Technology Development for the Advanced Technology Large Aperture Space Telescope (ATLAST) as a Candidate Large UV-Optical-Infrared (LUVOIR) Surveyor

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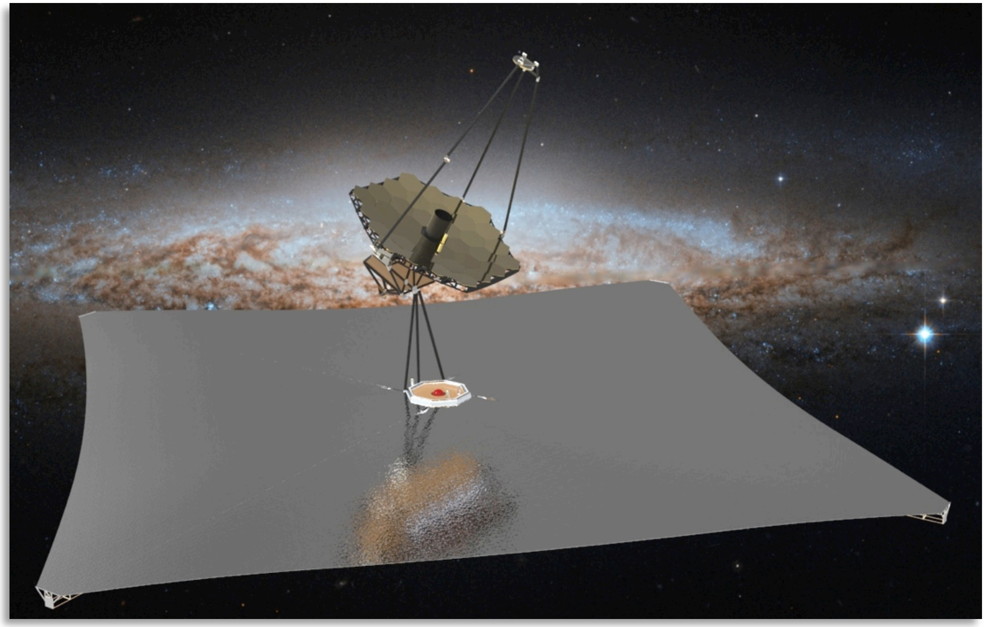
What is ATLAST?

- Mission concept study for a large UV-Optical-Infrared space telescope ("LUVOIR")

- Multiple engineering reference designs being explored by a multi-institutional team
  - See: N. Rioux, "A future large-aperture UVOIR space observatory: reference designs", paper 9602-4

- Similar in scope to AURA's High Definition Space Telescope (HDST)



What is ATLAST?

- “ATLAST”, “LUVOIR”, “HDST” are all ***mostly*** interchangeable
- **LUVOIR:** defined in NASA Astrophysics 30-year roadmap
  - Architecture is non-specific
- **HDST:** see:

  From Cosmic Birth to Living Earths
  Tuesday, Aug. 11, 8:00 pm – 10:00 pm Marriot Marquis, Marina E

  - Advocates for a large segmented aperture
- **ATLAST:** multiple architectures being considered
  - Has engineering reference designs for segmented and monolithic systems
- All have very similar science goals

ATLAST Science

- Detect and characterize a statistically significant population of habitable exoplanets
  - Discover dozens of exoEarths
  - Look for, and potentially confirm, presence of life
  - Observe general planet populations for comparative studies

- Perform a broad array of UVOIR general astrophysics:
  - Galaxy, star, and planet formation
  - Flow of material between galaxies
  - Observations within our own solar system

- ATLAST's science portfolio is very similar to that outlined in AURA's *From Cosmic Birth to Living Earths* report

Top-Level System Requirements

Parameter		Requirement	Stretch Goal	Traceability
Primary Mirror Aperture		≥ 8 meters	12 meters	Resolution, Sensitivity, Exoplanet Yield
Telescope Temperature		273 K – 293 K	-	Complexity, Fabrication, Integration & Test, Contamination, IR Sensitivity
Wavelength Coverage	UV	100 nm– 300 nm	90 nm – 300 nm	-
	Visible	300 nm – 950 nm	-	-
	NIR	950 nm – 1.8 μm	950 nm – 2.5 μm	-
	MIR	Sensitivity to 5.0 μm	-	Transit Spectroscopy
Image Quality	UV	< 0.20 arcsec at 150 nm	-	-
	Vis/NIR/MIR	Diffraction-limited at 500 nm	-	-
Stray Light		Zodi-limited between 400 nm – 1.8 μm	Zodi-limited between 200 nm – 2.5 μm	Exoplanet Imaging & Spectroscopy SNR
Wavefront Error Stability		< 10 pm RMS uncorrected system WFE per control step	-	Starlight Suppression via Internal Coronagraph
Pointing	Spacecraft	≤ 1 milli-arcsec	-	-
	Coronagraph	< 0.4 milli-arcsec	-	-

Technology Development for ATLAST

- Our team identified 5 key technology areas to enable the ATLAST mission:
    - Internal Coronagraph
    - Starshade
    - Ultra-stable large aperture systems
    - Detectors
    - Mirror Coatings

Assumptions

- Assume a new mission start circa 2024
  - Technologies must be TRL 5 by this time
  - Technology development plan must be credible in time for 2020 Decadal Survey

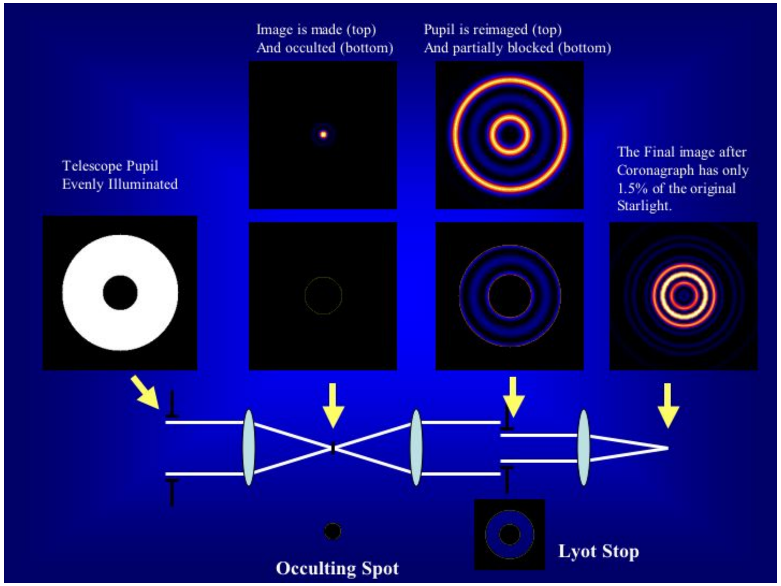
- Assume flexibility with respect to ATLAST architecture
  - Explore multiple solutions at this early stage of development
  - i.e. develop for both monolithic and segmented apertures, develop both internal coronagraphs and starshades, etc.

- Adopt a conservative approach in identifying gaps
  - This a systems-level problem: every technology impacts every other
  - Requires detailed integrated design cycles
  - For now, assume conservatively and refine as technologies develop and modeling is performed

Technologies

Internal Coronagraph

- Instrument internal to the observatory that suppresses the on-axis starlight



- Nimble: allows the observation of many planetary systems in a fixed mission lifetime
  - Dozens of exoEarths predicted with reasonable assumptions[1]
- Impose stringent wavefront stability requirements on the telescope
- Limited inner-working angle at long wavelengths
  - Difficult to observe some biosignature spectral features in the NIR

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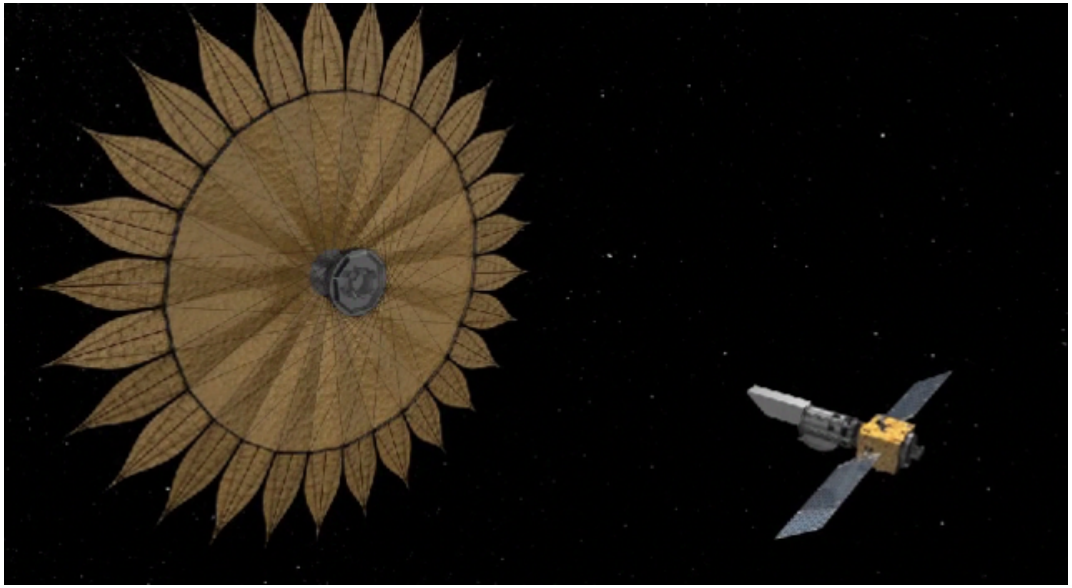
[1] Stark, *et al.*, "Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission", *ApJ*, **795** (2014)

Internal Coronagraph	Parameter	Need	Capability	Current TRL
Broadband High-Contrast Coronagraph includes Wavefront Sensing & Control (WFSC)	Raw Contrast	1×10^{-10} (detect) 5×10^{-10} (char.)	3.2×10^{-10}	3
	IWA	3.6 λ/D (detect) 2.0 λ/D (char.)	3 λ/D	
	OWA	~ 64 λ/D	16 λ/D	
	Bandpass	10-20% (instantaneous) 400 nm – 1.8 μm (total) 200 nm – 2.5 μm (goal)	10%	
	Aperture	Obscured, segmented	Unobscured	
	WFSC	Fast, low-order, at stellar photon rates	Slow, tip/tilt, bright lab source	
Deformable Mirrors	Actuator count	128×128 (continuous) >3000 (segmented)	64×64 (continuous) <200 (segmented)	3
	Environmental	Robust, rad. hard	Testing underway	
	Electronics	>16 bits, high-throughput	~16 bit, dense cabling	
Autonomous Onboard Computation	Bandwidth	Closed-loop > a few Hz	Human-in-the-loop	3
	Electronics	Rad. hard, >100 GFLOPS/W	<20 GFLOPS/W	
Starlight Suppression Image Processing	PSF Calibration	Factor of 50-100× improvement in contrast	25× demonstrated 30× goal for WFIRST	3

Starshade

- Separate spacecraft that flies in formation with telescope to block incoming starlight



- Not nimble: long slew times between observations limits the exoplanet yield for a fixed mission lifetime

- No special requirements imposed on telescope

- Inner working angle is independent of wavelength or telescope diameter

Starshade	**Parameter**	**Need**	**Capability**	**Current TRL**
Starshade Construction and Deployment	-	Petal and central truss design consistent with an 80-m class starshade Demonstrate manufacturing and deployment tolerances	Demonstrated prototype petal for 40-m class starshade Demonstrated deployment tolerances with a 12-m Astromesh antenna with 4 petals	3
Optical Edges	Edge radius	≤ 1 µm	≥ 10 µm	3
	Reflectivity	≤ 10%	-	
	Stowed radius	≤ 1.5 m	-	
Formation Flight	Lateral sensing error	≤ 20 cm	-	3
	Peak-to-peak control	< 1 m	-	
	Centroid estimation	≤ 0.3% of optical resolution	≥ 1%	
Contrast Performance Demonstration and Model Validation	-	1×10^{-10} broadband contrast at Fresnel numbers ≤ 50	3×10^{-10} contrast, excluding petal edges, narrowband, at Fresnel number of ~500	3
Starshade Propulsion & Refueling	-	Propulsion & refueling to enable > 500 slews during 3 years of a 5-year mission	Requires study; robotic refueling appears feasible	3

Ultra-stable Large Aperture Telescopes

- Provide wavefront stability for an internal coronagraph

- Incorporates entire optical system:
  - Mirrors
  - Structure
  - Thermal control system
  - Vibration isolation system
  - Metrology & Actuators

Ultra-stable Large Aperture Telescopes	**Parameter**	**Need**	**Capability**	**Current TRL**
Mirrors	Areal Density	< 36 kg/m^2 (Delta IVH) < 500 kg/m^2 (SLS)	~12 kg/m^2 (SiC) ~35 kg/m^2 (ULE) ~70 kg/m^2 (JWST)	4
	Areal Cost	< \$2 M/m^2	~\$6 M/m^2 (JWST)	
	Areal Production Rate	30-50 m^2/year	~4 m^2/year (JWST) ~1 m^2/year (HST) ~100-300 m^2/year planned by TMT but not yet demonstrated	
Stable Structures	Moisture Expansion	Zero after initial moisture release	Continuous moisture release	3
	Lurch	< 10 pm / wavefront control step	Micro-lurch at joint interfaces	
	Metrology	High-speed picometer metrology to validate performance	Nanometer speckle interferometry on JWST	
Thermal Stability	Material Stability	~10 nm/K	~100 nm/K	3
Disturbance Isolation System	End-to-end Attenuation	140 dB at frequencies > 20 Hz	80 dB at frequencies > 40 Hz (JWST passive isolator only)	4
Metrology & Actuators	Sensing Accuracy	~1 pm	~1 nm	4
	Control Accuracy	~1 pm	~5 nm	

Detectors

- Need improvements to enable and enhance exoplanet science

- Better UV science enabled by improvements in sensitivity and format

- See:

B. Rauscher, “Detector requirements for coronagraphic biosignature characterization”, paper 9602-12

Detectors	Parameter	Need	Capability	Current TRL
Visible-NIR Single-photon Detectors for Enabling Exoplanet Science	Bandwidth	400 nm – 1.8 µm (2.5 µm goal)	EMCCD is promising, need rad.-hard testing, has hard cutoff at 1.1 µm; HgCdTe APDs good for NIR but need better dark current; MKID & TES meet requirements but require cryo ops.	3-5
	Read Noise	<< 1 e^-		
	Dark Current	< 0.001 e^-/pix/s		
	Spurious Count Rate	Small compared to dark current		
	Quantum Eff.	> 80% over bandwidth		
	Format	> 2k × 2k		
UV Single-photon Detectors for Enhanced Exoplanet Science	Bandwidth	200 nm – 400 nm	EBCMOS and MCP detectors need better quantum eff., and improvements in lifetime; MKID & TES detectors also apply here	2-4
	Read Noise	<< 1 e^-		
	Dark Current	< 0.001 e^-/pix/s		
	Spurious Count Rate	Small compared to dark current		
	Quantum Eff.	> 50% over bandwidth		
	Format	> 2k × 2k		
Large-Format High-Sensitivity UV Detectors for General Astrophysics	Bandwidth	90 nm – 300 nm	Same as above; δ-doped EMCCD also a candidate, but needs rad.-hard testing and lower clock-induced charge	4
	Read Noise	< 5 e^-		
	Quantum Eff.	> 70%		
	Format	> 2k × 2k		

Mirror Coatings

- Needed for Primary & Secondary mirror surfaces

- Broadband performance from UV to NIR

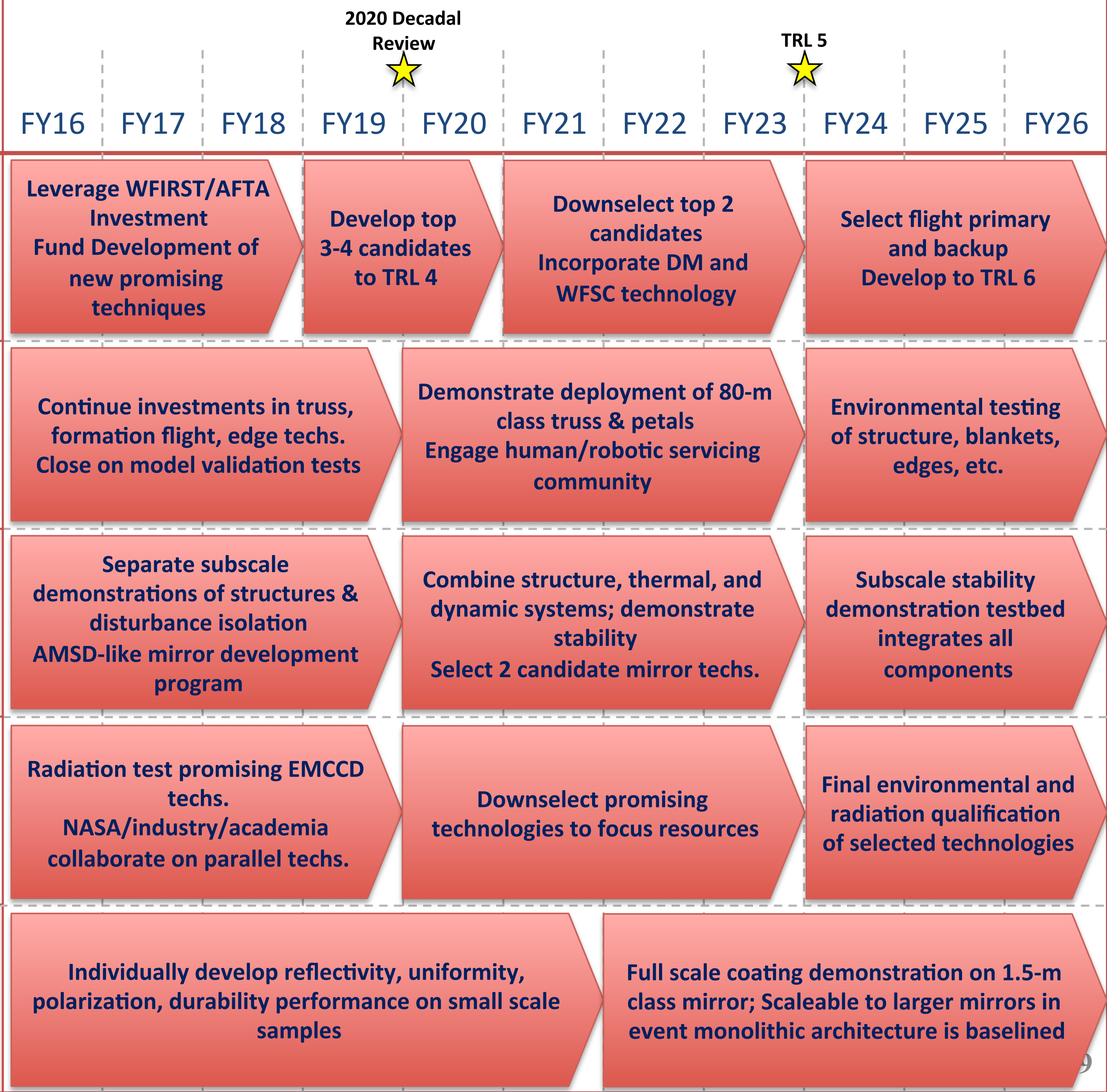
- Compatible with high-contrast imaging by internal coronagraph

- See:

K. Balasubramanian, *et al.*, "Coatings for UVOIR telescope mirrors", paper 9602-19

Mirror Coatings	Parameter	Need	Capability	Current TRL
Reflectivity	90 nm – 120 nm	> 70%	< 50%	2
	120 nm – 300 nm	> 90%	80%	3
	> 300 nm	> 90%	> 90%	5
Uniformity	90 nm – 120 nm	< 1%	TBD	2
	120 nm – 250 nm	< 1%	> 2%	3
	> 250 nm	< 1%	1-2%	4
Polarization	≥ 90 nm	< 1%	Not yet assessed; requires study	2
Durability	-	Stable performance over mission lifetime (10 years minimum)	Stable performance, but with limited starting reflectivity below 200 nm	4

Development Activities



Internal Coronagraph

- Leverage WFIRST/AFTA Investment Fund Development of new promising techniques
- Develop top 3-4 candidates to TRL 4
- Downselect top 2 candidates Incorporate DM and WFSC technology
- Select flight primary and backup Develop to TRL 6

Starshade

- Continue investments in truss, formation flight, edge techs. Close on model validation tests
- Demonstrate deployment of 80-m class truss & petals Engage human/robotic servicing community
- Environmental testing of structure, blankets, edges, etc.

Ultra-stable Large Aperture Telescopes

- Separate subscale demonstrations of structures & disturbance isolation AMSD-like mirror development program
- Combine structure, thermal, and dynamic systems; demonstrate stability Select 2 candidate mirror techs.
- Subscale stability demonstration testbed integrates all components

Detectors

- Radiation test promising EMCCD techs. NASA/industry/academia collaborate on parallel techs.
- Downselect promising technologies to focus resources
- Final environmental and radiation qualification of selected technologies

Mirror Coatings

- Individually develop reflectivity, uniformity, polarization, durability performance on small scale samples
- Full scale coating demonstration on 1.5-m class mirror; Scaleable to larger mirrors in event monolithic architecture is baselined

Conclusions

- A multi-institutional team, studying a large UV-Optical-IR telescope with two science goals:
    - Detect and characterize habitable exoplanets
    - Broad array of general astrophysical observations

- Identified 5 key technologies to enable ATLAST
    - Internal Coronagraph
    - Starshade
    - Ultra-stable large-aperture telescopes
    - Detectors
    - Mirror Coatings

- Recommended actions for developing technologies to TRL 5 in time for a new mission start in 2024

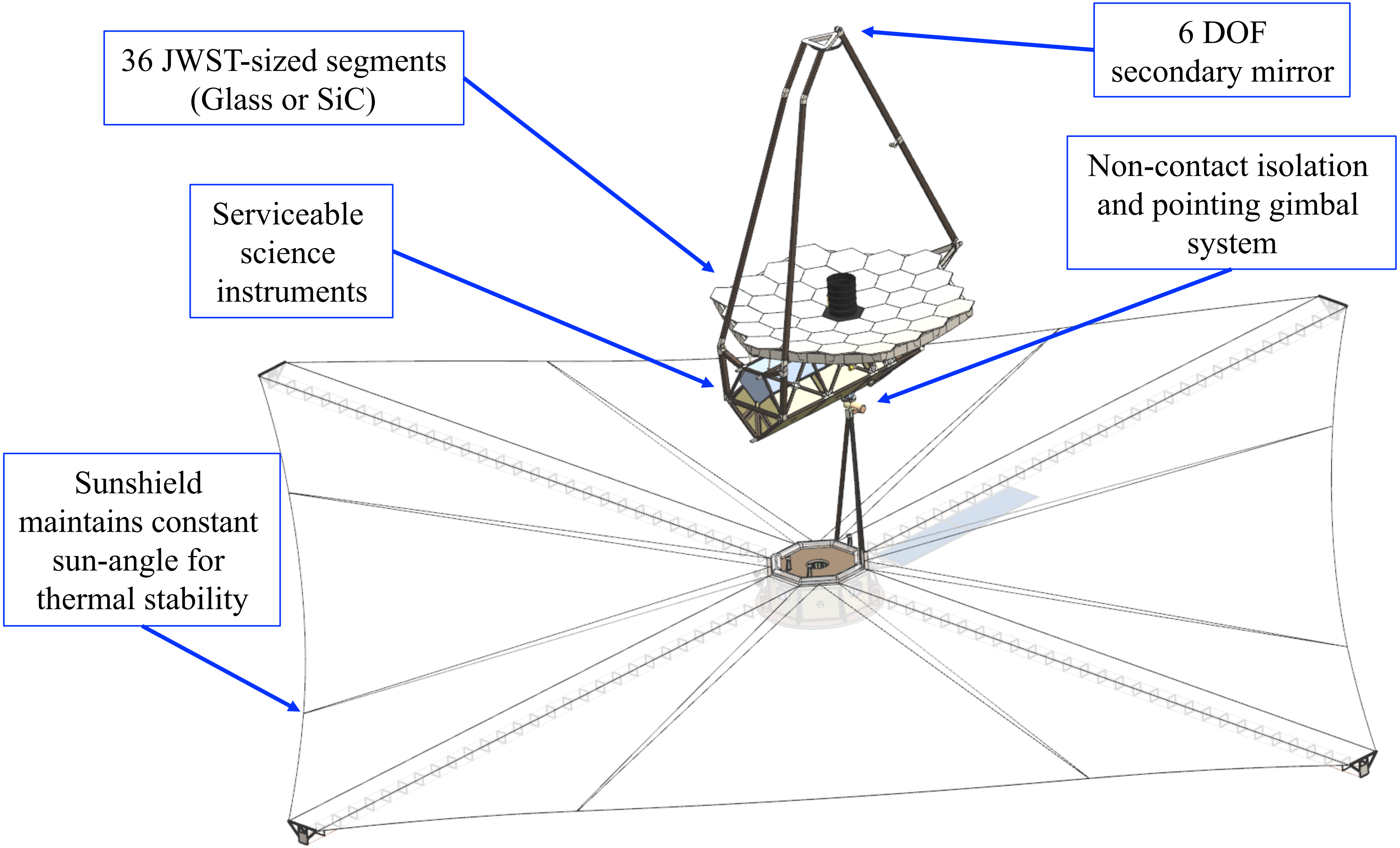
Questions?

BACKUP

Historical Context

- 2009
    - Multi-institutional team studies ATLAST concept; proposed to 2010 Decadal Survey
- 2010
    - Decadal Committee recommends “a New Worlds Technology Development Program” as the highest priority medium-scale activity
- 2014
    - NASA Astrophysics 30-year Roadmap recommends a large UV-Optical-Infrared (LUVOIR) telescope in the “Formative Era”
- 2015
    - AURA releases *From Cosmic Birth to Living Earths*; recommends the High Definition Space Telescope (HDST) as a general astrophysics observatory with the “killer app” of detecting and characterizing habitable exoplanets
- Early to mid-2016
    - NASA Astrophysics Division initiates Science and Technology Definition Teams (STDTs) to perform detailed mission concept studies in preparation of the 2020 Decadal Survey: LUVOIR is one of four missions to be studied

ATLAST Segmented Architecture: At a Glance



36 JWST-sized segments (Glass or SiC)

6 DOF secondary mirror

Serviceable science instruments

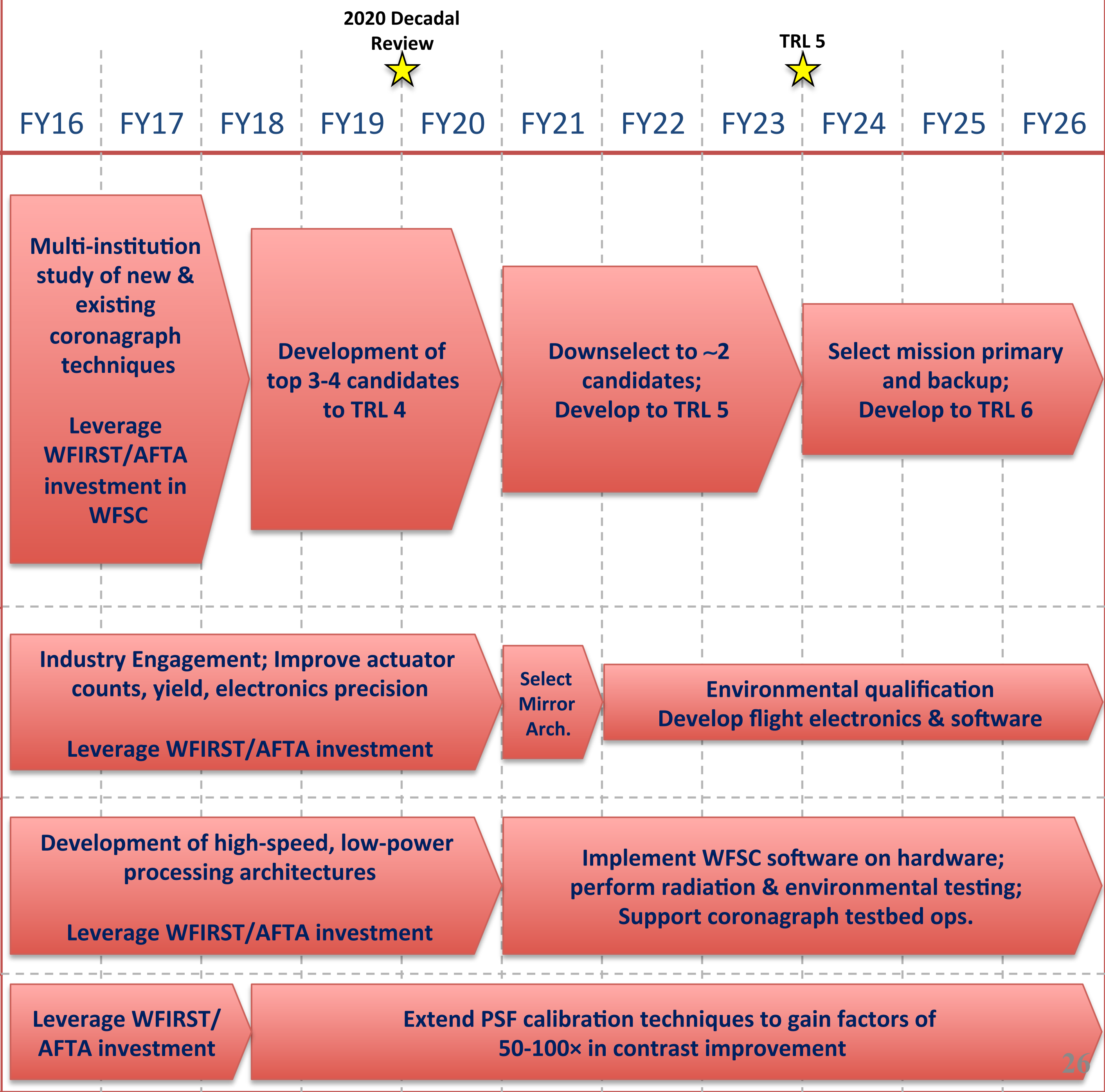
Non-contact isolation and pointing gimbal system

Sunshield maintains constant sun-angle for thermal stability

Notional Instrument Requirements

Science Instrument	Parameter	Requirement	Stretch Goal
UV Multi-Object Spectrograph	Wavelength Range	100 nm – 300 nm	90 nm – 300 nm
	Field-of-View	1 – 2 arcmin	-
	Spectral Resolution	R = 20,000 – 300,000 (selectable)	-
Visible-NIR Wide-field Imager	Wavelength Range	300 nm – 1.8 µm	300 nm – 2.5 µm
	Field-of-View	4 – 8 arcmin	-
	Image Resolution	Nyquist sampled at 500 nm	-
Visible-NIR Integral Field Spectrograph	Wavelength Range	300 nm – 1.8 µm	300 nm – 2.5 µm
	Field-of-View	4 – 8 arcmin	-
	Spectral Resolution	R = 100 – 10,000 (selectable)	-
MIR Transit Spectrograph	Wavelength Range	Sensitivity to 5 µm	-
	Field-of-View	TBD	-
	Spectral Resolution	R = 200	-
Starlight Suppression System	Wavelength Range	400 nm – 1.8 µm	200 nm – 2.5 µm
	Raw Contrast	1×10^{-10}	-
	Contrast Stability	1×10^{-11} over integration	-
	Inner-working angle	36 milli-arcsec @ 1 µm	-
	Outer-working angle	> 0.5 arcsec @ 1 µm	-
Multi-Band Exoplanet Imager	Field-of-View	~0.5 arcsec	-
	Resolution	Nyquist sampled at 500 nm	-
Exoplanet Spectrograph	Field-of-View	~0.5 arcsec	-
	Resolution	R = 70 – 500 (selectable)	-

Internal Coronagraph



2020 Decadal Review

TRL 5

FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26

Broadband High-Contrast Coronagraph

includes Wavefront Sensing & Control (WFSC)

- Multi-institution study of new & existing coronagraph techniques

  Leverage WFIRST/AFTA investment in WFSC
- Development of top 3-4 candidates to TRL 4
- Downselect to ~2 candidates; Develop to TRL 5
- Select mission primary and backup; Develop to TRL 6

Deformable Mirrors

- Industry Engagement; Improve actuator counts, yield, electronics precision

  Leverage WFIRST/AFTA investment
- Select Mirror Arch.
- Environmental qualification Develop flight electronics & software

Autonomous Onboard Computation

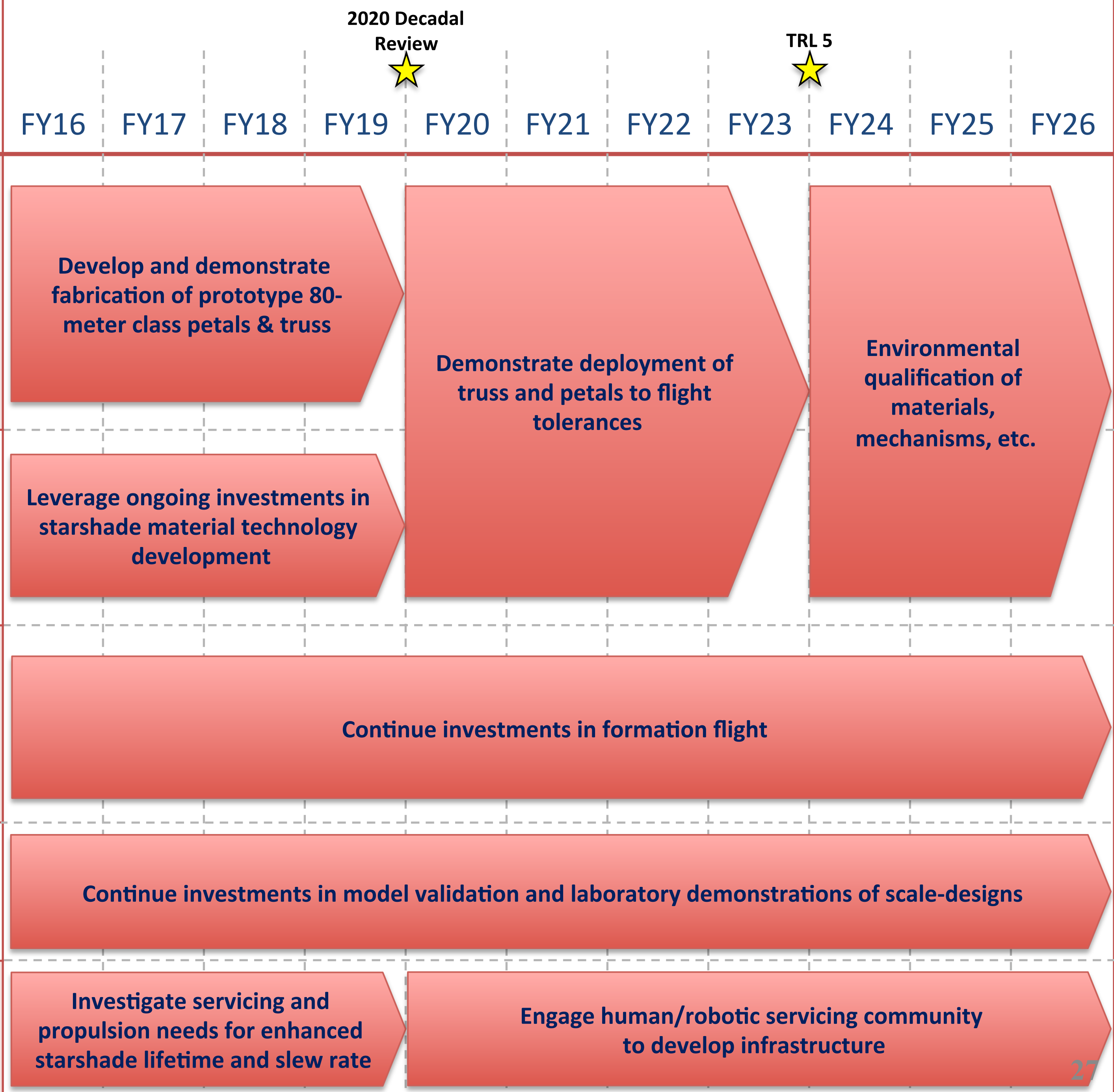
- Development of high-speed, low-power processing architectures

  Leverage WFIRST/AFTA investment
- Implement WFSC software on hardware; perform radiation & environmental testing; Support coronagraph testbed ops.

Starlight Suppression Image Processing

- Leverage WFIRST/ AFTA investment
- Extend PSF calibration techniques to gain factors of 50-100× in contrast improvement

Starshade



Starshade Construction and Deployment

- Develop and demonstrate fabrication of prototype 80-meter class petals & truss

Optical Edges

- Leverage ongoing investments in starshade material technology development

Starshade Construction and Deployment / Optical Edges

- Demonstrate deployment of truss and petals to flight tolerances
- Environmental qualification of materials, mechanisms, etc.

Formation Flight

- Continue investments in formation flight

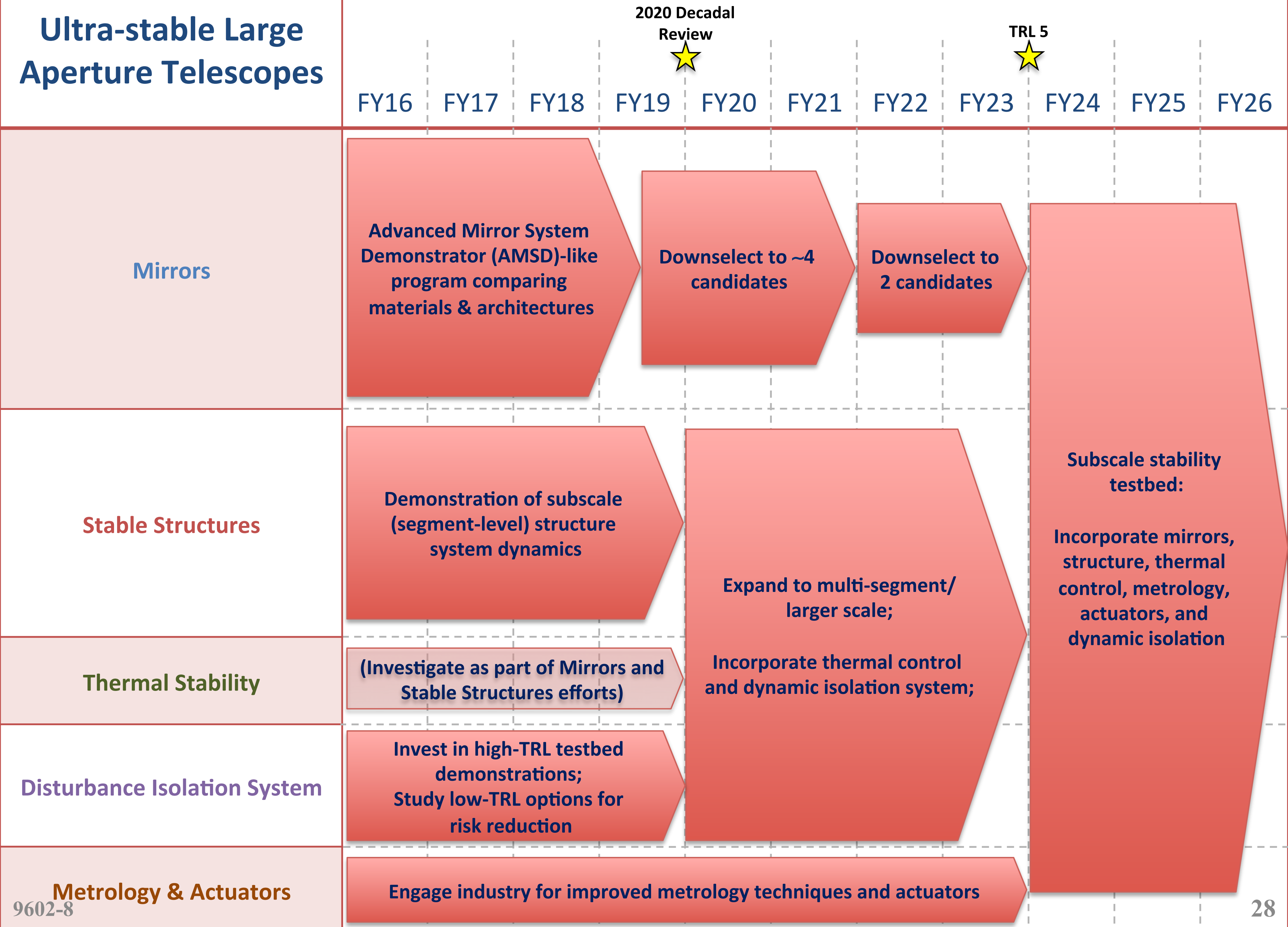
Contrast Performance Demonstration and Model Validation

- Continue investments in model validation and laboratory demonstrations of scale-designs

Starshade Propulsion & Refueling

- Investigate servicing and propulsion needs for enhanced starshade lifetime and slew rate
- Engage human/robotic servicing community to develop infrastructure

Ultra-stable Large Aperture Telescopes



2020 Decadal Review ☆

TRL 5 ☆

FY16 FY17 FY18 FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26

Mirrors

Advanced Mirror System Demonstrator (AMSD)-like program comparing materials & architectures

Downselect to ~4 candidates

Downselect to 2 candidates

Stable Structures

Demonstration of subscale (segment-level) structure system dynamics

Thermal Stability

(Investigate as part of Mirrors and Stable Structures efforts)

Disturbance Isolation System

Invest in high-TRL testbed demonstrations;
Study low-TRL options for risk reduction

Expand to multi-segment/ larger scale;

Incorporate thermal control and dynamic isolation system;

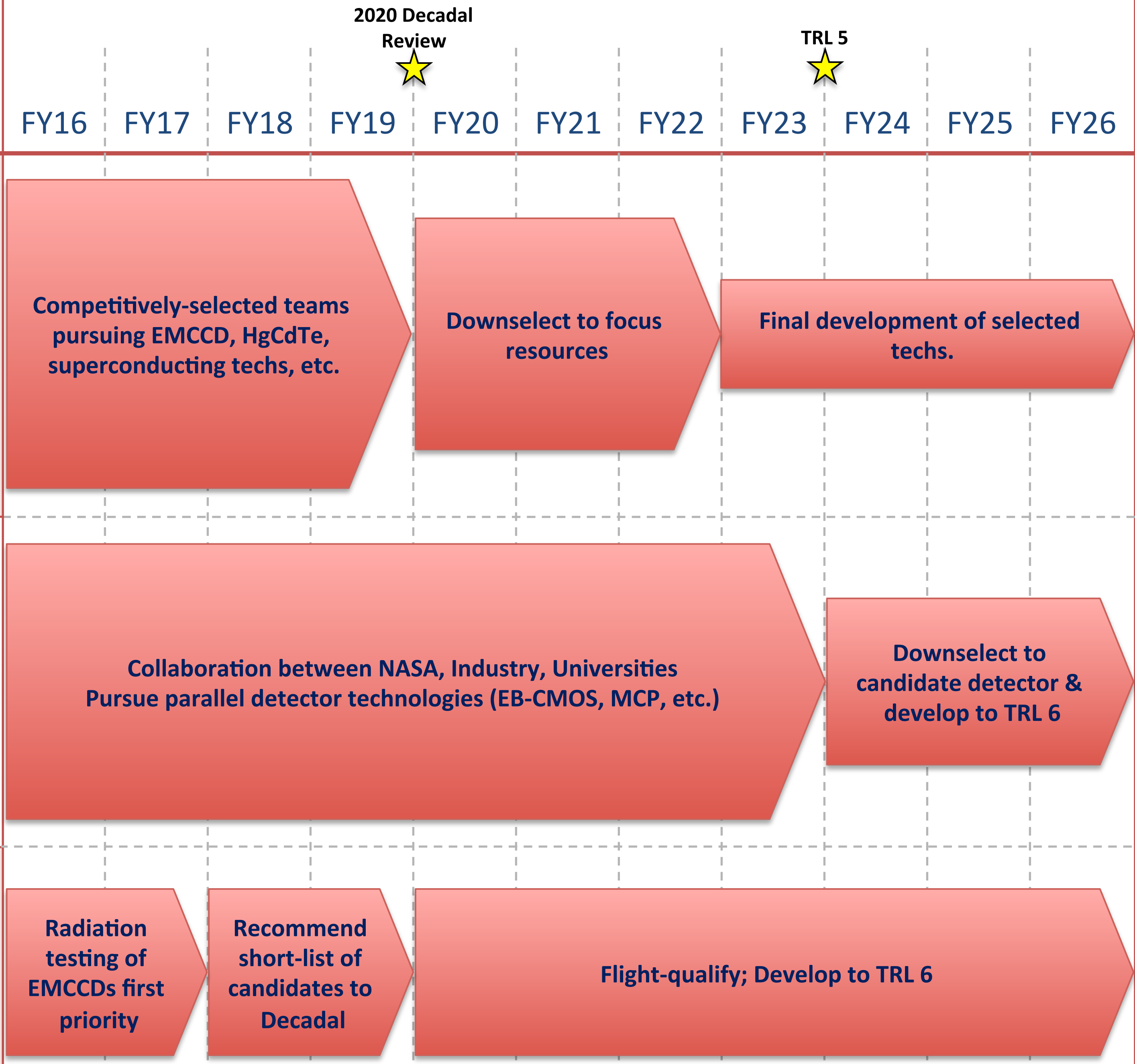
Subscale stability testbed:

Incorporate mirrors, structure, thermal control, metrology, actuators, and dynamic isolation

Metrology & Actuators

Engage industry for improved metrology techniques and actuators

Detectors



Visible-NIR Single-photon Detectors for Enabling Exoplanet Science

- Competitively-selected teams pursuing EMCCD, HgCdTe, superconducting techs, etc.
- Downselect to focus resources
- Final development of selected techs.

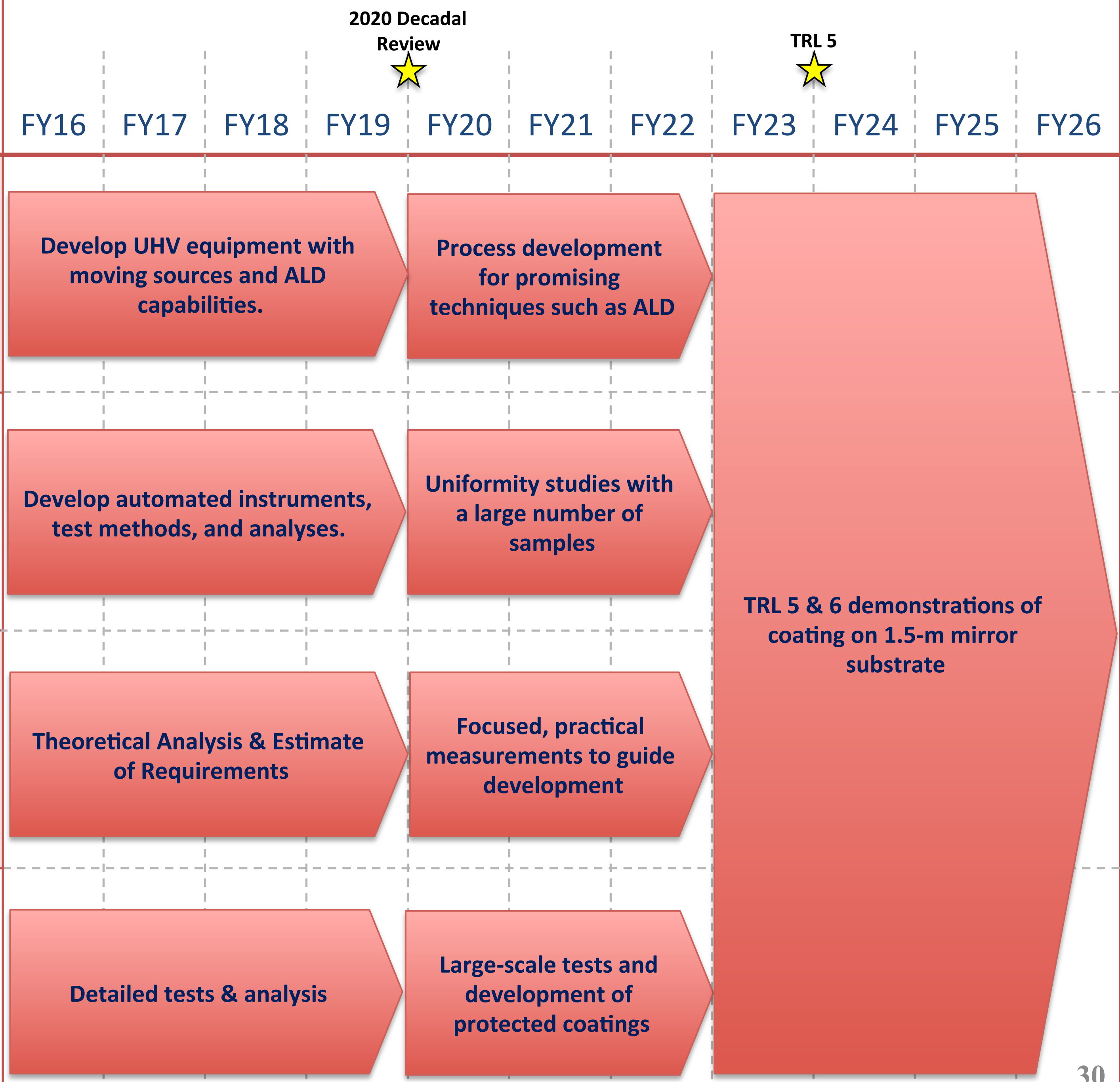
UV Single-photon Detectors for Enhanced Exoplanet Science

- Collaboration between NASA, Industry, Universities Pursue parallel detector technologies (EB-CMOS, MCP, etc.)
- Downselect to candidate detector & develop to TRL 6

Large-Format High-Sensitivity UV Detectors for General Astrophysics

- Radiation testing of EMCCDs first priority
- Recommend short-list of candidates to Decadal
- Flight-qualify; Develop to TRL 6

Mirror Coatings



Reflectivity

Develop UHV equipment with moving sources and ALD capabilities.

Process development for promising techniques such as ALD

Uniformity

Develop automated instruments, test methods, and analyses.

Uniformity studies with a large number of samples

Polarization

Theoretical Analysis & Estimate of Requirements

Focused, practical measurements to guide development

Durability

Detailed tests & analysis

Large-scale tests and development of protected coatings

TRL 5 & 6 demonstrations of coating on 1.5-m mirror substrate