

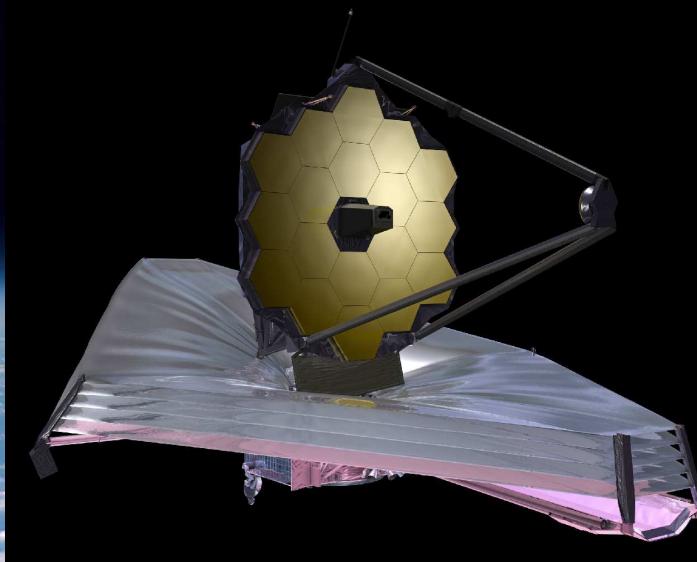
# The Search for First Light: James Webb Space Telescope Hardware Update 2017.

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



*Colloquium at the Giant Magellan Telescope Organization, Pasadena, CA; Thursday October 26, 2017.*

*All presented materials are ITAR-cleared.*

*(Expressed opinions are my own, not necessarily NASA's or ASU's).*

# Outline

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- (1) James Webb Space Telescope Hardware Update as of 2017.
- (2) How will JWST measure Galaxy Assembly & Supermassive Blackhole Growth?
- (3) How will JWST measure the Epoch of First Light (using gravitational lensing) — handshake with Planck 2016 results.
- (4) The Future: Synergy between GMT and JWST
- (5) Summary and Conclusions.

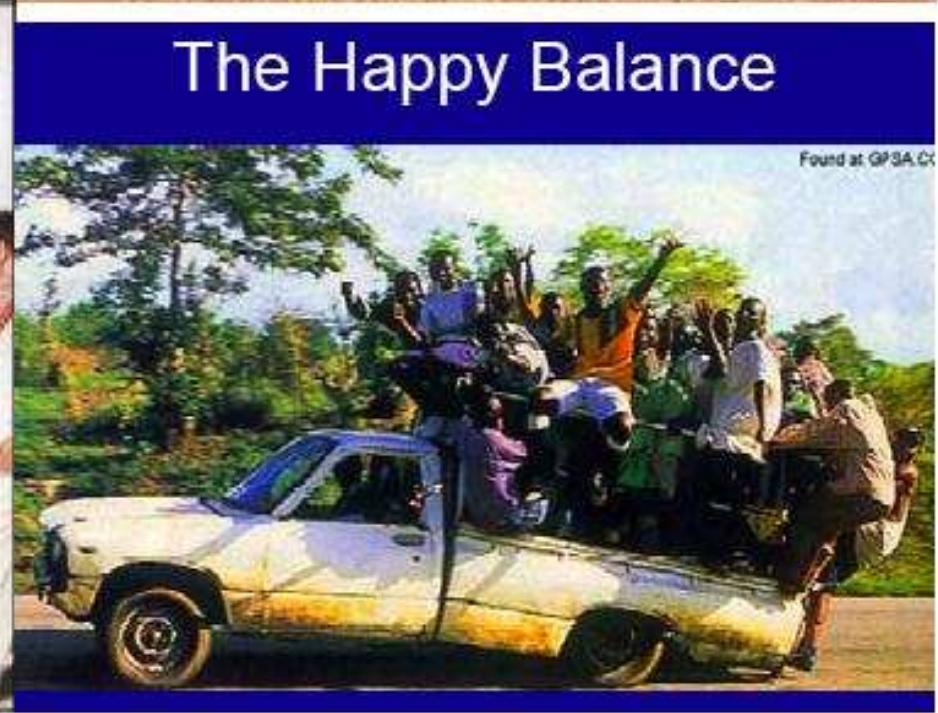


Sponsored by NASA/HST & JWST

Talk is on: [http://www.asu.edu/clas/hst/www/jwst/jwsttalks/gmto17\\_jwst.pdf](http://www.asu.edu/clas/hst/www/jwst/jwsttalks/gmto17_jwst.pdf)

What the Scientists See:

What the Project Manager Sees:



The Happy Balance

Found at GP3A.CX

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



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

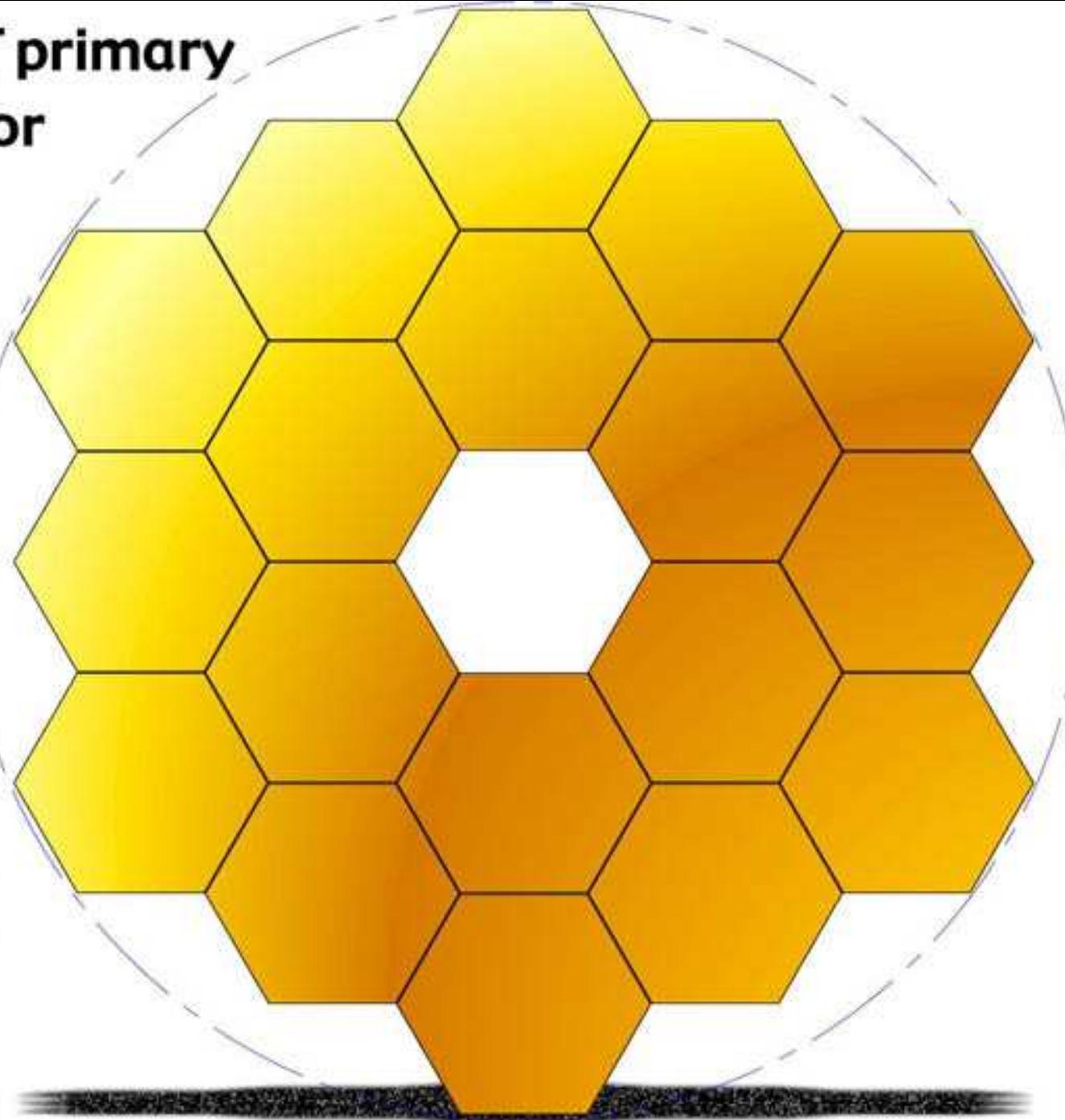


James E. Webb (1906–1992) — Second NASA Administrator

Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2018?.

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

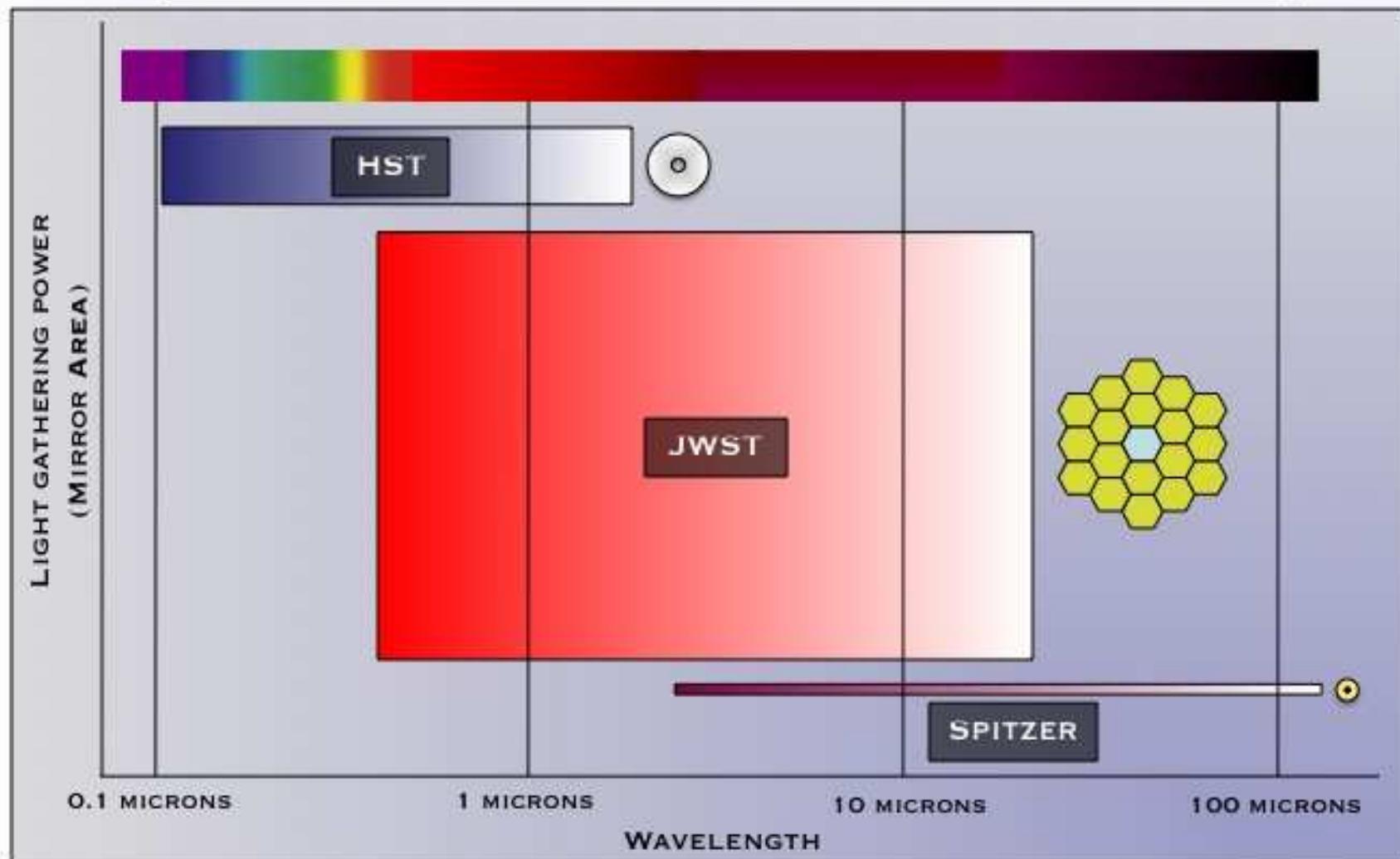
**JWST primary  
mirror**



**Hubble primary  
mirror**

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.

# THE JAMES WEBB SPACE TELESCOPE



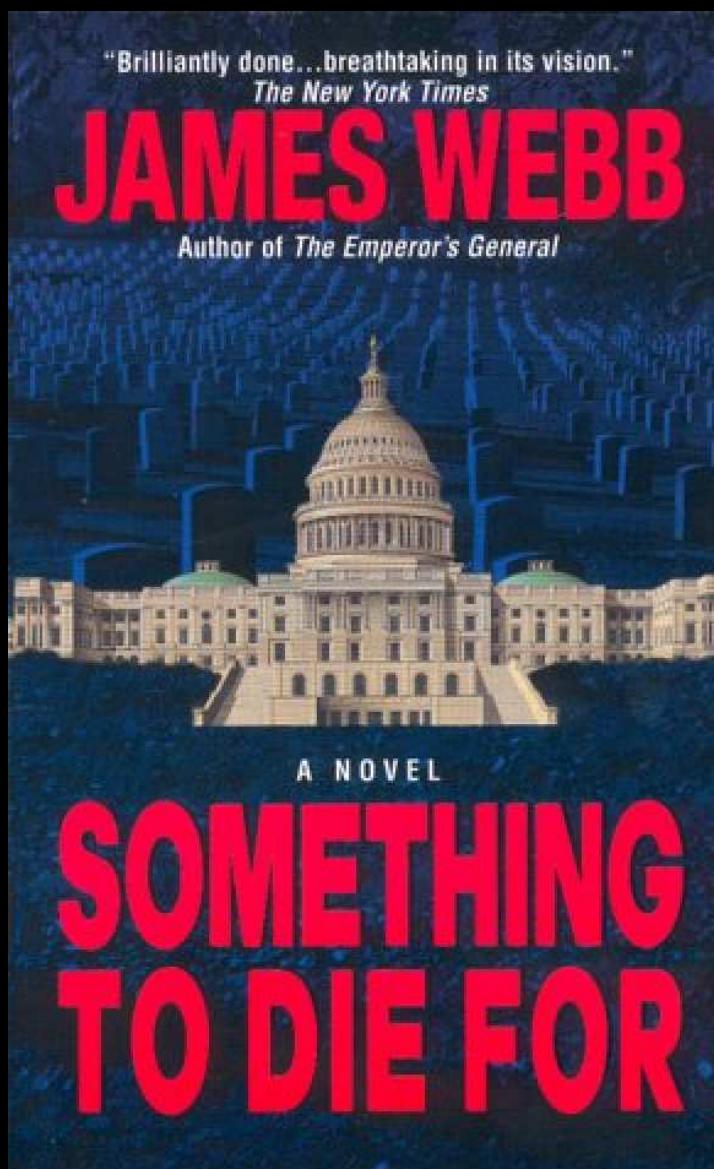
## LIGHT GATHERING POWER

JWST =  $25 \text{ m}^2$ ; Hubble =  $4.5 \text{ m}^2$ ; Spitzer =  $0.6 \text{ m}^2$

JWST is the perfect near-mid-IR sequel to HST and Spitzer:

Vastly larger collecting area than HST in UV-optical and Spitzer in mid-IR.

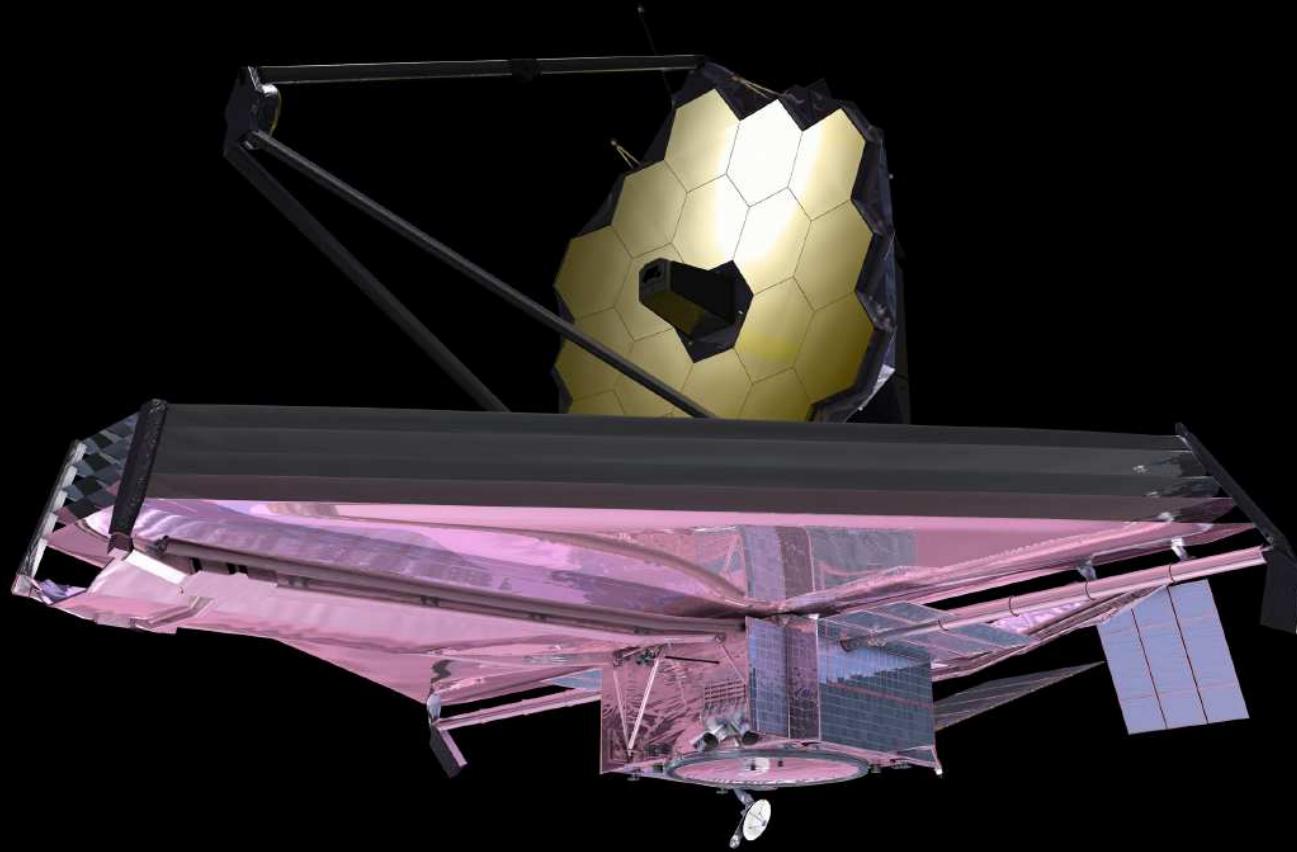
(1) Update of the James Webb Space Telescope (JWST), 2017.



To be used by students & scientists starting 2019 ... It'll be worth it.

(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007.

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



- A fully deployable 6.5 meter ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy at  $0.6\text{--}28 \mu\text{m}$  wavelength, to be launched in Spring 2019.
- 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

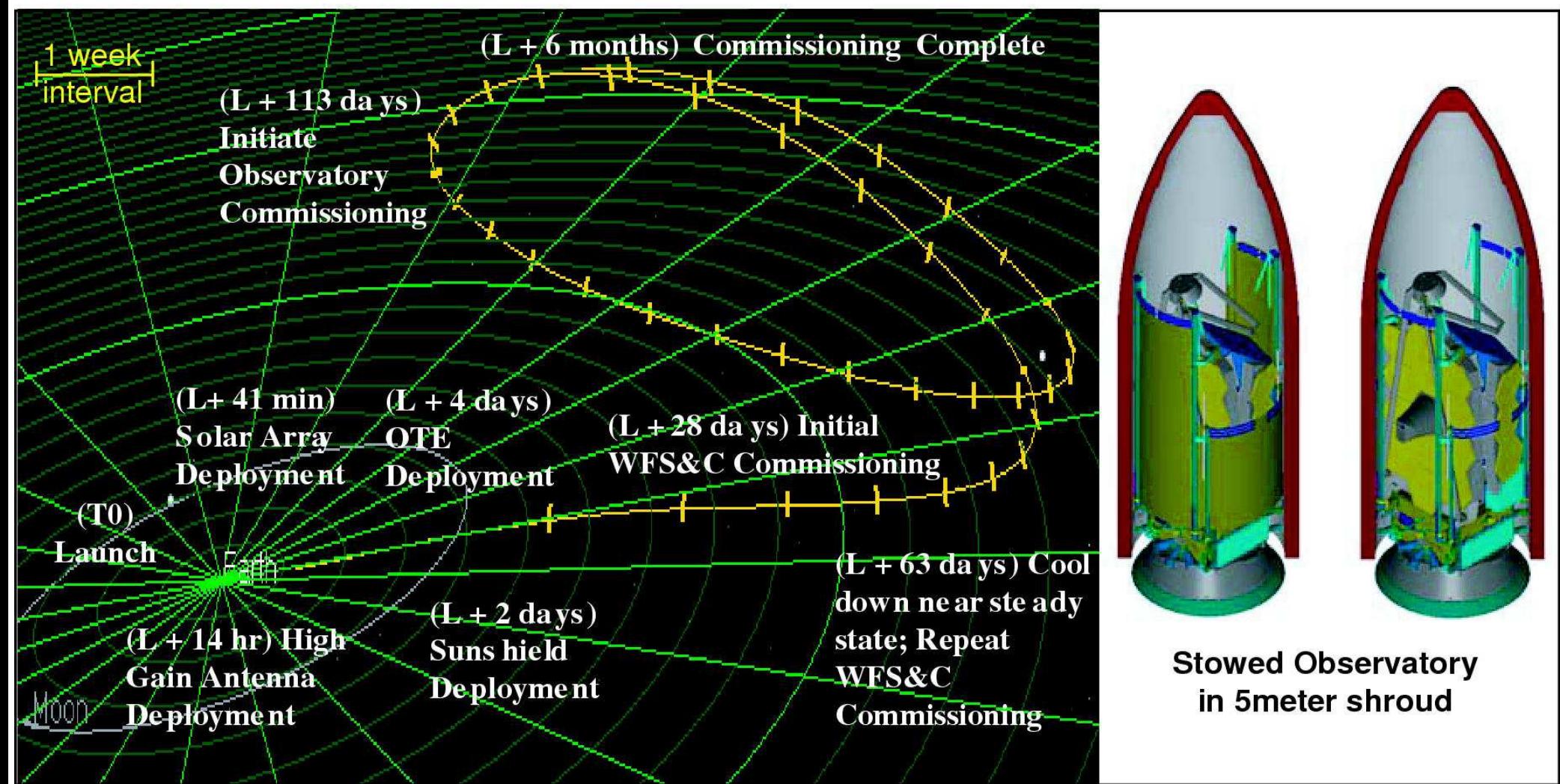
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



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.

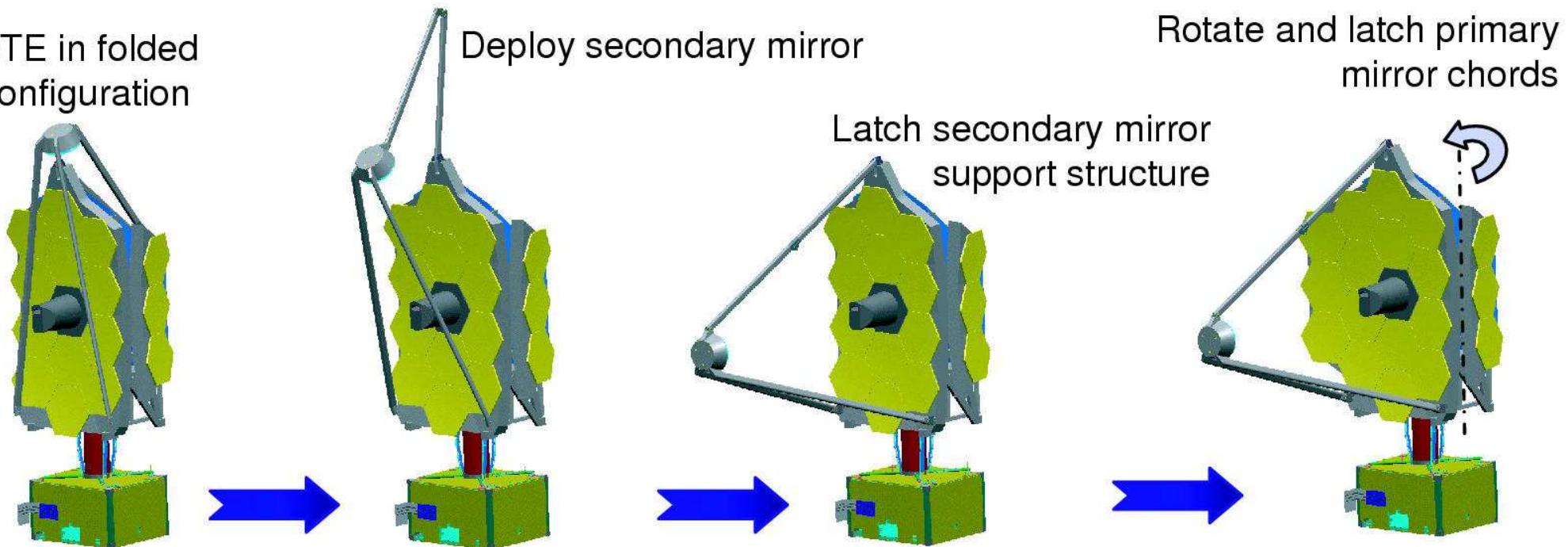
## (1a) How will JWST travel to its L2 orbit?



- 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.

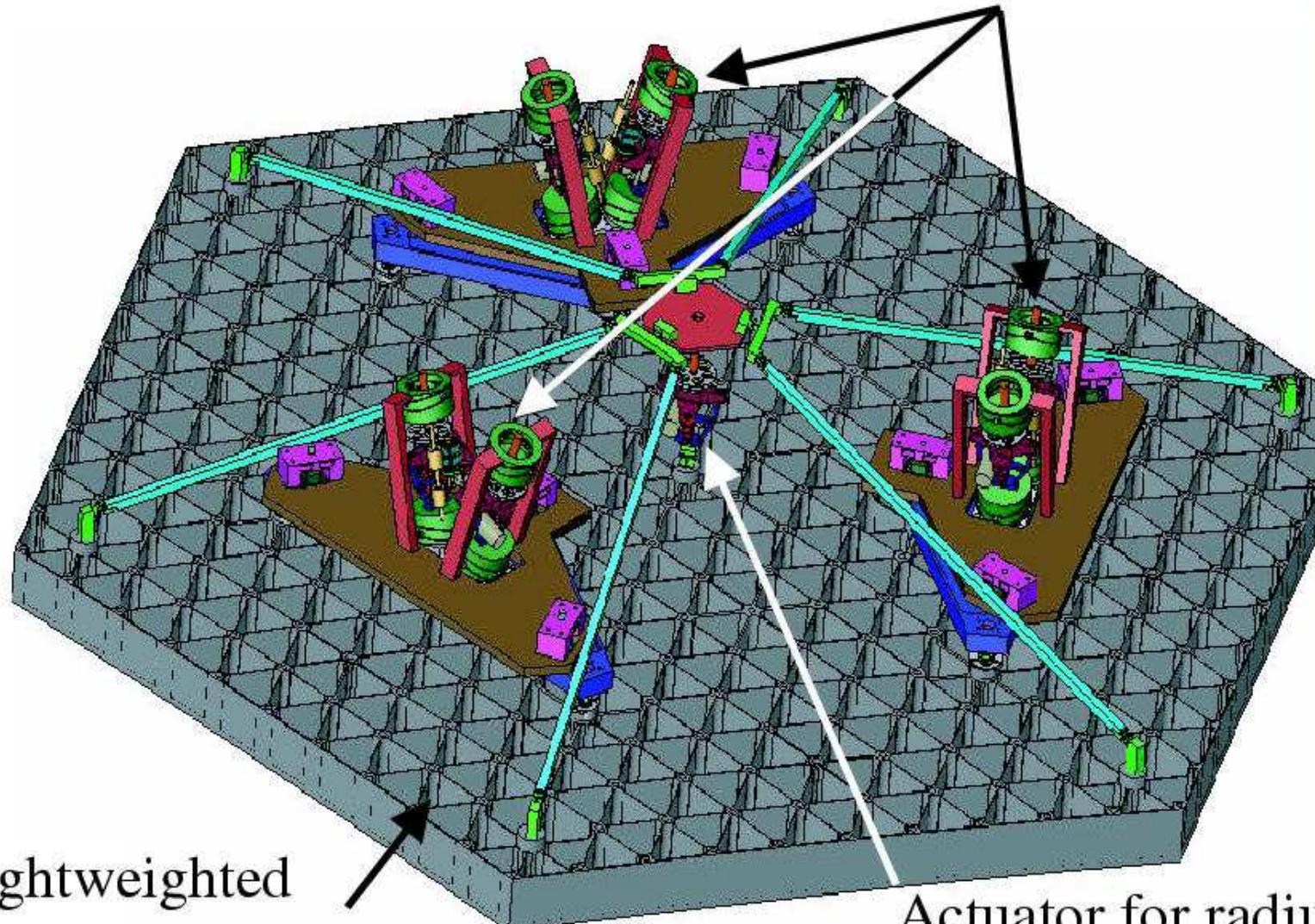
## (1b) How will JWST be automatically deployed?

OTE in folded configuration



- 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 GSFC (MD), JSC (Houston), and Northrop (CA).
- Component fabrication, testing, & system integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications.

# Actuators for 6 degrees of freedom rigid body motion



Actuator  
development  
unit

Lightweighted  
Beryllium Mirror

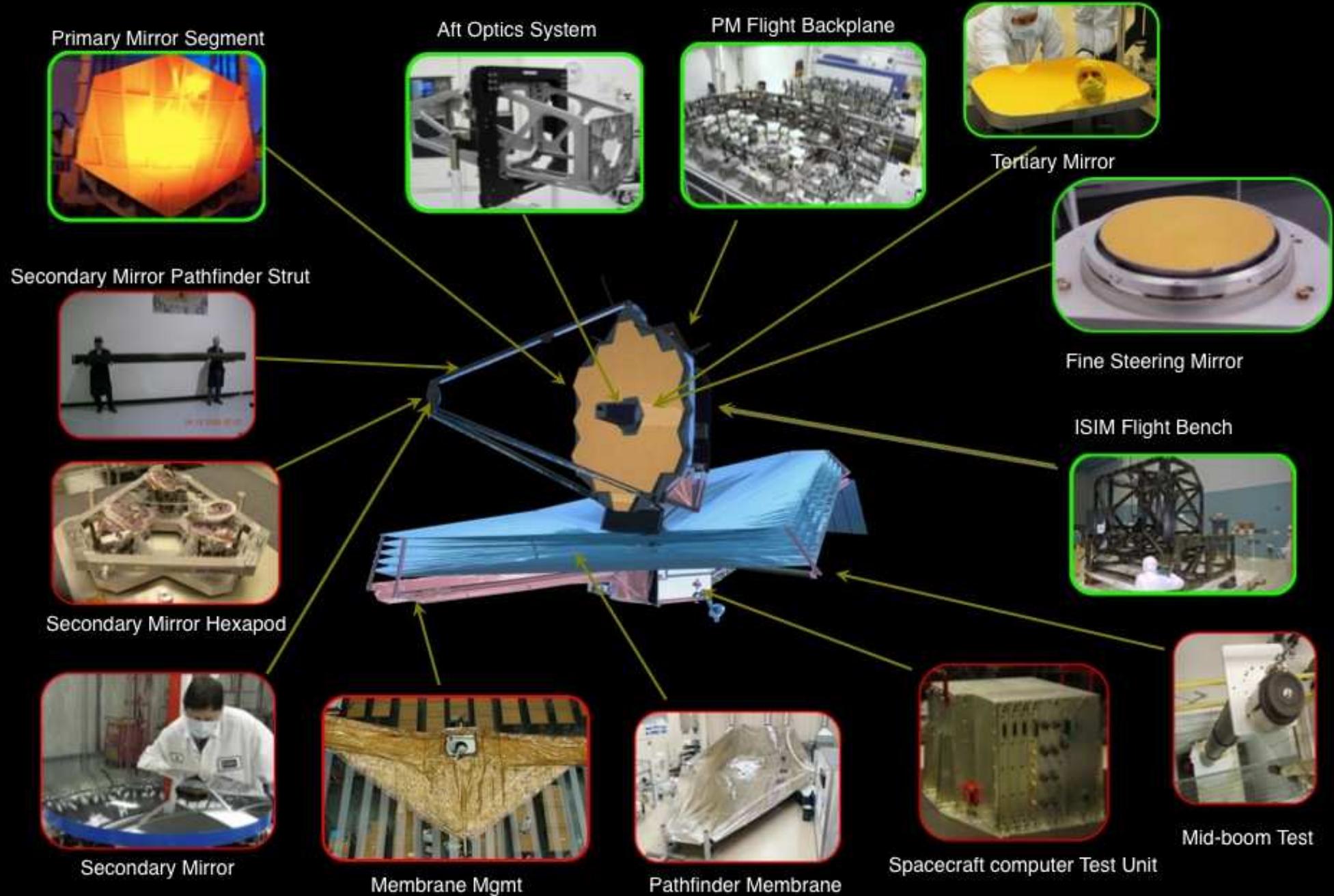
Actuator for radius  
of curvature adjustment

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

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

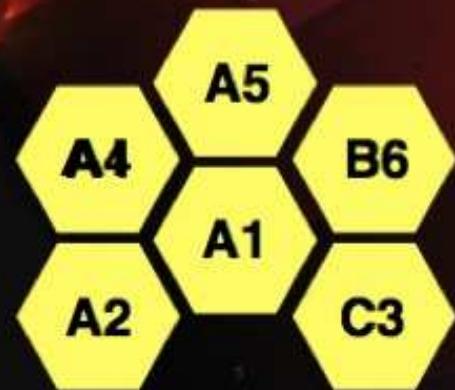
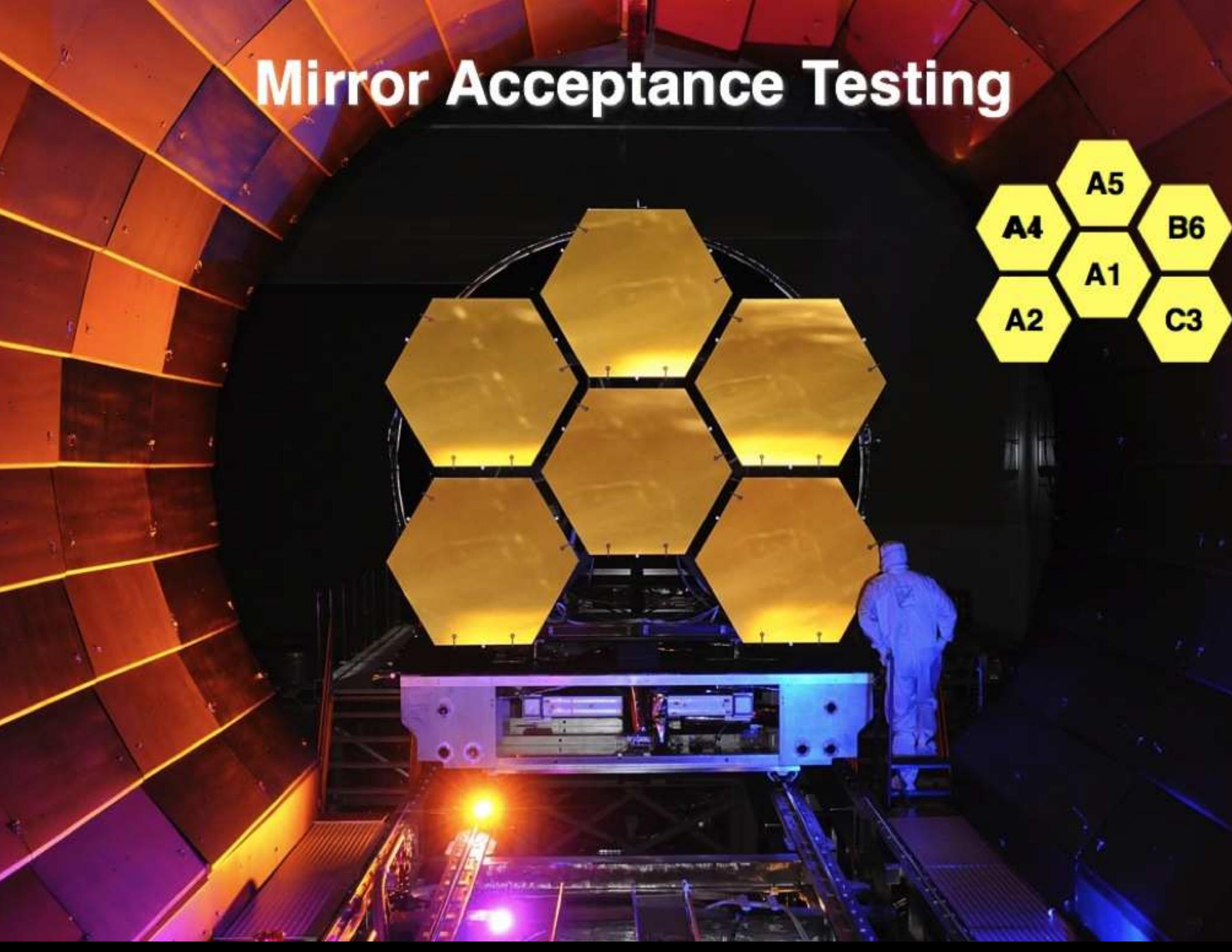


# JWST Hardware Status



Oct. 2017:  $\gtrsim 99.5\%$  of launch mass<sup>3</sup> designed and built ( $\gtrsim 97\%$  weighed).

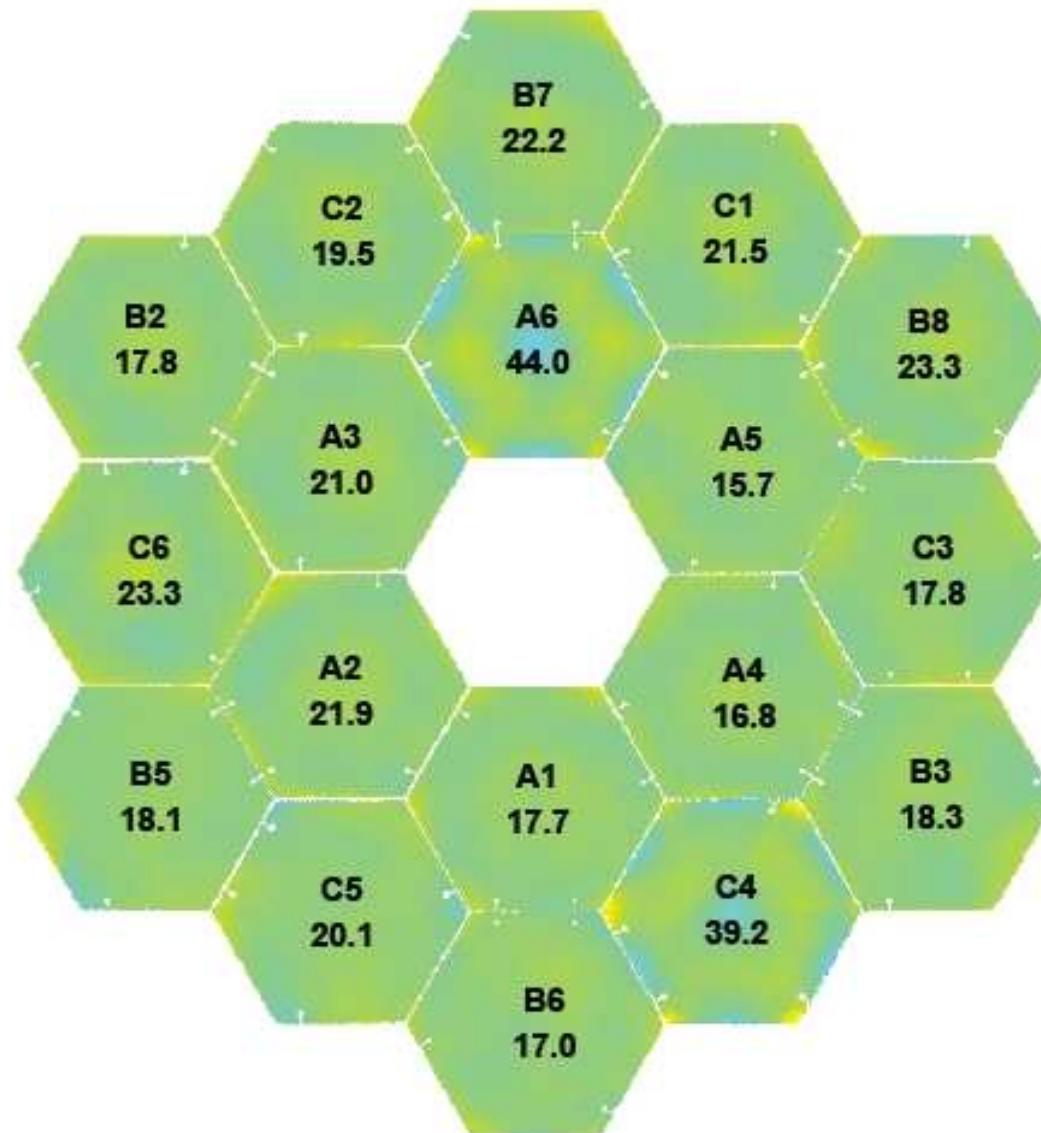
# Mirror Acceptance Testing







# Primary Mirror Composite



RMS:  
**23.2 nm**

PV:  
**515.5 nm**

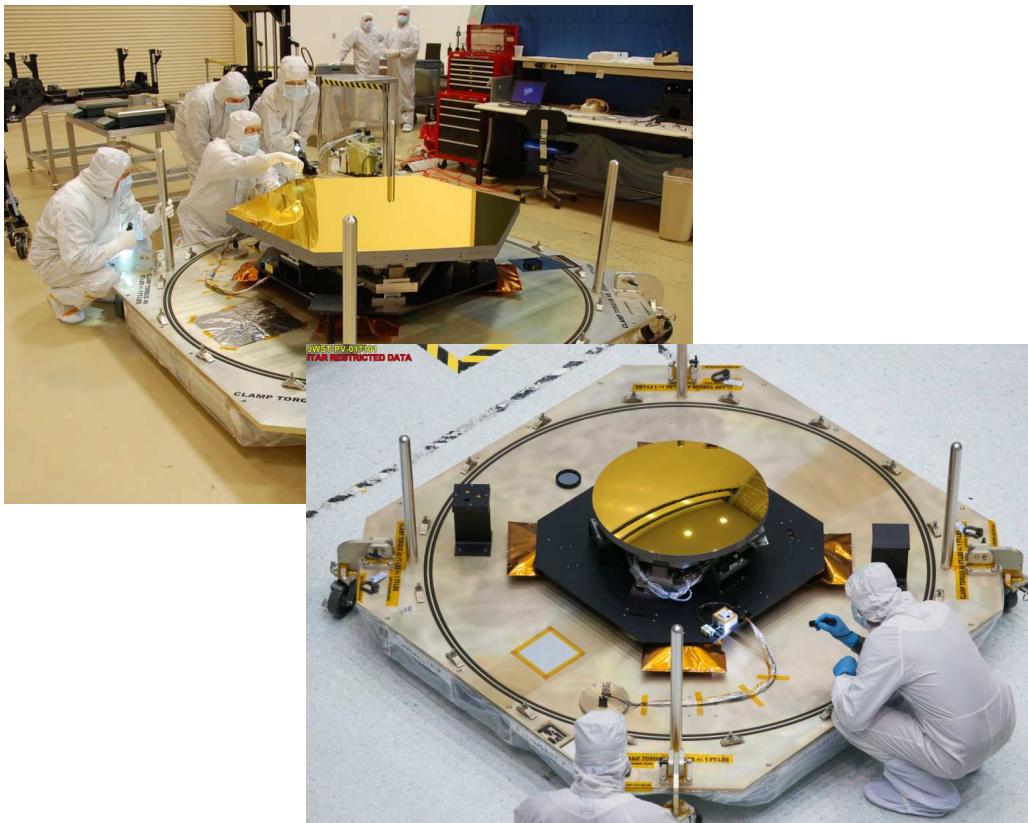




# Mirror Status



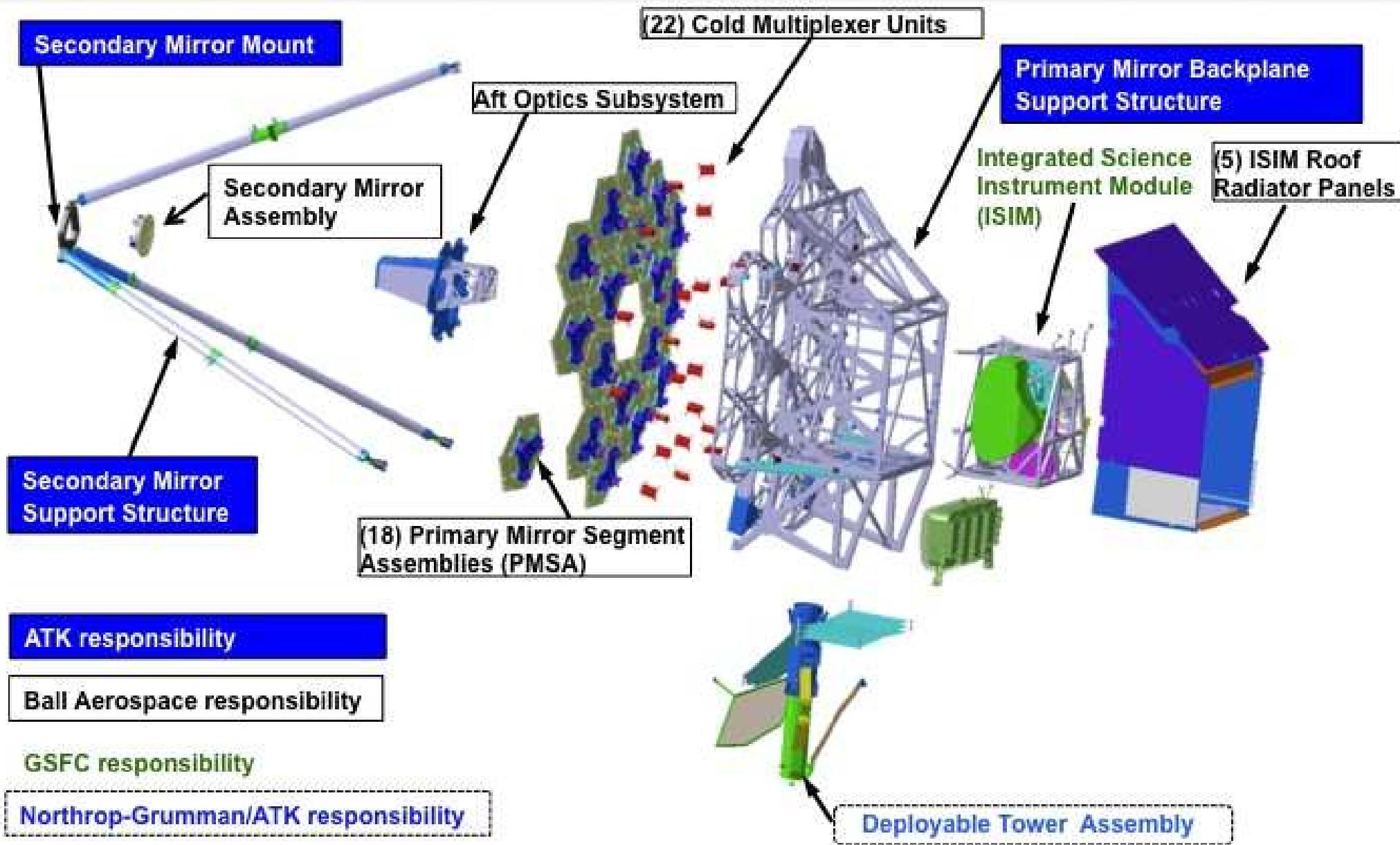
- **15 flight primary mirrors and the flight secondary mirror are at GSFC in storage**
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC by end of year, needed in 2015



Spring 2014: All 18 flight mirrors delivered to NASA GSFC (MD).



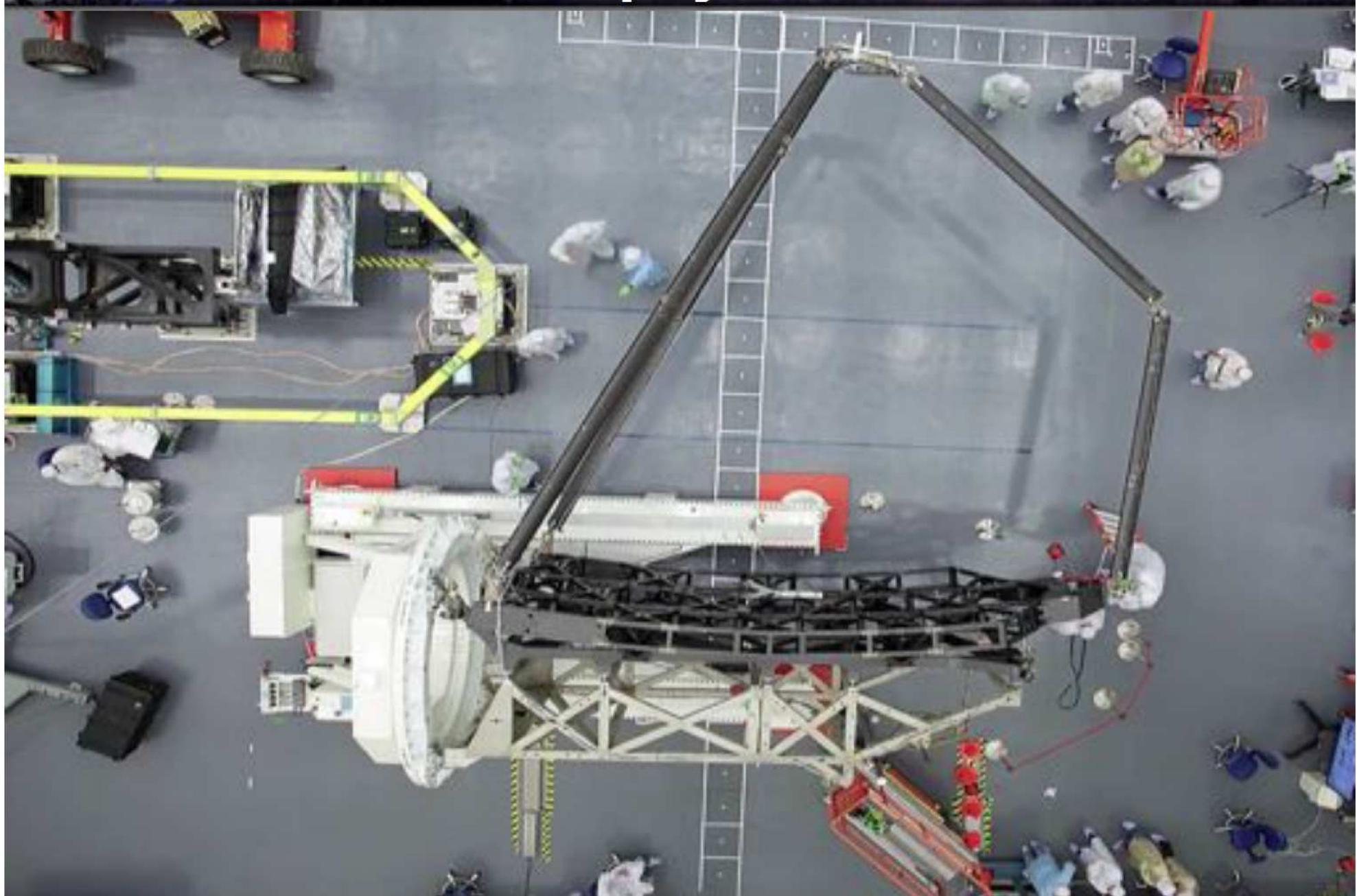
# TELESCOPE ARCHITECTURE



3/31/11

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

# Pathfinder: Powered Deployment of SMSS



July 2014: Secondary Mirror Support deployment successfully tested.

# (1c) JWST hardware to date, and how to best use it for high redshift lensing.



[LEFT]: Aug. 2014: Engineering Kapton Sunshield; 2017: Flight Sunshield.

[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors mounted Spring 2016.

- Our Galaxy is a bright IR source at  $\lambda \gtrsim 1-5\mu\text{m}$ : In certain directions of the sky, some straylight can hit secondary mirror via Sunshield.
- This can effect JWST (lensing) studies of First Light objects.

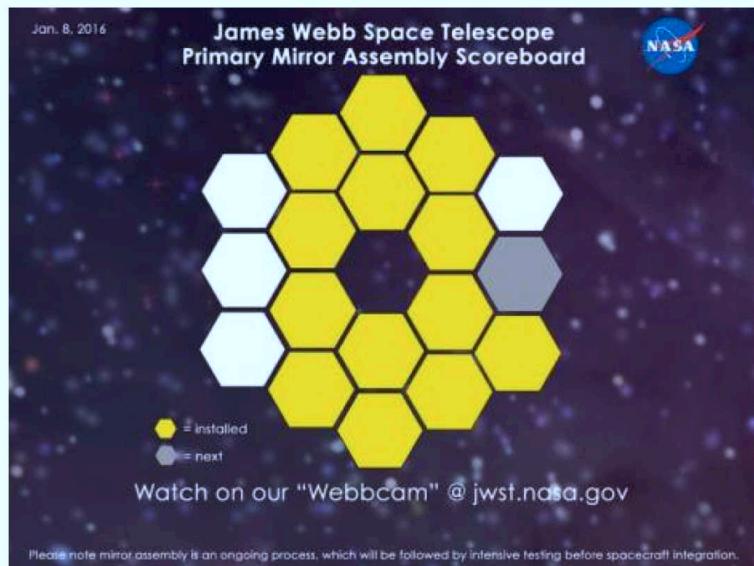


# Telescope Pathfinder – Risk Reduction

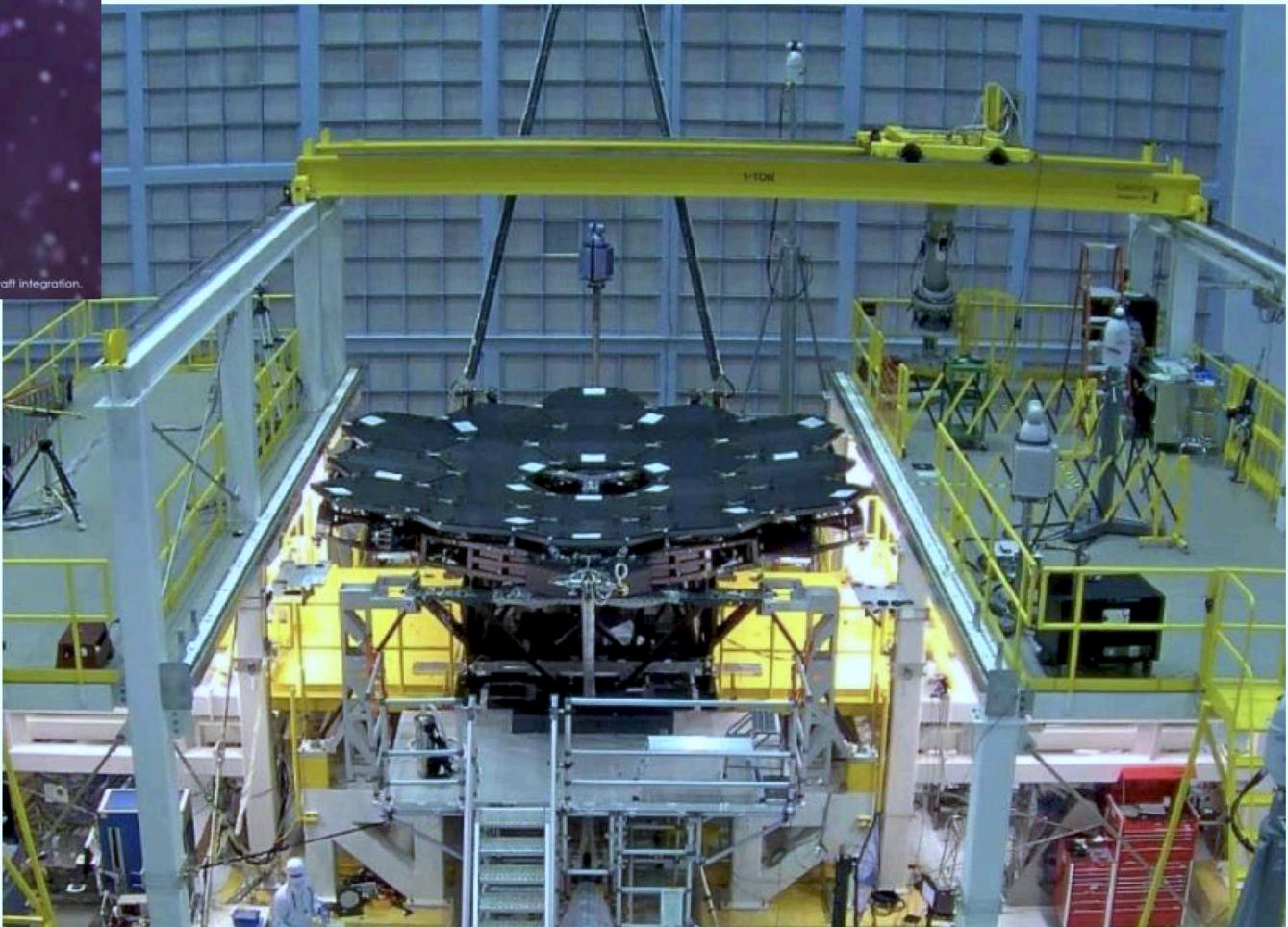


JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly

# Much progress has been made in OTE integration



Where we were at last month's call



Current: all 18 PMSAs installed, liquid-shim-cured, & metrologized. Alignments meet specifications, and actuator motions verified  
*Big milestone!*



8 February 2016 JWST Monthly Telecon 8

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



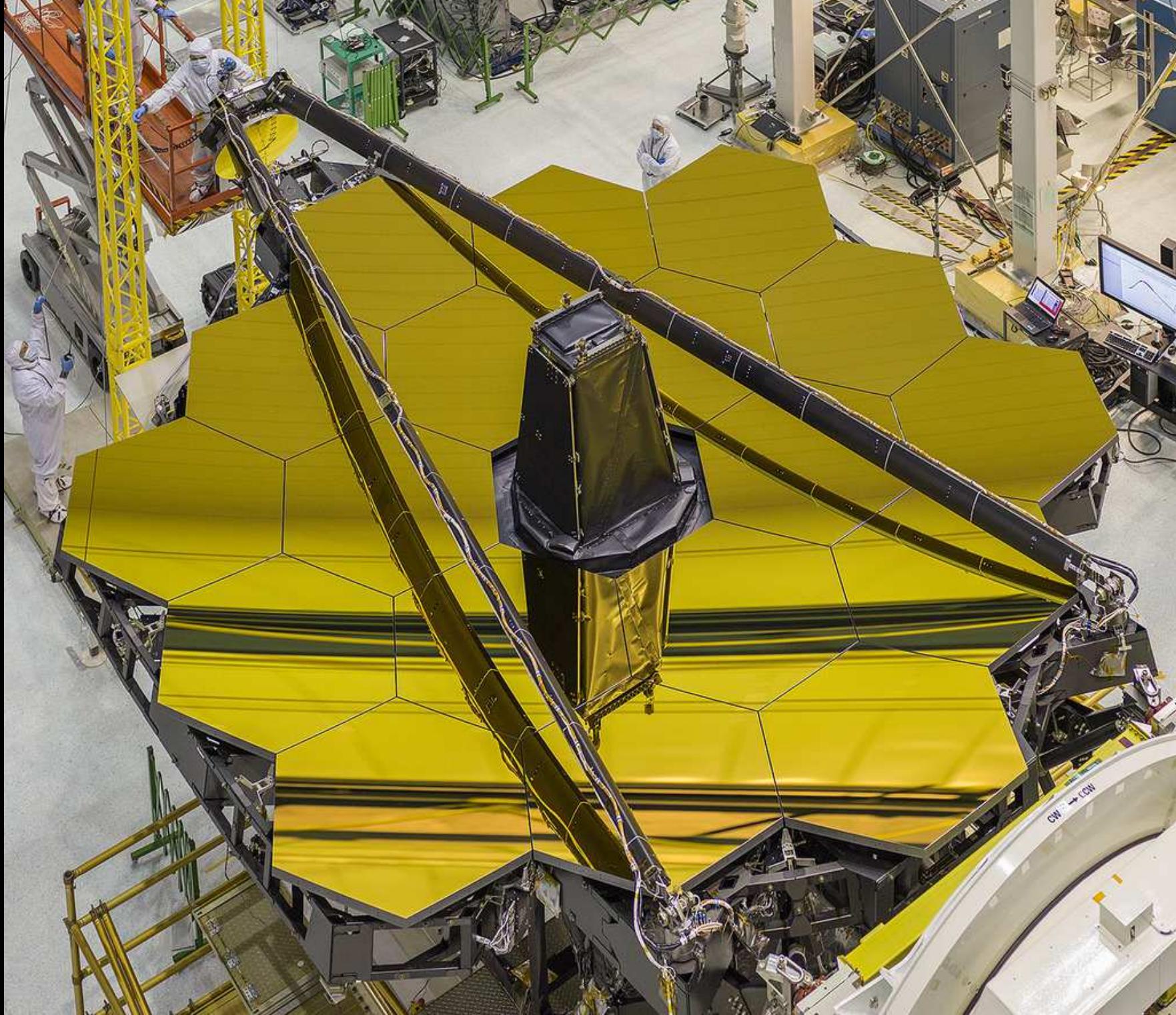
April 2016: NASA team-work to take JWST mirror covers off!



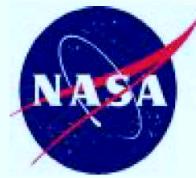
May 2016: JWST being tilted into the right position to stow.



May 2016: Webb mirrors finally mounted and ready!



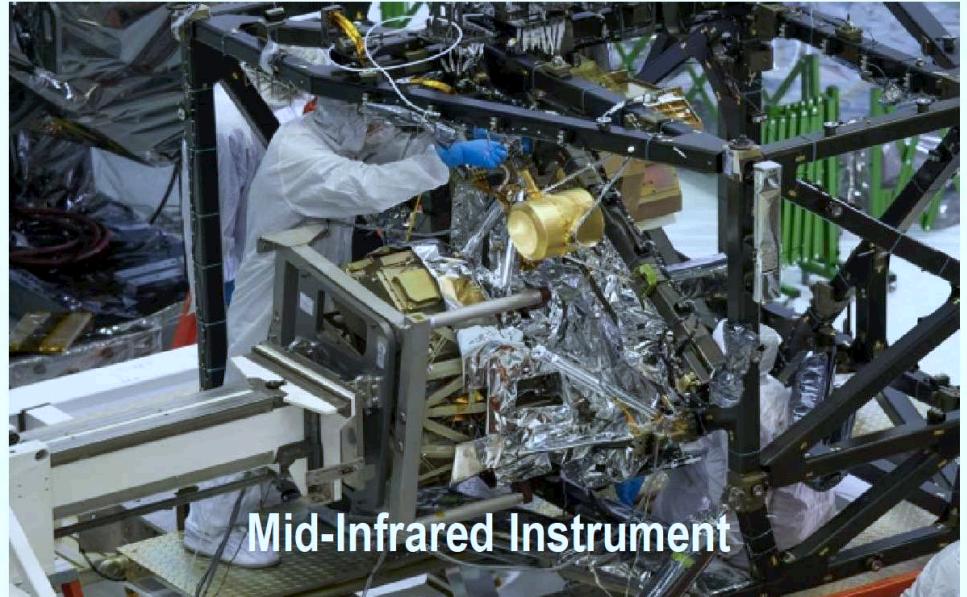
May 2016: JWST stowed for further instrument mounting.



# All Instruments Integrated



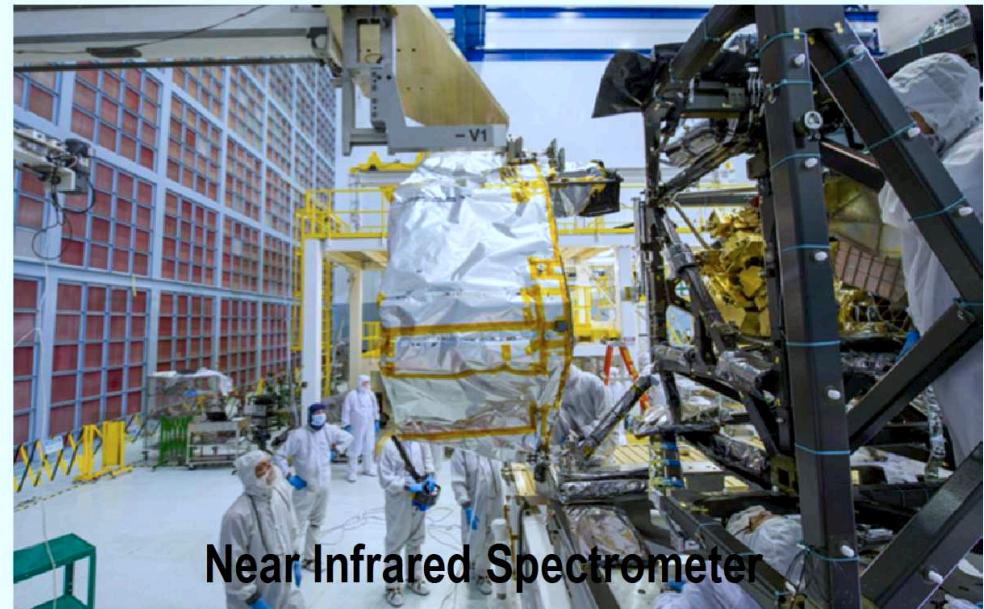
Fine Guidance Sensor



Mid-Infrared Instrument



Near Infrared Camera



Near Infrared Spectrometer

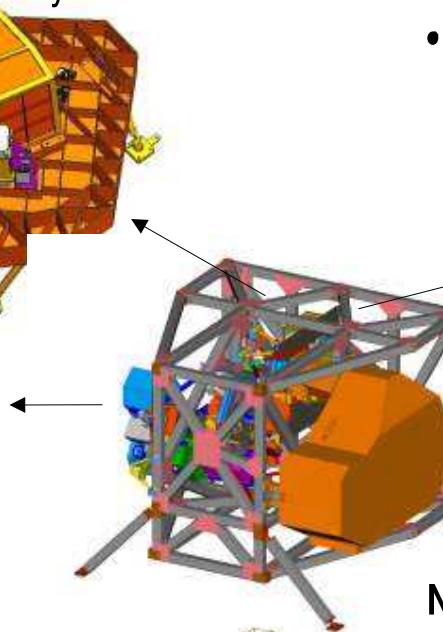
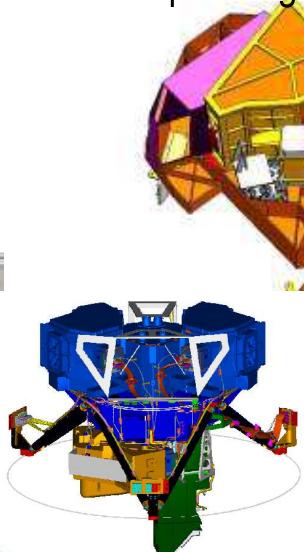


## Instrument Overview



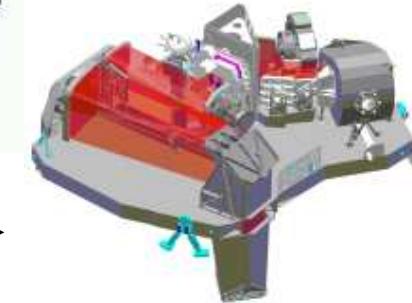
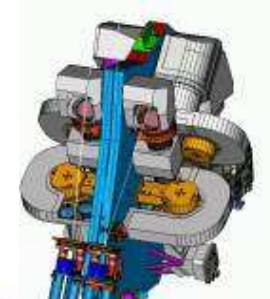
### Fine Guidance Sensor (FGS)

- 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



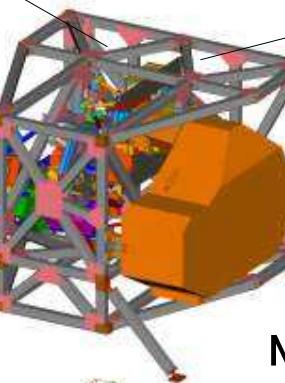
### Near Infra-Red Camera (NIRCam)

- 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

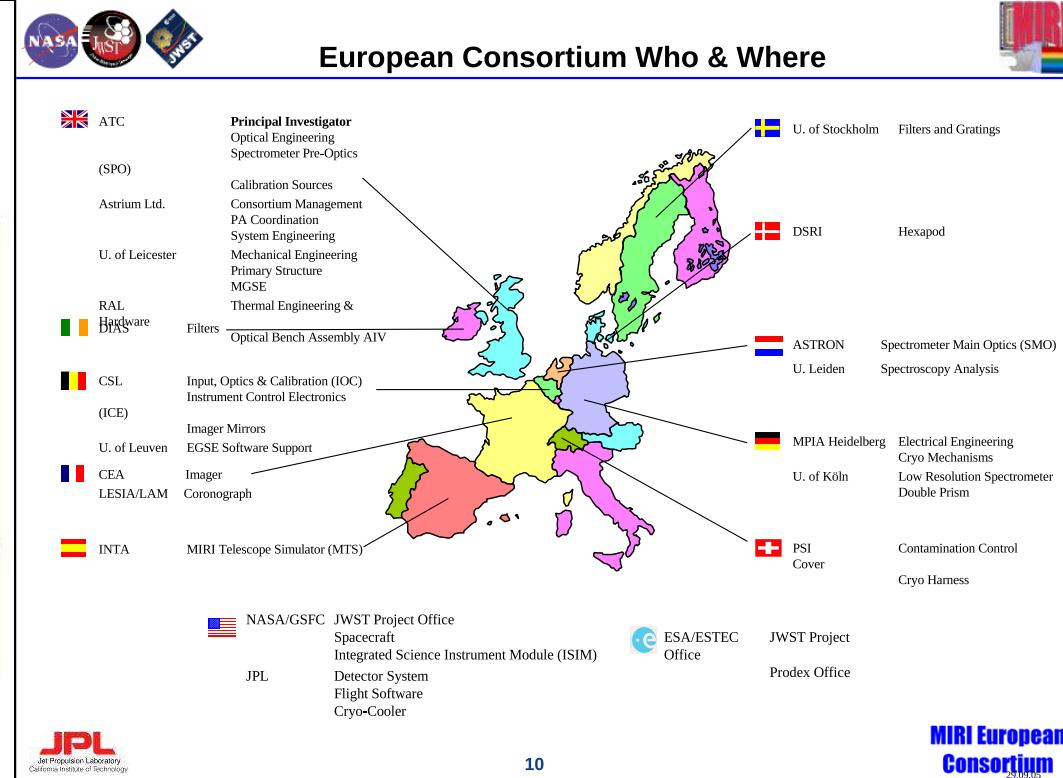
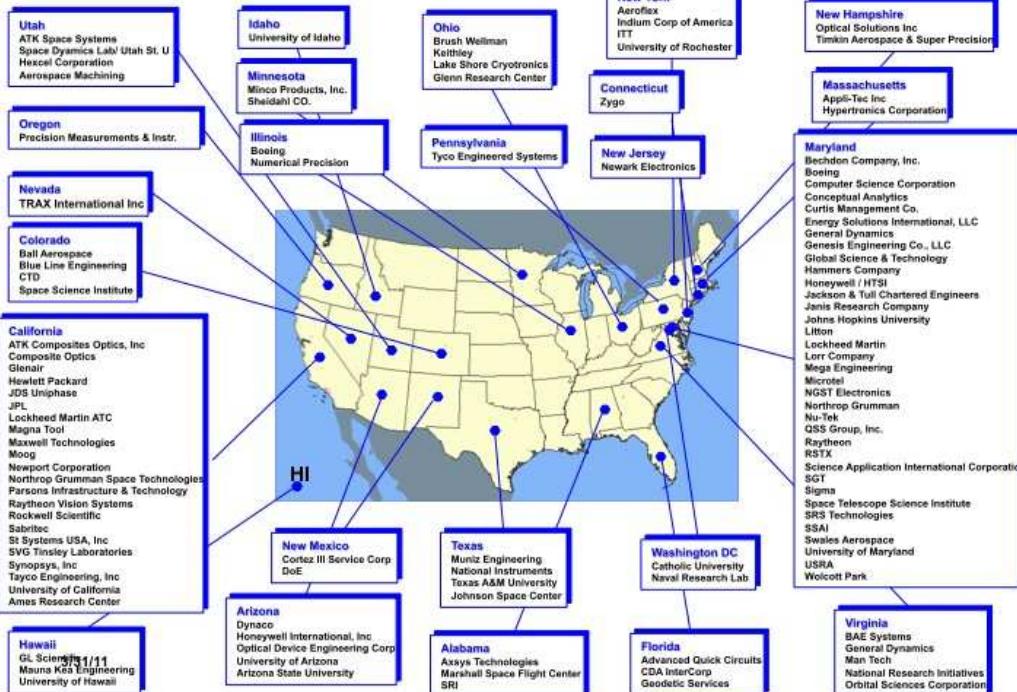


### Near Infra-Red Spectrograph (NIRSpec)

- 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



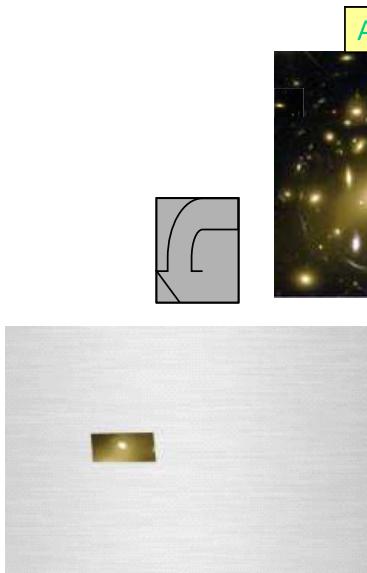
# JWST: A Product of the Nation



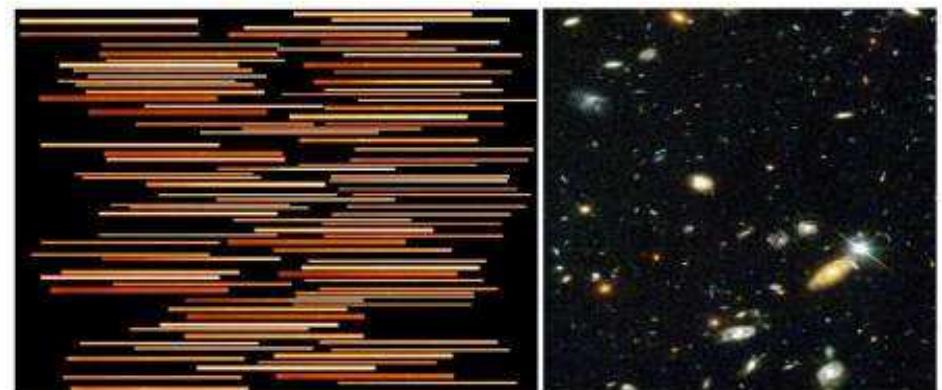
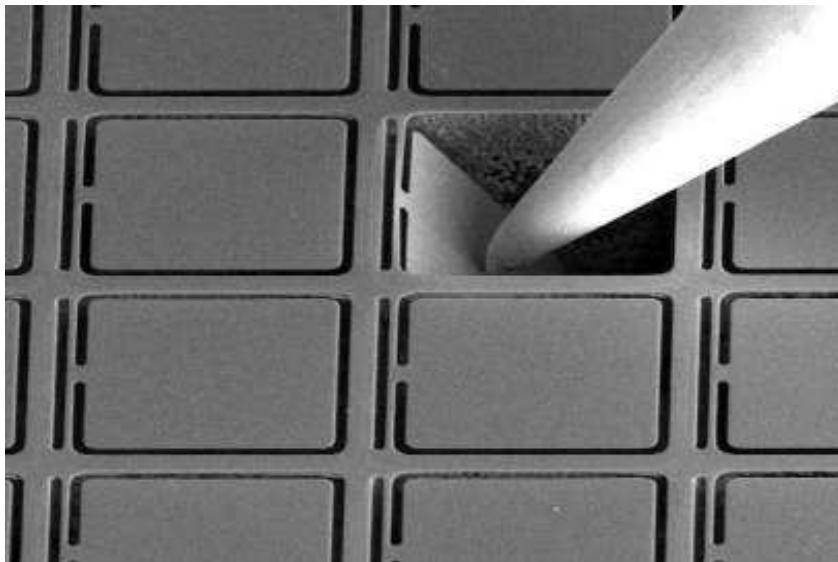
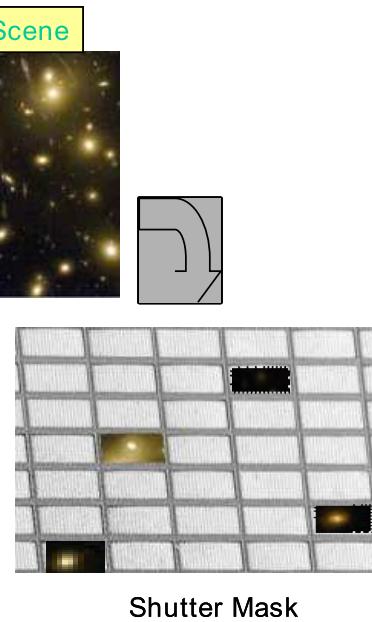
- JWST hardware made in 27 US States:  $\gtrsim 99.5\%$  of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.

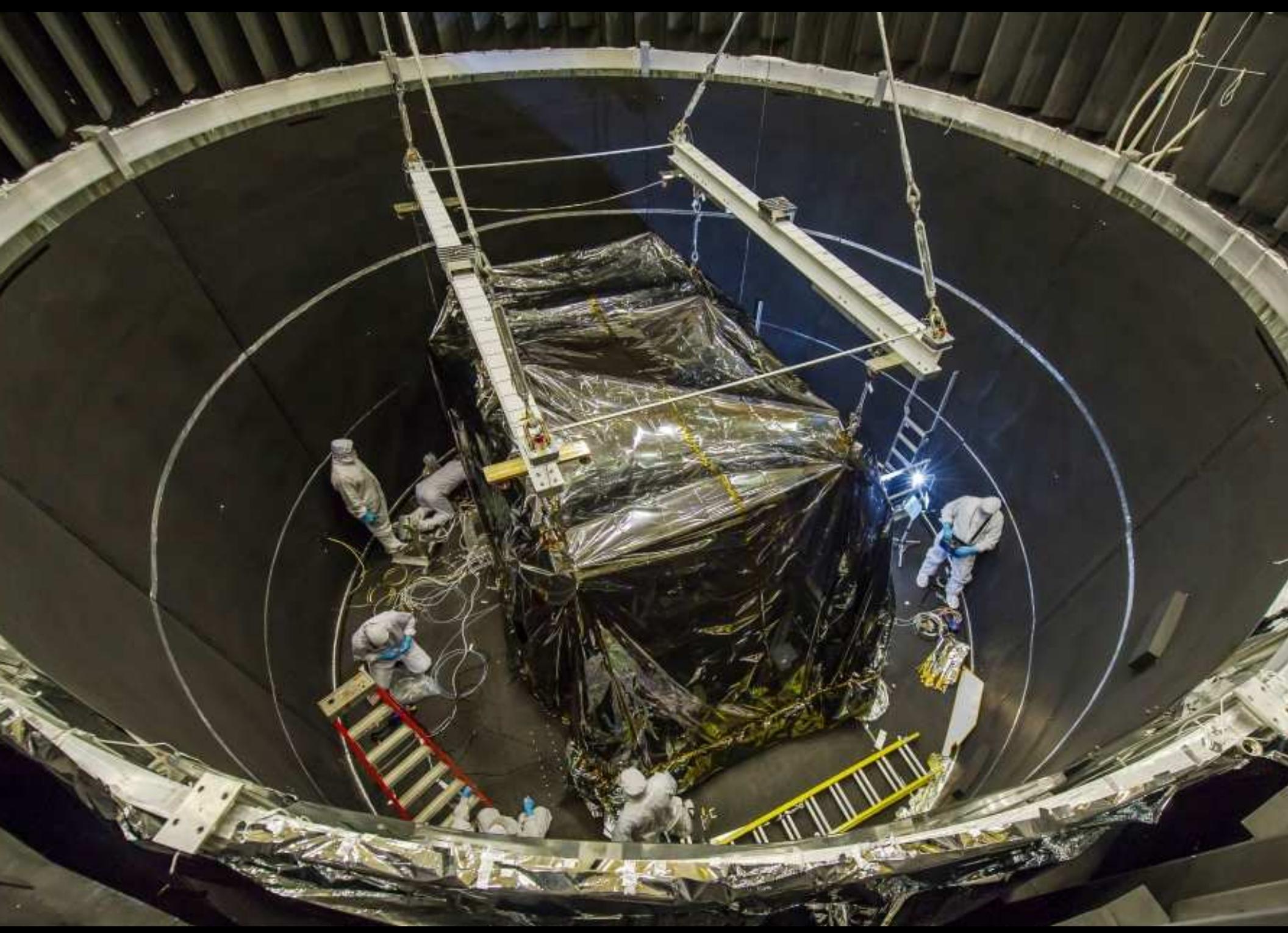
This nationwide + international coalition was critical for project survival!

# Micro Shutters



Metal Mask/Fixed Slit





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

# Program Update: OTE + ISIM = OTIS

NORTHROP GRUMMAN



3

160613 JWST Monthly Telecon 28

June 2016: Flight ISIM mated with Optical Telescope Element (OTE).  
JWST is now a real working telescope (albeit not yet at 40 K & in 0 G)!



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



# OTIS Test GSE Architecture and Subsystems



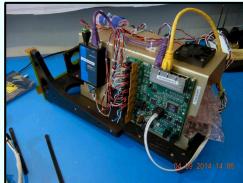
Chamber Isolator Units  
Dynamically isolates OTIS Optical Test  
– Integration 6 units complete



Cryo Position Metrology (CPM)  
Photogrammetry System  
Integration Complete

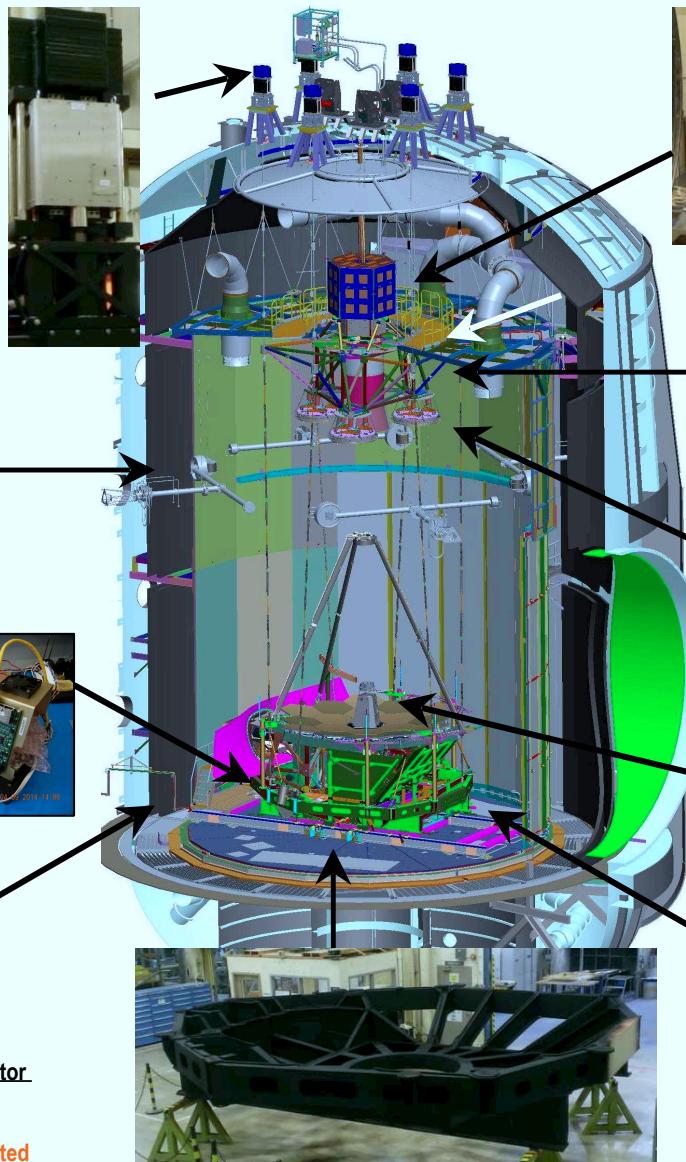


ADM - new Leica  
delivered and under test



Space Vehicle Thermal Simulator  
(SVTS)  
and Sunshield Simulator

Passed design review and started  
Procurements and fab subcontracts

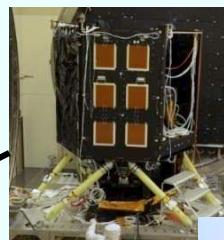


HOSS – OTIS support structure  
HOSS – will be in the chamber for Bake out in June

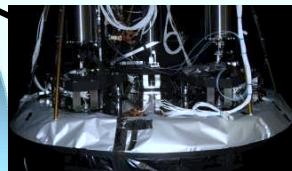


Center of Curvature Optical Assembly (COCOA)

- Multiwavelength interferometer (MWIF), null, calibration equipment, coarse/fine PM phasing tools, Displacement Measuring Interferometer – COCOA was exercised at MSFC in December

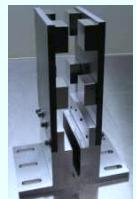


USF Structural Frame – supports Metrology  
ready for chamber integration and Cryo Load tests

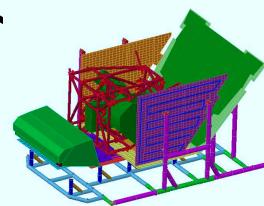


3 Auto collimating Flat Mirrors (ACFs)  
1.5 M Plano for Pass and Half Testing  
Cryo testing underway, ACF 1 complete, ACF 4 in  
Cryo test complete , ACF 5 ready for Cryo.

AOS Source Plate  
Sources for Pass and Half Test  
72 optical fiber support cont.



Mag Damper Cryo  
Test Article  
Fabrication started

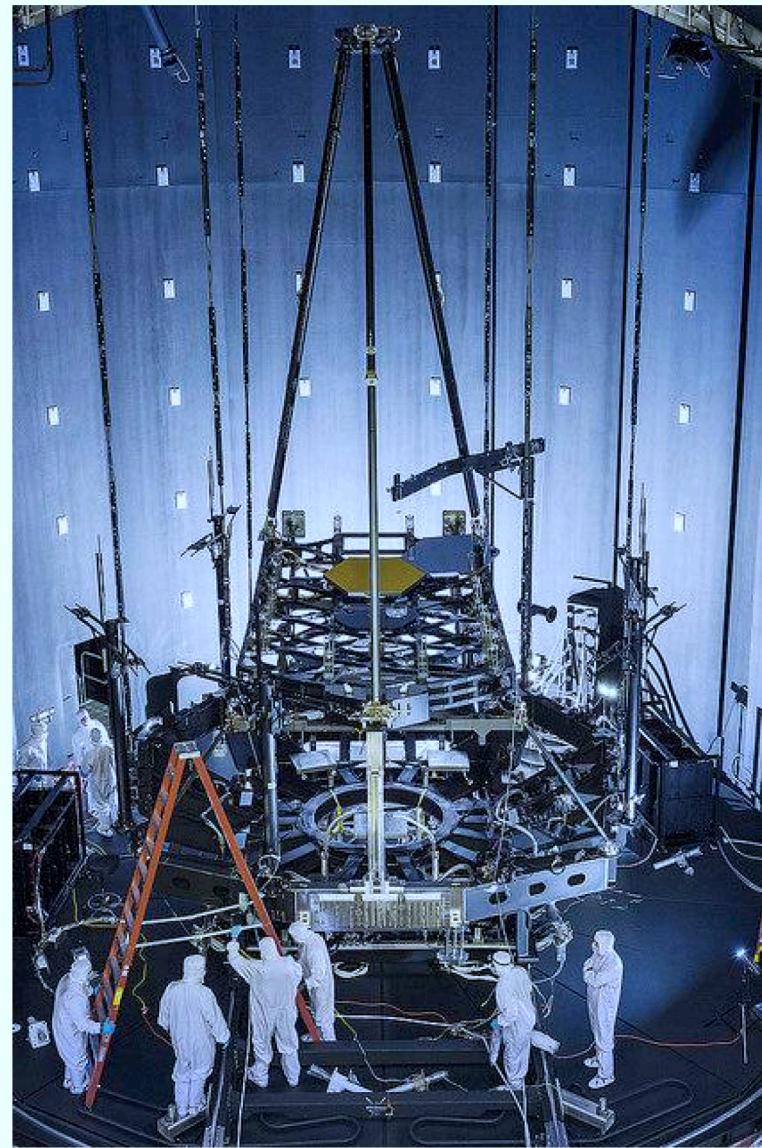
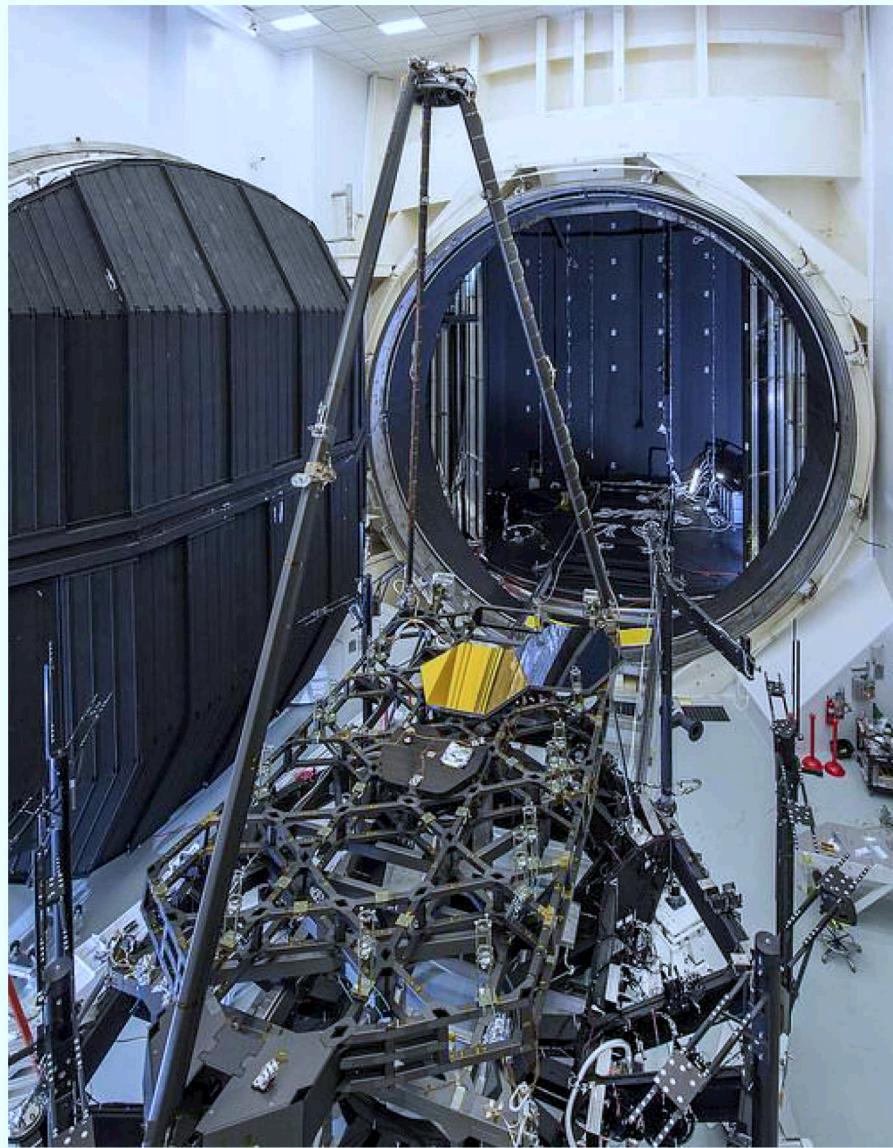


Deep Space Edge Radiation Sink (DSERS)

Thermal modeling of payload and DSERS  
started

World's largest TV chamber OTIS, to test JWST OTE July–Oct. 2017.

# Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)



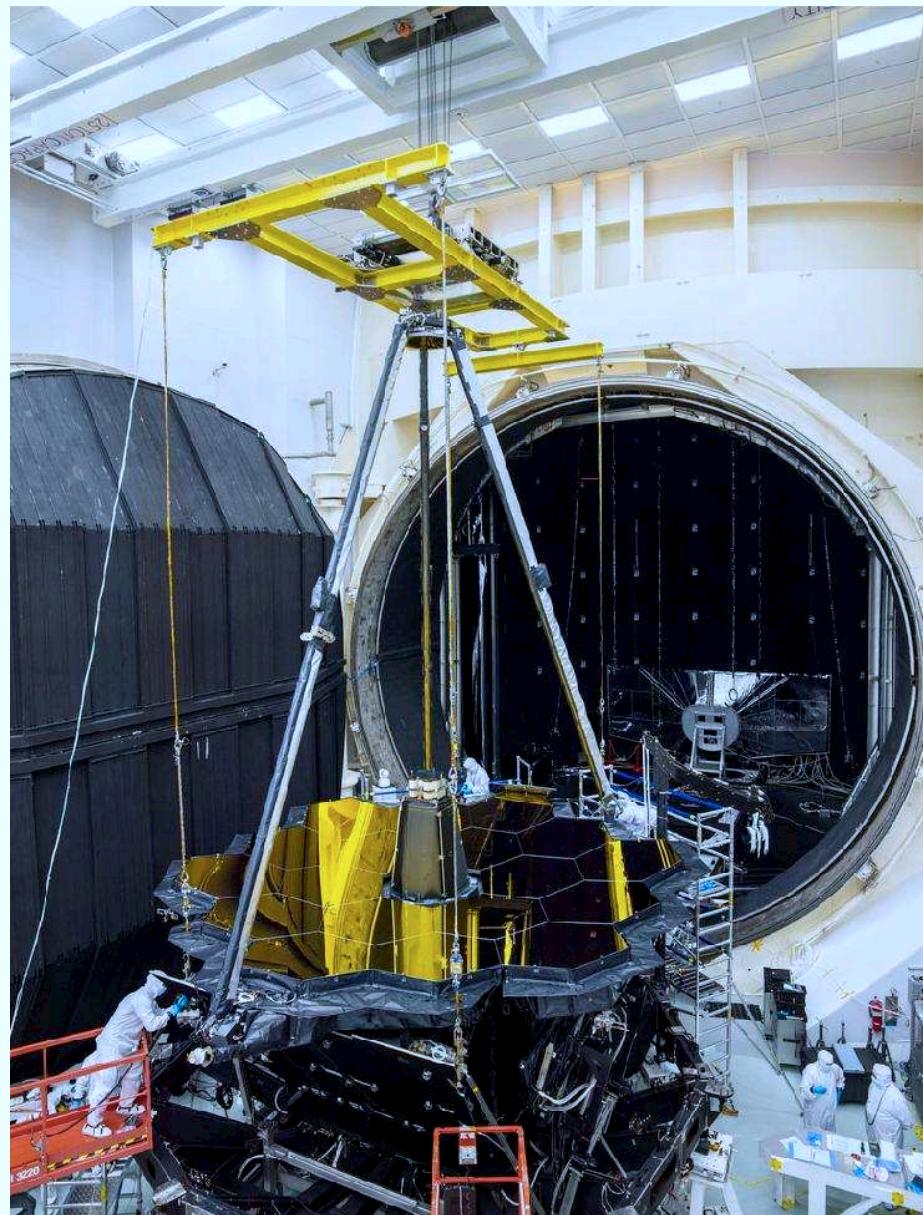
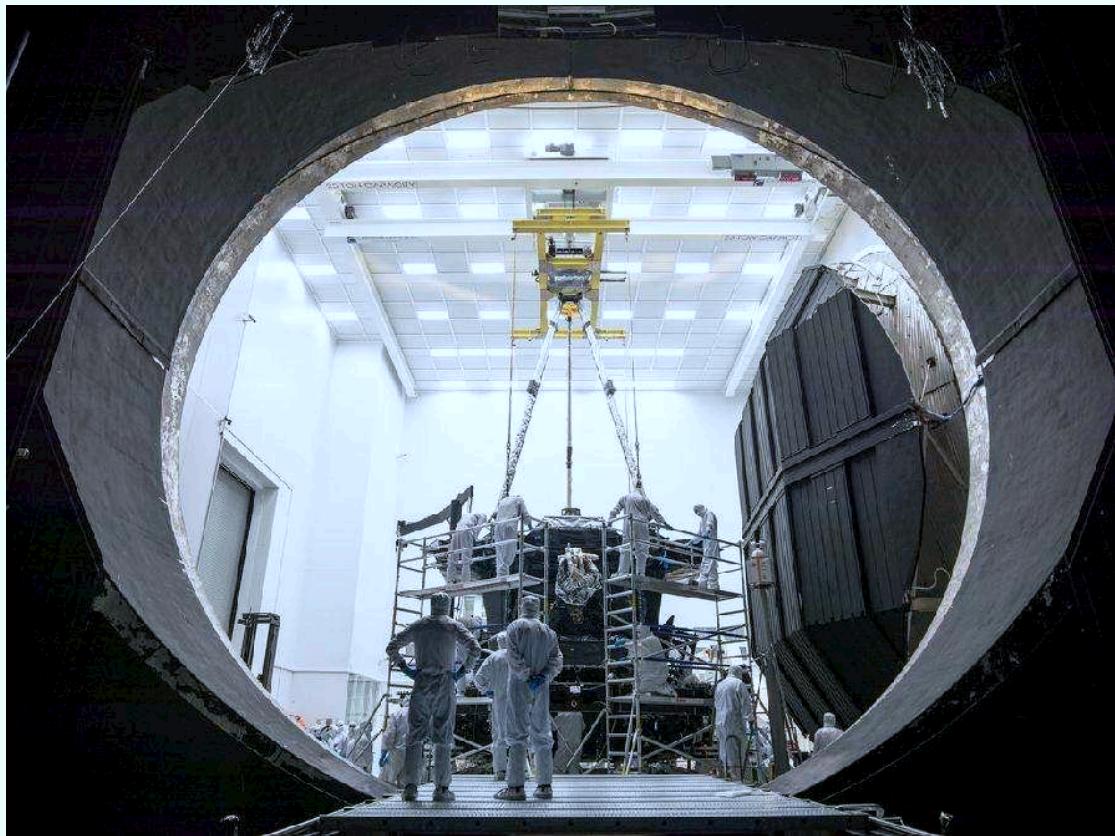
2015–2016: Testing OTIS chamber with the JWST Engineering model.

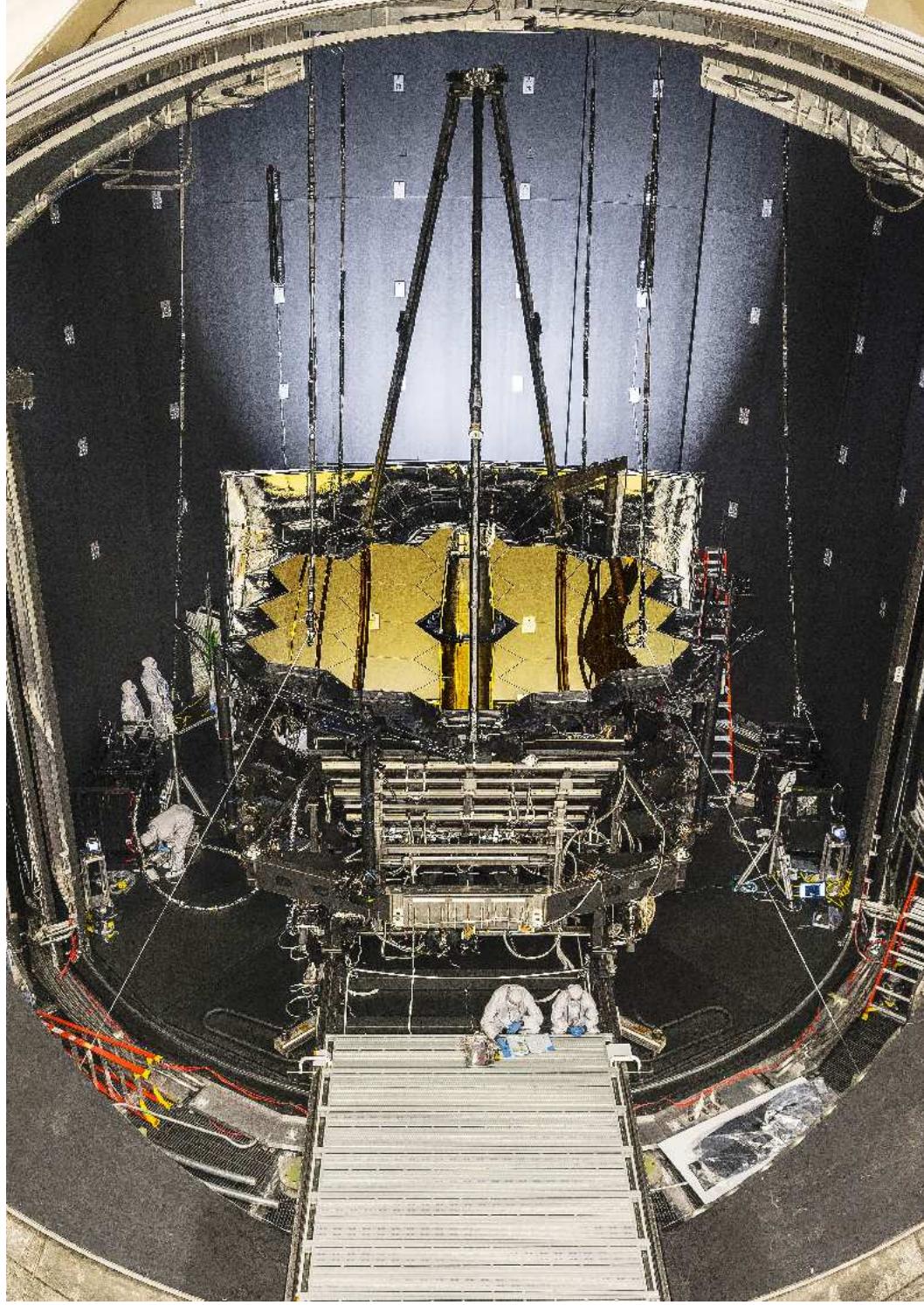


May 2017: JWST OTE in enclosure at Johnson Space Center in Houston.

# Program Update: OTIS

NORTHROP GRUMMAN

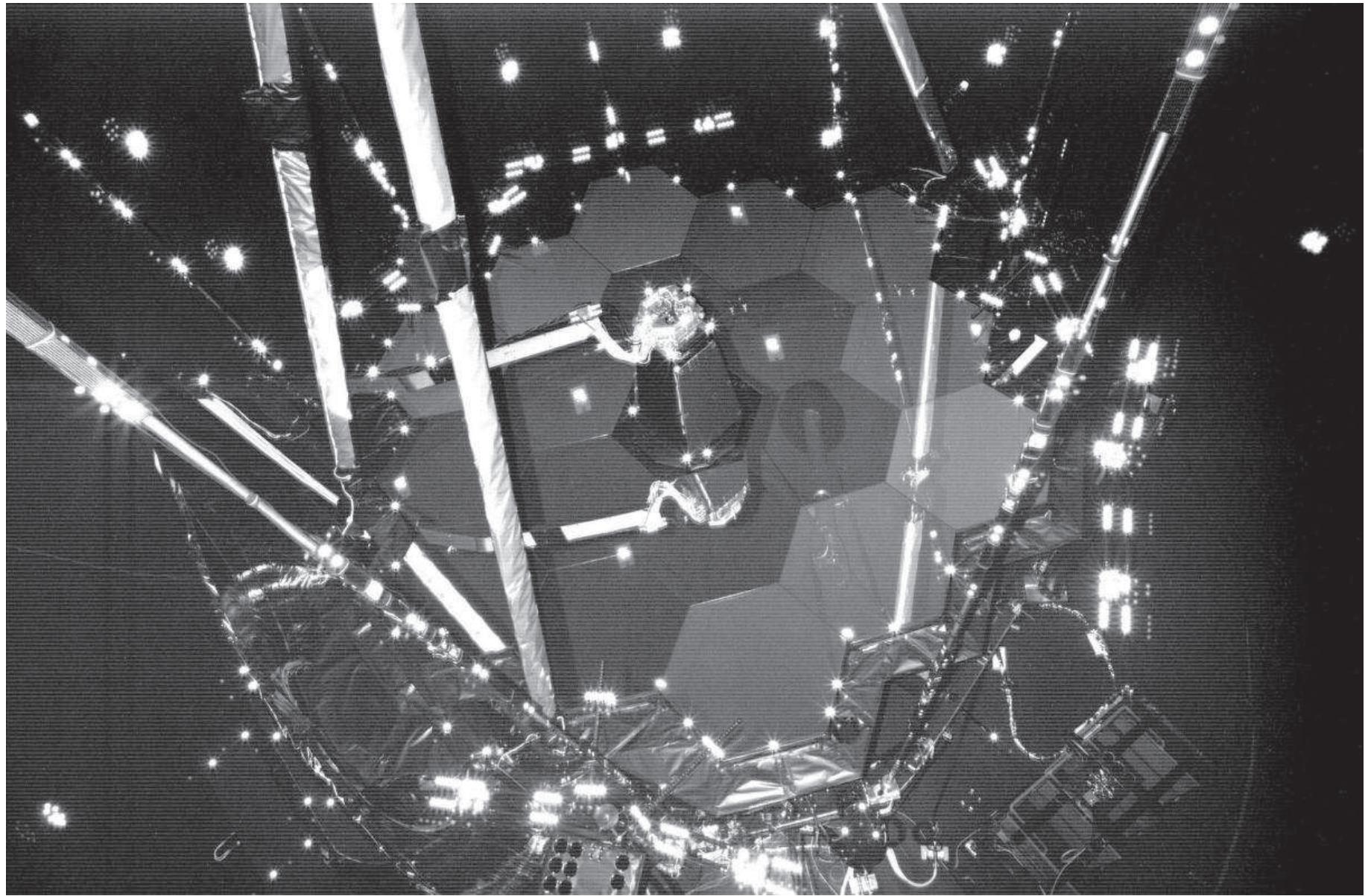




July–Oct. 2017: OTE in Chamber A at Johnson Space Center in Houston.

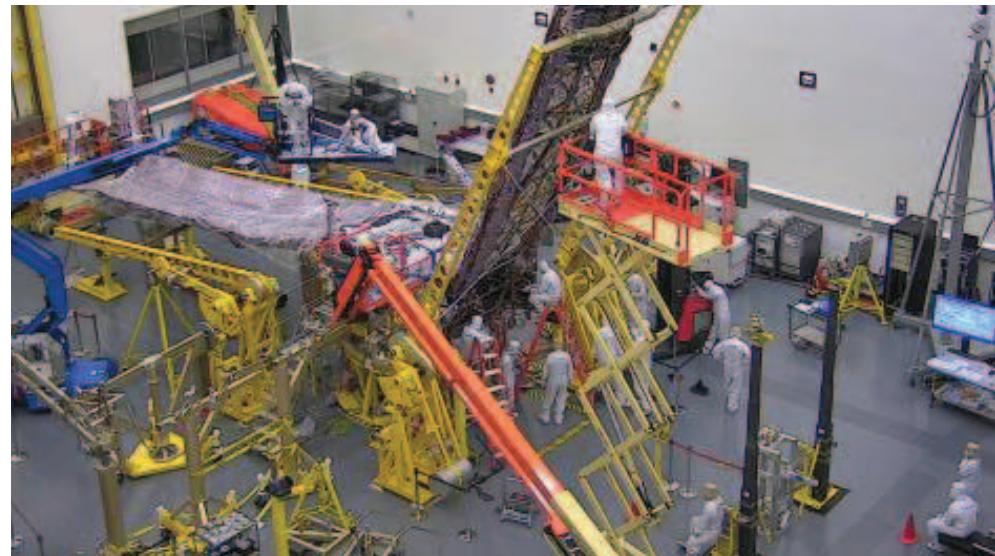


# It's Still in There



171016 JWST Monthly Telecon 11

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



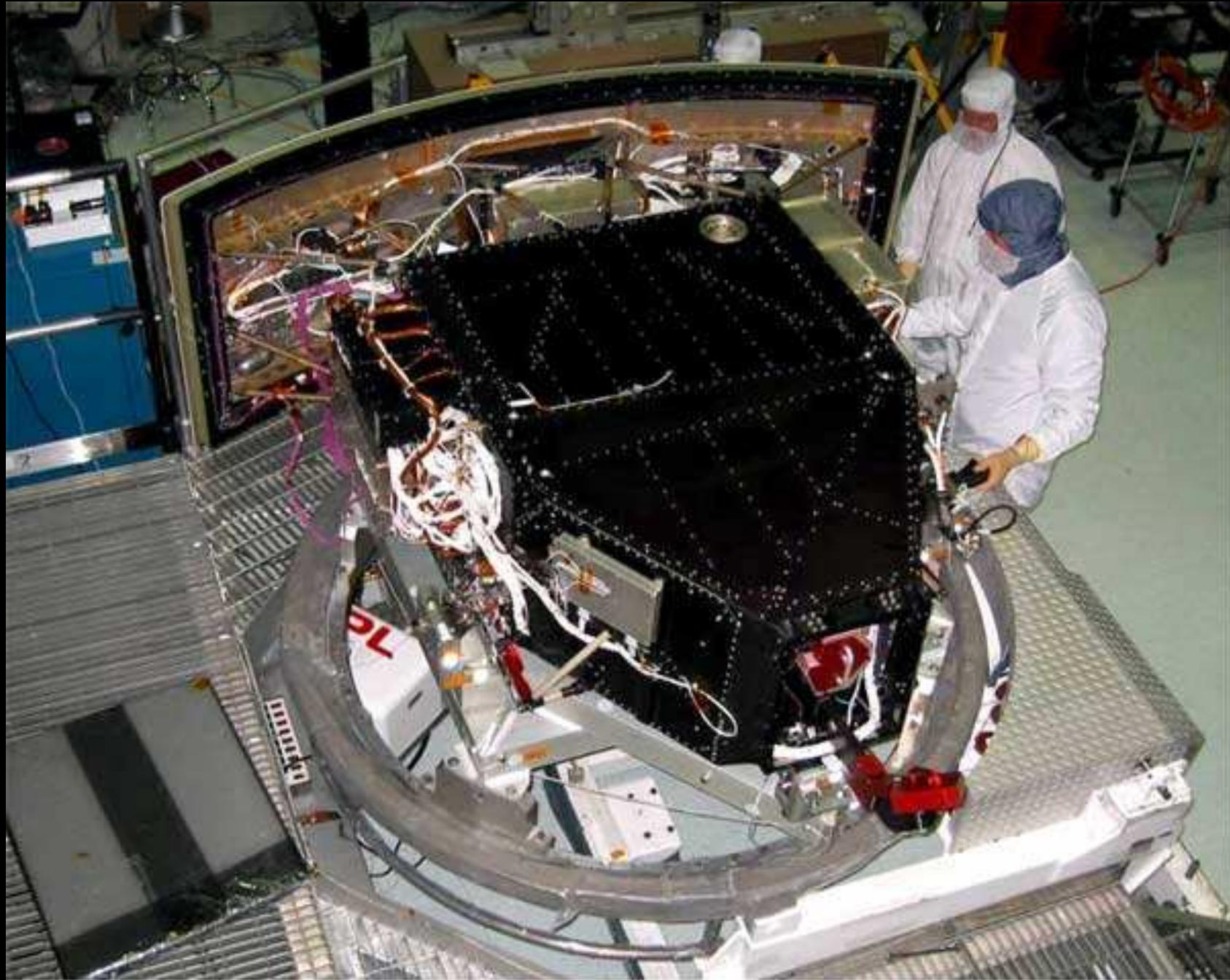
Spring–Fall 2017: JWST Flight Sunshield assembled and tested at Northrop.

## (2) How can JWST measure Galaxy Assembly and SMBH/AGN Growth?



$\beta$ 10 filters with HST/WFC3 & ACS reaching AB=26.5–27.0 mag (10- $\sigma$ ) over 40 arcmin<sup>2</sup> at 0.07–0.15" FWHM from 0.2–1.7 $\mu$ m (UVUBVizYJH). JWST adds 0.05–0.2" FWHM imaging to AB $\simeq$ 31.5 mag (1 nJy) at 1–5 $\mu$ m, and 0.2–1.2" FWHM at 5–29 $\mu$ m, tracing young+old SEDs & dust.

## (2a) WFC3: Hubble's new Panchromatic High-Throughput Camera



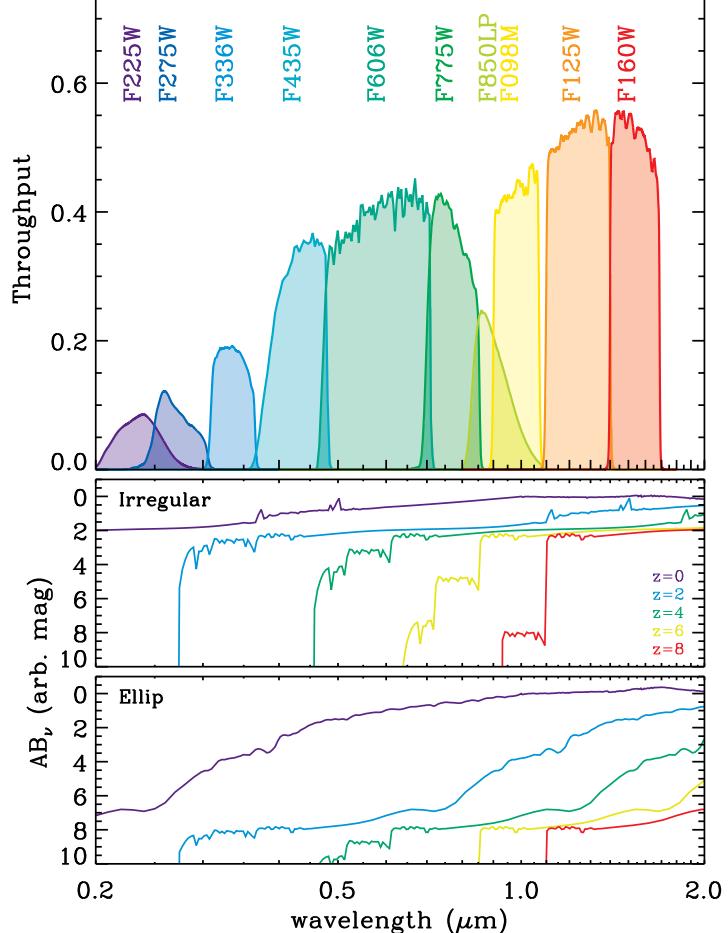
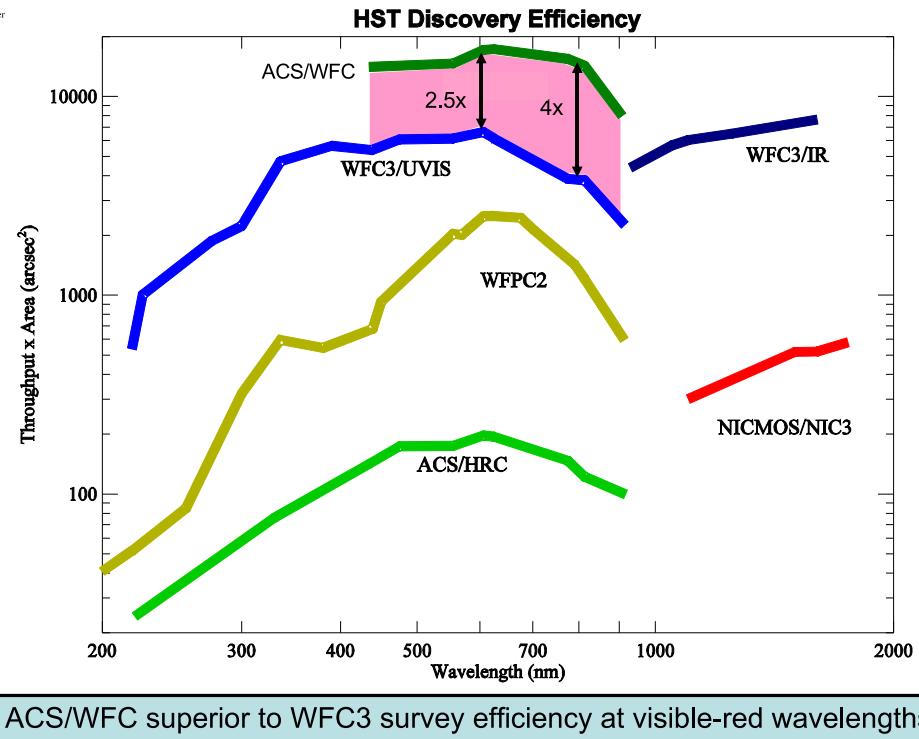
HST WFC3 and its IR channel: a critical pathfinder for JWST science.



Goddard Space Flight Center

Hubble Space Telescope Program

## Role of ACS in HST Post-SM4 Imaging Capability



9

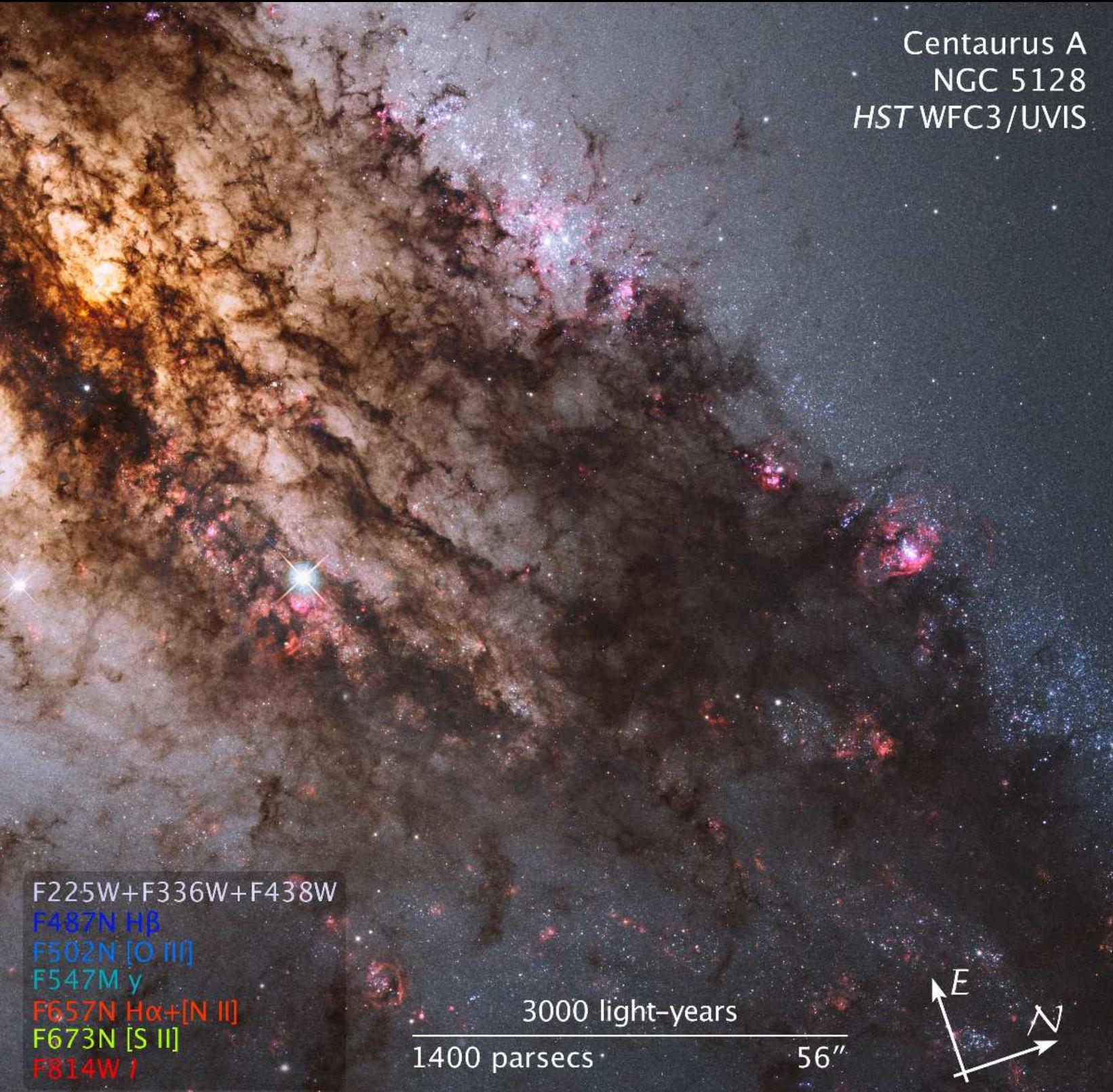
WFC3/UV & IR channels unprecedented throughput & areal coverage:

- QE  $\gtrsim 70\%$ ,  $4k \times 4k$  array of  $0''.04$  pixel,  $\text{FOV} \simeq 2''.67 \times 2''.67$ .
- QE  $\gtrsim 70\%$ ,  $1k \times 1k$  array of  $0''.13$  pixel,  $\text{FOV} \simeq 2''.25 \times 2''.25$ .

$\Rightarrow$  WFC3 opened major new parameter space for astrophysics in 2009:  
WFC3 filters designed for star-formation and galaxy assembly at  $z \simeq 1-8$ .

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

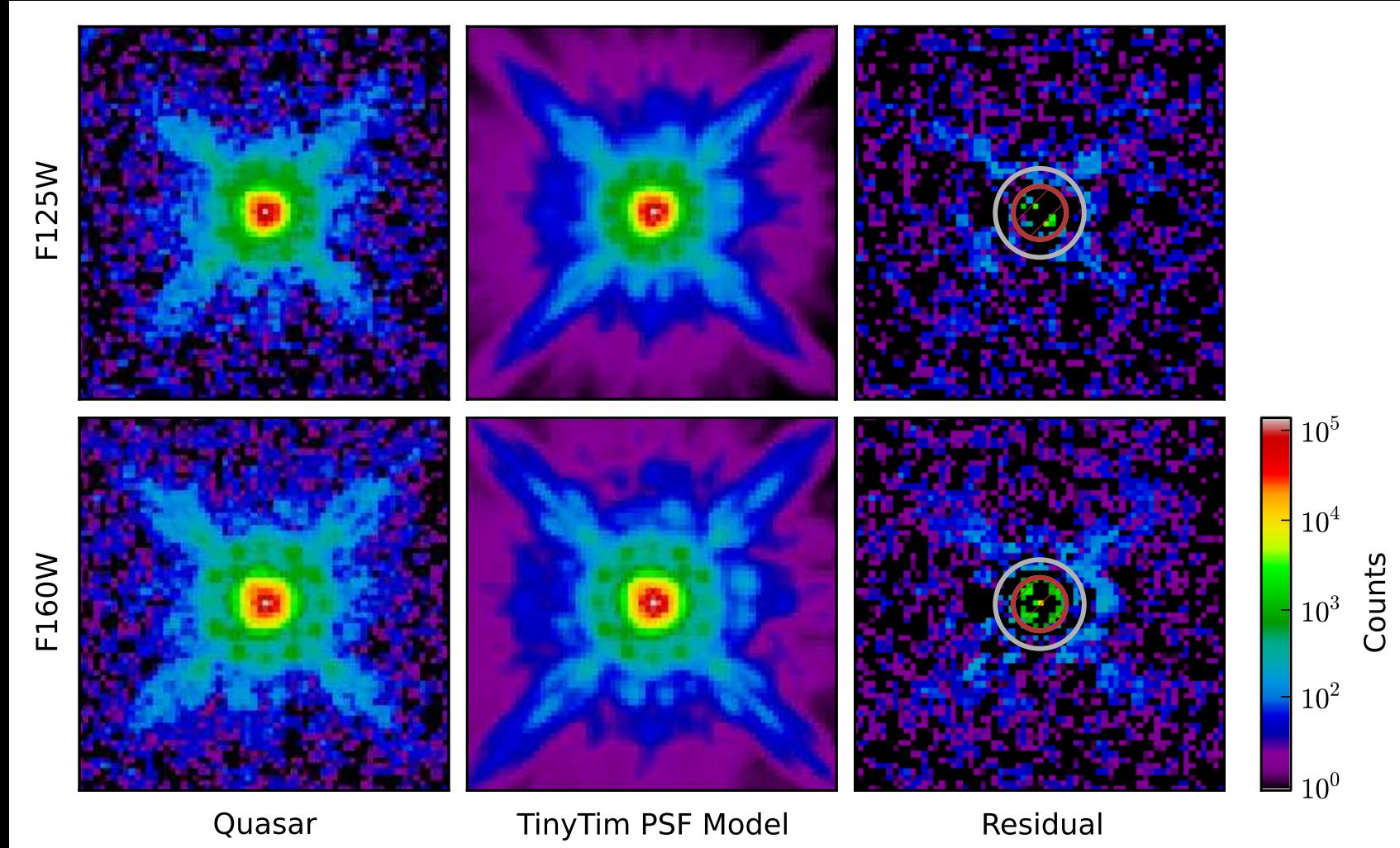
Centaurus A  
NGC 5128  
*HST WFC3/UVIS*





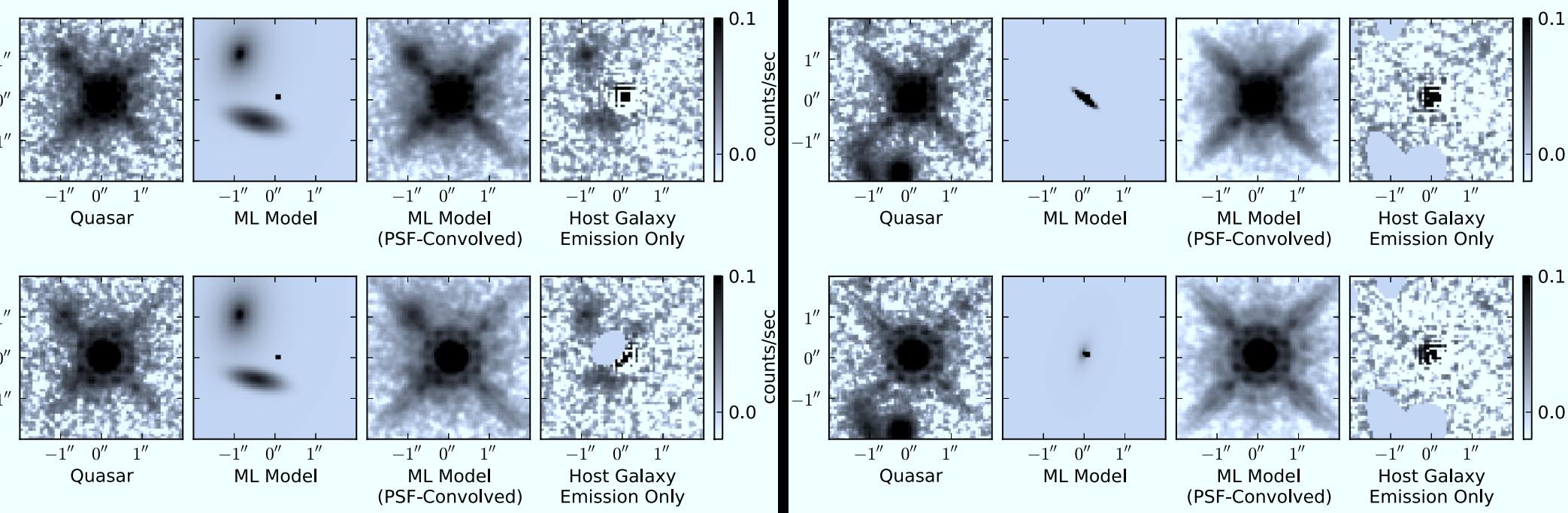
Blue=X-rays; White=Optical; Orange=Radio

## (2b) HST WFC3 observations of QSO host systems at $z \simeq 6$ (age $\lesssim 1$ Gyr)



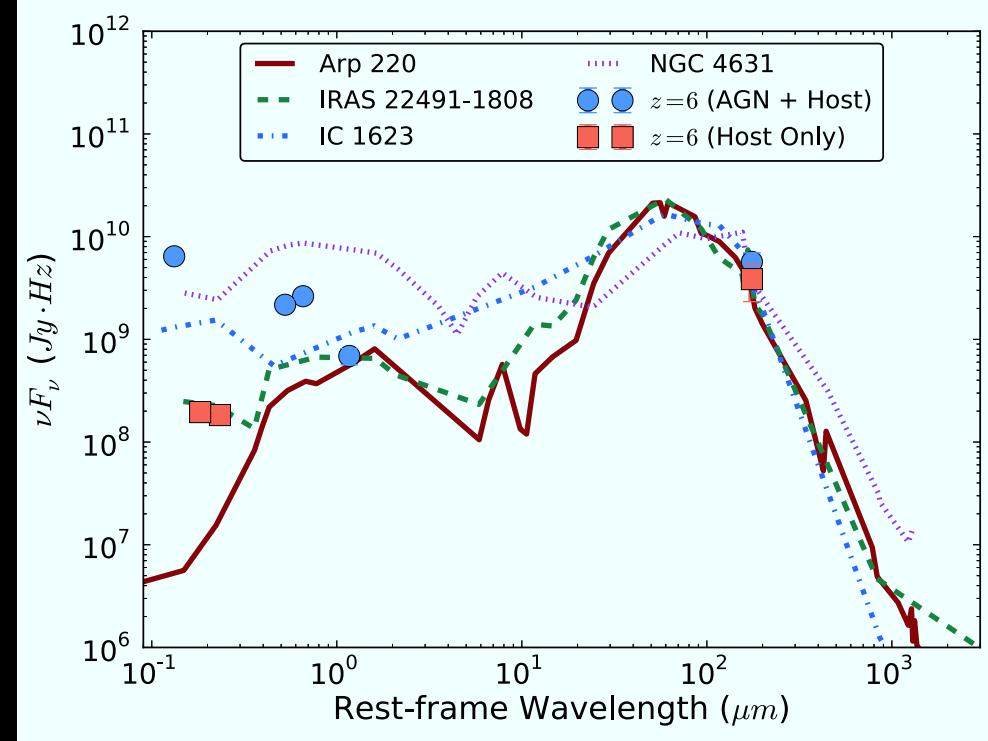
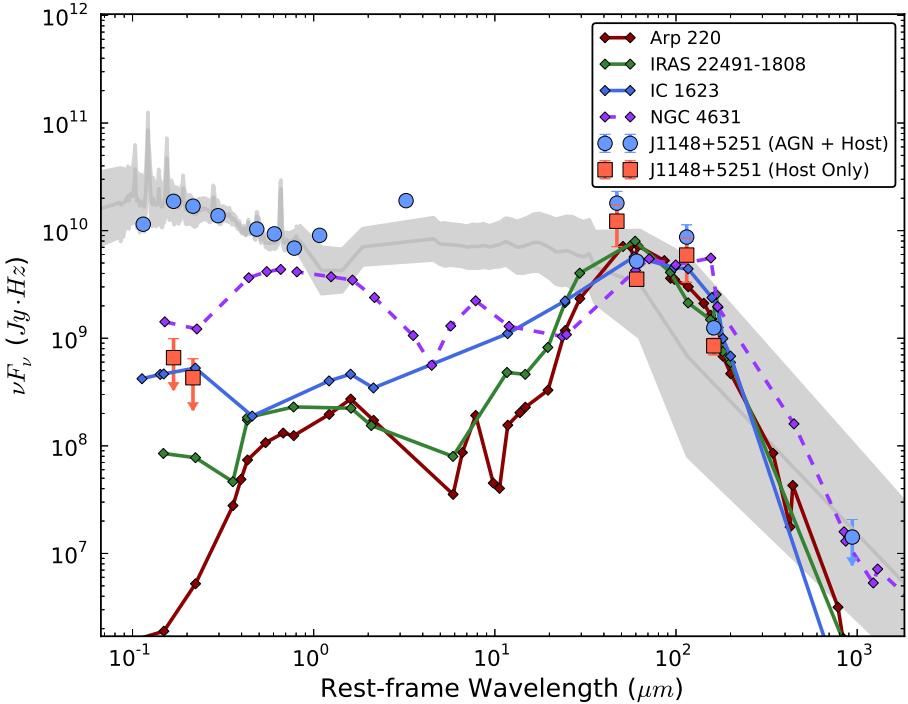
- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley ea 2012, ApJL, 756, L38).
- PSF-star ( $AB \simeq 15$  mag) subtracts  $z=6.42$  QSO ( $AB \simeq 18.5$ ) nearly to the noise limit: NO host galaxy detected  $100 \times$  fainter ( $AB \gtrsim 23.5$  at  $r \gtrsim 0\farcs3$ ).
- The most luminous Quasar in the universe has NO visible host galaxy!

## (2b) WFC3: Detection of one QSO Host System at $z \simeq 6$ (Giant merger?)



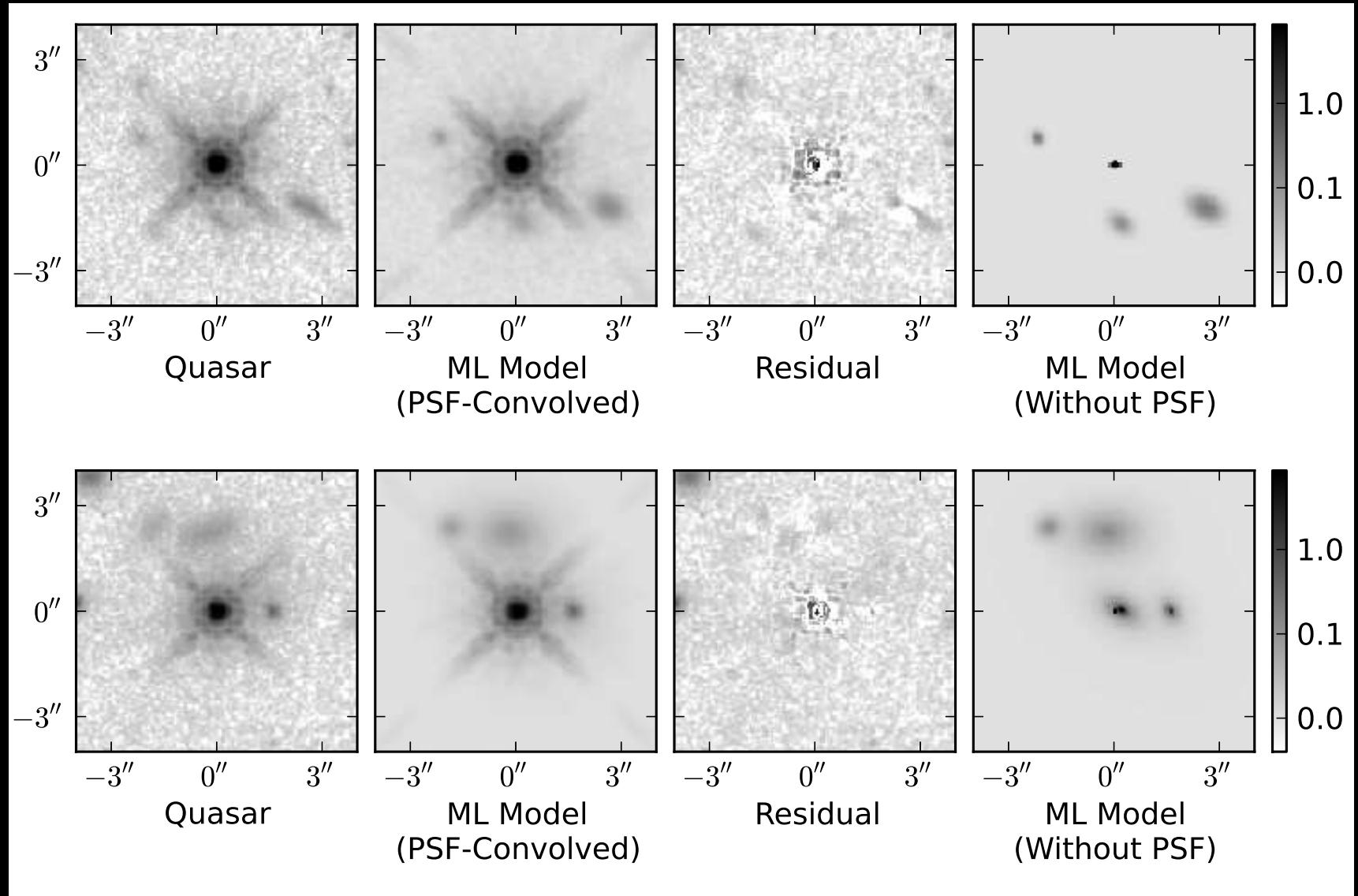
- Markov Chain Monte Carlo posterior model of observed PSF-star + Sersic light-profile. Gemini AO images to pre-select PSF stars (Mechtley<sup>+</sup> 2016).
- One  $z \simeq 6$  QSO host galaxy: Giant merger morphology + tidal structure?
- Same  $\lambda = 1.25$  &  $1.6 \mu\text{m}$  structure.  $(J-H) \simeq 0.19$  color constrains dust.
- IRAS starburst-like SED from rest-frame UV–far-IR:  $A_{FUV} \sim 1$  mag.
- $M_{AB}^{host}(z \simeq 6) \lesssim -23.0$  mag, i.e.,  $\sim 2$  mag brighter than  $L^*(z \simeq 6)$ .
- JWST can detect  $10\text{--}100 \times$  fainter dusty hosts (for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu\text{m}$ ).
- GMT can detect & map fainter QSO hosts at  $4 \times$  better resolution.

## (2b) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$



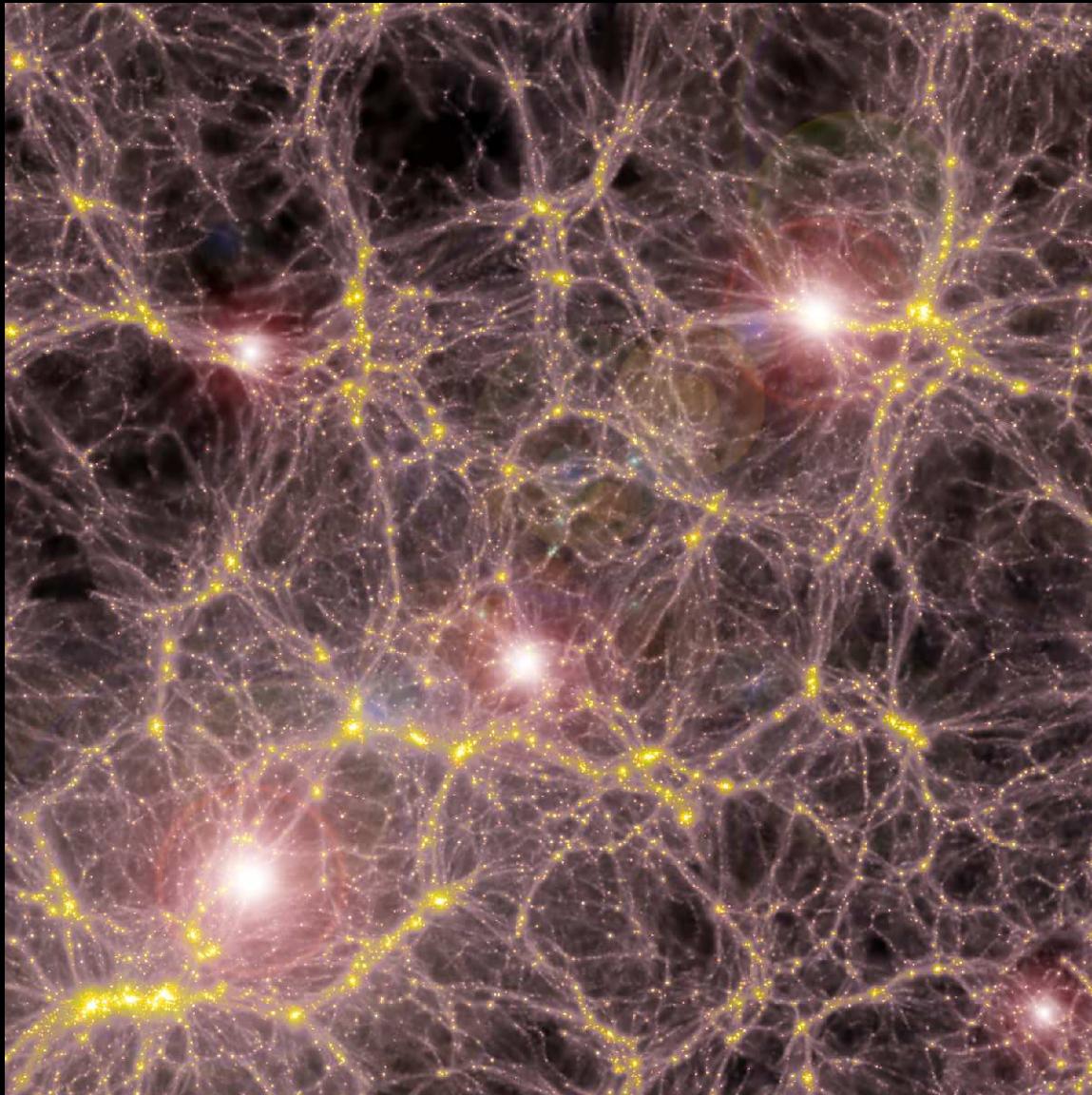
- Blue dots:  $z \simeq 6$  QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at  $z \gtrsim 1$  (normalized at  $0.5\mu$ ). Red:  $z \simeq 6$  host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages  $\lesssim 1$  Gyr) normalized at  $100\mu\text{m}$ :  
 [LEFT] Rules out  $z = 6.42$  spiral or bluer host galaxy SEDs for 1148+5251.  
 (U)LIRGs & Arp 220s permitted (Mechtley et al. 2012, ApJL, 756, L38).  
 [RIGHT] Detected QSO host has IRAS starburst-like SED from rest-frame UV–far-IR,  $A_{FUV}(\text{host}) \sim 1$  mag (Mechtley 2013 PhD; et al. 2016).
- JWST (+Coronagraphs) can do this  $\gtrsim 10 \times$  fainter: in restframe V for  $z \gtrsim 6$ .

## (2b) WFC3 observations of QSO host galaxies at $z \simeq 2$ (evidence for mergers?)



- Markov Chain Monte Carlo posterior model of observed PSF-star + Sersic light-profile: merging neighbors (some with tidal tails?; Mechtley, M., Jahnke, K., Windhorst, R. A., et al. 2016, ApJ, 830, 156).
- JWST (+Coronagraphs) can do this  $\gtrsim 10 \times$  fainter: in restframe V for  $z \gtrsim 6$ .

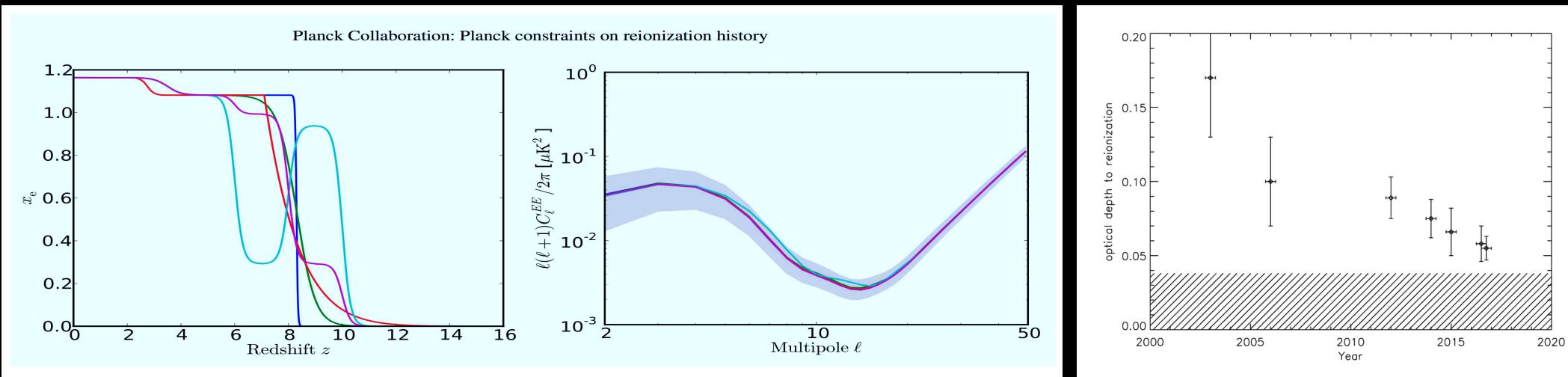
### (3) How will JWST Observe First Light and Reionization?



- Detailed cosmological models (V. Bromm) suggest that massive “Pop III” stars ( $\gtrsim 100 M_{\text{sun}}$ ) started to reionize the universe at  $z \lesssim 10-30$  (0.1–0.5 Gyr; “First Light”).
- This should be visible to JWST as the first Pop III stars or surrounding (Pop II.5) star clusters, and perhaps their extremely luminous supernovae at  $z \simeq 10 \rightarrow 30$ .

We must make sure that we theoretically understand the likely Pop III mass-range, their mass function, their clustering properties, their SN-rates, etc., before JWST flies, so we know what to look for.

### (3a) Implications of Planck 2016 results for JWST First Light:



WFC3  $z \lesssim 7\text{--}9 \longleftrightarrow \rightarrow$  JWST  $z \simeq 8\text{--}25$

(Courtesy: Dr. Bill Jones).

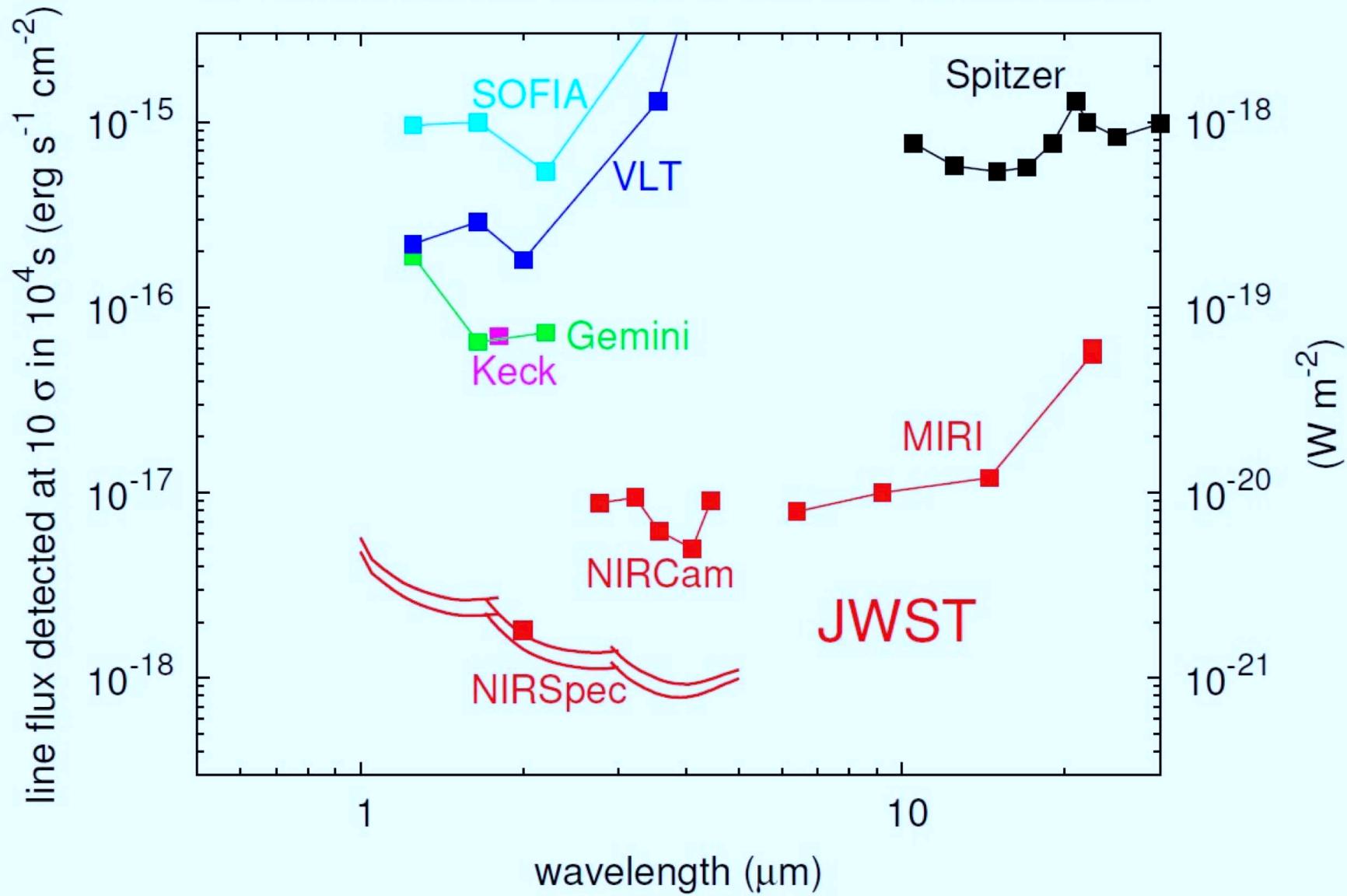
Planck 2016 data provided better foreground removal (Planck 2016 papers XLVIII & XLVII; astro-ph/1605.02985 & astro-ph/1605.03507):

Reionization appears to have occurred between these extremes:

- (1) Instantaneous:  $z \sim 8.2 \pm 0.9$  (polarization optical depth  $\tau \simeq 0.055 \pm 0.009$ ).
  - (2) or Inhomogeneous & drawn out: starting at  $z \gtrsim 12?$ , peaking at  $z \sim 8$ , ending at  $z \simeq 6\text{--}7$ . The differences between both are now very small.
- Since Planck 2016's polarization  $\tau$  has come down considerably ( $\tau \simeq 0.055\text{--}0.058$ ), how many reionizers will JWST actually see at  $z \simeq 10\text{--}15$ ?

# Sensitivities - spectroscopy

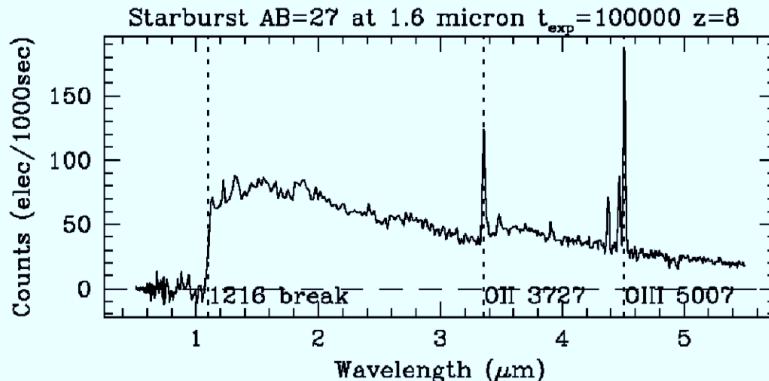
R=600-2400 spectroscopy, emission line, point source



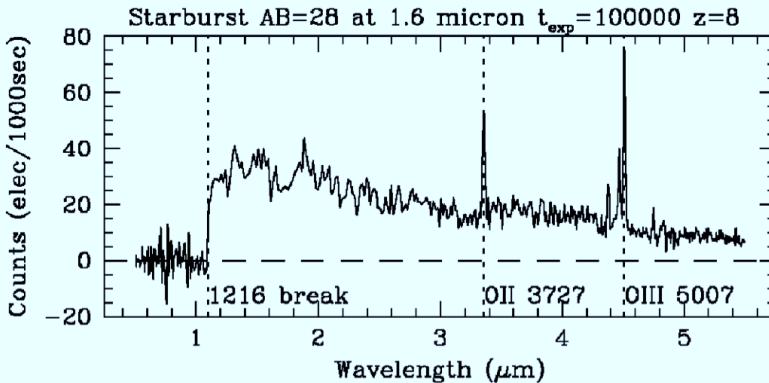
NIRCam, NIRSpec and MIRI sensitivity (cgs) compared to VLT, Keck, Spitzer.  
JWST R<sub>spec</sub>  $\lesssim 2700$ . GMT gets fainter spectra at  $\lambda \lesssim 2 \mu\text{m}$ , or do higher R.

# What NIRSPEC can do !

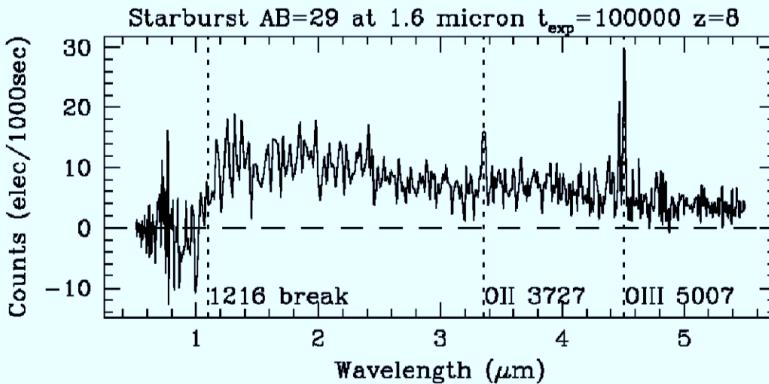
AB=27



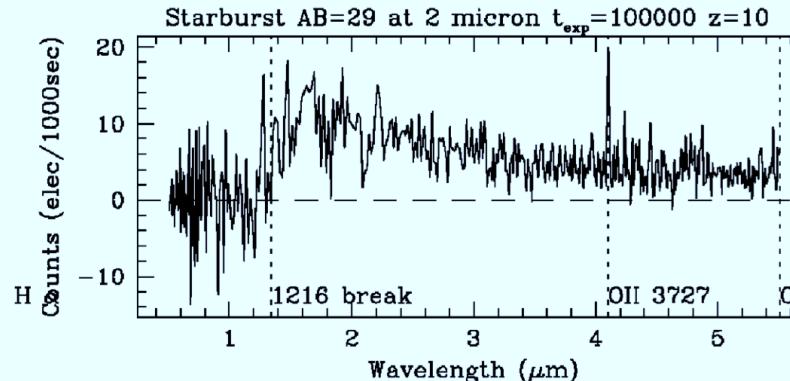
AB=28



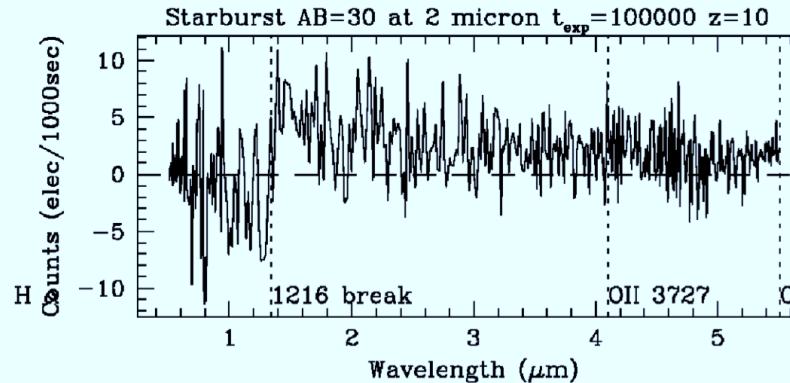
AB=29



AB=29



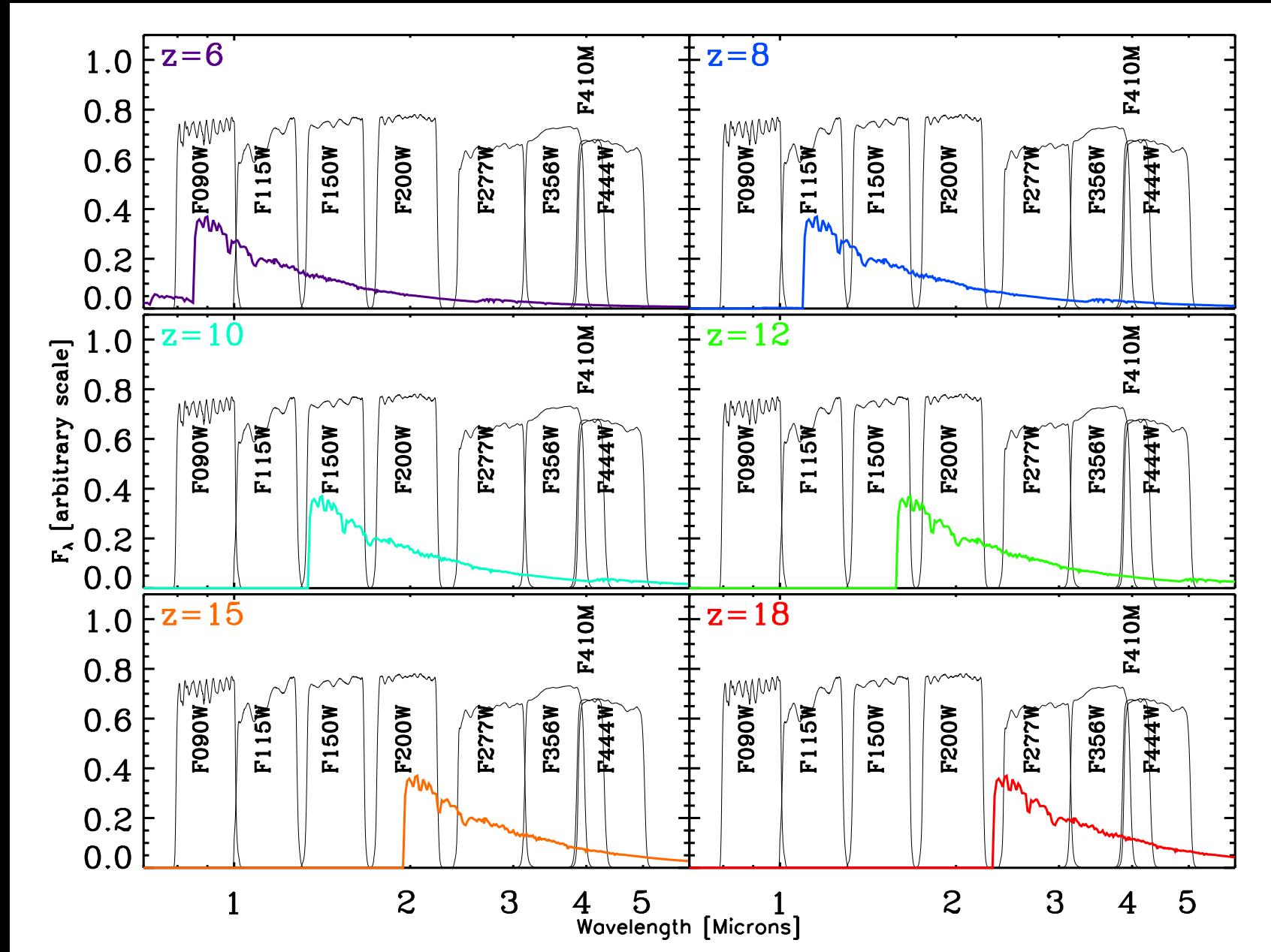
AB=30



Derive redshifts, stellar masses, stellar ages, gas ionization and metallicities, star formation rates, kinematics, pop III stars, Ly- $\alpha$  LF to z=10, etc.

JWST NIRSpec sensitivity to SF reionizers at z=8–10, AB $\simeq$ 27–30 mag.

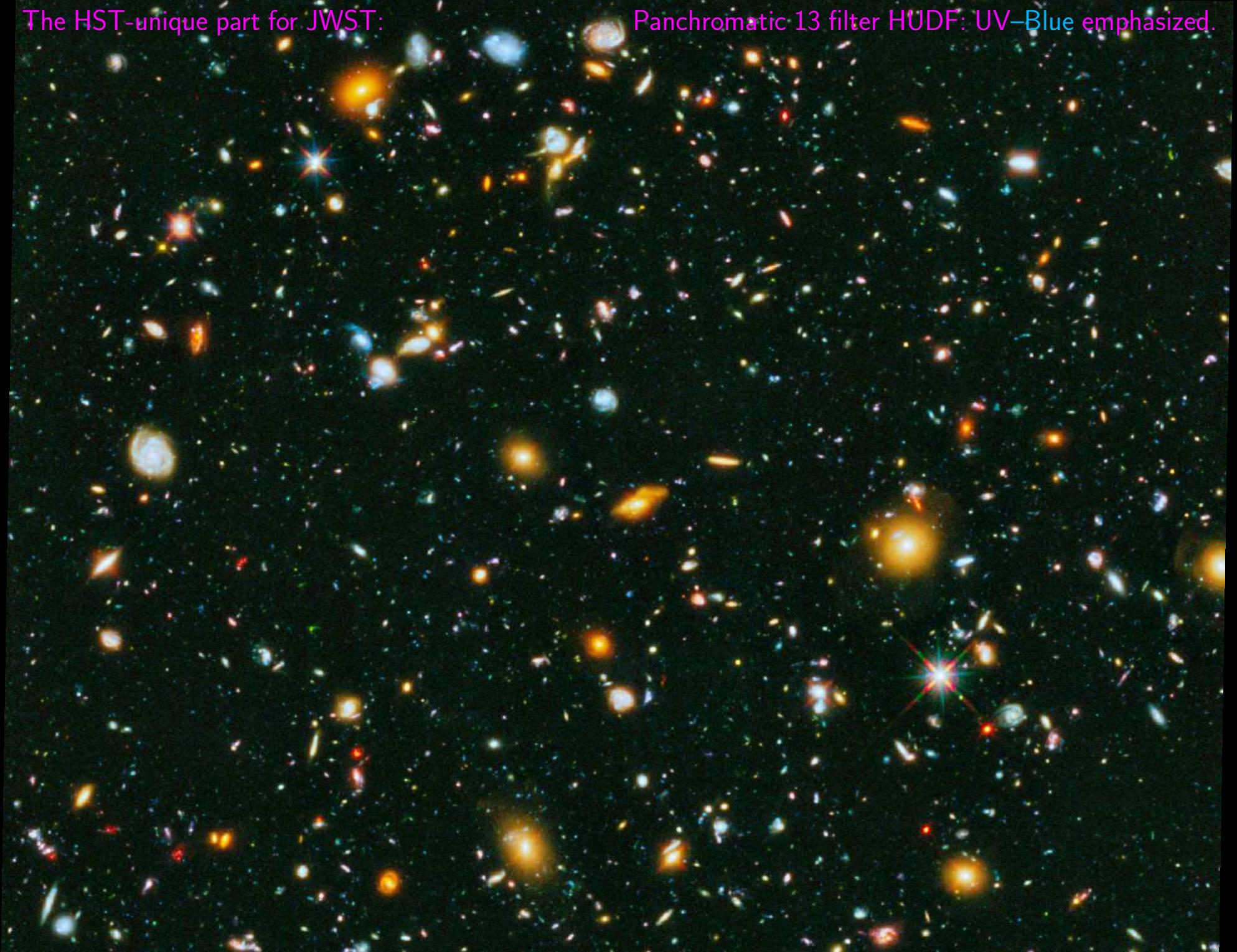
### (3b) How will Webb measure First Light: what to expect in (Ultra)Deep Fields?



- Can't beat redshift: to see First Light, must observe near-mid IR.  
⇒ This is why JWST needs NIRCam at  $0.8\text{--}5 \mu\text{m}$  and MIRI at  $5\text{--}28 \mu\text{m}$ .

The HST-unique part for JWST:

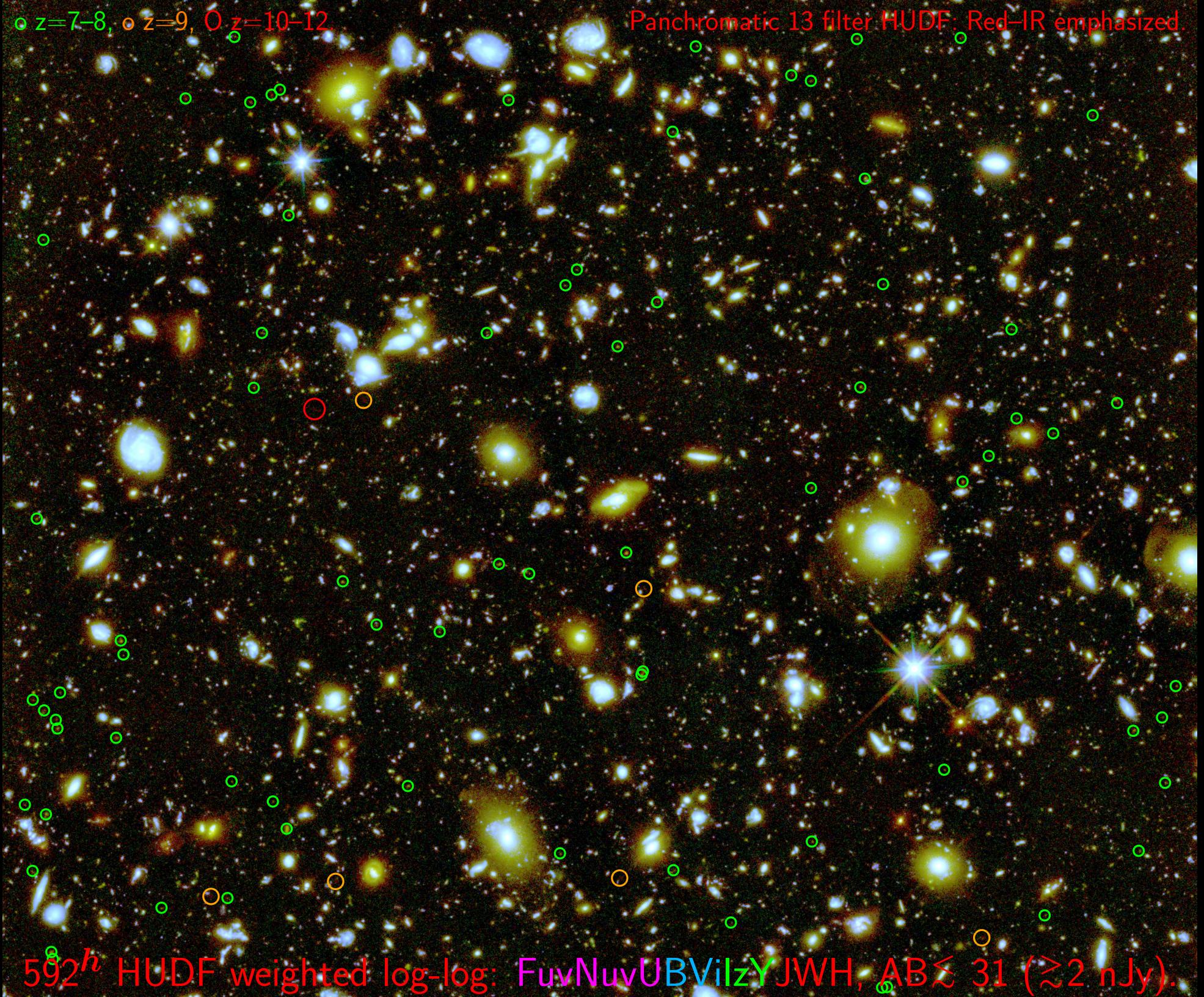
Panchromatic 13 filter HUDF: UV–Blue emphasized.



592<sup>h</sup> HUDF weighted log-log: F<sub>UV</sub>N<sub>UV</sub>U<sub>B</sub>V<sub>I</sub>zYJWH, AB $\lesssim$ 28–31 ( $\gtrsim$ 2 nJy).

○  $z=7-8$ , ○  $z=9$ , ○  $z=10-12$ .

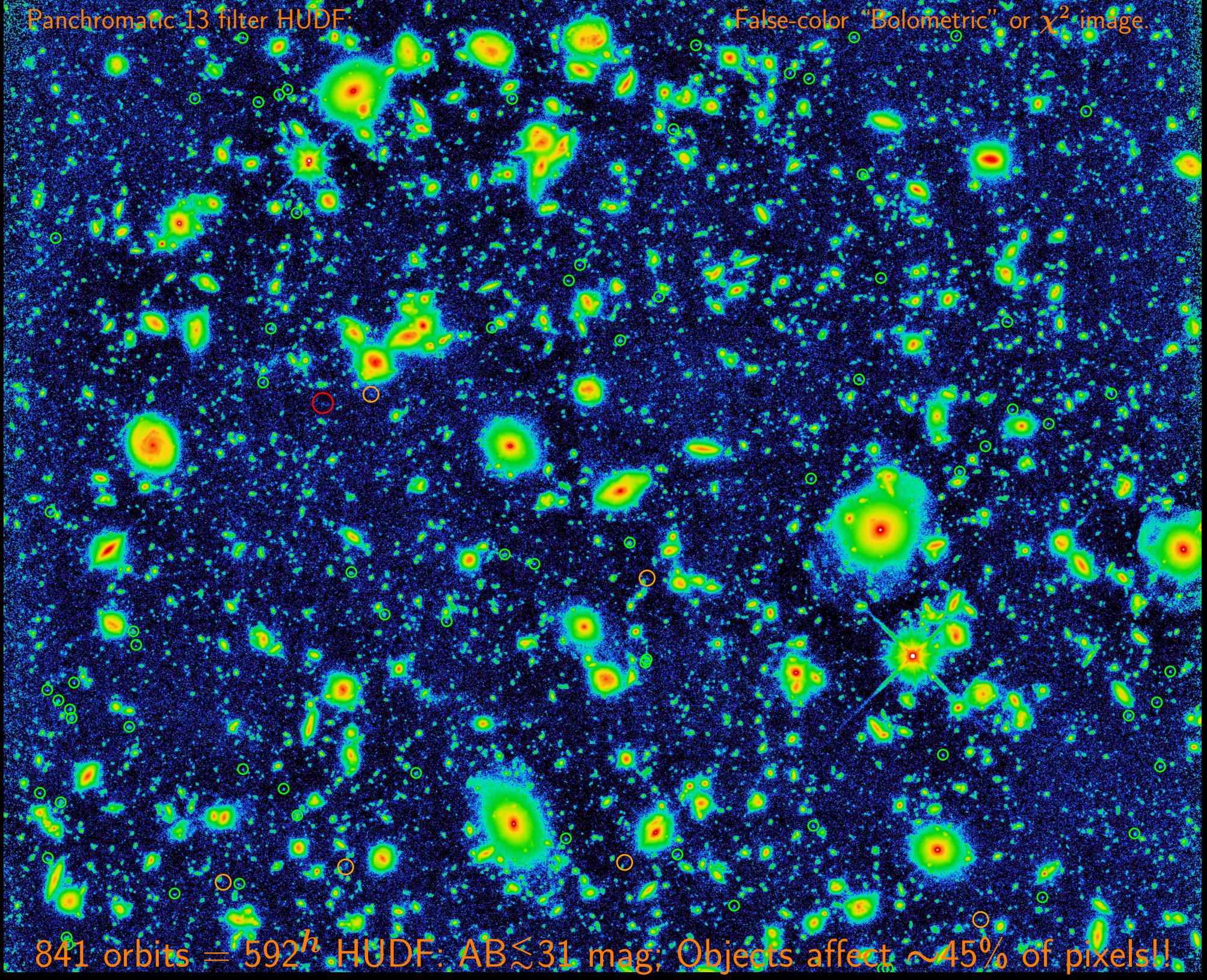
Panchromatic 13 filter HUDF; Red-IR emphasized.



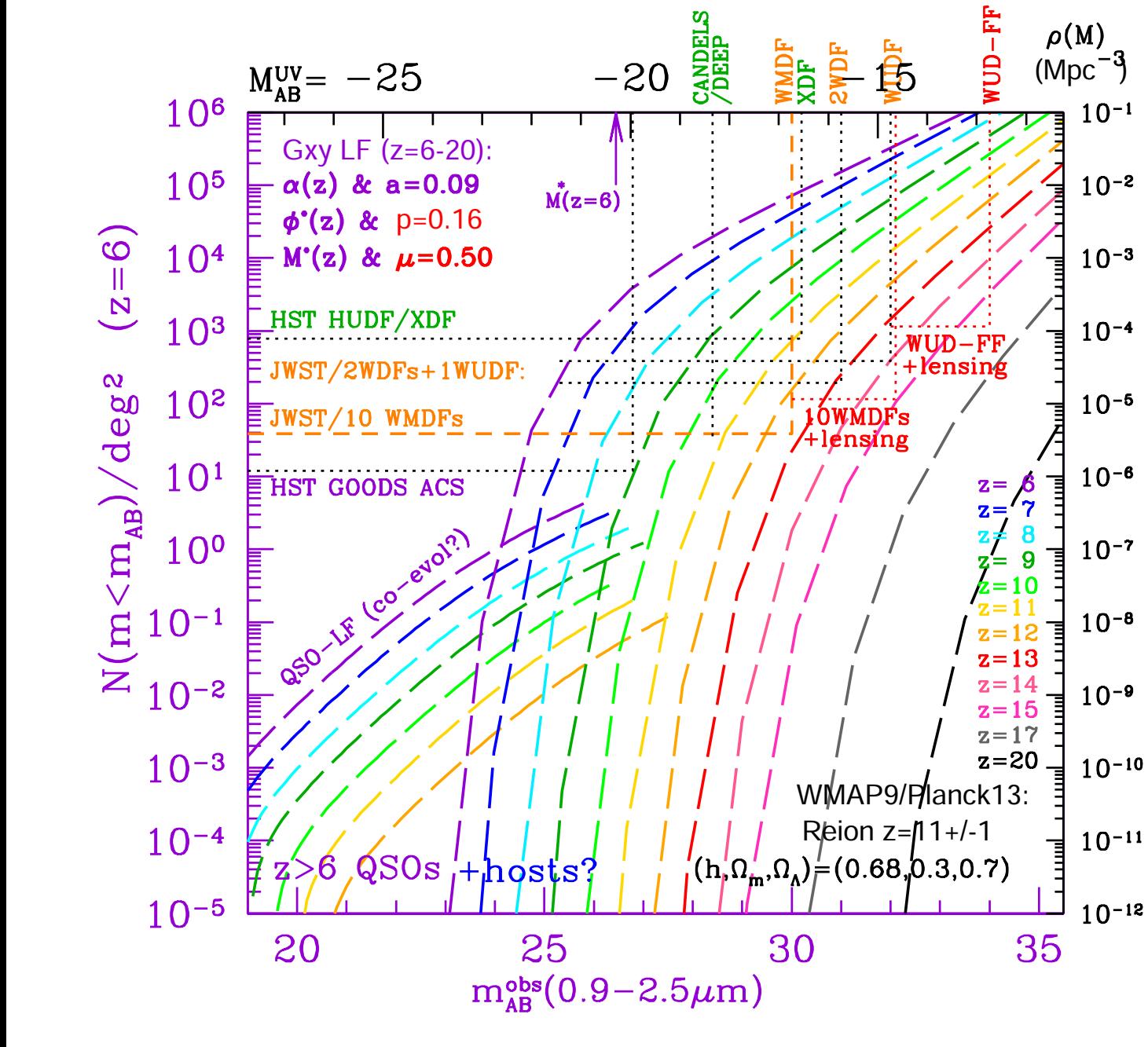
$592^h$  HUDF weighted log-log: FuvNuvUBVilzYJWH, AB  $\lesssim 31$  ( $\gtrsim 2$  nJy).

Panchromatic 13 filter HUDF

False-color "Bolometric" or  $\chi^2$  image.

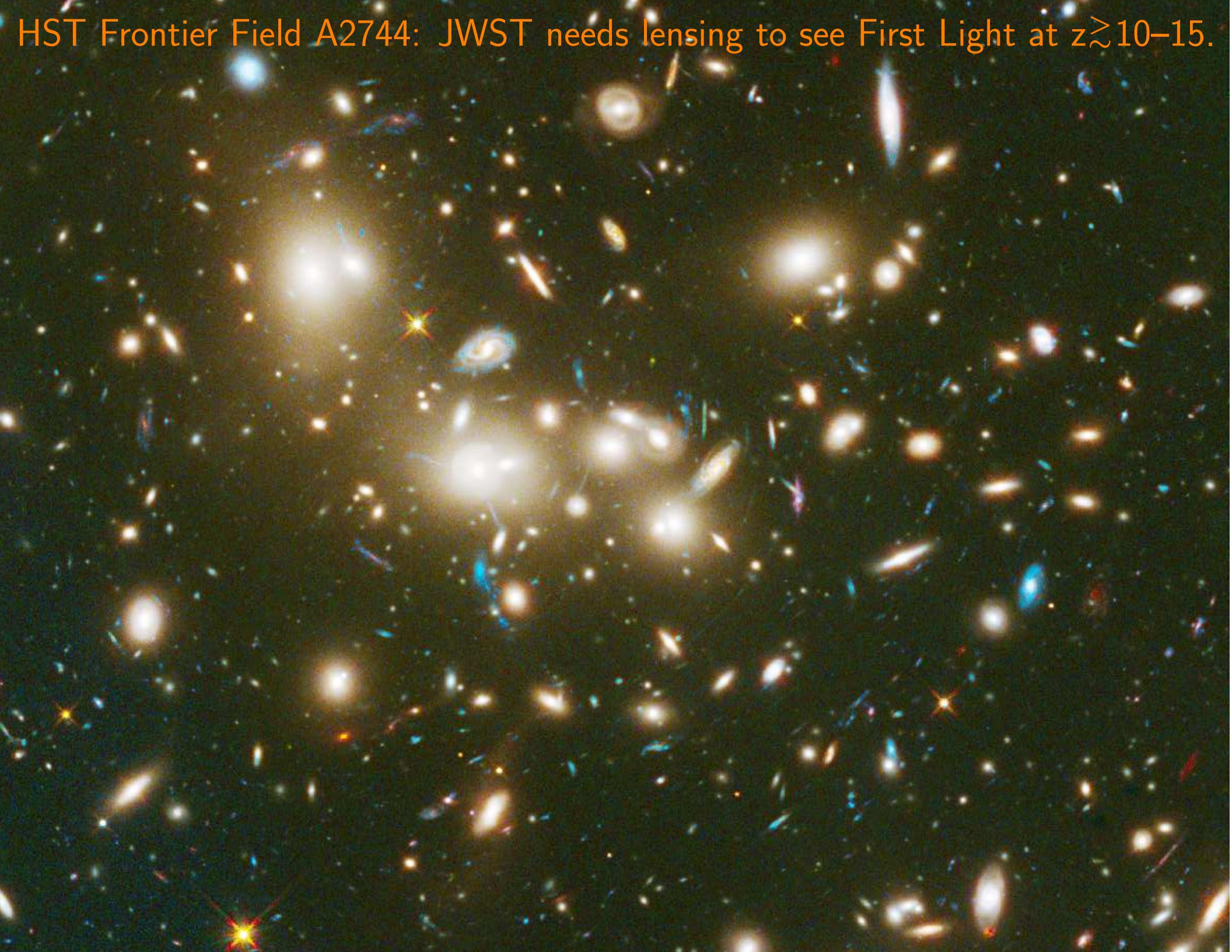


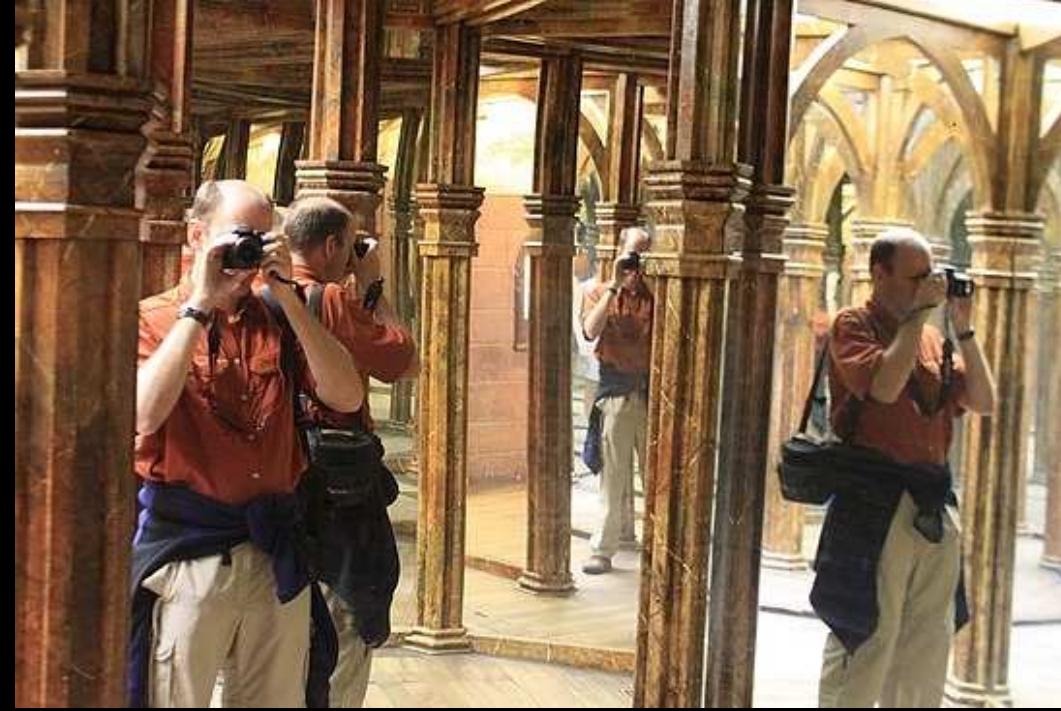
841 orbits = 592<sup>h</sup> HUDF: AB  $\lesssim$  31 mag; Objects affect  $\sim$  45% of pixels!!



Predicted Schechter Luminosity Function (LF) at redshifts  $6 \lesssim z \lesssim 20$ :  
 Area/Sensitivity for: Hubble UDF, Webb: 10 MDFs, 2 DFs, & 1 UDF.  
 • JWST needs to use lensing targets to see many  $z \simeq 12-15$  objects.

HST Frontier Field A2744: JWST needs lensing to see First Light at  $z \gtrsim 10-15$ .



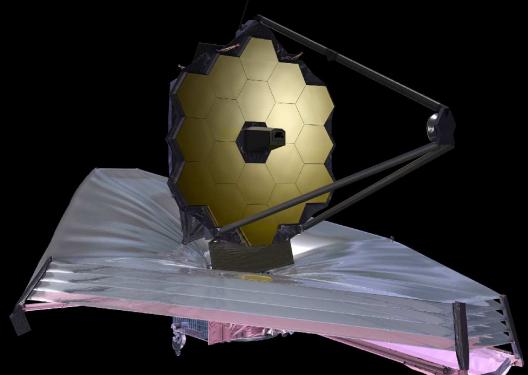


Conclusion: JWST First Light strategy must consider three aspects:

- (1) The catastrophic drop in the LF (space density) for  $z \gtrsim 8$ .
- (2) Cannot-see-the-forest-for-the-trees effect [“Natural Confusion” limit]:  
Background objects blend into foreground because of their own diameter.
- (3) House-of-mirrors effect [“Gravitational Confusion”]:
  - JWST needs to find most First Light objects at  $z \gtrsim 10-15$  through the best cosmic lenses (this will make the images even more crowded):
  - Lensing is needed to see what Einstein thought was impossible to observe!

## (4) Future: Next generation 20–40 m ground-based telescopes and ATLAST

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



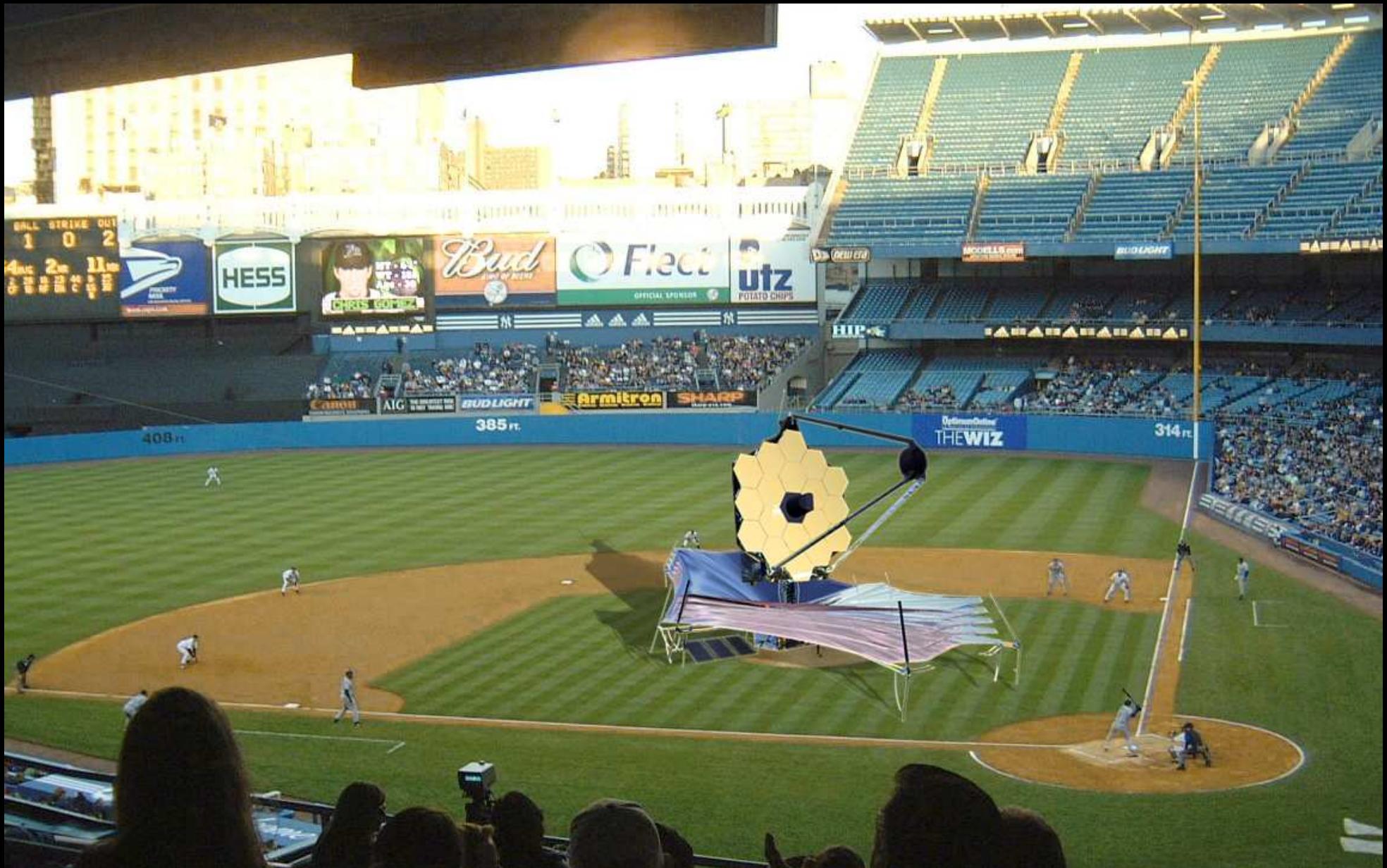
(1973~2020<sup>+</sup>);

(1996~2029);

(2000's  $\sim$  2021+ $\infty$ ).

- JWST has superbly dark L2-sky & SB-sensitivity, and stable PSF.
- GMT has 4×higher Res (AO), high-Res spectra, long-term time-domain.

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



Each of GMT (& ATLAST) facilities nearly fills the whole Yankee ballpark ...

- New paradigm: They are too large for an individual university to take on.
- Universities need to collaborate nation-wide to make this happen.

## (5) Summary and Conclusions

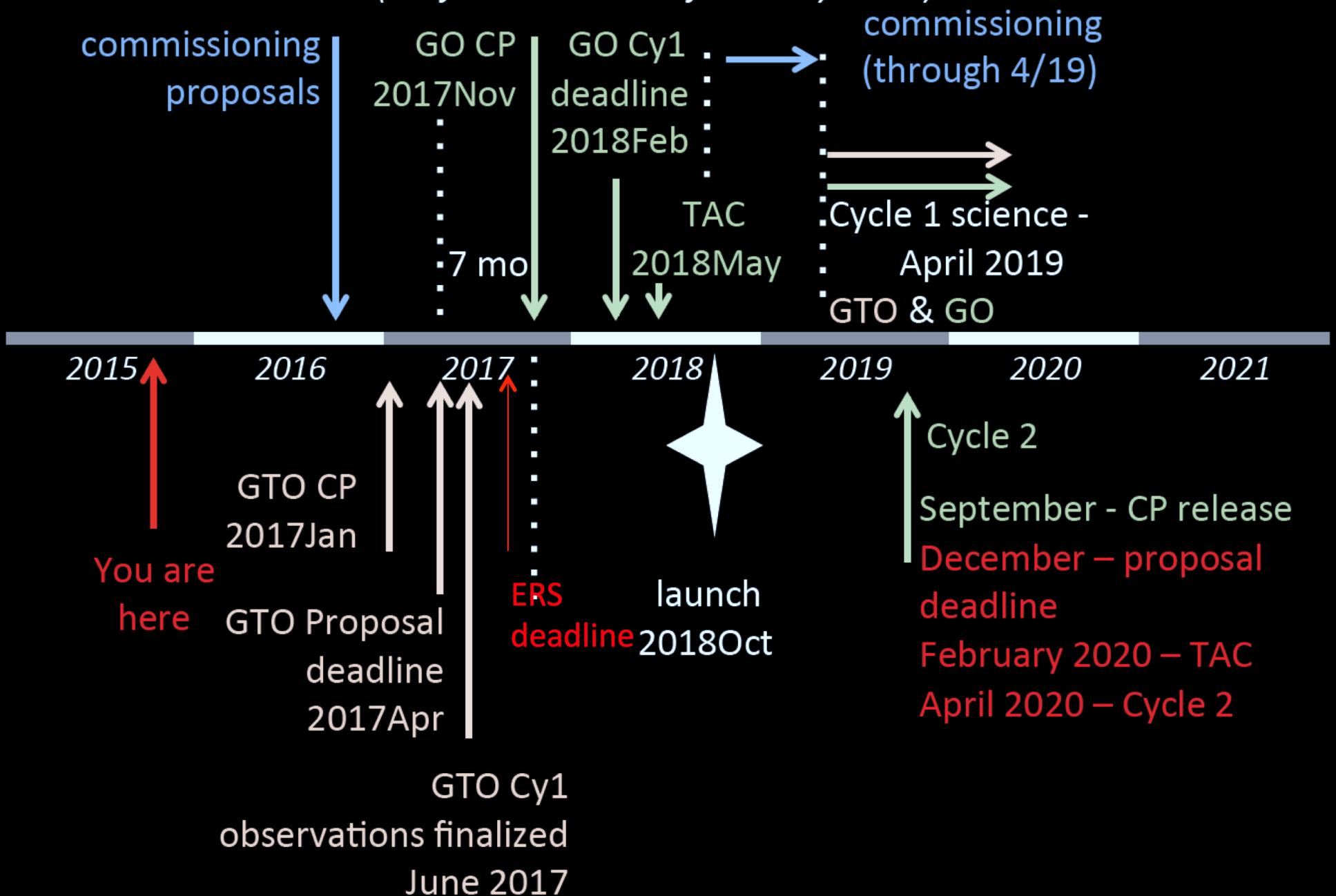
- (1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.
- (2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.
  - More than 99% of JWST H/W built or in fab, & meets/exceeds specs.
- (3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail.
  - Measure rapid growth of first supermassive blackholes & host galaxies.
  - To see the most First Light, JWST must cover the best lensing clusters!
  - Must *routinely* observe what Einstein thought impossible.
- (4) JWST will have a major impact on astrophysics end of decade:
  - IR sequel to HST in 2019: Training the next generation researchers.
  - JWST proposals due Aug. 2017 (ERS) and Feb. 2018 (Cycle 1 GO)!
  - Critical synergy with GMT's high-res AO, high-res spectra, and long-term time-domain.

# SPARE CHARTS

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# JWST Science Planning Timeline

(draft schedule as of January 2015)



2017–2019 (Launch) and beyond: When are your ERS & GO proposals due?

- 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://ircamera.as.arizona.edu/MIRI/>

<http://www.stsci.edu/jwst/instruments/nirspec/>

<http://www.stsci.edu/jwst/instruments/fgs>

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

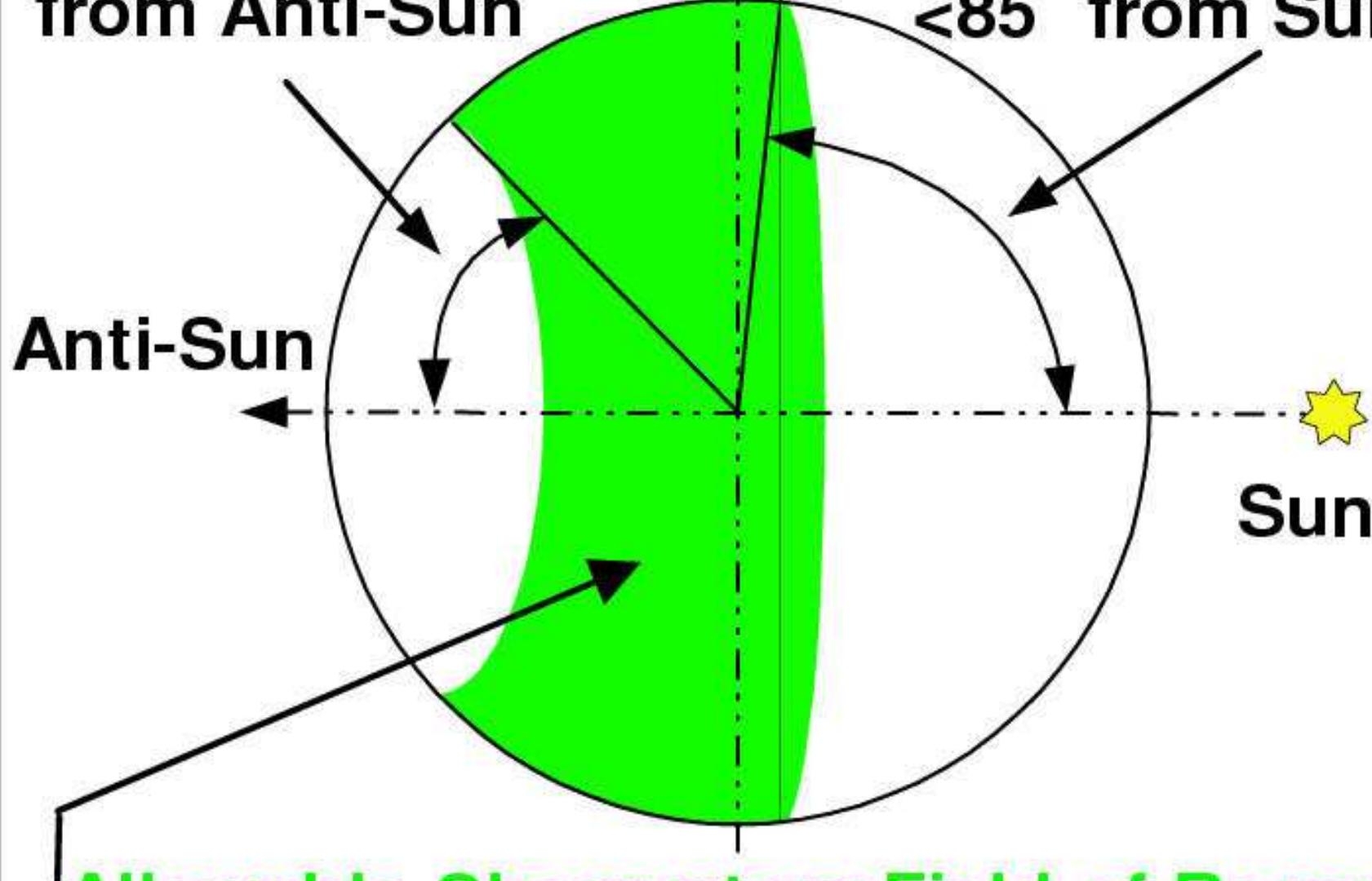
Mather, J., & Stockman, H. 2000, *Proc. SPIE Vol. 4013*, 2

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

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

**Exclusion zone <45° from Anti-Sun**

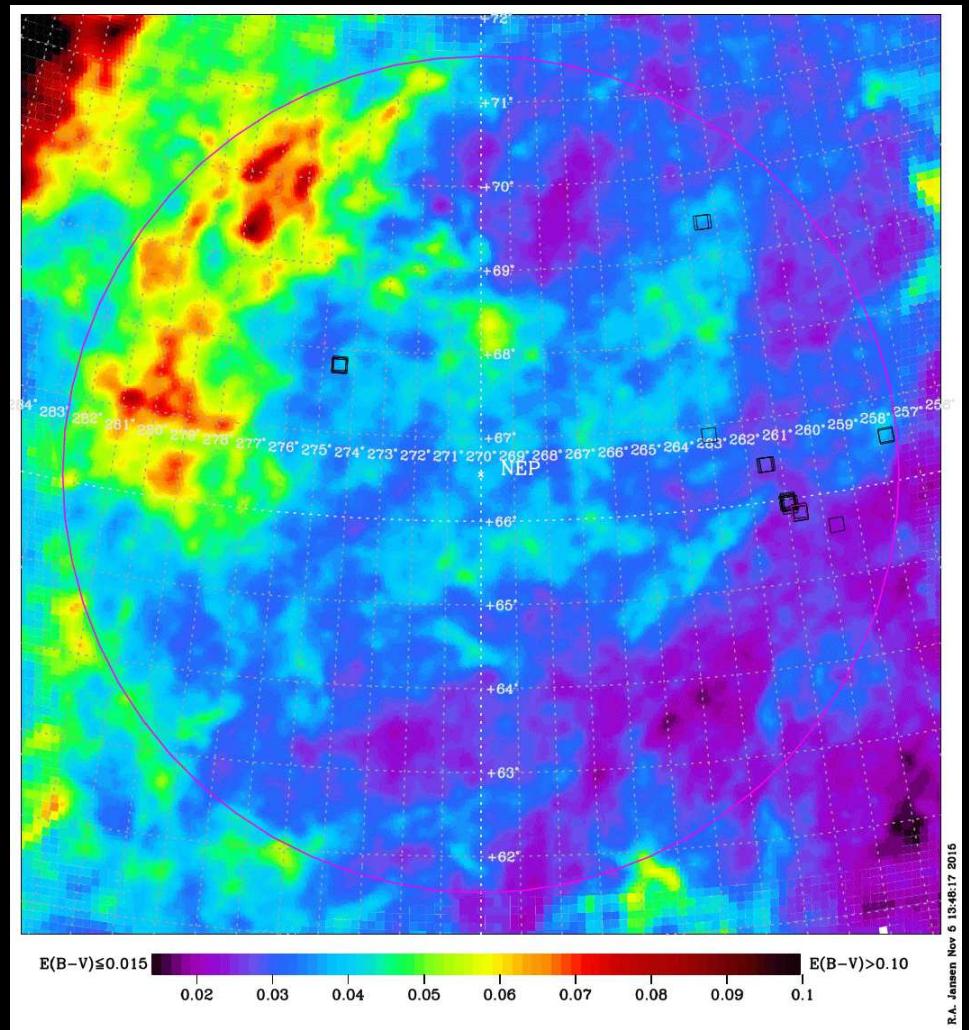
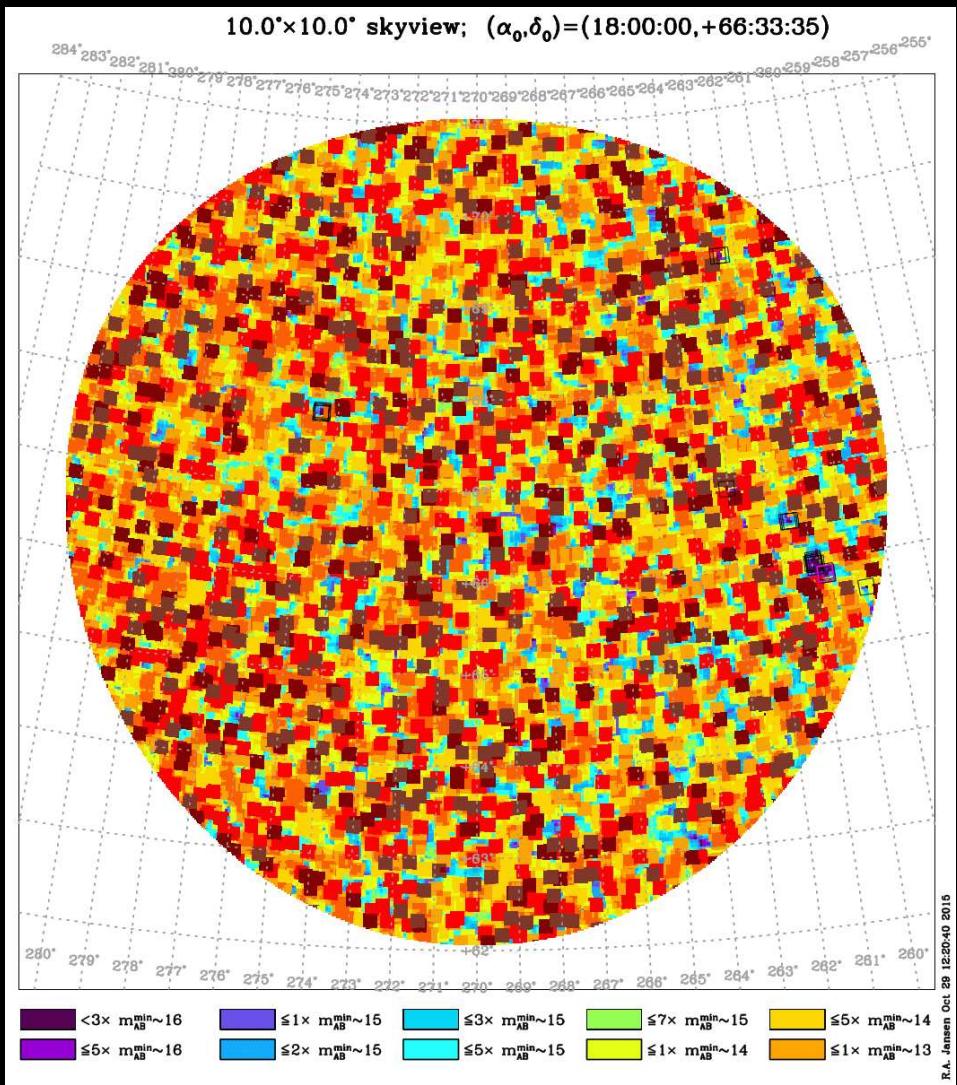
**Exclusion zone <85° from Sun**



**Allowable Observatory Field-of-Regard**

JWST can observe North/South Ecliptic pole targets continuously:

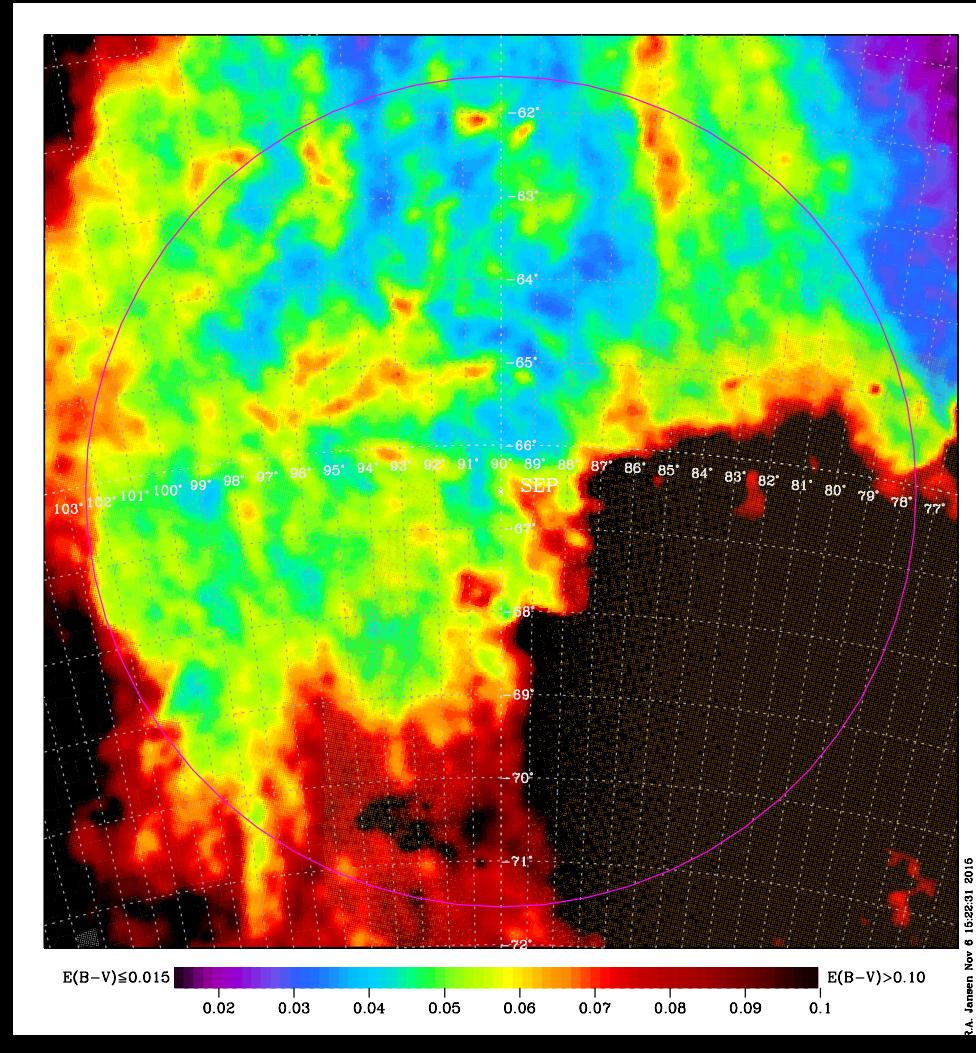
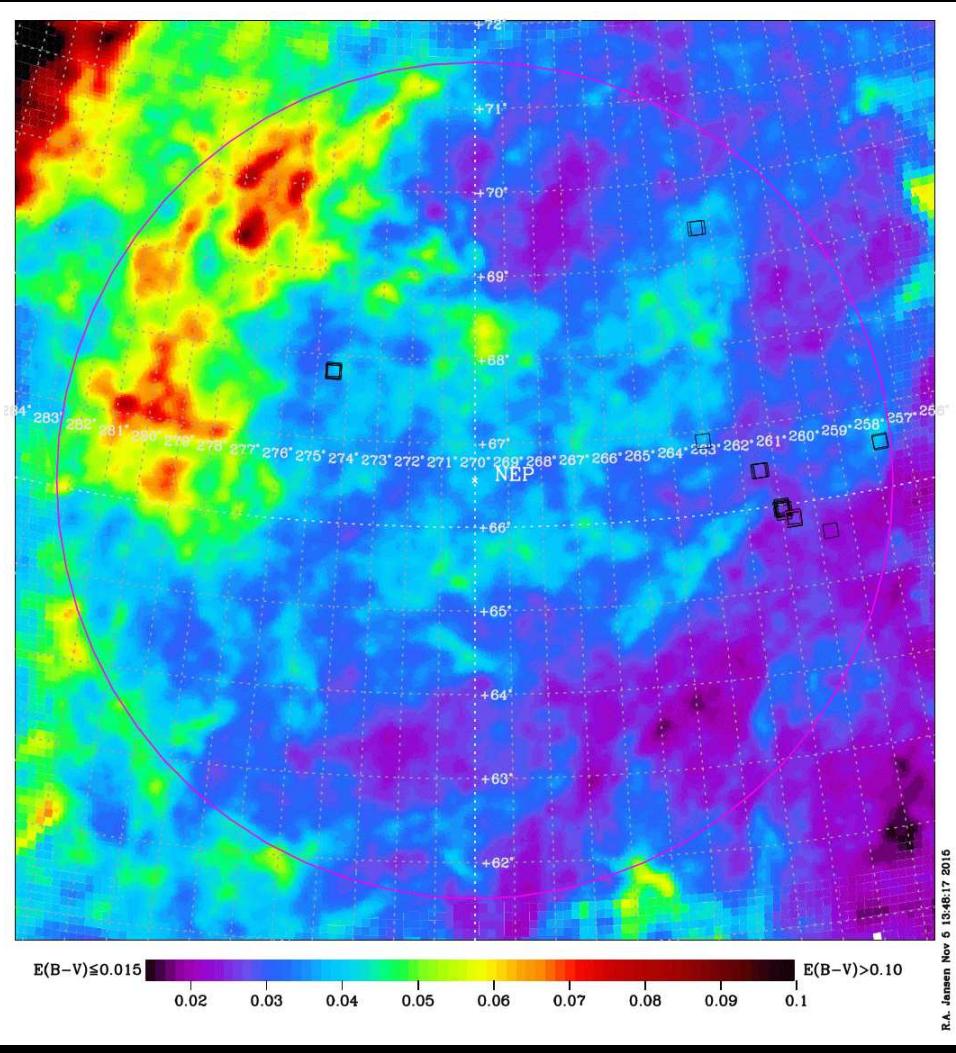
- ~500-hr JWST projects swap back/forth between NEP/SEP targets.



[LEFT]: *WISE* 4 $\mu$ m bright-object penalties in 10' grid: Very few regions (purple) exist *without bright stars* ( $AB \lesssim 16$ ) to minimize persistence.

[RIGHT]:  $E(B-V)$  map (Schlegel et al. 1998) in same NEP-region.

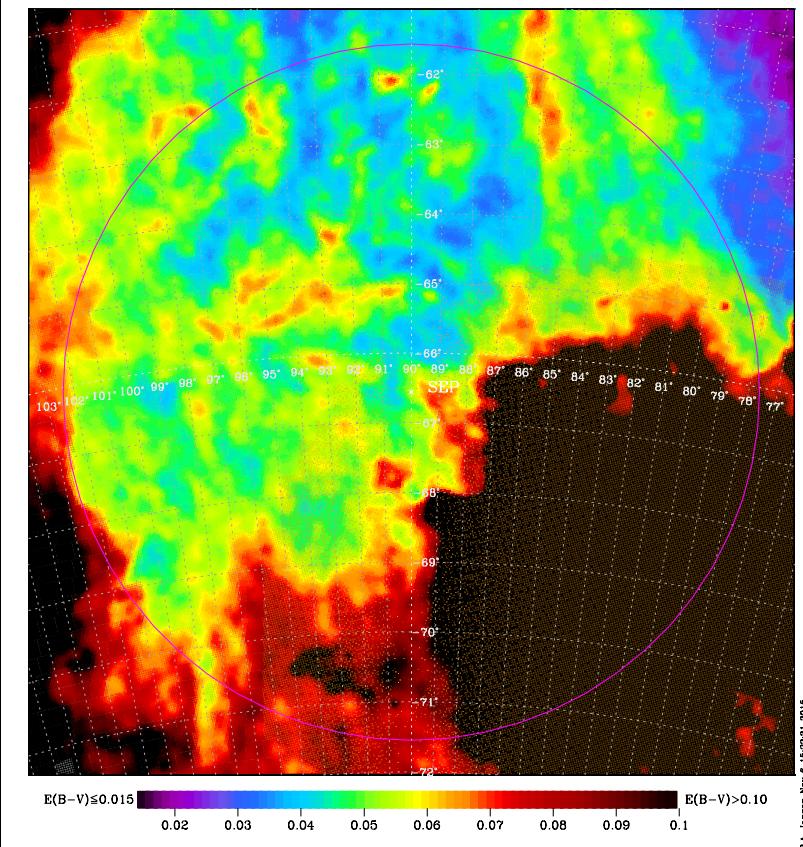
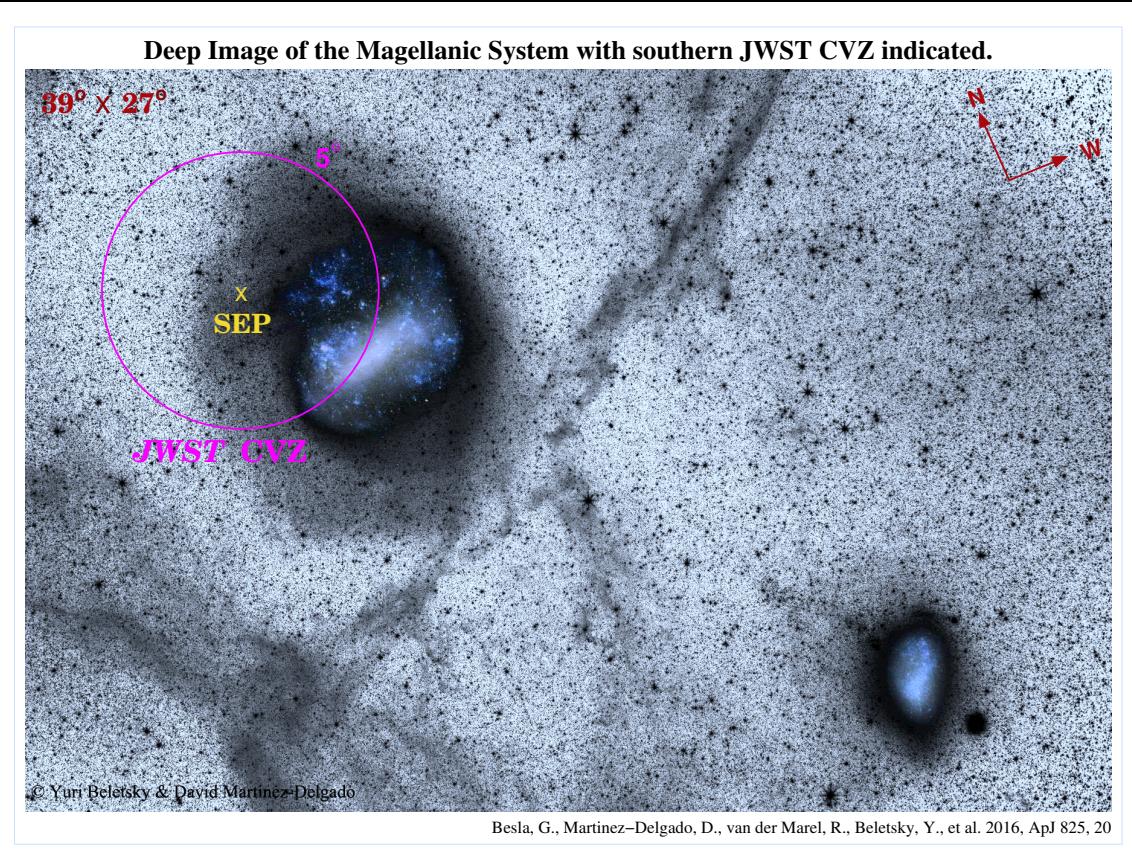
Cleanest 10×10' region for JWST has modest extinction:  $E(B-V) \lesssim 0.028^m$ .



Comparison of  $E(B-V)$ -maps of NEP [Left] and SEP [Right].

- NEP contains clean  $10 \times 10'$  region: no  $AB \lesssim 16$  stars,  $E(B-V) \lesssim 0.028^m$ .
- SEP contains *no* clean, bright-star free regions with  $r \lesssim 5^\circ$  due to LMC.

Only NEP CVZ can be used for (*far-extragalactic*) time-domain science.

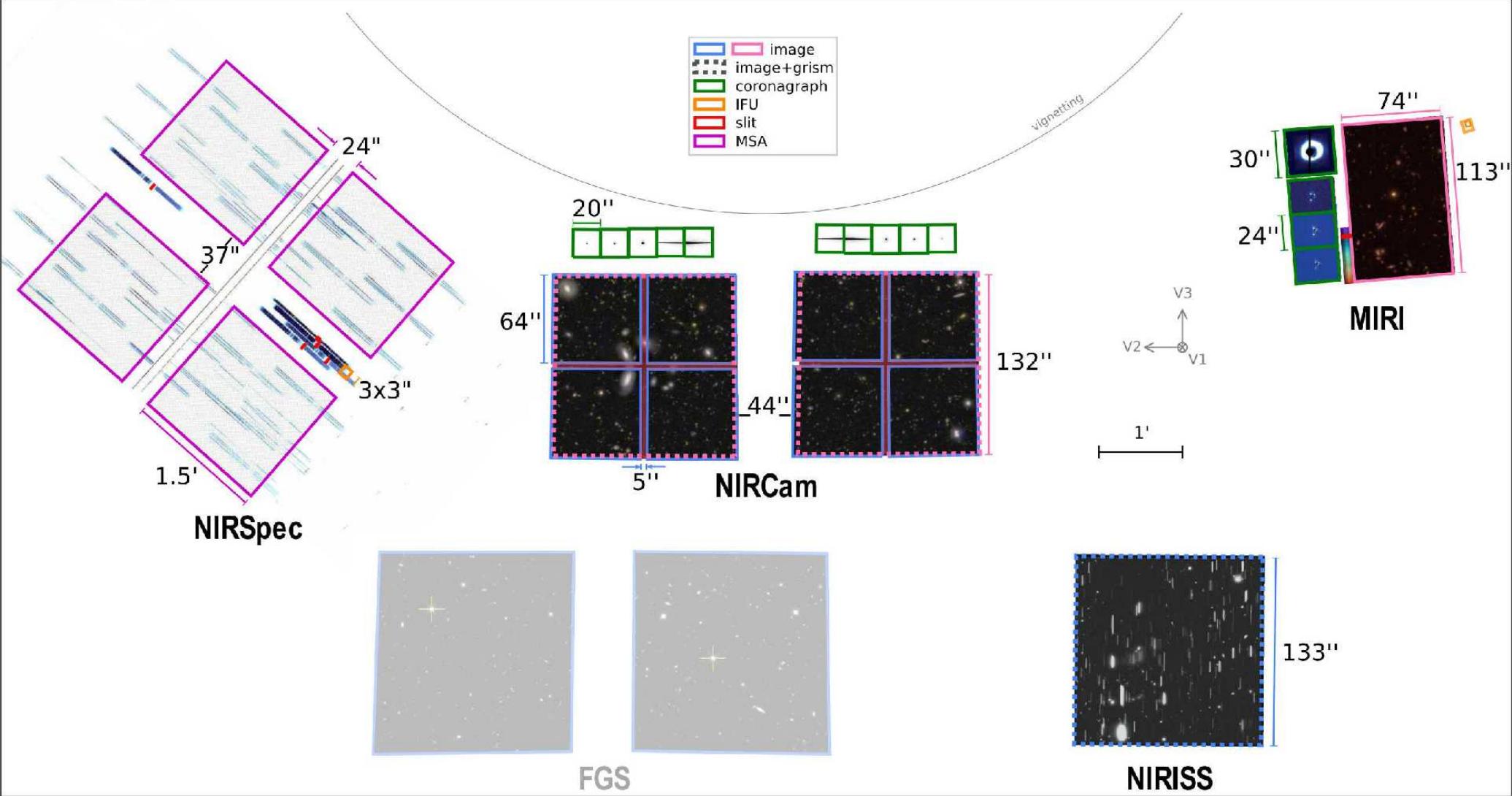


[LEFT] Map of LMC+SMC and spurs (Besla et al. 2016, ApJ, 825, 20).

[RIGHT]:  $E(B-V)$  map (Schlegel et al. 1998) in SEP-region.

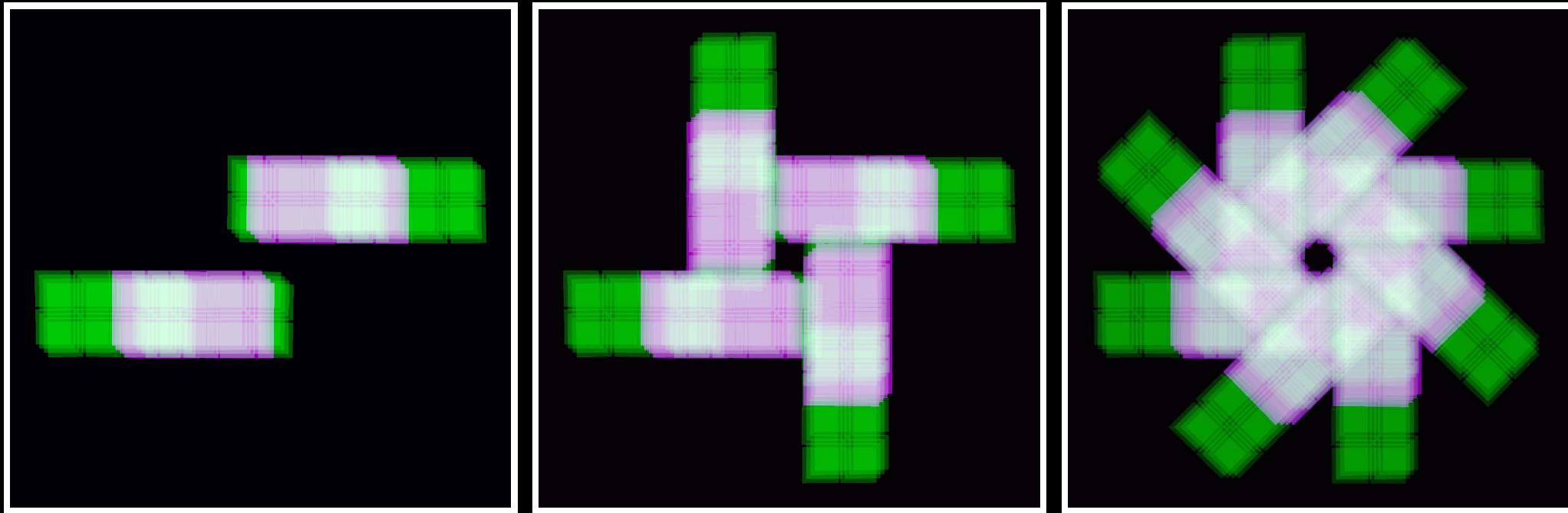
- SEP will be perfect for CVZ studies of LMC+outskirts (bottom of IMF!).
- SEP/LMC can serve as counter-target for NEP surveys: offsets accumulated angular momentum, and so help save JWST propellant/lifetime!

## (2) NIRCam + NIRISS-parallels optimally cover the best NEP CVZ field.



- As of FY16, JWST instruments can be used for science parallels.
- Currently being implemented for most-used JWST instrument pairs.
- CVZ enables well-overlapping *dark-sky* NIRCam+NIRISS-parallel mosaics.

# Exposure Maps of NEP JWST-Windmill & GO-Extensions:



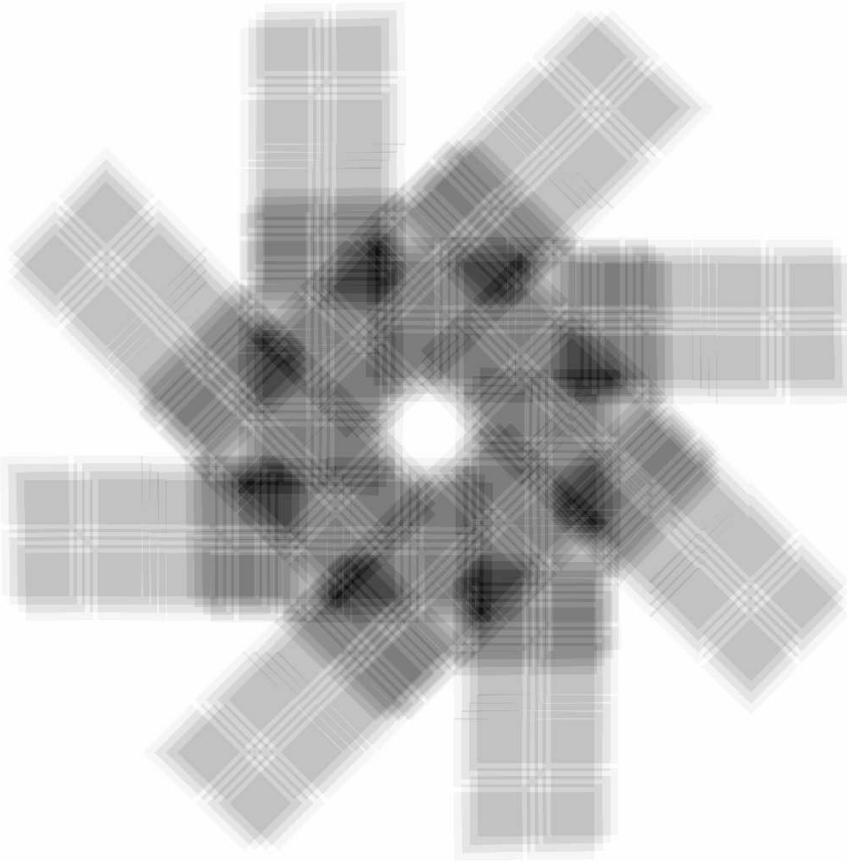
[LEFT]: Parallel NIRISS R150C+R150R grism spectra (purple) observed at  $\Delta PA = 0 + 180^\circ$ , overlayed on primary NIRCam images (green).

[MIDDLE]: Same with  $\Delta PA = 90 + 270^\circ$  added: This is our 50-hr GTO plan.

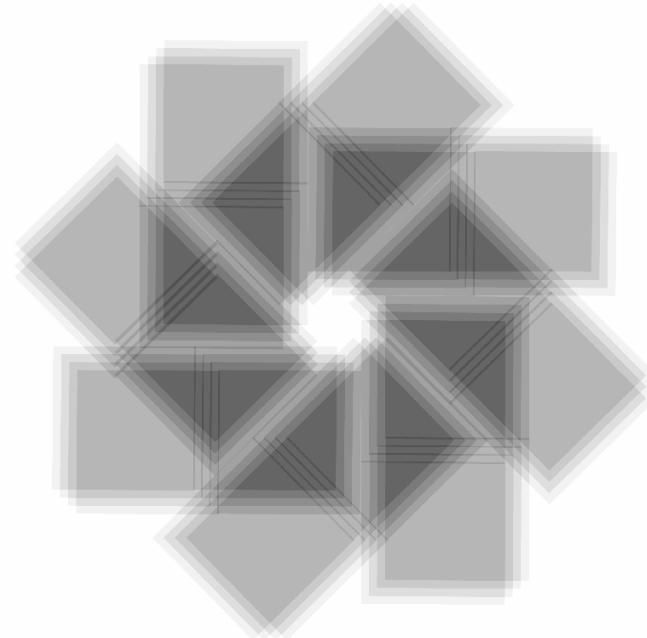
[RIGHT]: Anticipated GO-Community extensions in JWST Cycle  $\gtrsim 1$ .

White regions: NIRCam exposures overlap, reaching  $\lesssim 0.75$  mag deeper.

- GO's can repeat NIRCam primaries+NIRISS parallels as often as needed during JWST's 5–14 year lifetime at ANY PA!



NIRCam+NIRISS Windmills combined



NIRISS-parallel Windmill alone

Exposure map of a community-driven GO extension of the JWST-Windmill adds, e.g., relative position angles  $\Delta PA=45, 135, 225$ , and  $315^\circ$ .

Increases area by  $\sim 60\%$ , provides new epochs, and go  $\lesssim 0.75$  mag deeper.

- NIRISS parallel grism spectra increase the number of PA's grism angles to robustly disentangle overlapping object spectra to AB  $\lesssim 27.5$ –28 mag.

# 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



## Baseline "Cup Down" Tower Configuration at JSC (Before)



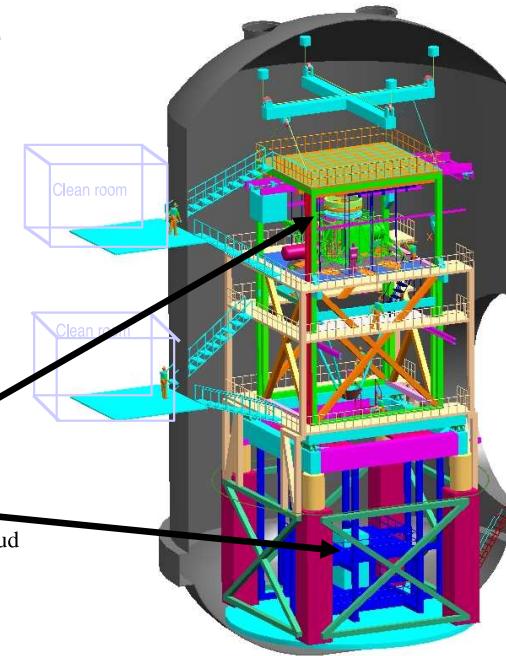
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

Current plan calls for 33KW cooldown capability, 12 KW steady state, 300-500mW N2 cooling

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

Interferometers, Sources, Null Lens and Alignment Equipment Are in Upper and Lower Pressure Tight Enclosure Inside of Shroud



## JSC "Cup Up" Test Configuration (New Proposal)

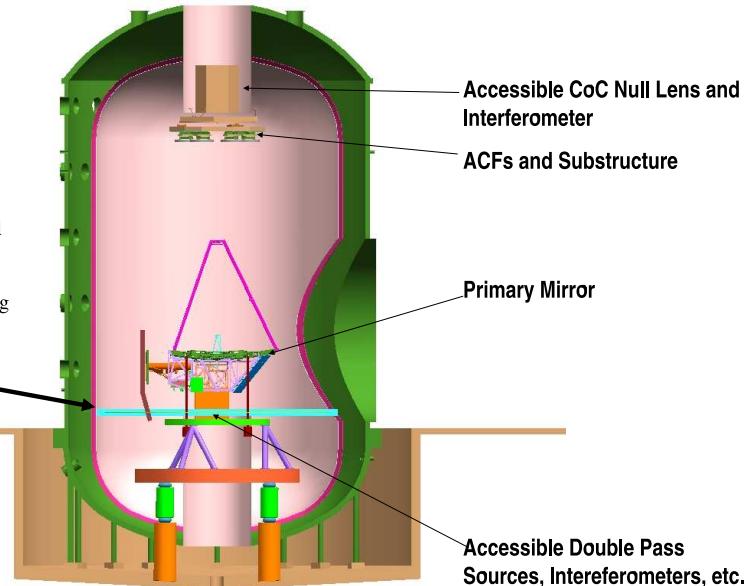


No Metrology Tower and Associated Cooling H/W. External Metrology

Two basic test options:

1. Use isolators, remove drift through fast active control + freeze test equipment jitter
  2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
- Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

Possible payload "floor" to separate ambient pressure and temperature.



Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

- ≈2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 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.

# Milestone Performance

- Since the September 2011 replan JWST reports high-level milestones monthly to numerous stakeholders

	Total Milestones	Total Milestones Completed	Number Completed Early	Number Completed Late	Deferred to Next Year	Deferred more than one quarter
FY2011	21	21	6	3	0	0
FY2012	37	34	16	2	3	3
FY2013	41	38	20	5	3	2
FY2014♦	36	23	10	8	11	10
FY2015	48	44	22	12	4	3
FY2016	45	39	25	7	6	2
FY2017	38	24	11	17*	3	1

\*Late milestones have been completed late within the year or are forecast to complete late within the year. Deferred milestones are not included in the number-completed-late tally.

♦ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

3

170612 JWST Monthly Telecon 4

FY14: 8 milestones late by 1 month due to Oct 13 Government shutdown.

FY15: Most “Lates” not on critical path.

FY16: Most “Lates” anticipated to finish with FY.

# Fiscal Year 2017 JWST HQ Milestones

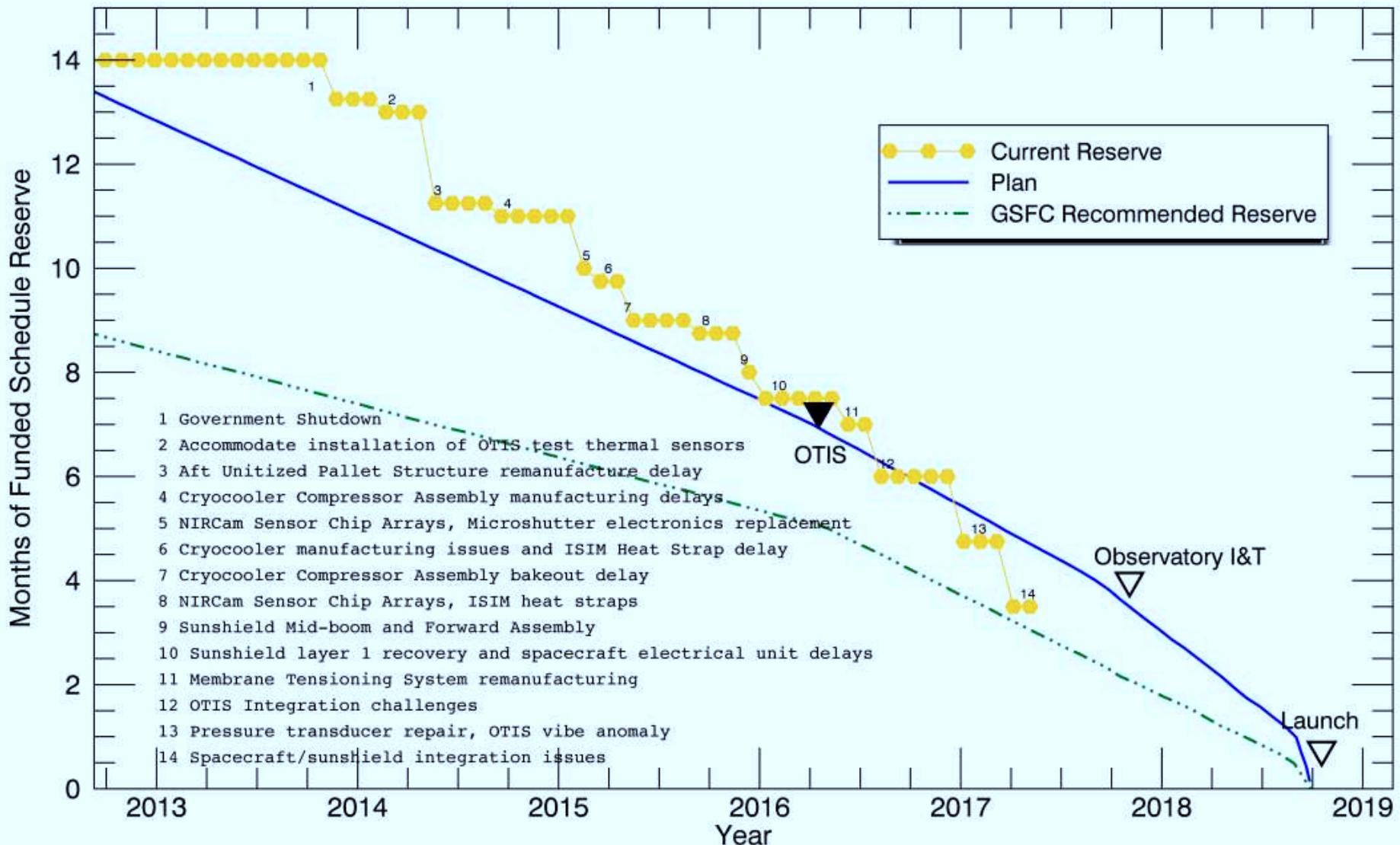
Month	Milestone	FY2016 Deferral	Comment
Oct-16	1 Complete portable clean room for Telescope and Science Instruments (OTIS) 2 Complete final checkout of new shaker tables at Goddard Space Flight Center 3 Begin making electrical connections between spacecraft panels 4 Complete Sunshield Mid-Boom Assembly #2 functional test		<u>Completed 10/13/16</u> • <u>Completed 10/13/16</u> <u>Completed 10/7/16</u> • <u>Completed 12/5/16</u>
Nov-16	5 Start optical measurements of OTIS prior to vibration and acoustic tests 6 Deliver Science and Operations Center release 1 7 Perform Cryocooler installation into the spacecraft bus and begin functional testing 8 Complete Aft Unitized Pallet Structure assembly 9 Deliver Aft Unitized Pallet Structure to Observatory I&T		<u>Completed 10/24/16</u> <u>Completed 9/30/16</u> <u>Completed 10/29/16</u> • <u>Completed 10/29/16</u> • <u>Completed 3/14/17</u>
Dec-16	10 Deliver Forward Sunshield Pallet Structure to Observatory Integration and Test (I&T) 11 Start OTIS vibration and acoustic testing program 12 Complete final test of engineering model of telescope center section at Johnson Space Center (JSC) 13 Deliver sunshield flight membranes to Observatory I&T		• <u>Completed 3/28/17</u> <u>Completed 11/19/16</u> <u>Completed 10/31/16</u> <u>Completed 12/15/16</u>
Jan-17	14 Complete OTIS vibration and acoustics testing 15 Deliver observing proposal and planning subsystem software build that supports launch 16 Complete electrical testing of the spacecraft at Northrop-Grumman		<u>Completed 3/2/17</u> <u>Completed 1/12/17</u> <u>Completed 3/7/17</u>
Feb-17	17 Complete OTIS optical measurements after vibration and acoustic tests 18 Deliver wavefront and control software that supports launch (controls telescope mirror shape) 19 Deliver horizontal deployable radiators to Observatory I&T		<u>Completed 3/31/17</u> <u>Completed 1/20/17</u> <u>Delayed June for release testing</u>
Mar-17	20 Deliver OTIS to the Johnson Space Center 21 Deliver the pre-launch Flight Operations System software build 22 Delivery of sunshield extension boom #2 membrane attachment assembly to Observatory I&T		<u>Completed 5/7/17</u> <u>Completed 2/17/17</u> <u>Completed 4/13/17</u>
Blue font(underline) denotes milestones accomplished ahead of schedule, orange font denotes milestones accomplished late. "*" denotes 2016 milestones carried forward.			

170612 JWST Monthly Telecon 2

Milestones: How the Project reports its progress monthly to Congress.

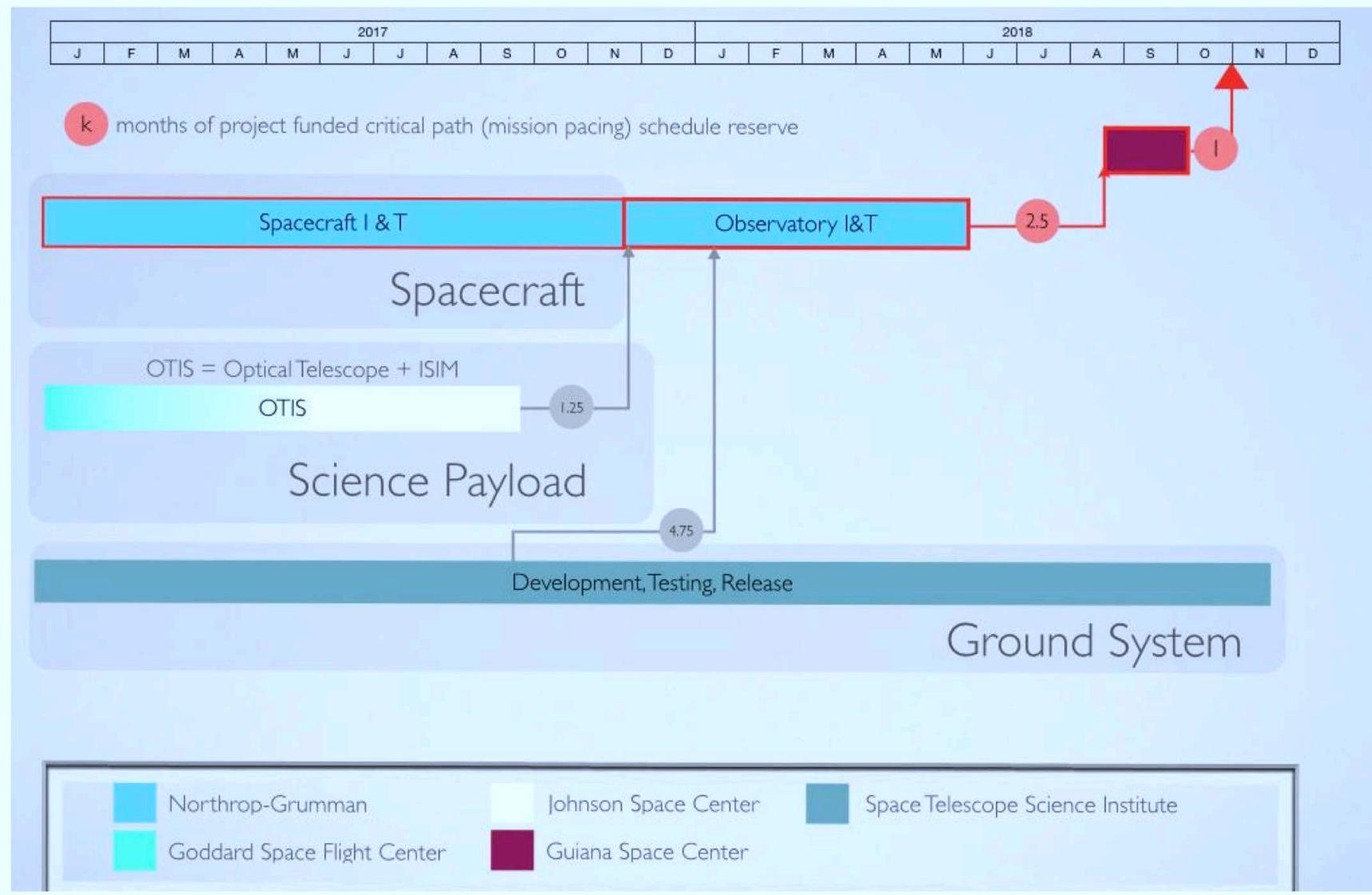
Summer–Early Fall 2017: Lates started to outnumber the Early's.

# 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).

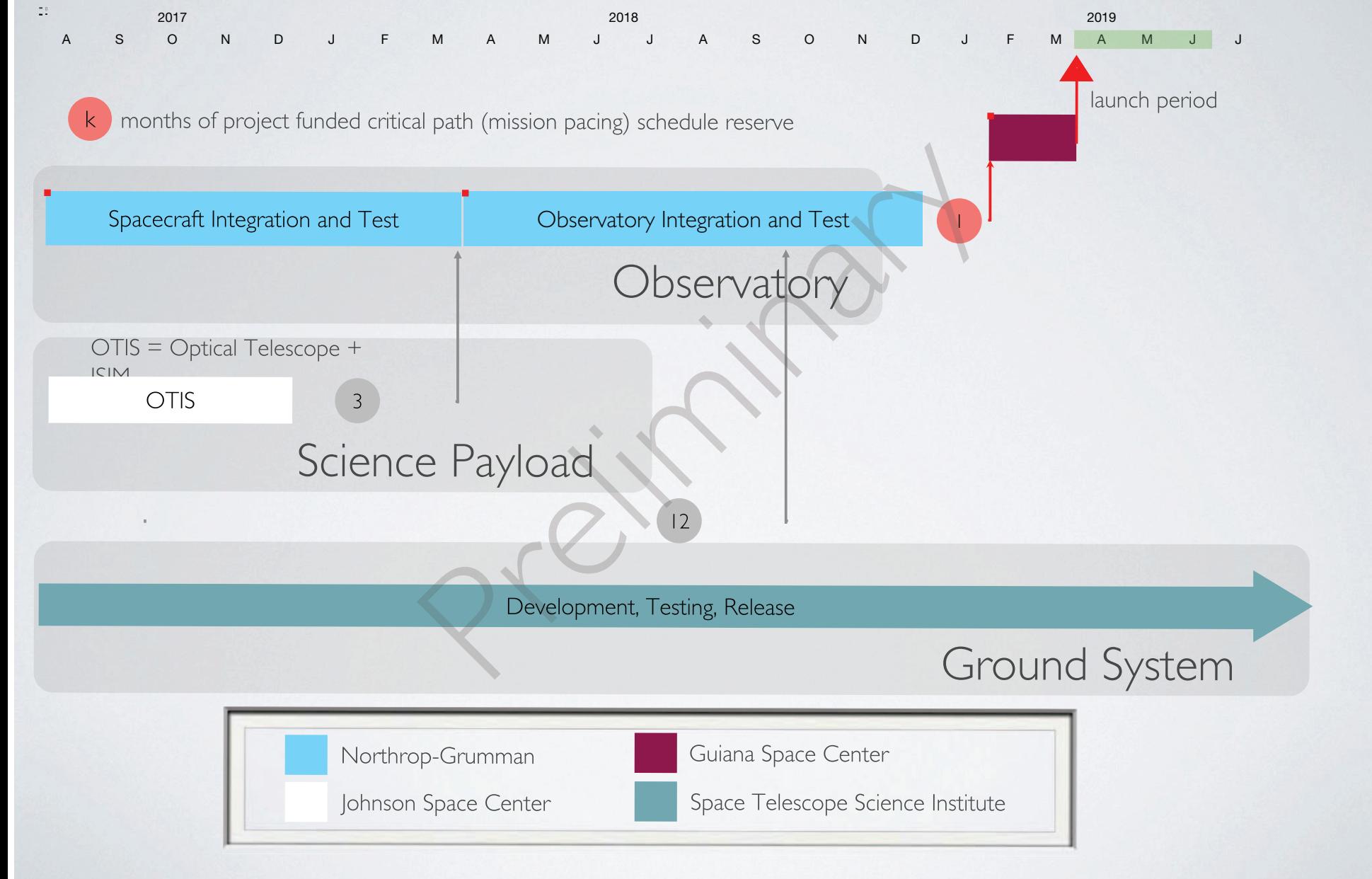
# Simplified Schedule



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

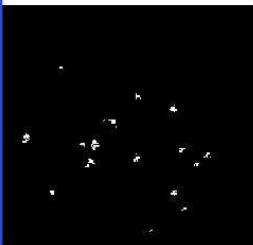
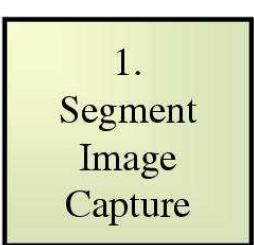
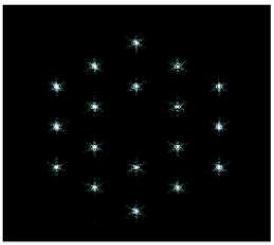
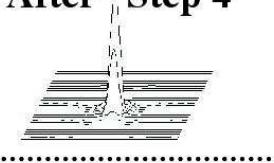
- Instruments+detectors & Optical Telescope Element were on critical path.

# SIMPLIFIED SCHEDULE



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

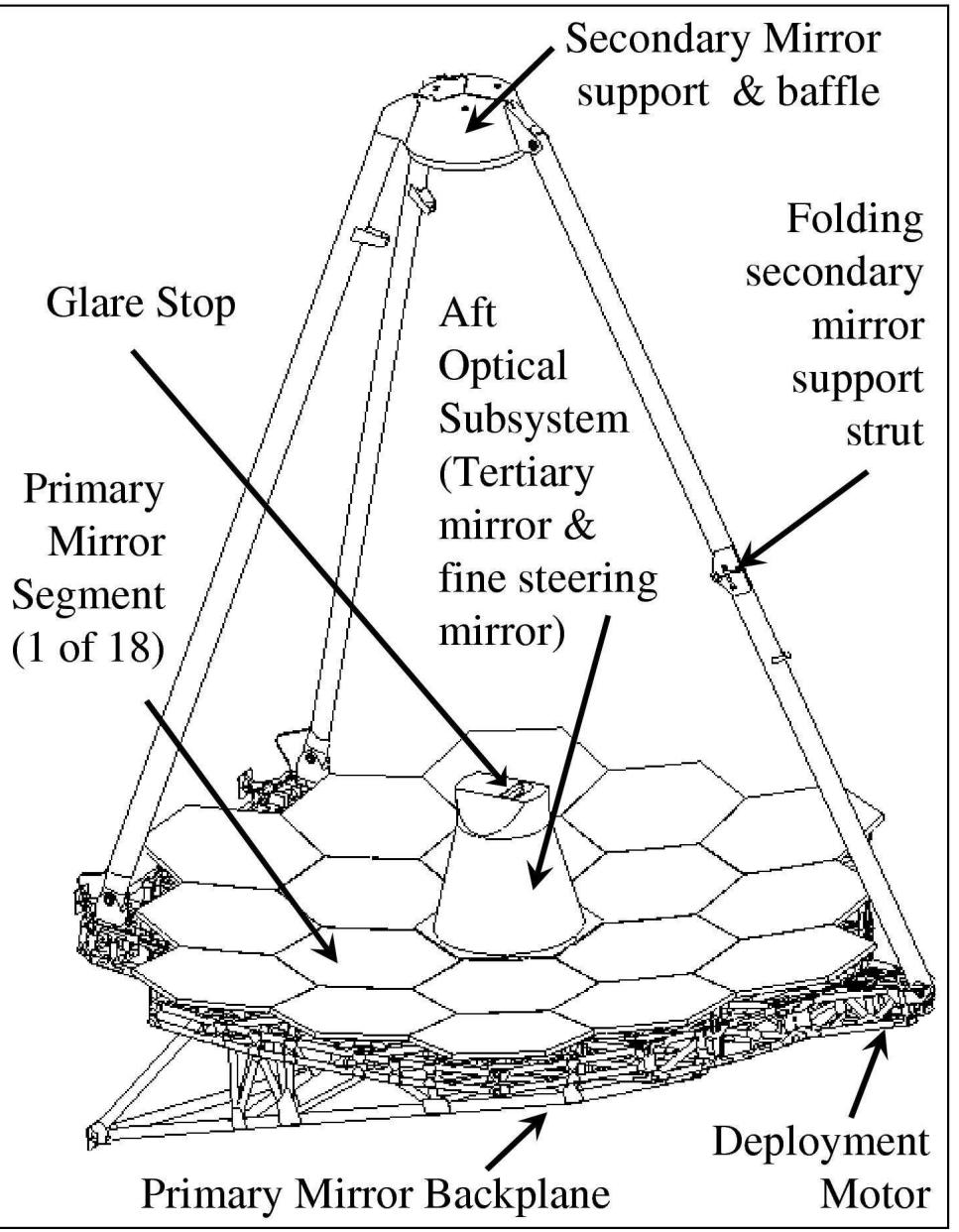
- Spacecraft and Sunshield are now on critical path (at Northrop).

<i>First light NIRCam</i>	<i>After Step 1</i>	<i>Initial Capture</i>	<i>Final Condition</i>
		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 $\mu\text{m}$ , < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
<b>2. Coarse Alignment</b> Secondary mirror aligned Primary RoC adjusted		Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 $\mu\text{m}$ (rms)
<b>3. Coarse Phasing - Fine Guiding (PMSA piston)</b>		WFE: < 250 $\mu\text{m}$ rms	WFE < 1 $\mu\text{m}$ (rms)
<b>4. Fine Phasing</b>		WFE: < 5 $\mu\text{m}$ (rms)	WFE < 110 nm (rms)
<b>5. Image-Based Wavefront Monitoring</b>		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.

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

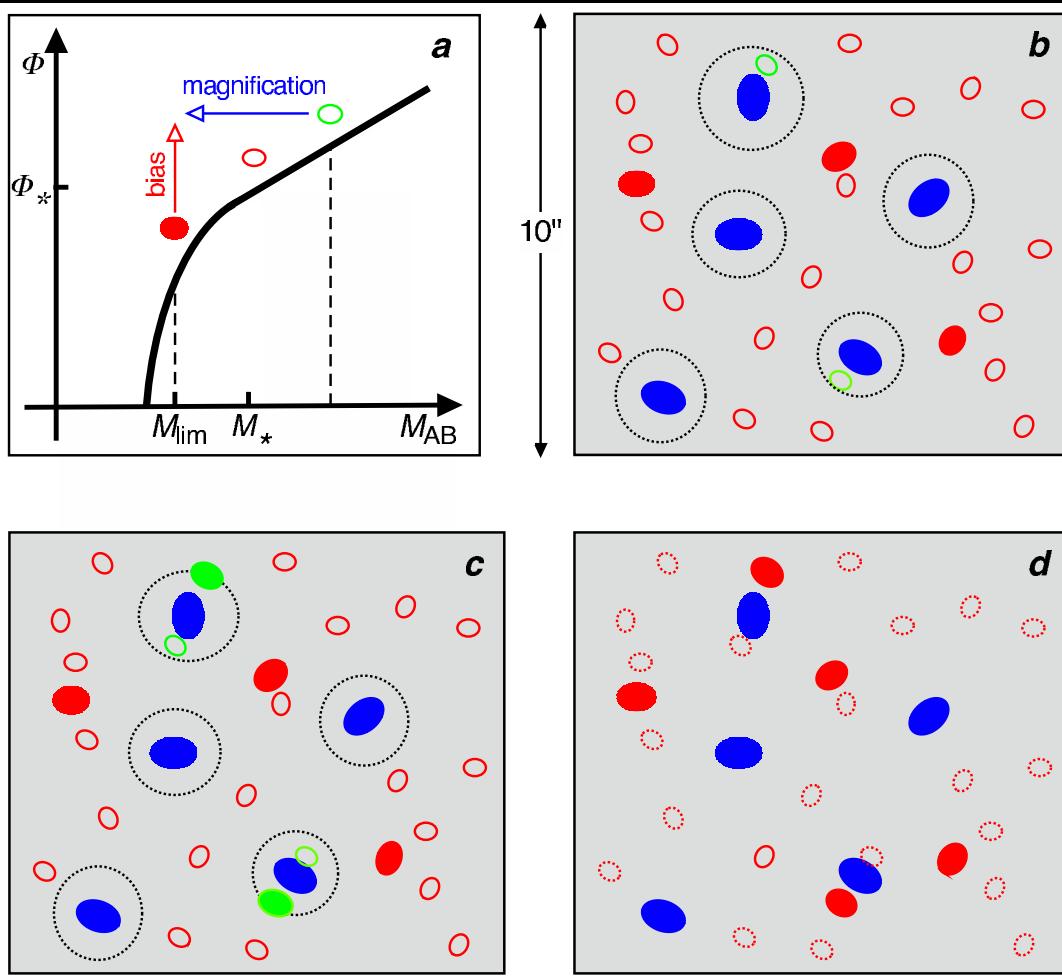
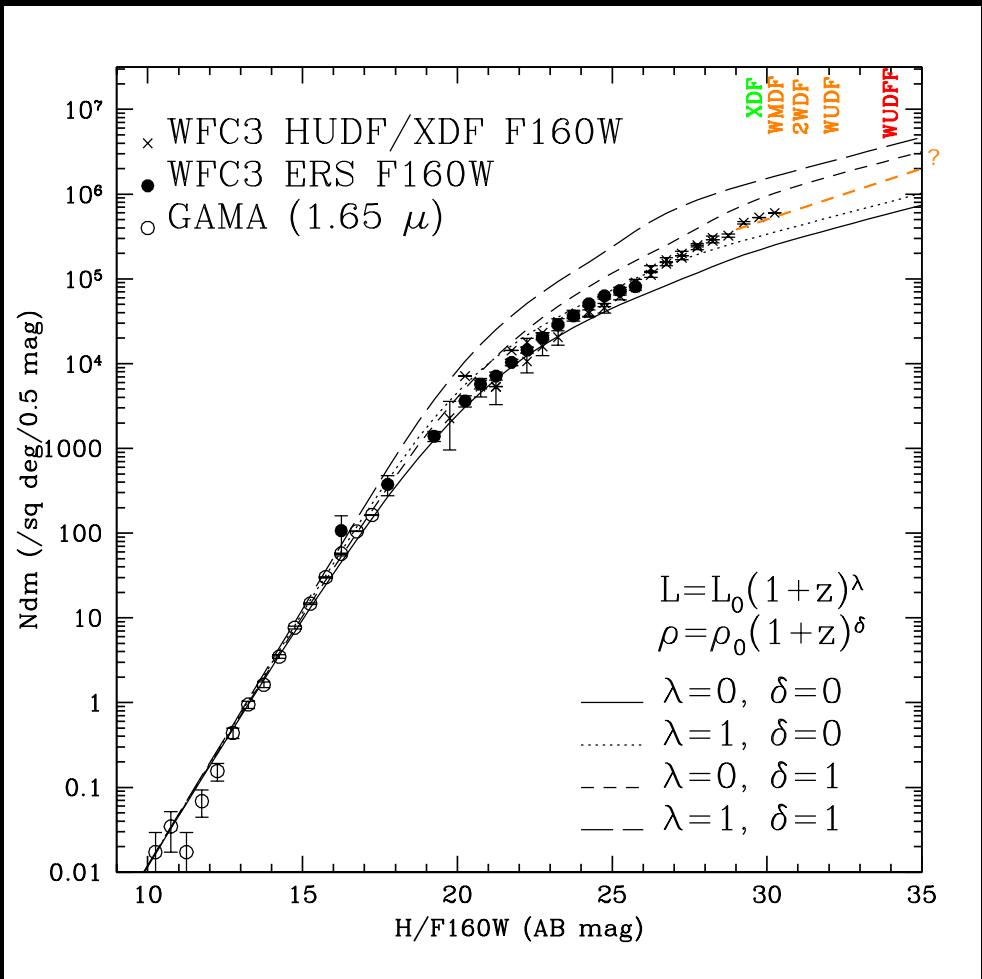


Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2017.

Ball 1/6 scale-model for WFS: produced diffraction-limited 2.0  $\mu\text{m}$  images.

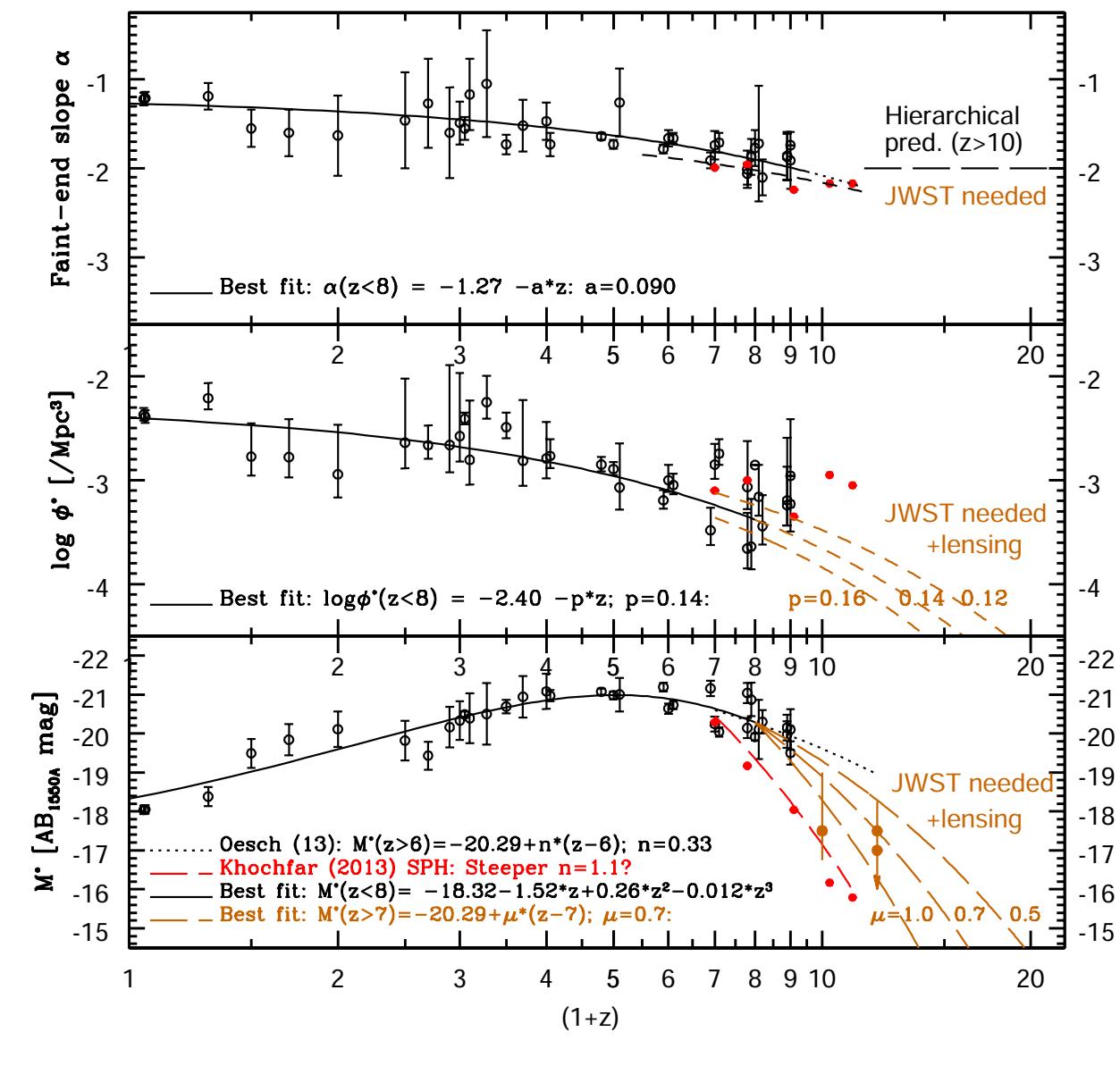
In L2, WFS updates every 10 days depending on scheduling/ SC-illumination.

### (3c) How can JWST best observe First Light using lensing?



1.6  $\mu$ m counts (Windhorst<sup>+</sup>2011). [F150W, F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F105W, F125W, F140W not shown].

- Faint-end of near-IR galaxy counts has a steep slope.
- ⇒ Faint-end of luminosity function at median redshift is also steep.
- In 800-hr JWST can see to  $\sim 32$  mag: dwarf galaxy at  $z \simeq 11$ !
- Lensing will change the landscape for JWST observing strategies.



Evolution of Schechter UV-LF: faint-end LF-slope  $\alpha(z)$ ,  $\Phi^*(z)$  &  $M^*(z)$ :

- For JWST  $z \gtrsim 8$ , expect  $\alpha \lesssim -2.0$ ;  $\Phi^* \lesssim 10^{-3}$  ( $\text{Mpc}^{-3}$ ) (Bouwens<sup>+</sup> 15).
  - HUDF: Characteristic  $M^*$  may drop below  $-18$  or  $-17.5$  mag at  $z \gtrsim 10$ .
- ⇒ Will have significant consequences for JWST survey strategy.