WISH: wide-field 1-5µm imaging from space

— a white paper for the Mid-Term Review —

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Abstract: WISH is a proposed 1.5-metre space telescope dedicated to wide-field (~0.25 deg^2 per pointing) imaging at 1–5µm. These wavelengths are crucial for a variety of scientific uses but are unreachable by either WFIRST or Euclid; among major future space missions only JWST will reach this far into the NIR, but only over extremely small fields. WISH will survey at wavelengths that will enable research on luminous galaxies and quasars in the Epoch of Reionization, galaxy evolution studies at intermediate redshifts, cosmological parameter measurements using type-Ia supernovae to z~2, as well as studies of stellar populations in nearby galaxies and objects in our own Solar System. Canada has the opportunity to join this Japanese-led mission as a partner, along with the US and France, by leveraging Canadian industrial expertise in space cryogenics to build a key component of the the observatory (the filter exchanger) at a very moderate cost.

1. Introduction

Space missions such as Spitzer have conclusively demonstrated the tremendous scientific importance of infrared imaging at wavelengths beyond those that are readily accessible from the ground (λ>2.5µm). Imaging at these wavelengths is essential for discovering the first galaxies and quasars expected to exist at z~15, studying the growth and evolution of galaxies at later epochs, and even characterizing ices in objects in our own Solar System.

Among the upcoming flagship space missions only JWST will be able to image at these long wavelengths, but with only a tiny field of view (~10 arcmin^2). Neither Euclid (λ<2.0µm) nor WFIRST (<2.0µm, with the possibility to extend to 2.4µm) will observe at these key wavelengths. The WISH mission (WISH = Wide-field Imaging Surveyor for High-redshift) is a proposed Japanese-led project to fly, in the early 2020's, a dedicated wide-field (~0.25 deg^2/pointing) space imaging telescope that will survey the universe at λ=1–5µm.

WISH will carry out a 5-year program focused predominantly on collecting a "wedding-cake" set of surveys that will span an unprecedented combination of area and depth (see Fig. 7). These surveys will surpass what has been possible with Spitzer, the current benchmark at 3—5µm. Additionally, approximately 10—20% of WISH observing time will be available for ancillary science projects.

2. WISH Science

WISH will carry out a 5-year mission focused predominantly on a "wedding-cake" set of surveys spanning a combination of area and depth (see Section 3 and Fig. 7). Additionally, approximately 10-20% of the telescope's time will be allocated to ancillary science projects. This section gives several examples of the landmark science that WISH will enable in the areas of interest and strength for Canadian astronomy.

2.1. In the Epoch of Reionization

Understanding the earliest generation of collapsed objects to have formed after the Big Bang is a key goal of modern astrophysics. Current studies point to z~15 as the epoch at which galaxies first appeared in the Universe in significant numbers. It is now clear that neither luminous galaxies nor quasars are sufficient to provide enough ionizing radiation to account for the reionized state of the intergalactic medium (IGM) at z>6. Consequently, it is thought that a very numerous population of low-luminosity galaxies must exist at these epochs. These very faint objects are going to be the subject of major search efforts by the JWST, but their faintness means that while we will be able to constrain their statistics, they will be extremely difficult to follow-up in astrophysical detail either with JWST or with the next generation of Extremely Large Telescopes (ELTs). For deep physical understanding spectroscopic follow-up will be critical and this will only be possible for very rare, bright systems: either intrinsically-luminous, super-L* objects or ones whose fluxes have been boosted by gravitational lensing. Such detailed follow-up can be undertaken with either JWST or (better still) AO-assisted ELTs, but only once these luminous objects are first found. Finding them in numbers sufficient for meaningful studies will require large area surveys at wavelengths λ>2.5µm.

High-redshift star-forming galaxies can be identified in broad-band imaging using the Lyman Break technique, which requires two broadband filters above the spectre break located at 1215A. At z~15, this Lyman Break Galaxy (LBG) method thus needs two filters at (1+z)>1215A, i.e., longward of 2µm (Fig. 1). For detailed, spectroscopic investigations with the TMT (or

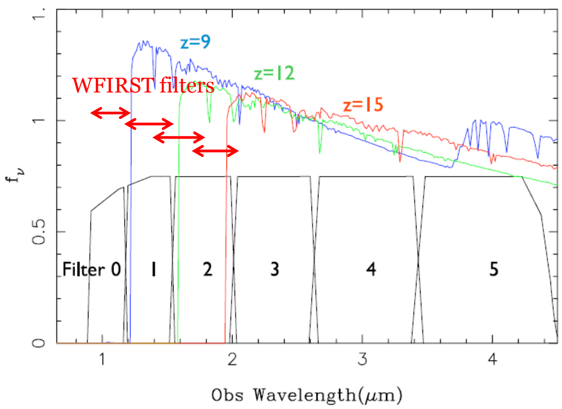

Figure 1. Detection of Lyman Break Galaxies (LBGs) in the Epoch of Reionization with WISH. Coloured lines show star-forming galaxies at different redshifts, overplayed on the WISH bandpasses. At high redshift the LBG selection technique requires long-wave-

other ELTs) we need bright objects — either lensed objects or intrinsically luminous systems from the L>L* part of the populations's luminosity function. These bright systems are intrinsically rare (~1/deg^2 z~15 objects expected to m(2μm)=28AB) and thus will not be found in sufficient numbers without the use of large-area (10s-100s of square degrees) surveys. WISH will discover several hundred of these bright z~15 objects, providing Canadian astronomers with a rich source of exciting Epoch-of-Reionization targets for detailed spectroscopic follow-up with the TMT.

2.2. The assembly of galaxies at z~1—8

A major achievement of observational cosmology has been the detailed characterization of the large scale structure (LSS) in the local and high redshift universe and its successful explanation in the ΛCDM cosmological framework. However, within this broad paradigm, our understanding of the formation of structures on the scales of galaxies contains vast gaps: we still do not fully understand the link between galaxy properties and the properties of their host dark matter halos or the

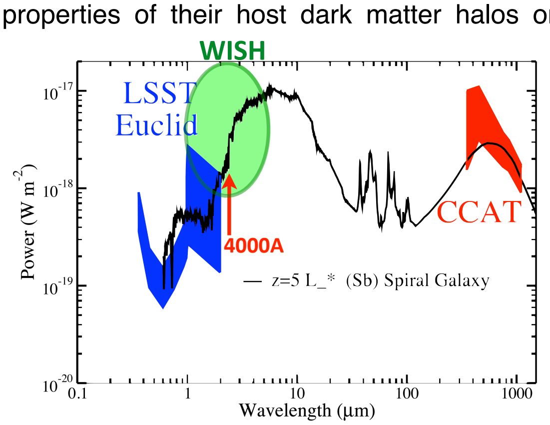

Figure 3. High-z sources selected by large-area CCAT (red) will need λ>2.5μm followup (green) to determine their stellar masses and photometric redshifts.

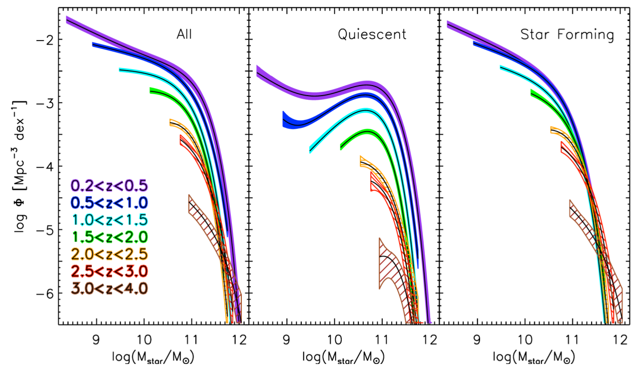

Figure 2. State-of-the-art stellar mass functions from NIR-selected surveys (Muzzin et al. 2013, ApJ, 777, 18). Beyond z~2, current surveys only reach ~M and that only with poor statistics (diagonally-hashed regions). To probe these populations we need λ>2μm over large sky areas.*

baryonic physics from gaseous infall, through star formation (SF), to SF-regulating feed- back processes. It is clear, however, that mass (both the stellar mass of a galaxy and the dark matter mass of its halo) likely play key roles.

Because galaxy evolution is a very slow process that we cannot observe directly due to the long timescales involved, we must piece it together using large statistical samples that span a range of epochs and galaxy properties. Such studies of galaxy evolution are dominated by two key observational drivers: *(1)* galaxy stellar masses (M_{stars}) and *(2)* their star formation rates (SFR = dM_{stars}/dt). Together, these two parameters encapsulate a galaxy's present and past star formation rates, and characterize its present star-forming activity by means of the specific SFR (sSFR = SFR/M_{stars}). With these key parameters in hand we can employ many other techniques such as clustering strength measurements, halo abundance matching, or environmental analysis to study how galaxies grow in mass and size over cosmic time, how they transition between star-forming and quiescent populations, and how these processes depend on environment and host dark matter halo masses.

These approaches have been very successful at low redshifts (z~0—2; Fig. 2) but at higher redshifts they run into the difficulty of characterizing stellar masses as these require at least two (and preferably more) broadband filters above the Balmer/4000A break. At z>2 this means we need data at K-band and beyond and here the Spitzer Space Telescope proved itself invaluable over the past decade. However, Spitzer's field of view is small and thus it can provide only rather limited samples, inadequate for definitive studies of clustering and environmental effects. These limitations will be lifted by WISH, which will provide large-area samples (giving both statistical power and sufficient sky areas for environmental studies), allowing us to trace how galaxies assemble and grow at epochs intermediate between the Epoch of Reionization and the peak of cosmic star formation history at z~2.

In addition to mass-selected studies such as described above, WISH will be ideally complementary to CCAT. CCAT will carry out large-area blank-sky surveys to discover large samples of distant dust-enshrouded galaxies out to high redshifts. Characterizing these galaxies and placing them in the broad context of galaxy assembly will require the determination of their redshifts and stellar masses. Observations at <2.5μm will not be able to pin-point the location of the Balmer/4000 break for z~5 CCAT sources, nor measure galaxy stellar masses from the stellar continuum level above it (Fig. 3). Wide-field WISH surveys overlapping CCAT fields will be ideal for providing these mass and redshift measurements and thereby helping constrain the role that high-z starburst galaxies play in the process of galaxy formation and evolution.

2.3. Galaxy clusters at high redshift

Large samples of galaxy clusters at high redshifts are important for *(i)* understanding the role that the most massive, dense environments have on galaxy evolution and for *(ii)* measurements of cosmological parameters via observations of the growth of cosmic structure that are independent of geometric methods such as supernova standard candles and the standard rulers of the CMB and Baryon Acoustic Oscillations (BAO). This work requires finding large samples of clusters beyond z~1. Optical/NIR cluster searches provide one of the most cost-effective ways of identifying large samples of high-redshift clusters, as demonstrated, e.g., by the RCS survey at z<1. Using the 1.6μm stellar bump, ubiquitous in virtually all stellar populations, allows the detection of high-z clusters, as has been successfully demonstrated using Spitzer IRAC data (Fig. 4). WISH large-area surveys will be ideally suited for such work and will yield rich samples of z>1 clusters for both cosmological and galaxy-evolution studies.

2.4. Supernova cosmology to z~2

Type Ia supernova standard candles were instrumental in discovering the acceleration of cosmic expansion and subsequent (e.g., CFHTLS) detailed measurements of cosmological parameters. Repeat observations in the deep WISH survey fields will yield samples of hundreds of supernovae out to z~2. These samples will improve on previous observations in two important respects: First, working at long wavelengths (out to 5μm) allows supernova detection out to z~2 (Fig. 5), thereby giving a longer redshift baseline for studies of the evolution of cosmological parameters. Second, supernovae discovered at z~1 will be observed in the rest-frame NIR, thereby minimizing the systematic effects of dust attenuation.

2.5. Stellar population in nearby galaxies

WISH would be a powerful facility for probing the stellar contents and structural characteristics of nearby galaxies. The wide field-of-view is ideal for surveying the stellar contents of Local Group galaxies, which can subtend a few degrees on the sky, as well as galaxies in nearby groups, the largest of which can subtend ≳10 arcmin. The wavelength region sampled by WISH is sensitive to the most evolved stars in galaxies, and these provide information on the star-forming history (SFH) and metallicity of the system. The 3-5μm regime is of particular interest as circumstellar envelopes around AGB stars can contribute significantly to the light at these wavelengths. This emission (1) makes these stars stand out with respect to the majority of stars in a galaxy, making it easier to resolve individual objects than at visible wavelengths, and (2) gives these objects distinctive colors on CMDs, so that they are

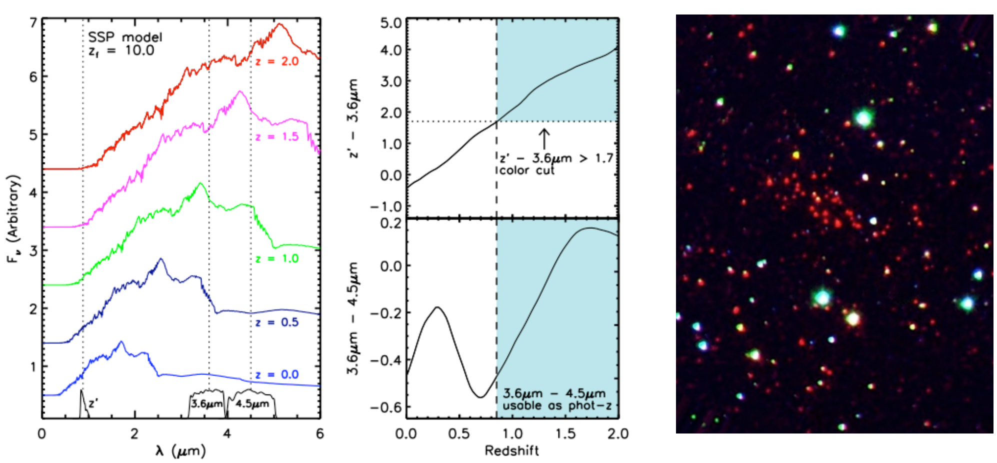

Figure 4. Cluster-finding with NIR imaging: 1.6μm Stellar Bump method relies on >2.5μm imaging to identify clusters beyond z=1. Right panel shows a high-redshift cluster discovered in Spitzer IRAC data (Muzzin et al. 2013, ApJ, 767, 39). WISH will find large samples of such clusters, ideal for both cosmology and galaxy evolution work.

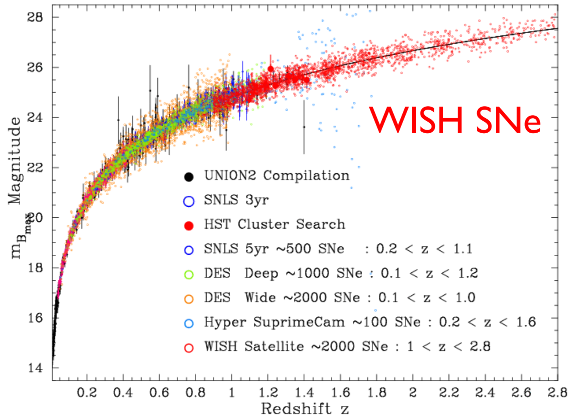

Figure 5. Cosmological type Ia supernovae discovered to date, along with expectations for z>1 for WISH (red points). Figure courtesy of Nao Suzuki.

less susceptible to contamination from foreground stars and background galaxies. In addition to resolved populations studies, 3-5µm imaging, which probes the distribution of the low-mass stars in a galaxy, also constrains the structural characteristics of star-forming galaxies. At 3-5µm the light distribution is not affected by dust or skewed by younger stars that dominate at shorter wavelengths.

3. Technical Overview

3.1. Telescope and Spacecraft

WISH will have a 1.5-m primary mirror (Fig. 6) and optics that will yield diffraction-limited images over 1–5µm. It will have 32 Hawaii-2RG 2Kx2K detectors with 0.155", 18 µm pixels, cooled to ~50K and set on a very flat, ring-shaped focal plane. WISH is optimized for wide-field imaging and will have 11 filters (broadband + narrowband). It will be launched on a JAXA H-IIA launcher and placed at the Sun-Earth L2 point in ~2023. The telescope will be passively cooled to 80-100K, yielding low background and consequently high observing sensitivity for faint sources.

3.2. Observing with WISH

WISH will have a 5-year lifetime and will operate primarily in survey mode, with ~10-20% of observing time set aside for ancillary science projects. In survey mode WISH will carry out a series of "wedding-cake" surveys spanning a range of depth and area. These surveys will be fine-tuned to maximize the scientific return of studies such as those listed in Sec. 3. The current survey concept calls for surveys shown in Fig. 7, although the details of these will be refined further over time.

4. The WISH Partnership

4.1 International partners

WISH will be a Japanese-led mission, with contributions from several international partners. In addition to

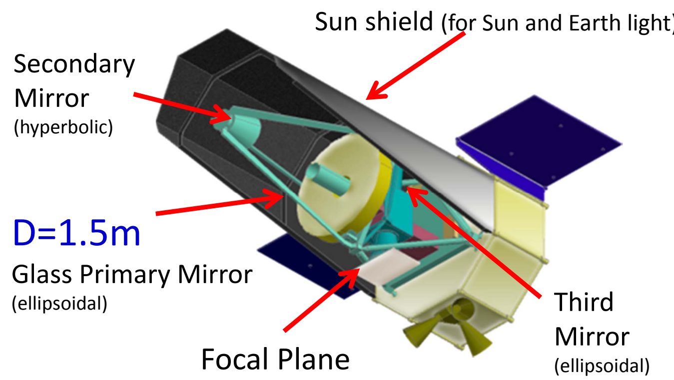

Figure 6. WISH telescope and spacecraft.

Japan, teams in the US, France, and Canada are planning to contribute to the project.

The Japanese WISH team, led by Toru Yamada (Tohoku University) and Ikuru Iwata (NAOJ) was funded by JAXA to carry out a five-year, pre-Phase-A mission concept study along with the prototyping of some key hardware concepts. The results of this work have been documented in the 400+ page mission concept study report and the team is ready to proceed to Phase-A. JAXA has recently released and Announcement of Opportunity for a mission with a target launch date of 2023 and the Japanese WISH team is preparing a proposal, due February 2015.

The US team, led by Giovanni Fazio (CfA) is proposing to supply the WISH infrared detector arrays along with the associated hardware and testing work, valued at $60M. They are submitting a proposal to the NASA call for mission-of-opportunity proposals in December 2014.

The French team, led by Denis Burgarella (LAM, Marseille) aims to supply a spectrograph (~$10M) that will operate in parallel to the WISH imaging operations. Participation in an infrared space mission aiming to study the Dark Ages and the formation of first objects (i.e., WISH) is a P2 priority with the French community.

4.2 Canadian contribution

On the strength of Canadian scientific expertise and industrial experience in space cryogenic mechanisms, Canada and the Canadian Space Agency are invited to participate in the WISH project. The agreed-upon Canadian contribution to WISH would be the development and construction of the Filter Exchange Unit (FEU) — a key component of the WISH system. To assure potential participation in WISH, Canada should carry out a design study of the FEU in the near term, followed by constructing the instrument in synchrony with work carried out by the other partners.

The Japanese WISH study team has developed a preliminary design for the FEU that addresses the need (imposed by the overall optical design) to place the detectors in a ring-shaped configuration on the focal

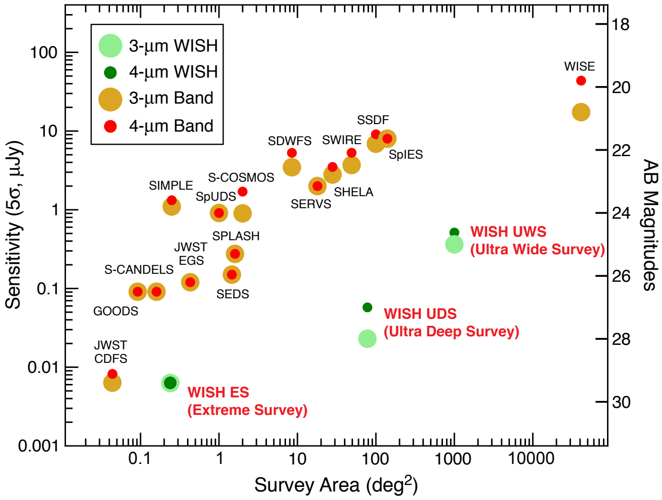

Figure 7. Proposed WISH surveys in the landscape of current and future surveys in the crucial 2.5 –5µm band that enables characterization of high-z galaxies and rest-IR detections of z = 0.5 – 1.5 SNe. Figure courtesy of G.Fazzio et al.

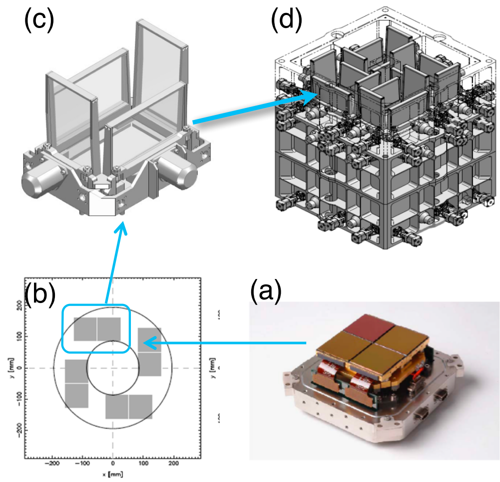

Figure 8. The WISH Filter Exchange Unit (FEU) concept. Detectors (a) are mounted in groups of four in a ring pattern on the focal plane (b) whose doughnut shape is dictated by the optical design of the telescope. Each group of eight detectors is served by dedicated flip-type filter exchangers (c) which are mounted in the FEU (d). This seemingly complex arrangement actually provides redundancy and thus operational reliability over a single, large filter wheel (which would be too large and heavy, in any case).

plane (Fig. 7). They have also done initial prototyping work on the flip-type filter exchangers, showing that these systems are reliable in cryogenic environments. While the geometric arrangement of the FEU appears complex at first glance, it is has significant advantages: unlike with a single filter wheel, the multiple stacks of filters provide redundancy against failure in any individual stack; additionally, the manufacturing of multiple identical elements provides economies of scale. The cost to develop and build the FEU is estimated at ~$5M based on initial prototypes.

Canada has been offered the opportunity to take on the FEU development and construction work. This would build on Canadian expertise in space cryogenic mechanisms gained through projects such as the JWST FGS/NIRISS instrument.

5. Summary and Future Steps

The LRP2010 document highlighted the need for the CSA to be ready for participating in small missions of opportunity as such missions arise. WISH is precisely such an opportunity. WISH would, for Canada, be on a completely different financial scale than flagship missions such as WFIRST or CASTOR (~$5M vs ~$50M). It would launch in ~2023, at the end of JWST's 5-year planned lifetime, and would let Canadian astronomers build on the discoveries they make with JWST by expanding their view at similar wavelengths but over larger fields of view.

To ensure Canadian participation in WISH requires us in the first instance to carry out a study of the Filter Exchange Unit to identify and refine the best technical solution and to better constrain its implementation cost. This study would take 6–12 months and cost $100—200k if carried out by Canadian space industry and supported by the astronomy community. It should take place to coincide with the Japanese and US work mentioned in Sec. 4.1. Following a successful outcome of this study, and in synchrony with developments in other partner countries, we then need to proceed to a construction phase, delivering a completed FEU in time for integration before the ~2023 launch.

Pushing wide-field imaging out to 5µm builds on a strong Canadian science heritage in wide-field imaging (e.g., MegaCam) and opens the doors for a wide range of new scientific discoveries across many astronomy sub-disciplines. Joining WISH is also a great fit to Canada's Space Policy Framework: it proceeds through partnerships (both international, and, within Canada, industry-government-academia) and it engages Canadian space industry in an area of existing key excellence (cryogenic space mechanisms).

WISH is a new opportunity for Canada, which the CSA should be willing to seize, as recommended in the LRP2010 document (Recommendation 25). To enable Canadian participation in WISH, the CSA should fund, in the first instance, a technical study of the FEU mechanism design options and costs. Carried out promptly, this study will place Canada in an informed position to join WISH as the mission selection processes proceed at JAXA and the other WISH partners in the next ~1—2 years.