

# Galactic cosmic rays : Current status and open questions

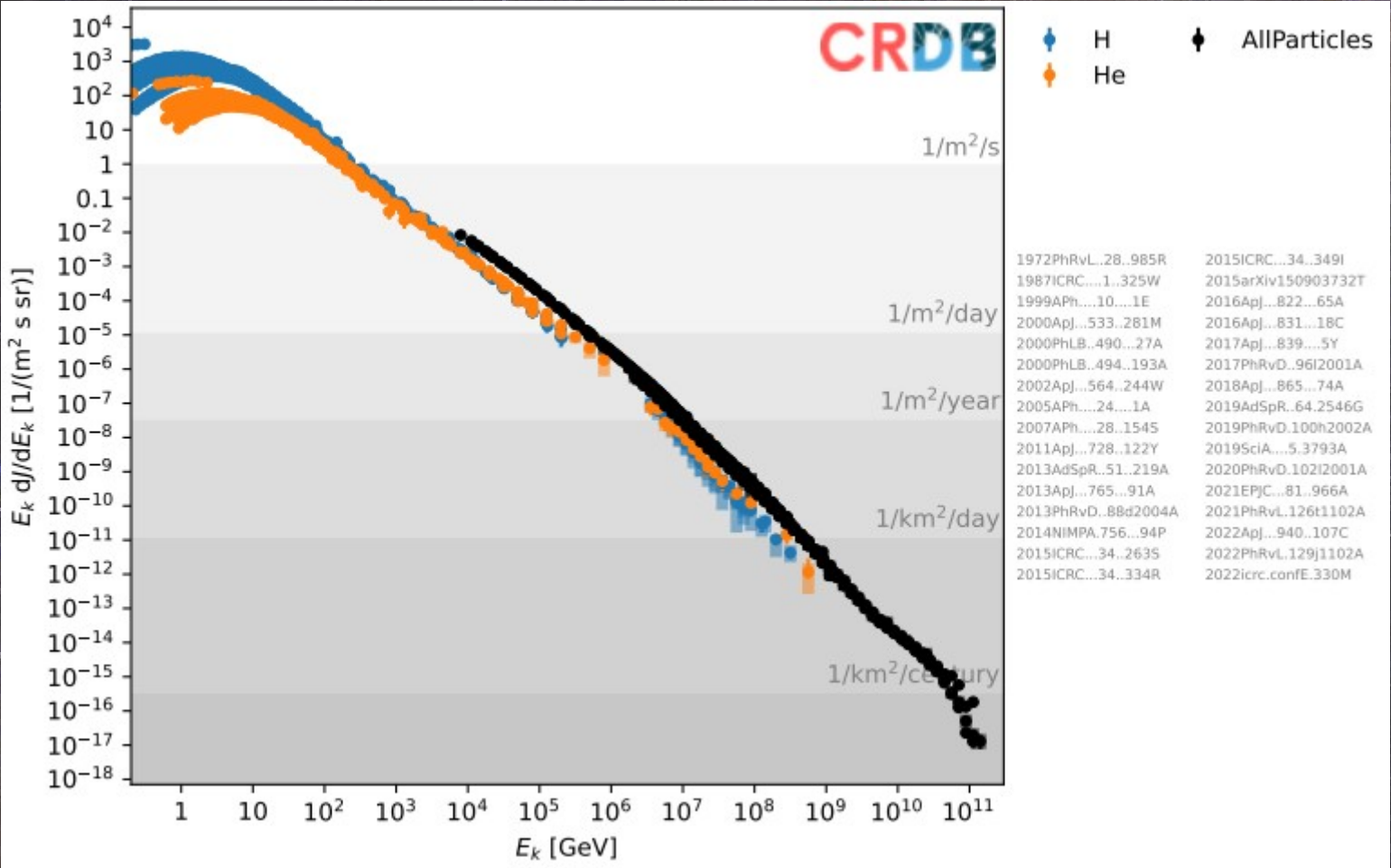
Yoann Génolini

Collaborators :

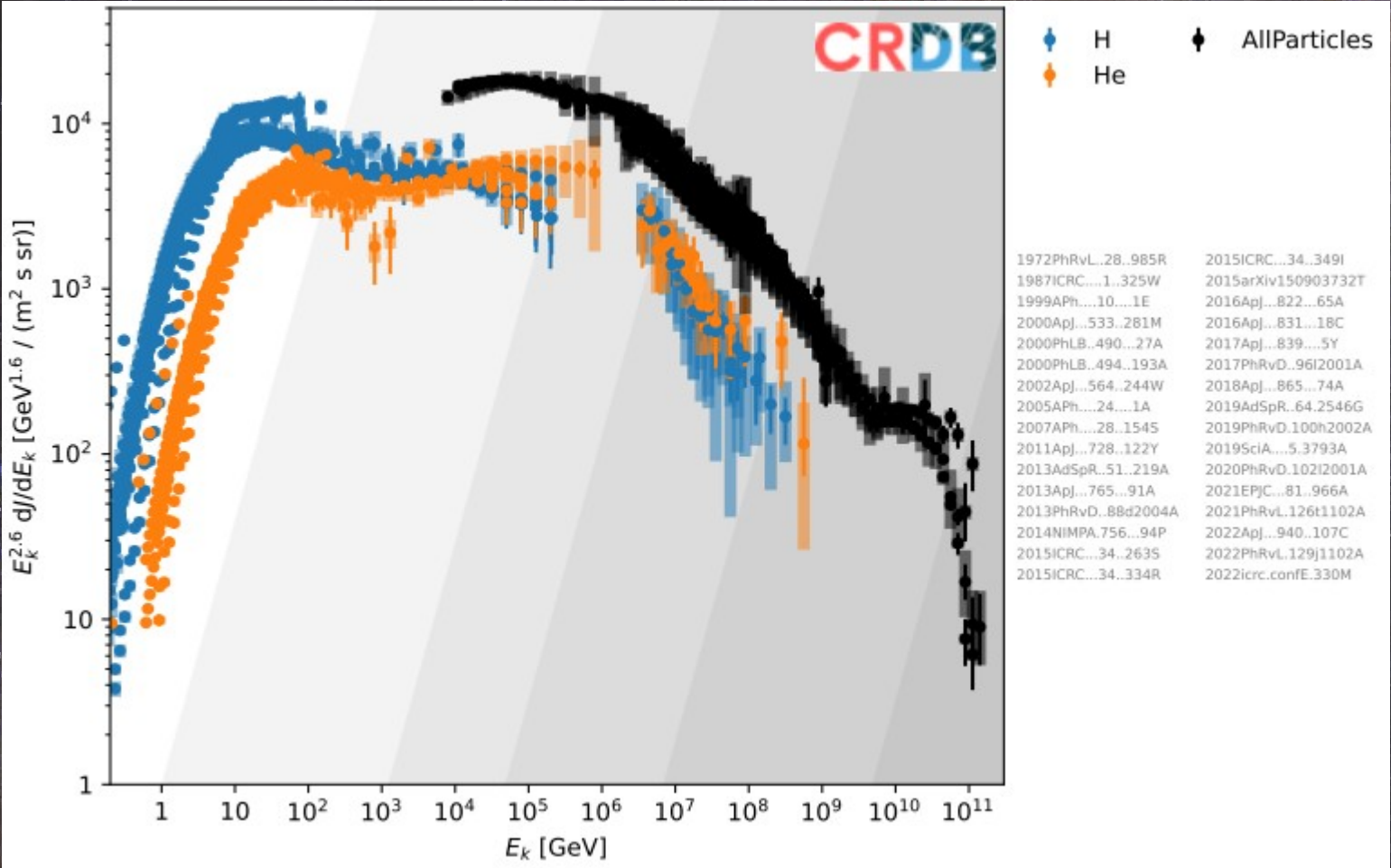
M. Boudaud, P.-I. Batista, S. Caroff,  
M. Cireli, L. Derome, J. Lavalle,  
A. Marcowith, D. Maurin, I. Moskalenko  
V. Poireau, V. Poulin, S. Rosier, P. Salati,  
P. D. Serpico, M. Unger,  
M. Vecchi and N. Weinrich



# Introduction : the precision era



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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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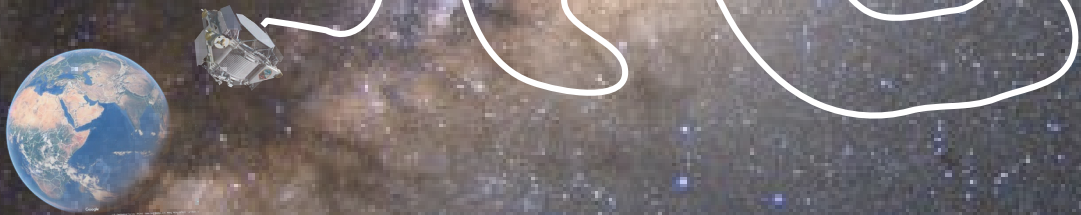
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- How does the transport depend on the ISM?
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- What is the effect of the solar wind on local fluxes?
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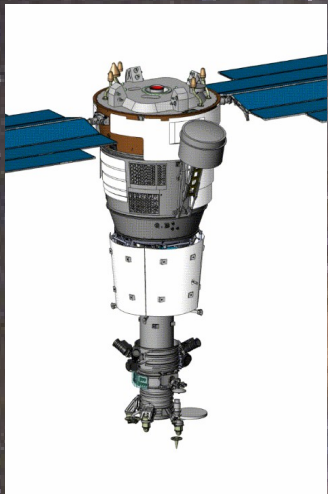
Game changer: high-quality data!

→ In this talk focus on direct detection experiments

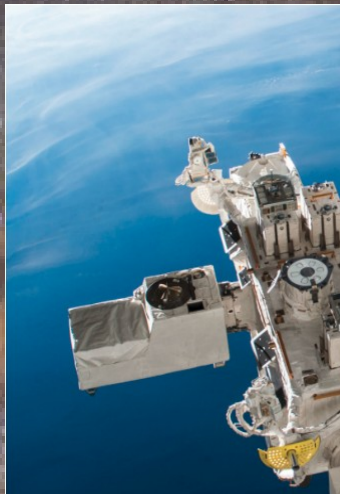
AMS02



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

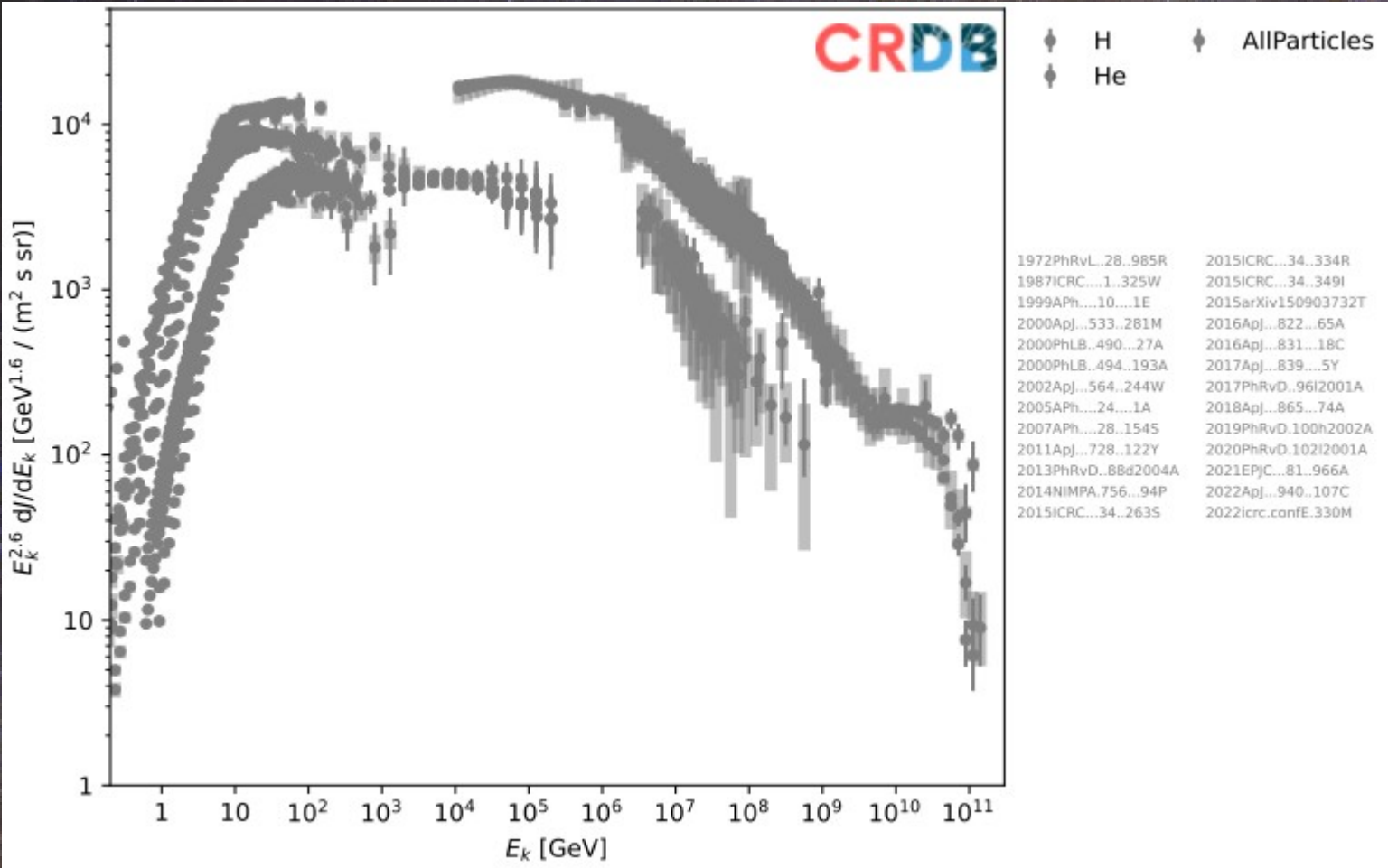
- Precision level % from GV to TV
- Spectrometer : able to measure isotopes

Calorimeters

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

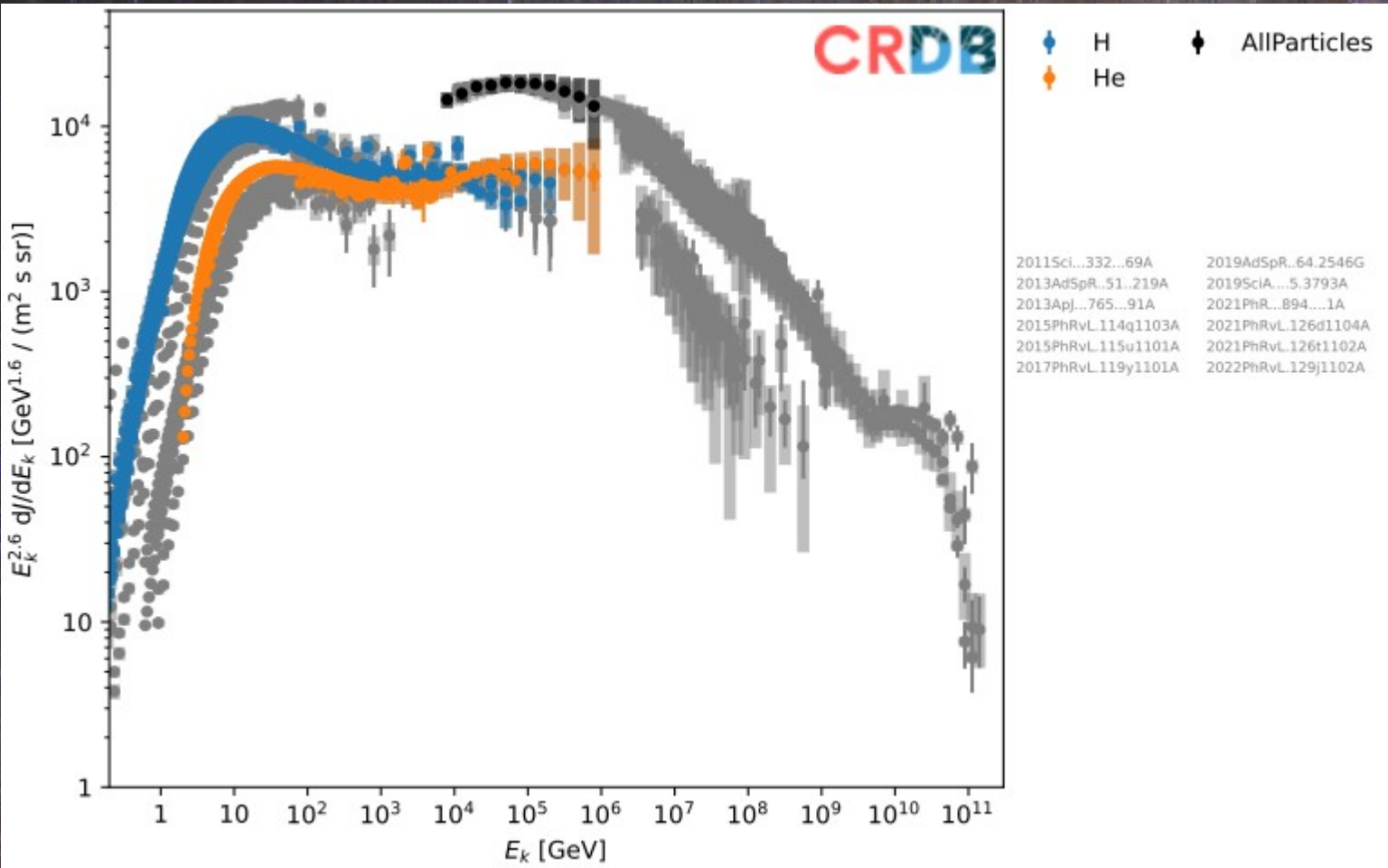
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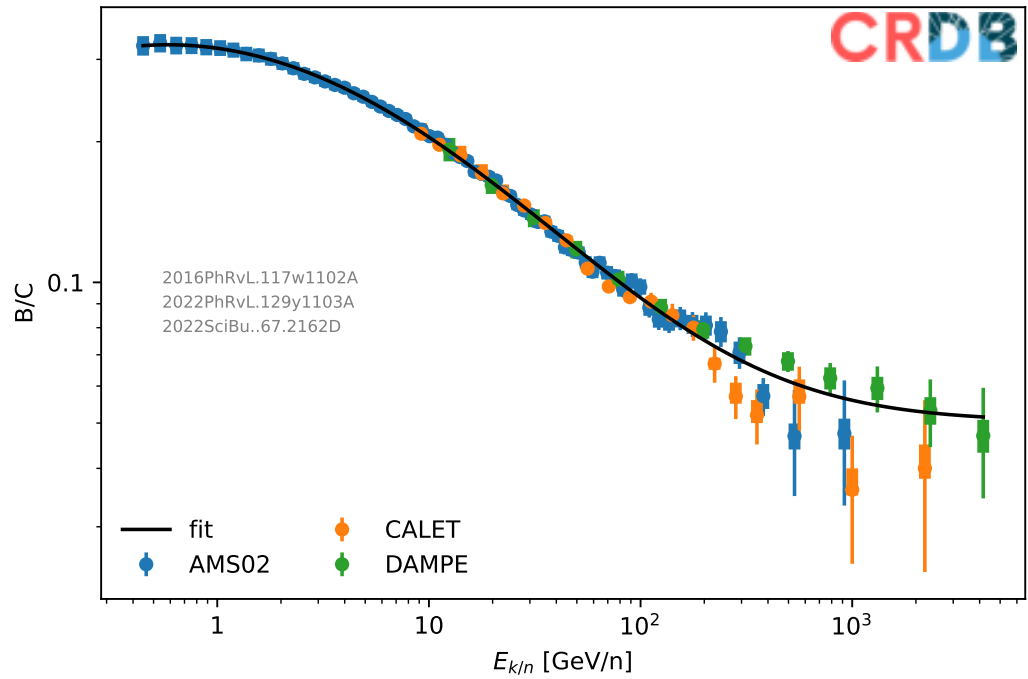
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Game changer: high-quality data! → **Disappointment : no COVARIANCE MATRICES of errors**

Examples : AMS02 and DAMPE error splitting of B/C

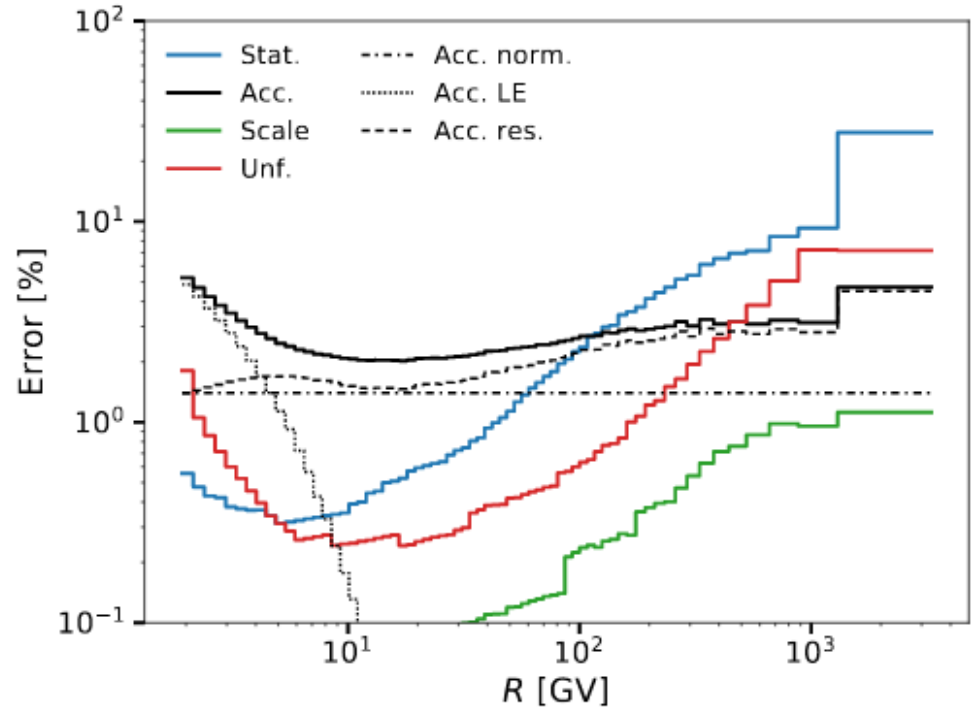




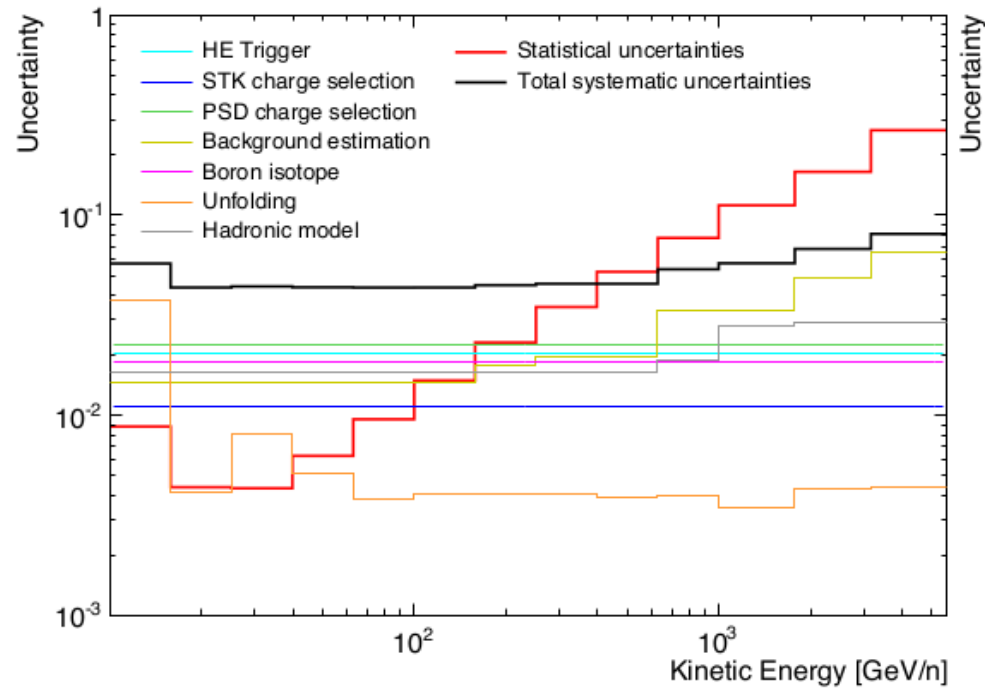
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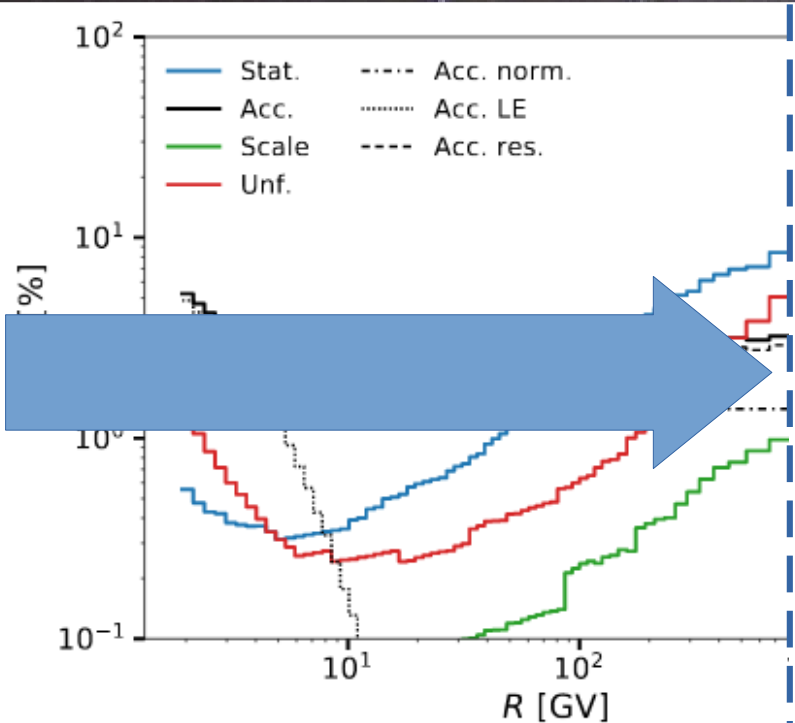
DAMPE Collab., SciBu (2022)

Systematic uncertainties dominate → Even more so for combine fits

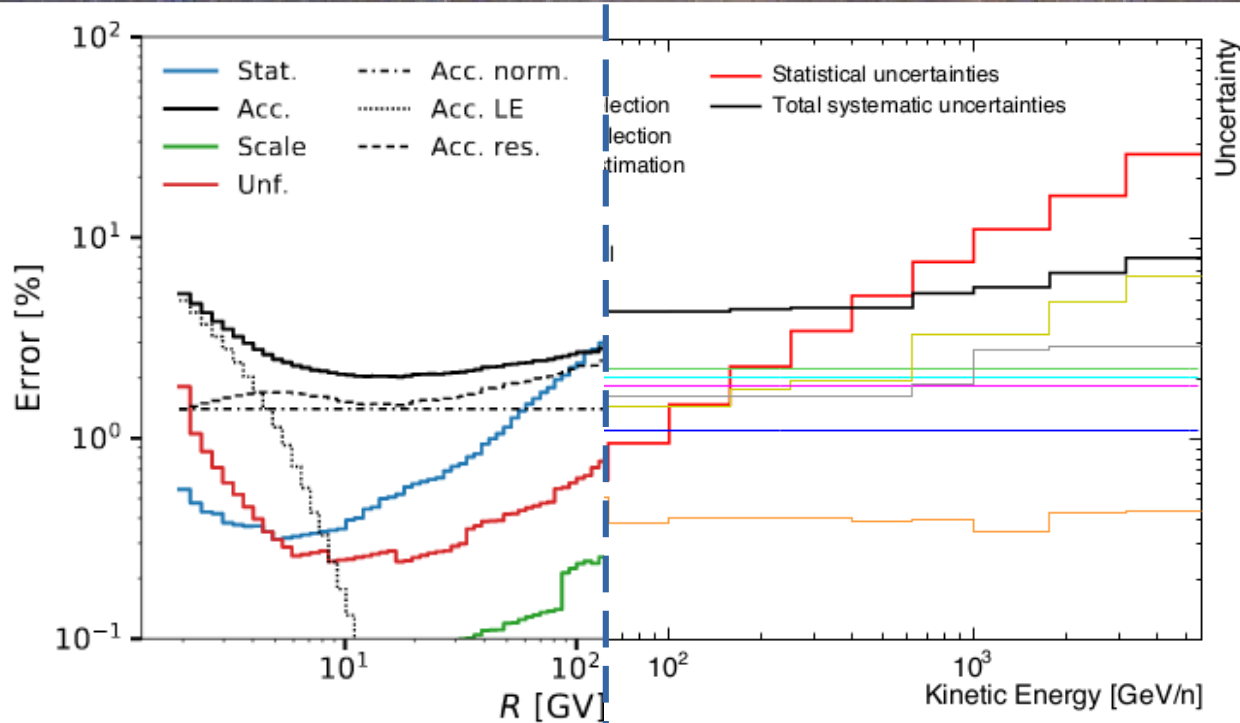
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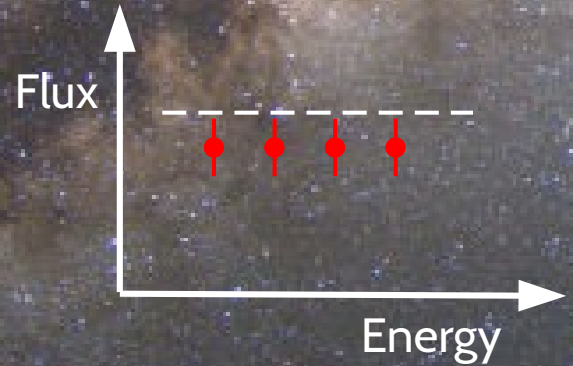


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Systematic uncertainties dominate → Even more so for combine fits

$$\chi^2 = (\text{data}_i - \text{model}_i) C_{ij}^{-1} (\text{data}_j - \text{model}_j)$$

**Reminder :**



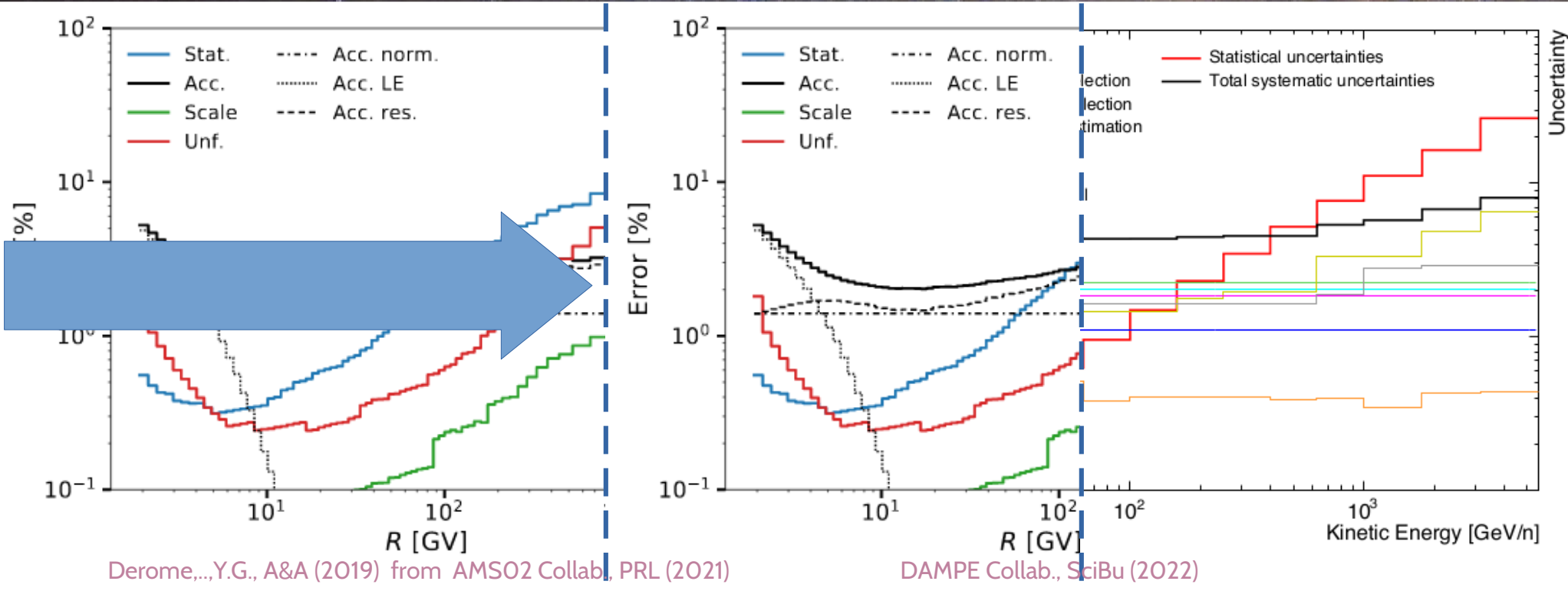
Fully correlated errors →  $c = \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \rightarrow \chi^2 = 1$

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

# Introduction : the precision era

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

Examples : AMSO2 and DAMPE error splitting of B/C



Derome, Y.G., A&A (2019) from AMSO2 Collab., PRL (2021)

DAMPE Collab., SciBu (2022)

Systematic uncertainties dominate → Even more so for combine fits

- Proper hypotheses testing impossible
- Decrease the constraining power of the new data..

**Experimental collaborations should systematically provide the covariance matrix of systematic errors.**

- Hopes with next AMSO2 releases of isotopes?
- First-guess covariance matrix for AMSO2 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?**



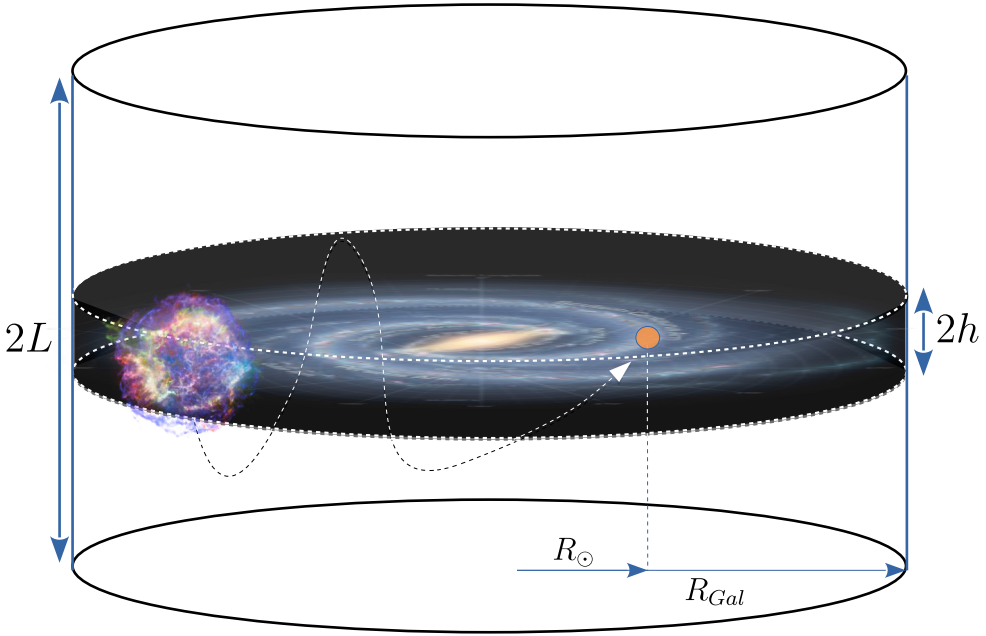
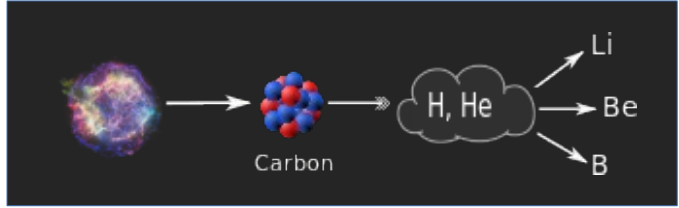
# Cosmic-ray transport → Equation

Resolution of CR transport equation in steady state:

$$\begin{aligned}
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 \end{aligned}$$

Ginzburg&Syrovatskii (1964)

in a cylindrical geometry.



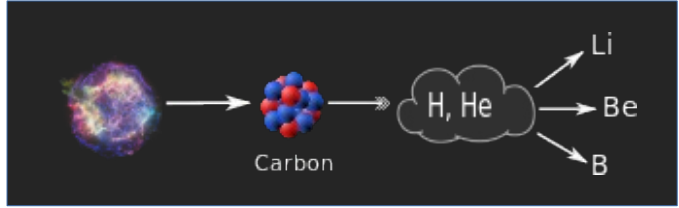
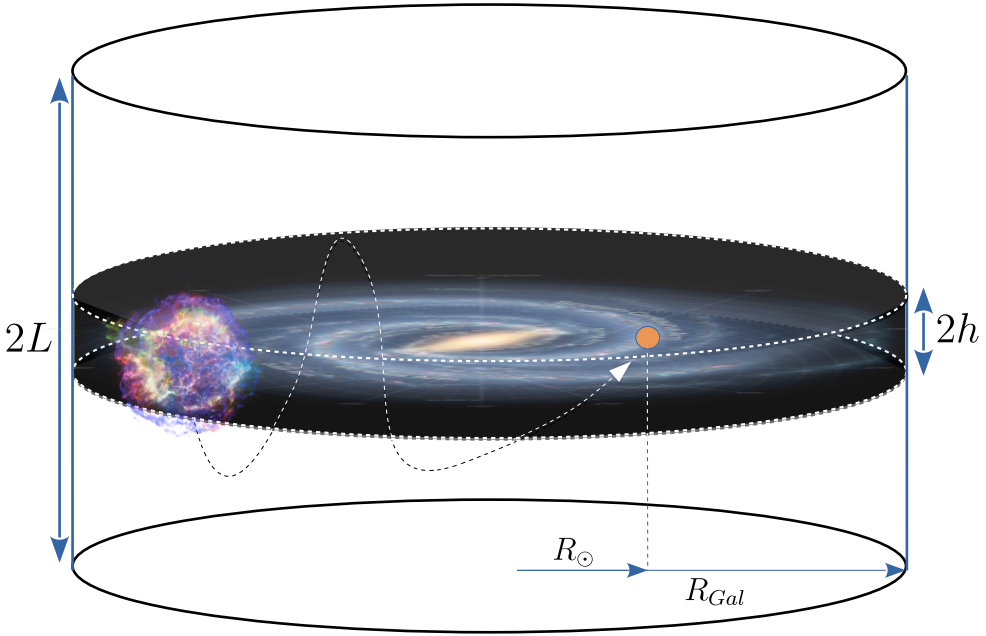
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### Remarks on the CR transport equation

- Diffusion, convection, E-losses, reacceleration, spallation
- Ingredients introduced ~60 yrs ago still satisfying
- Non exhaustive list of fitted parameters :
 
$$K = K_0 \beta R^{\delta} / V_c / V_A / L / \dots$$
- **Effective** transport param. = average over kpc scales
  - pros : learn generic properties of transport/sources
  - cons : several processes intricated
- Precise determination of transport param.
  - link  $\mu$ -physics
  - prediction secondaries (antipart.)

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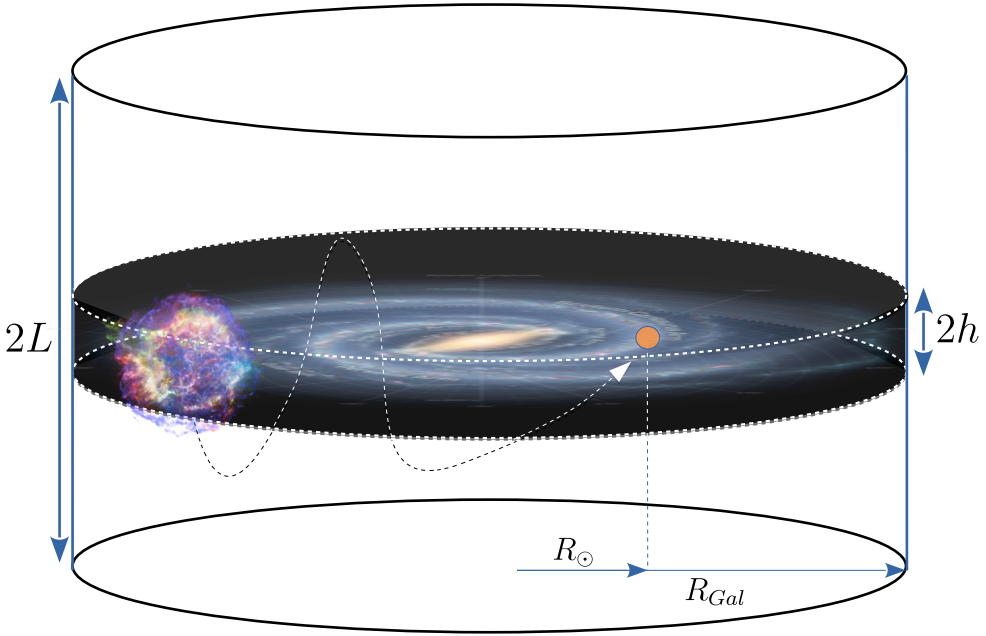
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### Usual assumptions of the resolution



- 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-section are well-known
- Energy losses are well-known
- Local ISM has no impact on local fluxes
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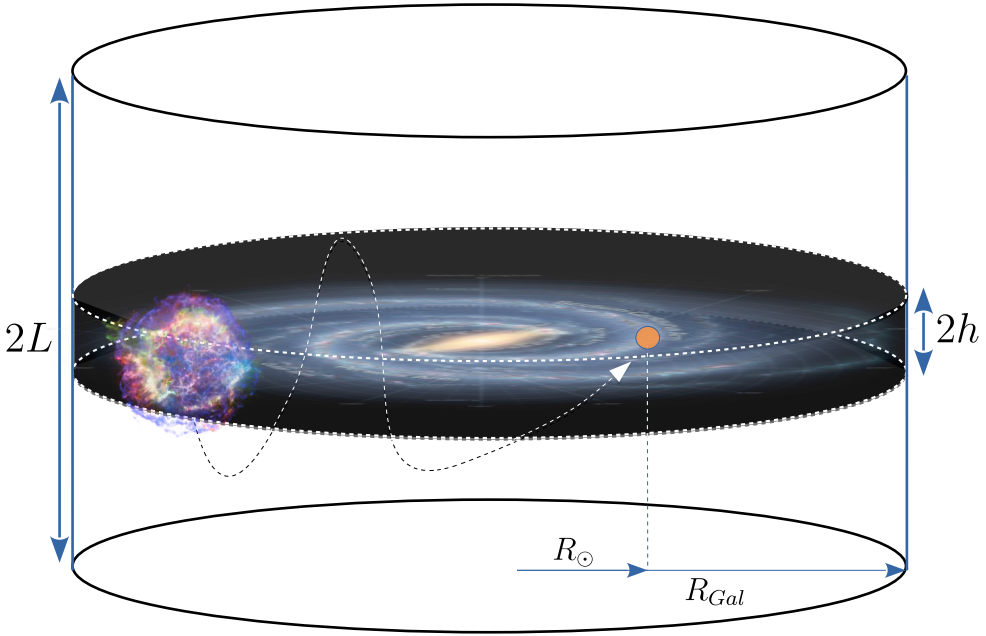
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Challenged by % precise data! → Usual assumptions of the resolution



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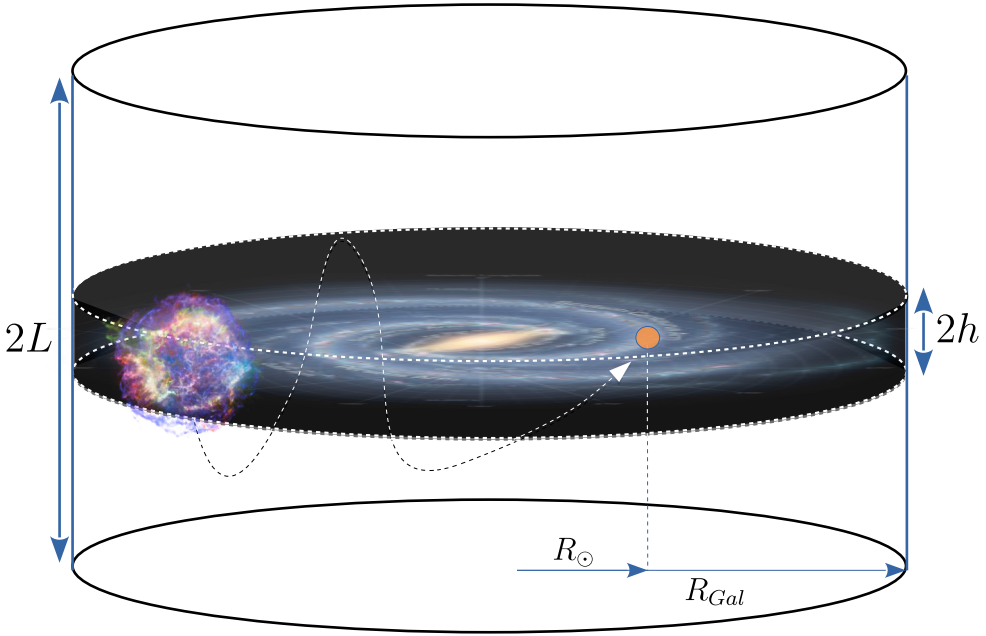
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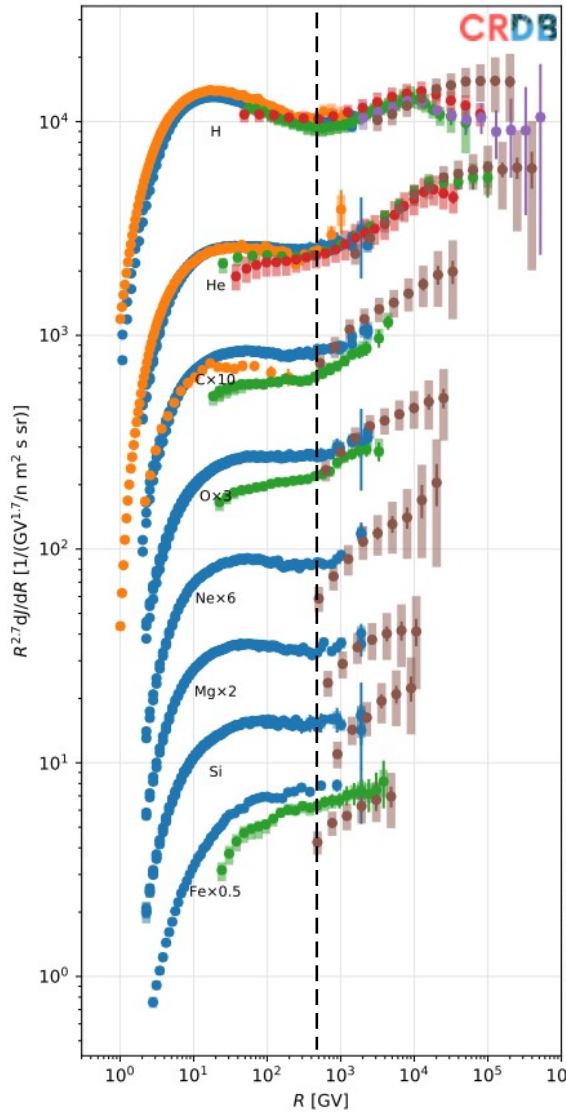
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- Steady state is reached
  - Sources are distributed homogeneously in the galaxy
  - Injection scaling : single powerlaw  $q = C \times R^\alpha$
  - Diffusion is homogeneous and isotropic
- Rules to challenge hypothesis**
- Chose a minimal setup based on usual assumptions
  - Add a novel ingredient
  - Check the preference of the data on statistical basis
  - Energy losses → Covariance matrix required
  - Local ISM has no impact on local fluxes
  - ...

# Cosmic-ray transport → Breaks?

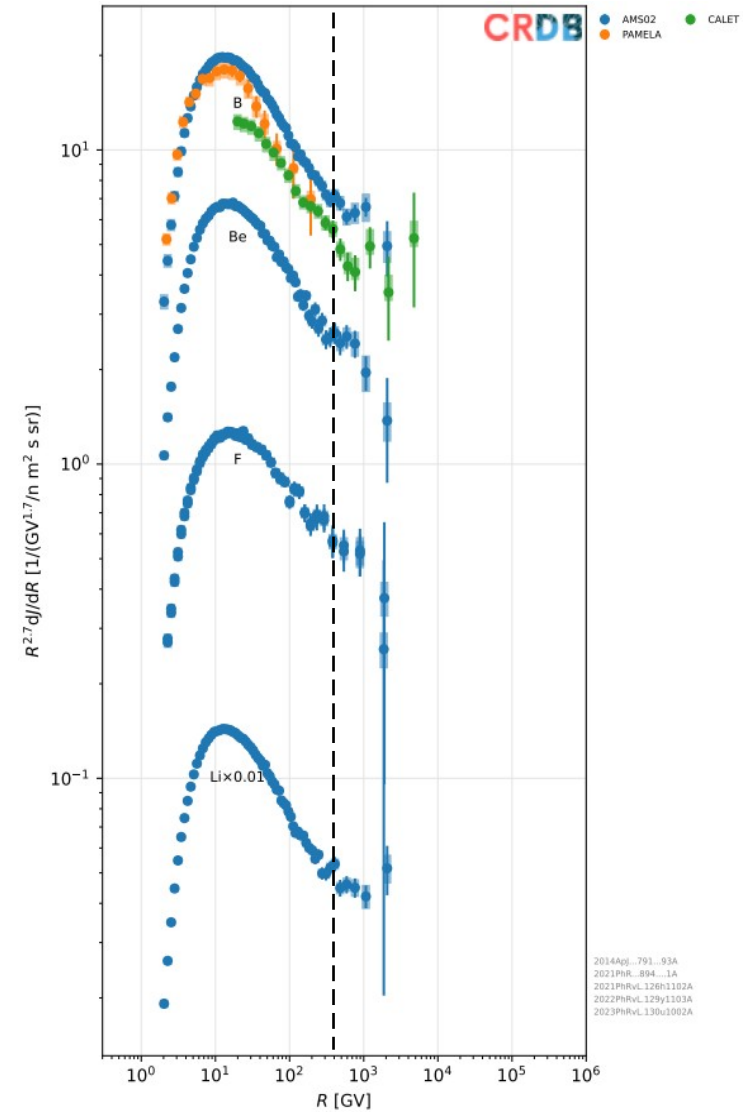
## Universal break in the spectra around 300 GV!



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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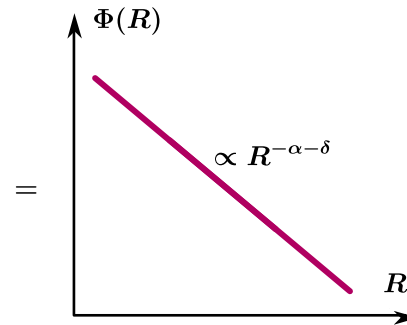
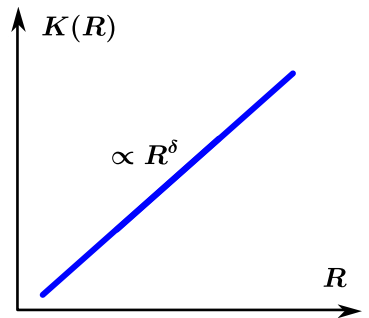
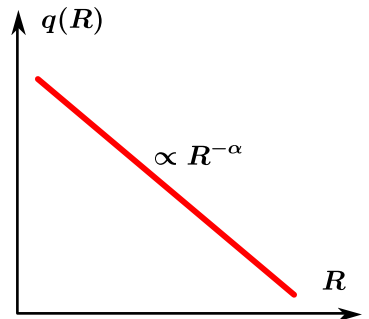
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For pure primary species:

$$\Phi(R) \propto \frac{q}{K} =$$





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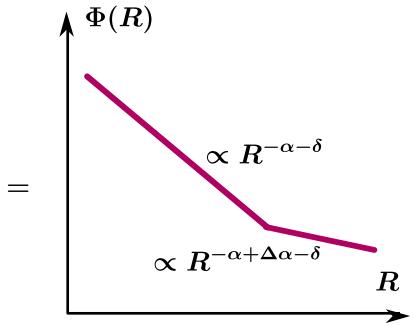
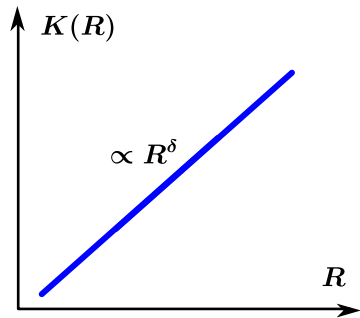
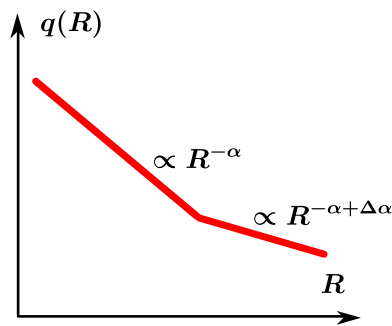
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- Primaries e.g. Vladimirov+ (2012), Niu+ (2018, 2019, 2020); Tomassetti+ (2015)
- Secondaries e.g. Tomassetti+ (2012); Y.G.+ (2014); Tomassetti+ (2017); Zhang+ (2023)
- Reacceleration e.g. Tomassetti+ (2012); Yuan+ (2020)

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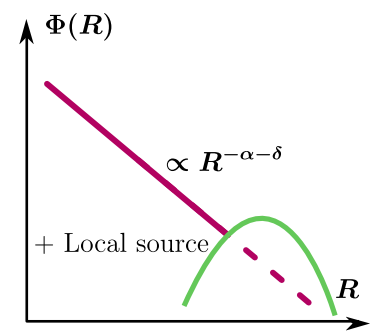
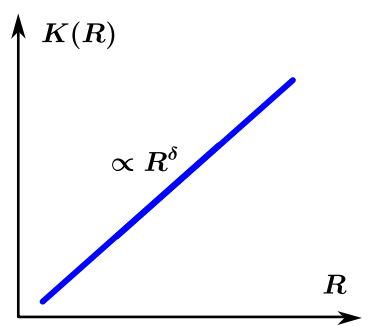
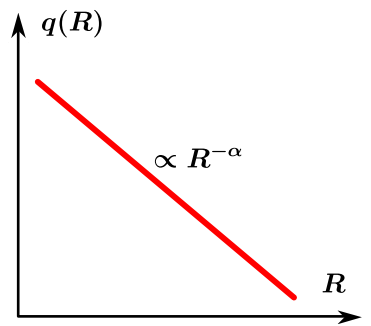
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Solution of CR transport equation : pure diffusive case

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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

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Universal break(s) in the spectra!

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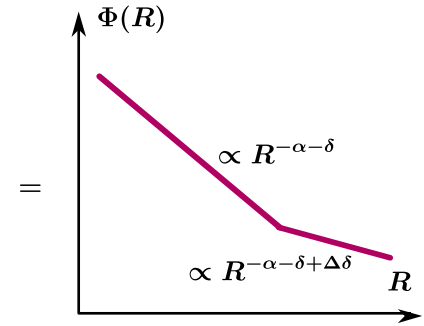
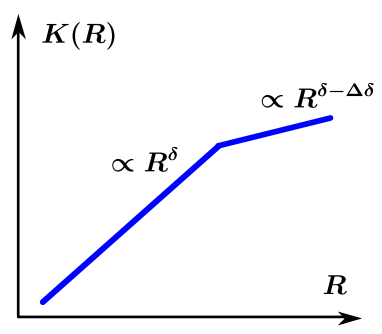
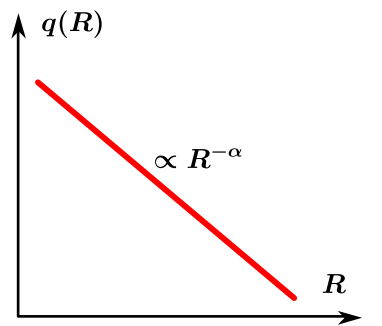
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Pheno : Vladimirov+ (2012); Y.G+ (2017); Niu+ (2020);  
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# Cosmic-ray transport → Breaks?

Universal break(s) in the spectra!

What is their origins?

Injection?

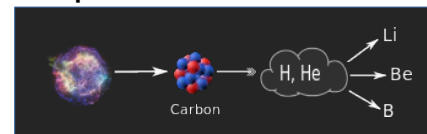
Local source?

**Diffusion?**

$$\cancel{\frac{\partial \psi_\alpha}{\partial t}} - \cancel{\vec{\nabla}_x \{ K(E) \vec{\nabla}_x \psi_\alpha - \vec{V}_e \psi_\alpha \}} + \cancel{\frac{\partial}{\partial E} \{ b_{\text{tot}}(E) \psi_\alpha - \beta^2 K_p \frac{\partial \psi_\alpha}{\partial E} \}} + \cancel{\sigma_\alpha v_\alpha n_{\text{ism}} \psi_\alpha} + \cancel{\Gamma_\alpha \psi_\alpha} = q_\alpha + \sum_\beta \{ \cancel{\sigma_{\beta \rightarrow \alpha} v_\beta n_{\text{ism}}} + \cancel{\Gamma_{\beta \rightarrow \alpha}} \} \psi_\beta$$

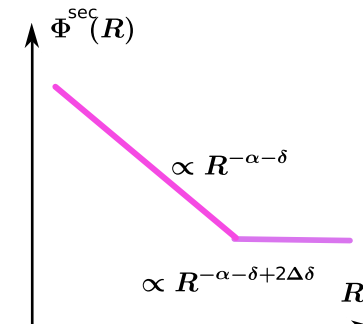
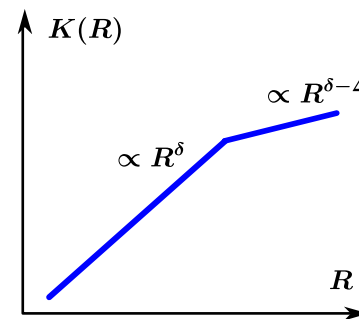
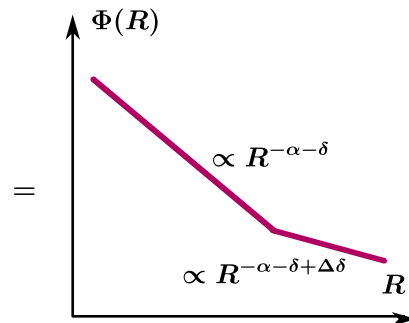
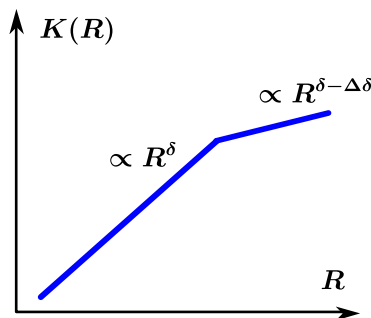
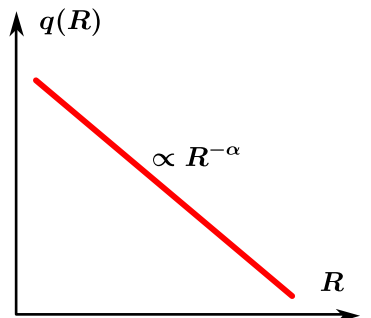
Solution of CR transport equation : pure diffusive case

For pure secondary species:



For pure primary species:

$$\Phi(R) \propto \frac{q}{K}$$



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



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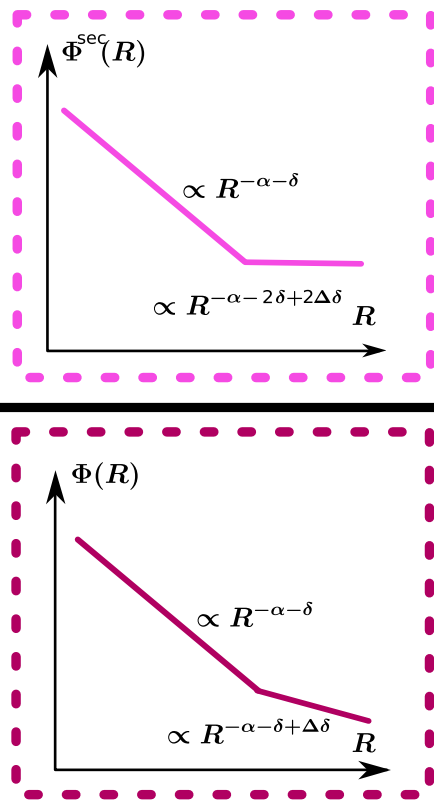
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For secondary/primary ratio:

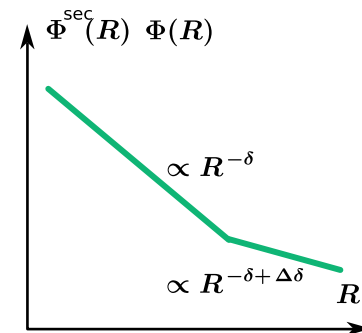
Secondary flux

Primary flux

=



=

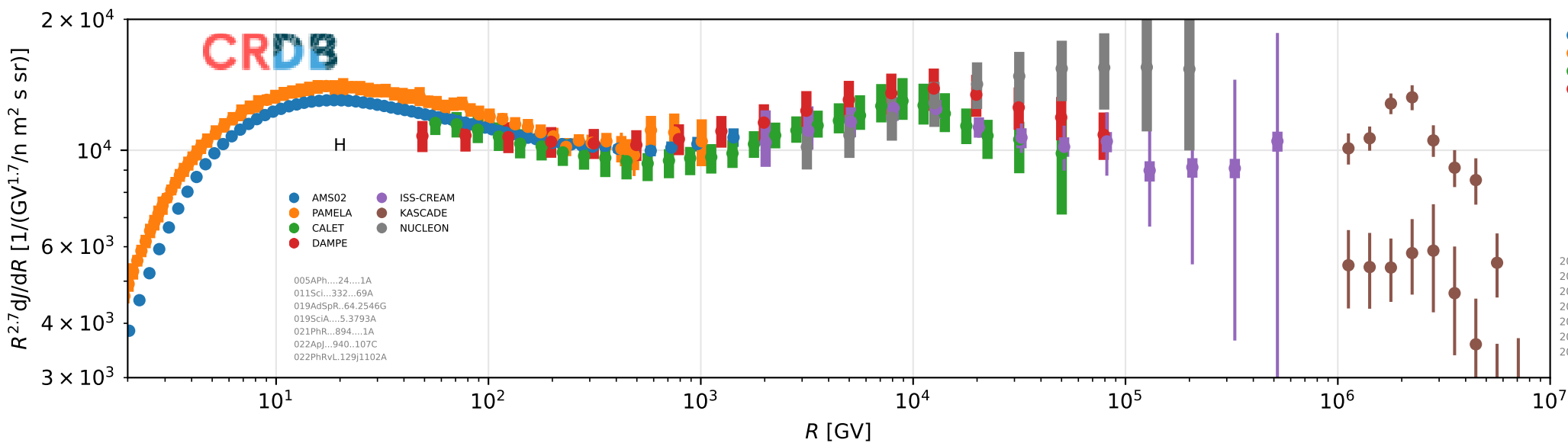


Some words of caution:  
Vecchi et al. (2022)

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

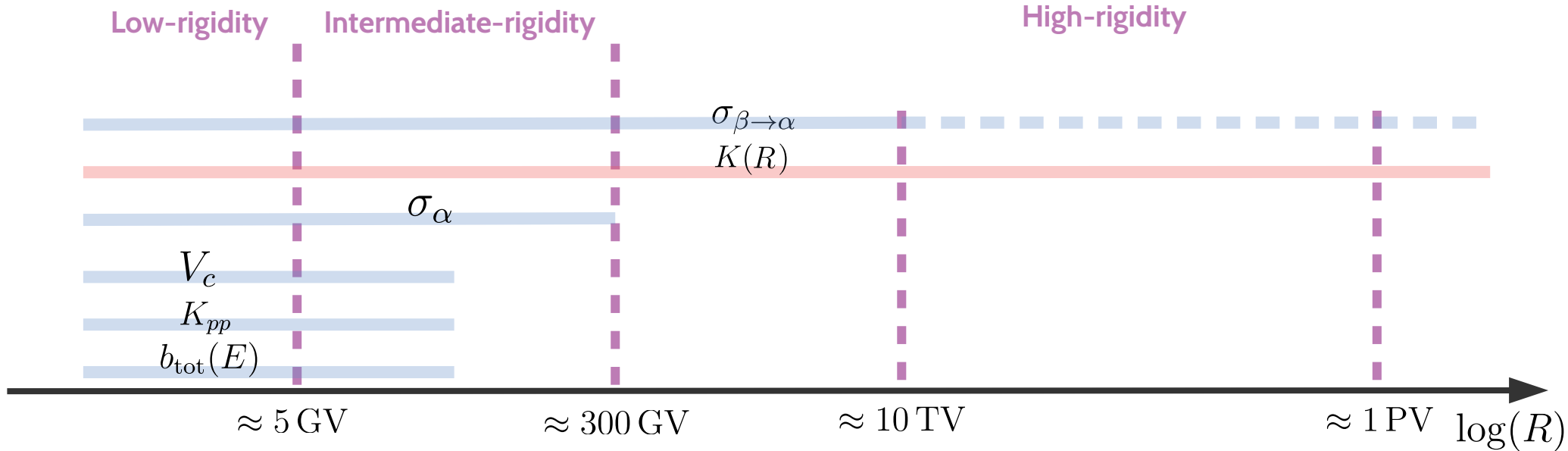
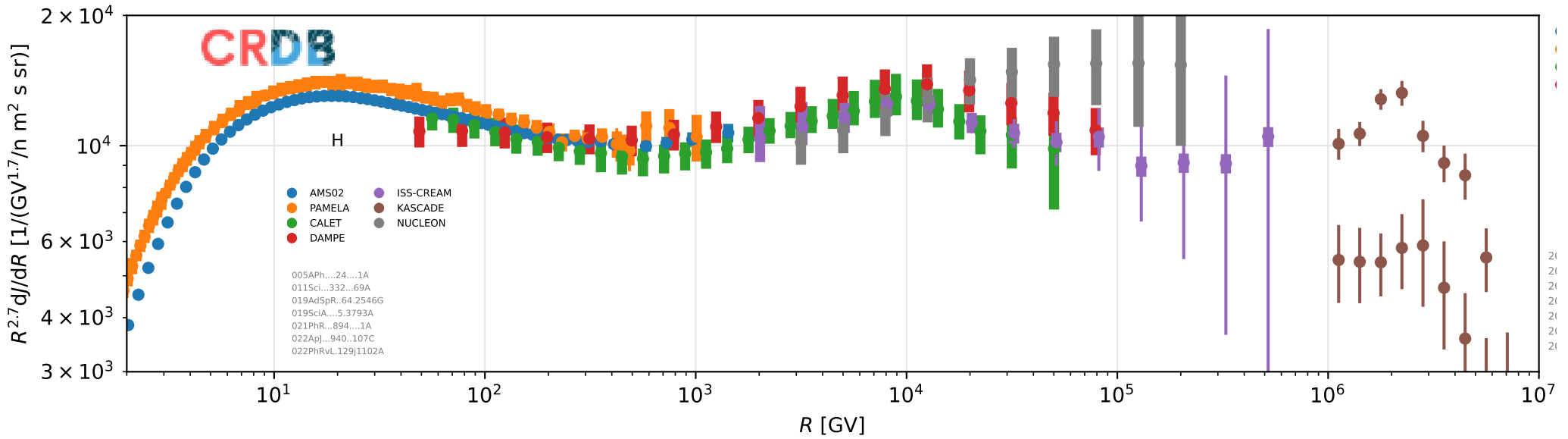
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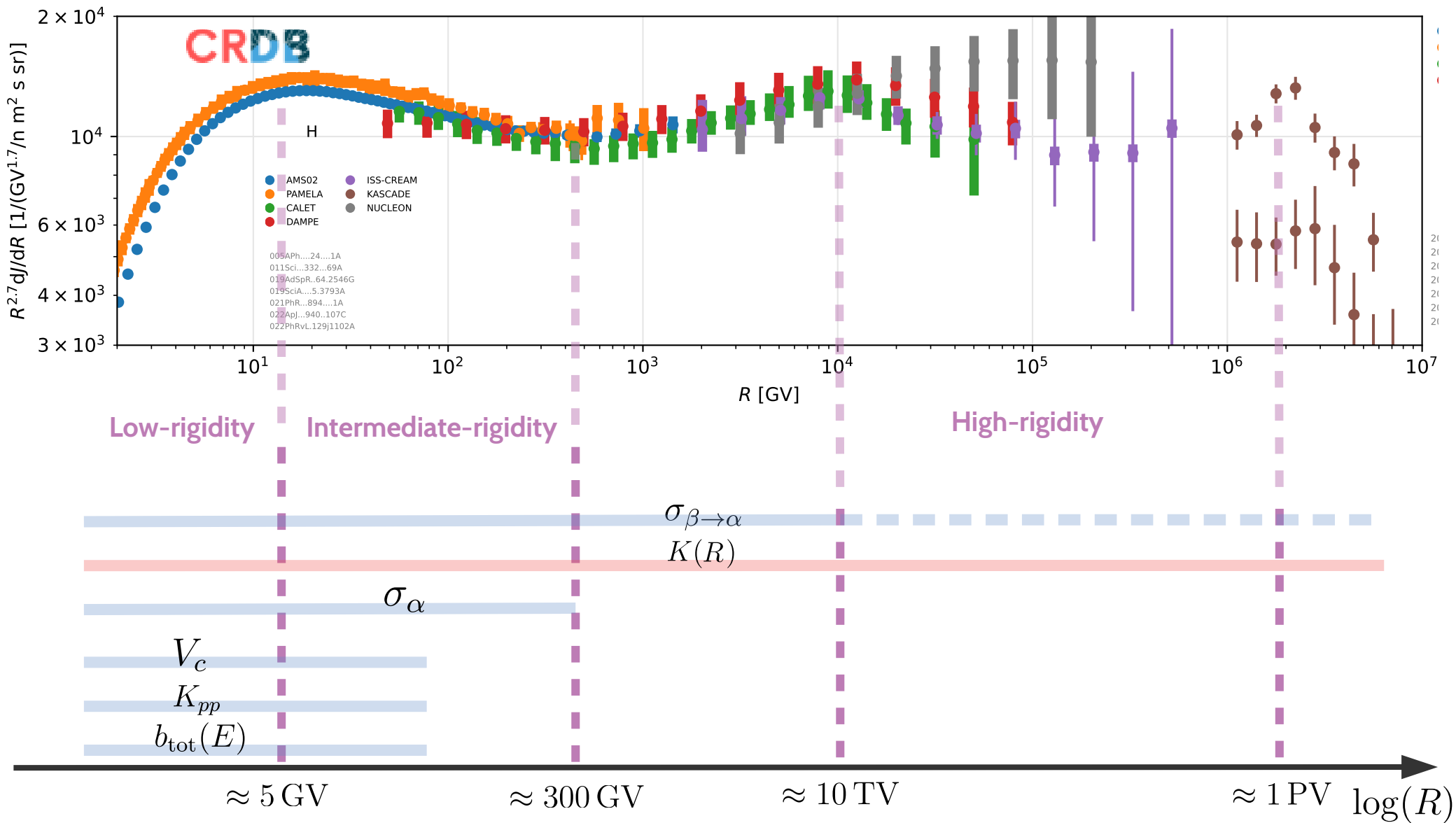
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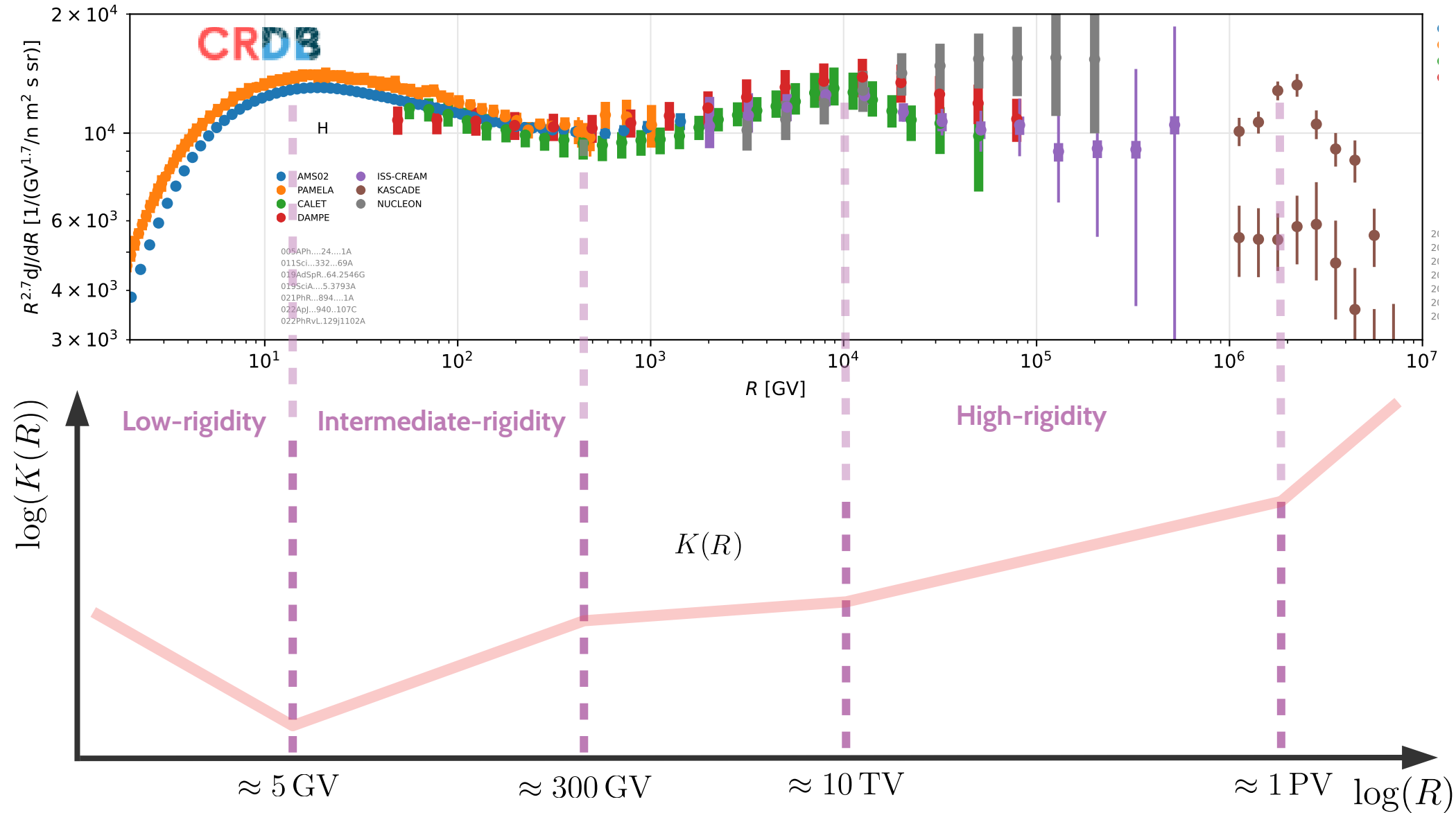
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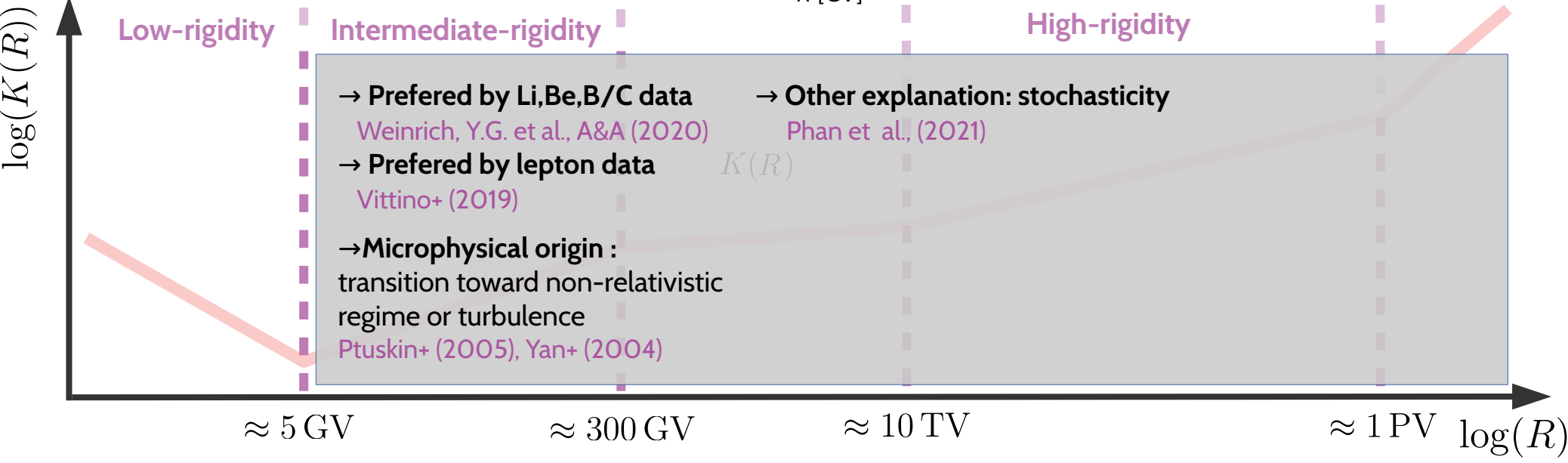
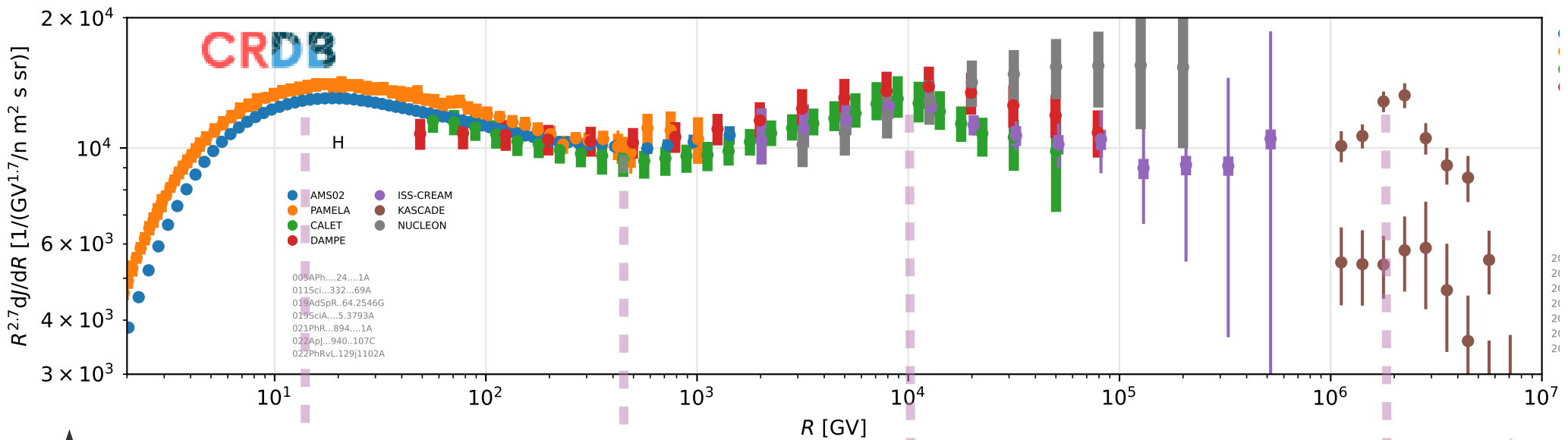
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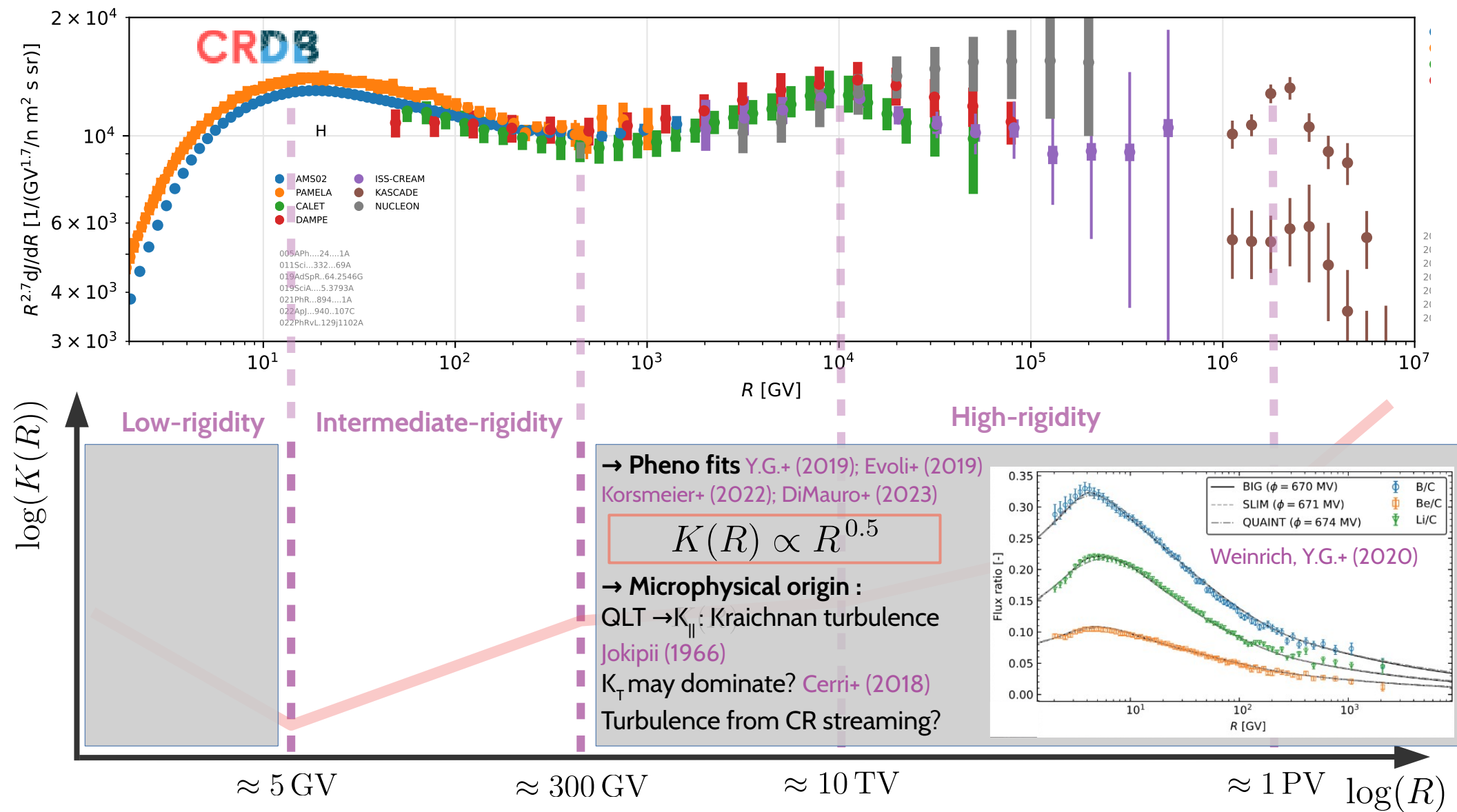
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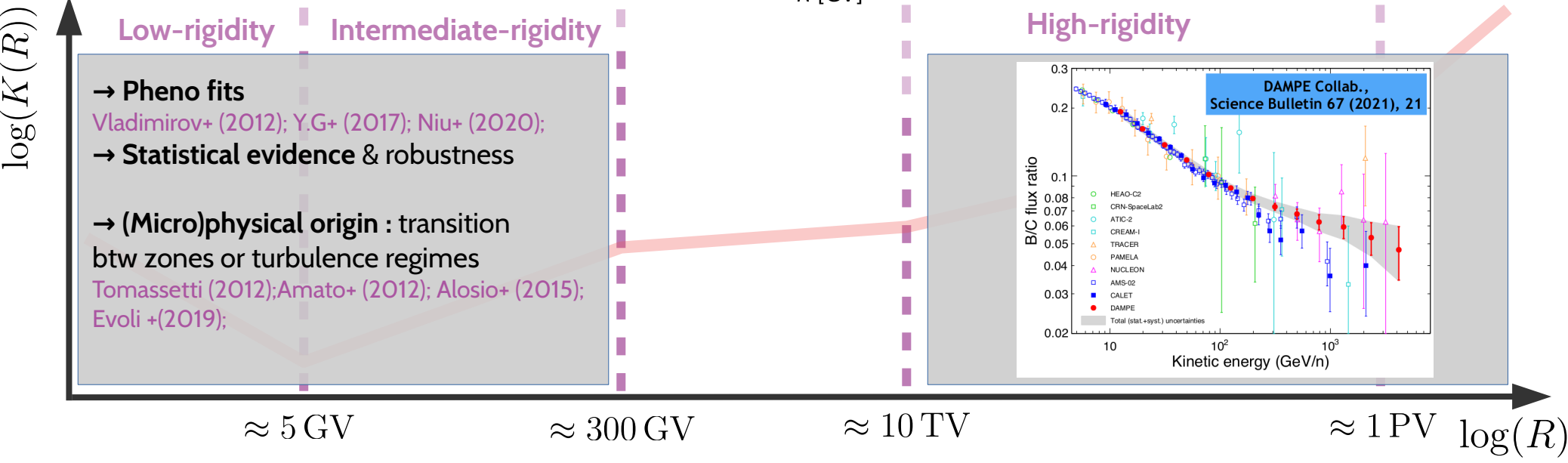
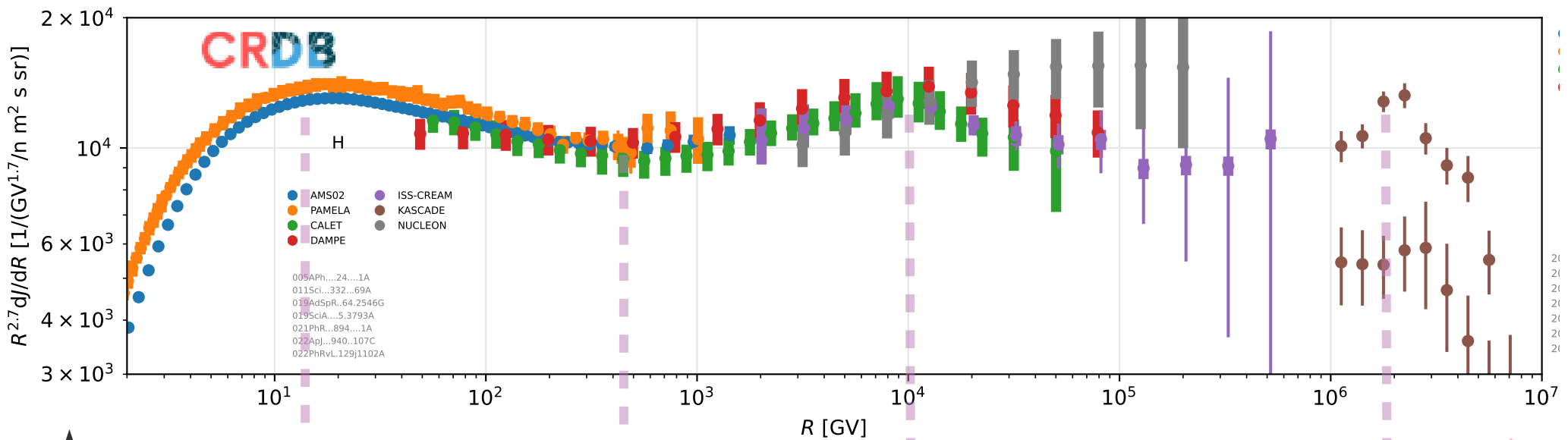
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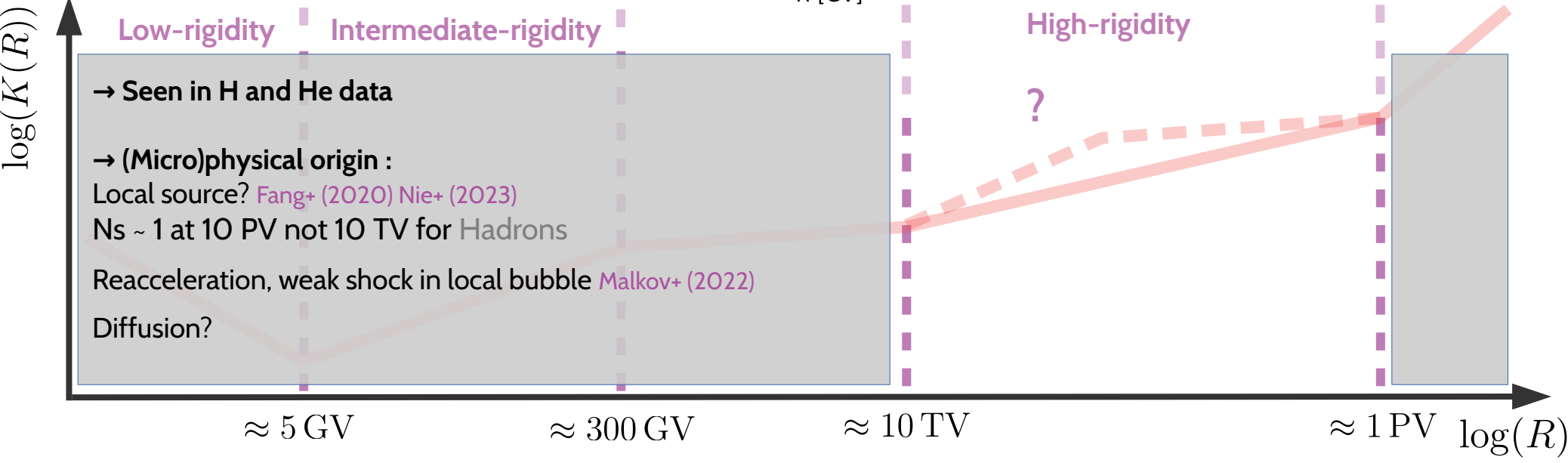
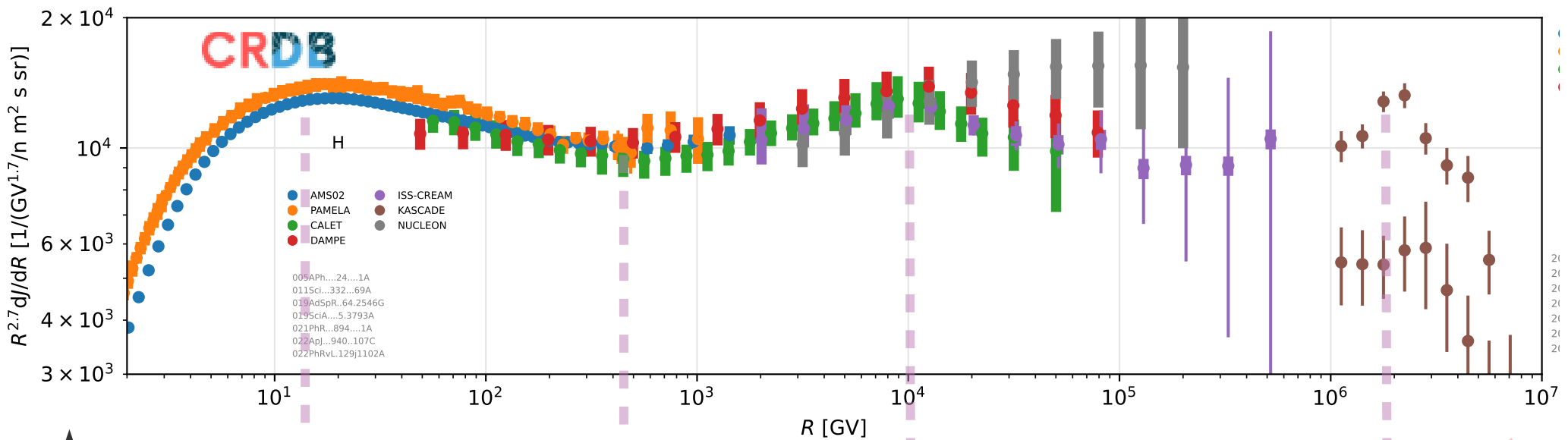
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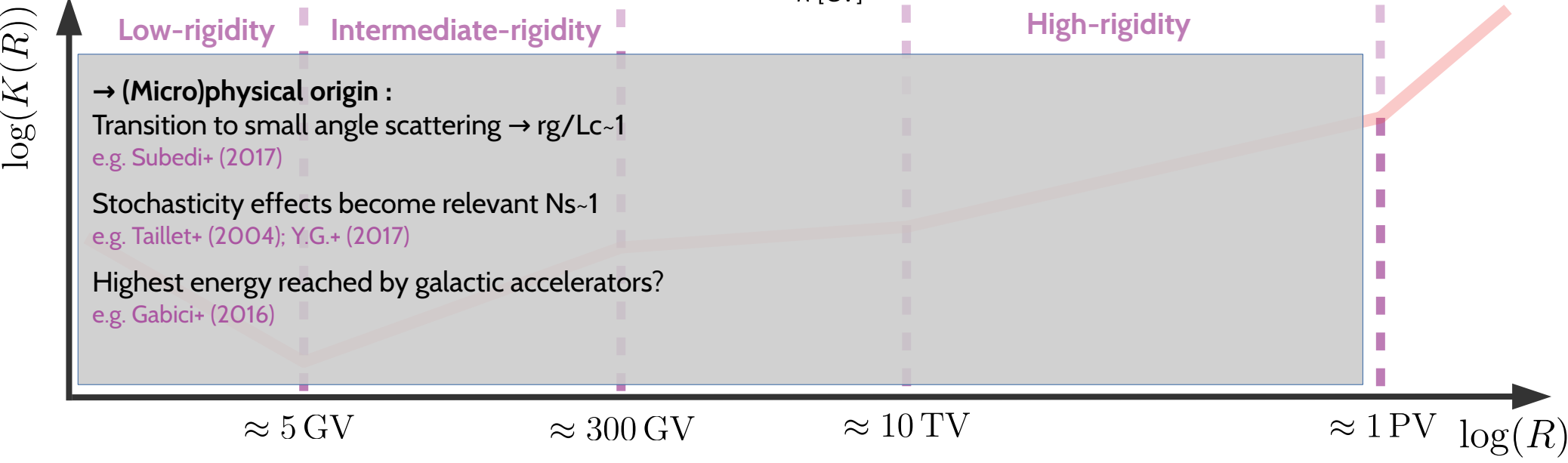
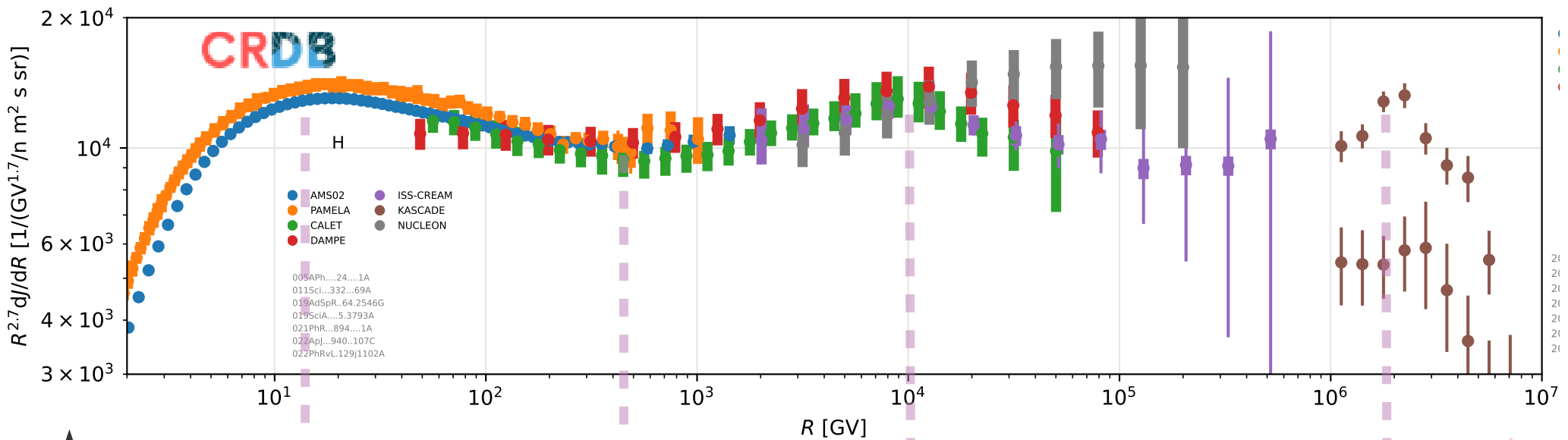
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Introduction : the precision era

Cosmic-ray transport

**Prediction of secondary (anti)particles**

What is next ?

# Prediction of secondary (anti)particles

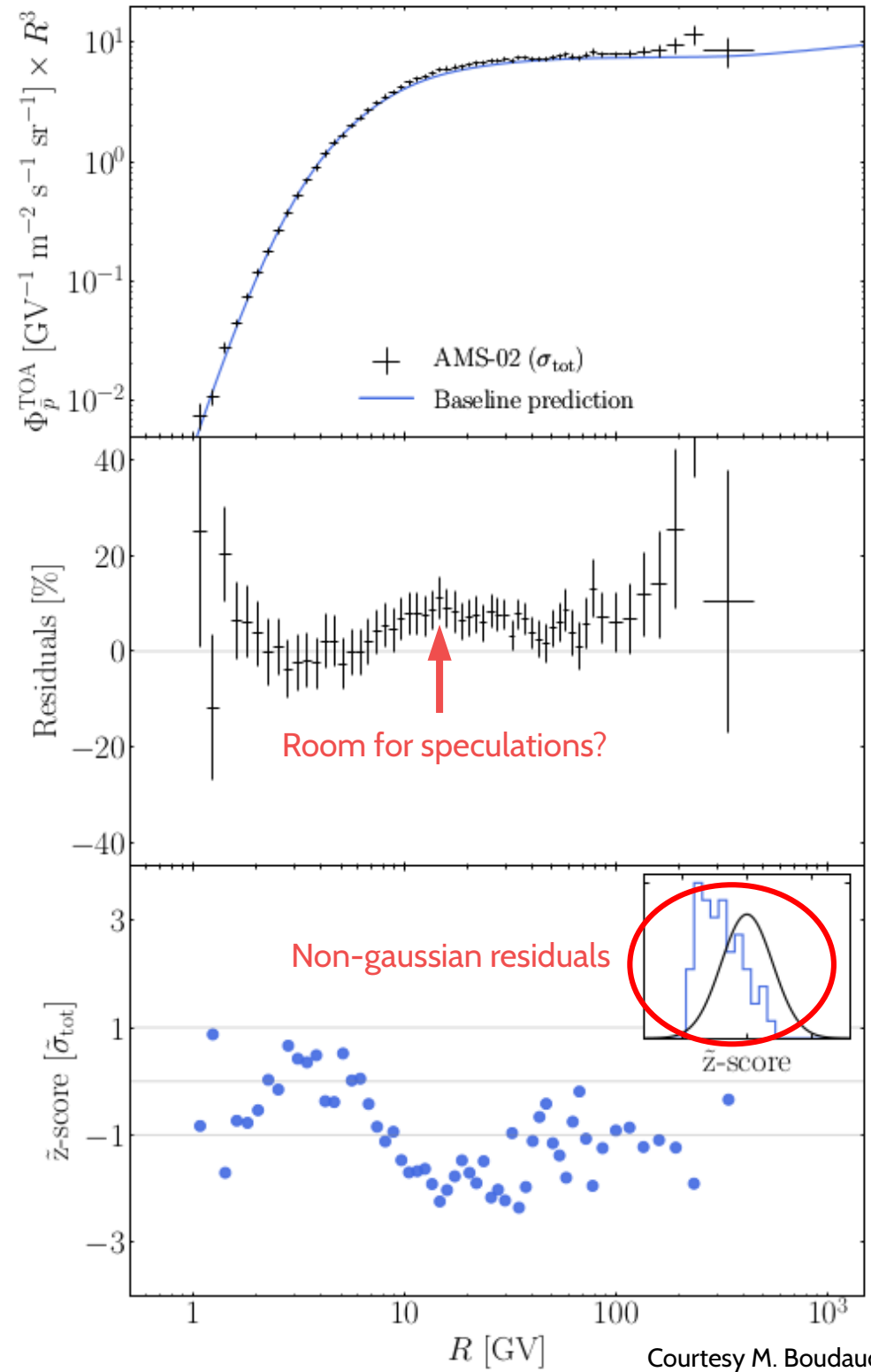
## A refined treatment of uncertainties

- Data: AMS02 antiproton from 2016
- Model: semi-analytical (USINE) (Maurin 2020)
- Comparison with data = discrepancy ~ few 10GV*

→ Chi2-test:

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

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

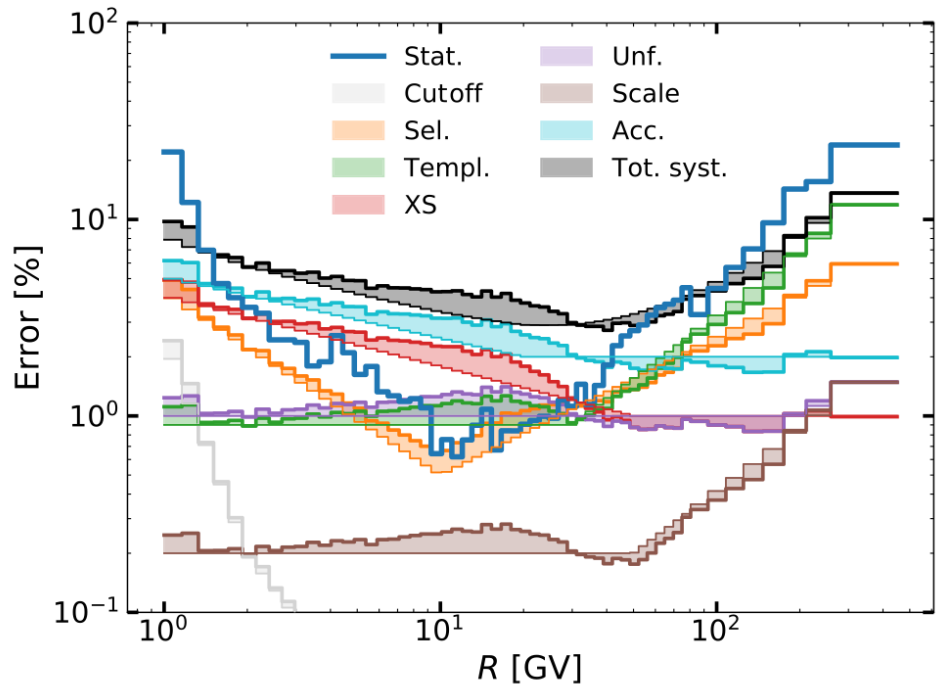


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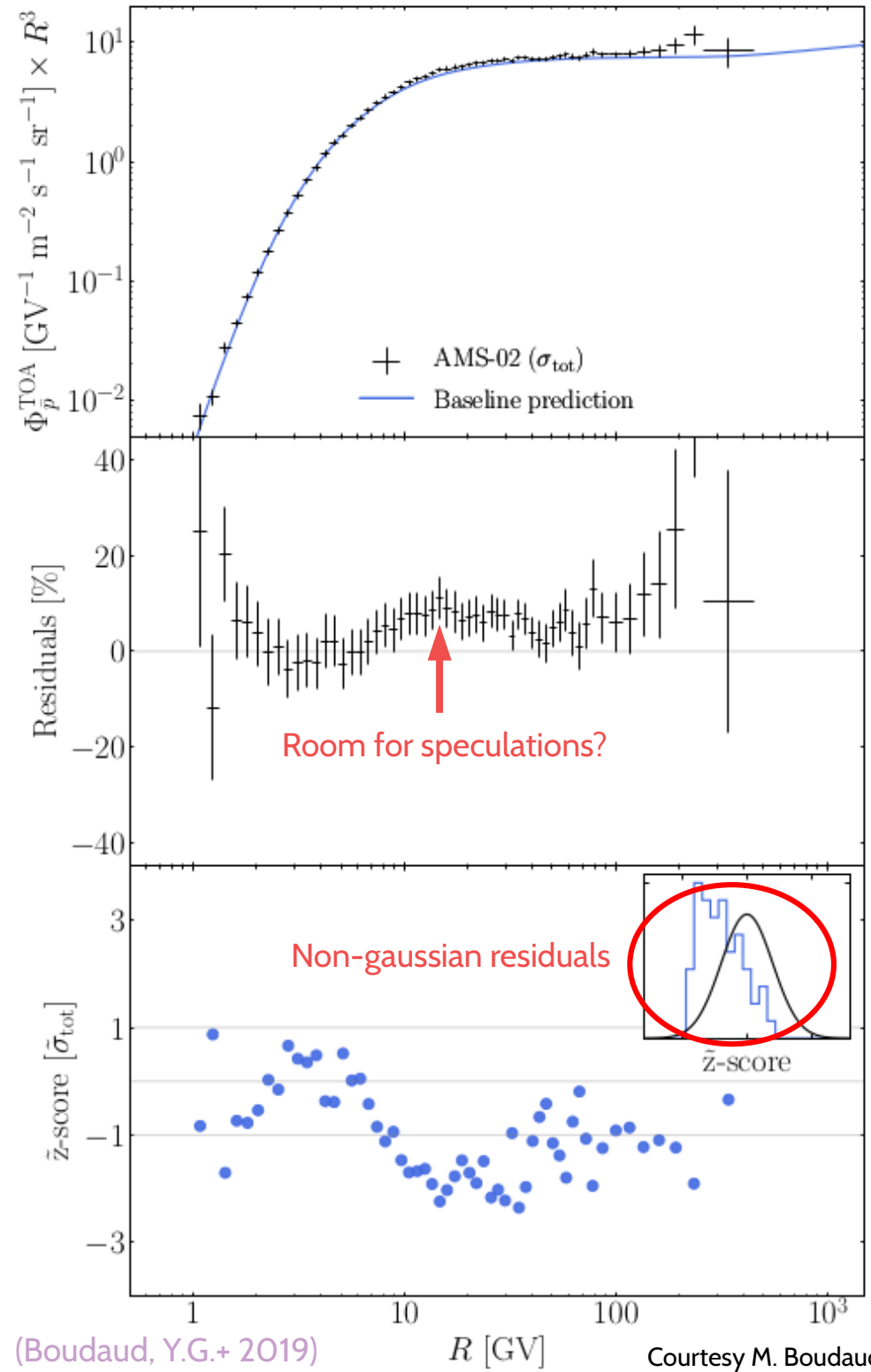
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*Small total error / Different correlation lengths  
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→ Covariance matrix estimated from detector info.

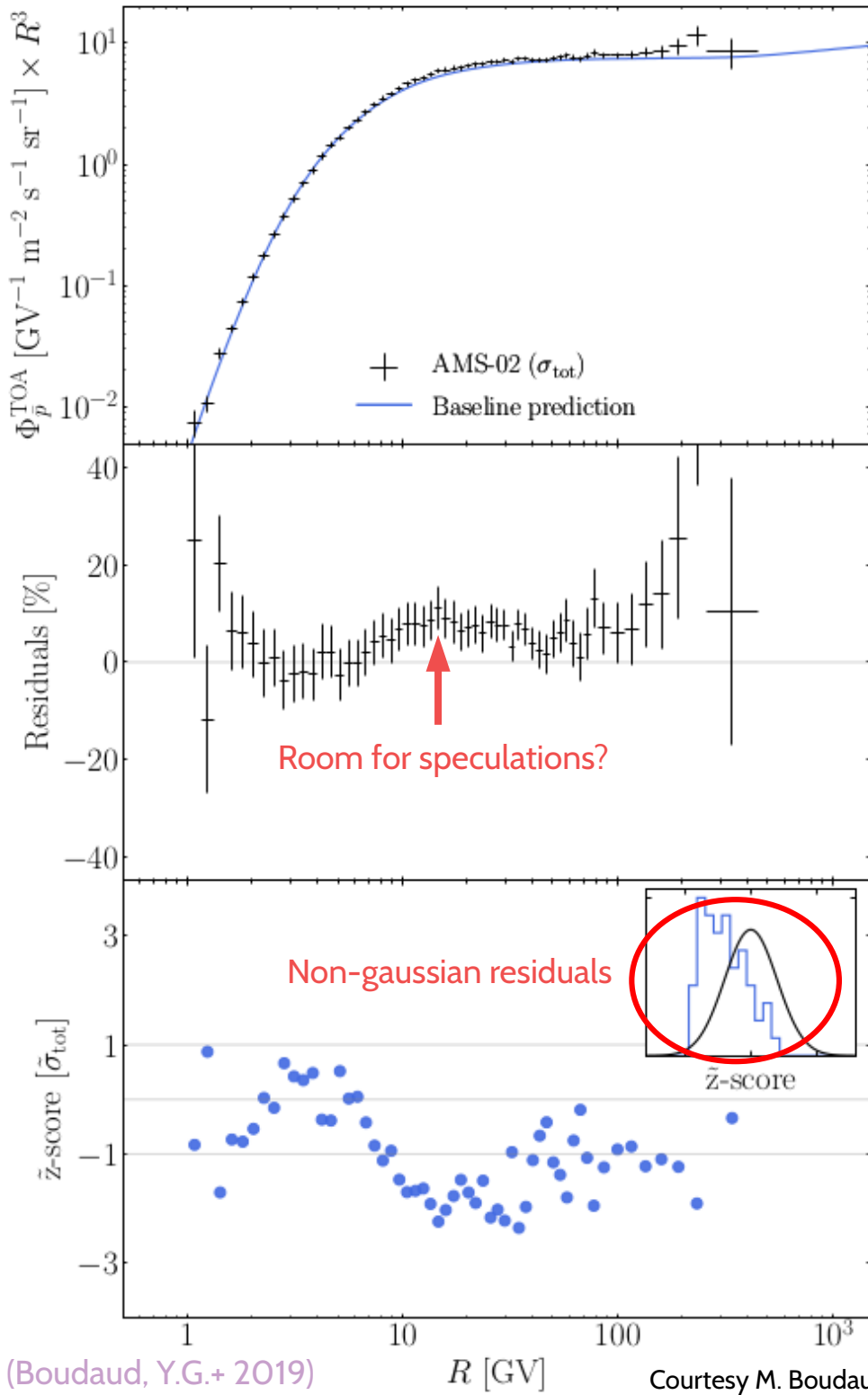


(Boudaud, Y.G.+ 2019) Courtesy M. Boudaud

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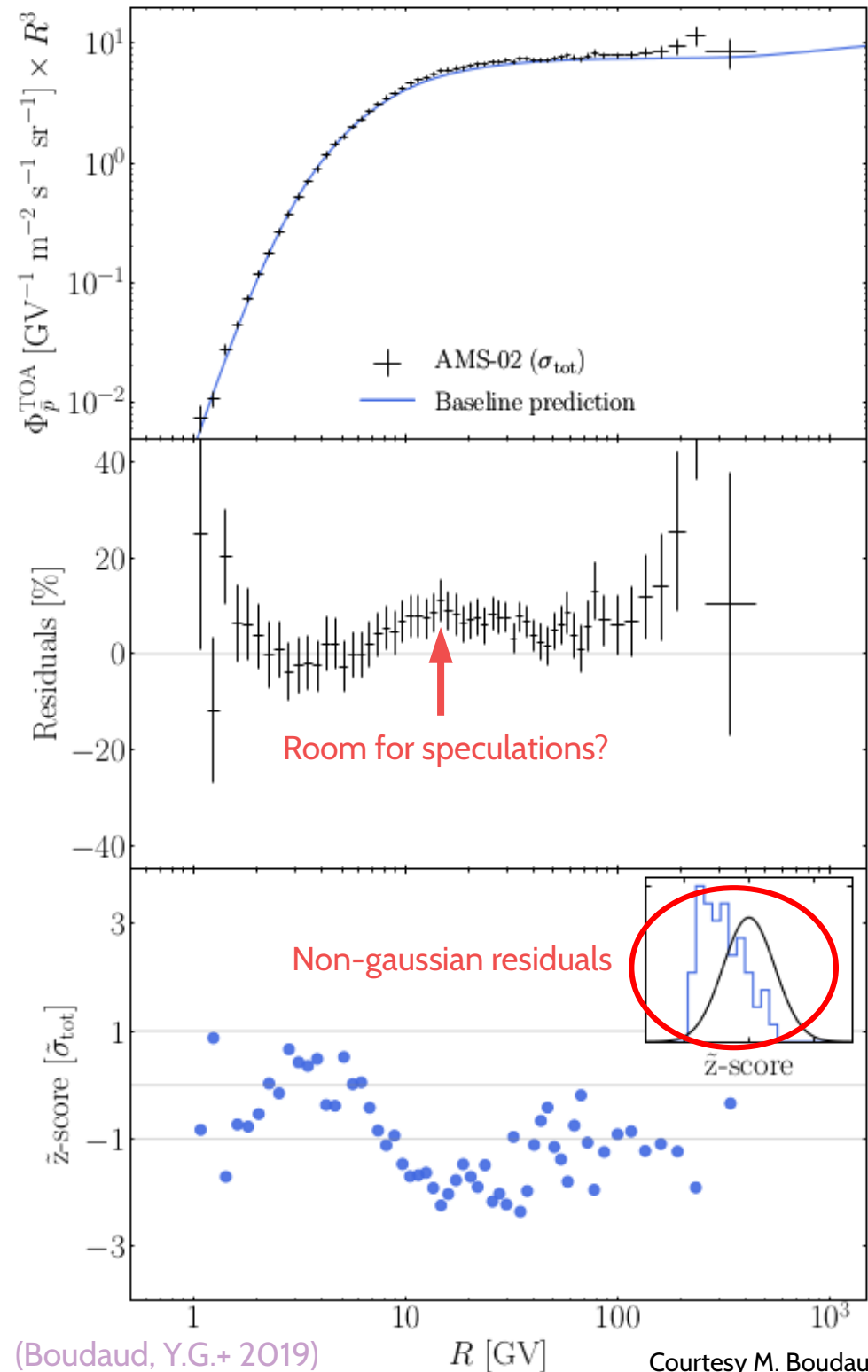
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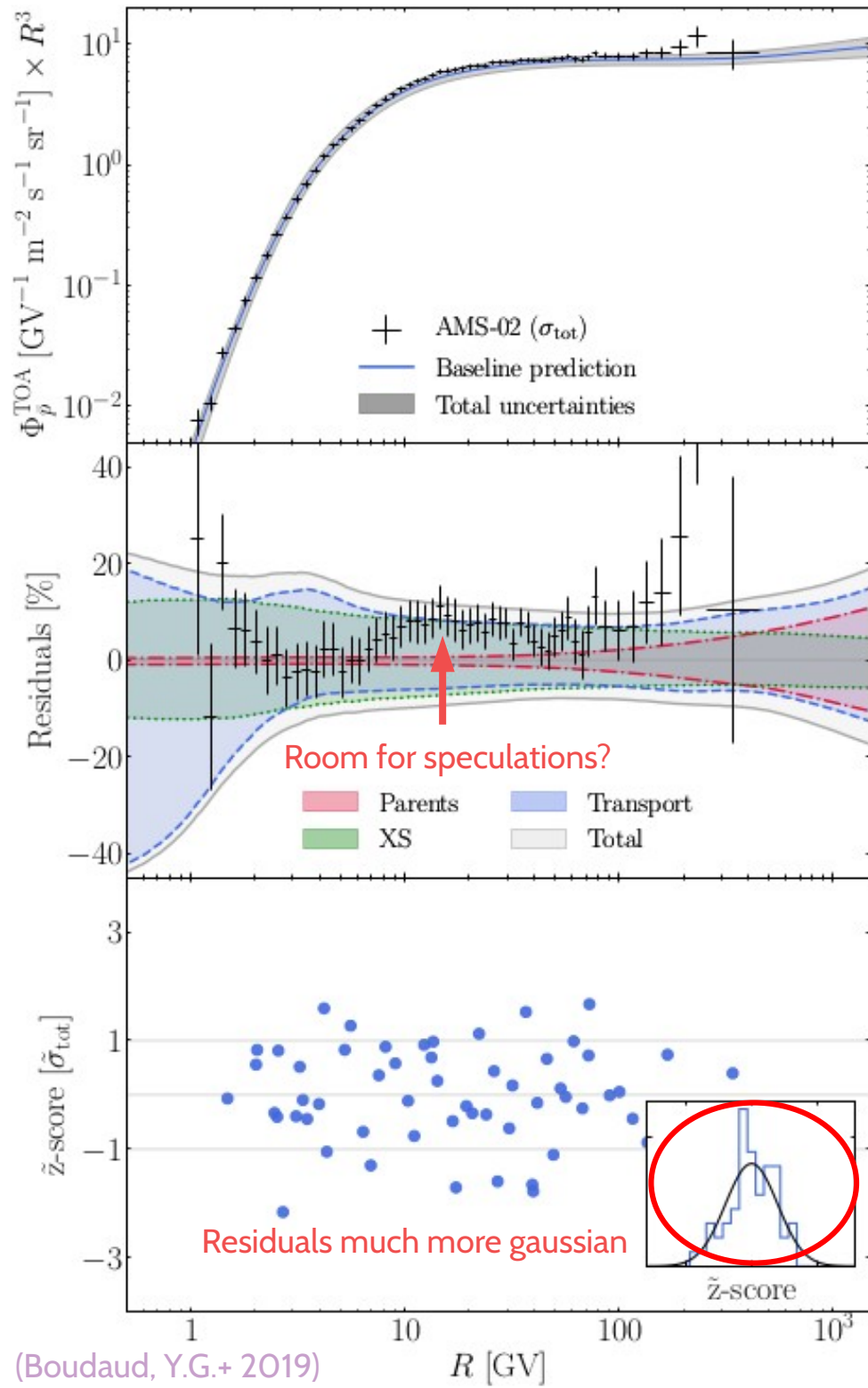




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# Prediction of secondary (anti)particles

## 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:

$$\chi^2 / \text{dof} = 0.77$$

$$p_{\text{value}} = 0.90$$

→ KS-test:

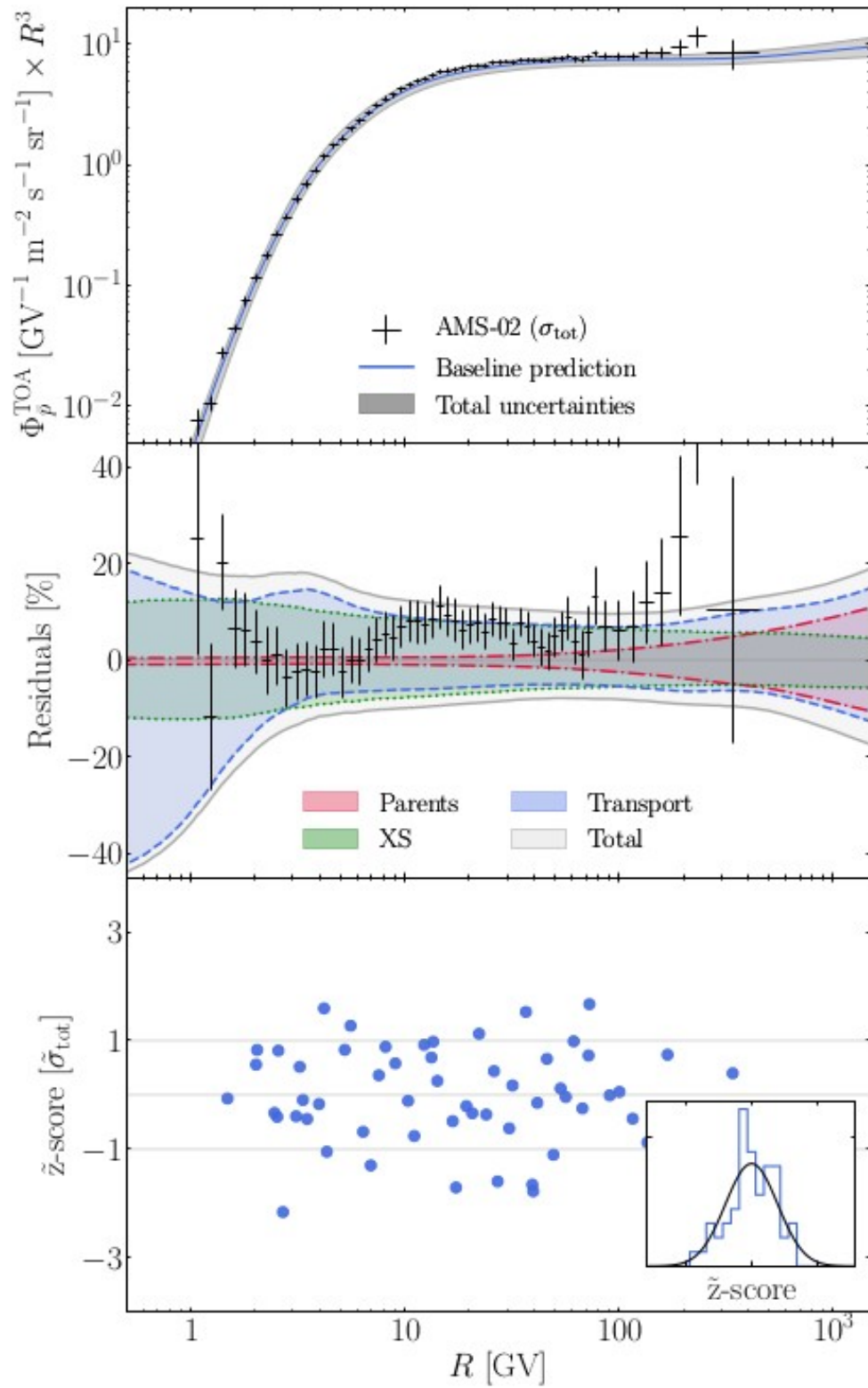
$$p_{\text{value}} = 0.27$$

AMS-O2 antiprotons are consistent with a secondary astrophysical origin

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

Before claiming excesses careful 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

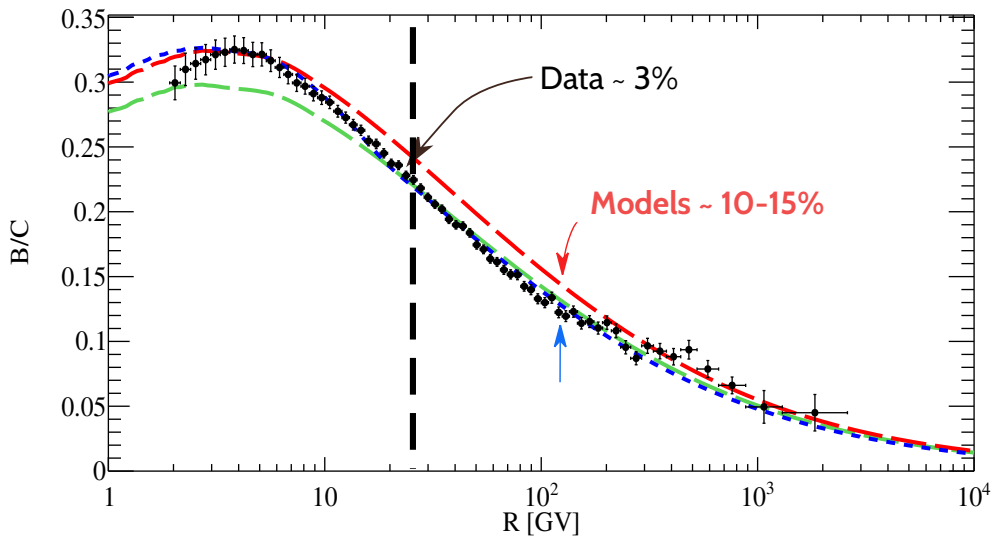
Cosmic-ray transport

Prediction of secondary (anti)particles

**What is next?**

## Critical role of fragmentation cross-sections

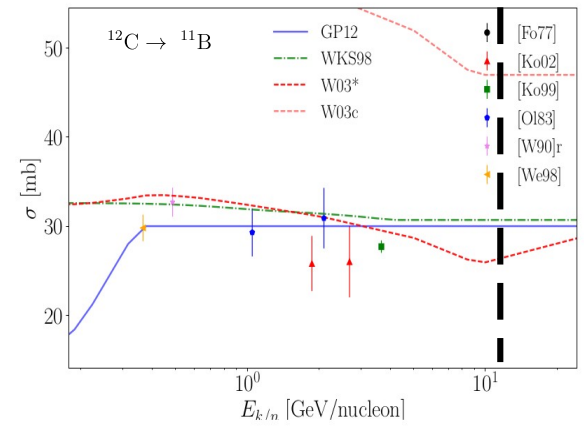
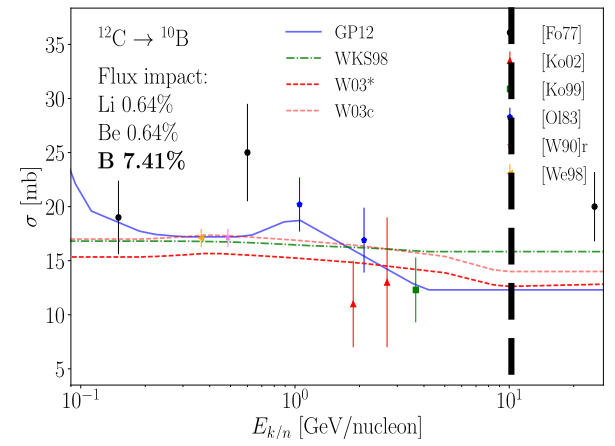
Models  $\propto \sigma(\text{C} + (\text{H}, \text{He}) \rightarrow \text{B})$



### Cross-sections status

- No/few data above 1GeV
- Flat extrapolation high-E
- Inconsistent data/models

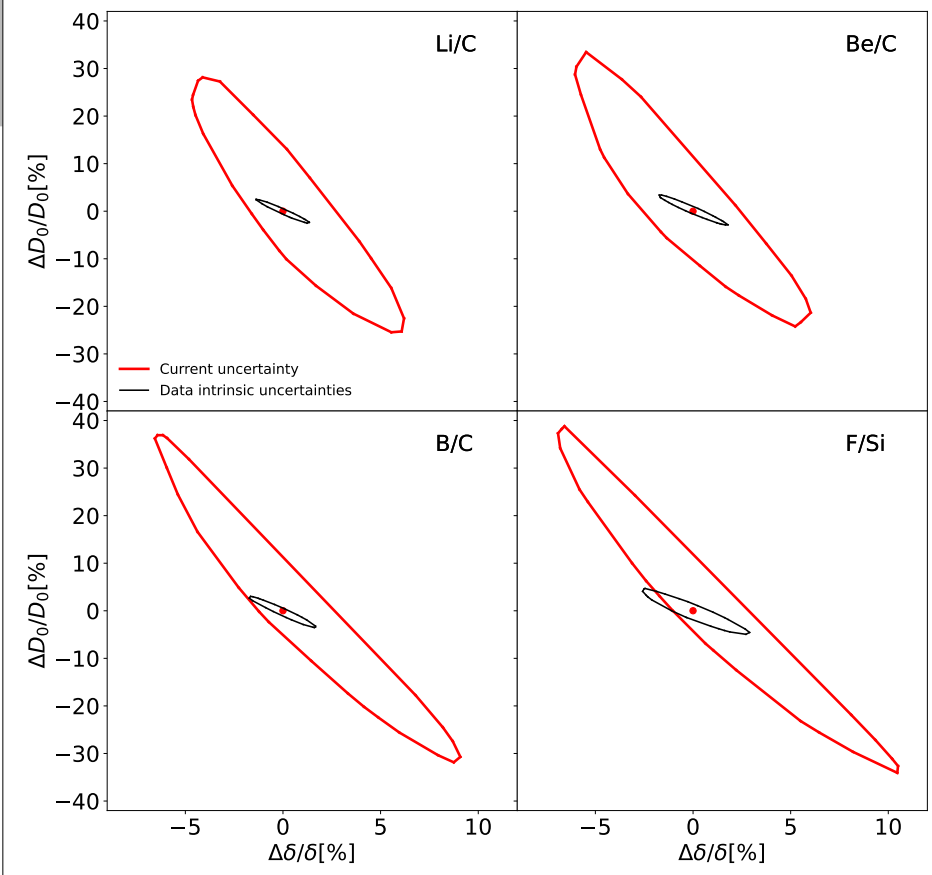
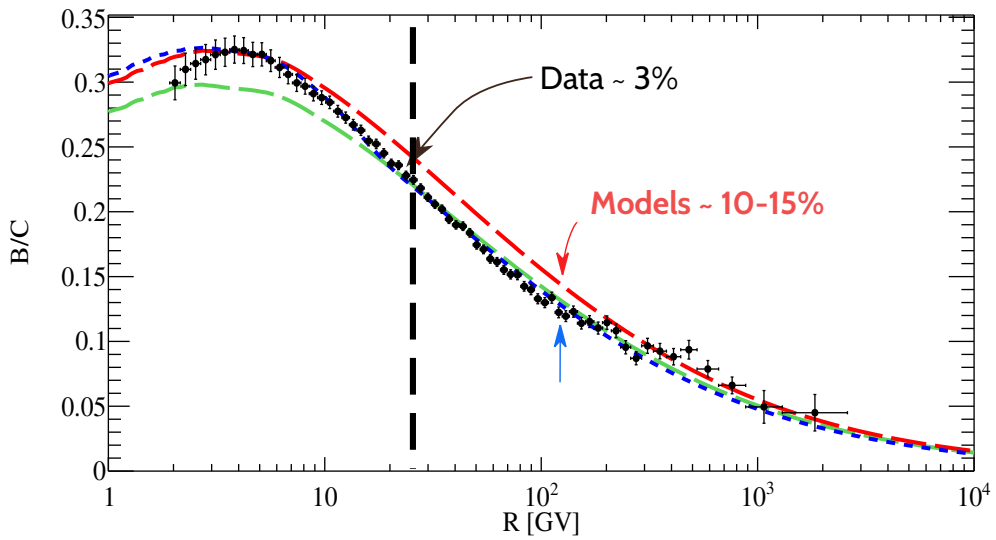
State of the art in Y.G.+ (2018)



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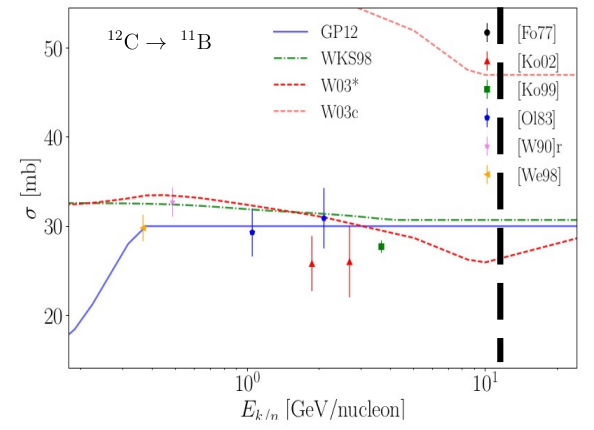
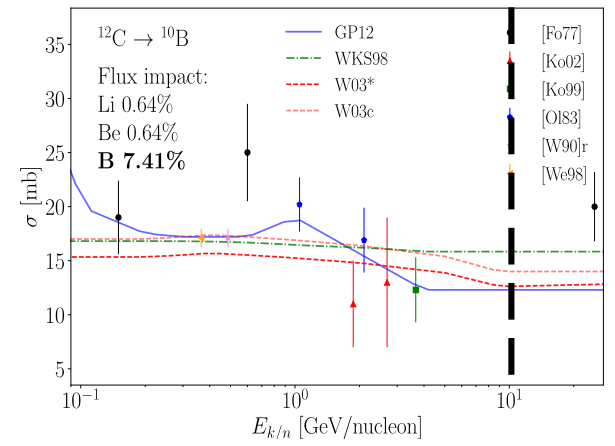
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Consequences on transport param.

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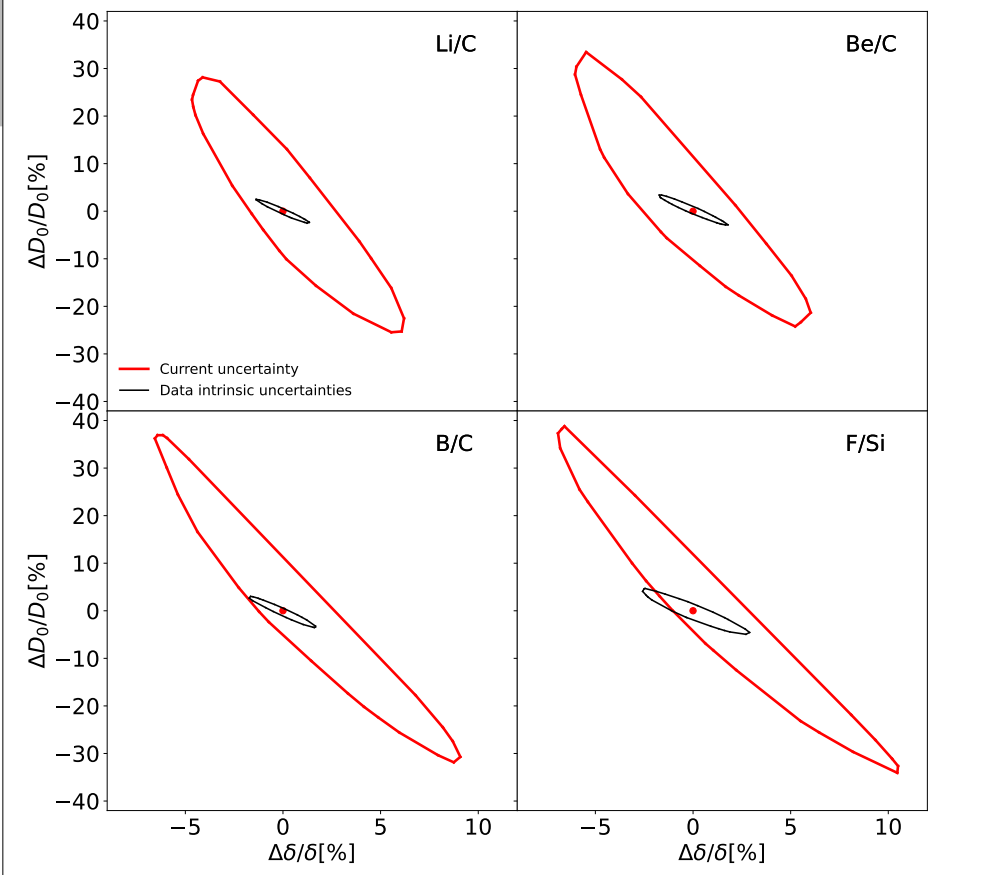
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Difficulty : more than 1000 reactions are involved ..

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

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

→ Quantifying the **improvements**:

- **Precise determination of transport parameters**
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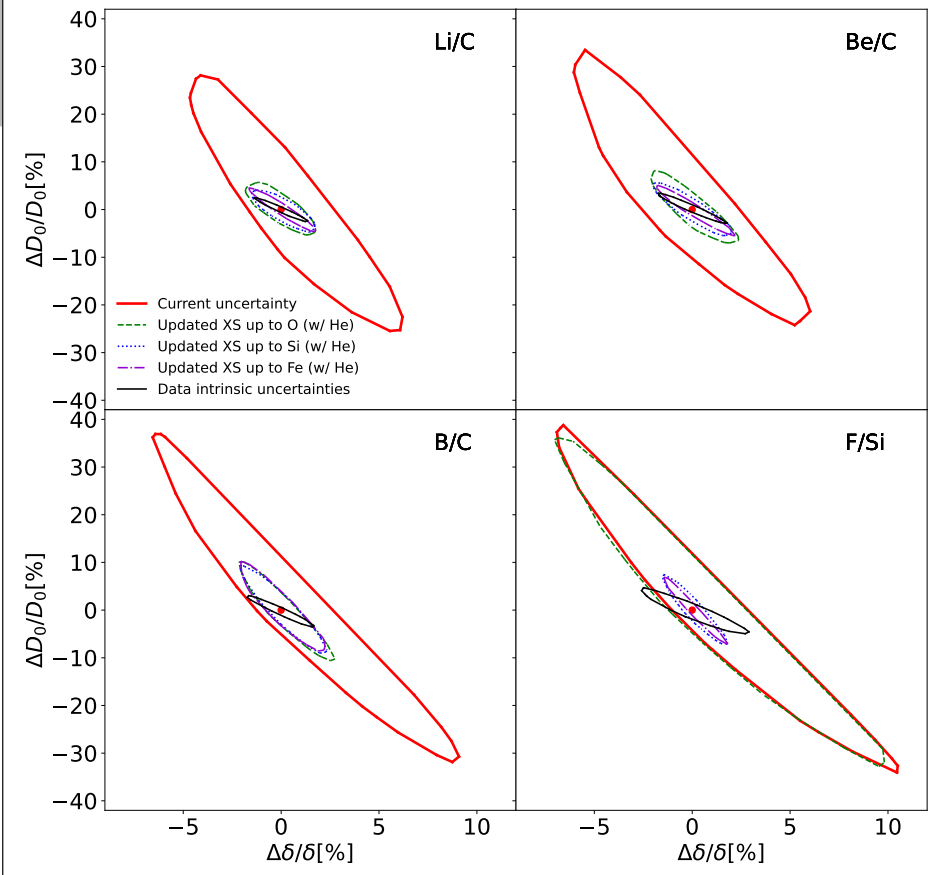
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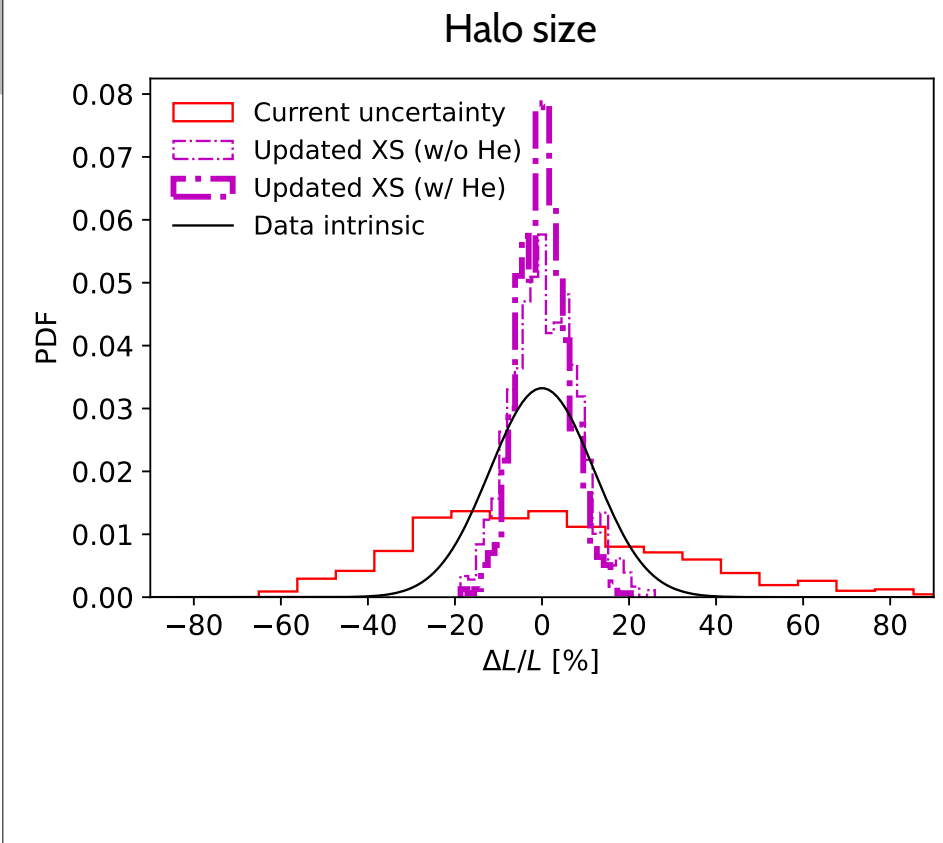
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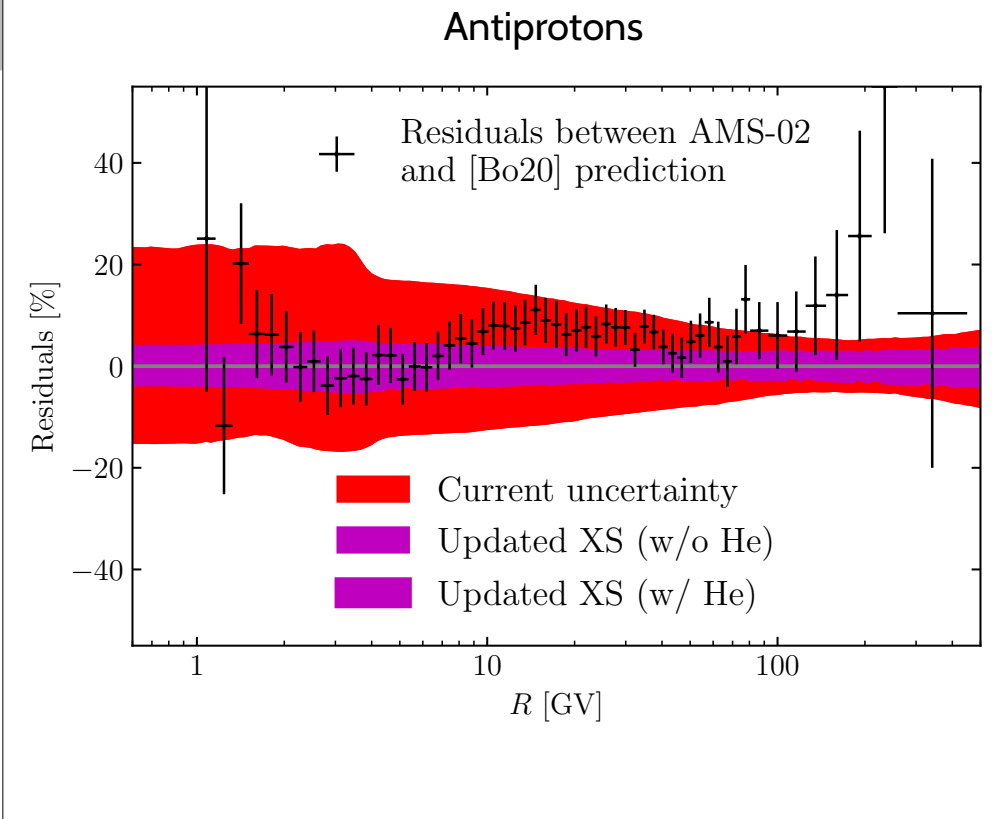
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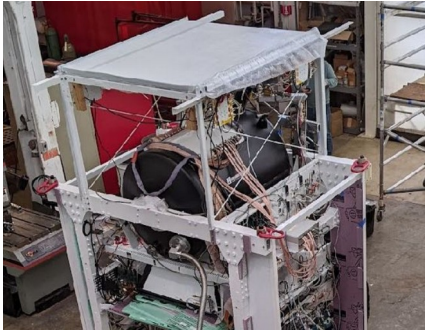


→ Effort has started for E=13.5 A GeV  
 Unger (NA61/SHINE Collab.) ICRC (2019)  
 Amin (NA61/SHINE Collab.) ICRC (2021/2023)

# What is next?

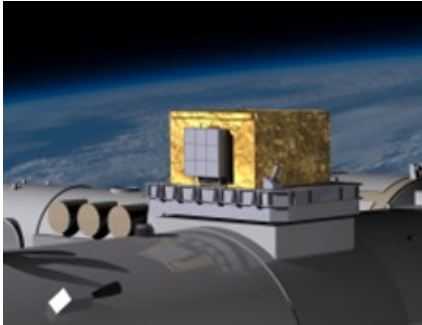
## Next generation experiments:

### HELIX



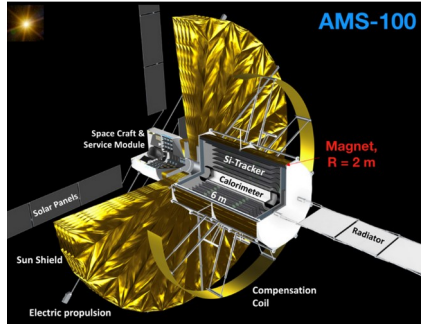
Park+ (2019)

### HERD



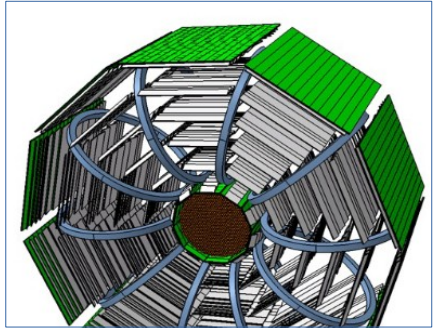
Mori+ (2022)

### AMS100



Shael+ (2019)

### ALADINO



Battiston+ (2021)

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

## 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, antiprotos, antideuterons?, antihelium?) still intriguing

## 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/subtle effects ( %! )  
- link the phenomenology with micro-physics

# What is next?

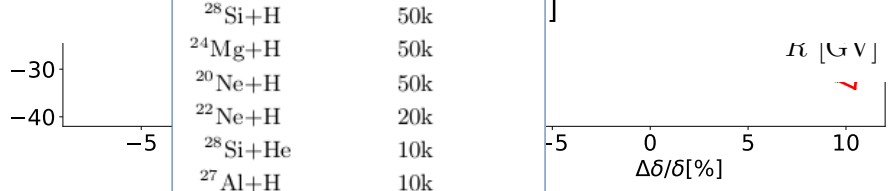
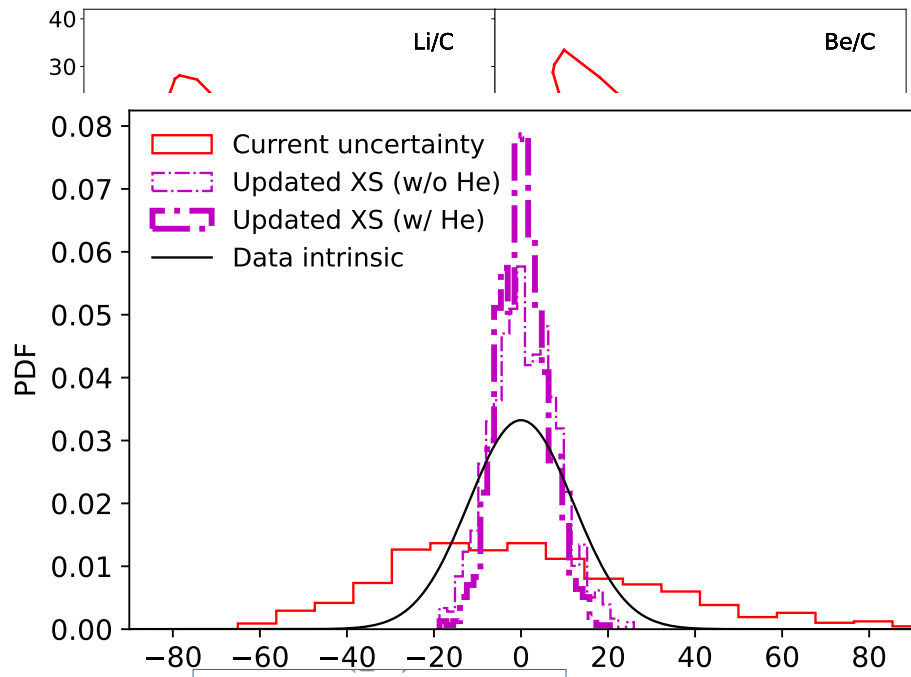
New measurements are required!

Difficulty : more than 1000 reactions are involved ..

reaction	$N_{int}$
$^{16}O+H$	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
$^7Li+H$	5k

$N(\leq O) = 1.9 \times 10^5$

- Selection rules [Y.G. + \(2018\)](#)
- Proposition of new measurements beam + target experiment (e.g. : NA61) [Y.G., Maurin, Moskalenko, Unger \(2023\)](#)
- Quantifying the **improvements**



$^{28}Si+H$	50k
$^{24}Mg+H$	50k
$^{20}Ne+H$	50k
$^{22}Ne+H$	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
$N(\leq Si) = 3.8 \times 10^5$	
$^{56}Fe+H$	30k
$^{56}Fe+He$	10k
$N(\leq Fe) = 4.2 \times 10^5$	

- Precise transport parameters
- Characterization of boundaries