The Future of Astronomy will be Built:
Results from the NASA in-Space Assembled Telescope (iSAT) Study

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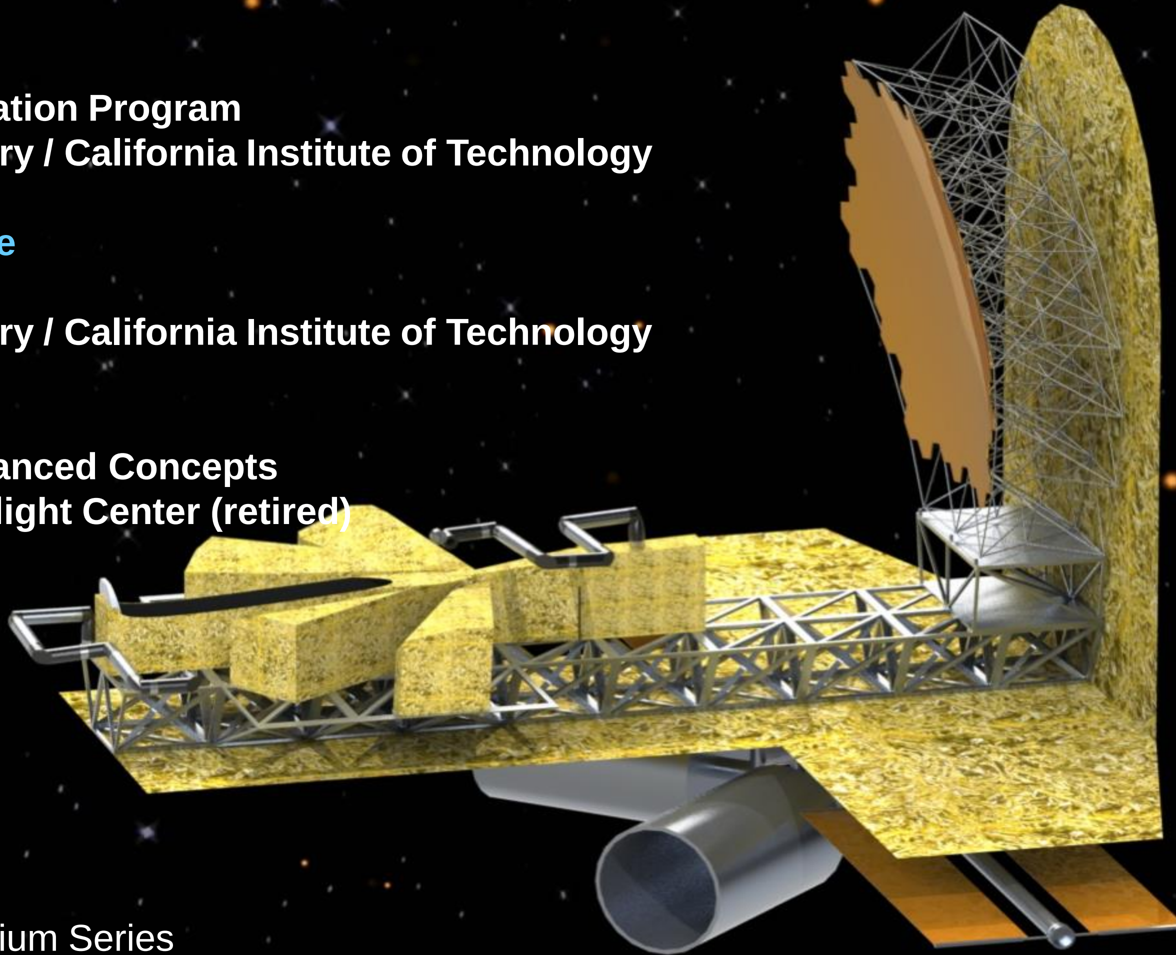
NASA Goddard Space Flight Center (retired)



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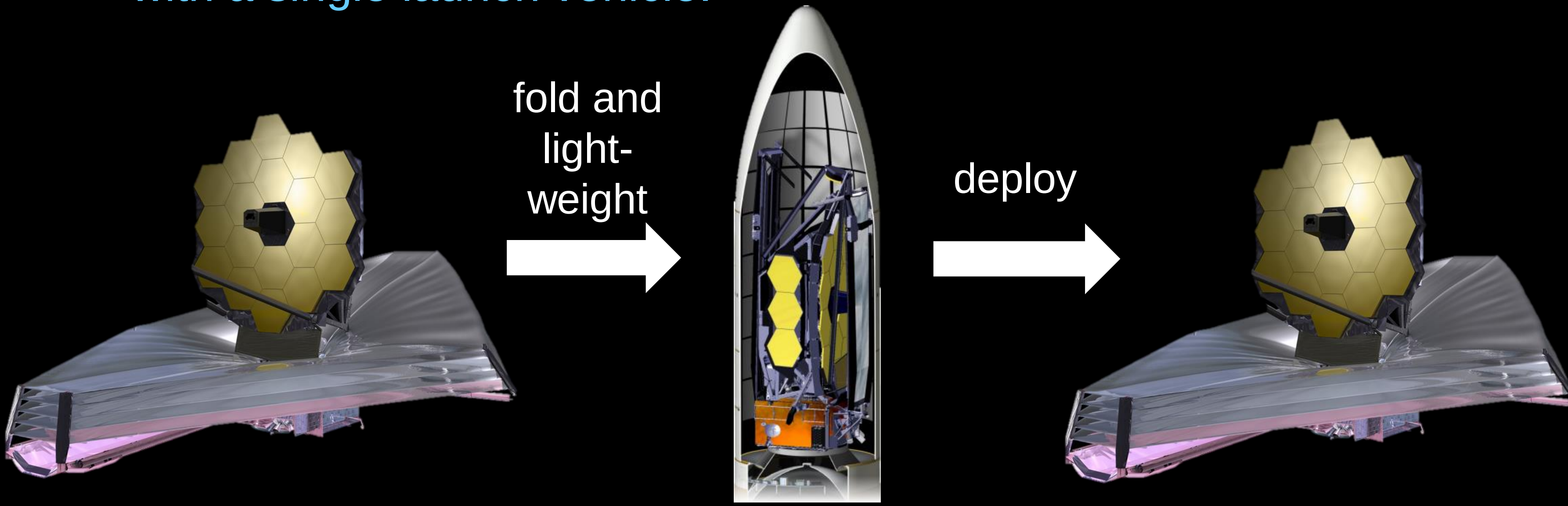
The Future of Space Telescopes

Will benefit from…

- increased aperture size
- lowered mission risk
  - ❖ As they will be expensive as their sizes and capabilities grow
- extended mission lifetime
  - ❖ Through refueling, repairing, replenishing
  - ❖ Enabling total cost to be spread out over decades
- improved capability over time
  - ❖ Replacing instruments with more advanced ones

The Current Approach to Space Telescopes

- Designed to meet the volume and mass requirements associated with a single launch vehicle.



- Relies on all going perfectly during deployment
  - ❖ JWST: Over 20 sequential deployment events, 40 deployable structures, 178 release mechanisms – all of which must work.
  - ❖ Repair capabilities do not yet exist other than with astronauts
  - ❖ Astronauts are not planned to go to Geo or Sun-Earth L2
- Mission lifetime is fuel or cryogen limited
  - ❖ Servicing capabilities to repair or extend lifetime not yet in place
- No new instruments - you live with what you have

One potential approach that addresses these current challenges and achieves that future is in-Space Assembly.

Dr. Paul Hertz
Director
Astrophysics Division
Science Mission Directorate
NASA Headquarters

Study Objective:

- ***“When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from single launch vehicles?”***

In-Space Assembled Telescope study commenced in May 2018

Study Participants

Name	Institution	Expertise
1. Ali Azizi	NASA JPL	Metrology
2. Larry Dewell	LMC	Pointing/Stability/Control
3. Oscar Salazar	NASA JPL	Pointing/Stability/Control
4. Phil Stahl	NASA MSFC	Telescopes
5. Jon Arenberg	NGAS	Thermal/Sunshade
6. Doug McGuffey	NASA GSFC	Telescopes/SE
7. Kim Aaron	NASA JPL	Structures
8. Dave Redding	NASA JPL	Telescopes
9. Bi		
10. Al		
11. Bo		
12. Er		
13. Sh		
14. M		
15. M		
16. Ra		
17. Se		
18. Te		
19. Pa		
20. Ji		
21. Al		
22. David Stubbs	LMC	Telescopes/Design
23. John Dorsey	NASA LaRC	Structures
24. Jeff Sokol	Ball	Mechanical/AIT
25. Atif Qureshi	SSL	Robotics SE
26. Carlton Peters	NASA GSFC	Thermal
27. Kan Yang	NASA GSFC	Thermal
28. Paul Lightsey	Ball	SE
29. Kim Mehalick	NASA GSFC	Thermal/Sunshade
30. Bo Naasz	NASA GSFC	RPO
31. Keith Havey	L3Harris	Mirror Segments
32. Harley Thronson	NASA GSFC	Mission Concepts
33. Scott Knight	Ball	Optics

Study Involvement

- 72 participants
- 6 NASA Centers
- 14 private companies
- 2 gov't agencies
- 5 universities

Name	Institution	Expertise
34. John Lymer	SSL	Robotics
45. Lynn Bowman	NASA LaRC	Programmatic
46. John Grunsfeld	ex-NASA	Astronaut
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72. Nick Siegler	NASA JPL	Technologist

Missions and Concepts

JWST, HST, ISS, Restore-L, RSGS, NASA's Tipping Point, Gateway, and future large mission concepts

Discipline Experts

- RPO
- telescope optics
- robotics
- structures
- sunshade
- instruments
- I&T + V&V
- launch vehicles
- orbital dynamics

Detailed Process Approach

Four-step approach

Step 1: Select a reference mission concept

Step 2a: Conduct a qualitative assessment based on experiences and lessons learned

Step 2b: Conduct a quantitative assessment using a grass-roots costing and risk exercise by SMEs from various subsystems

Step 2c: Independent parametric cost estimate for conventional telescope building

Study Assumptions

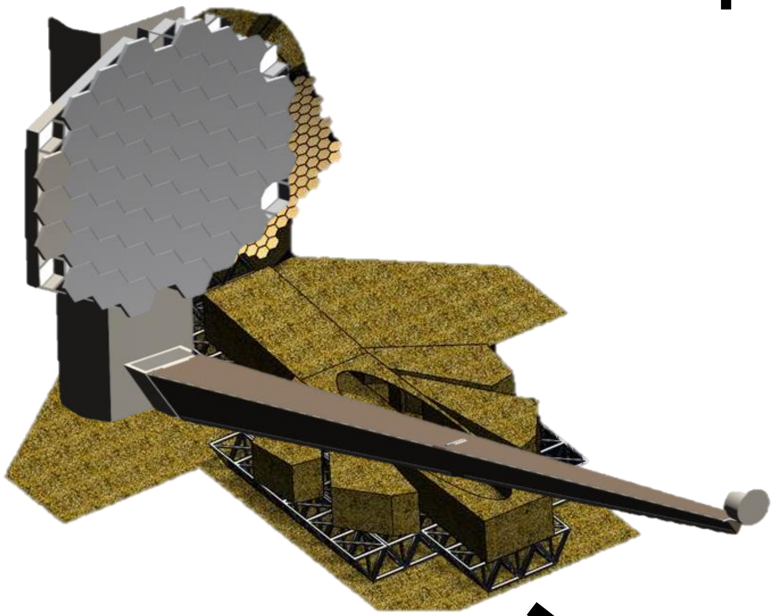
1. Reference telescope:
   – Non-cryogenic operating at UV/V/NIR assembled in space
   – Four sizes between 5 – 20 m

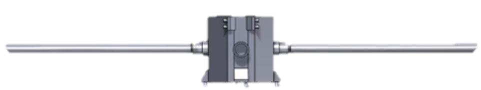
2. Driving requirement:
   – Structural stability required by coronagraphy of exo-planets

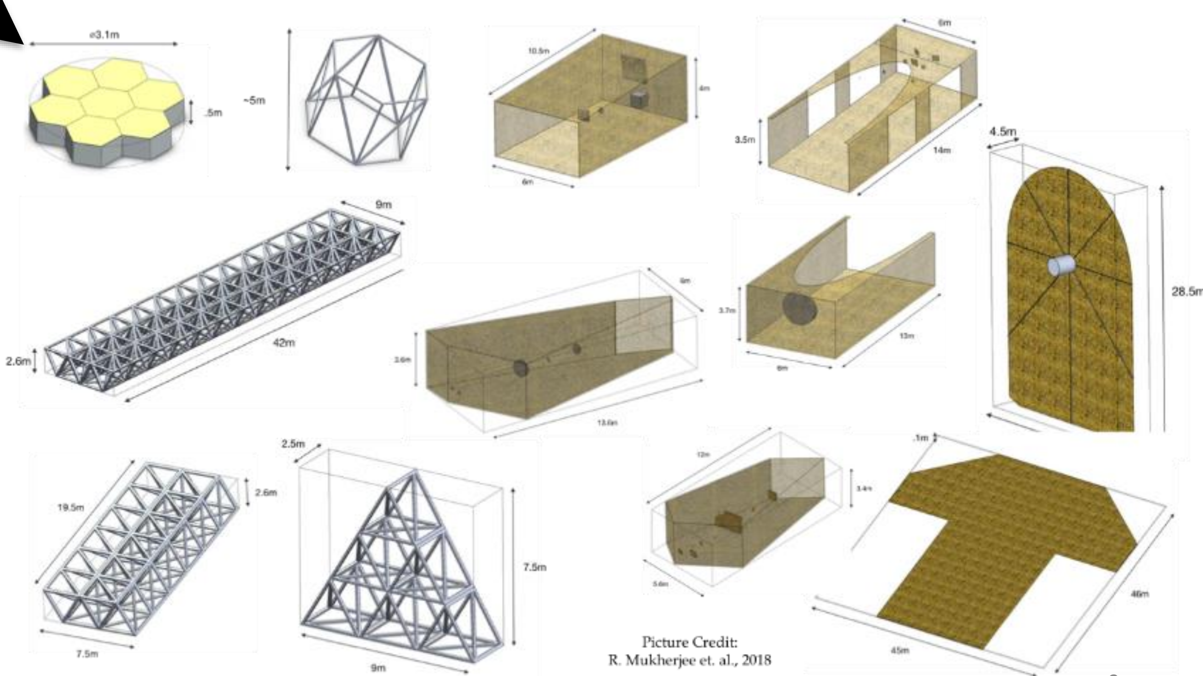
3. Operational destination:
   – Sun-Earth L2

4. Launch vehicles:
   – Use of 5 m-class launch vehicle fairings

Modularization of a Space Telescope





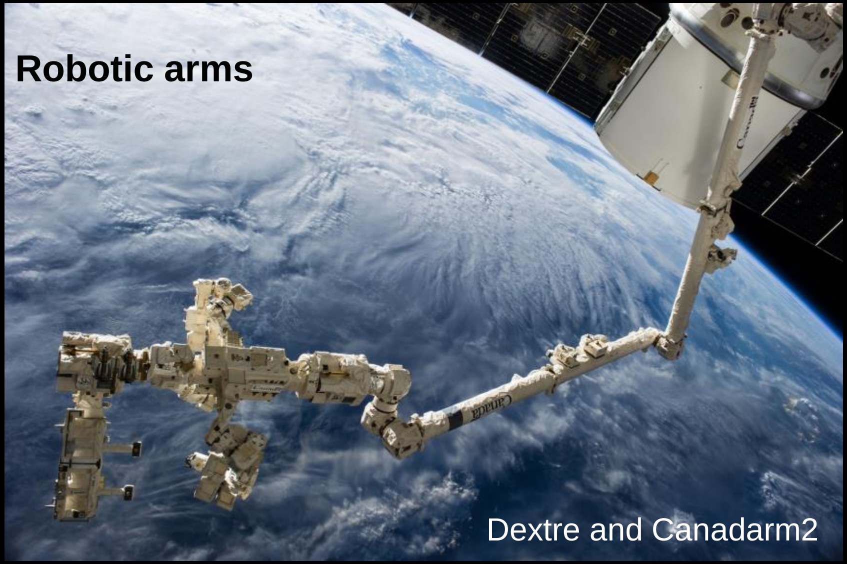


Picture Credit:
R. Mukherjee et. al., 2018

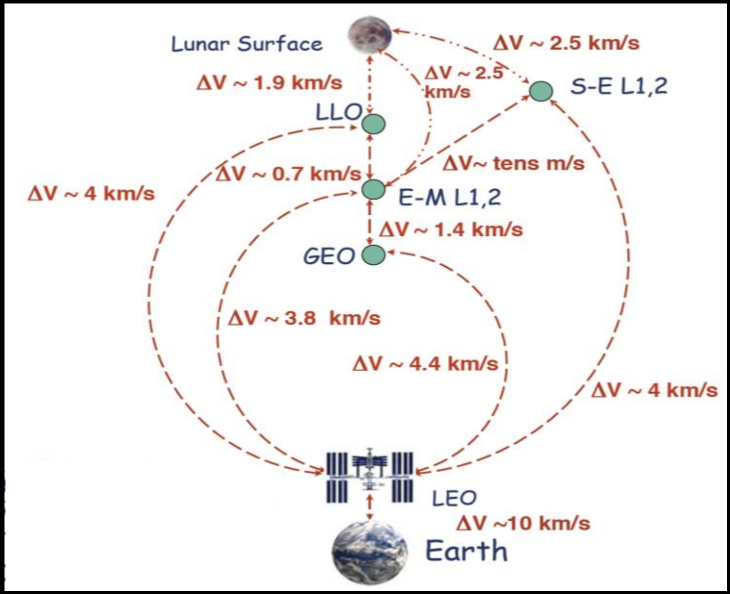
Reference Mission Concept

Very large option space

Assembly Agent



Assembly Orbit



Launch Vehicles

ULA's Delta IV Heavy

Photo: United Launch Alliance

ULA's Atlas V

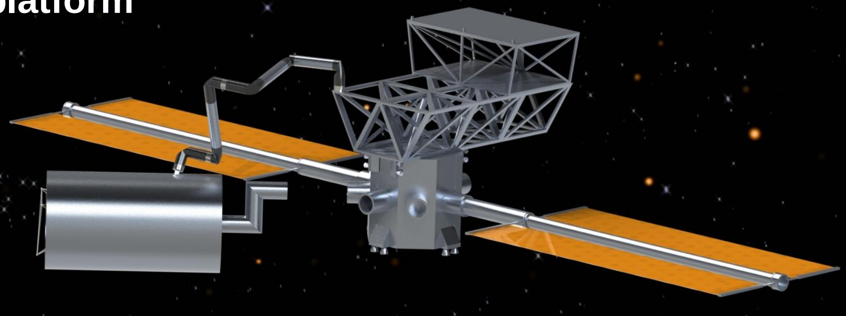
Photo: United Launch Alliance

SpaceX's Falcon Heavy

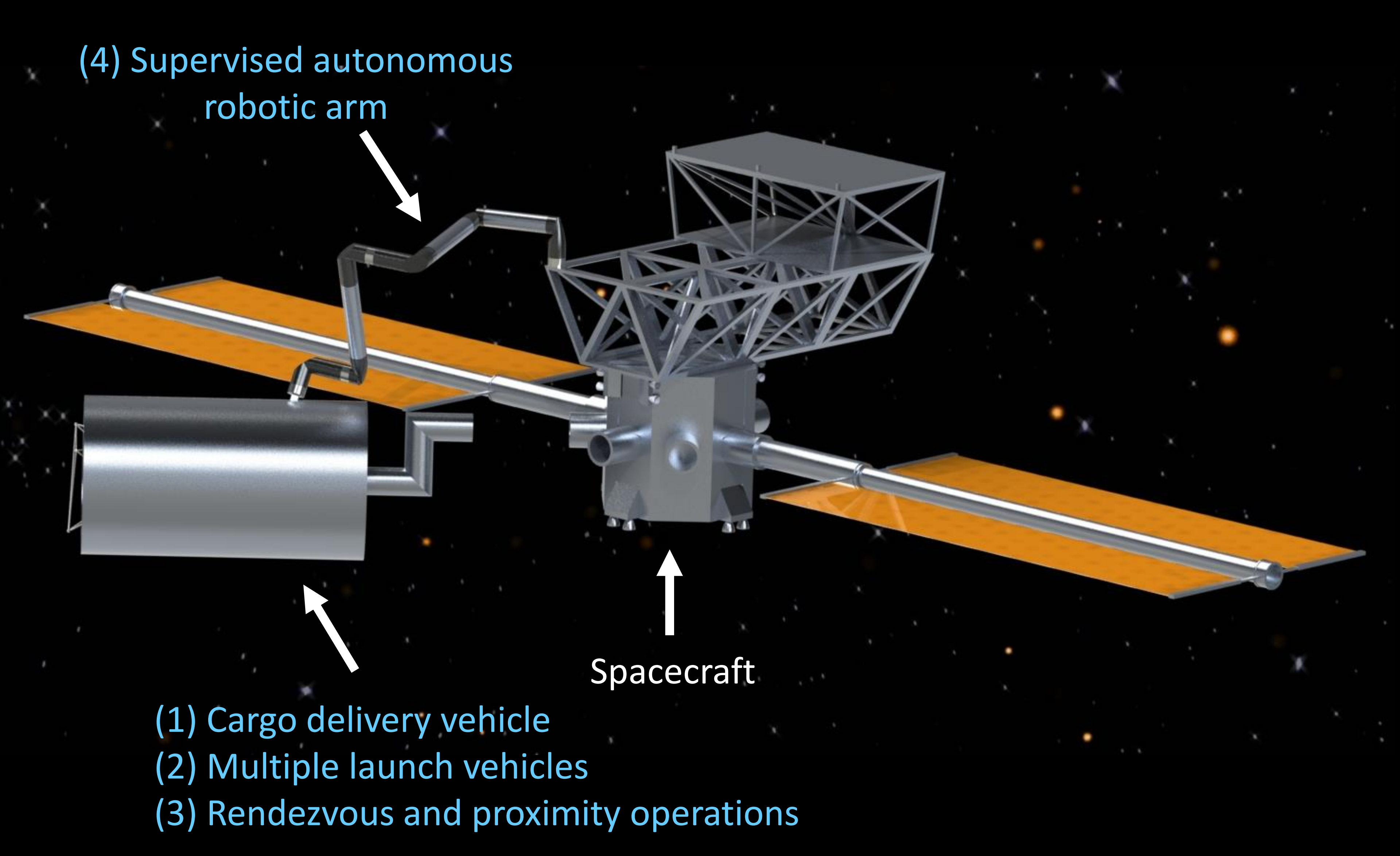
Photo: SpaceX

Assembly Platform

Telescope's spacecraft bus as the assembly platform

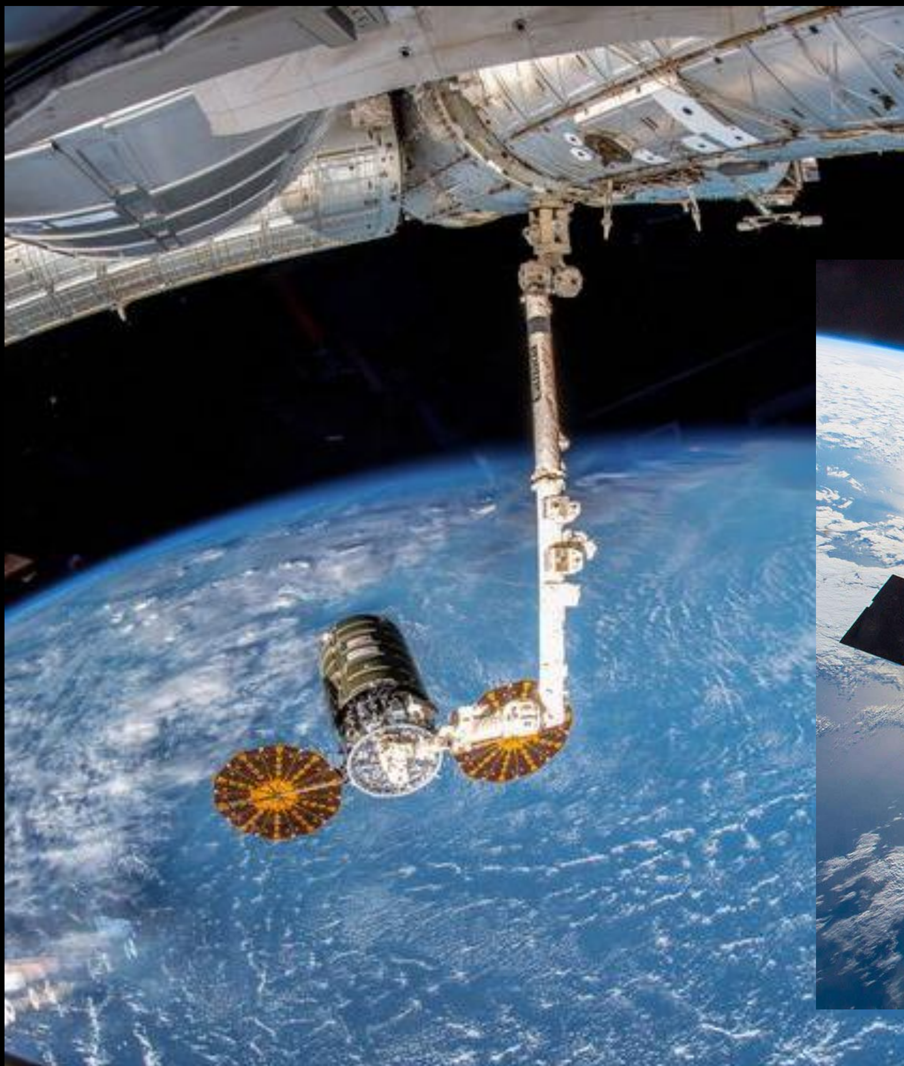


Key Aspects of the iSAT Paradigm



Existing Cargo Delivery Vehicles

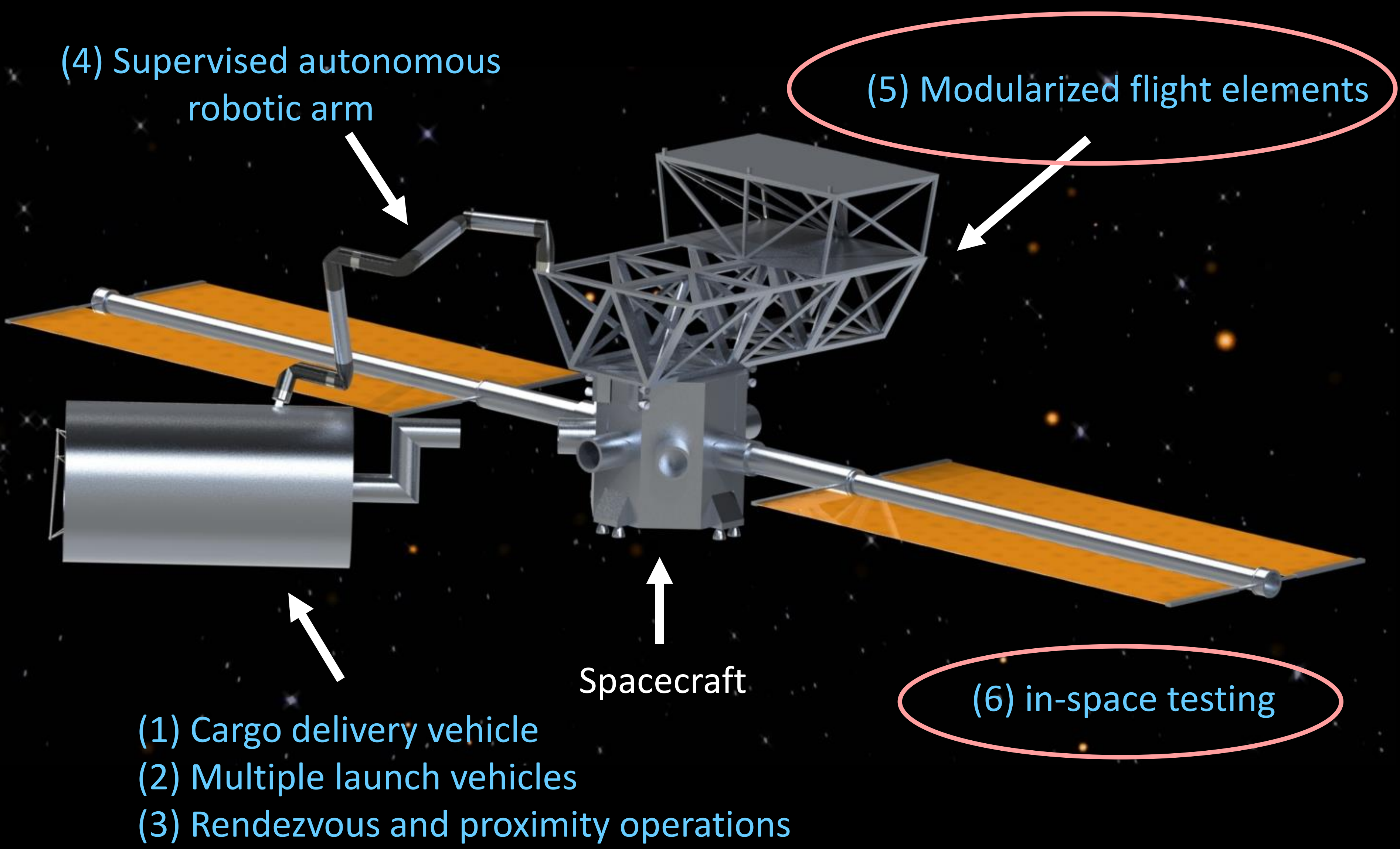
Rendezvous, Grappled, and Berthed

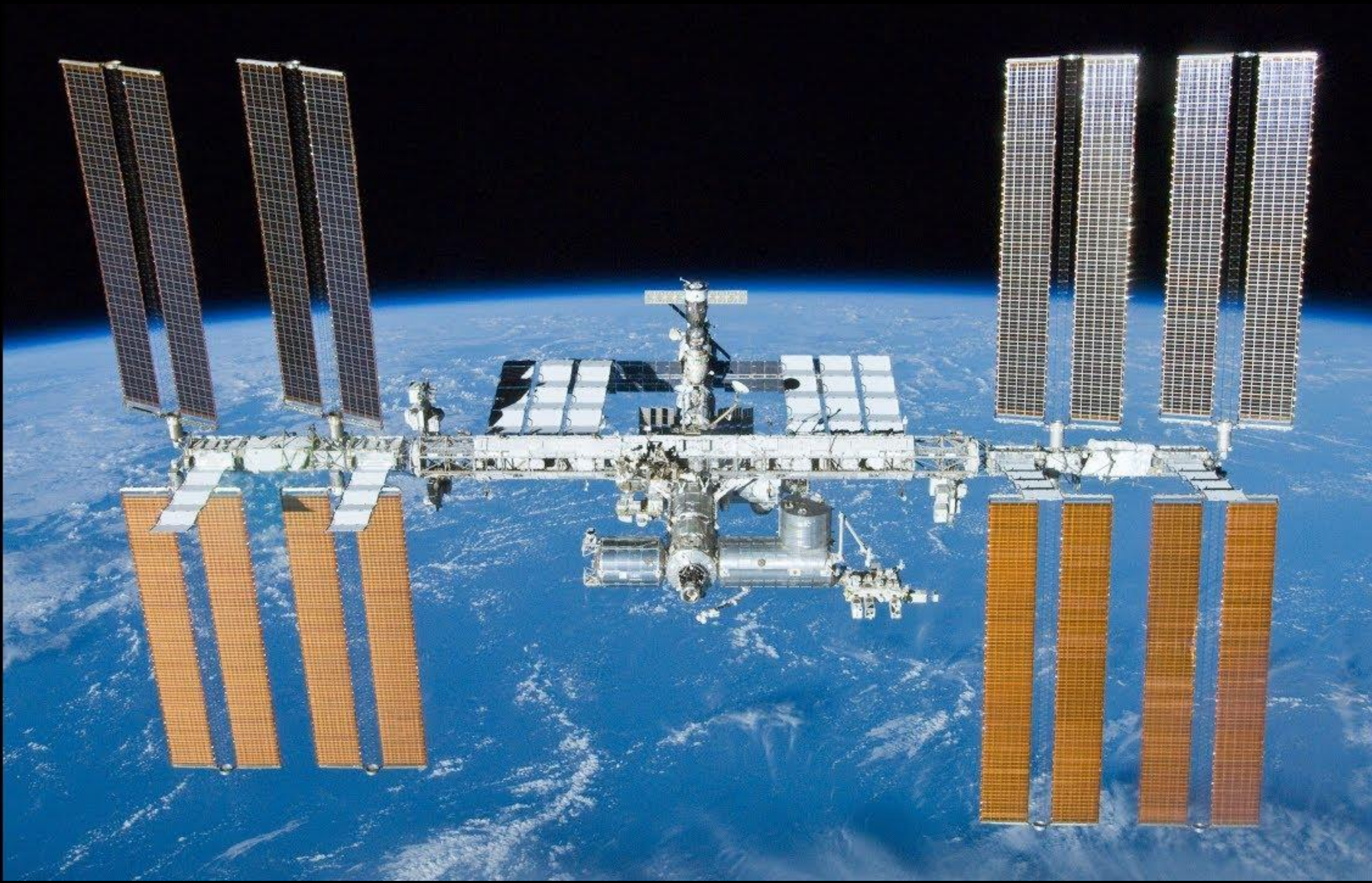


SpaceX's Dragon

Northrop Grumman's Cygnus

Key Aspects of the iSAT Paradigm





Delivery ConOps

Disposable Cargo Delivery Vehicle (CDV)

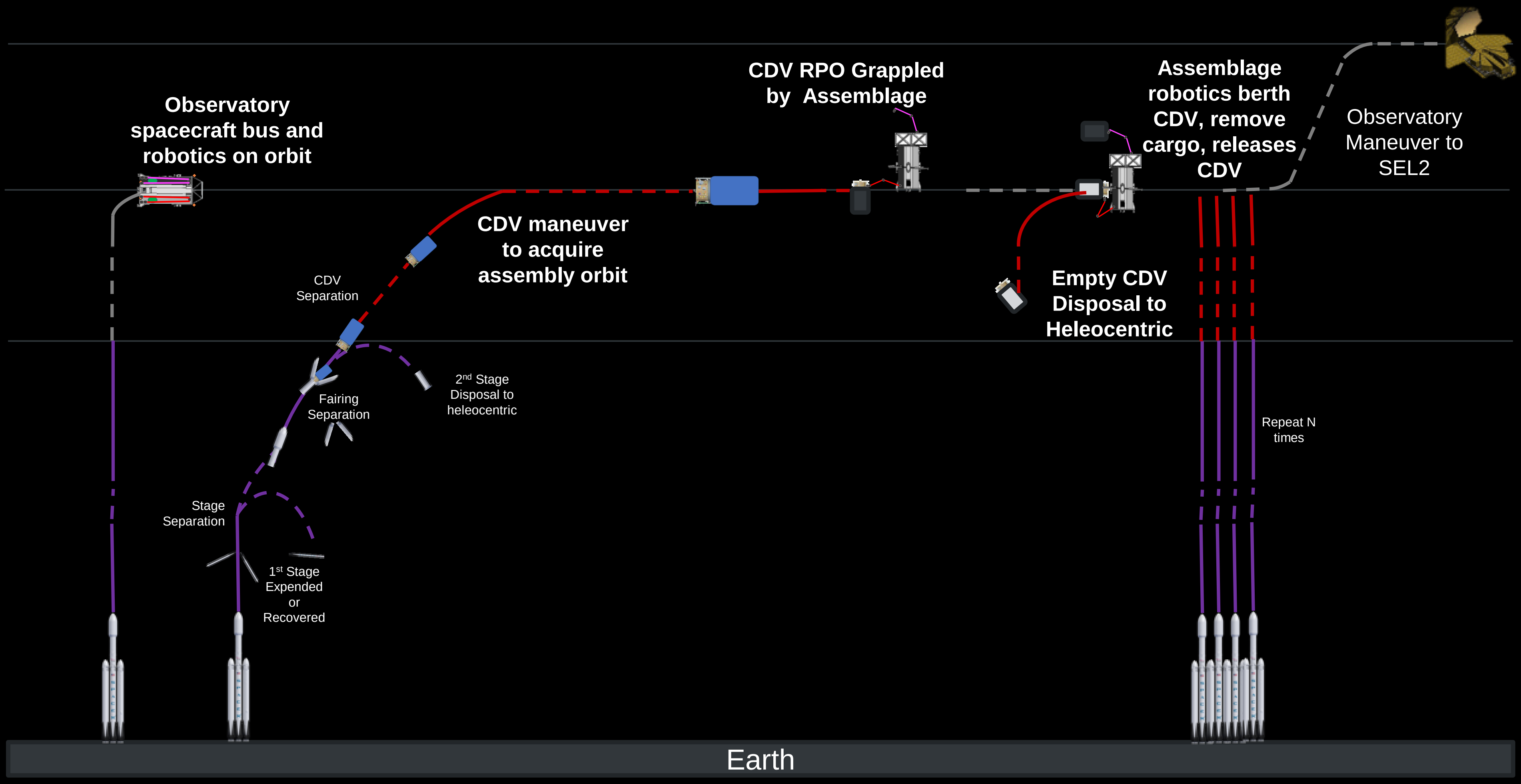


Illustration: Bo Naasz (NASA GSFC)

Delivery Via Disposable Cargo Delivery Vehicle

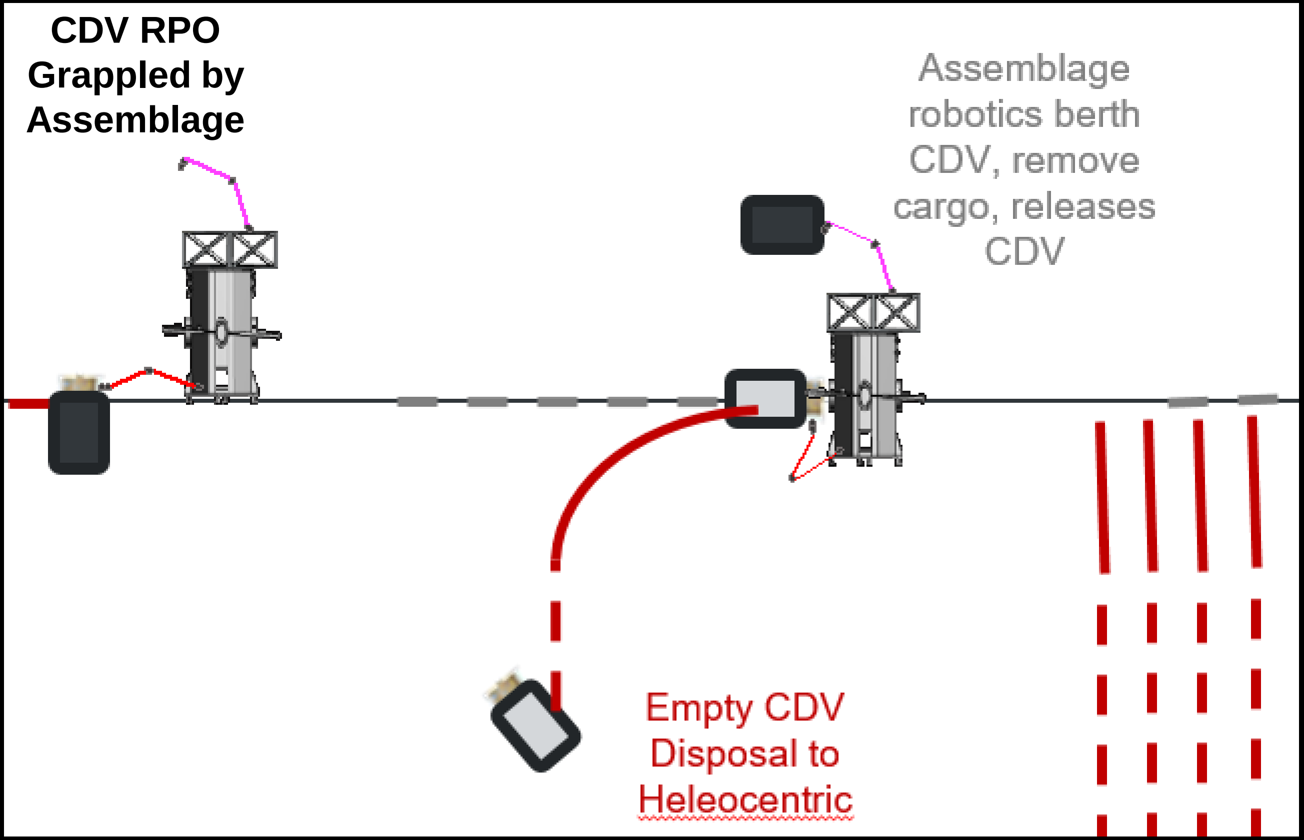
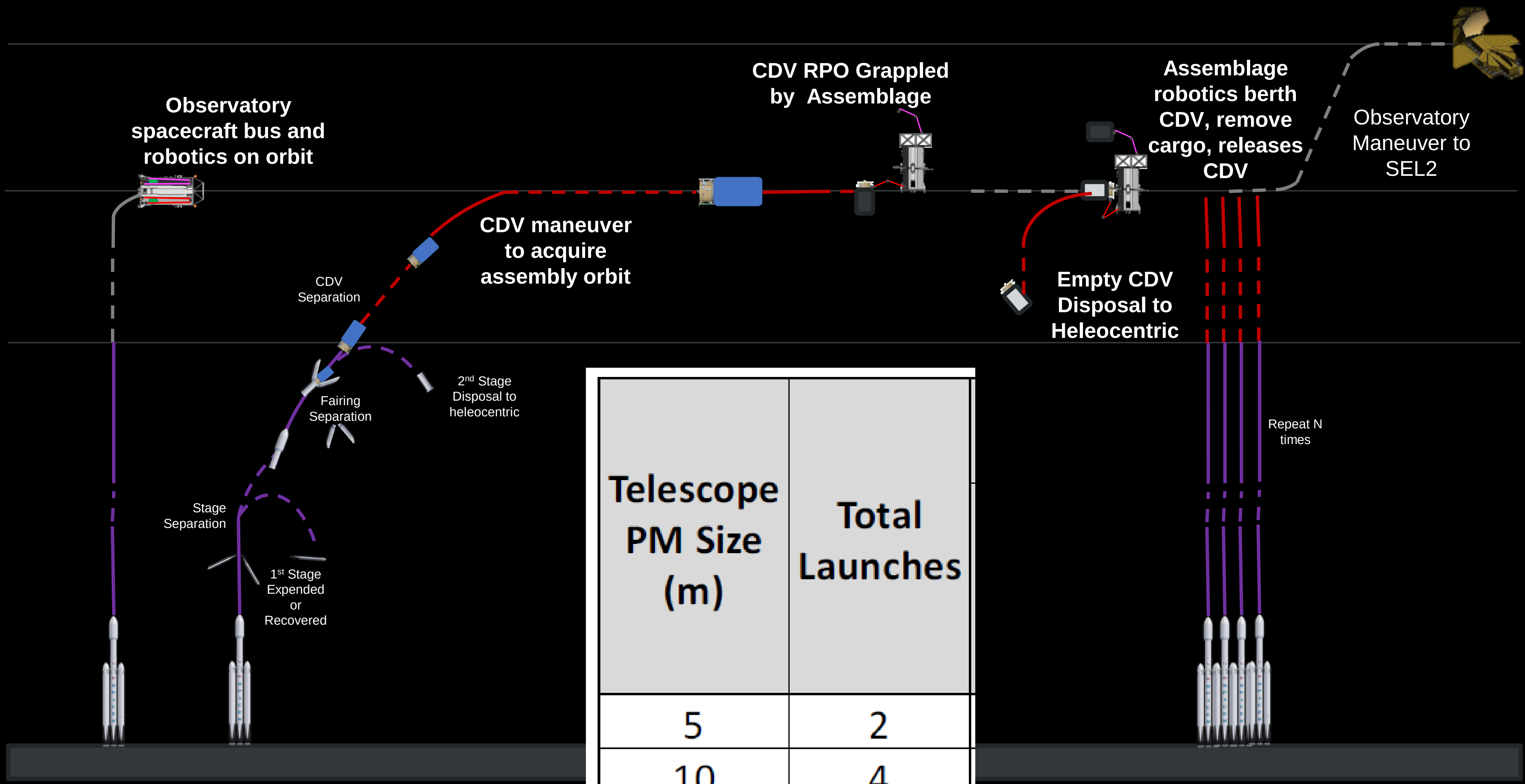


Illustration: Bo Naasz (NASA GSFC)

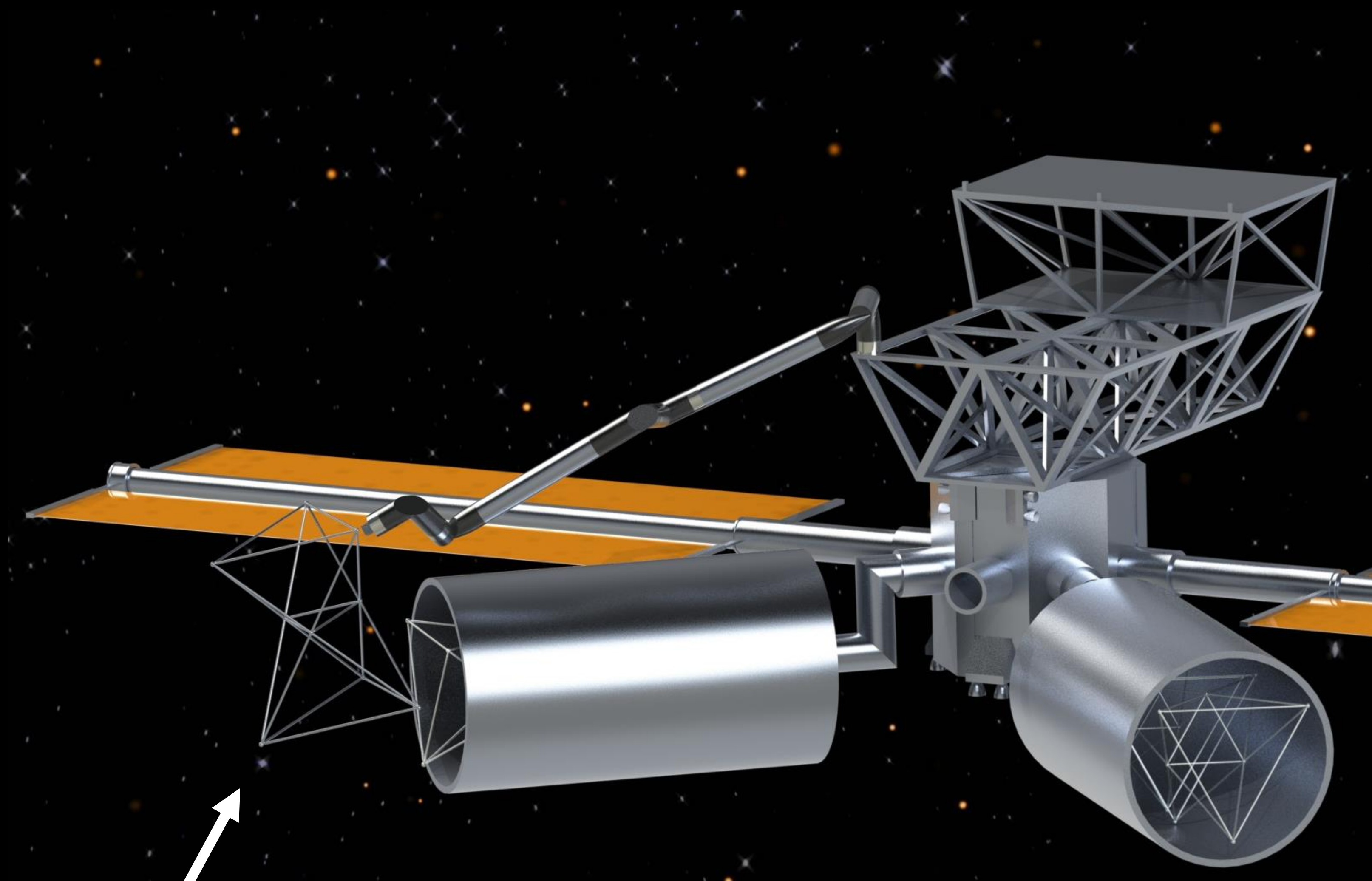
Delivery ConOps

Disposable Cargo Delivery Vehicle (CDV)

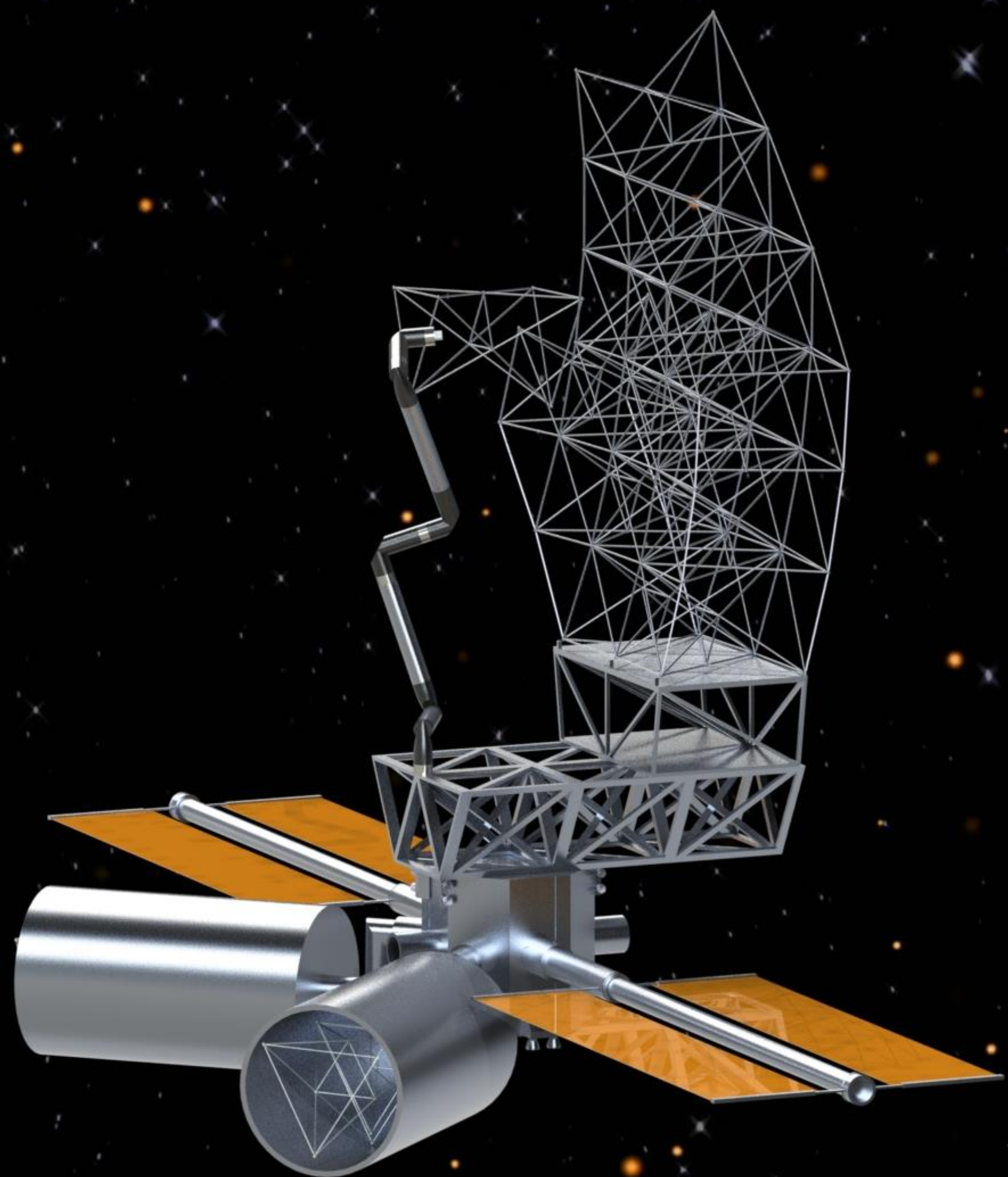


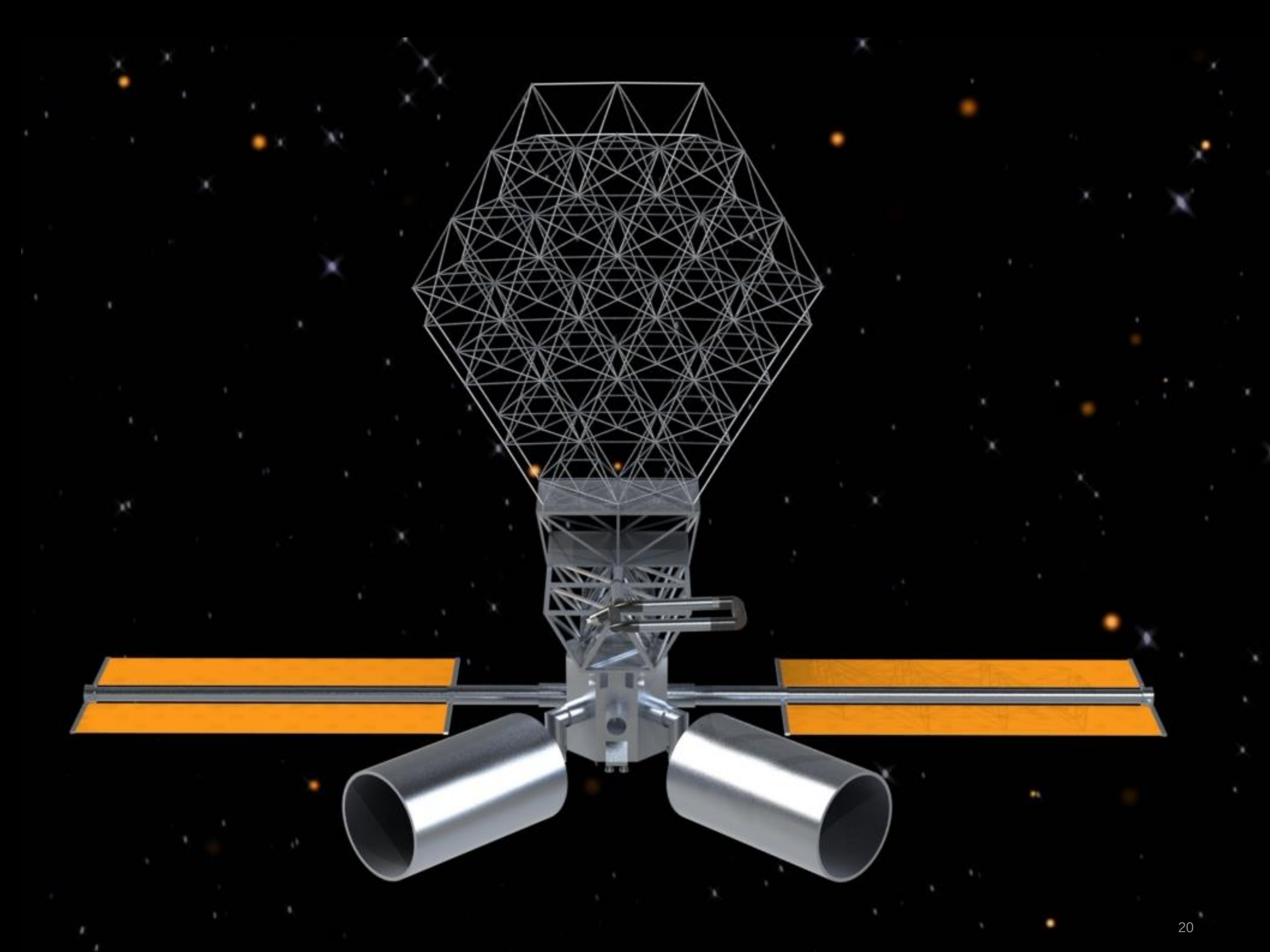
Telescope PM Size (m)	Total Launches
5	2
10	4
15	7
20	12

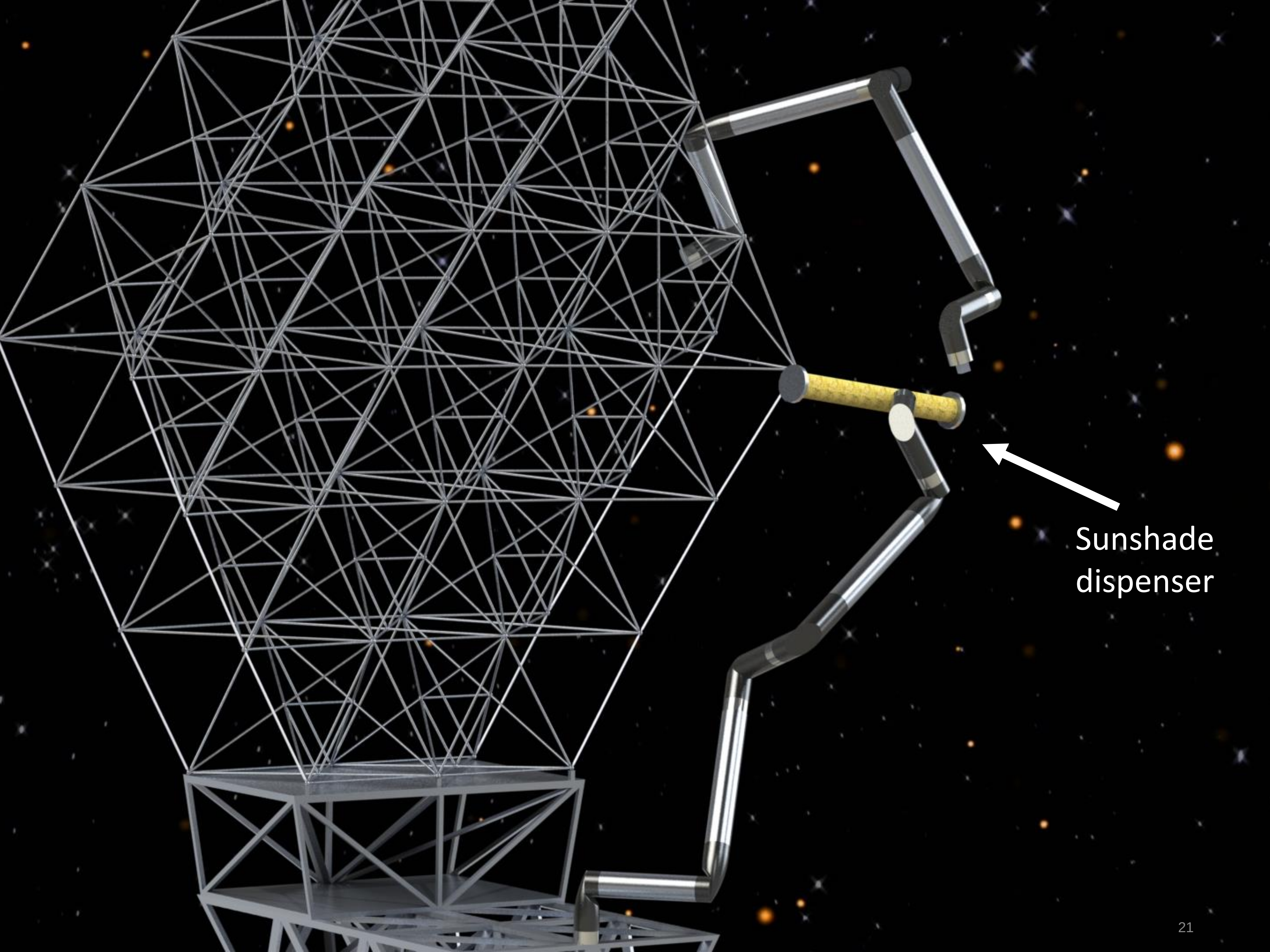
Illustration: Bo Naasz (NASA GSFC)

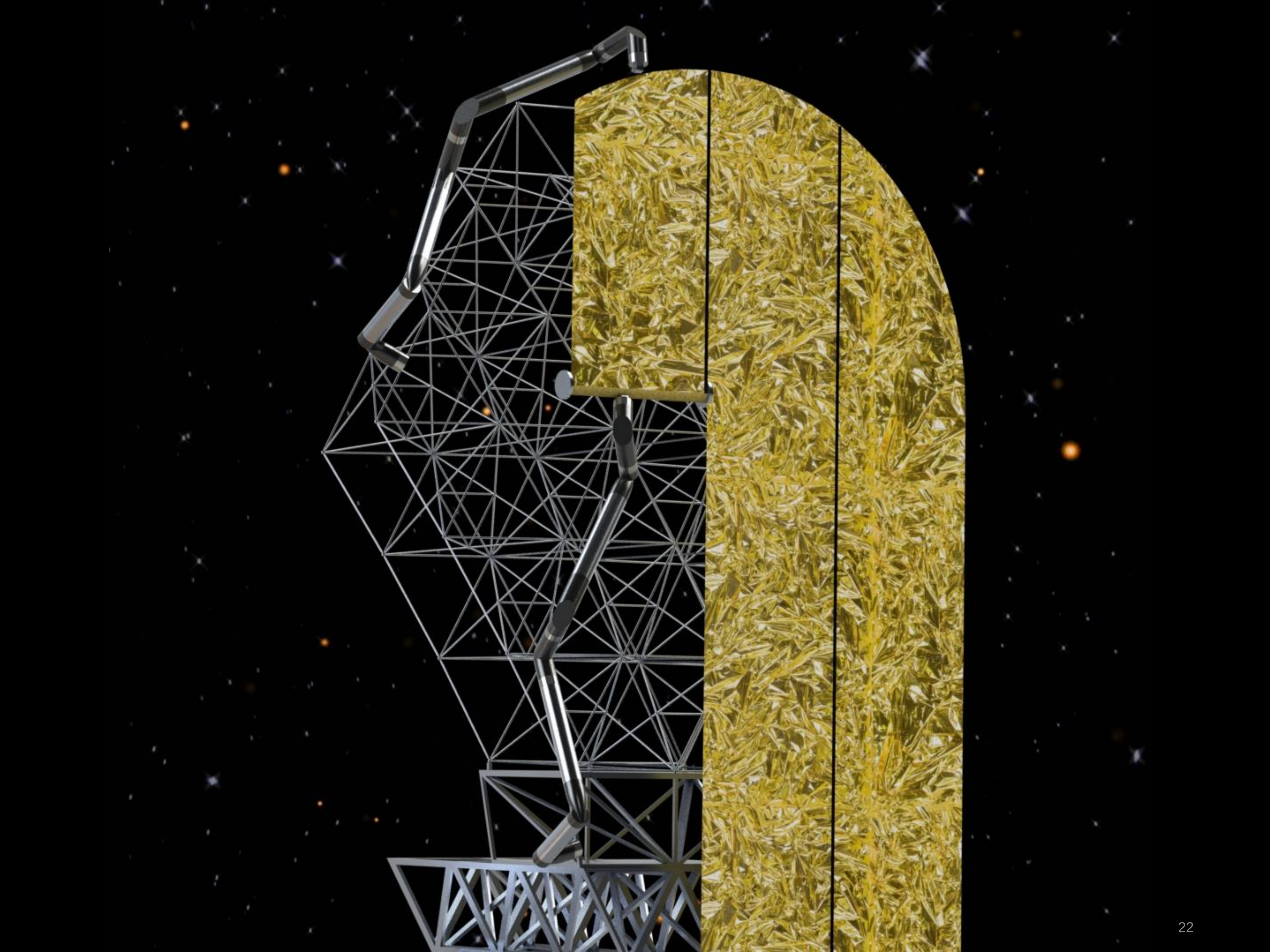


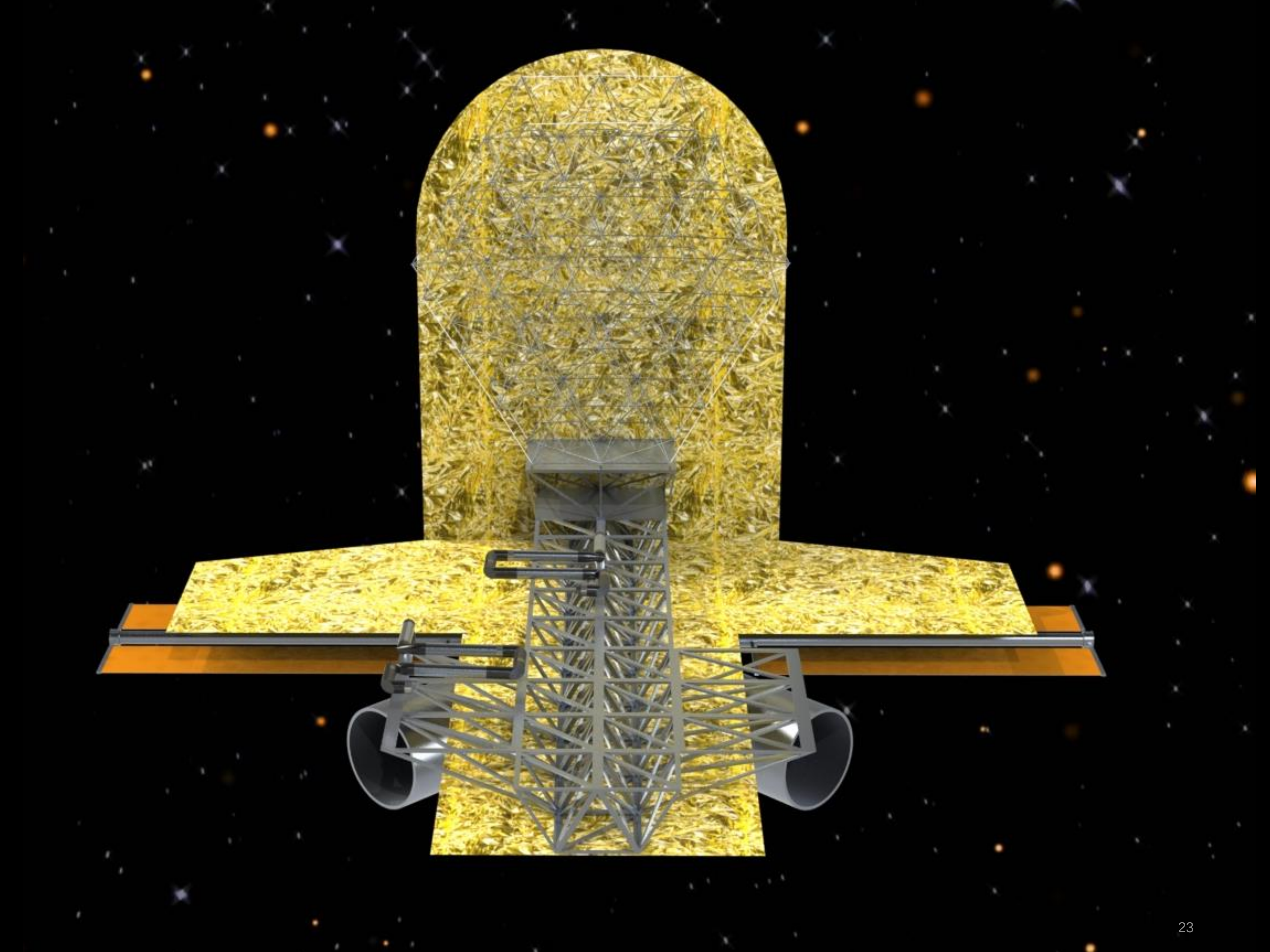
telescope
backplane truss

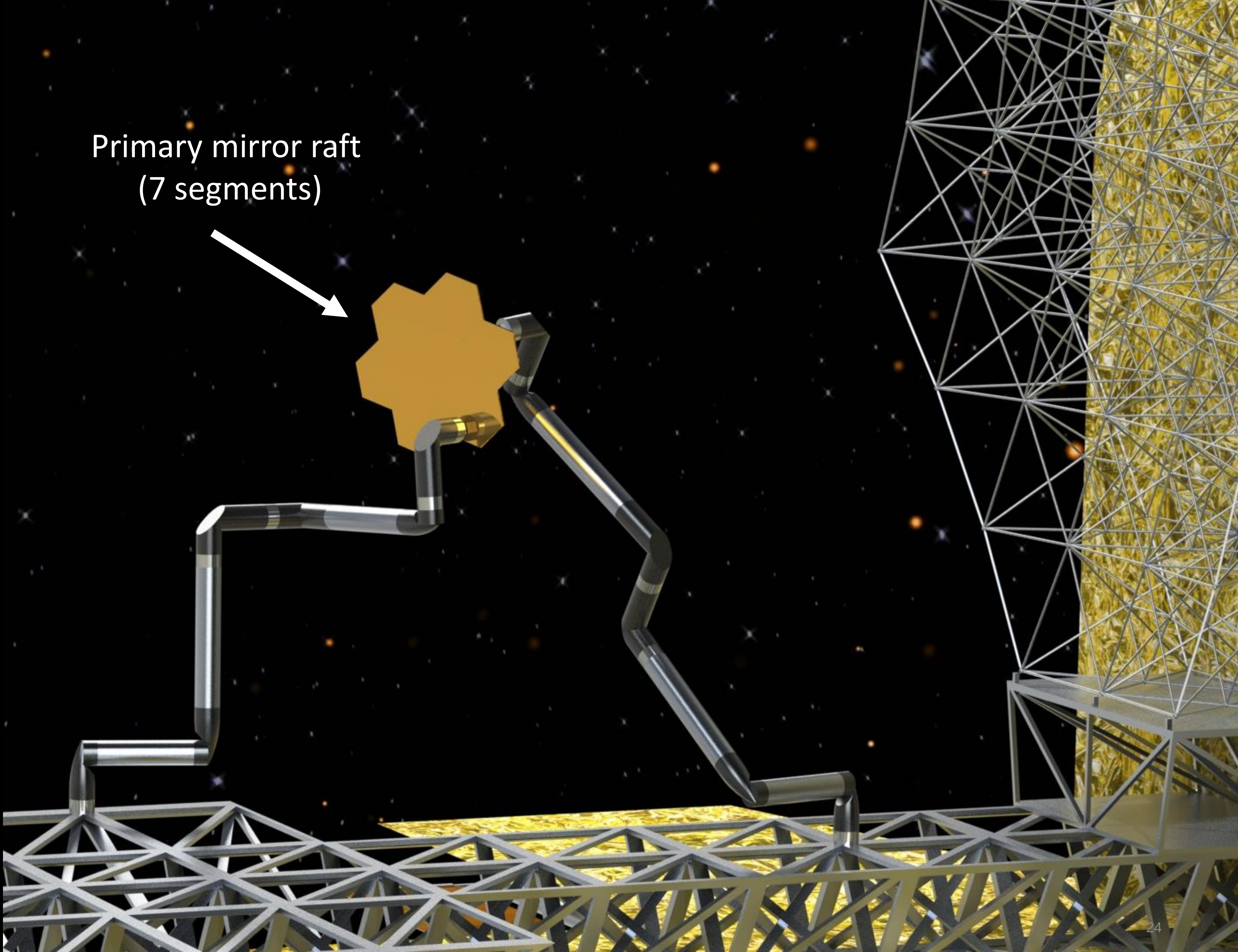


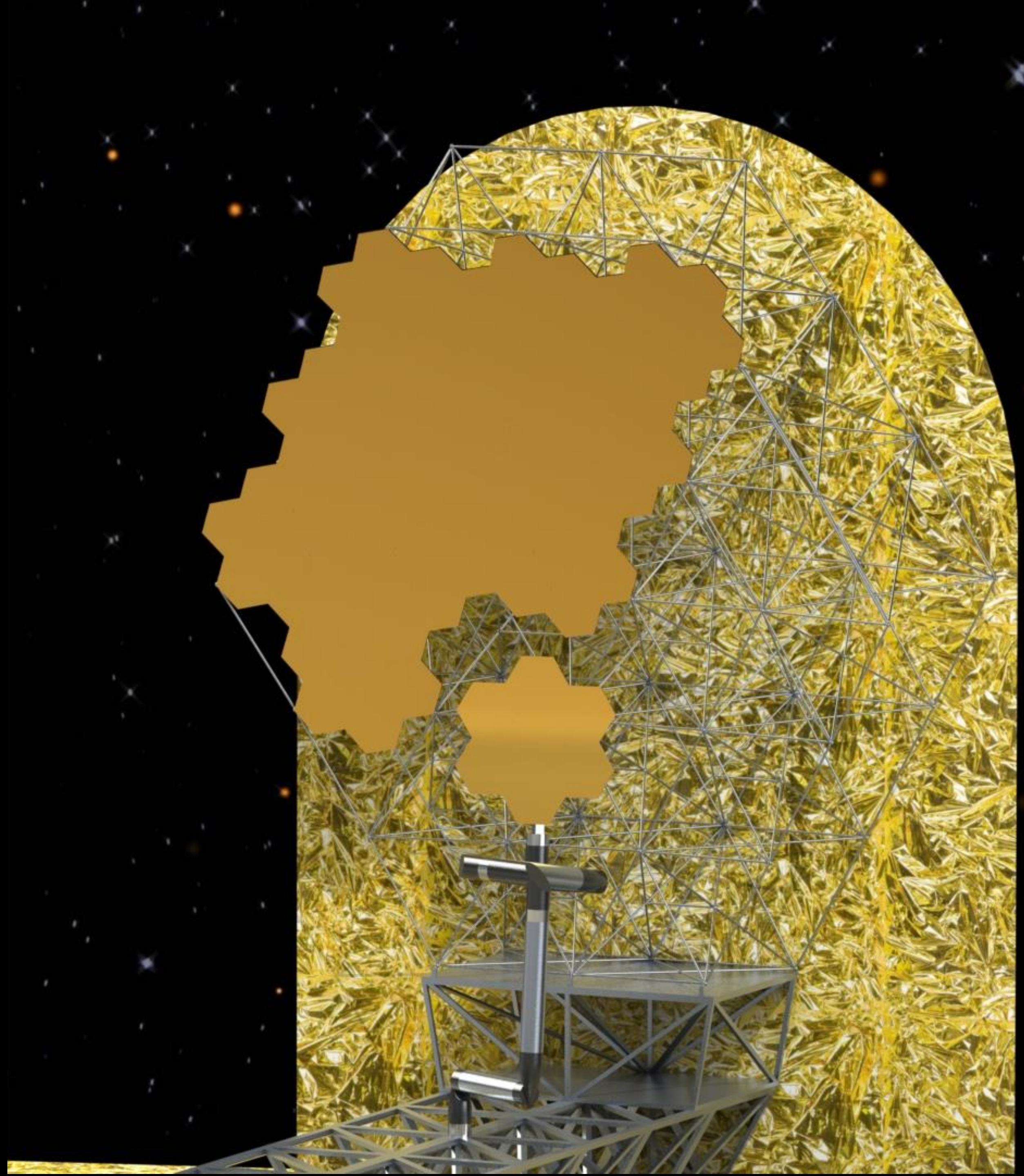


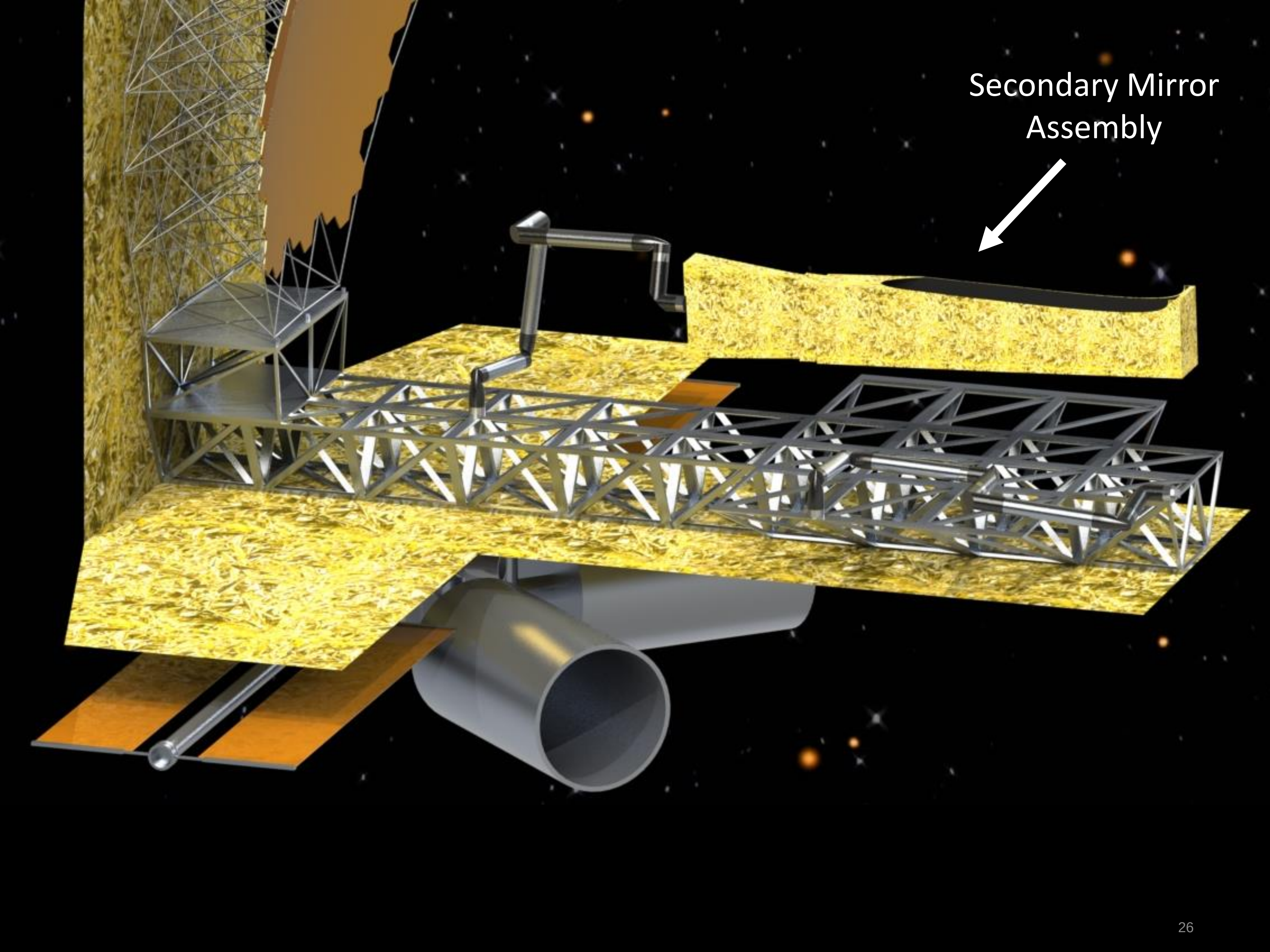

Sunshade
dispenser

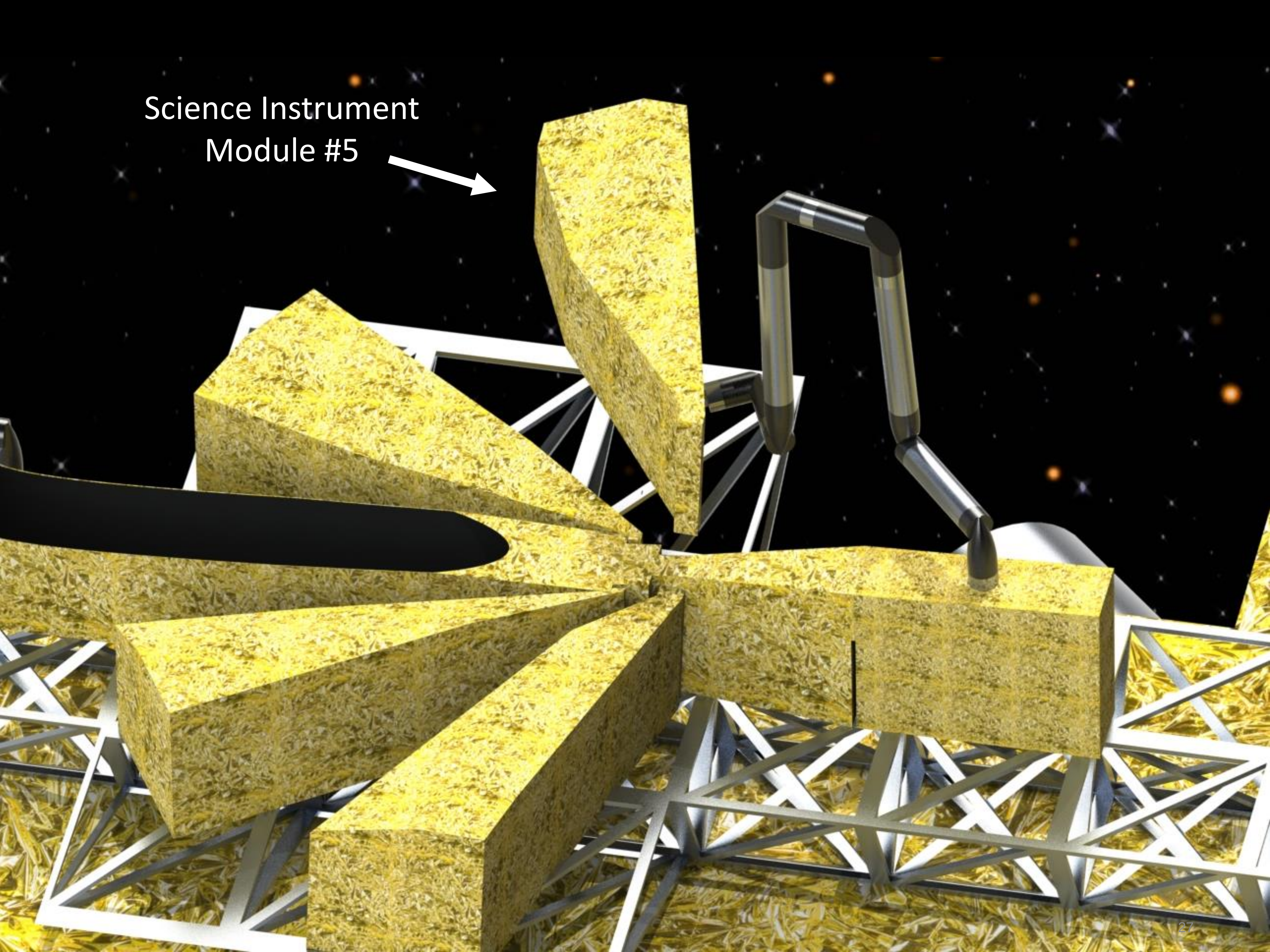




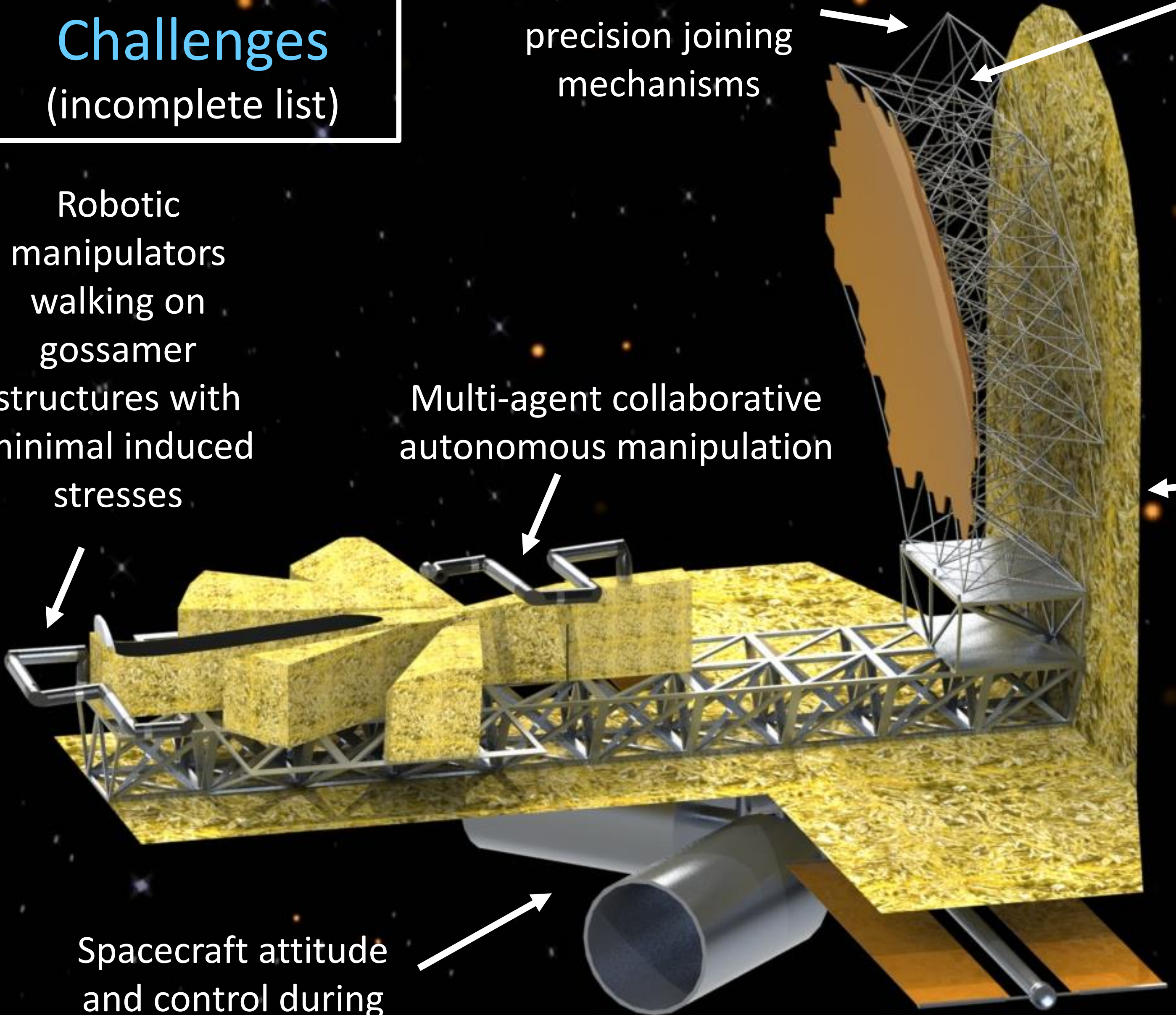

Primary mirror raft
(7 segments)




Secondary Mirror
Assembly


Science Instrument
Module #5

iSAT Technical Challenges
(incomplete list)



Stiff linear structures and precision joining mechanisms

Precise, adjustable, reversible interfaces with harnesses

Robotic manipulators walking on gossamer structures with minimal induced stresses

Multi-agent collaborative autonomous manipulation

Assembly and manipulation of soft goods such as Mylar sheets and blankets

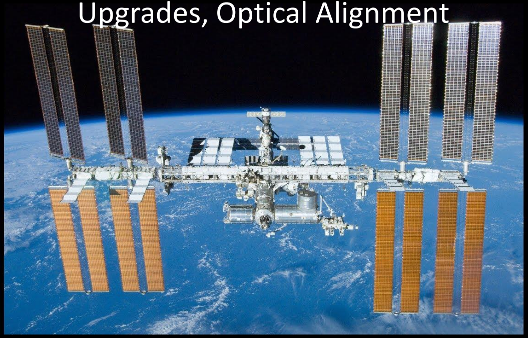
Spacecraft attitude and control during assembly

Study Key Findings

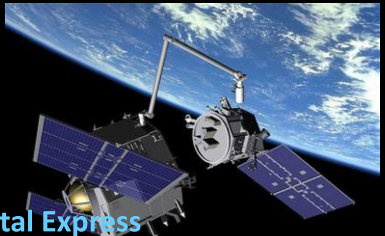
iSAT Leverages Many TRL 9 Capabilities

Past Capability Advances

HST Servicing – Inspects, Repairs, Upgrades, Optical Alignment



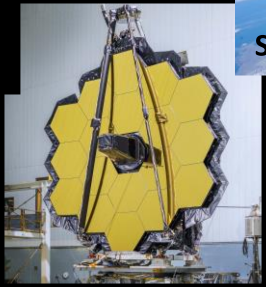
ISS Assembly – Modularity, Multiple LV's, Robotic Arms



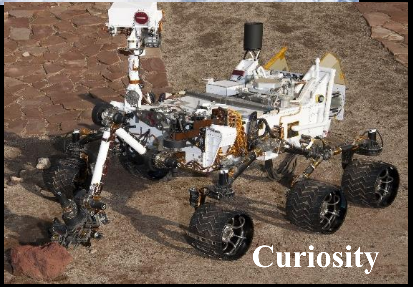
Orbital Express
Autonomous Rendezvous and Soft Capture, Removal/installation of ORUs, Fluid Transfer

Ongoing Capability Improvements

ISS Servicing and Assembly – Robotic Repairs, Autonomous Docking, Instrument Assembly



JWST:
Segmented Optics
WFS&C Phasing

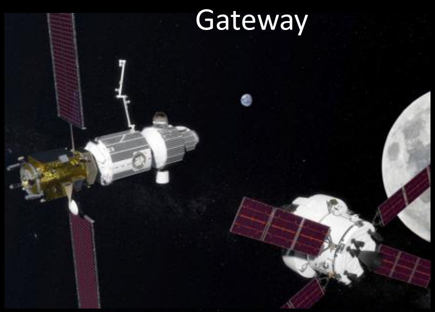


Supervised Autonomy Robotics

Commercial LEO – Infrastructure Buildup, Support Services

Future Capability

Advanced Servicing – Autonomy, Telerobotics, Refueling, Servicing



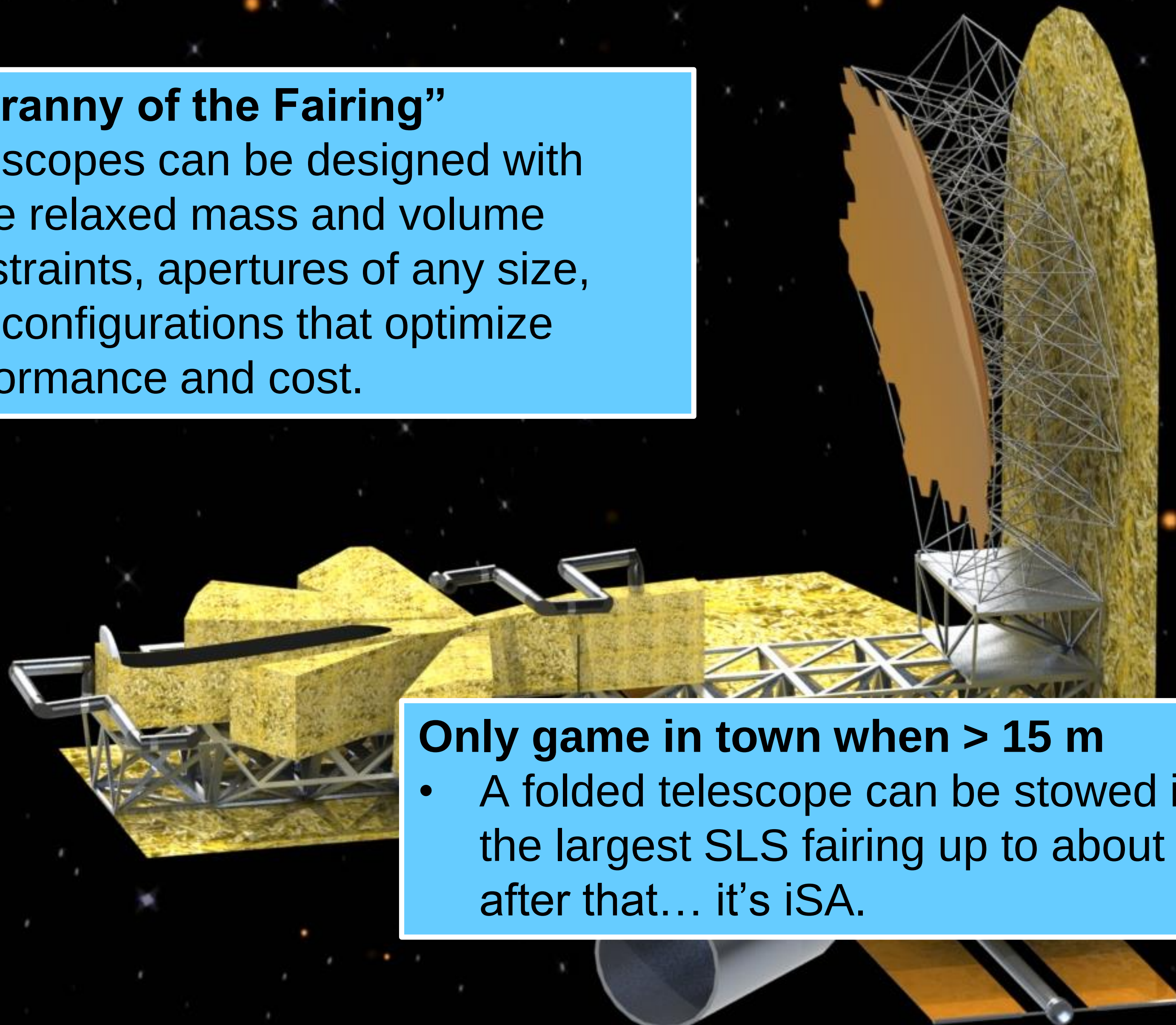
No technical showstoppers

Further engineering development required; several technology gaps

#	ISA Key Capabilities	Status	Representative Examples	Readiness for Observatory ISA
1	**Modular Elements**	Flight Demonstrated	Instruments on HST, instruments installed on ISS	**Low**
		Active Development	JWST primary mirror segments	
2	**Launch Vehicles**	Flight Demonstrated	SpaceX Falcon, Falcon Heavy, ULA's Delta IV	**High**
		Active Development	SLS, Blue Origin, Starship, Vulcan Centaur	
3	**RPO**	Flight Demonstrated	DARPA Orbital Express, NASA OSIRIS-Rex, Cygnus, Dragon, Crew Dragon, ATV, HTV, Progress, Soyuz	**High**
4	**CDVs**	Flight Demonstrated	SpaceX Dragon, Cygnus from Northrop Grumman	**High**
5a	**Space Robotics Hardware**	Flight Demonstrated	Several robotic arms on ISS (e.g. Canadarm 2), Orbital Express robotic arm, Mars Rover arms, Shuttle arm	**High**
		Active Development	NASA Restore-L and DARPA RSGS robotic servicing arms, Canadarm 3, Maxar's Dragonfly arm, Mars 2020 rover	
5b	**Space Robotics Software**	Flight Demonstrated	Mars Rover Autonomy (e.g. MSL, MER), ISS, Orbital Express	**Medium**
		Active Development	Mars 2020, Mars Sample Return, NASA Restore-L, DARPA RSGS, NASA Tipping Point Demonstrations	
6	**In-space Verification and Validation**	Flight Demonstrated	Instruments on HST, instruments installed on ISS	**Low**
		Active Development	JWST primary mirror segments and wavefront control	

Technology investments needed most in items 1 and 6

Mass and Volume Constraints Decoupled



No "Tyranny of the Fairing"

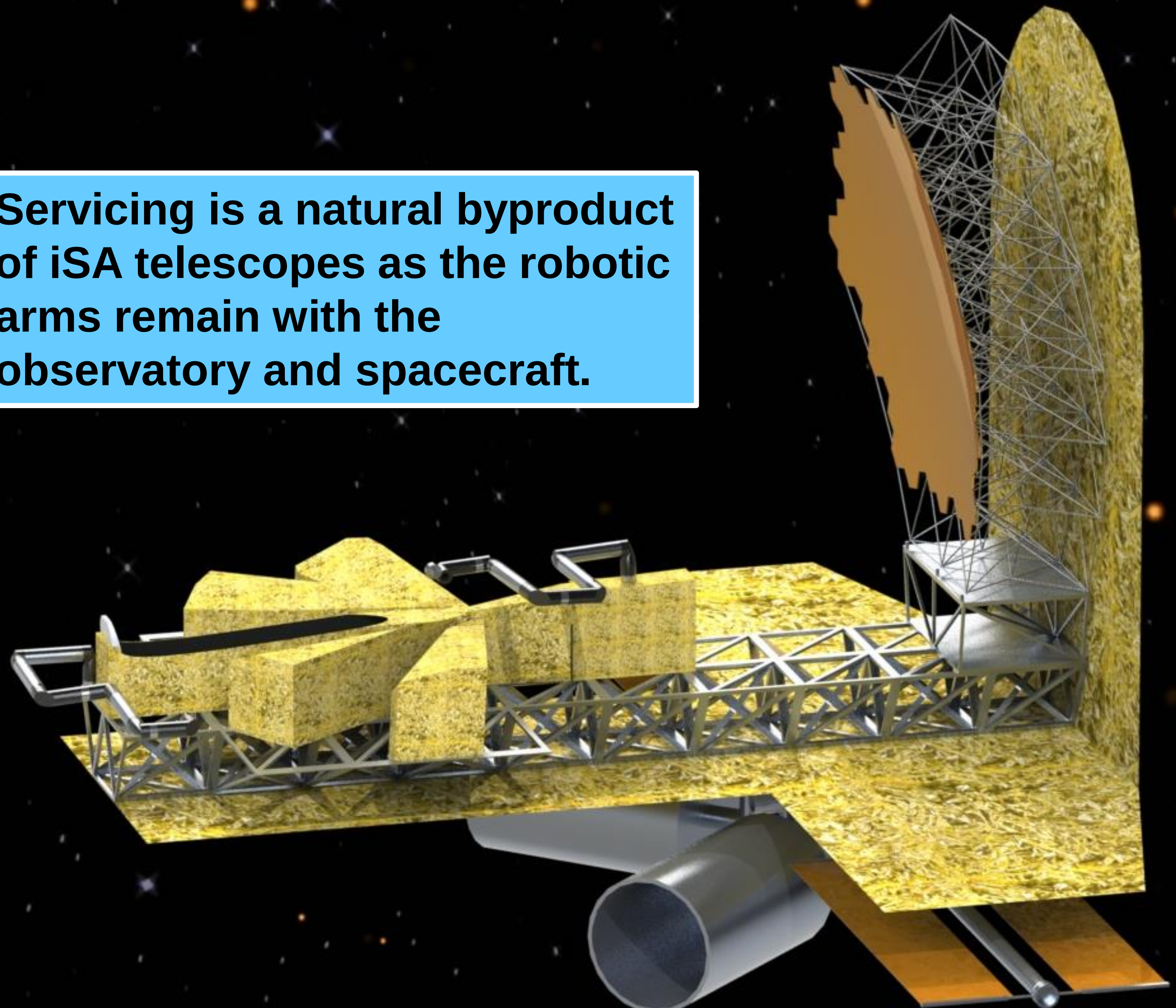
- Telescopes can be designed with more relaxed mass and volume constraints, apertures of any size, and configurations that optimize performance and cost.

Only game in town when > 15 m

- A folded telescope can be stowed into the largest SLS fairing up to about 15 m, after that… it's iSA.

iSA Solves the in-Space Servicing Question

Servicing is a natural byproduct of iSA telescopes as the robotic arms remain with the observatory and spacecraft.

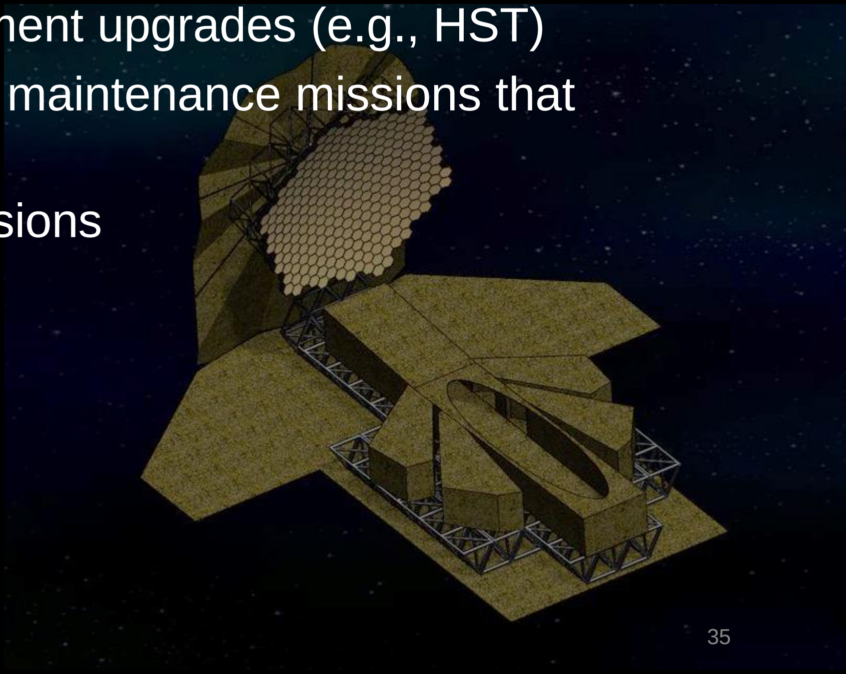


Welcomed, but not required…

- **Future space infrastructures (e.g. Lunar Gateway, ISS)**
- **Astronauts**
- **Large future launch vehicles (e.g. BFR, New Glenn, SLS)**

Key Science Benefits Enabled by iSA

- No "Tyranny of the fairing"
  - Telescope diameters and configurations that achieve science goals not possible with apertures constrained by single launches
  - Instruments may be more capable as they are independently launched and less constrained by mass and volume
- Telescopes can evolve and last decades
  - Continuous stream of planned instrument upgrades (e.g., HST)
  - Can plan for refueling and preventive maintenance missions that extend useable lifetime
  - Can authorize unexpected repair missions
- No explicit servicer needed
  - Cost and science benefits



iSA can Reduce Mission Risk

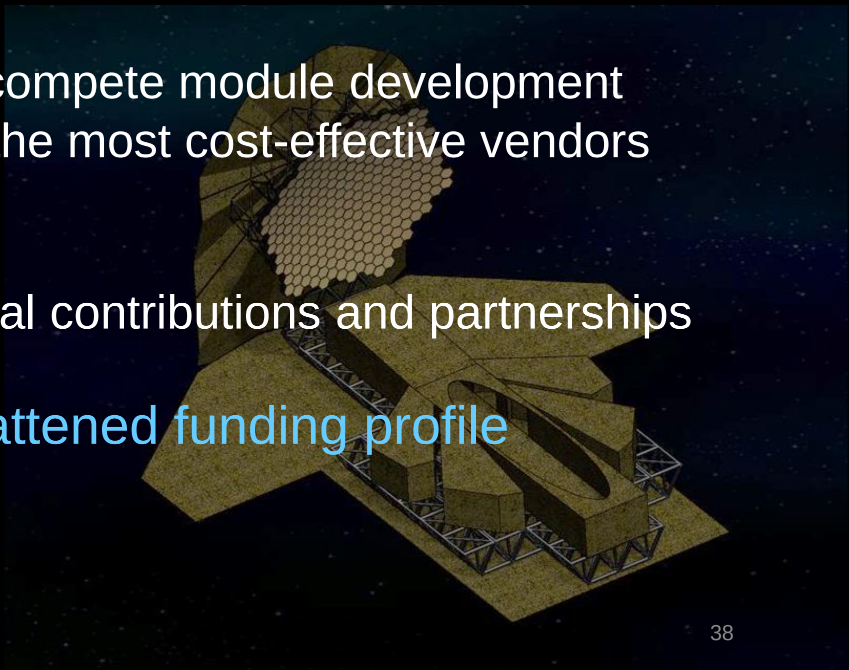
- Eliminates complex autonomous self-deployments
- Mitigates the risks associated with a deployment anomaly
  - ❖ Faulty modules can be replaced during commissioning
  - ❖ Or during operations, with servicing (second chances)
- Mitigates the risks associated with a single launch vehicle
  - ❖ *Launch failure need not be mission failure*

Key Cost Benefits Enabled by iSA (1 of 2)

- Relaxes mass and volume constraints
  - Reduces engineering design complexity and time (i.e. cost)
  - Eliminates complex folding designs, reduces mass iterations, less need for complex modeling
- More versatile scheduling
  - More work conducted in parallel
  - Multiple parallel deliveries (swim lanes) so AIT team can move to different module deliveries when there are schedule delays (and not turn into a large marching army)
- Modules with standardized interfaces help speed up AIT, especially during anomaly resolution
- Eliminates costly systems-level testing activities
  - Enabled by greater degrees of designed on-orbit adjustability and correctability to meet system tolerance requirements

Key Cost Benefits Enabled by iSA (2 of 2)

- Diminishes cost and schedule impacts from late-stage hardware re-design changes and iterations.
- Reduces need for ruggedizing the system and its interfaces to survive launch
- Less need for new and larger ground test facilities
- Spread the wealth: Can distribute and compete module development work across NASA and industrial base to the most cost-effective vendors and facilities
- Share the wealth: Enhances international contributions and partnerships
- More readily enables prescribed or flattened funding profile programs



Cost Estimation

ISA will incur additional cost compared to a conventional, single launch observatory. These include:

- Modularity, multiple launches, cargo delivery vehicles, rendezvous and proximity operations, assembly robotics

ISA will likely offer opportunities for cost savings in the development of flight system elements such as the telescope, instruments, spacecraft

- These elements typically represent 60-70% of mission costs. Hence, this can be a source of significant savings.
- Flight system assembly, I&T are other areas of potential savings.

→ What is the net effect?

WBS 1-3 Mng. SE. SMA	WBS 4 SCI	WBS 5.1 Telescope Structure	WBS 5.2 Telescope Optics	WBS 5.3 Sunshade	WBS 5.4 Inst	WBS 5.5 Robotics	WBS 6 SC	WBS 7-9 MOS/GDS	LV	CDV	Ops	WBS 10 SI&T

Caption: Relative cost comparison between single-launch vehicle observatory and iSAT. Green represents WBS elements where ISA may provide cost benefits while red represents elements where ISA may have a cost increase in comparison to a conventional, single-launch approach

These cost estimates and approaches are from the iSAT Study and have not been reviewed by JPL for institutional approval.

Study Conclusions

- Even telescopes with apertures as small as 5 m <u>may</u> benefit from iSA as the implementation approach due to potentially better risk postures and opportunities for potential cost savings in comparison to the conventional approach of deployment from a single launch.

- When including future servicing missions the benefits may be even more important.

Actual cost and risk differences will depend ultimately on the mission and point design selected.

Suggestions to NASA

If the Astro2020 Decadal Survey recommends a large space observatory, we suggest:

1) *NASA (a) conduct a detailed study of an iSA implementation of the specific observatory and (b) trade it against the conventional single launch approach*

2) *and*

   NASA initiate a technology development program to reduce the technology gaps associated with in-space assembled observatories

Moving Forward

- iSA has made significant progress over the last 15 years to the point it can now be considered as an alternative implementation approach to realize large space telescopes.
  - *"another tool in the tool box"*

- Designers can now consider hybrid solutions to reduce cost and risk (some elements deployed, some elements assembled).

- Next step is to focus on technology gaps and technologies:
  - Develop technology roadmaps
  - Recommend risk reduction demonstrations for future flight mission

Please contact the Study leads if you are interested in advancing this work.

More Information on our Website

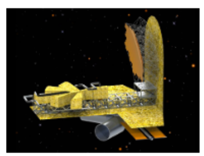
https://exoplanets.nasa.gov/exep/technology/in-space-assembly/iSAT_study/

NASA in-Space Assembled Telescope (iSAT) Study

NASA in-Space Assembled Telescope (iSAT) Study | Steering Committee Telecons | Study Workshops and F2F Meetings | Study Member Telecons

Large aperture telescopes benefit all astrophysics as well as planetary and Earth science. They provide unprecedented spatial resolution, spectral coverage, and signal to noise, advancing all of these science areas. Envisioning the need for future large segmented telescopes to one day exceed the fairing size of existing or even planned launch vehicles, NASA will need to begin considering the in-space assembly (iSA) of these future assets. In addition, robotically assembling space telescopes in space rather than deploying them from single launch vehicles offers the possibility, in some circumstances, of reduced cost and risk for even smaller telescopes. This possibility, however, has not been proven. Therefore, following discussions within NASA's Science Mission Directorate (SMD) and Astrophysics Division (APD), the SMD Chief Technologist and APD Division Director have commissioned a study to assess the cost and risk benefits, if any, of the iSA of space telescopes.

In particular, the study must answer the question: ***"When is it advantageous to assemble space telescopes in space rather than to build them on the Earth and deploy them autonomously from individual launch vehicles?"*** The Study Charter (on the right) describes the plan for the study deliverables, process, and membership. The goal for completion of the study is May 2019 culminating in a submitted whitepaper to the National Academies' 2020 Astronomy & Astrophysics Decadal Survey.



iSAT ConOps Graphical Storyboard: 20m Segmented UV/V/NIR telescope

iSAT: Benefits and Challenges Table

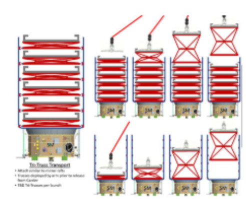
iSAT Astro2020 Whitepaper

When is it Worth Assembling Observatories in Space? Astro 2020 APC Whitepaper, Mukherjee et al. 2019

iSAT Study Final Report

View Report PDF

iSAT Study Additional Information



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