Developing a Microlensing Generator to Determine Efficiency in Detecting Gravitational Effects of Primordial Black Holes in the Milky Way Dark Matter Halo

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Massive Primordial Black Holes (MPBH) could constitute the majority of the dark matter, an idea revived by the LIGO observations of merging 30 solar mass black holes. In this model, the mass distribution of MPBH ranges from 0.01 to 100 solar masses, peaking perhaps at 50 solar masses. This project uses the Dark Energy Survey data to perform a microlensing measurement of massive compact objects at 10-100 solar masses. Microlensing occurs when MPBH passes in front of a background star, briefly brightening the output from that star. The key idea is that a microlensing event has a duration of roughly t = 2.5 years and thus masses in the range expected for MPBH are observable in the DES.

In this project, we created mock light curve events for stars in the Dark Energy Survey (DES). First, we reduce our sample size by removing galaxies and over-saturated objects. We then utilized the initial magnitudes, the observation times, and the calculated errors in our code. By using these data, as well as varying unknown parameters of the MPBHs, we create approximately 50,000 light curves per sampled star. These mock light curves will support in determining the efficiency of the current fitting algorithm, as well as any future algorithms. Our project will directly support the creation of efficiency maps which will help determine the number of actual events to expect within the DES.

I. INTRODUCTION

Ever since Swiss Astrophysicist Fritz Zwicky first suggested the existence of dunkle materie in 1933, astrophysicists have been trying to understand what this Dark Matter (DM) is made of. While many candidates have been suggested, this paper will discuss Massive Primordial Black Holes (MPBHs) as the premiere candidate. When Zwicky observed the Coma Galaxy Cluster, he attempted to determine the amount of mass within the cluster. Zwicky was able to compare the mass of the cluster based on the calculated velocity to the mass of the cluster based on the luminosity by applying the Virial Theorem:

$$K = -\frac{1}{2}U \tag{1}$$

where Kinetic Energy (K) = $\frac{1}{2}mv^2$
Potential Energy (U) = $-\frac{GM}{mr}$, and
Circular/Orbital Velocity (v_c) = $-\frac{GM}{r}$

He found that the galaxies were moving too fast to be held together in the cluster - therefore some of the mass must be hidden from view - or dark. He concluded that this unseen matter provided the mass and associated gravitation attraction to hold the cluster together. While Zwicky was off by more than an order of magnitude, mainly due to an obsolete value of the Hubble constant, this remains the first formal inference about the existence of dark matter.

Since then, multiple candidates have been posed regarding what could make up DM. The two main categories include Baryonic and Non-Baryonic Particles. Non-Baryonic particles are largely hypothesized particles that have yet to be found in nature, or even in the highest energy particle accelerators. These would include Weakly Interacting Massive Particles (WIMPs) and/or Massive Neutrinos, Cosmic Strings, or even a modified gravity theory. There are many Baryonic candidates, including Neutron Stars, Planets, Rocks, Brown Dwarf Stars and Black Dwarf stars. However, there is not yet sufficient evidence that enough could have been created in the big bang to explain the extreme discrepancy observed in galaxy clusters and galaxies.

In this paper, we will be focusing on the Black Hole candidate. Like other baryonic candidates, there has been insufficient evidence of enough Black Holes existing in the universe. However, Steven Hawking suggested in 1971 that MPBHs might be the explanation. These primordial holes would have been created 1^{-5} seconds after the big bang due to density fluctuations, and could have created black holes with masses ranging from a Planck mass all the way up to hundreds of thousand of solar masses. This certainly makes MPBHs an interesting candidate to study.

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II. THEORY

When the light emitted from a source passes a massive object, more light is bent toward the observer, causing the image to appear brighter. This effect is known as gravitational microlensing (ML).

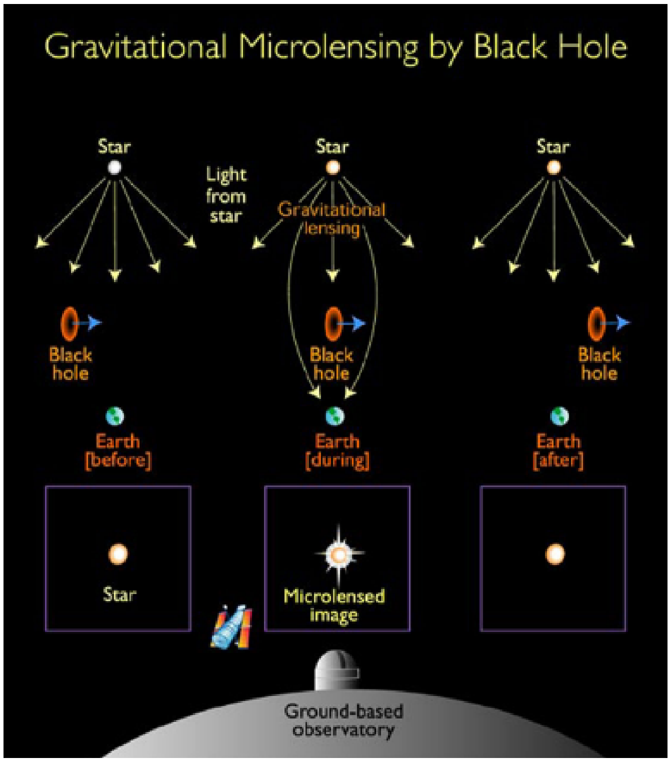

FIG. 1. Microlensing Event Example

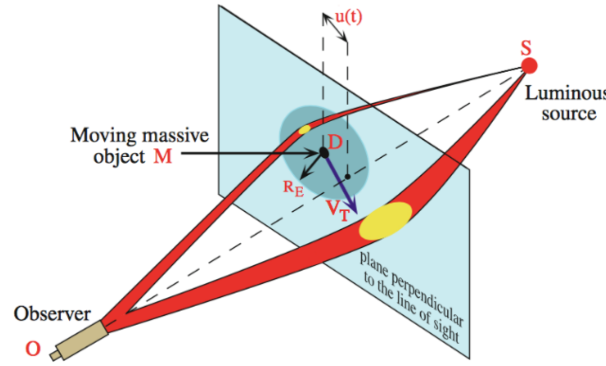

FIG. 2. Microlensing Event Example

In the Fig. 2, O is the observer. In our project, this observer is the Earth - specifically the DECam in Chile. S, the luminous source, is a star within the Milky Way. The object D has a mass M, and is moving in a trajectory V_T relative to S. R_E is depicted by the dark circle and is the Einstein radius of the massive object D. Finally, u(t) is the distance of the object D to the line of sight between O and S.

MPBHs between 1-100$M_\odot$ have a unique benefit of creating Microlensing Events with a duration of $t_E = 2.5$ yrs $(M/10M_\odot)^{1/2}$. This duration allows these events to be observed within the observing time frame of the Dark Energy Survey (DES). The time of crossing 1/2 of the Einstein Ring's radius can also be described as follows:

$$t_E = \frac{R_E}{v_t} \tag{2}$$

This equation takes the radius of the Einstein ring and divides the relative transverse velocity of the source and lensing objects. In our study, we assumed a $v_t = 220$ km/s. The Einstein Radius (RE) is expressed by:

$$R_E = \sqrt{\frac{4GM}{c^2} D_S x(1-x)} \simeq 4.54 A.U. \times \left[\frac{M}{M_\odot}\right]^{\frac{1}{2}} \left[\frac{D_S}{10kpc}\right]^{\frac{1}{2}} \frac{[x(1-x)]^{\frac{1}{2}}}{0.5} \tag{3}$$

Where G is Newton's gravitational constant; M is mass of the MPBH; c is speed of light; D_S is distance to the source; x distance of MPBH (%) between source and observer. For this project, we assumed a constant $D_S =$ 30 kpc. The constants G and c were converted to proper units, and M and x were varied. Our M ranged from $10M_\odot$ to 100 $M_\odot$ in increments of 10; x ranged from 0.1 to 0.9 in increments of 0.1.

After calculating Einstein radius based on varying masses and distances, we were then able to use the Einstein time to determine the possible paths of the MPBH using this equation:

$$u(t) = \sqrt{u_0^2 \left(\frac{t - t_0}{t_E}\right)^2} \tag{4}$$

Where u_0 is the distance of closest approach between the MPBH and the line of sight of the source; and t_0 is the time at which u_0 occurs. u_0 is unitless, as it is scaled with respect to the Einstein radius. Therefore, when $u_0 = 0$, the MPBH is passing directly over the line of sight of the source, and when $u_0 = 1$, the MPBH is passing exactly at the Einstein radius. Therefore, it is possible for $u_0 > 1$ and for the source to be gravitationally microlensed. We chose to vary this parameter from 0 to 2, in increments of 0.2. t_0, of course, can happen at anytime in the history of the universe, however, we chose to use 5 specific dates due to limited computing bandwidth. These five dates center around the dates of DESs observations. The first date is the first day of observing in the survey, and the final date is the last day of observing for year 3 data. The other 3 days are equidistantly chosen between the two.

Finally, once all of these parameters have been calculated, we can input the u(t) - the path of the MPBH near the source - into the final equation:

$$A(t) = \frac{u(t)^2 + 2}{u(t)\sqrt{u(t)^2 + 4}} \tag{5}$$

A(t) is the linear flux magnification. The simple Microlensing light curve above is the Paczynski Curve and is visually depicted in Fig. 3.

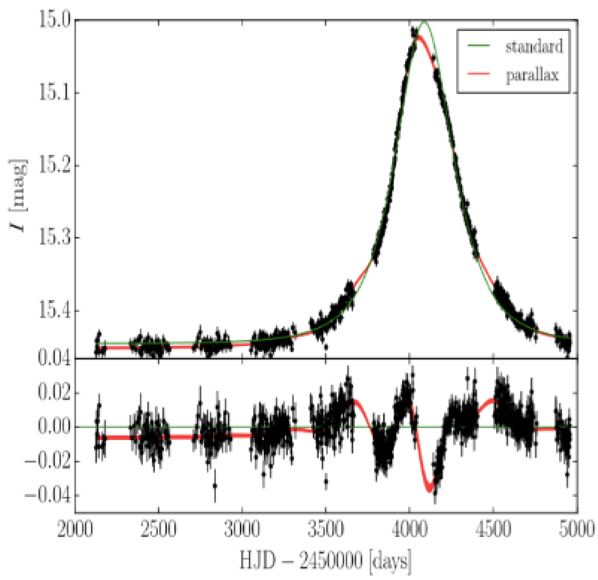

FIG. 3. Microlensing Event Example

Henning Peter Schmitz developed a light curve fitter by accounting for the fact that Microlensing is an achromatic event. In Fig. 4 Schmitz compares the difference of magnitude between two band passes. In an actual Microlensing event (on the left) the difference is negligible. However, with real data, the difference in magnitude is significant.

III. METHODOLOGY

Our project began by researching previous work. Henning Peter Schmitz created a fitting engine but found no microlensing events (Fig. 4) in the DES data set of the first three years. Josh Calcino developed code to generate many generic mock microlensing curves(Fig. 9).

Over the summer, Celeste Keith, Mishelle Mironov and I familiarized ourselves with the math behind the microlensing equations, as well as coding using Python. The bulk of the summer was dedicated to editing Calcinos original code to take in actual data from the Dark Energy Survey, and produce visual plots of the mock light curves. The next step will be to send these curves to Calcino for further analysis.

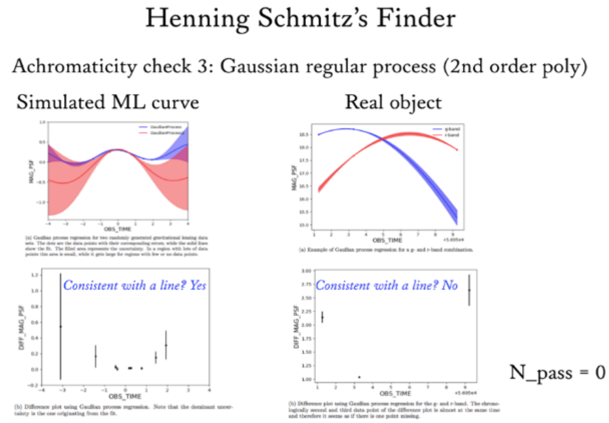

FIG. 4. Left two images depict a model microlensing event. The right two images depict real data observed.

The code consists of two (2) object classes: GenerateMLEvent, getData; and two (2) script files: fakeplots, driver; and a number of supporting files. The meat of the work happens in driver. Within driver, we create a getData object, which loads a unit of data, we pull the required parameters from that object, and pass it through to create billions of GenerateMLEvent objects - called curves. With another command, we can take any number of curves, and plot them using fakeplots. This allows us to visually compare multiple curves.

The driver class utilizes all other classes and scripts to create approximately 54,000 light curves (or microlensing events) per star within each HPIX pixel. This happens in five (5) steps:

1. Since the DES data is saved into approximately 1700 HPIX pixels, we developed a script that returns the names of each file, and converts the names into a usable format. The data was saved into fits files in

   `/des51.b/data/kadrlica/projects/y3q2/v7/cat/`

   The script *getHPIX* first imports files lists with structure ”cat_hpx_#.fits” then removes ”cat_hpx_” and ”.fits”, leaving only the ”#”. It returns a final list of HPIX values.

2. The driver class then loops through all HPIX values, and for each creates a *getData* object. *getData* creates a data object that may contain anywhere between 11,000 and 250,000 objects. It is here that we reduce our sample to only stars using two parameter cuts:

   (a) Based on the Fig. 5, we excluded object to the right of the red line, m = 21.5. This excludes objects that are dimmer than this magnitude and are likely galaxies instead of stars.

(b) the spread error: WAVG_SPREAD_MODEL < (0.003+SPREADERR_MODEL) . This removed objects with a large spread indicating a galaxy rather than a star.

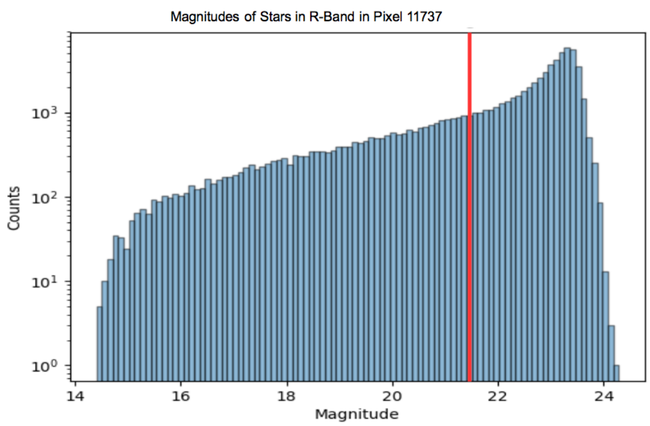

FIG. 5. Histogram of Magnitudes of Stars

This decreased the number of object within each HPIX by up to 80%, significantly reducing the sample size. To further simplify our sample size, we randomly choose 100 unique stars to continue to the next step.

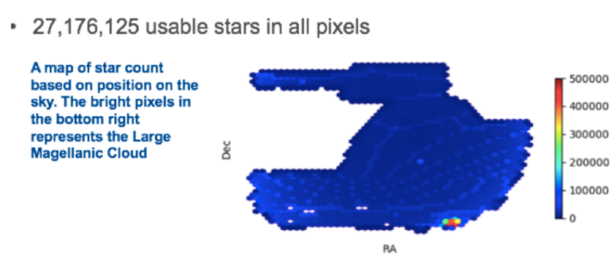

FIG. 6. Number of stars in the Survey, N_*

3. We then create a GenerateMLEvent object for all parameters with the following variables inputs:

   (a) For ALL stars:
   v_t = 220 km/s
   D_S = 30 kpc

   (b) For each individual star with n observations:
   Note: n may range between 2 and 60+.
   $times$: list of n MJDs (modified julian dates)
   $bandpass$: combination of n values; g,r,i,z,Y
   $m0$: list of n initial magnitudes for each observation
   $tEff$: n effective observation times
   RA: right ascension
   DEC: declination
   $objID$: ID of the object within the HPIX

   (c) Combination of the following parameters, t_0, u_0, $Mlens$, x:

      i. t_0 =
      56353 [Aug 31, 2013]
      56747 [Mar 31, 2014]
      56992 [Dec 1, 2014]
      57234 [Jul 31, 2015]
      57430 [Feb 12, 2016]

      ii. $0 \leq u_0 \leq 2$

      iii. $10M_\odot \leq Mlens \leq 100M_\odot$

      iv. $0 < x < 1$

      v. $lcID$: an ID for each combination of t_0, u_0, $Mlens$, and x

   This GenerateMLEvent object takes the above parameters and calculates:
   del_mag, the change in magnification for each observation
   $final\_mag$, the initial magnitude + del_mag + error

4. Driver stores the curves into fits files. The columns are labeled:
   'LCID' 'OBJID' 'RA' 'DEC' 'MAG' 'MAGERR' 'MJD' 'BAND' 'M_LENS' 'T_0' 'U_0' 'X'

   All curves from all objects in each HPIX are stored in a single fits file containing millions of rows.

5. Finally, we can take the information from each GenerateMLEvent object and make valuable plots:
   del_mag vs. time
   final_mag vs. time

IV. PLOTS

In Fig. 7 and Fig. 8, the following parameters are selected unless specifically stated otherwise:
$HPIX = 11737$
$objID = 11173700000001$
$M = 50M_\odot$
$u_0 = 1$
$t_0 = 56965$
$x = 0.5$

V. DISCUSSION

The DES Y3Q2 data contains approximately 1700 HPIX pixels of data. Each pixel contains between 13,000

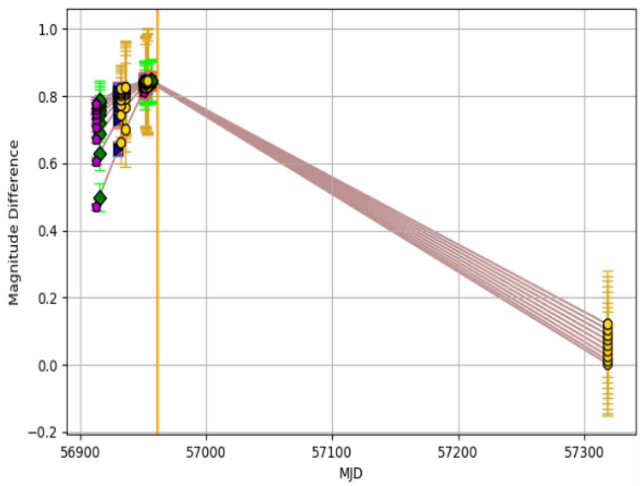

FIG. 7. $10M_\odot < M < 100M_\odot$

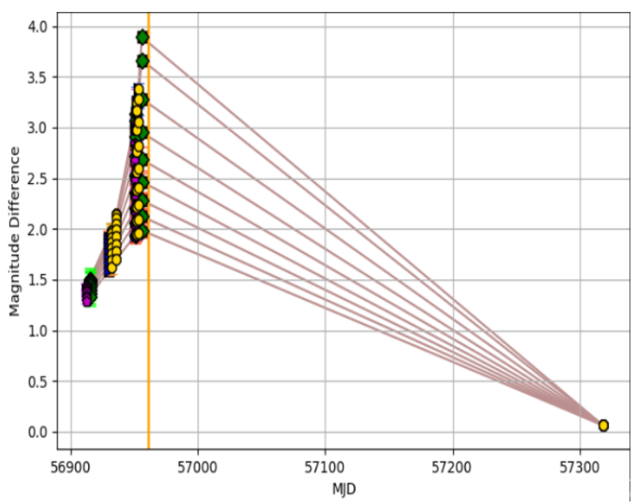

FIG. 8. $0 \leq u_0 \leq 1$

to 250,000 objects (both stars and galaxies). Our Microlensing Generator takes the information from the survey to determine the change in magnitude due to Gravitational Microlensing. We currently sample 100 stars in each object.

Many of our choices were made to support realistic use of computing power and time. Each HPIX can take from a few 10^{-2}s to 10^{1}s to load. This time multiplied by the time is take to generate light curves (GenerateMLEvent objects), can seriously impact the production. We settled on creating 54,000 curves per star, by varying the parameters listed in III above. Depending on the number of the observations directly impacts the speed of computing. We found that even the smaller HPIXs with only 13,000 objects could take up to 4 hours to process. Since the final fits file is saved with each observation as its own row, the fits files can become significantly large. With more time or computing power, we may be able to refine and/or extend our parameters to smaller increments be-

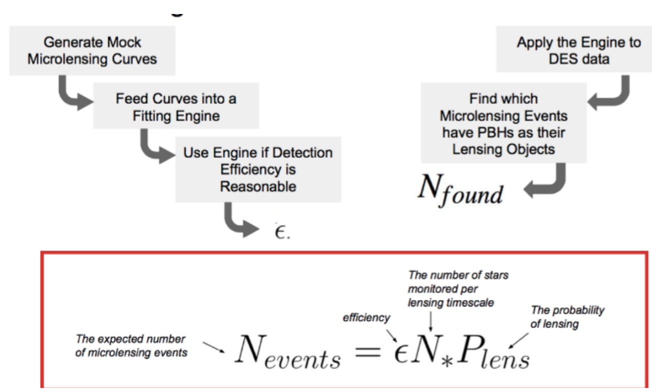

FIG. 9. Flowchart regarding the overall goal of the project.

tween values, or even extending their range. Once all of the light curves are produced, the team will be able to develop efficiency maps that validate Schmitz's current microlensing detector. By using the results, we can compute the efficiency as a function of $Mlens$, u_0, t_0, and x and then encode these into efficiency maps.

VI. CONCLUSIONS

The project has made significant progress in determining values and limit for our equation

$$N_{events} = \epsilon N_* P_{lens}$$

We have determined $N_* \approx 2^7$. See Fig. 6. We have made significant progress in determining efficiency ϵ, by developing the mock lensing curves, and soon we will be able to apply the original fitting algorithm. We also have a preliminary value for N_{events} from Schmitz's work in Fig. 4.

The scope of this project assumed many simplifications, including only accounting for a simple Paczynski curve. Future work will include accounting for parallax of the Earth $see Fig.$11, MPBH clusters $see Fig.$10 and other complex concepts.

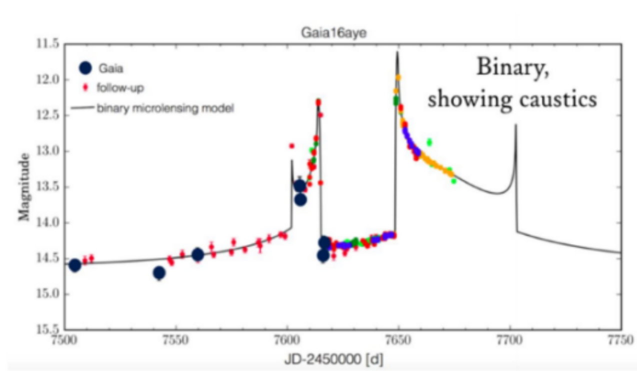

FIG. 10. Microlensing Curve caused by a cluster of MPBHs. This distorts the "simple" curve.

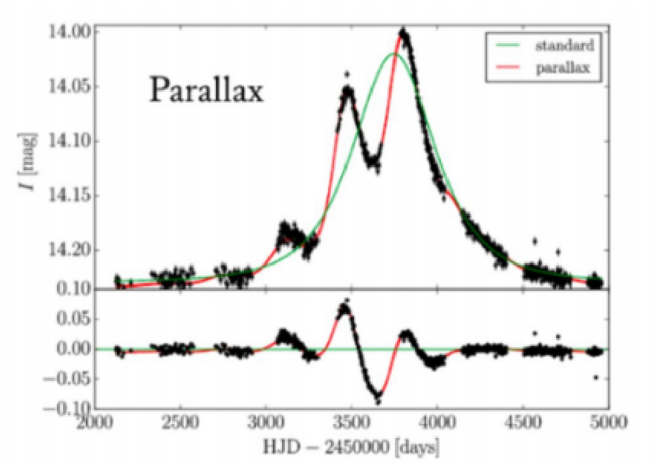

FIG. 11. Microlensing Curve that accounts for the Earth's natural orbit around the sun.

VII. SOURCES

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[2] Moniez, Marc. "Microlensing as a Probe of the Galactic Structure: 20 Years of Microlensing Optical Depth Studies." General Relativity and Gravitation, vol. 42, no. 9, Sept. 2010, pp. 20472074., doi:10.1007/s10714-009-0925-4.

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[4] Moniez, M. 2010, General Relativity and Graviation, 42, 2047.