Dark Matter Decay in Andromeda and Virgo

Christopher Dessert and Ben Safdi

Department of Physics, University of Michigan

Abstract

One of the most promising methods to search for dark matter (DM) is indirect detection of DM decay products, including photons, in the centers of galaxies. We present preliminary results on the DM lifetime limit for decays to b quarks using 413 weeks of Fermi Large Area Telescope (Fermi-LAT) Pass 8 gamma-ray data. The dataset contains photon counts with energies ranging from 200 MeV to 2 TeV, along with the spatial distribution. We can compare this distribution with the expected distribution of photon flux due to DM decays given the known spatial distribution of DM. We preform a stacked analysis of two nearby galaxies, Andromeda and Virgo, on the University of Michigan (UM) Flux cluster using python, cython, and Jupyter to obtain these limits. The procedure is as follows: we preform a Poissonian template fit with open-source code package NPTFit to model sources of flux which do not arise from DM decays and attribute the potential remaining flux as due to DM decays, yielding likelihood profiles for the decay intensity. We constrain the DM lifetime for masses between 20 GeV to 20 TeV. In the future, we will use a galaxy group catalog to preform the analysis across the full sky. We would like to additionally incorporate data up to larger redshifts, first with a cosmological simulation to understand uncertainties in the analysis and then with the Dark Energy Survey (DES) dataset pending release.

Introduction

GeV scale DM can decay to Standard Model (SM) products that cascade to gamma-rays detectable by Fermi-LAT. We set preliminary constraints on the DM lifetime using a profile-likelihood method with the Fermi data. This procedure is outlined in detail in [1]. We use known properties of two galaxies, Andromeda and Virgo, to infer the properties of its DM halo and thus the expected associated gamma-ray flux. We fit a Poissonian model to the Fermi data using this flux and background templates for diffuse emission, isotropic emission, and point sources (PS), which are provided by the Fermi collaboration [2]. The Fermi data is in the form of counts (photons/pixel), where the pixels are defined by a HEALPIX map of $nside = 128$.

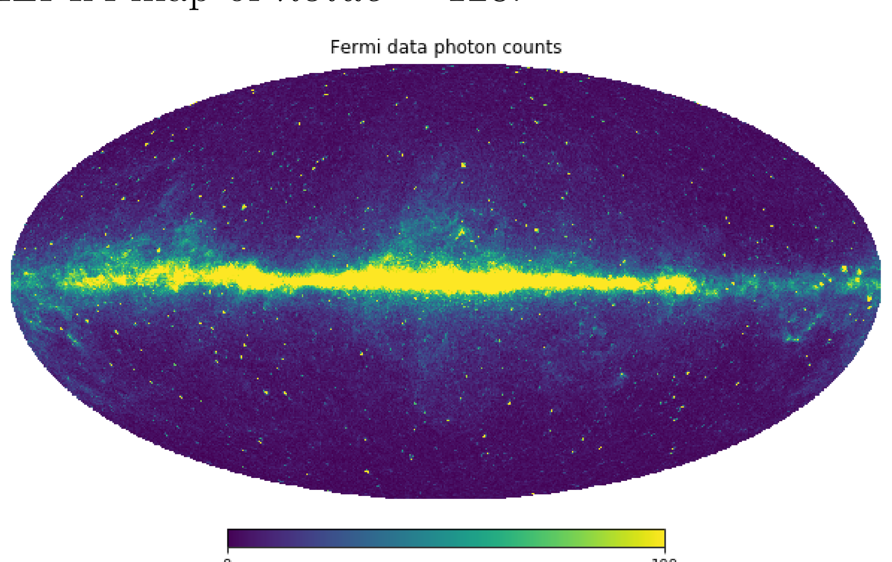

Figure 1: HEALPIX map of raw Fermi data in counts cut off after 100.

Dark Matter Decay Flux

DM decay to b quarks produces a photon flux

$$\frac{d\Phi}{dE_\gamma} = \frac{1}{4\pi m_\chi \tau}\frac{dN}{dE_\gamma} \times D,$$

where m_χ is the DM mass, τ is the DM lifetime, N is the number of photons produced per interaction, and

$$D = \int ds d\Omega \rho_{\rm DM}(s,\Omega) \approx \frac{M_{\rm vir}}{d_{\rm A}^2}.$$

This is known as the D-factor and describes the astrophysical properties of the DM, where $\rho_{\rm DM}$ describes the DM halo with the Navarro-Frenk-White (NFW) profile

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}.$$

Here, ρ_s is the normalization such that the density integrates to the galaxy mass and r_s is the scale radius

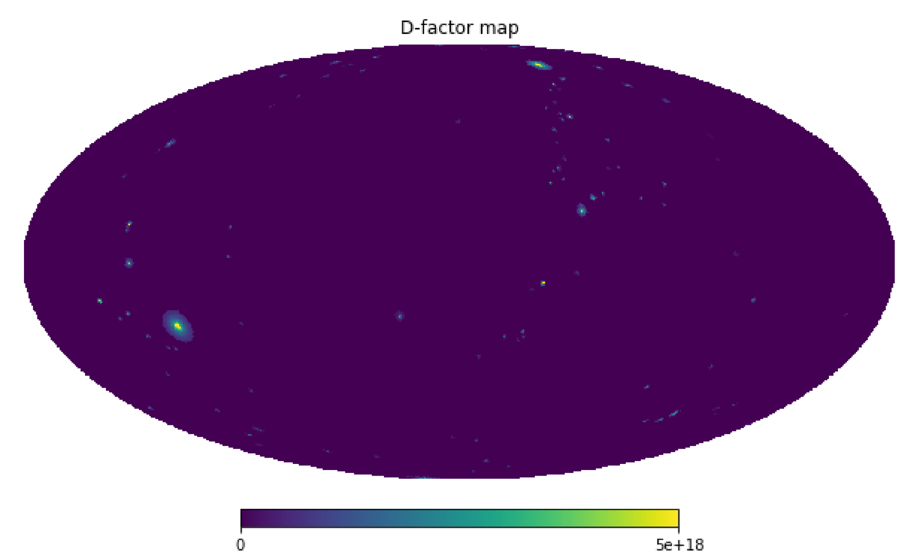

Figure 2: The extragalactic D-factor, giving DM density in every direction. Andromeda and Virgo are the brightest and largest structures visible.

Profile-Likelihood Method

The Fermi data is broken into 40 log-spaced energy bins between 200 MeV to 2 TeV, indexed i and spatially indexed by pixels p, so that the number of counts in pixel p and energy bin i is a 2 dimensional integer array n_i^p. For each galaxy, indexed r, we restrict to the set of pixels $n_i^{p,r}$ within 15° of the center of the halo. Similarly, the templates are described by arrays $T_i^{p,l}$ where l indexes the template. Then the number of counts expected is

$$\mu_i^{p,r} = \sum_l A_i^{r,l} T_i^{p,l},$$

where $A_i^{r,l}$ denotes the normalization of each template. We denote the DM decay flux template as ψ_i, the astrophysical templates as the nuisance parameters λ_i^l. Since particle decay is a Poisson process, we define the likelihood in bin i and galaxy r as

$$\mathcal{L}_i^r(n_i^r|\{A_i^{r,l}\}) = \prod_p \frac{(\mu_i^{p,r})^{n_i^{p,r}} e^{-\mu_i^{p,r}}}{n_i^{p,r}!}$$

To obtain dependence only on the DM model $\mathcal{M}$, τ, and m_χ, let

$$\mathcal{L}^r(n^r|\mathcal{M},\tau,m_\chi) = \prod_i \max_{\{\lambda_i^l\}} \mathcal{L}_i^r(n_i^{p,r}|\{A_i^{r,l}\}).$$

Finally, to obtain the stacked likelihood for both galaxies, we let

$$\mathcal{L}(n|\mathcal{M},\tau,m_\chi) = \prod_r \mathcal{L}^r(n^r|\mathcal{M},\tau,m_\chi).$$

We define a test statistic (TS) profile

$$\mathrm{TS} = 2[\log\mathcal{L}(n|\mathcal{M},\tau,m_\chi) - \log\mathcal{L}(n|\mathcal{M},\hat{\tau},m_\chi)],$$

where $\hat{\tau}$ is the lifetime that maximizes the likelihood. We use this TS to set limits on the DM lifetime; the limit is the lifetime such that $\mathrm{TS} = -2.71$, yielding a 95% confidence interval.

Individual Limits

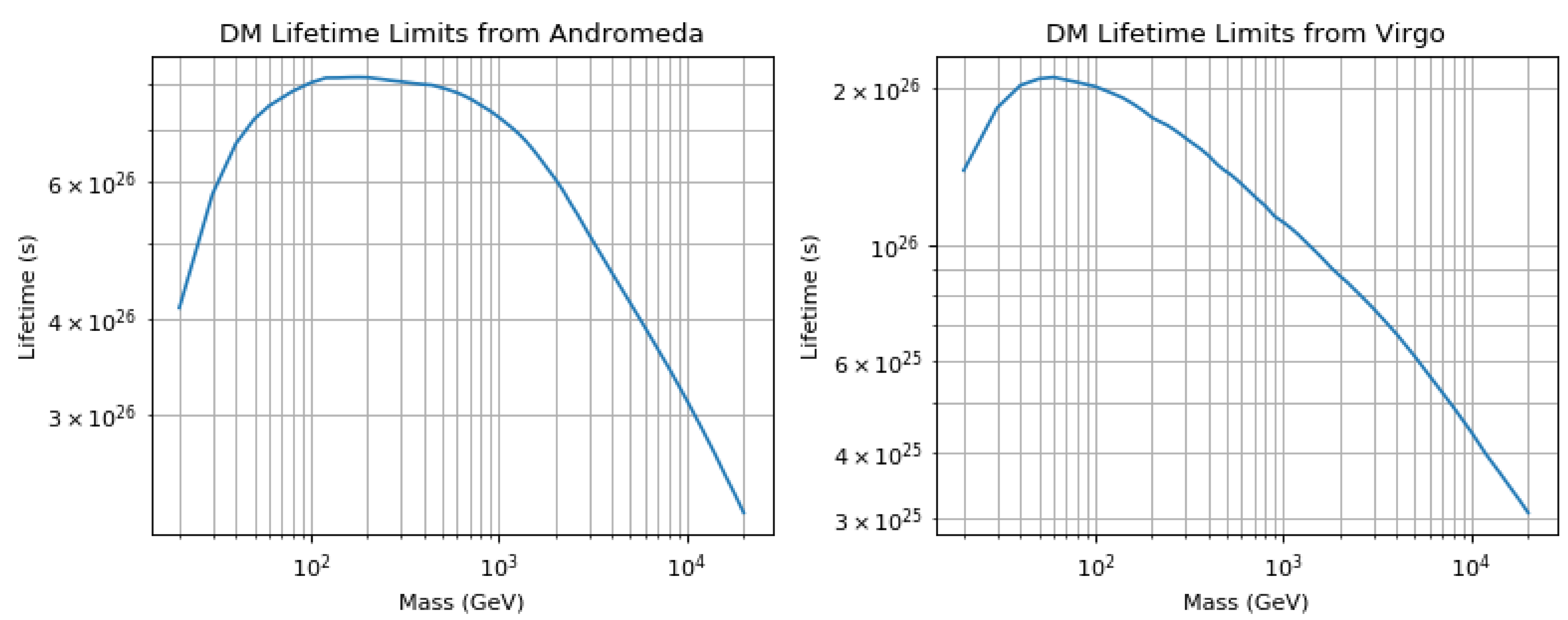

Figure 3: (Left) DM lifetime 95% confidence limits computed with only the Andromeda data. The limits peak around 8×10^{26} s for $m_\chi = 200$ GeV. (Right) DM lifetime 95% confidence limits computed with only the Virgo data. The limits peak around 2×10^{26} s for $m_\chi = 60$ GeV. Note that $D_{\rm Andromeda} = 5.7 \times 10^{20}$ GeV cm^{-2} sr is approximately 3 times larger than $D_{\rm Virgo} = 2.1 \times 10^{20}$ GeV cm^{-2} sr, so the limits will naturally be smaller. Our sensitivity drops off sharply near $m_\chi = 20$ GeV because the b quark mass is 5 GeV.

Stacked Limits

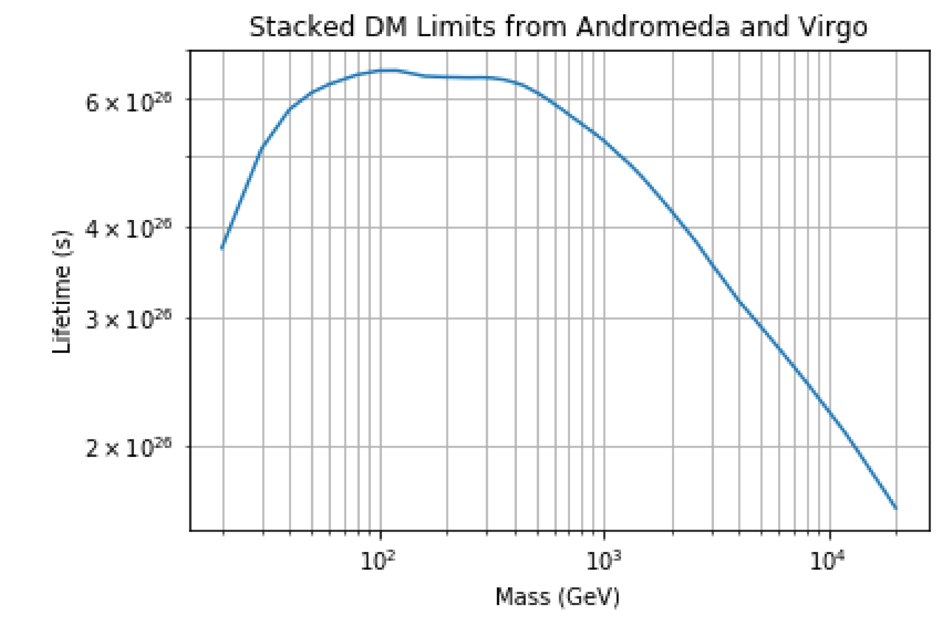

Figure 4: Stacked DM lifetime 95% confidence limits computed by summing the TS for both galaxies. The lifetime peaks at 6×10^{26} s for $m_\chi = 100$ GeV. Note that the limits are lower than computed by Andromeda. This is because the TS peaks at different lifetimes for the two galaxies, indicating any evidence for decays is statistical fluctuation.

Conclusion

We have presented a stacked analysis of two nearby galaxies, Andromeda and Virgo, and set limits on the DM lifetime using Fermi data. In the future, making use of galaxy catalogs to include more galaxies in our analysis can increase the limits to competitive constraints. Additionally, we expect that the same type of analysis is possible with the DES data upon release. The DES data should allow us to make a 3D map of the DM density up to larger redshifts, which will reduce the uncertainties in analysis significantly.

References

[1] M. Lisanti, S. Mishra-Sharma, N. L. Rodd, B. R. Safdi, and R. H. Wechsler, arXiv:1709.00416 [astro-ph.CO].

[2] The Fermi-LAT Collaboration, arXiv:1501.02003 [astro-ph.HE]

Acknowledgements

We thank Nick Rodd and Siddharth Mishra-Sharma for helpful conversations. This research used the Minuit and NPTFit software packages with python, cython, and Jupyter. CD is supported by a University of Michigan Physics Department Fellowship.

LSA LEINWEBER CENTER FOR THEORETICAL PHYSICS
UNIVERSITY OF MICHIGAN