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Building on the HST Legacy:
UVOIR Space Astronomy for the Coming Decades

The Advanced Technology Large-Aperture Space Telescope (ATLAST)

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Senior Scientist for Advanced Concepts (Code 660)

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Lee Feinberg
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and the ATLAST Study Team

Systems Engineering Seminar
April 1, 2014

NASA's UV, Visual, & IR Astrophysics Facilities

AFTA

JWST

Kepler

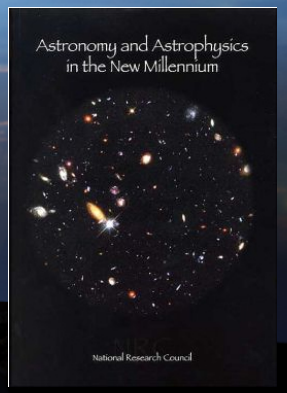
Observatory for the 2020s

Spitzer

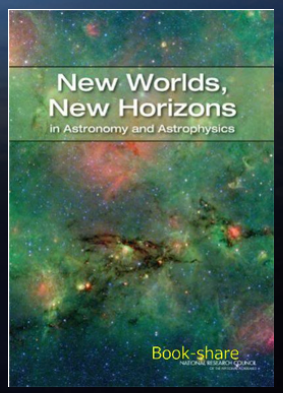
Hubble

Ground-based Observatories

2001 Decadal Survey



2010 Decadal Survey



Adapted from Testimony to Congress Given by J. Grunsfeld (May 5, 2013)

Agenda

H. Thronson

Overview, context, and notional science priorities

N. Rioux

Mission parameters, technology roadmap, mission architecture

L. Feinberg

Telescope architecture, optics, starlight suppression

The GSFC ATLAST Team

Management

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Avi Mandell

Deborah Padgett

Jane Rigby

Aki Roberge

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Karl Stapelfeldt

Chris Stark

Partner Leadership

NASA MSFC: H. P. Stahl

JPL: D. Redding

STScI: M. Postman

Acknowledgements

Joan Centrella

Peter Hughes

Michael Kienlen

Bill Oegerle

Azita Valinia

My one major disappointment is that I am not alive to participate in this exciting project. – Edwin Hubble

Background and Programmatic Context

Leading to the 2010 NRC Decadal Survey, a multi-institutional team produced three options for a future, large-aperture UVOIR observatory for consideration (cf., Postman *et alia* SPIE Optical Engineering, 51(1), 011007 (2012)).

The NRC 2010 Decadal Survey recommended as its highest-priority medium-sized activity funding technology to enable a future observatory "capable of studying nearby Earth-like planets . . . to be mature for consideration by the 2020 decadal survey" pending a mid-decade review.

Expecting the next NRC Decadal Survey to begin in 5 ½ years, many of the same partners that succeeded with the previous Survey are again jointly developing the priority science goals, enabling technologies, and conceptual designs for a large-aperture observatory to carry on the legacy of the Hubble Space Telescope.

Starting in March, 2013, this work has been supported by internal resources of the four participating institutions.

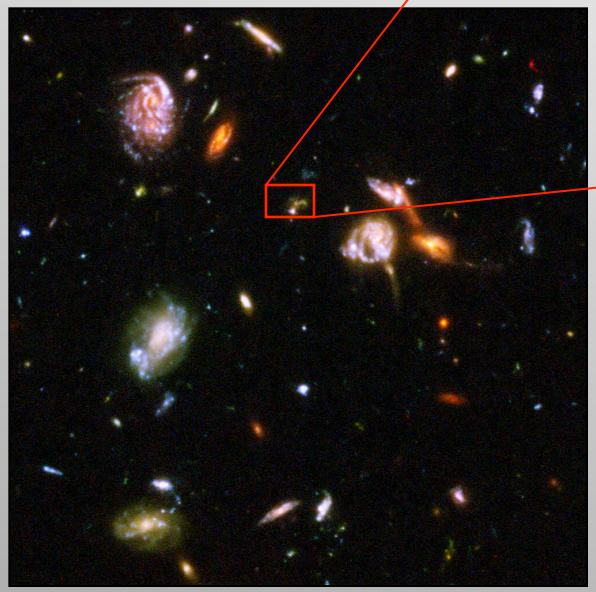
Basic Observatory Concepts

- The ATLAST team is focusing on designs enabled via existing launch vehicles, specifically Delta IV-H, which among existing EELVs is capable of launching the largest mass
  - Deployment architecture adapted from JWST
  - New approaches being considered to allow more efficient packaging
- Team has demonstrated that a 9.2 m aperture using an existing fairing appears feasible
- Team has also demonstrated an 11 m aperture is plausible, although more challenging without lower areal-density mirrors
- Parallel activities pursued as funding is available:
  - Concept for larger (16+ m) deployed telescope compatible with SLS
  - Serviceability and assembly with robots and/or astronauts *a la* HST
  - More modest (~ 8 m monolith) option compatible with SLS

General Astrophysics Drivers

- Larger aperture allows greater throughput & resolution
- Approximately HST's wavelength coverage: UV (~100 nm) through NIR (~2.5 μm, although non-cryogenic)
- Large FOV + Spectroscopic Multiplexing
  - *Issues: Tradeoff between cost of more complex instruments vs. efficiency gains*
- Example priority science goals
  - *Enabling a comprehensive theory of star formation via detailed observations of stars in many times more galaxies than heretofore possible*
  - *Producing a detailed history of the evolution of local galaxies via observations of the kinematics of circumgalactic gas*
  - *The astronomical search for biosignatures in Earth-like planets in the solar neighborhood*

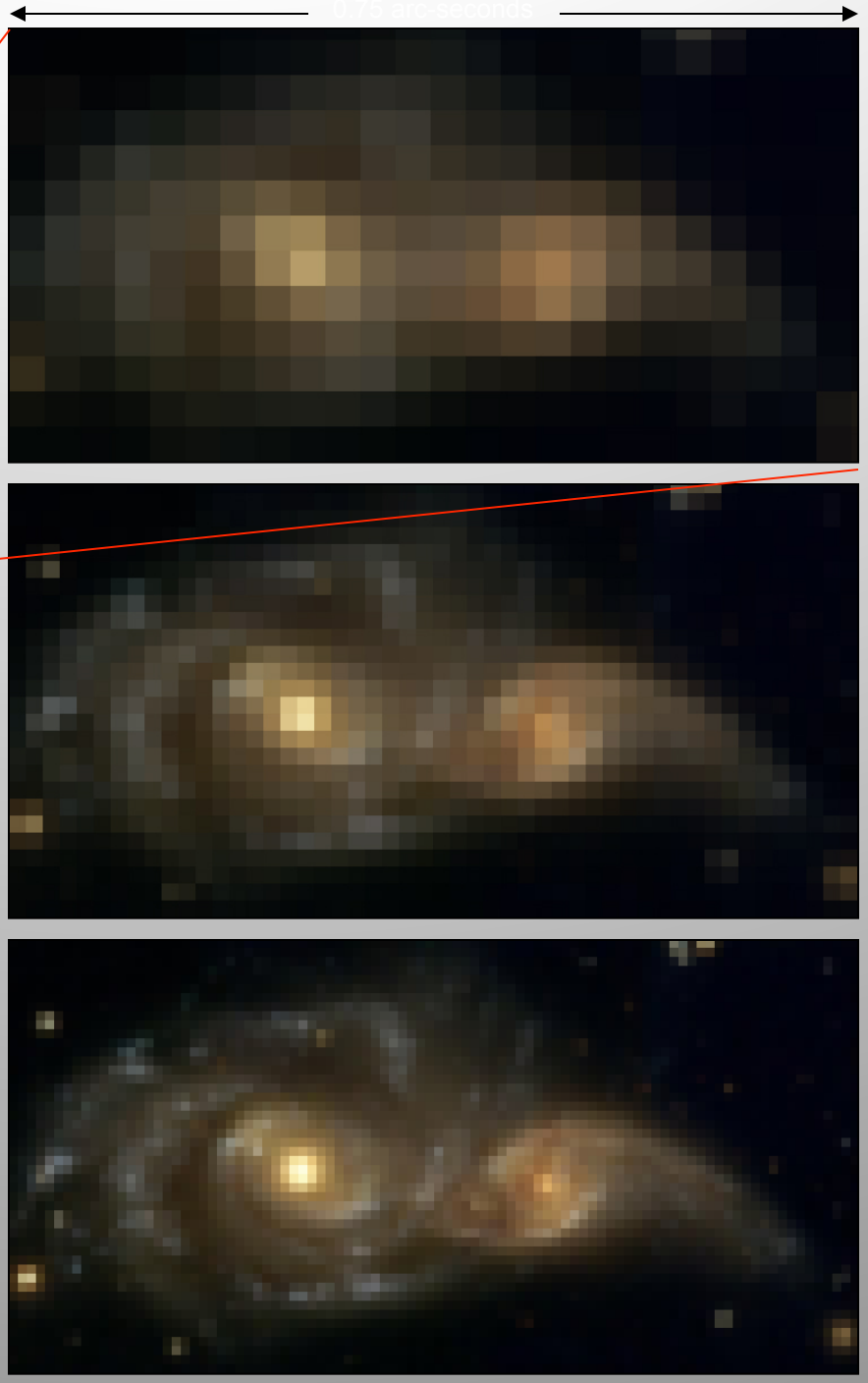
Bigger is Better . . . And More Revealing



HST Ultra Deep Field

Faint Galaxy:

- 25.1 AB mag (330 nJy) in I-band
- 100 million times fainter than what the naked eye can see!
- 2 “peaks” in light distribution
- Morphology unknown



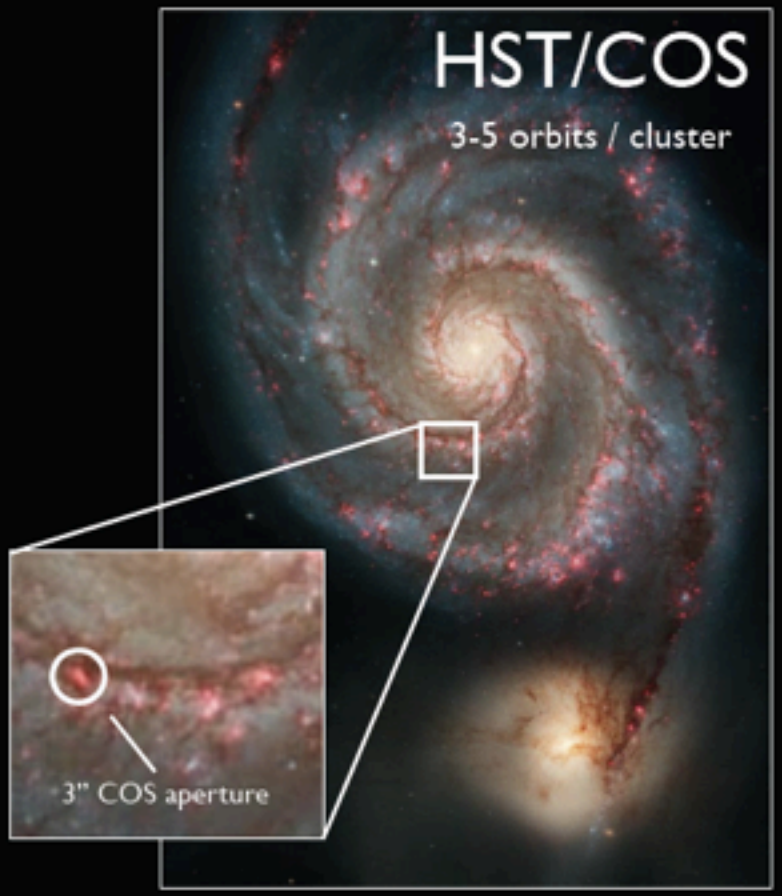
HST 2.4 m,
t ~ 900 ksec
(10 days)

8 m
ATLAST,
t ~ 25 ksec
(7 hours)

16 m
ATLAST,
t ~ 3 ksec
(1 hour)

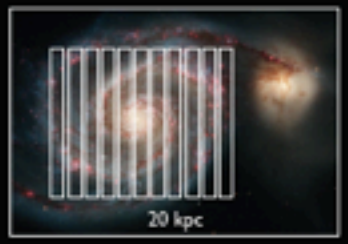
The Case for UV Multiplexing

A true UV multi-object/IFU capability would be a revolution in our ability to dissect gas flows, and the stellar populations that give rise to them, with dense sampling of spatial variations and all relevant physical variables.



Would also support intensive spectroscopy of every Magellanic Cloud OB star.

3′ MOS
at z ~ 0

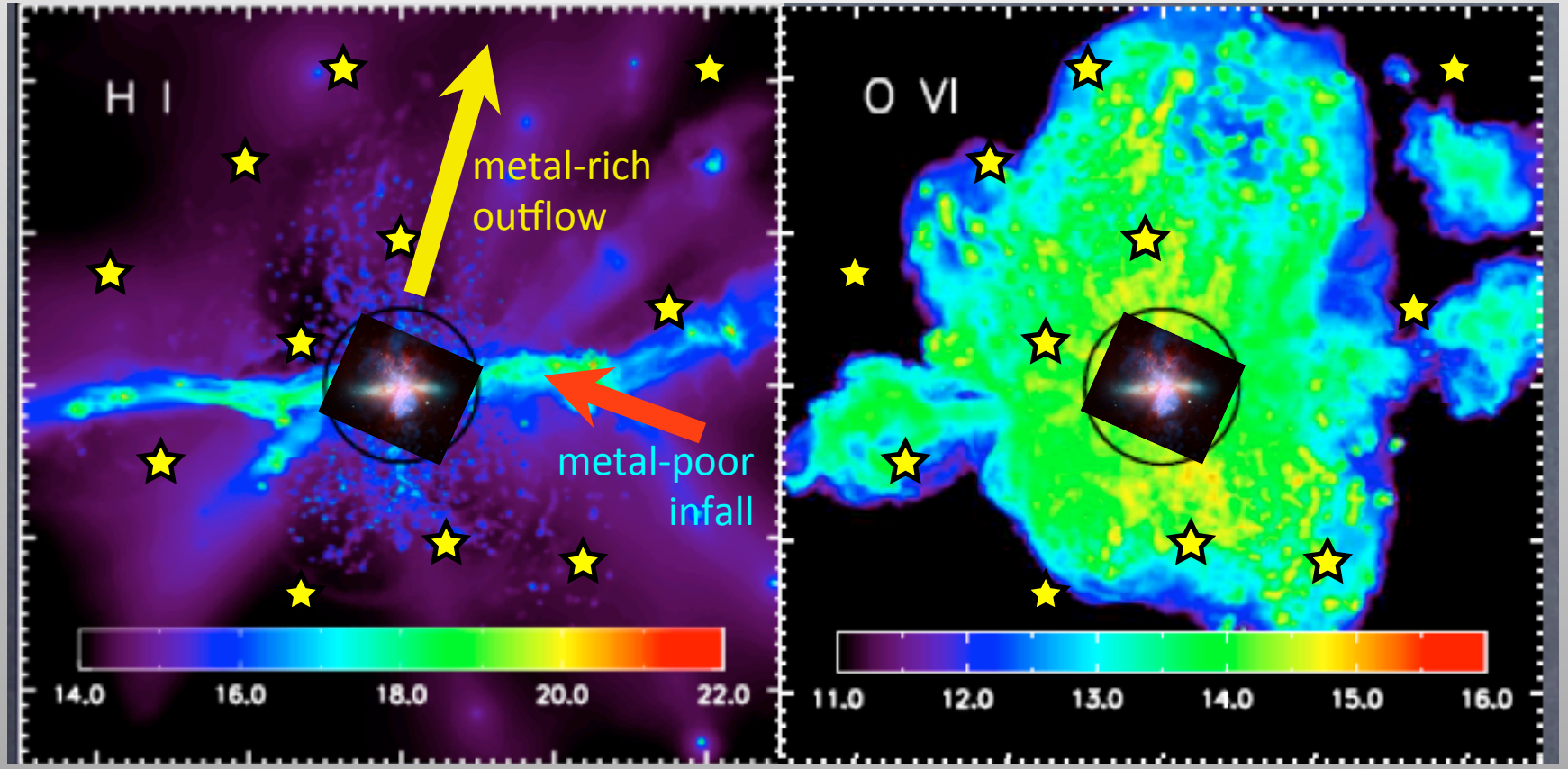


3″ IFU
at z ~ 0.5

Also would permit detailed mapping of UV continuum and line SFR metrics, spatially resolved, from z = 0 to z ~ 1.

Dissecting Halo Gas using Background QSOs

Simulations from Shen et al. 2012



900 - 1150 Å

HI column densities & OVI

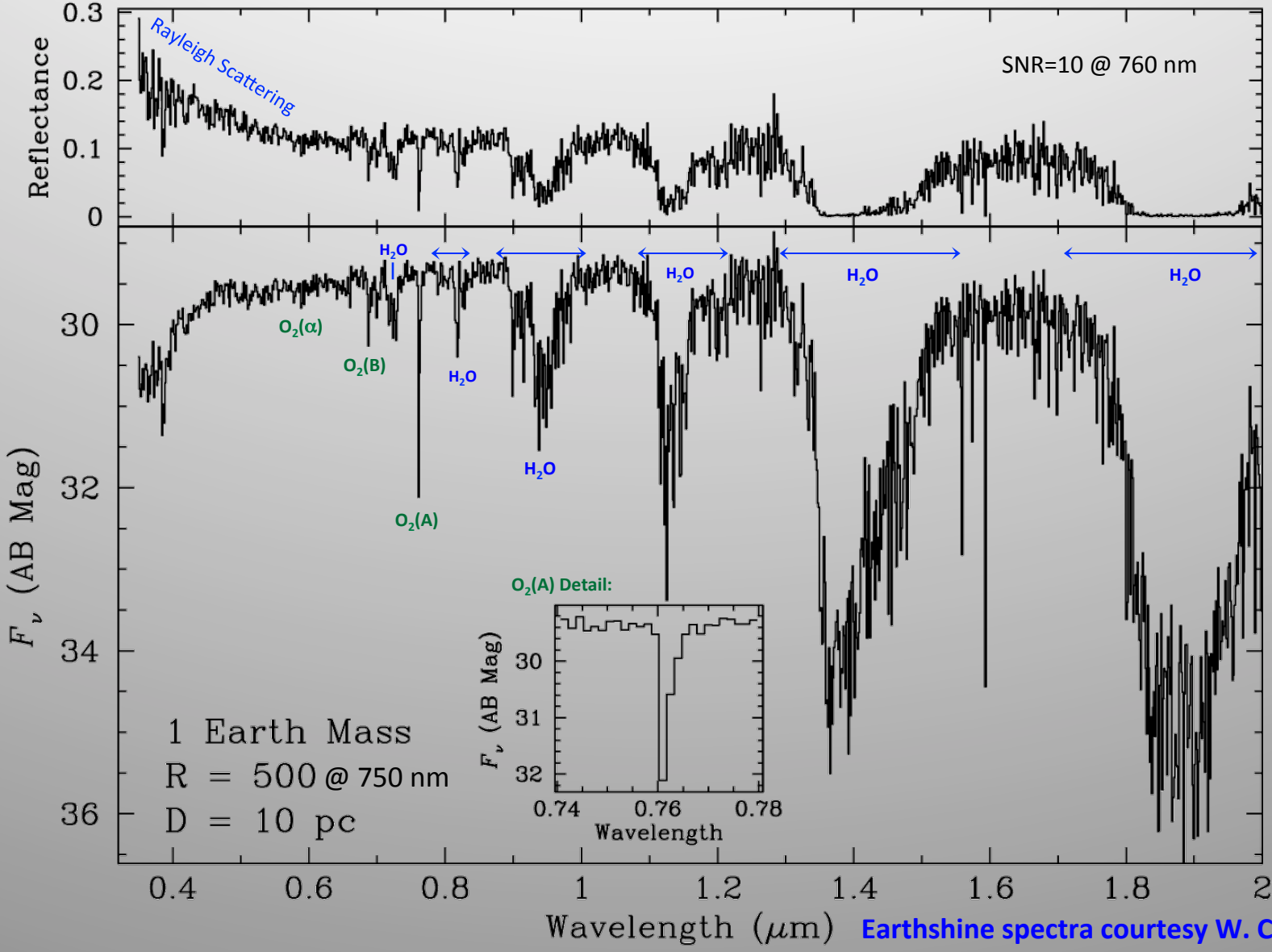
Slide credit: J. Tumlinson

R = 500 Spectrum of 1 Earth-mass Terrestrial Exoplanet at 10 pc

Exposure: 503 ksec on 8-m
56 ksec on 16-m

Reflectance ∝ (Planet Mass)$^{2/3}$
5 Earth-mass: 172 ksec on 8-m

Bkgd: 3 zodi
Contrast: 10^{-10}

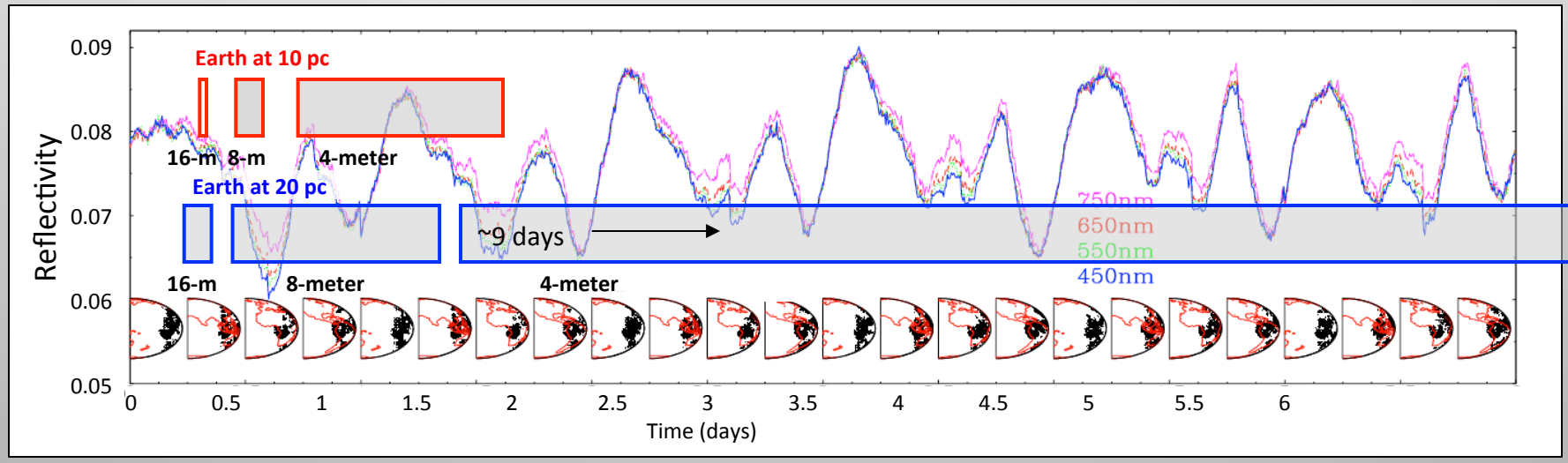


Earthshine spectra courtesy W. Cash.

We don't expect all habitable worlds to have spectra like this but interpreting their spectra will require this kind of instrumental capability.

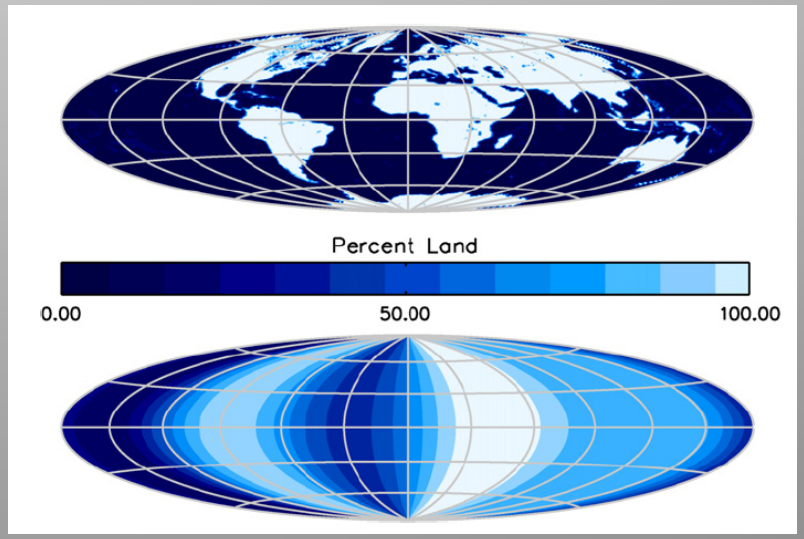
Detecting Diurnal Photometric Variability in Exoplanets

Earth as exo-planet (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 (nee Deep Impact) mission.



ATLAST As Essential For the Survival of Humanity

A Necro-Biological Explanation for the Fermi Paradox

http://arxiv.org/abs/1403.8146

The Fermi Paradox appears best explained by the interstellar spread of a zombie-producing virus.

From the conclusion:

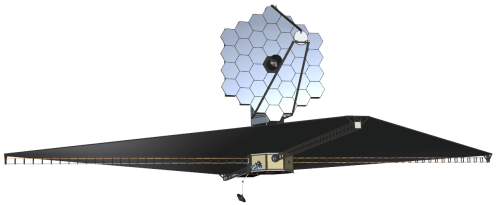
"The best chance that we as a civilization has of preventing a future encounter with a zombie virus is to carefully monitor and catalog the SNAP-contaminated planets. Although this requires the dedicated use of the James Webb Space Telescope (JWST) to perform this task, this will likely be insufficient to meet the challenge of monitoring all stars with the needed signal-to-noise. Thus we strongly advocate the construction of a fleet of no fewer than 10 JWSTs with increased apertures (12 meters should do the trick!). These should be designed to also operate together as a nuller interferometer so they can survey non-transiting nearby exoplanets, which represent the main threat. . . .Whatever the course of action, we must actively strive to address the threat and to mitigate the risk of annihilation by an exoplanet zombie infection"

Potential Space Science Strategy

HST "The people's telescope"

JWST Large-aperture IR observatory
segmented optics in space

WFIRST/AFTA active mirror control
giga-pixel array
robotic servicing
test HP Coronagraph



ATLAST: The UVOIR Legacy of HST
light-weight segmented optics
fully active optics control
human/robotic assembly
giga-pixel array
ultra-high contrast imaging

Tests light-weight segmented optics
active optics control
human-operated robotic assembly

ISS

commercial crew & SLS

Kepler

TESS

Finding potentially habitable exoplanets that can be characterized by ATLAST

PLATO

Today

Decadal Survey Begins

ESA L4 Selection

2015 2020 2025 2030 2035

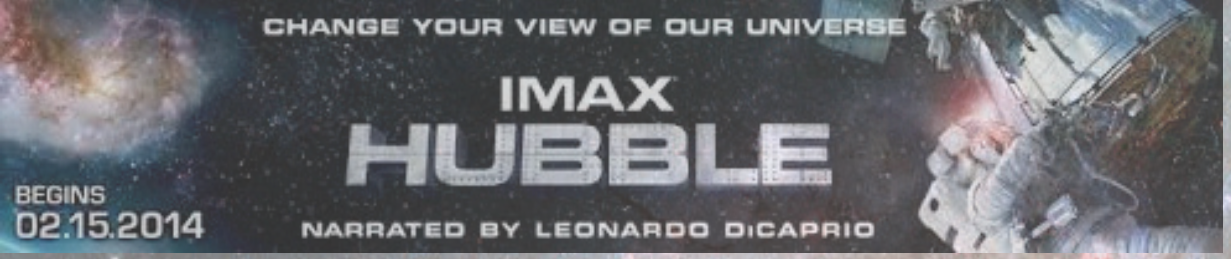
Major Study Schedule Milestones

We have only 5 ½ years to advance significantly the astrophysics mission that continues the legacy of HST.

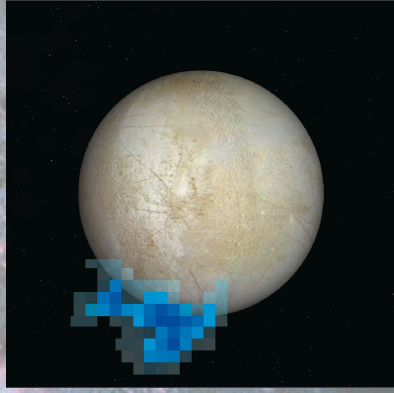
- ATLAST Milestones
  - *Technology plan: early April, although with continuing updates*
  - *Sufficiently advanced design and tech plan for mid-decade NRC review*
- Community Milestones
  - *AURA study well underway: completion "later this year"*
  - *NRC 2015 Mid-Decade Review of status of 2010 Survey recommendations*
    - "Readiness" for significant technology funding this decade
  - *NRC 2020 Decadal Survey: starts in FY2019*
  - *AAS "splinter session": early June – first public presentation*
  - *SPIE: late June – first technical presentation*

Where Our Team Is Now

- Four-institution team using internal resources to develop the design(s), priority science goals, and technology roadmap to be selected by the NRC in 2020 as the highest-priority major space missions for the 2020s
- UVOIR access from space is fundamental to understanding the universe and the life within it.
- “Game Changing” science requires substantial increase in aperture for operation over roughly the same wavelength range as HST.
- Early introduction of “best practices” based on experience with HST, JWST, other major missions
- NASA can lead such a mission, but the mission will require significant international partnerships.



HST Reveals Water on Europa



ATLAST: The Cosmic Legacy of HST . . . and the Search for Life's Other Homes

Hundreds of Target Planets in the Solar Neighborhood

ATLAST
Mission Systems Engineering

Norman Rioux (Code 599)

April 1, 2014

Science Flow Down to Telescope

Telescope Parameter	Requirement
Primary Mirror Aperture	> 8 meters (minimum)
Visible/NIR Coverage	300 nm – 2.5 μm (background limited)
UV Coverage	90 nm – 300 nm
Mid-IR Coverage	Sensitivity up to 8 μm (but with non-cryogenic optics)
Visible/NIR Image Quality	Diffraction-limited performance at 500 nm
UV Image Quality	Not worse than 0.10 arcsec at 150 nm
Wavefront Error / Stability for General Astrophysics	~35 nm wavefront error, 1.3 – 1.6 mas pointing stability
Wavefront Error / Stability for Exoplanet Imaging	< 0.01 nm effective wavefront error over a band pass (10 minutes or better)

"Science Requirements Flow-Down Tables for the Next Generation UVOIR Space Telescope", Postman et. al., Nov. 2013

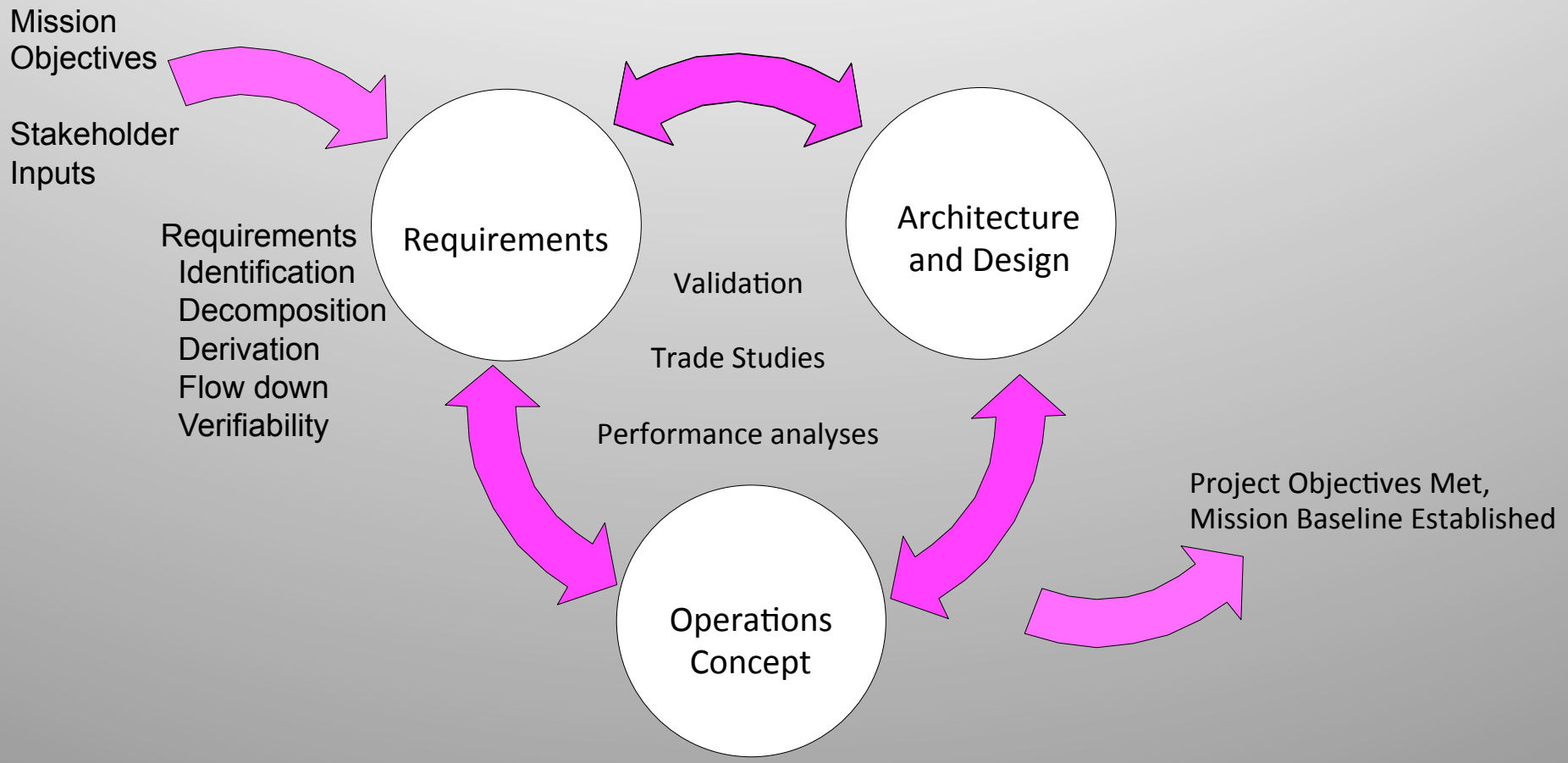
Science Flow Down to Instruments

Science Instrument	Requirement
Starlight Suppression System	10^{-11} suppression to IWA of ~40 mas with internal active wavefront sensors and control (may be used in conjunction with or in lieu of an external starshade)
Exoplanet Spectrograph	IFU design with R = 70, 500; FOV ~10 arcsec; 0.3 – 2.5 μm
Exoplanet Imager	IFU design with UV and Visible channel; FOV ~10 arcsec.
UV Spectrograph	90 – 250 nm, multiple modes covering R = 20,000 – 300,000; FOV 1 – 2 arcminutes, with multi-object spectroscopy capability
UV Imager	90 – 300 nm, FOV 1 – 2 arcminutes
Visible/NIR Imager	FOV 4 – 8 arcminutes, Nyquist sampled at 500 nm, 0.3 – 2 μm
NIR Spectrograph	FOV 3 – 4 arcminutes, 0.6 – 2.5 microns, R=100 (Grism), 500, 2000
MIR Imager/Spectrograph	FOV 3 – 4 arcminutes, 3 – 8 μm, R=5, R = 500

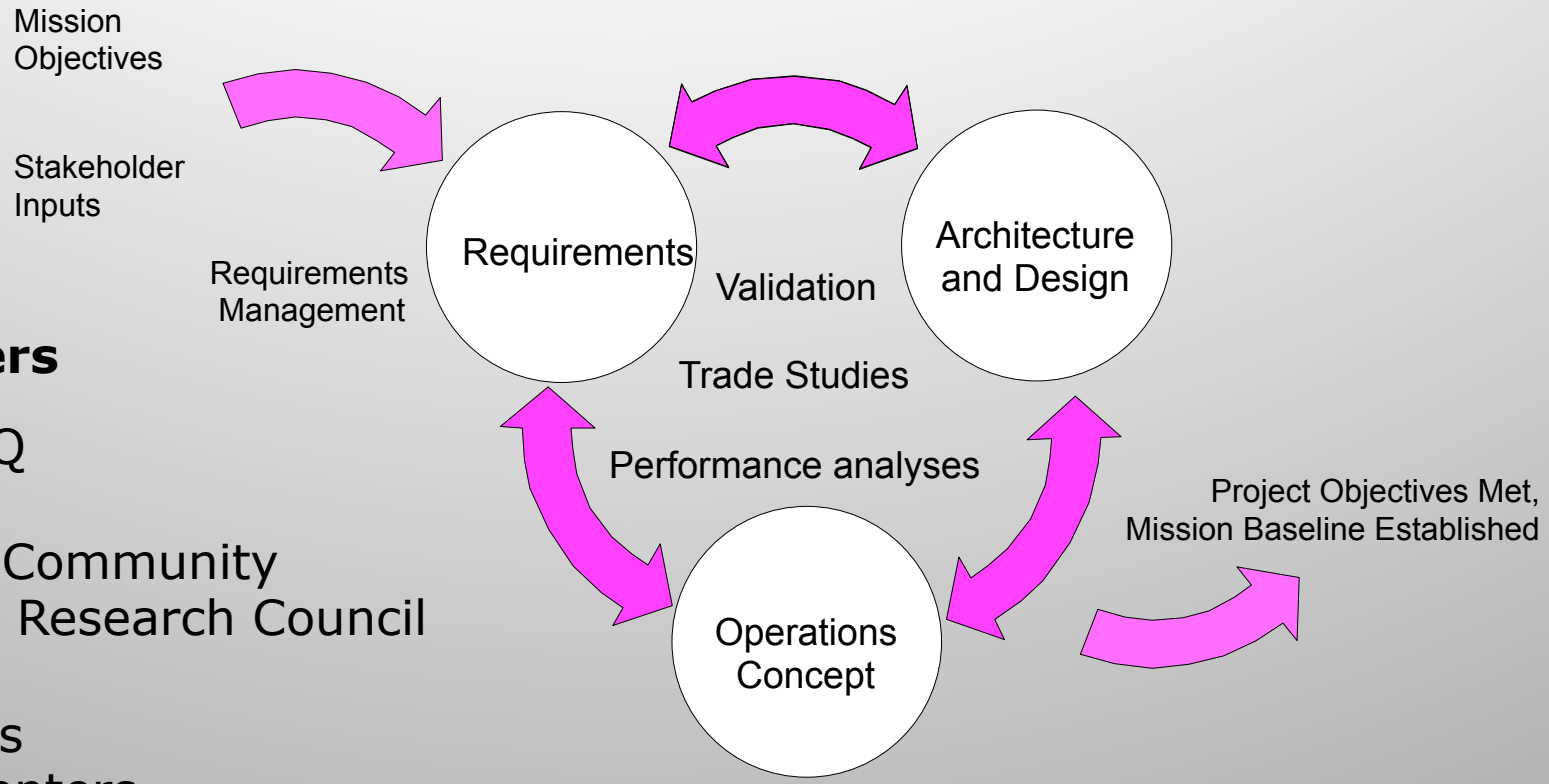
Key Design Drivers

- Huge Telescope Aperture > 8 m diameter
- Contrast of 10^{-11}
  - ~100 X WFIRST/AFTA
- Effective Wavefront Stability of 10 pm/10 min
  - Applies to coronagraph implementation option only
  - ~1000 X JWST
- UV sensitivity to 90 nm
  - Not done by HST

Mission Formulation Process



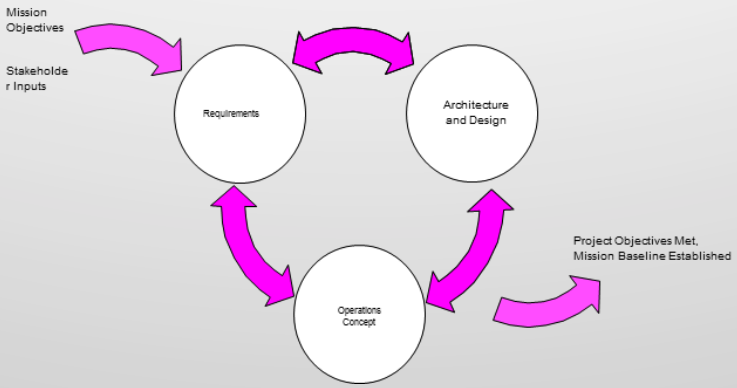
Mission Formulation Interdependencies

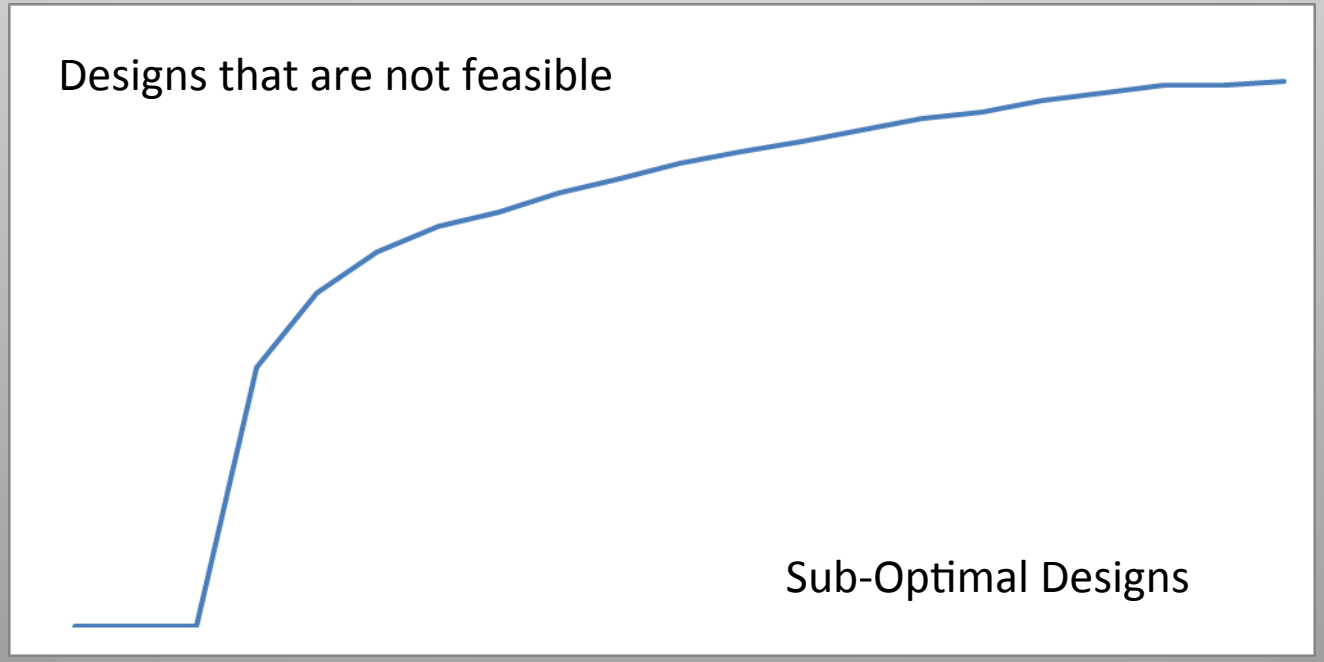


Stakeholders

- NASA HQ
- OMB
- Science Community
- National Research Council
- Public
- Congress
- NASA Centers
  - GSFC
  - MSFC
  - JSC
  - KSC
- JPL
- Space Telescope Science Institute (STScI)
- Aerospace Contractors
- Foreign Partners (Potential)

System Cost Effectiveness





Technology Roadmap Goals

- Identify and prioritize enabling technologies
- Recommend path forward for technology investments
- Influence technology priorities
  - *Science Mission Directorate / Astrophysics at HQ*
  - *Space Technology Mission Directorate*
  - *Cosmic Origins Program Office*
  - *Exoplanet Program Office*
- Provide input to OCT/NRC technology roadmap
- Prepare for 2015 NRC Mid-Decade Review
- Complete in April

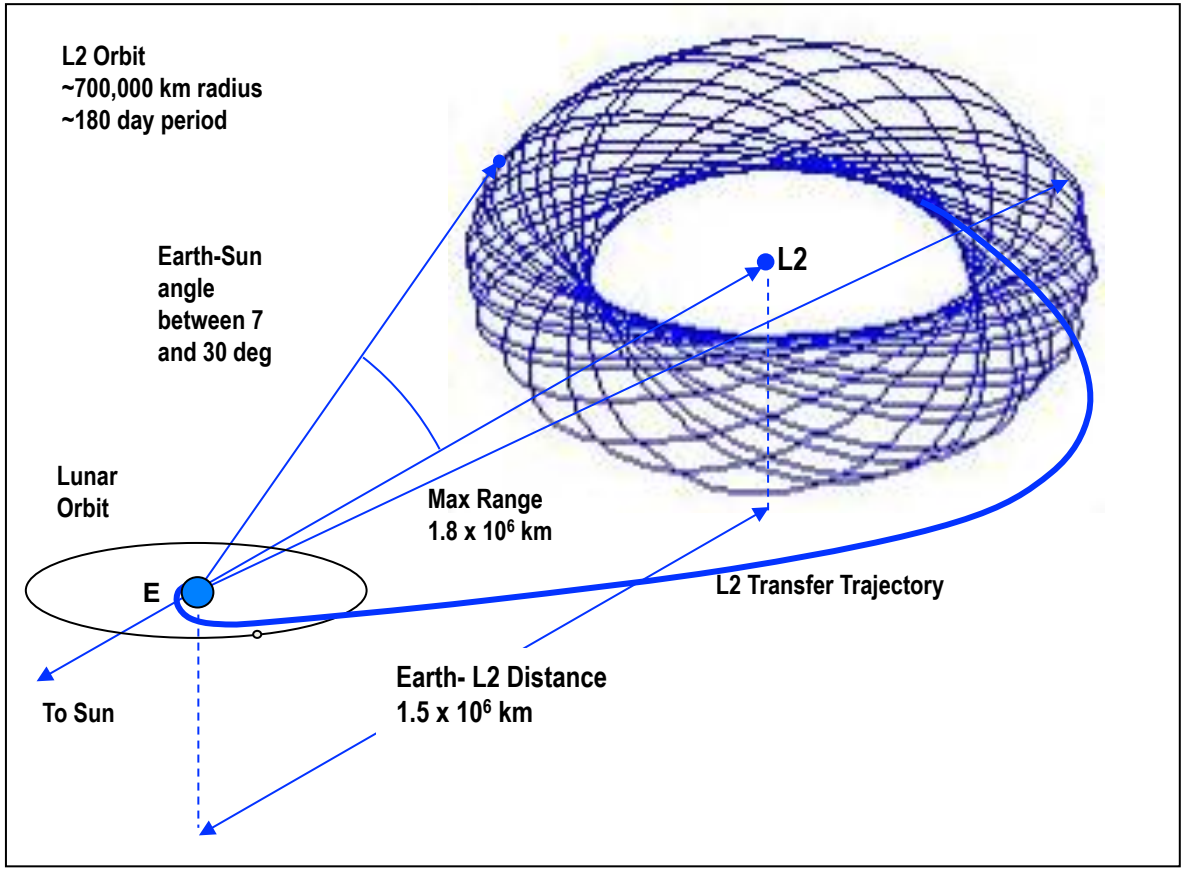
Snapshot Preview of Technology Roadmap

- Astro 2010 Decadal Survey recommends technology investments in Large UVOIR Telescope
- Current structure of roadmap
  - *Science Traceability to Technical Needs*
  - *Mission Architecture Options*
  - *Summary of Technology Needs and Plans*
  - *Provide priorities, recommendations, and actionable items*
- Initial Assessment of Enabling Technologies
  - *Optics*
  - *Starlight Suppression System*
  - *Ultra-stable Structure and Systems*
  - *High Reflectivity UV Coatings*
  - *Detectors*
- Maps to Highest Priorities in Office of Chief Technologist Technology Roadmap (NRC, 2012)
  - *Optical Systems*
  - *High-Contrast Imaging and Spectroscopy*
  - *Detectors and Focal Planes*

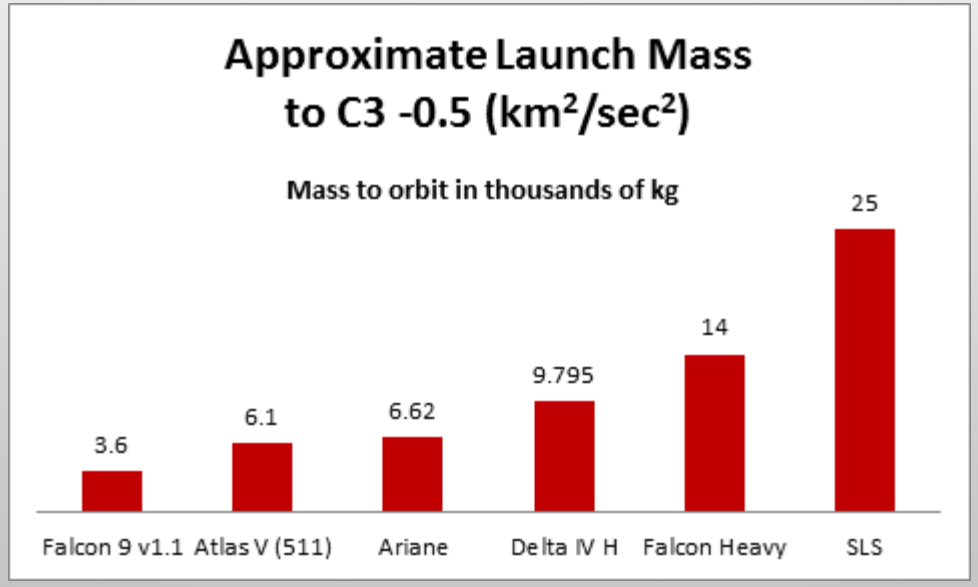
L2 Orbit Choice Driven by Stability

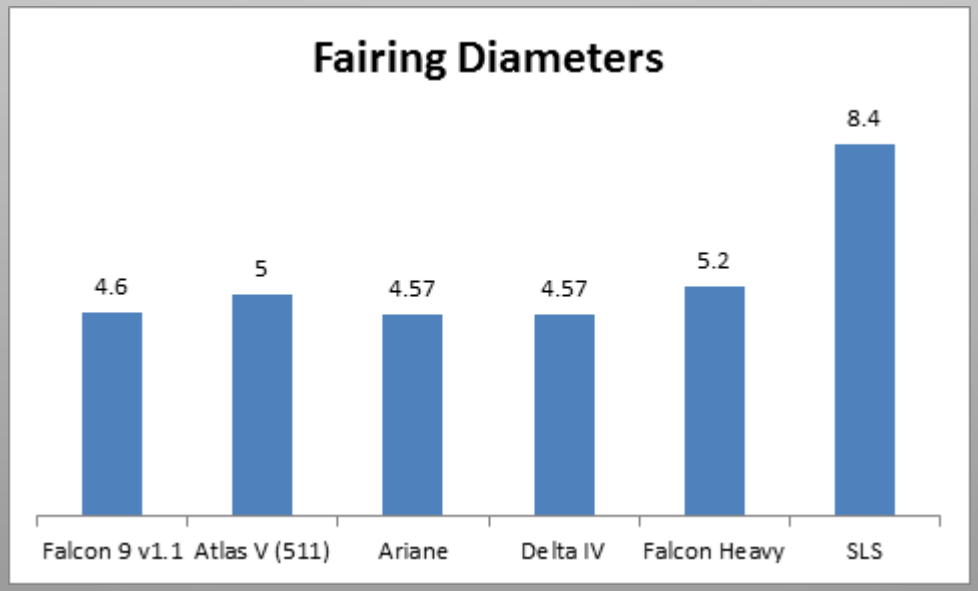
Sun-Earth Second Lagrange Point (L2)

- 1.5 million km along the Sun-Earth axis
- Metastable – requires some station-keeping
- Nominal Mission Parameter C3 = -0.5 km^2/sec^2



Fundamental Mission Constraints
Mass-to-Orbit and Fairing Diameter





Primary Mirror Architecture Driven by Fairing Diameter

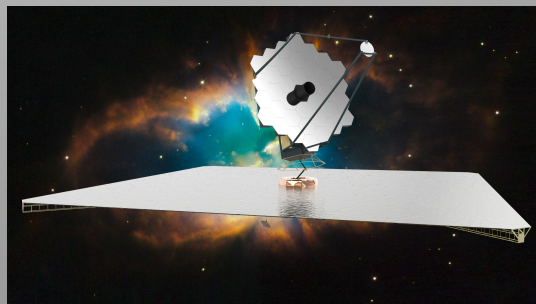
Launch Vehicle / Fairing	Segmented Primary Mirror	Monolith Primary Mirror
Existing Launch Vehicle; 5 m Fairing Dia.	EELV enables 9 - 11 m class deployable aperture	Currently available vehicles could launch no greater than 4 m monolith
SLS	8.4 m or 10 m fairings to be developed could accommodate deployable apertures > 11 m	10 m SLS fairing may accommodate up to 8 m monolith
Assembly in Space	Enables largest apertures	

ATLAST Mission Architecture Options

Description	Strengths	Shortcomings
Segmented deployable telescope launched with EELV	9-11 m class aperture using a currently available, proven launch vehicle.	Need validation that 9-11 m class aperture will deliver acceptable exoplanet science performance.
Segmented deployable telescope launched with SLS	Enables larger apertures (>11m). Enables the largest extrapolation of established investments in chord fold segmented mirror design.	Readiness of SLS with an appropriate fairing not certain for 2020 Decadal Survey. Mass to orbit is outstanding, but may put mission into a different cost class than previous great observatories.
8m monolith launched with SLS in 10m fairing	Leverages the possible advantages offered by a monolithic aperture telescope in terms of high-contrast imaging and wave front error (WFE) control.	Need validation that 8 m class aperture will deliver acceptable exoplanet science performance. Monolith primary mirror limits technology future growth potential.
Assembly in Space - human and/or robotic	Enables truly large apertures in space (>14 m) and provides risk reduction against malfunction of deployment of appendages. Provides potential coupling into future astronautic/ robotic servicing infrastructure in space.	Establishment of assets in space for astronautic/robotic assembly not certain for 2020 Decadal Survey timeframe.
Occulter approach to observatory star light suppression	Trades cost and risk of a large free-flying precision structure in space against the cost and risk of a coronagraph internal to the observatory.	See cost-risk trade at left.

Engineering Design Reference Mission (EDRM)

- Select a relatively low risk, relatively low cost large aperture architecture for conceptual study
- Readiness for 2015 Decadal Review and the 2020 Decadal Survey
- EDRM: Largest deployable aperture that will fit in an existing launch vehicle
  - Lowers launch vehicle risk for 2020 Decadal Survey
  - Builds on existing investments in segmented mirror and chord fold deployment architectures
  - Provides scalability to larger apertures if necessary
  - Preliminary geometrical studies have validated ~9 m aperture can fit in an EELV fairing
    - Mass, thermal control, stability design constraints to be applied
- Observatory designed for serviceability & upgradability



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ATLAST Architecture, Optical Design, and Starlight Suppression

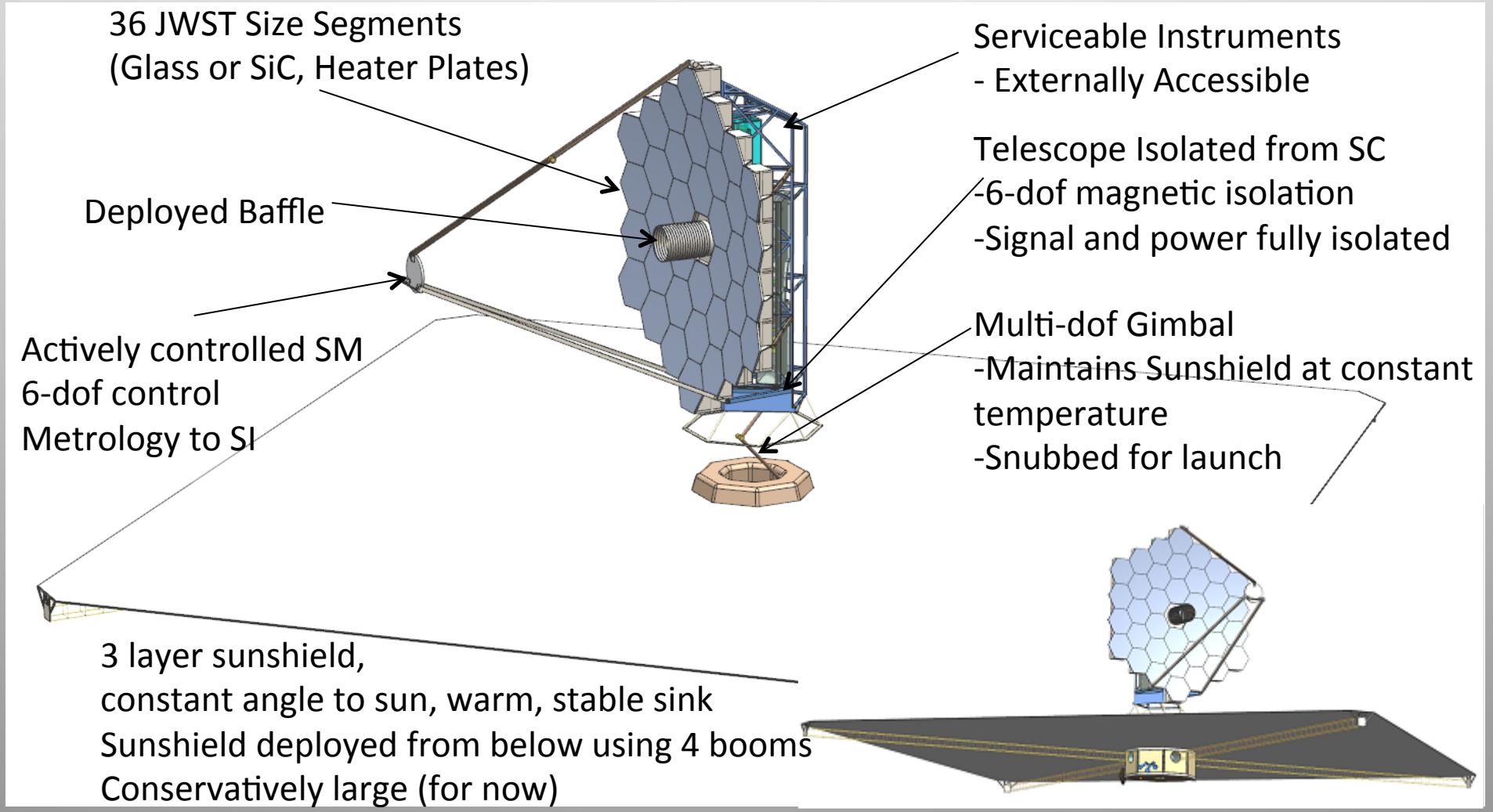
Lee Feinberg (Code 550)

April 1, 2014

Topics

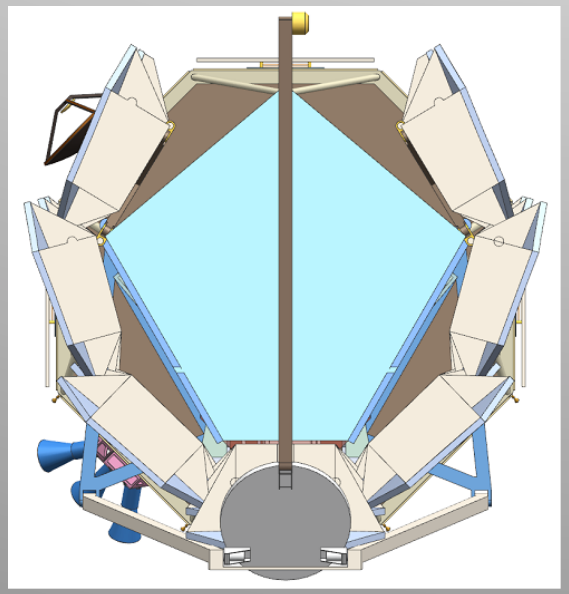
- Notional 9.2 m architecture
- 11 m architecture
- Optical Architecture
- Mirror Technology
- Wavefront Sensing and Control Architecture
- Starlight Suppression

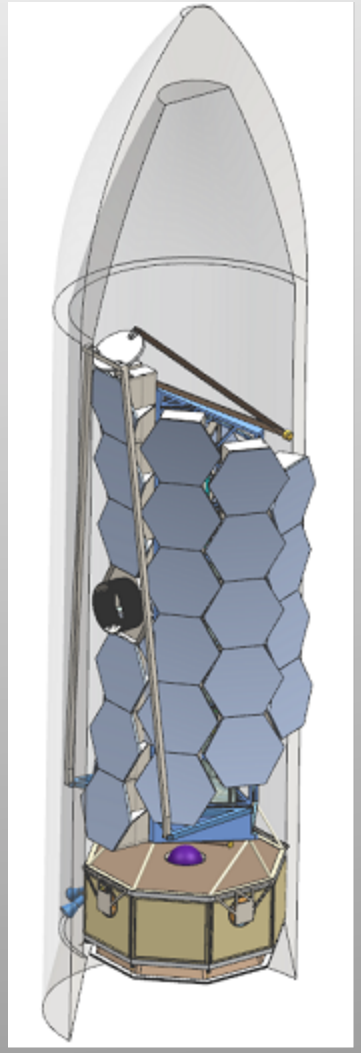
Notional 9.2m Architecture Deployed Configuration



Notional 9.2 m Architecture Launch Configuration

- Circular launch geometry packages better, 3 wings on each side
- JWST-like SM deployment and Wing Deployments
  - Leverages latch and hinge approach

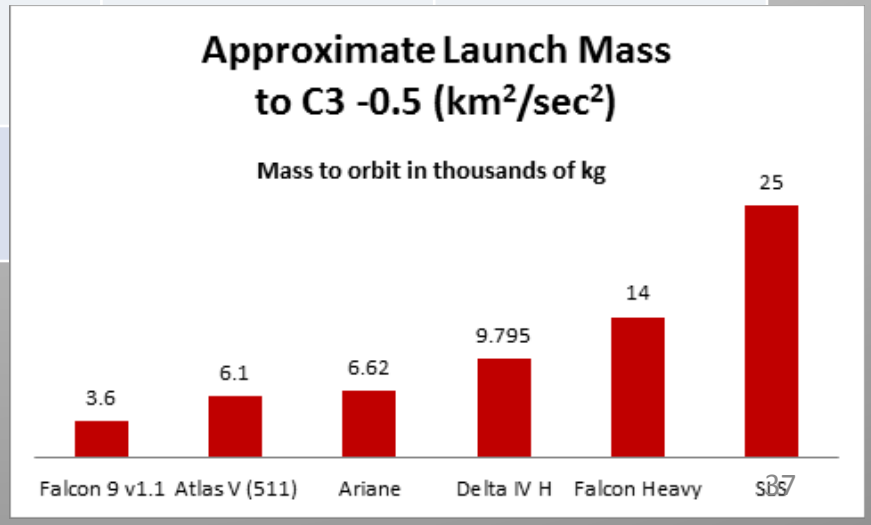




9.2m Meter Deployment Video

Mass vs. Launch Capability

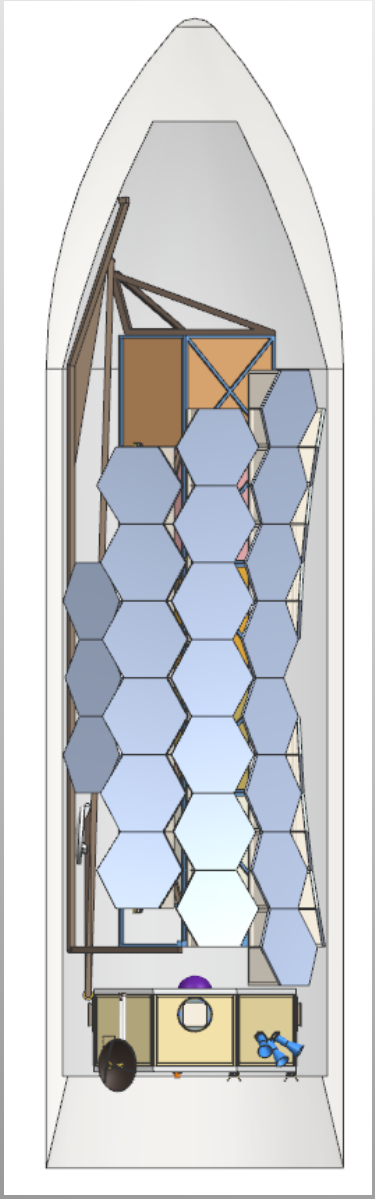
	6.5 m	9.2 m	11 m	16 m
Mirror Mass (kg)*	1600	3200	4888	12444
Total Observatory Mass (kg)	6600	8200	9888	17444
50% Lower Areal Density Mirrors (kg)	800	1600	2444	6222
Observatory Mass w/ Lower Areal Density Mirrors (kg)	5800	6600	7444	11222
Approx. # of segments	18	36		



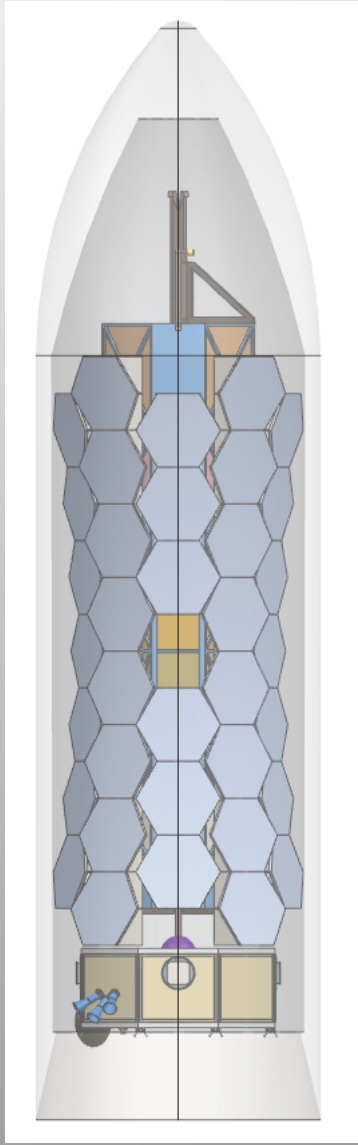
*backplane plus mirrors only

Scaled from JWST

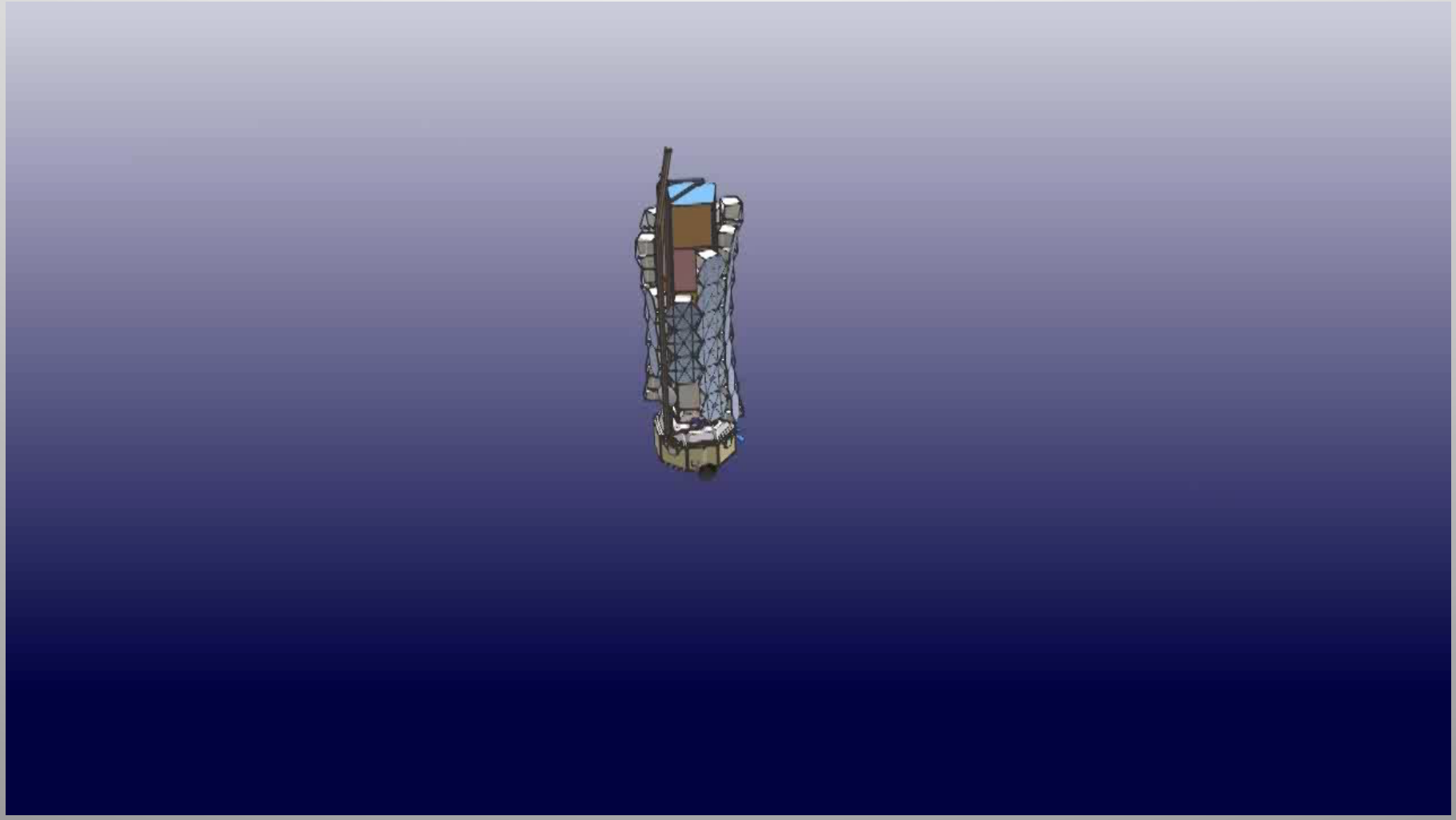
11 meter Considerations



- An 11 meter using the circular geometry was just able to fit
- Required changing the SM deployment approach
- Using JWST areal density, mass exceeds Delta IV Heavy capability
- Potential areal density improvements possible

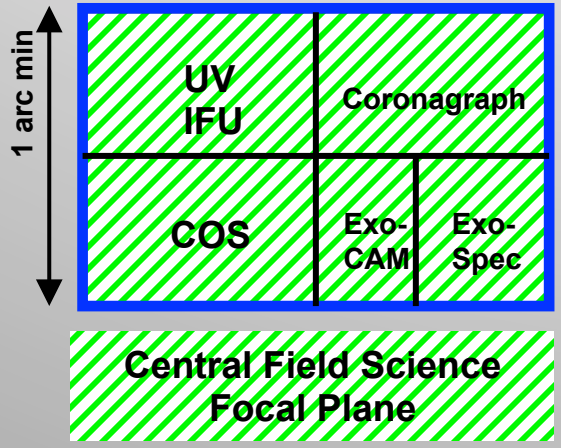


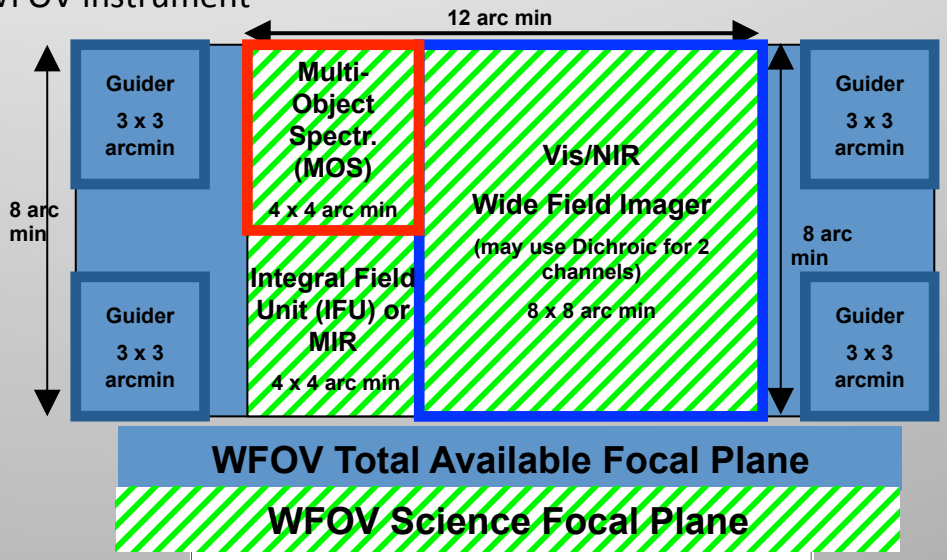
11 Meter Deployment Video

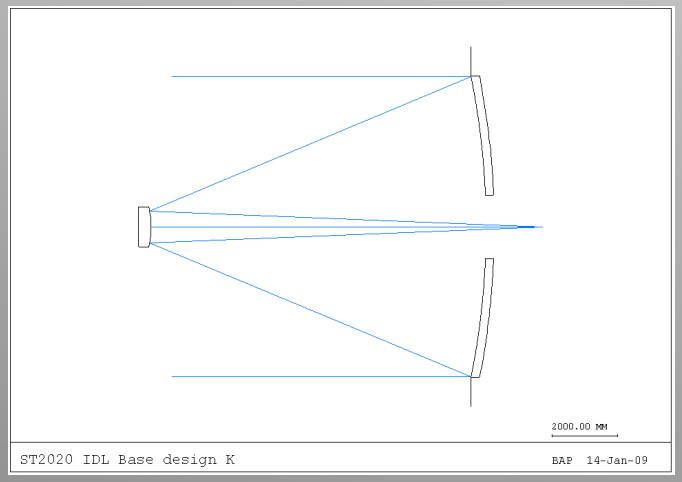


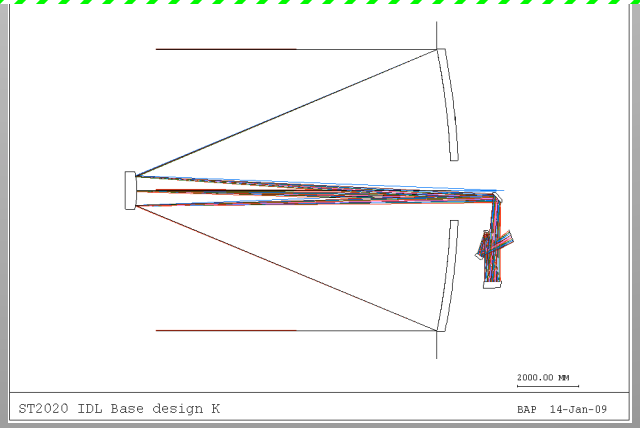
Notional Optical Architecture

- Front end 2 mirror Cassegrain with UV-optical coatings (eg, AlMgF)
  - UV instrument and Coronagraph sample the Cassegrain focus
- Tertiary mirror used for WFOV instruments
  - Visible WFOV instrument use Silver coatings for high throughput
  - Shared Fine steering mirror for WFOV instrument





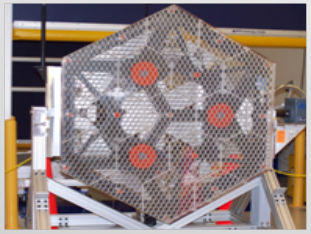


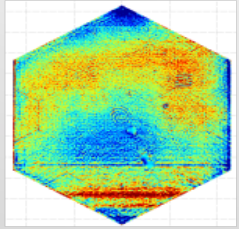


Optical Stability Architecture

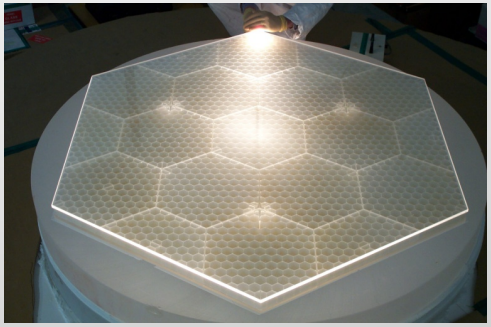
- Key science driver: survey hundreds of stars for bio-signatures of Earth-like planets. Requires > 10^{-11} contrast, which equates to <10 pm wavefront stability
- Baseline approach: an internal coronagraph, which places tight stability requirements on wavefront error over ~ 10 minute bandpass
  - Achieved by controlling dynamics and thermal stability
  - Occulter (starshade) approach is also being studied and has much looser requirements on the PM, although requires ~2 weeks between targets and has additional technology challenges
  - Different types of internal coronagraphs have different sensitivities to telescope stability and are characterized by other key features (e.g., bandpass, throughput and inner and outer working angle)
- Dynamic isolation scaling from JWST shows even <10 pm PM stability is achievable; modeling will confirm
    - Key is complete (disturbance-free) isolation between telescope and spacecraft
    - Similar approached developed for JWST was assessed at TRL 5/6
- Thermal stability control can be accomplished through either heaters or using optical metrology and/or sense and control strategies
    - An area of study is using heater plates to control mirror stability

Mirror Technology Candidates

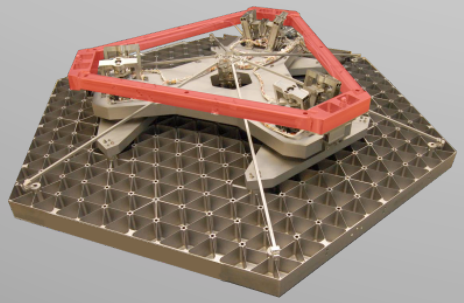




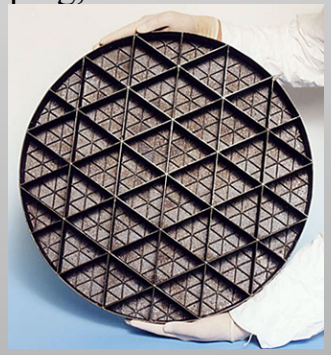
1.4 m ultra-lightweight ULE mirror (low CTE)
Passive surface figure of 8.2 nm RMS



Parallel Mass Manufacturing Techniques:
Slumping, Water Jet etc.



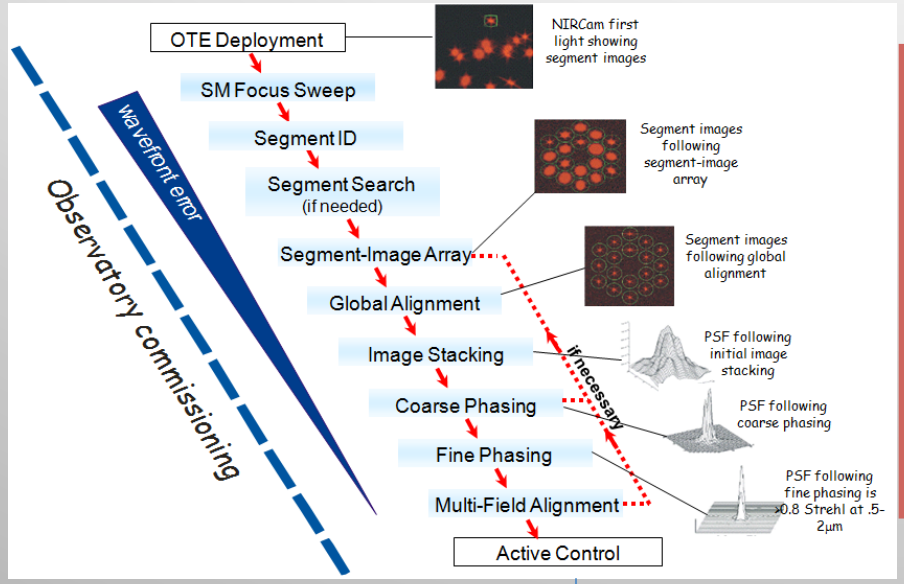
JWST Segment (left) had 3 layers of flexures delta frame
More efficient design and lighter actuators will save mass

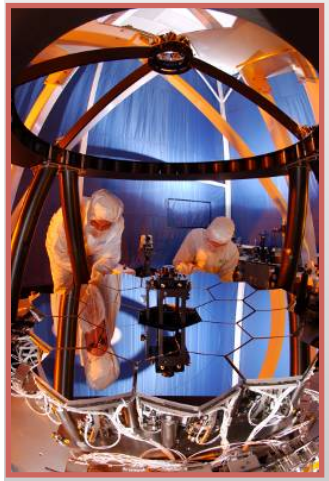


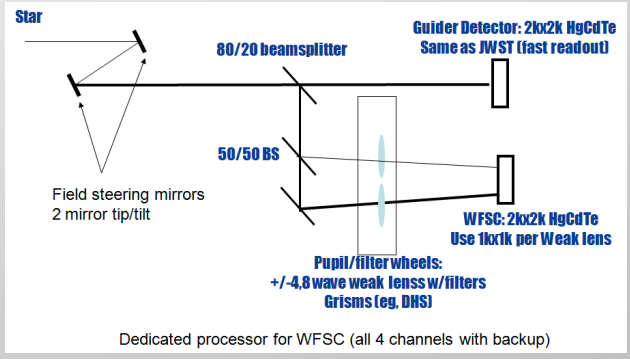
Another candidate is Cladded SiC
High Stiffness/mass enables lower areal density mirrors, high thermal conductivity, can be combined with high authority

Excellent options exist which are already at TRL 6 for a general class observatory
Emphasis is on demonstrating mirror thermal stability to support an internal coronagraph.

Wavefront Sensing and Control Notional Architecture

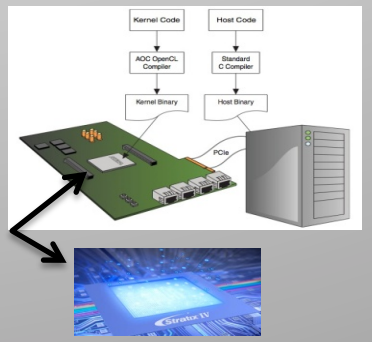






SM actively controlled with laser metrology
- High speed

PM control:
  WFOV instruments:
    -Hybrid guider/PR camera provides update every 10 minutes
  Coronagraph
    -Internal sensing and control

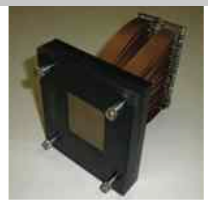


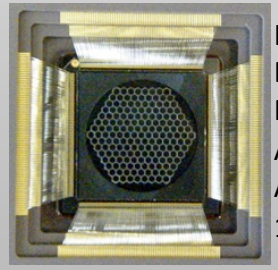
FPGA
Onboard Algorithm Implementation

Starlight Suppression

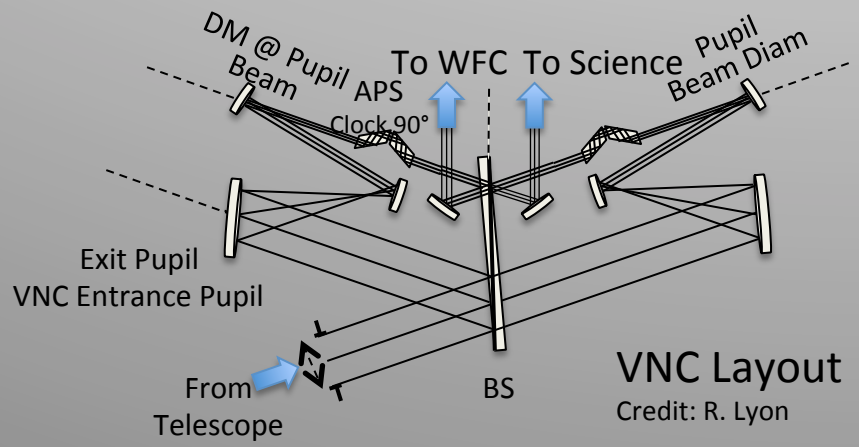
- Internal Coronographs
  - For segmented systems, R. Lyon et al at GSFC have achieved 5 x 10^{-9} contrast at 2 λ/D narrowband with Visible Nulling Coronagraph, higher contrast and broader band planned
  - VNC Designs for broadband achromatic phase shifter (+-300nm) exist, in progress
  - VNC and other approaches like PIAA have shown to be compatible with segmented

48x48 Xinetics deformable mirror has been shake tested



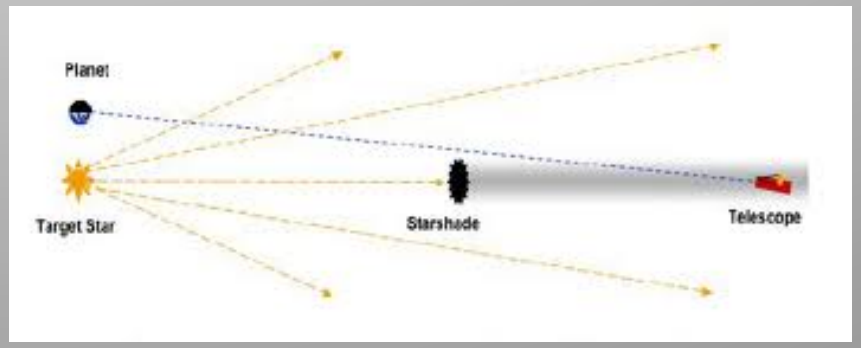


Hexagonal Deformable Mirror Arrays Approach 1000 mirrors



VNC Layout
Credit: R. Lyon

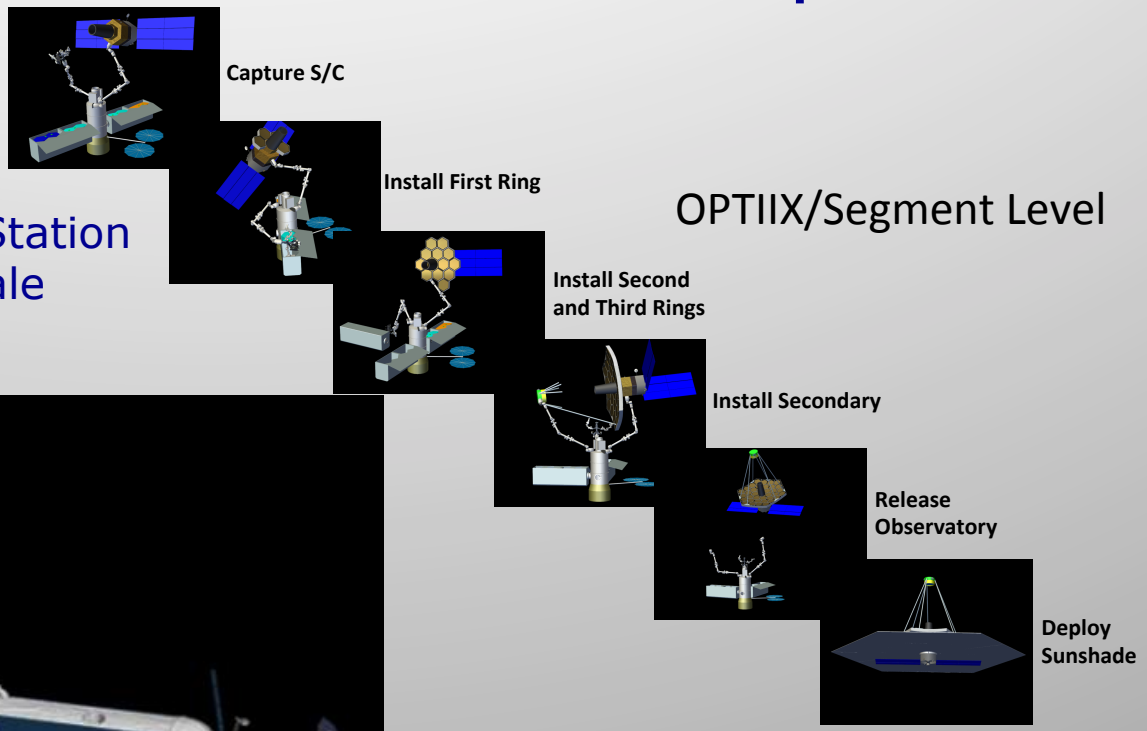
- Occulters
  - 8 m telescope requires about an 80 m occulter, 50 - 100 km from telescope
  - Edge tolerances <100um RMS, no picometers
  - Target repointing times: a few weeks
    - Good enough for spectroscopy but not for detection….??
    - Unless you have more than one?
  - Higher throughput, possibly larger bandpass
  - Very tight specifications on edges, sensitivity to straylight
  - More limiting sun angles



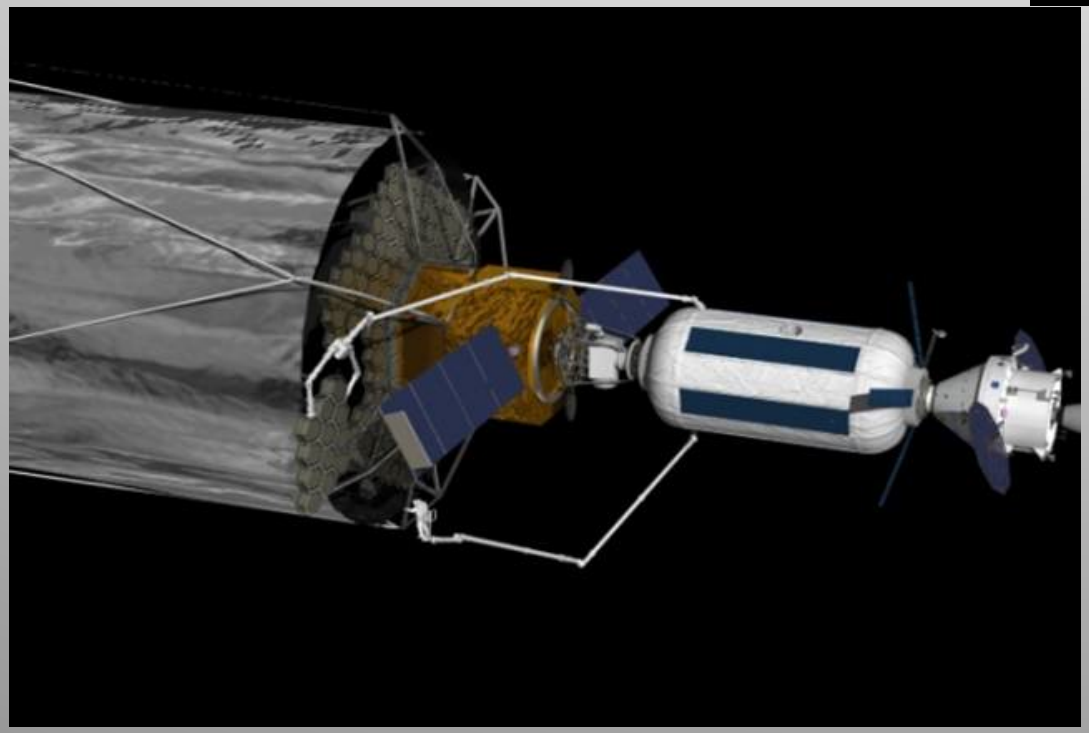
Notional Architecture and Technologies are Scaleable to a 20 meter in Space

Assembly options studied:
- Segment-level assembly
- Panel level assembly

Requires a hab module or Space Station
Uses modularity, economies of scale



OPTIIX/Segment Level



MAST

Summary

- The ATLAST architecture options continue to be refined
- Focus is now on a 9.2 m notional architecture that can fit in an existing rocket
- Optical stability for the internal coronagraph is a key area of emphasis to demonstrate the feasibility of that approach
  - *Keeping options for using an occulter*
- Key technologies are defined and a roadmap is nearly complete
- Activity about to enter a second-year collaboration with JPL, MSFC, SAO and STScI