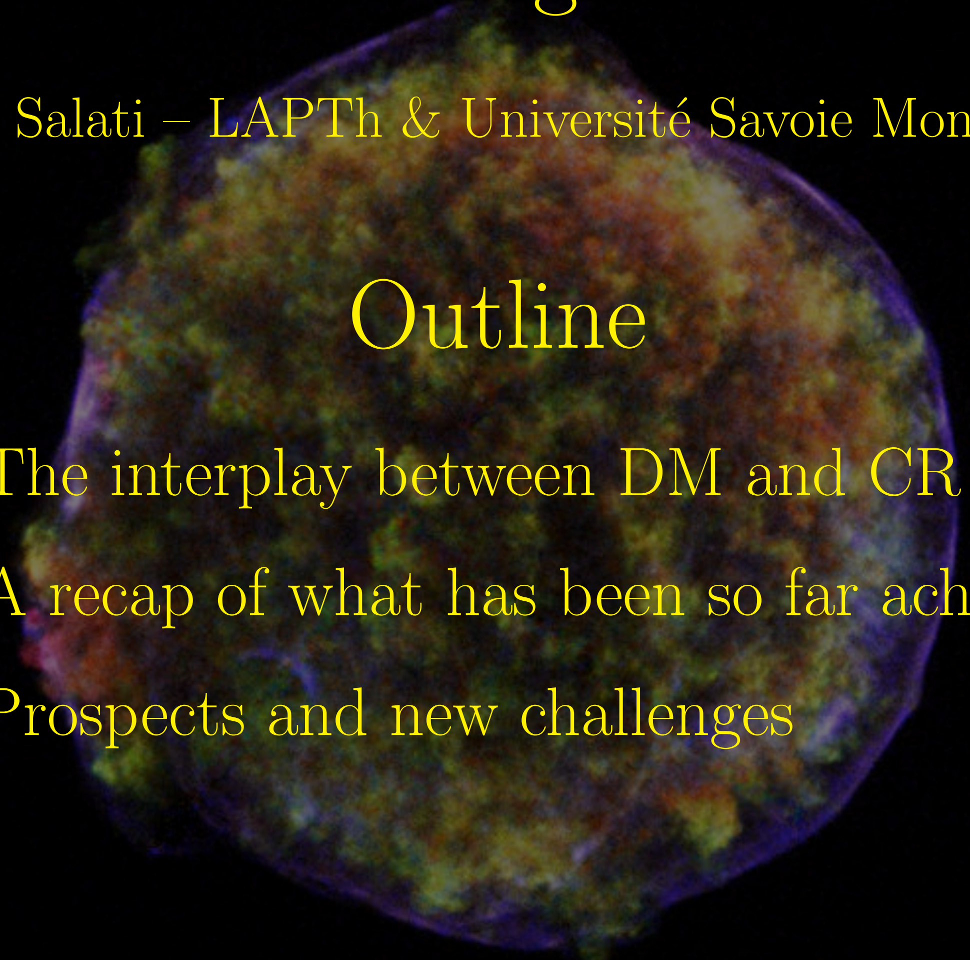
Dark Matter in the light of Cosmic Rays

Pierre Salati – LAPTh & Université Savoie Mont Blanc



Outline

1) The interplay between DM and CR

2) A recap of what has been so far achieved

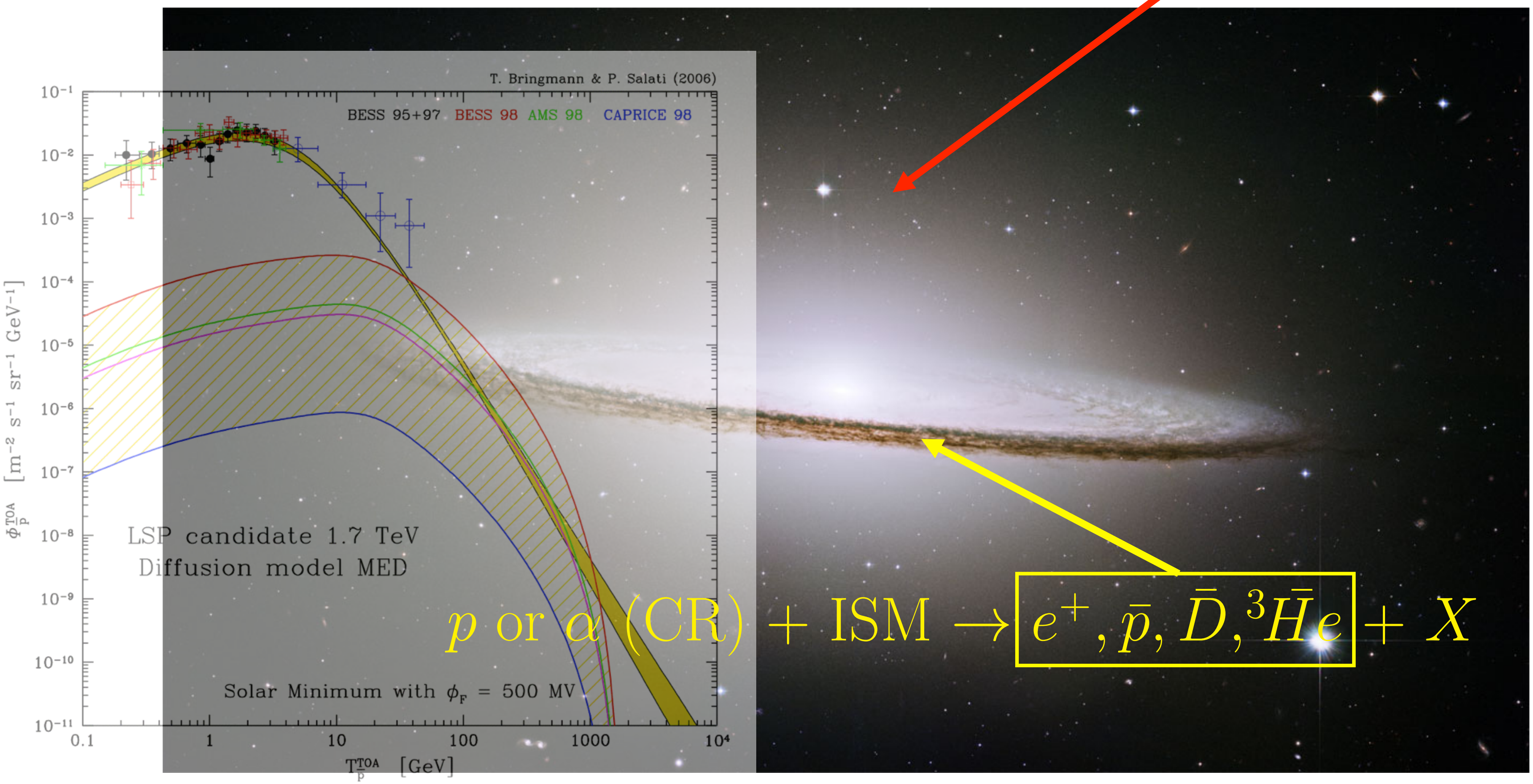
3) Prospects and new challenges

Atelier CFRCOS de prospective – Laboratoire APC Paris – mardi 27 mars 2018

1) The interplay between DM and CR

Dark Matter particles could be the major component of the haloes of galaxies. Their mutual annihilations or decays would produce an **indirect signature** under the form of high-energy **cosmic rays**.

$$\chi + \chi \;\rightarrow\; q\bar{q}, W^+W^-, \ldots \rightarrow\; \gamma, \boxed{e^+, \bar{p}, \bar{D}, {}^3\bar{He}} \,\&\, \nu's$$



Antimatter is already manufactured inside the Galactic disk

Dark Matter candidates and Cosmic Rays

- The DM reference framework corresponds to **early Universe cold thermal relics** with mass in the **GeV to TeV range** as predicted in most of the extensions of the Standard Model – SUSY & extra-dim.

- The prototypical candidate is a **weakly interacting massive particle (WIMP)** whose primordial production through **freeze-out** leads to the relic abundance

$$\Omega_\chi h^2 \simeq \left\{ \frac{3 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}}{< \sigma_{\mathrm{an}} v >} \right\}$$

B.W. Lee & S. Weinberg, PRL **39** (1977) 165

Benjamin W. Lee

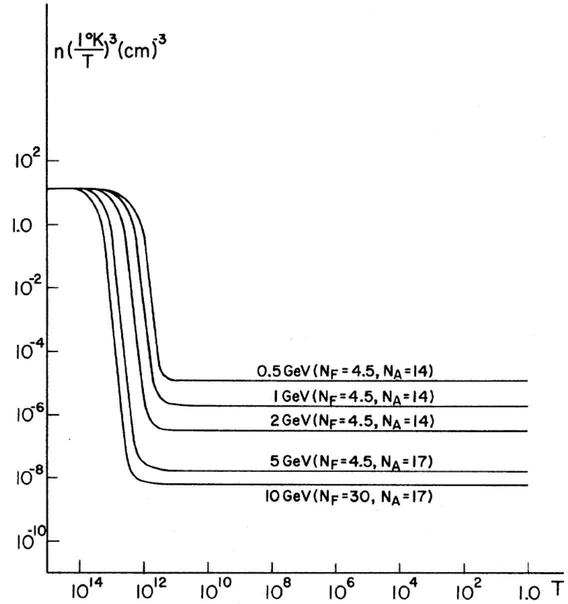


FIG. 1. n/T^3 vs T for a variety of special cases of m_L, N_F, and N_A.

Steven Weinberg

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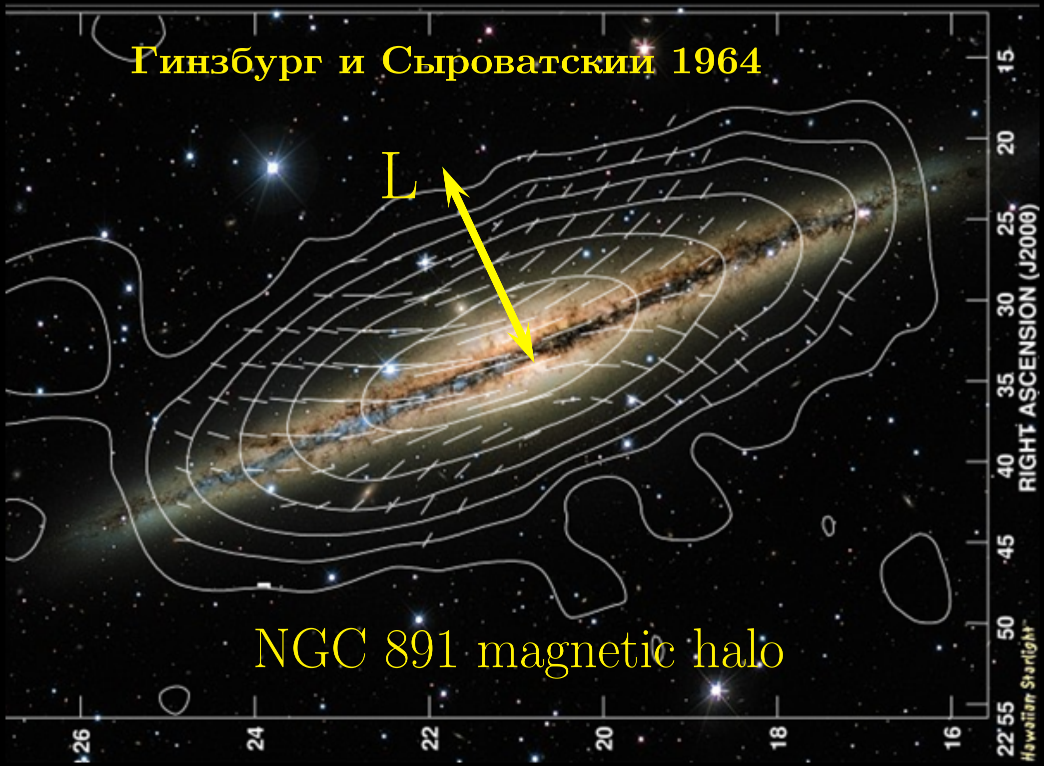
• For weak interactions, the relic abundance **miraculously** matches the value measured by Planck.

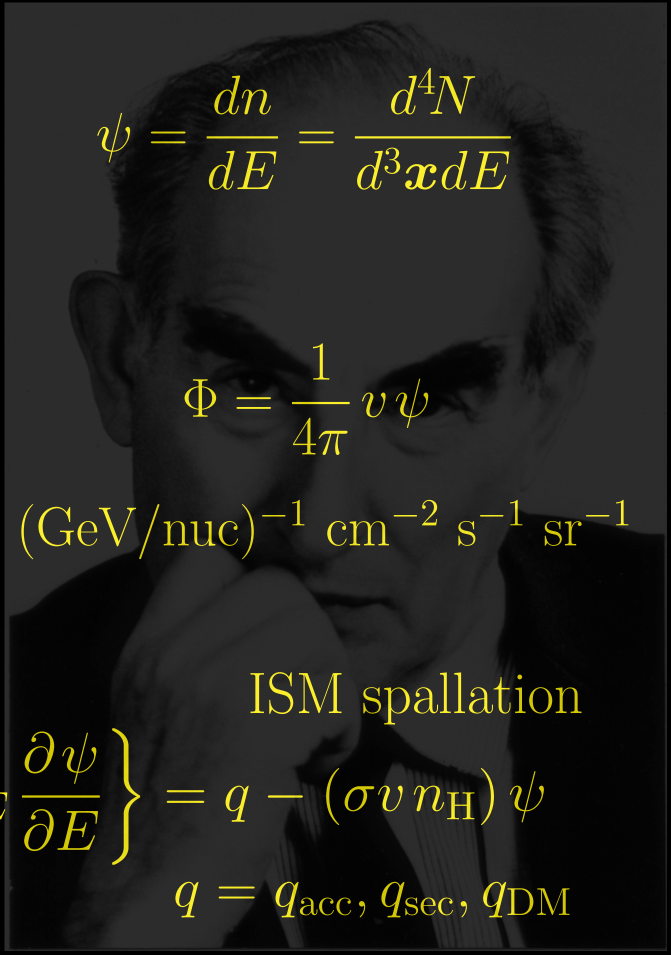
$$\Omega_{\rm CDM} h^2 = 0.1106 \pm 0.0031$$

• Many other possibilities exist though, including for instance **co-annihilation, freeze-in, formation of bound states**, so that in practice we can extend the mass range and go down to the MeV scale and also above the TeV scale.

• **Primordial black holes** are also considered as potential DM candidates. They can inject CR in outer space as they evaporate.

Galactic cosmic ray diffusion model





$$\psi = \frac{dn}{dE} = \frac{d^4N}{d^3\boldsymbol{x}\,dE}$$

$$\Phi = \frac{1}{4\pi} v\,\psi$$

$$(\mathrm{GeV/nuc})^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

ISM spallation

$$\dot{\psi} + \boldsymbol{\nabla}\cdot\{-K\,\boldsymbol{\nabla}\psi + \psi \boldsymbol{V}_C\} + \frac{\partial}{\partial E}\left\{b\,\psi - D_{EE}\frac{\partial \psi}{\partial E}\right\} = q - (\sigma v\, n_{\mathrm{H}})\,\psi$$

convection

E losses

$$q = q_{\mathrm{acc}},\, q_{\mathrm{sec}},\, q_{\mathrm{DM}}$$

$\boldsymbol{x}$ diffusion

E diffusion

$$K = K_0\,\beta\,\mathcal{R}^{\delta}$$

$$D_{EE} = \frac{2}{9}\frac{V_A^2\beta^4E^2}{K}$$

Galactic cosmic ray diffusion model

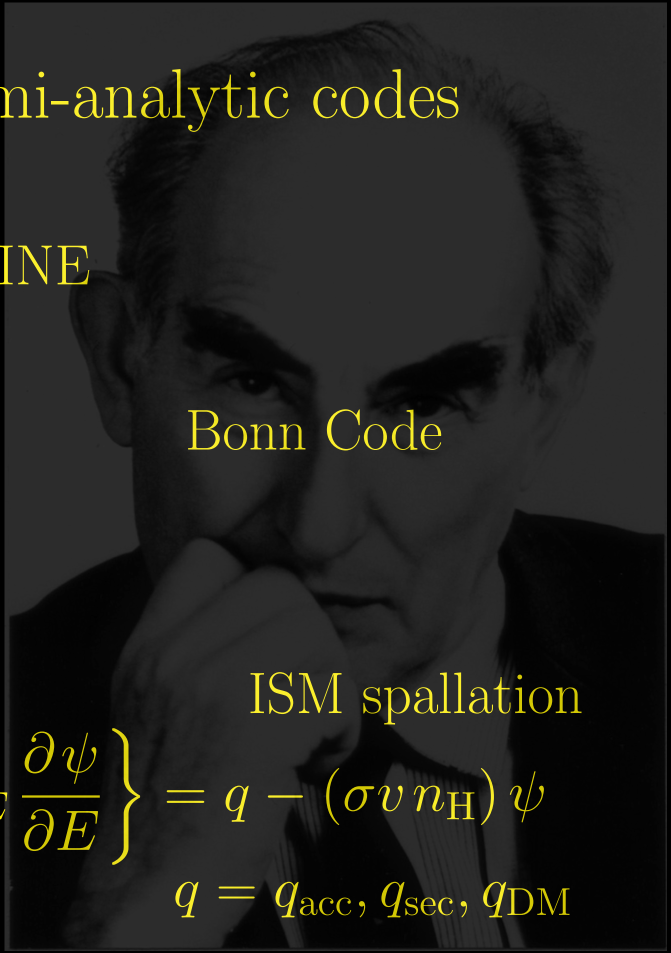
Fully numerical codes

Galprop

DRAGON

Picard

Semi-analytic codes



USINE

Bonn Code

ISM spallation

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2) A recap of what has been so far achieved

(i) Even though we are not strictly interested here in γ rays, the observation of DM in **dSph galaxies** by HESS or CTA has motivated a renewed interest in **modeling the DM distribution** in these objects.

(ii) The discovery in 2008 of an **excess in the positron spectrum above a few GeV** has triggered a feverish activity in building **viable but quite exotic** models of DM candidates, based for instance on **Sommerfeld enhancement** or on displaced annihilation through **long-lived mediators**.

(iii) Significant improvements in modeling positron propagation have also been made. In particular, the so-called **pinching method** allows to scan the positron spectrum all over the measured range. It **excludes the excess to be explained by DM particles alone**.

(iv) We understand now that a **cut-off** in the lepton spectrum above a few TeV **does not necessarily mean** that we have found DM particles. A nearby pulsar would do as well, as shown by **T. Delahaye, K. Kotera & J. Silk, ApJ 794 (2014) 168**.

(v) The putative discovery of an antiproton excess or of a few $^3\overline{\mathrm{He}}$ events by AMS-02 has stimulated a renewed interest in modeling the production and propagation of these species.

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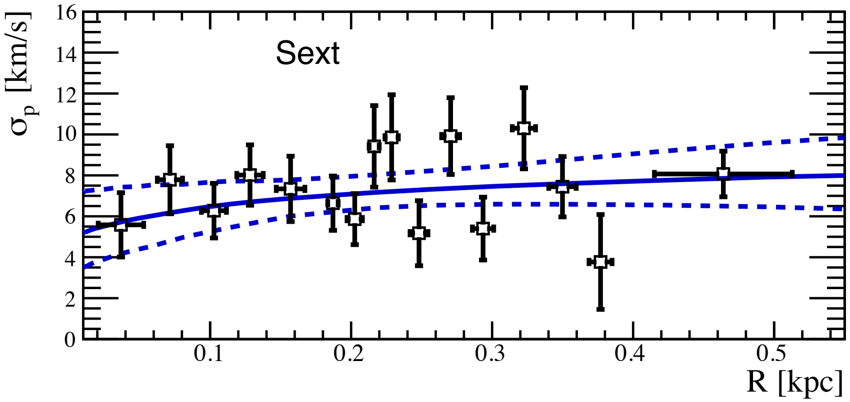
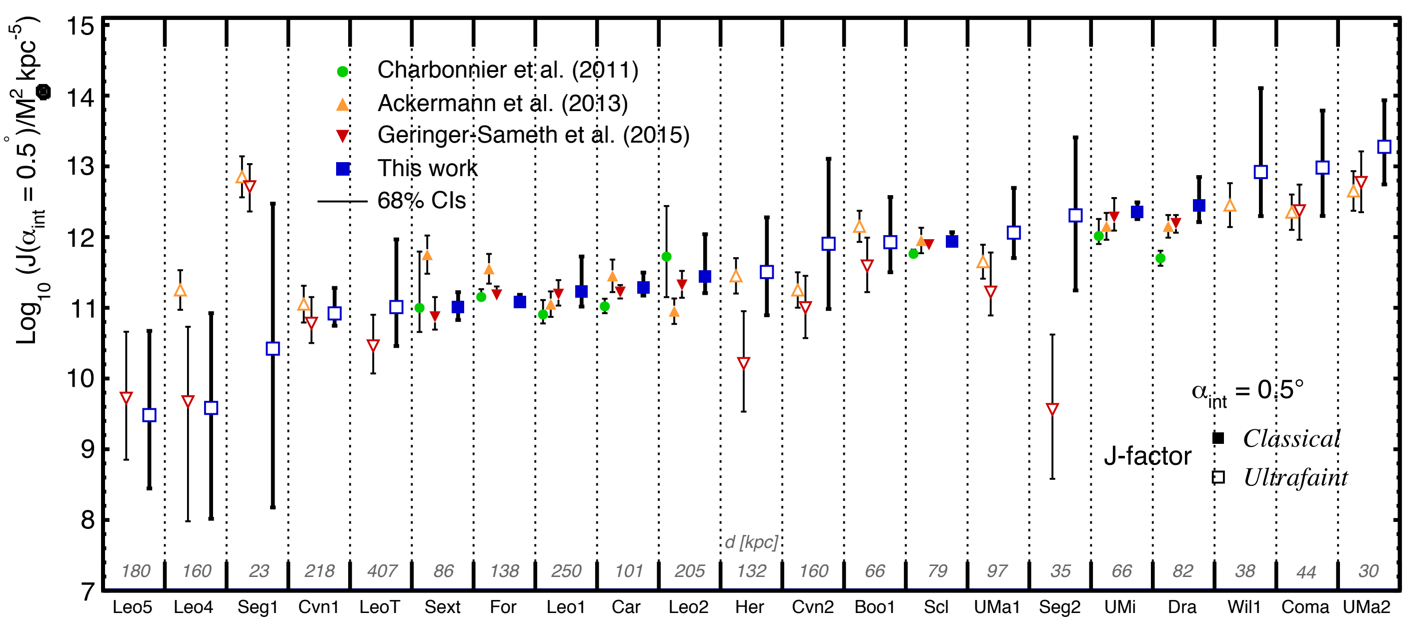


V. Bonnivard et al., MNRAS **453** (2015) 849

$$\Sigma(R) = 2\int_R^{+\infty} \frac{\nu(r)\, r\, dr}{\sqrt{r^2 - R^2}}$$

$$\sigma_p^2(R) = \frac{2}{\Sigma(R)} \int_R^{\infty} \left(1 - \beta_{ani}(r)\frac{R^2}{r^2}\right) \frac{\nu(r)\, \bar{v}_r^2(r)\, r}{\sqrt{r^2 - R^2}} dr$$



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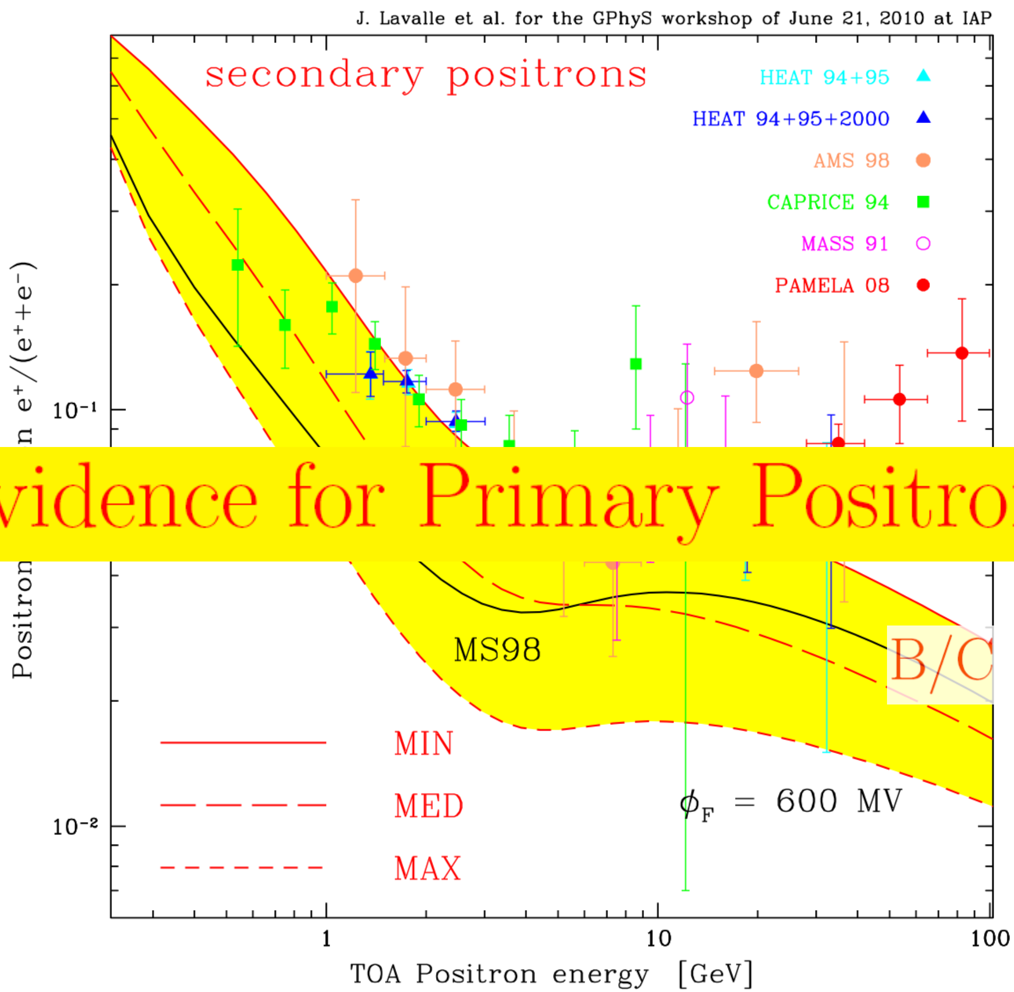
T. Delahaye et al. A&A **501** (2009) 821



Evidence for Primary Positrons

B/C compatible band

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$$\sigma = \sigma_0 \left(1 + \frac{v_{esc}^2}{v^2}\right)$$

M. Pospelov & A. Ritz, Phys. Lett. **B671** (2009) 391

N. Arkani-Hamed et al., Phys. Rev. **D79** (2009) 015014

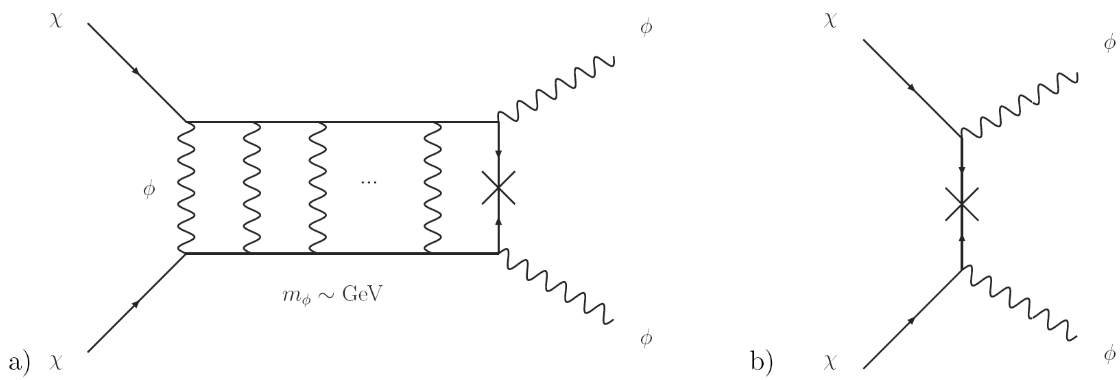
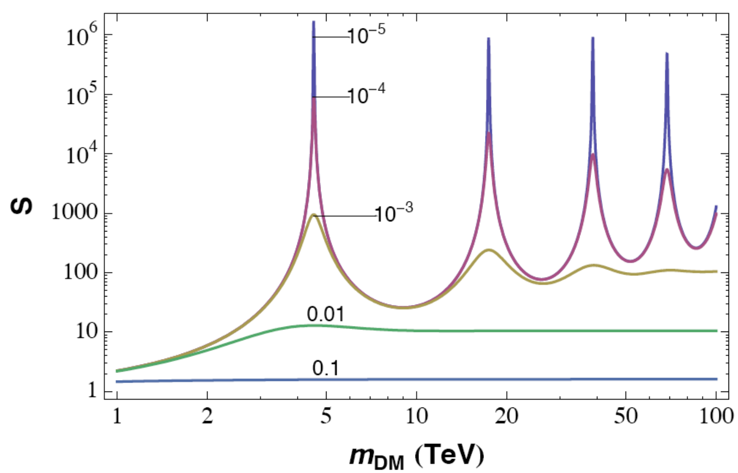


FIG. 3: The annihilation diagrams $\chi\chi \to \phi\phi$ both with (a) and without (b) the Sommerfeld enhancements.

$$\sqrt{\frac{\alpha\, m_\phi}{m_\chi}} \leq \beta \leq \alpha$$



$$1/m_\phi \sim n^2/\alpha\, m_\chi$$

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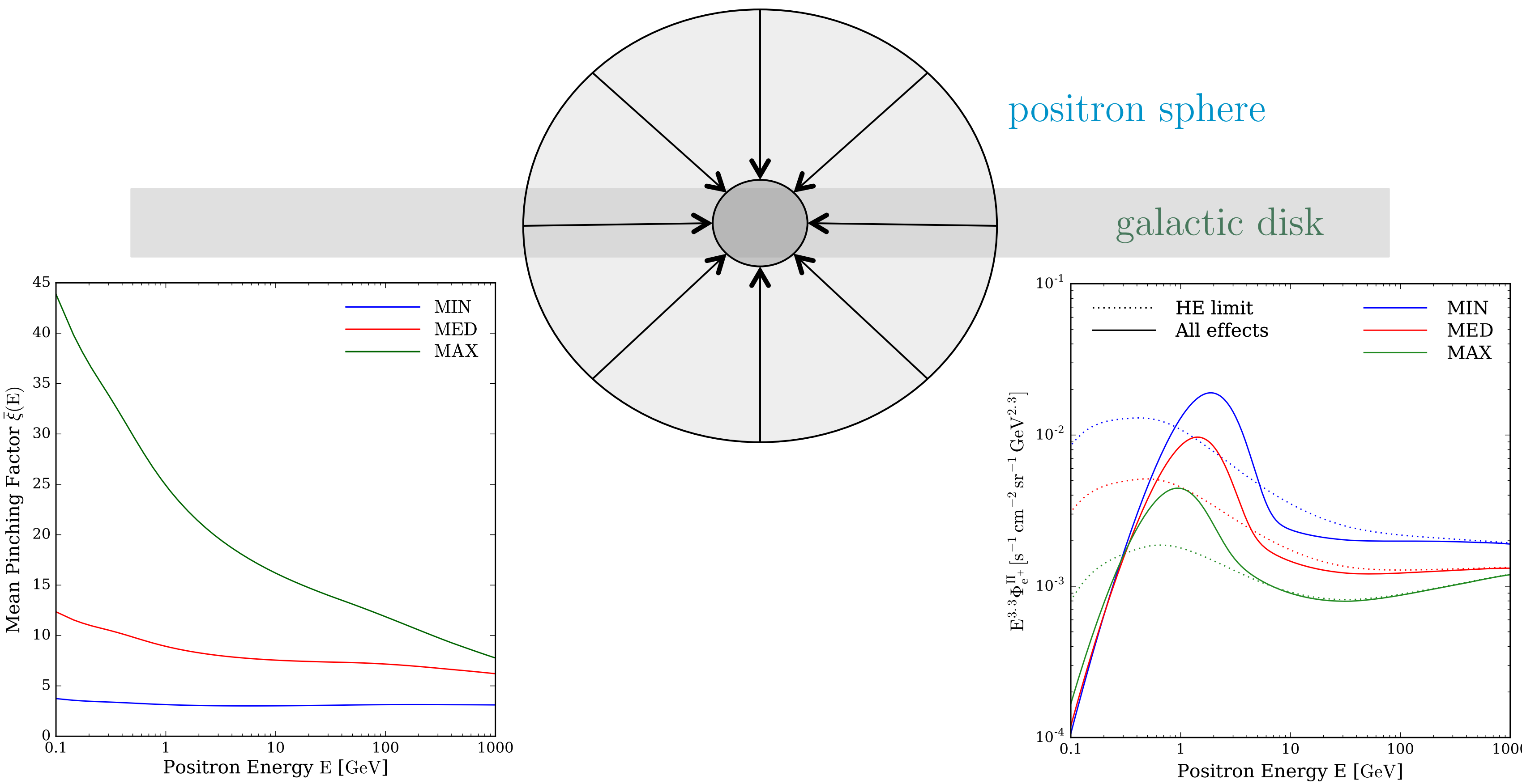
M. Boudaud et al., A&A **605** (2017) A17

$$b^{\rm MH}(z) \equiv b^{\rm IC} + b^{\rm S} \Longrightarrow 2\,h\,\delta(z)\,b^{\rm MH}_{\rm eff}$$

$$b^{\rm MH}_{\rm eff}(E) = \xi(E, E_S)\, b^{\rm MH}(E) \;\; \text{with} \;\; \psi^h(E, E_S) = \psi^d(E, E_S)$$



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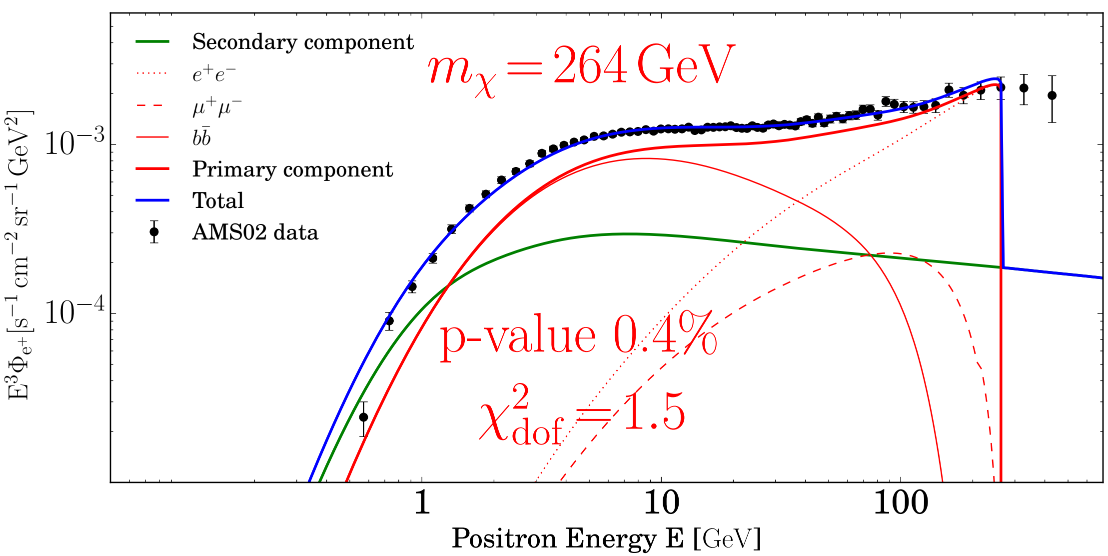
M. Boudaud et al., A&A **605** (2017) A17

$$\Phi_{e^+} = \Phi_{e^+}^{\rm sec} + \Phi_{e^+}^{\rm DM}\{\chi\chi \to b\bar{b} + W^+W^- + e^+e^- + \mu^+\mu^- + \tau^+\tau^-\}$$

For each DM mass, surviving CR model and $\phi_{\rm F}$
a fit is performed on $\langle\sigma_{\rm ann} v\rangle$ and branching ratios

$\Downarrow$

$\chi^2_{\rm min}$



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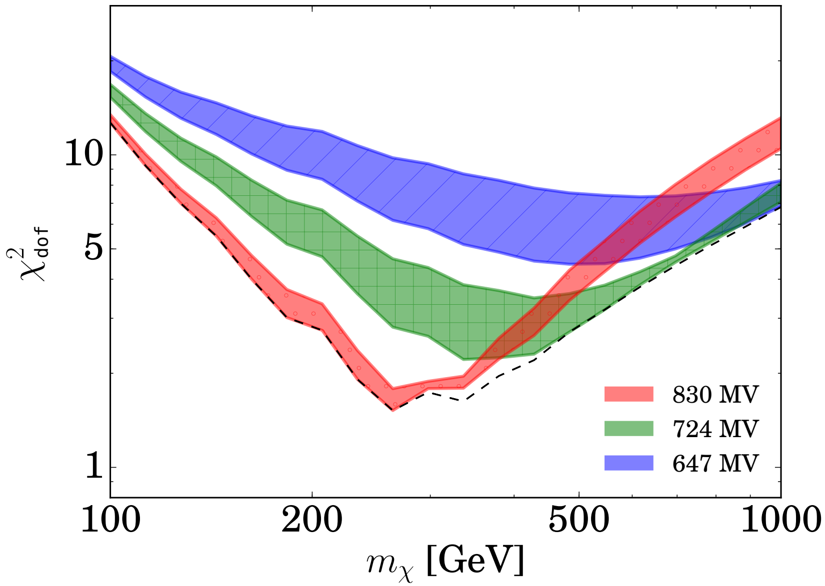
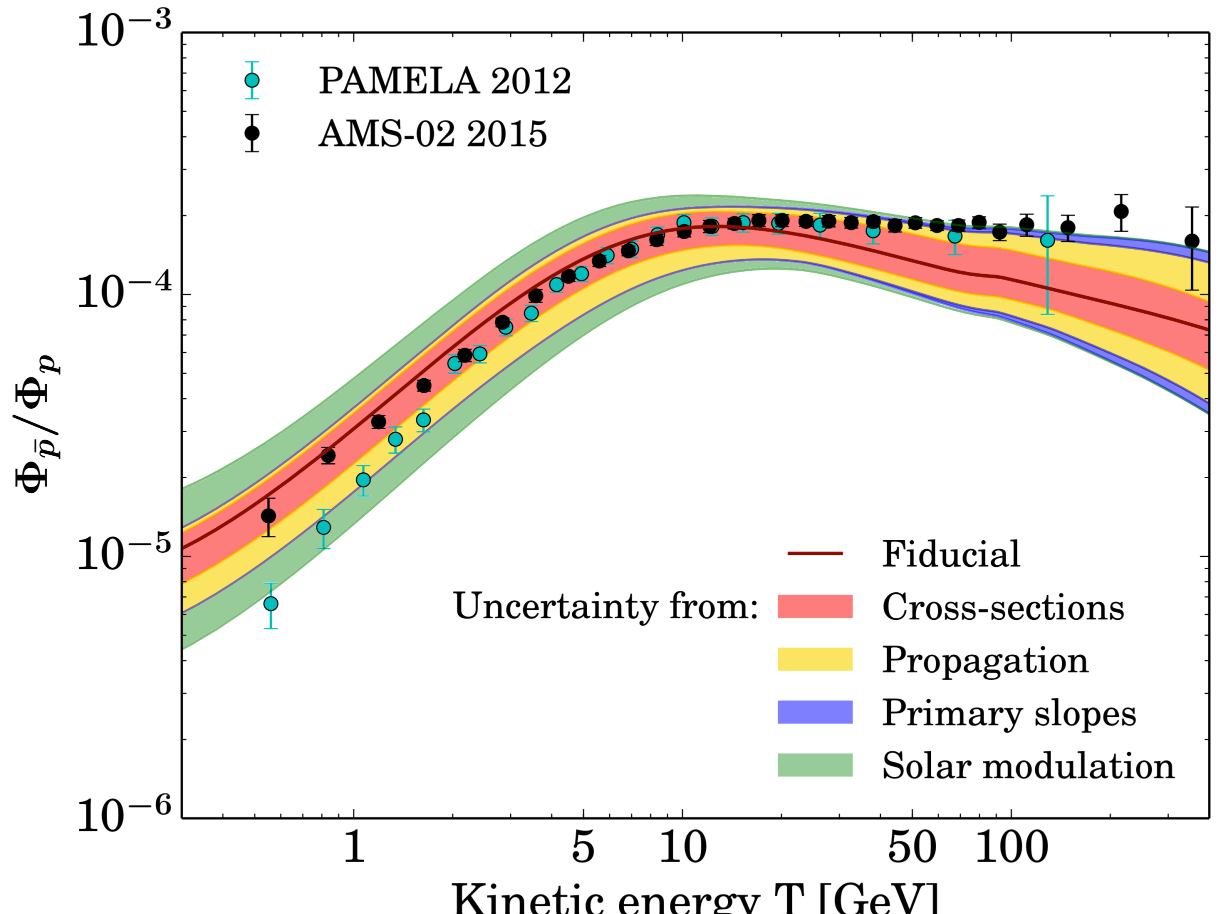


AMS Collaboration
CERN, Geneva, 15 April 2015

"AMS Days at CERN" and Latest Results from the AMS Experiment on the International Space Station

Backgrounds to a putative DM signal need to understood

Production cross sections – solar modulation – cosmic ray propagation



3) Prospects for the future – the new challenges

(i) CTA will deeply probe the γ rays emission from dSph satellites. We need to model as best as we can its distribution. Setting limits on the **p-wave annihilation of DM** in the Galaxy also requires that we know its **velocity distribution function**.

(ii) The γ ray observations of nearby sources are crucial to check whether or not the **positron excess** is generated by **local pulsars**.

(iii) Massive DM candidates will be difficult to observe. The CR differential flux which they yield is $\Phi \propto 1/m_{\chi}^{3}$ and **becomes exceedingly small** Another conceptual problem arises from $\sigma_{\rm an} v \propto \alpha'/m_{\chi}^{2}$. At fixed cross section, α' becomes **non-perturbative at the PeV scale**.

(iv) At high energy, CR physics becomes tricky and very exciting ! Sources of primary CR are **sporadic and discrete** – see the Myriad model. At the PeV scale, diffusion starts to be replaced by **ballistic motion**. It is unclear how to deal properly with that transition.

(v) At low energy, CR observations are plagued with **solar modulation** though Voyager 1 has opened a new window. A crucial issue arises from the **production, spallation, destruction cross-sections** which need to be better determined.

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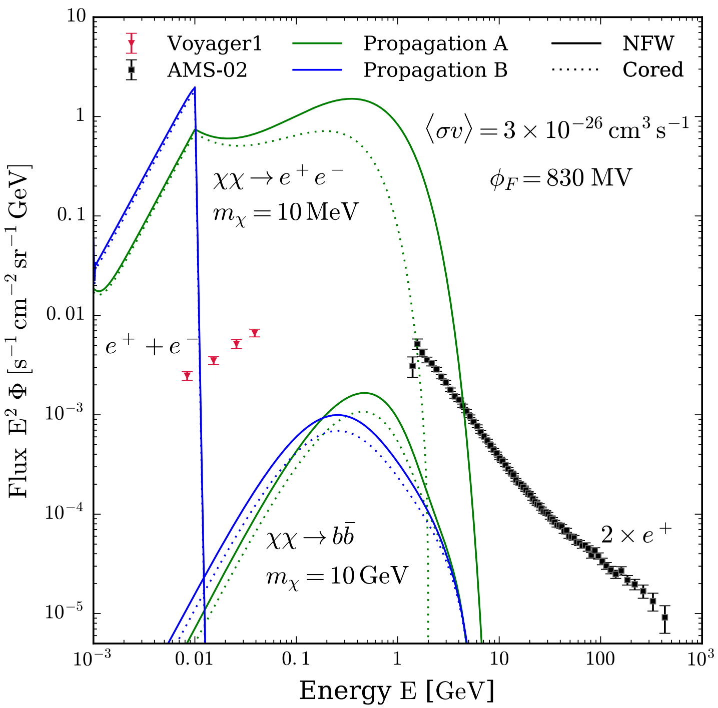
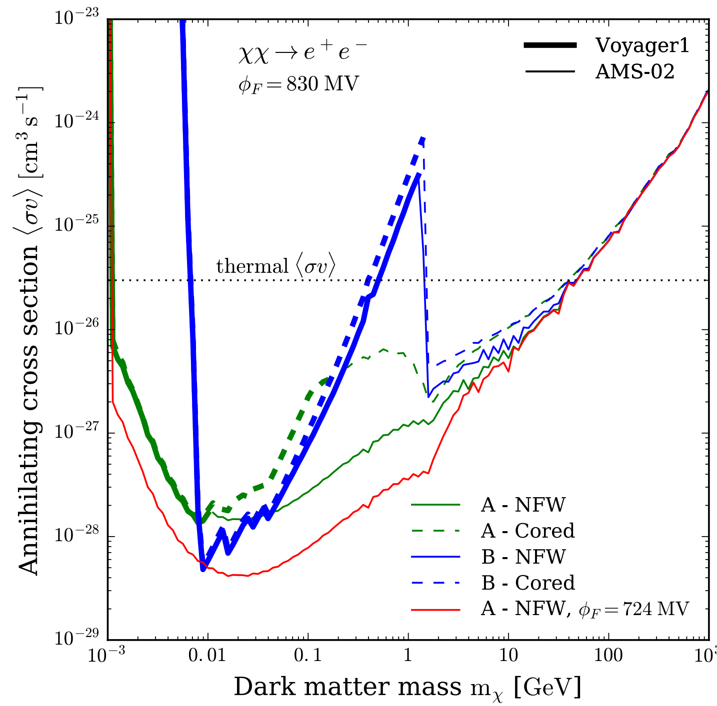
Eddington's inversion formula

T. Lacroix, M. Stref & J. Lavalle, JCAP (2018)

$$\mathcal{E} = \Psi(r) - \frac{v^2}{2} \qquad f(\mathcal{E}) = \frac{1}{\sqrt{8}\pi^2}\left[\frac{1}{\sqrt{\mathcal{E}}}\left(\frac{d\rho}{d\Psi}\right)_{\Psi=0} + \int_0^{\mathcal{E}} \frac{d^2\rho}{d\Psi^2}\frac{d\Psi}{\sqrt{\mathcal{E}-\Psi}}\right]$$

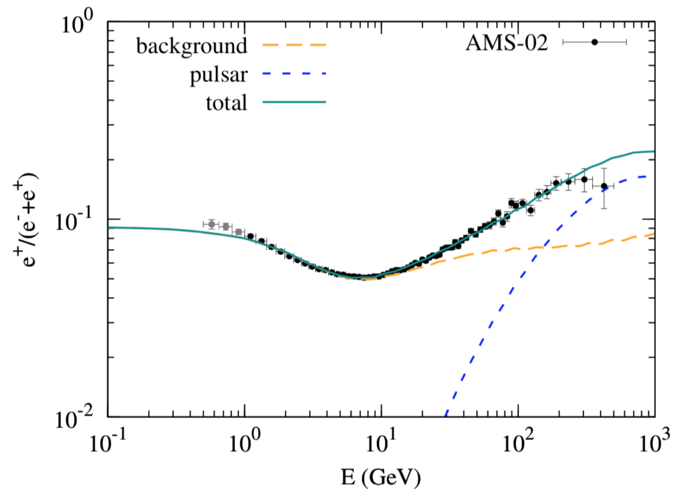


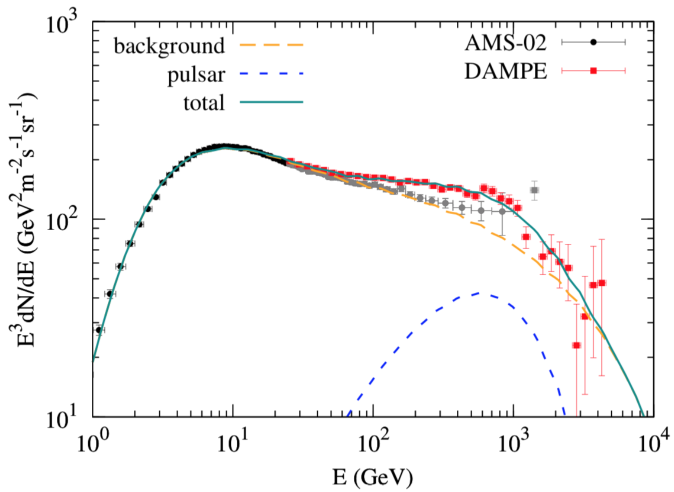


M. Boudaud, J. Lavalle & P. Salati, PRL **119** (2017) 021103

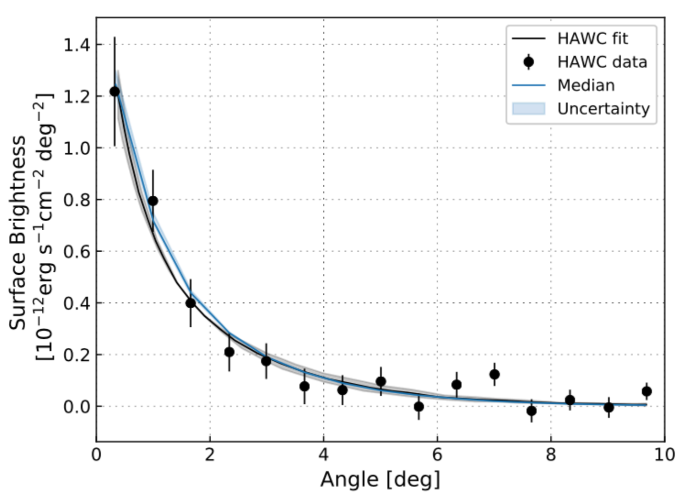
(ii) The γ ray observations of nearby sources are crucial to check whether or not the **positron excess** is generated by **local pulsars**.

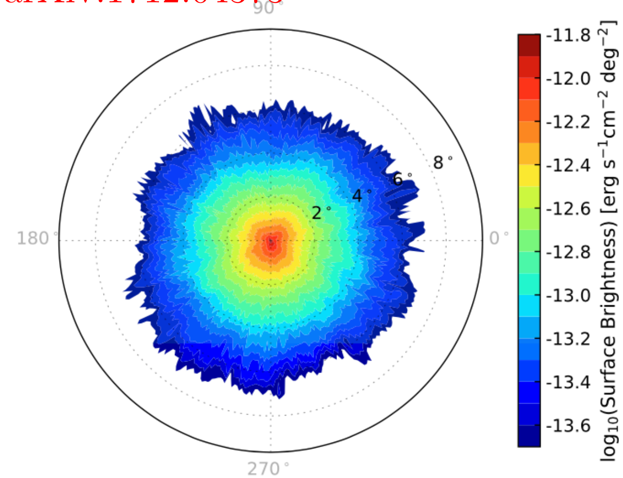
Q. Yuan et al., *Interpretations of the DAMPE electron data*, arXiv:1711.10989





R. López-Coto & G. Giacinti, arXiv:1712.04373

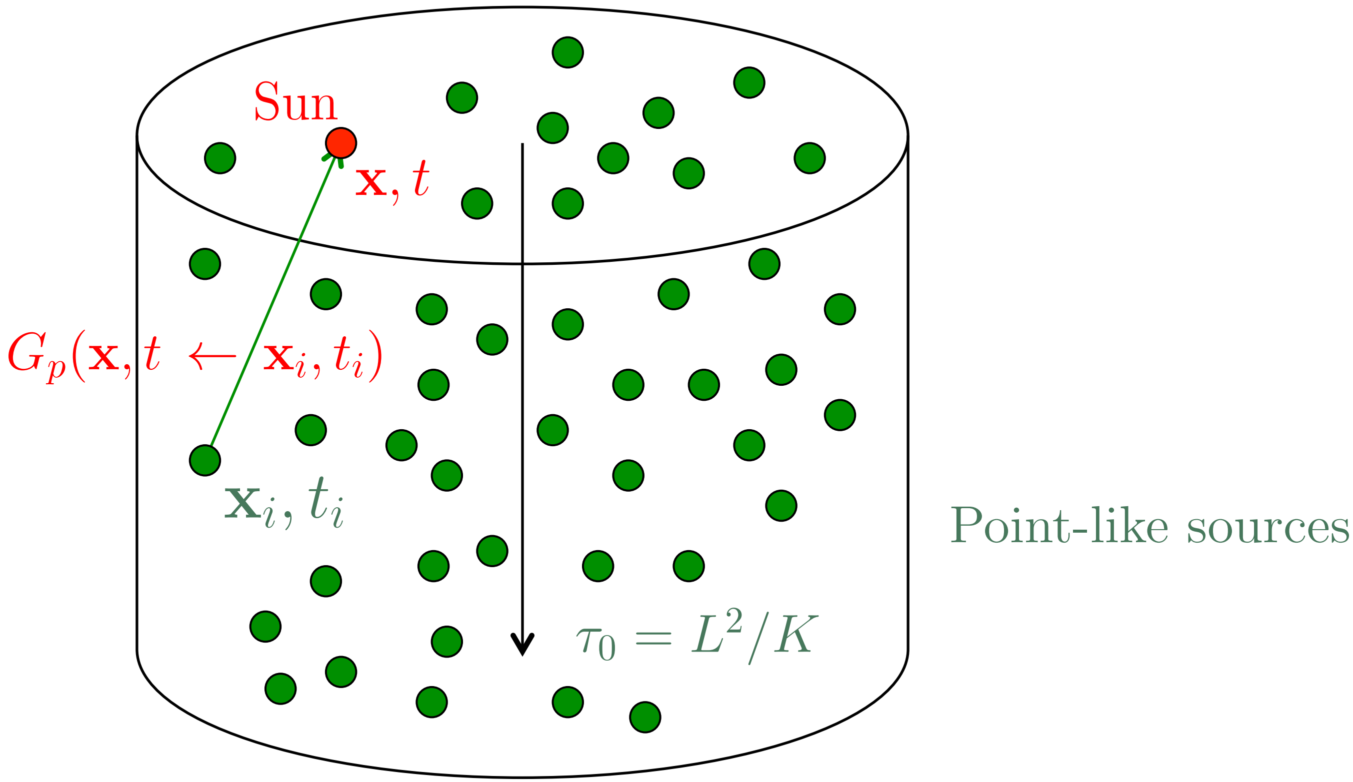




$$K_\gamma(100\,\text{TeV}) = (4.5 \pm 1.2) \times 10^{27}\ \text{cm}^2\ \text{s}^{-1} \ll K_{\text{B/C}}(100\,\text{TeV})$$

(iv) At high energy, CR physics becomes tricky and very exciting ! Sources of primary CR are **sporadic and discrete** – see the Myriad model. At the PeV scale, diffusion starts to be replaced by **ballistic motion**. It is unclear how to deal properly with that transition.

Space-time diagram



The actual flux is generated by a population $\mathcal{P}$ of discrete sources

$$\Phi_{\mathcal{P}} = \sum_{i \in \mathcal{P}} \varphi_i = \sum_{i \in \mathcal{P}} \frac{v_p}{4\pi} \times G_i \times q_{\rm SN}$$

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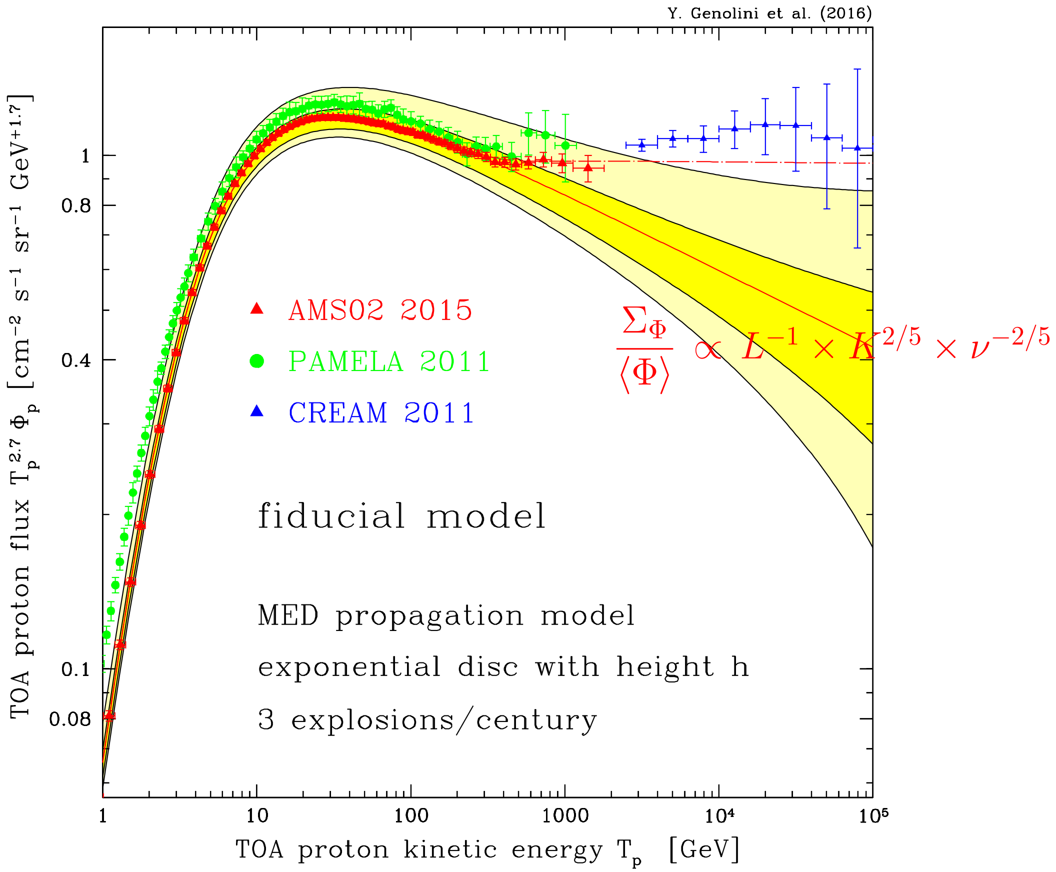

Kinetic energy [TeV]	0.724	0.96	1.41	3.16	5.02	7.94	12.6
P value in %	10.2	8.68	7.67	1.6	1.23	1.18	0.98

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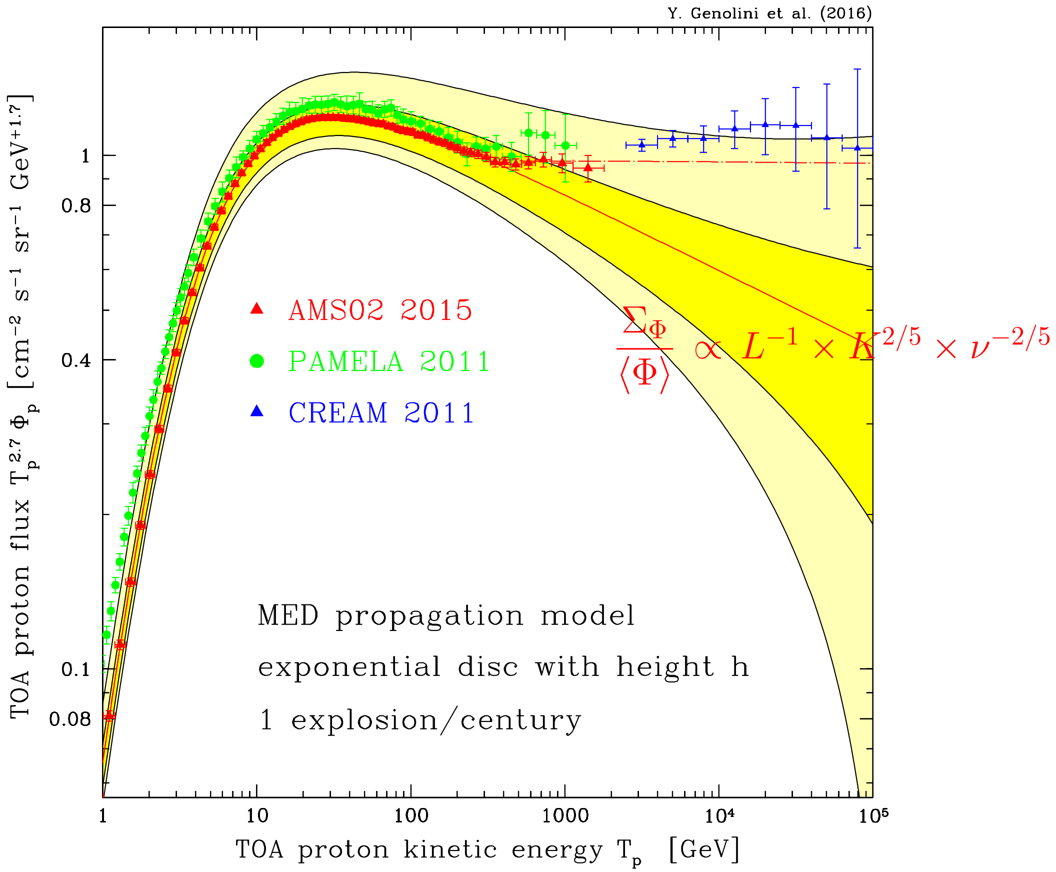

Kinetic energy [TeV]	0.724	0.96	1.41	3.16	5.02	7.94	12.6
P value in %	16.2	14.2	12.6	3.52	2.7	2.59	2.16

A few typical scales can be compared

• The cosmic ray **magnetic halo** extends vertically over a distance L which we will set equal to ~ 5 kpc.

• Charged particles spiral along the turbulent magnetic field which is of order 1 μG in the Milky Way. The **Larmor radius** is given by

$$R_{\rm L} = \frac{p}{qB} \simeq 10^{-6}\,{\rm pc} \times (E/1\,{\rm GeV})$$

• Cosmic rays diffuse on the knots of the turbulent Galactic magnetic field. This process is described through the diffusion coefficient $K \propto E^{\delta}$. We may derive a typical diffusion length $\lambda_{\rm diff}$ through Fick's relation.

$$K(E) = \frac{1}{3} v \lambda_{\rm diff} \equiv \frac{hL}{\tau_{\rm esc}}$$

$$\Downarrow$$

$$\lambda_{\rm diff} \simeq 1.5\,{\rm pc} \times (E/1\,{\rm GeV})^{\delta} \text{ with } \delta \sim 0.3 - 0.5$$

• We find that $L = \lambda_{\rm diff}$ for $E = 10^7$ GeV. The Larmor radius exceeds the Galaxy size when $L = R_{\rm L}$ at $E = 5 \times 10^9$ GeV.

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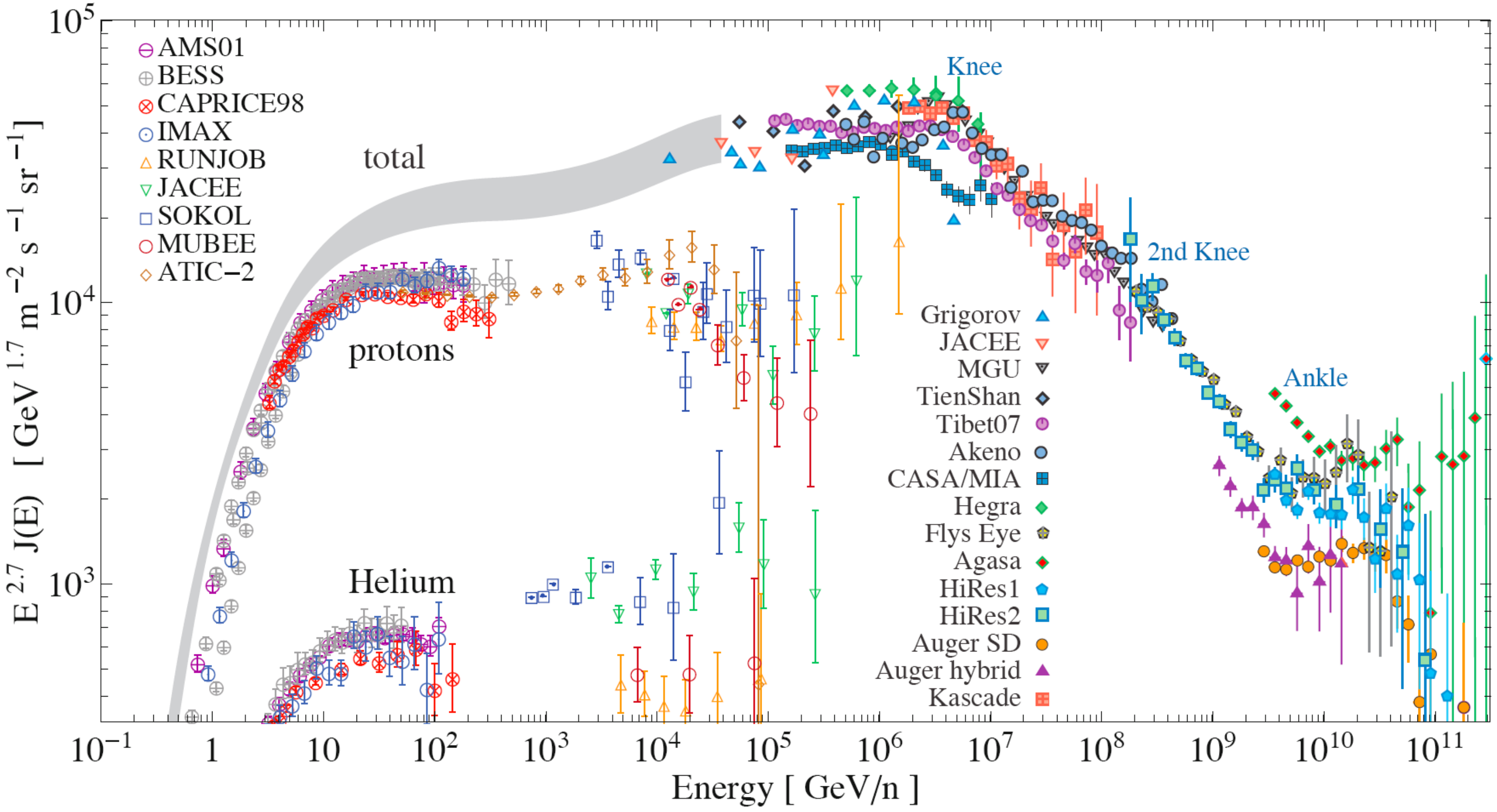

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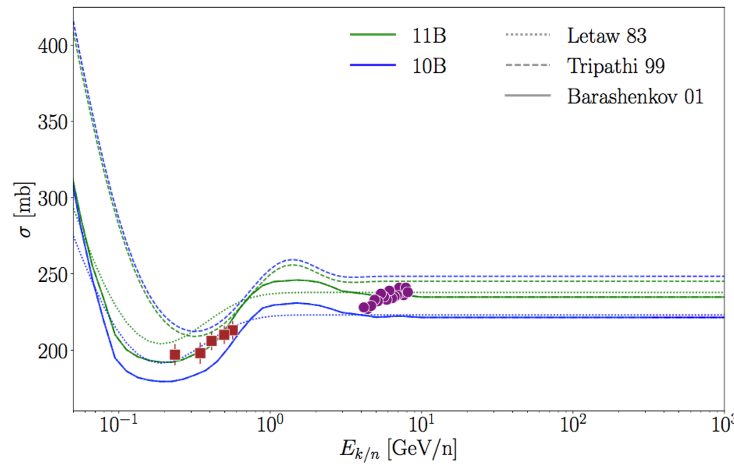
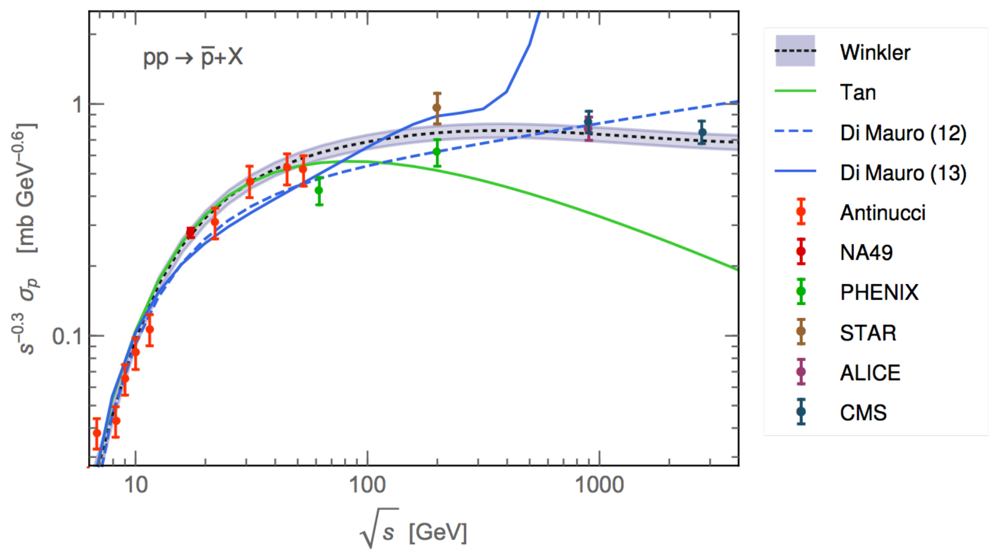
(v) At low energy, CR observations are plagued with **solar modulation** though Voyager 1 has opened a new window. A crucial issue arises from the **production, spallation, destruction cross-sections** which need to be better determined.

Y. Génolini, D. Maurin, I.V. Moskalenko & M. Unger, arXiv:1803.04686



A. Reinert & M.W. Winkler, JCAP **1801** (2018) 055



• DM searches under the form of neutral and massive particles has been a driving force for CR studies, especially on antimatter fluxes and associated secondary backgrounds. This will probably go on a few more years with CR measurements at TeV energies.

• Between the knee (10 PeV) and the ankle (5000 PeV), a transition takes place between diffusion and ballistic motion. Is there a satisfactory treatment of the problem ? Numerical vs analytical ?
As regards the discreteness of primary sources, the Myriad model allows to gauge the Galactic variance of the fluxes.

• γ-ray studies of nearby pulsars is a powerful tool yielding informations on how CR propagate near these sources. HAWC versus DAMPE debate.

• But the absolute must is a better determination of the cross-sections of the processes implied in CR production and destruction. CR observations are now so accurate that interpreting them requires to measure cross-sections with the same precision.

• ...

The discussion is now opened

The B/C ratio : a probe of cosmic ray transport

• Assuming that steady state holds – a common assumption – we find that the carbon and boron cosmic ray abundances are given by

$$\psi_C = \frac{q_C}{\sigma\, n_H\, v + 1/\tau_{\rm esc}} \quad \text{and} \quad B/C = \frac{\psi_B}{\psi_C} = \tau_{\rm esc} \times \sigma\, n_H\, v$$

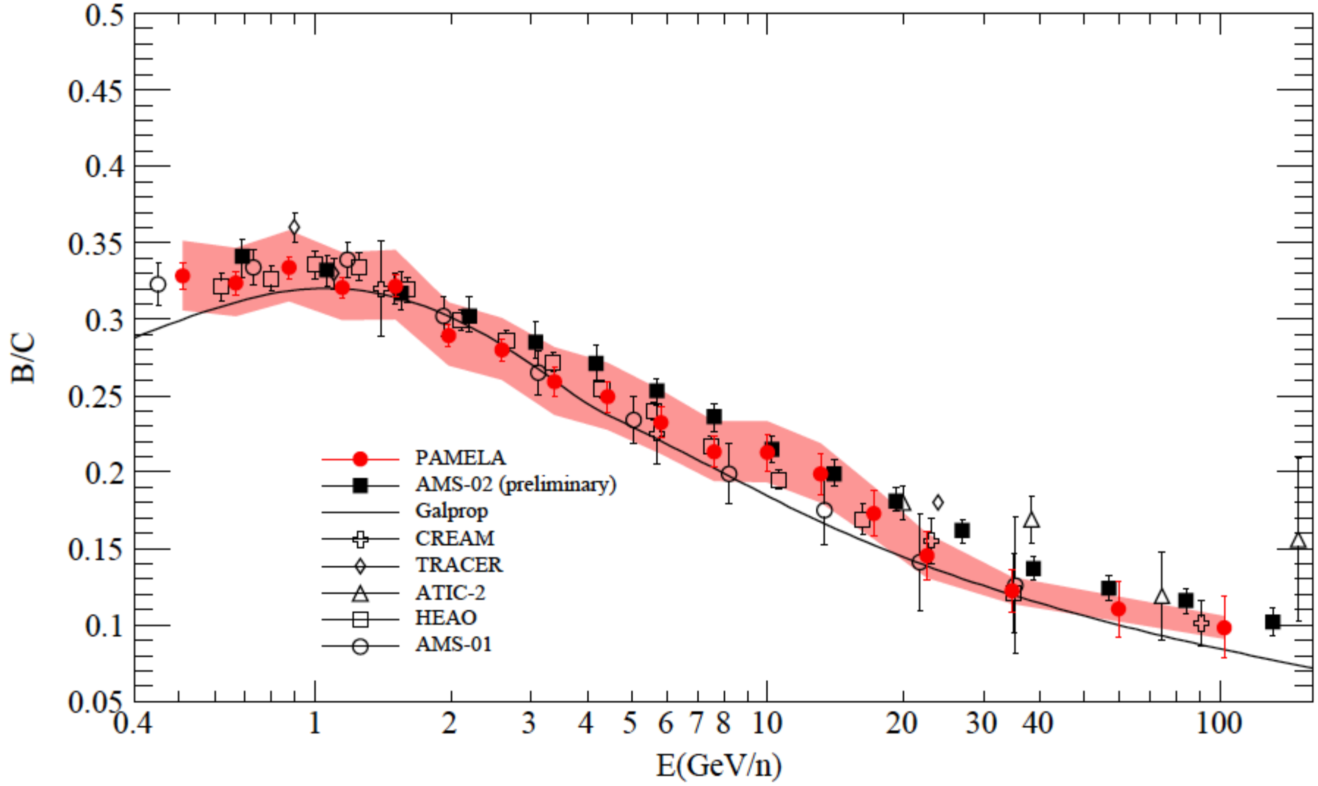
• Measuring the B/C ratio allows to determine the escape timescale $\tau_{\rm esc}$ from the Galactic disc. The density of the ISM is $n_H = 1$ cm^{-3}. The cosmic ray velocity is $v \simeq c \equiv 3 \times 10^{10}$ cm s^{-1}. The carbon to boron destruction cross section is measured to be $\sigma = 100$ mb $= 10^{-25}$ cm^2.

$$\tau_{\rm esc} = \frac{B/C}{\sigma\, n_H\, v} \simeq B/C \times 10 \text{ My}$$

• For kinetic energies of order a few GeV/nuc, we find that $\tau_{\rm esc}$ is 3 Myr. In comparison, the crossing time of the Galactic disc $\tau_{\rm dc}$ is given by $h/v \simeq 100\,{\rm pc}/c \sim 300$ yr. **Cosmic rays do not propagate ballistically**.

Cosmic rays diffuse inside the Galaxy

The B/C ratio : a probe of cosmic ray transport



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