LSST’s DC Bias Against Planets and Galactic-Plane Science

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ABSTRACT

An LSST-like survey of the Galactic plane (deep images every 3-4 days) could probe the Galactic distribution of planets by two distinct methods: gravitational microlensing of planets beyond the snow line and transits by planets very close to their hosts. The survey would identify over 250 disk-lens/disk-source microlensing events per year that peak at \( r < 19 \), including 10% reaching the high magnification \( A > 100 \) that makes them especially sensitive to planets. Intensive followup of these events would be required to find planets, similar to what is done presently for Galactic bulge microlensing. The same data would enable a wealth of other science, including detection of isolated black holes, systematic study of brown-dwarf binaries, a pre-explosion lightcurve of the next Galactic supernova, pre-explosion lightcurves of stellar mergers, early nova lightcurves, proper motions of many more stars than can be reached by GAIA, and probably much more. As usual, the most exciting discoveries from probing the huge parameter space encompassed by Galactic-plane stellar populations might well be serendipitous. Unfortunately, the LSST collaboration plans to exclude the first and fourth quadrants of the Galactic plane from their “synoptic” observations because the DC image that resulted from repeated observations would be limited by crowding. I demonstrate that the majority of this science can be recovered by employing well-developed image subtraction analysis methods, and that the cost to other (high Galactic latitude) science would be negligible.

Subject headings: gravitational lensing: micro — planetary systems — supernovae: general – black hole physics

1. Introduction

The past two decades have seen a tremendous growth of precision optical photometric surveys. The first of these were microlensing surveys [Paczyński 1986, 1991, Griest et al.]
carried out by the MACHO (Alcock et al. 1993), EROS (Aubourg et al. 1993), and OGLE (Udalski et al. 1993) collaborations, which monitored tens of square degrees at several hundred (now thousand) epochs. These have also yielded an immense range of scientific results that are unrelated to microlensing, from transiting planets (Udalski et al. 2002a), to proper motion catalogs (Sumi et al. 2004), to pre-explosion lightcurves of stellar mergers (Tylenda et al. 2011) and of other outbursts (Wagner et al. 2012). The Sloan Digital Sky Survey (SDSS, Gunn & Knapp 1993; Aihara et al. 2011) then mapped $\sim 10^4 \text{deg}^2$ in five bands at a single epoch, supplemented by a synoptic survey that covered hundreds of square degrees at several dozen epochs. Influenced largely by SDSS’s spectacular success (over 5000 publications to date), the Decadal Survey Committee (2010) gave top ground-based priority to a new survey that would combine the principal features of these two. Like SDSS, it would cover a large fraction of the sky, and like microlensing surveys, it would do so at $\sim 10^3$ epochs. Strangely, however, there has been little discussion of the microlensing potential of an all-sky synoptic survey. Investigation of this potential leads immediately to the conclusion that many other applications are being overlooked, perhaps at great scientific cost.

Among the properties one would like to know about extrasolar planets is their distribution in the Galaxy. This question is particularly difficult to address because most planet-search techniques depend on subtle changes in light from the host and so are restricted to planets orbiting bright (hence generally nearby) stars. Thus, the overwhelming majority of the roughly 4000 planets and strong planetary candidates detected to date are within a kpc or so of the Sun.

The microlensing technique is an important exception to this rule. Planetary systems give rise to microlensing signals when they act as “lenses”, deflecting the light of unrelated, more distant “source” stars. Hence, detection does not depend in any way on the light from the host, nor even the existence of a host. The principal challenge for the microlensing technique is that the source and lens must be aligned exquisitely on the sky, typically $< 1 \text{mas}$, to generate a microlensing signal. Even for the densest star fields toward the Galactic bulge, the chance that any given source is microlensed is only about $10^{-6}$. Moreover, only a small fraction of microlensed stars yield planetary signatures. Hence, all planetary microlensing surveys have been carried out toward the Galactic bulge and, ipso facto, all microlensing planets have been discovered in this direction.

Because the source stars in these surveys are near the Galactic center, current microlensing surveys are already sensitive, in principle, to planetary systems at all Galactocentric radii $R$ in the range $0 \lesssim R \lesssim R_0 \simeq 8 \text{kpc}$. However, one of the prices that microlensing must pay for being indifferent to host light is that generally the hosts are not detected, so that neither their masses nor their distances are known. Fortunately, in the case of lenses with planetary
signatures, one almost always sees “finite source effects” when the source passes over or near a “caustic” induced by the planet. In these cases, one can directly measure $\rho = \theta_s / \theta_E$ from the lightcurve, where $\theta_s$ is the source radius, $\theta_E$ is the angular Einstein radius,

$$\theta_E \equiv \sqrt{\kappa M \pi_{\text{rel}}}; \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} = 8.1 \frac{\text{mas}}{M_\odot},$$

(1)

$M$ is the lens mass, and $\pi_{\text{rel}}$ is the lens-source relative parallax. Since $\theta_s$ can be determined from the dereddened color and magnitude of the source (Yoo et al. 2004), this means that a combination of the host mass and distance is almost always measured.

Nevertheless, it is generally quite difficult to disentangle $M$ and $\pi_{\text{rel}}$, and for this reason the distribution of microlens planets along the line of sight toward the Galactic bulge remains unknown.

An alternate approach would be a microlensing survey of the Galactic disk. I argue here that such a survey would be much more sensitive to the distribution of planets as a function of $R$ than surveys toward the bulge, in part because it is easier to estimate the distribution of planet distances and in part because a larger range of $R$ is surveyed.

Of course, such a survey would be much more challenging than current microlensing planet searches. Thousands (rather than dozens) of square degrees would have to be monitored because the event rate per unit area is much lower. There is no foreseeable way to monitor such a huge area with the roughly hourly cadence required to find planets. Instead, there would have to be one wide-field survey that monitored the target fields every few days from which one would identify the promising microlensing candidates, and then these candidates would have to be monitored much more frequently from a network of narrow-angle telescopes (Gould & Loeb 1992).

Fortunately, the Large Synoptic Survey Telescope (LSST) is well adapted to the first component of this search. It plans to observe 15,000 square degrees every 3–4 nights (covering a total of more than 20,000 deg$^2$) over the course of 10 years to flux levels that are sufficient to find all microlensing events that could plausibly be followed up. The network of narrow-angle telescopes required for the second component, high-cadence followup observations, is already under construction. Hence, such a survey is quite feasible.

Unfortunately, the current plans of the LSST consortium are to exclude from normal-cadence observations the majority of Galactic disk that is accessible to LSST, including all of the disk within 90° of the Galactic center where the overwhelming majority of “disk-disk” (disk-lens/disk-source) microlensing events occur.

Up until now, the prospects for very wide field microlensing surveys have only been considered to fairly bright magnitudes. In particular, Han (2008) calculated event rates
over the whole sky with magnitude limits of $V = 12, 14, 16,$ and 18. However, due to “magnification bias”, which favors the detection of highly magnified, faint sources, together with the much higher sensitivity to planets of high-magnification events, most sensitivity to planets comes from substantially fainter sources than these, which happen to be momentarily magnified to near the faintest of these limits.

Here, I investigate this potential. I then briefly review a subset of the other vast scientific opportunities that such a survey would enable. Finally, I discuss the DC bias that is leading the LSST consortium to ignore these possibilities.

2. Microlensing Event Rate in the Galactic Disk

From the standpoint of finding planets, what constitutes a “microlensing event” is determined by what can plausibly be monitored in follow-up observations. For present purposes, I define this as events for which the source 1) enters the Einstein ring ($u_0 < 1$) 2) reaches magnitude $r_{\text{peak}} < 19$ at the peak of the event, and 3) has a baseline magnitude $r_{\text{base}} < 26$. The third requirement is needed because it would be difficult or impossible to recognize fainter sources that satisfy (2) in time for intensive monitoring over the peak. For simplicity, I consider only disk-disk lensing, and also consider only main-sequence sources and lenses. Of course, giant-star sources are also microlensed, but these also strongly degrade the microlensing signal of the main-sequence sources that are superposed within $1''$. For similar reasons, giant-star lenses are rare and virtually unobservable.

I adopt a simple double-exponential profile for both the stars and the dust. The scale heights of these are 300 pc and 130 pc, respectively, while the scale lengths are both 2500 pc. For the local normalization of the dust, I adopt $dA_r/d\ell = 0.6$ mag kpc$^{-1}$. For the stars, I adopt a local luminosity function of $\phi = (0.34, 0.48, 1.087, 1.96, 2.51, 3.15, 3.02, 3.89, 3.78, 6.97, 10.90, 15.14, 8.86, 5.48, 2.50, 2.50, 2.50, 2.50) \times 10^{-3}$ pc$^{-3}$ for $M_V = 1, \ldots, 18$, with corresponding masses $M = (2.0, 1.7, 1.4, 1.2, 1.0, 0.9, 0.83, 0.65, 0.51, 0.39, 0.32, 0.25, 0.20, 0.17, 0.13, 0.10, 0.09, 0.08) M_\odot$. I assume that the Galaxy has a flat rotation curve characterized by $v_{\text{rot}} = 235$ km s$^{-1}$, with local dispersions in the radial, tangential, and vertical directions of $(35, 28, 18)$ km s$^{-1}$, that the Sun is moving with respect to the Local Standard of Rest at $(10, 12, 7)$ km s$^{-1}$ and that it lies 15 pc above the Galactic plane.

1I note that the problem of time-variable photometry in crowded fields has been solved by the invention of difference imaging [Alard & Lupton 1998], which is routinely implemented in fields that are much more crowded than those discussed here by all microlensing teams, who achieve a systematics floor of a few mmag when reasonable ($\sim 1''$) seeing obtains.
I evaluate the event rate for each source star \( i \) at distance \( D_{S,i} \) by a sum over lenses at \( D_{L,j} \),

\[
\Gamma(D_{S}, l, b) = \sum_j 2\theta_{E,ij}D_{L,j}^2\mu_{rel,ij} \rightarrow \phi_M \int_0^{D_{S,i}} dD_{S} D_{L}^2 \frac{\rho(D_{L,l,b})}{\rho_0} \left( \frac{AU}{D_L} - \frac{AU}{D_S} \right)^{1/2} \langle \mu_{rel}(D_S, D_L, l, b) \rangle 
\]

where \( \theta_{E,ij} \) is the Einstein radius of the lens (Equation (1)), \( \mu_{rel,ij} \) is the source-lens relative proper motion, \( \rho(D_L, l, b)/\rho_0 \) is stellar density at the lens location relative to the local one, \( \langle \mu_{rel}(D_S, D_L, l, b) \rangle \) is the mean magnitude of the lens-source proper motion at the specified coordinates, and

\[
\phi_M \equiv \sum_k \phi_k \sqrt{\kappa M_k} \simeq 0.131 \text{ mas}^{1/2} \text{ pc}^{-3} \tag{3}
\]

I then evaluate the total event rate per square degree for each line of sight \((l, b)\) by

\[
\Gamma(l, b) = \left( \frac{\text{deg}}{\text{radian}} \right)^2 \sum_k \phi_k \int_0^\infty dD_S D_s^2 u_{\text{max}}(r[M_r,k, D_S, l, b]) \Gamma(D_s, l, b), \tag{4}
\]

where \( r(M_r, D_s, l, b) = M_r + A_r + 5 \log(D_S/10 \text{ pc}) \), \( A_r \) is calculated by integrating through the above-assumed dust profile from the Sun to the source, and

\[
u_{\text{max}}(r) = \min \left( 1, \sqrt{2 \left( \frac{A_{\text{min}}}{\sqrt{A_{\text{min}}^2 - 1}} - 1 \right)} \right) \Theta(26 - r); \quad A_{\text{min}} = \max \left( \sqrt{\frac{9}{5}}, 10^{0.4(r-19)} \right) \tag{5}\]

is obtained by inverting the Euler (1936) point-lens magnification: \( A(u) = (u^2 + 2)(u^4 + 4u^2)^{-1/2} \).

Figure \( \text{I} \) shows the resulting rates in events yr\(^{-1}\) deg\(^{-2}\) for the region within 20.5\(^{\circ}\) of the Galactic plane. The total rate in the area shown is \( \Gamma = 557 \text{ yr}^{-1} \) of which 86\% is inside the dashed-black rhombus, which contains just 2076 deg\(^2\), i.e., 14\% of the total area shown. Note from the lower panel of Figure \( \text{I} \) that the dashed-black rhombus also contains the great majority of events for which the lenses are more than a few kpc from the Sun.

### 3. Planet Searches

Of course, not all of these \( \Gamma = 557 \text{ yr}^{-1} \) could be detected. First, most regions of the Galactic disk come too close to the Sun to be observed all year. Second, any given telescope will be restricted to observing those portions of the sky that do not remain too close to (or below) the horizon at that site. Nevertheless, a telescope at a southern site could observe most or all of the rhombus shown in Figure \( \text{I} \) for more than half the year, and therefore
could detect of order 250 events per year, or more. This is of order 15% of the rate of event
detection by the OGLE collaboration (Udalski et al. 1993) toward the Galactic bulge in its
OGLE-IV phase. And it is roughly 35% of the current rate for the MOA collaboration
(Bond et al. 2004) in MOA-II phase or the previous detection rate of OGLE-III. In the
period 2007-2009 when OGLE-III and MOA-II were in operation, microlensing planets were
being discovered at a rate of roughly 3 per year despite the fact that less than 5% of the
discovered events were being aggressively monitored by follow-up collaborations, such as
PLANET (Beaulieu et al. 2006), μFUN (Gould et al. 2006b), RoboNet (Street et al. 2013),
and MiNDSTEp (Bozza et al. 2012). Hence, it is plausible that aggressive monitoring of
these 250 events could yield a dozen planet detections per year.

I note that there is a strong magnification bias induced by selecting on peak flux, so
that a disproportionate share of the events will be at high magnification even relative to
the OGLE-III survey. See Figure 2. Half the events have \( A_{\text{max}} > 6 \) and thus significantly
enhanced sensitivity to planets (Gould & Loeb 1992), while 10% have \( A_{\text{max}} > 100 \), which
implies greatly enhanced sensitivity (Griest & Safizadeh 1998; Gould et al. 2010).

However, given that the magnified flux threshold required to achieve this event rate is
\( r_{\text{peak}} < 19 \), whereas the densely monitored Galactic bulge events typically had
\( I_{\text{peak}} \lesssim 15.5 \), it is clear that Galactic-plane followup observations would require much more telescope
resources than earlier bulge searches. This requirement is not as exacting as it may sound;
many earlier planet detections relied heavily on amateur class telescopes (e.g., Han et al.
2013). What is needed now is a dedicated network of 1m class telescopes. Fortunately,
such a world-wide network is currently under construction by the Las Cumbres Observatory
Global Telescope Network (LCOGT) (Tsapras et al. 2009), with planet discovery being an
important component of its science program.

4. LSST: An Ideal Disk Microlens Survey

Therefore, the most difficult aspect of organizing such a planet search is to conduct the
underlying survey that will identify the microlensing events for high-cadence followup. This
survey must satisfy four key requirements: (1) observe a large fraction of the Galactic plane
(2) from the southern hemisphere (3) every few days (4) to very deep magnitudes. These
characteristics can mostly be inferred by examination of Figures 1 and 2.

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2http://ogle.astrouw.edu.pl/ogle4/ews/ews.html
3https://it019909.massey.ac.nz/moa/alert2013/alert.html
From Figure 1, it is clear that most of the survey sensitivity comes from the dashed-black rhombus centered on the \((l, b) = (0, 0)\), whose area is \(\sim 2000 \, \text{deg}^2\). Since its center has a declination of \(\delta \sim -30^\circ\), both of the first two criteria are necessary. Much of the potential planet sensitivity comes from high-magnification events. For example, Gould et al. (2010) found 6 planets in a sample of 13 events that were well-monitored over peaks of \(A_{\text{max}} > 200\). Figure 2 shows that there are 35 such events per (full) year, with about half these occurring in the rhombus at times when they are observable. But if such an \(A_{\text{max}} = 200\) event has a typical timescale of \(t_E = 50\) days and peaks at my adopted \(r_{\text{peak}} = 19\) threshold, then 3 days prior to peak, it will be \(A = 50/3 \sim 17\) and so have a magnitude \(r = r_{\text{peak}} + 2.5 \log(200/17) = 21.7\). To recognize such an incipient high-magnification event therefore requires observations every 3–4 days with good enough (few percent) photometry to both identify the most recent point as “interesting” and to recover the previous lightcurve in order to predict its future behavior. This justifies the final two criteria, “(3) every few days (4) to very deep magnitudes”. Note that the photometry does not have to be good enough to unambiguously predict future behavior. As with current followup photometry carried out by \(\mu\)FUN, it is enough to identify candidate high-magnification events that can be checked on subsequent nights by a few observations, to then determine whether they are suitable for intensive followup over peak.

Figure 1 shows the approximate boundaries of the high cadence zone of the proposed LSST survey in Galactic coordinates. These are derived from the equatorial-coordinate diagram from Figure 18 of Ivezić (2013), which is an updated version of Figure 4.4 of Abate et al. (2012). The white contours indicate the limits imposed by geography, i.e., the northern and southern declinations at which the air mass begins to seriously degrade the quality of observations. The dashed-black rhombus at the center is the region that is excluded for reasons discussed in Section 7. Table 1 summarizes the integrated event rate inside and outside this rhombus, both for the entire area shown in Figure 1 and for the region robustly accessible to LSST.

### Table 1: Event Rates by Zone

| Subset (Fig. 1) | Rhombus | Event Rate \((\text{yr}^{-1})\) | Area \((\text{deg}^2)\) |
|-----------------|---------|------------------------------|------------------|
| All Inside      |         | 477                          | 2076             |
| All Outside     |         | 80                           | 12411            |
| LSST Inside     |         | 431                          | 1685             |
| LSST Outside    |         | 47                           | 5639             |
5. Advantages of Disk-Disk Lensing

While Galactic disk fields have many fewer microlensing events than bulge fields despite much larger area, they do possess several significant advantages, which combine to make mass measurements easier. Recall from Section [1] that $\theta_E$ is routinely measurable for planetary events. This means that the lens mass $M$ can be determined provided that the microlens parallax $\pi_E$ can be measured (Gould 1992, 2004),

$$M = \frac{\theta_E}{\kappa \pi_E}, \quad \pi_{\text{rel}} = \theta_E \pi_E.$$  \hspace{1cm} (6)

The microlens parallax is a vector $\pi_E$ whose magnitude is the size of Earth’s orbit relative to the Einstein radius projected onto the observer plane $\pi_E = \text{AU}/\tilde{r}_E$ and whose direction is that of the lens-source relative proper motion.

Microlens parallax is usually measured from distortions in the lightcurve due to the accelerated motion of the observer (on Earth). Hence, if the event is very short, Earth’s motion can be approximated as being uniform during the event, so the effect is negligible. For disk-disk lensing, the observer, lens, and source all share, to some extent, the motion of the disk, which tends to make the event last longer than in disk-bulge lensing.

Second, just by chance, the Galactic bulge lies very near the ecliptic. In the limit that the source lies exactly on the ecliptic, the direction of Earth’s acceleration remains constant. Since the component of $\pi_E$ that is parallel to this acceleration $\pi_{E,\parallel}$ is third-order in time (Gould et al. 1994) while the perpendicular component $\pi_{E,\perp}$ is fourth order (Smith et al. 2003; Gould 2004), virtually all of the uncertainty is concentrated in one component for bulge sources, making it exceptionally difficult to measure the amplitude of $\pi_E$, which goes into Equation (6). By contrast, much of the Galactic disk lies well away from the ecliptic.

Third, for disk-disk lensing, the direction of lens-source relative proper motion is expected to be approximately aligned with the Galactic plane, both because dispersions in the radial and rotation directions are larger than in the vertical direction and because the bulk relative motions of the local standards of rest of the observer, lens, and, source lie almost exactly in the plane. This implies that even for the cases that only one component of $\pi_E$ is measured, there is significant prior information on the direction of $\pi_E$ to deproject its amplitude, at least statistically.

Finally, in strong contrast to disk-bulge lensing, the source direction itself provides important statistical information of the Galactocentric distance of the lens in disk-disk lensing. That is, just from the ratios of planet detections to total microlensing events monitored along different lines of sight, one already learns something about the Galactic distribution of planets.
6. Other Synoptic Disk Science

While microlensing planet searches are the immediate focus the present work, there are a range of other applications of the same many-epoch survey of the Galactic disk. These all basically stem from the fact that the majority of Galactic stars lie within the dashed-black rhombus of Figure 1.

6.1. Other Microlensing

First, there are other microlensing applications. Even without the follow-up observations discussed in this work, the survey itself would yield the event rate and optical depth over many lines of sight, which in turn probe the compact-matter distribution of the disk as a function of Galactocentric radius. The EROS collaboration carried out such a study over four non-bulge lines of sight (Derue et al. 2001; Rahal et al. 2009). See Figure 1 of Rahal et al. (2009). However, an order-of-magnitude larger survey is now feasible. Such an investigation would be complementary to GAIA kinematic measurements, which will be similar to the Hipparcos-based studies of Crézé et al. (1998) and Holmberg & Flynn (2004), but on a much larger scale. That is, while the kinematic measurements are sensitive to total mass (stars, brown dwarfs, gas, dark matter), the microlensing measurements are only sensitive to compact objects. In addition, the two surveys may be sensitive to non-standard gravity (e.g. Milgrom 1983) in different ways.

The same microlensing data would probe the distribution of isolated black holes in the Galactic disk, which cannot be investigated in any other way. Because black-hole events are typically very long, they will generally yield microlens parallaxes and so the parameter combination \( \pi_E^2 = \pi_{\text{rel}}/\kappa M \). Such measurements do not unambiguously identify black holes because small \( \pi_E \) can in principle be produced by either large \( M \) or small \( \pi_{\text{rel}} \). However, the black holes will also have large \( \theta_E^2 = \kappa M \pi_{\text{rel}} \), and this is potentially detectable through astrometric measurements (Miyamoto & Yoshii 1995; Hog et al. 1995; Walker 1995), either from the survey itself (see below) or high-resolution followup observations.

In addition, the survey would yield an immense wealth of data on the low-mass binaries, including close brown dwarf binaries (Choi et al. 2013) over vast regions of the Galaxy, which cannot be probed in any other way.
6.2. Transiting Planets

Second, the same survey would probe the Galactic distribution of planets by a completely independent method: transits. With roughly $N \sim 800$ epochs, the survey could identify close-in planets characterized by

$$N \frac{R_*}{\pi a} \frac{r_p^4}{R_4^4} \sqrt{1 - b^2 \sigma^{-2}} > \Delta \chi_{\text{thresh}}^2$$

where $R_*$ is the radius of the star, $r_p$ is the radius of the planet, $a$ is the semi-major axis of the orbit (assumed circular), $b$ is the normalized impact parameter, $\sigma$ is the fractional error of the measurements, and $\Delta \chi_{\text{thresh}}^2$ is the minimum $\Delta \chi^2$ required for detection.

For reference, the number of images is similar to that collected by the OGLE-III project toward two fields (in Carina and the Galactic center) totaling about $2.2 \text{deg}^2$ (Udalski et al. 2002a,b), while the integrations would be several magnitudes deeper and the sky coverage more than 1000 times larger. Since the OGLE-III survey found five planets, these figures alone demonstrate the planet finding potential of such a survey.

Of course, before making a direct comparison with OGLE, one must take account of the fact that the $\sim 800$ observations are spread out over $T \sim 10 \text{yr}$ rather than a few months. This implies many more ways to fold the data to search for transits, and hence a higher probability that purely statistical noise will masquerade as transits. However, the following explicit calculation shows that this is not the limiting factor.

At fixed period $P$ and transit duration $t$, there are $P/t$ independent locations to search for the transit. If the period is changed by $\delta P$, then the offset between the first and last transit will be displaced in time by $\delta P(T/P)$. Setting this equal to $t$ yields the period change at which the set of folds are independent: $\delta P = Pt/T$. At each $P$ a small (typically factor 5) range of $t$ must be searched, but this is basically accounted for just by using the minimum $t$ searched. Hence, to probe periods $P < P_0$ requires $P_0 T/t^2$ independent searches. If we demand a false detection probability $f = 10^{-6}$ (which is conservative, since the transit frequency is about 1000 times higher than this), then

$$\Delta \chi_{\text{thresh,stat}}^2 \sim 2 \ln \frac{P_0 T}{t^2 f} \sim 63$$

where I have adopted $T = 10 \text{yr}$, $P_0 = 5 \text{day}$, $t = 0.5 \text{hr}$. For the OGLE survey, A. Udalski searched for transits down to $\Delta \chi^2 = 81$. Gould et al. (2006a) conducted double-blind tests and found that this search was complete to $\Delta \chi^2 = 121$. A calculation of the purely statistical limit using Equation (8) yields $\Delta \chi_{\text{thresh,stat}}^2 \sim 56$ for OGLE. Thus the OGLE survey was not fundamentally limited by statistical noise, and it is therefore plausible that a future study could do at least as well.
Now, it must be emphasized that the five OGLE detections required aggressive followup of about 100 candidates, an effort that would be difficult to duplicate on a 1000-fold larger scale. However, by restricting the search to planets that are smaller than Jupiter (and thus also smaller than late M dwarfs and brown dwarfs) and also by focusing on closer planets, which are both rarer and have higher signal-to-noise ratio according to Equation (7), one could develop a tractable search program. This would provide an additional valuable probe to the Galactic distribution of planets at very different host-planet separations compared to the microlensing search, albeit at closer distances from the Sun.

To make quantitative estimates of this potential, I make the following assumptions. First, I adopt the planet frequencies of Howard et al. (2012), derived from Kepler data. Second, I adopt the single-epoch photometric precision from Iv{e}zi{c} et al. (2012), except that I adopt a photometric error floor of $2 \times 10^{-3}$ rather than the value of $5 \times 10^{-3}$ shown in their Figure 21. This is because difference photometry can be done much more accurately than absolute photometry. For example the OGLE collaboration routinely achieves a systematics limit of $4 \times 10^{-3}$ using their 1.3m telescope, while Hartman et al. (2009) showed that $1 \times 10^{-3}$ can be achieved for individual sources when data from larger telescopes are carefully analyzed. See their Figure 3. Finally, I adopt $\Delta \chi^2 = 121$ which was achieved in the OGLE transit survey (Gould et al. 2006a). For “sub-Jupiters” ($4 < r_p/R_\oplus < 8$), I find a total of 6000 planet detections within the LSST zone of Figure 1, of which 1800 lie in the dashed-black rhombus. These have a mean distance from the Sun of about 1 kpc, almost independent of direction. Of course, one might argue that since less than one-third of these planets lie in the rhombus, not much is lost by ignoring it. However, from the standpoint of learning about the Galactic distribution of planets, it is critically important to look both inside and outside the solar circle. I also find a total of 200 “sub-Neptunes” ($2 < r_p/R_\oplus < 4$), with mean distances of 340 pc.

### 6.3. Explosions

Another unique application of a deep synoptic survey of the Galactic disk would be to provide a pre-supernova lightcurve of the next Galactic supernova. Szczygiel et al. (2012) are systematically obtaining such lightcurves for about 25 external galaxies with a cadence of a few times per year. Given the fact that a supernova in our own Galaxy will be subject to extremely detailed study at multiple wavelengths, as well as neutrinos and perhaps gravitational waves, much more detailed pre-supernova lightcurves would be of immense value. This would be true whether the next supernova takes place during the first such high-cadence photometric survey or many decades later.
Similarly, such a survey would obtain pre-outburst lightcurves of a variety of explosive phenomena, including nova and stellar mergers. For example, Tylenda et al. (2011) measured the inspiral of the eclipsing-binary progenitor of a merger explosion based on OGLE data. Tylenda et al. (2013) found, unfortunately, that the pre-explosion lightcurve of another stellar merger began too late to capture the eclipsing phase, so that the inspiral rate could not be measured. This points to the importance of long time baselines over very wide areas. And the MOA collaboration recognized $P = 2 \text{ hr}$ periodic variations in the rising lightcurve of MOA-2012-BLG-320 (D. Bennett 2012, private communication), a week after it was triggered at $I \sim 18.5$ as a “microlensing candidate”, but five days before it was spectroscopically classified as a nova (Wagner et al. 2012). Of course, a 2-hr period could not be recognized in data having a 3-day cadence, but the rising lightcurve could trigger the required followup.

### 6.4. Proper Motions

Ivezić et al. (2012) estimate that LSST will attain proper-motion precision of $\sigma_\mu \sim 200 \mu\text{as yr}^{-1}$ for $16 < r < 21$ and parallax precision of $\sigma_\pi \sim 500 \mu\text{as}$ (see their Figure 21). These measurements will not be competitive with GAIA in the magnitude range that it covers, $V \lesssim 20$, but with modest reddening near the plane, $V - r \sim 1$ even for G stars. Hence LSST could obtain proper motions for these numerous tracers out to a factor 2.5 farther than GAIA. Note that at, e.g., 8 kpc, $\sigma_\mu$ corresponds to just 8 km s$^{-1}$. Hence LSST could probe the Galactic potential by measuring vertical dispersions and find streaming motions in regions that are either inaccessible to or poorly probed by GAIA. This same astrometric precision would be adequate to measure the astrometric microlensing signatures of black holes mentioned above in favorable cases, although precision followup would be required in others.

### 6.5. Serendipity

There may be many other specific applications of such a data set as well, but I close this section with a few remarks on serendipitous discovery. “Serendipitous discovery” is usually (and correctly) justified by past precedent in proposals for surveys that probe new parameter space. By its very nature, the only thing that can be “predicted” about serendipity is that the more parameter space that is probed, the more likely it is that something interesting will “turn up”. A large synoptic survey can make serendipitous discoveries either outside or inside the Galaxy. The former potential is basically maximized by viewing as large a fraction
of the low-extinction sky as possible. The latter is maximized by observing as many stars as possible, which basically means observing the first and fourth quadrants of the Galactic plane, which contain the great majority of Galactic stars. There is some tension between these two goals because the plane is heavily extincted and is also “contaminated” by stars. However, the gain that comes from avoiding the plane is a minor increase in extragalactic cadence, whereas the loss to Galactic serendipity that comes from avoiding the plane is catastrophic.

7. DC Response to a Dynamic Question

LSST was the highest ground-based priority specified by the Decadal Survey Committee (2010), who entitled their report “New Worlds, New Horizons”, thereby placing equal emphasis on extrasolar planets and cosmology as leading components of the next decade of astrophysical research. And indeed, their highest priority for space-based research, a Wide-Field Infrared Space Telescope (WFIRST) actually does give leading emphasis to these two areas. However, neither the word “extrasolar” nor “planet” even appears in Abate et al. (2012). As I have shown in this paper, this is not because the proposed telescope would be incapable of finding or characterizing extrasolar planets: it could contribute greatly, primarily via microlensing but also via transits.

The science described in this paper could be achieved if LSST monitored the regions of the sky available to it (given its southern location) with approximately uniform coverage. This is the region defined by the white contours in Figure 1. In this case, it would cover this region, including a large fraction of the dashed-black rhombus, roughly 800 times over 10 years (Abate et al. 2012).

Unfortunately, LSST plans to avoid the region of the dashed-black rhombus in Figure 1. The reasoning behind this decision is not easy to trace. For example, in their 133 page document describing the experiment, Abate et al. (2012) do not mention any analysis leading to the exclusion zone that appears in their Figure 4.4.

To try to understand the reason for avoiding the plane, I interviewed the LSST Project Scientist. He informed me that there was no point in repeatedly imaging the Galactic plane because the “DC image” (i.e., the co-add of successive images) would quickly run out of new identifiable sources due to crowding. That is, the “synoptic” second initial of LSST was really intended only for extragalactic supernovae, asteroids, and proper motions of halo stars, but not for the majority of stars in the Galaxy.

Close examination of Figure 18 of Ivezić (2013) shows that no substantive purpose is
served by excluding the “blue stripe” in that figure (dashed-black rhombus in Figure 1). The regions just to west of the center of the “blue stripe” are colored “deep brown” indicating that they are slated for all the “extra” observations freed up by the non-observation of the “blue stripe”. But this region with extra observations is not of especially high interest. From an extragalactic standpoint, it is much less useful than high-latitude regions because of higher foreground extinction as well as higher stellar “contamination”. And from a Galactic standpoint, it is far less interesting to double the observations of this region than it would be to observe the Galactic plane.

The potential for exoplanetary science, stellar science, and Galactic-structure science in the plane of the Milky Way is immense and could easily be achieved at essentially no cost to other LSST science.

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4In Figure Î, this brown region lies just north of the dashed-black rhombus, and is centered at \((l, b) \sim (0, +15)\).
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Fig. 1.— Upper panel: Event rate for disk-disk microlensing within ±20.5° of the Galactic plane, for events peaking at $r < 19$ according to assumptions described in the text. Zones in black, red, yellow, green, cyan, blue, magenta signify rates above $10^{(0,-0.5,-1,-1.5,-2,-2.5,-3)} \, \text{yr}^{-1} \, \text{deg}^{-2}$. The regions interior to the white semi-circle and exterior to the white lines are excluded by LSST because they are too far south and north, respectively. The region interior to the dashed black rhombus is excluded from high cadence observations. For the region accessible to LSST, the total microlensing rate is 47 yr$^{-1}$ outside the rhombus and 431 yr$^{-1}$ inside the rhombus. Lower Panel: Mean lens distance for events shown in upper panel. Zones in black, red, yellow, green, cyan, blue, magenta signify mean distances above 5, 4, 3, 2.5, 2, 1.5, 1 kpc.
Fig. 2.— Cumulative distribution of inverse magnifications of proposed disk-disk microlensing survey compared to actual magnification distribution of OGLE-III events from 2008 (adapted from Cohen et al. 2010) scaled to the same total. Half the events have \( A_{\text{max}} > 6 \) and thus significantly enhanced sensitivity to planets (Gould & Loeb 1992), while 10% have \( A_{\text{max}} > 100 \), which implies greatly enhanced sensitivity (Griest & Safizadeh 1998; Gould et al. 2010).