Connecting cosmic-ray physics, gamma-ray data and dark matter detection.

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SISSA

Outline

1) The basic picture of CR propagation in the Galaxy

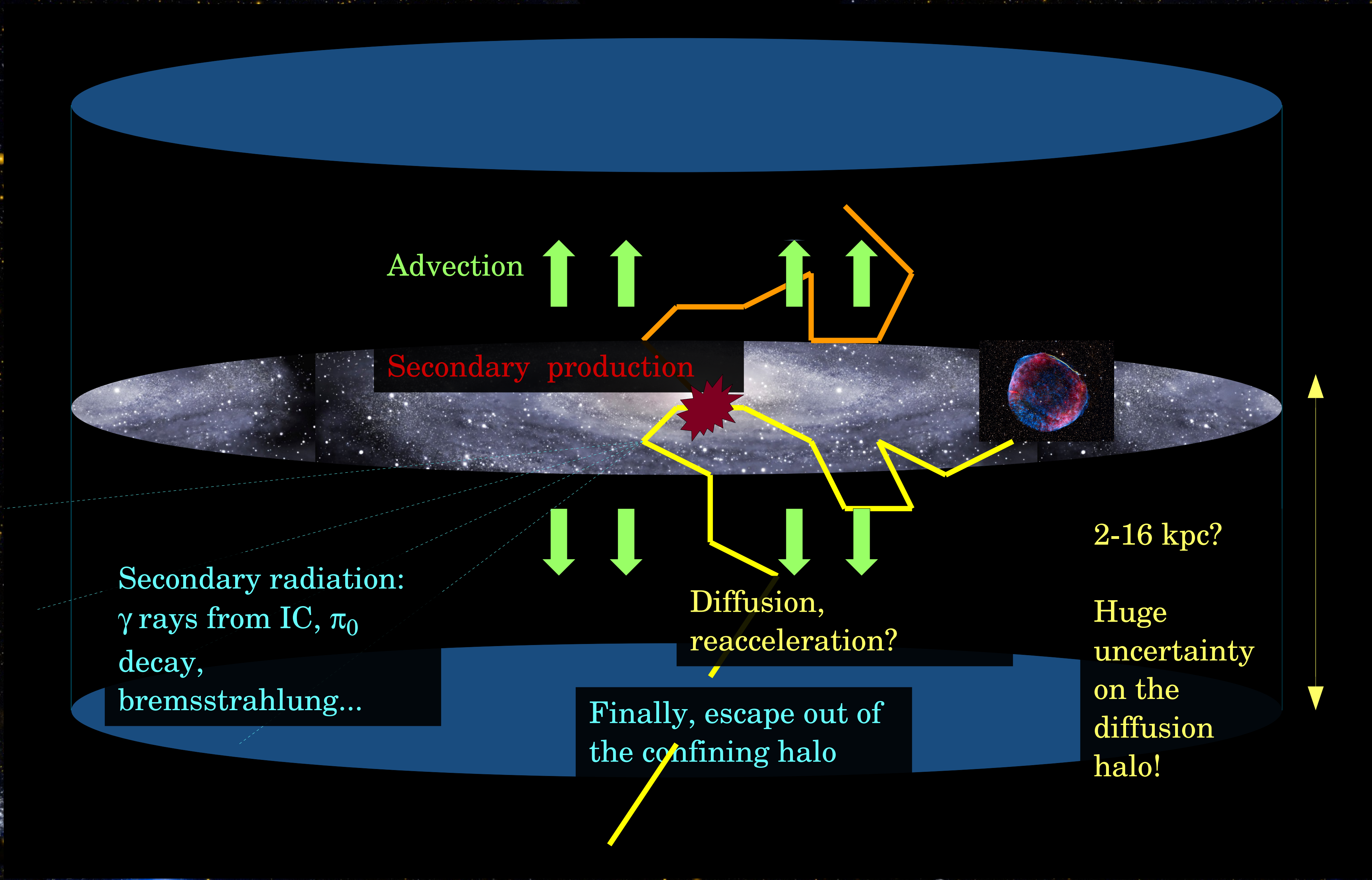
2) Going beyond the standard lore:

→ 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

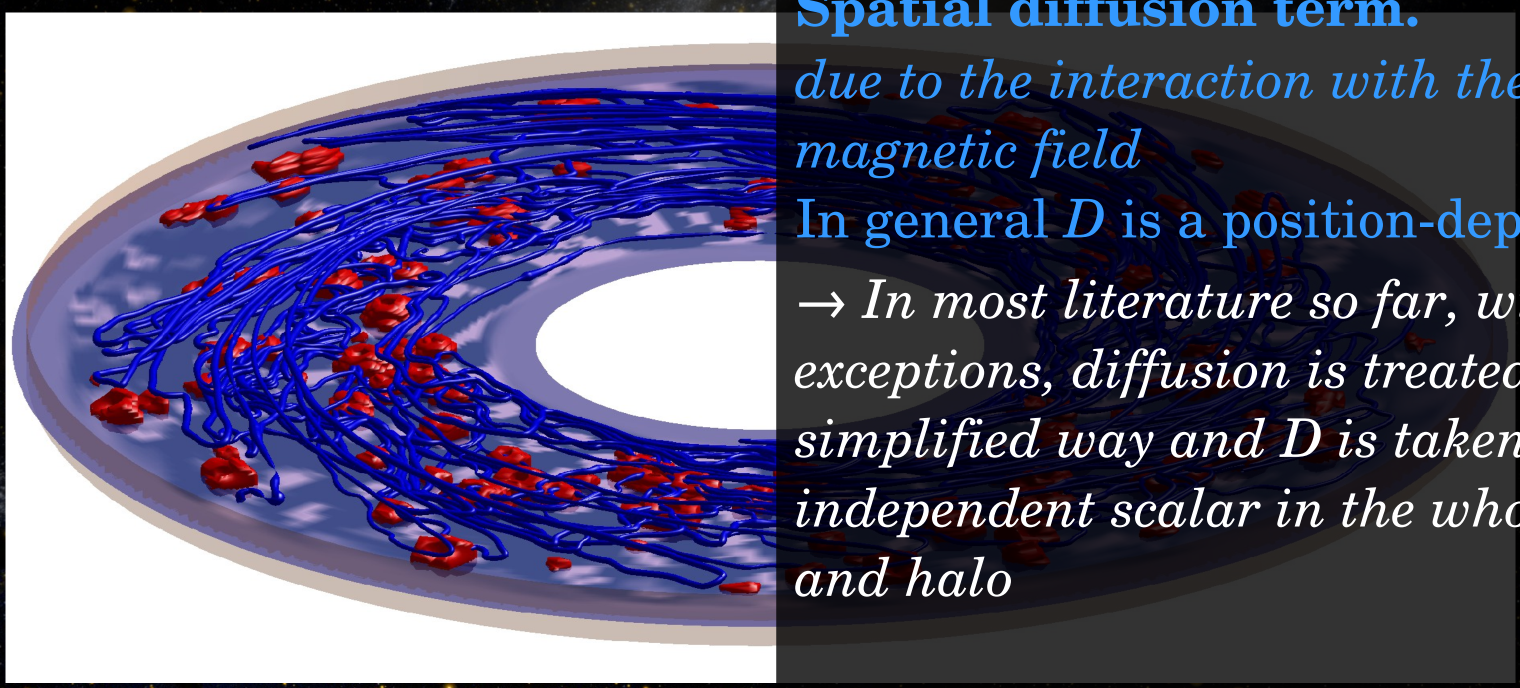
The basic picture of CR propagation



The basic picture

The equation describing CR propagation is the following:

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



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*

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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 hardons and high-energy leptons (IC scattering, synchrotron emission)

The basic picture

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$$+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)$$

Reacceleration

The basic picture

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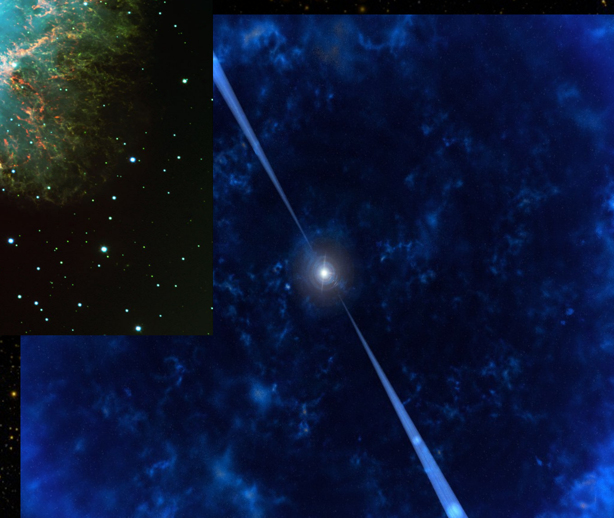
$$+ Q^i(\vec{x},p,t) + \sum_{j>i} c\beta n_{\rm gas}\sigma_{ij}N^j - c\beta n_{\rm gas}\sigma_{\rm in}N^i(\vec{x},p,t)$$

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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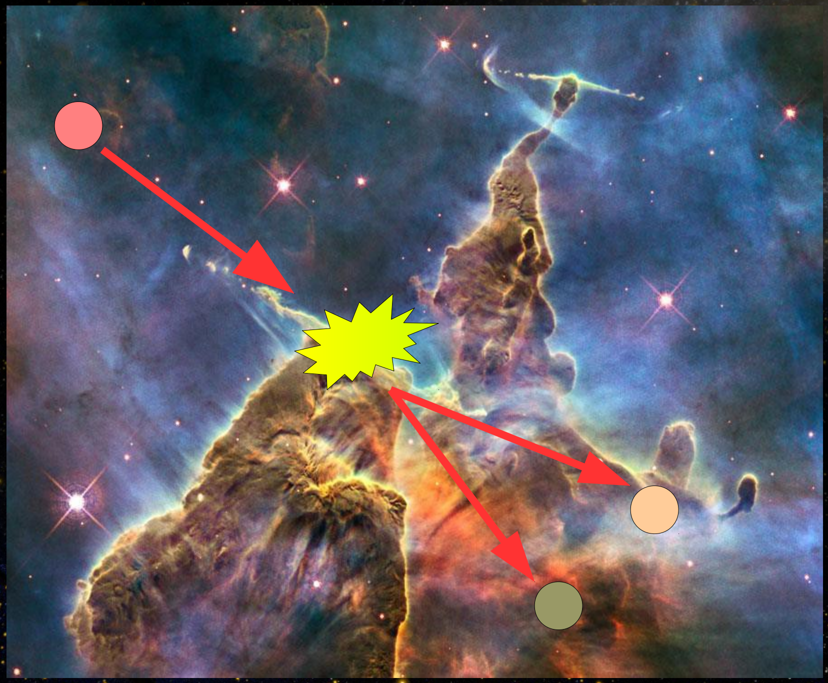

Spallation source term from heavier nuclei interacting with interstellar gas.

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

The basic picture

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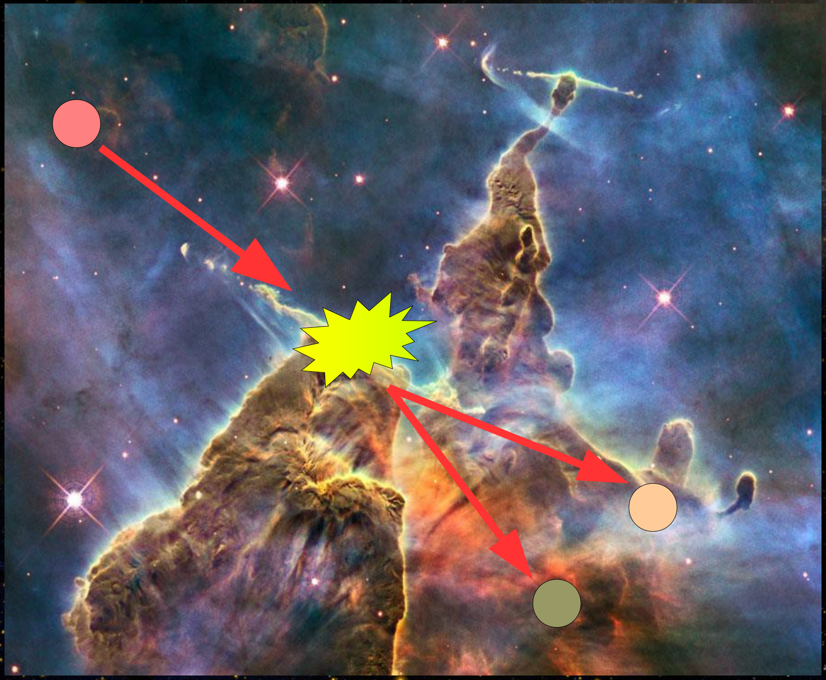


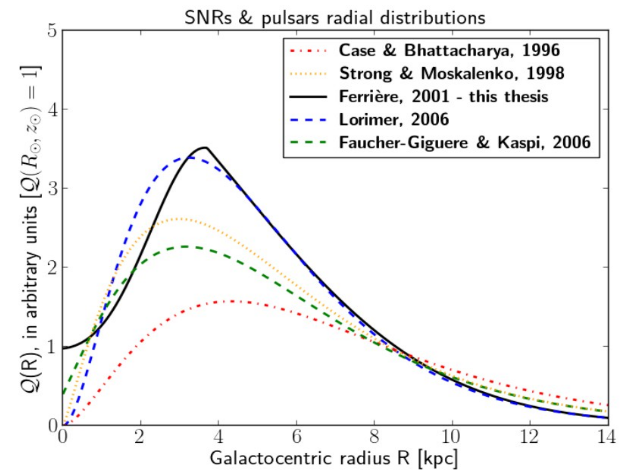
Spallation loss term

Cosmic ray physics is apparently easy...

The complicated physics describing the interaction between CRs and Alfvén waves can be parametrized by a relatively simple diffusion-reacceleration-loss equation.

The usual assumpions are:

1) CRs are injected in the Galaxy mainly by SNRs.



(a) *Radial profile of the distribution functions of the CRs sources*

SNRs are located on the Galactic plane.
Catalogues are incomplete; many tracers exist
A smooth spatial source function is assumed,
with small contribution from the central region
Injection spectrum: power law in rigidity,
with arbitrary number of breaks

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

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

The Galaxy is a uniform box with no structure.

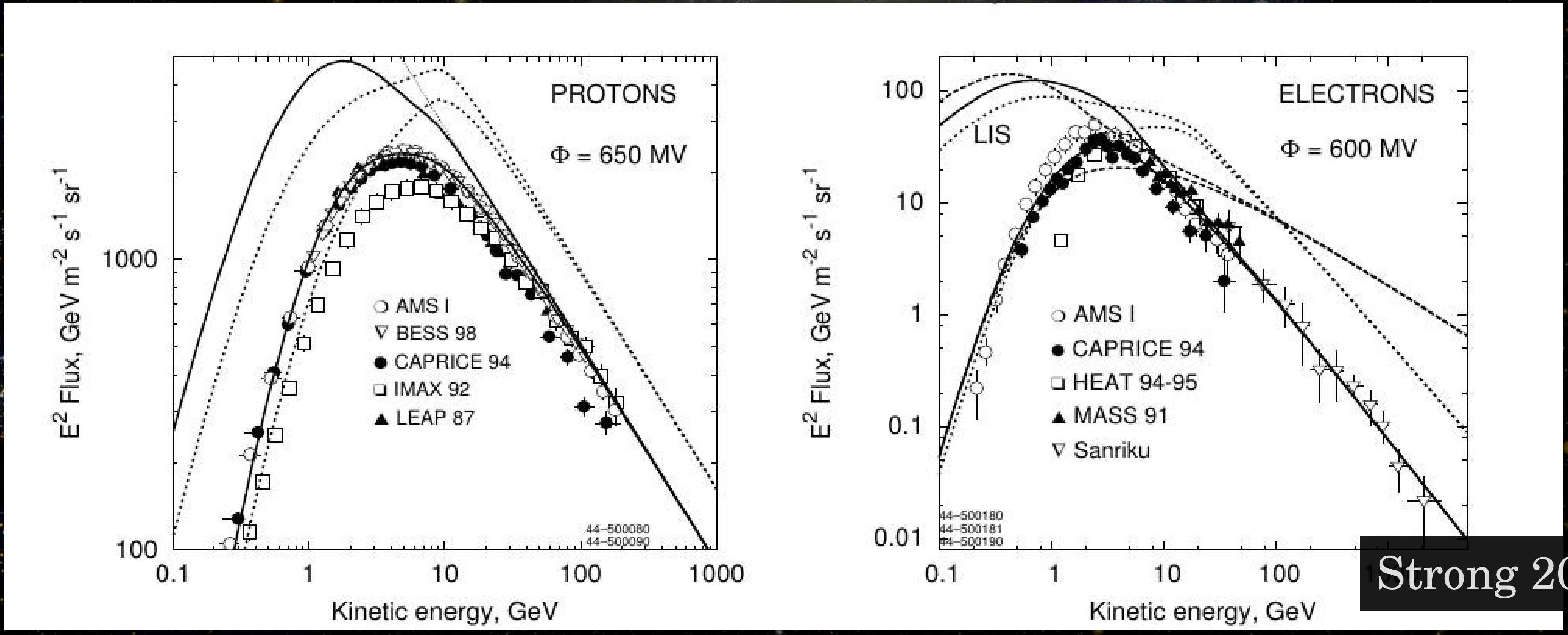
$$D = D_0 \beta p^{\delta}$$

The diffusion coefficient is rigidity dependent

Cosmic ray physics is apparently easy...

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

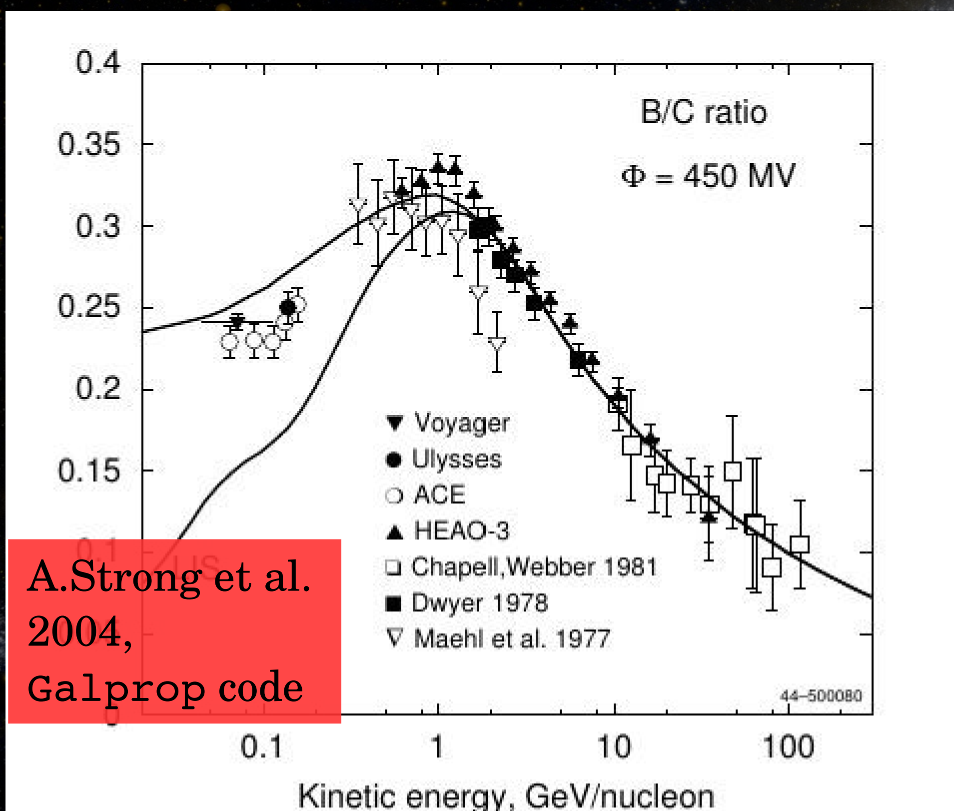


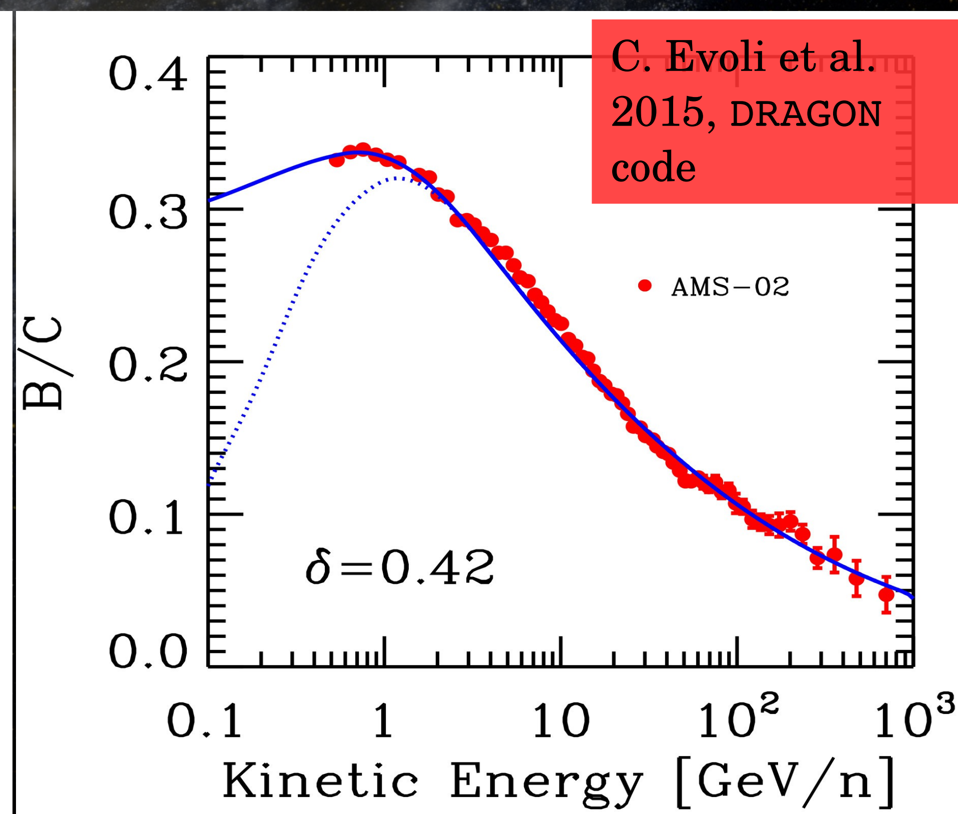
Cosmic ray physics is apparently easy...

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 → they do no depend on the inj. slope.

Data quality has dramatically improved through the years! Now it is important to look at the uncertainty in the spallation cross section (check M.N.Mazziotta contribution for a comprehensive computation of nuclear cross sections with `Fluka` code; this new set of cross section will be implemented in the new release of `DRAGON`)





Going beyond the standard lore

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

Two numerical codes in the market for CR propagation:

→ Galprop (`http://galprop.stanford.edu`, Strong & Moskalenko 1998)

→ DRAGON (`www.dragonproject.org` Evoli *et al.* JCAP 2008, Gaggero *et al.* PRL 2013)

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With DRAGON it is possible to solve the diffusion equation in the most general 3D anisotropic mode.

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

$$\begin{aligned}
\alpha_{xx}(x,y,z) &= (D_\parallel - D_\perp)b_x^2 + D_\perp \\
\alpha_{yy}(x,y,z) &= (D_\parallel - D_\perp)b_y^2 + D_\perp \\
\alpha_{zz}(x,y,z) &= (D_\parallel - D_\perp)b_z^2 + D_\perp \\
\delta_{xy}(x,y,z) &= (D_\parallel - D_\perp)b_x b_y + D_\perp \\
\delta_{xz}(x,y,z) &= (D_\parallel - D_\perp)b_x b_z + D_\perp \\
\delta_{yz}(x,y,z) &= (D_\parallel - D_\perp)b_y b_z + D_\perp \\
u_x(x,y,z) &= \partial_x\alpha_{xx} + \partial_y\delta_{xy} + \partial_z\delta_{xz} \\
u_y(x,y,z) &= \partial_x\delta_{xy} + \partial_y\alpha_{yy} + \partial_z\delta_{yz} \\
u_z(x,y,z) &= \partial_x\delta_{xz} + \partial_y\delta_{yz} + \partial_z\alpha_{zz}
\end{aligned}$$

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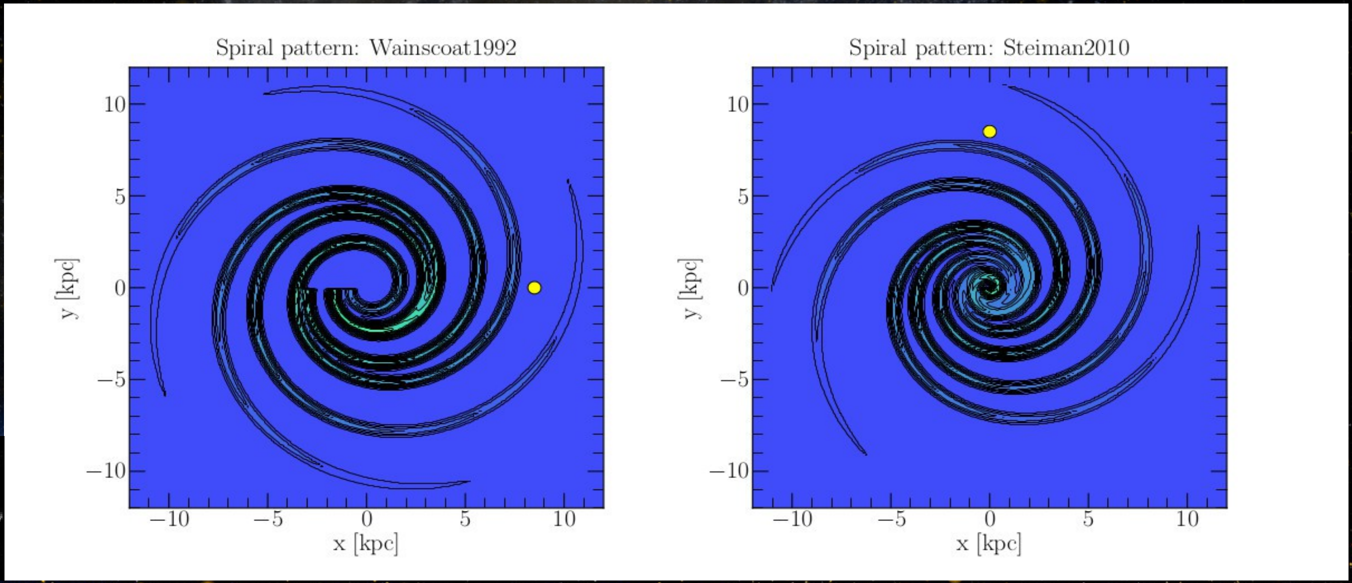
DRAGON (www.dragonproject.org Evoli *et al.* JCAP 2008, Gaggero *et al.* PRL 2013)

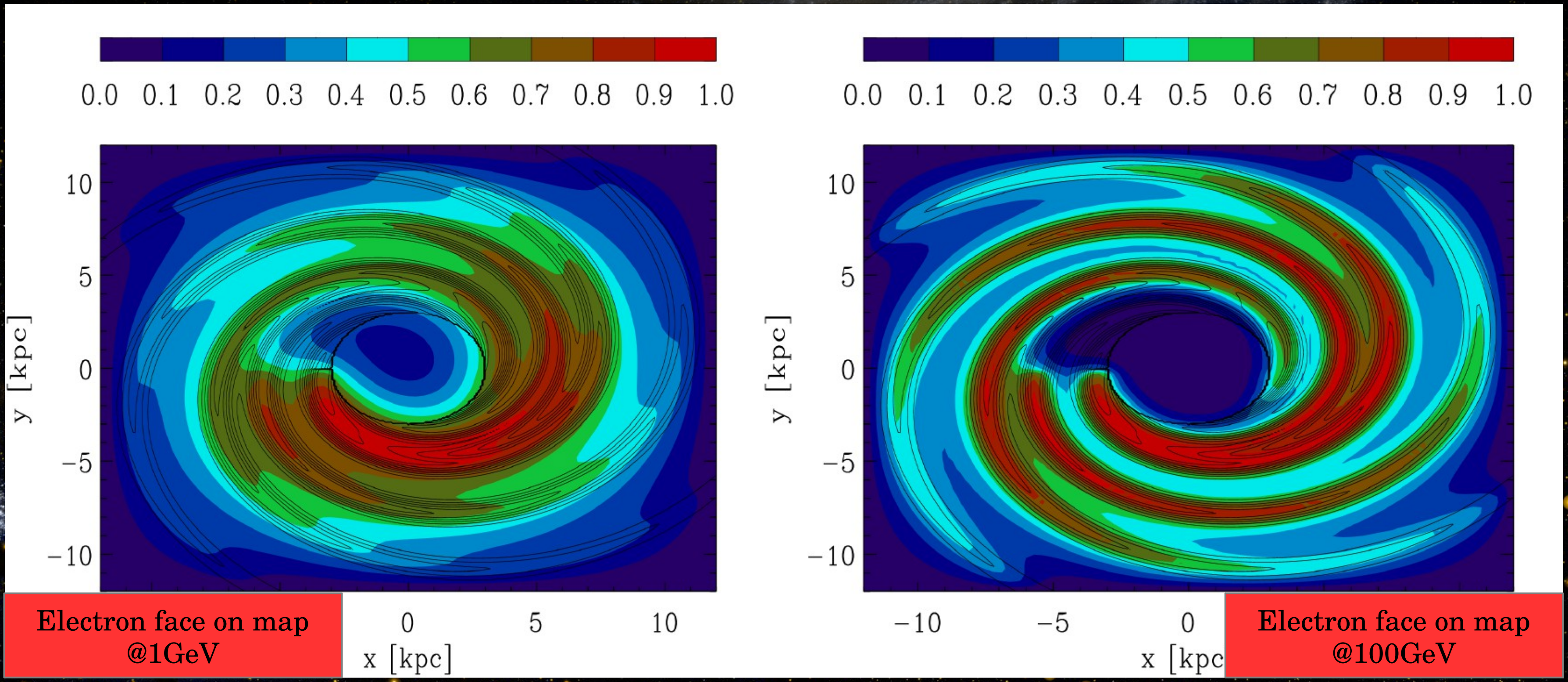
The 3D spiral structure of the Galaxy is implemented in DRAGON
(models from Wainscoat 1992, used also by Blasi&Amato 2011; Steiman 2010)



Going beyond the standard lore

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

The impact of the spiral structure is huge for the high-energy leptons
This is due to the energy losses!
CR electrons and positrons lose energy very efficiently due to IC and synchrotron emission: they stay closer to the sources



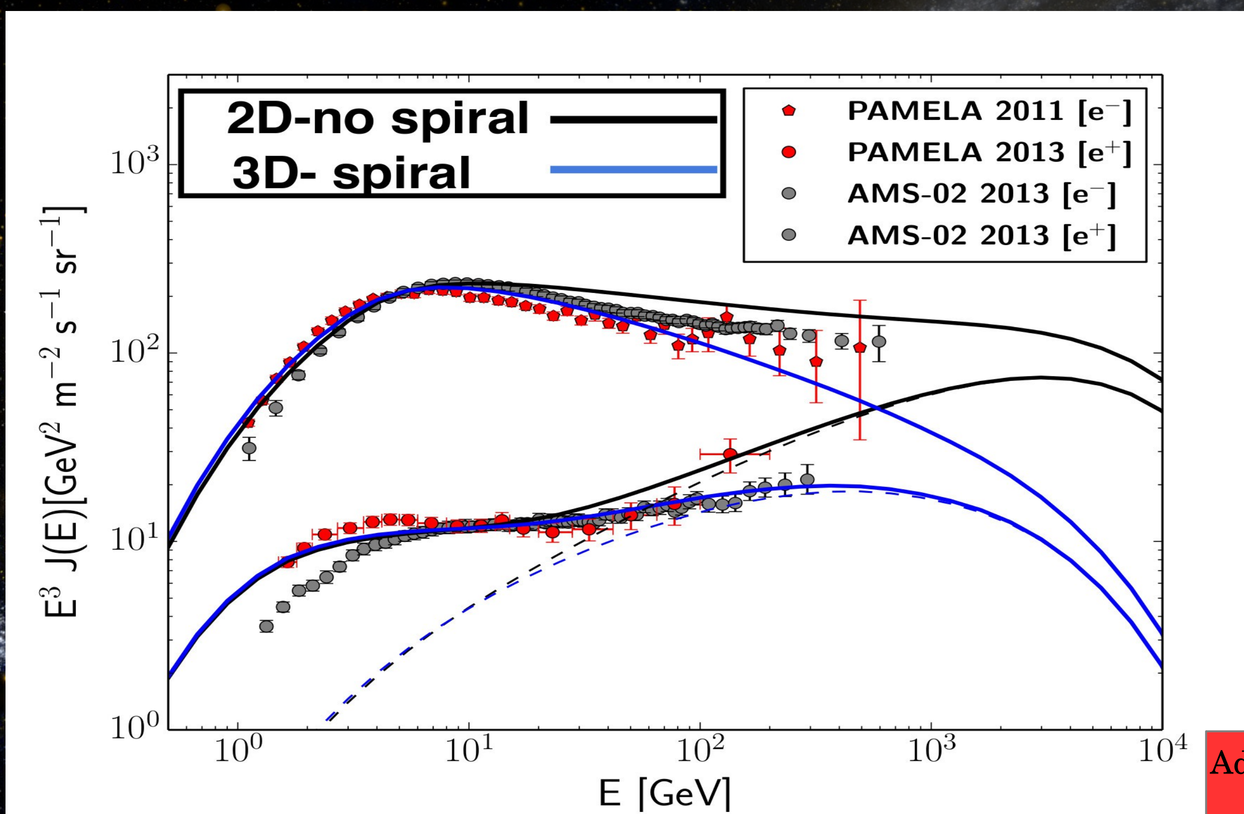
Electron face on map @1GeV

Electron face on map @100GeV

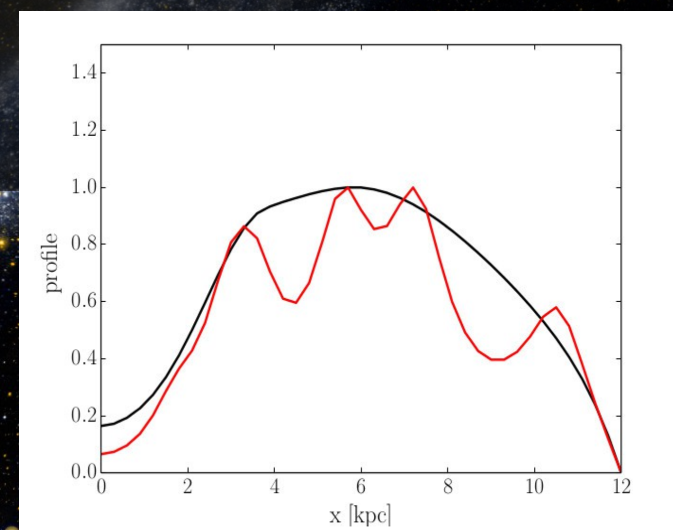
Going beyond the standard lore

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

The impact of the spiral structure is huge for the high-energy leptons
This is due to the energy losses!
It is impossible to neglect the spiral structure when considring high-energy CR leptonic spectra



Adapted from D. Gaggero et al., PRL **111** (2013)

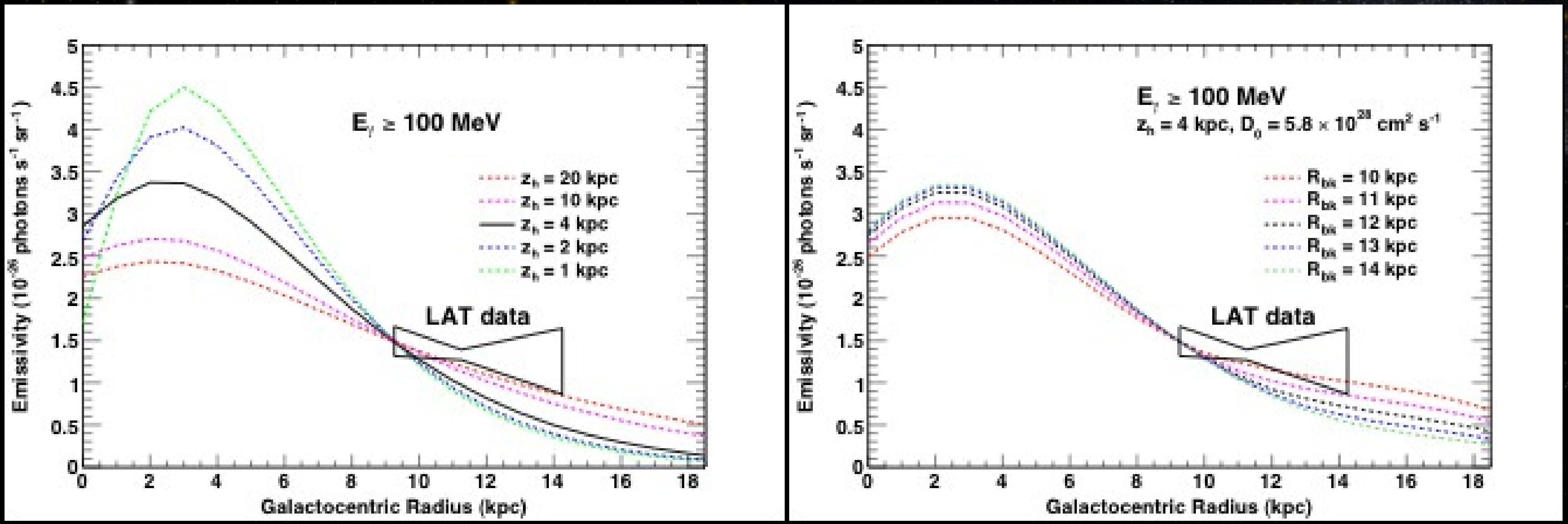


G. Di Bernardo et al. 2015

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;

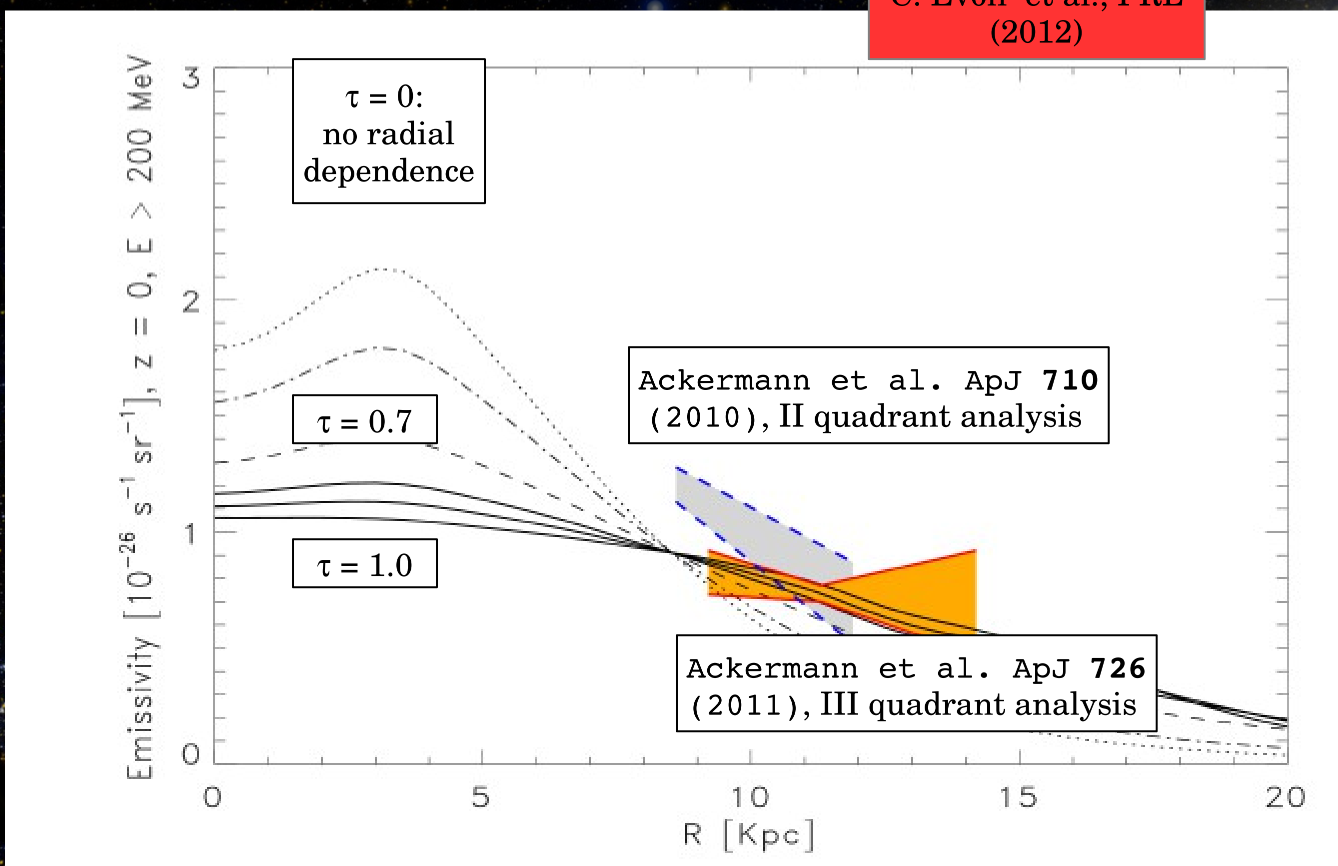
→ the CR gradient derived from numerical simulations (in which the SNR or pulsar profile is used as a source function) turns out to be steeper than the observed one!

Going beyond the standard lore

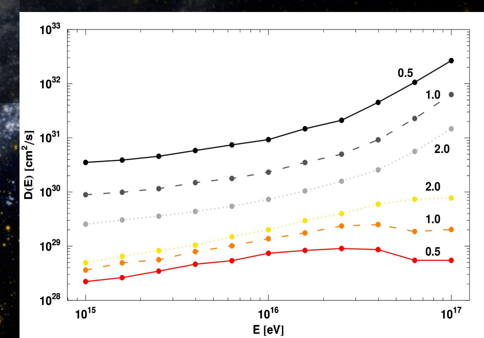
2. Spatial gradients in the **normalization** of the CR diffusion coefficient

Results: Gradient Problem solved if the diffusion coefficient is assumed to vary with R: $D(r,z) = D_0\, Q(r,z)^{\tau}$

C. Evoli et al., PRL (2012)



This scenario is strongly supported by numerical simulations about diffusion in a turbulent magnetic field (see *De Marco et al. 2007*)



Perpendicular diffusion plays a major role in CR escape. Simulations show that *Dperp increases with increased turbulence level, and a larger turbulence level is expected near CR sources!*

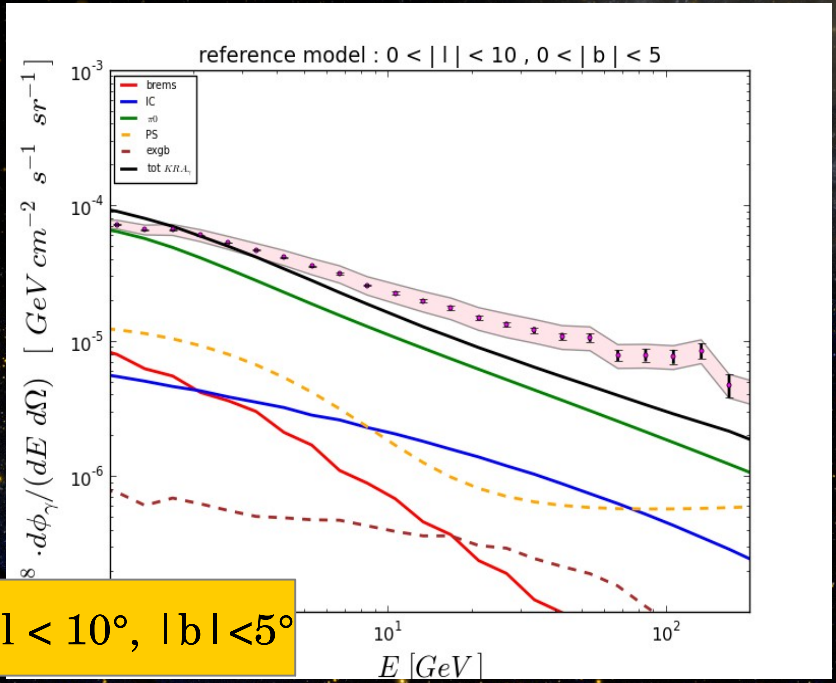
Going beyond the standard lore

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

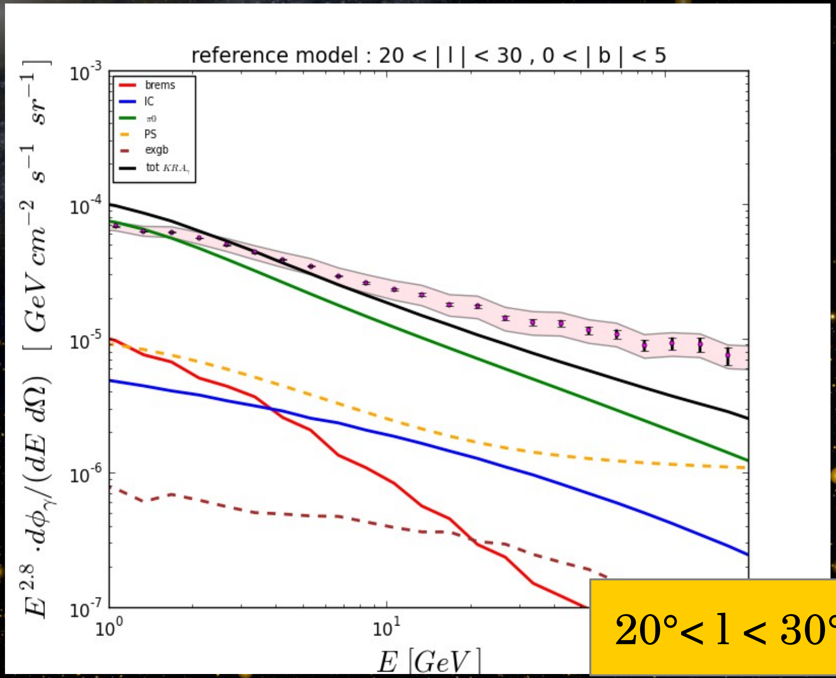
Motivation: **“slope problem”**

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!*



0°< l < 10°, |b|<5°



20°< l < 30°, |b|<5°

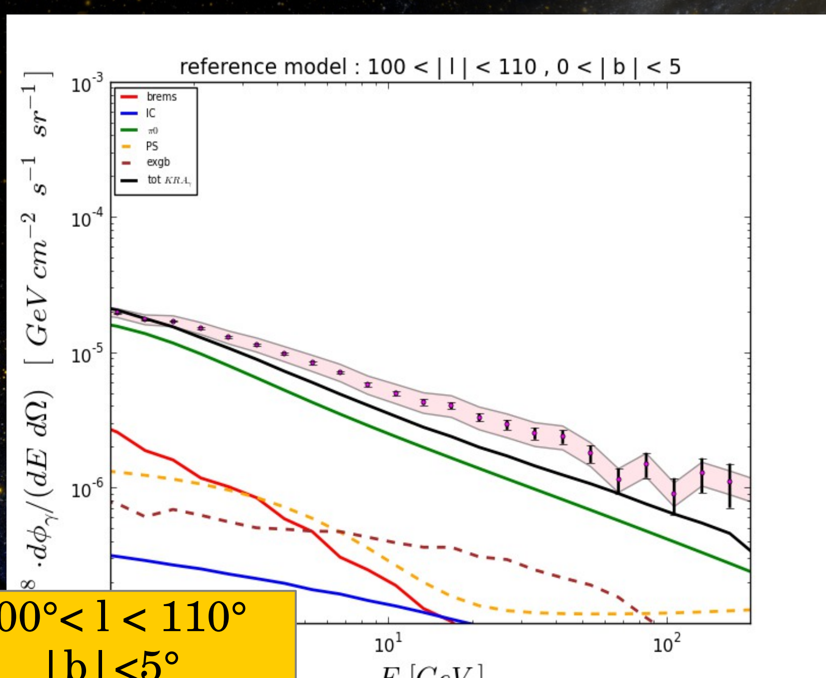
Going beyond the standard lore

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

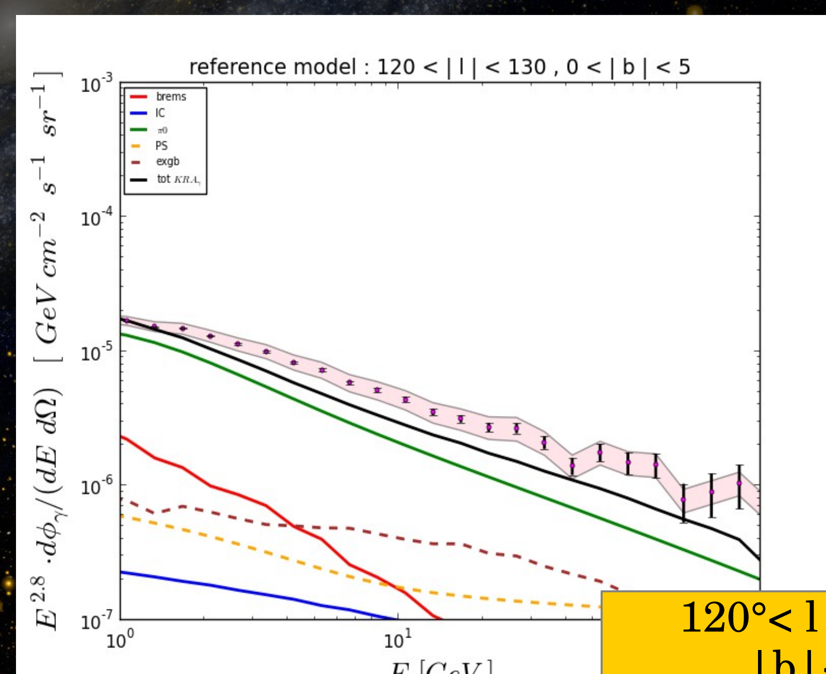
Motivation: **"slope problem"**

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

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



100°< l < 110°
|b|<5°



120°< l <130°,
|b|<5°

Going beyond the standard lore

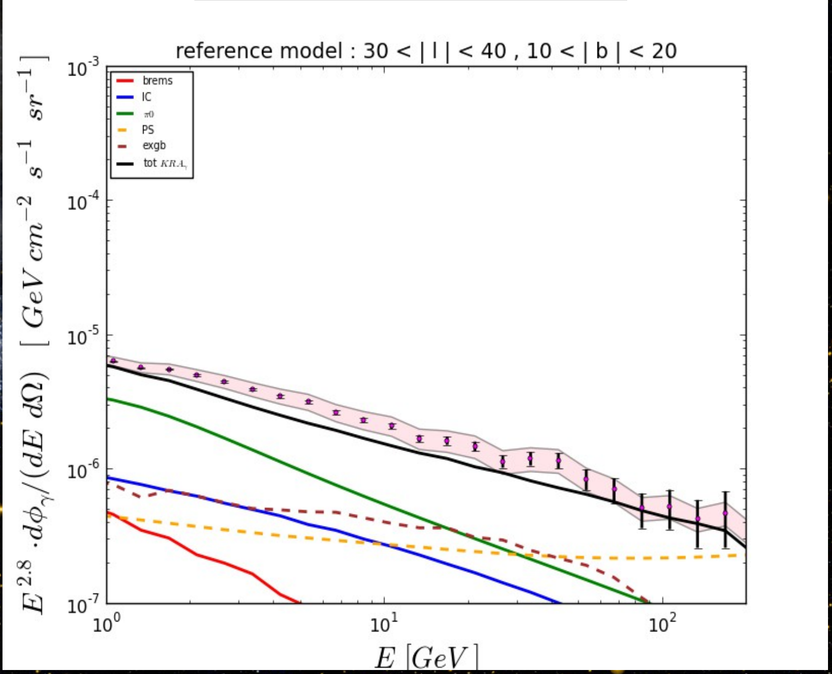
3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

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° < l < 40°
10° < |b| < 20°



Going beyond the standard lore

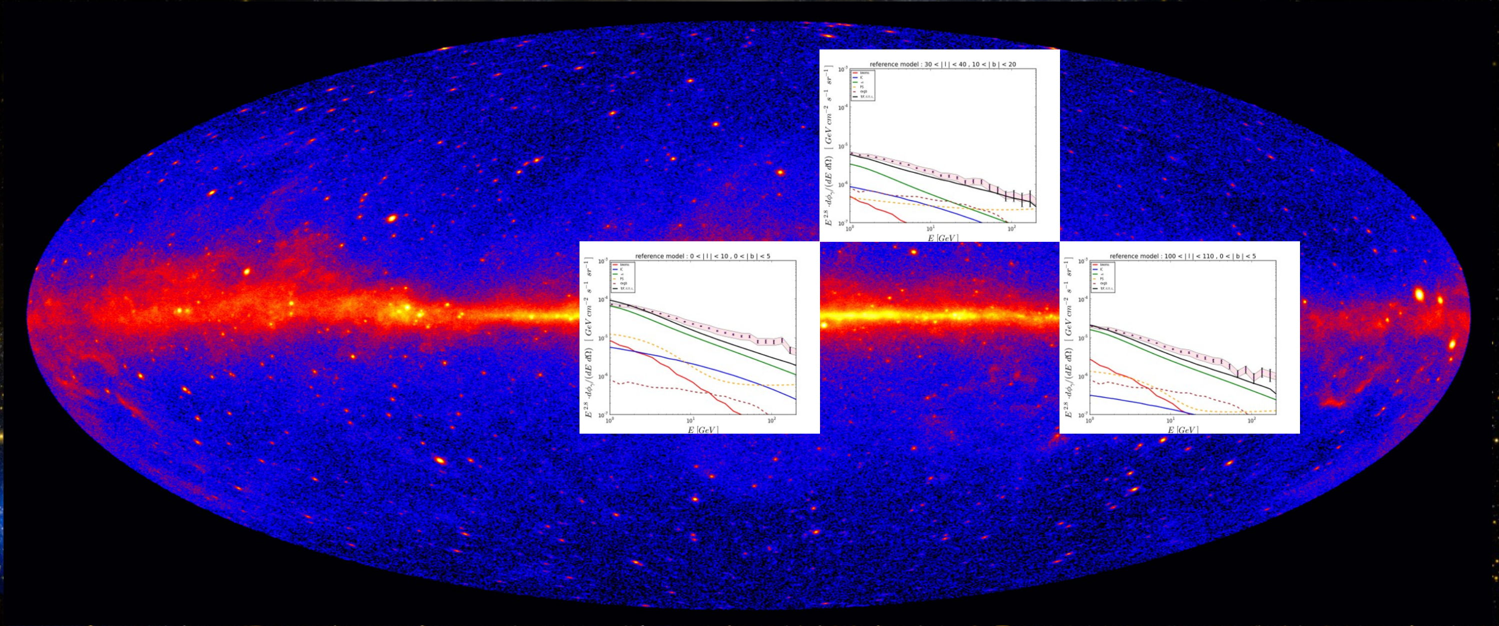
3. Spatial gradients in the rigidity scaling of the CR diffusion coefficient

The idea:

→ we drop the over-simplified assumption of homogeneous diffusion

→ we consider a harder diffusion coefficient in the inner Galaxy

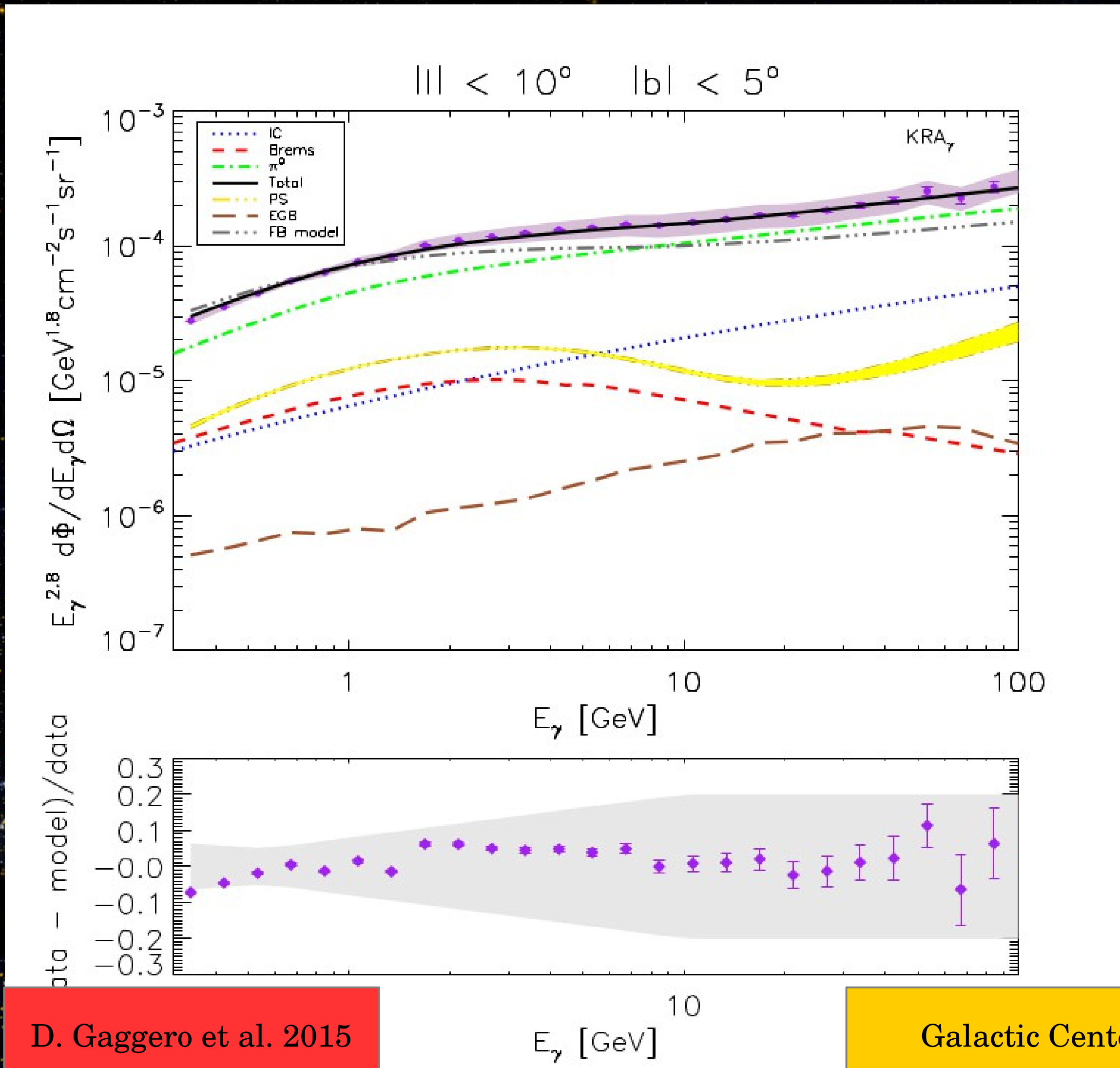
$$\delta(R) = aR + b$$



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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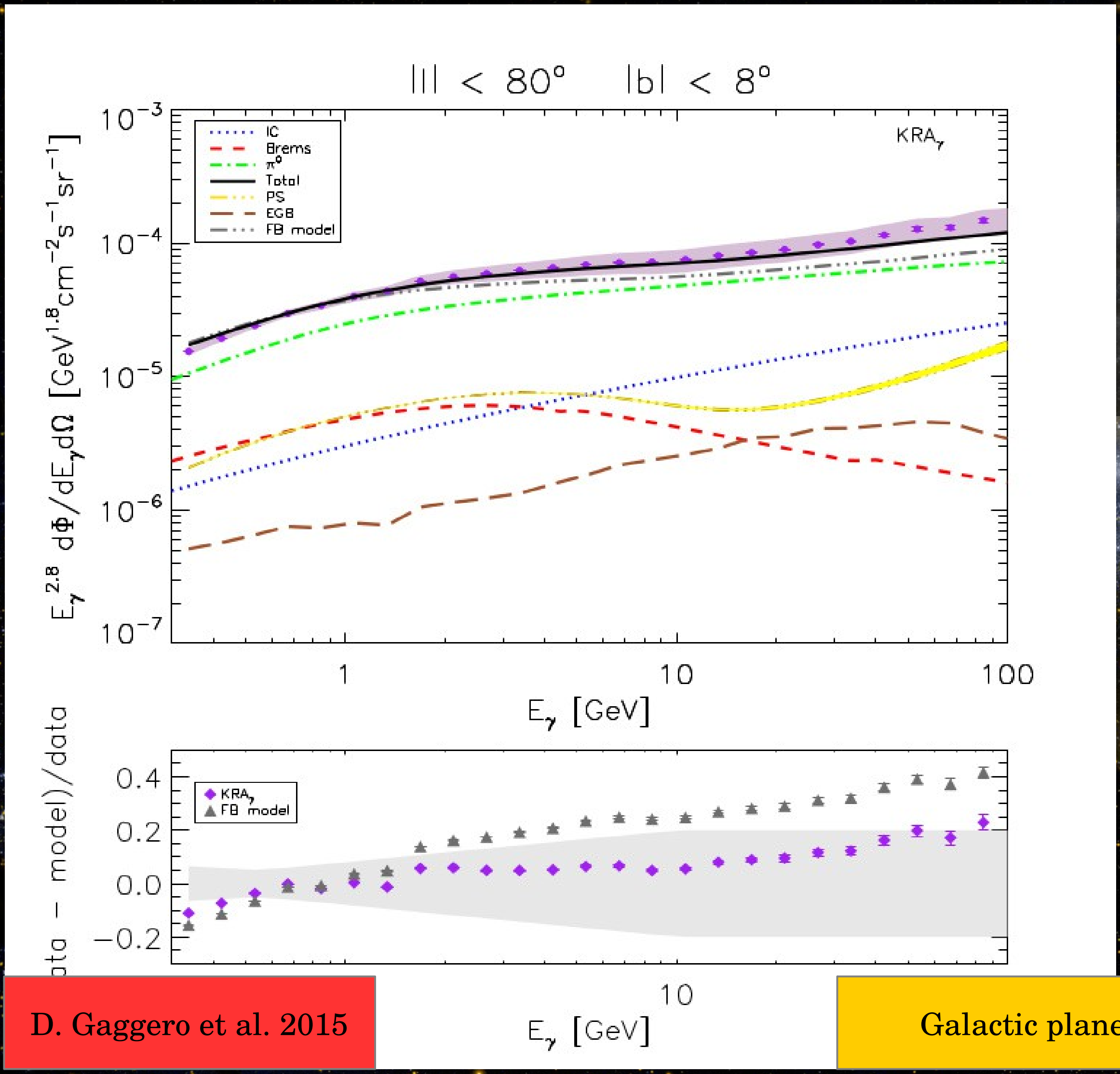

D. Gaggero et al. 2015

Galactic plane

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 $\delta(R) = aR + b$
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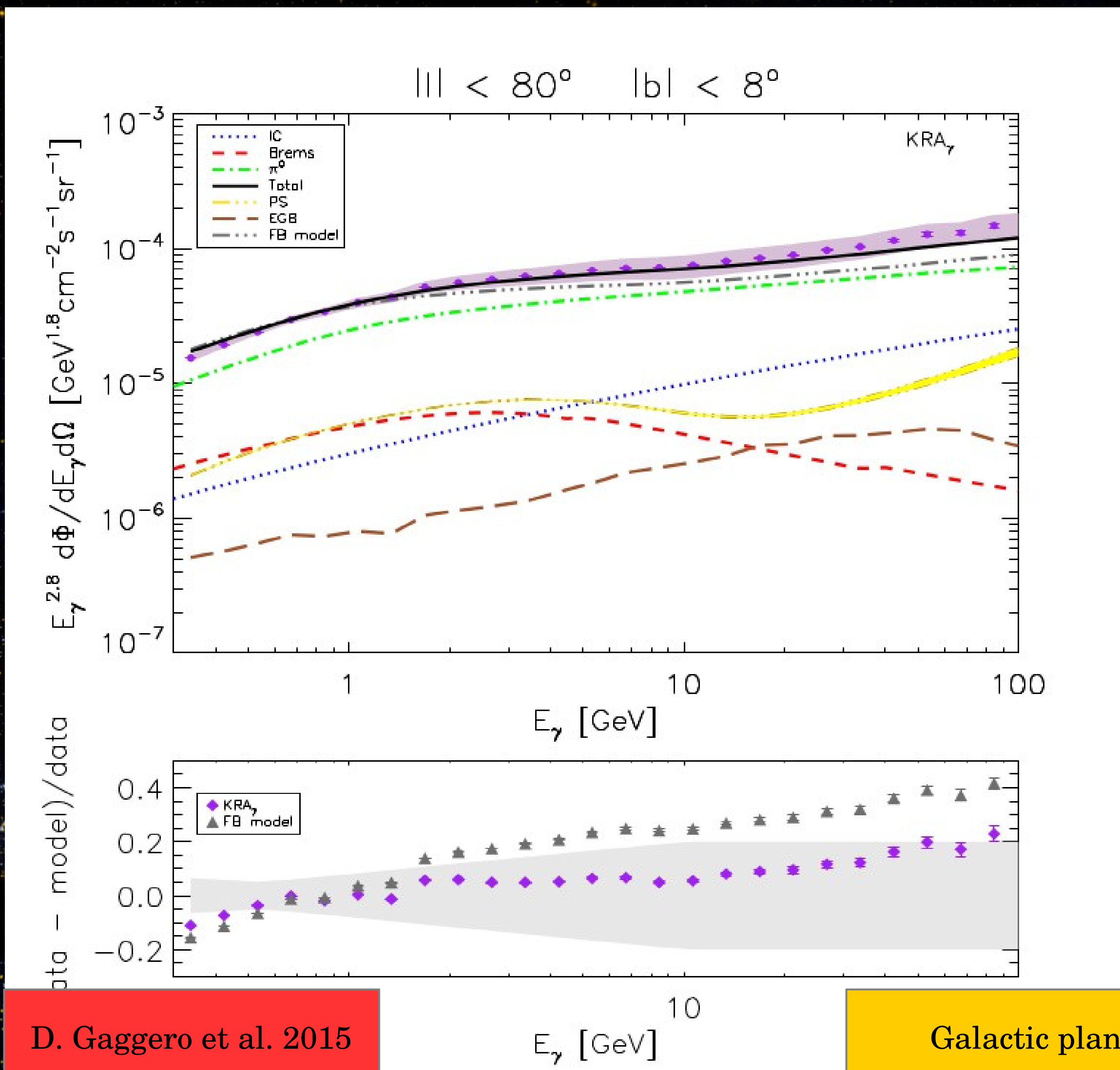
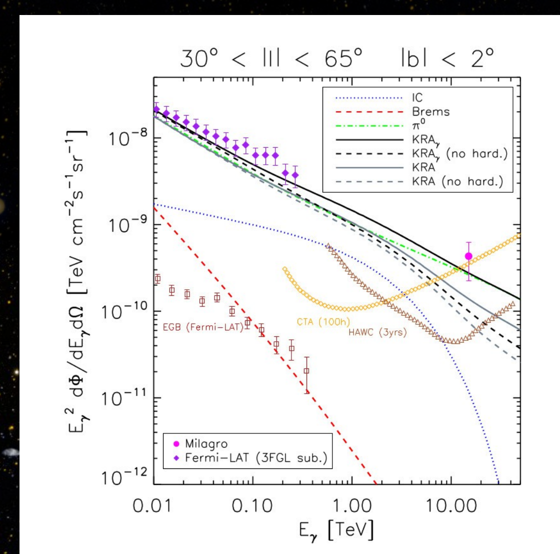


D. Gaggero et al. 2015

Galactic plane

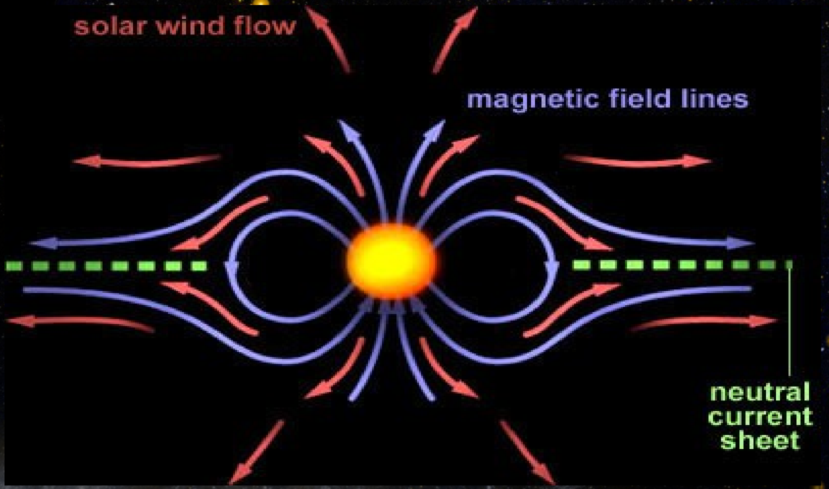
Check the talks by Dario Grasso and Antonio Marinelli for implications at the TeV!

The MILAGRO excess is explained with this framework



Going beyond the standard lore

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

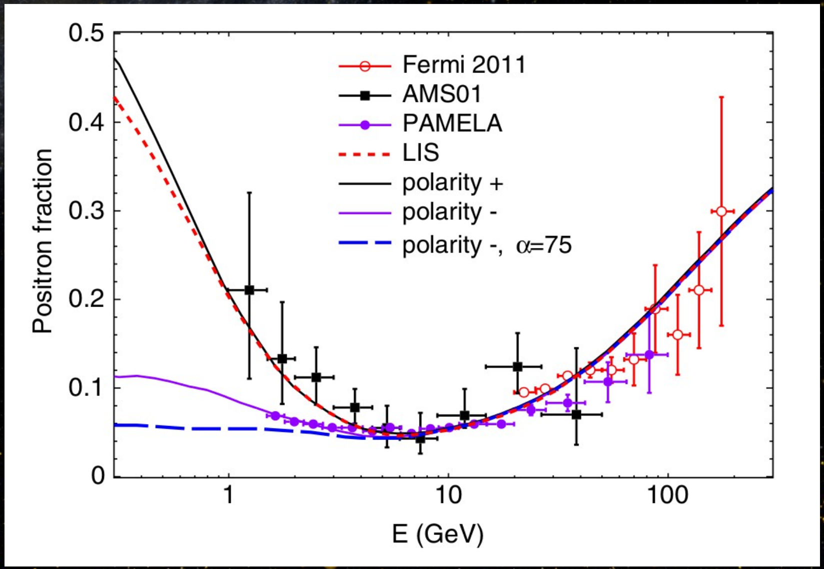


The interaction of low-energy CRs with the Heliosphere is very complicated.

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, Jokpii 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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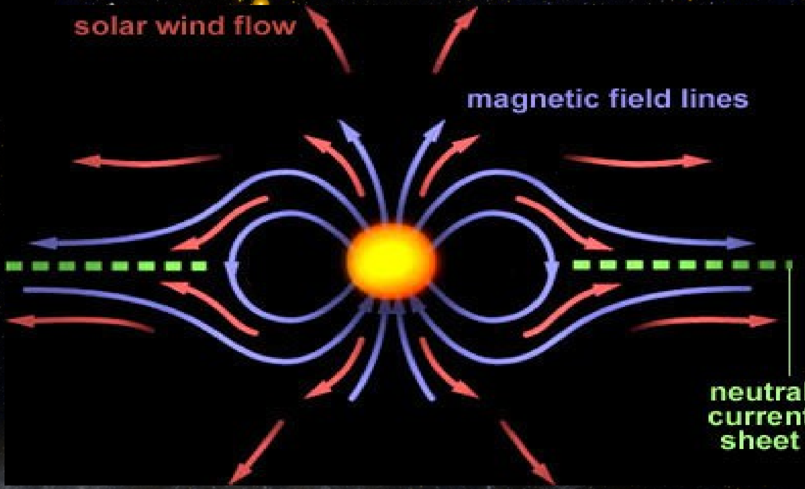

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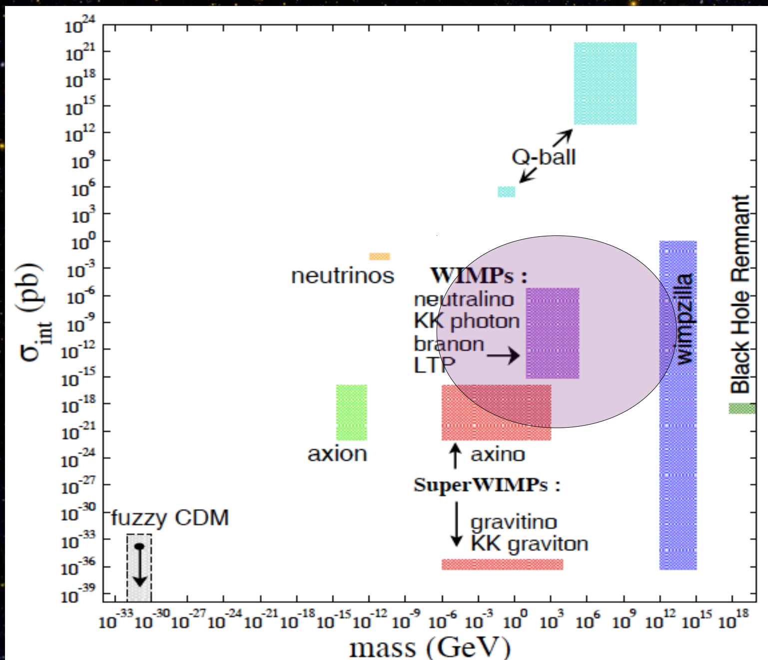
Motion is described by an equation taking into account diffusion, drift and loss terms *(see e.g. papers by Parker, Burger, Jokpii In the '60s and '70s, more recently Strauss et al. 2012, Maccione 2013)*

→ 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?

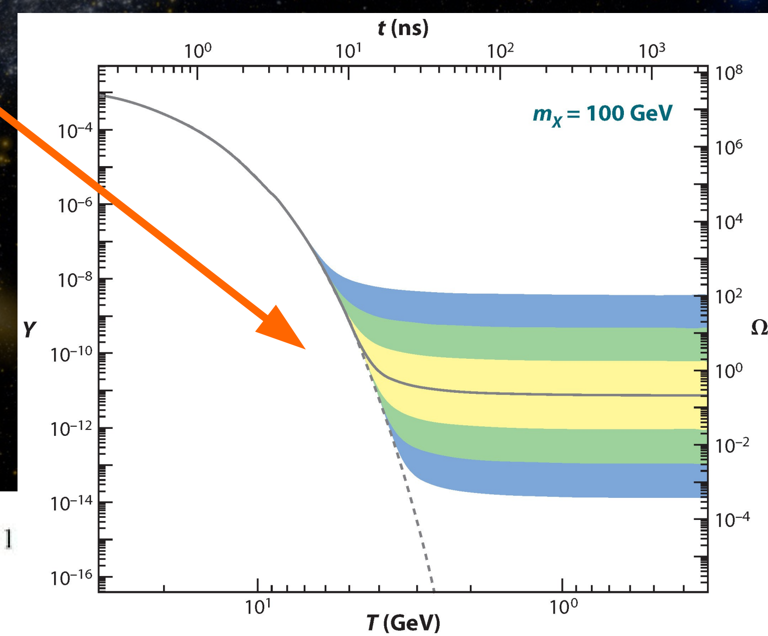


Particle physics provides many DM candidates

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(GeV)* → *O(TeV)*

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

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



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

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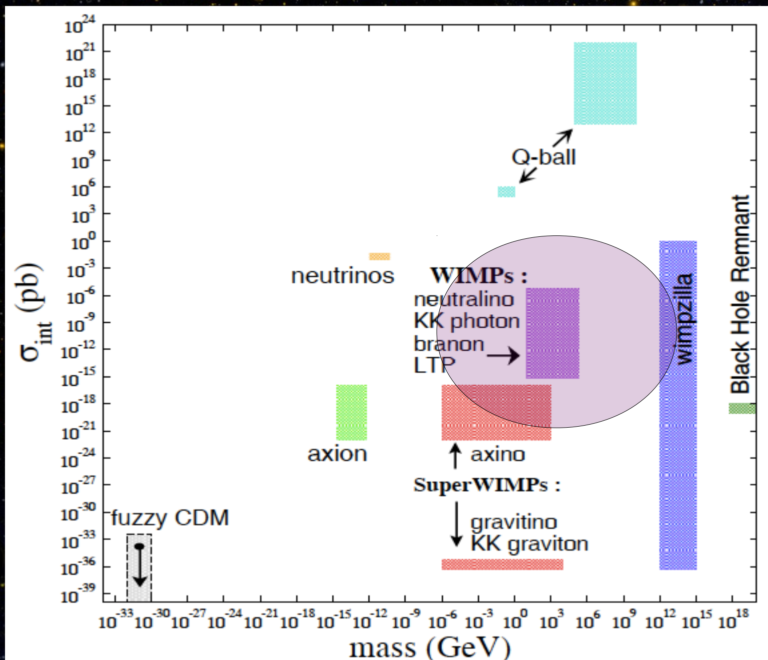

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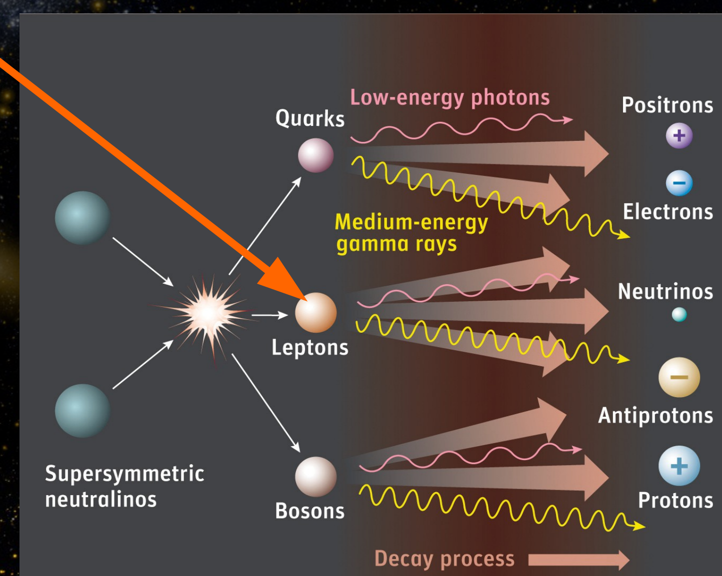
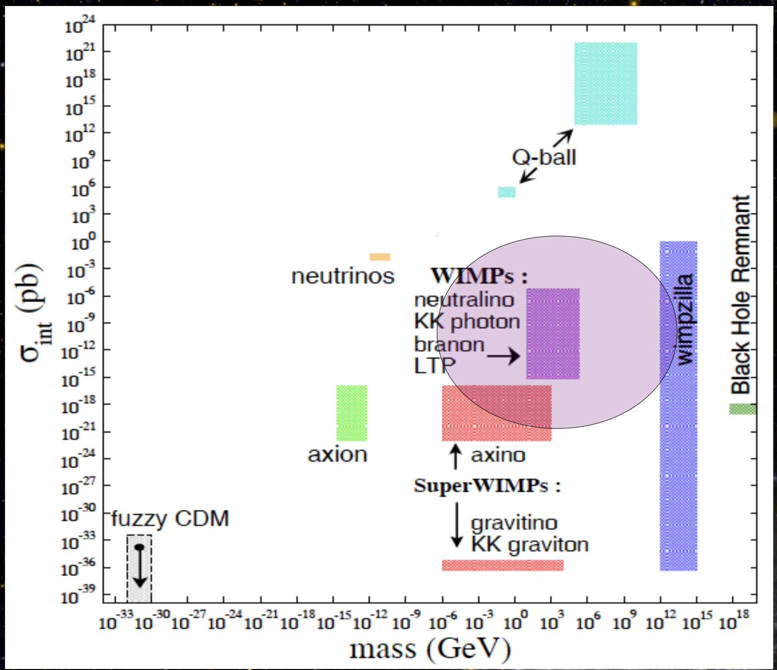
→ ***they may show up in either CRs or gamma-ray/ synchrotron emission ("multimessenger indirect detection")***



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

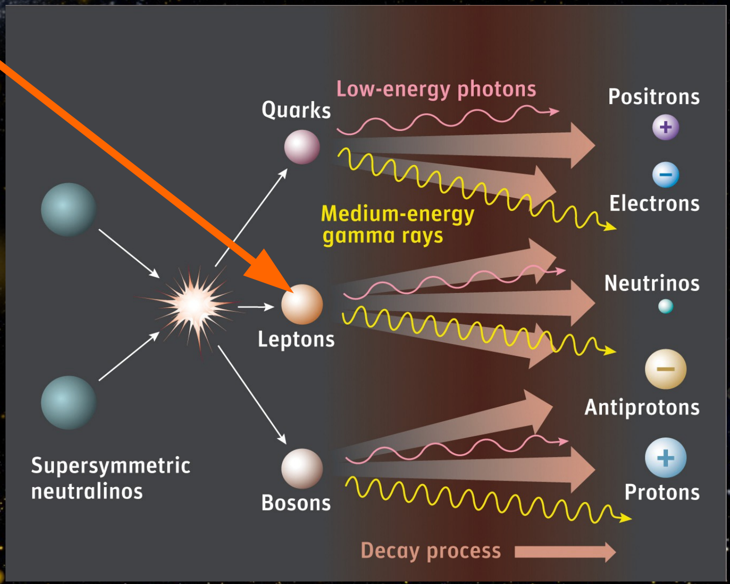


Particle physics provides many DM candidates

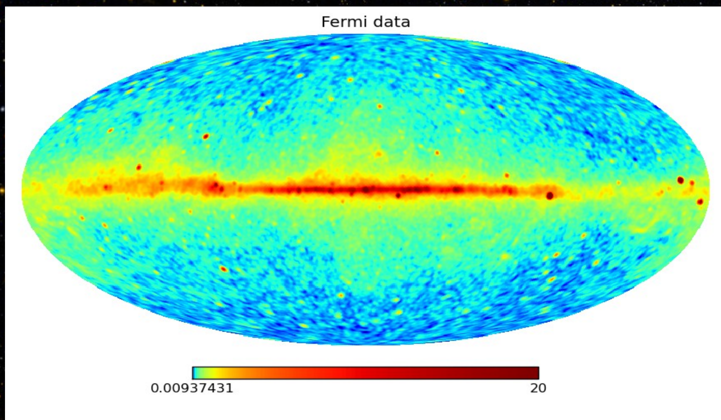
The most popular ones (namely the WIMPS, e.g. the lightest supersymmetric particle in the minimal supersymmetric extension of the SM) are in the mass range *O(GeV)* → *O(TeV)*

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

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

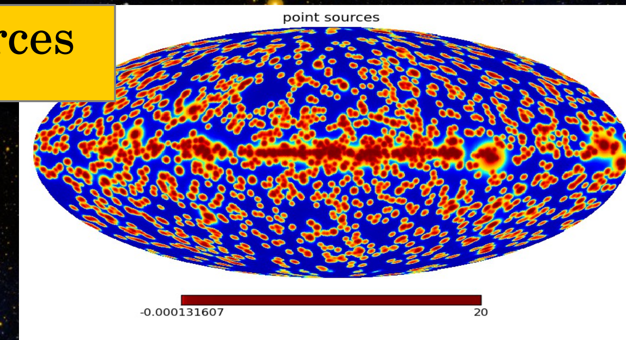


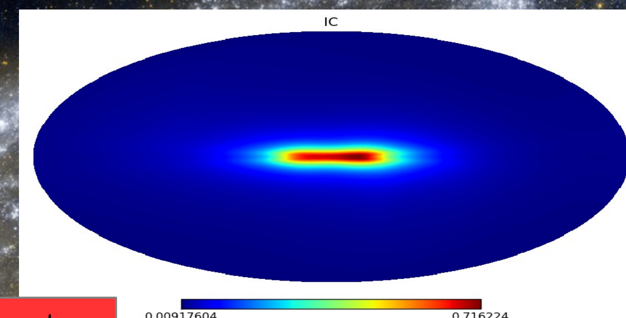
The Galactic center excess



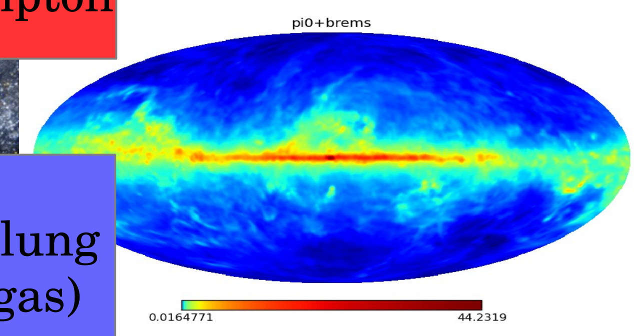
Fermi-LAT data

Point Sources

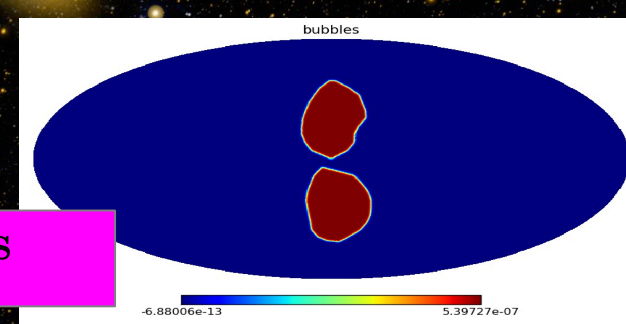




Inverse Compton



π_0 +
bremsstrahlung
(traces IS gas)

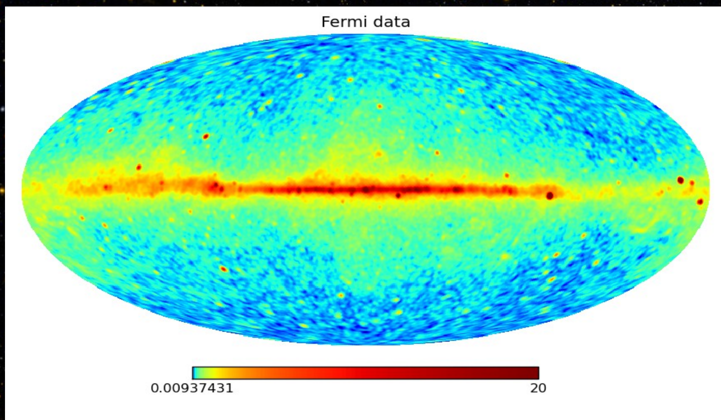


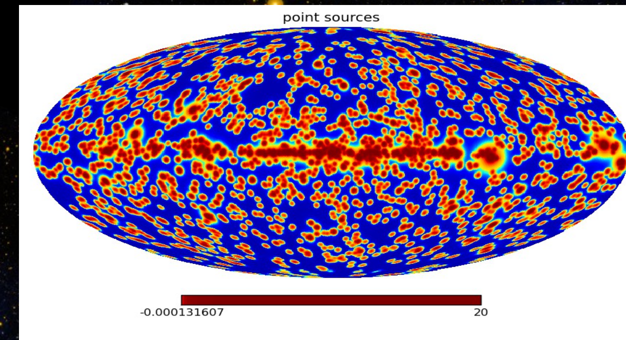
Bubbles

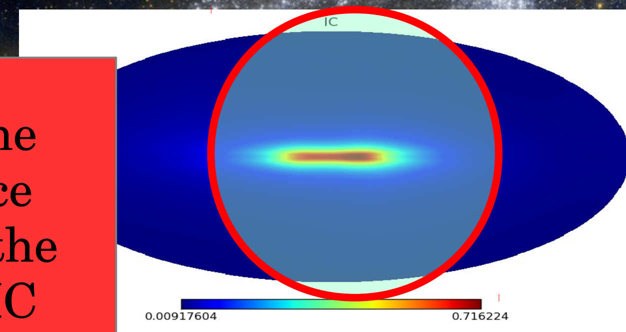
Given the high accuracy of Fermi-LAT data, the diffuse emission is very promising for DM indirect detection

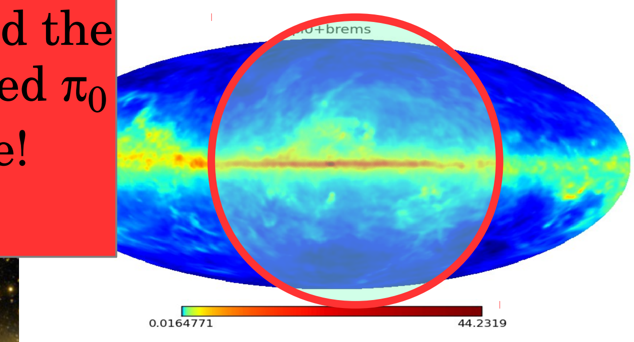
→ The goal is to understand if, once all known components are substracted, a significant residual is left

The Galactic center excess

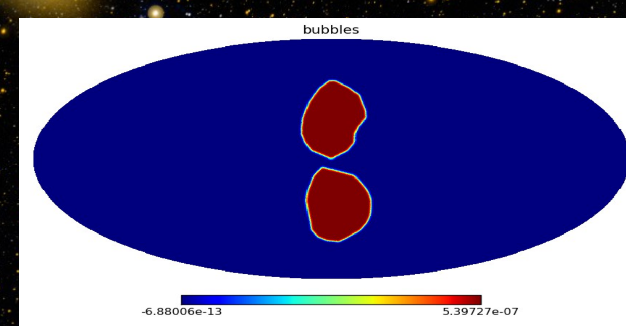








Notice the difference between the smooth IC template and the high-detailed π_0 template!



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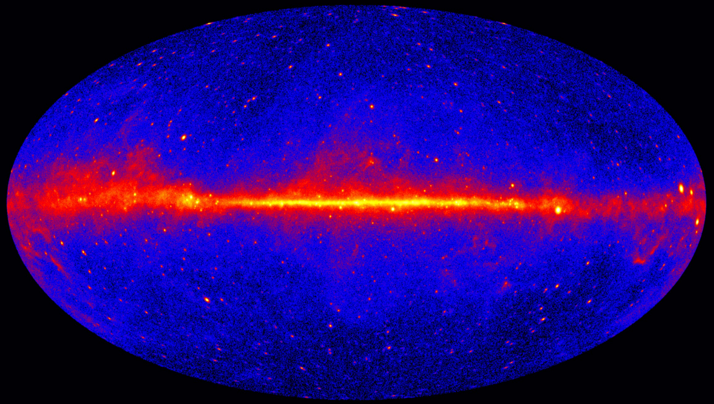
The Galactic center excess



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 substracted, a significant residual is left

There is a robust indication for an anomaly! (and a dedicated session few days ago)

- D. Dixon et al. 1998 [arXiv:9803237]
- V. Vitale et al. 2009 [arXiv:0912.3828]
- L Goodenough and D. Hooper, 2009
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- 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 [arXiv:1402.6703]
- F. Calore, I. Cholis, C. Weniger, 2014 [arXiv:1409.0042]
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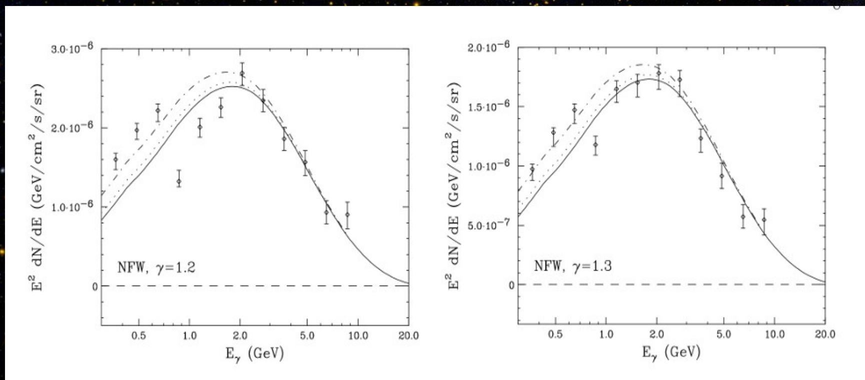
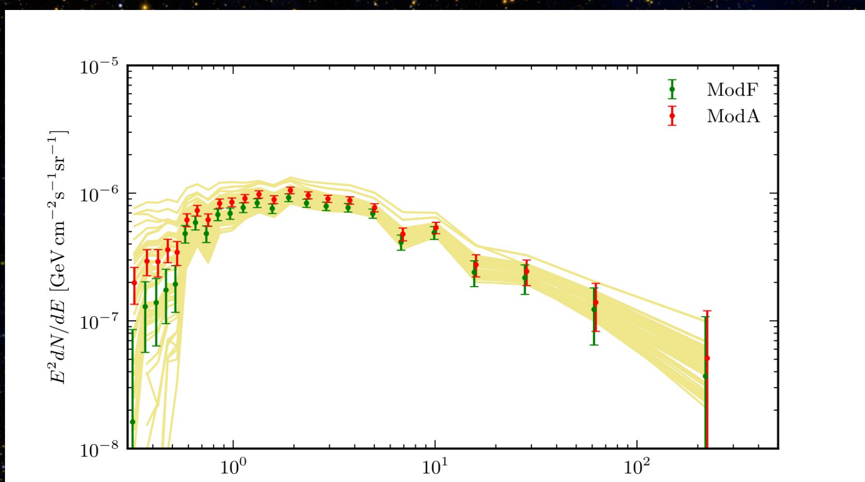
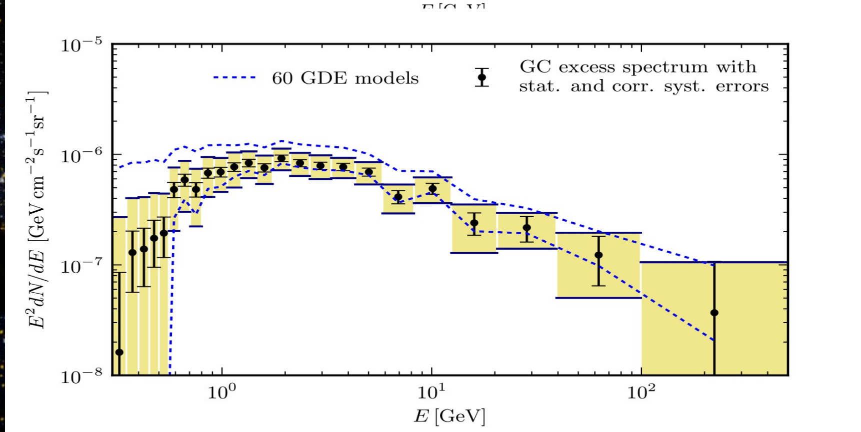
The Galactic center excess







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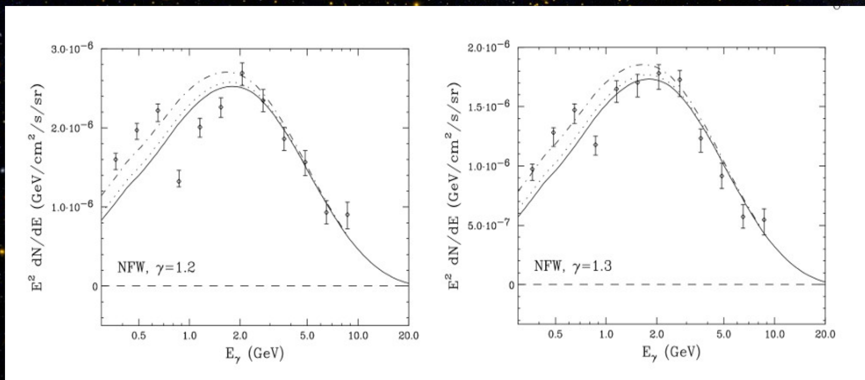

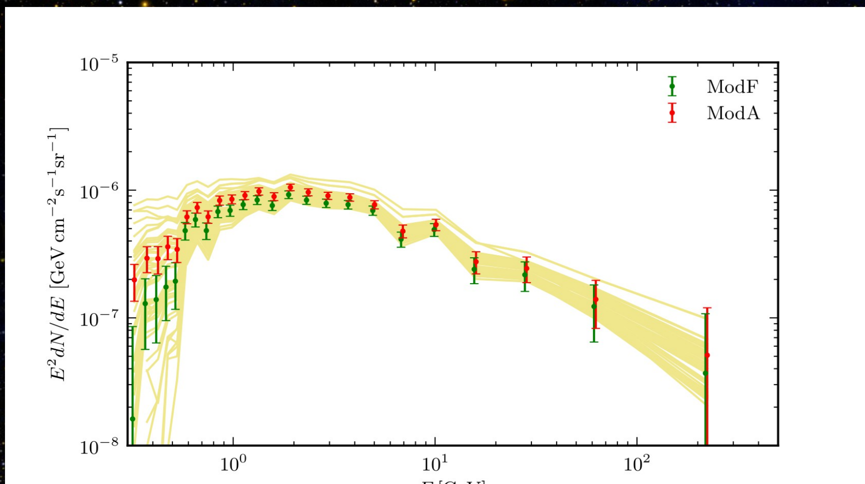

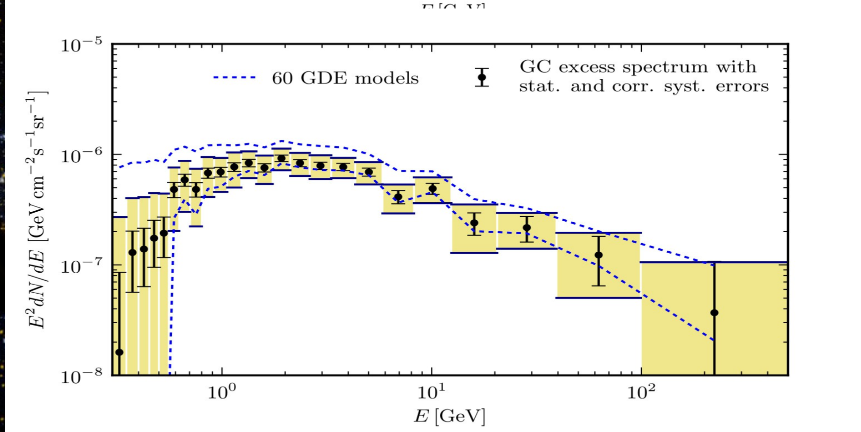

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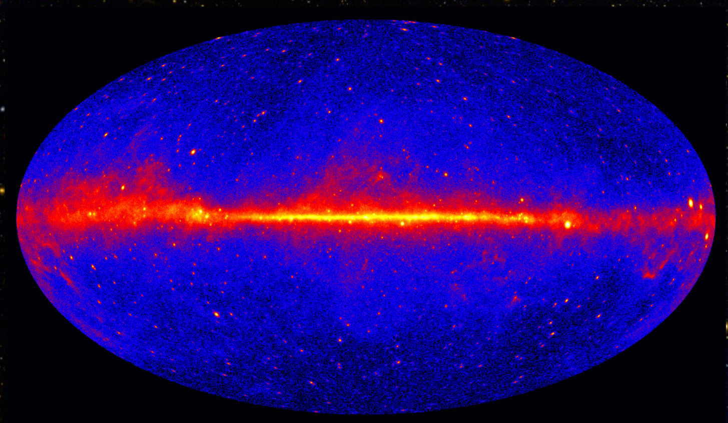
→ Very natural explanation of the excess spectrum in terms of DM particles annihilating with standard cross section predicted from cosmology

→ Comprehensive analysis by *Calore et al.* about uncertainties of the spectrum, relying on 60 `Galprop` runs for the background + principal component analysis of the correlation matrix

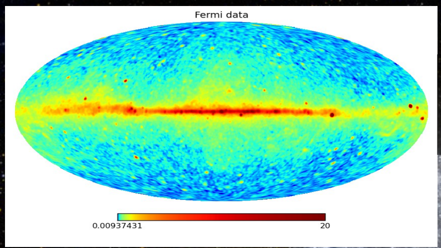
The Galactic center excess



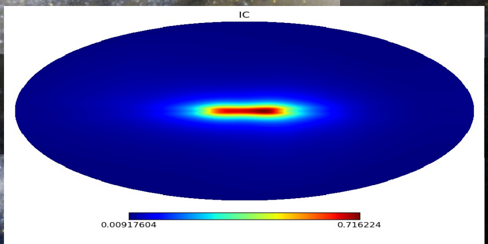
Fermi-LAT data

All these results rely on the "template fitting" technique:

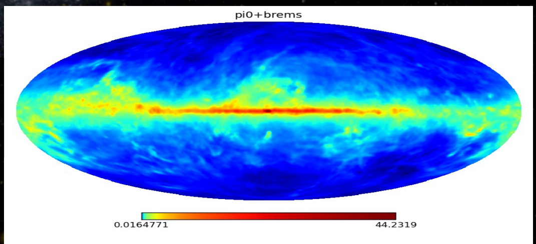
→ the gamma-ray map is written, for each energy bin, as a sum of the astrophysical templates, and the coefficients are left free to float



$= c_1$

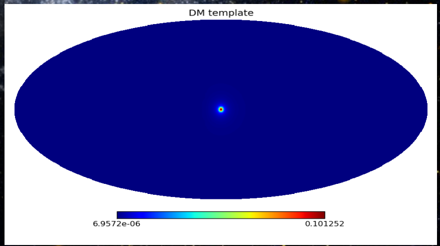


$+ c_2$



…

… $+ c_{DM}$



The interesting result is that the DM template is preferred by the template fitting algorithm

The Galactic center excess

Two key questions are:

Can we explain this excess with astrophysics?

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

Is the DM interpretation in tension with other observables?

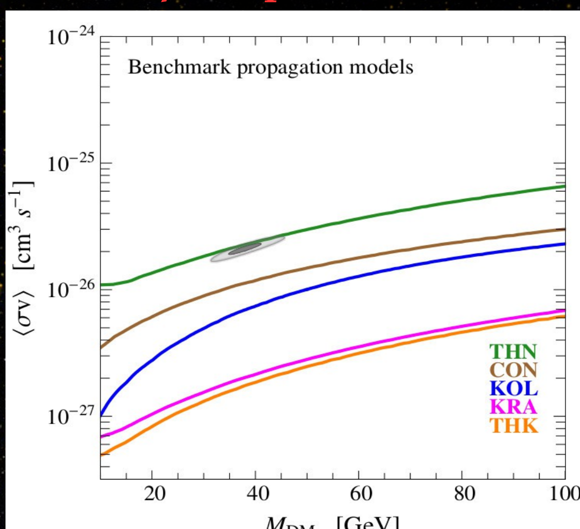
→ in particular, the antiprotons may provide a stringent bound

Let's see how these questions connect with all the issues presented in the first part!

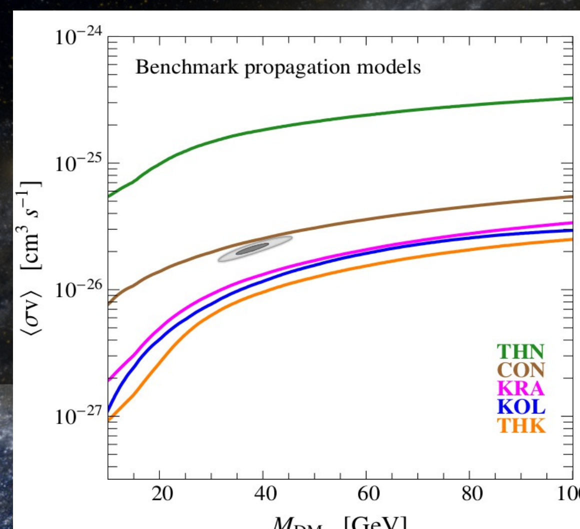
The Galactic center excess

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

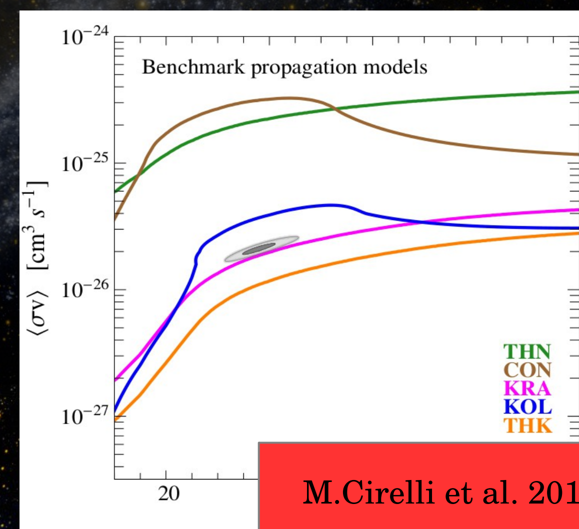
→ *it depends on how much you trust the current knowledge on charge dependent modulation and on the halo size (the first uncertainty I pointed out in the first part)!!* ←



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



M.Cirelli et al. 2014

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

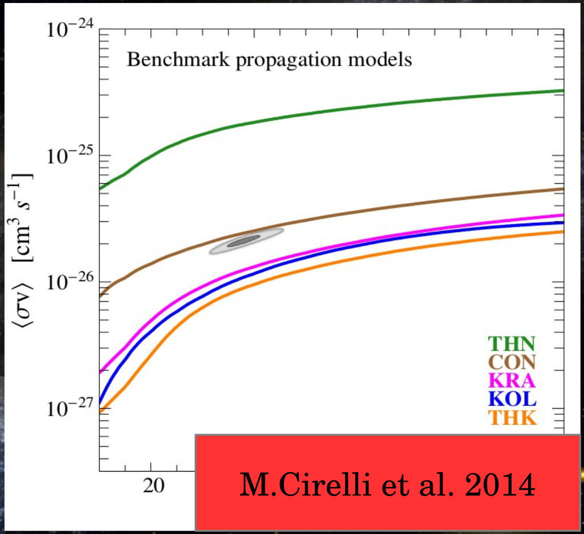
The Galactic center excess

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 (the first uncertainty I pointed out in the first part)!!* ←

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!



M.Cirelli 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*

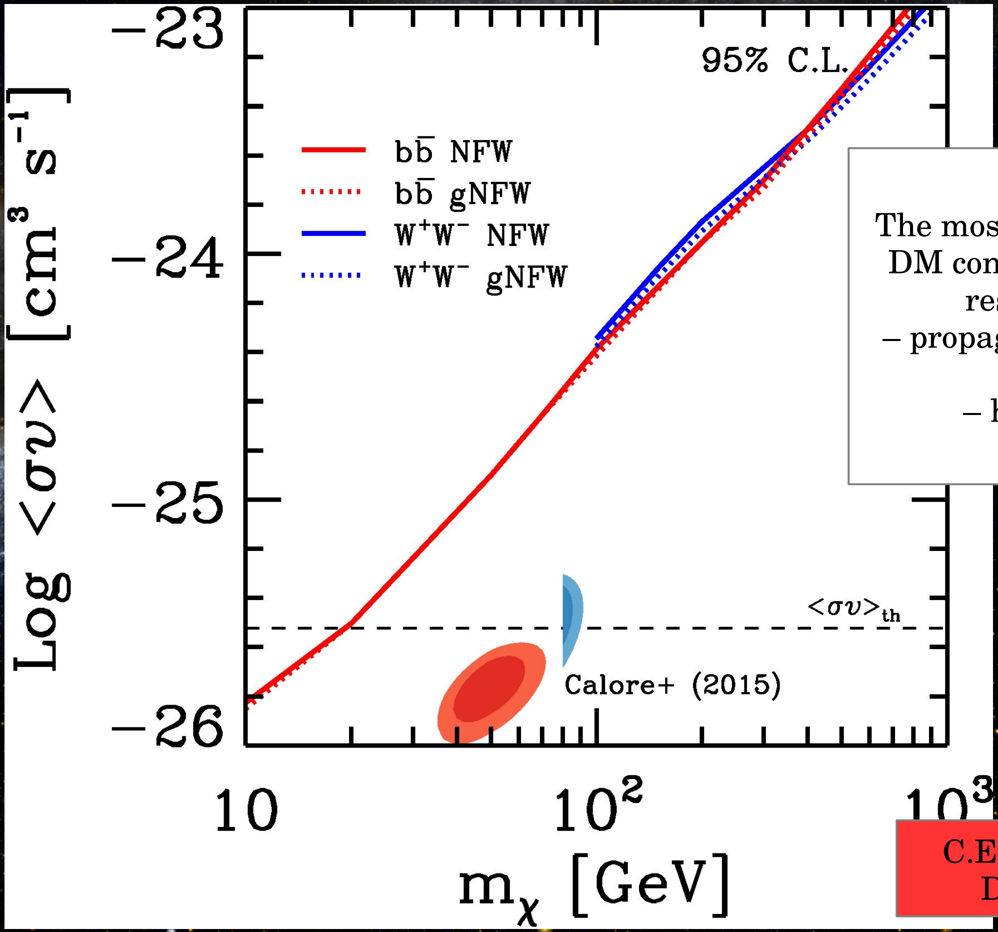
The Galactic center excess

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 (the first uncertainty I pointed out in the first part)!!* ←

The bottom line of all this issue is:

Although the best-fit propagation models of CRs are in tension with the DM interpretation, ***the current status of the uncertainties do not allow to rule out the scenario!***

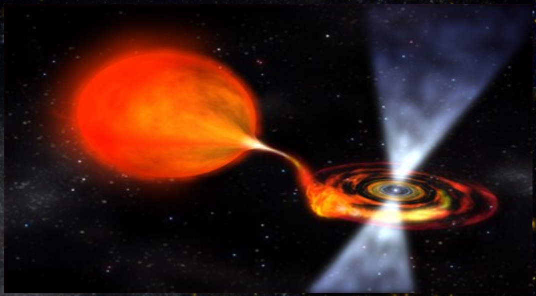


The most conservative DM constraints with respect to:
– propagation models
– halo size

C.Evoli, D.Gaggero, D.Grasso 2015

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?

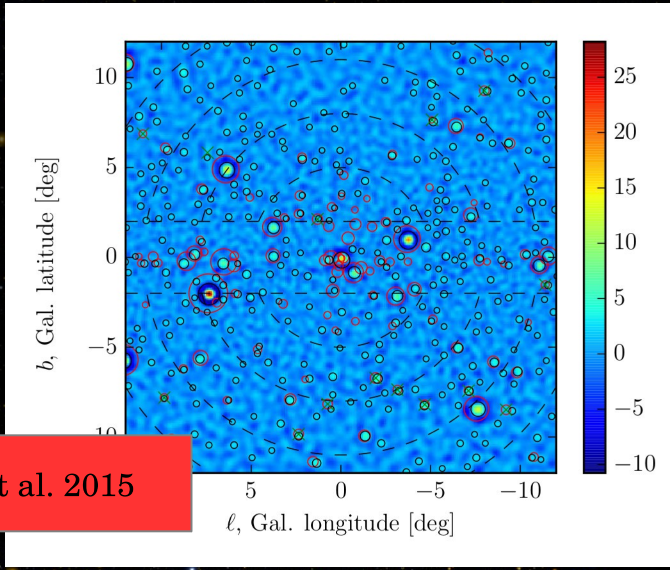
under debate: see Petrovic et al. 2014

→ strong hints in favour of this interpretation come from two independent analyses based on

Non-Poissonian photon statistics: see Lee et al. 2015

Wavelet tranforms: see Bartels et al. 2015

A population of point sources is favoured by these analyses



Bartels et al. 2015

The Galactic center excess

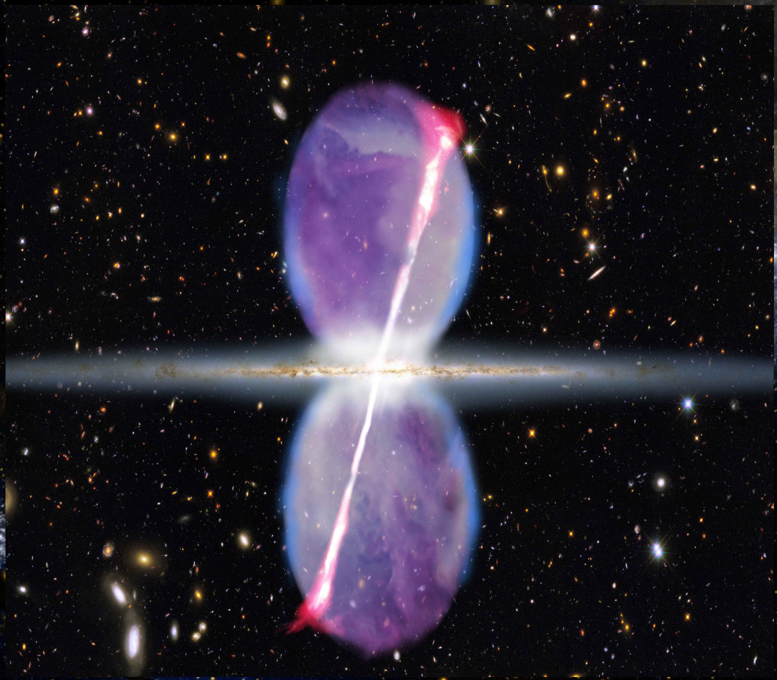
Can we explain this excess with astrophysics?

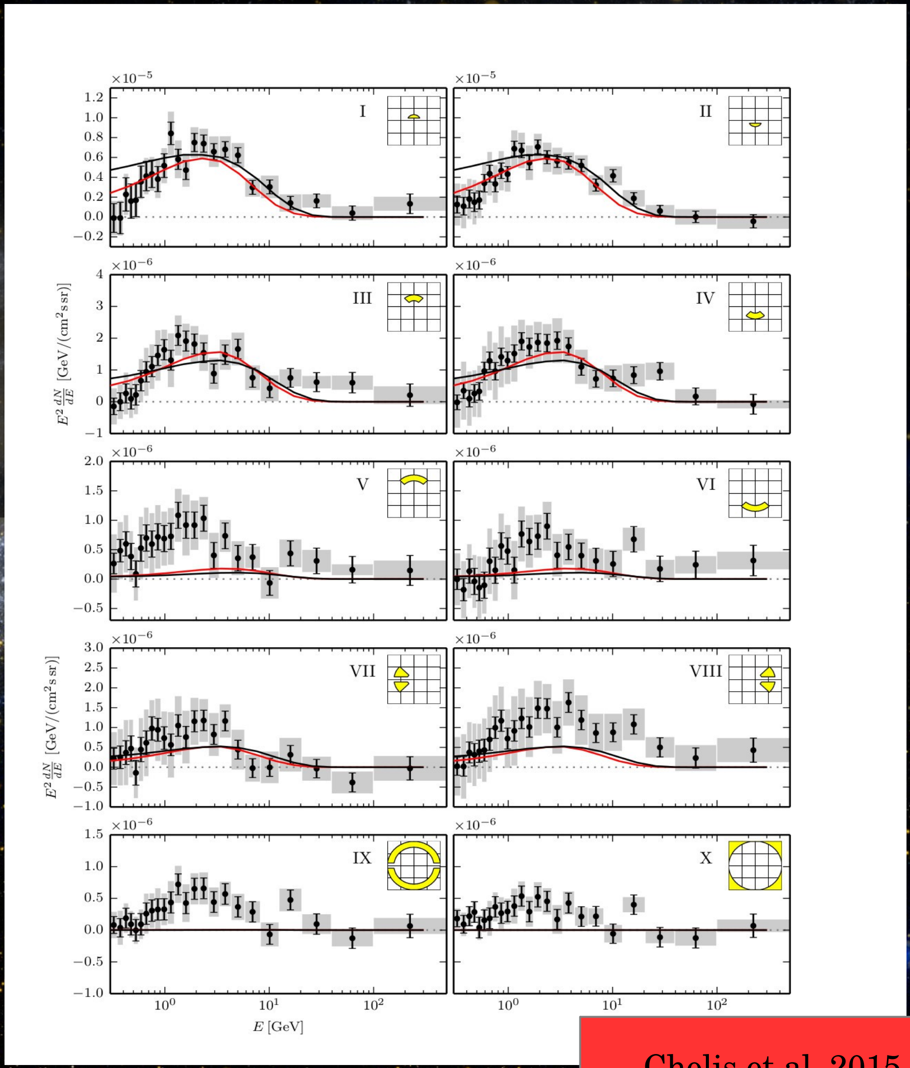
Transient phenomena?

Carlson et al. 2014 – Petrovic et al. 2015

More recently: Cholis et al. 2015

→ problems with spectra and morphology





Cholis et al. 2015

The Galactic center excess

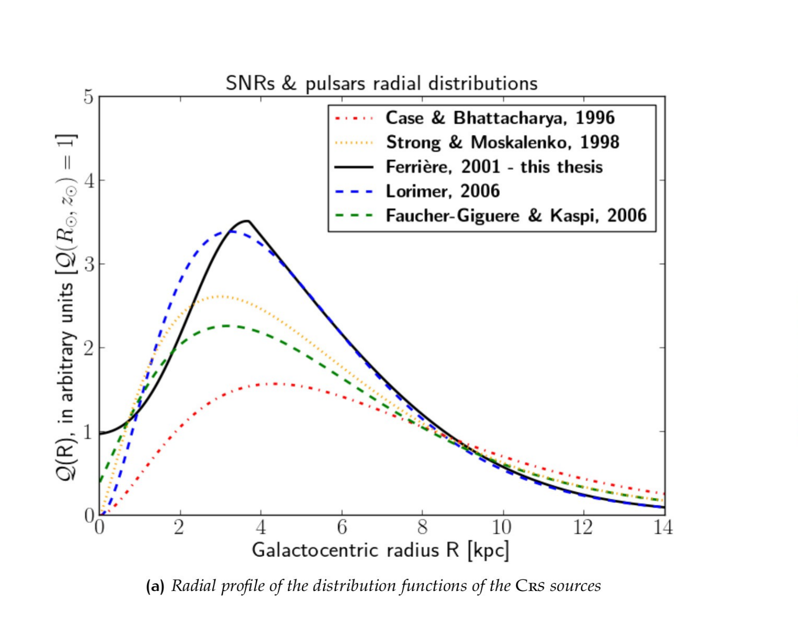
What about a standard CR source?

→ The spirit of this talk is to show that understanding details about CR propagation and diffusion is crucial to understand any DM claim

→ **We know that all CR models used in these analyses are not designed to reproduce correctly the GC region!**

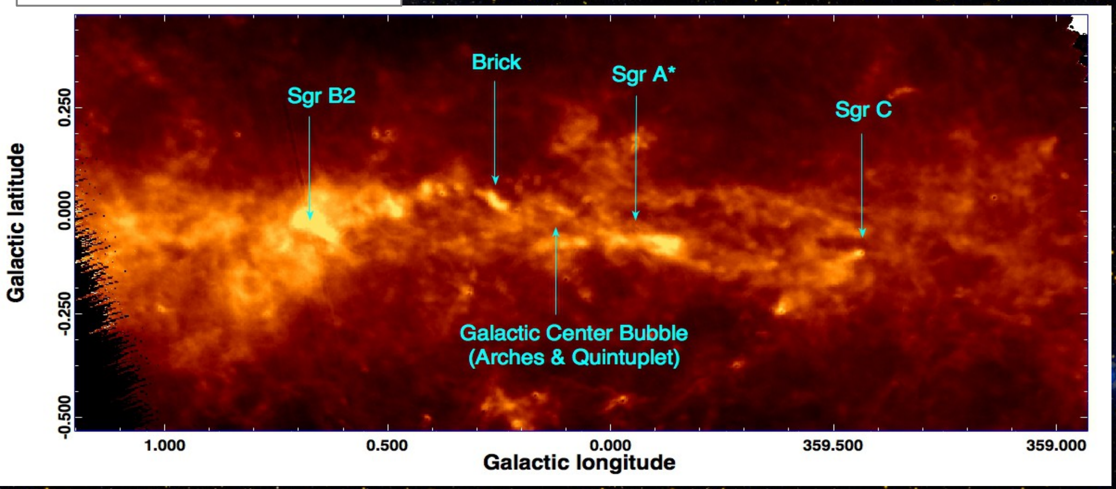
→ In particular there are problems with the CR source term.

The source function is extrapolated from SNR and pulsar catalogues fail to account for the very active star-forming region located in the inner Galaxy



(a) *Radial profile of the distribution functions of the* CRs *sources*

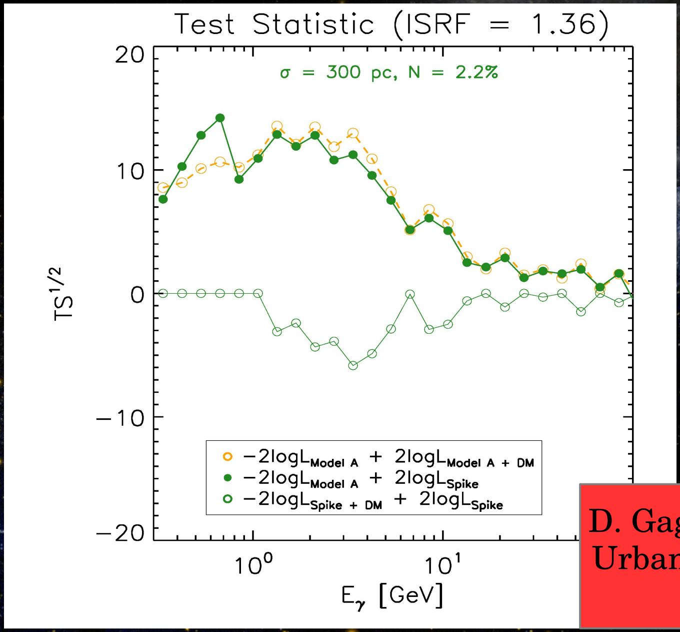
Dust temperature map of the inner Central Molecular Zone

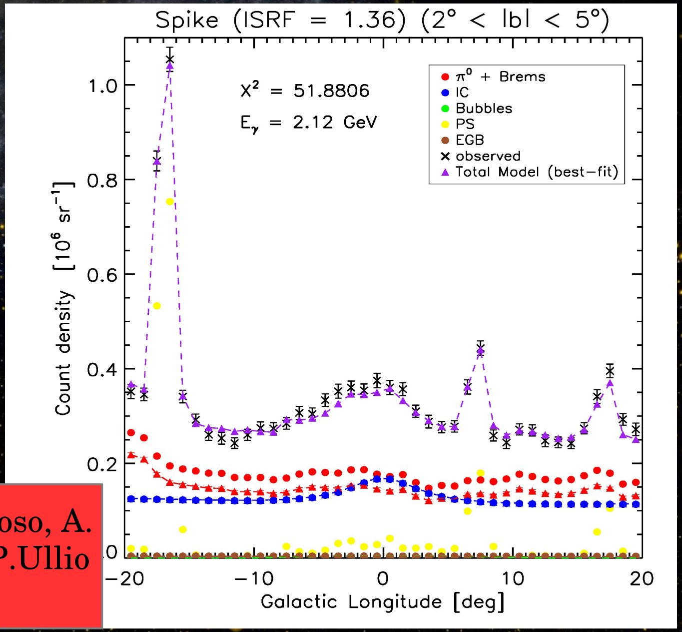


The Galactic center excess

What about a standard CR source?

→ We considered a steady-state source in the center (see Alfredo Urbano's talk) compatible with current estimates on the Star Formation Rate in the inner Galaxy
~1% of the total SFR in the Galaxy according to several papers
e.g. *Figer, ApJ 601 (2004)*
and re-implemented the template-fitting algorithm with the IC template computed accordingly. This scenario does not show any evidence of excess. From the likelihood point of view, this picture works almost as well as the DM case.



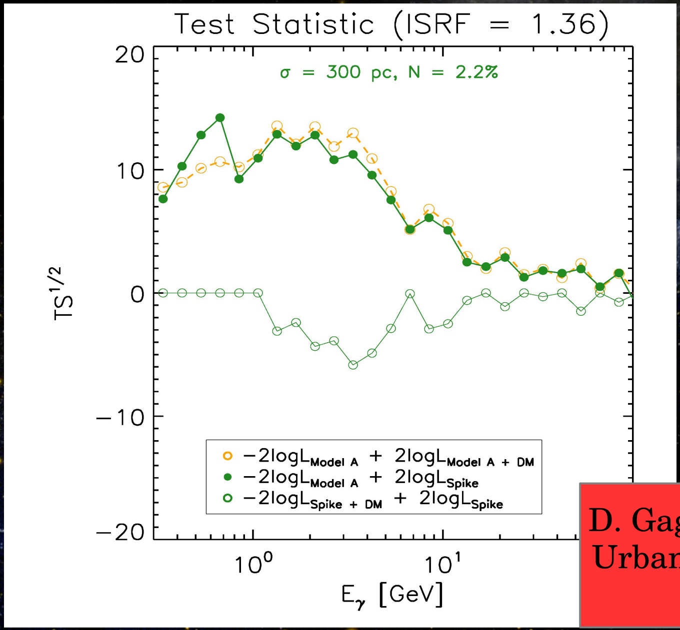


D. Gaggero, M. Taoso, A. Urbano, M.Valli, P.Ullio 2015

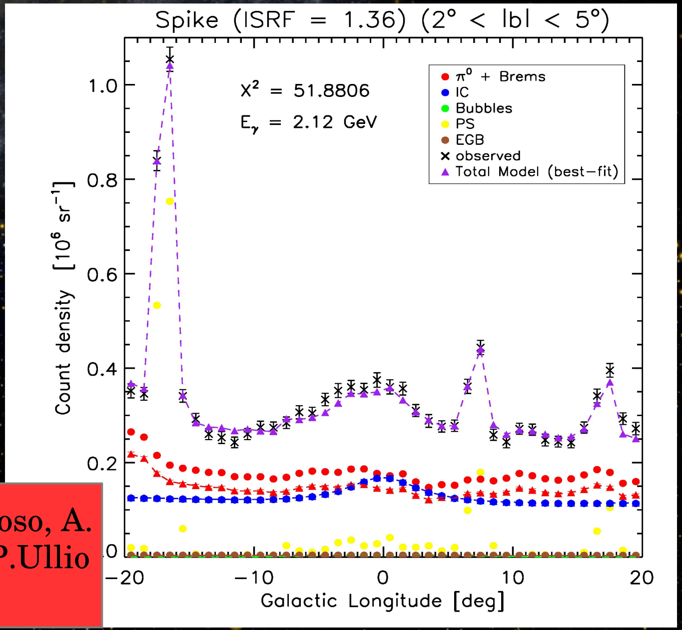
The Galactic center excess

The bottom line on the GC issue is that we still have to understand what is going on.
→ The DM scenario is appealing and viable
→ Astrophysical interpretations are still possible

In this context:
- A more accurate modelling of the CR source distribution and propagation in the inner Galaxy is compelling – better characterization of the sources – role of anisotropic diffusion? Rembember from the first part of the talk that diffusion may behave in a not trivial way!



D. Gaggero, M. Taoso, A. Urbano, M.Valli, P.Ullio 2015



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:

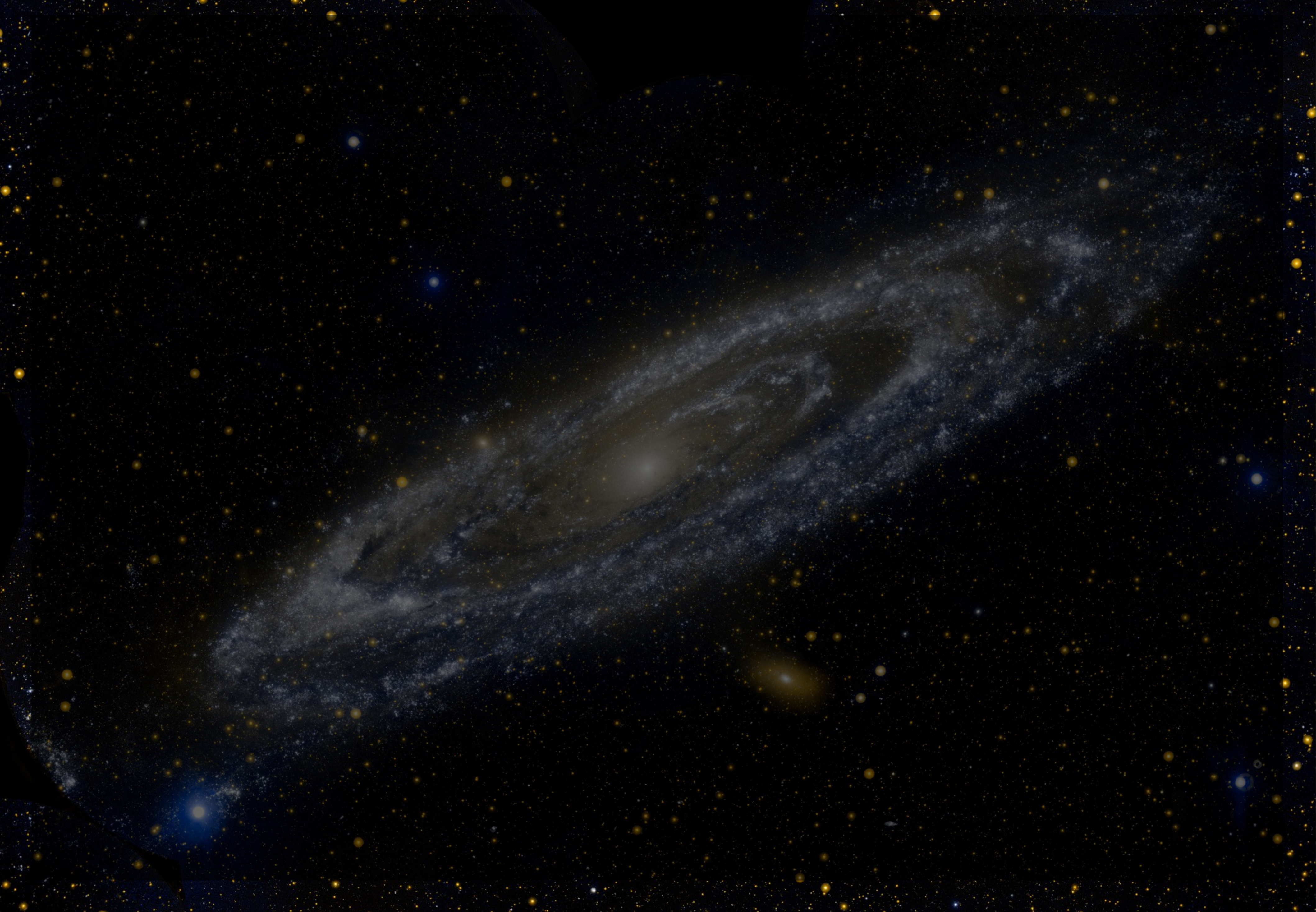
→ *the CR gradient inferred from gamma rays is too flat* compared to simulations
→ *the gamma-ray spectra turn out to be harder* in the Galactic Center region (tension with the outcome of numerical codes)
→ *there is evidence for charge-dependent effects* in solar modulation

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

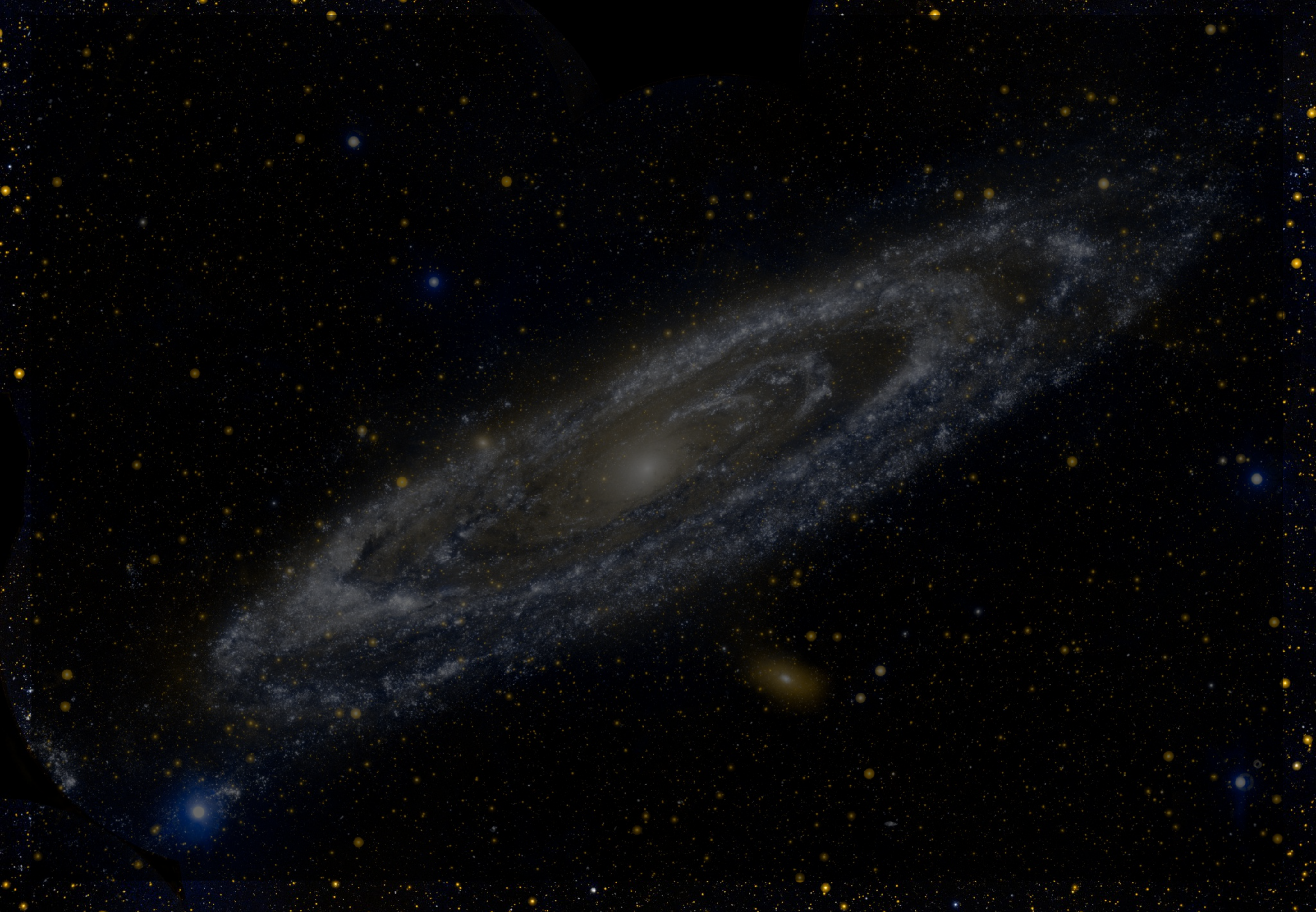
•We considered the GC excess and tried to address several questions:

→ *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 interperation
→ *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? A millisecond pulsar population? A enhanced CR acceleration in the central region (steady-state or sequence of bursts)

Backup slides



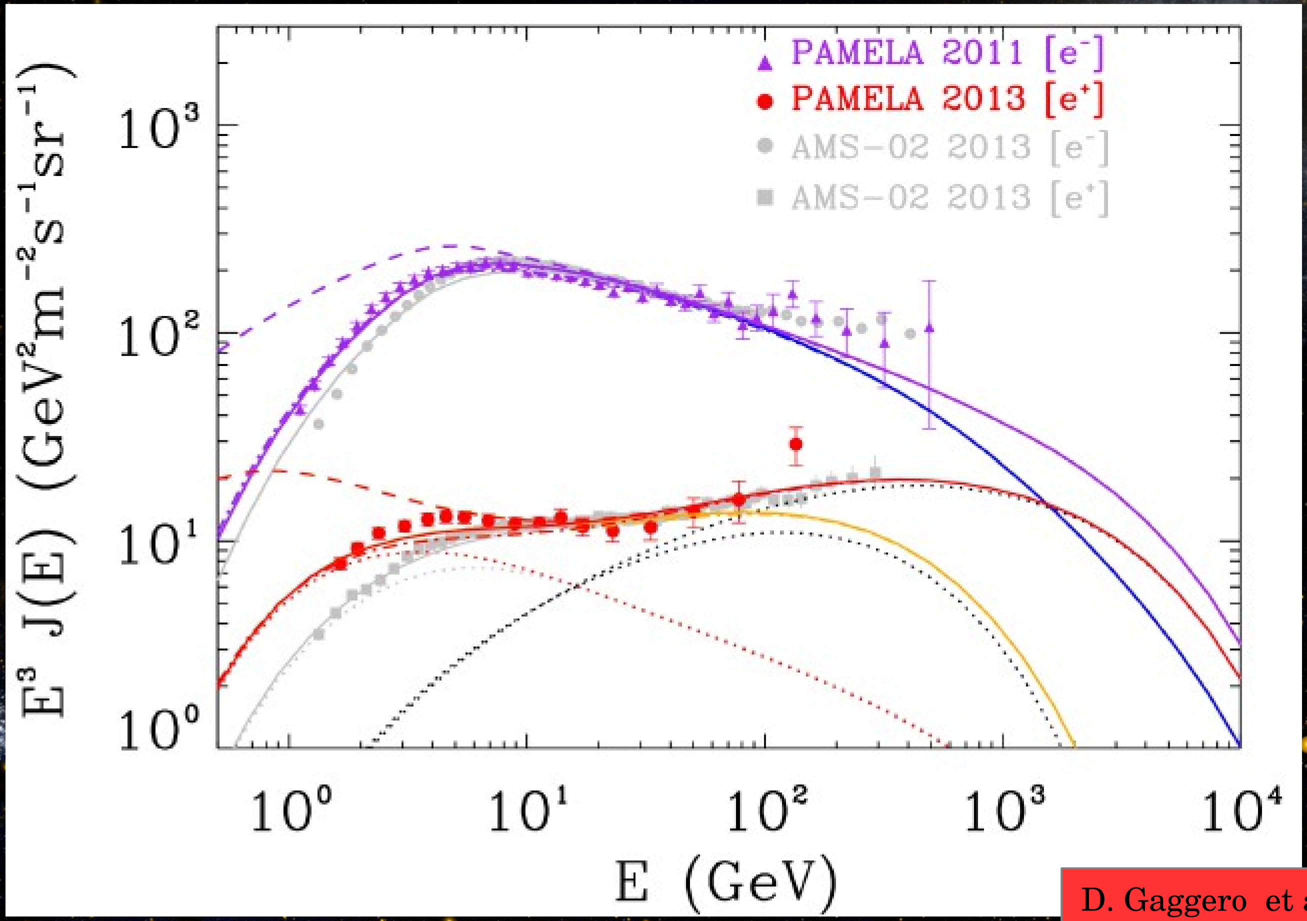
Backup slides



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



D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

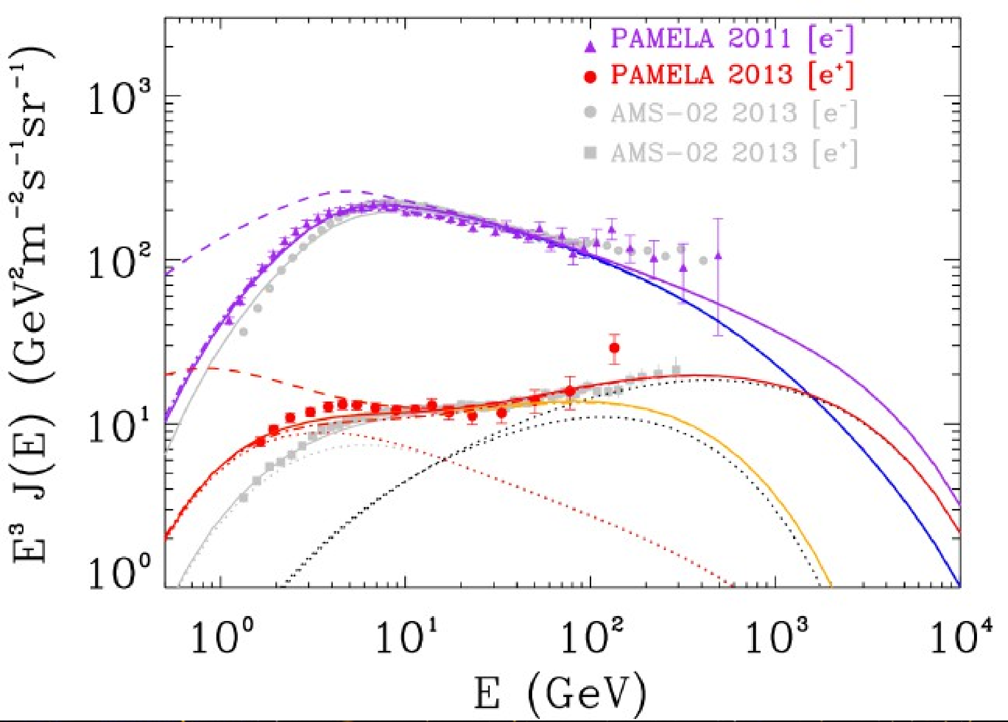
A 3D model of the Galaxy

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.**

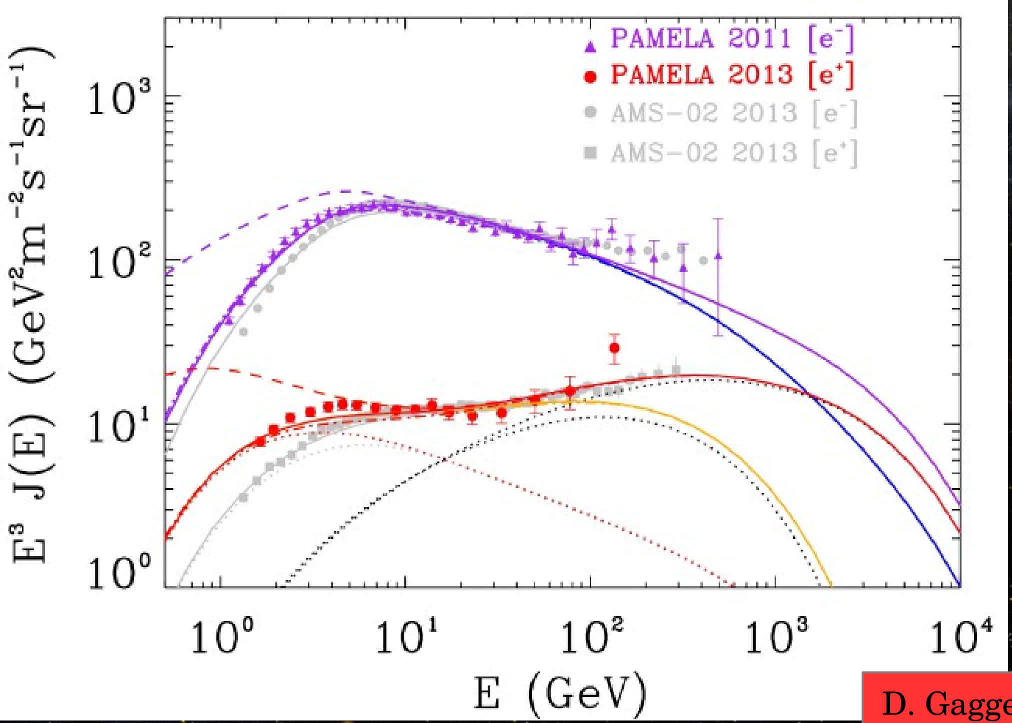
The residual discrepancy with the predicted value from the theory (-2 – -2.3) can be due to the details of the escape mechanism from the source



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!



D. Gaggero et al., PRD **89** (2014)

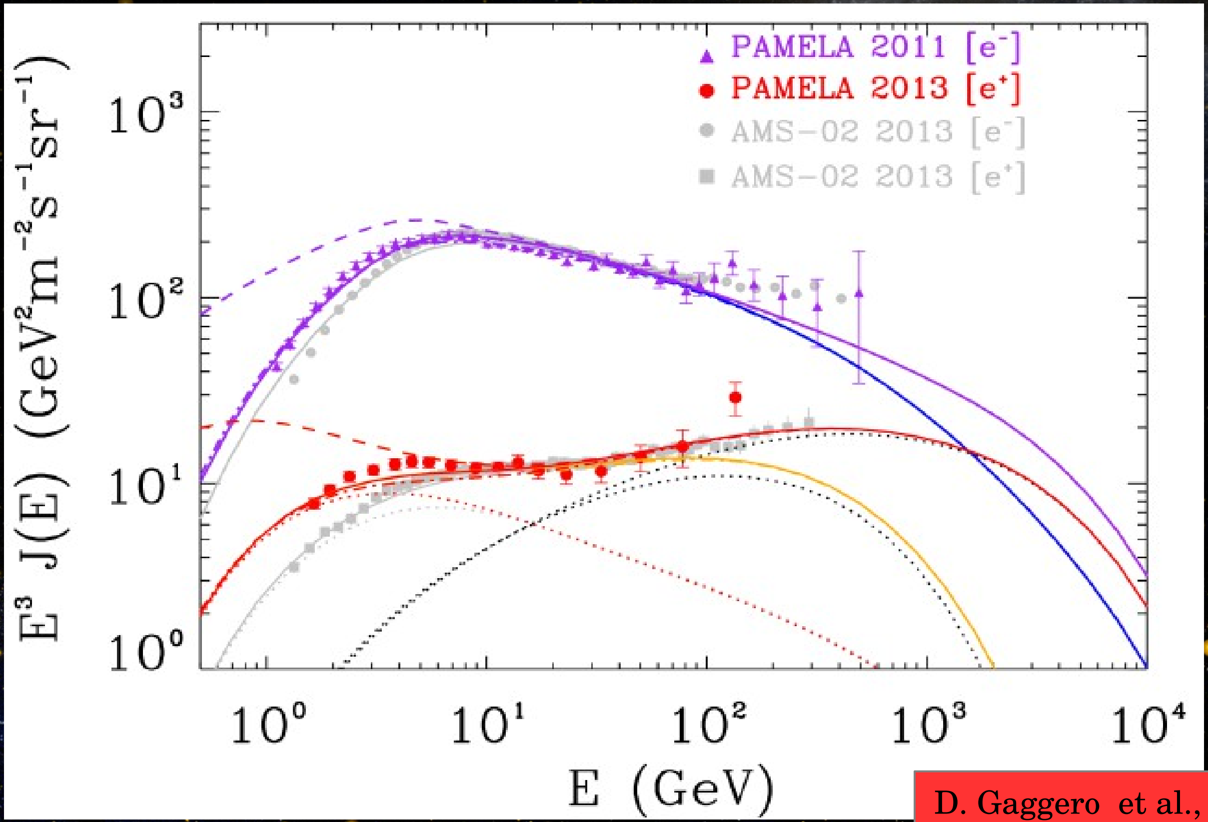
Ongoing work using DRAGON

A 3D model of the Galaxy

Ingredients of our models:

3) <u>*Primary "extra" component* of electrons and positrons</u> with source term in the arms and harder injection spectrum

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



D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

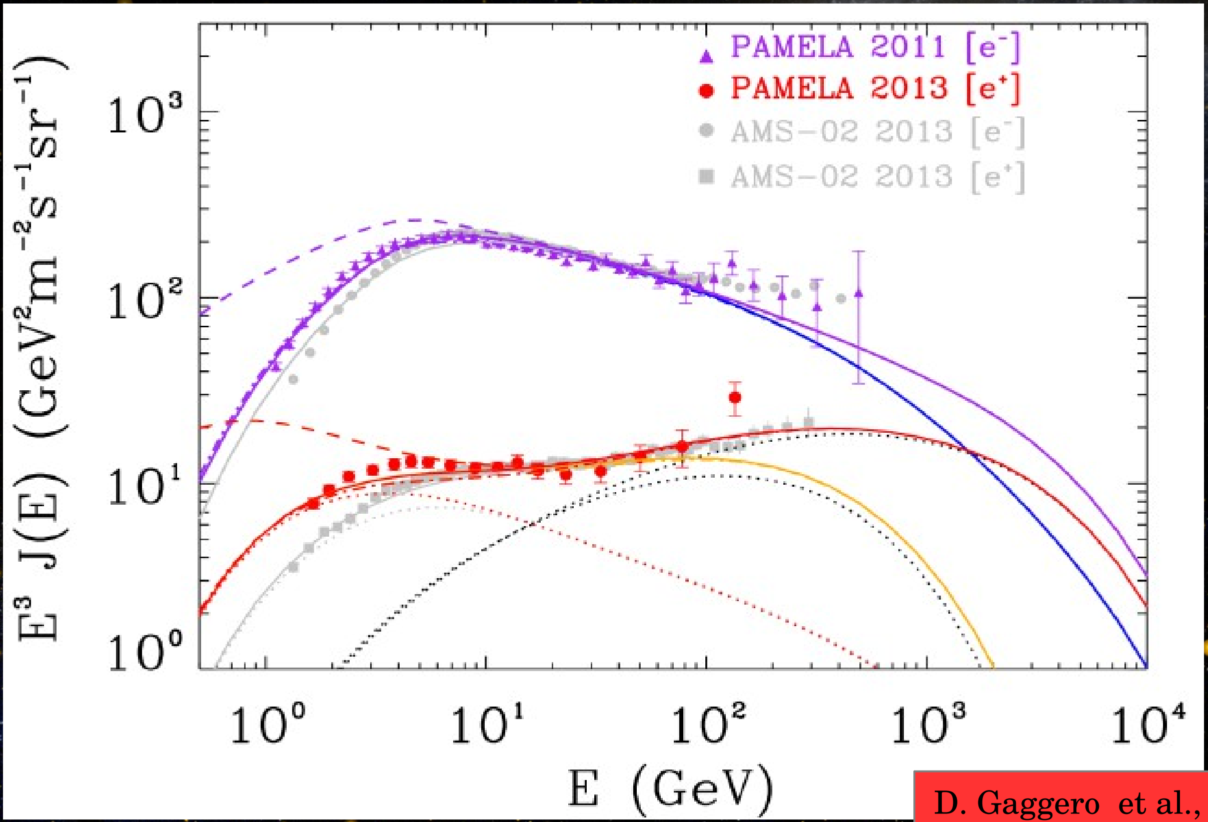
A 3D model of the Galaxy

A few words on the extra component.

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

Red line → 10 TeV

Yellow line → 1 TeV



D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

A 3D model of the Galaxy

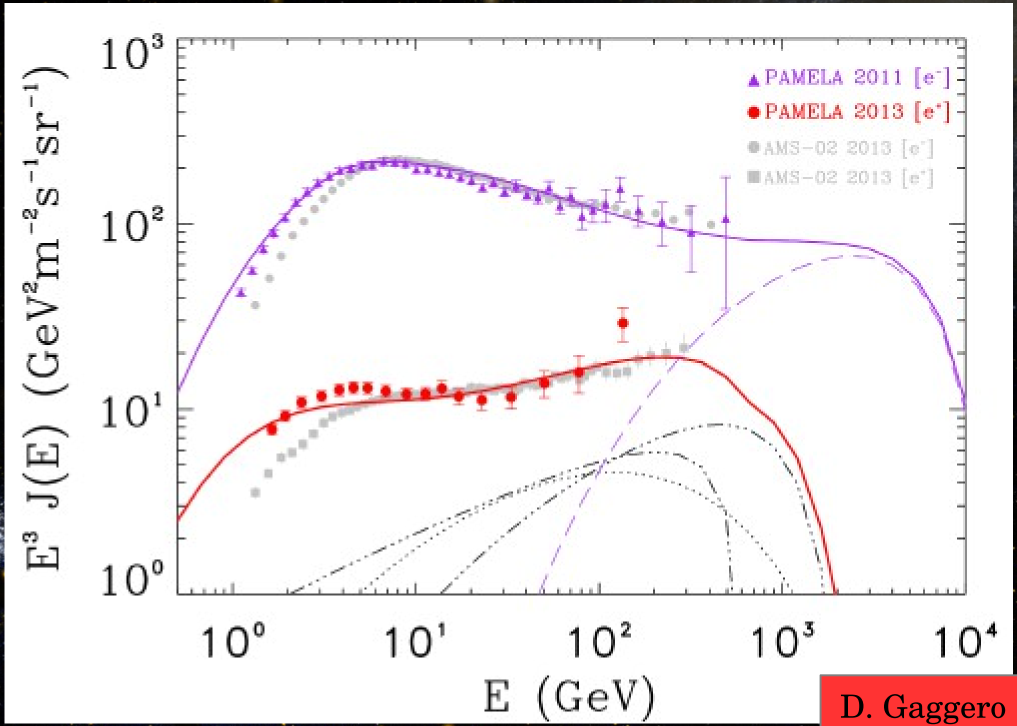
<u>A few words on the extra component.</u>

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

Red line → 10 TeV

Yellow line → 1 TeV

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

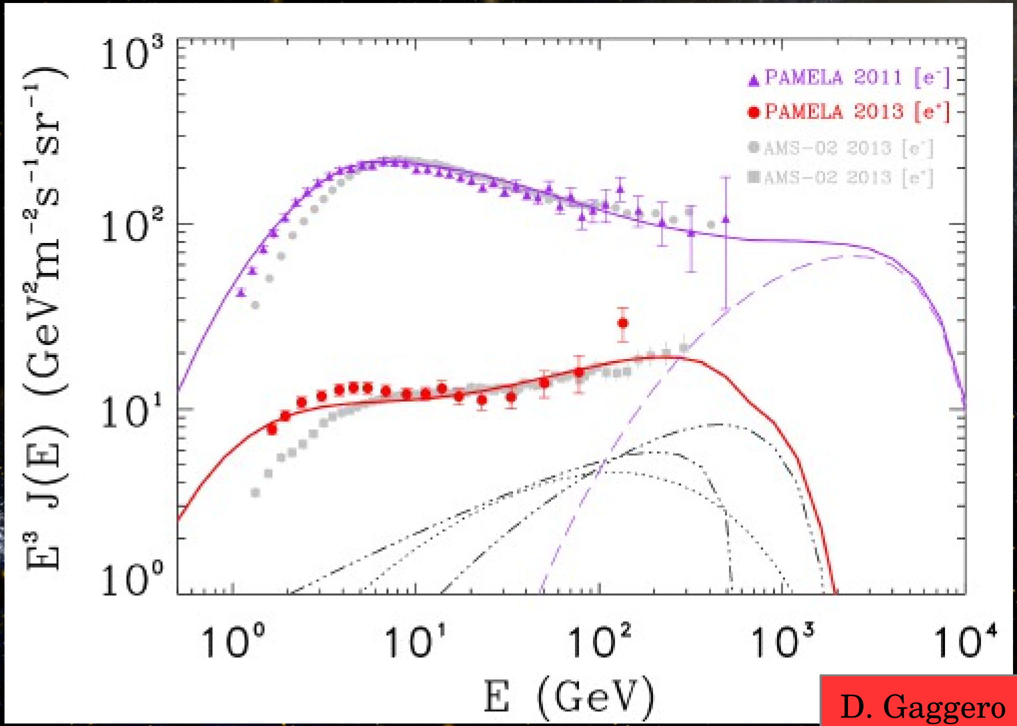


D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

A 3D model of the Galaxy

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



D. Gaggero et al., PRD **89** (2014)

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!

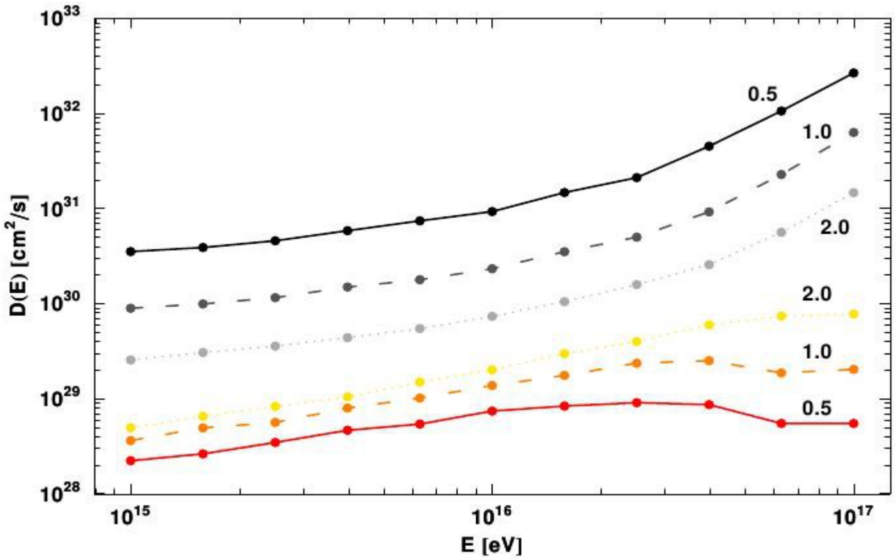


Figure 3. Parallel and perpendicular diffusion coefficients as a function of energy for three levels of turbulence. The upper three lines are the parallel diffusion coefficients, while the bottom three represent the perpendicular one. The level of turbulence, $\delta B/B_0$ is given by the numbers attached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