

Connecting cosmic-ray physics, gamma-ray data and Dark Matter detection.

Oslo
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Daniele Gaggero
SISSA, Trieste
daniele.gaggero@sissa.it

Outline

1) The basic picture of CR propagation in the Galaxy

2) Going beyond the standard lore:

- the role of large-scale structure: 2D vs 3D simulations
- dropping the assumption of homogeneous diffusion and implications for the gamma rays: solving the “gradient problem”, and the “slope problem”
- the role of charge-dependent modulation

3) The importance of CR physics for a better understanding of DM indirect detection: the GC excess as a reference case

- constraining the DM origin of the GC excess with antiprotons
- the importance of accurate physical modeling of the GC region

(very quick) Introduction to CR physics

Two well known facts:

1) CR spectrum is a broken power law

extending from the GeV to extremely high energies (Oh-My-God particle energy = 10^{20} eV).

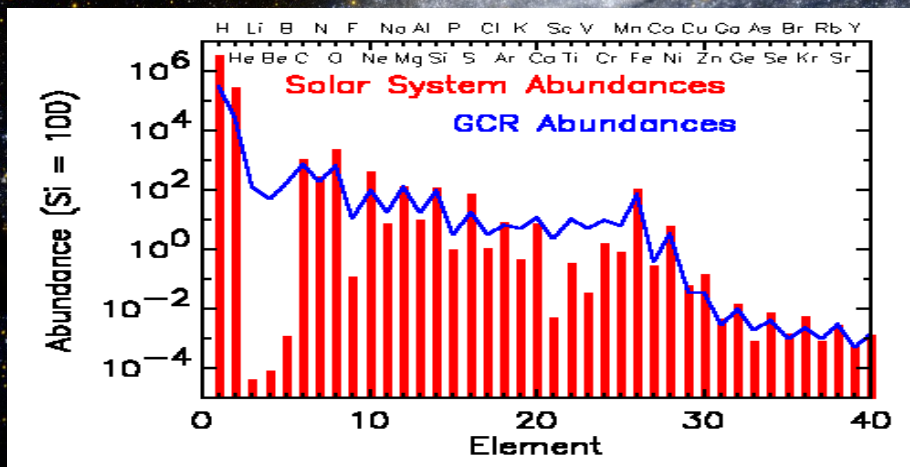
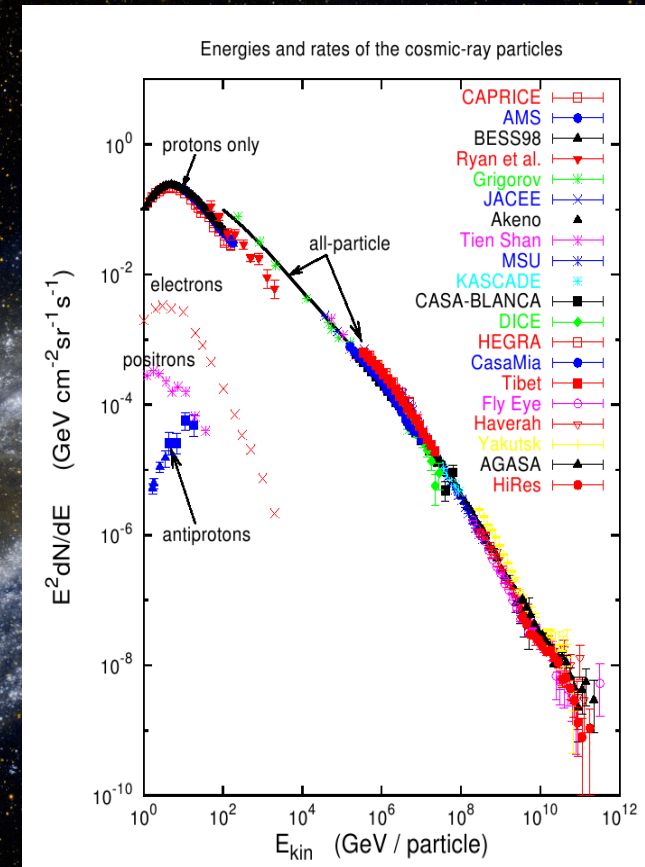
→ CRs up to the “ankle” have Galactic origin

2) There is evidence for CR confinement in the Galaxy:

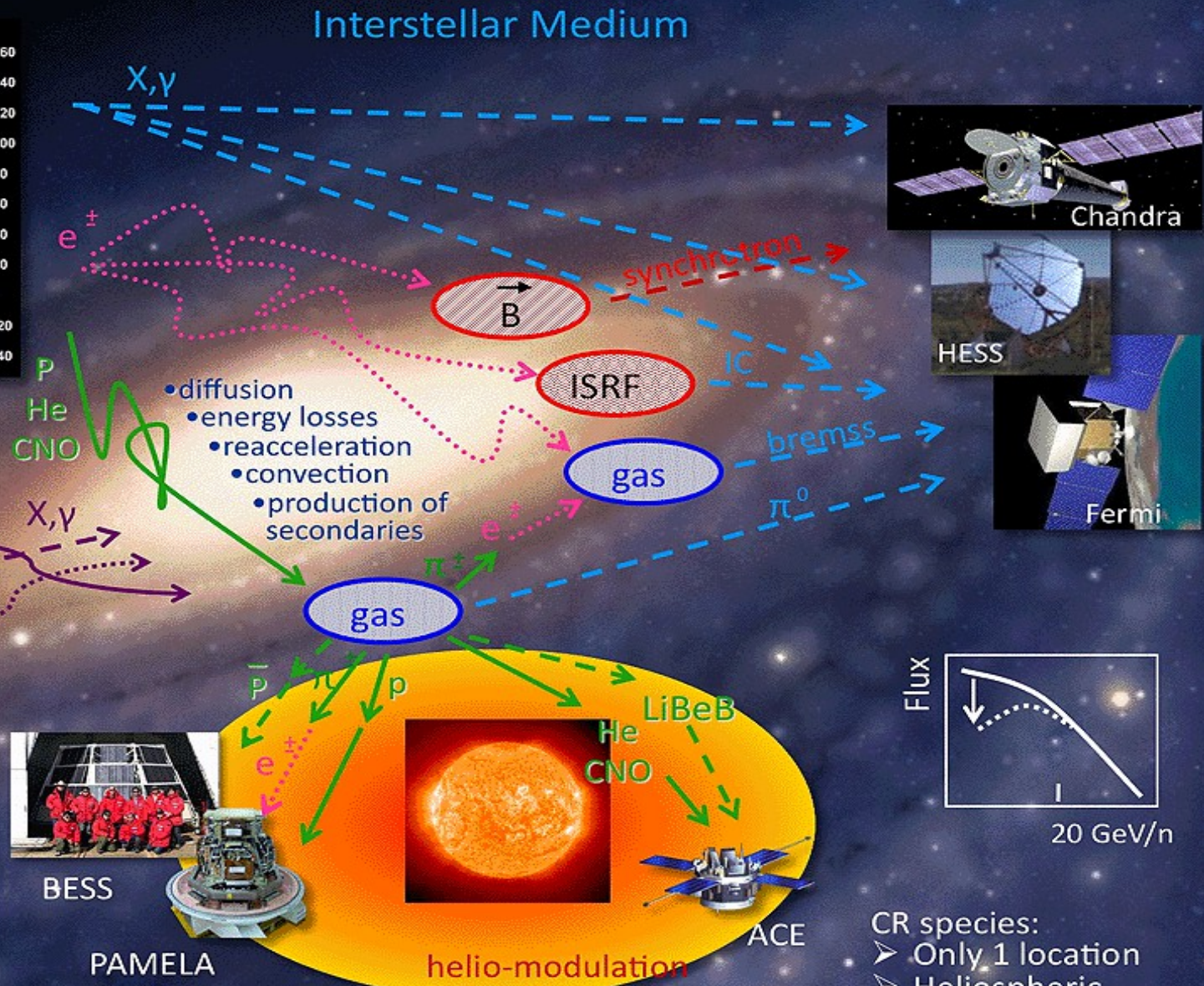
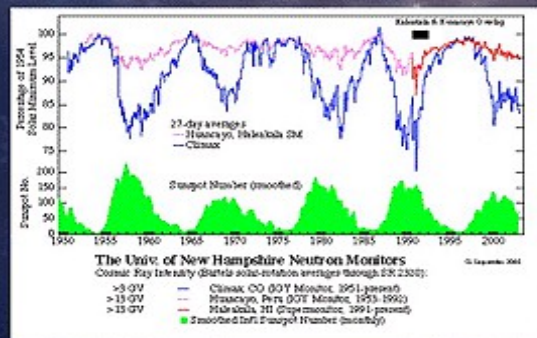
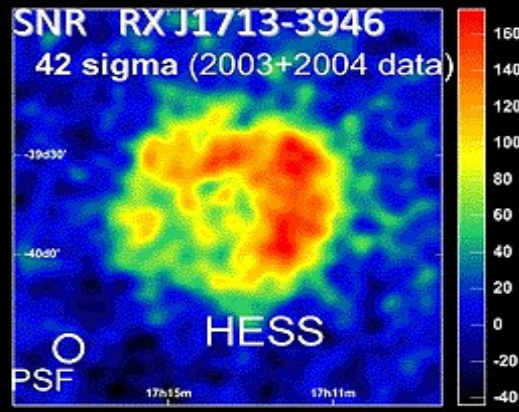
In order to reproduce the measured abundance of stable nuclei, CRs should have traversed

~ 10 g/cm^2 of interstellar material

→ $L = \text{grammage} / (n m_p) \sim 10^4 \text{ kpc} \gg \text{Galaxy size!!!}$



The basic picture of CR propagation



Courtesy of A. Strong

CR species:
➤ Only 1 location
➤ Heliospheric modulation

The basic picture

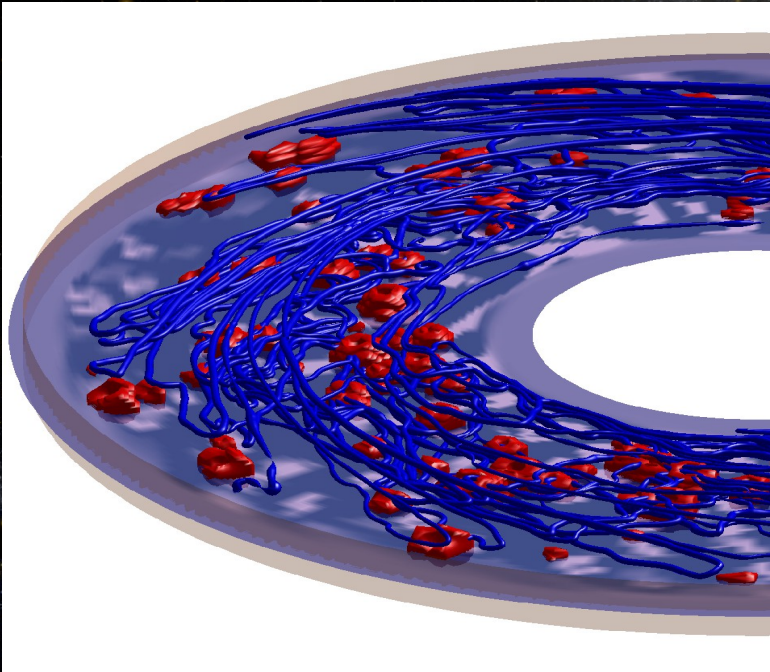
The equation describing CR propagation is the following:

$$\begin{aligned} \frac{\partial N^i(\vec{x}, p, t)}{\partial t} = & \nabla \cdot (D \nabla N^i - \mathbf{v}_C) N^i(\vec{x}, p, t) + \\ & + \frac{\partial}{\partial p} \left(\dot{p} - \frac{p}{3} \cdot \mathbf{v}_C \right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N^i(\vec{x}, p, t)}{p^2} \\ & + Q^i(\vec{x}, p, t) + \sum_{j>i} c \beta n_{\text{gas}} \sigma_{ij} N^j - c \beta n_{\text{gas}} \sigma_{\text{in}} N^i(\vec{x}, p, t) \end{aligned}$$

Spatial diffusion term.

due to the interaction with the Galactic magnetic field

In general D is a position-dependent tensor D_{ij}
→ In most literature so far, with only very few exceptions, diffusion is treated in a over-simplified way and D is taken as a spatial-independent scalar in the whole Galactic disk and halo



The basic picture

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Energy losses due to the interaction with the ISM: gas, magnetic fields, diffuse radiation field in the IR, optical, UV

→ this term is important for low-energy hadrons and high-energy leptons (IC scattering, synchrotron emission)

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Reacceleration

The basic picture

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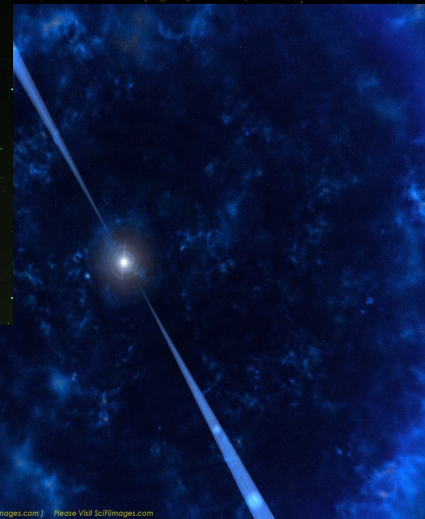
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Primary source term.

Protons, nuclei, electrons are accelerated by SNR shocks

→ Other classes of CR accelerators?
(maybe pulsars?)

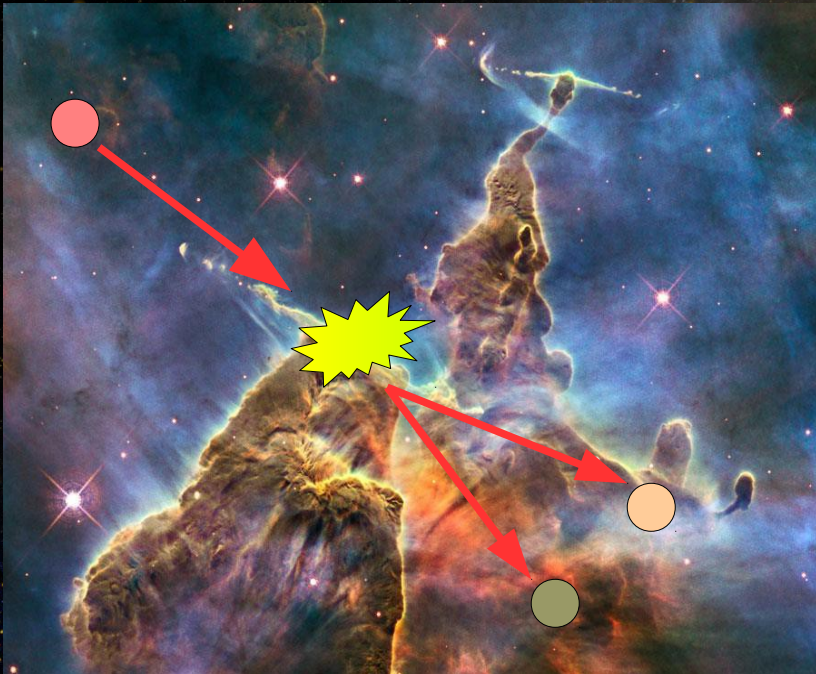
→ CRs coming from DM annihilation / decay?



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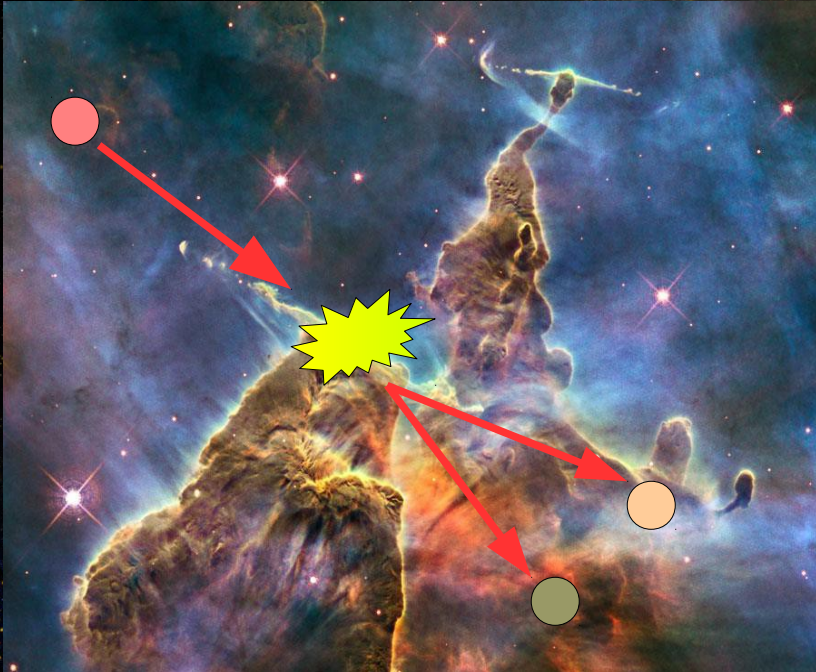
Spallation source term from heavier nuclei interacting with interstellar gas.

For Li, Be, B and antiparticles (positrons, antiprotons) this is the dominant source term.

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Spallation loss
term

Cosmic ray physics is apparently easy...

What people have done for so many years in order to model the data is quite easy:

1) assume that **CRs are injected in the Galaxy** mainly by SNRs located on the Galactic plane. Injection spectrum: power law in rigidity, with arbitrary number of breaks

$$\frac{\partial Q}{\partial p} = p^{\alpha}$$

2) assume that **CRs diffuse in the same way all through the Galactic halo.**

The Galaxy is a uniform box with no structure.

The diffusion coefficient is rigidity dependent:

$$D = D_0 \beta p^{\delta}$$

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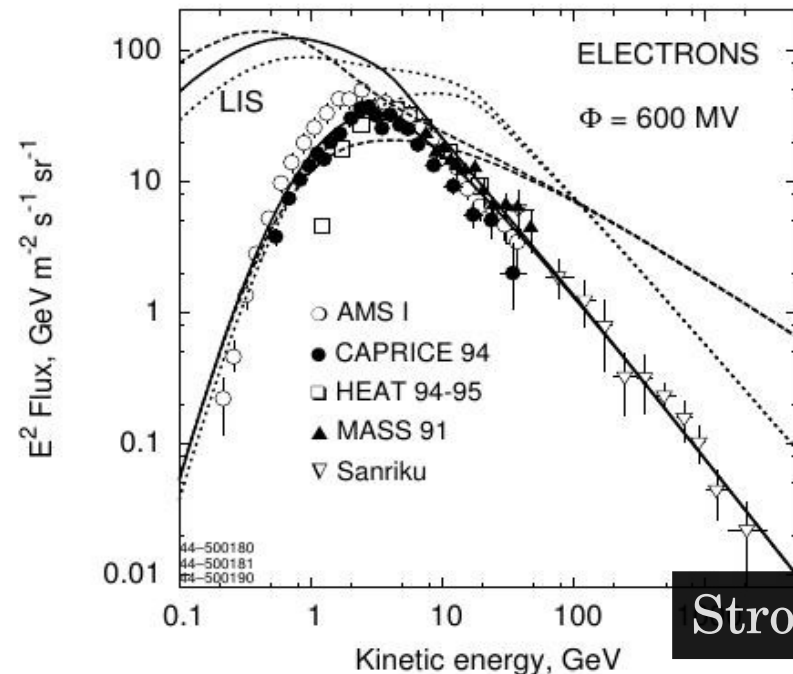
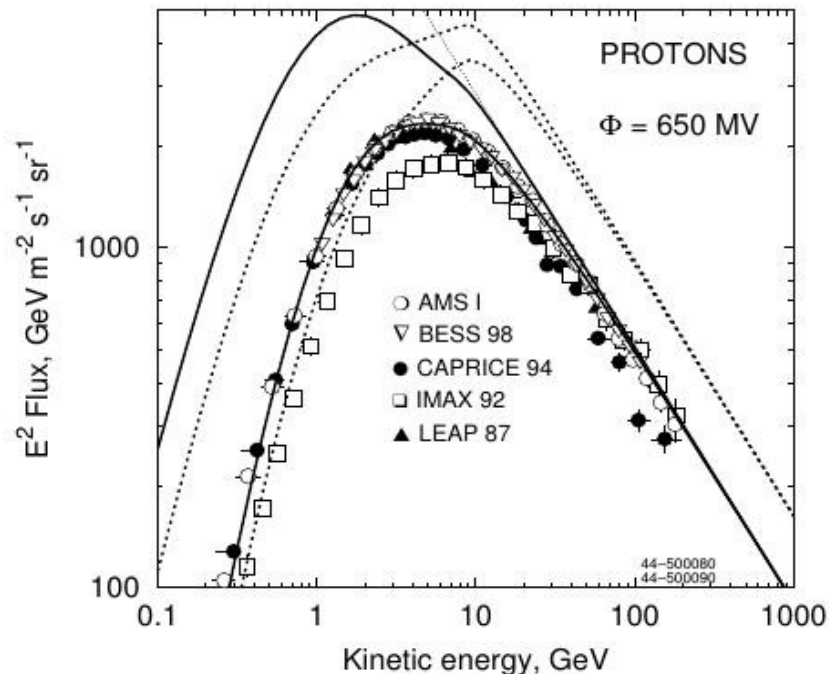
In this framework, the propagated spectra of nuclei are easily computed solving the diffusion equation in 2D (R, z): azimuthal symmetry.

At high energy

→ Propagated slope = inj. Slope + δ

At low energy (< 10-20 GeV)
modulation...)

→ Other effects (reacceleration, convection, solar modulation...)



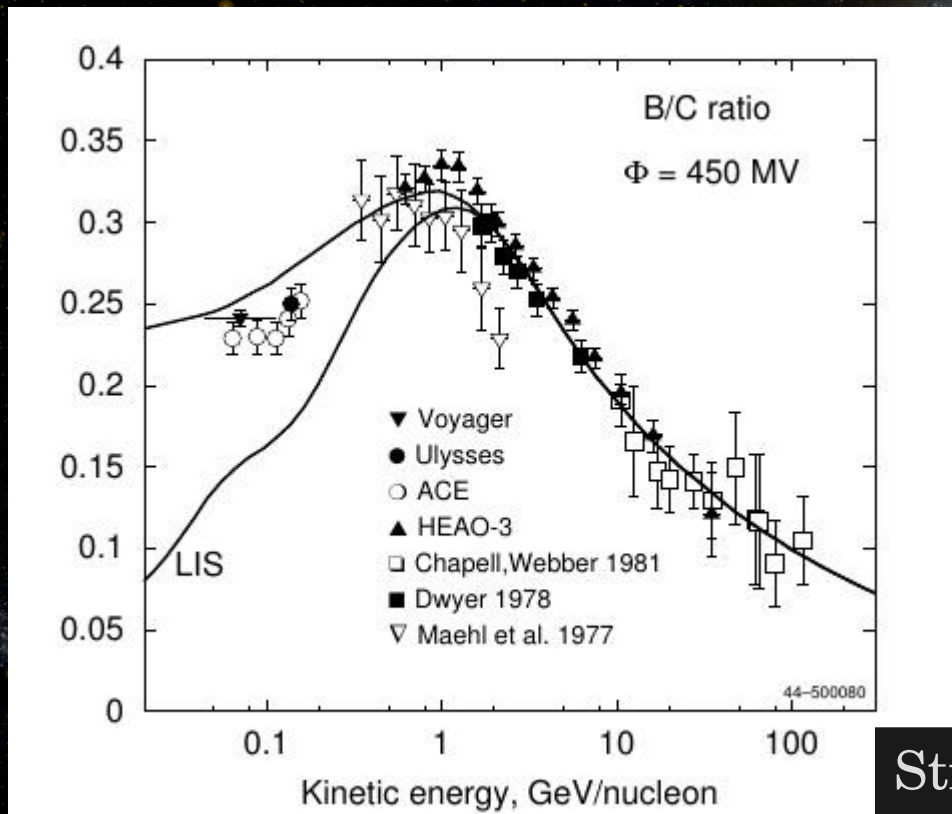
Strong 2004

Cosmic ray physics is apparently easy...

What people have done for so many years in order to model the data is quite easy:

The value of δ is not determined by primary species because of the degeneracy with the injection slope

It is fixed by Secondary/Primary ratios \rightarrow they do not depend on the inj. slope



Strong 2004

Going beyond the standard lore

1. The spiral arm structure of the Galaxy and its impact on CR leptonic spectra



→ With the propagation code **DRAGON**, developed by Luca Maccione, Carmelo Evoli and me (Evoli *et al.* JCAP 2008, Gaggero *et al.* PRL 2013), *it is possible to simulate the processes relevant for the propagation of all CR species*: nuclei, protons, antiprotons, electrons, positrons.

→ diffusion, spallation, reacceleration, convection, energy losses are implemented in a realistic framework.

→ the simulations can be performed in both 2D and 3D mode, taking into account isotropic or anisotropic diffusion (*still work in progress on this last point*).

$$\begin{aligned} \frac{\partial f}{\partial t} = & Q + \alpha_{xx} \partial_x^2 f + \alpha_{yy} \partial_y^2 f + \alpha_{zz} \partial_z^2 f \\ & + 2\delta_{xy} \partial_x \partial_y f + 2\delta_{xz} \partial_x \partial_z f + 2\delta_{yz} \partial_y \partial_z f \\ & + u_x \partial_x f + u_y \partial_y f + u_z \partial_z f \end{aligned}$$

$$\alpha_{xx}(x, y, z) = (D_{\parallel} - D_{\perp})b_x^2 + D_{\perp}$$

$$\alpha_{yy}(x, y, z) = (D_{\parallel} - D_{\perp})b_y^2 + D_{\perp}$$

$$\alpha_{zz}(x, y, z) = (D_{\parallel} - D_{\perp})b_z^2 + D_{\perp}$$

$$\delta_{xy}(x, y, z) = (D_{\parallel} - D_{\perp})b_x b_y + D_{\perp}$$

$$\delta_{xz}(x, y, z) = (D_{\parallel} - D_{\perp})b_x b_z + D_{\perp}$$

$$\delta_{yz}(x, y, z) = (D_{\parallel} - D_{\perp})b_y b_z + D_{\perp}$$

$$u_x(x, y, z) = \partial_x \alpha_{xx} + \partial_y \delta_{xy} + \partial_z \delta_{xz}$$

$$u_y(x, y, z) = \partial_x \delta_{xy} + \partial_y \alpha_{yy} + \partial_z \delta_{yz}$$

$$u_z(x, y, z) = \partial_x \delta_{xz} + \partial_y \delta_{yz} + \partial_z \alpha_{zz}$$

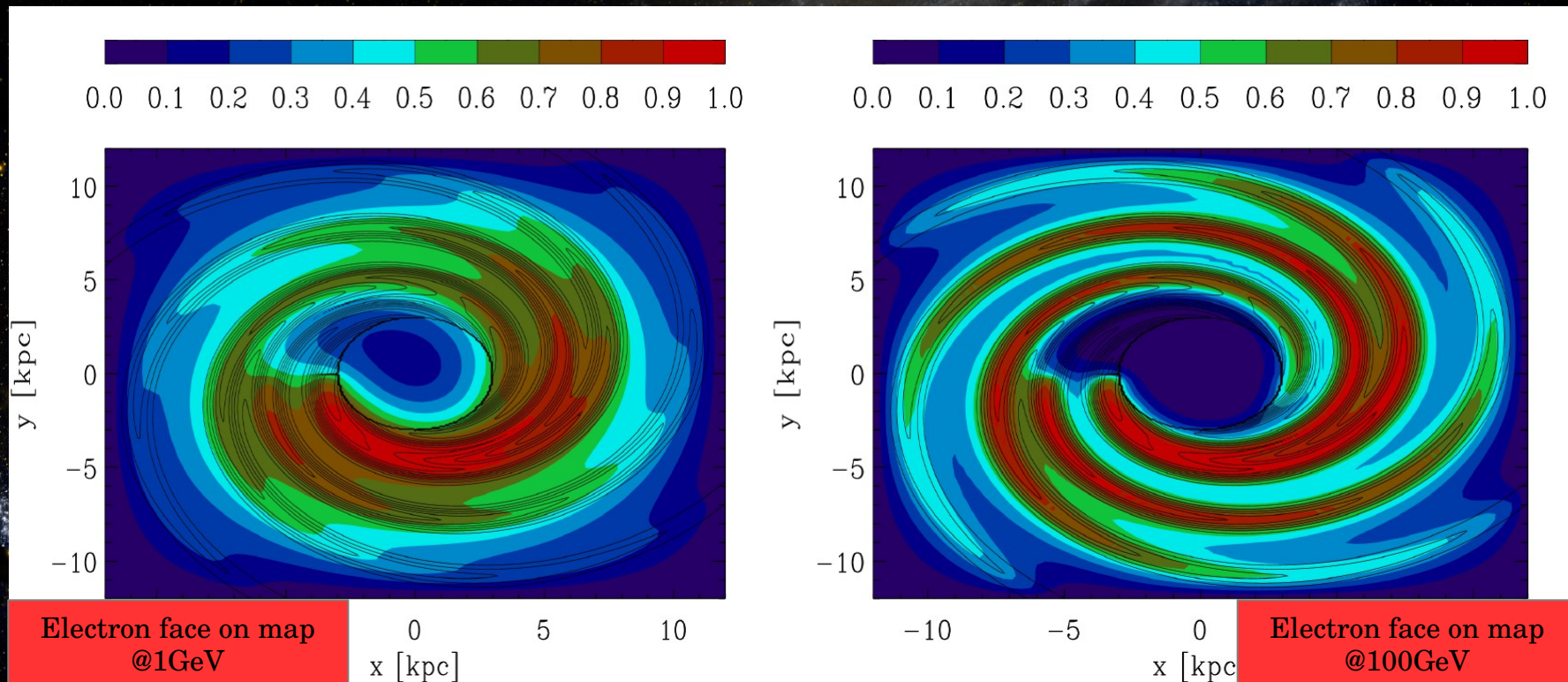
Going beyond the standard lore

1. The spiral arm structure of the Galaxy and its impact on CR leptonic spectra



A 3D model of the Galaxy

Spiral arm model from Blasi&Amato, [arXiv:1105.4529](#)
3D isotropic version of the code, sources within the spiral arms.



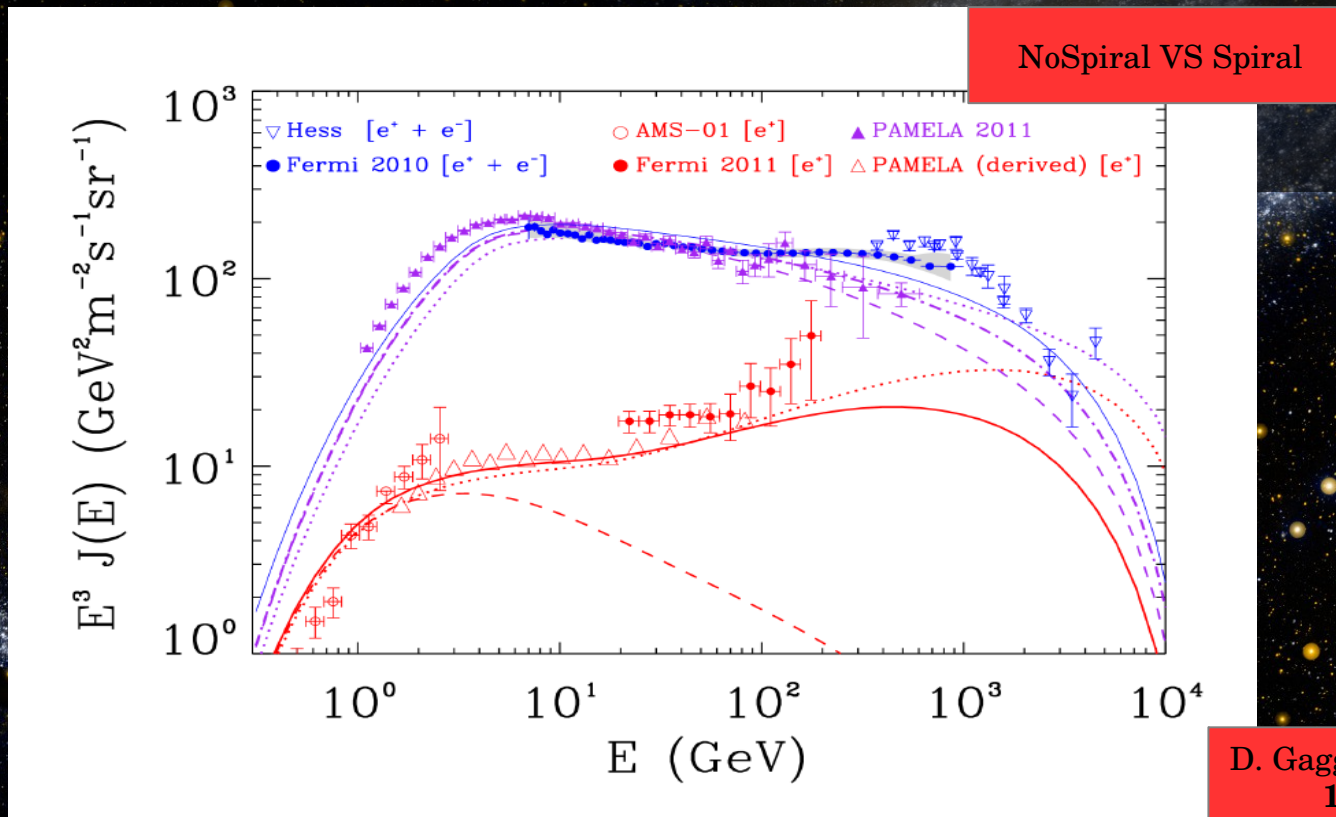
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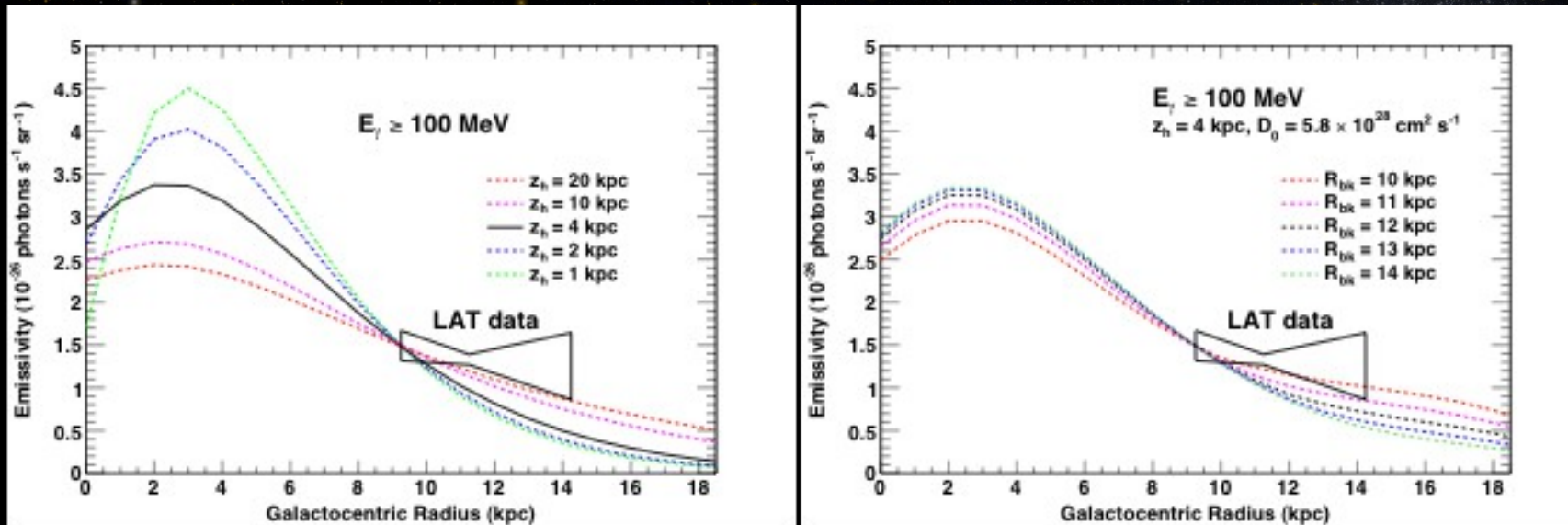


Going beyond the standard lore

2. Spatial gradients in the **normalization** of the CR diffusion coefficient



Motivation: Gradient problem



This problem was already known in the EGRET era and then confirmed by Fermi-LAT

- the CR gradient *along the Galactocentric R* can be inferred from gamma-ray diffuse data;
- the CR gradient derived from numerical simulations (in which the SNR or pulsar profile is used as a source function) turns out to be steeper than the observed one!

Going beyond the standard lore

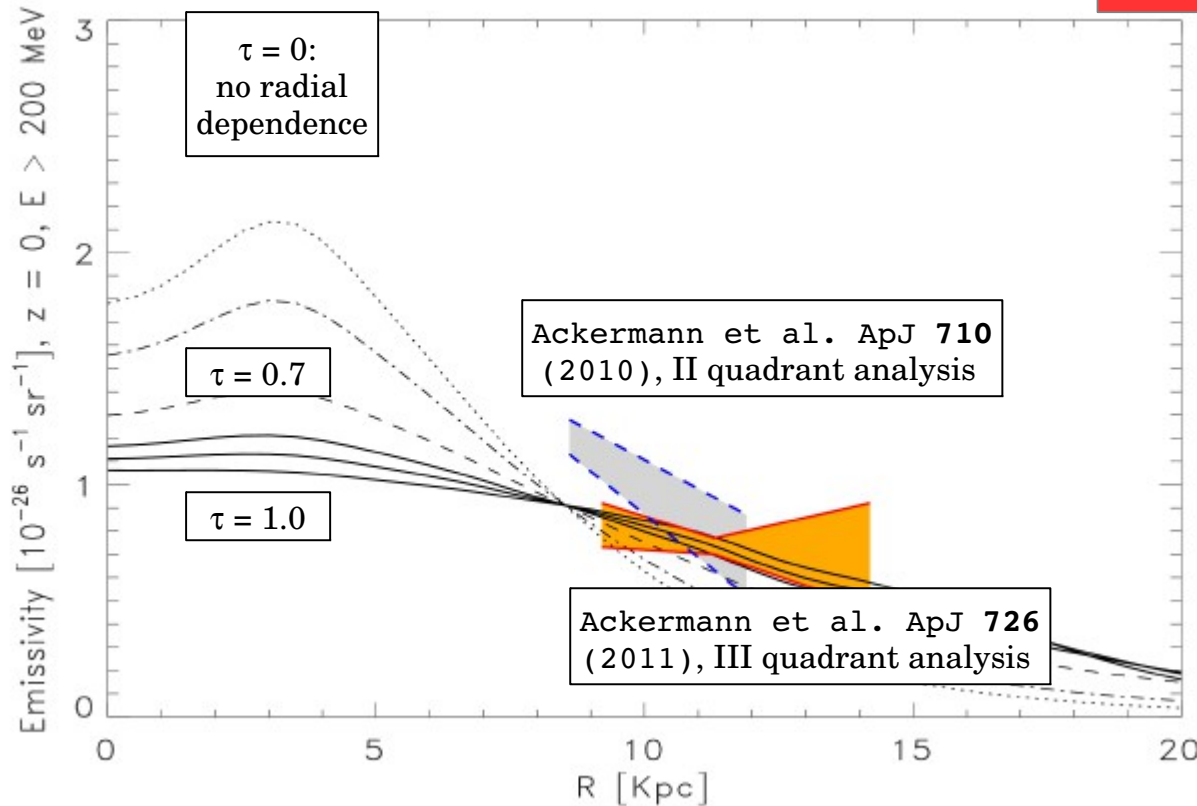
2. Spatial gradients in the **normalization** of the CR diffusion coefficient



Results: Gradient Problem solved!

$$D(r,z) = D_0 Q(r,z)^\tau$$

C. Evoli et al., PRL
(2012)



Going beyond the standard lore

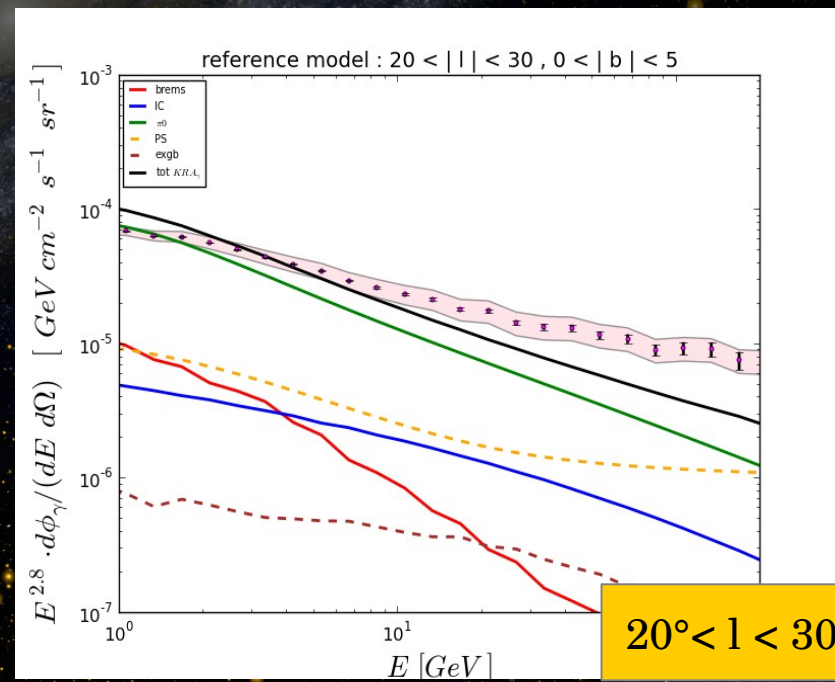
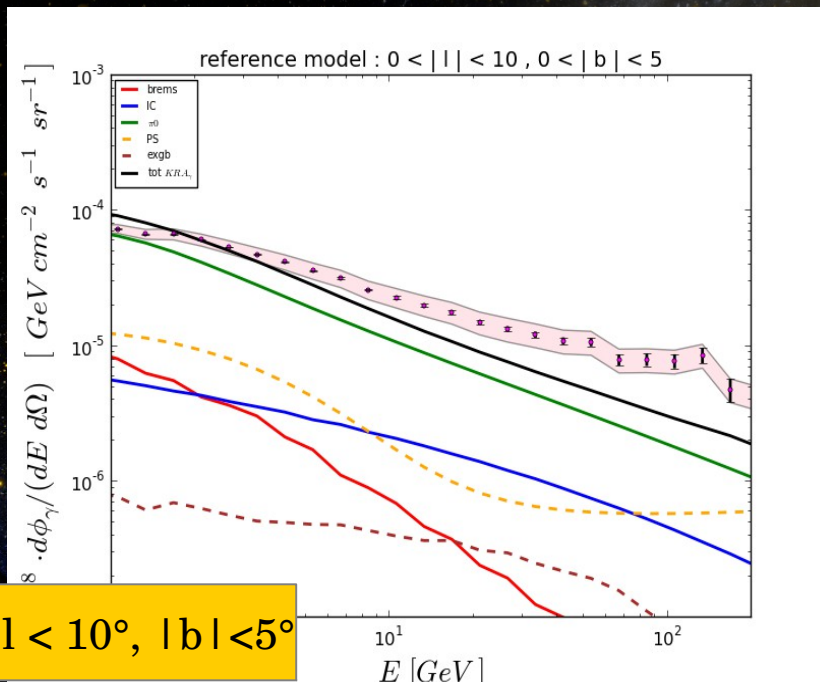
3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient



Motivation: “slope problem”

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *the problem is more serious on the Galactic plane, especially looking at sky windows pointing towards the inner Galaxy!*

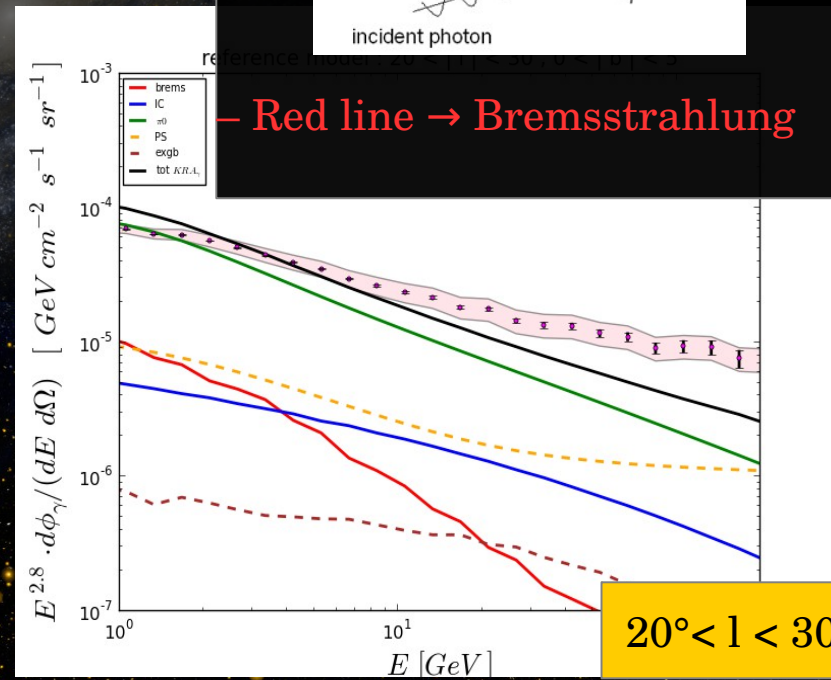
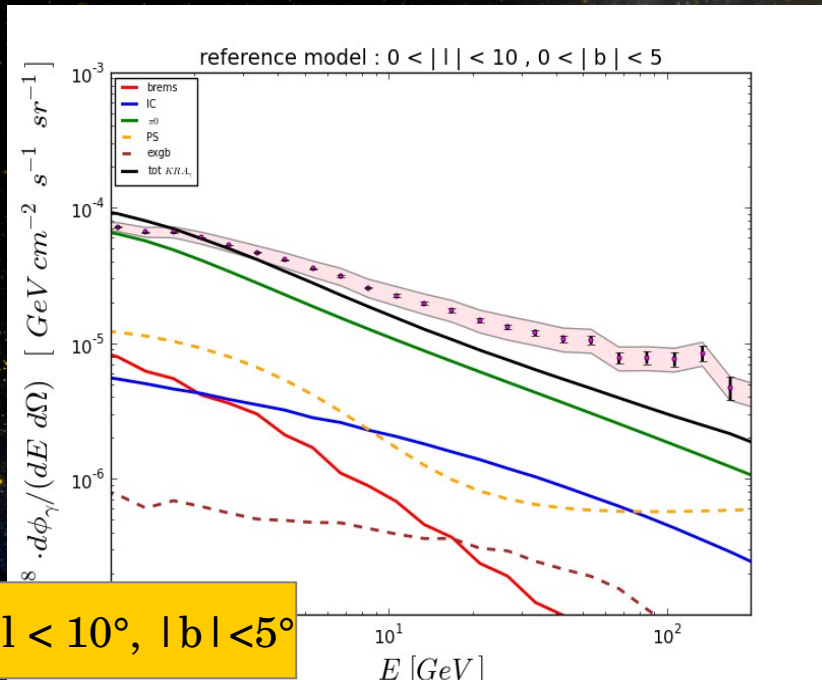


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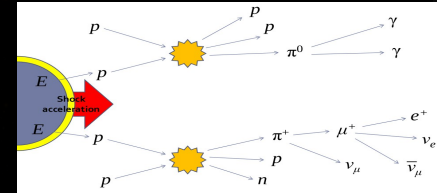
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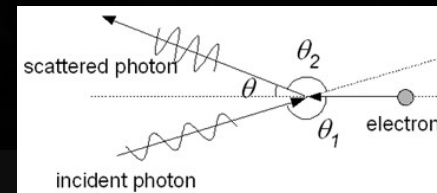
All CR propagation models underestimate the gamma-ray emission at high energy.



– Green line → Pion decay (pions come from proton – proton collisions)



– Blue line → Inverse Compton emission (leptons interacting with interstellar photon field)



– Red line → Bremsstrahlung

Going beyond the standard lore

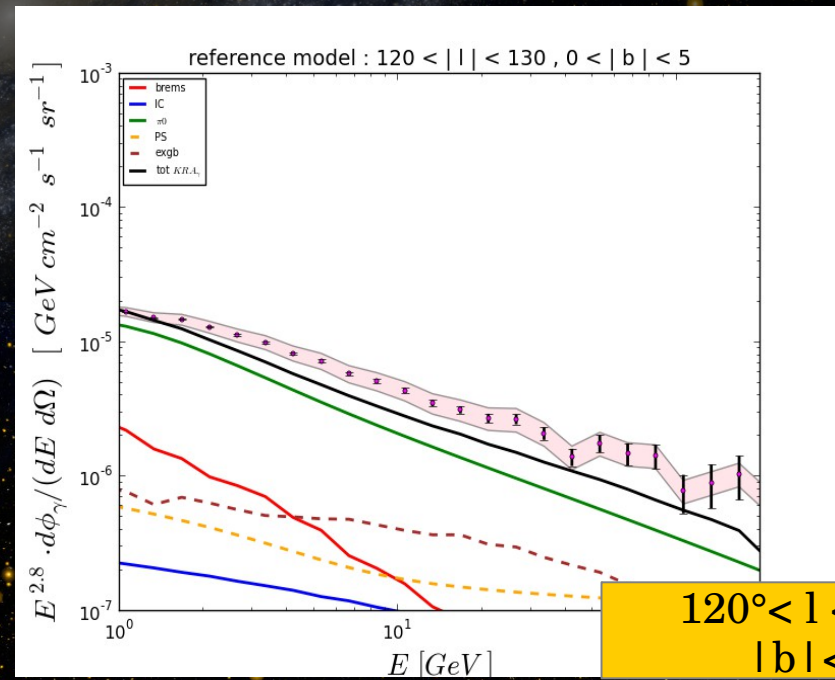
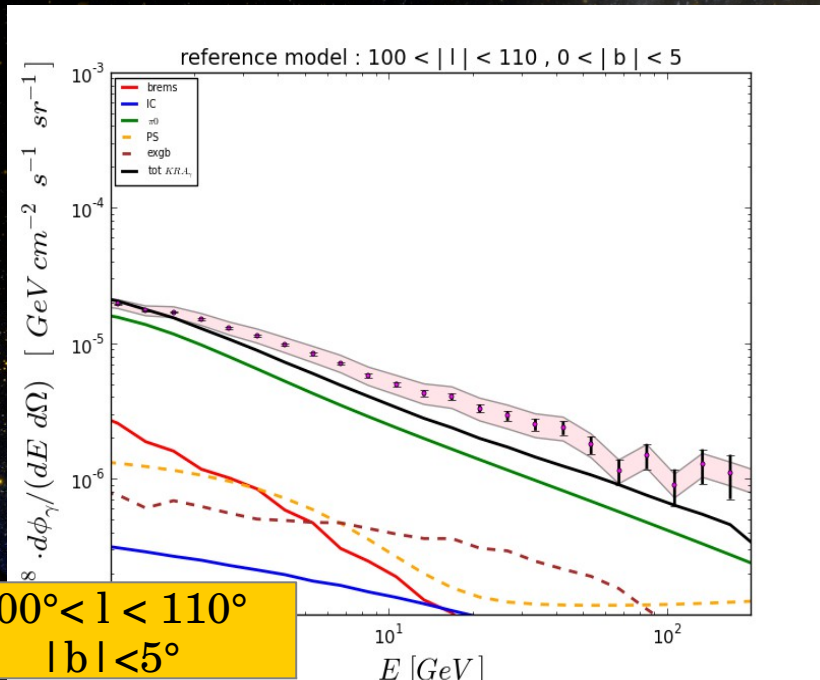
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Motivation: “slope problem”

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *looking far from the GC region, the discrepancy is less evident:*



Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

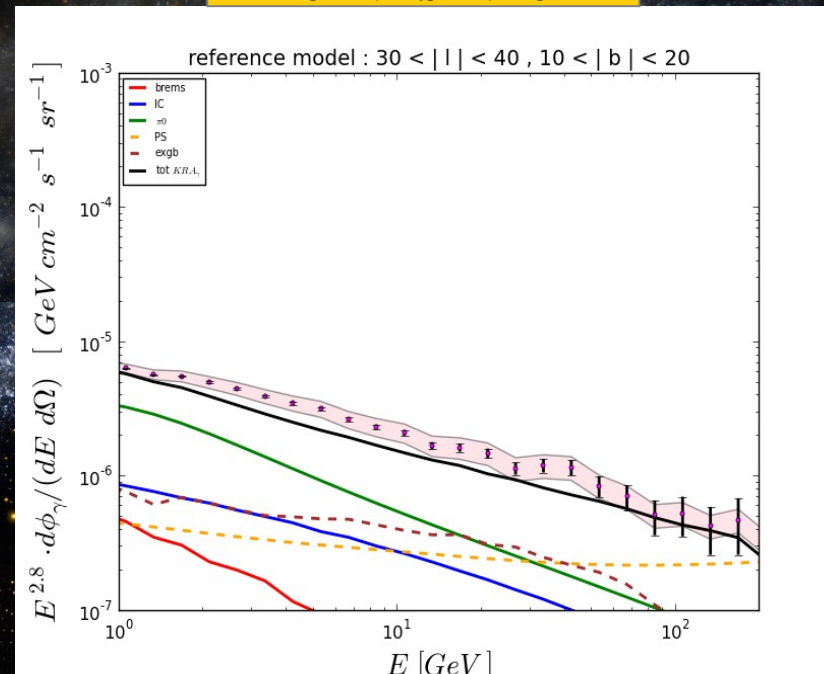


Motivation: “slope problem”

All CR propagation models underestimate the gamma-ray emission at high energy.

→ *looking at high latitude, the discrepancy is less evident:*

$$30^\circ < l < 40^\circ \\ 10^\circ < |b| < 20^\circ$$



Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

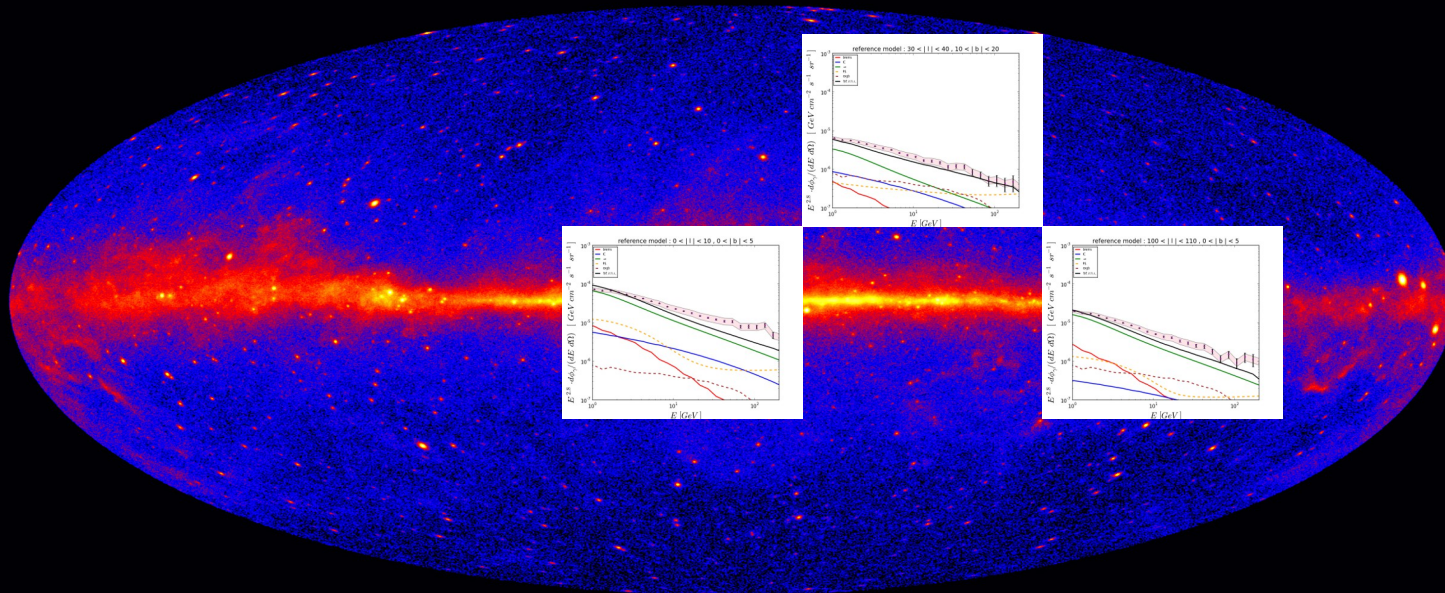


The idea:

→ we drop the over-simplified assumption of homogeneous diffusion

→ we consider a **harder diffusion coefficient in the inner Galaxy**

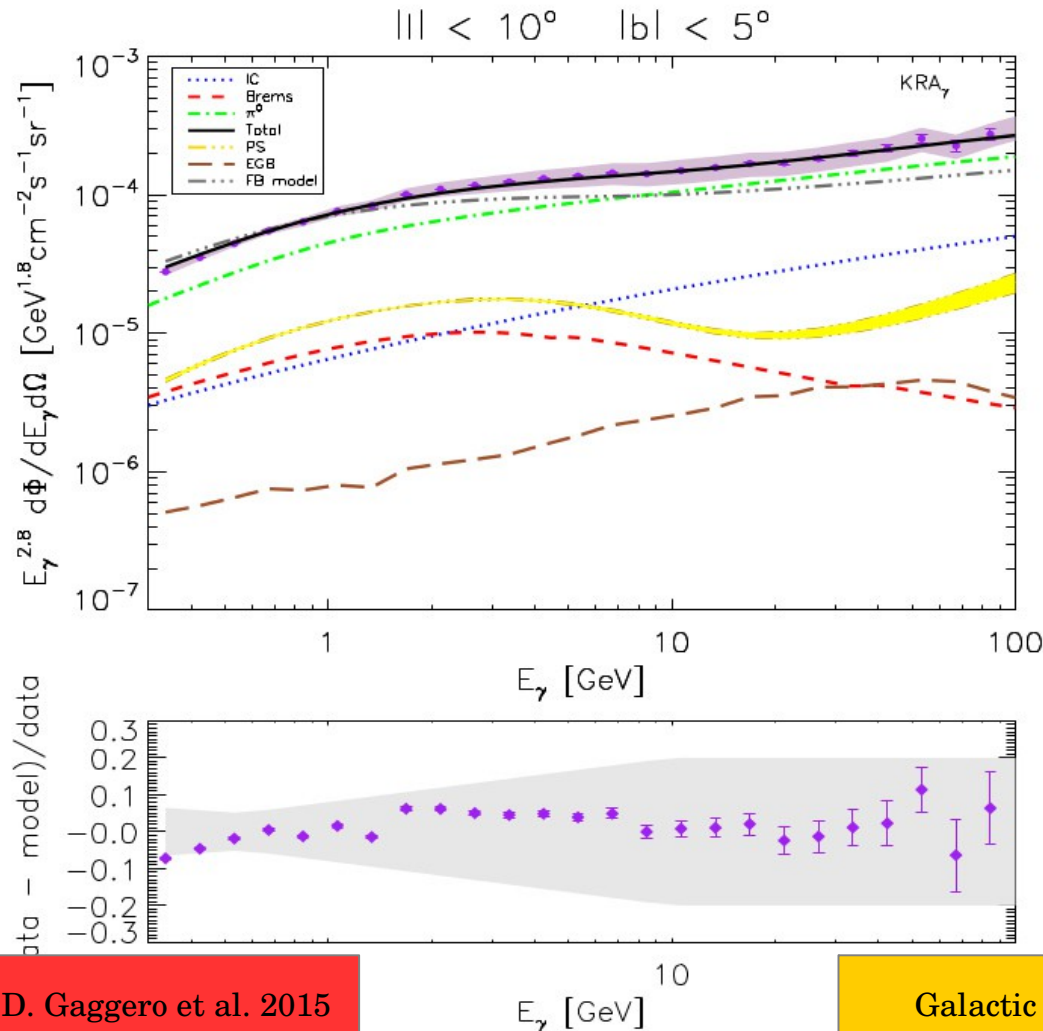
$$\delta(R) = aR + b$$



Going beyond the standard lore

3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

Results obtained with DRAGON and GammaSky:



D. Gaggero et al. 2015

Galactic Center

Starting with a standard propagation models, we fit the data with the combination of two simple non-standard ingredients, namely:

→ a harder diffusion coefficient in the inner Galaxy
 $\delta(R) = aR + b$

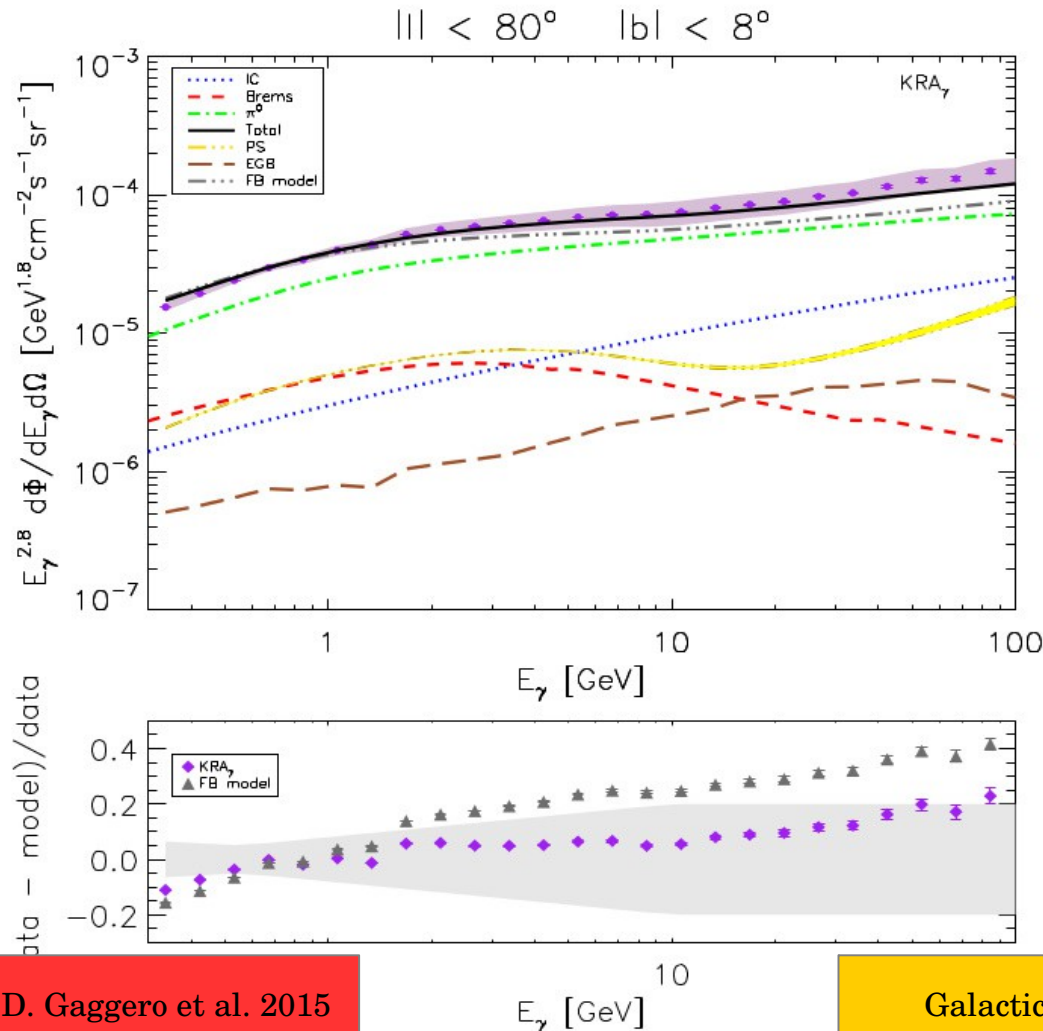
(physical interpretation: CRs near the sources propagate in SN-driven turbulence, while CRs in the outer Galaxy propagate in self-generated turbulence (see Blasi 2013, Tommassetti 2014))

→ a high convective wind in the inner Galaxy (observed e.g. by ROSAT and other experiment)

Going beyond the standard lore

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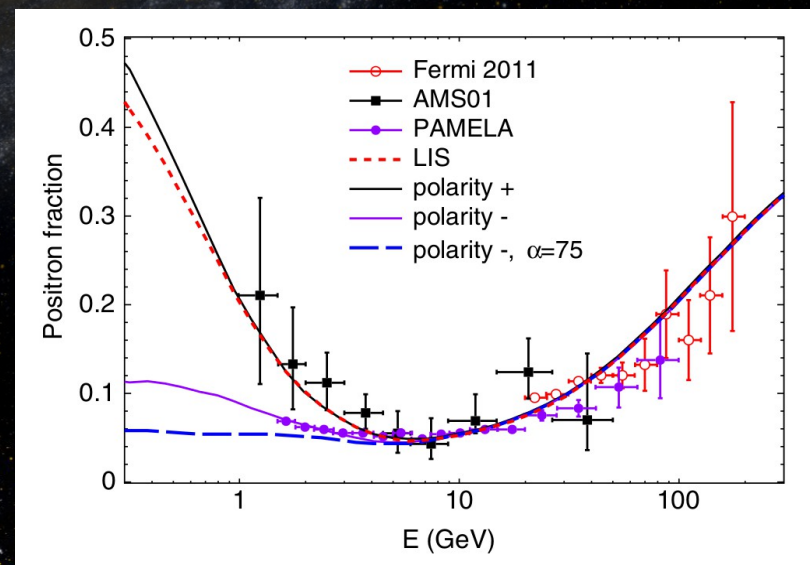
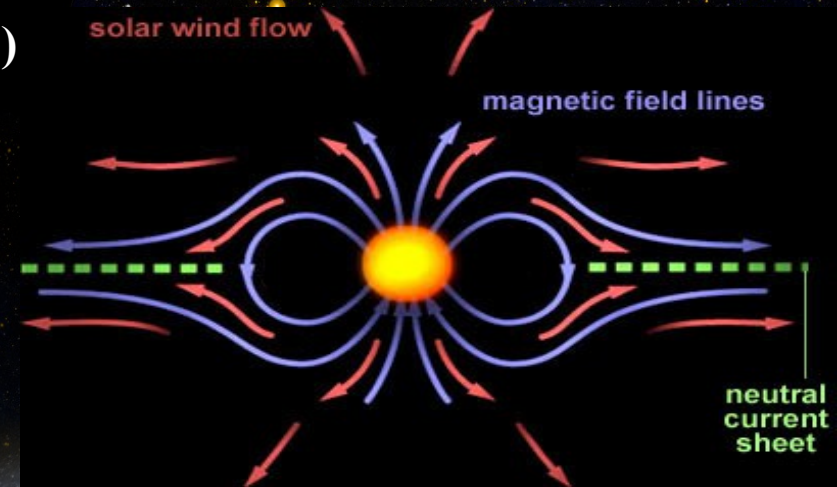
4. Charge-dependent solar modulation (just few remarks)

The interaction of low-energy CRs with the Heliosphere is very complicated.

CRs are affected by the outward flowing solar wind and the embedded turbulent heliospheric magnetic field (HMF).

Motion is described by an equation taking into account diffusion, drift and loss terms (*see e.g. papers by Parker, Burger, Jokipii In the '60s and '70s, more recently Strauss et al. 2012, Maccione 2013*)

→ The effect of this process is very different for positive and negative particles (*see e.g. Maccione 2013*)



Going beyond the standard lore

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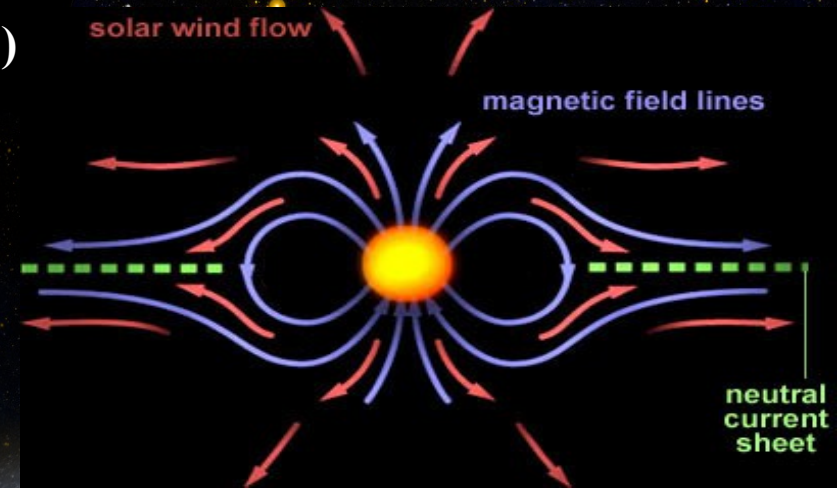
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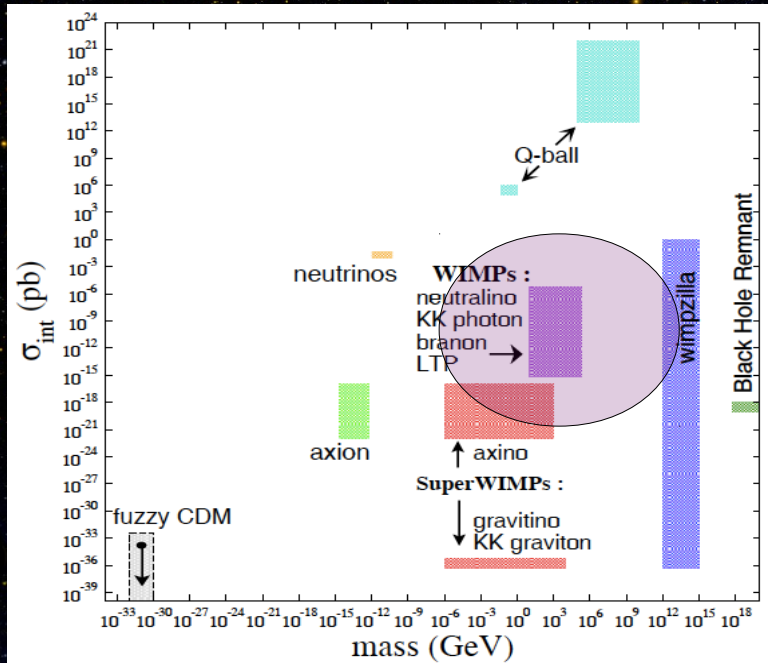
→ In spite of that, the standard way to treat Solar modulation consists in a phenomenological formula (*Gleeson and Axford 1964*) where charge-dependent effects are completely neglected!

J is the
CR flux

$$\frac{J(r, E, t)}{E^2 - m^2} = \frac{J(\infty, E + \Phi)}{(E + \Phi)^2 - m^2}$$



Why is all this so relevant for the Dark Matter puzzle?

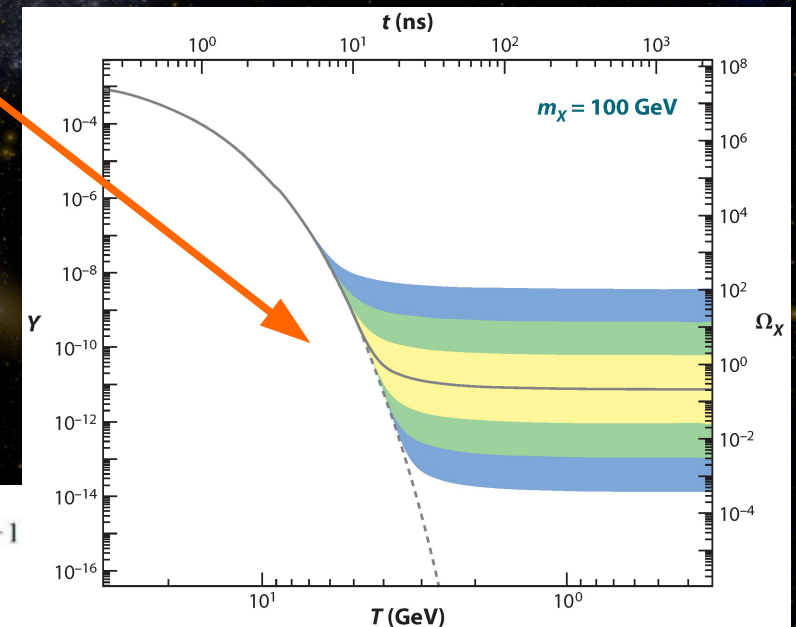


Particle physics provides many DM candidates

The most popular ones (namely the WIMPS, e.g. the lightest supersymmetric particle in the minimal supersymmetric extension of the SM) are in the mass range $O(\text{GeV}) \rightarrow O(\text{TeV})$

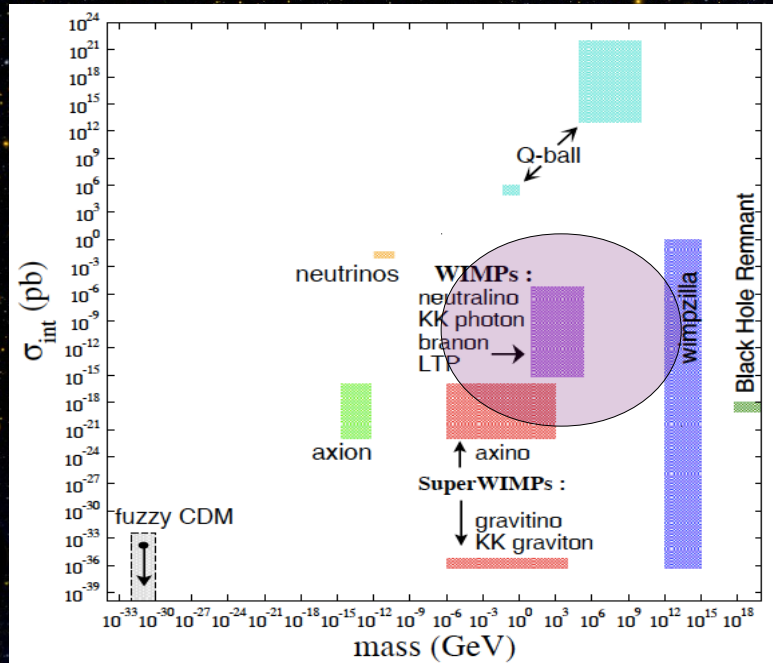
→ It is well known that *WIMPs can provide the correct relic density*

(Lee&Weinberg
PRL 1977,
Gondolo&Gelmini,
NuPhB 1990)



$$\Omega h^2 \simeq 0.1 \times \left(\frac{\langle \sigma v \rangle_{\text{freeze}}}{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}} \right)^{-1}$$

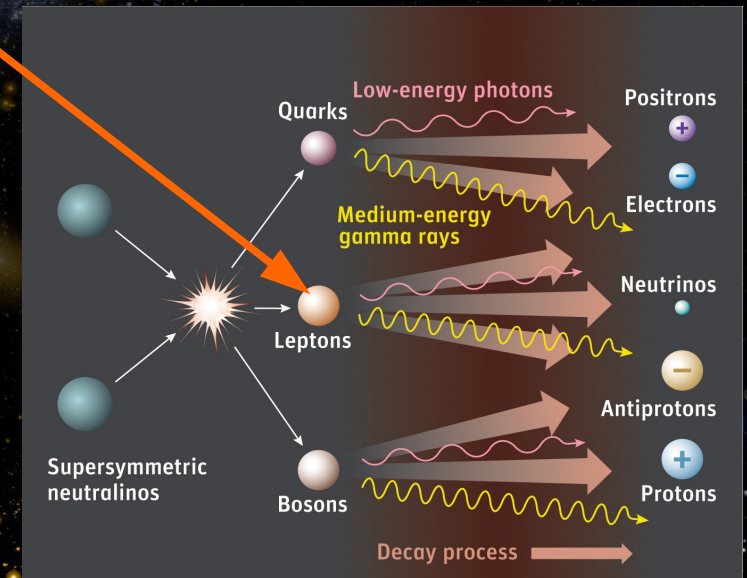
Why is all this so relevant for the Dark Matter puzzle?



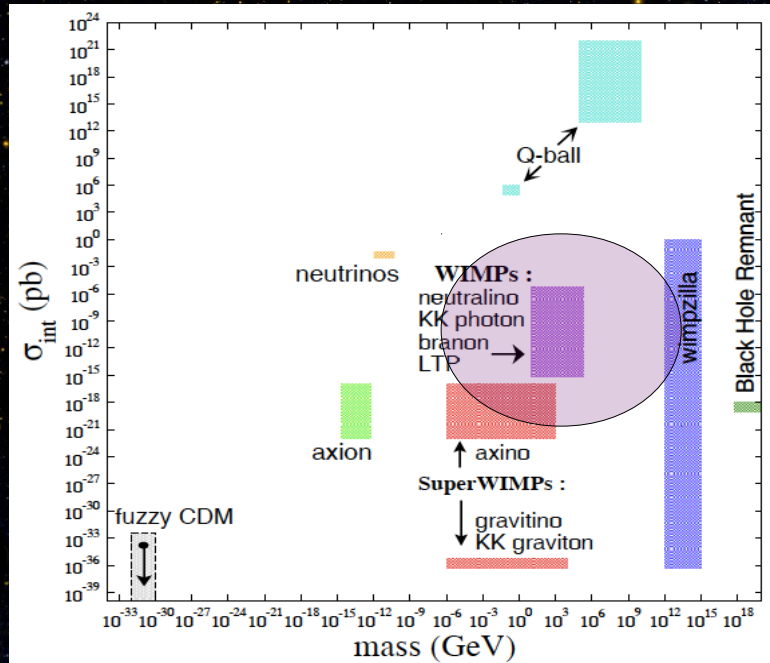
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→ they may show up in either CRs or gamma-ray/synchrotron emission (“multimessenger indirect detection”)



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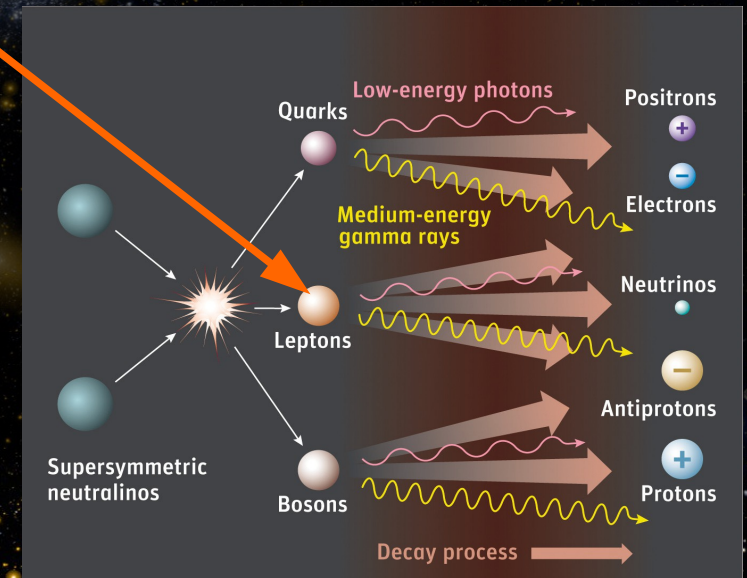


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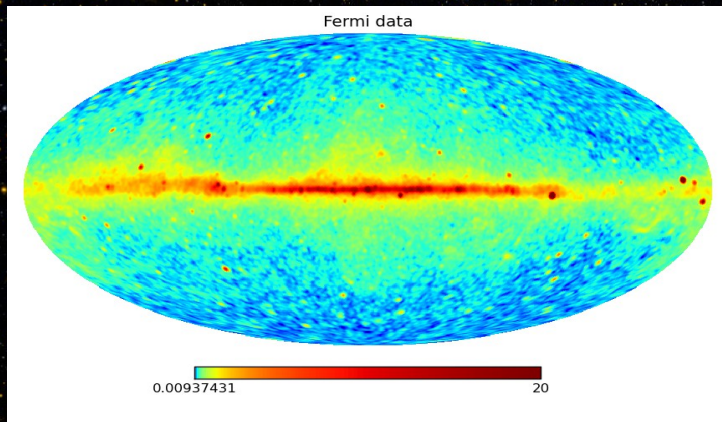
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That's why the DM community has been so interested for a long time in CR physics!



The Galactic center excess

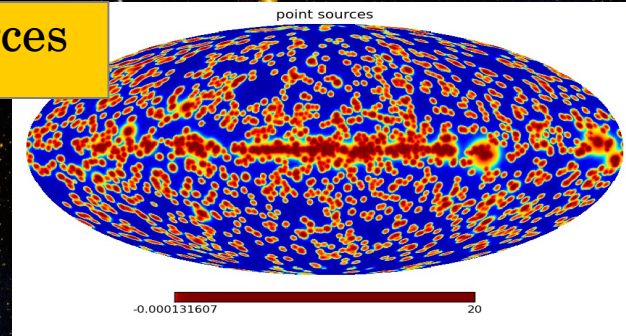


Fermi-LAT data

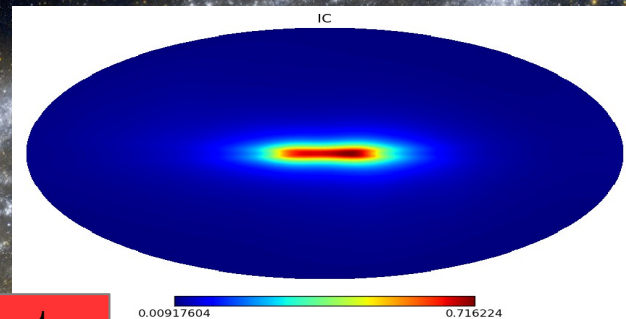
Given the high accuracy of Fermi-LAT data, the diffuse emission is very promising for DM indirect detection

→ The goal is to understand if, once all known components are subtracted, a significant residual is left

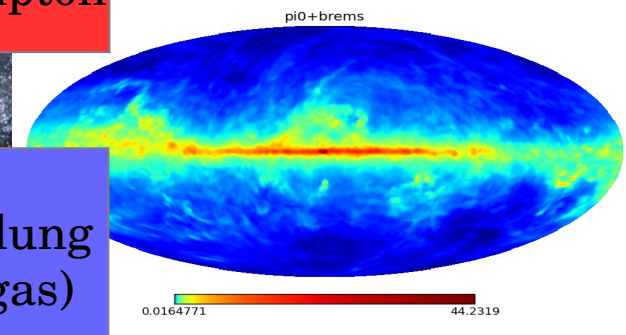
Point Sources



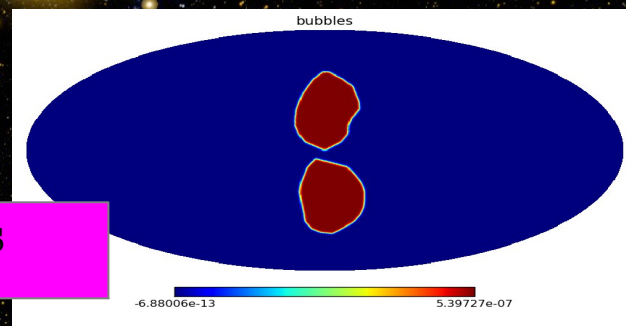
Inverse Compton



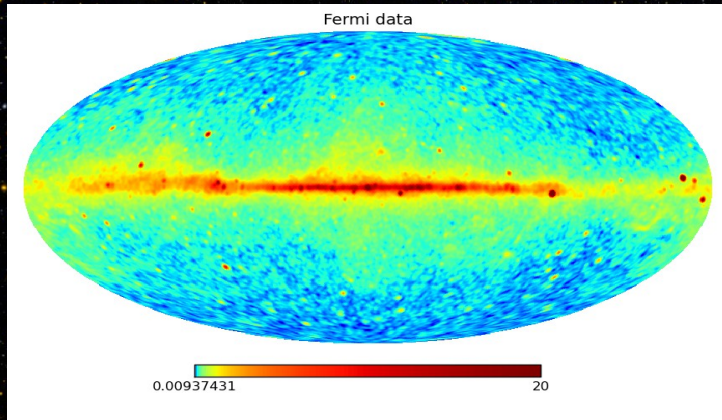
π_0 +
bremsstrahlung
(traces IS gas)



Bubbles



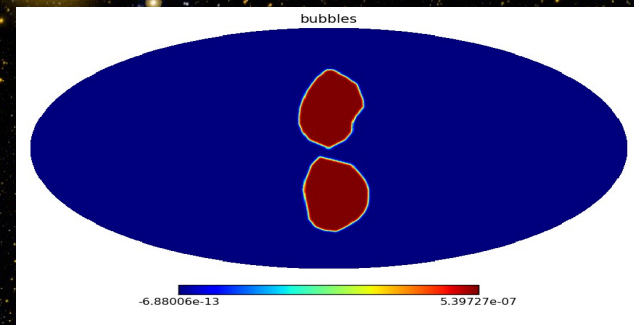
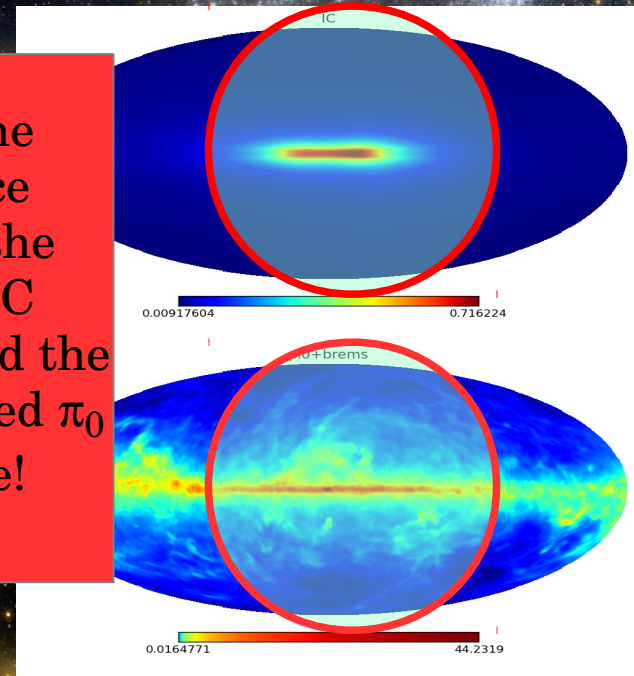
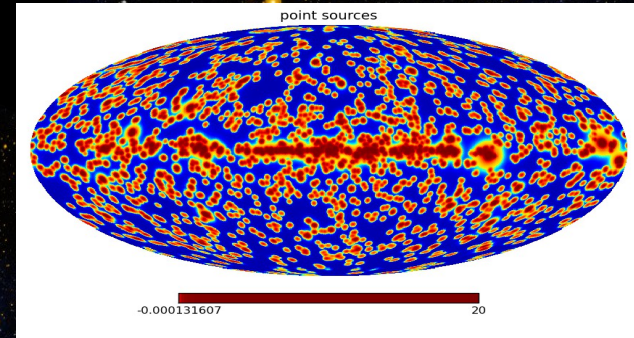
The Galactic center excess



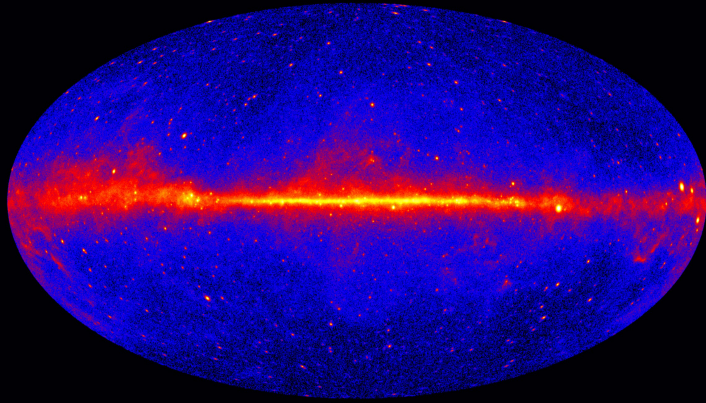
Given the high accuracy of Fermi-LAT data, the diffuse emission is very promising for DM indirect detection

→ The goal is to understand if, once all known components are subtracted, a significant residual is left

Notice the difference between the smooth IC template and the high-detailed π_0 template!



The Galactic center excess



Fermi-LAT data

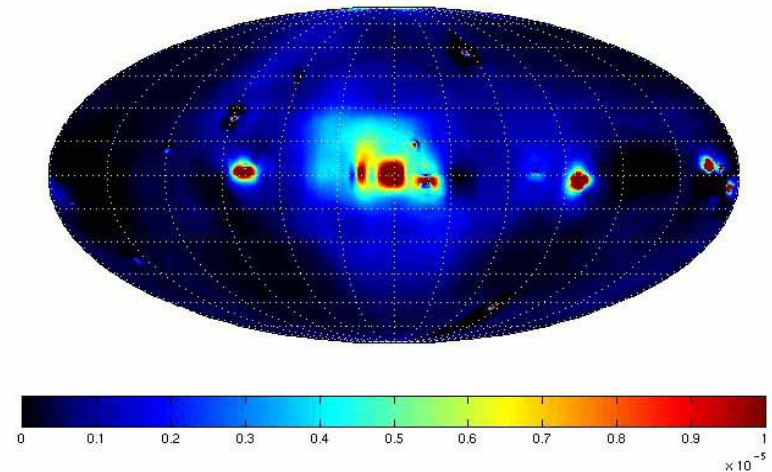
Given the high accuracy of Fermi-LAT data, the diffuse emission is very promising for DM indirect detection

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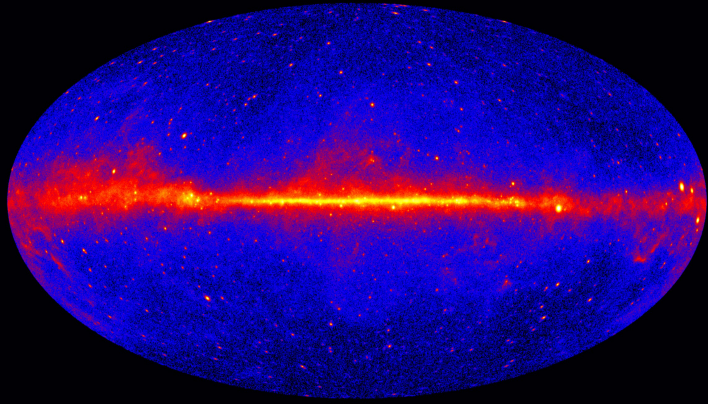
→ It is not well known that the very first claim of a gamma-ray excess centered on the GC region dates back to the pre-Fermi era!

(Dixon *et al.* 1998:

arXiv::astro-ph/9803237v2)



The Galactic center excess



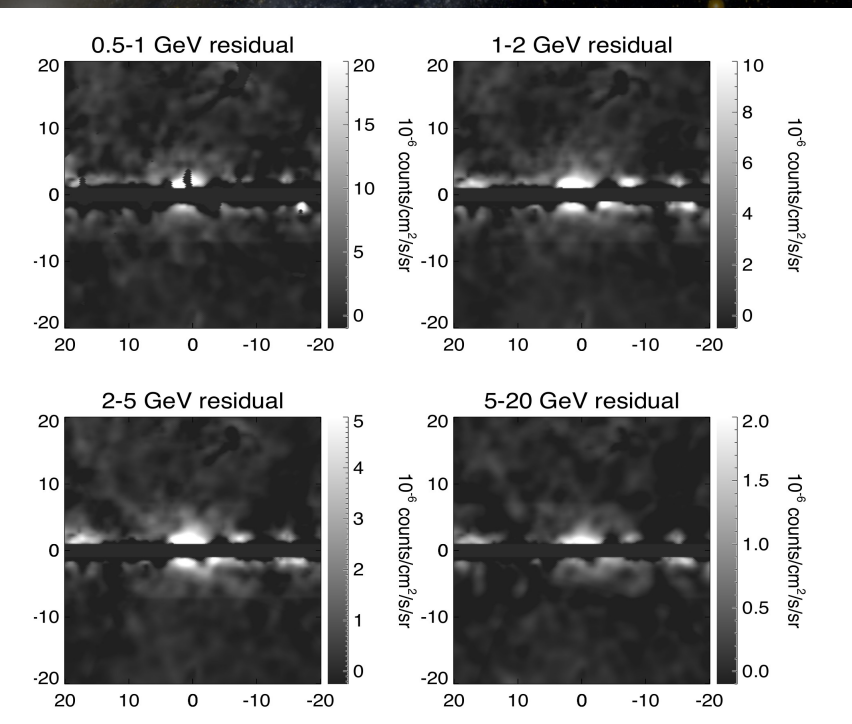
Fermi-LAT data

Given the high accuracy of Fermi-LAT data, the diffuse emission is very promising for DM indirect detection

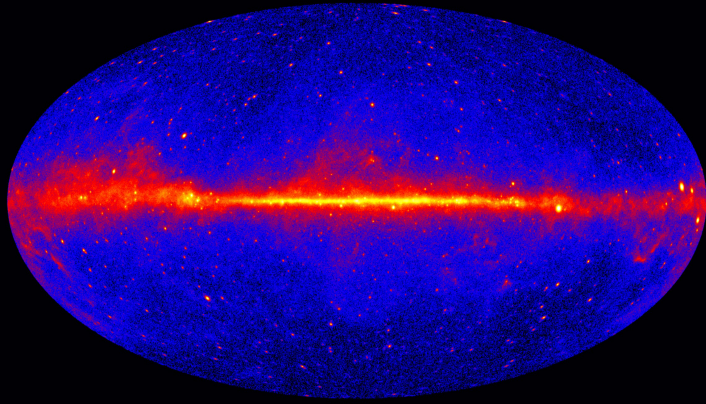
→ The goal is to understand if, once all known components are subtracted, a significant residual is left

→ More recently: the “Hooperon”

- L. Goodenough and D. Hooper, 2009
- D. Hooper and L. Goodenough, 2010
- D. Hooper and T. Linden, 2011
- K. N. Abazajian and M. Kaplinghat, 2012
- D. Hooper and T. R. Slatyer, 2013
- C. Gordon and O. Macias, 2013
- T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. Portillo, N. L. Rodd and T. R. Slatyer, 2014
- F. Calore, I. Cholis, C. Weniger, 2014



The Galactic center excess



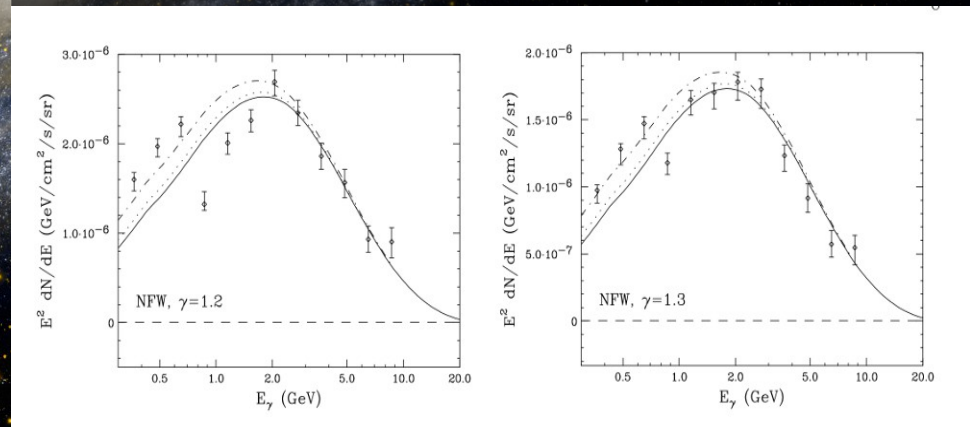
Fermi-LAT data

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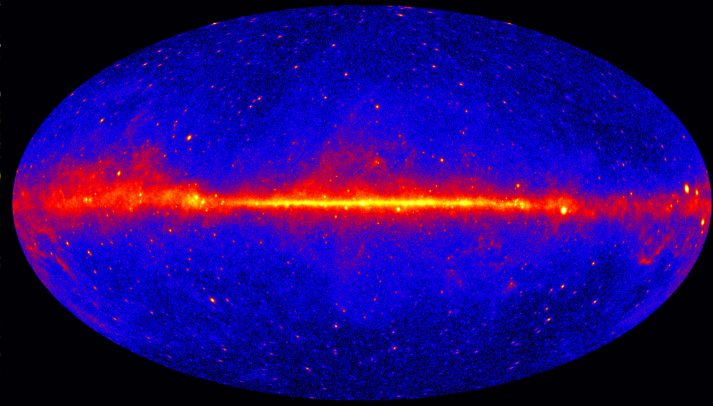
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- F. Calore, I. Cholis, C. Weniger, 2014



→ the spectrum of the excess is well fitted by a DM particle with $m = 35 \text{ GeV}$ annihilating into bb with a cross section close to the thermal one.

The Galactic center excess

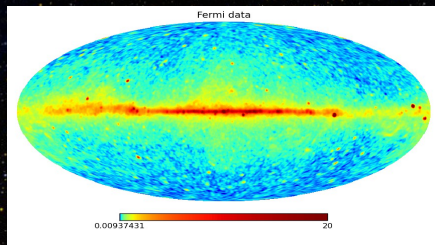


Fermi-LAT data

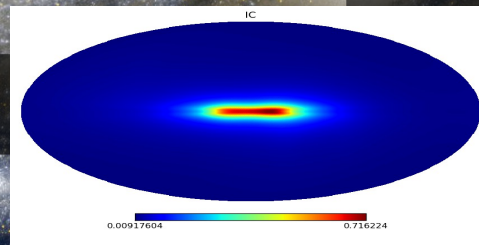
→ More recently: the “Hooperon”

All these results rely on the “template fitting” technique:

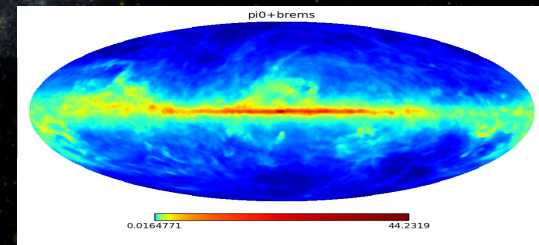
→ the gamma-ray map is written, for each energy bin, as a sum of the astrophysical templates, and the coefficients are left free to float



= c_1

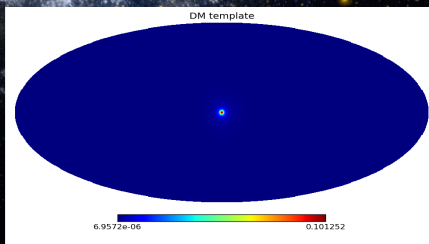


+ c_2



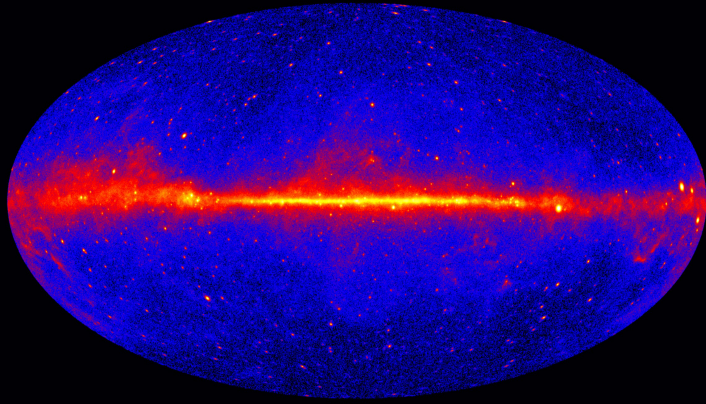
...

... + c_{DM}



The interesting result comes if the DM template is preferred by the template fitting algorithm

The Galactic center excess



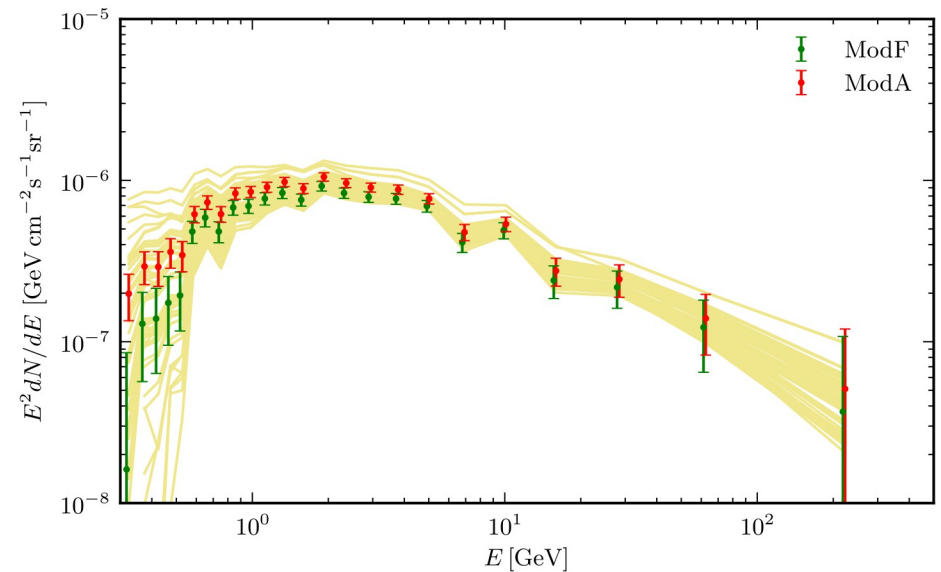
Fermi-LAT data

In *Calore et al. 2014* the fitting procedure is performed with a set of templates generated with GALPROP corresponding to a wide class of physical models.

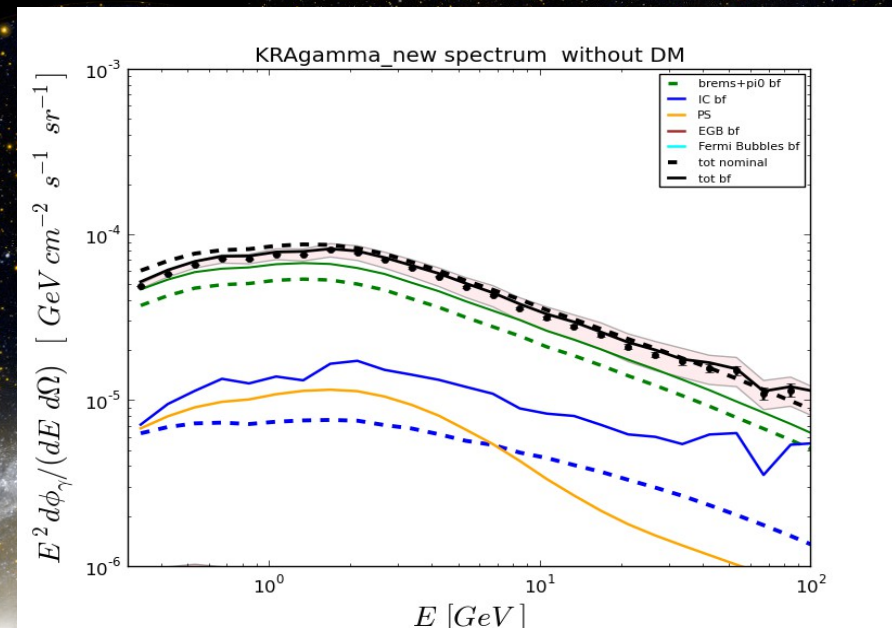
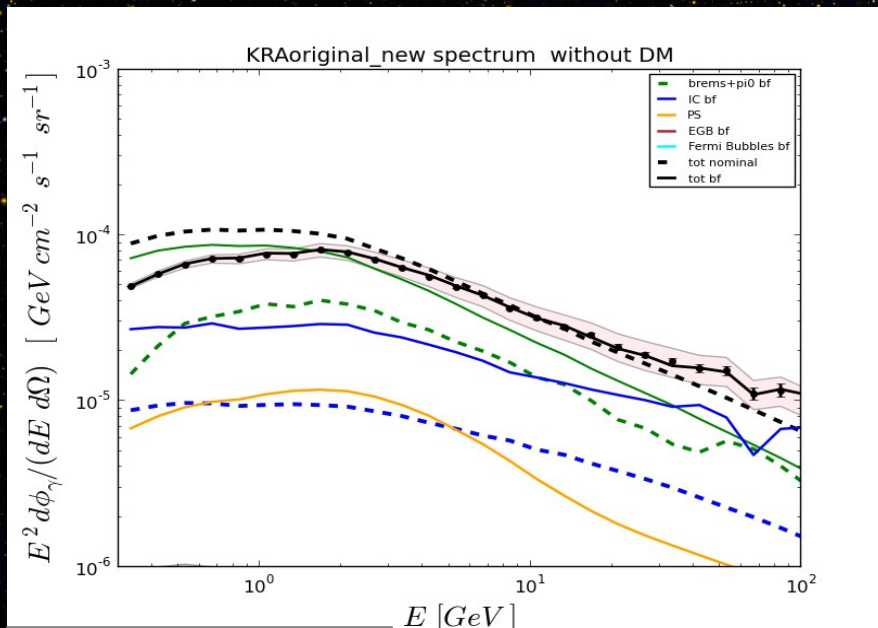
The template fitting machinery provides the best combination of the various templates
→ With this scan, it was possible to determine a systematic band for the spectrum of the excess!

→ More recently: the “Hooperon”

All these results rely on the “template fitting” technique:



The Galactic center excess



Work in progress...

→ WARNING ←

- The template fitting procedure may deform the spectra of the various components.
- This tilting is not physically justified, in particular for the pi0 component.

→ *The physical models described in the first part, in which the spectra turn out to be correct in every sky window, don't show this problem: the template fitting just provides a rigid shift in this case!*

The Galactic center excess

Two key questions are:

Can we explain this excess with astrophysics?

→ or may it be reabsorbed by a particular astrophysical template?

Is the DM interpretation in tension with other observables?

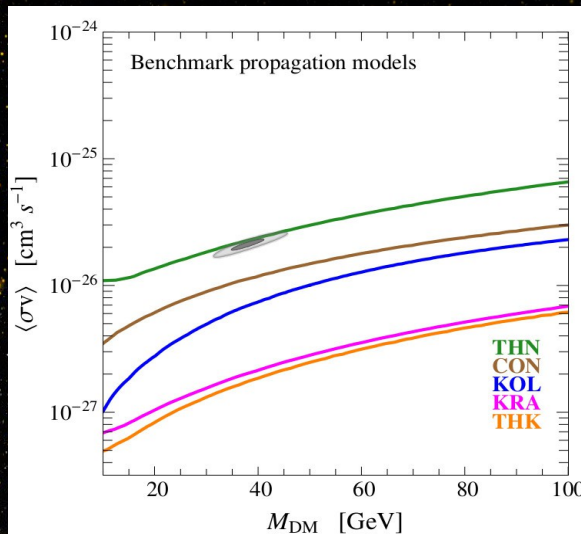
→ in particular, the antiprotons may provide a stringent bound

The Galactic center excess

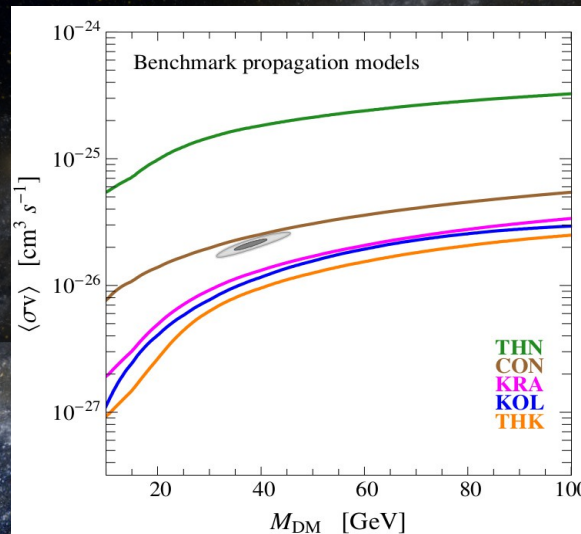
Is the DM interpretation of the Galactic center excess in tension with antiprotons?

→ it depends on how much you trust the current knowledge on charge dependent modulation and on the halo size!! ←

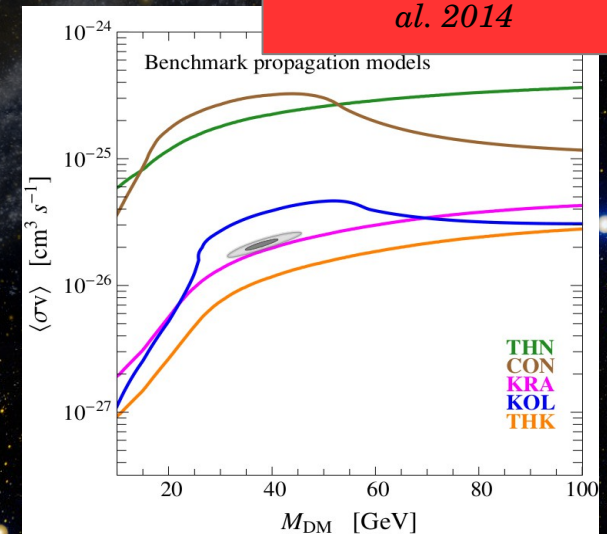
Cirelli, Gaggero et al.
2014
See also: Bringmann et
al. 2014



In this case the modulation potential of the antiprotons is the same as the modulation potential of the antiprotons (ok as first guess)



In this case the modulation potential of the antiprotons is allowed to vary by a 50% around the modulation potential of the protons



In this case the modulation potential of the antiprotons is free (a bit unrealistic!!)

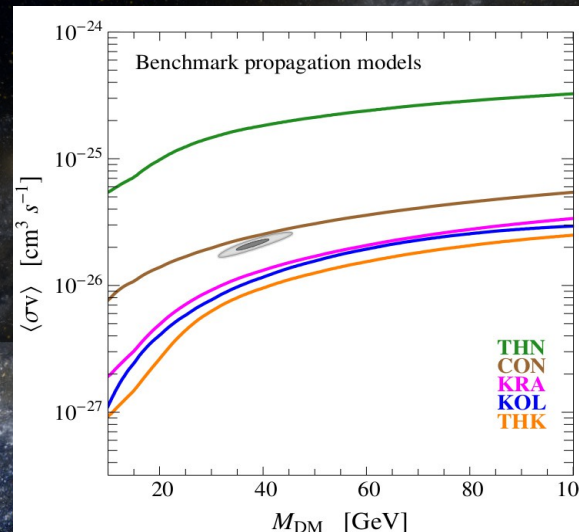
The Galactic center excess

Is the DM interpretation of the Galactic center excess in tension with antiprotons?

→ *it depends on how much you trust the current knowledge on charge dependent modulation and on the halo size!!* ←

Cirelli, Gaggero et al.
2014

See also: Bringmann et
al. 2014



In this case the modulation potential of the antiprotons is allowed to vary by a 50% around the modulation potential of the protons

This is, in our opinion, the most realistic case, and we verified with the Heliospheric propagation code Helioprop (Maccione 2013) that *the modulated antiproton spectra are well approximated with a force-field approach with a potential equal to the proton one plus / minus 50%, depending on the parameters involved*

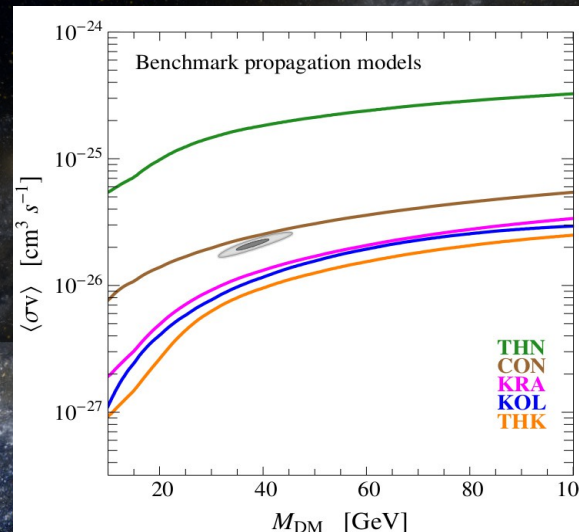
The Galactic center excess

Is the DM interpretation of the Galactic center excess in tension with antiprotons?

→ *it depends on how much you trust the current knowledge on charge dependent modulation and on the halo size!!* ←

Cirelli, Gaggero et al.
2014

A more precise knowledge of
→ the details of solar modulation
→ the halo size of the Galaxy
→ the details of the propagation models
are important to produce a solid bound!



In this case the modulation potential of the antiprotons is allowed to vary by a 50% around the modulation potential of the protons

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The Galactic center excess

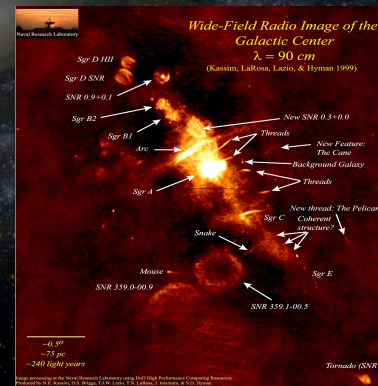
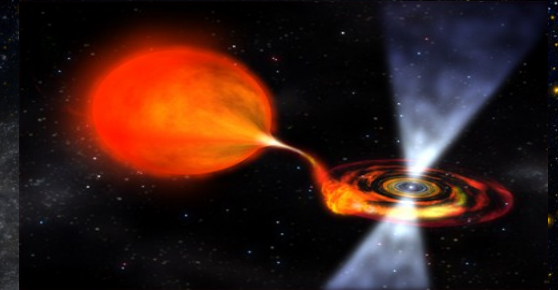
Can we explain this excess with astrophysics?

A population of millisecond pulsars?

Wang et al. 2005 – Gordon and Macias 2013 – Hooper et al. 2013 – Calore et al. 2014 – Cholis et al. 2014 ...

→ problems with the
luminosity function?

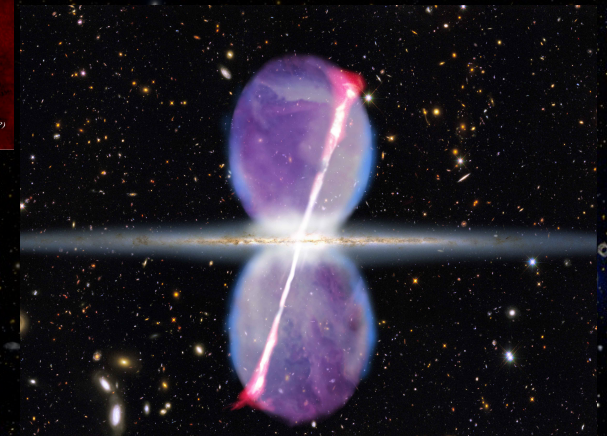
under debate: see Petrovic et al. 2014



Transient phenomena?

Carlson et al. 2014 – Petrovic et al. 2015

→ problems with spectra and morphology



The Galactic center excess

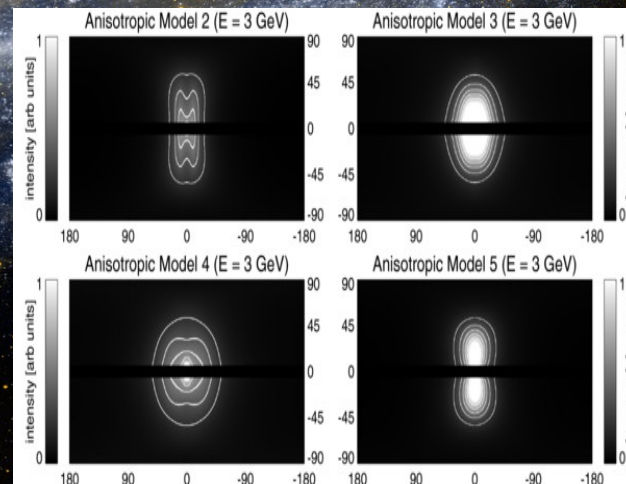
Can we explain this excess with astrophysics?

Anisotropic diffusion may play a role?

(In preparation, with M. Taoso, A. Urbano, P. Ullio, M. Valli)

- Again it is worth considering non-standard propagation models
- Enhanced parallel diffusion along z may elongate the DM template and mimic the GC excess

Work in progress...



I. Cholis et al. 2011

Conclusions

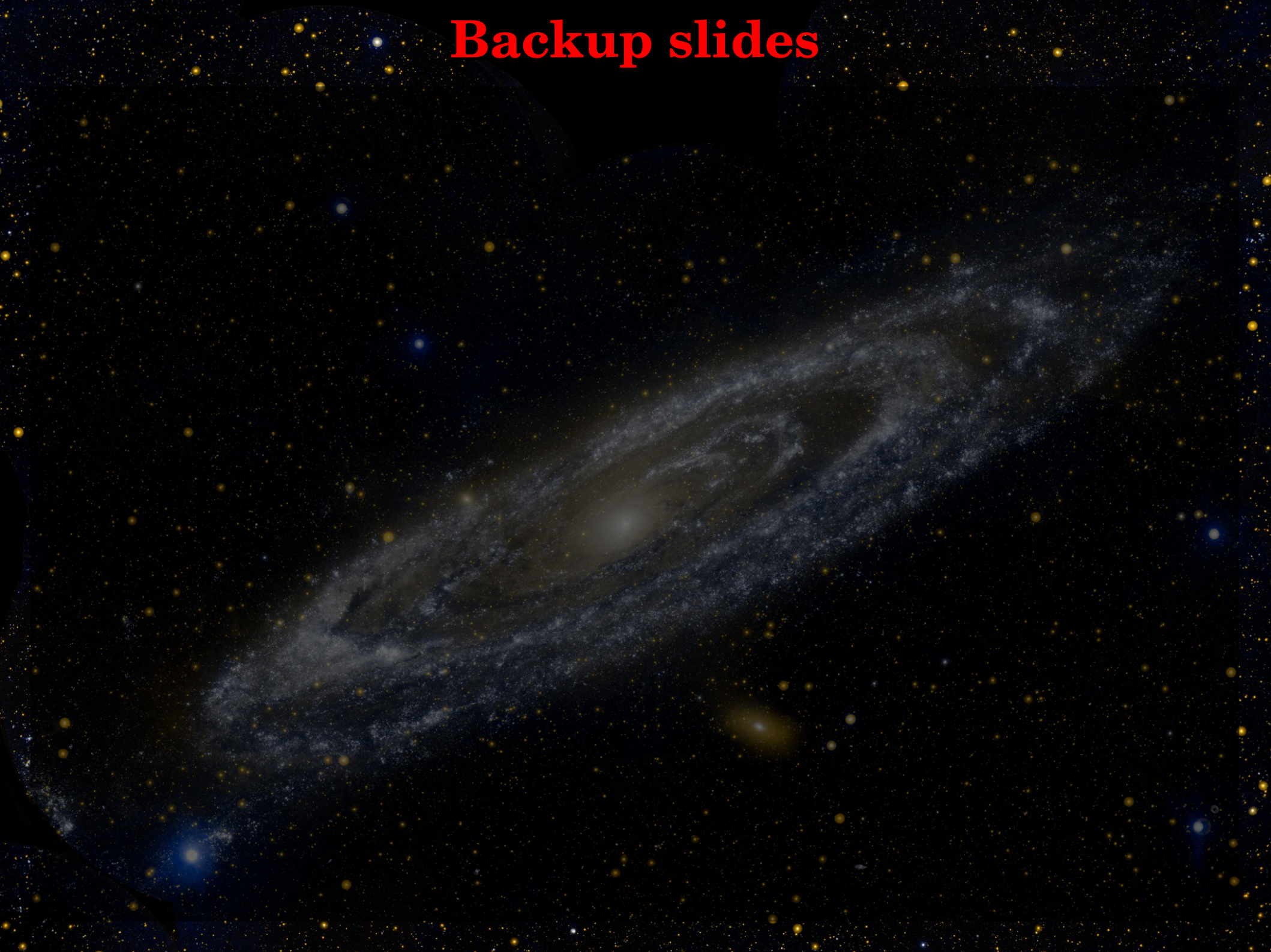
1) Many observations in several channels suggest that it is necessary to go beyond the standard simplified picture of CR propagation in the Galaxy and in the Heliosphere:

- *the CR gradient inferred from gamma rays is too flat* compared to simulations
- *the gamma-ray spectra turn out to be harder* in the Galactic Center region (tension with the outcome of numerical codes)
- *there is evidence for charge-dependent effects* in solar modulation

2) **DM indirect detection requires a detailed knowledge of all these issues.**

- We considered the GC excess and tried to address several questions:
 - *how do we interpret the template fitting machinery used to identify the excess?* we find that models with harder diffusion coefficient in the inner Galaxy provide an interpretation
 - *is the DM interpretation of the excess in tension with the antiproton data?* we find that the knowledge of solar modulation and CR propagation plays a crucial role
 - *can we explain the excess with astrophysics?* maybe anisotropic diffusion can play a role. Otherwise transient CR injection bursts and millisecond pulsar populations may fit the data.

Backup slides



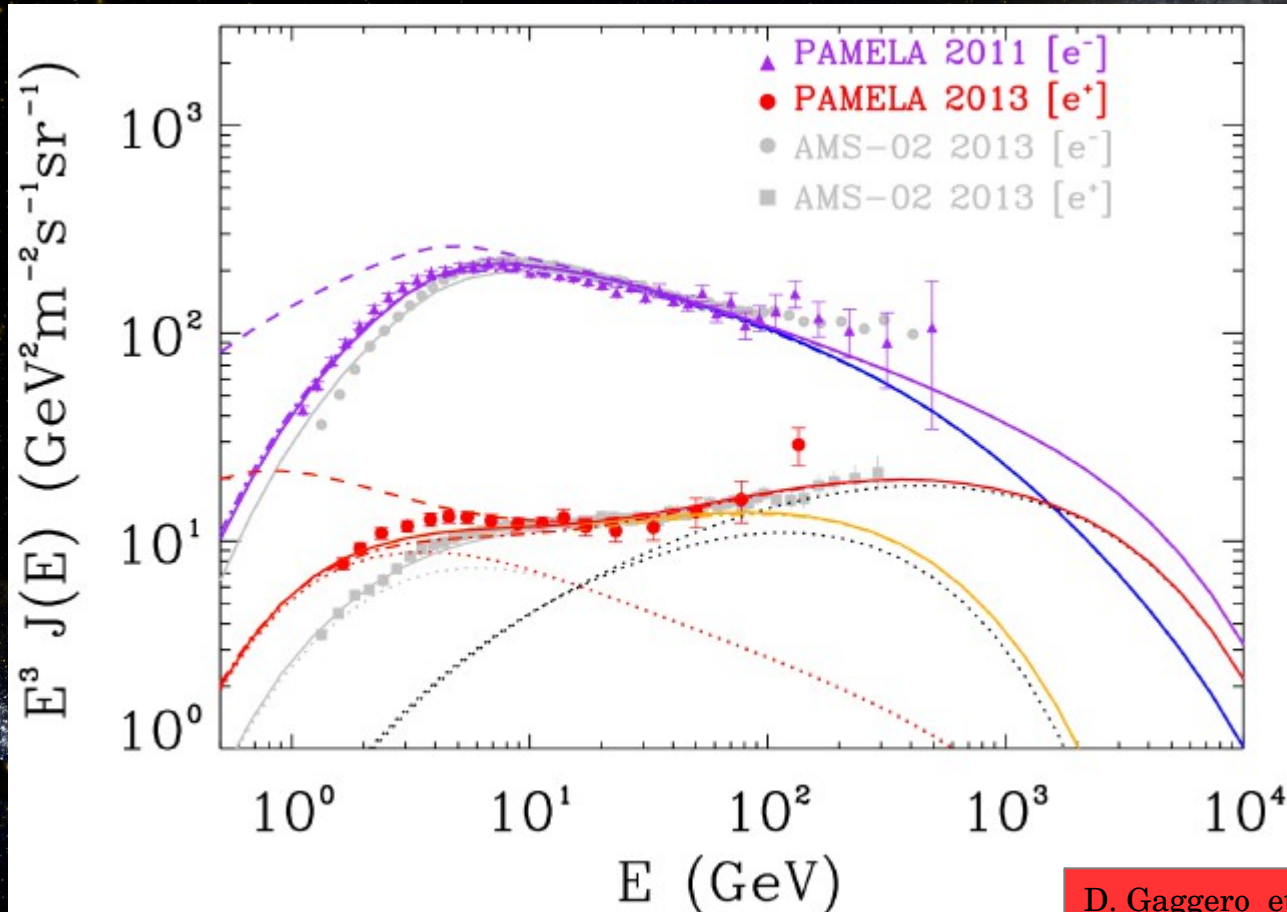
Ongoing work using DRAGON



A 3D model of the Galaxy

Our models are able to reproduce PAMELA and AMS-02 leptonic spectra (AMS separate lepton fluxes are still preliminary)

The propagation setups are tuned on light nuclei ratio



Ongoing work using DRAGON

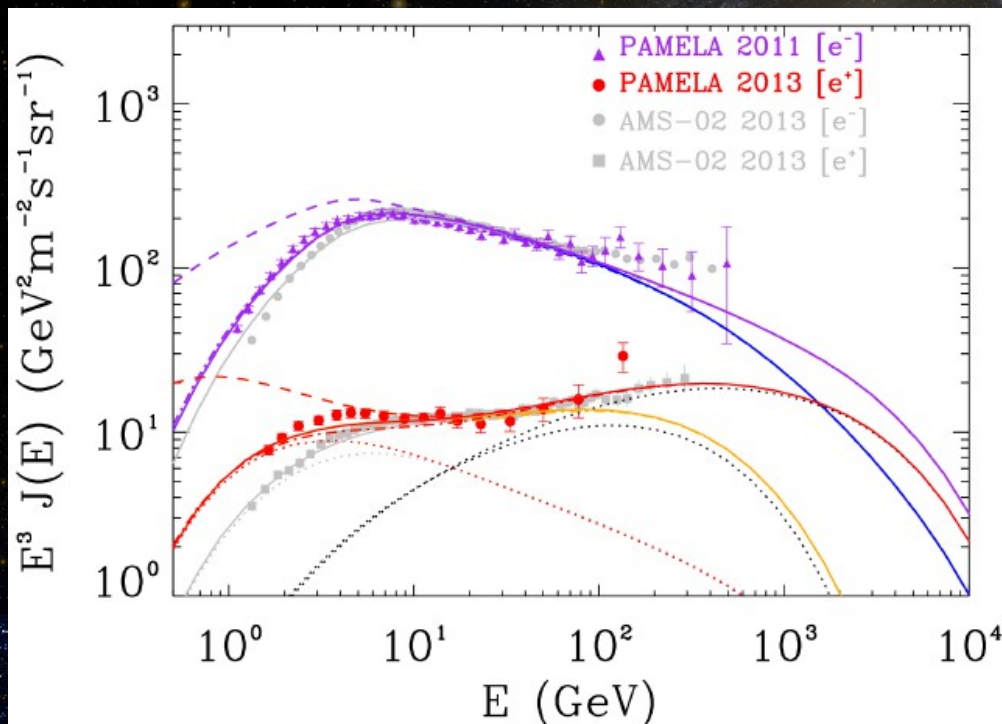


A 3D model of the Galaxy

Ingredients of our models:

1) Primary electron component with sources located in the arms;
injection index = -2.5, **much harder than the value needed in a 2D scenario and in less tension with CR shock acceleration theory.**

The residual discrepancy with the predicted value from the theory (-2 – -2.3) can be due to the details of the escape mechanism from the source



Ongoing work using DRAGON



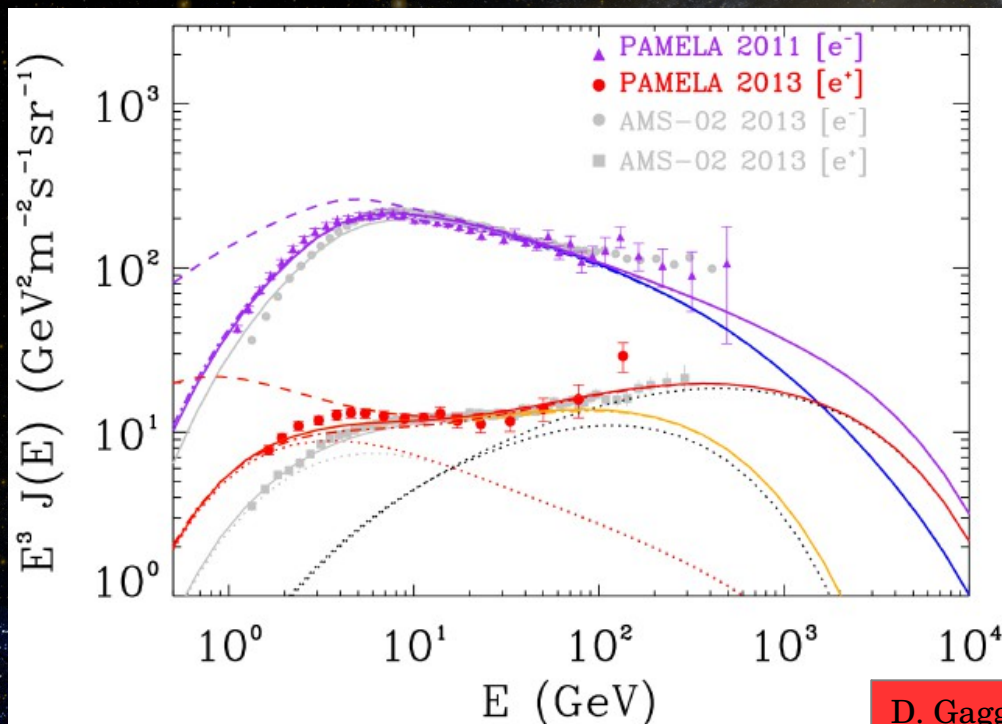
A 3D model of the Galaxy

Ingredients of our models:

2) Secondary electrons and positrons produced by spallation of heavy nuclei on interstellar gas

Dotted red line: secondary positrons

Notice (again) that the secondary positrons cannot account for the measured positrons at high energy by PAMELA and AMS!



Ongoing work using DRAGON

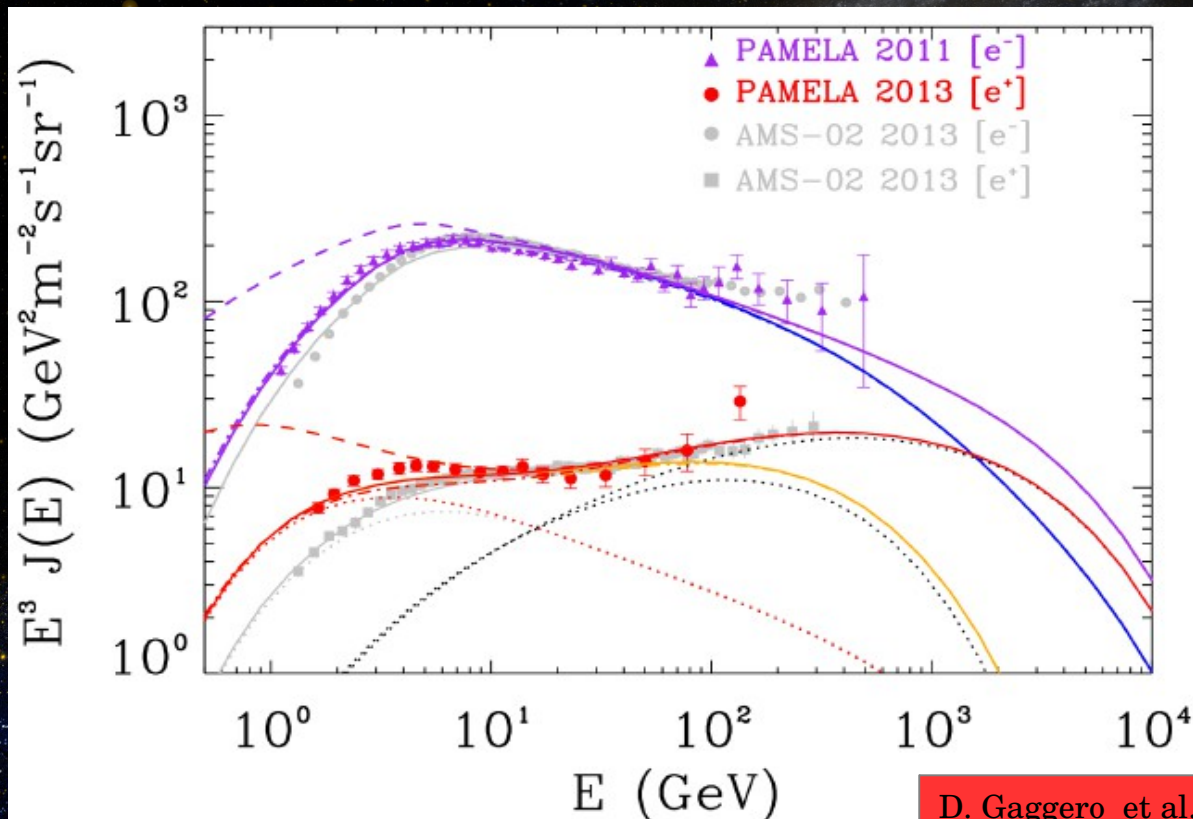


A 3D model of the Galaxy

Ingredients of our models:

3) Primary “extra” component of electrons and positrons with source term in the arms and harder injection spectrum

→ Origin: *pulsar population?* *Enhanced production of secondaries within the accelerator?* *DM?*



Ongoing work using DRAGON



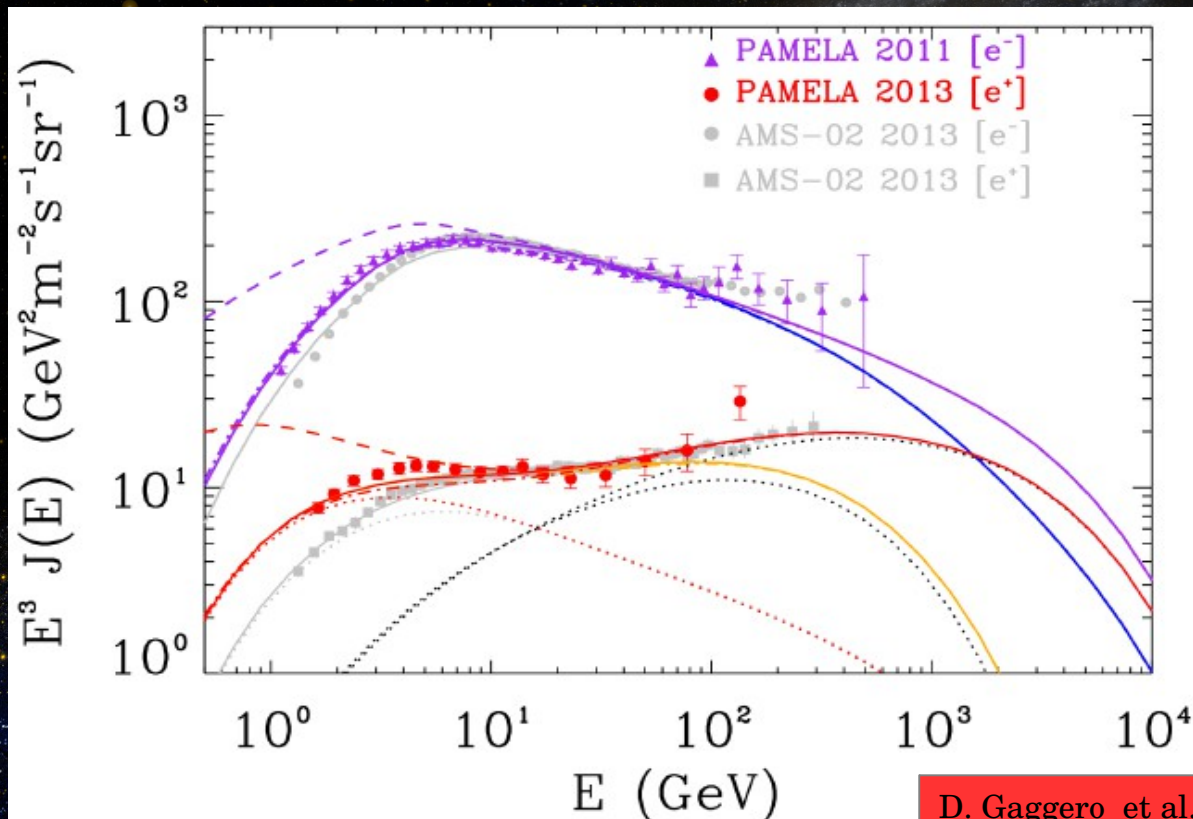
A 3D model of the Galaxy

A few words on the extra component.

AMS preliminary data seem to favour a high energy cutoff for the extra component

Red line \rightarrow 10 TeV

Yellow line \rightarrow 1 TeV



Ongoing work using DRAGON



A 3D model of the Galaxy

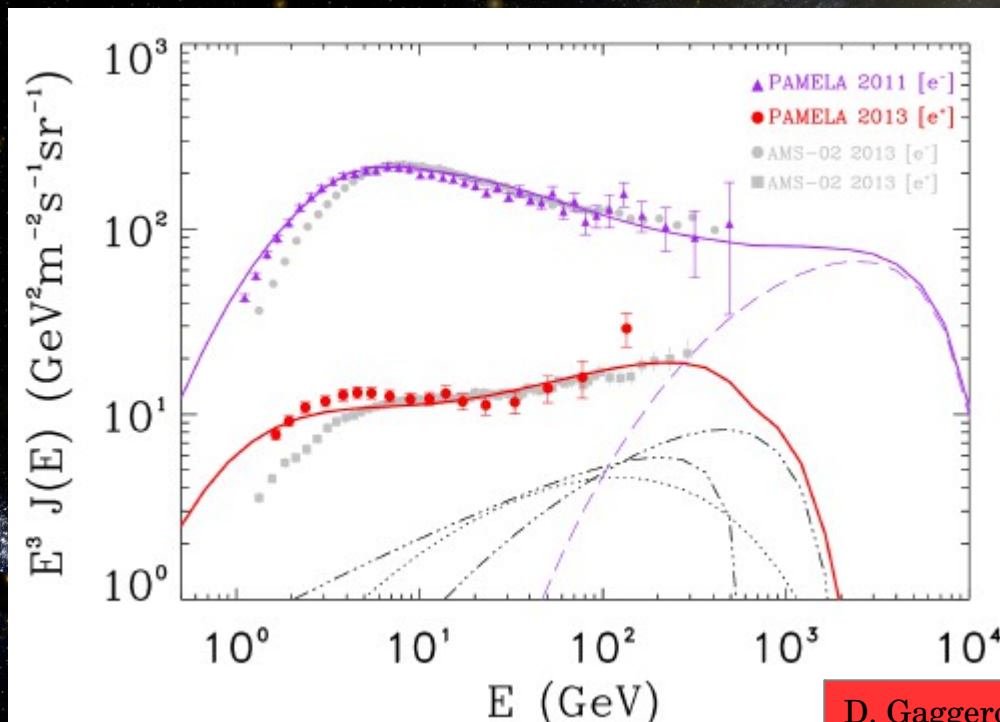
A few words on the extra component.

AMS preliminary data seem to favour a high energy cutoff for the extra component

Red line \rightarrow 10 TeV

Yellow line \rightarrow 1 TeV

The pulsar scenario is more compatible with a 1 TeV cutoff \rightarrow in that case the contribution of some local sources is needed

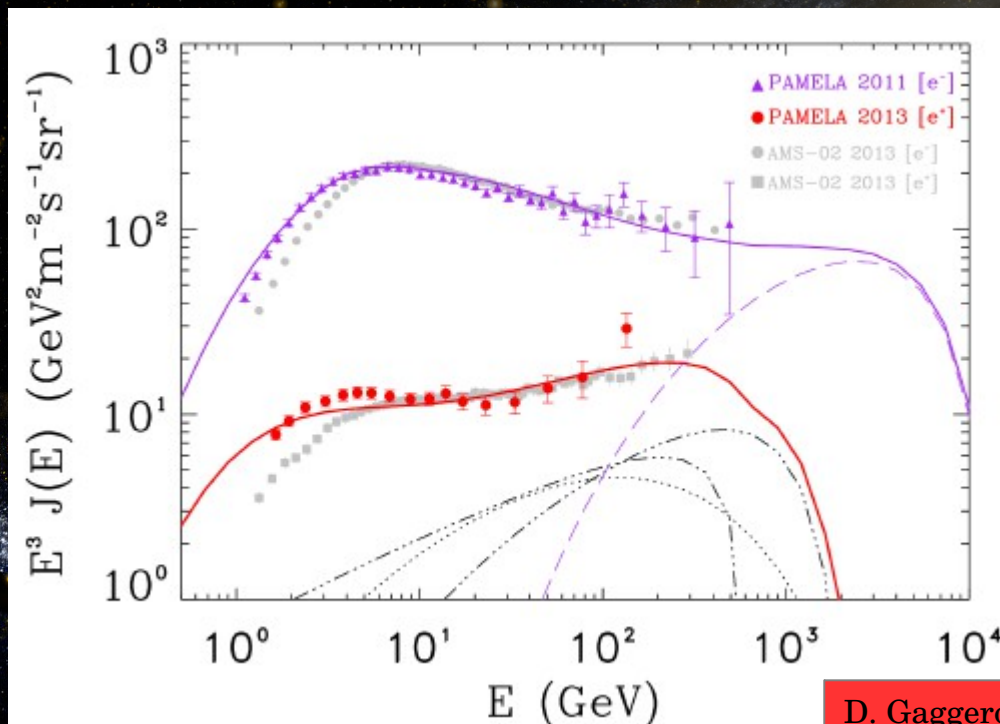


Ongoing work using DRAGON



A 3D model of the Galaxy

Solar modulation is treated in a realistic way using the numerical package **HelioProp**



Going beyond the standard lore

2. Spatial gradients in the **normalization** of the CR diffusion coefficient



The idea:

→ the properties of diffusion should depend on the turbulence level!

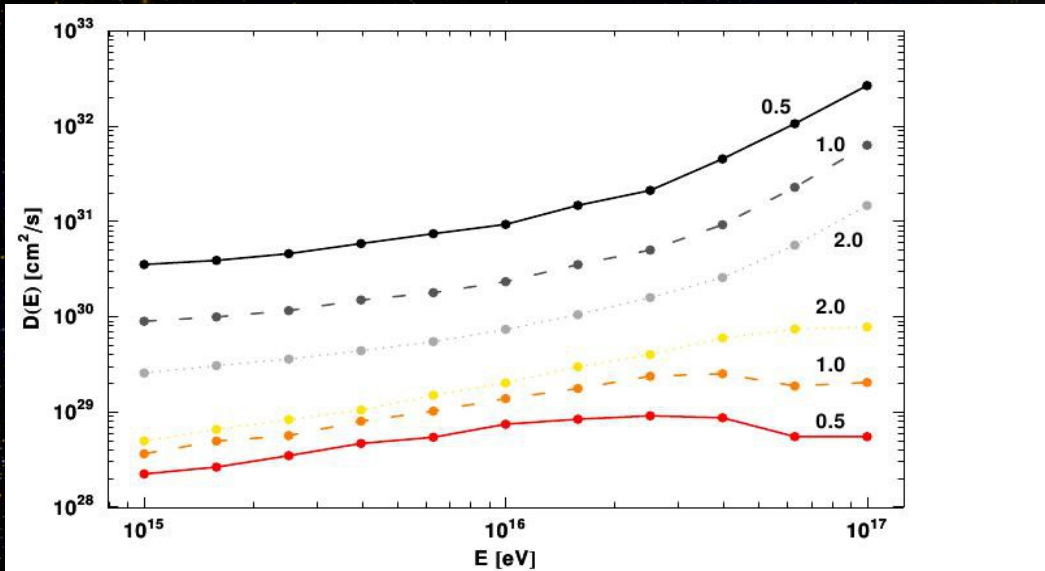


Figure 3. Parallel and perpendicular diffusion coefficients as a function of energy for three levels of turbulence. The upper three lines are the parallel diffusion coefficients, while the bottom three represent the perpendicular one. The level of turbulence, $\delta B/B_0$ is given by the numbers attached to the lines.

The parallel diffusion coefficient ***decreases*** with increasing turbulence

The perpendicular diffusion coefficient ***increases*** with increasing turbulence

Going beyond the standard lore

2. Spatial gradients in the **normalization** of the CR diffusion coefficient



Our model:

We consider a diffusion coefficient that changes with the position using DRAGON
We use the 2D version for now just to illustrate the effect!

The idea is that where more CR sources are present, more turbulence is expected → a faster CR perpendicular diffusion

We link the diffusion coefficient to the source function in a phenomenological way:

$$D(r,z) = D_0 Q(r,z)^\tau$$

We consider τ as a free parameter and tune it against recent data on CR gradient inferred from gamma-ray observation

Going beyond the standard lore

2. Spatial gradients in the **normalization** of the CR diffusion coefficient



Results: Gradient Problem solved!

$$D(r,z) = D_0 Q(r,z)^\tau$$

C. Evoli et al., PRL
(2012)

