Search for Dark Matter in the sky in the Fermi era

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Abstract. To uncover the dark matter, to connect what is astrophysically observed to what will be seen as new particles produced in the LHC, we need new measurements. The Fermi Large Area Telescope is providing the measurement of the high energy (7 GeV to 1 TeV) cosmic ray electrons and positrons spectrum with unprecedented accuracy. This measurement represents a unique probe for studying the origin and diffusive propagation of cosmic rays as well as for looking for possible evidences of Dark Matter. In this talk we focus mainly on astrophysical sources of cosmic ray electrons and positrons which include the standard primary and secondary diffuse galactic contribution, as well as nearby point-sources which are expected to contribute more significantly to higher energies. In this framework, we discuss possible interpretations of Fermi results in relation with other recent experimental data on energetic electrons and positrons and with recent results in the searches of gamma-ray fluxes coming from WIMP pair annihilations in the sky.

1. The Cosmic Ray Electron spectrum

Recently the experimental information available on the Cosmic Ray Electron (CRE) spectrum has been dramatically expanded as the Fermi LAT Collaboration [1] has reported a high precision measurement of the electron spectrum from 7 GeV to 1 TeV performed with its Large Area Telescope (LAT) [2], [3]. The spectrum shows no prominent spectral features and it is significantly harder than that inferred from several previous experiments. These data together with the PAMELA data on the rise above 10 GeV of the positron fraction [4] are quite difficult to explain with just secondary production [5], [6], [7], [8].

The temptation to claim the discovery of dark matter from detection of electrons from annihilation of dark matter particles is strong but there are competing astrophysical sources, such as pulsars, that can give a strong flux of primary positrons and electrons (see [9], [10], [11] and references therein). At energies between 100 GeV and 1 TeV the electron flux reaching the Earth may be the sum of an almost homogeneous and isotropic component produced by Galactic supernova remnants and the local contribution of a few pulsars with the latter expected to contribute more and more significantly as the energy increases.

Two pulsars, Monogem, at a distance of 290 pc and Geminga, at a distance of 160 pc, can give a significant contribution to the high energy electron and positron flux reaching the Earth and with a set of reasonable parameters of the model of electron production the Fermi LAT data and the PAMELA positron fraction can be well fit fraction [4] (see figure 1). However we have a lot of freedom in the choice of these parameters because we still do not know much about these processes, so further study on high energy emission from pulsars is needed in order to confirm or reject the pulsar hypothesis.
Figure 1. Cosmic ray electron + positron spectrum as measured by Fermi Large Area Telescope for one year of observations (filled circles), along with other recent high energy results. The gray band represents systematic errors on the Fermi LAT data [2], [3]. The solid line is the computed conventional GALPROP model but with an injection index $\Gamma = 1.6/2.7$ below/above 4 GeV (dotted line). An additional component with an injection index $\Gamma = 1.5$ and exponential cut-off is shown by the dashed line. Blue line shows $e^-$ spectrum only.

Figure 2. The parameter space of dark matter particle mass versus pair-annihilation rate, for models where dark matter annihilates into monochromatic $e^\pm$. Models inside the regions shaded in gray and cyan over-produce $e^\pm$ from dark matter annihilation with respect to the Fermi LAT and H.E.S.S. measurements, at 2-$\sigma$ level. The red and blue contours outline the regions where the $\chi^2$ per degree of freedom for fits to the PAMELA and Fermi LAT data is less than 1.

Figure 3. Counts spectra from the likelihood analysis of the Fermi LAT data (number of counts vs reconstructed energy) in a $7^\circ \times 7^\circ$ region around the Galactic Center (number of counts vs reconstructed energy)

Figure 4. Residuals $(\text{exp.data - model})/\text{model}$ of the above likelihood analysis. The blue area shows the systematic errors on the effective area.

Nevertheless a dark matter interpretation of the Fermi LAT and of the PAMELA data is still an open possibility. Figure 2 shows the parameter space of dark matter particle mass versus pair-annihilation rate, for models where dark matter annihilates into monochromatic $e^\pm$ [10]. The preferred range for the dark matter mass lies between 400 GeV and 1-2 TeV, with larger masses increasingly constrained by the H.E.S.S. results [12]. The required annihilation rates,
when employing a particular dark matter density profile imply typical boost factors ranging between 20 and 100, when compared to the value $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$/sec expected for a thermally produced dark matter particle relic.

How can one distinguish between the contributions of pulsars and dark matter annihilations? Most likely, a confirmation of the dark matter signal will require a consistency between different experiments and new measurements of the reported excesses with large statistics.

Another possibility is to look for anisotropies in the arrival directions of the electrons. The Fermi LAT detected more than 1.6 million cosmic-ray electrons/positrons with energies above 60 GeV during its first year of operation. The arrival directions of these events were searched for anisotropies of angular scale extending from $\sim 10^\circ$ up to $90^\circ$, and of minimum energy extending from 60 GeV up to 480 GeV. An upper limit for the dipole anisotropy has been set to 0.5 - 10% depending on the energy [14]. The levels of anisotropy expected for Vela-like and Monogem-like sources (i.e. sources with similar distances and ages) seem to be greater than the scale of anisotropies excluded by the results. However, it is worth to point out that the model results are affected by large uncertainties related to the choice of the free parameters.

2. The gamma-ray signals
A strong leptonic signal should be accompanied by a boost in the $\gamma$-ray yield providing a distinct spectral signature detectable by Fermi LAT. The Galactic center (GC) is expected to be the strongest source of $\gamma$-rays from DM annihilation, due to its coincidence with the cusped part of the DM halo density profile [15], [16]. A preliminary analysis of the data, taken during the first 11 months of the Fermi satellite operations, is shown in figures 3 and 4. The diffuse gamma-ray backgrounds and discrete sources, as we know them today, can account for the large majority of the detected gamma-ray emission from the Galactic Center. Nevertheless a residual emission is left, not accounted for by the above models [17], [18]. Improved modeling of the Galactic diffuse model as well as the potential contribution from other astrophysical sources (for instance unresolved point sources) could provide a better description of the data. Analyses are underway to investigate these possibilities. An excess in gamma-ray from dark matter annihilation also should be seen in the Galactic diffuse spectrum. Overall, the agreement between the LAT-measured spectrum and the model shows that the fundamental processes are consistent with our data, thus providing a solid basis for future work in understanding the Diffuse Galactic emission (DGE) [19], [20].

3. Dwarf spheroidal galaxies and Clusters of galaxies
Local Group dwarf spheroidal galaxies, the largest galactic substructures predicted by the cold dark matter scenario, are attractive targets for dark matter indirect searches because they are nearby and among the most extreme dark matter dominated environments. With the data taken during the first 11 months no significant $\gamma$-ray emission was detected above 100 MeV from any dwarf galaxies. So we can determine upper limits to the $\gamma$-ray flux assuming both power-law spectra and representative spectra from WIMP annihilation. The resulting integral flux above 100 MeV is constrained to be at a level below around $10^{-9}$ photons cm$^{-2}$s$^{-1}$ [21]. Using recent stellar kinematic data, the $\gamma$-ray flux limits can be combined with improved determinations of the dark matter density profiles in 8 of the 14 candidate dwarfs to place limits on the pair annihilation cross-section of WIMPs in several widely studied extensions of the standard model, including its supersymmetric extension and other models that received recent attention. With the present data we are able to rule out large parts of the parameter space where the thermal relic density is below the observed cosmological dark matter density and WIMPs (neutralinos here) are dominantly produced non-thermally. These $\gamma$-ray limits also constrain some WIMP models proposed to explain the Fermi LAT and PAMELA $e^+e^-$ data, including low-mass wino-like neutralinos and models with TeV masses pair-annihilating into muon-antimuon pairs. The
same kind of analysis can be made for the clusters of galaxies [22].

Finally a line at the WIMP mass, due to the $2\gamma$ production channel, could be observed as a feature in the astrophysical source spectrum [13]. Such an observation would be a “smoking gun” for WIMP DM as it is difficult to explain by a process other than WIMP annihilation or decay and the presence of a feature due to annihilation into $\gamma Z$ in addition would be even more convincing. Up to now however no lines have been observed and we obtain $\gamma$-ray line flux upper limits in the range $0.6 - 4.5 \times 10^{-9} \text{cm}^{-2} \text{s}^{-1}$ and corresponding DM annihilation cross-section and decay lifetime limits [23].

4. Conclusion

Fermi Gamma-ray Space Telescope has opened a new era in DM searches and a large variety of analyses have been developed for clusters of galaxies, DM satellites, DM subhalos, cosmological DM and spectral lines. No significant detections have been made, but constraints that start to probe the available phase space have been put on the annihilation cross-section and decay lifetimes. The CRE spectrum measured by Fermi LAT is significantly harder than what was expected on the basis of previous data. Adopting the presence of an extra $e^\pm$ primary component with $\sim 2.4$ spectral index and $E_{\text{cut}} \sim 1 \text{ TeV}$ allows a consistent interpretation of the Fermi LAT CRE data, HESS and PAMELA. Such an extra-component can be produced by nearby pulsars for a reasonable choice of relevant parameters or by annihilating dark matter for models with $M_{\text{DM}} \sim 1 \text{ TeV}$. Improved analysis and complementary observations (CRE anisotropy, spectrum and angular distribution of diffuse $\gamma$, DM sources search in $\gamma$) are required to possibly discriminate the right scenario. The dark matter origin of any exotic signal has to be confirmed by complementary findings in $\gamma$-rays by Fermi LAT and atmospheric Cherenkov telescopes, and by LHC in the debris of high-energy proton destructions. On the other hand, if the signal is due to a conventional astrophysical source of cosmic rays, it will mean a direct detection of particles accelerated at an astrophysical source, again a major breakthrough. However, independent of the origin of these excesses, exotic or conventional, we can expect a very exciting several years ahead of us.

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