

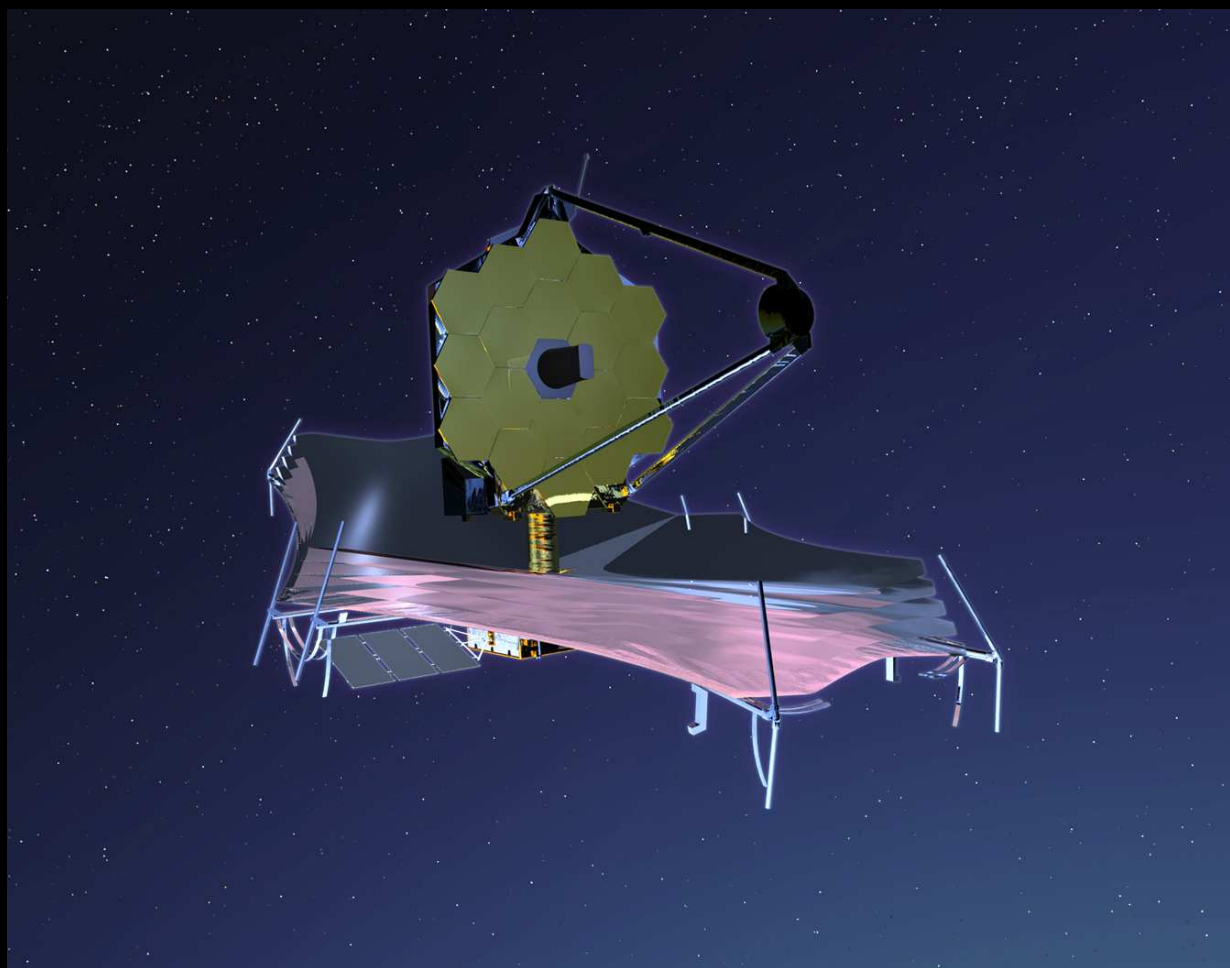
# How will the Webb Space Telescope measure First Light Reionization, & Galaxy Assembly in the post WFC3 era?

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

*Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (OSU)*

*& (Ex) ASU Grad Students: N. Hathi, H. Kim, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura*



*Review at the New Worlds New Horizons Workshop, Sante Fe, NM, Monday March 7, 2011*

# Outline

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James Webb Space Telescope: NASA's next Flagship mission after Hubble  
Astro 2010 Decadal Survey assumed: JWST science is done after 2015.

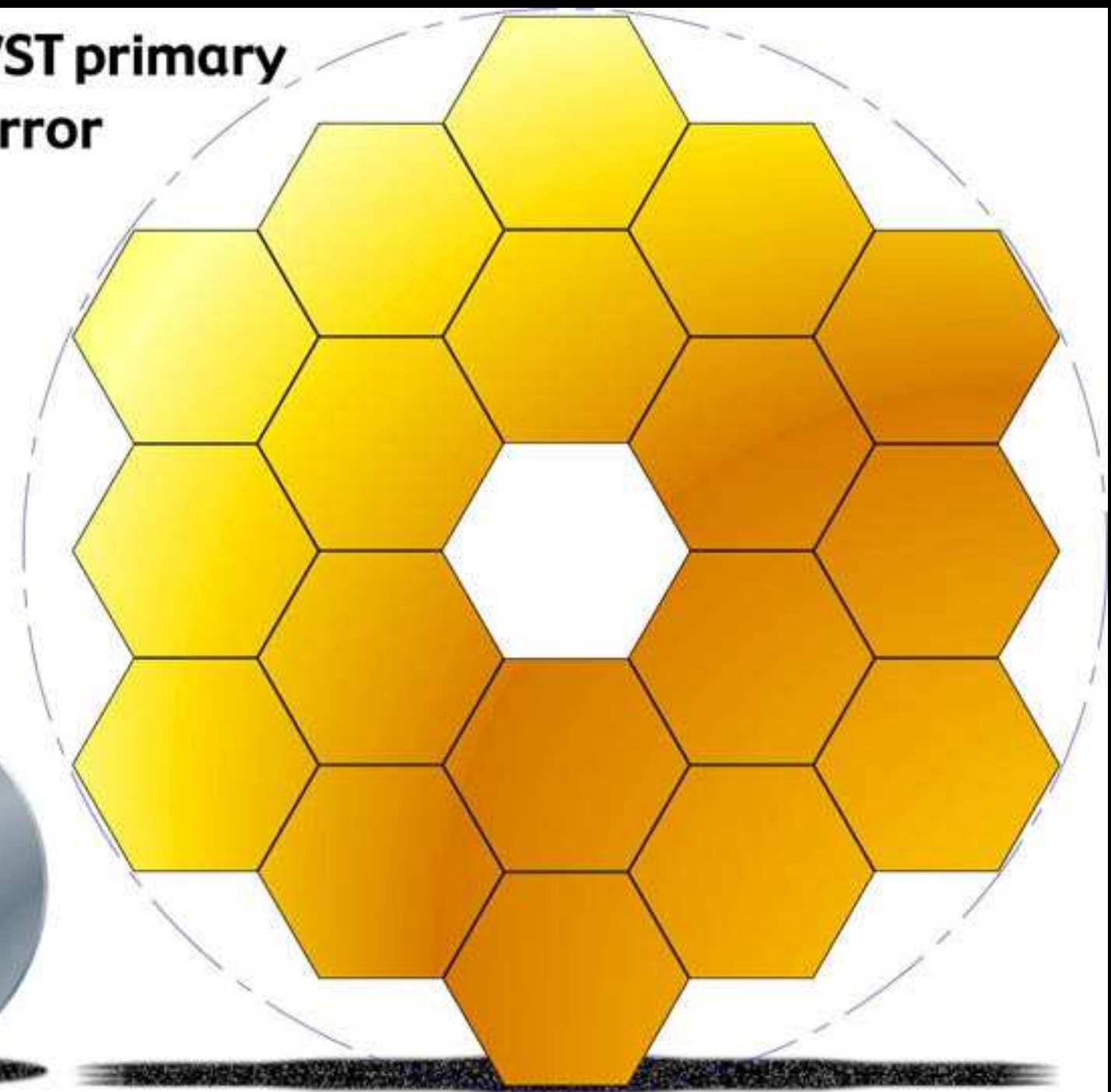
- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) How can JWST can measure First Light & Reionization?
- (4) How can JWST measure Galaxy Assembly?

[With recent Hubble WFC3 results: Gravitational lensing bias for  $z \gtrsim 8$ ].

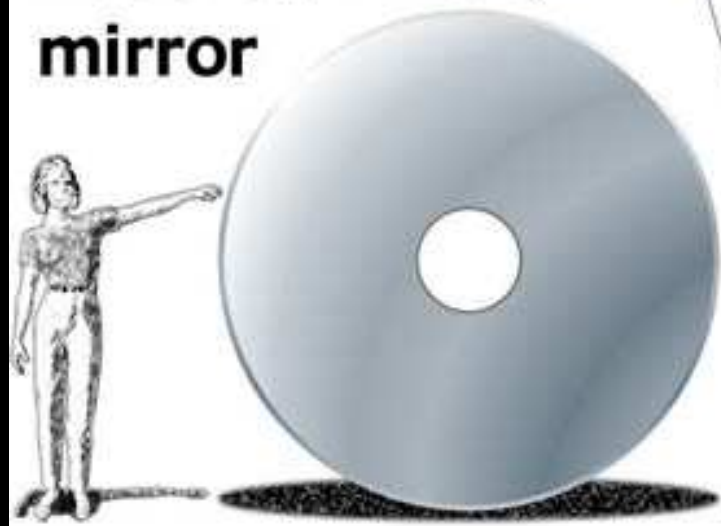
- (5) Predicted Galaxy Appearance for JWST at redshifts  $z \simeq 1-15$ .
- (6) Summary and Conclusions

Sponsored by NASA/JWST & HST

**JWST primary  
mirror**



**Hubble primary  
mirror**



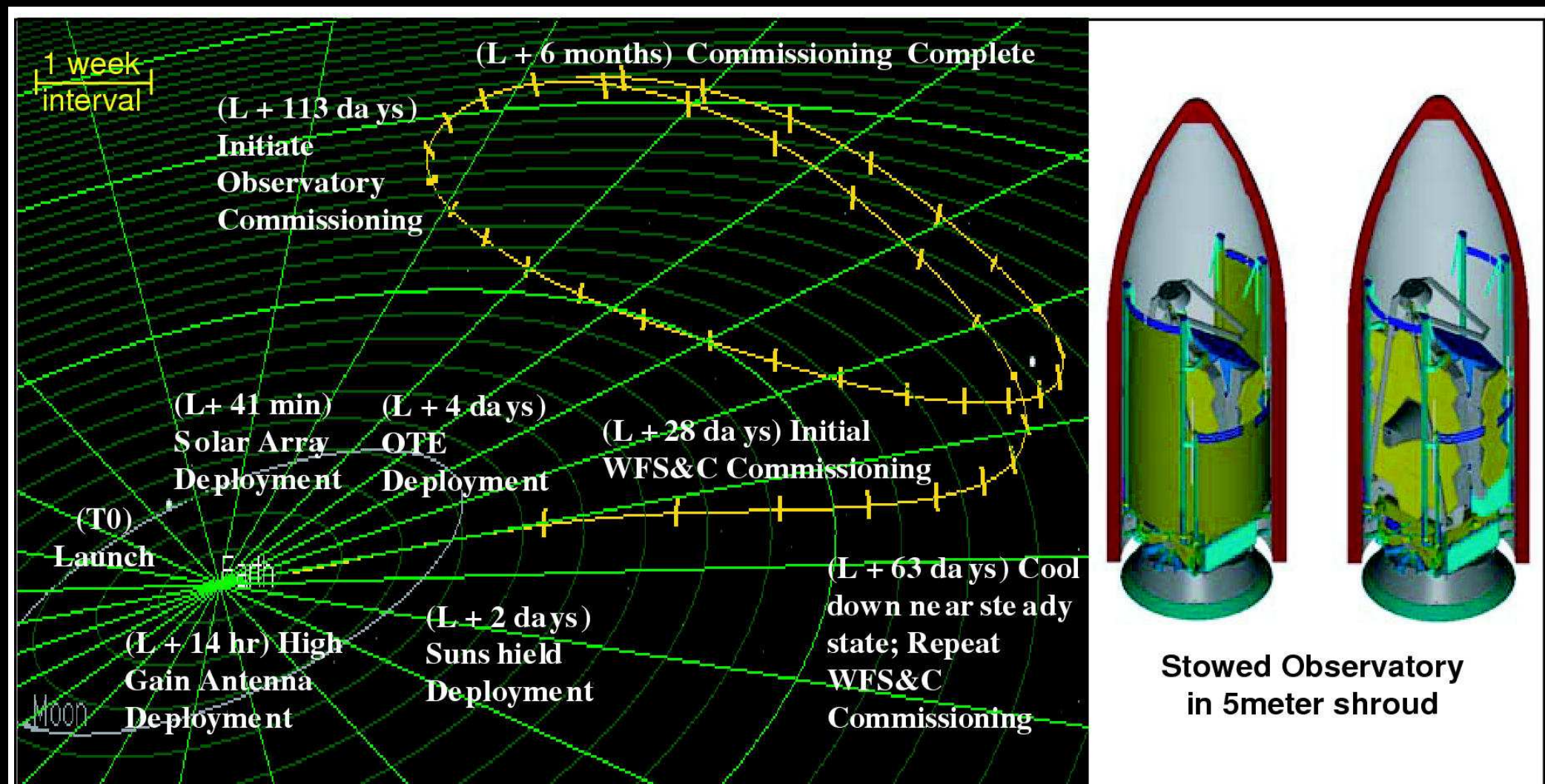
JWST  $\sim 2.5\times$  larger than Hubble, so at  $\sim 2.5\times$  larger wavelengths:  
JWST has the same resolution in the near-IR as HST in the optical.

- (1) What is the James Webb Space Telescope (JWST)?



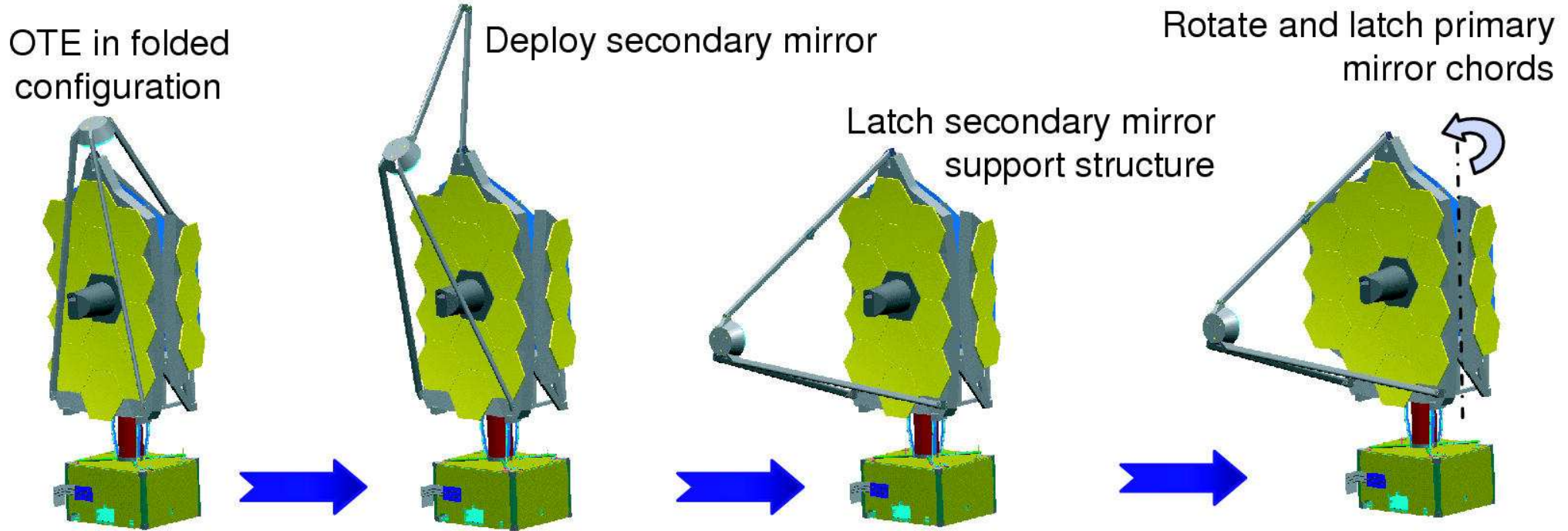
- A fully deployable 6.5 meter ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy from  $0.7$  to  $29 \mu\text{m}$ , to be launched in June  $\gtrsim 2015$ .
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging ( $AB \lesssim 31.5$ ) and spectroscopy ( $AB \lesssim 29 \text{ mag}$ ).

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

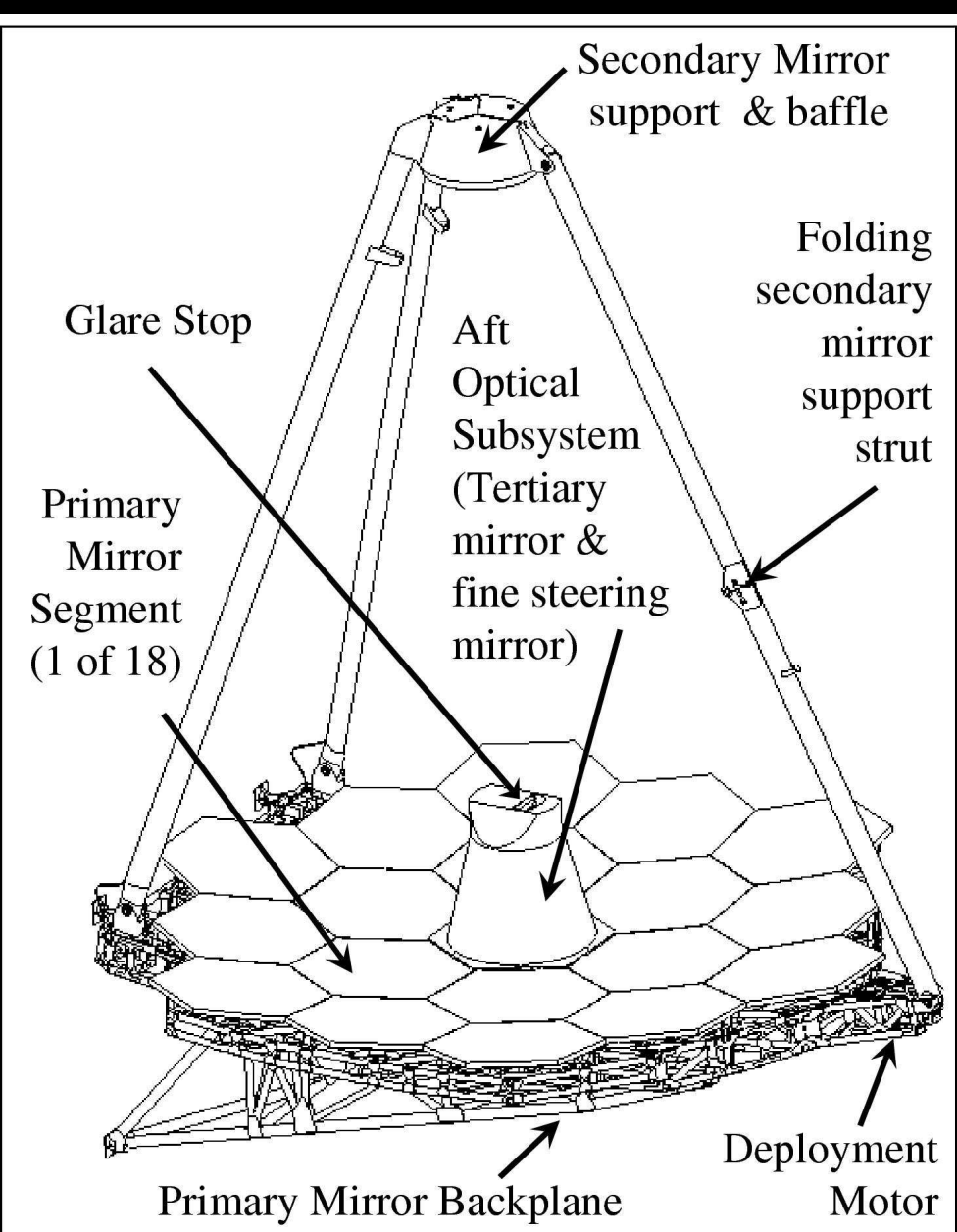


- After launch in June 2015 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe  $\gtrsim 70\%$  of the time, and send data back to Earth every day.

- (1) How will JWST be automatically deployed?

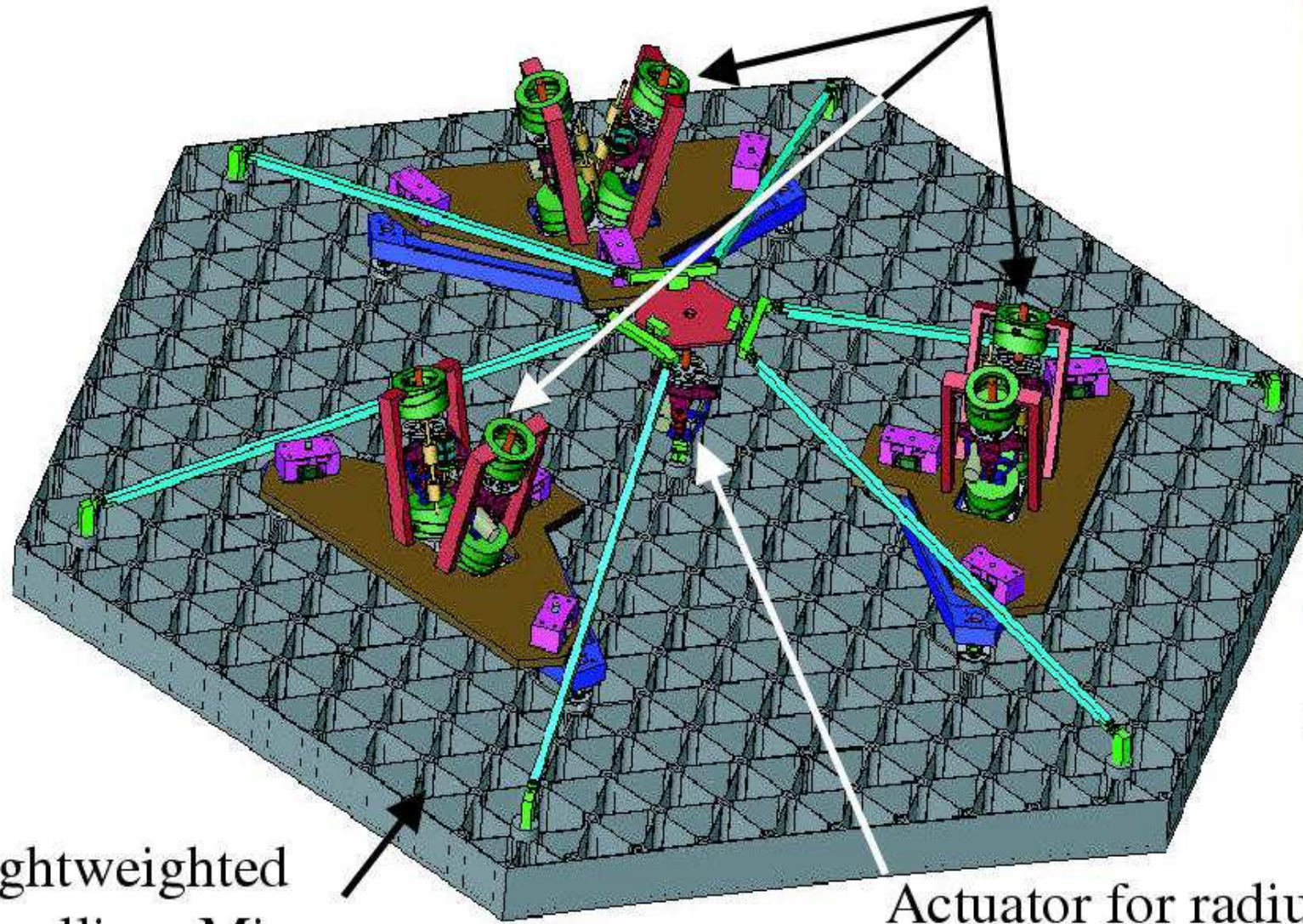


- During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit, 1.5 million km from Earth.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: component and system tests at JSC.
- Component fabrication, testing, & integration is on schedule: 3 out of 18 flight mirrors completely done, and at the 45K  $2.0\mu\text{m}$  diffraction limit!



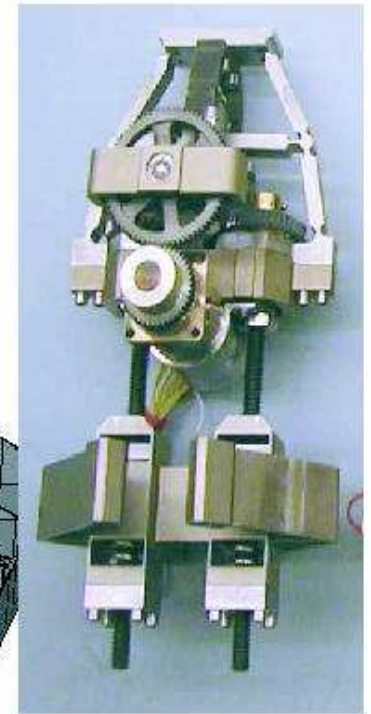
Ball 1/6-model for WFS: diffraction-limited  $2.0 \mu\text{m}$  images ( $\text{Strehl} \gtrsim 0.85$ ).  
 Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2012-2014.  
 In L2, WFS updates every 10 days depending on scheduling/SC-illumination.

# Actuators for 6 degrees of freedom rigid body motion



Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment

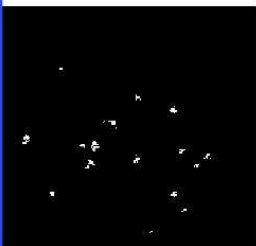


Actuator  
development  
unit

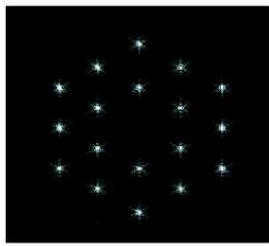
Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.  
Redundant & doubly-redundant mechanisms, quite forgiving against failures



**First light  
NIRCam**



1. Segment Image Capture



After Step 1

**Initial Capture**

**Final Condition**

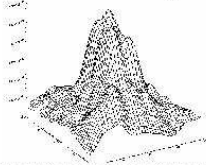
18 individual 1.6-m diameter aberrated sub-telescope images  
 PM segments: < 1 mm, < 2 arcmin tilt  
 SM: < 3 mm, < 5 arcmin tilt

PM segments:  
 < 100  $\mu\text{m}$ ,  
 < 2 arcsec tilt  
 SM: < 3 mm,  
 < 5 arcmin tilt

**2. Coarse Alignment**

Secondary mirror aligned  
 Primary RoC adjusted

After Step 2

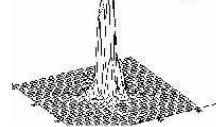


Primary Mirror segments:  
 < 1 mm, < 10 arcsec tilt  
 Secondary Mirror :  
 < 3 mm, < 5 arcmin tilt

WFE < 200  $\mu\text{m}$  (rms)

**3. Coarse Phasing - Fine Guiding (PMSA piston)**

After Step 3

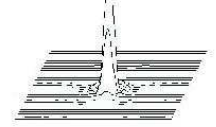


WFE: < 250  $\mu\text{m}$  rms

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)

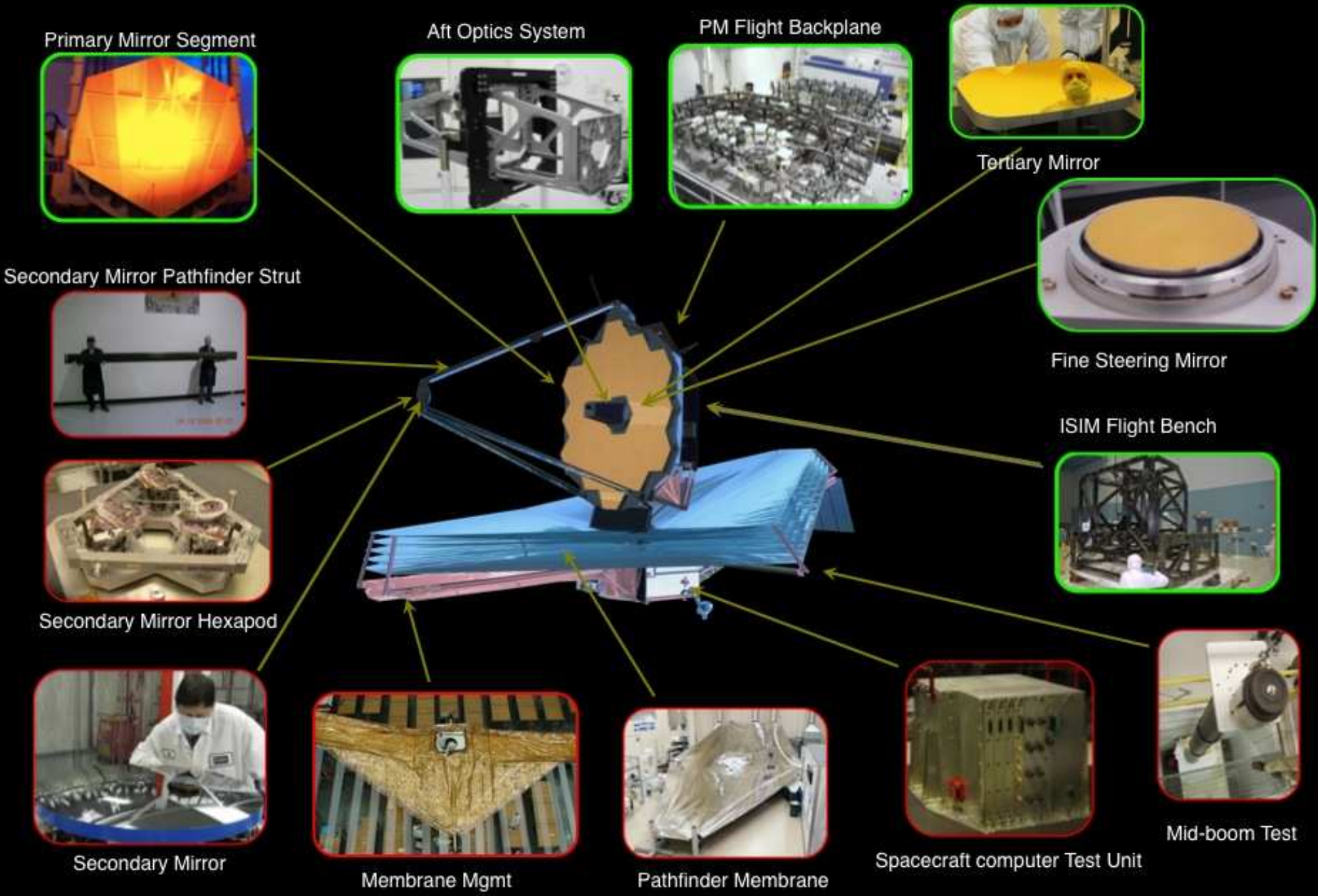
WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to that at Keck and HET.

Successful WFS demo of H/W, S/W on 1/6 scale model ( $2 \mu\text{m}$ -Strehl  $\gtrsim 0.85$ ).

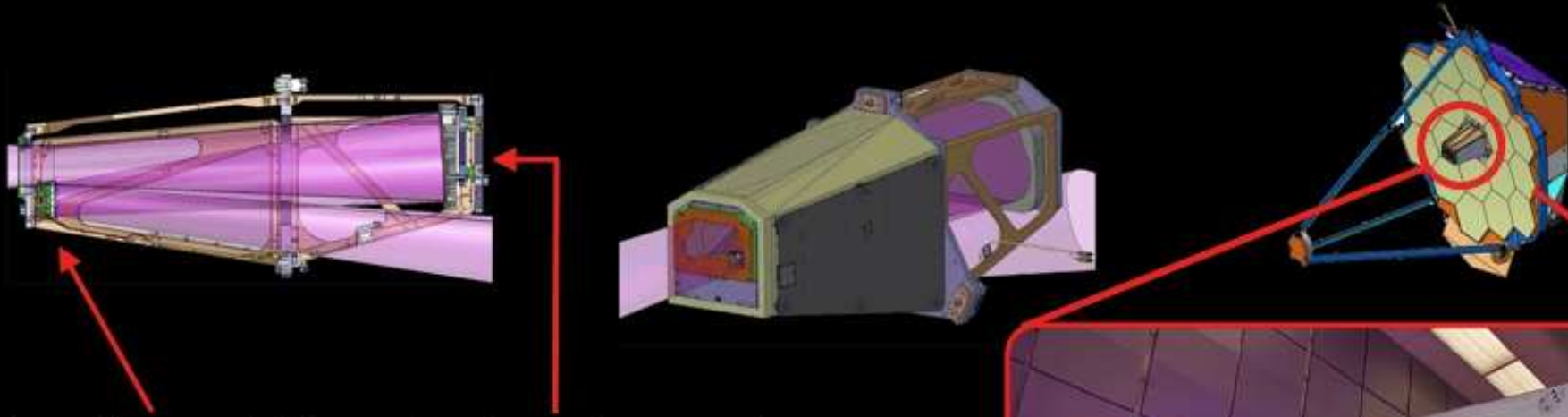
Need WFS-updates every  $\sim 14$  days, depending on scheduling/SC-illumination.

# JWST Hardware Status





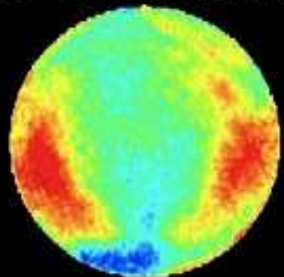
# Aft-Telescope Optical System



**Aft optics and Aft optics bench complete**



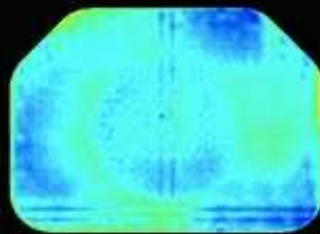
**Fine Steering Mirror**



**3.8 nm RMS SFE**



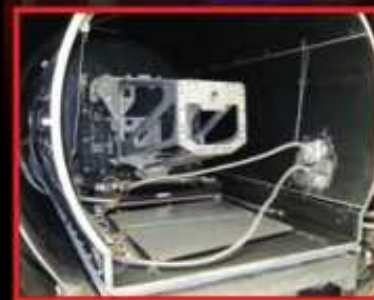
**Tertiary Mirror**



**4.3 nm RMS SFE**

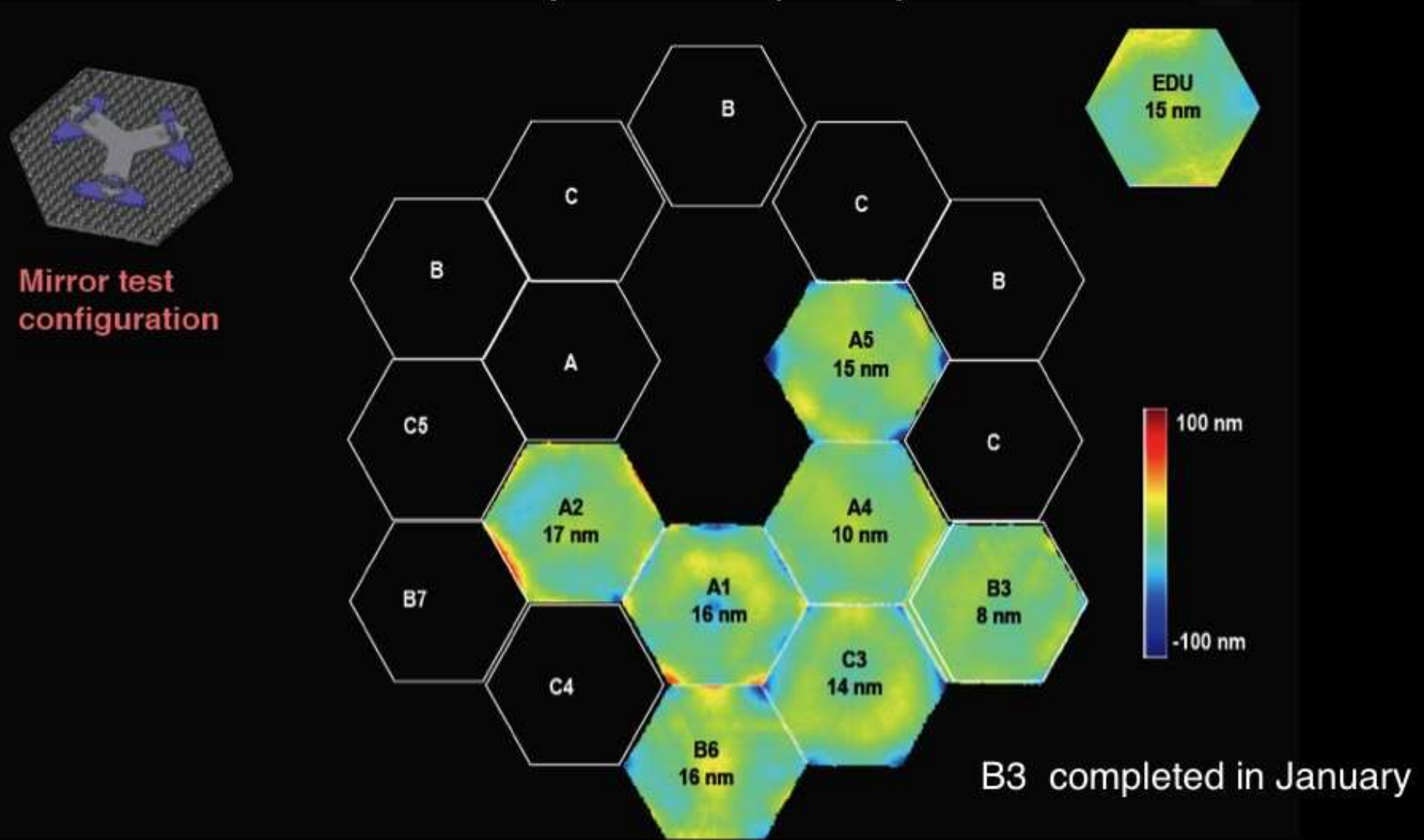


**AOS Bench in cryo-test**

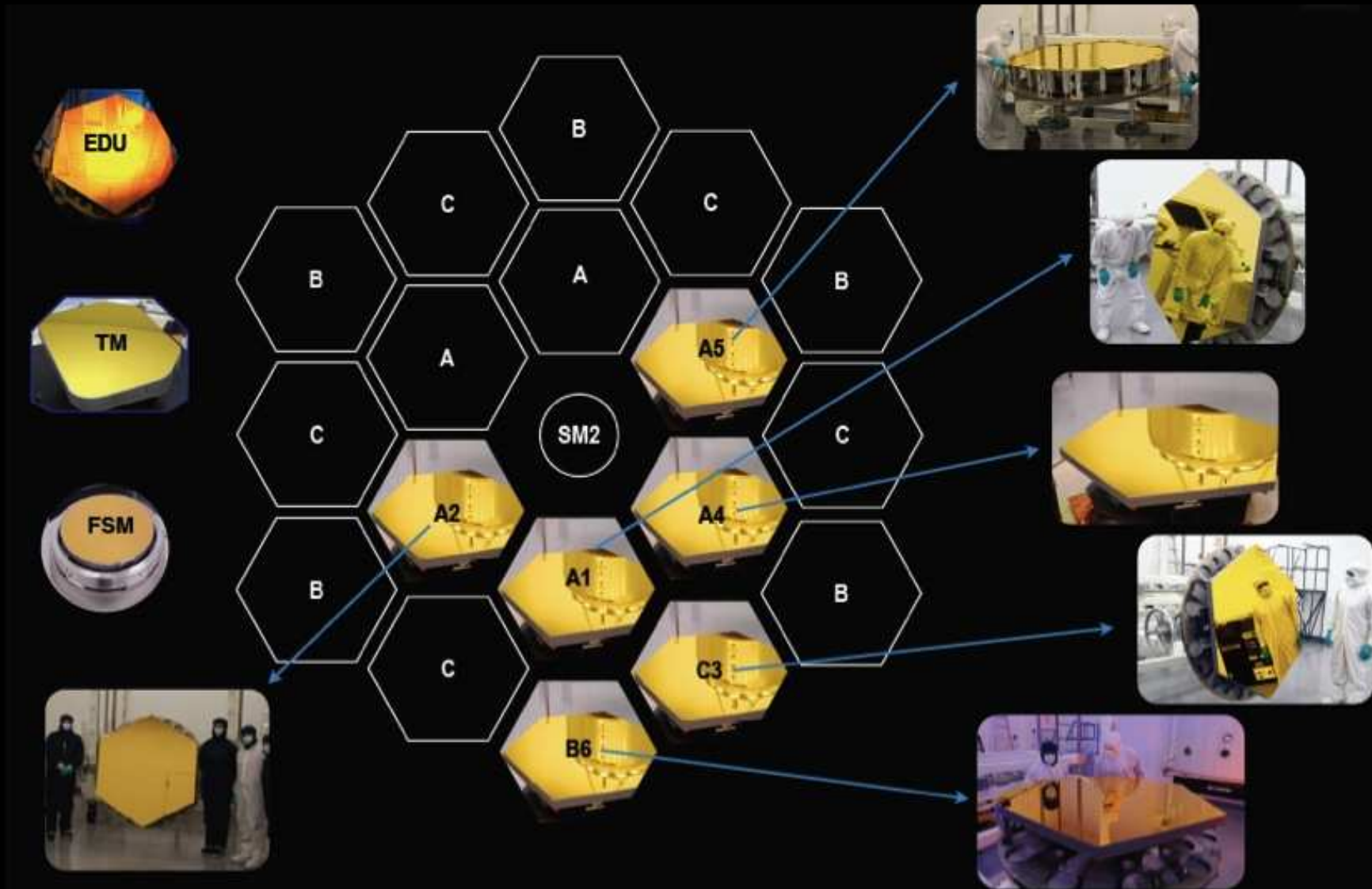


# Flight Mirrors Meet Specification

- Flight mirrors delivered by Tinsley at completion of polishing
  - ➔ Mirrors meet element specification (17 nm)

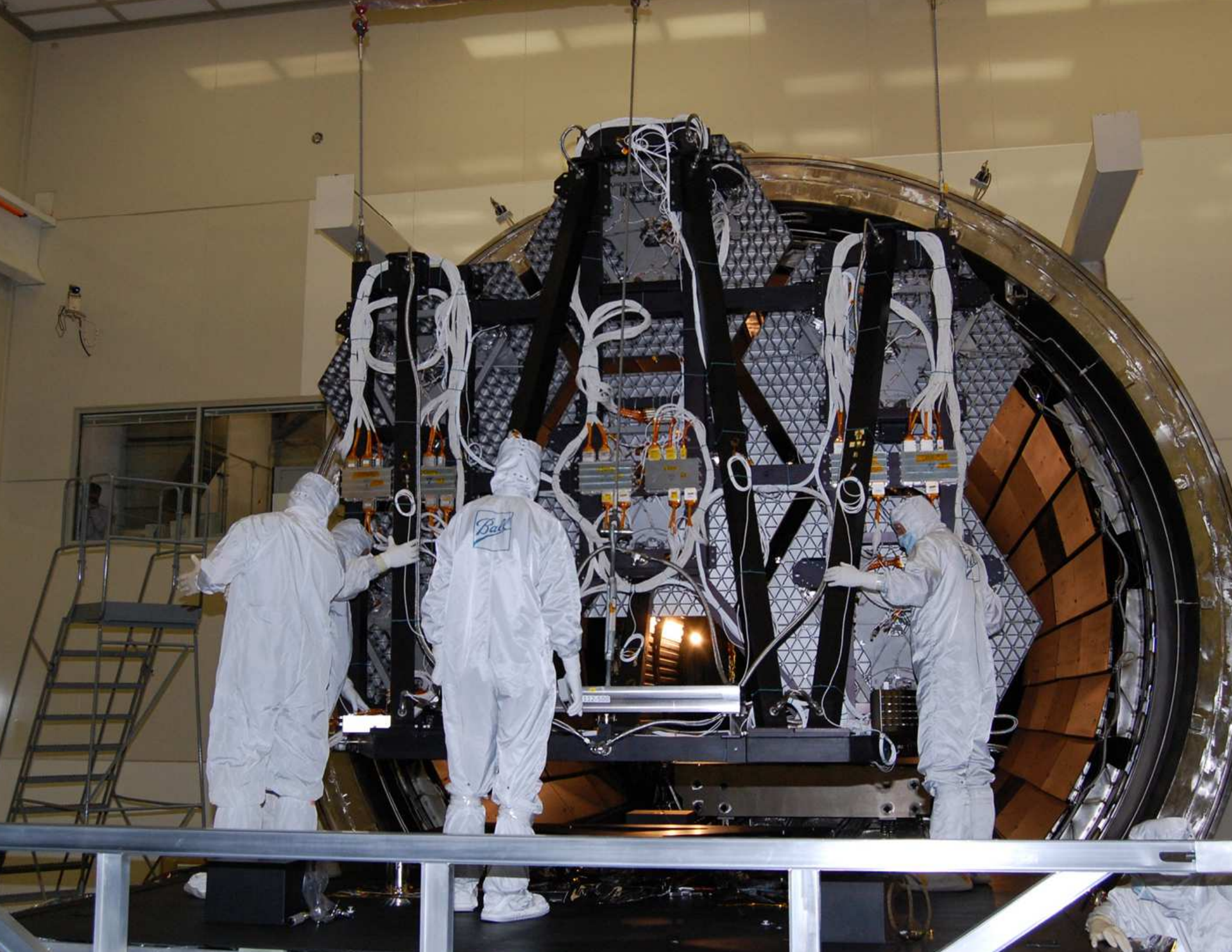


# Gold Coated Mirror Assemblies



- After coating, final steps for flight mirrors are 3 axis vibrate + optical testing











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

# ● (2) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.



## Instrument Overview

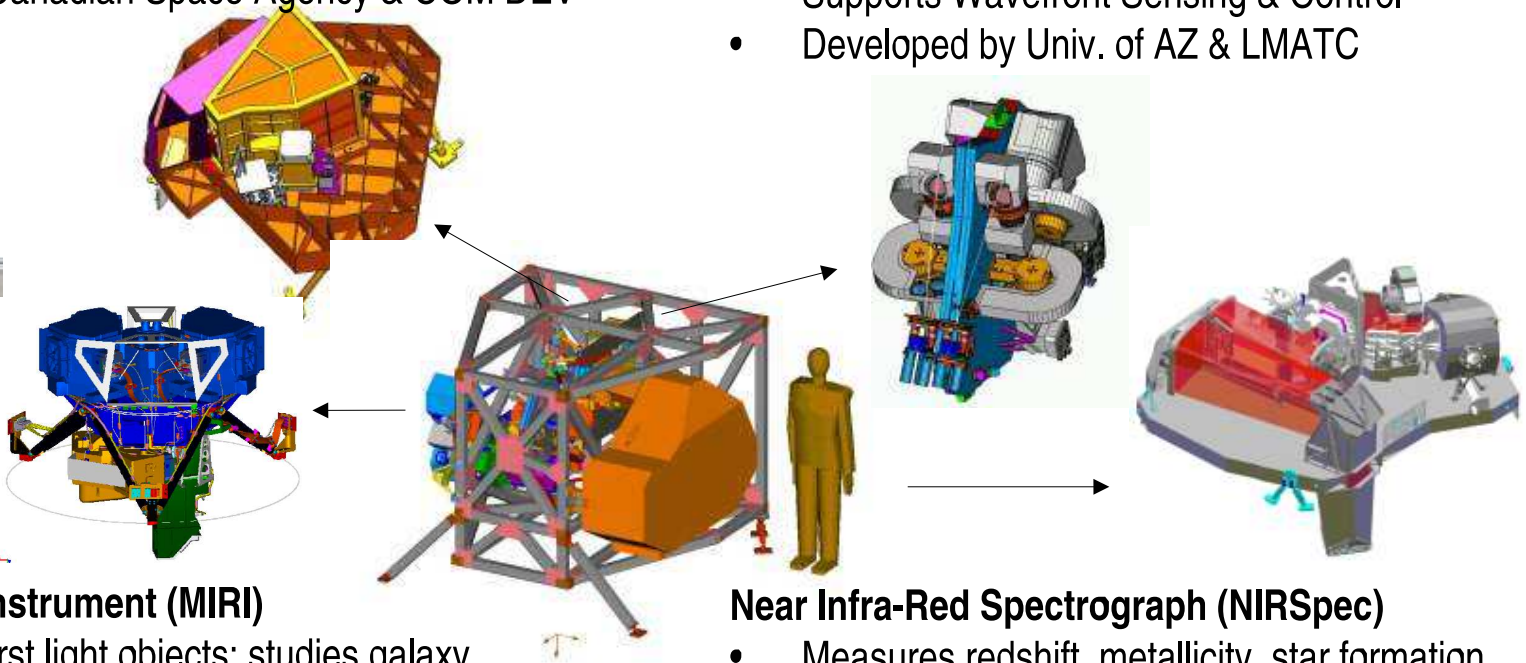


### Fine Guidance Sensor (FGS)

- 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



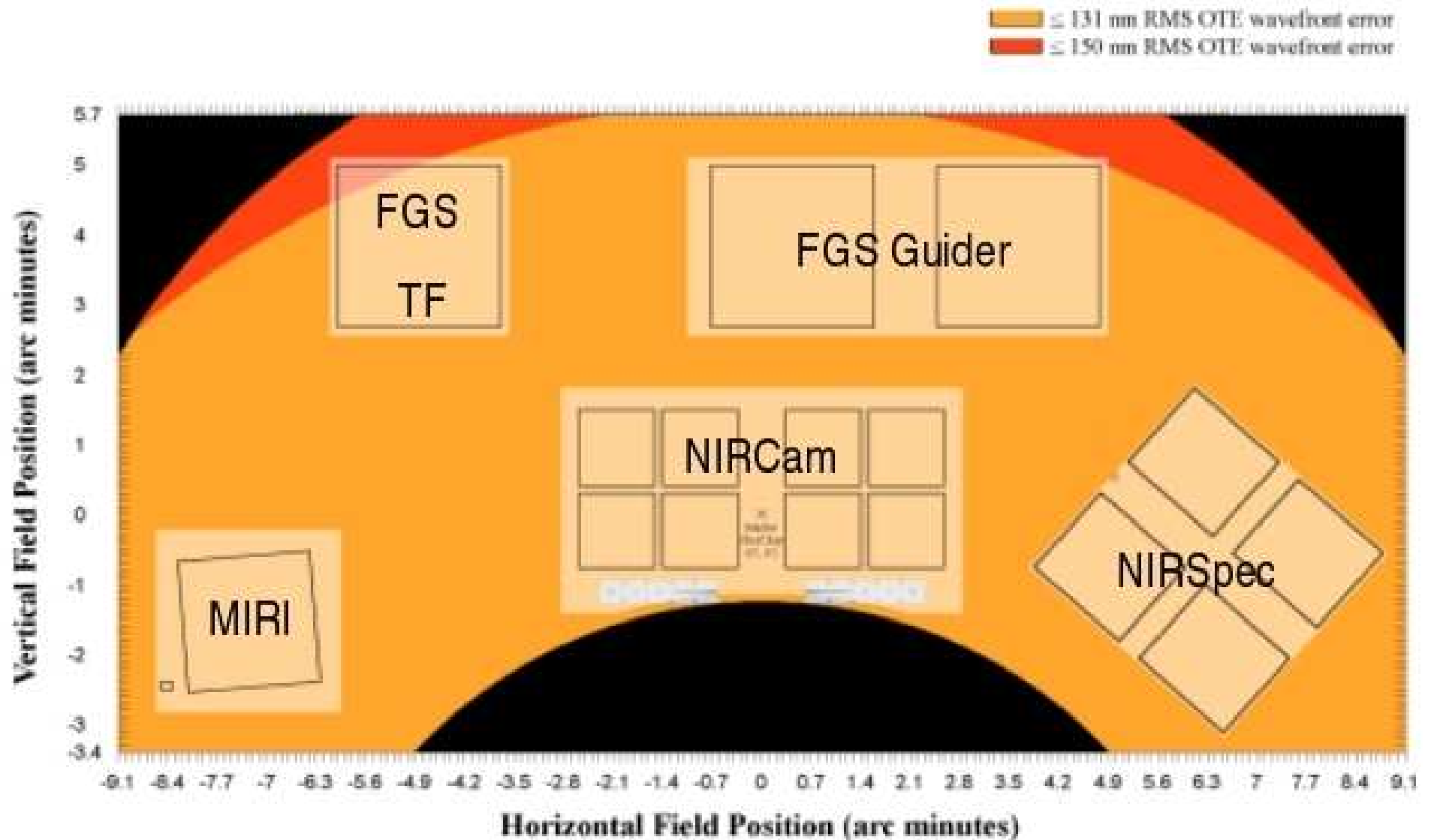
### Mid-Infra-Red Instrument (MIRI)

- 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

- (2) What instruments will JWST have?



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

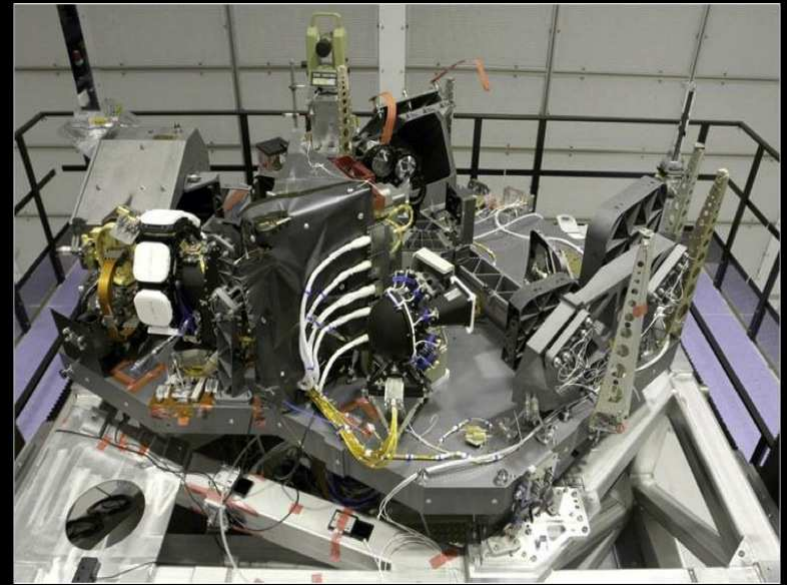
- Currently only being implemented for parallel *calibrations*.



**ETU NIRCam**



**FLIGHT NIRSpec**



**Flight MIRI**

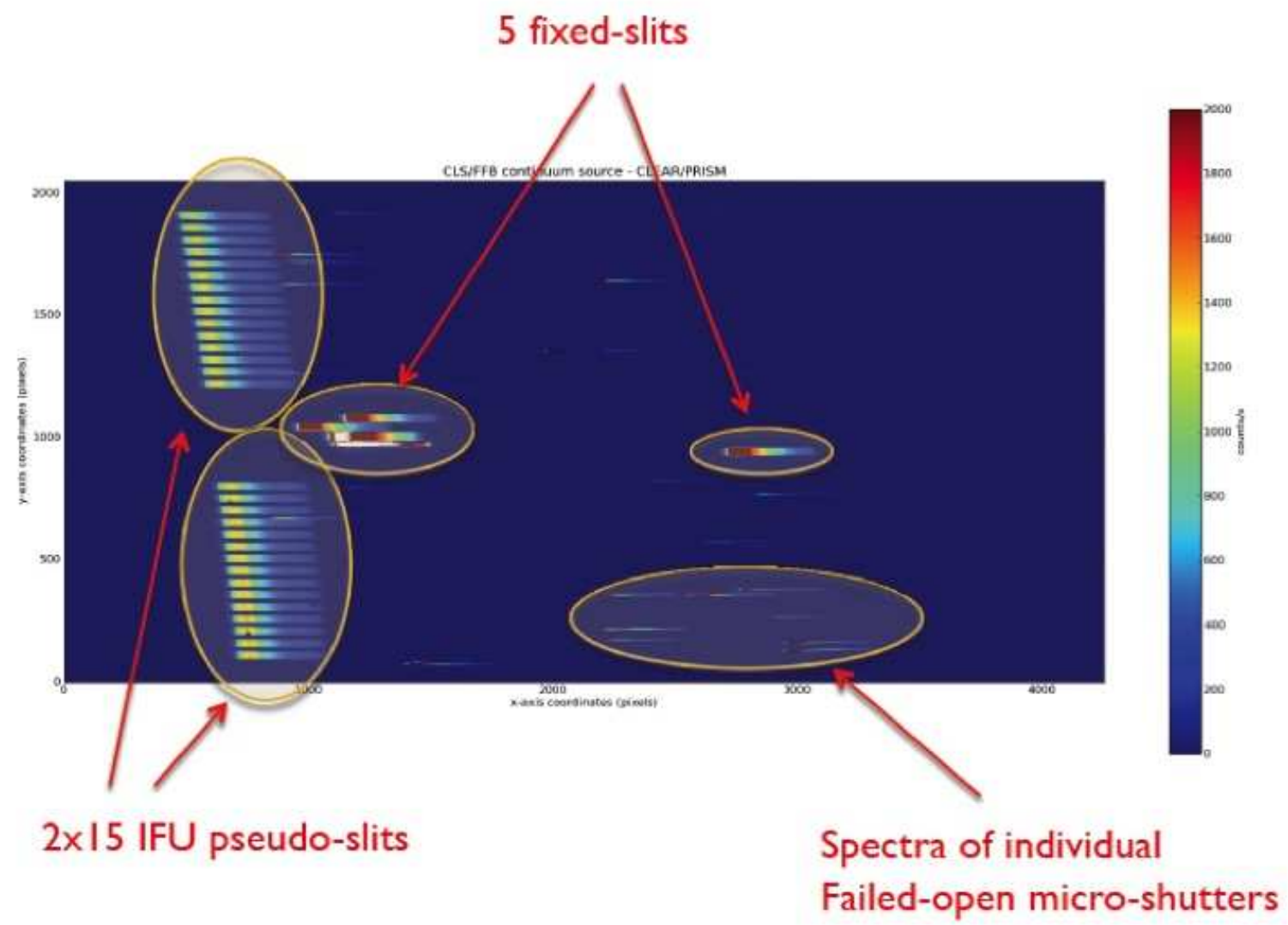


**Flight Fine Guidance Sensor**



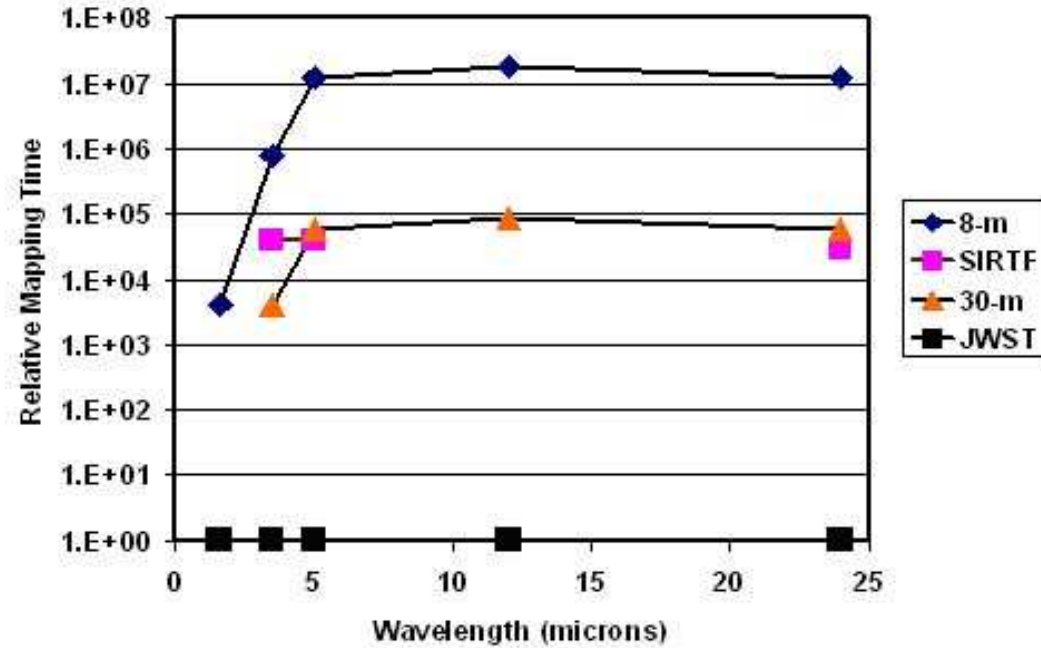
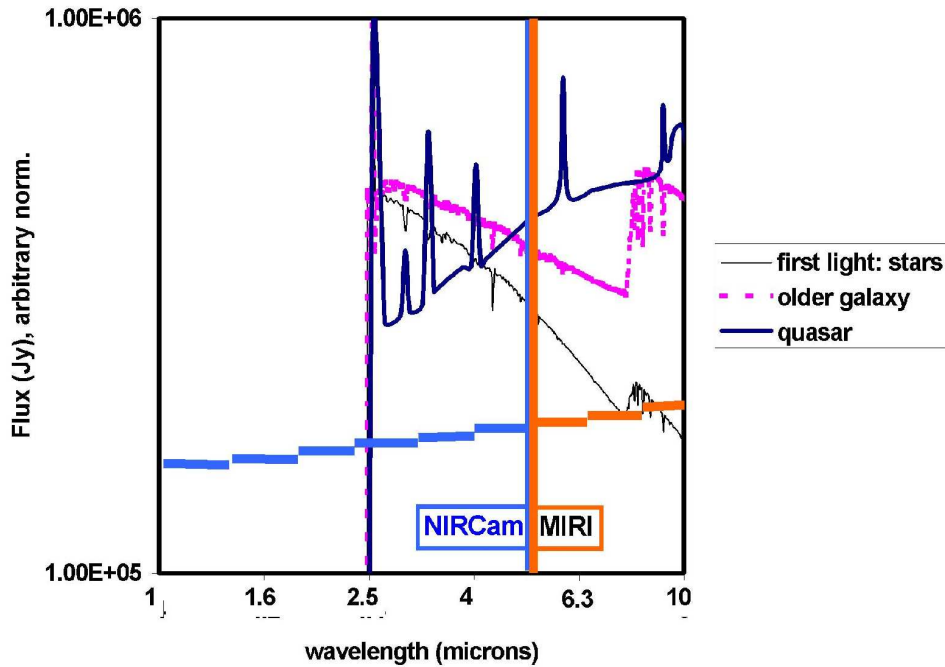
All JWST Flight instruments to be delivered to GSFC in Fall 2011.

# Flight NIRSpec First Light



ESA's JWST NIRSpec has seen First Light (at  $z \simeq 0!$ ) in late 2010.

- (2) What sensitivity will JWST have?



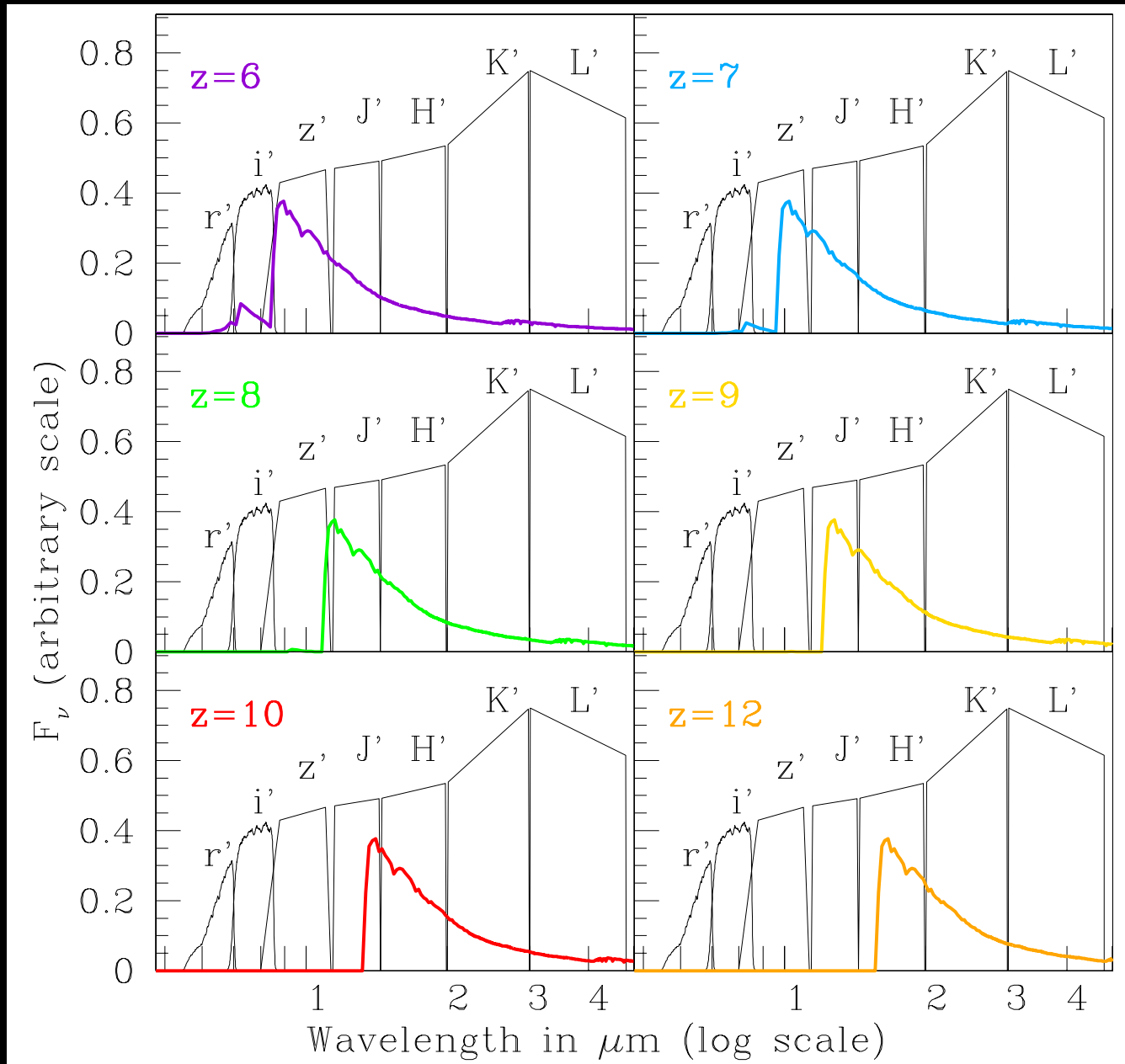
NIRCam and MIRI sensitivity complement each other, straddling  $\lambda \simeq 5 \mu\text{m}$ .

Together, they allow objects to be found to  $z=15-20$  in  $\sim 10^5$  sec (28 hrs).

LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a “First Light” galaxy dominated by massive stars, and a 50 Myr “old” galaxy at  $z=20$ .

RIGHT: Relative survey time vs.  $\lambda$  that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

- (3) How can JWST measure First Light and Reionization?



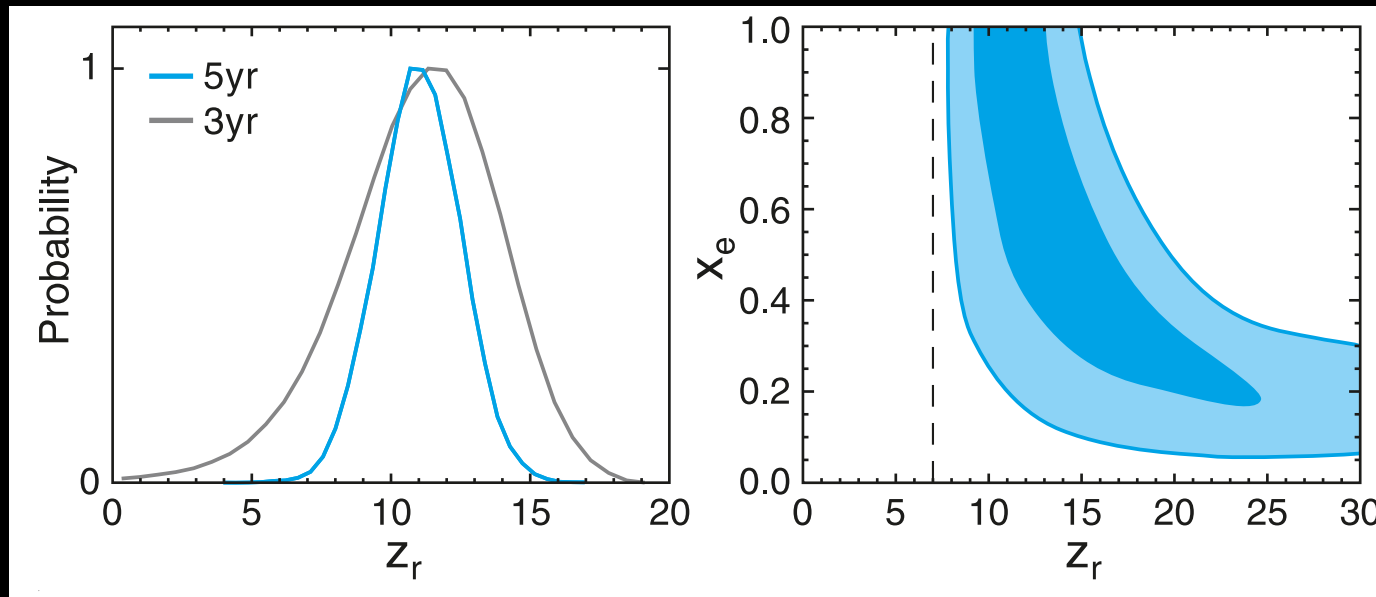
- Can't beat redshift: to see First Light, must observe near-mid IR.

⇒ This is why JWST needs NIRC*am* at 0.8–5  $\mu\text{m}$  and MIRI at 5–29  $\mu\text{m}$ .

# Implications of the (2010) 7-year WMAP results for JWST science:

HST/WFC3  $z \lesssim 7-9$  ←

→ JWST  $z \simeq 8-25$



The year-7 WMAP data provided much better foreground removal (Dunkley et al. 2009; Komatsu et al. 2009, 2010; astro-ph/1001.4538)

⇒ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at  $z \simeq 10.4 \pm 1.2$  ( $\tau = 0.087 \pm 0.014$ ), or, more likely:
- (2) Inhomogeneous & drawn out: starting at  $z \gtrsim 20$ , peaking at  $z \simeq 11$ , ending at  $z \simeq 7$ . The implications for HST and JWST are:

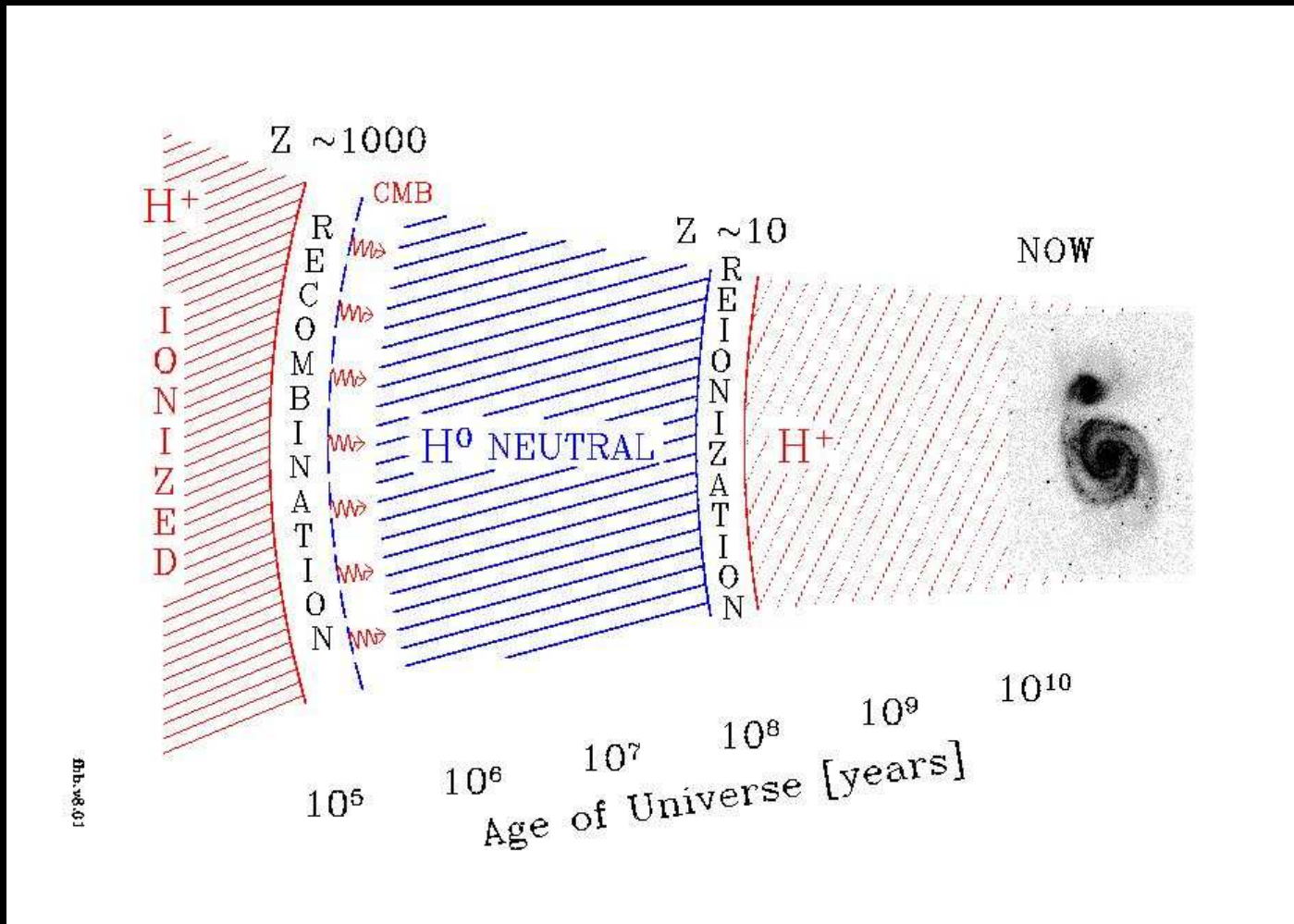
- HST/ACS has covered  $z \lesssim 6$ , and WFC3 is now covering  $z \lesssim 7-9$ .

- For First Light & Reionization, JWST must sample  $z \simeq 8$  to  $z \simeq 15-20$ .

⇒ JWST must cover  $\lambda = 0.7-29 \mu\text{m}$ , with its diffraction limit at  $2.0 \mu\text{m}$ .

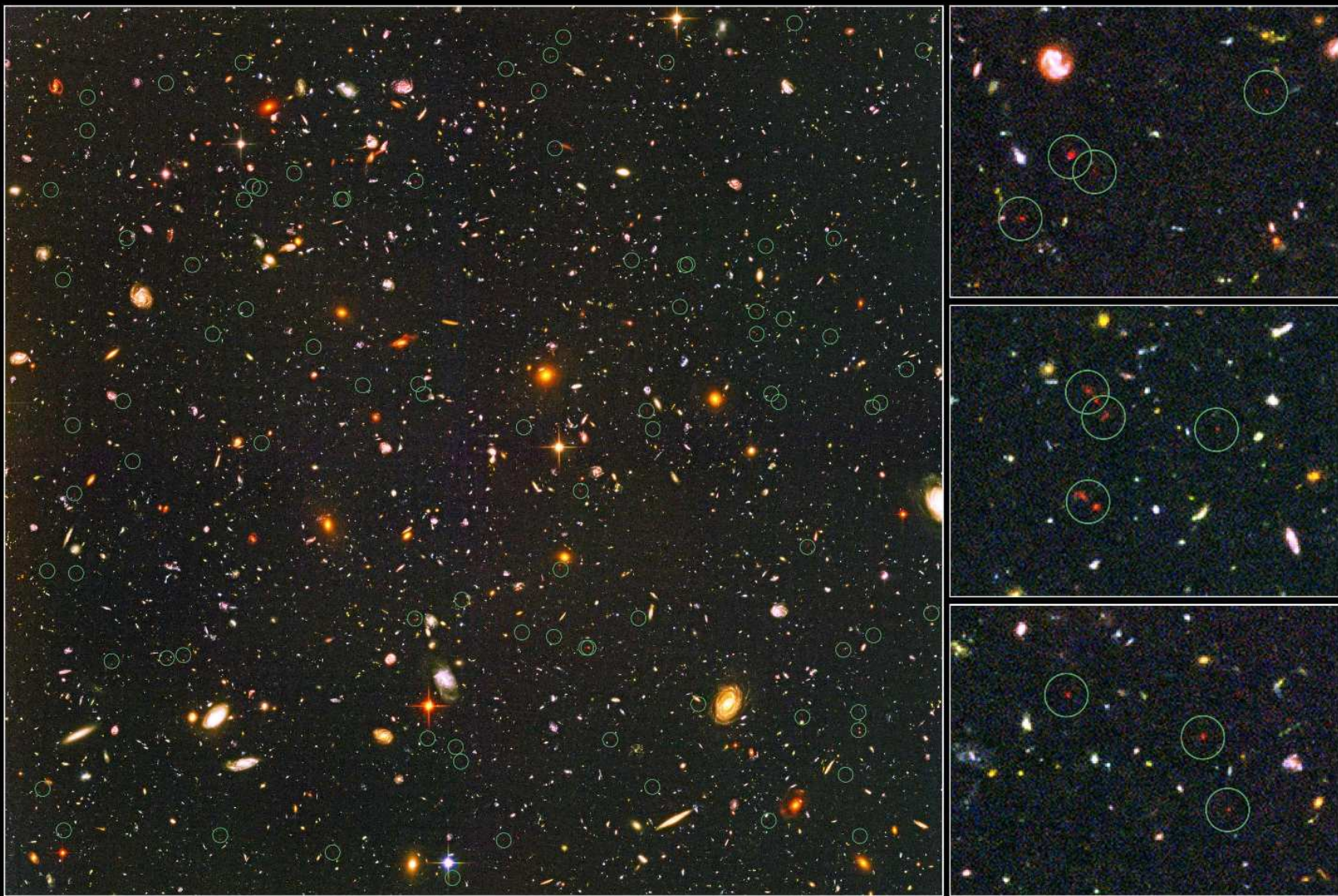


### ● (3) What is First Light and Reionization?



WMAP: First light may have happened as follows (Cen 2003; Spergel 2007):

- (1) Population III stars with  $\gtrsim 200 M_{\odot}$  at  $z \simeq 11-20$  (First Light).
  - (2) First Population II stars (halo stars) form in dwarf galaxies of mass  $\simeq 10^7$  to  $10^9 M_{\odot}$  at  $z \simeq 6-9$ , which complete reionization by  $z \simeq 6$ .
- ⇒ JWST needs NIRCam at  $0.8-5 \mu\text{m}$  and MIRI at  $5-29 \mu\text{m}$ .

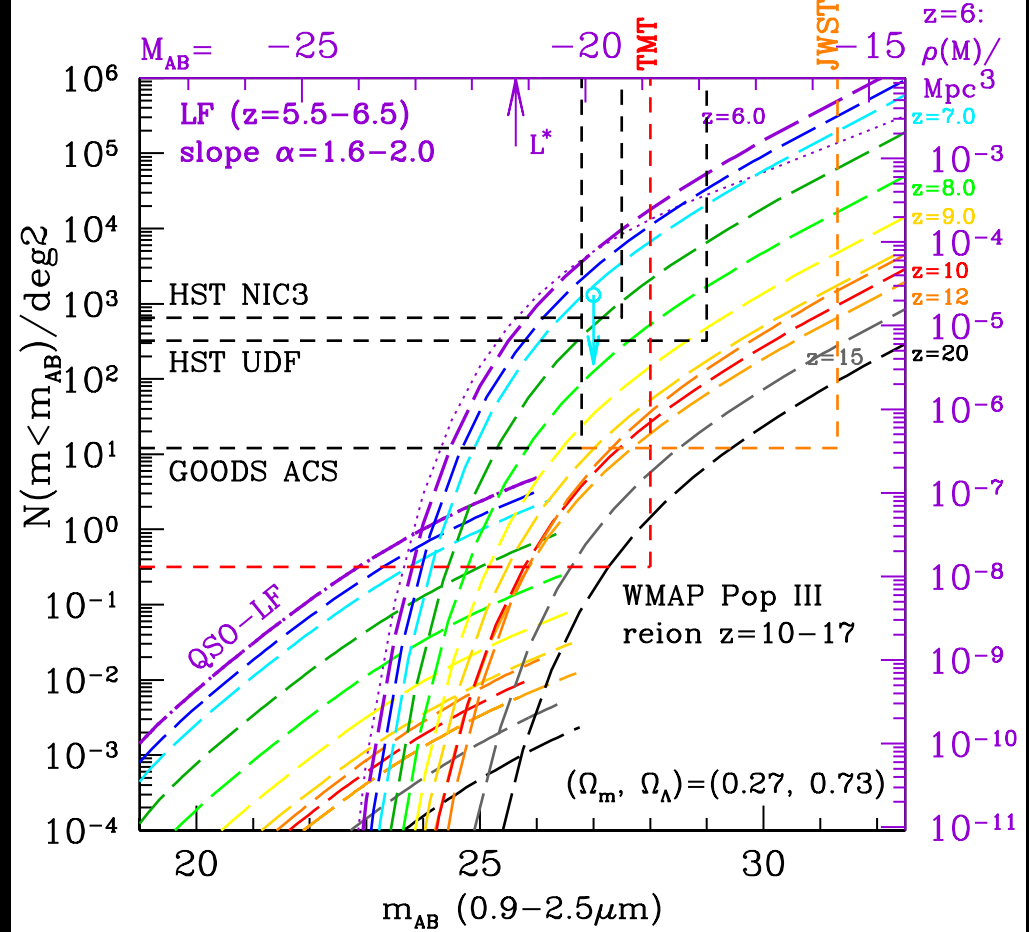
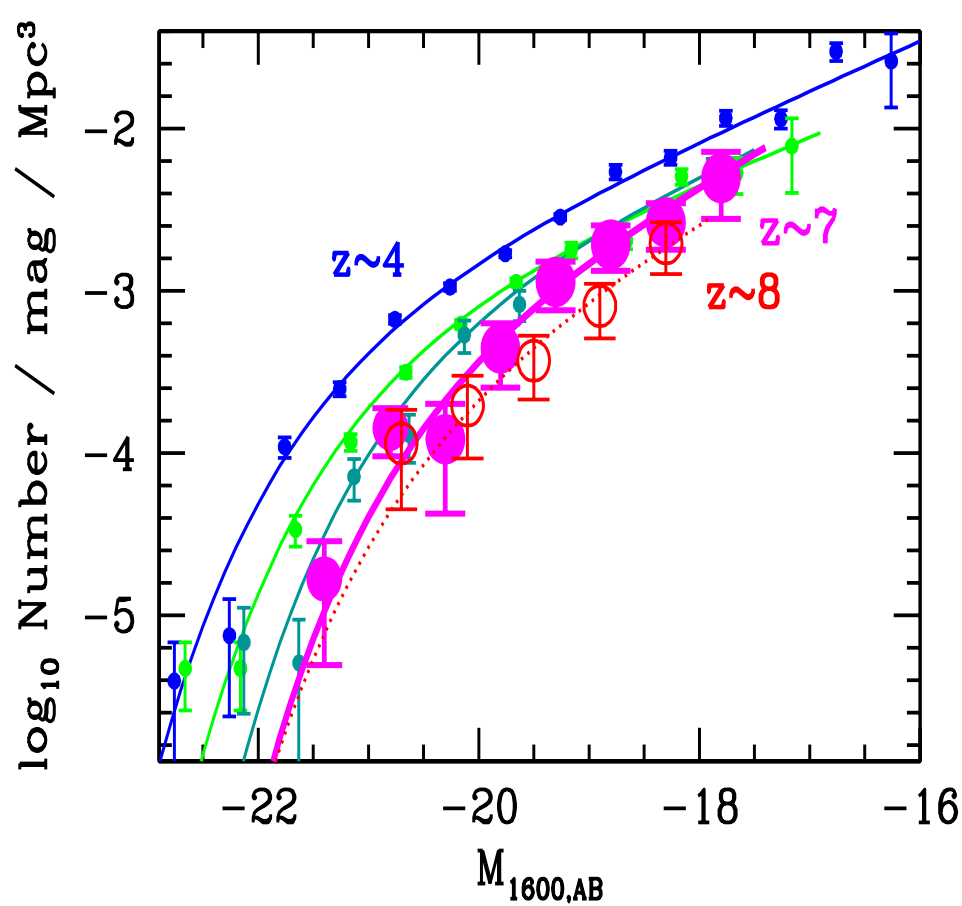


**Distant Galaxies in the Hubble Ultra Deep Field  
Hubble Space Telescope • Advanced Camera for Surveys**

NASA, ESA, R. Windhorst (Arizona State University) and H. Yan (Spitzer Science Center, Caltech)

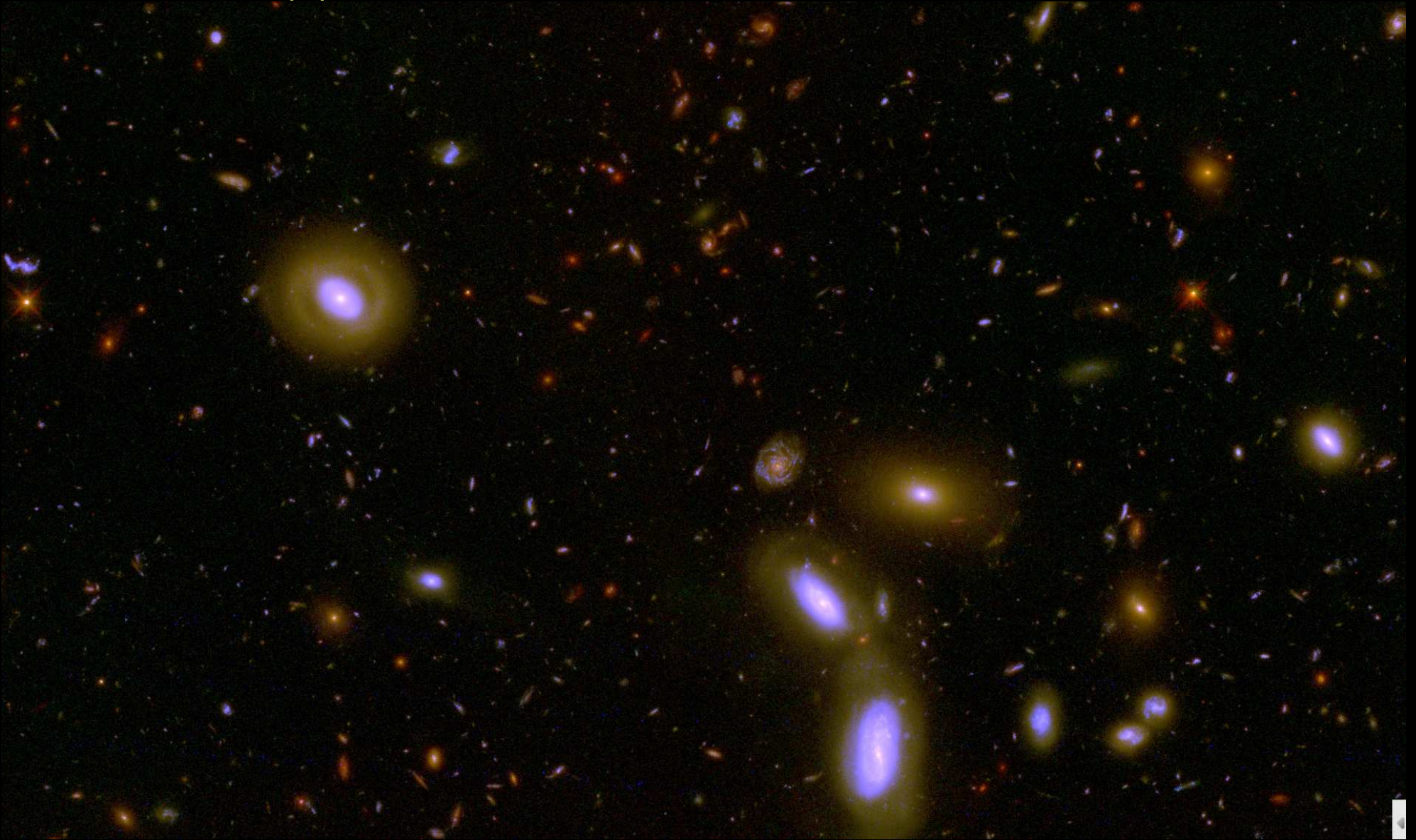
STScI-PRC04-28

HUDF i-drops: faint galaxies at  $z \simeq 6$  (Yan & Windhorst 2004), most spectroscopically confirmed at  $z \simeq 6$  to  $AB \lesssim 27.0$  mag (Malhotra et al. 2005).



- Objects at  $z \gtrsim 9$  are rare (Bouwens<sup>+</sup> 2010, Yan<sup>+</sup> 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture ( $A$ ), field-of-view ( $\Omega$ ), and  $\lambda$ -range ( $0.7\text{-}29 \mu\text{m}$ ).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- To study co-evolution of SMBH-growth and proto-bulge assembly for  $z \lesssim 10\text{-}15$  requires new AGN finding techniques for JWST.

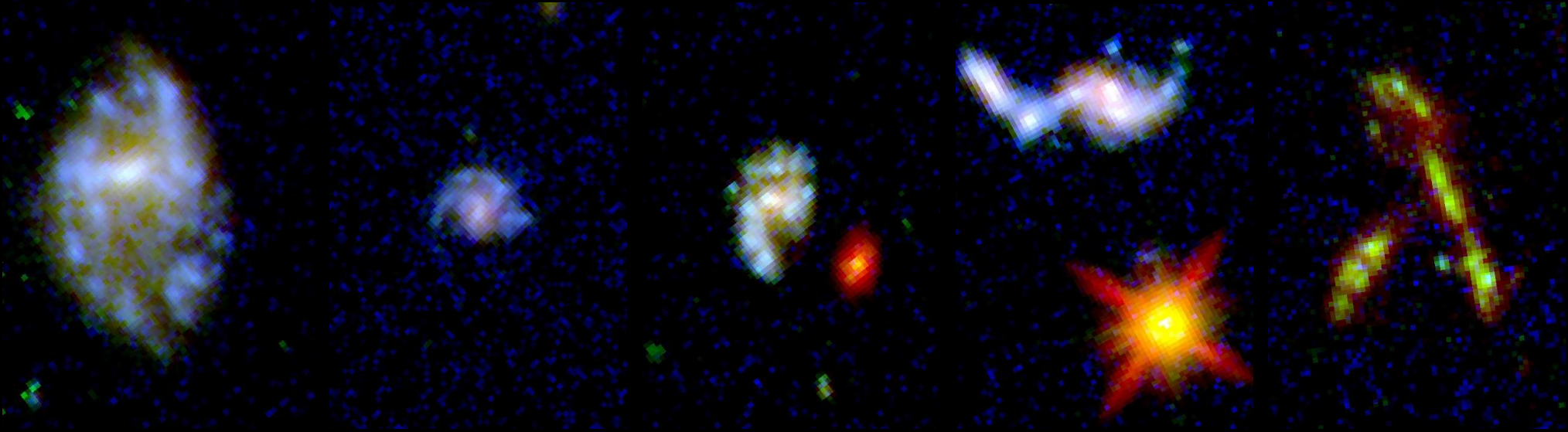
- (4) How can JWST measure Galaxy Assembly?



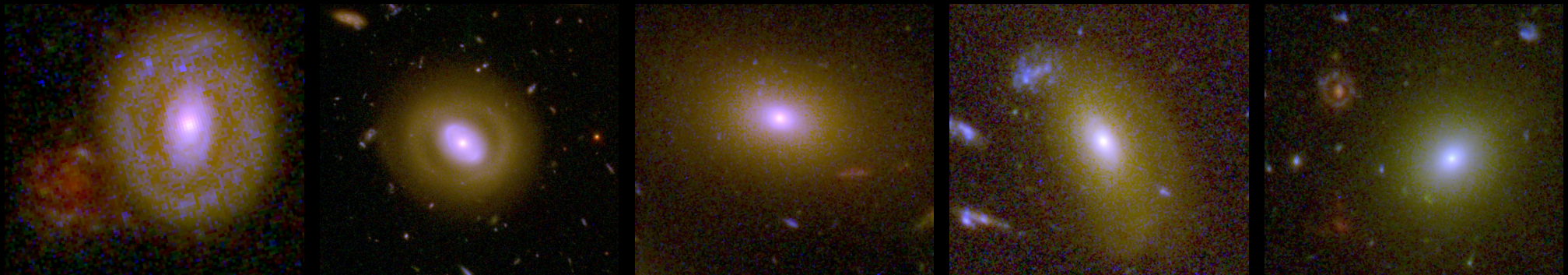
10 filters with HST/WFC3 & ACS reaching  $AB=26.5-27.0$  mag ( $10-\sigma$ ) over  $40 \text{ arcmin}^2$  at  $0.07-0.15''$  FWHM from  $0.2-1.7 \mu\text{m}$  (UVUBVizYJH).

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.

## Some science results of the Wide Field Camera Early Release Science data



Galaxy structure at the peak of the merging epoch ( $z \simeq 1-2$ ) is very rich: some resemble the cosmological parameters  $H_0$ ,  $\Omega$ ,  $\rho_0$ ,  $w$ , and  $\Lambda$ , resp.

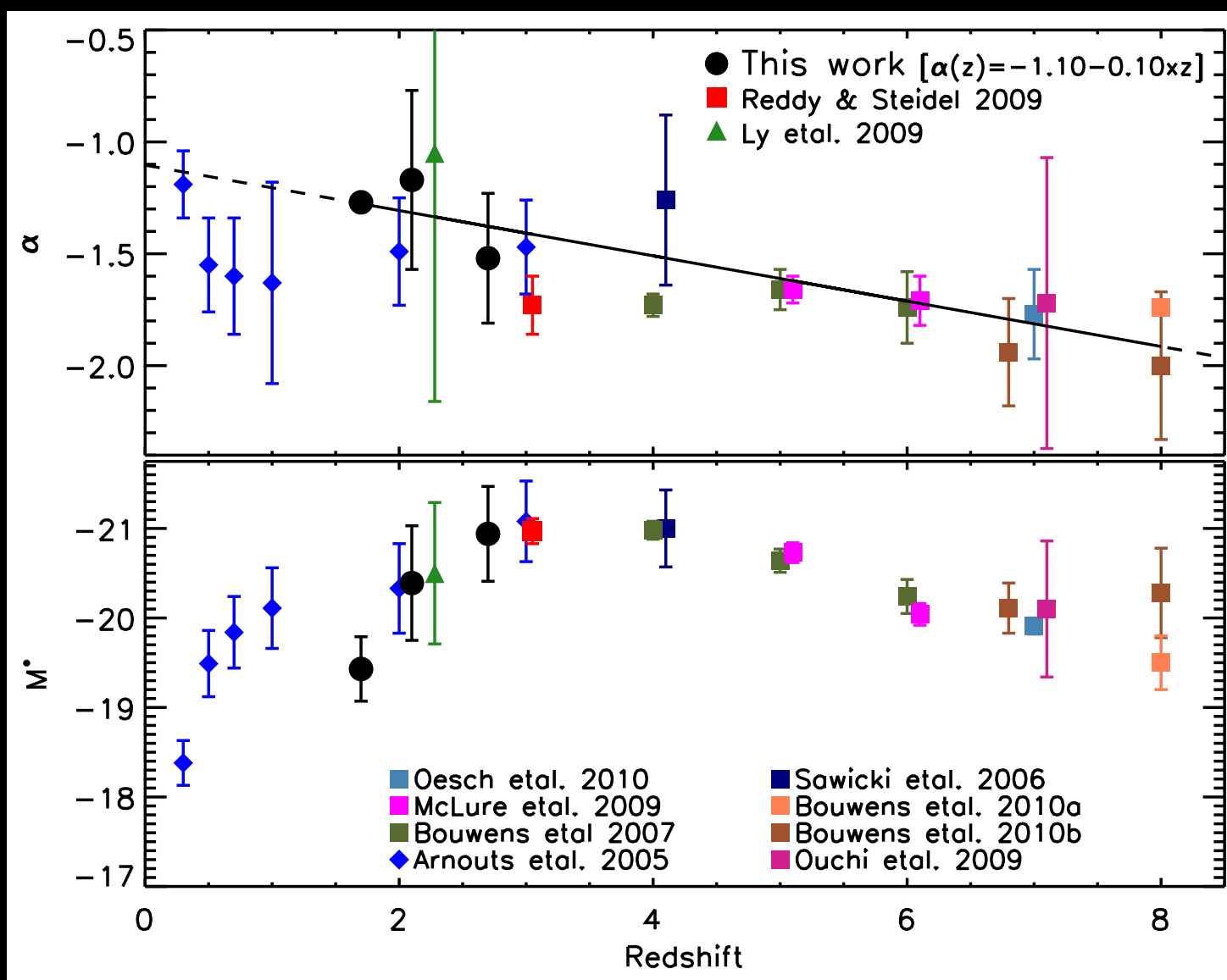


Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(Rutkowski et al. 2010)  $\implies$  “Red and dead” galaxies aren’t dead!

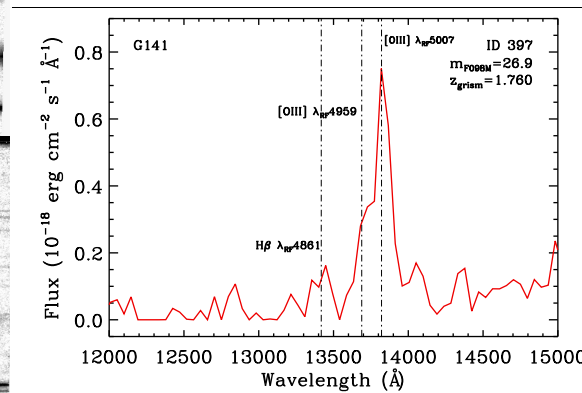
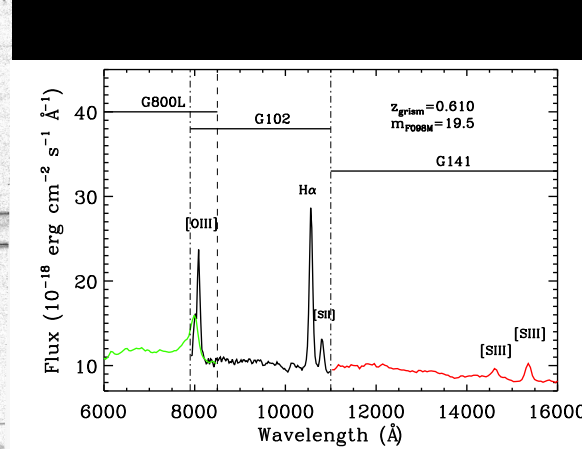
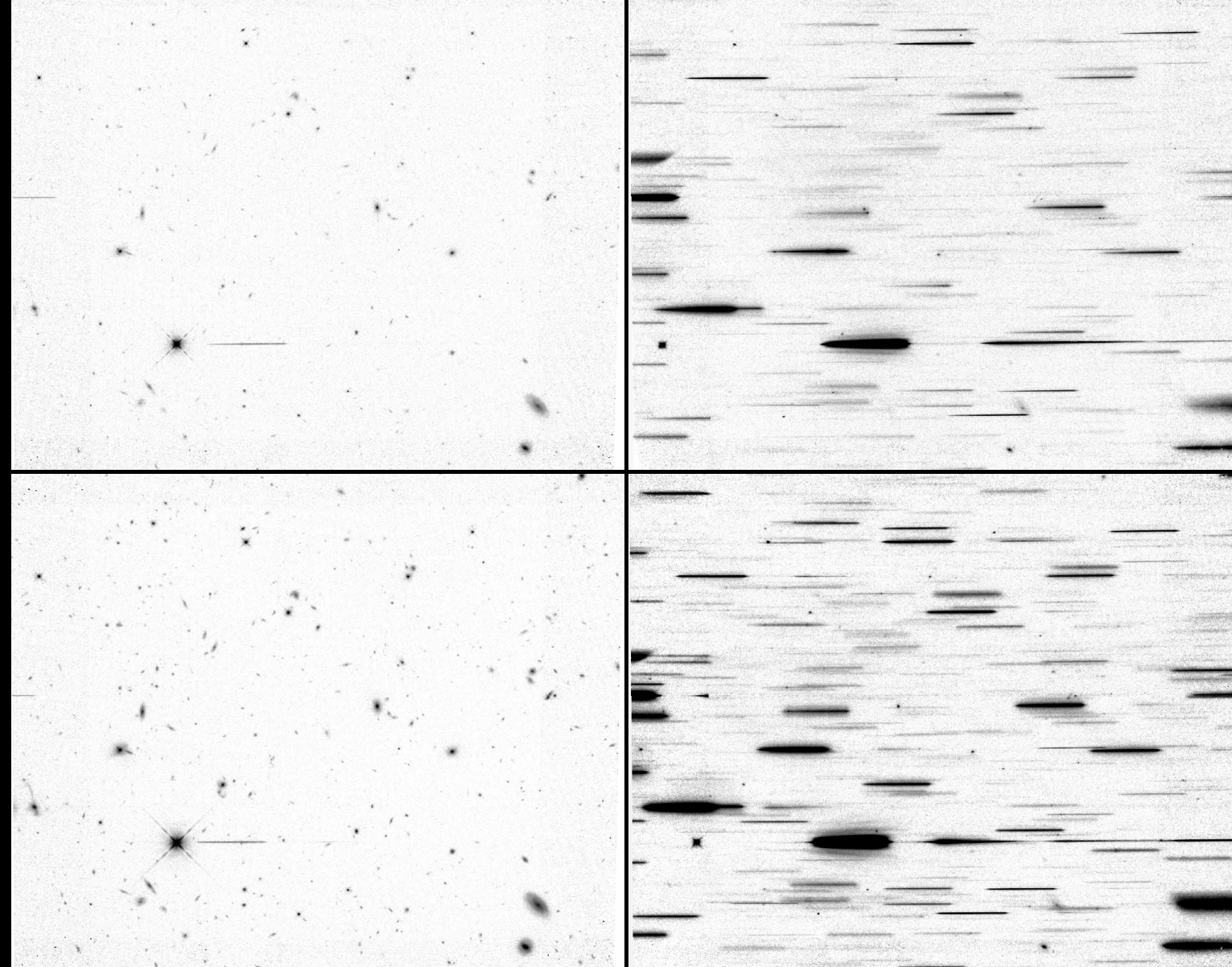
- JWST will observe all such objects from 0.7–29  $\mu\text{m}$  wavelength.





Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010, ApJ, 720, 1708 (arXiv:1004.5141v2).

- In the JWST regime at  $z \gtrsim 8$ , expect faint-end LF slope  $\alpha \simeq 2.0$ !
- Also at  $z \gtrsim 10$ , expect characteristic Schechter luminosity  $M^* \gtrsim -19$ .



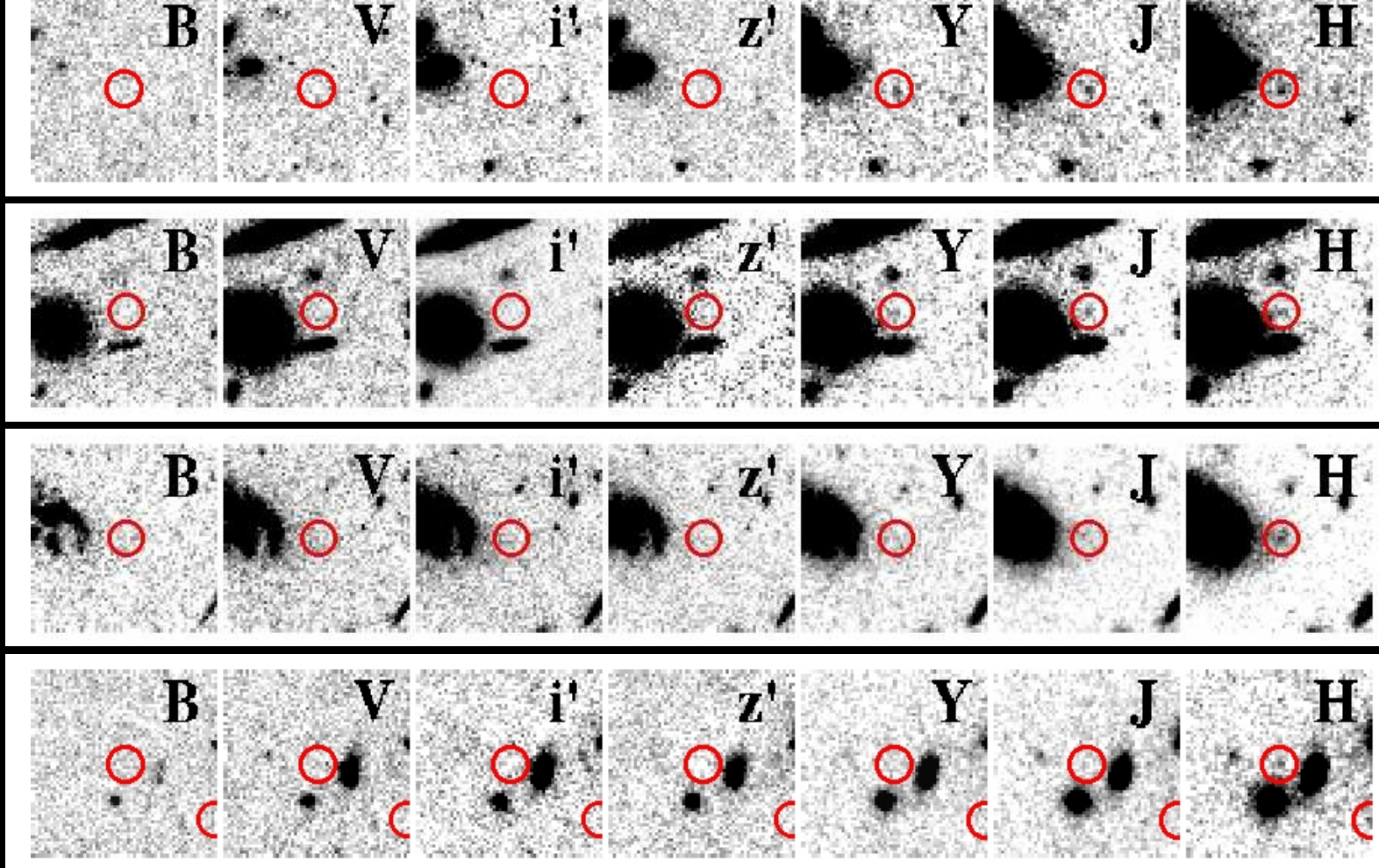
Low-res grism z's in 2 orbits for  $AB \lesssim 27$ .

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

IR grisms bode well for WFIRST: unprecedented opportunities in astrophysics.

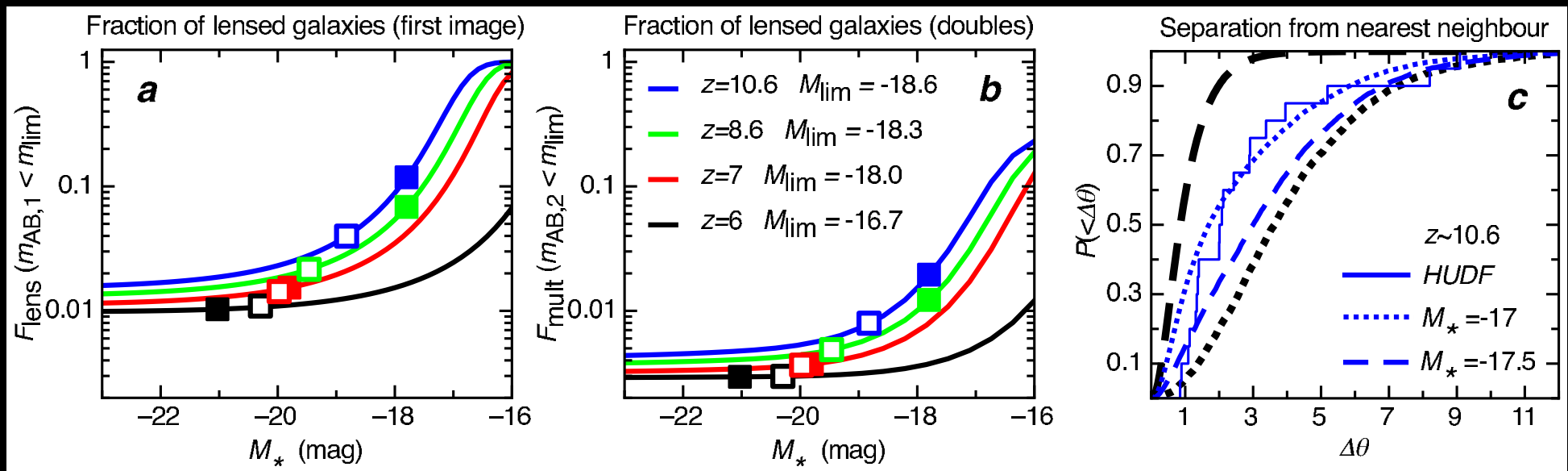
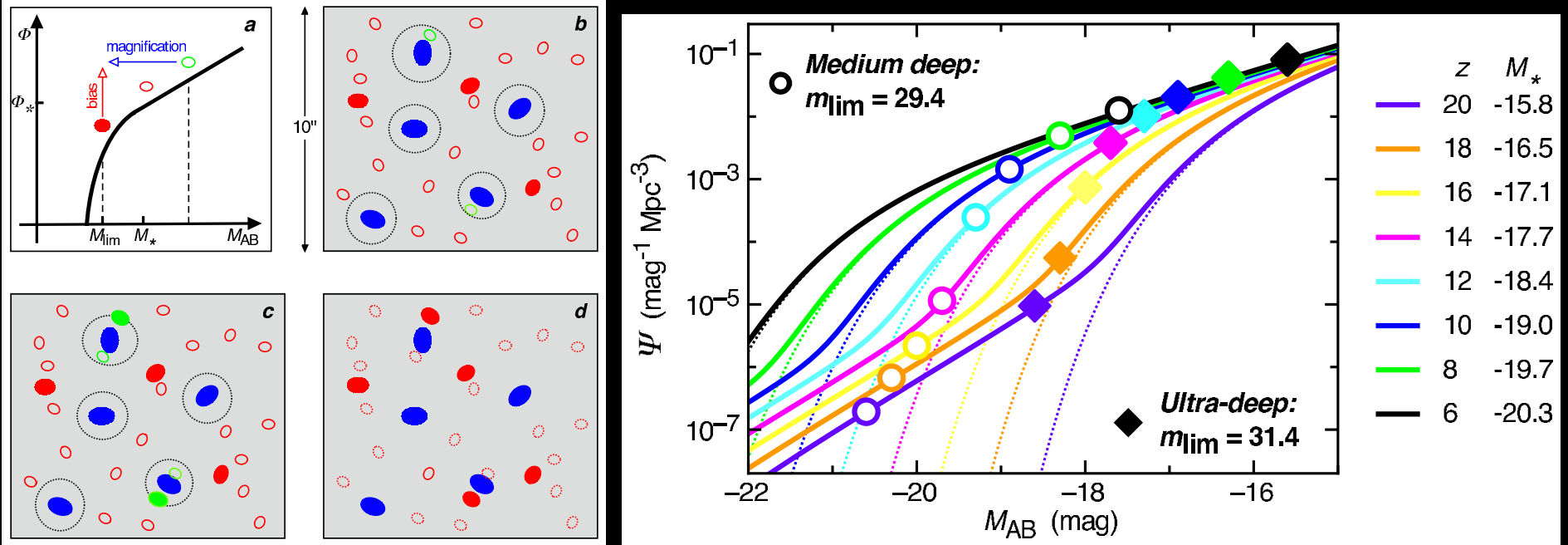
- JWST will provide near-IR grism spectra to  $AB \lesssim 29$  mag from 2–5.0  $\mu\text{m}$ .





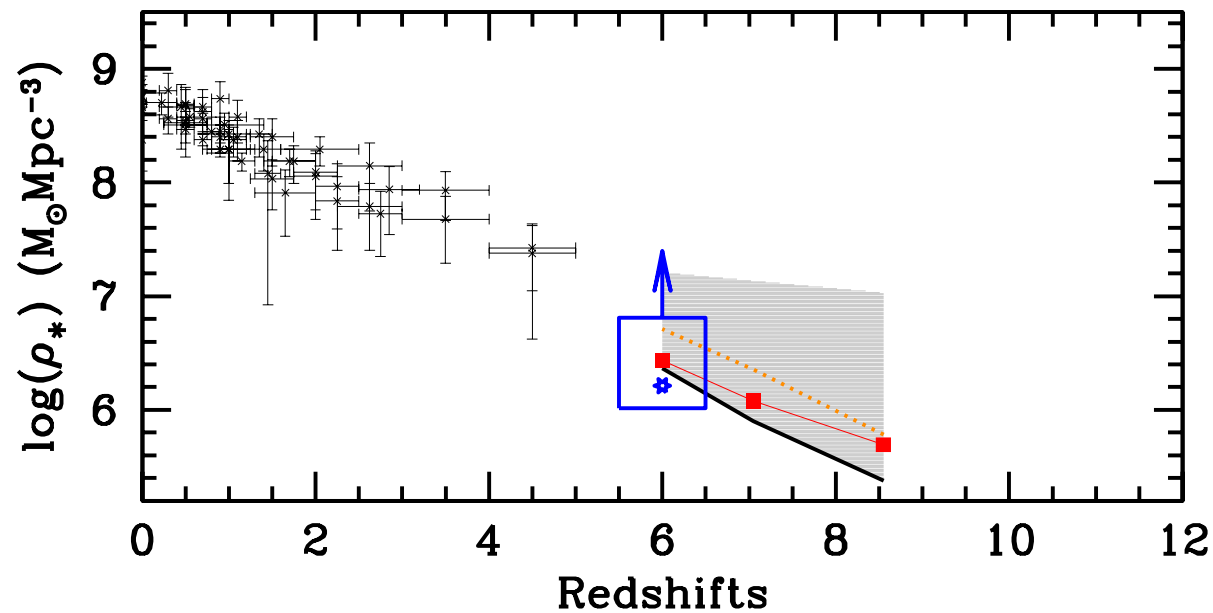
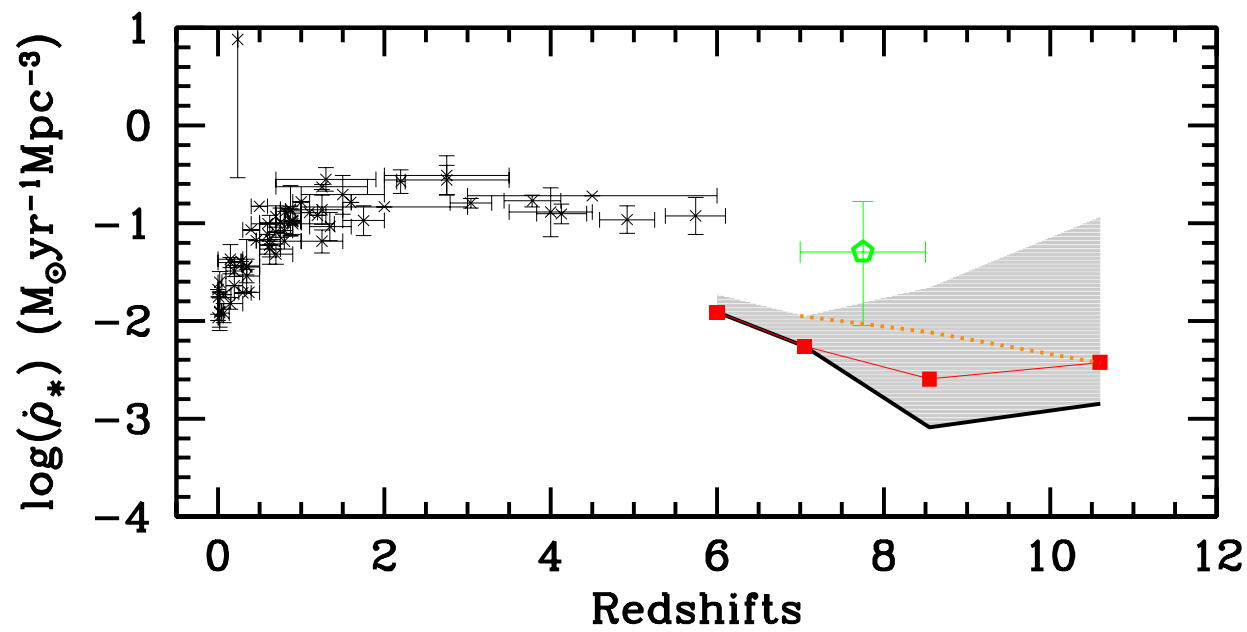
- Gravitational lensing bias is significant:  $\gtrsim 20\%$  of Y-drops ( $z \simeq 8$  candidates) and  $\gtrsim 40\%$  of J-drops ( $z \simeq 10$  candidates) close to foreground galaxies ( $z \simeq 1-2$ ; Yan et al. 2010, Res. Astr. & Ap., 10, 867; astro.0910.0077).
- This is expected from gravitational lensing bias by galaxy dark matter halo distribution at  $z \simeq 1-2$  (Wyithe et al. 2011, Nature, 469, 181).
- Need JWST to measure  $z \gtrsim 9$  LF, and see if it's fundamentally different from the  $z \lesssim 8$  LFs. Does gravitational lensing bias cause power-law LF?





Wyithe et al. (2011, Nature, 469, 181): With a steep faint-end LF-slope  $\alpha \gtrsim 2$ , and a characteristic faint  $M^* \gtrsim -19$  mag, foreground galaxies (at  $z \simeq 1-2$ ) may cause significant boosting by gravitational lensing at  $z \gtrsim 8-10$ .

- This could change the landscape for JWST observing strategies.



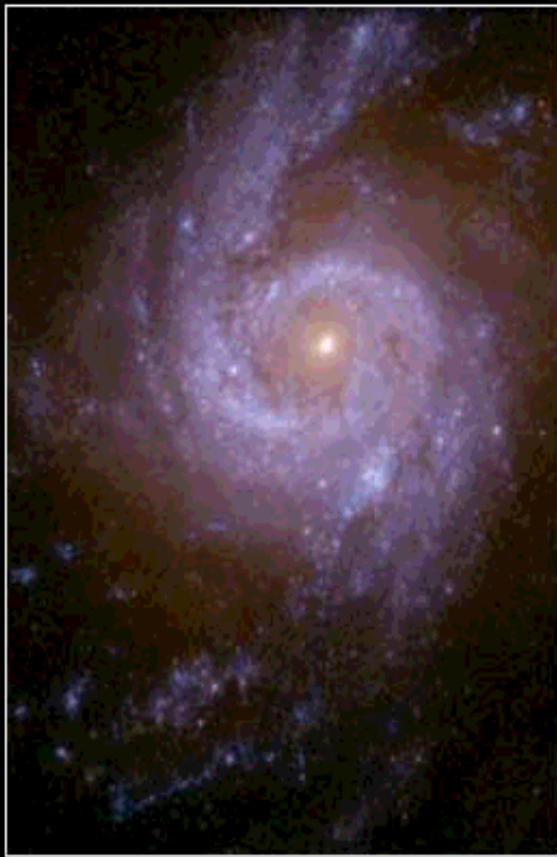
- The current WFC3 uncertainties on Y, J-drops large enough that at  $z \gtrsim 8$ , a wide range of possibilities is allowed (Yan et al. 2010, RAA, 10, 867).
- Need JWST to fully measure the LF and SFR for  $8 \lesssim z \lesssim 15$ .

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

NGC 3310

ESO0418-008

UGC06471-2



### Ultraviolet Galaxies

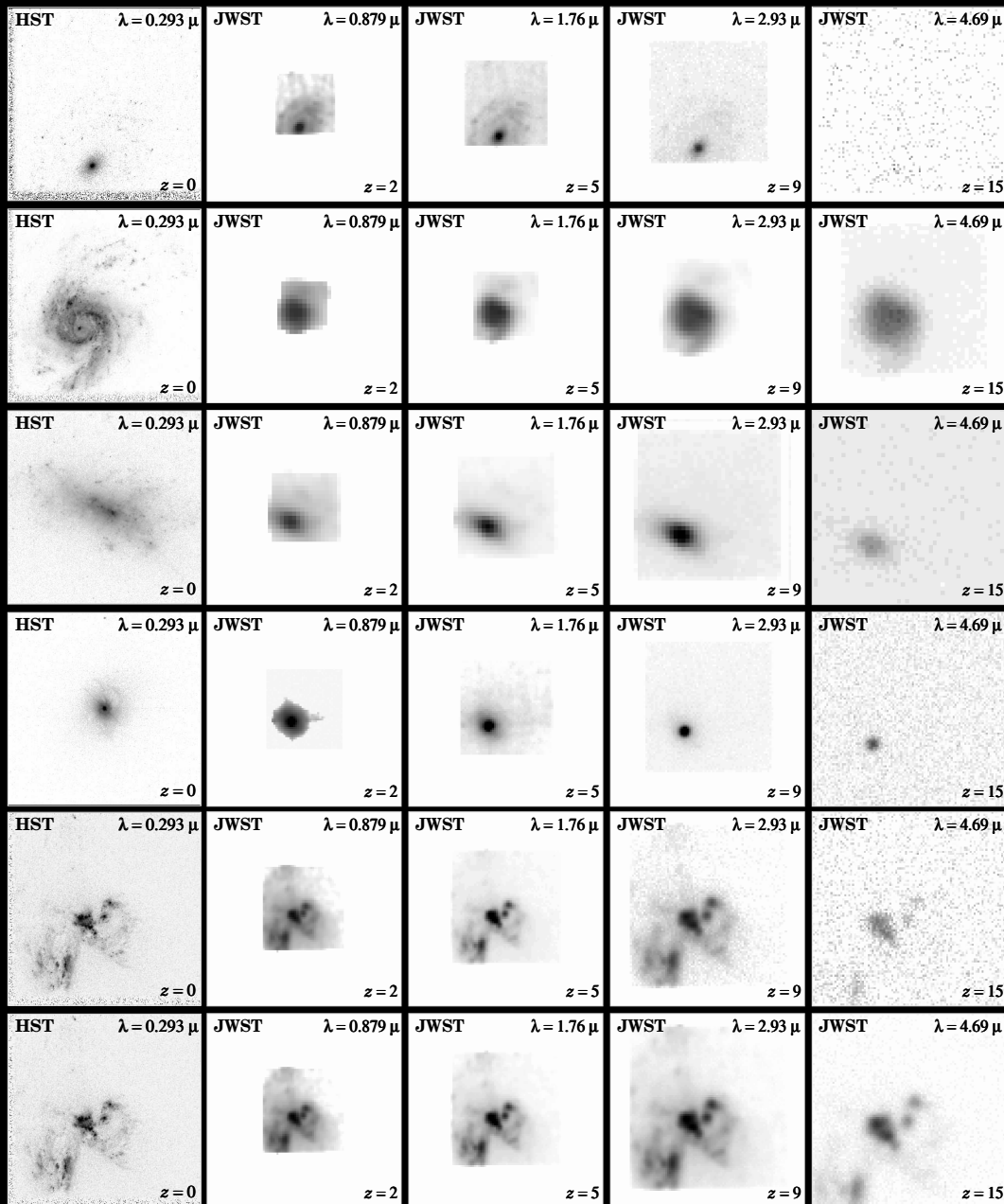
HST • WFPC2

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 copious amounts of dust imprinted.
- High-resolution HST UV images are benchmarks for comparison with very high redshift galaxies seen by JWST, enabling quantitative analysis of the restframe- $\lambda$  dependent structure, B/T, CAS, SFR, mass, dust, etc.

# (5) Predicted Galaxy Appearance for JWST at $z \simeq 1-15$ (w/ C. Conselice)

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



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

- (1) Most disks will SB-dim away at high  $z$ , but most formed at  $z \lesssim 1-2$ .
- (2) High SB structures are visible to very high  $z$ .
- (3) Point sources (AGN) are visible to very high  $z$ .
- (4) High SB-parts of mergers/train-wrecks, etc., are visible to very high  $z$ .

## (6) Conclusions

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(1) JWST Project is technologically front-loaded and on track:

- Passed Non-Advocate Review (T-NAR) in 2007, and Mission Preliminary Design Review (PDR) in 2008. Mission CDR in 2010. Replan in 2011.
- More than half of JWST H/W built, & meets/exceeds specs as of 03/11.

(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail. JWST will determine:

- The formation and evolution of the first (reionizing) Pop III star-clusters.
- Gravitational lensing bias at  $z \gtrsim 10-12$ : may not be negligible for JWST.
- Faint-end LF-slope evol: (how) did dwarf galaxies finish reionization?
- The origin of the Hubble sequence in hierarchical formation scenarios.

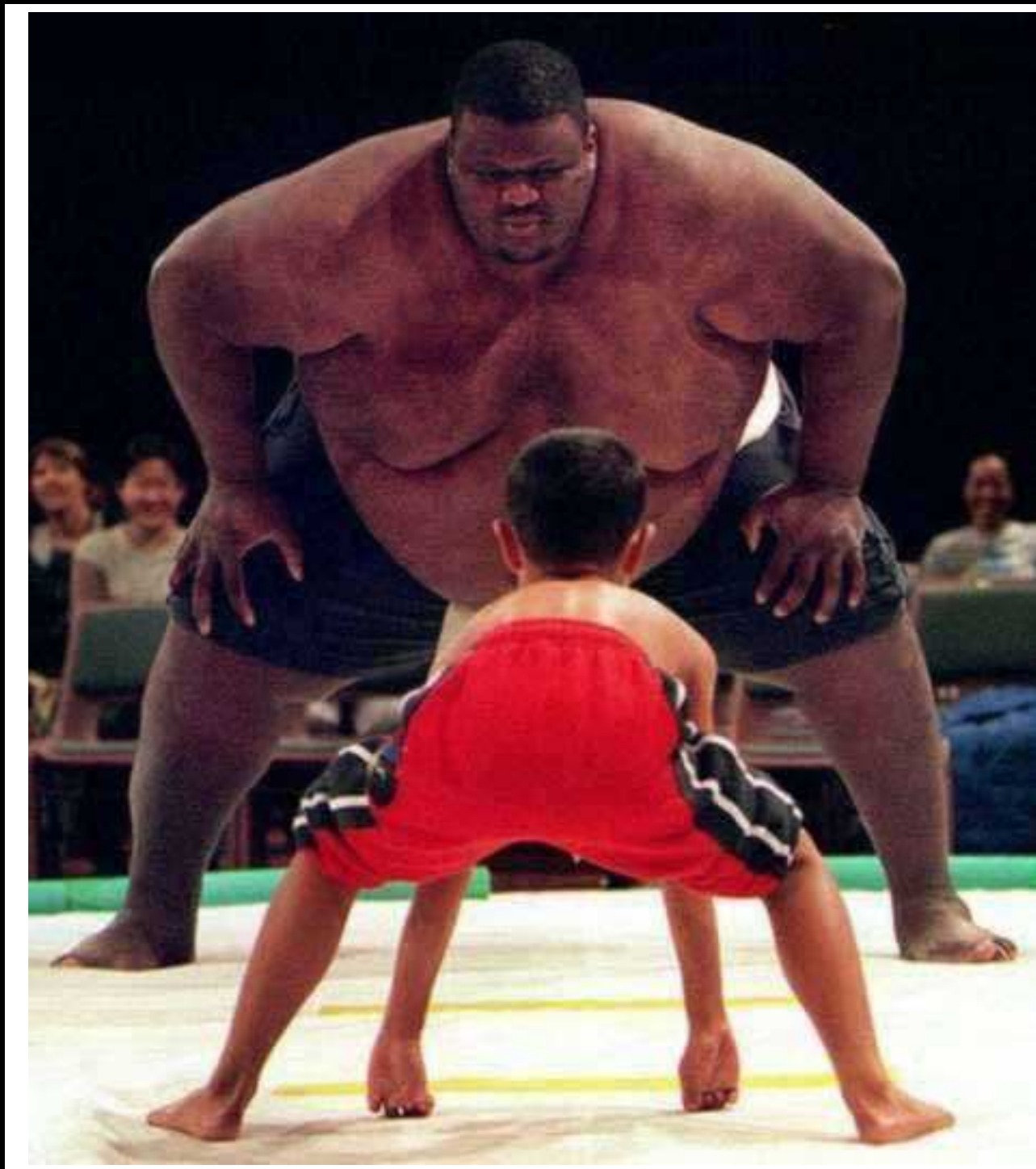
(3) JWST will have a major impact on astrophysics after 2015:

- Current generation students, postdocs will use JWST during their career
- JWST will define the next frontier to explore: the Dark Ages at  $z \gtrsim 20$ .

# SPARE CHARTS

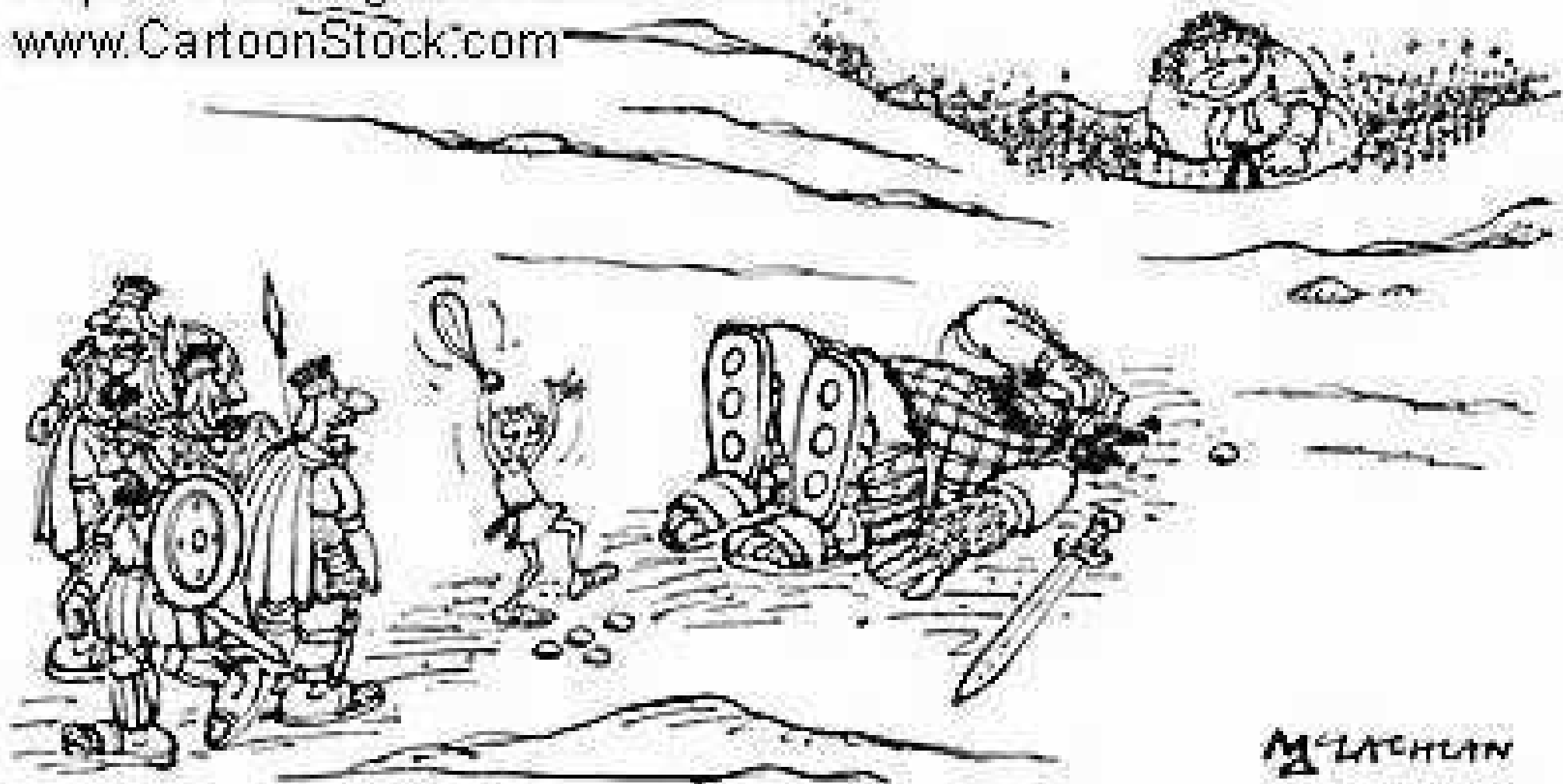
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At the end of reionization, dwarfs had beaten the Giants, but ...

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"You've done it now, David - Here comes his mother."

What comes around, goes around ...

# 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)



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



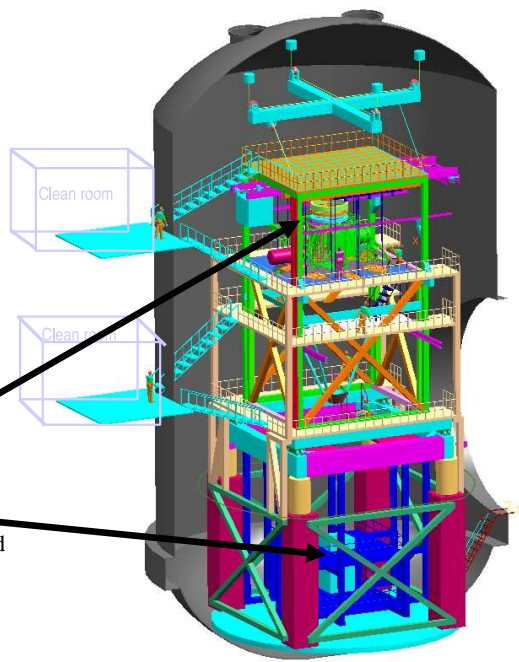
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

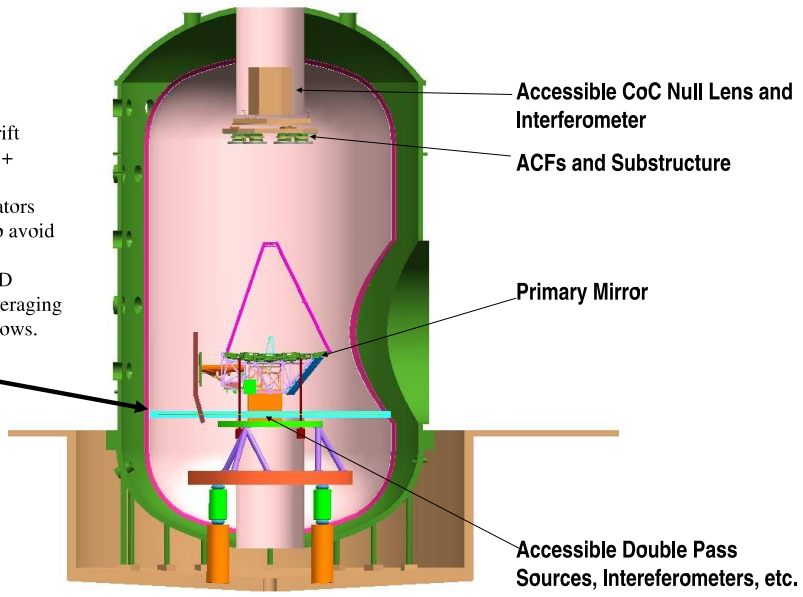
Current plan includes 10 trucks of LN2/day during cooldown

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



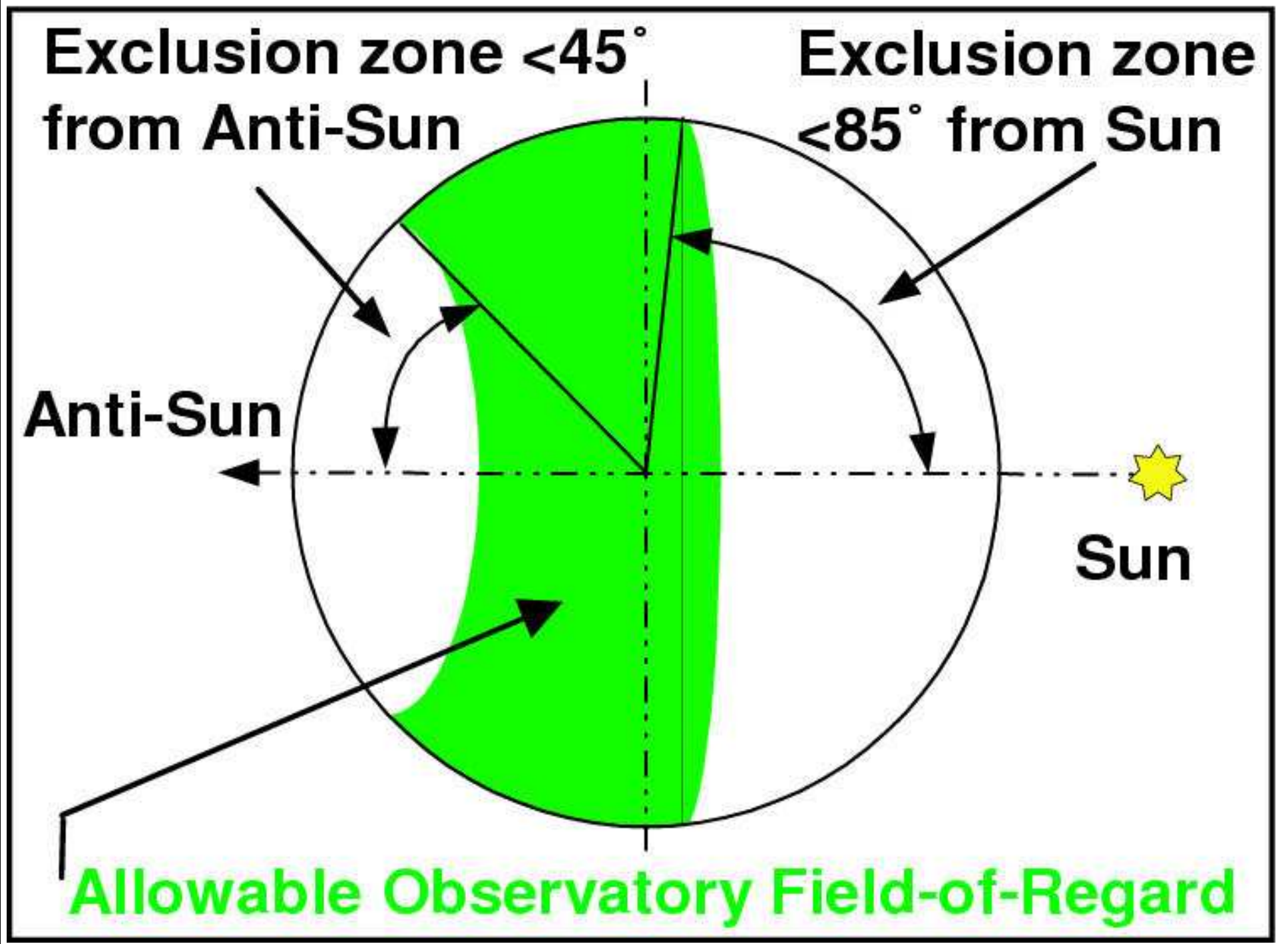
No Metrology Tower and Associated Cooling H/W. External Metrology  
Two basic test options:  
1. Use isolators, remove drift through fast active control + freeze test equipment jitter  
2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter  
Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

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

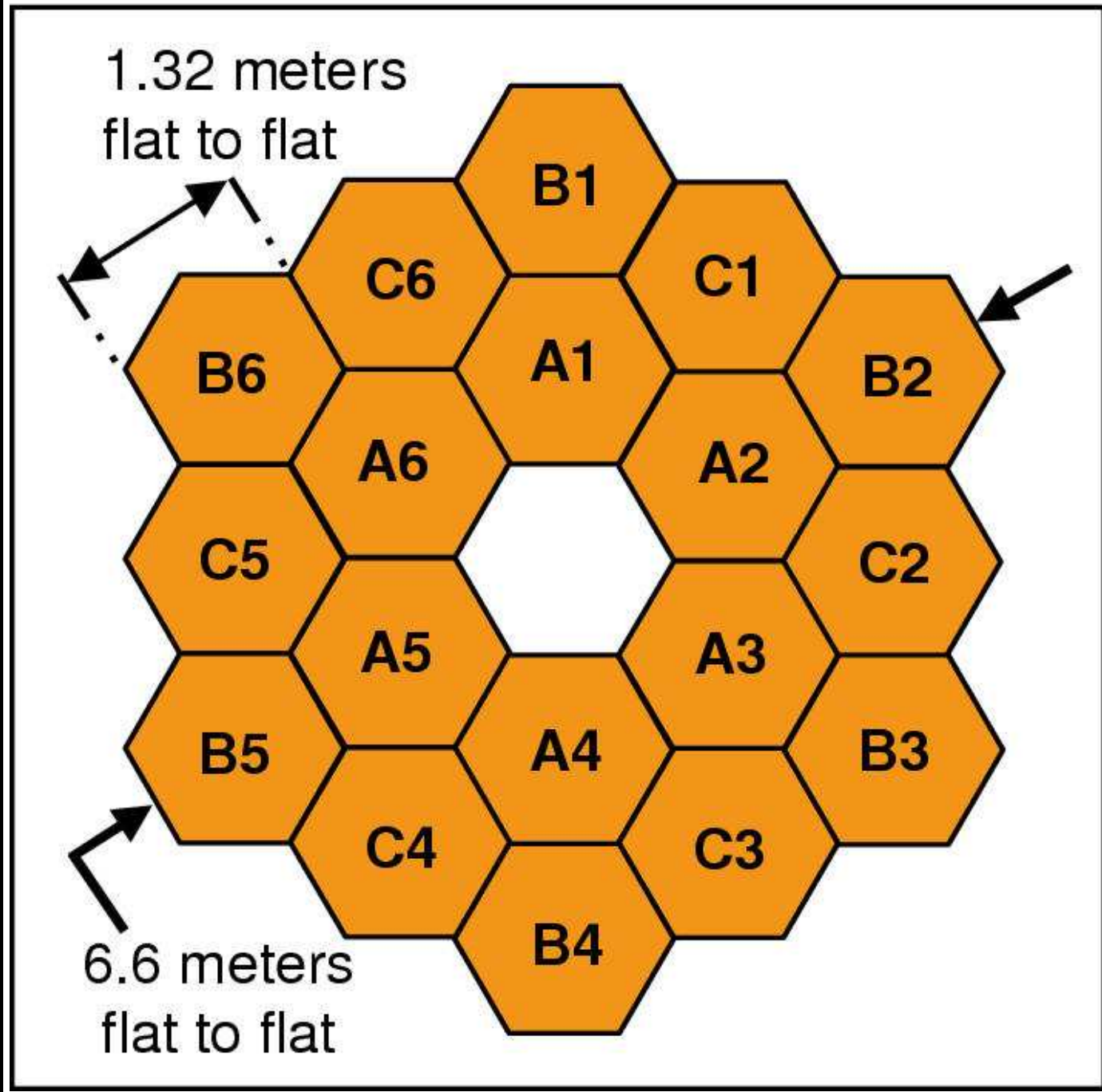


Drawing care of ITT

- 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: Passes Mission Critical Design Review — Reviewing Testing.

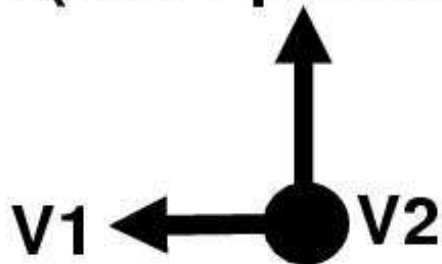


JWST can observe segments of sky that move around as it orbits the Sun.



Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m.  
 Primary mirror segments made (AxSys),  $\geq 6/18$  fully polished (Tinsley).

V3 (anti-spacecraft)



OTE ISIM



(V1, V3)  
origin

Tertiary  
Mirror

Secondary mirror

Cassegrain  
focus

Fine  
Steering Mirror

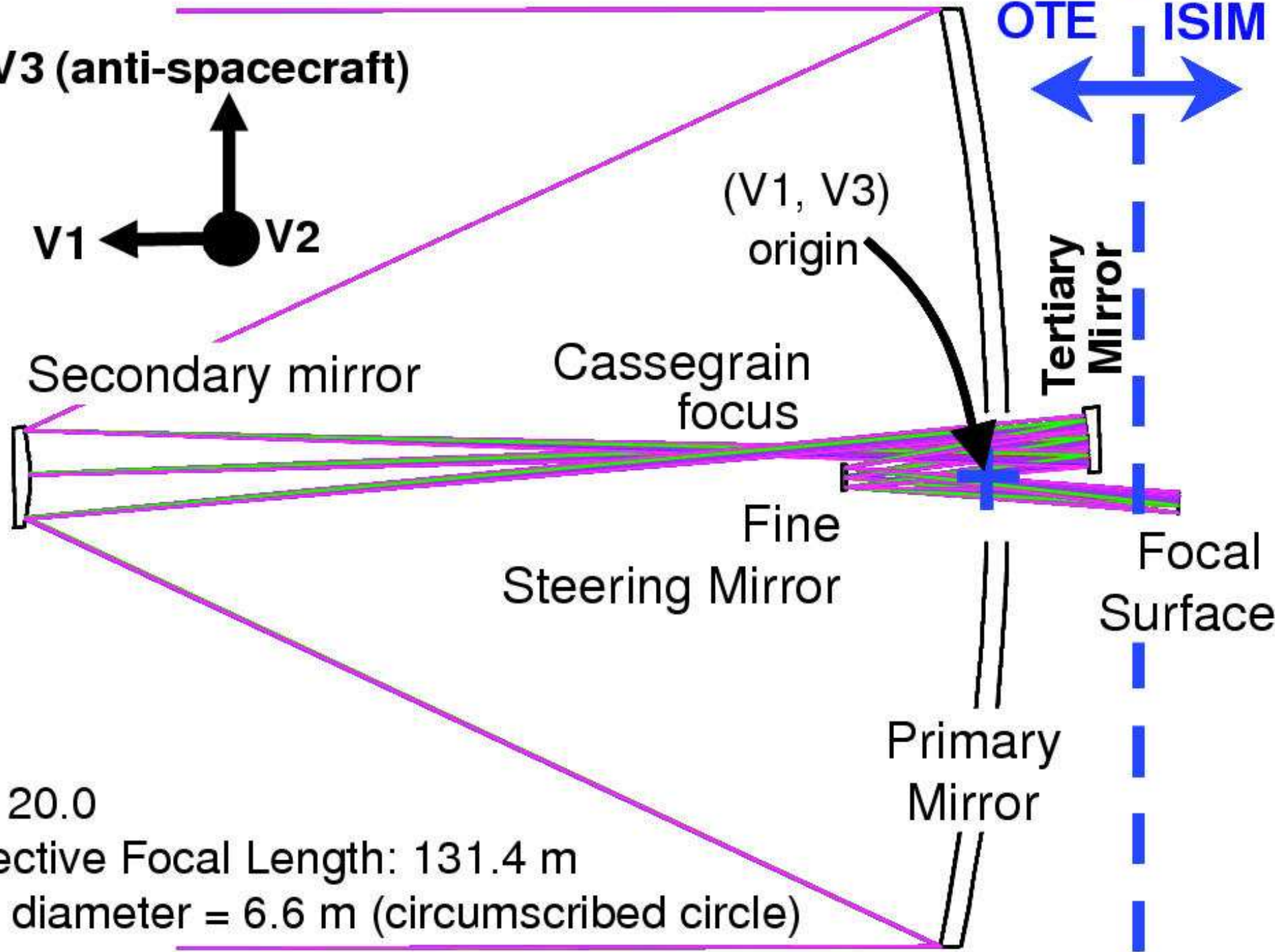
Focal  
Surface

Primary  
Mirror

f/#: 20.0

Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)



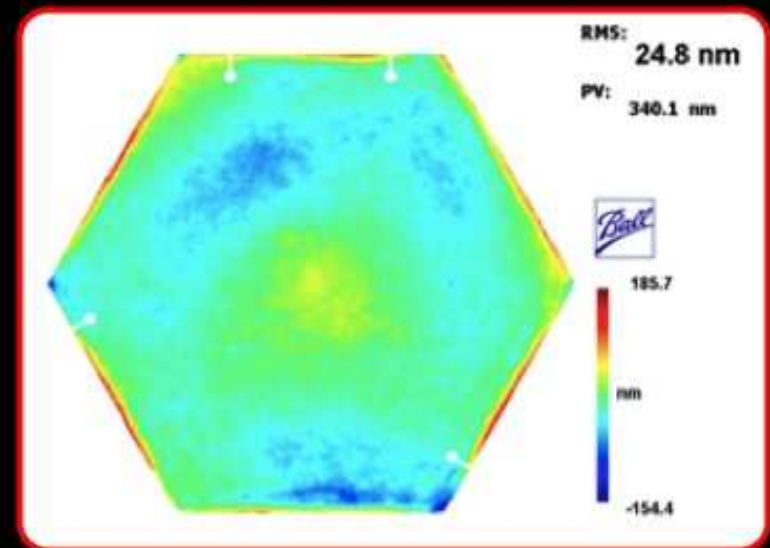


# Flight Mirror Status

- 7 flight primary mirrors completed w/gold coating
  - Acceptance testing under way



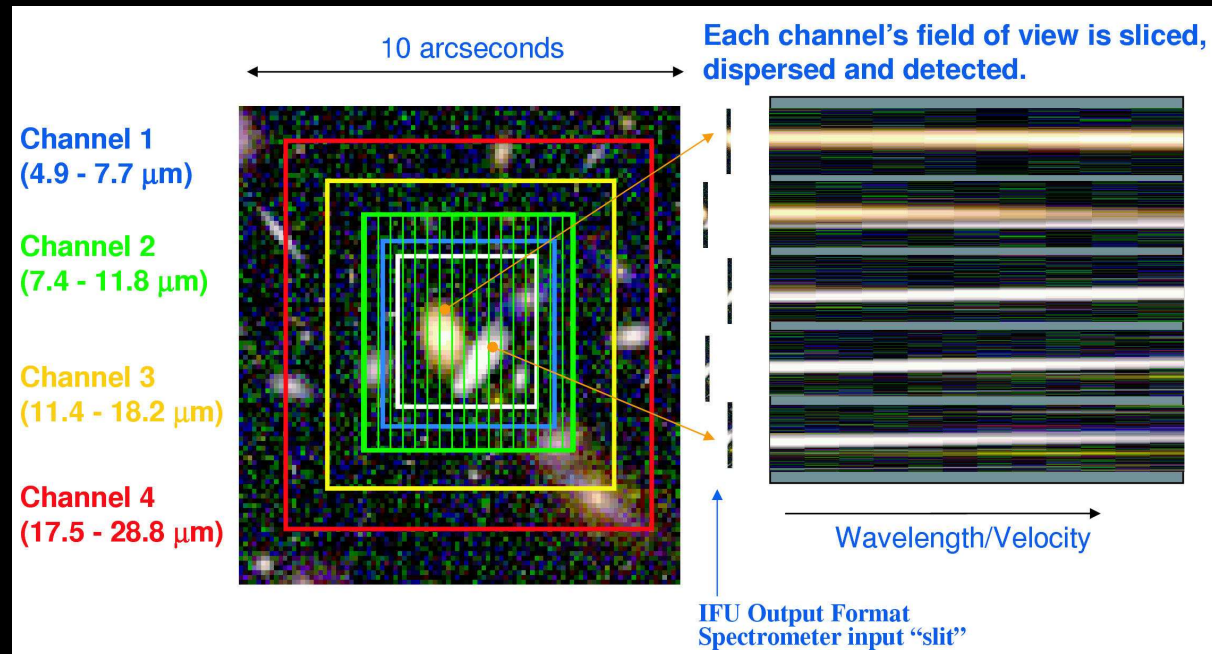
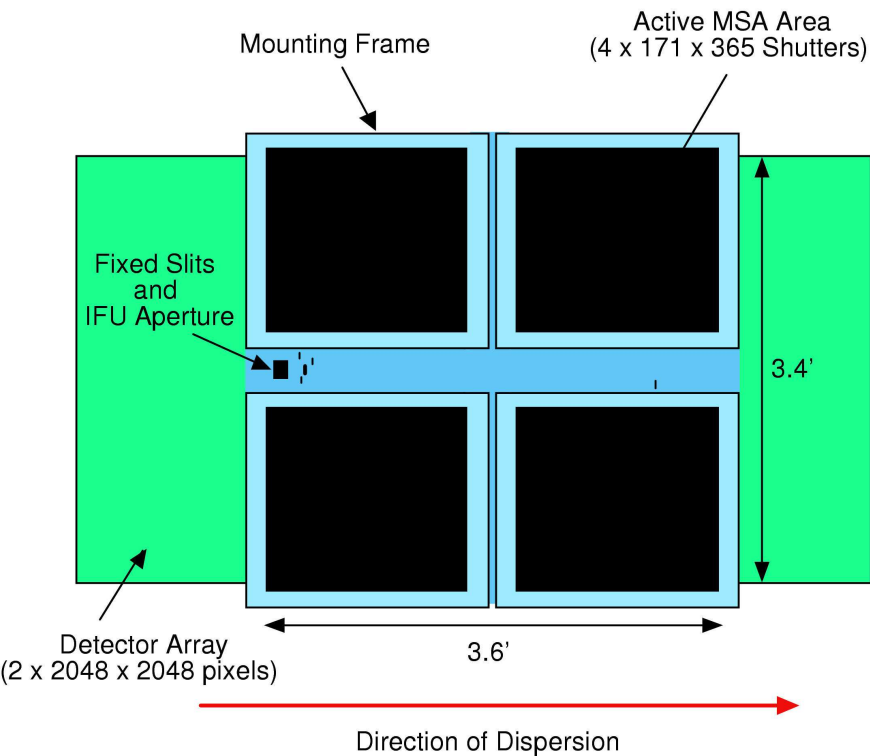
**Flight Mirror A4  
in acceptance vibe**



**EDU Mirror Assembly Complete:  
- Cryogenic optical test (post-vibe)  
meets 25.8 nm requirement**

- 11 flight mirrors in final polishing cycle
- Flight Secondary in final polishing cycle
- *Flight mirror fabrication program will be completed this year*

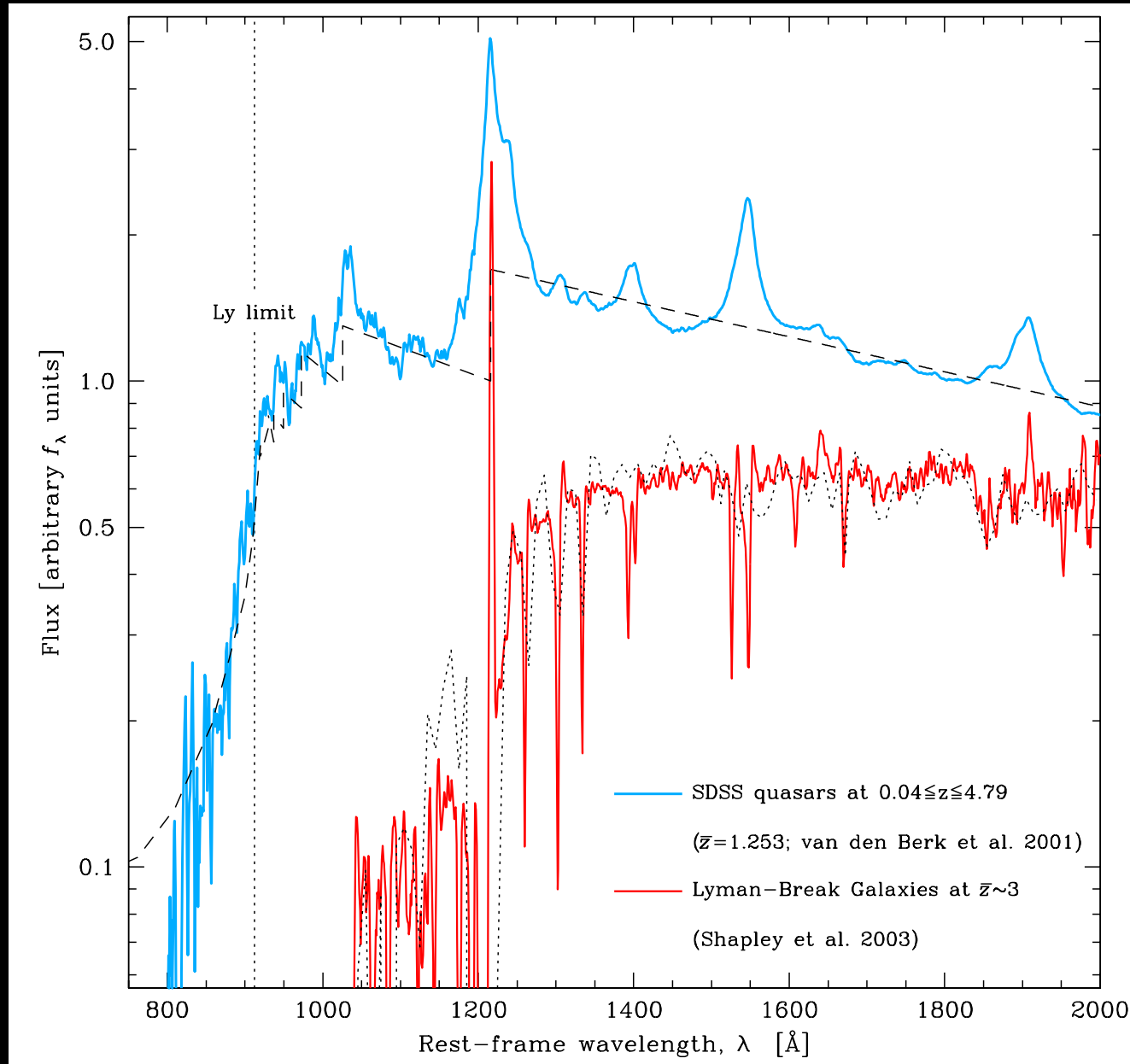




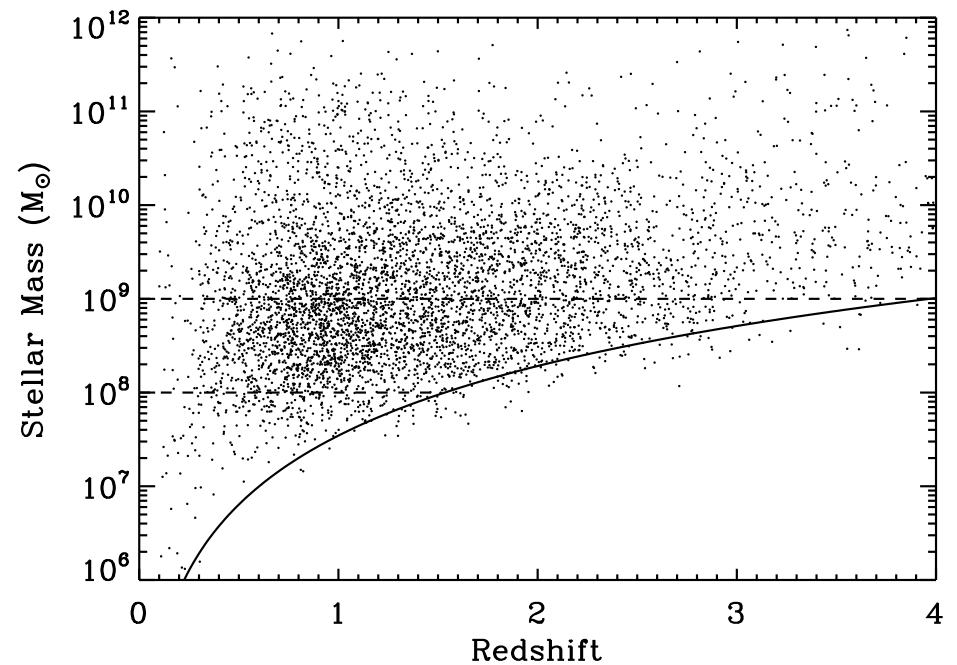
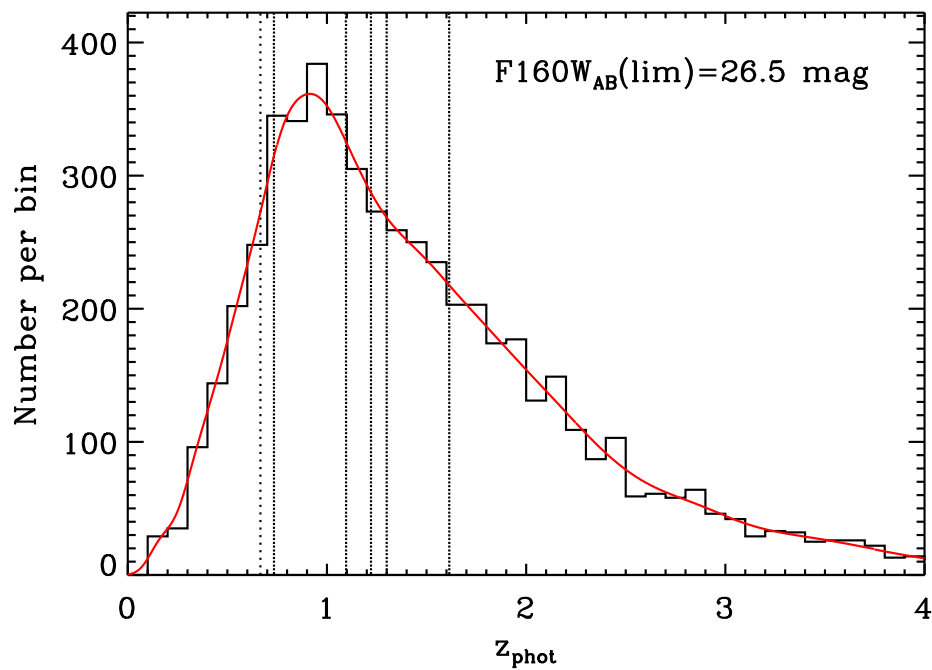
JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MSA with  $4 \times 62,415$  independently operable micro-shutters (MEMS) that cover  $\lambda \simeq 1\text{--}5 \mu\text{m}$  at  $R \simeq 100\text{--}1000$ .
- MIRI/IFU with 400 spatial pixels covering  $5\text{--}29 \mu\text{m}$  at  $R \sim 2000\text{--}4000$ .
- FGS/TFI that covers a  $2!2 \times 2!2$  FOV at  $\lambda \simeq 1.6\text{--}4.9 \mu\text{m}$  at  $R \simeq 100$ .
- [● NIRCcam offers  $R \simeq 5$  imaging from  $0.7\text{--}5 \mu\text{m}$  over two  $2!3 \times 4!6$  FOV's.]

# Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?



- In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than  $\gtrsim 1$  dex.



WFC3 ERS 10-band redshift estimates accurate to  $\sim 4\%$  with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

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

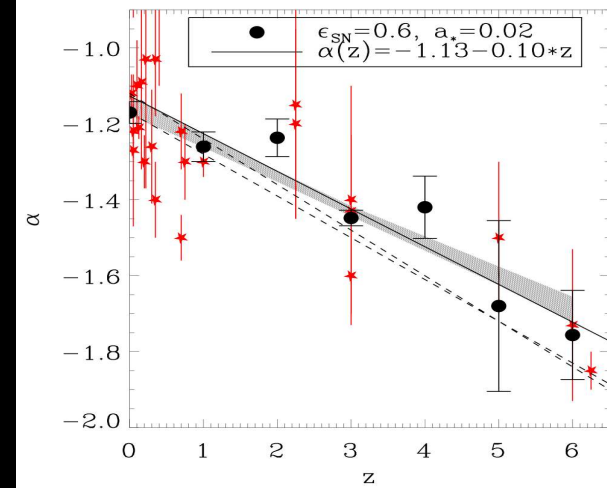
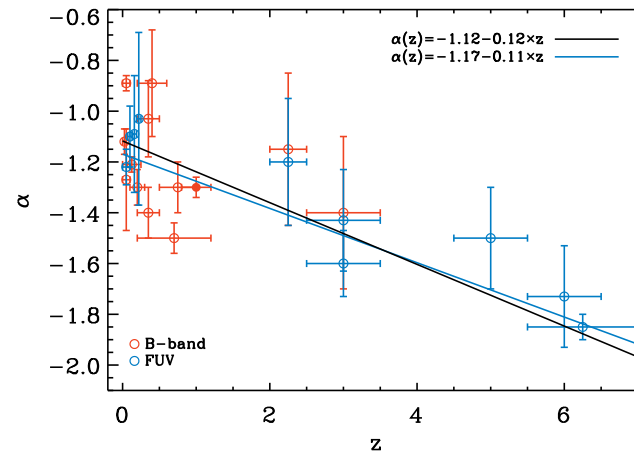
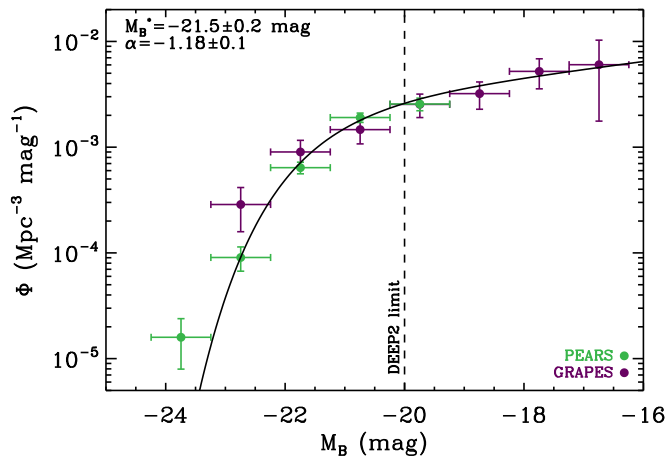
ERS shows WFC3's new panchromatic capabilities on galaxies at  $z \simeq 0-7$ .

- HUDF shows WFC3  $z \simeq 7-9$  capabilities (Bouwens<sup>+</sup> 2010; Yan<sup>+</sup> 2010).

$\Rightarrow$  WFC3 is an essential pathfinder at  $z \lesssim 8$  for JWST ( $0.7-29 \mu\text{m}$ ) at  $z \gtrsim 9$ .

- JWST will trace mass assembly and dust content 3-4 mags deeper from  $z \simeq 1-12$ , with nanoJy sensitivity from  $0.7-5 \mu\text{m}$ .

# Faint-end LF-Slope Evolution (fundamental, like local IMF)



Faint-end LF-slope at  $z \gtrsim 1$  with accurate ACS grism  $z$ 's to  $AB \lesssim 27$  (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- Star-formation and SN feedback produce different faint-end slope-evolution: new physical constraints (Khochfar et al. 2007, ApJL, 668, L115).
- JWST will provide fainter spectra ( $AB \lesssim 29$ ) and spectro-photometric redshifts to much higher  $z$  ( $\lesssim 20$ ). JWST will trace  $\alpha$ -evolution for  $z \lesssim 12$ .
- Can measure environmental impact on faint-end LF-slope  $\alpha$  directly.
- Expect convergence to slope  $|\alpha| \equiv 2$  at  $z > 6$  before feedback starts?
- Constrain onset of Pop III SNe epoch, Type II & Type Ia SN-epochs.

- (4) How can JWST measure Galaxy Assembly?

HST helped show how galaxies formed and evolved in the last 12–13 Gyrs:

- Galaxies of all types formed over a wide range of time, but with a notable transition around  $z \sim 1-1.5$ , when Hubble sequence appears:
- Subgalactic units rapidly merge from  $z \simeq 7 \rightarrow 1$  to grow bigger units.
- Merger products settle as galaxies with large bulges or disks at  $z \lesssim 1$ . These evolved mostly passively since then, resulting in the giant galaxies that we see today.

JWST is designed to observe the following re. Galaxy Assembly:

- Formation and evolution of Pop III star-clusters in the first 0.5 Gyr.
- Faint-end LF-slope evolution: (how) did dwarf galaxies finish reionization after 0.5–1 Gyr? Was there a transition to Pop-III objects?
- Measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their SF, mass, Fe/H, and dust distributions, rest-frame structure and type, etc., as function of redshift for  $z \lesssim 15$ .

- References and other sources of material shown:

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

[www.asu.edu/clas/hst/www/ahah/](http://www.asu.edu/clas/hst/www/ahah/) [Hubble at Hyperspeed Java-tool]

[http://wwwgrapes.dyndns.org/udf\\_map/index.html](http://wwwgrapes.dyndns.org/udf_map/index.html) [Clickable HUDF map]

<http://www.jwst.nasa.gov/> and <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/guider/>

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, p. 1965  
(astro-ph/0703171) “High Resolution Science with High Redshift Galaxies”

Wyithe, J. S. B., Yan, H., Windhorst, R. A., & Mao, S. 2011, *Nature*, Vol. 469, Issue 7330, 181–184 (astro-ph/1101.2291)