From Cosmic Birth to Living Earths

A Study Commissioned by the Associated Universities for Research in Astronomy

Beyond JWST: a technology path to the next great UVOIR space telescope

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The AURA "Beyond JWST" Study

Develop a shared vision for UVOIR astronomy in the 2020s and after. . .

. . . based on common ground between "exoplanet" and "cosmic origins" communities. . .

. . . and a conviction that requirements for transformative science in both areas are compatible, that they are **BETTER TOGETHER**.

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Heidi Hammel (AURA)

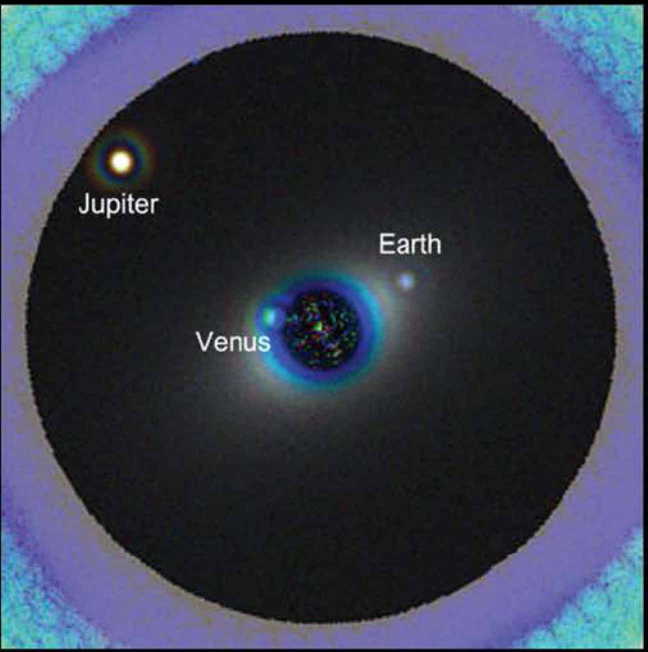
Technologists   Research Astronomers   Instrument Builders

hdstvision.org

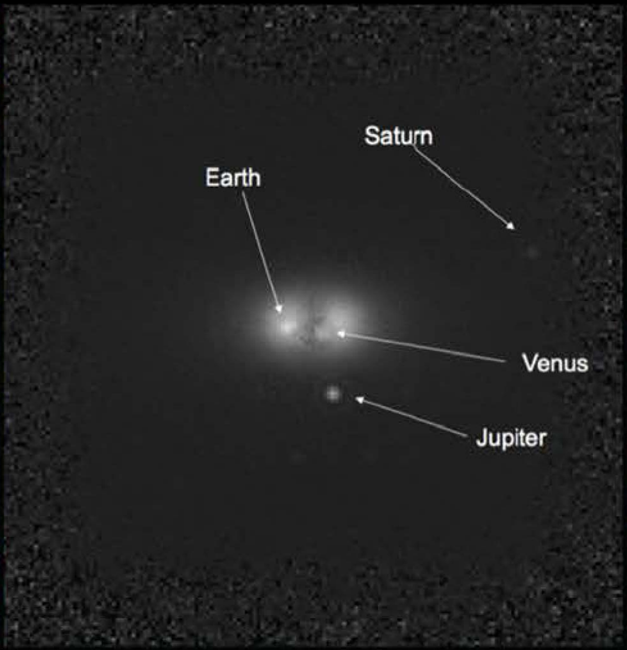
From Cosmic Birth to Living Earths

- Are we alone? How did we get here? These 2 fundamental questions can be addressed with a large ***High Definition Space Telescope***:
  - Operating in high orbit (e.g., Sun-Earth L2)
  - Goal of 12 m aperture
  - A segmented, deployable mirror with active wavefront control
  - A full complement of coronagraphic, imaging, and spectroscopic instruments
  - UV to near-IR wavelengths (but with non-cryogenic optics)
  - Diffraction-limited performance at visible (500-600 nm) wavelengths, with very high stability
  - Launch in the early-mid 2030s
- This paper reviews ***HDST*** technology needs

Direct Exoplanet Imaging



Binary anodized pupil coronagraph (L. Pueyo).



Phase-Induced Amplitude Apodization coronagraph with small IWA (Guyon).

Free-flying 100 m starshade (Kuchner).

- *HDST* will provide direct imaging and spectrometry of hundreds of exoplanets, and dozens of exoEarth candidates
  - Imaging for discovery, spectroscopy for exoPlanet atmospheric chemistry, for the discovery of habitability, and of life

Exo-Earth Yield Drives Mission Design

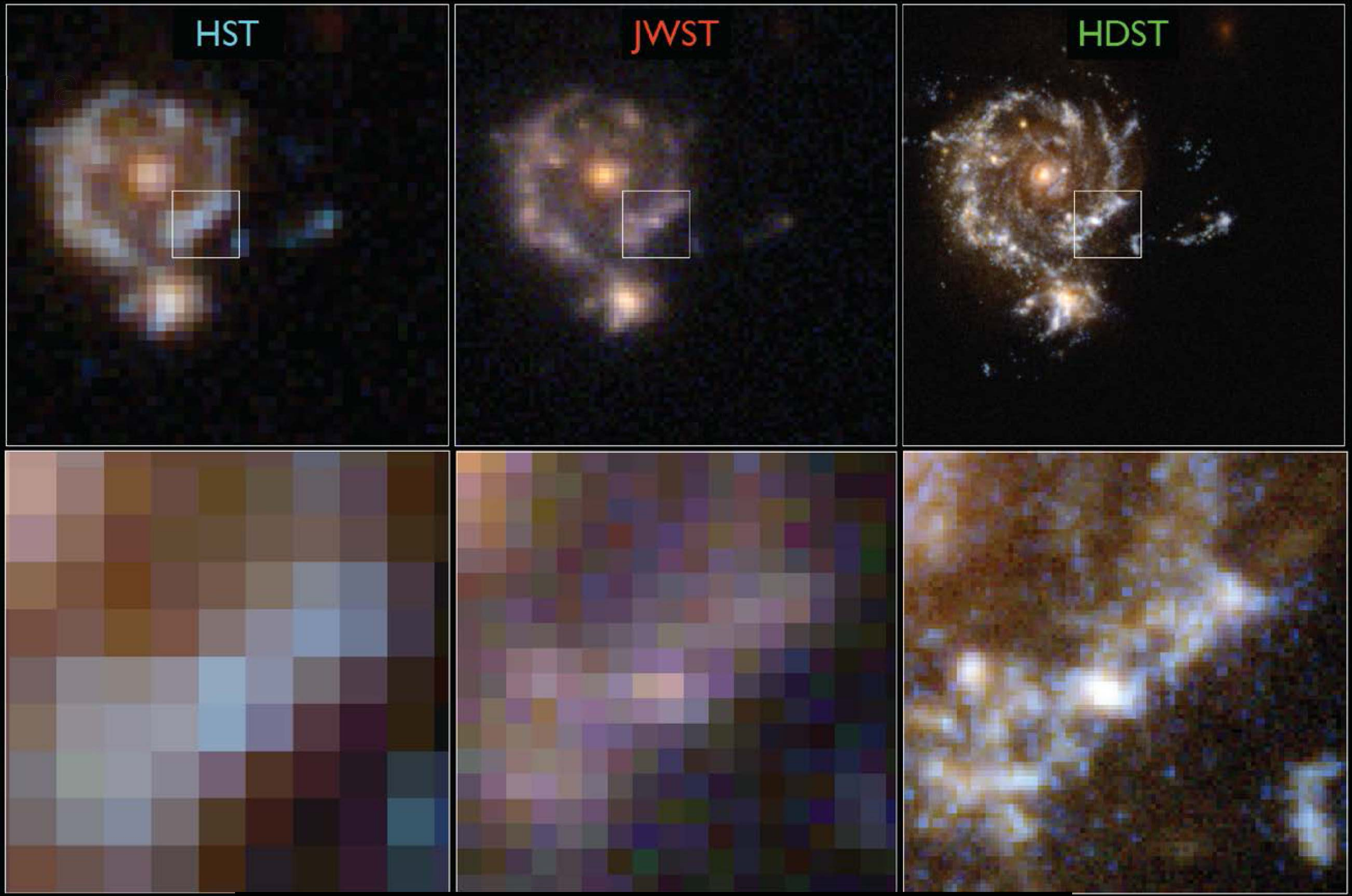
- For a direct-imaging exoplanet survey, the yield of exo-Earths is approximated by:

$$\text{Yield} \approx 25 \left[\frac{\text{D}}{10\text{ m}}\right]^{1.97} \times \left[\frac{\text{T}_{\text{exp}}}{1\text{ yr}}\right]^{0.32} \times \left[\frac{\text{IWA}}{3.5\ \lambda/\text{D}}\right]^{-0.98} \times \left[\frac{\text{Throughput}}{0.20}\right]^{0.35}$$
$$\times \left[\frac{\Delta\lambda}{0.10\mu}\right]^{0.30} \times \left[\frac{\text{Contrast}}{10^{-10}}\right]^{-0.10} \times \left[\frac{\eta_{Earth}}{0.10}\right]^{0.89} \times \left[\frac{\text{Bkgd}}{3.0\text{ zodi}}\right]^{-0.23}.$$

(Stark et al. 2015)

- The *HDST* objective is to detect and characterize *dozens of exo-Earths*
  – For natural parameters $\eta_{\text{Earth}} = 0.1$, Bkgd = 3 zodi; for a coronagraph with 10^{-10} contrast at an IWA of 3.5 λ/D...
  – An aperture D of 10-12 m will yield ~24 to 36 exo-Earths

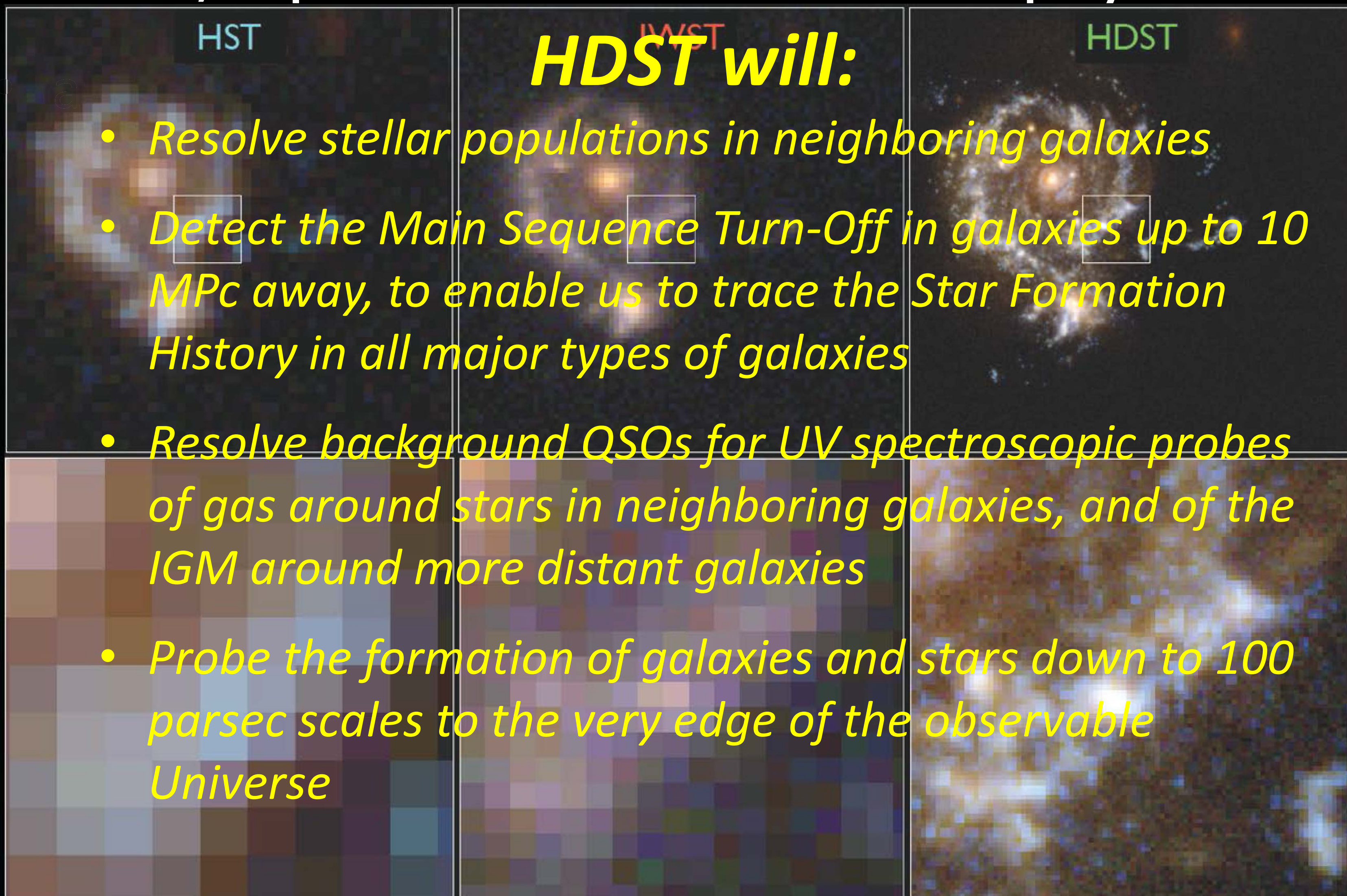
UV, Optical and Near IR Astrophysics



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

Images simulated by Greg Snyder (STScI)

UV, Optical and Near IR Astrophysics



HDST will:

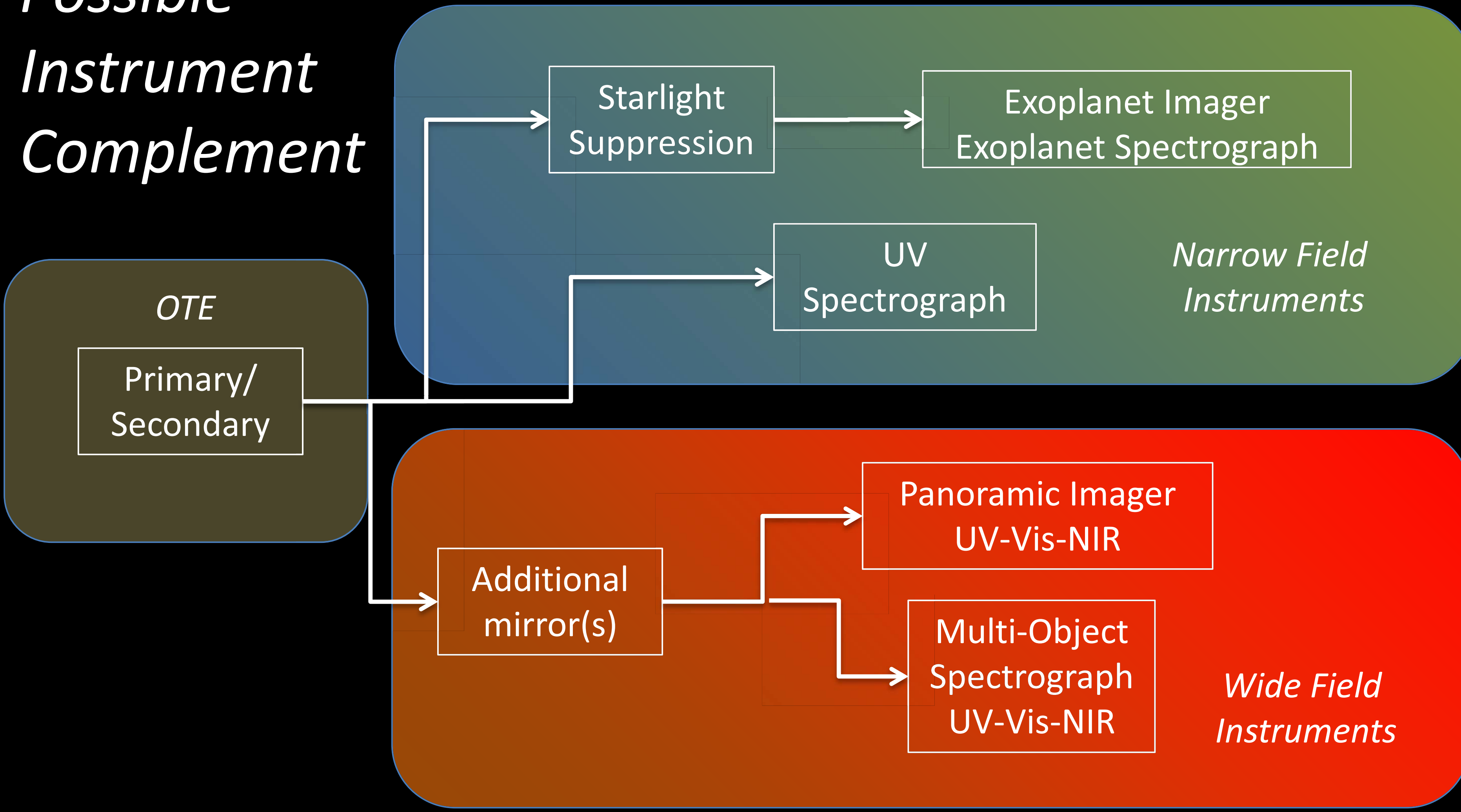
- *Resolve stellar populations in neighboring galaxies*
- *Detect the Main Sequence Turn-Off in galaxies up to 10 MPc away, to enable us to trace the Star Formation History in all major types of galaxies*
- *Resolve background QSOs for UV spectroscopic probes of gas around stars in neighboring galaxies, 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*

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

Images simulated by Greg Snyder (STScI)

HDST Requirements

Possible Instrument Complement



Parallel Observing Capability

HDST Requirements

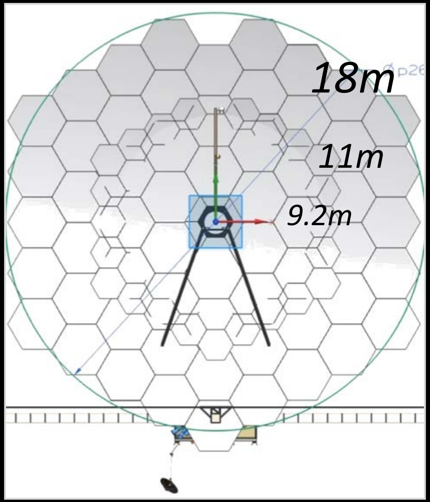
as a Large Aperture Space Telescope

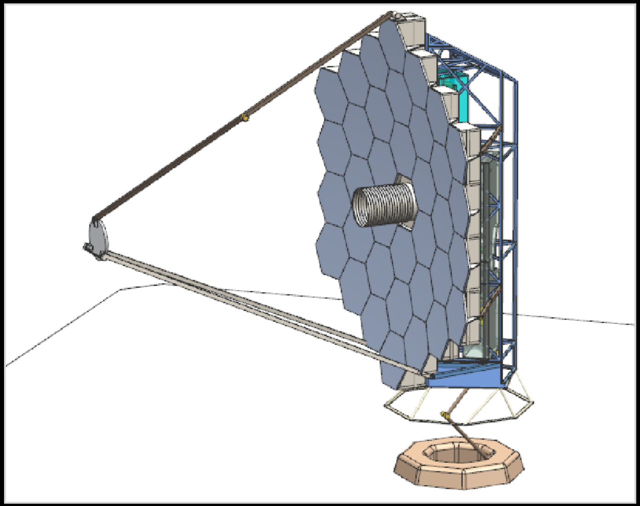
An aperture of 10-12m can be supported by currently available launch vehicles.

- *Segmented apertures are scalable and can reach the largest collecting areas.*

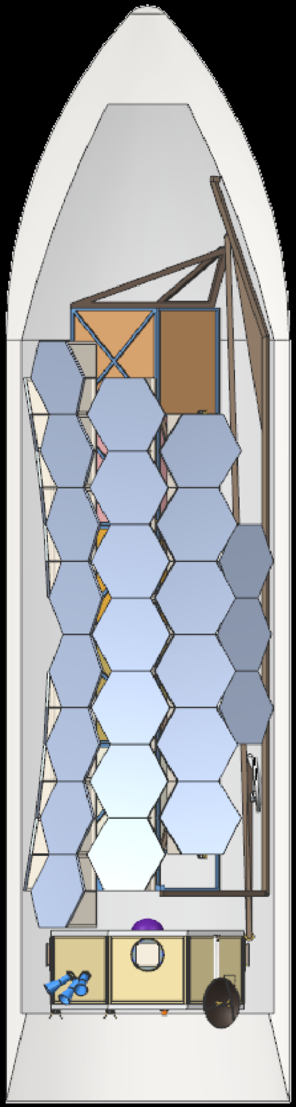
The SLS Block 2 vehicle will have a larger shroud and more lift capability.

- *Could accommodate monoliths of up to 8m, or segmented apertures to 16m.*





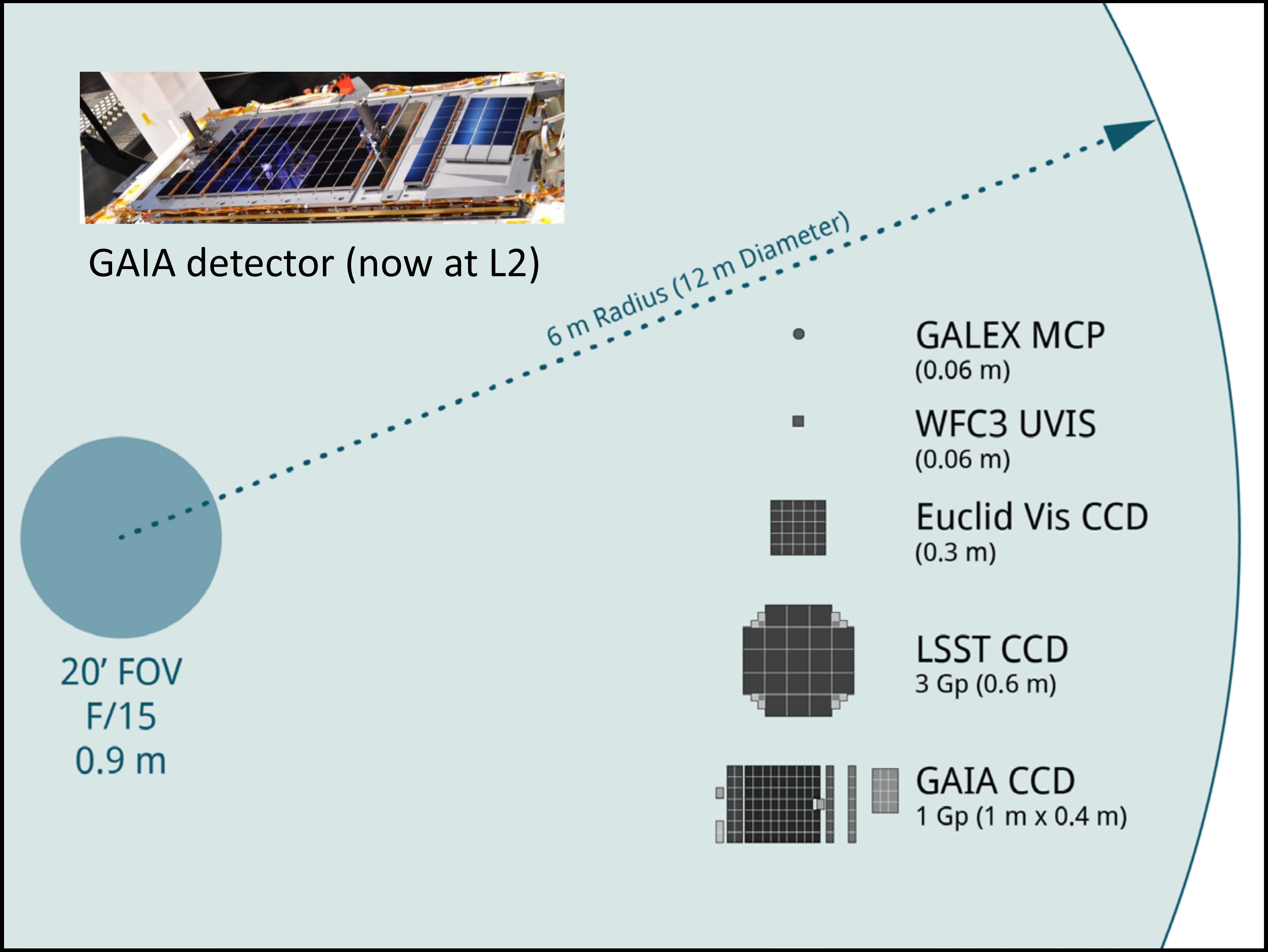
An 11m segmented-aperture space telescope within an EELV or SLS-1 shroud



Images courtesy of the NASA ATLAST study group.

HDST Requirements

Detector Gigapixel Arrays



Large format, gigapixel-scale arrays have been flown or are being developed

HDST Requirements

as a Large Aperture Space Telescope

Capability		HDST Increase vs.	
Parameter	Requirement	HST	JWST
Aperture	10-12 m	x5	X1.5-2
Wavelength	0.10 to 2 microns	Same high efficiency DUV	UV-vis (blue) JWST: 0.6 to >28.5 um
Field of View	6 arcminutes	x2-4	x2-4
Pixel Count per Instrument Channel	0.5-1 gigapixel	x20-40 WFC3	x25 NIRCAM
Angular Resolution	<0.01" (Diff lim. @ 500 nm)	x5 @ 500 nm	x1.5-2 @ 1 um

HDST Requirements
for Starlight Suppression

Capability		*HDST* Gain vs.	
Parameter	Requirement	*HST*	*JWST*
Raw Contrast	1e-9 to 1e-10	x100-1000 better	x100-1000 better
Inner Working Angle	3.6 λ/D (img., 0.5 μm) 2 λ/D (sp., 1 μm)	x20 smaller	X20 smaller
Throughput	0.2	N/A	N/A
Stability	10 picometer* per 10 minutes	x1000 lower	x1000 lower
Metrology	10 picometer*	N/A	N/A

*Can be relaxed for starshade

HDST – Key Technology Challenges

Highest-priority challenges

- Starlight suppression
  - Coronagraphy with segmented apertures
  - Starshades
- Ultra-stability
- Mirrors

High-priority challenges

- Low noise or photon-counting detectors for exoplanet spectroscopy
- UV technologies (coatings and high,efficiency low-noise detectors)

Coronagraphy and Segmented Apertures

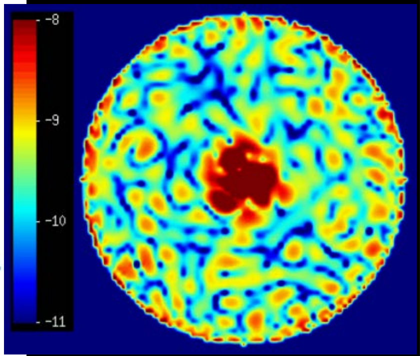
*In the TPF days, it was assumed that high contrast (>1e9) imaging required an unobscured, monolithic pupil **… but recent research shows that segmented apertures can indeed be used for high contrast imaging***

WFIRST-AFTA ongoing development

By combining wavefront control and coronagraph design, high performance solutions have been identified for an "unfriendly" aperture (large central obstruction + spiders)

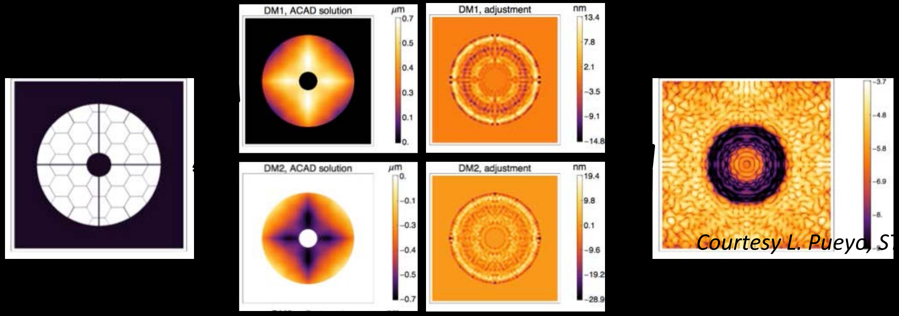
3 solutions are now being pursued: HLC & SPC (baseline) and PIAACMC

2.4-m telescope assembly



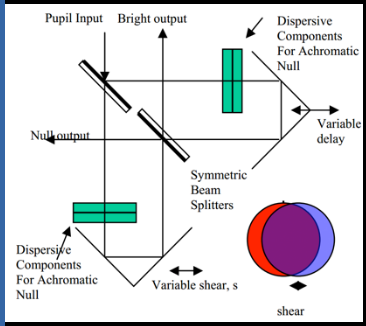
WFIRST-AFTA HLC simulated image (J. Krist, JPL)

Wavefront control can significantly reduce residual segment diffraction



Coronagraph solutions exist that are, by construction, fully insensitive to pupil segmentation

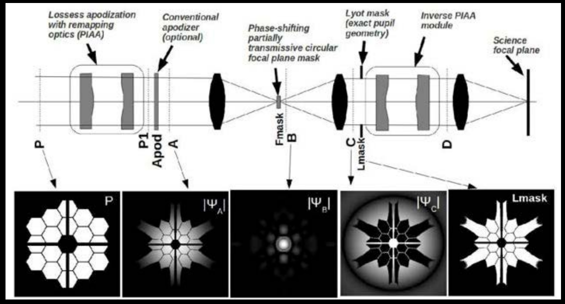
Visible Nulling Coronagraph (VNC)



VNC is a shearing nulling interferometer

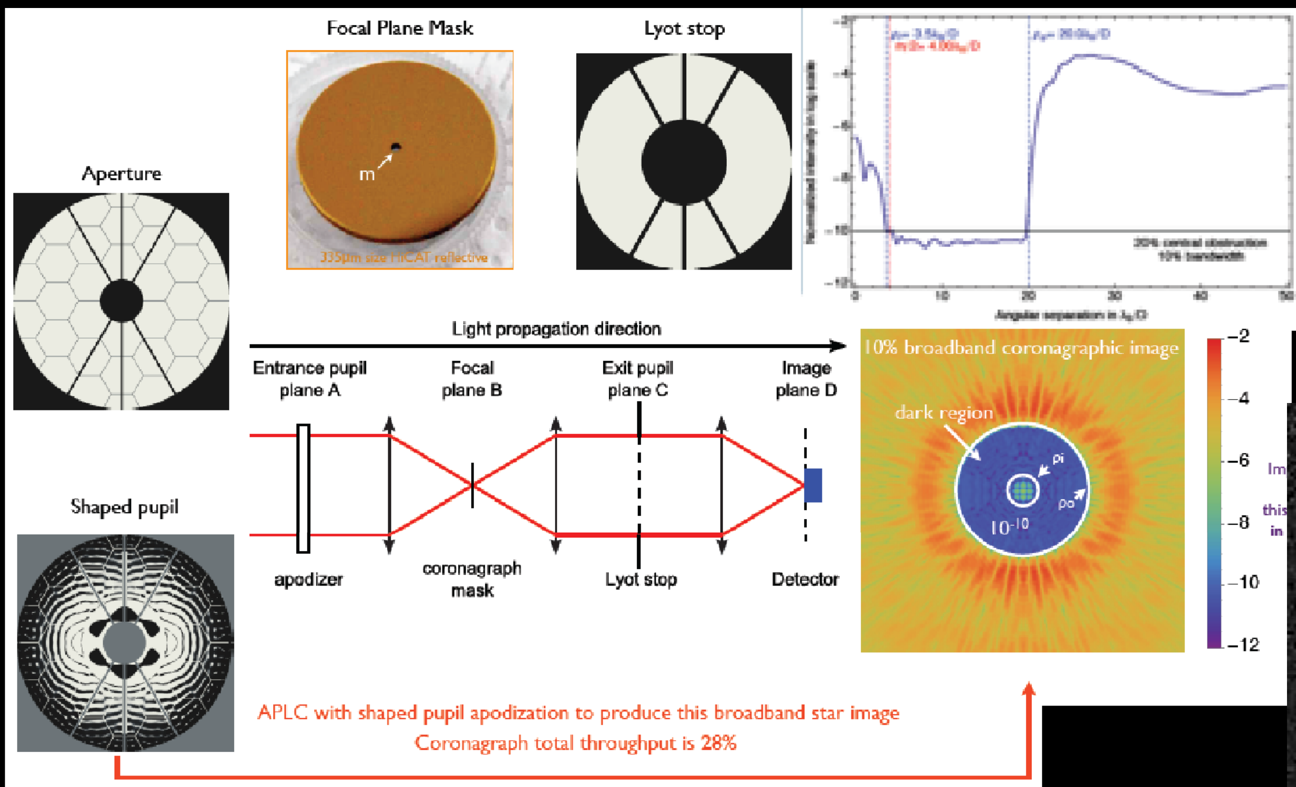
Shear can be set to an integer number of segments

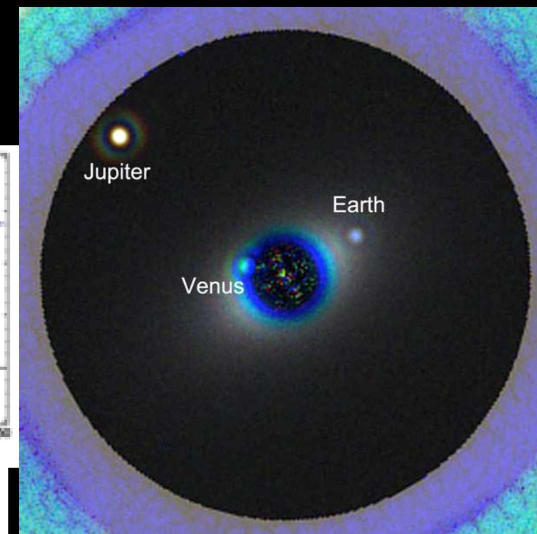
Produces full suppression with 100% throughput for any pupil shape

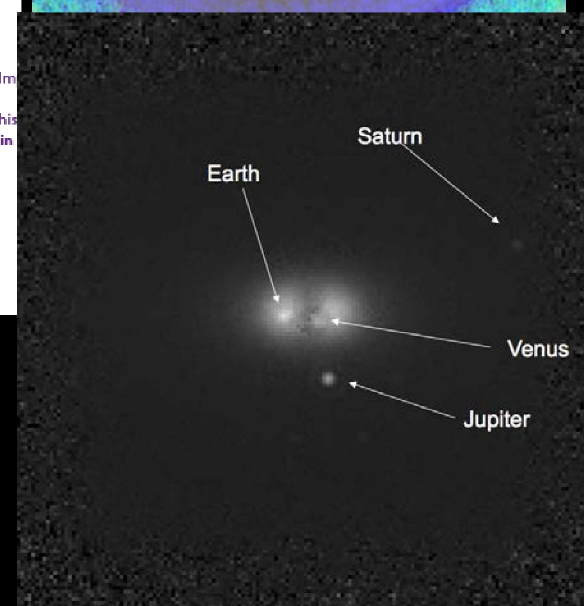


Advances with Segmented, Obscured Aperture Coronagraphy

- *Mamadou N'Diaye et al., (2015)*
- *Guyon (2015)*







Ultra-Stability

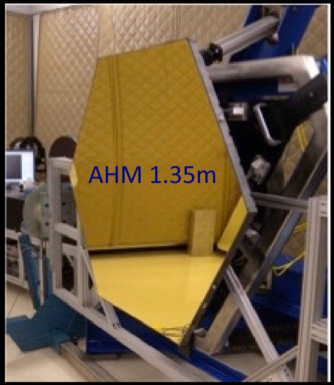
- Raw contrast of 10^{-9} to 10^{-10} requires ~10 picometer stability of the combined telescope and coronagraph wavefront*
- Acheivable with a multi-tiered approach, some combination of:
  - Passive thermal control: L2 orbit, flat-plate sunshield, long-dwell observations → ***JWST heritage***
  - Active thermal control of optics (and structures) → ***< 1 mK performance needs to be demonstrated***
  - Vibration suppression → ***industry-developed non-contact isolation***
  - Continuous Speckle Nulling Wavefront Control, at very low BW
  - Continuous Wavefront Sensing, using in- and out-of-band light → ***builds on the developing AFTA Coronagraph LOWFS technology***
  - Picometer laser metrology→ ***SIM and non-NASA heritage < 1 nm***
  - Small Deformable Mirrors: corrector mirrors in the coronagraph → ***also consider segmented DMs and active PM segments***

Needed: System-level design for ultra-stability, and the key device technologies

*Ref. S. Shaklan, JPL

Mirrors

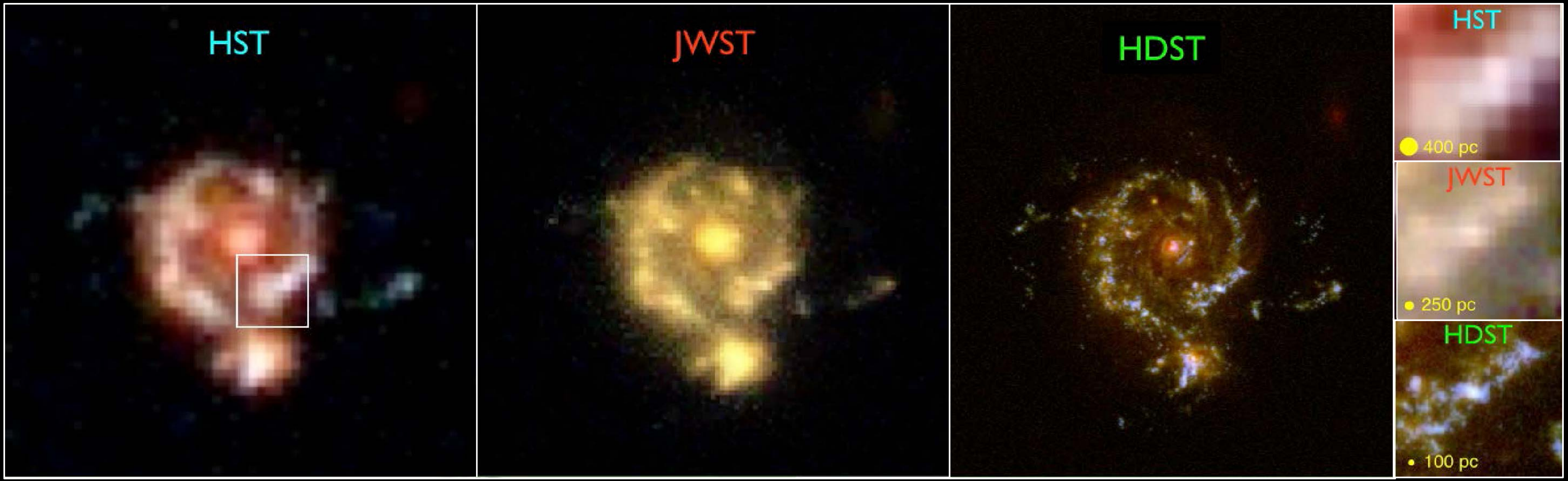
- *Primary Mirror systems* for HDST will benefit from NASA and non-NASA heritage, room temperature OTE
- Systems include substrates, passive and active thermal control, and (most likely) some level of figure control



- Key challenges include:
  - Diffraction-limited optical quality
  - UV compatibility (μroughness, contamination, …)
  - Low cost, low mass, and rapid fabrication
- Trades include:
  - Thermal control approach (low CTE vs. high conductivity)
  - Level of figure control

Needed: mirror system wavefront stability to 10 picometers per 10 minutes – and the ability to measure this level of performance

Maximizing Sensitivity and Throughput, FUV to NIR



- "Photon counting detectors" - Low read noise and dark current
  - Exo-Earth Spectroscopy: Count rate per pixel requires ultra-low noise detectors in Vis/NIR
  - UV General Astrophysics – sensitivity boost
- Coatings: enhancing across the board throughput
  - Broadband, UV-NIR coatings with high R down to 92 nm
  - Possible impact of enhanced coatings on WFE being assessed

<u>Needed</u>: ultra-low noise, photon counting detectors in the visible and near IR

Highest Priority Tech Challenges – Key Milestones

Challenge	Current Status	Goal 2019 (pre decadal)	Goal 2024 (phase A)
Starlight suppression	Developing	TRL 4	TRL 5-6
Coronagraphy w/ segmented apertures	Developing	TRL 4	TRL 5-6
Ultra-stability and Wavefront Control	TRL 3-4	TRL 5	TRL 5-6
Mirrors	Substrate: TRL 4, System: TRL 3	TRL 5	TRL 5-6
Starshade	Developing	TRL 3-4	TRL 4-5
Detectors	TRL 4-6	TRL 6	TRL 6-7

BACKUP

HDST Technology Heritage and Synergies

- ***HDST*** will be one in a sequence of missions and technology projects that are evolving the key technologies
- ***HST*** and its repair missions: wavefront sensing; servicing; PSF Calibration and Subtraction image processing
- ***TPF-C*** and ***TPF-I***: coronagraph technologies; modeling
- ***SIM***: picometer precision optical path metrology and control
- ***JWST***: segmented primary; deployment; wavefront sensing and control; sunshield
- ***WFIRST/AFTA***: *ongoing* obscured-aperture coronagraphy
- ***ExEP*** technology development: coronagraphy; deformable mirrors; small-scale testing; starshade
- ***Exo-C*** and ***Exo-S*** Probe studies of possible probe-class missions (but these will not do ***HDST*** science)

HDST Starlight Suppression Goals and Challenges

- Goal: a sample of dozens of exoEarth candidates in order to search for signs of biological activity
- Achievable with (Stark et al (2015)):
  - 12 meter deployed, segmented aperture
  - Inner Working Angle of 35 - 50 mas
  - An internal coronagraph with 2 modes
    - Discovery: Contrast = 1e-10; IWA = 3.6 λ/D; λ ≤ 0.55 um
    - Characterization: Contrast = 1e-9; IWA = 2 λ/D; λ ≤ 1 um; R = 70
- Challenges:
  - Segmented, obscured aperture makes coronagraphy more difficult
  - Ultra-stable telescope is needed, to preserve contrast over a ~10 minute control interval
  - Ultra-low noise and photon-counting UV and VIS detectors

Why 12 Meters?

- To find enough candidate ExoEarths to make a meaningful search for life
  - Resolution: to enable the separation of dim planets from the glare of their stars
    - Contrast < 10^{-10}, the brightness ratio between earth and sun...
    - ...at an Inner Working Angle (IWA) < 50 mas, to search the Habitable Zones of many stars, out to >20 parsecs
  - Sensitivity: even a 10 m aperture will need a week of observing to obtain an exoEarth spectrum
    - To identify water, and O_2, and O_3, in exoPlanet atmospheres
  - To access enough stars to find life, or to know that it is rare
- To provide 100 parsec resolution everywhere in the visible universe

Starshades

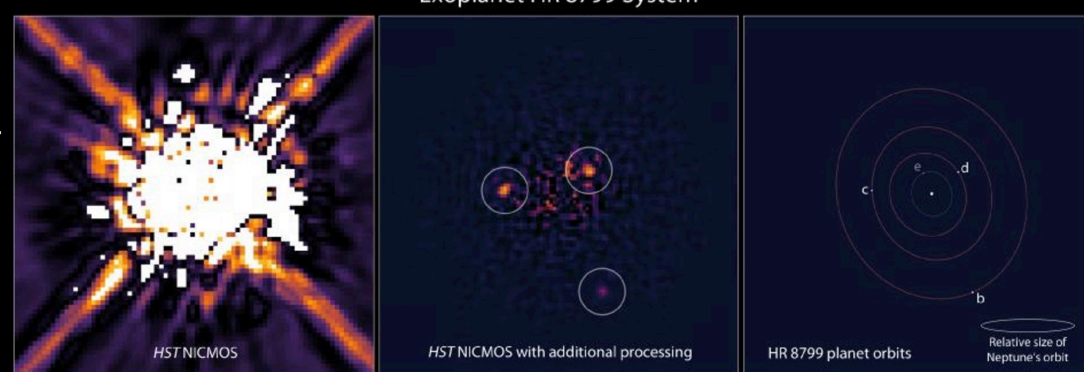
- An HDST-optimized starshade would have:*
  - A diameter of 80 m, with petals ~20 m long, for Fr = 12
  - A distance from the HDST telescope of 160,000 km
  - IWA of 50 mas for $\lambda \leq 1$ um, and 100 mas for $\lambda \leq 2$ um
  - ~100% throughput (vs. 10-50% projected for coronagraph)
  - Wide bandpass (vs. 10-20% projected for coronagraph)
- Starshades are better than coronagraphs for deep spectral characterization, but retargeting time is likely to be days to weeks
- ExEP and Exo-S Probe studies have developed many key elements for ~40 m-class Starshades
  - Edge control, deployment, etc.
- Chief challenge for HDST is a design for an 80 m-class Starshade → *candidate for on-orbit construction? or stop down and use a smaller Starshade? or Fr < 10?*
- <u>*Needed*</u>*: exoEarth yield analysis incorporating a Starshade, either stand-alone or as a complement to a survey-optimized coronagraph*

A large starshade could provide a supplemental exoplanet characterization tool but will not be optimal for conducting a survey of hundreds of star systems.

Coronagraph Contrast Performance

- <u>Inner Working Angle (IWA) < </u> – *within the Sun-Earth separation as seen from 20 parsecs distance*
  - Coronagraph IWA: *< 2.5 λ/D for D = 10 m at λ = 1 um; <3 λ/D for D = 12 m*
- <u>Detection Contrast < 10^{-10}</u> – *combining raw contrast and PSF calibration and subtraction*
  - Raw Contrast ~10^{-9} → *demonstrated on subscale unobscured coronagraphs*
    - Consistent with <u>predicted</u> AFTA Coronagraph obscured aperture performance → *soon to be demonstrated*
  - PSF Subtraction: 10x to 30x contrast improvement
    - Exploiting techniques developed for HST high dynamic-range imaging (and ground-based observatories)
    - Roll calibration and other speckle identification methods will provide further contrast improvement

Exoplanet HR 8799 System *



NASA, ESA, and R. Soummer (STScI) STScI-PRC11-29

WFIRST/AFTA, HST and ExEP heritage provides a strong foundation for HDST.
<u>Needed</u>: coronagraph studies for 10-12 m, segmented, obscured aperture HDST

*Ref. R. Soummer, STScI

Highest Priority Technologies

Technology Needed for HDST				Current Status			
Technology Category	*Technology*	*Performance Goal*	*Details*	*Heritage*	*Current Performance*	*Maturity of Goal Perf.*	*Priority*
Coronagraph	Segmented Aperture Coronagraphy	Raw contrast < 1e-9	Image-Plane and/or Pupil-Plane Coronagraph Designs	WFIRST/AFTA Coronagraph, ExEP studies, TPF	Unobscured Aperture, Contrast < 1e-9	Developing	Highest
	Continuous speckle nulling WF control	WF sensing error < 5 pm			< 5 pm	Developing	Highest
	PSF Subtraction	10 - 30x contrast reduction	PSF matching, roll calibration, etc.	HST	100x contrast reduction on noisier images	Developing	Highest
Segmented mirror system	Mirror Segments	<20nm WFE; <5pm WFE drift/10 min	Improve production to reduce cost and lower mass; UV performance	Non-NASA MMSD; NASA AMSD, COR/AMTD, Industry R&D	ULE and SiC substrates to 1.4 m size, <30 nm WFE, actuated	Substrate: TRL 4+; System: TRL 3	Highest
Ultra stability	Mirror Thermal Control	pm stability for coronagraph	Combining passive and active methods	Non-NASA; NASA various	nm stability	TRL 4	Highest
	Dynamically stable structures	Picometer stability	Dynamically stable structures and fixtures	JWST	nm accuracy	TRL 3	Highest
Starshade	Advanced Starshade design	D ≥ 80m, Fr = 12	Deployment; edge precision; long life	NASA EXEP; Industry R&D	D to 40 m	Developing	Highest
Sensitivity and Throughput	Ultra-low Noise and UV-sensitive Detectors	Detector noise & QE: Read: <0.1-1 e-; Dark <0.01 e-/s; QE(FUV): > 50%	Exoplanet spectroscopic characterization and UV general astrophysics	NASA COR, commercial sources	Low noise, high QE photon-counting Vis-NIR and UV detectors	TRL 4-6	Highest
Wavefront Control	Metrology (pm)	Picometer precision	Compact, lightweight laser truss metrology	SIM, Non-NASA	nm accuracy	TRL 3	Highest

- HDST highest priority technologies address key performance issues supporting multiple potential HDST architectures, building on past and current NASA project and program investments

Starlight Suppression Status

Starlight Suppression Goals and Achievements to Date

	Method	Description	Pupil	Raw Contrast	IWA	OWA	Bandpass	Throughput	Comments
HDST Goals	Science goal	24 exoEarths at D = 10 m, 36 exoEarths at D = 12 m			<50 mas up to λ=1um	>1.5 asec			50 mas corresponds to Sun-Earth separation at 20 parsec
	Coronagraph goals	Survey mode	Obscured, segmented	1.00E-10	<3.6 λ/D up to λ=0.55um	>75 λ/D	20%	10-30%	Challenges are (1) telescope stability, (2) throughput, (3) bandpass, (4) contrast
		Characterization mode		1.00E-09	<2 λ/D up to λ=1um	>90 λ/D	R = 70		
	Starshade goals	Required performance for a 10 m aperture, >80 m Star-shade, at 166 Mm distance, with Fresnel number Fr = 12	Any	1.00E-10	<50 mas up to λ=1um	Inf	λ≤1um	100%	Challenges are (1) large size of Starshade spacecraf, (2) deployment, (3) retargeting time, (4) petal shape precision, (5) formation flying sensing
Coronagraph Demos	Lyot coronagraph demonstration (2009)	Demonstrated on the subscale High Contrast Imaging Testbed (HCIT-1 or HCIT-2)	Unobscured, circular	5.00E-10	4 λ/D	10 λ/D	10%		Demonstration for TPF Milestone 2
	Hybrid Lyot coronagraph demonstration			1.20E-10	3.1 λ/D	15.6 λ/D	2%	56%	Current best demonstrated results; achieved with a linear mask
				3.20E-10			10%		
				1.30E-09			20%		
	Shaped-pupil coronagraph			1.20E-09	4.5 λ/D	13.8 λ/D	2%	10%	
				2.50E-09			10%		
	PIAA Coronagraph			5.70E-10	1.9 λ/D	4.7 λ/D	0%	46%	
				1.80E-08	2.2 λ/D	4.6 λ/D	10%		
	Vector vortex coronagraph (2013)			5.00E-10	2 λ/D	7 λ/D	0%		From Serabyn et al (2013).
				1.10E-08	3 λ/D	8 λ/D	10%		
	Visible Nuller Coronagraph (2012)	Demonstrated in ambient lab conditions at GSFC	Segmented pupil	5.30E-09	1.5 λ/D	2.5 λ/D	2%		6% bandpass to be demonstrated in early CY15.
	Shaped-pupil coronagraph	Demonstrated on HCIT	Obscured AFTA pupil	5.90E-09	4.5 λ/D	10 λ/D	2%	11%	First lab demo of high contrast with AFTA pupil; 10% bandpass milestone scheduled for September 2015
	Hybrid Lyot coronagraph demonstration	Demonstrated on HCIT		6.92E-09	3 λ/D	9 λ/D	0%	13%	Work in progress for AFTA, 10% bandpass milestone scheduled for September 2015
	Future PIAACMC coronagraph demonstration	To be demonstrated on HCIT		~1e-8 ~1e-9	1.3 λ/D 2 λ/D	9 λ/D	10%	58%	Work in progress for AFTA; predictions based on modeling by Krist (2015)
Starshade Demos	Tabletop lab demo	Princeton, Fr =588	Any	1.00E-10	400 mas	800 mas	0%	100%	
	Desert demonstration	Demonstrated at km scale using artificial star; Fr = 240		1.00E-09	70 as	n/a	450-700 nm	100%	NGAS TDEM demo; performance as of Spring 2015
	On-sky demonstration at McMath Telescope	Demonstrated with 10 cm mask 140 m baseline; Fr = 19		1.00E-06	75 as	n/a	450-700 nm	100%	NGAS TDEM demo; performance as of Spring 2015
	Large-scale shape TDEM-1	Full scale petal		n/a	n/a	n/a	n/a	n/a	Petal built to 1e-10 system contrast requirements.
	Large-scale deployment TDEM-2	2/3 scale truss		n/a	n/a	n/a	n/a	n/a	Truss with petals deployed to 1e-10 system contrast requirements.
	Future tabletop lab demo	Princeton, Fr = 15		3.00E-10	equiv 82 mas, for D = 2 m	TBD	>50%	100%	Approximately to scale, matching the target Fresnel number; Princeton TDEM demo starts CY15

Architecture-Dependent Technologies

- These technologies include telescope architecture-dependent options, as well as higher-TRL technologies needed for any HDST

Technology Needed for Candidate Architectures				Current Status				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Ultra Stability	Structural Thermal Control	pm stability for coronagraph, nm for starshade		Non-NASA; NASA various	um stability	TRL 3	High	Architecture
Ultra Stability	Non-contacting vibration isolation	140 dB Isolation		Industry R&D	80 dB Isolation	TRL 5	High	Architecture
Ultra Stability	Micro-thruster pointing control	Ultra-low vibration; uas pointing control	A possible option for low-disturbance LOS pointing, in lieu of RWs	Industry		TRL 3	High	Architecture
Monolithic Mirrors	4m Monolithic Mirrors	WFE < 20 nm; to 14" thick and 4m wide for ƒ>60 Hz	4 m monolith may provide a reduced-performance option	NASA COR/AMTD	to 14" thick and 30 cm wide	TRL 4	High	Architecture
Monolithic Mirrors	8m Monolithic Mirrors	WFE < 20 nm; to ~30" thick and 8m wide for ƒ>60 Hz	Launch requires development of SLS Block 2 10m fairing	NASA COR/AMTD	to 14" thick and 30 cm wide	TRL 3	Low	Architecture
Spacecraft	Deployment	2-fold, 6.5m aperture	S/C architecture dependent	JWST	2-fold, 6.5m aperture	TRL 6	Medium	Architecture
Spacecraft	Sunshade	T to ~90K, gimballed	S/C architecture dependent	JWST	T to 30K, fixed	TRL 6	Medium	Architecture
Wavefront Sensing & Control	WFS&C for initial alignment	<10 nm	Can use qualified methods	Non-NASA; NASA JWST	<10 nm	TRL 6	Low	Architecture
Coronagraph	Segmented DMs for coronagraph WF control	Segmented to match PM, <10pm WFC	Needs control concept development	Industry R&D	Segmented facesheet, <100pm WFC	TRL 3	Medium	Device
Coronagraph	DMs for coronagraph WF control	<10pm WFC	Demoed at 32x32, needs scaling up to 48x48	NASA EXEP	Continuous facesheet, <100pm WFC	TRL 4	Highest	Device
Segmented mirror system	RB Actuators	pm accuracy, 1 Hz operation, infinite life		Non-NASA; NASA JWST; Industry	cm stroke, nm accuracy	TRL 4-6	Medium	Device
Throughput	Coatings	Below 120 nm >50-70%, UV/Vis: >85-90%		NASA COR	High reflectance FUV Mirror Coatings	TRL 4-6	High	Device
Science data processing	PSF Subtraction	Additional 1e-1 contrast	Low cost	HST		Operational	Highest	Science

Starshade and Far-Term Technologies

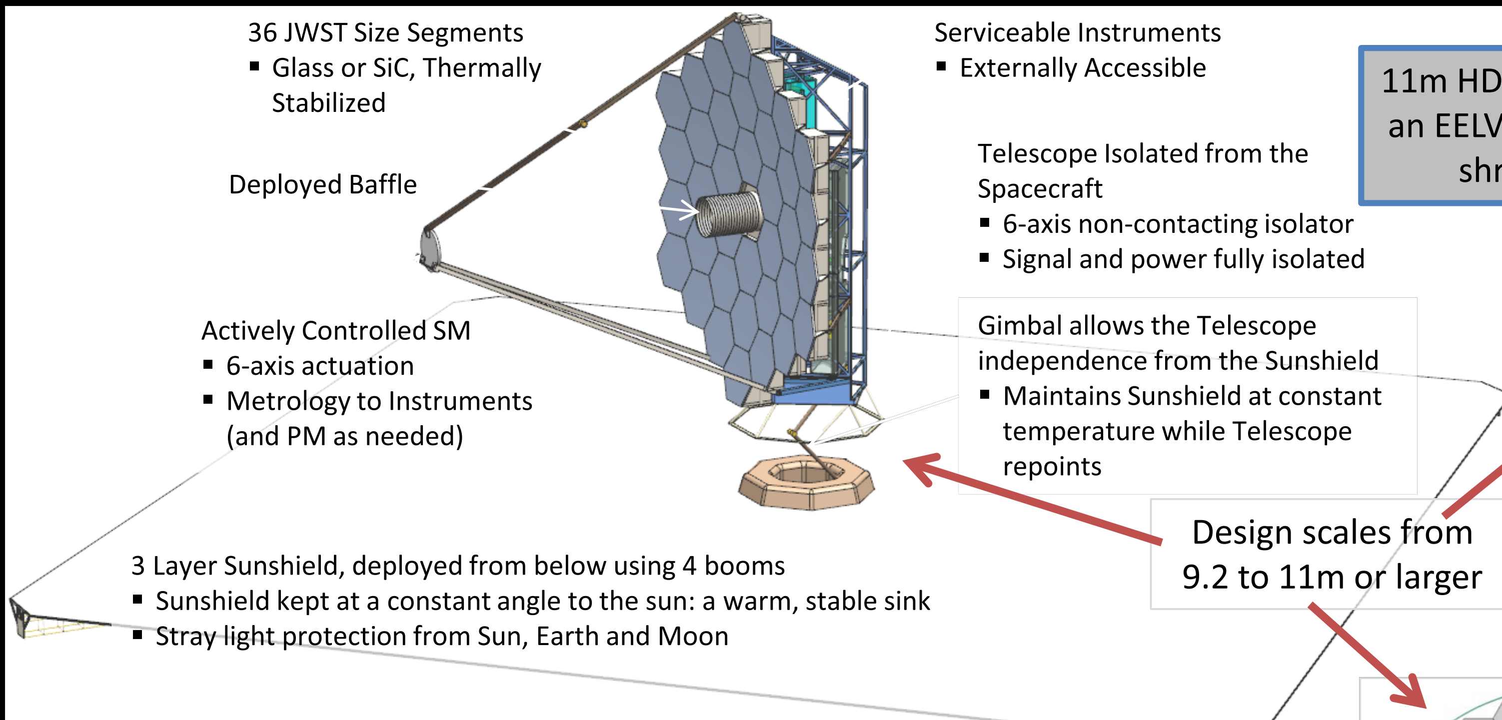
- Starshades provide an important alternative in case coronagraphs fall short, and a potentially useful complement for deeper characterization of identified exoEarths
- These starshade technologies are needed for scale-up to HDST-optimized capabilities

Technology Needed for Starshades				**Current Status**				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Starshade	Starshade modeling and model validation	Validation at Fr = 12 or less	Full-scale starshades are not possible on the ground -- need other methods to prove out	NASA EXEP	Models not yet validated at traceable Fresnel number	Developing	High	Starshade
Starshade	Starshade operations	Optimized for exoEarth yield and characterization	Operating strategies that minimize effects of retargeting	NASA EXEP	Days to weeks retargeting time	Developing	High	Starshade
Starshade	Starshade formation flying	Shadow control < 1 m over >100,000 km sight lines	Includes metrology, propulsion, etc.	NASA EXEP		Developing	High	Starshade

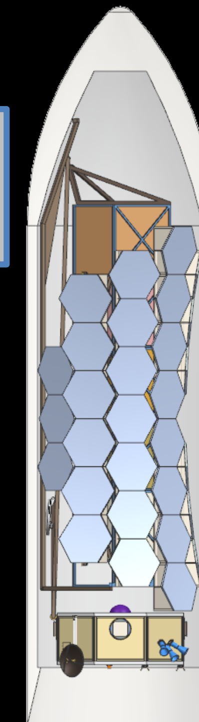
- Servicing has been vital for the Hubble Space Telescope performance and longevity

Technology Needed for Candidate Architectures				**Current Status**				
Technology Category	*Technology Provided*	*Performance Needed*	*Details*	*Heritage*	*Current Performance*	*Maturity*	*Priority*	*Scope*
Far term	Servicing	Robotic infrastructure required	High cost; high value; scope is multi-project	HST	Astronauts, Using STS	Mature, Abandoned	Low	Far term
Far term	On-orbit assembly of Starshade or Telescope	Robotic infrastructure required	Needed for largest structures; cost impact not known	NASA OPTIIX, DARPA, others		Early phase	Low	Far term

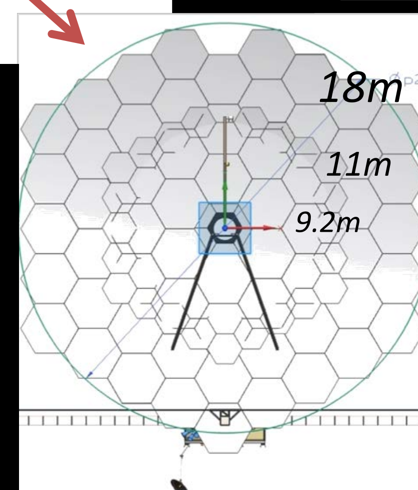
The NASA "ATLAST" Study



11m HDST within an EELV or SLS-1 shroud



Design scales from 9.2 to 11m or larger



- The NASA/STScI Advanced Technology Large Aperture Space Telescope engineering reference design concept
  - JWST heritage: sunshield, deployment, passive thermal control, wavefront control, many lessons learned
  - NASA heritage: starlight suppression, metrology
  - Non-NASA heritage: light-weight non-cryogenic optics, non-contacting isolation, detectors and electronics
  - Launch vehicle: EELV-class or SLS Block 1 to ~12 m aperture; SLS Block 2 for larger apertures

Science Traceability Matrix

	SCIENCE INVESTIGATION	Possible Parallel?	Instrumentation Exo-Im	Exo-Sp	UV	PI	MOS	Aperture Area	PSF	Band UV	NIR	Spectral Resolution	Detector Req.	Photon Min CR
Exoplanets	Detect earth-like planets in HZ		●					●				5		0.05
	Obtain orbital parameters		●					●				5		0.05
	Obtain spectra, detect biosignatures			●				●			●	>70-500	PC	**<0.005**
	Characterize planetary systems			●				●			●	>70-500	PC	**<0.005**
	Transit spectroscopy/atmospheres				●		●				●	100-3000	Dyn Rg	**1E+05**
IGM+	Study disk/halo interface				●		●	●		●		>6000	PC	**1E-05**
	Probe using brt. QSO, or gal.				●		●	●		●		10k-100k		0.003
	Detect in emission	●			●		●	●		●		>1000	PC	**1E-06**
Galaxies & SN	SF and Chemical Enrichment, all z	●			●		●	●	●			500-5000	PC	**0.0001**
	First galaxies/reionization, high z	●				●		●	●		●	5		0.03
	First galaxies SF and Metals, high z	●					●	●	●		●	100-2000		0.01
	Resolved massive SFR regions z=1-4	●				●		●	●	●	●	5		0.03
	Transient stellar progenitors and hosts	●				●		●	●			5		0.03
	Resolved SFH, to Msun, <25 Mpc	●				●		●	●	●		5		0.03
	Proper motions of stars in LG dwarf					●			●			5		0.03
	Low mass dwarfs and features, all z	●				●		●	●	●		5		0.03
AGN	SMBH mass function vs. z, env.	●			●		●		●			1k-5k		0.01
	Accretion disk and ionized flows				●		●		●	●		100-5k		0.01
Stars	Low Metallicity, high mass					●			●	●		5, 100k	PC	**0.0001**
	Circumstellar disk, protoplanetary						●		●	●		100-100k	PC	**0.0001**
	IMF and remnant MF microlensing	●				●			●			5		1
	Globular cluster ages, WDs					●			●	●		5		0.1
	IMF vary w/ environment?	●				●			●			5		0.01
Solar System	Surface/clouds <200 km @ Kuiper Belt					●			●			5		-
	Outer Solar System Census	●				●		●	●			5		-
	Planetary Magnetospheres				●	●				●		5		-
	Coronae, Aurora, Volcanism				●	●			●	●		5		-