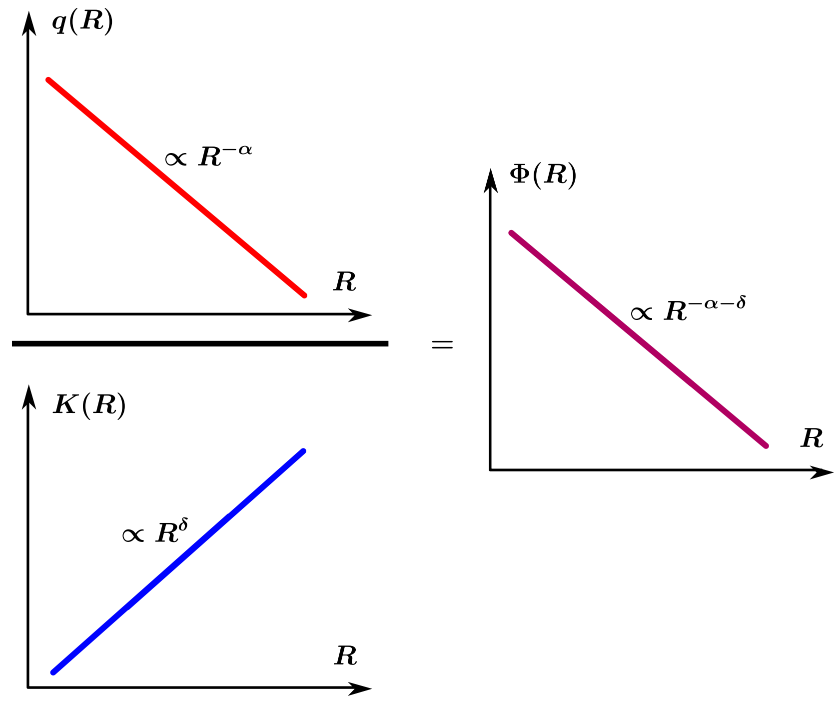
For pure primary species: $\Phi(R) \propto \frac{q}{K} =$



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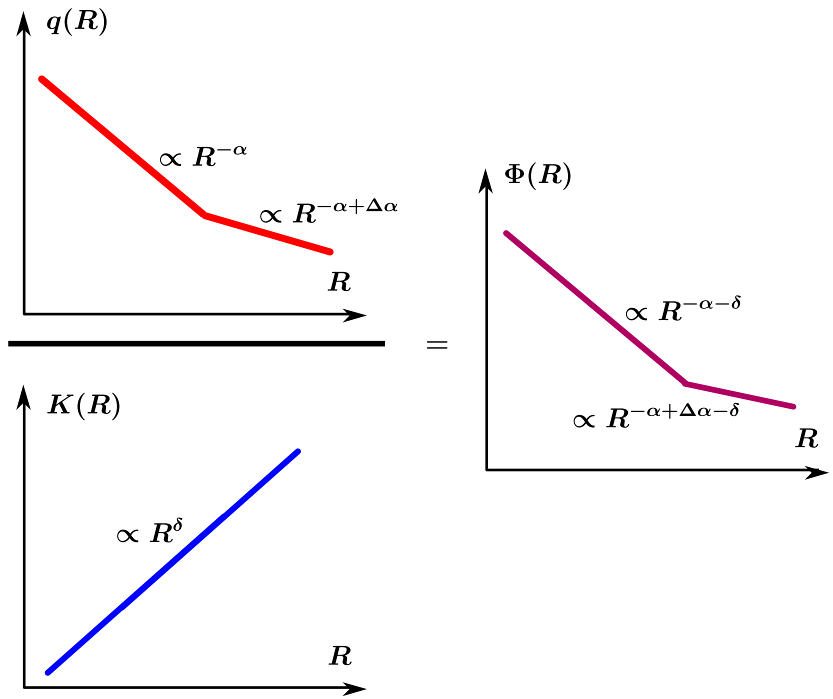

Primaries e.g. Vladimirov+ (2012), Niu+ (2018, 2019, 2020); Tomassetti+ (2015)
Secondaries e.g. Tomassetti+ (2012);Y.G.+ (2014);Tomassetti+ (2017); Zhang+ (2023)
Reacceleration e.g. Tomassetti+ (2012); Yuan+ (2020)

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Solution of CR transport equation : pure diffusive case

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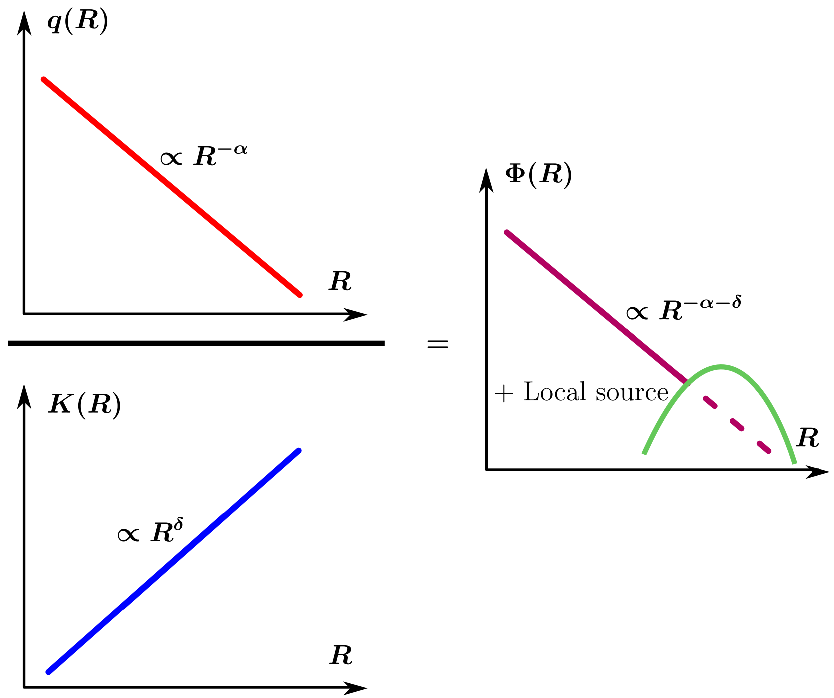

Local source fits:
Bernard+ (2012)
Thoudam+ (2012)
Wei+ (2014)
Mertsch+ (2014/2021)
Savchenko+ (2015)
Bouyahiaoui+ (2018)
Lagutin+ (2019)
Yue+ (2020)
Tang+ (2022)
Anisotropies
Ahlers+ (2016)

Statistical approach:
Hadrons
Y.G+ (2017)
Evoli+ (2022)
Leptons
Mertsch (2011,2018,2018)

Stochasticity kicks in when the effective number of sources (Ns) is close to 1 →

Ns ~ 1 at 10 TV for Leptons
Ns ~ 1 at 10 PV for Hadrons

Cosmic-ray transport → Breaks?

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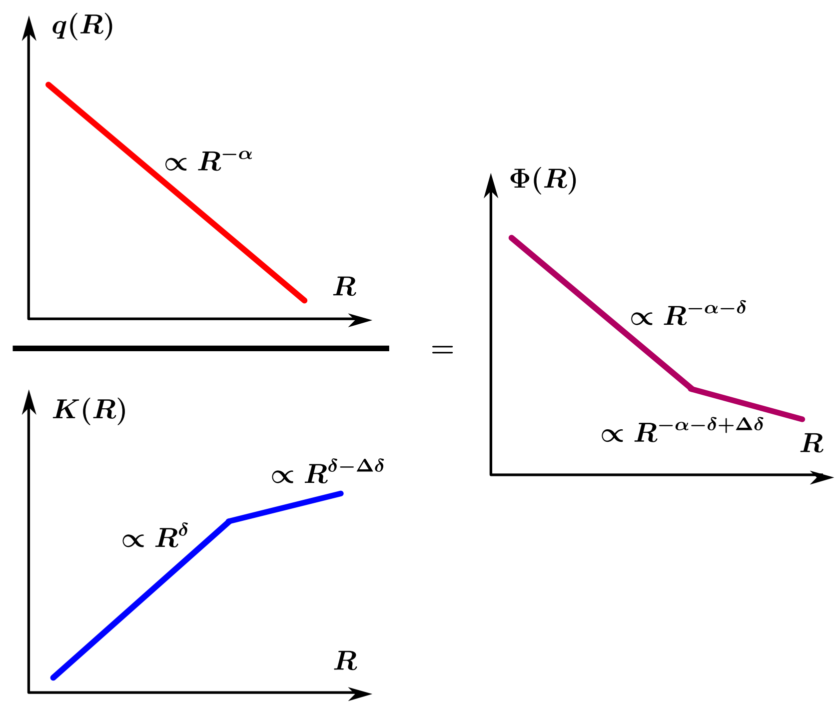

Pheno : Vladimirov+ (2012); Y.G+ (2017); Niu+ (2020);
Explanation : Tomassetti (2012);Amato+ (2012);Evoli +(2019);

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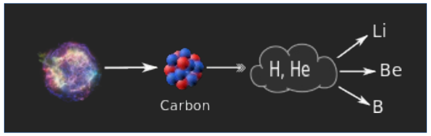
Solution of CR transport equation : pure diffusive case

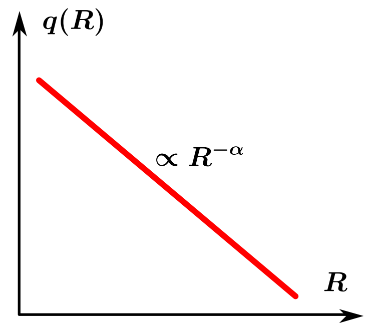
For pure secondary species:

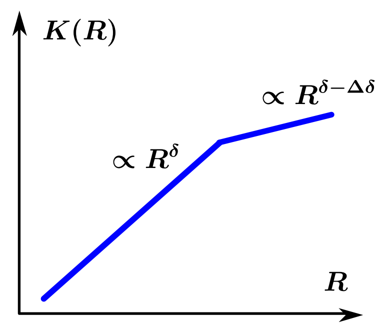


$\Phi^{sec}(R)$

$\|$

For pure primary species: $\Phi(R) \propto \frac{q}{K} =$





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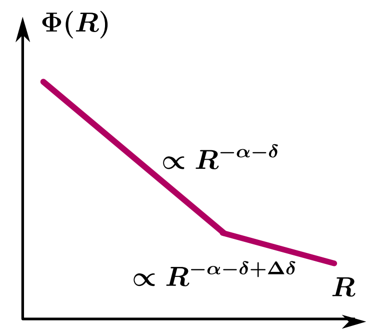

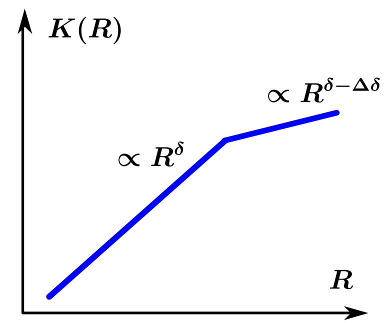

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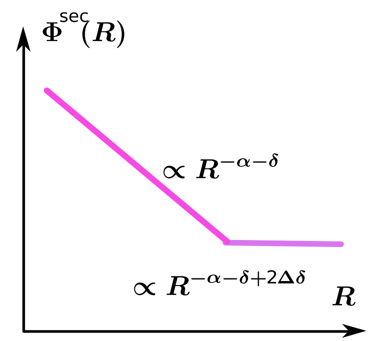


Pheno : Vladimirov+ (2012); Y.G+ (2017); Niu+ (2020);
Explanation : Tomassetti (2012);Amato+ (2012);Evoli +(2019);

Cosmic-ray transport → Breaks?

Universal break(s) in the spectra!

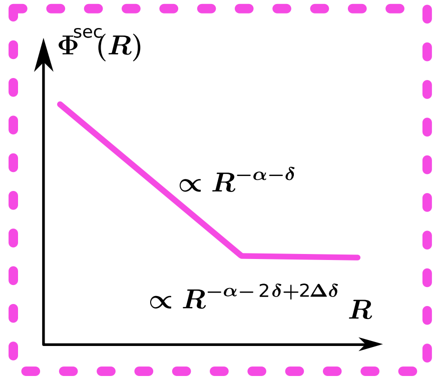
What is their origins?

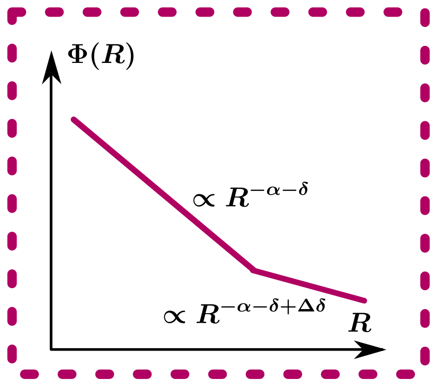
Injection? **Local source?** **Diffusion?**

$$\frac{\partial \psi_\alpha}{\partial t} - \vec{\nabla}_x\left\{K(E)\,\vec{\nabla}_x\psi_\alpha - \vec{V}_c\psi_\alpha\right\} + \frac{\partial}{\partial E}\left\{b_{tot}(E)\,\psi_\alpha - \beta^2 K_{pp}\frac{\partial\psi_\alpha}{\partial E}\right\}$$
$$+\sigma_\alpha v_\alpha n_{ism}\,\psi_\alpha + \Gamma_\alpha\psi_\alpha = q_\alpha + \sum_\beta\left\{\sigma_{\beta\to\alpha}v_\beta n_{ism} + \Gamma_{\beta\to\alpha}\right\}\psi_\beta \,.$$

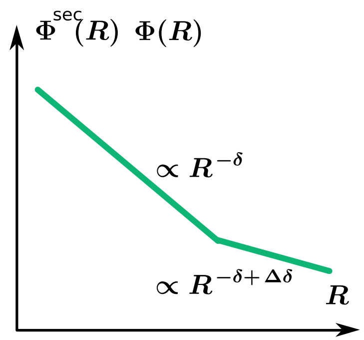
Solution of CR transport equation : pure diffusive case

For secondary/primary ratio: $\frac{\text{Secondary flux}}{\text{Primary flux}}$ =





=

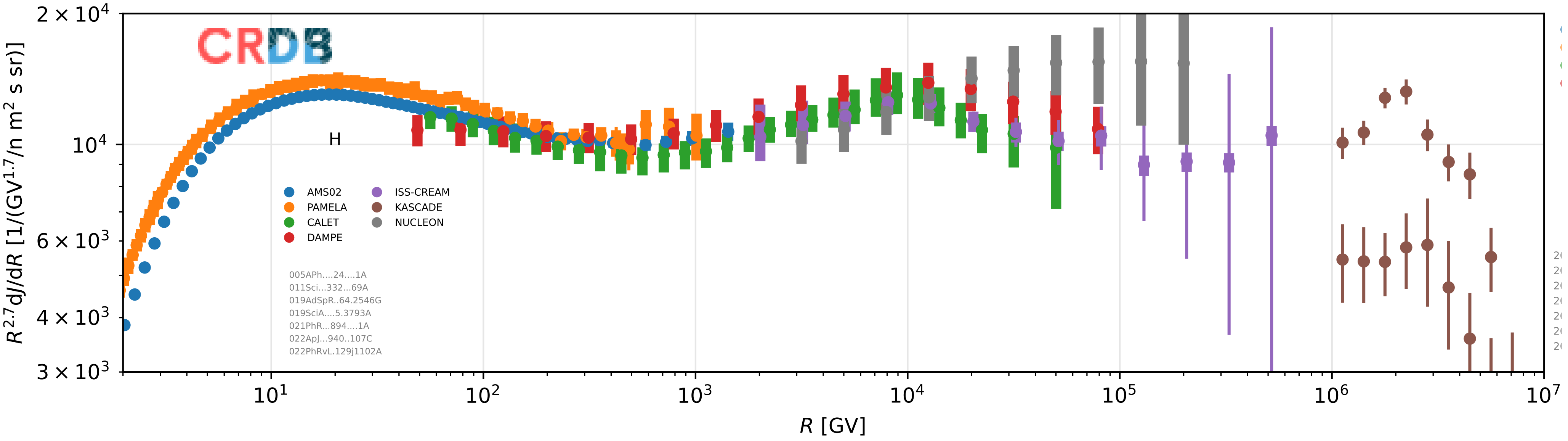


e.g. Li/C, Be/C, B/C, B/O, ...

Some words of caution:
Vecchi et al. (2022)

Cosmic-ray transport → Explaining the spectra

Universal break(s) in the spectra!



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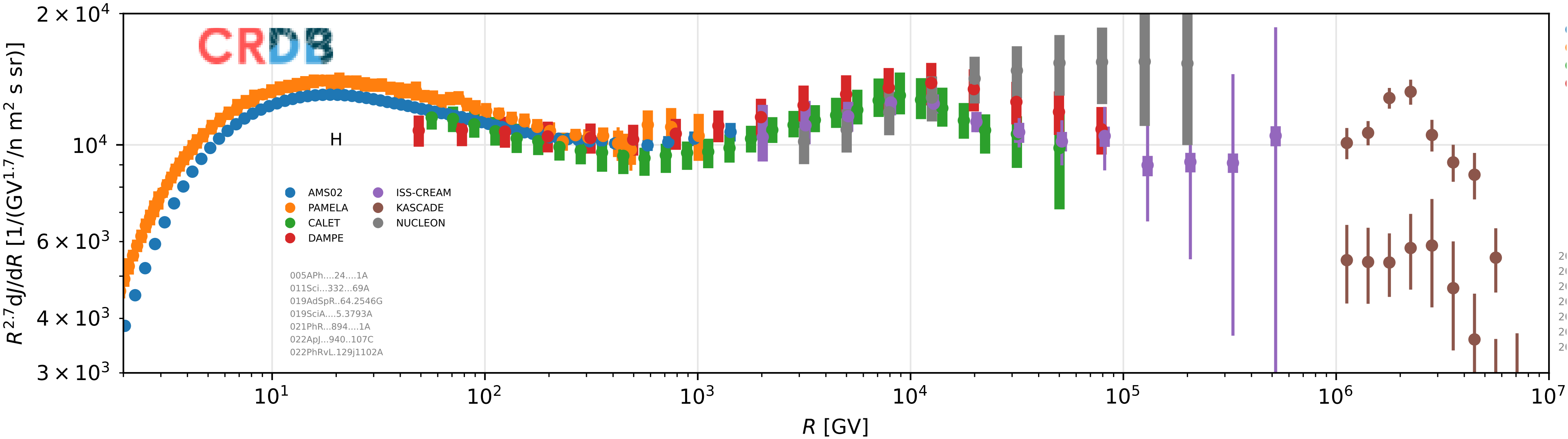

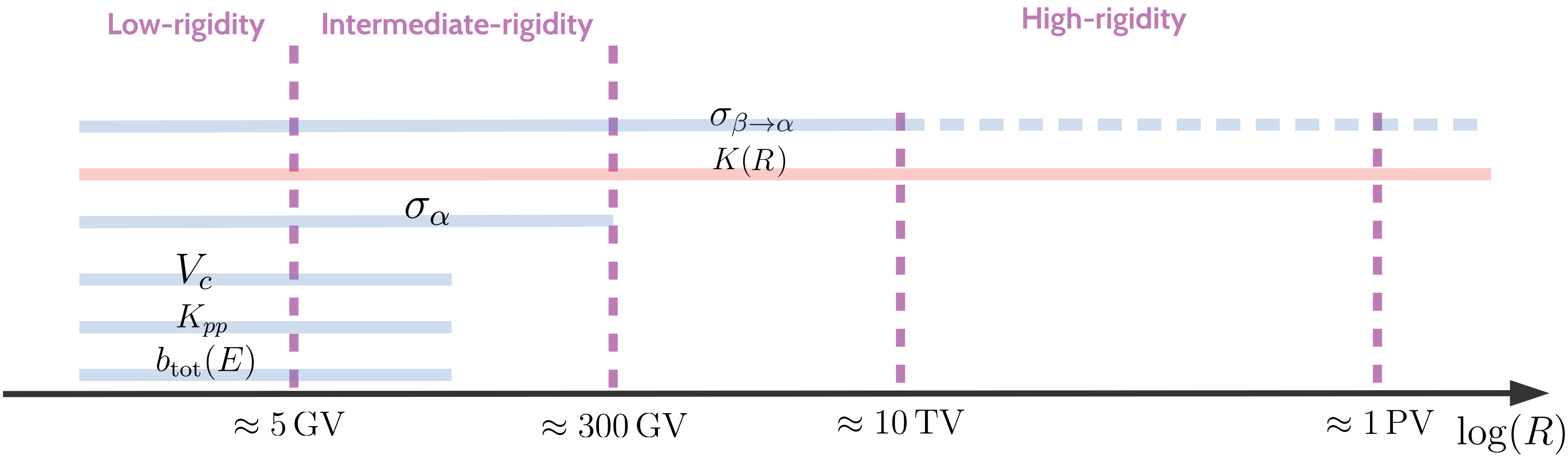

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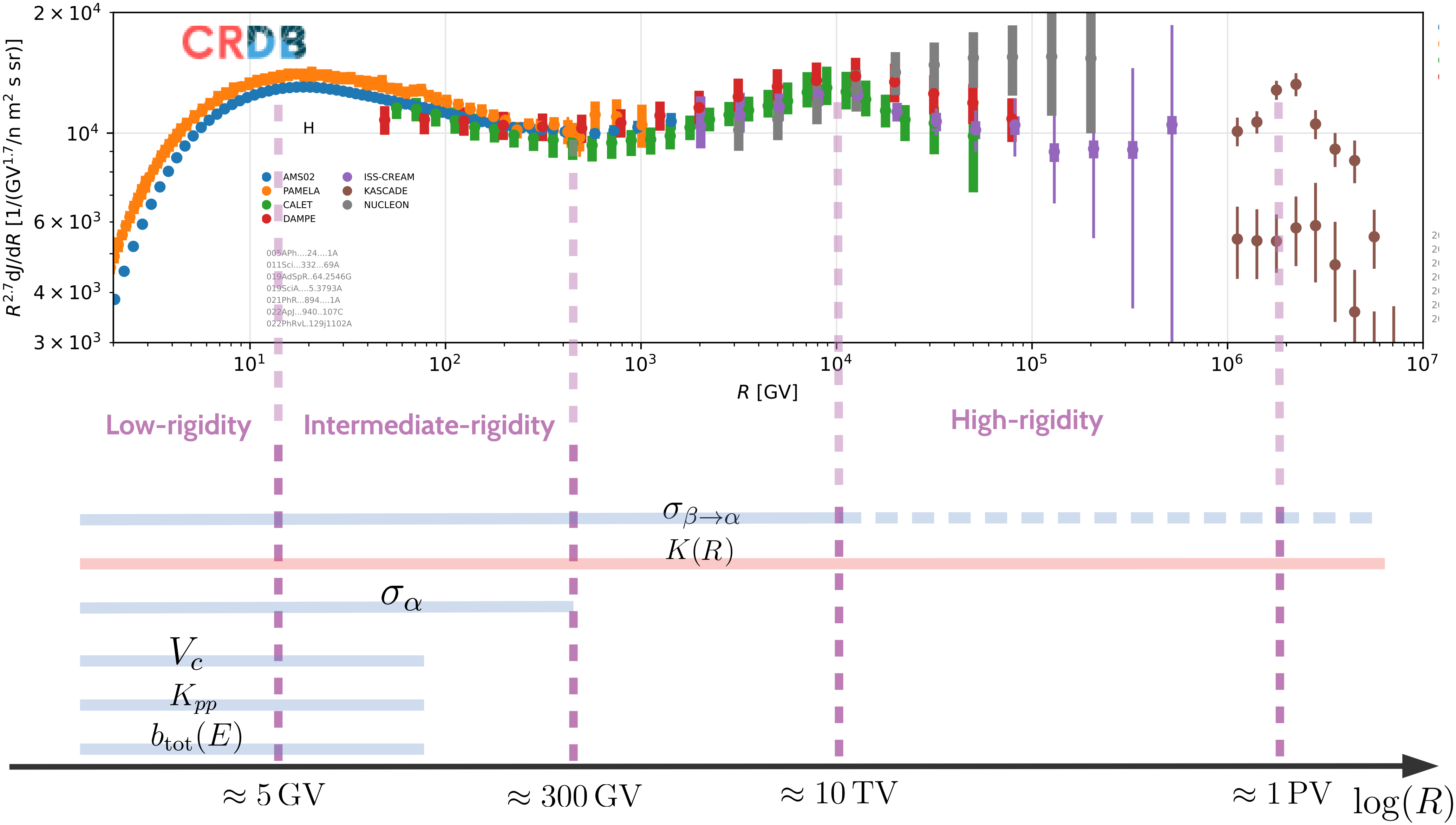

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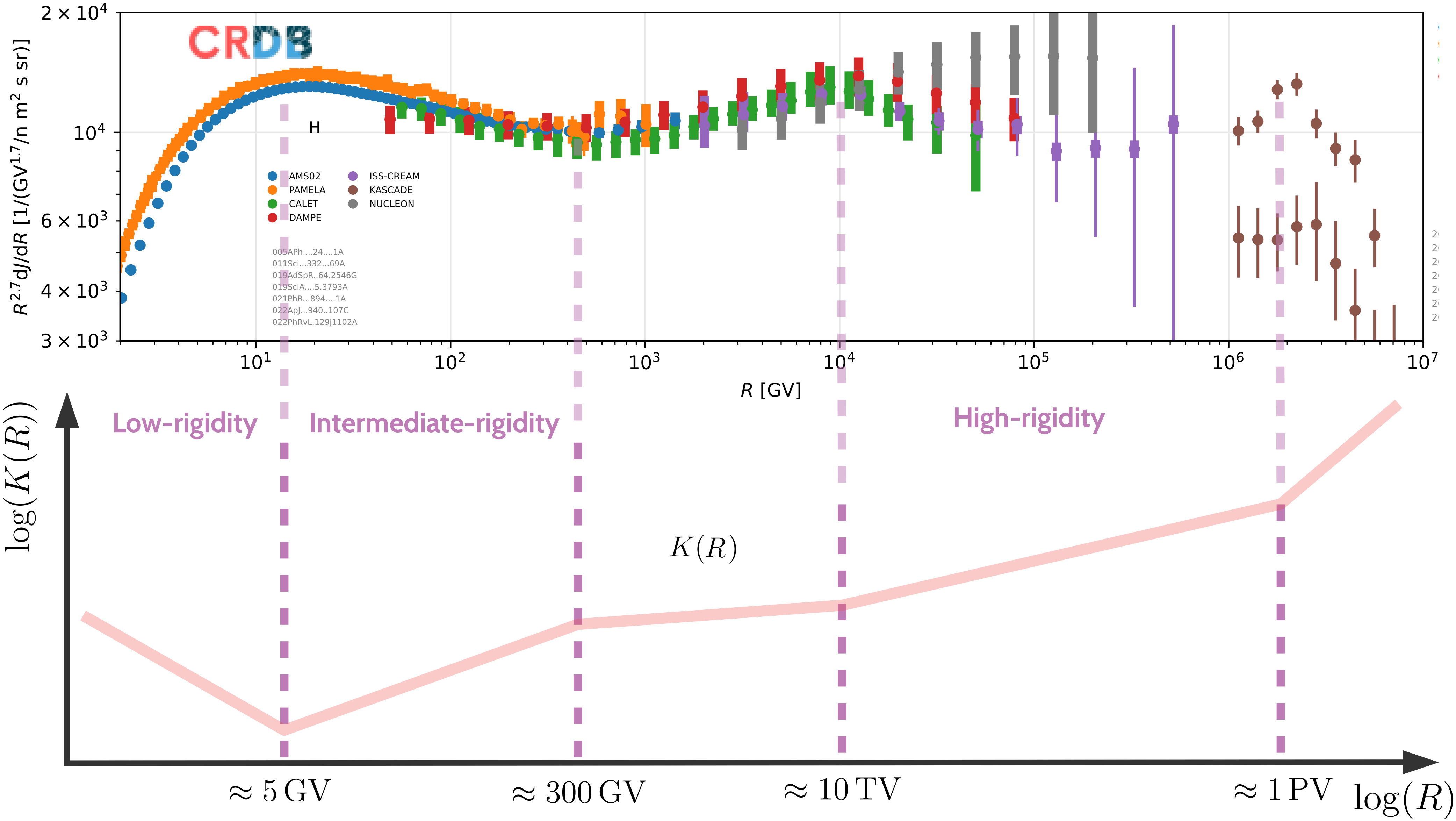

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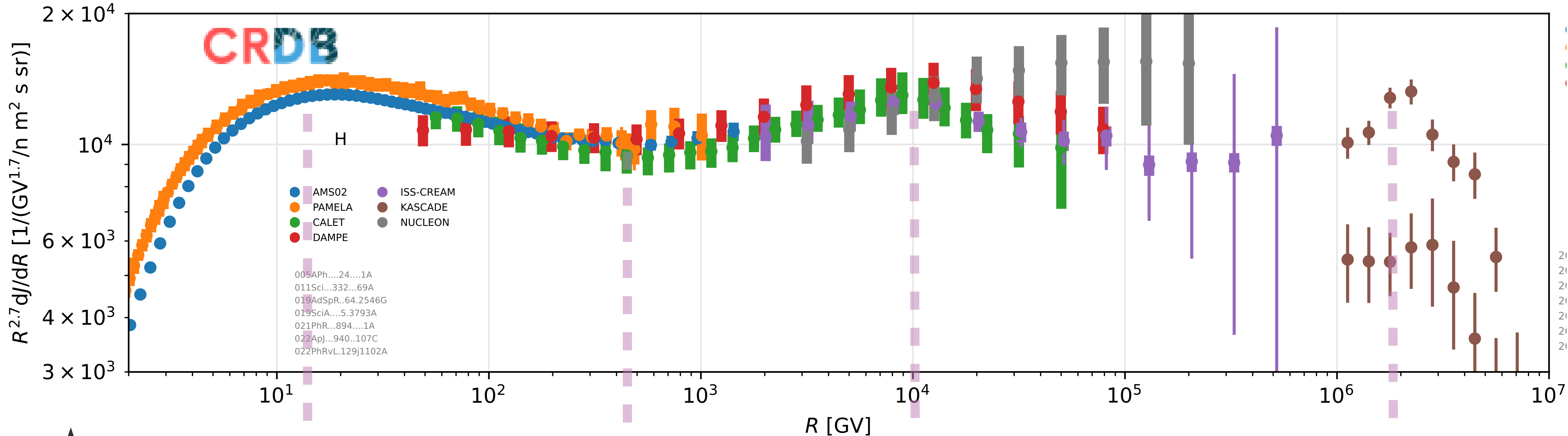
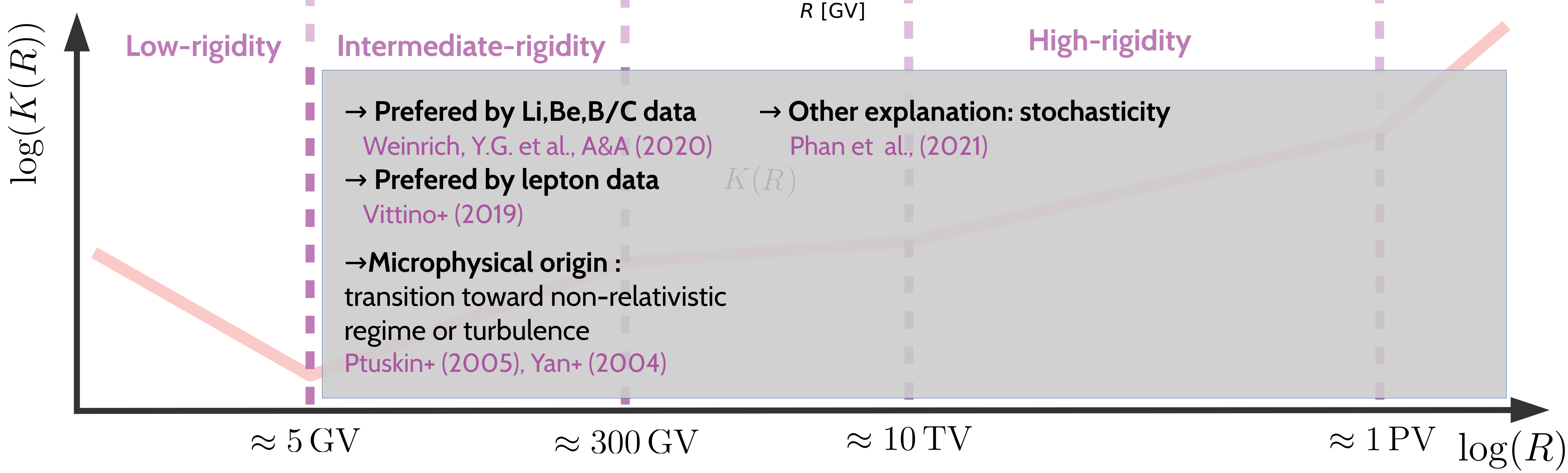




→ Prefered by Li,Be,B/C data
Weinrich, Y.G. et al., A&A (2020)

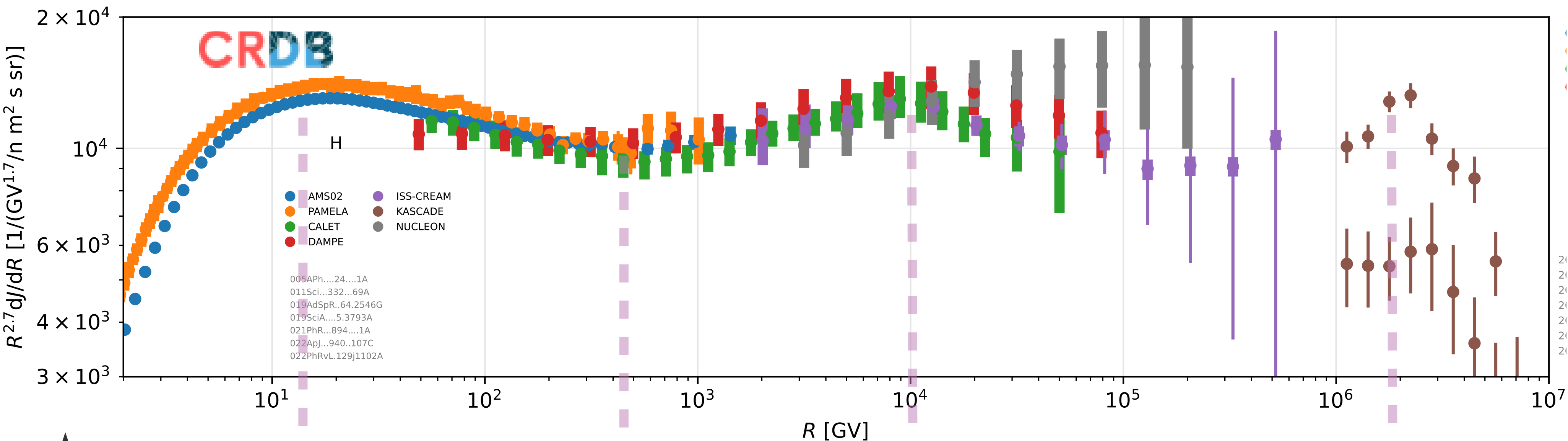
→ Prefered by lepton data
Vittino+ (2019)

→Microphysical origin :
transition toward non-relativistic regime or turbulence
Ptuskin+ (2005), Yan+ (2004)

→ Other explanation: stochasticity
Phan et al., (2021)

Cosmic-ray transport → Explaining the spectra

Universal break(s) in the spectra!



$\log(K(R))$

Low-rigidity

Intermediate-rigidity

High-rigidity

→ Pheno fits Y.G.+ (2019); Evoli+ (2019) Korsmeier+ (2022); DiMauro+ (2023)

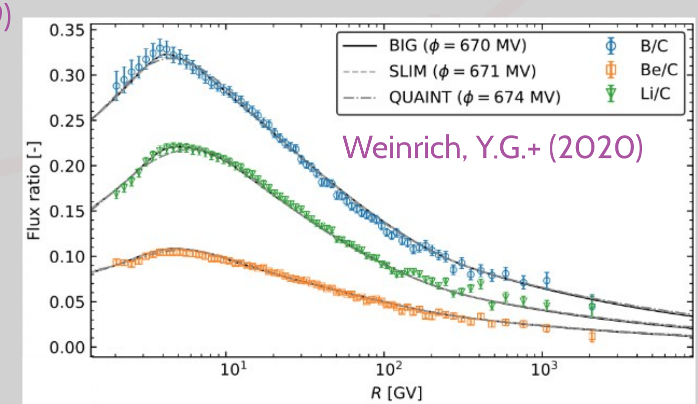
$$K(R) \propto R^{0.5}$$

→ Microphysical origin :

QLT → $K_{\parallel}$: Kraichnan turbulence Jokipii (1966)

K_T may dominate? Cerri+ (2018)

Turbulence from CR streaming?

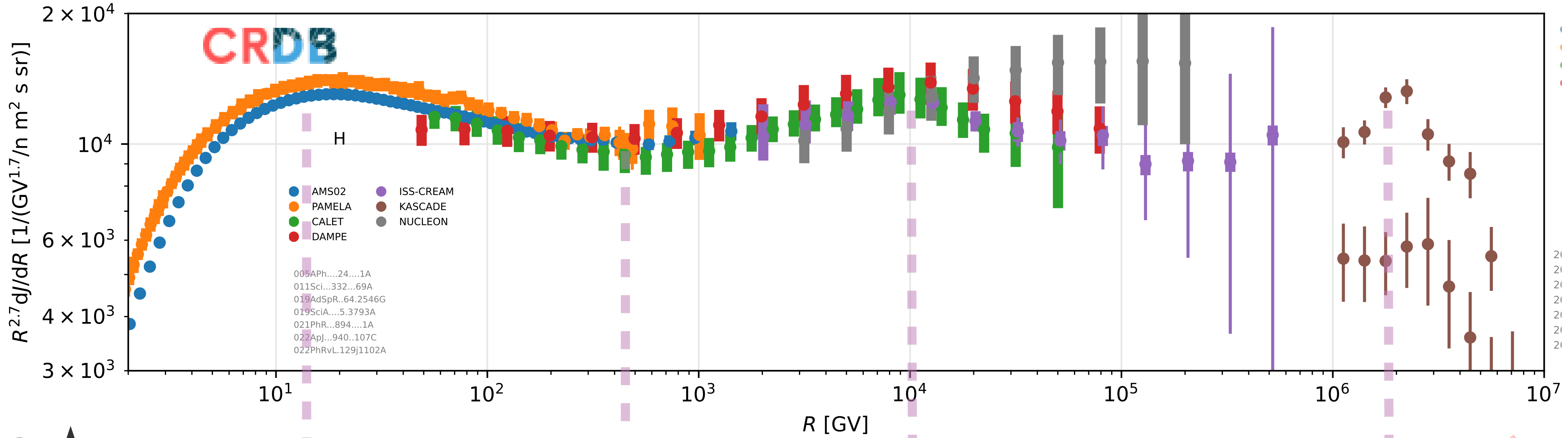


Weinrich, Y.G.+ (2020)

$\approx 5\,\mathrm{GV}$ $\approx 300\,\mathrm{GV}$ $\approx 10\,\mathrm{TV}$ $\approx 1\,\mathrm{PV}$ $\log(R)$

Cosmic-ray transport → Explaining the spectra

Universal break(s) in the spectra!



$\log(K(R))$

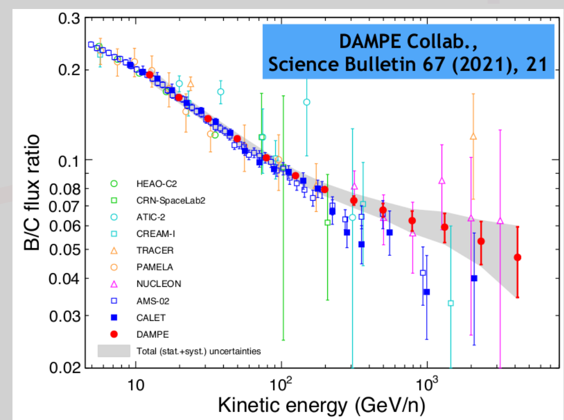
Low-rigidity

Intermediate-rigidity

High-rigidity

→ Pheno fits
Vladimirov+ (2012); Y.G+ (2017); Niu+ (2020);
→ Statistical evidence & robustness

→ (Micro)physical origin : transition btw zones or turbulence regimes
Tomassetti (2012);Amato+ (2012); Alosio+ (2015); Evoli +(2019);



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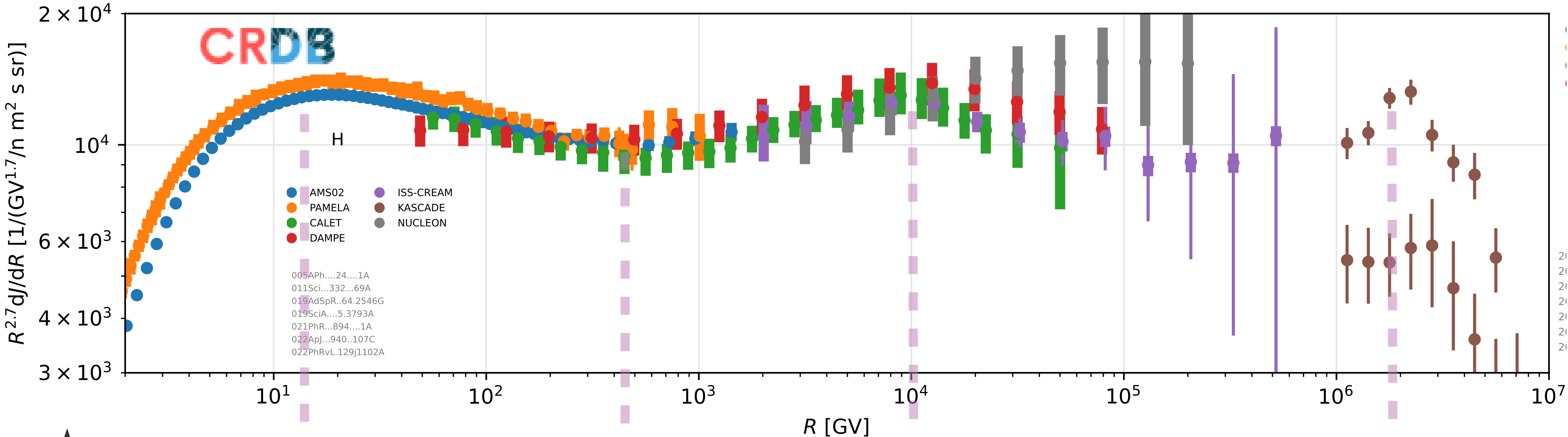
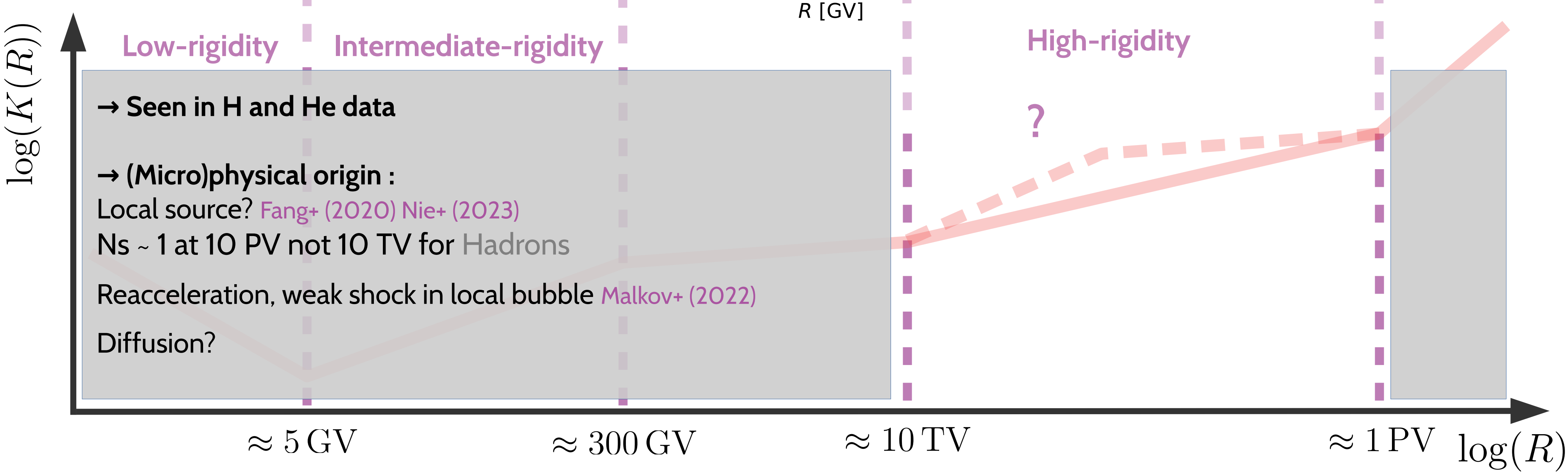




→ Seen in H and He data

→ (Micro)physical origin :

Local source? Fang+ (2020) Nie+ (2023)

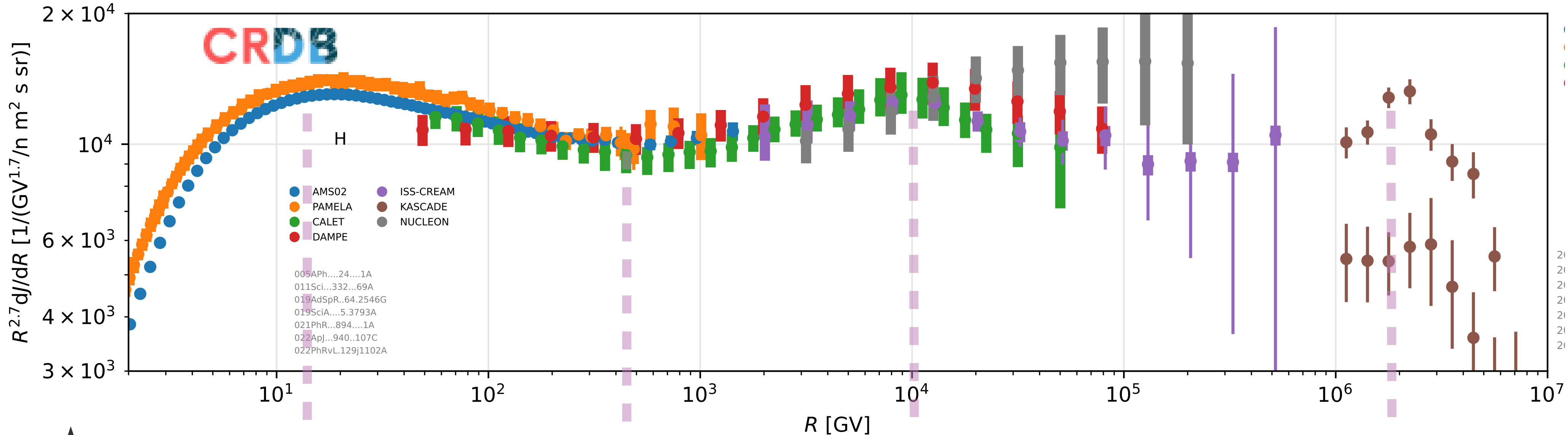
Ns ~ 1 at 10 PV not 10 TV for Hadrons

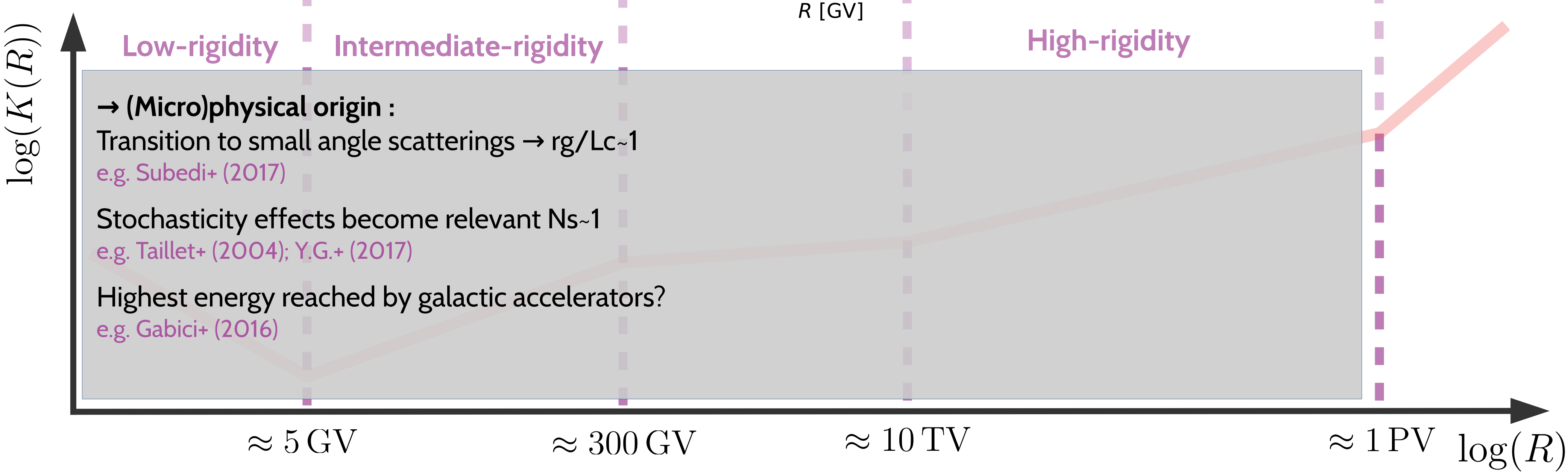
Reacceleration, weak shock in local bubble Malkov+ (2022)

Diffusion?

Cosmic-ray transport → Explaining the spectra

Universal break(s) in the spectra!





→ (Micro)physical origin :

Transition to small angle scatterings → rg/Lc~1
e.g. Subedi+ (2017)

Stochasticity effects become relevant Ns~1
e.g. Taillet+ (2004); Y.G.+ (2017)

Highest energy reached by galactic accelerators?
e.g. Gabici+ (2016)

Introduction : the precision era

Cosmic-ray transport

Prediction of secondary (anti)particles

What is next ?

A refined treatment of uncertainties

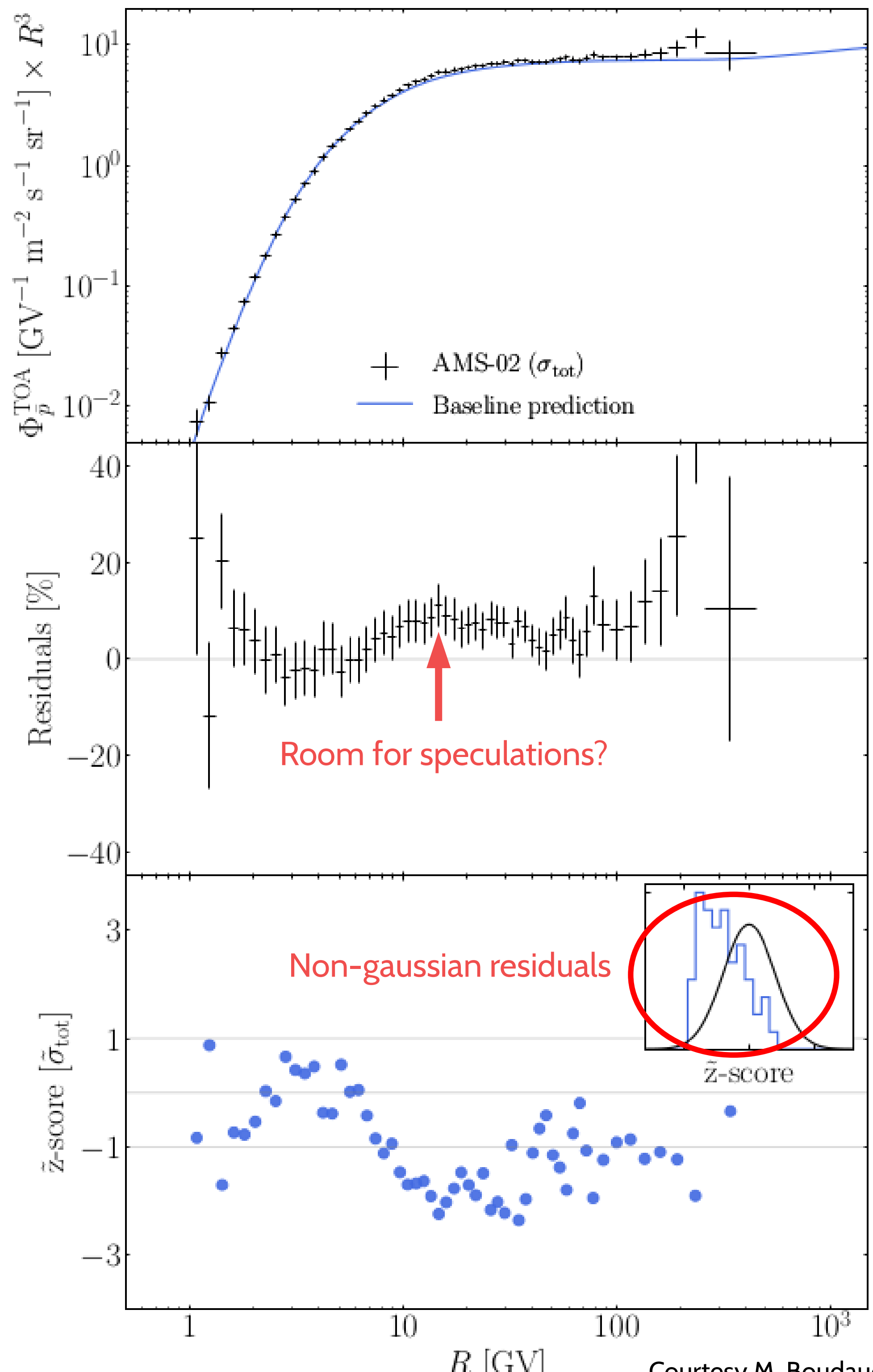
→ Data: AMS02 antiproton from 2016
→ Model: semi-analytical (USINE) (Maurin 2020)

Comparison with data = discrepancy ~ few 10GV

→ Chi2-test:

$$\chi^2/dof \approx 1.7$$

$$p_{value} \approx 10^{-3}$$



Courtesy M. Boudaud

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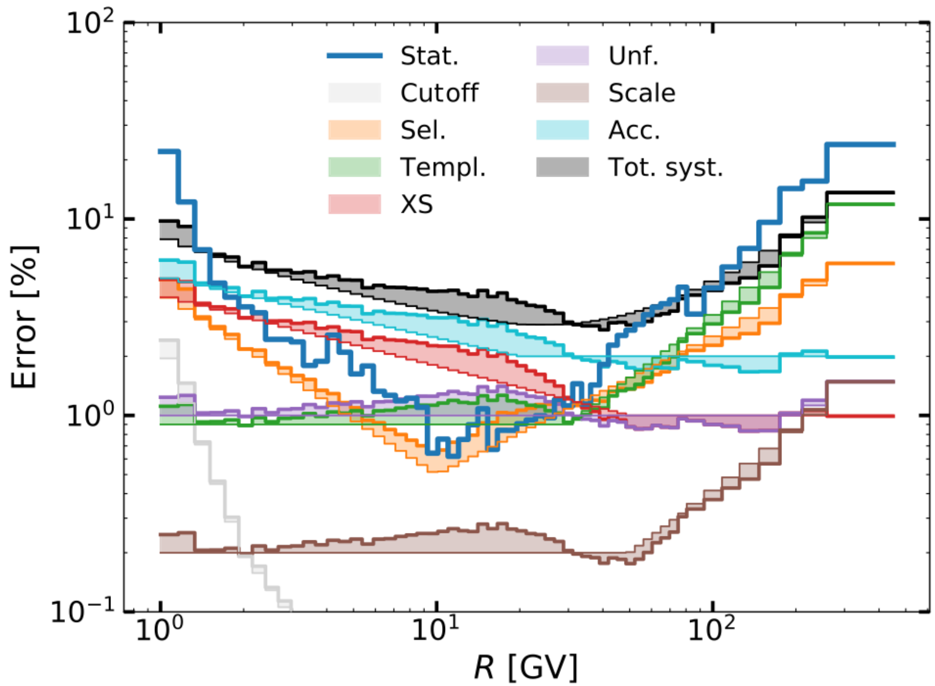
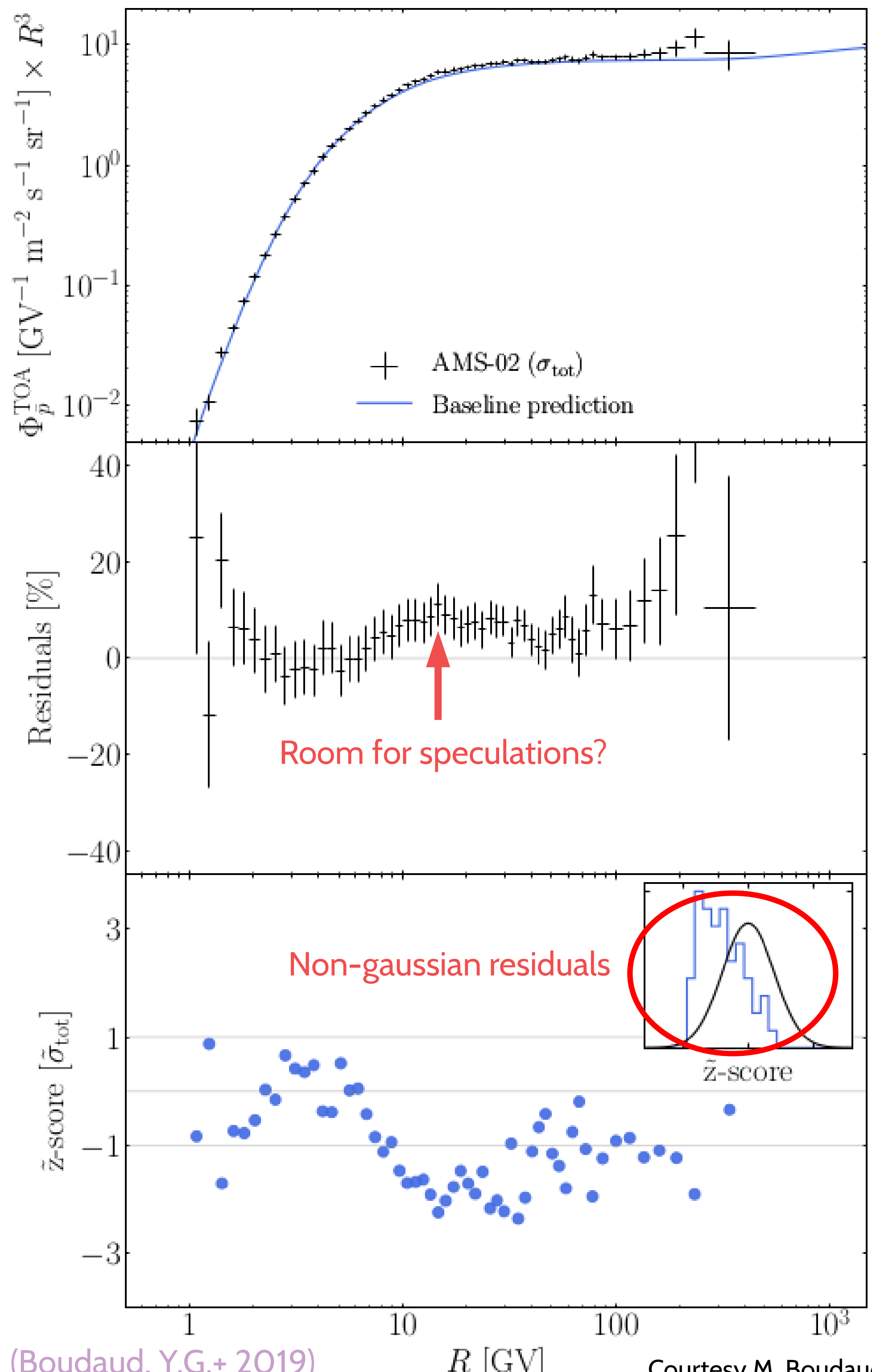


Small total error / Different correlation lengths
Dominated by acceptance around the excess

→ Covariance matrix estimated from detector info.



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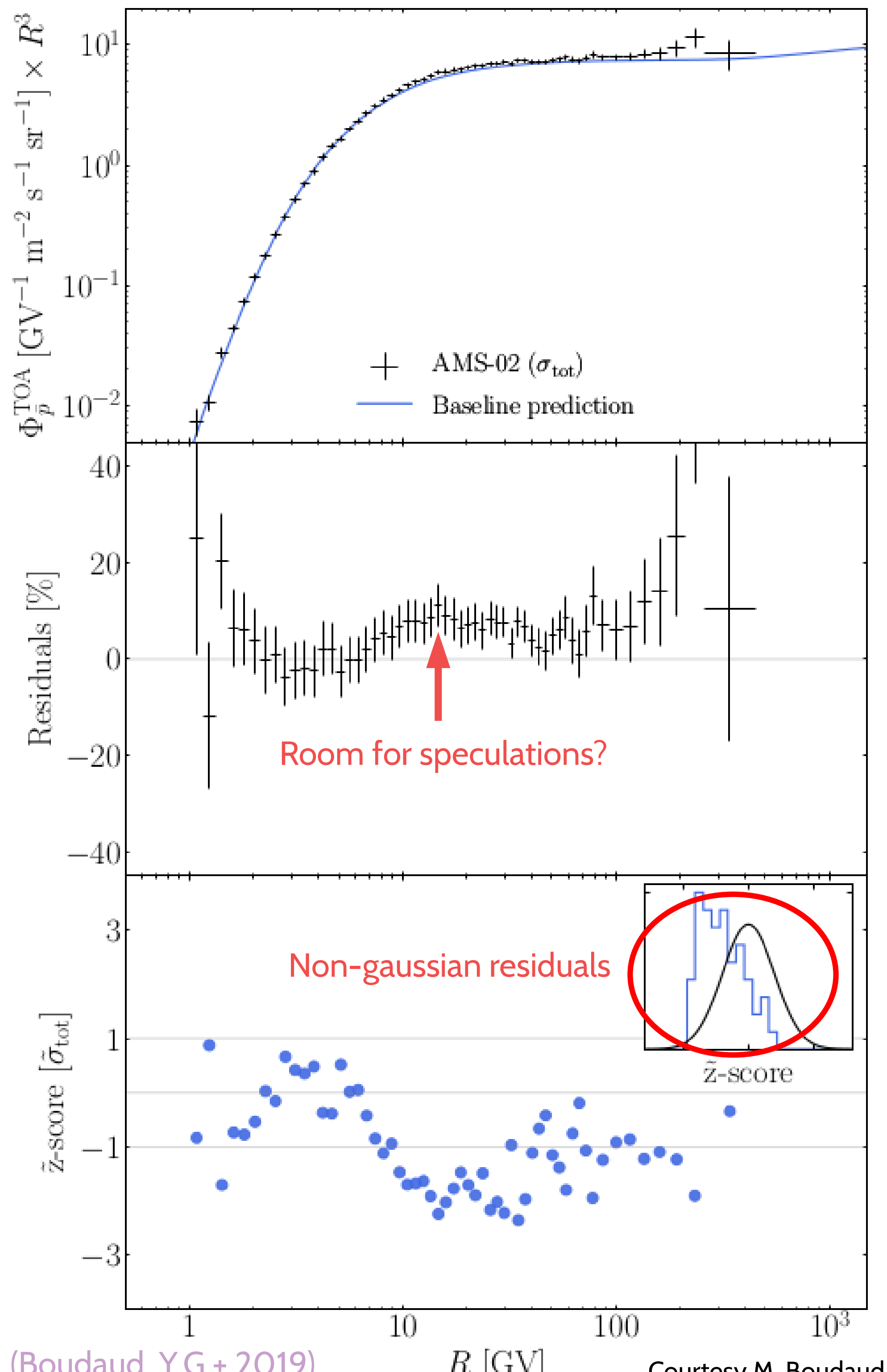

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- Pbar production cross-sections

(Winkler, M. 2016, Korsmeier+ 2018)

(Aduszkiewicz+2017,*Anticic+ 2010, Aaij+2018)*

→ Updated parameterisation and uncertainties

- Transport

(Y..G.+ 2017/19/21, Derome+ 2019, Weinrich, Y.G.+ 2020)

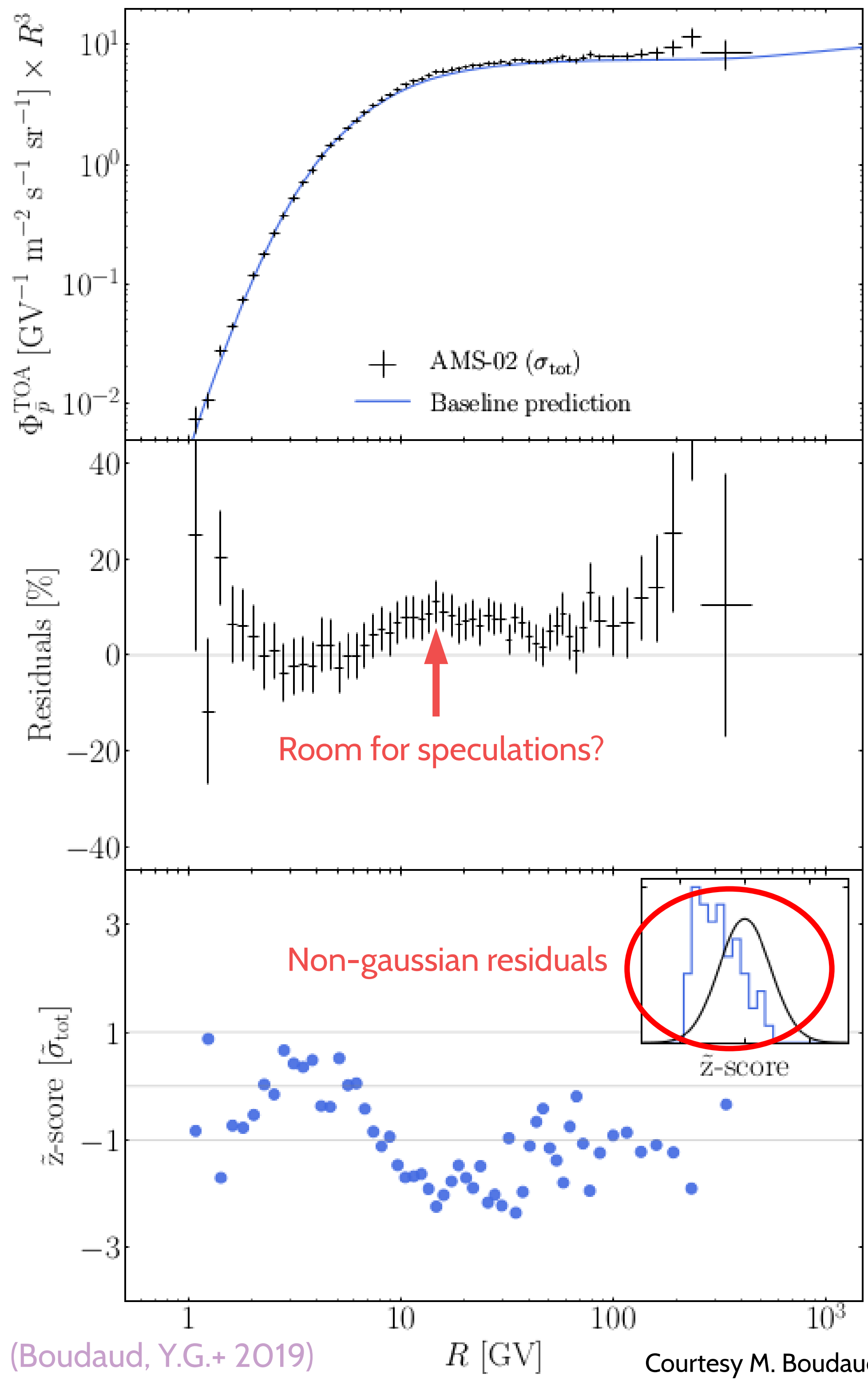
→ Updated transport models and uncertainties

- Parents

(AMS02 Collab. 2017, 2019)

→ Updated fit and contribution of high-Z elements

→ Refined covariance matrix for the model



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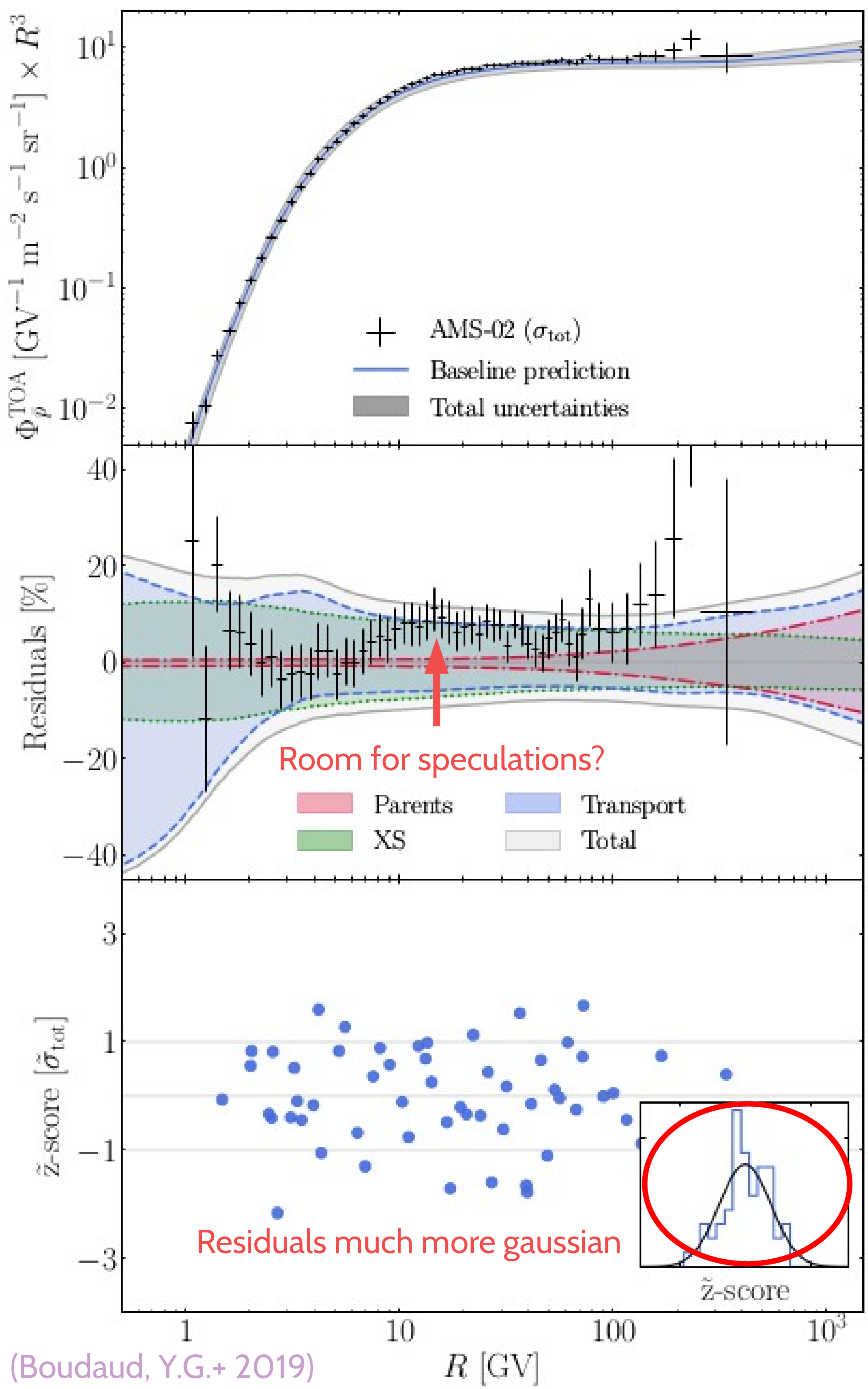


(Boudaud, Y.G.+ 2019)

Statistical tests (Boudaud, Y.G.+ 2019)

→ Chi2 definition:

$$\chi^2 = (\text{data}-\text{model})^T (\mathcal{C}^{\text{model}} + \mathcal{C}^{\text{data}})^{-1} (\text{data}-\text{model})$$

→ Chi2-test:

$$\chi^2/dof = 0.77$$

$$p_{value} = 0.90$$

→ KS-test:

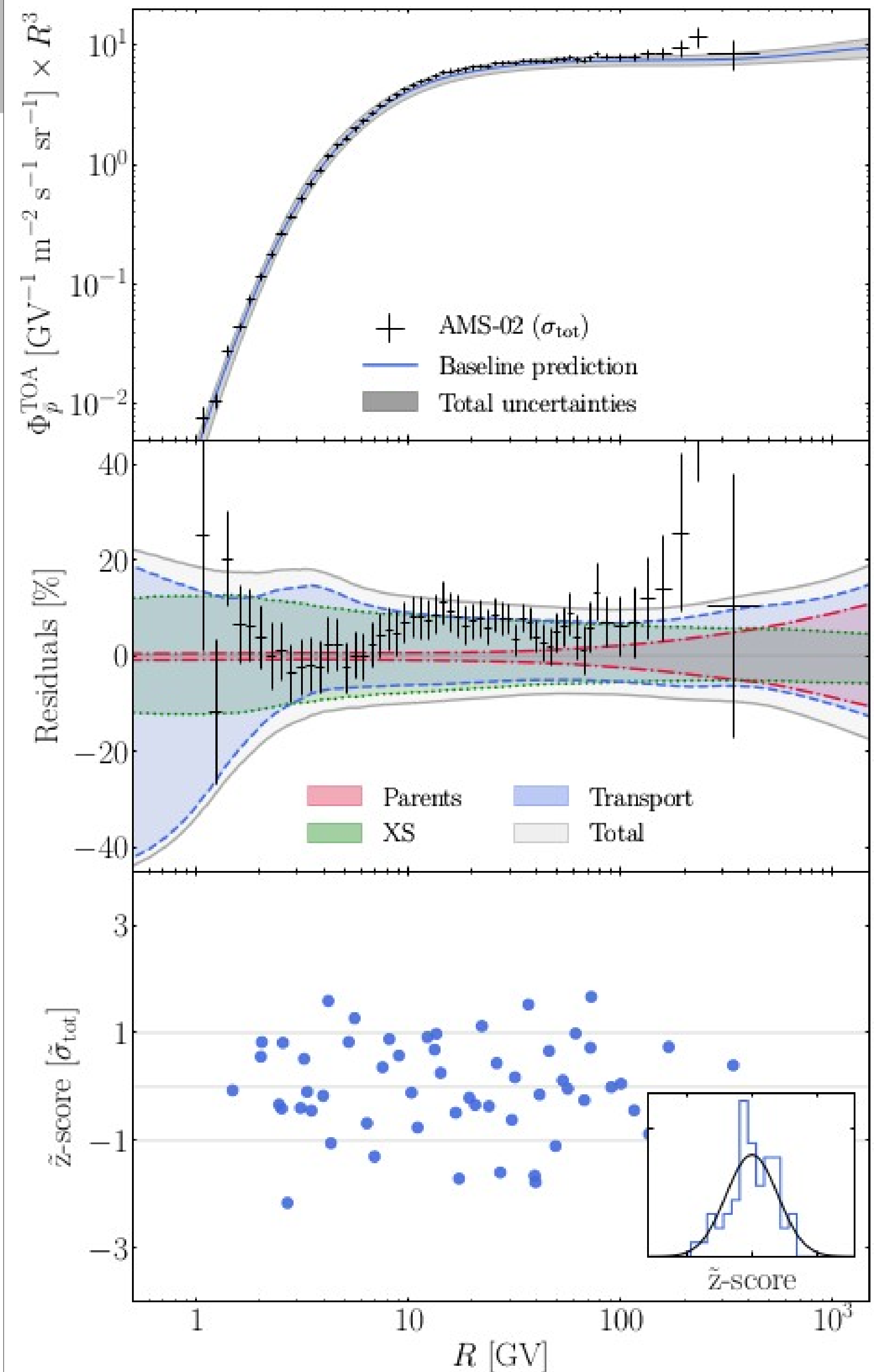
$$p_{value} = 0.27$$

AMS-02 antiprotons are consistent with a secondary astrophysical origin

Other studies confirmed Heisig+ (2020); Reneirt+ (2018)

Before claiming execesses carefull statistical studies must be performed! e.g. claimed excess in Li, Fe, …

Going beyond : transport and cross-sections main uncertainties Korsmeier+ (2018);Y.G.+ (2018);



Introduction : the precision era

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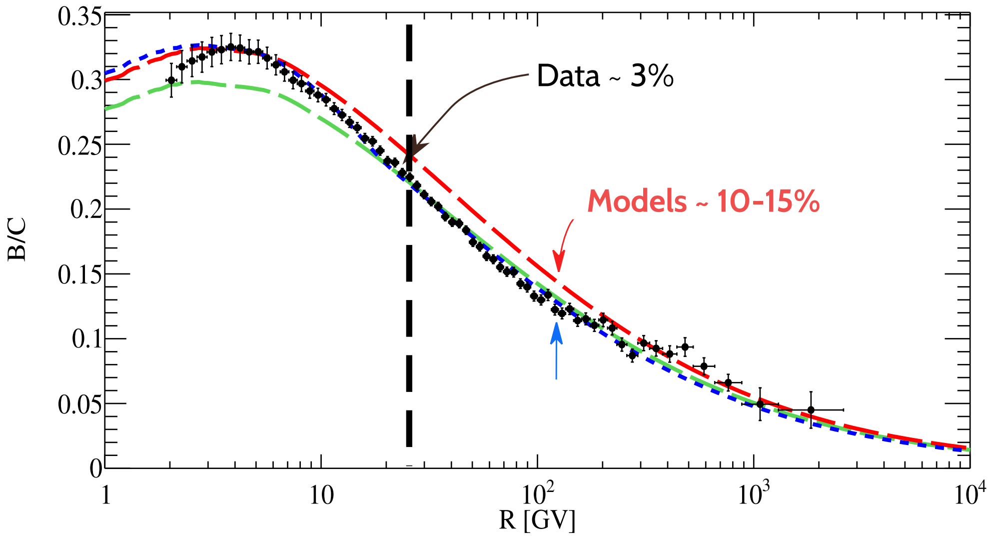
Critical role of fragmentation cross-sections

Models $\propto$ $\sigma(\mathrm{C} + (\mathrm{H}, \mathrm{He}) \rightarrow \mathrm{B})$



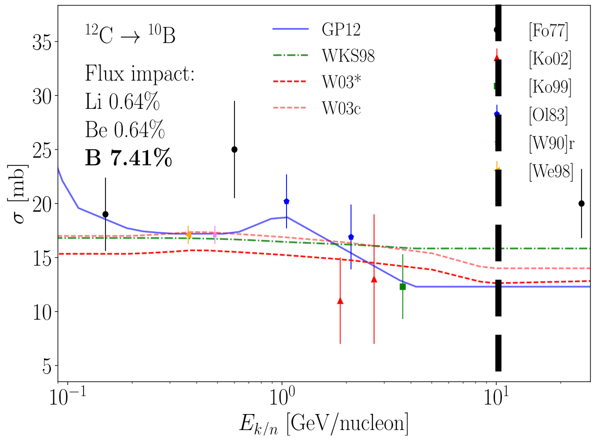
Cross-sections status

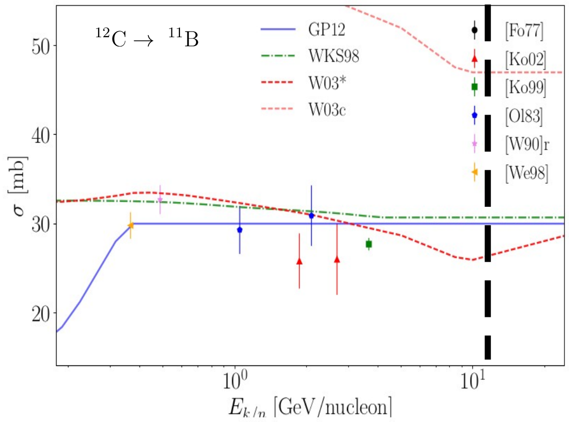
→ No/few data above 1GeV

→ Flat extrapolation high-E

→ Inconsistent data/models

State of the art in Y.G.+ (2018)





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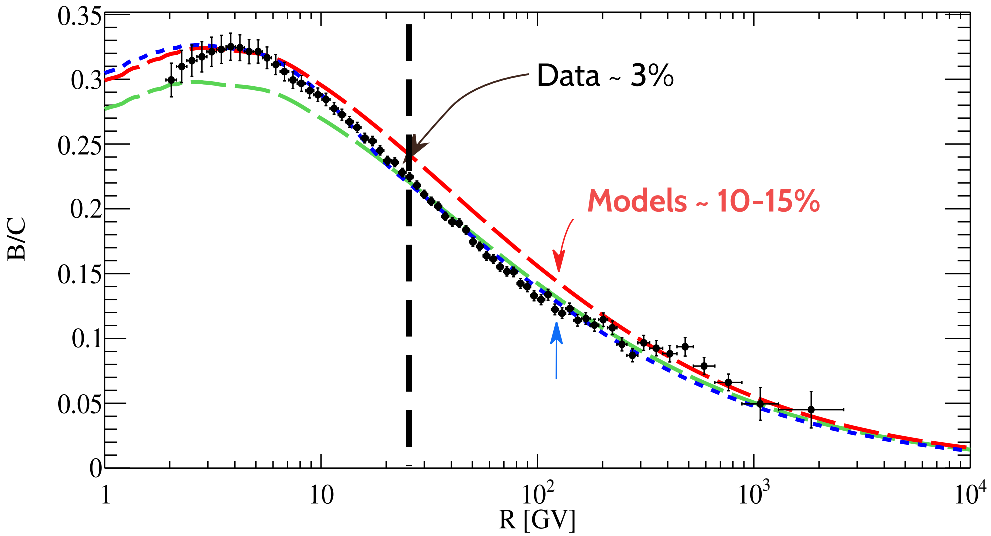

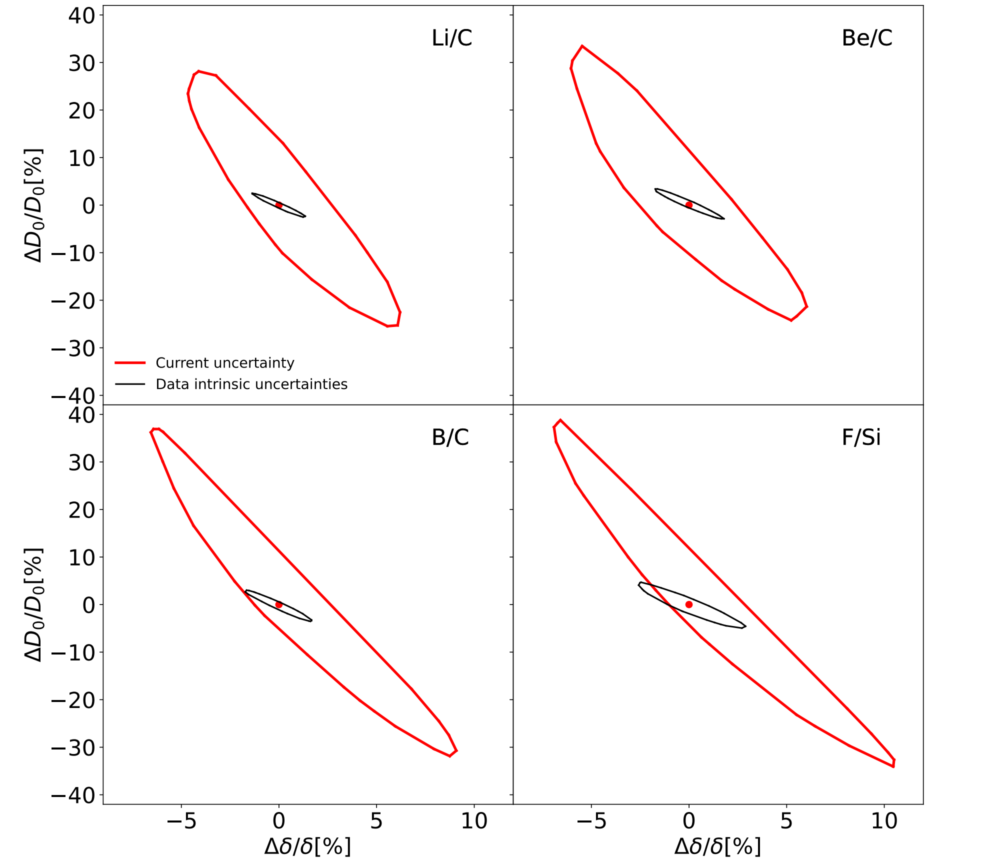

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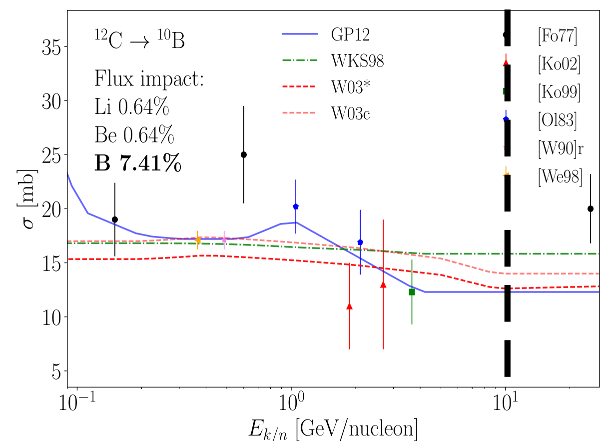
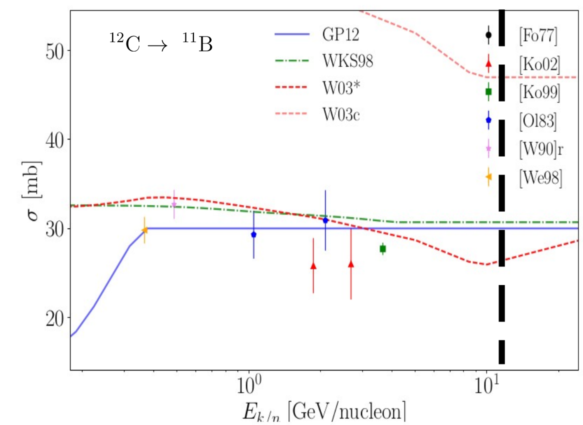




Consequences on transport param.

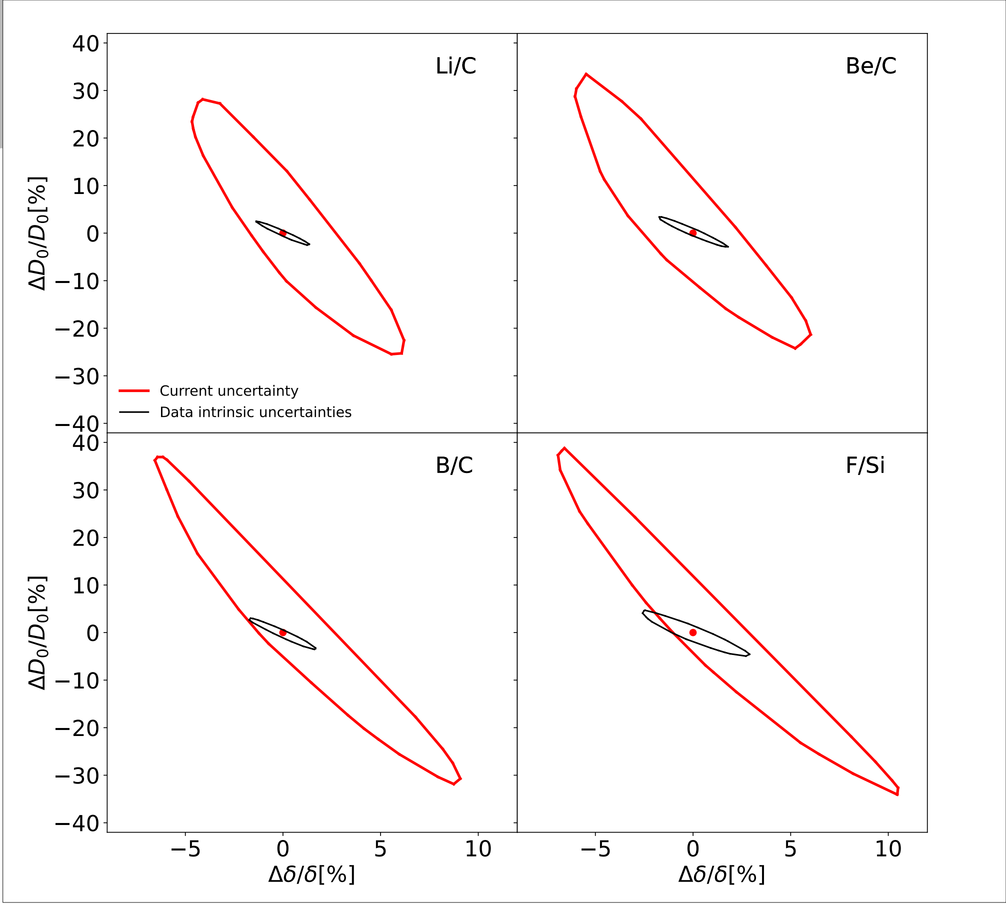
New measurements are required!

Dificulty : more than 1000 reactions are involved ..

→ Selection rules Y.G.+ (2018)

→ Proposition of new measurements
beam + target experiment (e.g. : NA61)
Y.G., Maurin, Moskalenko, Unger (2023)

reaction	$N_{\rm int}$
^{16}O+H	60k
^{12}C+H	50k
^{16}O+He	20k
^{11}B+H	10k
^{15}N+H	10k
^{14}N+H	10k
^{12}C+He	10k
^{10}B+H	5k
^{13}C+H	5k
^{7}Li+H	5k
	$N(\leq \mathrm{O}) = 1.9 \times 10^5$
^{28}Si+H	50k
^{24}Mg+H	50k
^{20}Ne+H	50k
^{22}Ne+H	20k
^{22}Ne+H	20k
^{28}Si+He	10k
^{27}Al+H	10k
^{26}Mg+H	10k
^{24}Mg+He	10k
^{23}Na+H	10k
^{25}Mg+H	10k
^{21}Ne+H	10k
^{20}Ne+He	10k
^{32}S+H	5k
^{29}Si+H	5k
^{22}Ne+He	5k
	$N(\leq \mathrm{Si}) = 3.8 \times 10^5$
^{56}Fe+H	30k
^{56}Fe+He	10k
	$N(\leq \mathrm{Fe}) = 4.2 \times 10^5$



Y.G., Maurin, Moskalenko, Unger (2023)

→ Quantifying the **improvments:**

- **Precise determination of transport parameters**
- **Challenging universality**
- **Scrutinize excesses in secondaries**

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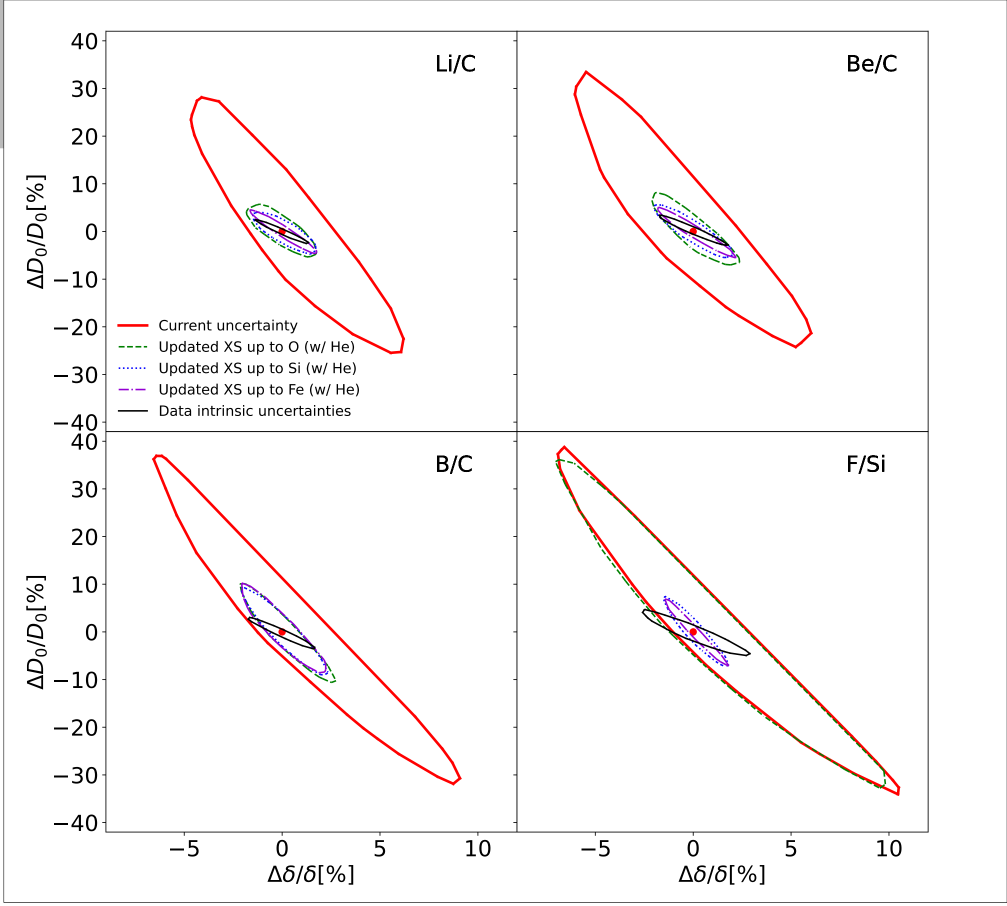

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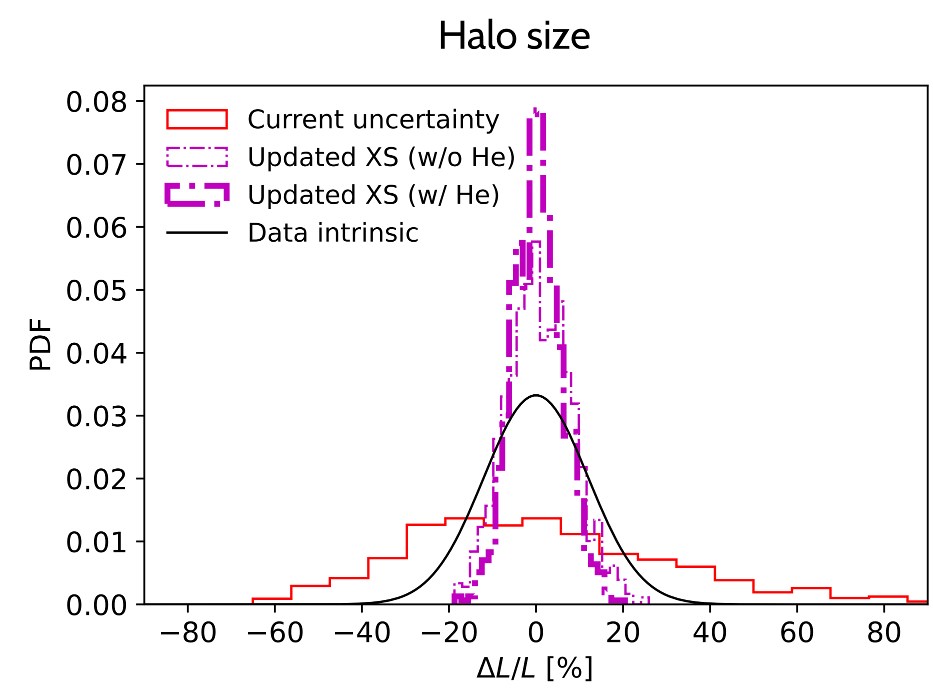

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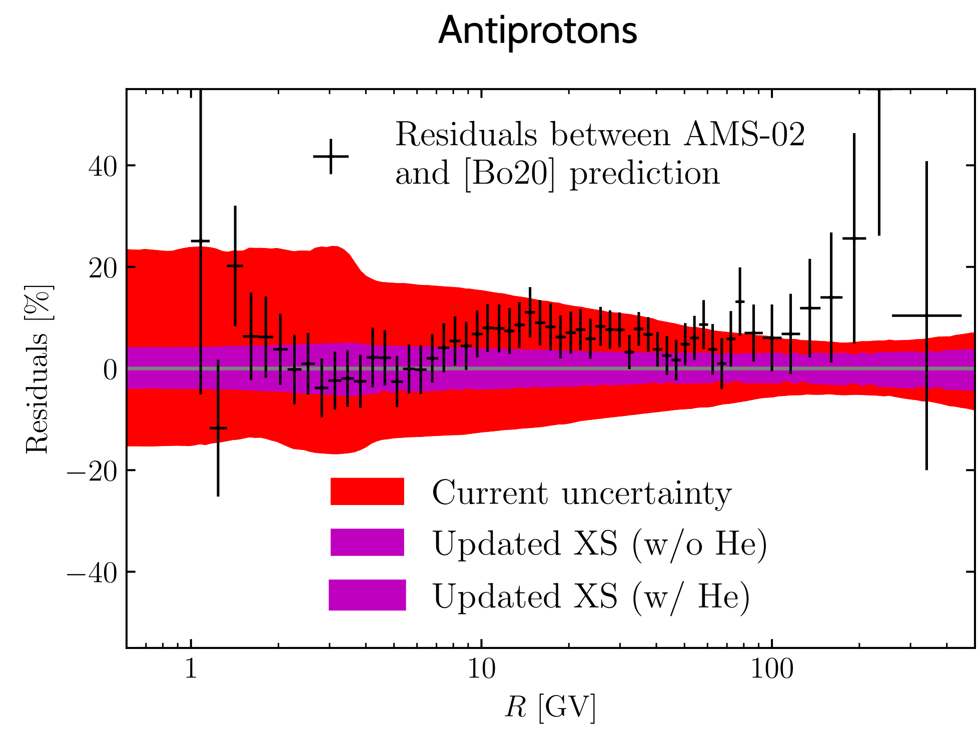
beam + target experiment (e.g. : NA61)
Y.G., Maurin, Moskalenko, Unger (2023)

reaction	$N_{\rm int}$
^{16}O+H	60k
^{12}C+H	50k
^{16}O+He	20k
^{11}B+H	10k
^{15}N+H	10k
^{14}N+H	10k
^{12}C+He	10k
^{10}B+H	5k
^{13}C+H	5k
^{7}Li+H	5k
	$N(\leq \text{O}) = 1.9\times10^5$
^{28}Si+H	50k
^{24}Mg+H	50k
^{20}Ne+H	50k
^{22}Ne+H	20k
^{22}Ne+H	20k
^{28}Si+He	10k
^{27}Al+H	10k
^{26}Mg+H	10k
^{24}Mg+He	10k
^{23}Na+H	10k
^{25}Mg+H	10k
^{21}Ne+H	10k
^{20}Ne+He	10k
^{32}S+H	5k
^{29}Si+H	5k
^{22}Ne+He	5k
	$N(\leq \text{Si}) = 3.8\times10^5$
^{56}Fe+H	30k
^{56}Fe+He	10k
	$N(\leq \text{Fe}) = 4.2\times10^5$



Y.G., Maurin, Moskalenko, Unger (2023)

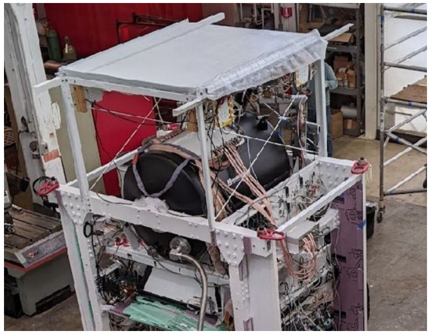
→ Quantifying the **improvments:**

- **Precise determination of transport parameters**
- **Challenging universality**
- **Scrutinize excesses in secondaries**

→ Effort has started for E=13.5 A GeV
Unger (NA61/SHINE Collab.) ICRC (2019)
Amin (NA61/SHINE Collab.) ICRC (2021/2023)

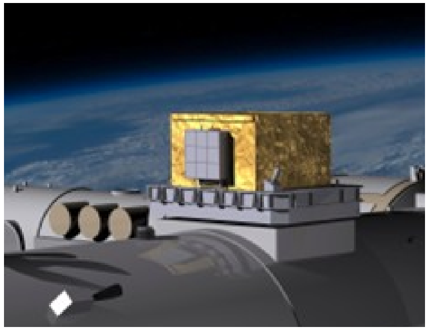
Next generation experiments:

HELIX



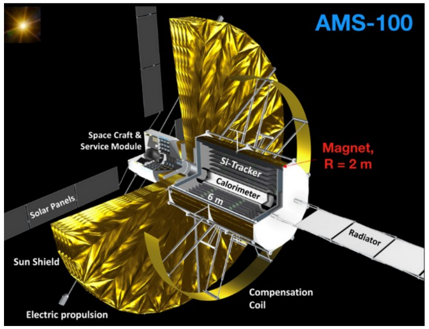
Park+ (2019)

HERD



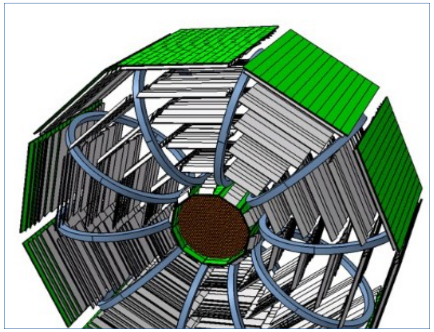
Mori+ (2022)

AMS100



Shael+ (2019)

ALADINO



Battiston+ (2021)

	HELIX	HERD	AMS100	ALADINO
Expected in	2024	2027	2030?	2040?
Type	Spectrometer	Calorimeter	Spectrometer	Spectrometer
Main focus	10Be/9Be	gamma, e+e-, nuclei	(anti)leptons,(anti)nuclei	(anti)leptons,(anti)nuclei
	0.2→ 10GeV/n	0.5, 10GeV→ 100TeV 30 GeV → 3PeV	100TV and beyond	20TV and beyond

Conclusion

Important points :

→ Precision era, % precision data GeV-TeV

→ The main process of CR transport – diffusion - is being elucidating

→ Many open questions (universality, homogeneity, local effect, ..) need finer (multimessenger) studies & proper modeling
see e.g. Korsmeier+ (2022); Zhao+ (2021); Bouyahiaoui+ (2018)

→ Antinuclei (positrons, antipotons, antideuterons?, antihelium?) are still intringuing

Take home messages :

CR experimental collaborations : please provide covariance matrices of data

Particle physicists : please (re)measure nuclear fragmentation cross-sections

Phenomenologist/Theorist : - please keep in mind systematics (e.g. exp. and cross section)
- continue investigating unexplored/sublte effects (%!)
- link the phenomenology with micro-physics

Thank you!

What is next?

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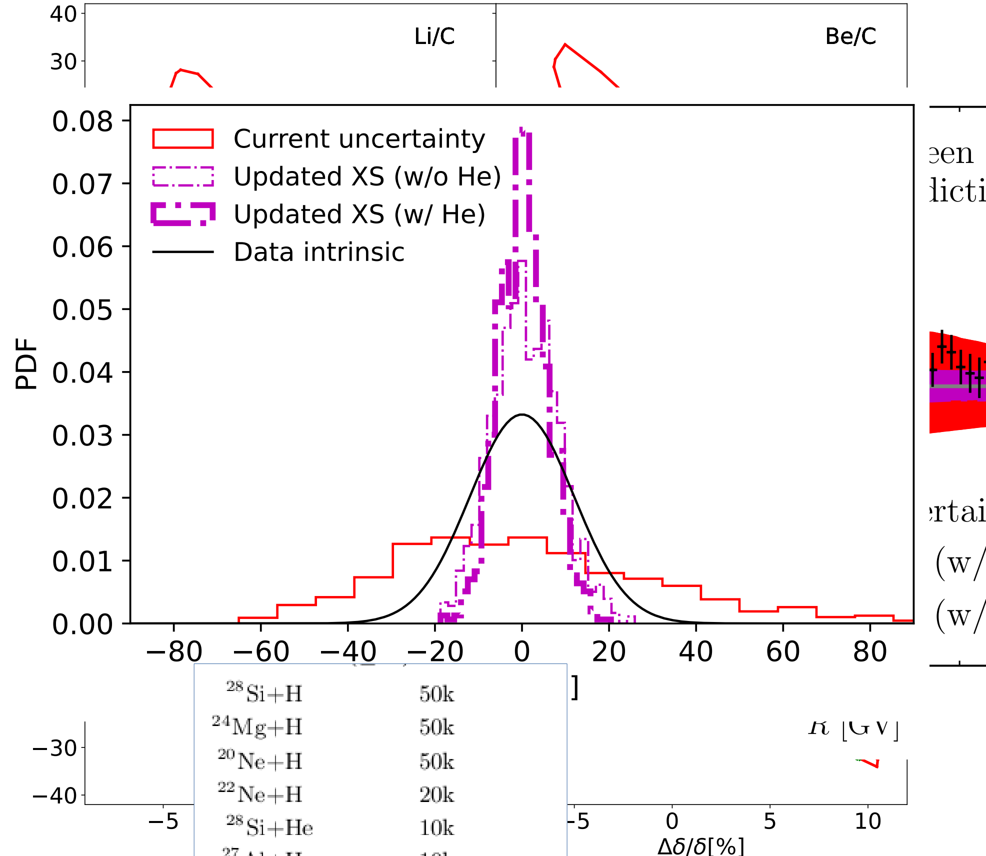

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...kalenko, Unger (2023)

→ **Pre... transport parameters**

→ **Cha...**

→ **Scru... ondaries**