

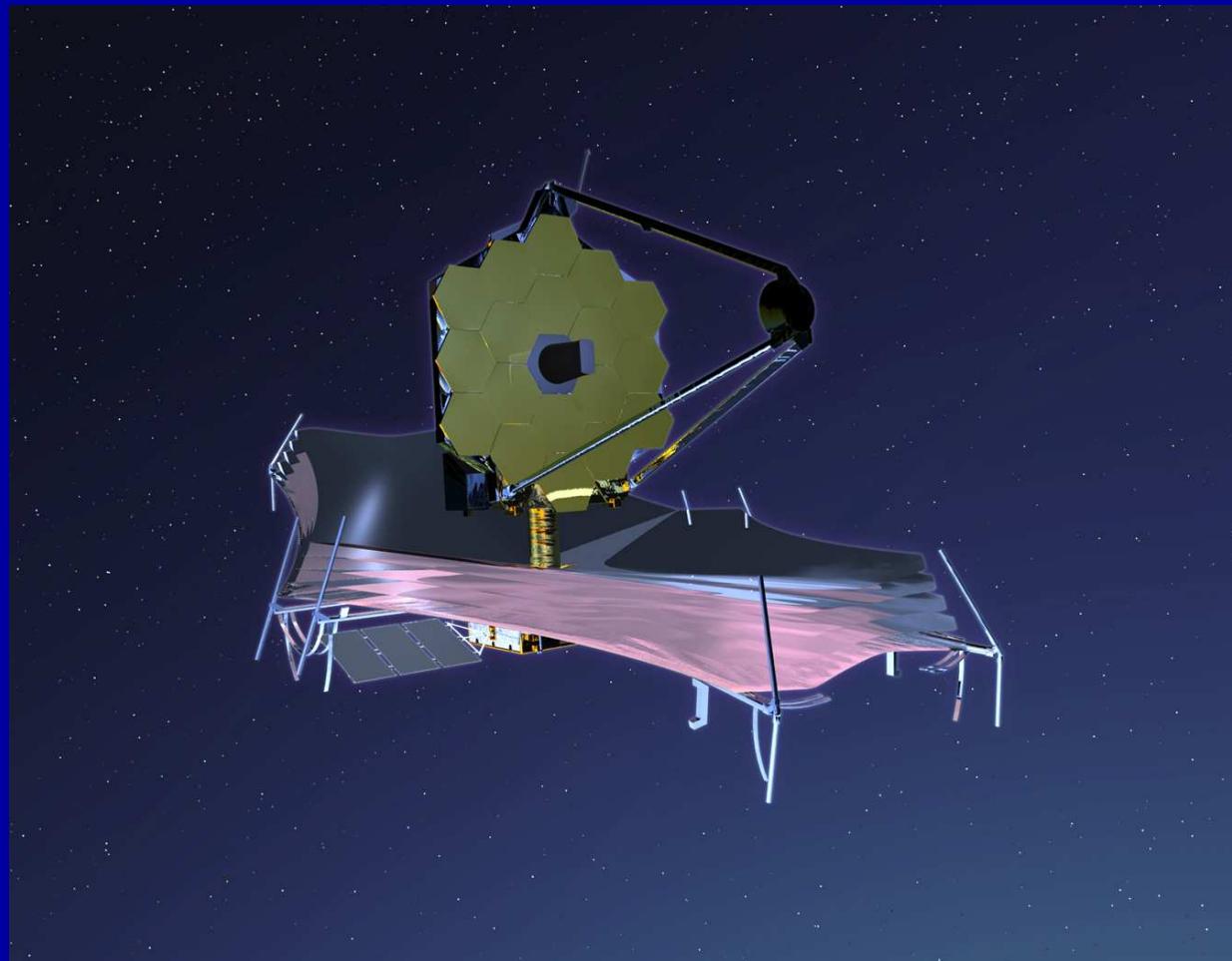
# How can the James Webb Space Telescope Measure First Light, Reionization, & Galaxy Assembly?

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Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

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



*Colloquium at the School of Earth & Space Exploration, ASU, Tempe, Wednesday, November 14, 2007*

# Outline

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- (0) Introduction: Cosmic Expansion and Contents of the Universe
  - (1) What is JWST and how will it be deployed?
  - (2) What instruments and sensitivity will JWST have?
  - (3) What is, & how can JWST measure First Light & Reionization?
  - (4) What is, & how can JWST measure Galaxy Assembly?
  - (5) Predicted Galaxy Appearance for JWST at redshifts  $z \simeq 1-15$
  - (6) Summary and Conclusions
- Appendix 1: Future Studies with the Hubble Wide Field Camera 3
- Appendix 2: What is the Lyman continuum escape fraction  $f_{esc}(z)$  of dwarf galaxies?

Sponsored by NASA/JWST & HST

# (0) Intro: Cosmic Expansion and Contents of the Universe

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Expansion  $\Rightarrow$  redshift

Hubble's Law:

$$\lambda_{obs} = \lambda_{rest} \cdot (1+z)$$

$$D \simeq v / H_0 \simeq (c/H_0) \cdot z = R_0 \cdot z$$

Item:

Numbers inside  $R_0 = (c/H_0) \simeq 13.65$  Gyr:

$$\Rightarrow t_{univ} = (211 \pm 1 !) \cdot t_{dino} [= 65 \text{ Myr}]$$

$$N_{h\nu} \sim 10^{89}$$

$$N_b \sim 10^{80}$$

$$\eta \sim 10^9 \Rightarrow \text{He/H ratio} = 0.235$$

Energy Density:

Baryons (atoms):

Dark Matter:

Dark Energy:

(Supermassive) black holes:

as fraction of critical closure density (WMAP):

$$\Omega_b = \rho_b / \rho_{crit} \simeq 0.042$$

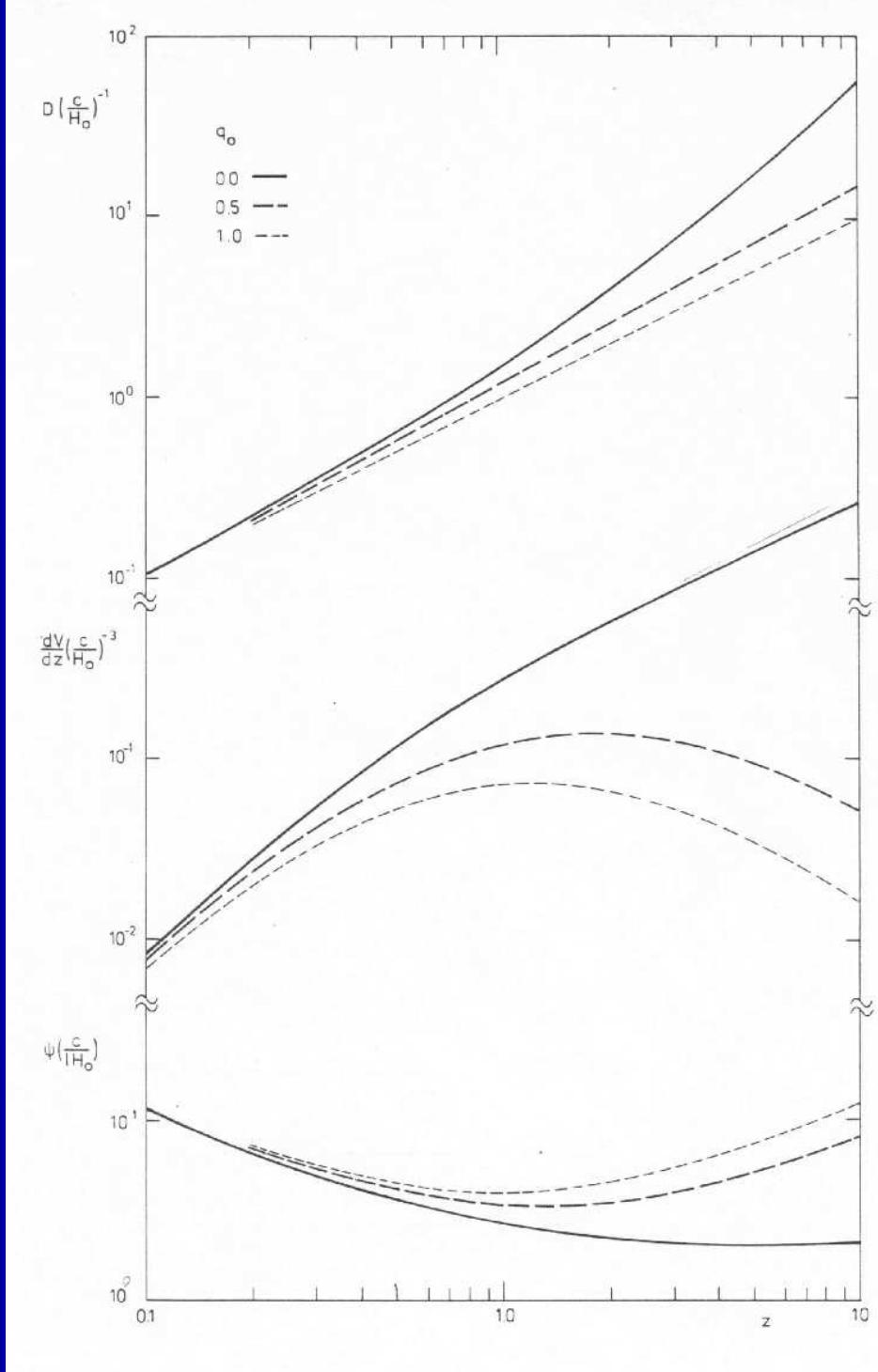
$$\Omega_d = \rho_d / \rho_{crit} \simeq 0.20$$

$$\Omega_\Lambda = \rho_\Lambda / \rho_{crit} \simeq 0.76$$

$$\Omega_{smbh} = \rho_{smbh} / \rho_{crit} \simeq 0.0001$$

Total

$$\Omega_{tot} = \rho_{tot} / \rho_{crit} \simeq 1.00 \pm 0.02$$
$$(\rho_{crit} \simeq 10^{-29} \text{ gr/cm}^3)$$



Relativistic Distance, Volume Element, and Angular Size vs.  $z$ .

"Brilliantly done...breathtaking in its vision."

*The New York Times*

# JAMES WEBB

Author of *The Emperor's General*



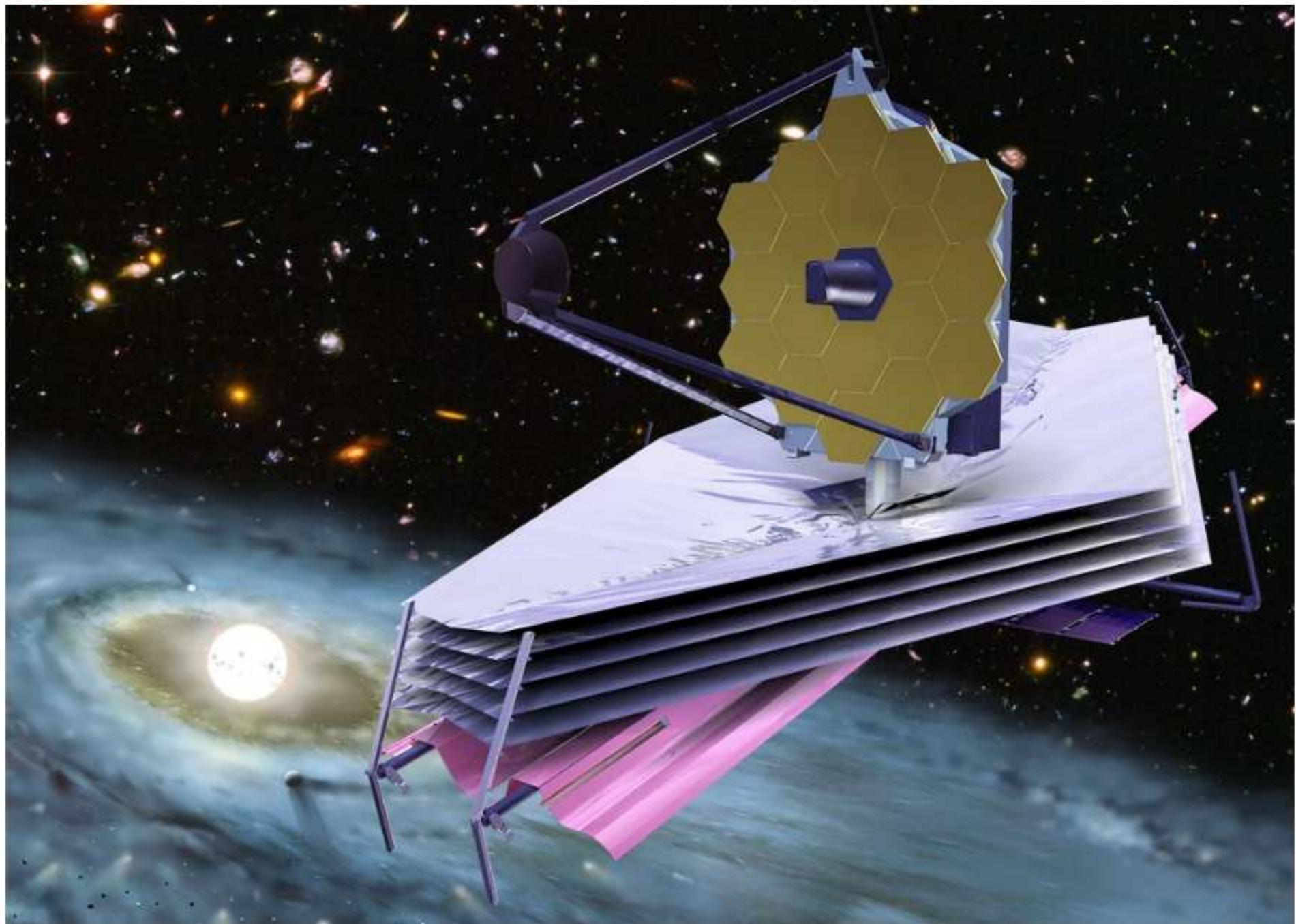
A NOVEL

# SOMETHING TO DIE FOR

Need hard-working grad students & postdocs in  $\gtrsim 2013$  ... It'll be worth it!



# James Webb Space Telescope



- (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 0.6 to  $28 \mu\text{m}$ , to be launched by NASA  $\gtrsim 2013$ . It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging ( $\text{AB} \lesssim 31.5$ ) and spectroscopy ( $\text{AB} \lesssim 29$  mag).



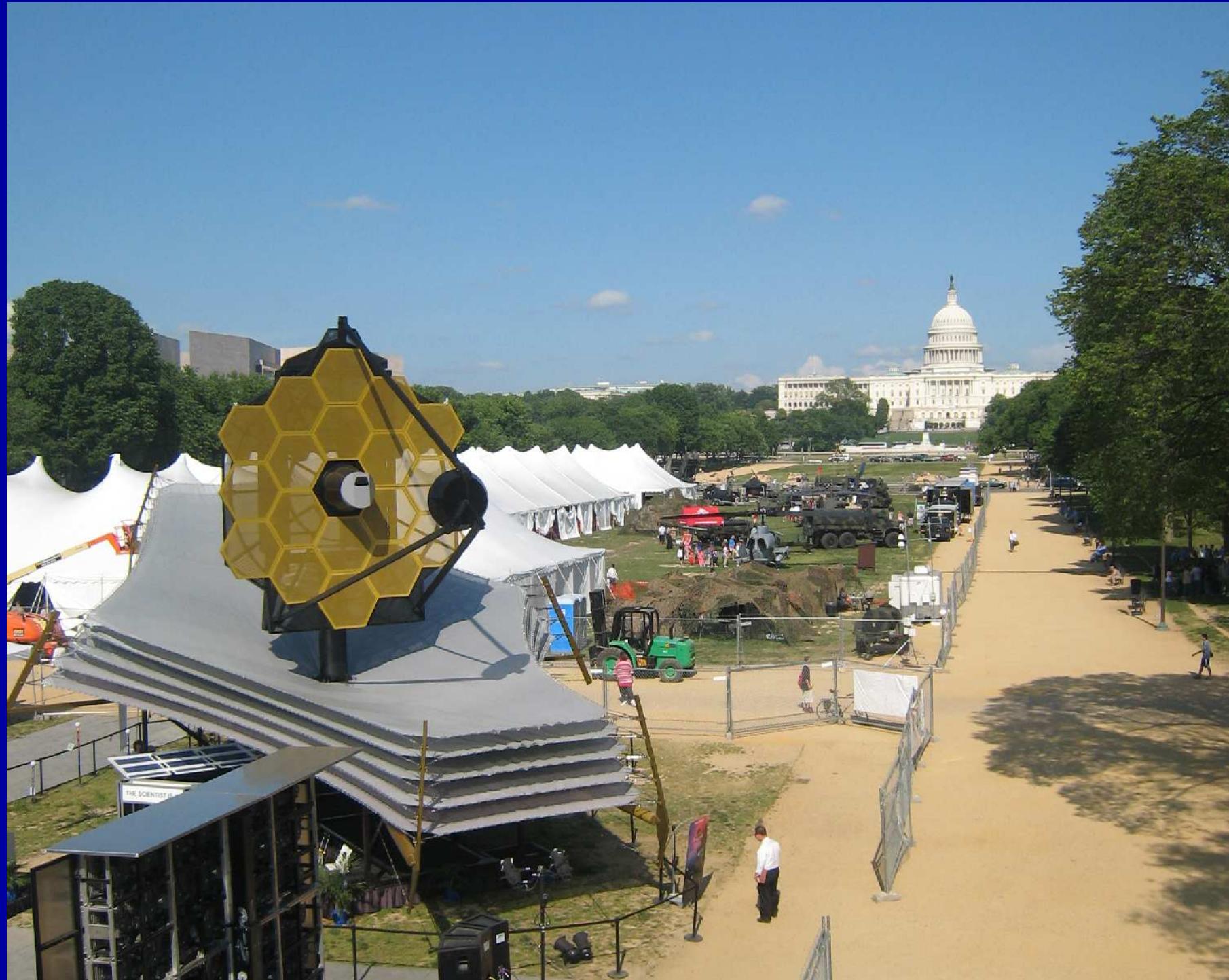
Life size model of JWST: displayed at the Jan. 2007 AAS mtg in Seattle.



Life-sized model of JWST, used to test its sun-shield.

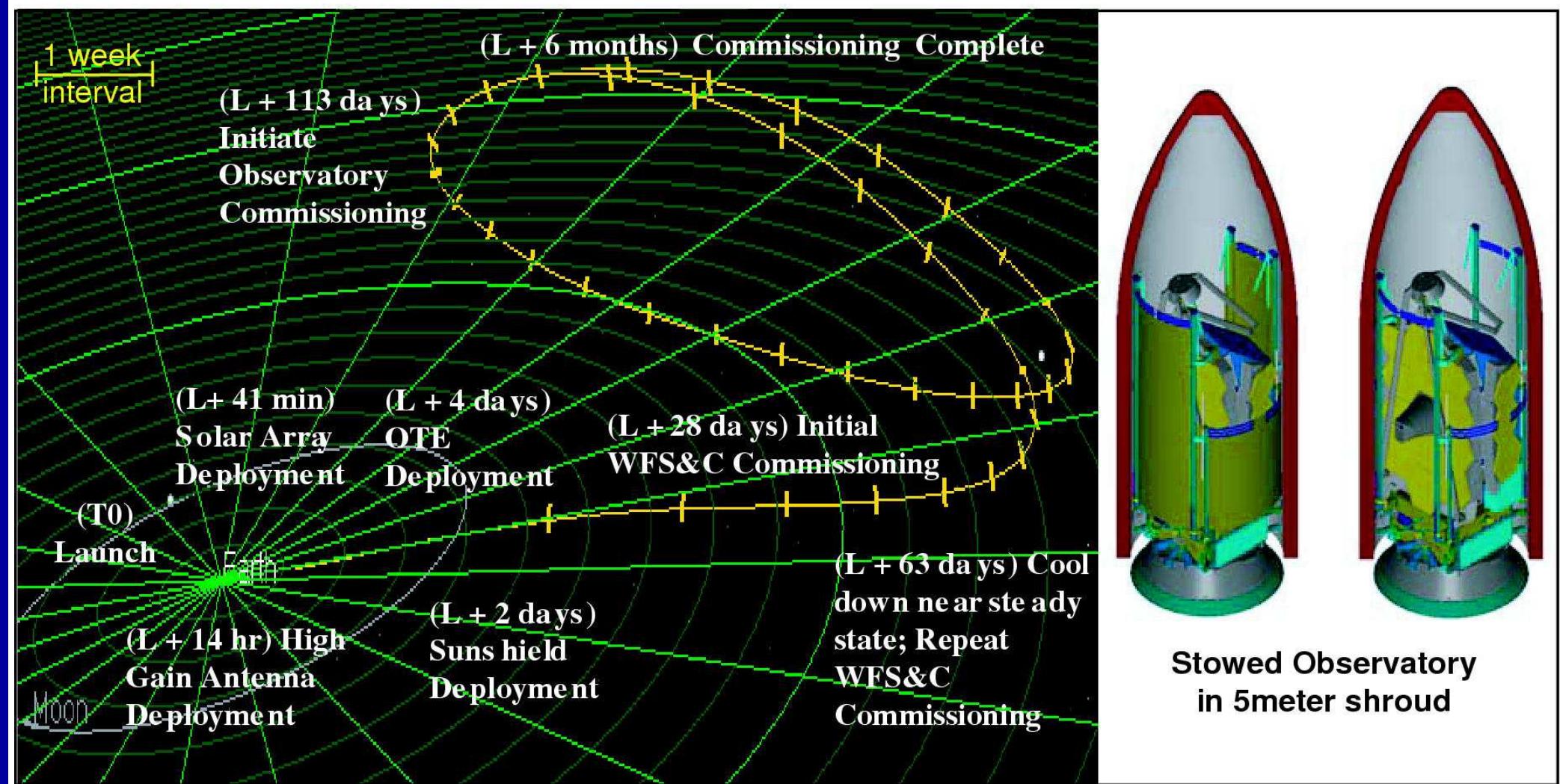


Life-sized model of JWST, at NASA/GSFC Friday afternoon after 5 pm ...



JWST on the Capitol Mall, May 2007 ...

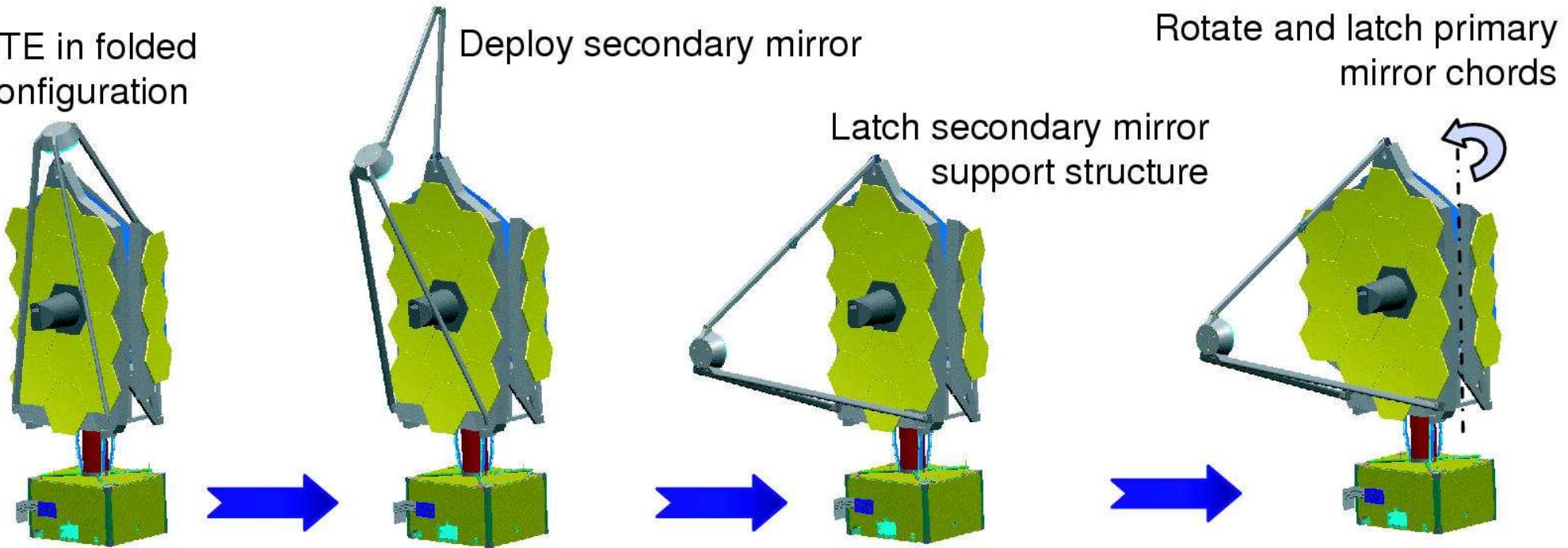
- (1) How will JWST travel to its L2 orbit?



After launch in June 2013 with an Ariane-V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency  $\gtrsim 70\%$ , and send data back to Earth every day.

- (1) How will JWST be automatically deployed?

OTE in folded configuration

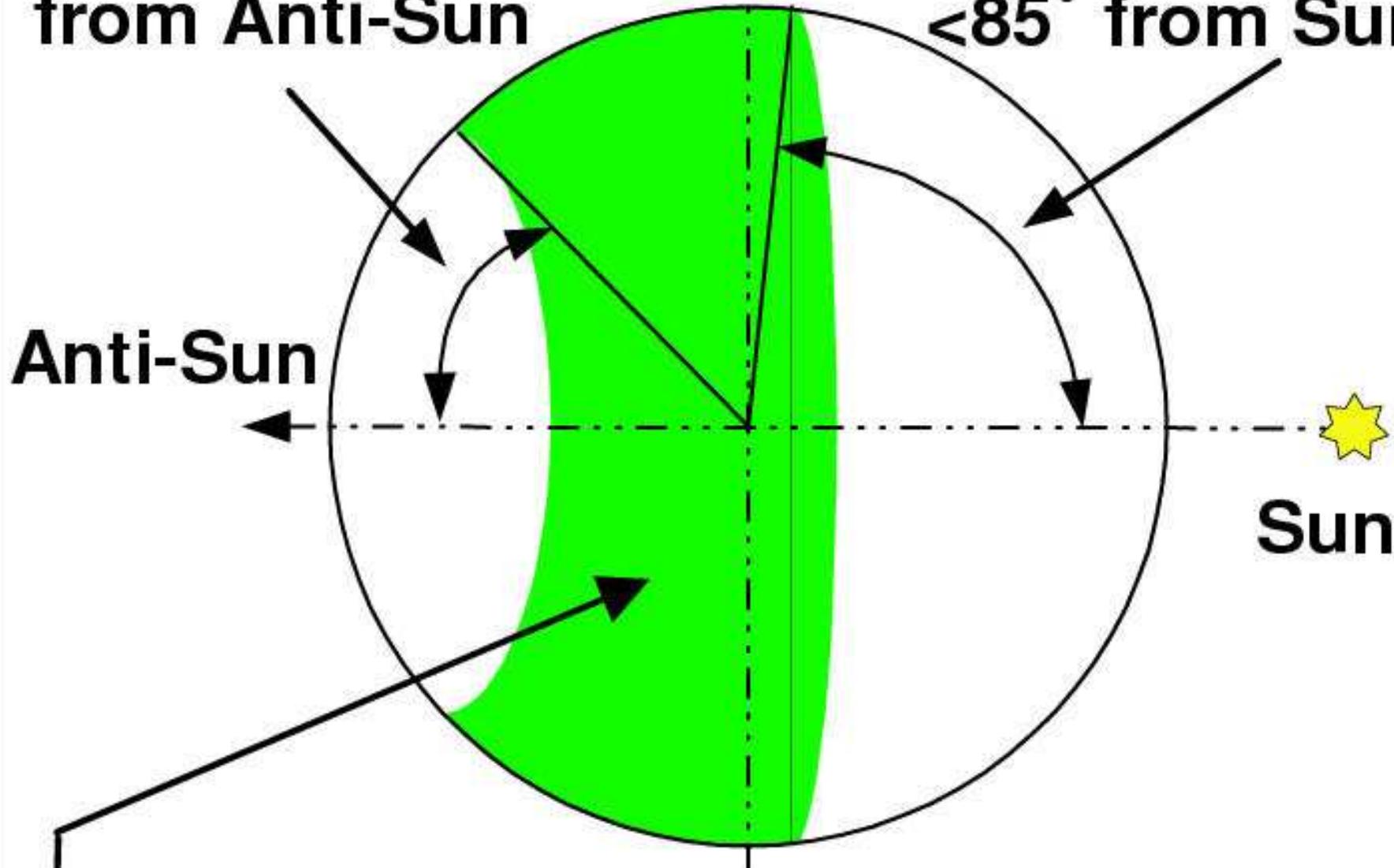


During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit.

The entire JWST deployment sequence can and will be tested several times on the ground — but in 1-G.

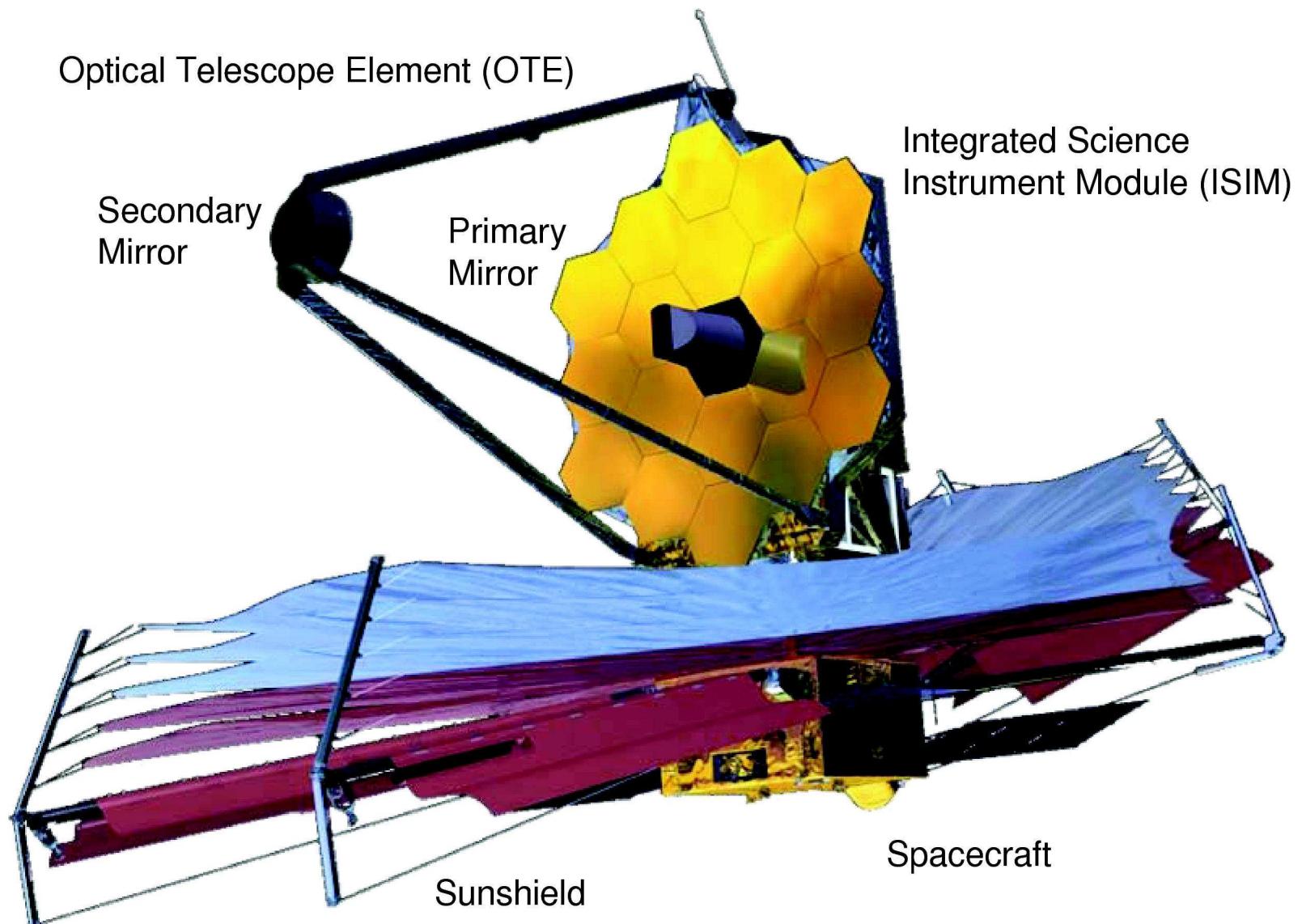
**Exclusion zone <45° from Anti-Sun**

**Exclusion zone <85° from Sun**

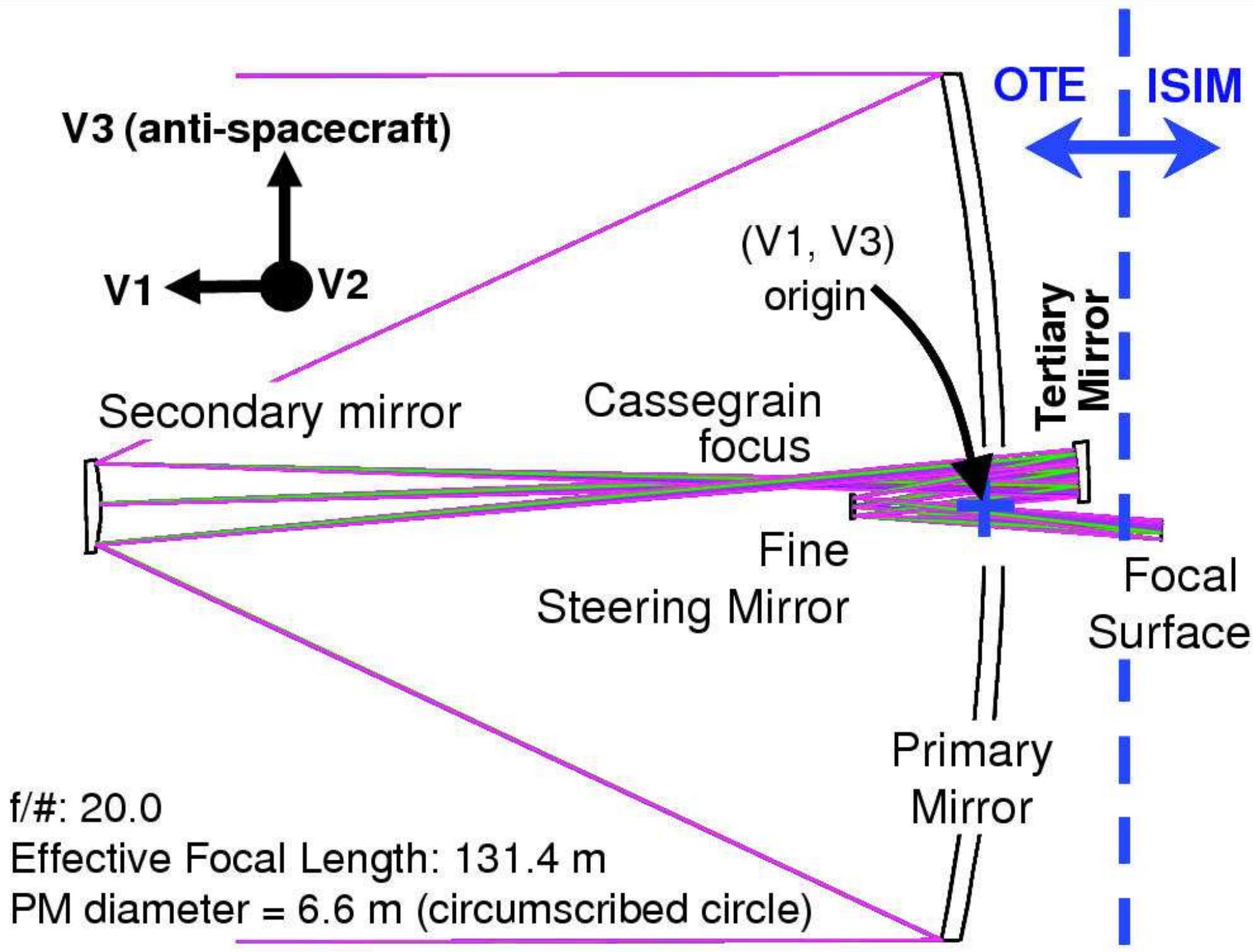


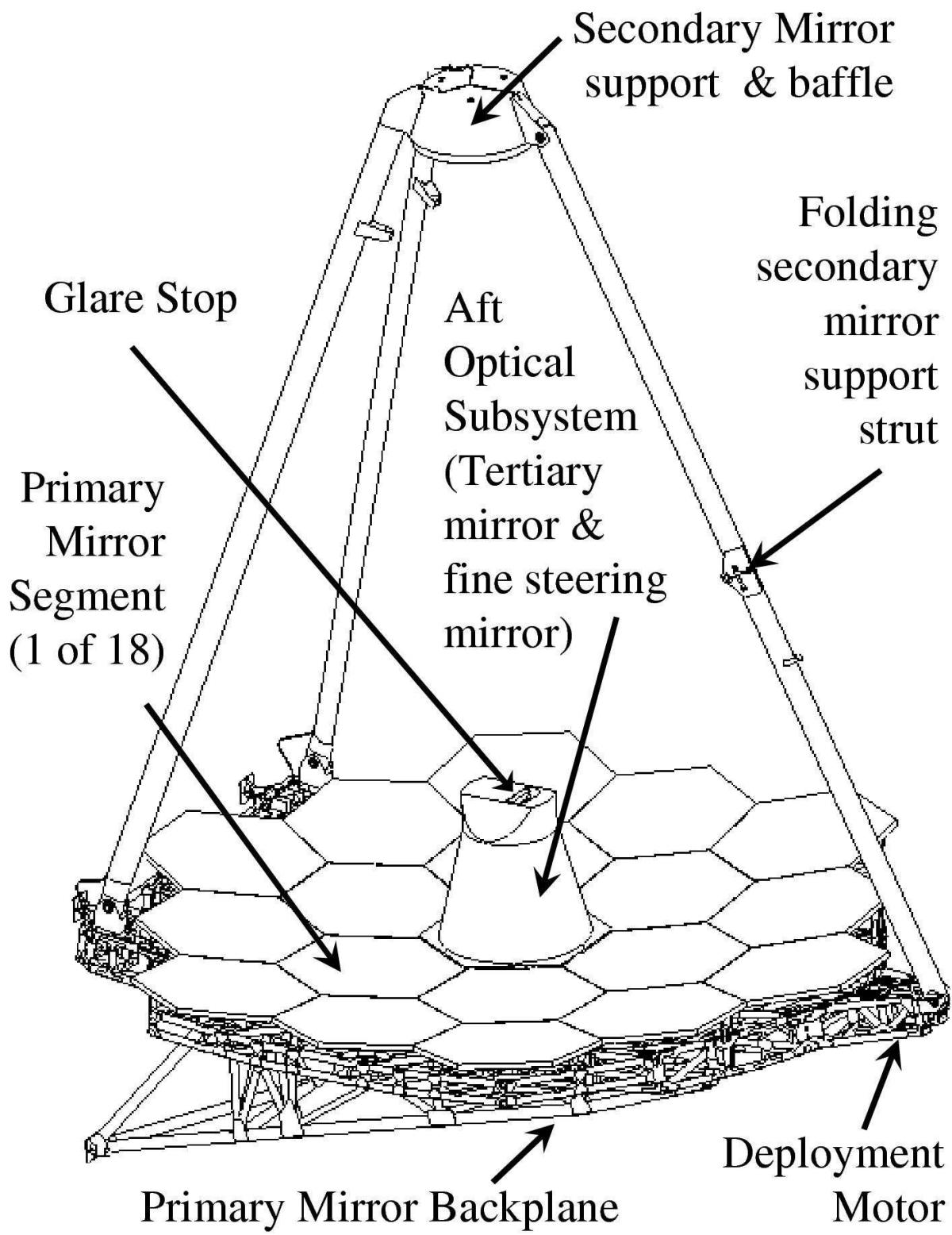
**Allowable Observatory Field-of-Regard**

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

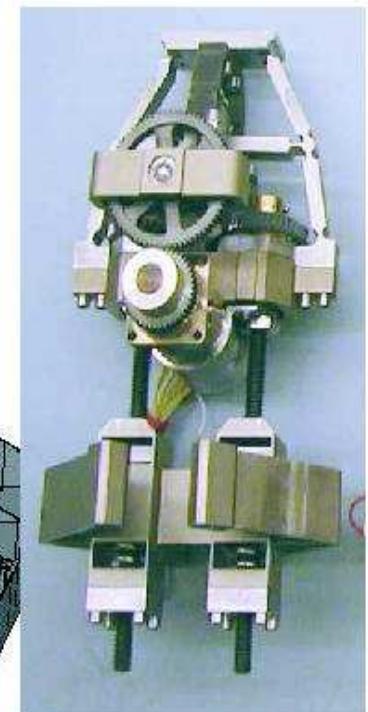
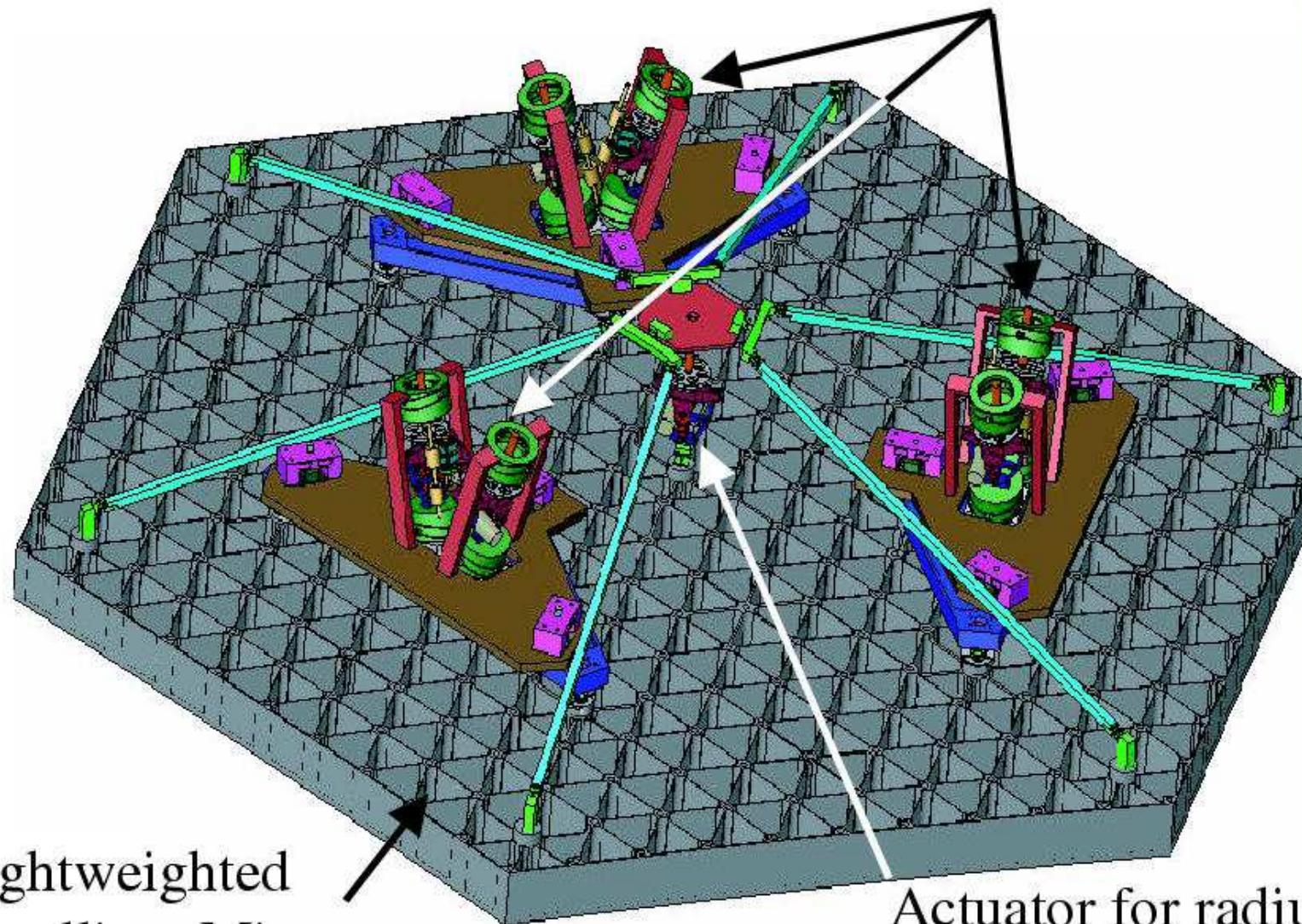


JWST mission reviewed in Gardner, J. P., Mather, J. C., et al. 2006, Space Science Reviews, Vol. 123, pg. 485–606 (astro-ph/0606175)





## Actuators for 6 degrees of freedom rigid body motion

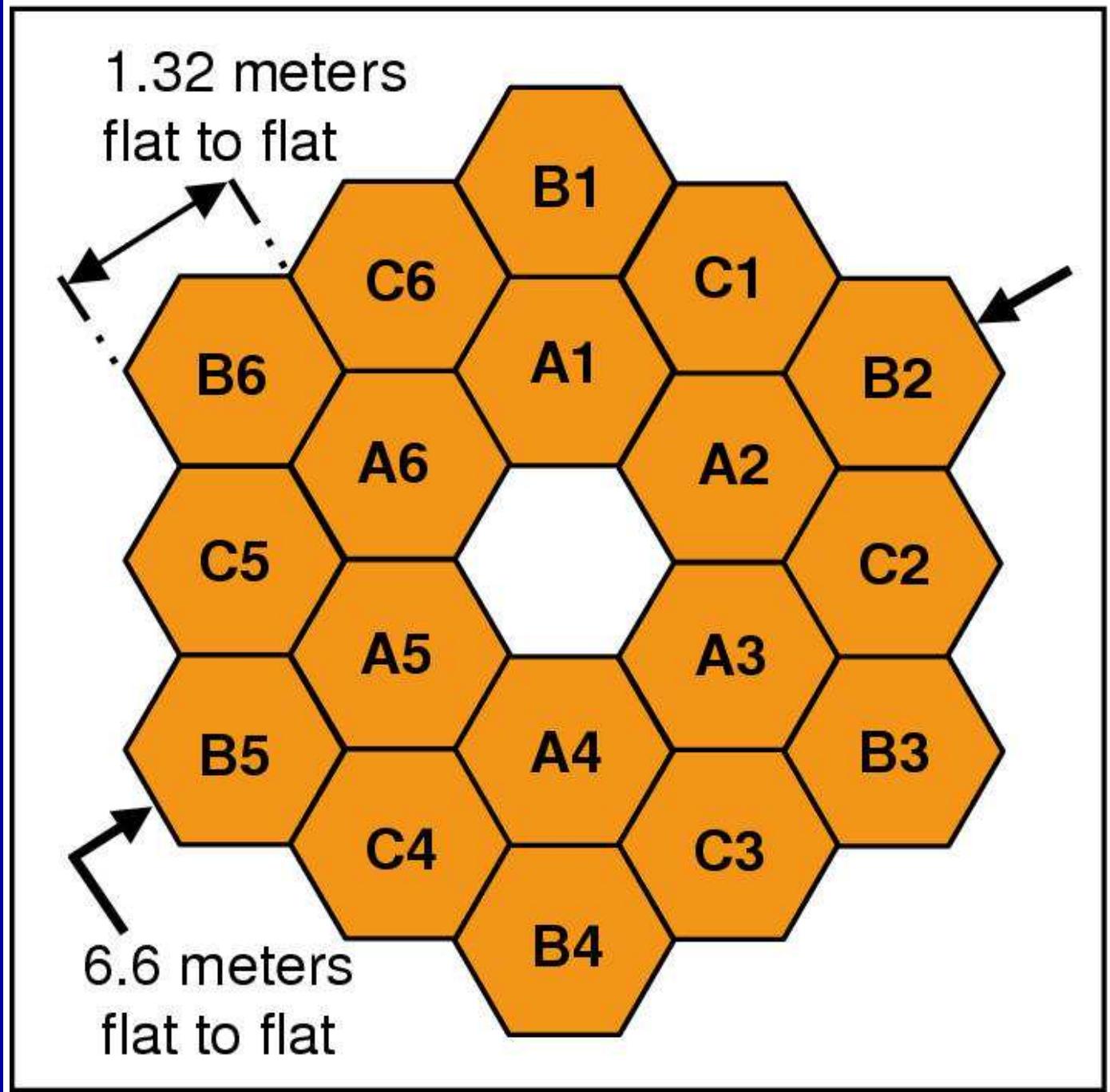


Actuator development unit

Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment

Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.

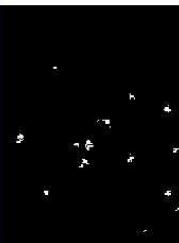


Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m.  
Primary mirror segments are made (AxSys). Now being polished (Tinsley).



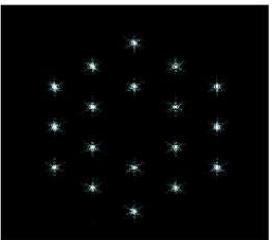
Despite NASA's CAN-do approach: Must find all the cans-of-worms ...

*First light  
NIRCam*



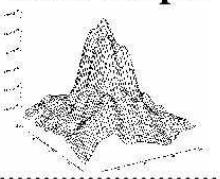
1.  
Segment  
Image  
Capture

After Step 1



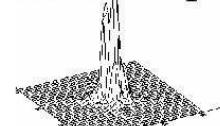
**2. Coarse Alignment**  
Secondary mirror aligned  
Primary RoC adjusted

After Step 2



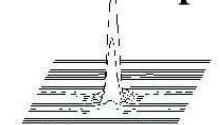
**3. Coarse Phasing - Fine Guiding (PMSA piston)**

After Step 3



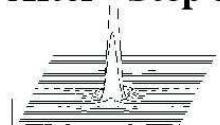
**4. Fine Phasing**

After Step 4



**5. Image-Based Wavefront Monitoring**

After Step 5



**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

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

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

WFE < 110 nm (rms)

WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to that at Keck and HET. Successful 2006 demo of H/W, S/W on 6/1 scale model ( $2 \mu\text{m}$ -Strehl  $\gtrsim 0.85$ ). Need WFS-updates every  $\sim 14$  days, depending on scheduling/SC-illumination.



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

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

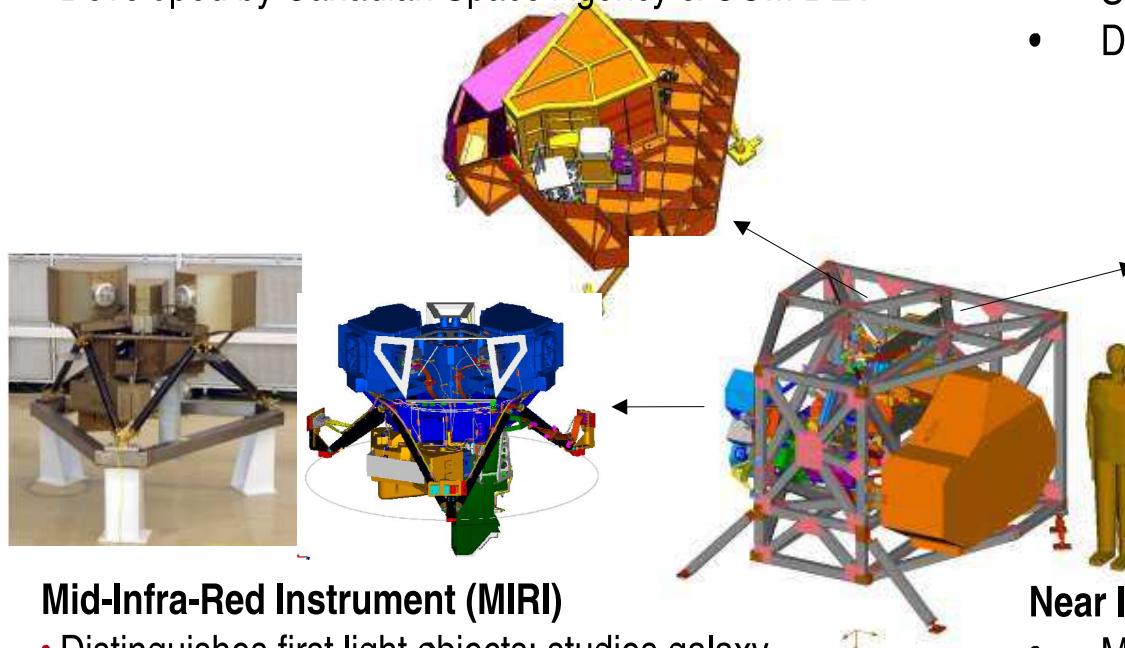


# Instrument Overview



### 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

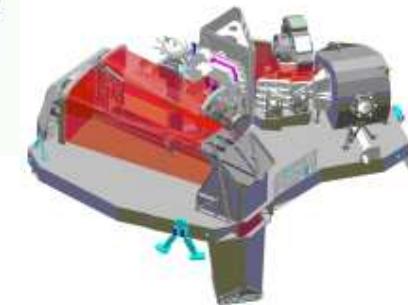
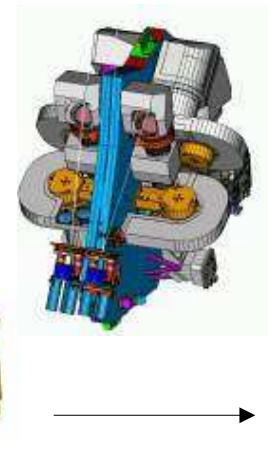


### Mid-Infra-Red Instrument (MIRI)

- 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 Camera (NIRCam)

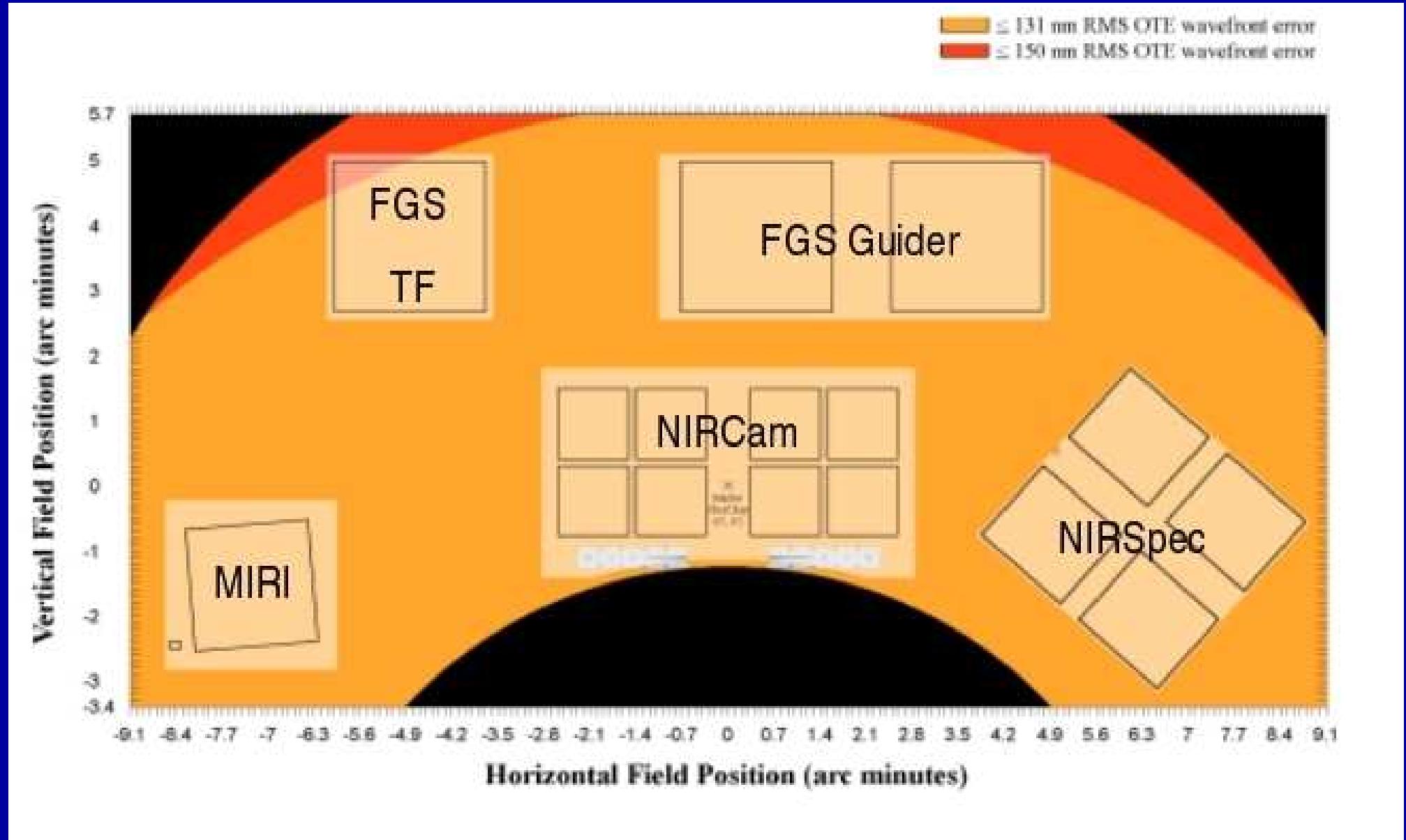
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



### Near Infra-Red Spectrograph (NIRSpec)

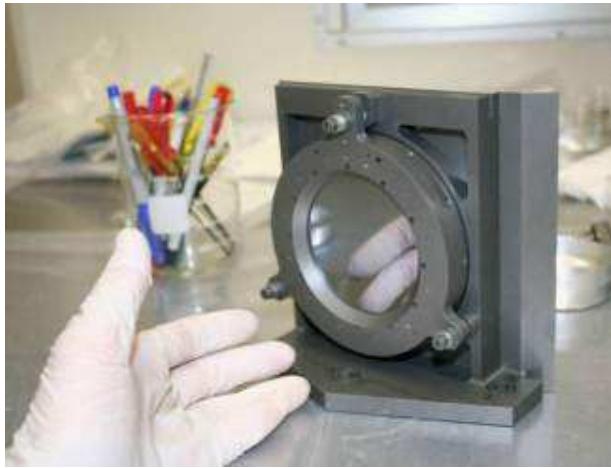
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

- (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*.

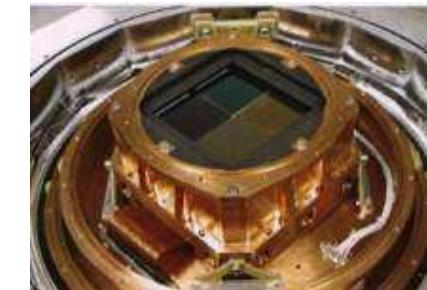
# Instrument Qual and ETU Model Hardware



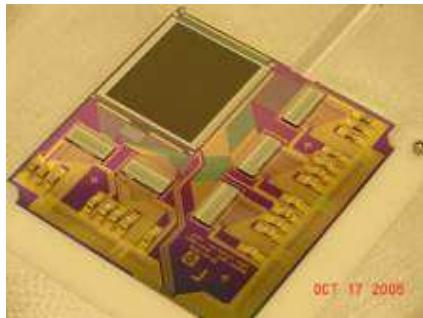
NIRCam Dichroic Beamsplitter



NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



NIRSpec  
Calibration  
Assembly



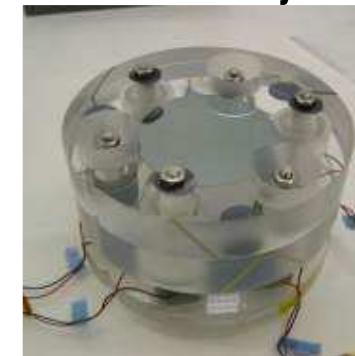
NIRSpec Mirror



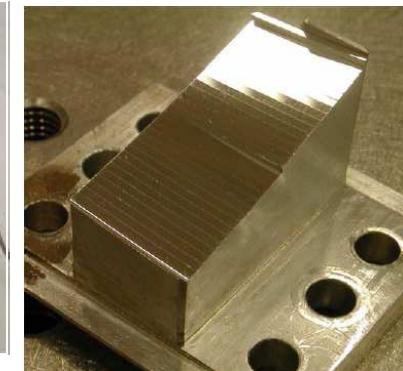
SiAs MIR Detector



NIRSpec Fore Optics Mirror Assembly

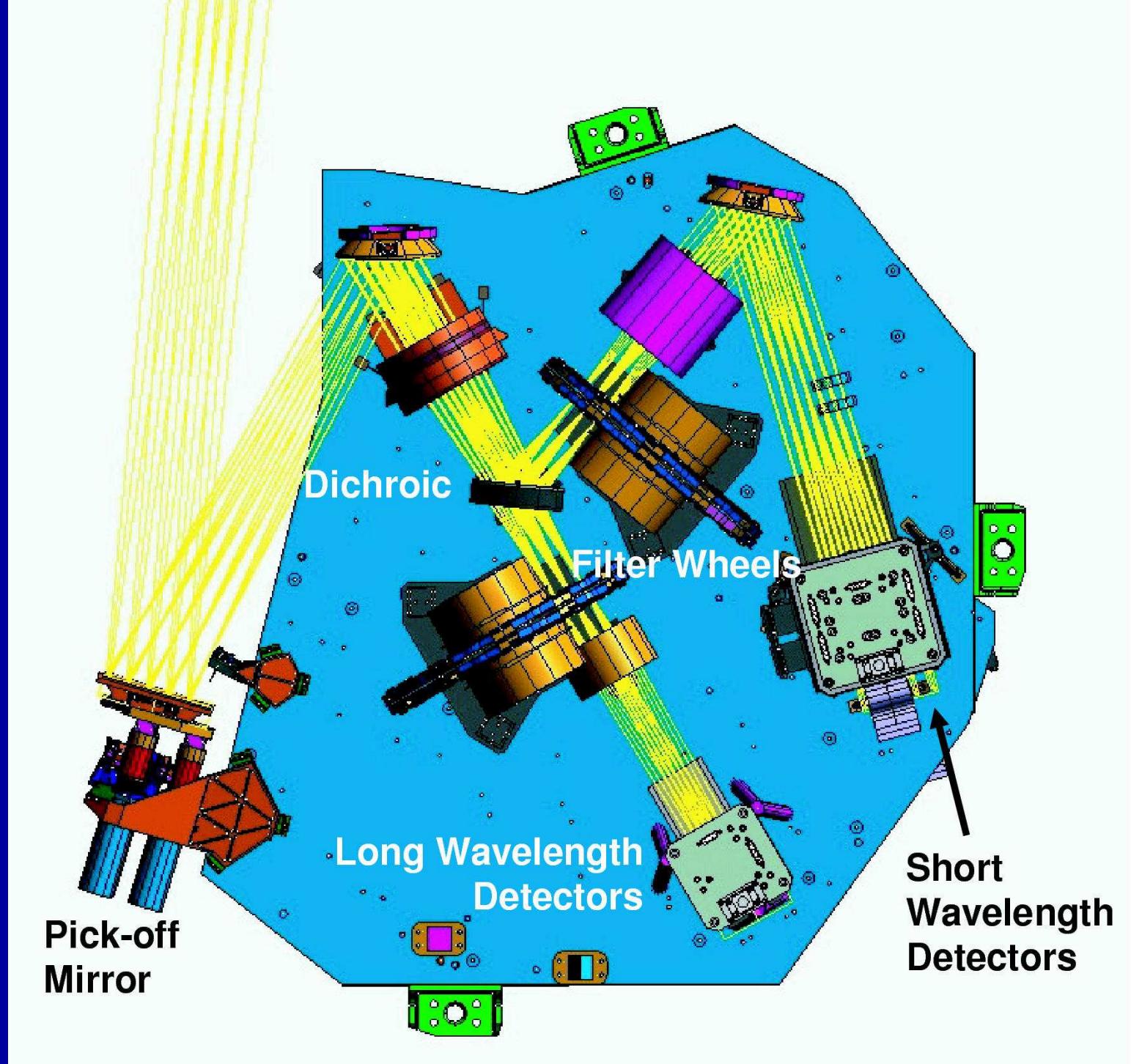


FGS/TF Etalon Filter



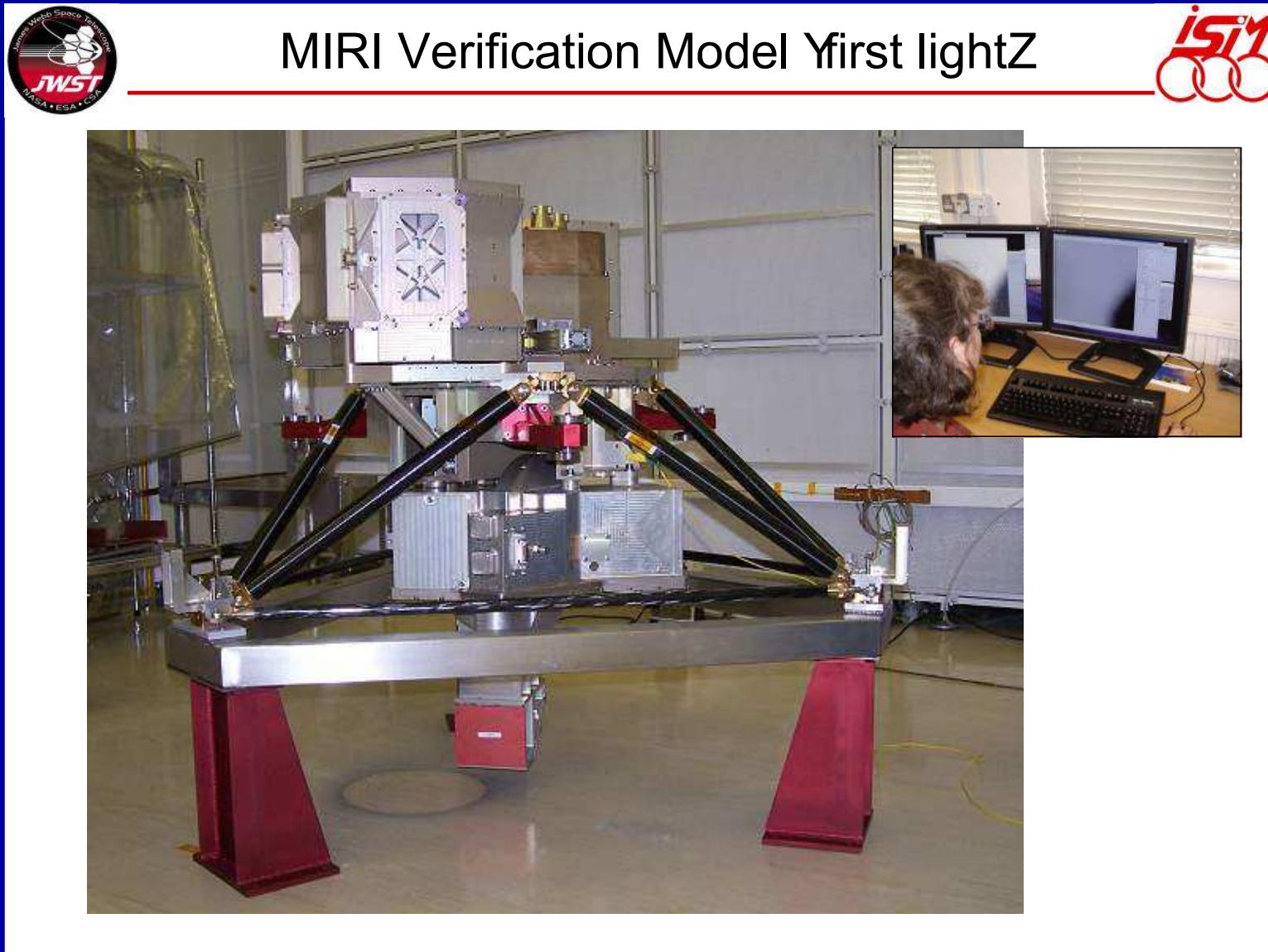
NIRSpec Image  
Slicer Mirror

Some critical-path JWST flight hardware is currently being constructed.



Layout of JWST NIRCam — the UofA–Lockheed NIR-Camera

- (2) What instruments will JWST have?



The Mid-Infra-Red Instrument MIRI made by an UofA + JPL + ESA consortium will do imaging and spectroscopy from 5–28  $\mu\text{m}$ . MIRI is actively cooled by a cryocooler, so that its lifetime is not limited by consumables.

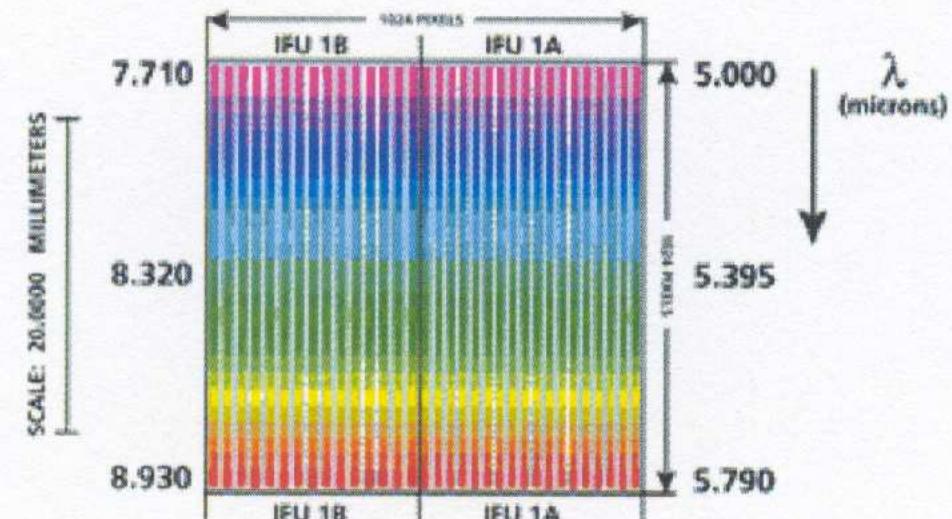
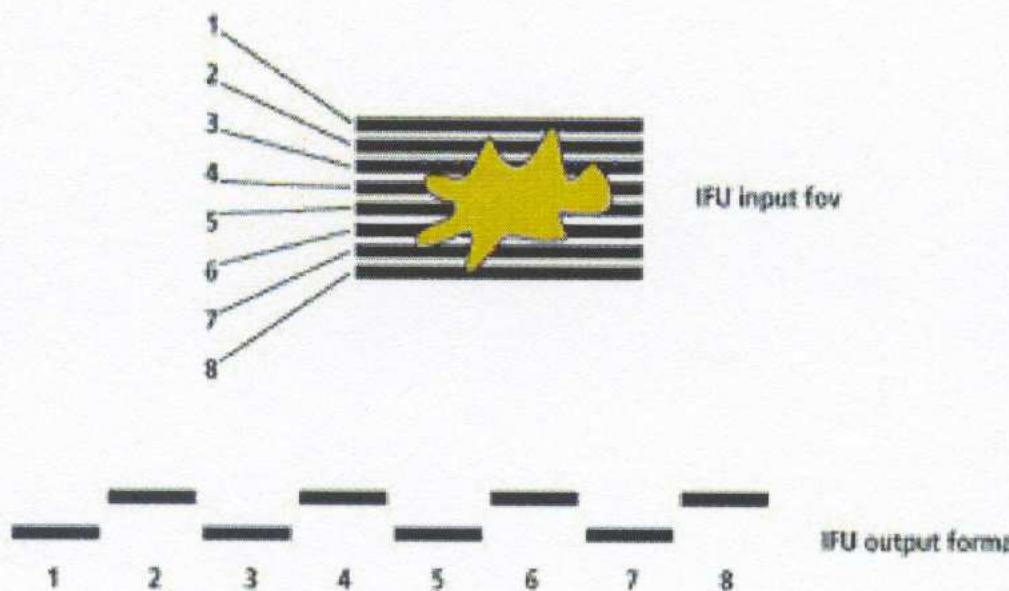
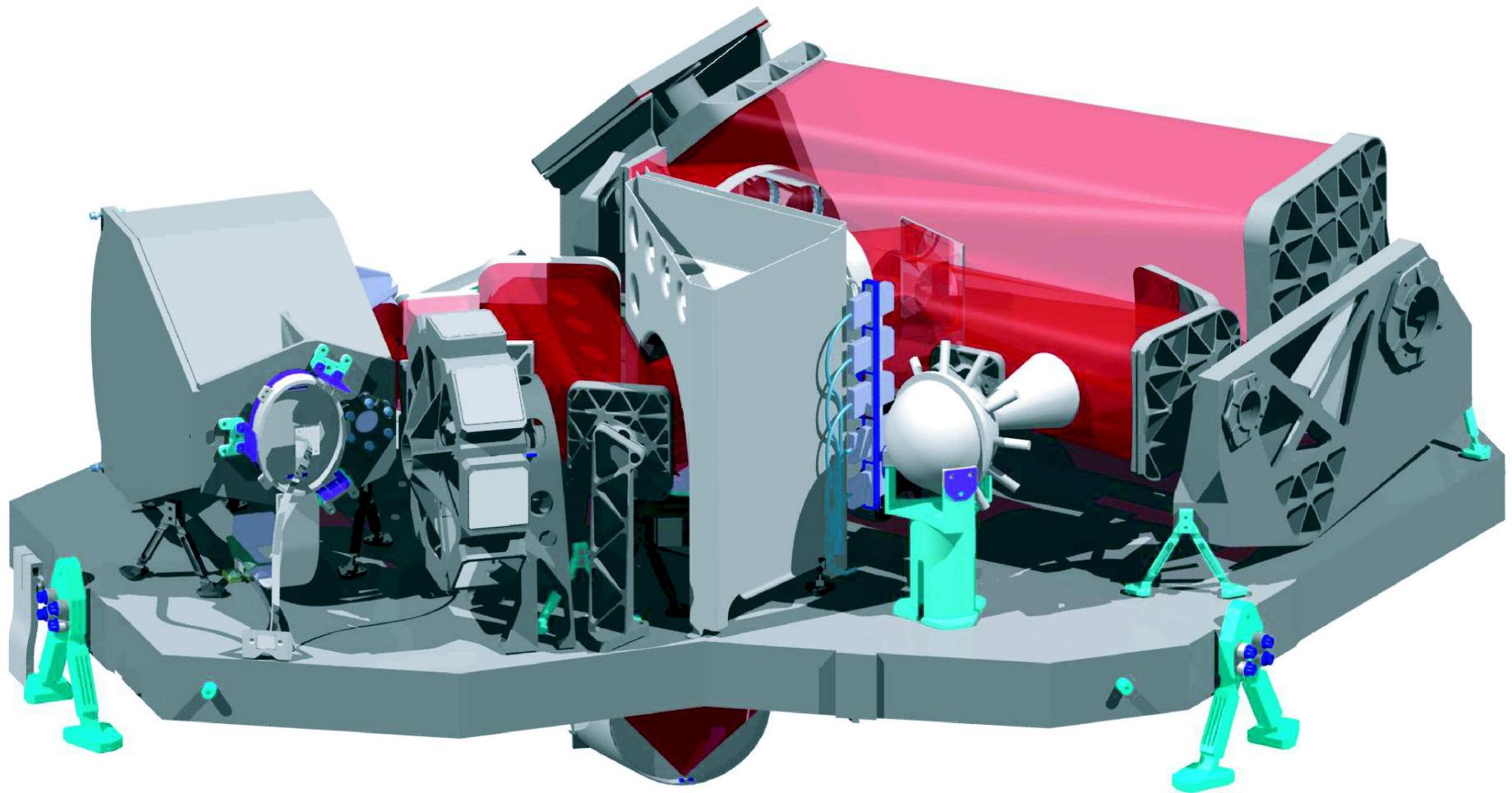
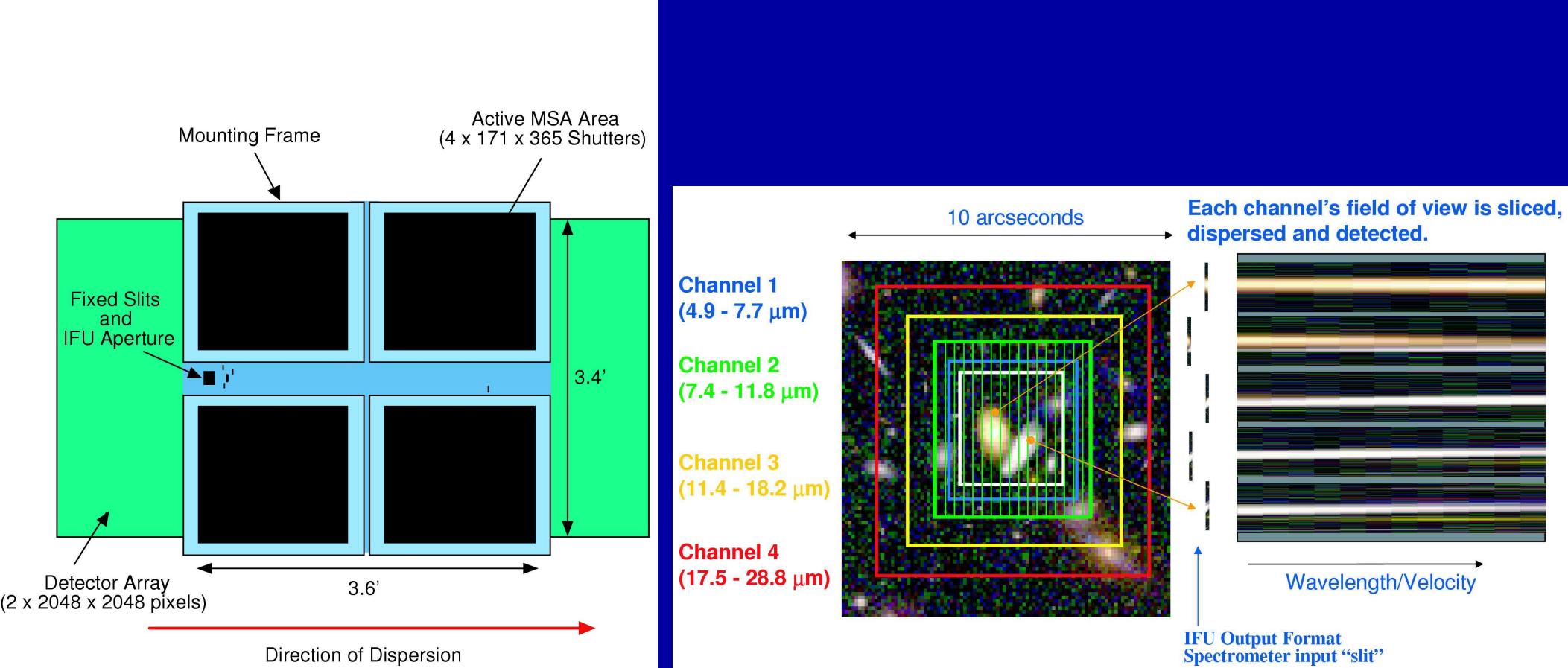


Figure 50. Schematic illustration of the MIRI IFU image slicer format (left) and dispersed spectra on detector (right)

The MIRI Integral Field Unit (IFU) has an image slicer that makes spatially resolved spectra at wavelengths  $5 \mu\text{m} \lesssim \lambda \lesssim 9 \mu\text{m}$ .



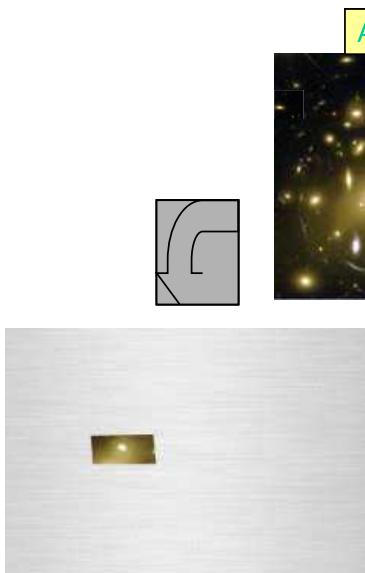
Layout of NIRSpec — the EU NIR-Spectrograph



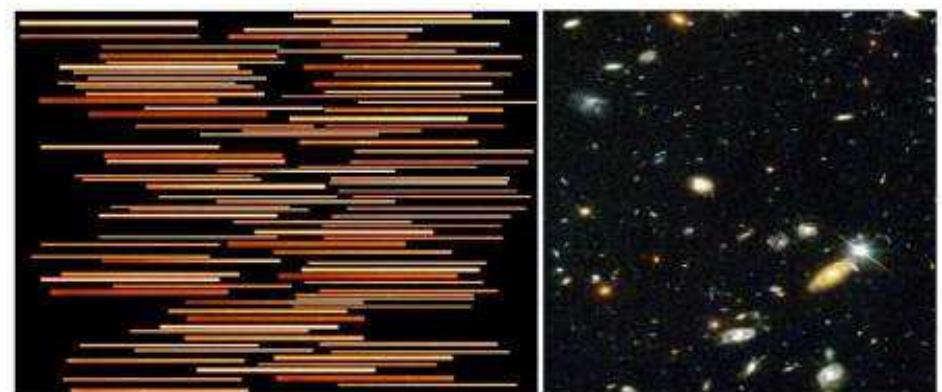
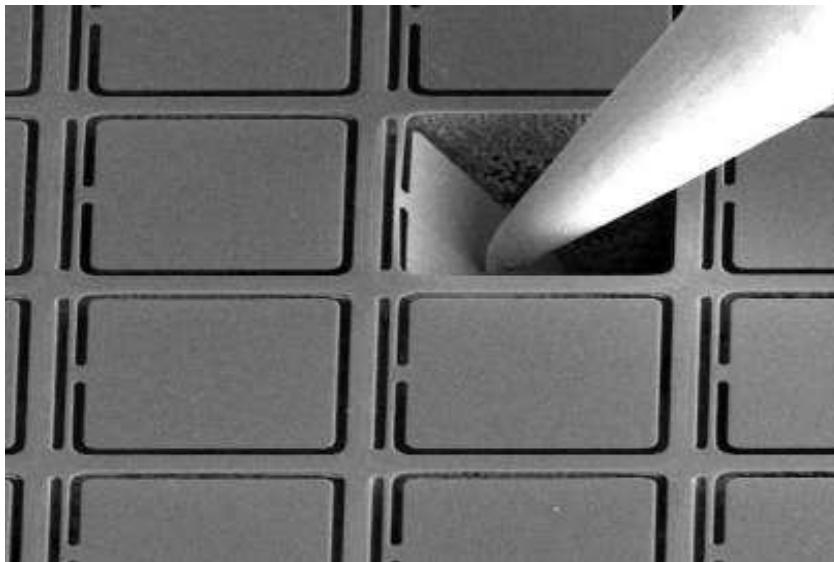
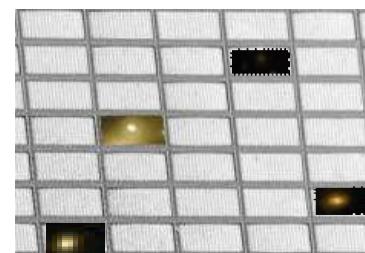
JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MSA with  $4 \times 62,415$  independently operable micro-shutters that cover  $\lambda \simeq 1\text{--}5 \mu\text{m}$  at  $R \simeq 100\text{--}1000$ .
- MIRI/IFU with 400 spatial pixels covering  $5\text{--}28.5 \mu\text{m}$  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  $R \simeq 100$ .

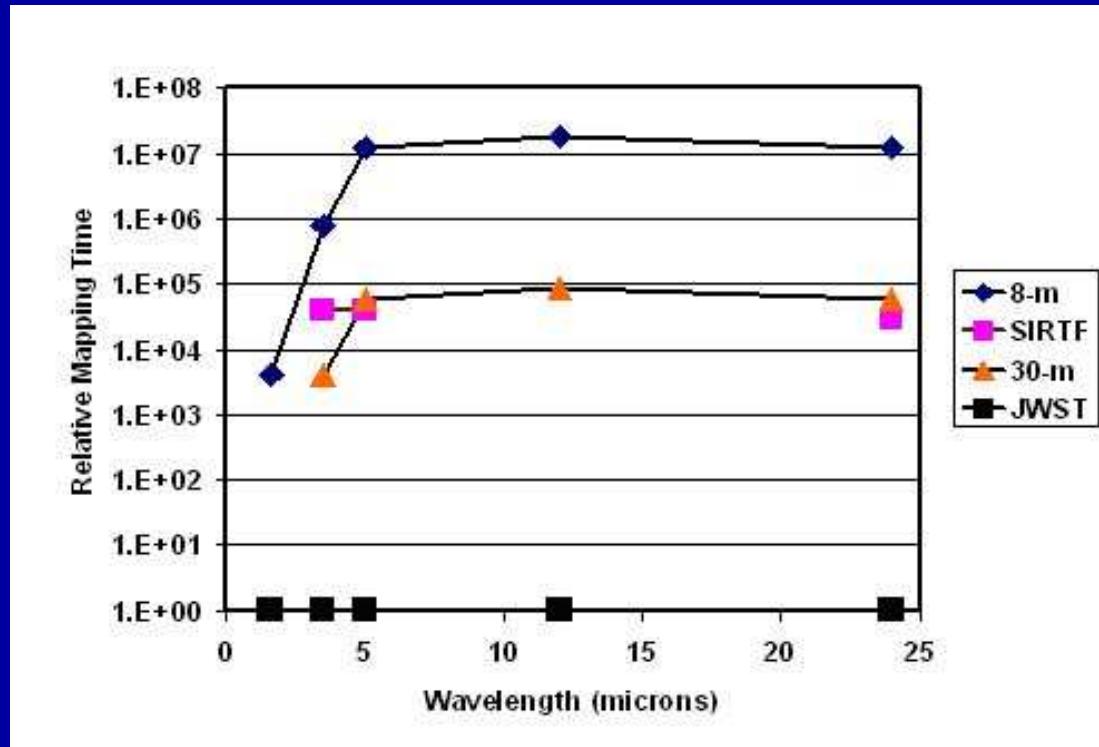
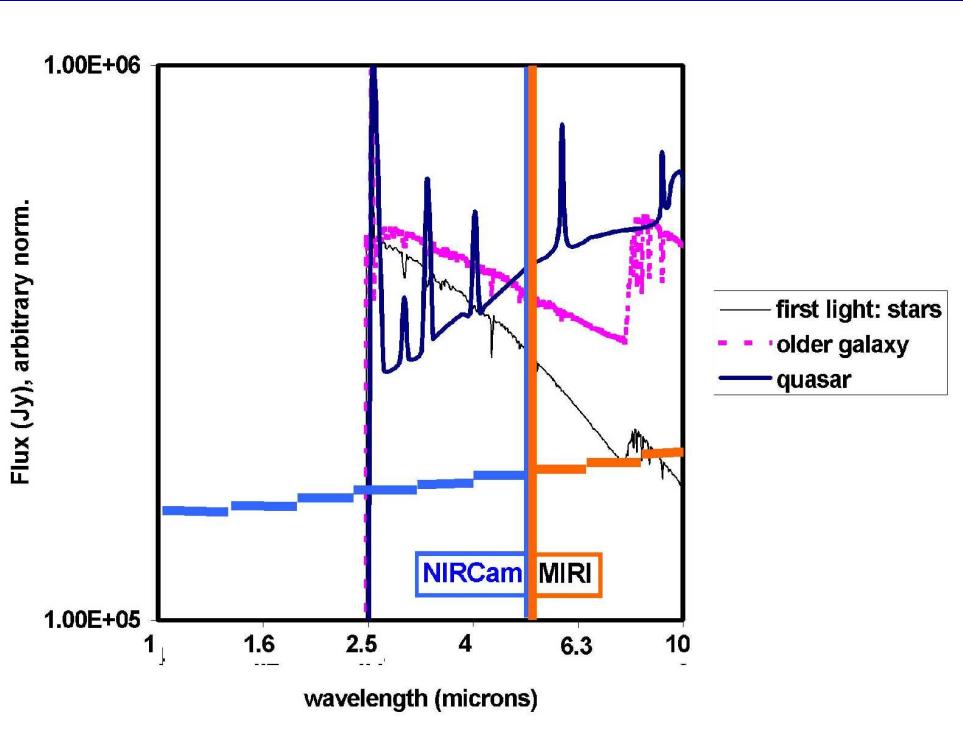
# Micro Shutters



Metal Mask/Fixed Slit



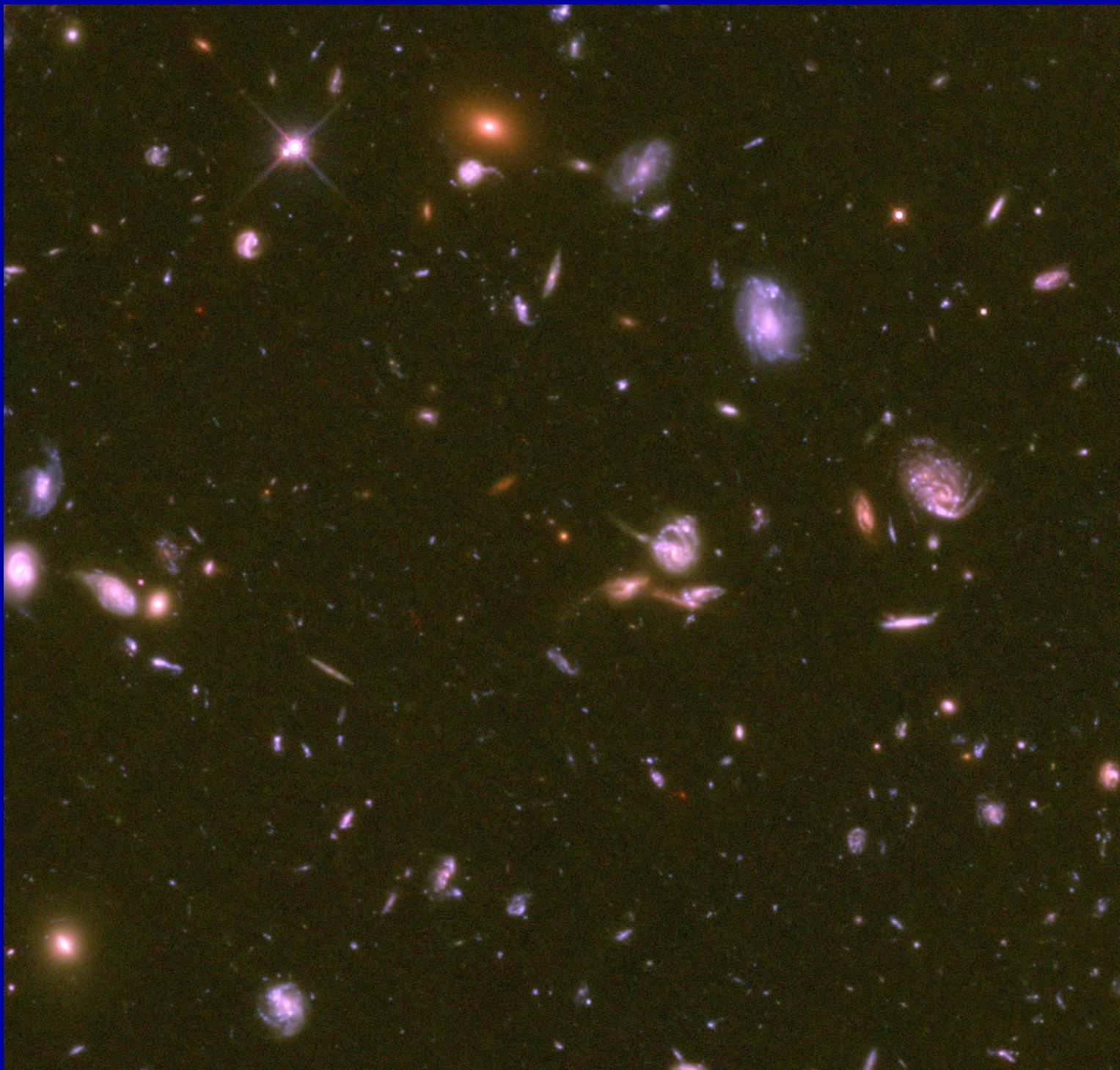
- (2) What sensitivity will JWST have?



The NIRCam and MIRI sensitivity complement each other, straddling  $5 \mu\text{m}$  in wavelength, and together allow objects to be found to redshifts  $z=15-20$  in  $\sim 10^5$  sec (28 hrs) integration times.

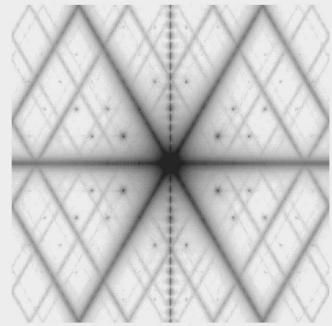
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a “First Light” galaxy dominated by massive stars, and a 50 Myr “old” galaxy at  $z=20$ .

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

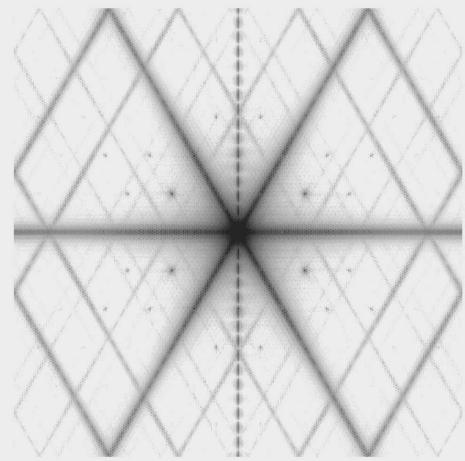


240 hrs HST/ACS in  $V_i'z'$  in the Hubble UltraDeep Field (HUDF)

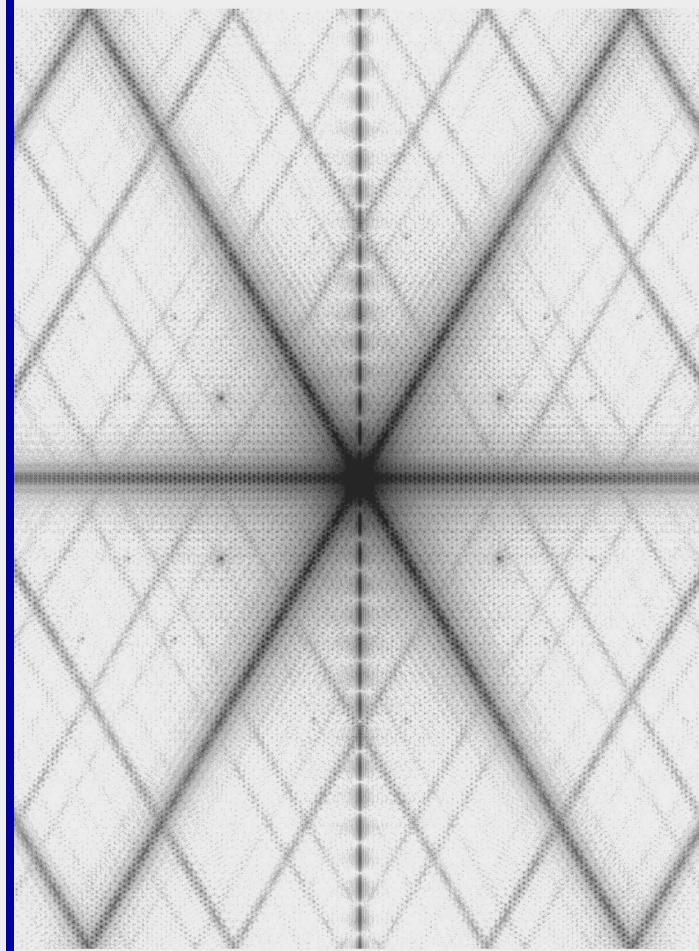
## 6.5m JWST Point-Spread-Function (PSF) models (Ball Aerospace & GSFC):



NIRCam 0.7  $\mu\text{m}$



1.0  $\mu\text{m}$  (<150 nm WFE)



2.0  $\mu\text{m}$  (diffr. limit)

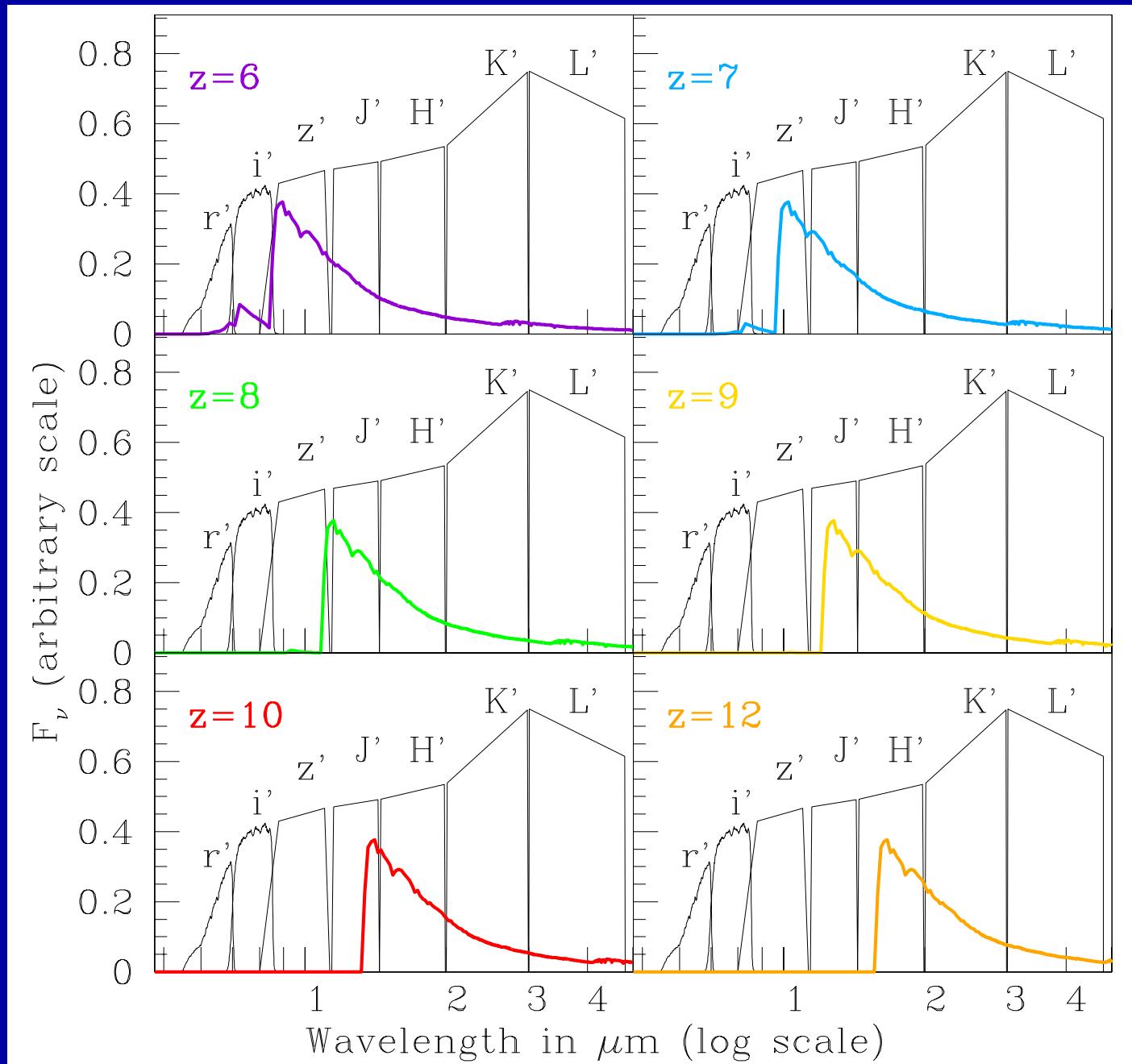
Design PSF's are shown at logarithmic stretch: they have  $\gtrsim 74\%$  EE at  $r \lesssim 0.15''$  at  $1.0\mu\text{m}$ , and are diffraction limited at  $2.0\mu\text{m}$  (Strehl  $\gtrsim 0.80$ ).



~18 hrs JWST NIRCam at 0.7, 0.9, 2.0  $\mu\text{m}$  in the HUDF

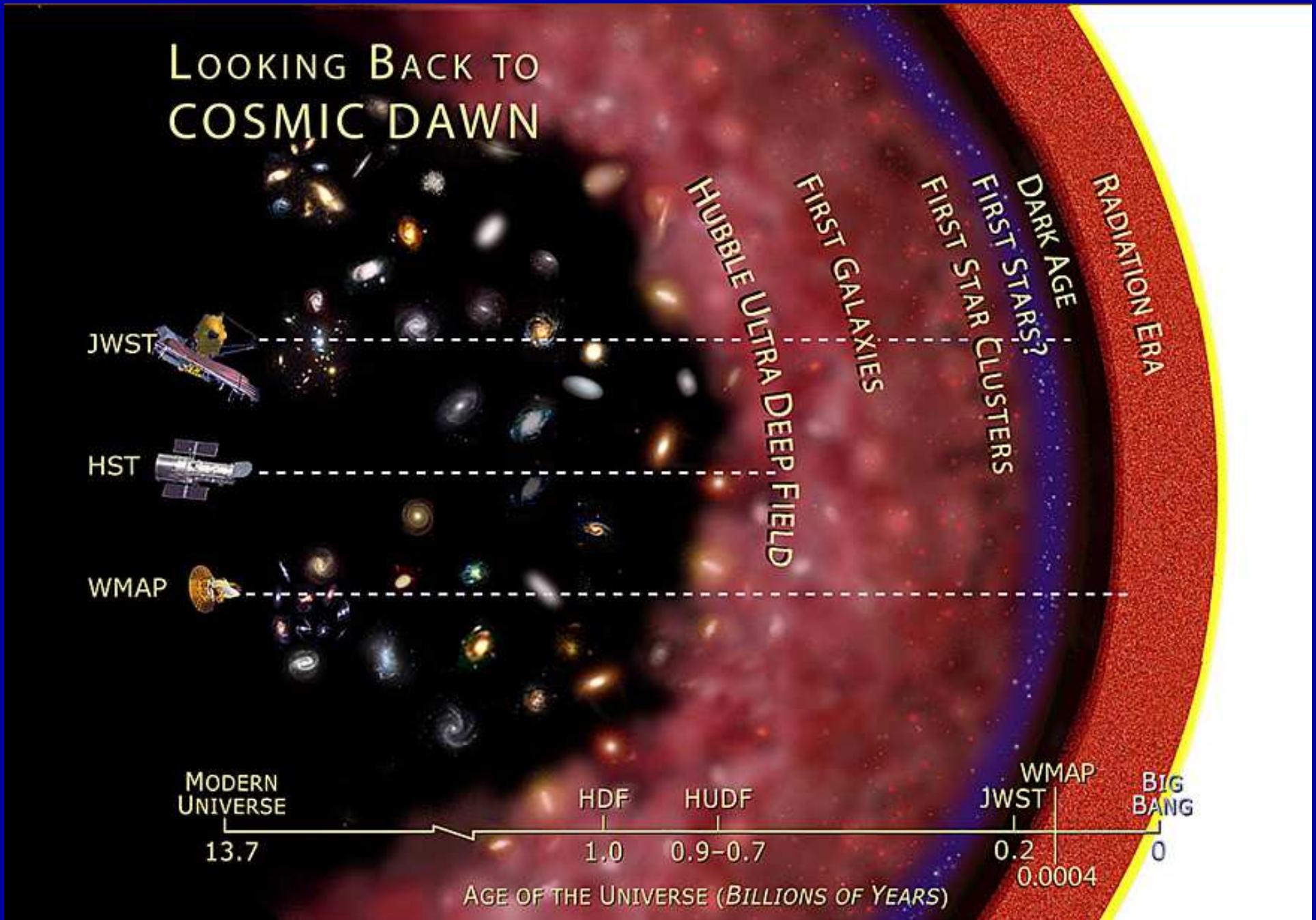


Truth $\equiv$ 240 hrs HUDF Vi'z' 18 hrs JWST 0.7, 0.9, 2.0  $\mu$ m



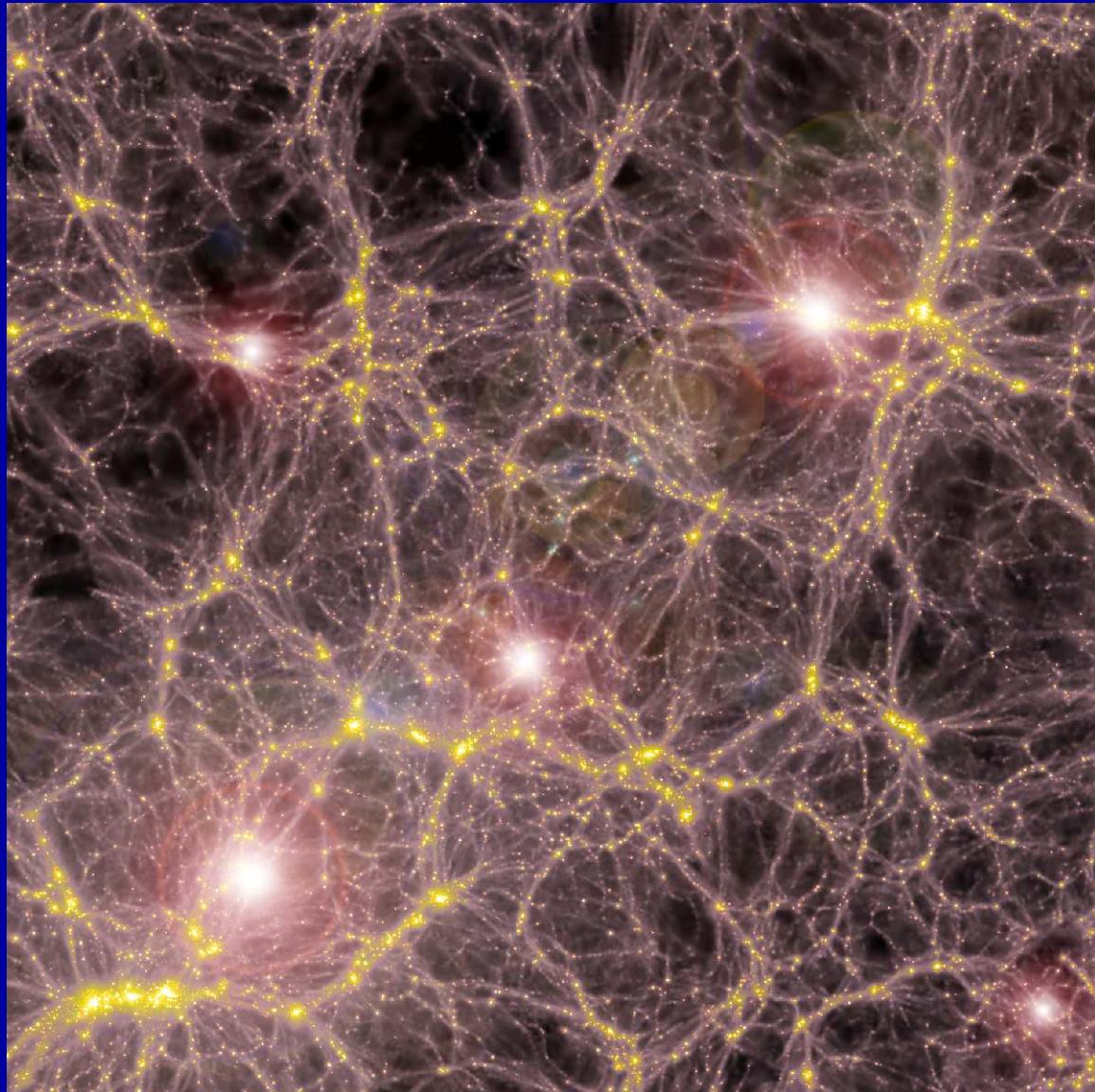
- Can't beat redshift: to see First Light, must observe near-mid IR.  
⇒ This is why JWST needs NIRCam at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .

### (3a) What is First Light, Reionization, and Galaxy Assembly?



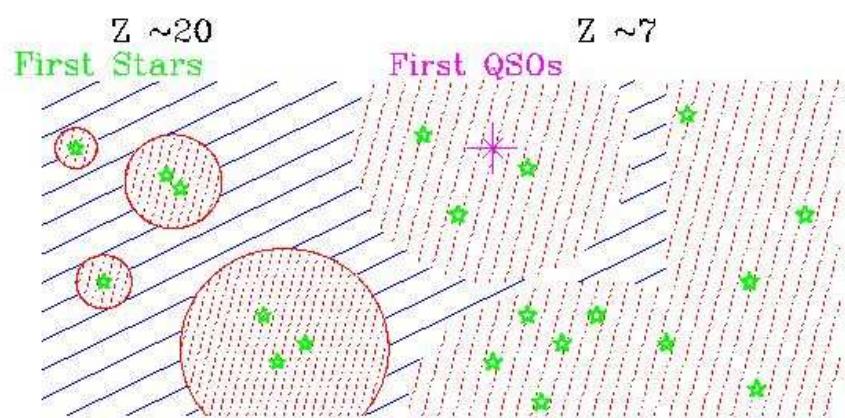
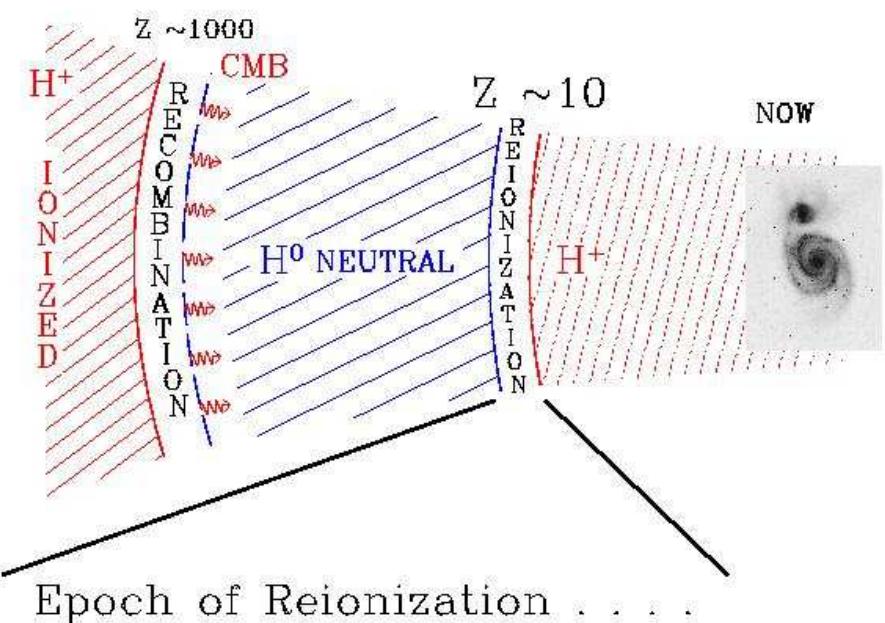
NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination

- (3a) What is First Light and Reionization?



- Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars reionized universe for the first time at  $z \lesssim 10-30$  (First Light).
- A this should be visible to JWST as the first Pop III stars and surrounding star clusters, and perhaps their extremely luminous supernovae at  $z \simeq 10-30$ .

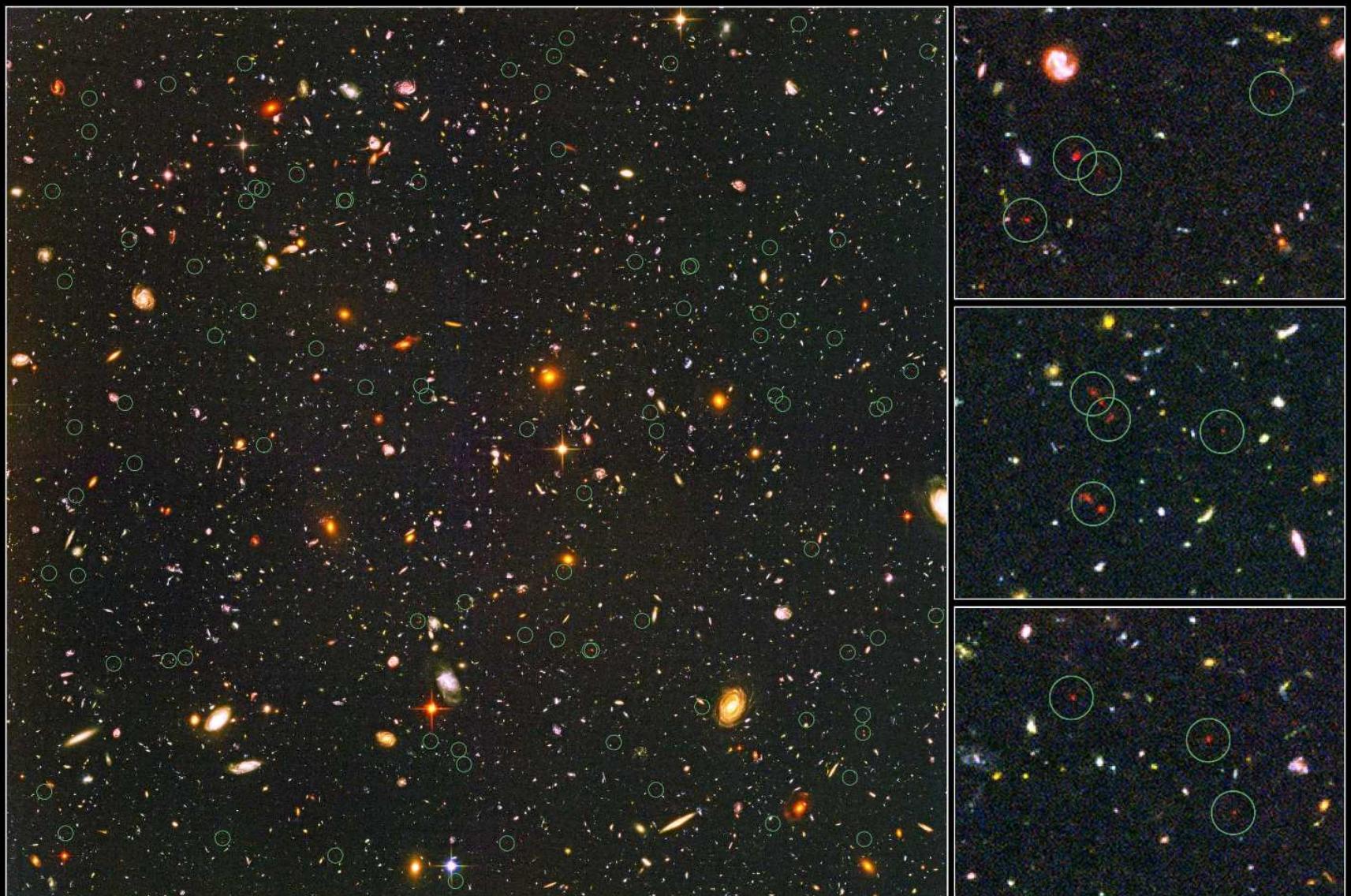
## End of ‘The Dark Age’



WMAP: First Light may have happened as following:

- (0) Dark Ages since recombination ( $z=1089$ ) until First Light objects started shining ( $z \gtrsim 11-20$ ).
- (1) First Light when Population III stars start shining with mass  $\gtrsim 100-200 M_{\odot}$  at  $z \gtrsim 11-20$ .
- (2) Pop III supernovae heated IGM, which perhaps could not cool and form normal Pop II halo stars in bulk until  $z \simeq 9-10$ .
- (3) This is followed by Pop II stars forming in dwarf galaxies (mass  $\simeq 10^7-10^9 M_{\odot}$ ) at  $z \simeq 6-9$ , ending the epoch of reionization.

(Fig. courtesy of Dr. F. Briggs)



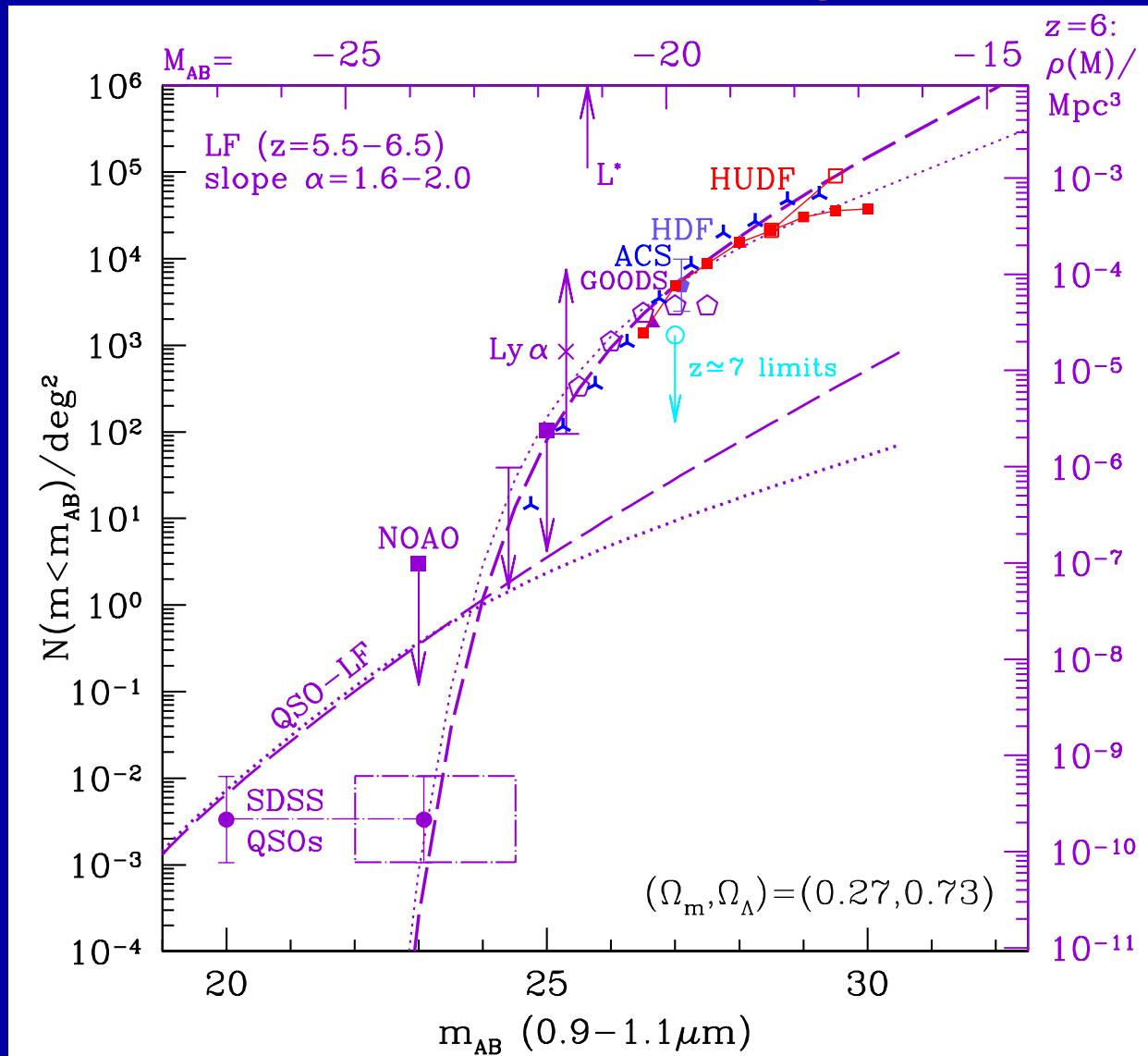
**Distant Galaxies in the Hubble Ultra Deep Field**  
**Hubble Space Telescope • Advanced Camera for Surveys**

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

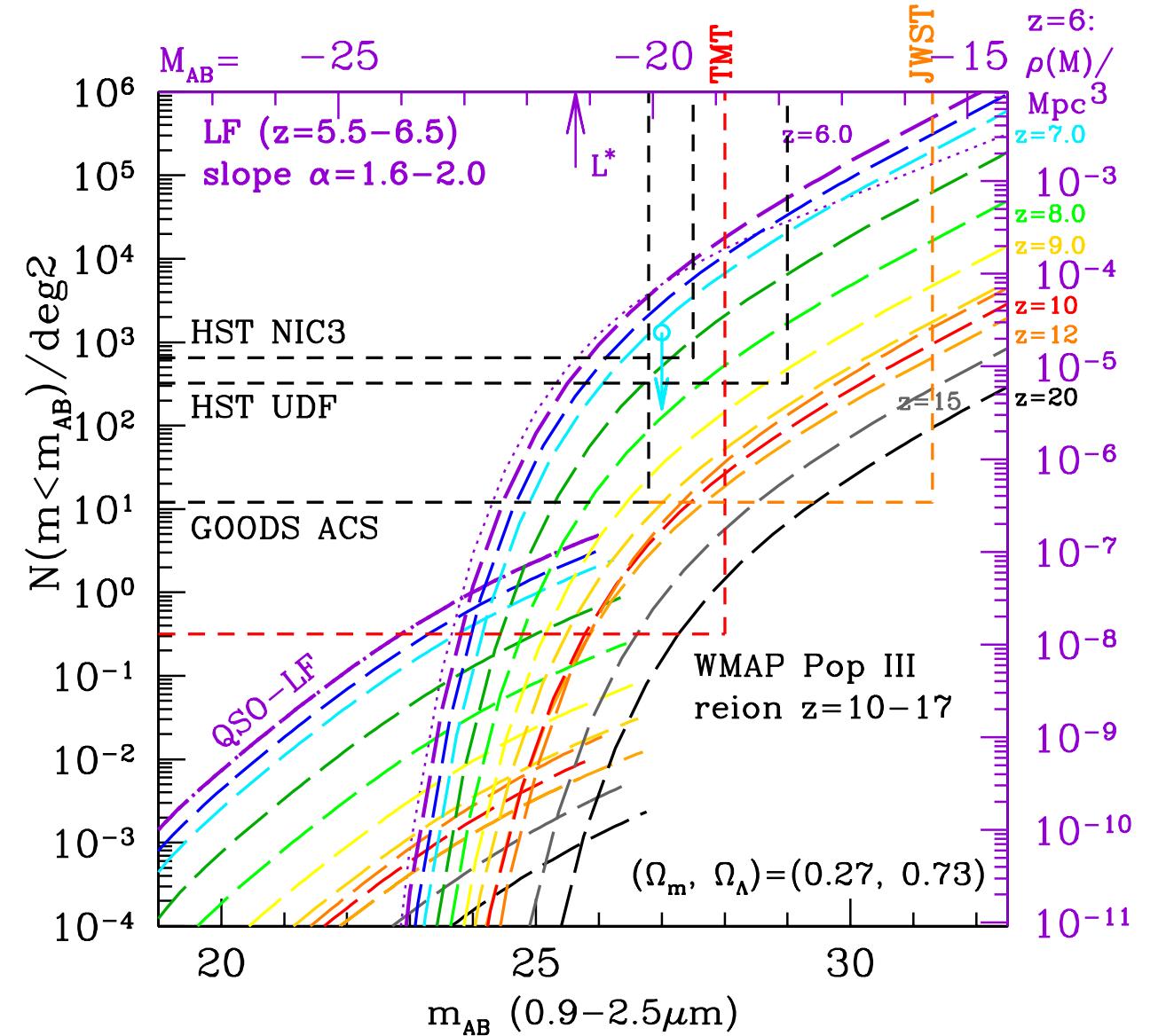
STScI-PRC04-28

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

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

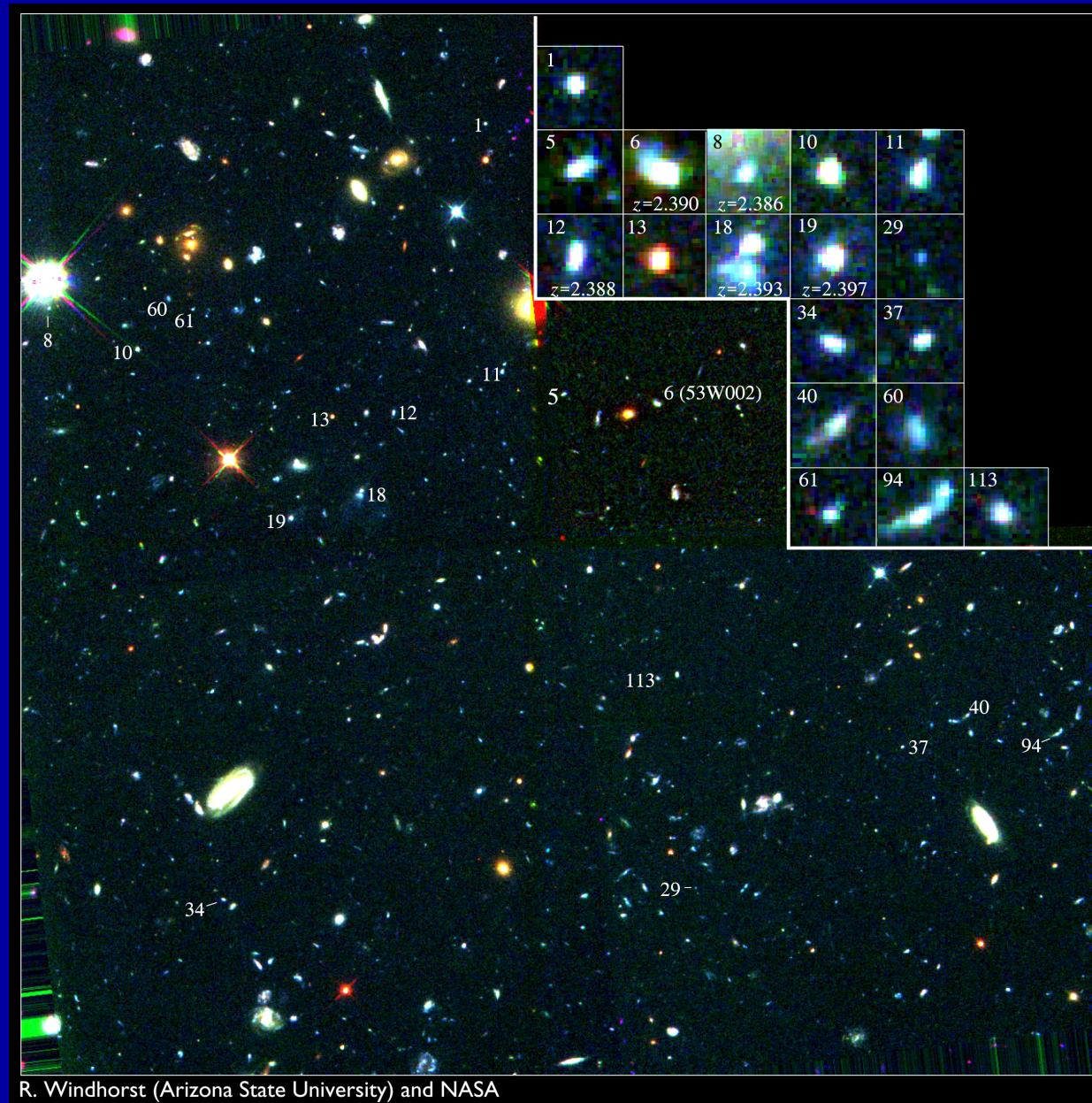


HUDF shows that luminosity function of  $z \simeq 6$  objects (Yan & Windhorst 2004a, b) may be very steep: faint-end Schechter slope  $|\alpha| \simeq 1.6-2.0$ .  
 ⇒ Dwarf galaxies and not quasars likely completed the reionization epoch at  $z \simeq 6$ . This is what JWST will observe in detail for  $z \gtrsim 7-20$ .



- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- Objects at  $z \gtrsim 9$  are rare, since volume element is small and JWST samples brighter part of LF. JWST needs the quoted sensitivity/aperture ( $A$ ), field-of-view ( $\text{FOV} = \Omega$ ), and wavelength range ( $0.7 - 28 \mu\text{m}$ ).

- (4) What is, & how can JWST measure Galaxy Assembly?

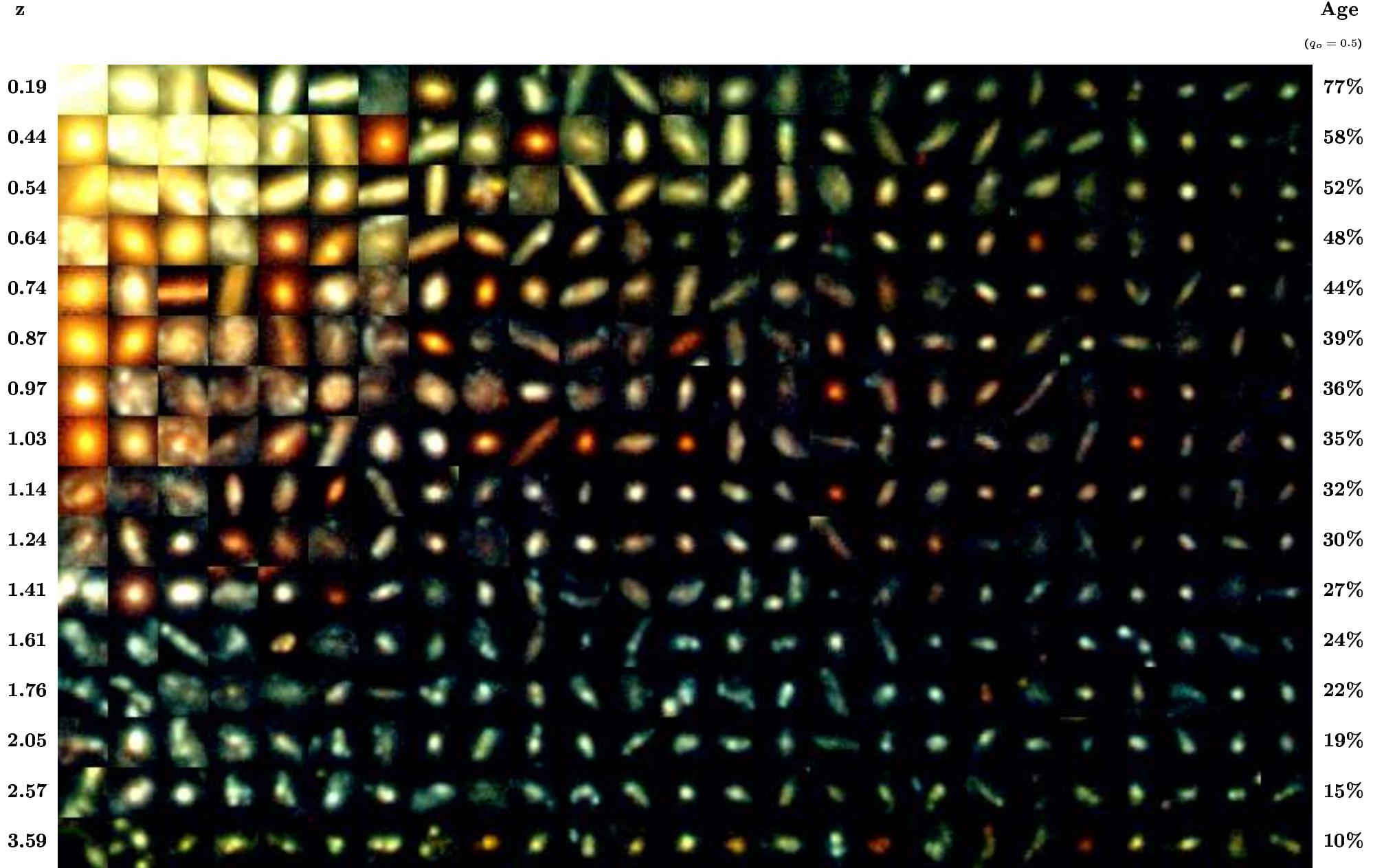


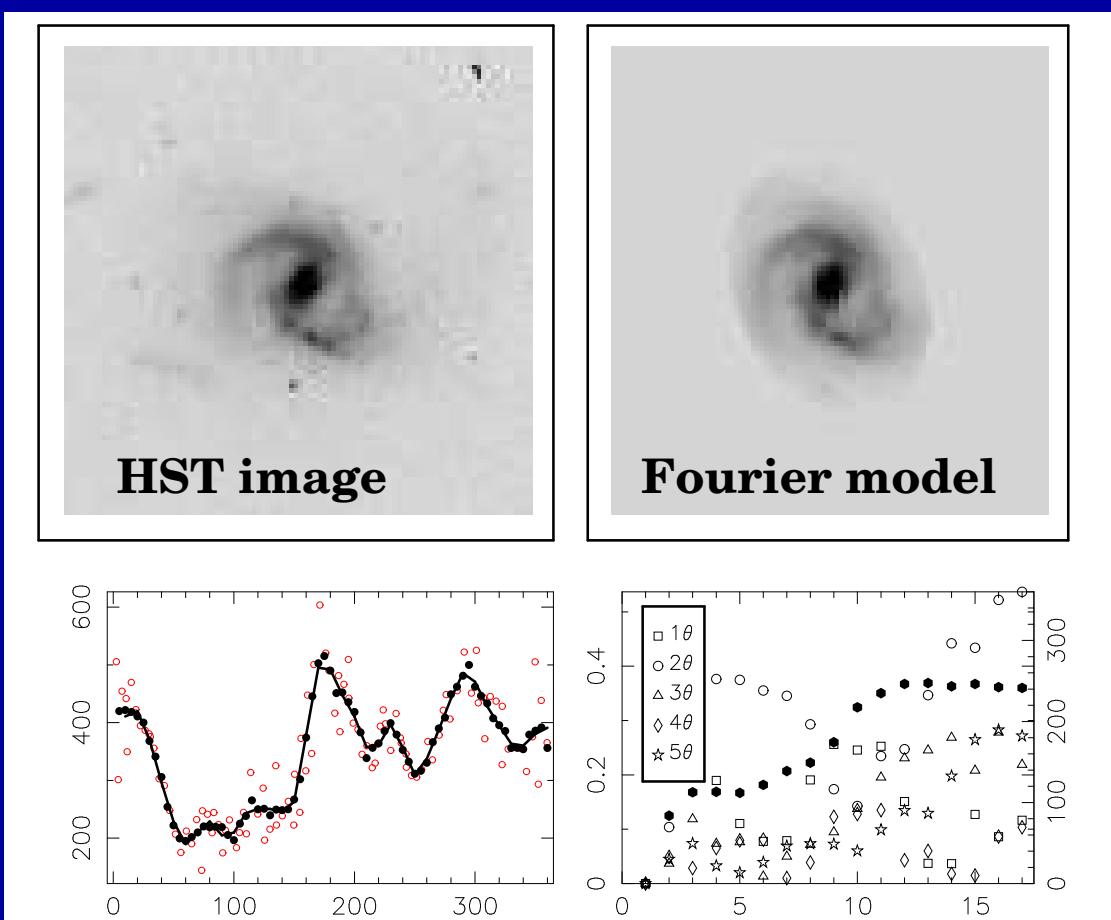
One of the remarkable discoveries of HST was how numerous and small faint galaxies are — the building blocks of the giant galaxies seen today.

- (4a) What is Galaxy Assembly?

- Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable phase transition around  $z \simeq 0.5$ –1.0:
  - (1) Subgalactic units rapidly merge from  $z \simeq 7 \rightarrow 1$  to grow bigger units.
  - (2) Merger products start to settle as galaxies with giant bulges or large disks around  $z \simeq 1$ . These evolved mostly passively since then, resulting in the giant galaxies that we see today.
- JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame structure and type as a function of redshift or cosmic epoch.

# THE HUBBLE DEEP FIELD CORE SAMPLE ( $I < 26.0$ )

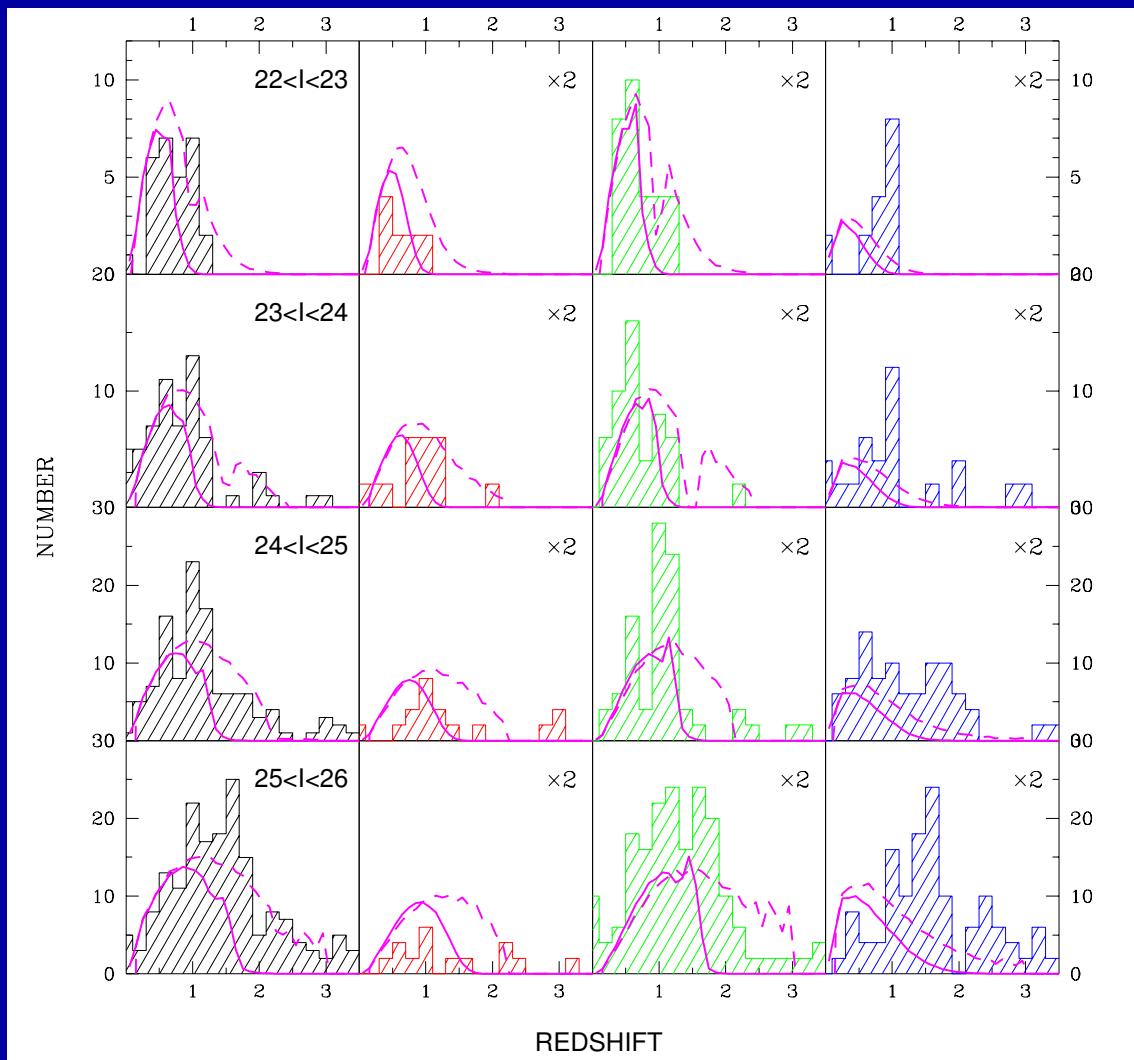




Fourier Decomposition is a robust way to measure galaxy morphology and structure in a quantitative way (Odewahn et al. 2002):

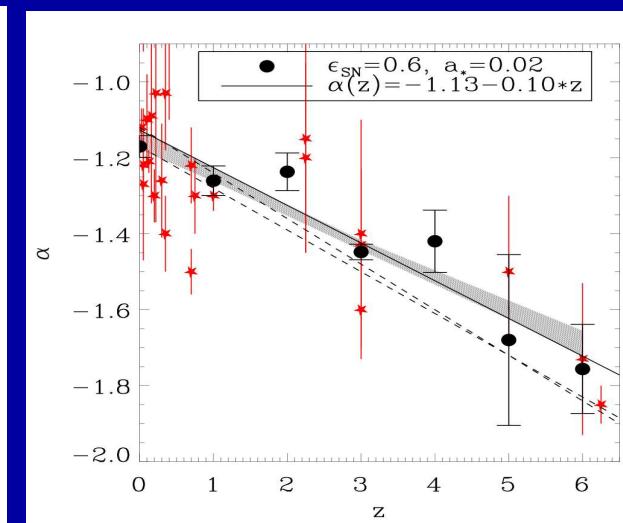
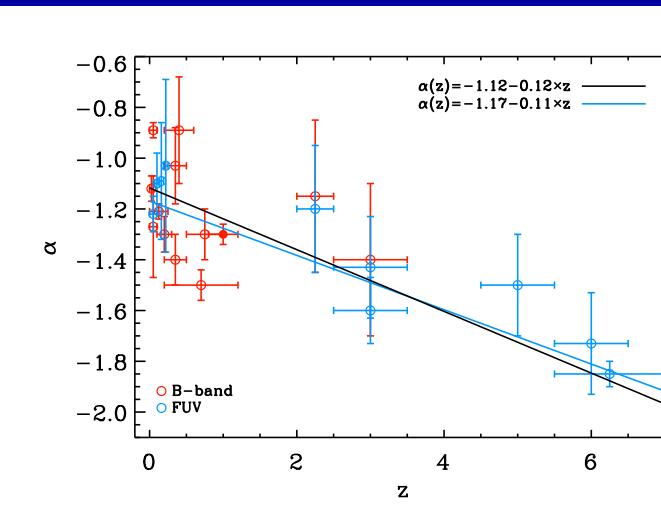
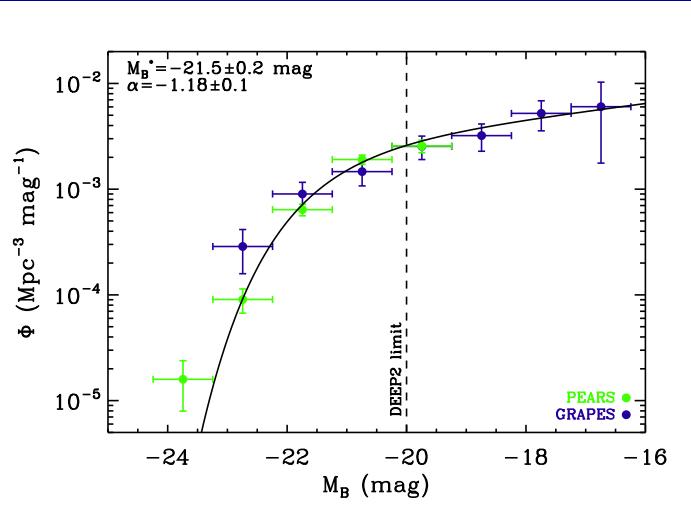
- (1) Fourier series are made in successive concentric annuli.
- (2) Even Fourier components indicate symmetric parts (arms, rings, bars).
- (3) Odd Fourier components indicate asymmetric parts (lopsidedness).
- (4) JWST can measure the evolution of each feature/class directly.

# Total Ell/S0 Sabc Irr/Mergers



- JWST can measure how galaxies of all Hubble types formed over a wide range of cosmic time, by measuring their redshift distribution as a function of rest-frame type.
- For this, the types must be well imaged for large samples from deep, uniform and high quality multi-wavelength images, which JWST can do.

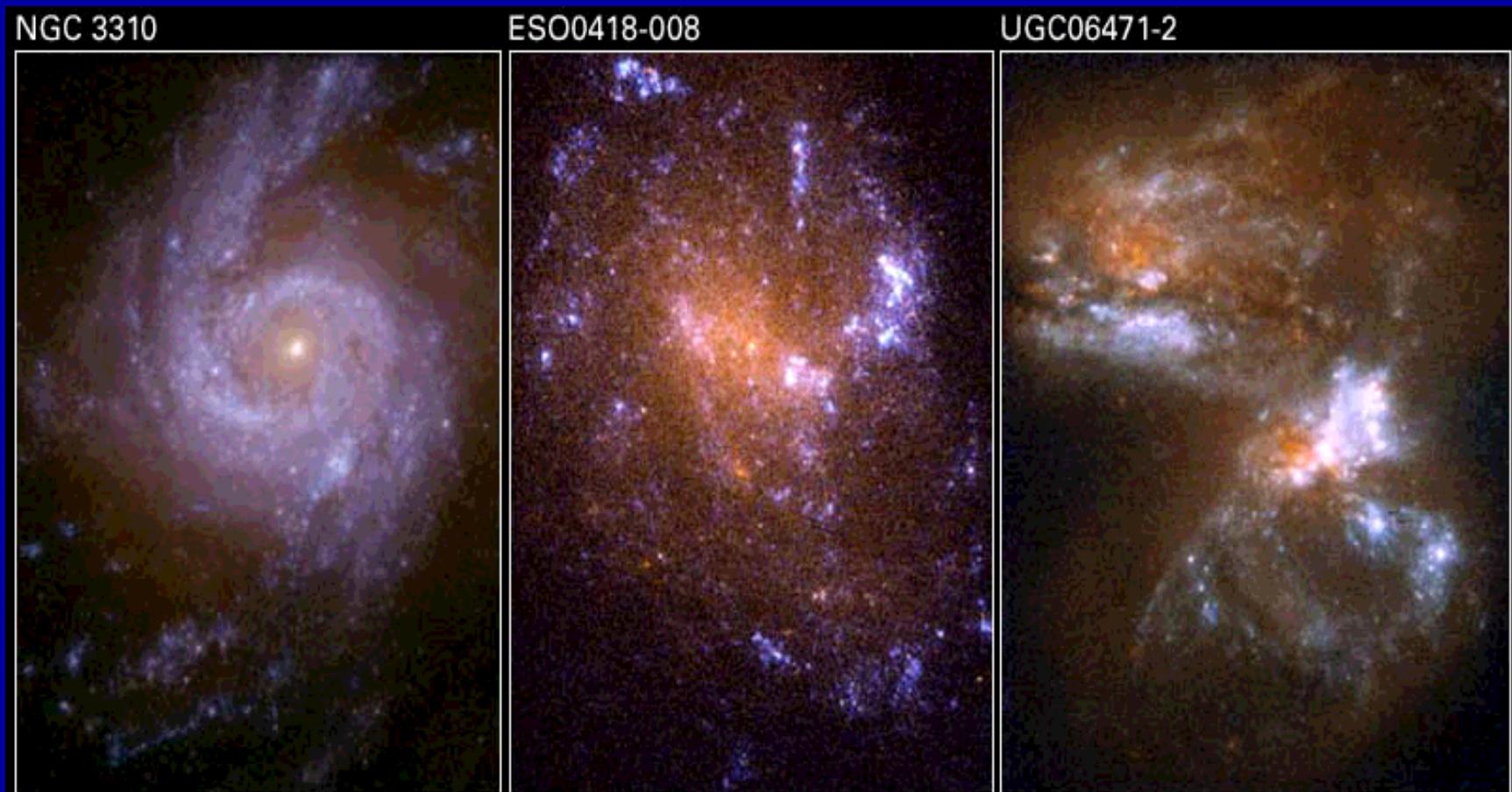
# Faint-end LF-Slope Evolution (fundamental, like local IMF)



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 ea. 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.

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



### Ultraviolet Galaxies

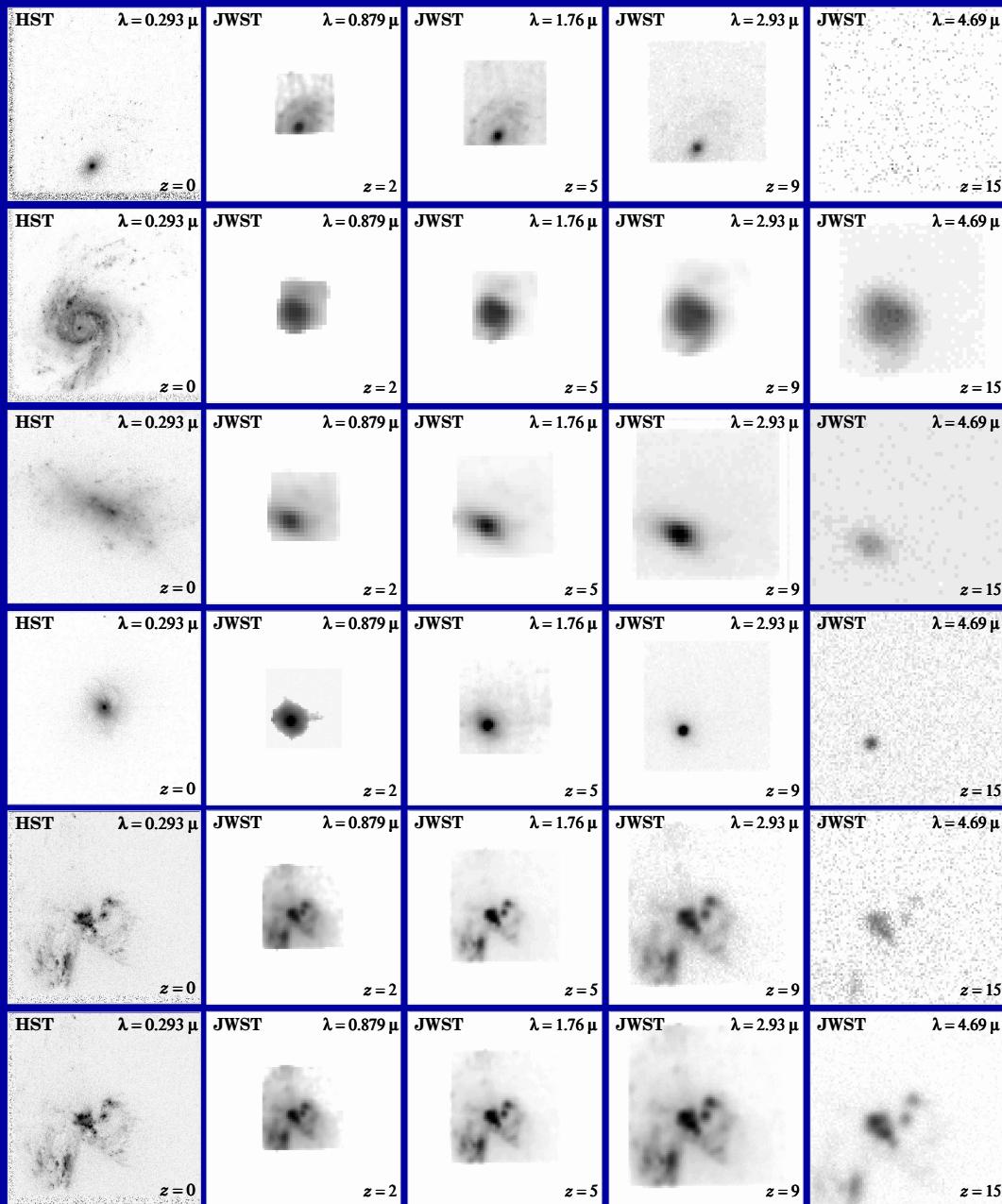
HST • WFPC2

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

- The uncertain rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust superimposed.
- This makes comparison with very high redshift galaxies seen by JWST complicated, although with good images a quantitative analysis of the restframe-wavelength dependent morphology and structure can be made.

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

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



With proper restframe-UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure 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

---

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

- All critical items at Technical Readiness Level 6 (TRL-6) by Jan. 2007 (*i.e.*, demonstration in a relevant environment — ground or space).
- Passed Technical Non-Advocate Review (T-NAR) in 2007, and will undergo Mission Preliminary Design Review (PDR) in March 2008.

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

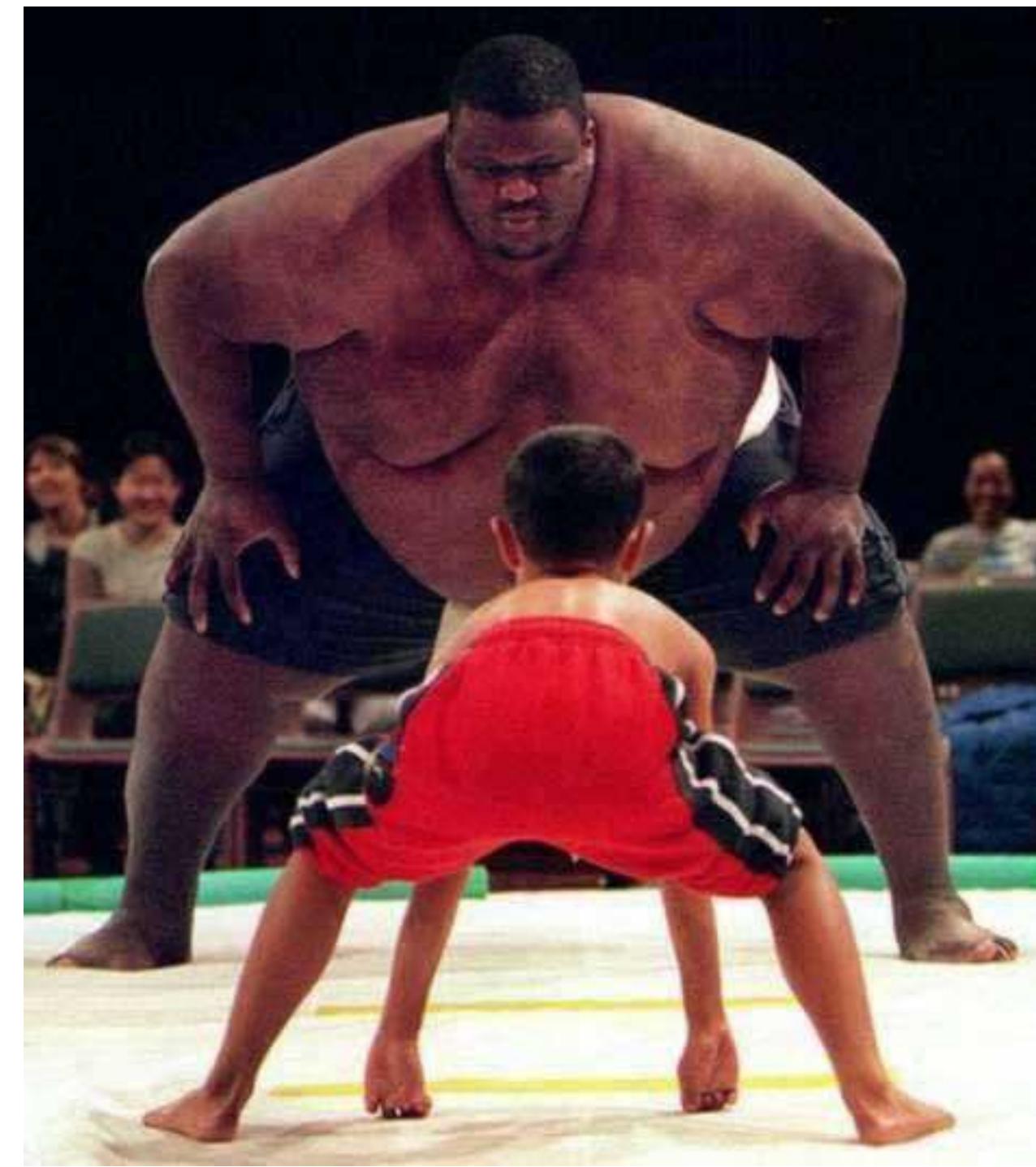
- The formation and evolution of the first (reionizing) Pop III star-clusters.
- Faint-end LF-slope evolution: how dwarf galaxies finished reionization.
- The origin of the Hubble sequence in hierarchical formation scenarios.

(3) JWST will have a major impact on astrophysics after 2013:

- Current generation of graduate students and postdocs will be using JWST during their professional career.
- JWST will define the next frontier to explore: the Dark Ages at  $z \gtrsim 20$ .

# SPARE CHARTS

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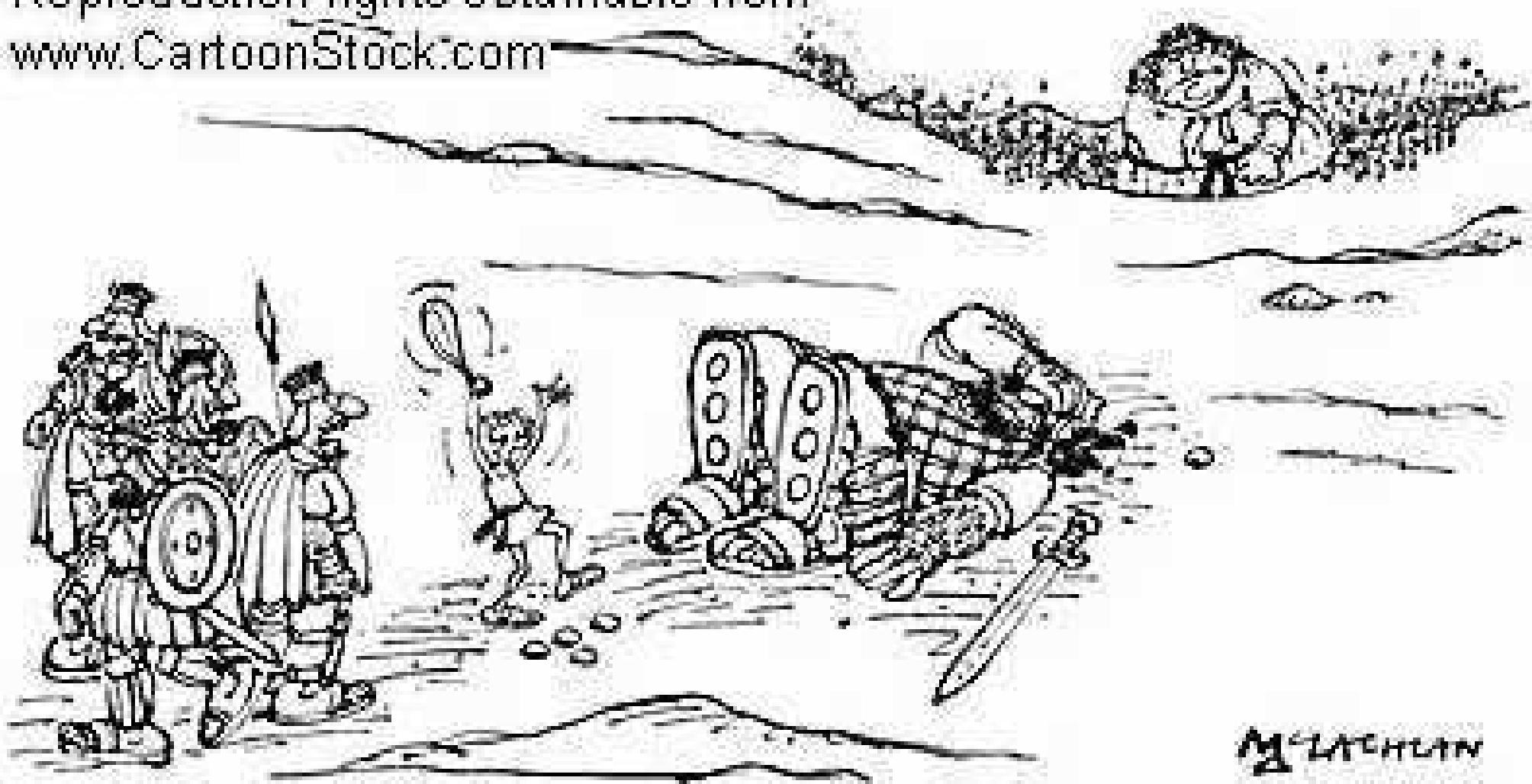


At the end of reionization, dwarfs had beaten the Giants, but ...

© Original Artist

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[www.CartoonStock.com](http://www.CartoonStock.com)



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

What comes around, goes around ...

- References and other sources of material shown:

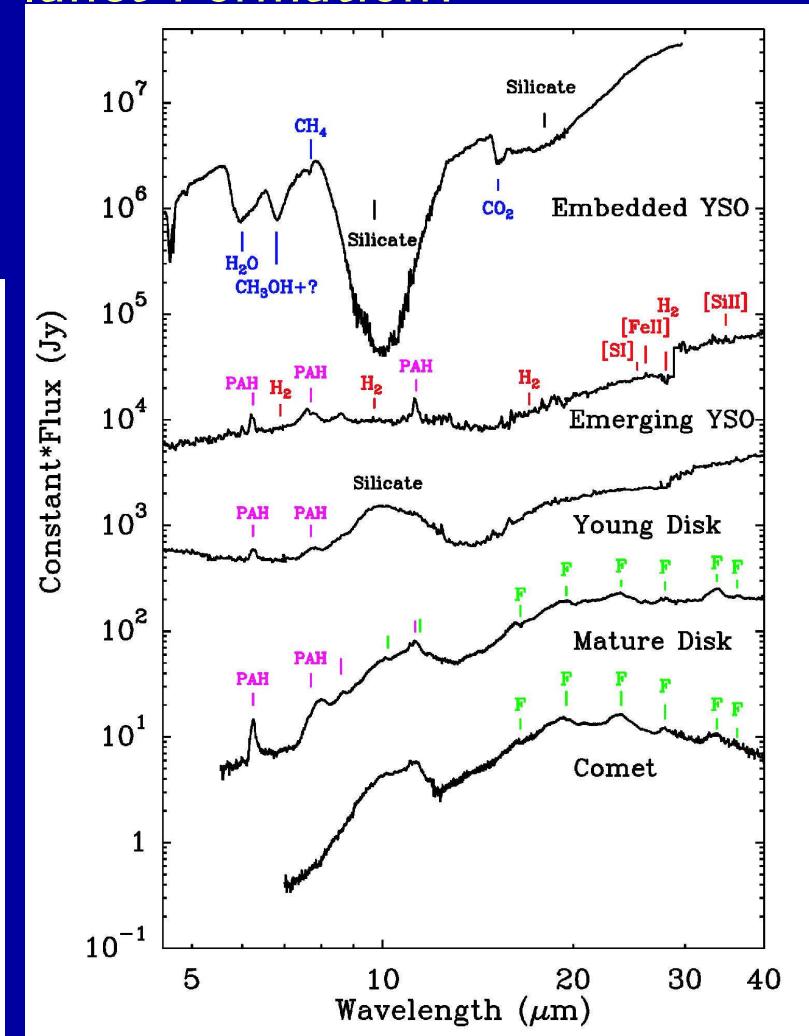
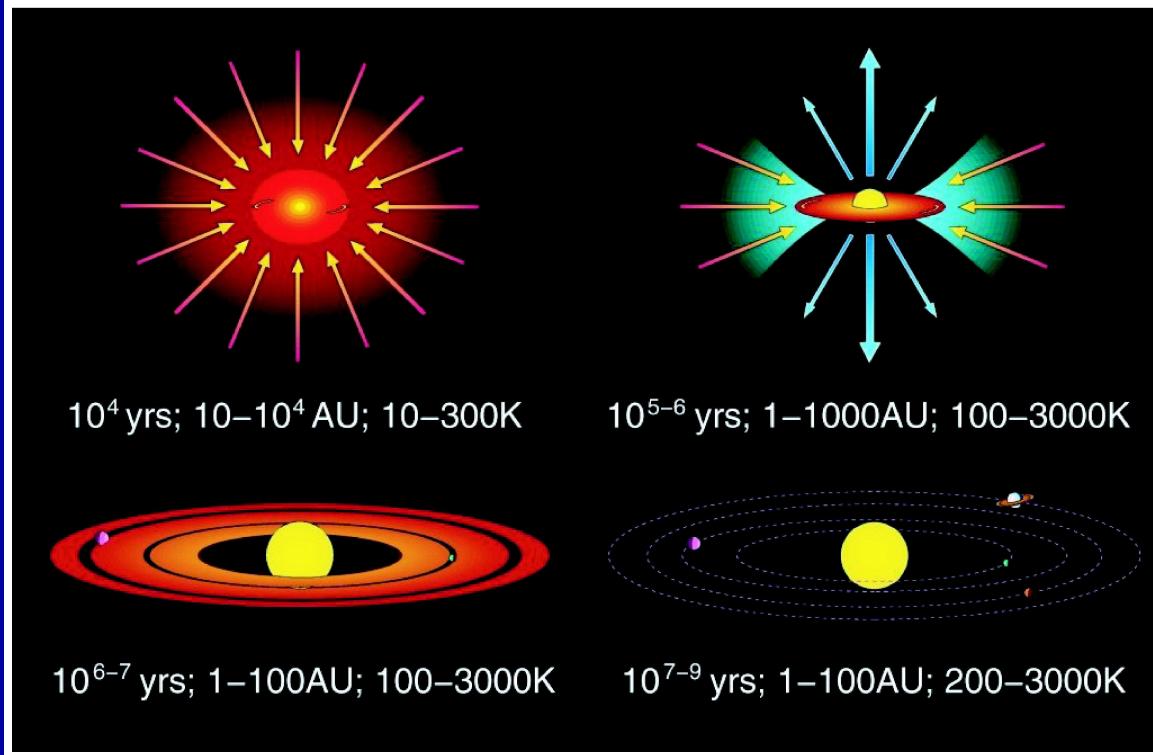
<http://www.asu.edu/clas/hst/www/jwst/> [Talk, Movie, Java-tool]  
[www.asu.edu/clas/hst/www/ahah/](http://www.asu.edu/clas/hst/www/ahah/) [Hubble at Hyperspeed Java–tool]  
[http://wwwgrapes.dyndns.org/udf\\_map/index.html](http://wwwgrapes.dyndns.org/udf_map/index.html) [Clickable HUDF map]  
<http://www.jwst.nasa.gov/> 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., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly, S. J., Long, K. S., Lunine, J. I., McCaughrean, M. J., Mountain, M., Nella, J., Rieke, G. H., Rieke, M. J., Rix, H.-W., Smith, E. P., Sonneborn, G., Stiavelli, M., Stockman, H. S., Windhorst, R. A., & Wright, G. S. 2006, Space Science Reviews, 123, 485–606 ([astro-ph/0606175](#))

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

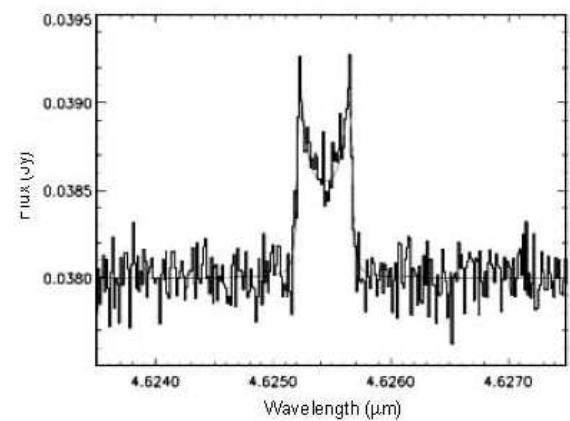
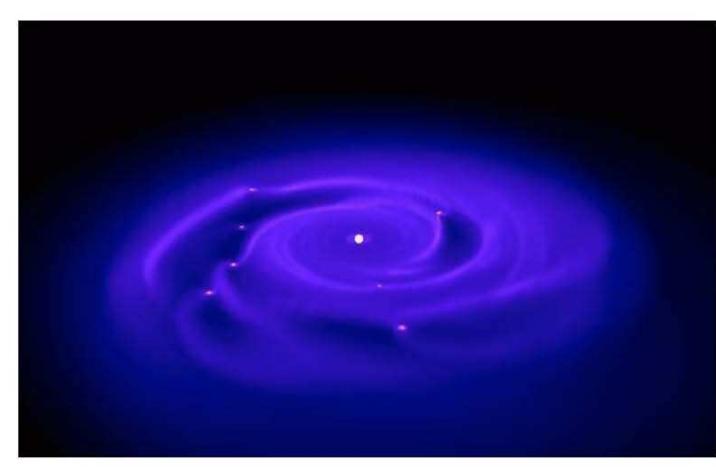
Windhorst, R., et al. 2007, Advances in Space Research, 42, 1–10 ([astro-ph/0703171](#)) “High Resolution Science with High Redshift Galaxies”

# What can JWST do Star- and Planet Formation?

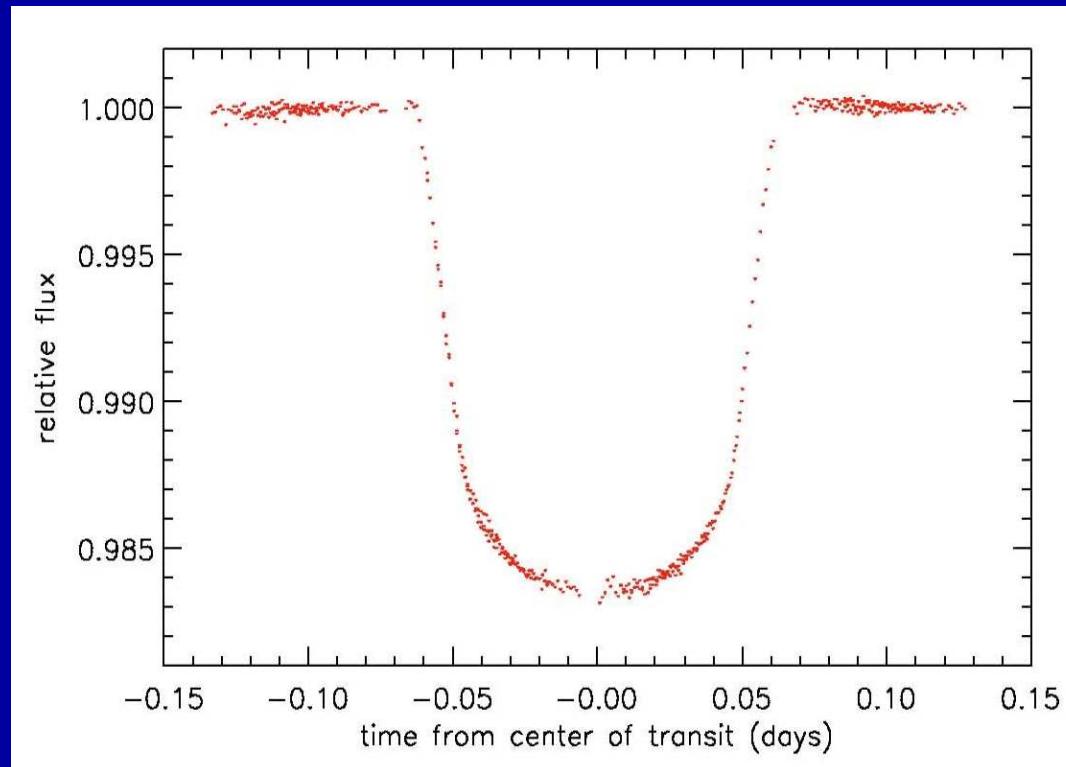
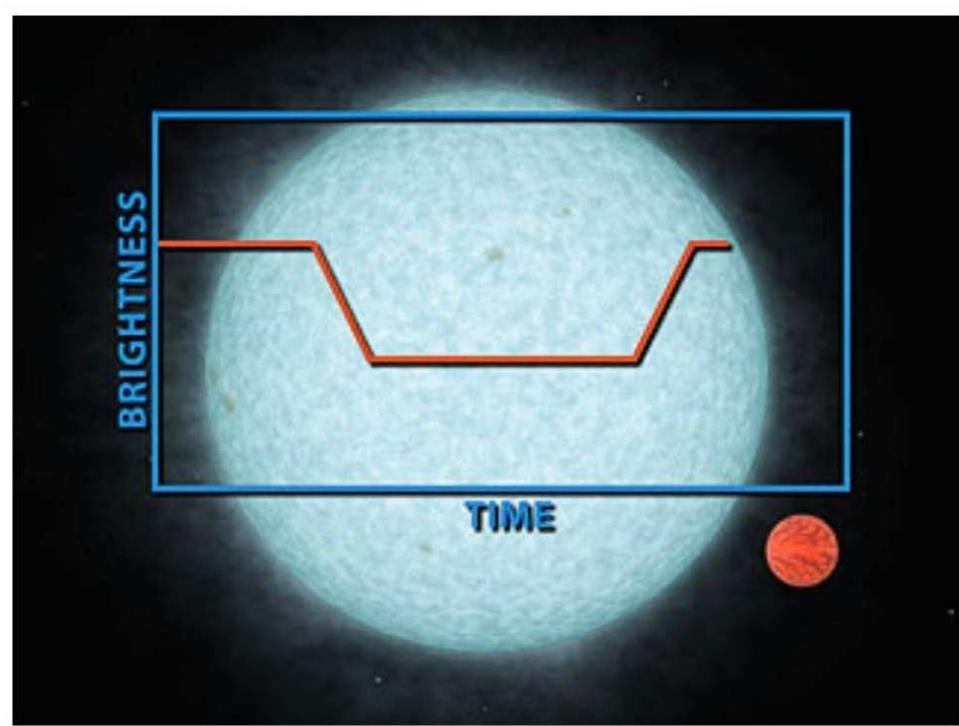


JWST will trace various stages of star-formation, YSO's, debris-disk formation and planet formation through very high-resolution imaging, coronagraphy, & high-resolution optical–IR spectra.

JWST provides high time-resolution photometry & coronagraphy for planet detection, and *panchromatic* low-resolution near–mid-IR spectra.



JWST: Very high-res imaging, coronagraphy, & high-res optical-IR spectra.



JWST: High time-res photometry, coronagraphy, & low-res mid-IR spectra.

# Northrop Grumman Expertise in Space Deployable Systems

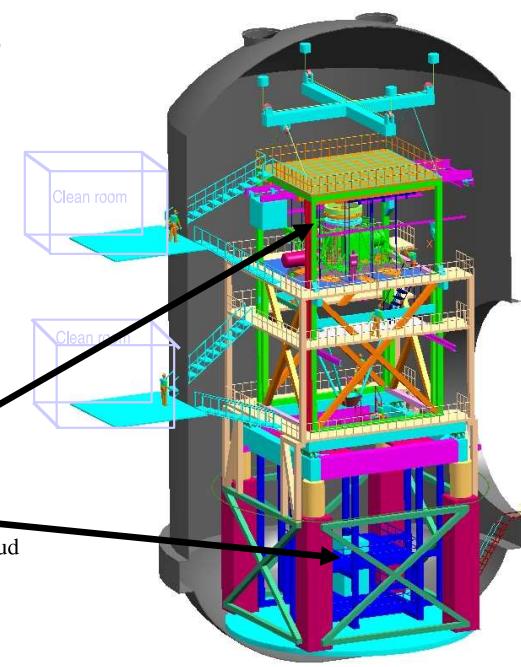
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements



### Baseline “Cup Down” Tower Configuration at JSC (Before)



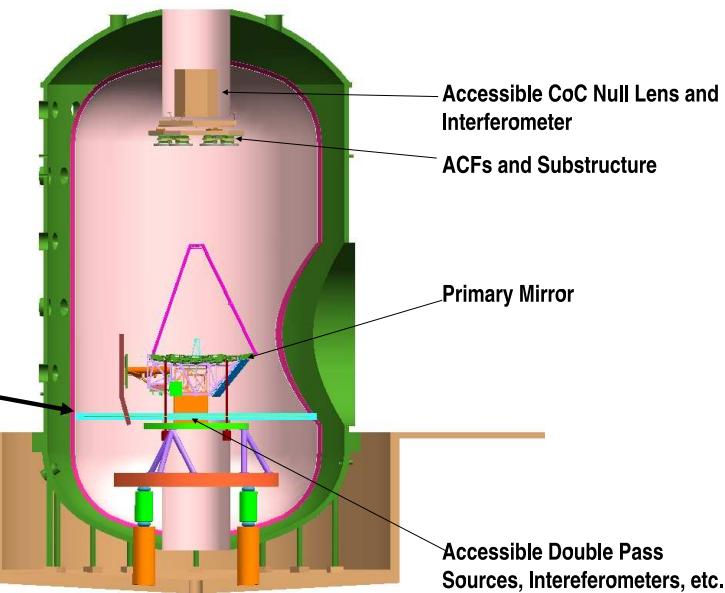
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.



### 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.



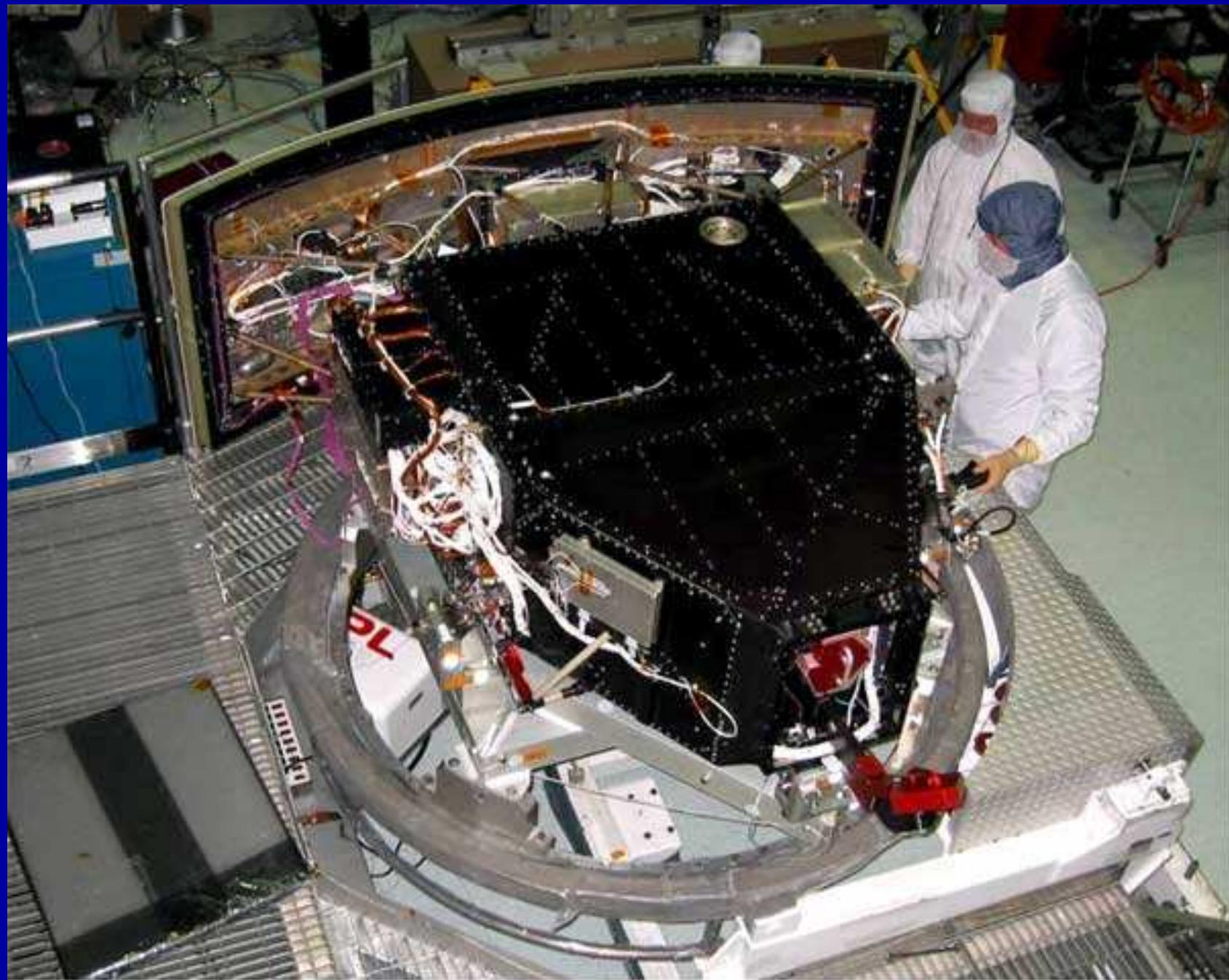
Drawing care of ITT

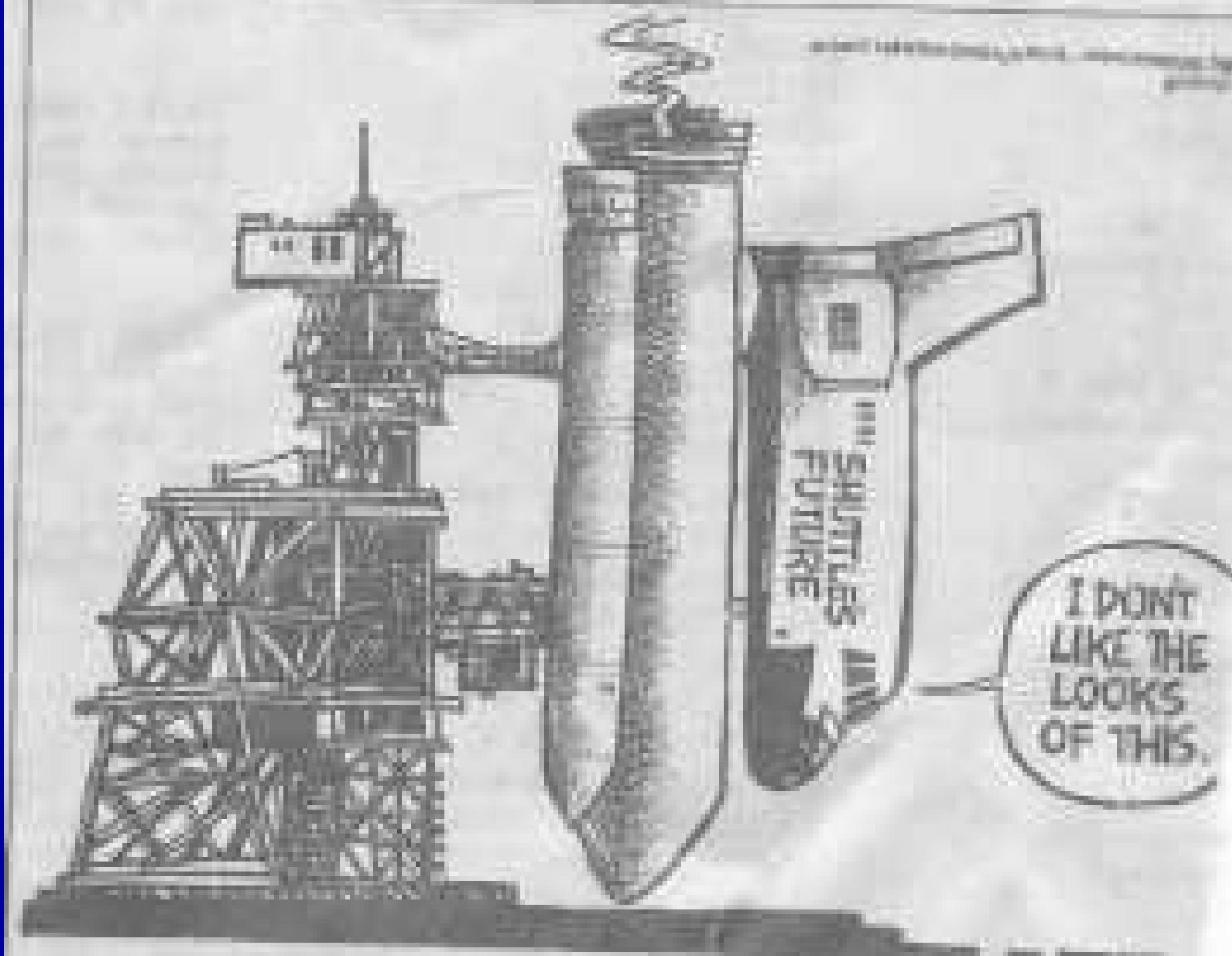
Page 6

JWST underwent several significant replans and risk-reduction schemes:

- ≈2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6), i.e., demonstration in a relevant environment — ground or space.
- 2007: Further simplification of sun-shield and end-to-end testing.

## Appendix 1: Future studies with the Hubble Wide Field Camera 3





If there are no further Shuttle issues, WFC3 will get launched in Aug. 2008 ...

For detailed flow operations refer to  
Preliminary Manifest Option 07B-10A

# Flight Assignment Working Group (FAWG) Planning Manifest

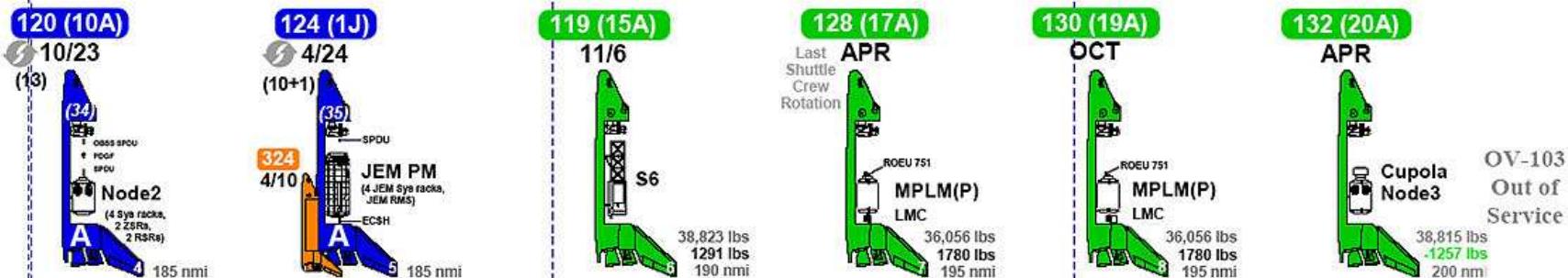
NASA Official: John Coggeshall

Prepared by: USA/700C/Barton K. Gibson

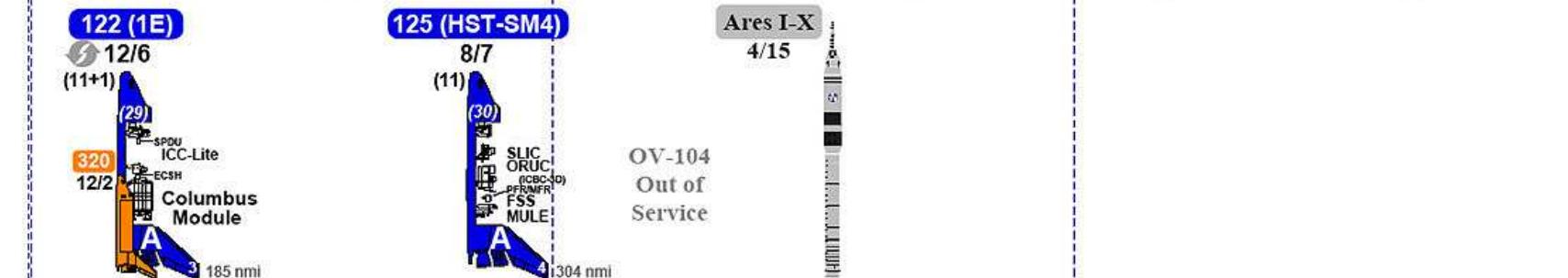


Chart updated: 28-September-2007

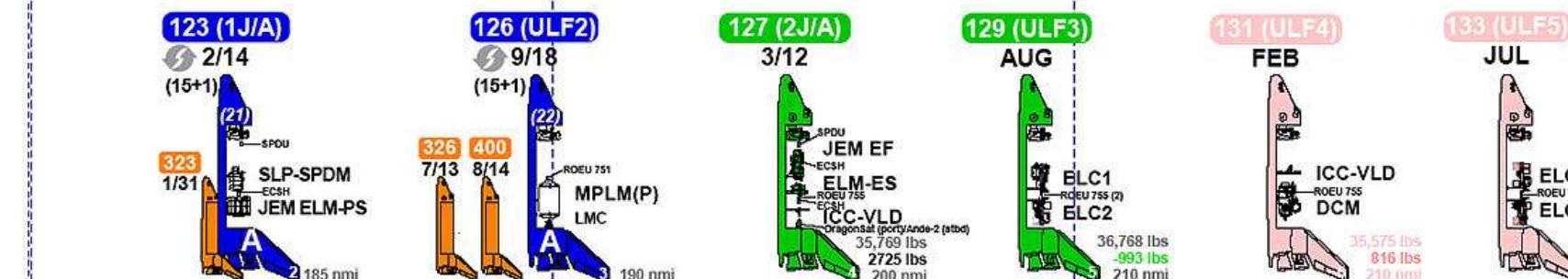
**103**  
Discovery



**104**  
Atlantis



**105**  
Endeavour



This chart represents cargo bay configurations approved by the JCAWG

Flight Rate: FY-3/CY-4												FY-6/CY-5												FY-4/CY-4																			
Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep					
Launch Beta Angle Cutouts*			15	β	29			10	β	23	7	β	21	Beta Exceedance																													
* being above +/- 65 degrees (for 135min Orbit) during Orbiter/ISS combined mated ops (3 days)																																											
Flight Rate: FY-3/CY-4	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep				
Launch Beta Angle Cutouts*				15S	10/10	ATV1	1/31	16S	4/8	17S	10/12	18S-1	Apr	18S-2	May	HTV1	Jul																										
* Under Review				15S	10/10	ATV1	1/31	16S	4/8	17S	10/12	18S-1	Apr	18S-2	May	HTV1	Jul																										
Green APM#: Flight specific vehicle & launch month				27P	12/23	28P	2/7	29P	5/14	30P	8/12	31P	9/11	32P	Dec	33P	Feb	34P	Mar																								
Black APM#: Generic specific vehicle & launch month																																											
Soyuz (S)																																											
Progress (P)																																											

Contingency Logistic Flights

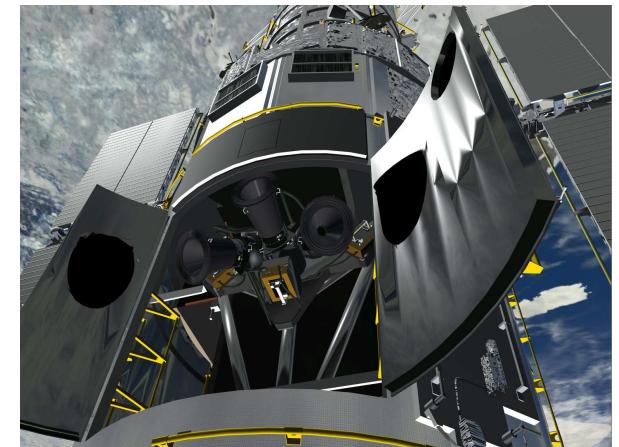
Contingency Shuttle Crew Support (CSCS) (Empty Cargo Bay)

Not baselined in the FDRD

ISS Chargeable weight (kg) APN (kg) Rendezvous altitude (nm) has flown since last CMDF

FDRD Launch Date STS# (ISS#) (baselined) → Launch Date Mission duration → # of times the OV has flown → Assessed Cargo Bay Element(s) Launch Pad Rendezvous altitude (nm) 1

# High Level SM4 Mission Status Overview



**Hubble Space Telescope Program  
IMAX Camera on ORUC for HST SM4**

**IMAX Location with FOVs**

This diagram illustrates the IMAX camera's location relative to the Hubble Space Telescope's (HST) structure. It shows the IMAX camera mounted on the Optical Remote Utility Cabinet (ORUC). Four different Field of View (FOV) areas are highlighted: a large light brown area labeled '100mm FOV', a smaller light green area labeled '40mm FOV', a small orange area labeled 'IMAX', and a very small red area labeled '30mm FOV'. The diagram also indicates the 'HST Aft Shroud Doors (open)' and the 'BISIPE on ORUC'. A large arrow points downwards, labeled 'FWD'.

**Hubble Space Telescope Program  
IMAX Camera on ORUC for HST SM4**

**IMAX Location on SM4 ORUC**

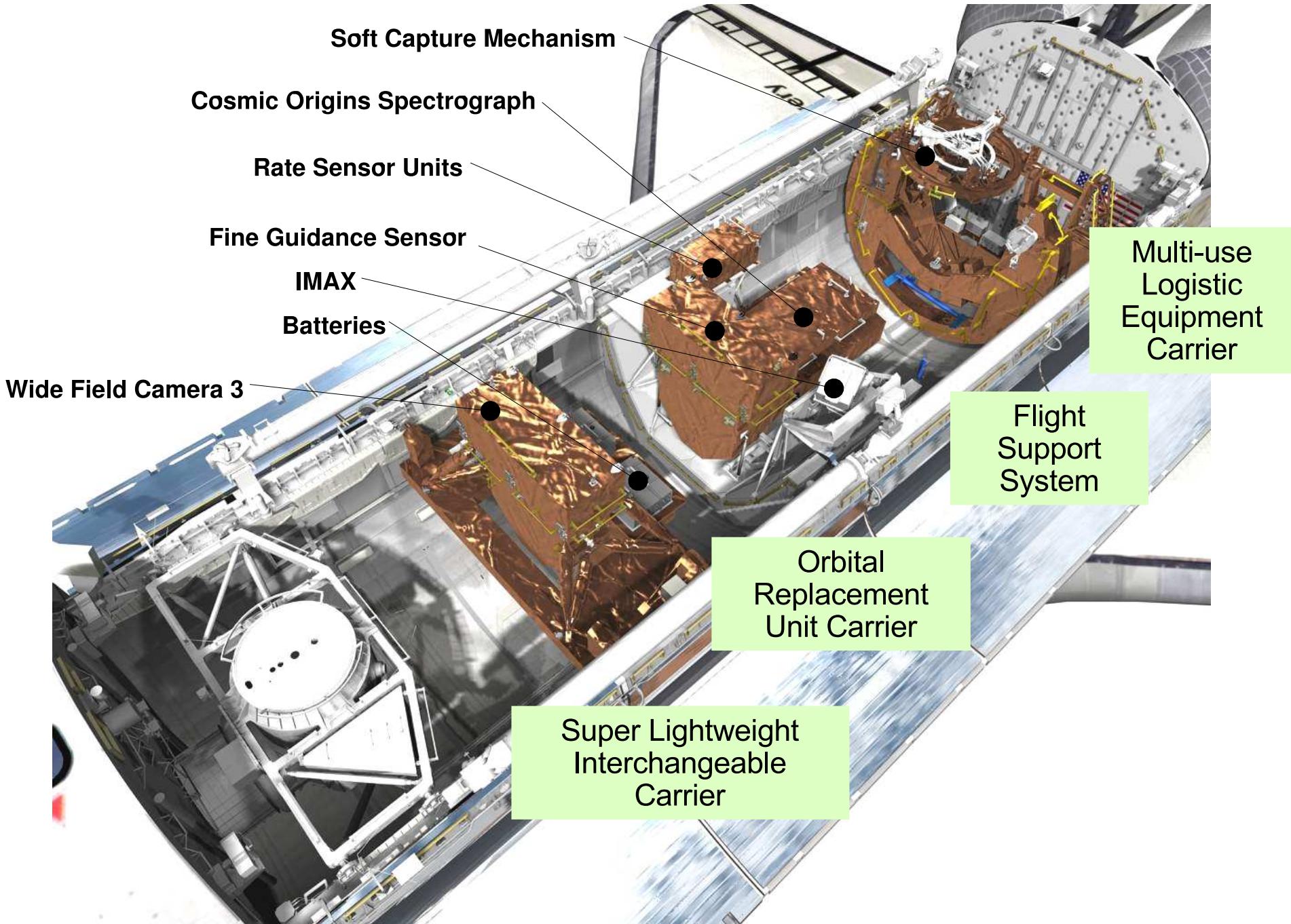
This diagram provides a detailed view of the IMAX camera's location on the SM4 Optical Remote Utility Cabinet (ORUC). The IMAX camera is shown mounted on the side of the ORUC. Labels include 'HST Aft Shroud Doors (open)', 'IMAX', 'BISIPE on ORUC', and a large arrow pointing downwards labeled 'FWD'. A small NASA logo is visible in the top right corner.

ORUC-IMAX-12Dec2006.ppt  
J. Neuman x6-1328

ORUC-IMAX-12Dec2006.ppt  
J. Neuman x6-1328



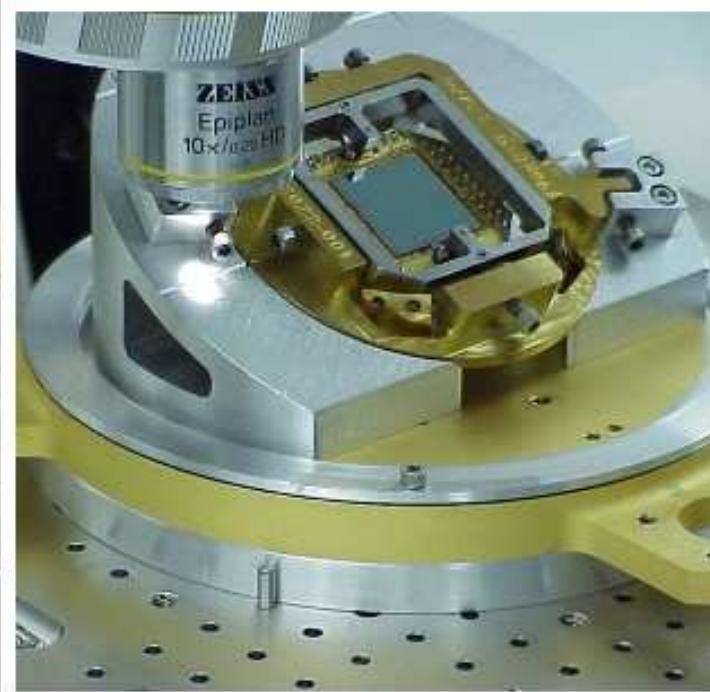
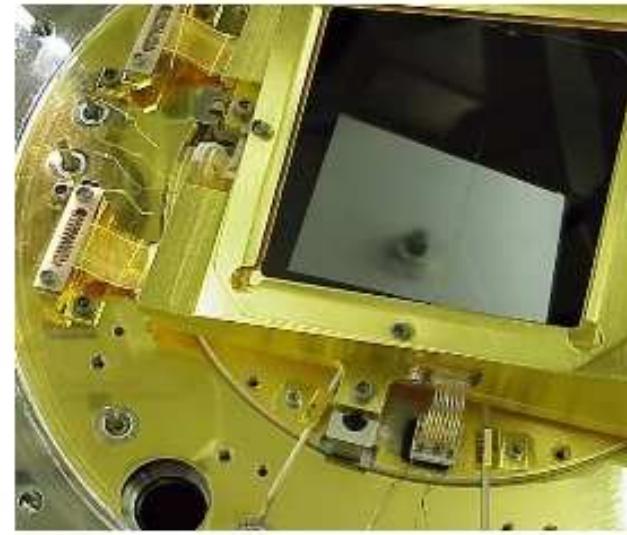
# HST Servicing Mission 4 (SM4) Configuration

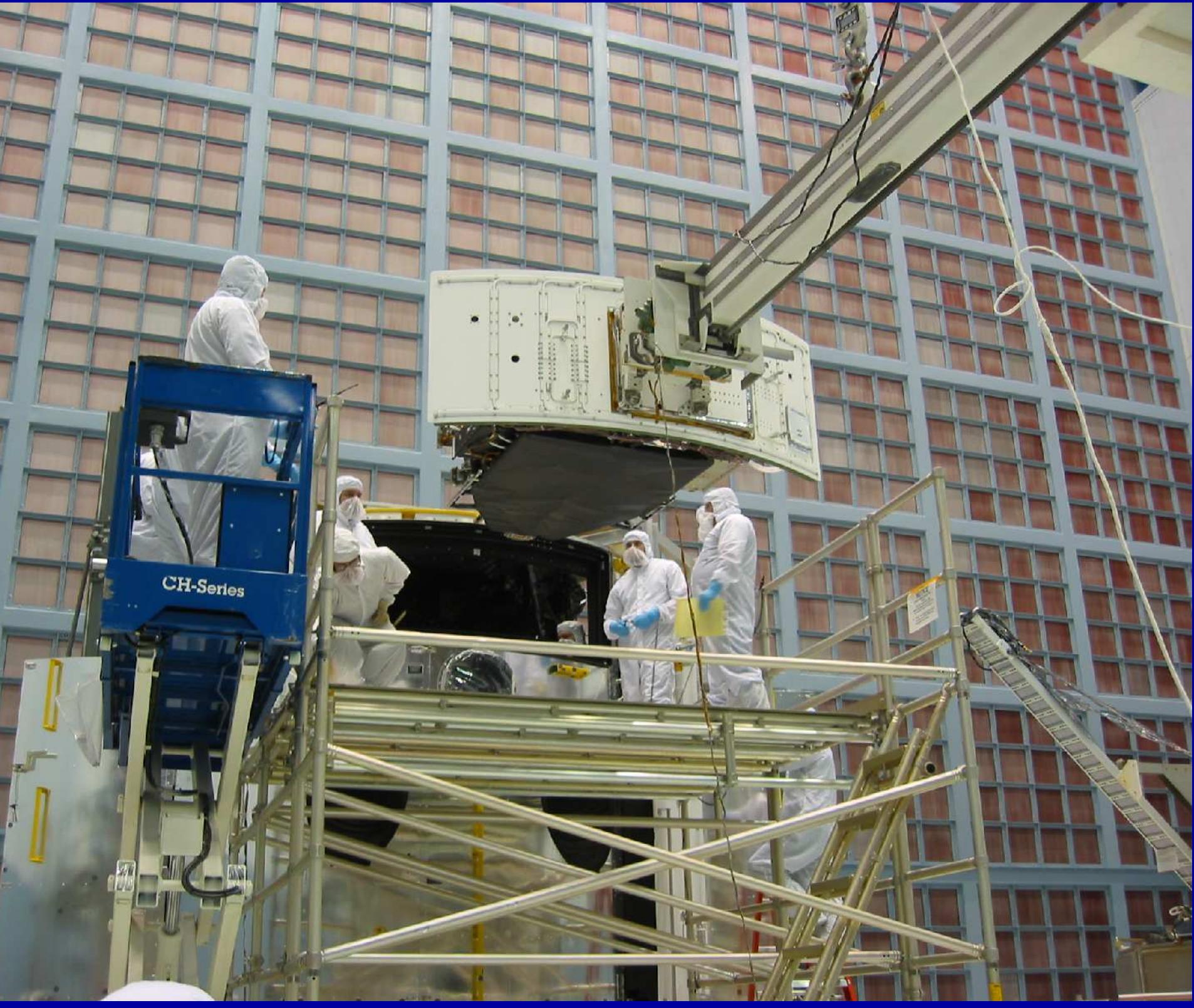




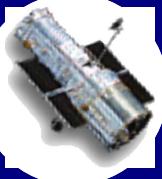
# WFC3 SOC Meeting

## June 14, 2007





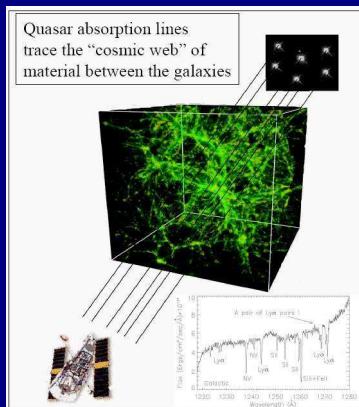
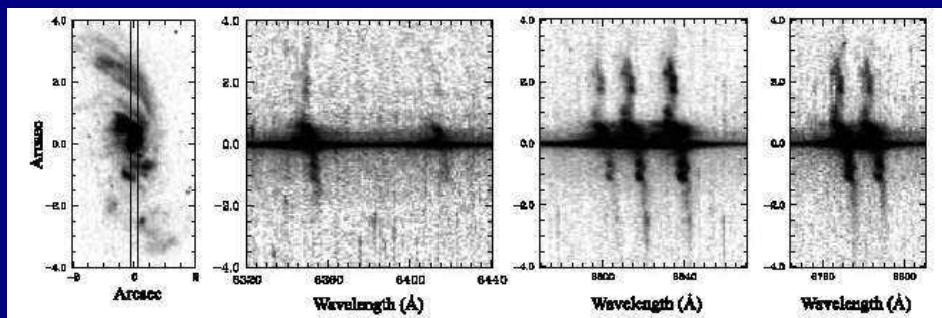
**MISSION GOAL:** Five working, complementary instruments for the first time since 1993; Hubble at its APEX.



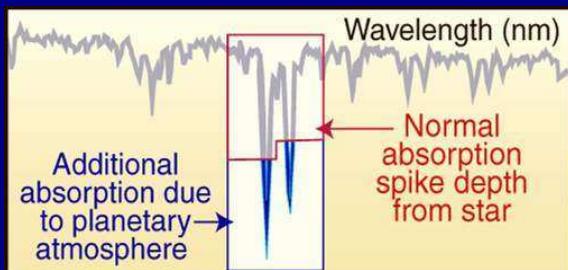
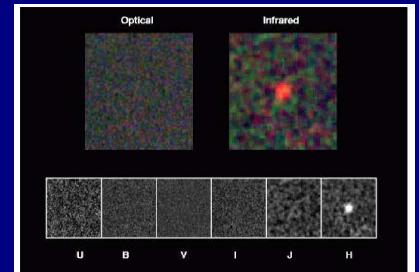
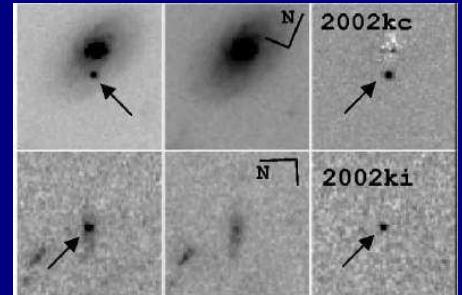
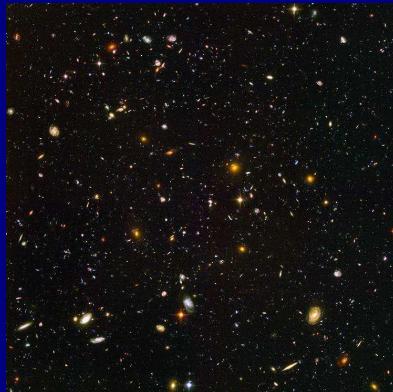
Batteries+Gyros+FGS =  
Sustained HST Lifetime



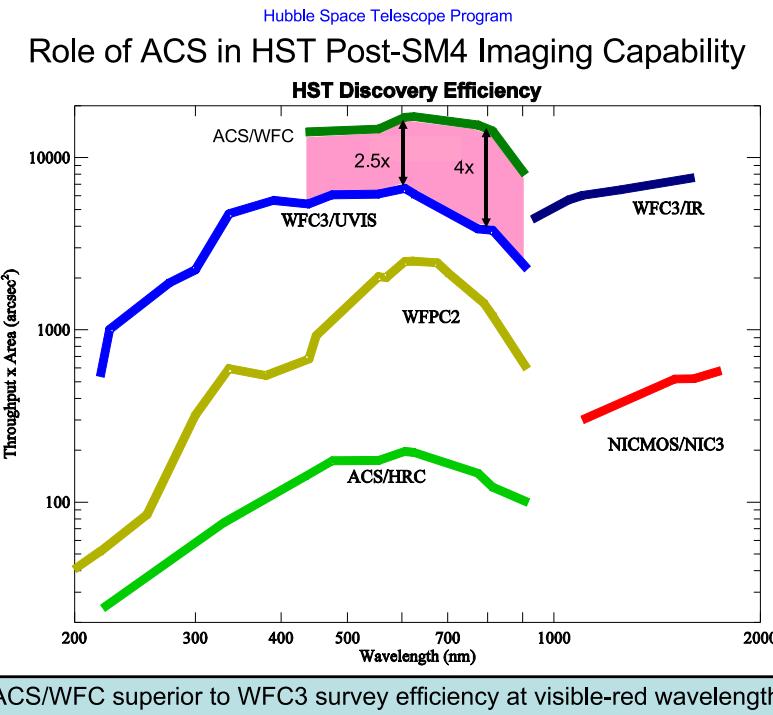
COS+STIS = Full set of tools for astrophysics



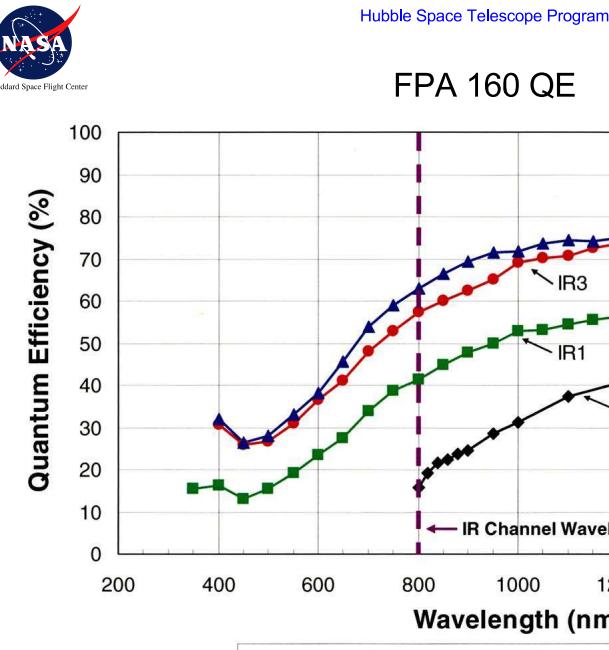
WFC3+ACS = Most powerful imaging ever



# WFC3: Hubble's new Panchromatic High-Throughput Camera



Hubble Space Telescope Program



May 2, 2007

Wide Field Camera 3 Monthly Status Review

11

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

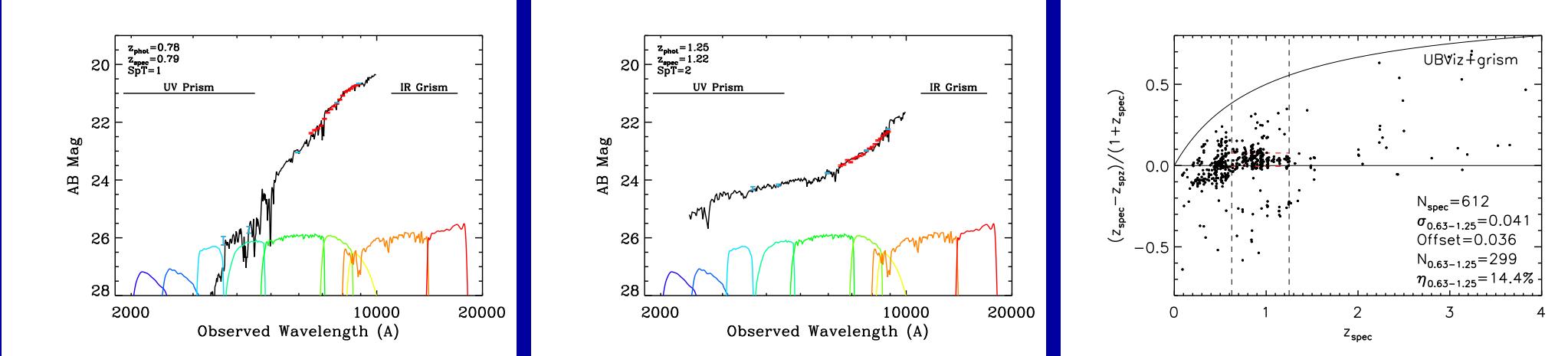
- QE  $\gtrsim 70\%$ ,  $4k \times 4k$  array of  $0''.04$  pixel,  $\text{FOV} \simeq 2''.67 \times 2''.67$

WFC3/IR channel has unprecedented near-IR throughput & areal coverage:

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

$\implies$  WFC3 will offer major new parameter space for astrophysics in  $\gtrsim 2008$

# Power of combination of Grism and Broadband for WFC3



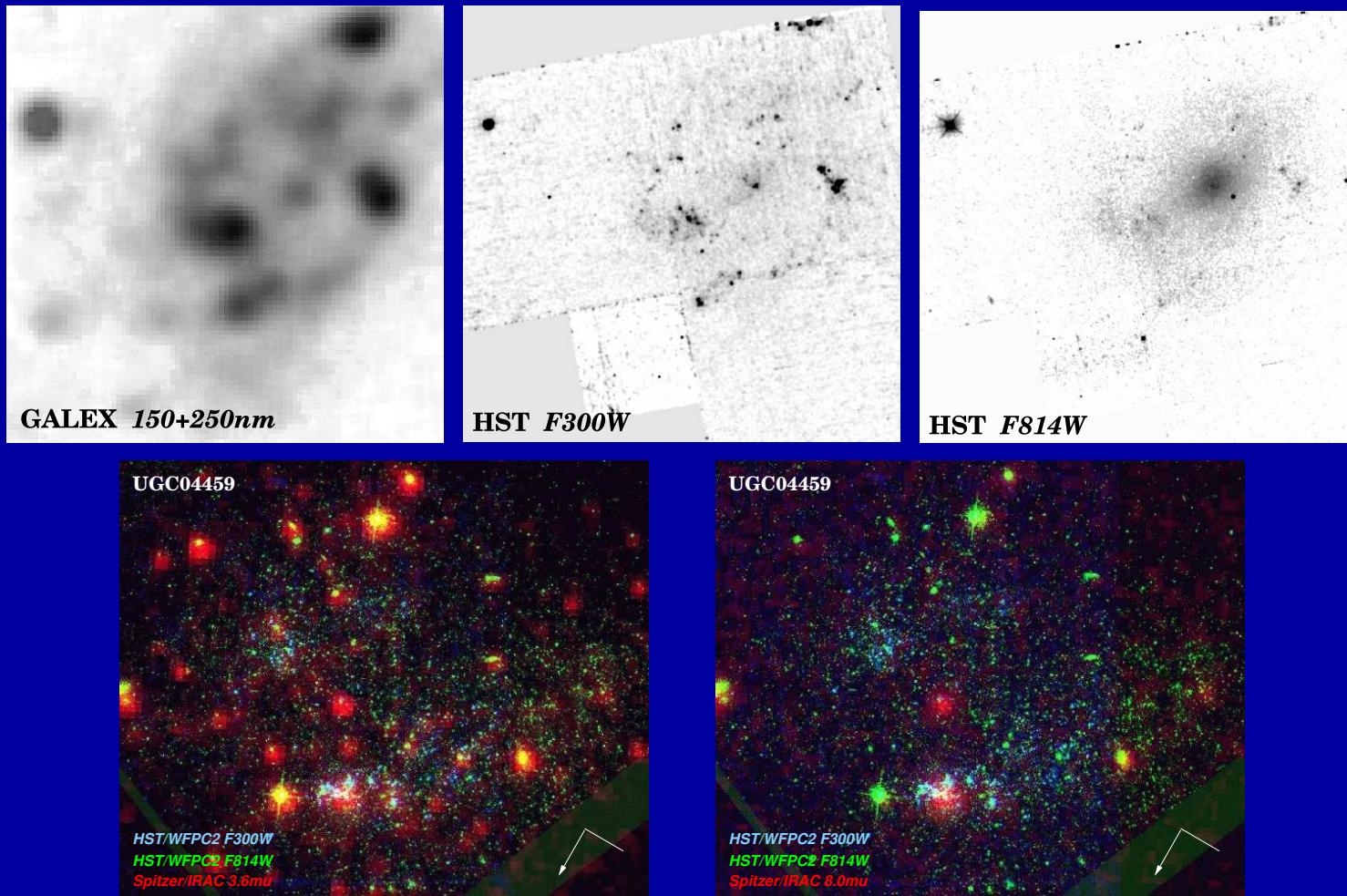
Lessons from the Hubble ACS grism surveys “GRAPES” and “PEARS” (Malhotra et al. 2005; Cohen et al. 2007; Ryan et al. 2007, ApJ, 668, 839):

- (a) Spectro-photo-z's from HST grism + BViz(JH) considerably more accurate than photo-z's alone, with much smaller catastrophic failure %.
- (b) Redshifts for  $\gtrsim 13,000$  objects to  $AB \gtrsim 27.0-27.5$  mag;  $\sigma_z/(1+z) \lesssim 0.04$ .
- (c) Expect  $\lesssim 0.02-0.03$  accuracy when including new capabilities of WFC3: UV and near-IR broad-band imaging and low-res grism spectroscopy.
- WFC3 will provide full panchromatic sampling of faint galaxy spectra from 0.2–1.7  $\mu\text{m}$ , permitting high accuracy photo-z's for faint galaxies of all types to  $AB \simeq 27.0-29.0$  mag (for  $\sim 2-80$  orbits/filter).

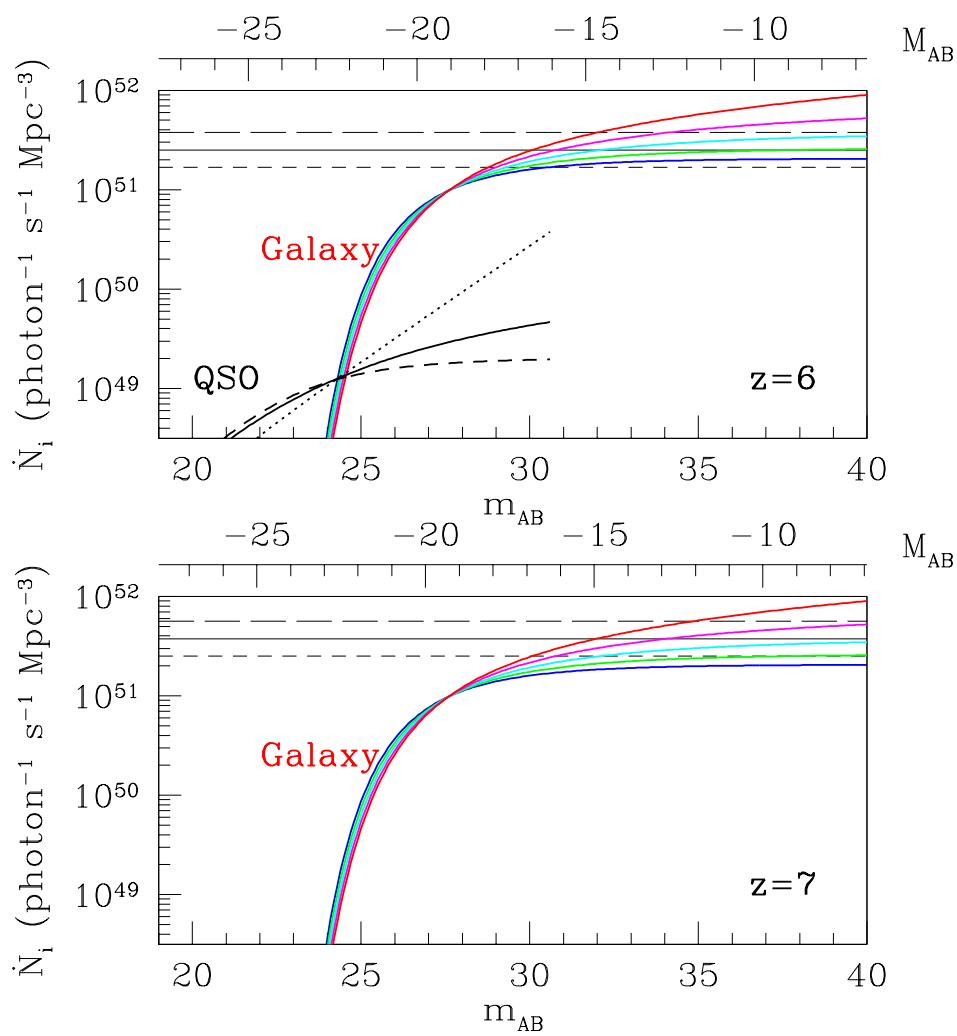
## MORE SPARE CHARTS

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## App. 2: What is the Lyman continuum escape fraction of Dwarf Galaxies?

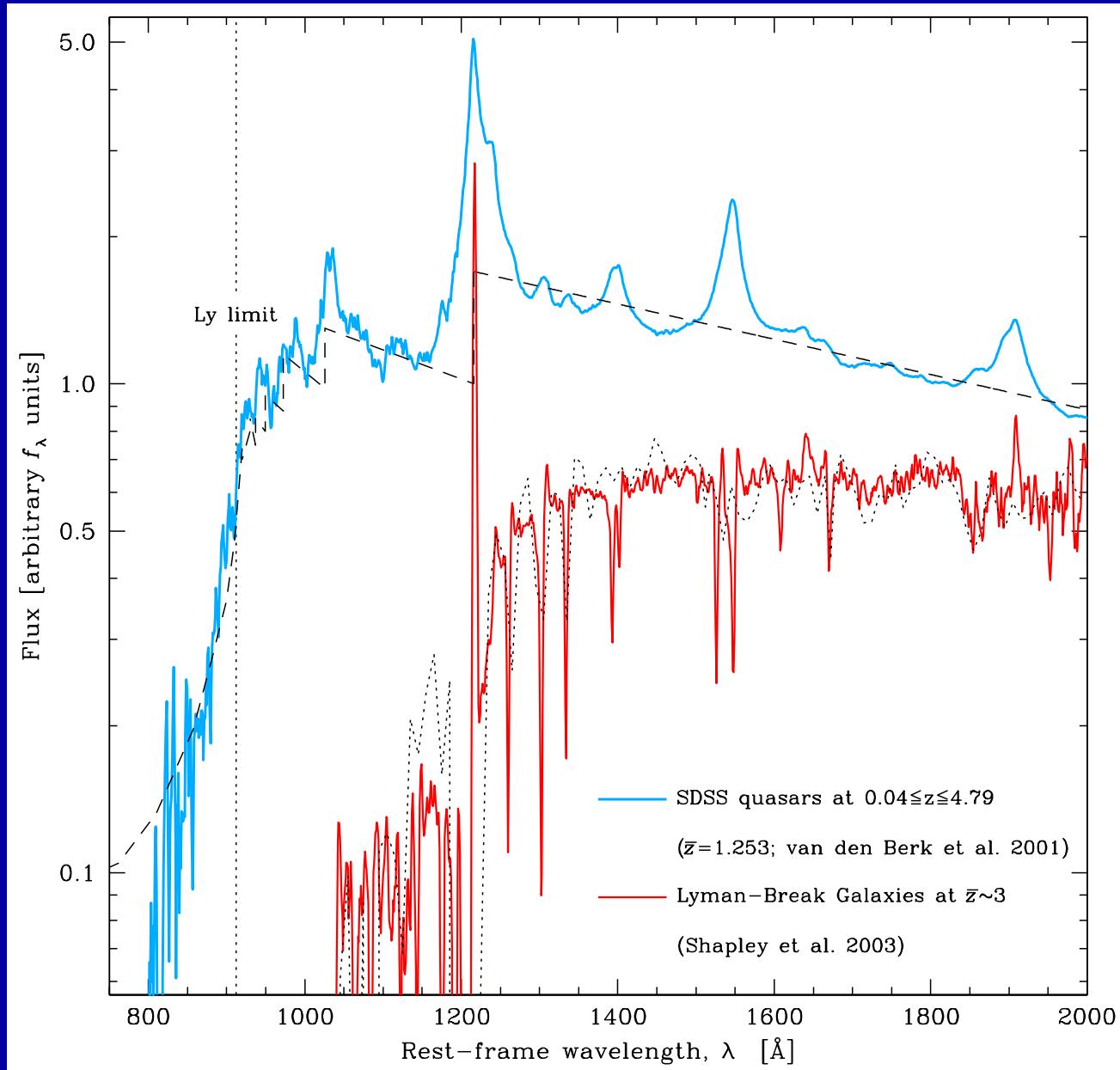


- GALEX, HST/UV and Spitzer IRAC images of nearby late-type dwarf galaxies suggests enough (SN-driven?) holes between their dust that UV-photons can escape: covering factors  $\gtrsim 20\%$  ( $\propto f_{esc}$  ?  $\leftrightarrow \text{HI}$ ).
- Steidel et al. (2001):  $z \simeq 3$  LBG's have UV-escape fraction  $f_{esc} \simeq 10\%$ .
- Yan & Windhorst (2004) assume that  $f_{esc}$  at  $z \simeq 6$  is at least as high.

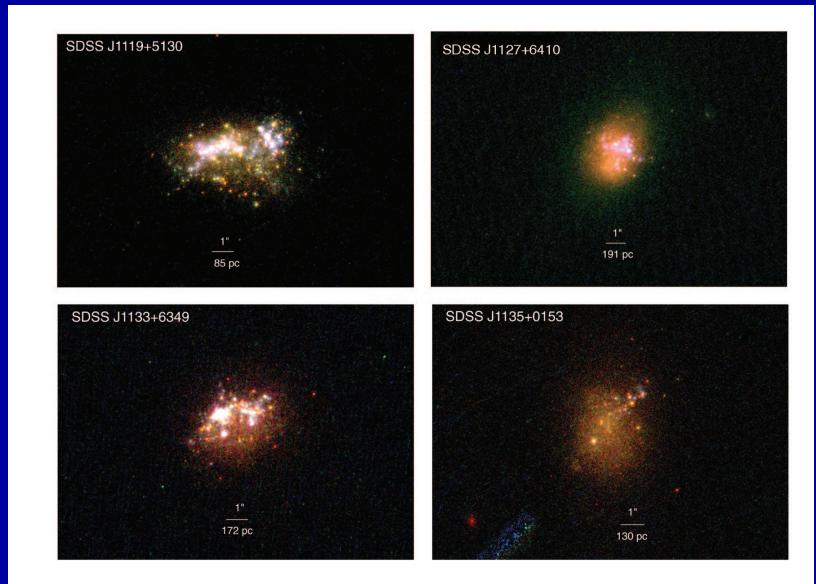
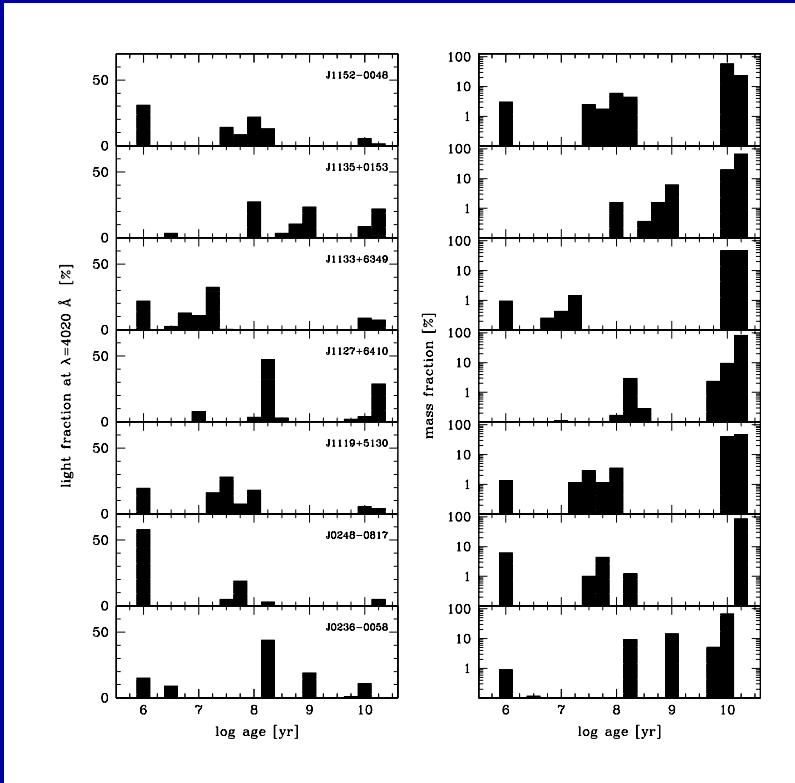
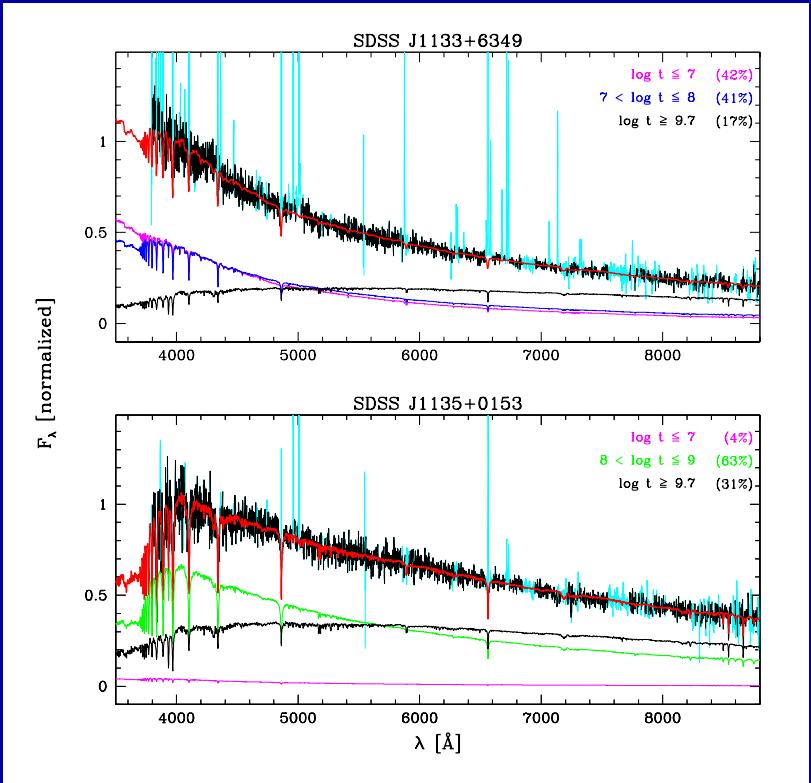


- A steep LF of  $z \simeq 6$  objects (Yan & Windhorst 2004a, ApJL, 600, L1) could provide enough UV-photons to complete the reionization epoch at  $z \simeq 6$  (if  $f_{esc} \gtrsim 10\%$ ).
- Pop II dwarf galaxies may not have started shining *pervasively* much before  $z \simeq 7$ –8, or no H-I would be seen in the foreground of  $z \gtrsim 6$  quasars.
- JWST will measure this numerous population of dwarf galaxies from the end of the reionization epoch at  $z \simeq 6$  into the epoch of First Light (Pop III stars) at  $z \gtrsim 10$ .

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



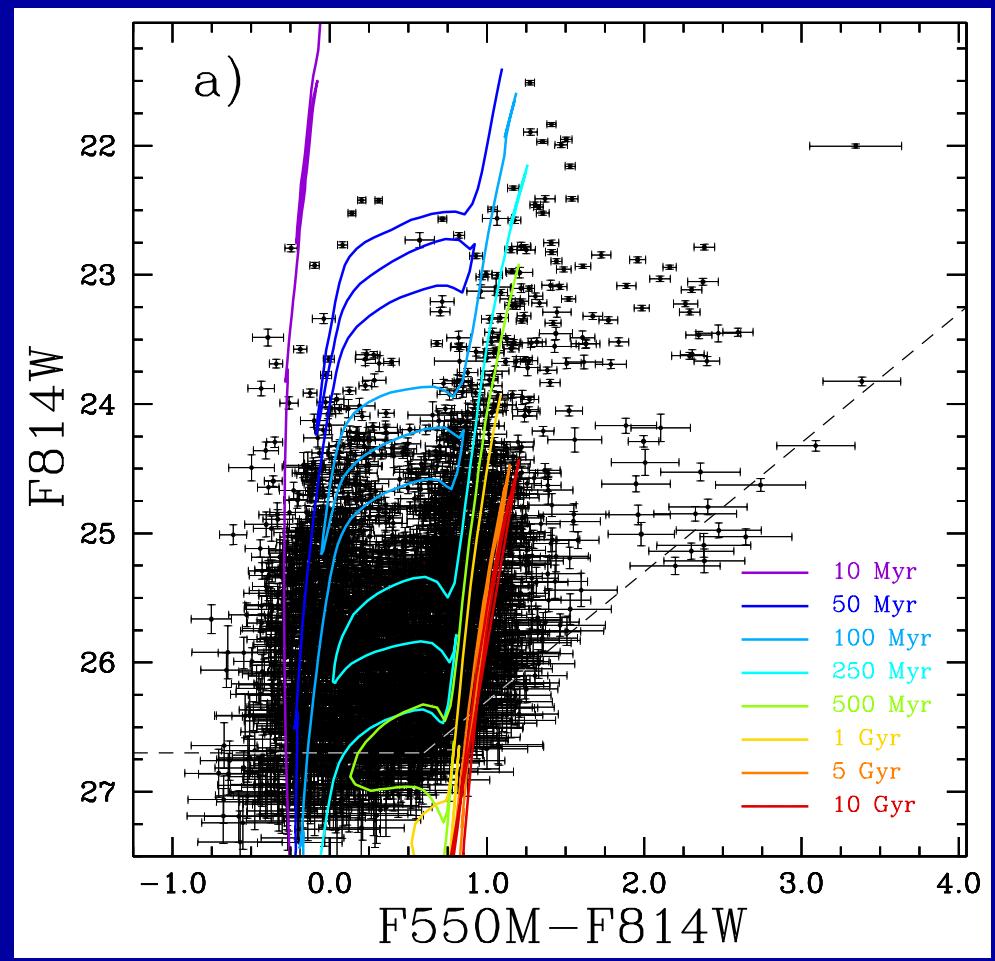
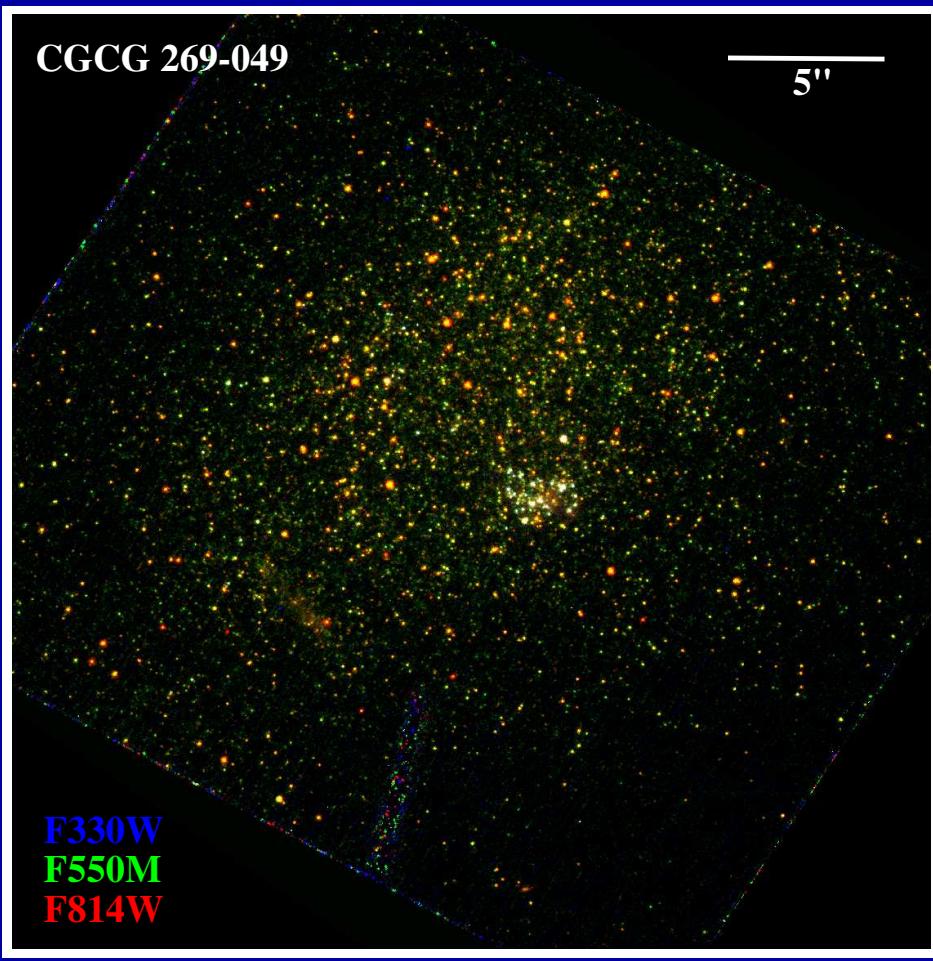
- In principle, the hard-UV of QSO's and weak AGN can outdo the young SED's of LBG's or dwarf galaxies, but likely by no more than  $\gtrsim 1$  dex.



Possible local analogs for dwarf galaxies that finished reionization at  $z \gtrsim 6$ ?:

- Low metallicity Ultra-Blue Compact Dwarf galaxies in voids (Corbin et al. 2006, 2007). ACS/HRC (Corbin et al. 2006) shows that:
  - All have an old ( $\gtrsim 10$  Gyr) stellar pop.
  - All have young 1-100 Myr star-clusters.

Their low metallicities are more likely SN-driven, rather than due to purely young stellar populations  $\Rightarrow$  must measure Lyman continuum  $f_{esc}$ .

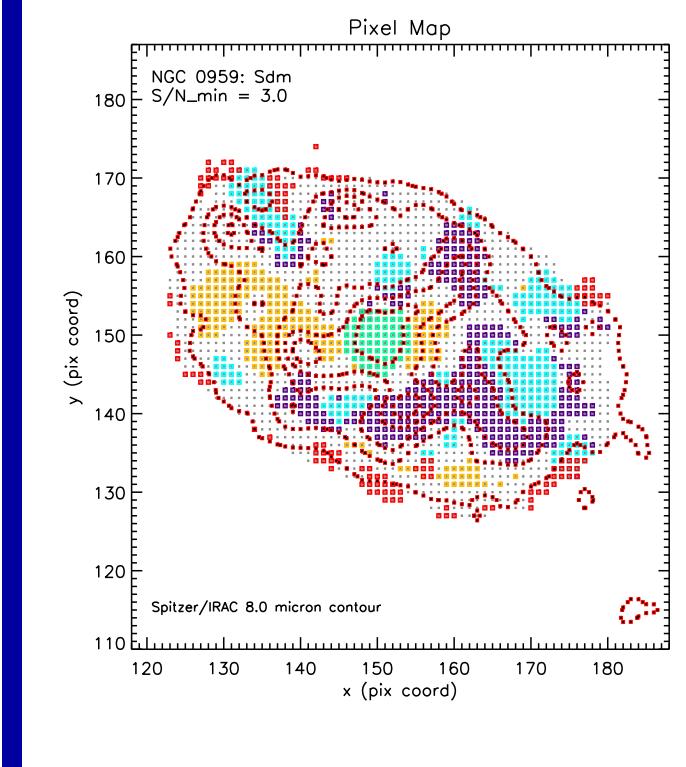
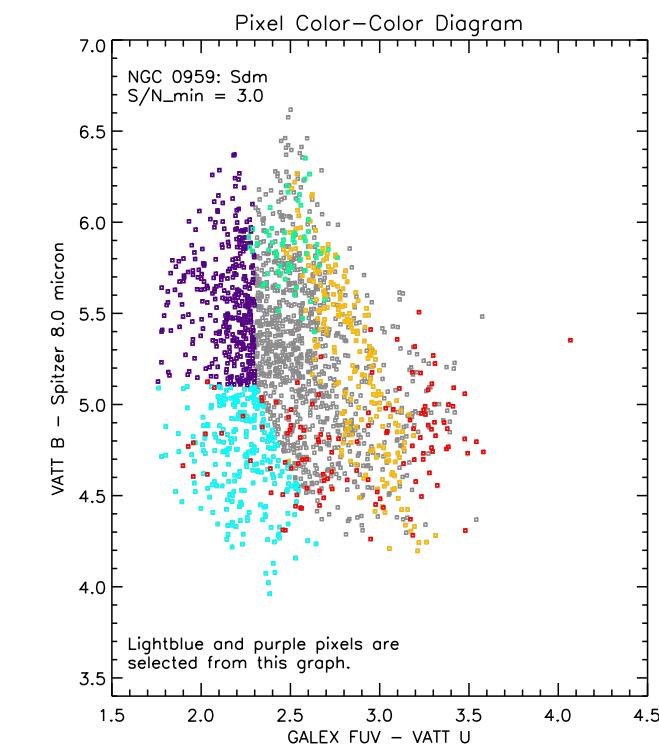
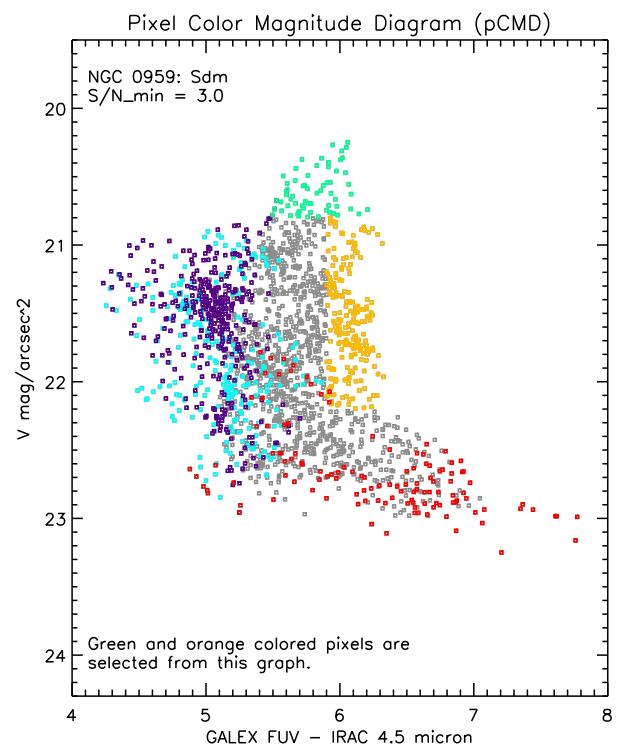


Possible local analogs for dwarf galaxies that finished reionization at  $z \gtrsim 6$ :

- Low metallicity Ultra-Blue Compact Dwarf galaxies in voids (Corbin et al. 2006, 2007).

High-res ACS/HRC (H. Kim et al. 2008) resolves individual (super) giants.

Color-magnitude and color-color diagrams imply very little dust extinction  
 $\Rightarrow$  must measure  $f_{esc}$ .



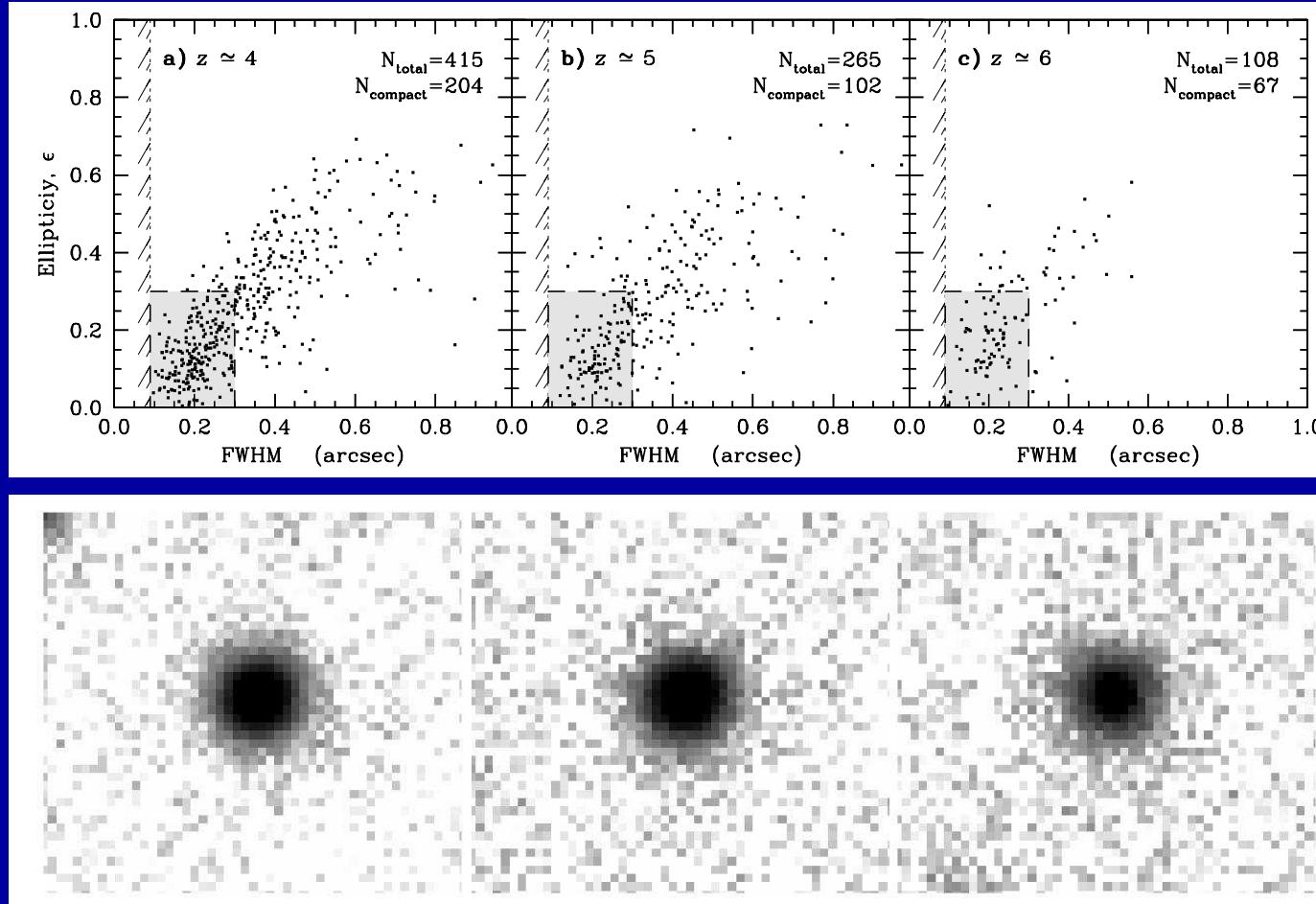
## Possible local analogs for dwarf galaxies that finished reionization $z \gtrsim 6$ ?

- Small late-type/Irregular galaxies that dominate the FBG population and its  $N(z)$  at  $z \gtrsim 1.5$  (Driver et al. 1998). Also, UVLG's (Overzier et al. 2007).
- Combination of GALEX FUV+NUV, HST-mid-UV, ground-based UB-VRI, & Spitzer IRAC on local late-types/Irr's shows:

Hot stars and  $8 \mu\text{m}$  dust more spatially anti-correlated than correlated (Tamura et al. 2007): SN-driven? Localized, large  $f_{esc}$  from SN-bubbles?

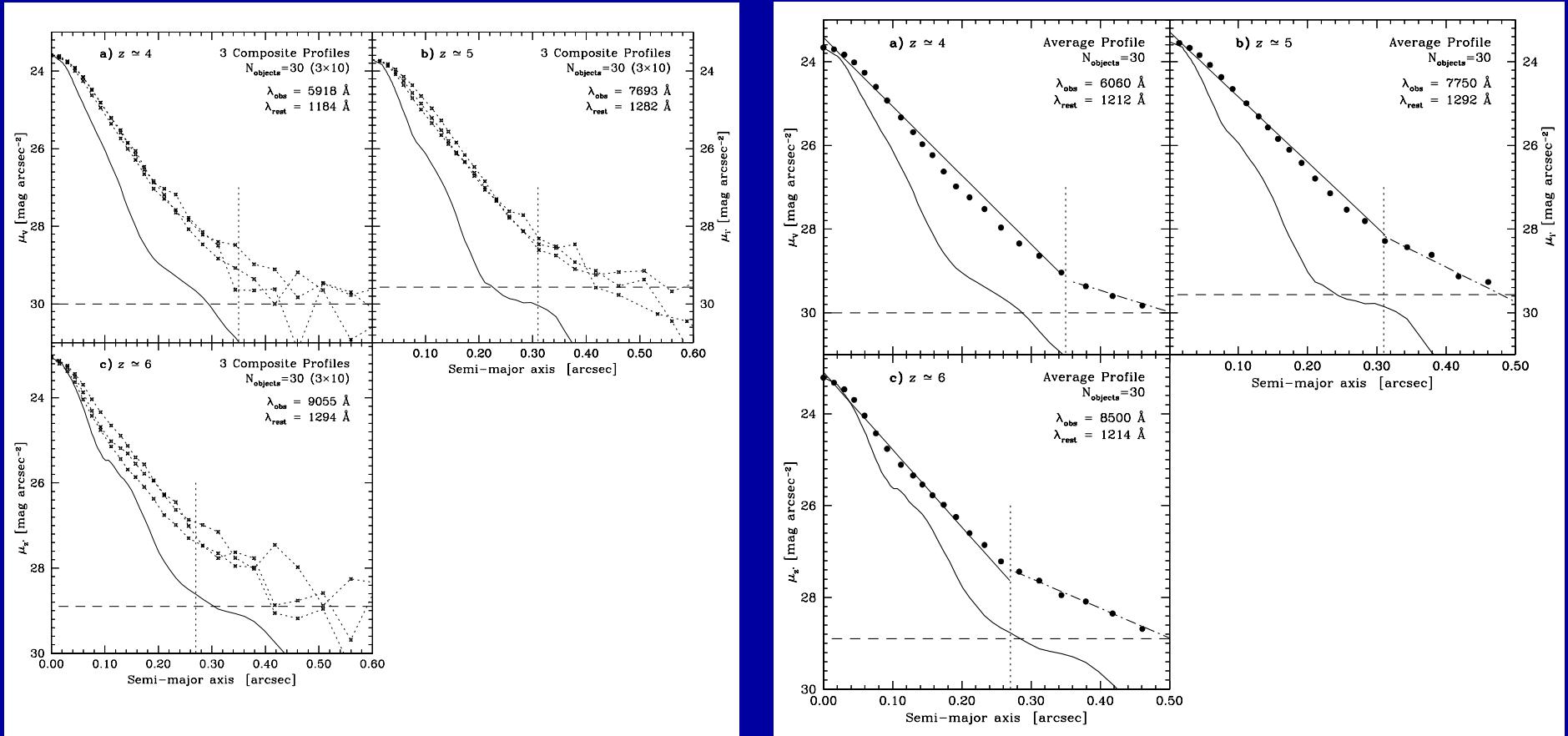
- Measure Lyman continuum escape fraction and its geometry with a dedicated FUV space mission (Lyman).

# Dynamical ages of Dwarf Galaxies at $z \simeq 4-6$ ?



- Select all isolated, nearly unresolved ( $2r_e \lesssim 0''.3$ ), round ( $1-b/a \lesssim 0.3$ ) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at  $z \simeq 4$ ,  $z \simeq 5$ , and  $z \simeq 6$ .
- If these compact, round objects are intrinsically comparable, each stack has the S/N of  $\sim 5000$  HST orbits ( $\simeq 300$  JWST hrs; Hathi et al. 2007).

# Dynamical ages of Dwarf Galaxies at $z \simeq 4-6$ ?



- HUDF sky-subtraction error is  $2-3 \cdot 10^{-3}$  or  $AB \simeq 29.0-30.0 \text{ mag/arcsec}^2$
- Average 5000-orbit compact, round dwarf galaxy light-profile at  $z \simeq 6-4$  deviates from best fit Sersic  $n \simeq 1.0$  law (incl. PSF) at  $r \gtrsim 0!27-0!35$ .
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of  $\tau_{\text{dyn}} \simeq 0.1-0.2 \text{ Gyr}$  at  $z \simeq 6-4$  for the enclosed masses.
- ⇒ Comparable to their SED ages (Hathi et al. 2007, AJ; astro-ph/0710.0007).
- ⇒ Global starburst that finished reionization at  $z \simeq 6$  started at  $z \simeq 6.6$ ?