THE SCIENCE ADVANTAGE OF A REDDER FILTER FOR WFIRST

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ABSTRACT

WFIRST will be capable of providing Hubble-quality imaging performance over several thousand square degrees of the sky. The wide-area, high spatial resolution survey data from WFIRST will be unsurpassed for many decades into the future. With the current baseline design, the WFIRST filter complement will extend from the bluest wavelength allowed by the optical design to a reddest filter (F184W) that has a red cutoff at 2.0 microns. In this white paper, we outline some of the science advantages for adding a K_s filter (λ_c ∼ 2.15 μm) in order to extend the wavelength coverage for WFIRST as far to the red as the possible given the thermal performance of the observatory and the sensitivity of the detectors.

1. INTRODUCTION

WFIRST was the top priority of the National Academy of Sciences’ 2010 Decadal Survey for Astronomy and Astrophysics. Its design has been optimized to conduct groundbreaking studies of dark energy and exoplanet demographics. Those dark energy and exoplanet research programs are enabled by WFIRST’s wide-field camera which will provide imaging with HST sensitivity and spatial resolution over an instantaneous field of view that is nearly two orders of magnitude larger. While the majority of the observing time during WFIRST’s prime mission will be devoted to the core dark energy and exoplanet microlensing surveys, about 25% of the observing time is being set aside for community-specified and peer-reviewed Guest Observer (GO) programs that could address any science topic. The ability of WFIRST to address the most diverse and exciting science at the time of the mission would be greatly enhanced by providing a long wavelength filter that is centered as far to the red as allowed by the telescope and detector design. Compelling science enabled by such a red filter include, but are not limited to:

- Exploring galactic structure through kinematics of the inner disk and bar/bulge;
- Determining the fragmentation limit for star formation and detecting free-floating planets in nearby star-forming regions;
- Characterizing the substellar population of the thick disk and halo;
• Anchoring a $K$-band cosmic distance ladder to be constructed with JWST;
• Better characterizing the end points of stellar evolution for the most massive stars;
• Enabling a range of improved extragalactic studies for $z > 3$ galaxies, including the ability to identify $11 < z < 15$ galaxies, should they exist;
• Identifying water ice on a sample of the most distant objects in the solar system.

We discuss each of these points in more detail in the remainder of the document.

2. DISCOVERY SPACE ADVANTAGE OF A $K$ FILTER

The deepest, wide-area $K$-band survey of the sky is the VISTA VHS survey (Banerji et al. 2015), now nearing completion. The VHS covers the entire southern sky to a depth of about $K$(Vega) = 18 mag, 5$\sigma$. As illustrated in the Appendix, a $K_s$ filter on WFIRST could obtain survey data to a depth that is five magnitudes deeper than the VHS. Using the same exposure times and dithering strategy as for the planned WFIRST high-latitude survey, the WFIRST survey speed will be about 20 square degrees per day per filter. No other existing or planned wide-area survey could come anywhere close to imaging such large areas to these faint limits at this wavelength.

There is no viable replacement for the kind of very deep, wide-field $K_s$ band imaging that WFIRST could provide. WFC3 on HST does not go longward of $H$ band; neither does EUCLID. Those facilities did not avoid $K_s$ band because it was of little interest – it was simply not feasible to include because thermal emission from the optics would have badly degraded performance at those wavelengths. The baseline plan for WFIRST is that it will be operated at < 270K, cold enough to allow efficient use of a $K$-band filter. We should make the most of this opportunity of a cool, wide-field telescope in space by providing WFIRST with the reddest possible filter. This red-filter discovery potential is still great even if WFIRST is not natural-background-limited at $K_s$ because the potential gain in sensitivity at $K_s$ relative to the ground is so large. All of the benefits of a redder filter described here rely on a relatively cold operating temperature and the stable PSF, small pixel size and accurate photometry that will be available at L2 regardless of the exact operating temperature. Moreover, the addition of a $K_s$ filter would make WFIRST more consistent with the Decadal recommendation for a near – infrared telescope.

There are simple astrophysical arguments why a redder filter would open up important new regions of discovery space. For giants, IR colors that include a $K$ band are optimal for separating populations (see Nikolaev & Weinberg 2000 and Figure 2). The H$^+$ opacity minimum (and Rayleigh-Jeans spectra) results in stars with a very broad range of spectral types and luminosities having very similar H-K colors; the range from types B to K is less than 0.2 magnitudes. This means that this color can be used to estimate extinction when it is large, with relatively small errors (see §3). Similarly, the strong molecular bands in brown dwarfs result in their J-K color providing a means to accurately estimate their metallicity, making it possible for WFIRST to identify and characterize the substellar population of the thick disk and halo better than any other facility (see §5). Finally, accurate distances to RR Lyrae stars (to map the structure of tidal streams in the MW or as the first rung of a Pop II distance ladder) is best done with WFIRST with a $K$ filter - the Period-Luminosity (PL) relation is shallower (or non-existent) at shorter wavelengths and both extinction and metallicity effects are lower at $K$ than at shorter bands. We address specific science enabled by a redder filter in more detail in the next several sections.

3. STRUCTURE AND KINEMATICS OF THE MW BULGE, NUCLEAR CLUSTER AND INNER DISK

The inner 3 kpc region of our galaxy is much more complex than once thought. The existence of a strong bar was first recognized more than 25 years ago (Blitz & Spergel 1991); Spitzer IRAC data (Benjamin et al. 2005) and ground-based NIR data (Wegg et al. 2015) have recently provided much improved maps of the extent and orientation of the bar. The shape of the bulge is tri-axial rather than spheroidal, resulting in an X-shaped or boxy appearance (Ness & Lang 2016). Most of the mass in the bulge resides in a relatively metal rich (Fe/H ∼ −0.5 to 0), rotationally supported population which traces the bar. However, a minority “hot” (high RMS velocity, low rotation), more spheroidal, more metal poor population (Fe/H ∼ −1) is also present (Dekany et al. 2013, Gran et al. 2016). Finally, there is possible evidence for a young population interior to the 3 kpc arm which may have more disk-like structure, possibly containing up to 10% of the bulge mass (Portail et al. 2016).

While there has been much progress in the past decade, observations of the bulge and bar from the ground are inherently difficult due to the large extinction towards the galactic center. Going into the infrared can remove much of the obscuring effects of the dust, but then the limitation becomes the high stellar source density encountered in the
Figure 1. Comparison of the sensitivities of WFIRST, EUCLID and LSST. The LSST values are for the full 10 year co-add data at the end of the survey. Depth in AB magnitudes. WFIRST limits are for its High Latitude Survey (HLS). The current baseline for WFIRST, although not shown here, includes a “V” filter (λλ 0.45-0.7 µm) and a z-filter (λλ 0.76-0.98 µm). In this white paper, we advocate adding a filter longward of 2.0 microns, similar in properties to the 2MASS K\textsubscript{s} filter. The sensitivity for our proposed K\textsubscript{s} filter is shown in the figure based on an assumed telescope temperature of 260 K (the F184 filter sensitivity is also for that assumed temperature).

central regions. WFIRST with the reddest possible filter would offer the best means to enable new research. Figures 3 and 4 illustrate the advantages of redder filters and smaller PSFs for studies of the inner disk and bulge.

One example of new science that would come from a wide-area H/K or J/K survey of the bulge with WFIRST would be a much more detailed map of the spatial distribution of red-clump giants (tracers of the metal rich bulge population) than possible from the ground, definitively measuring the orientation, length, and width of the bar and plausibly allowing one to trace whether spiral arms originate from the ends of the bar. A more demanding role for WFIRST, but one that could provide unique and far-reaching new data, would be to obtain several epochs of that map at K over the 5-year WFIRST prime mission (or, better, sampling also over an expanding mission timeframe). Such data, when combined with the dense astrometric grid expected from Gaia, could provide proper motions for tens to hundreds of thousands of red-clump giants and thousands of RR Lyr stars, thereby providing kinematic data needed to help empirically constrain the origins and evolution of the metal poor and metal rich populations of the inner galaxy (100 km/s at 8.5 kpc corresponds to about 2.4 mas/yr), as well as providing constraints on the relative contributions of dark and luminous matter in the inner Galaxy. There are plans already to use data from the 2.8 square degrees of the microlensing campaigns to address these questions. A GO program that provided H/K-band imaging of significantly more sight-lines through the bulge and inner disk, particularly where extinction limits sensitivity at shorter wavelengths, could not be obtained by any other facility and would greatly improve the results from the planned microlensing survey.
Figure 2. Two versions of the color-magnitude diagram for giant stars in the LMC, one utilizing $I - H$ for the $x$-axis and one using $J - K$. The same stars are plotted in the two panels. The $J - K$ diagram clearly distinguishes different sequences better than the former, particularly for carbon stars (the finger pointing up and to the right for $J - K > 1.4$, and oxygen rich supergiants (the narrow finger extending above the giant branch, beginning at $J - K = 1.2$ and $K = 10.5$). The stars plotted are those in the Spitzer SAGE (Meixner et al. 2006) LMC survey; we have cross-matched those stars to the 2MASS and SDSS databases. See Boyer et al. (2011) for a discussion of the post-main sequence demographics that can be distinguished if a K filter is available.

Another specific project would be to obtain synoptic K band imaging of the inner ∼30’ of the Galaxy (four WFI fields) in order to identify all of the RR Lyrae stars in the Nuclear Star Cluster (NSC) and Nuclear Bulge/disk. A dozen or so RR Lyr have recently been identified in the NSC using HST and data from the VVV survey (Dong et al. 2017; Minniti et al. 2016); however, those surveys are very incomplete due to the extreme crowding and variable reddening (see Figure 4). Yet determination of the total number of RR Lyr in the NSC is vital for constraining its formation mechanism. Is most of the mass of the NSC from the merger of a previous generation of globular clusters (Tremaine et al. 1975) or from in-situ star-formation (Agarwal & Milosavljevic 2011)? A survey with WFIRST (single epoch at J band, multi-epoch at K band) would be the best way to identify the complete RR Lyr population of the NSC and much of the Nuclear Bulge and thereby answer that question. The same data could be used to measure the proper motions of these RR Lyr and thereby determine their kinematics.

4. THE FRAGMENTATION LIMIT OF STAR FORMATION: FREE-FLOATING PLANETS IN STAR-FORMING REGIONS

One of the goals of the WFIRST microlensing program is to determine the number of free-floating planets in the disk of the Milky Way and to attempt to infer their properties and origin. WFIRST will be able to address this same goal in a very different and complementary way by obtaining deep, multi-epoch imaging of nearby, rich star-forming regions to identify the planetary-mass extension of the stellar-substellar mass function and possibly to determine the lower mass limit for objects which form as separate entities from direct collapse of molecular-cloud cores. Both projects together will make it possible to determine whether the free-floating planets detected by the WFIRST microlensing survey formed in isolation or were formed in circumstellar disks and subsequently ejected. The star-forming regions best surveyed for this project should be old enough (> 3-4 Myr) so that there is little on-going accretion and few or no primordial disks remaining, both of which can alter the apparent colors of young stars. However, the best regions should also be young so that the planetary mass objects are still bright and so that dynamical evolution has
Figure 3. The extinction “horizon” in the H, F184 and K band, i.e. the distance where $A_{\text{band}} > 2.5$, as a function of Galactic longitude superimposed on an “artist’s conception” of the Milky Way Galaxy by Robert Hurt. This uses the three-dimensional dust extinction model of Marshall et al (2006). At each longitude slice, we plot the distance corresponding to the maximum extinction at that distance for any latitude value. Note the volume of the Galaxy with modest (less than a factor of ten) extinction expands dramatically by going to the K band.

not significantly affected the at-birth IMF, either through mass segregation or preferential ejection of the lowest mass members.

Fortunately, there are a number of good, nearby target regions such as the Scorpius-Centaurus (Sco-Cen) association or older portions of Orion. A K-band filter would significantly improve the ability of WFIRST to address this science because the planetary mass objects of most interest – with masses 0.5 to 10 $M_{\text{Jup}}$ – should have temperatures in the range 1200-2000 K at ages of 5-15 Myr (appropriate for Sco-Cen); they should thus have L dwarf spectral types and be very red, with $V-K \sim 10$ mag and $J-K \sim 2$ mag or more. In fact, these planetary mass, very young objects have been found to be even redder than old L dwarfs of the same spectral type - possibly due to enhanced dust formation at low surface gravities (Bowler et al. 2017).

Initial attempts to identify the fragmentation limit for formation of free-floating objects in Sco-Cen have already been made using the best available ground-based facilities (Lodieu et al. 2007; 2013). Figure 5 shows the result of the deepest search to date, which covers a 13 square degree region and appears to have identified more than a dozen planetary mass members based on their CMD position, proper motions consistent with Upper Sco membership, and spectroscopic confirmation for 12 of the faintest 15 objects (which shows that they are young L dwarfs). The faintest objects have $K \sim 17$ mag and estimated mass of about 6 $M_{\text{Jup}}$, with no evidence that the sequence has ended. A WFIRST survey of the entire 50-sq-deg Upper Sco region could go more than 5 magnitudes fainter at K, to a mass
well below $1 \, M_{\text{Jup}}$. With two epochs of $K$ imaging separated by five years, and one epoch at both $J$ and $K$, such a survey could provide much better proper motion membership data (relative to ground surveys), a much larger sample, and definitively measure the fragmentation limit or show that it is below a Saturn mass. Because Upper Sco’s proper motion is about 30 mas/yr, the proposed WFIRST data would easily prove or refute membership. If these solivagant planetary mass objects have space motions of a few km/sec relative to their stellar counterparts (because they have been ejected from a forming disk, for example), that might also be within the grasp of these data (1 km/s at 150 pc corresponds to 1.3 mas/yr motion).

5. DETECTING AND CHARACTERIZING THE SUBSTELLAR POPULATION OF THE THICK DISK AND HALO
In the past 20 years, the number of substellar objects (or, more loosely, the number of LTY dwarfs) has gone from essentially zero to well over a thousand\(^1\). As the intermediate step between stars and planets, brown dwarfs provide insights into the fundamental physics governing the formation and evolution of both their smaller and larger cousins. However, because substellar objects are both cool and small, the existing substellar census is almost entirely representative of the Pop I disk of the Milky Way. Only about two dozen subdwarf L and T dwarfs (i.e. L and T dwarfs with low metallicities characteristic of the halo or thick disk) have been discovered. WFIRST could provide the capability to not only identify a very large sample of L and T subdwarfs, but also to sort them by temperature and metallicity and thereby allow that census to provide fundamentally new data on the dependence of the star-forming process on metallicity at low mass. Figure 6 illustrates that a filter set which includes J and K band can be used very effectively to sort L dwarfs by metallicity; this is due to collision-induced H\(_2\) absorption, which most strongly suppresses the K-band flux and thereby causes L dwarfs to have increasingly blue J – K colors with decreasing metallicity (Borysow et al. 1997).

The largest areal survey to date (Kirkpatrick et al. 2014, 2016) used proper motion measurements from the all-sky AllWISE processing (Cutri et al. 2013) to identify nine L subdwarfs that, because they are bright and nearby, serve as the prototypes of their class. The deepest survey for L subdwarfs to date (Zhang et al. 2017a) used imaging of 3000 square degrees from the UKIRT Large Area Survey and SDSS, identifying eleven L subdwarfs down to K \(\sim\) 17 mag (Vega) and to distances of order 100 pc. If the WFIRST 2000-sq-deg HLS included a K-band filter – yielding 5\(\sigma\) K-band detections to K \(\sim\) 23.5 mag (Vega) – that survey could cover a volume five thousand times larger than the Zhang et al. study and to distances of 2 kpc.

The Pop I disk is rotationally supported; the halo is mostly pressure supported. Therefore, halo stars in the solar neighborhood have streaming motions in the direction of the disk rotation of order 200 km s\(^{-1}\). Thick disk stars are intermediate in their kinematics, but still have a quite large streaming motion relative to the Pop I disk. A single-band second epoch of the HLS taken several years after the original HLS can essentially identify every halo and thick-disk star in the HLS survey area via its proper motion as long as K-band images are available for color/metallicity discrimination at one of the epochs. Specifically, at a distance of 2 kpc, 200 km/s corresponds to about 20 mas/yr if the motion is in the plane of the sky. This can be compared to the expectation\(^2\) that the HLS will be able to produce proper motions of order 0.1 mas/yr for a baseline of 5 years for stars brighter than magnitude 23.

Intriguing additional science is also possible with these data. One expects the luminosity function of old populations to show a gap between the bottom of the stellar sequence and the most luminous substellar objects. The gap should increase as the population ages. It may be possible to measure this gap as a function of metallicity class (surrogate for age) in a K-band supplemented, dual-epoch HLS, providing a direct measure of the cooling timescale for high mass brown dwarfs.

### 6. USING A K FILTER ON WFIRST TO PROVIDE A NEW H\(_0\) DISTANCE LADDER

The most accurate current cosmic distance ladders to determine the value of the Hubble constant are based, respectively, on data primarily at J and H bands (Riess et al. 2011) and at IRAC [3.6] and [4.5] micron bands (Freedman et al. 2012). The fact that the HST ladder did not use K band was not because K band is disfavored for some astrophysical or cosmological reason, but simply because the thermal operating temperature of HST greatly reduces its sensitivity at that wavelength. All of the primary initial rungs used in such distance ladders (Cepheids, RR Lyr variables, TRGB) work better at longer wavelengths because the longer wavelengths are less affected by reddening and metallicity variations. If HST had the same thermal environment as now expected for WFIRST, WFC3 would have had a K filter and the HST distance ladder would very likely have used K band data.

In order to construct a PopII distance ladder (Beaton et al. 2016), accurate RR Lyræe distances require a well defined PL relation. Differently than for Cepheids, this relation exists only at long wavelengths. For short wavelengths the slope of the PL relation is just too shallow, and the intrinsic scatter too large (>5%), to produce accurate distances. The turnaround in the slope of the PL relation happens in the near-IR, where the intrinsic scatter due to evolutionary effects and temperature dependence is greatly reduced because of a narrowing in the instability strip and because the brightness variations are mainly driven by radius changes. In fact, RR Lyræe distances in the K band are as accurate as the distances that can be derived in the L and M bands, with just a small penalty for the larger extinction at K compared to L or M. The accuracy in the distances obtained in the J and H bands will instead be lower, not just because of the higher extinction, but also because of the larger intrinsic scatter in the PL relation (in the V band there

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\(^1\) See DwarfArchives.org.

\(^2\) https://conference.ipac.caltech.edu/wfirst2016/system/media_files/binaries/29/original/WFIRST_Astrometry_Spergel.pdf
is no PL relation). The distances obtained in the K band are very accurate even for individual stars: this means that these variables can also be used to probe the geometry of the host galaxies, in addition to anchor the distance scale.

Given the importance of reconciling the tension between the measured local value of $H_0$ and the large-scale value of $H_0$ inferred from CMB data (Bernal et al. 2016), it seems likely that JWST will be used to produce a new distance ladder. In the absence of a true K band filter, the most efficient way for JWST to obtain high precision distances of RR Lyrae in Local Group galaxies will be to use the NIRCam F200W or F277W wide filters (best for reducing crowding), in addition to the Spitzer/IRAC-like F356W and F444W passbands (where the extinction is even lower). For most of these galaxies however, the small size of NIRCam detectors will limit these observations to narrow areas in each galaxy, a limitation that does not exist with the huge WFIRST field of view. A survey of these extended targets with WFIRST in the K band would allow to efficiently sample a much larger population of RR Lyrae than feasible with JWST, allowing to statistically reduce the scatter in their PL relation due to the metallicity dispersion within those galaxies, providing more accurate anchors for the JWST PopII distance scale. By observing these fields with both F184W and a K$_s$ filter, synthesized WFIRST magnitudes closely matched to the F200W bandpass could be produced, allowing the WFIRST and JWST data to be precisely aligned.

7. IDENTIFYING AND CHARACTERIZING INFRARED TRANSIENTS WITH WFIRST

In addition to the survey science potential, a K-band filter on WFIRST would make for a powerful and unique capability for Time-Domain Astronomy (TDA) in the near-infrared. It would go much deeper than ground-based K-band surveys, much deeper than LSST on a visit-by-visit basis and therefore for the same cadence, and much deeper (5mag) than Spitzer. WFIRST would also offer much better spatial resolution than LSST or Spitzer, a critical advantage for exploring the transient source populations in more crowded parts of galaxies. Two examples of science applications of this TDA capability are discussed below, but the most recent illustration comes from the first detection of electromagnetic counterparts to gravitational waves from neutron star mergers; by 10 days after its discovery, the peak of the SED of the NS-NS merger event GW 170817 had shifted to 2.1 $\mu$m (Pian et al. 2017). This was predicted by Kasen et al. (2013) and Barnes & Kasen (2013) who showed that the peak of the emission is beyond 1.4$\mu$m due to the large number of line transitions in heavy elements produced by r-process nucleosynthesis. More recent opacity

Figure 6. Color-color plot for low mass stars and brown dwarfs, from Zhang et al. (2017b), illustrating the ability to distinguish metallicity classes for late-M, L, and early T dwarfs/subdwarfs using $J – K$ color. Grey and light green dots, along with green circles demarcate the solar-metallicity sequence from F through L spectral types. Other colored points mark the locations of known late-M and L subdwarfs. The magenta lines represent families of curves from the BT-Settl model grids (Allard et al. 2014, Baraffe et al. 2015) whose metallicities (in magenta) and $T_{eff}$ values (in black) are shown. If K-band data were added to the High-Latitude Survey, WFIRST could survey a volume of space 5000 times larger than represented in this figure.
calculations (Fryer et al. in prep.) suggest that the emission could be even redder and even fainter than initially predicted.

The SPIRITS survey with Spitzer has recently uncovered a population of transients that show predominantly (and often exclusively) infrared emission (see Kasliwal et al. 2017). These transients, dubbed SPRITEs, lie in the luminosity gap between novae and supernovae and photometrically evolve on a wide range of timescales. Half a dozen have been discovered in nearby galaxies surveyed by SPIRITS out to 7 Mpc, but they would be easily detected by WFIRST at K-band out to ~100 Mpc. The much larger sample that could be discovered by WFIRST would provide the data necessary to firmly identify the progenitor types and physical mechanisms which give birth to the SPRITEs. Current possible interpretations of SPRITEs include formation of massive star binaries, stellar mergers, birth of stellar mass black holes, electron capture supernovae on extreme AGB stars etc. Since the emission from SPRITEs peaks in the mid-IR, with T_eff between 350 and 1000 K, a redder WFIRST filter would be much more sensitive to discovering and characterizing these events. Moreover, without a K-band filter, the most interesting SPRITEs may go unidentified as such, even if detected at optical wavelengths.

A WFIRST galactic plane survey would provide the first epoch data needed to identify and characterize the explosive events in high-mass star-forming regions that we have only recently begun to detect (Bally et al. 2015; Caratti o Garatti et al. 2017; Hunter et al. 2017). These events have been found in very crowded, heavily embedded regions, requiring good spatial resolution and the longest wavelength filters possible. Do young high mass stars grow primarily from mergers or from intermittent, high accretion rate bursts from their circumstellar disks? A K-band enabled WFIRST could best help provide the data to answer that question. When the next Type II supernova occurs in the Milky Way, this same WFIRST galactic plane survey could provide the data needed to characterize the progenitor of that event.

8. IMPROVING EXTRAGALACTIC POPULATION STUDIES AT Z > 3

Extragalactic surveys would benefit in several ways from extending the wavelength coverage to the red. The left hand panel of Figure 7 shows current measurements of the global star formation history along with regions where a WFIRST K_s band would add critical information. First, as shown in the right hand panel of Figure 7, a K_s-band survey on WFIRST would extend the redshift range for which stellar masses can be estimated from z ~ 3.5 to z ~ 4.5. This enables one to probe beyond the peak of the global star formation at z ~ 2-3 (Madau & Dickinson 2014).
The combination of sensitivity and area that WFIRST could provide compared to ground based and existing Spitzer surveys would enable studies of early dwarf galaxy formation linked to dark matter formation via galaxy clustering measurements (Lee et al. 2012, 2009, Finkelstein et al. 2015). This co-measurement of clustering and galaxy mass provides a strong constraint on the duty cycle and possible star formation histories in the early universe (Lee et al. 2009, Finkelstein et al. 2015).

Second, the addition of a longer-wavelength filter would significantly improve the selection efficiency of $9 < z < 11$ galaxies and enable measurements of their rest-frame UV spectral slopes, which are very sensitive to their evolving stellar populations and dust content (Finkelstein et al. 2012, Madau and Dickinson 2014, Figure 7).

Figure 8. The thick red and black lines show the depth and area reachable by WFIRST and JWST in 1000h respectively. A given 1000h survey would be one point on the line and probe areas and depths smaller than the point. For WFIRST we assumed a survey in 5 filters (Y,J,H,F184W, K_s) and used the current overhead estimates provided by C. Hirata (private communication). For JWST we assumed a 3 filter (F115W, F150W, F200W) NIRCAM survey with the actual overheads given by the Astronomers Proposal Tool (APT) excluding the 0.5h slew to field overhead. Galaxies were assumed to be 0.1" FWHM gaussians when estimating sensitivity. The area where one object is expected in a given survey per magnitude and redshift interval is indicated with thin dashed lines for redshift ranges accessible with the existing WFIRST filter complement and solid lines for redshift ranges only reachable if WFIRST had a K_s band filter. With these filters JWST would not be able to select $z < 9$ galaxies due to the lack of Y band data. The lines are based on models of measured data at $8 < z < 10$ from Yung et al. (2018). At $11 < z < 15$ the $z = 10$ Yung et al. (2018) estimate is scaled by the density evolution of dark matter given in Mashian et al. (2016). The error on the density in these models is $\pm 0.2 - 0.5$ dex due to a combination of current measurement error, cosmic variance, and the assumptions in the extrapolations.

Finally, as shown in Figures 7 and 8 the longer wavelength lever arm could also be used to find $11 < z < 15$ galaxies if they exist (Madau and Dickinson 2014), a task that only a many square degree WFIRST deep field could address due to the limited survey speed of JWST (Yung et al. 2018, Mashian et al. 2016). Such a deep survey would also find heavily obscured super-starbursts at $z > 4$ (Caputi et al. 2012, Wang et al. 2012), which are also very faint and
rare on the sky.

Another key advantage of a red filter for extra-galactic science is the ability to find and differentiate quasars from stars and galaxies to low luminosities, which is difficult without longer-wavelength IR data (Masters et al. 2012, Figure 9). It appears that the population of very massive black holes that form quasars is dropping rapidly at $z > 6$ (e.g. Banados et al. 2016; Mazzucchelli et al. 2017). The ability to measure the upper envelope of the quasar luminosity function to $z \sim 10$ combined with fainter quasars at lower redshifts will place strong constraints on early black hole formation models.

![Figure 9](image_url)

**Figure 9.** Adding a $K_s$ band to WFIRST (right), increases the separation between stars (red) and other objects (black) compared with the H band (left) allowing for clear differentiation between stars and other objects. Actual data from the COSMOS (Laigle et al. 2016) catalog are shown using HST F814W as a stand in for WFIRST Z band and Ultra-Vista Y, H, and $K_s$ bands. The star/galaxy separation in this plot is based on HST F814W morphology along with the Laigle et al. (2016) catalog.

9. CHARACTERIZING WATER ICE ON DISTANT SOLAR SYSTEM OBJECTS WITH WFIRST

A $K$–band filter, particularly a $K_s$–band filter, can facilitate searches for volatiles on the surfaces of the outer solar system small bodies (Figure 10; Trujillo et al. 2011). Both planned and possible GO large-area surveys (e.g. HLS) will yield imaging data that will contain many small bodies, and those with apparent slower non-sidereal motions, i.e. the outer solar system small bodies, Centaurs and Trans-Neptunian Objects (TNOs), will have only slightly elongated images in $\sim 3$ minute medium-deep exposures, thus minimizing confusion and read-noise effects due to trailing. These TNOs and Centaurs are also the most likely bodies to have detectable surface water ice, since most or all of them will have formed beyond the “snow line” where the water-ice sublimation rate rapidly drops off (c.f. Dones et al. 2015). Furthermore, because within that population the larger objects are more likely to have retained their surface volatiles since their formation (Schaller & Brown 2008), it is likely that it is the brighter objects which will manifest water ice features.

While not exclusively within the water-ice band at 2-$\mu$m, a strong absorption feature would dominate the $K_s$ band, relative to the Y, J and F184 bands which should be unaffected by strong water-ice absorption. Adding $K_s$-band imaging to such wide-area surveys would allow identification of potentially hundreds of icy outer-solar system bodies, with the brightest TNOs or Centaurs being promising targets for follow-up spectral observations with JWST or other future facilities. The surveys themselves would place meaningful constraint on the ubiquity of water ice among the TNO and Centaur populations.
Figure 10. As adopted from Trujillo et al. (2011), a Ks-band filter is dominated by strong water-absorption, though even a K-band filter would be diagnostically useful.

10. SUMMARY AND CONCLUSIONS

The discovery space available for a redder WFIRST filter is huge, and there is no foreseeable alternative source for a comparable $K$-band deep/wide survey. We are confident the community would find a myriad of ways to exploit that discovery space.
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APPENDIX

Table 1 provides estimated WFIRST sensitivities for a filter similar to the 2MASS $K_s$ filter, for three possible operating temperatures (J. Kruk, private communication).

Table 1. S/N Achieved as a Function of $K_s$-band mag in an HLS Survey

| $K_s$ mag (AB) | $K_s$ mag (Vega) | T=260K | T=270K | T=284K |
|---------------|-----------------|-------|-------|-------|
| 18.00         | 16.15           | 946.1 | 930.9 | 879.5 |
| 18.50         | 16.65           | 754.4 | 727.0 | 668.0 |
| 19.00         | 17.15           | 584.7 | 562.7 | 497.9 |
| 19.50         | 17.65           | 455.5 | 430.2 | 362.6 |
| 20.00         | 18.15           | 351.3 | 323.3 | 257.3 |
| 20.50         | 18.65           | 267.3 | 237.8 | 178.0 |
| 21.00         | 19.15           | 199.6 | 170.6 | 120.2 |
| 21.50         | 19.65           | 145.7 | 119.2 | 79.6  |
| 22.00         | 20.15           | 103.7 | 81.3  | 51.9  |
| 22.50         | 20.65           | 71.9  | 54.2  | 33.5  |
| 23.00         | 21.15           | 48.6  | 35.6  | 21.4  |
| 23.50         | 21.65           | 32.2  | 23.0  | 13.6  |
| 24.00         | 22.15           | 21.1  | 14.8  | 8.7   |
| 24.50         | 22.65           | 13.6  | 9.4   | 5.5   |
| 25.00         | 23.15           | 8.7   | 6.0   | 3.5   |
| 25.5          | 23.65           | 5.5   | 3.8   | 2.2   |

*a Assumes five exposures with a total observing time of 868 s. For $K_s$ band, m(AB) − m(Vega) = 1.85. Zodiacal level set at 1.44 times the minimum.