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Mapping Correlation of Two Point Sources in the Gamma-Ray Sky

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Abstract

The Fermi Gamma-Ray Space Telescope has been taking data on high energy photons or γ rays since June 11th, 2008, and people have been cataloging and profiling point sources of these γ rays ever since. After roughly one year of being in operation over 1400 sources were cataloged. Now, in 2015 we have 3033 sources cataloged. With the increasing amount of sources it's important to think about the limitations of likelihood analysis for highly correlated sources. In this paper I will present the problems of using likelihood analysis for sources that are highly correlated as well as show under what circumstances sources can be considered highly correlated. Dark matter over densities may show up as a point source, so it is a necessary step to learn how the two signals will interact to allow for a proper search for dark matter.

1 Introduction

We have had evidence suggesting the existence of dark matter since the 1930's when Fritz Zwicky noted a missing mass while studying the movement of galaxies inside the Coma Cluster. Since then we have learned very little about it. It is appropriately named dark matter as the only way we have been able to detect it is through gravity, as opposed to it emitting or reflecting light. A few of the big candidates for what dark matter is are: MACHOS, MOND, and WIMPS. MACHOS or massive compact halo objects would be massive objects in the halos of galaxies that don't reflect light. As more data comes out these are seeming less and less likely for the cause of "excess" gravity attributed to dark matter. MOND is modified Newtonian dynamics and would need to explain the motion of celestial bodies based on new mathematical formulas. The most popular candidate for dark matter, currently, is a WIMP or weakly interacting massive particle. These particles are predicted by supersymmetric extensions to the Standard Models of physics that have each standard model particle having a heavy suppersymmetric particle associated with it. Many models also predict that these heavy particles would be able to annihilate and decay into observable particles such as photons. Since WIMPS are massive, their annihilations may

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emit high energy photons or γ rays that would be detectable by the FGST (Fermi Gamma-Ray Space Telescope). N-body simulations suggest that dark matter clumps into subhalos, meaning if dark matter does annihilate into observable particles these subahlos would show up as point sources. After 7 years of taking data an obvious dark matter signal has yet to emerge.

2 Method

2.1 The Models

In order to determine the correlation of a theoretical dark matter point source and a known point source we used Monte Carlo simulations. Within these we had point sources and Instrument Response Functions (IRFs). In these simulations we used two types of γ ray sources: diffuse background, and point sources. The point sources were given a location in galactic coordinates. Probability Density Functions were used to model the sources. A Probability Density Function gives the probability of finding a photon at a with a specific energy in a specific space. We represented the energy spectrum of these point sources as power law functions, that is as the energy increased, the probability of simulating a photon decreased as a function of some best fit power law function. In our case, we used the best fit function from the 3FGL (4-year Fermi point source catalog). To model our dark matter points sources energy spectrum, we had a theoretical dark matter mass in GeV annihilate into a pair of b-quarks. The dark matter source was placed various distances away from the non-dark matter point source. All the spectral parameters for the sources were fixed. Also, all the normalizations except for the normalization of the dark matter point source and the closest non-dark matter point source were fixed. The Instrument Response Functions are designed to imitate the detecting capabilities of the LAT(Large Area Telescope) aboard the FGST. For example, the Point Spread Function smears what would be a point to account for the LAT's resolving power.

2.2 Likelihood

Likelihood is defined as the product of the probability of detecting the predicted counts in each bin. This can be mathematically represented as

$$Likelihood = \Pi p_k \tag{1}$$

or specifically for a Poisson Distribution

$$Likelihood = \Pi \frac{{m_k}^{n_k} e^{-m_k}}{n_k!} \tag{2}$$

Maximizing Likelihood will give you the best fit value for whatever parameter you're fitting to. However, oftentimes we would rather look at the -2log(likelihood) as it is easier to deal with. Another useful piece of information

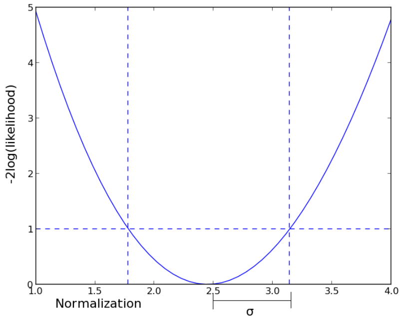


Figure 1: -2log(likelihood) as a function of Normalization for a dark matter source

contained within the likelihood is the uncertainty associated with the parameter. To get this you simply look at how much the parameter must change to increase -2log(likelihood) by 1. Because -2log(likelihood) is often parabolic, this is fairly easy to calculate.

2.3 Correlation

Correlation is what's known as a nuisance parameter. That is it isn't of direct interest, but must be accounted for. Correlation is a scaled version of covariance. It can have values from -1 to 1. Mathematically correlation can be represented as

$$Correlation = \frac{\sigma_{XY}}{\sqrt{\sigma_{XX} * \sigma_{YY}}} \tag{3}$$

Where σ_{XY} is the covariance of x and y and σ_{XX} and σ_{YY} are the standard deviation of their respective variables. A positive correlation means as you increase one variable the other will increase, a negative correlation means as you increase one variable the other decrease (you can't distinguish between the two), and if two variables are uncorrelated it means the variable have no affect on one another.

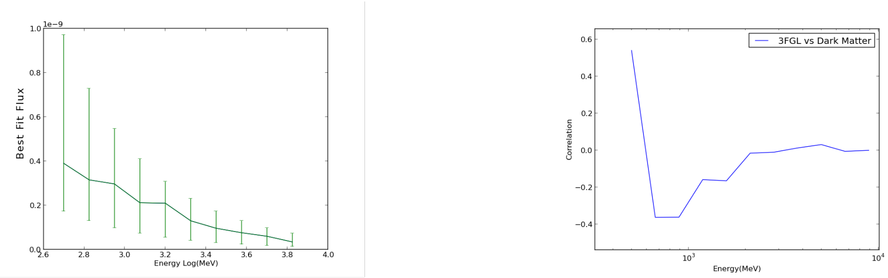
3 Data

20 simulations were ran in total, 10 for a 50 GeV dark matter particle, and 10 for a 5 GeV dark matter particle. The 10 simulations for each particle were ran at different distances (0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0) in degrees separating the inserted dark matter source and the point source. For reference the PSF within 68% containment for 1 GeV is roughly 1 degrees and for 10 GeV is roughly 0.2 degrees. 4 normalization parameters were set to free, the dark matter normalization, the points source normalization, the galactic diffuse emissions, and the isotropic background. The data was then ran through an

optimizer, Minuit, to maximize the likelihood of the simulated data to the model in each energy bin. Minuit also gave a covariance matrix which allowed us to extract the correlation for each distance and energy bin. Finally we were able to make a 2d histogram of correlation as a function of distance and energy for 2 different theoretical dark matter masses.

4 Analysis

First, the effects of having two largely correlated sources should be discussed. One of the main affects of a high correlation is an increase in fit parameter uncertainty. Having more correlation flattens out the likelihood function increasing the distance a parameter must change to increase -2log(likelihood) by 1. This is explicitly demonstrated in Figure 2. A solution to this would be to constrain the non-dark matter piece, reducing the uncertainty on the dark matter piece. This suggests that when two sources are highly correlated more sophisticated statistical analysis methods are necessary.



(a) Best Fit Flux vs. Gamma Ray Energy for a dark matter source at 1.5 degrees from a non-dark matter point source

(b) Correlation vs. Gamma Ray Energy between dark matter point source and non-dark matter point source at 1.5 degrees apart

Figure 2

Next, we should discuss when correlation is a problem.

As is made apparent by the graph of Correlation vs. Distance, correlation becomes a problem at smaller distances. This makes sense because at smaller distances it is harder to distinguish one source from the other.

Another effect that happens is at lower energy, the point sources are much more correlated. This seems logical because at lower energy the LAT's resolving power becomes significantly worse.

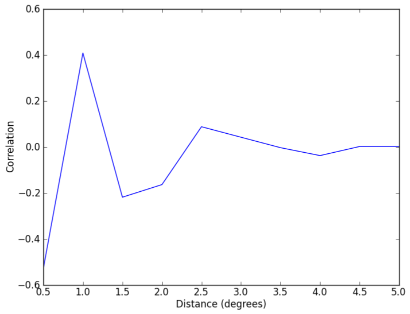
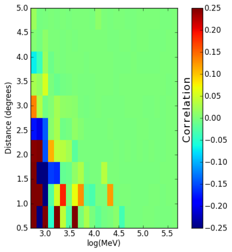
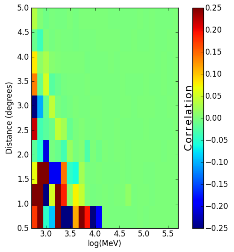


Figure 3: Correlation vs. Distance of Separation for a 50 GeV dark matter particle



(a) Correlation clipped to be between -.25 and .25, 5 GeV dark matter particle



(b) Correlation clipped to be between -.25 and .25, 50 GeV dark matter particle

5 Conclusion

This analysis offers insight into what causes sources to be highly correlated as well as how correlation affects likelihood analysis; which is an important first step in searching for a dark matter point source. This will become more and more relevant as we discover more sources, some of which may be right on top of each other. The methods for calculating correlation are also sound and could be used in the future to determine how to better analyze sources in the γ ray sky.

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7 References

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