Cosmic-ray propagation with a semi-analytical approach

Yoann Genolini

Annecy-Le-Vieux, FRANCE

Qui-Nhon, July 24th, 2017

Advertisement!

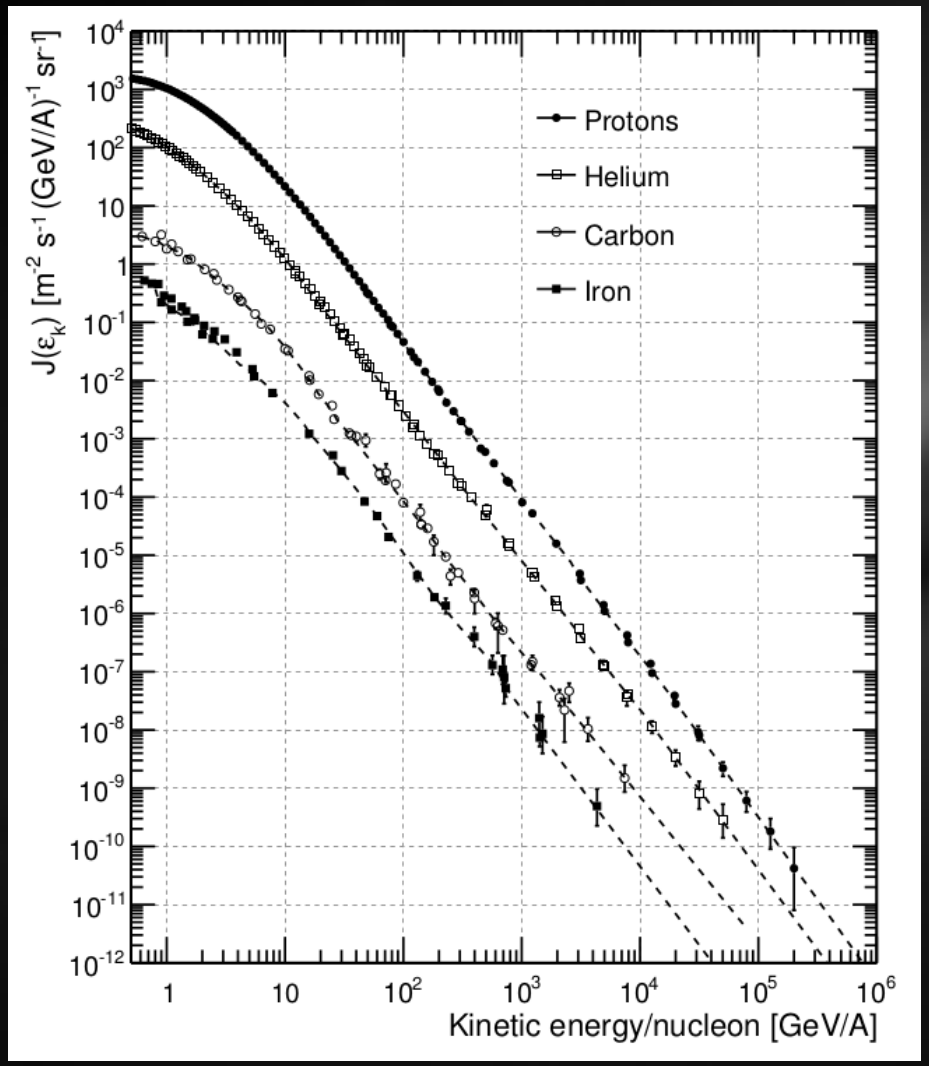
```
USINE V3.3

USAGE:
   ./bin/usine_run -l  => Local flux calculation, show only selected quantities
   ./bin/usine_run -m1 => List of fit-able parameters
   ./bin/usine_run -m2 => Chi2 minimisation on TOA fluxes (best chi2)
   ./bin/usine_run -t  => Text-user interface (interactive run)
```

USINE by David Maurin
Public release in october !

Some results of this presentation are directly output from USINE

Precision era for CRs

Composition of cosmic rays :



Particle	Fraction
protons	85%
helium nuclei	12.5%
heavier nuclei	1%
Electrons	1.5%

⇒ **Very small fraction of otherthings than proton and helium.**

Baldini, L. (2014). Space-Based Cosmic-Ray and Gamma-Ray Detectors: a Review. arXiv:1407.7631

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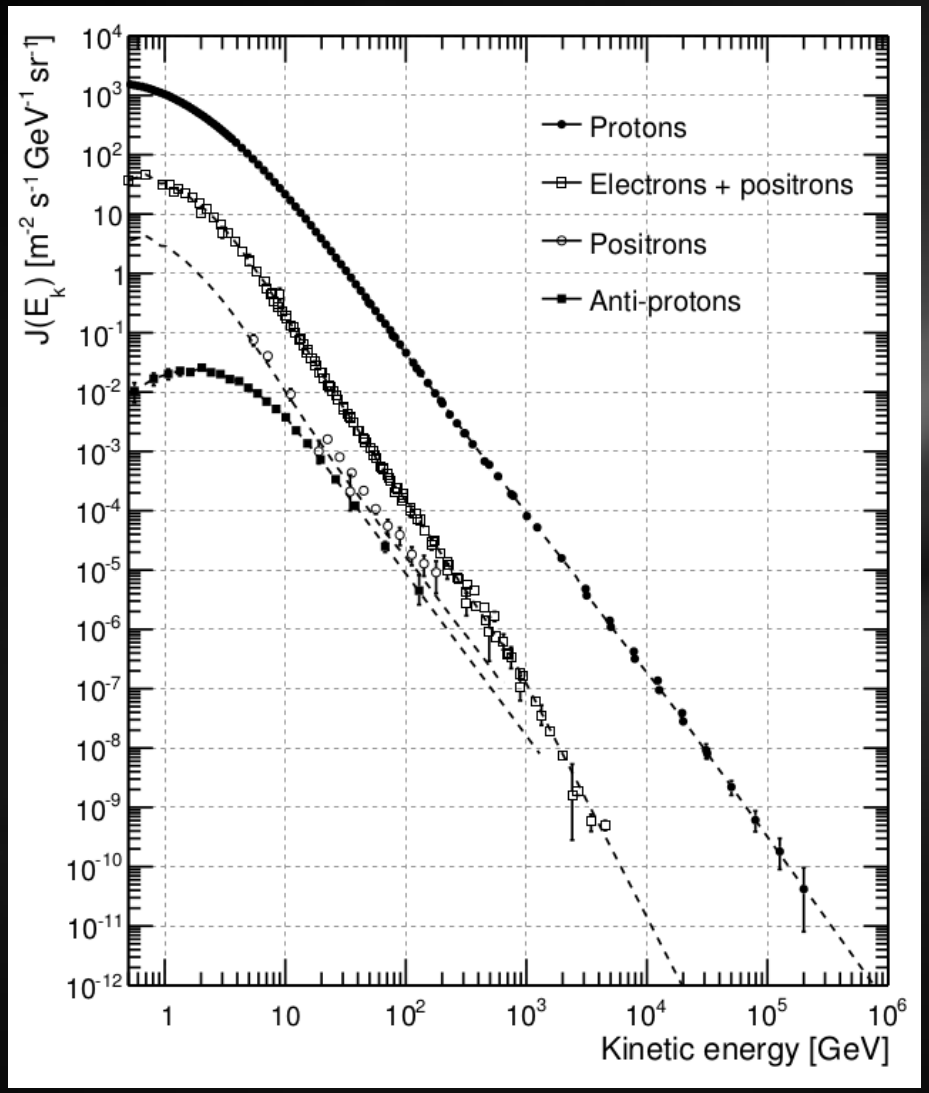

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⇒ **1** $e^+/10^3$ **Protons, 1** $\bar{p}/10^4$ **Protons !**

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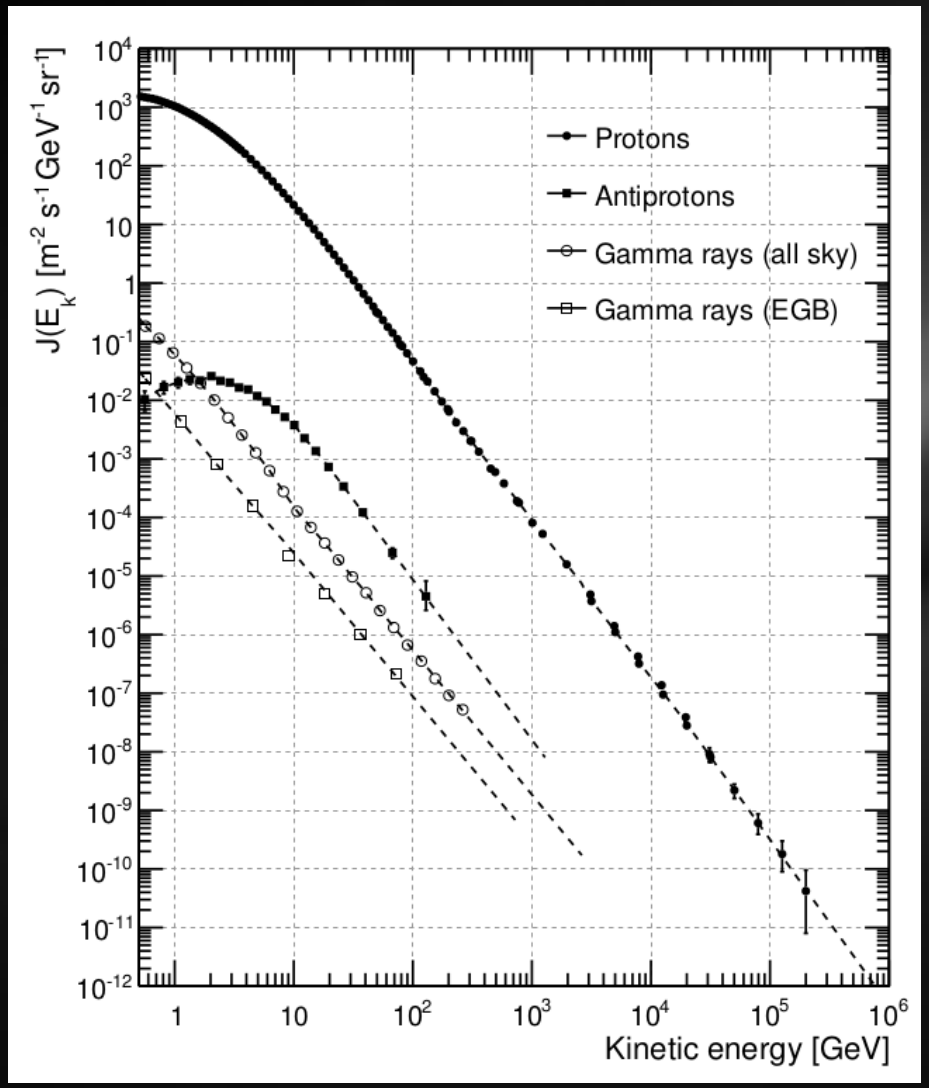

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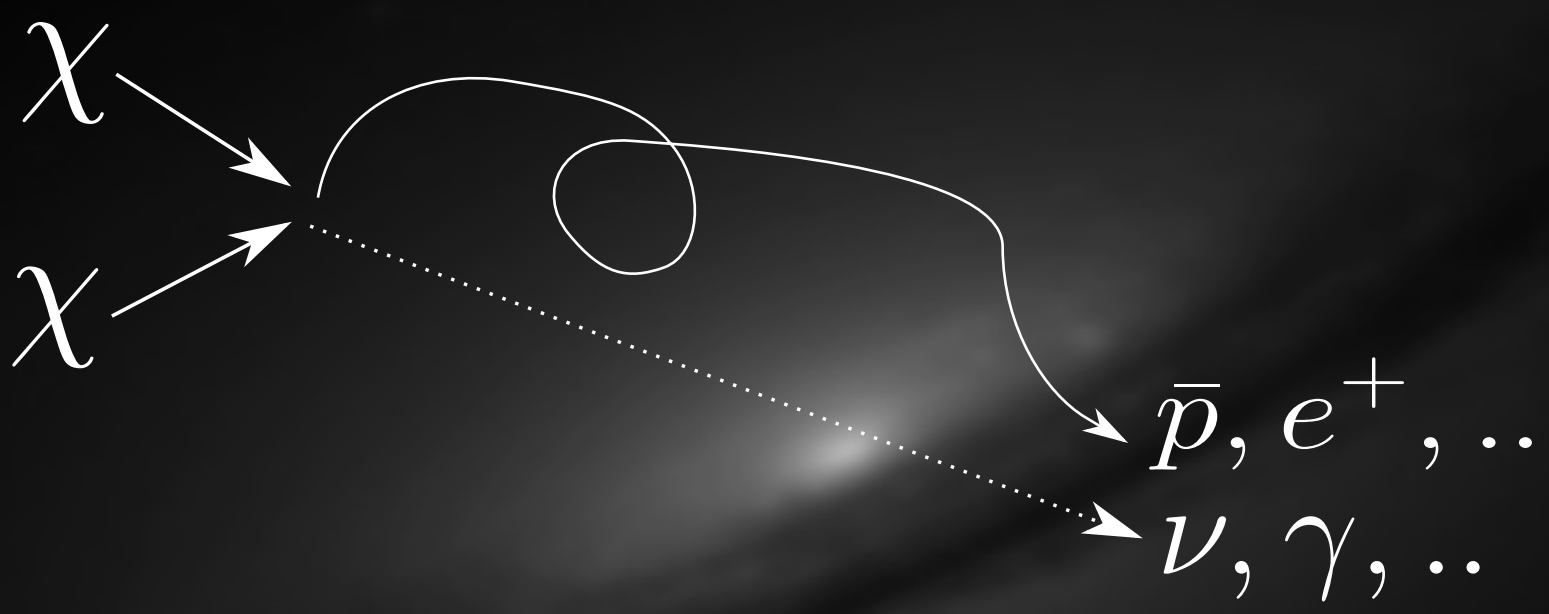
Indirect dark matter searches

The Principle :

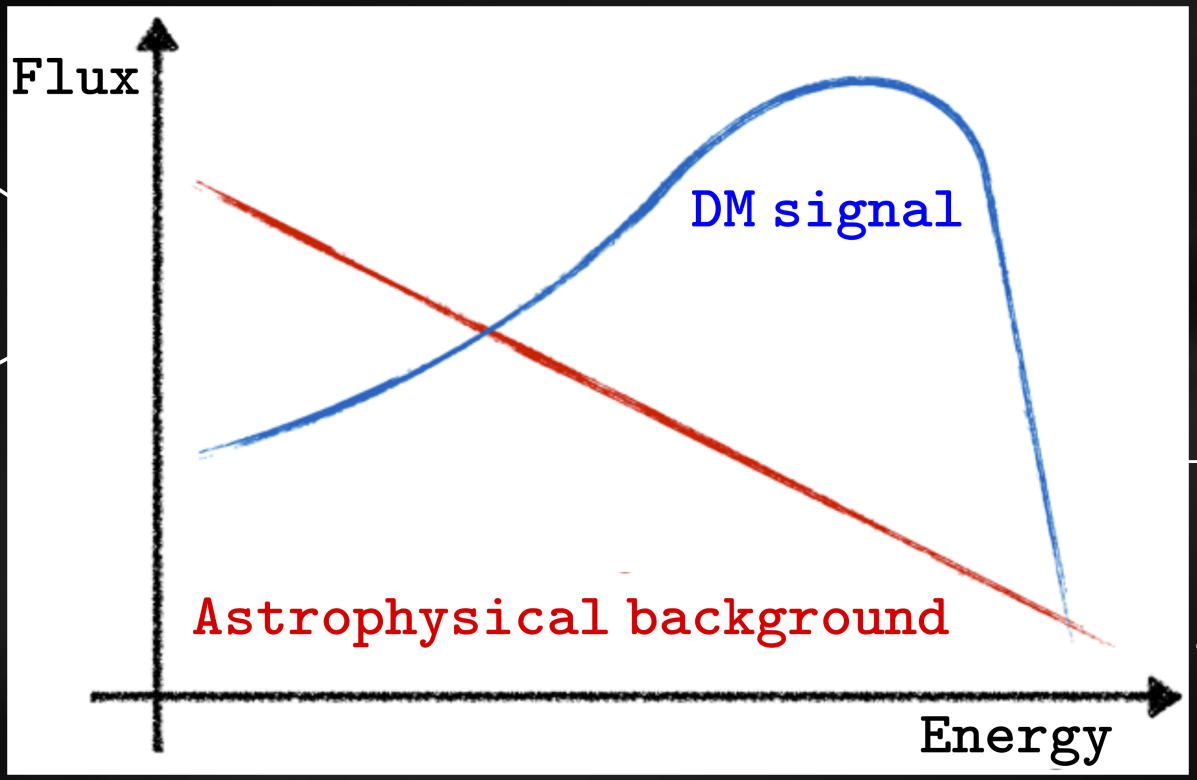


Indirect dark matter searches

The Principle :

χ

χ



$+$

$, \cdots$

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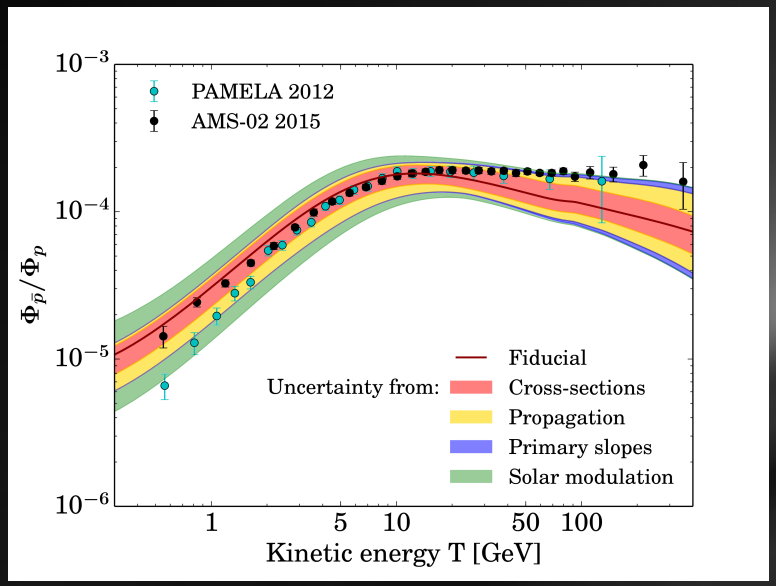
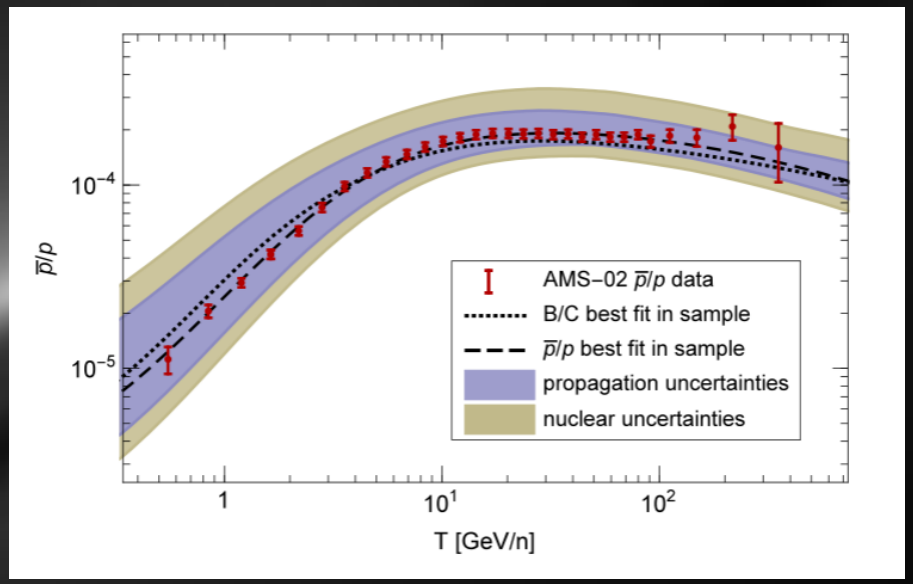
A fair evaluation of the atrophysical background is needed !

Example: the secondary antiprotons

Semi-analytical treatment agree...

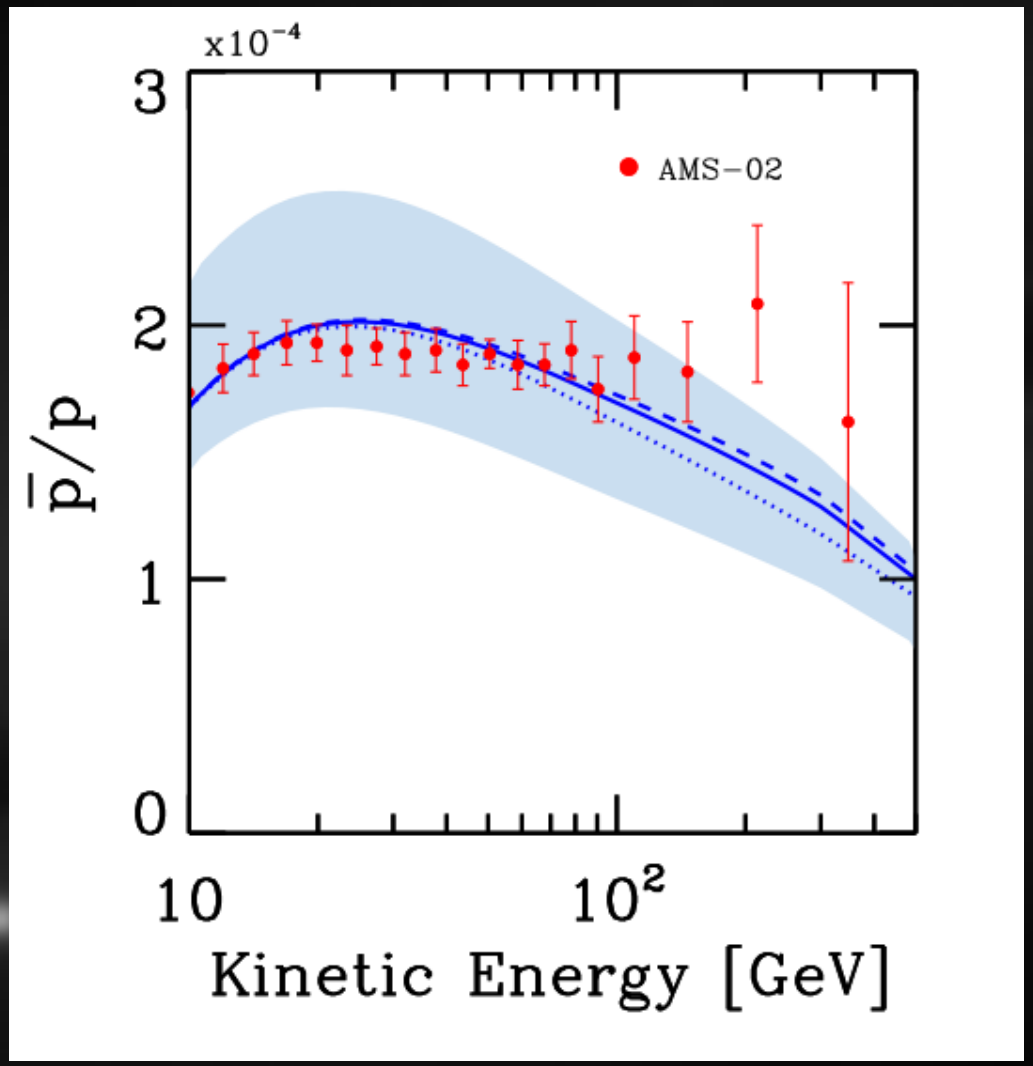




Giesen, G. et al, 2015 JCAP and *Kappl, R. et al, 2015 JCAP*

Example: the secondary antiprotons

...with numerical treatment !



Evoli, C. et al (2015). JCAP, 12, 039.

Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects

Introduction

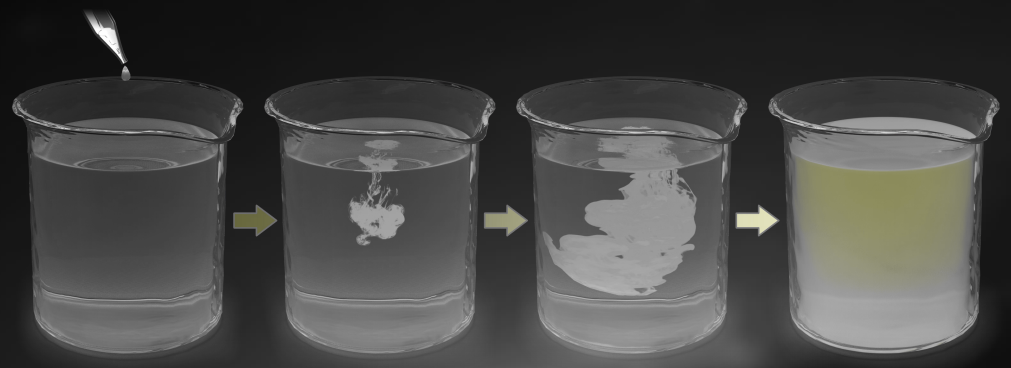
Semi-analytical approach

Hints for a new propagation paradigm?

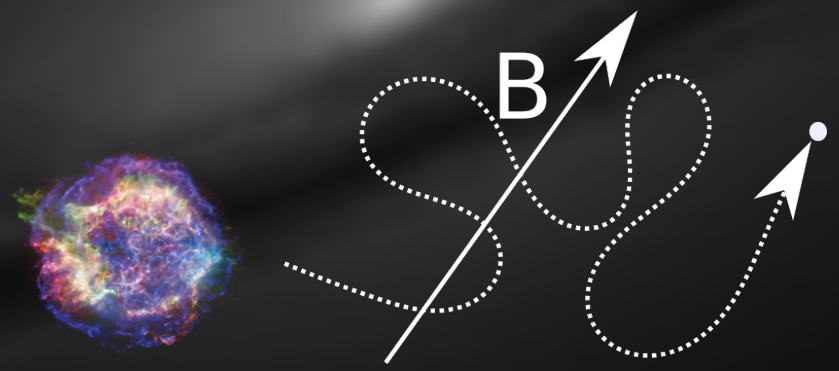
Conclusion & Prospects

The propagation of CRs

CRs diffuse in the turbulent magnetic field..

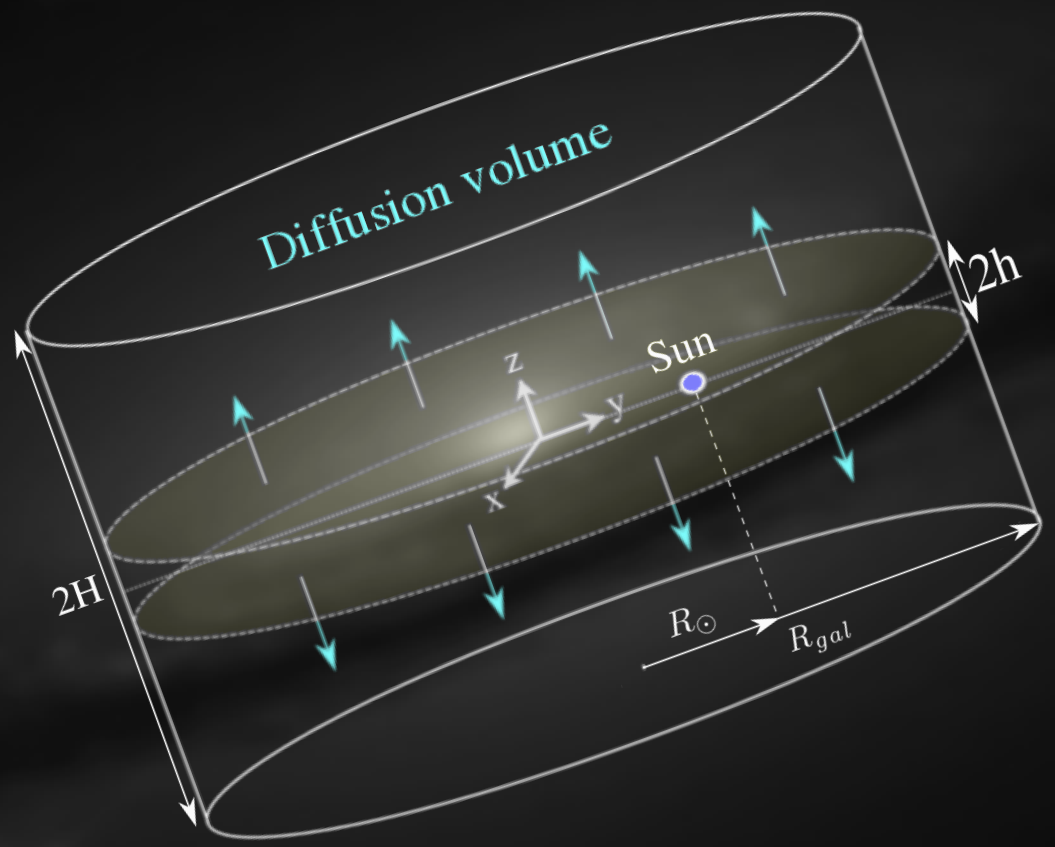


Diffusion



..and undergo a large variety of processes

The propagation of CRs



The propagation equation

- Source term $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$

$$\frac{\partial f_a}{\partial t}$$

$$= \boxed{q_a}$$

The propagation equation

- Source term $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$
- Diffusion in phase space $K = K_0 \beta R^{\delta}$

$$\frac{\partial f_a}{\partial t} - \nabla_{\boldsymbol{x}} \cdot (K \, \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}} \cdot (D \, \nabla_{\boldsymbol{p}} f_a)$$

$$= q_a$$

The propagation equation

- Source term $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$
- Diffusion in phase space $K = K_0 \beta R^{\delta}$
- Convection

$$\frac{\partial f_a}{\partial t} - \nabla_{\boldsymbol{x}} \cdot (K \, \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}} \cdot (D \, \nabla_{\boldsymbol{p}} f_a) + \boldsymbol{V_c} \cdot \nabla_{\boldsymbol{x}} f_a - \frac{1}{3} (\nabla_{\boldsymbol{x}} \cdot \boldsymbol{V_c}) p \frac{\partial f_a}{\partial p}$$

$$= q_a$$

The propagation equation

- Source term $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$
- Diffusion in phase space $K = K_0 \beta R^{\delta}$
- Convection
- Interaction with the ISM

$$\frac{\partial f_a}{\partial t} - \nabla_{\boldsymbol{x}}.(K\ \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}}.(D\ \nabla_{\boldsymbol{p}} f_a) + \boldsymbol{V_c}.\nabla_{\boldsymbol{x}} f_a - \frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{V_c}) p \frac{\partial f_a}{\partial p}$$

$$+ \nabla_{\boldsymbol{p}}(b(\boldsymbol{p}) f_a) + \sigma_a v_a n_{ISM} f_a$$

$$= q_a + \sum_{Z_\beta \geqslant Z_a}^{Z_{max}} \sigma_{b \to a} v_b n_{ISM} f_b$$

The propagation equation

- Source term $q_a \propto R^{-\alpha}$, $\alpha \in [2, 2.5]$
- Diffusion in phase space $K = K_0 \beta R^{\delta}$
- Convection
- Interaction with the ISM
- Radioactivity

$$\frac{\partial f_a}{\partial t} - \nabla_{\boldsymbol{x}}.(K\ \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}}.(D\ \nabla_{\boldsymbol{p}} f_a) + \boldsymbol{V_c}.\nabla_{\boldsymbol{x}} f_a - \frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{V_c}) p \frac{\partial f_a}{\partial p}$$

$$+ \nabla_{\boldsymbol{p}}(b(\boldsymbol{p}) f_a) + \sigma_a v_a n_{ISM} f_a + \frac{f_a}{\tau_a}$$

$$= q_a + \sum_{Z_\beta \geqslant Z_a}^{Z_{max}} \sigma_{b \to a} v_b n_{ISM} f_b + \frac{f_b}{\tau_b}$$

Simplifications of the equation

Our motto..

Reduce the computing time without loosing the physics!

Observable ?

$$\psi(E, \boldsymbol{r}, t)$$

At the Earth **Now!**

Simplifications by studying the time scales of the processes at stake

and / or

1 st

Neglect terms in the equation

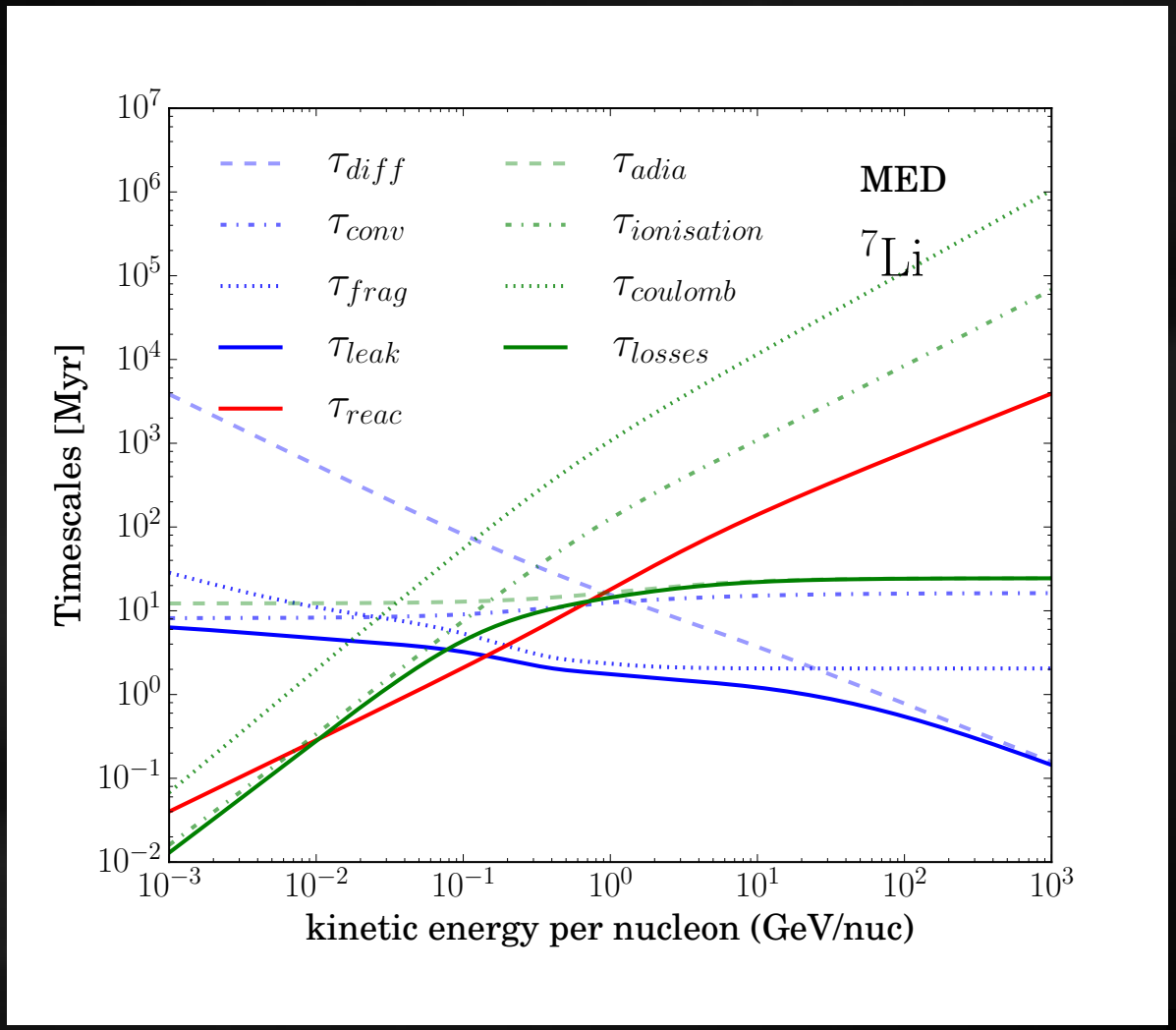
2 nd

Geometrical assumptions based on the typical lenght probed by CRs

Both are energy dependent!

Timescales of propagation processes

^{7}Li – ^{12}C – ^{56}Fe



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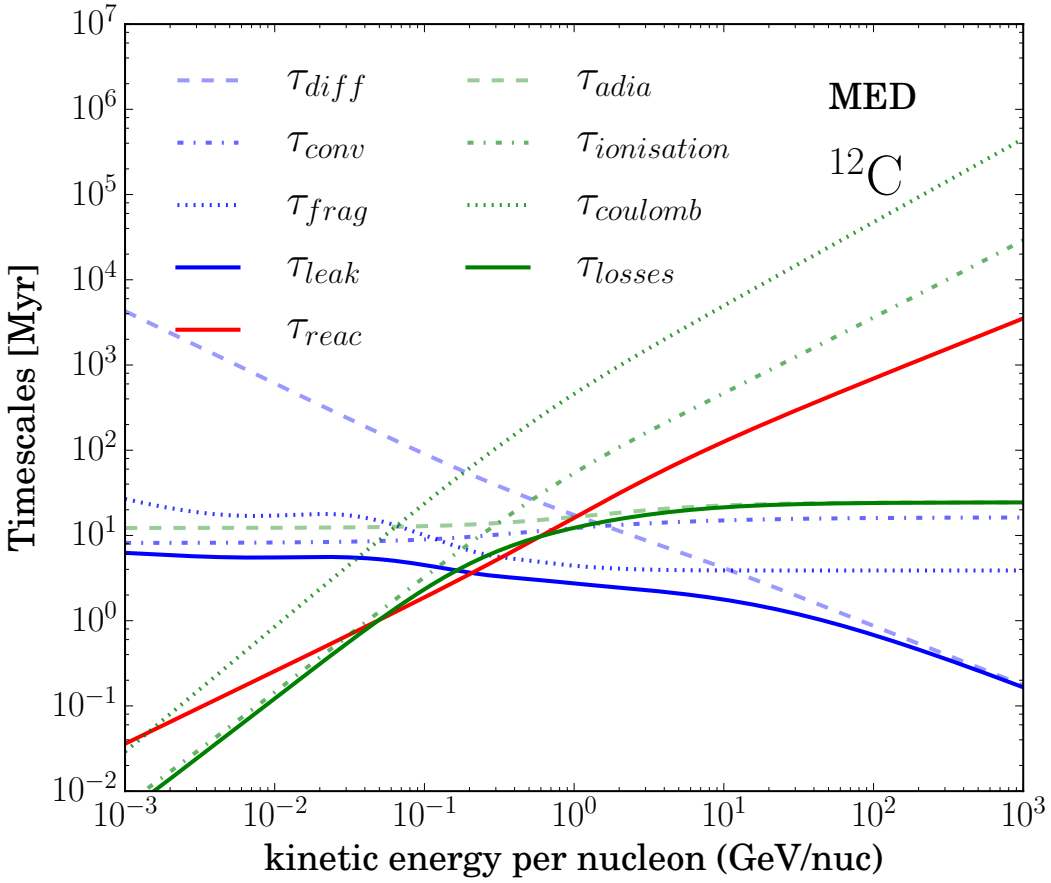

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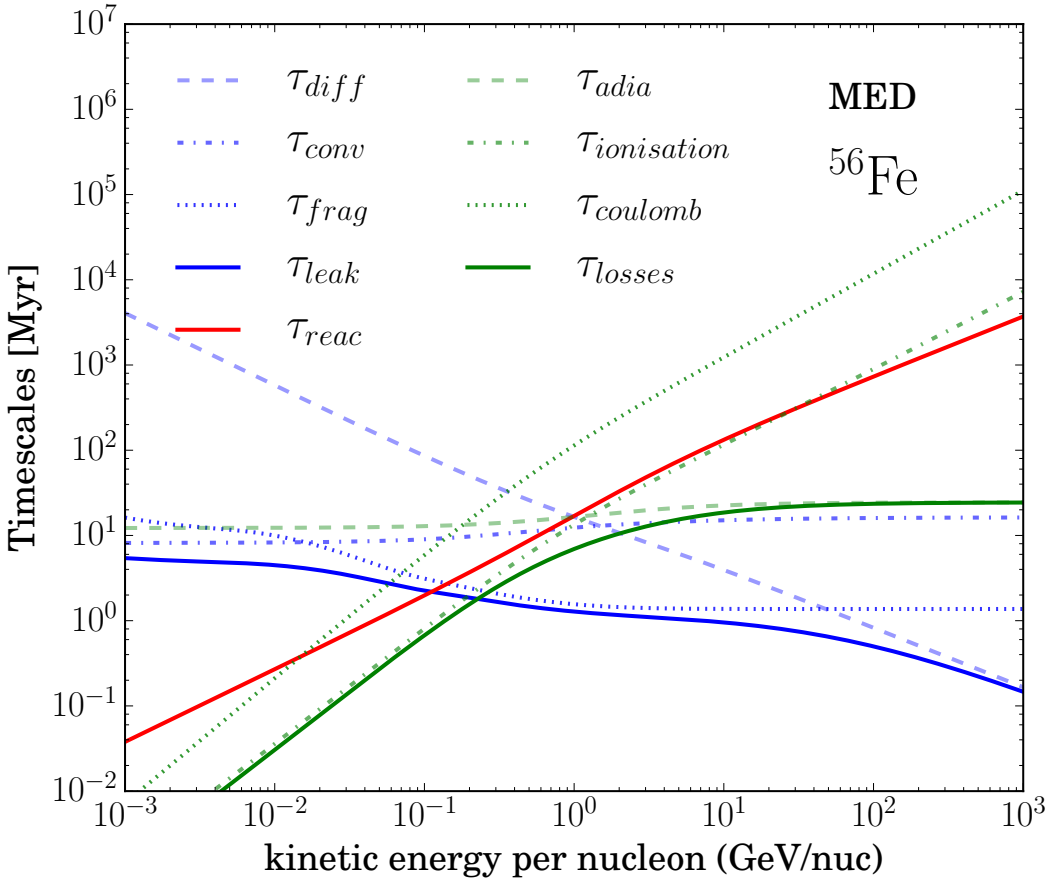
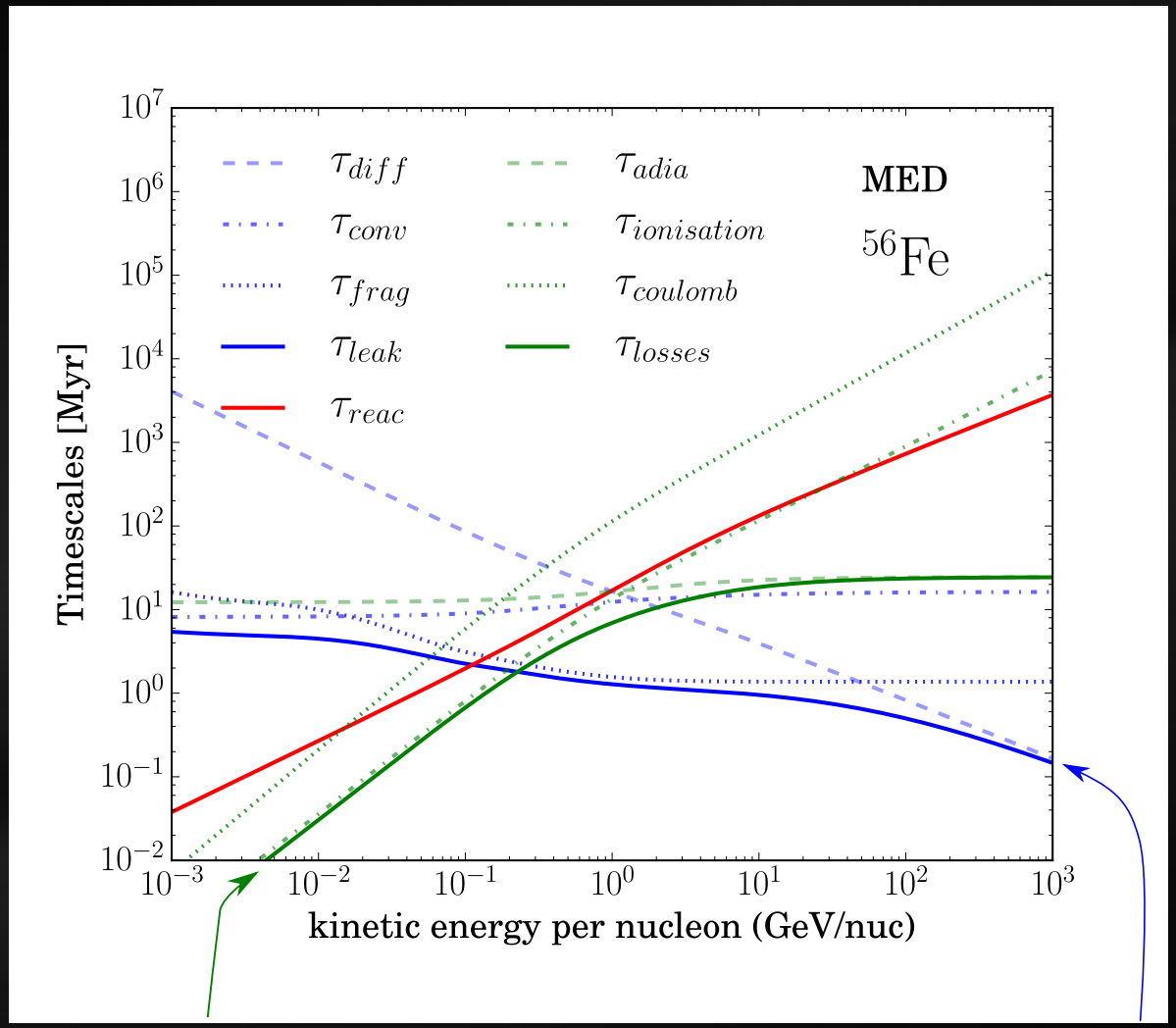


1st Neglect terms in the equation

^{7}Li – ^{12}C – ^{56}Fe



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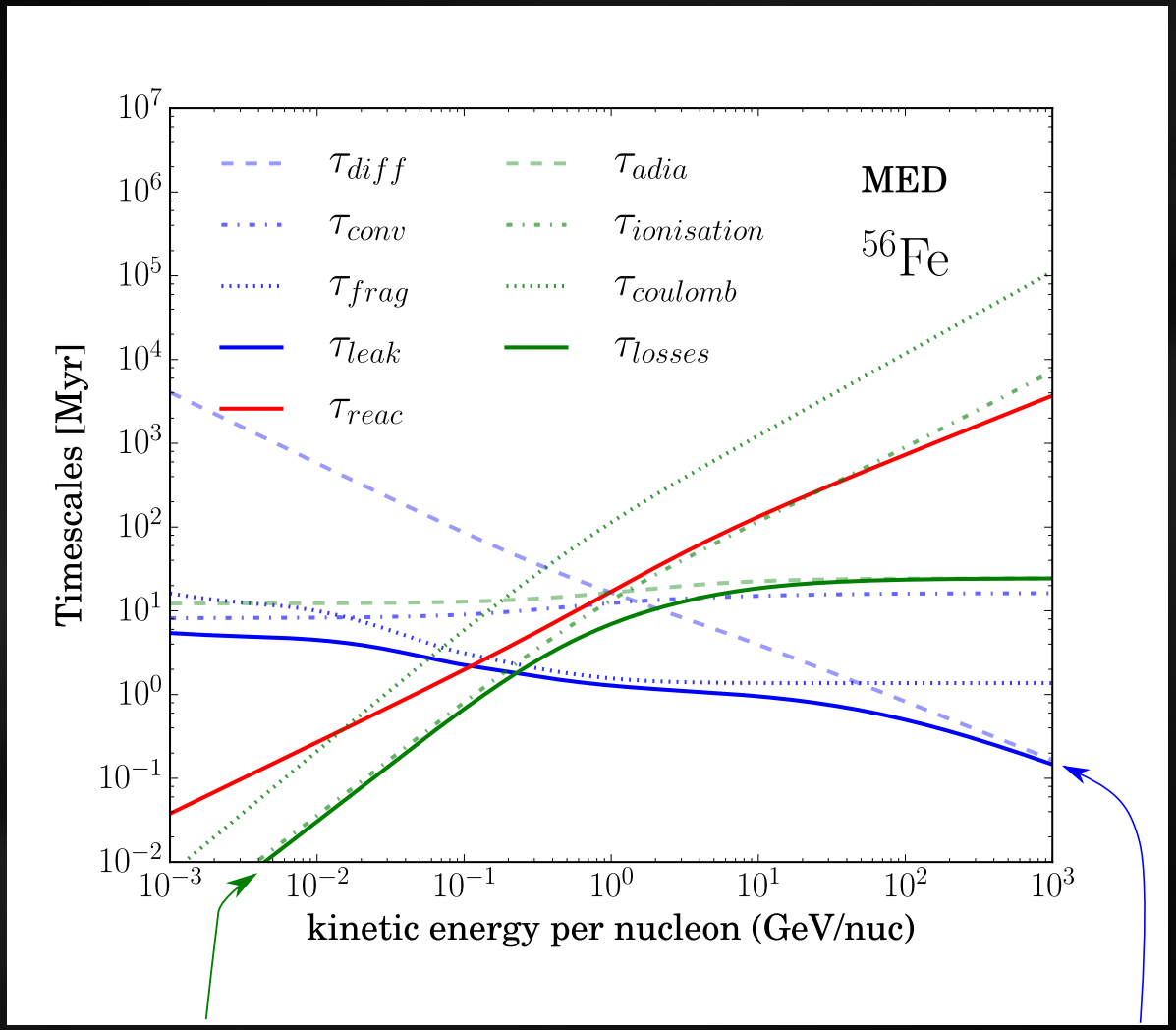


Low Energy

High Energy

1st Neglect terms in the equation

Limiting behavior for $\psi = 4\pi p E f_a$
(a stable)

Low Energy :

$$\partial_t \psi + \partial_E \{ b^{loss}(E)\psi - D(E)\partial_E \psi \} = Q$$

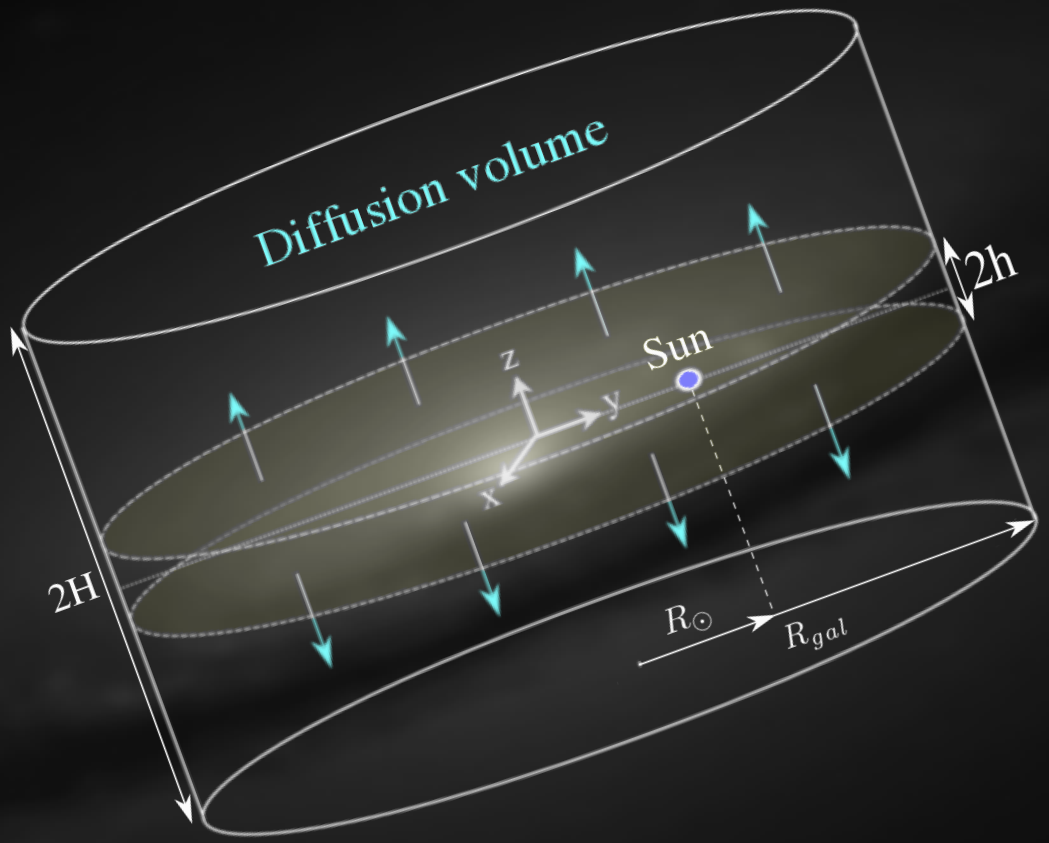
Intermediate Energy :

$$\partial_t \psi + \nabla_{\boldsymbol{x}} (V_C \psi - K \nabla_{\boldsymbol{x}} \psi) + \partial_E \{ b^{loss}(E)\psi - D(E)\partial_E \psi \} + \Gamma \psi = Q$$

High Energy :

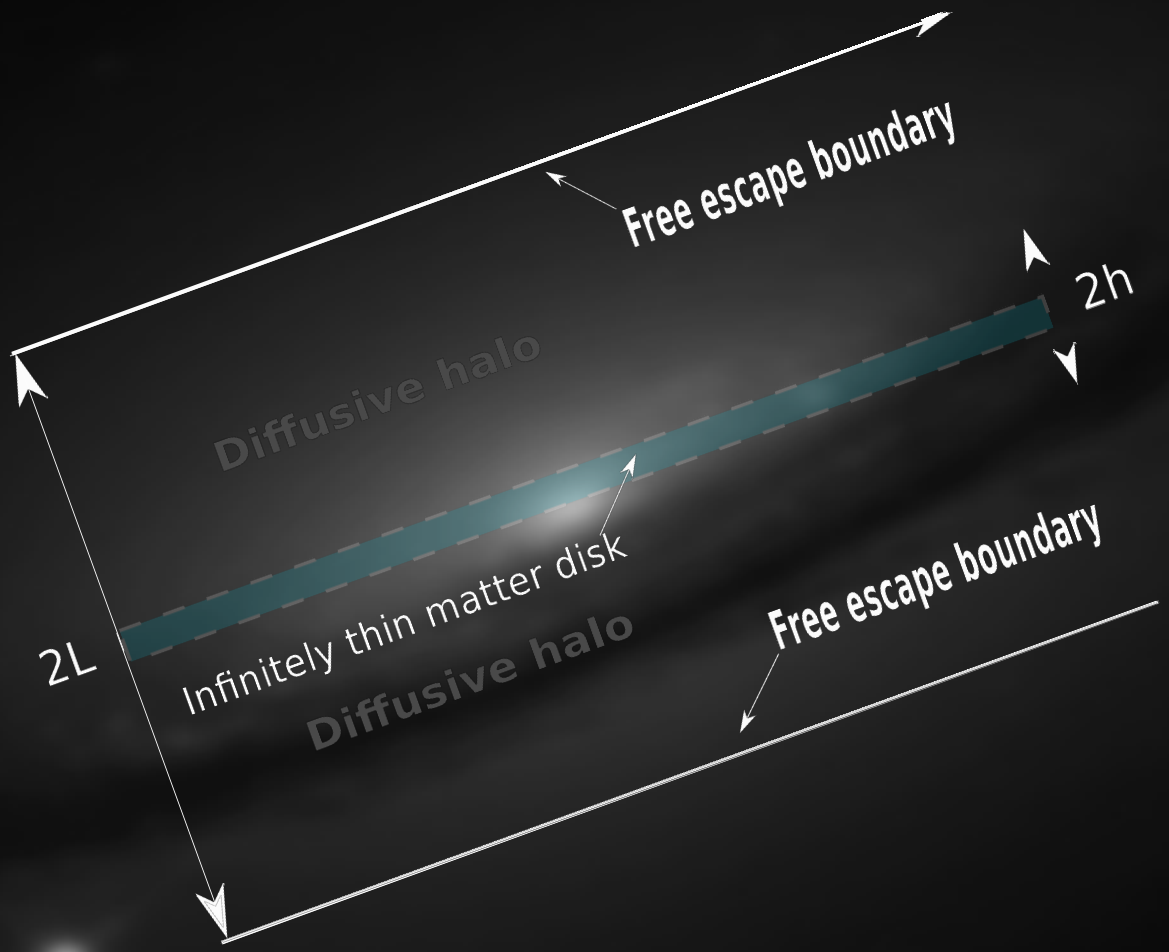
$$\partial_t \psi + \nabla_{\boldsymbol{x}} (K \, \nabla_{\boldsymbol{x}}) \psi = Q$$

2nd Geometrical assumptions



Sources and gas pinched inside the disk.

2nd Geometrical assumptions



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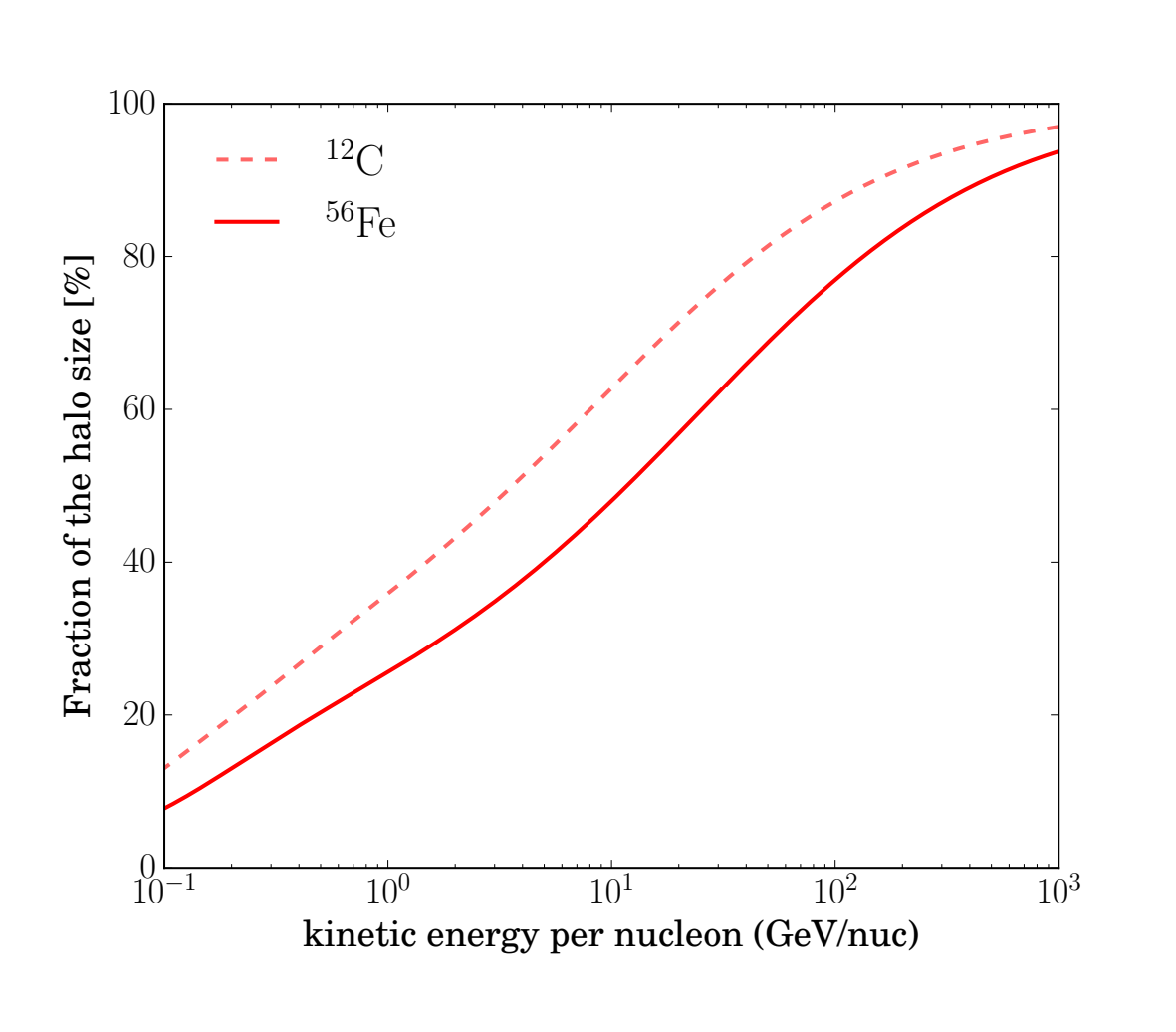
2nd Geometrical assumptions

Typical length probed by CRs



@1GeV for $L \sim 10$kpc the distance probed ~ 2kpc

Typical assumptions $\rightarrow$ USINE

Standard approximations :

- Continuous source term in space and time $\rightarrow$ steady state regime
- Homogeneous diffusion : $K(E, \cancel{\boldsymbol{r}})$
- Cylindrical symmetry of the diffusive halo :

$$\psi_a(E_{kn}, r, z) = \sum_i^{\infty} \psi_a^i(E_{kn}, z)\, J_0(\xi_i \frac{r}{R_{gal}})$$

- For a diffusive halosize $L < R_{Gal}$ $\rightarrow$ 1D approximation
- Source disk thickness $h \ll L$ the diffusive halo size :

$$n \rightarrow 2h\delta(z)\, n$$
$$b_{loss} \rightarrow 2h\delta(z)\, b_{loss}$$

Assumptions required by the SA treatment :

- The ISM density n does not depend on the radius r
- Pinched reaaceleration and galactic wind gradient :

$$K_{pp} \rightarrow 2h\delta(z)\, K_{pp}$$
$$\nabla_{\boldsymbol{x}}.\boldsymbol{V}_c \rightarrow 2h\delta(z)\, \nabla_{\boldsymbol{x}}.\boldsymbol{V}_c$$

Simplified equation and degeneracies

Example in the 1D case, the two variables are (z, E) :

$$\partial_z(V_C\psi) - K\partial_z\psi + \partial_E\{b^{loss}(E)\psi - D(E)\partial_E\psi\} + \Gamma\,\psi = Q$$

This equation can be cast into the form,

$$u + \alpha(x)\frac{d}{dx}\left[\beta(x)u - \gamma(x)\frac{du}{dx}\right] = u^0 \ ,$$

...and solved with a Crank Nicholson scheme.

Complete degeneracies for a stable nuclei a :

- V_C, K_0, D are degenerated with n_{ISM}
- K_0 and the halo size L

Summary about the SA approach

- Fast computing time (e.g. MCMC)
- Clear physical dependencies of the result

- A new solution for each model tested
- Lack of flexibility (e.g. homogeneous K)

Althought..mathematical tricks can be used !

e.g. the pinching method presented by Mathieu

To compare the results of different analyses,

consistency checks with numerical code should be performed !

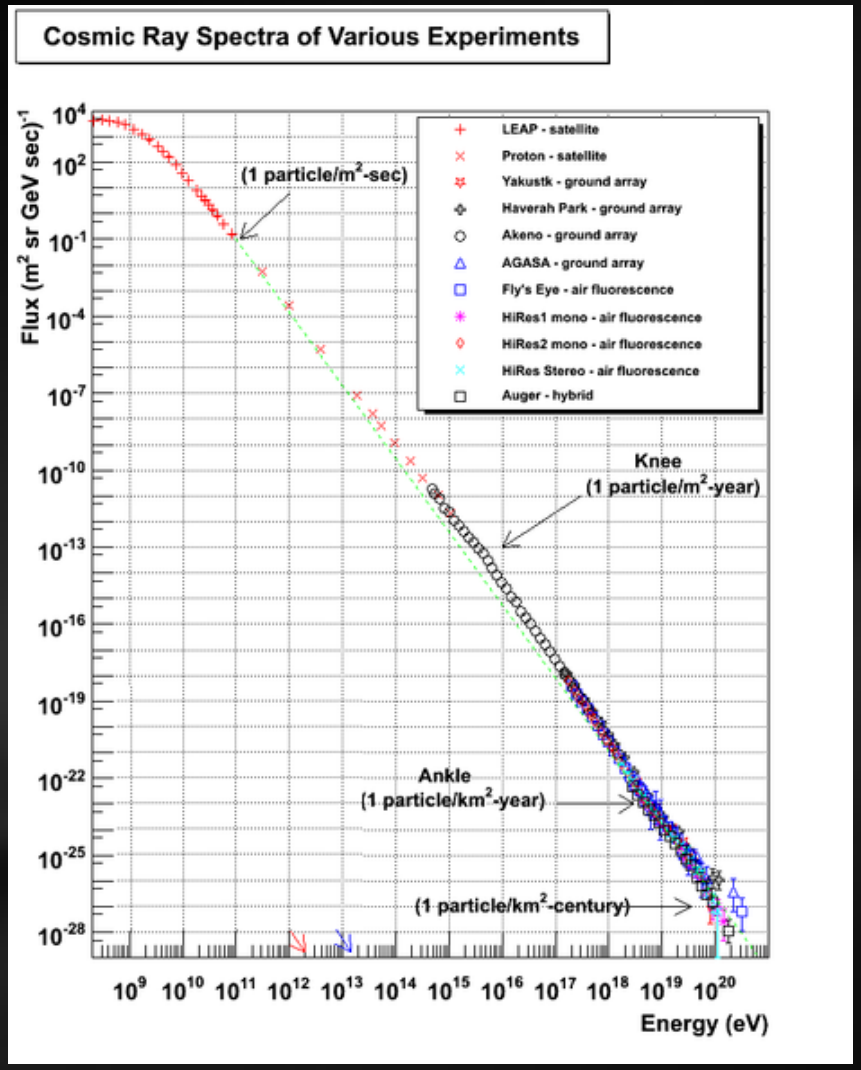
Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects

Features in cosmic-ray spectra



http://www.physics.utah.edu/ whanlon/spectrum.html

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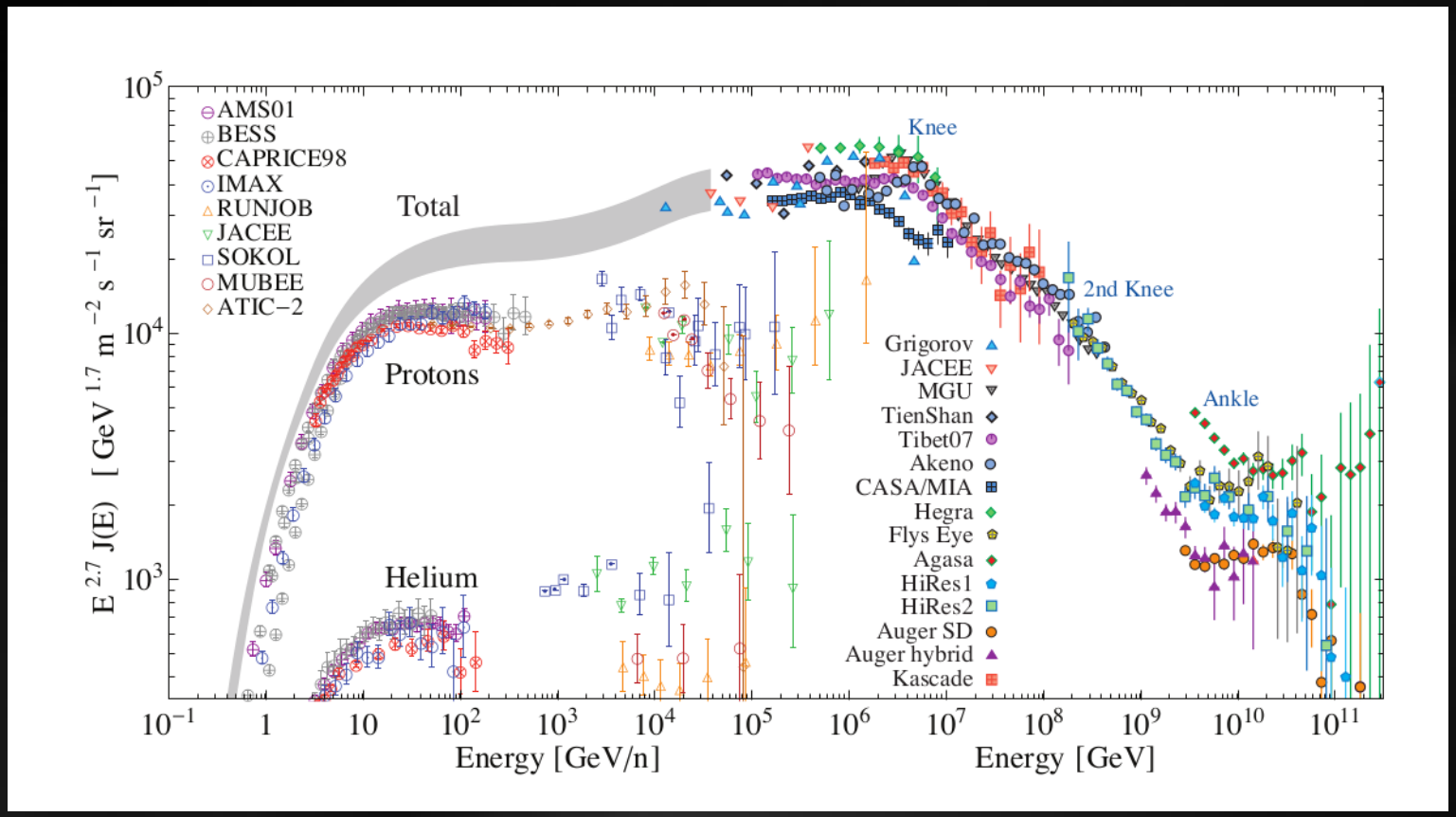
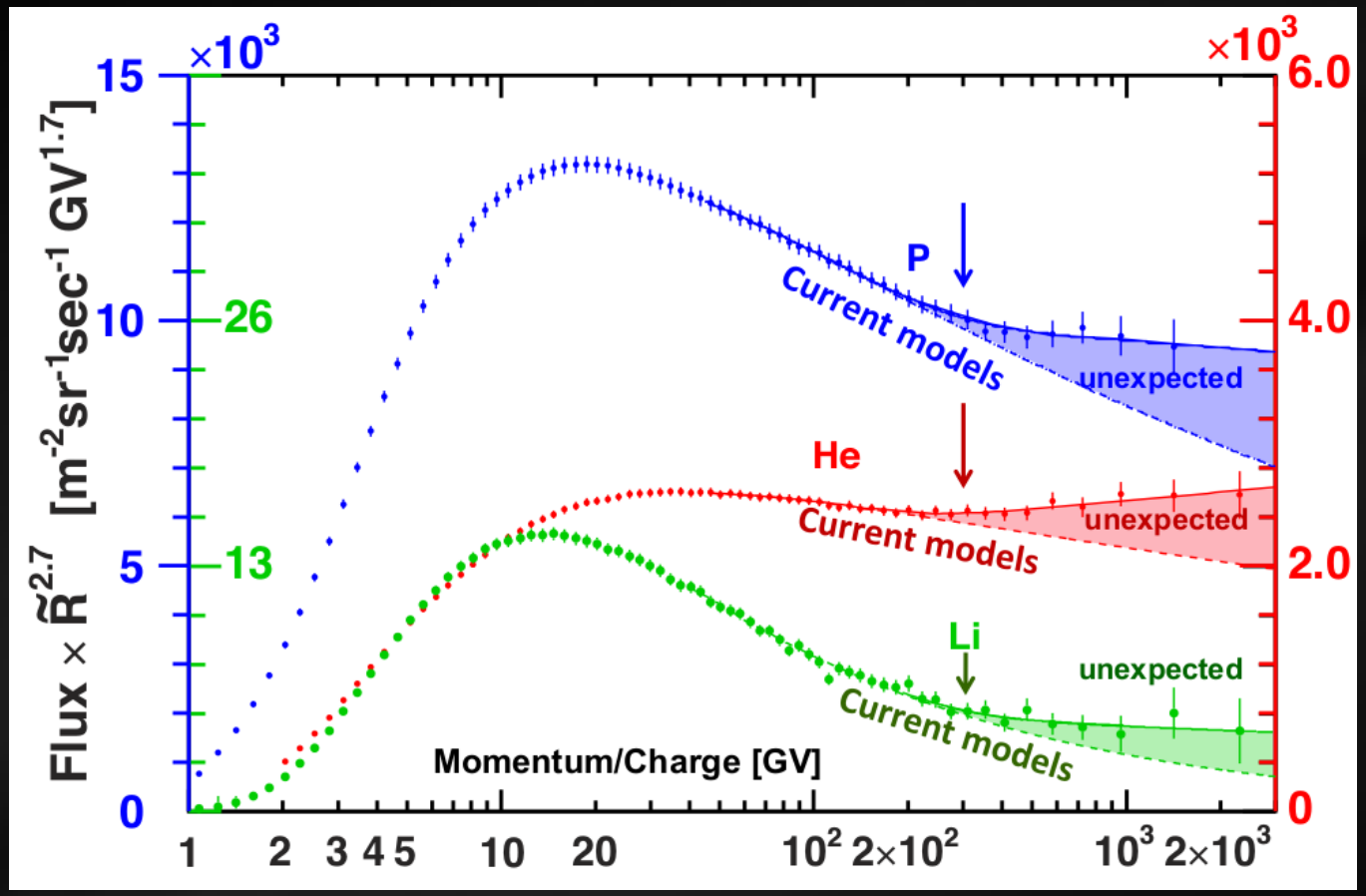


Mertsch, P. (2010). PhD. arXiv:1012.4239.

Most beautiful powerlaw in nature ?

$$\Psi \propto E^{-2.7+\Delta} \quad \Rightarrow \quad \Delta_{knee} \approx -0.3 \quad \Delta_{ankle} \approx +0.37$$

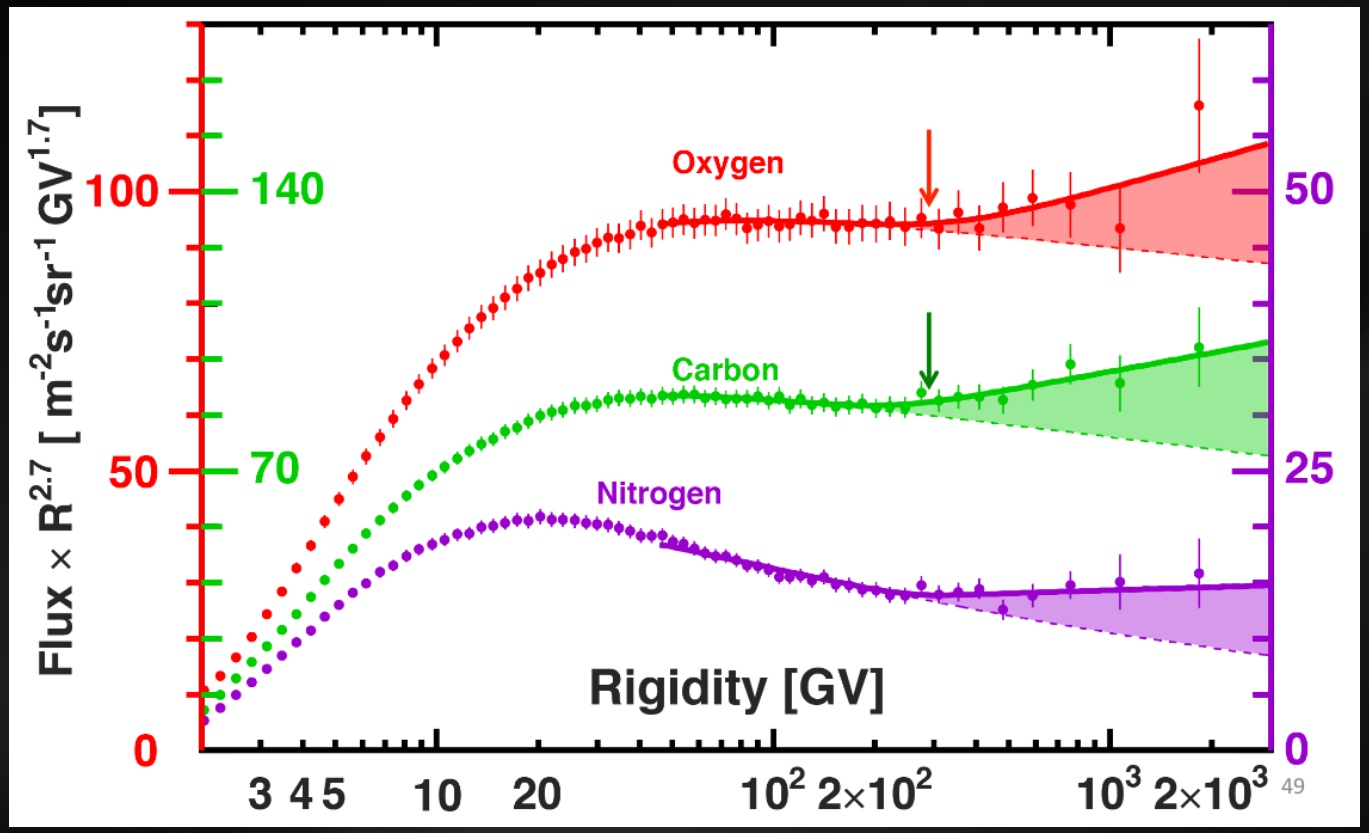
Features in cosmic-ray spectra



S.Ting presentation, CERN, december 2016

$\Rightarrow$ **A universal kinck at** $R \geq 200GV$ **?** $\Delta_{kinck} \approx 0.12 - 0.13$

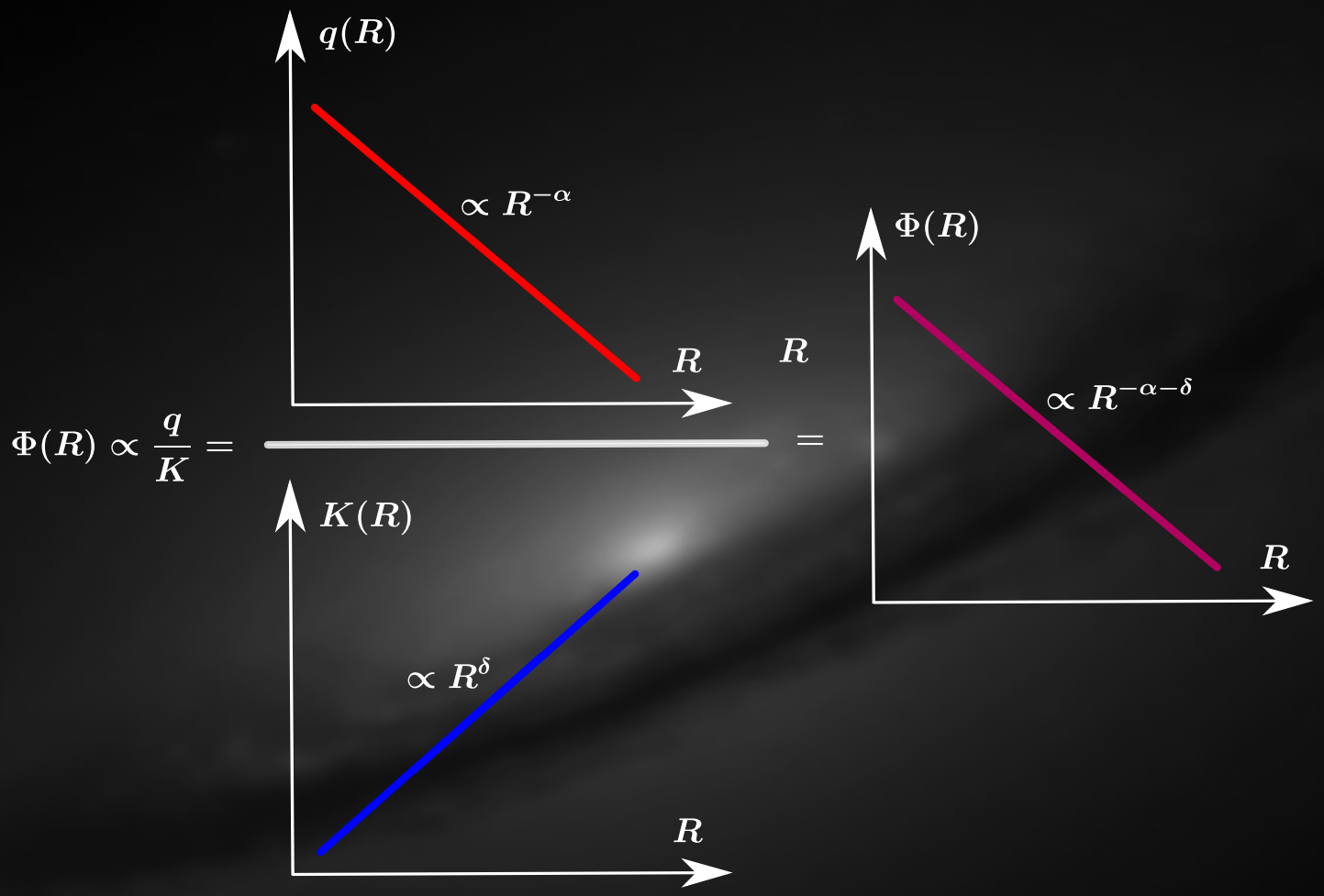
Features in cosmic-ray spectra



Yang presentation, XSCR, march 2017

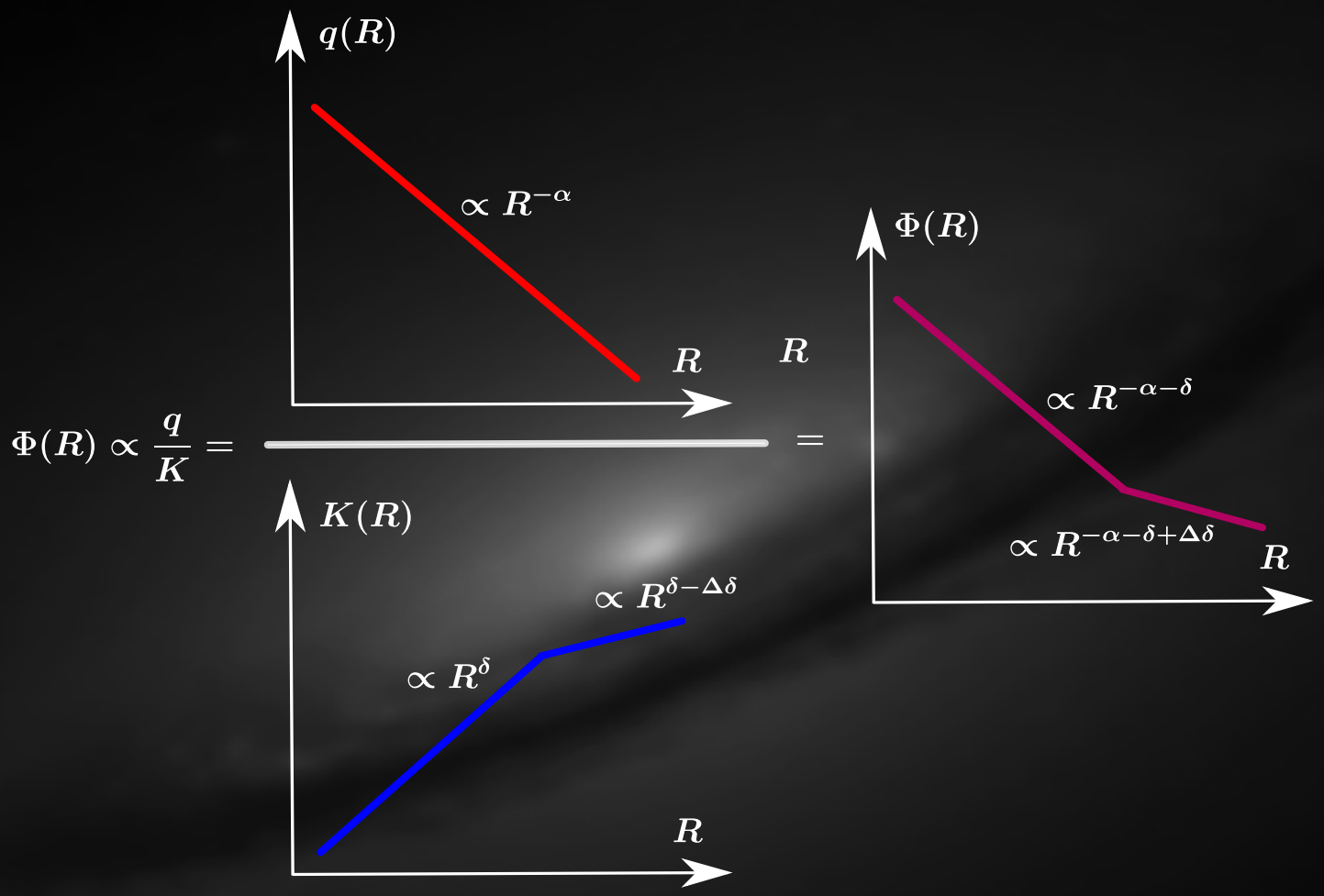
$\Rightarrow$ **A universal kinck at** $R \geq 200GV$ **?** $\Delta_{kinck} \approx 0.12 - 0.13$

Origin of the break?



Standard expectation?

Origin of the break ?

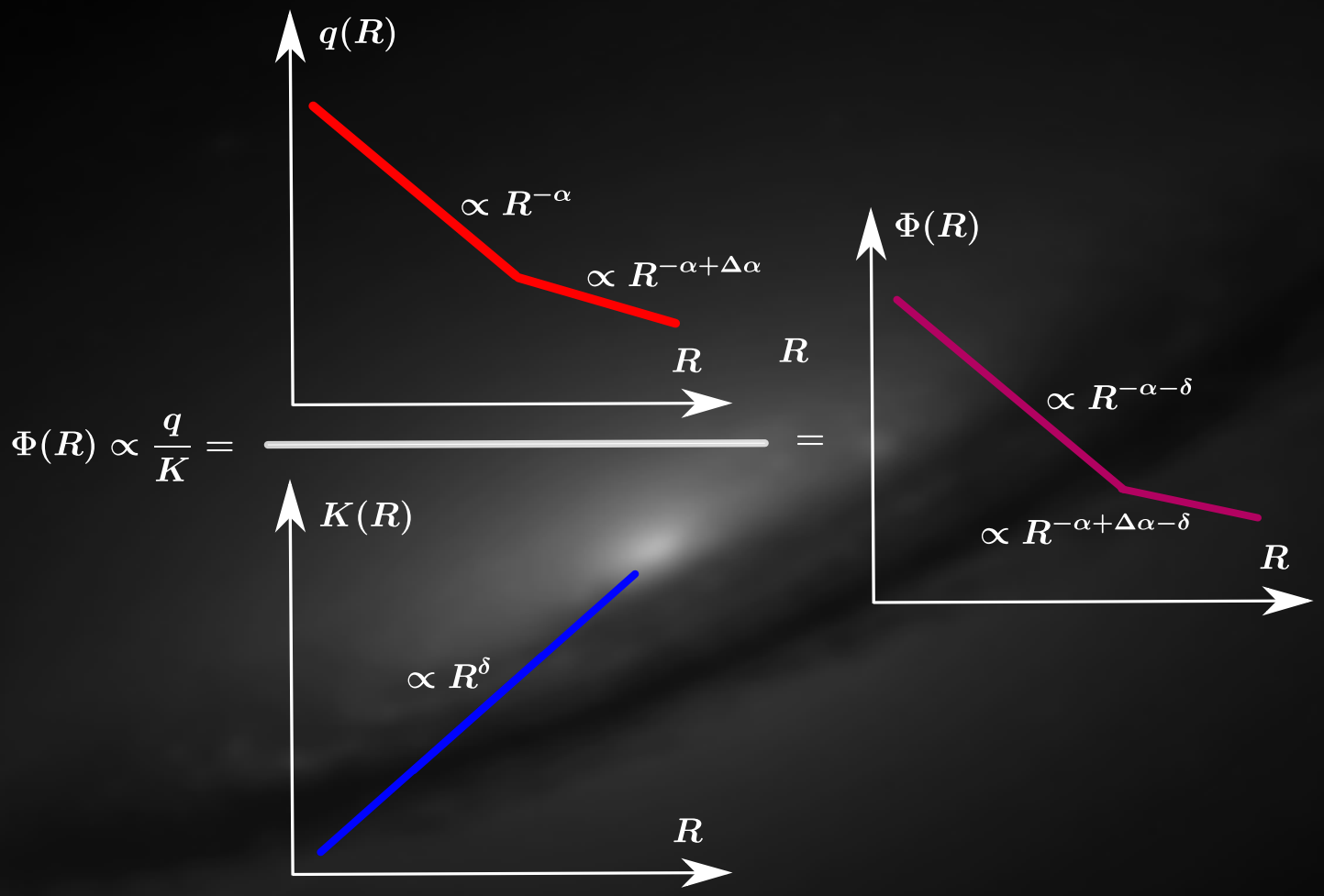


⇒**Explanation 1** : **break in the diffusion coefficient ?**

-Blasi, P., Amato, E., Serpico, P. D. (2012). PRL, 109(6), 061101.

-Tomassetti, N. (2012). The Astrophysical Journal Letters, 752(1), L13.

Origin of the break ?

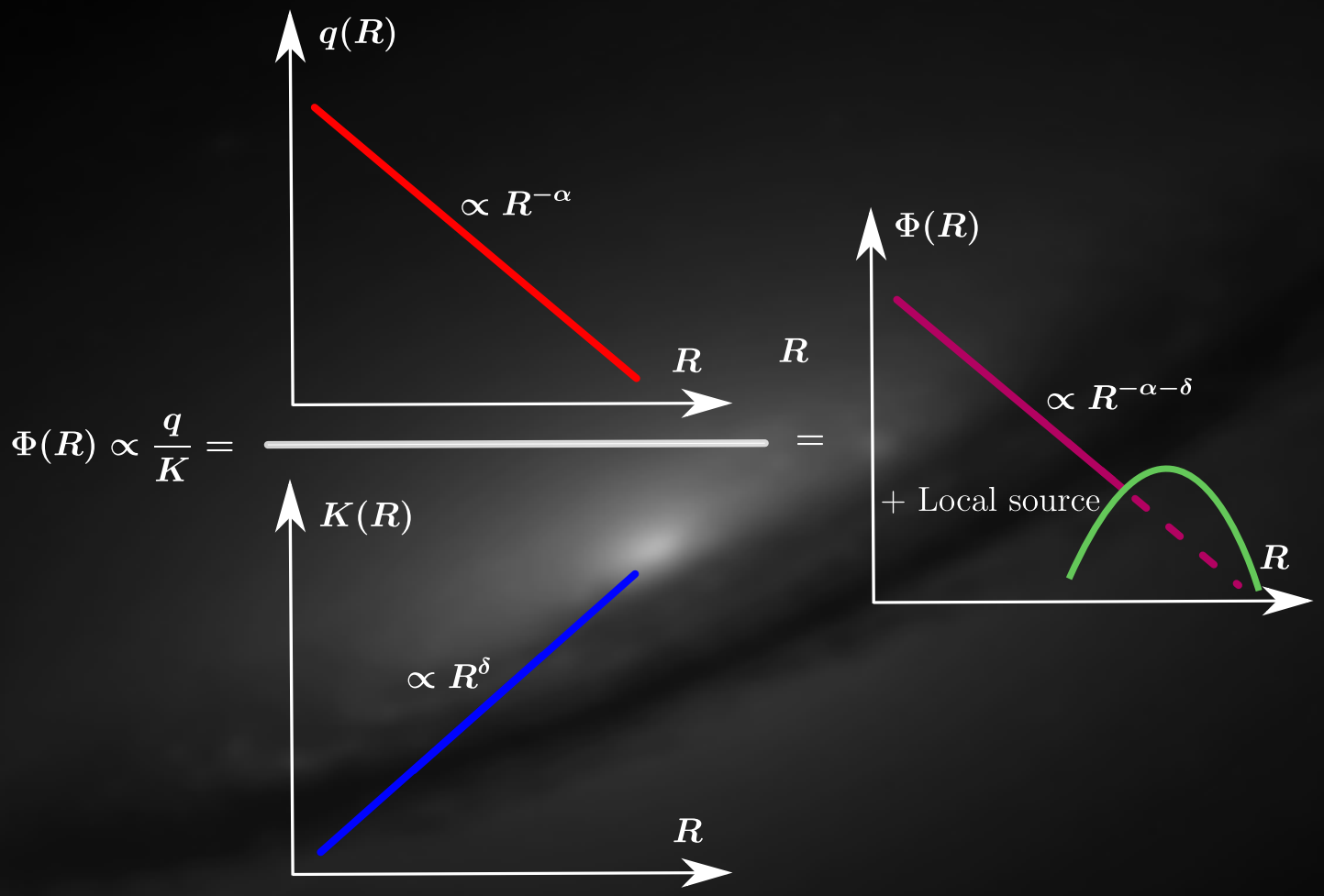


⇒Explanation 2 : break in the source spectrum ?

-Ptuskin, V., Zirakashvili, V., Seo, E. S. (2013). APJ, 763(1), 47.

-Tomassetti, N., Donato, F. (2015). APJL, 803(2), L15.

Origin of the break ?



⇒**Explanation 3** : **local source contribution ?**

-Kachelriess, M., Neronov, A., Semikoz, D. V. (2015). PRL, 115(18).

-Erlykin, A. D., Wolfendale, A. W. (2015). JPG, 42(12), 125201.

Origin of the break ?

⇒ Explanation 3 : local source contribution ?

Genolini, Y., Salati, P., Serpico, P. D., & Taillet, R. (2017). Stable laws and cosmic ray physics. A&A, 600, A68.

⇒ Explanation 1 : break in the diffusion coefficient ?

Indications for a high-rigidity break in the cosmic-ray diffusion coefficient, Preprint arxiv: 1706.09812

Origin of the break ?

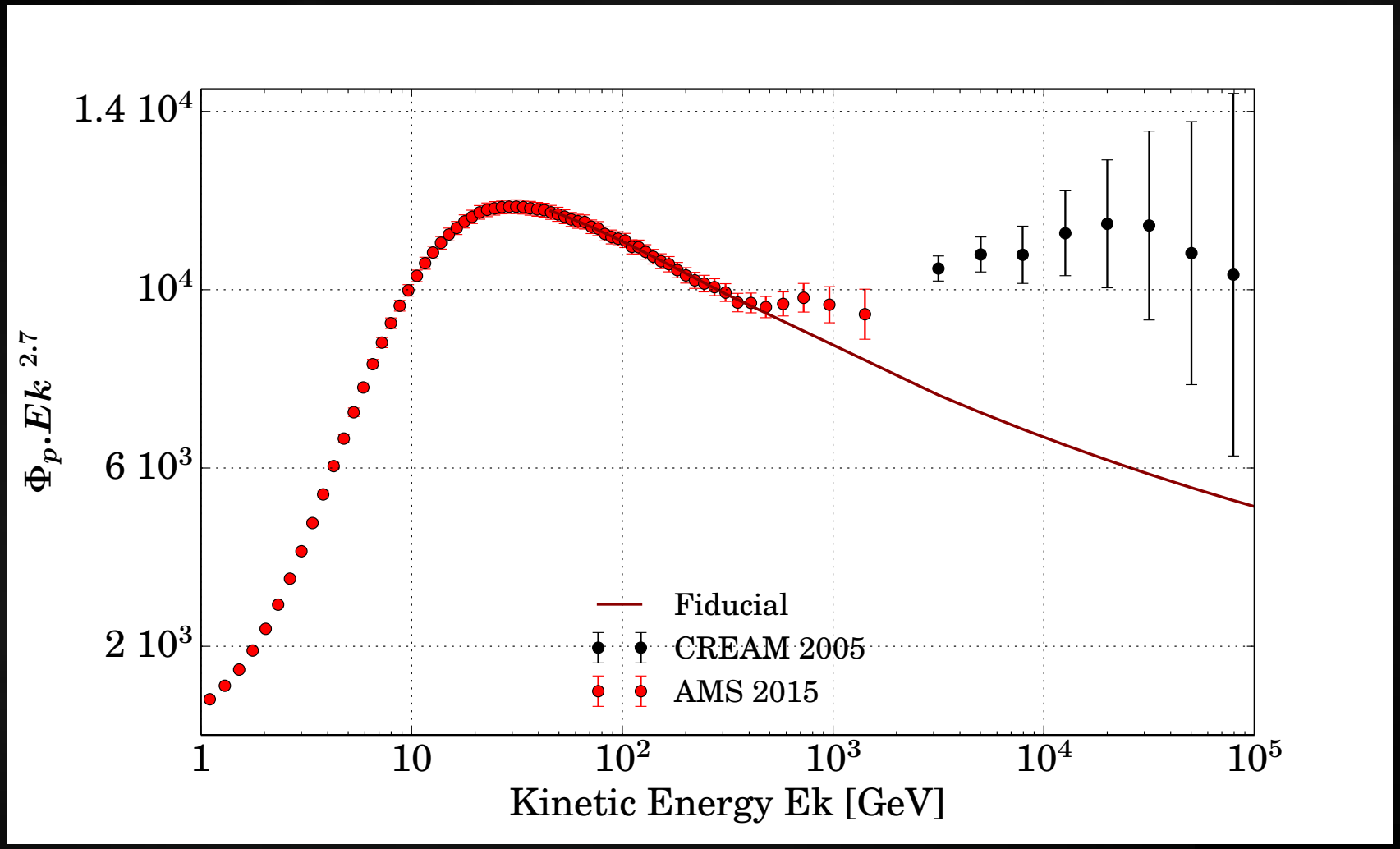
⇒ Explanation 3 : local source contribution ?

Genolini, Y., Salati, P., Serpico, P. D., & Taillet, R. (2017). Stable laws and cosmic ray physics. A&A, 600, A68.

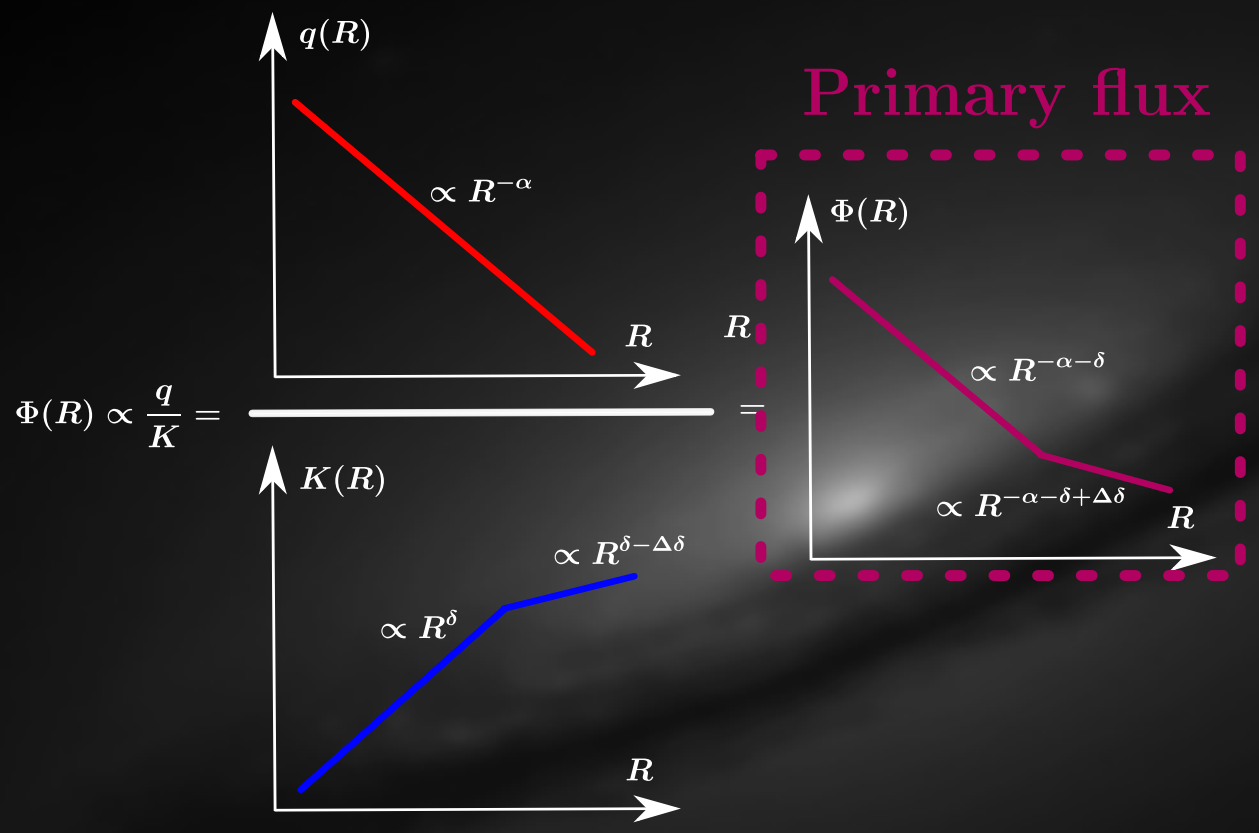
⇒ Explanation 1 : break in the diffusion coefficient ?

Indications for a high-rigidity break in the cosmic-ray diffusion coefficient, Preprint arxiv: 1706.09812

Explanation 1: a break in the diffusion coefficient?



The break in secondary fluxes



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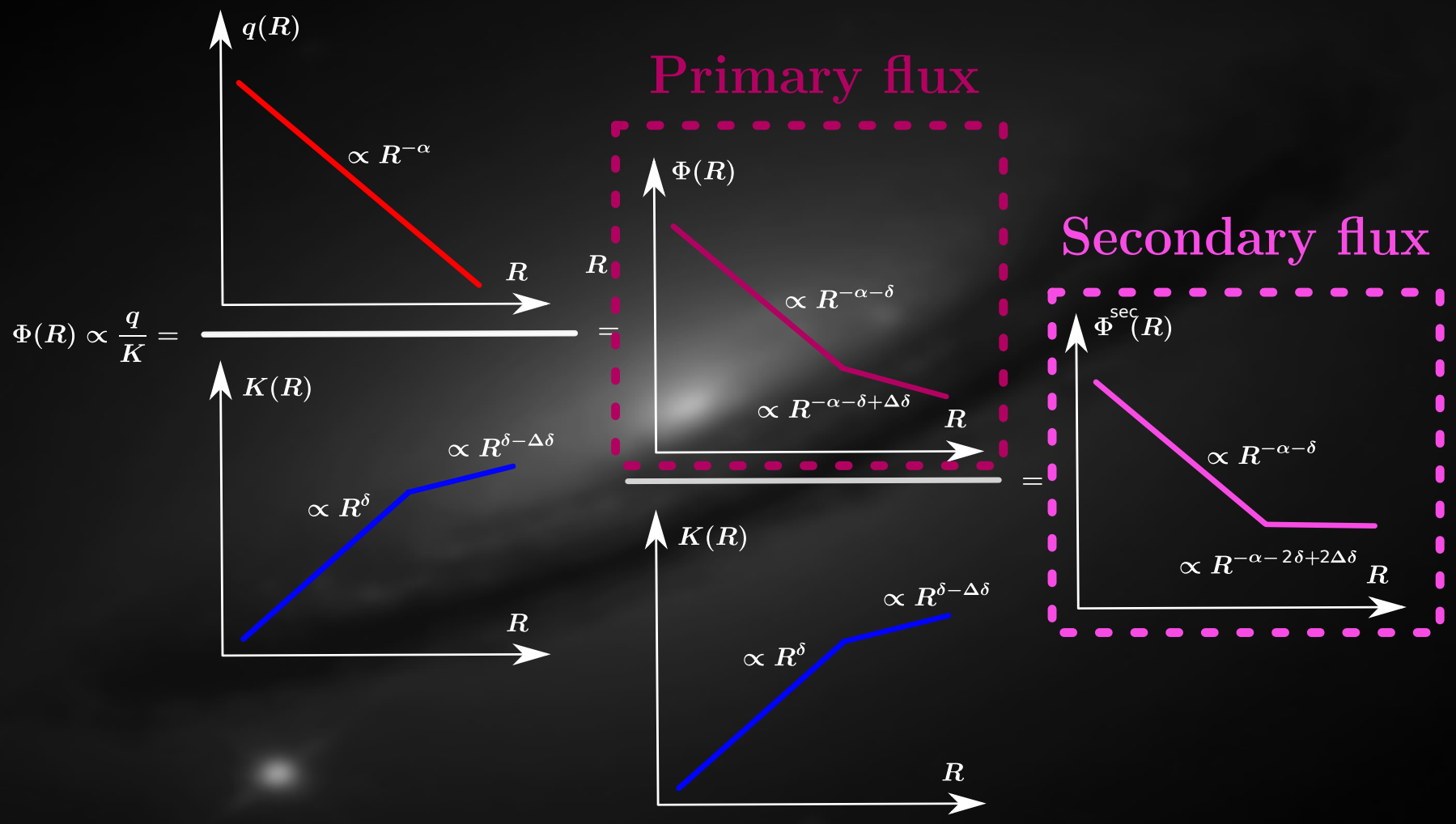
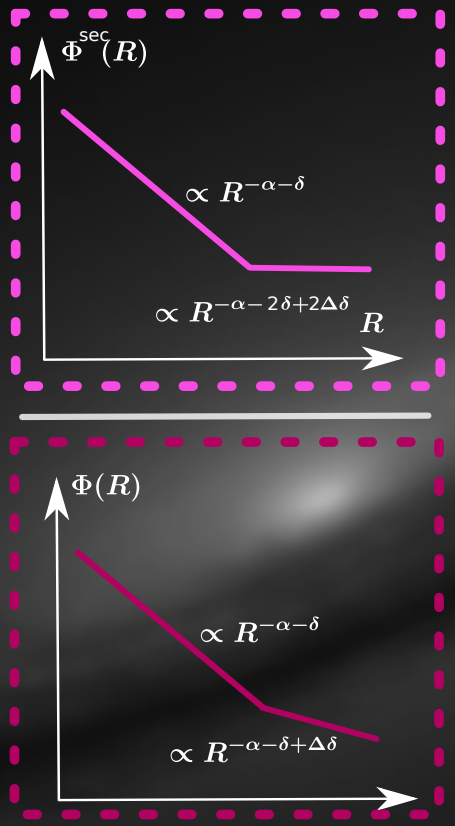


The break in the B/C ratio

$$\frac{\text{Secondary flux}}{\text{Primary flux}} = \frac{\Phi^{\text{sec}}(R)}{\Phi(R)}$$



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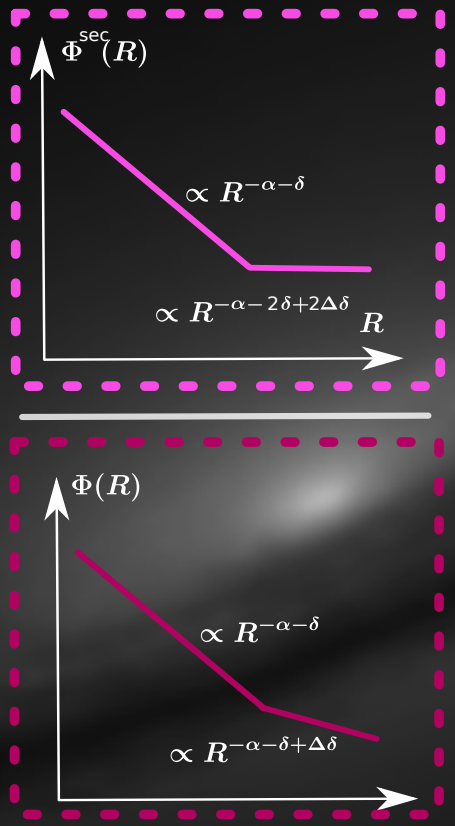

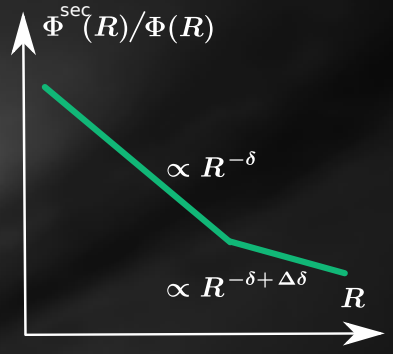

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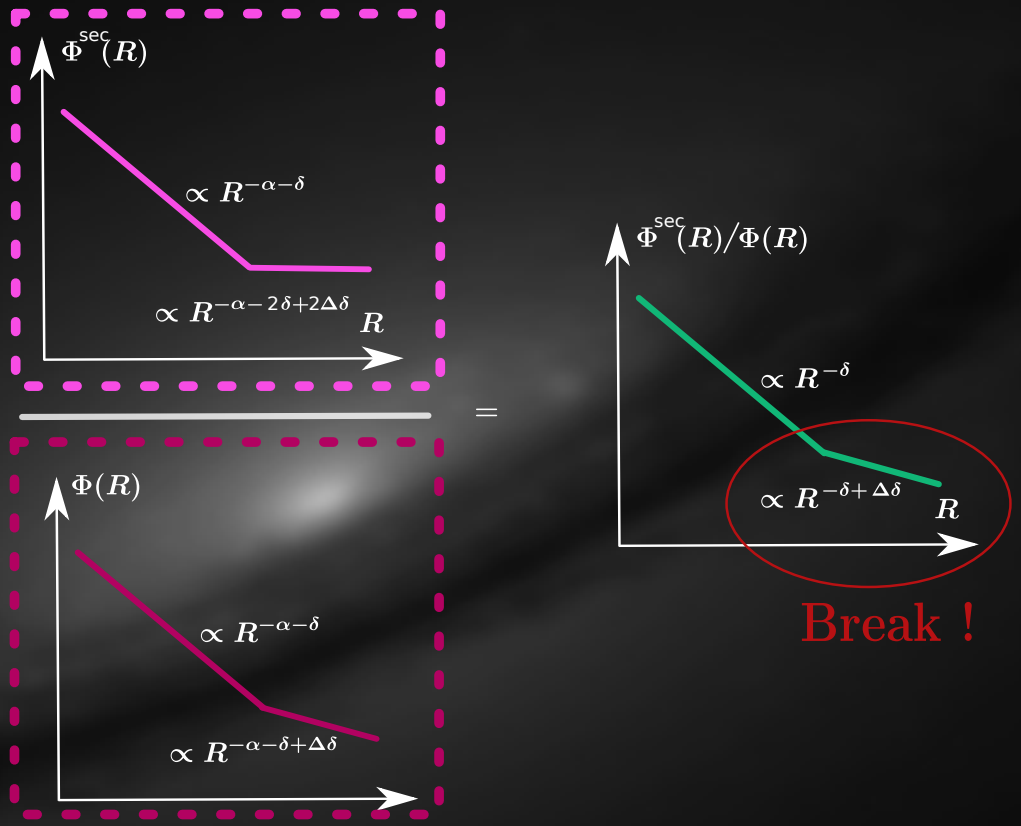


$\Rightarrow$ **One should observe a break in the B/C ratio !**

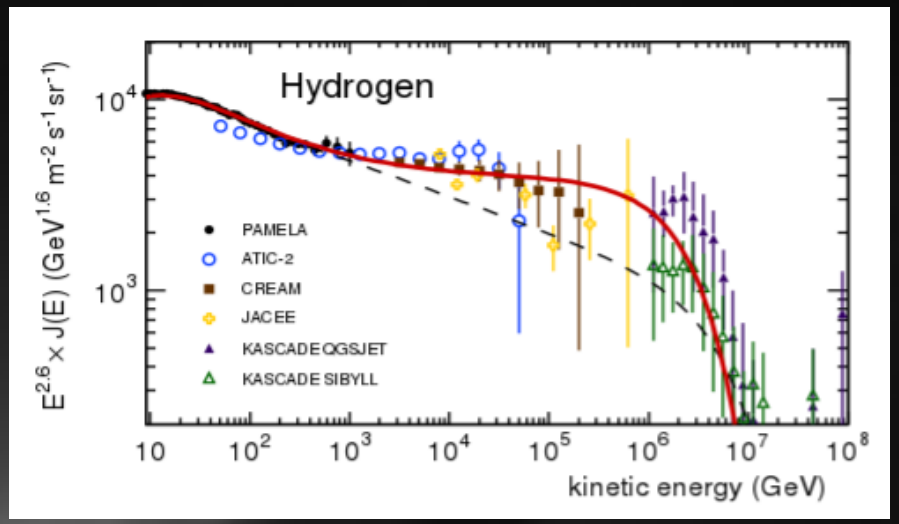
Theoretical motivations?

Two zones model:

N. Tomassetti, Astrophys.J. 752, L13 (2012)[arXiv:1204.4492]

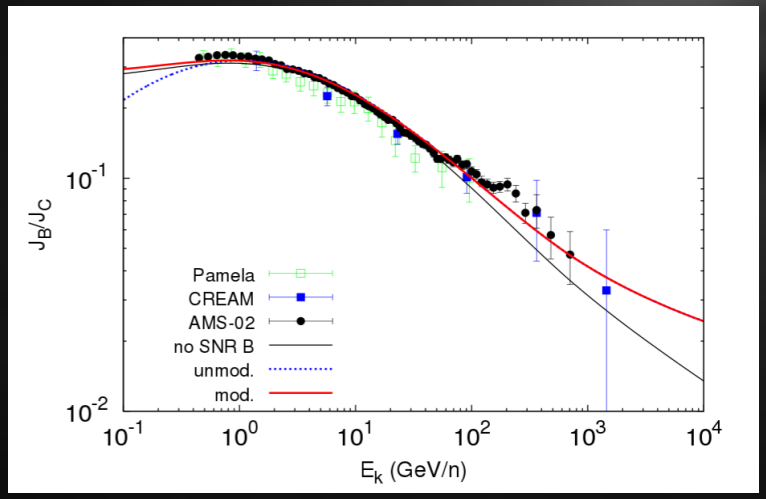
$$K(z,\rho) = \begin{cases} k_0 \beta \rho^{\delta \sim 0.3} & \text{for} |z| < \xi L \text{ (inner halo)} \\ k_0 \beta \rho^{\delta + \Delta \sim 0.8} & \text{for} |z| > \xi L \text{ (outer halo)} \end{cases}$$

Turbulence is different between the halo (SNRs) and the disk (CR-driven)



Damping of CRs on self generated plasma waves:

P. Blasi, E. Amato, P. D. Serpico, PRL 109, 061101 (2012) [arXiv:1207.3706]



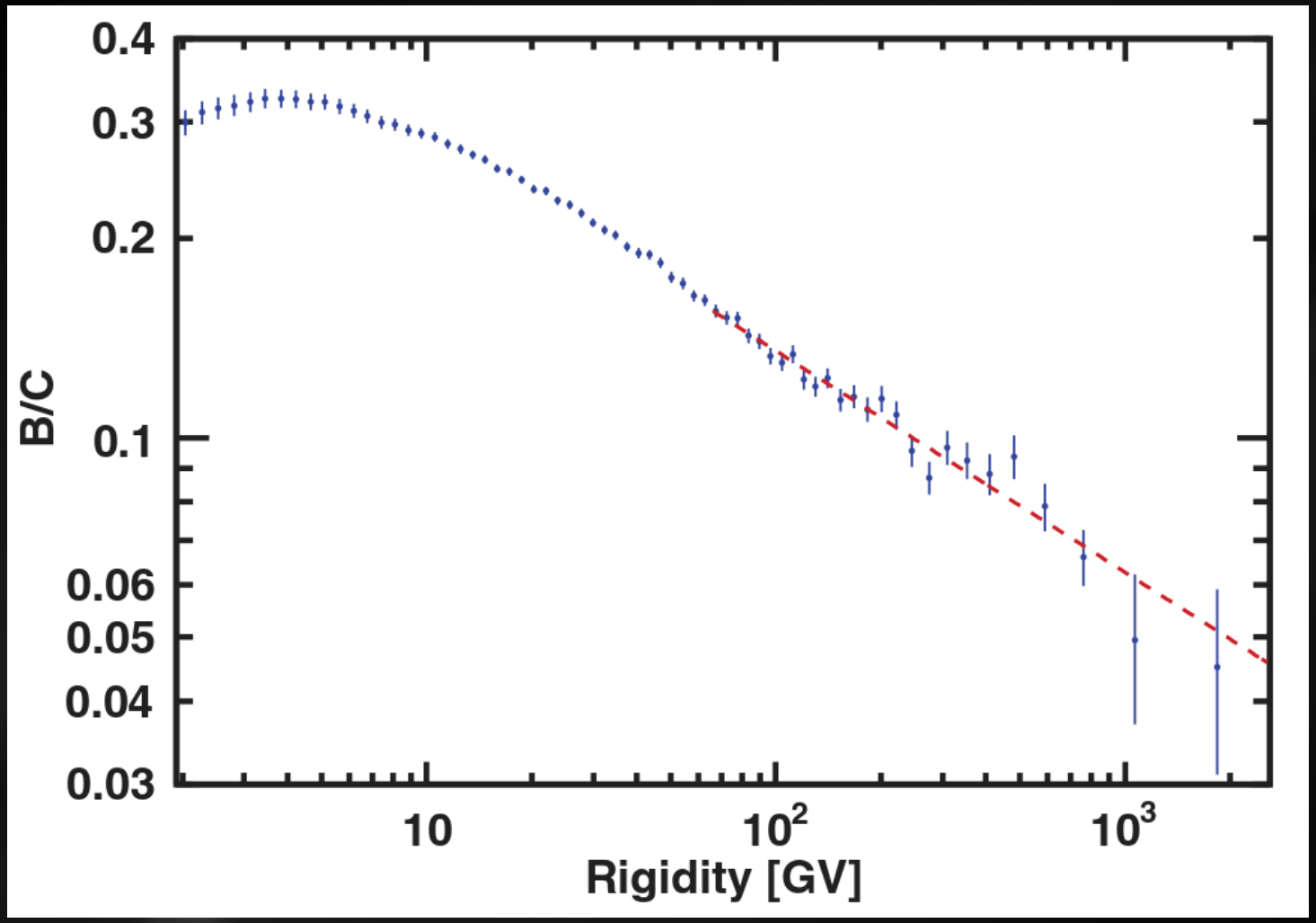
Coupled system of equations:

$$\begin{cases} \dfrac{\partial}{\partial k}\left[D_{kk}\dfrac{\partial W}{\partial k}\right] + \Gamma_{\rm CR} W = q_W(k). \\ -\dfrac{\partial}{\partial z}\left[D\dfrac{\partial f}{\partial z}\right] + v_{\rm A}\dfrac{\partial f}{\partial z} - \dfrac{dv_{\rm A}}{dz}\dfrac{p}{3}\dfrac{\partial f}{\partial p} = q_{\rm CR}(z,p) \end{cases}$$

Wave spectrum

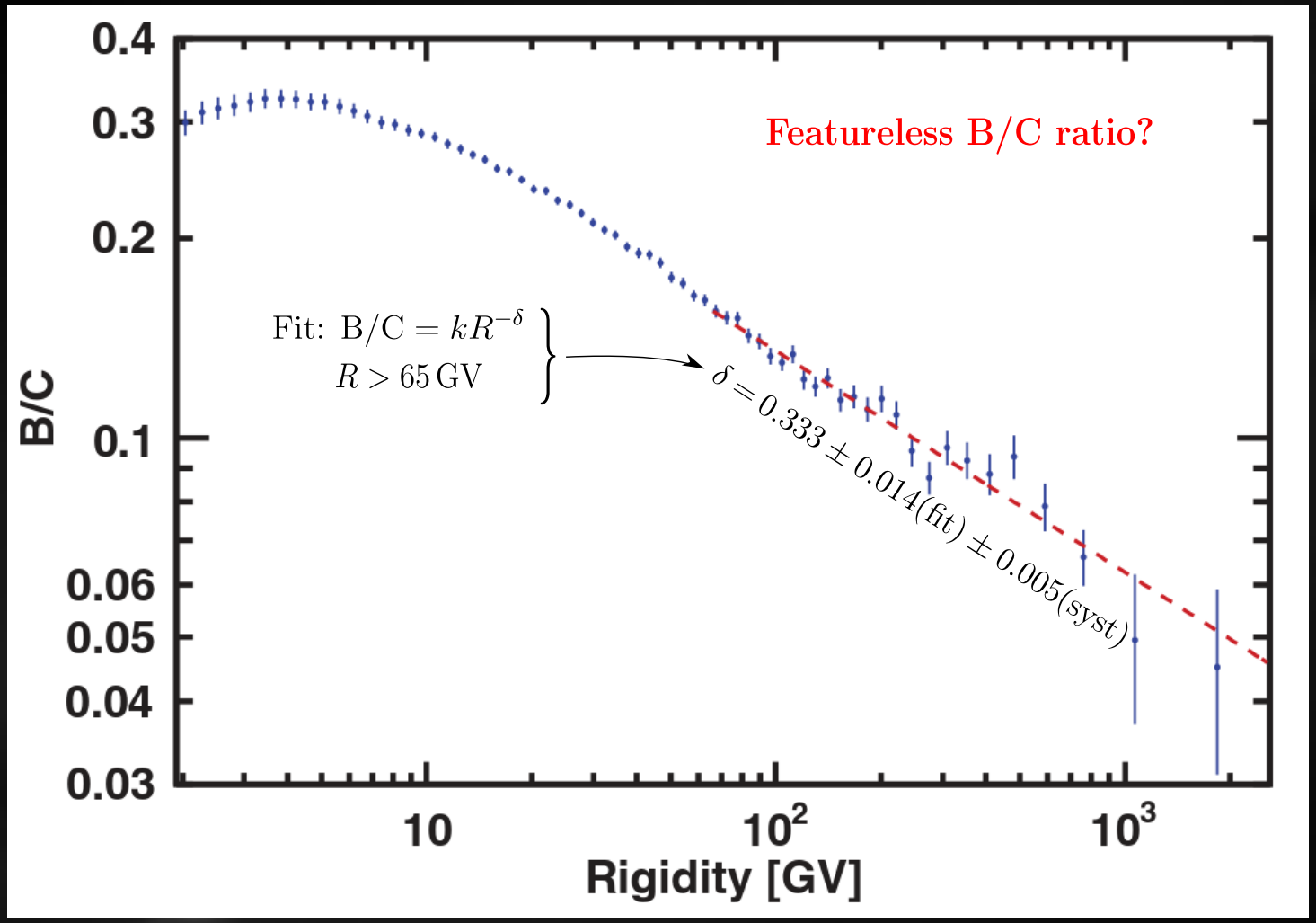
CR density

The break in the B/C ratio



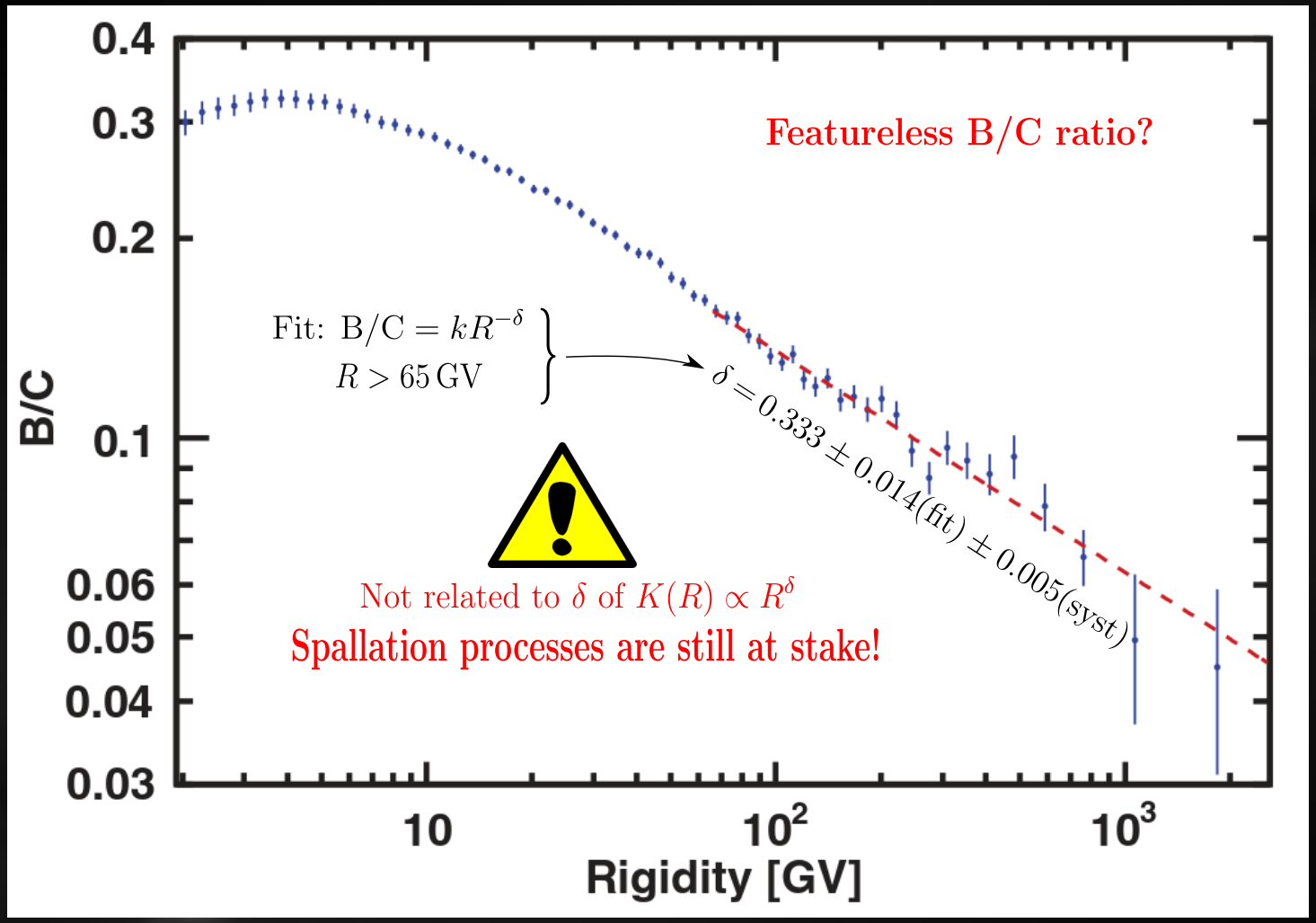
Aguilar, M., (2016) Physical review letters, 117(23), 231102.

The break in the B/C ratio



Aguilar, M., (2016) Physical review letters, 117(23), 231102.

The break in the B/C ratio



Aguilar, M., (2016) Physical review letters, 117(23), 231102.

Test of the break hypothesis

We compare the two cases :

H1 H2

$$K(R) = \quad K_0\,\beta\,(R/\mathrm{GV})^{\delta} \quad \text{or } K_0\,\beta\,\frac{(R/\mathrm{GV})^{\delta}}{\left\{1+(R/\mathbf{R_b})^{\mathbf{\Delta\delta/s}}\right\}^{\mathbf{s}}}$$

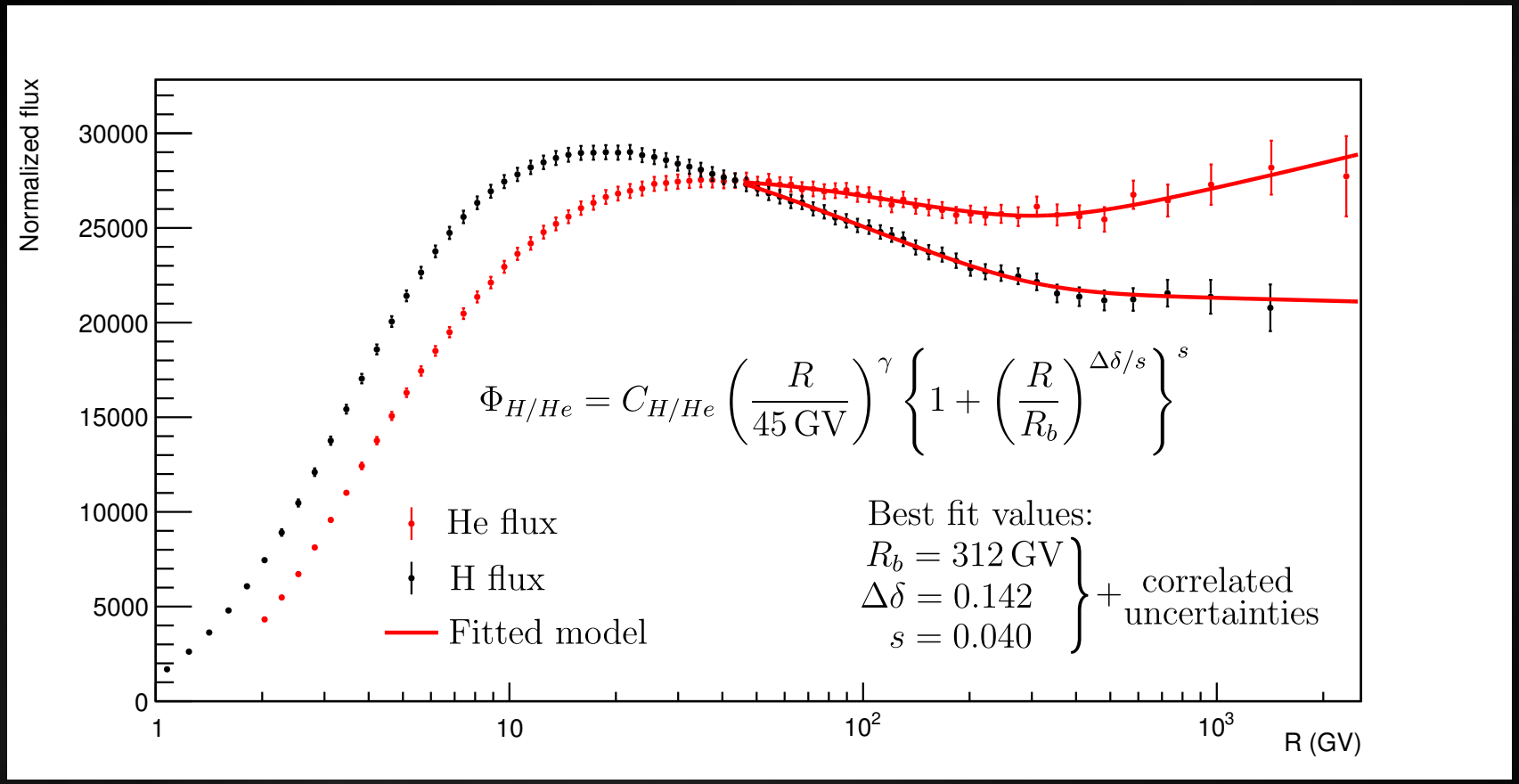
Methodology :

- Semi analytical code **USINE** used.
- High-energy fit of the B/C, above $R_{min} = 15\,\mathrm{GV}$.
- Fixed number of free parameters : only δ and K_0.
- V_a, V_c, R_b, $\Delta\delta$, s are treated as nuisance parameters.
- Fit quality comparison : w/ and w/o the break.
- Study of the robustness of the result.

$\Rightarrow$ Our goal is not to provide benchmark parameters over the all energy range.

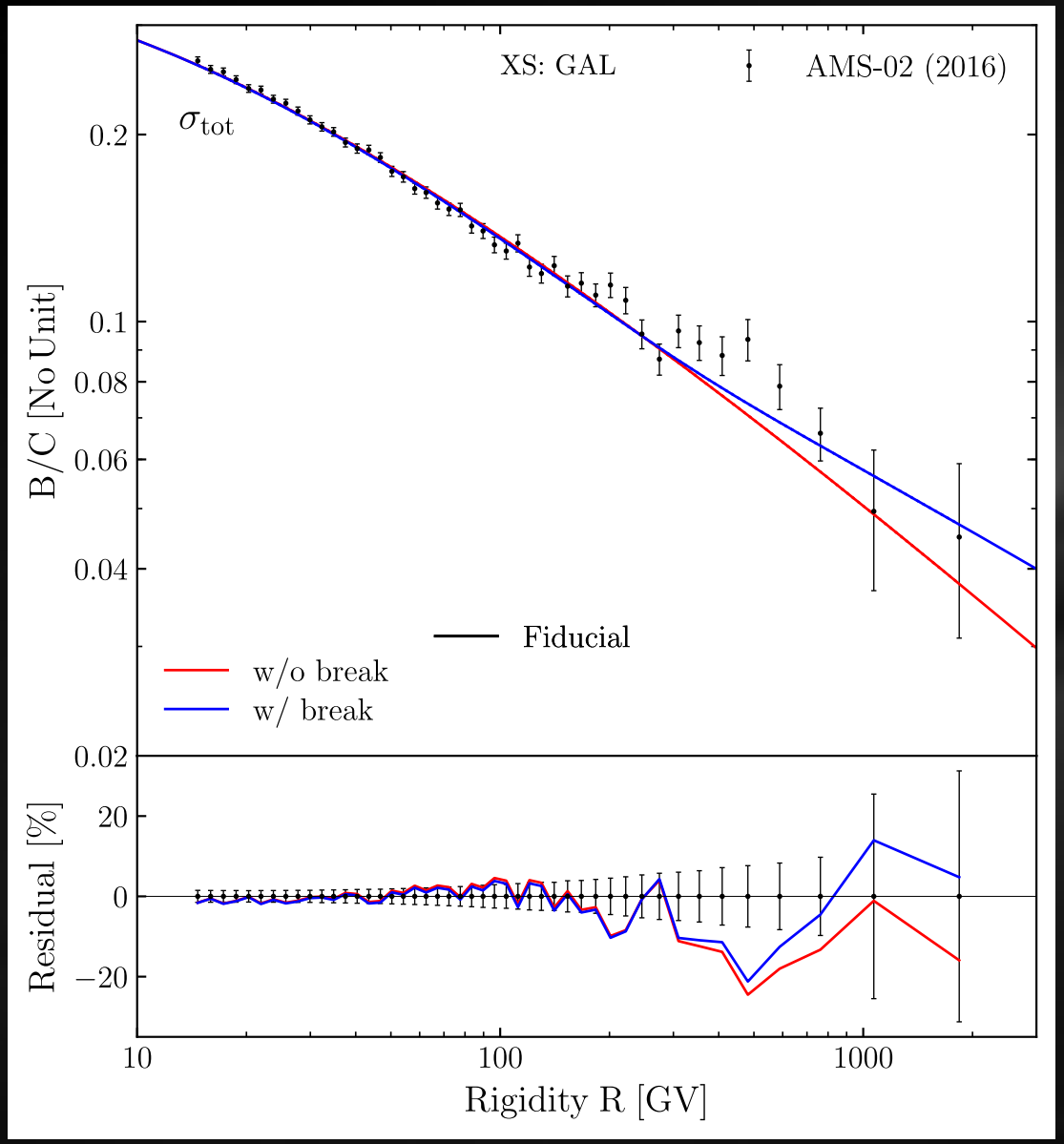
First step: fix the break

⇒ **Combined fit of AMS-02 proton and helium fluxes**



This fixes the break parameters in : $K(R) = K_0\,\beta\,\frac{(R/\mathrm{GV})^{\delta}}{\left\{1+(R/\mathbf{R_b})^{\mathbf{\Delta\delta/s}}\right\}^{\mathbf{s}}}$

Second step: fit of the B/C ratio



- **H1** (without) : $\chi^2 = 62$

  $\delta = 0.52$

  $K_0 = 7.4 \times 10^2 .\mathrm{kpc}^2.\mathrm{Myr}^{-1}$

- **H2** (with) : $\chi^2 = 50$

  $\delta = 0.53$

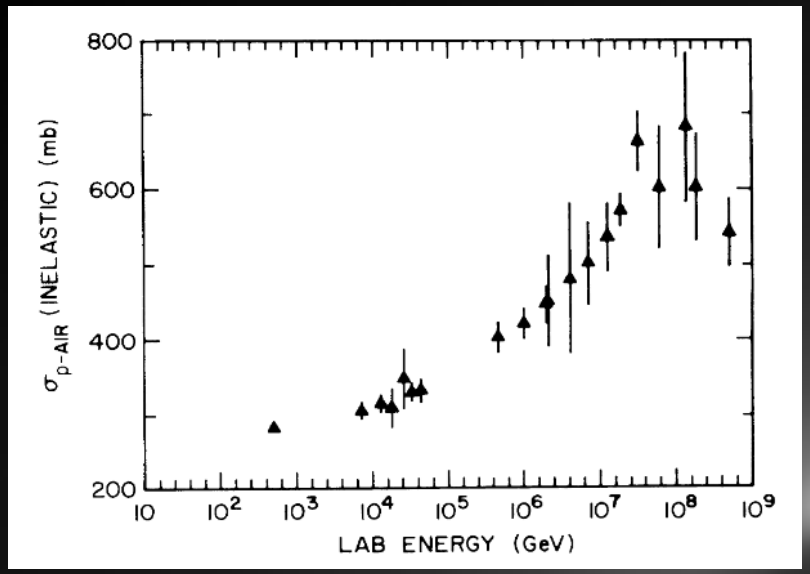
  $K_0 = 7.1 \times 10^2 .\mathrm{kpc}^2.\mathrm{Myr}^{-1}$

- $\Delta\chi^2 = \mathbf{12}$ *decisive evidence !* (in Bayesian terms)

  H. Jeffreys (1961).

Third step: robustness of the result

1st effect which can mimic a break : E-dependent XS



Gaisser et al (1987).PRD, 36(5), 1350.

Usually taken flat above$\sim$5GeV/nuc

Enhancement observed in :
$\rightarrow$ pp collisions

$\rightarrow$ air showers experiments

$\rightarrow$ Increasing interaction range

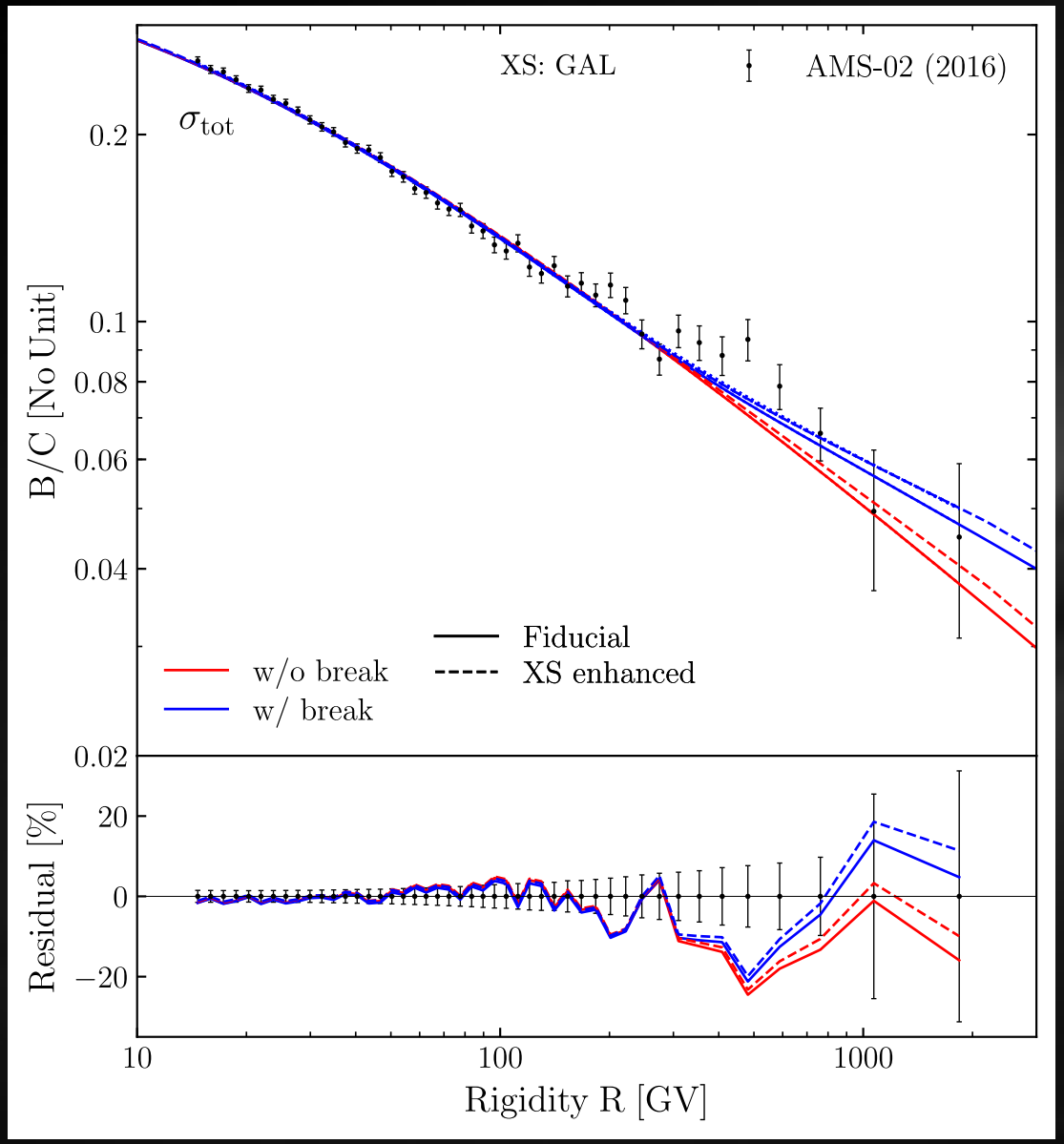
see i.e. Stodolsky, L. (2017). arXiv:1703.05668.

$$\frac{\mathcal{J}_B}{\mathcal{J}_C}(E_k) \underset{H.E.}{=} \sum_{Z_b \geqslant Z_C}^{Z_{max}} \sigma_{b\rightarrow B} \frac{\mathcal{J}_b}{\mathcal{J}_C} / \left\{\sigma^{\text{diff}} + \sigma_B\right\}$$

$\Rightarrow$We callibrate this enhancement on σ_{pp}^{tot}

M. M. Block et al (2015) Phys. Rev. D92, no. 11, 114021

Third step: robustness of the result



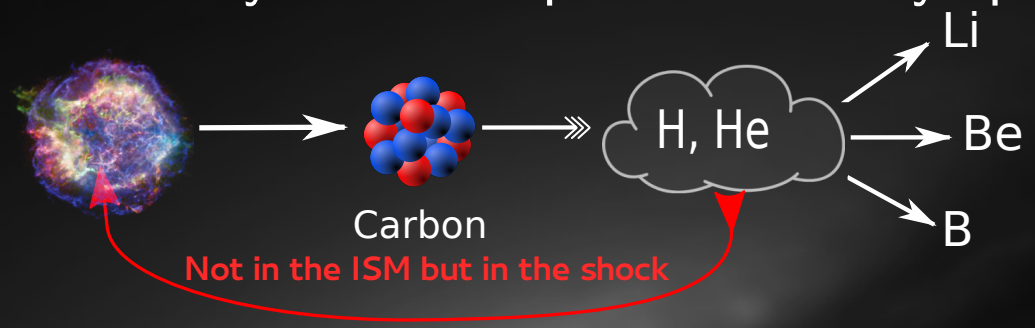
E-dependent XS

- **H1** (without) :
  $\chi^2 = 59$
  $\delta = 0.52$
  $K_0 = 7.4 \times 10^2 .\mathrm{kpc}^2.\mathrm{Myr}^{-1}$
- **H2** (with) :
  $\chi^2 = 48$
  $\delta = 0.53$
  $K_0 = 7.1 \times 10^2 .\mathrm{kpc}^2.\mathrm{Myr}^{-1}$
- $\Delta\chi^2 = 11$
  decisive evidence !
  (in Bayesian terms)
  H. Jeffreys (1961).

Example of the boron to carbon ratio

2nd effect which can mimic a break : primary boron

The boron may not be a pure secondary species.



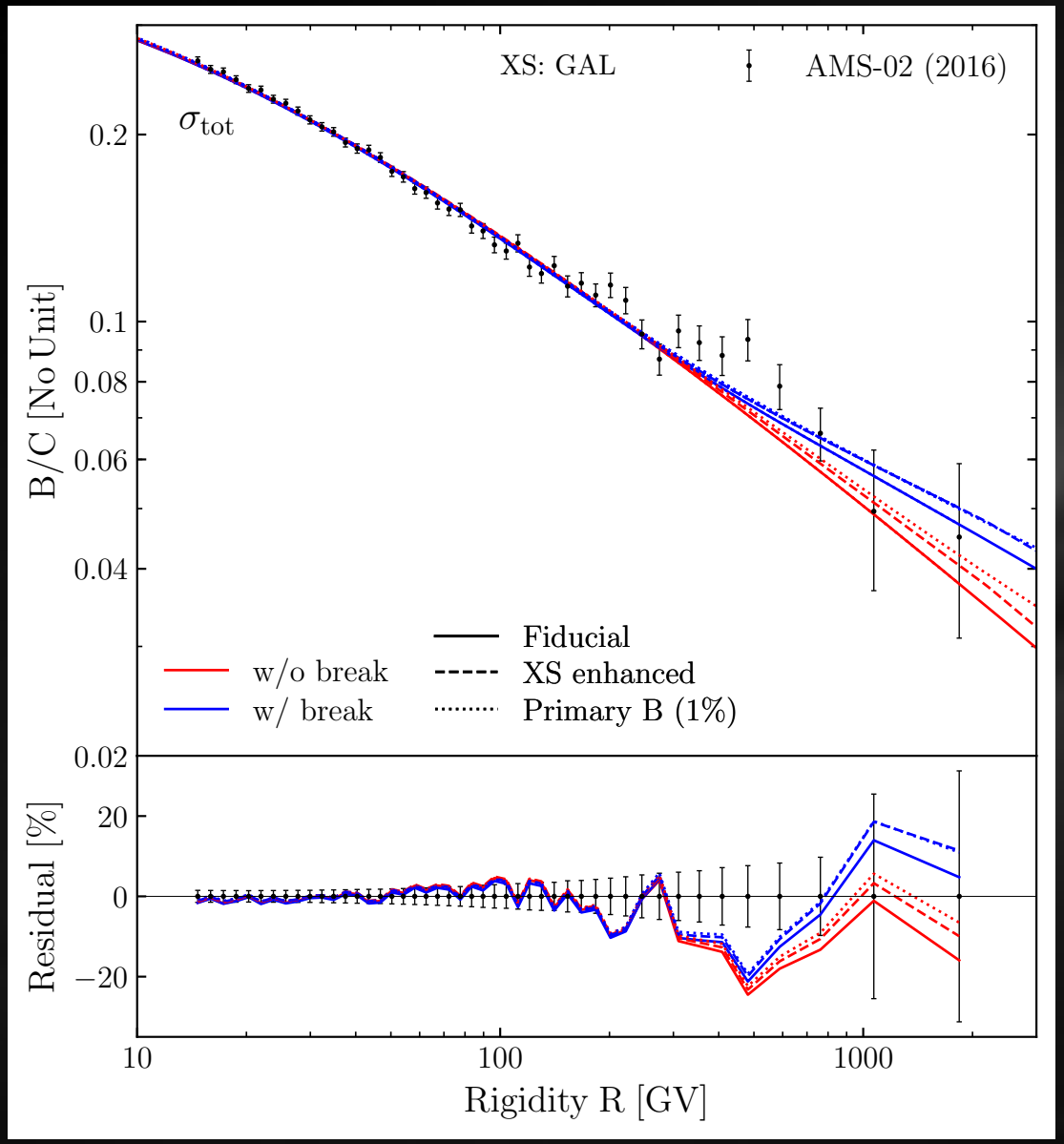
Probability of a carbon nuclei to interact during acceleration :

$$r\,\sigma_{\mathrm{B}\to\mathrm{C}}\,n_{ISM}\,\tau \sim 1\%$$

We expect an effective source term

$$Q_B/Q_C \approx 1\%$$

Third step: robustness of the result



Primary B (1%)

- **H1** (without) :
  $\chi^2 = 52$

  $\delta = 0.54$

  $K_0 = 7.2 \times 10^2 . \mathrm{kpc}^2 . \mathrm{Myr}^{-1}$
- **H2** (with) :
  $\chi^2 = 42$

  $\delta = 0.55$

  $K_0 = 6.9 \times 10^2 . \mathrm{kpc}^2 . \mathrm{Myr}^{-1}$
- $\Delta\chi^2 = \mathbf{10}$
  decisive evidence !
  (in Bayesian terms)
  H. Jeffreys (1961).

Third step: robustness of the result

Uncertainties in the inputs :

Spallation XS

?

GALPROP (GAL) Webber 2003 (W03)

Data uncertainties

?

Total σ_{tot} Statistical σ_{stat}

$\Rightarrow$ **In all cases the *decisive evidence* is confirmed**

Discussion...

⇒ **Indication for a diffusive explanation of the spectral breaks**

⇒ **The spectral shape of B/C can be completely explained by $\frac{Q_B}{Q_C}$ ∼5% but :**

i) We loose the common explanation for the breaks

ii) Lead to $\delta \sim 0.8$ in tension with antiprotons and anisotropy.

⇒ **Direct consequences for DM indirect searches**

⇒ **Enlarge data set in needed (Li, B, Be, C, N, O, ..) @∼100GeV-1TeV.**

⇒ **Further data from AMS-02, CALET, DAMPE, ISS-CREAM are eagerly awaited !**

Introduction

Semi-analytical approach

Hints for a new propagation paradigm?

Conclusion & Prospects

Conclusion & Prospects

Claims for DM discovery from CRs only have to wait !

⇒ **Propagation processes are not yet under control !**

↳ **This is partly due to dramatic low quality XS data**

⇒ **More advance scenarios of propagation should be tested**

↳ **anisotropic, inhomogeneous..**

⇒ **Till now the semi-analytical approach has proven very usefull !**

↳ **Gives a first order understanding of CR fluxes**

↳ **Learns us the physics through toy models and simplifications**

↳ **Completely complementary with the numerical approach**

Public version of USINE in october !

Questions

BACKUP

Primary boron

1st This determination is model dependent..

Example : boron may not be a pure secondary species.

Well motivated in litterature :

-*Blasi, P. (2009). Origin of the positron excess in cosmic rays. Physical Review Letters, 103(5), 051104.*

-*Blasi, P., & Serpico, P. D. (2009). High-energy antiprotons from old supernova remnants. Physical review letters, 103(8), 081103.*

-*Mertsch, P., & Sarkar, S. (2009). Testing astrophysical models for the PAMELA positron excess with cosmic ray nuclei. Physical review letters, 103(8), 081104.*

-*Tomassetti, N., & Donato, F. (2012). Secondary cosmic-ray nuclei from supernova remnants and constraints on the propagation parameters. Astronomy & Astrophysics, 544, A16.*

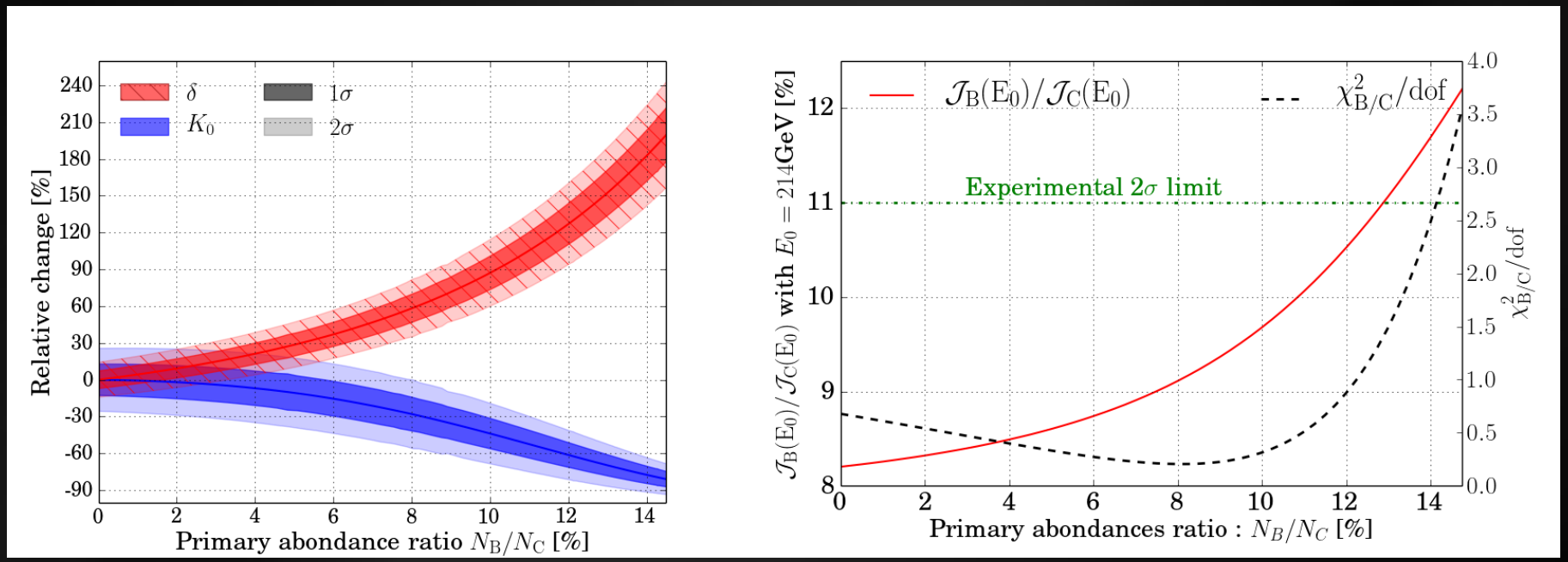
-*Mertsch, P., & Sarkar, S. (2014). AMS-02 data confront acceleration of cosmic ray secondaries in nearby sources. Physical Review D, 90(6), 061301.*

$\Rightarrow$ Used to explain anti particle excess !

Primary boron

Parametric study in :

Genolini, Y., Putze, A., Salati, P., & Serpico, P. D. (2015). Theoretical uncertainties in extracting cosmic-ray diffusion parameters: the boron-to-carbon ratio. Astronomy & Astrophysics, 580, A9.



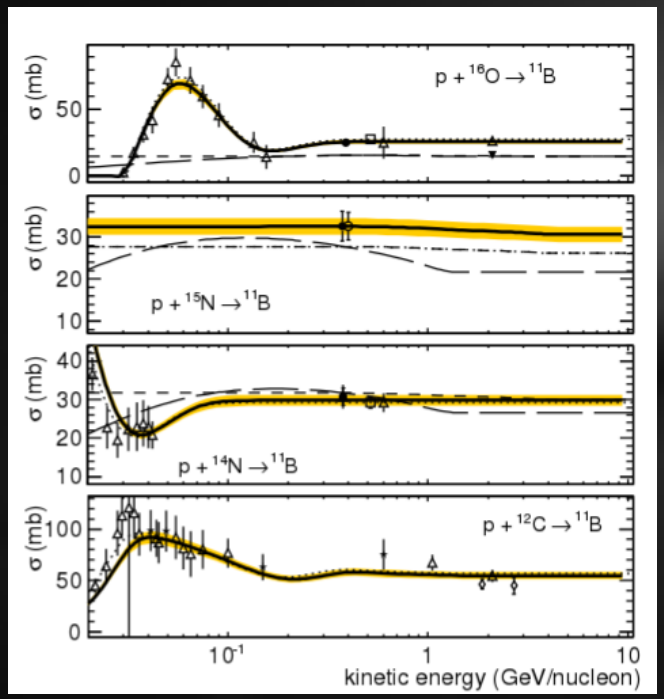
⇒**Scan over $\frac{N_B}{N_C}$ with preliminary AMS02 data.**

⇒**Few percent of contamination of primary boron → 30% uncertainty on delta !**

XS problem

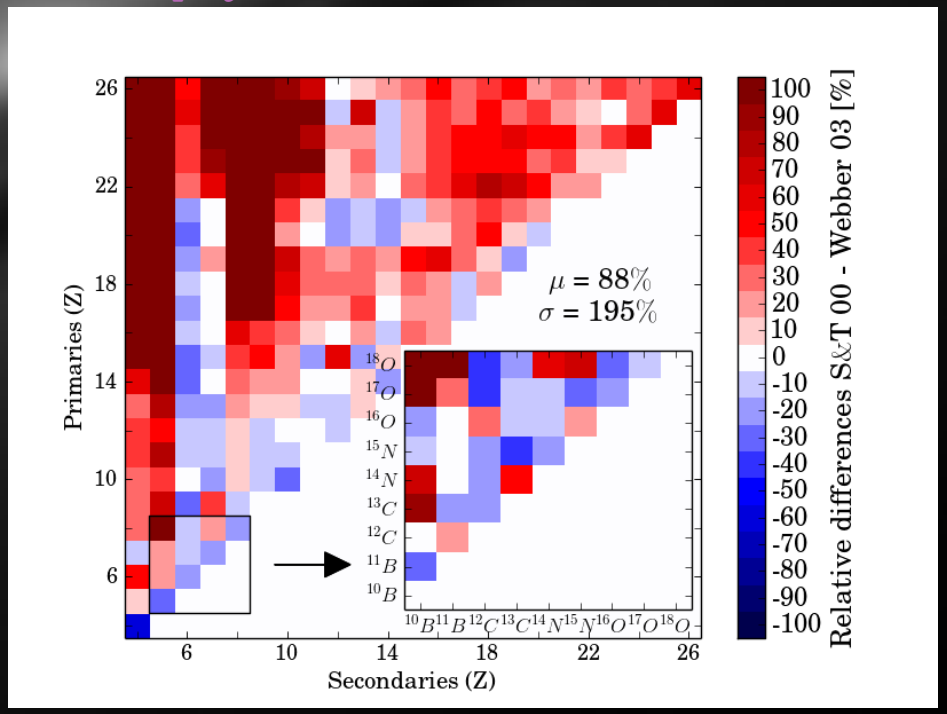
2nd This determination relies on very unprecise data.

$$\frac{\mathcal{J}_B}{\mathcal{J}_C}(E_k) = \sum_{Z_b \geqslant Z_C}^{Z_{max}} \sigma_{b\to B} \frac{\mathcal{J}_b}{\mathcal{J}_C} / \left\{ \sigma^{\text{diff}} + \sigma_B \right\}$$



Tomassetti, N. (2015). Physical Review C, 92(4), 045808.

Genolini, Y. et al (2015). Astronomy & Astrophysics, 580, A9.

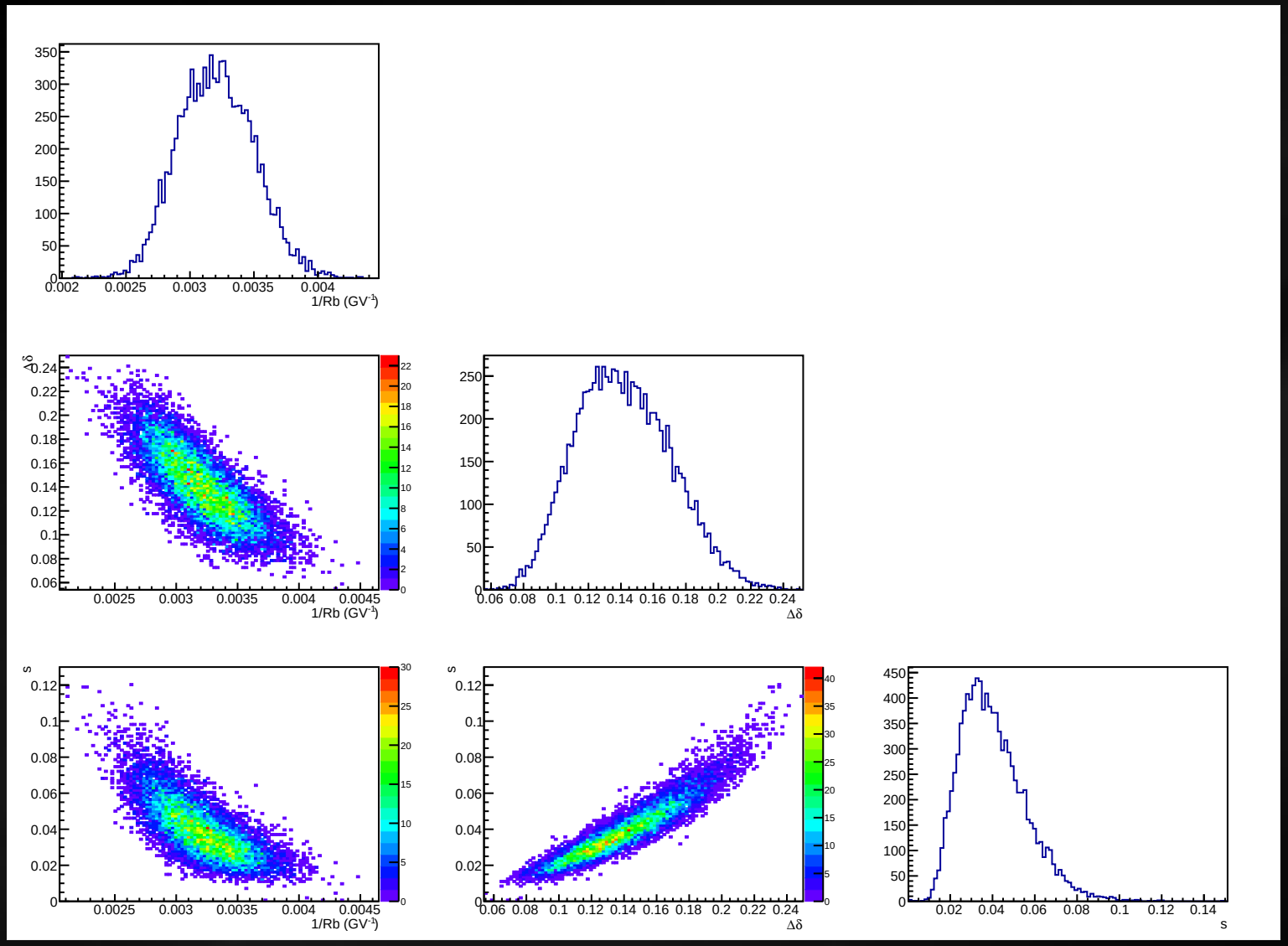


Summary of the evidence in all cases

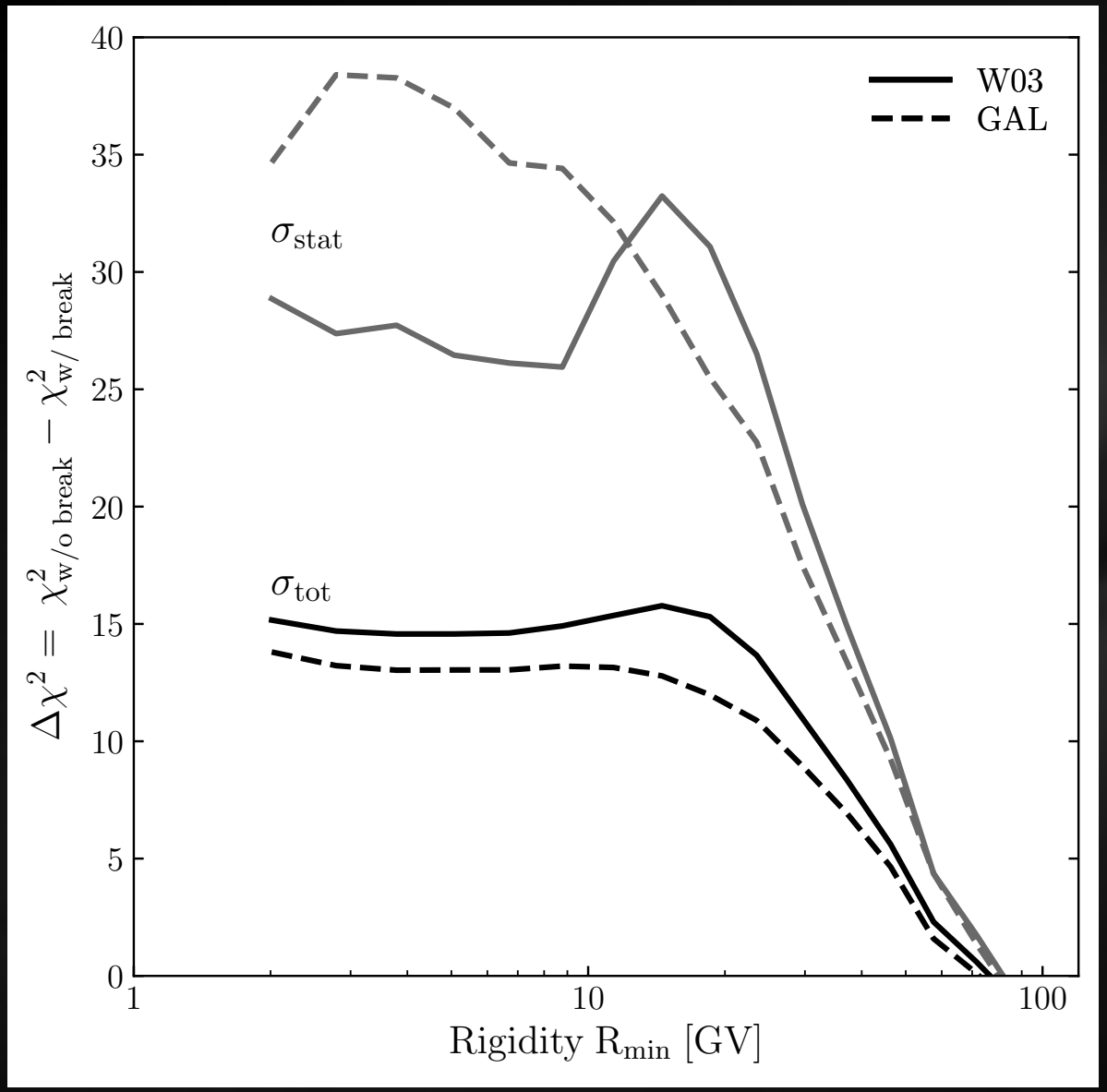
Fit cases		Fiducial							Cross section enhanced							Primary boron $Q_B/Q_C = 1\%$						
Error	Spal. XS	w/o break			w/ break				w/o break			w/ break				w/o break			w/break			
		K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$	K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$	K_0	δ	χ^2	K_0	δ	χ^2	$\Delta\chi^2$
$\sigma_{\rm stat}$	W03	2.7	0.67	197	2.7	0.68	164	**33**	2.7	0.67	190	2.7	0.68	160	**30**	2.8	0.69	155	2.8	0.69	131	**24**
	GAL	4.3	0.62	160	4.3	0.62	131	**29**	4.3	0.62	154	4.2	0.62	127	**27**	4.4	0.64	126	4.3	0.64	105	**21**
$\sigma_{\rm tot}$	W03	4.5	0.58	84	4.3	0.59	68	**16**	4.4	0.58	80	4.3	0.59	65	**15**	4.4	0.60	69	4.2	0.61	57	**12**
	GAL	7.4	0.52	62	7.1	0.53	50	**12**	7.3	0.52	59	7.0	0.53	48	**11**	7.2	0.54	52	6.9	0.55	42	**10**

TABLE I: Best fit values for K_0 (in units of 10^2 kpc^2.Myr^{-1}) and δ, using AMS-02 B/C data above $R_{\rm min} = 15$ GV. The number of degrees of freedom is $46 - 2 = 44$. For each cases described in the paper, we compare the best χ^2 with and without the break. Two different spallation cross-section (Spal. XS) datasets are tested, i.e., GALPROP (GAL) and Webber (W03), as well as different choices for the data uncertainties.

Correlations of the break parameters:



Scan on R_{min}


W03
GAL
$\sigma_{\rm stat}$
$\sigma_{\rm tot}$
$\Delta\chi^2 = \chi^2_{\rm w/o\ break} - \chi^2_{\rm w/\ break}$
Rigidity $R_{\rm min}$ [GV]
0
5
10
15
20
25
30
35
40
1
10
100

Status of antiprotons

NEWS : Two PRLs pointing toward an excess around $\sim$20-80 GeV

↳ consistent with the *Galactic center gamma-ray excess*.

Cuoco, A. et al (2017).PRL,118(19),191102. & Cui, M. Y. et al (2017).PRL,118(19),191101.

$\Rightarrow$ Compatibility numerical vs analytical codes ?

↳ tertiary contribution under control ?

Refinement of this prediction includes :

→ Refreshing XS measurement *Donato et al arXiv:1704.03663.*

→ Recalibrating the propagation parameters from i.e. B/C

→ Better understanding of the solar modulation

Main channels contributing to boron

XS dataset : Webber 2003 Usine output !

Energy	1 GeV/nuc		10 GeV/nuc	
1 step	74.6%		80.6%	
2 steps	19.4%		15.9%	
>2 steps	6%		3.5%	
>1%	$^{11}B \leftarrow^{12} C$	33%	$^{11}B \leftarrow^{12} C$	32.4%
	$^{11}B \leftarrow^{16} O$	15.9%	$^{11}B \leftarrow^{16} O$	18.8%
	$^{10}B \leftarrow^{12} C$	10.3%	$^{10}B \leftarrow^{12} C$	10.4%
	$^{10}B \leftarrow^{16} O$	7.4%	$^{10}B \leftarrow^{16} O$	9.0%
	$^{10}B \leftarrow^{11} B \leftarrow^{12} C$	3.0%	$^{10}B \leftarrow^{11} B \leftarrow^{12} C$	2.3%
	$^{11}B \leftarrow^{12} C \leftarrow^{16} O$	2.3%	$^{11}B \leftarrow^{24} Mg$	1.8%
	$^{11}B \leftarrow^{15} N \leftarrow^{16} O$	2.2%	$^{11}B \leftarrow^{12} C \leftarrow^{16} O$	1.7%
	$^{10}B \leftarrow^{11} B \leftarrow^{16} O$	1.5%	$^{11}B \leftarrow^{15} N \leftarrow^{16} O$	1.6%
	$^{11}B \leftarrow^{24} Mg$	1.4%	$^{11}B \leftarrow^{14} N$	1.5%
	$^{11}B \leftarrow^{14} N$	1.3%	$^{11}B \leftarrow^{28} Si$	1.4%
	$^{11}B \leftarrow^{14} N \leftarrow^{16} O$	1.2%	$^{11}B \leftarrow^{20} Ne$	1.4%
	$^{11}B \leftarrow^{13} C \leftarrow^{16} O$	1.1%	$^{10}B \leftarrow^{11} B \leftarrow^{16} O$	1.3%
	$^{11}B \leftarrow^{20} Ne$	1.1%		
	$^{11}B \leftarrow^{28} Si$	1.0%		
	# of reactions	Total	# of reactions	Total
$[0.1\%, 1\%]$	28	7.2%	28	8.8%
$[0.01\%, 0.1\%]$	89	3.3%	90	3.5%
$< 0.01\%$	276	0.7%	277	0.7%

XS Precision measurements

⇒ Production XS are a limiting factor to reach the percent accuracy in modelling

- A few key channels should be measured with high accuracy (contribute to 50%)
- A huge number of individually-low-level contributions can make up up to 10%

⇒ Dominant production channels do not depend too much on the level of accuracy we presently have on the XS

↳ **In preparation : tables with channels ranking to define priorities of future nuclei XS measurements**

In collaboration with David Maurin, Igor Moskalenko, Leslie M. Kerby