Search for the origin of the cosmic-ray positrons

Master Thesis

Manuel Rocamora Bernal

supervised by

Yago Ascasibar, Daniele Gaggero & Miguel Á. Sánchez-Conde

Universidad Autónoma de Madrid

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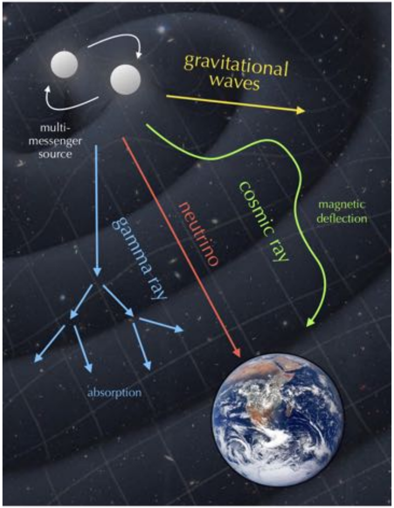
1. Introduction

Cosmic rays

Contributors to the galactic pressure and ionization

Sources

- Supernovae
- AGNs
- DM annihilations
- Young star forming regions



1. Introduction

Cosmic rays

Extremely-high energy charged particles (up to 10^{20} eV)

Components

- Primaries: produced directly by the cosmic-ray source
- Secondaries: produced by collisions or decays of the primaries

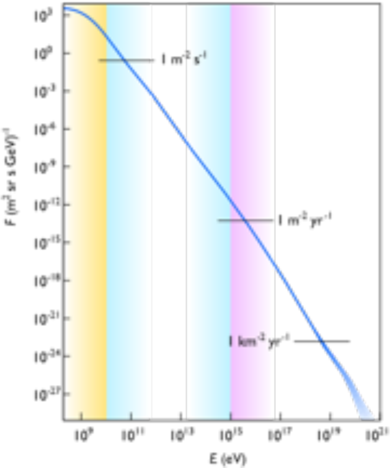


Figure: All particle spectrum of cosmic rays [Swordy, 2001]

1. Introduction

For decades, it was though that cosmic-ray positrons were only produced in collisions of cosmic-ray nuclei (from supernovae) with interstellar matter [Moskalenko & Strong, 1998]

Observational problems

- Excess in the local positron fraction above 10 GeV [Adriani et al., 2009]
- Excess of 511 keV emission near the Galactic Centre [Knödlseder et al. 2005]

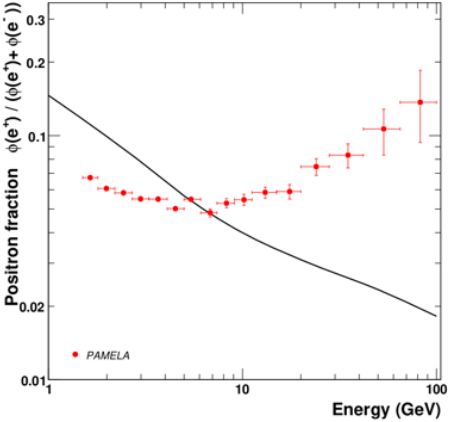


Figure: Positron fraction in the cosmic-ray spectrum measured by the PAMELA experiment [Adriani et al, 2009].

1. Introduction

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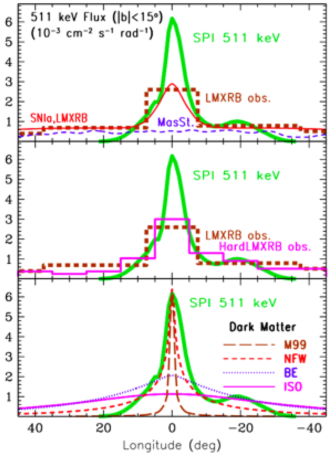


Figure: 511 keV flux as a function of galactic longitude [Prantzos et al., 2011].

1. Introduction

The nature of this source is still heavily debated
The favoured candidates are pulsars and the annihilation of dark matter particles

Aim

Most works focus separately on the origin of the local positron excess or on the observed gamma-ray flux
We explore the possibility of building a simple, self-consistent model that is able to explain them simultaneously, as a proof-of-concept

Procedure

Introduce an extra component
DRAGON: Compute cosmic-ray propagation [Evoli et al., 2017]
HERMES: Compute their associated radiation sky maps [Dundovic et al., 2021]
Comparison with Fermi-LAT gamma-ray and radio sky maps

Codes available at `https://github.com/cosmicrays`
Gamma-ray data at `https://fermi.gsfc.nasa.gov/ssc/data/access/`
Radio data at `https://lambda.gsfc.nasa.gov/product/foreground/fg_diffuse.cfm`

2. Cosmic rays: Propagation

Diffusion - loss equation

$$\frac{\partial}{\partial t}\frac{dn}{dE}(\mathbf{x},E) = \nabla\left[K(\mathbf{x},E)\nabla\frac{dn}{dE}(\mathbf{x},E)\right] + \frac{\partial}{\partial E}\left[b(\mathbf{x},E)\frac{dn}{d\gamma}(\mathbf{x},E)\right] + Q(\mathbf{x},E) \quad (1)$$

Diffusion term | Energy loss term | Source

- $K = K_0\left(\frac{E}{E_0}\right)^{\delta}$
- $b(\mathbf{x},E) \equiv -\frac{dE}{dt}(\mathbf{x},E) = \sum_i b_i(\mathbf{x},E)$

2. Cosmic rays: Energy loss processes

Processes

- Inverse Compton Scattering
- Synchrotron radiation
  1. B_{ord} by [Pshirkov et al., 2011]
  2. $B_{ran} \propto exp\left(-\frac{r}{R_B}\right) exp\left(-\frac{|z|}{z_t}\right)$
     with $R_B = 8.5$ kpc, $z_t = 4$ kpc
- Coulomb interactions
- Bremsstrahlung
- Ionization of hydrogen atoms

Hadrons:

- Pion production

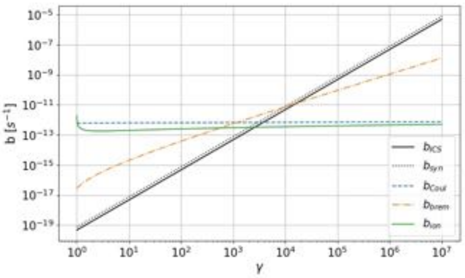


Figure: Energy loss for an electron in the solar neighborhood

2. Cosmic rays: Source

Primaries

Shape: broken power-laws

Morphology: Supernovae [Ferriere, 2001]

Extra

Shape: power-law with cutoff

Morphology:

- Squared NFW [Navarro et al., 1996]: Dark Matter
- Lorimer [Lorimer et al., 2006]: Pulsars
- McMillan [McMillan, 2016]: Old stars (tracing millisecond pulsars)

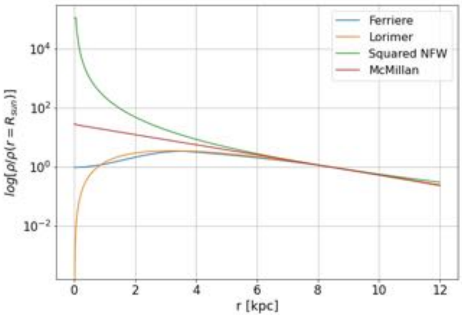


Figure: Injection profiles at z = 0 and normalised to their values at $r = R_{sun}$

3. Cosmic-ray spectra: Nuclei

Species	α_1	$E_{b,1}$ [GeV]	α_2	$E_{b,2}$ [GeV]	α_3
p	1.8	7	2.40	335	2.26
He	2.0	7	2.28	165	2.15
C	2.0	7	2.38	165	2.15
O	2.0	7	2.38	165	2.15

Table: Injection parameters used for nuclei. Taken from [Fornieri et al., 2020].

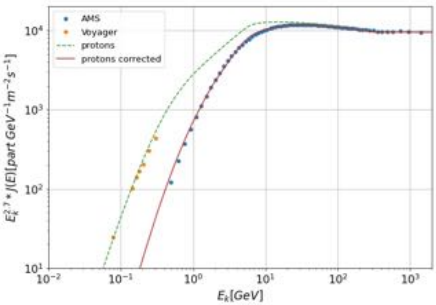


Figure: Proton spectrum in the solar neighbourhood

$K_0 = 3.7\ 10^{28}\ cm^2/s$
$\delta = 0.45$
$< \phi > = 0.54$

3. Cosmic-ray spectra: Lepton injection parameters

α_1	$E_{b,1}$ [GeV]	α_2	$E_{b,2}$ [GeV]	α_3	$E_{b,3}$ [GeV]	α_4
1	4	2.3	9	2.75	40	2.55

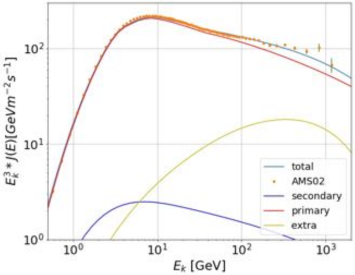
Table: Injection parameters used for primary electrons. Taken from [Fornieri et al., 2020].

Morphology	α	Cutoff [GeV]	χ^2_ν
Squared NFW	1.55	1800	2.37
Lorimer	1.70	900	2.41
McMillan	1.65	1000	2.48

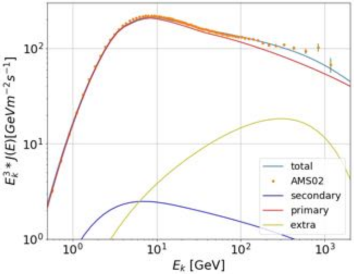
Table: Injection parameters used for the extra e^+e^- injection.

3. Cosmic-ray spectra: Electrons

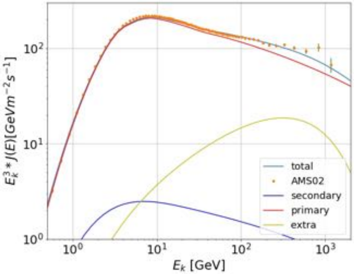
Squared NFW



Lorimer

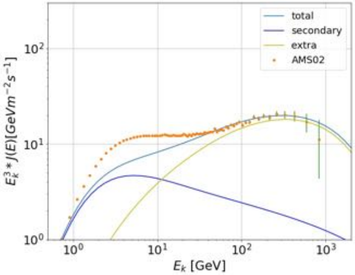


McMillan

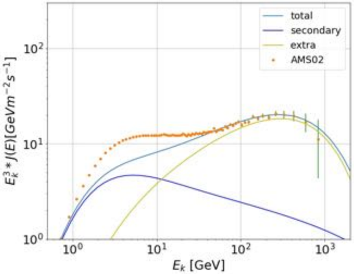


3. Cosmic-ray spectra: Positrons

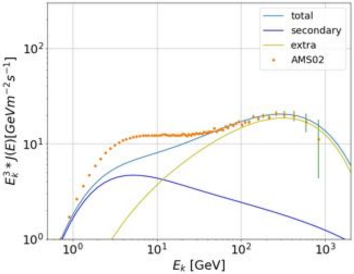
Squared NFW



Lorimer

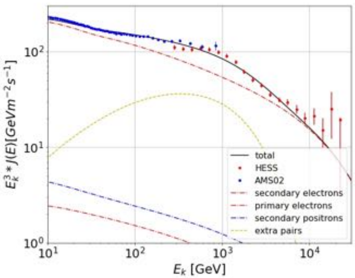


McMillan

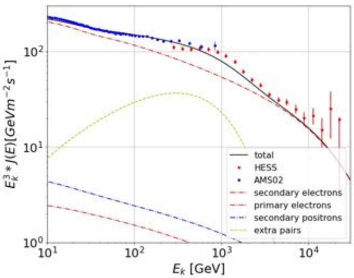


3. Cosmic-ray spectra: Leptons

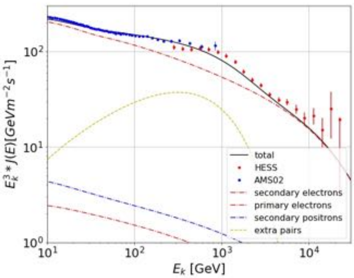
Squared NFW



Lorimer

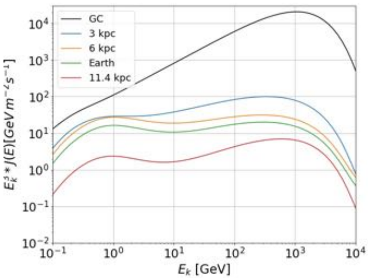


McMillan

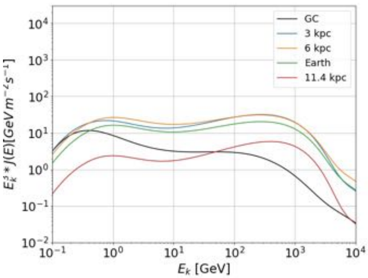


3. Cosmic-ray spectra

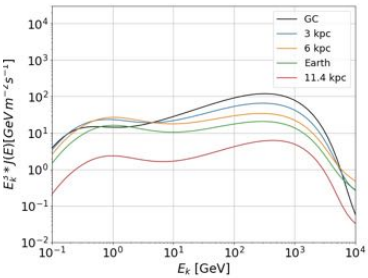
Squared NFW



Lorimer

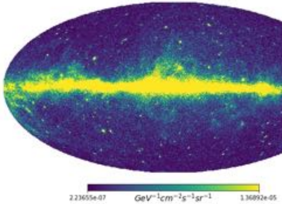


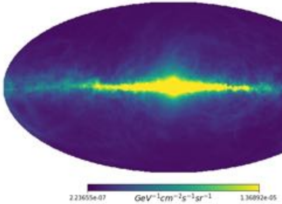
McMillan



4. Sky maps: 1 GeV gamma-ray sky maps

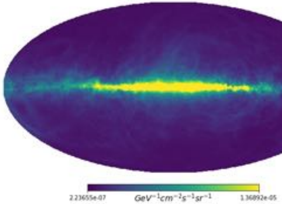
FERMI-LAT

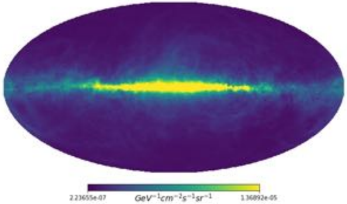




Squared NFW

Lorimer





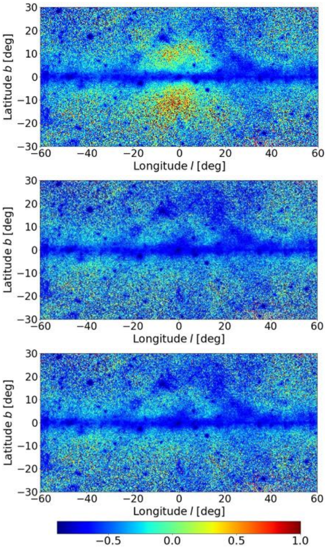
McMillan

4. Sky maps: 1 GeV Residuals

Squared NFW

Lorimer

McMillan



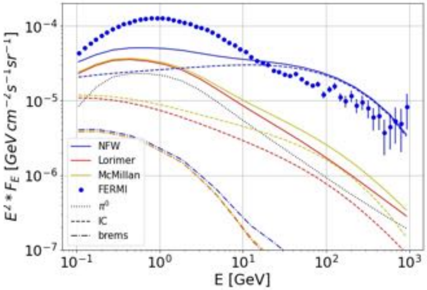
Residuals: (model-data)/data

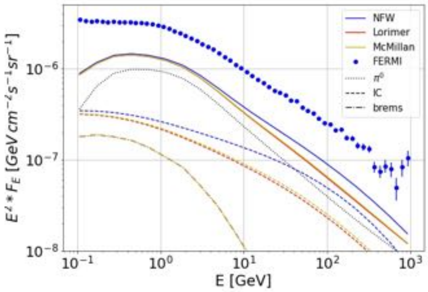
Lack of $\sim$ 60% in the galactic plane in every model

Overshooting of $\sim$ 50% above and below the center of the galaxy in the Squared NFW model

Lack at high latitudes ($|b| > 20^{\circ}$) in every model

4. Sky maps: Galactic center & local gamma-ray spectra





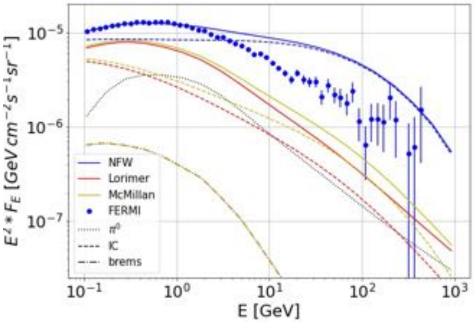
Galactic center

Lack at low energies
The squared NFW model reach the data at high energies

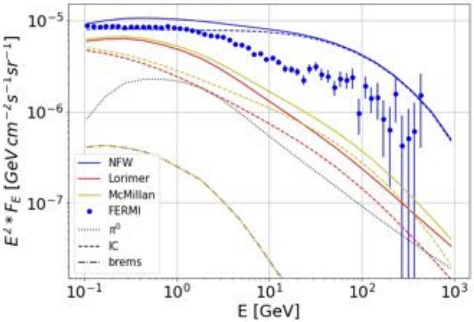
Local (40º<l<340º & 10< |b| <45º)

Models well below the data

4. Sky maps: (0º, ±10º) gamma-ray spectra



(0º, 10º)



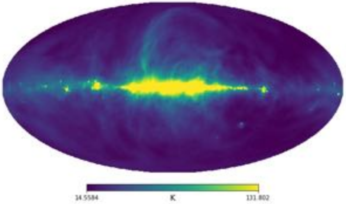
(0º, -10º)

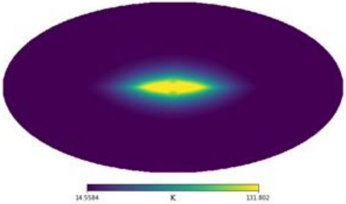
(0º, ±10º)

Squared NFW model is exceeding by roughly a factor of 2 in both regions

4. Sky maps: 408 MHz radio sky maps

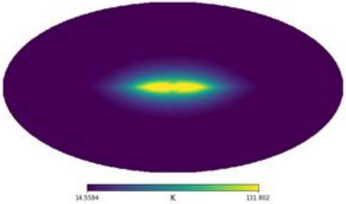
Haslam

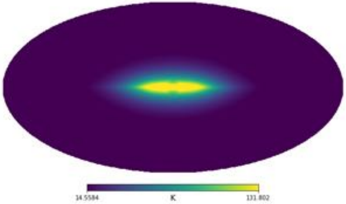




Squared NFW

Lorimer





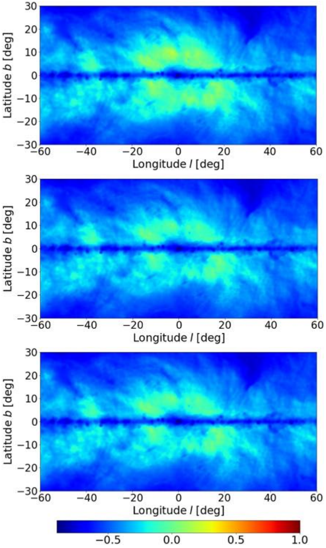
McMillan

4. Sky maps: 408 MHz Residuals

Squared NFW

Lorimer

McMillan

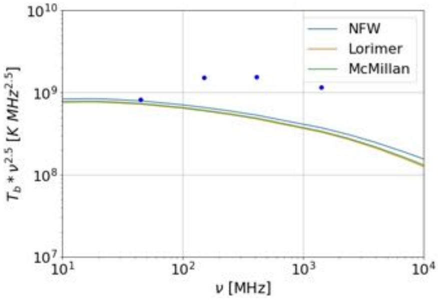


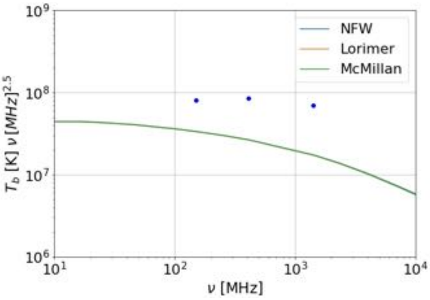
Residuals: (model-data)/data

Lack in the galactic plane for every model

Lack at high latitudes ($b > 20^{\circ}$) for every model

4. Sky maps: Galactic center & local radio spectra





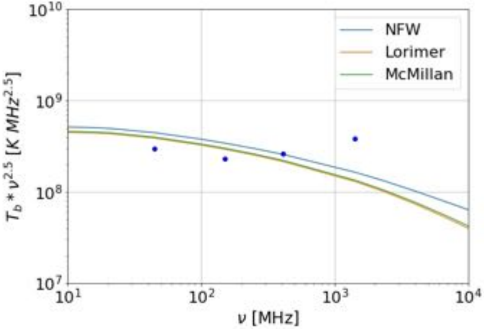
Galactic center

Lack at high frequencies

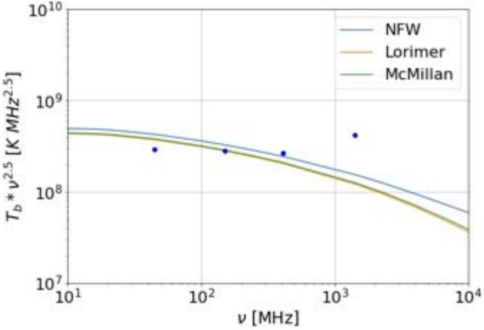
Local

Models well below the data

4. Sky maps: (0º, ±10º) radio spectra



(0º, 10º)



(0º, -10º)

0º, ±10º

The models fit the data at medium frequencies in both regions

5. Conclusions

Cosmic-ray spectra

Models fail at low energies

Sky maps

Astrophysical source models are well below the experimental data

DM model may overshoot the data by roughly a factor of 2 in some regions

Overall conclusion

These results should be taken as a proof-of-concept. Reproducing simultaneously both excess of positrons and gamma-ray sky seems possible, but requires further modelling (in-flight annihilation, radio absorption) and more careful investigation of the parameter space (cross section, magnetic fields)

The End