Lessons learned from JWST: What is required to make Mega-Science Projects succeed?

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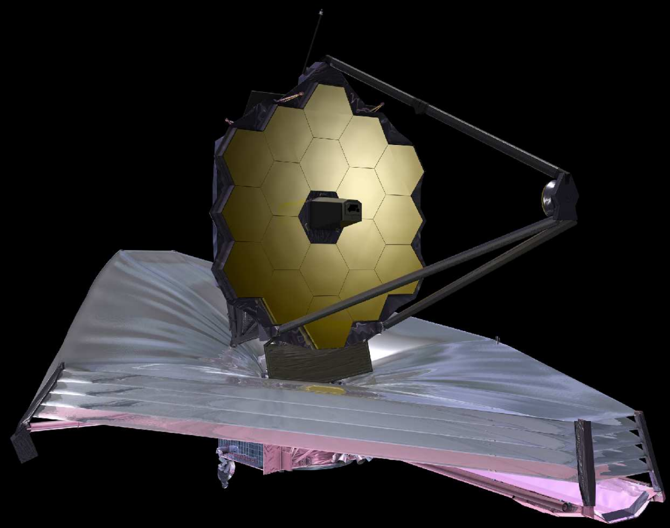
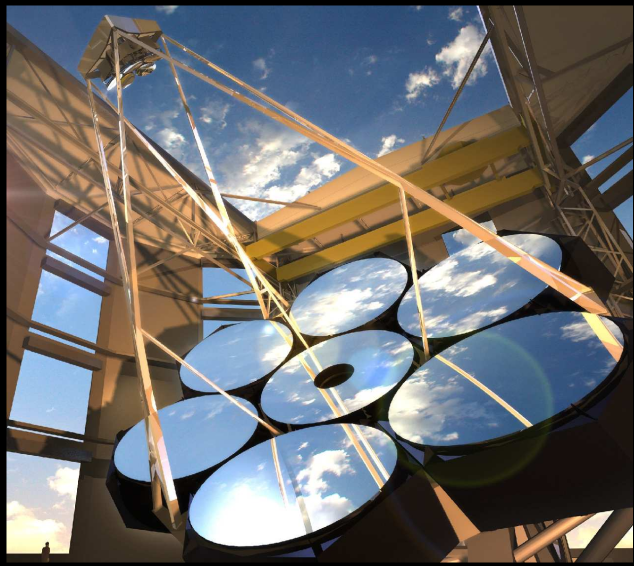
and Robert W. Smith (Univ. of Alberta, Edmonton, Canada) — HST and JWST Historian

Invited talk at the Australian Astronomical Observatory — Engineers and Managers; North Ryde, NSW, Australia;

Wednesday, July 31, 2013; All presented materials are ITAR-cleared. These are my opinions only, not necessarily NASA's or ASU's.

Outline: Lessons learned from JWST

(1) Overview of JWST (for those not at Tuesday's science talk).

(2) JWST Lessons: Mega-project lessons also apply to HST & Supercollider. Key is that scale of efforts goes beyond what people are used to.

- Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates.

Consumers Report: Very Good $\Rightarrow$ Good $\Rightarrow$ Neutral $\Rightarrow$ Fair $\Rightarrow$ Poor.

- (A) Scientific/Astro-Community Lessons
- (B) Technical Lessons
- (C) Management/Budget/Schedule Lessons
- (D) Political/Outreach Lessons

(3) Synergy between the 20–30 m class telescopes (GMT/TMT/E-ELT) and JWST: When $1 + 1 > 2$.

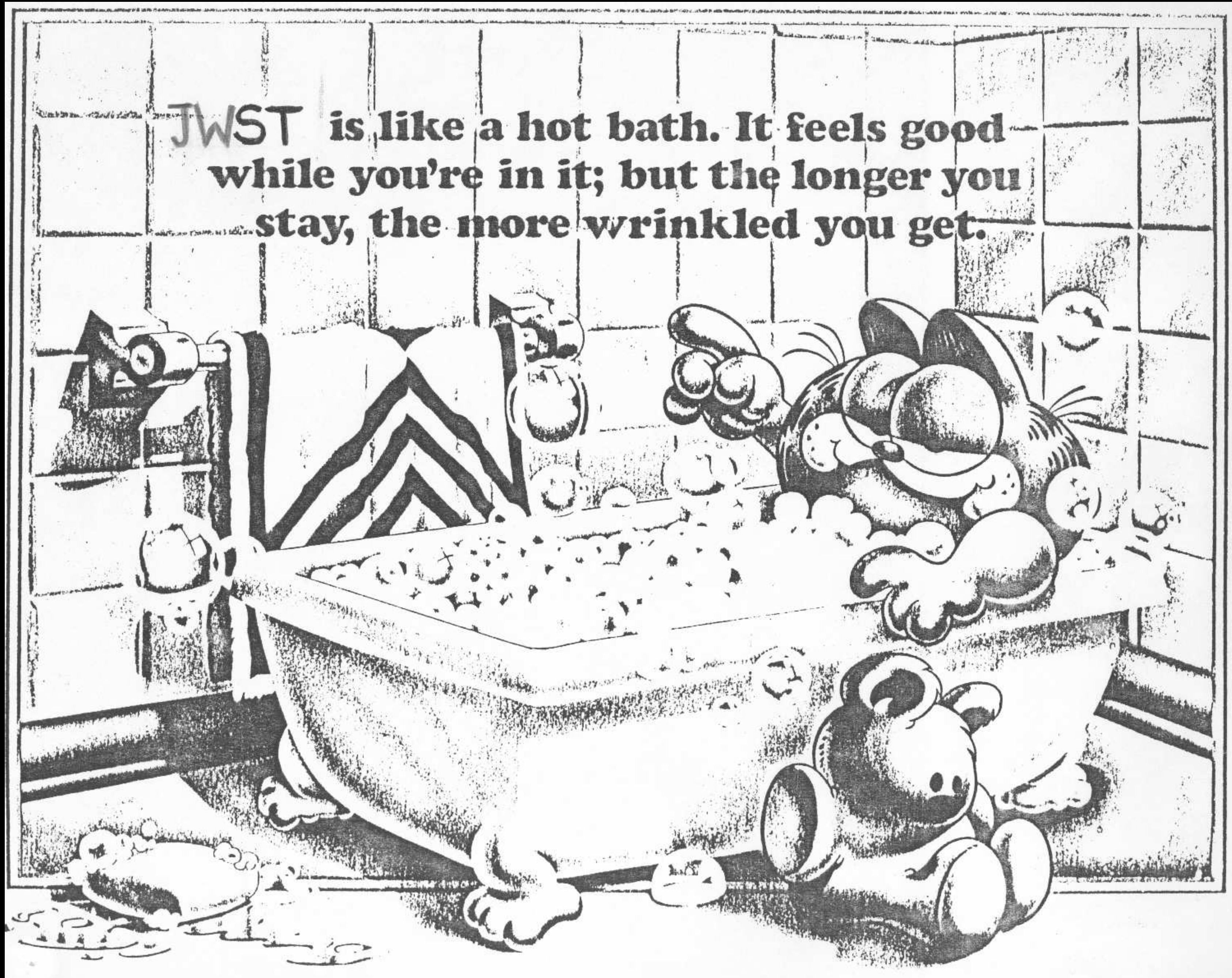
(1) Brief Overview of the James Webb Space Telescope (JWST).

Edwin P. Hubble (1889–1953) — Carnegie astronomer

James E. Webb (1906–1992) — Second NASA Administrator

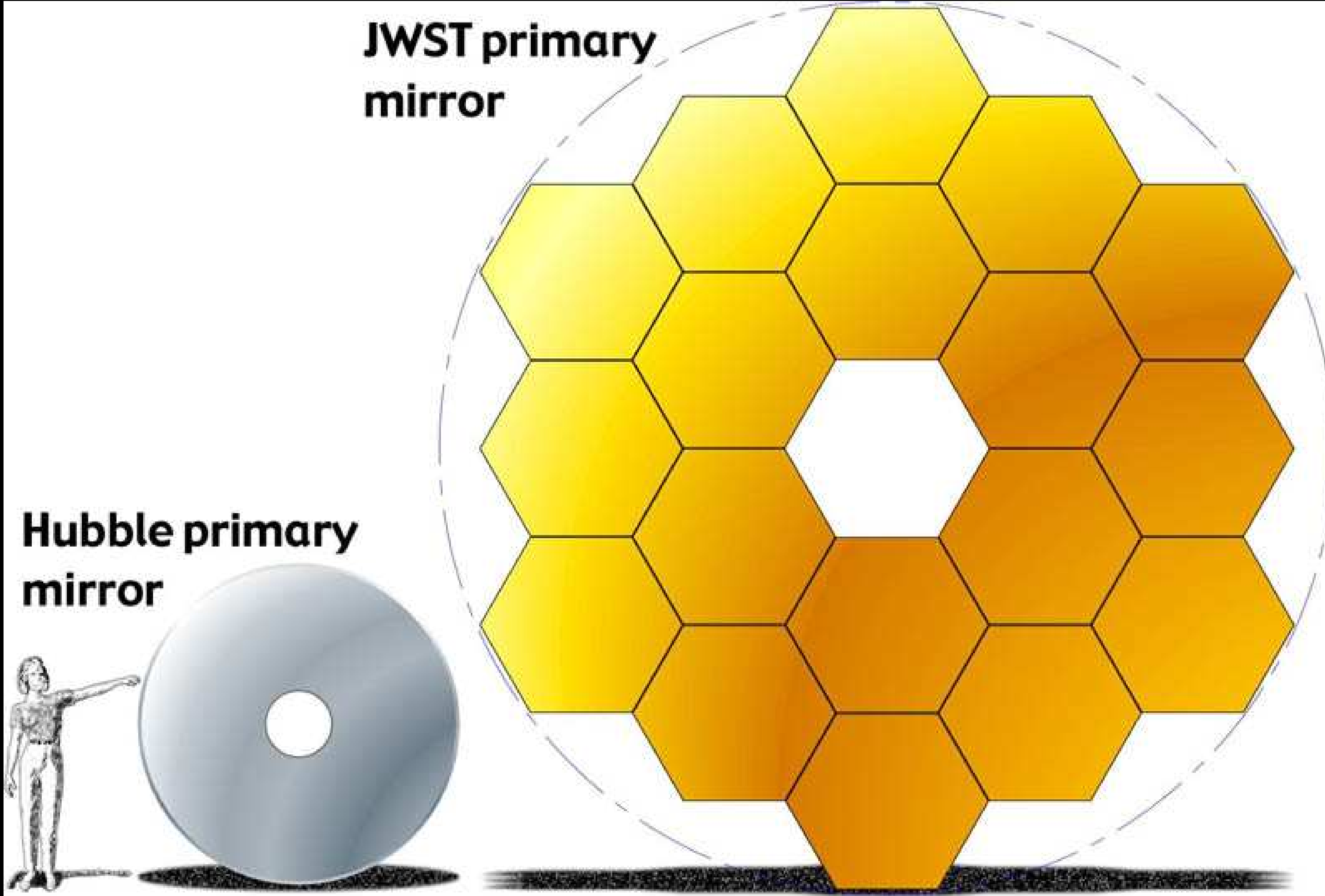
Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2014.

JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).



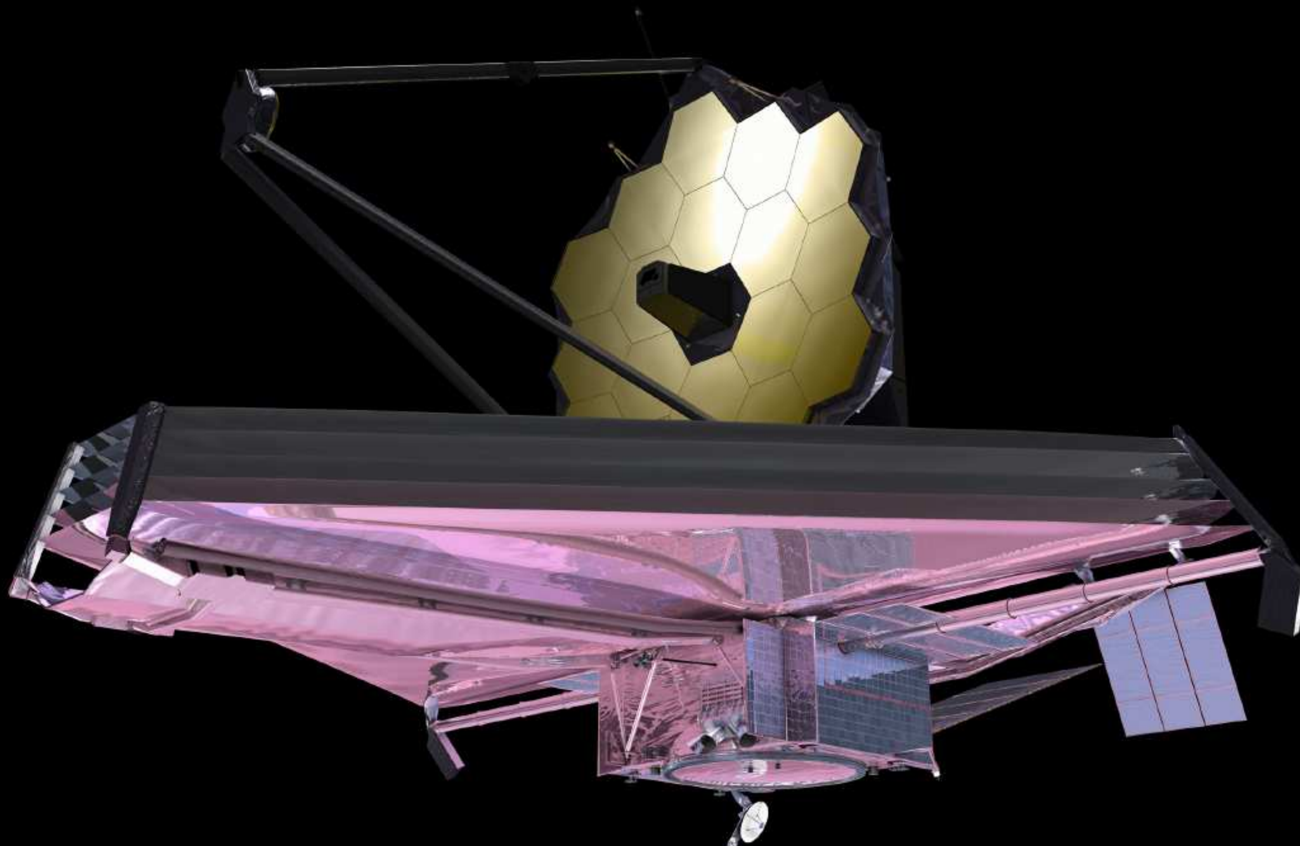
WARNING: Both Hubble and James Webb are 30–40$^+$ year projects:

You will feel wrinkled before you know it ... :)



JWST $\simeq$2.5$\times$ larger than Hubble, so at $\sim$2.5$\times$ larger wavelengths:
JWST has the same resolution in the near-IR as Hubble in the optical.

(1a) What is the James Webb Space Telescope?

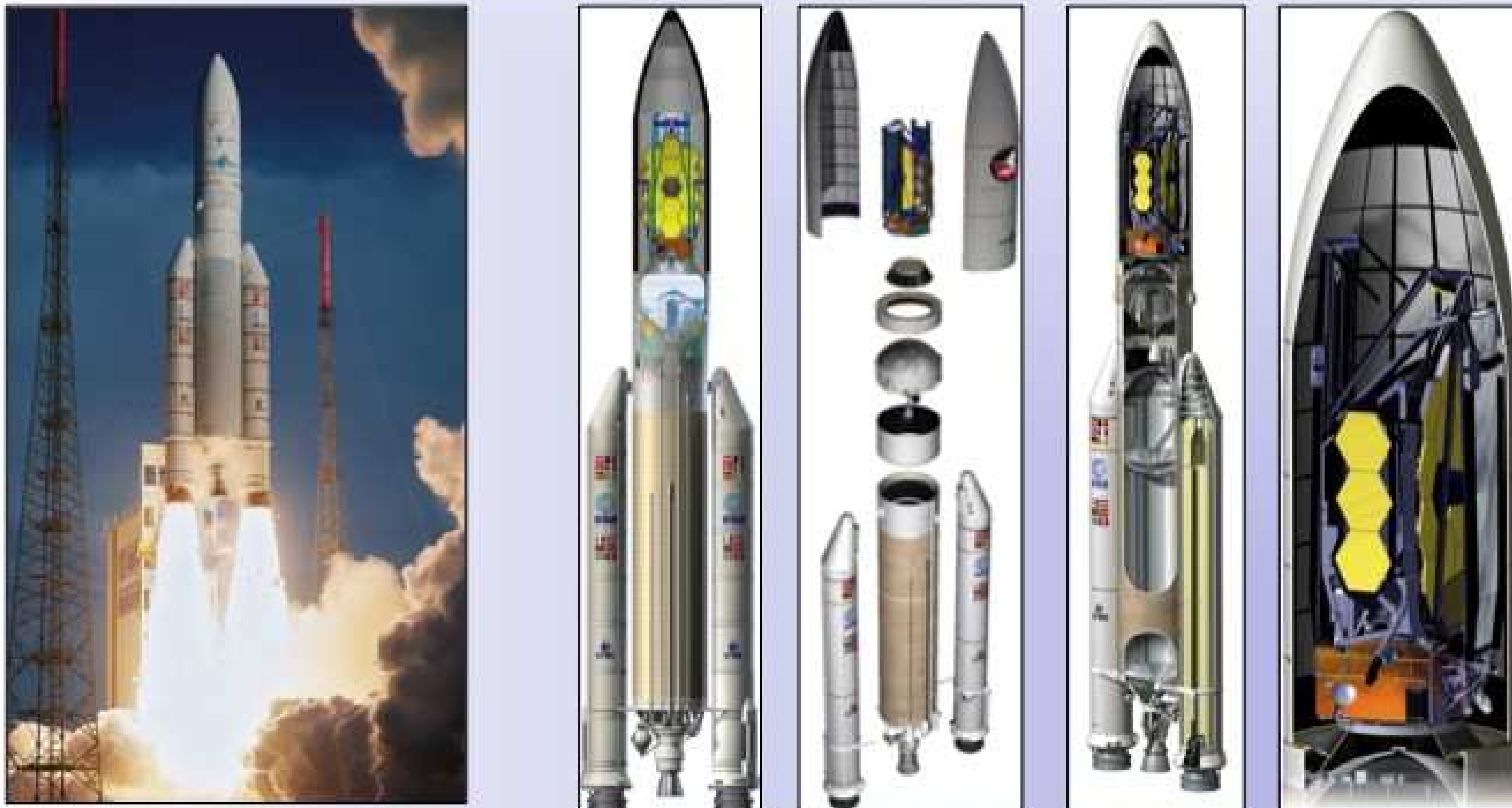


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–28 μm wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (AB=31.5 mag) and spectroscopy.

The James Webb Space Telescope

JWST Launch

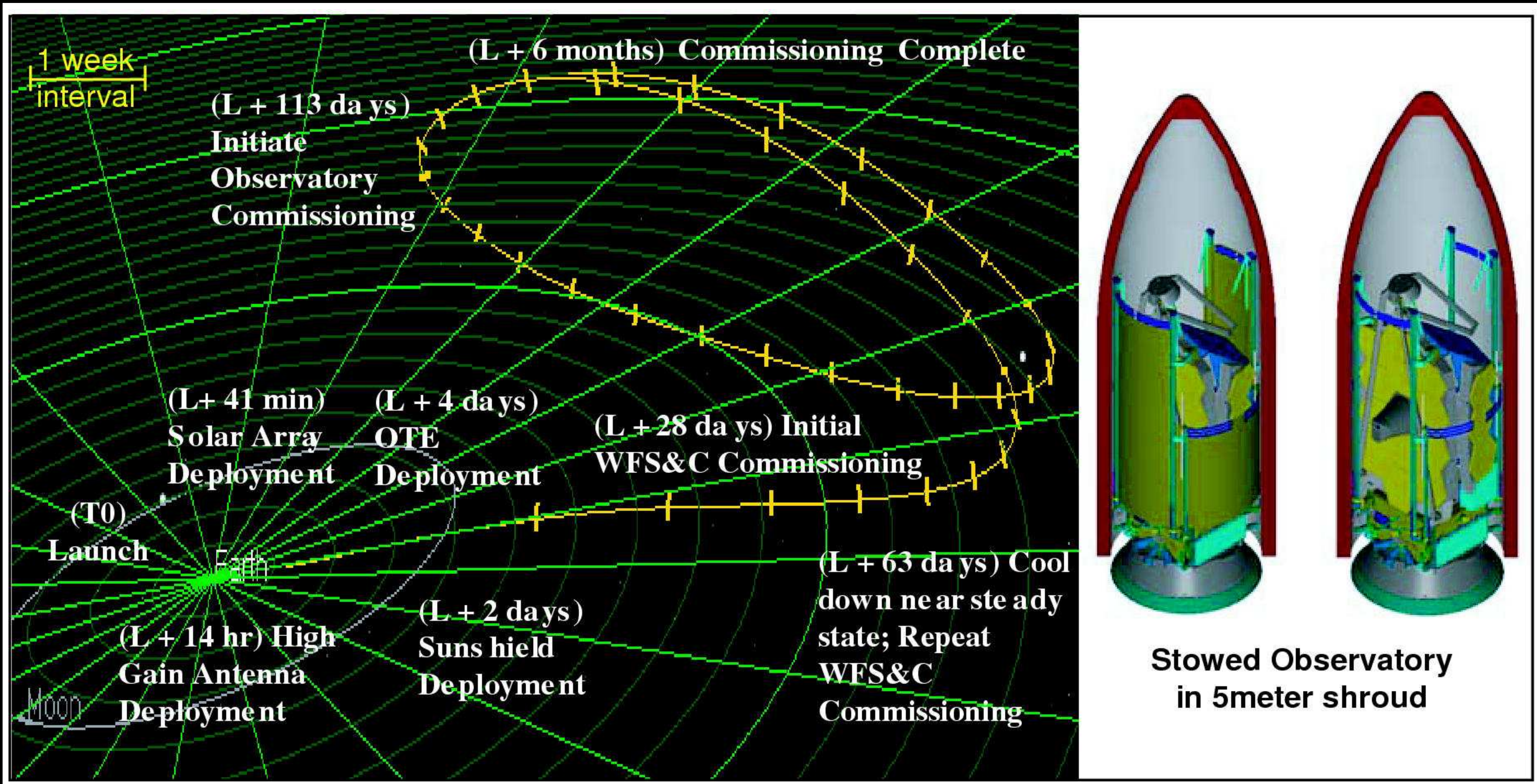
- Launch vehicle is an Ariane 5 rocket, supplied by ESA
- Site will be the Arianespace's ELA-3 launch complex near Kourou, French Guiana



Arianespace – ESA - NASA

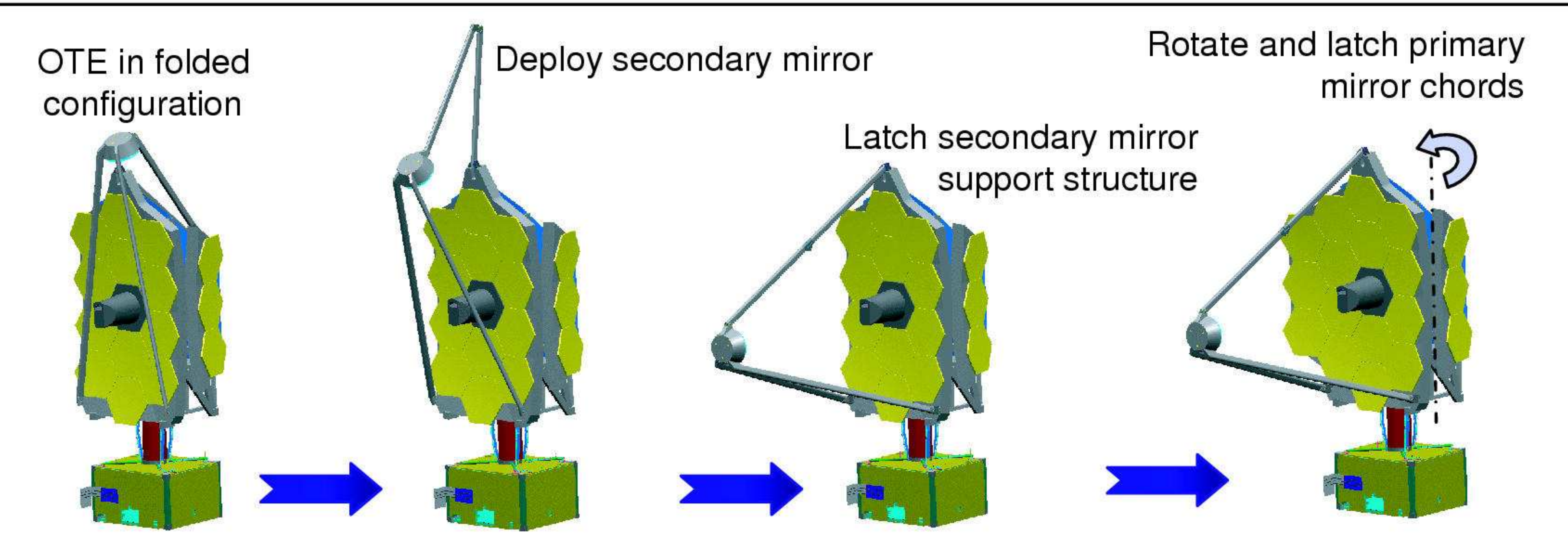
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

(1b) How will JWST travel to its L2 orbit?



- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

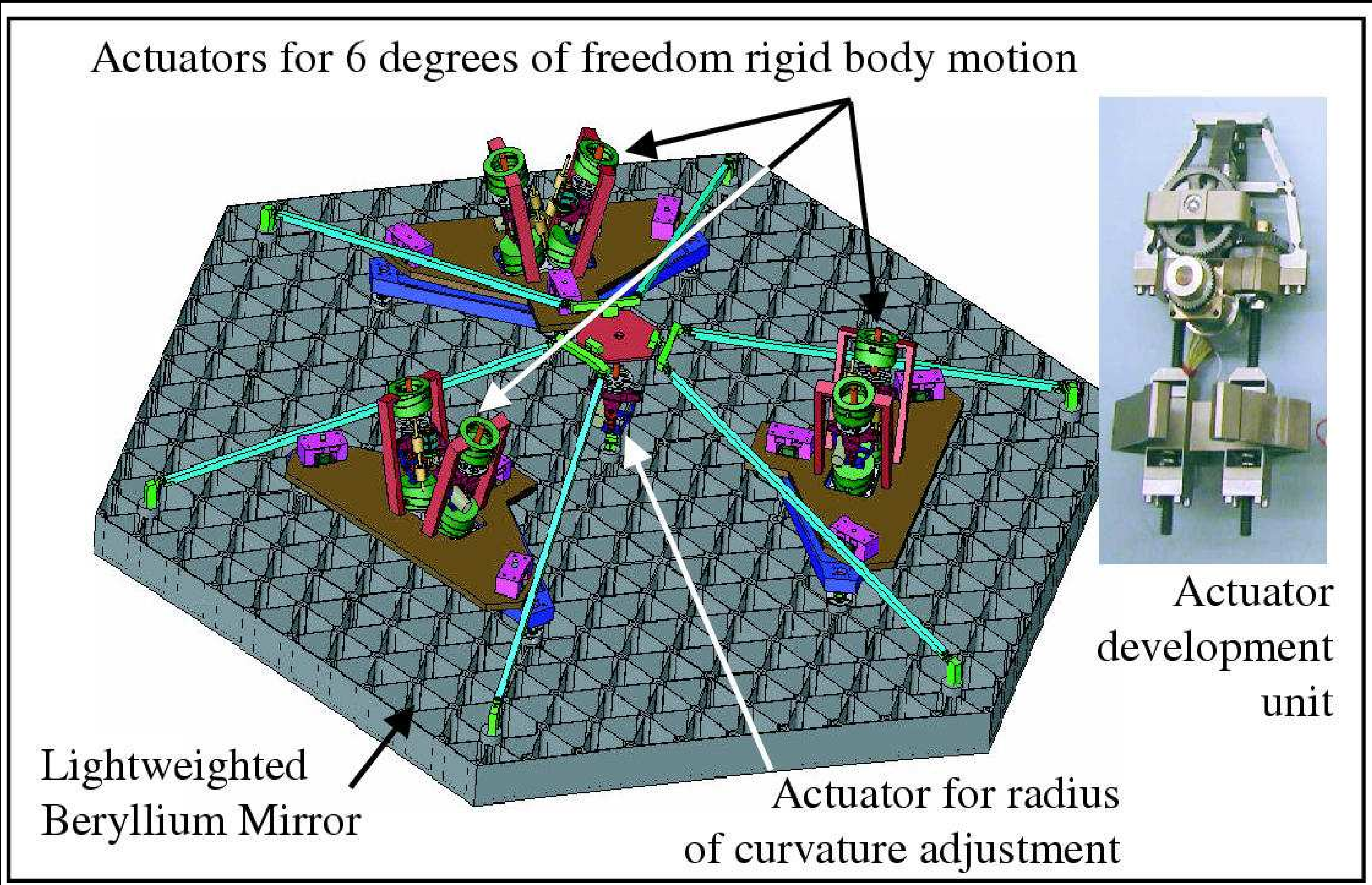
• (1b) How will JWST be automatically deployed?



• During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.

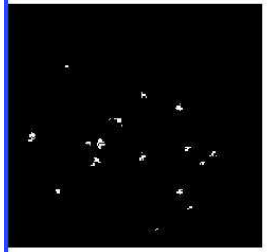
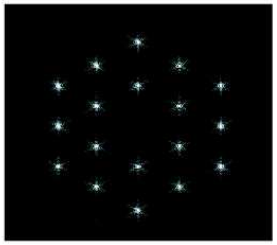
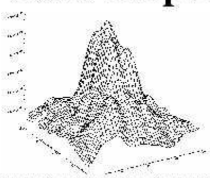
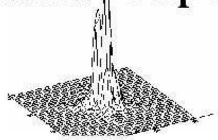
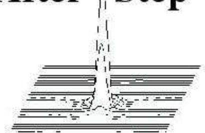
• The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.

• Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.



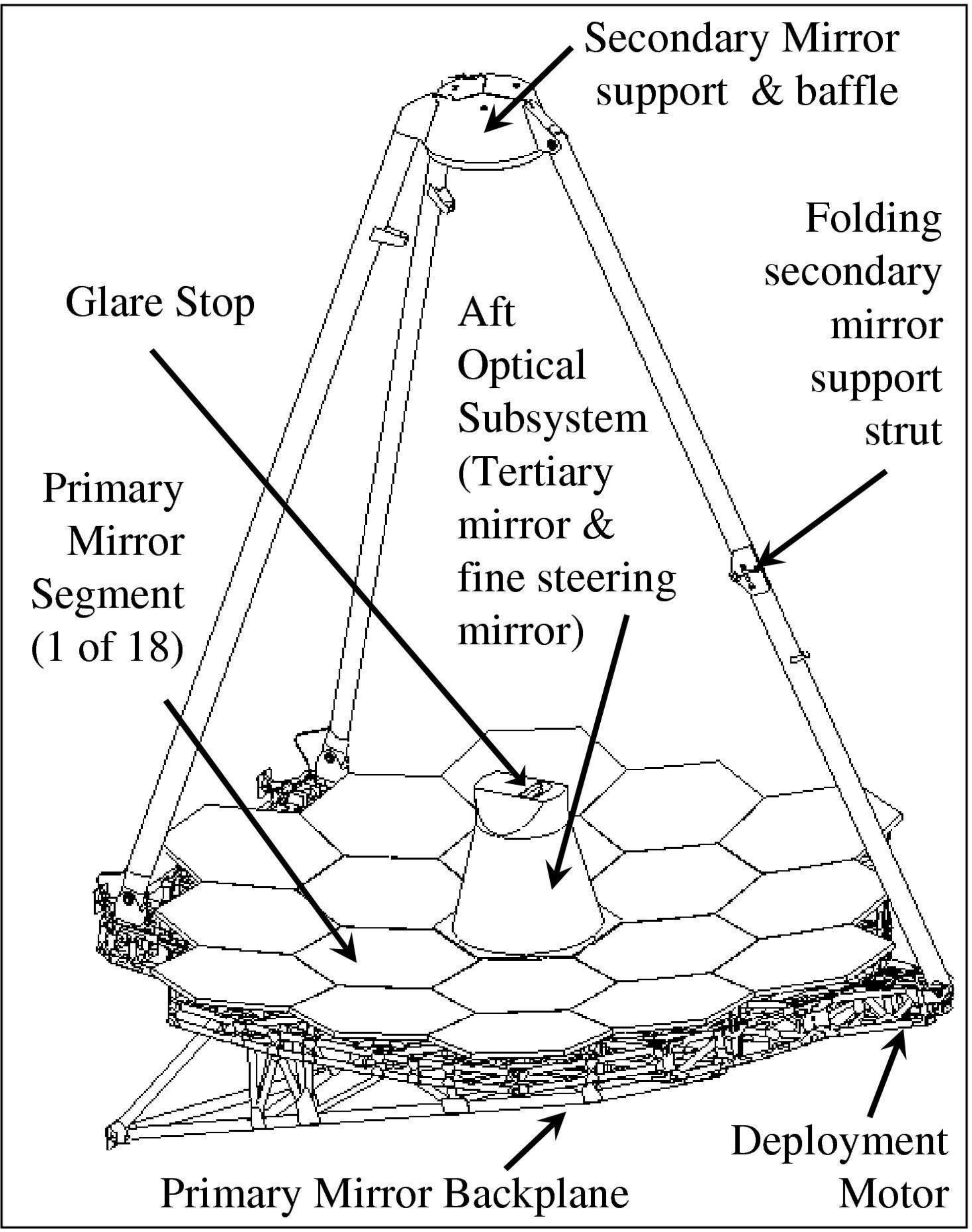
Active mirror segment support through “hexapods”, similar to Keck.

Redundant & doubly-redundant mechanisms, quite forgiving against failures.

		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 µm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	After Step 2 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 µm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	After Step 3 	WFE: < 250 µm rms	WFE < 1 µm (rms)
4. Fine Phasing	After Step 4 	WFE: < 5 µm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	After Step 5 	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to the Keck telescope.

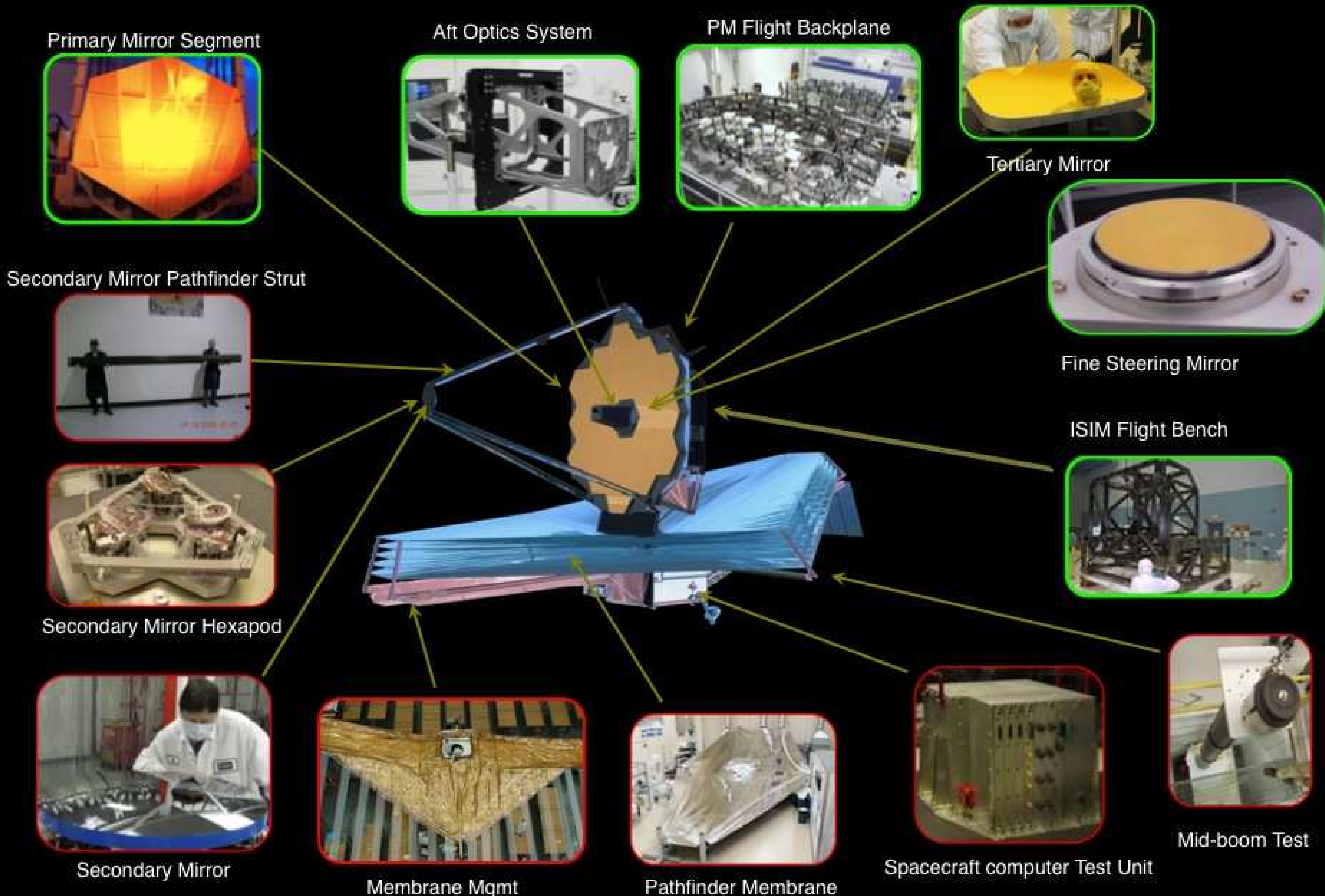
In L2, need WFS updates every 10 days depending on scheduling/illumination.



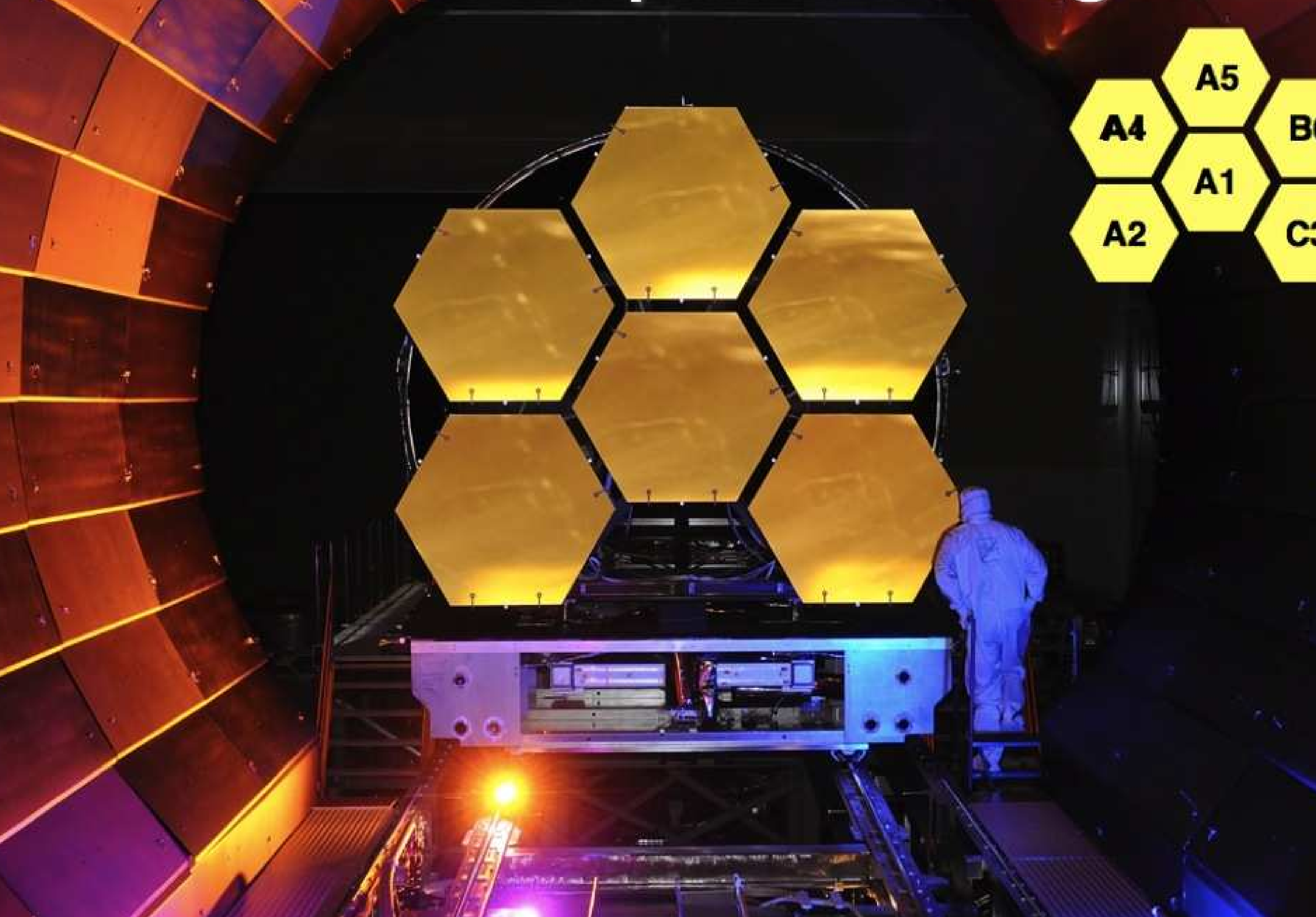
Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

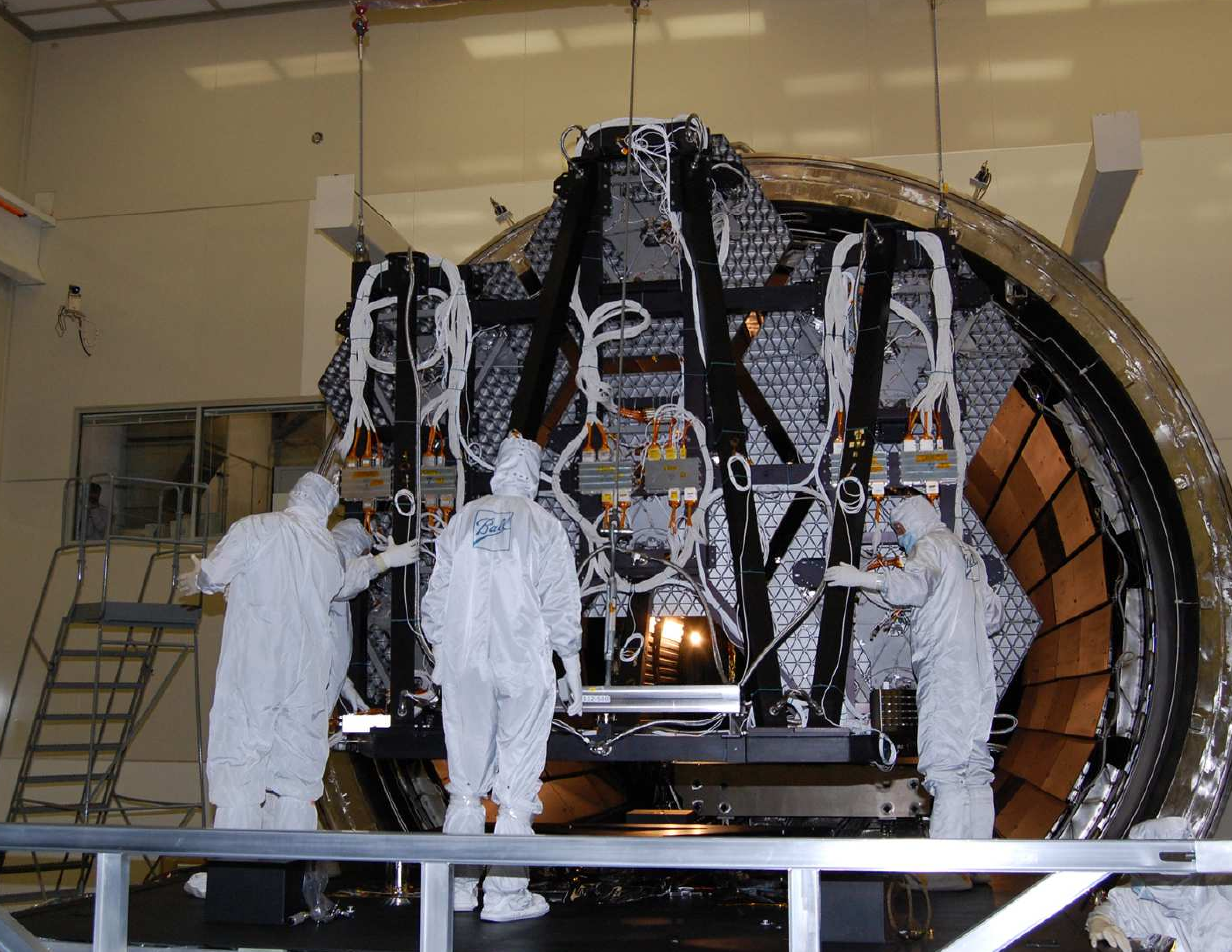
Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0 μm images.

JWST Hardware Status

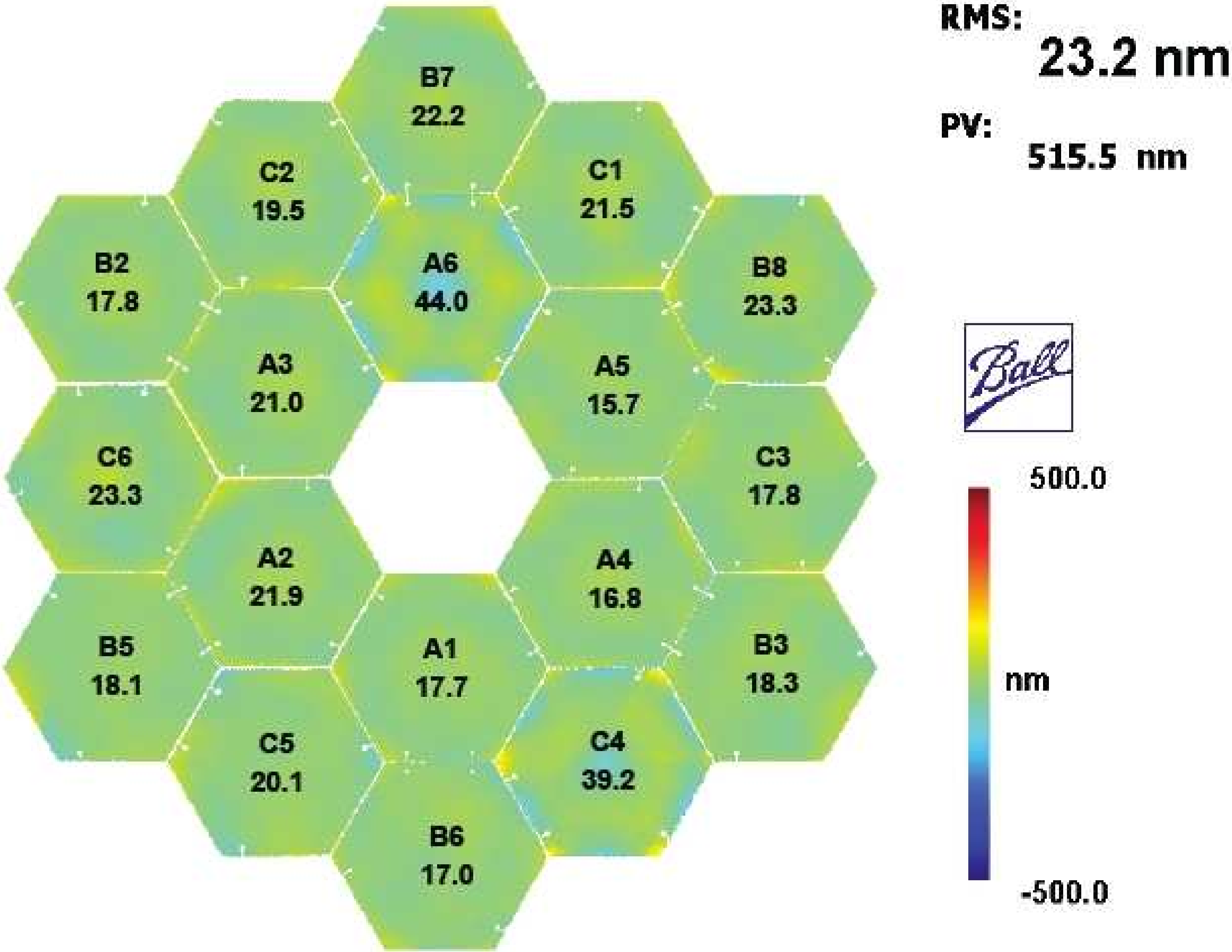


Mirror Acceptance Testing

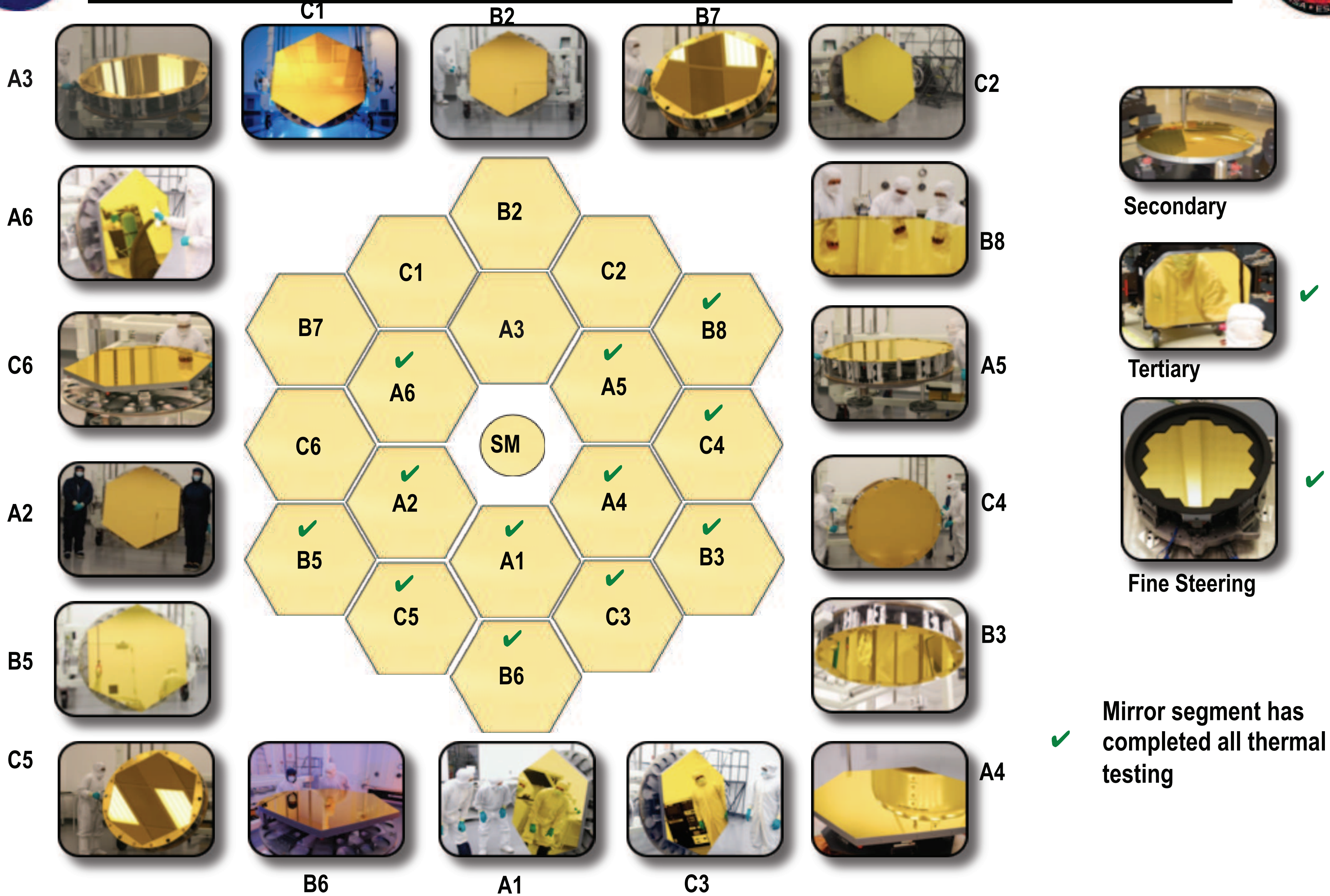



Ball

Primary Mirror Composite

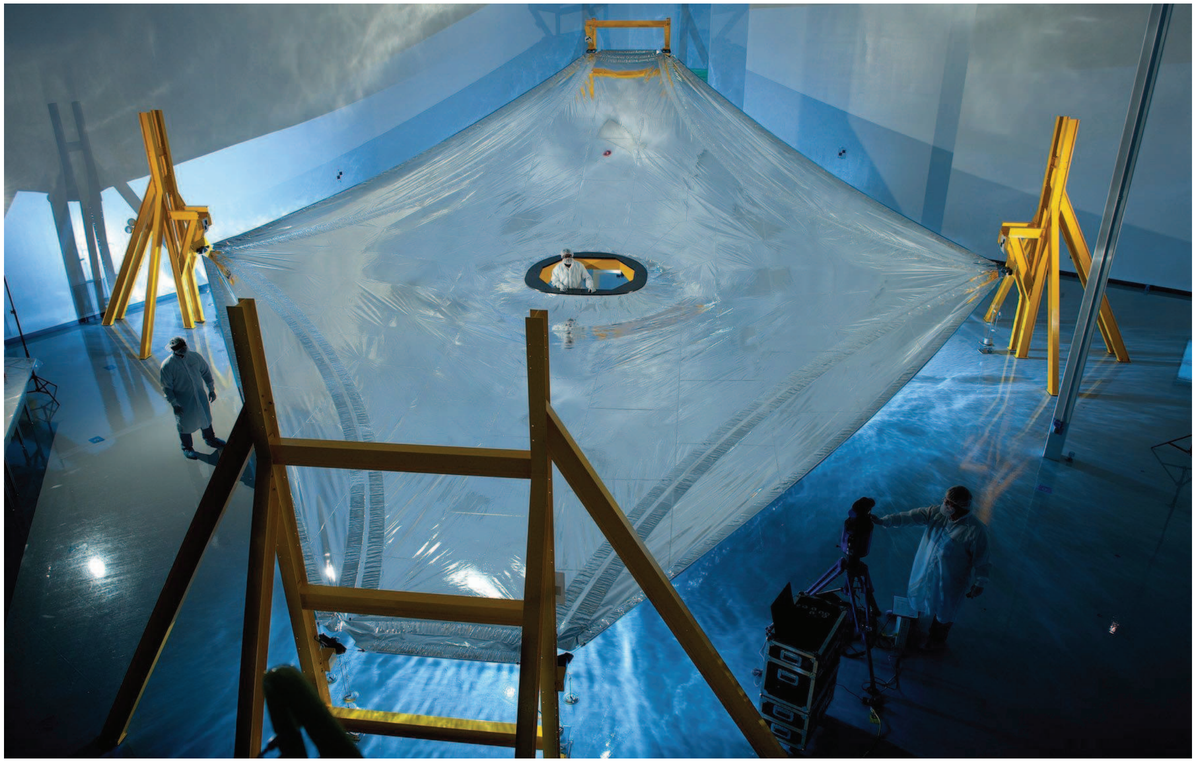


Family Portrait



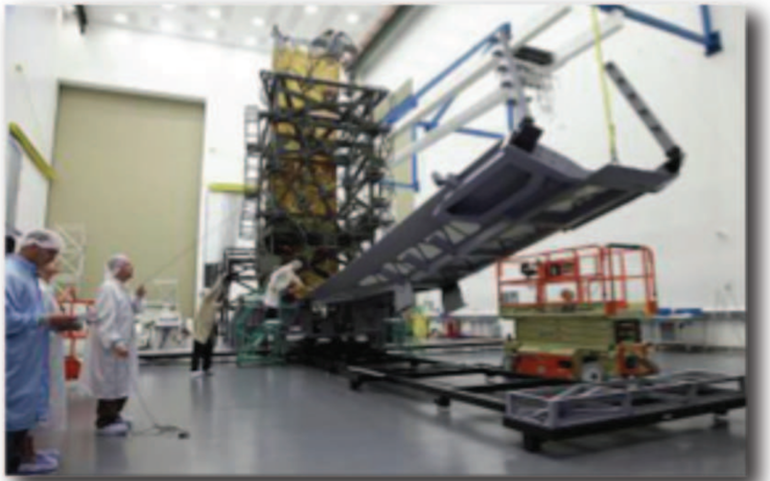
Sunshield

- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape measurements completed

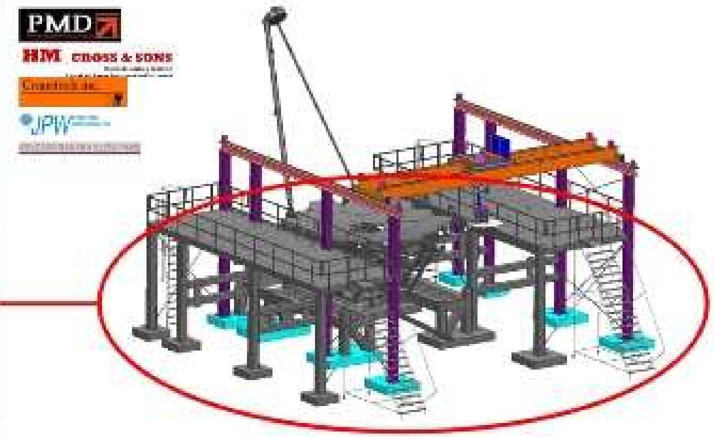


←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette ↓



Telescope Assembly Ground Support Equipment



Hardware has been installed at GSFC approximately 8 weeks ahead of schedule

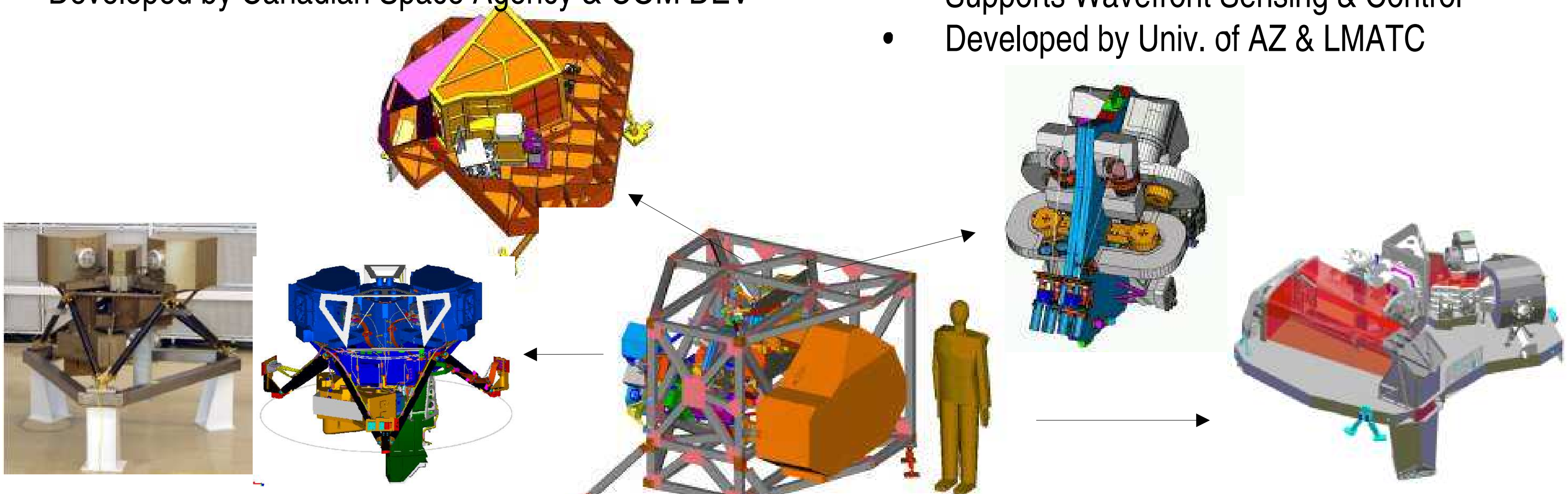
Landing a mirror onto backplane simulator

(1c) JWST instrument update: US (UofA, JPL), ESA, & CSA.

Instrument Overview

Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

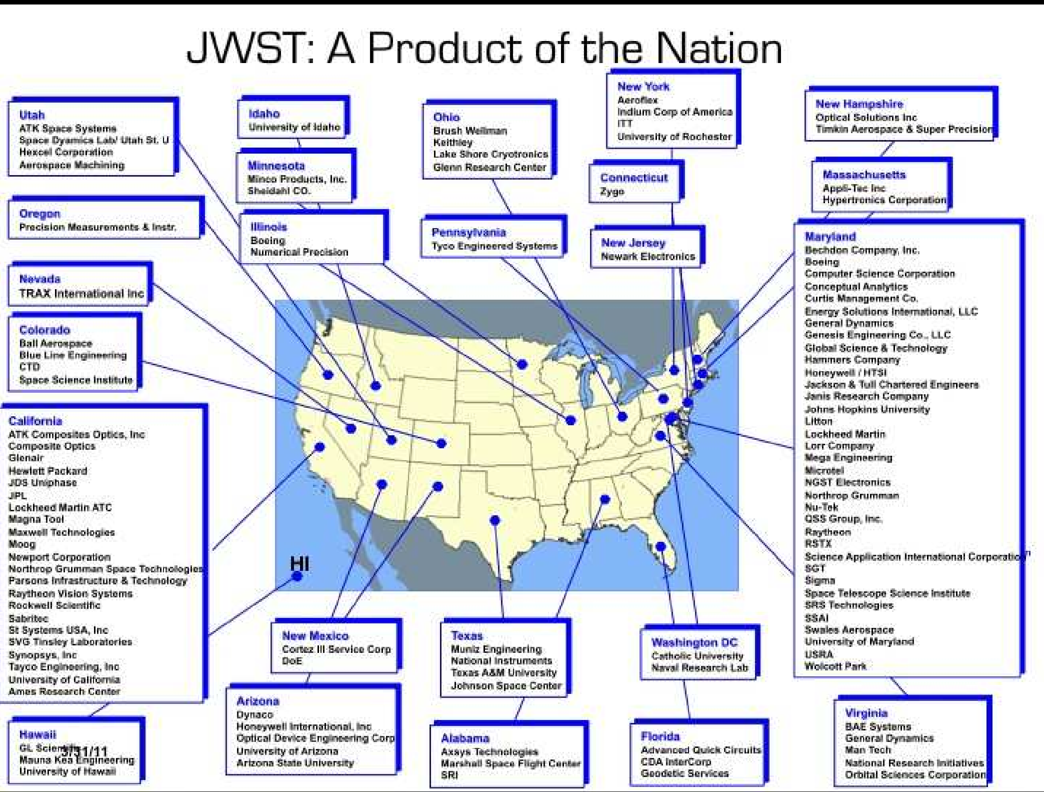
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

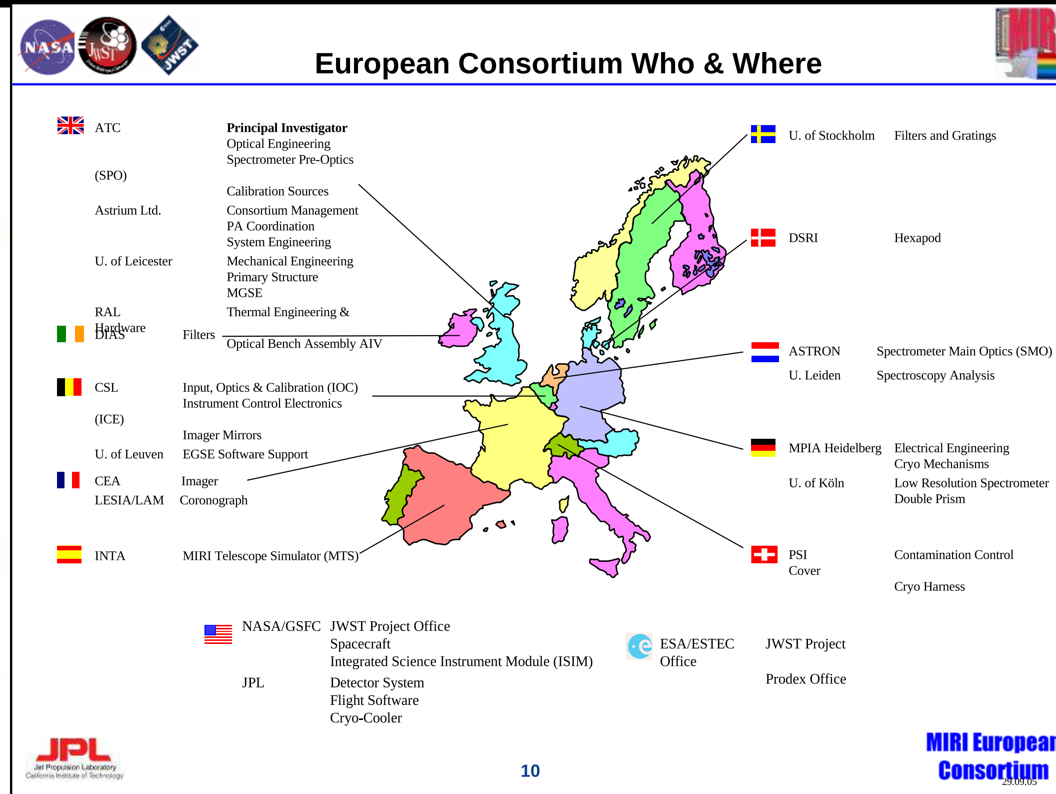


Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

Near Infra-Red Spectrograph (NIRSpec)
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

MIRI delivery 05/12; FGS 07/12; NIRCam 07/28/13(!), NIRSpec Fall 2013.



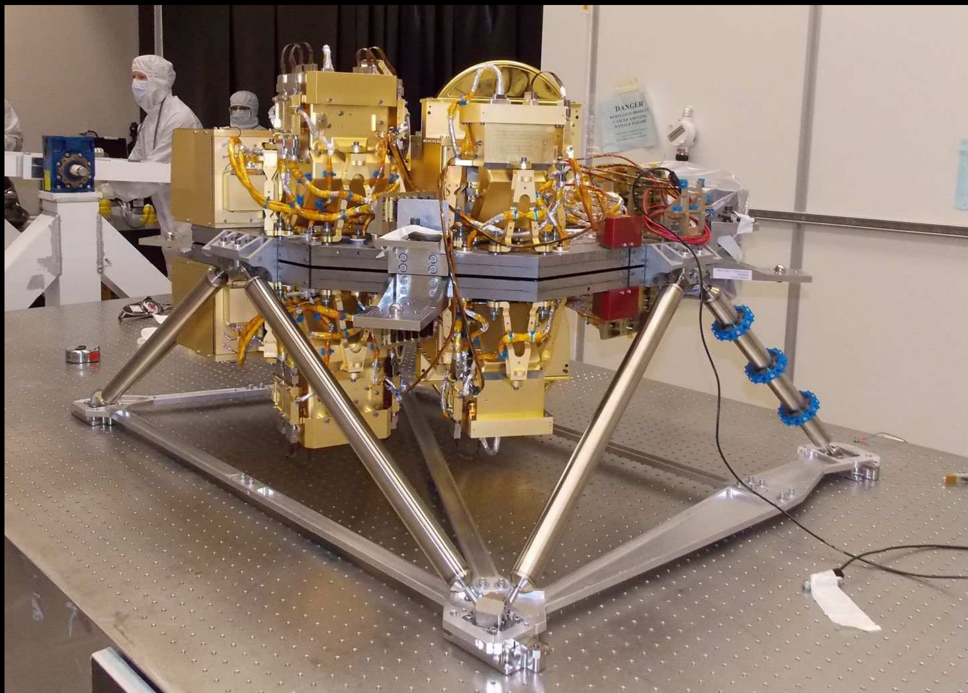


- JWST hardware made in 27 US States: $\gtrsim$75% of launch-mass finished.

- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

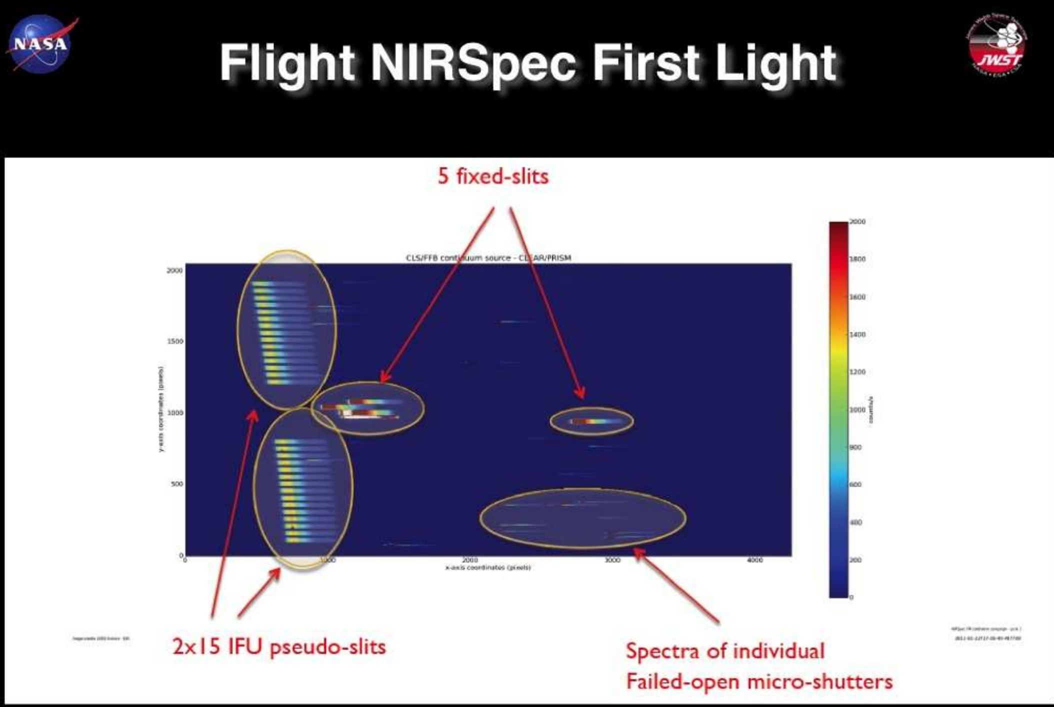
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.

- JWST NIRCam made by UofA and Lockheed.

JWST's short-wavelength (0.6–5.0μm) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& 1–5 μm grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered July 28, 2013!.

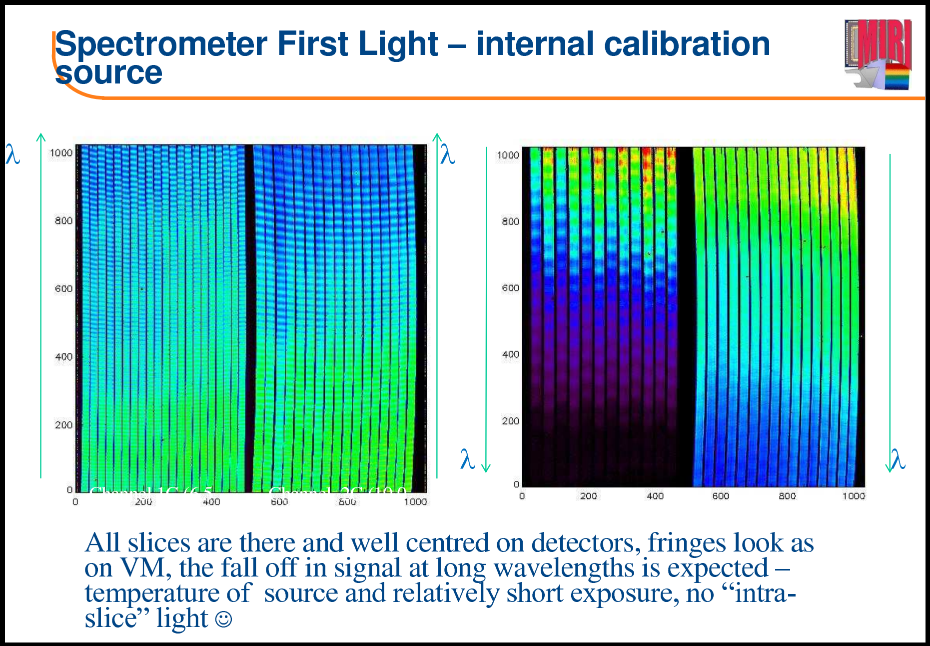


JWST's short-wavelength (0.6–5.0μm) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

NIRSpec delivery to NASA/GSFC scheduled for Fall 2013.

Flight MIRI



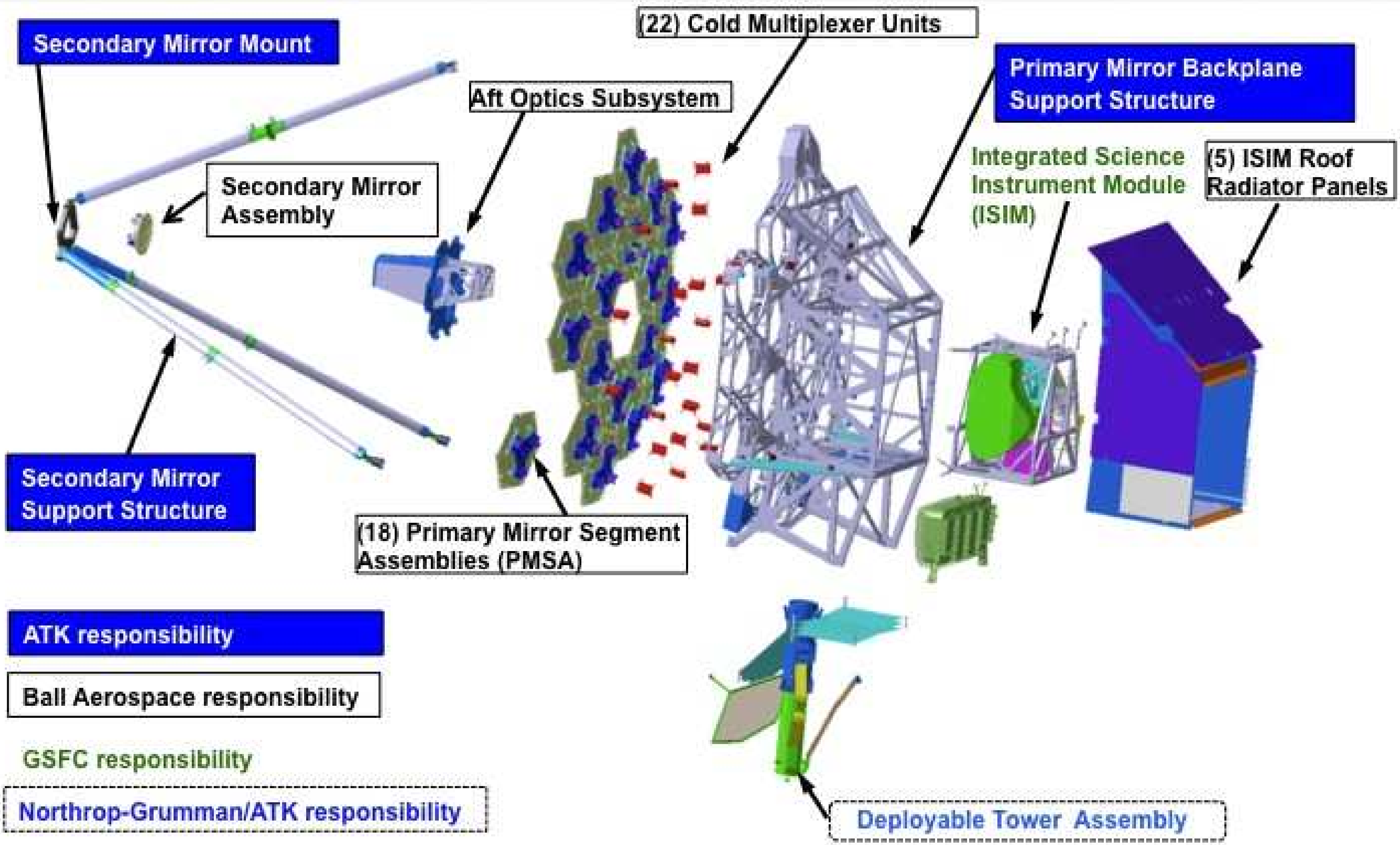
JWST's mid-infrared (5–29μm) camera and spectrograph:

- MIRI — built by ESA consortium of 10 ESA countries & NASA JPL.
- Flight build completed and tested with First Light in July 2011.

MIRI delivered to NASA/GSFC in May 2012.

OSIM: Here is where JWST Instruments inside ISIM are being tested.

TELESCOPE ARCHITECTURE



ATK responsibility

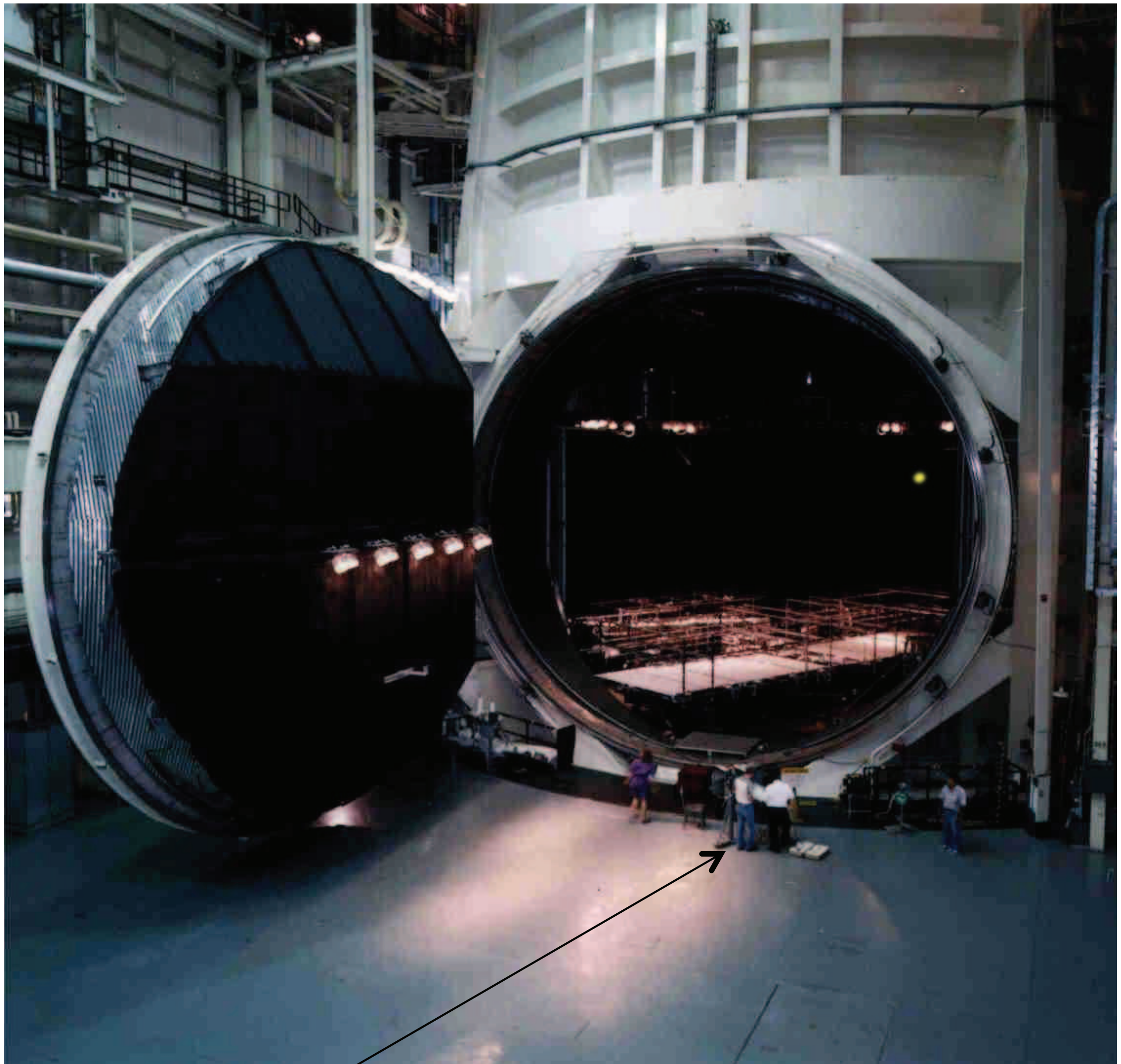
Ball Aerospace responsibility

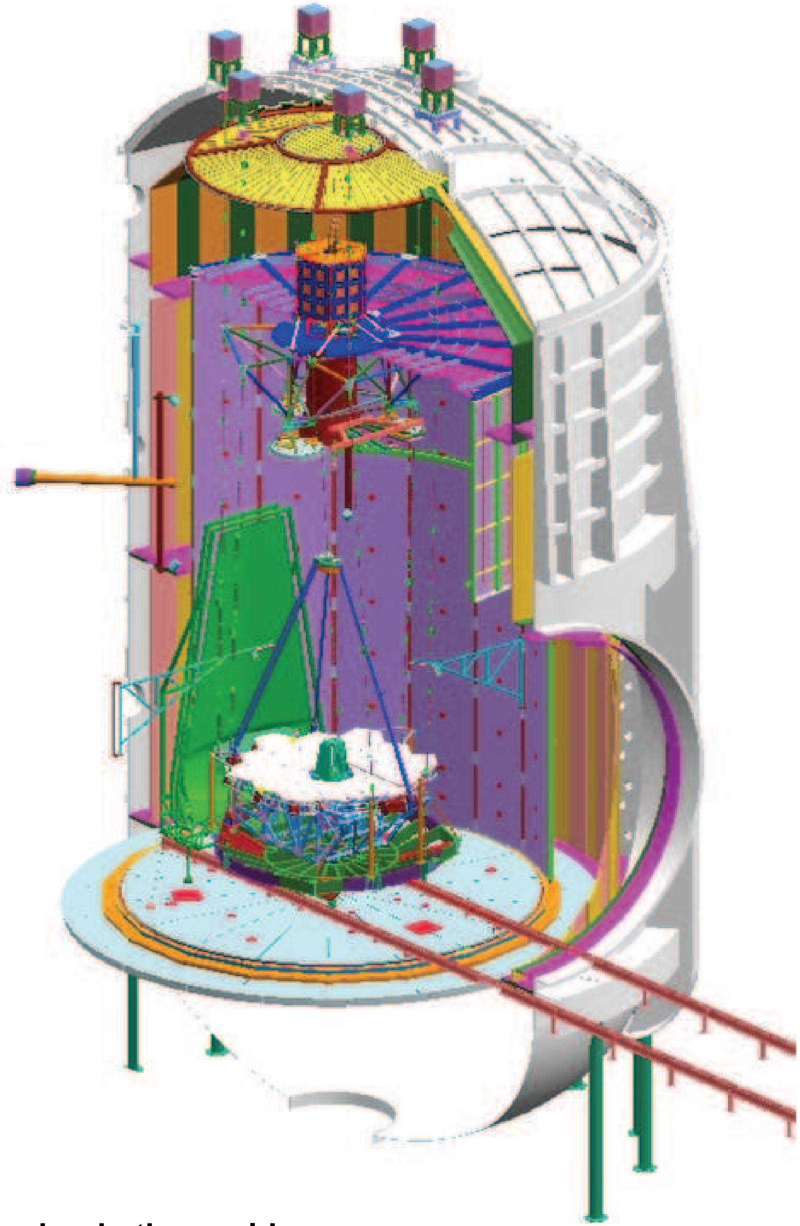
GSFC responsibility

Northrop-Grumman/ATK responsibility

Despite NASA's CAN-do approach: Must find all the cans-of-worms ...

OTE Testing – Chamber A at JSC





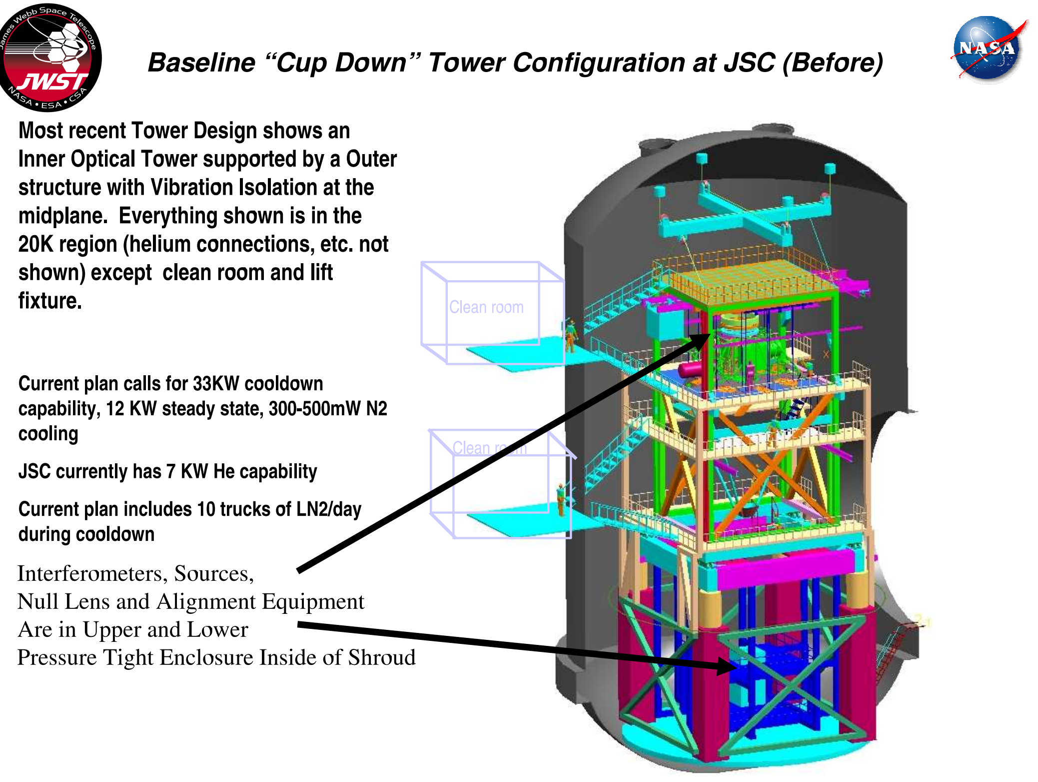
Notice people for scale

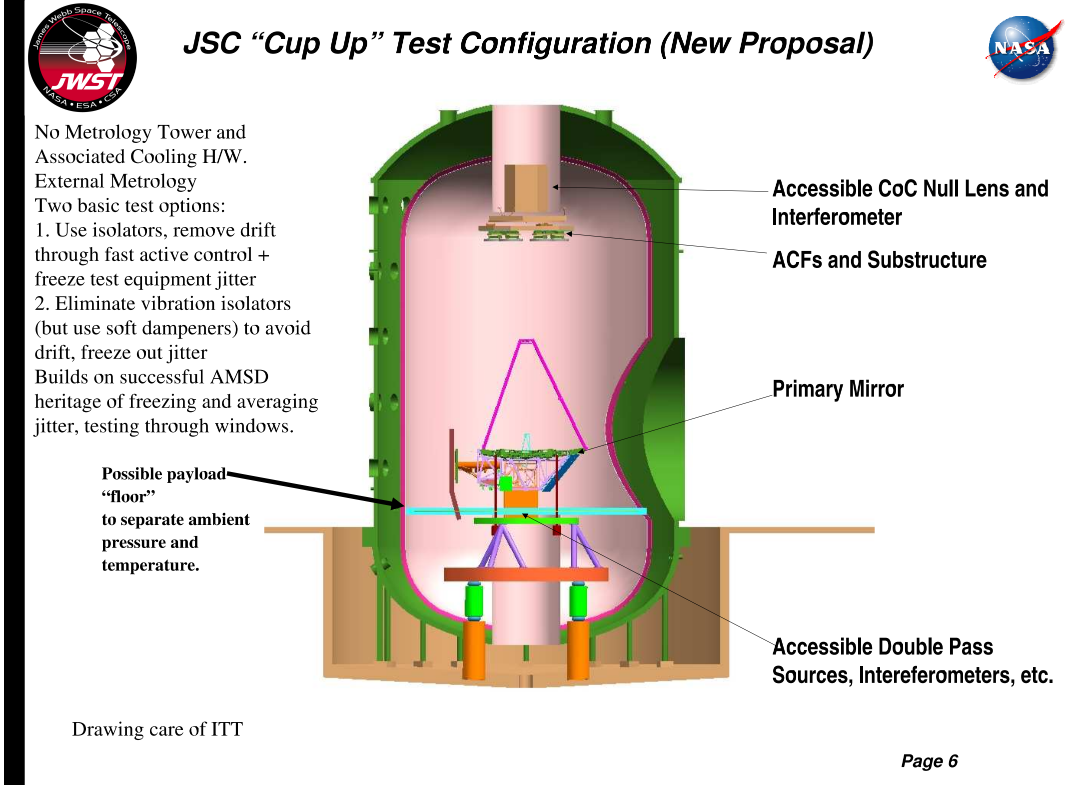
Will be the largest cryo vacuum test chamber in the world

OTIS: Largest TV chamber in world: will test whole JWST in 2015–2016.

Northrop Grumman Expertise in Space Deployable Systems

- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010, 2011: Passes Mission Critical Design Review: Replan Int. & Testing.

(2) JWST Lessons: (Hubble WFC3 images, 10 years after it was canceled twice ...)

10 filters HST/WFC3 & ACS in ERS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

JWST provides 0.05–0.2" FWHM images to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

(A) Scientific/Astro-community lessons learned from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Have a killer app with full community support. (Be exciting enough that some dedicate a good fraction of their careers to make it happen).
- 2) Project is a must-do scientifically and cannot be done any other way.
- 3) Project highly ranked by community reviews/Decadal surveys.
- 4) Identify, highlight, & sell complementarity with other large facilities.
- 5) Still like the science and the project $\gtrsim$10–20 years later.
- 6) Offer project science and grant support to the whole community.
- 7) Keep selling the Mega-project to community until launch/first light.

(A) Scientific/Astro-community lessons learned from JWST

For a Mega-project to succeed, make sure that you DON'T:

- 1) Have community infighting ("My mission is better than yours" — One key reason for Supercollider (SSC) demise).

- 2) Have other projects canceled because of your Project, or perception thereof. Don't make enemies whenever possible.

- 3) Have science and grant support for a selected few.

- 4) Have GTO's be elite: they must serve & represent the community.

- 5) Ignore community input on project science priorities.

- 6) Ever ignore importance of great communication with U.S. patrons: Scientists, contractors, tax-payers, Congress, White House.

- 7) Ever ignore importance of great communication with foreign partners. (International projects are more robust politically, see SSC).

Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. Richard Ellis).

(B) Technical Lessons learned from the JWST Project

For a Mega-project to succeed, make sure that you DO:

- 1) Use advanced technologies being developed elsewhere, if possible.
- 2) Use latest proven technology where you can for killer science app.
- 3) Know when not to select the most risky technologies.
- 4) Do your hardest technology development upfront. Have all critical components at TRL-6 before Mission Preliminary Design Review (PDR).
- 5) Only design to specs you need and can afford to fabricate & test.
- 6) Test, test, and retest where needed.

Def: TRL-6 = "(Sub-)system model or prototyping demonstration in a relevant end-to-end environment (ground or space)."

(B) Technical Lessons learned from the JWST Project

For a Mega-project to succeed, make sure that you DON'T:

- 1) Use technologies below TRL-6 at Mission PDR.

- 2) Defer project component PDR's or CDR's to well after Mission PDR or CDR, resp.

- 3) Do system tests whose outcome do not make you change course.

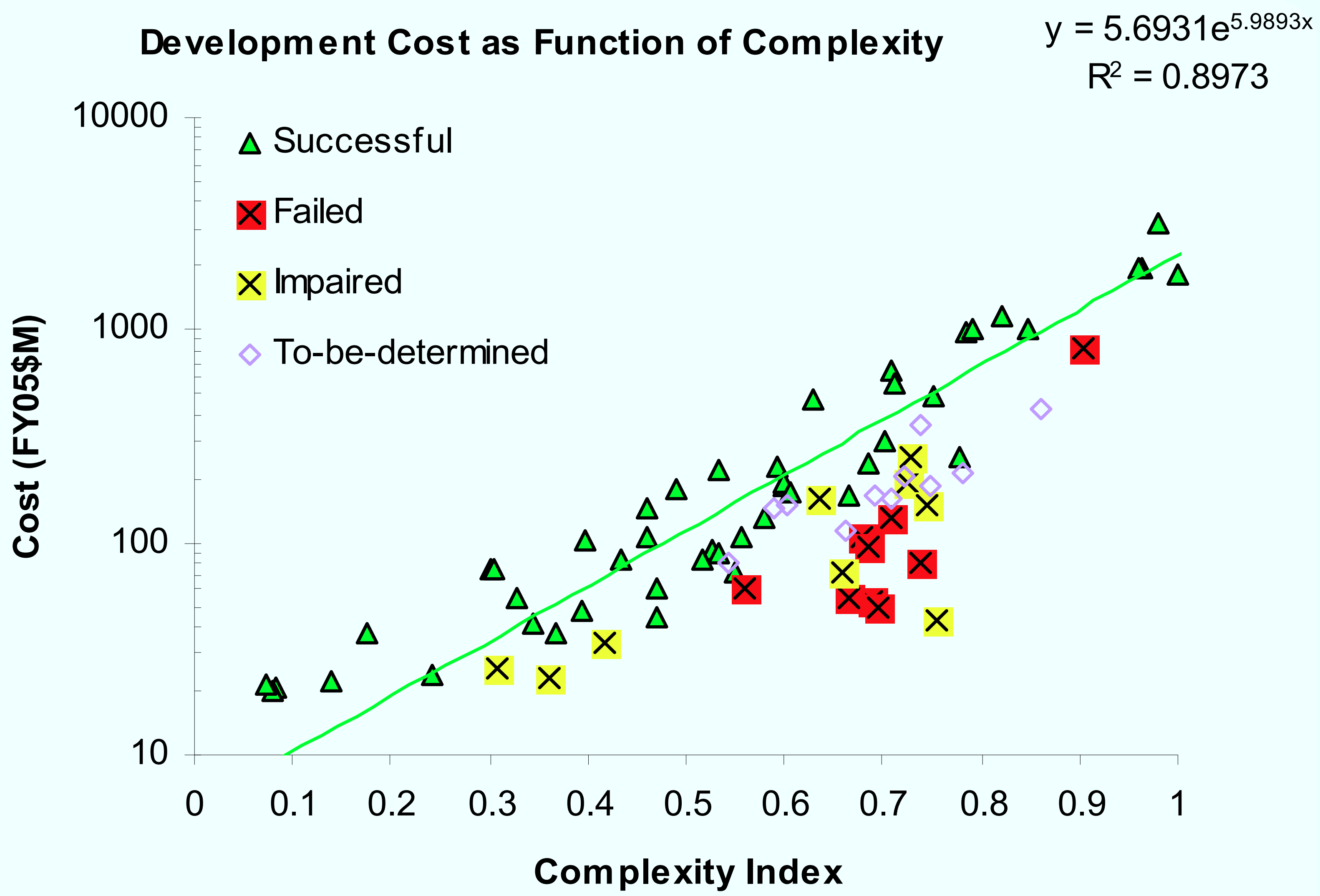
- 4) Ask for 1μm diffraction limit unless you must have & can afford it.

- 5) [If you can't afford 1μm JWST diffraction limit, HOLD ground at 2.0μ, AND insist best effort made at 1μ without being cost-driver.]

- 6) Allow scientists to change requirements after Phase A (unless to reduce risk).

Def: PDR = Preliminary, CDR = Critical Design Review.

When is a Mission Too Cheap?*



* "A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?", Bearden, D. A.

(C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Have competent *AND* project-friendly management in *ALL* of NASA.
- 2) Make conservative full end-to-end budget before Mission CDR.
- 3) Make sure budgets are externally reviewed, and at $\gtrsim$80% joint cost+ schedule confidence level. (Could not do $\lesssim$2010; Did so early 2011).
- 4) Plan *&* effectively use 25–30% (\$+schedule!) contingency each FY.
- 5) Have a viable list of cost-saving and meaningful descopes.
- 6) Have great communication with all (sub-)contractors.
- 7) Put management pressure on contractors, when necessary.
- 8) Have best work-force from contractors for entire length of project.
- 9) Prioritize testing, and test extensively.

(C) Management/Budget/Schedule Lessons from JWST

For a Mega-project to succeed, make sure that you DON'T:

- 1) Sell project with initial unrealistic budget estimates.
(Lesson number 1 from HST: Don't buy in at bargain prices!).

- 2) Cut project contingency to below critical mass (*i.e.* $\lesssim$25-30%/yr).

- 3) Try (or allow Contractors to try) to save funds by cutting corners.

- 4) Change science requirements after Phase A (unless essential to simplify, reduce risk and cost).

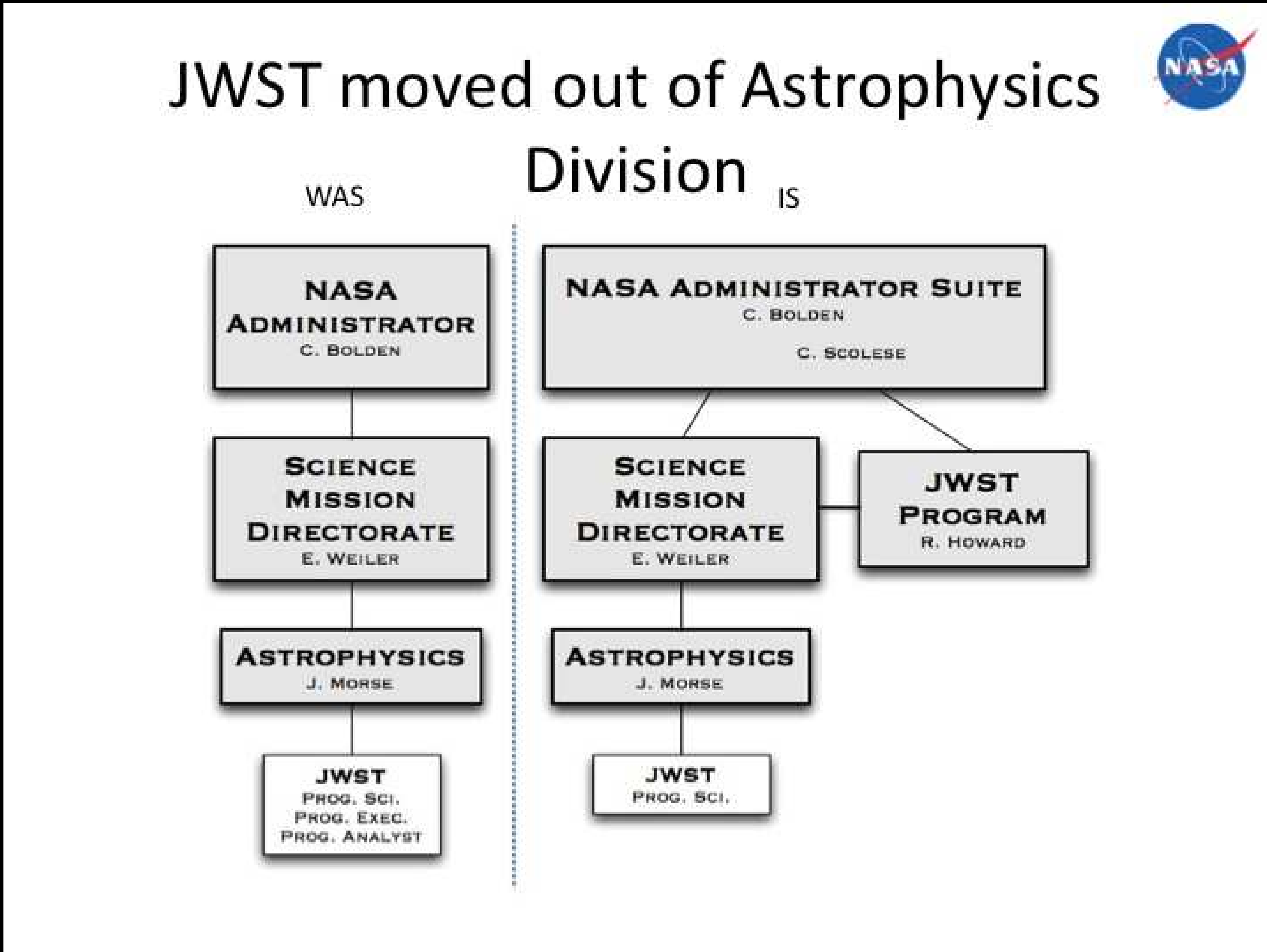
- 5) Change contract midstream, unless it is to reduce risk.

- 6) Allow contractors to change requirements at will, nor to hold requirements hostage against project budget/schedule.

- 7) Allow contractors to defer project component PDR's or CDR's to well after Mission PDR or CDR, resp.

- 8) Test items without a clearly defined decision path.

How to launch JWST while minimizing impact on NASA Space Science?



NASA HQ Reorg: JWST budget no longer comes directly from SMD/Ap.

(D) Political/Outreach Lessons learned from JWST

For a Mega-project to succeed, make sure that you DO:

- 1) Assemble, maintain and fully use a *strong Coalition* of supporters and advocates who will fight for the project, since there will be storms and budget cancellations (HST did so successfully, SSC didn't).

- 2) Understand & foresee full political landscape of contractor world.

- 3) Have strong multi-partisan & multi-national support for project.

- 4) Educate, educate, and re-educate government & general public about project's essence.

- 5) Strong heritage/links to technology *from* other parts of government.

- 6) Strong technology benefits/lessons *TO* other parts of government.

- 7) Strong, compelling benefits to society ("must-have" applications). (SSC could not explain to a broad audience: Why SSC?).

(D) Political/Outreach Lessons learned from JWST

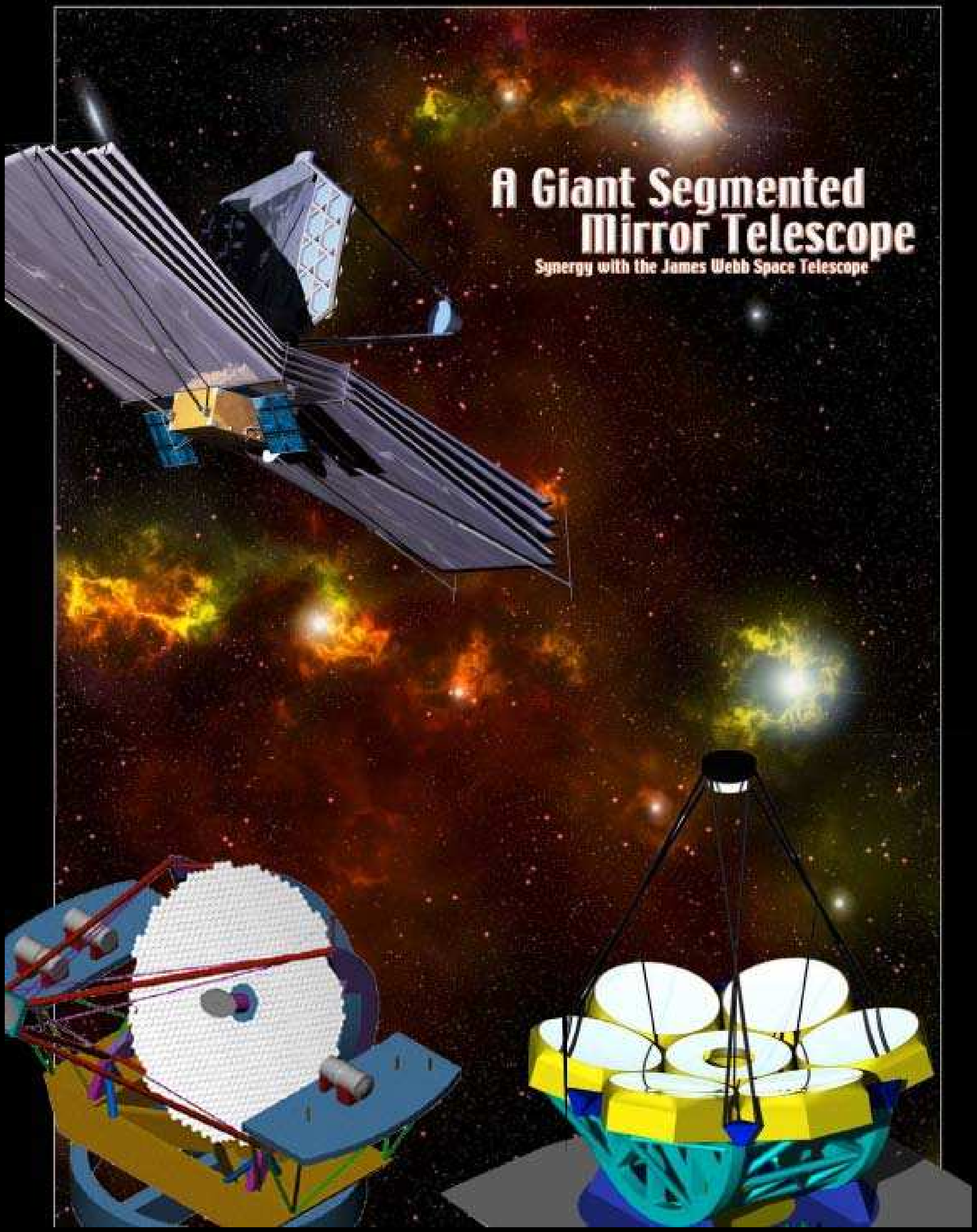
For a Mega-project to succeed, make sure that you DON'T:

- 1) Have project politicized in the government (lesson from SSC).
- 2) Assume your government understands or likes the project: Educate, educate, and re-educate.
- 3) Have project become target of social media: Must continuously educate instead and reach out to opponents.
- 4) Have project too concentrated in one state (or nation): MUST distribute efforts and wealth.
- 5) Ever fall asleep, not until launch anyway ...

OVERALL CONCLUSION: JWST is now on the right track, but we did have to learn our lessons.

G. W. F. Hegel (1832): "History teaches us that mankind learned nothing from history."

Mega-Projects must learn how to build Coalition / fit into community ...



(3) GMT/TMT/E-ELT & JWST Synergy:
(Kudritzki, Frogel+ 2005):

- (1) Are the top two priority missions of the 2001 Decadal Survey in Astronomy & Astrophysics.

- (2) Each give orders of magnitude gain in sensitivity over existing ground and space telescopes, resp.

- (3) Have complementary capabilities that open a unique new era for cosmic and planetary discovery.

- (4) Maximize concurrent operation of GMT/TMT/E-ELT and JWST!

(3a) Unique Capabilities of the 6.5 meter JWST in L2

- (1) Full sky coverage & high observing efficiency.

- (2) Above the atmosphere, JWST will have:
- Continuous wavelength coverage for 0.6 $\lesssim \boldsymbol{\lambda} \lesssim$ 28.5 $\boldsymbol{\mu}$m.
- High precision and high time-resolution photometry and spectroscopy.

(3) JWST is a cold telescope ($\lesssim$40 K):
- Minimizes thermal background (for $\boldsymbol{\lambda}\lesssim$10 $\boldsymbol{\mu}$m, set by the Zodi: 10^{3}–$10^{4}\times$ or 7–10 mag lower than ground-based sky!).
- Very high sensitivity for broad-band IR imaging ($\Leftarrow$ no atm OH-lines).

(4) Diffraction limited for $\boldsymbol{\lambda}\gtrsim$2.0 $\boldsymbol{\mu}$m over a wide FOV ($\gtrsim 5'$), hence:
- PSF nearly constant across the FOV.
- PSF stable with time — WFS updates on time-scales of ($\sim$10) days.
- Very high dynamic range.

(3b) Unique Capabilities of the GMT/TMT/E-ELT

(1) Sensitivity 25$\times$ greater than JWST in accessible spectral regions.

• Very high optical sensitivity (0.32–1.0 μm) over a wide FOV ($\gtrsim$10$'$).

(2) Very high spatial resolution, diffraction-limited imaging in mid- and near-IR — with AO can get PSF 4–6$\times$ better than JWST.

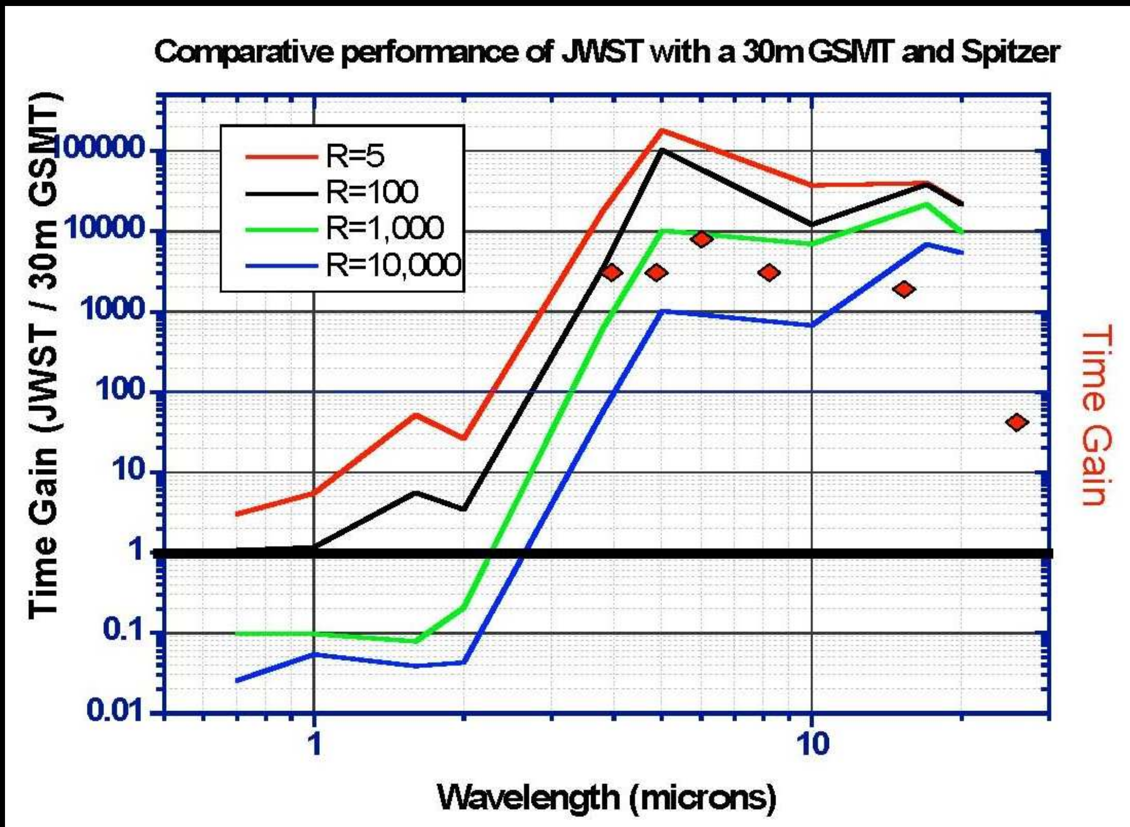
• High sensitivity for non-background limited IR imaging and high-resolution spectroscopy (between OH-lines).

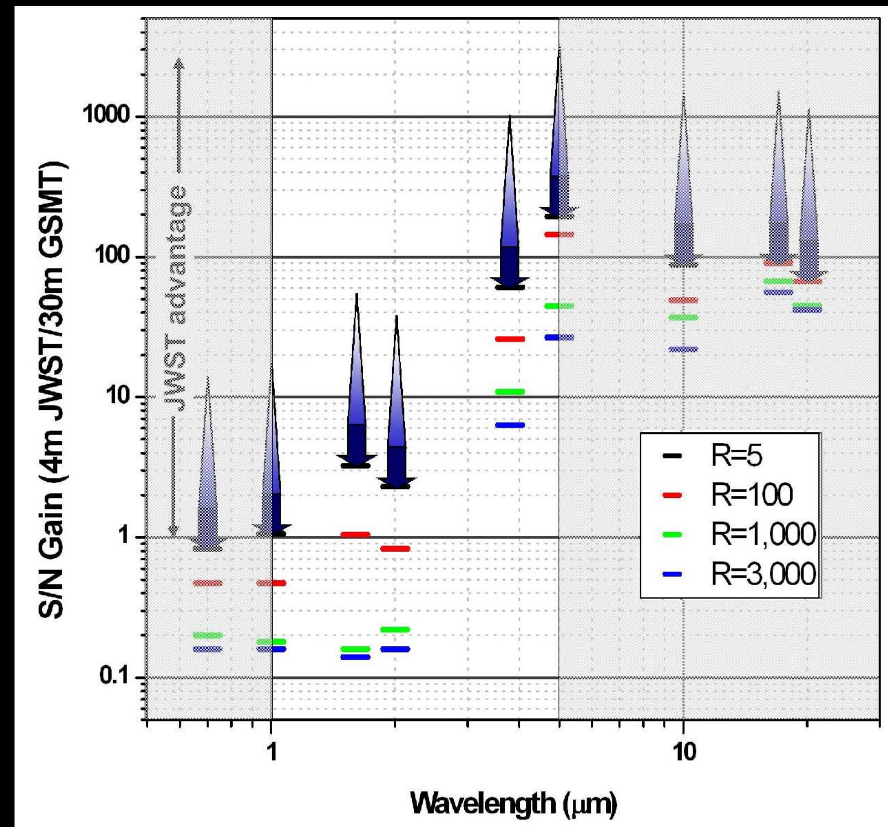
(3) Very high resolution spectroscopy — (R $\gtrsim 10^5$) in optical–mid-IR.

(4) Short response times — few minutes for TOO's.

(5) Flexible and upgradable — take advantage of new developments in instrumentation in the next decades.

(3) Synergy between the GMT/TMT/E-ELT and JWST





LEFT: Time-gain(λ) of JWST compared to GMT/TMT/E-ELT and Spitzer. GMT/TMT-AO competition is why JWST no longer has specs at $\lambda \lesssim 1.7 \mu$m.

RIGHT: S/N-gain(λ) of JWST compared to ground-based:

- Top of arrows: 6m JWST/Keck; Middle: 6m JWST/TMT; Bottom: 4m JWST/TMT.

(3) Comparison of GMT/TMT/E-ELT and JWST — areas of unique strength

Instrument Capabilty	*Uniqueness*
Imaging 0.7-1.7 microns	20-30m MCAO will be comparable
Imaging 1.7 - 5.0 microns	JWST Unique
Imaging 5-28 microns	JWST Unique
Coronagraphy 0.7 - 2.3 microns	Extreme AO on 8-10m superior
Coronagraphy 2.4 - 5 microns	JWST Unique
Coronagraphy 5 - 28 microns	JWST in principle unique
Tunable filter 1.0 - 2.0 microns	8-10m AO & narrow band filters comparable
Tunable filter 2.4 - 5 microns	JWST in principle unique
Slit Spectroscopy 0.7-1.7 microns	20-30m MCAO superior
Slit Spectroscopy 1.6 - 5 microns	JWST Unique
MOS spectroscopy 0.7- 1.7 microns	20-30m MCAO superior
MOS spectroscopy 1.7 - 5 microns	JWST Unique
IFU spectroscopy 1.0- 1.7 microns	20-30m MCAO superior
IFU spectroscopy 1.7 - 5 microns	JWST Unique
(IFU) spectroscopy 5-28 microns	JWST Unique

JWST: diffraction limited wide-FOV imaging and low-res spectra at $\gtrsim 2\mu$m.

GMT/TMT: high-res imaging, coronagraphy, TF-imaging & IFU spectra at $\lesssim 1.7\mu$m, and high-res spectroscopy at $\lesssim 2\ \mu$m (with AO beyond).

Summary: Main Lessons learned from the JWST Project:

(1) Mega-projects demand new rules, in particular regarding building and keeping together a *strong Coalition* of project supporters and advocates:

(A) JWST Scientific/Astro-Community Lessons:

- 1) Project is a must-do scientifically and cannot be done any other way.
- 2) Keep selling the Mega-project to community until launch/first light.
- 3) Don't ignore importance of communication with patrons: Scientists, international partners, contractors, tax-payers, Congress, White House.
- 4) Don't have community infighting ("My mission is better than yours" — One key reason for Supercollider (SSC) demise).

(B) JWST Technical Lessons:

- 1) Use advanced technologies being developed elsewhere, if possible.
- 2) Know when not to select the most risky technologies.
- 3) Do your hardest technology development upfront. Have all critical components at TRL-6 before Mission Preliminary Design Review (PDR).

(C) JWST Management/Budget/Schedule Lessons:

- 1) Make conservative full end-to-end budget before Mission CDR.

- 2) Make sure budgets are externally reviewed, and at $\gtrsim$80% joint cost+schedule confidence level. (Could not do $\lesssim$2010; Did so early 2011).

- 3) Plan & effectively use 25–30% ($+schedule!) contingency each FY.

(D) JWST Political/Outreach Lessons:

- 1) Assemble, maintain and fully use a broad Coalition of supporters and advocates who will fight for the project (SSC didn't).

- 2) Have strong multi-partisan & multi-national support for project.

- 3) Strong technology benefits/lessons *TO* other parts of government.

(2) GMT/TMT/E-ELT lessons: JWST provides a critical *concurrent* complement to GMT/TMT/E-ELT: Panchromatic near–mid-IR imaging & spectral follow-up of GMT/TMT/E-ELT discoveries:

- Expect to need JWST for the unexpected GMT discoveries !

Some things are better left discussed during ...

Miller time!

Het Borrel uur!

References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

http://www.jwst.nasa.gov/ & http://www.stsci.edu/jwst/

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Casani, J. et al. 2010, Final Report of the JWST Independent Comprehensive Review Panel (ICRP) (NASA: http://www.nasa.gov/pdf/499276main_casani_letter.pdf)

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Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

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SPARE CHARTS

(from Robert Smith's Sarton talk on HST Lessons)

The Making of Successful Mega-projects: Coalition Building

To succeed, Mega-projects like HST must:

- 1) Be scientifically enormously attractive for an entire community.
- 2) Be made technically feasible.
- 3) Be made politically feasible.
- Assemble a Mega-project team in technical, institutional and political terms: Patronage matters! (Not simply an issue of securing enough money to proceed).
- The ‘selling’ of a Mega-project has to be done over and over and over again.

SSC Failed its Efforts at Coalition Building:

- 1) Lack of international partners.
- 2) Dissent among physicists.
- 3) Program ‘design’ created serious tensions.
- 4) Congressional concern over deficits.
- 5) Widespread perception of unrealistic cost estimates.
- 6) Shift in the ‘political economy’ and loss of influence for Texas.

Successful Mega-projects before and after World War II

World War II and the Cold War meant an enormously enlarged role for the federal government as scientific patron, starting with the Manhattan Project.

This was not just a matter of project size, but contained:

- 1) New social roles.
- 2) Scientists as Coalition Builders.
- 3) Coalition Builders and the Hubble Space Telescope as prime example.

The Hubble Space Telescope and Coalition Building

A big scientific instrument placed at the frontiers of knowledge represents a political and managerial achievement every bit as significant as the technical feat:

- Hubble Space Telescope (HST) helped to reconstitute the astronomical enterprise.

- HST helped remake what it means to be an astronomer.

- Advocacy of new telescopes was no longer left to a few elite astronomers: we engaged a community of scientists.

Coalition Building: The Ground-Based Astronomers

- Assured ground-based astronomers that space astronomers would promote a 'balanced' program.

Coalition Building: Gain the Interest of NASA

- Not just state-of-art science,
- But also provided a justification for the Space Shuttle,
- And ties to the human space flight program.

Coalition Building: The Contractors

- Financial interest in new projects.
- Institutional interest in bringing new sorts of business and skilled engineers of various sorts into companies.

Coalition Building: The White House

- Justification of the national investment in the space shuttle.
- U.S. leadership in science.
- Attractive science.

Coalition Building: The U.S. Congress

- Jobs across all 50 states.
- U.S. leadership in science.
- International partnership.

Coalition Building: The Department of Defense

- An important part of the Hubble Space Telescope's technical heritage comes from reconnaissance satellites.
- NASA and the DOD therefore had to agree on how to build HST without revealing classified information.

Coalition Building For Hubble's last Servicing Mission

- NASA canceled the final planned servicing mission to HST in 2004.
- 2004: Coalition of Supporters enters the field one more time.
- In time, the Coalition would involve members of the media and the public.
- Public and Congressional outcry resulted in the decision being overturned.

Steven Weinberg's Question: Is Big Science in Crisis?

- "We may see in the next decade or so an end to the search for the laws of nature which will not be resumed again in our own lifetimes".

- What is the Answer? It depends on the success of scientists as coalition builders.