Beyond the James Webb Space Telescope

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David Redding
Jet Propulsion Laboratory, California Institute of Technology

Marc Postman
Space Telescope Science Institute

Lee Feinberg
NASA Goddard Space Flight Center

H. Philip Stahl
NASA Marshall Space Flight Center

Cosmic Births to Living Earths

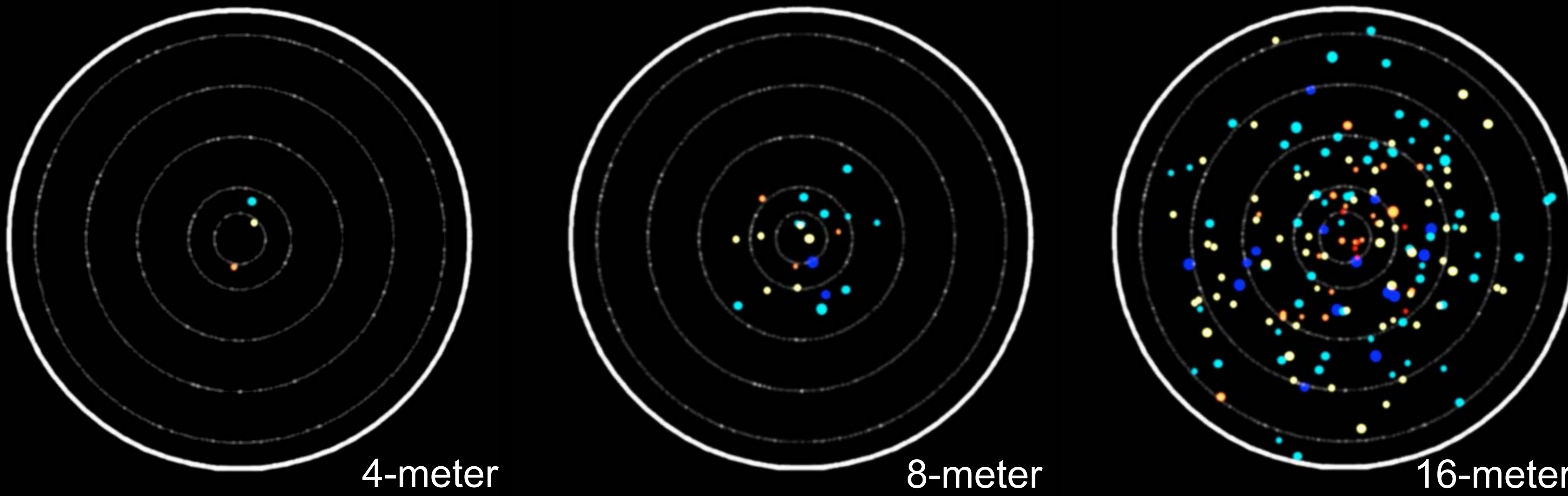
- Are we alone? How did we get here? These 2 fundamental questions can be addressed with a large UVOIR space telescope, with:
  - Large aperture
  - Starlight suppression to enable exoplanet observations
  - UV to NIR wavelength coverage
  - Diffraction-limited optical quality
- This paper examines the performance required of such a telescope.

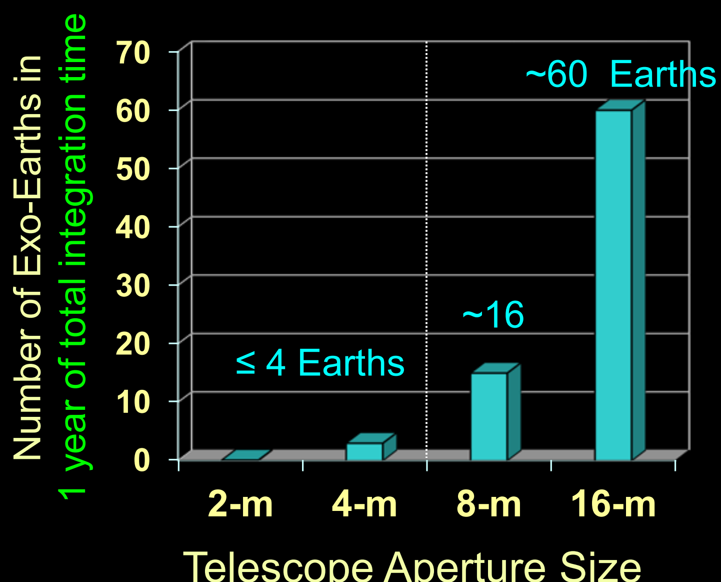
What Aperture?

- **Aperture diameter requirement will be based on *ExoEarth Yield*, to discover and characterize enough exoEarths to:**
  - Confirm η_{Earth} – the rate of occurrence of exoEarths around other stars
  - Establish η_{Life} – the rate of occurrence of the conditions for life on exoEarths
  - And to probe the actual presence of life on planets that could support it

- **Large aperture is needed for the angular resolution to probe the Habitable Zone, and the sensitivity to spectrally characterize sufficient numbers of exoEarth candidates**
  - For deep suppression of starlight and a small inner working angle
  - Covering a large volume of space
  - With spectral resolution to find water, and then O_2 and O_3, and then methane

Based on the DRM simulation code from C. Stark et al. 2014.
Assumes 10% of solar type stars have Earth-like planets in their habitable zone.





Estimated number of Earth-like planets around long-lived stars for which spectra can be obtained as a function of the space telescope's primary mirror diameter.

$$N_{Earth} \sim 25\,(D / 10m)^{1.8}(t / 1\ yr)^{0.4}$$

The number of exo-Earth spectra obtained with a given aperture can be increased by extending the total mission time allocated to exoplanet observations

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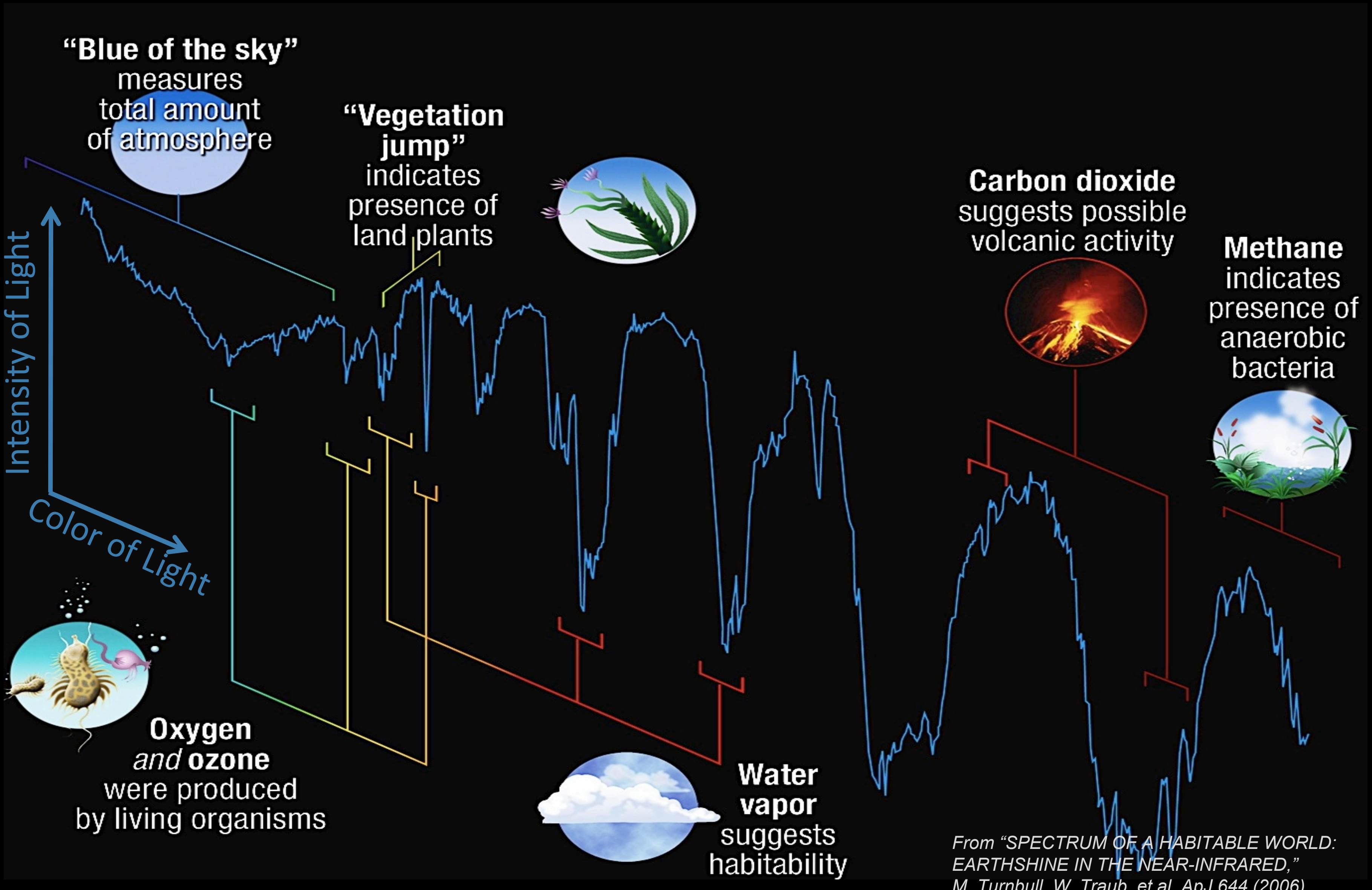
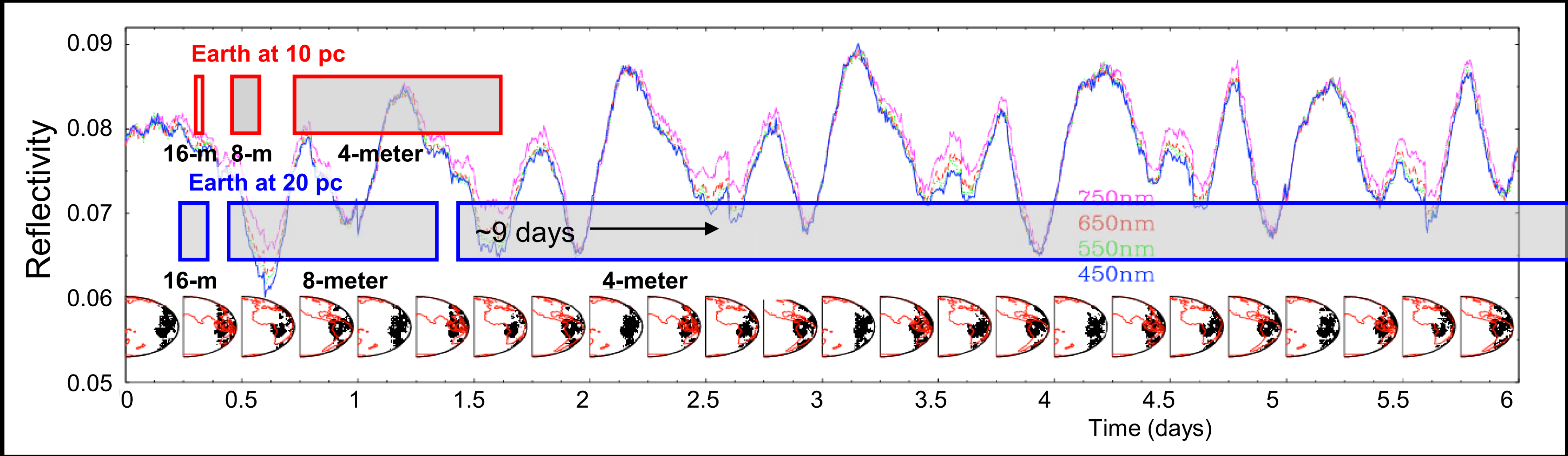
- **Under current assumptions, a "10 meter-class" telescope is the minimum size to provide an exoEarth sample size sufficient to establish η_{Life} with confidence**

The signature of life is likely to be encoded in the spectra of a planet's atmosphere.



Detecting Diurnal Photometric Variability in Exoplanets

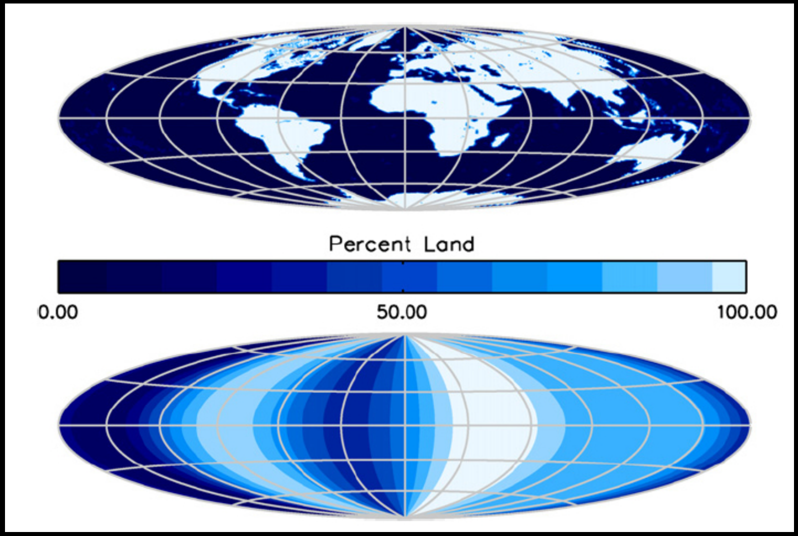
Ford et al. 2003: Model of broadband photometric temporal variability of Earth



Require S/N ~ 20 (5% photometry) to detect ~20% temporal variations in reflectivity.

Reconstruction of Earth's land-sea ratio from disk-averaged time-resolved imaging with the EPOXI mission.

A 10m class space telescope will have the power to make such maps for many exoplanets.



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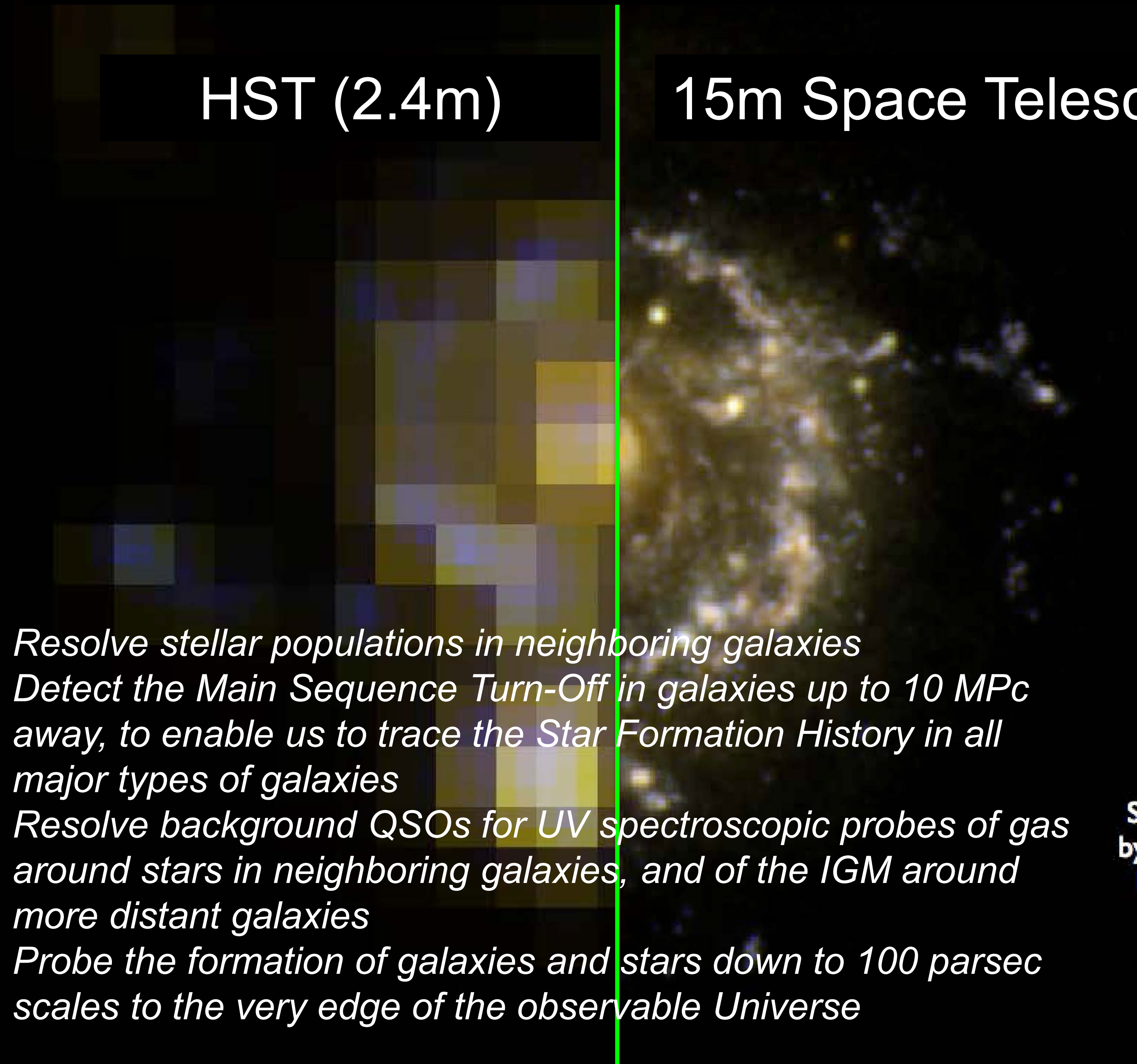
- **Under current assumptions, a "10 meter-class" telescope is the minimum size to provide an exoEarth sample size sufficient to establish η_{Life} with confidence**

- **Astronomy and astrophysics requirements will also be met with a 10 meter-class aperture or larger…**

z = 2 Galaxy: Look-back time = 76% age of universe



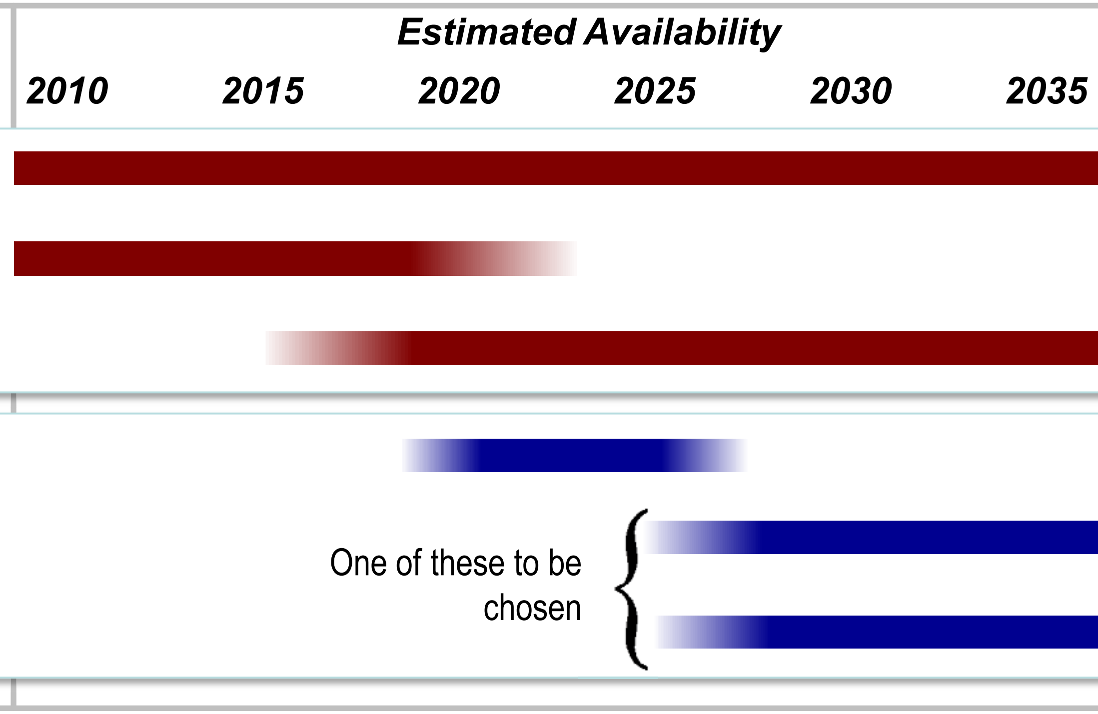
- *Resolve stellar populations in neighboring galaxies*
- *Detect the Main Sequence Turn-Off in galaxies up to 10 MPc away, to enable us to trace the Star Formation History in all major types of galaxies*
- *Resolve background QSOs for UV spectroscopic probes of gas around stars in neighboring galaxies, and of the IGM around more distant galaxies*
- *Probe the formation of galaxies and stars down to 100 parsec scales to the very edge of the observable Universe*

Simulated Galaxies by HydroART Team Primack/Ceverino Klypin/Dekel

Simulated Images by Greg Snyder (STScI)

Approximate Launch Vehicle Availability

		Shroud Size	Mass to L2
EELV-Class	Atlas V 551	4.6x11 m	6,100 kg
	Delta IV Heavy	4.6x11 m	9,800 kg
	Falcon 9 Heavy	4.6x11 m	14,000 kg
SLS	SLS Block 1	5x14 m	25,000 kg
	SLS Block 2 8.4m	8.4x29 m	50,000 kg
	SLS Block 2 10m	10x31 m	50,000 kg

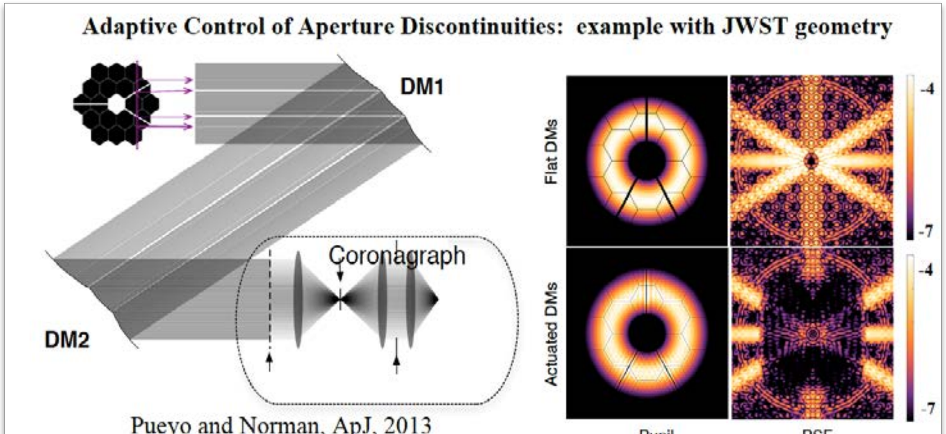


- **EELV-class launch vehicles have limited shroud volume**
  - Dynamic envelope is an approximately 4.6 m diameter by 11 m circular cylinder
- **Space Launch System (SLS)**
  - Block 1 offers more mass capability, but only the same 4.6 m shroud diameter
  - Block 2 with a 10 m shroud could fly an 8.4 m monolithic aperture
  - Block 2 with an 8.4 m shroud could fly a scaled-up 16 m ATLAST

Monolith or Segmented?

Candidate Aperture Architecture	Meets Threshold Reqts	Scalable to Apertures > 8m?	Launch Options	Heritage	Relative Mass Areal Density	Relative Complexity	Tech Issues
4m aperture monolith	No	No	Atlas V 551; Falcon 9H; SLS Block 1	HST	High	Low	Mirror scale-up; Thermal and dynamical stability; coronagraph performance
8m aperture monolith	Yes	No	SLS Block 2 with 10m shroud only	HST	High	Medium	Mirror scale-up; Thermal and dynamical stability; coronagraph performance
10m-class segmented aperture, deployed on orbit	Yes	Yes	Delta IV H; Falcon 9H; SLS Block 1	JWST	Low	High	Thermal and dynamical stability; coronagraph performance
16m-class segmented aperture, deployed on orbit	Yes	Yes	SLS Block 2 with 8.4 or 10m shroud	JWST	Low	High	Mirror scale-up; Thermal and dynamical stability; coronagraph performance
>8m segmented aperture, assembled on orbit	Yes	Yes	Various; requires new infrastructure	JWST, ISS	Low	High	On-orbit assembly; stability; coronagraph performance

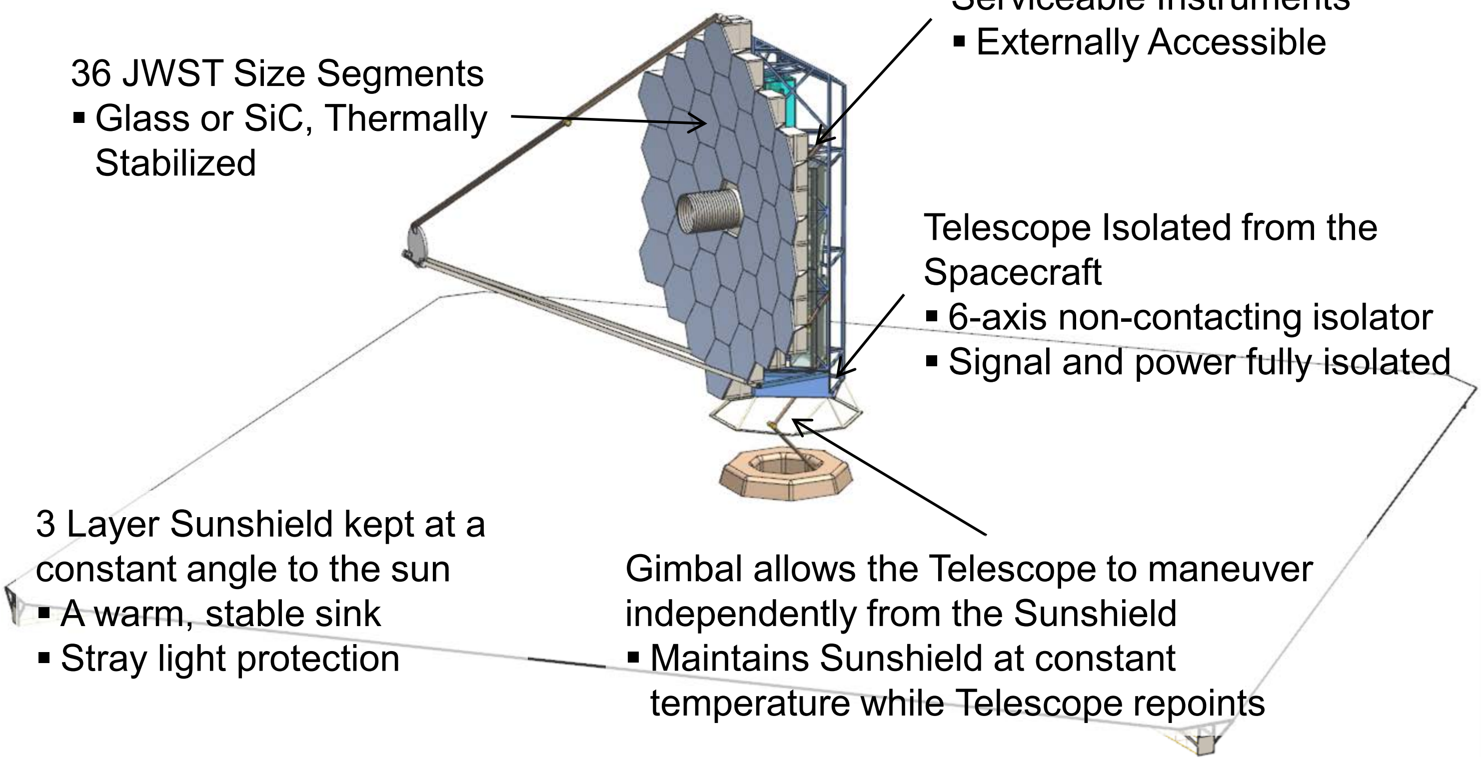
- **Segmented apertures…**
  - Can meet threshold science requirements at 10m
  - Scalable to larger sizes if requirements change
  - Can be launched using existing LVs to 12m
  - Can be assembled to sizes > 12m
- **If NASA builds the SLS Block 2…**
  - A 16 m deployed telescope could be launched
  - An 8 m monolith becomes an option if the 10 m shroud is provided



- **Coronagraph for ExoPlanet imaging**

9.2 Meter ATLAST Telescope

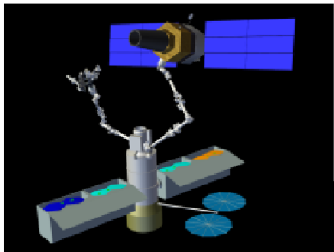
JWST-like deployment approach fits 10m-class aperture into Delta 4-H shroud volume

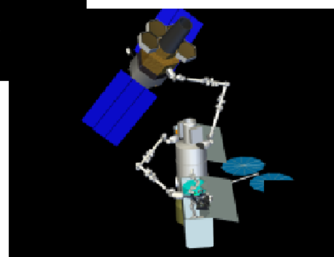


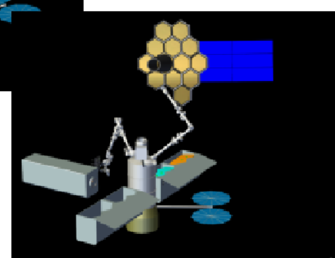
Design similarities leverage many JWST lessons learned, while avoiding some key cost drivers

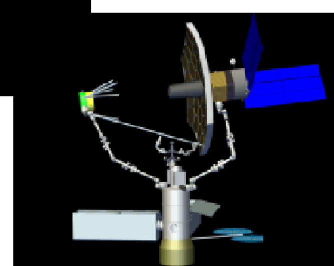
An On-Orbit Assembly Concept

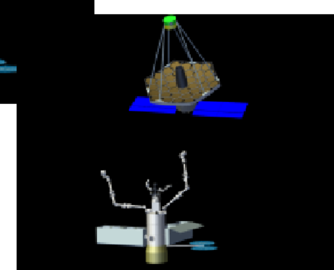
- **OPTIIX Feed-Forward concept (JPL/GSFC/JSC/STScI, 2012)**
  - **Observatory uses 5 Atlas V 551 LV launches**
    - LV cost ~$440M each

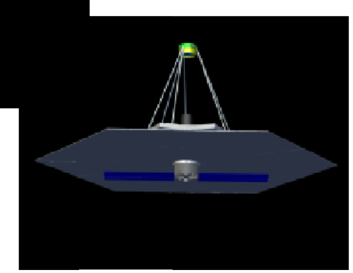








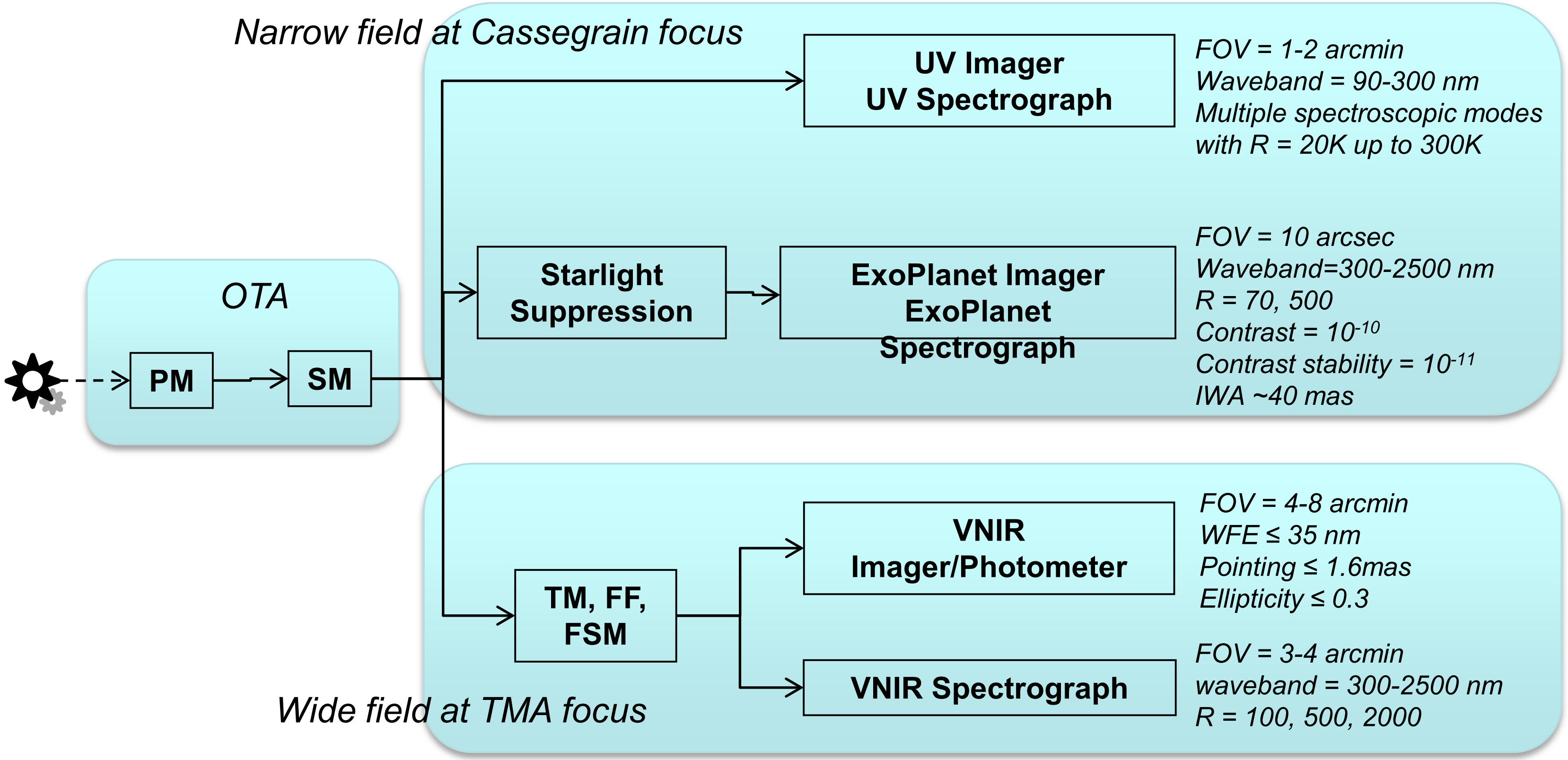




20 Modules for Assembly

- **Segmented 17m aperture**
- **Assembled robotically**
  - ISS-derived robotic infrastructure to be developed by others
  - ISS, HST and OPTIIX-developed telescope assembly technology
  - Active optics correct mechanical alignments
- **System cost not estimated**

Notional Science Instrumentation



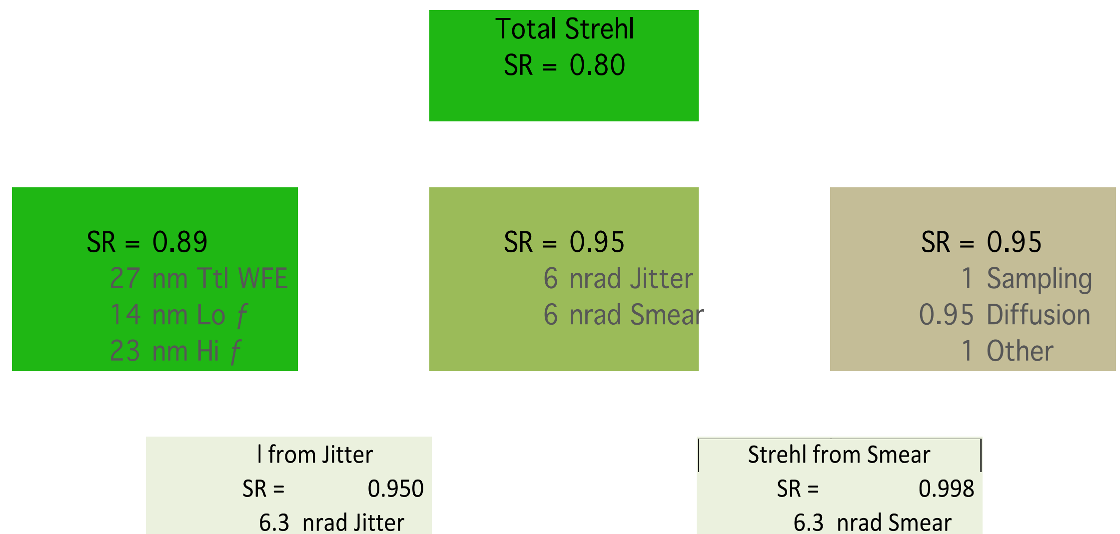
- **Placing UV and ExoPlanet instruments at Cass focus minimizes bounces, to maximize throughput and minimize aberration**
- **TMA focus affords wider (12x6 amin) field for VNIR instruments**
  - Room for 2 guider cameras as well

Flow Down from Strehl to Telescope WFE

Telescope Parameter	Consensus Value
Primary mirror diameter	≥ 8 meters
UV Sensitivity	(900 Å) 1100 Å – 3000 Å
Vis / NIR Sensitivity	0.3 µm – 2.5 µm (8 µm)
Pointing stability	~1.3 – 1.6 mas
WFE:	
General Astrophysics	Diffraction limited at 0.5 µm (~35 nm WFE)
Exoplanet Observations	~0.01 nm WF stability over ~600 sec (w/ actively controlled coronagraph)

Instrument Parameters	Consensus Value
Starlight suppression	10^{-10} down to IWA ~40 mas
UV Spectroscopy	R = 20,000 – 150,000
Exoplanet Spectroscopy	R = 70 - 500
Vis / NIR Imaging	FOV: 4 – 8 arcmin, Nyquist
UV Imaging	FOV: ~1-2 arcmin

- **Driving requirements for Strehl:**
  - "Diffraction limited at 500 nm," interpreted as 80% Strehl
  - "Pointing stability < 1.6 mas," limits the LOS contribution to Strehl



- **Flowdown, assuming 10 meter class aperture:**
  - Total WFE ≤ 27 nm RMS
  - Jitter and smear ≤ 6.3 nrad
- **Other image quality requirements: Encircled energy; Ellipticity; SNR**
- **Must meet Exoplanet Imager capture and stability requirements…**

Flow Down from Telescope WFE to Mirrors

27 nm Total
14 nm Lo *f*
23 nm Hi *f*

32 nm Spec
18 nm Margin
80 % EE

WFE at TMA imaging focus, after Wavefront Control

SM Alignment Control

	Static WFE 24 nm 10 nm Lo *f* 22 nm Hi *f*	4 4 0		10 nm 8 nm Lo *f* 6 nm Hi *f*	
22 nm 8 nm Lo *f* 21 nm Hi *f*	8 nm 7 nm Lo *f* 4 nm Hi *f*	5 nm 1 nm Lo *f* 5 nm Hi *f*	5 nm 5 nm Lo *f* 2 nm Hi *f*	rument Errors 1 nm 1 nm Lo *f* 0 nm Hi *f*	8 nm 6 nm Lo *f* 6 nm Hi *f*
9 nm 5 nm Lo *f* 8 nm Hi *f*	19 nm 3 nm Lo *f* 19 nm Hi *f*	7 nm 5 nm Lo *f* 5 nm Hi *f*	4 nm 4 nm Lo *f* 2 nm Hi *f*	3 nm 3 nm Lo *f* 1 nm Hi *f*	3 nm 3 nm Lo *f* 0 nm Hi *f*

- **Static errors are post-control residuals**
  - Doable with current technology
- **Drift errors occur over WF sensing intervals of hours to days**
  - Short-term drift is another matter…

Preliminary Look at Contrast

Contrast	=	1E-10
Static WFE	=	12 pm
Dynamic WFE		

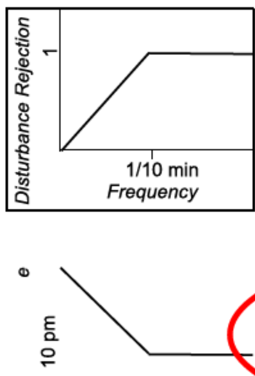
Static WFE is with respect to a speckle-nulling condition achieved in XPI closed loop DM control

- *WFE-to-contrast from Shaklan et al*

Periodic XPI WFS&C

Periodic OTA WFS&C

Low BW XPI WFS&C

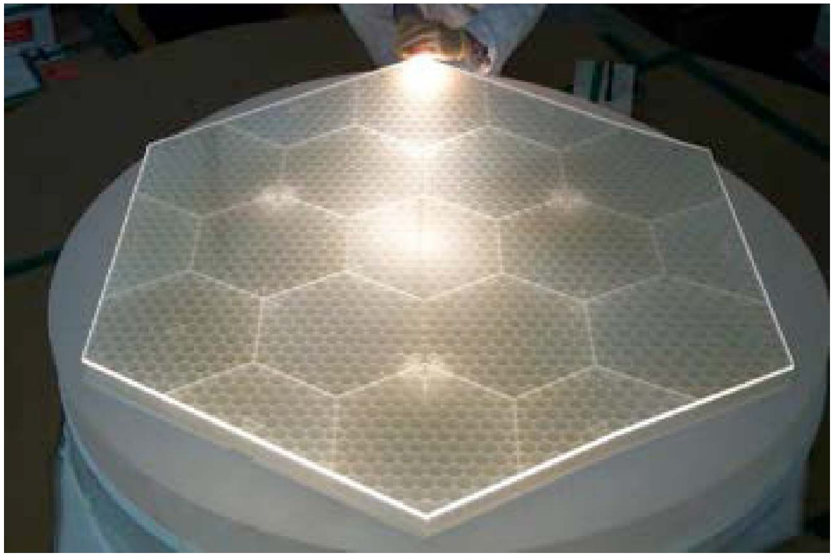


XPI WFS&C is signal limited to a bandwidth < 1 per 10 minutes

Telescope disturbances faster than 10 minutes must be < 10 pm

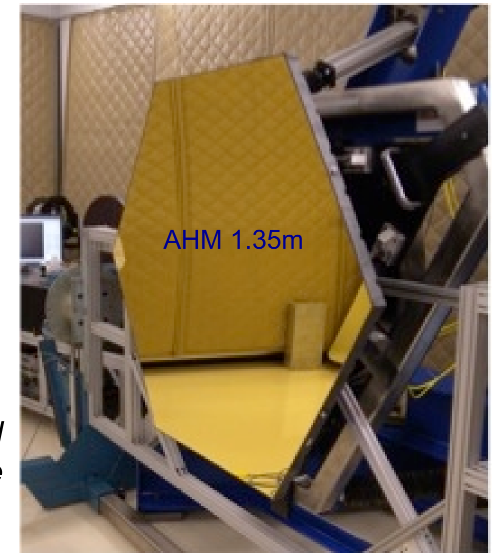
- **ExoPlanet Instrument (XPI) adds more WF control stages to achieve 20 pm WFE and 10 pm stability**
  - Sensed by low- and mid-spatial frequency WF sensing; plus Metrology
  - Actuated by Deformable Mirrors (DMs)
- **OTA WF errors below the XPI bandwidth < 10 pm over 10 min**

Mirror Technology



MMSD Lightweight ULE Segment Substrate

AHM SiC-based Segment Substrate



- **Primary mirror segment technologies have been developed at the needed size by NASA and others**
  - ULE glass and SiC-based designs offer alternatives
    - Thermal control for figure stability: design and material differences affect performance
    - Figure control: few actuators, many, or none
  - Both are lower cost and faster to make than JWST Beryllium mirrors
- **Limited further development could demonstrate required stability**
  - Complete and test mirror *systems*, including UV quality, actuation and thermal control, to ATLAST specifications

Technology Recommendations

Development of internal coronagraph designs capable of 10^{-10} contrast at an inner working angle of 2-3 λ/D, with an obscured, segmented aperture, suitable for operation with a 10m-class telescope; and concurrent **development of large starshade designs** suitable for operation with a 10-meter-class telescope.

Investment in segmented mirror systems, to prove performance, stability and cost for 10 meter-class apertures in support of UV/optical science. To include detailed model-based analysis of mirror system performance, especially addressing dynamic and thermal stability, to the levels required for coronagraphy; and mirror system testing to validate the models.

Advancement in UV-Visible-NIR detector and mirror coating technologies, to realize the high spatial resolution enabled by a large telescope and to maximize the scientific return of its instruments. Detectors with large formats, small pixels, and/or photon-counting capability are highly desired. Development efforts should also demonstrate performance stability and long lifetimes in flight or mission-equivalent environments. Technologies that boost observatory efficiency in the UV are also a high priority.

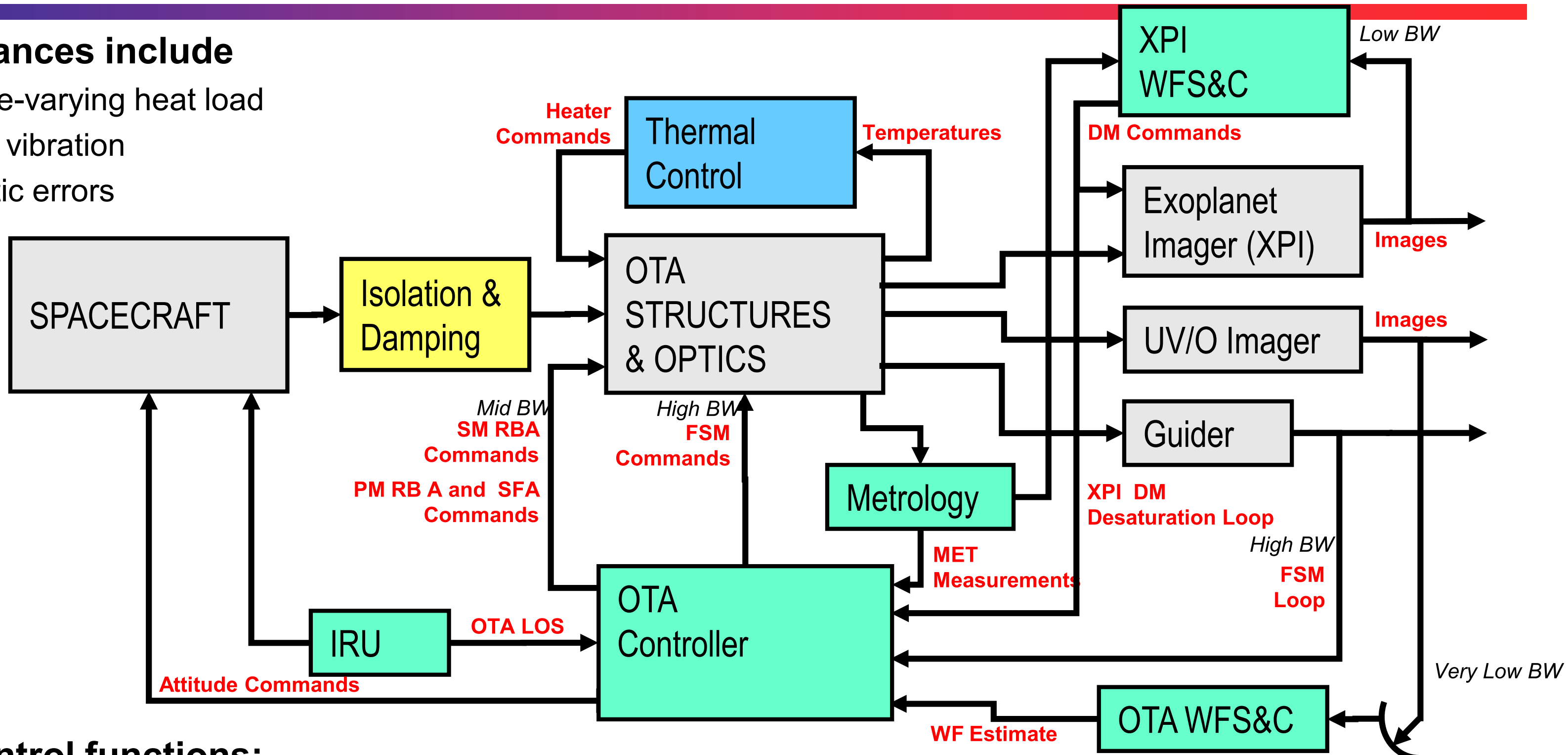
BACKUP

Breaking the Cost Curve

- **Build on experience**
  - JWST deployment, WFS&C technology, structure, sunshade
  - WFIRST/AFTA coronagraphy
- **Invest early in technology to avoid standing armies**
  - Complete TRL5 for all critical technologies before project start
- **Avoid cryogenic systems**
  - Non-cryo telescope systems can be built and tested more rapidly at lower cost
- **Keep mass down**
  - Minimum aperture to do the job
- **Make cost a priority for technology development**
  - Rapid fabrication
  - Lower mass
- **Don’t pay for new infrastructure – but consider it if it is provided**
  - Others could benefit from servicing and assembly capabilities
  - SLS vs. EELV-class

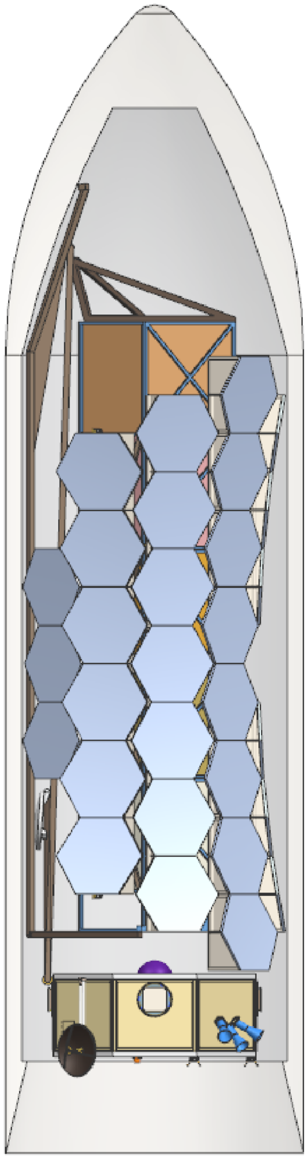
Control Block Diagram

- **Disturbances include**
  - Time-varying heat load
  - S/C vibration
  - Static errors

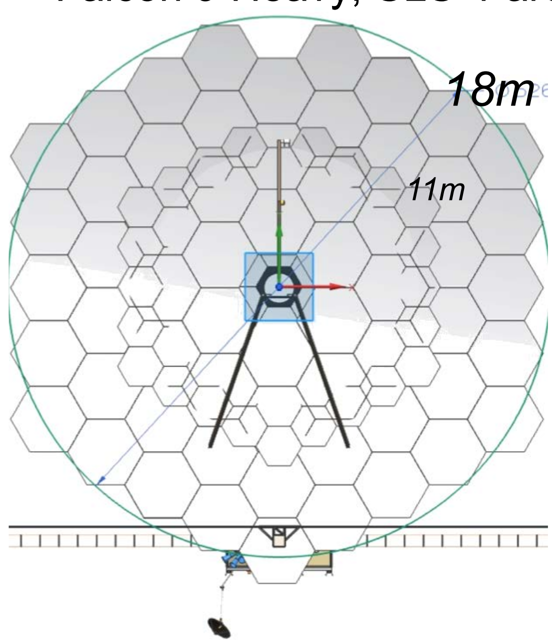


- **OTA control functions:**
  - High BW LOS control using a FSM, based on IRU and Guider inputs, with follow-up by the Spacecraft ACS
  - Mid BW WF maintenance based on Metrology
  - WF control using segment and SM RBAs and segment SFAs, based on periodic WF sensing
  - Thermal control to stabilize mirror figure
- **XPI has additional internal WF control**
  - Periodic or low BW WF control using DMs and possibly a small segmented mirror, based on imagery
  - Low BW DM Desaturation Loop drives SM and PM actuators
  - Possible feed-forward of Metrology to provide a high BW signal for compensation of OTA RB drift

Scaling Up



- **An 11 meter PM using a similar geometry can fit in a Delta 4-H shroud**
- **Deployment approach changes:**
  - PM: 4 hinges per wing
  - SM: struts are separated for launch, must join during deployment
- **Using JWST mirror areal density, estimated mass exceeds Delta 4-H capability**
  - Areal density improvements are available
  - Falcon 9 Heavy, SLS-1 are also higher launch mass options



- **Scaling to 18 m is possible using the SLS-2 8.4 m shroud**
- **Larger sizes could be assembled on orbit**

If needed to support evolving science requirements…

Key Science Requirements

			Measurement Requirements		Telescope		Instrument	Performance Requirements			Mission Requirements
	Science Goals	Science Objectives	Observables	Physical Parameters	OTA	Occulter		Measurement	Required Capability	Current Capability	
Driving Science Goals	"Is there another Earth out there?"	Search for the signature of life in spectra of >10 HZ XPs	Absorption lines of O2, H2O, methane in the planet spectrum	Bandpass = 300-2400nm;	WFE = 10nm; WFE stability	Internal Coronagraph or External Occulter	VNIR Integral Field Unit (IFU)	R=500 spectrum of an XP at 10 parsecs	Contrast = 1e-11; IWA = 40 mas; resolution=diffraction limited at 500nm; R=500		(ConOps)
		Land-sea ratio	Diurnal photometric variability					Disk-averaged, time-resolved photometric imaging	R=5; SNR≥20 for 5% Photometry		Precursor mission to ID targets
		Identify super-earths									Precursor mission to ID targets
		Search mode?						Imaging	High SNR		
		Mass loss from hot planets		UV spectra	UV coated PM and SM; instrument at Cassegrain focus	*Note: coatings may reduce coronagraph performance*	UV Imaging Spectrograph	Transit spectroscopy	High SNR		
	Establish a Comprehensive Theory of Star and Galaxy Formation	Sample resolved star populations in a broad range of galactic environments	Detect individual solar-type stars in at least 1 nearby giant elliptical galaxy	D up to 10 Mpc; Vmag≤34; Kmag≤35	Wide FOV=5-8amin; WFE<25nm; 1.3mas pointing stability	None	Widefield VNIR Imager/Photometer	4-8 arcmin FOV; SR>0.8@500nm; photometry SNR>5 at mag 34	4-8 arcmin FOV; SR>0.8@500nm; photometry SNR>5 at mag 34		
	Understand the Galaxy-IGM Interplay	Dissect the gaseous halos of the same local galaxy population	Absorption lines in IGM back-illuminated by QSOs	Observe ~10 QSOs behind all galaxies ≤10Mpc, and ~1 QSO to 30Mpc	UV coated PM and SM; instrument at Cassegrain focus; diffraction-limited at 500nm	*Note: UV coatings may reduce coronagraph performance*	UV Imaging Spectrograph		R=5K-40K; sensitivity to 90nm wavelengths		
			Emission spectra in IGM and resolved stars								
	Explore the Nature of Dark Matter	Map Dark Matter in the Local Group	Proper motions of the stars in Local Group dwarf galaxies		Wide FOV=5-8amin; WFE<25nm; 1.3mas pointing stability	None	Widefield VNIR Imager/Photometer	Astrometry	Star centroids to 0.1mas; centroid accuracy to 0.005% over 5 years; PSF ellipticity<0.3		

Key Science Goals	Spectroscopy of outer solar system planetary atmospheres (including moons of gas giants)	VNIR Imager, VNIR Spectrograph
	High-resolution Imaging of asteroids and comets	VNIR Imager, VNIR Spectrograph
	Build-up of chemical abundances in 1< z < 4 galaxies	VNIR Spectrograph
	Masses of Active Galactic Nuclei and Super-massive Black Holes in z≤7 galaxies	VNIR Spectrograph

- **Drawn from "Science Requirements for a 2030-era UVOIR Space Telescope," M. Postman, August 7, 2013.**