Microlensing of stars in M31 by relics from the Early Universe

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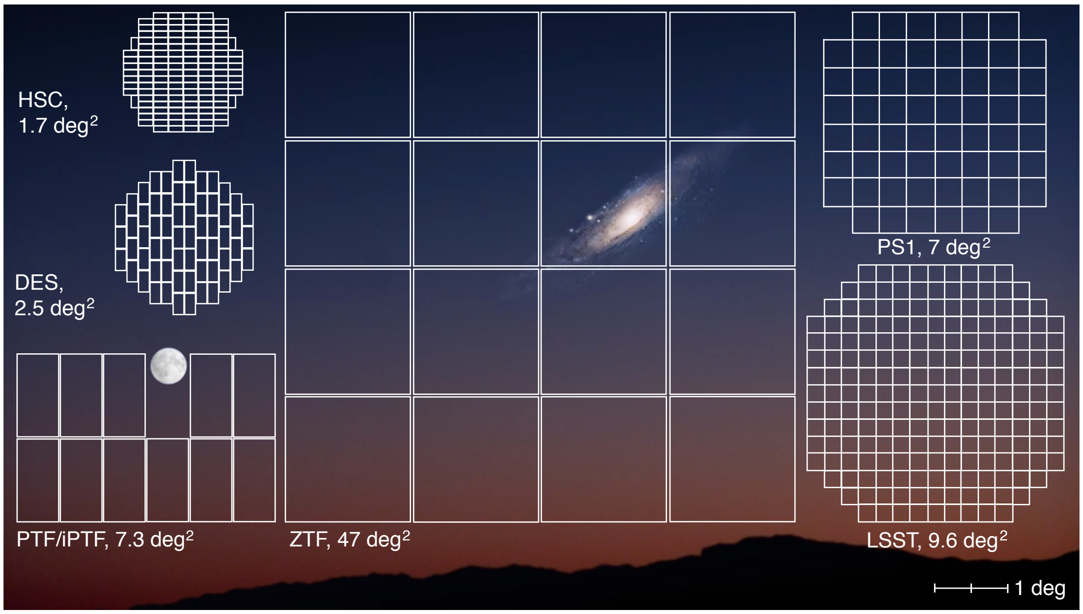
With contributions from external collaborators:
David Chernoff (Cornell), expert in microlensing by cosmic strings.
Monika Soraisam (NOAO, Tucson), stellar astronomy with iPTF experience in observations of M31
Malcolm Fairbairn, David J. E. Marsh and Jérémie Quevillon (Kings College London), axion physics, axion miniclusters and primordial black holes.



We propose a high-cadence survey of the Andromeda galaxy, monitoring ∼ 1 million resolved stars, in the search for microlensing events with duration from just a few minutes up to several days. This scenario has not been studied systematically and holds great promise to explore Early Universe physics.
The lenses we are trying to uncover are not "known" stellar objects, but rather relics from the beginning of time: *Cosmic Strings*, *Axion Miniclusters* and *Primordial Black Holes*. These are hypothetical (dark) macroscopic fossil remnants emerging in many leading theories of the Early Universe. It has been speculated that these objects still exist, and current experimental limits are not very constraining.
Surprisingly, we have found a survey mode for ZTF that could shed new light into the physics of the origin of the Universe and the nature of dark matter. The expected contributions to our understanding of stellar astronomy are also very important part of the program.

1 Scientific motivation of the project

Probing the physics of the Early Universe is normally thought to be beyond the means of optical astronomy. However, there are compelling scenarios for the epoch of exponential expansion in the first instances of the Universe, the inflationary period, that leave behind relics that can generate exotic transient signatures at optical wavelengths even today. We propose an experiment including high-cadence observations of M31, well suited to the capabilities of ZTF, that is both very competitive in searching for traces of new fundamental physics, as well as charting new territory in stellar astronomy. The exotic phenomena we are targeting involves microlensing of stars in Andromeda, but where the lens is *not* a stellar object. Instead, we consider the exotic (but plausible) cases where either *cosmic strings*, *primordial black holes* or *axion miniclusters* in the line of sight perturb the path of light, boosting the observable flux for a short period of time. Targeting stars in M31, as opposed to the MW, greatly enhances the discovery potential, mainly due to the much larger volume probed. There are also advantages with the duration of the lensing event and its cross-section. Our proposed observing strategy probes transient phenomena at three different time scales: seconds, hours and days. This allows for a broad range of model parameters to be probed. ZTF has an unobscured view of about 1 million resolved stars (1) that can be lensed by exotic massive objects in either the halo of the Milky-Way or Andromeda.

Cosmic strings: String theory inspired models of the inflationary period in the first instances of the universe predict a possible relic density of topological defects, *cosmic strings* (CS), whose existence may be tested through time-domain studies within reach for ZTF. The sought signature is primarily ”digital” microlensing of stellar bodies, i.e., whenever there is a CS in the line of sight to a star, space is perturbed so that the flux of the source object is **doubled**, as there are two paths for the light to travel around the CS. The two images cannot be spatially resolved, resulting in a microlening event. See (2) for a review of the theory. While the lensing signature to search for cosmic strings has a long history (3), the practical implementations to date have not been very successful, mainly because the time scales and cross-sections for the sources that have been targeted to date have been very challenging to monitor.

Digital microlensing events with typical durations ranging from just seconds to up to about an hour, depending on the energy content of CS encoded in what is called the ”string tension”, quantified by the dimensionless quantity, $G\mu/c^2$. Relativistic vibrations of the strings perturb the alignment between source and lens. This leads to a repetition of the microlensing event about 10^3 times, although the characteristic time scale for repetitions is months or even years, as shown in figure 1. The strings are expected to move with typical halo object velocities, $\sim$ 300 km/s, and move eventually out of the line of sight. *The expected signal differs from any known astrophysical transient*.

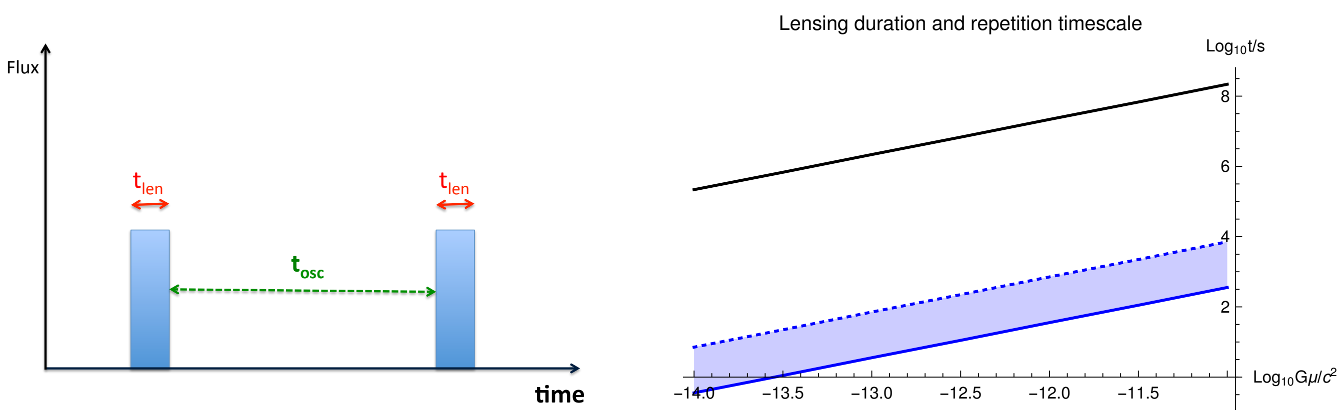


Figure 1: *Left:* A cartoon of a binary microlensing event showing the two characteristic time scales. The lensing time, t_{len} and the oscillation time of the string giving rise to repetitions of the lensing signal with time intervals, t_{osc}. *Right:* Expected median and maximal length of the microlensing event (blue), t_{len} as a function of the string tension, $G\mu/c^2$. We also show the typical repetition time, t_{osc} (black) due to the string oscillation.

Axion miniclusters: Axions are hypothetical very light scalar particles that have been proposed 40 years ago to solve a major problem in the theory of strong interactions, known as the "strong CP problem in QCD". Since then, it has been realised that axions, produced in the very early universe, are excellent dark matter (DM) candidates. Similarly to CS, relic axions if they indeed are a major component of the DM today, can be detected through microlensing of stars. This is because they are expected to have formed macroscopic "miniclusters" (4), with masses comparable to stellar objects like planets or the moon. The large range of possible axion minicluster masses allows for a very wide range in possible microlensing time scales, from just a few seconds up to years. See (6) for a recent study of the feasibility of the proposed technique.

Primordial black holes: These are hypothetical black holes which are not formed by dying stars but rather may be produced in the Early Universe during inflation or violent cosmological phase transitions. These black holes might make up a significant fraction of the dark matter in the Universe. If this is the case, then there are various mass windows where they are excluded due to their effect on the CMB or on the cosmic gamma ray background. However, many mass intervals remain unconstrained. ZTF would effectively be able to rule out primordial black holes being any significant part of the dark matter over an impressively wide mass range, $10^{-17} M_\odot$ to $1 M_\odot$. This result which would have a really significant impact on the theoretical cosmology community and the ongoing efforts to understand dark matter.

Stellar astronomy: While mainly targeting new fundamental physics, the data will provide exciting new insights into stellar astronomy, e.g., by searching for novae with decline time scales less than a day. Such events have not been observed to-date but are theoretically predicted, arising from the most massive white dwarfs close to the Chandrasekhar limit (5). Further, the high cadence of this program may facilitate detections of stellar flares from red dwarfs in our Galaxy along the line of sight to M31. This program would also enable finding a large number of short-period eclipsing systems in M31, including ultra-short systems, even with periods of about an hour. As we will discover a large number of variable stars in M31 we have the opportunity to make significant contributions to the study of massive stars. For instance, we could find very rare stars like Luminous Blue Variables and other hypergiants, representing short-lived stages in massive-star evolution.

1.1 Goals and competitiveness of ZTF for the project

Through (single pointing) monitoring of M31 with high cadence we will have a unique chance to detect early universe relics through microlensing of background stars. Figure 2 shows the discovery potential of the proposed P48 survey, assuming *all* the dark matter is either in the form of single mass primordial black holes (left) or axion miniclusters (right). We will be able to probe an unprecedentedly wide range of masses in both cases. An interesting aspect of the search for axion miniclusters is that it is complementary to the laboratory axion searches: if we find a signal from miniclusters it likely means that direct detection of individual axion particles is much more unlikely.

For the CS science, string tension is the most basic string parameter to be determined empirically. Current upper limits from CMB lensing, galaxy lensing and gravitational waves imply $G\mu/c^2 \lesssim 10^{-7}$, while model-dependent pulsar timing measurements have enlarged the exclusion region to $G\mu/c^2 \lesssim 3 \cdot 10^{-9}$. With the M31 experiment we have a chance to probe the region $10^{-13.5} \lesssim G\mu/c^2 \lesssim 10^{-11}$, a truly remarkable progress in the empirical tests of early universe physics.

A discovery of an exotic lens would be a major breakthrough for cosmology and fundamental physics. A non-detection would provide stringent limits to a theory otherwise lacking experimental tests. Major advances in stellar astronomy are also very likely.

1.2 Figures of merit

The success of the project hinges on the high-cadence, long term monitoring of ~ 1 million resolved stars in M31, probing the dark content of the MW and M31 halos. The key element is successive exposures which enables us to probe rare transient phenomena at the time scales from about about one minute up to several months. The FoMs in our study are I) the total number of consecutive exposures; II) the total number of same nigh exposures and III) the total survey monitoring period.

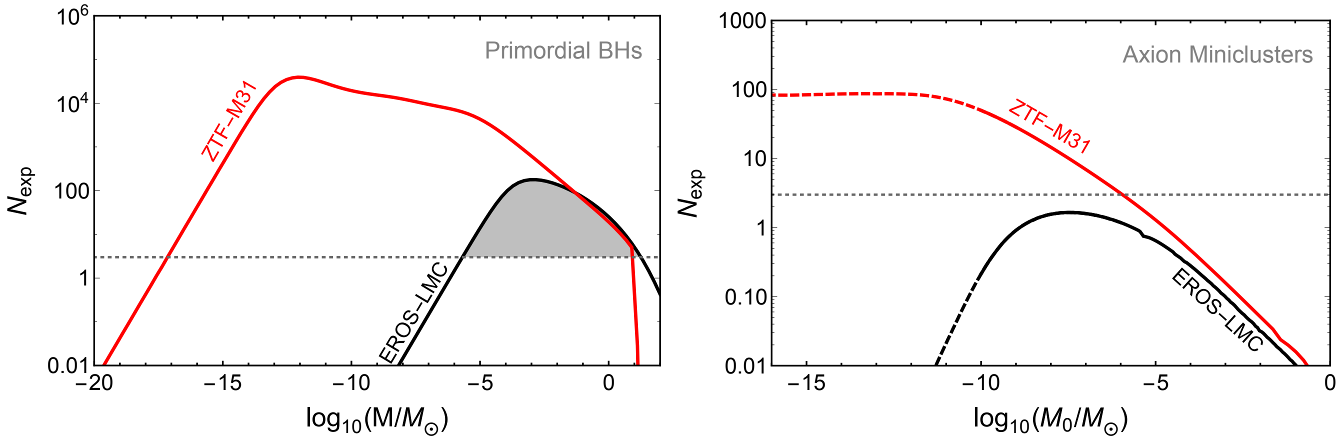


Figure 2: *Left:* Expected number of microlensing events where the lens is a single mass primordial black hole, accounting for 100% of the dark matter in the MW and M31 halos. Also shown are the expectations for survey of LMC carried out by EROS. As can be seen by the shaded area, the mass range $(10^{-6} - 10^{1})\,M_\odot$ is excluded. However, with the proposed survey (labeled ZTF-M31), we can probe another 11 orders of magnitude(!) in PBH mass. *Right:* Expected number of axion minicluster microlensing events in this program (ZTF-M31), compared with other microlensing limits by the EROS collaboration's observations of the MC. As for the case of PBHs, these numbers assume that axion miniclusters make up all the DM in the MW and M31 halos. Unlike EROS-LMC, ZTF-M31 has a significant sensitivity.

1.3 Rejection of false positives

Image differing in crowded fields like M31 poses a big challenge, as image artefacts are likely unavoidable. However, recent improvement in this technique (7) makes this effort very timely. Moreover, this experiment benefits greatly from the experience of studies of M31 with PTF/iPTF in (8). In fact, we may not need image differencing at all, but rather a continuos monitoring of the stellar fluxes.

Of course, we may also see ”ordinary” microlensing events with long time baseline. The success of the project does not depend on real-time discovery.

2 Proposed observations

2.1 Cadence and filters

We propose five consecutive observations of M31, single pointing, and a second same night 5 image sequence 40 to 90 minutes later. The repeats need not be in the same filter. The microlensing signature is achromatic. Adding read-out overheads, this corresponds to $10 \times 40 = 400$ sec of partnership time, every clear night.

2.2 Sensitivity of the expected science to cadence and calibration

The science potential lies in being able to search for transient with time scales of minutes. That requires consecutive observations. This project does not have any *absolute* calibration, but relies heavily on the ability to do accurate subtractions in crowded fields and reliable relative photometry between consecutive exposures.

2.3 Suitable periods for the observations

M31 is visible for at least an hour most of the year. Thus, this program could be carried out nearly throughout the entire year, with the possible exception of April.

3 Supporting observations

3.1 Photometric follow-up

We are searching for very rare transients. A serious candidate detection will be screened with all available optical telescopes, e.g., through the GROWTH network.

3.2 Can any of the cadence/filter requirements be relaxed with more use of other telescopes?

No, regular monitoring with P48 is ideally suited for the purpose, at modest ”cost” for the partnership.

3.3 Specify the need for spectral classification and SEDM time

We do not anticipate any major use of spectroscopic resources for the exotic transients.

3.4 Indicate any other external resources (e.g., radio, X-ray)

We do not expect a significant signature in any other part of the EM spectrum that we can use.

4 Expertise to undertake project

4.1 Team composition

The project requires expertise in working with crowded fields. This is an area where Thomas Kupfer and Monika Soraisam provide very valuable expertise. They are also stellar astronomers capable of extracting the novel science in that field. The PI has also recruited external experts to interpret the findings of the experiment. David Chernoff is a world leader expert in microlensing by cosmic strings. He has developed a Monte-Carlo simulation tool that can be used to interpret discoveries, as well as help to establish limits if we do not make a detection. Similarly, the London colleagues Fairbairn, Marsh and Quevillon have developed tools to make predictions of the expected signal from primordial black holes and axion miniclusters and will be involved in the interpretation of the ZTF findings.

4.2 Specify tools required to deliver science products

Accurate image or photometry differencing tools for crowded fields. To estimate signal efficiencies we will use custom made Monte-Carlo simulation packages, mainly provided by the external members of the team.

5 Manpower and time-line

5.1 Specify the people that will carry out the project as well as milestones for the publication plan

The lightcurves of variable stars will be built by Thomas Kupfer and colleagues in the stellar group, using techniques developed by external collaborator Monika Soraisam. The search for exotic lenses will be carried out by the OKC group. The interpretation, either in the form of detection or upper limits on the number densities and string tensions, will be done involving the whole team.

5.2 Is this a thesis project? If so provide name(s) of student(s)

Not clear yet.

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