Title: Canadian Initiatives in Wide Field Astrophysics: CASTOR and the Maunakea Spectroscopic Explorer

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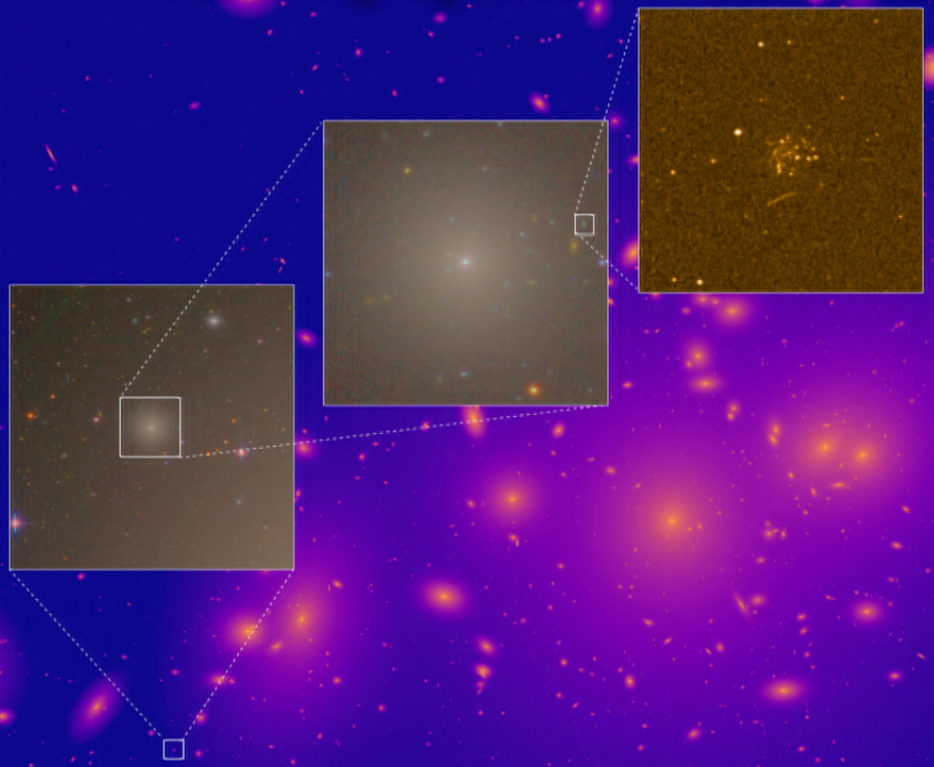
Abstract:

Canadian Initiatives in Wide-Field Astrophysics: CASTOR and MSE



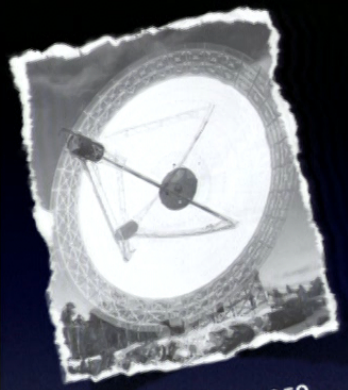
Patrick Côté (NRC Herzberg Astronomy & Astrophysics Research Centre)

PI-NRC Meeting, May 7-8, 2018

Canadian Initiatives in Wide-Field Astrophysics

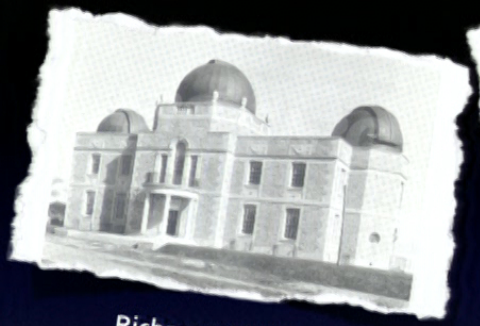
- NRC-Herzberg, national planning, and the "**Long Range Plan (LRP) for Canadian Astronomy**".
- International landscape in the 2020s.
- Canadian LRP initiatives in wide-field astrophysics.
- **C**osmological **A**dvanced **S**urvey **T**elescope for **O**ptical and ultraviolet **R**esearch (**CASTOR**)
  - Technology, Science and Programmatics
- **M**aunakea **S**pectroscopic **E**xplore (**MSE**):
  - Technology, Science and Programmatics

Evolving Research Facilities



Algonquin 1959

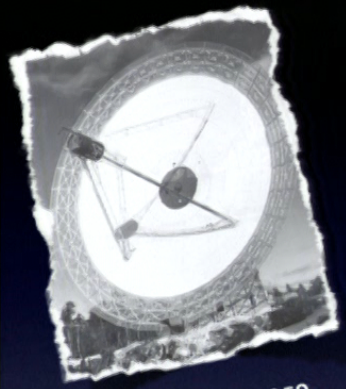
Victoria 1918



Richmond Hill 1935

Penticton 1960

Evolving Research Facilities



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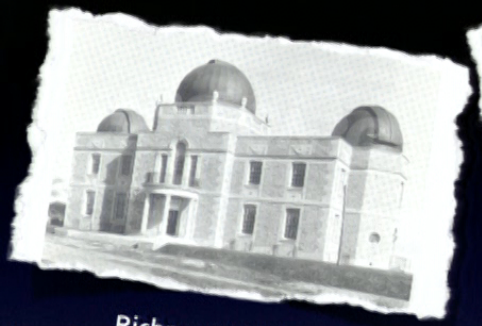

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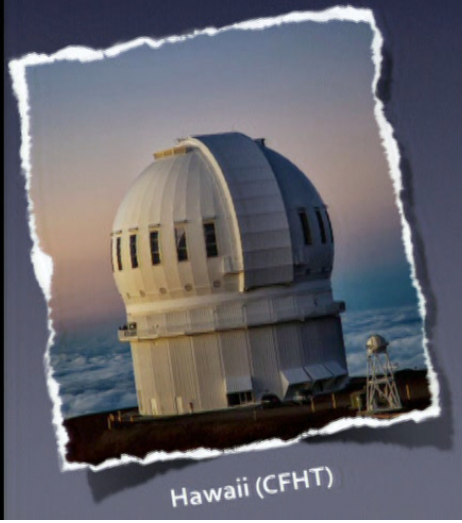


Hawaii (CFHT)

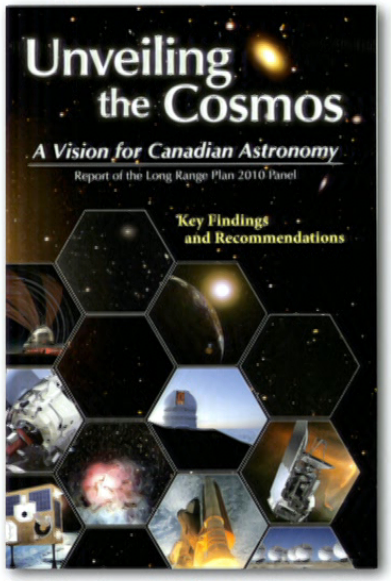
Chile (ALMA)

Hawaii (Gemini)

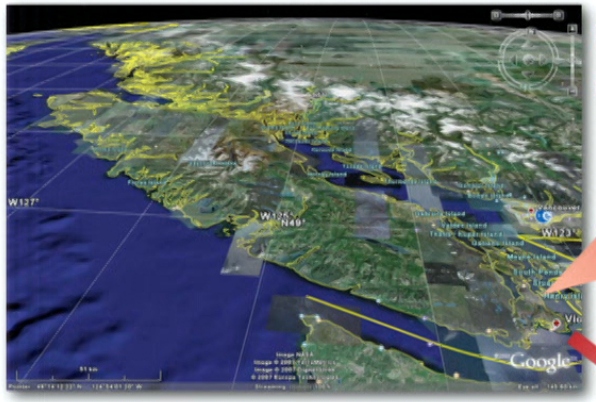
Long Range Plan (LRP) for Canadian Astronomy

- The Long Range Plan is a once-per-decade (2000, 2010, 2020) community planning exercise.
- It gives community recommendations on ground- and space-based telescopes.
- Community-wide reviews at the mid-points (e.g., 2005, 2015).

Long Range Plan (2010)



http://www.casca.ca/lrp2010/



NRC-Herzberg Astronomy and Astrophysics Research Centre

Dominion Astrophysical Observatory, Victoria, BC

National Research Council Act, R.S.C., 1985, C. N15: "NRC is mandated to operate and administer any astronomical observatories established or maintained by the Government of Canada."

Lead Agency	NSF/DoE (USA)
Aperture	6.7m
Location	Cerro Pacon, Chile
Launch	2021

Lifetime	10 years
Sky coverage	20,000 deg^2 (50% of sky)
Imaging Camera	visible and infrared
Cost	$700M

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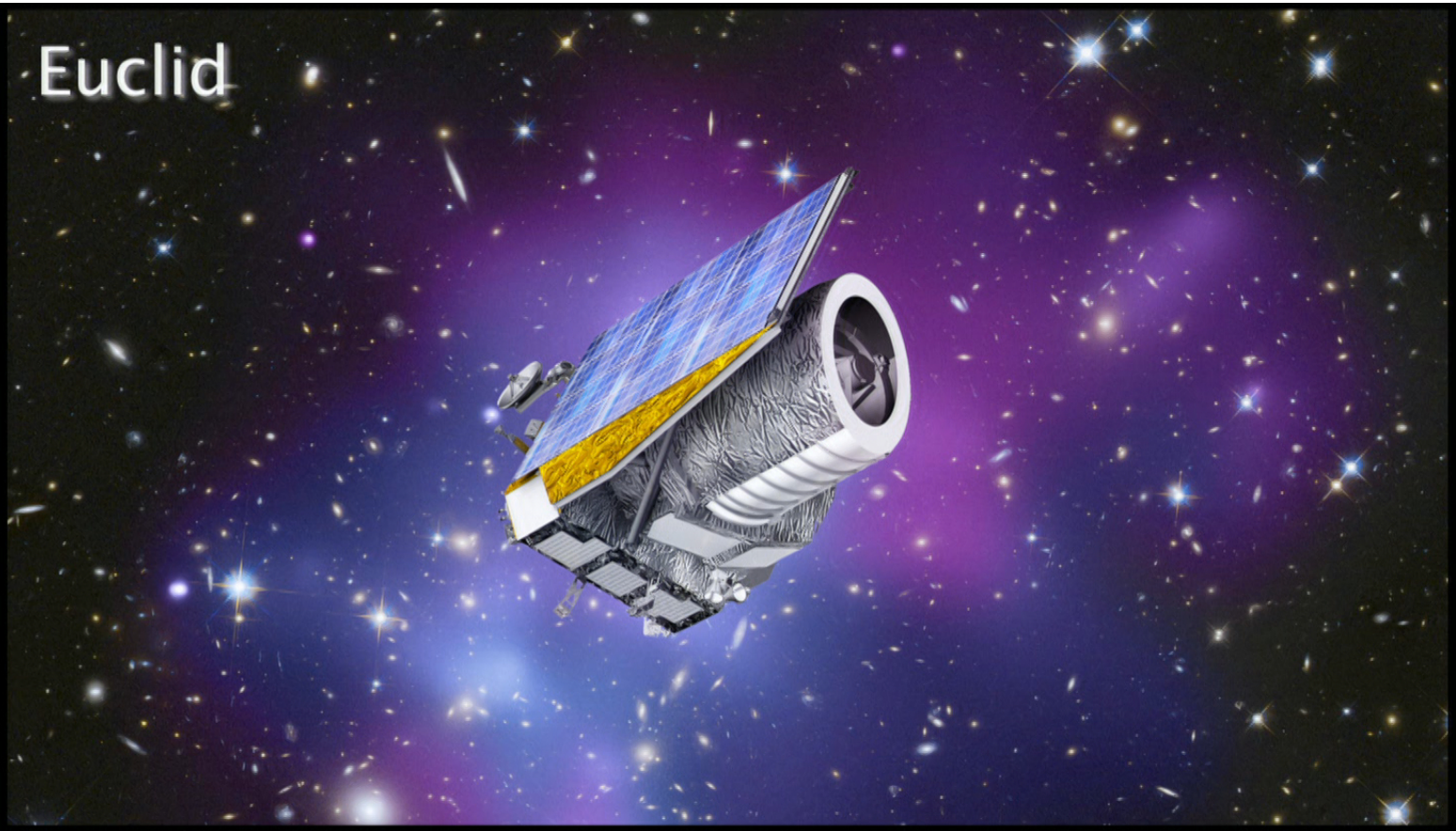
Euclid

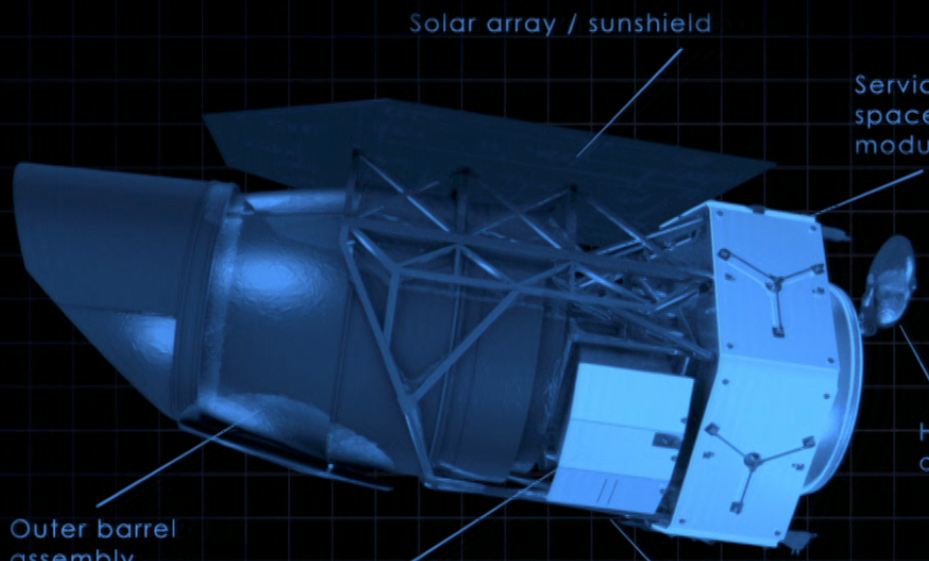


Lead Agency	ESA
Aperture	1.2m
Location	Earth-Sun L2 point
Launch	2022

Lifetime	6 years
Sky coverage	15,000 deg^2 (34% of sky)
Imaging Camera	red visible and infrared
Cost	$800M

esa
European Space Agency

WFIRST



Lead Agency	NASA
Aperture	2.4m
Location	Earth-Sun L2 point
Launch	2025

Lifetime	6 years
Sky coverage	2200 deg^2 (5% of sky)
Imaging Camera	red visible and infrared
Cost	$3.2B

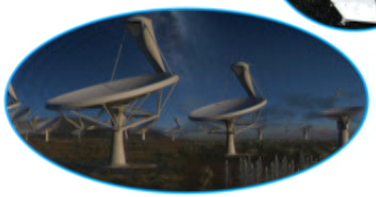
International Facilities in the 2020s

Gaia (Galactic Archaeology)
All-sky point sources to G=20; 1 billion sources; moderate and high resolution follow-up

WFIRST (Cosmology and extragalactic surveys)
>2000 sq. deg to Y>26.7 in multiple surveys; G.O. mode
Euclid (Cosmology and extragalactic surveys)
20000 sq. deg to RIZ=24.5; 40 sq. deg to RIZ=26.5

Ground based OIR imaging
LSST: >10000 sq.deg overlap; Single visit depth of r=24.5; billions of sources; opportunistic transient studies
Subaru/HSC: co-located on Maunakea; 1.5 degree FoV; r=27.2 in 1hr

PLATO (stellar physics and exoplanetary hosts)
>2000 sq. deg to g=16; high SNR@R40K monitoring campaigns of faintest sources



- Many multi-wavelength photometric and astrometric astrophysical surveys are planned for the next decade.
- Two missing capabilities:
  - a dedicated wide-field spectroscopic facility on a 10m-class telescope (MSE).
  - a high spatial resolution UV/blue-optical space telescope (CASTOR).
- For maximum synergy, these capabilities will be needed by the mid 2020s.

Very Large Optical Telescopes
GMT, TMT and E-ELT: Feeder facility for individual sources for study with high SNR, high R, AO-assisted IFUs

Radio, sub-mm, far-IR
Long wavelength synergies including **ALMA, CCAT** and **SPICA**
SKA1: >20000 sq. deg overlap; Billions of sources to r>24; opportunistic transient studies; spectral stacking

Recommendations: LRP 2010 and MTR2015

	Category	Priority	Project
GROUND	Very Large	1	VLOT (TMT)
	Large	1	SKA
	Medium	1	CHIME (see talk by Michael Rupen)
		2	CFHT new instrumentation
		3	CCAT
	Small	1	Arctic
		2	ngCFHT (MSE)
SPACE	Large		Euclid/WFIRST/CST (CASTOR)
	Medium	1	IXO
		2	SPICA
	Small		Astro-H
			Balloon
			Microsatellite

LRP2010:

- "The science case for an ngCFHT is unassailable..."
- "...but neither the scope, cost or schedule of the concept are well determined, so it is important to establish better estimates for these before the project can proceed..."
- "The LRPP recommends that Canada develop the ngCFHT concept (science case, technical design, partnerships, timing)."

MTR2015:

- "The MTR panel strongly recommends that Canada develop the MSE project, and supports the efforts of the project office to seek financial commitments from Canadian and partner institute sources."

LRP2010:

- The 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)."
- "Leading such a project would break new ground for Canadian space astronomy and present numerous opportunities for Canadian companies to showcase technological capabilities."
- "... Canadian space astronomy technology has reached the point that we could now lead a large space astronomy mission (Canadian Space Telescope, CST)."

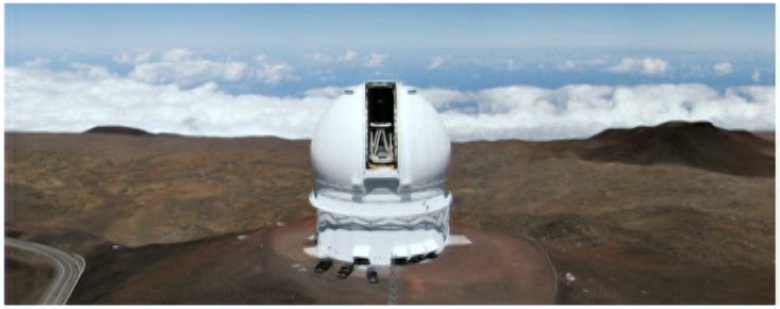
MTR2015:

- "There remains the possibility of contributing ground-based imaging with CFHT through a Large Program, in return for some scientific participation within the large Euclid consortium. But with no opportunity to contribute directly to satellite instrumentation, no arrangement of this type will satisfy the LRP2010 recommendation. Two viable options remain: WFIRST and CST (now CASTOR)."
- "CASTOR is well aligned with Canada's Space Policy Framework; in particular, it has the potential to become a high profile mission producing exceptional scientific results, as well as being a flagship for Canadian industry and the CSA."
- "The MTRP strongly recommends that the CSA launch a Phase 0 study for CASTOR, with study results required within 12 months...."

The Maunakea Spectroscopic Explorer (MSE)

Maunakea Spectroscopic Explorer

MSE Concept



- **CFHT** is a 3.6m optical/IR telescope on the summit of Mauna Kea (4204 m). Arguably the world's premier astronomical site:
  - median seeing (free atmosphere) of 0.4″.
  - median precipitable water vapour = 0.9 mm.
  - useable nights: 80% spectro., 55% photo.
- CFHT is a partnership between **Canada** (NRC), **France** (CNRS) and the **University of Hawaii.**

- A dedicated, wide-field, large-aperture spectroscopic survey telescope will be urgently needed by the mid 2020s.
- Repurpose the existing 3.6m CFHT into a 10m-class spectroscopic survey facility. Leverage Canada's strategic assets (telescope, personnel, site).
- Expand the CFHT partnership and re-establish a leadership role for Canada in wide-field astrophysics.

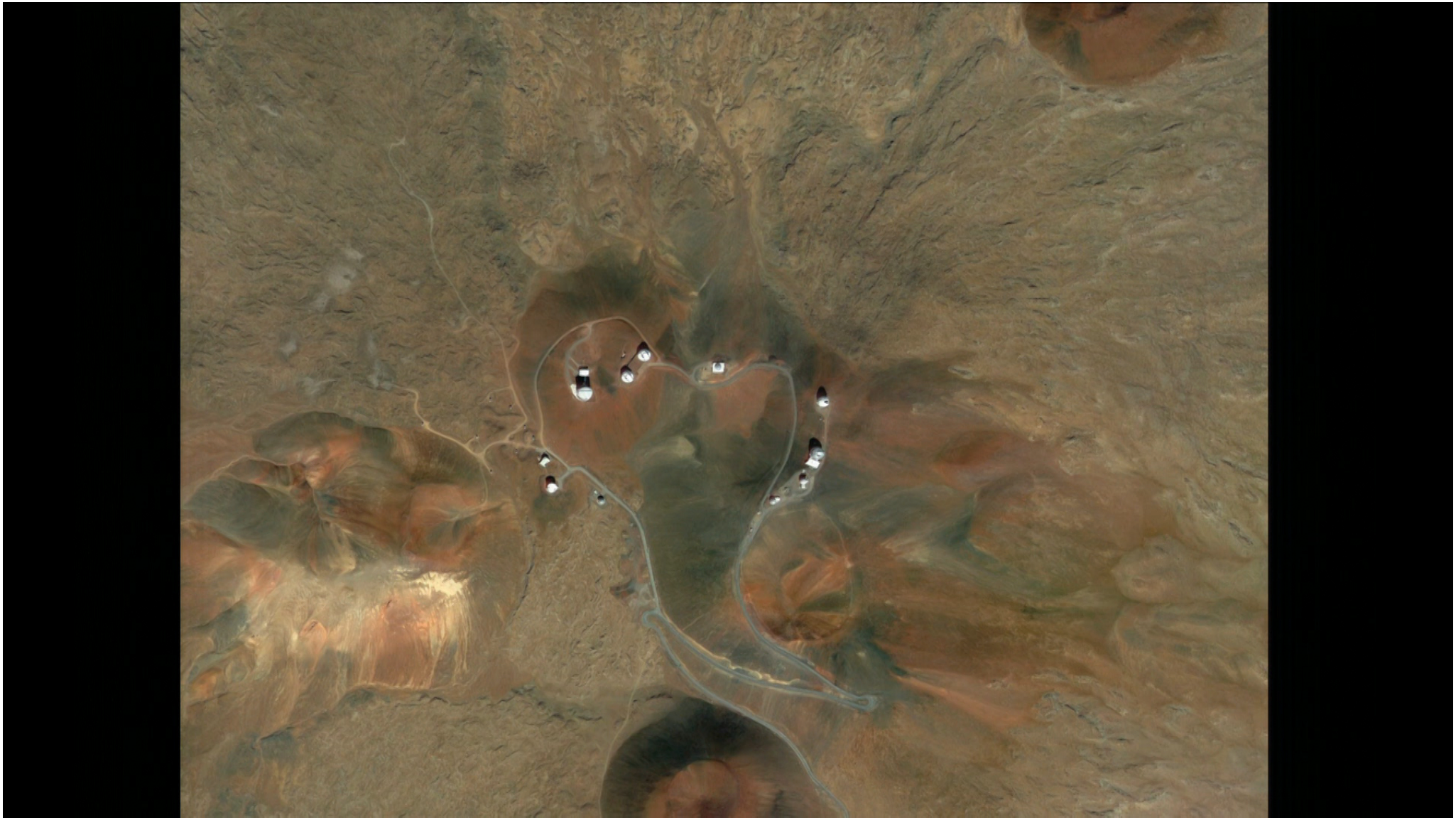
Table 1: Summary of major science capabilities of MSE.

Accessible sky	30000 square degrees (airmass<1.55)					
Aperture (M1 in m)	11.25m					
Field of view (square degrees)	1.5					
Etendue = FoV x π (M1 / 2)²	149					
Modes	**Low**		**Moderate**	**High**		**IFU**
Wavelength range	0.36 - 1.8 μm		0.36 - 0.95 μm	0.36 - 0.95 μm #		IFU capable; anticipated second generation capability
	0.36 - 0.95 μm	J, H bands		0.36 - 0.45 μm	0.45 - 0.60 μm	0.60 - 0.95 μm
Spectral resolutions	2500 *(3000)*	3000 *(5000)*	6000	40000	40000	20000
Multiplexing	>3200		>3200	>1000		
Spectral windows	Full		≈Half	$\lambda_c/30$	$\lambda_c/30$	$\lambda_c/15$
Sensitivity	m=24 *		m=23.5 *	m=20.0 ¤		
Velocity precision	20 km/s ♪		9 km/s ♪	< 100 m/s ★		
Spectrophotometic accuracy	< 3 % relative		< 3 % relative	N/A		

Dichoric positions are approximate

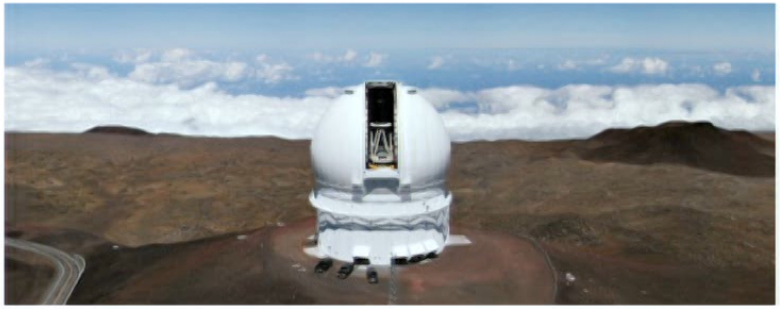
* SNR/resolution element = 2 ♪ SNR/resolution element = 5

¤ SNR/resolution element = 10 ★ SNR/resolution element = 30



Maunakea Spectroscopic Explorer

MSE Concept



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Spectral resolutions	2500 *(3000)*	3000 *(5000)*	6000	40000	40000 20000	
Multiplexing	>3200		>3200	>1000		
Spectral windows	Full		≈Half	$\lambda_c/30$	$\lambda_c/30$ $\lambda_c/15$	
Sensitivity	m=24 *		m=23.5 *	m=20.0 ¤		
Velocity precision	20 km/s ♪		9 km/s ♪	< 100 m/s ★		
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Dichoric positions are approximate

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Maunakea Spectroscopic Explorer

MSE Development History

- **2010: MSE** started life as the **Next Generation CFHT** as a grassroots proposal by members of the Canadian astronomy community, in response to the 2010 Long Range Plan. LRP2010 recommended that the concept should be developed further.
- **2012: Scientific and technical feasibility studies submitted** to the CFHT Board and Science Advisory Committee. International workshop on ngCFHT in Hilo, Hawaii.
- **2014:** CFHT Board of Directors act on SAC recommendation and set up the **MSE Project Office** at the Waimea Headquarters. **Name changes to MSE**. **Partnership formation begins**.
- **2015 – 2016:** Detailed Science Case v1.0 written by International Science Team (>100 members). Science Requirements Document drafted by Project Office.
- **2015 – 2017:** Major subsystem Conceptual Design studies conducted by partners.
- **2017:** 10 different subsystem Conceptual Design Reviews for 8 different subsystems.
- **January 2018:** Transition to Preliminary Design Phase begins. Development of Design Reference Survey.

- Organizationally, MSE is one of the **Maunakea Observatories**.
- It is a project of the CFHT Corporation to upgrade to an 11.25m dedicated spectroscopic facility.
- All MSE partners - currently Australia, Canada, China, France, Hawaii, and India - have equal status (i.e., it is an international project, not a C-F-H project)

Maunakea Spectroscopic Explorer

MSE Science Requirements

			Resolved stellar sources					Extragalactic sources						
			DSC-SRO-01	DSC-SRO-02	DSC-SRO-03	DSC-SRO-04	DSC-SRO-05	DSC-SRO-06	DSC-SRO-07	DSC-SRO-08	DSC-SRO-09	DSC-SRO-10	DSC-SRO-11	DSC-SRO-12
			Exoplanet hosts	*Time domain stellar astrophysics*	*Chemical tagging in the outer Galaxy*	*CDM subhalos and stellar streams*	*Local Group galaxies*	*Nearby galaxies*	*Virgo and Coma*	*Halo occupation*	*Galaxies and AGN*	*The InterGalactic Medium*	*Reverberation mapping*	*Peculiar velocities*
Spectral resolution	REQ-SRD-011	*Low spectral resolution*		R~2000 (white dwarfs)				R~3000	R~3000	R~2000-3000	R~3000		R~3000	R~1000-2000
	REQ-SRD-012	*Intermediate spectral resolution*		Any repeat observations	Essential, R~6500	Essential, R~6500	Essential, R~6500	Velocities of low mass galaxies	Velocities of low mass galaxies			R~5000		
	REQ-SRD-013	*High spectral resolution*	R>=40000	R>=20000	Essential, R~20-40K	Essential	Young stars		Bright globular clusters					
Focal plane input	REQ-SRD-021	*Field of view*	~2000 sq. deg	all-sky	1000s sq. deg	1000s sq.deg	100s sq. deg	3200 (100) sq.deg	~100sq.deg	~1000sq.deg	~300 sq.deg	40 sq.deg	7 sq. deg	all-sky
	REQ-SRD-022	*Multiplexing at lower resolution*						~5000 galaxies/sq. deg	100s targets (galaxies/GCs) / sq.deg	>5000 galaxies/sq. deg	770 galaxies/sq. deg		600AGN/deg	1000s galaxies/sq. deg
	REQ-SRD-023	*Multiplexing at moderate resolution*			1000s stars/sq.deg to g~23	1000s stars/sq.deg to g~23	few thousands stars/sq. deg	~5000 galaxies/sq. deg				500 galaxies/sq. deg		
	REQ-SRD-024	*Multiplexing at high resolution*	~100 stars/sq.deg @ g = 16	~1000 stars/sq.deg to g=20.5	~1000 stars/sq.deg to g=20.5	1000s stars/sq.deg to g~23								
	REQ-SRD-025	*Spatially resolved spectra*						Goal	Goal					Yes
itivity	REQ-SRD-031	*Spectral coverage at low resolution*						0.37 - 1.5um	0.37 - 1.5um	0.36 - 1.8um	0.36 - 1.8um	0.36 - 1.8um (0.36 -	0.36 - 1.8um	Optical emission lines
	REQ-SRD-032	*Spectral coverage at moderate resolution*			Strong line diagnostics in optical	CaT essential	CaT essential	Goal: complete	Goal: complete			Goal: complete		
	REQ-SRD-033	*Spectral coverage at high resolution*	Strong lines for velocities; tagging	Strong lines for velocities	Chemical tagging	Strong lines for velocities								

Maunakea Spectroscopic Explorer

MSE Science Requirements

			osts	physics n	gging Galaxy	los and rms		ixies	orma	xtion	d AGN	lactic	on	ocities
Spectral resolution	REQ-SRD-011	Low spectral resolution		R~2000 (white dwarfs)				R~3000	R~3000	R~2000-3000	R~3000		R~3000	R~1000-2000
	REQ-SRD-012	Intermediate spectral resolution		Any repeat observations	Essential, R~6500	Essential, R~6500	Essential, R~6500	Velocities of low mass galaxies	Velocities of low mass galaxies			R~5000		
	REQ-SRD-013	High spectral resolution	R>=40000	R>=20000	Essential, R~20-40K	Essential	Young stars		Bright globular clusters					
Focal plane input	REQ-SRD-021	Field of view	~2000 sq. deg	all-sky	1000s sq. deg	1000s sq.deg	100s sq. deg	3200 (100) sq.deg	~100sq.deg	~1000sq.deg	~300 sq.deg	40 sq.deg	7 sq. deg	all-sky
	REQ-SRD-022	Multiplexing at lower resolution						~5000 galaxies/sq. deg	100s targets (galaxies/GCs) / sq.deg	>5000 galaxies/sq. deg	770 galaxies/sq. deg		600AGN/deg	1000s galaxies/sq. deg
	REQ-SRD-023	Multiplexing at moderate resolution			1000s stars/sq.deg to g~23	1000s stars/sq.deg to g~23	few - thousands stars/sq. deg	~5000 galaxies/sq. deg				500 galaxies/sq. deg		
	REQ-SRD-024	Multiplexing at high resolution	~100 stars/sq.deg @ g = 16	~1000 stars/sq.deg to g=20.5	~1000 stars/sq.deg to g=20.5	1000s stars/sq.deg to g~23								
	REQ-SRD-025	Spatially resolved spectra						Goal	Goal					Yes
Sensitivity	REQ-SRD-031	Spectral coverage at low resolution						0.37 - 1.5um	0.37 - 1.5um	0.36 - 1.8um	0.36 - 1.8um	0.36 - 1.8um (0.36 -	0.36 - 1.8um	Optical emission lines
	REQ-SRD-032	Spectral coverage at moderate resolution			Strong line diagnostics in optical	CaT essential	CaT essential	Goal: complete	Goal: complete			Goal: complete		
	REQ-SRD-033	Spectral coverage at high resolution	Strong lines for velocities; tagging	Strong lines for velocities	Chemical tagging	Strong lines for velocities								
	REQ-SRD-034	Sensitivity at low resolution						i=24.5	i=24.5	i=25.3	i=25 / H=24		i=23.25	i=24.5
	REQ-SRD-035	Sensitivity at moderate resolution			g>20.5	g~23	i=24	i=24.5	i=24.5			r~24		
	REQ-SRD-036	Sensitivity at high resolution	g=16 @high SNR	g=20.5	g=20.5	g~22								
ion	REQ-SRD-041	Velocities at low resolution						v~20km/s	v~20km/s	v~100km/s	v~20km/s		v~20km/s	v~20km/s
	REQ-SRD-042	Velocities at moderate resolution			v~1km/s	v~1km/s	v~5km/s	v~9km/s	v~9km/s			v~20km/s (10km/s goal)		
		Velocities at high	v<100m/s	v~100m/s	v~100m/s	v<1km/s								

Maunakea Spectroscopic Explorer

MSE Science Requirements

	REQ-SRD-013	*High spectral resolution*	R>=40000	R>=20000	R~20-40K	Essential	stars		globular clusters					
Focal plane input	REQ-SRD-021	*Field of view*	~2000 sq. deg	all-sky	1000s sq. deg	1000s sq.deg	100s sq. deg	3200 (100) sq.deg	~100sq.deg	~1000sq.deg	~300 sq.deg	40 sq.deg	7 sq. deg	all-sky
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Sensitivity	REQ-SRD-031	*Spectral coverage at low resolution*						0.37 - 1.5um	0.37 - 1.5um	0.36 - 1.8um	0.36 - 1.8um	0.36 - 1.8um (0.36 -	0.36 - 1.8um	Optical emission lines
	REQ-SRD-032	*Spectral coverage at moderate resolution*			Strong line diagnostics in optical	CaT essential	CaT essential	Goal: complete	Goal: complete			Goal: complete		
	REQ-SRD-033	*Spectral coverage at high resolution*	Strong lines for velocities; tagging	Strong lines for velocities	Chemical tagging	Strong lines for velocities								
	REQ-SRD-034	*Sensitivity at low resolution*						i=24.5	i=24.5	i=25.3	i=25 / H=24		i=23.25	i=24.5
	REQ-SRD-035	*Sensitivity at moderate resolution*			g>20.5	g~23	i=24	i=24.5	i=24.5			r~24		
	REQ-SRD-036	*Sensitivity at high resolution*	g=16 @high SNR	g=20.5	g=20.5	g~22								
Calibration	REQ-SRD-041	*Velocities at low resolution*						v~20km/s	v~20km/s	v~100km/s	v~20km/s		v~20km/s	v~20km/s
	REQ-SRD-042	*Velocities at moderate resolution*			v~1km/s	v~1km/s	v~5km/s	v~9km/s	v~9km/s			v~20km/s (10km/s goal)		
	REQ-SRD-043	*Velocities at high resolution*	v<100m/s	v~100m/s	v~100m/s	v<1km/s								
	REQ-SRD-044	*Relative spectrophotometry*						~4%					Critical:3%	
	REQ-SRD-045	*Sky subtraction, continuum*	few %	few %	few %	few %	<1%	<1%	<1%	<0.5%	<0.5%	<1%	<1%	<1%
	REQ-SRD-046	*Sky subtraction, emission lines*				important (CaT region)	important (CaT region)	critical	critical	critical	critical	critical	critical	
			Plato	Gaia	Gaia	Gaia, PS1,	Northern	LSST overlap	NGVS	LSST overlap	LSST overlap	LSST overlap	all sky	all sky

Maunakea Spectroscopic Explorer

MSE Science Requirements

Fo	REQ-SRD-024	resolution	g @ g = 16	g to g=20.5	g to g=20.5	g to g~23								
	REQ-SRD-025	*Spatially resolved spectra*						Goal	Goal					Yes
Sensitivity	REQ-SRD-031	*Spectral coverage at low resolution*						0.37 - 1.5um	0.37 - 1.5um	0.36 - 1.8um	0.36 - 1.8um	0.36 - 1.8um (0.36 -	0.36 - 1.8um	Optical emission lines
	REQ-SRD-032	*Spectral coverage at moderate resolution*			Strong line diagnostics in optical	CaT essential	CaT essential	Goal: complete	Goal: complete			Goal: complete		
	REQ-SRD-033	*Spectral coverage at high resolution*	Strong lines for velocities; tagging	Strong lines for velocities	Chemical tagging	Strong lines for velocities								
	REQ-SRD-034	*Sensitivity at low resolution*						i=24.5	i=24.5	i=25.3	i=25 / H=24		i=23.25	i=24.5
	REQ-SRD-035	*Sensitivity at moderate resolution*			g>20.5	g~23	i=24	i=24.5	i=24.5			r~24		
	REQ-SRD-036	*Sensitivity at high resolution*	g=16 @high SNR	g=20.5	g=20.5	g~22								
Calibration	REQ-SRD-041	*Velocities at low resolution*						v~20km/s	v~20km/s	v~100km/s	v~20km/s		v~20km/s	v~20km/s
	REQ-SRD-042	*Velocities at moderate resolution*			v~1km/s	v~1km/s	v~5km/s	v~9km/s	v~9km/s			v~20km/s (10km/s goal)		
	REQ-SRD-043	*Velocities at high resolution*	v<100m/s	v~100m/s	v~100m/s	v<1km/s								
	REQ-SRD-044	*Relative spectrophotometry*						~4%					Critical:3%	
	REQ-SRD-045	*Sky subtraction, continuum*	few %	few %	few %	few %	<1%	<1%	<1%	<0.5%	<0.5%	<1%	<1%	<1%
	REQ-SRD-046	*Sky subtraction, emission lines*				important (CaT region)	important (CaT region)	critical	critical	critical	critical	critical	critical	
Operations	REQ-SRD-051	*Accessible sky*	Plato footprint (ecliptic)	Gaia footprint (all sky)	Gaia footprint (all sky)	Gaia, PS1, HSC footprint	Northern hemisphere (M31, M33, dec~+40)	LSST overlap useful (10000 sq.deg)	NGVS footprint; dec +12	LSST overlap useful (10000 sq.deg); Euclid (all sky)	LSST overlap useful (10000 sq.deg); Euclid (all sky)	LSST overlap useful (10000 sq.deg); Euclid (all sky)	all sky target distribution	all sky target distribution
	REQ-SRD-052	*Observing efficiency*	maximise	maximise	maximise	maximise	maximise	maximise	maximise	maximise	maximise	maximise	maximise	maximise
	REQ-SRD-053	*Observatory lifetime*	Monitoring >=years	Monitoring >=years	Survey >=5 years	Survey >=5 years	Survey ~100s nights	Survey ~ few years	Survey ~100s nights	Survey ~7 years	Survey ~100s nights	Survey ~100s nights	Monitoring ~5 years	Survey ~years

Science Reference Observations

Science Requirements Drive Design Choices:

- Wide redshift range of interest.
- Stellar chemical tagging.
- Intervening absorption (IGM, CGM) / sky lines.
- Continuum flux levels.
- Small velocity dispersions.
- High surface density of targets.
- Many targets.
- Faint targets, many targets.
- Faint targets.
- Surveys ranging from few nights to 1000s of deg^2.

Science Reference Observations

Science Requirements Drive Design Choices:

• Wide redshift range of interest.	→ UV to Near-IR, R~3000 mode.
• Stellar chemical tagging.	→ R~40,000 mode.
• Intervening absorption (IGM, CGM) / sky lines.	→ R~6000 mode.
• Continuum flux levels.	→ accurate spectrophotometry.
• Small velocity dispersions.	→ precise velocities.
• High surface density of targets.	→ many close-packed fibres.
• Many targets.	→ wide field of view.
• Faint targets, many targets.	→ large primary aperture.
• Faint targets.	→ great image quality, optimal fibre size & positioning.
• Surveys ranging from few nights to 1000s of deg^2.	→ dedicated facility to deliver data for legacy and PI surveys.

Maunakea Spectroscopic Explorer

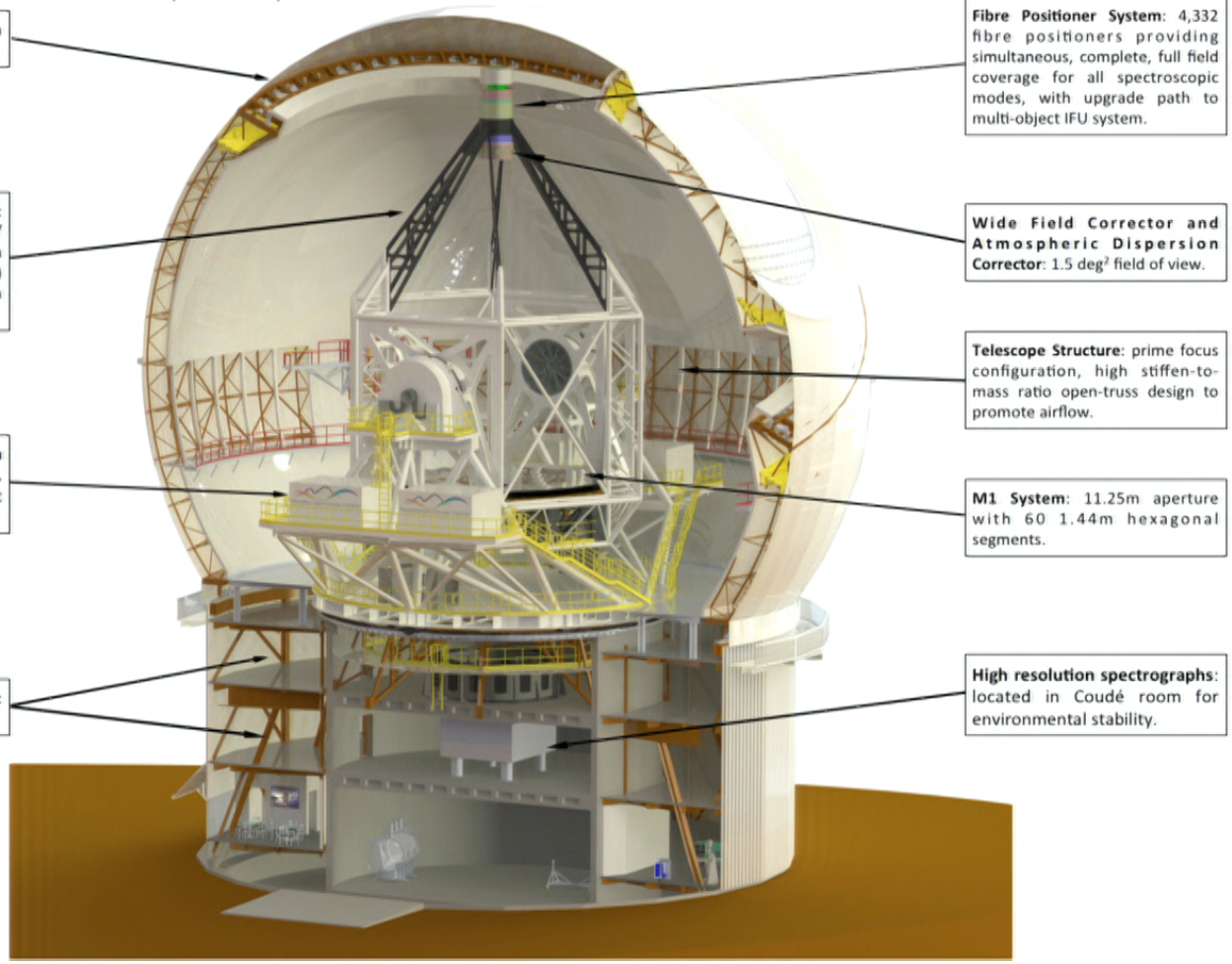
MSE Conceptual Design Configuration

Enclosure: Calotte design with vent modules for smooth airflow.

Fibre Transmission System (FTS): 3,249 fibres (1") leading to low/moderate resolution spectrographs; 1,083 fibres (0.8") feeding high resolution spectrographs.

Low/Moderate resolution spectrographs: 0.37-1.8 um, located on both instrument platforms.

Telescope and Enclosure Piers: modified CFHT structures.



Fibre Positioner System: 4,332 fibre positioners providing simultaneous, complete, full field coverage for all spectroscopic modes, with upgrade path to multi-object IFU system.

Wide Field Corrector and Atmospheric Dispersion Corrector: 1.5 deg^2 field of view.

Telescope Structure: prime focus configuration, high stiffen-to-mass ratio open-truss design to promote airflow.

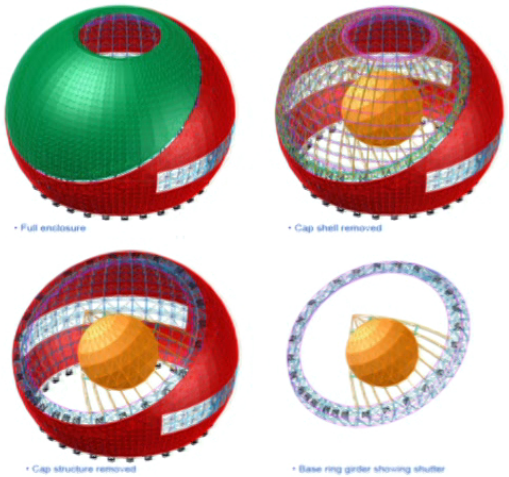
M1 System: 11.25m aperture with 60 1.44m hexagonal segments.

High resolution spectrographs: located in Coudé room for environmental stability.

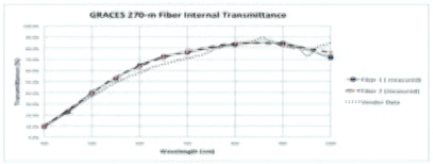
Maunakea Spectroscopic Explorer

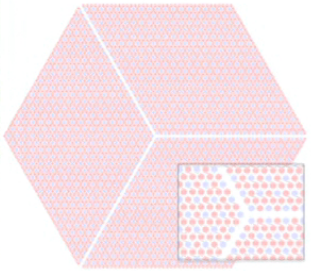
Canadian Industrial Contributions

- The **Calotte design** is the best-match option over other enclosure configurations for MSE.
- **Empire Dynamic Structures** (Port Coquitlam, BC) completed conceptual design, leveraging their TMT development efforts.



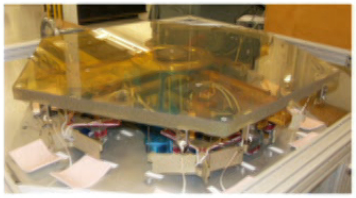
- Fibre bundles transmit light from the focal surface to spectrographs without connectors and reformatting microlens optics.
- by NRC-HAA (Canada) in partnership with **FiberTech Optica** (Kitchener, ON).
- Builds on their expertise on GRACES which is a 270m fibre link between **Gemini** and **CFHT ESPaDOnS**.



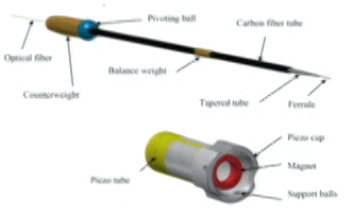


Focal surface layout of AAO positioners: LMR (red), HR (blue)

- Existing designs and technologies that can be utilized:
  - Segmented mirror system technologies from ELT projects
  - Fiber positioner and metrology technologies
  - Spectrograph designs
  - Commercial off-the-shelf optical fibers



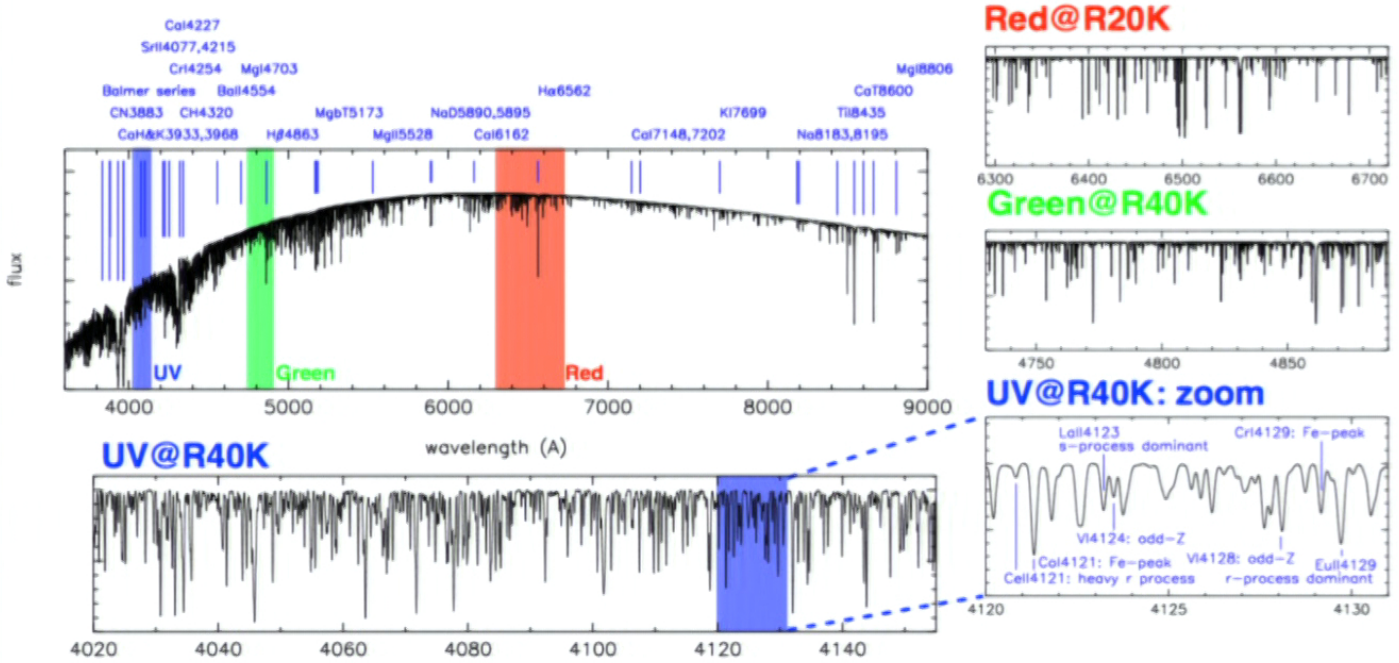
TMT M1 segment and support assembly



Echidna fiber positioner

Maunakea Spectroscopic Explorer

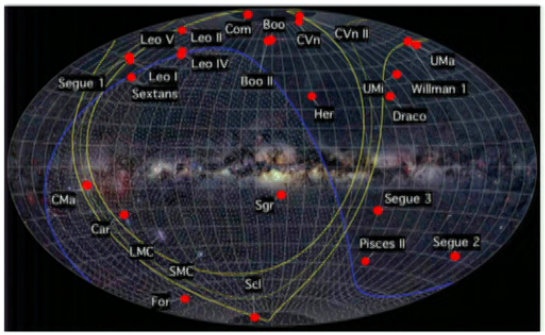
Galactic Archaeology: Synthesis of the Elements



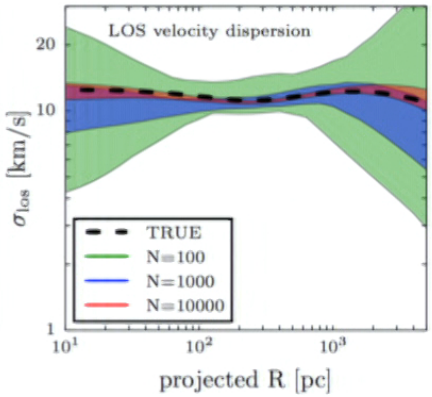
- Metal-poor red giant spectrum above: many ions spanning a broad range of nucleosynthetic pathways provide greatest leverage for chemical tagging.
- Diagnostics at both low/moderate resolution (stellar parameters, [Fe/H], strong spectral indicators) and high resolution (weak lines, precision abundances)

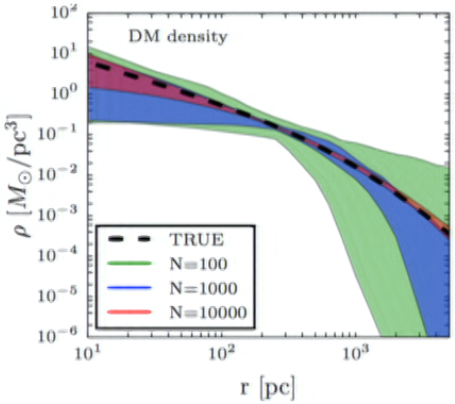
Maunakea Spectroscopic Explorer

Dark Matter, Gravity and Tides



Dark Energy Survey - Bechtol et al. (2015)





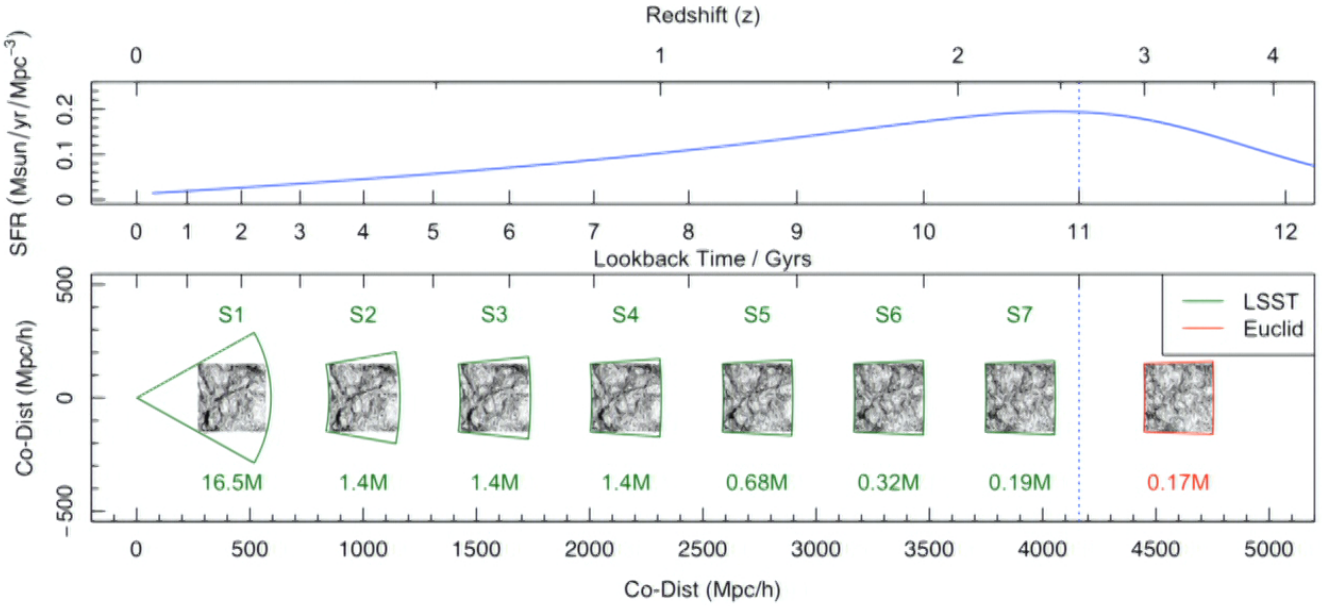
MSE will provide vast datasets of line-of-sight velocities to trace the distribution dark matter within halos.

- Hundreds or thousands of new satellites expected in the 2020s. What is responsible for their unexpected kinematics?
  1. **dark matter**
  2. **nonstandard gravity**
  3. **non-equilibrium dynamics**
  4. something else?

- Lowest mass sub-halos around the Milky Way accessible from heating of cold stellar streams.
- The shape and and structure of dark matter holes in external galaxies from dynamical tracer populations.
- Dark matter in dwarf galaxies from high precision velocities for hundreds, or thousands, of stars.
- Dark matter in galaxy clusters from velocities for tens of thousands, of baryonic structures.

Maunakea Spectroscopic Explorer

Multi-scale Galaxy Clustering and the Halo Occupation Function

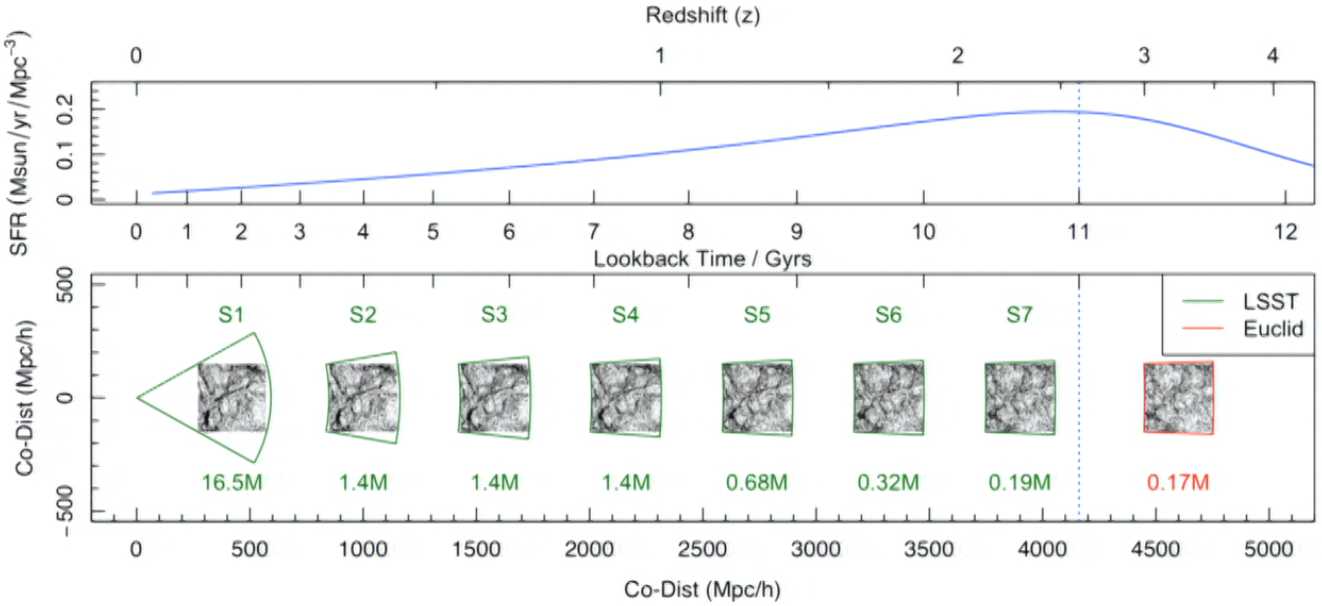


Multiple SDSS-Legacy-like galaxy surveys to the era of peak cosmic star formation:

- Eight survey cubes (300Mpc/h comoving on a side) to probe the build-up of large scale structure, stellar mass, halo occupation and star formation out to a redshift of z~3.
- >99% complete photo-z targeting per cube (reaching 0.1 M* for 4 lowest-z cubes).
- A seven year survey: impossible without a dedicated facility.

Maunakea Spectroscopic Explorer

Multi-scale Galaxy Clustering and the Halo Occupation Function



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Maunakea Spectroscopic Explorer

The Cosmological
Advanced Survey
Telescope for Optical
and uv Research
(CASTOR)

The Cosmological Advanced Survey Telescope for Optical and v Research (CASTOR)

•CASTOR, subst. masc.

A. - **"Mammifère** quadrupède, *rongeur, amphibie, originaire du Canada et du nord de l'Asie, vivant au bord des eaux du nord de l'Europe et de* **l'Amérique**, *remarquable par l'industrie avec* **laquelle** *il construit huttes et barrages, et* **très** *recherché principalement pour sa* **fourrure** *soyeuse.*

CASTOR History

- **2006**: CSA Space Astronomy Workshop. First discussions of a **Canadian Space Telescope** to provide wide-field imaging in the post-HST era.
- **2007-2009**: CSA study "Discipline Working Group Report on Wide-Field in Imaging From Space".
- **2010-2011**: **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)**."
  - "...Canadian space astronomy technology has reached the point that we could [now] lead a large space astronomy mission (**Canadian Space Telescope**)... Leading such a project would break new ground for Canadian space astronomy and present numerous opportunities for Canadian companies to showcase technological capabilities."
- **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:**
  - "MTR panel strongly recommends that the CSA launch a Phase 0 study for CASTOR, with study results required within 12 months, so that this compelling project can be developed, presented, and competed in the international community.
  - "The LRPIC and Joint Committee on Space Astronomy (JCSA) should review the outcome of that study and make further recommendations as appropriate, well in advance of LRP2020."
- **2016**: CSA Canadian Space Exploration Workshop: "Topical Team Final Reports"
  - "...the scientific potential of the mission is unparalleled."
- **2016-2017**: CSA Study: "Optical Design, Coatings, Filters, Dichroics"
- **2018-2019**: CSA Study: "Science Maturation Study for CASTOR"

CASTOR Status: Science Maturation Study

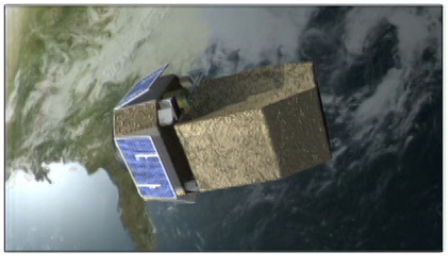
- **Scope**:
  - revise and update the CASTOR concept, with an emphasis on the science case.
  - revise and update technical requirements and mission design.
  - improved understanding of schedule, risk and cost.
  - explore opportunities for partnerships and collaborations (hardware and science).
- **Timeline**:
  - **Contract Start (Honeywell):** January 31, 2018.
  - **Mid-Term Review (CSA or Honeywell):** September 2018.
  - **Final Review (CSA):** March 2019.
- **Consortium**:
  - **Industry**:
    1. Honeywell Aerospace (Ottawa): mission architecture and implementation.
    2. ABB Inc (Laval): optical chain, including grism.
    3. Magellan Aerospace (Winnipeg): satellite bus, launch options.
  - **Government**:
    1. NRC-Herzberg (Victoria): science, optics, detectors, data handling.
    2. CSA (Montreal): contract management.
  - **Academia**: St. Mary's (Halifax), Laval (Quebec), Bishops (Sherbrooke), Toronto, Waterloo, McMaster (Hamilton), UBC (Vancouver).
  - **International**:
    1. **JPL/IPAC** (Pasadena): science, detectors, electronics, software.
    2. **India Institute of Astrophysics** (Bangalore): science, spectrograph, launch, optics.

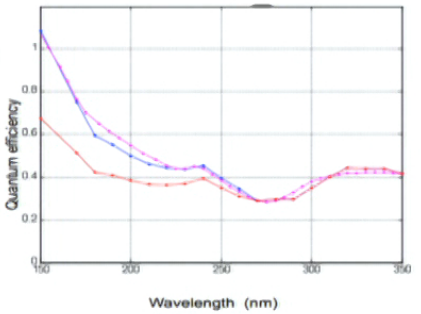
Science Working Groups

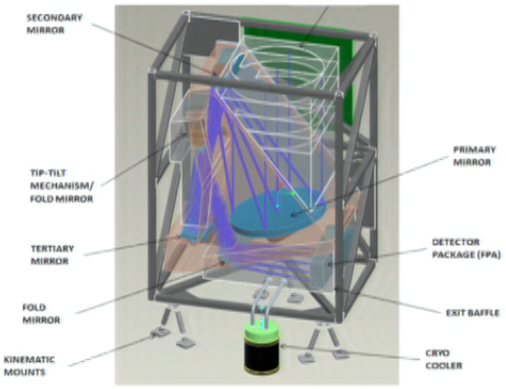
Cosmology	Time Domain	Galaxies	AGNs
Capak, Peter (IPAC)	Carlberg, Ray (Toronto)	Abraham, Roberto (Toronto)	Gallagher, Sarah (Western)
Doré, Olivier (JPL)	Drout, Maria (Toronto)	Balogh, Michael (Waterloo) ★	Gallo, Luigi (St. Mary's)
Heymans, Catherine (ROE)	Fabbro, Seb (NRC) ★	Hutchings, John (NRC-Herzberg)	Haggard, Daryl (McGill)
Krause, Elisabeth (Arizona)	Gallagher, Sarah (Western)	Lee, Janice (IPAC)	Hall, Pat (York)
Lang, Dustin (Toronto) ★	Haggard, Daryl (McGill)	Lokhorst, Deborah (Toronto)	Hlavacek-Larrondo, Julie (Montreal)
Moutard, Thibaud (St. Mary's)	Heinke, Craig (Alberta)	Moutard, Thibaud (St. Mary's)	Hutchings, John (NRC-Herzberg)
Parker, Laura (McMaster)	Hlozek, Rene (Dunlap)	Muzzin, Adam (York)	Khatu, Virajai (Western)
Percival, Will (Waterloo) ★	Hutchings, John (NRC-Herzberg)	Parker, Laura (McMaster)	Richards, Gordon (Drexel)
Rhodes, Jason (JPL)	Marois, Christian (NRC-Herzberg)	Sawicki, Marcin (St. Mary's)	Ruan, John (McGill)
Sawicki, Marcin (St. Mary's)	Ng, Cherry (Dunlap)	Teplitz, Hary (IPAC)	Thibert, Nathalie (St. Mary's)
Scott, Bryan (UC Riverside)	Peters, Cherry (Dunlap)		Willott, Chris (NRC-Herzberg)
Simet, Melanie Caltech)	Sivakoff, Greg (Alberta)		
van Waerbeke, Ludo (UBC)	Venn, Kim (Victoria)		
Near-Field Cosmology	**Stellar Astrophysics**	**Exoplanets**	**Solar System**
Bovy, Jo (Toronto)	Drout, Maria (Toronto)	Benneke, Björn (Montreal)	Bannister, Michele (QUB)
Côté, Patrick (NRC-Herzberg)	Drissen, Laurent (Laval)	Christiansen, Jessie (IPAC)	Brown, Peter (Western)
Fantin, Nick (Victoria)	Hénault-Brunet, Vincent (NRC-Herzberg)	Cowan, Nocolas (McGill)	Connors, Martin (Athabasca)
Grillmair, Carl (IPAC)	Heyl, Jeremy (UBC)	Doyon, Ren<E9> (Montreal)	Fraser, Wesley (QUB)
Navarro, Julio (Victoria)	Johnstone, Douglas (NRC-Herzberg)	Marois, Christian (NRC-Herzberg)	Gladman, Brett (UBC)
Spekkens, Kristine (RMC)	Neilsen, Hilding (Toronto)	Menou, Kristen (Toronto)	Kavelaars, JJ (NRC-Herzberg)
Starkenburg, Else (Postdam)	Robert, Carmell (Laval)	Metchev, Stan (Western)	Lawler, Samanatha (NRC-Herzberg)
Thomas, Guillaume (NRC-Herzberg)	Venn, Kim (Victoria)	Rowe, Jason (Bishop's)	Weigert, Paul (Western)
Valls-Gabaud, David (Paris)			

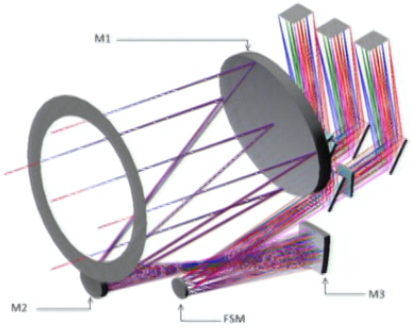
Mission Design

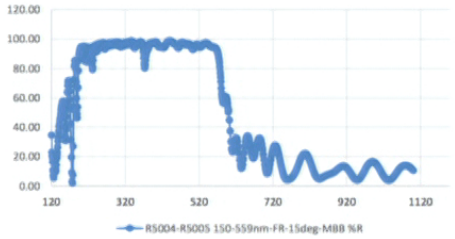
- **Telescope**
  - TMA with SiC optics.
  - 1m unobscured input aperture.
  - Customized broadband coatings to suppress red signal.
- **Focal Plane**
  - 4k × 2k e2v CIS113 detectors.
  - FWHM = 0.15”
  - field of view = 0.47° × 0.47°
  - three filter imaging
    - 400-550 nm (g)
    - 300-400 nm (u)
    - 150-300 nm (UV)
  - common FoV, three focal planes.
  - band separation by dichroics.
- **Launch Vehicle**
  - PSLV (ISRO)
- **Orbit**
  - 800 km sun synchronous LEO.
- **Mechanical Design**
  - customized MAC-200 SmallSAT bus.
  - payload mass = 572 kg.
  - spacecraft mass = 1320 kg.
- **Operation Mode**
  - minimum 5-year lifetime.
  - surveys and Guest Observer modes.

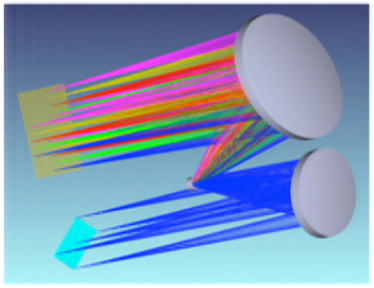


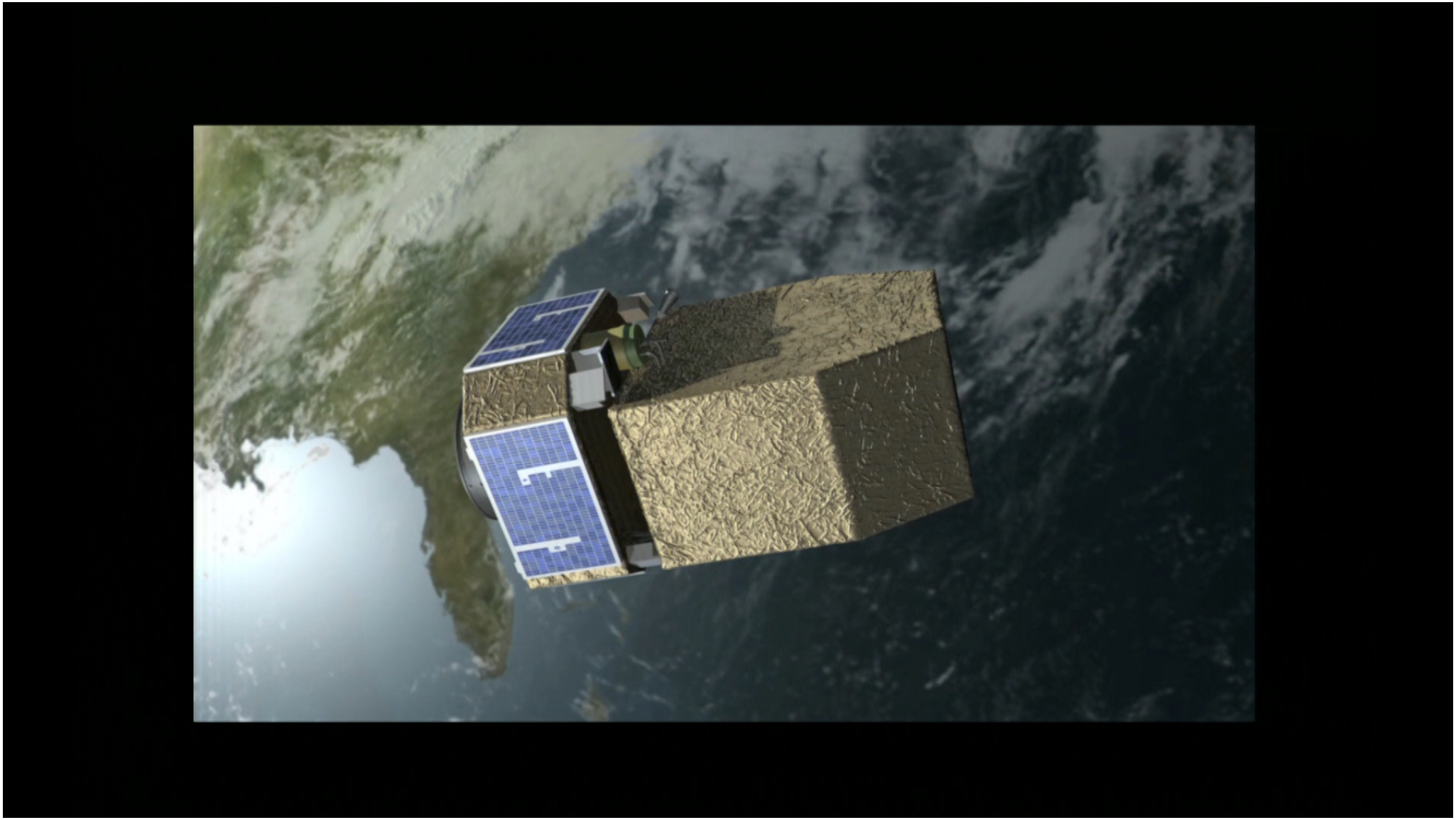


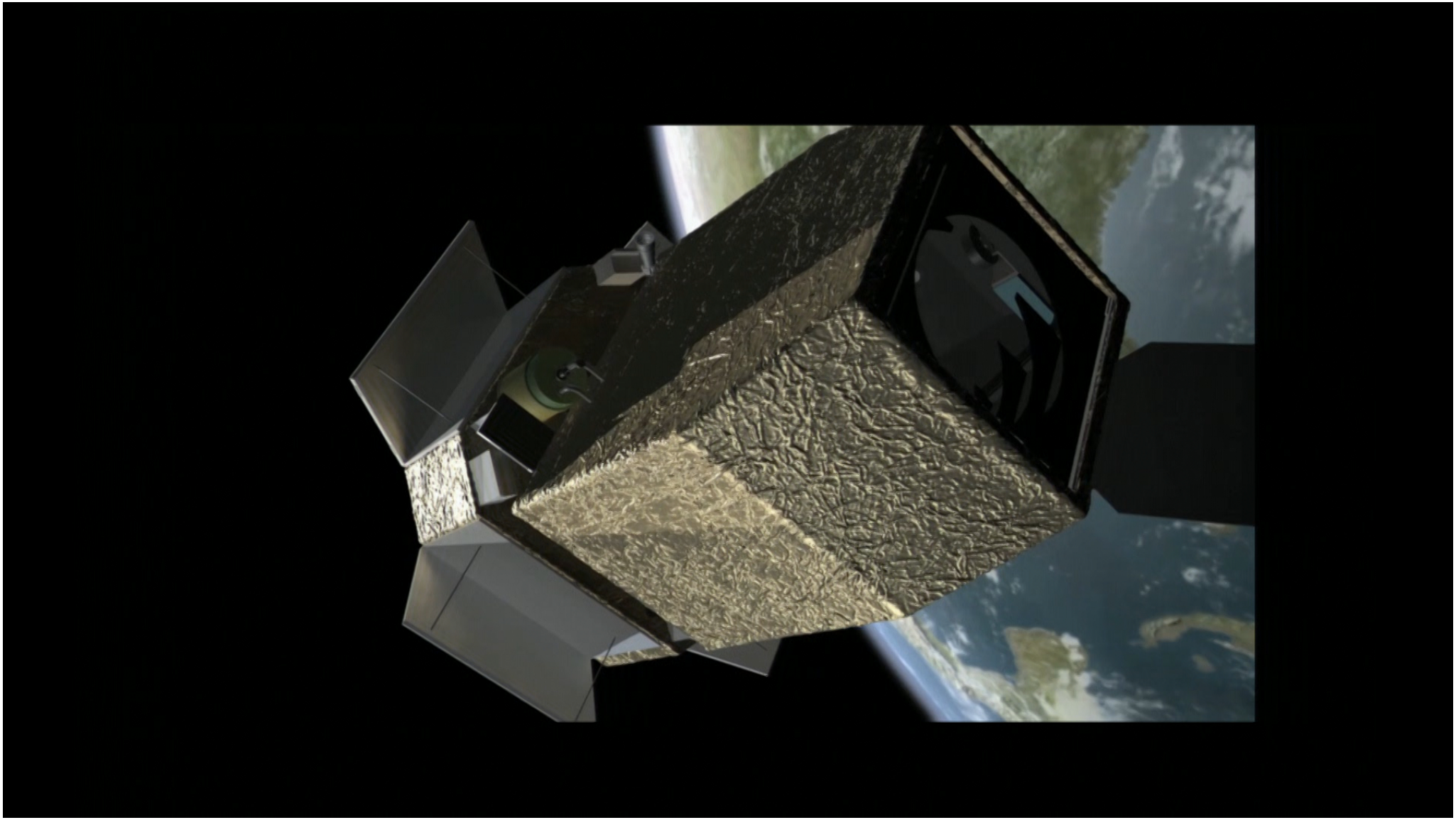


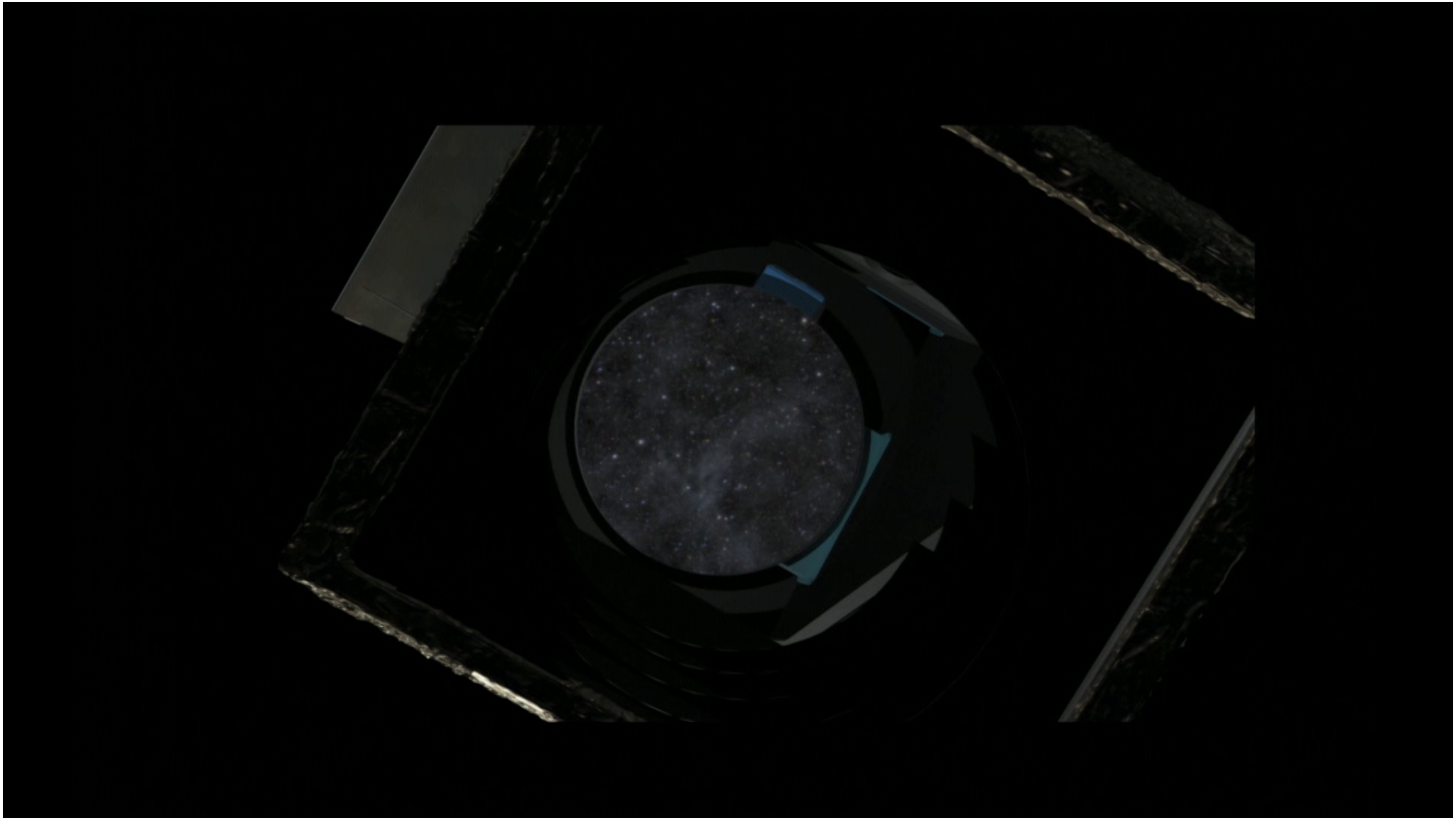


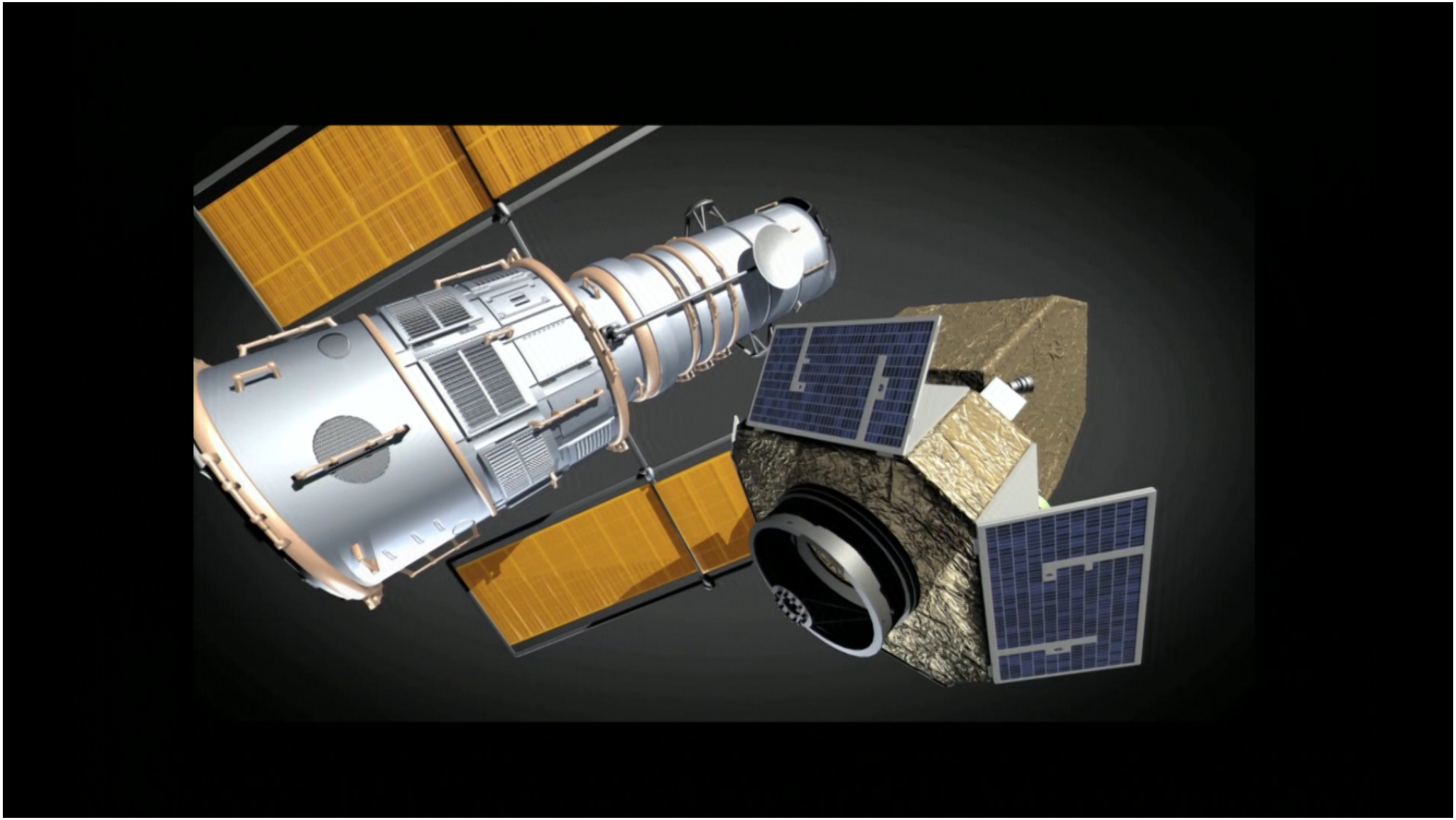


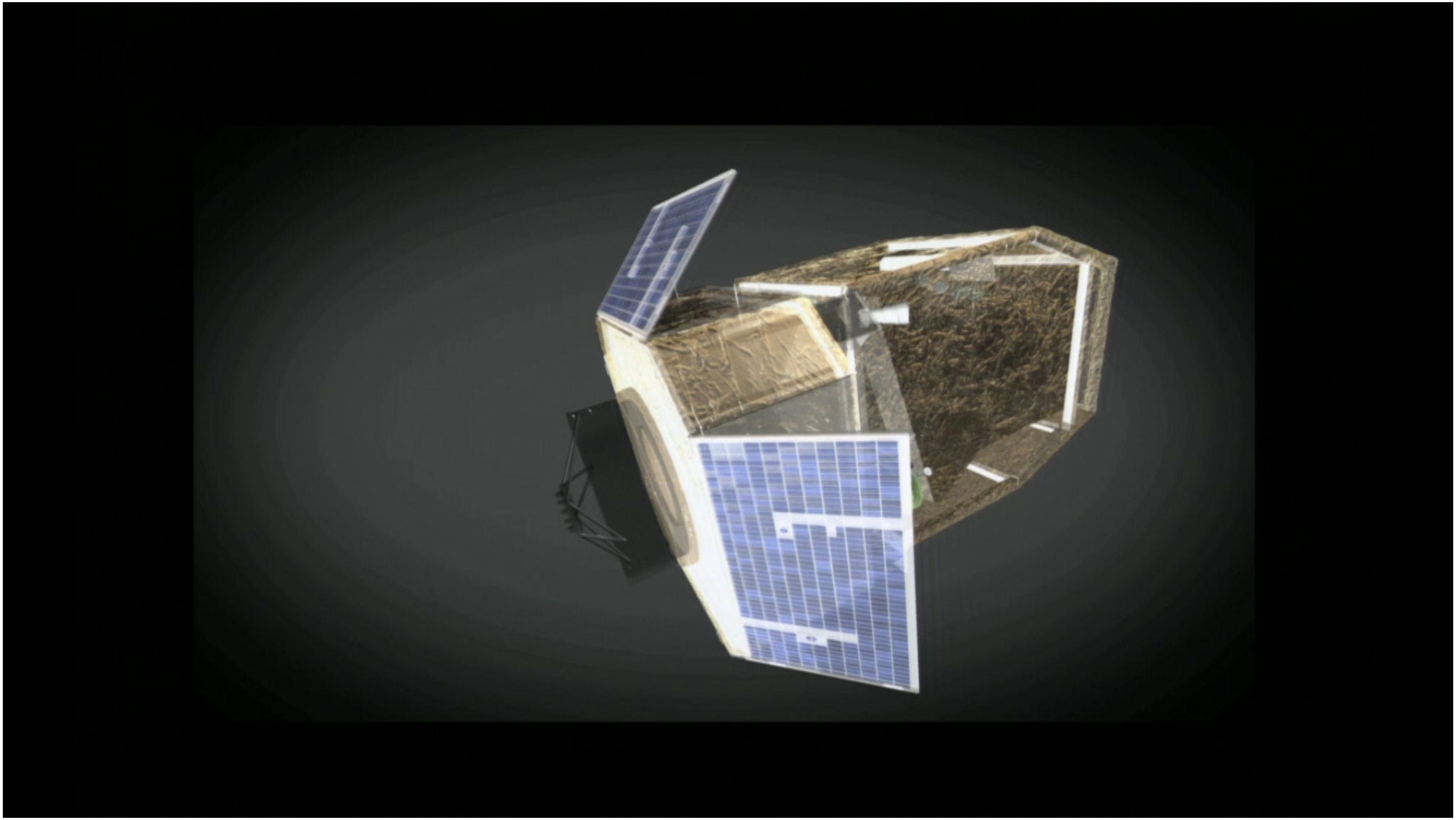


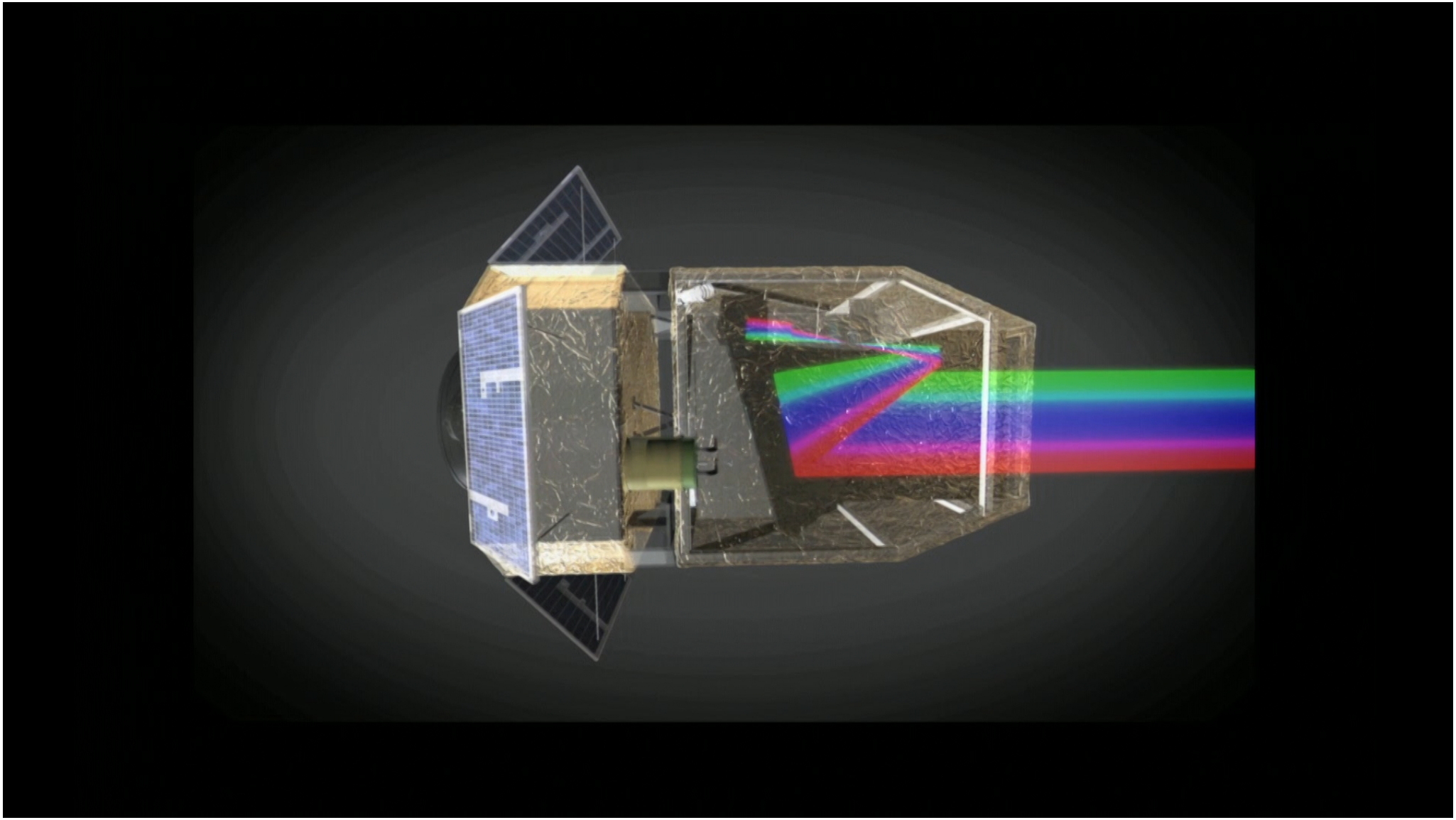


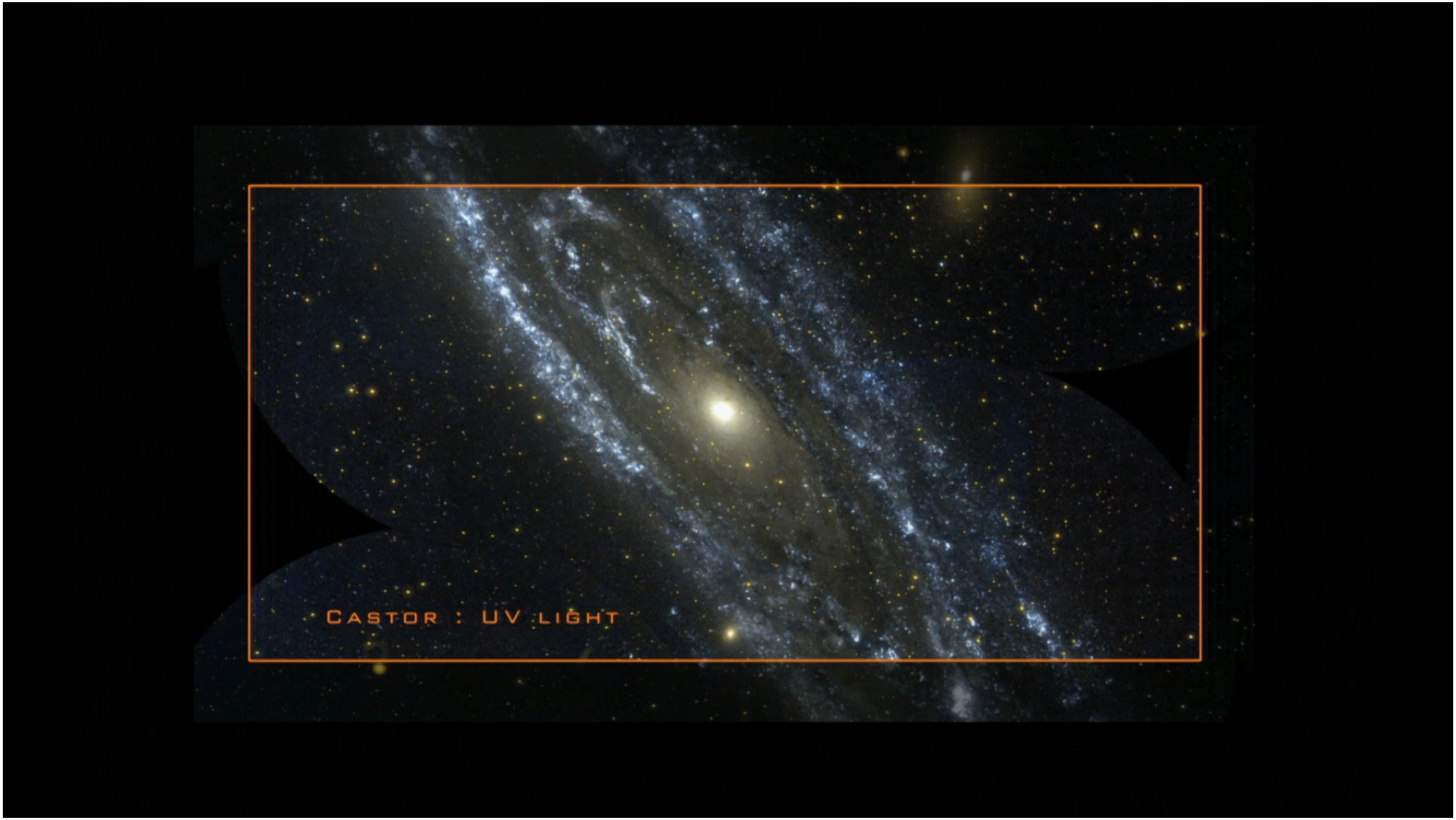


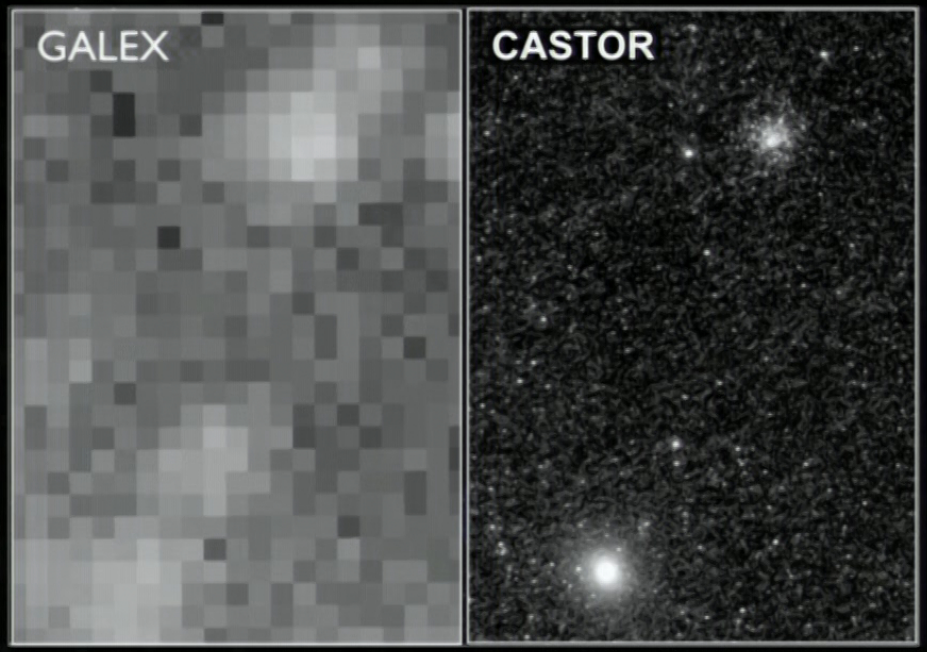


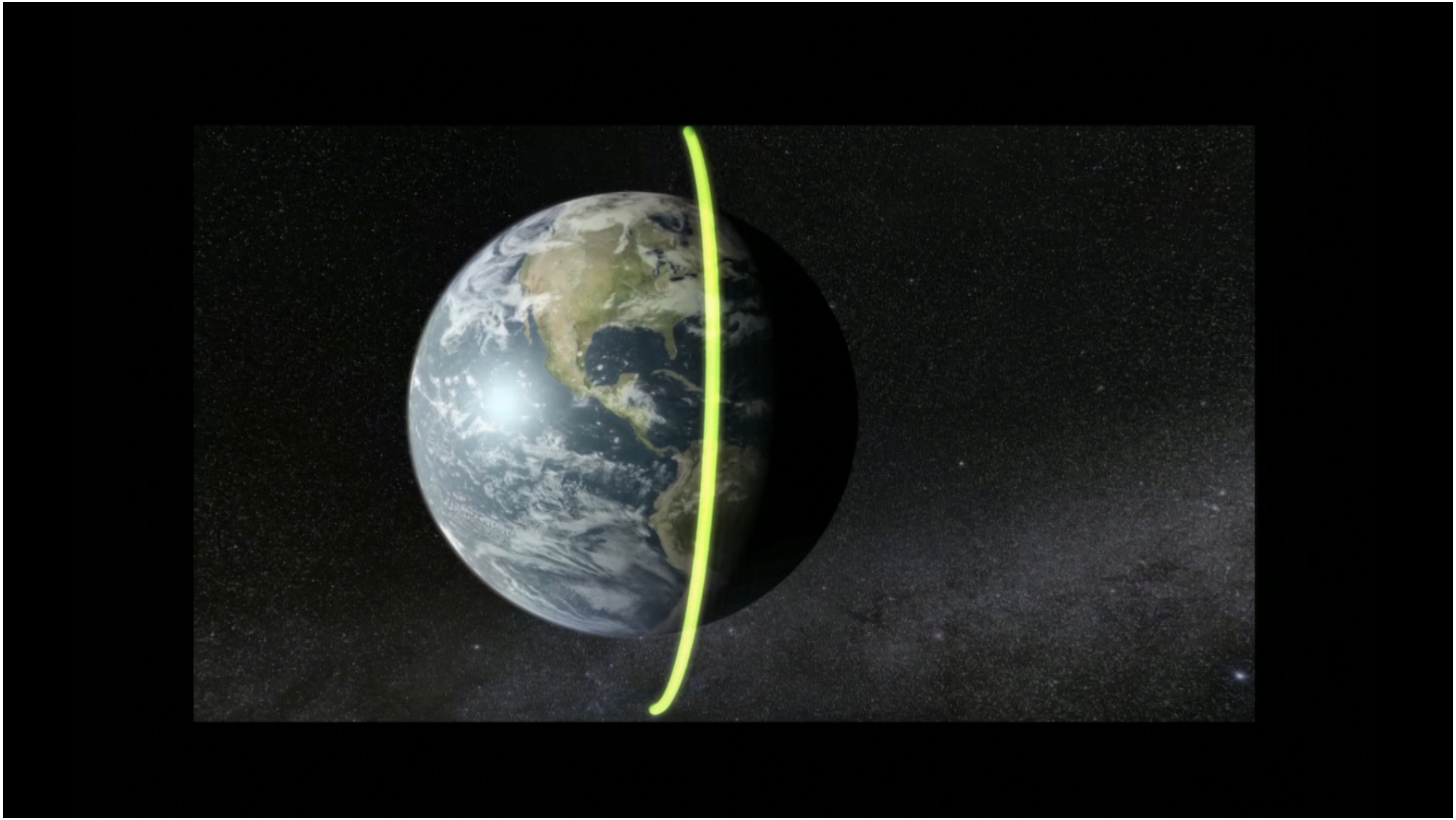


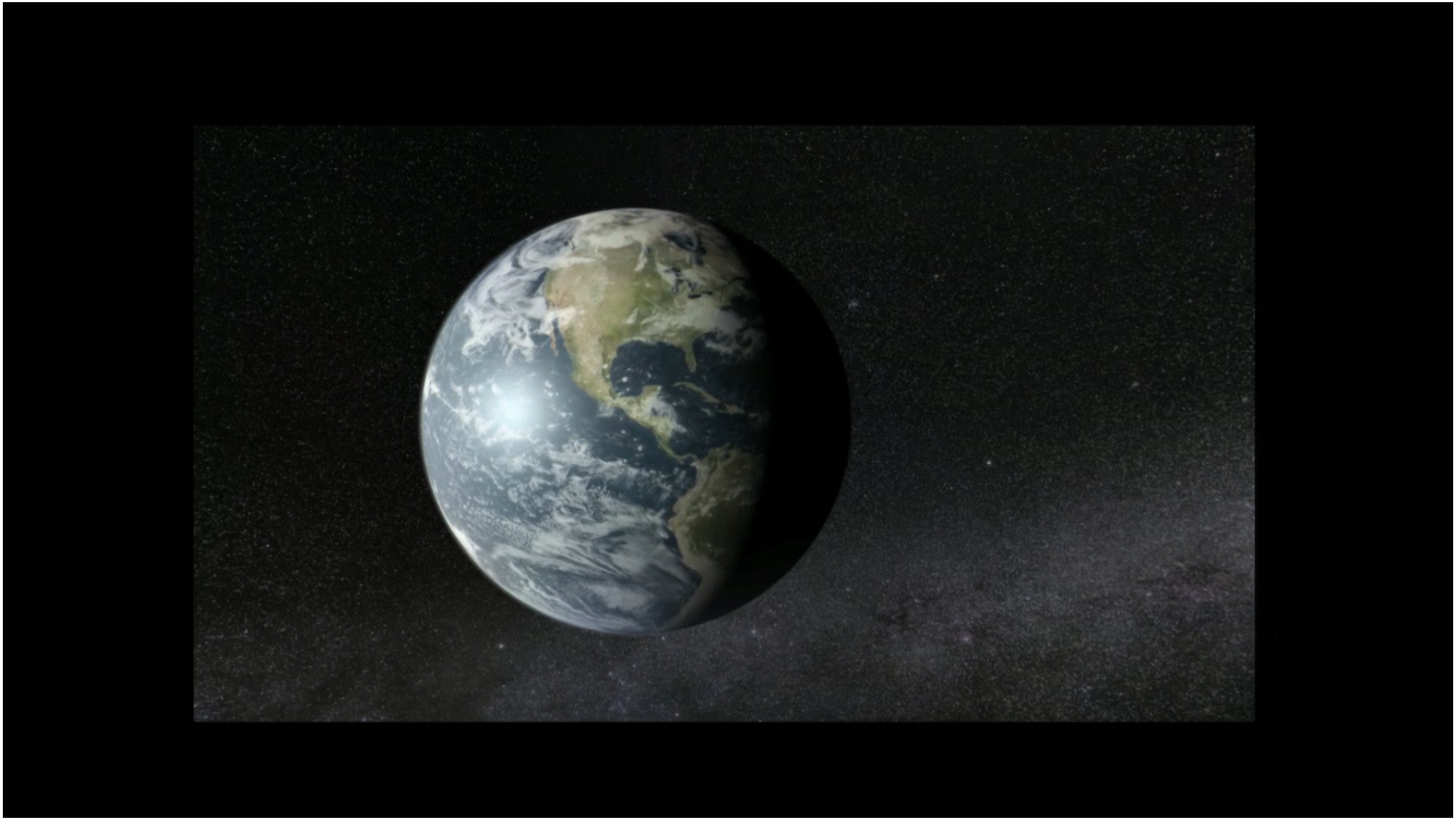


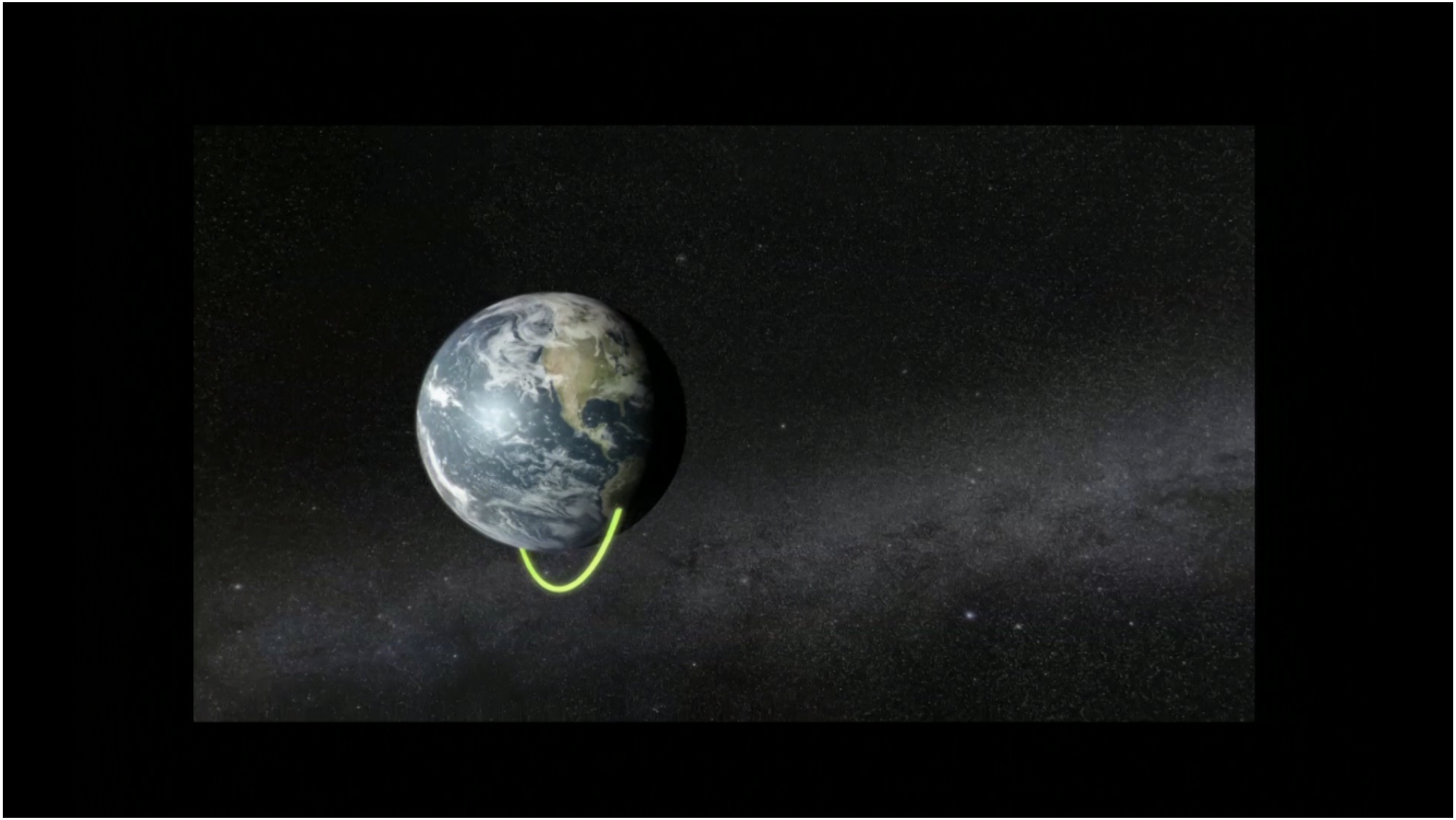


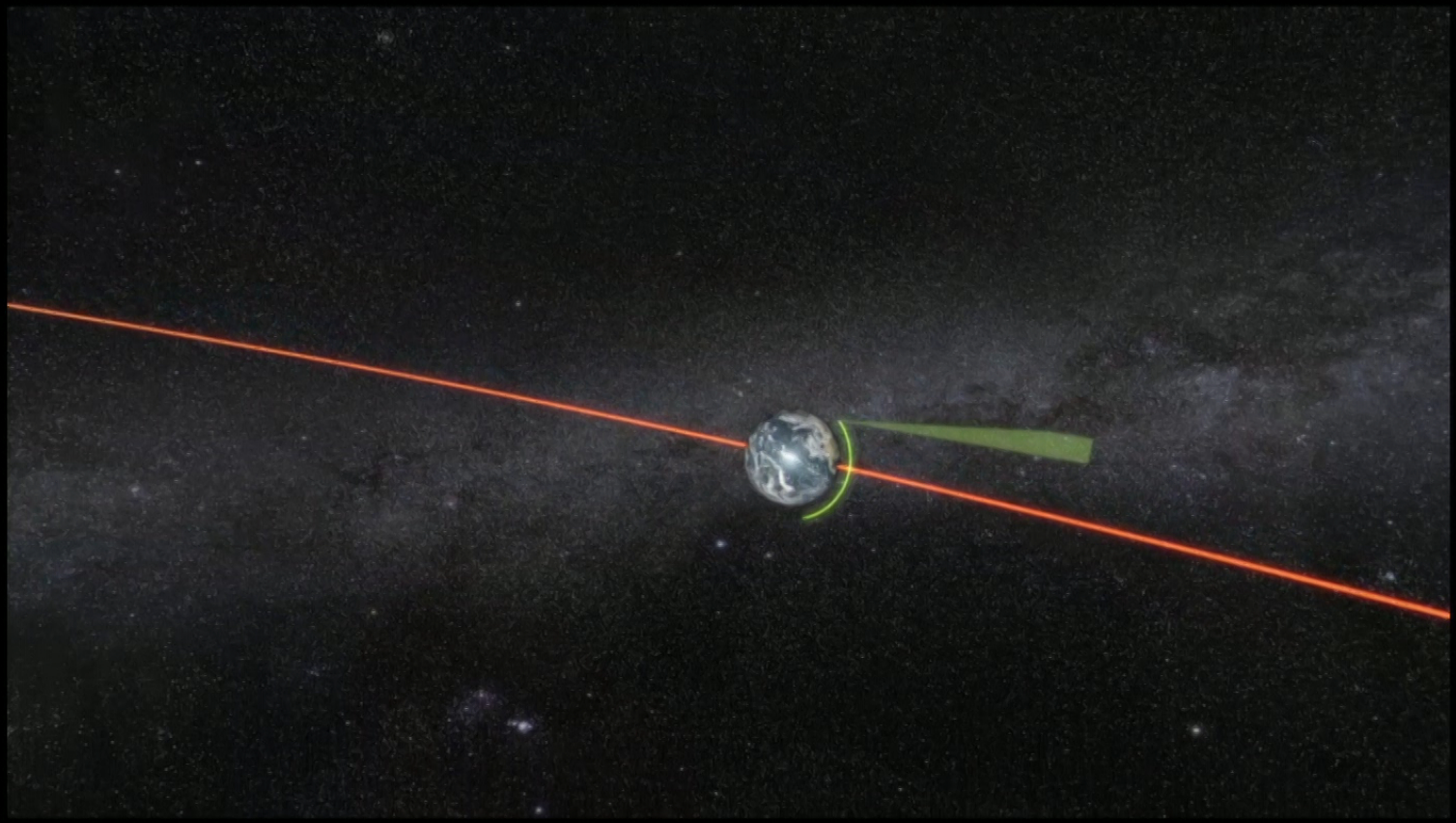

CASTOR : UV LIGHT

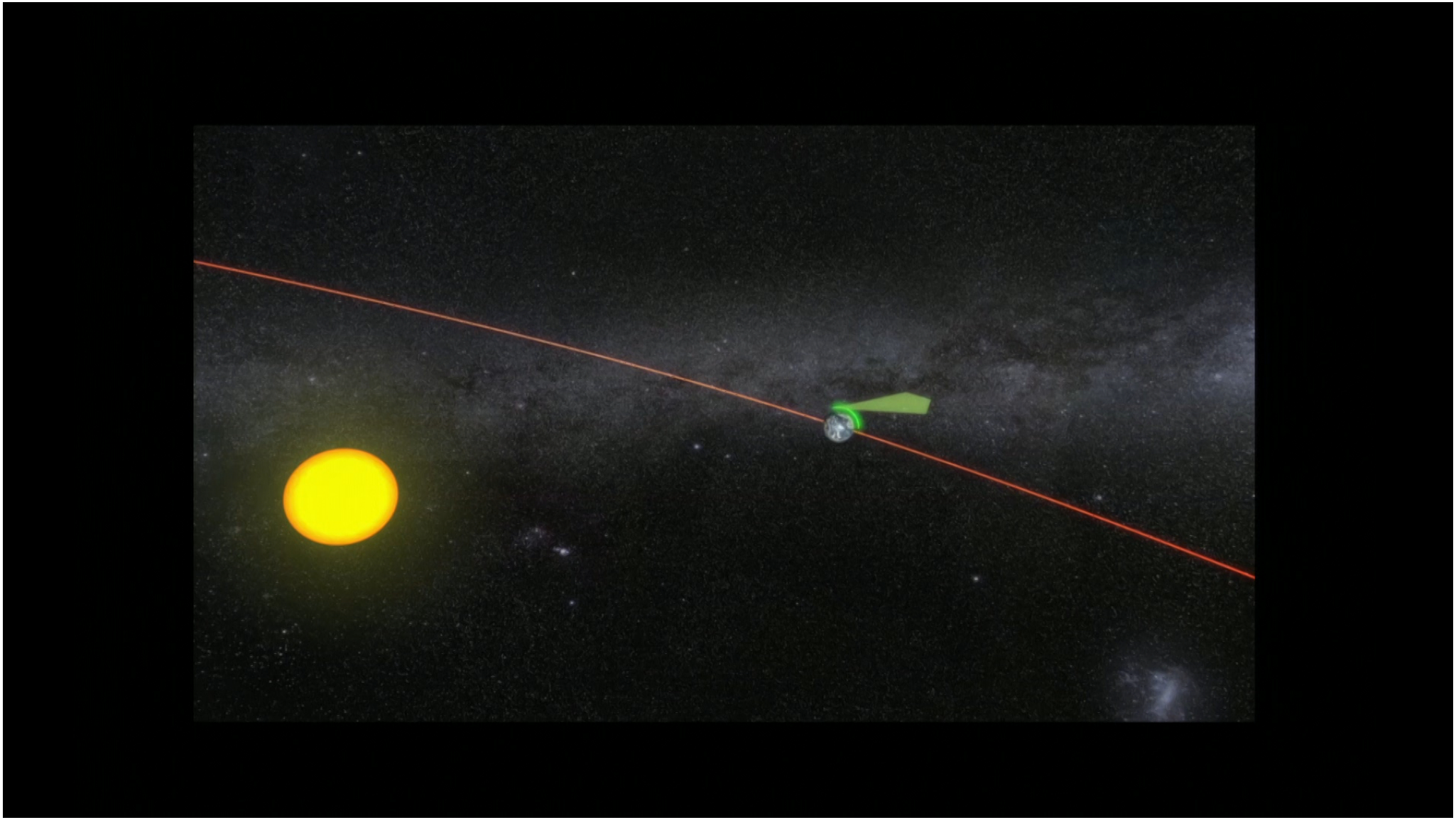

GALEX
CASTOR

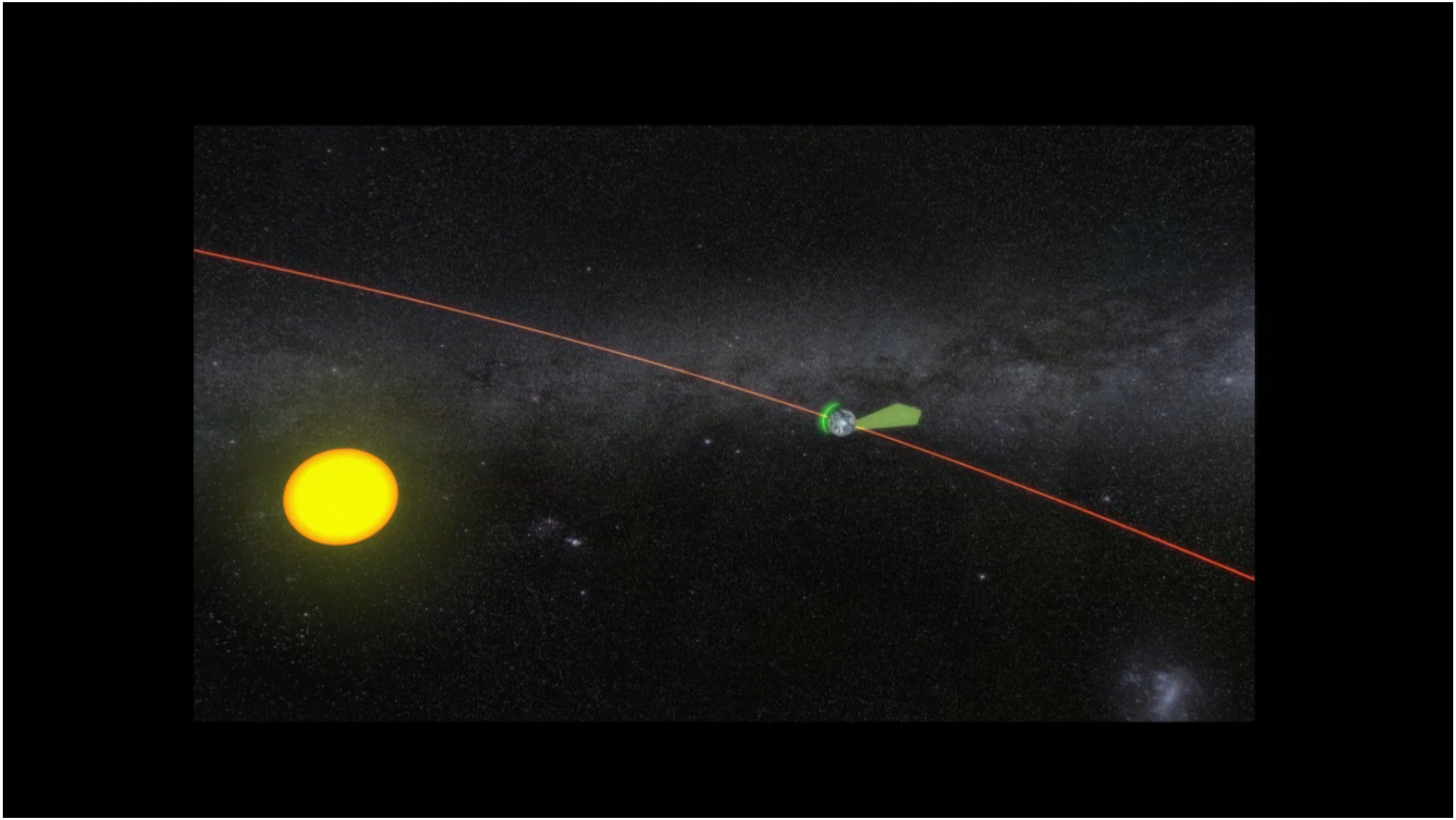


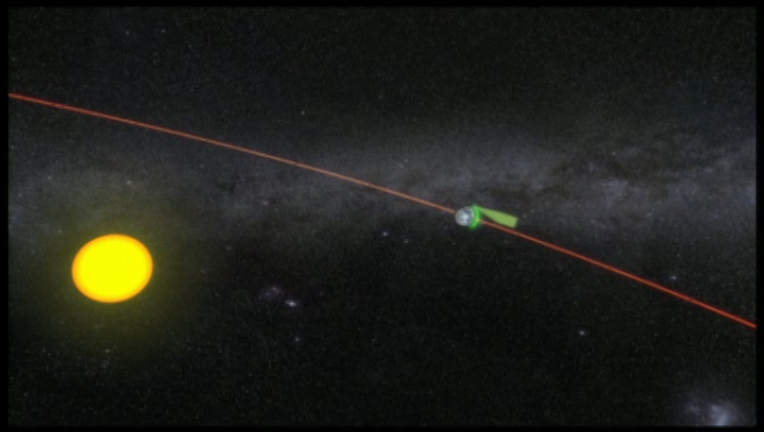


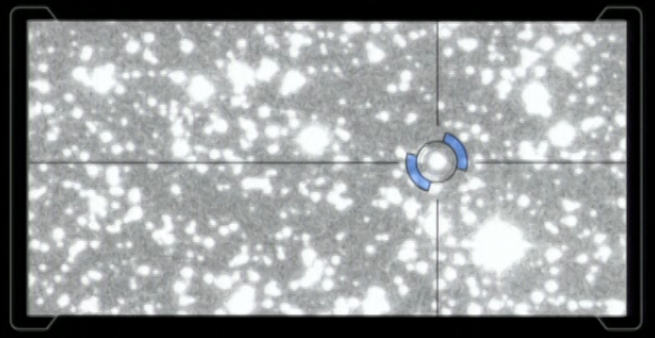






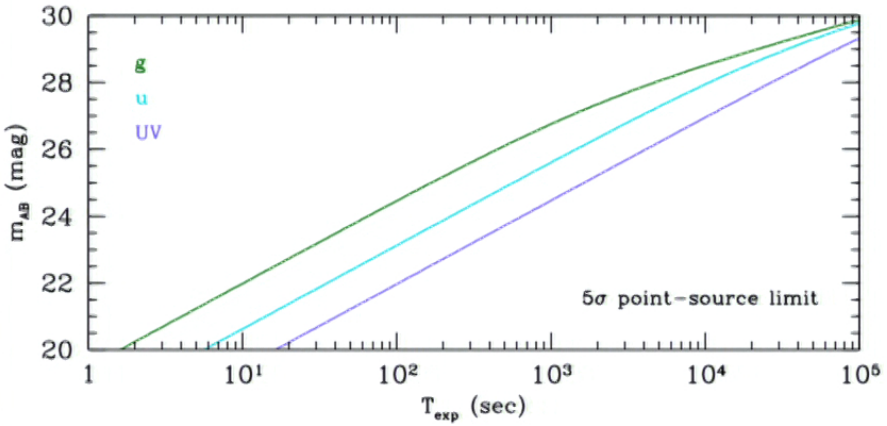


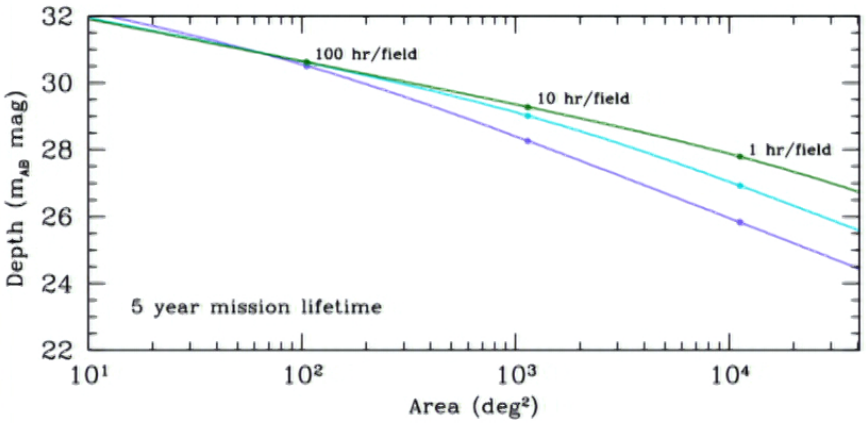




Options for CASTOR Surveys

- CASTOR has a nominal 5-year lifetime.
- current operations plan: a combination of legacy surveys and Guest Observer programs.





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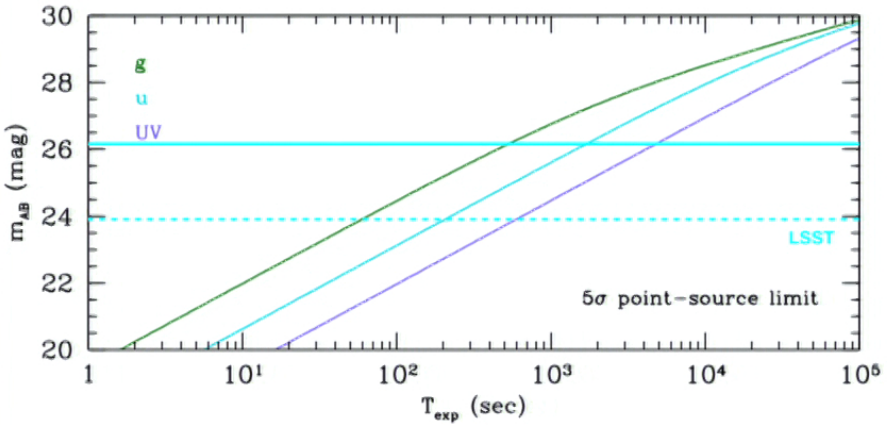

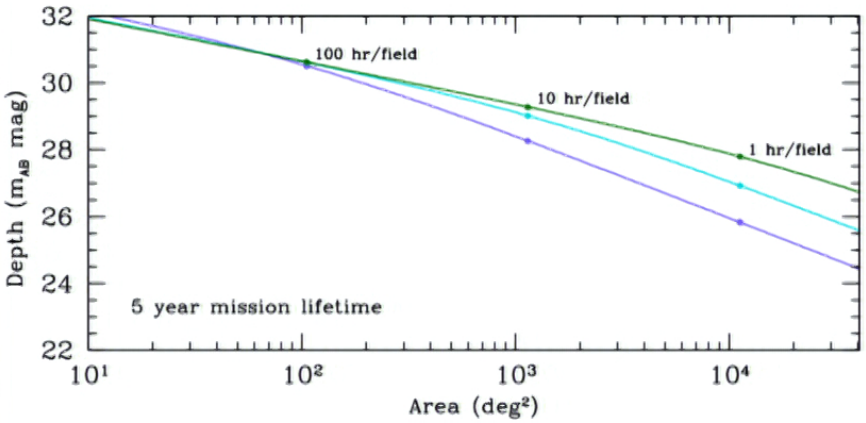

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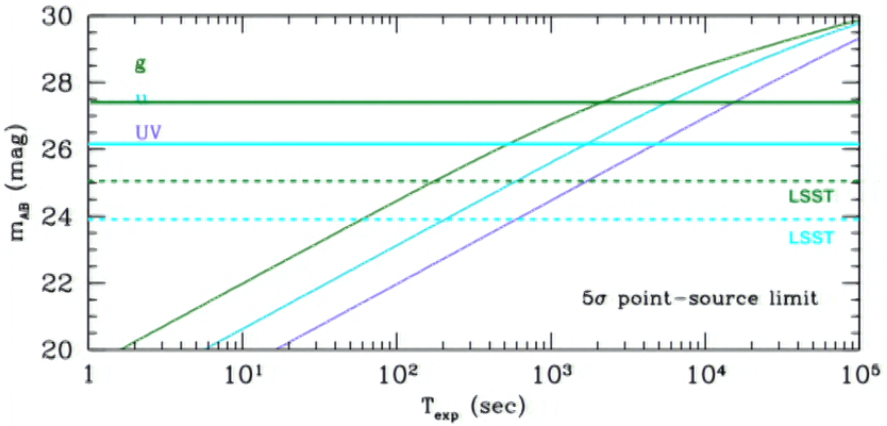
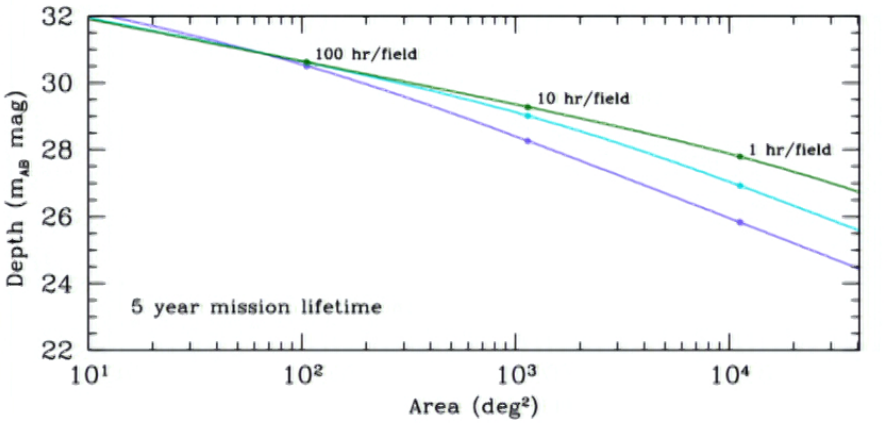
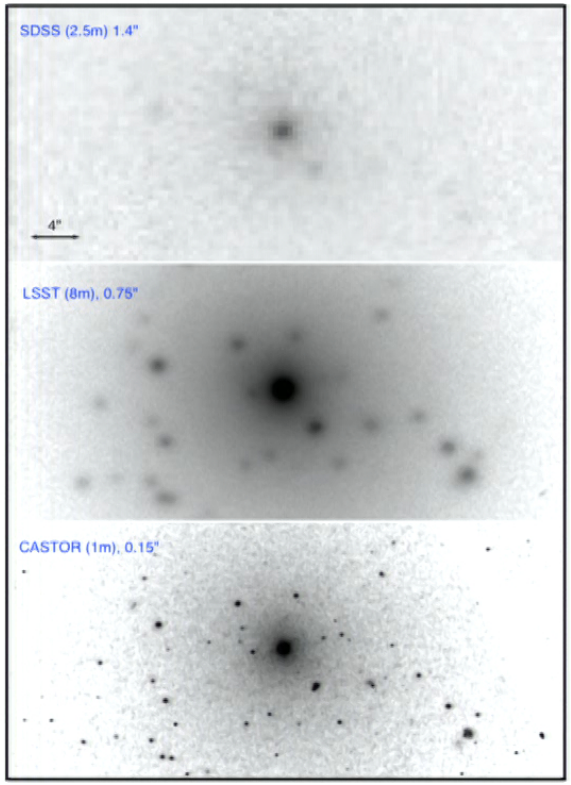
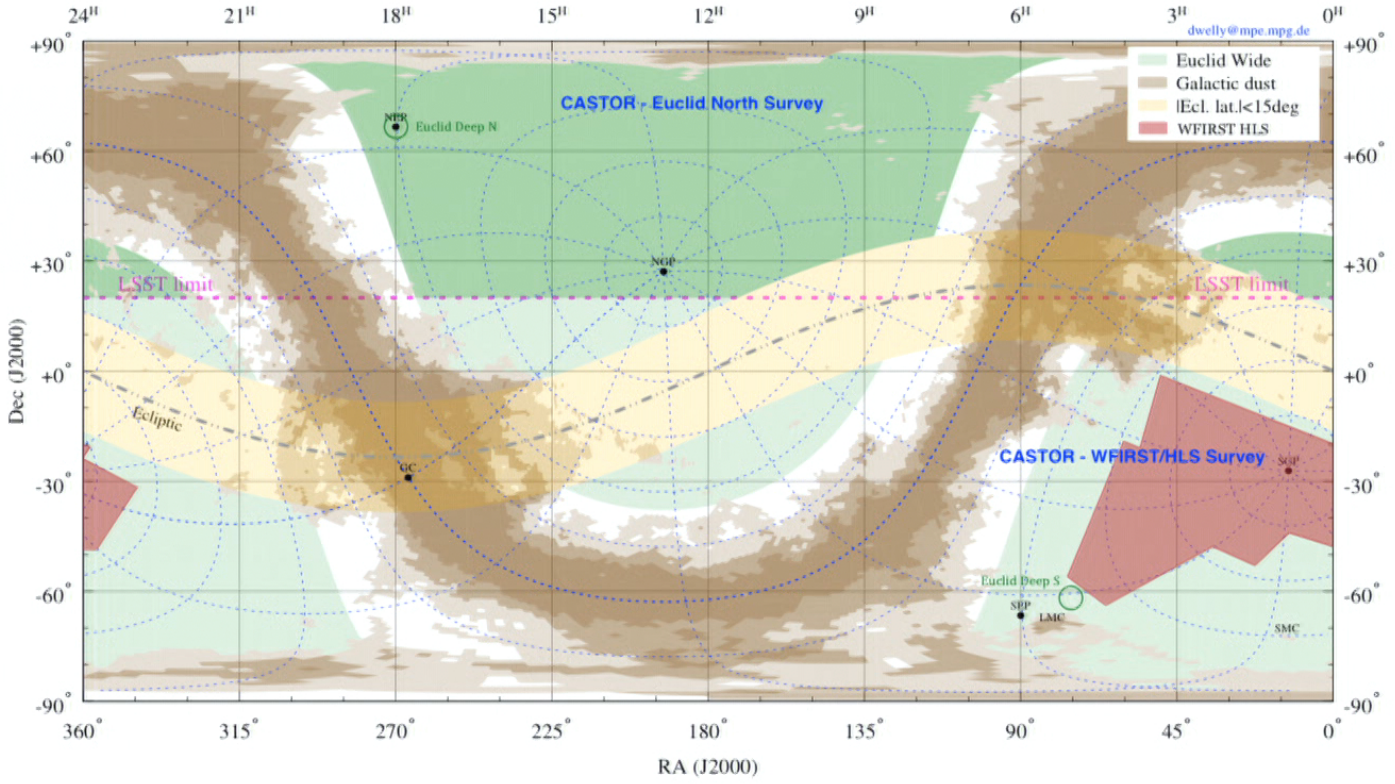






Options for CASTOR Surveys

- Consider two notional CASTOR surveys:
  1. deep coverage of the Euclid Wide Survey in the north (6100 deg^2)
  2. ultra-deep of the WFIRST HLS in the south (2213 deg^2)



CASTOR Science: Dark Energy, Weak Lensing

- Stage IV DE experiments (LSST, Euclid, WFIRST) 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.
- CASTOR's niches within the currently envisioned Stage IV landscape:

1. Photometric Redshifts:

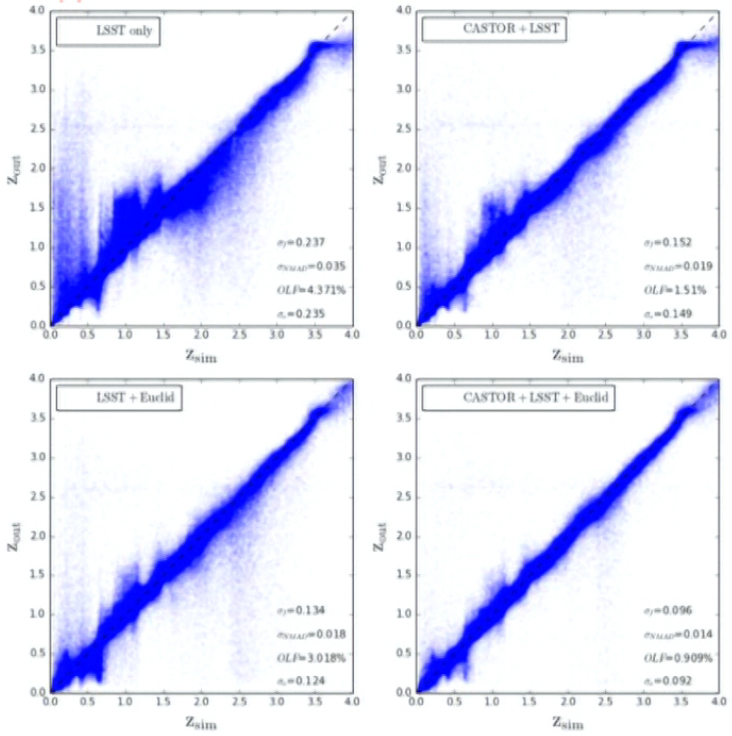
- short-wavelength bands for improved photometric redshifts, which are critical for DE measurements, particularly at low redshift.

2. Object detection and blending:

- high-resolution imaging in the blue to address the fundamental issue of blending, color mixing and object detection.

3. Shape measurements:

- a fourth shape measurement, in a unique wavelength region, to shed light on possible shape residual systematics as a function of wavelength.



Courtesy: Peter Capak and Shoubaneh Hemmati

CASTOR Science: Time Domain, GW Events

- Time domain astronomy is poised to "explode" in the 2020s (ZTF, LSST, LIGO, Virgo, etc).
- UV variable sky is relatively poorly explored, although early UV emission is critical for understanding the physical properties of the progenitors (kilonovae, GRB afterglows, TDEs, GW events).
- CASTOR's sensitivity at UV wavelengths would be unique among planned future facilities.

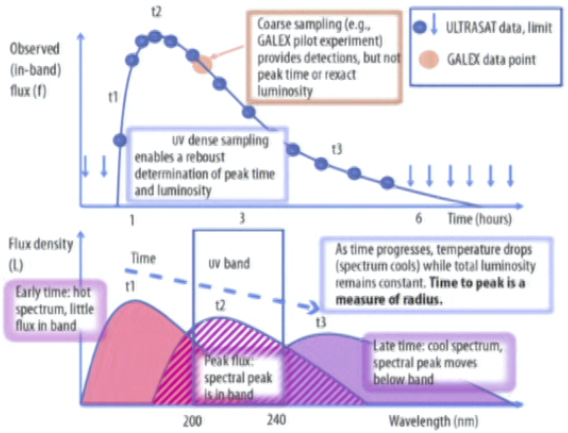
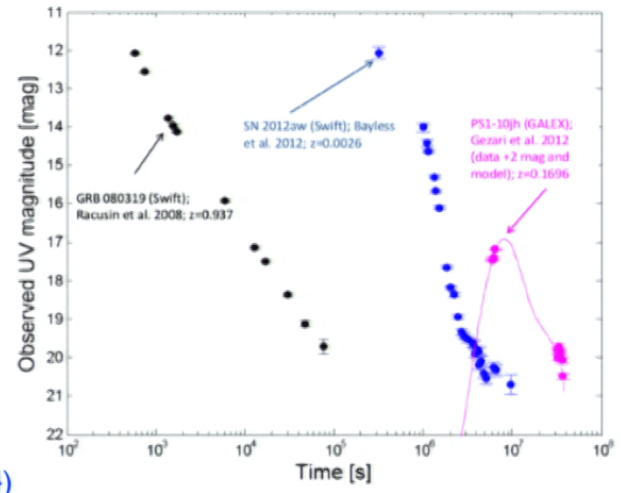


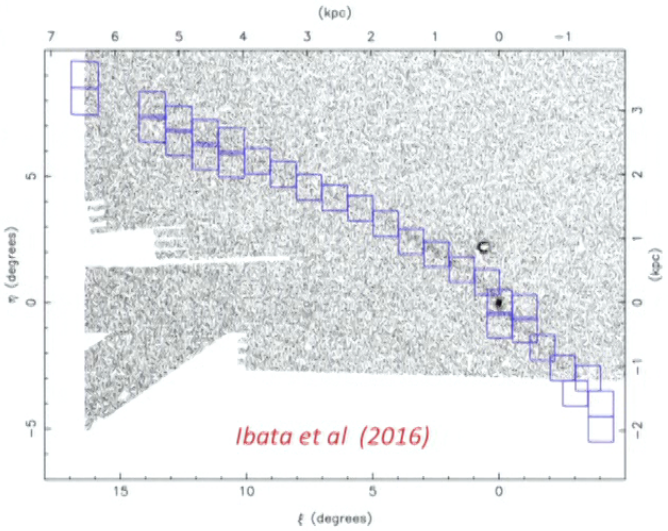
Figure 1. Bottom: a heuristic description of shock cooling emission from a massive star explosion. While the bolometric luminosity is almost constant, the decline in temperature leads to a rise and fall when observing in a given UV band. A well measured UV light curve (top) provides a measurement of the radius and surface composition of the exploding star. *ULTRASAT* is a proposed UV transient explorer—see Section 10.

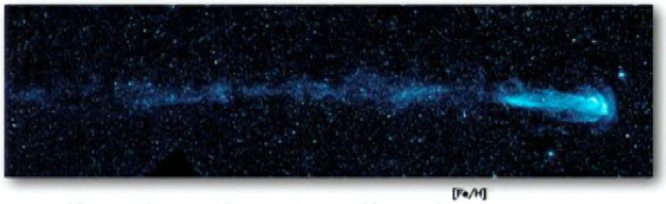


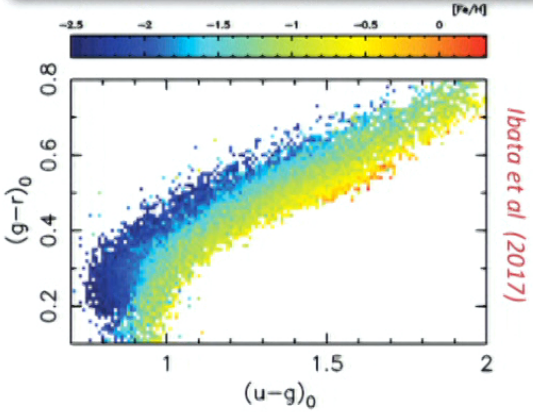
Sagiv et al. (2014)

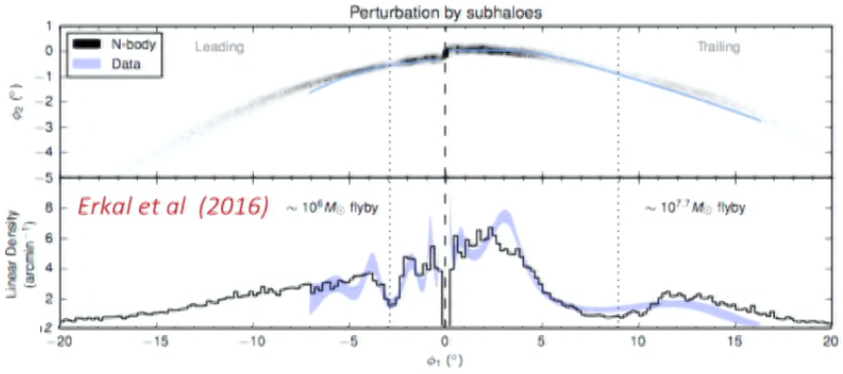
CASTOR Science: The Milky Way

- **Galactic Substructures.** Stellar streams, star clusters, ultra-faint and ultra-diffuse galaxies; tests of MOND and signatures of DM impactors.
- **Stellar Astrophysics.** Hot and massive stars; symbiotic binaries; degenerate stars in dense stellar systems; X-ray binaries and transients; pulsating variables; post-AGB stars and planetary nebulae; exoplanet hosts.
- **Extremely Metal-Poor Stars.** Identification from photometric indices (*Juric et al. 2009*); halo density distribution.
- **Galactic Cirrus and Foregrounds.** From UV/blue reflected light.





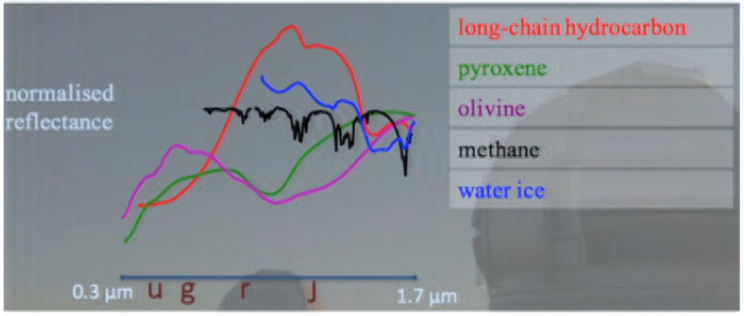


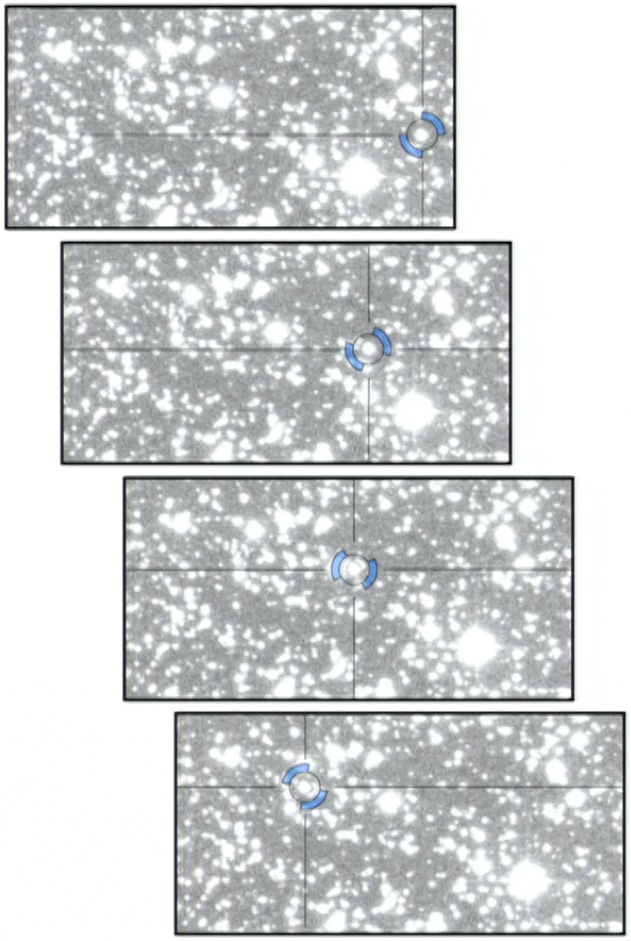


Science: Trans Neptunian Objects

- How many TNOs would be detected in a 2-year CASTOR survey of the WFIRST HLS?
- Combine the known distribution of high-latitude TNOs (Kavelaars et al. 2017) with TNO luminosity function of Fraser et al. (2014)
- Assume a cadence of 6x1200=7200s per pointing.
- **Estimated yield** = 2000 TNOs (~10% detected by LSST), with ~500 having ecliptic latitude ≳ 35 deg.

1. characterization of the smallest and most remote TNOs.
2. Surface chemistry constraints (including the presence of organic ices) for outer solar system objects are available from their UV-optical-IR SEDs.





Courtesy: JJ Kavelaars

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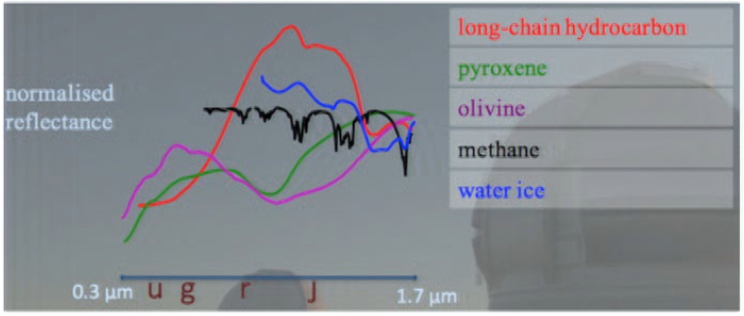

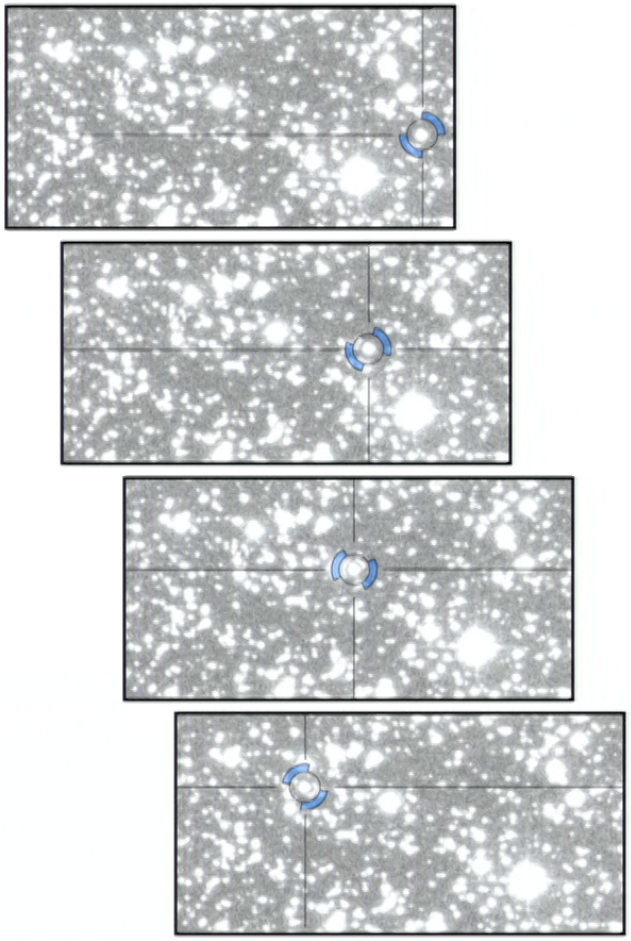

Courtesy: JJ Kavelaars

PI-NRC