The Search for First Light:
New Telescopes that will Expand Hubble's Frontier.

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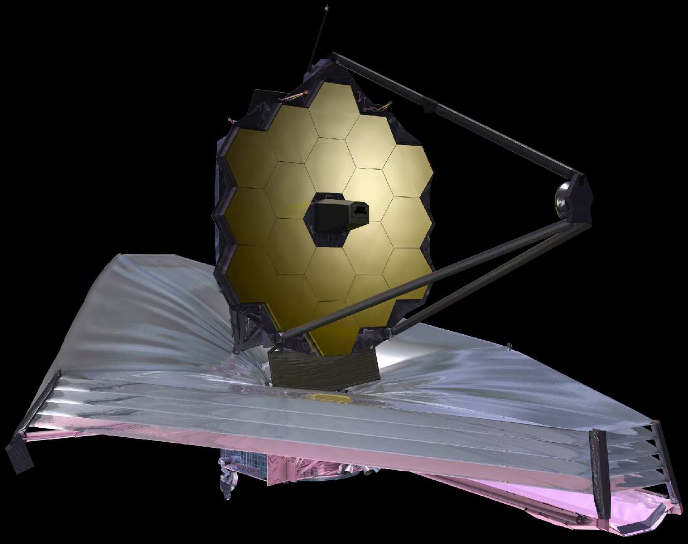
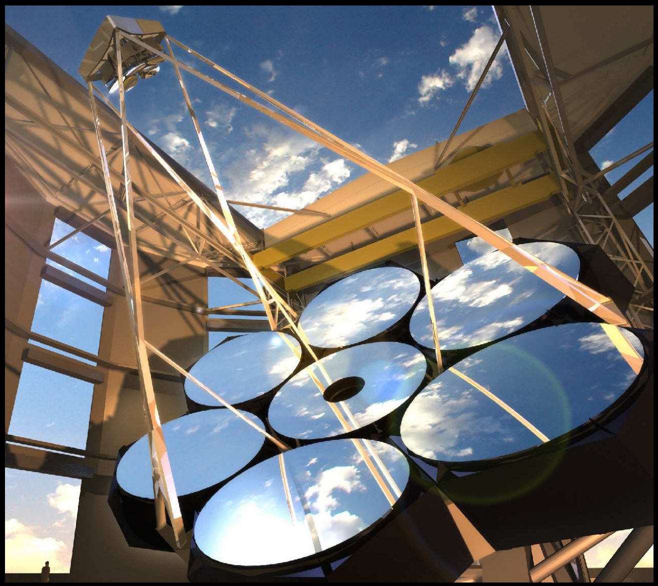
(Ex) ASU Grads: T. Ashcraft, N. Hathi, B. Joshi, D. Kim, M. Mechtley, R. Ryan, B. Smith, & A. Straughn.

Carpet slides: Dariannette Valentin, Jared Abbott, Harrison Bradley, Alicia Hyatt, Garrett Rand, & Alexa Twibell.

1973∼2020$^+$;



1996∼2029;



2000∼2100$^+$

Discoveries Lecture; Arizona State University; Thursday November 30, 2017.

Outline

- (1) James Webb Space Telescope: Hardware Update as of 2017.

- (2) Next generation ground-based: Giant Magellan Telescope (GMT).

- (3) How can JWST & GMT measure First Light & Galaxy Assembly?

— Synergy between JWST & GMT.

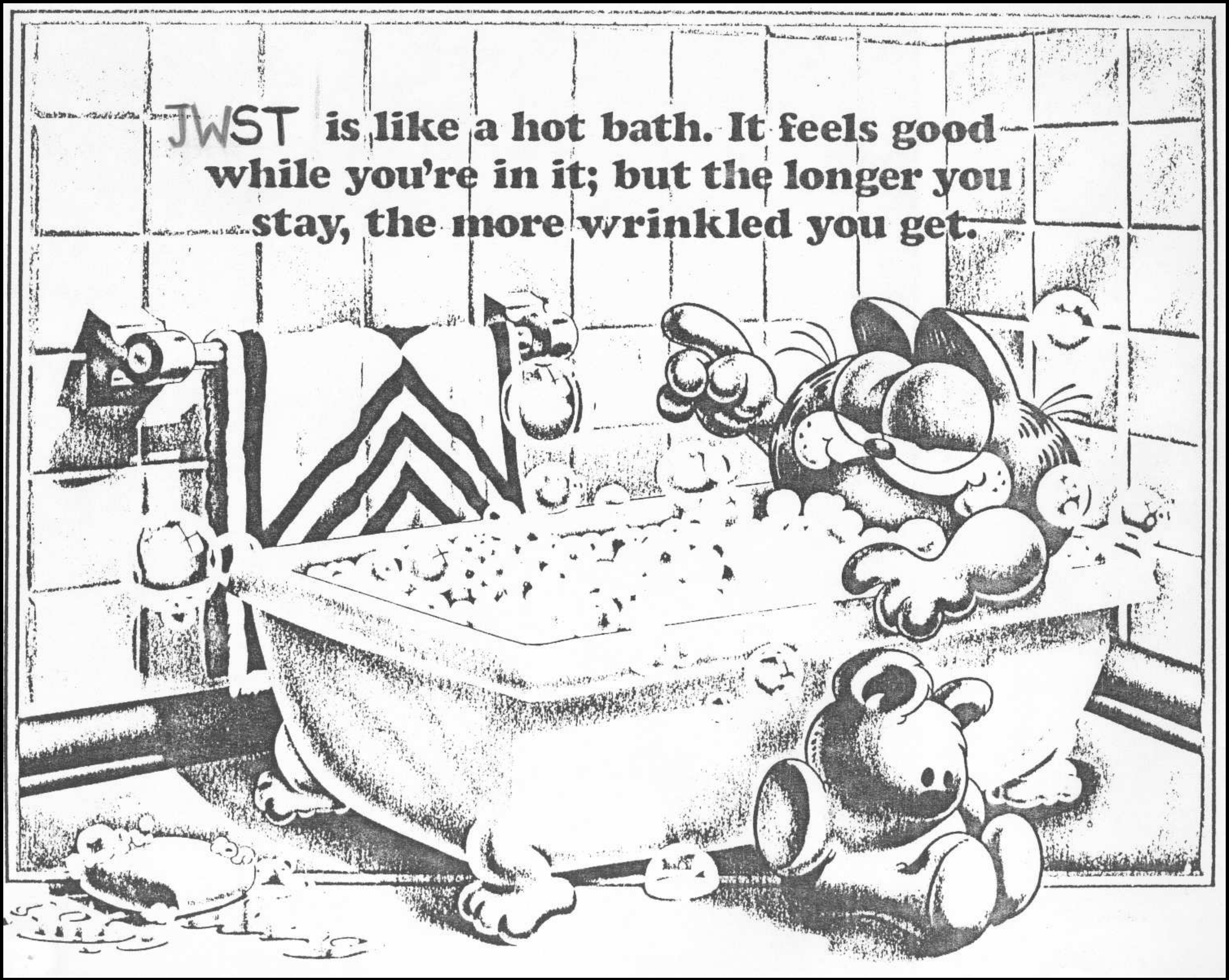
- (4) How can JWST & GMT measure Super-Massive Black Hole Growth?

— Handshake with 2016–2017 LIGO Gravitational Wave results.

- (5) Summary and Conclusions.

Sponsored by NASA/HST & JWST

Talk is on: `http://www.asu.edu/clas/hst/www/jwst/jwsttalks/asu_discoverieslecture17_jwstgmt.pdf`



WARNING: Hubble, James Webb & GMT are 30–40$^+$ year projects:

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

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

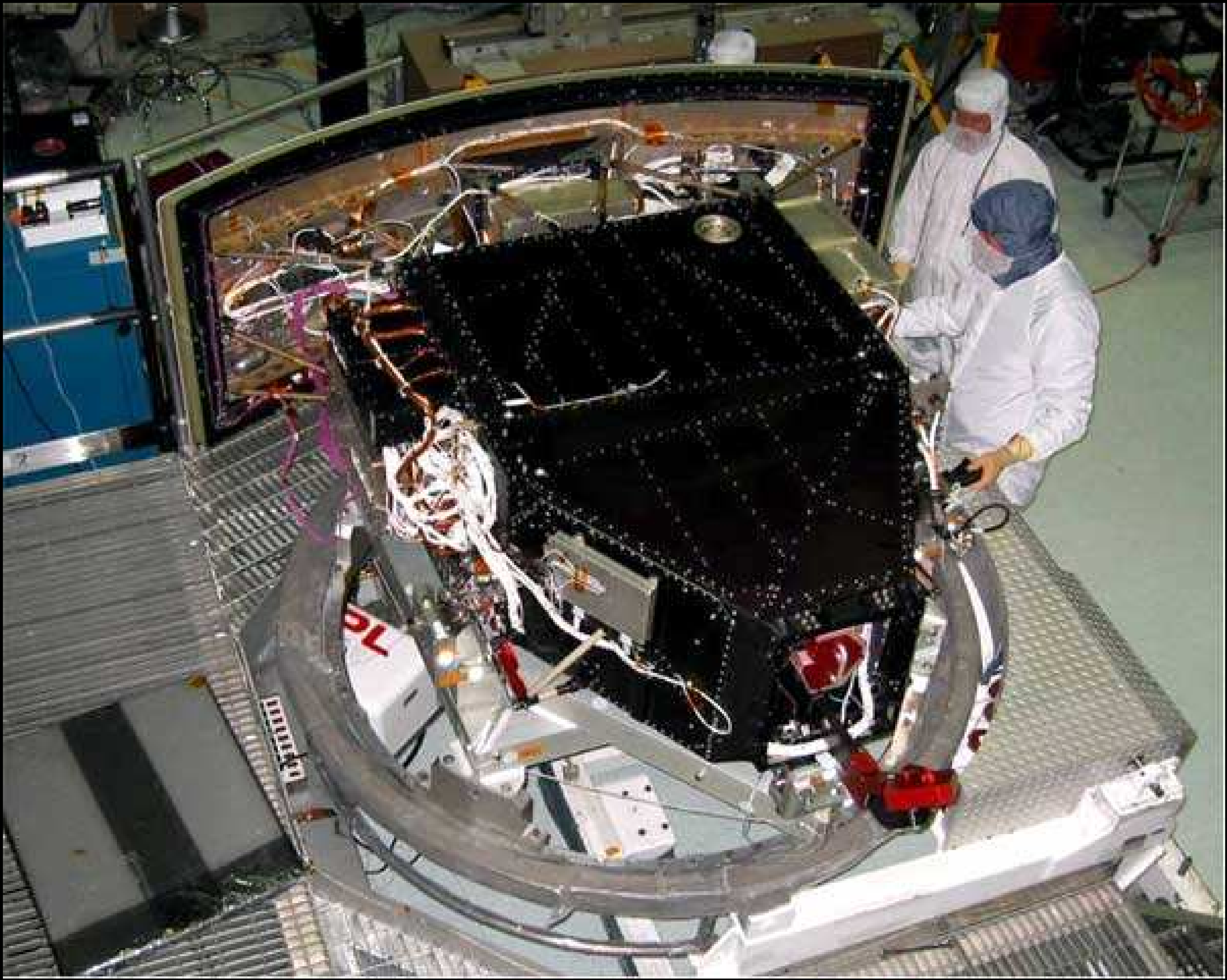
James E. Webb (1906–1992) — Second NASA Administrator

Hubble: Concept in 1970's; Made in 1980's; Operational 1990–$\gtrsim$2020^{+}?.

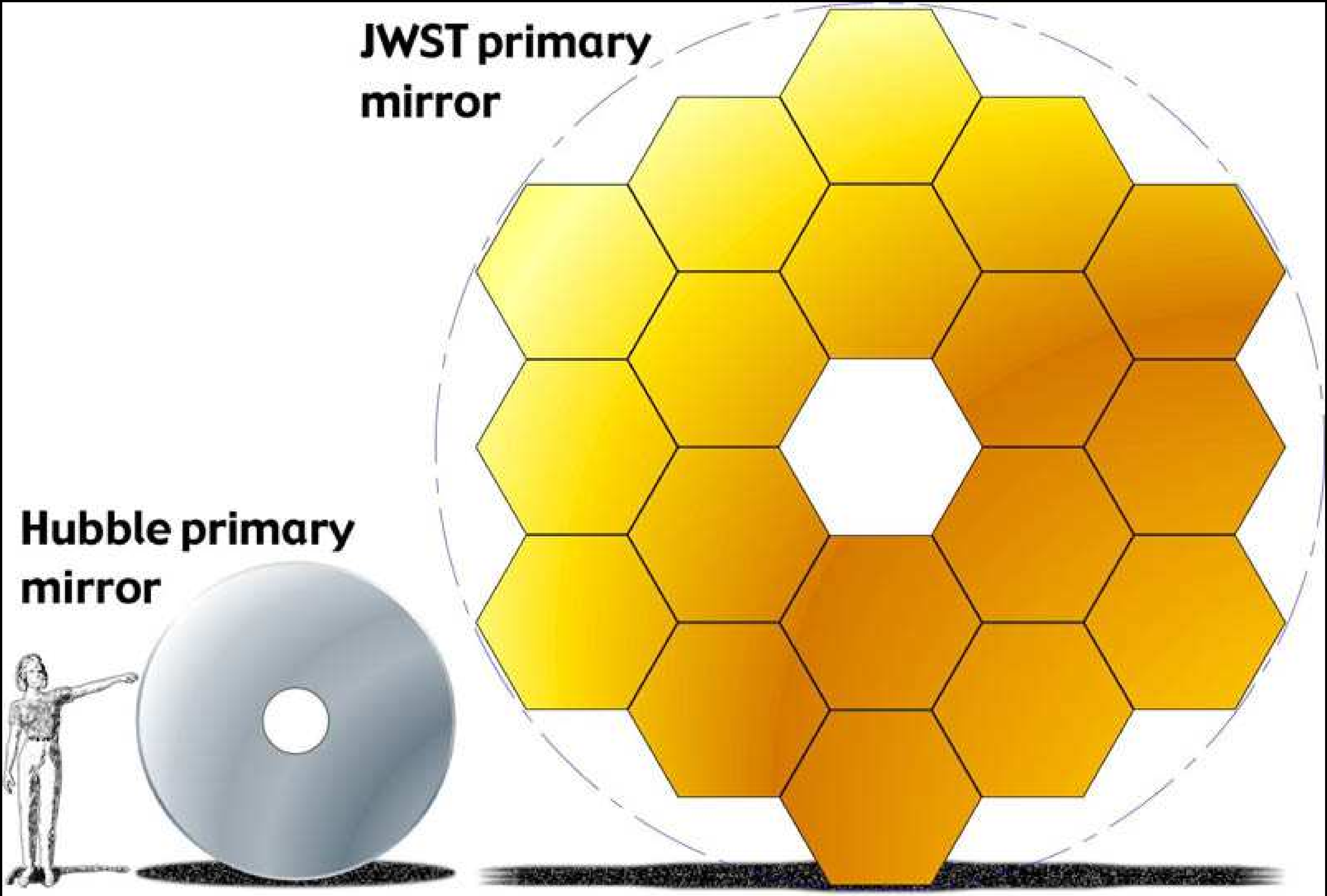
JWST: The infrared sequel to Hubble from 2019–2024 (–2029?).

May 2009: Last Shuttle Servicing Mission to the Hubble Space Telescope.

Hubble's new Wide Field Camera 3: Panchromatic High-Throughput Camera



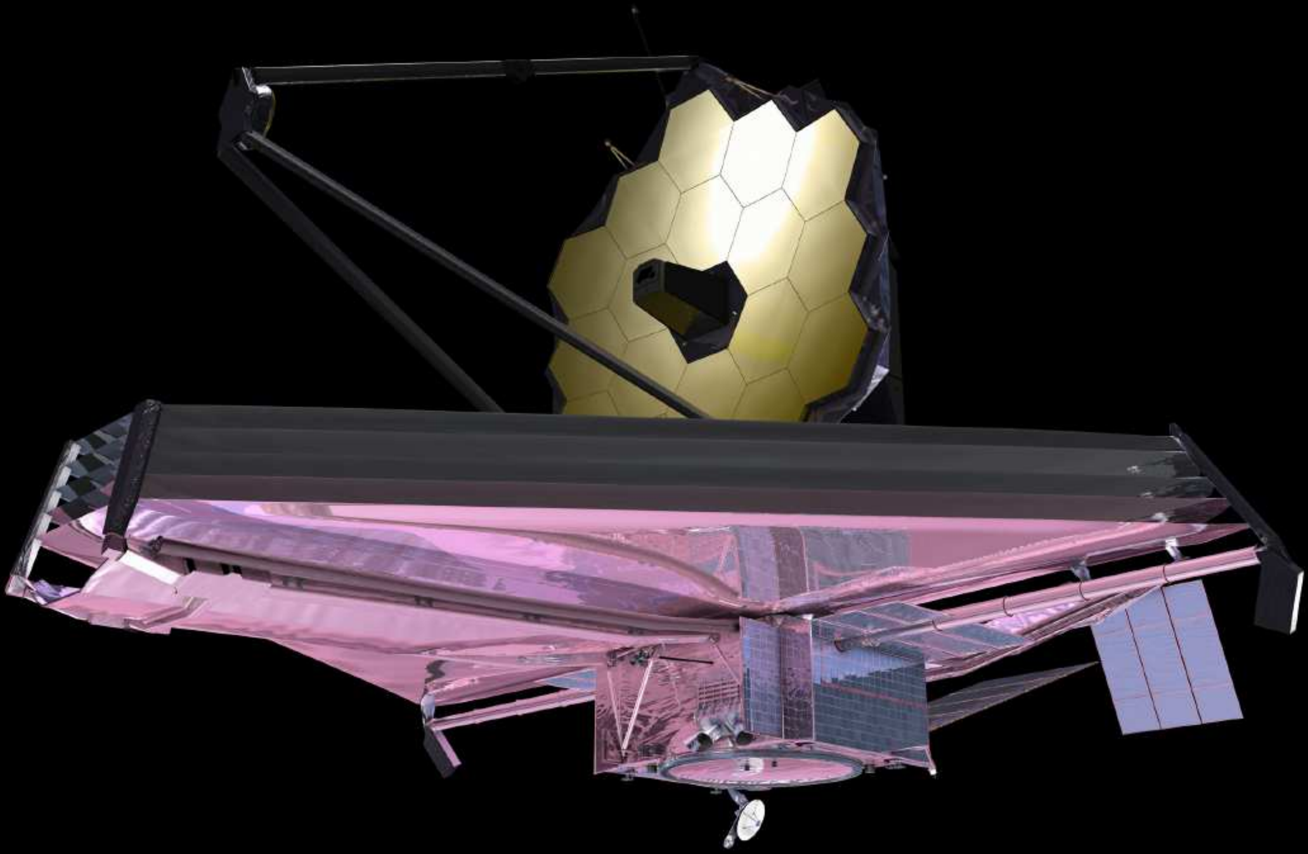
HST WFC3 and its IR channel: a critical pathfinder for JWST science.



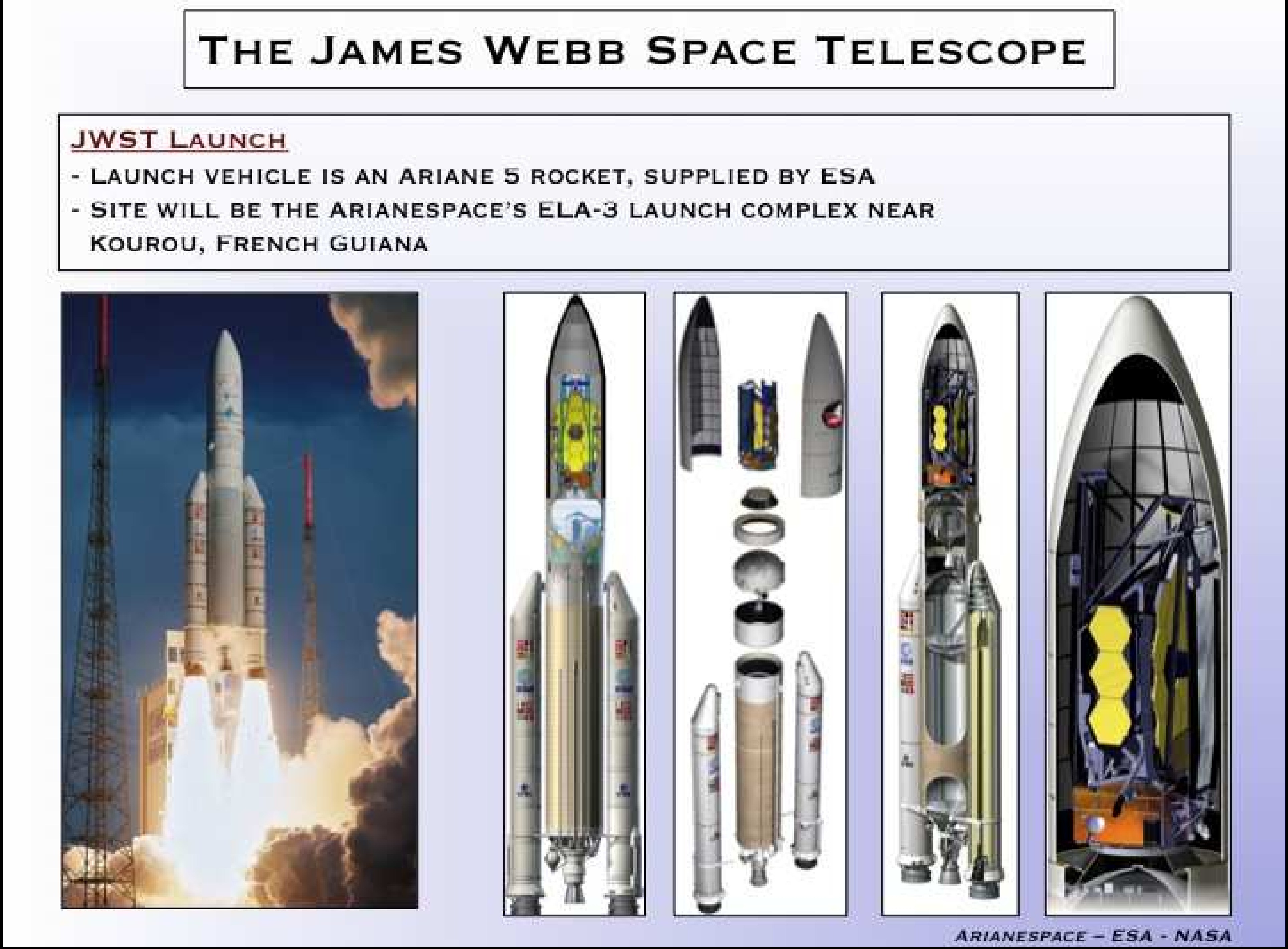
JWST $\simeq$2.5× larger than Hubble, so at $\sim$2.5× larger wavelengths:

JWST has the same resolution in the near-IR as Hubble in the optical.

(1) Update of the James Webb Space Telescope as of 2017.



- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy at 0.6–29 μm wavelength, to be launched in Spring 2019.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31 mag=1 firefly from Moon) and spectroscopy.



THE JAMES WEBB SPACE TELESCOPE

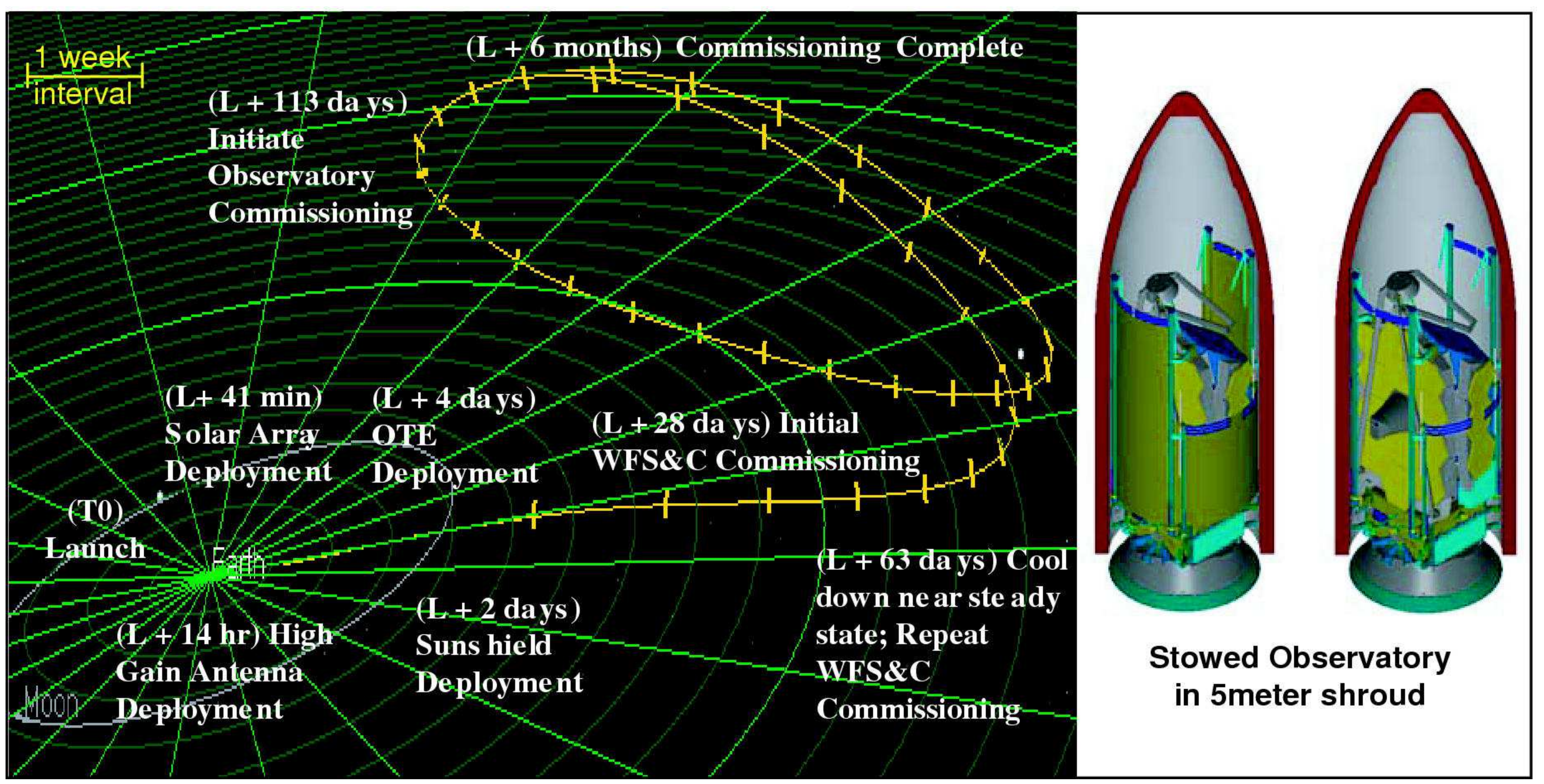
JWST LAUNCH

- 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

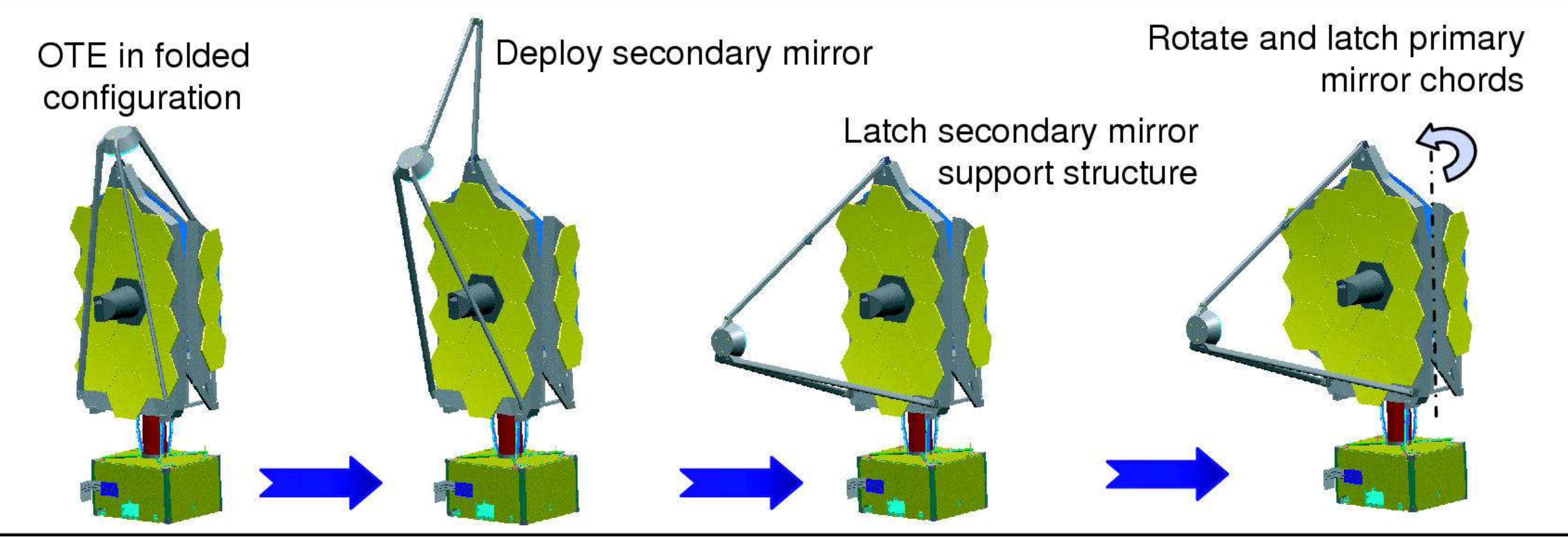
- The JWST launch weight will be $\lesssim$6500 kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

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



- After launch in Spring 2019 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.

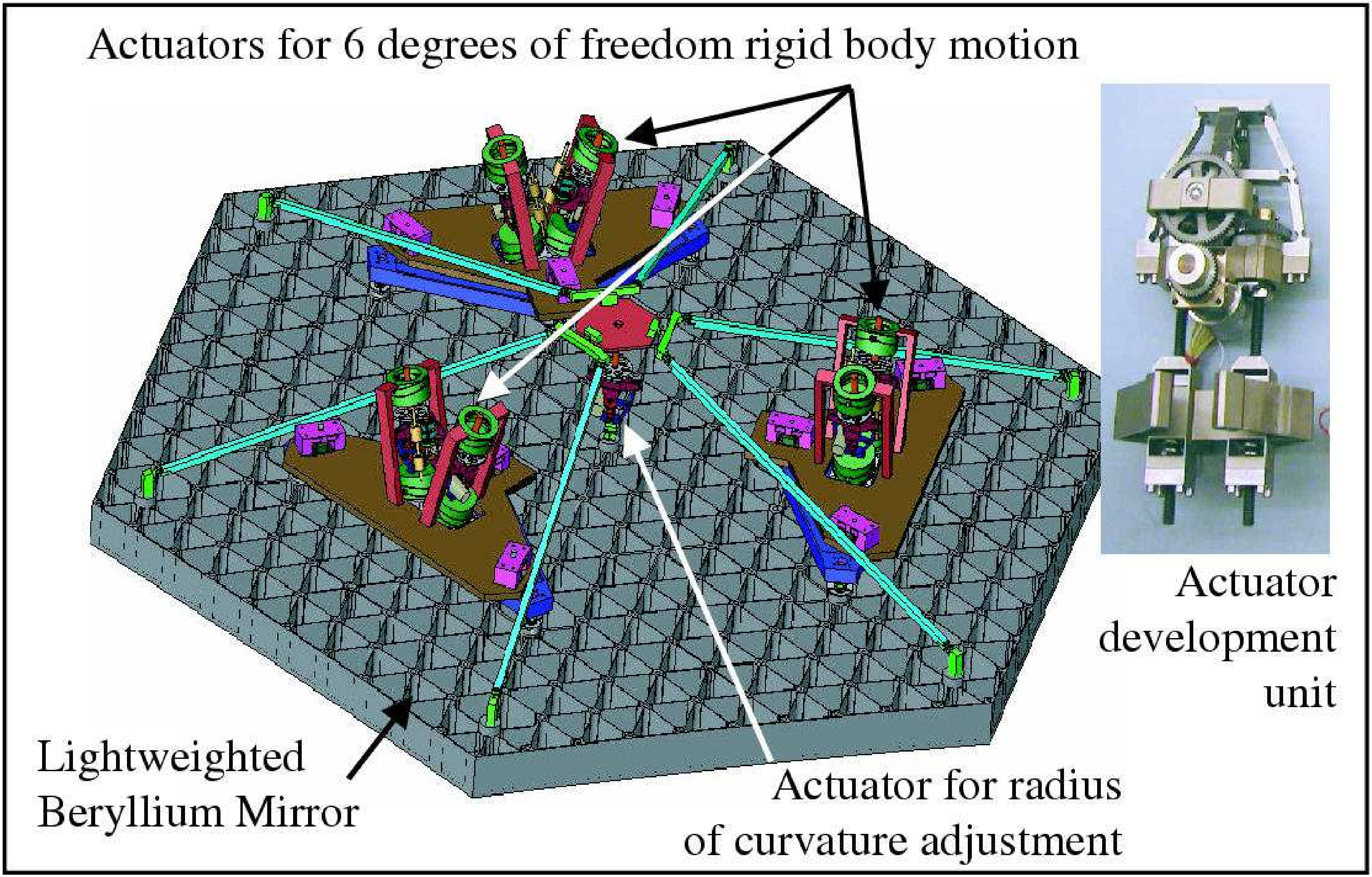
(1b) How will JWST be automatically deployed?



- 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 is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2018 at NASA Goddard (MD), Johnson (Houston), and at Northrop (CA).

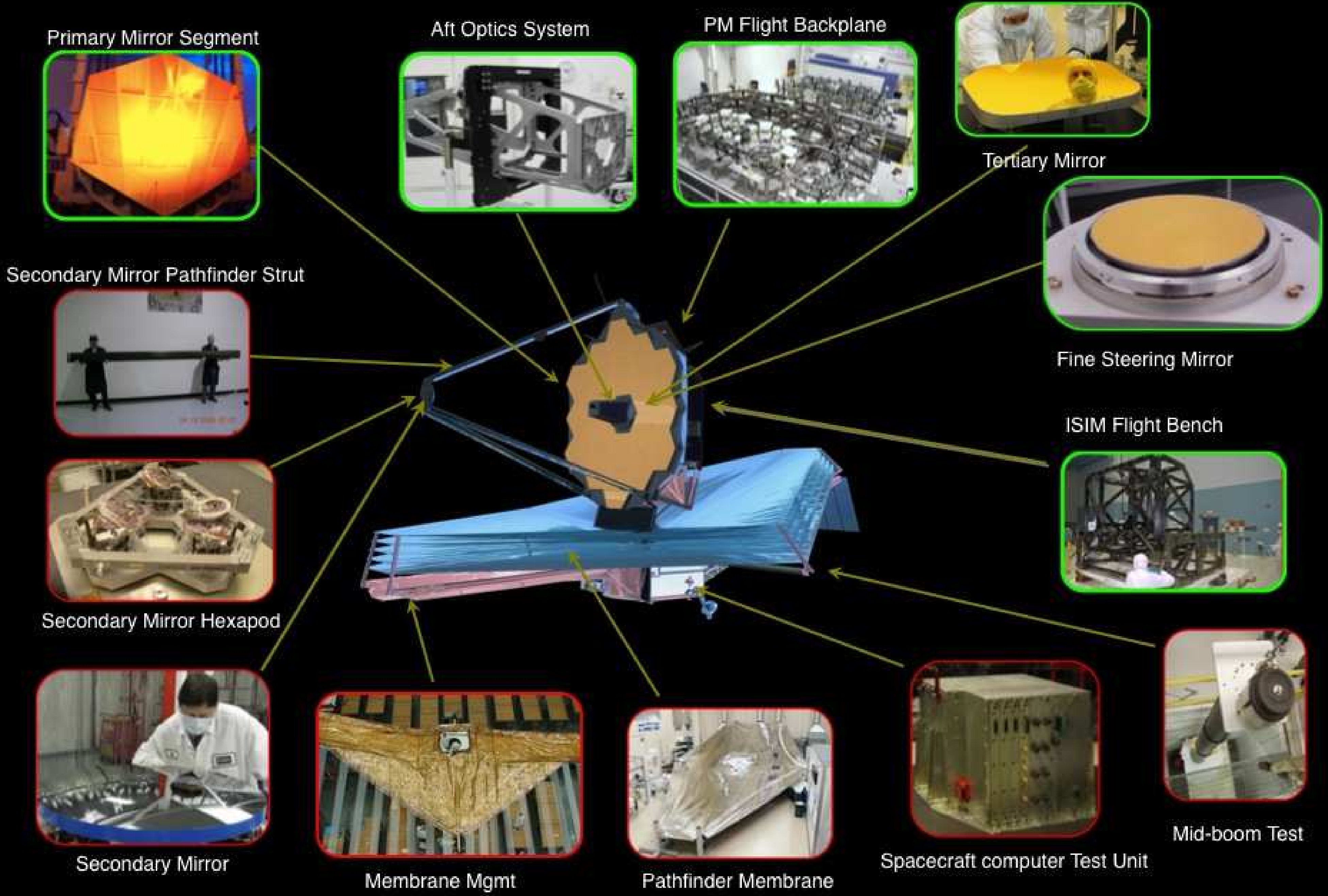
- Component fabrication, testing, & system integration is on schedule: all 18 flight mirrors completely done, and meet the 40K specifications.



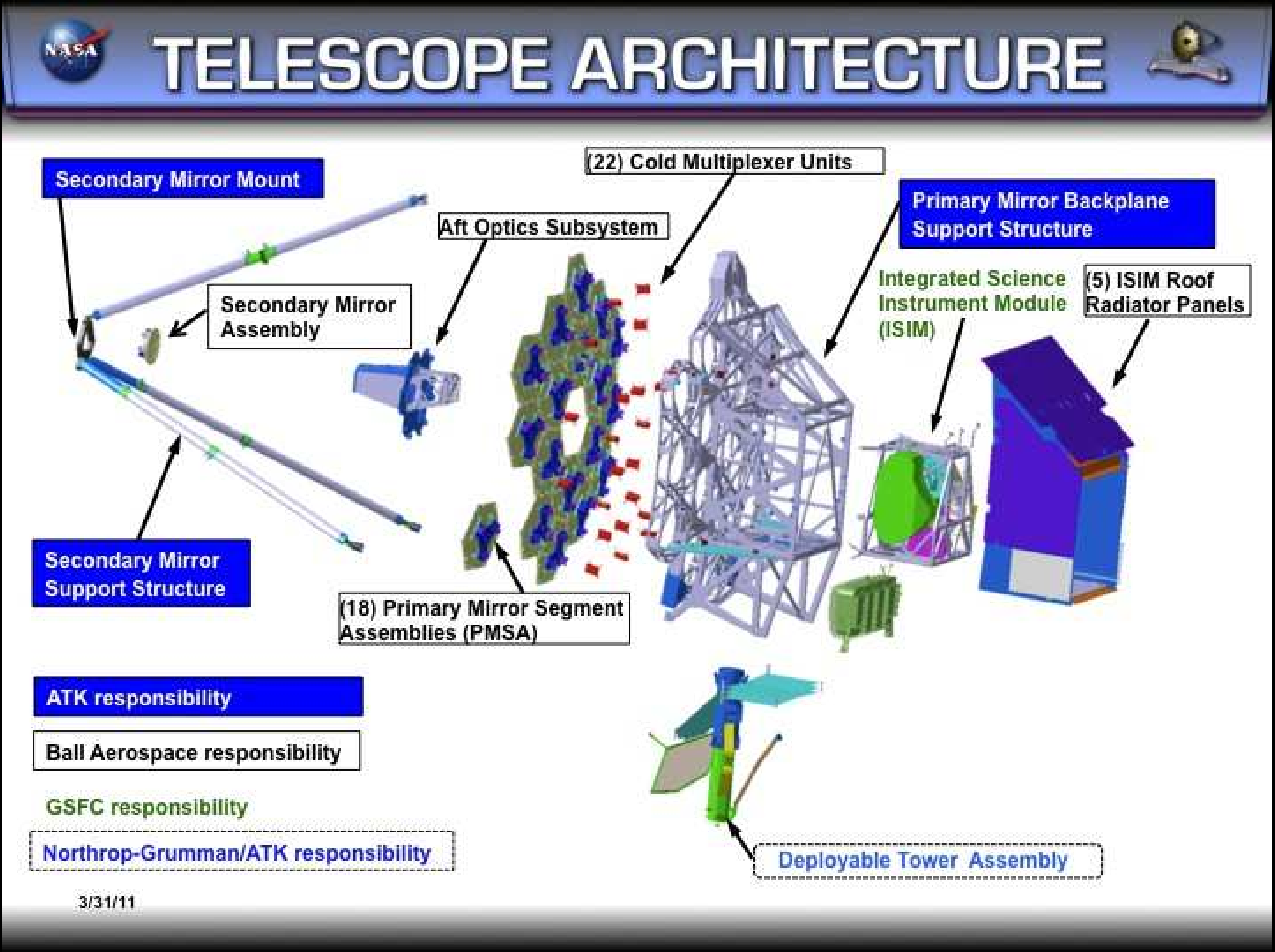
Active mirror segment support through “hexapods”, similar to Keck.

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

JWST Hardware Status



Oct. 2017: $\gtrsim$99.5% of launch mass designed and built ($\gtrsim$99% weighed).



TELESCOPE ARCHITECTURE

Secondary Mirror Mount

(22) Cold Multiplexer Units

Primary Mirror Backplane Support Structure

Aft Optics Subsystem

Secondary Mirror Assembly

Integrated Science Instrument Module (ISIM)

(5) ISIM Roof Radiator Panels

Secondary Mirror Support Structure

(18) Primary Mirror Segment Assemblies (PMSA)

ATK responsibility

Ball Aerospace responsibility

GSFC responsibility

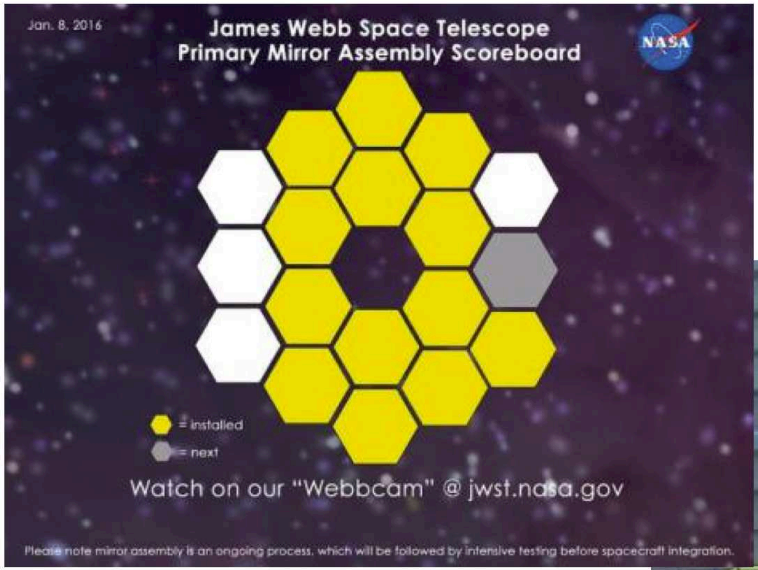
Northrop-Grumman/ATK responsibility

Deployable Tower Assembly

3/31/11

2014–2018: Complete system integration at GSFC and Northrop.

Much progress has been made in OTE integration



Jan. 8, 2016

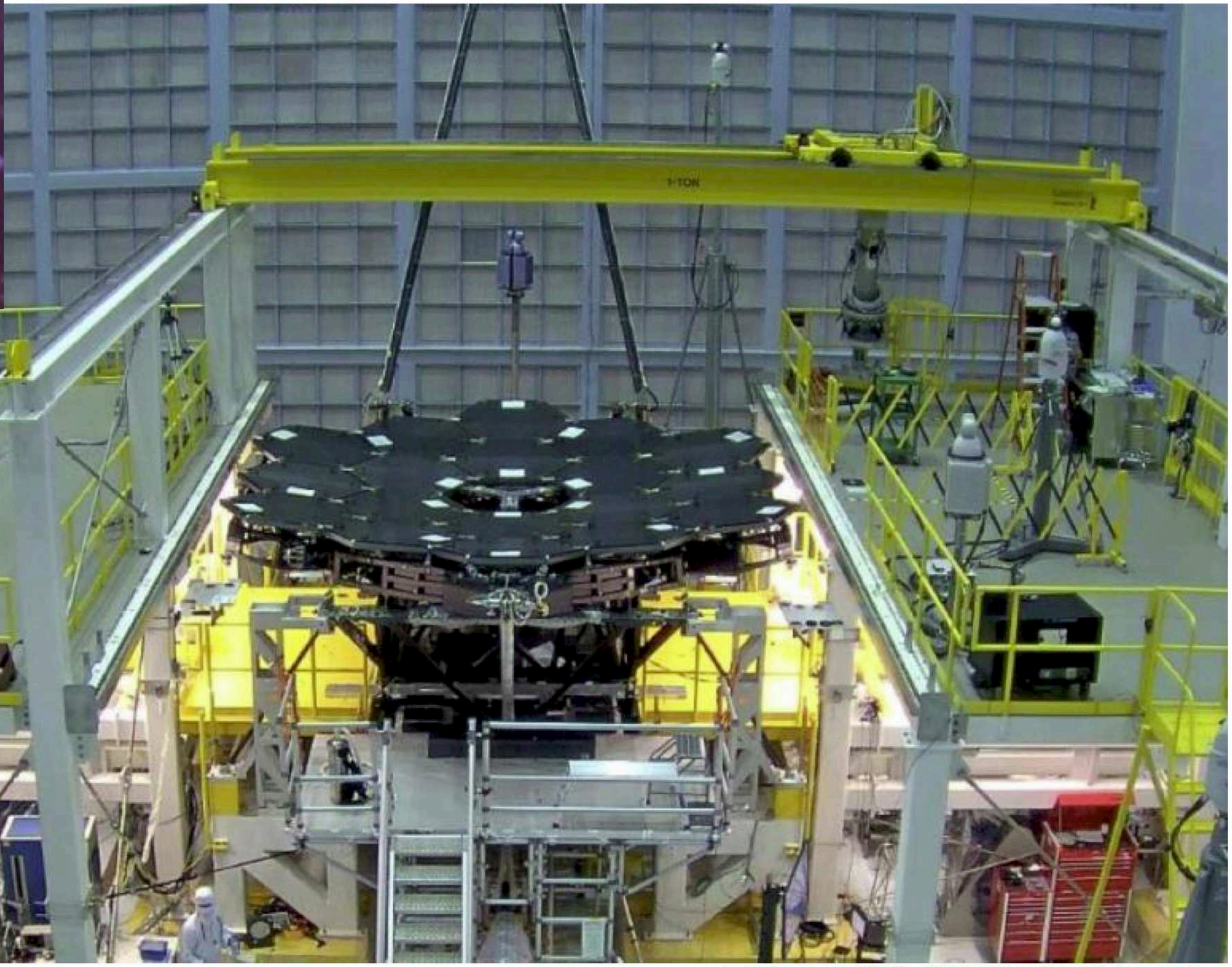
James Webb Space Telescope
Primary Mirror Assembly Scoreboard

⬢ = installed
⬢ = next

Watch on our "Webbcam" @ jwst.nasa.gov

Please note mirror assembly is an ongoing process, which will be followed by intensive testing before spacecraft integration.

← Where we were at last month's call



<u>Current</u>: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified →

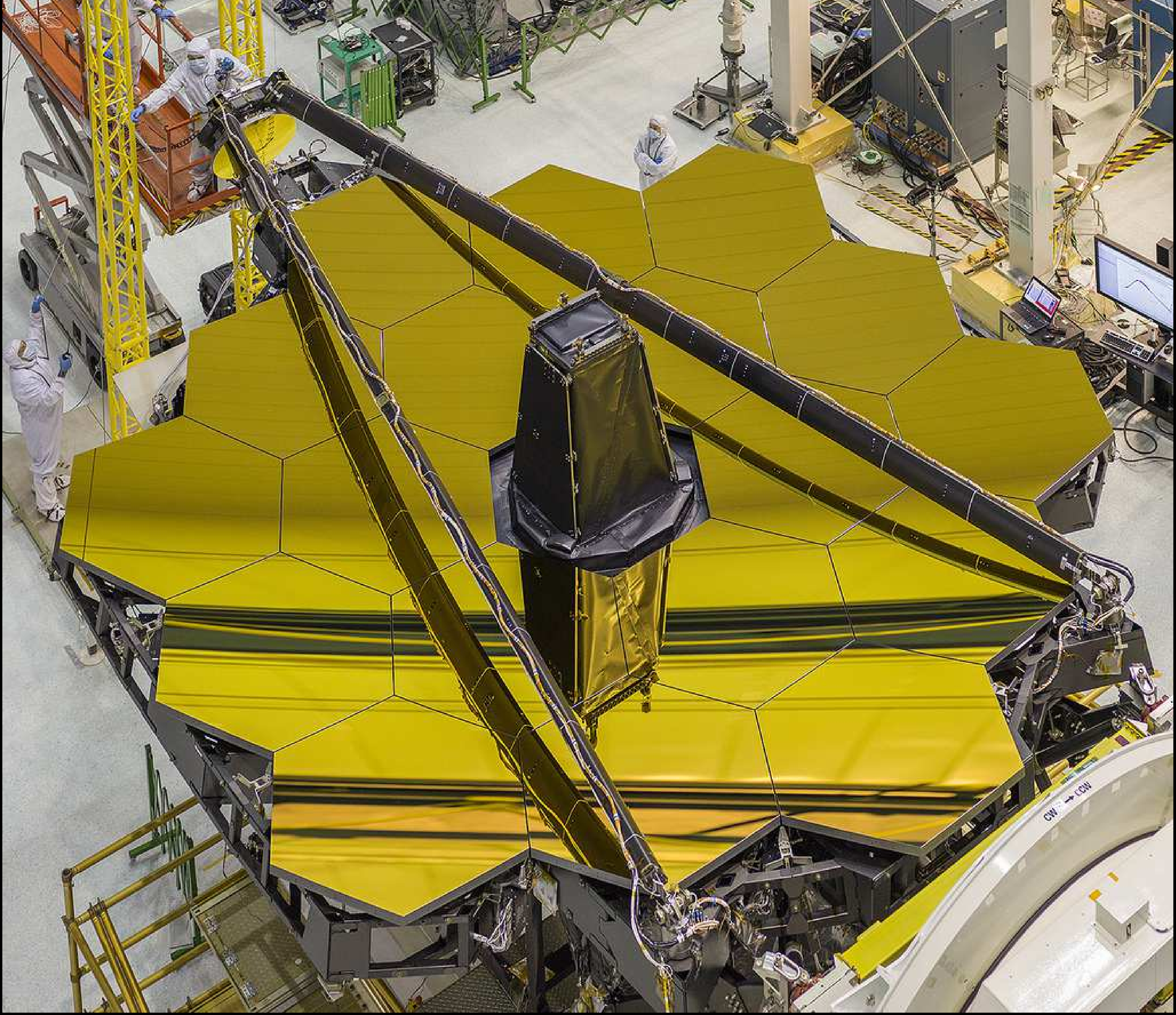
Big milestone!

JWST lifetime: Requirement: 5 yrs; Goal: 10 yrs; Propellant: $\lesssim$14 yrs.

April 2016: NASA team-work to take JWST mirror covers off!

May 2016: JWST being tilted into the right position to stow.

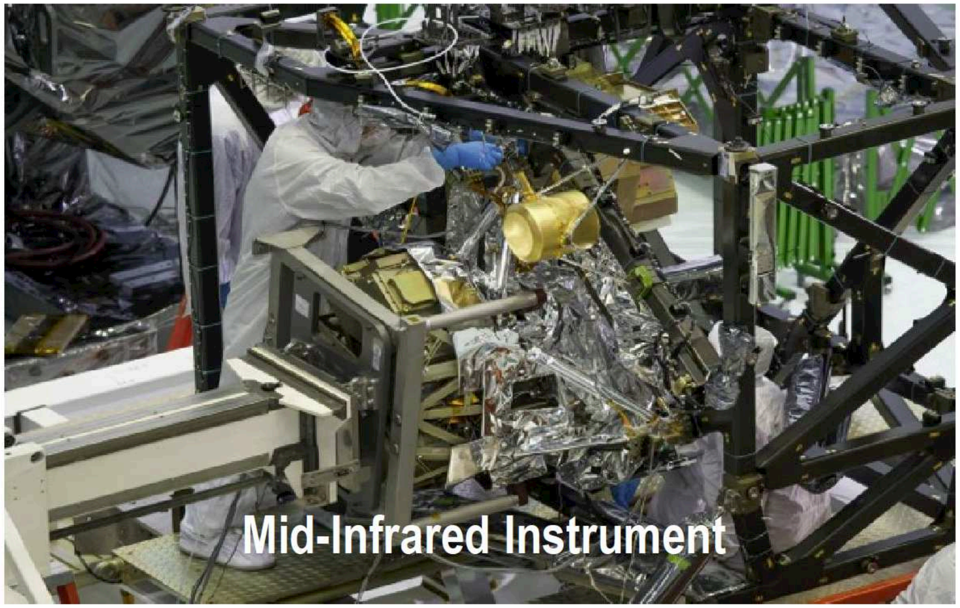
May 2016: Webb mirrors finally mounted and ready!

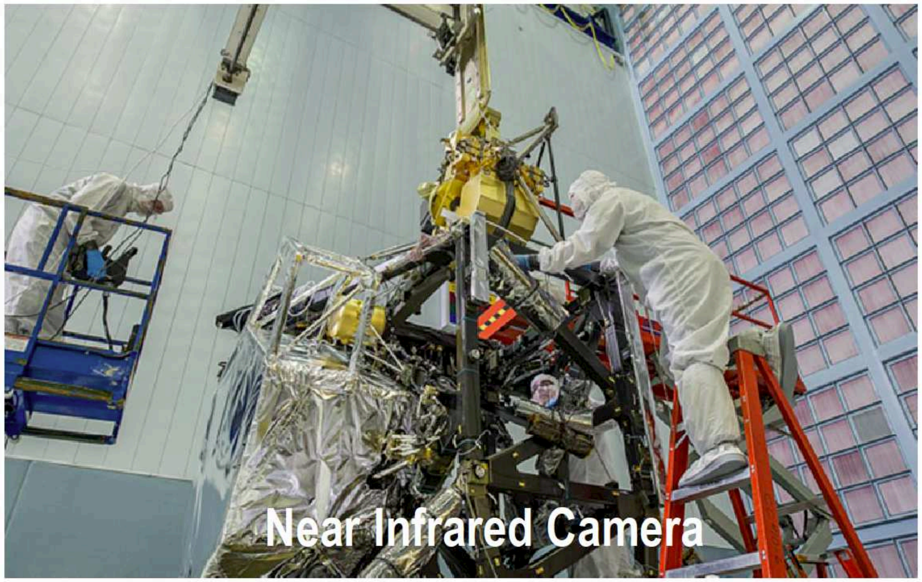


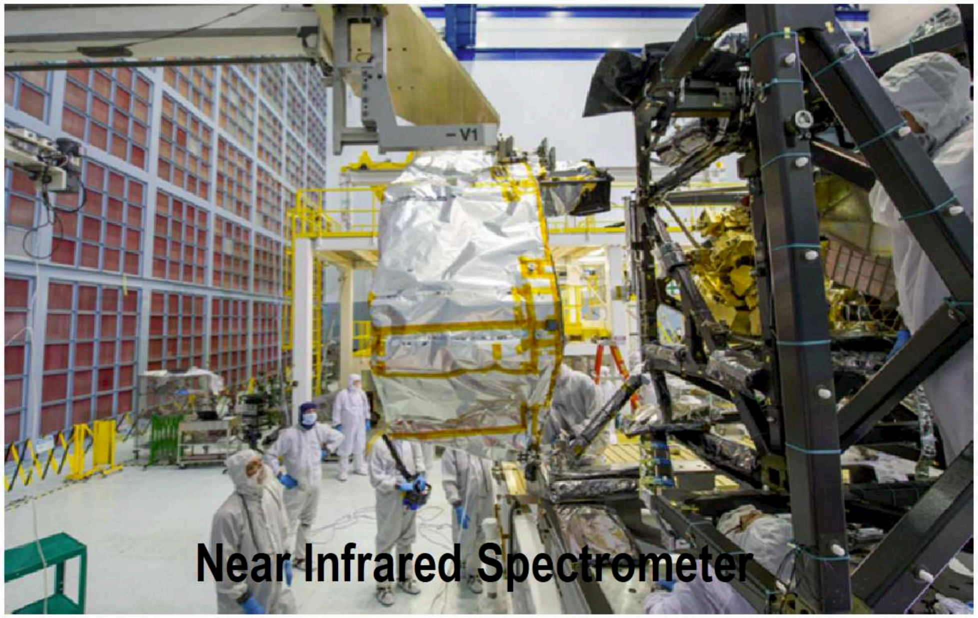
May 2016: JWST stowed for further instrument mounting.

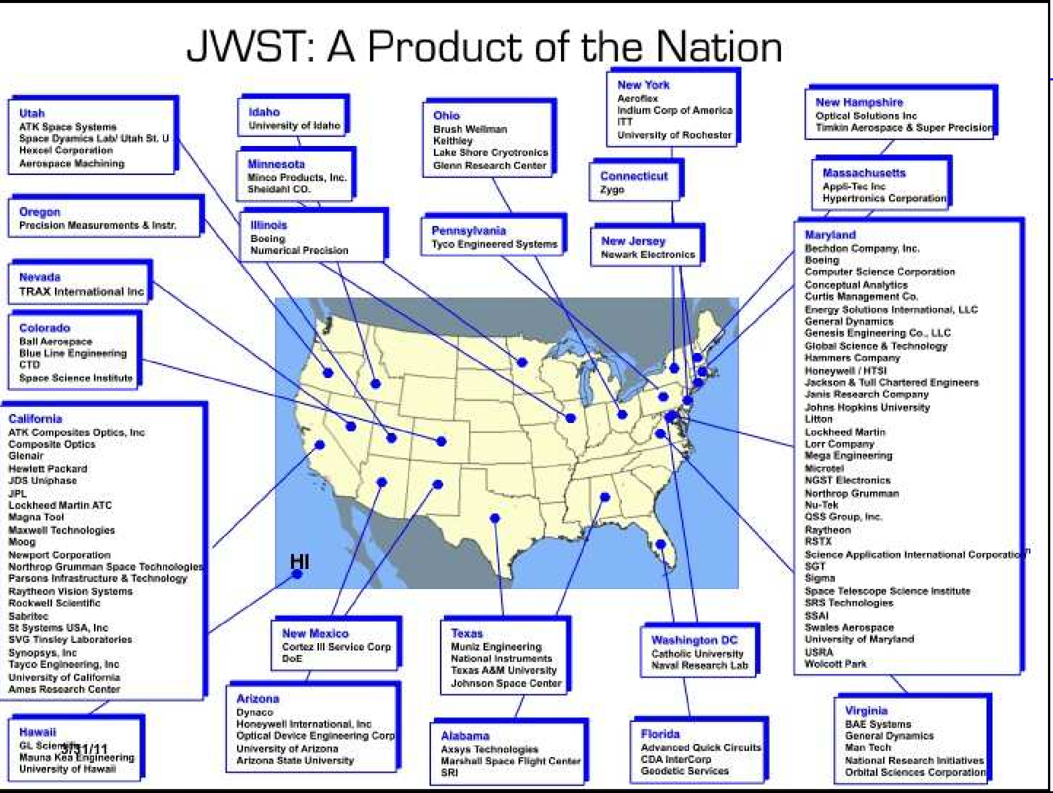
All Instruments Integrated


Fine Guidance Sensor


Mid-Infrared Instrument


Near Infrared Camera


Near Infrared Spectrometer



JWST: A Product of the Nation

Utah
ATK Space Systems
Space Dyamics Lab/ Utah St. U
Hexcel Corporation
Aerospace Machining

Oregon
Precision Measurements & Instr.

Nevada
TRAX International Inc

Colorado
Ball Aerospace
Blue Line Engineering
CTD
Space Science Institute

California
ATK Composites Optics, Inc
Composite Optics
Glenair
Hewlett Packard
JDS Uniphase
JPL
Lockheed Martin ATC
Magna Tool
Maxwell Technologies
Moog
Newport Corporation
Northrop Grumman Space Technologies
Parsons Infrastructure & Technology
Raytheon Vision Systems
Rockwell Scientific
Sabritec
St Systems USA, Inc
SVG Tinsley Laboratories
Synopsys, Inc
Tayco Engineering, Inc
University of California
Ames Research Center

Hawaii
GL Scientific
Mauna Kea Engineering
University of Hawaii

3/31/11

Idaho
University of Idaho

Minnesota
Minco Products, Inc.
Sheldahl CO.

Illinois
Boeing
Numerical Precision

Ohio
Brush Wellman
Keithley
Lake Shore Cryotronics
Glenn Research Center

Pennsylvania
Tyco Engineered Systems

New York
Aeroflex
Indium Corp of America
ITT
University of Rochester

Connecticut
Zygo

New Jersey
Newark Electronics

New Hampshire
Optical Solutions Inc
Timkin Aerospace & Super Precision

Massachusetts
Appli-Tec Inc
Hypertronics Corporation

Maryland
Bechdon Company, Inc.
Boeing
Computer Science Corporation
Conceptual Analytics
Curtis Management Co.
Energy Solutions International, LLC
General Dynamics
Genesis Engineering Co., LLC
Global Science & Technology
Hammers Company
Honeywell / HTSI
Jackson & Tull Chartered Engineers
Janis Research Company
Johns Hopkins University
Litton
Lockheed Martin
Lorr Company
Mega Engineering
Microtel
NGST Electronics
Northrop Grumman
Nu-Tek
QSS Group, Inc.
Raytheon
RSTX
Science Application International Corporation
SGT
Sigma
Space Telescope Science Institute
SRS Technologies
SSAI
Swales Aerospace
University of Maryland
USRA
Wolcott Park

New Mexico
Cortez III Service Corp
DoE

Arizona
Dynaco
Honeywell International, Inc
Optical Device Engineering Corp
University of Arizona
Arizona State University

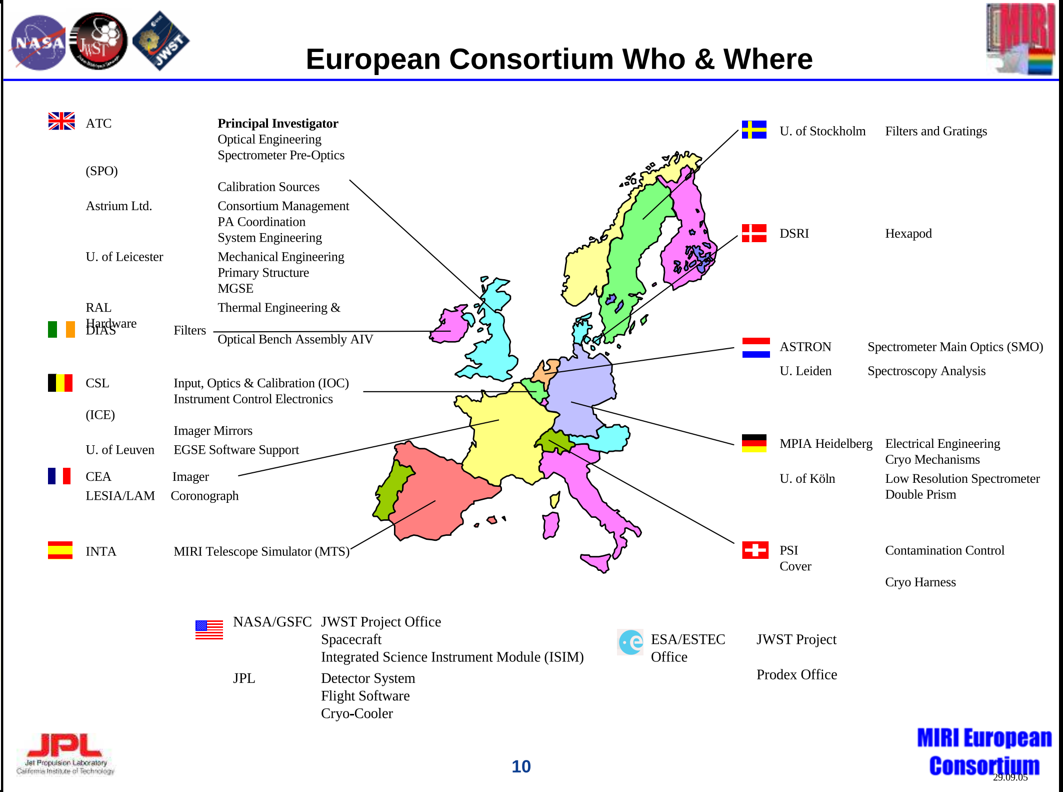
Texas
Muniz Engineering
National Instruments
Texas A&M University
Johnson Space Center

Alabama
Axsys Technologies
Marshall Space Flight Center
SRI

Washington DC
Catholic University
Naval Research Lab

Florida
Advanced Quick Circuits
CDA InterCorp
Geodetic Services

Virginia
BAE Systems
General Dynamics
Man Tech
National Research Initiatives
Orbital Sciences Corporation



European Consortium Who & Where

ATC **Principal Investigator**
Optical Engineering
Spectrometer Pre-Optics
(SPO)
Calibration Sources
Astrium Ltd. Consortium Management
PA Coordination
System Engineering
U. of Leicester Mechanical Engineering
Primary Structure
MGSE
RAL Thermal Engineering &
Hardware
DIAS Filters
Optical Bench Assembly AIV

CSL Input, Optics & Calibration (IOC)
Instrument Control Electronics
(ICE)
Imager Mirrors
U. of Leuven EGSE Software Support

CEA Imager
LESIA/LAM Coronograph

INTA MIRI Telescope Simulator (MTS)

U. of Stockholm Filters and Gratings

DSRI Hexapod

ASTRON Spectrometer Main Optics (SMO)
U. Leiden Spectroscopy Analysis

MPIA Heidelberg Electrical Engineering
Cryo Mechanisms
U. of Köln Low Resolution Spectrometer
Double Prism

PSI Contamination Control
Cover
Cryo Harness

NASA/GSFC JWST Project Office
Spacecraft
Integrated Science Instrument Module (ISIM)
JPL Detector System
Flight Software
Cryo-Cooler

ESA/ESTEC JWST Project
Office
Prodex Office

JPL
Jet Propulsion Laboratory
California Institute of Technology

10

MIRI European Consortium

29.09.05

- JWST hardware made in 27 US States: $\gtrsim$99.5% of launch-mass finished.

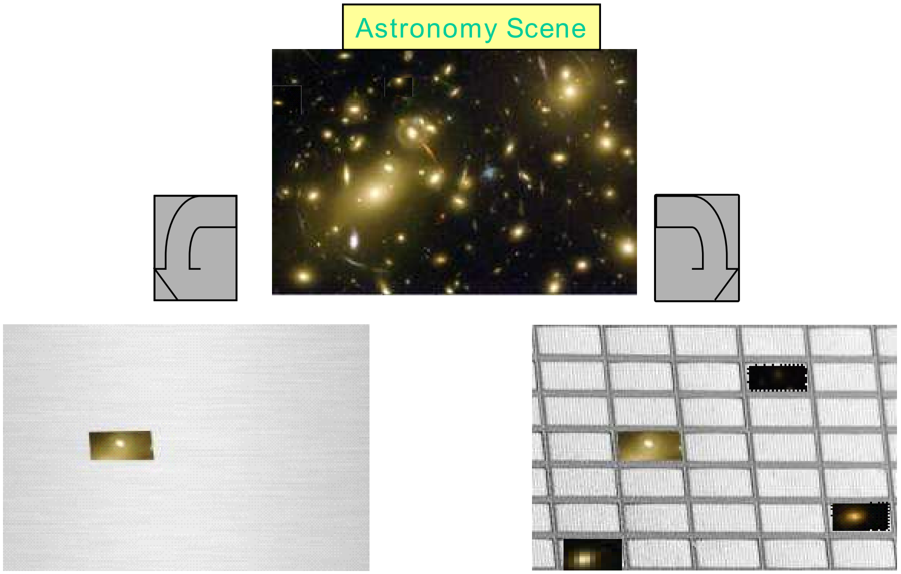
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.

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

- JWST NIRCam made by UofA and Lockheed.

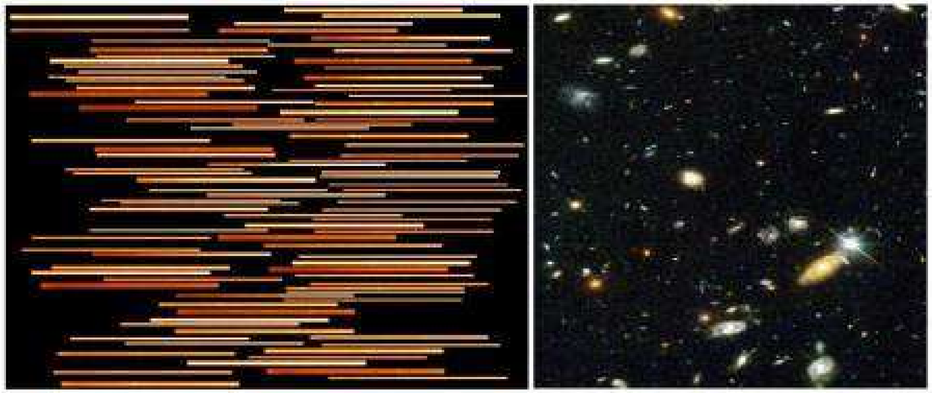
This nationwide + international coalition was critical for project survival!

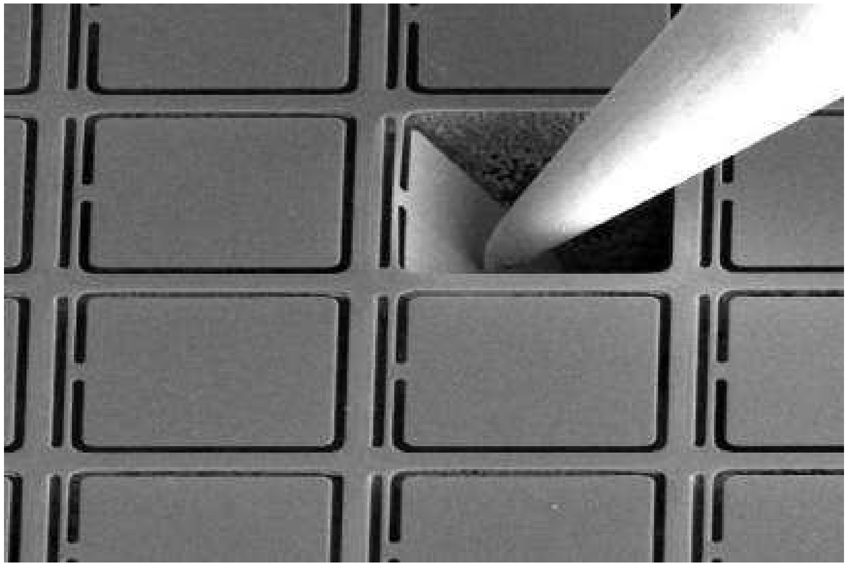
Micro Shutters


Astronomy Scene

Metal Mask/Fixed Slit

Shutter Mask





2014: Flight ISIM (all 4 instruments) in test. Oct. 15–Feb. 2016: CryoVac3.

April 2017: Last portrait of JWST at Goddard Space Flight Center (MD).

May 2017: JWST OTE in enclosure at Johnson Space Center in Houston.

Program Update: OTIS

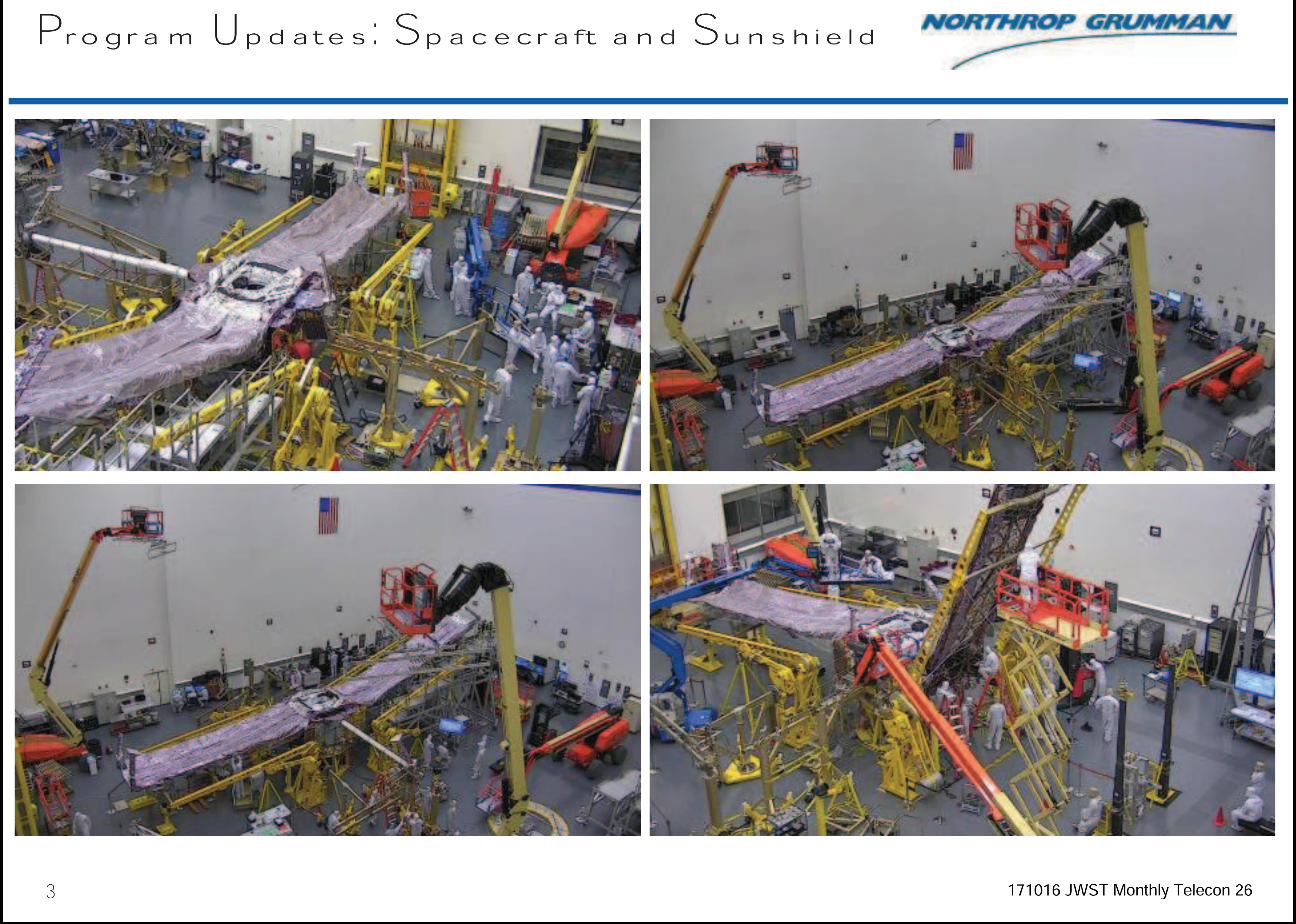
NORTHROP GRUMMAN

June 2017: JWST OTE going into Chamber A at Johnson Space Center.

It's Still in There

171016 JWST Monthly Telecon 11

Oct. 2017: IR pic of OTE before exiting Chamber A at Johnson Space Center.



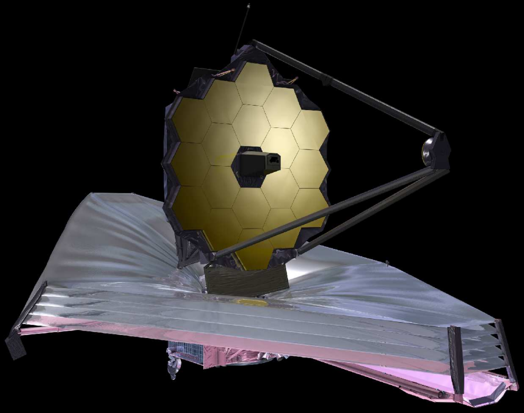
Program Updates: Spacecraft and Sunshield

NORTHROP GRUMMAN

Spring–Fall 2017: JWST Flight Sunshield assembled and tested at Northrop.

(2) Next generation ground-based: Giant Magellan Telescope (GMT).

True relative size: Hubble, James Webb, & Giant Magellan Telescope



(1973∼2020$^+$); (1996∼2029); (2000's∼2023 + $\gtrsim$100 yrs).

- JWST has superbly dark sky in L2, sensitivity, and stable images.
- GMT 4×higher resolution, high-res spectra, & long-term time-domain.

(2) Future: How can we knock it out of the ball-park in the next 30^+ years?

GMT and its dome would instead fill the whole Yankee ballpark ...

- New paradigm: Projects too large for a single university to take on.
- Universities need to collaborate world-wide to make this happen.

GMT and its dome would fill the whole Dodger stadium ...

Image credit: Damien Jemison (`http://www.gmto.org/`).

GMT would also fill the whole Rosebowl ... Image credit: Damien Jemison (`http://www.gmto.org/`).

Partners: Australia, Carnegie, Sao Paulo Brazil, Harvard, Korea, Smithsonian, Texas A&M, U. Texas, U. Arizona, U. Chicago,

and as of Fall 2017 also ...

ASU signed on to become a GMT partner, in Fall 2017! Go Sun Devils!

ASU signed on to become a GMT partner, in Fall 2017! Go Sun Devils!

But where do we build GMT — at the Sun Devil 50 yard-line?

(Image credit: Luis Martinez-Mella; ASU, Psyche Mission Science Outreach).

OK, that was a NO! How about at the Sun Devil 29 yard-line?

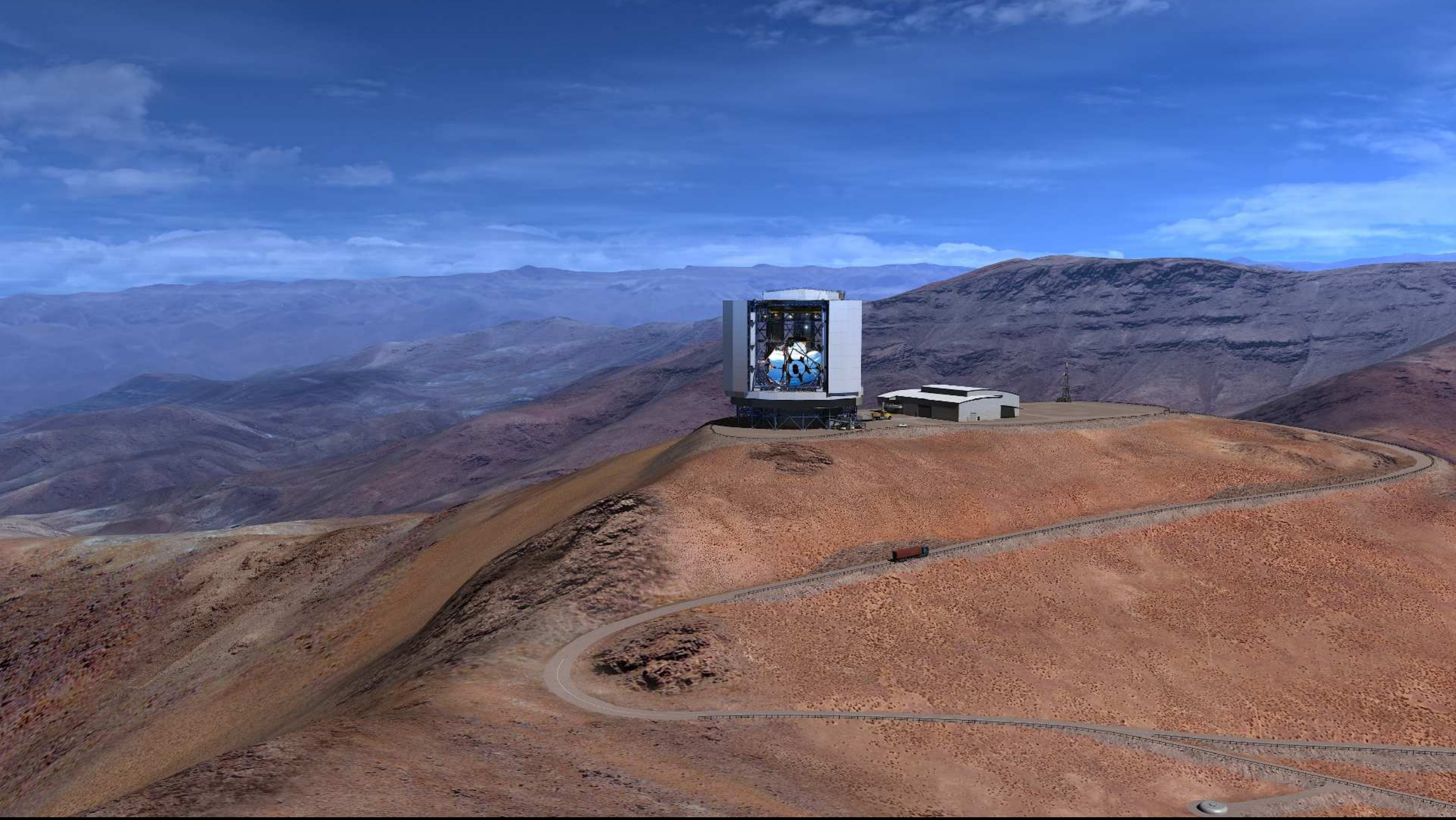
(Image credit: Luis Martinez-Mella; ASU, Psyche Mission Science Outreach).

OK, that was a NO! How about at the Sun Devil 29 yard-line?
Alright, that won't work either! Too many stadium lights and clouds ...

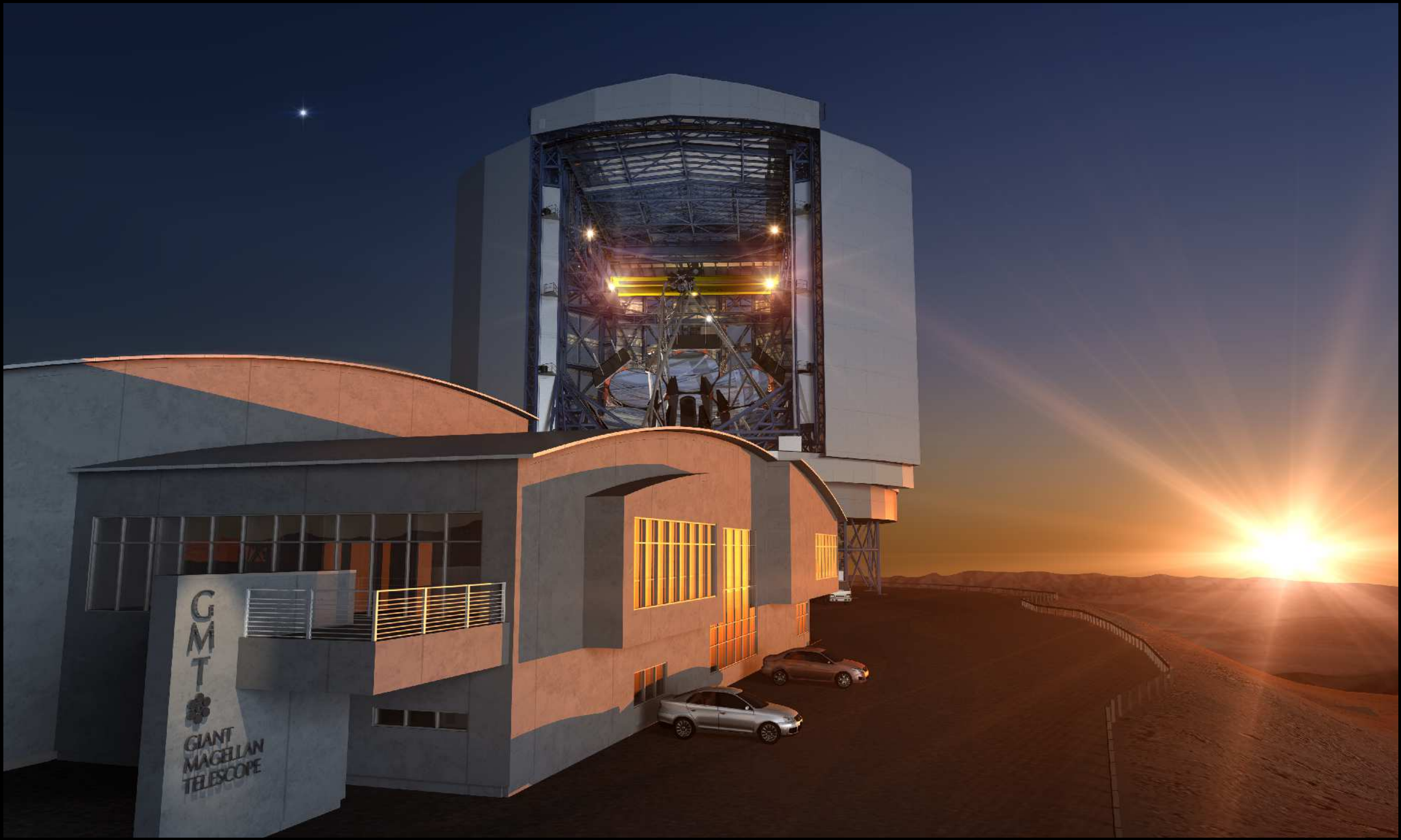
How about building GMT instead at –29° geographical latitude?

At the one of the darkest and driest mountain tops on Earth!

GMT is being built at the southern tip of the Atacama desert in Chile.

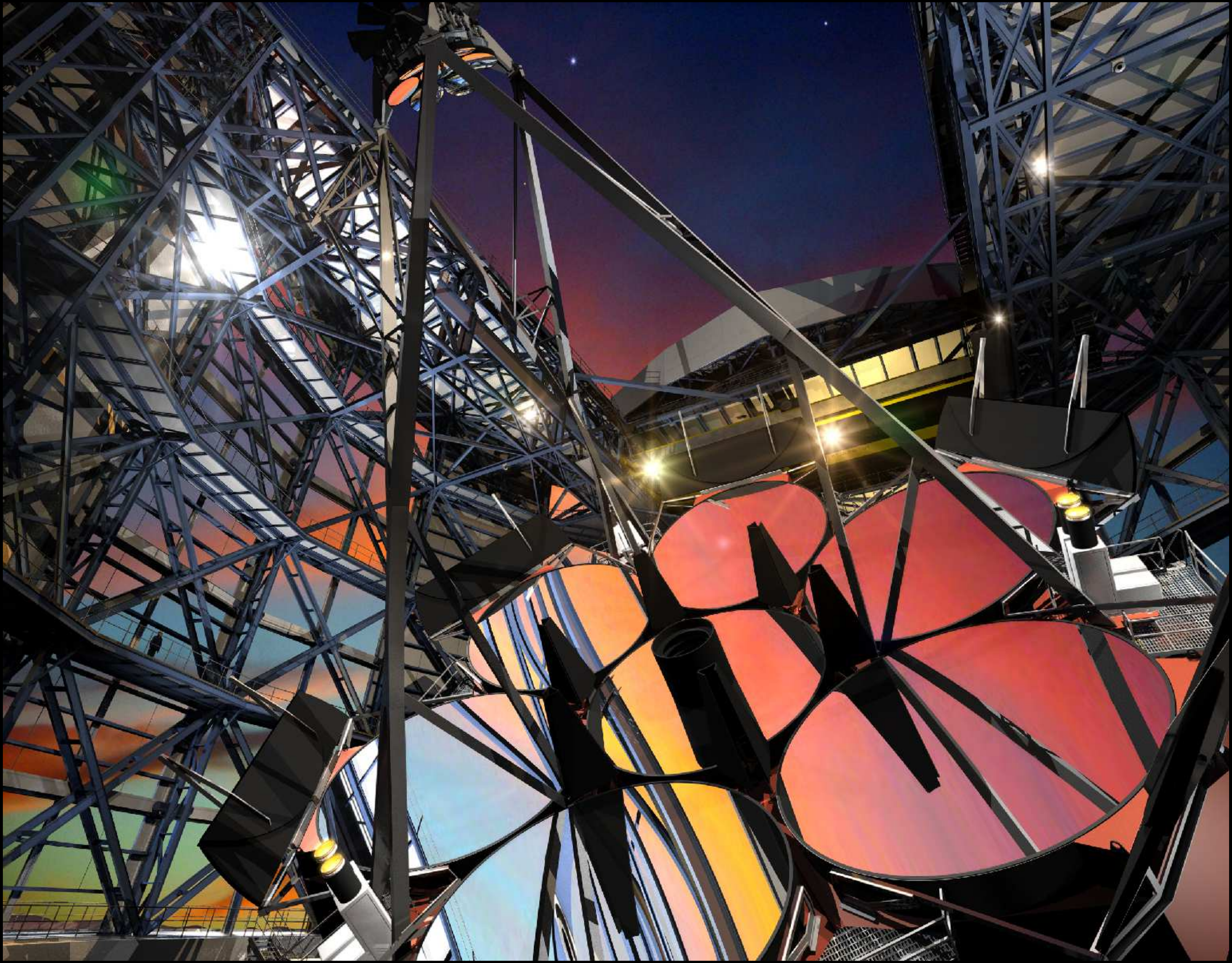


Some winter clouds, but less than 2 mm precipitation per year.

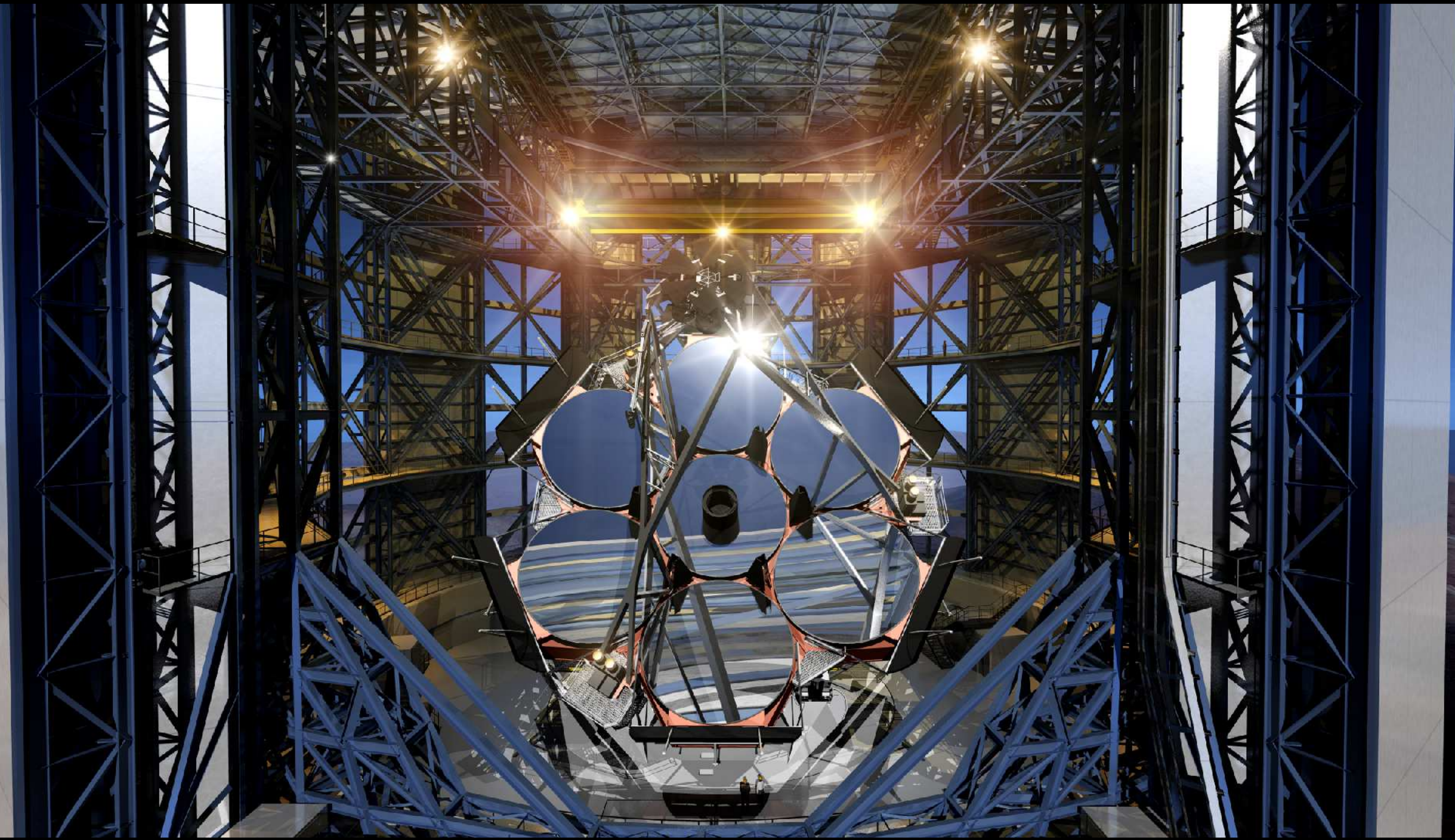


Waiting for that bright star to set in 2023 ...

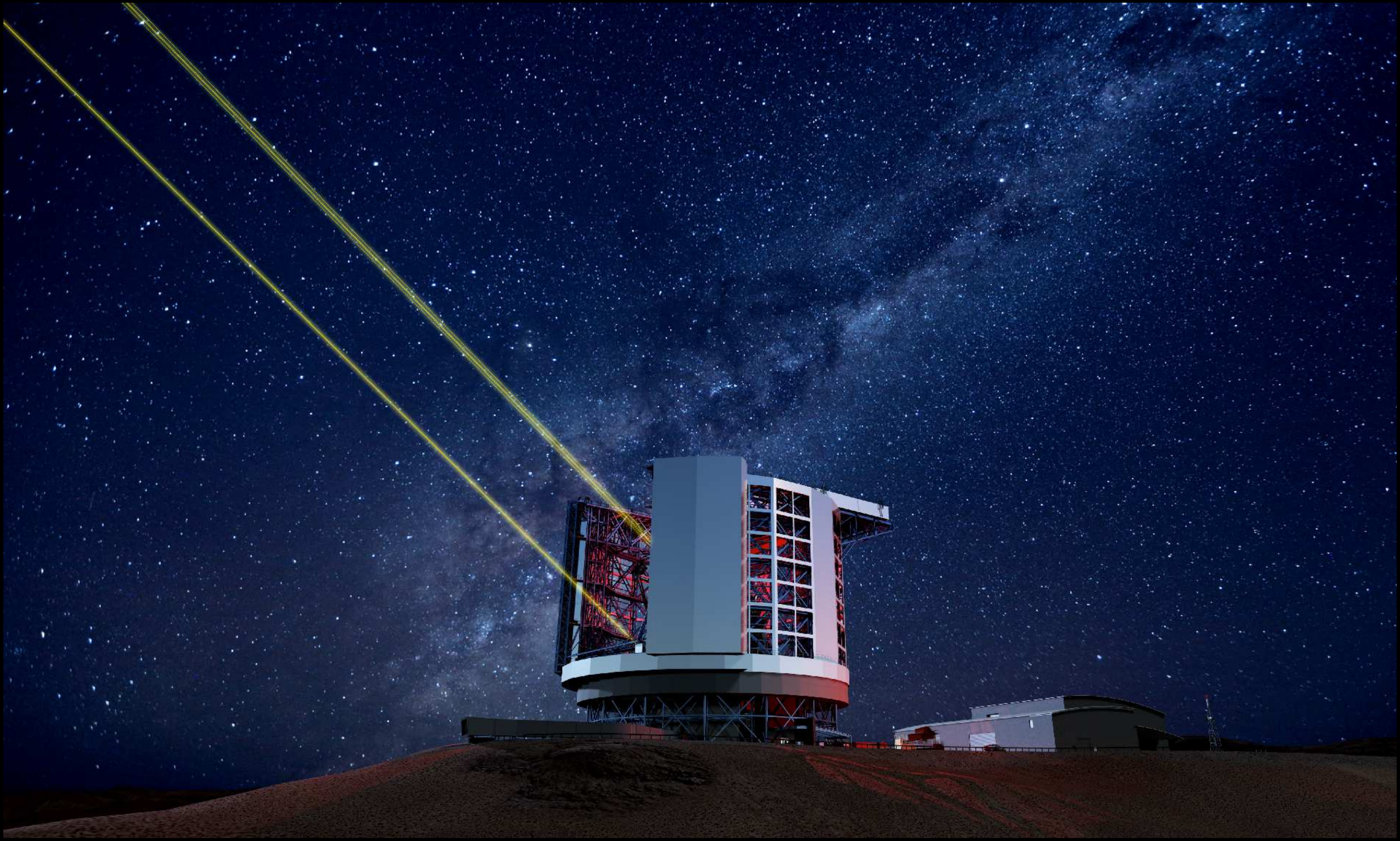
although GMT can also observe during the day, in the near-IR.



GMT's open dome structure allows for uniform airflow and good seeing.



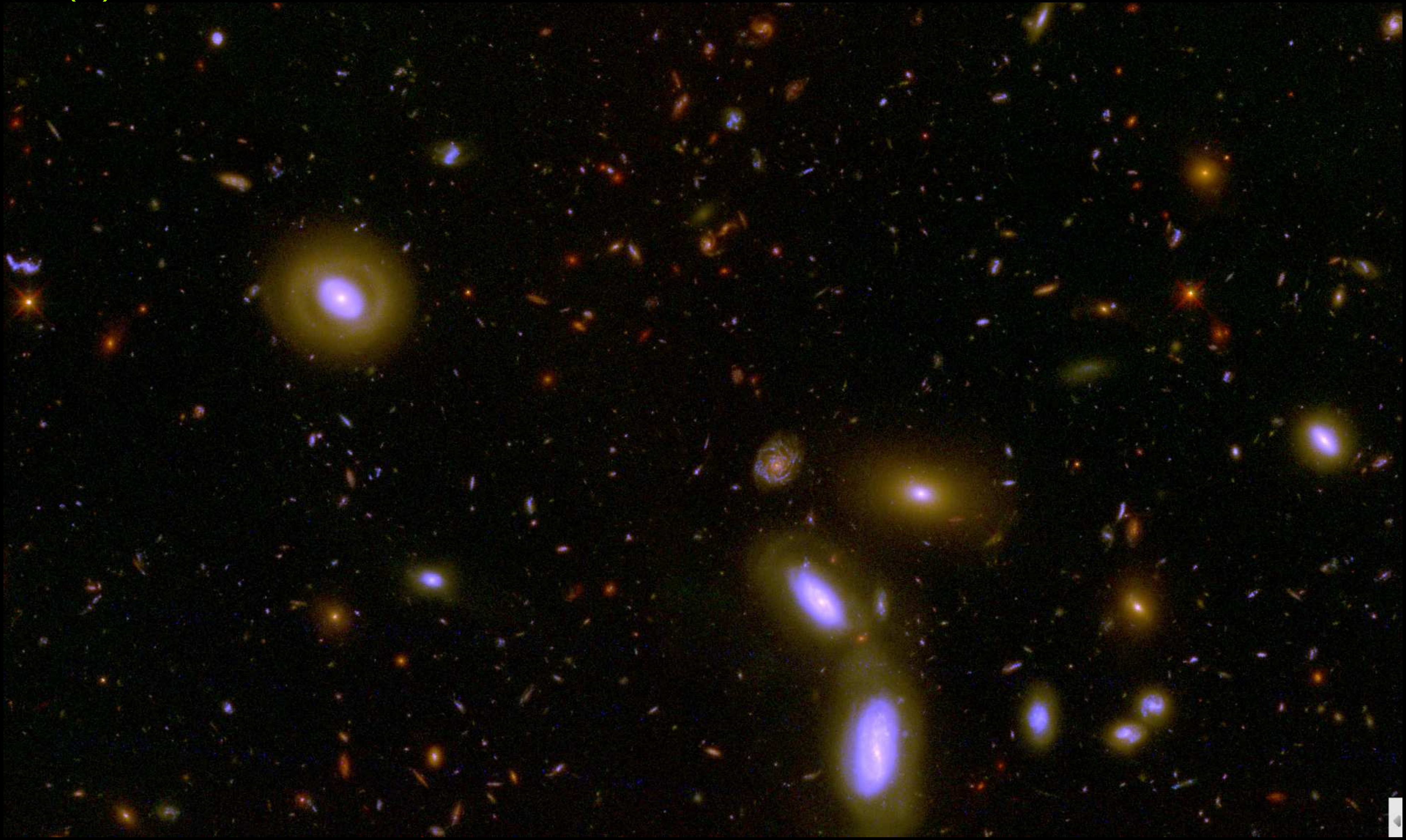
GMT’s seven 8.4-meter mirrors make a nearly-filled 25 m diameter mirror.



“Star Wars”: GMT will observe with laser guide stars.

Multi-Conjugate Adaptive Optics yields resolution 10× better than Hubble.

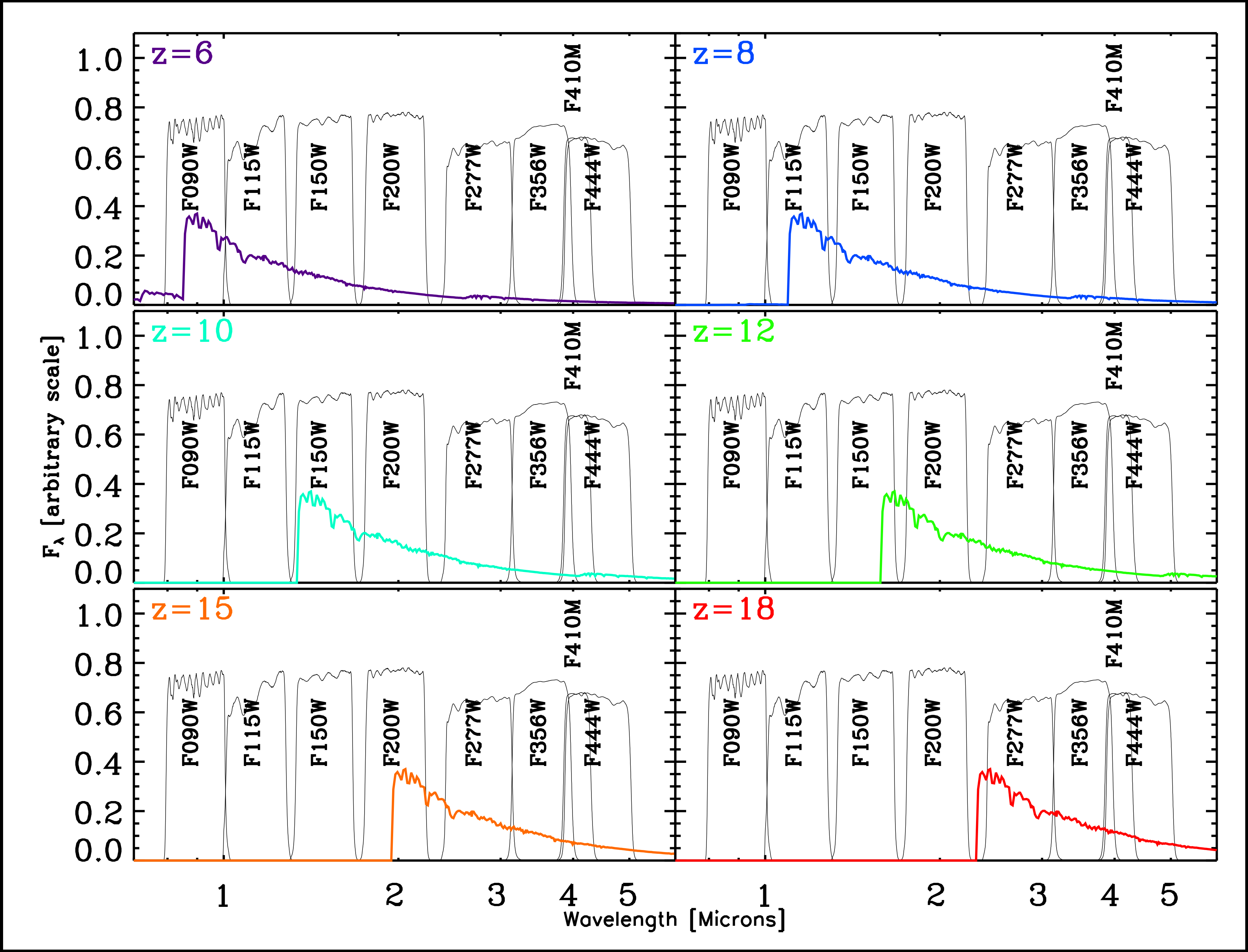
(3) How can JWST & GMT measure First Light & Galaxy Assembly?



Hubble (WFC3 & ACS) reach 26.5-27.0 mag ($\sim$100 fireflies from Moon) over 0.1×full Moon area in 10 filters from 0.2–2 μm wavelength.

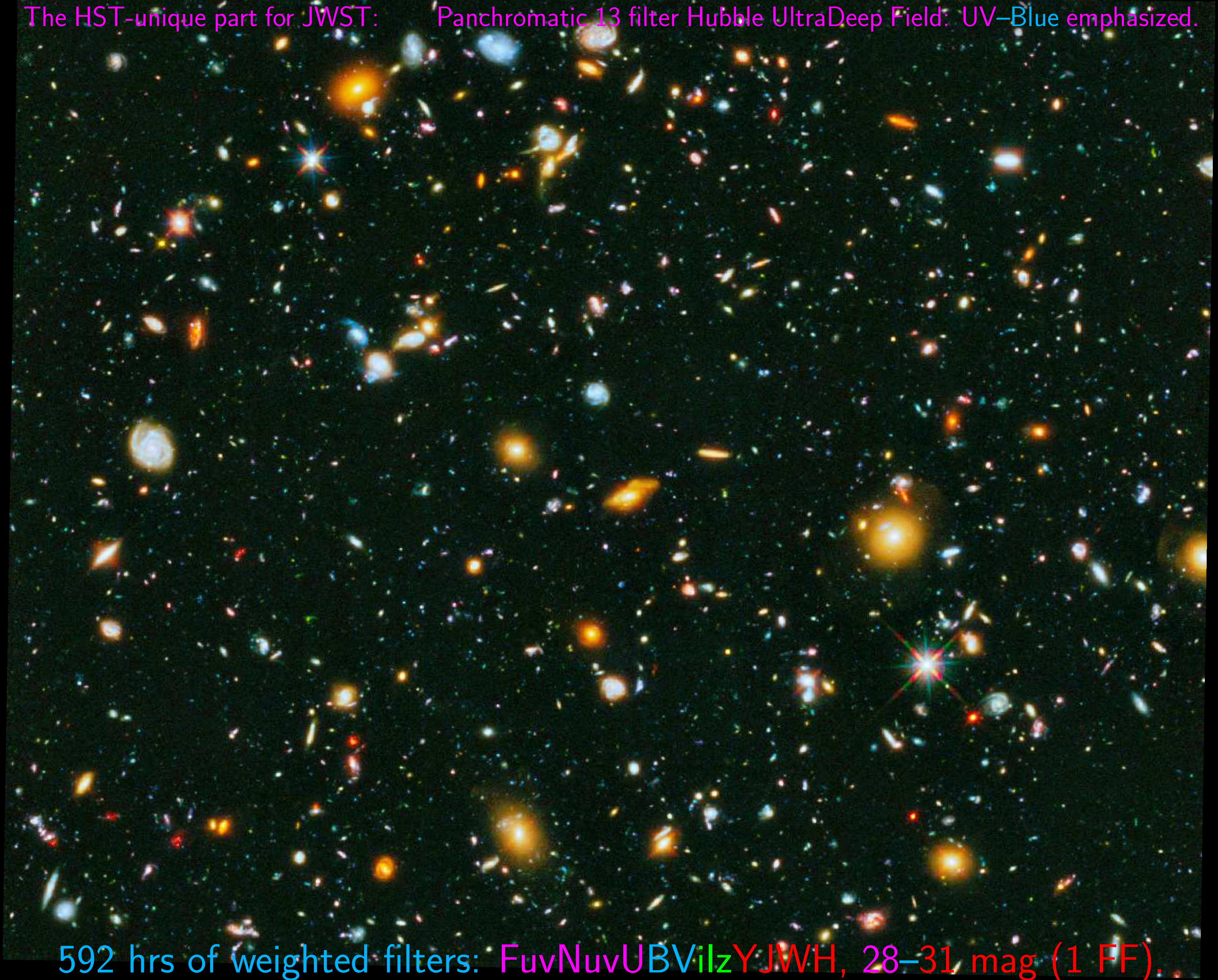
JWST has 3× and GMT 10× sharper imaging (31 mag=1 firefly from Moon) at red–near-IR wavelengths, tracing young and old stars + dust.

(3) How will Webb and GMT measure high-redshifted First Light objects?

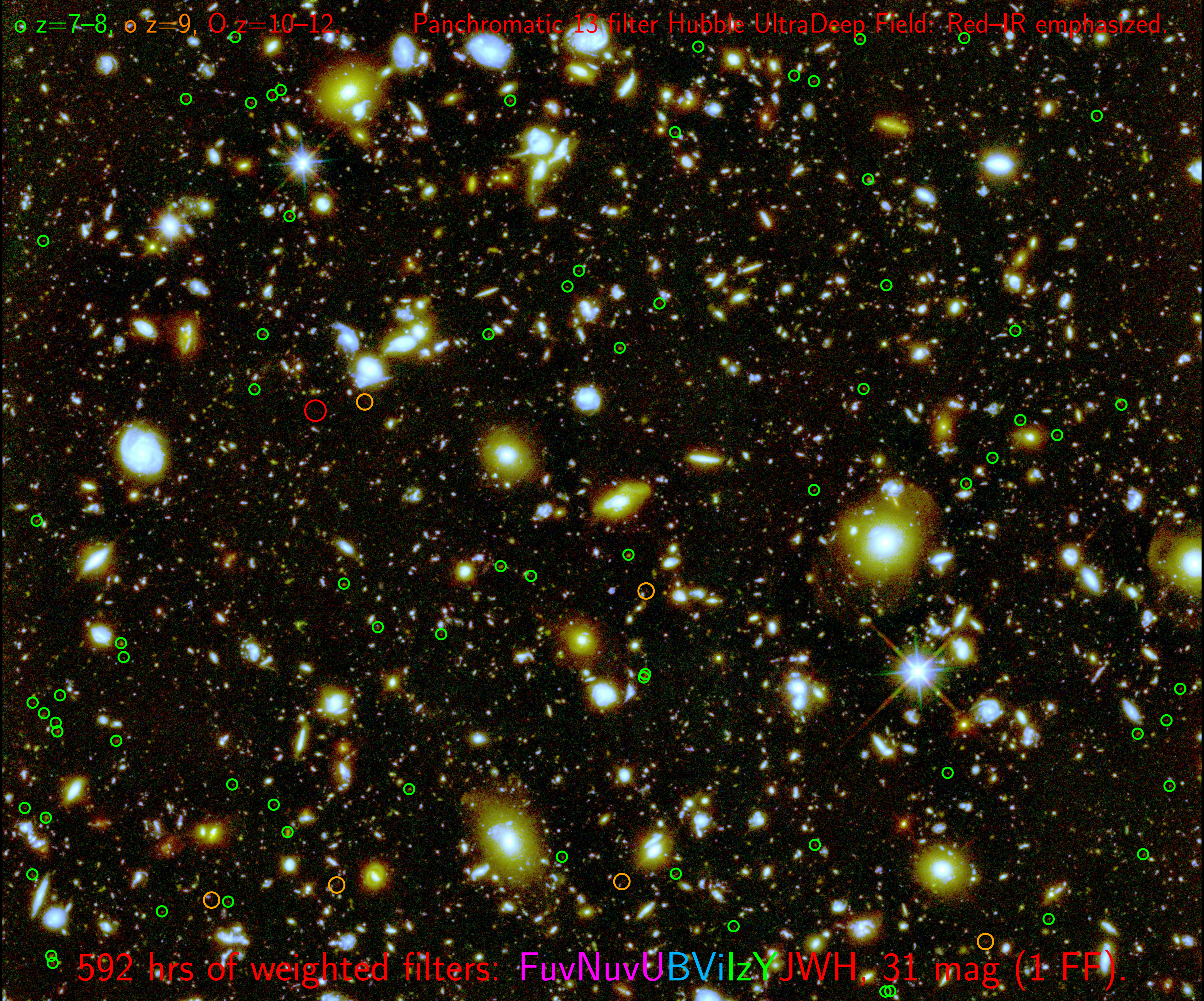


- Can't beat redshift: to see First Light, must observe near–mid IR.

The HST-unique part for JWST: Panchromatic 13 filter Hubble UltraDeep Field: UV–Blue emphasized.



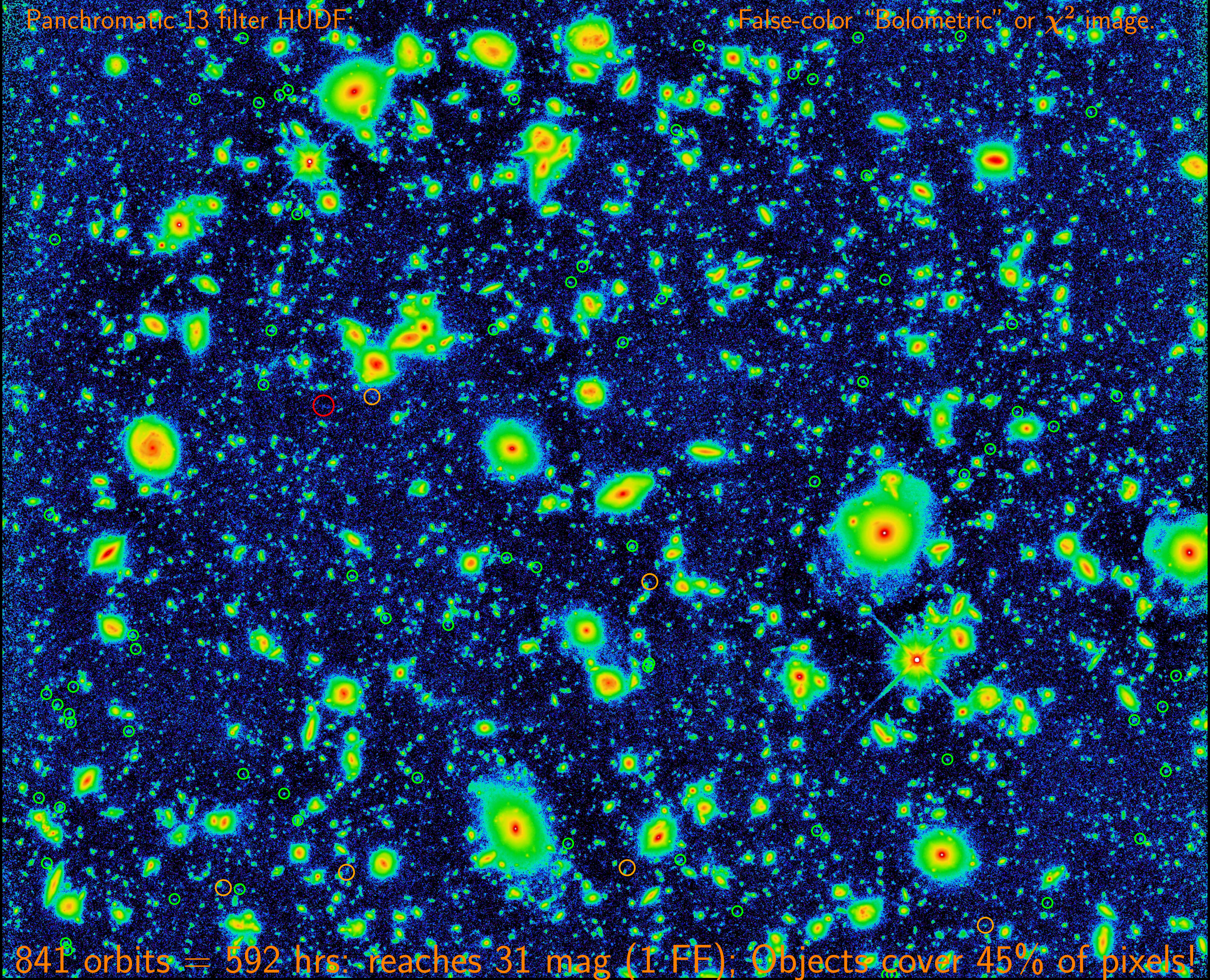
592 hrs of weighted filters: FuvNuvUBVizYJWH, 28–31 mag (1 FF).



○ z=7–8, ○ z=9, O z=10–12.

Panchromatic 13 filter Hubble UltraDeep Field: Red–IR emphasized.

592 hrs of weighted filters: FuvNuvUBViIzYJWH, 31 mag (1 FF).



Panchromatic 13 filter HUDF:

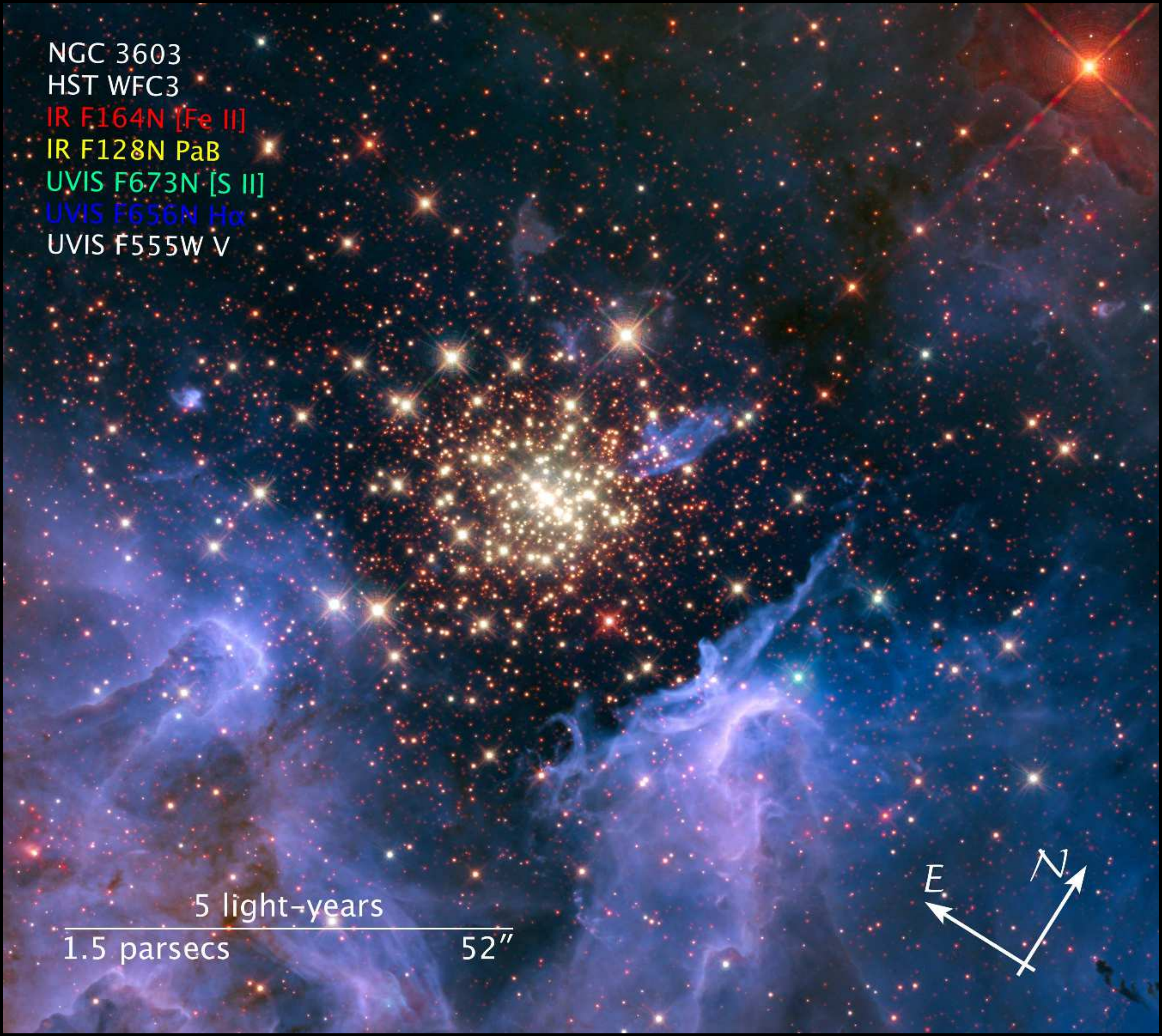
False-color "Bolometric" or χ^2 image.

841 orbits = 592 hrs: reaches 31 mag (1 FF); Objects cover 45% of pixels!

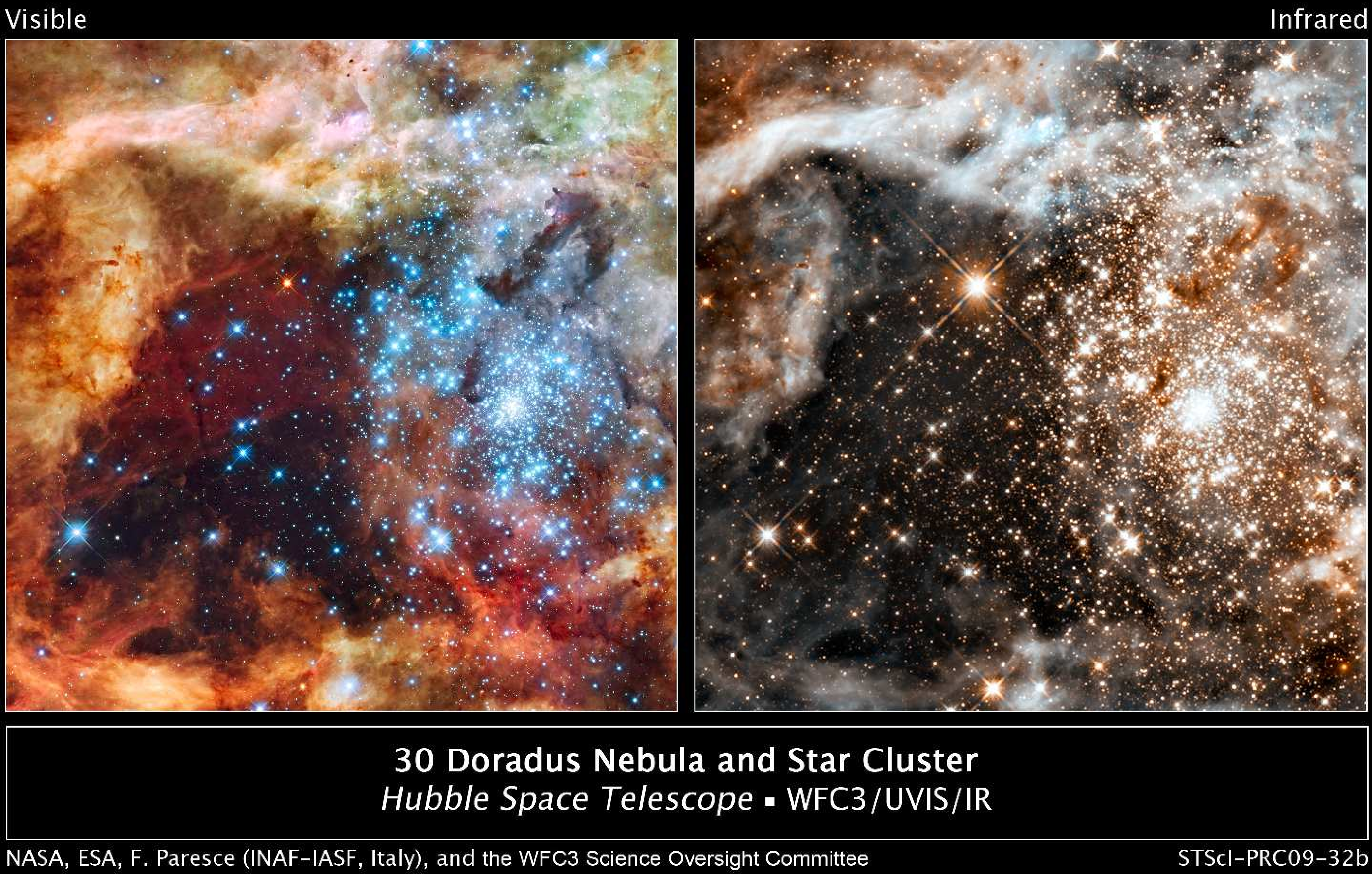
Frontier Field A2744: JWST & GMT need cluster lensing to see First Light ...

They must *routinely* observe what Einstein thought would be impossible.

(4) How can JWST & GMT measure Super-Massive Black Hole Growth?



NGC 3603: Young star-cluster triggering star-birth in "Pillars of Creation"



30 Doradus Nebula and Star Cluster

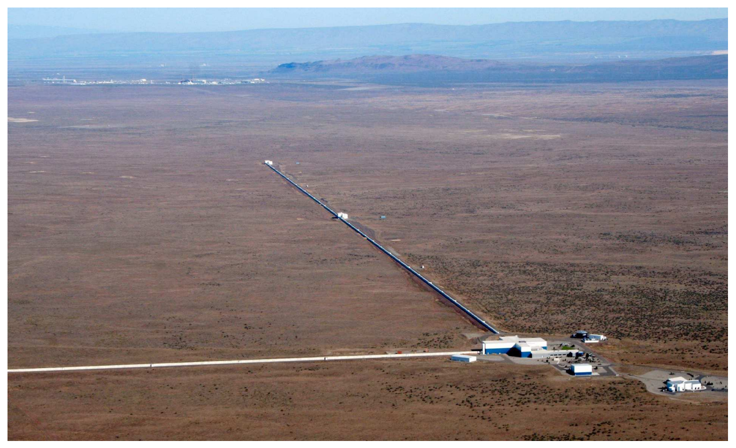
Hubble Space Telescope ▪ WFC3/UVIS/IR

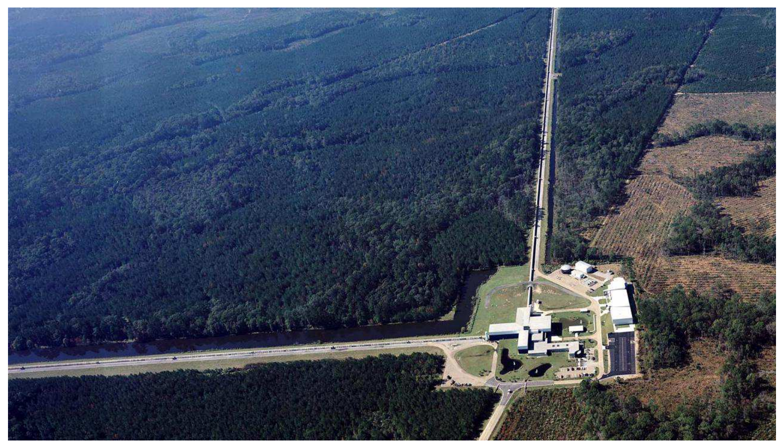
NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee

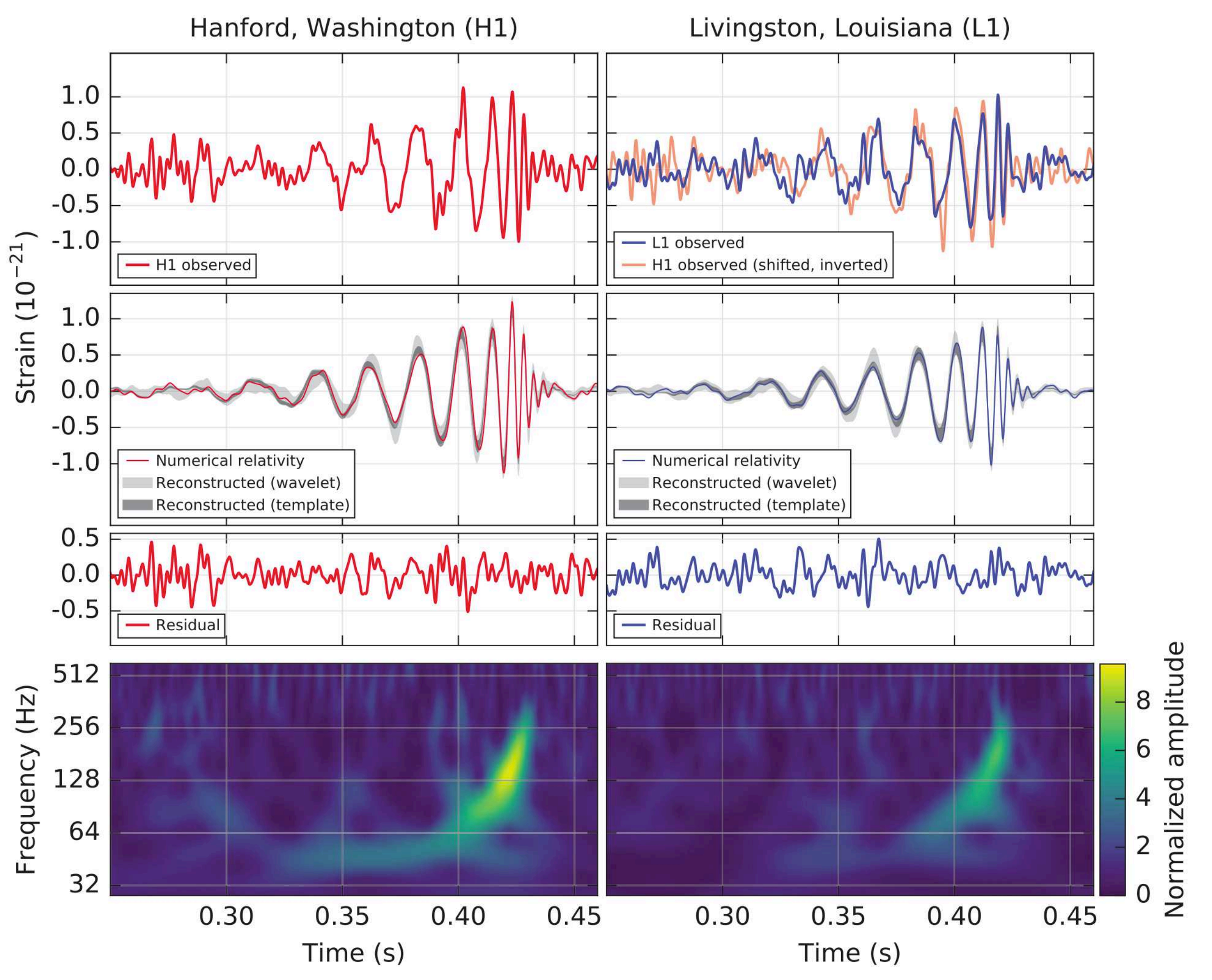
STScI-PRC09-32b

30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly).

Ordinary massive stars ($\geq 30\ M_{sun}$) leave modest black holes ($\geq 5\ M_{sun}$).







(1) LIGO first observed Gravitational Waves on Sept. 14, 2015.

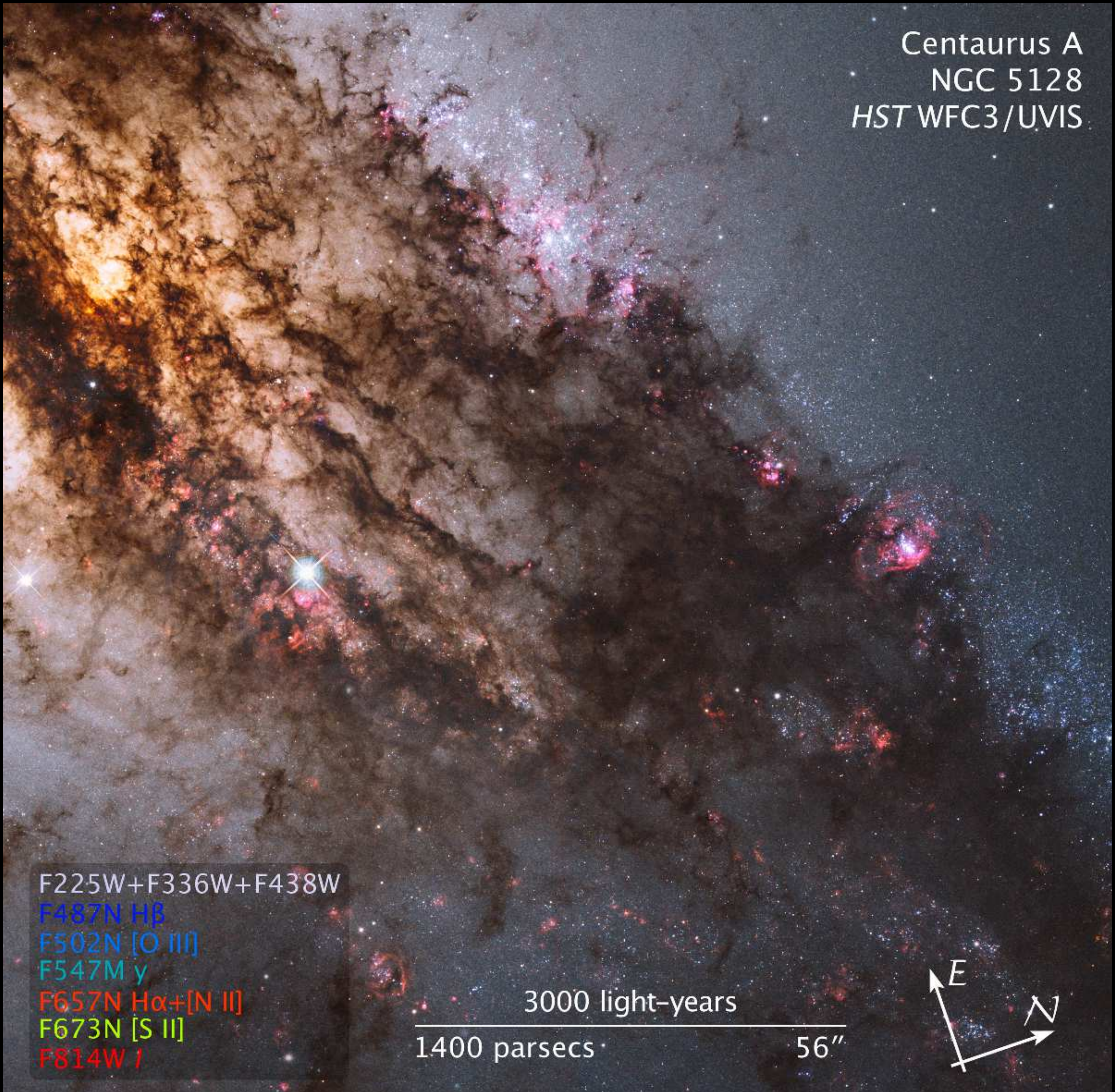
(2) These were caused by two merging (29+36 M$_{sun}$) black holes about 1 billion years ago!

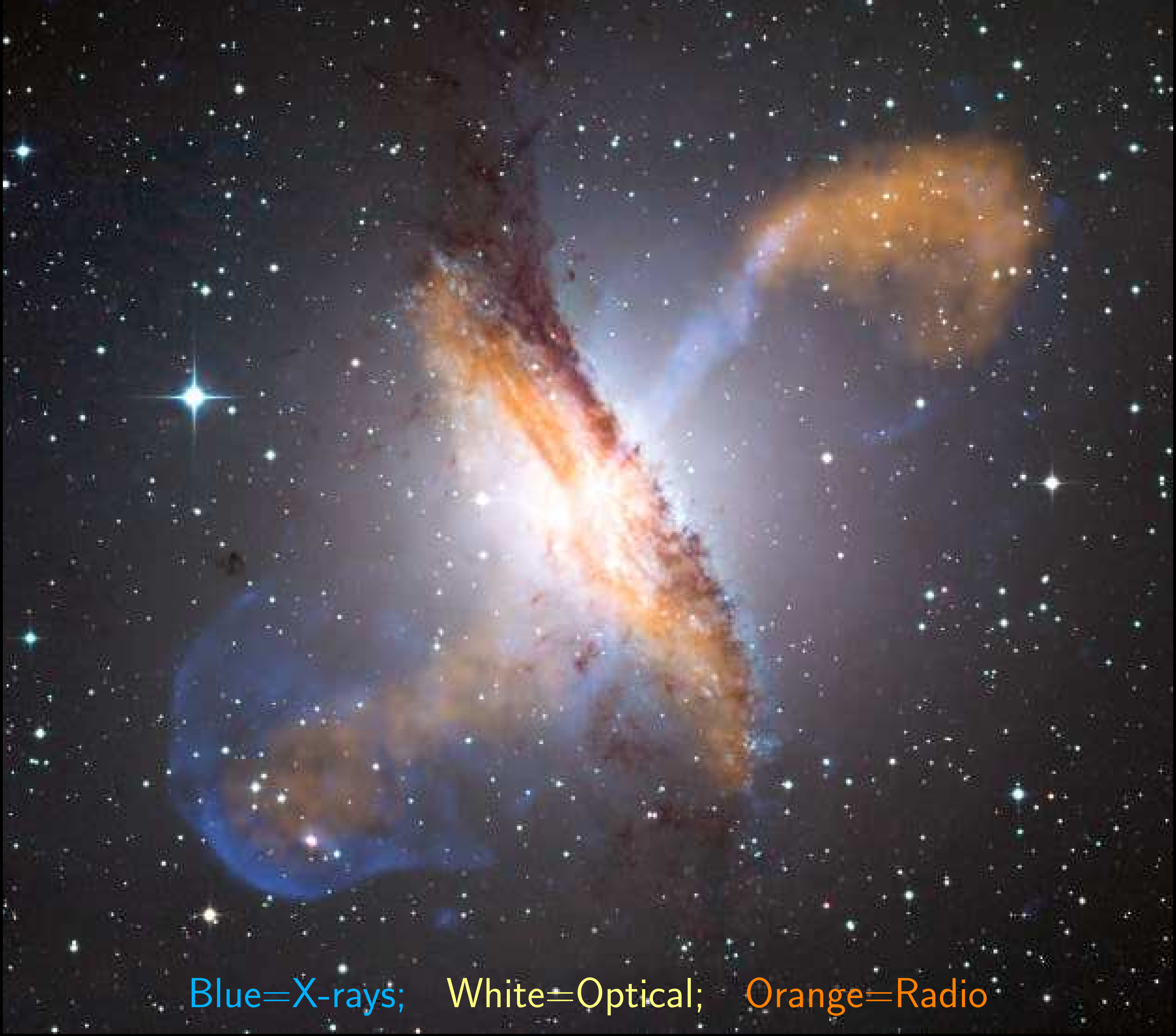
- E=Mc^2: 3 M$_{sun}$ was converted to energy in a fraction of a second!

Conclusion 1: Most low-mass black holes today are small, slow eaters:

- 29–36 M_{sun} blackholes may be leftover from First Stars (first 500 Myr).
- They were likely not fast & efficient eaters, but slow and messy ...

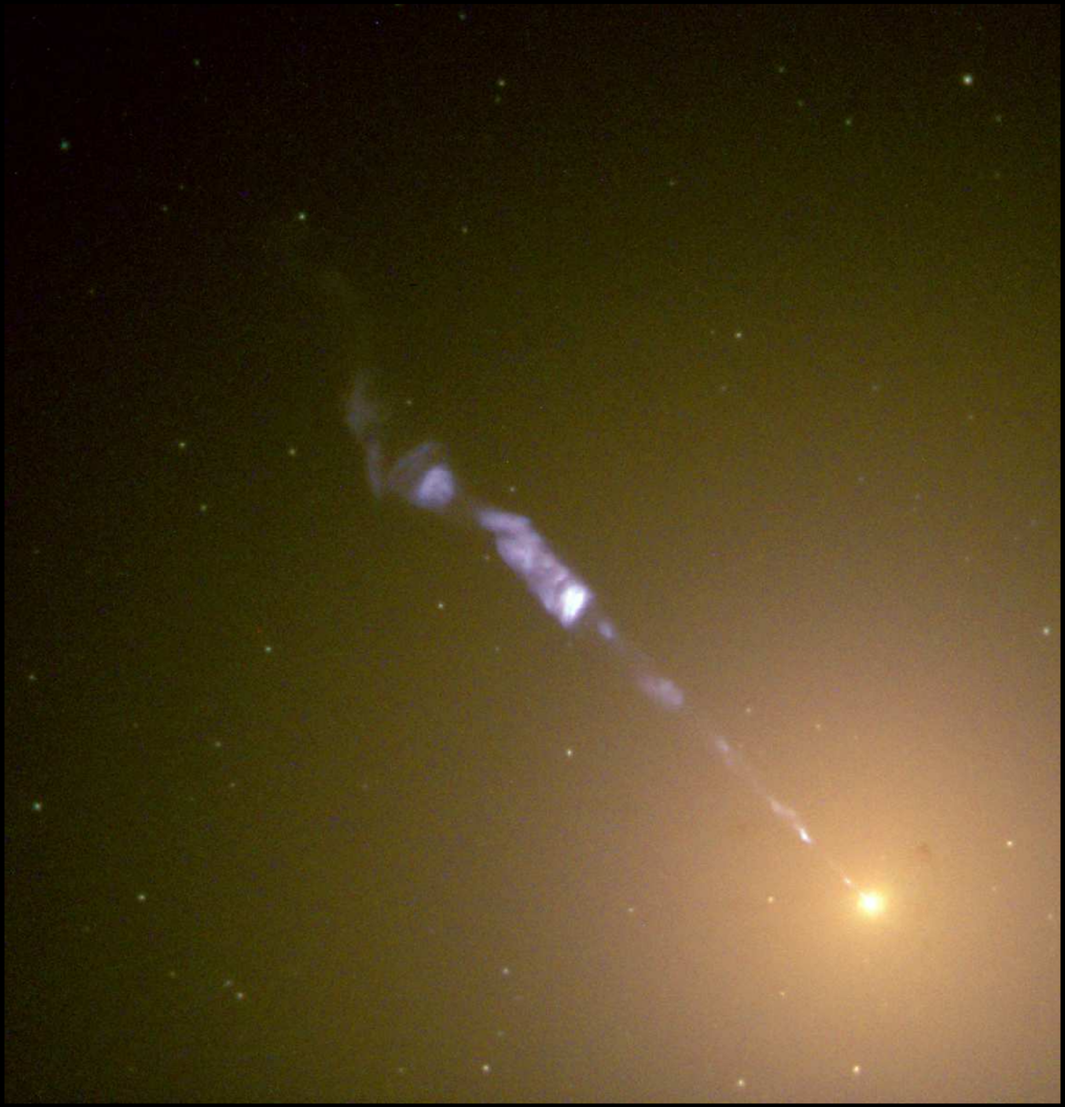
JWST and GMT may detect their accretion disks in the first Byr via lensing.

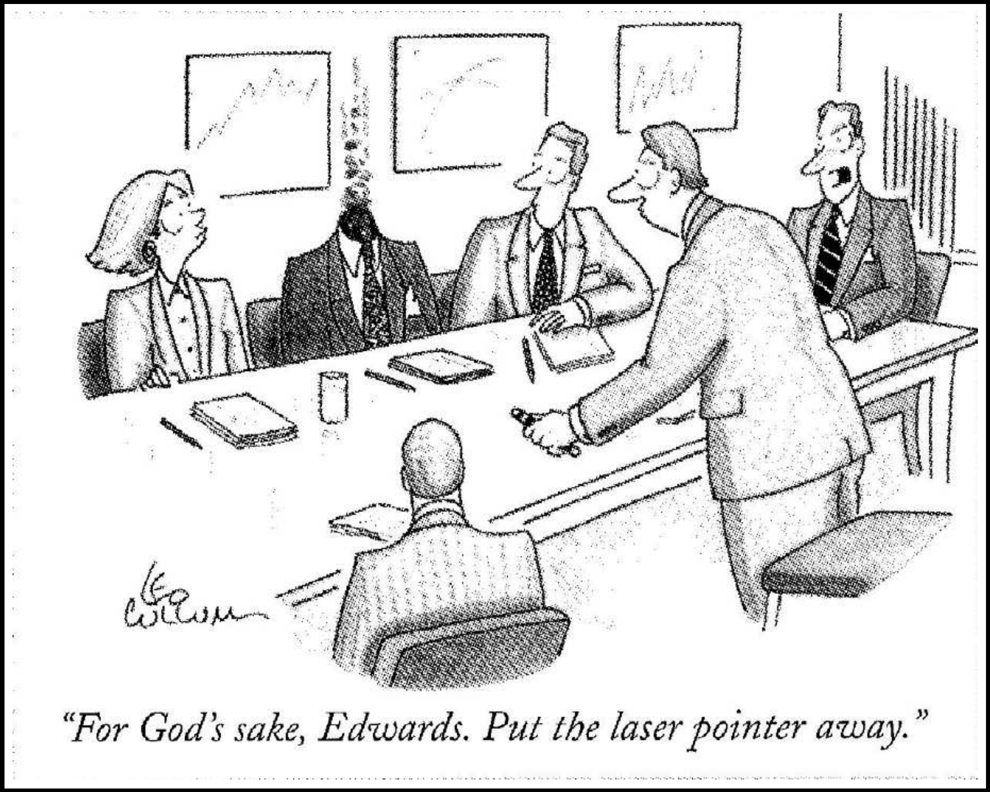

Centaurus A
NGC 5128
HST WFC3/UVIS
F225W+F336W+F438W
F487N Hβ
F502N [O III]
F547M y
F657N Hα+[N II]
F673N [S II]
F814W *I*
3000 light-years
1400 parsecs
56″
E
N



Blue=X-rays; White=Optical; Orange=Radio

The danger of having Quasar-like devices too close to home ...



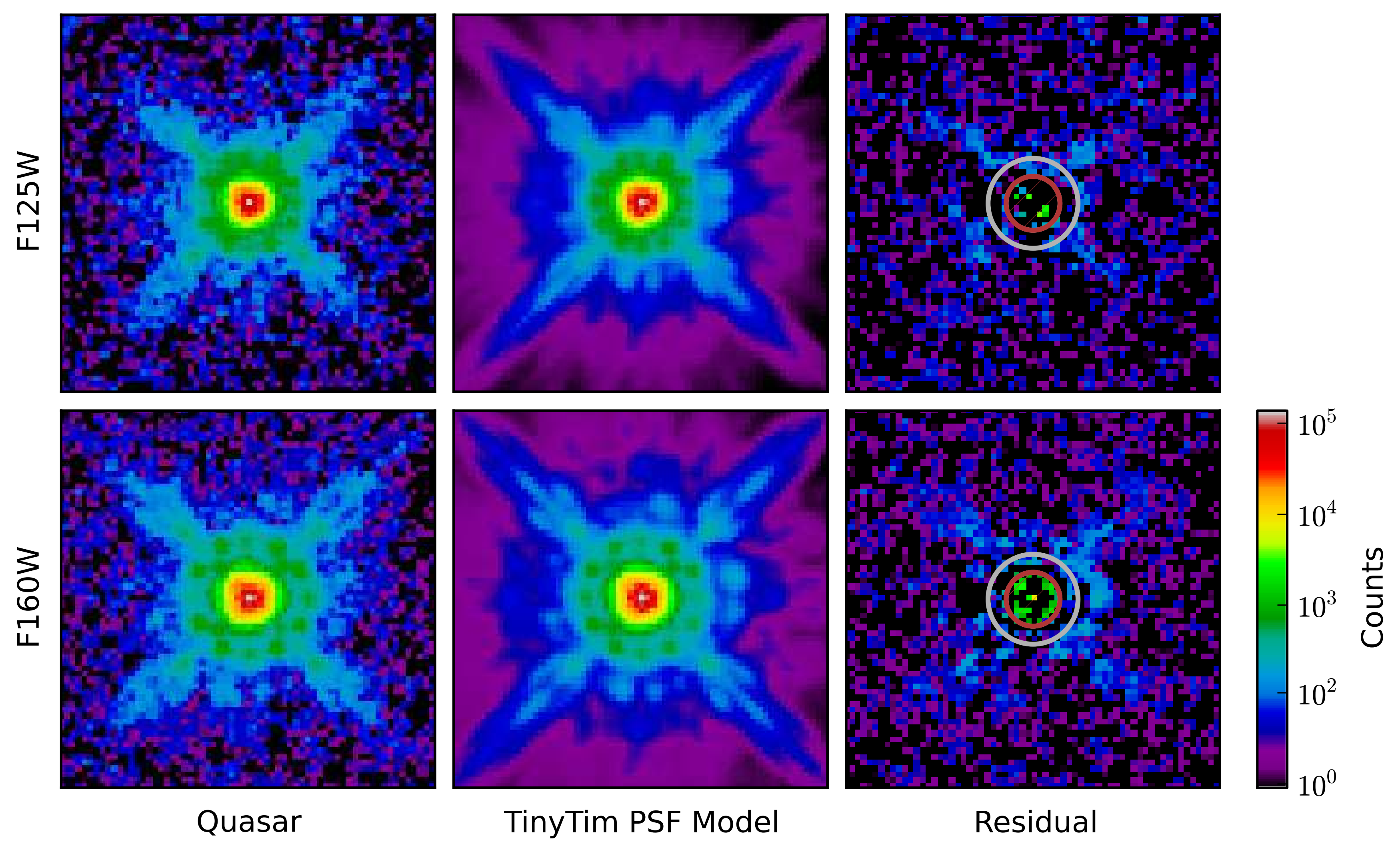


"For God's sake, Edwards. Put the laser pointer away."

Quasars are EXTREMELY bright sources if viewed "down-the-pipe".

Children: Please do NOT do this at home!

(3) Hubble WFC3 observations of Quasars in the first billion years.



- Contains 10^{14} solar luminosities within a region as small as Pluto's orbit!
- A feeding monster blackhole (3×10^9 solar mass), 900 Myr after BB!
- The most luminous Quasar in the universe has NO visible host galaxy!

Conclusion 2: Supermassive black holes started early & were very rapid eaters:

- Must have fed enormously rapidly in the first Byrs after the Big Bang.
- Were eating *cat*-astrophically (and secretly) until they ran out of food ...
- JWST and GMT can detect their host galaxies in first billion years.

(5) Summary and Conclusions

(1) HST set stage to measure galaxy assembly in the last 13.0 Byrs.

(2) More than 99% of JWST hardware built, & meets/exceeds specs.

(3) JWST & GMT will map epochs of First Light and Galaxy Assembly:

- Measure rapid growth of first supermassive blackholes & host galaxies.
- To see First Light, JWST & GMT must observe lensing clusters!
- Critical synergy: GMT's high-resolution imaging & spectra + long-term time-domain complement JWST's faint imaging + low-res spectra.

Like Ferdinand Magellan 500 years ago (and James Webb 50 years ago), we are about to explore major, new, unknown frontiers with both the GMT & JWST ...

SPARE CHARTS

- References and other sources of material shown:

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

`http://www.asu.edu/clas/hst/www/ahah/` [Hubble at Hyperspeed Java–tool]

`http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/` [Clickable HUDF map]

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

`http://ircamera.as.arizona.edu/nircam/`

`http://www.gmto.org/`

`http://www.gmto.org/2017/11/arizona-state-university-joins-the-giant-magellan-telescope-organization/`

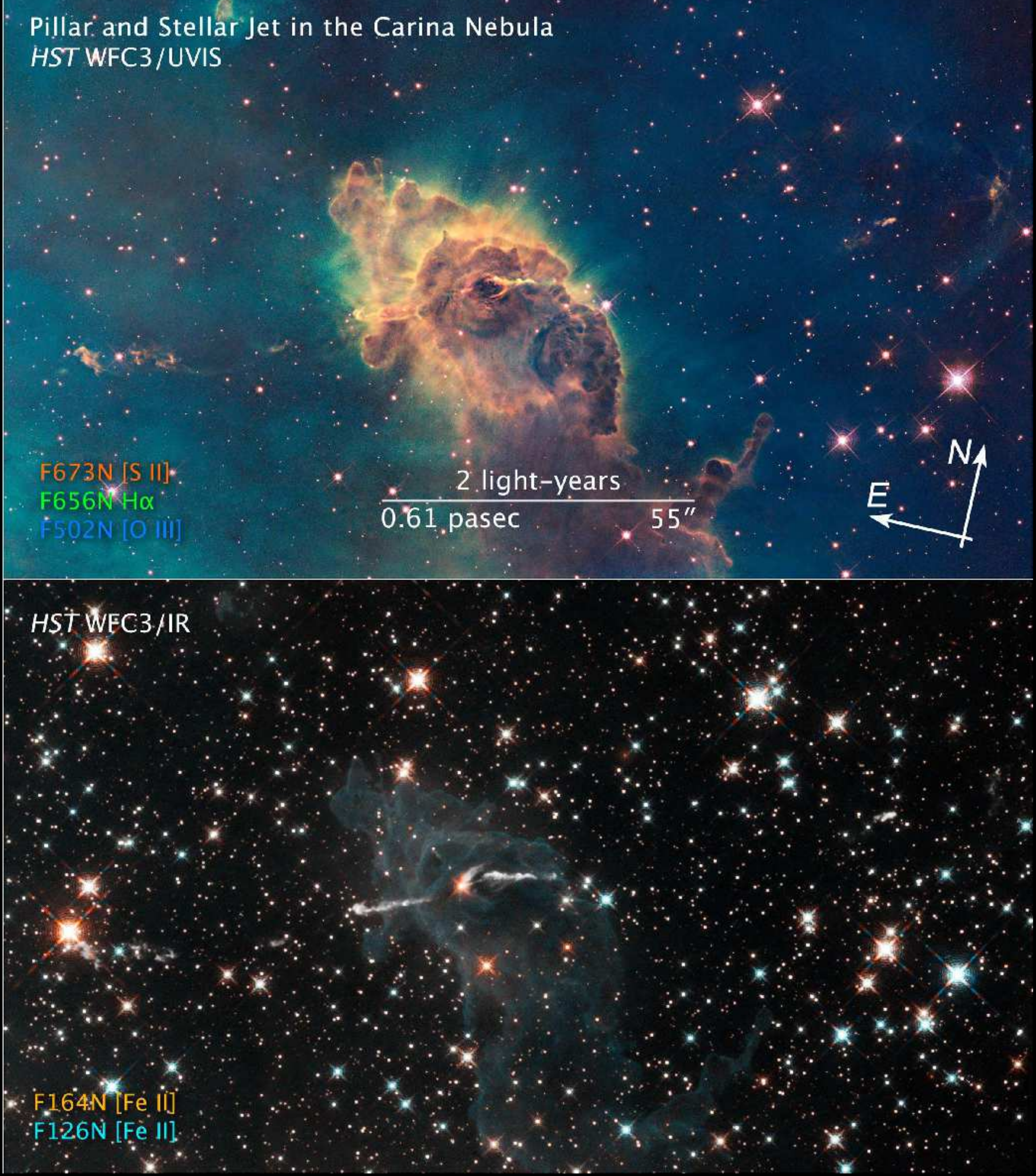
`https://asunow.asu.edu/20171129-discoveries-giant-magellan-telescope-asu-joins-consortium`

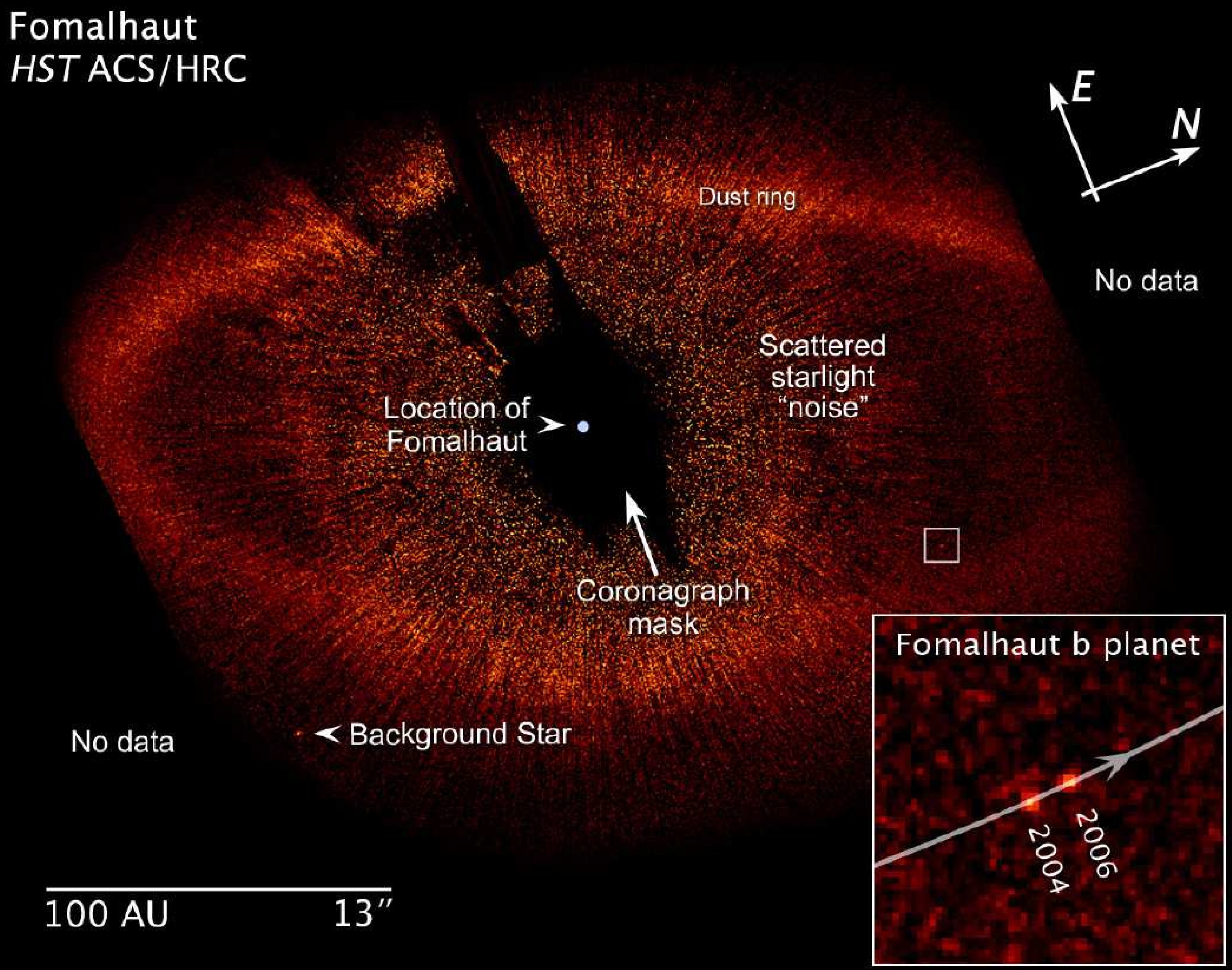
Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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

Windhorst, R., et al. 2008, Advances in Space Research, 41, 1965

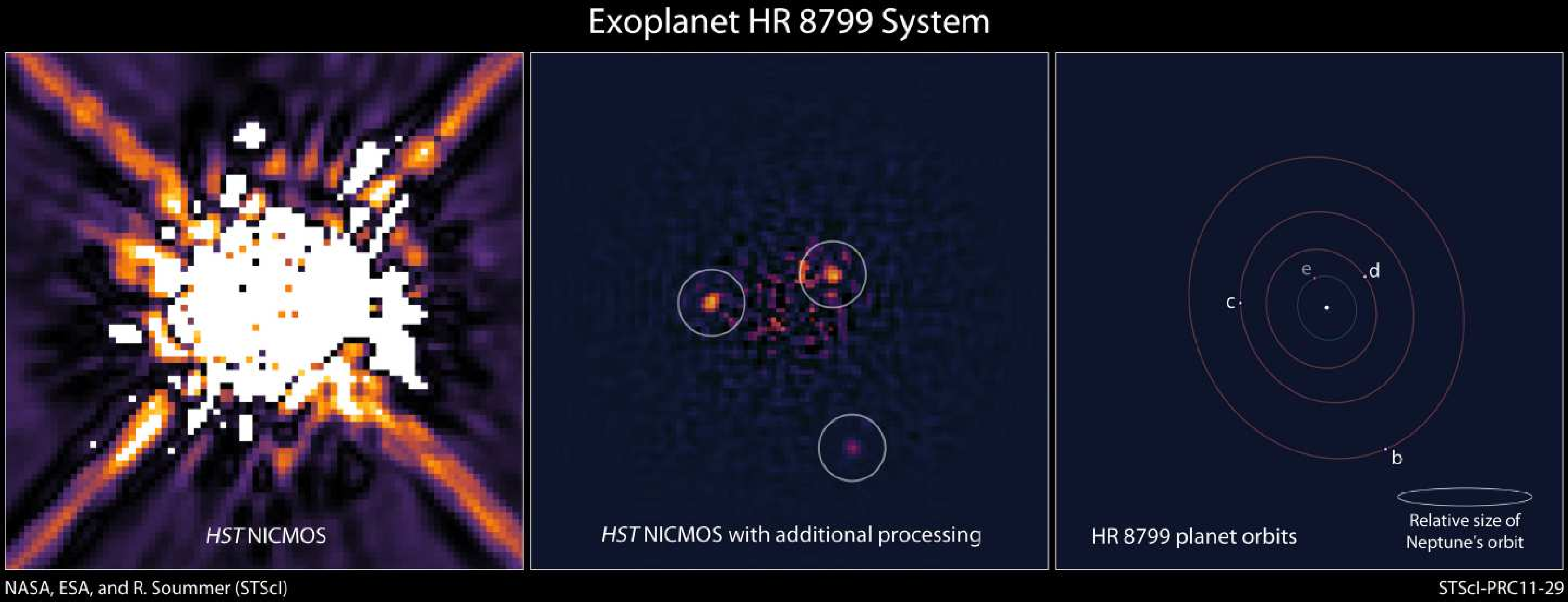
Windhorst, R., et al., 2011, ApJS, 193, 27 (astro-ph/1005.2776).


Pillar and Stellar Jet in the Carina Nebula
HST WFC3/UVIS
F673N [S II]
F656N Hα
F502N [O III]
2 light-years
0.61 pasec
55″
N
E
HST WFC3/IR
F164N [Fe II]
F126N [Fe II]



HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut: First direct imaging of a moving planet forming around a nearby star!

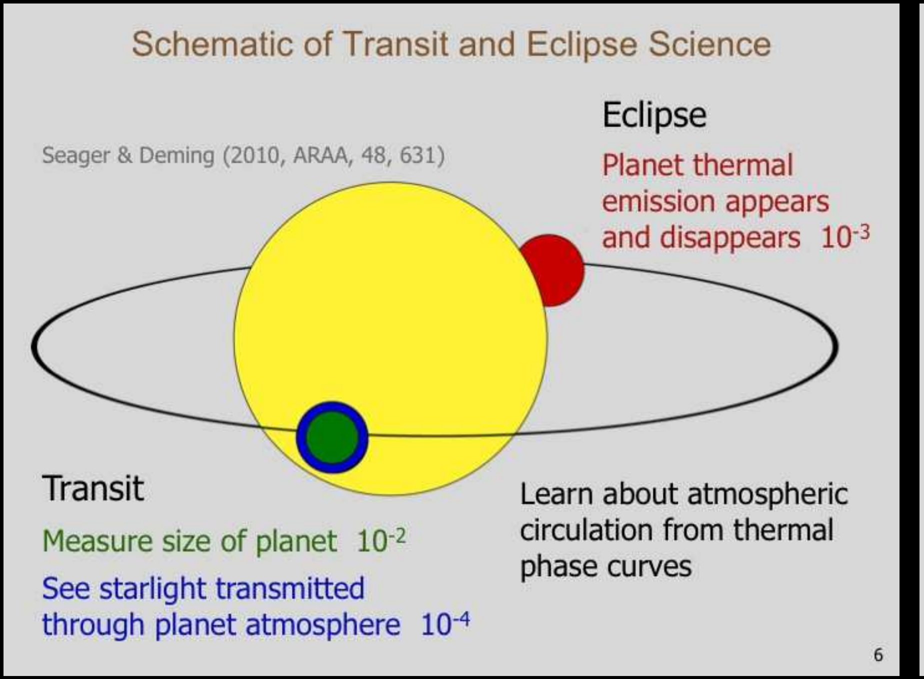
JWST & GMT will map proto-planets closer in for more distant stars.



HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star.

Press release: `http://hubblesite.org/newscenter/archive/releases/2011/29/`

JWST & GMT will map such planets closer in for more distant stars.



Schematic of Transit and Eclipse Science

Seager & Deming (2010, ARAA, 48, 631)

Eclipse

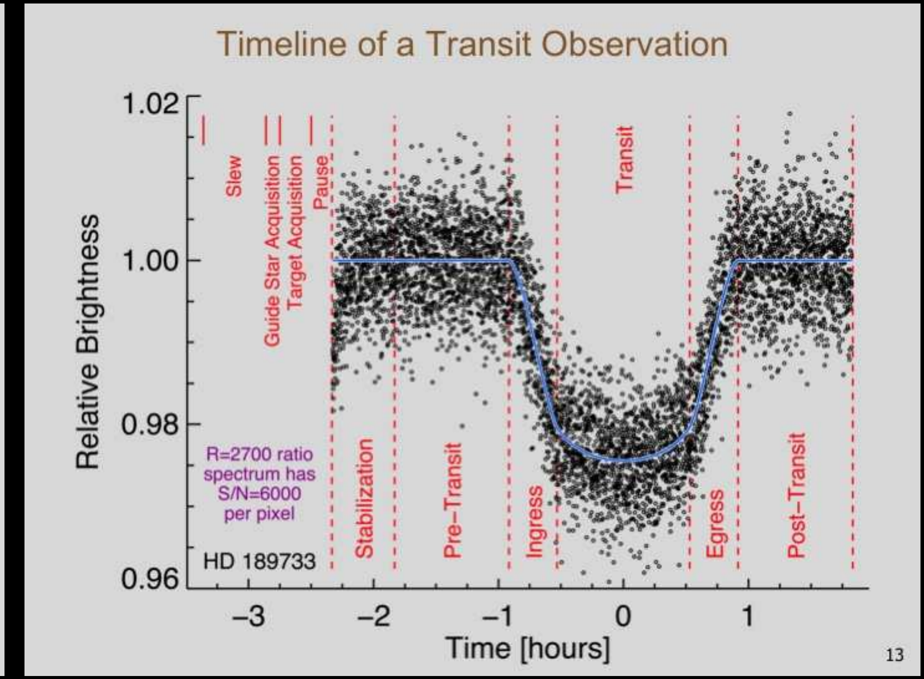
Planet thermal emission appears and disappears 10^{-3}

Transit

Measure size of planet 10^{-2}

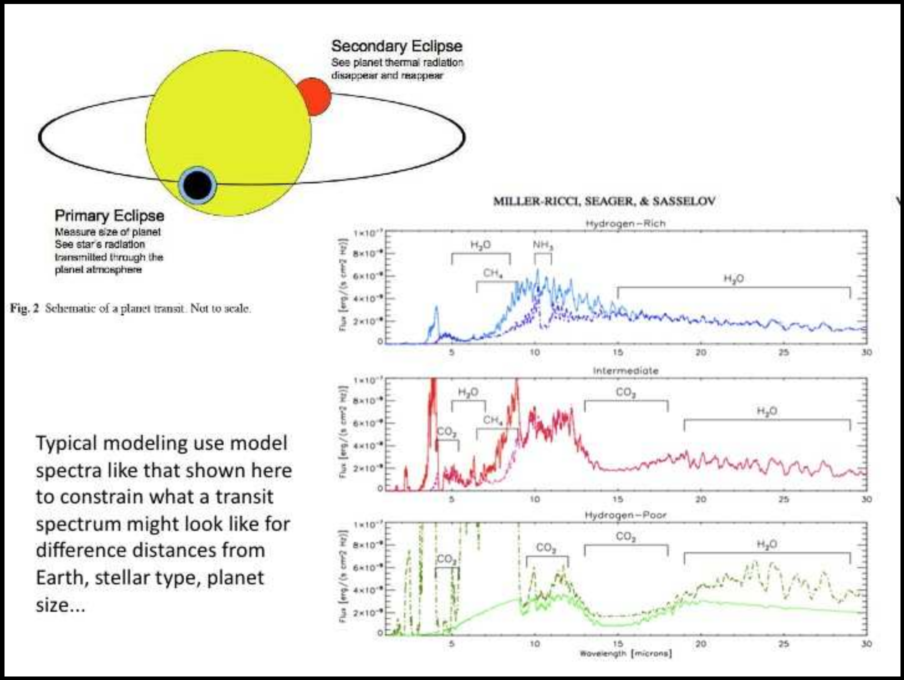
See starlight transmitted through planet atmosphere 10^{-4}

Learn about atmospheric circulation from thermal phase curves



Timeline of a Transit Observation

JWST & GMT will do precise photometry of transiting Earth-like exoplanets.



Secondary Eclipse
See planet thermal radiation disappear and reappear

Primary Eclipse
Measure size of planet
See star's radiation transmitted through the planet atmosphere

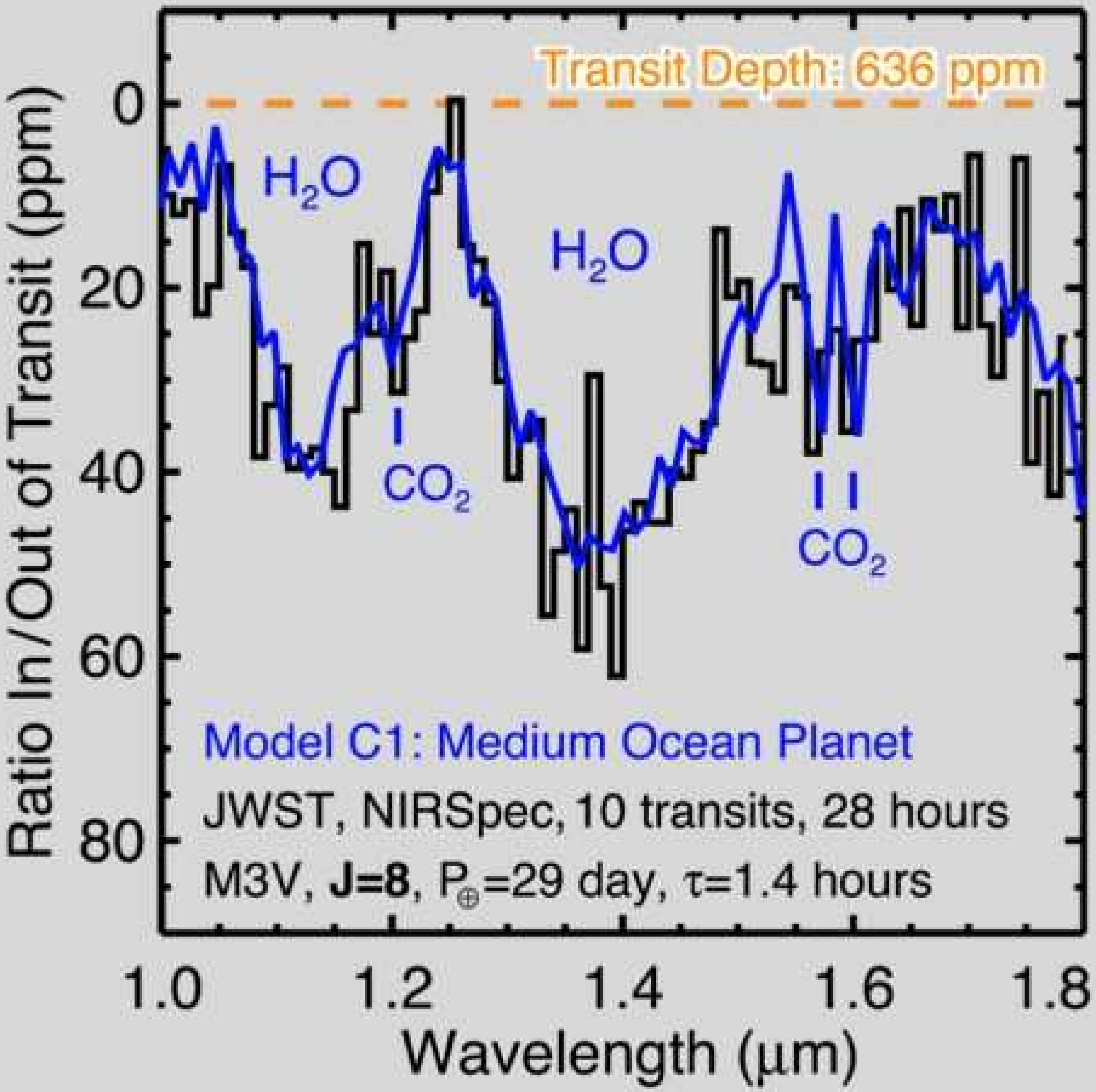
Fig. 2 Schematic of a planet transit. Not to scale.

MILLER-RICCI, SEAGER, & SASSELOV

Typical modeling use model spectra like that shown here to constrain what a transit spectrum might look like for difference distances from Earth, stellar type, planet size...

JWST & GMT spectra to find water, CO_2, etc., on Earth-like exoplanets.

Transit Spectrum of Habitable "Ocean Planet"



JWST & GMT spectra to find water, CO_2, etc., on Earth-like exoplanets.

Illustration Sequence of the Milky Way and Andromeda Galaxy Colliding

NASA, ESA, Z. Levay and R. van der Marel (STScI), T. Hallas, and A. Mellinger ▪ STScI-PRC12-20b

Will this ever happen to our own Galaxy?

YES! Hubble showed no lateral motion of Andromeda:

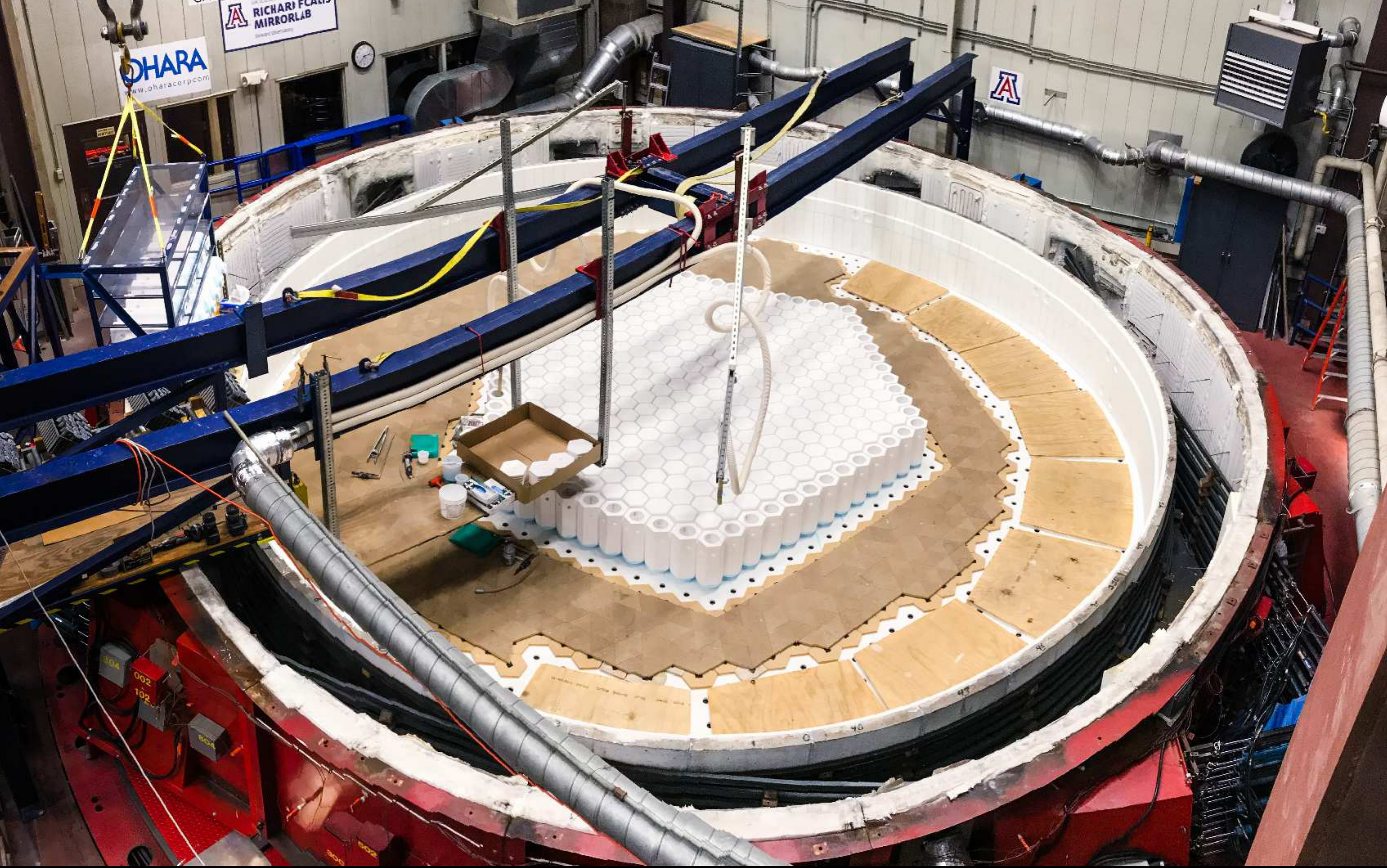
Approaches at –110 km/s.

Hence, Andromeda will merge with our Milky Way!

The two blackholes (10^6–10^7 M_{sun}) will also merge!

Not to worry: only 4–5 billion years from today!

But it will fire-up a quasar in the new elliptical galaxy!

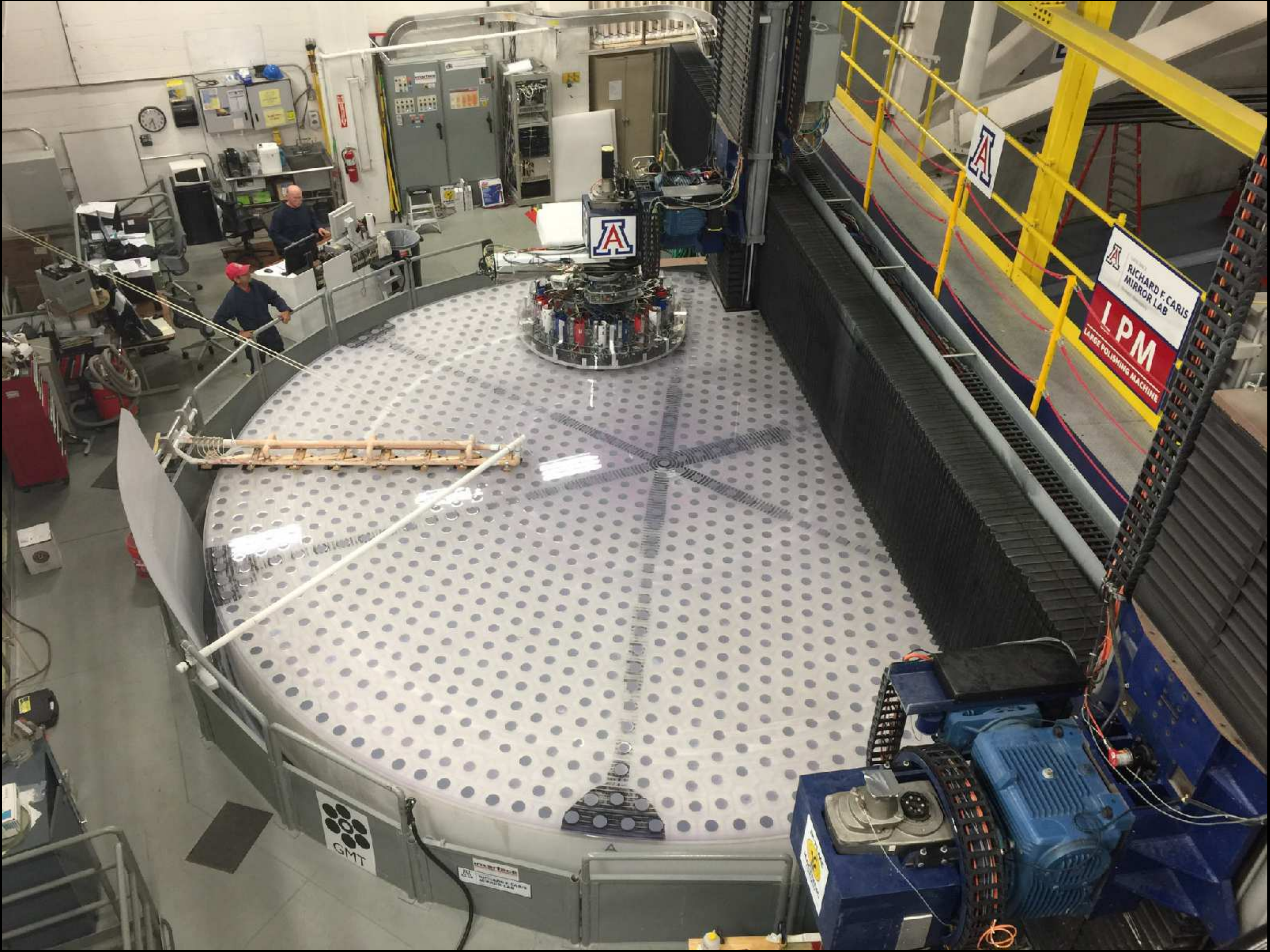


Richard F. Caris Mirror Lab (UofA): Filling the oven base with molds.

Filling the oven base with boro-silicate glass.

Heat the oven (to 1165°C) while spinning it (at 4.974 RPM) for several days, including the start of cooling.

Cool mirror, mirror (on the wall): Who is the fairest of them all?



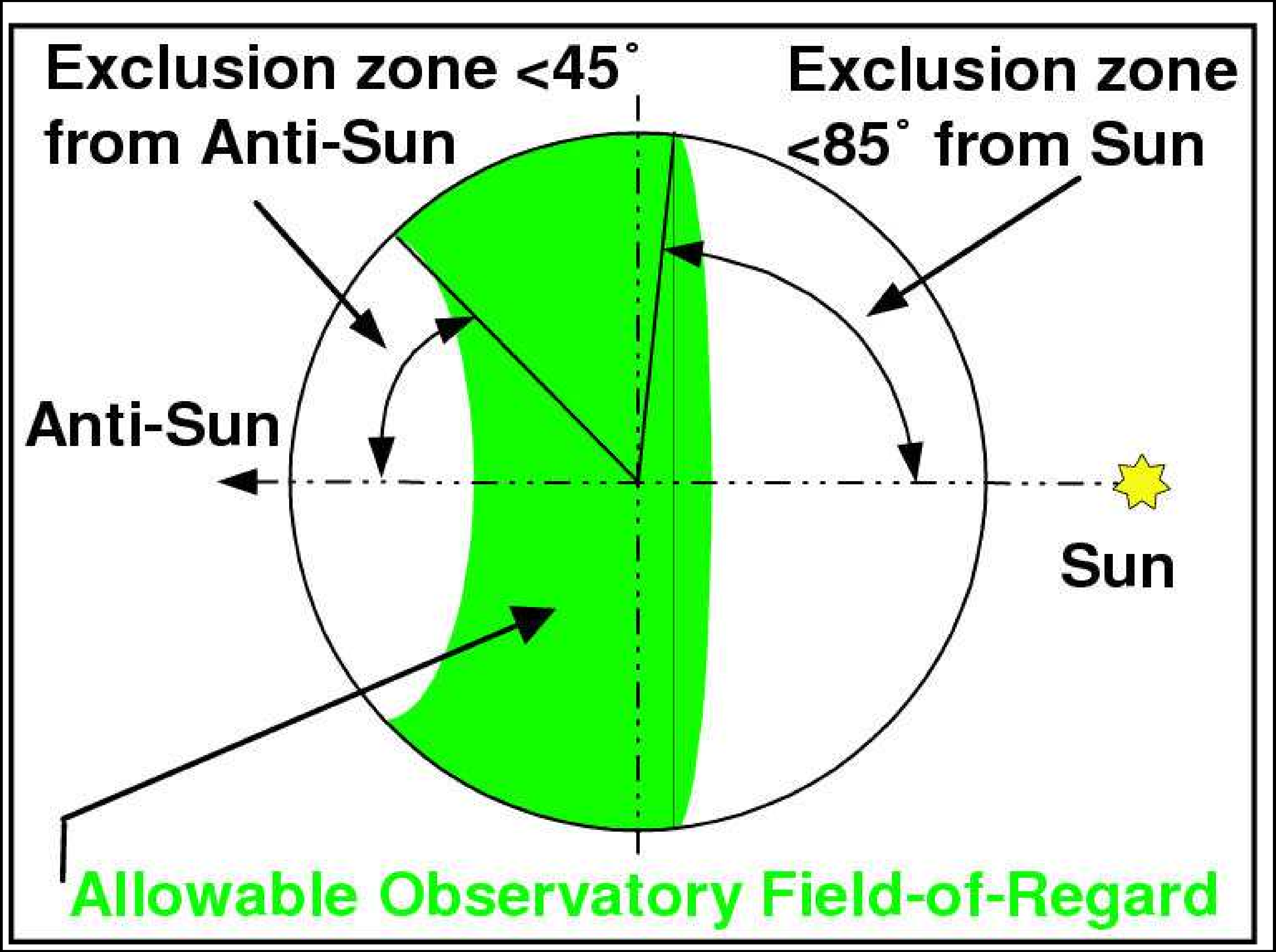
Nearly parabolic-surfaced mirror ready for final grinding and fine polishing.

Some of our ASU grad students do important outreach events:

Annual Girl Scout Stargazing at the White House South lawn (July 2015).

ASU graduate Amber Straughn (right; now at NASA GSFC working for Nobel Laureate Dr. John Mather) informs the Obama's about NASA.

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

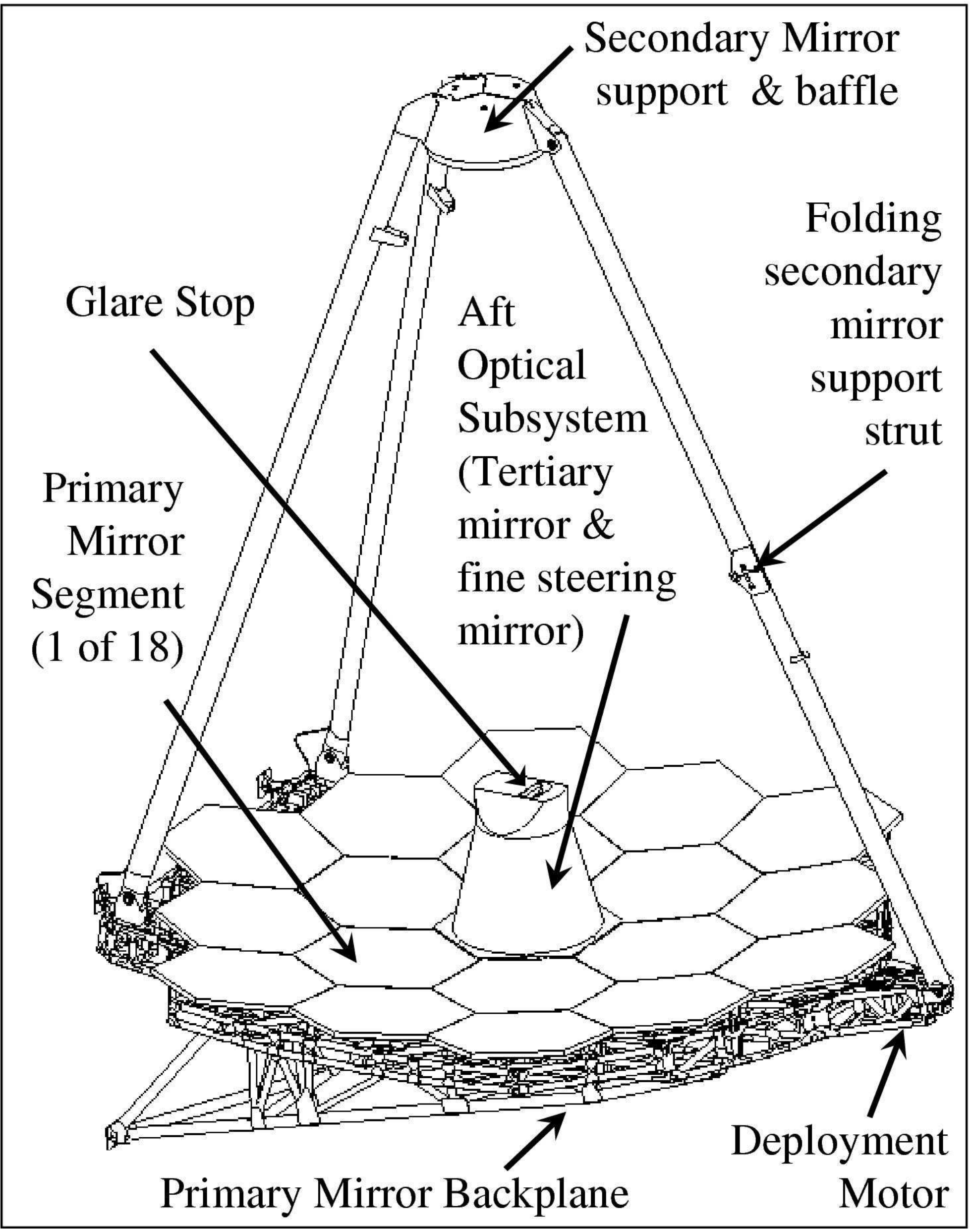


JWST can observe North/South Ecliptic pole targets continuously:

- ∼500-hr JWST projects swap back/forth between NEP/SEP targets.

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

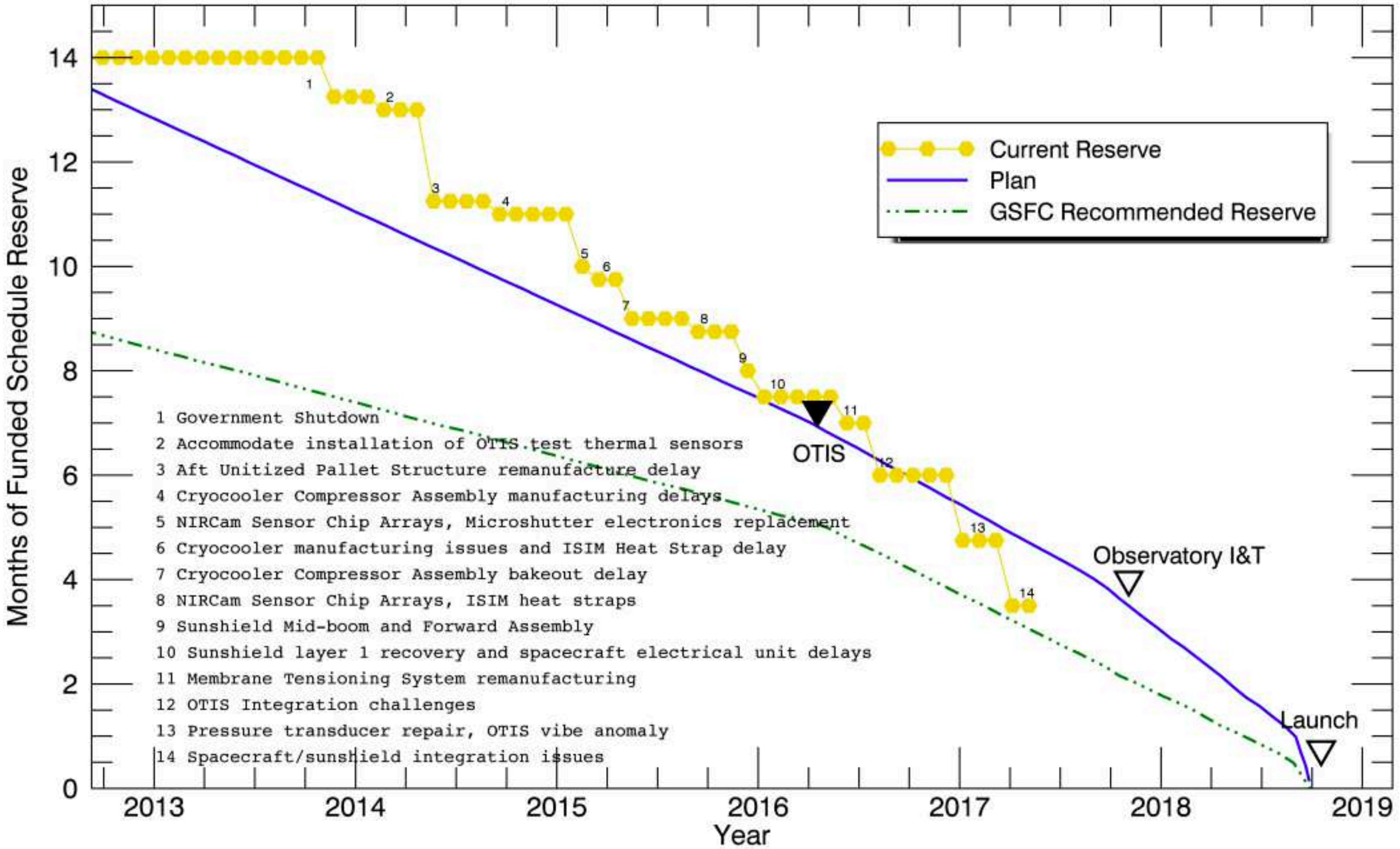


Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2017.

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

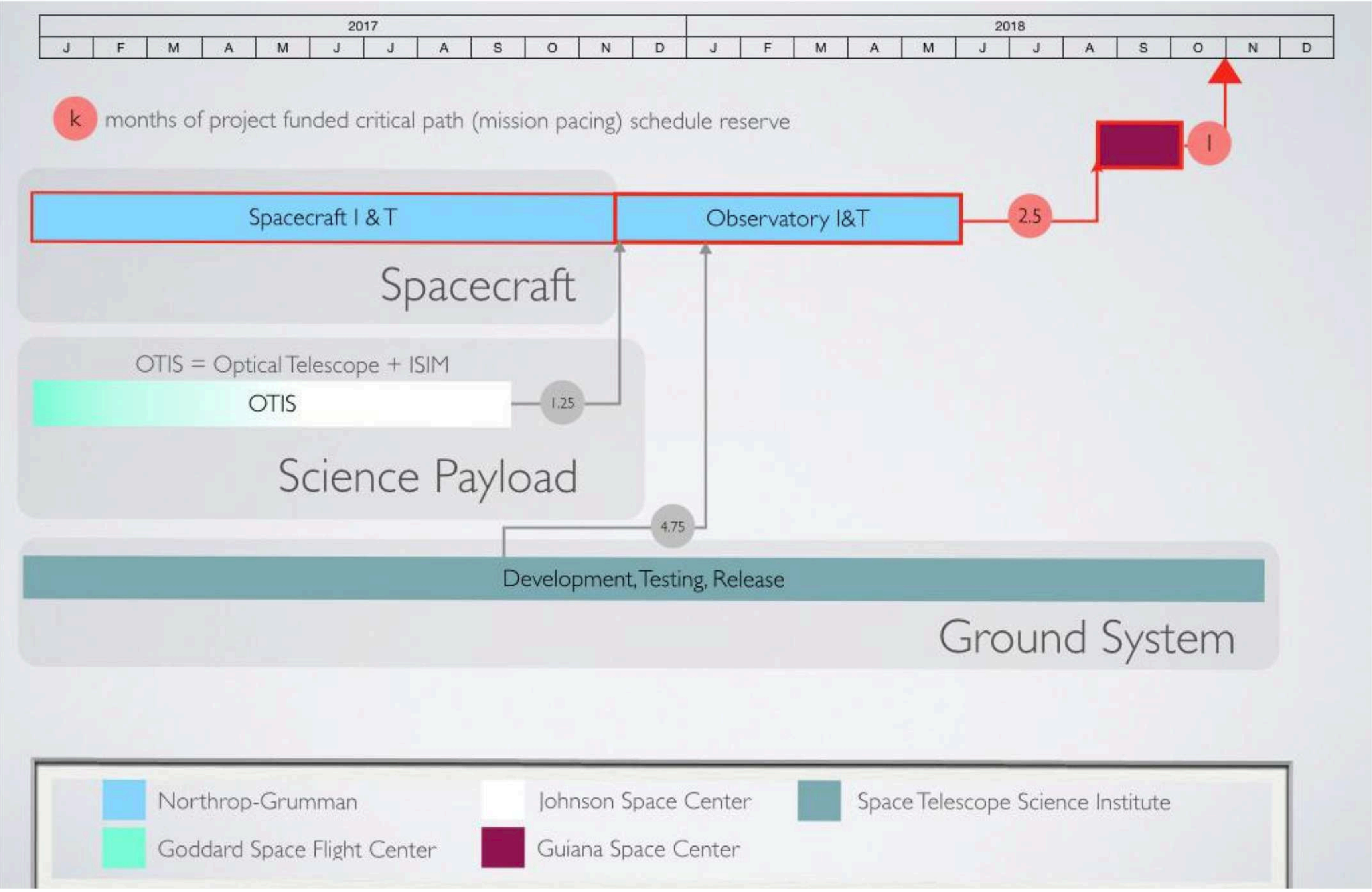
In L2, WFS updates every 10 days depending on scheduling/ SC-illumination.

Funded Schedule Reserve



To stay on schedule, need: 1) Sufficient Project contingency ($\gtrsim$25% of total).
2) Replanned and newly managed Project (starting late summer 2011).

Simplified Schedule

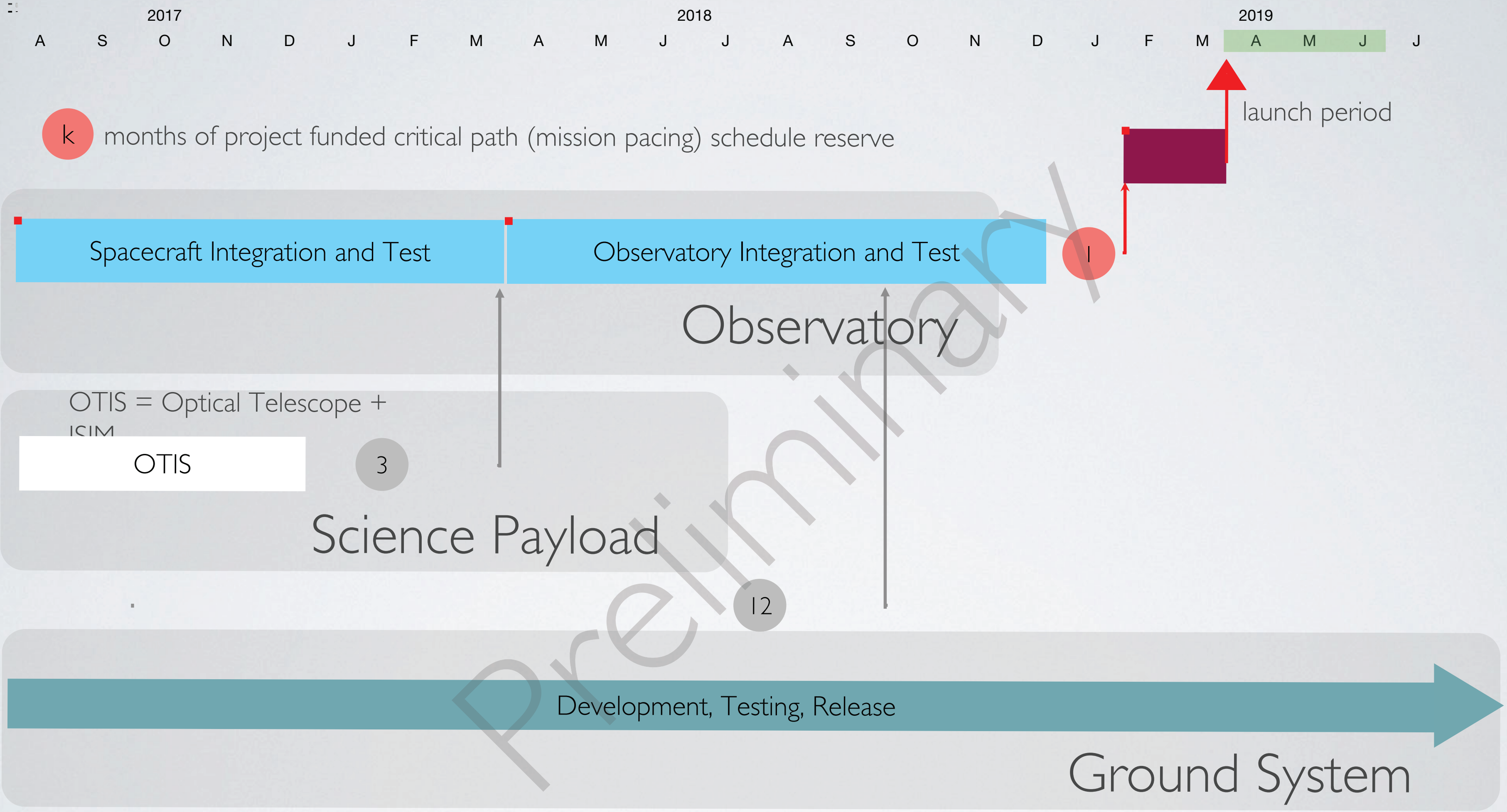


170612 JWST Monthly Telecon 5

Path forward to Launch (WAS: Oct. 2018): $\lesssim$5 months schedule reserve.

- Instruments+detectors & Optical Telescope Element were on critical path.

SIMPLIFIED SCHEDULE



🟦 Northrop-Grumman
⬜ Johnson Space Center
🟥 Guiana Space Center
🟩 Space Telescope Science Institute

Path forward to Launch (NOW: Spring 2019): $\lesssim$4 mos schedule reserve.

- Spacecraft and Sunshield are now on critical path (at Northrop).