**Wide Field InfraRed Survey Telescope Project**

**Microlensing Survey Science Requirements**

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# 1. Exoplanets : Introduction

The first discovery of planetary companions to Sun-like stars was, along with the discovery of dark energy, one of the greatest breakthroughs in modern astronomy in the last 20 years. These discoveries have excited the astronomical community and the broader public as well. Since then, the pace of exoplanet discovery has increased each year. There are now nearly 3000 confirmed exoplanets and Kepler has identified and additional ~2500 candidate planets that await confirmation.

Nature has surprised astronomers with the enormous and unexpected diversity of exoplanetary systems, containing planets with physical properties and orbital architectures that are radically different from our own Solar System. Since the very first discoveries, we have struggled to understand this diversity of exoplanets, and in particular how our solar system fits into this menagerie.

WFIRST will advance our understanding of exoplanets along two complementary fronts: the statistical approach of determining the demographics of exoplanetary systems over broad regions of parameter space beyond those that can be probed by current surveys, and via the approach of detailed characterization of the properties of a handful of nearby exoplanets.

First, through its comprehensive statistical census of the outer regions of planetary systems using microlensing, including a complete assay of planets with the mass of Earth and greater and with separations spanning from the outer habitable zone to free floating planets, WFIRST will complete the statistical census of planetary systems begun by Kepler. Indeed, WFIRST will be sensitive to analogs of all of the planets in our Solar System with the mass of Mars or greater, and thus will allow us to place our Solar System in the context of known exopolanetary systems.

Second, with a coronagraph, WFIRST will be capable, for the first time in human history, of directly imaging planets similar to those in our Solar System. It will make detailed studies of the properties of giant planets and debris disks around nearby stars, and will be the testbed for future coronagraphs capable of detecting signs of life in the atmospheres of Earth-like exoplanets.

With these two complementary surveys, WFIRST will provide the most comprehensive view of the formation, evolution, and physical properties of planetary systems. In addition, information and experience gained from both surveys will lay the foundation for, and take the first steps toward, the discovery and characterization of a “pale blue dots” — habitable Earth-like planets orbiting a nearby stars.

## 1.2 Exoplanets: Microlensing

Canonical theories of planet formation and evolution originally developed to explain our Solar System did not anticipate the incredible panoply of planetary systems that have been observed. They have since been expanded and altered to better describe the variety of planetary systems that we see. For example, the discovery of gas giant planets orbiting at periods of only a few days (also known as `Hot Jupiters’), as well as evidence for the migration of the giant planets in our own Solar System, have highlighted the fact that these theories must also account for the possibility of large-scale rearrangement of planet positions during and after the epoch of planet formation (Lin et al. 1996, Rasio & Ford 1996). These insights have also opened the way to deeper understanding of previously unsuspected rearrangements in our own solar system. One current popular example is the so-called Nice Model, which theorizes the migration of the four giant planets evolved from an initial compact configuration into their present position (e.g., Levinson et al. 2011). Many of these theories also predict a substantial population of “free-floating” planets that have been ejected from their planetary systems through interactions with other planets (Juric & Tremaine 2008, Chatterjee et al. 2008).

The rapid advancement in exoplanet research has been driven by both extensive observational searches around mature stars as well as the construction of planet formation models. Perhaps the most surprising discovery so far is the great diversity in the planets' dynamical properties, but these results are largely confined to planets that are unusually massive or reside in very close orbits. The core accretion theory suggests most planets are much less massive than gas giants and that the critical region for understanding planet formation is just beyond the "snow-line", which is the region (1.5-4 AU) of greatest microlensing sensitivity (Ida & Lin 2005; Kennedy et al. 2006). Early results from ground-based microlensing searches (Beaulieu et al. 2006; Gould et al. 2006; Bennett et al. 2008) appear to confirm these expectations. WFIRST and Kepler complement each other, and together they cover essentially the entire planet discovery space. Kepler is sensitive to close-in planets but is unable to sense the more distant ones; WFIRST is less sensitive to close-in planets, but surveys beyond the habitable zone better than Kepler. WFIRST's sensitivity extends out even to unbound planets, offering the possibility to constrain their numbers and masses. Other methods, including ground-based microlensing, cannot approach the sensitivity and comprehensive statistics on the mass and semi-major-axis distribution of extrasolar planets that a space-based microlensing mission provides. Thus, WFIRST provides the only way to complete the exoplanet census begun by Kepler and gain a comprehensive understanding of the architecture of planetary systems, needed to understand planet formation and habitability.

The physical basis of microlensing is the gravitational bending of light rays by a star or planet. When a "lens star" passes close to the line of sight to a more distant source star, the gravitational field of the lens star deflects the light rays from the source star. The gravitational bending effect of the lens star "splits", distorts, and magnifies the images of the source star, so the observer sees a microlensing event as a transient brightening of the source as the lens star's proper motion moves it across the line of sight. The lensing magnification is determined by the alignment of the lens and source stars measured in units of Einstein ring radius, so even low-mass lenses can give rise to high magnification microlensing events. Planets are detected via light curve deviations that differ from the normal stellar lens light curves (Mao & Paczynski 1991). A microlensing event's duration is given by the Einstein ring crossing time, typically 1-3 months for stellar lenses and a few days or less for a planet.

Microlensing observing programs rely upon the high density of source and lens stars towards the Galactic bulge to generate the stellar alignments needed to generate microlensing events, but this high star density also means that the bulge main sequence source stars are not generally resolved from one another in ground-based images. This means that the precise photometry needed to detect planets of less than a tenth of the Earth's mass is not possible from the ground unless the magnification due to the stellar lens is moderately high. This, in turn, implies that ground-based microlensing is only sensitive to terrestrial planets located close to the Einstein ring (at ~2-3 AU). The full sensitivity to terrestrial planets in all orbits from the outer habitable zone to ∞ comes only from a space-based survey.

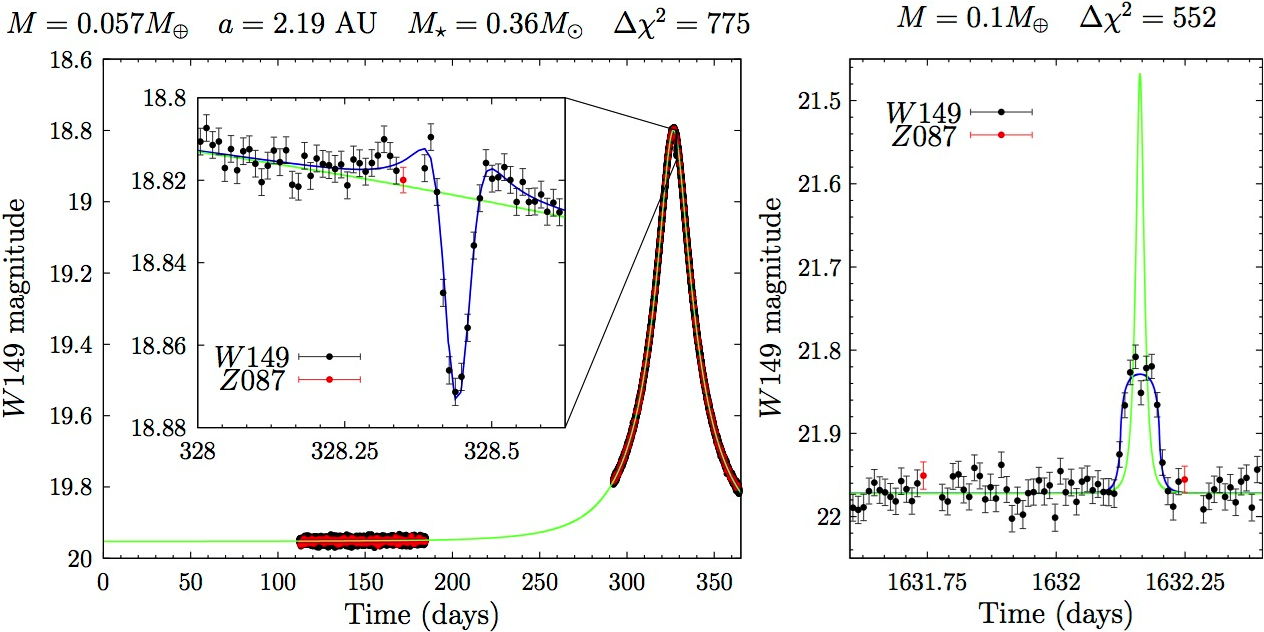


Figure 0‑1: Examples of simulated event light curves with detected planetary signals from simulations of a WFIRST exoplanet survey. The left panel shows the detection of a Mercury-mass planet orbiting a 0.36 solar mass star with a semi-major axis of 2.19 AU. The right panel shows a simulated detection of a free-floating Mars-mass planet.

# 2. Science Requirements Flowdown

The WFIRST Program Plan contains the Science Objectives and Level 1 requirements which drive the overall mission design. However, being a programmatic document, the WFIRST Program Plan does not contain a detailed description of the flowdown from the Objectives to the WFIRST requirements or the rationale for those requirements. The Baseline and Threshold Science Requirements held in the WFIRST Program Plan, the Science Requirements contained here and the Design Reference Mission documented in the Operations Concept Document together validate the WFIRST mission will meet the Science Objectives outlined in the Program Plan.

## 2.1 Primary Science Objective

The primary WFIRST Microlensing Science Objective, which will enable WFIRST to provide (along with Kepler) the ultimate empirical dataset with which to test theories planet formation and evolution, is to:

**Primary Microlensing Objective:** Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater.

## 2.2 Secondary Science Objectives

Testing theories of planet formation requires accurate and precise measurements of the demographics of planets over a wide range of planet and host star parameters. Kepler has begun this process by measuring the radius and period distribution of planets with periods of less than roughly one year and planet sizes of roughly greater than one Earth radii. Furthermore, Kepler has detected thousands of planets in this regime, and as a result the of the uncertainty arising from Poisson fluctuations in the empirically determined distributions of planet radii and period in this regime is relatively small, for reasonable bins in these parameters.

The WIFRST microlensing survey will complete this census by detecting a (roughly) similar number of planets with masses greater than that of the Earth and periods of greater than roughly one year. Again, to provide similarly stringent constraints on exoplanet demographics as Kepler, WFIRST must detect a comparable number of planets as Kepler.

Furthermore, since typical microlensing observables do not automatically ensure estimates of host star properties, the WFIRST microlensing survey must ensure that the majority of the microlensing planet detections are accompanied with the requisite data to allow for accurate (<~ 20%) estimates of the host star masses, and thus the exoplanet masses and projected separations.

In order to accurately measure the demographics of planets of planets beyond the snowline, and in order to measure the mass function of free-floating planets, WFIRST must meet the following requirements:

EML 1: WFIRST shall measure the mass function of exoplanets with masses > 1

MEarth and orbital semi-major axes ≥ 1 AU to better than 10% (TBV) per decade in mass.

EML 2: WFIRST shall measure the frequency of Mars-mass objects to 20% (TBV).

EML 3: WFIRST shall determine the masses of, and distances to, host stars of 50% (TBV) of the detected planets with a precision of 20% (TBV).

EML 4: WFIRST shall measure the frequency of free floating planetary-mass objects in the Galaxy from Mars to 10 Jupiter masses in mass. If there is one MEarth free-floating planet per star, measure this frequency to ~20% (TBV).

EML 5: WFIRST shall provide alerts that allow for the measurement of the masses of 50% (TBV) of free-floating detected planetary-mass objects to a precision of 20% (TBV) down to a mass of Mearth.

EML 6: WFIRST shall estimate ηEarth to a precision of 20% (TBV) via extrapolation from larger and longer-period planets.

We note that many of these numbers are “To Be Verified” (TBV) by additional data and simulations. As described in the appendix, estimating the survey yield and our ability to extract additional information about the microlensing events is currently fraught with uncertainty, both due to the lack of required observational inputs, and due to theoretical challenges. A large part of the work of the WFIRST Microlensing Science Investigation Team is going toward acquiring these additional observational inputs and retiring the theoretical challenges, so that we can better estimate the yield and our ability to measure higher-order quantities, and thus provide definitive numbers for the “TBV” values above.

We also note that EML1, EML2, and EML6 require assumptions about the frequency, semimajor axis, and mass distribution of explanets. We are assuming a Cassan et al. mass function and normalization, saturated at two planets per dex2 in mass and semimajor axis, and a uniform distribution in the logarithm of the semimajor axis.

## 2.3 Survey Requirements

Microlensing events require extremely precise alignments between a foreground lens star and a background source star, that are both rare and unpredictable. Furthermore, the probability that a planet orbiting the lens star in any given microlensing event will give rise to a detectable perturbation is generally much smaller than unity, ranging from a few tens of percent for a Jupiter-mass planet and a typical low-magnification event, to less than a percent for planets with mass less than that of the Earth. These planetary perturbations have amplitudes ranging from a few percent for the lowest-mass planets to many tens of percent for the largest perturbations, but are brief, ranging from a few days for Jupiter-mass planets to a few hours for Earth-mass planets.

Also, the time of the perturbations with respect to the peak of the primary event is unpredictable. Thus detecting a large number of low-mass exoplanets with microlensing requires monitoring of a very large number of stars (>~108) continuously with relatively short cadences (<~15 minutes) and photometric precision of a few percent or better. Practically, a sufficiently high density of source and lens stars, and thus a sufficiently high microlensing event rate, is only achieved in lines of sight towards the Galactic bulge. However, these fields are also crowded, and this high star density means that high spatial resolution is needed to resolve out the individual stars in order to achieve the required photometric precisions and to identify the light from the lens stars.

These requirements below are based on the results of sophisticated simulations of a microlensing exoplanet survey. However, to understand the order of magnitude of these requirements, simple back-of-the-envelope estimates are provided. Consider, as a specific example, the goal of detecting at least 150 Earth-mass planets. The typical detection probability for an Earth-mass planet at 2AU is ~1.5%, and thus ~150/0.015 ~ 104 microlensing events must be monitored to detect ~150 such planets, assuming every star hosts such a planet. The average microlensing event rate in the WFIRST microlensing survey fields is ~5x10-5 events/year/star, and thus 104/5x10-5 **~**10-5 ~200 million star-years must be monitored. The typical stellar density down to J=23 is ~108 stars per square degree, and thus we have the first data requirement below that at least ~2 square degrees must be monitored. In order to detect and accurately characterize the perturbations due to Earth-mass planets, which typically last a few hours and have amplitudes of several percent, photometric precisions of a few percent, continuous monitoring, and cadences of less than 15 minutes are needed. Finally, given the areal density of ~108 stars per square degree, an angular resolution of 10-4 degrees (0.4 arcseconds) is needed to resolve the faintest stars.

Given the extinction by dust present along lines of sight to the Galactic bulge, the highest signal to noise ratio for measurement of lightcurves will be obtained by means of a broad near infrared filter.

Typically, the measurement of a microlensing light curve provides allows extraction only of the Einstein ring crossing time. The desired quantities of planet mass and separation from the host star can be determined if the distances to the two stars can be determined and if the mass of the host star can be determined. The primary star-star lensing events typically last ~40 days. The distances to the stars and their masses can be determined from their spectral types and brightnesses; the stars will not be spatially resolved, but the change in colors and brightnesses during the event combined with relative proper motion over a period of years may enable placing the stars on a color-magnitude diagram and thus determine their distances and masses (Bennett et al. 2007). Furthermore, the changing line-of-sight geometry during the event modifies the shape of the primary lensing light curve, allowing an independent measurement of the distances to the stars (Gould 1992, Gould et al. 2014). Subtle distortions in the microlens light curves due to the orbital motion of the planet about the host will also enable constraints on the period, inclination, and eccentricity of the orbit in a subset of cases. Measurements in multiple filters are required to determine spectral types, and high-precision relative photometry is required for analysis of the light curve shapes.

The characteristic time-scale for planetary microlensing events is much shorter than that of the star-star lensing events, typically on timescales of one to a few hours. A minimum of four measurements is needed to sample the shape of the light curve of the planetary microlensing event.

The considerations in the preceding paragraphs lead to the following survey requirements:

EML 7: Observe for or at least 2.9x432 square degree-days, with relative photometric measurements in the primary microlensing filter that have a statistical S/N of ≥100 per exposure for a HAB=21.6 star.

EML 8: Microlensing seasons must occupy no more than 8/12 of the available seasons.

EML 9: Relative photometric measurements in the primary microlensing filter will have a systematic precision of 0.1% over a season and 0.01% over daily timescales.

EML 10: Relative photometric measurements from separate seasons are tied to better than 0.1%

EML 11: Absolute photometry is calibrated to better than 1%.

EML 12: The light curves shall be sampled with a wide filter spanning λ ≈ 1 – 2 μm.

EML 13: The photometric sampling cadence in the wide filter shall be ≤15 minutes.

EML 14: The EE50 radius of the PSF in the wide filter shall be <0.15”.

EML 15: Each observing season shall last at least 60 days and at least 36 days of each season should be on the opposition side of quadrature.

EML 16: The seasons will be monitored with a duty cycle of ≥90%.

EML 17: Monitor fields with a two filters in addition to wide filter: both R~4 filters, one with bandpass shortward of 1 μm and one with a bandpass longward of 1 μm, each with a cadence of 1 exposure every 12 hours.

EML 18: The first and last observing seasons shall be separated by >4 years.

EML 19: The relative astrometric measurements shall have a statistical precision of 1 mas per measurement for a star of HAB=21.6.

EML 20: The relative astrometric measurements will have a systematic precision of 10 μas over the full microlensing survey (stretch goal of 3 μas)

EML 21: Measure the FWHM in both axes of a HAB=21.6 star to 1% per day.

EML 22:  Measure the FWHM in both axes of a HAB=21.6 star to XX% over the entire duration of the microlensing survey.

## 2.4 Data Requirements

Ultimately, we would like to be able to download every read from every pixel of every exposure. However, it is clear that the bandwidth will not be high enough to accomplish this. Since there remains the possibility of adding an additional ground station, the number of reads per exposure we can download is not clear; thus the ambiguity in the numbers below. Likely we will want the last read and one in the middle, but this is TBV.

However, although we cannot download every read, we would like to download every read from a subset of pixels where the UTR sampling fails for diagnostic purposes. Finally, we would like to download all the reads from every pixel for a fixed fraction of exposures. If this is not possible due to on-board storage, then we would like to download all the reads from each exposure for a fixed fraction of the pixels.

Finally, we would like observations of all the fields in all of the available filters periodically, and we would like the data sent down to the GSN at most every 12 hours, and then delivered to the SSOC within 2 hours some fixed fraction of the time, in order to issue alerts.

EML 23: All pixels will be have 2-3 samples per exposure downloaded (3-4 if there is an additional ground station, these will be the 10th (TBV) and 20th (TBV) read of each exposure

EML 24:  Every pixel where the up-the-ramp (UTR) sampling fails by 3-sigma will have every read downloaded (including those due to saturated pixels, cosmic ray hits, and all other sources of UTR failure; we estimate this to be roughly 2% of all images)

EML 25: Every read from every pixel of every exposure will be downloaded for 1% (TBV) of all exposures of all fields. (Alternatively, 1% of the pixels of each exposure will have every read downloaded.)

EML 26: The data will be downloaded from the spacecraft to GSN at most every 12 hours.

EML 27: Data from GSN will sent to the SSOC within <2 hours 80% of the time during second half of the spring and first half of the fall microlensing seasons.

EML 28: Observations of all fields will be taken in all filters at least once per week

## 2.5 Calibration Requirements

The basic data products are raw and calibrated images of each of the Galactic Bulge fields being monitored, all with accurate world coordinate system data in the headers.

We expect that most of the higher-level calibration products will be derived internally from the microlensing survey datasets. This includes PSF size and shape, flat-fielding, detector characteristics, etc. However, in some cases the properties of the microlensing survey may not be ideal for characterizing all possible detector artifacts. In particular, the survey fields may be too crowded, and the dither strategy may not be able to calibrate large-scale astrometric offsets. Therefore, we will likely require the following calibration data.

EML 29:  Stepped observations of a crowded field (but less crowded than the microlensing fields) with offsets that would sample the scale of the astrometric detector artifacts.  These fields should have stars with good Gaia parallaxes to set the absolute scales.

## 2.6 Data Products

The microlensing survey requires several data products, produced at several different time intervals during the survey.

First, we require relatively unprocessed data on the shortest feasible time scale, in order to issue alerts for both planetary perturbations and free-floating planet events, which typically have durations of less than one day. These alerts will allow us to follow up these perturbations to acquire simultaneous ground-based observations, which will allow for better characterization of the perturbations and possibly the measurement of higher-order parameters, thereby allowing us to better interpret these perturbations. This science driver leads to EML29 and EML30.

Second, we require calibrated ‘moment curves’ (i.e., the generalization of a light curve: photometry, astrometry, ellipticity, etc., as a function of the epoch of observation). These should be produced on a daily timescale, with as many of the detector systematics removed as possible. This leads to EML31.

As mentioned previously, we expect that a natural by-product of the microlensing survey will be calibrations of the various detector artifacts. These need to be provided and updated on a relatively short time scale, not only for the microlensing survey, but also for the other surveys. This leads to EML32

We will require supersampled and stacked images of the microlensing fields once per season, for source identification and to measure source motions. This leads to EML 33.

In order to calibrate the microlensing event rate and planetary detection sensitivity, we require injection and recovery tests of the light curves. This leads to EML 34.

Our final, end-of-survey data products will include the final moment curves calibrated with all available data, a source catalog containing positions, proper motions, colors, and other basic data for each object in the field, detection efficiencies for microlensing events and planets, a catalog of binary and planetary detections, and calibrated detector artifacts and their change over time.

EML 30: Uncalibrated data and light curves will be provided for alerts on time scale of <20 hours, preferably <14 hours.

EML 31: The ISOC shall produce alerts and make them available to the community within 2 hours of the data arriving at the SSOC.

EML 32: Calibrated moment curves will be provided on a daily time scale.

EML 33: Derived calibration products will be provided on a weekly time scale.

EML 34: Supersampled stacked images will be provided every season.

EML 35: Results of injection and recovery tests will be provided every season.

EML 36: The final data products will include the calibrated moment curves, relative proper motions and parallaxes, flagged astrometric binaries, and detection efficiencies for microlensing events for each light curve and planet sensitivities for every microlensing event.

### Appendix: Deriving the Microlensing Survey Yield and Associate Uncertainties

Quantitative predictions for the yields of a given realization of an exoplanet survey dataset require sophisticated simulations that incorporate models for the Galactic distribution of lenses and sources to simulate and evaluate the detectability of events with realistic photometric precision. In particular, the source star density and event rate are strong functions of Galactic coordinates, and the detection probability of a planet with a given set of properties depends sensitively on the detailed properties of the event (host star mass and distance, event duration, angular source size, photometric precision, cadence).

The basic input ingredients that are required for estimating the yield of a microlensing exoplanet survey are a (1) model for the spatial, kinematic, and luminosity distribution of source stars, (2) model for the spatial, mass, and kinematic distributions of the host lenses, which are then used to estimate microlensing event rates and event parameter distributions, and (3) a model for the probability distribution of planets as a function of planet mass and semi-major axis, and host mass and distance. Unfortunately, for the regimes of interest for WFIRST, the properties of the populations of sources and host lenses are poorly constrained by empirical data, leading directly to relatively large uncertainties in the final yields. In particular, the magnitude distribution of source stars in the fields of interest has not been measured in the passbands and to the faint magnitudes that will be probed by WFIRST. Similarly, the microlensing eent rates for some of the fields of interest have not been measured, as these fields typically suffer high optical extinction, and to date all microlensing surveys have been performed in the far optical.

The event rates and source stars densities adopted for WFIRST were scaled to match published microlensing optical depth estimates (Popowski et al. 2005, Sumi et al. 2006, Hamadache et al. 2006, Alcock et al. 2000, Sumi et al. 2003) and source star luminosity function (Holtzman et al. 1998) from fields further from the plane than the preferred WFIRST fields. The MOA team has recently performed a preliminary analysis of the 2006-2007 MOA-II data (Sumi et al. 2011) and used this to determine the optical depth and event rate toward each of the 22 MOA fields, each covering 2.2 deg2. Four of these fields contain 45% of all the analyzed microlensing events and overlap with (or are very close to) some of the proposed WFIRST fields. These results indicate a significantly higher optical depth than assumed in this report. Because they are based on preliminary, unpublished MOA-II data and analysis, we have chosen to be conservative and not use these for our baseline yields. However, we note that they have much higher statistical weight than the published results, and if they are correct, our planet yields are significantly underestimated.

Another, somewhat subtler, source of uncertainty in the planet yields that may significantly impact the choice of target fields is the relative frequency of planets in the Galactic bulge versus risk. The relative contribution of the bulge and disk lenses to the event rate varies as a function of Galactic latitude **b**, with bulge lenses expected to dominate at low |**b**| (Gould 1995). If the Galactic bulge happens to be devoid of planets, e.g., because of an extreme radiation environment during a starburst-like bulge formation event (Thompson 2013), then it would likely be desirable to avoid such low latitude fields.

Finally, the yields for planets near the edge of the sensitivity of WFIRT suffer from additional uncertainties beyond those arising the sources discussed above. This is due to the relatively strong dependence of number of detections on Δχ2 in these regimes, which includes planets with very small or very large separations, and very low mass planets. As a result of the strong scaling with Δχ2, small differences in the assumptions and approximations needed to make these predictions result in large changes in the estimates of the number of detected planets.

Predictions for the yield of habitable planets suffer from all of the uncertainties above, but are also sensitive to additional assumptions, such as the mass-bolometric luminosity relationship for stars in the bulge and disk, the age and metallicity of the stars in the bulge and disk, and the precise definitions for the mass and semi-major axes boundaries of the habitable zone. Therefore, the yields of habitable planets are particularly uncertain. Initial estimates indicate that WFIRST will be sensitive to habitable planets, if the intrinsic frequency is large. However, substantially more work needs to be done to provide robust estimates of the habitable planet yield.