Second day.
Hot topics in CR physics. Multimessenger approach.

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Outline

1) The basic picture of CR production and propagation in the Galaxy: a recap

2) Multi-messenger framework: studying gamma ray to understand CRs

3) What do people study nowadays?
Some (data and theory driven) hot topics in CR propagation

→ Do the data suggest different CR transport properties in different regions of the Galaxy?
→ Where does the turbulence responsible for CR confinement come from?

4) Hot topics in CR production. **Connections with DM**

→ Smoking gun of hadronic acceleration. Looking for PeVatrons
→ The positron anomaly. CRs from pulsars?
→ Is there a GC excess? Is it DM? Or a new pulsar/SNR population?

CR discovery

Domenico Pacini (1910)

PENETRATING RADIATION AT THE SURFACE OF AND IN WATER

Note by D. PACINI

Translated and commented by Alessandro De Angelis
INFN and University of Udine

Observations that were made on the sea during the year 1910[5] led me to conclude that a significant proportion of the pervasive radiation that is found in air had an origin that was independent of direct action of the active substances in the upper layers of the Earth's surface.

Here, I will report on further experiments that support this conclusion.

The results that were previously obtained indicated that a source of ionization existed on the sea surface, where possible effects from the soil are small, that had such an intensity that could not be explained on the basis of the known distribution of radioactive substances in water and in air.

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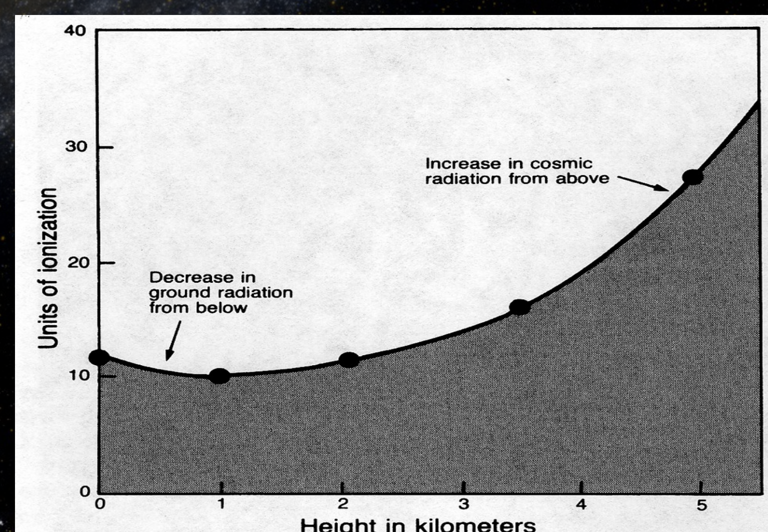
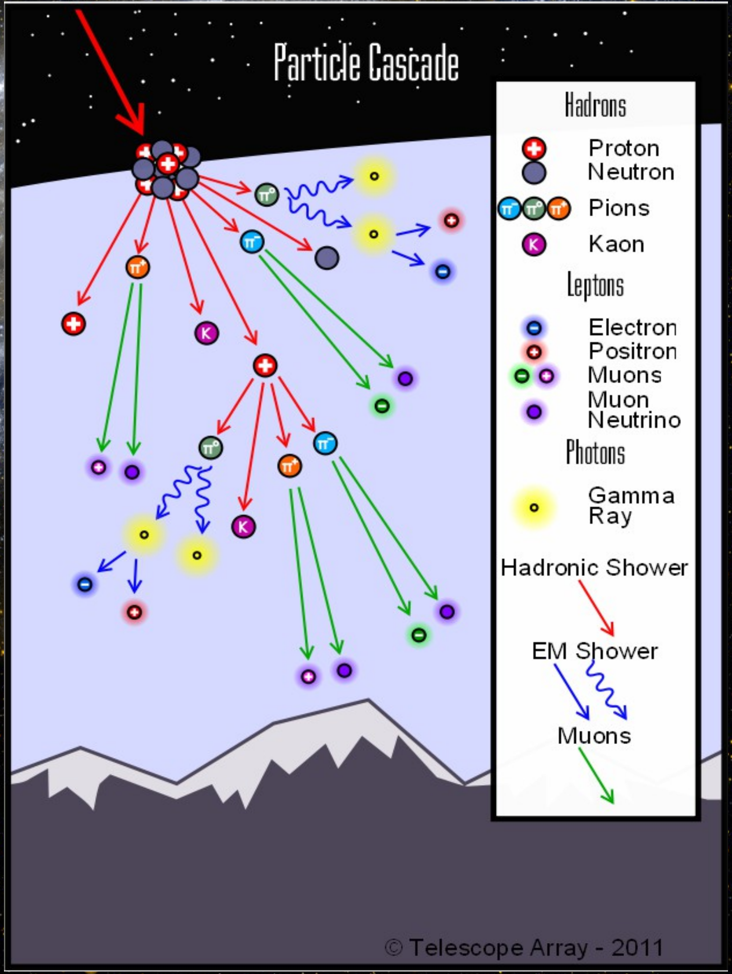
Victor Hess (1912)



Some reasons why CR physics is important

At the beginning of 20th century many new particles were discovered looking at CRs: e.g. positron (1932), muon (1936), pion (1947).

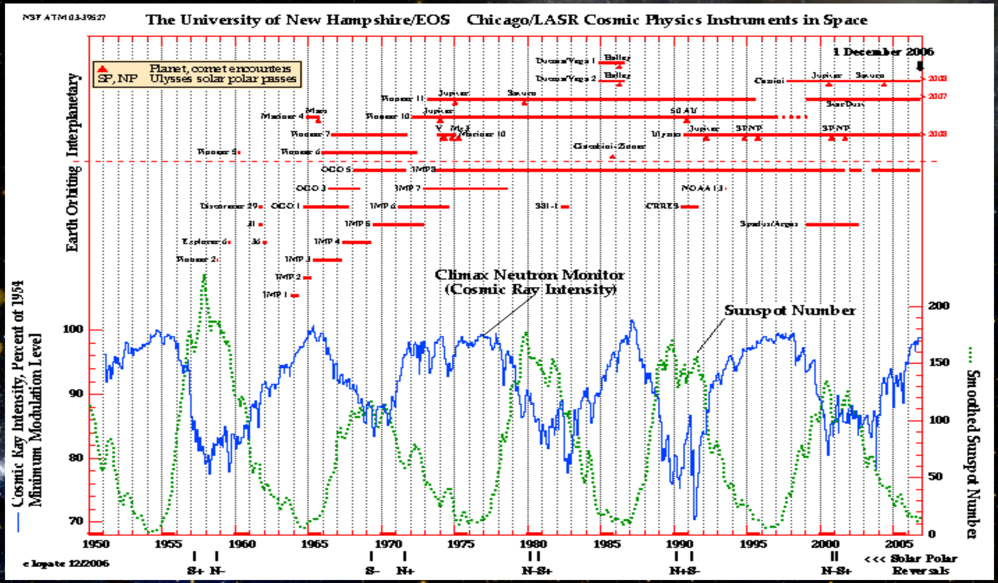
These particles are produced by the interactions of CRs with the atmosphere and were detected at ground level.



Some reasons why CR physics is important

Cosmic rays, climate and solar wind: fascinating connections.

Cosmic rays at low energy interact with the solar wind
(a flux of low-energy ~MeV particles from the Sun)
and suffer advection and energy losses – the so-called
"solar modulation"
During the phases of high solar activity, the cosmic-way
flux is lower

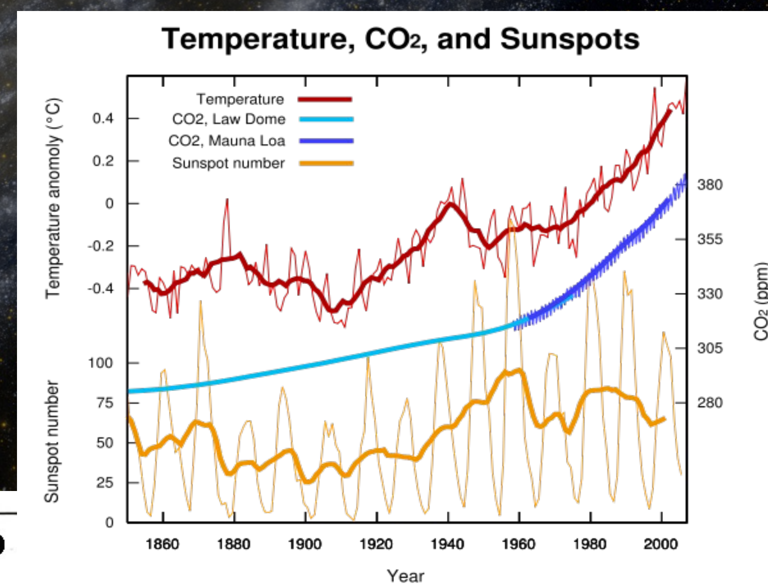


Some reasons why CR physics is important

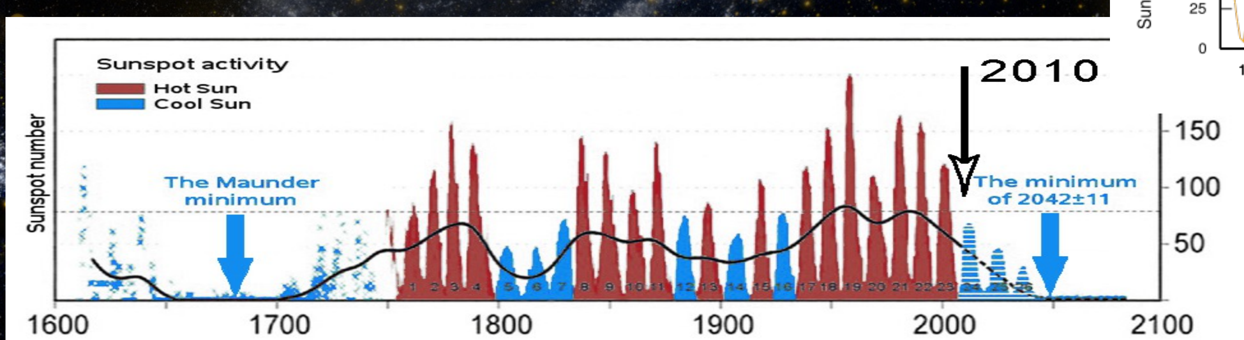
Cosmic rays, climate and solar wind: fascinating connections.

Since CRs increase the ionization of the atmosphere and may therefore trigger cloud formation, the idea (under debate) is that More solar activity → less CRs → less clouds → higher global temperature

These connections are still under debate, take these arguments with a pinch of salt



http://solar-center.stanford.edu/



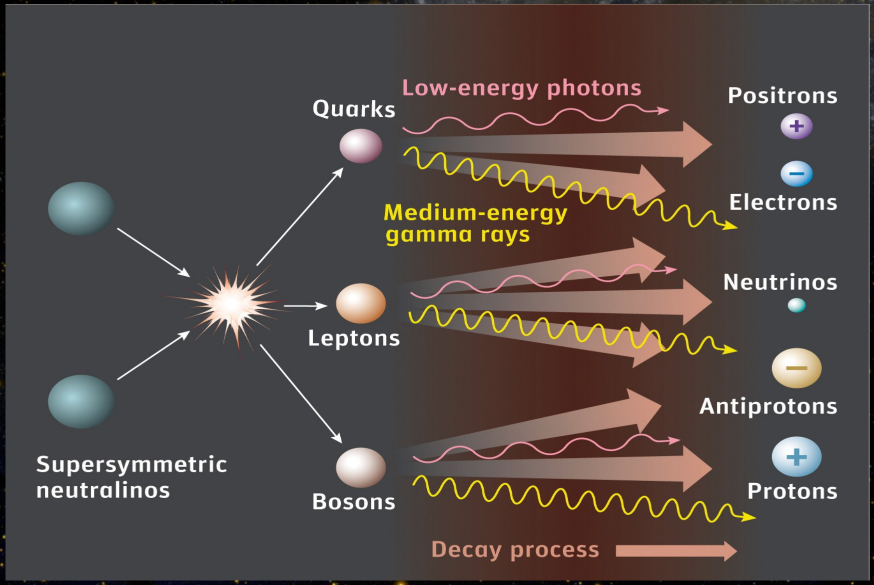
Some reasons why CR physics is important

Cosmic rays and Dark Matter

As Mauro explained in the DM class, nowadays the Dark Matter community is very interested in cosmic rays and in the gamma-ray emission originating from cosmic rays because some anomalies in the data may be interpreted as s signature of particle DM annihilation or decay.

It is often very hard to disentangle the DM interpreatation and the astrophysical interpretation of these anomalies!

I will briefly talk about the positron case at the end of the class.

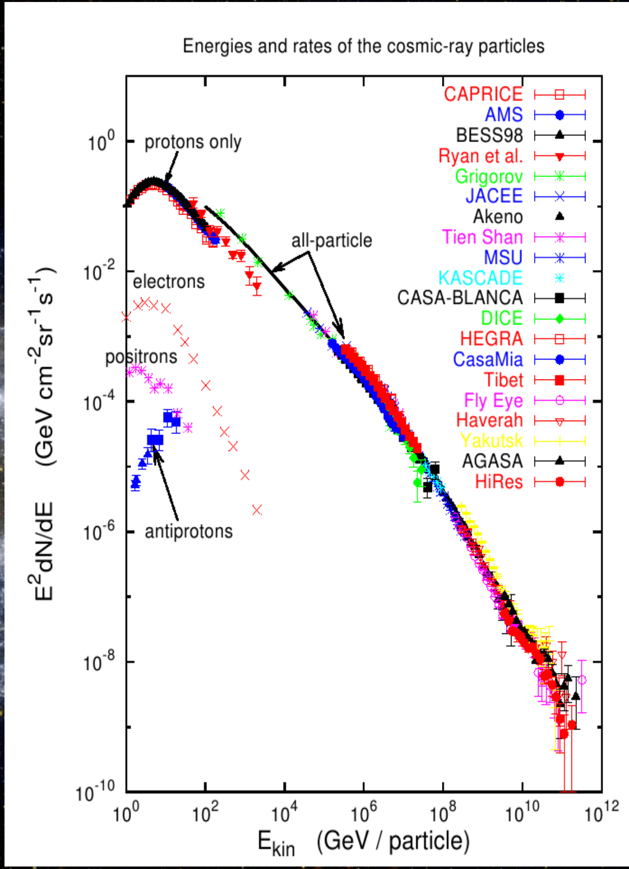


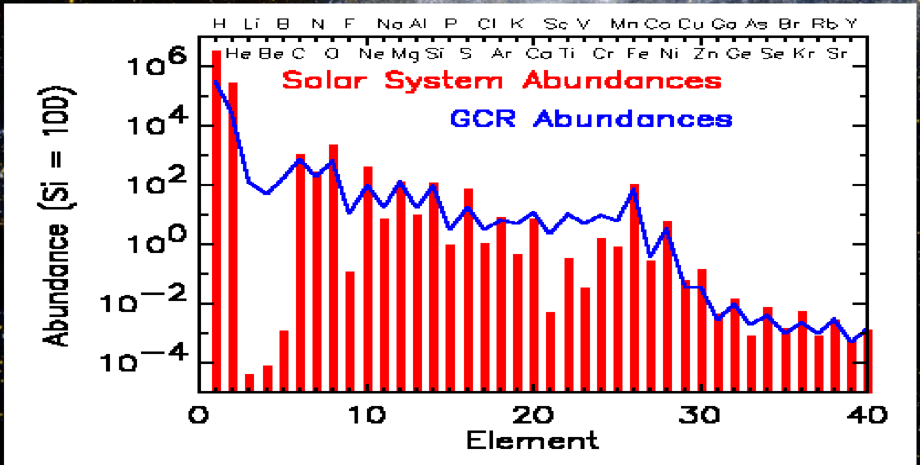
(very quick) recap of CR physics

As we saw yesterday:

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*

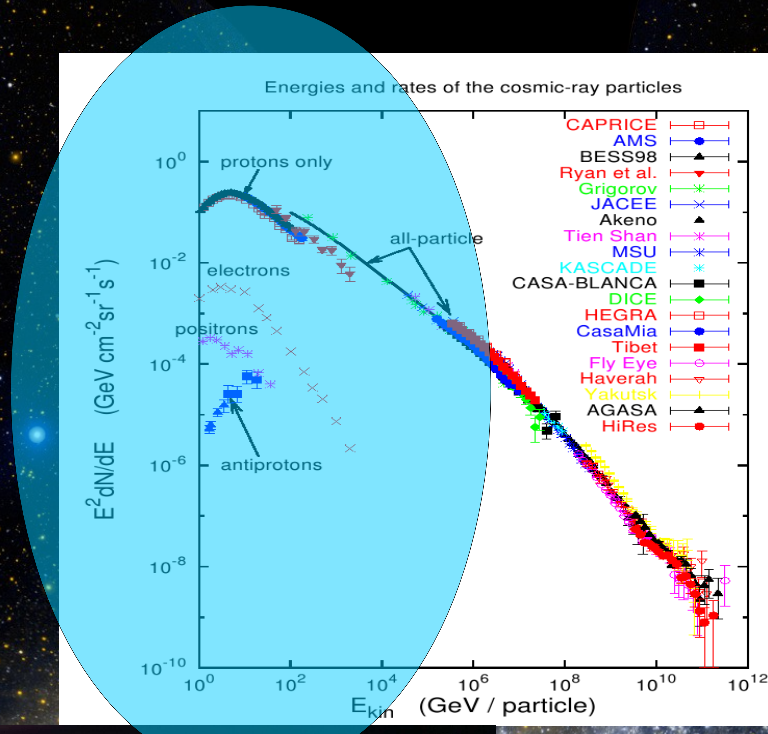
2) There is evidence for CR confinement in the Galaxy:
In order to reproduce the measured abundance of stable nuclei, CRs should have traversed
~ 10 g/cm^2 of interstellar material
→ L = *grammage* / ($n\ m_p$) ~ 10^4 *kpc* >> Galaxy size!!!



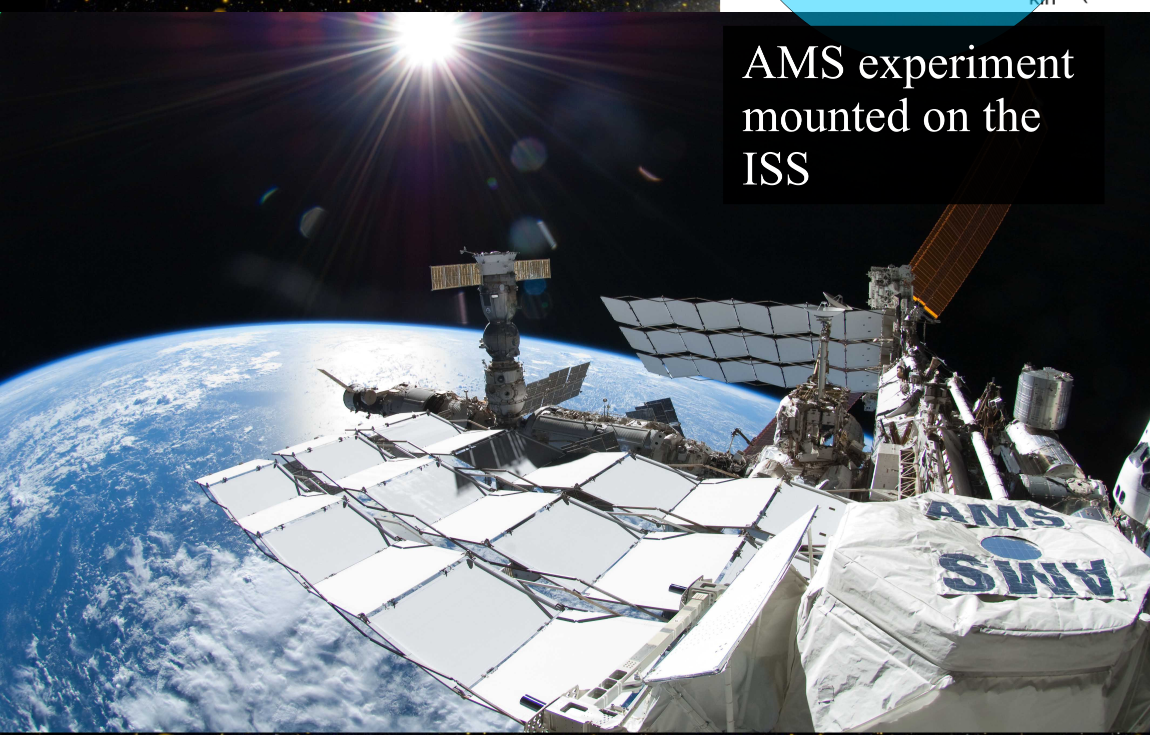


How CRs are measured

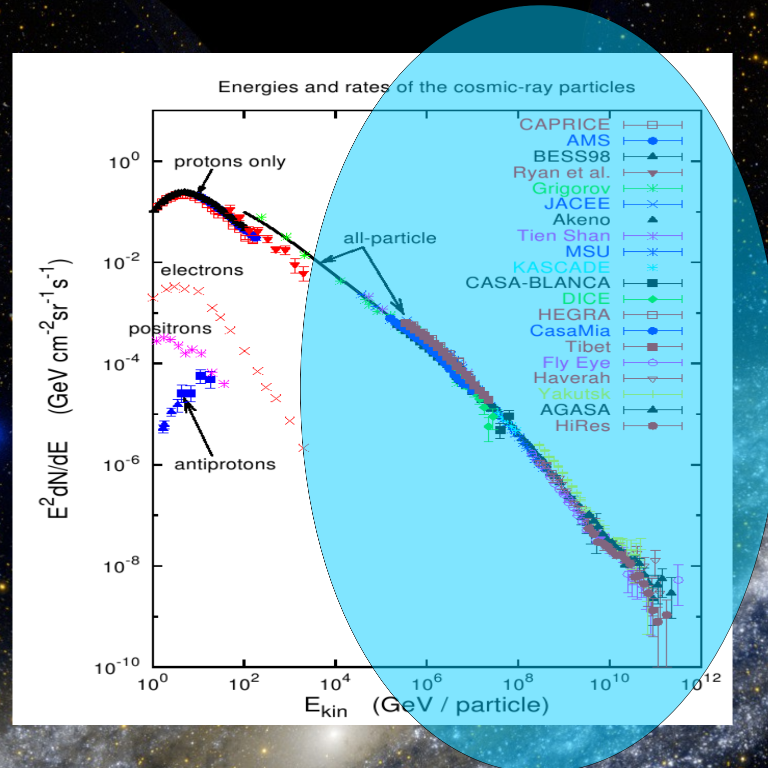
Low and intermediate energies (from GeV to TeV): the flux is large, experiments are in space.



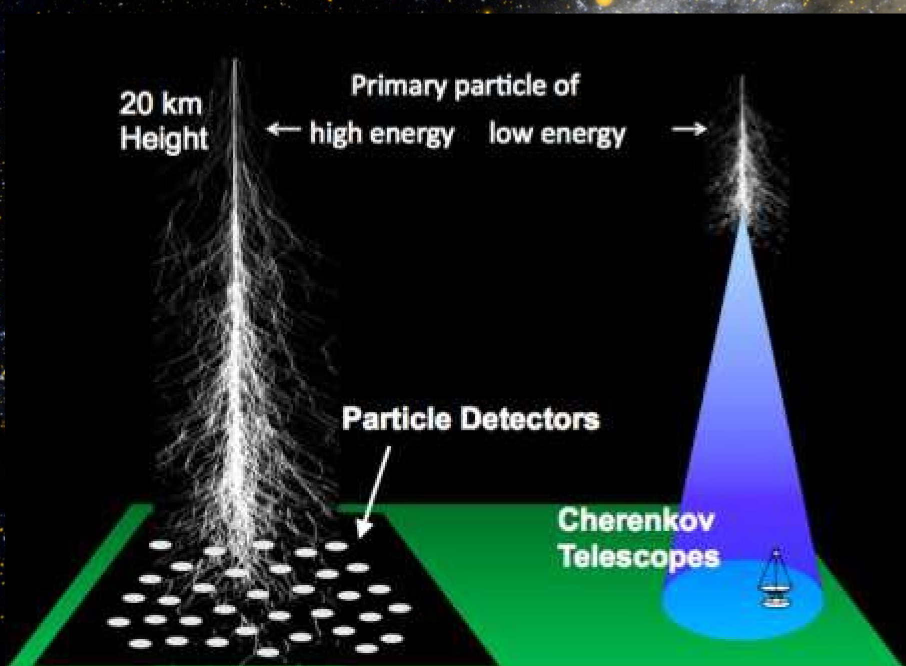
AMS experiment mounted on the ISS

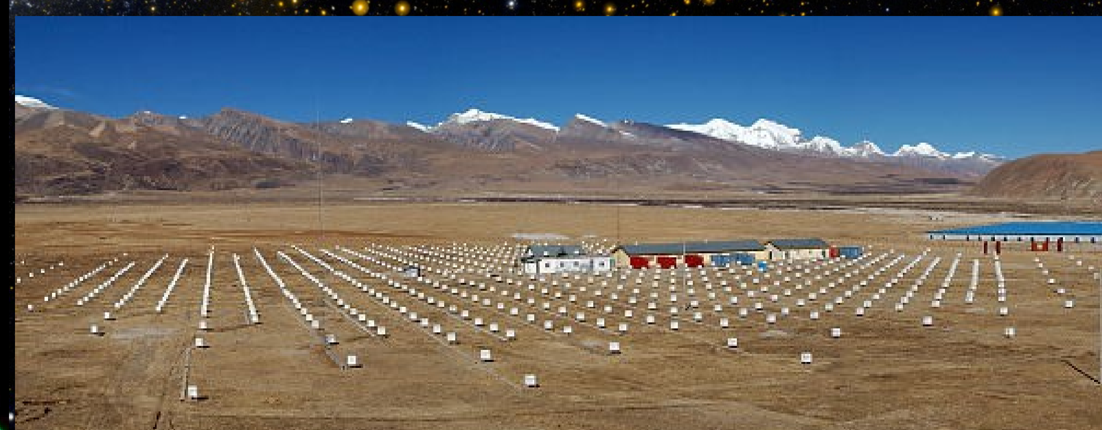


How CRs are measured

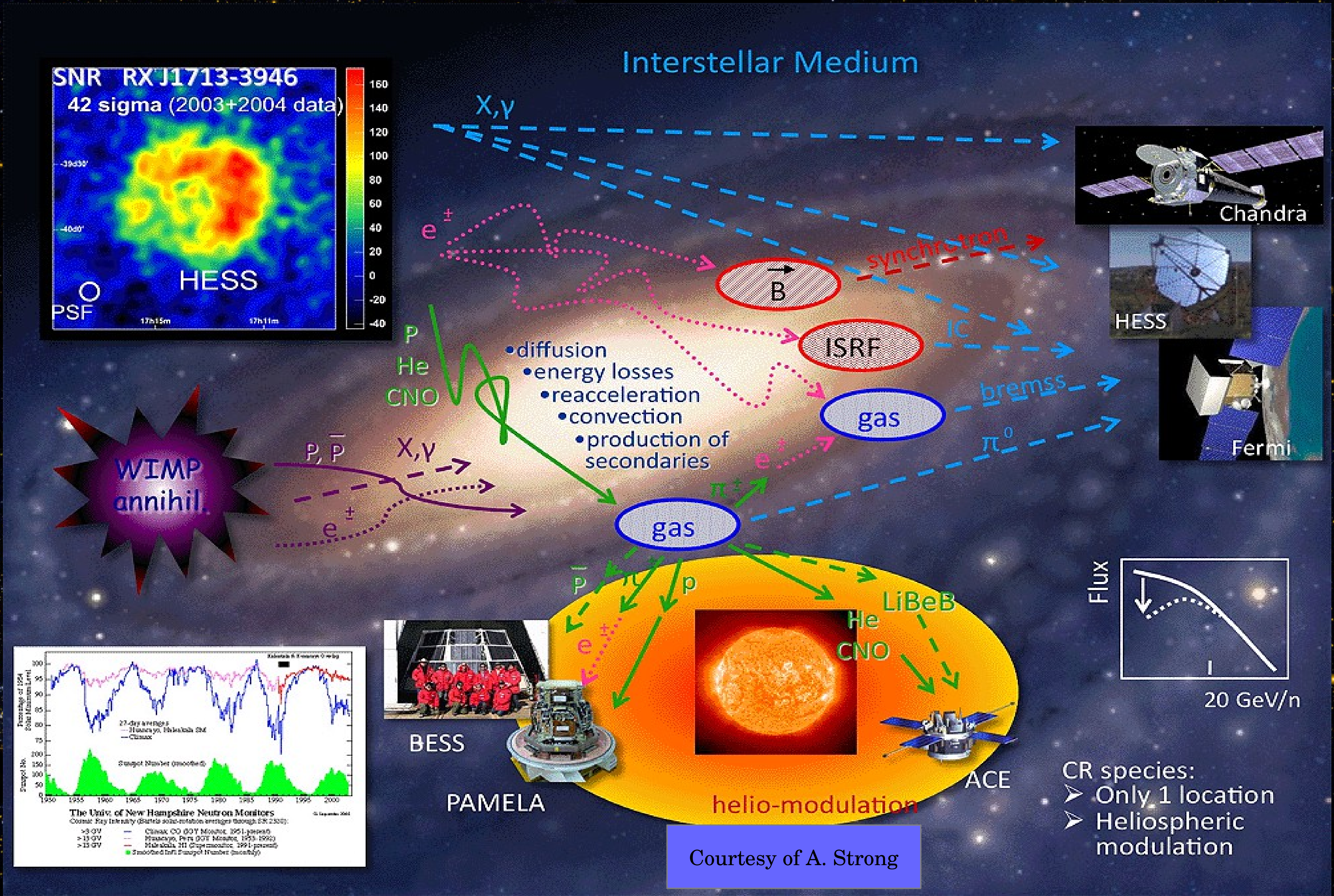


Very high energies (up to 10^{20} eV): the flux is low, ground-based experiments measure the secondary shower in the atmosphere





The basic picture of CR propagation

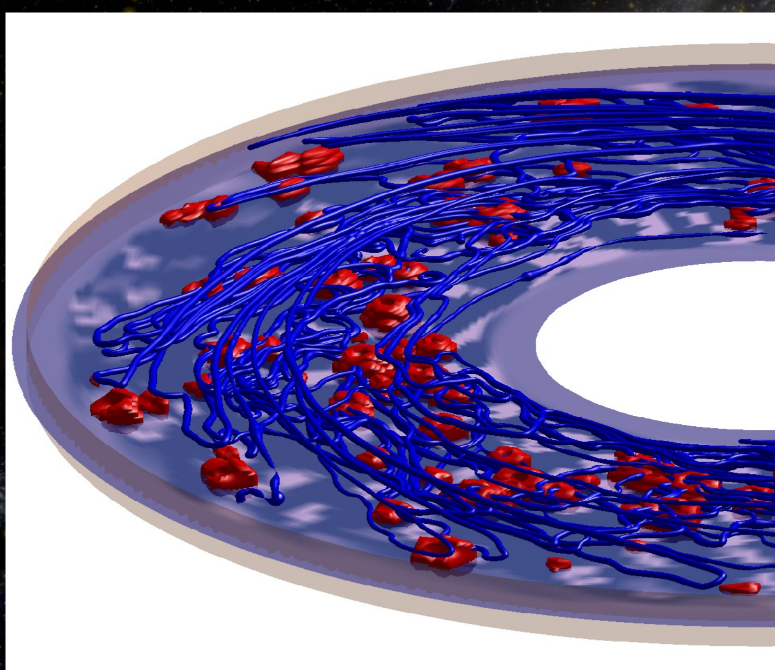


Courtesy of A. Strong

The basic picture

The complete equation describing CR propagation is the following:

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



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

The equation describing CR propagation is the following:

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

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

The equation describing CR propagation is the following:

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

Reacceleration

The basic picture

The equation describing CR propagation is the following:

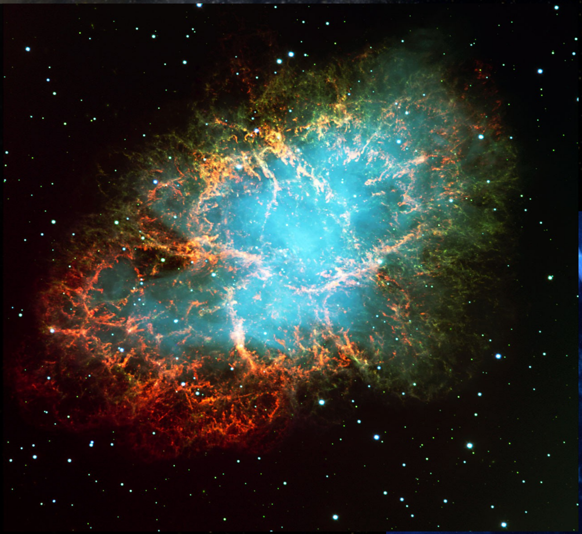
$$\frac{\partial N^i(\vec{x},p,t)}{\partial t} = \nabla \cdot (D\nabla N^i - \mathbf{v_C}) N^i(\vec{x},p,t) + $$
$$+ \frac{\partial}{\partial p}\left(\dot{p} - \frac{p}{3}\cdot \mathbf{v_C}\right) - \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{N^i(\vec{x},p,t)}{p^2}$$
$$+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

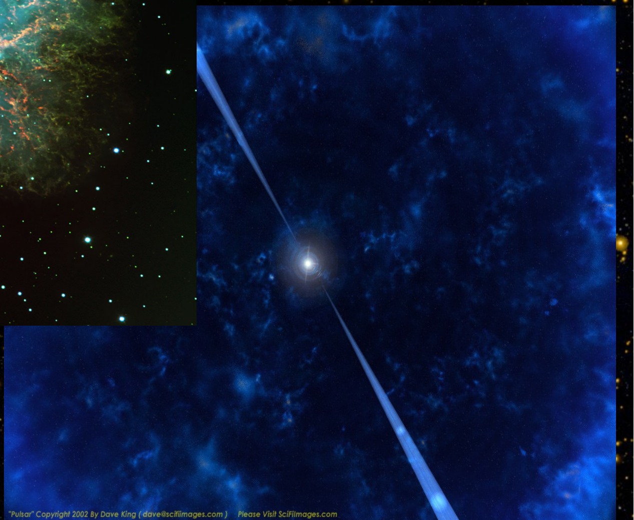
Primary source term.

Protons, nuclei, electrons are accelerated by SNR shocks

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

→ *CRs coming from DM annihilation / decay?*

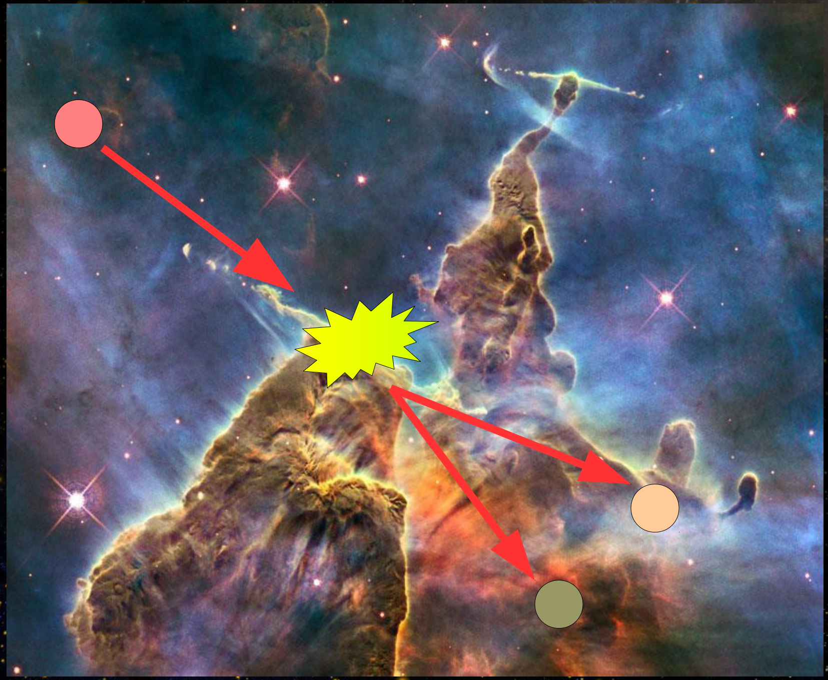




The basic picture

The equation describing CR propagation is the following:

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



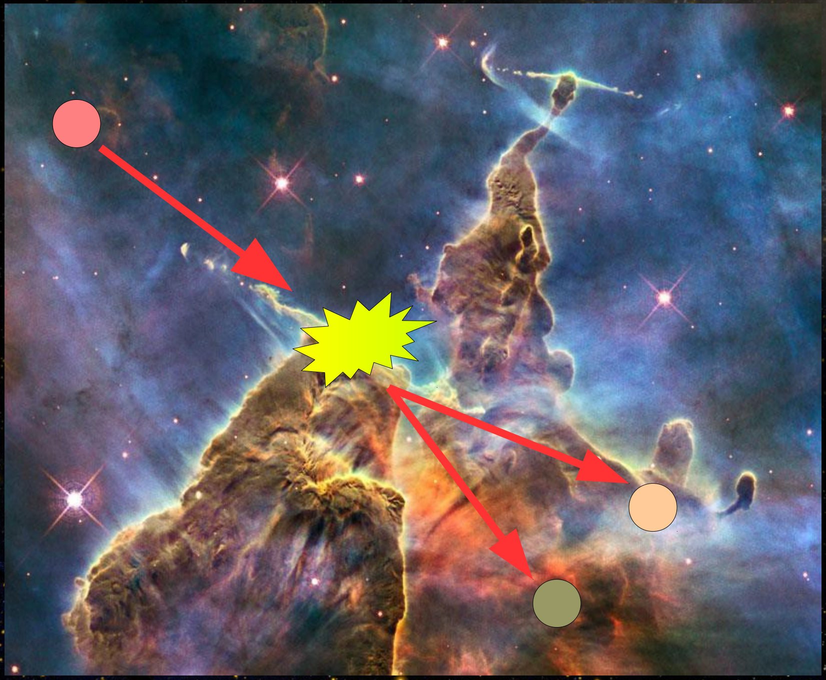
Spallation source term from heavier nuclei interacting with interstellar gas.

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

The basic picture

The equation describing CR propagation is the following:

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



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:

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

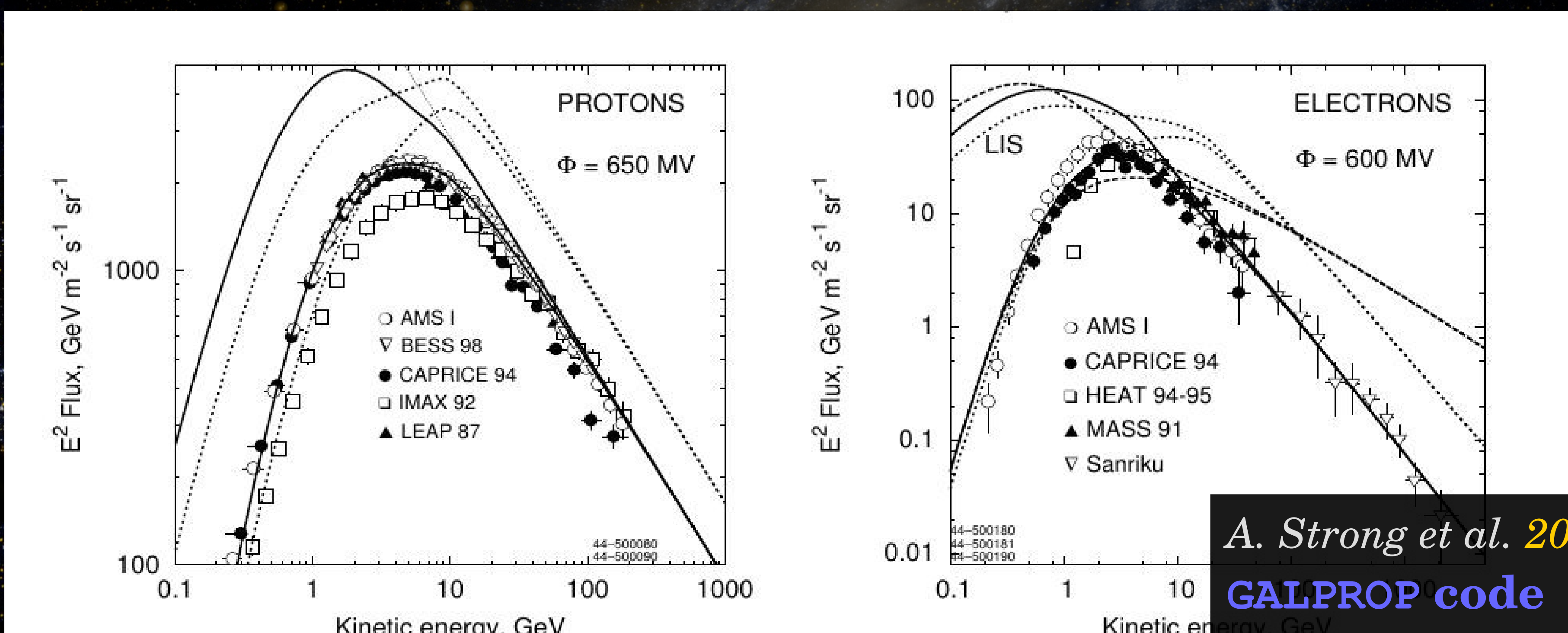
Cosmic ray physics is apparently easy...

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 in 2D *(R,z)*: azimuthal symmetry **with numerical or semi-analytical codes.**

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

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



A. Strong et al. 2004

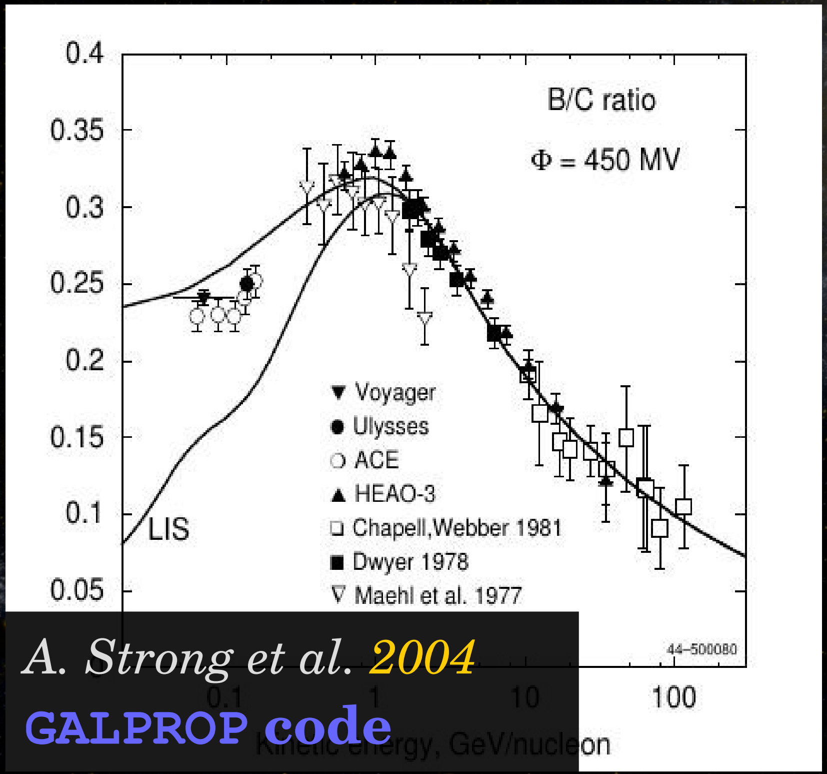
GALPROP code

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



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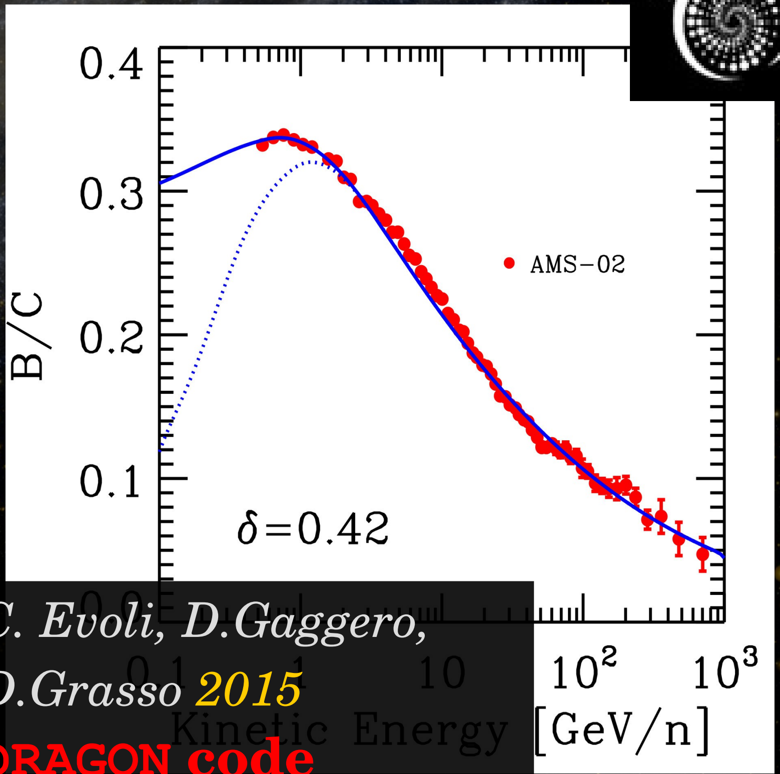

C. Evoli, D.Gaggero, D.Grasso 2015
DRAGON code

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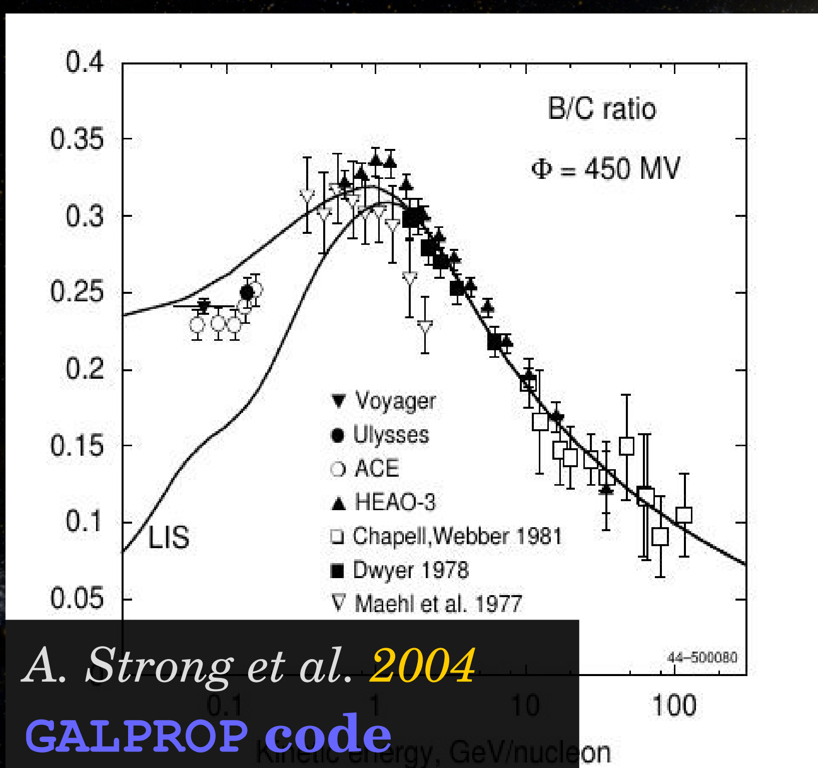

A. Strong et al. *2004*
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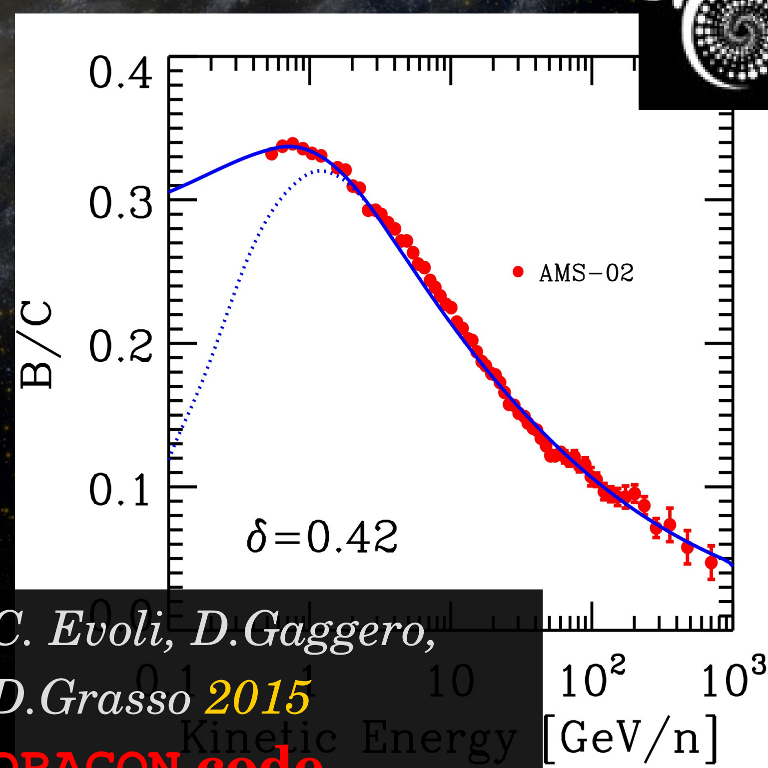
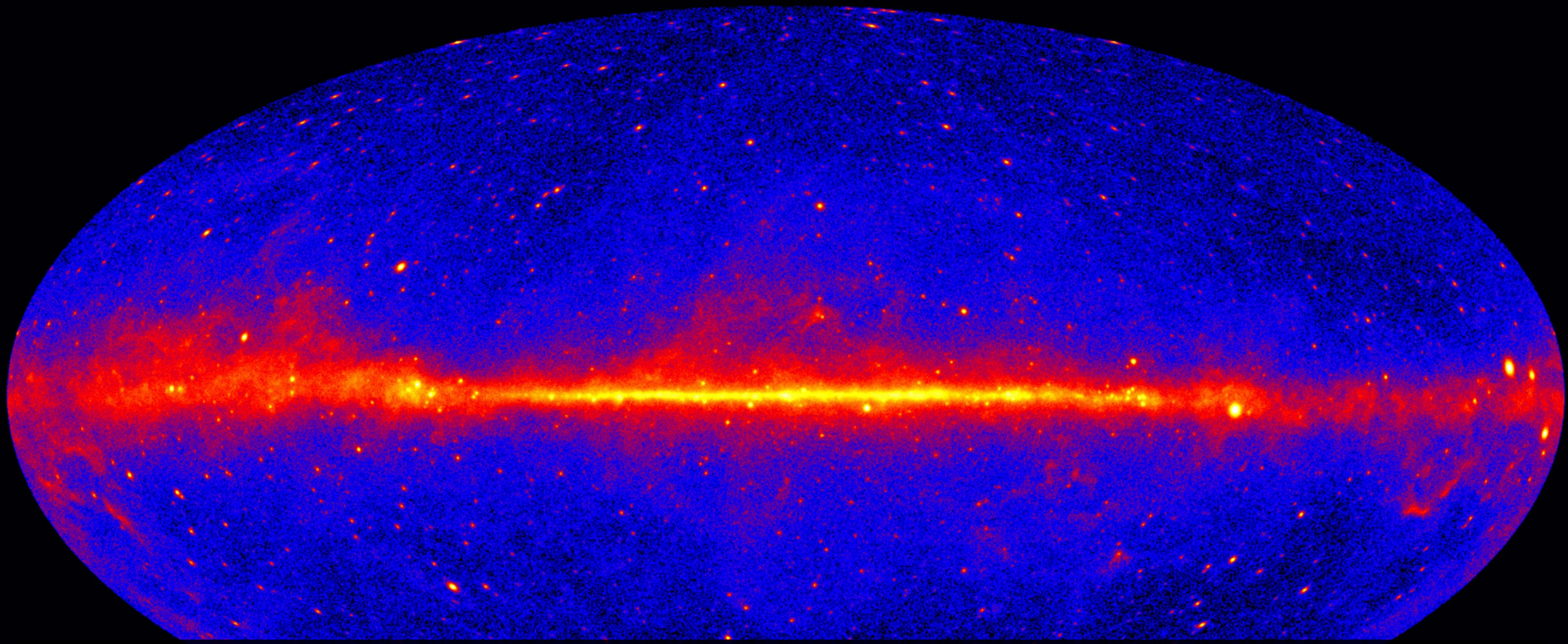


C. Evoli, D.Gaggero, D.Grasso *2015*
DRAGON code

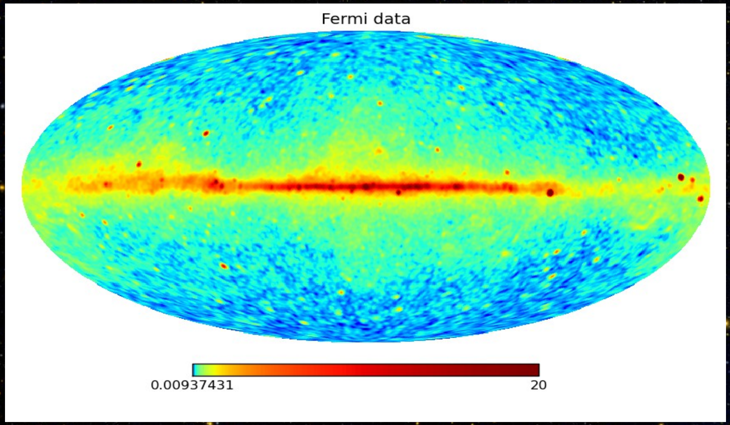
A multi messenger framework

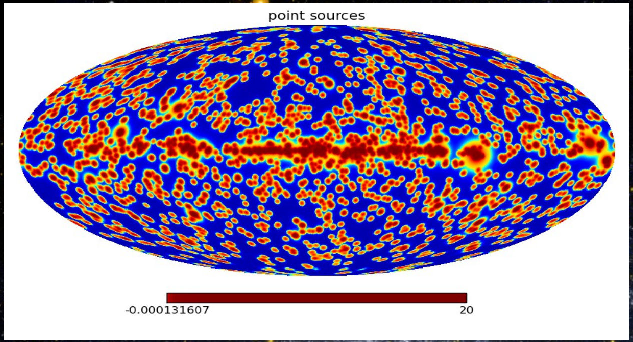


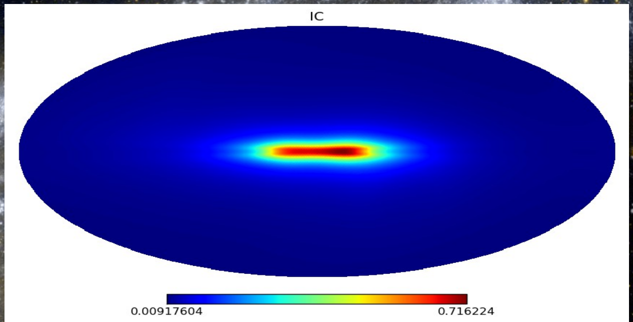
→ CRs produce gamma rays (do you remember Mauro's talk?)

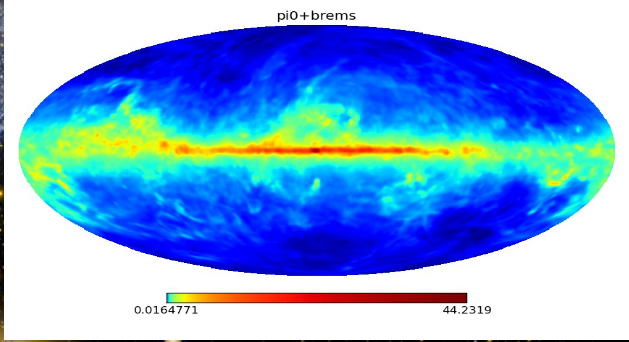
→ The gamma-ray emission is useful to trace the CR flux in different regions of the Galaxy

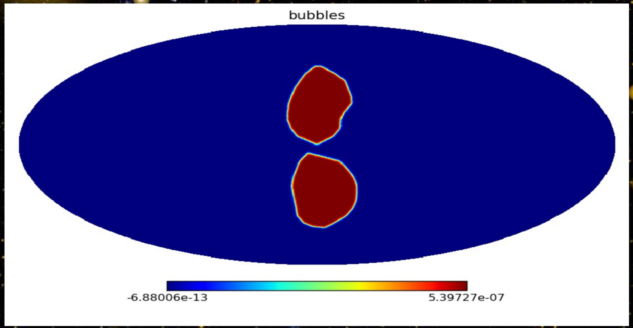
A multi messenger framework





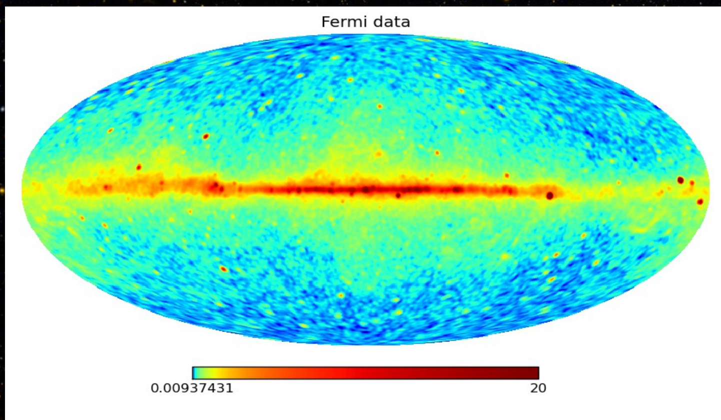






→ The gamma-ray map is being measured by
Fermi-LAT with high accuracy.
Understanding the mechanisms that generate
these gamma rays is important to understand
CR physics

A multi messenger framework



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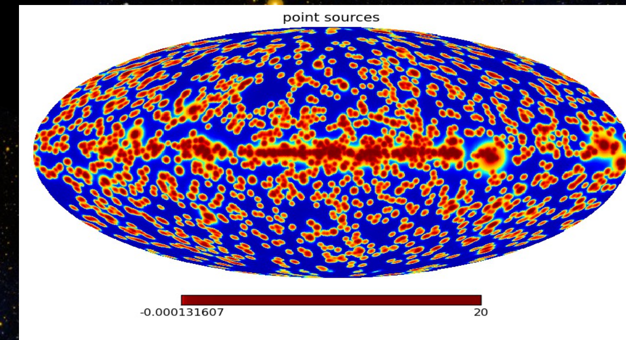
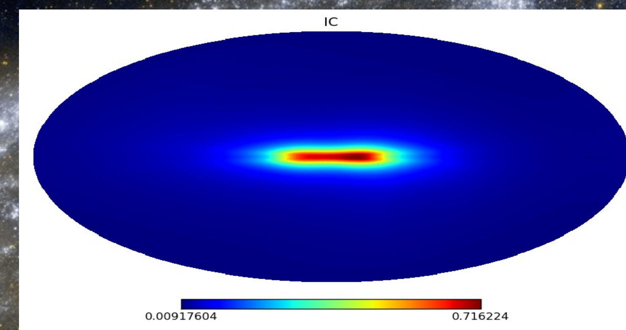
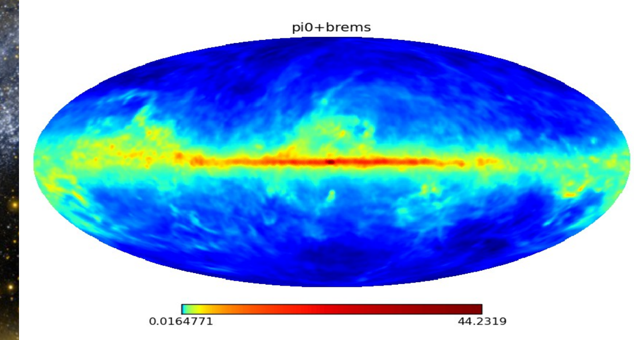
Many **Galactic and extragalactic point sources**



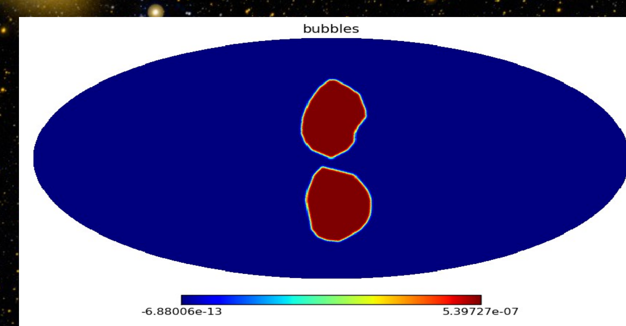
Inverse Compton emission: low-energy photons converted into high-energy photons



Neutral pions are produced in proton-proton interactions and **decay** into gamma rays



The bubbles: huge structures with hard spectrum of unknown origin



Hot topics regarding diffusion

→ Are the CR transport properties the same all through the Galaxy ?

Let's follow a data-driven approach.

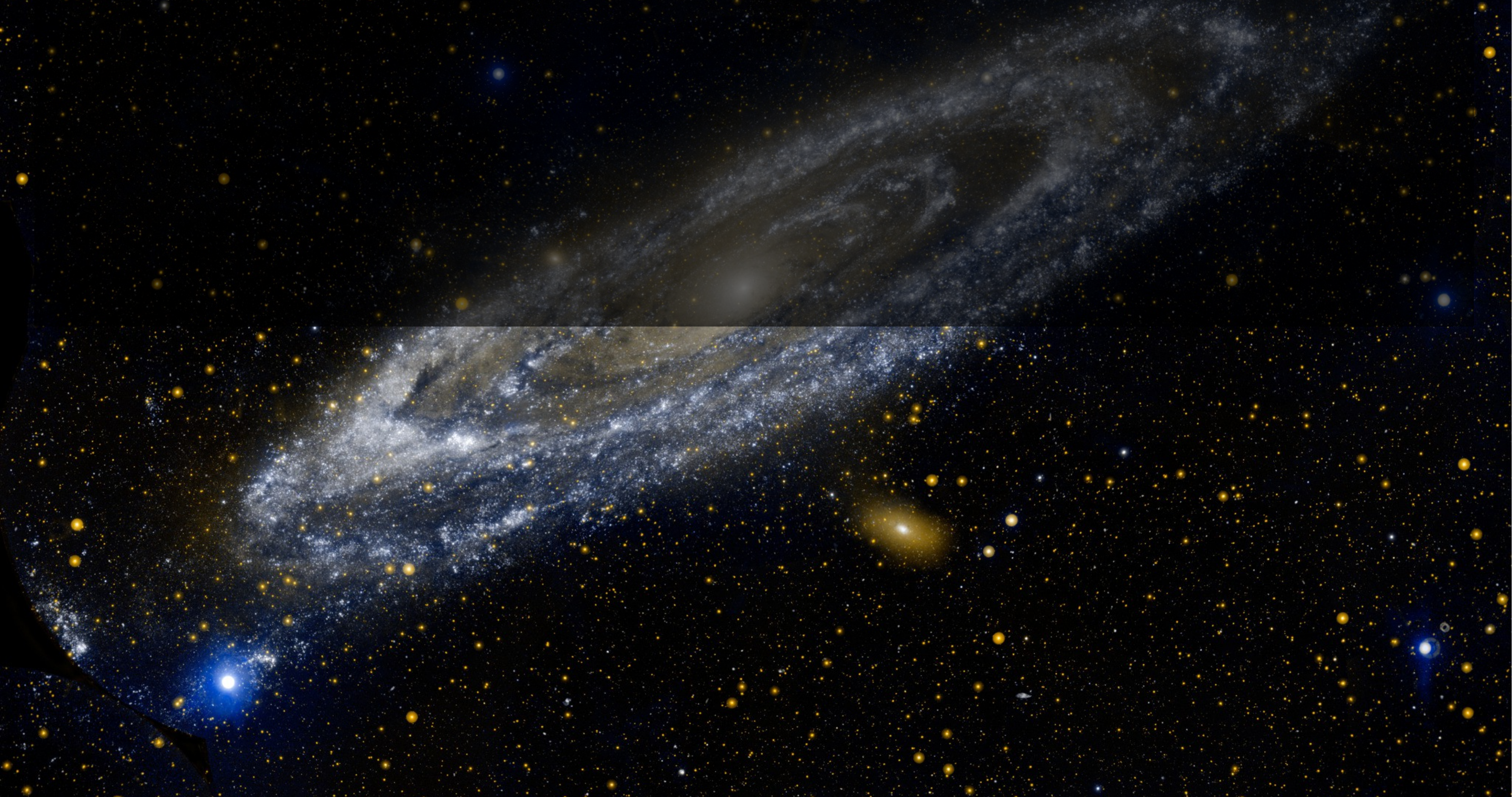
As anticipated before, **we look at gamma-ray data**. Why?
– because the gamma-ray distribution permits to trace the CR flux in different regions of the Galaxy.

Are there anomalies?

Hot topics regarding diffusion

Are there anomalies?

Yes!



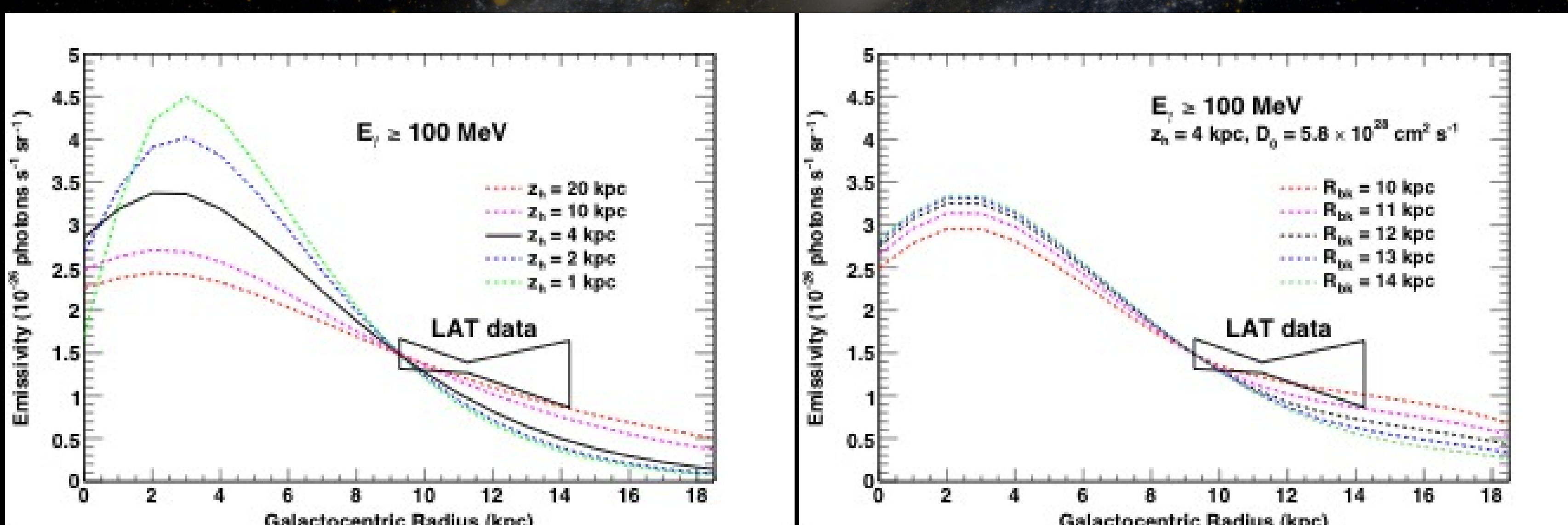
Hot topics regarding diffusion

Are there anomalies?

Yes!

1) Gradient problem

The CR gradient inferred by gamma-ray data along the Galactocentric radius is flatter than predicted



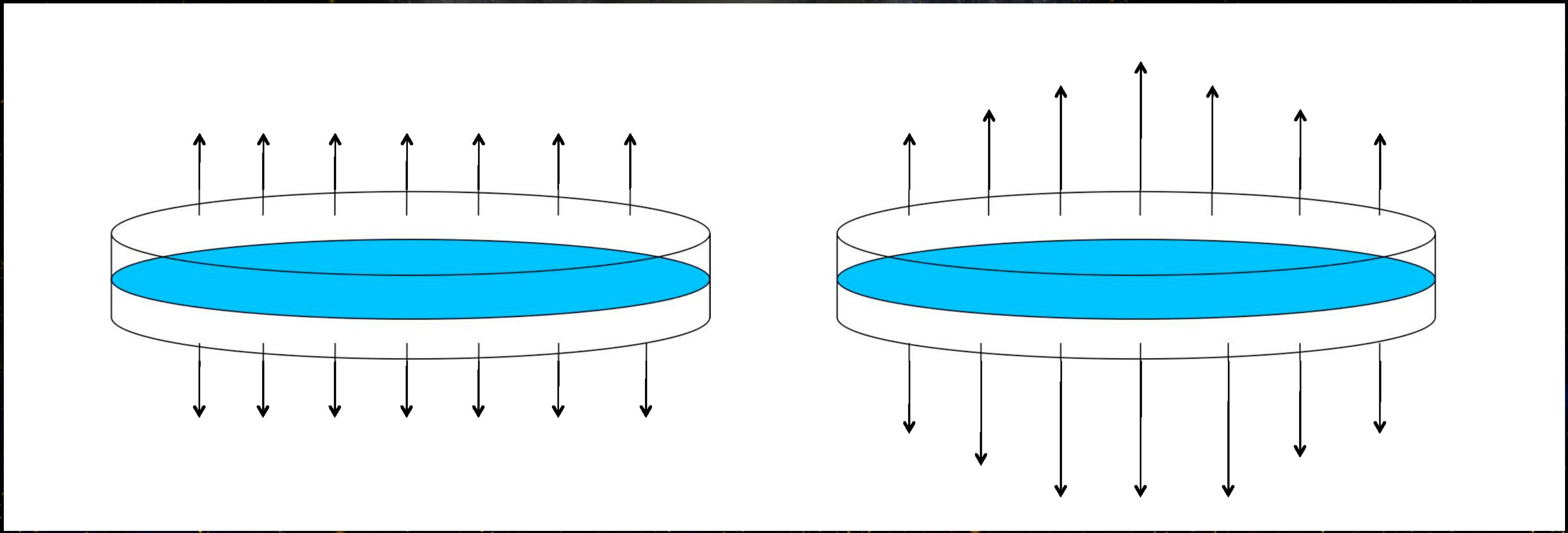
Hot topics regarding diffusion

Possible explanation:

– the CR escape of CRs along z is governed by the diffusion coefficient perpendicular to the regular field direction

– the perpendicular diffusion coefficient increases with turbulence level (*remember yesterday class*)

– the regions of the Galaxy with more CR sources are more turbulent → larger perpendicular diffusion coefficient → more efficient CR escape

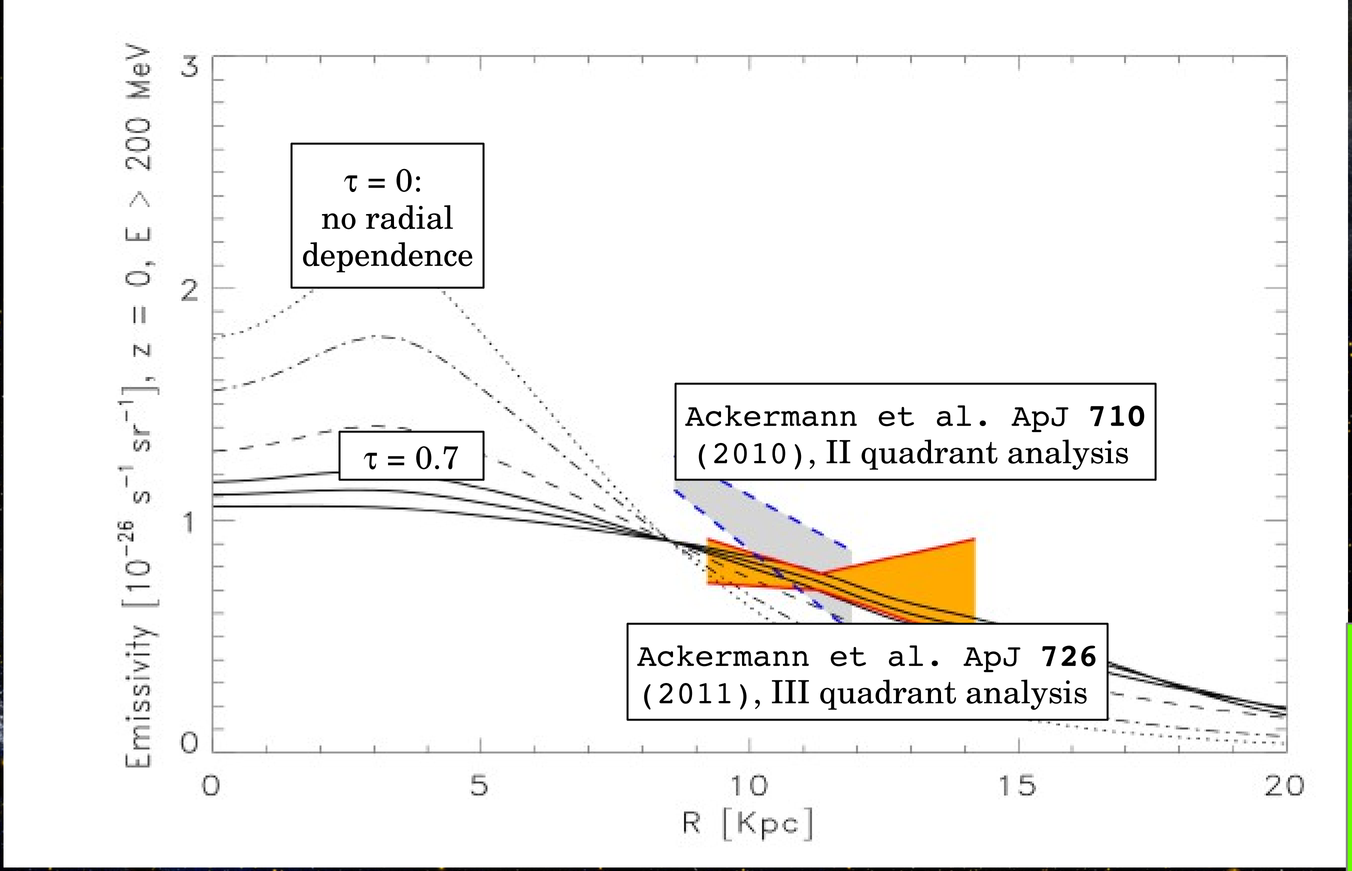


Hot topics regarding diffusion

1) Gradient problem

Phenomenological model:

$D_{perpendicular}(r,z) = D_0\, Q(r,z)^{\tau}$



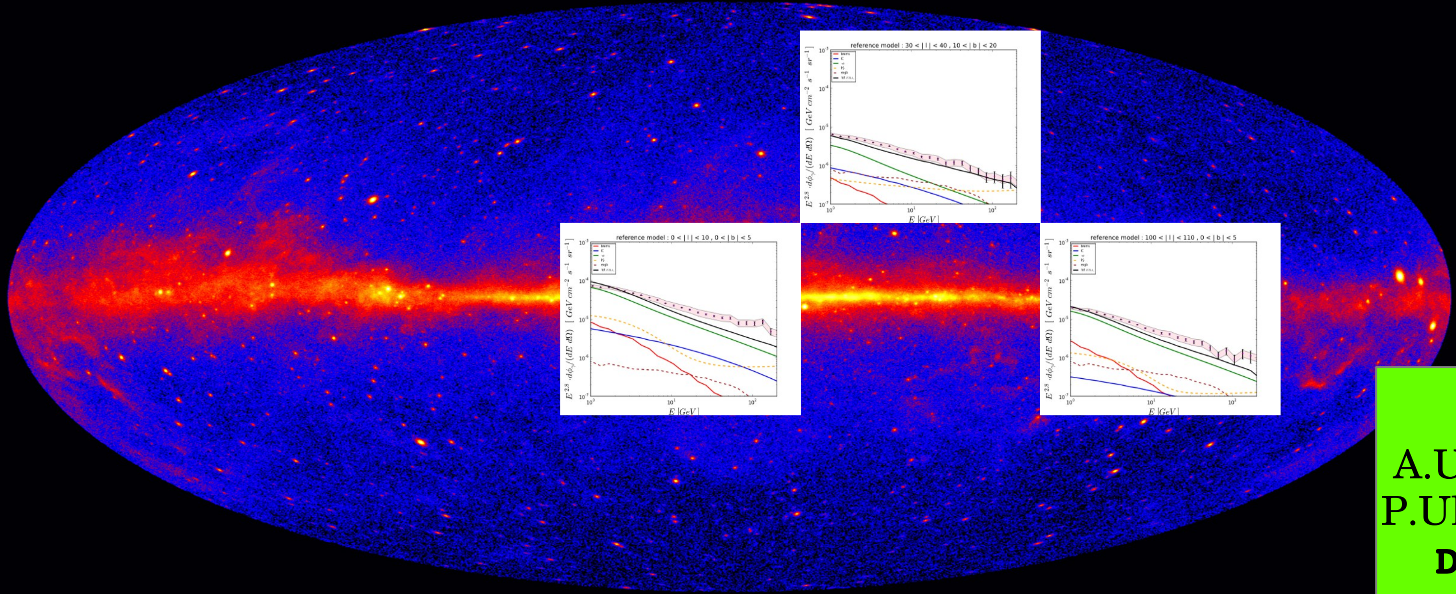
C. Evoli, D. Gaggero, D. Grasso, L. Maccione, PRL (2012)
DRAGON code

Hot topics regarding diffusion

2) Spatial gradients in the rigidity scaling of the CR diffusion coefficient?

→ The gamma-ray spectra are harder than predicted in the inner Galaxy!

→ The problem can be solved assuming a harder diffusion coefficient in the inner Galaxy: $\delta(R) = aR + b$



D.Gaggero, A.Urbano. M.Valli, P.Ullio, PRD (2015)
DRAGON code

Hot topics regarding diffusion

Many other interesting topics of research, beyond phenomenology:

→ where does the turbulence responsible for CR confinement come from?
→ can CRs generate by themselves the Alfvén waves they are scattered by?
(topic not covered here for time reasons)

Further reading:

- V.S. Berezinski *et al.*, *"Astrophysics of cosmic rays"*, Amsterdam: North Holland 1990
- R. Schlickeiser, *"Cosmic ray astrophysics"*, Springer 2002
- P. Blasi review papers (e.g. `arXiv:1311.7346`)

- PhD thesis by D. Gaggero and G. Di Bernardo:

D. Gaggero, *"Cosmic Ray Diffusion in the Galaxy and Diffuse Gamma Emission"*, Springer Berlin Heidelberg 2012
G. Di Bernardo, *"Transport, turbulence and instabilities in cosmic magnetic fields"*, `https://gupea.ub.gu.se/bitstream/2077/35797/5/gupea_2077_35797_5.pdf`

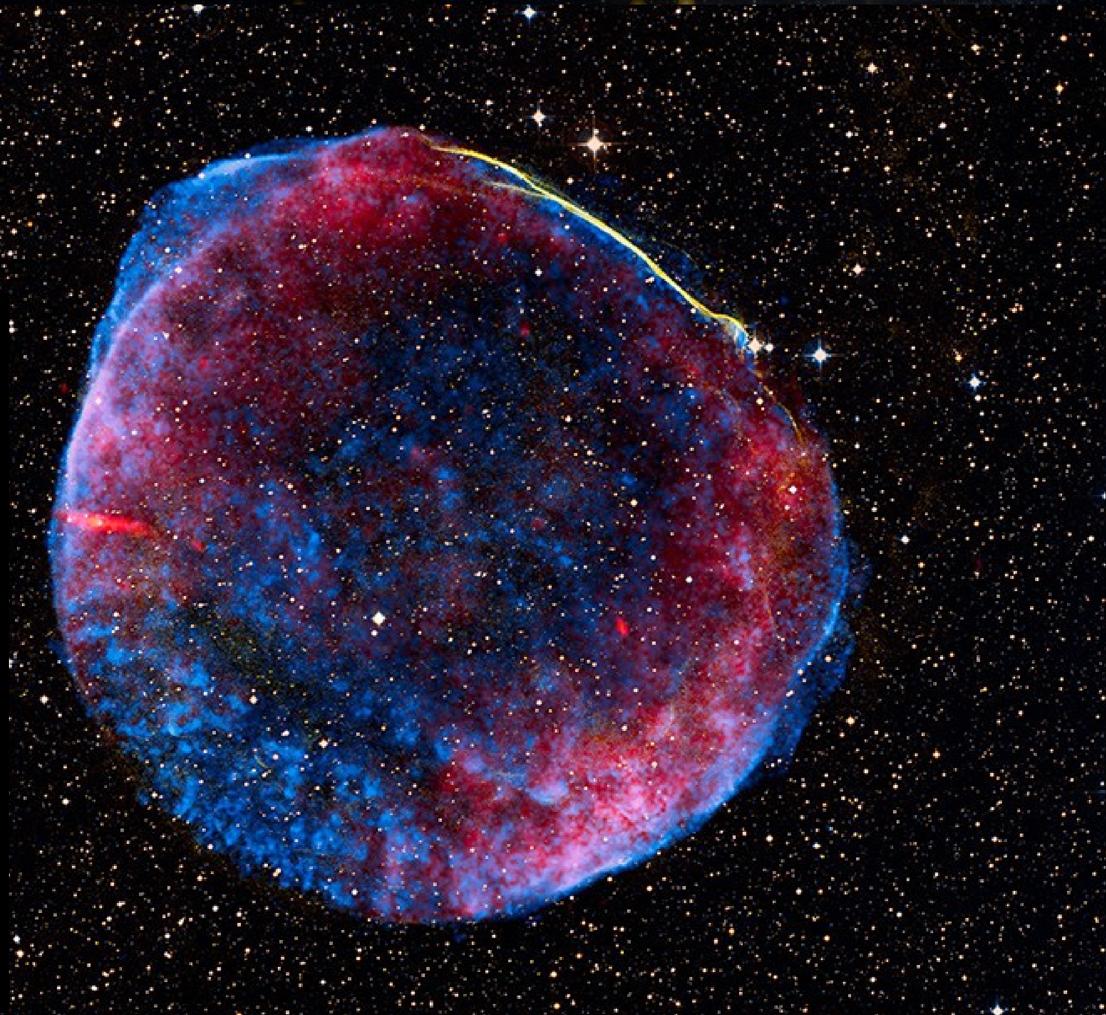
Hot topics regarding CR acceleration

As you remember from yesterday, SNRs are believed to be the sites where CR acceleration takes place.

SNR 1006

d = 2.2 kpc
age = 1009 y

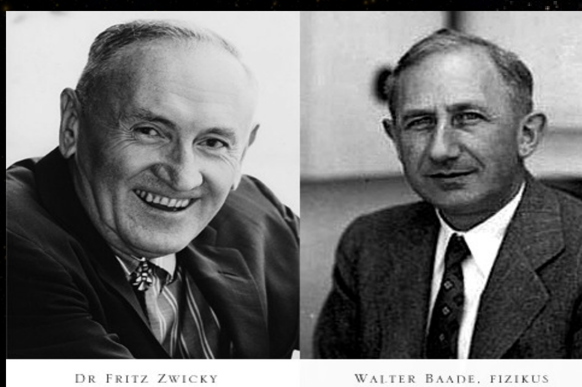
the brightest apparent magnitude stellar event in recorded history, reaching an estimated −7.5 visual magnitude (over ten times as bright as Venus and visible during daytime).



Hot topics regarding CR acceleration

As you remember from yesterday, SNRs are believed to be the sites where CR acceleration takes place.

• The original idea of SNRs accelerating CRs is due to Zwicky and Baade (1934)



• "1st order Fermi mechanism" proposed in 1970s (*Krymsky 1977, Bell 1978, Blandford & Ostriker 1978*). It was inspired by a different previoused idea by E. Fermi

• The "smoking gun" of hadronic acceleration up to TeV and PeV energies (TeVatrons, PeVatrons) has been one of the main topic of research in the latest decades!

Hot topics regarding CR acceleration

The "smoking gun" of hadronic acceleration up to TeV and PeV energies (TeVatrons, PeVatrons) has been one of the main topic of research in the latest decades!

Many evidences of hadronic CR acceleration is actually taking place in SNRs were collected through the years.
Morlino & Caprioli 2011 about Tycho SNR)
Fermi-LAT collaboration paper: *Ackermann et al. 2013*

This discussion has been going on for 80 years!

1934

Title: Cosmic Rays from Super-novae
Authors: Baade, W., ; Zwicky, F.
Publication: Contributions from the Mount Wilson Observatory, vol. 3, pp.79-83
Publication Date: 00/1934
Origin: ADS
Keywords: Supernovae
Comment: Reprinted from Proceedings of the National Academy of Sciences, 20, 259-262, 1934.
Bibliographic Code: 1934CoMtW...3...79B

Abstract

The hypothesis that supernova emit cosmic rays is in reasonable agreement with cosmic ray observations.

Hot topics regarding CR acceleration

The "smoking gun" of hadronic acceleration up to TeV and PeV energies (TeVatrons, PeVatrons) has been one of the main topic of research in the latest decades!

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Cosmic ray mystery solved

High-energy particles called cosmic rays that batter the Earth's atmosphere originate in the remnants of supernovae

2013

Hot topics regarding CR acceleration

The “smoking gun” of hadronic acceleration up to TeV and PeV energies (TeVatrons, PeVatrons) has been one of the main topic of research in the latest decades!

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Still many things are not clear

Hot topics regarding CR acceleration

– ***Are CRs are actually accelerated up to the knee?***
– ***Non-linear phenomena in CR acceleration***

The standard theory does not explain the very large energies reached CR particles.
A way to determine the maximum energy is compare the energy-dependent acceleration time with the lifetime of a SNR
If the diffusion coefficient is calculated in the same way as we saw yesterday, the acc. time is

$$\tau_{\rm acc} \sim \frac{D(E)}{V_{\rm sh}^2} \sim 10^5 \left(\frac{E}{10\,{\rm GeV}}\right)^{\delta} \left(\frac{V_{\rm sh}}{10^3\,{\rm km/s}}\right)^{-2} \,{\rm y}$$

If the magnetic field is amplified somehow, the acceleration time gets lower, and this makes it a bit easier to reach multi-TeV energies. If Bohm diff. Applies (D = kT/eB):

$$\tau_{\rm acc} \sim \frac{D(E)}{V_{\rm sh}^2} \sim 3,3 \cdot 10^4 \left(\frac{E}{1\,{\rm GeV}}\right) \left(\frac{V_{\rm sh}}{10^3\,{\rm km/s}}\right)^{-2} \left(\frac{B}{100\,\mu{\rm G}}\right)^{-1} \,{\rm s}$$

$$E_{\rm max} = 3 \cdot 10^5 \left(\frac{T_s}{300\,{\rm y}}\right) \left(\frac{V_{\rm sh}}{1000\,{\rm km/s}}\right)^2 \,{\rm GeV}$$

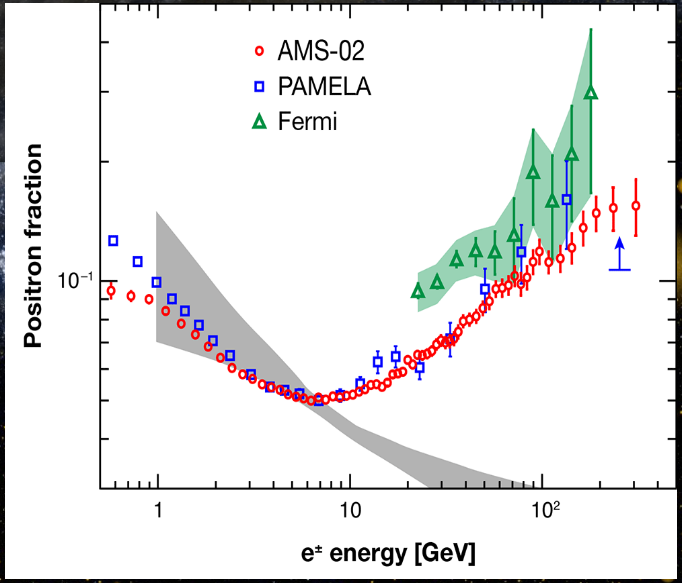
A magnetic field amplification mechanism is needed. This is still an open problem.
Again streaming instability may play a role? Accelerated CRs excite plasma waves that are responsible of their own confinement...

Hot topics regarding CR acceleration

Not only Supernova Remnants: new classes of sources?

We look, as usual, at anomalies in the data.
As Mauro explained, it is interesting to look at antiparticles.

E.g. let's focus on positrons.
As I explained yesterday, the seconday-to-primary ratios are expected to decrease with energy (remember the B/C?)
It is possible to show, using the same arguments, that also the positron-to-electron ratio is expected to decrease. But the data show the opposite trend!!



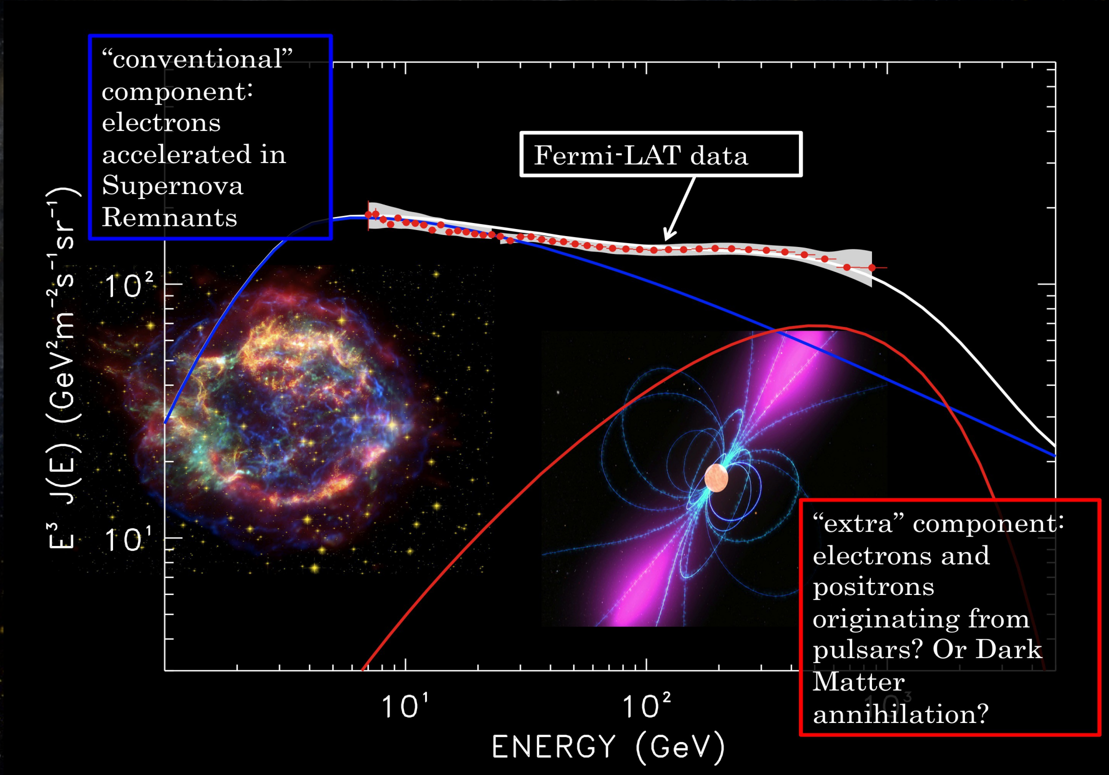
Hot topics regarding CR acceleration

Not only Supernova Remnants: new classes of sources?

It is well known that these results were interpreted in several ways.

1) A previously unaccounted population of primary electron and positrons with hard spectrum is present, coming from a local source (e.g. a pulsar)?

2) An exotic population of primary electron and positions is present, coming from Dark Matter annihilation or decay?



Hot topics regarding CR acceleration

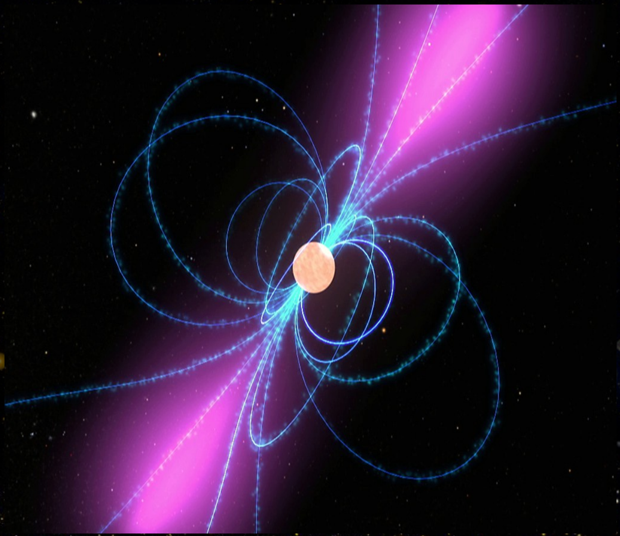
Not only Supernova Remnants: new classes of sources?

Summary of different interpreatations with pros and cons

Pulsar interpretation.

Quite natural: the energetic of observed nearby pulsars is compatible with observed fluxes.
Might be confirmed by the detection of a dipole anisotropy pointing towards a known pulsar..
No anisotropy detected so far, but the interpretation is fine with current upper limits.

<u>**Very incomplete list of papers:**</u>
P.D.Serpico arXiv:0810.4846, D. Hooper et al. ArXiv:0810.4846, S.Profumo arXiv:0812.4457, I. Buesching et al. ArXiv:0804.0220, D. Grasso et al. ArXiv:0905.0636, T.Delahaye et al. ArXiv:1002.1910, G. Di Bernardo et al. ArXiv:1010.0174, **and many others...**

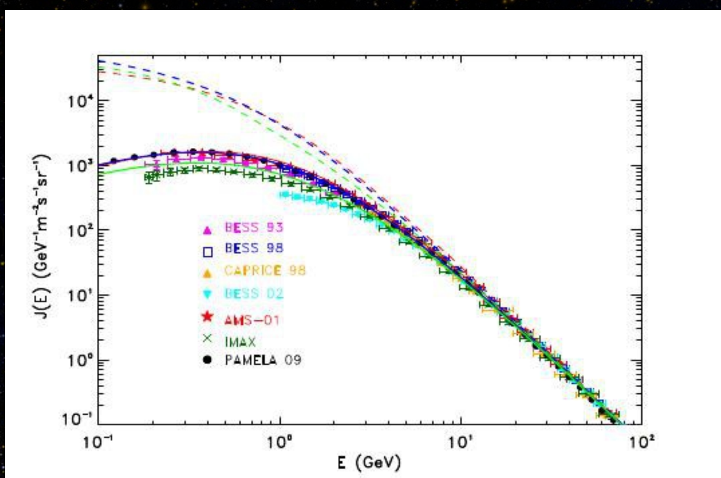


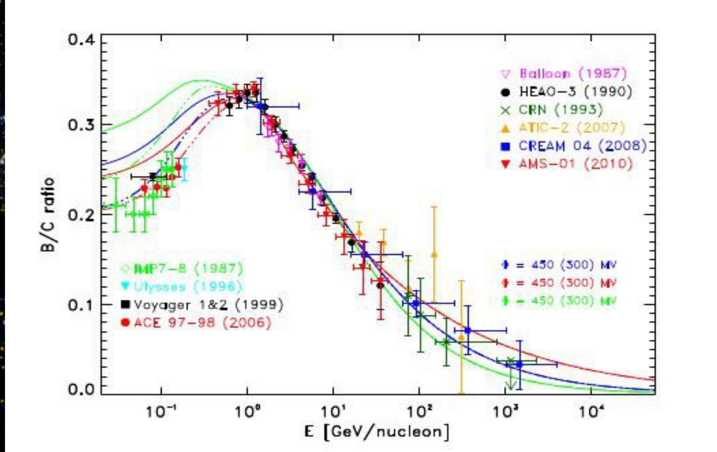
Hot topics regarding CR acceleration

Not only Supernova Remnants: new classes of sources?

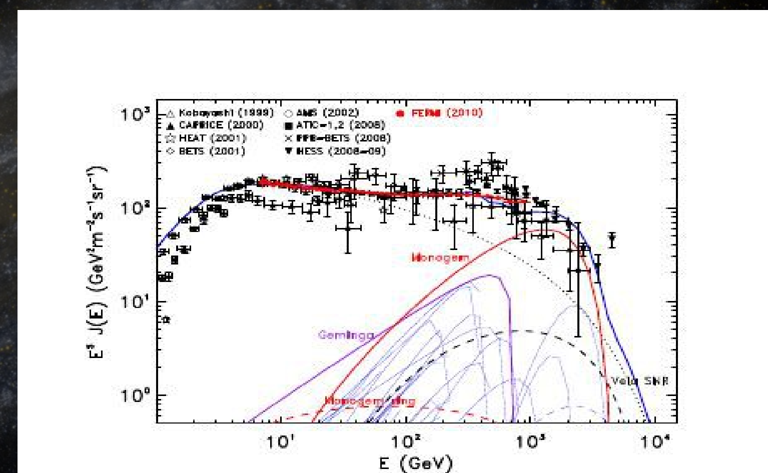
Results from the DRAGON team regarding the PULSAR scenario.

Using diffusion setups that consistently reproduce the protons, antiprotons, B/C and other nuclei ratio, we were able to fit the positron fraction rising as well as absolute leptonic fluxes with a conventional component + local sources (pulsars, SNRs)

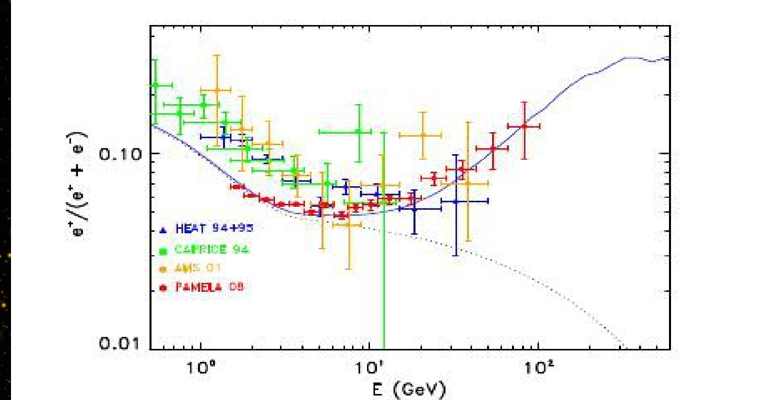




G. Di Bernardo, C.Evoli, D.Gaggero, D.Grasso, L.Maccione, M.N.Mazziotta, arXiv:1010.0174



(a)



Hot topics regarding CR acceleration

Not only Supernova Remnants: new classes of sources?

Summary of different interpreatations with pros and cons

Dark Matter interpretation.

Not so natural for many reasons. Very challenging for model builders:
- DM particle should be heavy
- it requires very high cross section (boost factor)
- it requires a "leptophilic" behaviour (no annihilation into hadrons)

(See e.g. Arkani-Hamed arXiv:0810.0713 for a model with Sommerfeld enhancement that includes all these features)

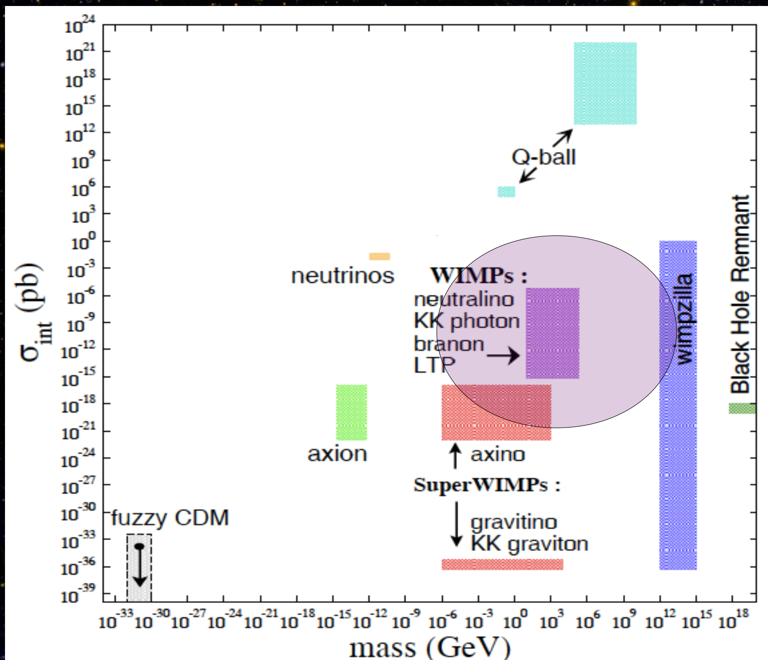
Might be strongly constrained or ruled out by antiproton measurements, gamma rays and other observables.

(See e.g. Evoli et al. ArXiv:1108.0664)

Very popular in the literature! (list taken from a slide by M.Cirelli)

M.Pospelov and A.Ritz, 0810.1502: Secluded DM - A.Nelson and C.Spitzer, 0810.5167: Slightly Non-Minimal DM - Y.Nomura and J.Thaler, 0810.5397: DM through the Axion Portal - R.Harnik and G.Kribs, 0810.5557: Dirac DM - D.Feldman, Z.Liu, P.Nath, 0810.5762: Hidden Sector - T.Hambye, 0811.0172: Hidden Vector – Yin, Yuan, Liu, Zhang, Bi, Zhu, 0811.0176: Leptonically decaying DM - K.Ishiwata, S.Matsumoto, T.Moroi, 0811.0250: Superparticle DM - Y.Bai and Z.Han, 0811.0387: sUED DM - P.Fox, E.Poppitz, 0811.0399: Leptophilic DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.0477: Hidden-Gauge-Boson DM – K.Hamaguchi, E.Nakamura, S.Shirai, T.T.Yanagida, 0811.0737: Decaying DM in Composite Messenger – E.Ponton, L.Randall, 0811.1029: Singlet DM - A.Ibarra, D.Tran, 0811.1555: Decaying DM - S.Baek, P.Ko, 0811.1646: U(1) Lmu-Ltau DM - C.Chen, F.Takahashi, T.T.Yanagida, 0811.3357: Decaying Hidden-Gauge-Boson DM - I.Cholis, G.Dobler, D.Finkbeiner, L.Goodenough, N.Weiner, 0811.3641: 700+ GeV WIMP - E.Nardi, F.Sannino, A.Strumia, 0811.4153: Decaying DM in TechniColor - K.Zurek, 0811.4429: Multicomponent DM – M.Ibe, H.Murayama, T.T.Yanagida, 0812.0072: Breit-Wigner enhancement of DM annihilation - E.Chun, J.-C.Park, 0812.0308: sub-GeV hidden U(1) in GMSB - M.Lattanzi, J.Silk, 0812.0360: Sommerfeld enhancement in cold substructures - M.Pospelov, M.Trott, 0812.0432: super-WIMPs decays DM - Zhang, Bi, Liu, Liu, Yin, Yuan, Zhu, 0812.0522: Discrimination with SR and IC - Liu, Yin, Zhu, 0812.0964: DMnu from GC – M.Pohl, 0812.1174: electrons from DM - J.Hisano, M.Kawasaki, K.Kohri, K.Nakayama, 0812.0219: DMnu from GC - A.Arvanitaki, S.Dimopoulos, S.Dubovsky, P.Graham, R.Harnik, S.Rajendran, 0812.2075: Decaying DM in GUTs - R.Allahverdi, B.Dutta, K.Richardson-McDaniel, Y.Santoso, 0812.2196: SuSy B-L DM- S.Hamaguchi, K.Shirai, T.T.Yanagida, 0812.2374: Hidden-Fermion DM decays - D.Hooper, A.Stebbins, K.Zurek, 0812.3202: Nearby DM clump - C.Delaunay, P.Fox, G.Perez, 0812.3331: DMnu from Earth - Park, Shu, 0901.0720: Split- UED DM - .Gogoladze, R.Khalid, Q.Shafi, H.Yuksel, 0901.0923: cMSSM DM with additions - Q.H.Cao, E.Ma, G.Shaughnessy, 0901.1334: Dark Matter: the leptonic connection - E.Nezri, M.Tytgat, G.Vertongen, 0901.2556: Inert Doublet DM - C.-H.Chen, C.-Q.Geng, D.Zhuridov, 0901.2681: Fermionic decaying DM - J.Mardon, Y.Nomura, D.Stolarski, J.Thaler, 0901.2926: Cascade annihilations (light non-abelian new bosons) - P.Meade, M.Papucci, T.Volansky, 0901.2925: DM sees the light - D.Phalen, A.Pierce, N.Weiner, 0901.3165: New Heavy Lepton - T.Banks, J.-F.Fortin, 0901.3578: Pyrma baryons - Goh, Hall, Kumar, 0902.0814: Leptonic Higgs - K.Bae, J.-H. Huh, J.Kim, B.Kyae, R.Viollier, 0812.3511: electrophilic axion from flipped-SU(5) with extra spontaneously broken symmetries and a two component DM with Z2 parity – and others...

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

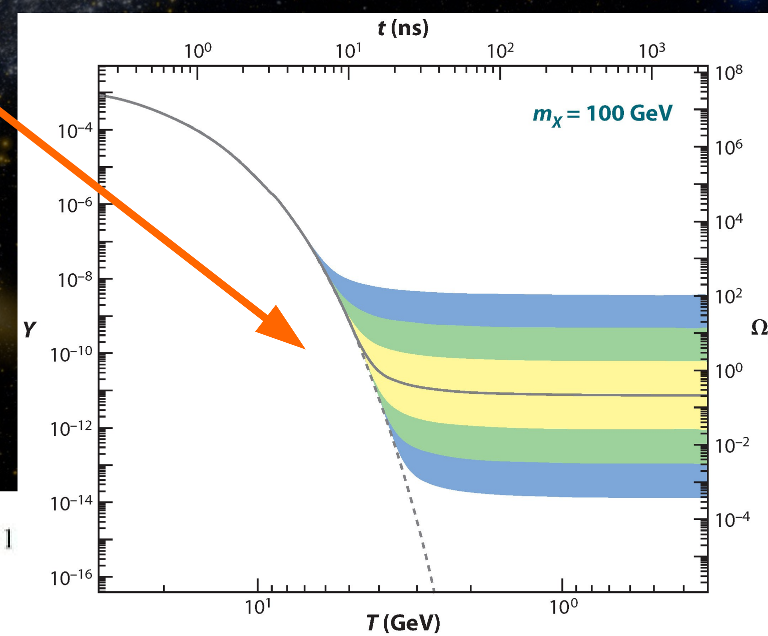


Particle physics provides many DM candidates

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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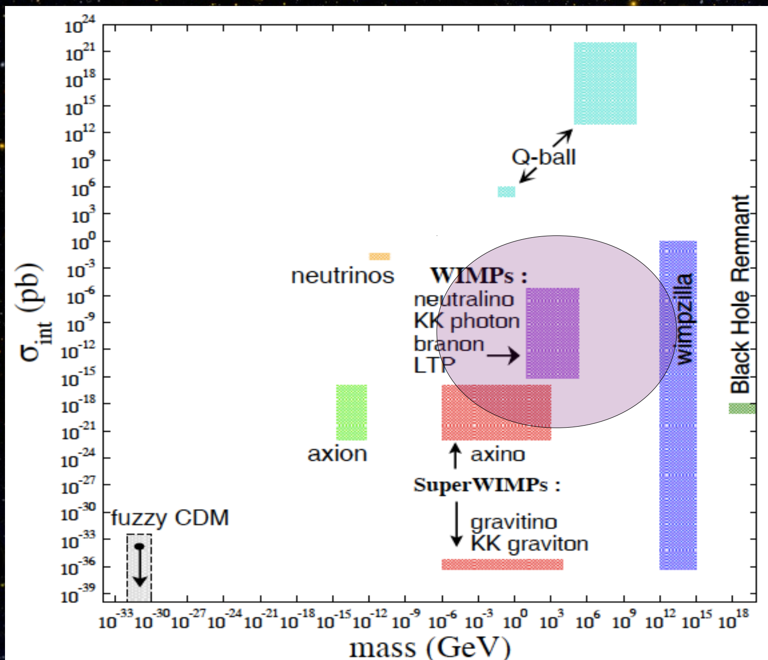

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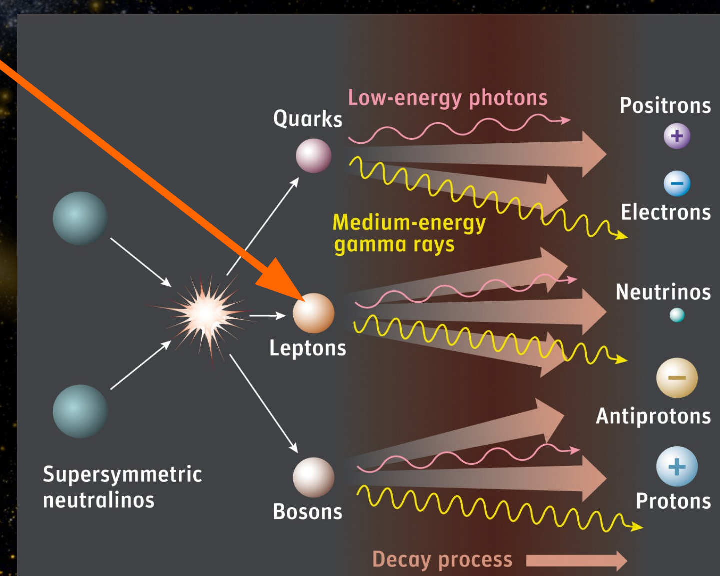

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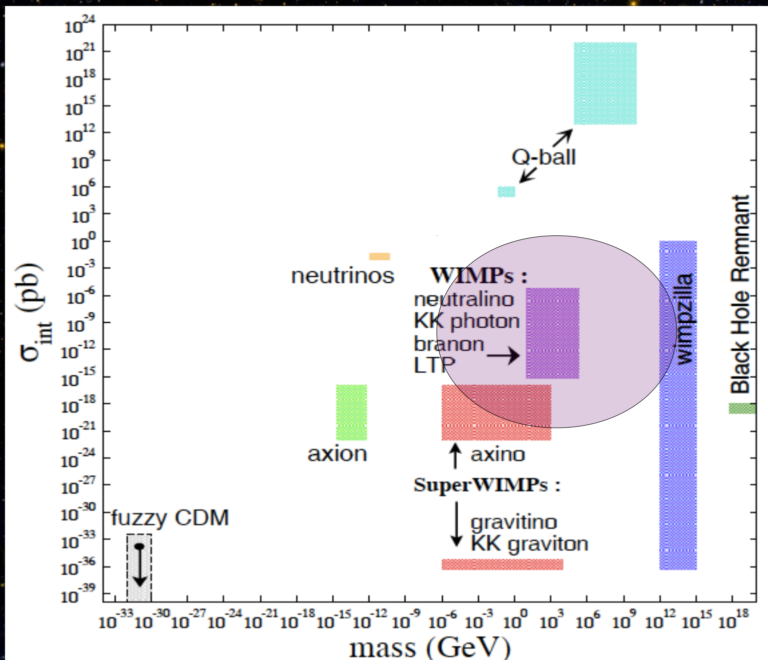

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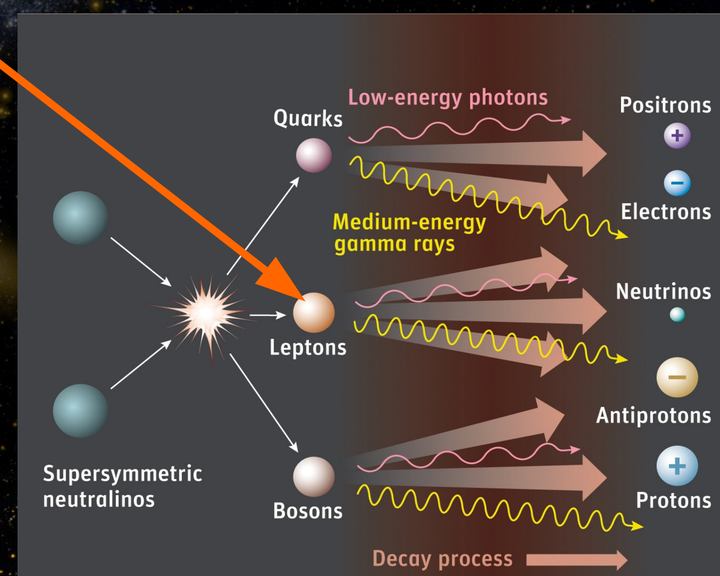
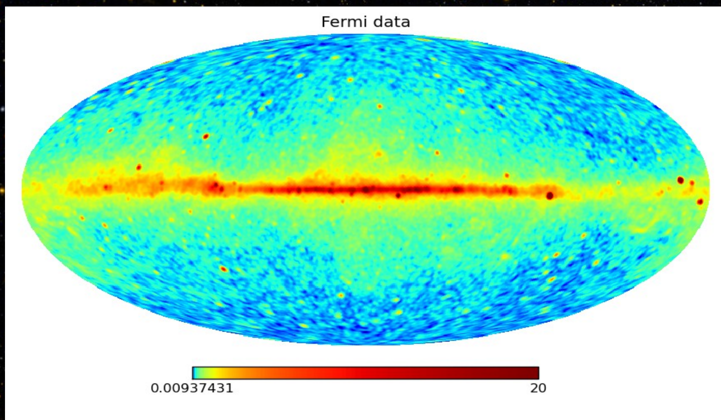


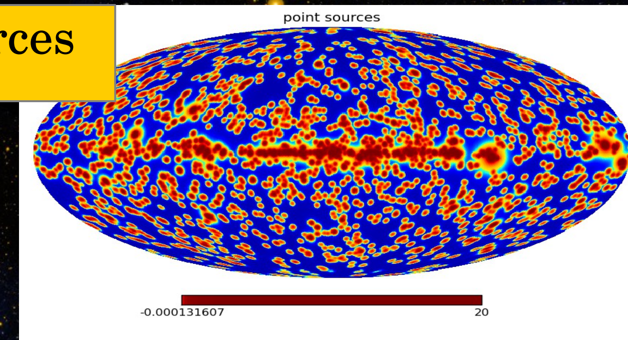
That's why the DM community has been so interested for a long time in CR physics!

The Galactic center excess

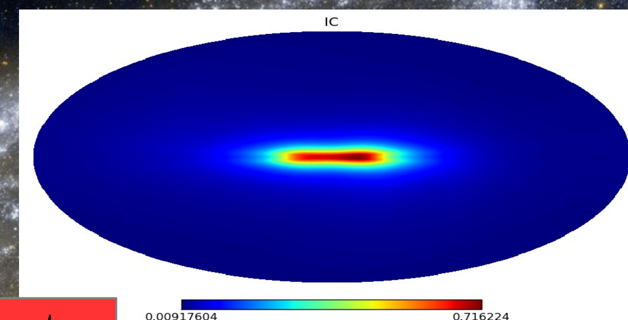


Fermi-LAT data

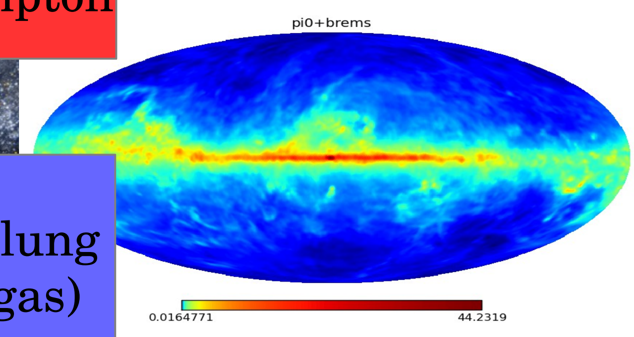
Point Sources



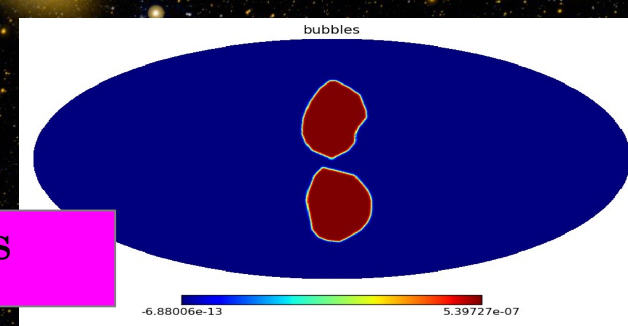
Inverse Compton



π_0 +
bremsstrahlung
(traces IS gas)



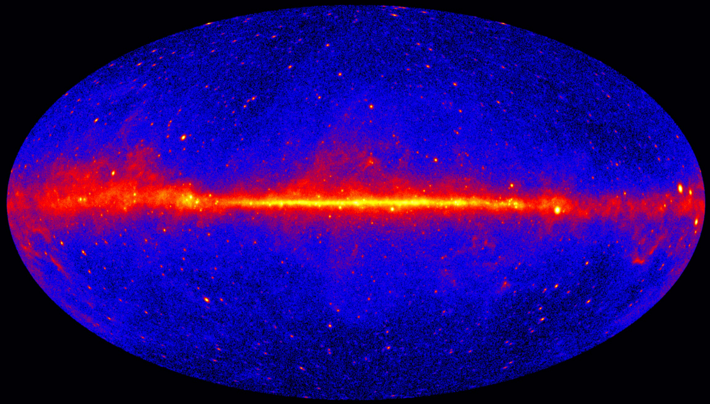
Bubbles



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



Fermi-LAT data

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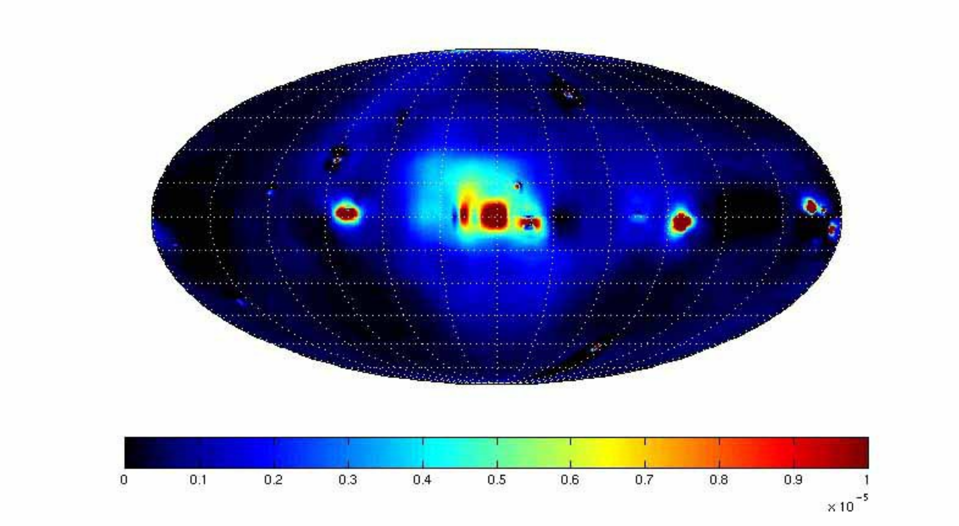
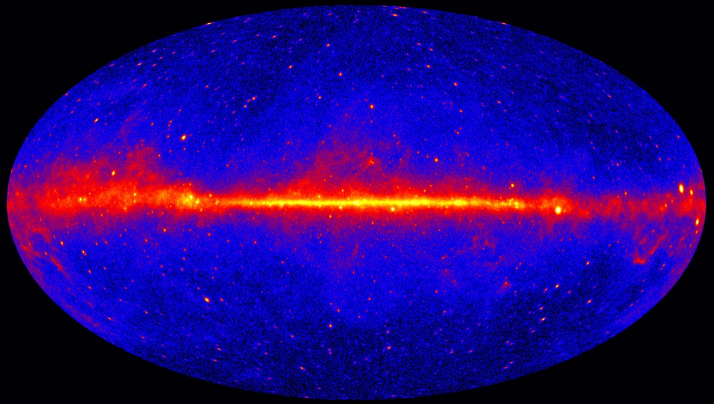
→ The goal is to understand if, once all known components are substracted, a significant residual is left

→ 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



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→ More recently: a long series of papers

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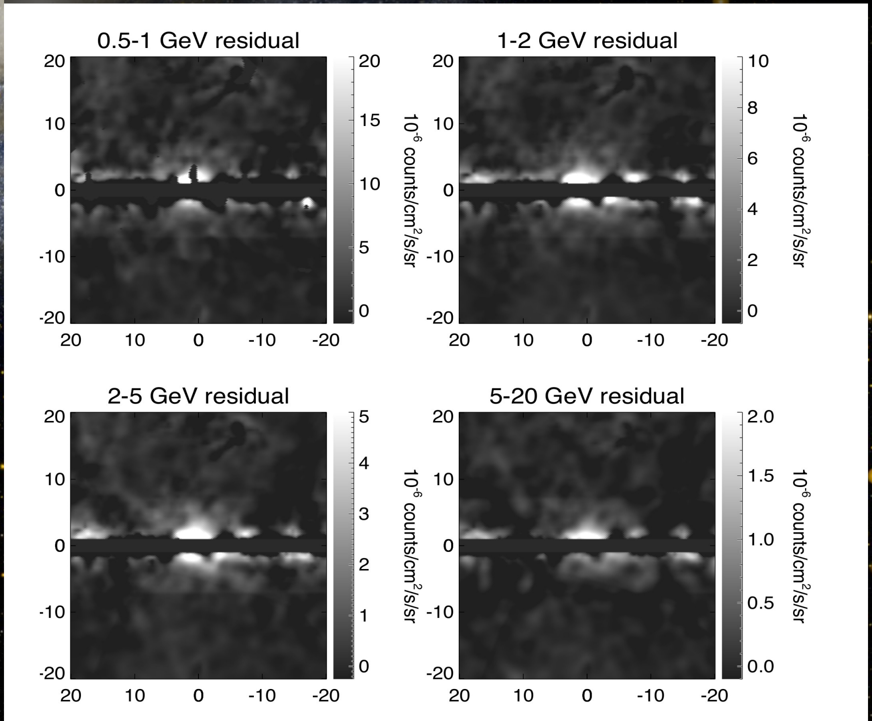
- K. N. Abazajian and M. Kaplinghat, 2012
- D. Hooper and T. R. Slatyer, 2013
- C. Gordon and O. Macias, 2013
- T. Daylan, D. P. Finkbeiner, D. Hooper, T. Linden, S. Portillo, N. L. Rodd and T. R. Slatyer, 2014
- F. Calore, I. Cholis, C. Weniger, 2014



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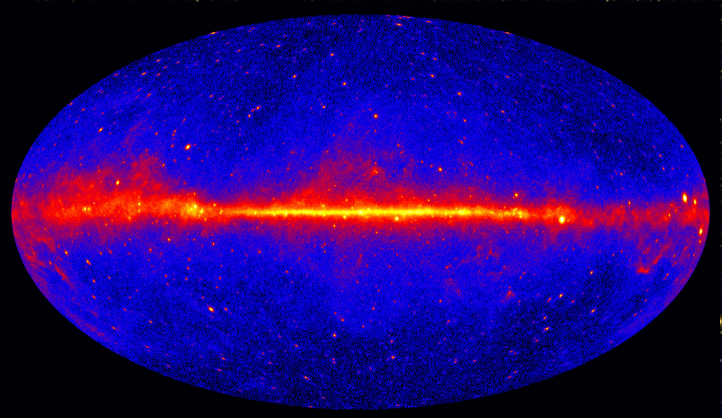

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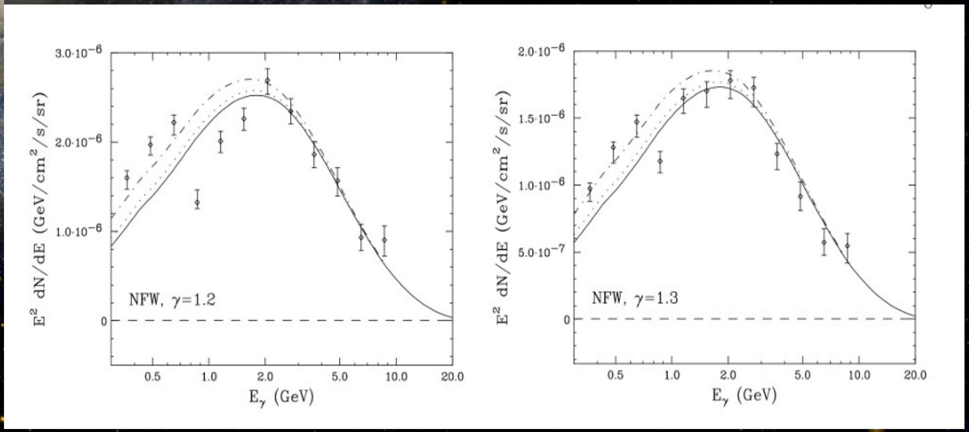
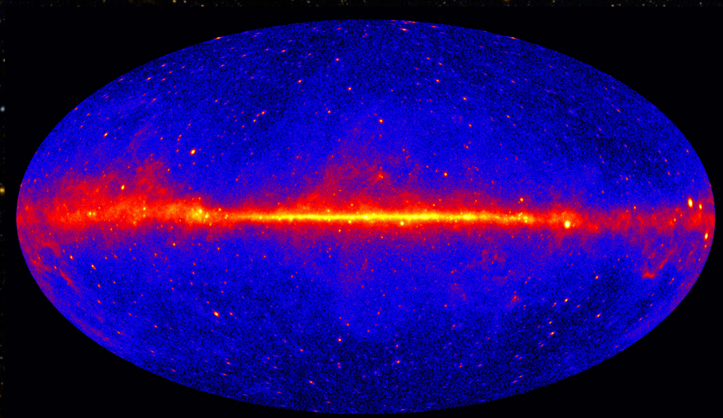


→ the spectrum of the excess is well fitted by a DM particle with m = 35 GeV annihilating into bb with a cross section close to the thermal one.

The Galactic center excess

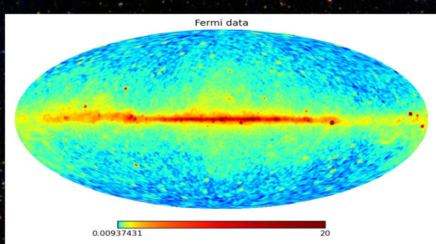


Fermi-LAT data

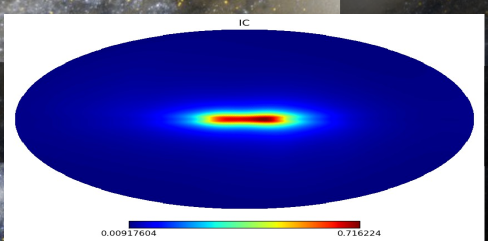
→ More recently: a long series of papers

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

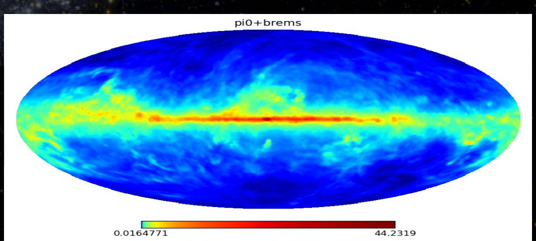
→ the gamma-ray map is written, for each energy bin, as a sum of the astrophyisical templates, and the coefficients are left free to float



$= c_1$

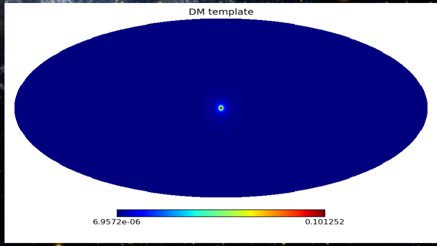


$+ c_2$



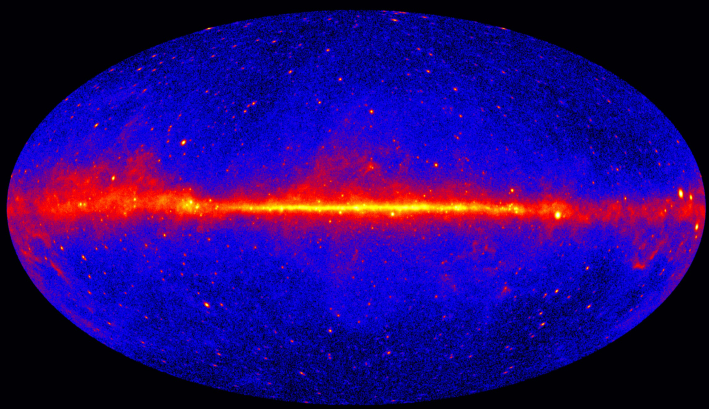
…

$\ldots + c_{DM}$



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

The Galactic center excess



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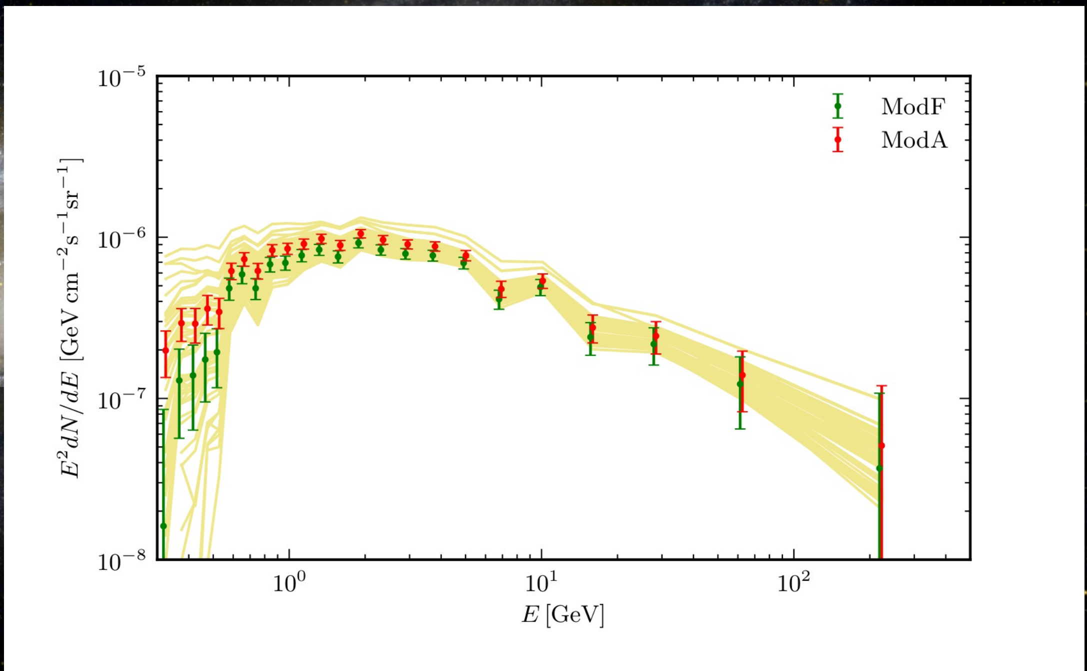


In *Calore et al. 2014* the fitting procedure is performed with a set of templates generated with GALPROP corresponding to a wide class of physical models.

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!

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?

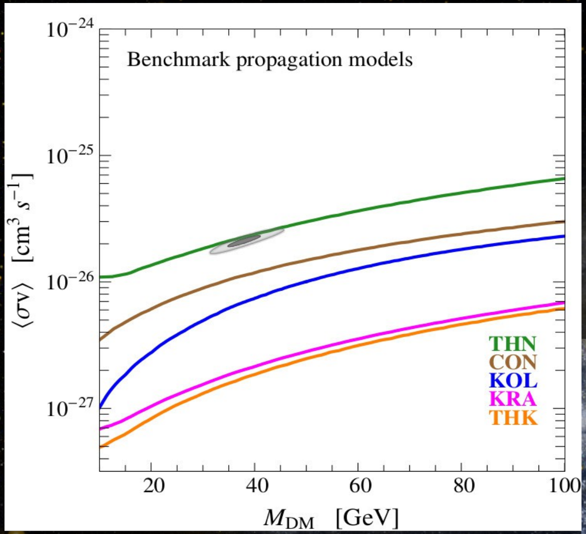
Is the DM interpretation in tension with other observables?

→ in particular, the antiprotons may provide a stringent bound

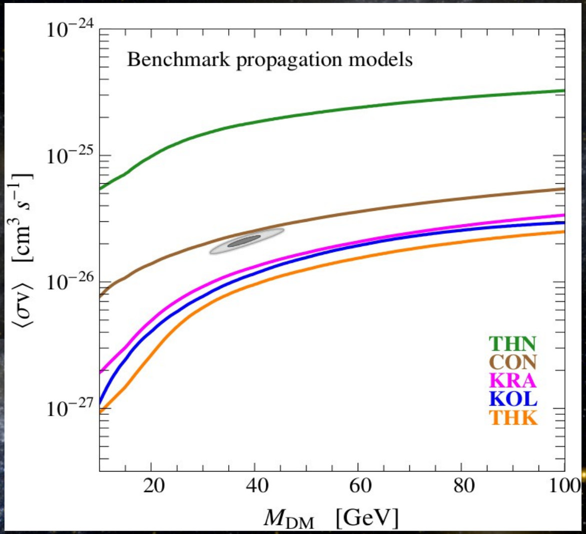
The Galactic center excess

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

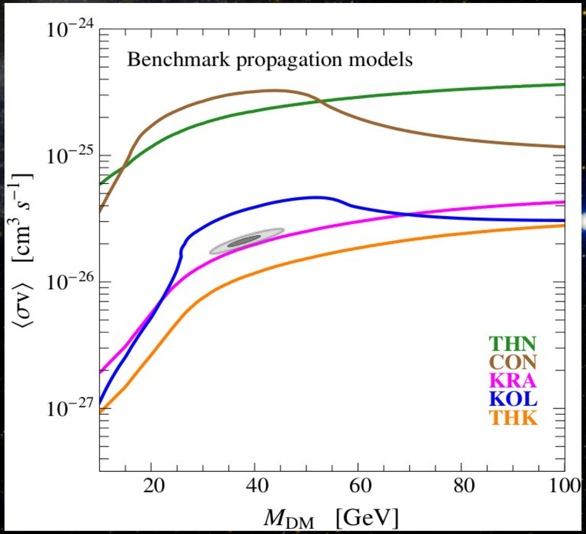
→ it depends on how much you trust the current knowledge on charge dependent modulation and on the halo size!! ←



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



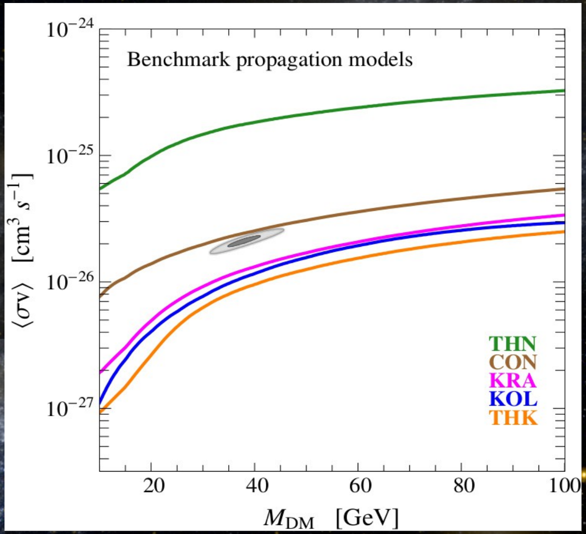
In this case the modulation potential of the antiprotons is free (a bit irrealistic!!)

The Galactic center excess

Is the DM interpretation of the Galacric 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!! ←

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

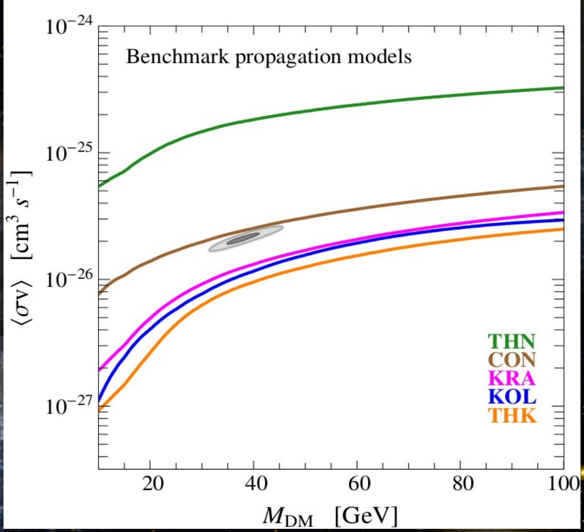
Is the DM interpretation of the Galacric center excess in tension with antiprotons?

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

M.Cirelli 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!



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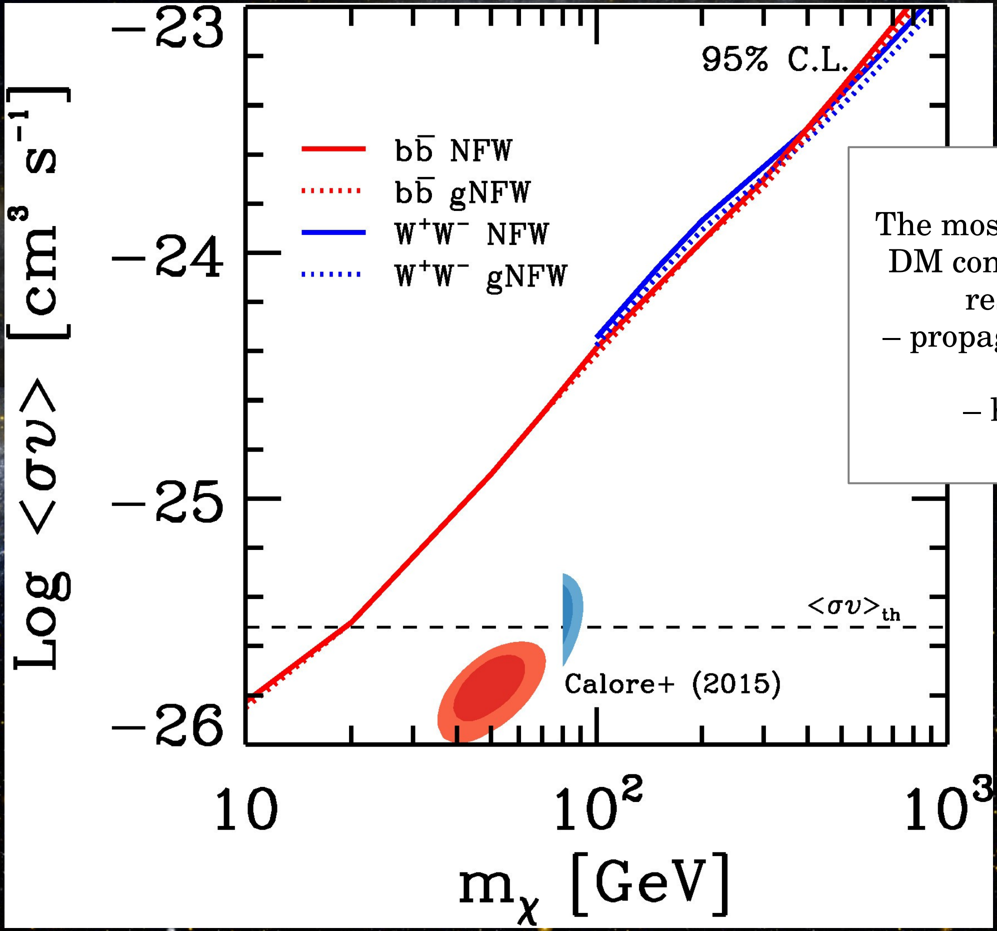
The Galactic center excess

Is the DM interpretation of the Galacric 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 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

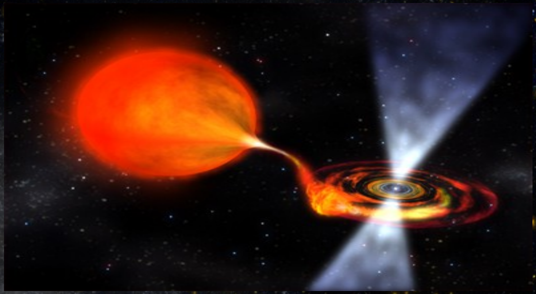
– halo size

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 …



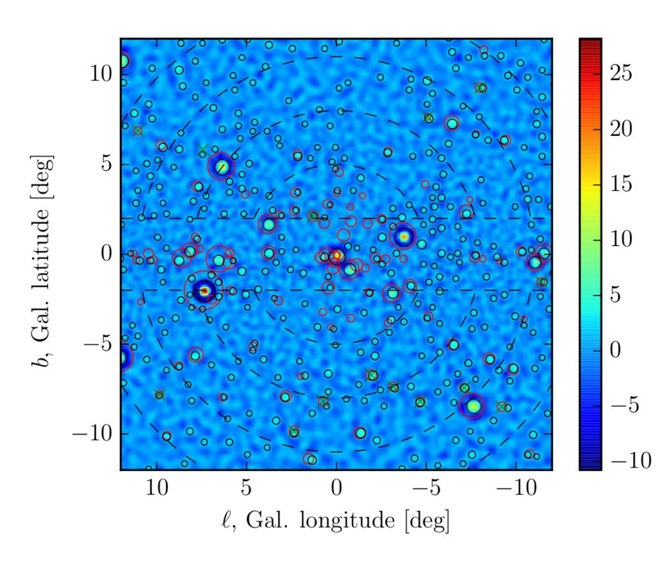
→ problems with the luminosity function?

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

The Galactic center excess

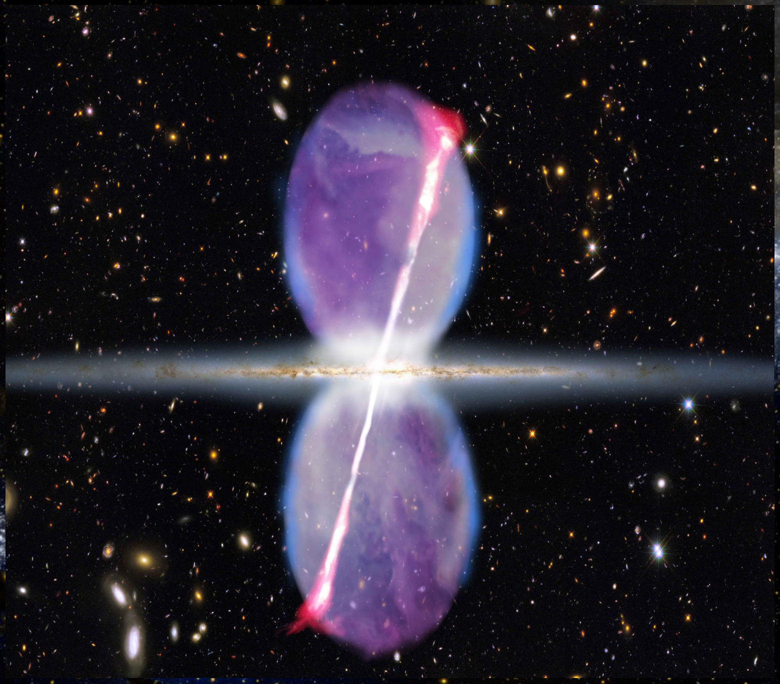
Can we explain this excess with astrophysics?

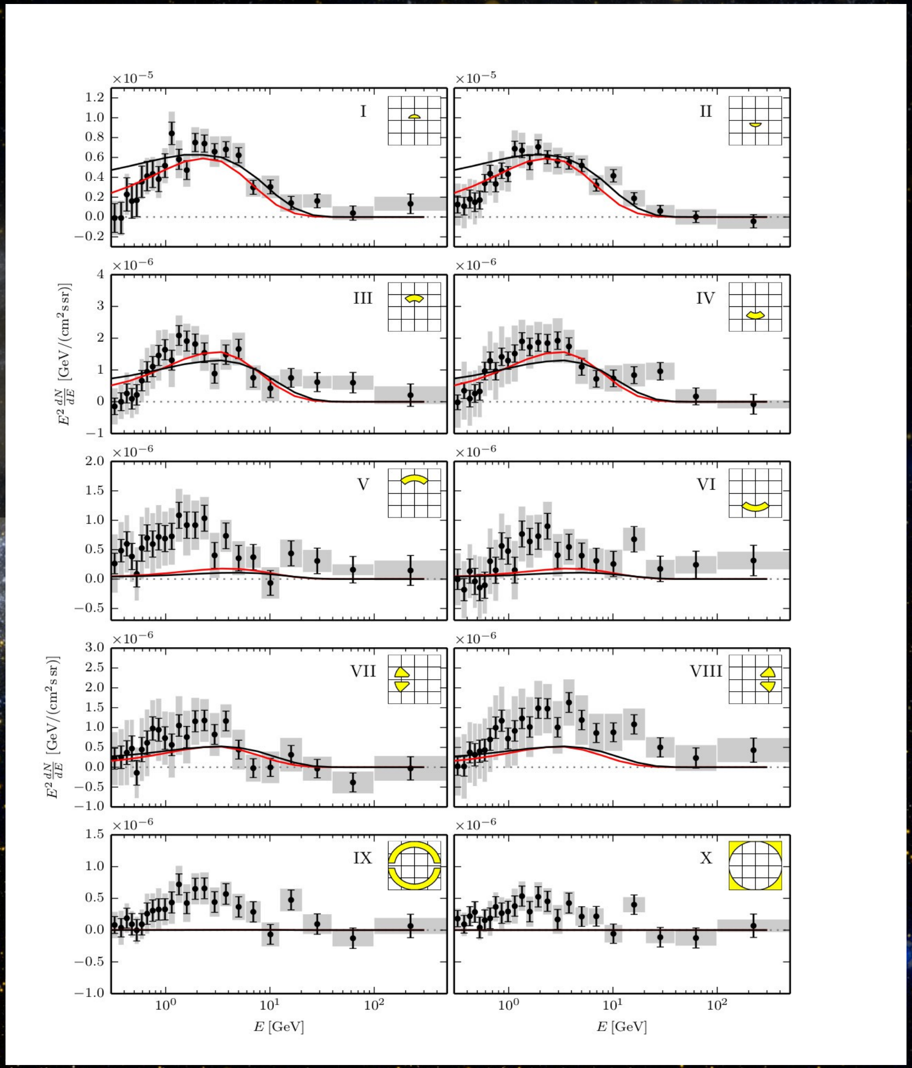
Transient phenomena?

Carlson et al. 2014 – Petrovic et al. 2015

More recently: Cholis et al. 2015

→ problems with spectra and morphology



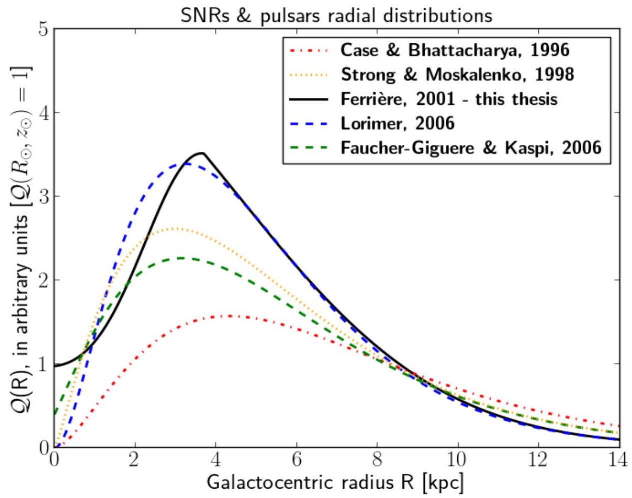


The Galactic center excess

What about a standard CR source?

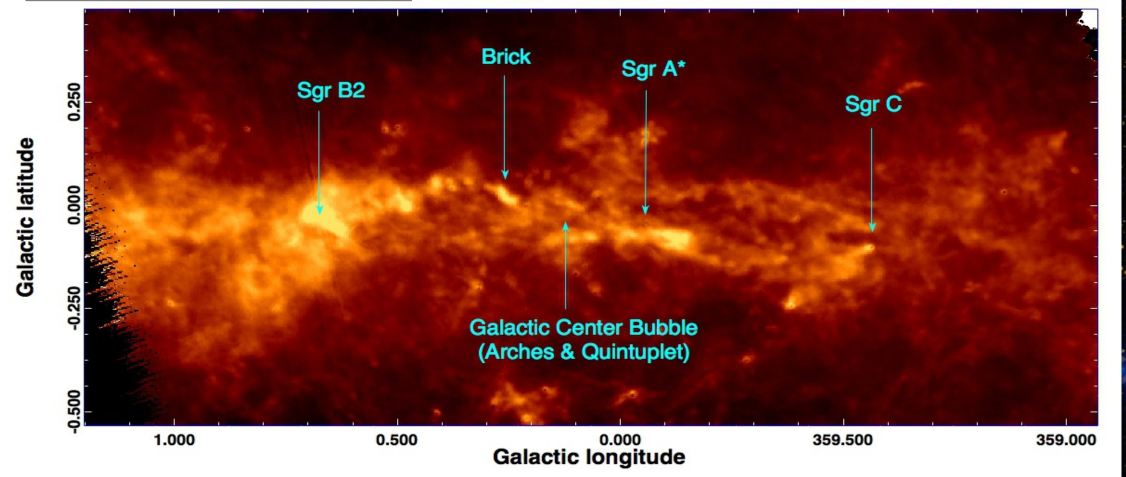
→ We know that all CR models used in these analyses are not designed to reproduce correctly the GC region!

→ 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*

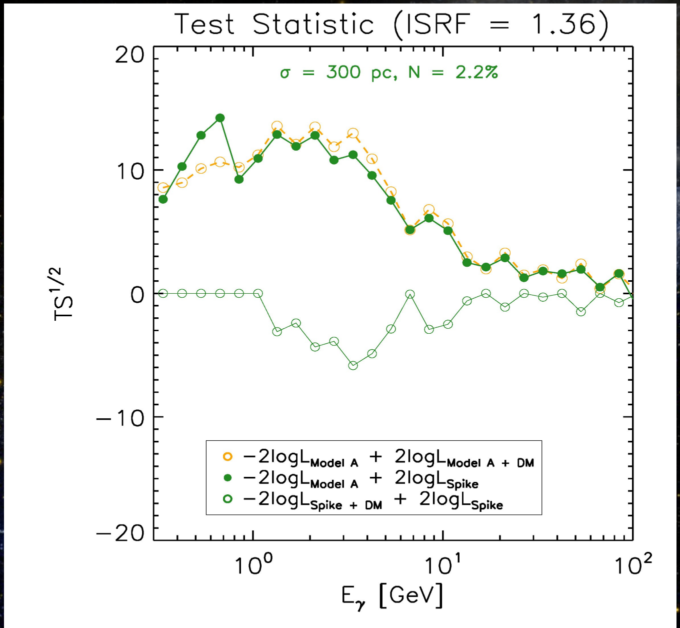
Dust temperature map of the inner Central Molecular Zone

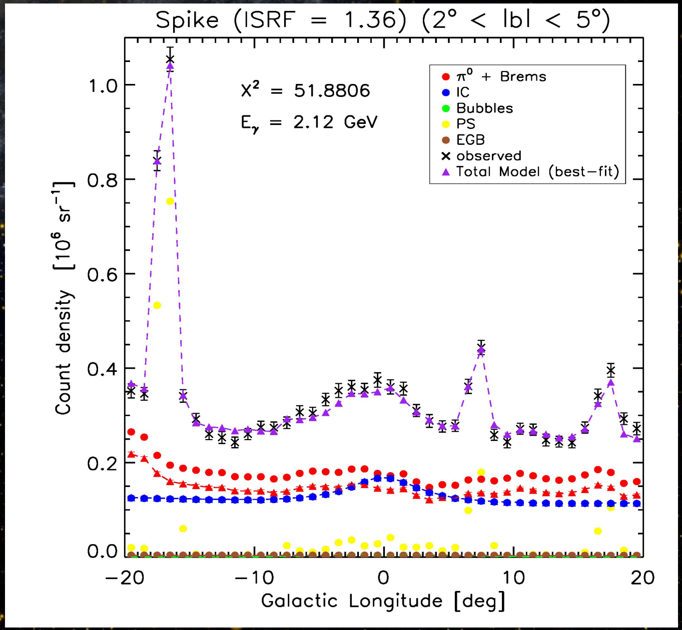


The Galactic center excess

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 as well as the DM case.

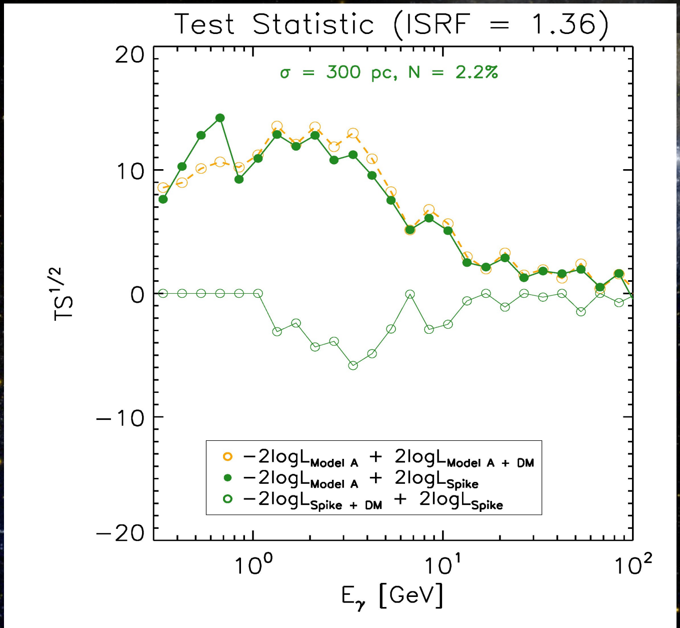


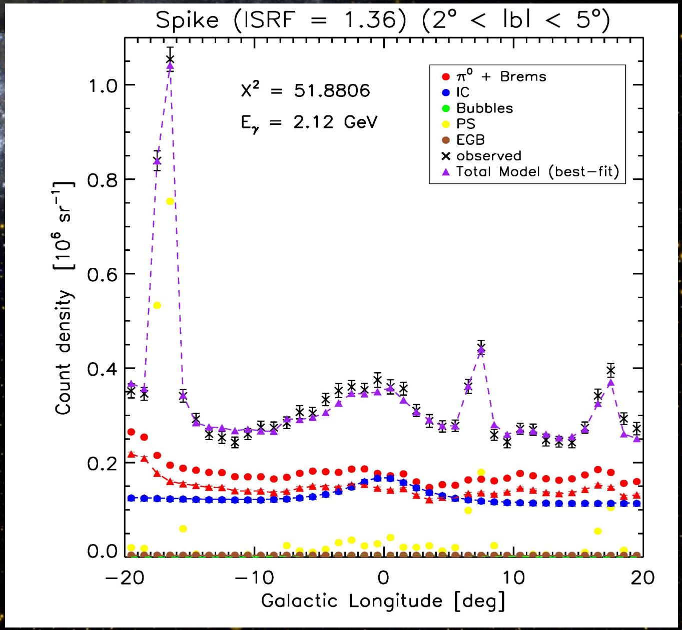


The Galactic center excess

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 acceleration and propagation in the inner Galaxy is compelling





Conclusions

– **CR physics is ~100 years old.** Very interesting from both the astrophysics and particle-physics point of view.

– **We have probably understood the main aspects of CR acceleration and propagation**, but many crucial points are still under debate

– **Many anomalies in the data**. We need a more detailed picture, more realistic simulations, more inputs from theory in order to understand what is going on.

– **Fascinating connections with different areas of science.** Will we ever indirectly detect Dark Matter looking at some anomaly in CR spectra, or in the gamma radiation originating from CRs?

Thanks for the attention!