Cosmic rays:
new insights in the precision era!

Yoann Genolini

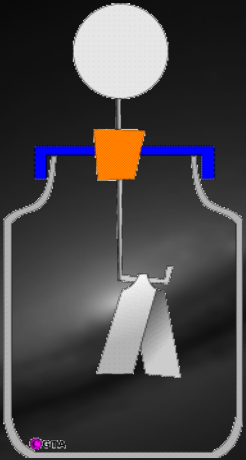
LAPTh
Annecy-Le-Vieux, FRANCE

cnrs dépasser les frontières

UNIVERSITÉ SAVOIE MONT BLANC

OSLO March 3rd, 2017

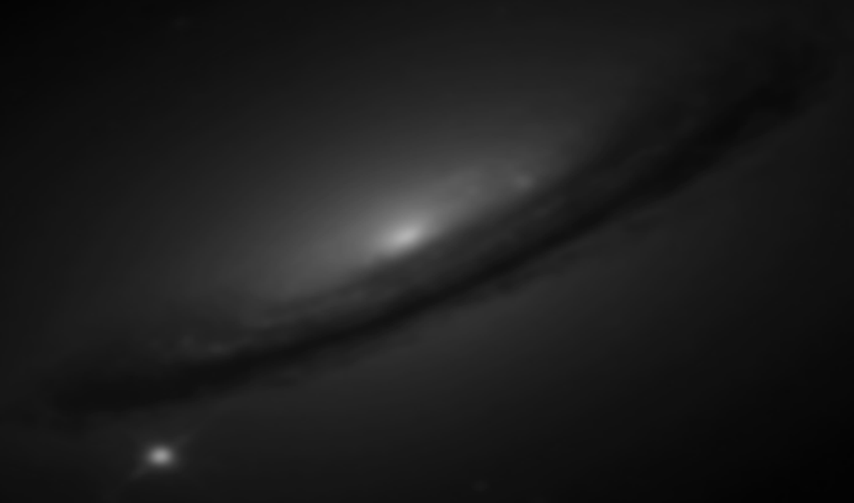
Introduction



Yoann Génolini

Introduction

Pioniers of the discovery :



Yoann Génolini

Introduction

Pioniers of the discovery :

- **1911** : Domenico Pacini

- **1912** : Victor Hess

Introduction

Pioniers of the discovery :

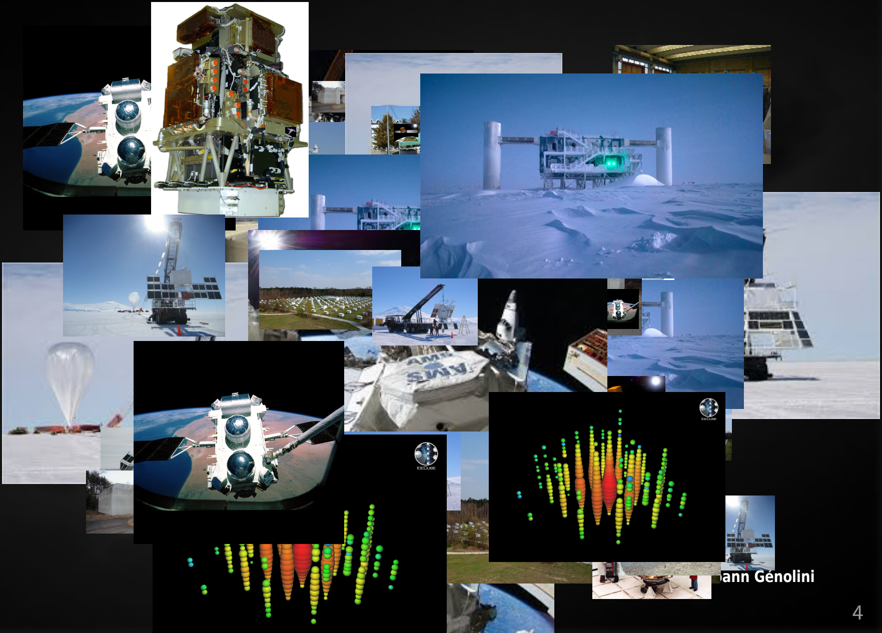
- **1911** : Domenico Pacini

  → *"Observations that were made on the sea during the year 1910 led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth's surface."* *Pacini, D. (1912). La radiazione penetrante alla superficie ed in seno alle acque.*

- **1912** : Victor Hess

  → *"The results of the present observations seem to be most readily explained by the assumption that a radiation of very high penetrating power enters our atmosphere from above . . . Since I found a reduction . . . neither by night nor at a solar eclipse, one can hardly consider the Sun as the origin."* *Hess, V. F. (1912). Observations of the penetrating radiation on seven balloon flights. Physik. Zeitschr.*

Introduction



Introduction

The precision era!

The challenge of CRs propagation

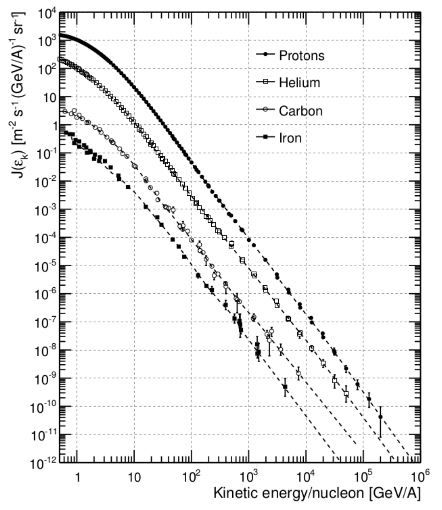
Impact on dark matter searches

Sensibility to the stochastic production of cosmic rays

Conclusion & Prospects

Salient feature 1

Composition of cosmic rays :



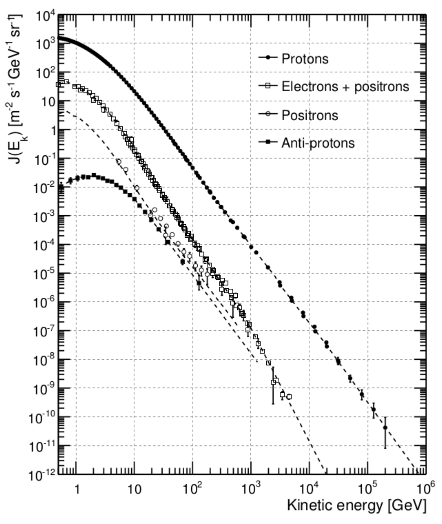
Particle	Fraction
protons	85%
helium nuclei	12.5%
heavier nuclei	1%
Electrons	1.5%

$\Rightarrow$ **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

Salient feature 1

Composition of cosmic rays :



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

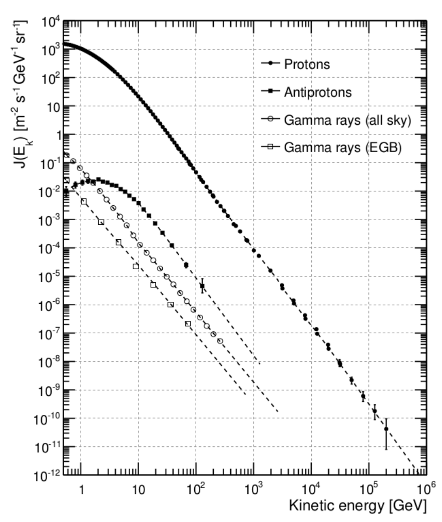
⇒ Very small fraction of otherthings than proton and helium.

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

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

Salient feature 1

Composition of cosmic rays :



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

$\Rightarrow$ **Very small fraction of otherthings than proton and helium.**

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

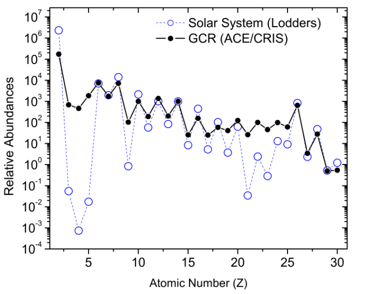
$\Rightarrow$ **Even less gamma-rays..but cleaner channel.**

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

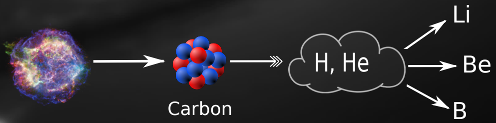
Yoann Génolini

Salient feature 1

Secondary or primary species ?



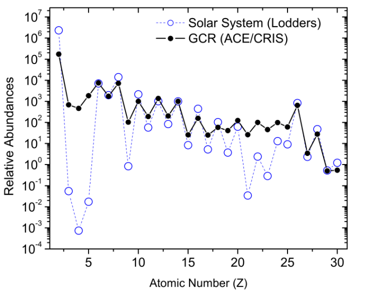
Israel et al (2005). Nuclear Physics, Nuclear Physics A, 758, 201-208



Yoann Génolini

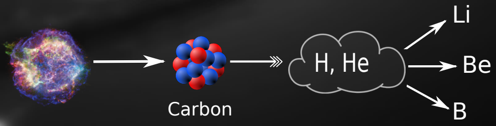
Salient feature 1

Secondary or primary species ?



Israel et al (2005). Nuclear Physics, Nuclear Physics A, 758, 201-208

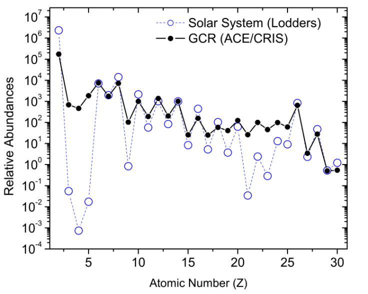
$\Rightarrow$ **Abundance differences explained by secondary production.**



Yoann Génolini

Salient feature 1

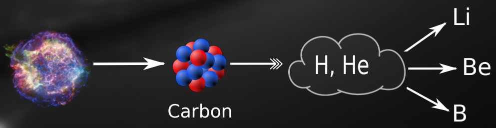
Secondary or primary species ?



Israel et al (2005). Nuclear Physics, Nuclear Physics A, 758, 201-208

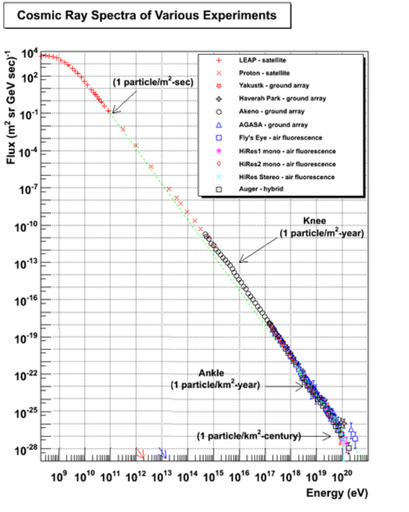
⇒ **Abundance differences explained by secondary production.**

⇒ **Quantitatively CR antiparticles are mostly secondary !**



Salient feature 2

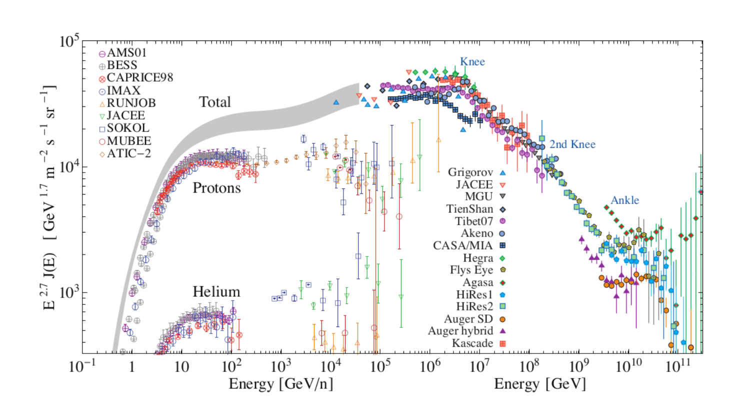
Cosmic rays spectrum :



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

Salient feature 2

Cosmic rays spectrum :



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

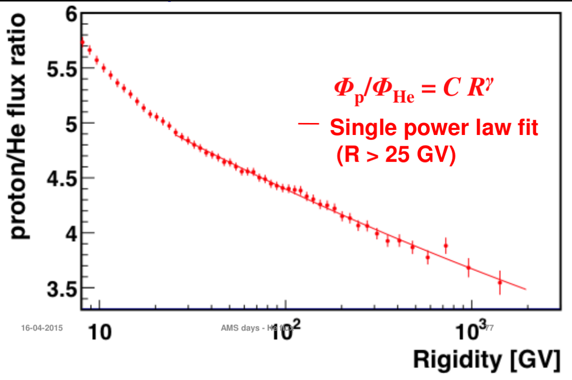
Most beautiful powerlaw in nature ?

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

Yoann Génolini

Salient feature 2

Cosmic rays spectrum :



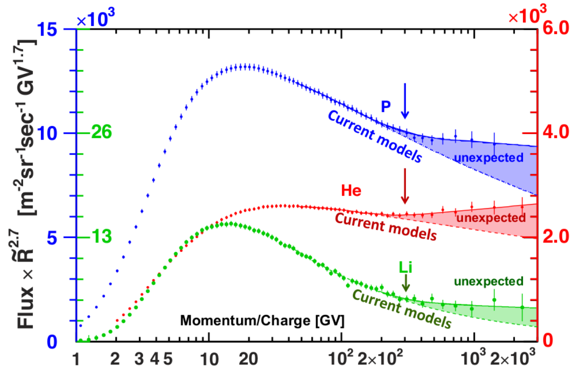
S.Ting presentation, CERN, december 2016

⇒ **Tiny difference of slopes** $\Delta_{H,He} \approx 0.1$

Yoann Génolini

Salient feature 2

Cosmic rays spectrum :



S.Ting presentation, CERN, december 2016

⇒ **Tiny difference of slopes** $\Delta_{H,He} \approx 0.1$

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

The precision era!

The challenge of CRs propagation

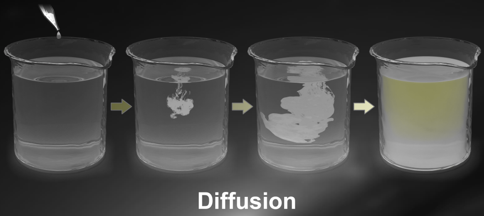
Impact on dark matter searches

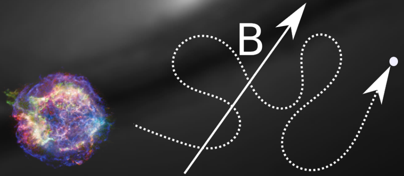
Sensibility to the stochastic production of cosmic rays

Conclusion & Prospects

The propagation equation

CRs diffuse in the turbulent magnetic field..



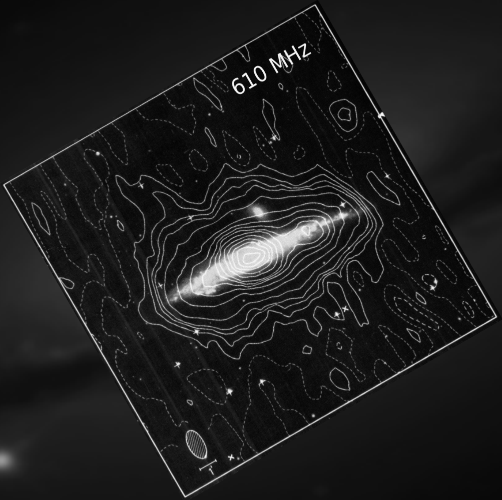


..and undergo a large variety of processes

Yoann Génolini

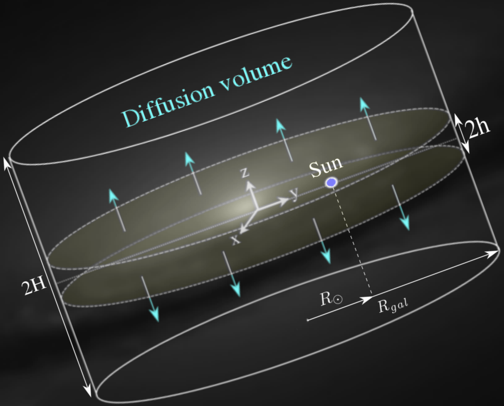
The propagation equation

CRs diffuse in the turbulent magnetic field..



Ekers, R.D. & Sancisi, R. (1977). The radio continuum halo in NGC 4631. Astronomy and Astrophysics

The propagation equation



Yoann Génolini

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** $K = K_0 \beta R^\delta$

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

$$= q_a$$

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**

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

$$= q_a$$

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**

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

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

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

Yoann Génolini

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

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

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

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

The propagation equation

There are many parameters to fix !

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

$$-\frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{V_c})\,p\,\frac{\partial f_a}{\partial p} + \nabla_{\boldsymbol{p}}(b(\boldsymbol{p})\,f_a) + \sigma_a v_a\, n_{ISM}\, f_a + \frac{f_a}{\tau_a}$$

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

The propagation equation

There are many parameters to fix !

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

$$- \frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{V_c})\, p\, \frac{\partial f_a}{\partial p} + \nabla_{\boldsymbol{p}}(\boldsymbol{b}(\boldsymbol{p})\, f_a) + \boldsymbol{\sigma_a} v_a\, \boldsymbol{n}_{ISM}\, f_a + \frac{f_a}{\boldsymbol{\tau_a}}$$

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

$\Rightarrow$ Fixed by “Laboratory” experiments or simulations

$\Rightarrow$ Fixed by cosmic ray fluxes depending on the choosen phenomenology

The propagation equation

There are many parameters to fix !

$$\begin{aligned}
&\frac{\partial f_a}{\partial t} - \nabla_{\boldsymbol{x}}.(\boldsymbol{K}\, \nabla_{\boldsymbol{x}} f_a) - \nabla_{\boldsymbol{p}}.(\boldsymbol{D}\, \nabla_{\boldsymbol{p}} f_a) + \boldsymbol{V_c}.\nabla_{\boldsymbol{x}} f_a \\
&- \frac{1}{3}(\nabla_{\boldsymbol{x}}.\boldsymbol{V_c})\, p\, \frac{\partial f_a}{\partial p} + \nabla_{\boldsymbol{p}}(\boldsymbol{b}(\boldsymbol{p}) f_a) + \boldsymbol{\sigma_a} v_a\, \boldsymbol{n}_{ISM}\, f_a + \frac{f_a}{\boldsymbol{\tau_a}} \\
&= q_a + \sum_{Z_\beta \geqslant Z_a}^{Z_{max}} \boldsymbol{\sigma_{b \to a}} v_b\, \boldsymbol{n}_{ISM}\, f_b + \frac{f_b}{\boldsymbol{\tau_b}}
\end{aligned}$$

$\Rightarrow$ Fixed by “Laboratory” experiments or simulations

$\Rightarrow$ Fixed by cosmic ray fluxes depending on the choosen phenomenology

$\hookrightarrow$Key observable : secondary to primary ratios !

Example of the boron to carbon ratio

Secondary/primary ratio in a 1D geometry :

$$\mathcal{J}_B(E_k) = \left\{ Q_B + \sum_{Z_b \geqslant Z_B}^{Z_{max}} \sigma_{b \to B}\, \mathcal{J}_b \right\} / \left\{ \sigma^{\text{diff}} + \sigma_B \right\} \quad (1)$$

Hypothesis :

Example of the boron to carbon ratio

Secondary/primary ratio in a 1D geometry :

$$\mathcal{J}_B(E_k) = \sum_{Z_b \geqslant Z_B}^{Z_{max}} \sigma_{b\to B}\, \mathcal{J}_b / \left\{\sigma^{\text{diff}} + \sigma_B\right\} \qquad (1)$$

Hypothesis :

- $Q_B = 0$

Example of the boron to carbon ratio

Secondary/primary ratio in a 1D geometry :

$$\mathcal{J}_B(E_k) = \sigma_{C \to B} \, \mathcal{J}_C / \left\{ \sigma^{\text{diff}} + \sigma_B \right\} \tag{1}$$

Hypothesis :

- $Q_B = 0$
- Double nuclei system (B,C)

Yoann Génolini

Example of the boron to carbon ratio

Secondary/primary ratio in a 1D geometry :

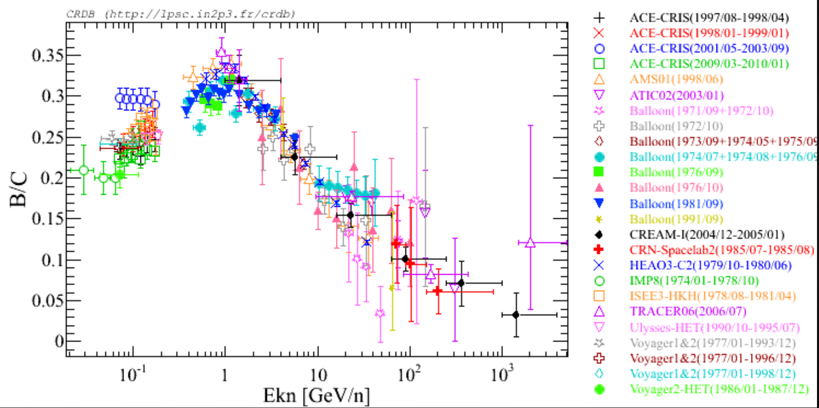
$$\frac{\mathcal{J}_B}{\mathcal{J}_C}(E_k) = \sigma_{C\to B}/\left\{\sigma^{\text{diff}} + \sigma_B\right\}.$$

When : $\sigma_B << \sigma^{diff} \propto K = K_0 R^\delta \Rightarrow \boxed{\frac{\mathcal{J}_B}{\mathcal{J}_C} \propto R^{-\delta}}$

Yoann Génolini

Example of the boron to carbon ratio

Experimental data :

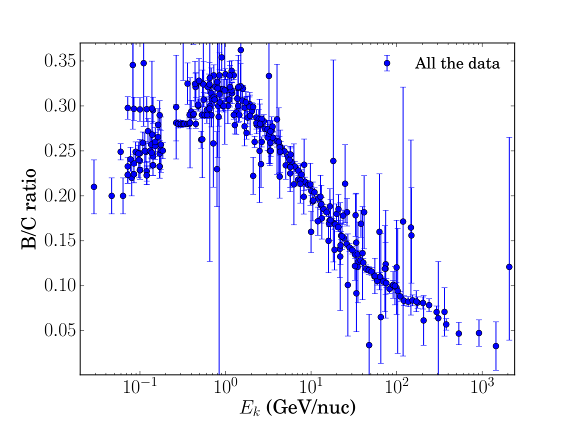


CRDB data base. Maurin et al

⇒ The decreasing powerlaw is well motivated by the data

Example of the boron to carbon ratio

Experimental data :



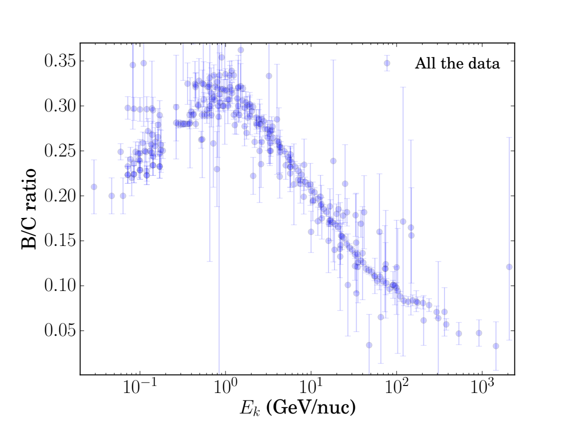
Engelmann, J. J. et al (1990). Astronomy and Astrophysics, 233, 96-111.

$\Rightarrow$ At $\simeq 10\text{GeV}$ $\frac{\sigma^{tot}_{PAMELA}}{\sigma^{tot}_{HEAO3}} \approx 6.5$ and $\frac{\sigma^{tot}_{HEAO3}}{\sigma^{tot}_{AMS02}} \approx 1.3$

Yoann Génolini

Example of the boron to carbon ratio

Experimental data :



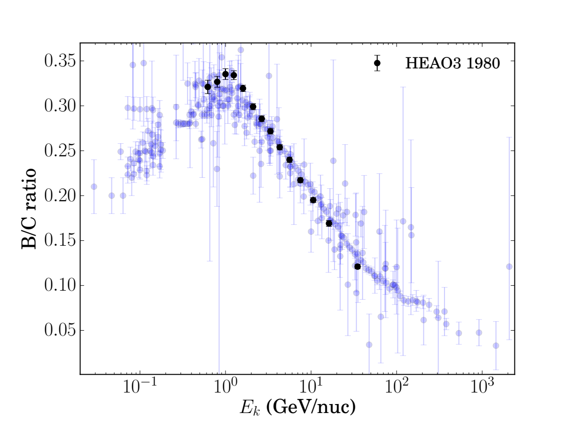
Engelmann, J. J. et al (1990). Astronomy and Astrophysics, 233, 96-111.

$$\Rightarrow \text{At} \simeq 10\text{GeV} \ \frac{\sigma^{tot}_{PAMELA}}{\sigma^{tot}_{HEAO3}} \approx 6.5 \text{ and } \frac{\sigma^{tot}_{HEAO3}}{\sigma^{tot}_{AMS02}} \approx 1.3$$

Yoann Génolini

Example of the boron to carbon ratio

Experimental data :



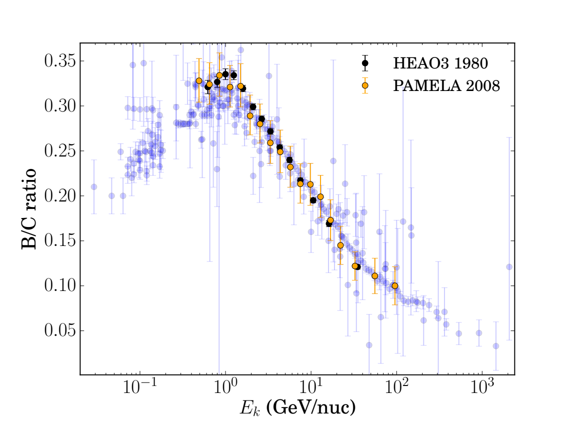
Engelmann, J. J. et al (1990). Astronomy and Astrophysics, 233, 96-111.

$\Rightarrow$ At $\simeq 10\text{GeV}$ $\frac{\sigma^{tot}_{PAMELA}}{\sigma^{tot}_{HEAO3}} \approx 6.5$ and $\frac{\sigma^{tot}_{HEAO3}}{\sigma^{tot}_{AMS02}} \approx 1.3$

Yoann Génolini

Example of the boron to carbon ratio

Experimental data :



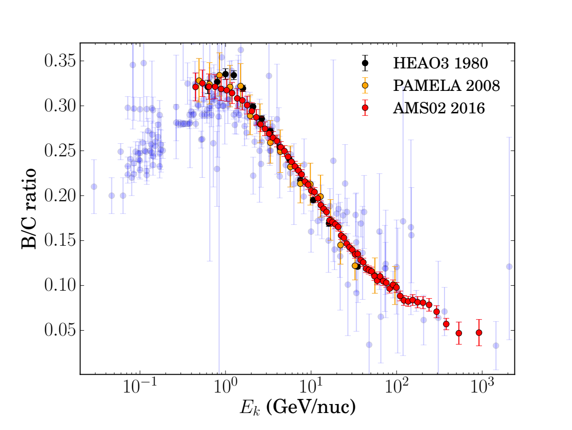
Adriani, O. et al (2014). The Astrophysical Journal, 791(2), 93.

$\Rightarrow$ At $\simeq 10\text{GeV}$ $\frac{\sigma^{tot}_{PAMELA}}{\sigma^{tot}_{HEAO3}} \approx 6.5$ and $\frac{\sigma^{tot}_{HEAO3}}{\sigma^{tot}_{AMS02}} \approx 1.3$

Yoann Génolini

Example of the boron to carbon ratio

Experimental data :



Aguilar, M. et al (2016). Physical Review Letters, 117(23), 231102.

$$\Rightarrow \text{At} \simeq 10\text{GeV} \ \frac{\sigma^{tot}_{PAMELA}}{\sigma^{tot}_{HEAO3}} \approx 6.5 \text{ and } \frac{\sigma^{tot}_{HEAO3}}{\sigma^{tot}_{AMS02}} \approx 1.3$$

Yoann Génolini

Example of the boron to carbon ratio

Secondary/primary ratio in a 1D geometry :

$$\frac{\mathcal{J}_B}{\mathcal{J}_C}(E_k) = \sigma_{C\to B} / \left\{ \sigma^{\text{diff}} + \sigma_B \right\}.$$

When : $\sigma_B << \sigma^{diff} \Rightarrow \boxed{\frac{\mathcal{J}_B}{\mathcal{J}_C} \propto R^{-\delta}}$

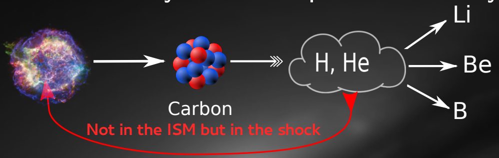
Using the all energy range $\frac{\mathcal{J}_B}{\mathcal{J}_C}$ can be used to constrain :

$$\boldsymbol{V_c \,,\; K = K_0\, R^{\delta} \,,\; D \,,\; L}$$

Example of the boron to carbon ratio

1^{st} This determination is model dependent..

Example : boron may not be a pure secondary species.



- Confinement inside a SNR at TeV/nuc :

$$X_{SNR} \approx 0.17 \text{ g. cm}^{-2} \frac{n_{ISM}}{\text{cm}^{-3}} \frac{T_{SNR}}{2.10^4 \text{ yr}}$$

- Galactic diffusion at TeV/nuc :

$$X_{Diff} \approx 1.2 \text{ g. cm}^{-2}$$

$\Rightarrow \simeq 10\%$ **of the boron may be "primary" !**

Yoann Génolini

Example of the boron to carbon ratio

1[st] 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.*

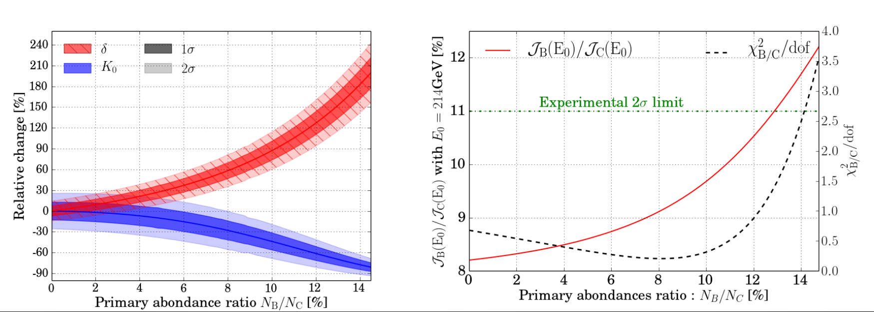
$\Rightarrow$ Used to explain anti particle excess !

Yoann Génolini

Example of the boron to carbon ratio

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.

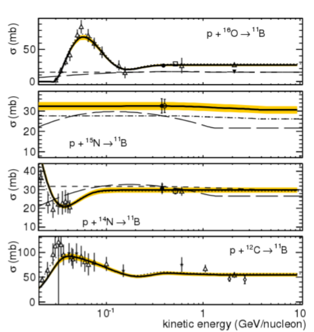
⇒Few percent of contamination of primary boron → 30% uncertainty on delta !

Yoann Génolini

Example of the boron to carbon ratio

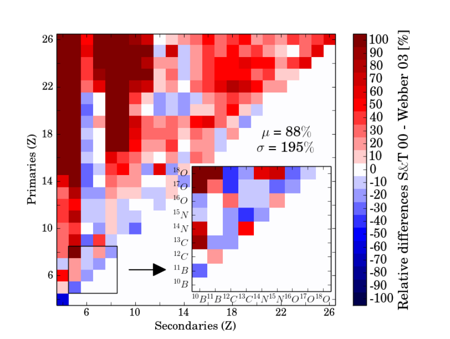
2nd This determination relies on very unprecise data.

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



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

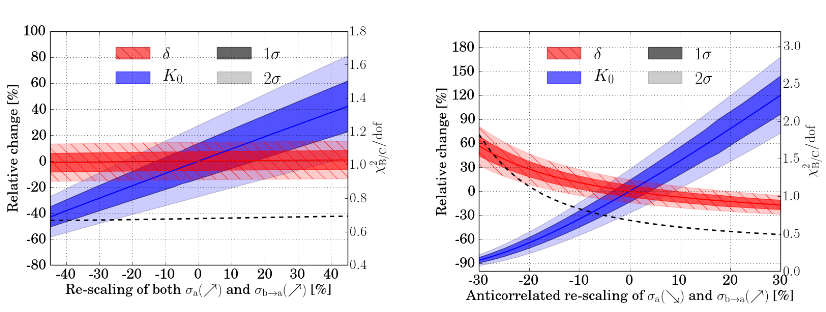
Genolini, Y. et al (2015). Astronomy & Astrophysics, 580, A9.



Example of the boron to carbon ratio

Parametric study in :

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



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

⇒10-20% of variation of the XS leads to 10-20% uncertainty on delta !

Note : Workshop @CERN XSCRC https ://indico.cern.ch/event/563277/timetable/

The precision era!

The challenge of CRs propagation

Impact on dark matter searches

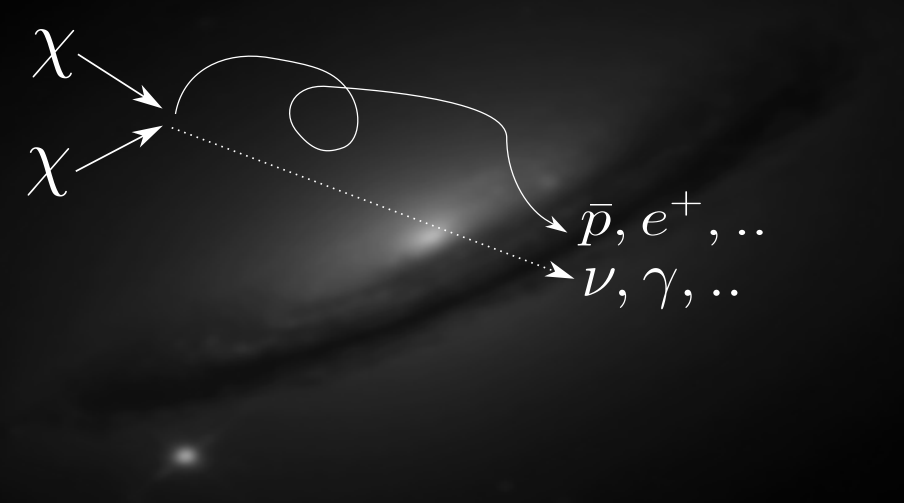
Sensibility to the stochastic production of cosmic rays

Conclusion & Prospects

Yoann Génolini

Indirect dark matter searches

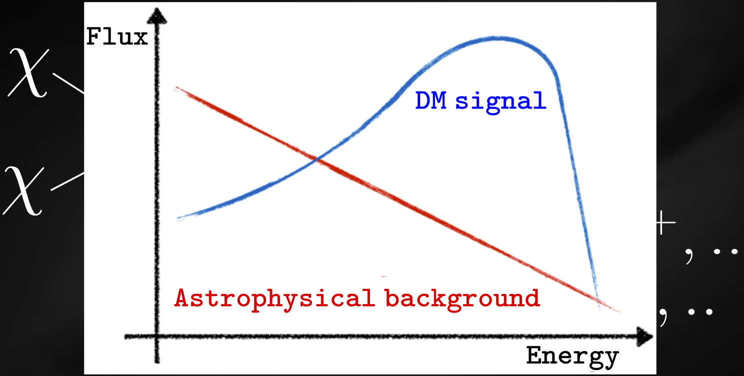
The Principle :



Yoann Génolini

Indirect dark matter searches

The Principle :



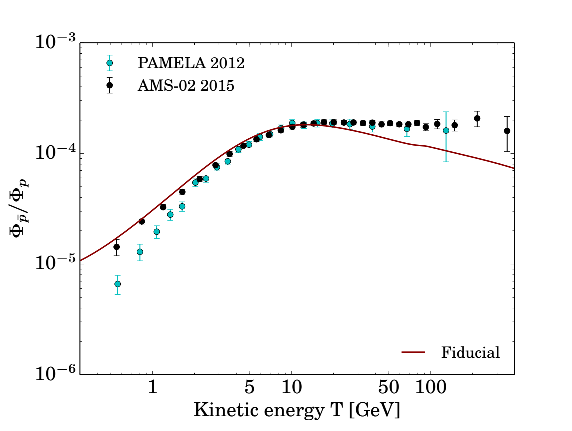
$\Rightarrow$ A fair evaluation of the atrophysical background is needed !

Yoann Génolini

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \longrightarrow ISM \longrightarrow \bar{p} + ..$$



Giesen, G., Boudaud, M., Génolini, Y., Poulin, V., Cirelli, M., Salati, P., & Serpico, P. D. (2015). JCAP, 2015(09), 023.

Yoann Génolini

Refreshing the astrophysical background

Equation of propagation in steady state :

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

With : $Q(\psi_p, \psi_{He}, \sigma_{pH\to\bar{p}}(E), ..)$

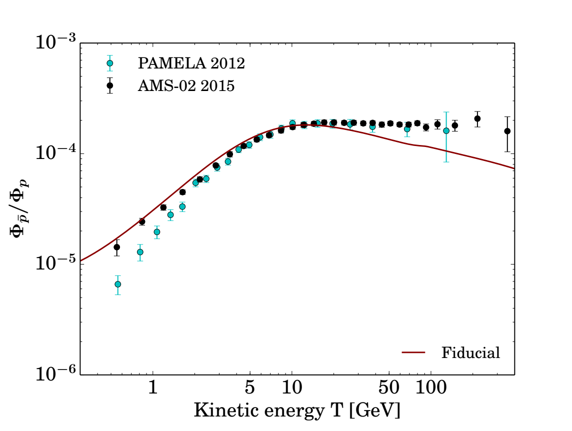
- **Propagation uncertainties** :
  → *Maurin, D., Donato, F., Taillet, R., & Salati, P. (2001). The Astrophysical Journal, 555(2), 585.*
- **Primary fluxes uncertainties** :
  → *Aguilar, M. et al (2015). 114(17), 171103.*
- **Production cross-section** :
  → *Di Mauro, M., Donato, F., Goudelis, A., & Serpico, P. D. (2014). Physical Review D, 90(8), 085017.*

Yoann Génolini

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \longrightarrow ISM \longrightarrow \bar{p} + ..$$



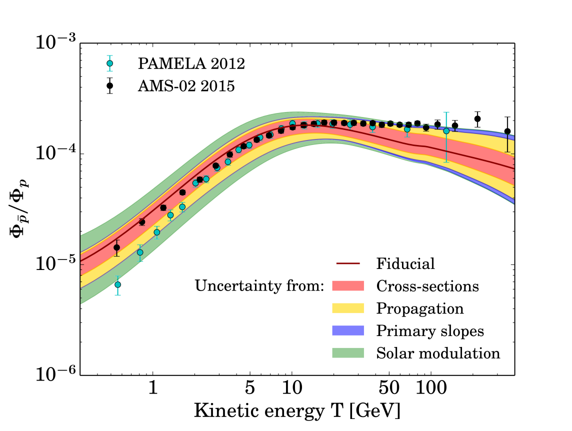
Giesen, G., Boudaud, M., Génolini, Y., Poulin, V., Cirelli, M., Salati, P., & Serpico, P. D. (2015). JCAP, 2015(09), 023.

Yoann Génolini

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \longrightarrow ISM \longrightarrow \bar{p} + ..$$



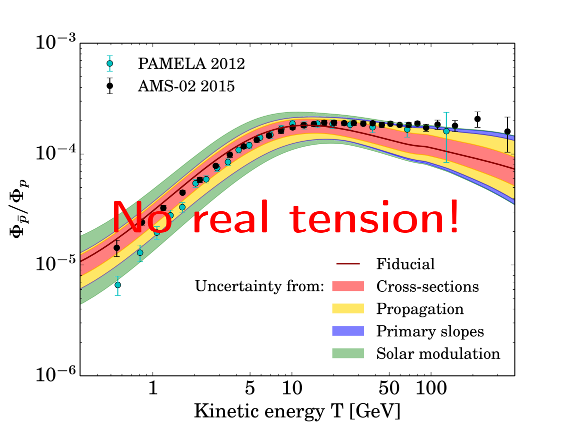
Giesen, G., Boudaud, M., Génolini, Y., Poulin, V., Cirelli, M., Salati, P., & Serpico, P. D. (2015). JCAP, 2015(09), 023.

Yoannn Génolini

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \quad \longrightarrow \quad ISM \quad \longrightarrow \quad \bar{p} + ..$$



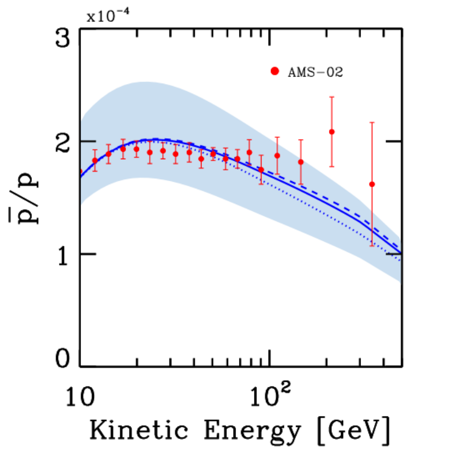
Giesen, G., Boudaud, M., Génolini, Y., Poulin, V., Cirelli, M., Salati, P., & Serpico, P. D. (2015). JCAP, 2015(09), 023.

Yoann Génolini

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \quad \longrightarrow \quad ISM \quad \longrightarrow \quad \bar{p} + ..$$



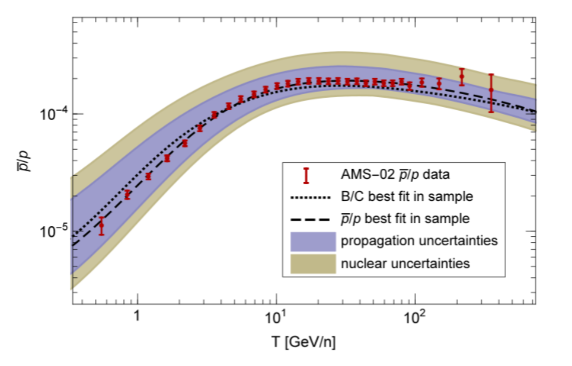
Yoann Génolini

Evoli, C., Gaggero, D., & Grasso, D. (2015). Secondary antiprotons as a Galactic Dark Matter probe. JCAP, 2015(12), 039.

Refreshing the astrophysical background

Case of **secondary antiprotons** :

$$p, He \longrightarrow ISM \longrightarrow \bar{p} + ..$$

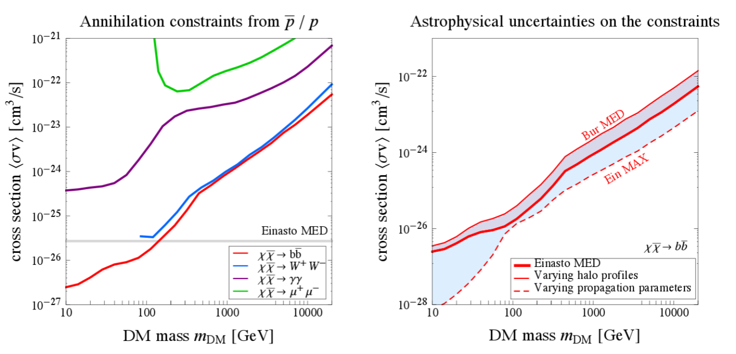


Kappl, R., Reinert, A., & Winkler, M. W. (2015). AMS-02 antiprotons reloaded. JCAP, 2015(10), 034.

Refreshing the astrophysical background

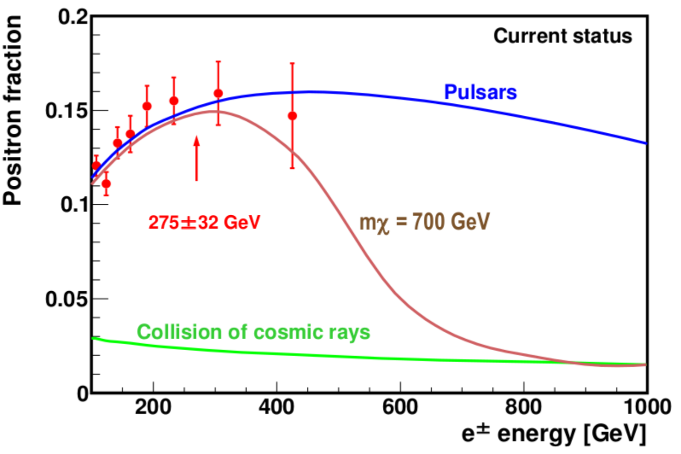
Case of **secondary antiprotons** :

$$p, He \longrightarrow ISM \longrightarrow \bar{p} + ..$$



Giesen, G., Boudaud, M., Génolini, Y., Poulin, V., Cirelli, M., Salati, P., & Serpico, P. D. (2015). JCAP, 2015(09), 023.

Impact in positrons searches



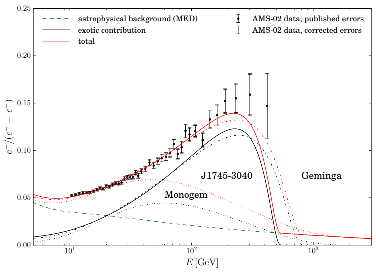
Pulsar or DM ?

Yoann Génolini

Typical fits of the positron fraction:

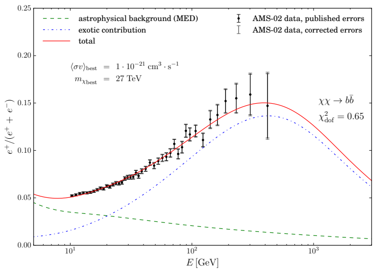
$$\Phi_{e+} = \Phi_{e+}^{\text{secondary}} + \Phi_{e+}^{\text{primary}}$$

Pulsar explanation ?



Fit of $\{fW_0, \gamma\}$

Dark matter explanation ?



Fit of $\{< \sigma v >, m_\chi\}$

Boudaud, M., Aupetit, S., Caroff, S., Putze, A., Belanger, G., Genolini, Y. et al. Astronomy & Astrophysics, 575, A67.

Yoann Génolini

But not below 10 GeV !

Motivations of :

Boudaud, M., Bueno, E. F., Caroff, S., Genolini, Y., Poulin et al (2016). The pinching method for Galactic cosmic ray positrons: implications in the light of precision measurements. arXiv:1612.03924.

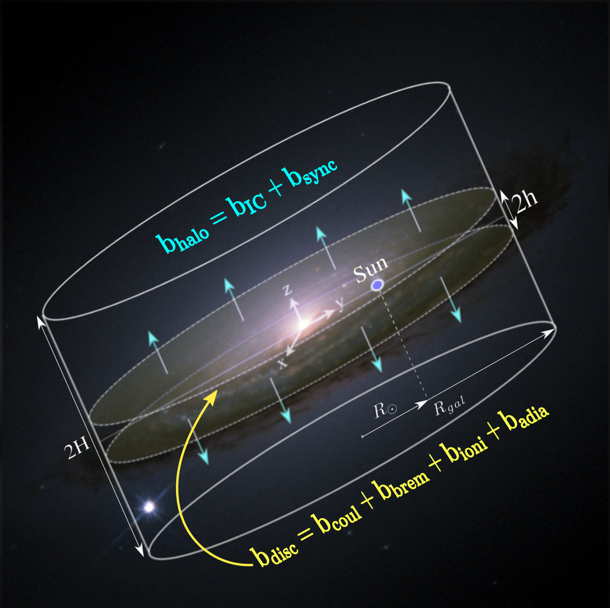
- A valid model should reproduce all the data
- Low energy data are of really good quality
- Low energy positron should be dominated by secondary particle
- **Surprisingly unexplored**

Why ?

- Prejudice of the high energy excess
- Astrophysical uncertainties in the model

Positrons energy losses

Positrons energy losses



Yoann Génolini

Positrons propagation in the Galaxy

$$
\begin{aligned}
V_C\,\partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi \\
+ \partial_E[\mathbf{b_{halo}}(E)\psi] \\
+ 2h\,\delta(z)\,\partial_E\left[\mathbf{b_{disc}}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x})
\end{aligned}
$$

Yoann Génolini

Positrons energy losses

Above 10 GeV halo energy losses dominate :

$$-K(E)\Delta\psi + \partial_E[\mathbf{b}_{\mathbf{halo}}(E)\,\psi] = Q(E,\vec{x}),$$

where $\quad \mathbf{b}_{\mathbf{halo}} = \mathbf{b}_{\mathbf{IC}} + \mathbf{b}_{\mathbf{sync}}.$

Below 10 GeV disc energy losses become important :

$$\begin{aligned} V_C\,\partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi \\ + \partial_E[\mathbf{b}_{\mathbf{halo}}(E)\psi] \\ + 2h\,\delta(z)\,\partial_E\left[\mathbf{b}_{\mathbf{disc}}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x}) \end{aligned}$$

where $\quad \mathbf{b}_{\mathbf{disc}} = \mathbf{b}_{\mathbf{coul}} + \mathbf{b}_{\mathbf{brem}} + \mathbf{b}_{\mathbf{ioni}} + \mathbf{b}_{\mathbf{adia}}.$

Positrons energy losses

Above 10 GeV halo energy losses dominate :

$$-K(E)\Delta\psi + \partial_E[\mathrm{b}_{\mathrm{halo}}(E)\,\psi] = Q(E,\vec{x}),$$

where $\mathrm{b}_{\mathrm{halo}} = \mathrm{b}_{\mathrm{IC}} + \mathrm{b}_{\mathrm{sync}}.$

Below 10 GeV disc energy losses become important :

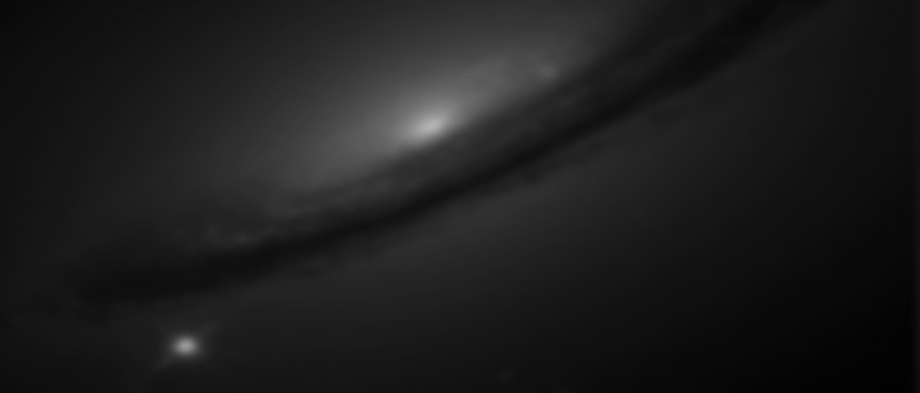
$$V_C\,\partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi$$
$$\cancel{+\partial_E[\mathrm{b}_{\mathrm{halo}}(E)]}$$
$$+\,2h\,\delta(z)\,\partial_E\left[\mathrm{b}^{\mathrm{eff}}_{\mathrm{disc}}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x})$$

where $\mathrm{b}^{\mathrm{eff}}_{\mathrm{disc}} = \mathrm{b}_{\mathrm{coul}} + \mathrm{b}_{\mathrm{brem}} + \mathrm{b}_{\mathrm{ioni}} + \mathrm{b}_{\mathrm{adia}} + \mathrm{b}^{\mathrm{eff}}_{\mathrm{halo}}.$

$$\mathrm{b}^{\mathrm{eff}}_{\mathrm{halo}} >> \mathrm{b}_{\mathrm{halo}}$$

Positron propagation in the Galaxy

$$V_C\,\partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi + 2h\,\delta(z)\,\partial_E\left[\mathbf{b}^{\mathbf{eff}}_{\mathbf{disc}}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x})$$



Yoann Génolini

Positron propagation in the Galaxy

$$V_C\, \partial_z[\mathrm{sign}(z)]\,\psi - K(E)\Delta\psi$$
$$+\, 2h\,\delta(z)\,\partial_E\left[b^{\mathrm{eff}}_{\mathrm{disc}}(E)\,\psi - D(E)\,\partial_E\psi\right] = Q(E,\vec{x})$$

Parameters to be determined :

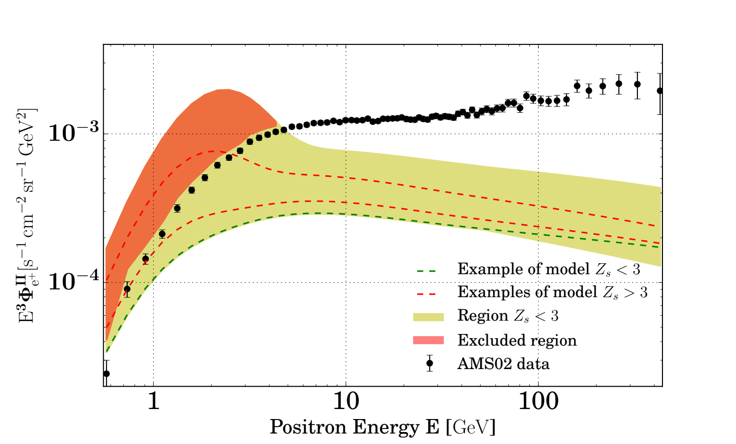
$$V_C \;|\; K(E) = K_0 R^{\delta} \;|\; D(E) \to V_A \;|\; +\; L$$

$$K_0, \delta, V_C, V_A, L$$

Maurin, D., Donato, F., Taillet, R., & Salati, P. (2001). The Astrophysical Journal, 555(2), 585.

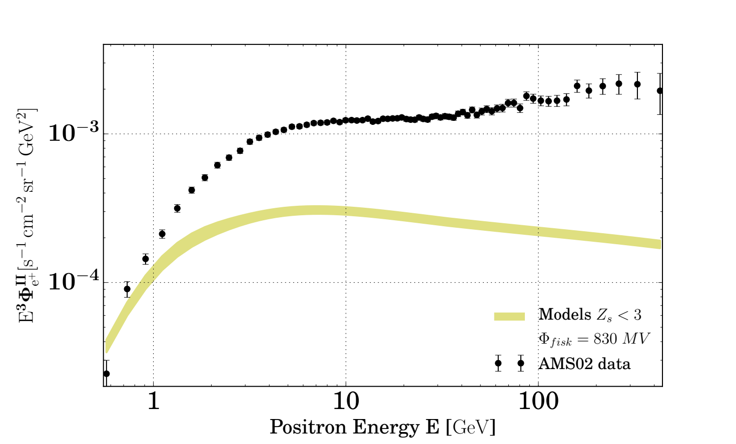
Yoann Génolini

Constraints on propagation



Yoann Génolini

Survival models



→ 56 survival models out of 1623 !

Yoann Génolini

Two cases for dark matter annihilation

- **Case 1** : DM annihiliation into a general final state :

$$\chi\chi \longrightarrow \begin{cases} b_1 & e^+e^- \\ b_2 & \mu^+\mu^- \\ b_3 & \tau^+\tau^- \\ b_4 & W^+W^- \\ b_5 & b\bar{b} \end{cases} \qquad \sum_i b_i = 1$$

6 free parameters !

- **Case 2** : DM annihiliation into leptonic final state through light scalar ϕ :

$$\chi\chi \longrightarrow \phi\phi \longrightarrow \begin{cases} b_1 & e^+e^- \\ b_2 & \mu^+\mu^- \\ b_3 & \tau^+\tau^- \end{cases} \qquad \sum_i b_i = 1$$

4 free parameters !

Analysis method

We scan on the DM mass $\mathbf{m}_\chi$ in the range [100GeV,1TeV].

$$m_\chi \rightarrow \begin{cases} +3\sigma \ 830\text{MV} \\ +0\sigma \ 724\text{MV} \\ -3\sigma \ 647\text{MV} \end{cases} \rightarrow \mathbf{56} \text{ propagation parameters}$$

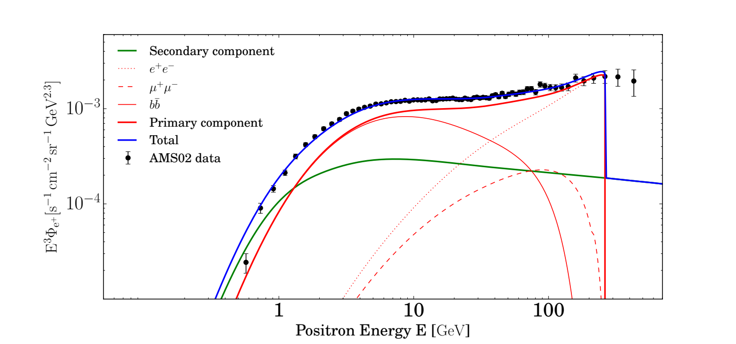
Ghelfi, A., Barao, F., Derome, L., & Maurin, D. (2016). Non-parametric determination of H and He interstellar fluxes from cosmic-ray data. Astronomy & Astrophysics, 591, A94.

For each $\mathbf{m}_\chi$ We adjust $(\langle\sigma \mathbf{v}\rangle, \mathbf{b_i}) \Rightarrow \chi^{\mathbf{2}}_{\text{min}}$

Yoann Génolini

Case 1: Best fit

DM annihilation into e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, W^+W^-, $b\bar{b}$

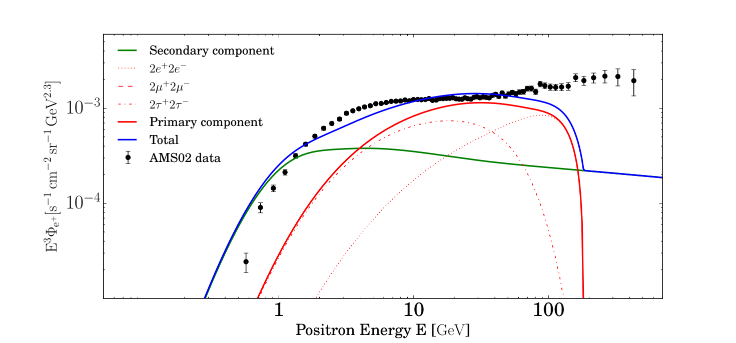


Best $\chi^2_{\rm dof} = 100/66 = 1.5$

Yoann Génolini

Case 2

DM annihilation into $\phi\phi \to (e^+e^-,\ \mu^+\mu^-,\ \tau^+\tau^-)$



Best $\chi^2_{\rm dof} = 1231/68 = 18$

Yoann Génolini

The precision era!

The challenge of CRs propagation

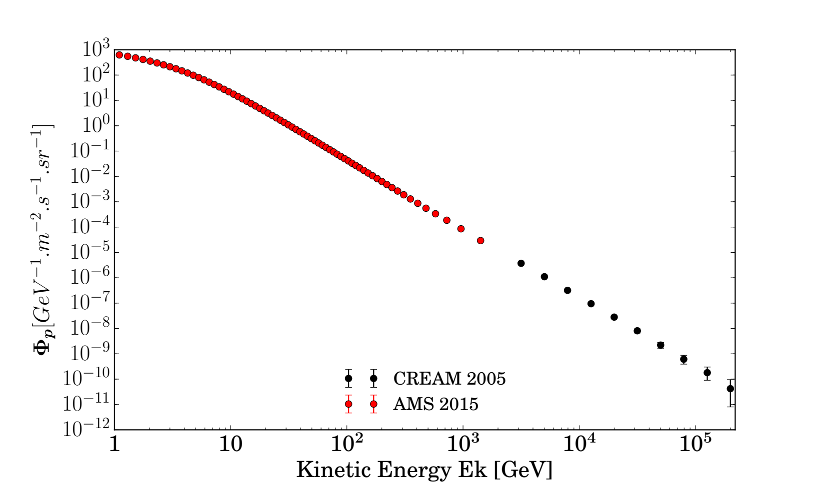
Impact on dark matter searches

Sensibility to the stochastic production of cosmic rays

Conclusion & Prospects

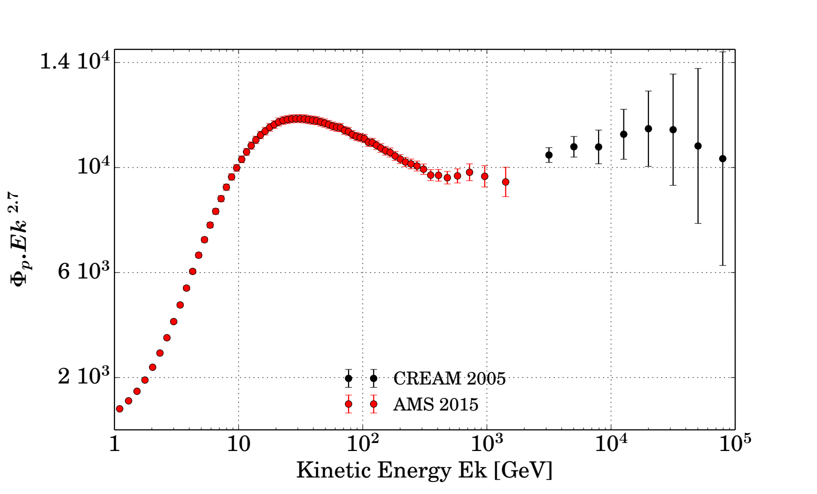
Yoann Génolini

The proton flux



Beautiful power law over many decades $\rightarrow \phi \propto E^{\gamma}$. **Yoann Génolini**

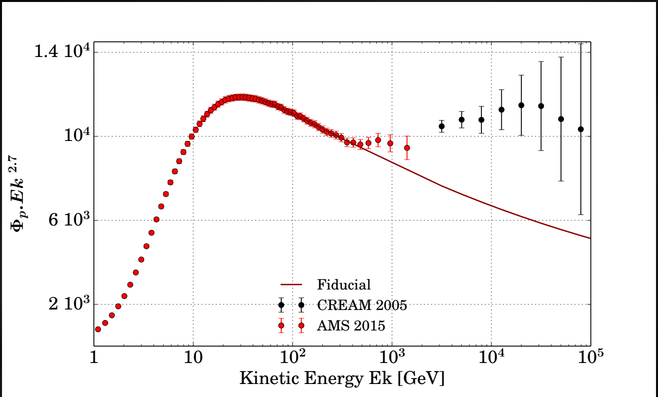
The proton flux



Yoann Génolini

One question would be..

May a particular configuration of the sources explain break features ?



$\Rightarrow \quad P(\Psi)$?

Yoann Génolini

The Pure diffusive regime

$$\frac{\partial \Psi}{\partial t} - \nabla_{\boldsymbol{r}}.(K \nabla_{\boldsymbol{r}} \Psi) = Q(\boldsymbol{r}, E)$$

$\Rightarrow$ Time independent equation !

The Pure diffusive regime

$$-\nabla_{\boldsymbol{r}}.(K\nabla_{\boldsymbol{r}}\Psi) = Q(\boldsymbol{r}, E)$$

$\Rightarrow$ Time independent equation !

$\Rightarrow$ Continuous production in space and time !

The Pure diffusive regime

$$- \nabla_{\boldsymbol{r}}.(K \nabla_{\boldsymbol{r}} \Psi) = Q(\boldsymbol{r}, E)$$

$\Rightarrow$ Time independent equation !

$\Rightarrow$ Continuous production in space and time !

$$Q(\mathbf{r}, t) = \sum_i^N \; q_i \, \delta(\boldsymbol{r_i} - \boldsymbol{r}) \, \delta(t_i - t)$$

The Pure diffusive regime

$$- \nabla_{\boldsymbol{r}}.(K \nabla_{\boldsymbol{r}} \Psi) = Q(\boldsymbol{r}, E)$$

⇒ Time independent equation !

⇒ Continuous production in space and time !

$$Q(\mathbf{r}, t) = \sum_i^N \; q_i \, \delta(\boldsymbol{r_i} - \boldsymbol{r}) \, \delta(t_i - t)$$

$$\langle Q(\mathbf{r}, t) \rangle = \left\langle \sum_i^N \; q_i \, \delta(\boldsymbol{r_i} - \boldsymbol{r}) \, \delta(t_i - t) \right\rangle$$

The Pure diffusive regime

$$-\nabla_{\boldsymbol{r}}.(K\nabla_{\boldsymbol{r}}\Psi) = Q(\boldsymbol{r}, E)$$

$\Rightarrow$ Time independent equation !

$\Rightarrow$ Continuous production in space and time !

$$Q(\mathbf{r}, t) = \sum_i^N \; q_i \, \delta(\boldsymbol{r_i} - \boldsymbol{r}) \, \delta(t_i - t)$$

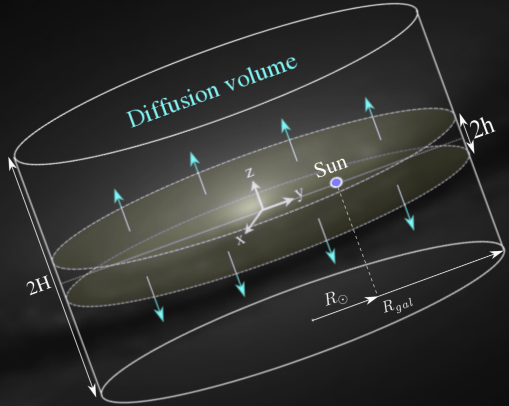
$$\langle Q(\mathbf{r}, t) \rangle \simeq \frac{q\,\nu}{V_{\mathrm{MW}}} \, \Theta(h - |z|) \, \Theta(R_{gal} - r)$$

$V_{\mathrm{MW}} = 2\,h\,\pi R^2$ and $\nu \approx 3\; SNs/century$

Yoann Génolini

The Pure diffusive regime

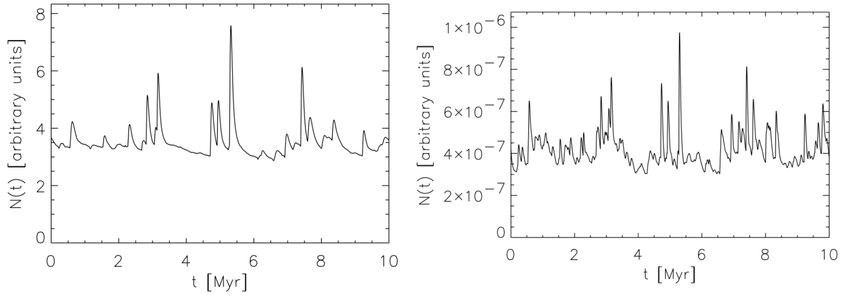
$V_{\mathrm{MW}} = 2\, h\, \pi R^2$
$\nu \approx 3\ SNs/century$



Yoann Génolini

Sources are discrete in space and time!

Büsching, I., Kopp, A., Pohl, M., Schlickeiser, R., Perrot, C., & Grenier, I. (2005). The Astrophysical Journal, 619(1), 314.

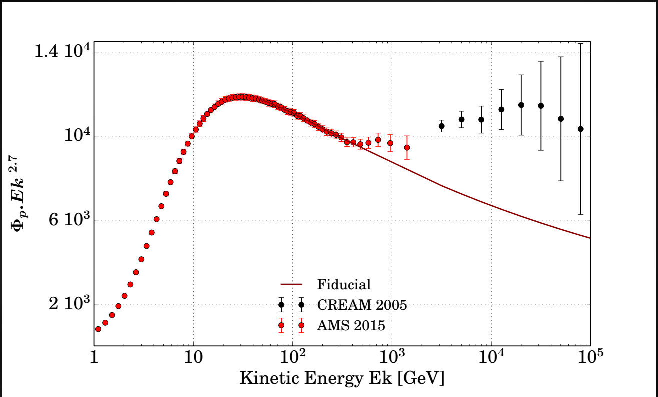


→ Stochastic behaviour !

Yoann Génolini

One question would be..

May a particular configuration of the sources explain break features ?



$\Rightarrow \quad P(\Psi)$?

Yoann Génolini

Statistical treatment of the flux

The flux from N sources writes :

$$\Psi = \sum_{i=1}^{N} \psi_i \quad \Rightarrow \quad \langle \Psi \rangle = \sum_{i=1}^{N} \langle \psi \rangle = N \, \langle \psi \rangle$$

One can expect to compute $\langle \psi \rangle$ from $p(\psi)$:

$$\langle \psi \rangle = \int_0^{\infty} d\psi \, \psi \, p(\psi)$$

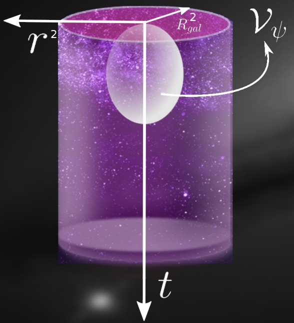
With :

$$p(\psi) = \int_{\mathcal{V}_\psi} \underbrace{\mathcal{D}(\boldsymbol{r}_s, t_s)}_{\text{Normalized distribution in space and time for one source}} \, \mathrm{d}\boldsymbol{r}_s \, \mathrm{d}t_s \tag{2}$$

Integration over the domain of space and time that gives a flux between ψ and $\psi + \mathrm{d}\psi$.

To measure ψ from one source

$$p(\psi) = \int_{\mathcal{V}_\psi} \mathcal{D}(\boldsymbol{r}_s, t_s)\, \mathrm{d}\boldsymbol{r}_s\, \mathrm{d}t_s \tag{3}$$



$\mathcal{V}_\psi$: domain of space and time that gives a flux between ψ and $\psi + \mathrm{d}\psi$.

Surface equation in pure diffusive regime :

$$\psi \; = \; \frac{q}{(4\,\pi\,K\,t)^{3/2}} \; \exp\left(\frac{r^2}{4\,K\,t}\right)$$

$\mathcal{D}(\boldsymbol{r}_s, t_s)$ can assume two limiting behaviours, 2D or 3D !

For : $\psi \gg \langle\psi\rangle$ we have, $\mathbf{p}(\psi) \propto \begin{cases} \psi^{-8/3} & 3D \\ \psi^{-7/3} & 2D \end{cases}$

Variance of the total flux

$$\Psi = \sum_{i=1}^{N} \psi_i \quad \Rightarrow \quad p(\psi) \rightarrow P(\Psi)$$

Central limit theorem ?

$$\sigma_\Psi^2 = \langle \Psi^2 \rangle - \langle \Psi \rangle^2 = N\ \sigma_\psi^2 = N \langle \psi^2 \rangle - \frac{\langle \Psi \rangle^2}{N}$$

$$\langle \psi^2 \rangle = \int_0^\infty \psi^2\ p(\psi) d\psi \ \propto \begin{cases} \left[\psi^{1/3}\right]_{cte}^{\infty} = \infty & 3D \\ \left[\psi^{2/3}\right]_{cte}^{\infty} = \infty & 2D \end{cases}$$

The variance diverges

Yoann Génolini

But actually the pdf exists!

Generalised central limit theorem ?

The heavy tail behaviour conditioned the stable law limit !

$$\forall \psi \geqslant 0, \quad C(\psi) \equiv \int_{\psi}^{\infty} p(\psi')\,\mathrm{d}\psi' \;\rightarrow\; \lim_{\psi \to \infty} \psi^{\alpha} C(\psi) = \eta > 0$$

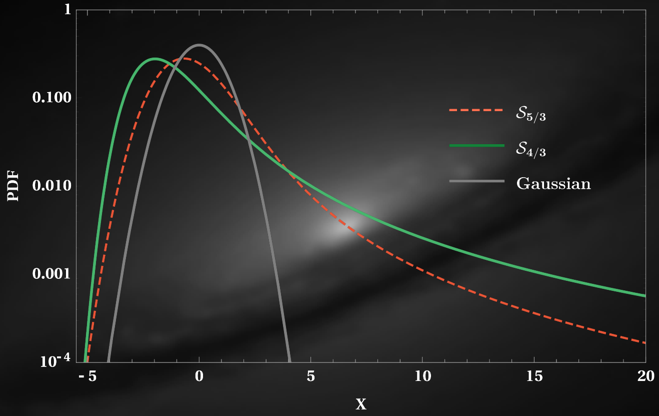
For N *sufficiently* large :

$$P(\Psi) \rightarrow \frac{1}{\sigma_N} S[\alpha, 1, 1, 0; 1] \left(\frac{\Psi - \langle \Psi \rangle}{\sigma_N} \right)$$

With : $\alpha = \begin{cases} 5/3 & 3D \\ 4/3 & 2D \end{cases}$ and $\sigma_N = \left(\dfrac{\eta\, \pi\, N}{2\Gamma(\alpha) \sin(\alpha\, \pi/2)} \right)^{1/\alpha}$

But actually the pdf exists!

$\sigma_N = 1$, $\alpha = 5/3 \to 3D$, $\alpha = 4/3 \to 2D$

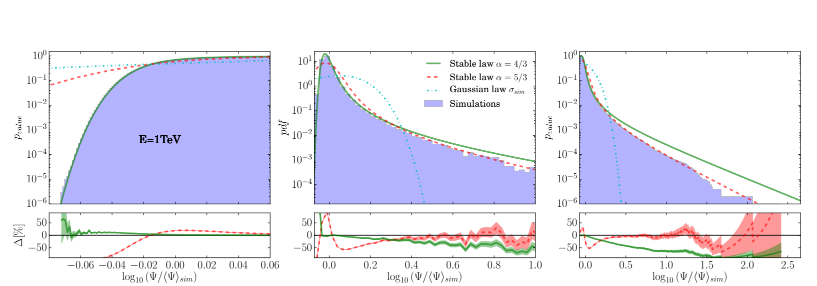


⇒ So one can define confidence intervals, pvalues...

Yoann Génolini

Simulation check

For example at 1TeV :



Simulation generated 10^6 configurations of galaxies.
Transition from the 2D to the 3D regime !

⇒ *Genolini, Y., Salati, P., Serpico, P., & Taillet, R. (2016). Stable laws and cosmic ray physics. arXiv preprint arXiv:1610.02010.*

Yoann Génolini

On the form of $p(\psi)$

The diffusive propagator is not causal for some region in space and time...

- **Loophole :** reevaluation of

$$p(\psi) = \int_{\mathcal{V}_\psi^{\text{causal}}} \mathcal{D}(\boldsymbol{r}_s, t_s)\, \mathrm{d}\boldsymbol{r}_s\, \mathrm{d}t_s$$

- $p(\psi) \propto \begin{cases} \psi^{-8/3} & \text{for : } \psi < \psi_c \\ \psi^{-11/3} & \text{for : } \psi > \psi_c \end{cases}$

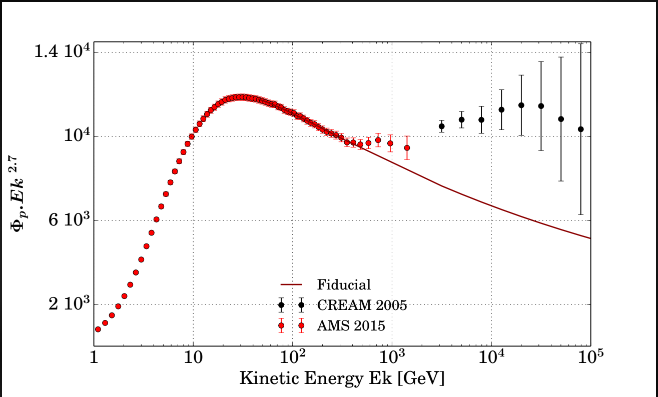
The variance converges again!

Shall we use the central limit theorem ?...**Not really** if ψ_c is very large.

Simulations : Stable law is a very good approximation till 10TeV !

Application of the theory!

May a particular configuration of the sources explain break features ?



$\Rightarrow \quad P(\Psi)$?

Probability of such an excess

We compute an upper value of the probability that a particular configuration of the sources gives a flux Ψ at 12.8TeV :

$$p_{value} = \int_{\Psi_{exp}}^{\infty} d\psi_{exp} \int_{0}^{+\infty} d\psi_{th}\; p(\psi_{exp}|\psi_{th})\; p(\psi_{th}|Model),$$

Example for the benchmark models :

Models	MIN	MED	MAX
Probabilities(Stable law 4/3)	0.031	0.0082	0.0013

A theory of stochasticity for CRs

Models	PAMELA		AMS02	
Model	50GeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	50GeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$	1TeV $p(\Psi > \langle\Psi\rangle + 3\sigma)$ $p(\Psi < \langle\Psi\rangle - 3\sigma)$
MIN	0.15 0.13	0.083 $< 10^{-6}$	0.28 0.63	0.26 0.51
MED	0.047 $< 10^{-6}$	0.014 $< 10^{-6}$	0.16 0.26	0.12 0.0025
MAX	0.009 $< 10^{-6}$	0.0018 $< 10^{-6}$	0.045 $< 10^{-6}$	0.016 $< 10^{-6}$

Yoann Génolini

The precision era!

The challenge of CRs propagation

Impact on dark matter searches

Sensibility to the stochastic production of cosmic rays

Conclusion & Prospects

Yoann Génolini

Conclusion & Prospects

⇒ Great time for CRs physics !

⇒ Propagation should be treated with care : need of new XS measurements

⇒ Low energy positrons are usefull to constrain propagation

⇒ Till now : no hints of DM in cosmic rays antiparticles

⇒ Refined predictions are needed

⇒ Plenty of problems to address in CR physics.

Yoann Génolini

Questions