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CASTOR: A FLAGSHIP CANADIAN SPACE TELESCOPE

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ABSTRACT

The Cosmological Advanced Survey Telescope for Optical and uv Research (CASTOR) is a proposed CSA-led mission that would carry out panoramic imaging in the ultraviolet and blue-optical region ($\approx$ 150–550 nm). Operating close to the diffraction limit, the 1m CASTOR telescope would have a spatial resolution comparable to the Hubble Space Telescope (HST), but with an instantaneous field of view about two hundred times larger. The scientific impact from such a facility would be immense, covering topics ranging from small bodies in the outer solar system to the equation of state of the universe. CASTOR has the potential to be a significant, unique and highly strategic Canadian contribution to the international portfolio of astronomical facilities in the 2020s, complementing high-profile optical/IR space missions (Euclid, WFIRST) and ground-based telescopes (LSST) currently under development in Europe and the United States. By placing Canada at the forefront of astronomical research in the coming decade, CASTOR would showcase the technological capabilities of Canadian industries to an international audience, and inspire the next generation of young Canadians to pursue careers in science, engineering and technology.

To achieve maximum scientific impact, and to enable effective international partnerships (including collaborations with the Euclid, LSST and WFIRST development teams), CASTOR should launch no later than the middle of the next decade. Since the time of the 2010 *Long Range Plan for Canadian Astronomy*, CSA has taken significant steps to advance CASTOR through the mission concept stage, including ongoing technology development studies. However, it is now imperative that CASTOR moves promptly to a Phase 0 study in order to refine estimates for cost and schedule, optimize the mission design and survey strategies, and lay the groundwork for international partnerships.

Subject headings: telescopes – satellites – instrumentation – techniques – surveys – cosmology – dark energy – dark matter – galaxies – stellar astrophysics – planetary systems – solar system – ultraviolet, optical and infrared astronomy – time domain astronomy

1. BACKGROUND AND CONTEXT

In the next decade, two landmark space missions will transform astronomy by carrying out deep, high-resolution, wide-field imaging in the red-optical and infrared (IR) spectral region ($0.55 \leq \lambda \lesssim 2\ \mu$m). The first of these, *Euclid*, is an ESA-led mission that is scheduled for launch in 2020 (Laureijs et al. 2011). Euclid will image an area of at least 15 000 deg^2 in the IR region (YJH), as well as in a single broad filter (`VIS`) at red-optical wavelengths. Around 2023, Euclid will be joined by NASA's *WFIRST* mission (Spergel et al. 2013), which will also carry out red-optical/IR imaging (YJH and $F184$), but to a depth ~ 3 mag deeper than Euclid over a smaller ($\simeq 2200$ deg^2) field. Both missions are primarily motivated by a desire to understand dark energy — a mysterious component of the universe that causes an acceleration in the cosmic expansion rate — but their legacy value is so immense that a vast amount of ancillary science will be enabled.

On the ground, the *Large Synoptic Survey Telescope* (LSST) is expected to begin its decade-long survey operations in 2022. LSST (Ivezić et al. 2008, Abell et al. 2009) will revolutionize time-domain astronomy by repeatedly imaging an area of $\sim 20\,000$ deg^2 every few nights. The combination of optical imaging from LSST and IR imaging from Euclid/WFIRST is expected to be a powerful resource that astronomers will exploit for decades to come. Indeed, LSST and WFIRST emerged as the top-ranked projects in ground- and space-based astronomy

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in the 2010 US Decadal Study (Blandford et al. 2010). But, at the time of writing, Canada — which has for several decades been a world leader in wide-field imaging — has no formal involvement in either of these facilities, nor in Europe's Euclid mission.

2. CASTOR AND 2010 LONG RANGE PLAN

In Nov. 2006, more than 100 astronomers from across Canada assembled at CSA headquarters in Saint-Hubert, QC, to take part in the *Canadian Space Astronomy Workshop*. Emerging from this workshop was the concept of a "flagship" space astronomy mission that would focus on wide-field UV/optical imaging and/or UV spectroscopy — capabilities that would either complement future IR-optimized space telescopes or will be lost when HST ceases operations, probably around the end of this decade. These concepts were further developed within the framework of CSA's Discipline Working Groups on wide-field space imaging and UV astronomy (Drissen et al. 2007, Drissen et al. 2009, Côté et al. 2009; see also Abraham et al. 2009), where the strong scientific case for a blue-optical/UV imaging telescope to complement ESA's and NASA's planned "dark energy" missions was identified as a unique opportunity for Canada.

Soon afterwards, the 2010 *Long Range Plan for Canadian Astronomy* (LRP; Pritchet et al. 2010) concluded that Canada's highest priority in space astronomy should be "*significant involvement in the next generation of Dark Energy missions — ESA's Euclid, or the NASA WFIRST mission, or a Canadian-led mission, the Canadian Space Telescope (CST).*"

Despite considerable subsequent effort by the community (e.g., Rowlands et al. 2011, Sawicki et al. 2012), no satisfactory mechanism to enable significant Canadian involvement in Euclid could be identified. Meanwhile, options for possible Canadian involvement in WFIRST have remained unclear due to changes and delays in establishing the mission design. However, in Nov. 2014, CSA initiated two concept studies intended to explore possible Canadian contributions to the mission.

In 2011 and 2012, the LRP's third option (CST = CASTOR) was examined in a CSA concept study carried out by a team of scientists and engineers from industry,[16] academia and government.[17] Full details on the mission concept developed in this study can be found in Piche et al. (2012ab), Côté et al. (2012) and Scott et al. (2012). From 2012 to 2014, the concept was presented by members of the science team at more than a half dozen international conferences, and received significant provisional interest from scientists from other countries (France, India, Taiwan, Australia, Switzerland, US).

The 2012 concept study was followed in 2013 by a two-year Space Technologies Development Program study intended to retire a key source of technical risk identified during the concept study: UV detectors and coatings. This ongioing detector assessment and focal plane array characterization study, which is being led by COM DEV, has proceeded with full participation of the CASTOR science team, who revisited the mission's scientific requirements at its outset. The preliminary conclusion is that there exist multiple silicon detector candidates capable of meeting the mission needs (Scott et al. 2014). While this is encouraging news, the study has also led directly to a need to review the detector layout and optical design in order to mitigate red leak issues, and to re-optimize the mission's overall observing strategy. As discussed in §6, these issues would likely comprise key components of any Phase 0 study.

[16] With participation by COM DEV, Magellan, ABB and Northeast Space.

[17] The mission cost, excluding launch, was constrained to the range of CSA's `small-SAT` program: \$50–\$200M.

3. CASTOR AS A STRATEGIC CANADIAN CONTRIBUTION TO INTERNATIONAL ASTRONOMY

The UV and blue-optical region has a special significance in astronomy, as it contains a wealth of information on the physical properties of gas, stars and galaxies. This region is especially important for characterizing emission from young and/or hot stars, as well as from hard non-thermal sources. For galaxies, UV/blue-optical SED coverage is critically important when estimating distances from photometric redshifts — a prerequisite in the use of weak lensing as a dark energy probe (a key element of both the Euclid and WFIRST missions). Of course, as a ground-based telescope, LSST will: (1) have no access to the UV region; (2) have comparatively low efficiency at wavelengths $\lesssim$ 400 nm; and (3) be unable to match the high angular resolution of Euclid and WFIRST.

CASTOR has been specifically designed to provide these "missing" capabilities in the 2020s: i.e., access to the UV region, high blue sensitivity and observing efficiency, and superb angular resolution over a large instantaneous field (see Table 1).[18] It would thus be a strategic asset that might used to negotiate some level of Canadian involvement in LSST, Euclid and/or WFIRST in exchange for European/US involvement in CASTOR.

In Figure 2, we illustrate the strong synergy between CASTOR, LSST, Euclid and WFIRST. In the specific case of the IR space missions, a area of concern is uncertainties in photo-z bias and error as potentially dominant sources of systematic errors in weak lensing measurements. For the Euclid mission, ultra-deep UV/optical imaging from CASTOR would not only allow it to meet (and exceed) its goals for photo-z precision, but would greatly enhance the overall legacy value of the mission. For WFIRST, the interplay with LSST is an area of active investigation within the US community since the blending and shredding of galaxies, especially at ultra-faint magnitudes where LSST approaches its confusion limit, are points of concern. Deep imaging from CASTOR has the potential to mitigate or eliminate many of these potential systematics, and thus needs immediate investigation in a Phase 0 study. But even at this stage it is abundantly clear that the addition of CASTOR imaging would prompt a complete reanalysis of the Euclid, LSST and WFIRST datasets and yield a state-of-the-art characterization of dark energy through weak lensing.

[18] By doing so, it fulfills one of the four "necessary conditions" that we believe any large-scale space astronomy project in Canada must satisfy: broad appeal to a large and diverse segment of the community. The other conditions are: it must enable scientific discoveries of the highest order thanks to a dramatic increase in capabilities over any existing or planned facility; it must be fully compatible with the government's Space Policy Framework (see §5) and; it must have widespread and diverse involvement by Canadian industry. In the specific case of a CST, we can add one additional condition: it must complement and enhance, rather than compete with, the Euclid and WFIRST missions.

Although much work is needed to optimize observing strategies, Figure 3 again illustrates the highly strategic nature of the mission. Comparing the LSST, Euclid and WFIRST survey footprints, two possible CASTOR surveys immediately present themselves: a northern survey (to $u' \simeq 27.1$ AB mag) covering some or all of the Euclid Wide region inaccessible to LSST, and a deeper ($u' \simeq 28.3$ AB mag) survey in the south covering the full WFIRST-HLS footprint. As an illustration of CASTOR's remarkable short-wavelength sensitivity, we estimate using the 2012 performance specifications that the latter survey could be carried out in $\sim$1.8 years.

Beyond the obvious synergy with these dark energy missions, CASTOR would also offer a powerful complement to JWST. This major international mission (a collaboration between NASA, ESA and CSA) is scheduled for launch in 2018. It will focus on the red-optical/IR region to explore "first light" and reionization in the early universe. By doing so, it will be observing these galaxies, stars and quasars at *rest-frame UV wavelengths.* Thus, UV/blue-optical emission from sources in the low-z universe is certain to take on a renewed importance in the post-JWST era. Farther ahead, CASTOR could serve as an important scientific and technical pathfinder for the next generation, large-aperture (8-16m) UV/optical/IR space telescope. Such a facility has emerged as a leading candidate for a possible NASA flagship mission in the post-2030 era (Postman et al. 2009).

Of course, CASTOR's legacy value would extend well beyond the "core" (i.e., dark energy) science of Euclid and WFIRST. An overview of mission's immense scientific potential may be found in Côté et al. (2012), and includes the detection and composition of remote bodies in the outer solar system; microlensing searches for exoplanets; the chronology and mass spectrum of accretion in the Milky Way and nearby galaxies from resolved stellar populations; and the definitive characterization of the history of cosmic star formation.

4. HERITAGE AND DEVELOPMENT PATH

Canada has a long, distinguished history in high-resolution and wide-field imaging: the key elements of the CASTOR concept. Beginning in the late 1980s, Canadian astronomers used the 3.6m Canada-France-Hawaii Telescope (CFHT) to pioneer the techniques of image stabilization and adaptive optics (e.g., HRCam, PUEO). Following the launch and servicing of the HST in the early 1990s, Canadian astronomers became world leaders in wide-field field imaging, through the development and/or use of mosaic CCD cameras of ever-increasing size: e.g., FOCAM, MOCAM, UH8K, UH12K, and, finally, MegaCam. This last instrument — which saw first light in 2003 and remains in active operation to this day — is chiefly responsible for the continued productivity and high impact of CFHT. Over the past decade, Canadian astronomers also became world leaders in the design and implementation of large imaging surveys, such as CFHTLS, CFEPS, CFHTLenS, NGVS, PAndAS, MATLAS, OSSOS, CLAUDS and LUAU.

With the development of new and more powerful mosaic cameras (such as HSC on Subaru and DECam on the CTIO 4m telescope), as well as dedicated imaging facilities (e.g., Pan-STARRS, VISTA, Skymapper), Canadian astronomers are now relinquishing their leadership roles in wide-field imaging. This will become all too obvious in the 2020s, when the next generation of ground- and space-based imaging telescopes (LSST, Euclid, WFIRST) begin operations. However, focusing as it does on high-resolution imaging in the blue-optical and UV bands, CASTOR would fill an important missing capability within the international portfolio of astronomy facilities in the 2020s.

Because CFHT retains one important performance advantage over its competitors at the present time — it is still the world's best blue-optical imaging telescope in the northern hemisphere — a natural development path for CASTOR could present itself. In the near term, strategic blue-optical surveys with CFHT (such as CLAUDS and LUAU) could ensure a continued leadership role for Canada until the end of the decade, while development work on CASTOR could proceed towards a launch early in the next decade. On intermediate timescales, the development of increasingly ambitious and sophisticated balloon-borne optical and UV imaging telescopes — such as BIT, SuperBIT and GigaBIT — could allow a smooth and productive transition from ground- to space-based imaging capabilities. In fact, this a proven path with demonstrated success for Canada (i.e., in the study of the cosmic microwave background, BLAST and BOOMERANG served as scientific and technological springboards for the WMAP and PLANCK missions). Moreover, the launch of Astrosat/UVIT (an ISRO-led mission with participation by Canada) in 2015 will provide an additional, important opportunity for Canadian astronomers over intermediate timescales.

In such a scenario, CASTOR would represent the culmination of a development process for Canadian astronomy that stretches back to CFHT in the mid 1980s.

5. CANADA'S SPACE POLICY FRAMEWORK

Released in Feb. 2014, Canada's *Space Policy Framework*, was developed to identify priorities and guide activities in space in the coming years. CASTOR's alignment with its five "guiding principles" is noteworthy.

5. *Inspiring Canadians.* As the world's preeminent blue-optical/UV imaging telescope, CASTOR would combine the wide-field and high-resolution elements of HST and CFHT imaging that has been so effective in capturing the imagination of the public. It would allow CSA to play a leading role in communicating the importance of science, engineering and technology to the Canadian public and would almost certainly supplant *Alouette 1* and *Canadarm* as the most visible space project ever undertaken by Canada.

4. *Excellence in Key Capabilities.* CASTOR would provide a natural next step in the growth of Canada's space hardware sector. Industries that participated in the development of smaller missions, and/or collaborated on large international projects like JWST, have developed unique expertise in the design, development, testing and fabrication of electro-optical payloads and large focal plane arrays. Moreover, by positioning Canadian astronomers, physicists, engineers and software developers at the leading edge of their professions,

it would help ensure that the next generation of scientists and engineers are retained in Canada.

3. *Progress Through Partnerships.* By its very design, CASTOR has strong scientific synergy with Euclid, LSST and WFIRST — three of the highest-priority projects planned for the 2020s by the European and American astronomical communities. It would thus foster closer scientific, industrial and programmatic partnerships with these two important communities.

2. *Positioning the Private Sector at the Forefront of Space Activities.* A preliminary evaluation of the potential impact of CASTOR on the high-tech industrial sector in Canada identified about two dozen companies — geographically distributed from coast to coast — that might participate in the design, development and fabrication of the mission. This level of industrial impact is unique to a scientifically ambitious and technical demanding project like CASTOR. As noted in the LRP, CASTOR would provide "*the ideal opportunity for high-tech Canadian companies to showcase their capabilities*", particularly in the areas of opto-electronics, high-volume data transmission technologies, X-band phased array transceivers, data handling units, memory boards, readout systems, and control software.

1. *Canadian Interests First.* As is the case with other developed nations, Canada's future sovereignty, security and prosperity are likely to rely increasingly on an active and vibrant space program. Space astronomy occupies a special place within the portfolio of most national space agencies (e.g., NASA, ESA, JAXA, ISRO) as it is arguably the most visible of endeavours, with public broad appeal and large scientific and industrial returns.

Though ambitious in scope, CASTOR would provide a unique opportunity for academia, industry and government to join forces on a project whose benefits to Canada would far surpass those that might be achieved through small partnerships in one or more international projects. We note that the overall cost to Canada would likely be comparable to its contribution over the past decade to JWST — the centerpiece of a multi-scale and multi-wavelength Canadian space portfolio that included MOST, FUSE, Herschel, Planck, BLAST, NEOSSat, BRITE-Constellation, as well as several other balloon and space missions that are currently in development.

6. SUMMARY AND FUTURE STEPS

Since 2010, the scientific motivation for a wide-field, high-resolution, blue-optical/UV imaging space telescope has only sharpened. However, despite initial progress in developing a scientifically attractive and technically viable mission concept, the "window of opportunity" for CASTOR is not unlimited, and a Phase 0 study is urgently needed to: (1) improve estimates for cost and schedule; (2) revisit the opto-mechanical design of the mission (e.g., filters, coatings, dichroics, detectors) armed with updated design and performance parameters for Euclid and (especially) WFIRST; (3) explore options for possible spectroscopic and/or coronagraphic modes; and (4) re-optimize observing strategies and overall balance between survey and Guest Observer science. It would provide an ideal opportunity to develop a more detailed science plan in consultation with the LSST, Euclid and WFIRST development teams.

Without such a study, it will be impossible for Canada to catch the attention of prospective international partners. If begun promptly, such a study would provide crucial information (on, e.g, cost, schedule, technical performance, opportunities for partnership and collaboration) that will be needed by the Canadian astronomical community if it is to develop a coherent roadmap for the coming decade.

"The greater danger... lies not in setting our aim too high and falling short, but in setting our aim too low and achieving our mark."

– Michelangelo

"In the second century of Confederation, the fabric of Canadian society will be held together by strands in space just as strongly as the railway and telegraph held together the scattered provinces in the last century."

– Chapman et al. (1967)

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TABLE 1
Mission Comparisons for HST, Euclid, WFIRST and CASTOR.

Mission	HST	Euclid	WFIRST	CASTOR
Lead Agency	NASA	ESA	NASA	CSA
Launch	1990	2020	2023	2022
Telescope Aperture (m)	2.4	1.2	2.4	1.0
Focal Ratio	f/24	f/24.5	f/7.9	f/20
Plate Scale (μm arcsec^{-1})	375	120 (VIS) 60 (NISP)	90	100
Orbit	low earth (559 km)	Sun-Earth L2	Sun-Earth L2 or geosynchronous	low earth ($\sim$700 km)
Mission Lifetime (years)	$>$ 25	7	$\geq$ 5–6	$\geq$ 5
Field of View (arcmin^2)	$11^{\otimes}$	$\sim$2000	$\sim$1000	$\sim$2400
Number of Filters/Bands	>50	4	6 (4 for HLS)	3
Imaging Wavelength Range (nm)	200–1700	550–2000	760–2000	150–550
Resolution – EE50 (arcsec)	$\sim$0.07	0.13 (VIS) <0.30 (NISP)	0.11–0.14	0.09
Sampling (arcsec pixel^{-1})	0.04–0.05	0.1 (VIS) 0.3 (NISP)	0.11	0.1 (0.05 drizzled)
Number of Pixels	2×2K×4K	36×4K×4K (VIS) 16×2K×2K (NISP)	18×4K×4K	21K×42K
Primary Survey Area (deg^2)	NA	$\geq$ 15 000	2213	$\geq$ 5 000
Spectroscopy	Slits, Apertures ($\mathcal{R}$ up to 10^5)	Slitless ($\mathcal{R}$ = 250)	Slitless ($\mathcal{R}$ = 550–800) IFU ($\mathcal{R}$ = 100)	Slitless TBD
Coronagraphy	yes	no	probable	TBD

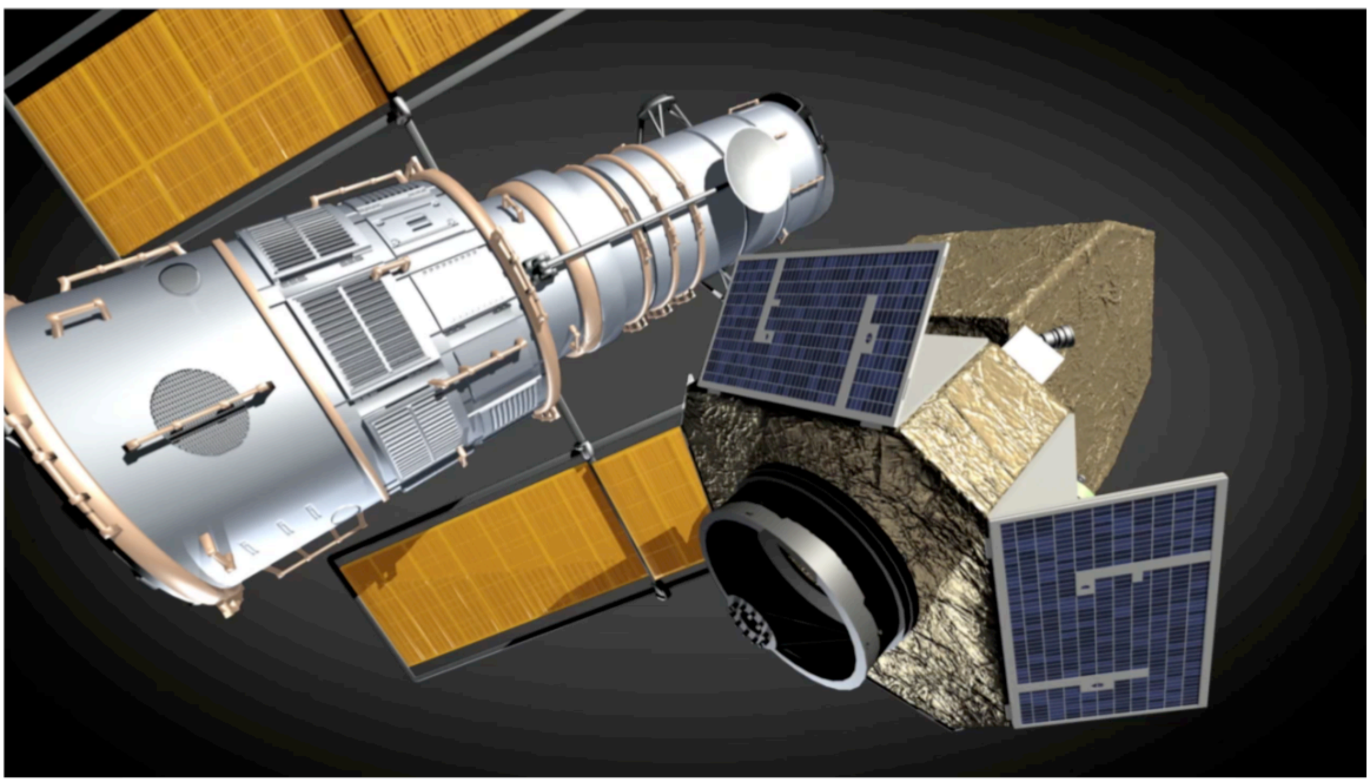

Fig. 1.— Comparison of CASTOR (foreground) to the Hubble Space Telescope (background). The former's compact, three mirror anastigmat design minimizes spacecraft volume, mass and cost.

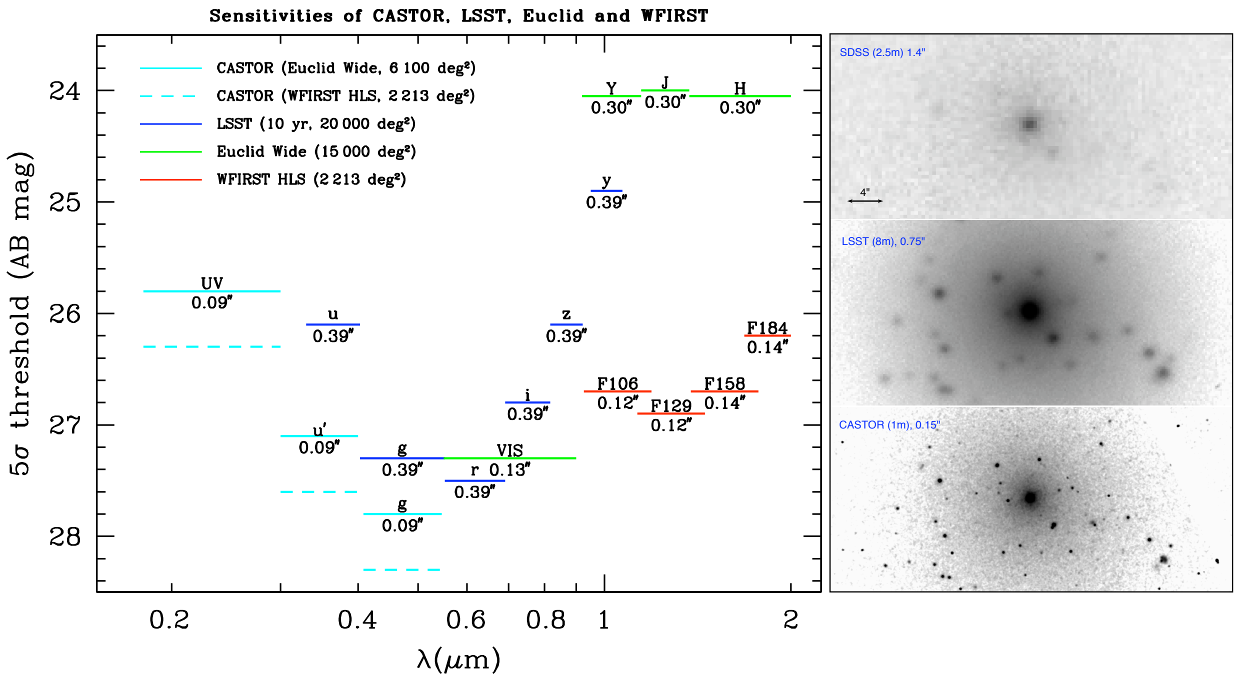

FIG. 2.— (Left) Depth of wide-field imaging surveys as a function of wavelength, adapted from a figure by Spergel et al. (2013). Results are shown for LSST, Euclid (Wide), WFIRST (HLS) and CASTOR. For CASTOR, two possible surveys are shown: (1) a 6 100 deg^2 survey in the northern hemisphere (a region that is unaccessible to LSST) covering the northern Euclid-Wide footprint to a depth of $u' = 27.1$; and (2) a deeper ($u' = 27.6$) survey covering the full 2 213 deg^2 WFIRST-HLS footprint in the south. The labels under each filter indicate the image quality (i.e., EE50 radius) for each survey. (Right) Comparison of g-band images for a low-mass galaxy in the Virgo cluster. From top to bottom, these panels show an actual image from the SDSS, and simulated images from LSST and CASTOR. The point-source depth (5σ) of the LSST and CASTOR images is $g \simeq 27.2$ AB mag, which is ≈ 0.3 mag brighter than the final (10-year) depth of LSST. CASTOR would be capable of reaching a 5σ point-source depth of g $\simeq 27.8$ AB mag in a 45-min exposure.

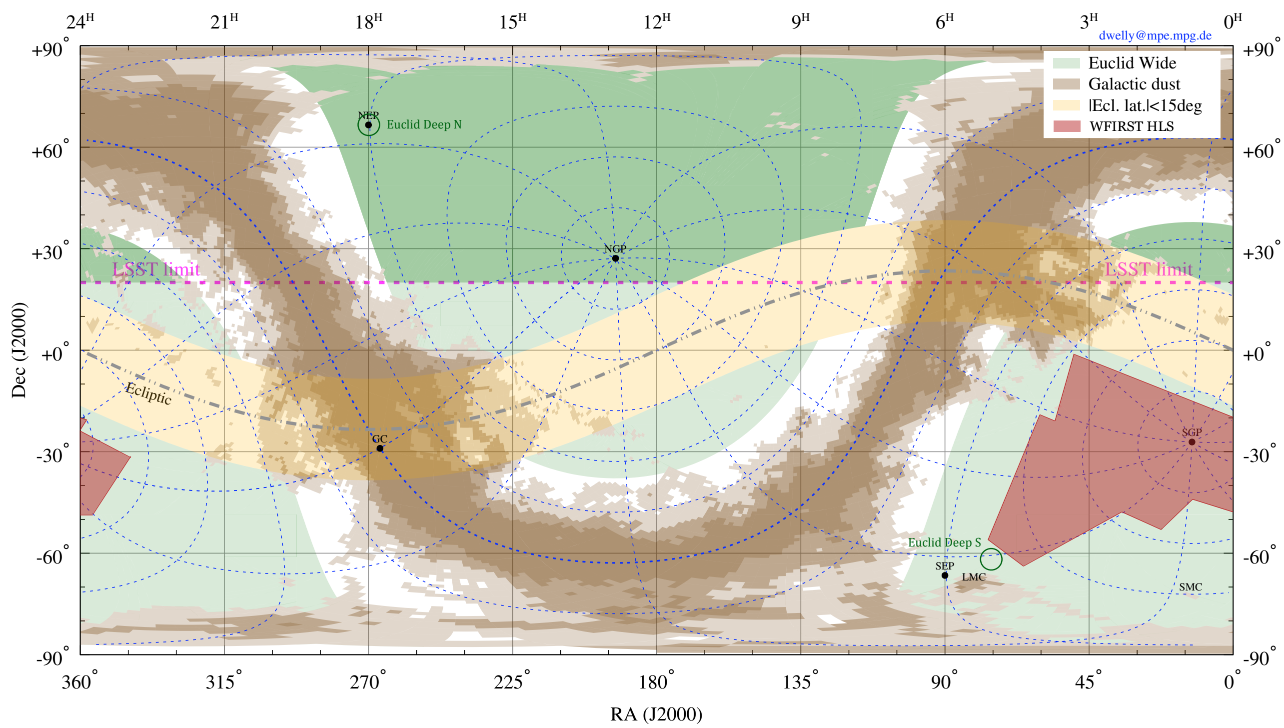

FIG. 3.— Wide-field space IR imaging surveys planned for the coming decade. Two possible CASTOR survey regions are indicated: (1) the 6 100 deg^2 Euclid Wide region that lies above $\delta = +20°$, the approximate northern limit of LSST (dark green); and (2) the WFIRST High Latitude Survey (HLS), whose 2 213 deg^2 footprint (as of January 2015) is shown in red (C. Hirata, private communication). *Figure credit Tom Dwelly (MPE).*