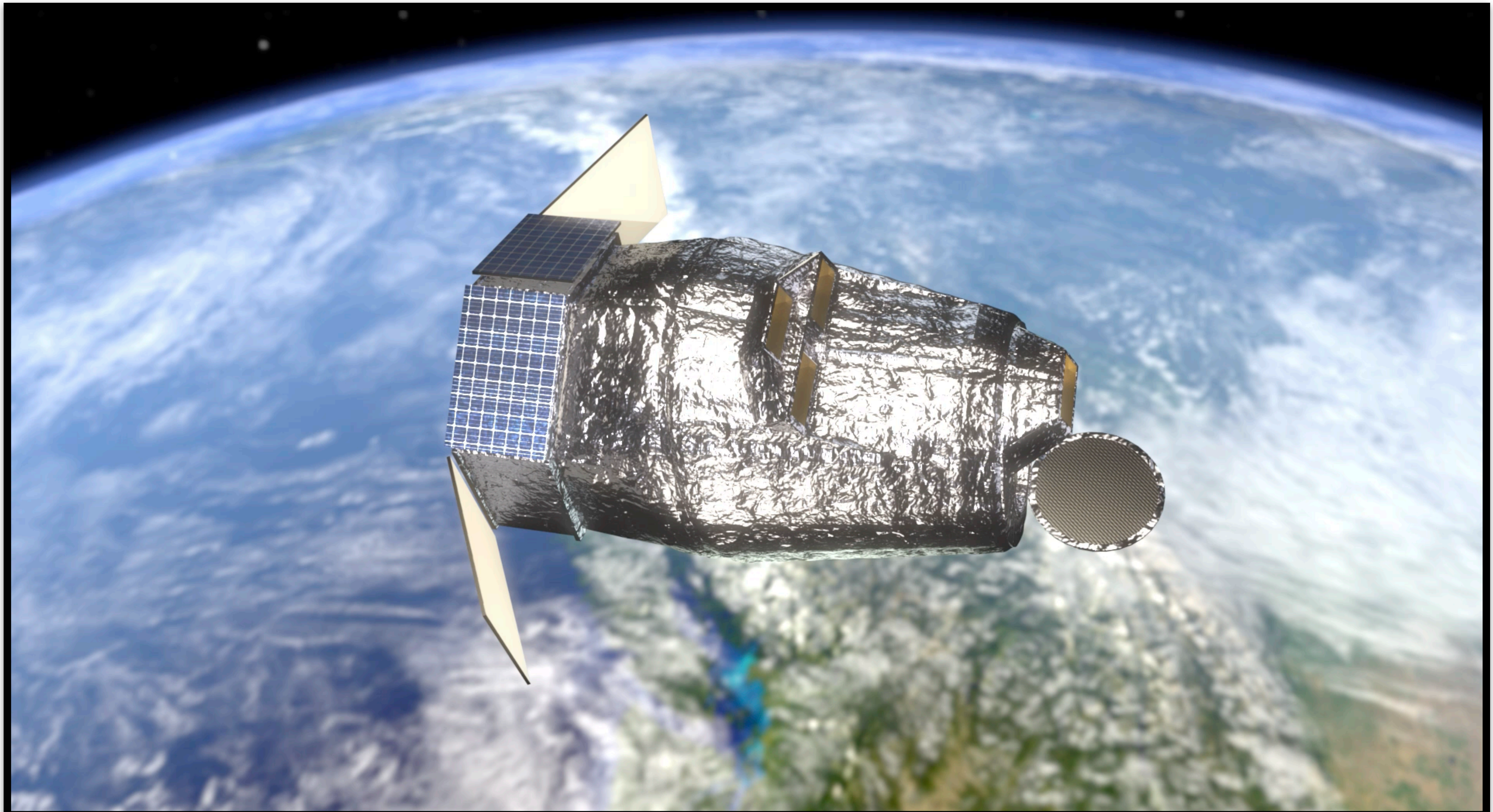
ULTRAVIOLET ASTRONOMY IN THE XXI CENTURY

e-Workshop 2020 – October 27-29

Update on CASTOR. I. Science

The Cosmological Advanced Survey Telescope for Optical and uv Research



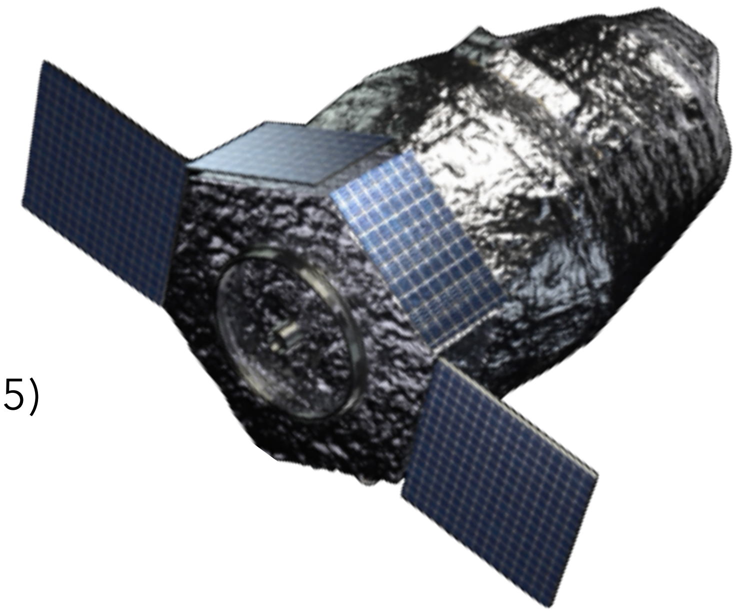
Patrick Côté (National Research Council of Canada, Victoria, BC)

5TH Workshop of the Network for Ultraviolet Astronomy, October 28, 2020

Talk Outline

The Cosmological Advanced Survey Telescope for Optical and uv Research

1. Development History
2. The Mission in Context
3. Science Capabilities and Programs
4. Technical Design
    - see talk by A. Scott (Thursday, 17:00)
    - see poster by J. Pazder and S. Sriram
    - see also INSIST talk by A. Subramaniam (Wed., 16:45)
5. Status and Future Work



CASTOR Development History

The Cosmological Advanced Survey Telescope for Optical and uv Research

- **2010-2011: 2010 Long Range Plan for Canadian Astronomy**. Highest priority in space astronomy is:

  - *"…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**)."*

  - **2011-2012:** CSA study "Canadian Space Telescope mission (**CASTOR**) Concept Study".
  - **2013-2015:** CSA study "Focal Plane Array Technologies for Astronomy".
  - **2015-2016:** CSA study "Single Photon Counting Large Format Detectors with Enhanced UV Response for Space Astronomy".
  - **2016: Mid Term Review of the Long Range Plan for Canadian Astronomy**
  - **2016-2017:** CSA Study: "Optical Design, Coatings, Filters, Dichroics".
  - **2018-2019:** CSA Study: "Science Maturation Study for CASTOR" with active participation of colleagues in India, JPL and the UK.

- **2020: 2020 Long Range Plan for Canadian Astronomy**. Highest priority in space astronomy is:

  - *"Our highest recommendation at the very large investments scale is for **CASTOR**, an exciting mission with a broad and compelling science case, and which would be Canada's first marquee space astronomy mission."*

  - **2020-2022:** CSA Study: "Wide-Field Astronomical Imaging in UV/Optical – Critical Technologies"

CASTOR Mission Specifications

The Cosmological Advanced Survey Telescope for Optical and uv Research

Primary aperture	1m off-axis, un-obscured, light-weighted Zerodur
Lifetime	5 years minimum, with possible extended lifetime.
Orbit	Low-earth, sun-synchronous, polar terminator, Dawn-Dusk orbit (circular, ~800 km, 98 degrees inclination)
Operational modes	(1) wide field imaging in three channels simultaneously. (2) slit-less spectroscopy in UV and u channels, simultaneously (full field). (3) multi-slit, medium resolution UV spectroscopy in parallel field.
	wide-field imaging
Imaging field of view	0.44° x 0.56° = 0.25 deg²
Image quality	FWHM = 0.15" in all channels
Baseline detector	SRI 8kx10k detectors with 10 um pixels (where 0.1" = 10 um). 2x2 arrays per channel, 12 in total.
Photometric channels	Two pass-band combinations under consideration 1. UV (150-300 nm) 2. u (300-400 nm) 3. g (400-550 nm) | 1. UV-Dark (135-260 nm) 2. u-Wide (260-400 nm) 3. g (400-550 nm)
Spacecraft orientation	Telescope is always pointed > 90 deg away from the sun. Long duration, continuous observing fields pointed in the anti-sun direction.
Data volumes	~200 GB/day with 10-min exposures in legacy survey mode
Downlink	High-speed optical downlink (~10 Gbps)
	Slit-less spectroscopy in UV and u imaging channels (single grism option)
Spectroscopic field	0.44° x 0.56° = 0.25 deg² [full imaging field of view]
Spectroscopic channels	1. UV (150-300 nm) 2. u (300-400 nm)
Resolving power	1. R~300 in UV channel, Δλ over 2 px, 1 px = 10 μm 2. R~420 in u channel, Δλ over 2 px, 1 px = 10 μm
Point Spread Function (PSF)	FWHM < 0.3" in both channels
	Multi-slit, UV spectroscopy in parallel field
Spectroscopic field	207" x 117", offset by ~3'-4' from the edge of the imaging field.
Spectroscopic channels	UV (150-300 nm) at R=1000; or UV (180-300 nm) at R=2000
DMD	TI 4K Ultra-HD DLP660TE DMD with 5.4 um pixels (3840 x 2160)
Spectrograph detector	SRI MkxNk detector with 10 um pixels (where 0.1" = 10 um)
Spectral dispersion	14 nm/mm at R=1000 with a 0.2" slit; or 7 nm/mm at R=2000 with a 0.2" slit
PSF in spatial direction	<0.30"
Spectral multiplexing	~600 maximum (i.e., 2 pixels height per spectrum, with 2 pixel gap between spectra)

Wide-Field Imaging:

- Wide-field, high-resolution imaging in three channels (UV, u, g) simultaneously.
- multiple science goals to be addressed through a primary science survey. Nominal 5-yr lifetime.
- other goals to be addressed in secondary surveys, and/or Guest Observer (GO) programs.

Precision Photometry:

- Photometric monitoring (10 ppm) in the UV-, u- and g-bands three CMOS detectors with transmissive diffuser plates.

Spectroscopy (costed add-ons)

1. Wide-field slit-less mode

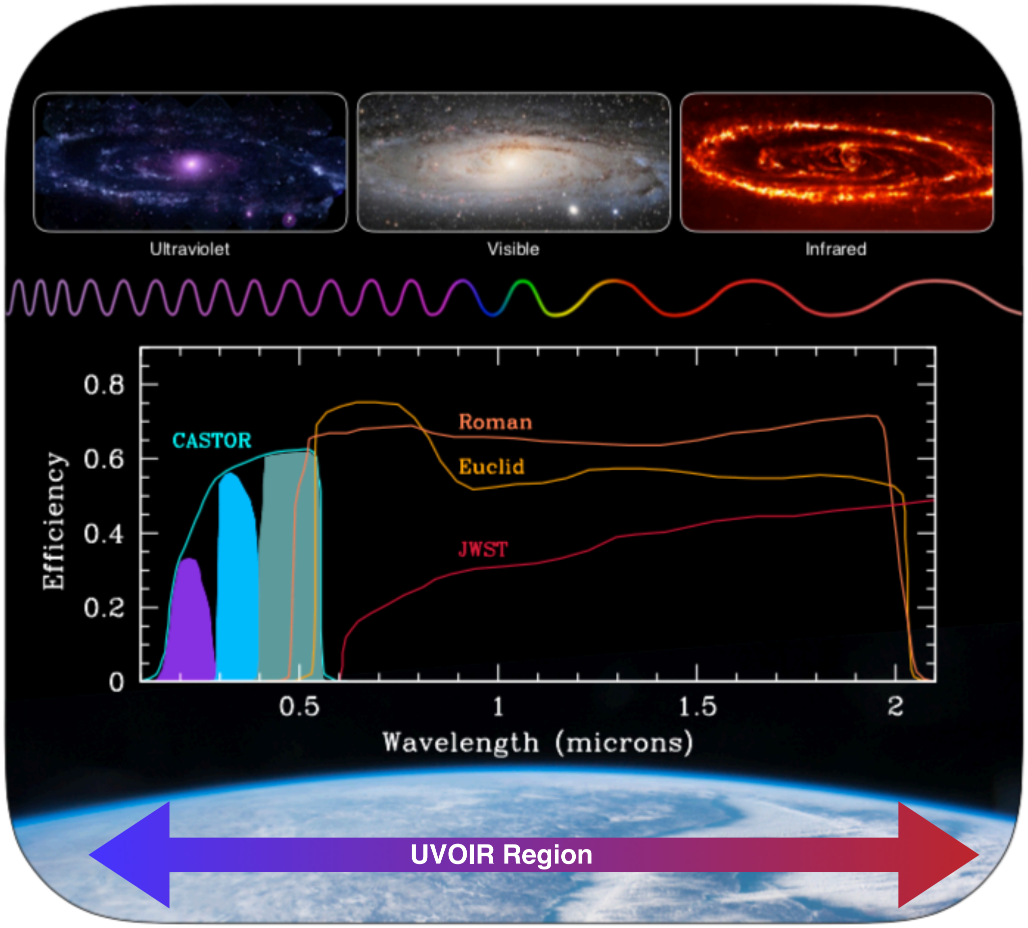
- full spatial coverage in UV and u, simultaneously.
- R ≈ 300 (UV), 420 (u)

2. Multi-slit, UV mode:

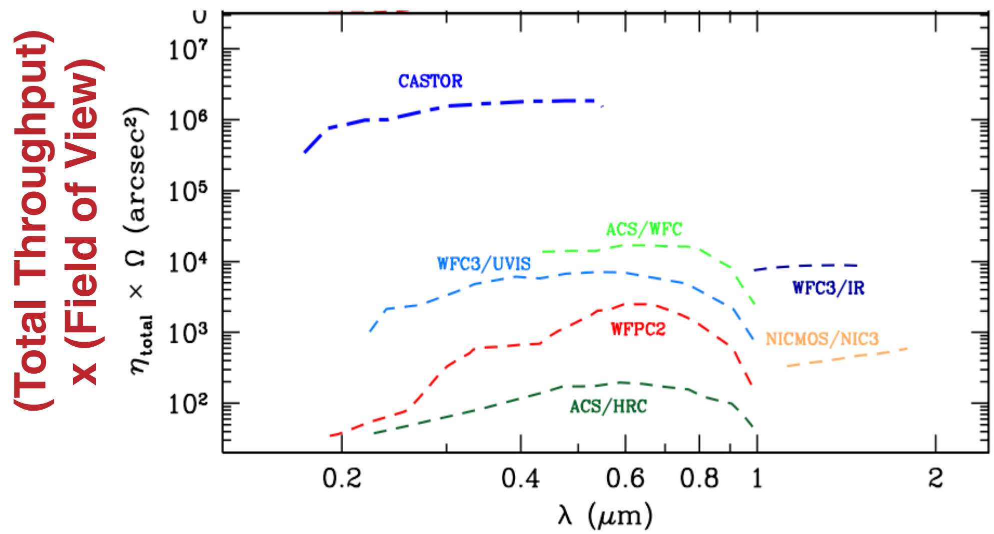
- parallel field in UV (150-300 nm) only. FoV = 207″x117″
- R ≈ 1000 - 2000.

CASTOR Strategic Capabilities

The Cosmological Advanced Survey Telescope for Optical and uv Research



CASTOR vs. Hubble: Discovery Efficiencies Compared



Scientific Capabilities:

- Wide-field (~0.25 deg², 3x), high-resolution (~0.15”) imaging at UV/blue optical wavelengths.
- Low- and medium-resolution spectroscopy in the UV region.
- Precision, high-speed photometry in the UV/blue region.

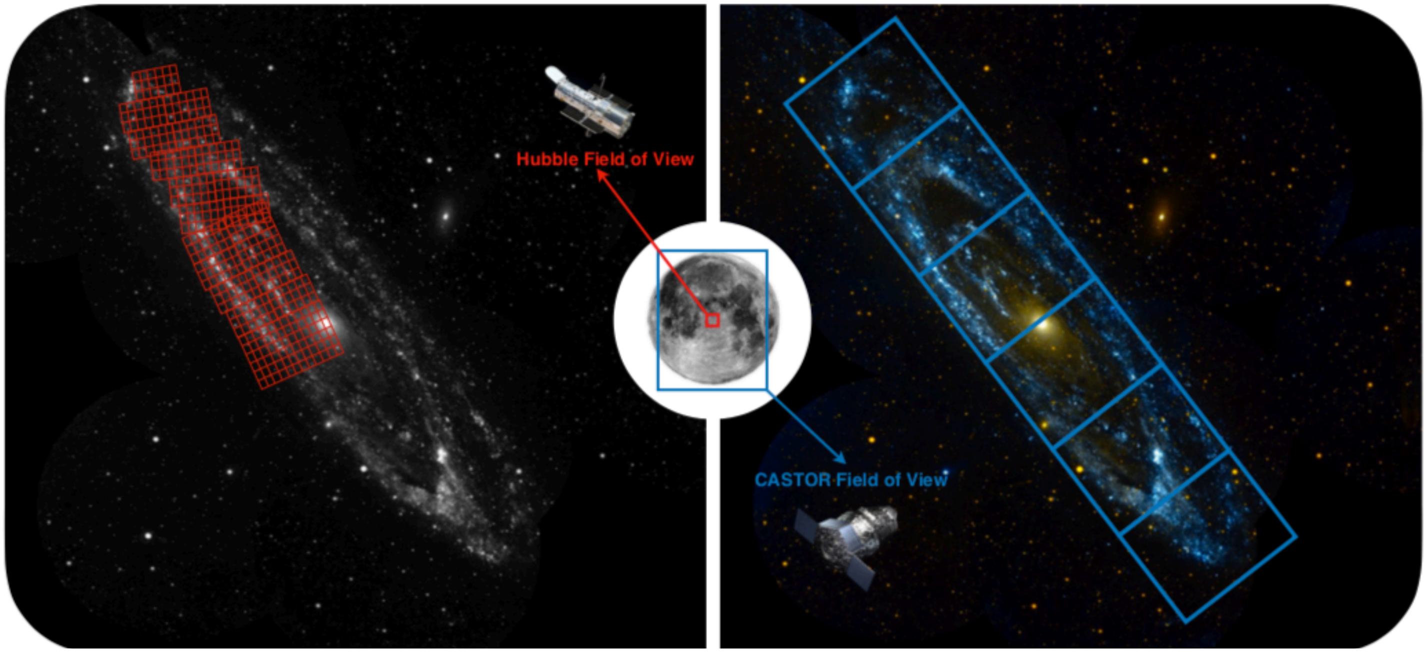
Uniqueness:

- State-of-the-art image quality at < 550 nm. **FWHM ≈ 5x better than LSST**.
- **Access to the UV/blue** in the post-Hubble era (imaging + spectroscopy).
- **FoV exceeding Hubble by two orders of magnitude**.

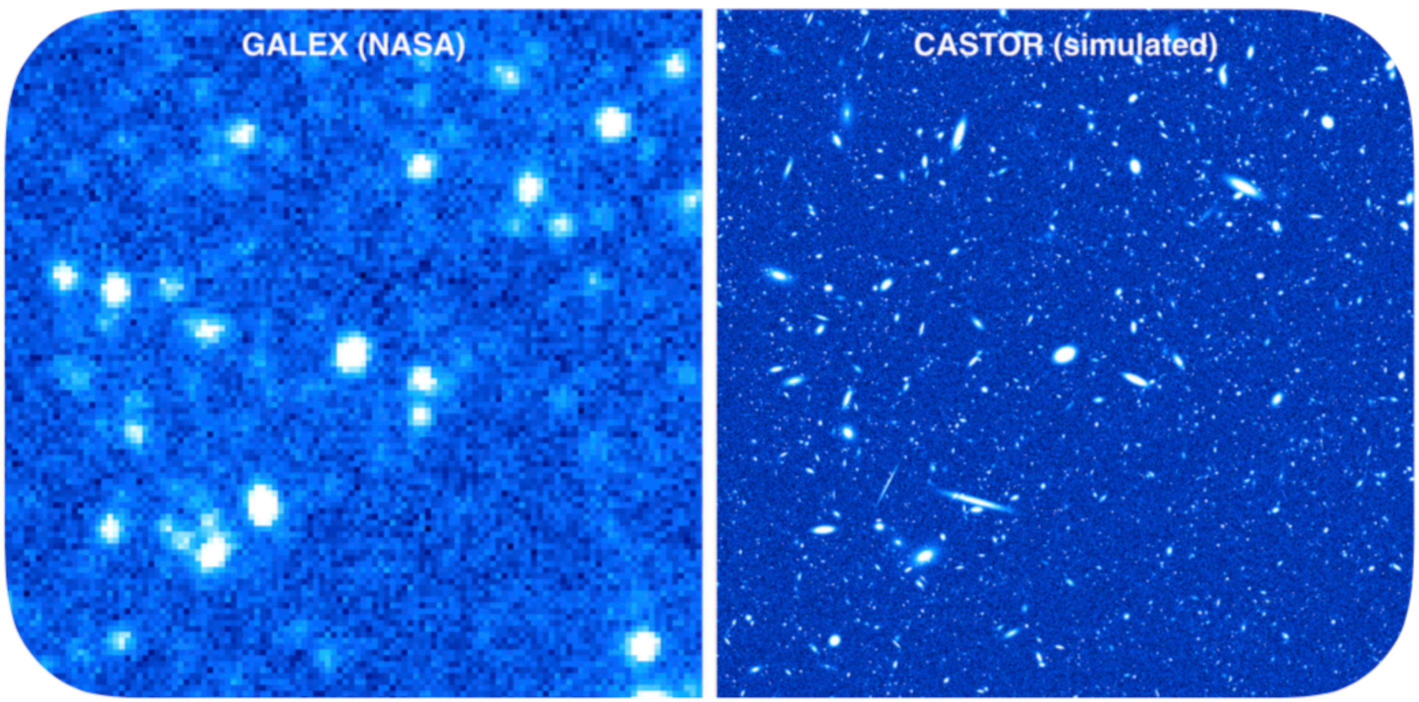
CASTOR: Wide-Field, High-Resolution Imaging

The Cosmological Advanced Survey Telescope for Optical and uv Research

PHAT/HST



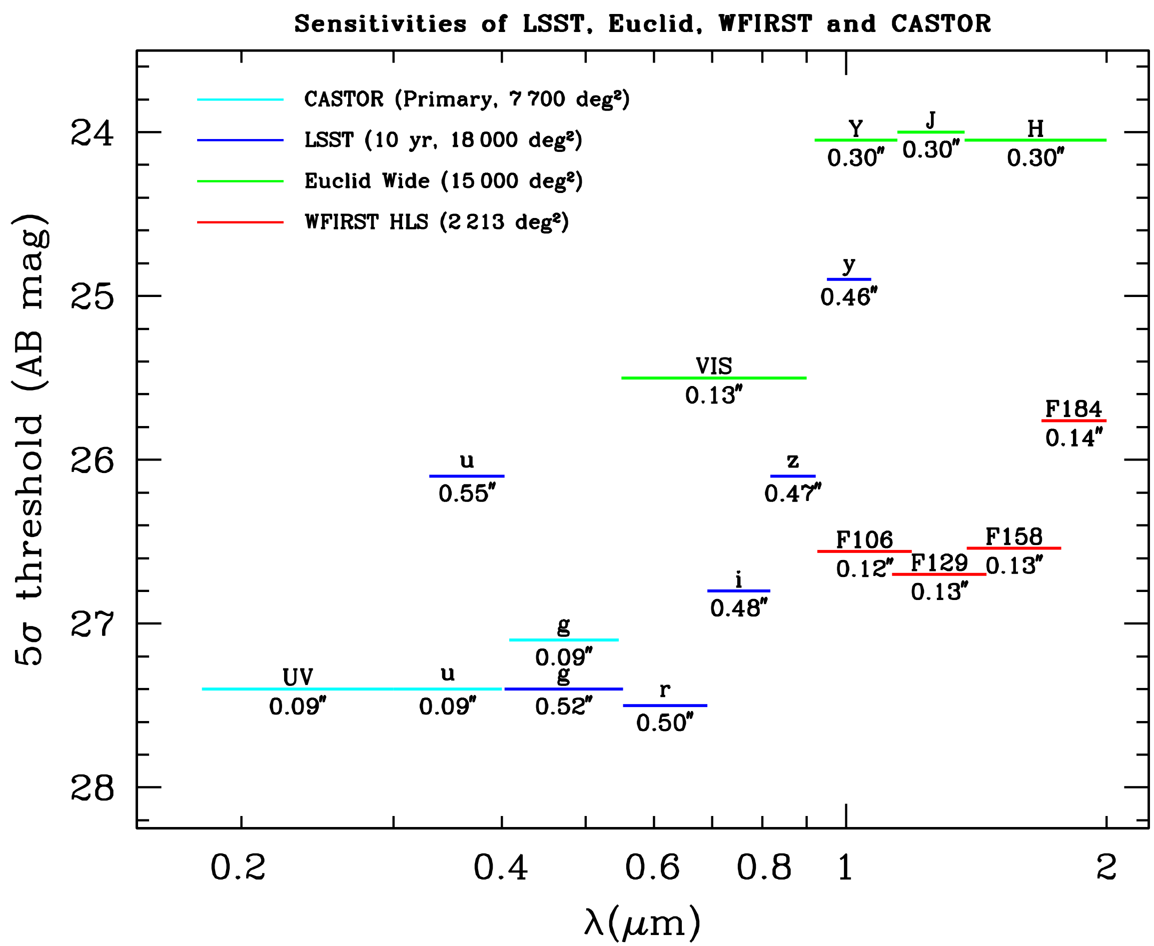
COSMOS/GALEX



The CASTOR Science Plan

The Cosmological Advanced Survey Telescope for Optical and uv Research

- **Primary survey**: mapping of the overlap region between LSST-WFD and Euclid-Wide, including the Roman HSL (1.8 years)
- **Science operations**: legacy surveys (~70%) and GO programs (~30%).
- More than a dozen candidate legacy programs identified by science working groups. Immense potential for an extended lifetime.



Science Working Groups:

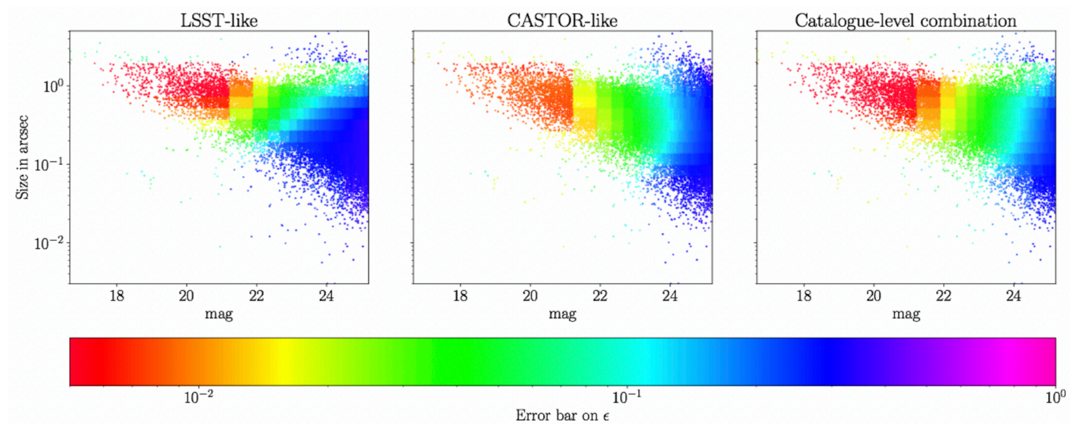
1. ***Cosmology, Dark Energy, Dark Matter***
2. ***Time Domain Astrophysics***
3. Galaxies and the Cosmic Star Formation
4. ***AGN and Galactic Nuclei***
5. Near-Field Cosmology
6. Stellar Astrophysics
7. ***Extrasolar Planets***
8. *Small Bodies in the Solar System*

Science. I. Cosmology and Dark Energy

The Cosmological Advanced Survey Telescope for Optical and uv Research

- Stage IV DE experiments (Rubin, Euclid, Roman) have been designed to combine **wide-field**, **high spatial resolution**, **broad wavelength coverage**, and **high cadence** to explore the nature of DE. No single experiment satisfies all criteria.

1. **Photometric redshifts**
   - short-wavelength data for improved photo-zs.
   - simulations show best results for CASTOR + Roman + Rubin.
2. **Object detection and blending**
   - to address the fundamental issue of blending, colour mixing and object detection.
3. **Shape measurements**
   - a unique wavelength region to shed light on possible shape residual systematics as a function of wavelength.



- CASTOR Science Report

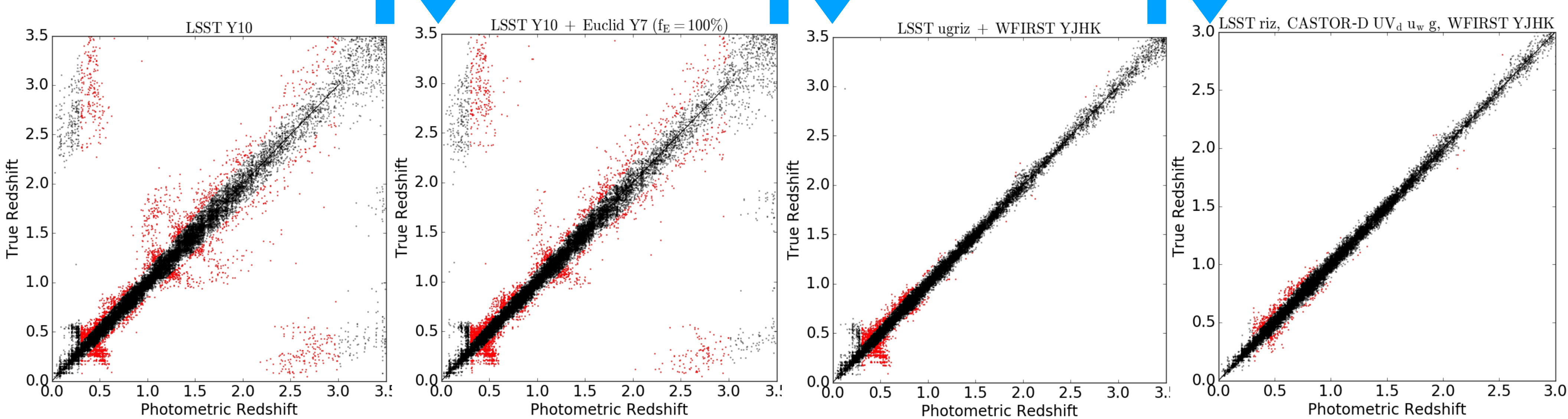
- Graham et al. (2020, ApJ).

Rubin alone (full depth)

add shallow NIR (Euclid)

add deep NIR (Roman)

add UV + deeper u,g (CASTOR)

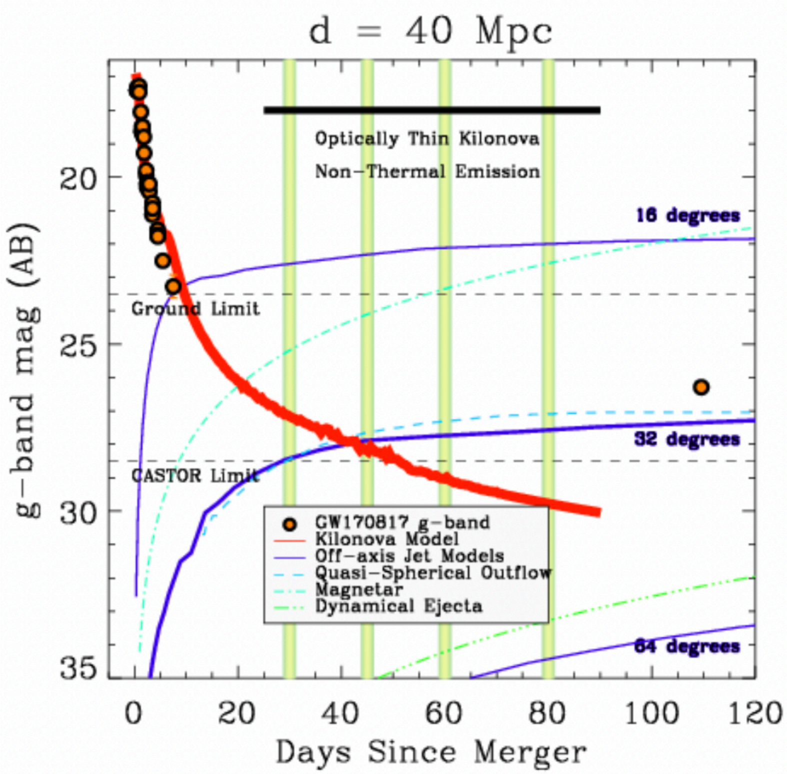


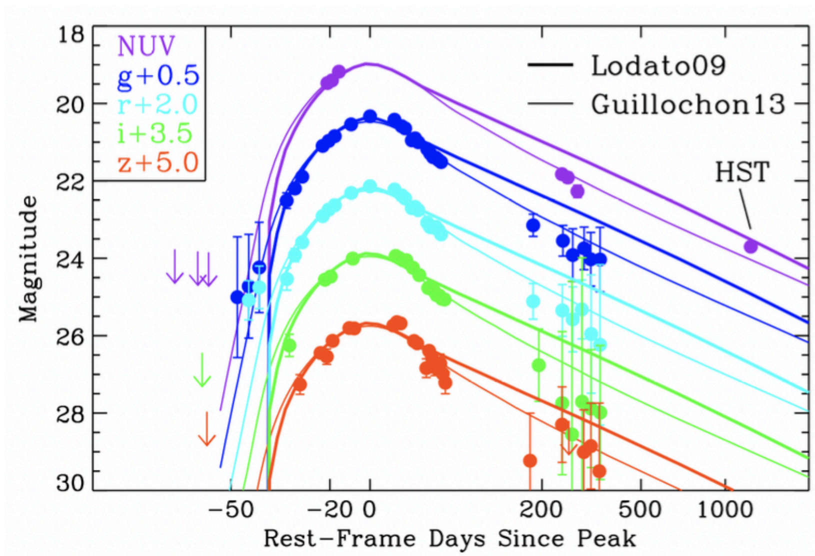
Science. II. Time Domain Astrophysics

The Cosmological Advanced Survey Telescope for Optical and uv Research

1. **CASTOR MMA: Target of Opportunity Observations for Multi-Messenger Events**
   - Phase 1: tiling the GW/neutrino localization regions for select MM events.
   - Phase 2: high-cadence monitoring of identified UV counterparts and characterization of host environments of known MM events.
   - multi-band photometry and spectroscopy.

2. **CASTOR Cadence: A Wide-Field UV Time Domain Survey**
   - Monitoring of two 10 deg^2 LSST deep drilling fields.
   - Daily cadence, with a six month baseline, to a depth of 24.5 mag.
   - Would probe >5x the volume of any UV survey to date, for 3x as long, with 2x the cadence using a fraction of CASTOR's time.
     - Progenitors of pre-explosion mass-loss of core-collapse supernovae.
     - Progenitors and explosion mechanism of thermonuclear supernovae.
     - Nature of peculiar astronomical transients.
     - Growth of quiescent supermassive black holes from tidal disruption events.



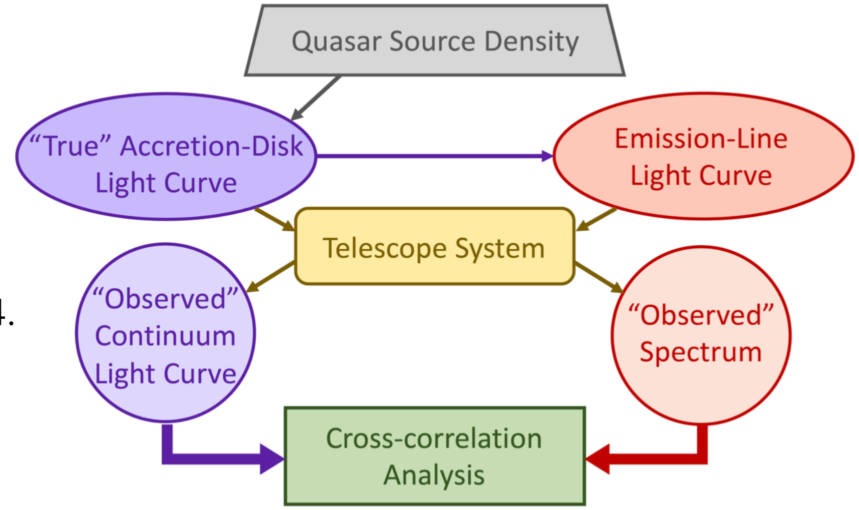


Science. IV. AGN and Supermassive Black Holes

The Cosmological Advanced Survey Telescope for Optical and uv Research

1. Active Galactic Nuclei Reverberation (AGN) Mapping Survey

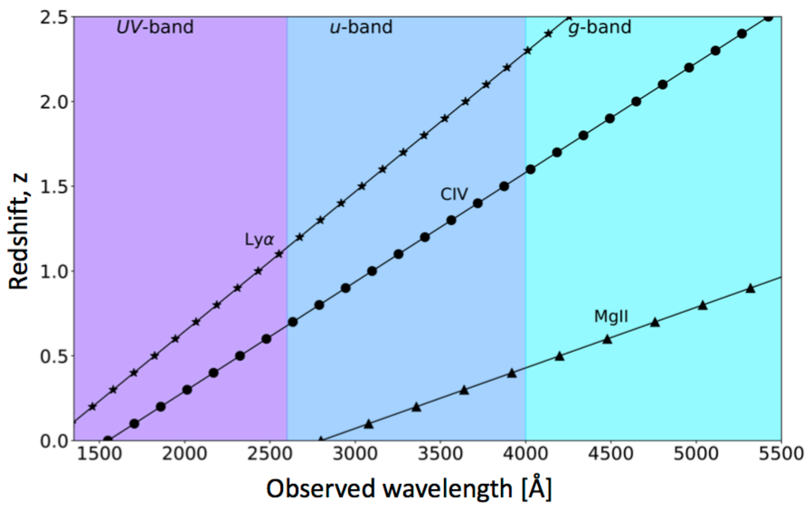
- How do supermassive black holes grow over cosmic time?
- For AGN, accretion disk power peaks in the ultraviolet region.
- Reverberation Mapping (RM) of 12.5 deg² (>1000 AGNs) for 6 months.
- Imaging (21 days) and slit-less spectroscopy (130 days), to $m_{UV} \sim 24$.
- Time lags ➜ black hole masses for 10x more AGN than all previous studies in a wider redshift space spanned by CASTOR.

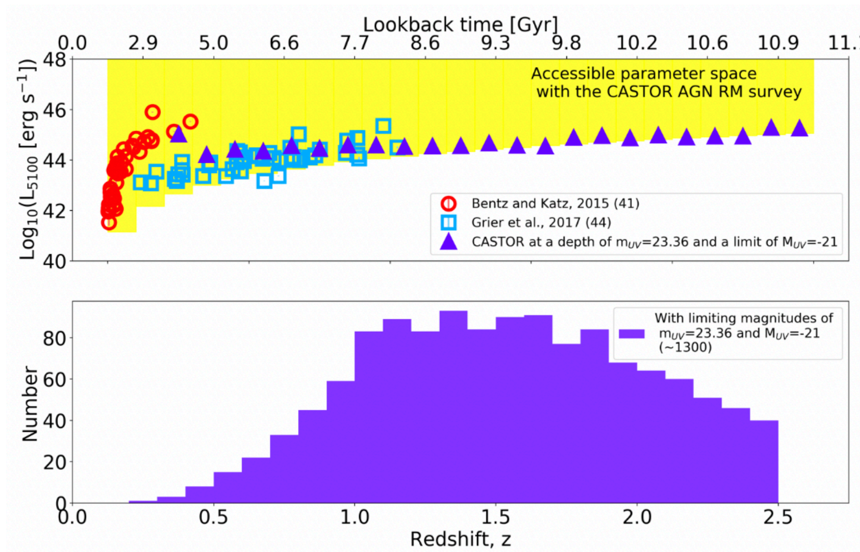


- CASTOR Science Report

2. AGN Studies with the CASTOR Primary Survey

- Identify new AGN from UV/blue-optical colours.
- Push far down the UV luminosity function.
- Studies of AGN host galaxies in the UV: AGN activity vs. host star formation.





Science. VII. Extra-Solar Planets

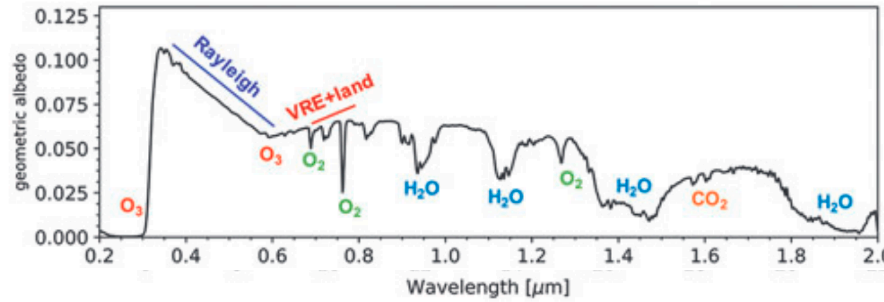
The Cosmological Advanced Survey Telescope for Optical and uv Research

1. **Transit Colour Survey**
   - transit-depths measured to ~10 ppm on 3 hr timescales in all passbands.
   - targets: 50 bright, transiting exoplanets.
   - scope: ~100 days over mission lifetime.
   - atmospheric opacities ➔ structure, composition, pressure and temperature.

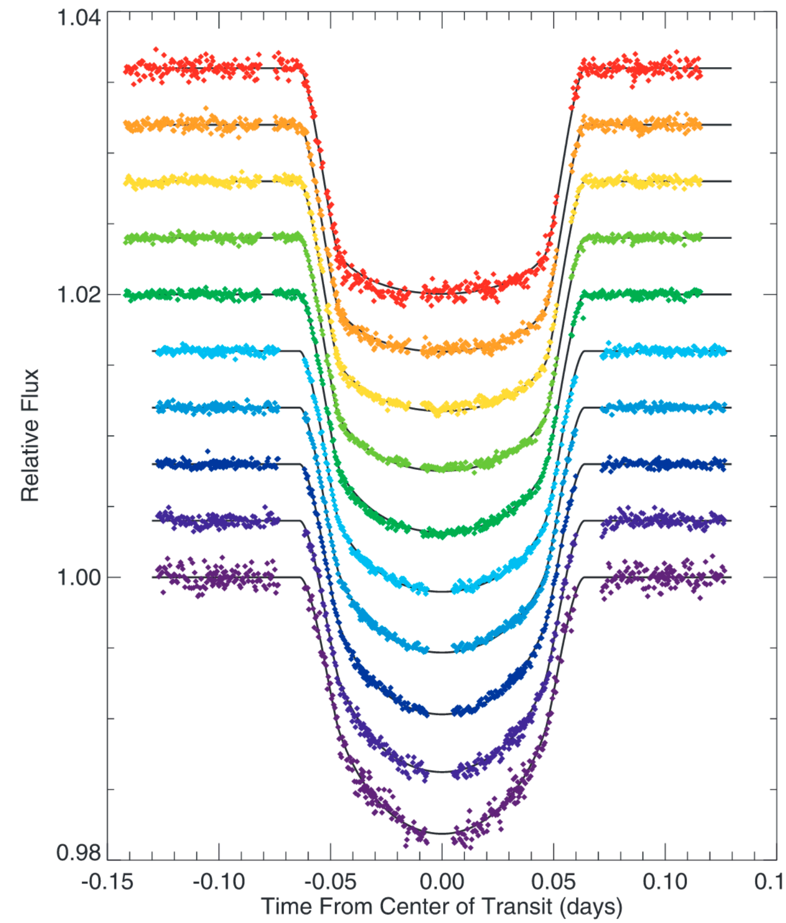
2. **Ultra-Precise Phase Curve Survey**
   - g~6 target with a hot-Neptune. 3-hr CDPP to 1 ppm.
   - UV phase curve measurements over ~80 days (continuous).
   - scattering properties of atmosphere ➔ particle sizes and compositions.

3. **Kepler Eta-Earth Project**
   - Earth-sized planets in the habitable zone of Sun-like stars.
   - targets: ten g~14 stars with low-S/B transits. Transit depths 5-200 ppm.
   - program: 30 days per year over mission lifetime.

4. **Exoplanets in Globular Clusters**
   - photometric monitoring of 1.5 million stars in Omega Cen.
   - sample: 50x that of Gilliland et al. (2000) and 10x that of Kepler.
   - detect: 15% - 65% of transits for planets with 0.6 - 0.8 $R_{Jupiter}$.



- Schwieterman et al. (2018, AsBio, 18, 663).



- Knutson et al. (2007, ApJ, 655, 564).

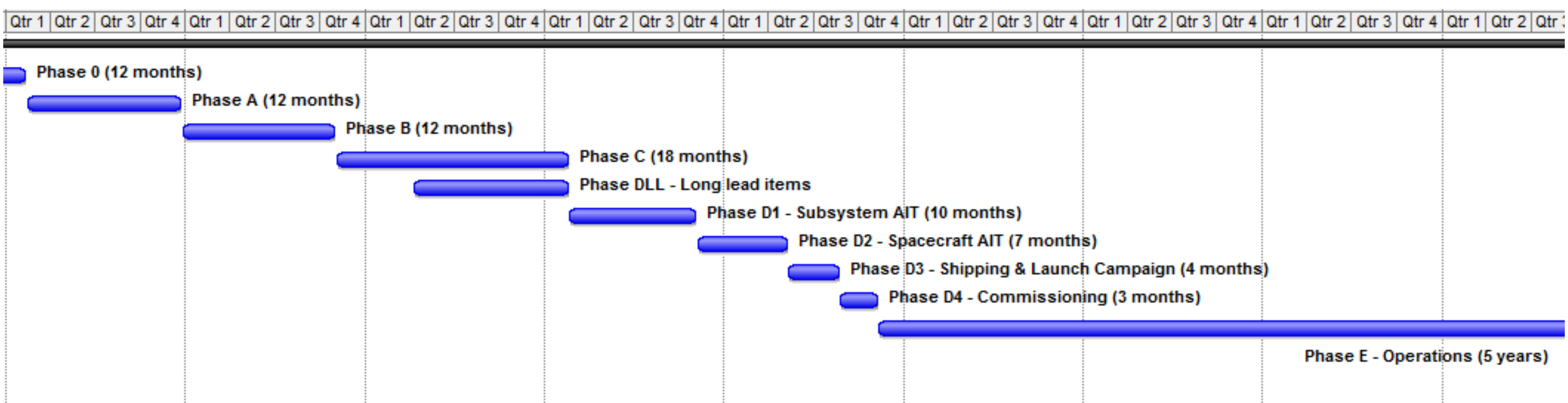
Status and Future Work

- Canadian community is now actively engaged in securing government approval. Partnership discussions (India/ INSIST, JPL, UK) are ongoing.

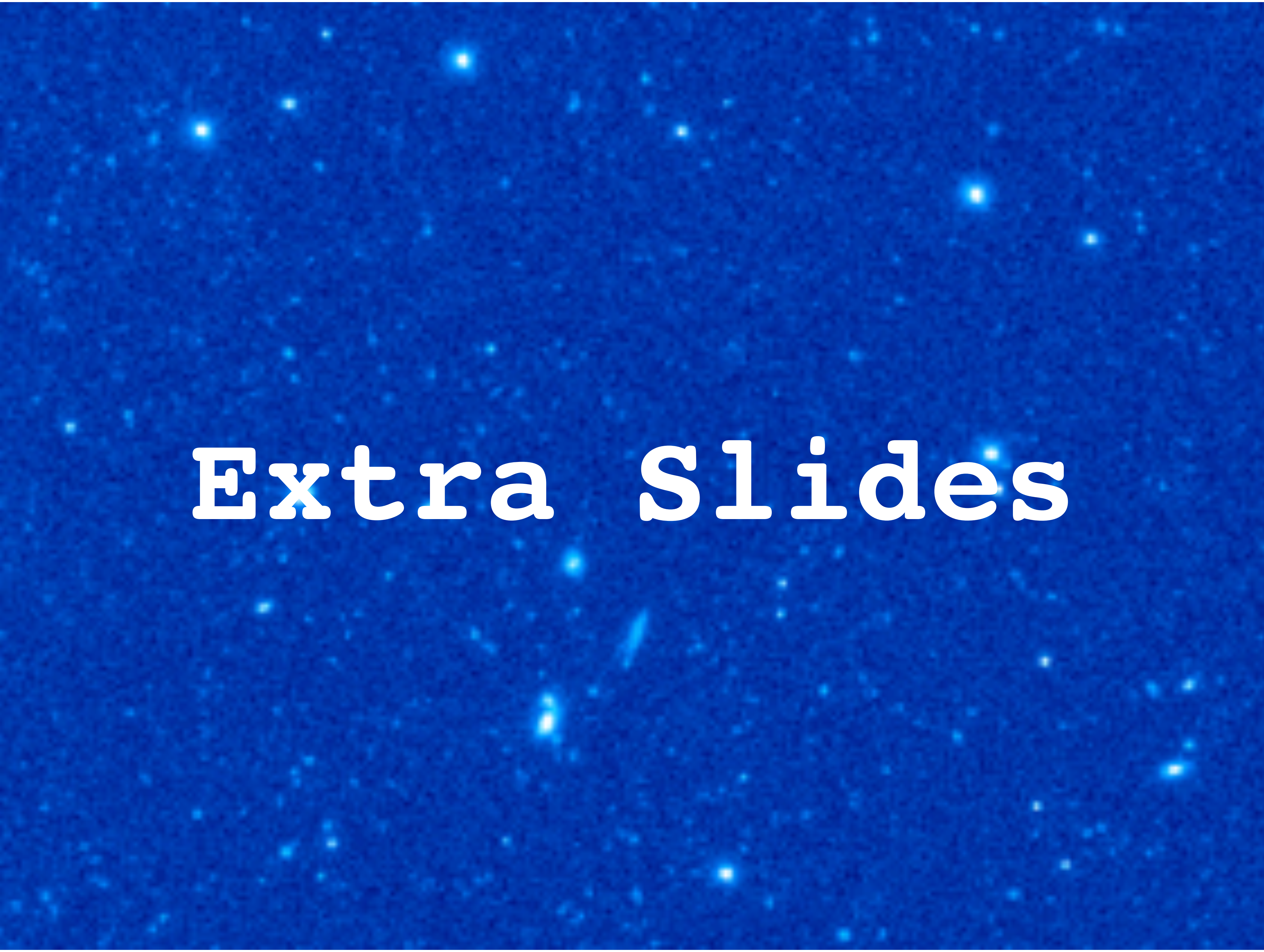
- An imminent CSA study ("Wide-Field Astronomical Imaging in UV/Optical – Critical Technologies") will focus on technology development for **five priority enabling technologies:**

    1. Telescope optical and mechanical design.
    2. Focal plane array.
    3. Fine Steering Mirror.
    4. DMD Multi-Object Spectrograph for the UV.
    5. Precision Photometer.

- A Phase 0 study (with an emphasis on the science mission) is expected in early 2021. Launch goal is 2027.



Questions?


Extra Slides

Science. III. Galaxies and Cosmic Star Formation

The Cosmological Advanced Survey Telescope for Optical and uv Research

1. Evolution of the Cosmic Star Formation Rate (SFR)

- measurement of the cosmic SFR from rest-frame UV fluxes out to z=1.5.
- UV data from CASTOR combined with OIR data from LSST, Euclid and WFIRST.

2. Ultra-Massive Galaxies (UMGs)

- a survey of UMGs ($\log M_*/M_\odot > 11.5$) based on their UVOIR emission.
- within the 2200 deg^2 region covered by CASTOR, LSST, Euclid and WFIRST, we expect 5600 and 8400 UMGs between $0.1 < z < 0.3$ and $0.4 < z < 0.6$.
- what is the nature of the UV upturn?

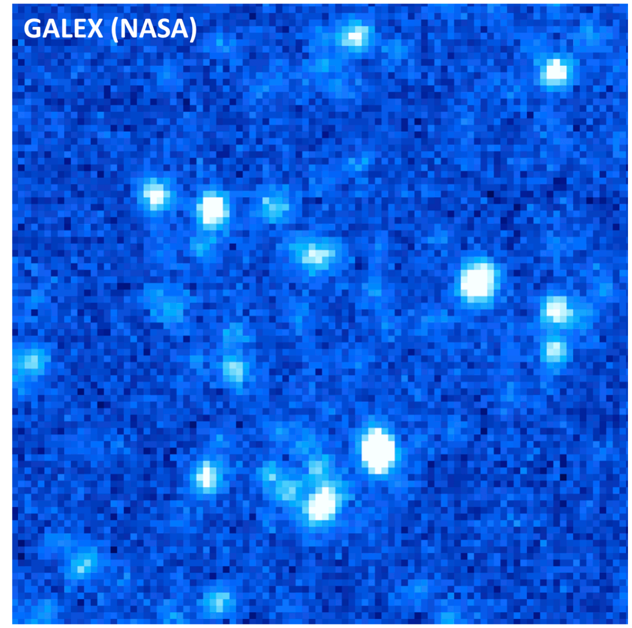
3. Galaxies at Cosmic Noon

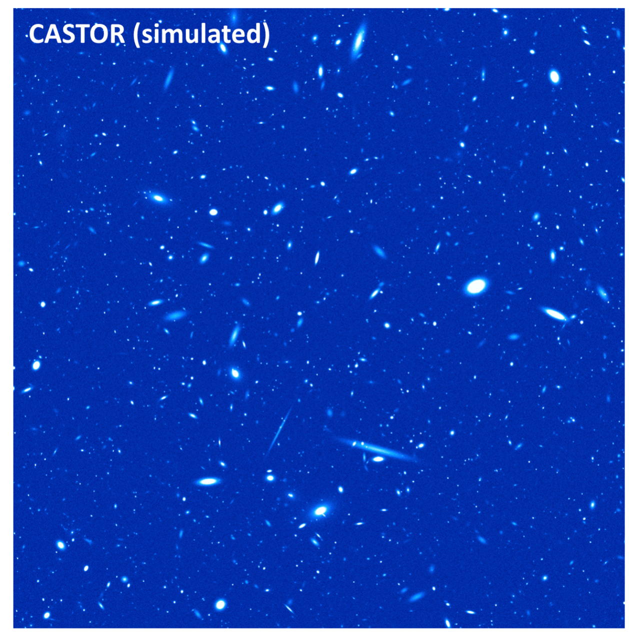
- unprecedented sample of z=2 galaxies that can be linked to their dark halo masses through clustering measurements.
- precise photometric redshifts at all redshifts will enable the mapping of large scale structure, and the environmental dependences of galaxy evolution.
- measurement of the Lyman continuum escape fraction from star forming galaxies and AGN at $z < 3$, including cosmic noon.

4. Spatially Resolved Star Formation Histories

- mapping of the SFR, dust distribution and stellar populations within galaxies at a resolution previously only achievable by HST, but with small samples.
- trace the growth of morphological components (disks, bars, bulges, etc) over cosmic time and across a range of environments.

COSMOS field





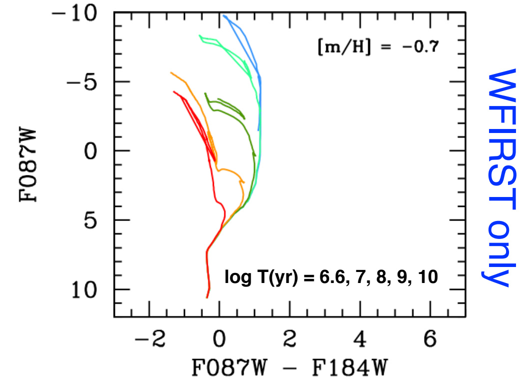
- courtesy Emily Pass & Michael Balogh

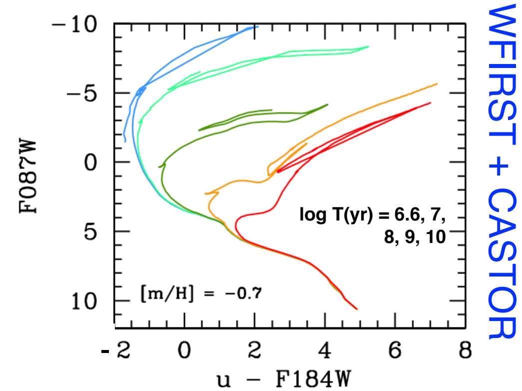
Science. V. Near Field Cosmology

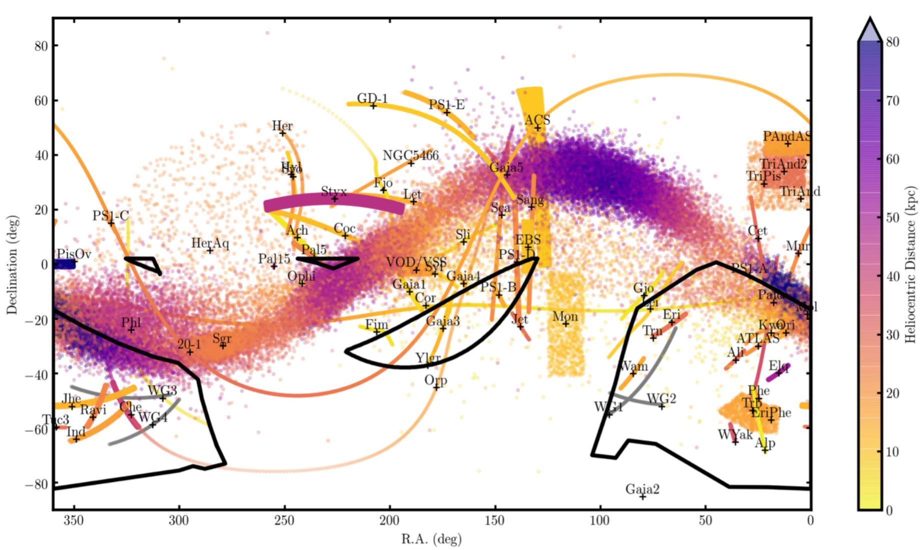
The Cosmological Advanced Survey Telescope for Optical and uv Research

1. **Tests of Cosmological Models on Sub-Galactic Scales**
   - Structure and stellar populations of Galactic satellites and stellar streams, including "missing satellites" predicted by **ΛCDM** models.
   - multi-epoch imaging for proper motion measurements and dynamics.

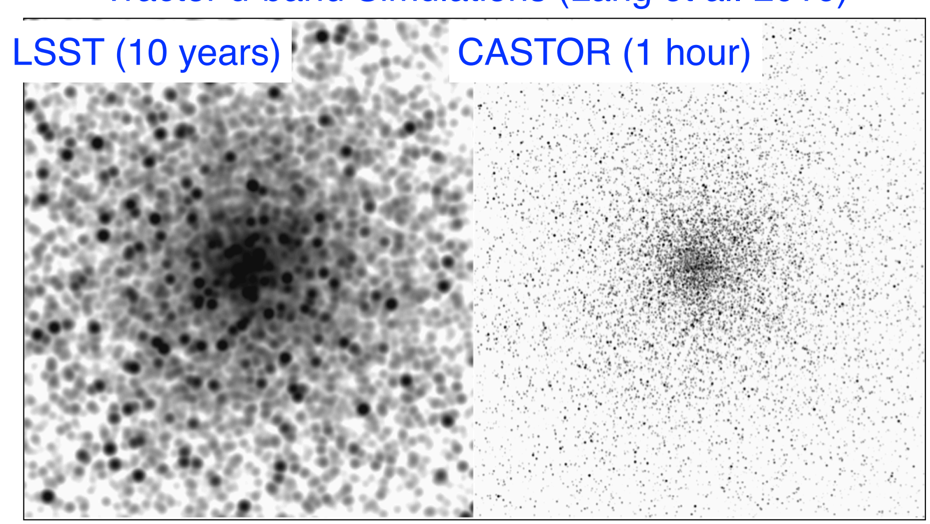
2. **The CASTOR Nearby Galaxies Survey**
   - How does the physics of star formation change as a function of density?
   - A (30 day) UV/u/g survey of 300 galaxies within ~20 Mpc to re-construct the star formation histories of galaxies in the Local Volume.
   - Resolution ~ 30x that of GALEX. Field of view ~80x that of HST.







Tractor u-band Simulations (Lang et al. 2016)



Science. VI. Stellar Astrophysics

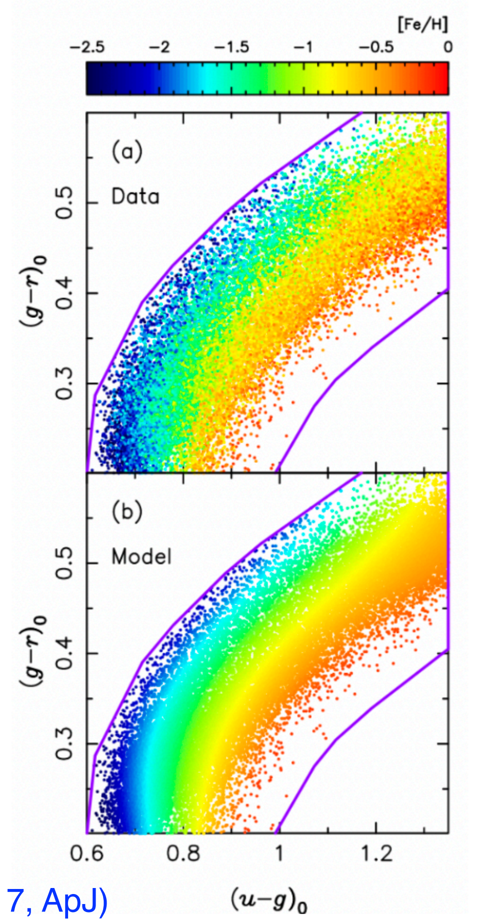
The Cosmological Advanced Survey Telescope for Optical and uv Research

1. **The Structure and Chemistry of the Galactic Halo**

- The three-dimensional metallicity distribution function for the Galactic halo.
- Reconstruction of the Galactic star formation history from white dwarfs.
- Identification of the the chemically pristine halo stars.
- Structure and shape of the Milky Way from Blue Horizontal branch stars.
- multiple populations and white dwarfs in star clusters; production of SN remnants and pulsar wind nebulae; variability in protostellar mass accretion rates.

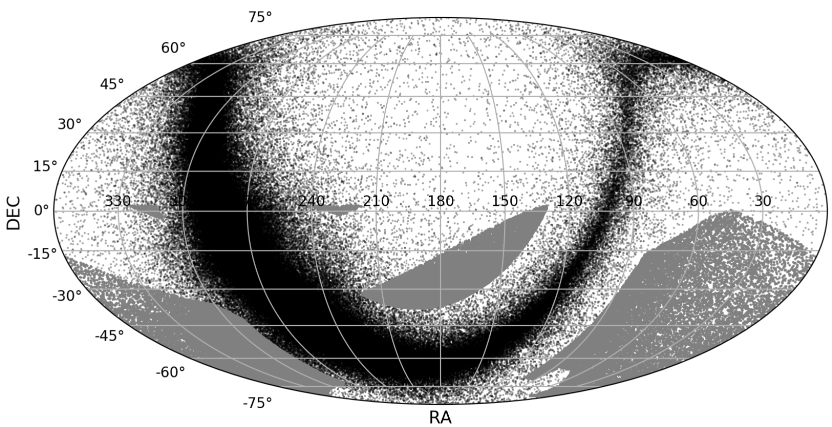
2. **The CASTOR Magellanic Clouds Survey**

- Deep UV/u/g imaging and UV/u spectroscopy for tests of stellar evolutionary models.
- Properties of the ISM across both galaxies.

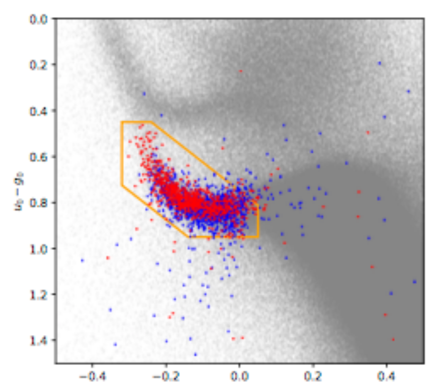


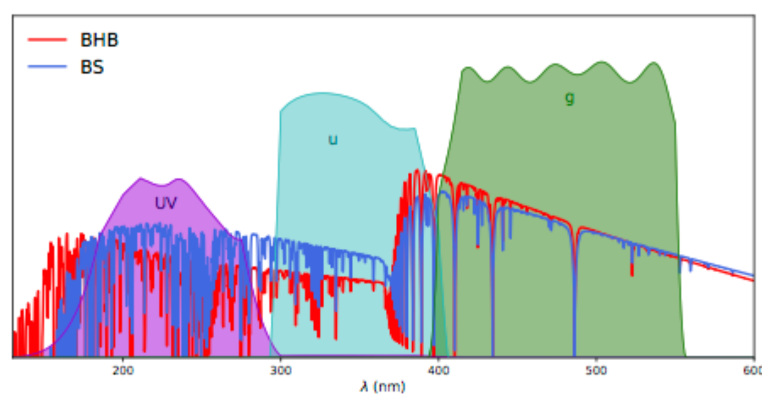
Ibata et al. (2017, ApJ)

simulated Galactic white dwarfs with the CASTOR primary survey shown.



- Fantin et al. (2020, ApJ)





- courtesy Guillaume Thomas

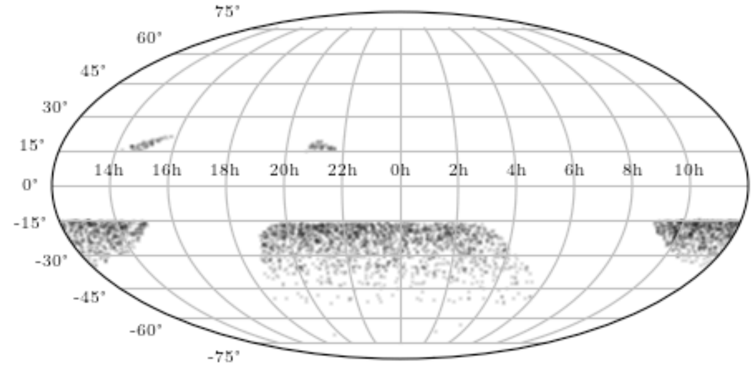
Science. VIII. Small Bodies in the Solar System

The Cosmological Advanced Survey Telescope for Optical and uv Research

1. **Physical Properties of Excited Trans Neptunian Objects**

- Simultaneous u/g and red-optical flux measurements for the 'excited' TNOs discovered by LSST that fall in the CASTOR primary survey.
- 2500 classical KBOs, 500 TNOs trapped in resonance with Neptune and over 700 TNOs on orbits that are actively scattering off Neptune.
- UVOIR photometry for taxonomy and mineralization; light-curve measurements for shape modelling; binarity detections for formation and evolution modelling.

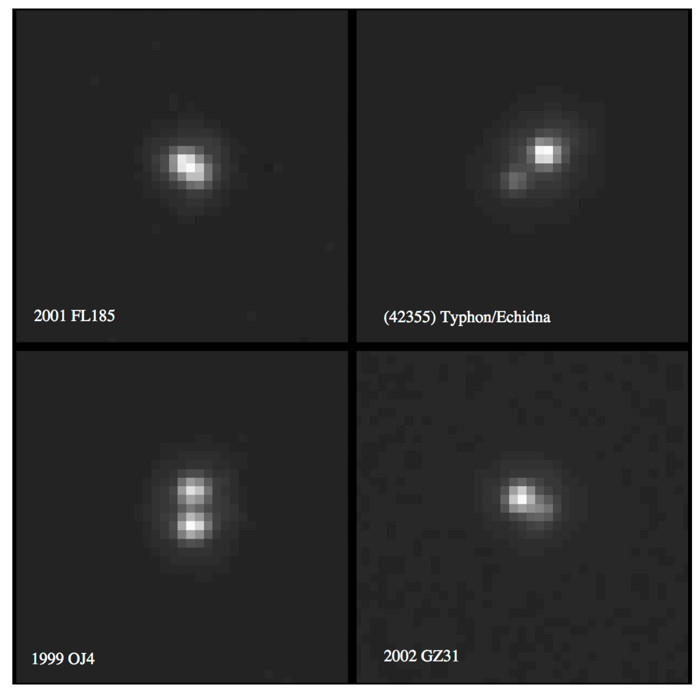
simulated TNOs detectable by LSST and measurable in the CASTOR primary survey



- CASTOR Science Report

2. **CBLS: The High-Resolution Kuiper Belt Binary Characterization Legacy Survey**

- Binarity is a key constraint on the nature of the planetesimal accretion process, and the dynamical environments in which planetesimals form.
- A combination of CASTOR primary survey data and pointed observations of Kuiper Belt Binaries (KBBs) discovered by LSST.
- Full characterization of orbits for ~600 KBBS (semi-major axes, eccentricities, inclinations and mass ratios), only possible with space-based observations.



- Noll et al. (2008, SSBN, 345).

3. **Solar System Legacy Survey**

- A deep survey of a ±0.5 deg strip centred on the ecliptic will provide UV and binarity sample for the cold-classical component of the Kuiper belt.
- Sample: a cold-classical sample similar to that of high-inclination members from primary sample.