

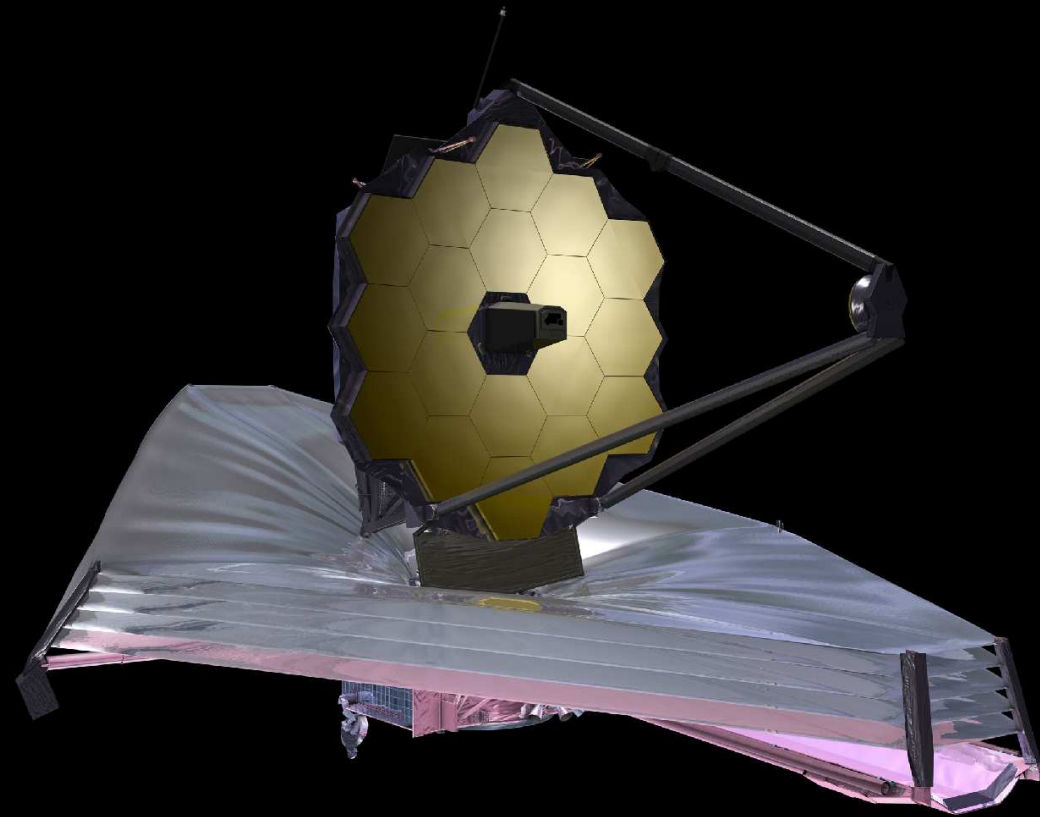
# How will JWST measure First Light, Reionization, & Galaxy Assembly: New Frontiers after Hubble

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**Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist**

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*(Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, B. Smith, & A. Straughn*



*Talk at Massachusetts Institute of Technology; Wednesday April 22, 2015 (Cambridge, MA)*

*All presented materials are ITAR-cleared.*

# Outline

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- (1) Brief Update on the James Webb Space Telescope (JWST), 2015.
- (2) Hubble (Ultra)Deep & Frontier Fields to find  $z \sim 9-11$  objects:  
— Current limitations
- (3) How can JWST measure the Epoch of First Light (using lensing)?
- How many random Webb Deep Fields (WDFs) compared, to the best lensing targets for JWST?
- (4) Summary and Conclusions.



Sponsored by NASA/HST & JWST

Talk is on: <http://www.asu.edu/clas/hst/www/jwst/jwsttalks/mit15hstjwst.pdf>



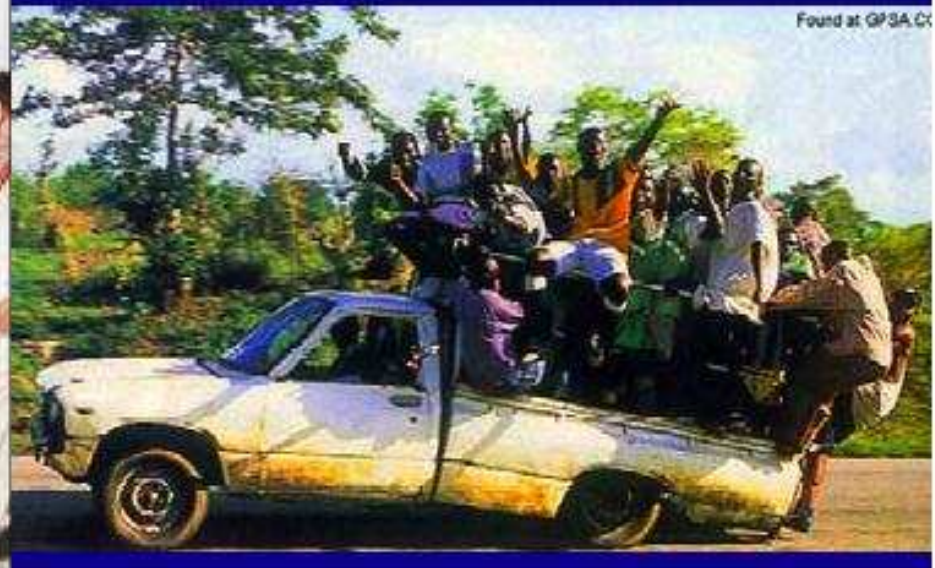
What the Scientists See:



What the Project Manager Sees:

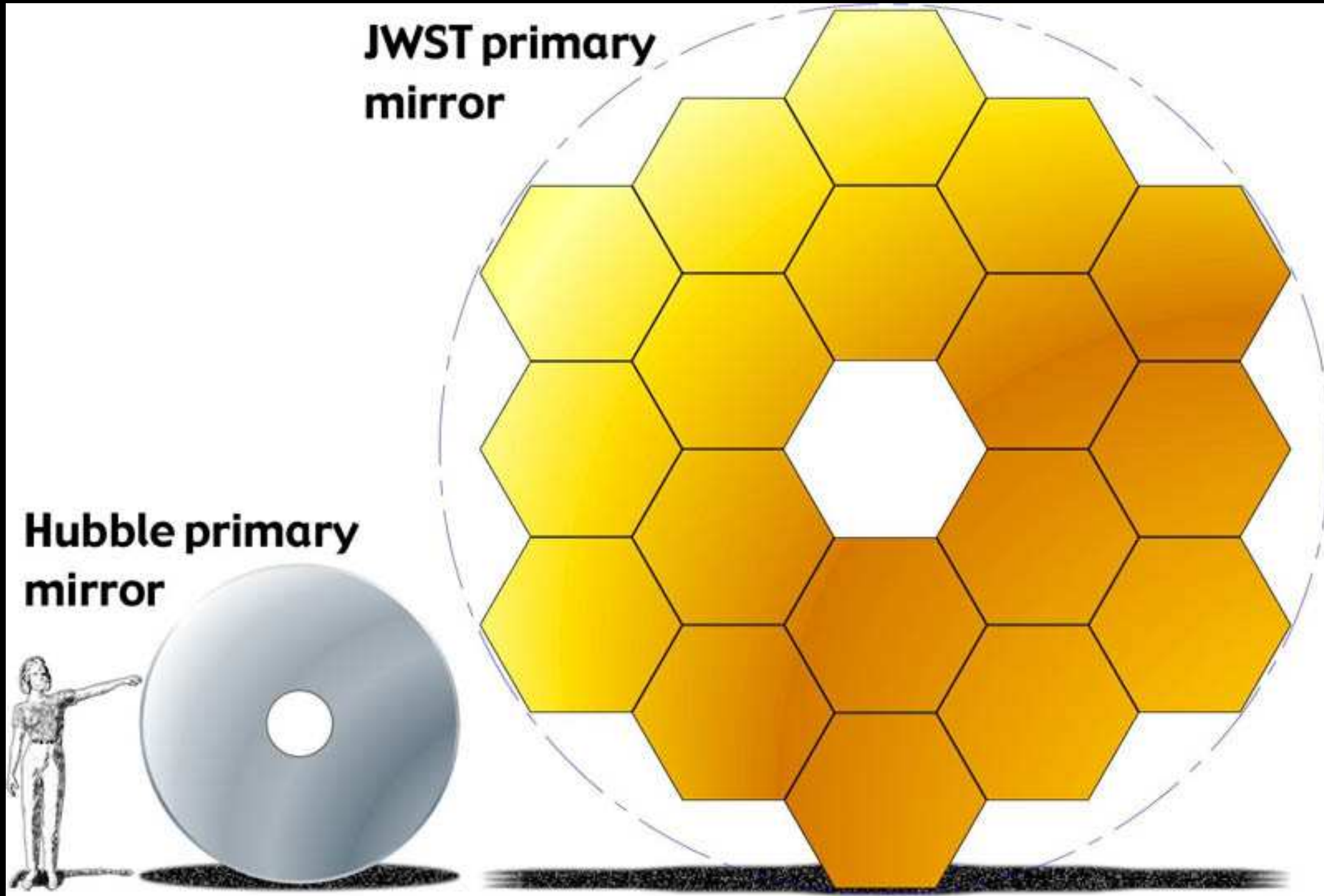


## The Happy Balance



Found at GPSA.CX

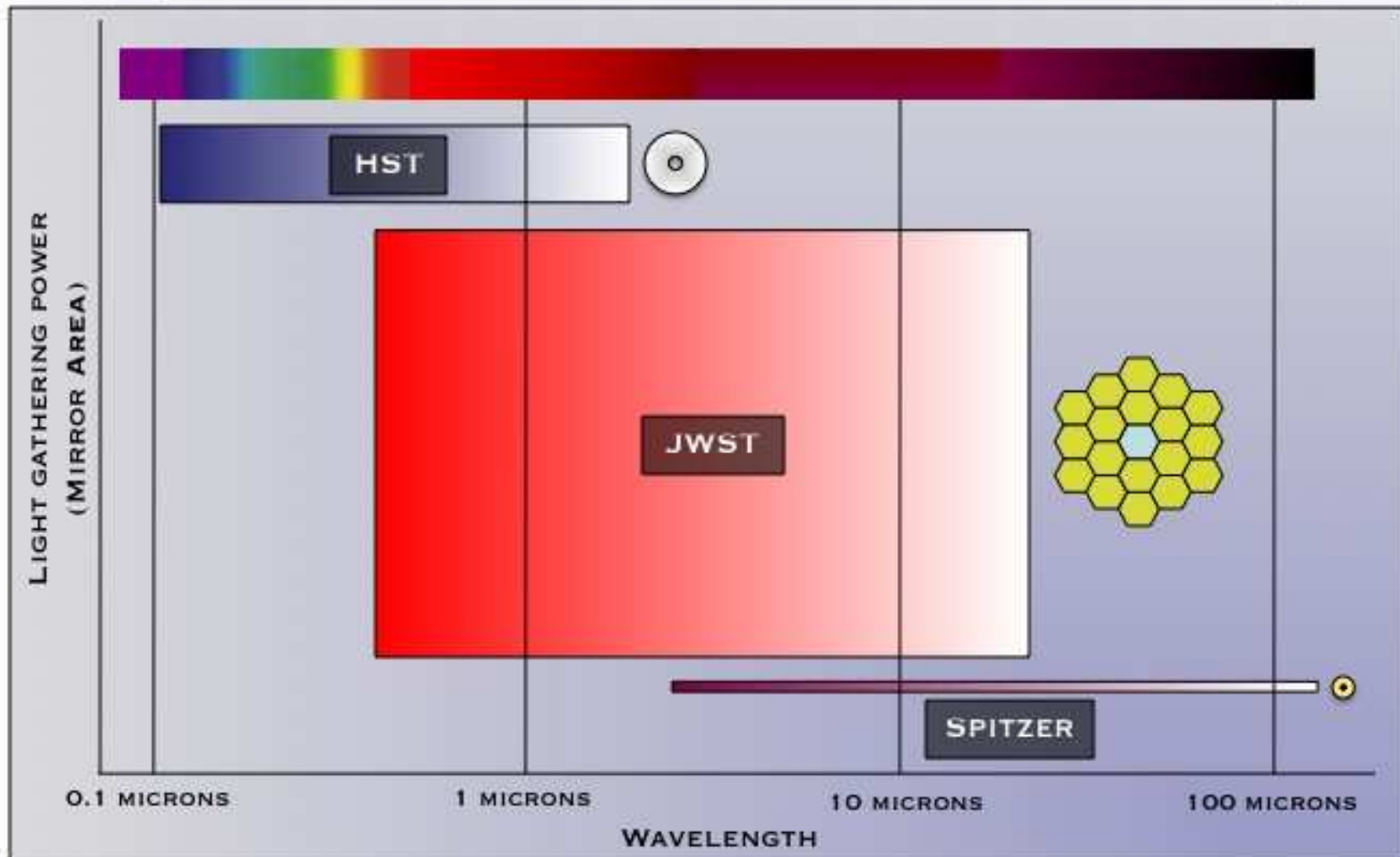
Any (space) mission is a balance between what science demands, what technology can do, and what budget & schedule allows ... (courtesy Prof. R. Ellis).



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

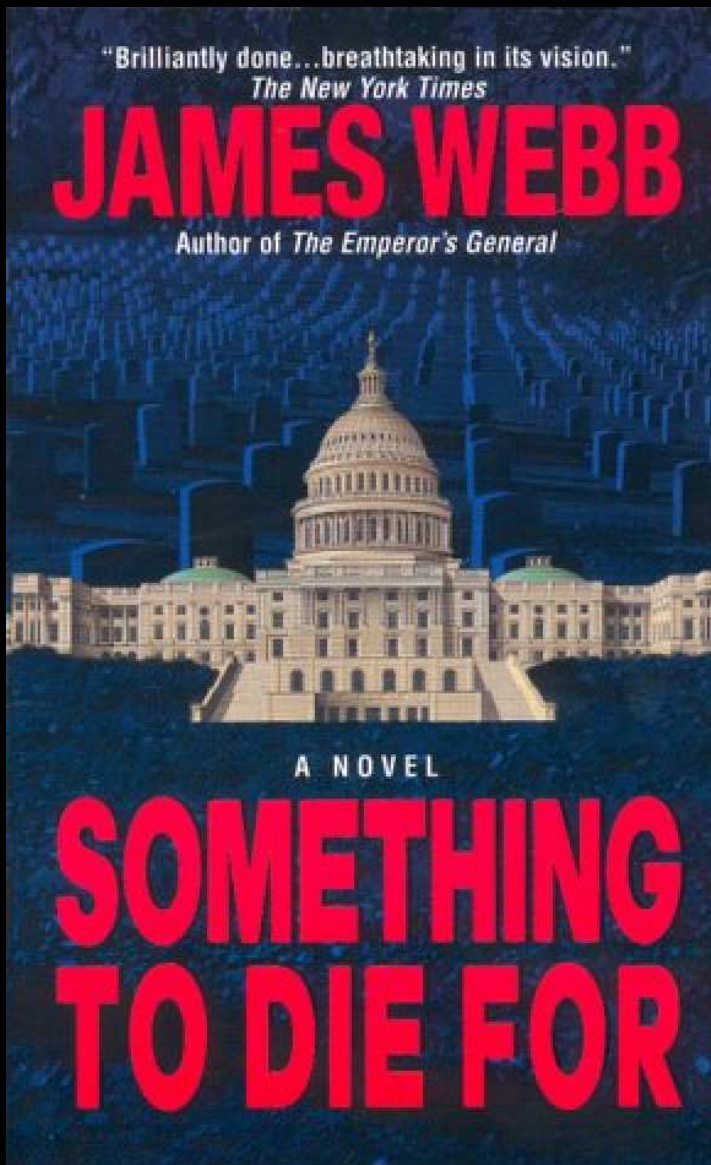


LIGHT GATHERING POWER  
JWST = 25 M<sup>2</sup> ; HUBBLE = 4.5 M<sup>2</sup> ; SPITZER = 0.6 M<sup>2</sup>

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

- Vastly larger  $A(\times\Omega)$  than HST in UV-optical and Spitzer in mid-IR.

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

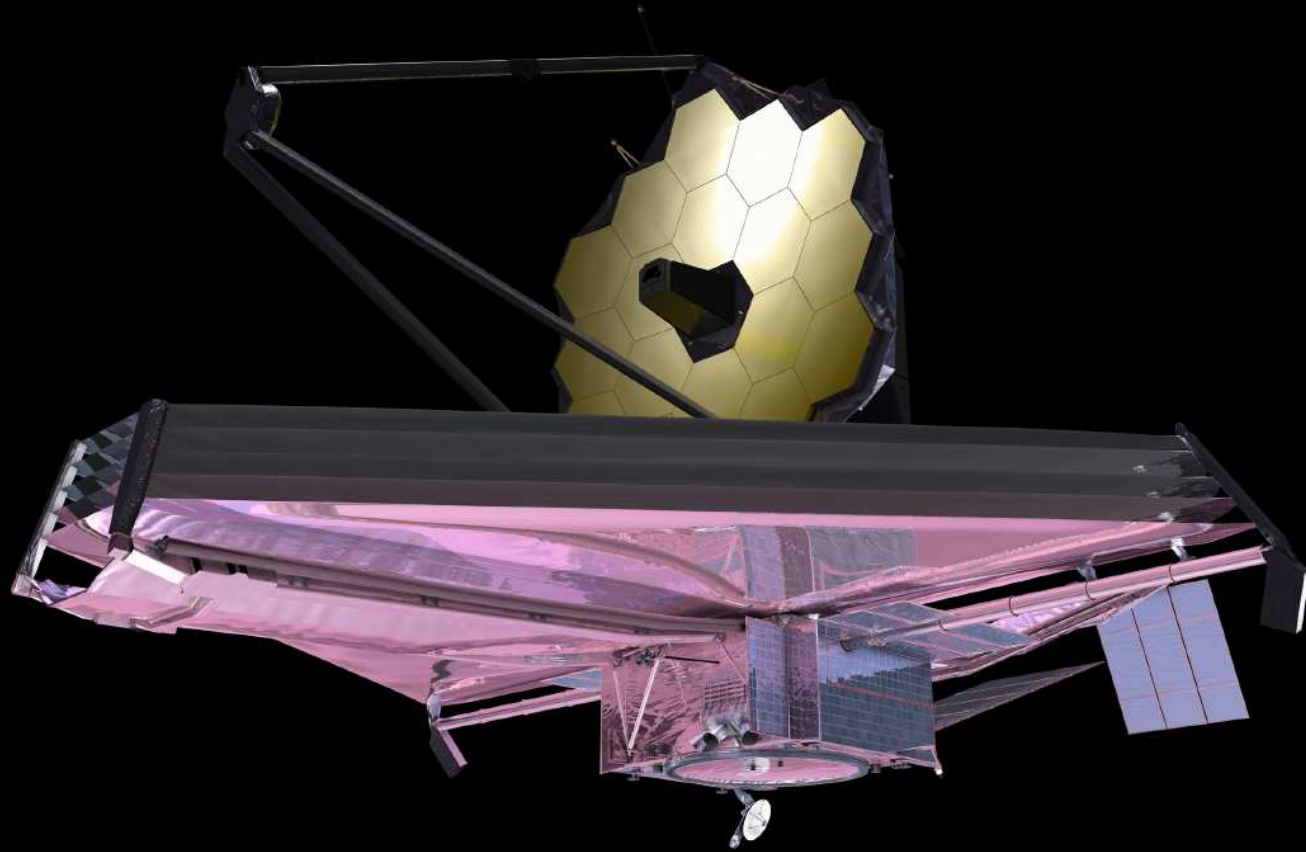


To be used by students & scientists after 2018 ... It'll be worth it.

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



# (1) Brief Update of the James Webb Space Telescope



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

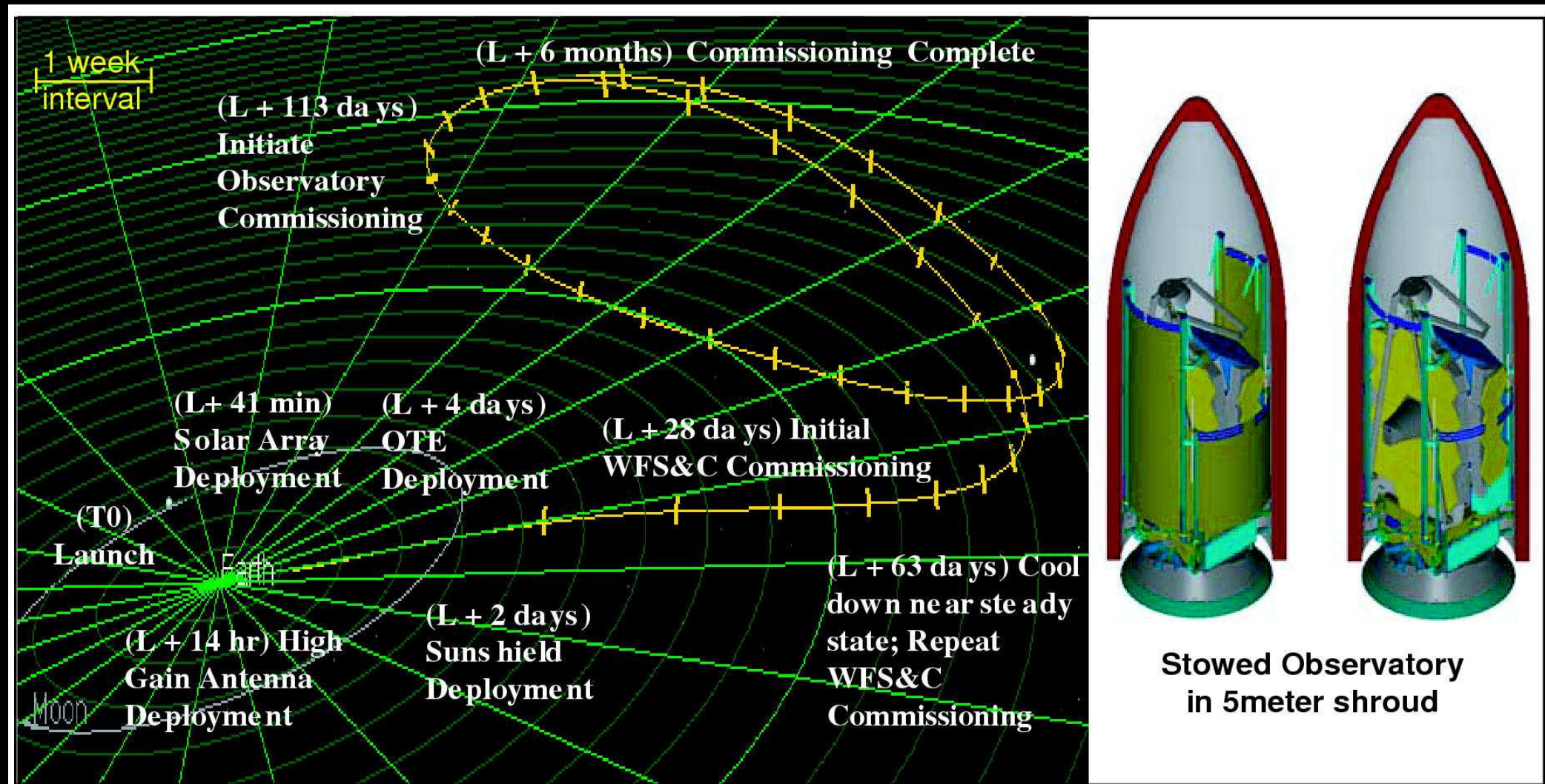


ARIANESPACE – ESA - NASA

- 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.

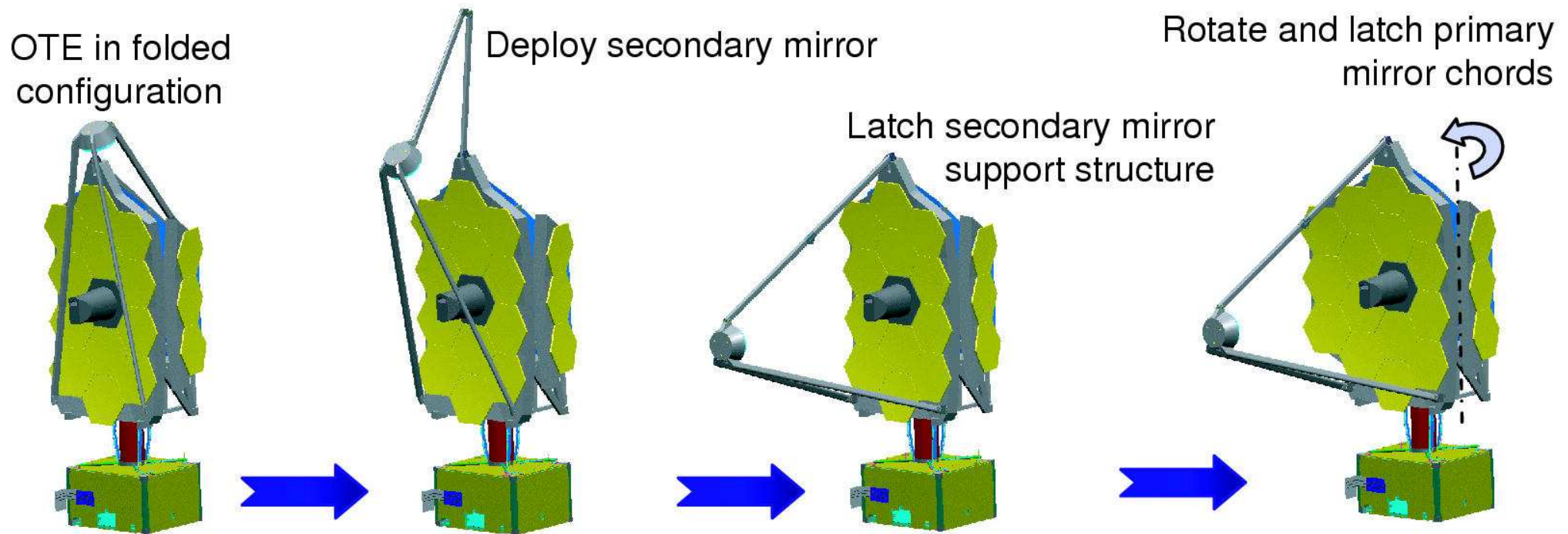


## (1a) How will JWST travel to its L2 orbit?



- After launch in (Oct.) 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.

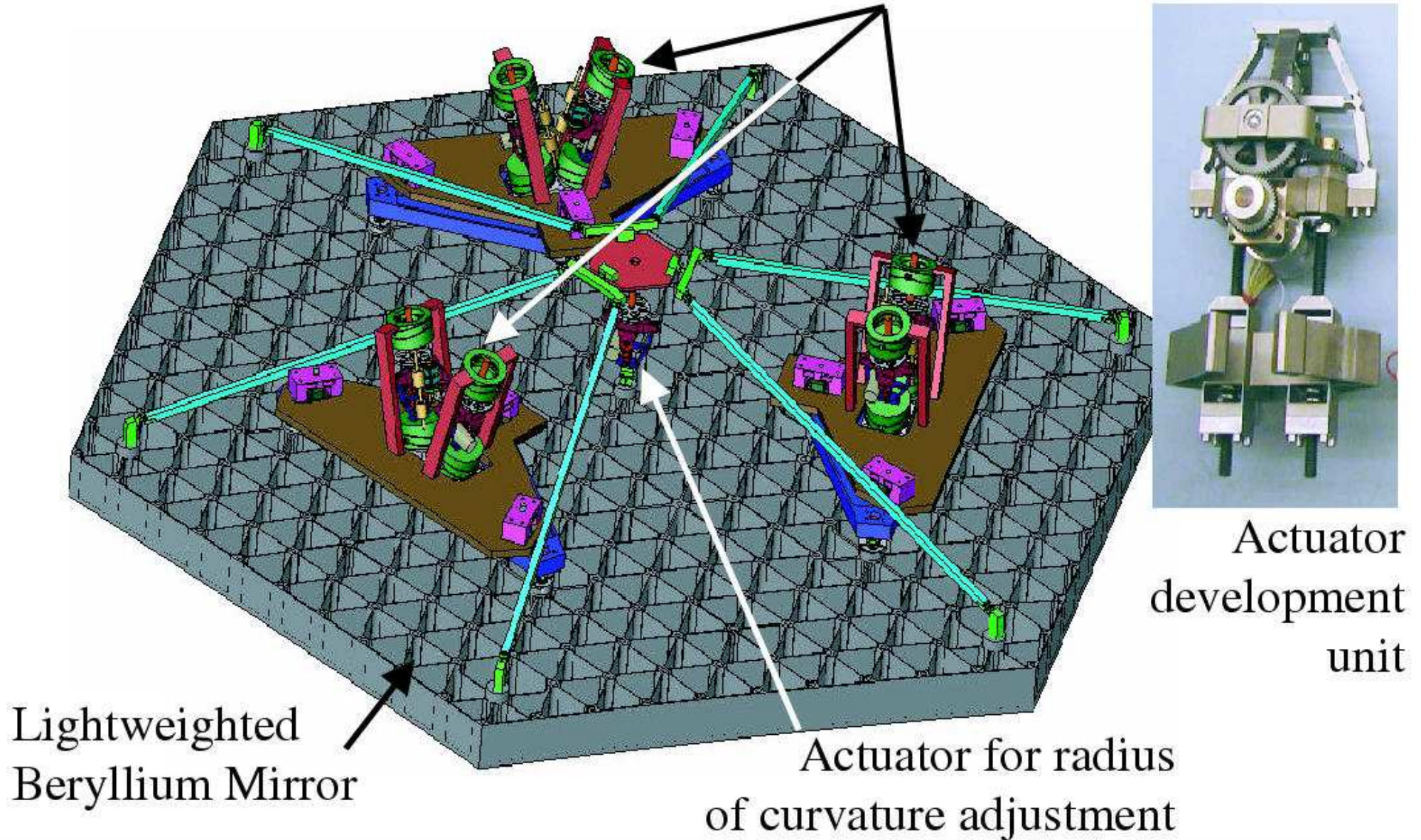
- (1b) How will JWST be automatically deployed?



- 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 is being tested several times on the ground — but only in 1-G: component and system tests in 2014–2016 at GSFC (MD), Northrop (CA), and JSC (Houston).
- 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



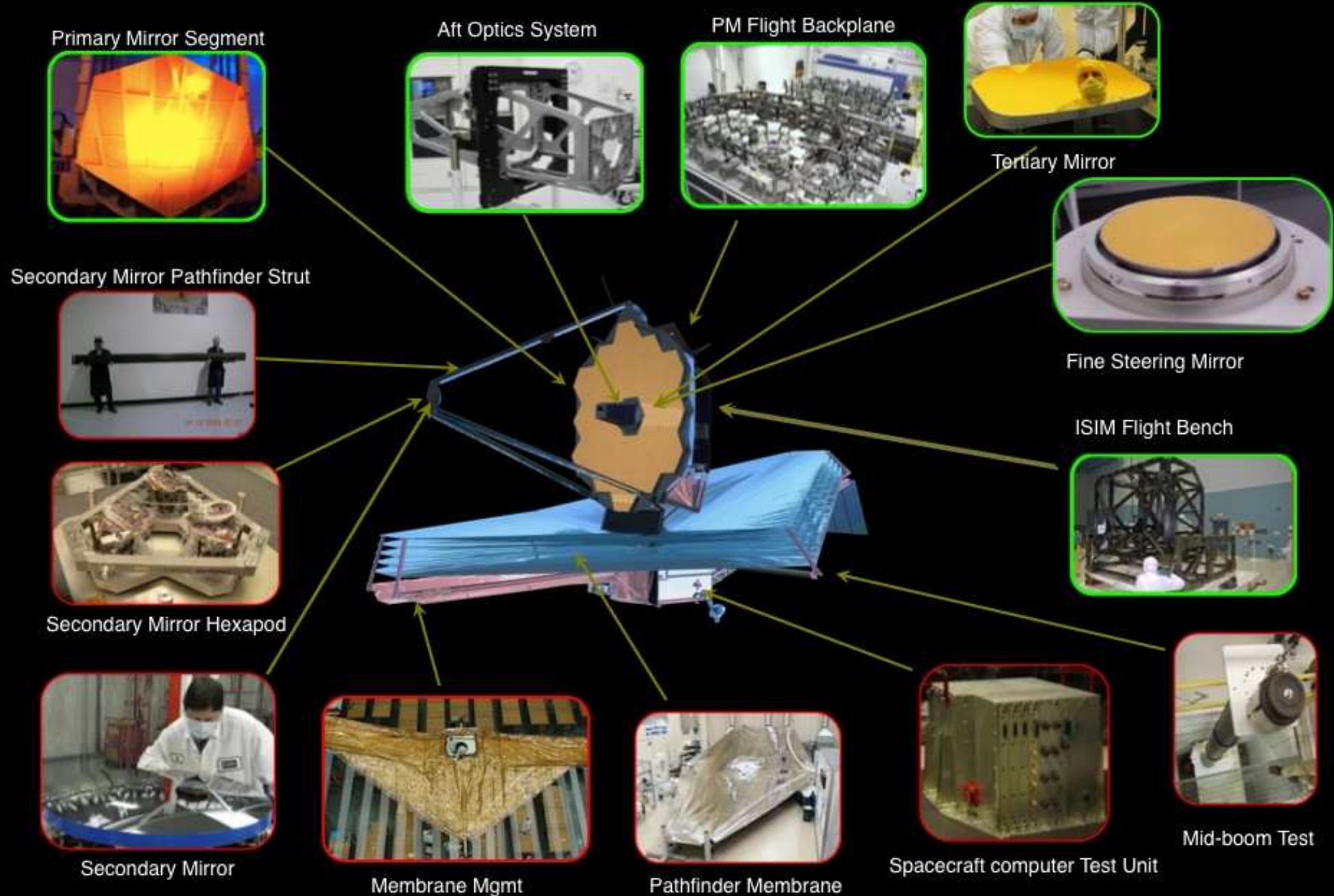
Active mirror segment support through "hexapods", similar to Keck.

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





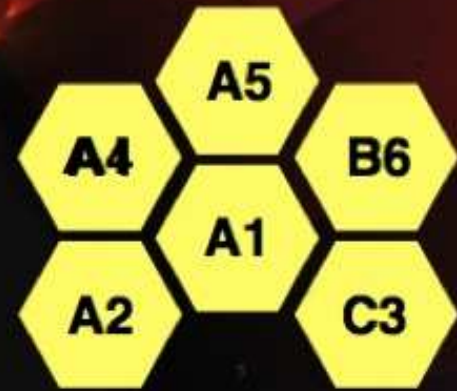
# JWST Hardware Status



April 2015:  $\gtrsim 98\%$  of launch mass designed and built ( $\gtrsim 65\%$  weighed).



# Mirror Acceptance Testing



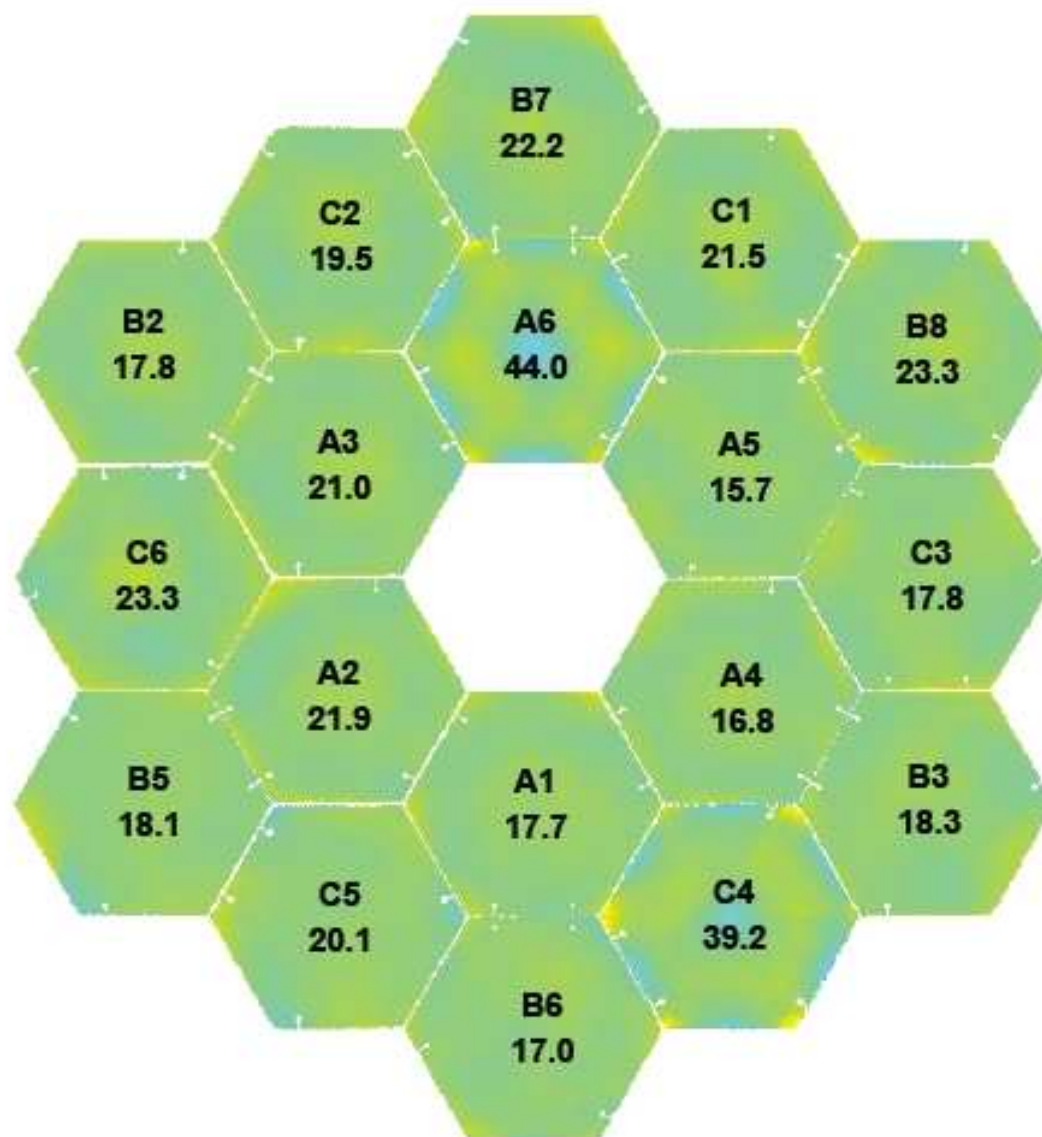








# Primary Mirror Composite



RMS: **23.2 nm**

PV: **515.5 nm**

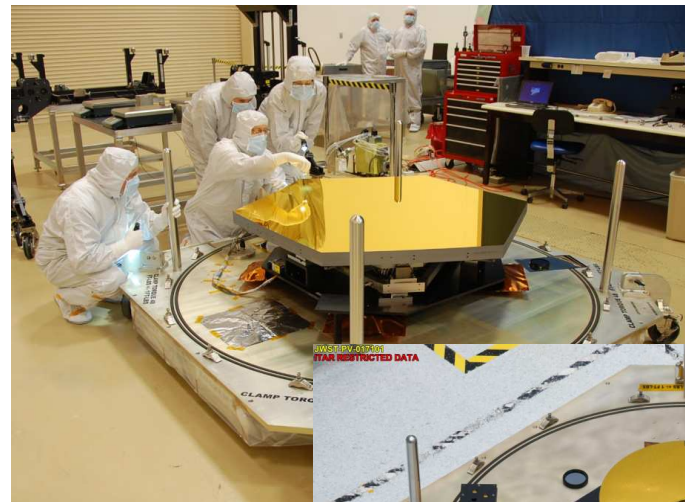




# Mirror Status



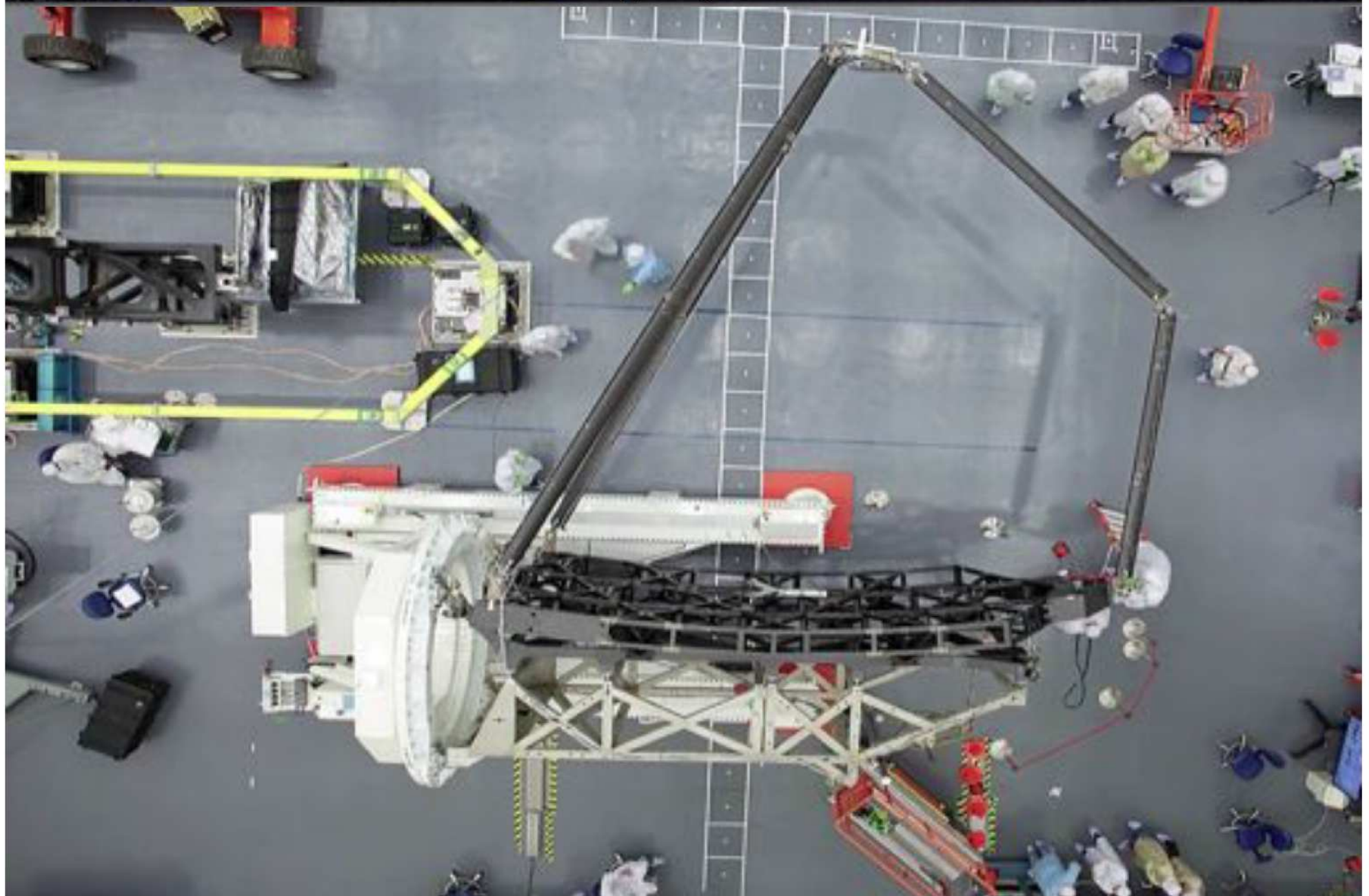
- 15 flight primary mirrors and the flight secondary mirror are at GSFC in storage
  - All spares were at GSFC in storage (SM spares, 3 PMSA spares)
    - 2 EDU mirrors sent back to Ball for gear motor rework
  - All flight gear motor refurbishment is complete
  - All flight mirrors will be at GSFC by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



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



# Pathfinder: Powered Deployment of SMSS



July 2014: Secondary Mirror Support deployment successfully tested.



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



[LEFT]: Aug. 2014: Engineering Kapton Sunshield; 2015: Flight Sunshield.

[RIGHT]: Nov. 2014: First JWST mirrors mounted onto support structure, using Engineering Demo mirrors — Flight mirrors to be mounted in 2015.

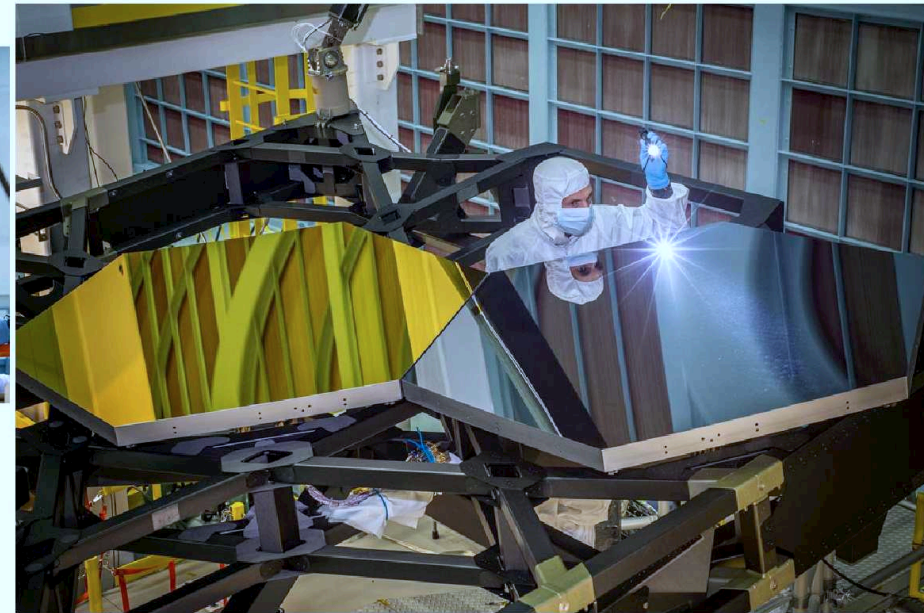
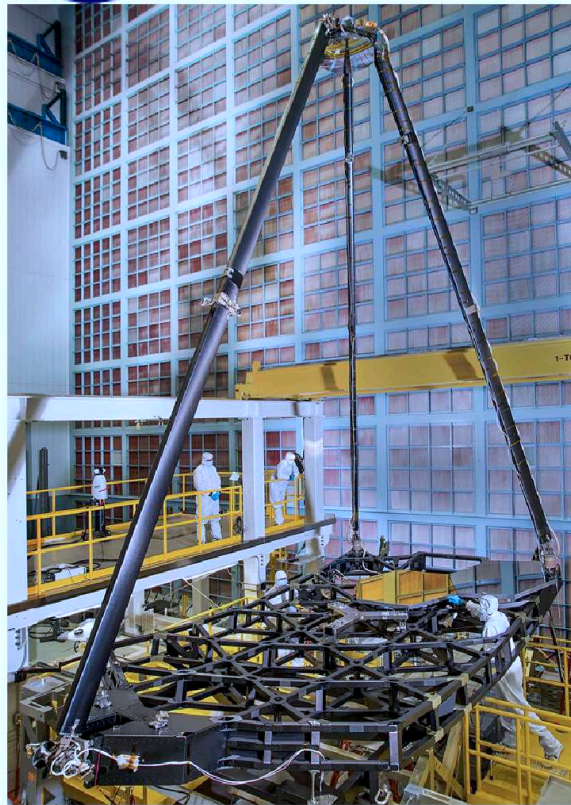
- Our Galaxy is a bright IR source at  $\lambda \gtrsim 1\text{--}5\mu\text{m}$ : In certain directions of sky, some straylight can hit secondary mirror via Sunshield:  $\lesssim 40\%$  of Zodi.

What does this mean for JWST lensing studies of First Light objects?

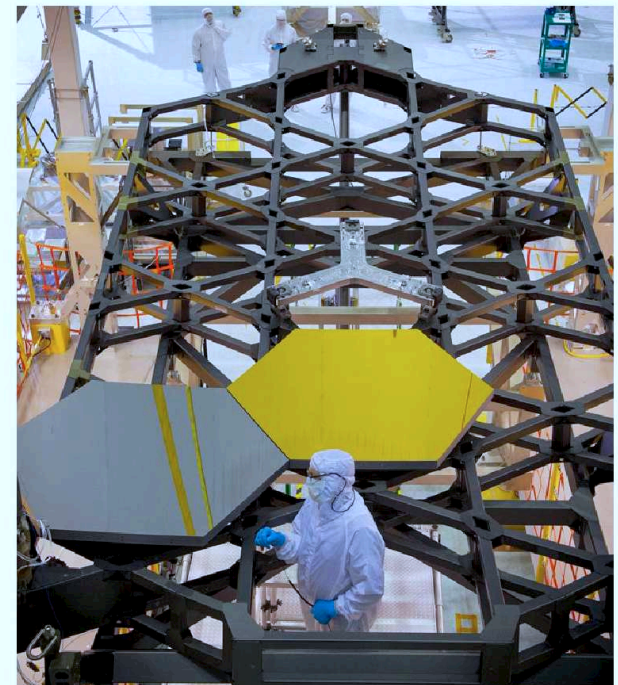
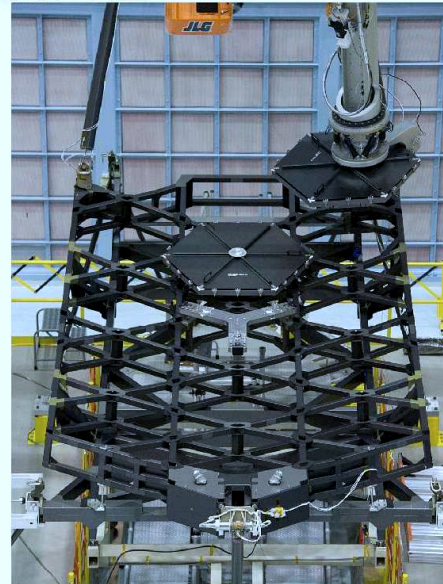




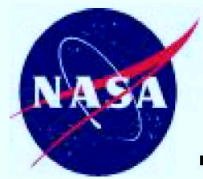
# Telescope Pathfinder – Risk Reduction



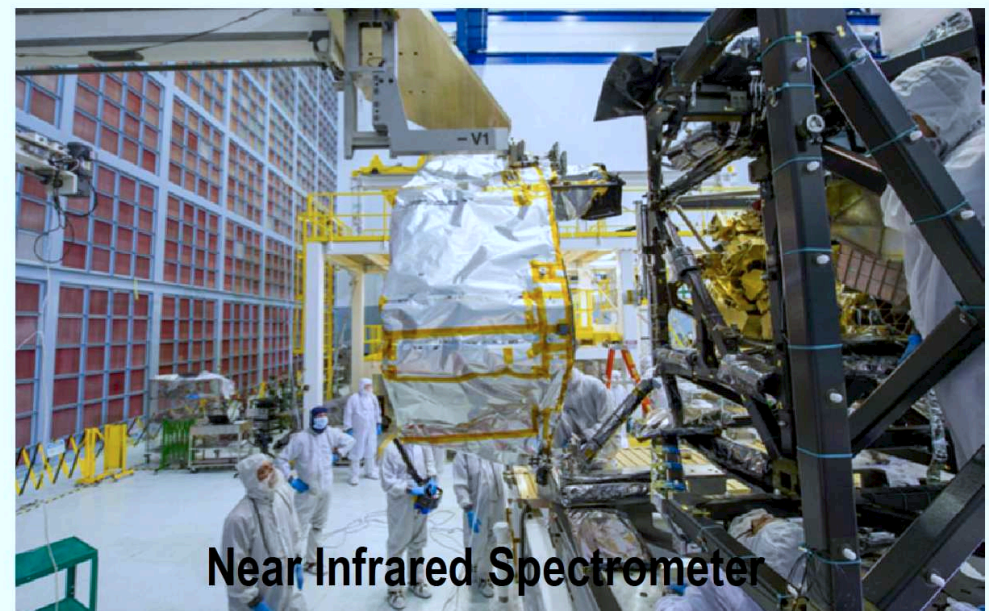
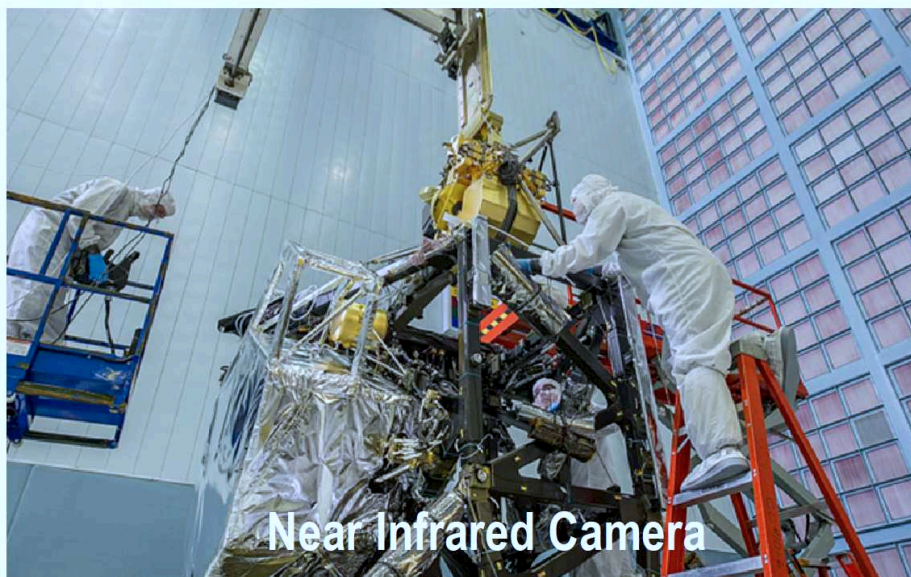
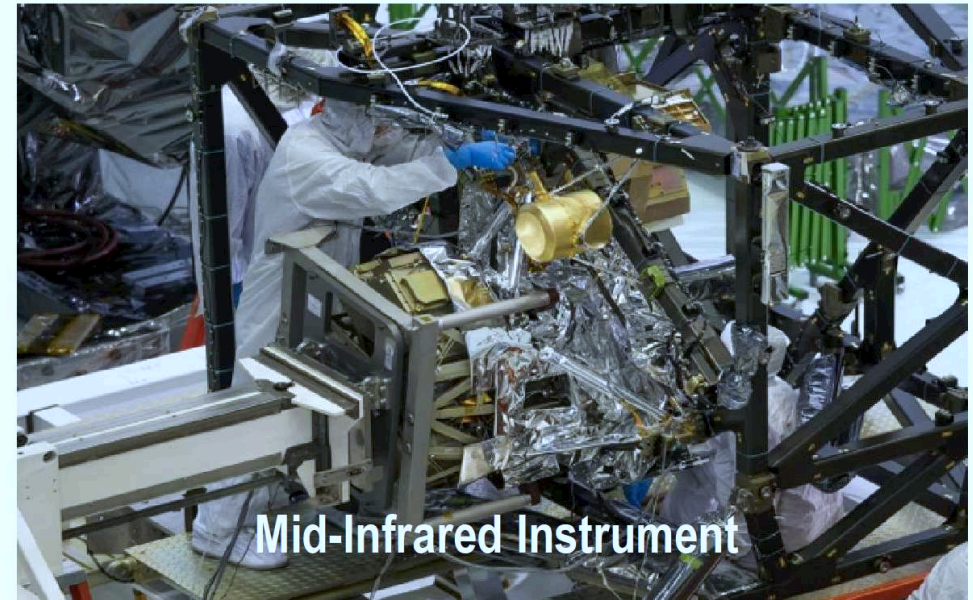
**JWST Pathfinder is a partial telescope that is intended to reduce the implementation risk of the assembly, integration, and cryogenic optical test of the JWST optical assembly**







# All Instruments Integrated





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



## Instrument Overview

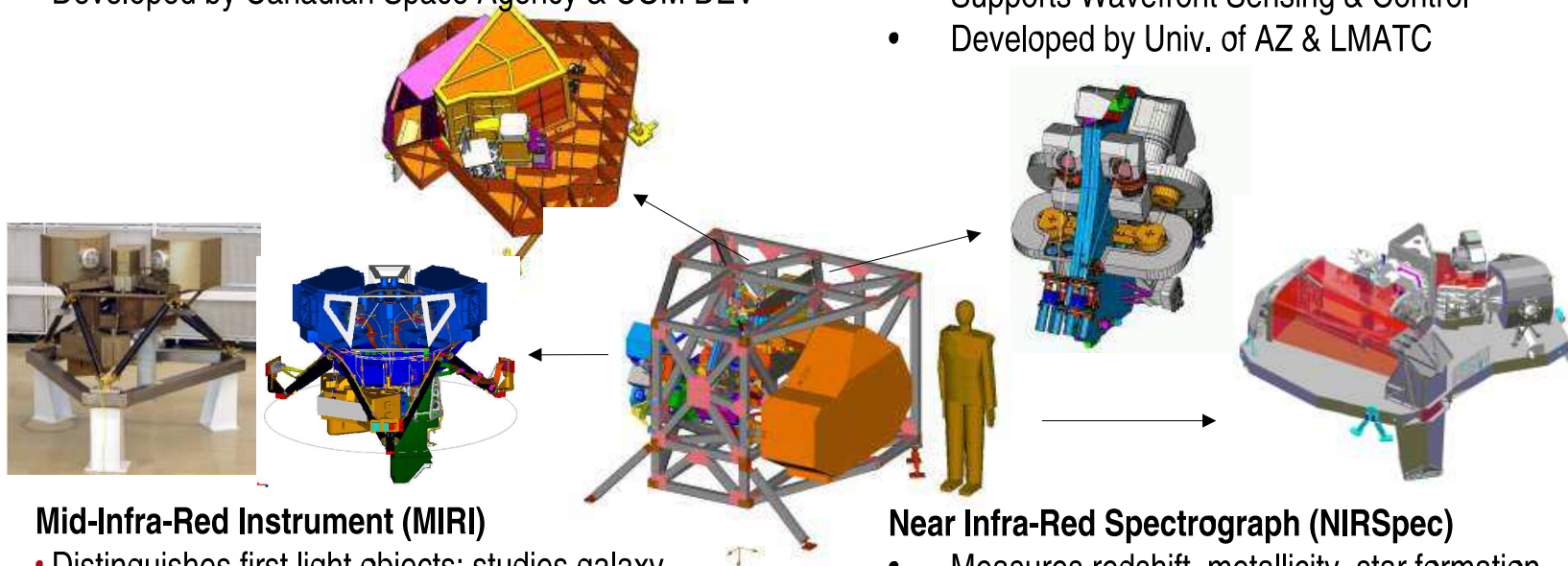


### Fine Guidance Sensor (FGS)

- 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)

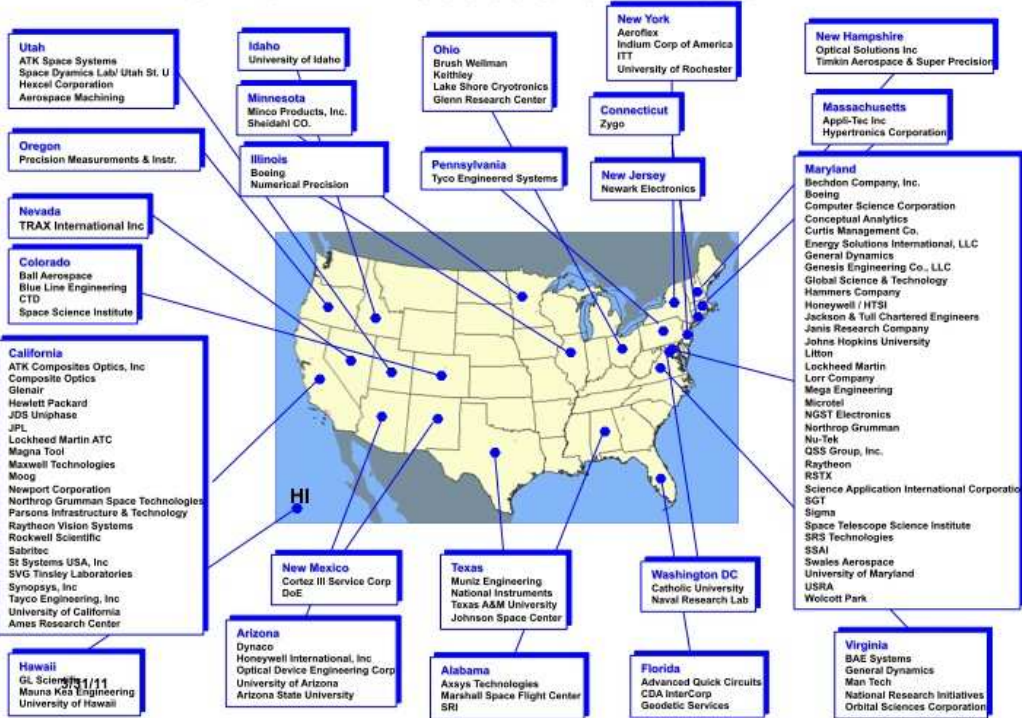
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

### Near Infra-Red Spectrograph (NIRSpec)

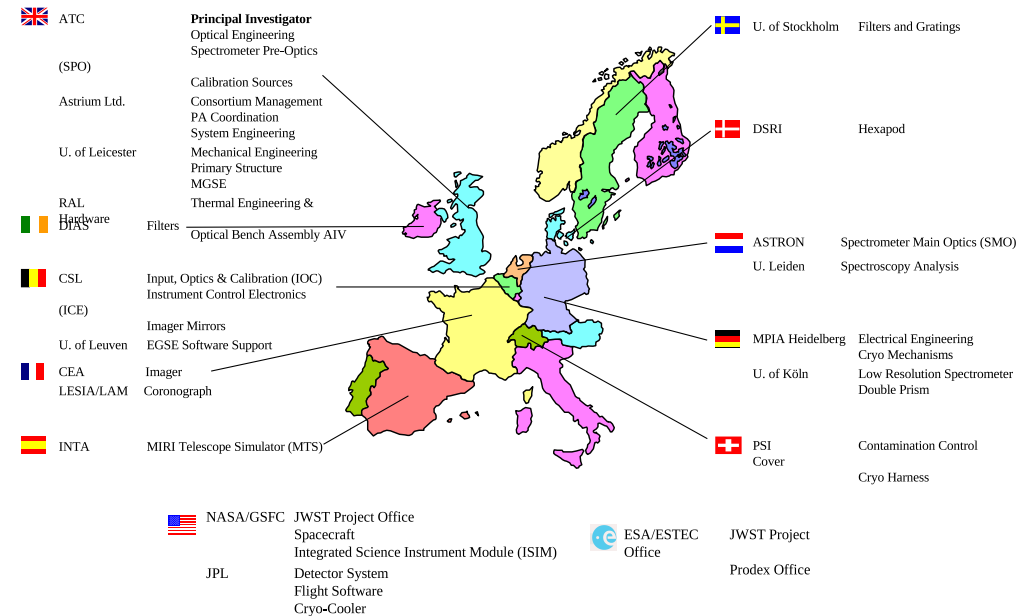
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

All delivered: MIRI 05/12; FGS 07/12; NIRCam 07/13, NIRSpec 9/13.

# JWST: A Product of the Nation



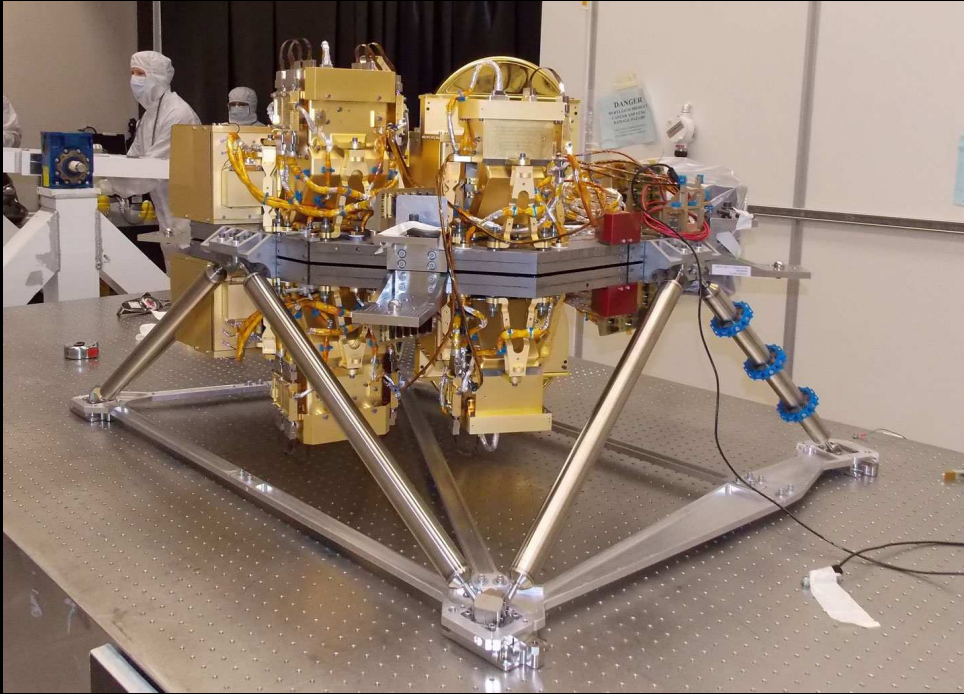
## European Consortium Who & Where



**MIRI European Consortium**  
28/05/05

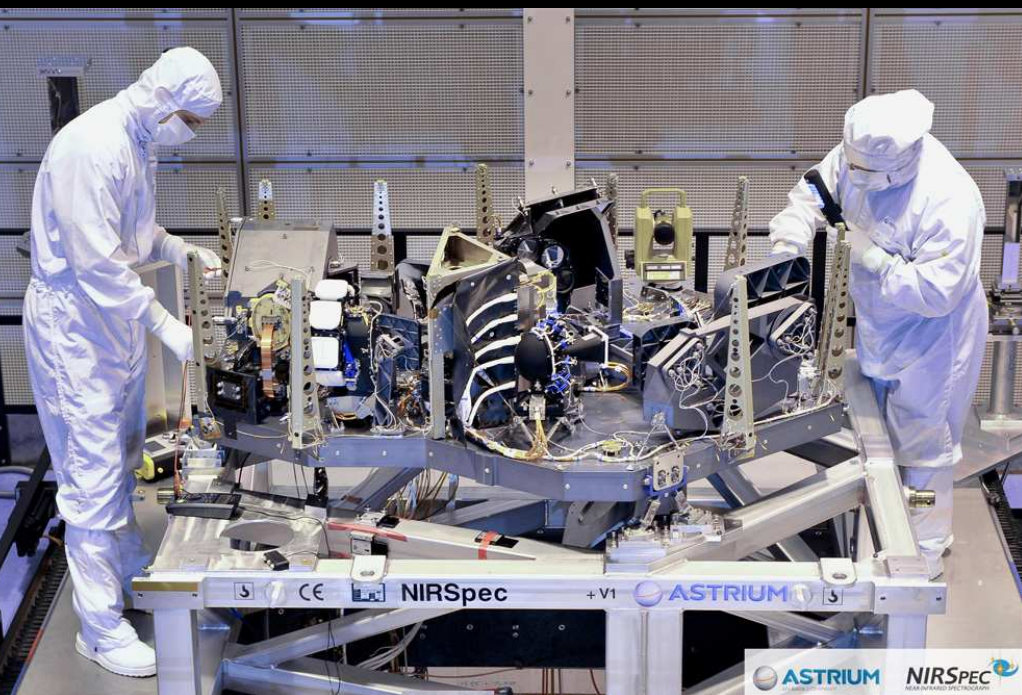
- JWST hardware made in 27 US States:  $\approx 98\%$  of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCам made by UofA and Lockheed.



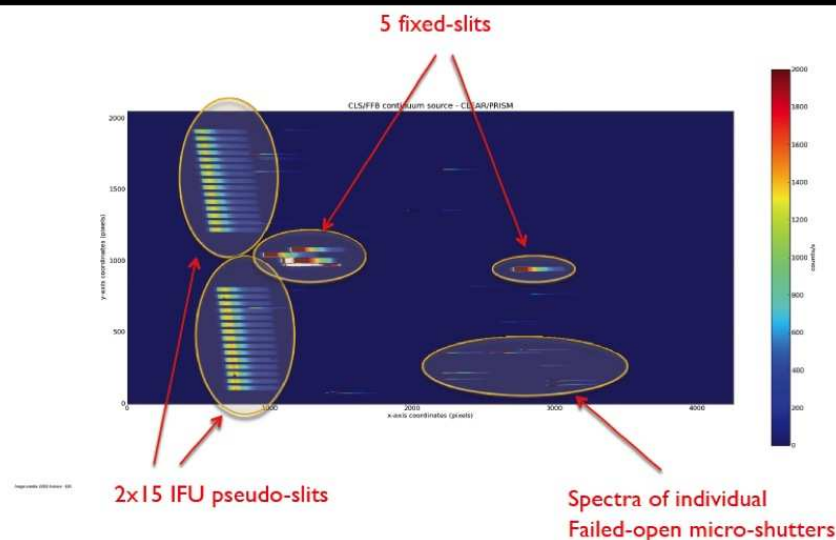


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) imagers:

- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (&  $1\text{--}5\mu\text{m}$  grisms) — built by CSA (Montreal).
- FGS includes very powerful low-res Near-IR grism spectrograph (NIRISS).
- FGS delivered to GSFC 07/12; NIRCam delivered 07/13.



## Flight NIRSpec First Light



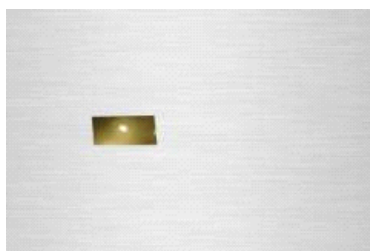
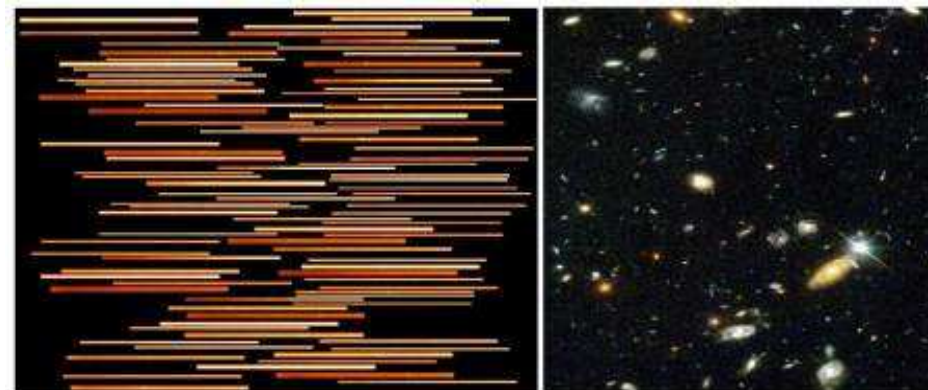
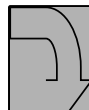
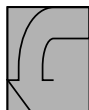
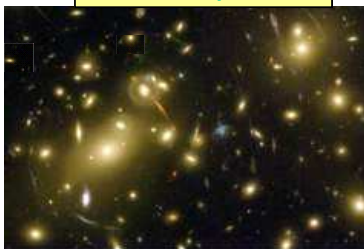
JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) spectrograph:

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

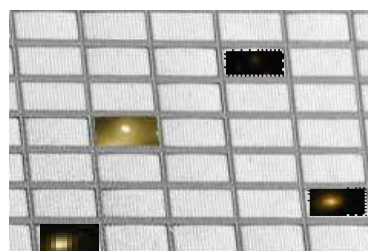
NIRSpec delivered to NASA/GSFC in 09/13.



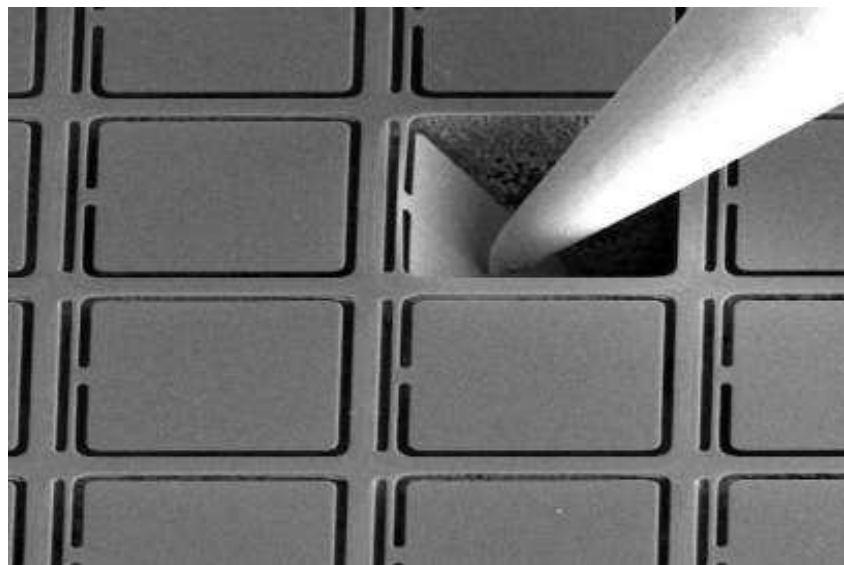
Astronomy Scene



Metal Mask/Fixed Slit



Shutter Mask

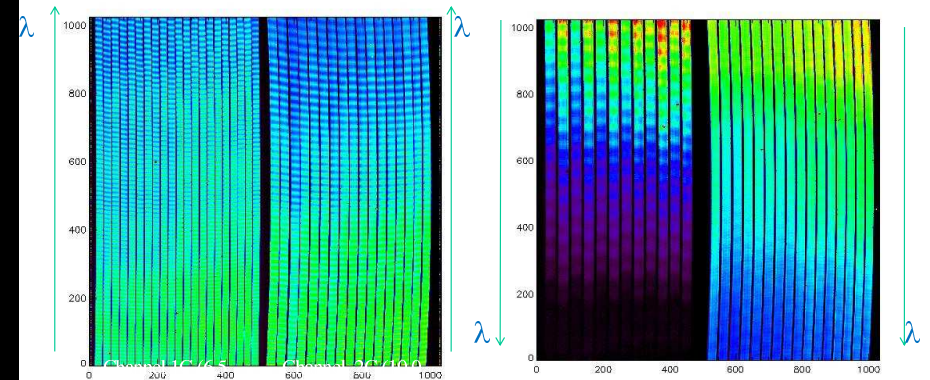




## Flight MIRI



### Spectrometer First Light – internal calibration source



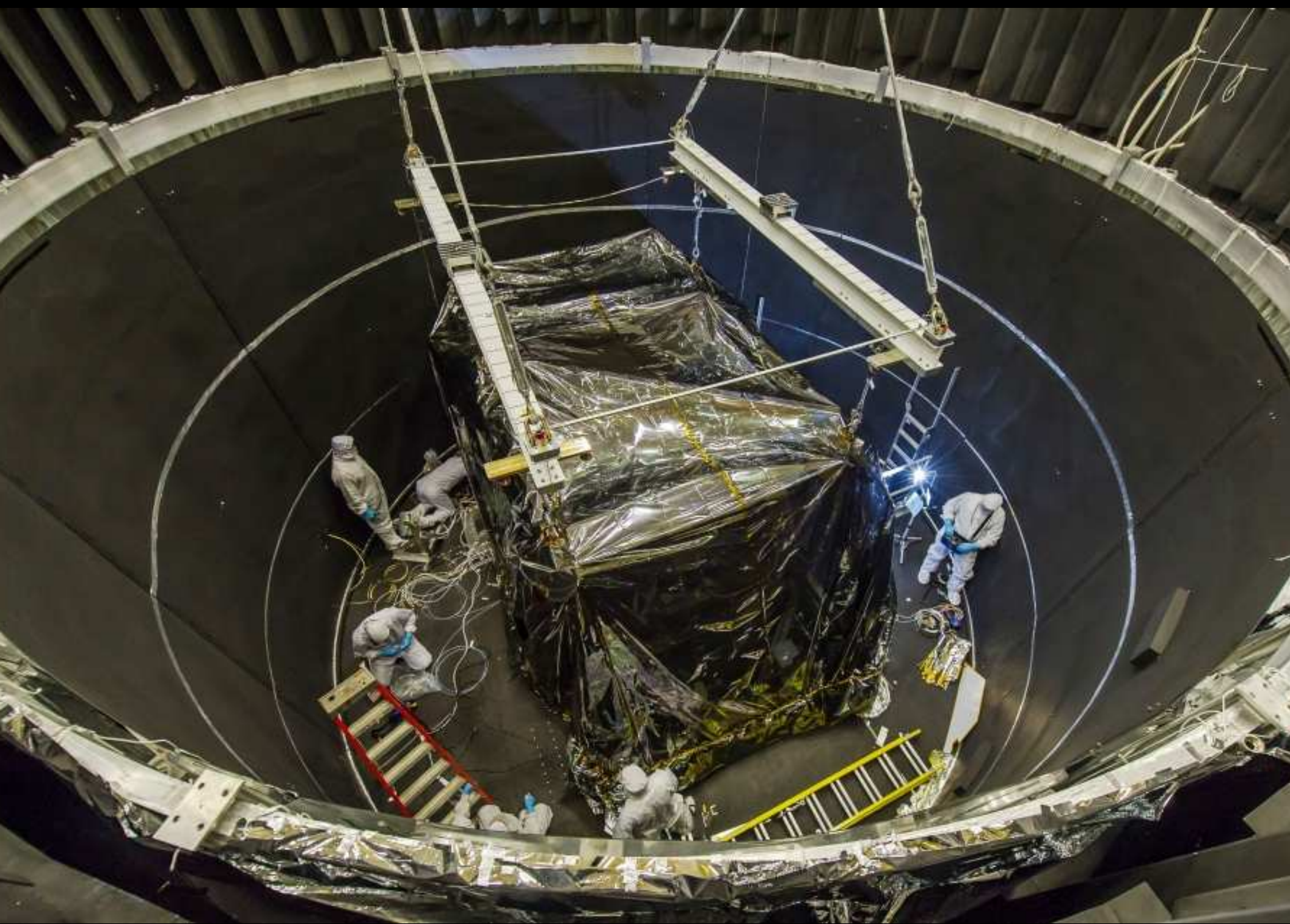
All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

JWST's mid-infrared (5–29 $\mu\text{m}$ ) 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 05/12.

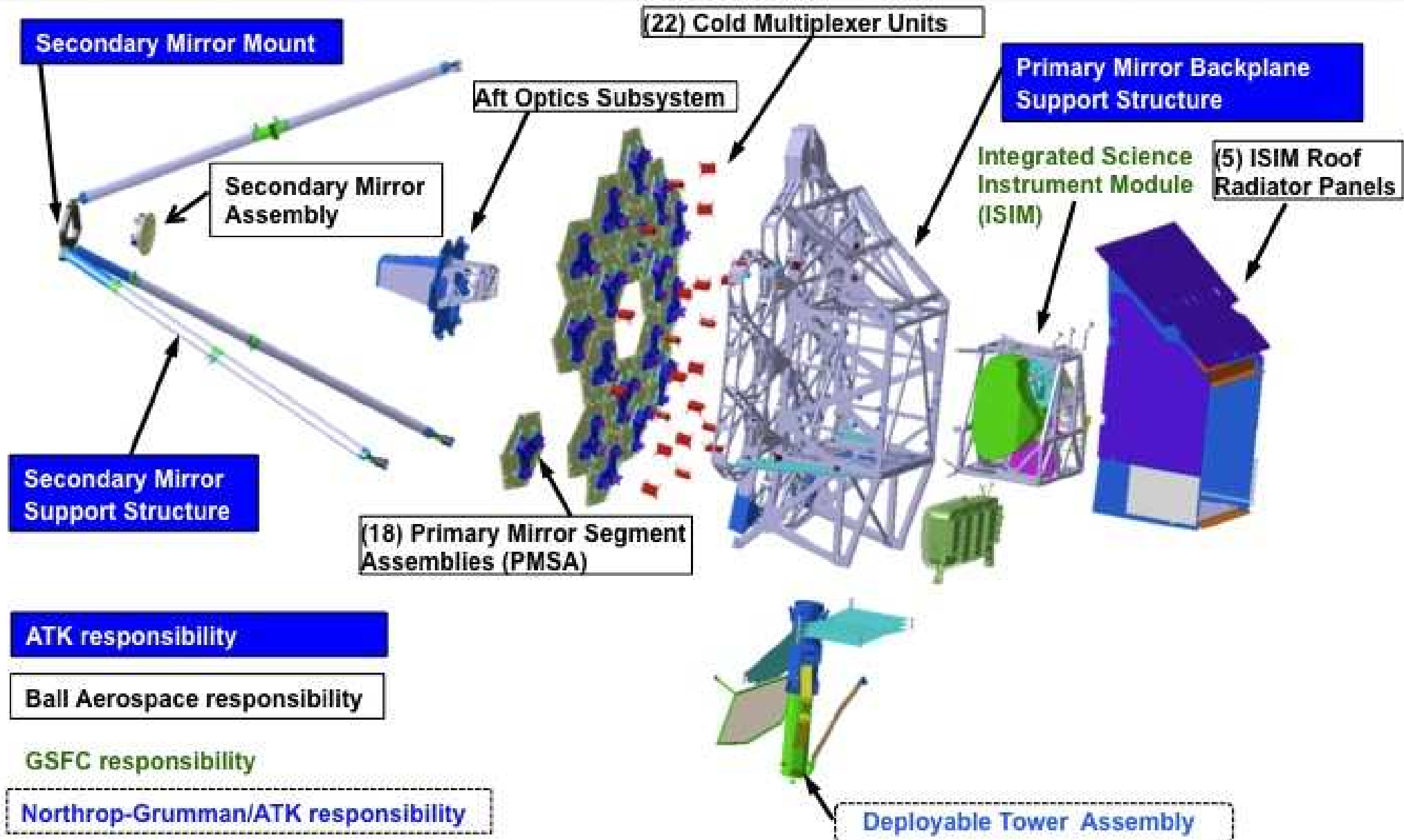




June 2014: Flight ISIM (with all 4 instruments) in OSIM; Aug. 2015: CryoVac3.



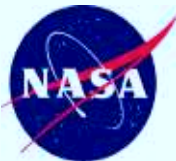
# TELESCOPE ARCHITECTURE



3/31/11

2014–2016: Complete system integration at GSFC and Northrop.





# OTIS Test GSE Architecture and Subsystems

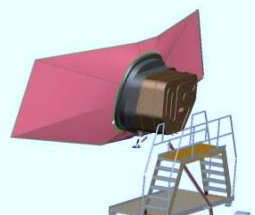
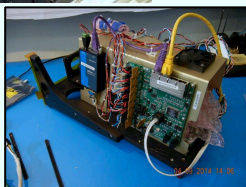


Chamber Isolator Units  
Dynamically isolates OTIS Optical Test  
– Integration 6 units complete

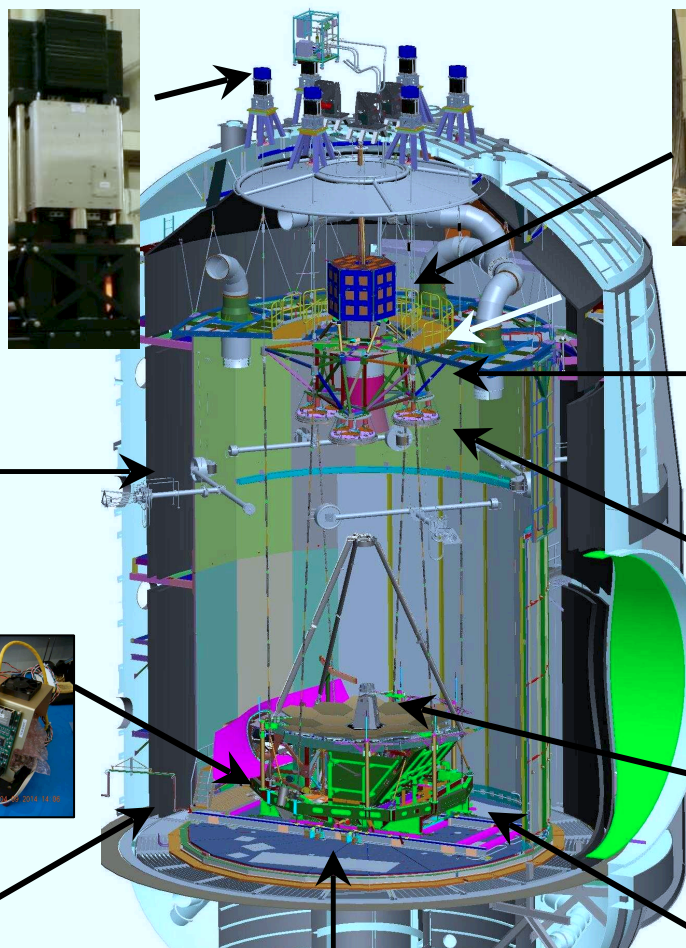
Cryo Position Metrology (CPM)  
Photogrammetry System  
Integration Complete



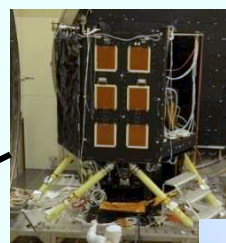
ADM - new Leica  
delivered and under  
test



Space Vehicle Thermal Simulator  
(SVTS)  
and Sunshield Simulator  
Passed design review and started  
Procurements and fab subcontracts



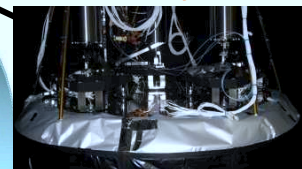
HOSS – OTIS support structure  
HOSS – will be in the chamber for Bake out in June



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



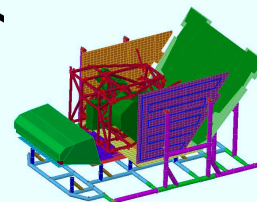
USF Structural Frame – supports Metrology  
ready for chamber integration and Cryo Load tests



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.

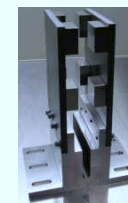


AOS Source Plate  
Sources for Pass and Half Test  
72 optical fiber support cont.



Deep Space Edge Radiation Sink (DSERS)

Thermal modeling of payload and DSERS  
started



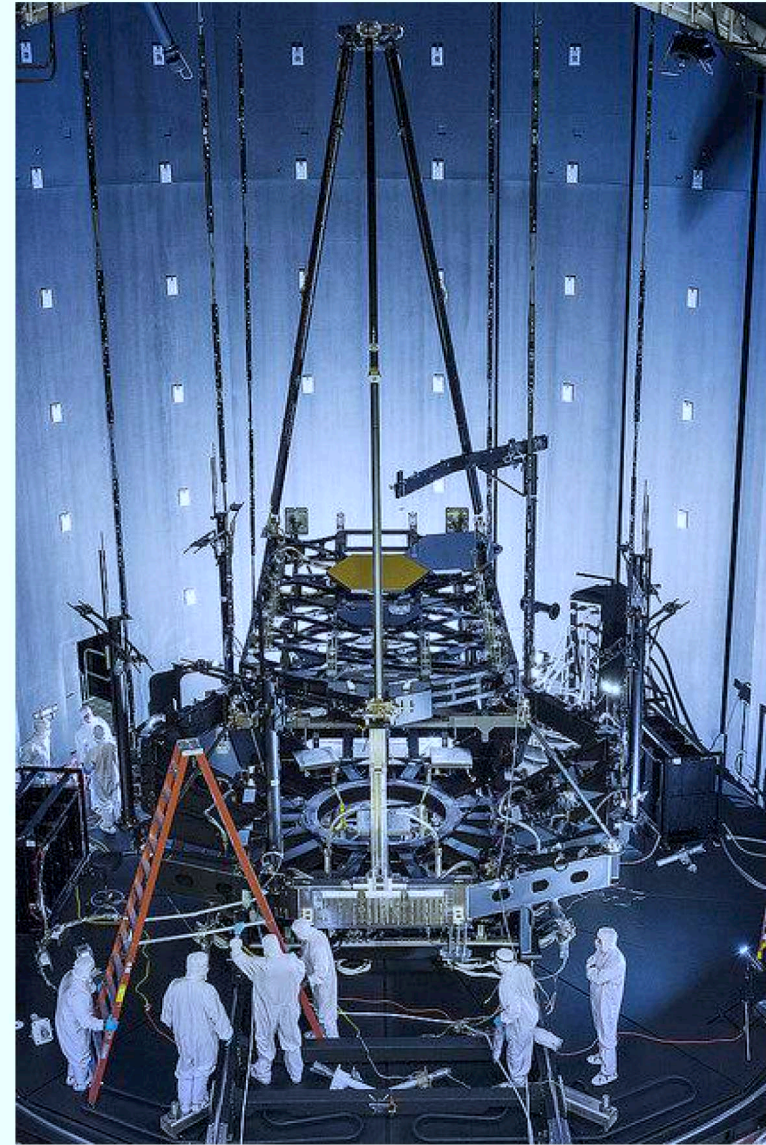
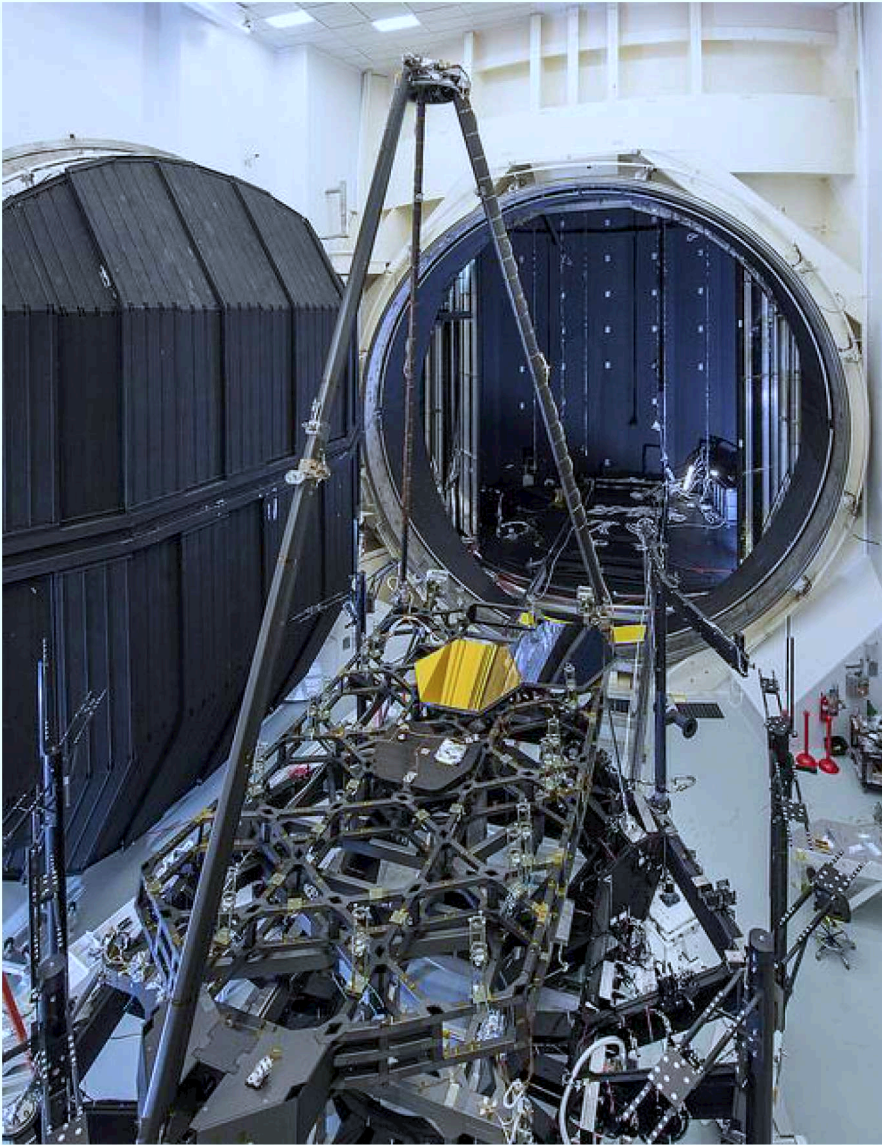
Mag Damper Cryo  
Test  
Article  
Fabrication started

<#>

World's largest TV chamber OTIS: will test whole JWST in 2016–2017.



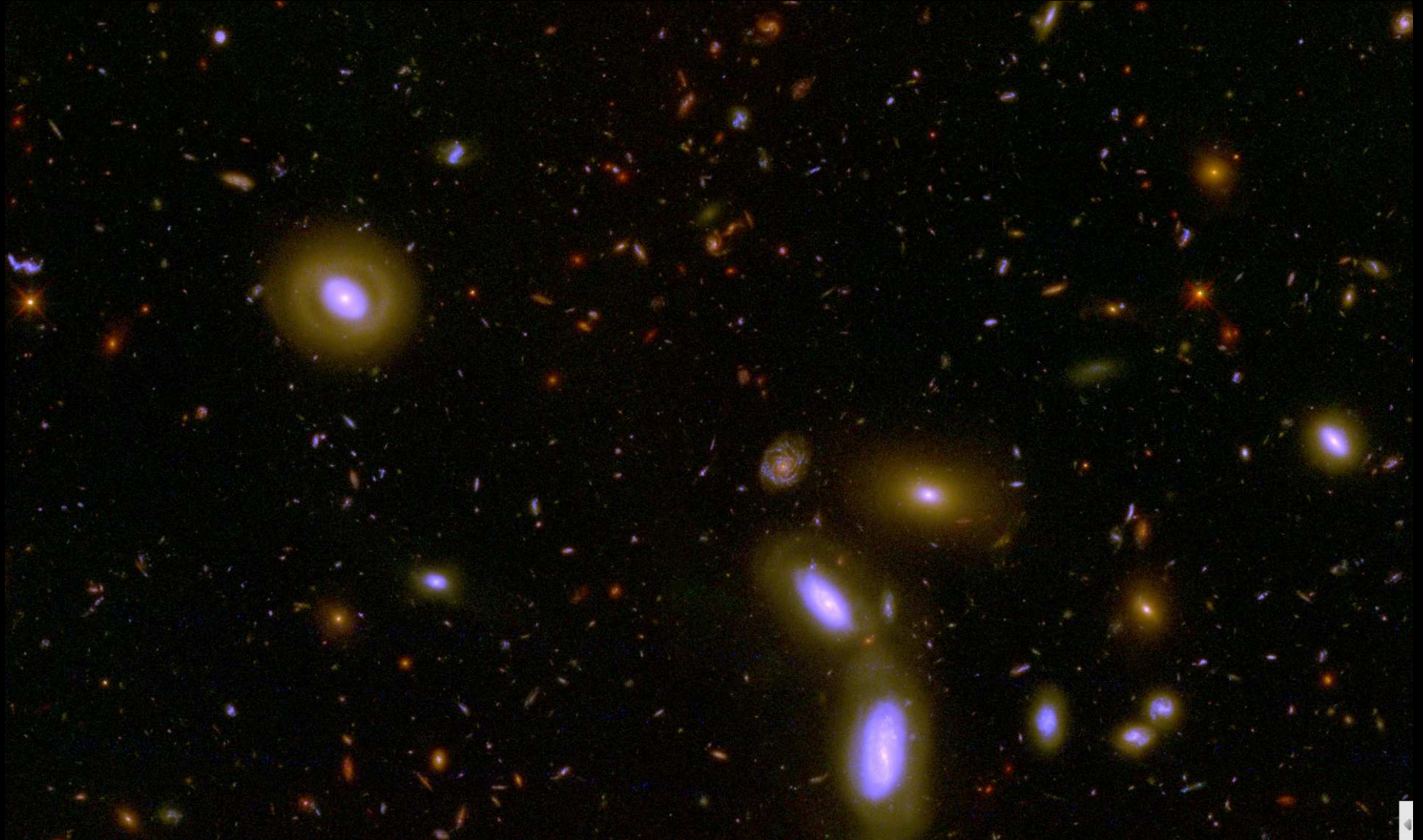
# Pathfinder & JSC Chamber A: getting ready for OGSE1 (and eventually OGSE2 & Thermal Pathfinder)



April 2015: Testing OTIS chamber with the JWST Engineering model.



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



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



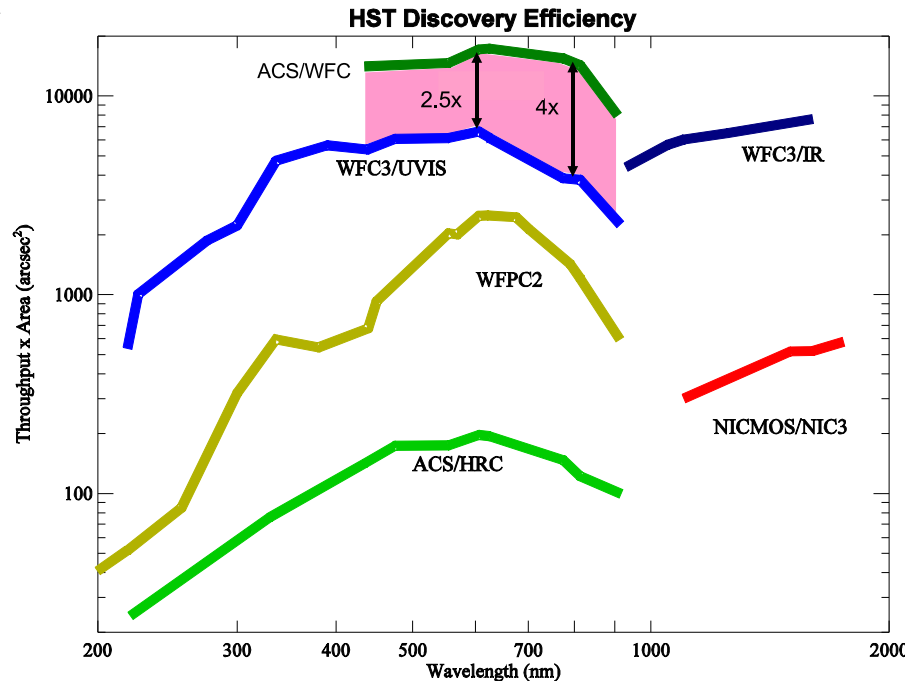
## (2a) WFC3: Hubble's new Panchromatic High-Throughput Camera



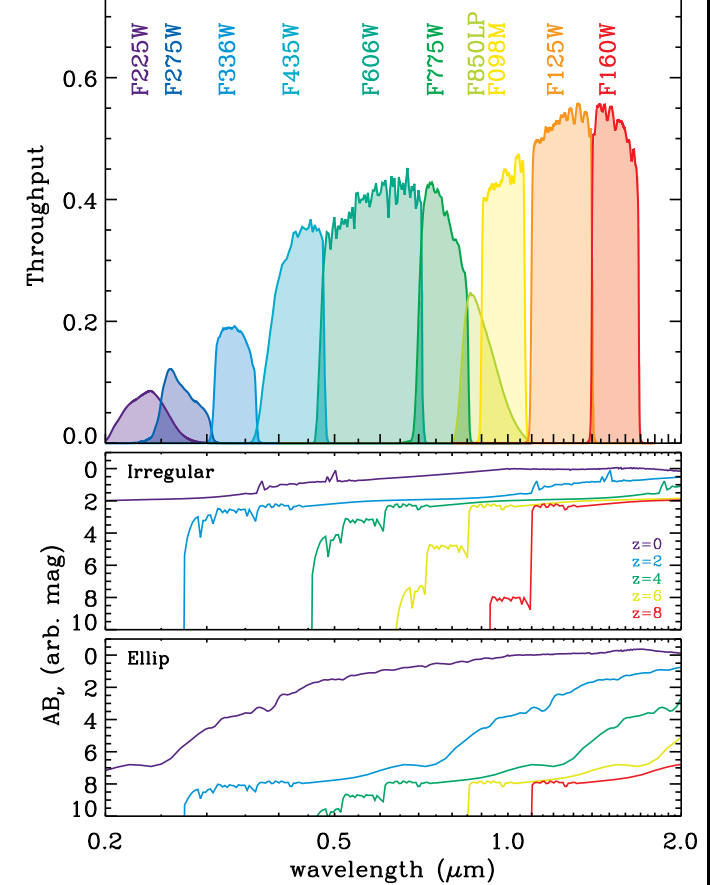
HST WFC3 and its **IR channel**: a critical pathfinder for JWST science.



# Role of ACS in HST Post-SM4 Imaging Capability



ACS/WFC superior to WFC3 survey efficiency at visible-red wavelengths



WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- $QE \gtrsim 70\%$ ,  $4k \times 4k$  array of  $0''.04$  pixel,  $FOV \simeq 2'67 \times 2'67$ .

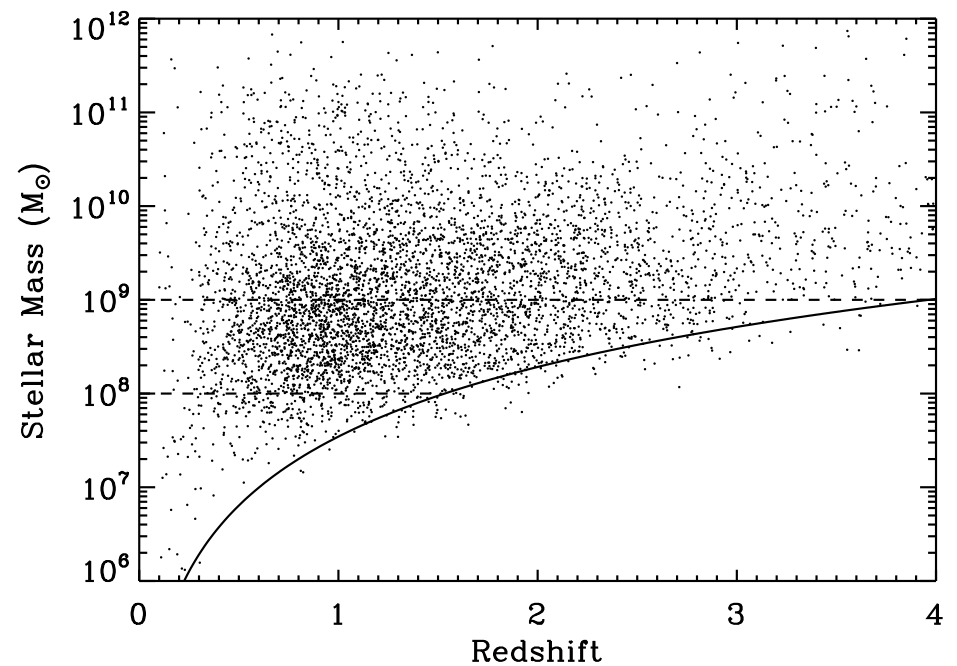
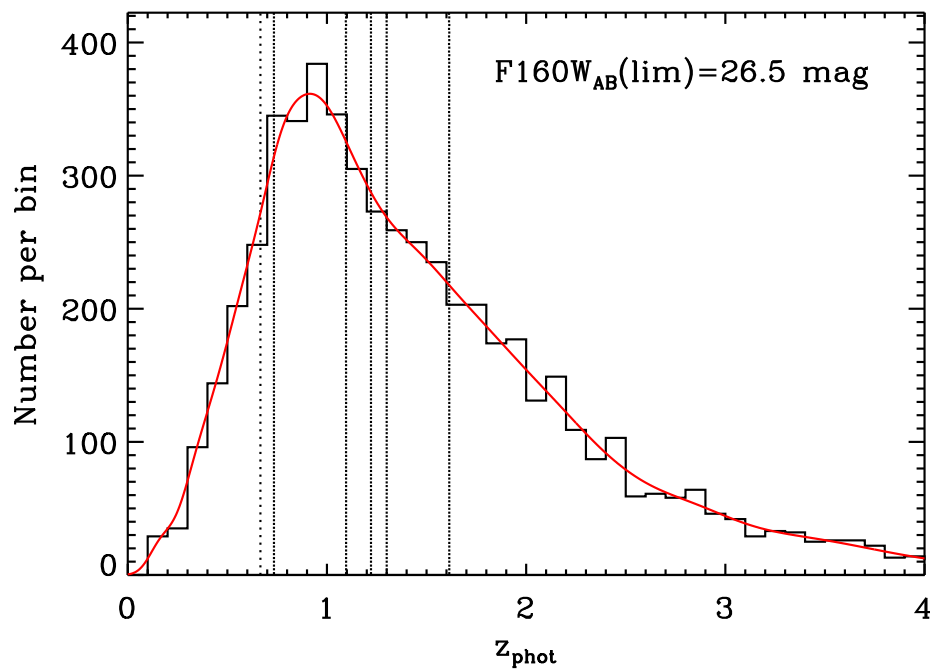
WFC3/IR channel unprecedented near–IR throughput & areal coverage:

- $QE \gtrsim 70\%$ ,  $1k \times 1k$  array of  $0''.13$  pixel,  $FOV \simeq 2'25 \times 2'25$ .

⇒ 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.



WFC3 ERS 10-band redshift estimates accurate to  $\lesssim 4\%$  with small systematic errors (Hathi et al. 2010, 2013), resulting in a reliable  $N(z)$ .

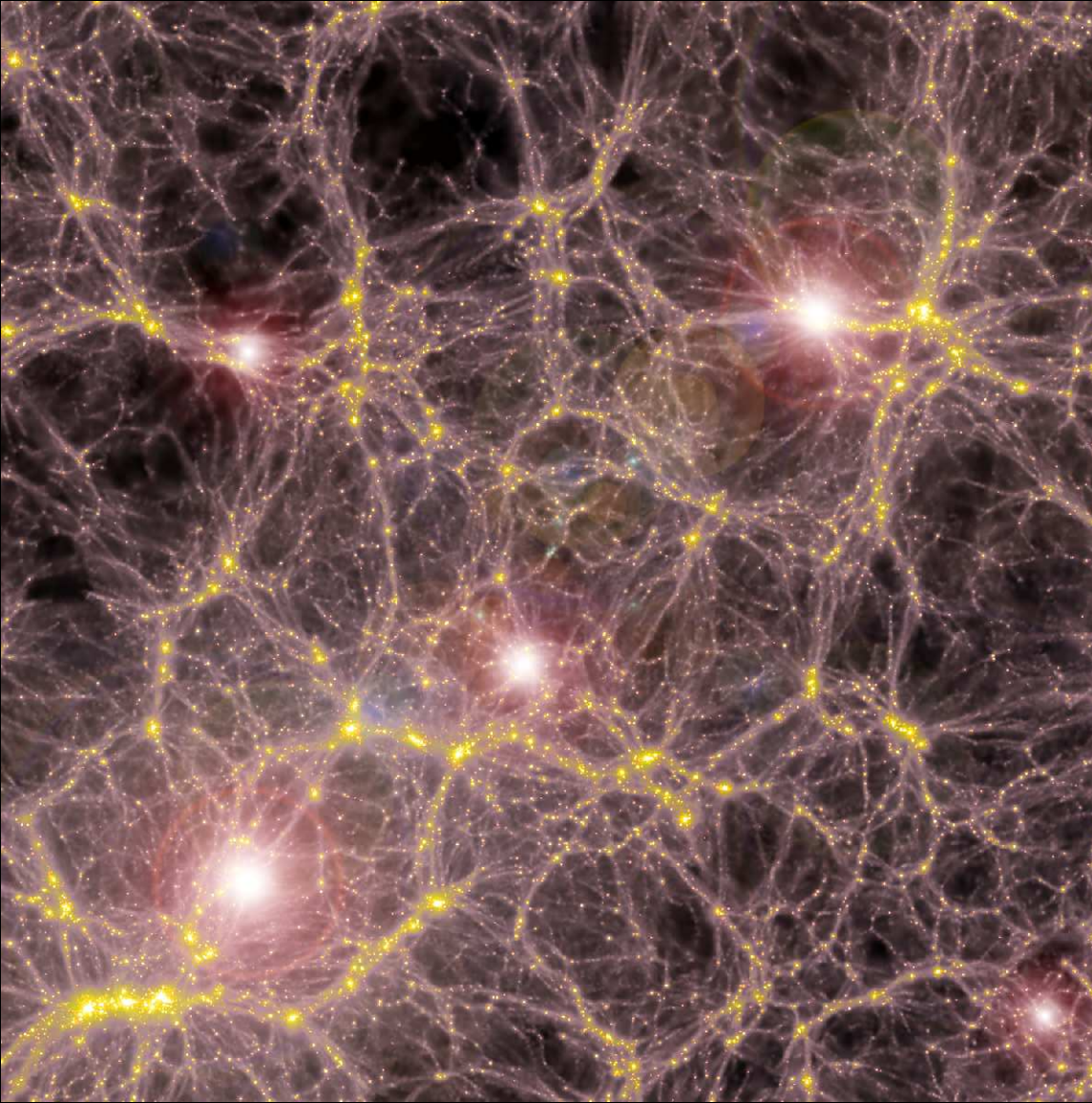
- Measure masses of faint galaxies to  $AB=26.5 \text{ mag}$ , tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?).

$\Rightarrow$  Median redshift in (medium-)deep fields is  $z_{med} \simeq 1.5-2$ .

- HUDF shows WFC3  $z \simeq 7-9$  capabilities (Bouwens<sup>+</sup> 2014; Yan<sup>+</sup> 2010).
- JWST will trace mass assembly and dust content  $\lesssim 5 \text{ mag}$  deeper from  $z \simeq 1-12$ , with nanoJy sensitivity from  $0.7-5 \mu\text{m}$ .



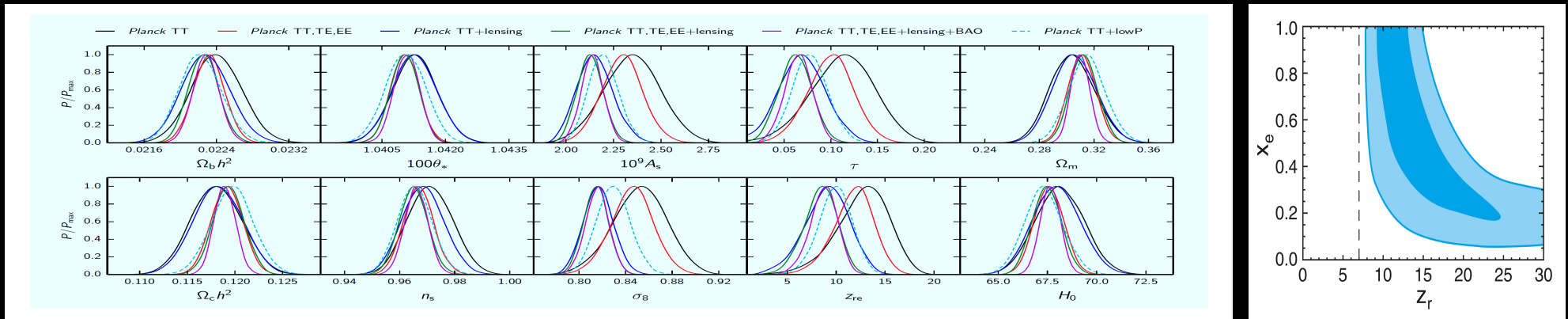
### (3) How will JWST Observe First Light and Reionization?



- Detailed cosmological models (V. Bromm) suggest that massive “Pop III” stars ( $\gtrsim 100 M_{\text{sun}}$ ) started to reionize the universe at  $z \lesssim 10-30$  (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 IMF, their duplicity and clustering properties, their SN-rates, etc., before JWST flies, so we know what to look for.

# Implications of WMAP year-9 & Planck 2015 results for JWST science:



HST/WFC3  $z \lesssim 7-10$   $\longleftrightarrow$  JWST  $z \simeq 8-25$

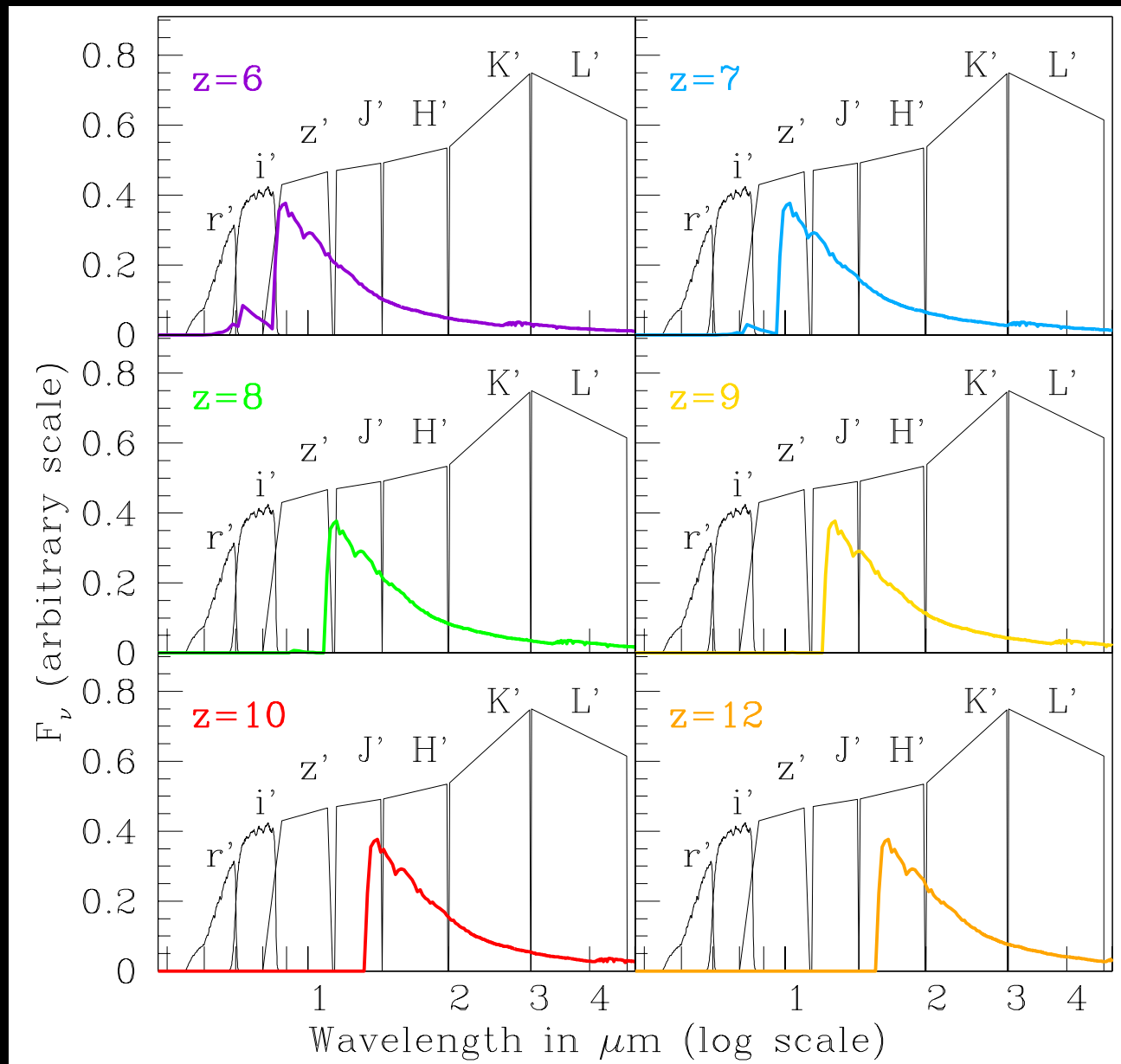
The year-9 WMAP and Planck 2015 data provided better foreground removal (Komatsu<sup>+</sup> 2011; Hinshaw<sup>+</sup> 2012; Planck VIII 2015):

$\implies$  First Light & Reionization occurred between these extremes:

- (1) Instantaneous:  $z \simeq 8.8 \pm 1.5$  (pol. optical depth  $\tau \simeq 0.066 \pm 0.016$ ), or:
- (2) Inhomogeneous & drawn out: starting at  $z \gtrsim 20$ , peaking at  $z \lesssim 9-10$ , ending at  $z \simeq 7$ . The implications for HST and JWST are:
- HST/ACS has covered  $z \lesssim 6$ , and WFC3 is covering  $z \lesssim 7-10$ .
- JWST designed to survey First Light/Reionization from  $z \simeq 8$  to  $z \simeq 15-20$ .
- Since Planck 2015's polarization  $\tau$  has come down considerably ( $\tau \simeq 0.066$ ), how many reionizers will JWST actually see at  $z \simeq 10-15$ ?



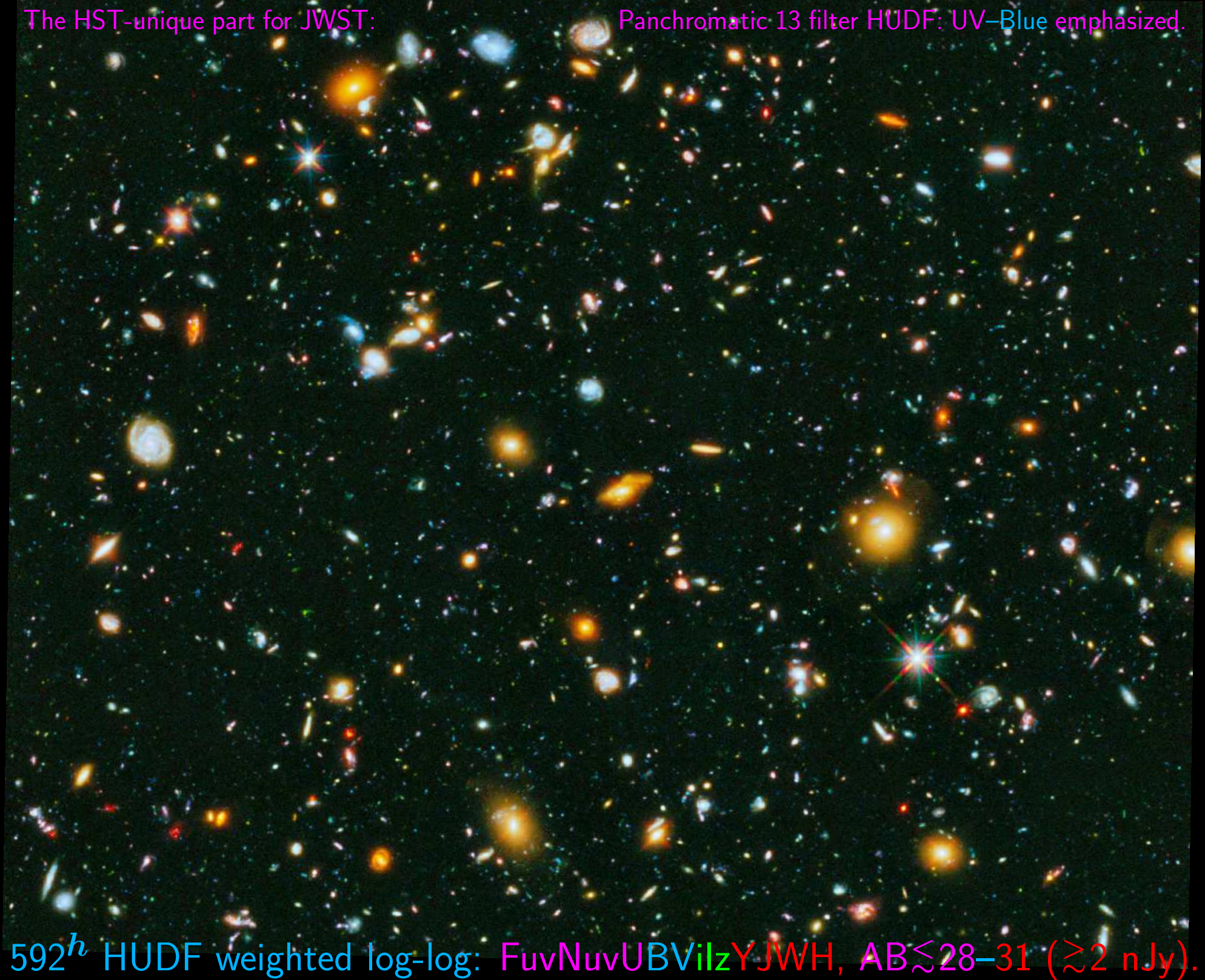
### 3) How will Webb measure First Light: What to expect in (Ultra)Deep Fields?



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

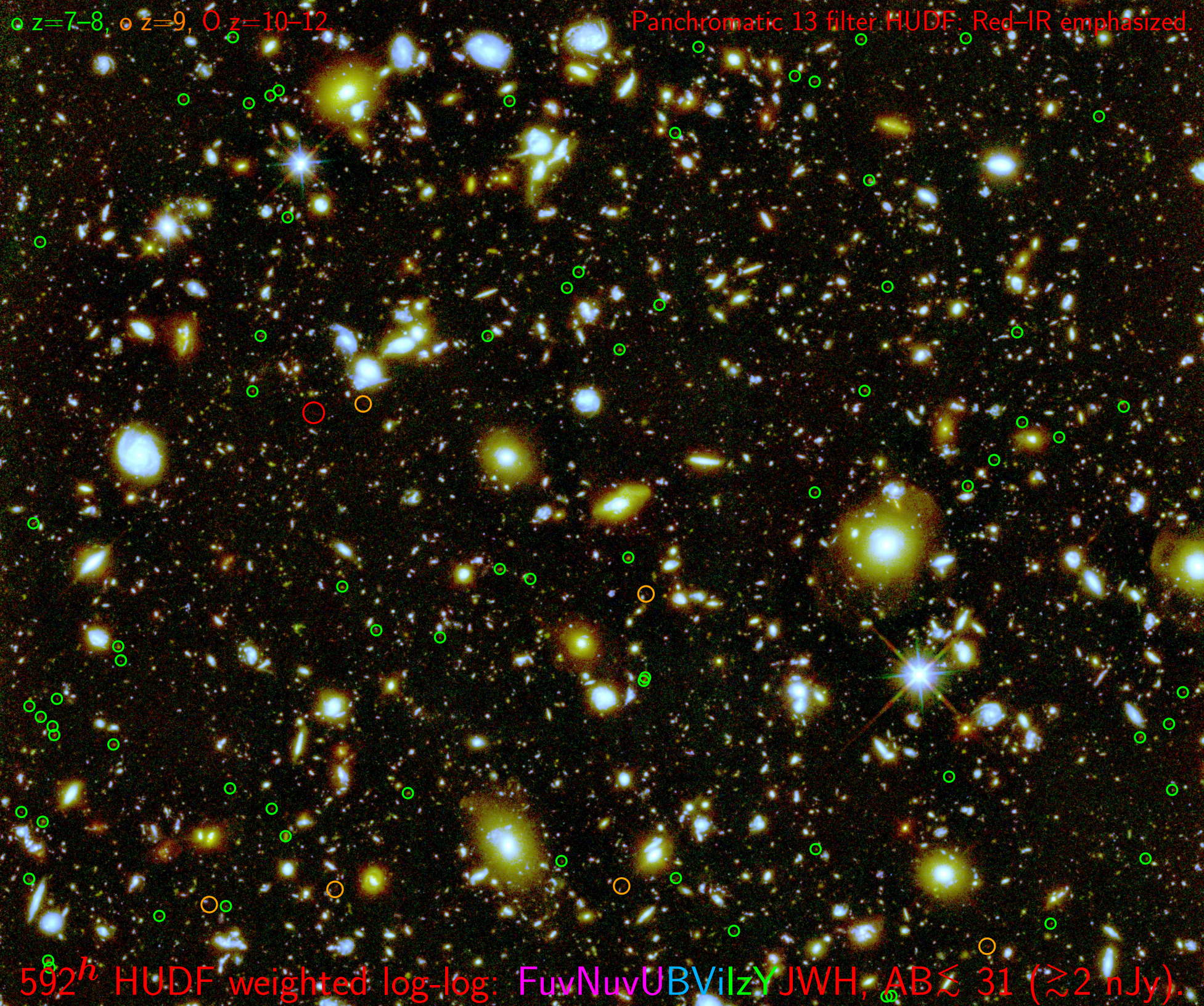
The HST-unique part for JWST:

Panchromatic 13 filter HUDF: UV–Blue emphasized.



592<sup>h</sup> HUDF weighted log-log: FuvNuvUBVilzYJWH, AB  $\lesssim 28-31$  ( $\gtrsim 2$  nJy).

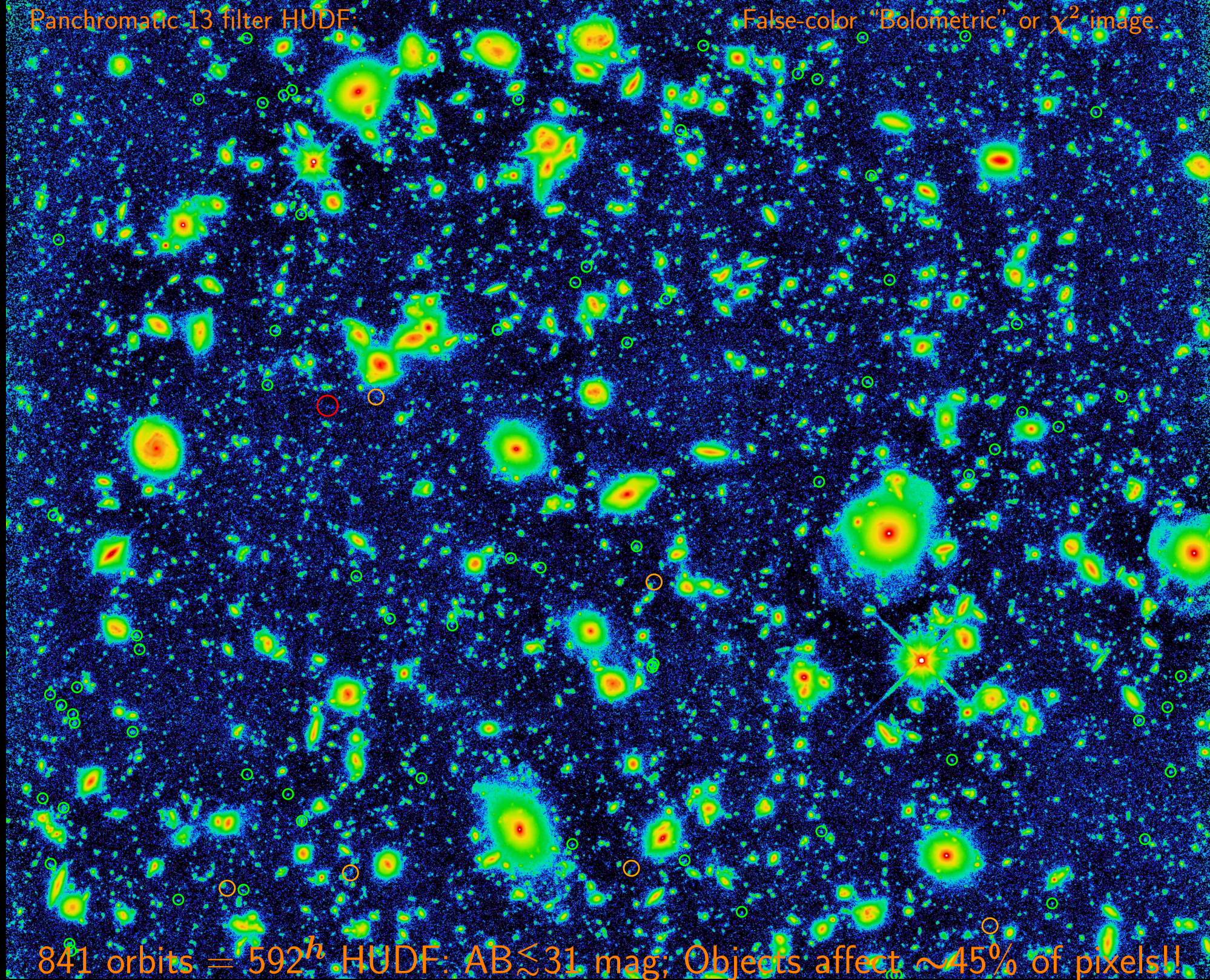






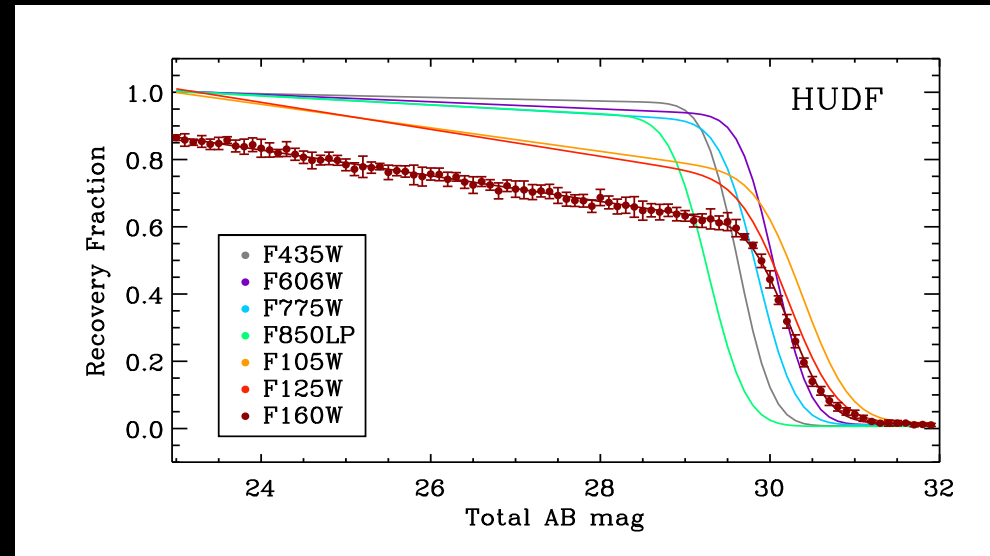
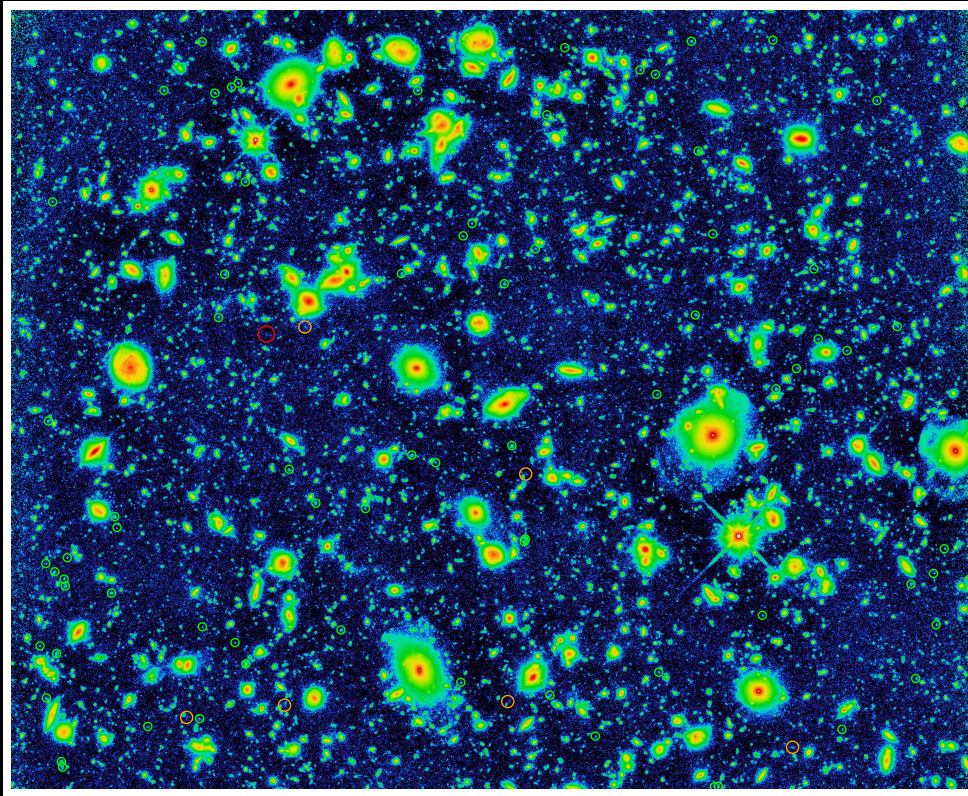
Panchromatic 13 filter HUDF:

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





## (2a) Current limitations: Wavelength-dependent Deep-Field Completeness limits



[LEFT]: HUDF bolometric or  $\chi^2$ -image (false-color log-log stretch): weighted average of 841 orbits (592 hr) in 13 filters reaching  $AB \lesssim 31$  mag.

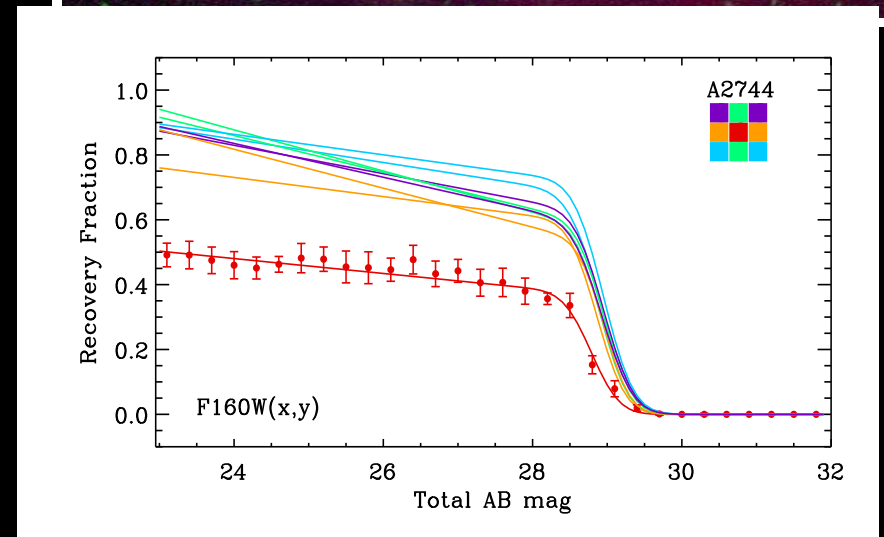
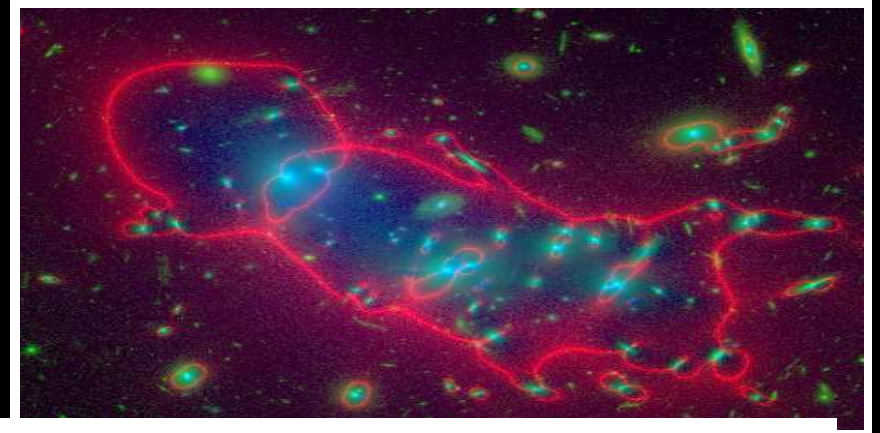
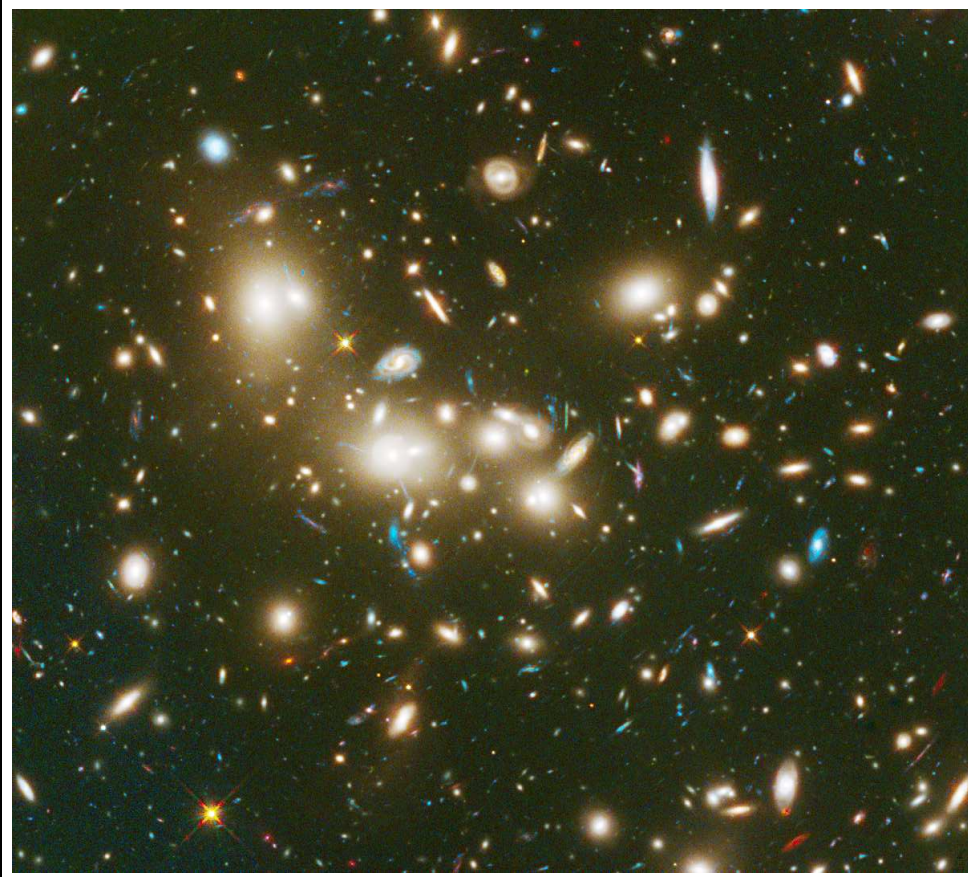
- Faint object wings cover  $\sim 45\%$  of all pixels (Koekemoer et al. 2013)!

[RIGHT]: HUDF *wavelength-dependent* completeness functions from Monte Carlo (MC) insertions:

- Faint-end recovery fractions drop to  $\sim 60\%$  at longer wavelengths.
- Even the bright-end at  $H \simeq 23$  AB-mag is  $\sim 15\%$  incomplete!



## (2b) Cluster-Position Dependence of Deep-Field Completeness limits



[LEFT]: HFF cluster A2744 in: F435W+F606W, F814W+F105W, F125W+F140W+F160W.

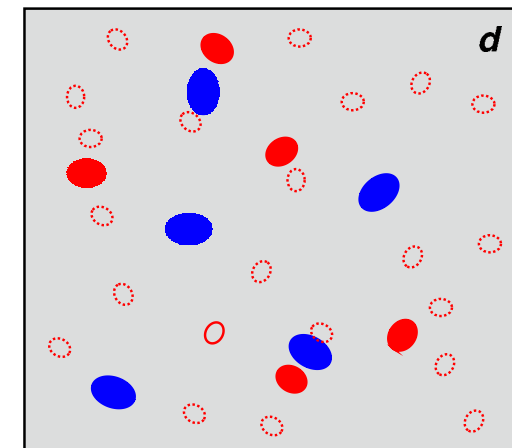
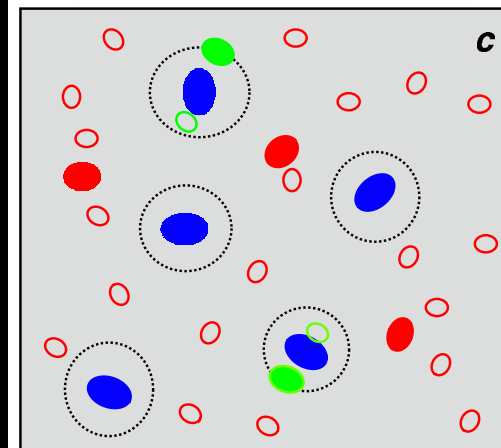
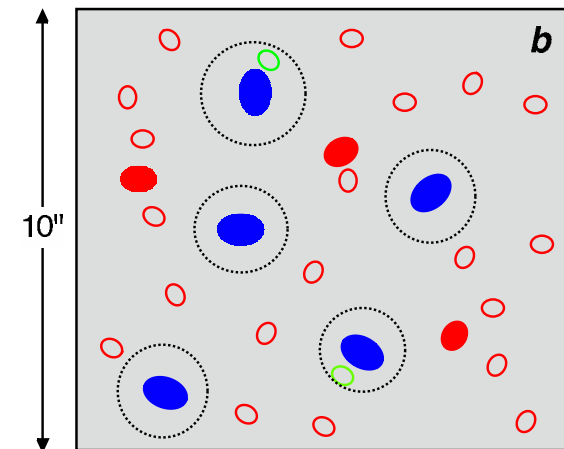
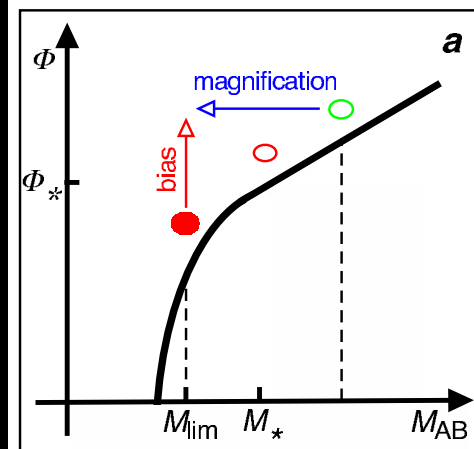
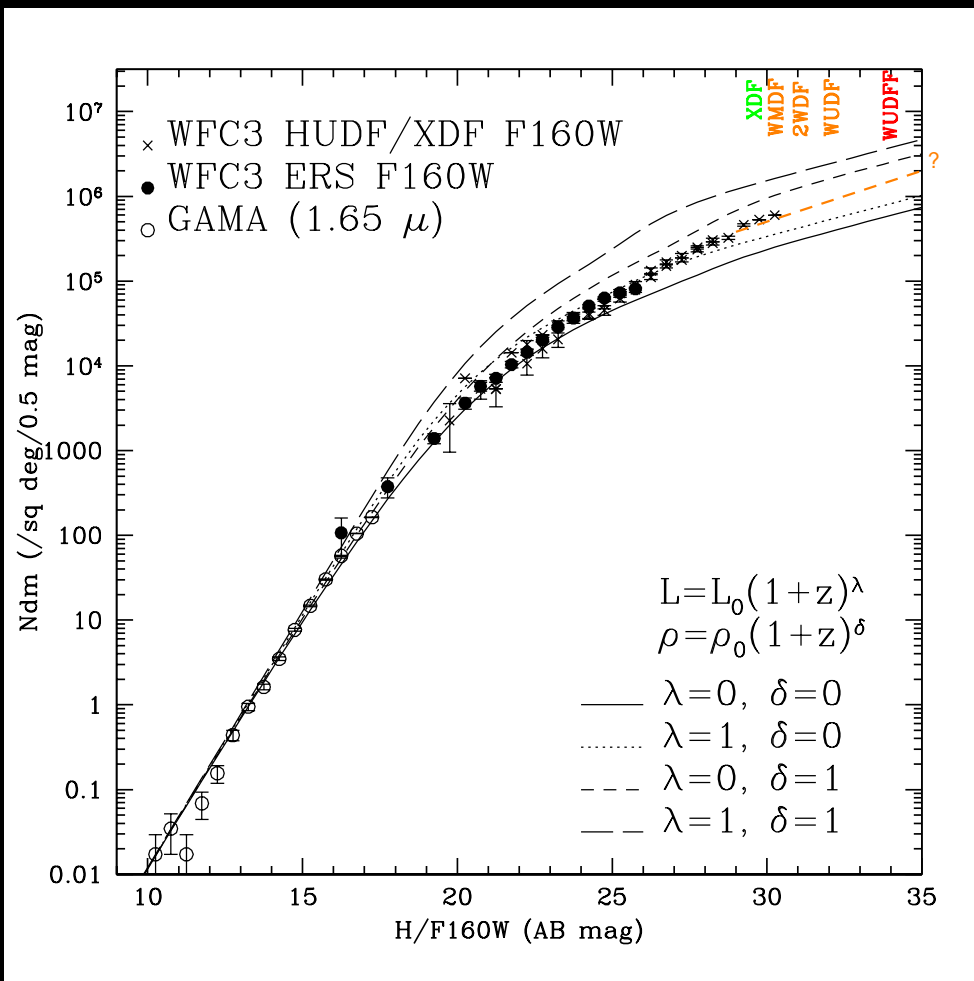
[RIGHT, TOP]: Lensing map for A2744 from Ebeling et al. (2014) [see updated models this Workshop].

[RIGHT BOTTOM]: *Position-dependent* completeness in a 3×3 MC-grid.

- Faint-end lensing sample *incompleteness* increases from  $\sim 10\text{--}40\%$  in the cluster outskirts/corners to  $\sim 50\text{--}65\%$  in cluster center [but see MUSE results!].
- Even bright-end of the cluster image is incomplete at the 5–50% level.



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



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

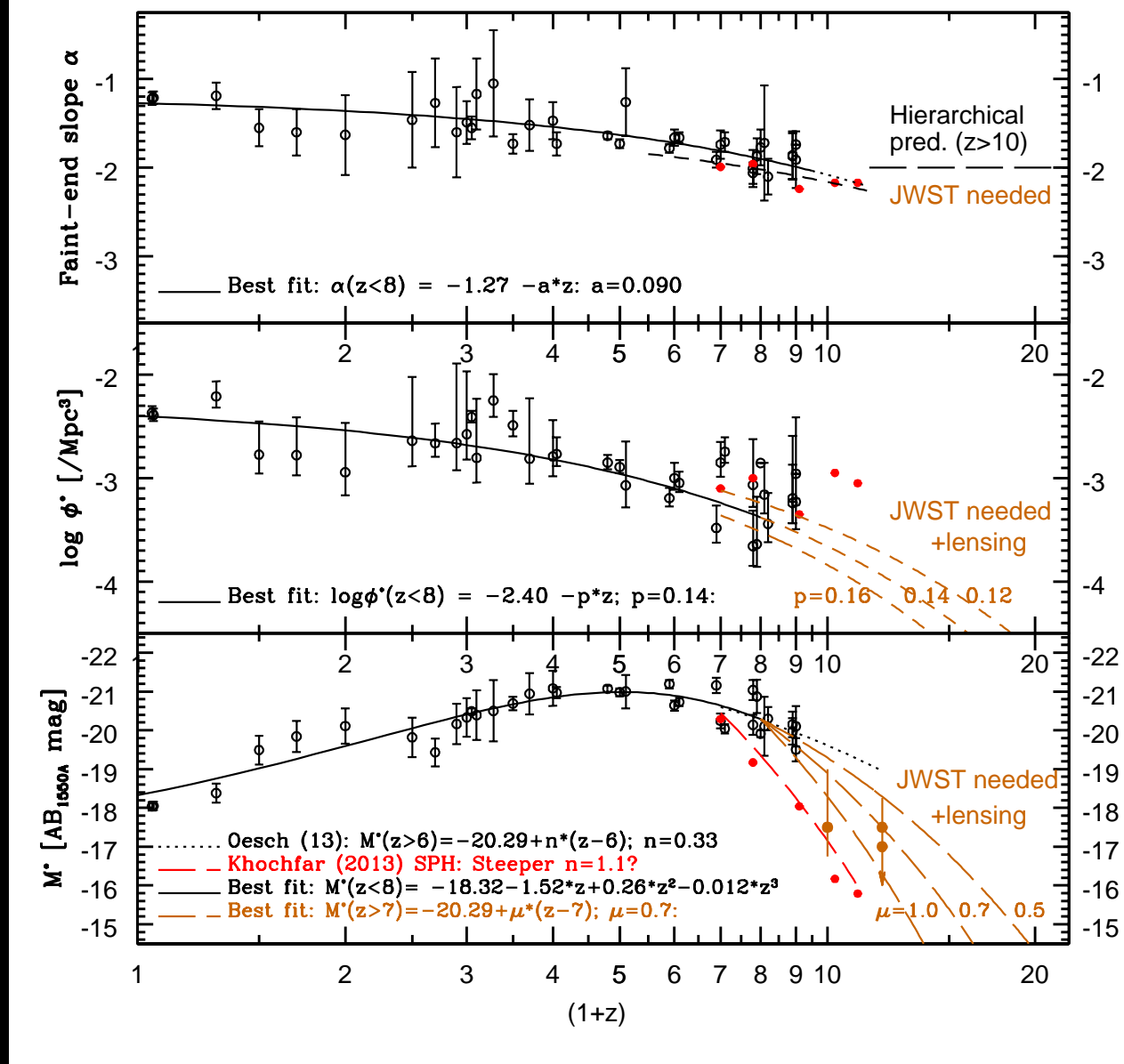
● Faint-end near-IR count-slope  $\simeq 0.16 \pm 0.02 \text{ dex/mag} \iff$

Faint-end LF-slope  $\alpha(z_{med} \sim 1.6) \simeq -1.4 \Rightarrow \text{reach } M_{AB} \simeq -14 \text{ mag.}$

● 800-hr WUDF can see  $AB \lesssim 32$  objects:  $M_{AB} \simeq -15$  (LMCs) at  $z \simeq 11$ !

● Lensing will change the landscape for JWST observing strategies (WUDFF).

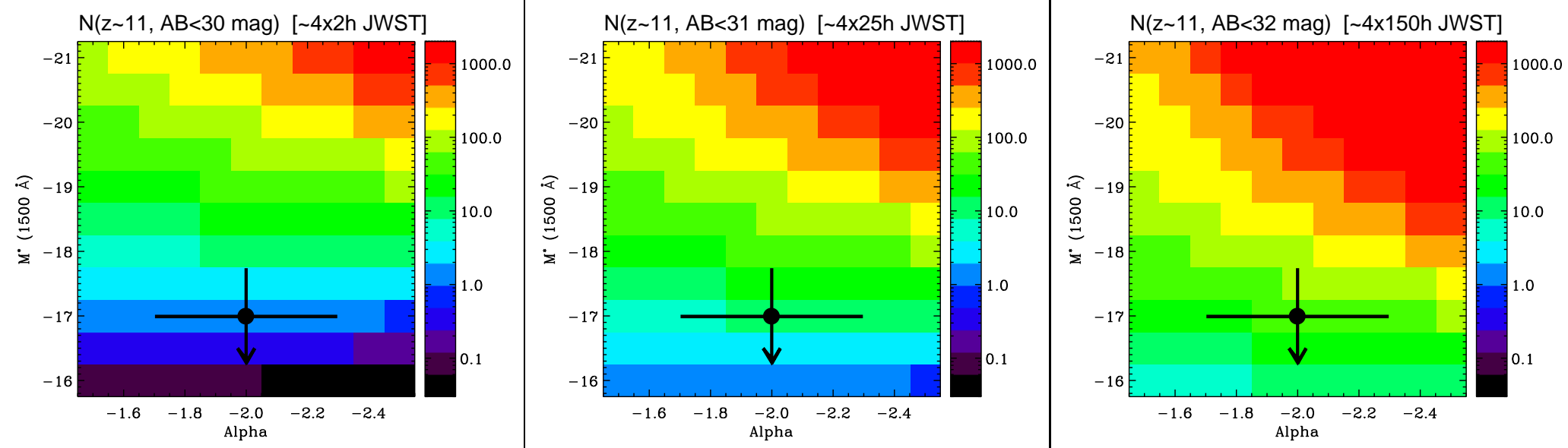




Evolution of Schechter UV-LF: faint-end LF-slope  $\alpha(z)$ ,  $\Phi^*(z)$  &  $M^*(z)$ :

- For JWST  $z \gtrsim 8$ , expect  $\alpha \lesssim -2.0$ ;  $\Phi^* \lesssim 10^{-3} \text{ (Mpc}^{-3}\text{)}$  (Bouwens<sup>+</sup> 14).
  - HUDF: Characteristic  $M^*$  may drop below  $-18$  or  $-17.5$  mag at  $z \gtrsim 10$ .
- $\Rightarrow$  Will have significant consequences for JWST survey strategy.



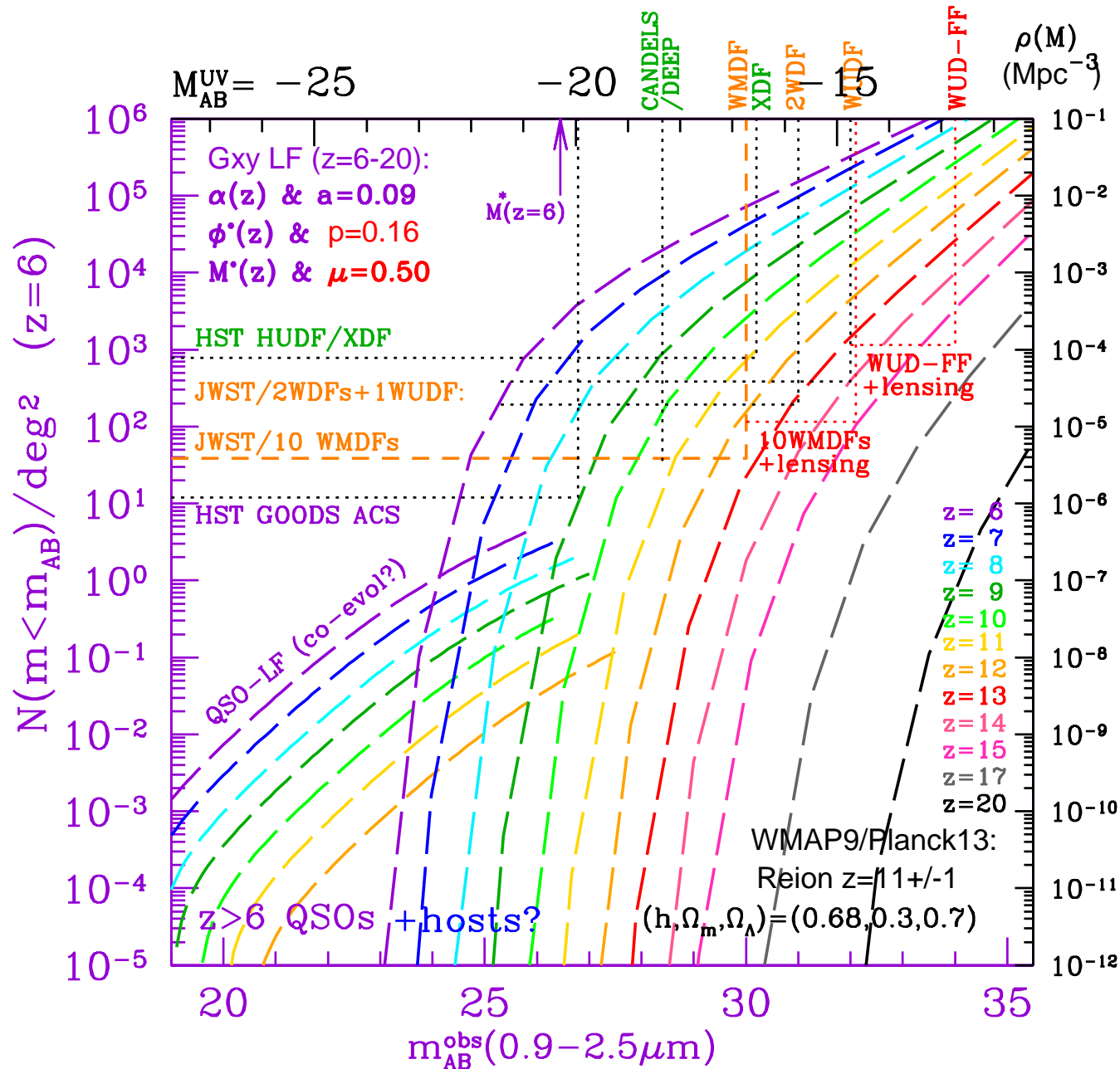


What do the 6 possible  $z \simeq 9$  and single  $z \gtrsim 10$  HUDF candidate mean?

Integrate Schechter LFs with  $\alpha(z)$ ,  $\Phi^*(z)$  and  $M^*(z)$ :  $\lesssim 45\%$  sky-coverage by  $AB \lesssim 30$  objects (Koekemoer<sup>+</sup>13). Cosmic Variance  $\gtrsim 30\%$ .

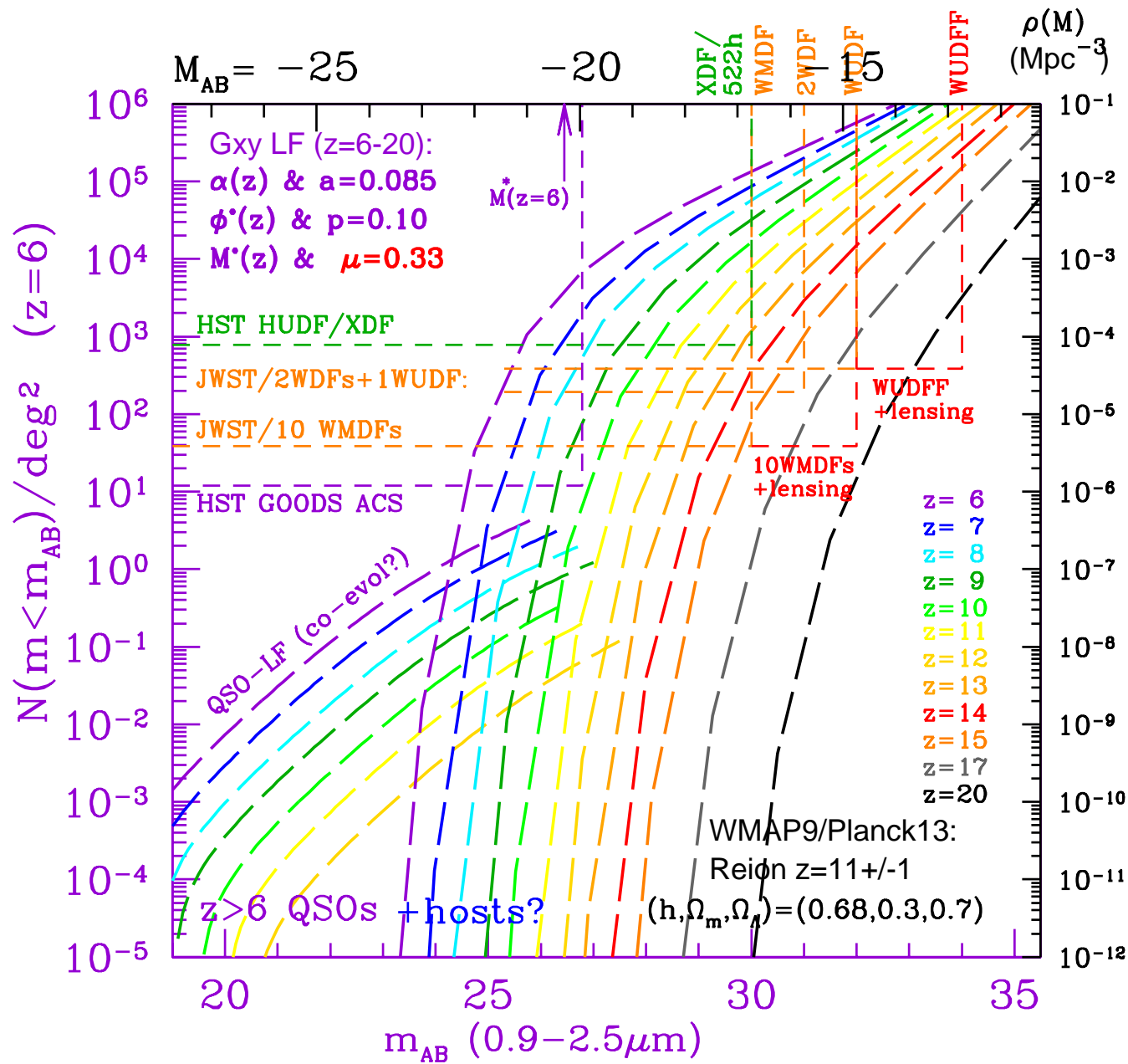
For any  $\alpha(z \gtrsim 9-10)$ , implies  $M^*(z \gtrsim 10) \gtrsim -17.5$  mag (fainter!), so plan:

- (1) [Left] Webb “Medium-Deep” Fields (**WMDF**) ( $10 \times 4 \times 2 \text{ h RAW}$ ): Expect few  $z \simeq 10-12$  objects to  $AB \lesssim 30$  mag, so plan lensing targets.
- (2) [Middle] Webb Deep Field (**WDF**) ( $4 \times 25 \text{ h 7-filt NIRCam GTO}$ ): Expect 8–25 objects at  $z \simeq 10-12$  to  $AB \lesssim 31$  mag.
- (3) [Right] Webb UltraDeep Field (**WUDF**) ( $4 \times 150 \text{ h; NIRCam DD?}$ ): Expect 30–90 objects to  $AB \lesssim 32$  mag, many more if lensing targets.



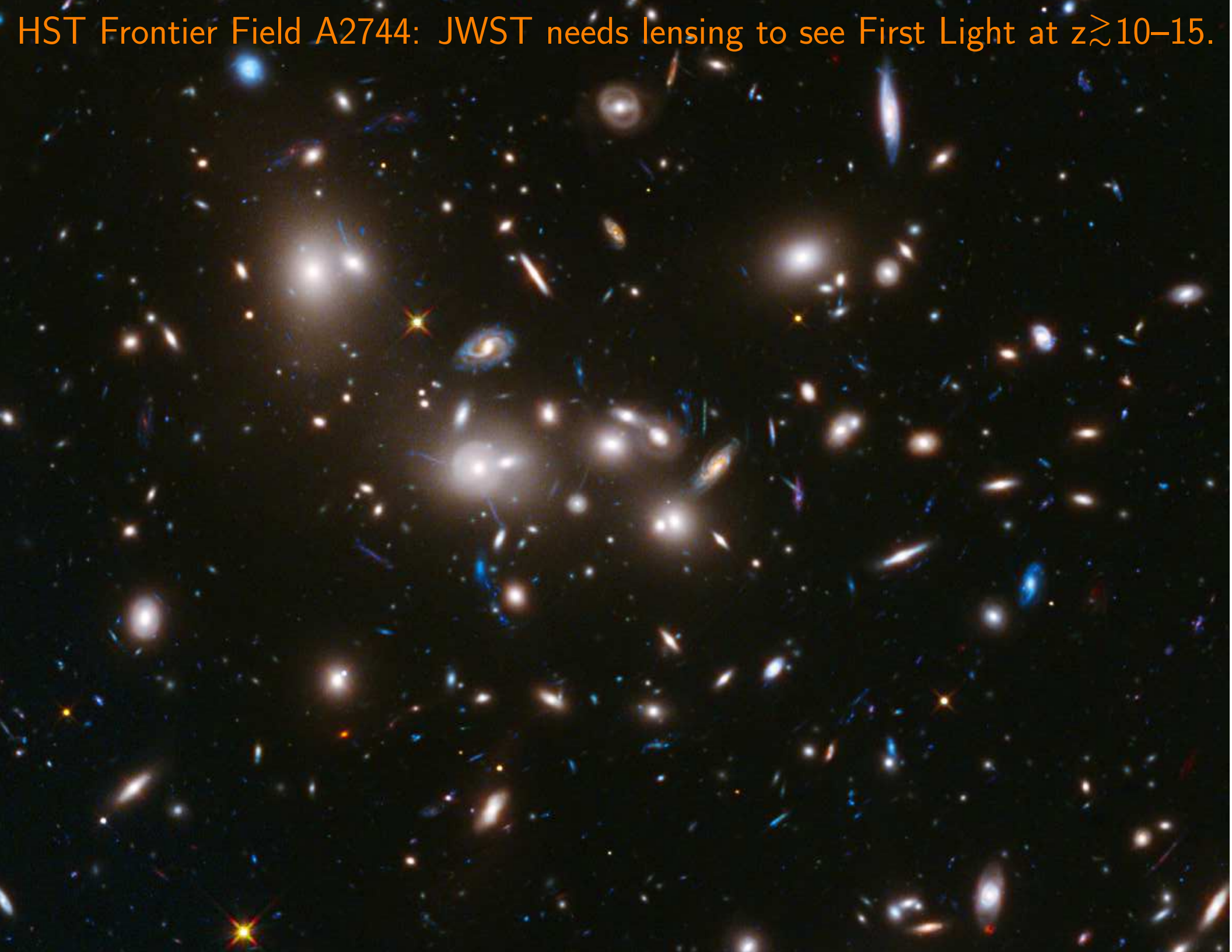
- Schechter LF ( $6 \lesssim z \lesssim 20$ ) with best-fit  $\alpha(z)$ ,  $\Phi^*(z)$ ,  $M^*(z)$  &  $\mu=0.50$ .  
 Area/Sensitivity for: HUDF/XDF, 10 WMDFs, 2 WDFs, & 1 WUDF.
- Will need lensing targets for WMDF-WUDFF to see  $z \simeq 12-15$  objects.





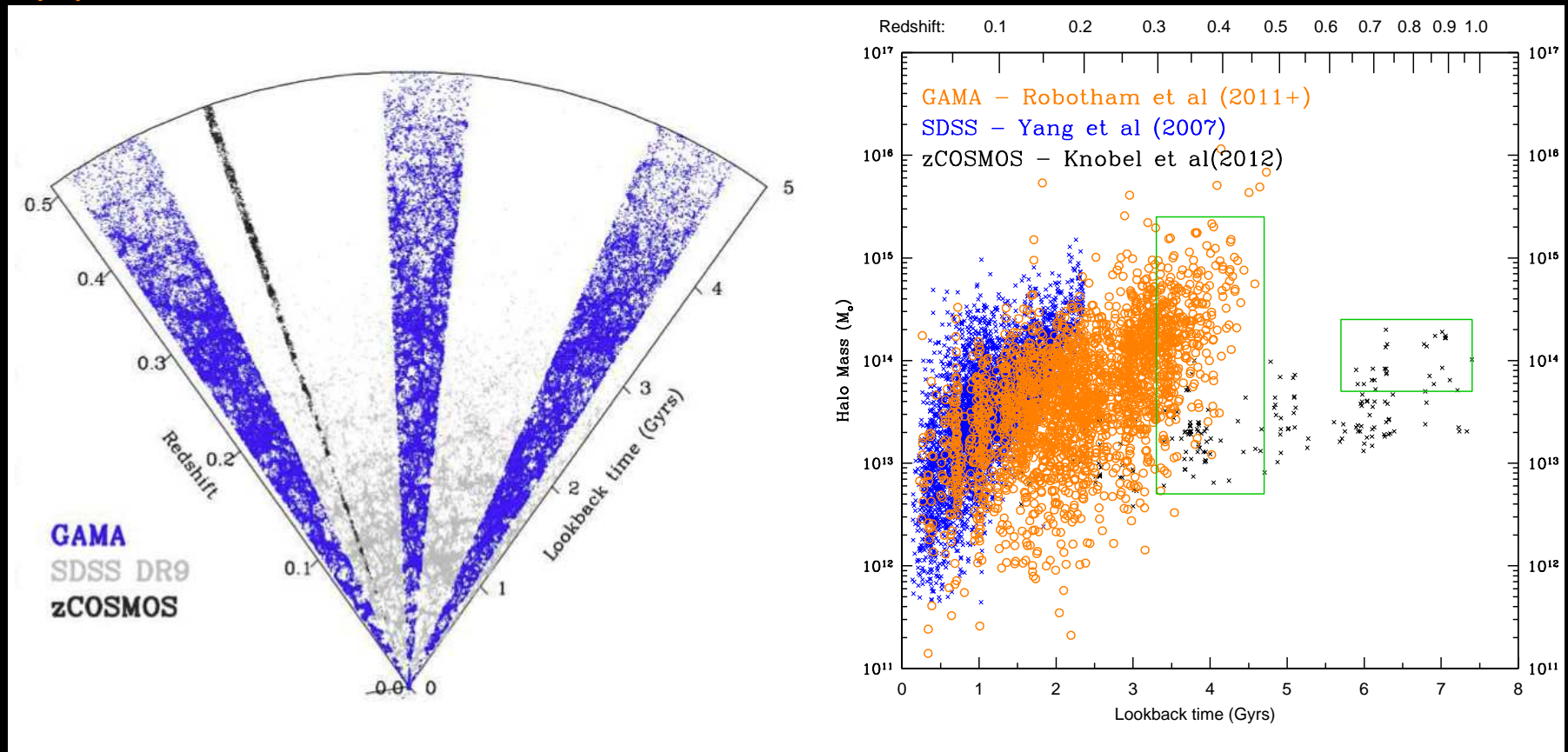
Same as p. 15, but optimistic  $M^*(z)$  drop:  $\mu=0.33$  (Oesch et al. 2013).

- If so, far more  $9 \lesssim z \lesssim 12$  objects expected in XDF, even though  $N(6 \lesssim z \lesssim 8)$  remains the same  $\iff M^*(z \simeq 11)$  fainter than  $-18 \pm 0.5$  mag?





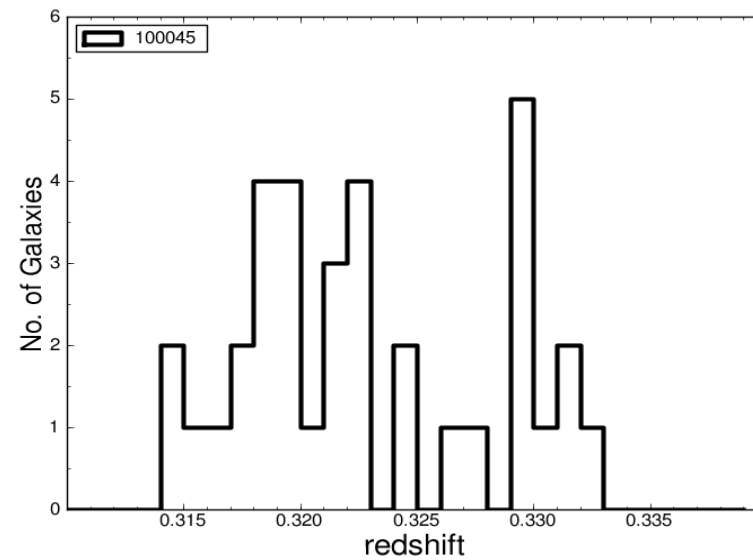
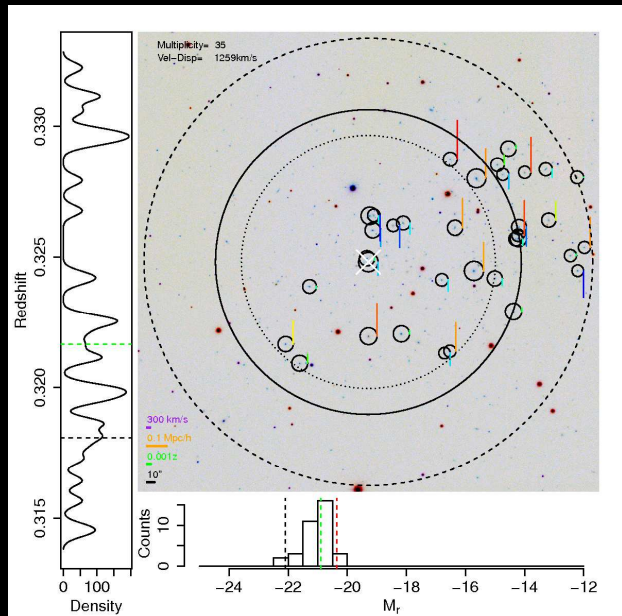
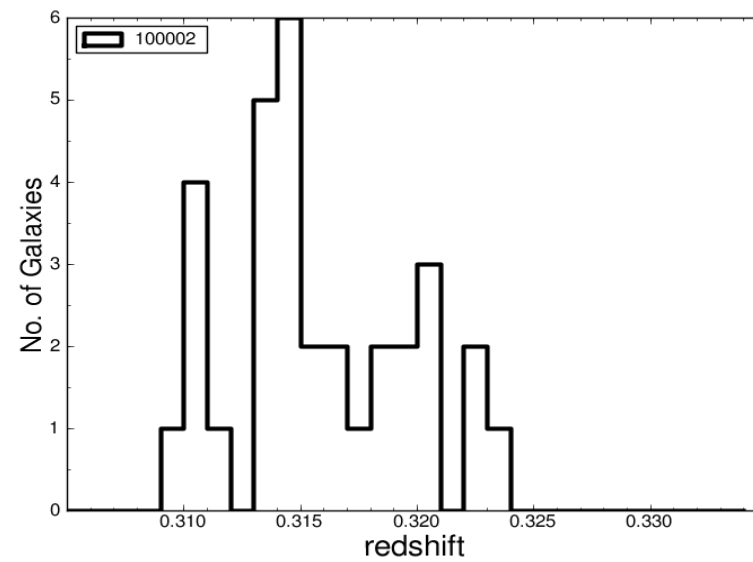
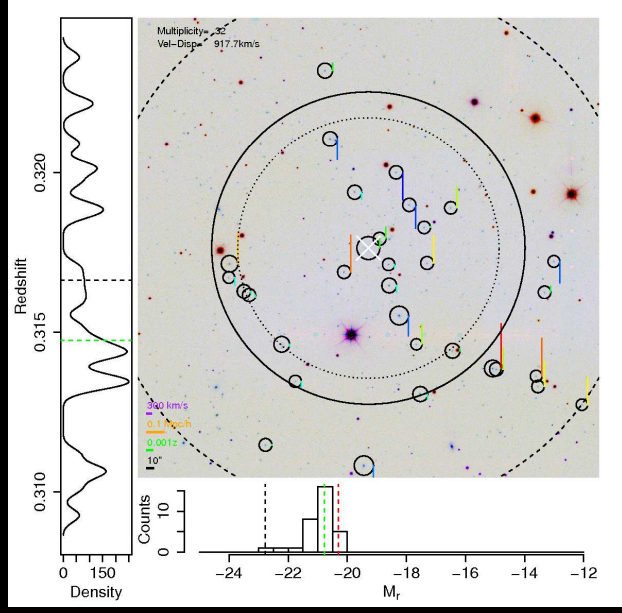
### (3) What are the best lensing targets for JWST to see First Light?



For JWST, use the best lenses in 2018: Rich clusters of high compactness!

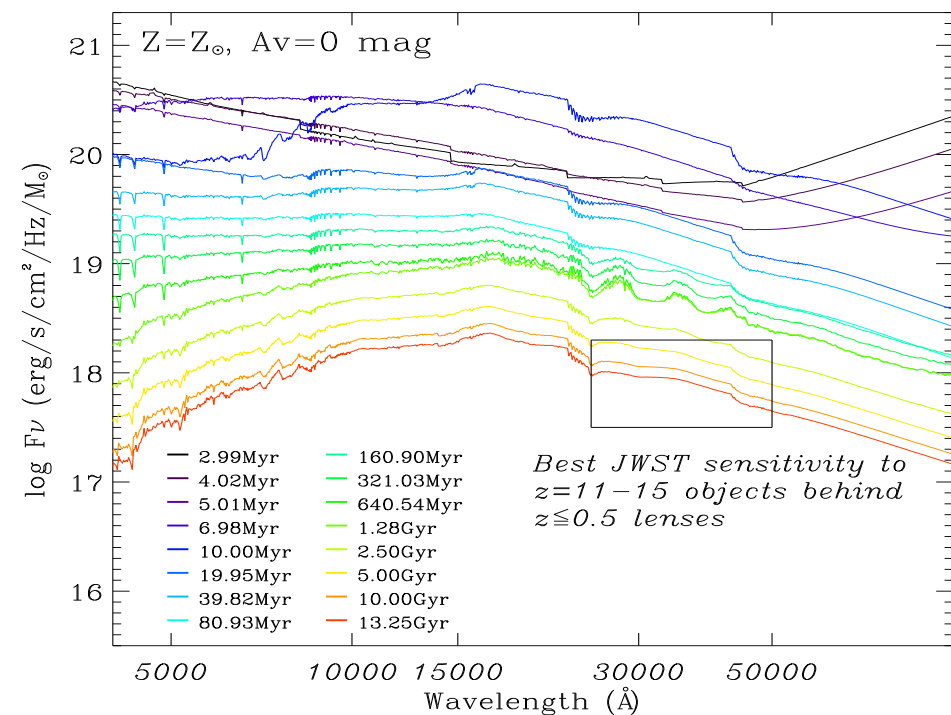
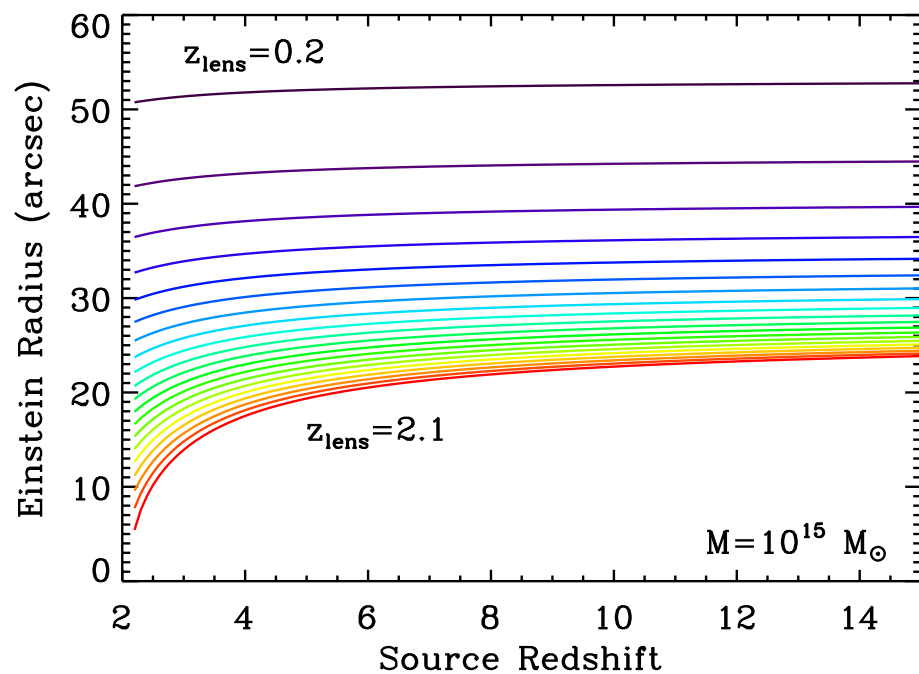
[Left] Redshift surveys: SDSS  $z \lesssim 0.25$  (Yang<sup>+</sup> 2007), GAMA  $z \lesssim 0.45$  (Robotham<sup>+</sup> 2011), and zCOSMOS  $z \lesssim 1.0$  (Knobel<sup>+</sup> 2012).

- GAMA: 22,000 groups  $z \lesssim 0.45$ ; 2400 with  $N_{spec} \gtrsim 5$  (Robotham<sup>+</sup> 11).
- $\lesssim 10\%$  of GAMA clusters compact for lensing (Konstantopoulos<sup>+</sup> 13).
- Need large sample to identify best lenses to find  $z \sim 6-15$  sources.



- [Left] GAMA clusters with secure AAT redshifts for  $R \lesssim 19.8$  AB-mag. Also show redshift probability and absolute magnitude ( $M_r$ ) distributions.
- [Right] Measured redshift distribution for two GAMA clusters.
- Will select our WMDF IDS targets on best-lensing compact clusters.

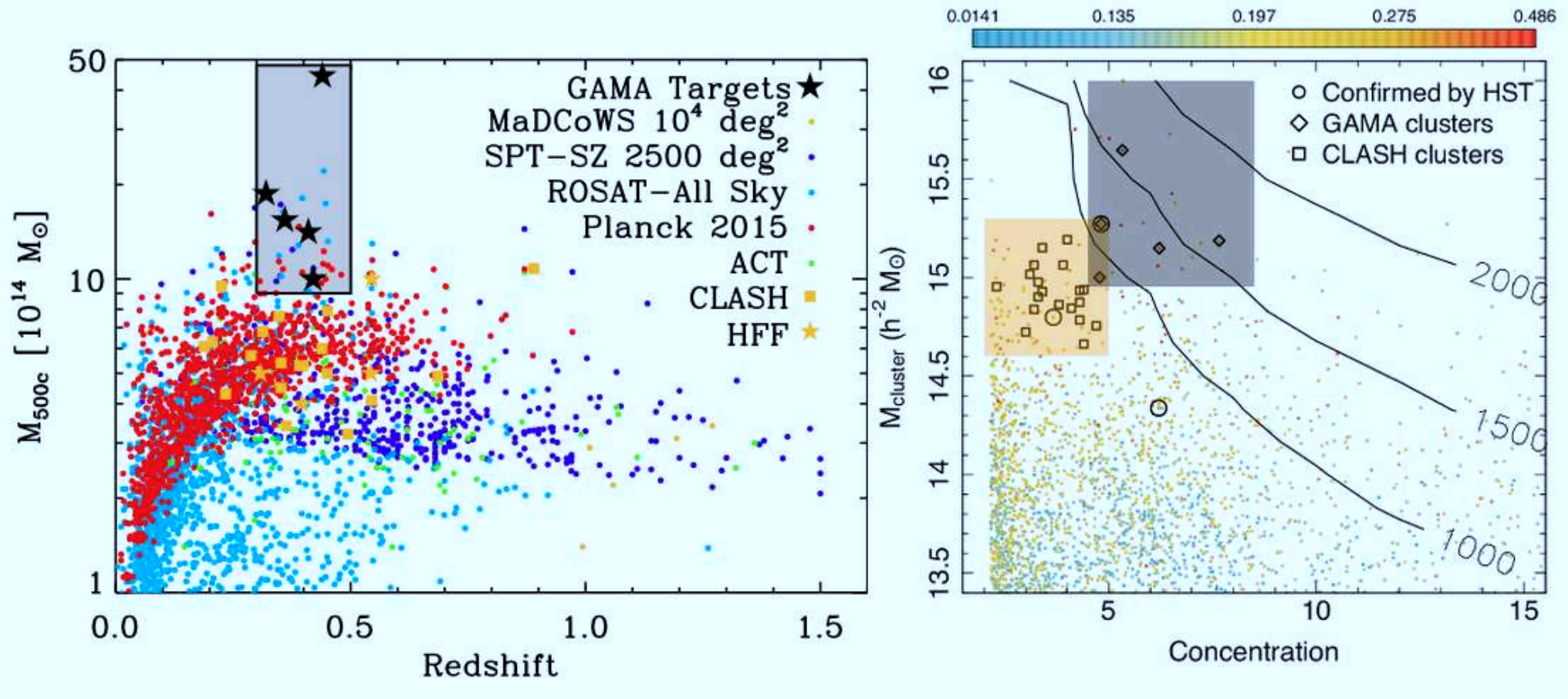




[LEFT] Must make sure Einstein angle at  $z \gtrsim 10$  doesn't overfill JWST FOV ( $2'3 \times 4'6$ ): use clusters at  $z \gtrsim 0.3$ !

[RIGHT] Must make sure JWST First Light sweet spot ( $\lambda \gtrsim 3.0 \mu\text{m}$ ) isn't ruined by K-correction of cluster galaxies+ICL: use clusters at  $z \lesssim 0.5$ !

- (This assumes 6–8 Gyr old stellar populations at  $z \simeq 0.3\text{--}0.5$ ).
- JWST sweet spot for First Light objects at  $z \gtrsim 10$  is  $\lambda \gtrsim 2.5\text{--}3.0 \mu\text{m}$ , where Zodiacal foreground is lowest (10 mag gain over ground!).



GAMA compact clusters compared to other cluster samples:

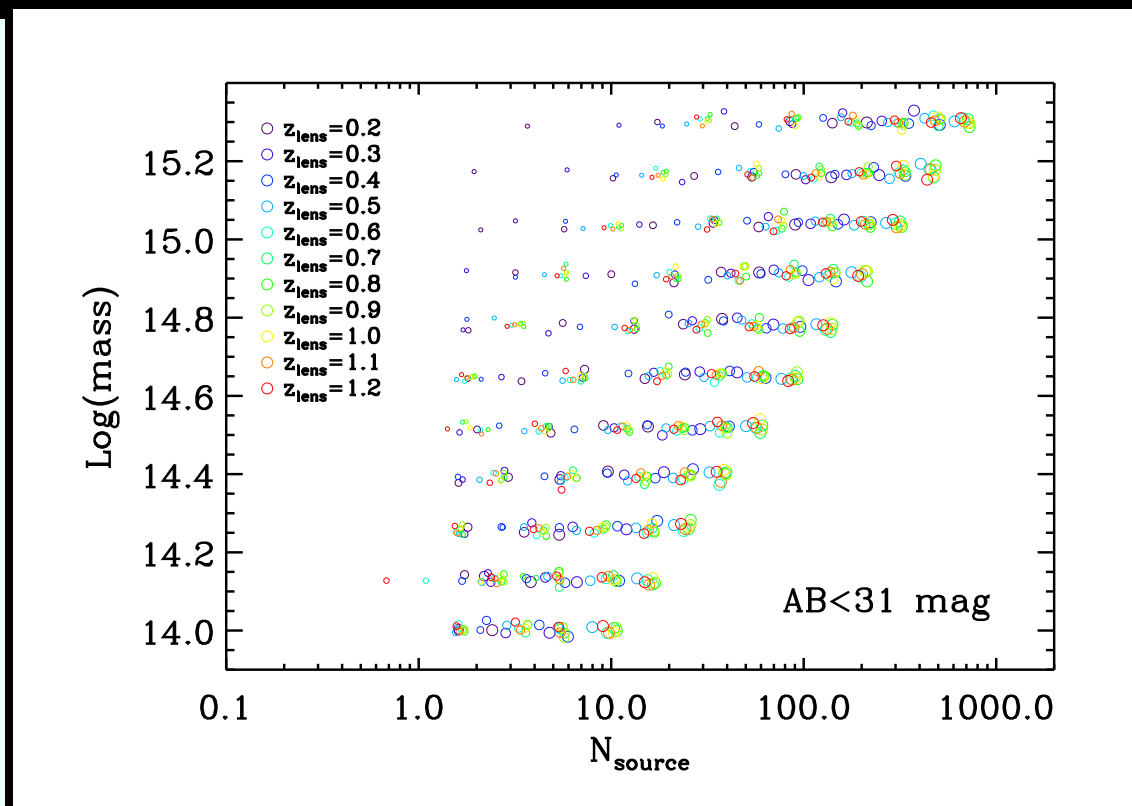
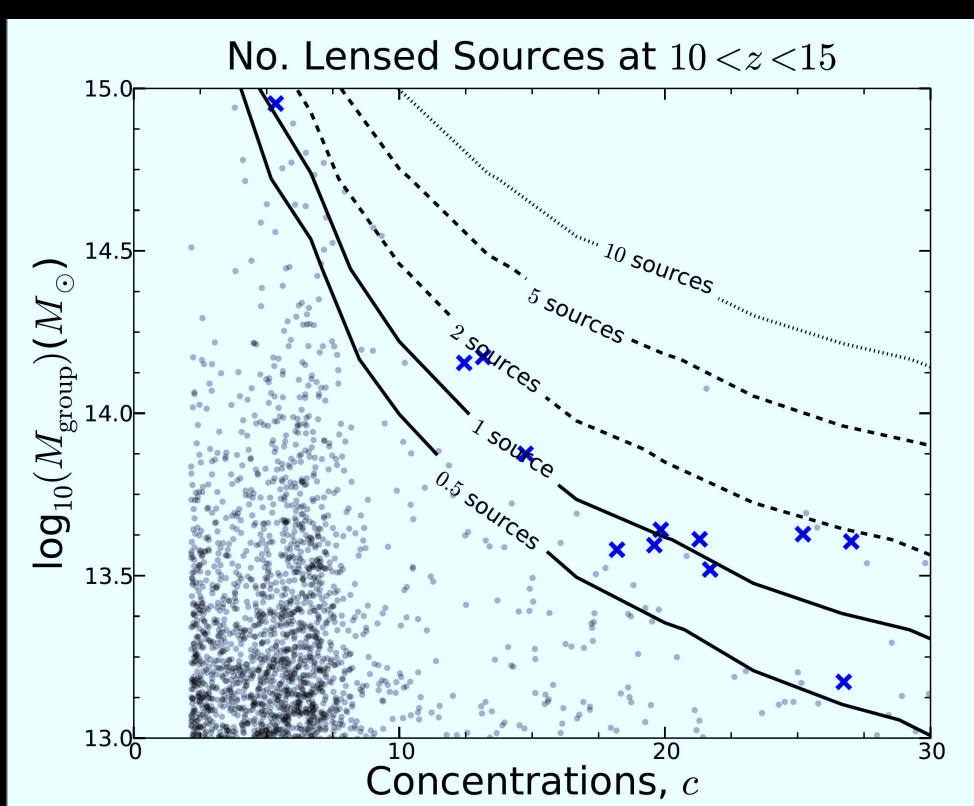
[LEFT] Best lensing GAMA clusters vs. ROSAT, Planck, SPT, MaDCoWS.

[RIGHT] Best lensing GAMA clusters vs. CLASH clusters.

(Contours: Number of lensed JWST sources at  $z \simeq 1-5$  to  $AB \lesssim 27$  mag).

- Resulting sweet spot for JWST lensing of First Light Objects ( $z \gtrsim 10$ ):  
Redshift:  $0.3 \lesssim z \lesssim 0.5$ ; Mass:  $10^{15} - 10^{15.6} M_{\odot}$ ; Concentration:  $4.5 \lesssim C \lesssim 8.5$
- GAMA clusters confirmed w/  $\gtrsim 24$   $z_{\text{spec}}$ 's, removing chance projections.





GAMA group/cluster mass vs. Concentration, fitted with NFW DM-halo profiles (Barone-Nugent<sup>+</sup> 15).

[LEFT] = Nr of expected lensed sources at  $10 \lesssim z \lesssim 15$  ( $AB \lesssim 30$  mag).

[RIGHT] = Nr of expected lensed sources at  $6 \lesssim z \lesssim 15$  ( $AB \lesssim 31$  mag).

- 10 WMDFs on best  $10^{15} M_{\odot}$  clusters:  $\sim 100$   $z \simeq 6-15$  sources ( $AB \lesssim 30$ ).
- WDF ( $AB \lesssim 31$  mag) will get  $\sim 250$  lensed sources at  $z \simeq 6-15$ .

WUDFF ( $AB \lesssim 32$ ) on best cluster yields  $\sim 800$  lensed sources at  $6 \lesssim z \lesssim 15$ !



Conclusion: JWST First Light strategy must consider three aspects:

(1) The rapid drop in the LF  $\Phi^*(z)$  and/or  $M^*(z)$  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  $\Rightarrow$   
Need multi- $\lambda$  deblending algorithms & object subtraction (e.g., wavelets).

(3) Gravitational Lensing: JWST will need to find most First Light objects  
at  $z \gtrsim 10$ –15 through the best lensing compact clusters.

- Need multi- $\lambda$  object-finder that works on sloped backgrounds.
- If  $M^*(z \gtrsim 10) \gtrsim -18$  or  $\Phi^* \lesssim 10^{-3.5}$ , must image, (subtract,) & model the entire gravitational foreground. Be mindful of extra (rogue-path) straylight.



## (4) 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.

Management replan in 2010-2011. No technical showstoppers thus far:

- More than 98% 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.

- To see the most First Light, JWST must cover the best lensing clusters!

- Need to consider brightness of — and low-level gradients in — IntraCluster Light (ICL) *and* low-level out-of-field (rogue-path) straylight.

(4) JWST will have a major impact on astrophysics this decade:

- IR sequel to HST after 2018: Training the next generation researchers.

- Your JWST proposals are due  $\lesssim 3$  years from today!

# SPARE CHARTS

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- 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).

# 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)



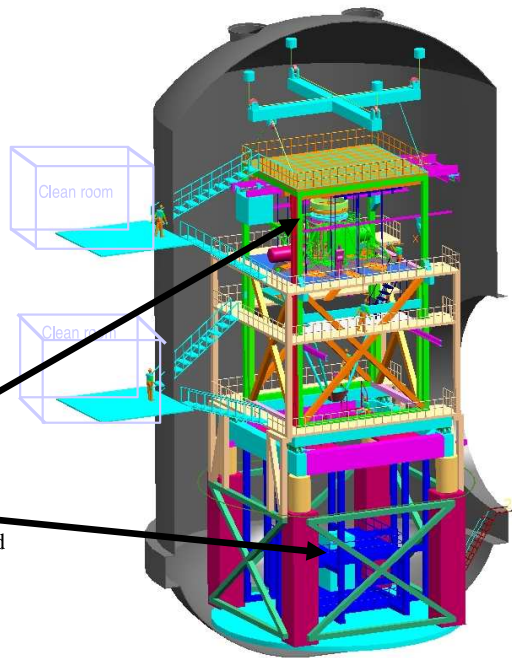
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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)

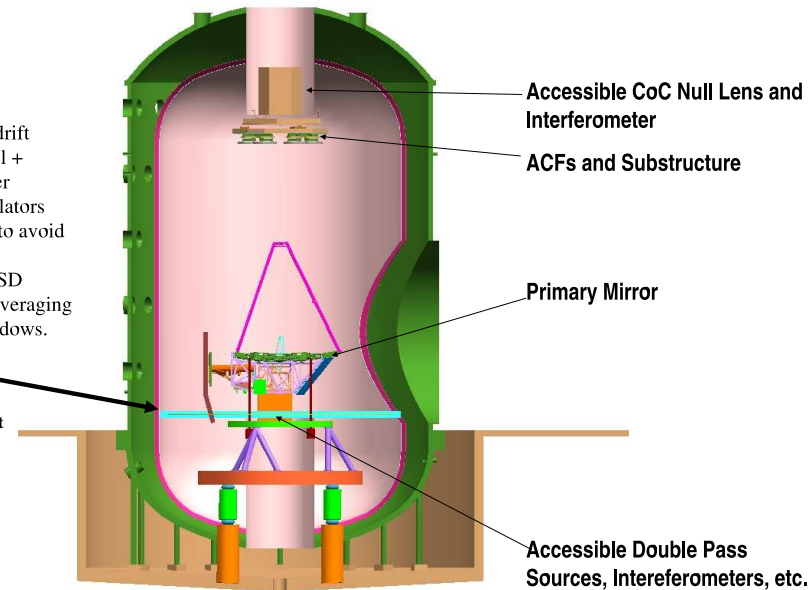


No Metrology Tower and Associated Cooling H/W.  
External Metrology

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.



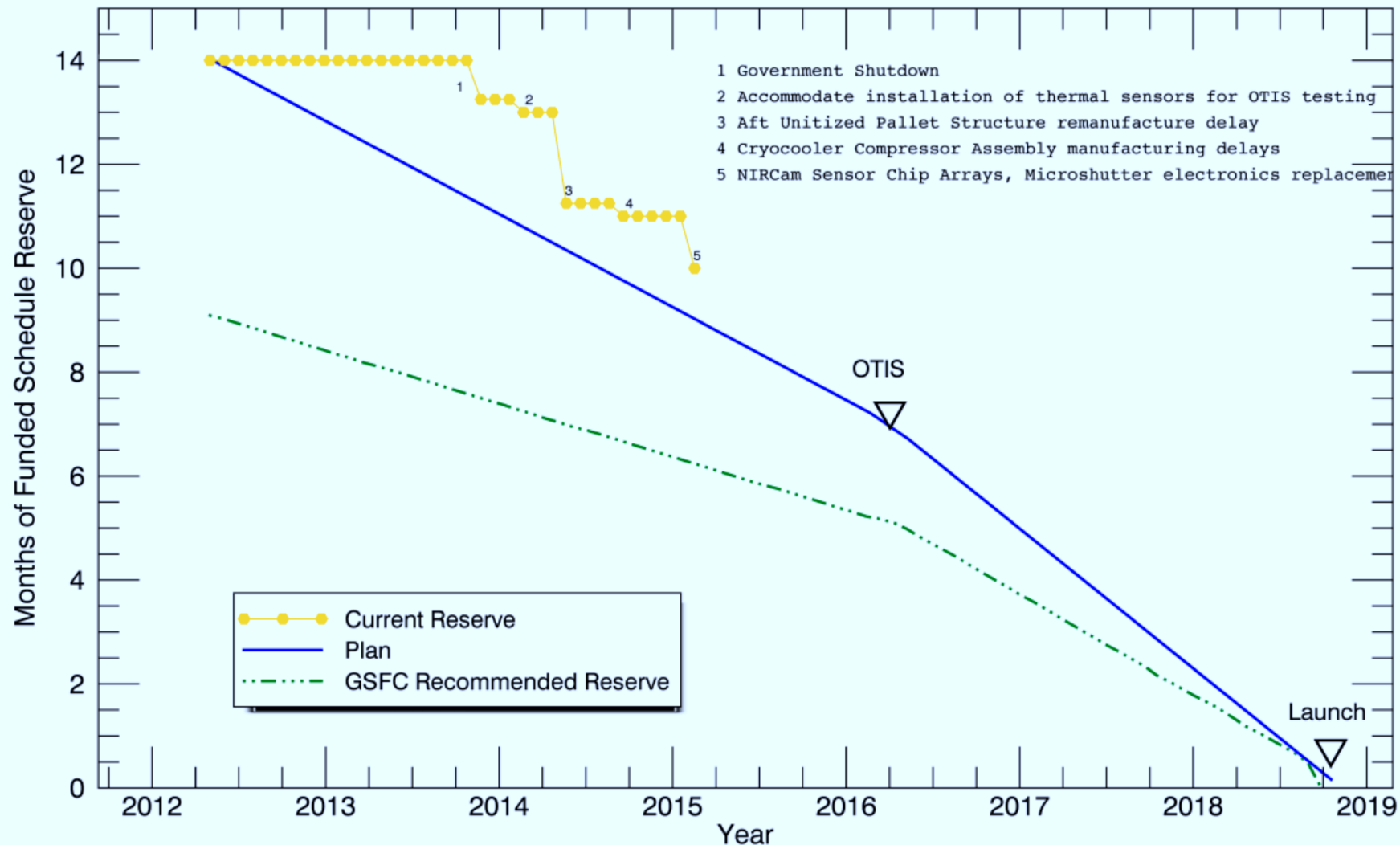
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim 2003$ : 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.

# Project Funded Schedule Reserve



Keys to stay on schedule: 1) Sufficient Project contingency ( $\gtrsim 25\%$  of total).  
2) Well replanned and managed Project (starting late summer 2011).



# Fiscal Year 2015 JWST HQ Milestones

Month	Milestone	FY2014 Deferral	Comment
Oct-14	1 Secondary Mirror Structure dynamics Test Readiness Review		Completed 11/20/14
	2 ISIM Cryo-vacuum Test #2 complete		Completed 9/23/14
	3 Flight and flight spare MIRI Cryocooler Electronics Assembly delivered to JPL		Completed 10/6/14
	4 Johnson Space Center Optical Ground Support Equipment integration complete		Completed 10/10/14
Nov-14	5 Install Engineering Development Unit Secondary Mirror Assembly onto Pathfinder		Completed 10/10/14
	6 Johnson Space Center (JSC) Chamber A commissioning test start		Completed 10/18/14
	7 Data Management Subsystem software Build 3 delivery		Completed 9/30/14
Dec-14	8 Demonstration model Mid-Boom Assembly thermal vacuum test start		Completed 11/19/14
	9 Transfer Telescope Pathfinder structure ownership to GSFC		Completed 10/31/14
	10 Flight Operations Subsystem Build 1 System Design Review		Completed 11/20/14
	11 Proposal Planning Subsystem Build 10 delivery		Completed 11/3/14
	12 Deliver flight Cold Head Assembly to ISIM for Cryo-vacuum test #3		Completed 11/10/14
Jan-15	13 Fine Guidance Sensor focal plane arrays ready for integration		Completed 12/9/14
	14 Deliver Spacecraft Simulator handbook, Rev B (flight software build 1) to GSFC		Completed 12/11/14
	15 JSC Chamber A Commissioning complete		Completed 11/27/14
Feb-15	16 Start formal Engineering Model Test Bed electrical integration		Completed 11/13/14
	17 Sunshield Mid-boom Manufacturing Readiness Review		Completed 2/9/15
	18 Sunshield Flight Layer 3 delivered to Northrop-Grumman (NGAS)		Completed 2/16/15
	19 Deliver Telescope Pathfinder Structure to JSC		Completed 2/4/15
	20 Observatory Operations Scripts Subsystem Build 4 delivery		Completed 1/16/15
Mar-15	21 Wavefront Sensing and Control Software Build 4 delivery		Completed 12/30/14
	22 Qualification Sunshield Membrane Retention Device thermal vacuum test start		Completed 3/12/15
	23 Deliver Cryocooler Jitter Attenuator Assembly to Optical Telescope Element		Delayed to April, ground support equipment issue
	24 NGAS Acceptance of Spacecraft propellant tank		Delayed to June due to test unit welding issue, no schedule impact
	25 Near Infrared Instrument Detector changeouts complete		Completed 4/3/2014
Apr-15	26 Start acceptance testing of flight Cryocooler Assembly and Electronics		
	27 Flight Observatory Deployment Tower Assembly complete		Completed 3/12/15
	28 ISIM Vibration Testing complete		
May-15	29 Start Optical Ground Support Equipment test #1 at JSC		
	30 Flight Cryocooler Compressor Assembly to JPL for Acceptance Test #3		
	Dual Thruster Module Test Readiness Review		Milestone deleted, due to change in thruster design, new milestone in June (#36).
	31 Spacecraft Flight Software Build 2.2 Test Readiness Review		
	32 Sunshield Forward Cover Assembly shipped to NGAS		Moved to July, reprioritizing work for efficiencies at Nexolve
Jun-15	33 Deliver Flight Aft Optics System to Telescope Pathfinder		
	34 Data Management Subsystem Build 4 delivery		
	35 Attitude Control System test set delivery to Observatory Integration and Test		Completed 2/6/15
	36 Propellant Mid-Course Correction testing complete		(modified milestone to include testing post build of hardware)
	37 Delivery of new Vibration Test System to GSFC		
Jul-15	38 ISIM Acoustic testing complete		
	39 Proposal Planning Subsystem Build 11		
	40 Thruster Module Test Readiness Review		Completed 2/23/15
Aug-15	41 Flight spare cryo-cooler assembly to JPL for Acceptance Test #4		
	42 Aft Deployable ISIM Radiator build complete		
	43 ISIM Electro-Magnetic testing complete		
Sep-15	44 Deliver Spacecraft Side Equipment Panels to Observatory integration and testing		
	45 Deliver Reaction Wheel Assemblies to Observatory integration & testing		
	46 Start ISIM Cryo-vacuum Test #3		
Sep-15	47 Start Optical Ground Support Equipment Test #2 at JSC		
	48 Deliver Communications Antenna Bi-Axial Gimbal Assembly to Observatory integration and testing		

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

# 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
FY2011	21	21	6	3	0
FY2012	37	34	16	2	3
FY2013	41	38	20	5	3
FY2014 ❖	36	23	10	8	11
FY2015	48	25	16	5*	0

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

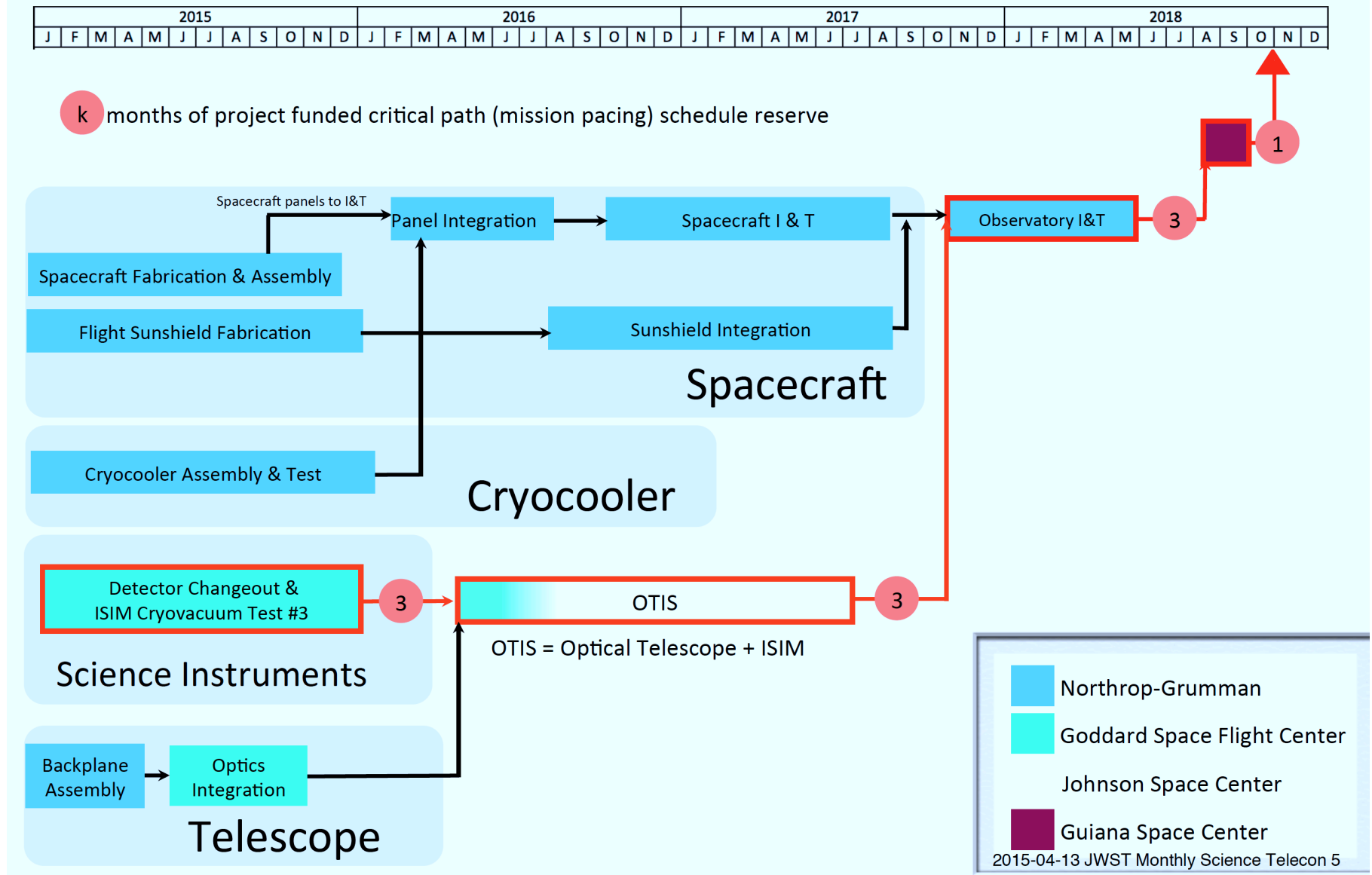
❖ Milestone accounting in FY2014 was complicated by the government shutdown and multicomponent milestones

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

FY15: 4/5 of the “Lates” not on critical path, causing no launch delay.



# Simplified Schedule



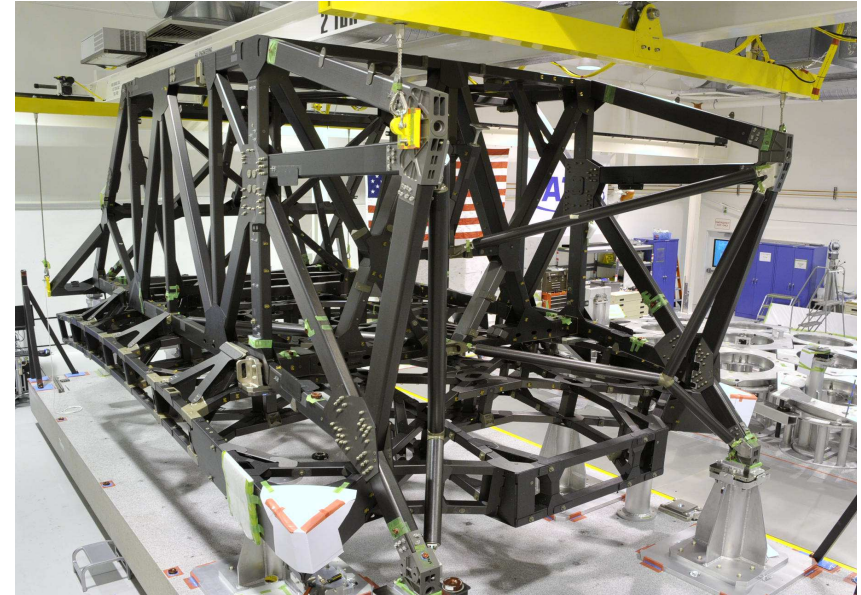
Path forward to Launch (in Oct. 2018): 10 months schedule reserve.  
 Instruments+detectors & Optical Telescope Element remain on critical path.



# Backplane Support Frame, Center Section, & Wings



- Center Section is complete
- Wings and cryo cycling is complete
- BSF assembly is complete
- Integration of the BSF to Center Section Complete
  - Cryo Cycling at MSFC XRCF complete



BSF and Center Section



BSF/Center Section coming out of

Flight back-plane ready to receive mirrors, starting in Fall 2014.



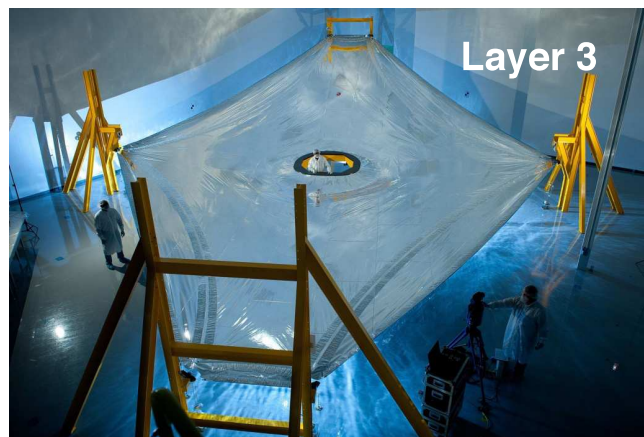
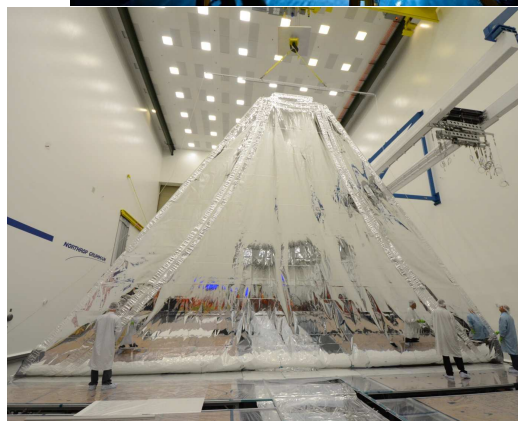


# Sunshield Template Membrane Work Completed

**Templates Verify Design/Manufacturing Prior to Flight Build**

- All Template Layers Completed
- Preparing for flight article manufacturing
- First two Flight Manufacturing Readiness Reviews Completed
- Membrane pull out test complete

Stringing Operations



Template  
Layers 3-5



Hole Tool Operations

Flight sunshield to be completed & tested in 2015 at Northrop (CA).



# Telescope Assembly Ground Support Equipment



Ambient Optical Alignment Stand

PMD  
HIVE CROSS & SONS  
CHARTERS & SONS  
JPW



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



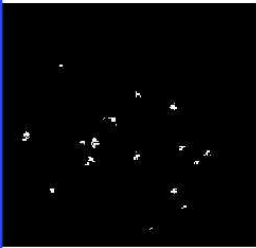
March 2012 NAC  
Science Meeting



Landing a mirror onto  
backplane simulator

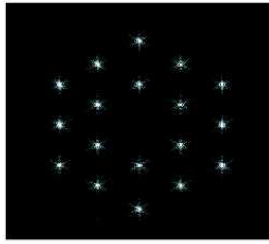


*First light  
NIRCam*



1.  
Segment  
Image  
Capture

After Step 1



Initial Capture

18 individual 1.6-m diameter aberrated  
sub-telescope images  
PM segments: < 1 mm, < 2 arcmin tilt  
SM: < 3 mm, < 5 arcmin tilt

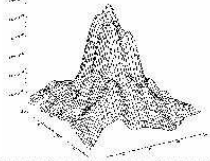
Final Condition

PM segments:  
< 100  $\mu\text{m}$ ,  
< 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  $\mu\text{m}$  (rms)

3. Coarse Phasing - Fine  
Guiding (PMSA piston)

After Step 3

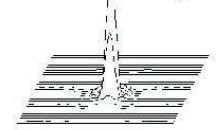


WFE: < 250  $\mu\text{m}$  rms

WFE < 1  $\mu\text{m}$  (rms)

4. Fine Phasing

After Step 4



WFE: < 5  $\mu\text{m}$  (rms)

WFE < 110 nm (rms)

5. Image-Based  
Wavefront Monitoring

After Step 5

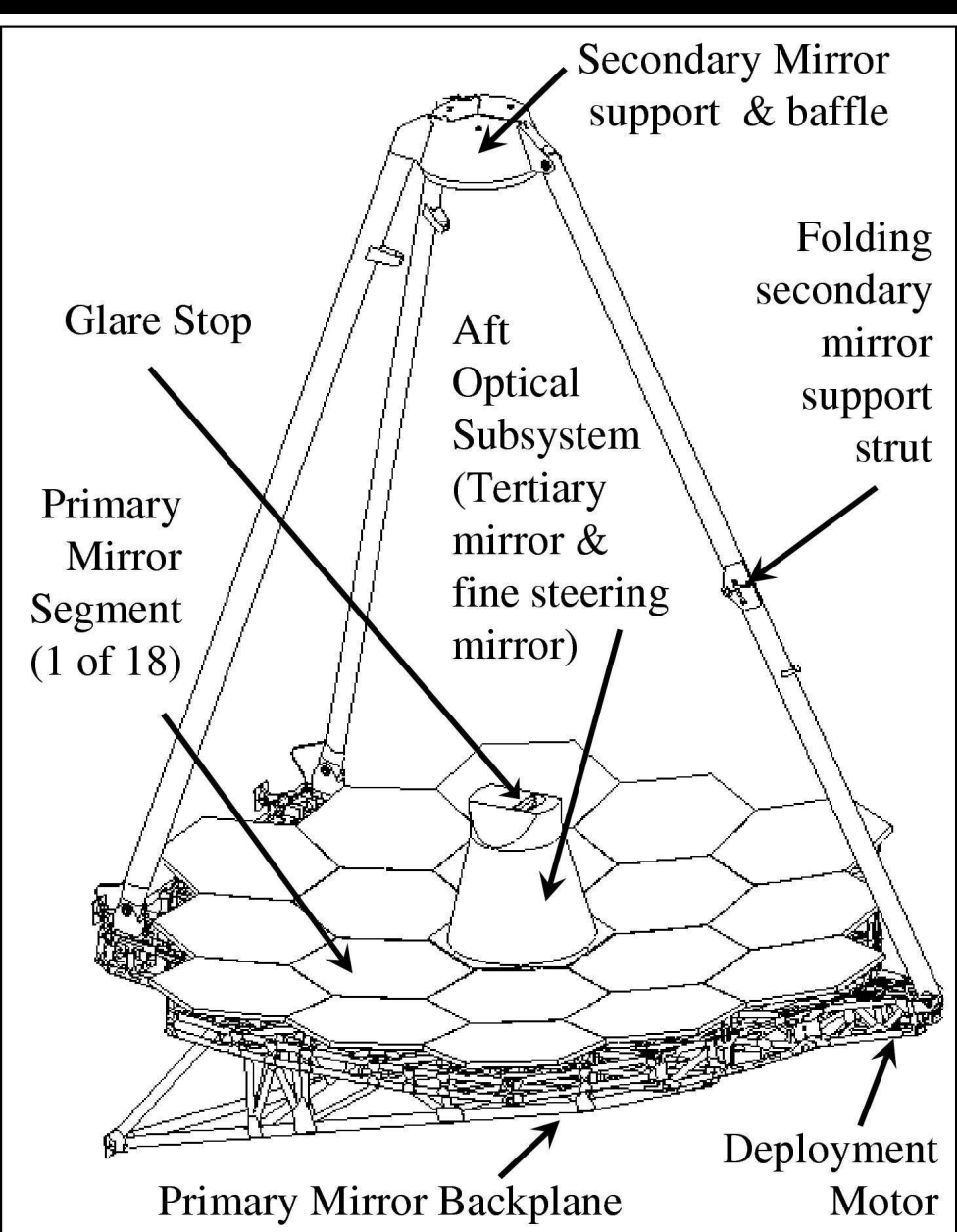


WFE: < 150 nm (rms)

WFE < 110 nm (rms)

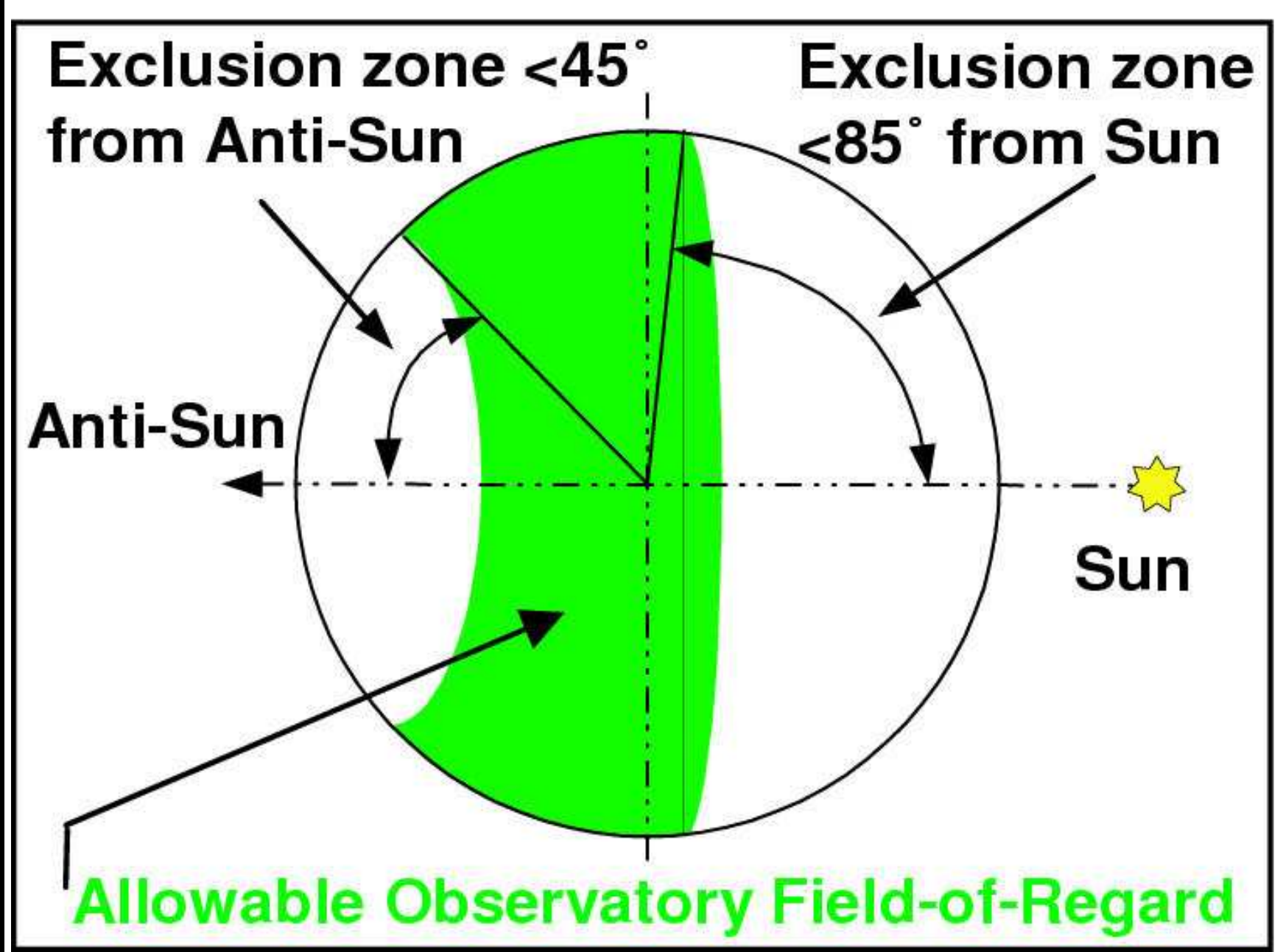
JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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  $2.0 \mu\text{m}$  images.

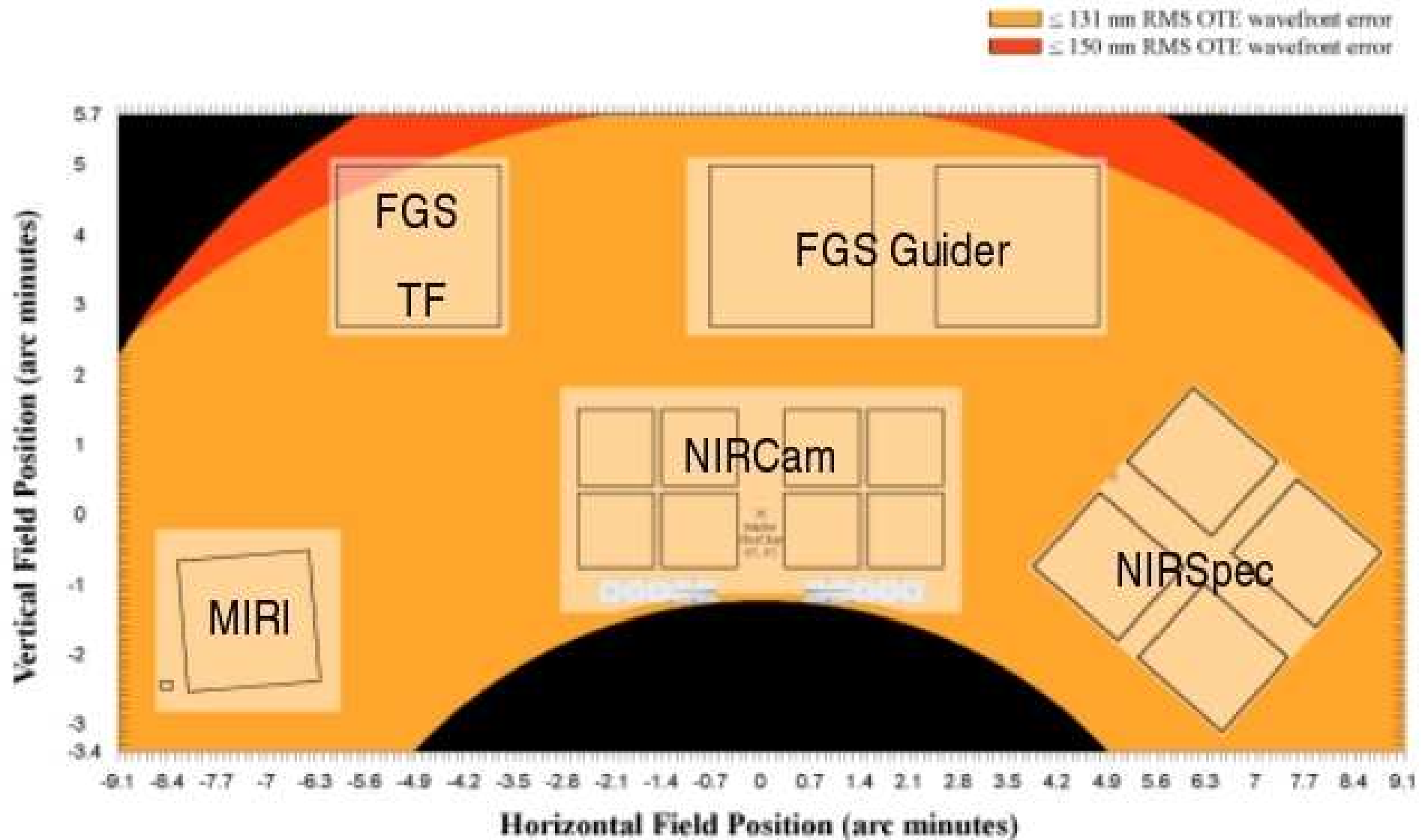




JWST can observe North/South Ecliptic pole targets continuously:

- 1000-hr JWST projects swap back/forth between NEP/SEP targets.
- They will rely a lot on Rockwell Collins' (Heidelberg) reaction wheels.

- (3c) What instruments will JWST have?



All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations*.



Centaurus A  
NGC 5128  
*HST* WFC3/UVIS

F225W+F336W+F438W

F487N H $\beta$

F502N [O III]

F547M  $\gamma$

F657N H $\alpha$ + [N II]

F673N [S II]

F814W I

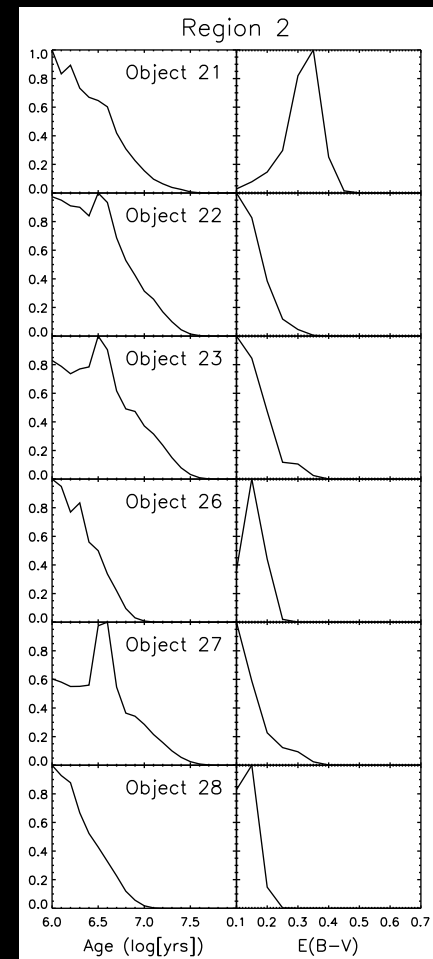
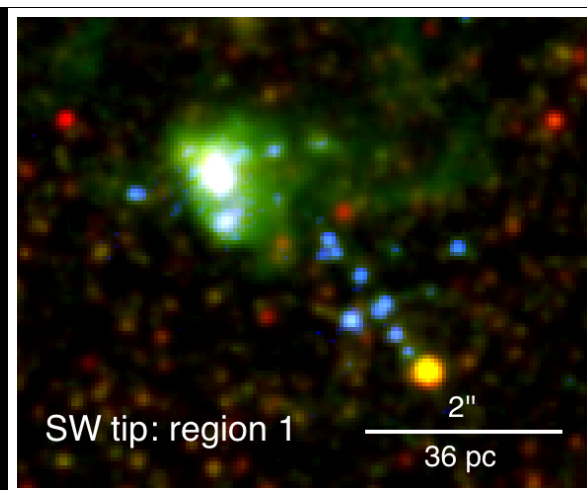
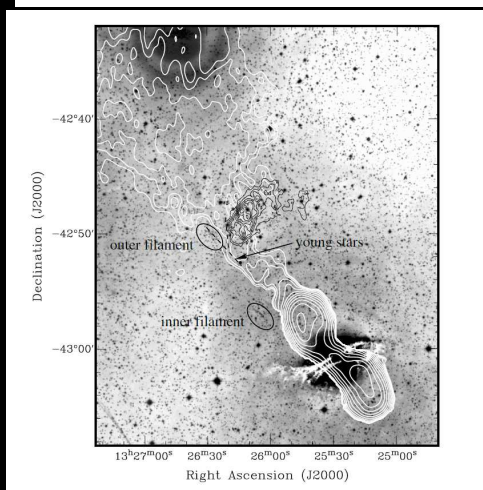
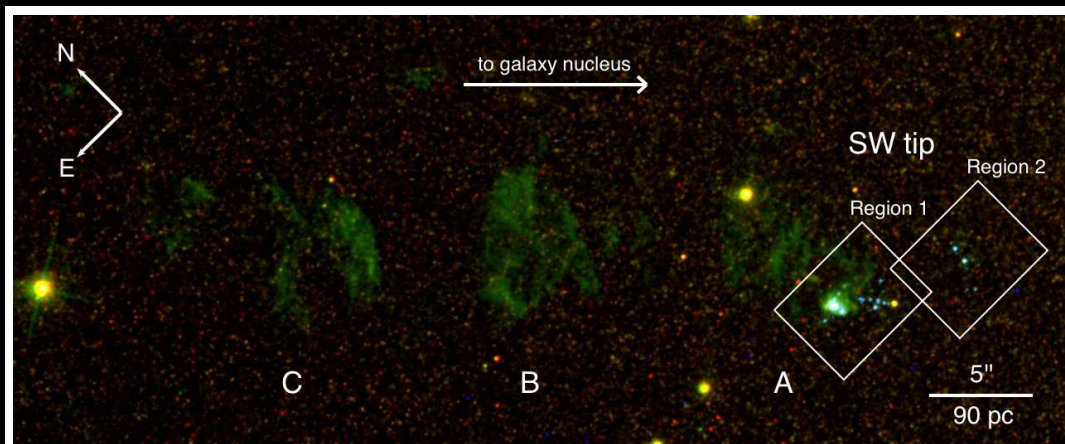
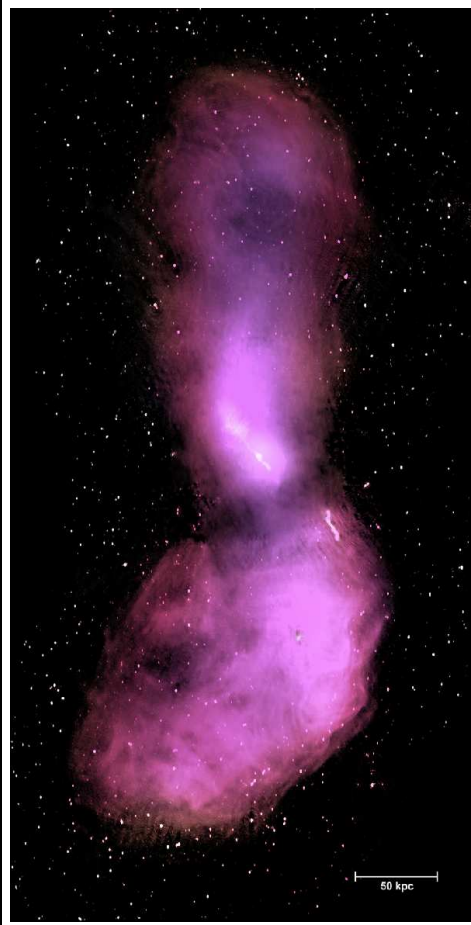
3000 light-years

1400 parsecs

56''





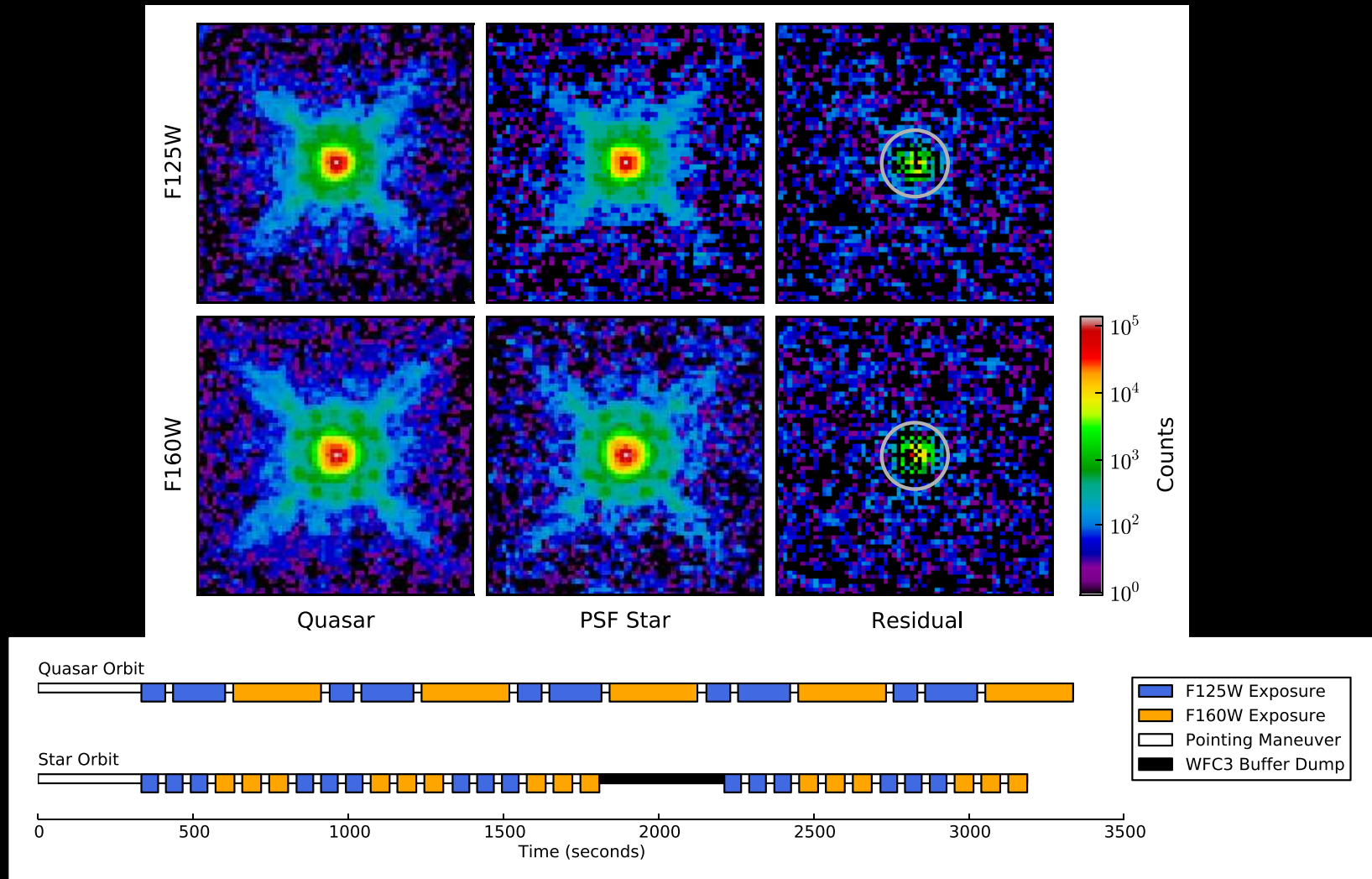


[Left] CSIRO/ATNF 1.4 GHz image of Cen A (Feain<sup>+</sup> 2009).  
 Fermi GeV source (Yang<sup>+</sup> 12); & Auger UHE Cosmic Rays (Abreu<sup>+</sup> 2010).  
 [Middle] SF in Cent A jet's wake (Crockett<sup>+</sup> 2012, MNRAS, 421, 1602).  
 [Right] Well determined ages for young ( $\sim 2$  Myr) stars near Cen A's jet.

- JWST will trace older stellar pops and SF in much dustier environments.
- We must do all we can with HST in the UV–blue before JWST flies.

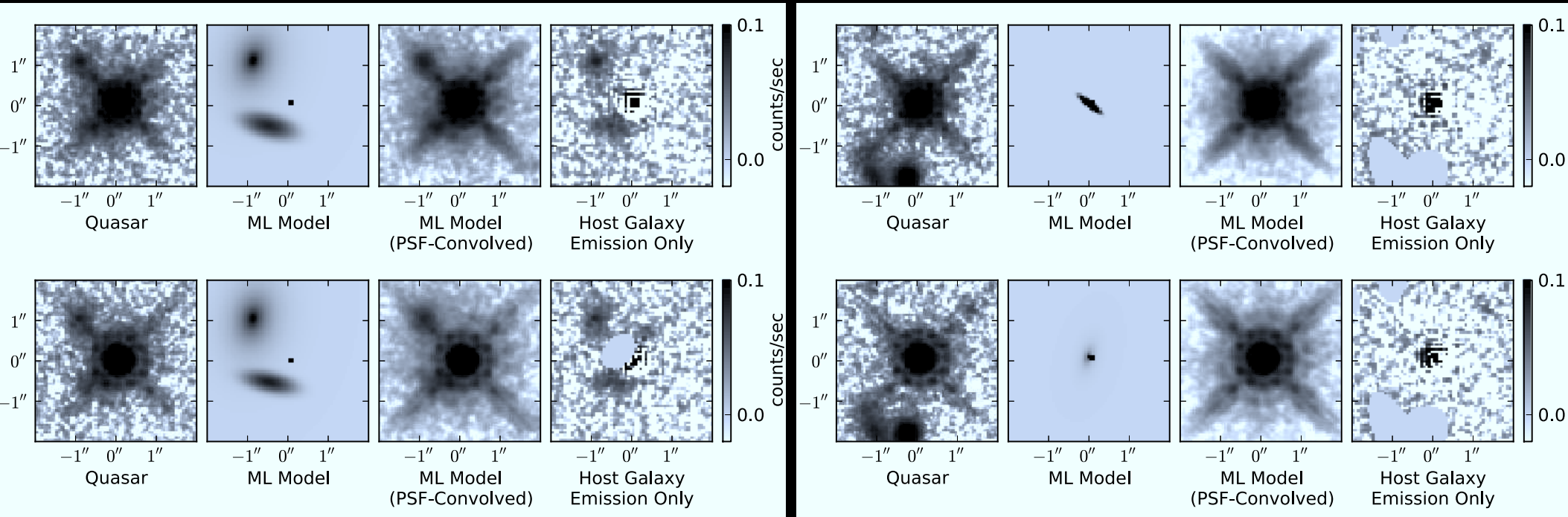


## (2b) HST WFC3 observations of QSO host systems at $z \simeq 6$ (age $\lesssim 1$ Gyr)



- Careful contemporaneous orbital PSF-star subtraction: Removes most of “OTA spacecraft breathing” effects (Mechtley et al 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  $r \gtrsim 0''.3$ ).

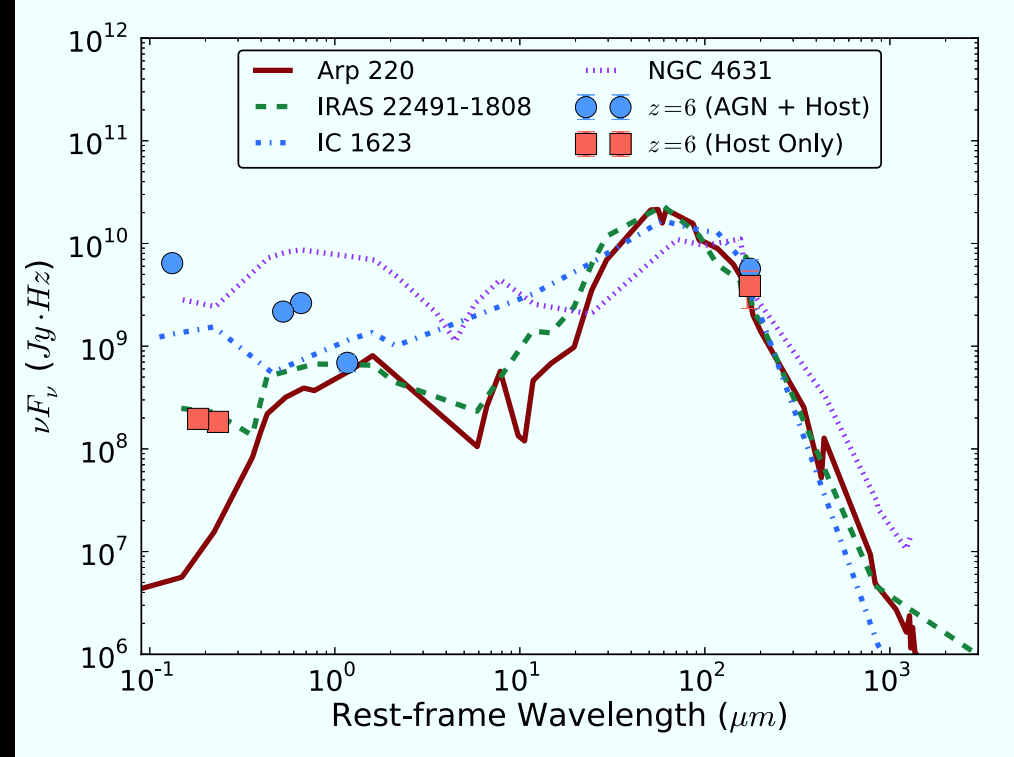
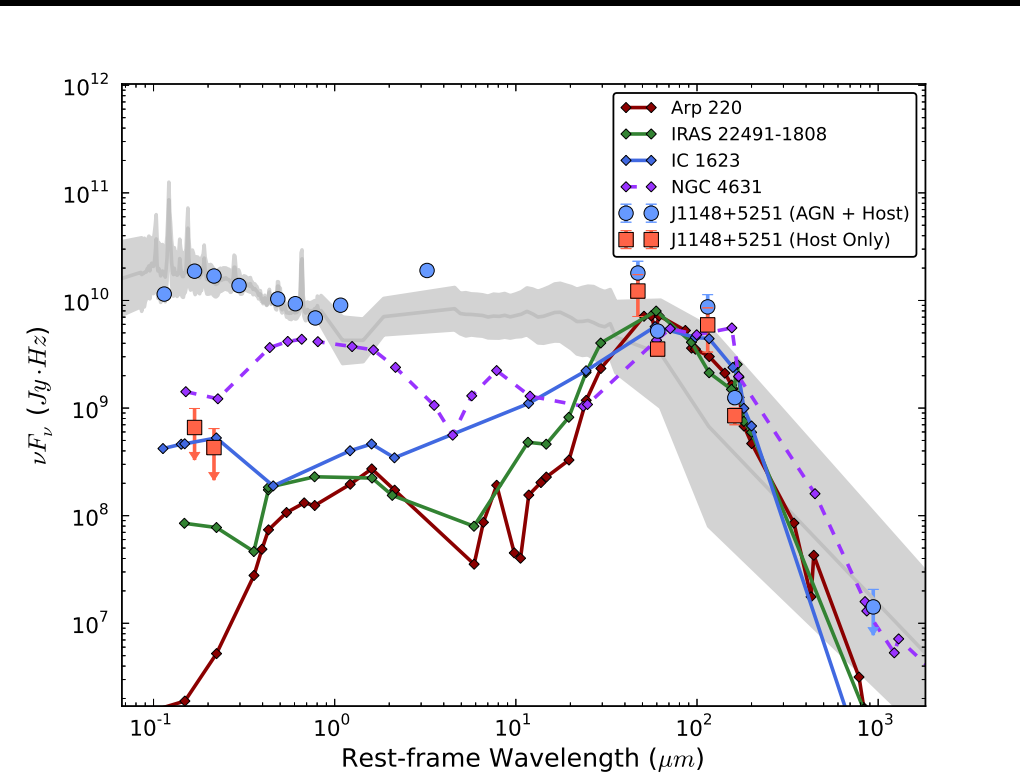
## (2b) WFC3: Detection of one QSO Host System at $z \simeq 6$ (Giant merger?)



- Monte Carlo Markov-Chain of observed PSF-star + Sersic ML light-profile. Gemini AO images to pre-select PSF stars (Mechtley<sup>+</sup> 2014).
  - First detection out of four  $z \simeq 6$  QSOs [2 more to be observed].
  - One  $z \simeq 6$  QSO host galaxy: Giant merger morphology + tidal structure??
  - Same J+H structure! Blue UV-SED colors:  $(J-H) \simeq 0.19$ , constrains dust.
  - $M_{AB}^{host}(z \simeq 6) \lesssim -23.0$  mag, i.e.,  $\sim 2$  mag brighter than  $L^*(z \simeq 6)$ !
- $\Rightarrow z \simeq 6$  QSO duty cycle  $\lesssim 10^{-2}$  ( $\lesssim 10$  Myrs); 1/4 QSO's close to Magorrian.
- JWST Coronagraphs can do this  $10-100\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28\mu\text{m}$ ).

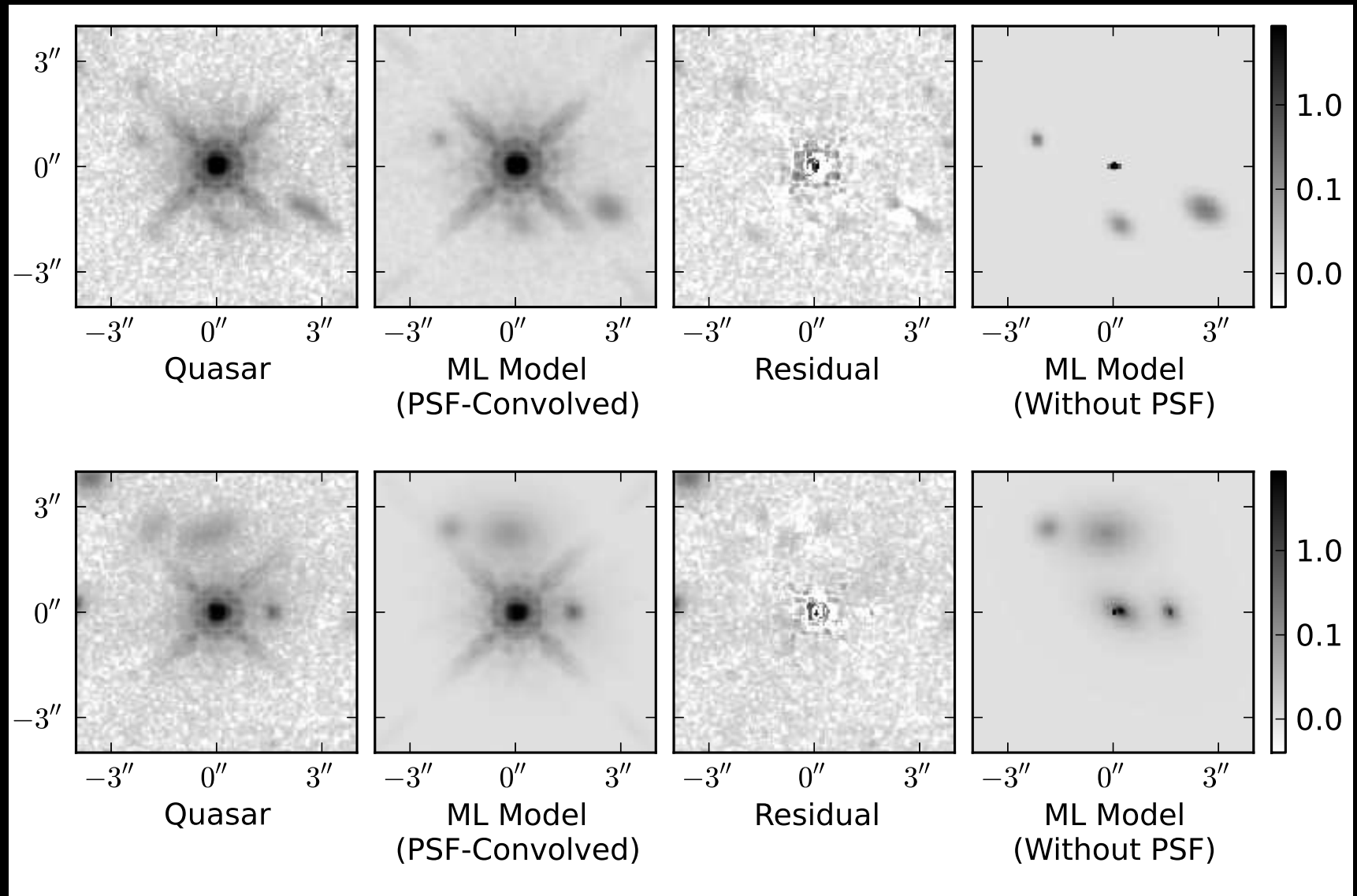


## (2b) HST WFC3 observations of dusty QSO host galaxies at $z \simeq 6$



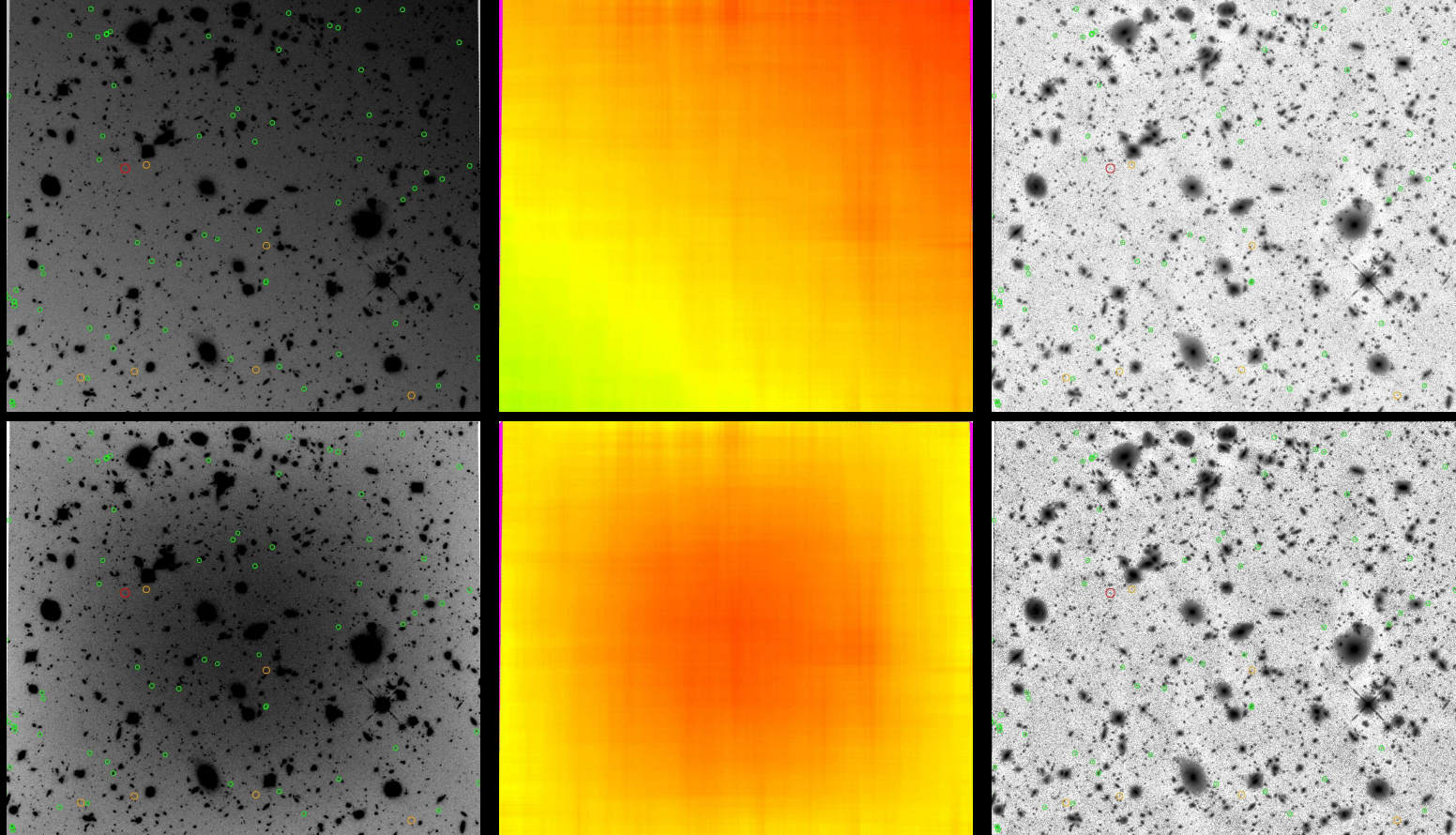
- Blue dots:  $z \simeq 6$  QSO SED, Grey: Average radio-quiet SDSS QSO spectrum at  $z \gtrsim 1$  (normalized at  $0.5 \mu m$ ). Red:  $z \simeq 6$  host galaxy (WFC3+submm).
- Nearby fiducial galaxies (starburst ages  $\lesssim 1$  Gyr) normalized at  $100 \mu m$ :  
 [LEFT] Rules out  $z=6.42$  spiral 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. 2014).
- JWST Coronagraphs can do this  $10\text{--}100\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu m$ ).

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



- Monte Carlo Markov-Chain runs of observed PSF-star + Sersic ML light-profile models: merging neighbors (some with tidal tails?; Mechtley, Jahnke, MPI, Koekemoer, Windhorst et al. 2014).
- JWST Coronagraphs can do this 10–100 $\times$  fainter (& for  $z \lesssim 20$ ,  $\lambda \lesssim 28 \mu\text{m}$ ).





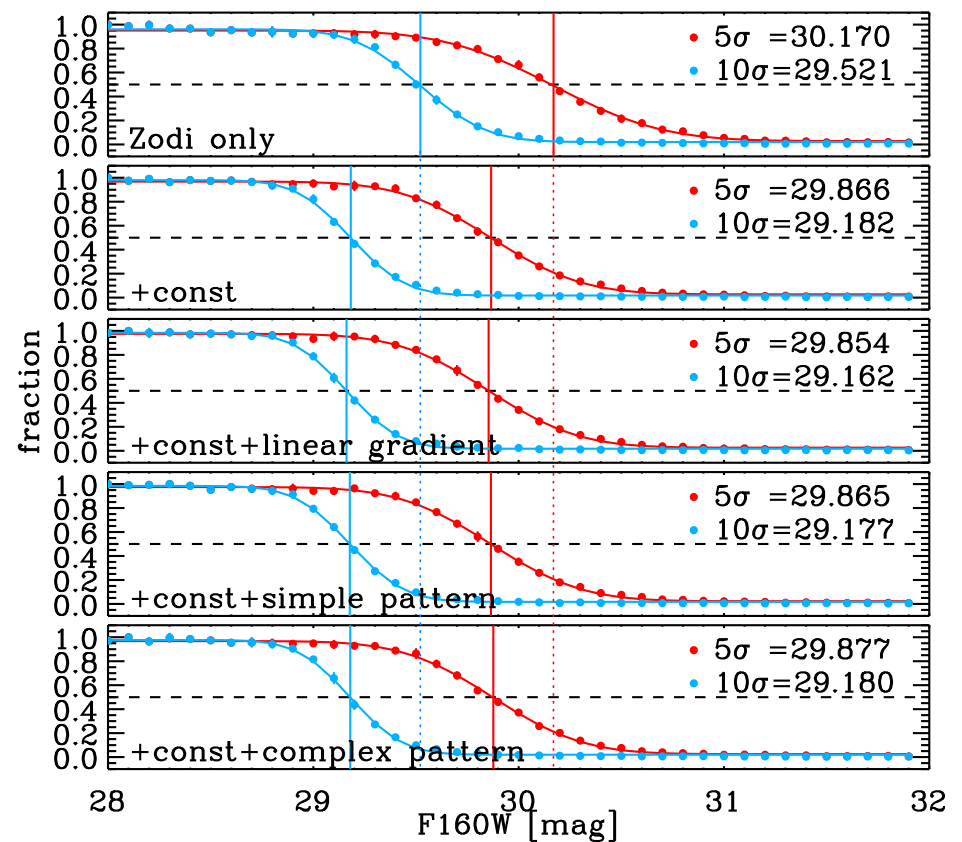
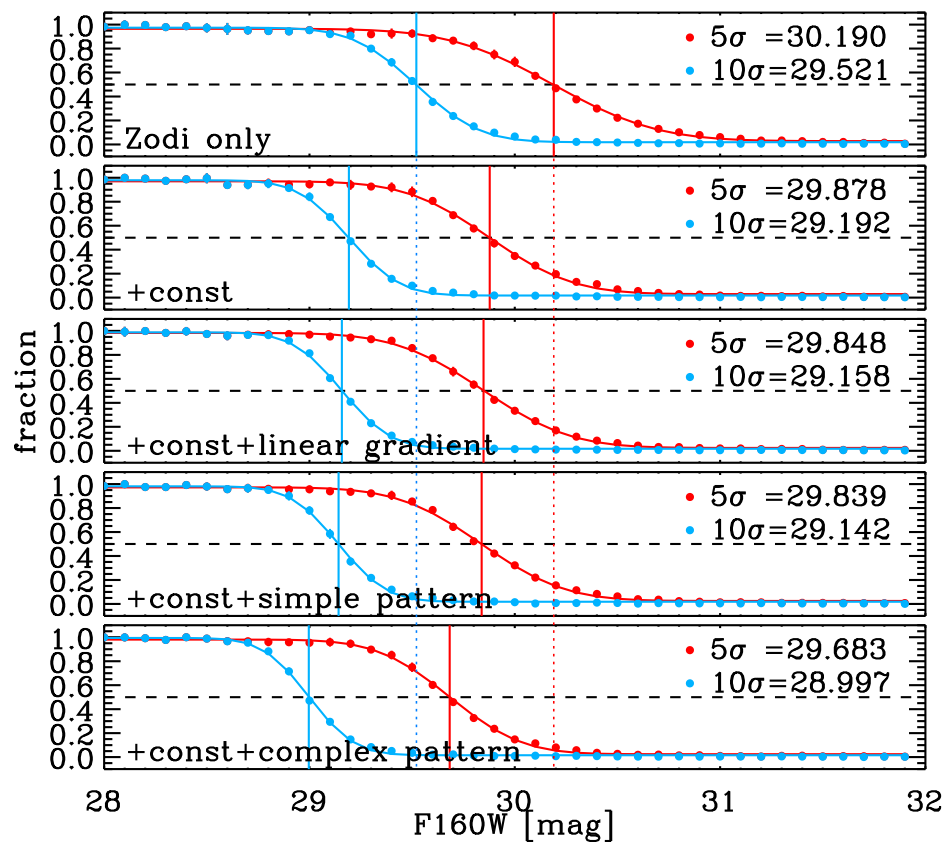
[TOP]: [Left] HUDF F160W image with *worst case* (95% of Zodi) rogue-path amplitude imposed  $\pm$  a 4% *linear gradient* from corner-to-corner.

[Middle]: Best fit to sky-background with R. Jansen's "rjbgfit.pro".

[Right]: HUDF image from left with best-fit sky-background subtracted.

[BOTTOM]: Same as top row, but with a *single-component simple 2D pattern* superimposed, modeled and removed, respectively.

- If JWST rogue-path straylight has slight or complex gradients, we must carefully plan JWST imaging of lensing clusters with strong ICL.



[LEFT]: Completeness tests in HUDF F160W image *before* imposing on top of Zodi ( $=22.70$  H-mag arcsec $^{-2}$ ; Petro 2001) [2nd–5th row]:

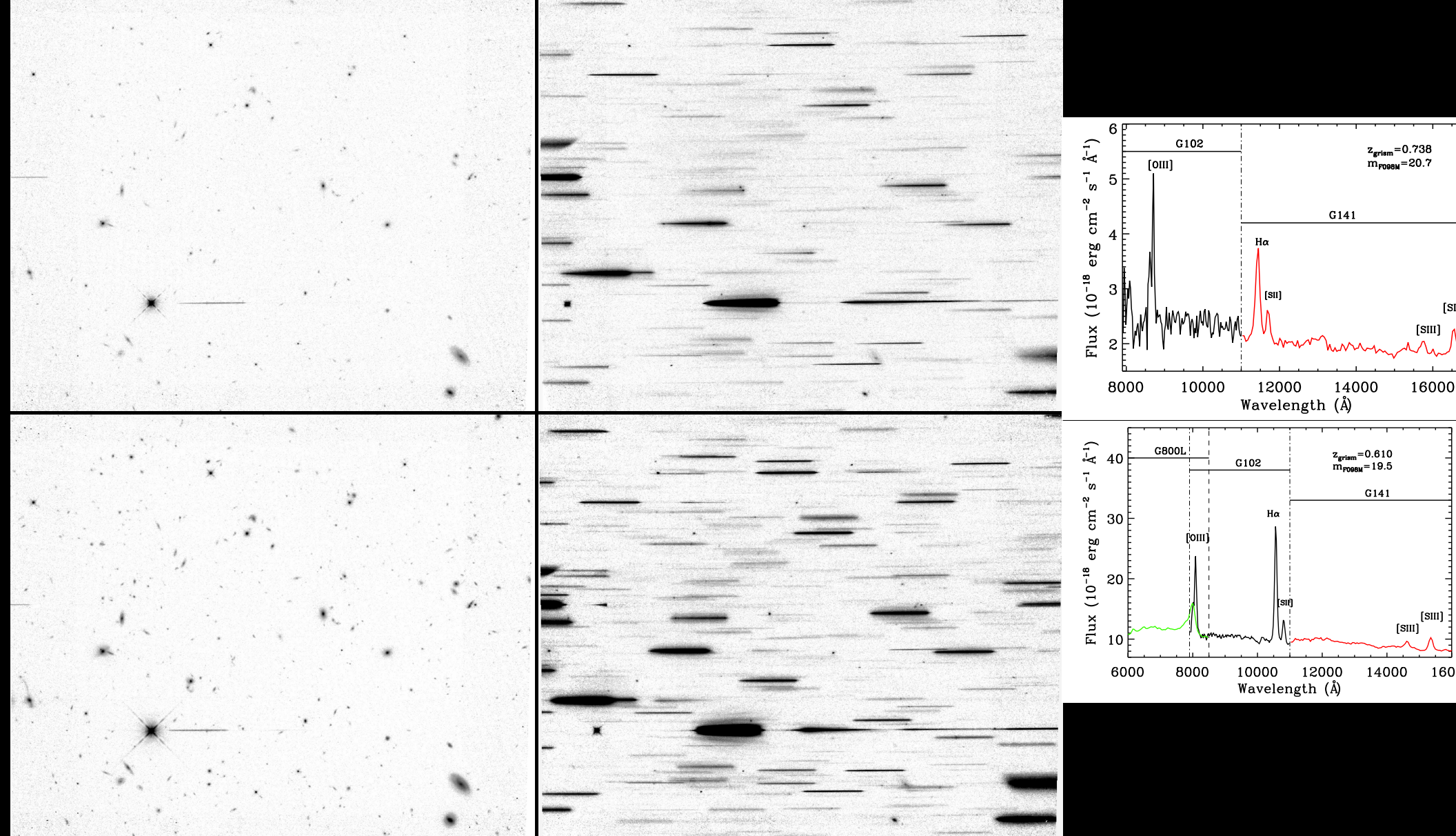
*Constant 95% of Zodi amplitude; + a  $\pm 4\%$  linear gradient; or simple 2D pattern of  $\pm 4\%$ ; or a more complex pattern.*

[RIGHT]: Same as left *after* best fit to + removal of image sky-background.

Red and blue lines: 50%  $5\text{-}\sigma$  and  $10\text{-}\sigma$  AB-completeness limits, resp.

● Simple low-frequency rogue-path gradients can be removed from “random” deep fields, without much extra loss in sensitivity. Clusters: TBD.





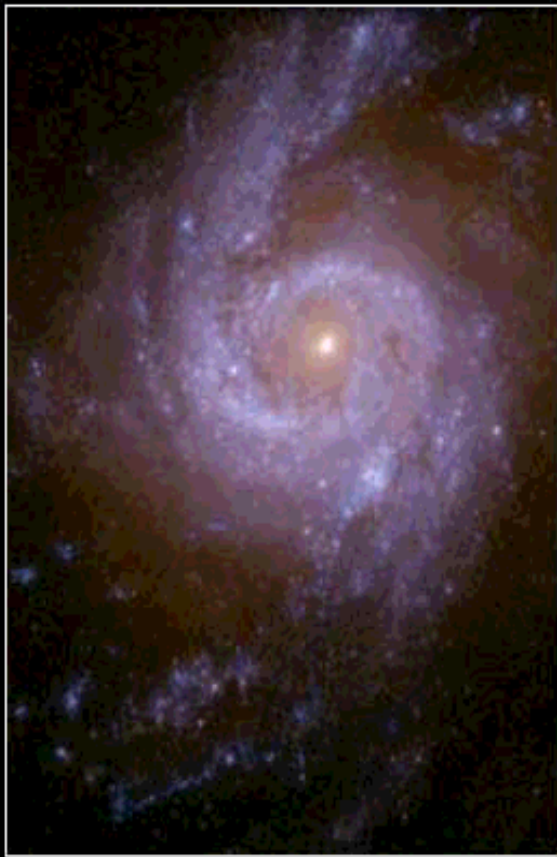
HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn<sup>+</sup> 2010)

IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to  $AB \lesssim 29$  mag from  $2\text{--}5.0\ \mu\text{m}$ .

## (4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

NGC 3310



ESO0418-008



UGC06471-2



**Ultraviolet Galaxies**

**HST • WFPC2**

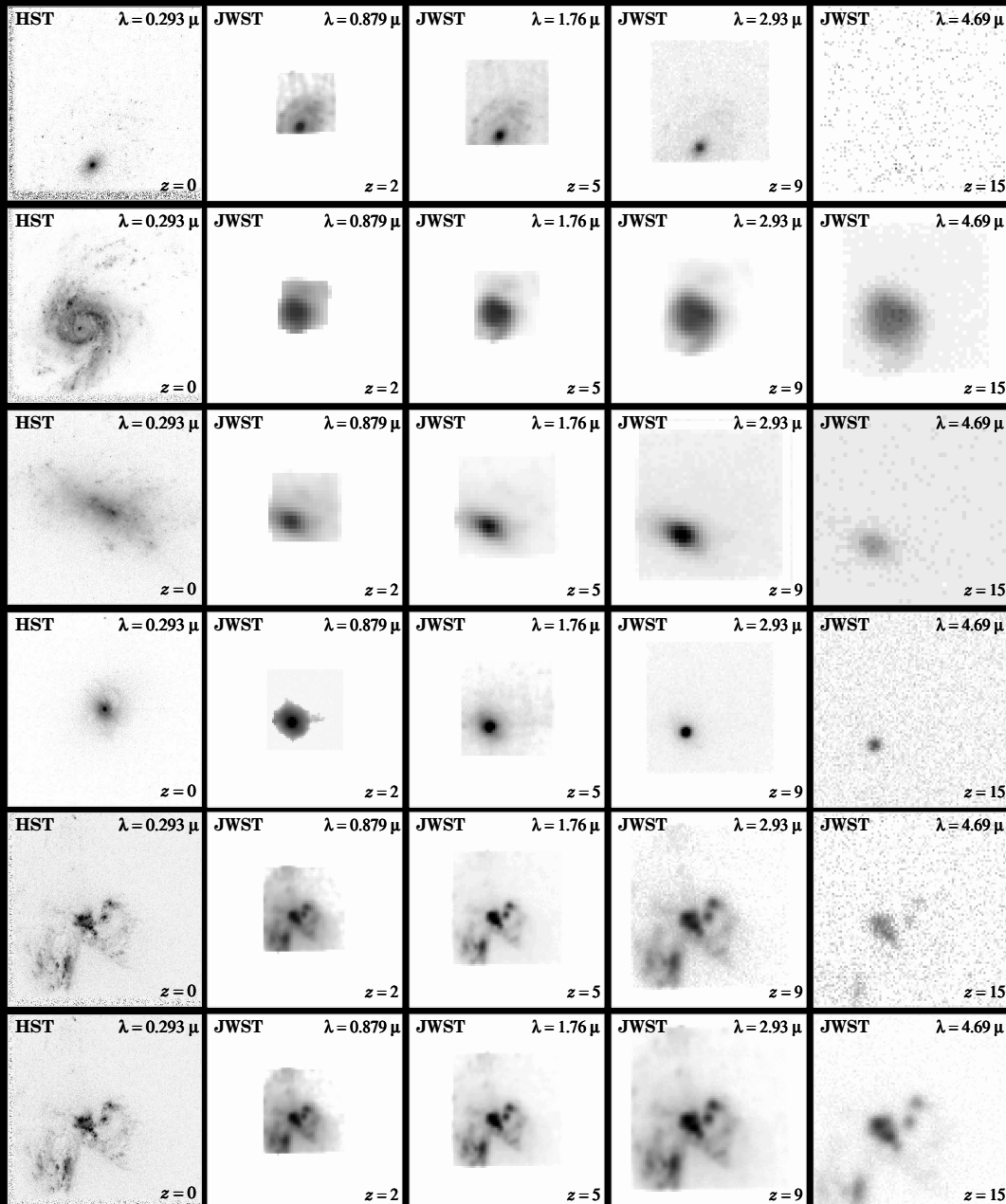
NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).
- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.



## (4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

HST  $z=0$  JWST  $z=2$   $z=5$   $z=9$   $z=15$



With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at  $z \lesssim 1-2$ .

Visible to JWST at very high  $z$  are:

- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

B, I, J AB-mag vs.  
half-light radii  $r_e$   
from RC3 to HUDF  
limit are shown.

All surveys limited by  
by SB (+5 mag dash)

Deep surveys bounded  
also by object density.

Violet lines are gxy  
counts converted to  
to natural conf limits.

Natural confusion  
sets in for faintest  
surveys ( $AB \gtrsim 25$ ).  
Will update for JWST.

