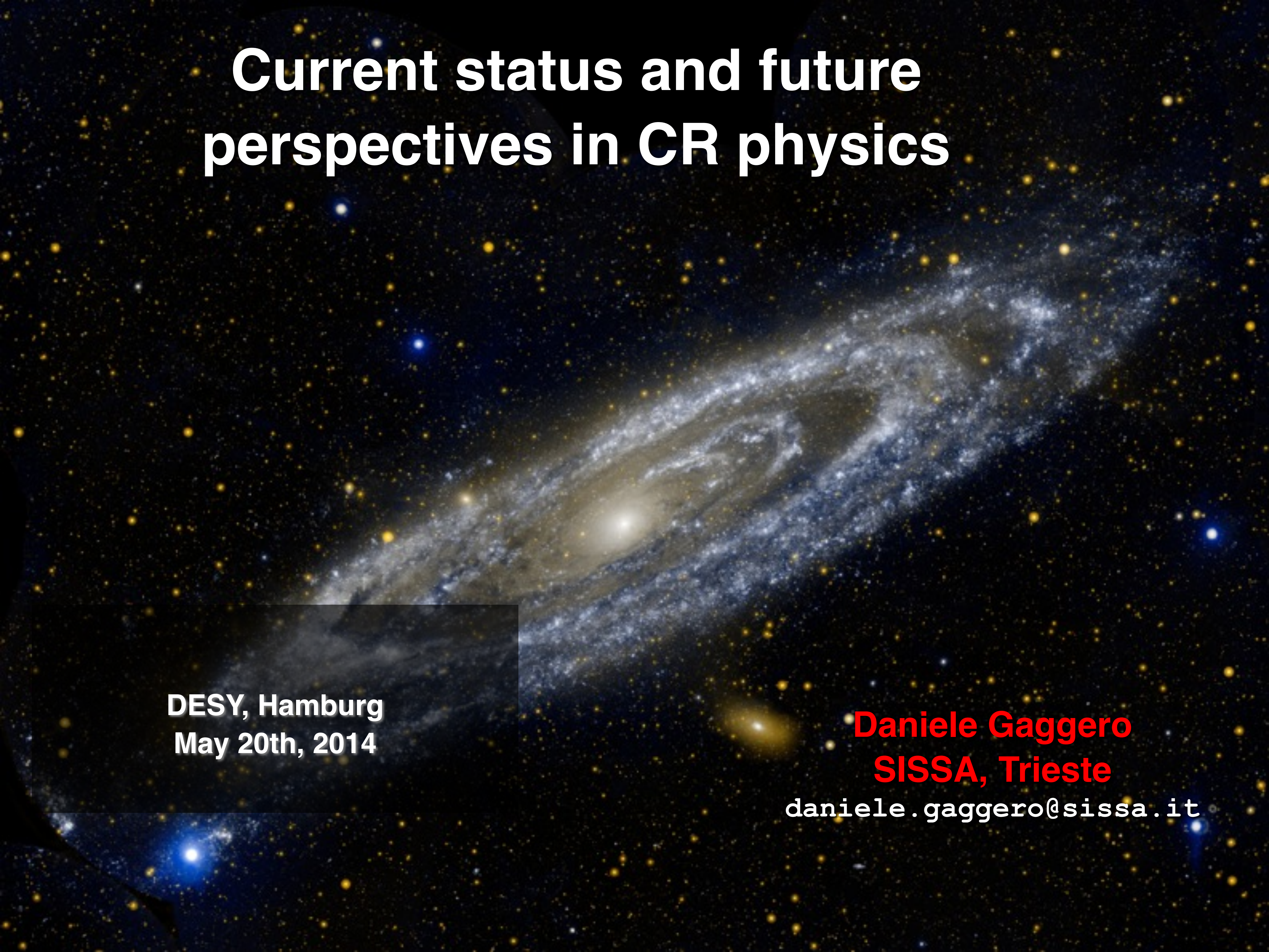
Current status and future perspectives in CR physics



DESY, Hamburg
May 20th, 2014

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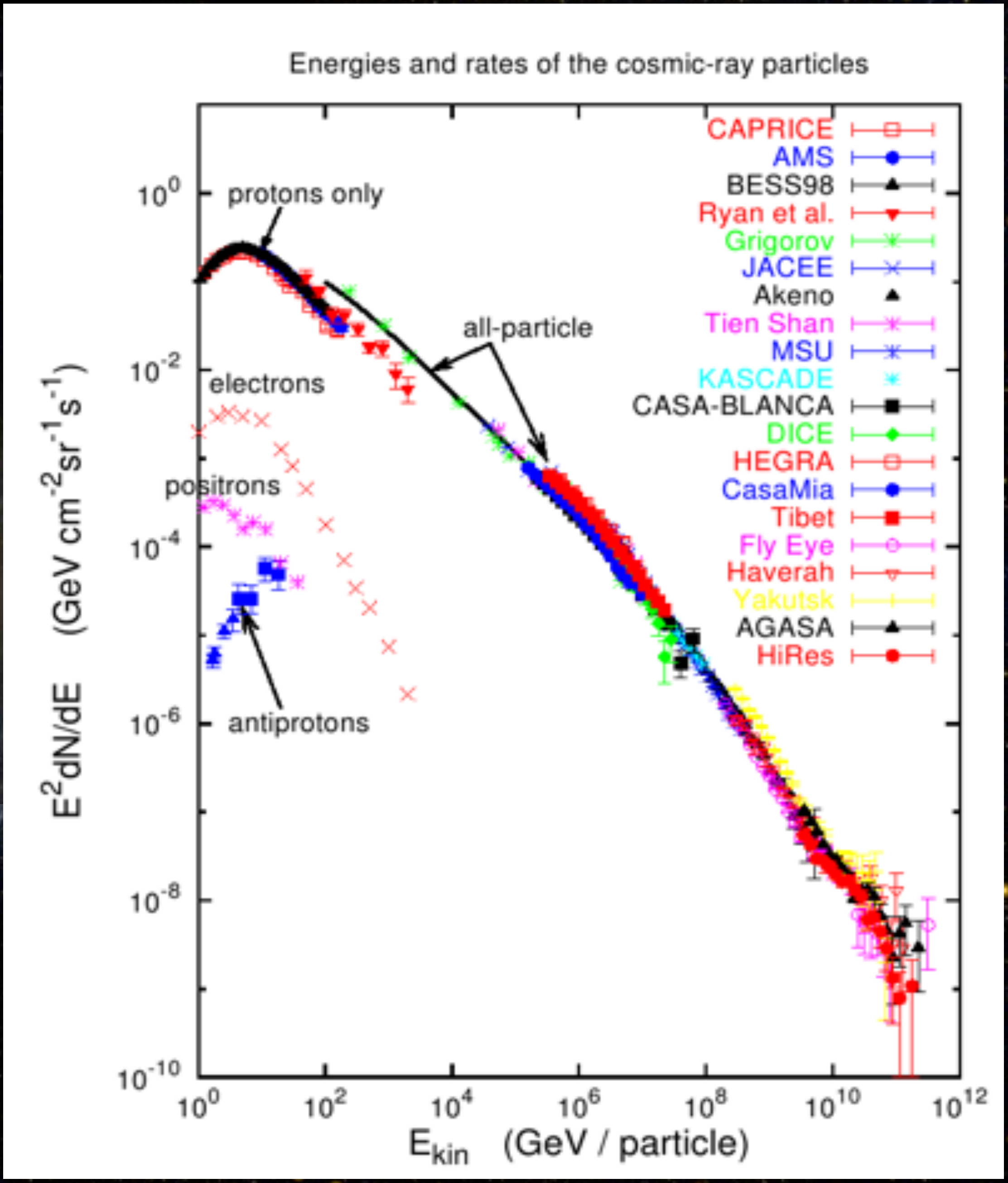
Introduction to CR physics

1) the all particle spectrum

2) evidence for CR confinement



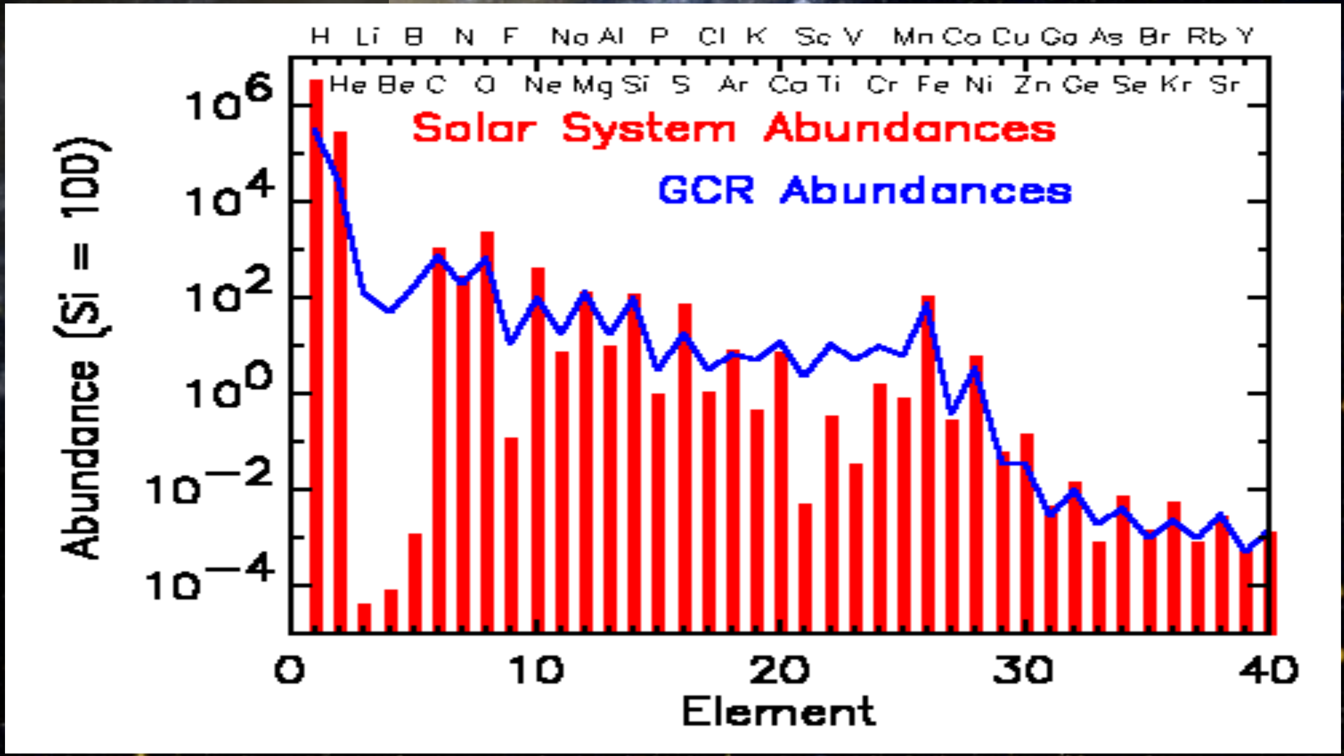
Introduction to CR physics

1) the all particle spectrum

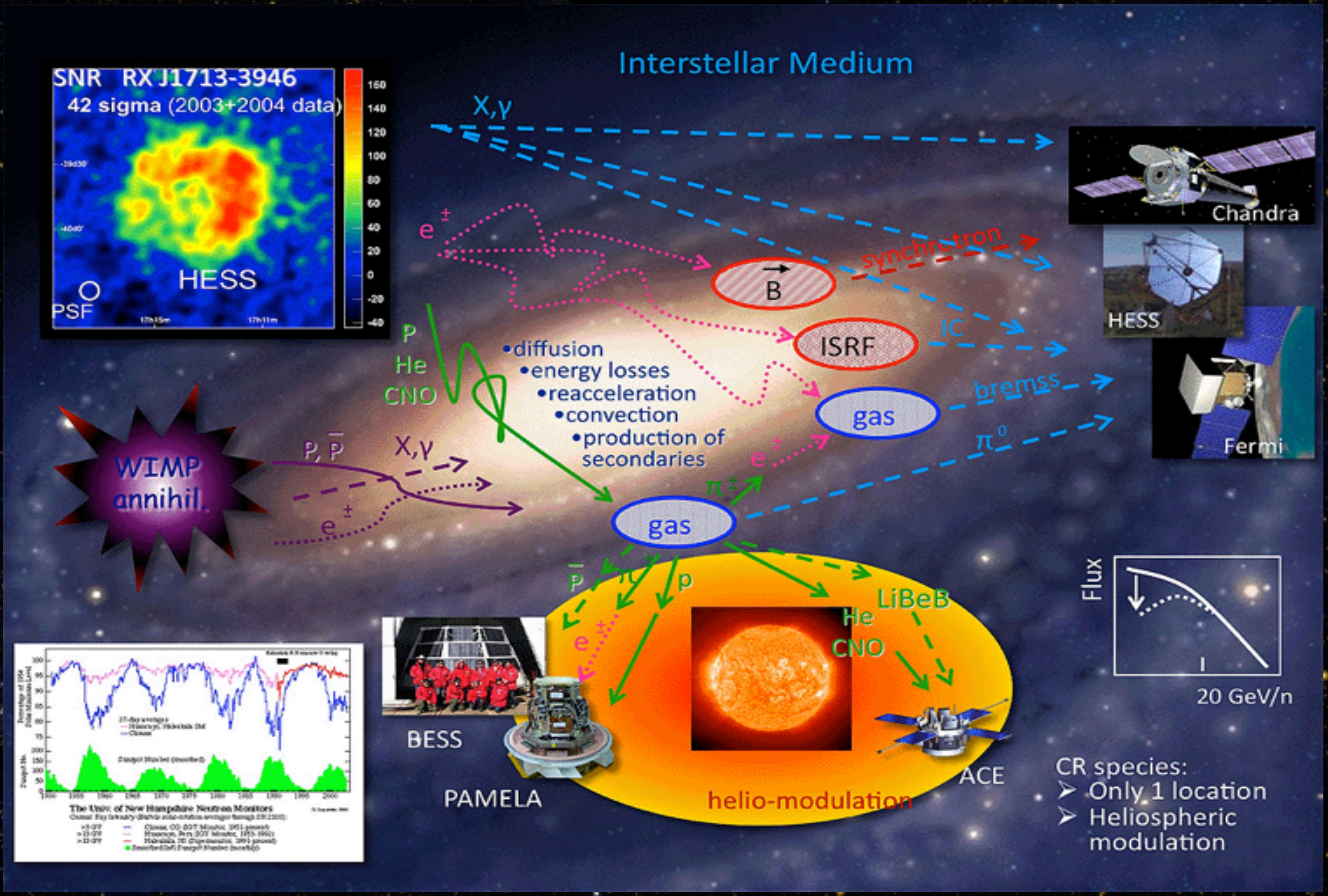
2) evidence for CR confinement

In order to reproduce
the measured abundance
of stable nuclei, CRs
should have traversed
~ 10 g/cm^2
of interstellar material

L = grammage / (n m_p)
~ 10^4 kpc
>> Galaxy size!!!



The basic picture



The basic picture

The equation describing CR propagation is the following:

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

Spatial diffusion term. In general D is a position-dependent tensor Dij

The basic picture

The equation describing CR propagation is the following:

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\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) - \\
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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)
\end{aligned}
$$

Energy losses

The basic picture

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\end{aligned}
$$

Reacceleration

The basic picture

The equation describing CR propagation is the following:

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\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} \\
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\end{aligned}
$$

Primary source term.
Protons, nuclei, electrons are directly accelerated in SNRs

The basic picture

The equation describing CR propagation is the following:

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\end{aligned}$$

Spallation source term from heavier nuclei.
For Li, Be, B and antiparticle (positrons, antiprotons) this is the dominant source term.

The basic picture

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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:

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

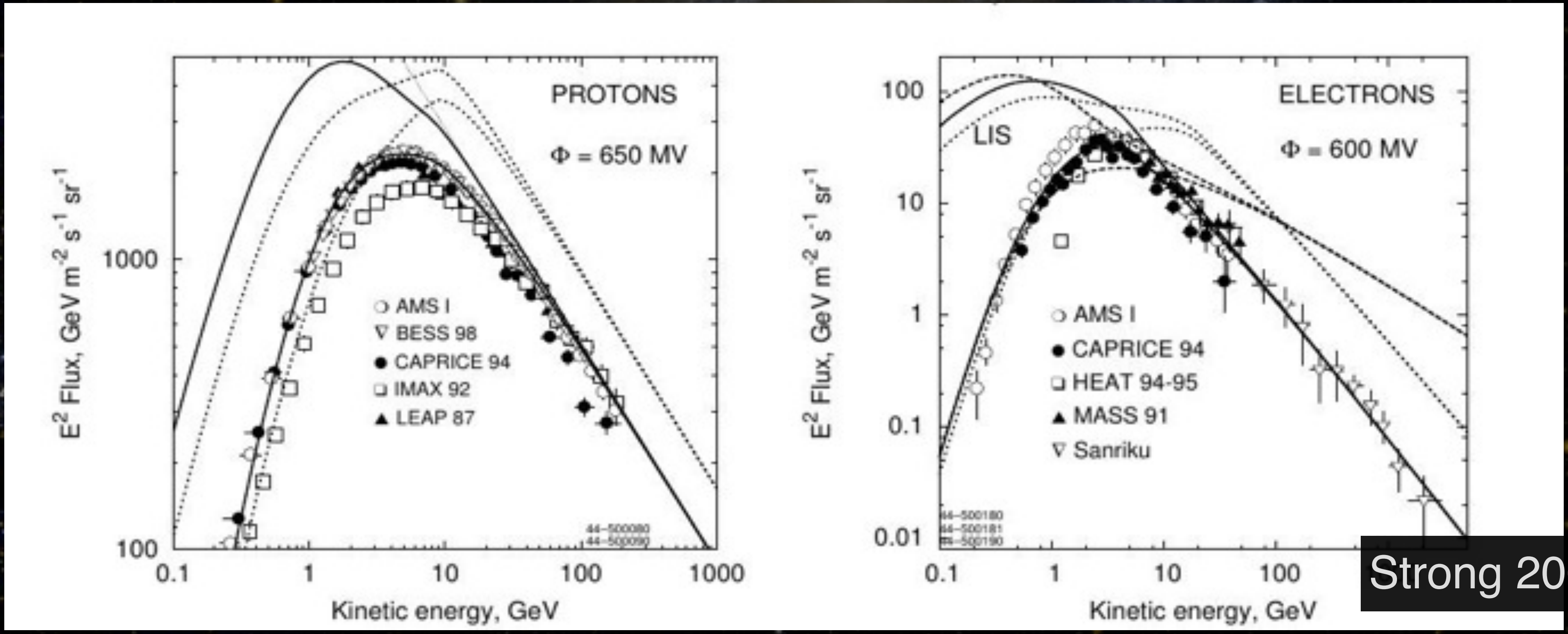
Cosmic ray physics is apparently easy...

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

In this framework, the propagated spectra of nuclei are easily computed solving the diffusion equation.

At high energy → Propagated slope = inj. Slope + δ

At low energy (< 10-20 GeV) → Other effects (reacceleration, convection, solar modulation...)



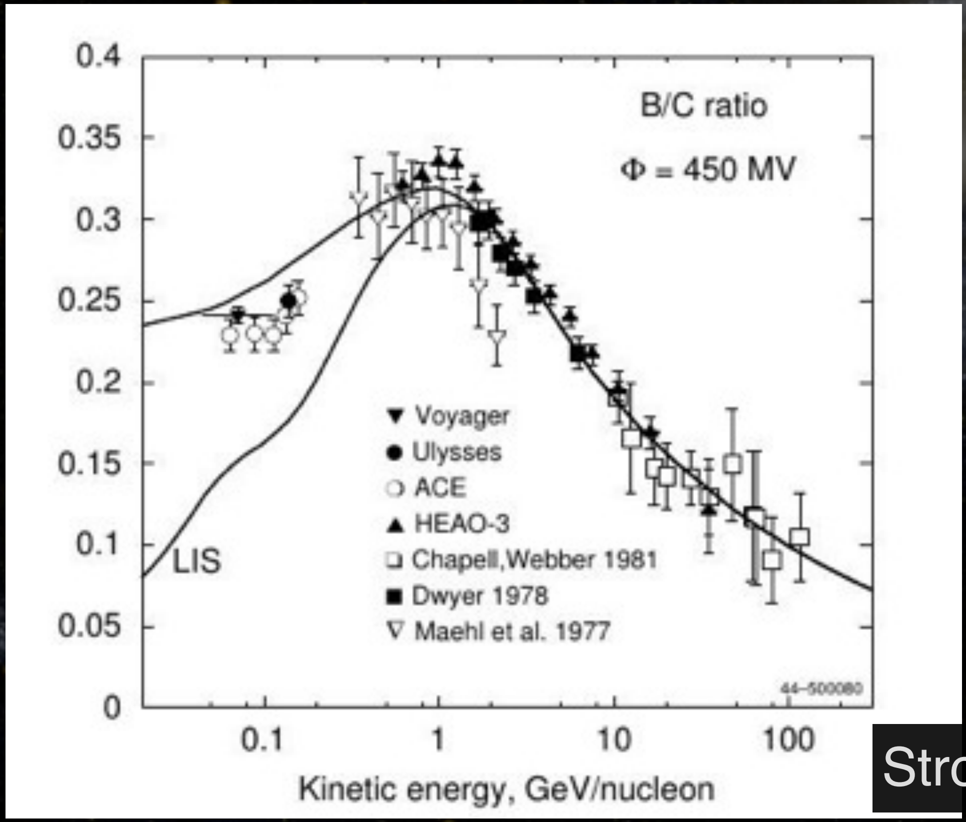
Strong 2004

Cosmic ray physics is apparently easy...

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

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

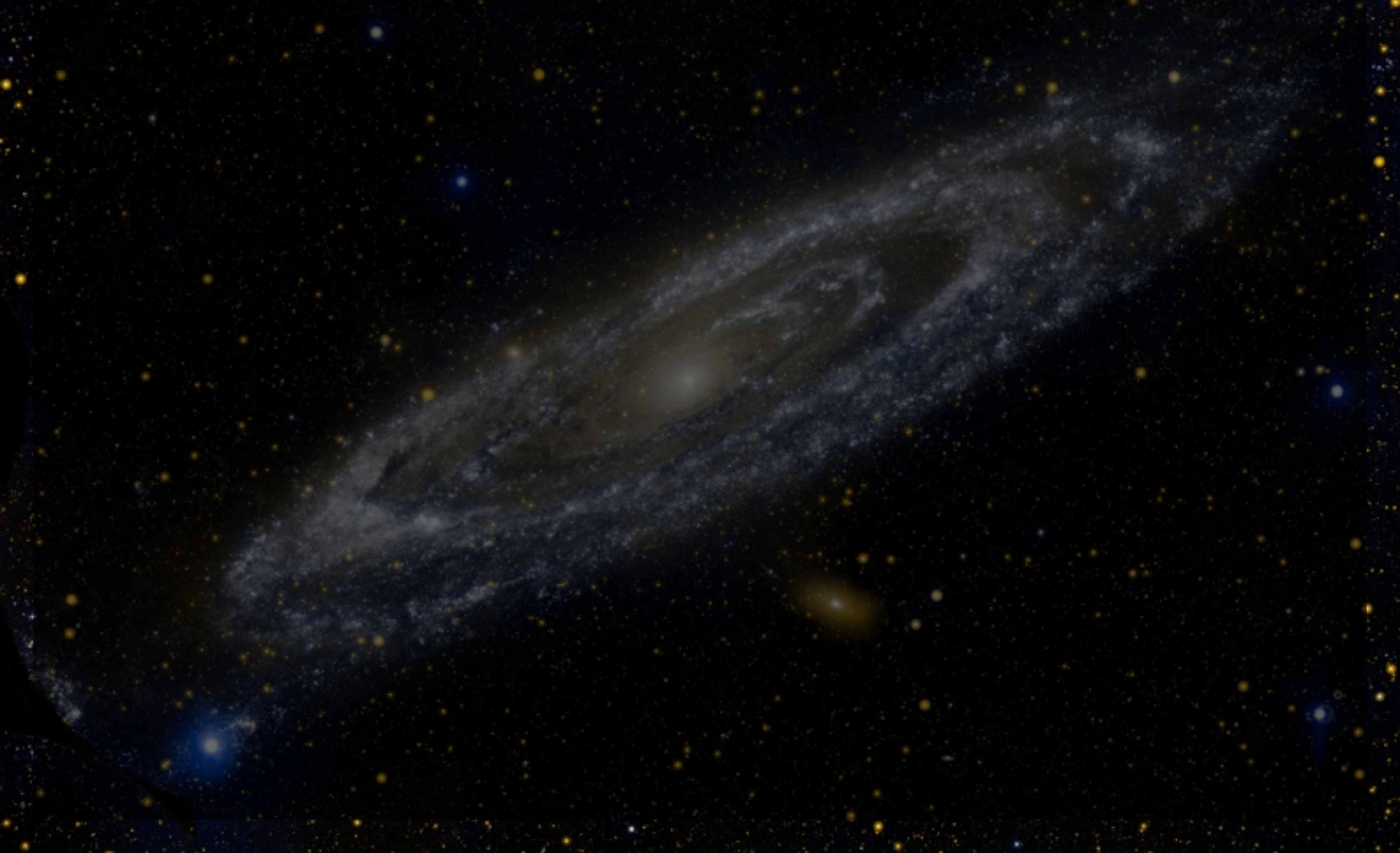
It is fixed by Secondary/Primary ratios → they do no depend on the inj. slope



Strong 2004

Current data

The latest years have been very exciting in Astroparticle physics and CR physics in particular: many new data were published by several imporant collaborations



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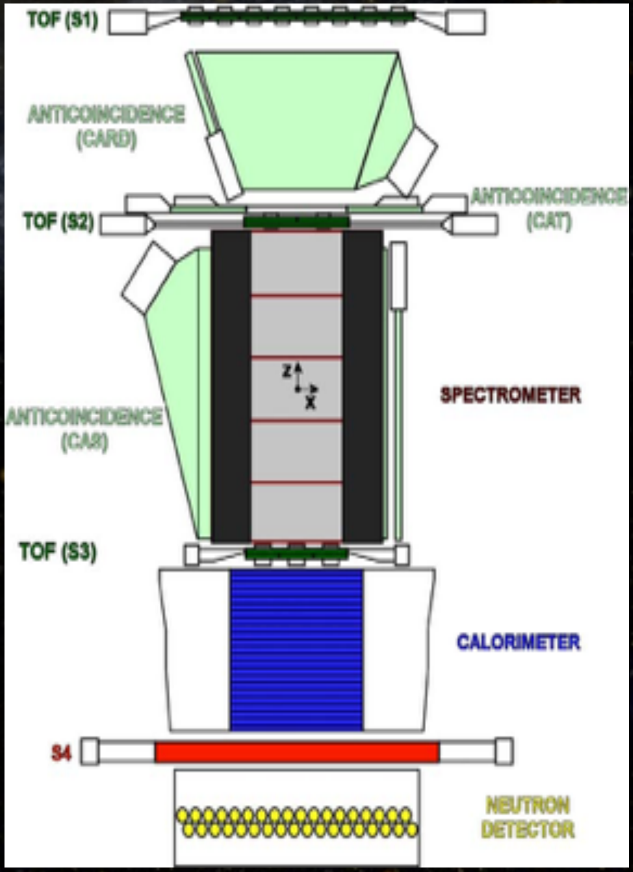
The latest years have been very exciting in Astroparticle physics and CR physics in particular: many new data were published by several imporant collaborations

PAMELA experiment – satellite designed to measure protons and antiprotons – helium (and antihelium??) – light nuclei (up to C) – electrons and positrons
Flying since 2006



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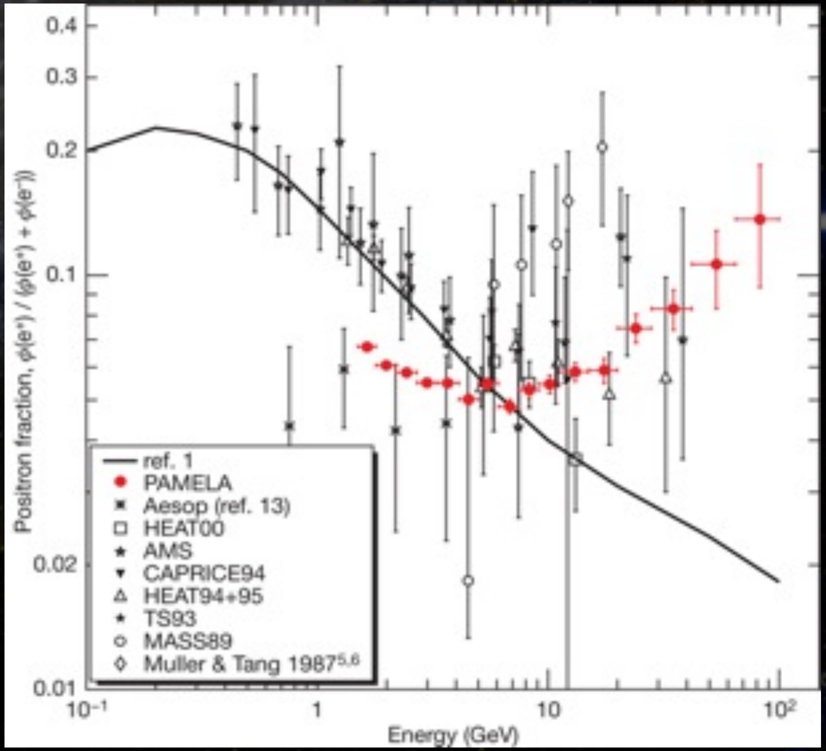
PAMELA experiment – discovered the *positron fraction anomaly*
(I'll talk more about this later)

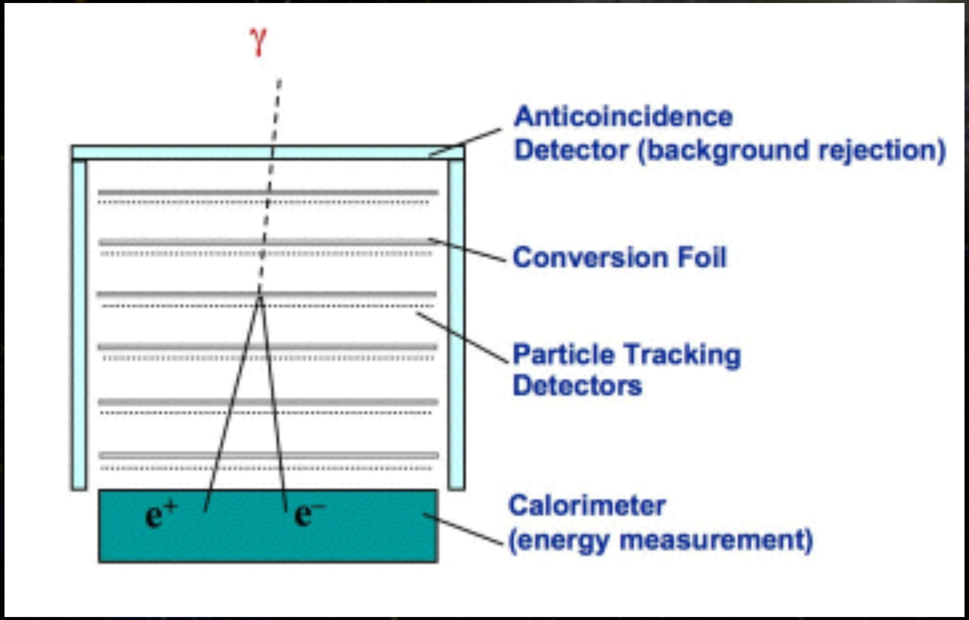


Current data

The latest years have been very exciting in Astroparticle physics and CR physics in particular: many new data were published by several imporant collaborations

Fermi-LAT – satellite mainly designed to produce very accurate maps of the Gamma-ray sky up to 300 GeV, is also able to measure the all-lepton spectrum with high statistic up to 1 TeV and the positron fraction (using the Earth magnetic field to distinguish electrons from positrons)

Flying since 2008



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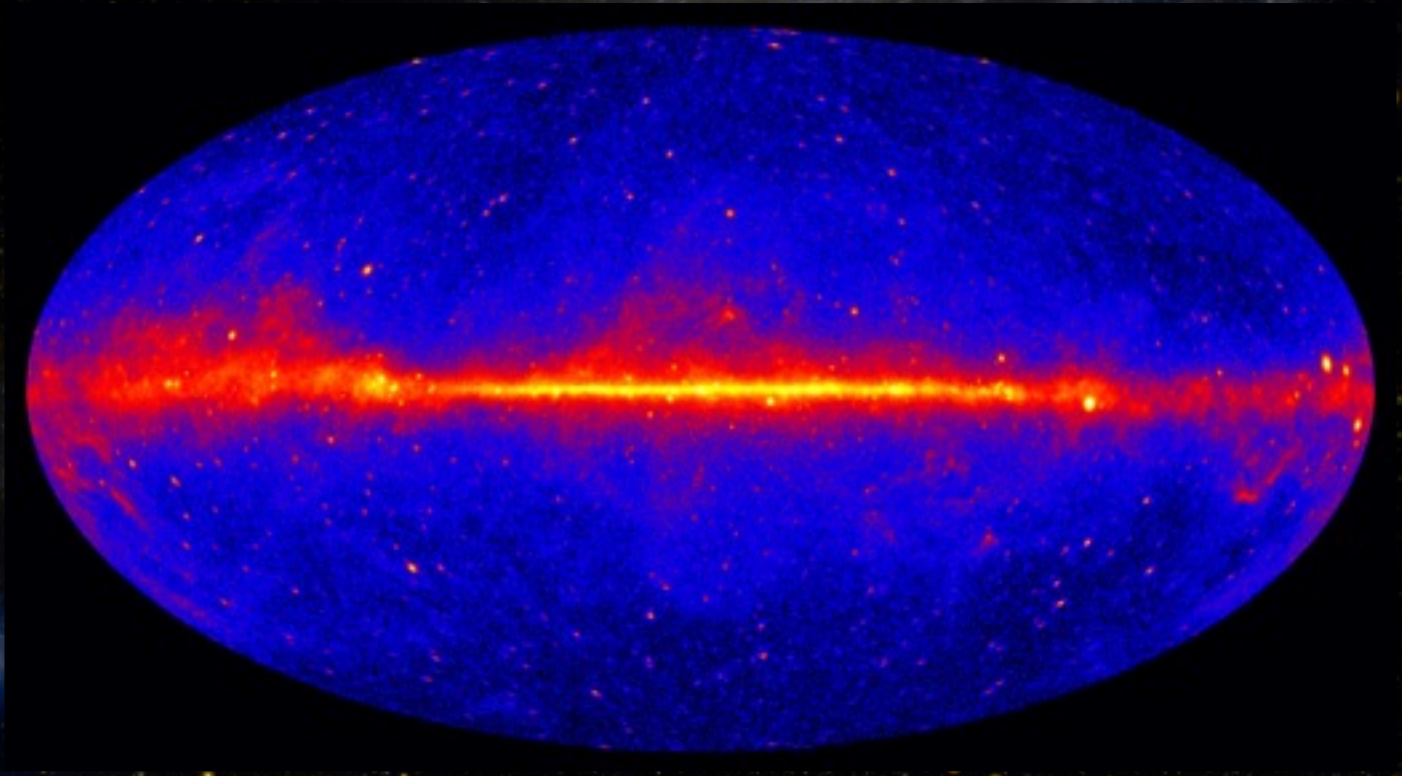

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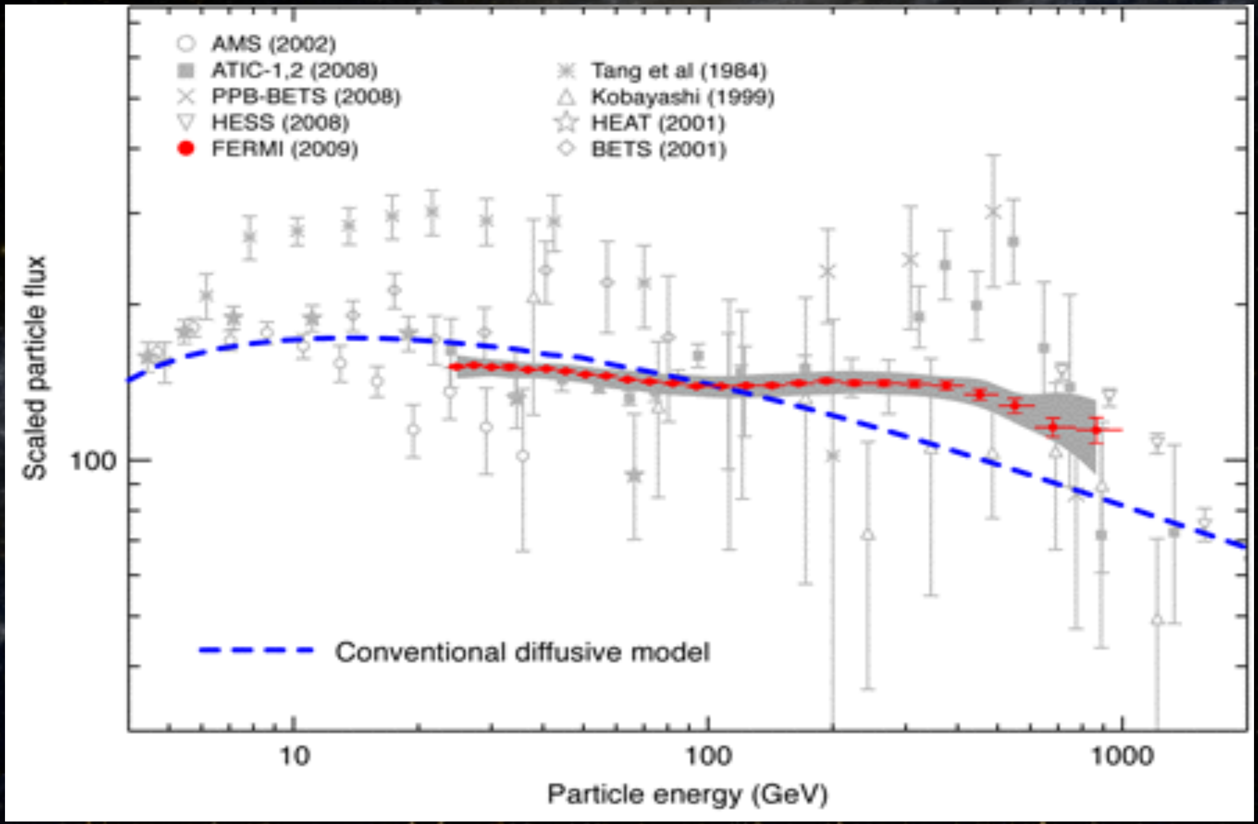

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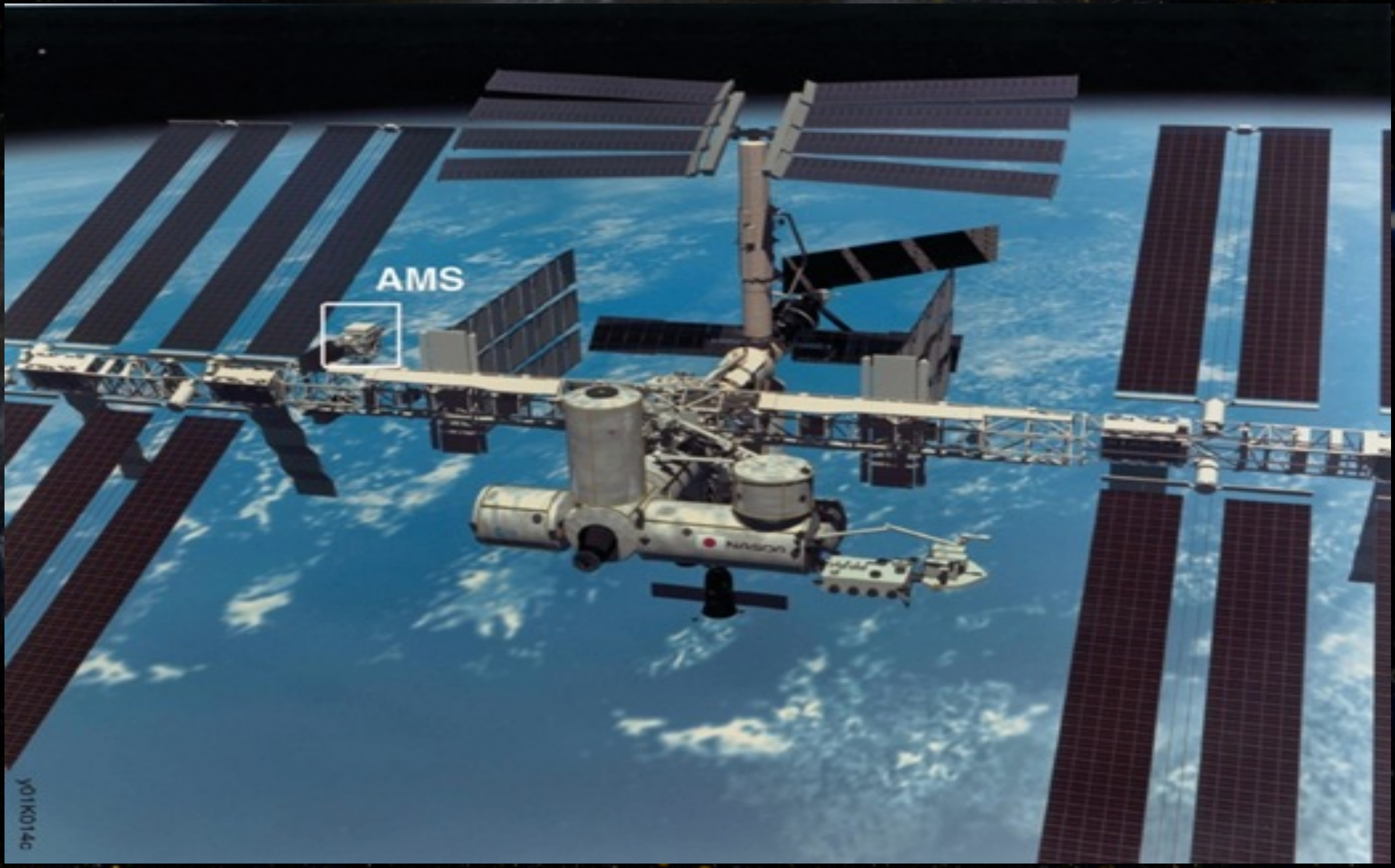
AMS experiment – satellite mounted on the ISS and designed to measure protons and antiprotons – helium (and antihelium??) – light nuclei (up to C) – electrons and positrons

Flying since 2011



Current data

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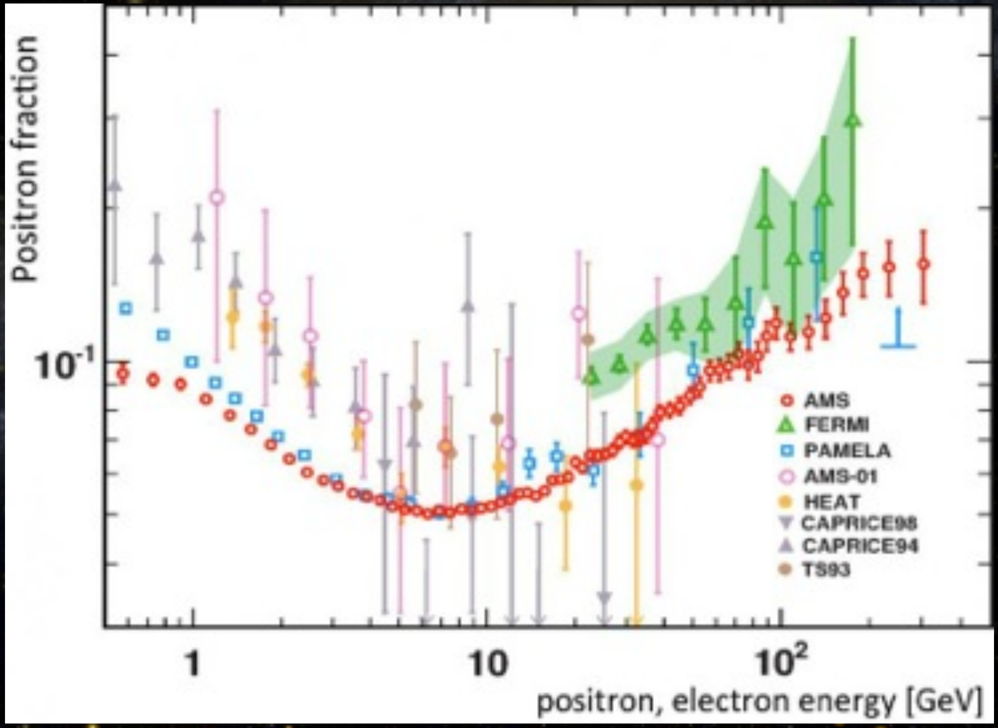
[AMS experiment]() – satellite mounted on the ISS and designed to measure protons and antiprotons – helium (and antihelium??) – light nuclei (up to C) – electrons and positrons

Flying since 2011

AMS is obtaining the most accurate data so far for both leptons and hadrons!



...more effort is needed to really understand what is going on!!

The new data are very accurate, and therefore a more detailed modeling is required.
Many things in the picture described at the beginning are not satisfactory!!

1) on one side, there are **too many free parameters**

→ we are basically free to put arbitrary injections indexes, arbitrary normalization and slopes in the diffusion coefficient, breaks in both the injection and diffusion energy dependence, solar modulation potential …

...more effort is needed to really understand what is going on!!

The new data are very accurate, and therefore a more detailed modeling is required. **Many things in the picture described at the beginning are not satisfactory!!**

2) on the other side, **<u>the description of the Galaxy is too simple</u>** and not realistic

→ the Galaxy is treated as a uniform box with constant diffusion; azimuthal simmetry is assumed, no large scale structure, nothing about the local environment, …

This is particulary unsatisfactory for high energy leptons!!

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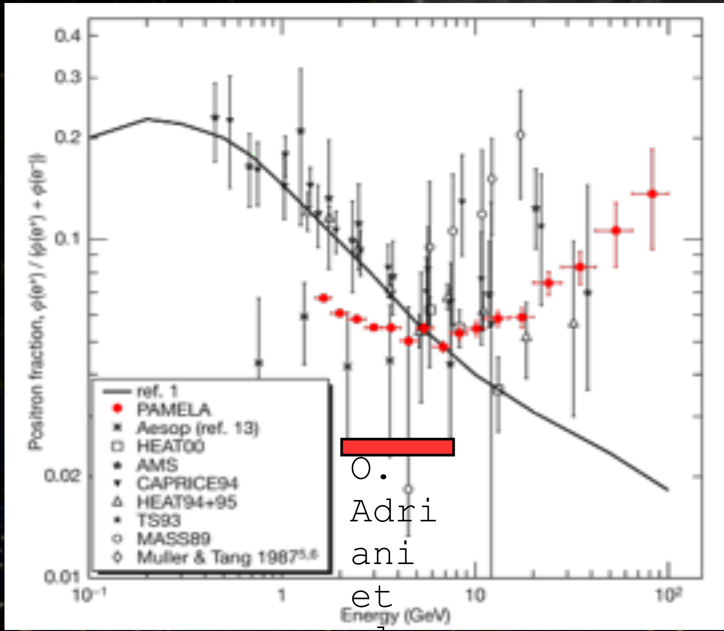
3) **<u>There are anomalies that cannot be explained</u>**
The most relevant one is the positron excess at high energy



This behaviour is surprising
If positrons are only secondary product of CR spallation, the ratio should decrease with energy:

$$\frac{e^+}{e^-} \propto \frac{E^{-\gamma_{protons}(propagated)} E^{-l}}{E^{-\gamma_e(injection)} E^{-l}}$$

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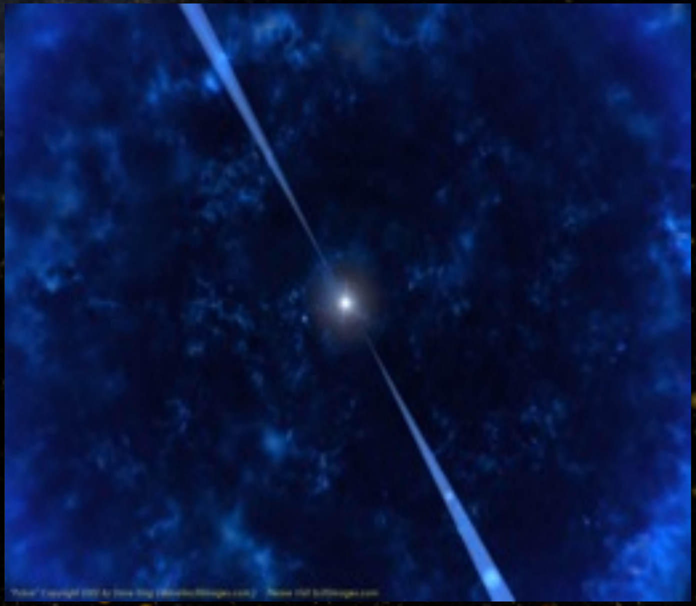
Possible explanations:

→ few nearby pulsars emit $e^- e^+$ pairs
well known mechanism
(of unknown efficiency),
provides a natural explanation



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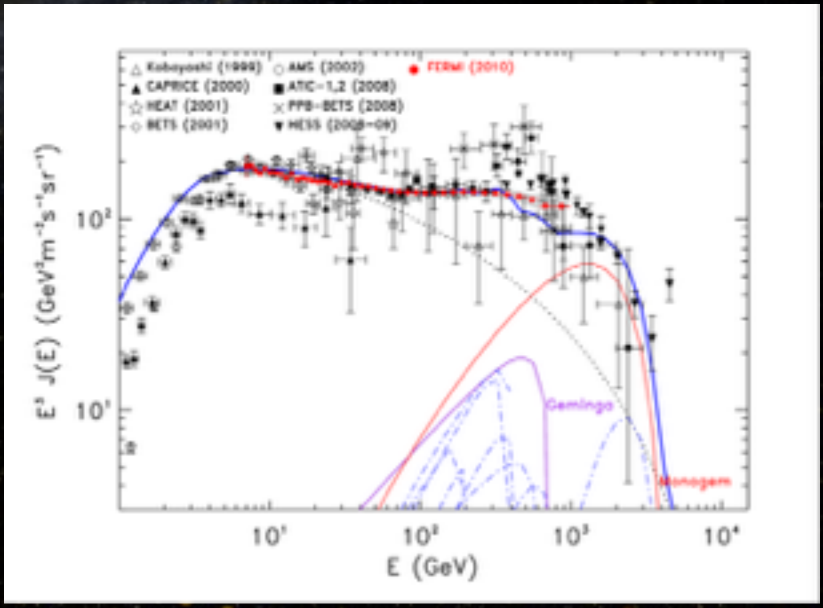

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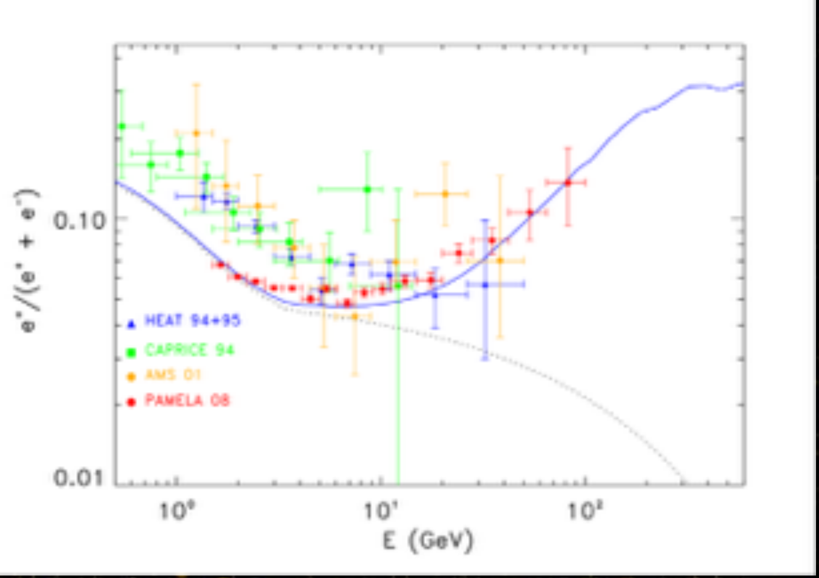

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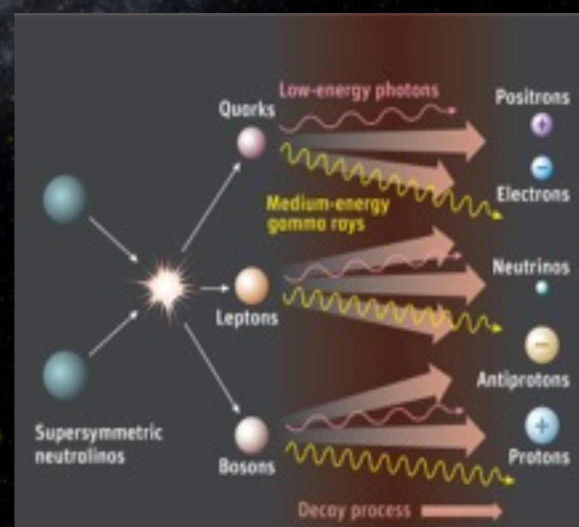
Possible explanations:

→ DM annihilation or decay



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3) **There are anomalies that cannot be explained**
The most relevant one is the positron excess at high energy

Possible explanations:

→ enhanced secondary production at the accelerator site
(see P.Blasi, astro-ph/0903.2794)

What do we need to do in order to improve the situation in this field?

→ we want a **<u>more realistic description of the Galaxy</u>** in which the 3D strucure of both the source term, the gas distribution, the magnetic field etc. is taken into account

→ we want a **<u>realistic treatment of the interaction with the heliosphere</u>**

→ we want to reduce the number of free parameters and the range in which the free ones are allowed to vary!!

e.g.

Injection of leptons and protons

Diffusion coefficient

Ongoing work using DRAGON

Three dimensional simulations of CR diffusion are now possible.

DRAGON is able to solve a very general diffusion-loss equation in which 3D anisotropic diffusion is taken into account.

A realistic 3D source term, magnetic field model, gas model can be implemented

In this framework we are able to compute the propagated spectra of all CR species all through the Galaxy and to simulate the gamma-ray and synchrotron emission

Ongoing work using DRAGON

Three dimensional simulations of CR diffusion are now possible.

DRAGON is able to solve a very general diffusion-loss equation in which 3D anisotropic diffusion is taken into account.

This is the most general equation that DRAGON can solve (spatial part)

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

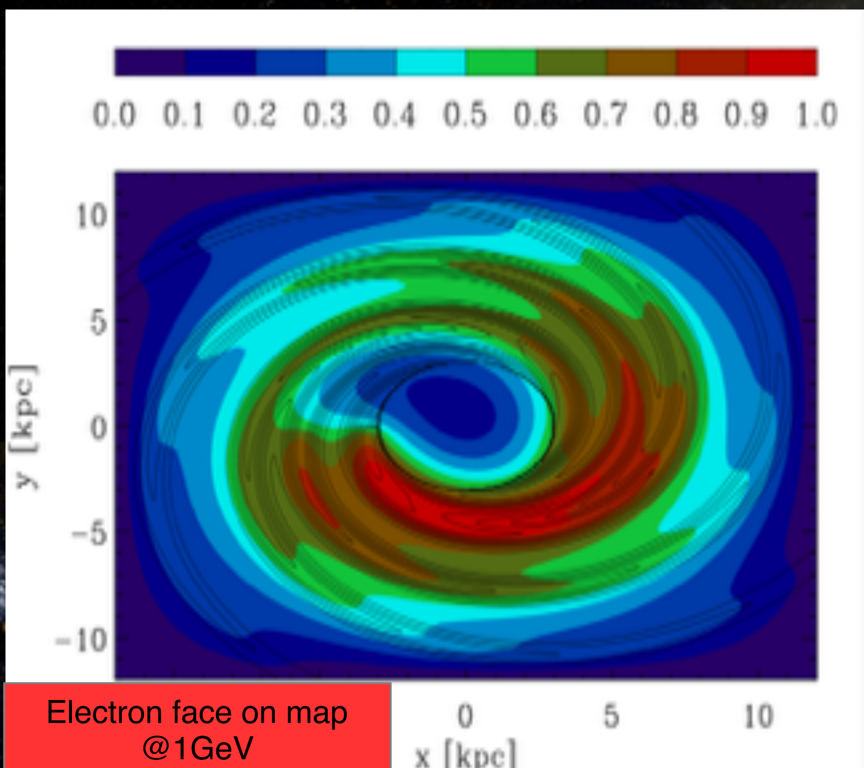
$$
\begin{aligned}
\alpha_{xx}(x,y,z) &= (D_{\parallel} - D_{\perp})b_x^2 + D_{\perp} \\
\alpha_{yy}(x,y,z) &= (D_{\parallel} - D_{\perp})b_y^2 + D_{\perp} \\
\alpha_{zz}(x,y,z) &= (D_{\parallel} - D_{\perp})b_z^2 + D_{\perp} \\
\delta_{xy}(x,y,z) &= (D_{\parallel} - D_{\perp})b_x b_y + D_{\perp} \\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

Ongoing work using DRAGON

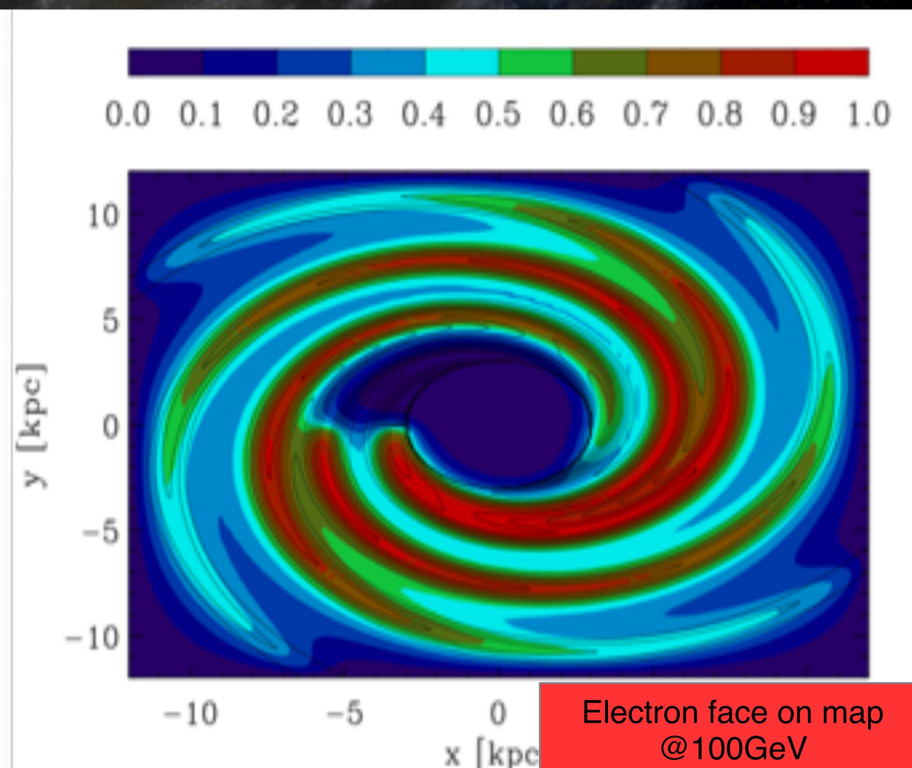
A 3D model of the Galaxy

We considered a spiral arm model from Blasi&Amato, arXiv:1105.4529

We used the 3D isotropic version of the code putting the sources within the spiral arms.



Electron face on map @1GeV

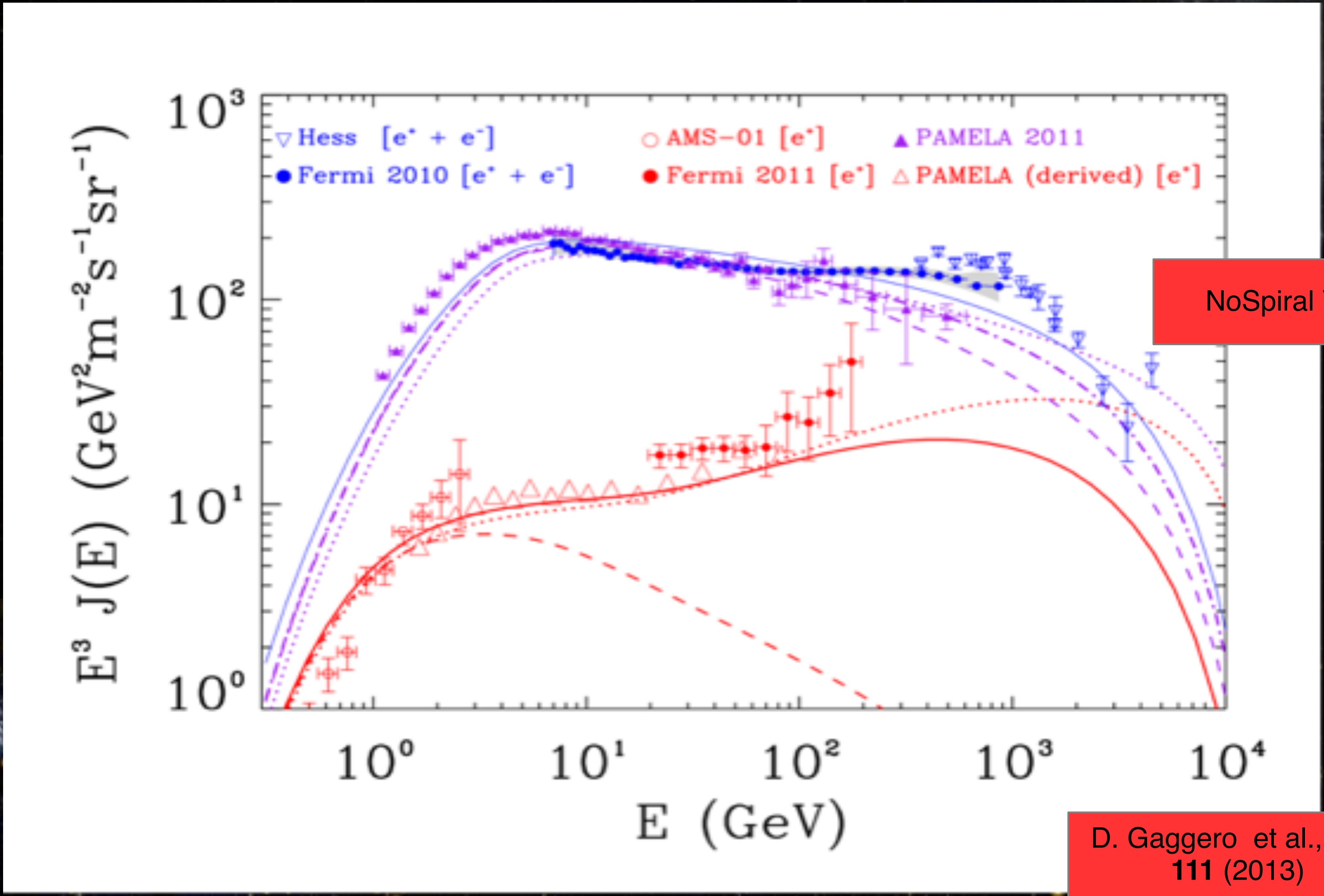


Electron face on map @100GeV

Ongoing work using DRAGON

A 3D model of the Galaxy

The impact of the 3D structure on the propagated leptonic spectra at high energy is very large!



NoSpiral VS Spiral

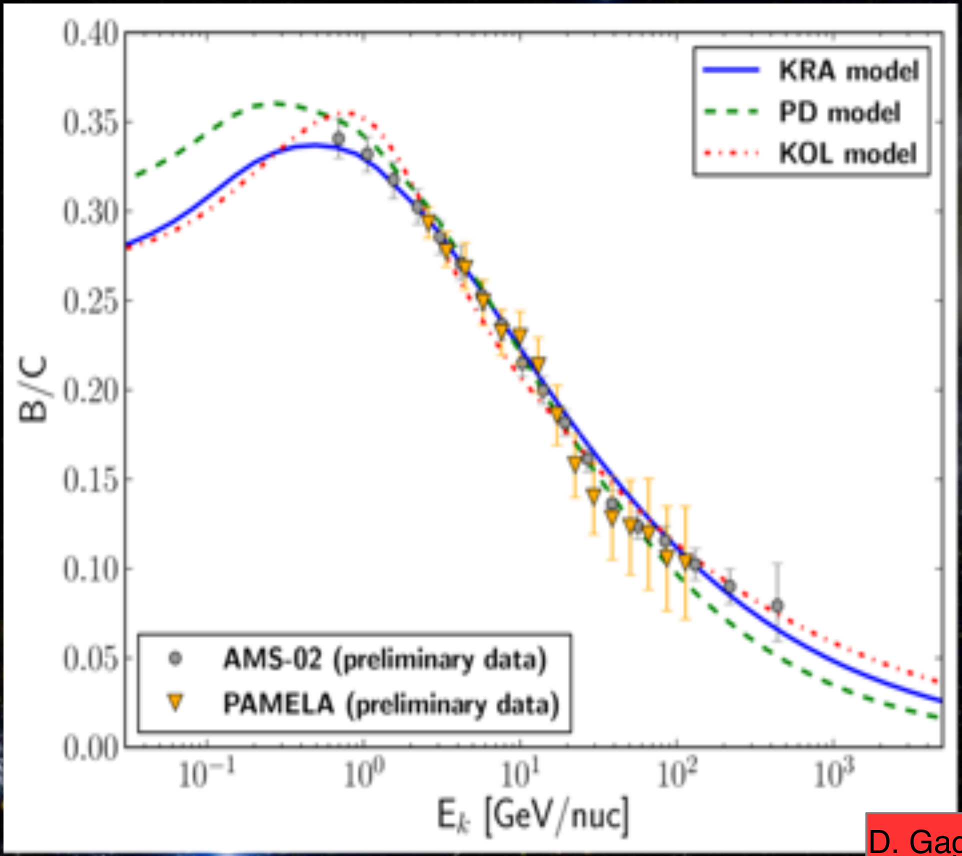
D. Gaggero et al., PRL **111** (2013)

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)

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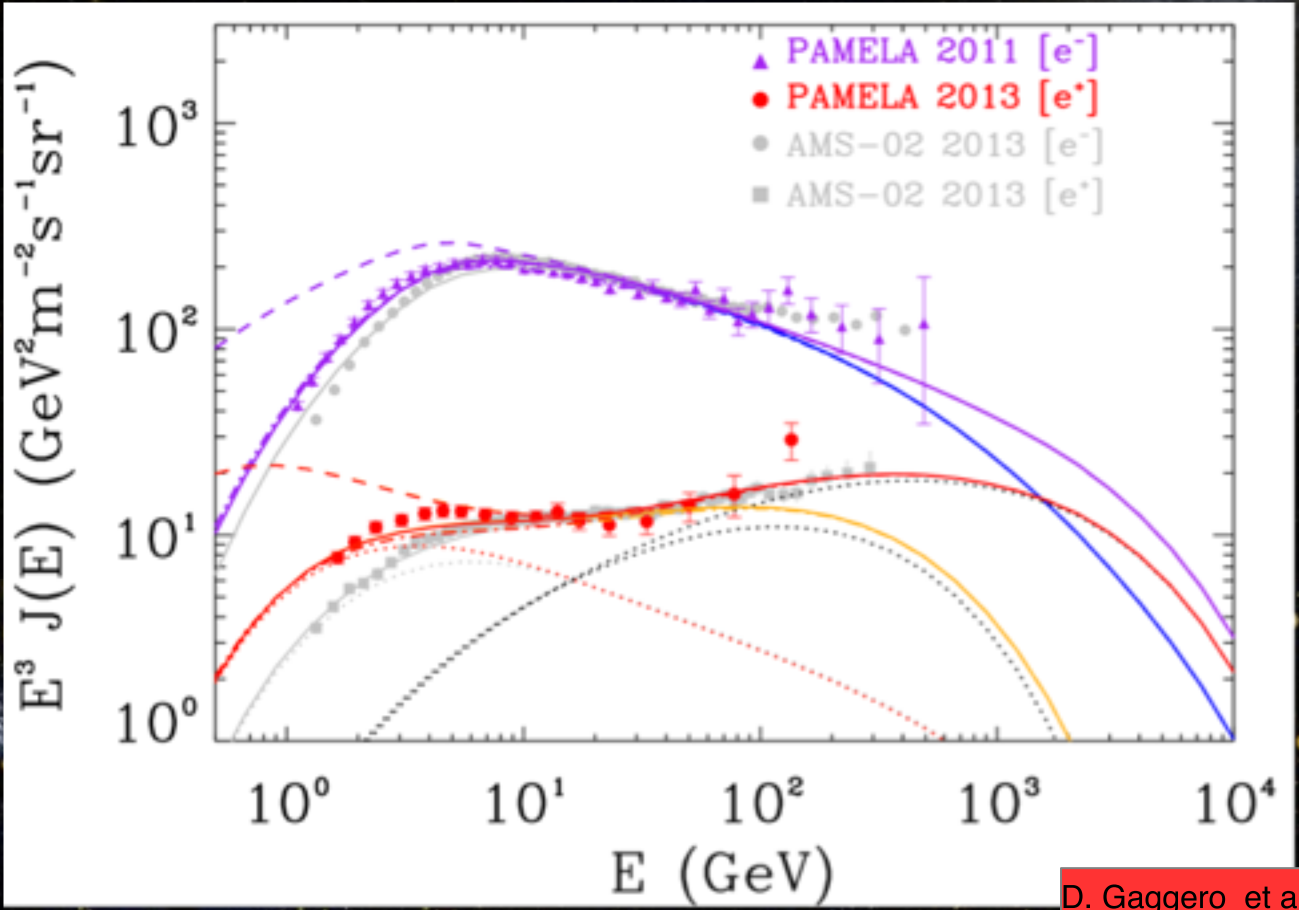


D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

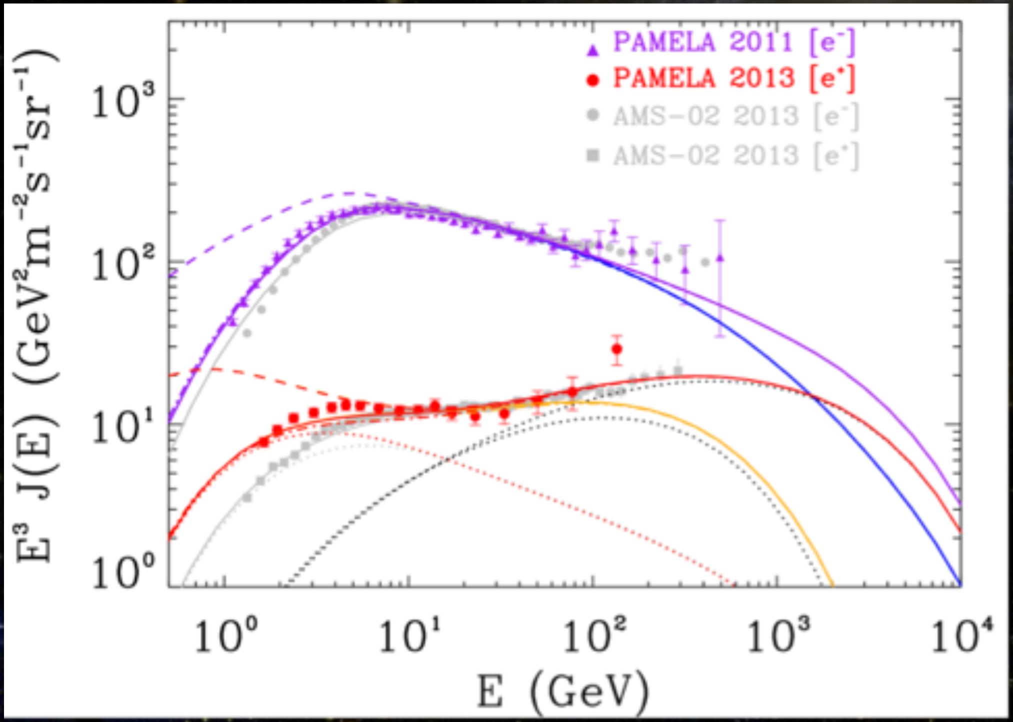
A 3D model of the Galaxy

Ingredients of our models:

1) <u>Primary electron component</u> 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.**

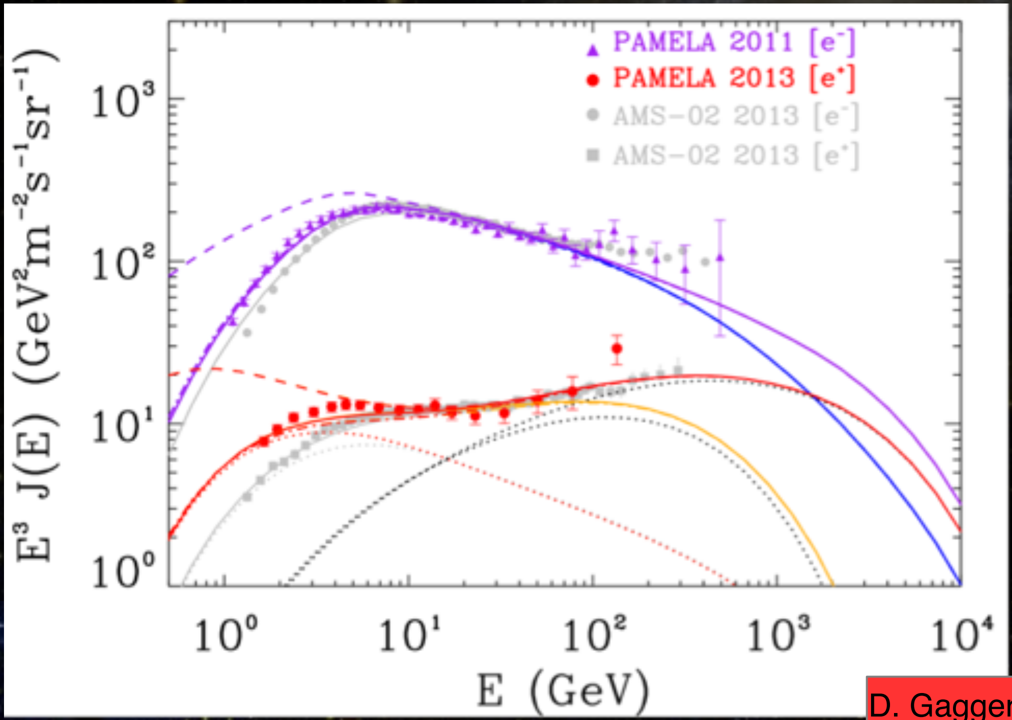
The residual discrepancy with the predicted value from the theory (-2 – -2.3) can be due to the details of the escape mechanism from the source



Ongoing work using DRAGON

A 3D model of the Galaxy

Ingredients of our models:
2) <u>Secondary electrons and positrons</u> 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)

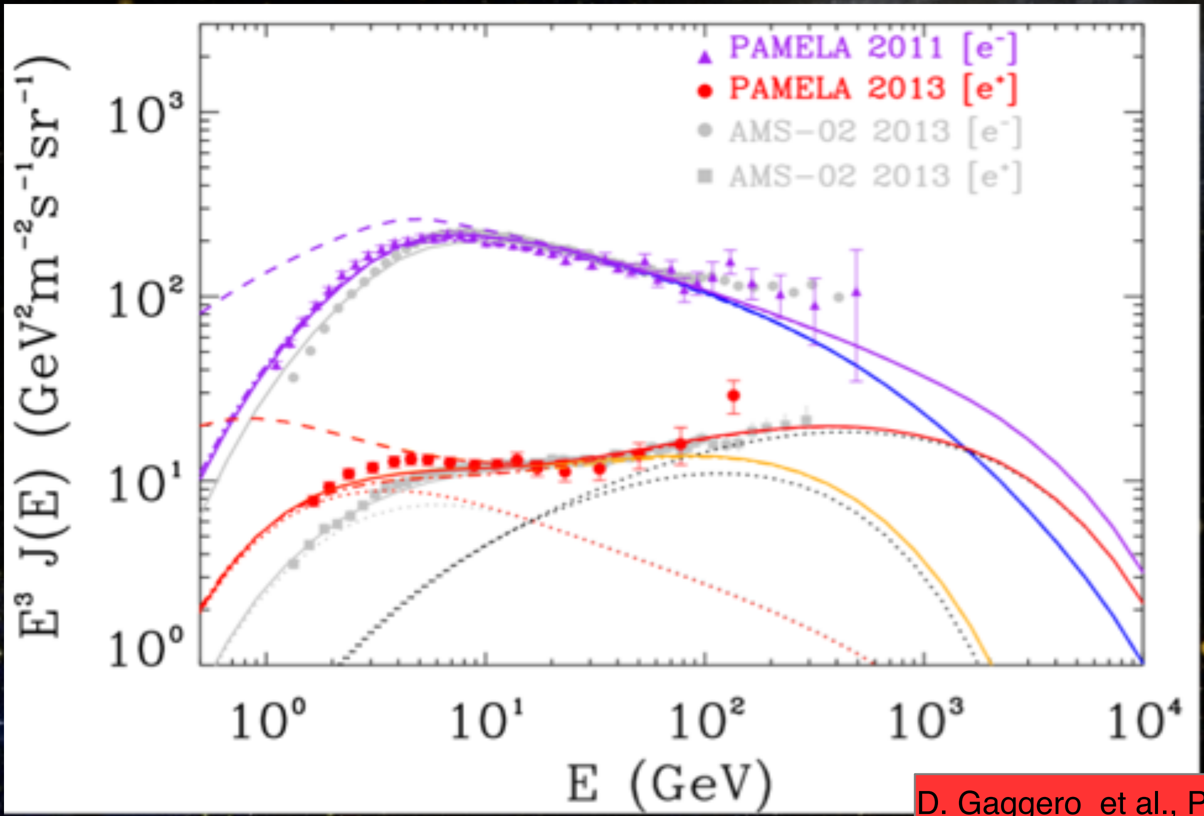
Ongoing work using DRAGON

A 3D model of the Galaxy

Ingredients of our models:

3) *<u>Primary "extra" component</u>* <u>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

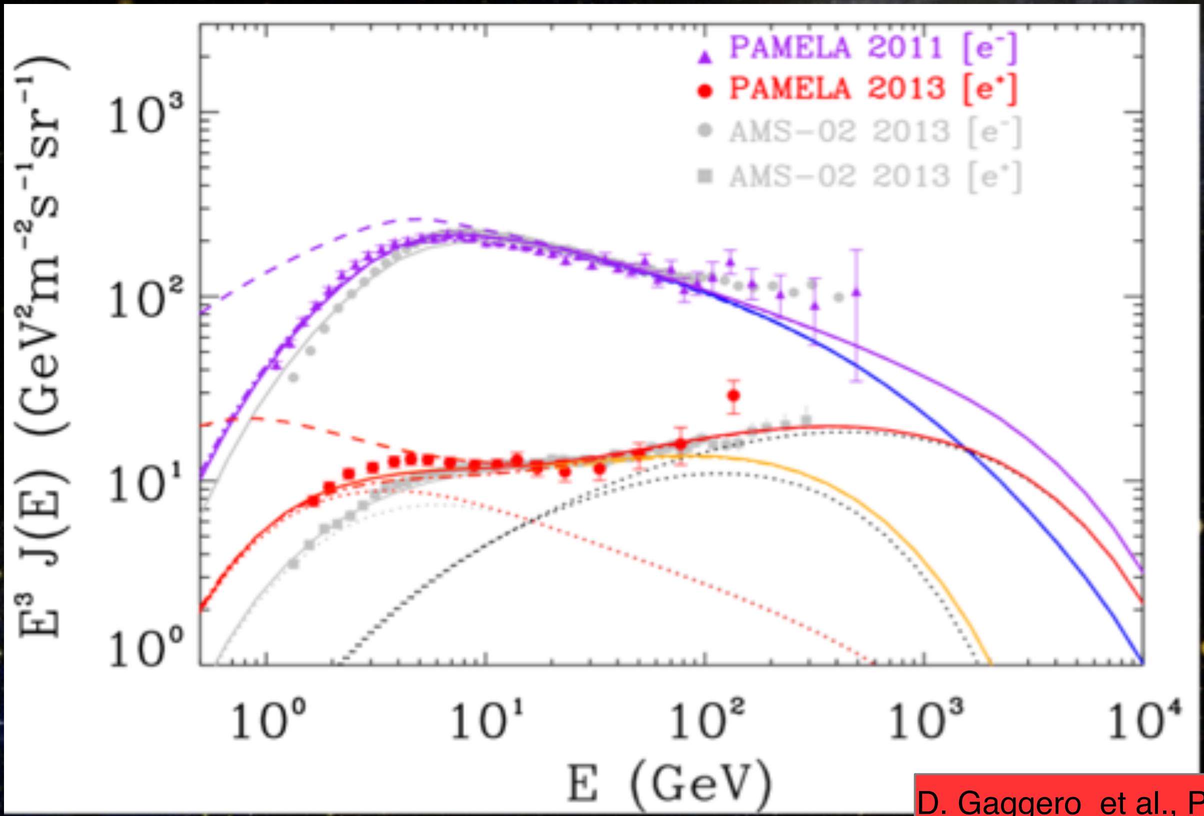
A 3D model of the Galaxy

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

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

Red line → 10 TeV

Yellow line → 1 TeV



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A 3D model of the Galaxy

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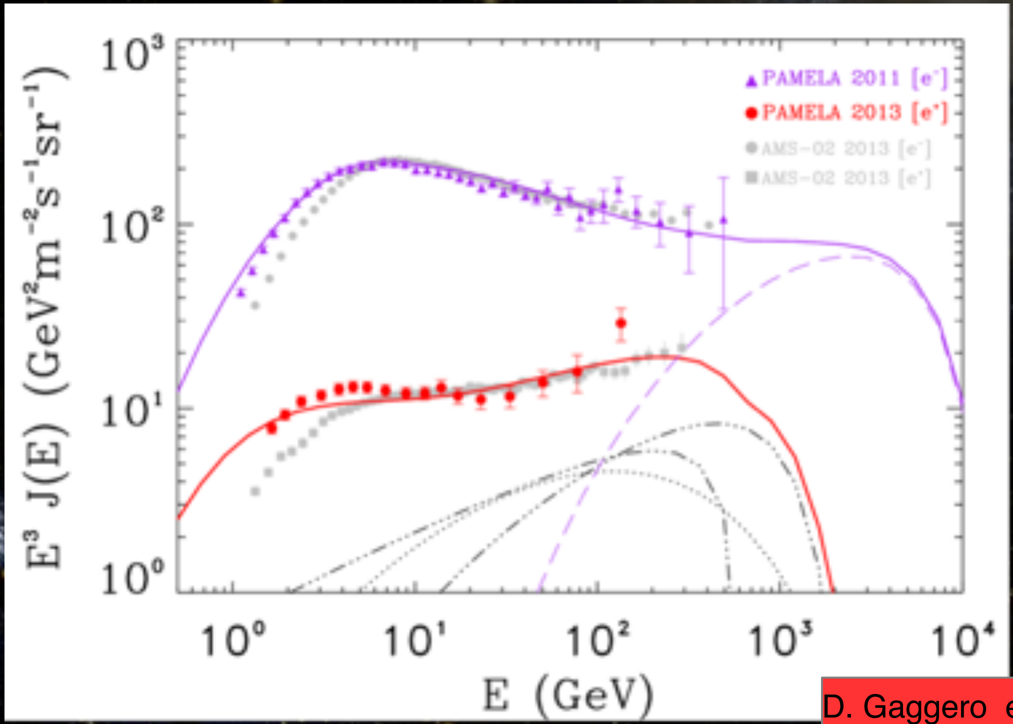
Red line → 10 TeV

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

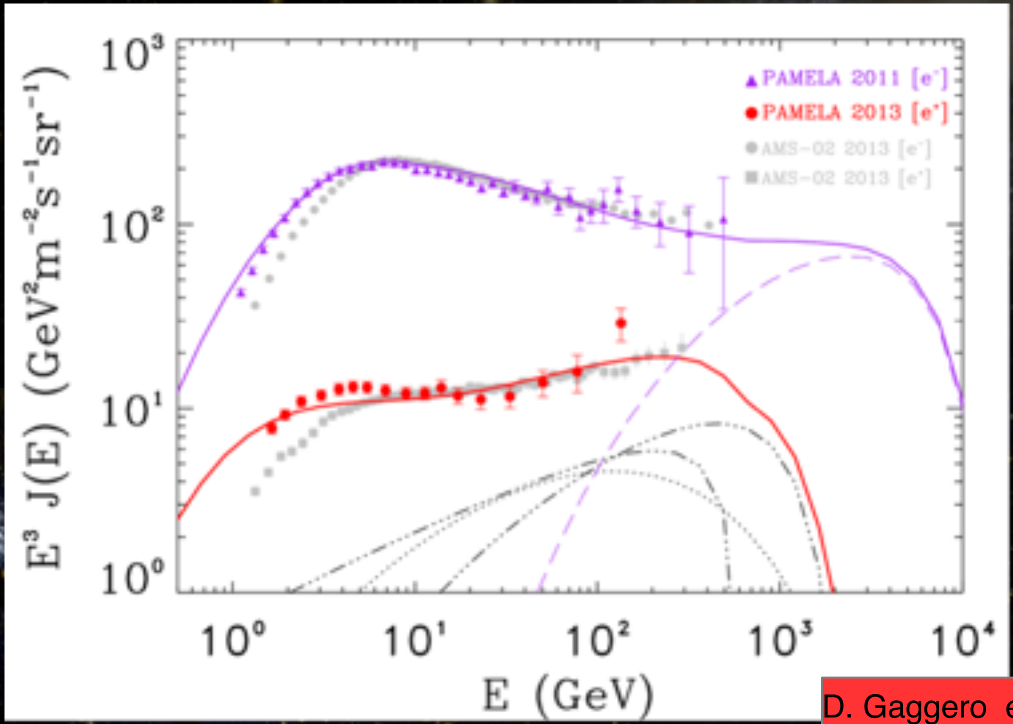


D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

A 3D model of the Galaxy

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

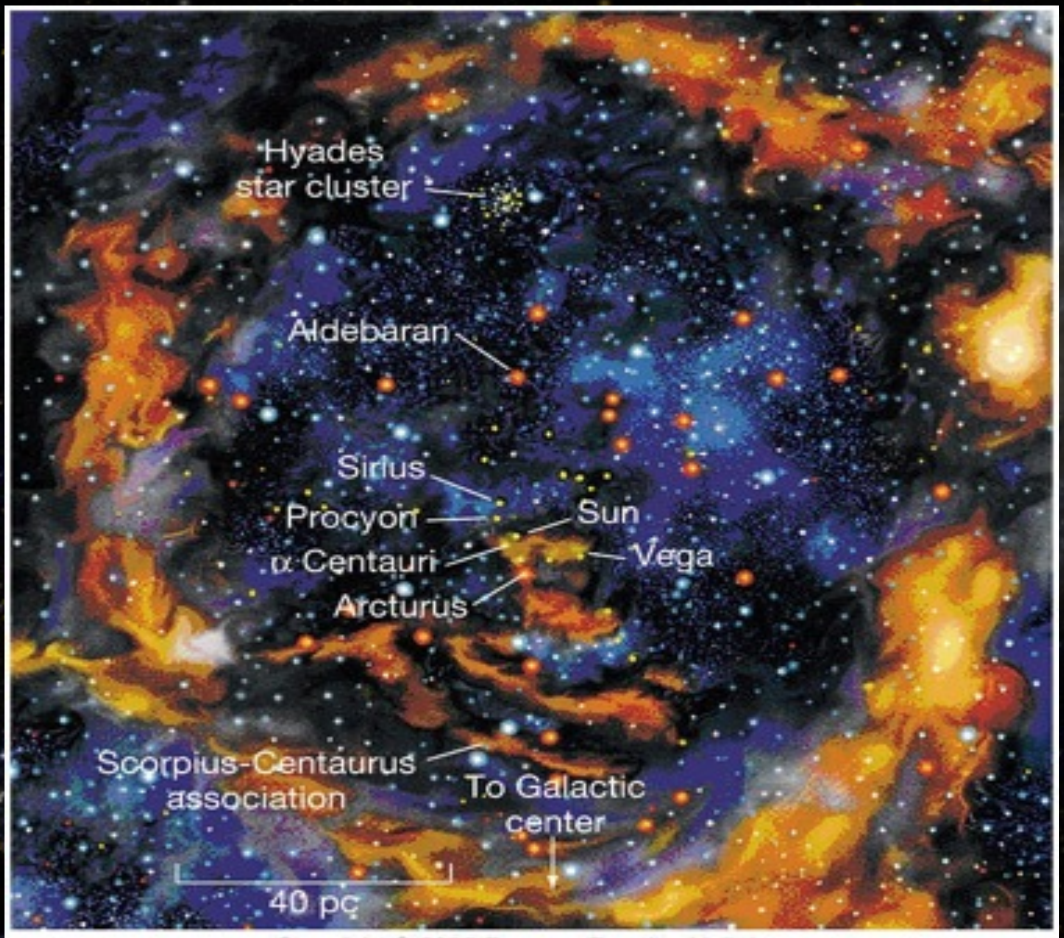


D. Gaggero et al., PRD **89** (2014)

Ongoing work using DRAGON

The effect of local structures

How the small scale structures (e.g. the local bubble) can influence some observables, e.g. the leptonic anisotropy.



The local bubble is a cavity in the interstellar medium where the Solar System is located.

The neutral hydrogen density in the bubble ($0.05\ \mathrm{cm}^{-3}$) is approximately one tenth of the average for the ISM in the Milky Way.
The bubble is filled with hot ionized gas that emits X rays.

There is ongoing work at KIT on the impact of the local bubble on CR observables

See e.g. some preliminary results in ICRC proceeding:

www.cbpf.br/~icrc2013/papers/icrc2013-1115.pdf

Ongoing work using DRAGON

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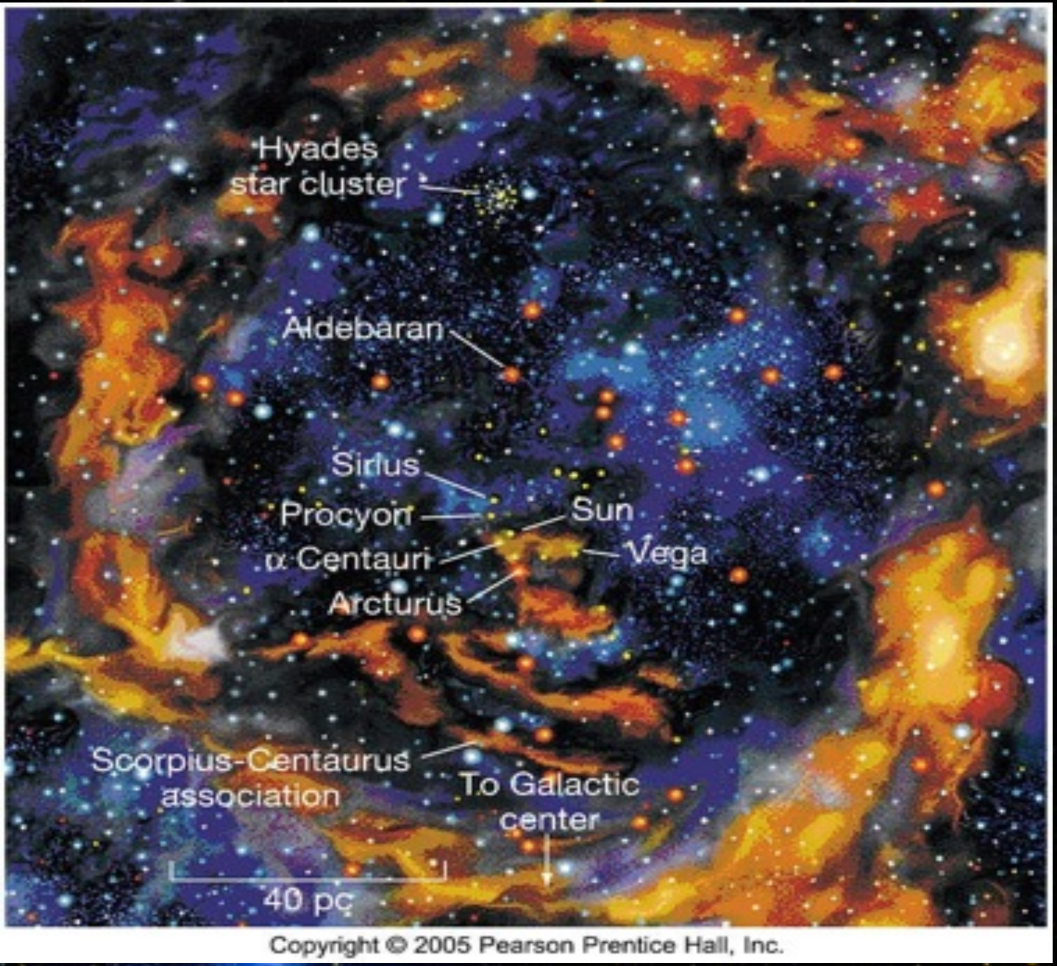


An interesting effect might be observable in the **leptonic anisotropy**.

If a nearby source situated outside the bubble, e.g. a pulsar, emits electrons and positrons, their propagation may be highly influenced by the change in the diffusion properties inside the bubble.
For examples the CRs should be more confined in the outer part (where many molecular clouds are located) and diffuse more quickly in the inner part

---> Effect on the anisotropy? The flux should be more isotropized

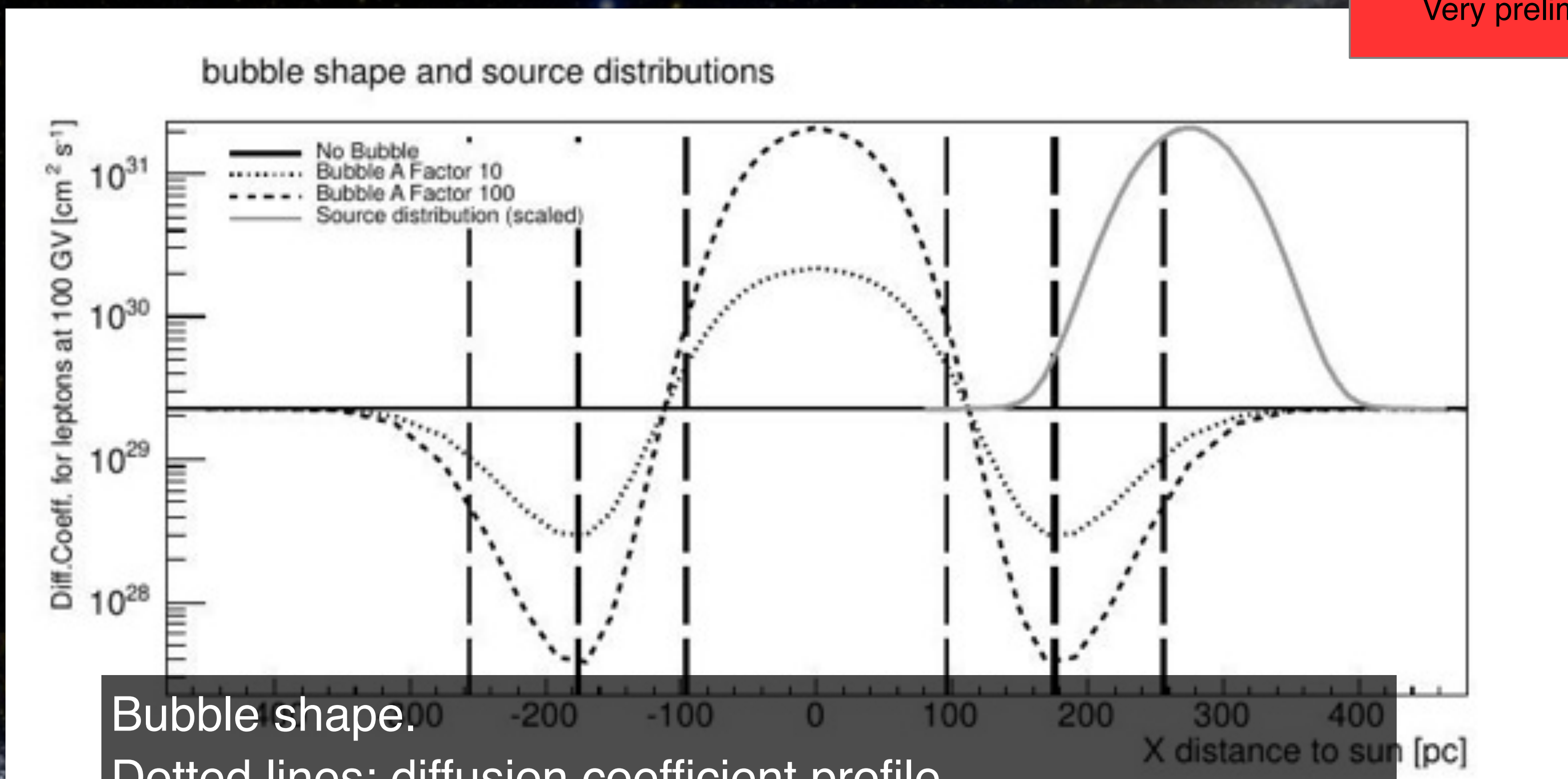
This is very important to investigate because Fermi-LAT and AMS are providing more stringent upper limits and the pulsar scenario may be seriously challenged!

Ongoing work using DRAGON

The effect of local structures

Preliminary results using **DRAGON 3D** with adaptative grid
(in collaboration with: I. Gebauer, M. Weinreuter):

Very preliminary!



Bubble shape.
Dotted lines: diffusion coefficient profile
Solid line: source term
I. Gebauer, M. Weinreuter, DG, et al.
In preparation

Ongoing work using DRAGON

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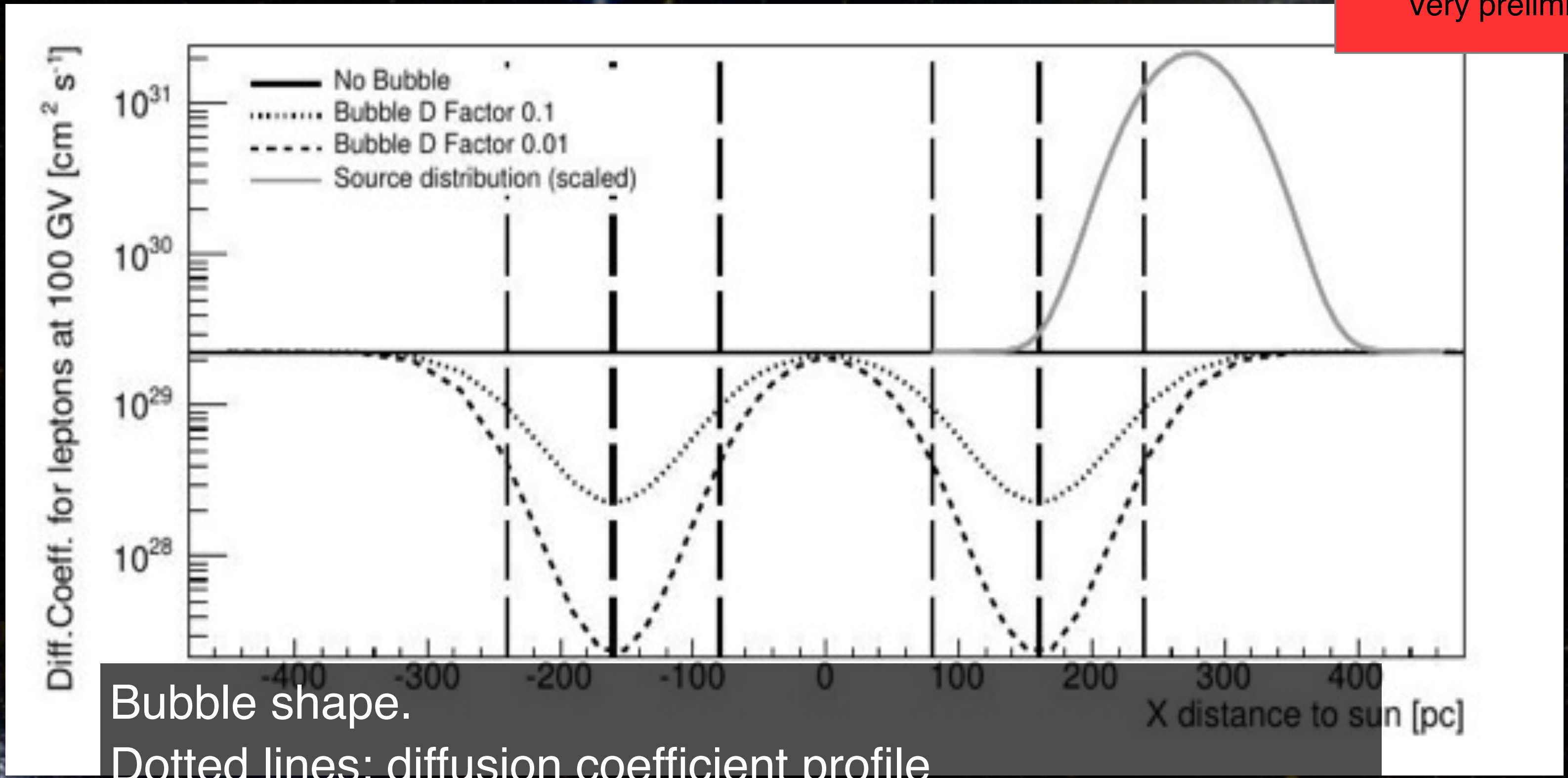

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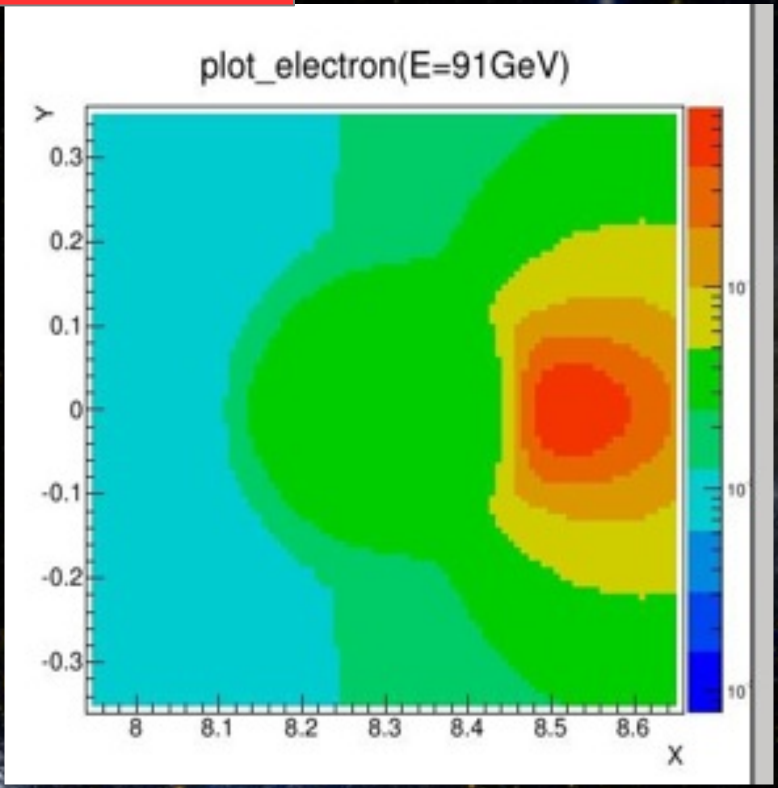

Electron density propagated with DRAGON 3D in the bubble region

I. Gebauer, M. Weinreuter, DG, et al.
In preparation

Ongoing work using DRAGON

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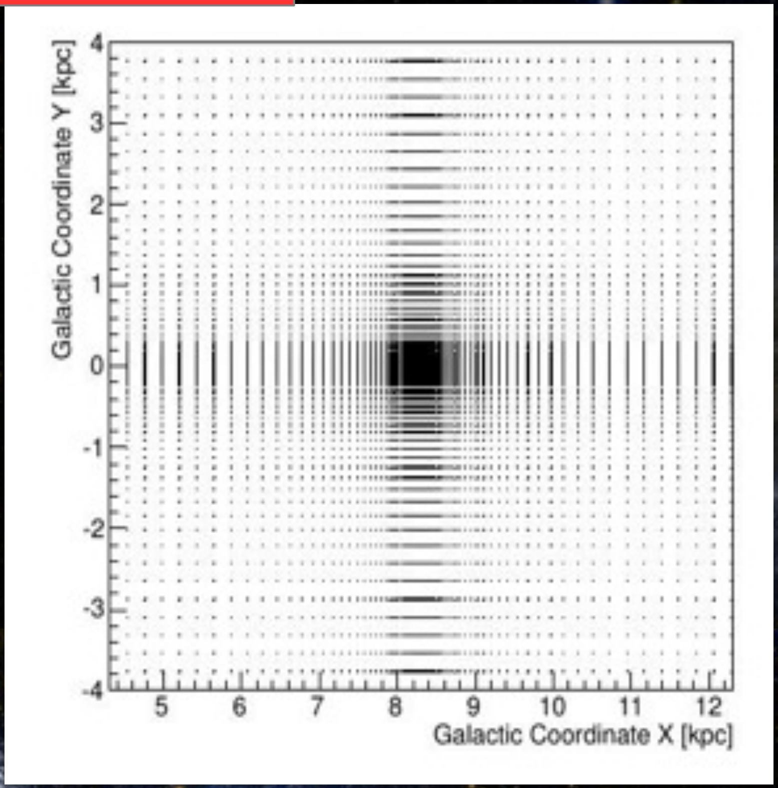

The binning we are using around the bubble region

I. Gebauer, M. Weinreuter, DG, et al.
In preparation

Ongoing work using DRAGON

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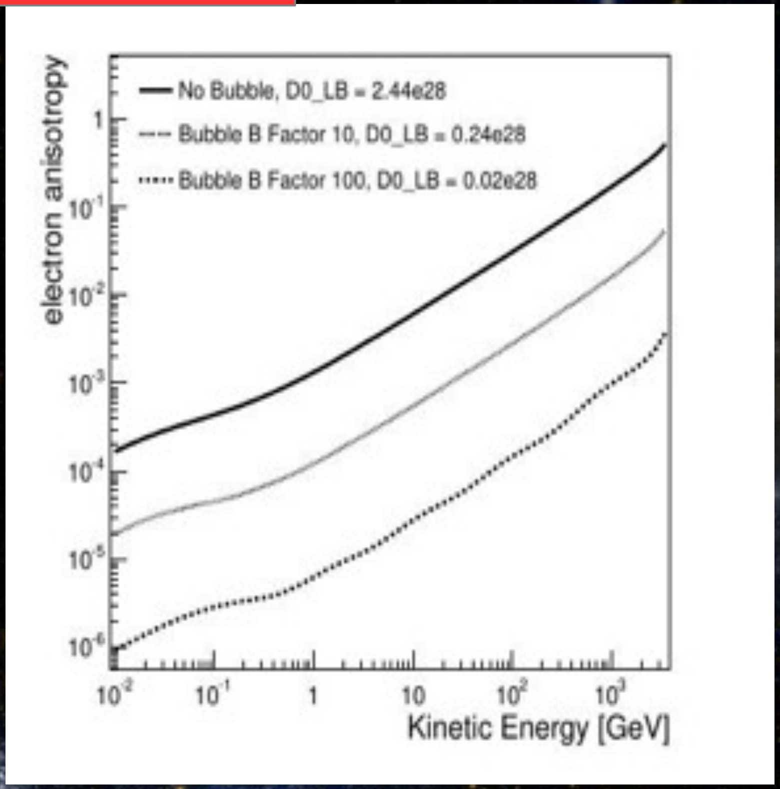


Impact on the electron anisotropy!!

Even in presence of a local point source, the anisotropy decreases by one-two orders of magnitude if the bubble is present!

Very important since more stringent upper limits on anisotropy are expected, that will challenge the pulsar interpretation of the positron excess

I. Gebauer, M. Weinreuter, DG, et al.
In preparation

Variable diffusion coefficient

The galaxy has always been modeled as a uniform box with uniform diffusion coefficient

But we actually know that the reality is very different from that!

The properties of diffusion should depend on the turbulence level!

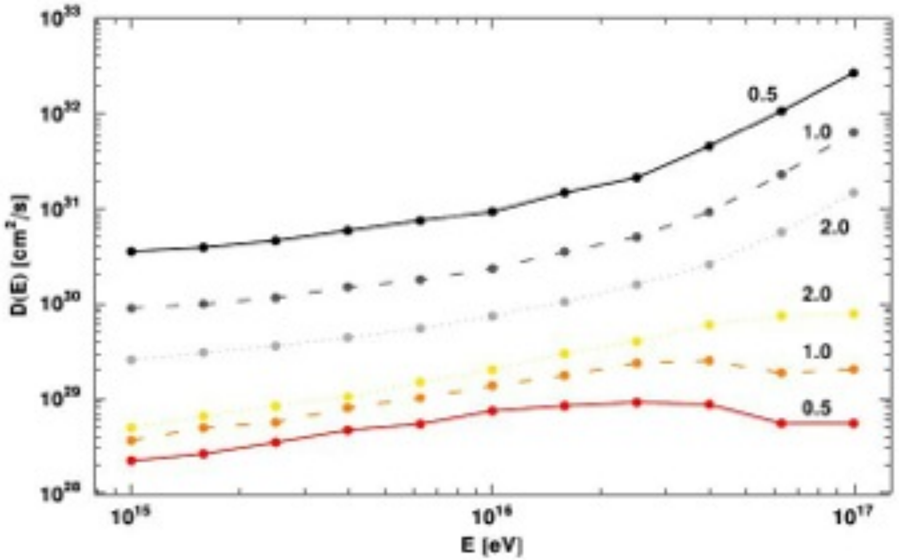


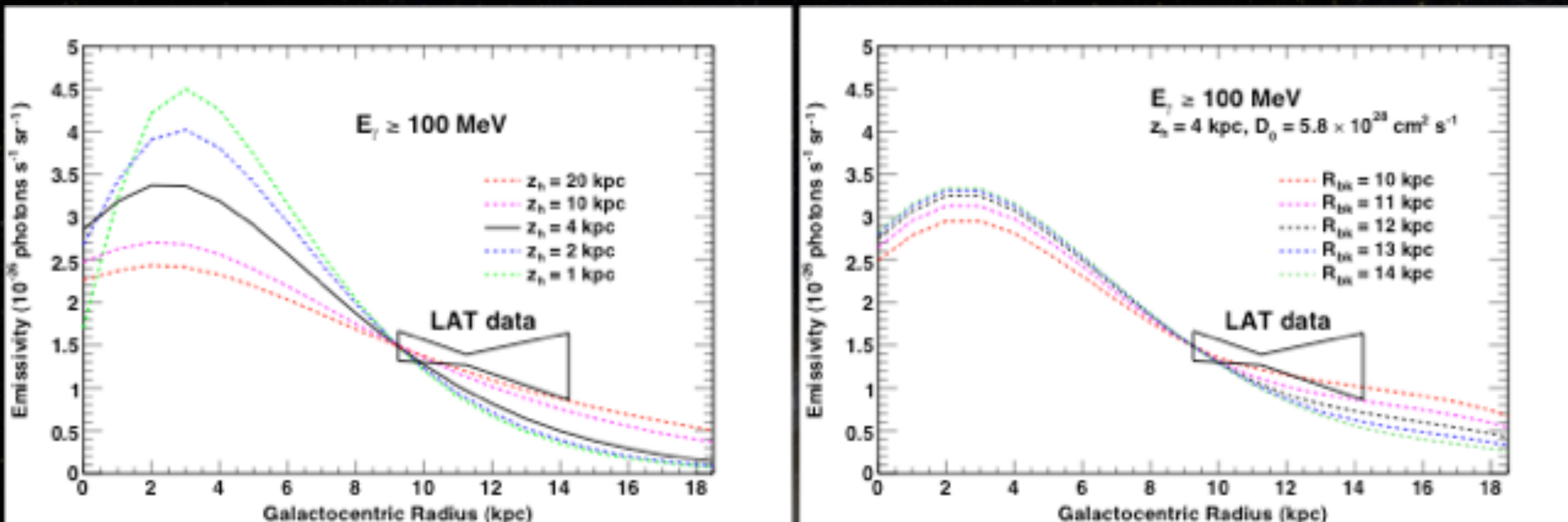
Figure 3. Parallel and perpendicular diffusion coefficients as a function of energy for three levels of turbulence. The upper three lines are the parallel diffusion coefficients, while the bottom three represent the perpendicular one. The level of turbulence, $\delta B/B_0$ is given by the numbers attached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

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

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

Variable diffusion coefficient

Application: the 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 coming 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!

Variable diffusion coefficient

Application: the gradient problem!

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:
$D(r,z) = D_0 \, Q(r,z)^t$
We consider t as a free parameter and tune it against recent data on CR gradient inferred from gamma-ray observation

Variable diffusion coefficient

Application: the gradient problem!

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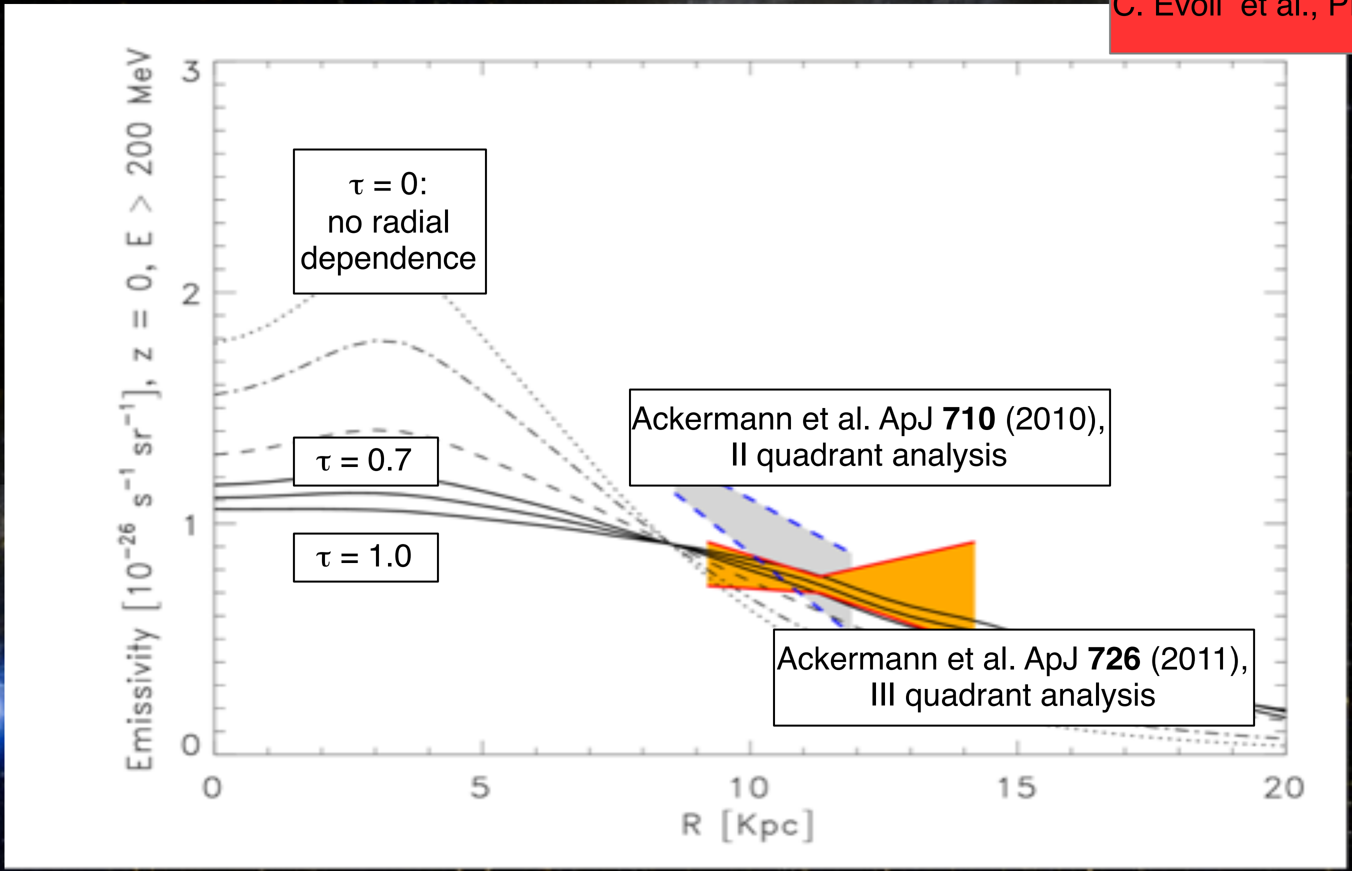
C. Evoli et al., PRL (2012)

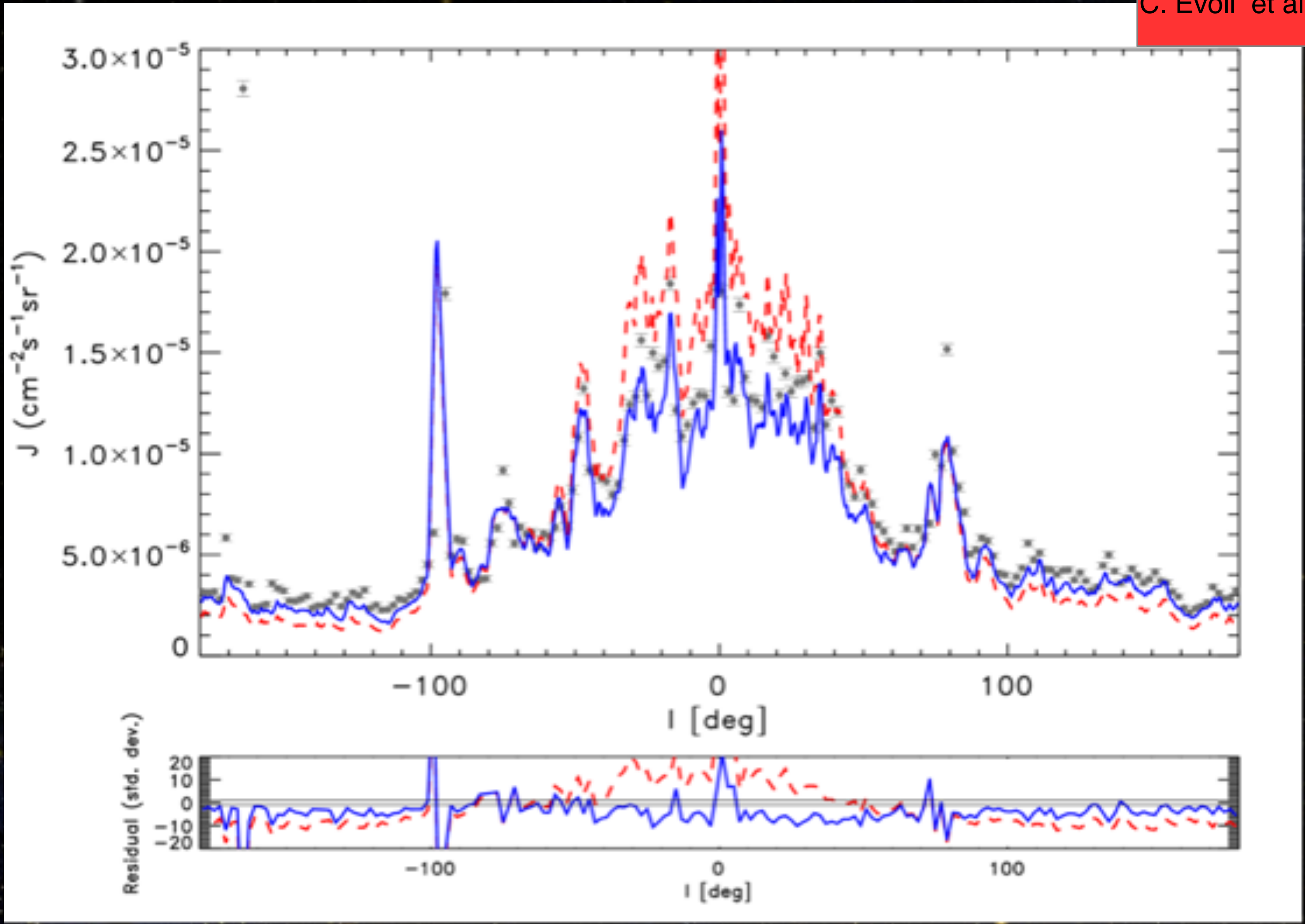


Variable diffusion coefficient

Application: the gradient problem!

The gamma ray longitudinal profile is also reproduced correctly!

C. Evoli et al., PRL (2012)



More effort is needed

→ better understanding of CR sources
the hadronic and leptonic inj. indexes should not be free parameters!
modelling of CR escape mechanism
for CR leptons the escape is quite complicated → electrons accumulated in the inner part of the SNR and cool → steeper spectrum
(work in preparation)

→ CR gradient problem should be solved with the 3D anisotropic code
(further development of anisotropic code needed)

→ Self consistent treatment of turbulence?
the diffusion coefficient should not be an input of the problem!

solving simultaneously CR diff. eq. and turbulence eq. → diff. Coeff.
(see Blasi, Amato, Serpico, astro-ph/1207.3706)

Conclusions

1) Simplified models of CR diffusion in the Galaxy are not suitable anymore to reproduce the huge amount of extremely accurate data that are being released from experiments

2) The most important anomaly in this field, the positron excess, is far from being well understood, but astrophysical interpretations are more likely than exotic ones (DM annihilation/decay)

3) There is a big effort from the DRAGON team to deliver more realistic simulations of CR diffusion in the Galaxy and in the Heliosphere

4) The impact of the large scale structures (spiral arms) and small scale structures (local bubble) is very important on the leptonic observables

5) A position-dependent diffusion coefficient may help to solve some long-standing problems in CR physics such as the gradient problem

6) More effort is needed to arrive at a more accurate and realistic description of the physics that stands behind CR propagation.