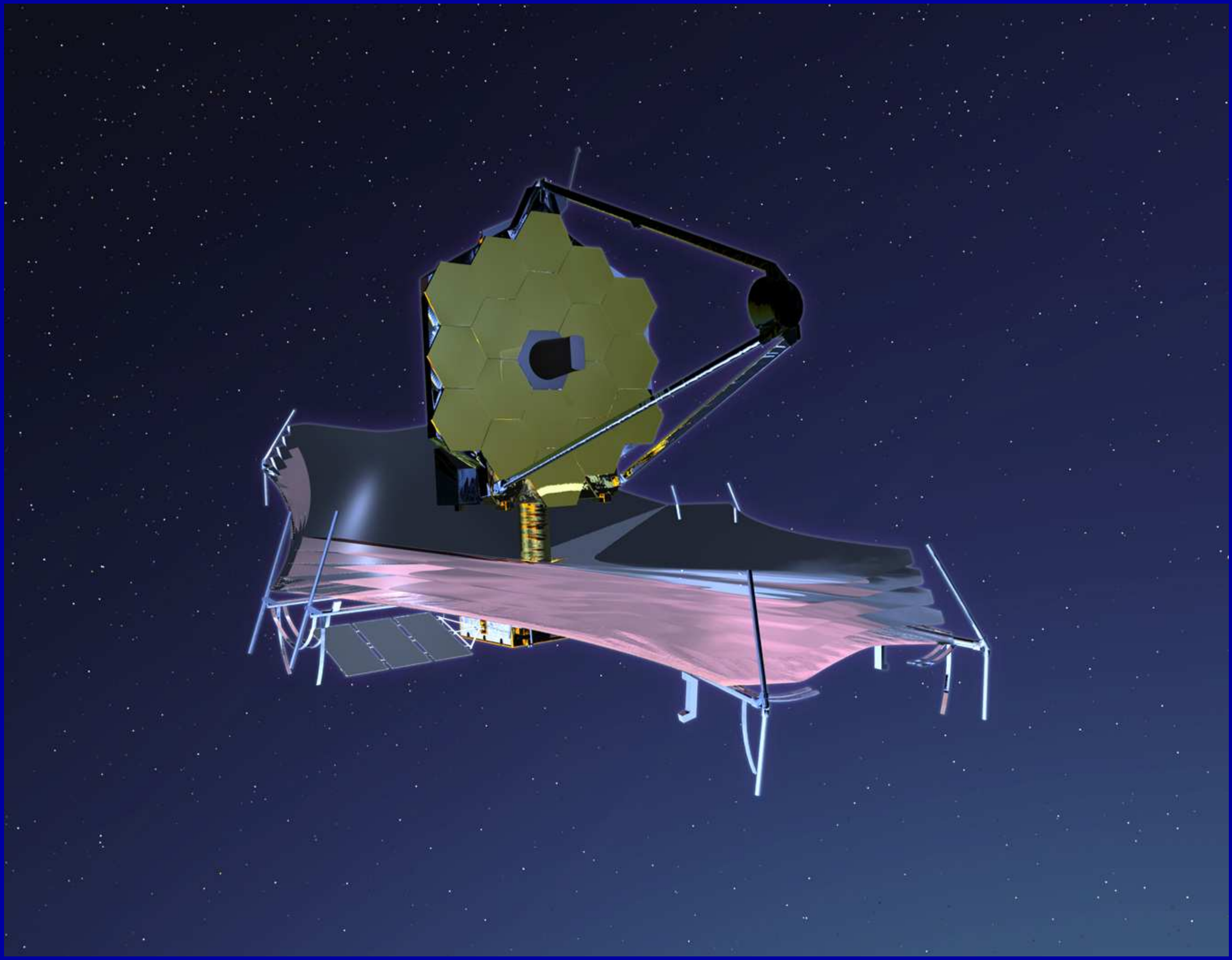
# How can the James Webb Space Telescope Measure First Light, Reionization, & Galaxy Assembly?

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

*Collaborators: S. Cohen, R. Jansen, N. Hathi (ASU), C. Conselice (UK), & H. Yan (Carnegie)*



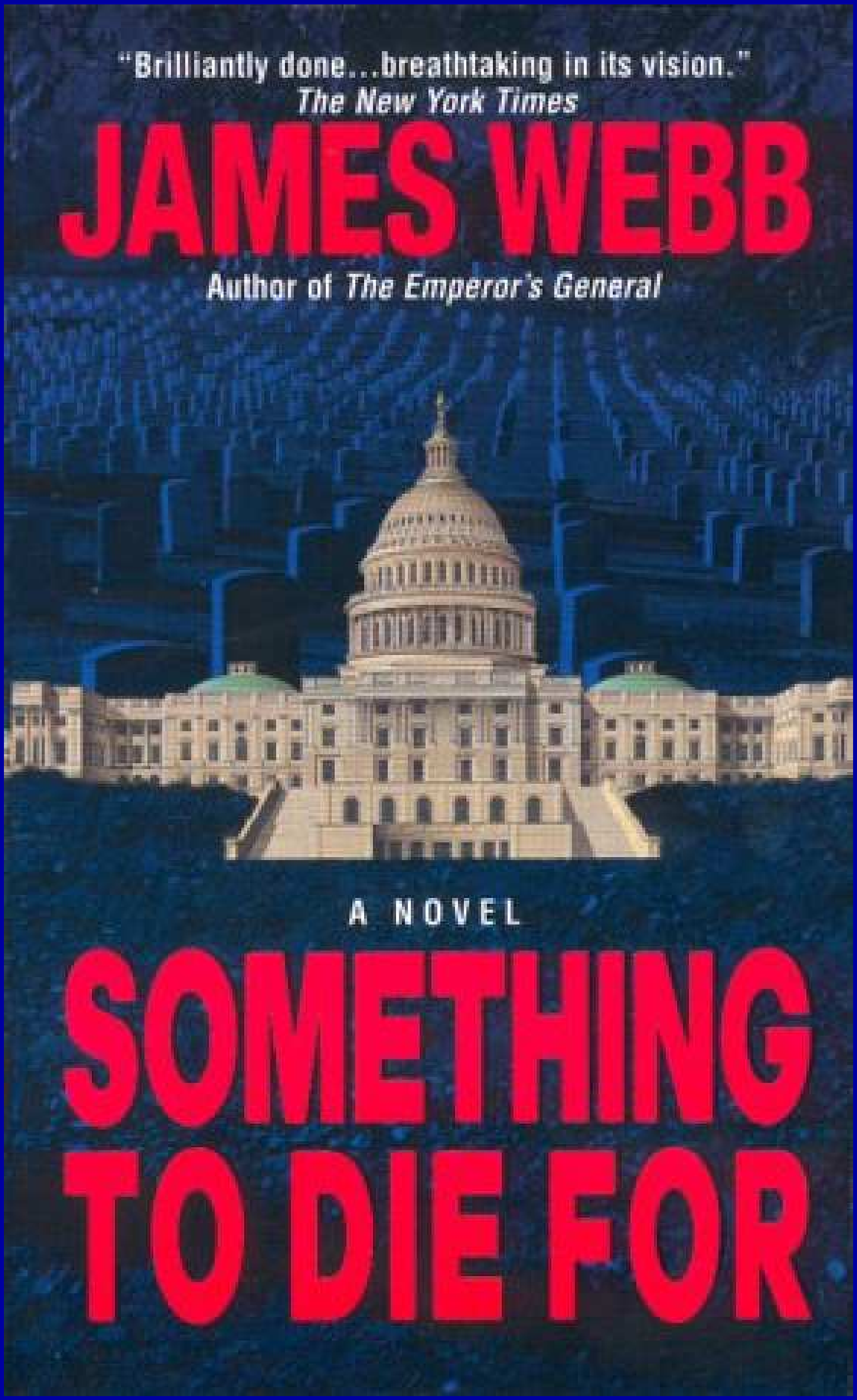
*Colloquium at the School of Physics, University of Sydney, Australia; Friday, June 20, 2008*

# Outline

- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) How JWST can measure First Light and Reionization
- (4) How JWST can measure Galaxy Assembly
- (5) Predicted Galaxy Appearance for JWST at $z \simeq 1$–$15$
- (6) Summary and Conclusions
- Appendix 1: Complementary studies with HST Wide Field Camera 3
- Appendix 2: Will JWST (& SKA) reach the Natural Confusion Limit?
- Appendix 3: The Lyman continuum escape fraction of dwarf galaxies

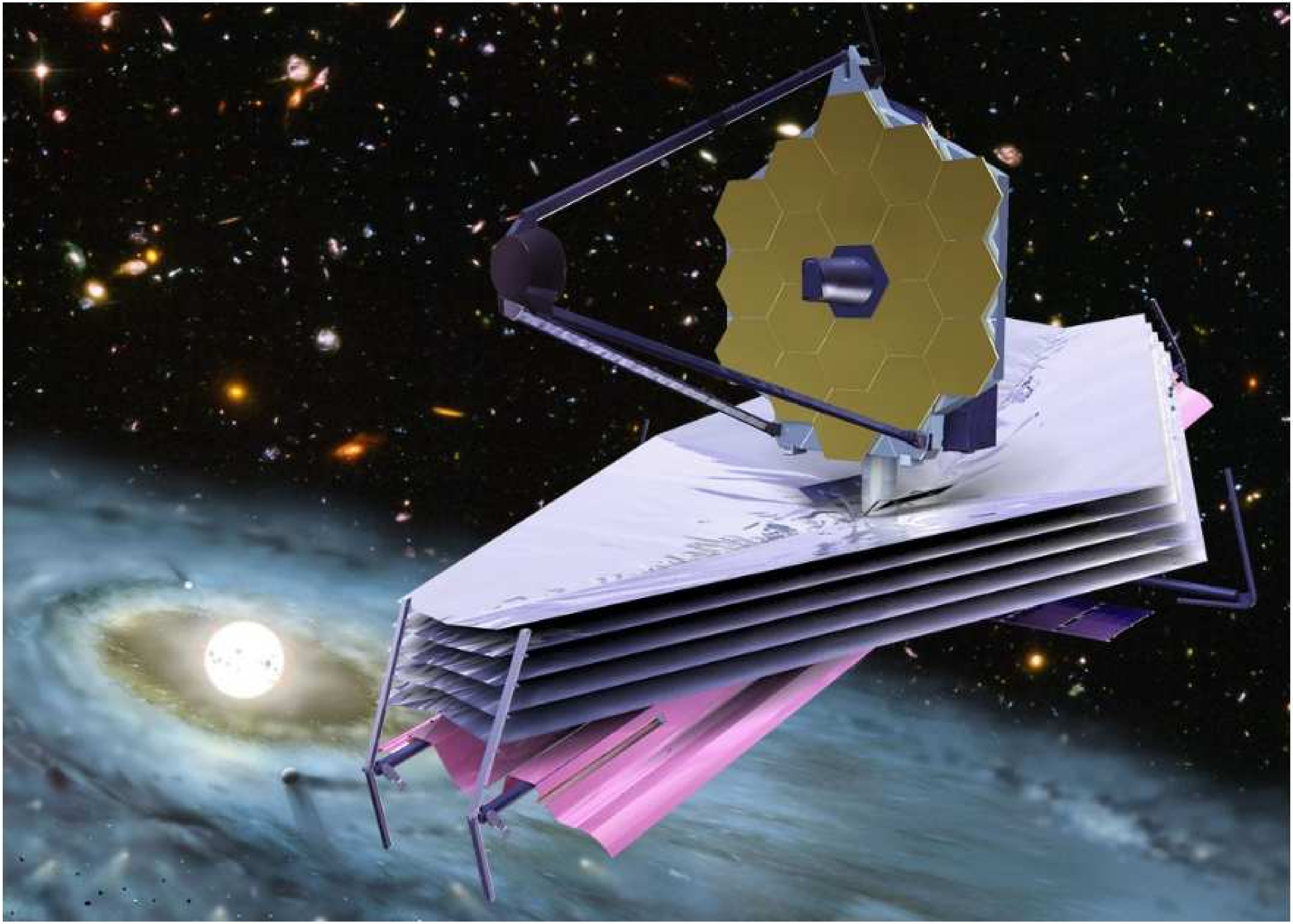
Sponsored by NASA/JWST

Arizona State University




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

# James Webb Space Telescope



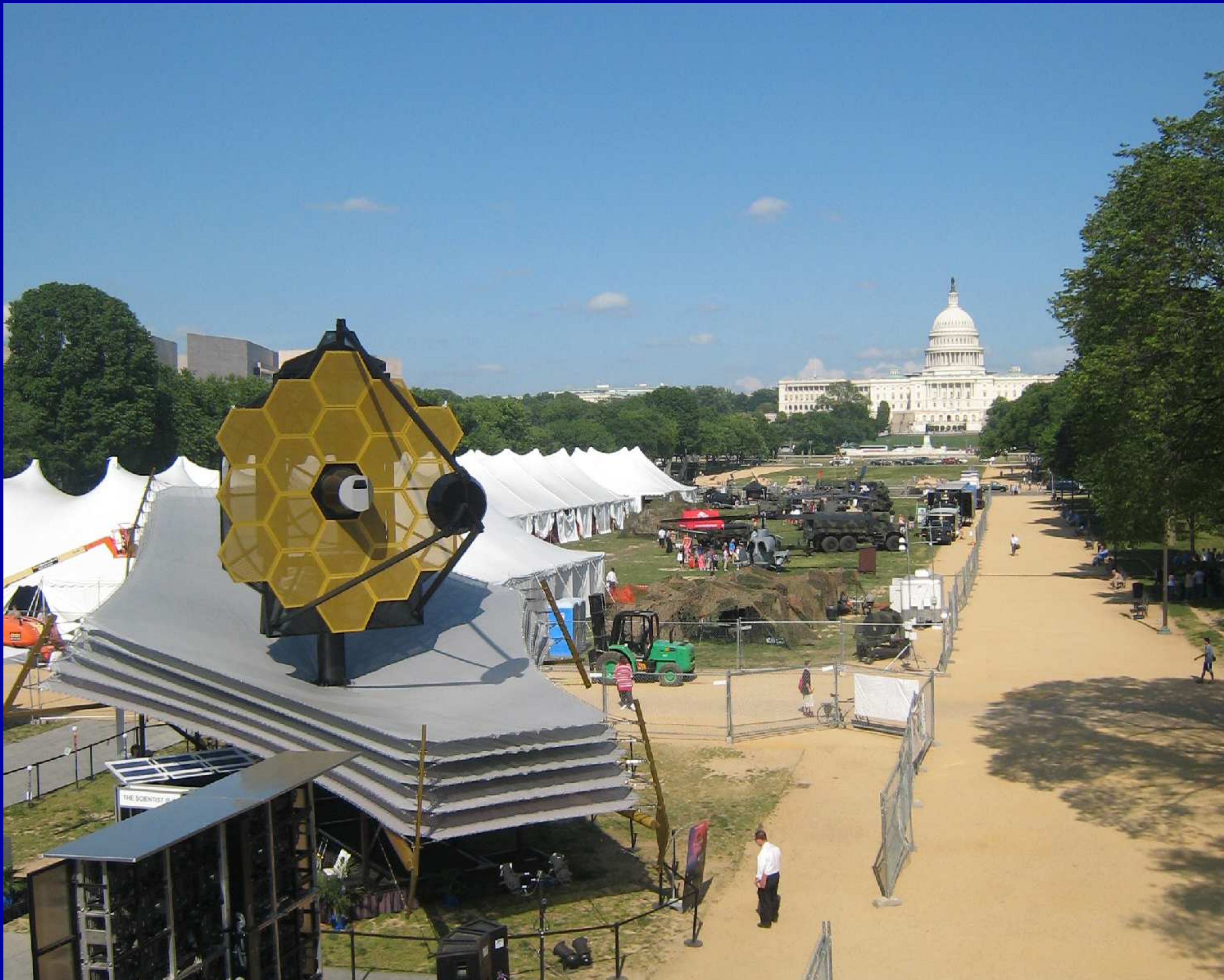
• (1) What is the James Webb Space Telescope (JWST)?

• A fully deployable 6.5 meter (25 $m^2$) segmented IR telescope for imaging and spectroscopy from 0.6 to 28 $\mu$m, to be launched by NASA $\gtrsim$2013. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

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

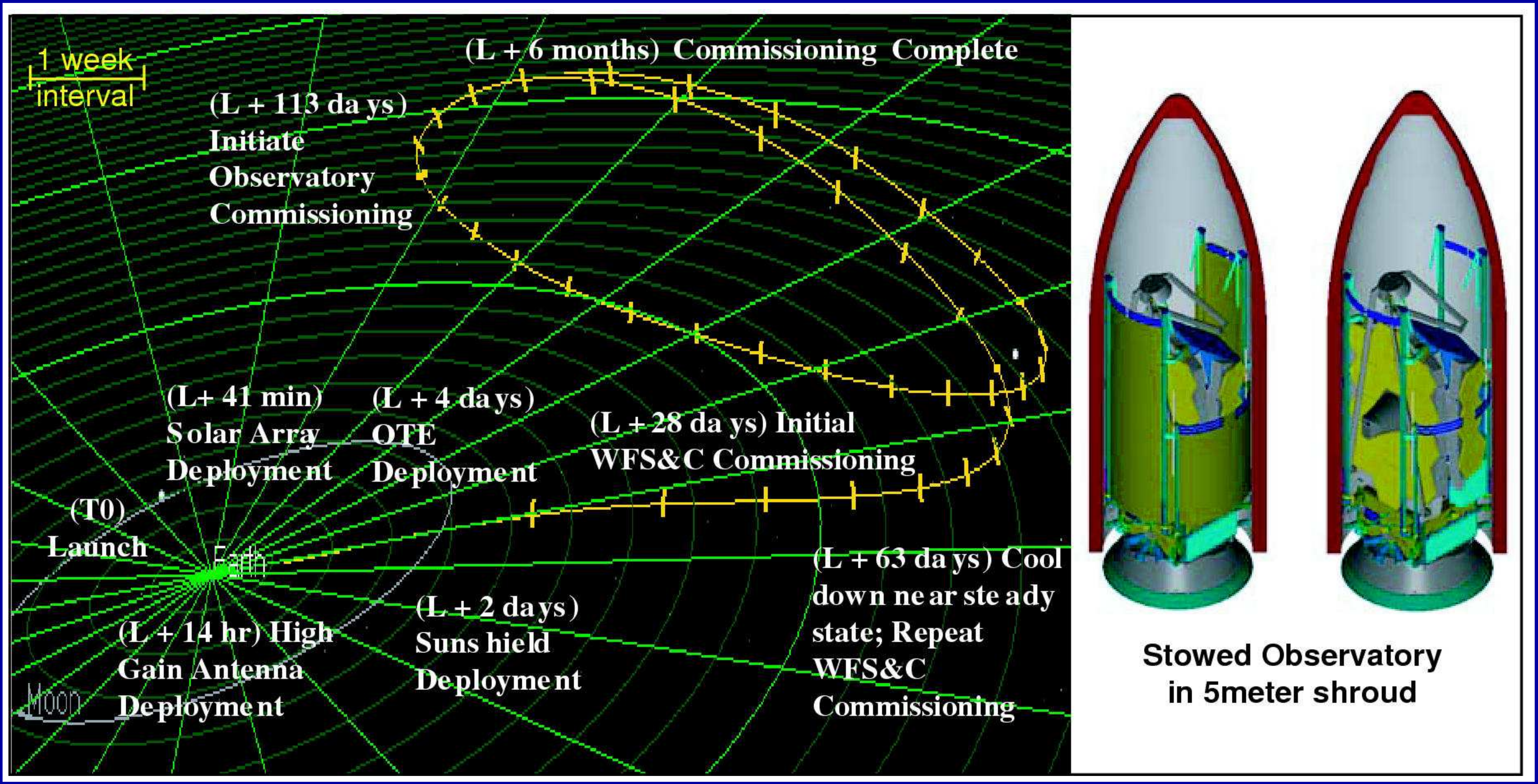
Life-sized model of JWST, used to test its sun-shield.

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



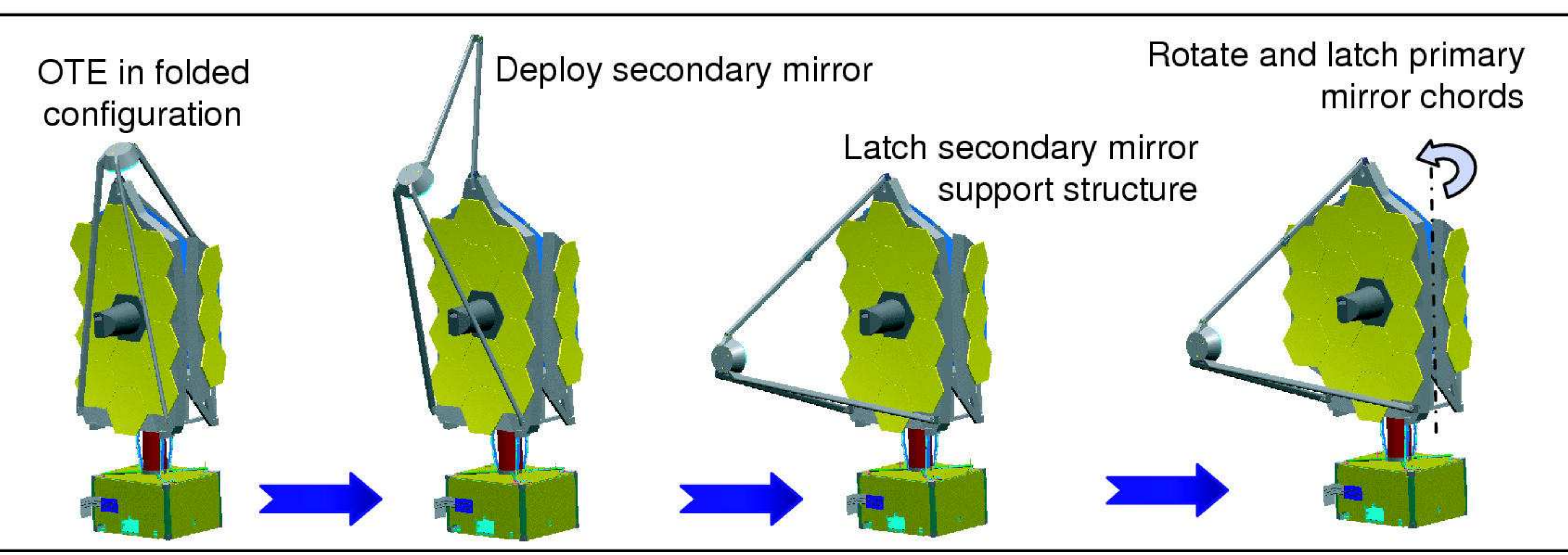
JWST on the Capitol Mall, May 2007 ...

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



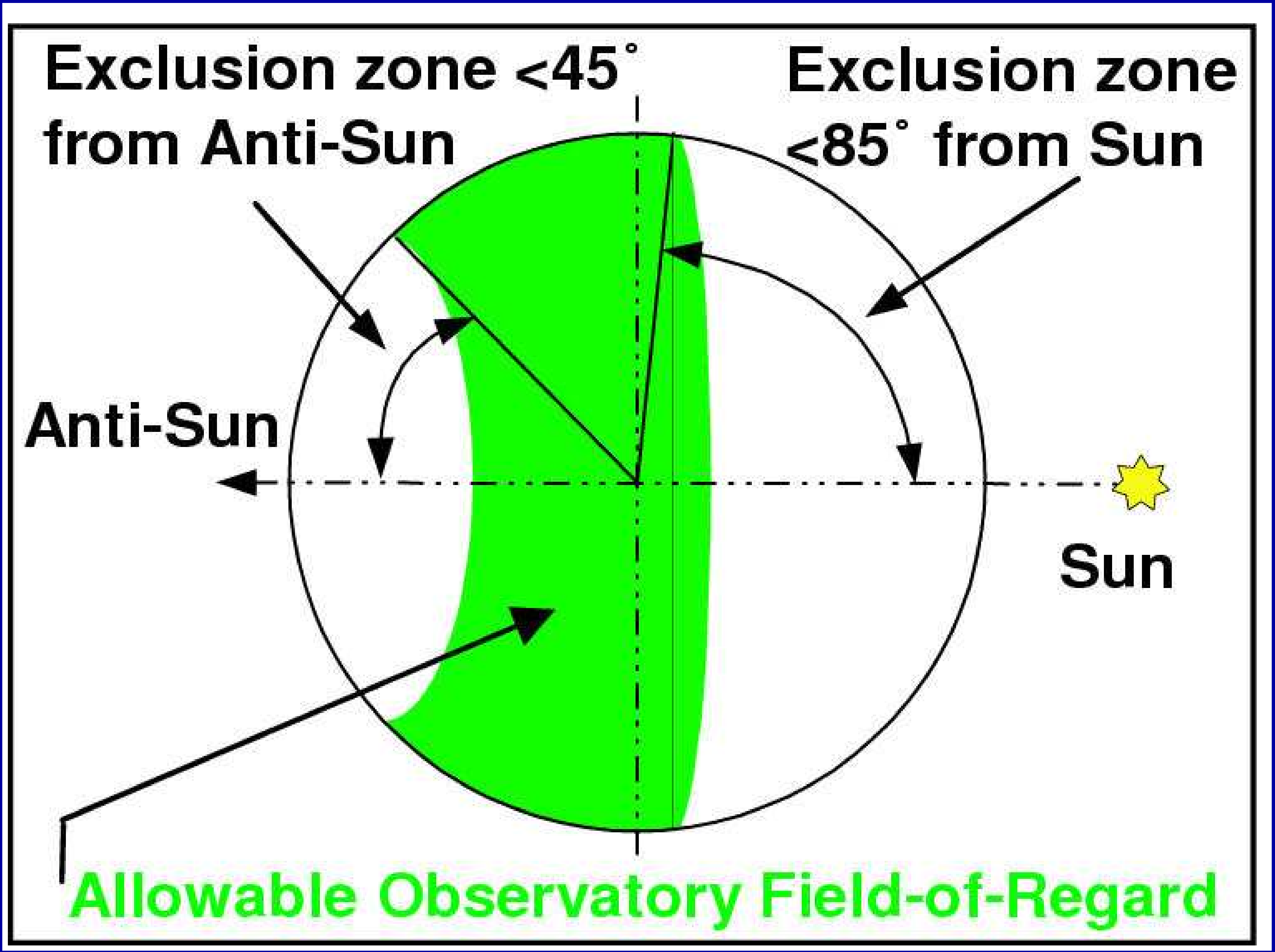

After launch in June 2013 with an Ariane-V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

• (1) How will JWST be automatically deployed?

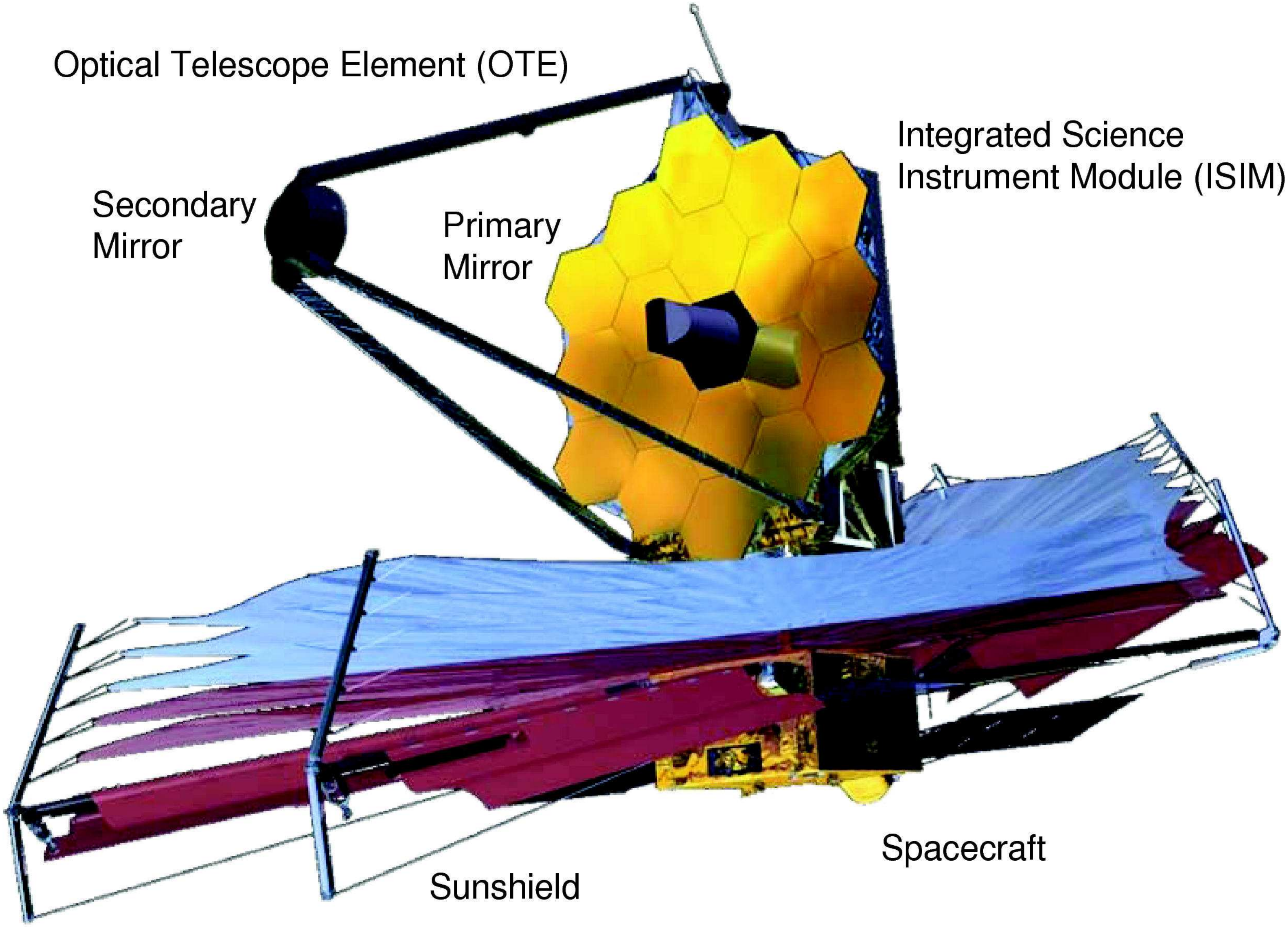



During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit.

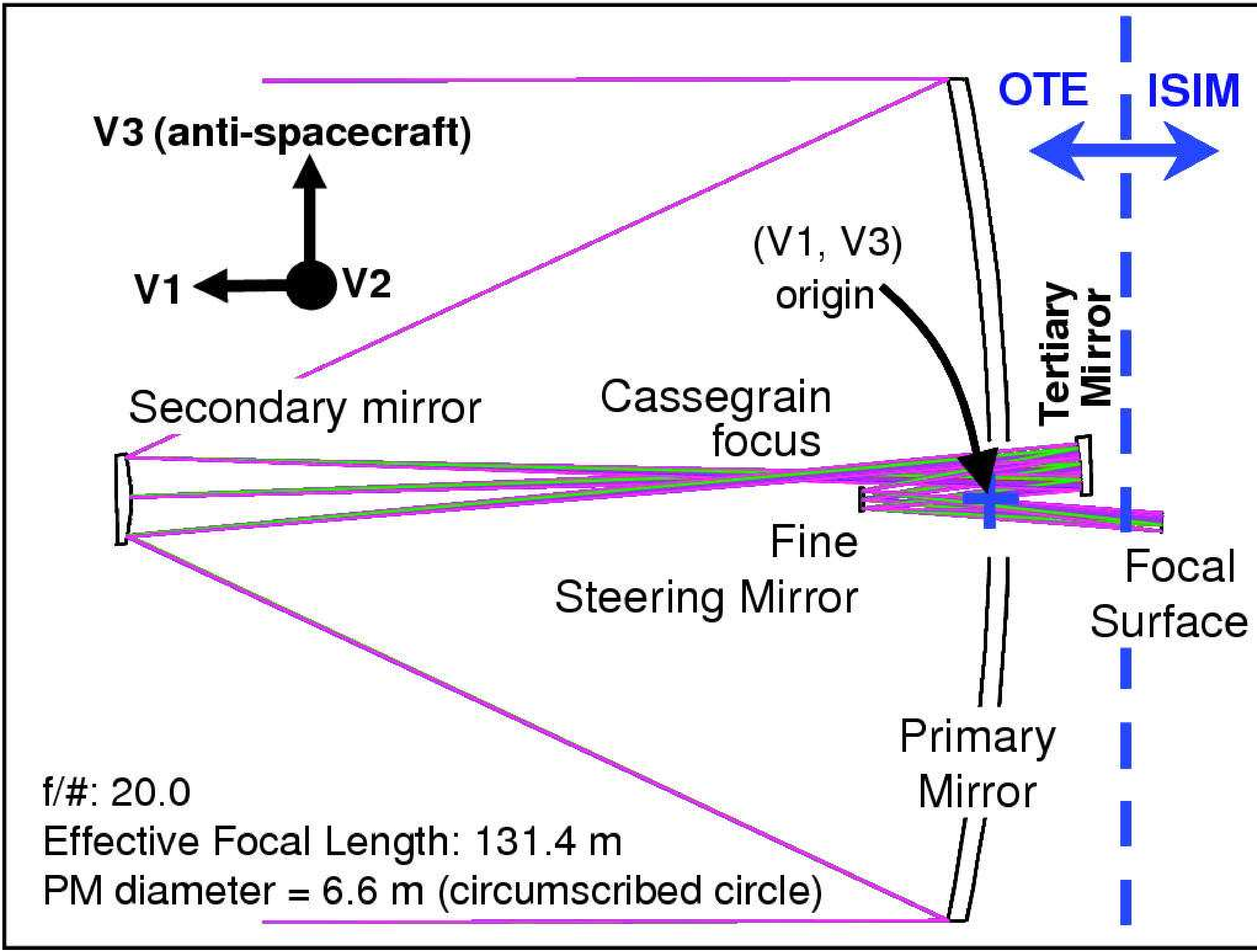
The entire JWST deployment sequence can and will be tested several times on the ground — but in 1-G.



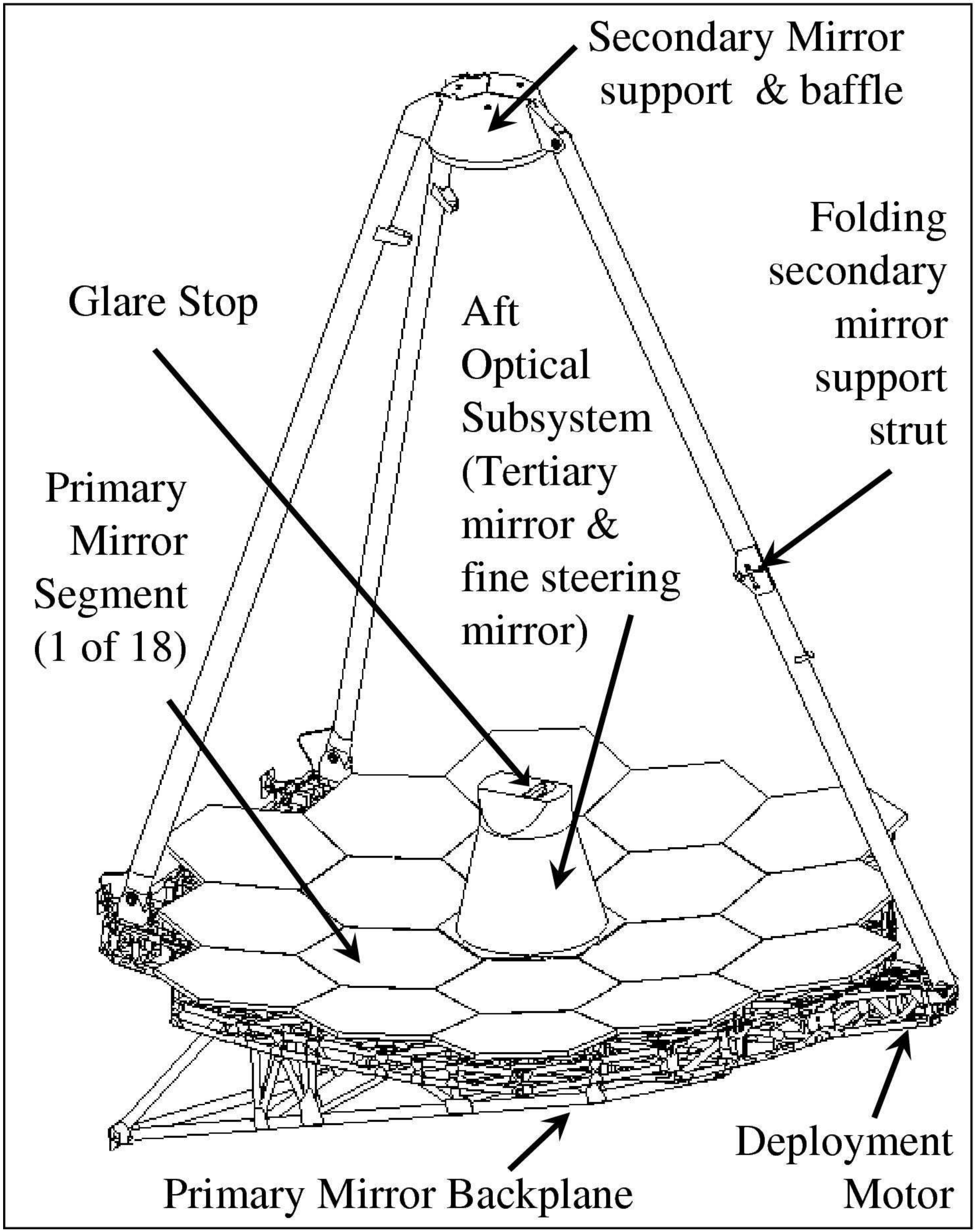

JWST can observe segments of sky that move around as it orbits the Sun.

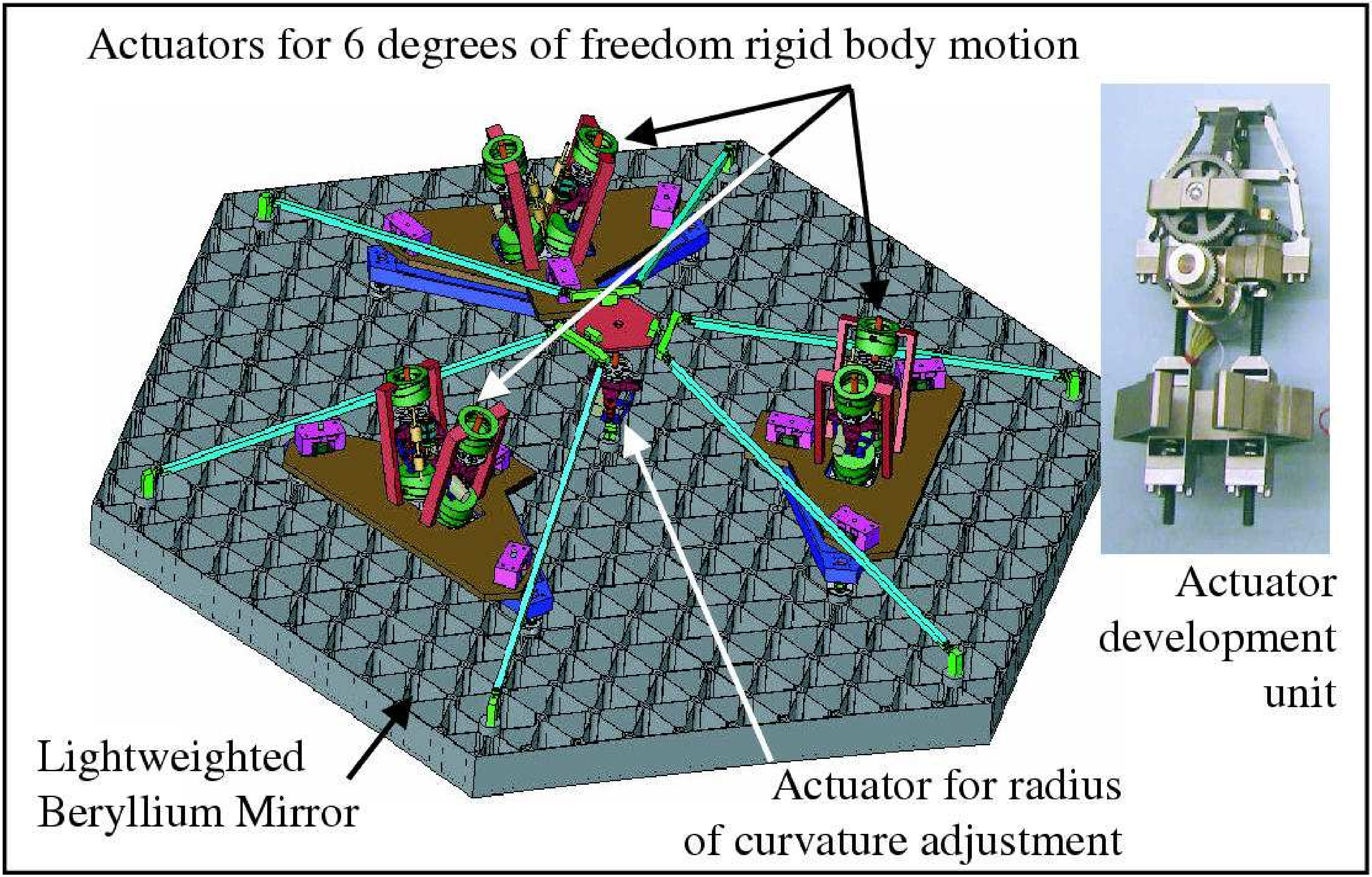



JWST mission reviewed in Gardner, J. P., et al. 2006, Space Science Reviews, Vol. 123, pg. 485–606 (astro-ph/0606175)

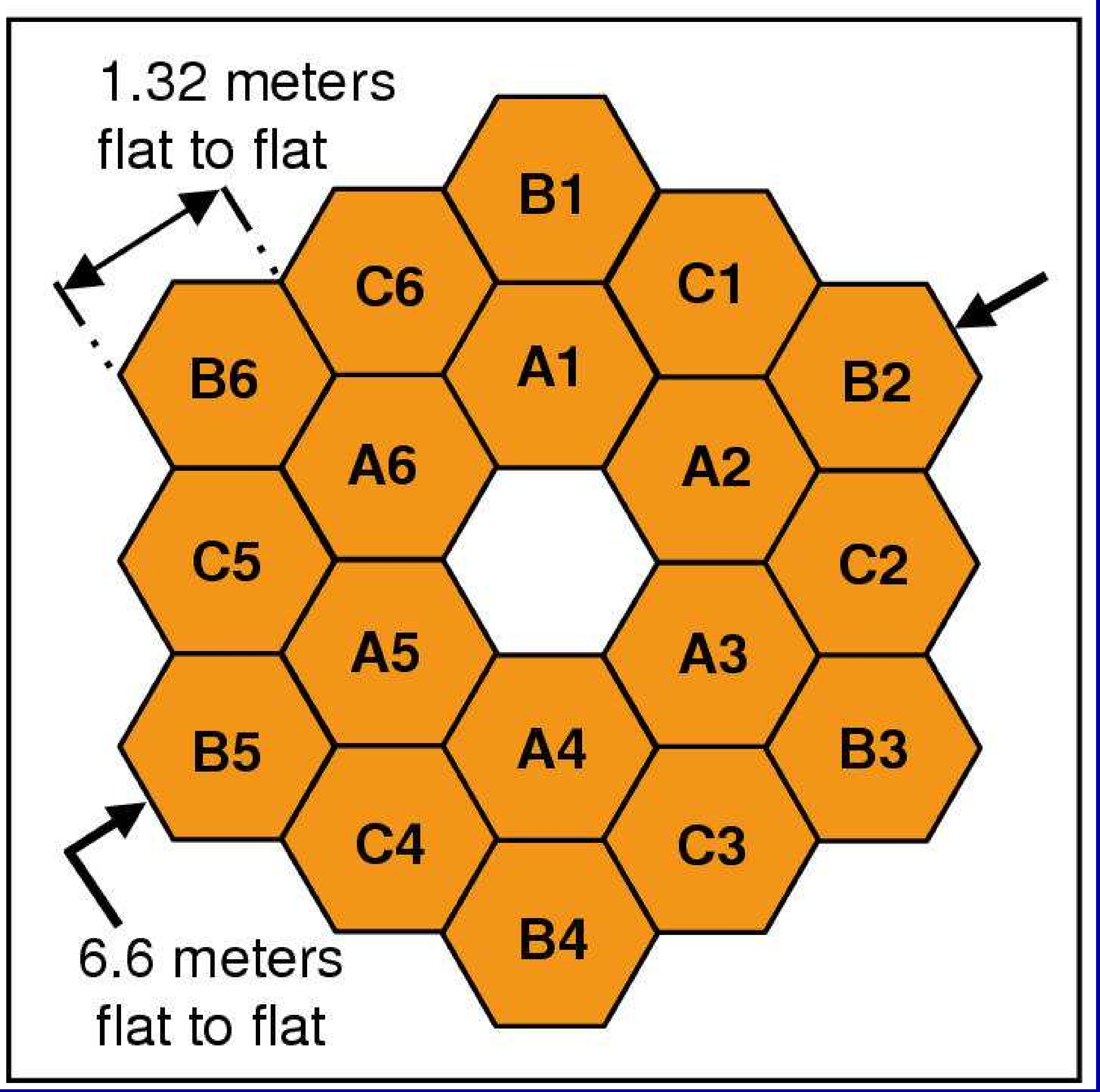


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)


Secondary Mirror support & baffle
Folding secondary mirror support strut
Glare Stop
Aft Optical Subsystem (Tertiary mirror & fine steering mirror)
Primary Mirror Segment (1 of 18)
Deployment Motor
Primary Mirror Backplane



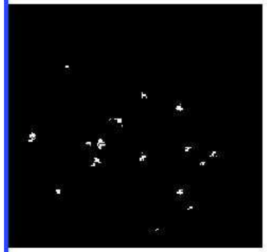
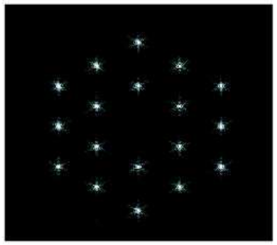
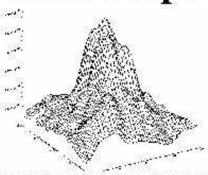
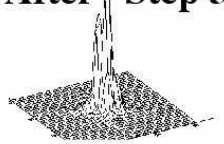
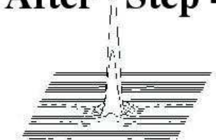

Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.




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 ...

| | | Initial Capture | Final Condition |
|---|---|---|---|
| *First light NIRCam*  1. Segment Image Capture | After Step 1  | 18 individual 1.6-m diameter aberrated sub-telescope images<br>PM segments: < 1 mm, < 2 arcmin tilt<br>SM: < 3 mm, < 5 arcmin tilt | PM segments: < 100 μm, < 2 arcsec tilt<br>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<br>Secondary Mirror : < 3 mm, < 5 arcmin tilt | WFE < 200 μm (rms) |
| **3. Coarse Phasing** - Fine Guiding (PMSA piston) | After Step 3  | WFE: < 250 μm rms | WFE < 1 μm (rms) |
| **4. Fine Phasing** | After Step 4  | WFE: < 5 μm (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 2006 demo of H/W, S/W on 6/1 scale model (2 $\mu$m-Strehl$\gtrsim$0.85).

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

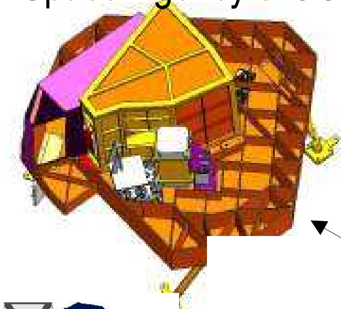
Ball 1/6-scale model: WFS produces diffraction-limited images at 2.0 $\mu$m.

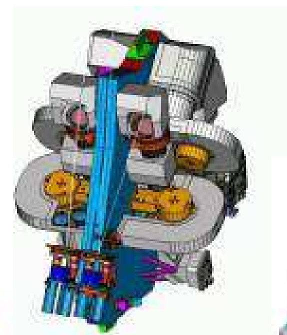
• (2) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

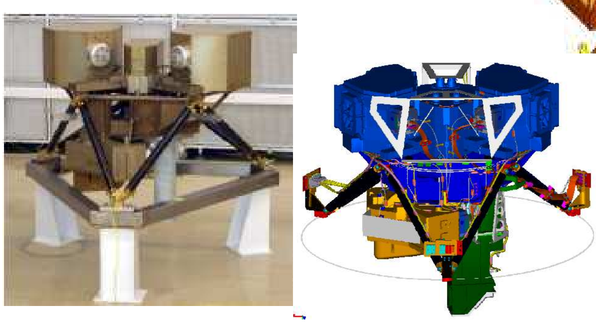
# Instrument Overview

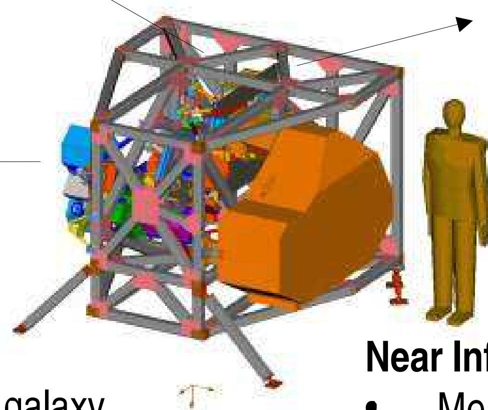
**Fine Guidance Sensor (FGS)**
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

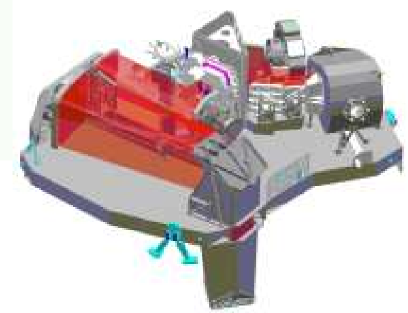
**Near Infra-Red Camera (NIRCam)**
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC







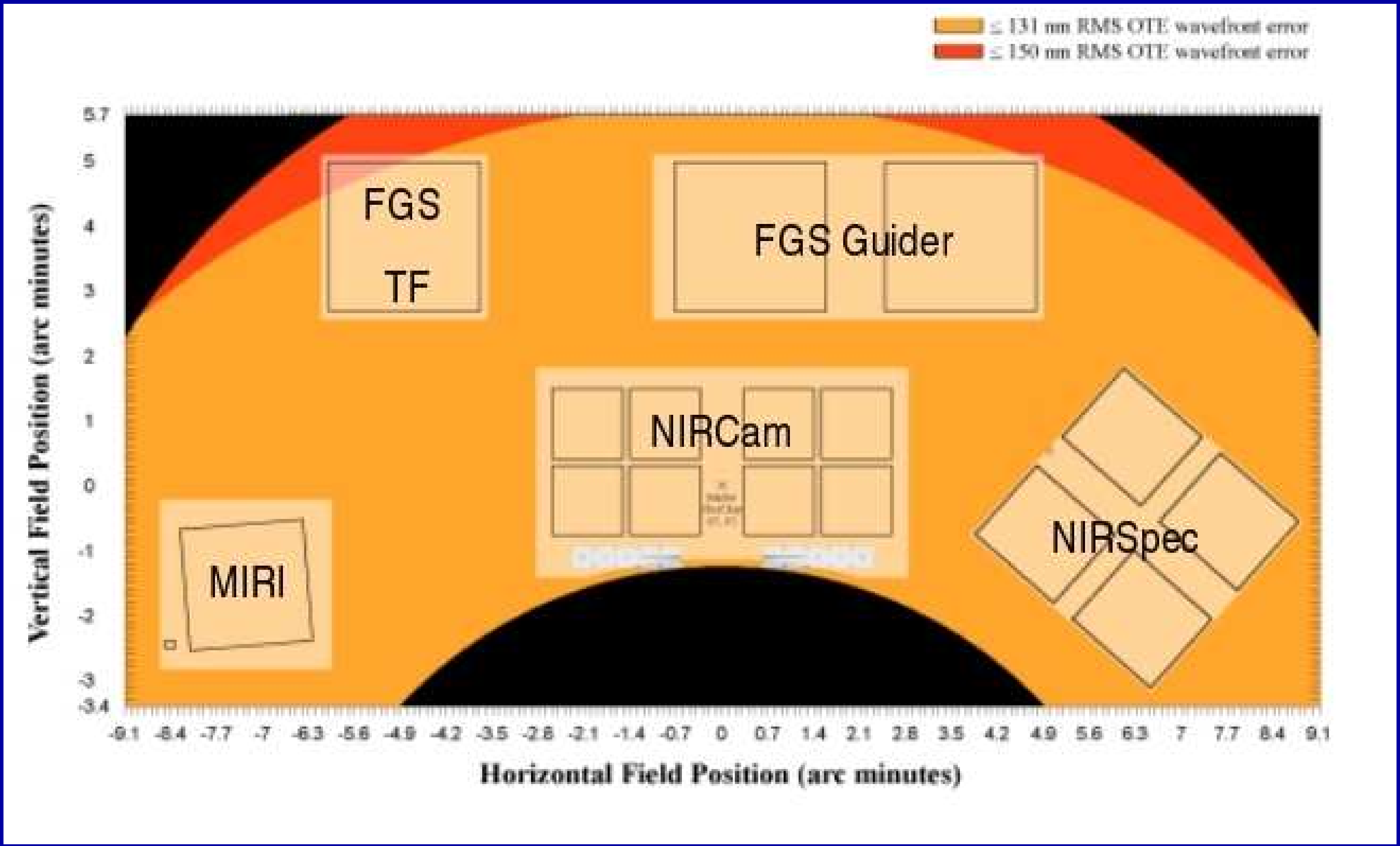




**Mid-Infra-Red Instrument (MIRI)**
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

**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

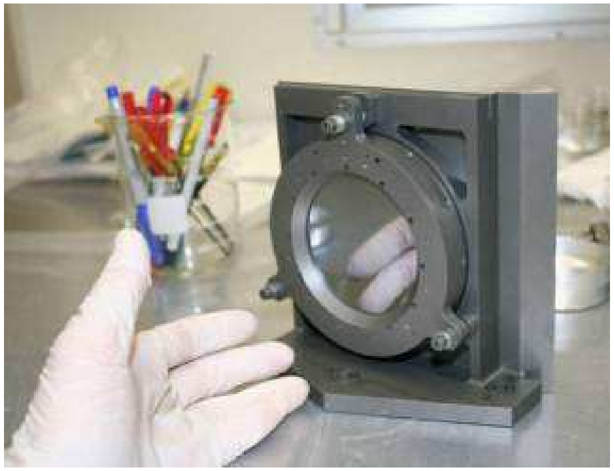
## • (2) What instruments will JWST have?




All JWST instruments can in principle be used in parallel:

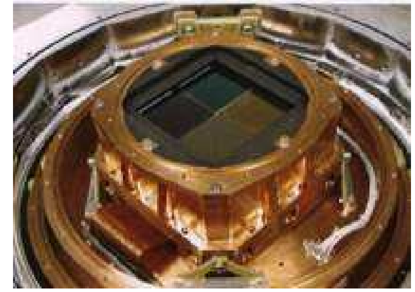
- Currently only being implemented for parallel *calibrations.*

# Instrument Qual and ETU Model Hardware

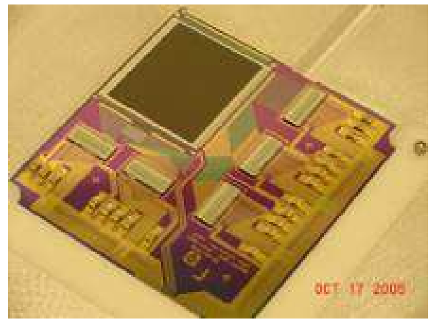


NIRCam Dichroic Beamsplitter

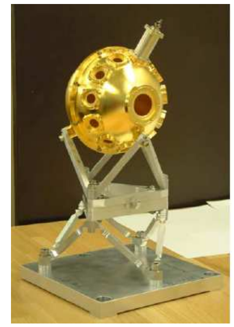
NIRCam Pupil Imaging Lens Set



NIRCam Detectors




NIRSpec Microshutter



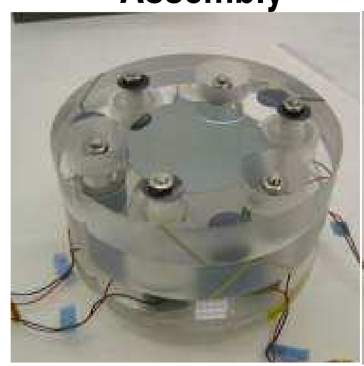
NIRSpec Calibration Assembly

NIRSpec Mirror

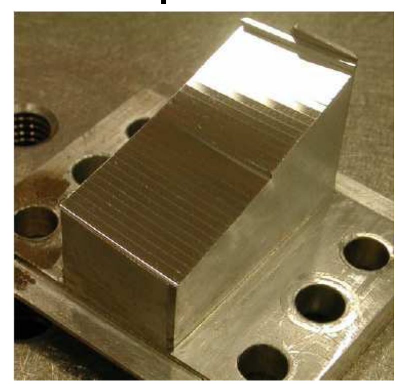
SiAs MIR Detector

MIRI Electronics

NIRSpec Fore Optics Mirror Assembly

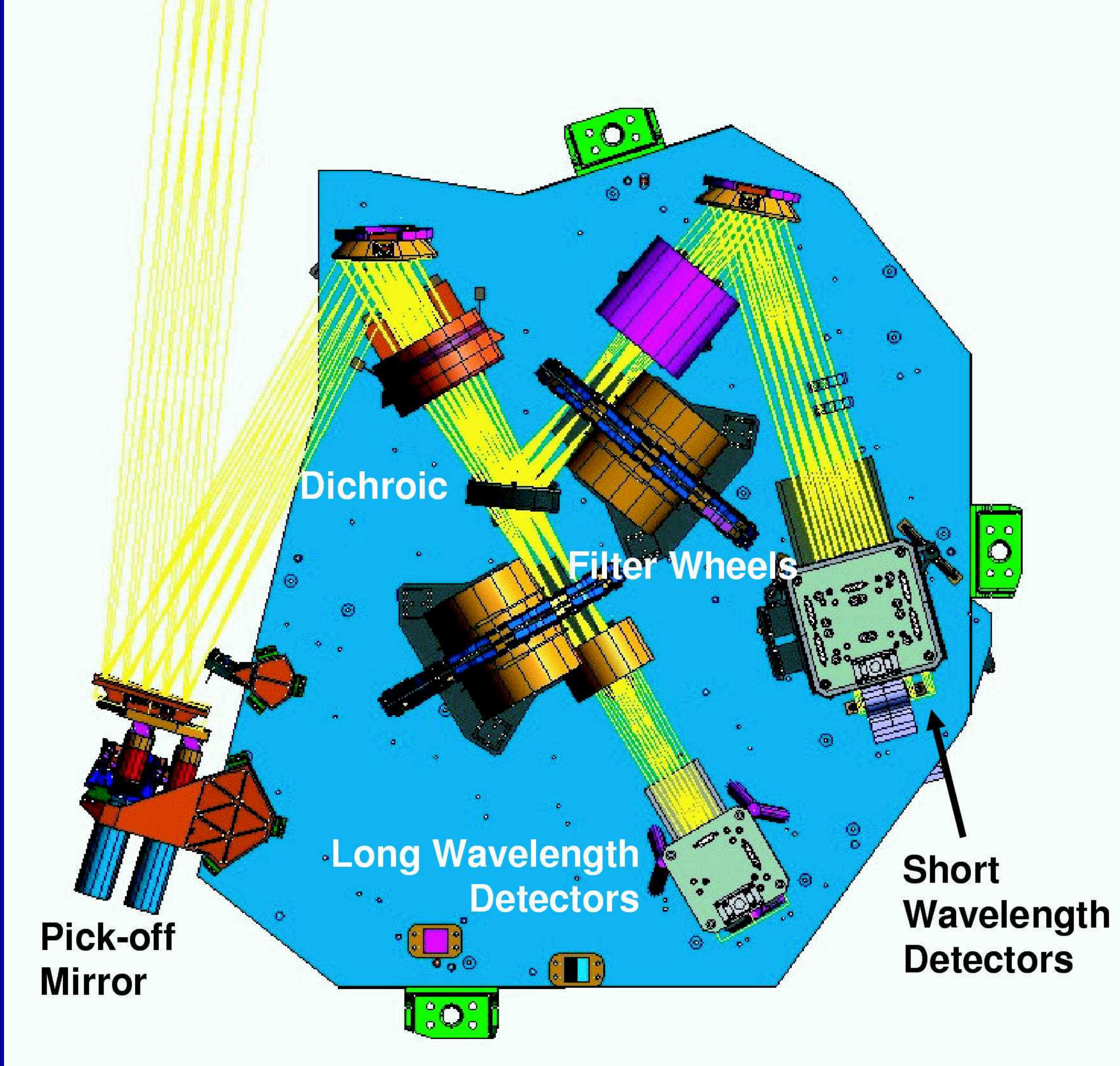


FGS/TF Etalon Filter



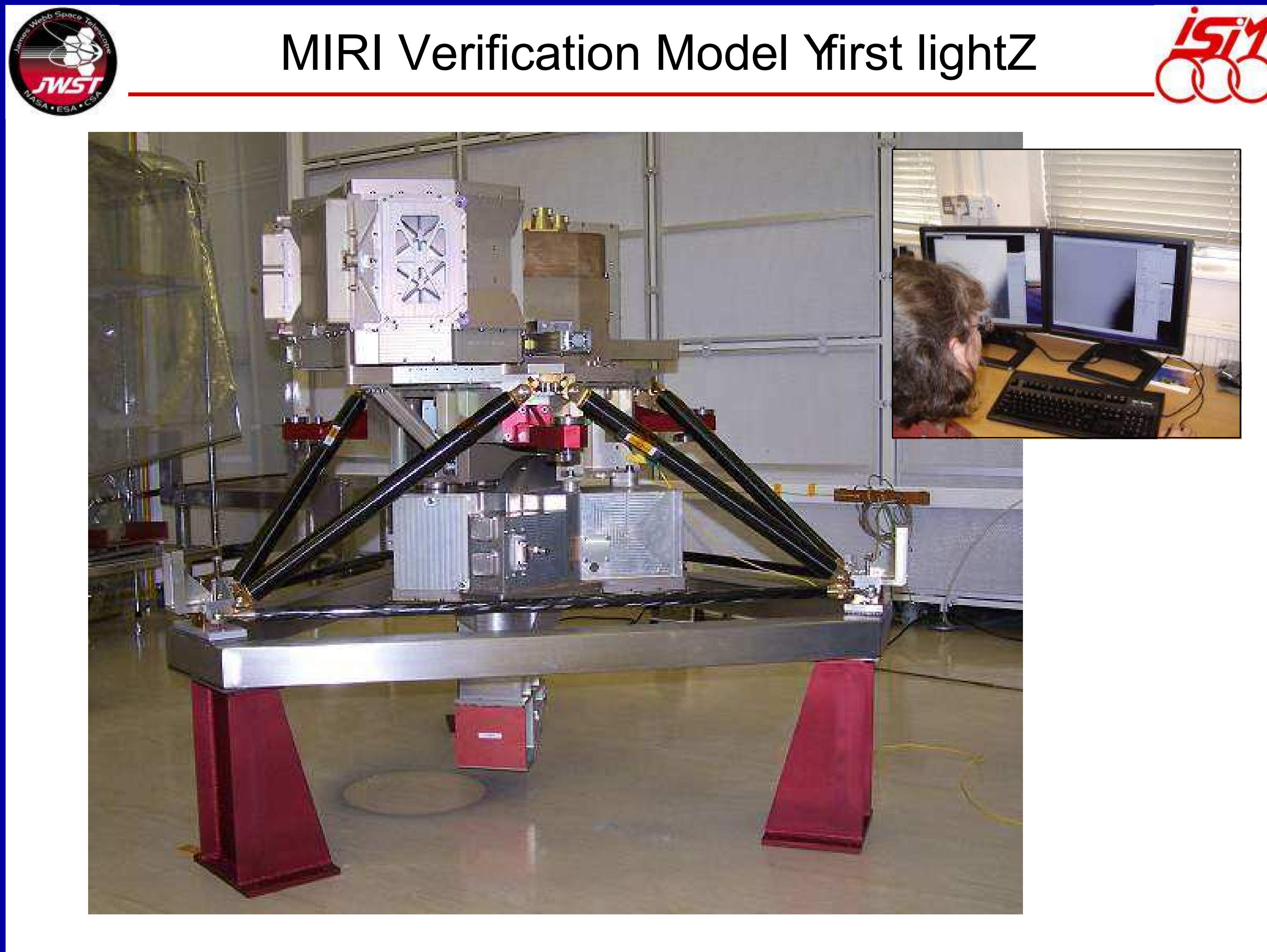
NIRSpec Image Slicer Mirror

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




Layout of JWST NIRCam

• (2) What instruments will JWST have?




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

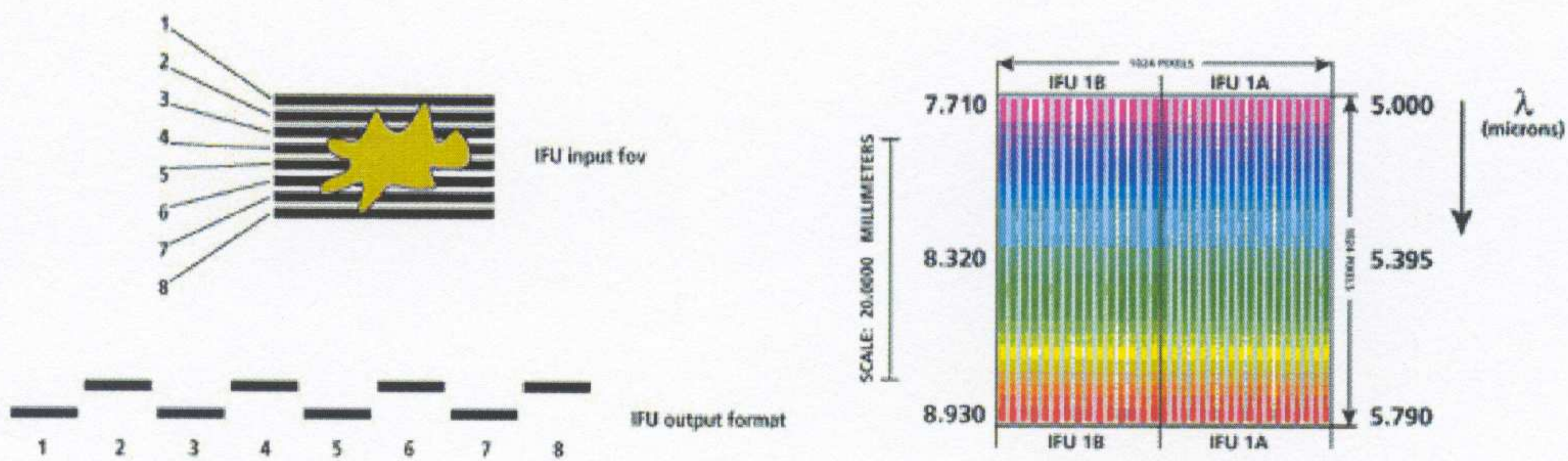
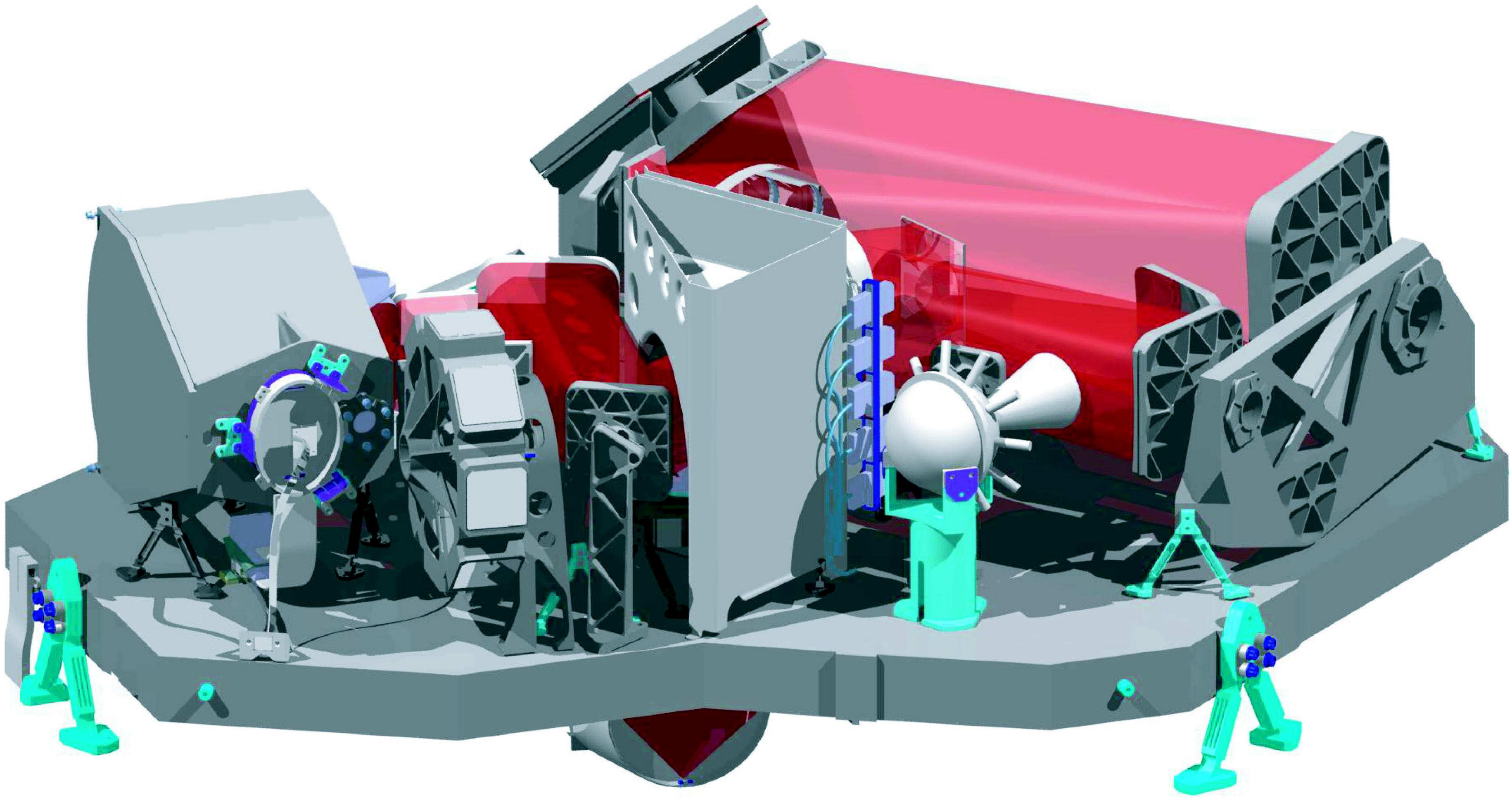
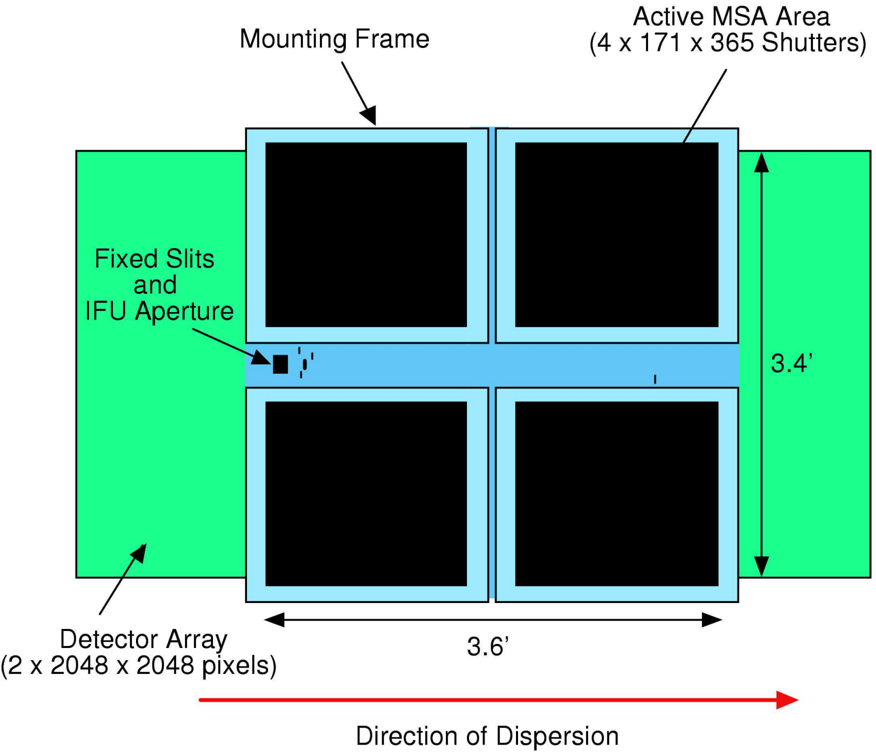


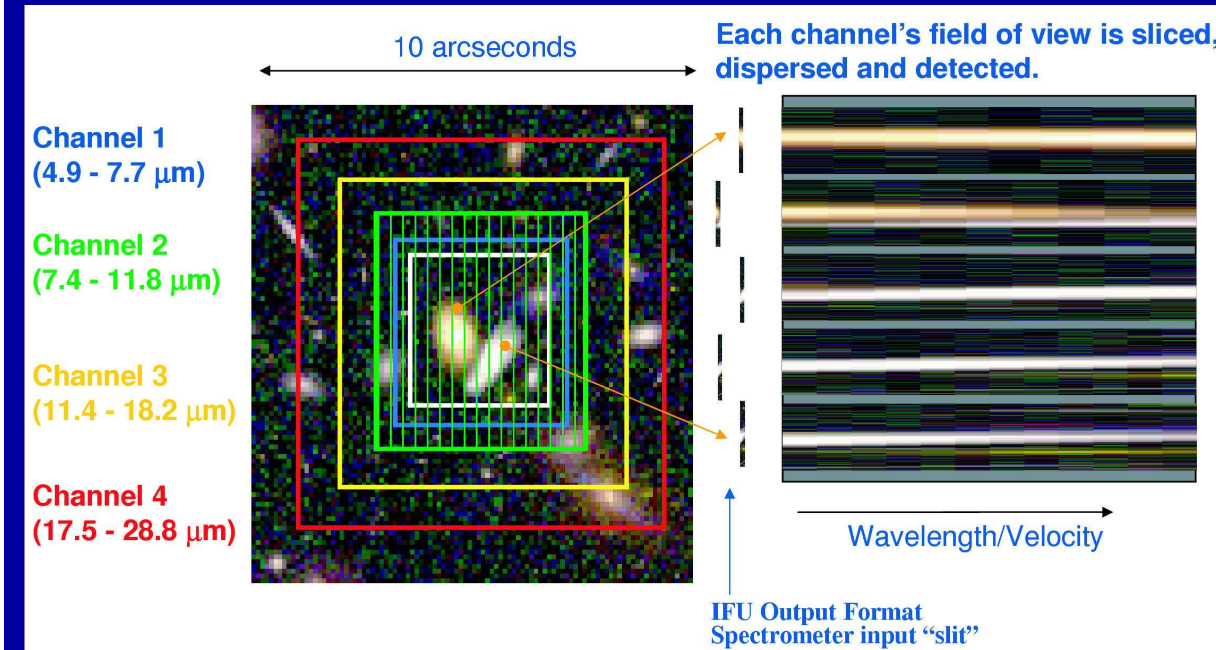

Figure 50. Schematic illustration of the MIRI IFU image slicer format (left) and dispersed spectra on detector (right)

The MIRI Integral Field Unit (IFU) has an image slicer that makes spatially resolved spectra at wavelengths 5 $\mu$m$\lesssim \boldsymbol{\lambda} \lesssim$28 $\mu$m.



Layout of NIRSpec



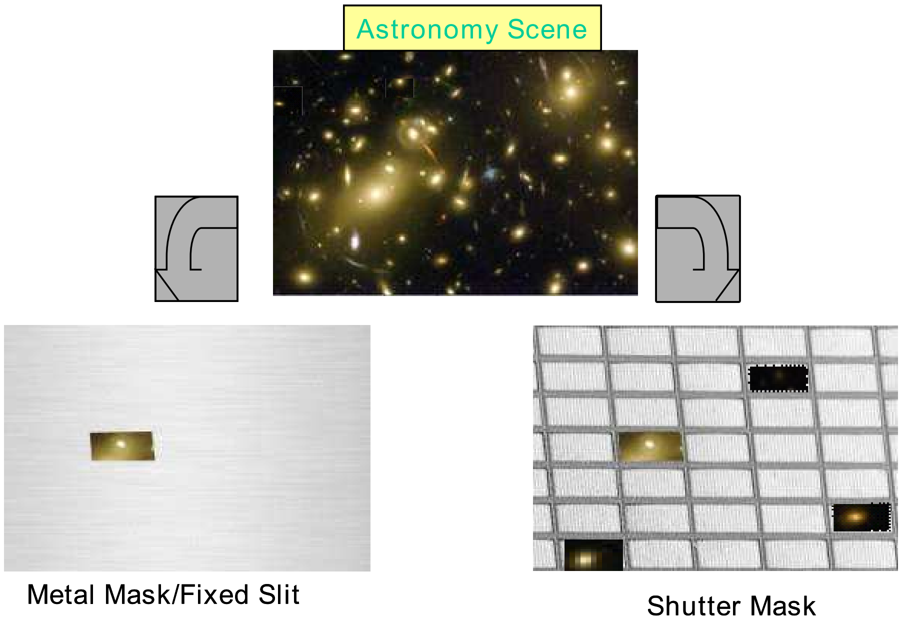

JWST offers significant multiplexing for faint object spectroscopy:

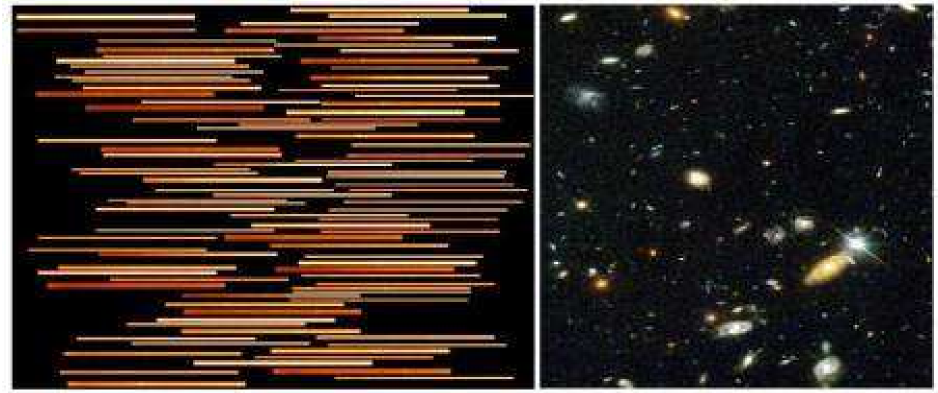
- NIRSpec/MSA with 4×62,415 independently operable micro-shutters that cover $\lambda \simeq 1$–$5\ \mu$m at R$\simeq$100–1000.

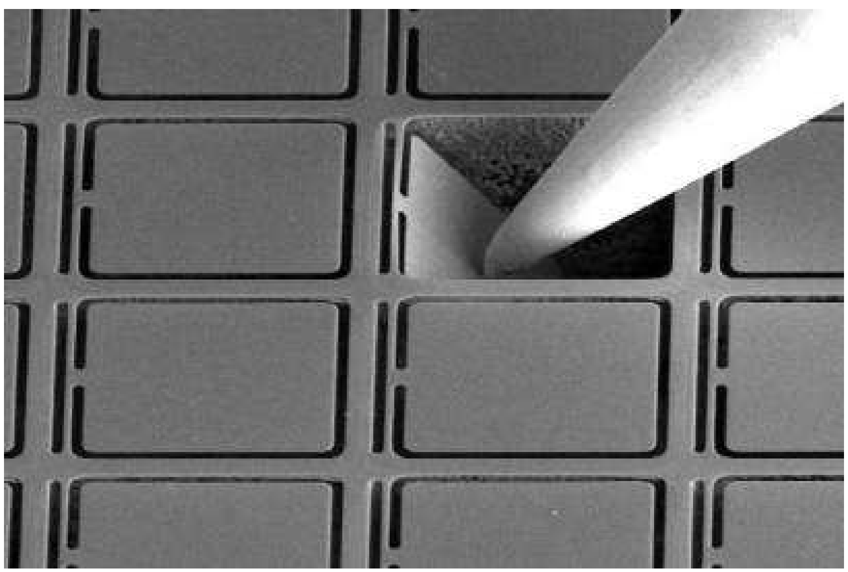
- MIRI/IFU with 400 spatial pixels covering 5–28.5 $\mu$m at R$\sim$2000–4000.

- FGS/TFI that covers a $2\farcm2 \times 2\farcm2$ FOV at $\lambda \simeq 1.6$–$4.9\ \mu$m at R=100.

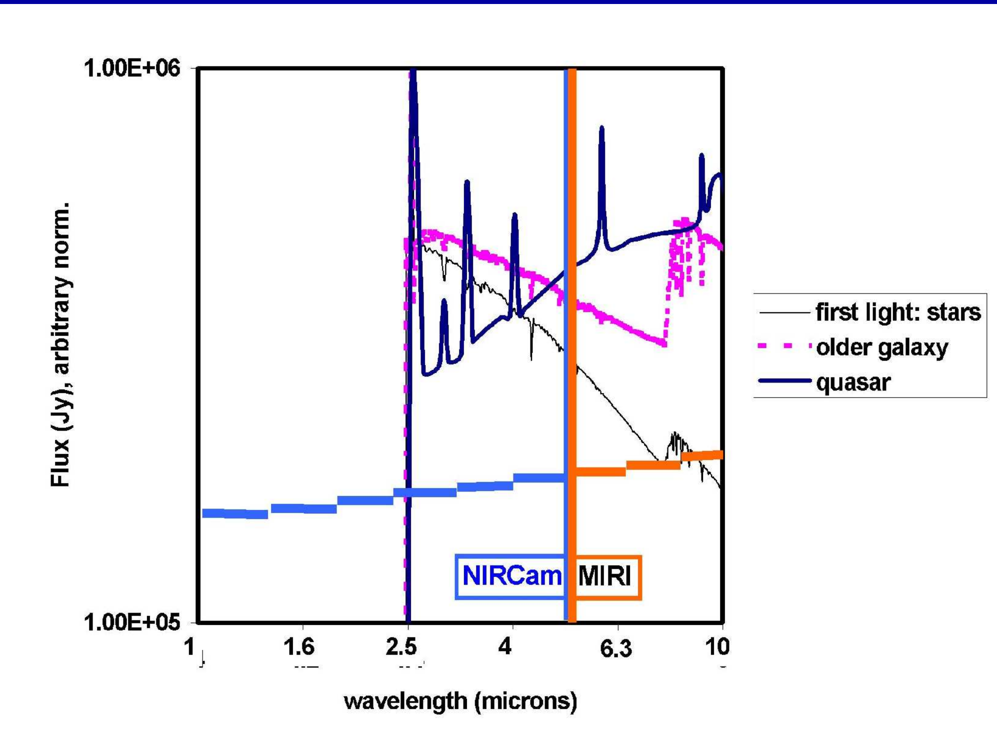
# Micro Shutters

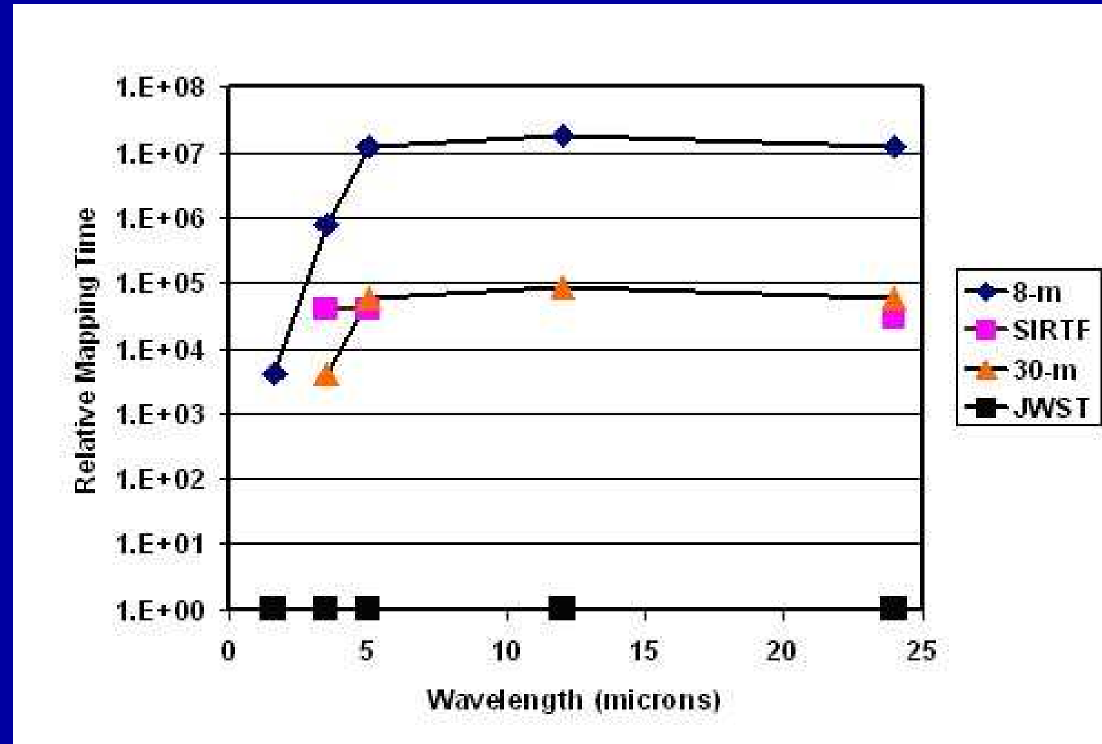




• (2) What sensitivity will JWST have?

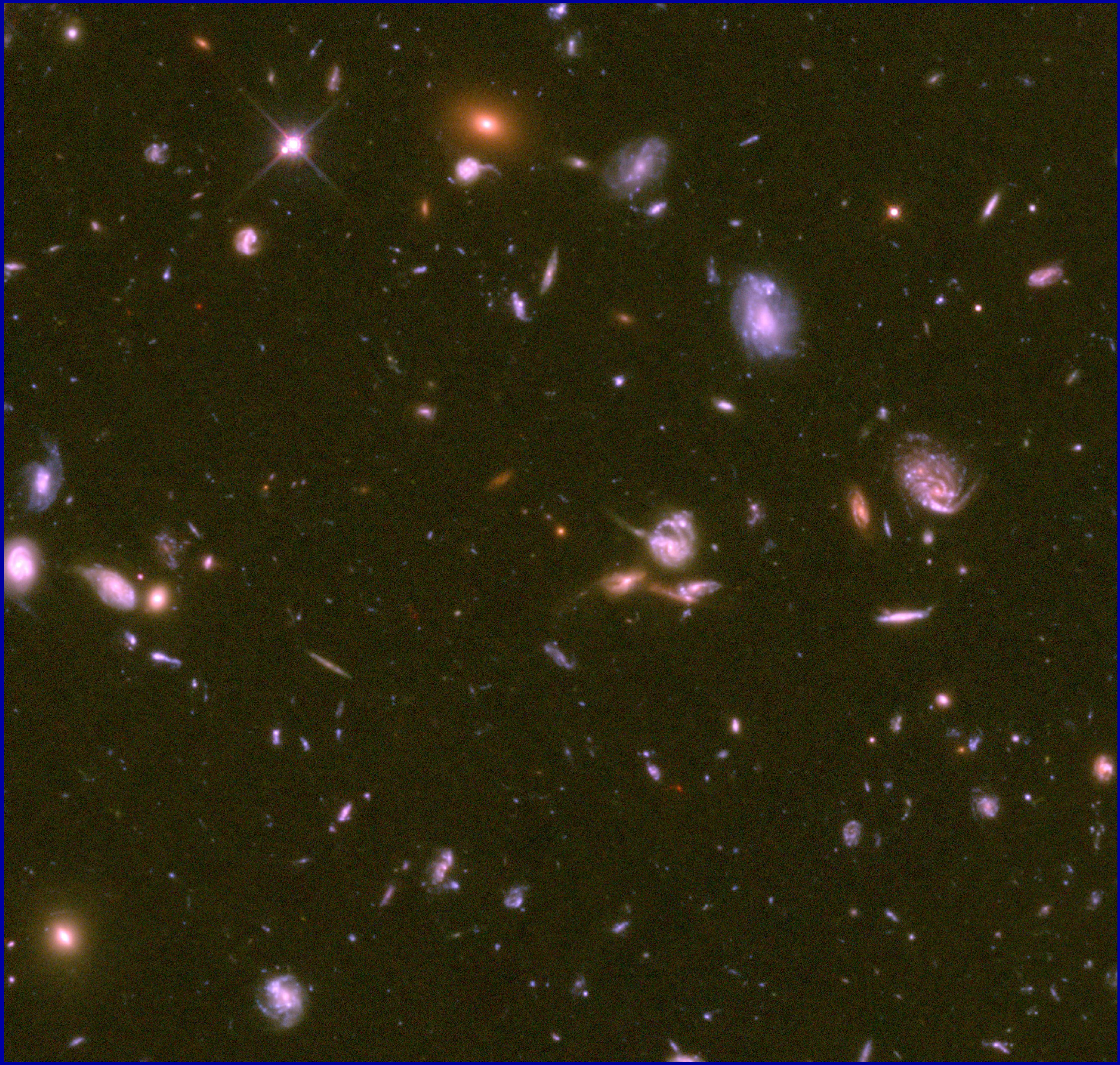



The NIRCam and MIRI sensitivity complement each other, straddling 5 $\mu$m in wavelength, and together allow objects to be found to redshifts z=15–20 in $\sim 10^5$ sec (28 hrs) integration times.

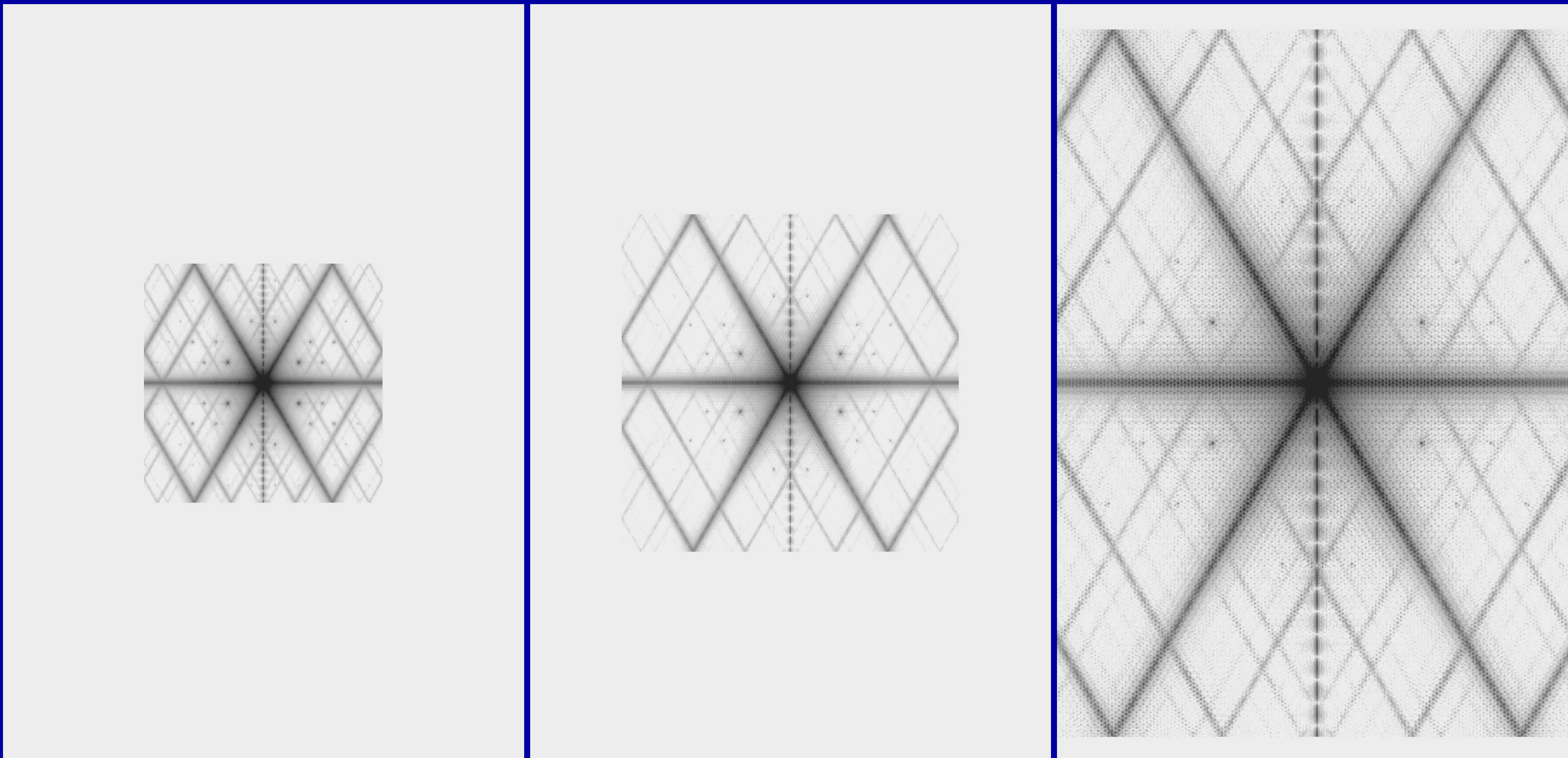
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

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 Vi'z' in the Hubble UltraDeep Field (HUDF)

# 6.5m JWST PSF's models (Ball Aerospace and GSFC):

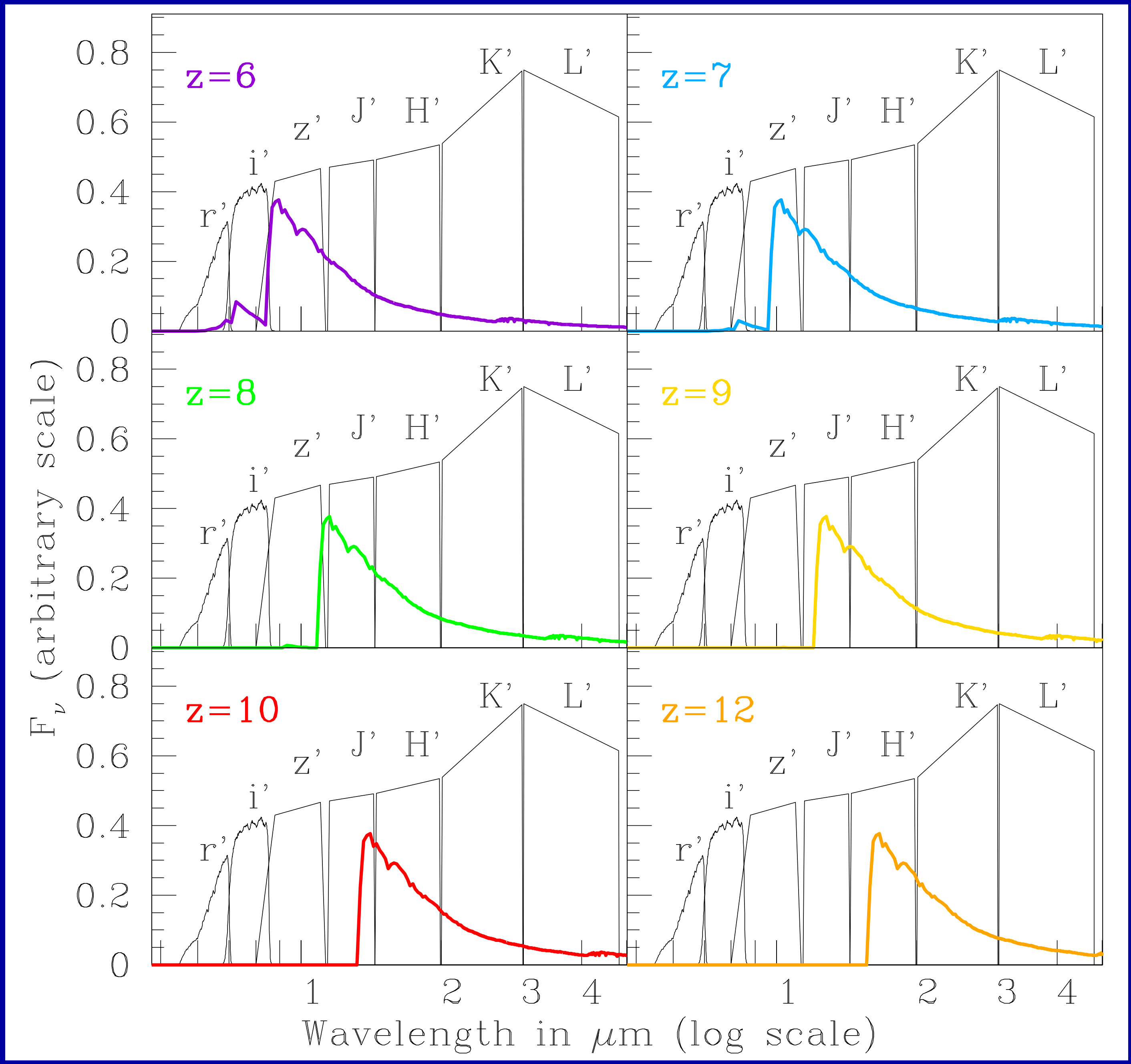


NIRCam 0.7 $\mu$m    1.0 $\mu$m (<150 nm WFE)    2.0 $\mu$m (diffr. limit)

Design PSF's are shown at logarithmic stretch: they have $\gtrsim$74% EE at r$\lesssim$0$''$.15 at 1.0$\mu$m, and are diffraction limited at 2.0$\mu$m (Strehl$\gtrsim$0.80).

∼18 hrs JWST NIRCam at 0.7, 0.9, 2.0 $\mu$m in the HUDF

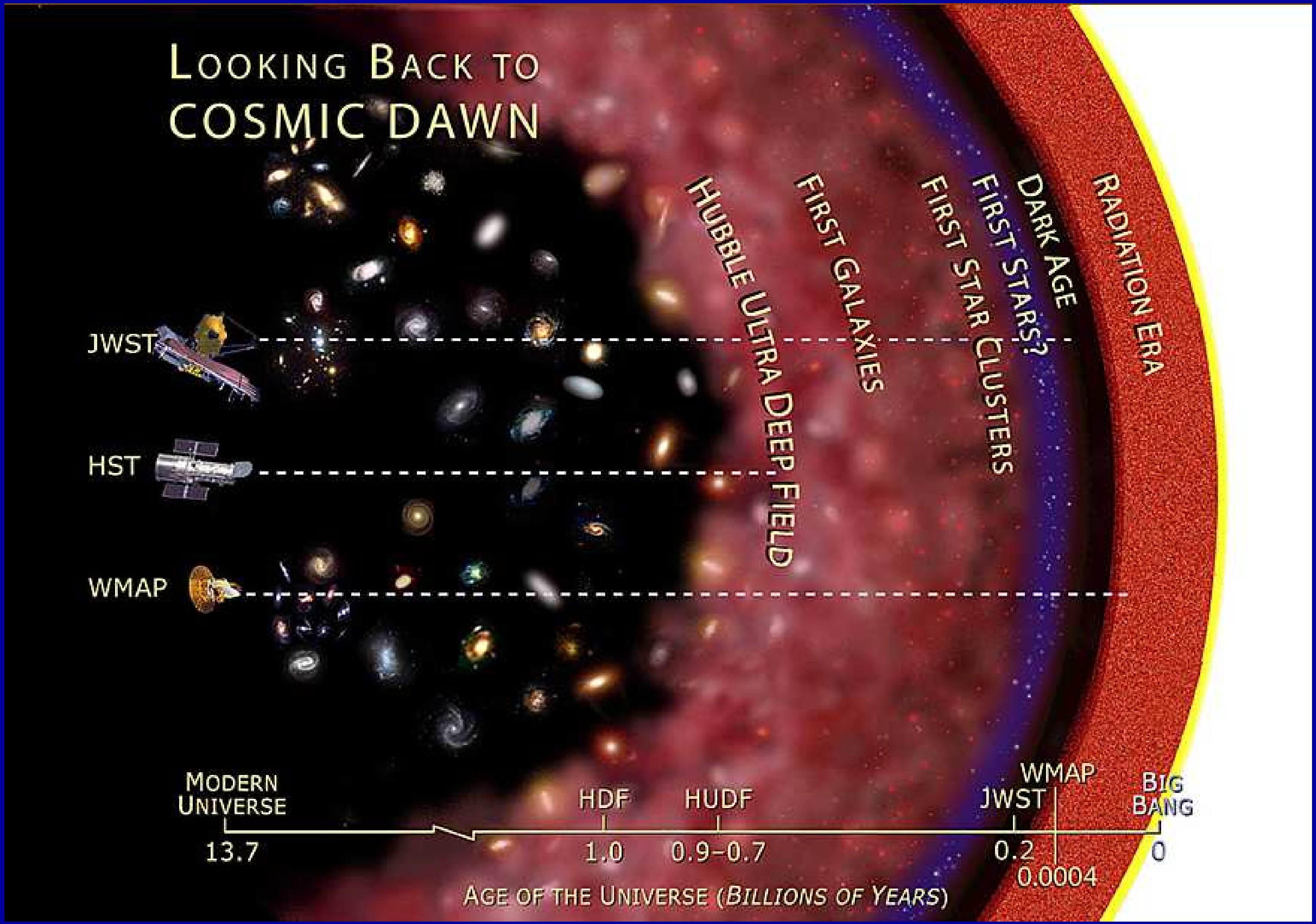
Truth≡240 hrs HUDF Vi'z'   18 hrs JWST 0.7, 0.9, 2.0 $\mu$m




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

⇒ This is why JWST needs NIRCam at 0.8–5 $\mu$m and MIRI at 5–28 $\mu$m.

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



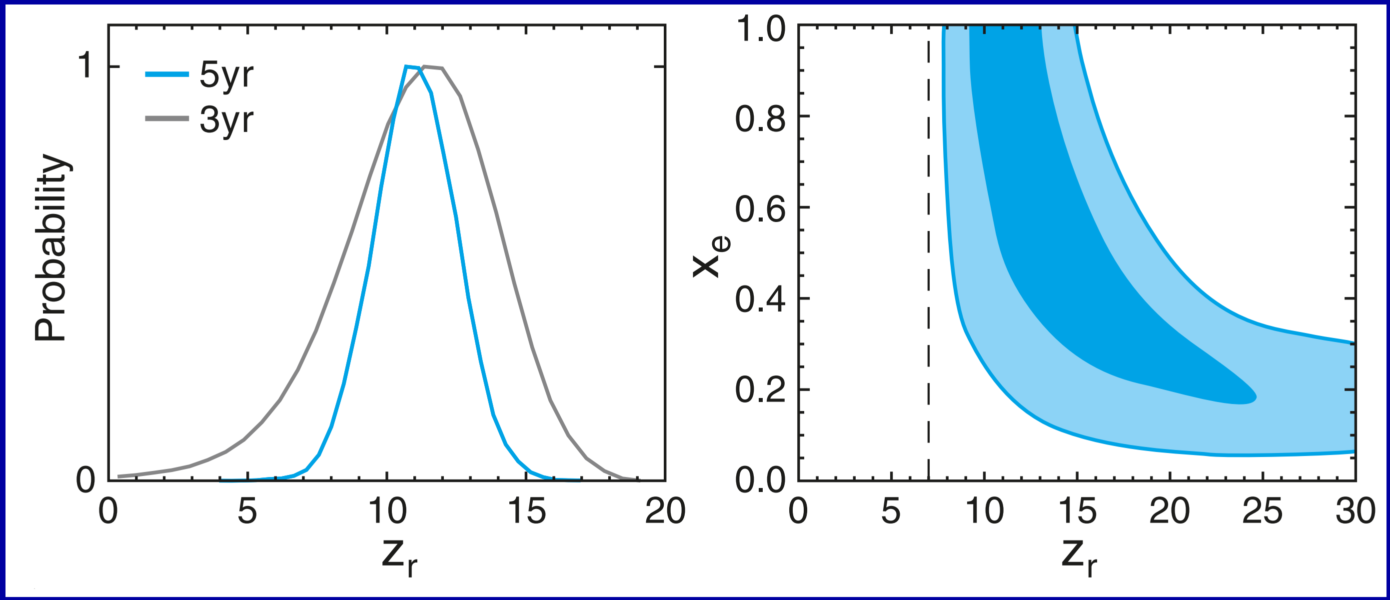

HST (+WFC3): Hubble sequence & galaxy evolution from z≃0 to z≃7–8.

JWST: First Light, Reionization, & (dwarf) Galaxy Assembly at z≃8–20.

WMAP: H-Recombination at z=1091±1. Imprints of all foregrounds.

# Implications of the March 2008 5-year WMAP results on JWST science:

HST/WFC3 $z \lesssim 7$–8 $\longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25




The year-5 WMAP data provided much better foreground removal (Dunkley ea. 2008 astro-ph/0803.0586; Komatsu ea. astro-ph/0803.0547). This implies that First Light & Reionization occurred between these extremes:

- (1) Universal & instantaneous at $z \simeq 10.8 \pm 1.4$, or, much more likely:

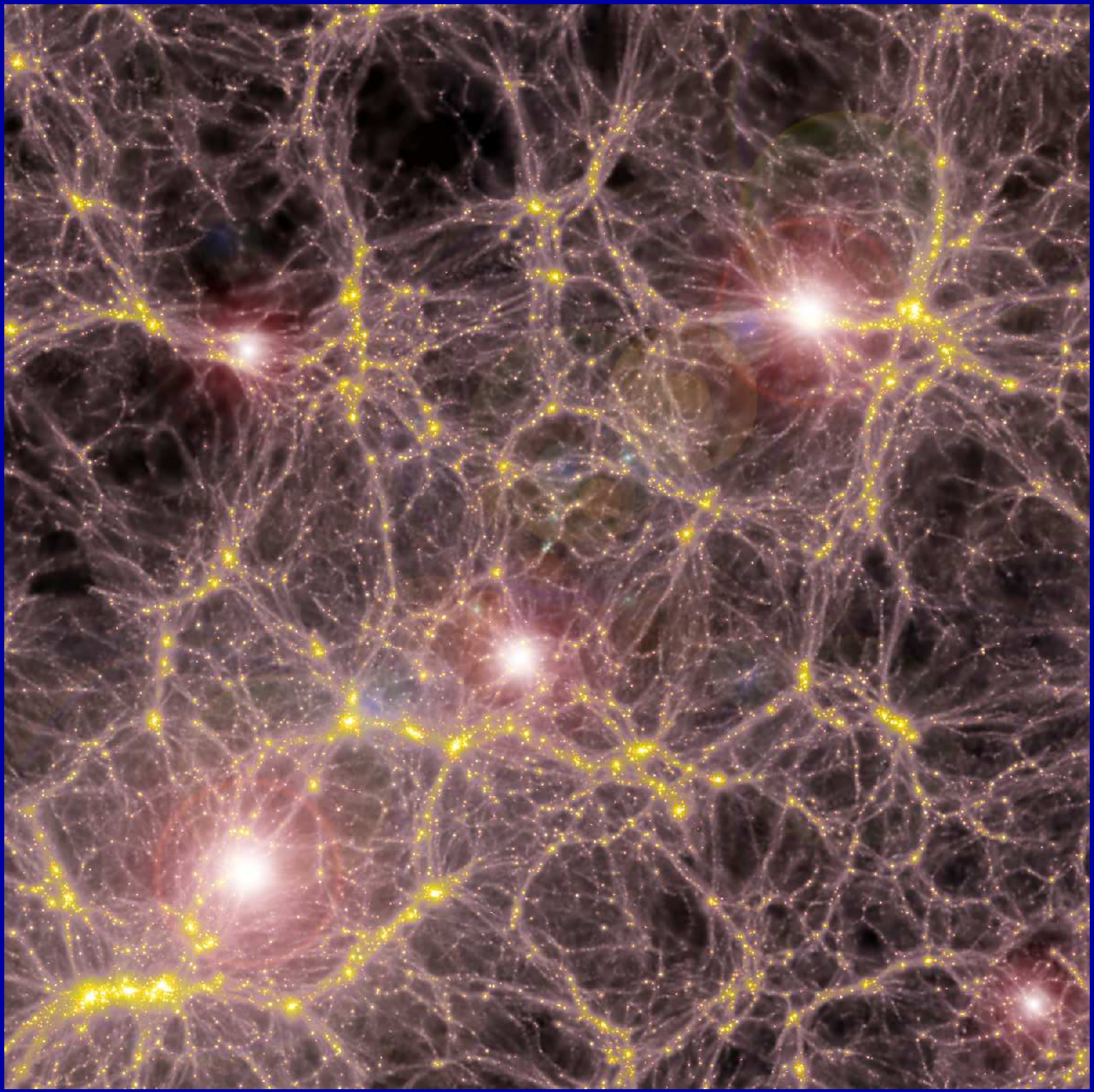
- (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. In both cases, the implications for HST and JWST are:

- HST has covered $z \lesssim 6$ and HST/WFC3 will cover $z \lesssim 7$–8.

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

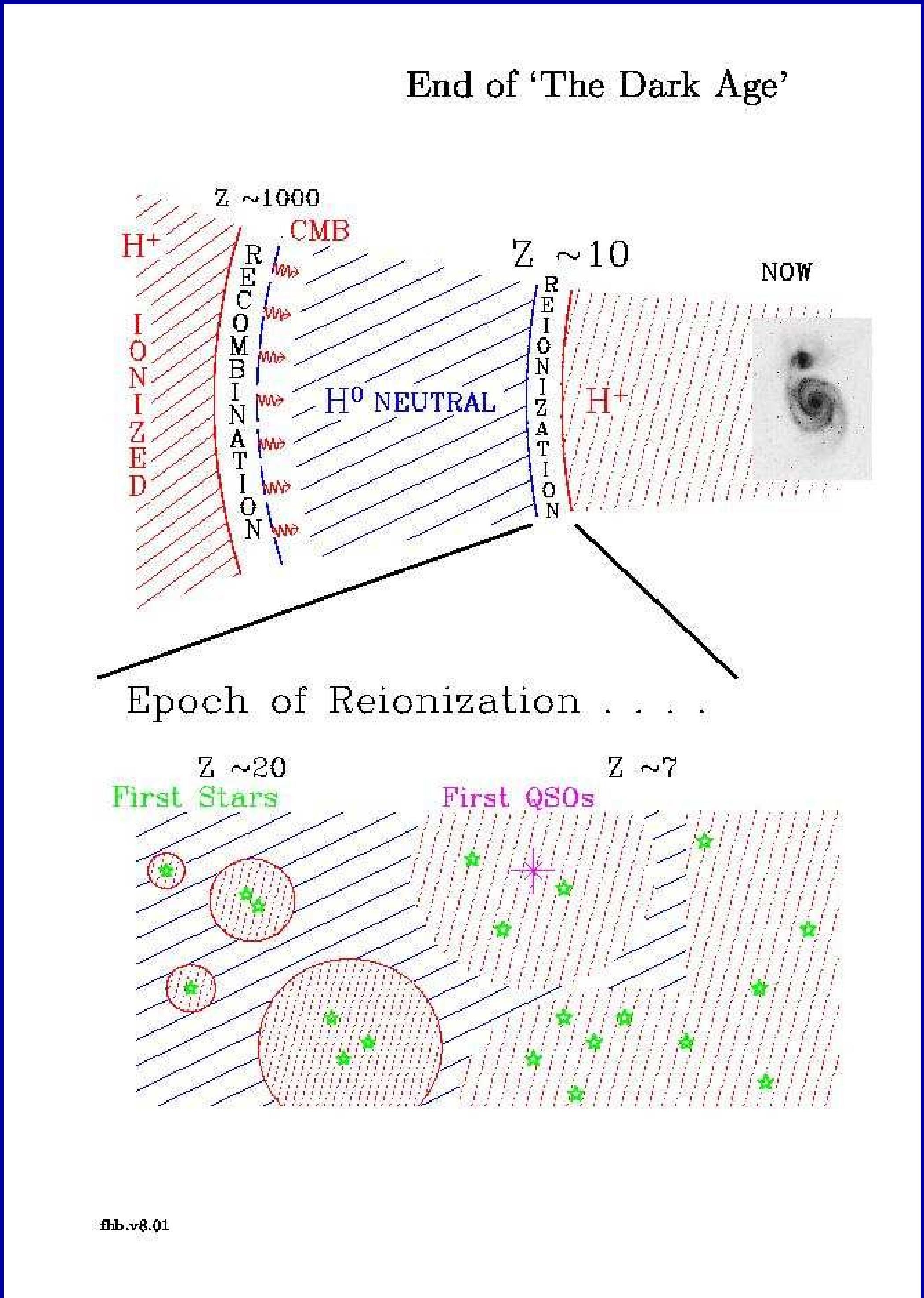
$\Rightarrow$ JWST must cover $\boldsymbol{\lambda}$=0.6–28 $\mu$m, with its diffraction limit at 2.0 $\mu$m.

• (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).

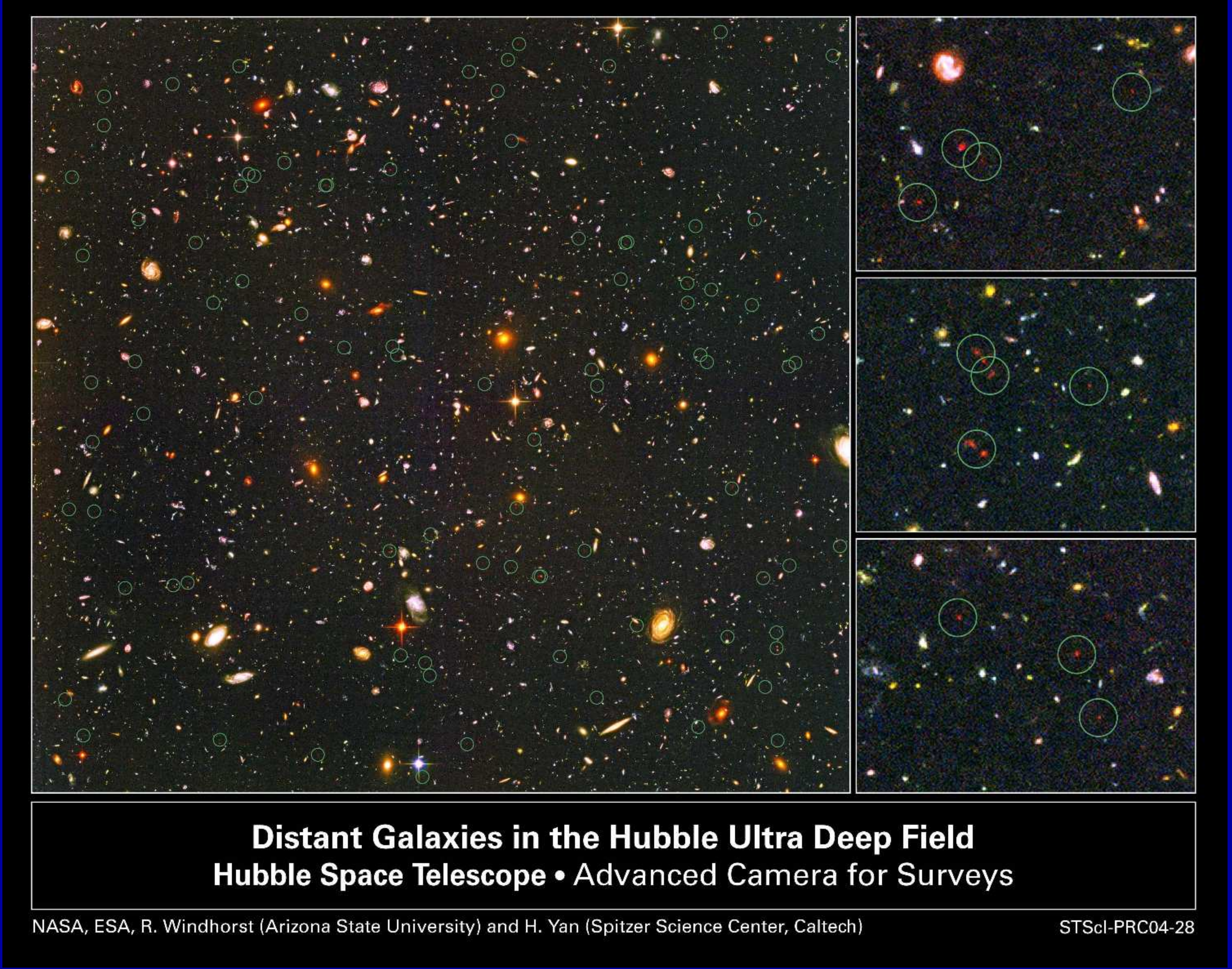
• A this should be visible to JWST as the first Pop III stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.




WMAP: First Light may have happened as following:

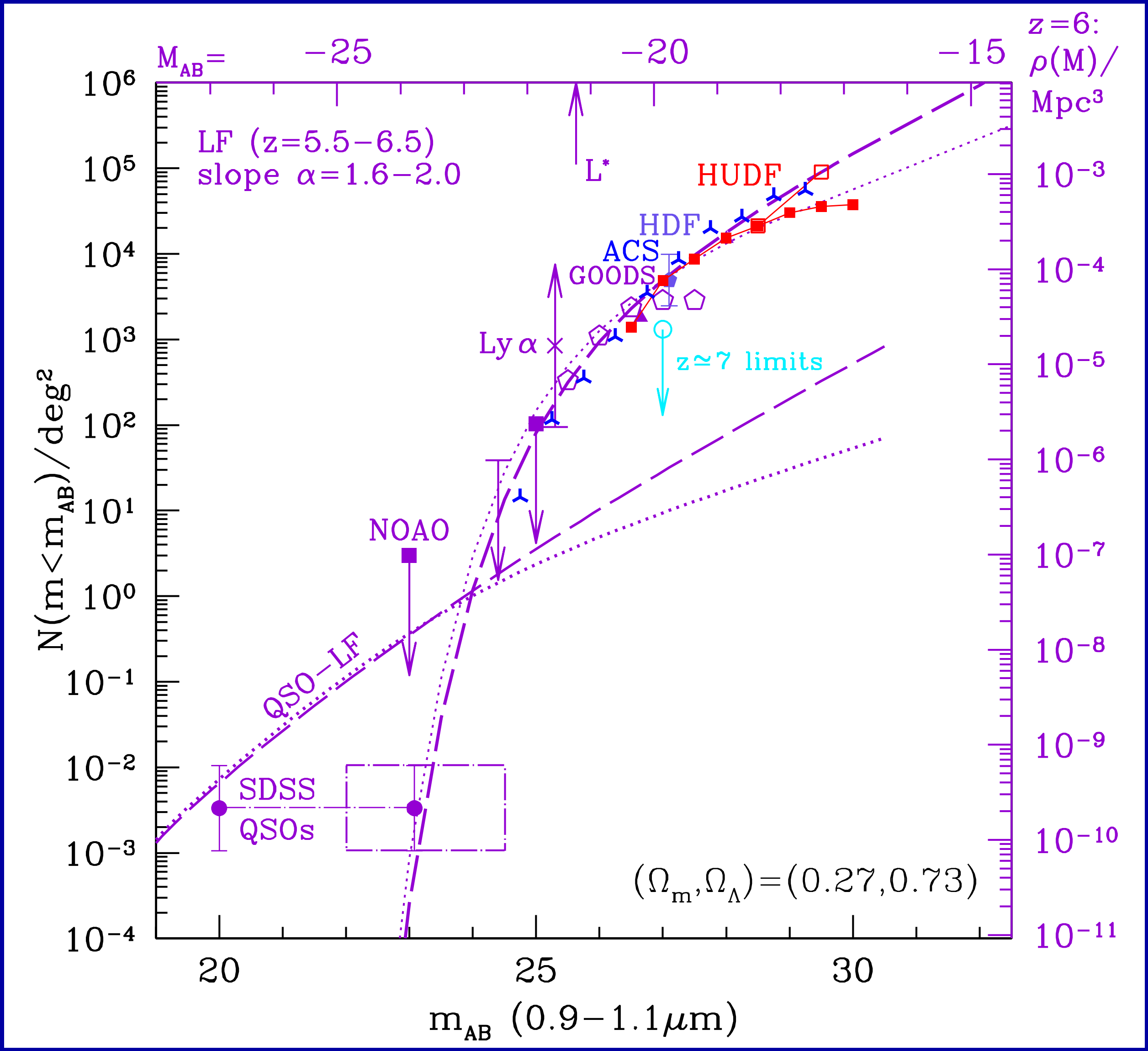
- (0) Dark Ages since recombination (z=1089) until First Light objects started shining ($z \gtrsim 11$–20).
- (1) First Light when Population III stars start shining with mass $\gtrsim 100$–200 $M_\odot$ at $z \gtrsim 11$–20.
- (2) Pop III supernovae heated IGM, which perhaps could not cool and form 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)



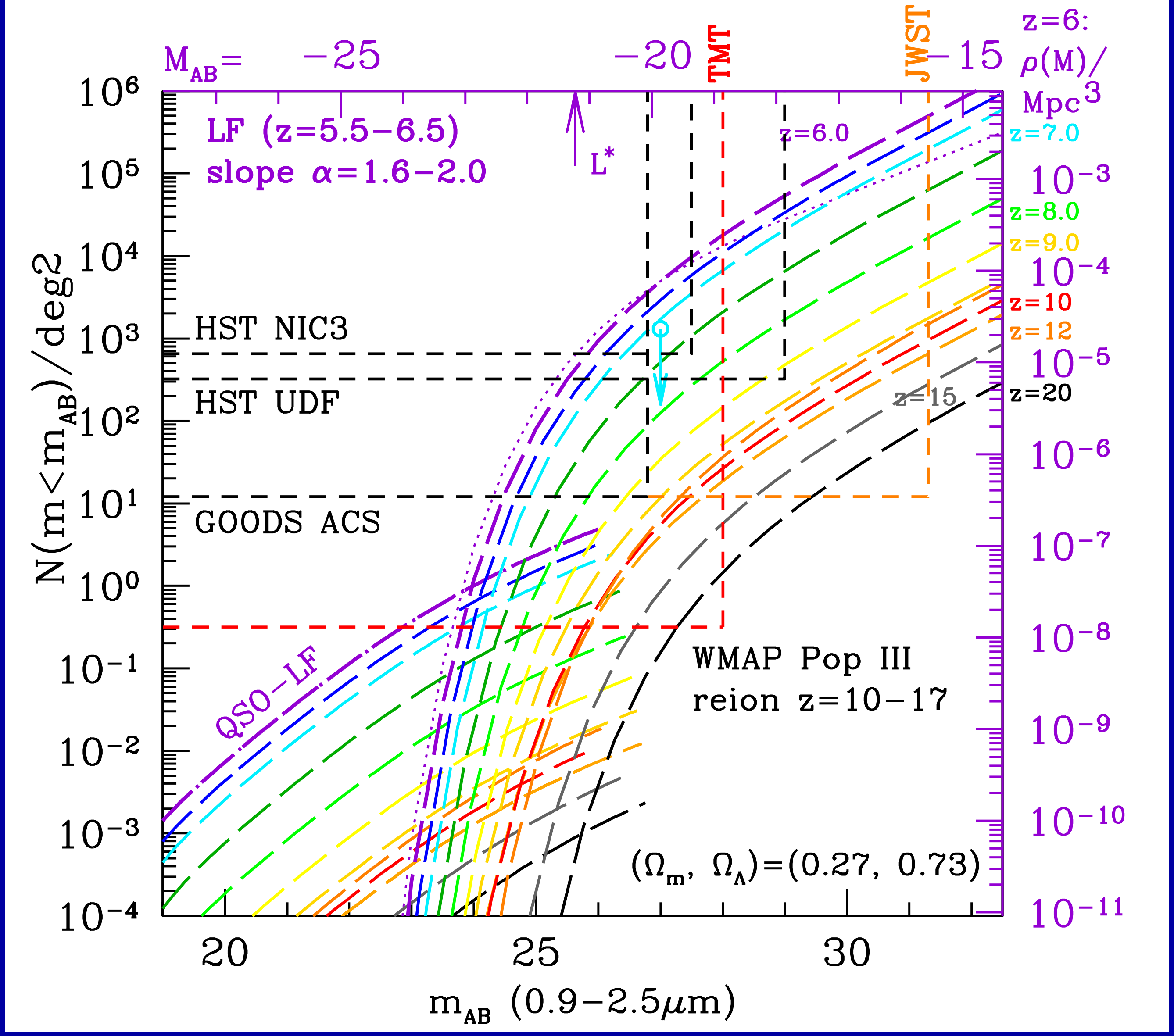

HUDF i-drops: faint galaxies at $z \simeq 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \simeq 6$ to AB$\lesssim$27.0 mag (Malhotra et al. 2005).

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



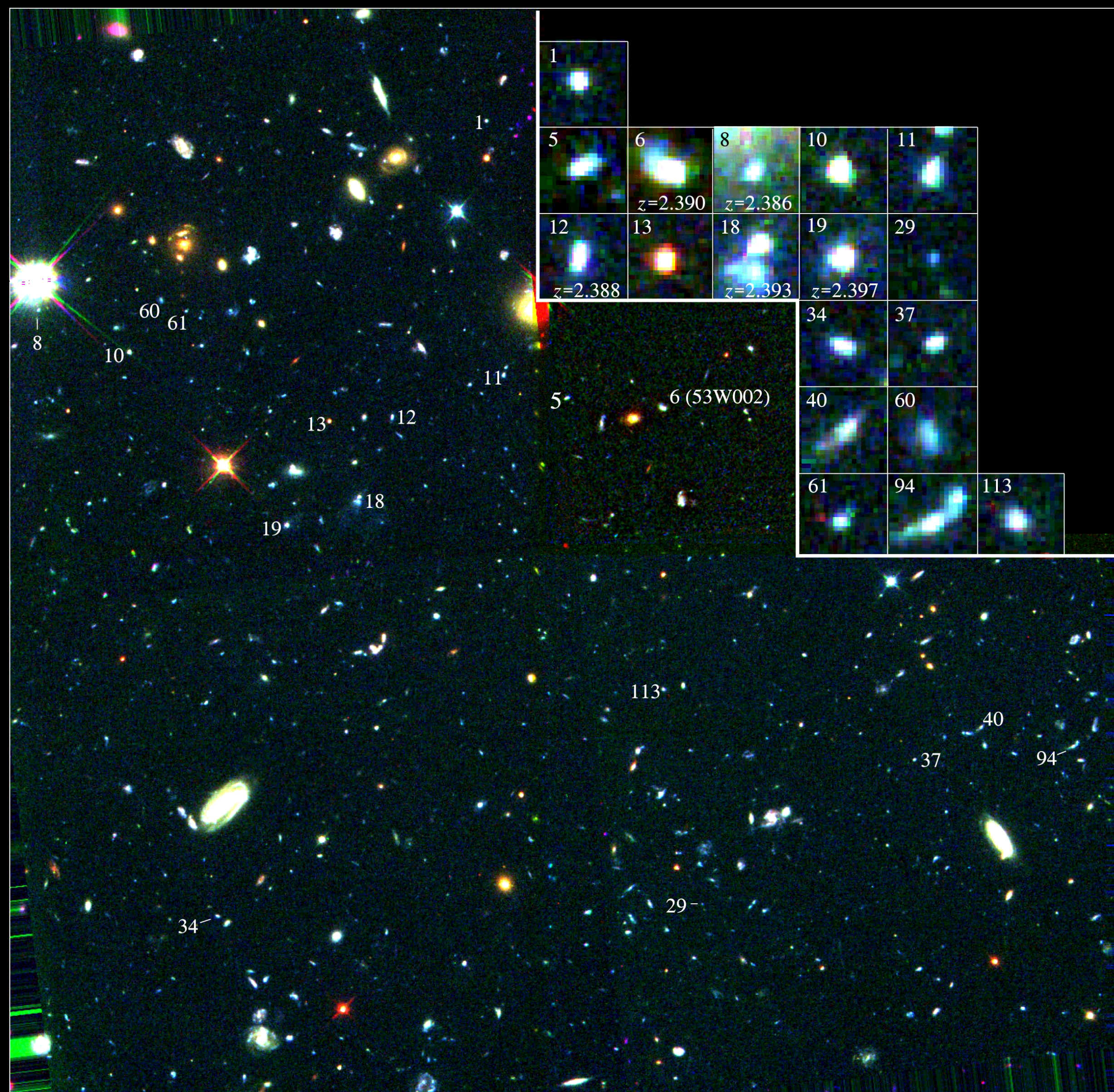

HUDF shows that luminosity function of $z \simeq 6$ objects (Yan & Windhorst 2004a, b) may be very steep: faint-end Schechter slope $|\alpha| \simeq 1.6$–$2.0$.

$\Rightarrow$ 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 (FOV=$\Omega$), and wavelength range (0.7-28 $\mu$m).

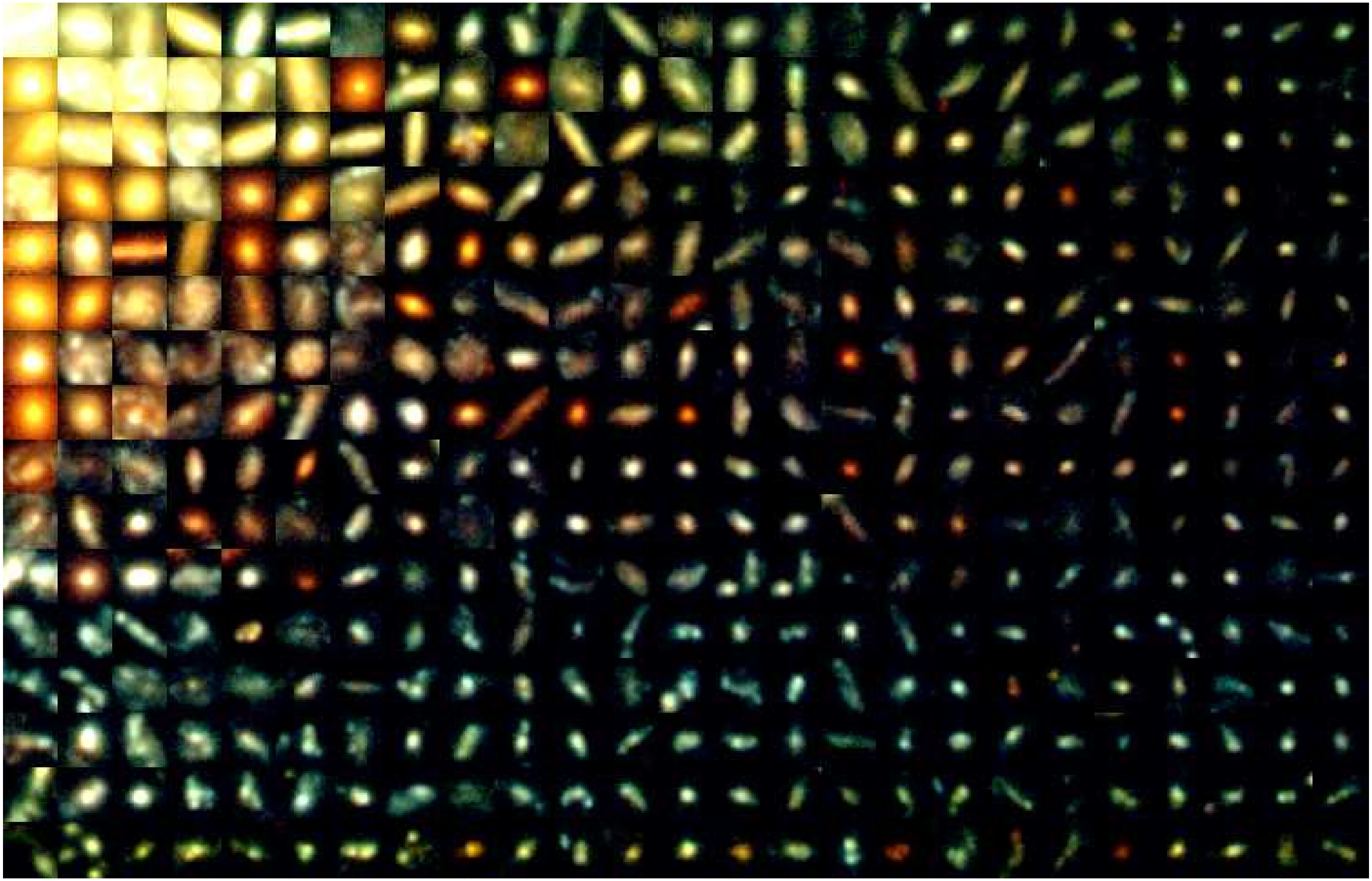
# • (4) How JWST can measure Galaxy Assembly



R. Windhorst (Arizona State University) and NASA

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

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



| z | Age ($q_o = 0.5$) |
|---|---|
| 0.19 | 77% |
| 0.44 | 58% |
| 0.54 | 52% |
| 0.64 | 48% |
| 0.74 | 44% |
| 0.87 | 39% |
| 0.97 | 36% |
| 1.03 | 35% |
| 1.14 | 32% |
| 1.24 | 30% |
| 1.41 | 27% |
| 1.61 | 24% |
| 1.76 | 22% |
| 2.05 | 19% |
| 2.57 | 15% |
| 3.59 | 10% |

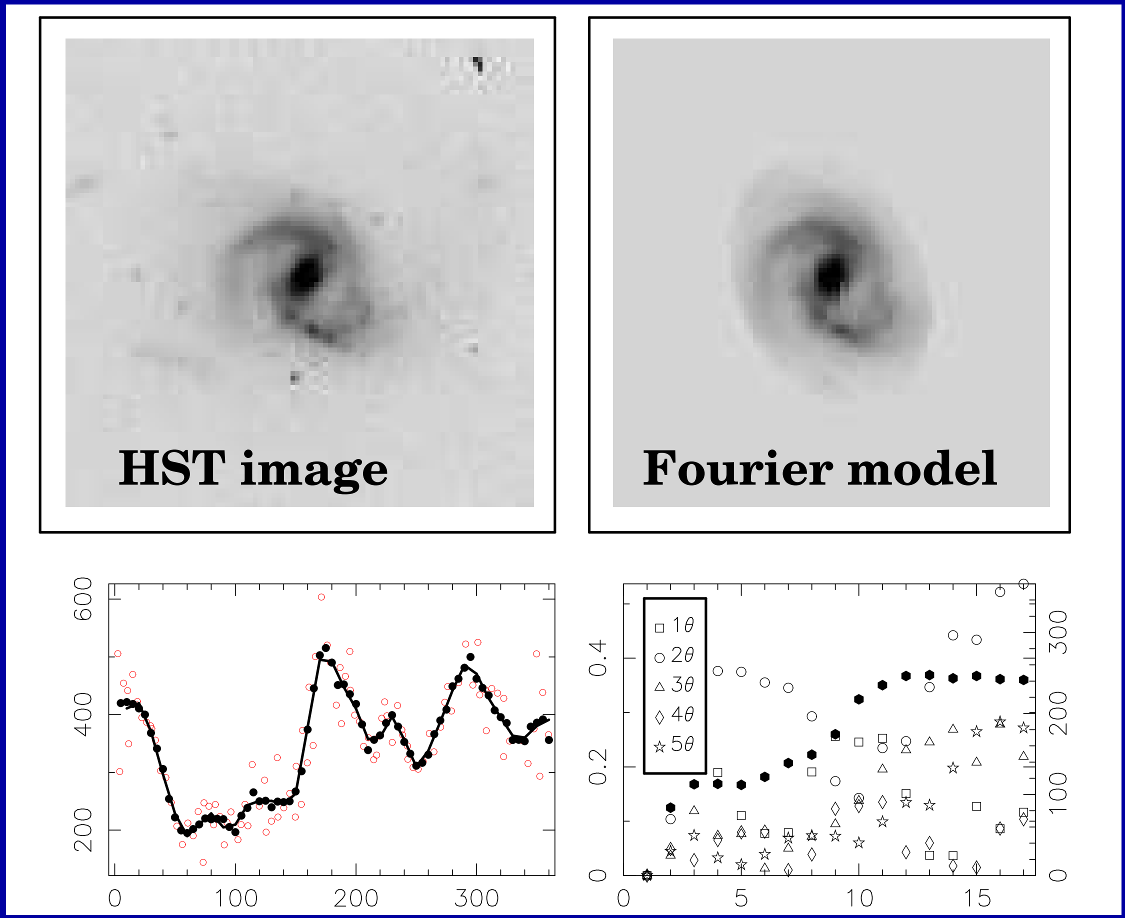
## • (4) How JWST can measure Galaxy Assembly

• Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable phase transition around $z\simeq0.5$–$1.0$:

(1) Subgalactic units rapidly merge from $z\simeq7\longrightarrow1$ to grow bigger units.

(2) Merger products start to settle as galaxies with giant bulges or large disks around $z\simeq1$. These evolved mostly passively since then, resulting in the giant galaxies that we see today.

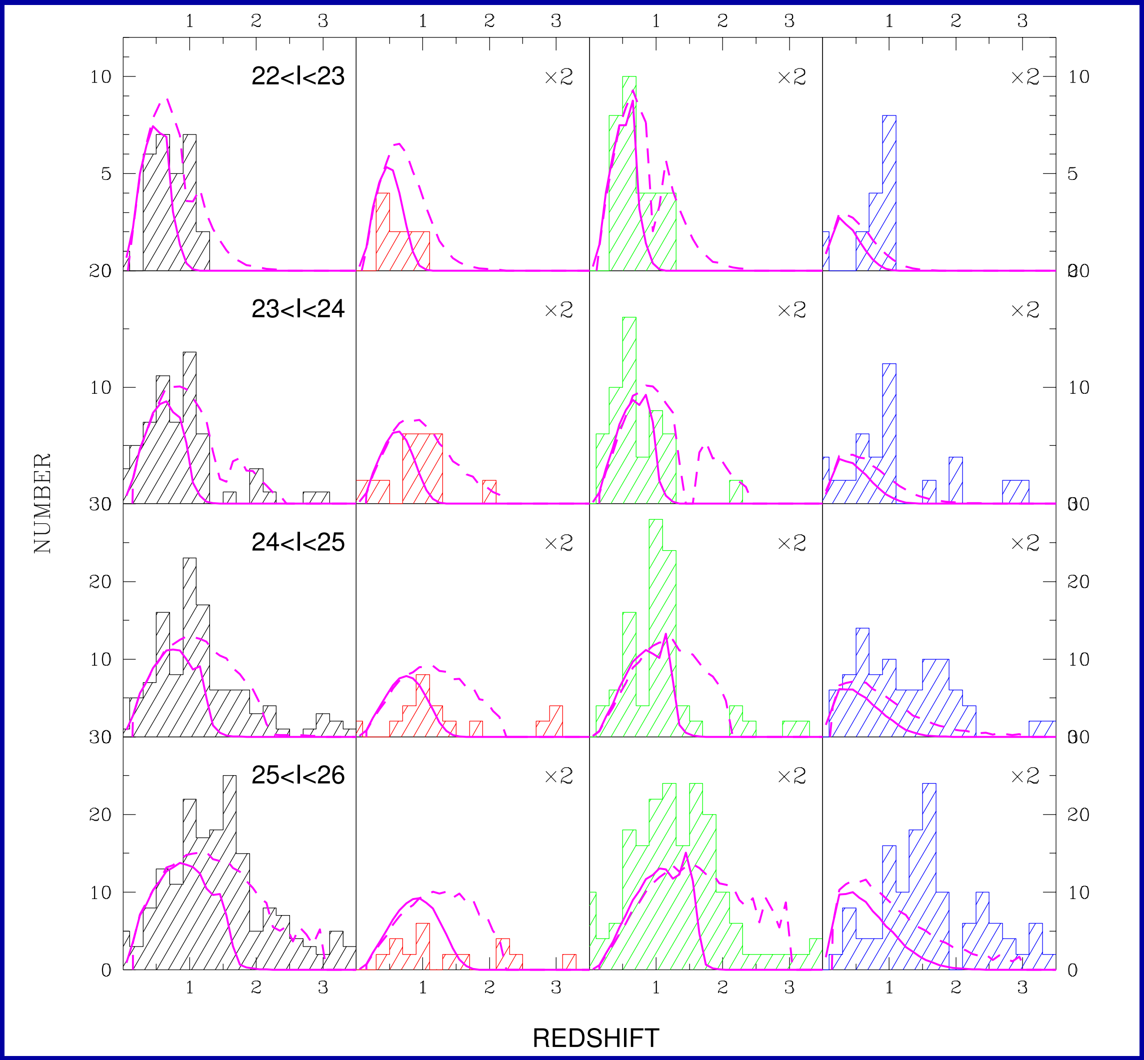
• JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame structure and type as a function of redshift or cosmic epoch.




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.

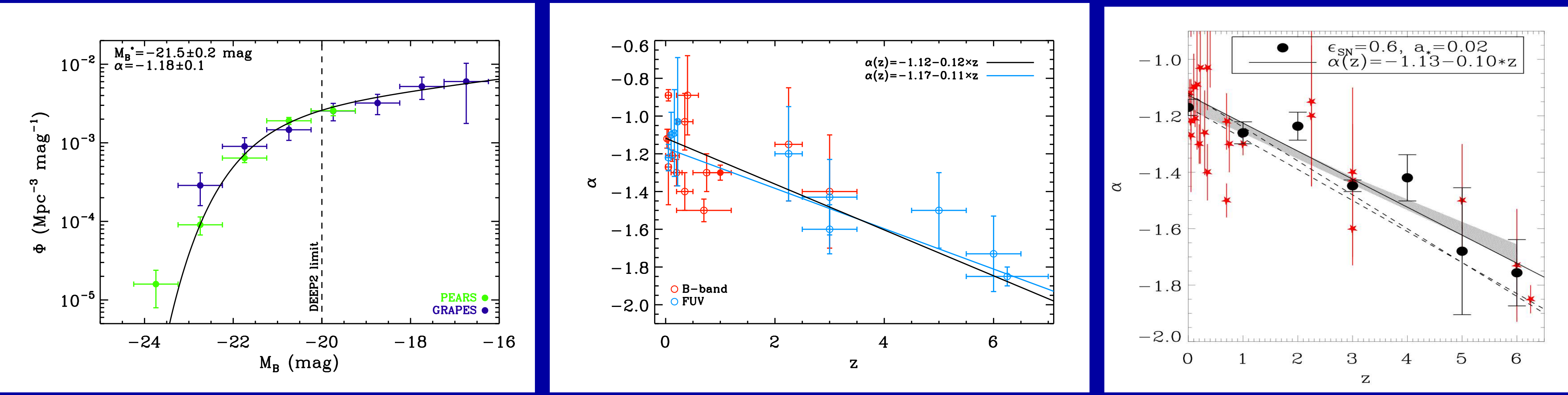
Total Ell/S0 Sabc Irr/Mergers




- 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.

Driver et al. 1998, Astrophys. J. Letters, 496, L93

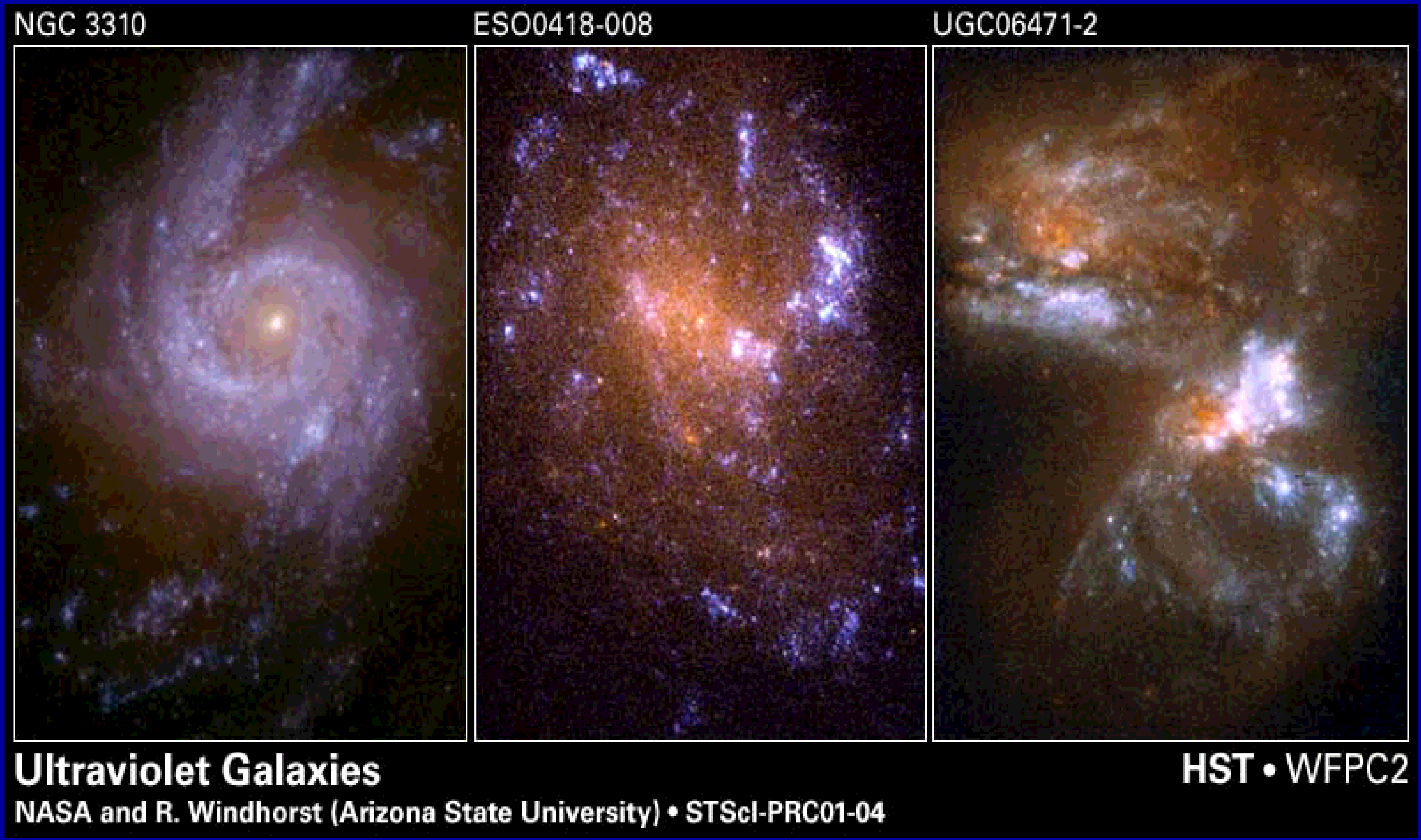
# Faint-end LF-Slope Evolution (fundamental, like local IMF)




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.

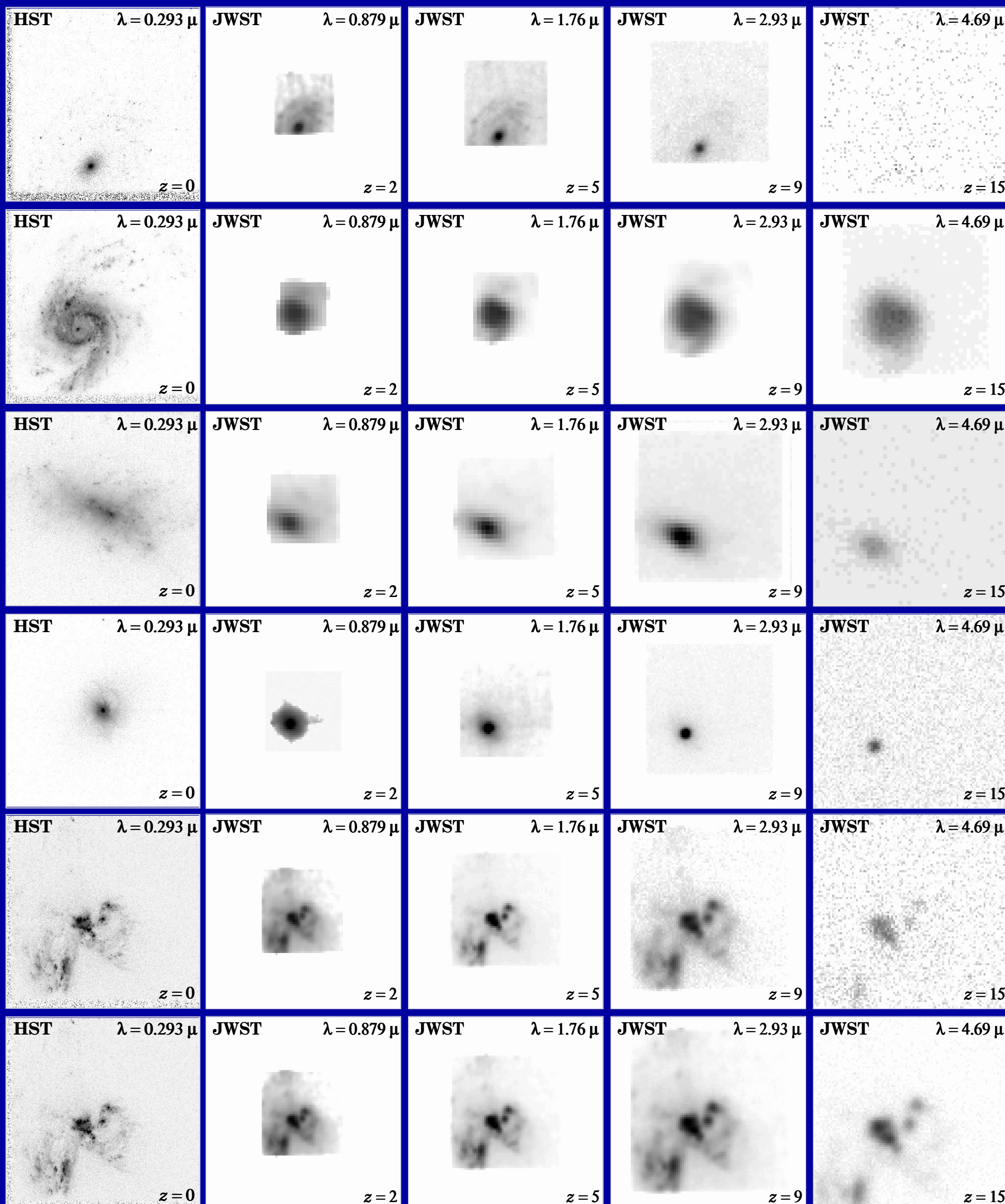
# (5) Predicted Galaxy Appearance for JWST at z≃1–15




- 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≃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) late 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.

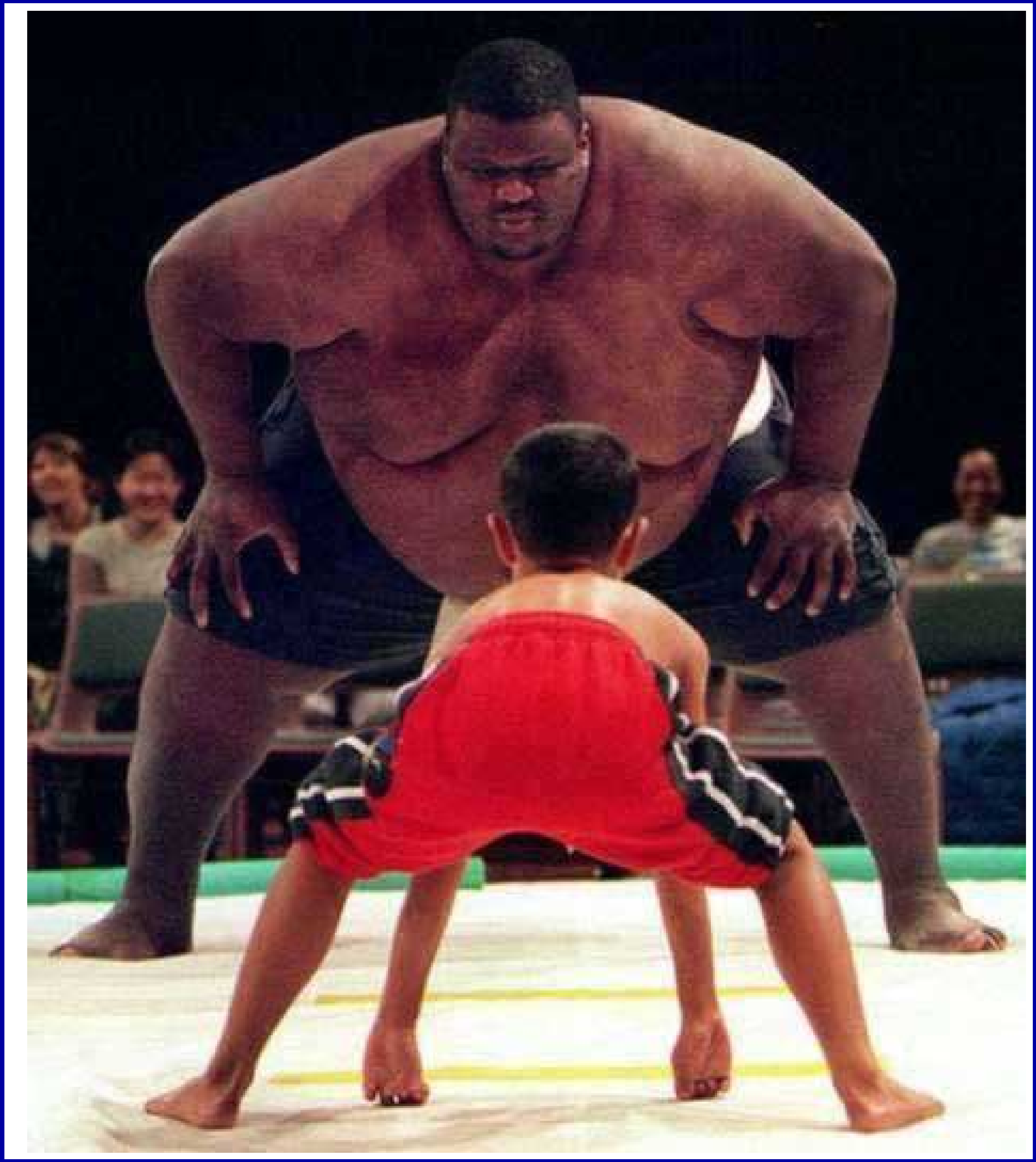
- The origin of the Hubble sequence in hierarchical formation scenarios.

(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



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


What comes around, goes around ...

- References and other sources of material shown:


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

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/

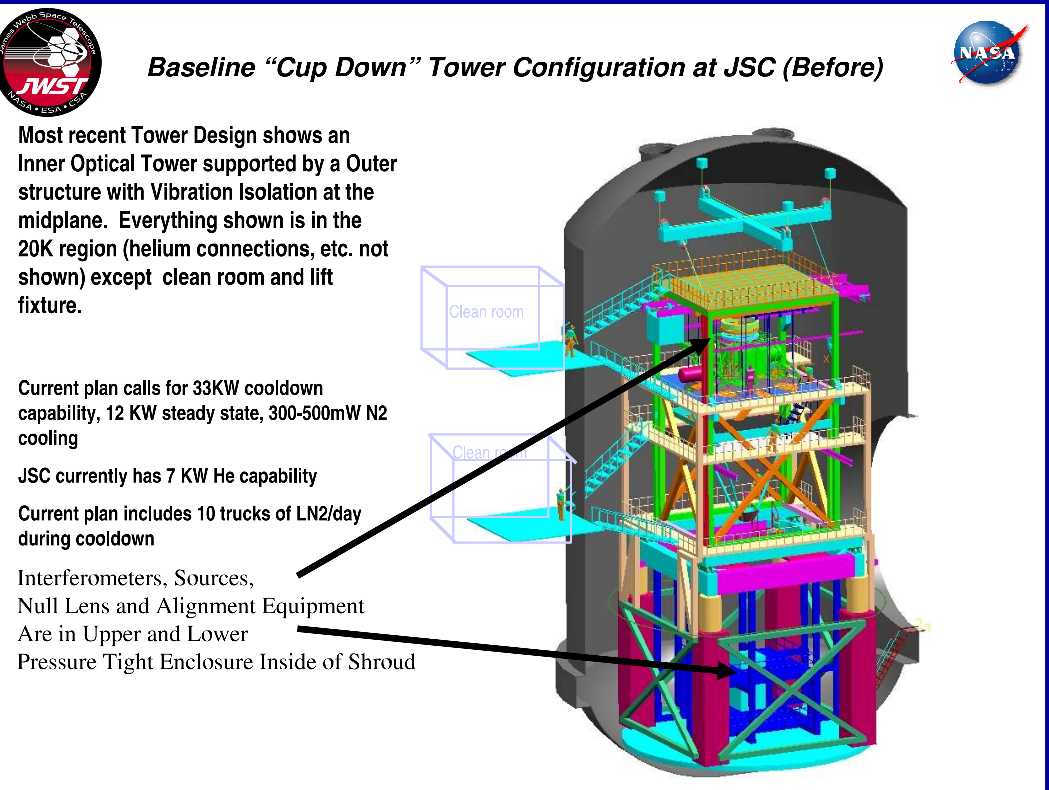
Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly,S. J., Long, K. S., Lunine, J. I., McCaughrean, M. J., Mountain, M., Nella, J., Rieke, G. H., Rieke, M. J., Rix, H.-W., Smith, E. P., Sonneborn, G., Stiavelli, M., Stockman, H. S., Windhorst, R. A., & Wright, G. S. 2006, Space Science Reviews, 123, 485–606 (astro-ph/0606175)

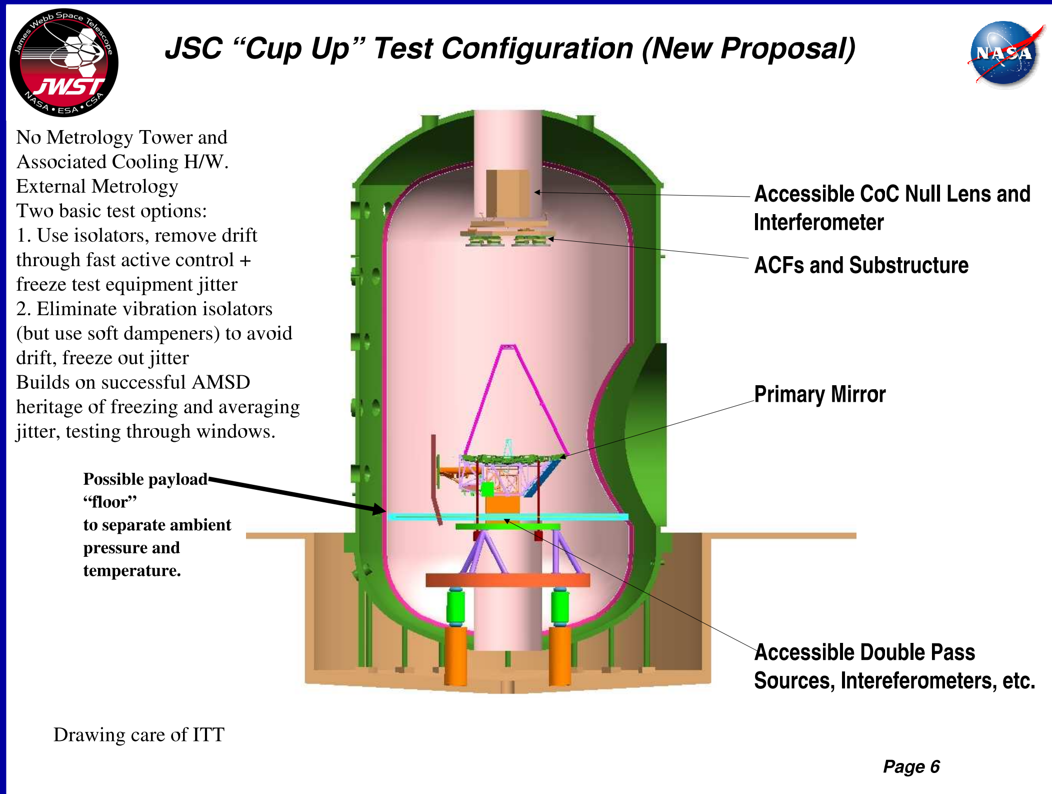
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

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

# 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

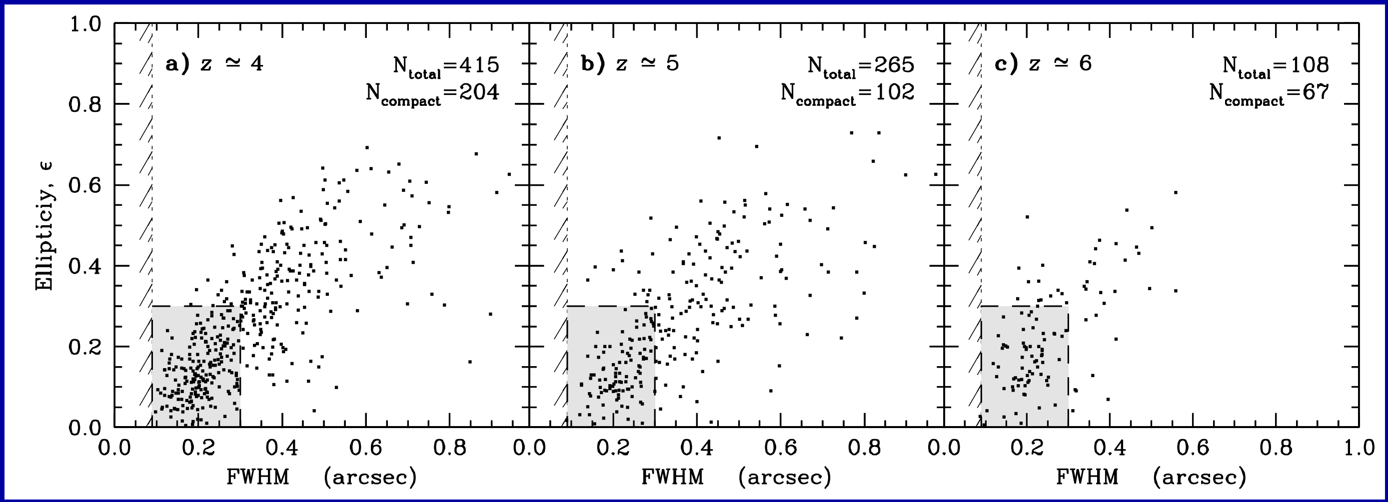


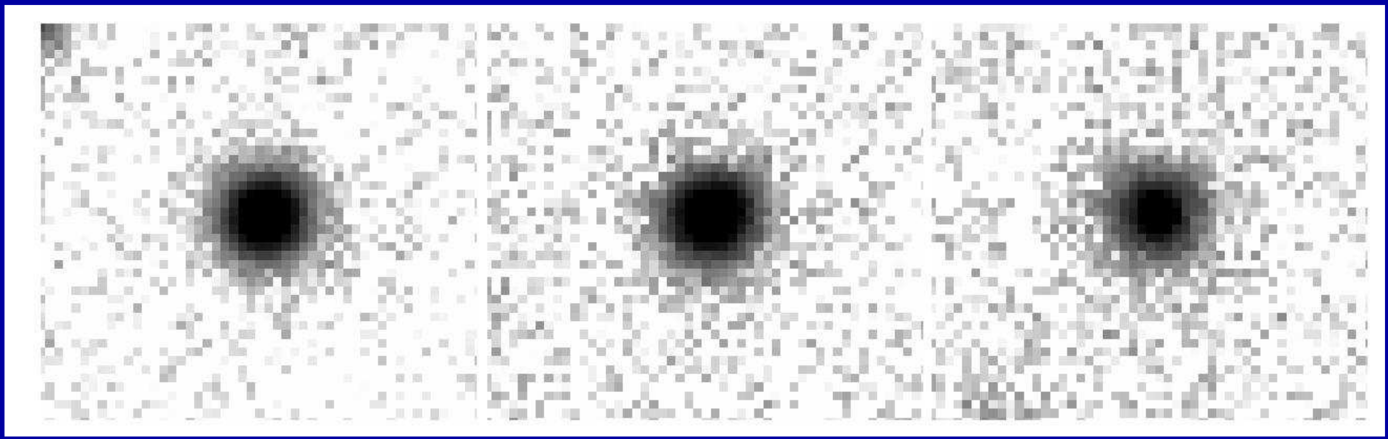




JWST underwent several significant replans and risk-reduction schemes:

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

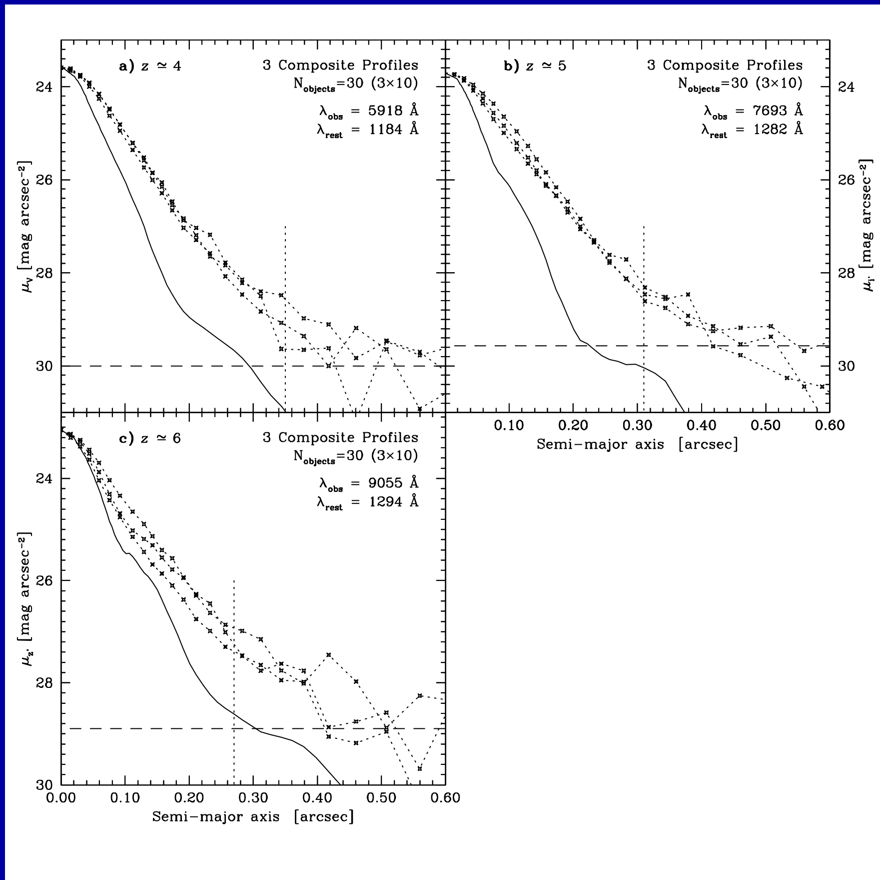
# Dynamical ages of Dwarf Galaxies at z≃4–6?

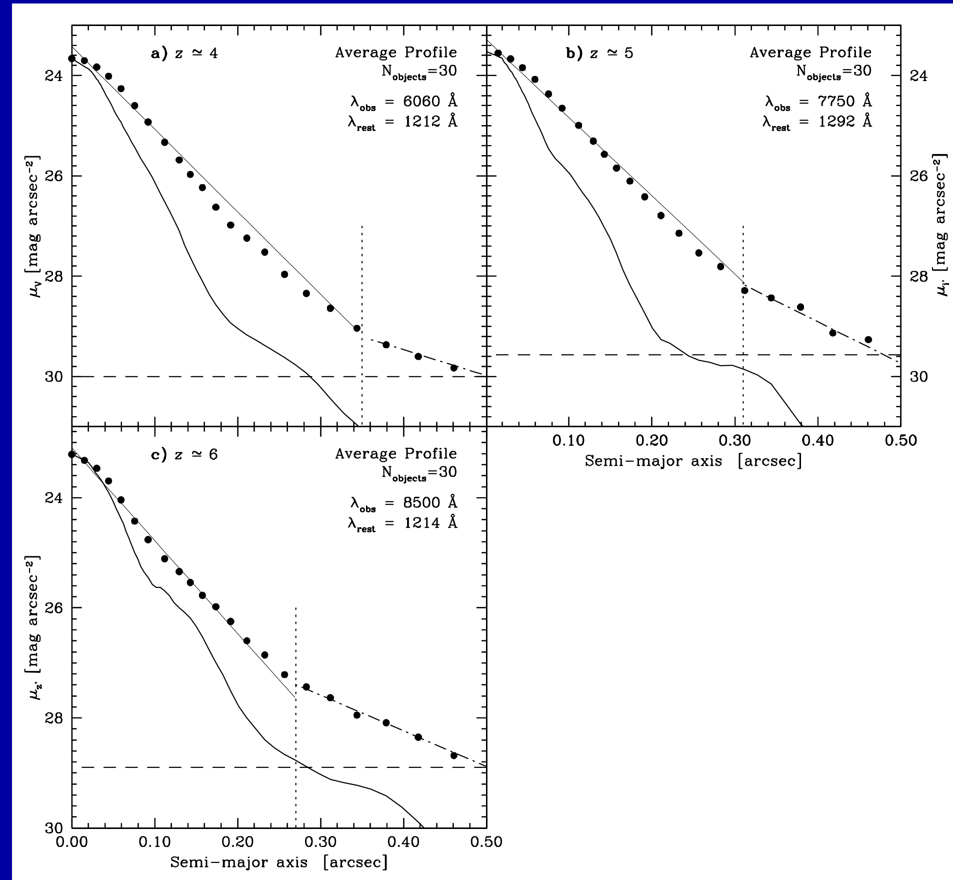


- Select all isolated, nearly unresolved ($2r_e \lesssim 0''.3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6.
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼5000 HST orbits (≃300 JWST hrs; Hathi ea. 2008 AJ).

# Dynamical ages of Dwarf Galaxies at z≃4–6?



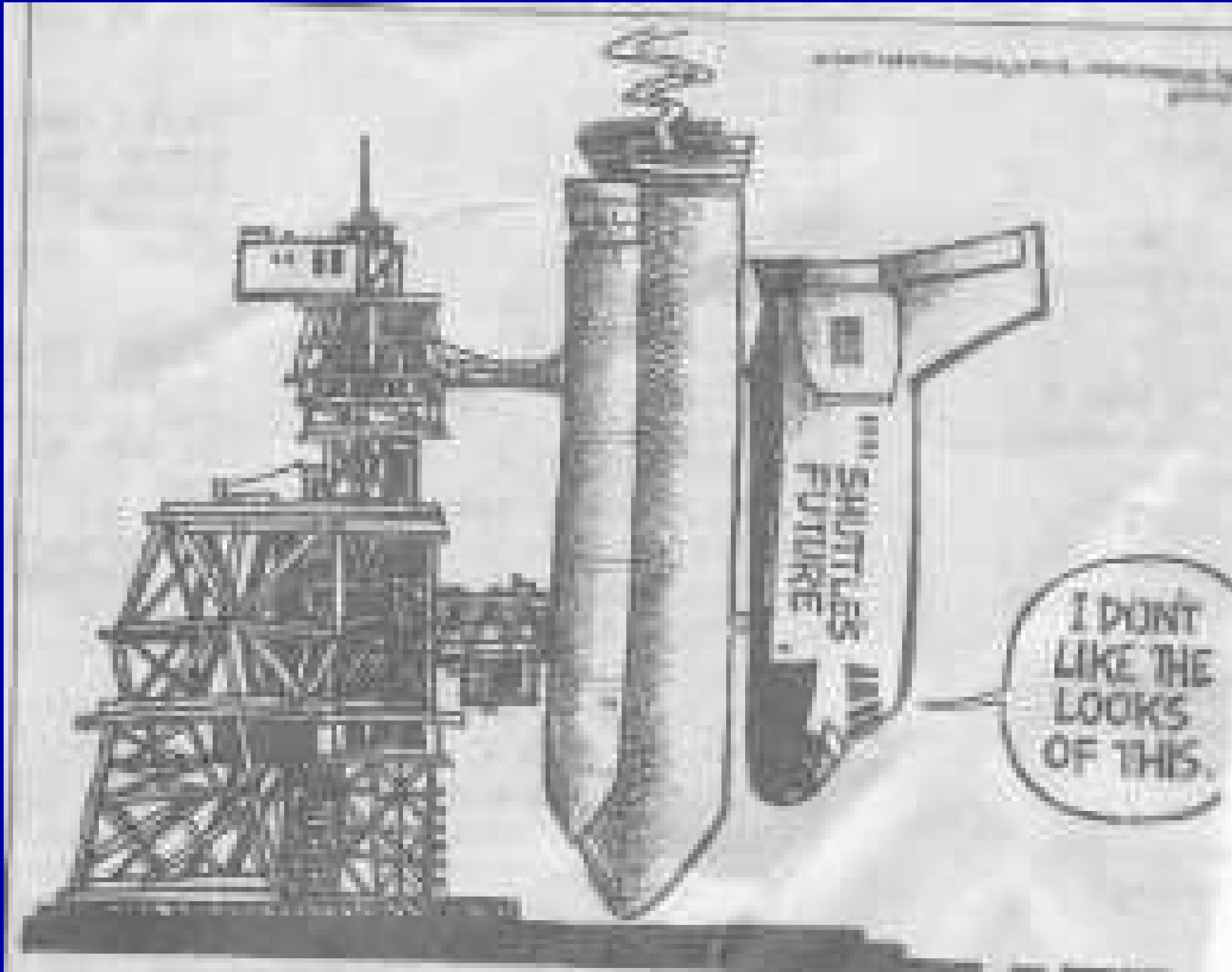




- HUDF sky-subtraction error is 2–3.$10^{-3}$ or AB≃29.0–30.0 mag/arcsec$^2$
- Average 5000-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r≳0″.27–0″.35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of $\tau_{dyn}$≃0.1-0.2 Gyr at z≃6–4 for the enclosed masses.

⇔ Comparable to their SED ages (Hathi et al.2007, AJ; astro-ph/0710.0007).

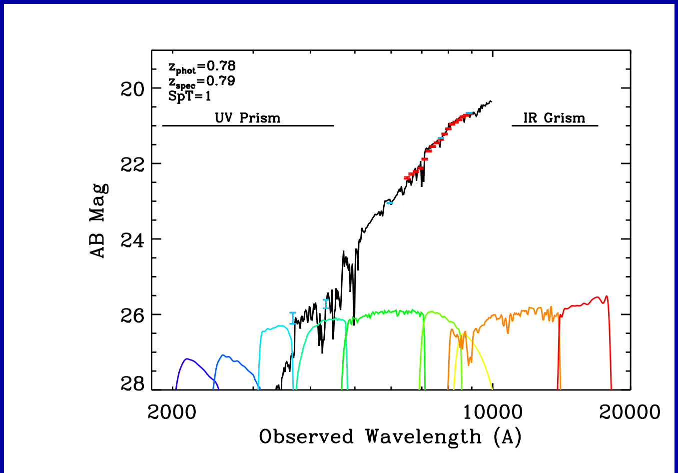
⇒ Global starburst that finished reionization at z≃6 started at z≃6.6?

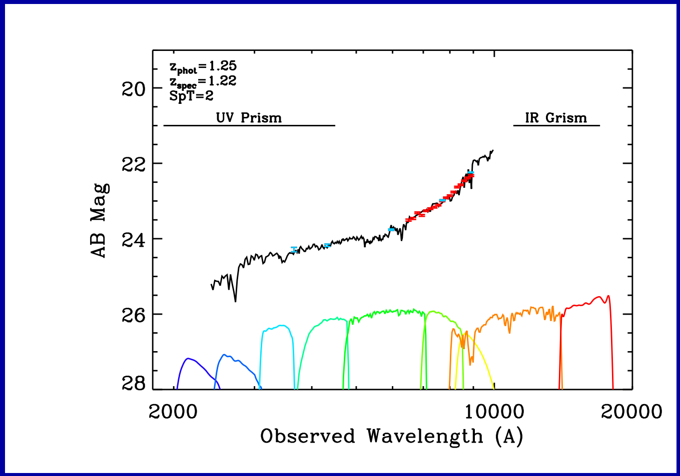
# Appendix 1: Complementary studies with the Hubble Wide Field Camera 3

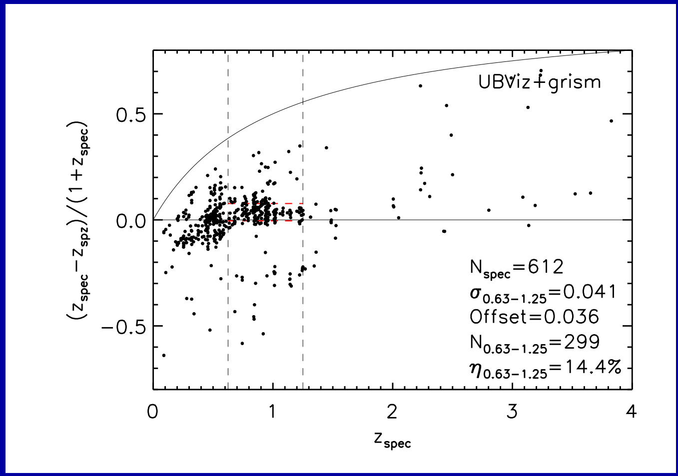



If there are no further Shuttle issues, WFC3 will get launched in Aug. 2008 ...

# 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):

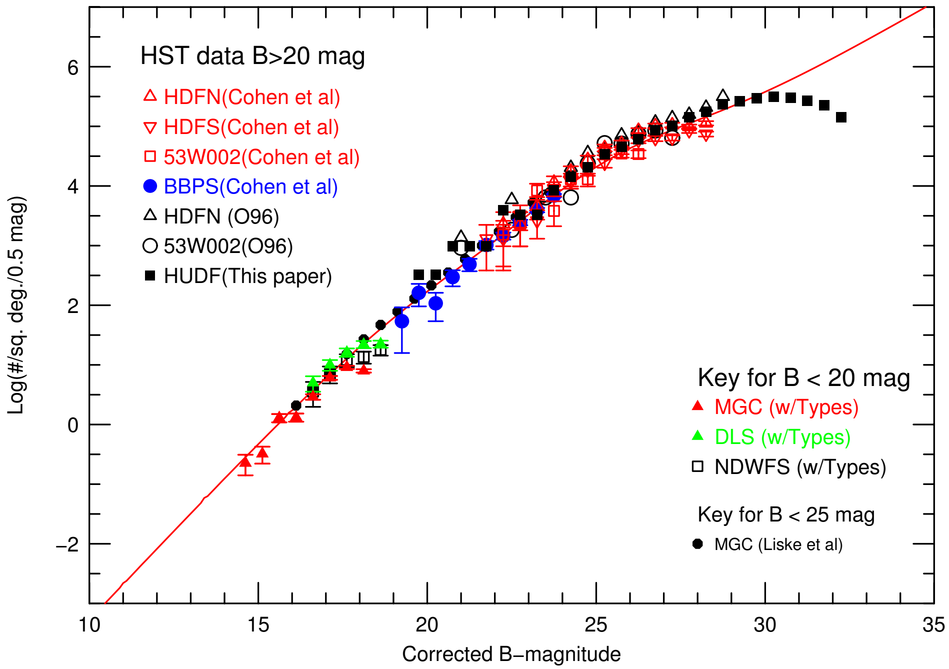
- (a) Spectro-photo-z's from HST grism + BViz(JH) considerably more accurate than photo-z's alone, with much smaller catastrophic failure %.

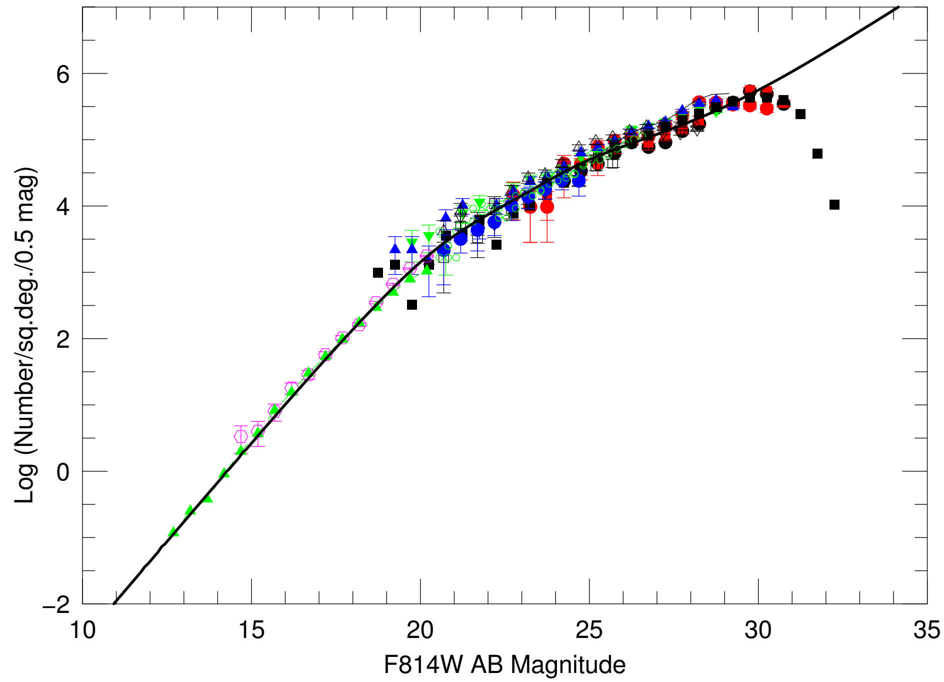
- (b) Redshifts for $\gtrsim$13,000 objects to AB$\gtrsim$27.0–27.5 mag; $\sigma_z/(1+z) \lesssim 0.04$.

- (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.

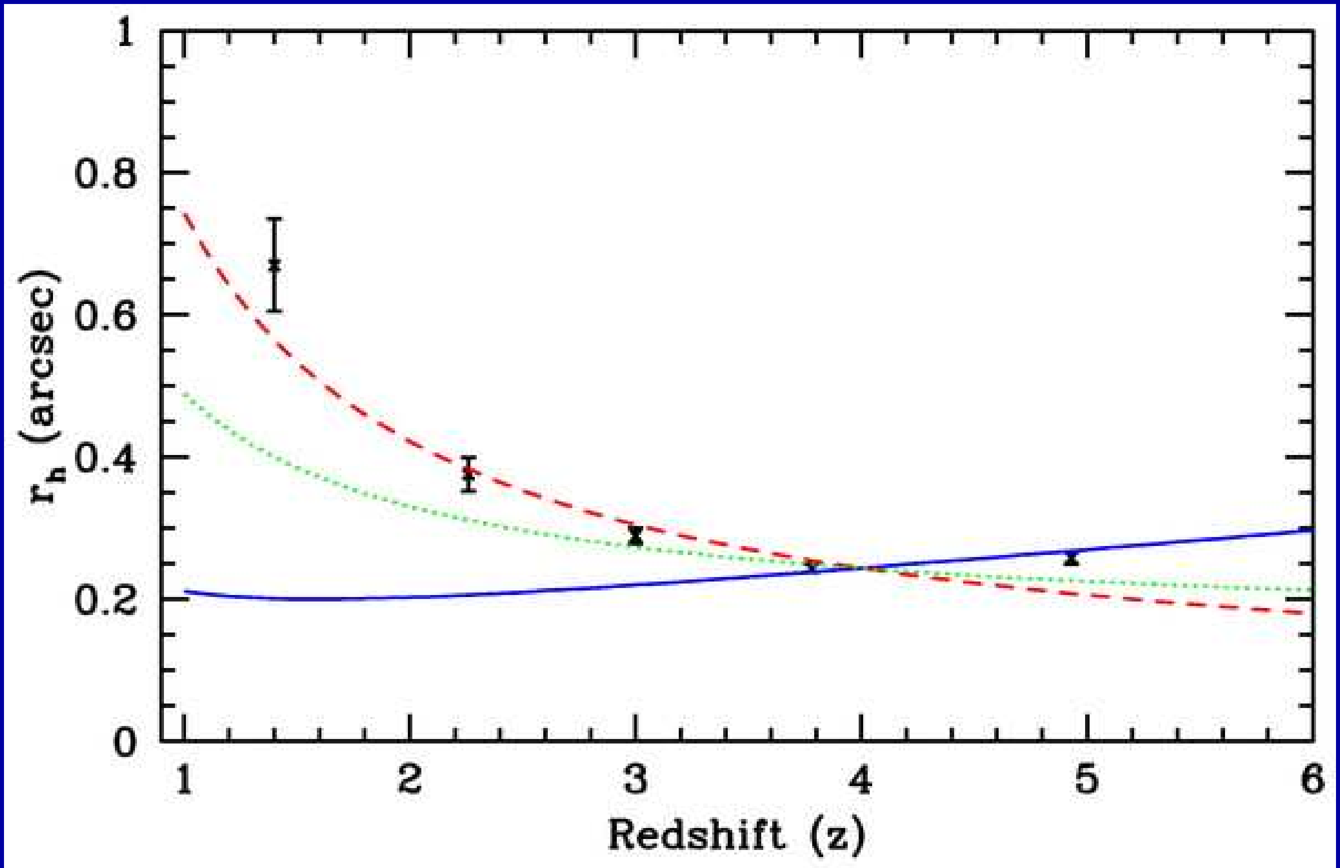
- WFC3 will provide full panchromatic sampling of faint galaxy spectra from 0.2–1.7 $\mu$m, permitting high accuracy photo-z's for faint galaxies of all types to AB$\simeq$27.0–29.0 mag (10$\sigma$ for $\sim$2–80 orbits/filter).

# Appendix 2: will JWST (& SKA) reach the Natural Confusion Limit?



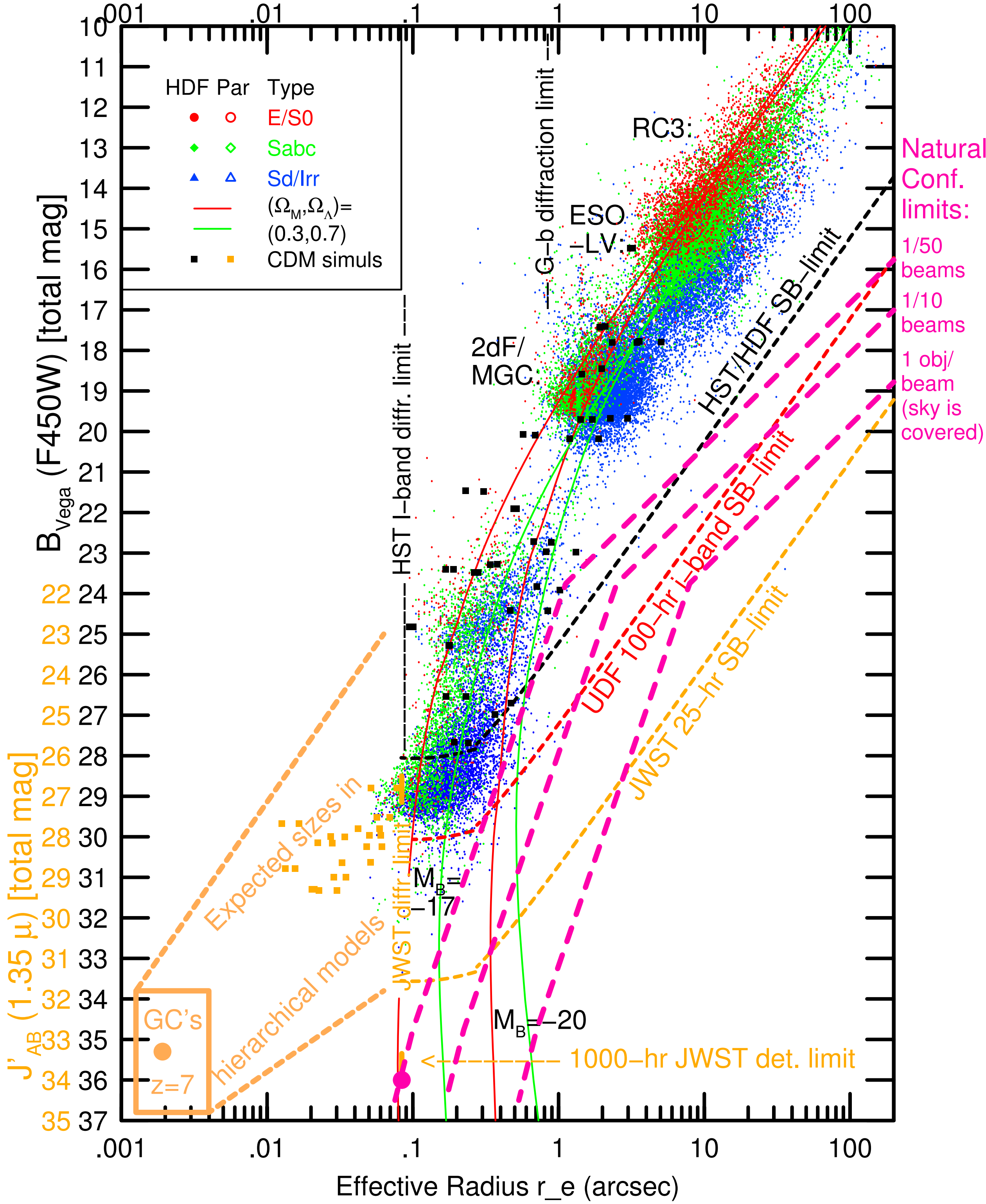




- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times 10^6$ galaxies/deg$^2$ to AB=31.5 mag ($\simeq$ 1 nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq$1 and 10 nJy, resp.
- $\Rightarrow$ Must carry out JWST and SKA nJy-surveys with sufficient spatial resolution to avoid object confusion (from HST: this means FWHM$\lesssim$0.″08).
- $\Rightarrow$ Observe with JWST/NIRSpec/MSA and SKA HI line channels, to disentangle overlapping continuum sources in redshifts space.




HST GOODS measured galaxy size evolution (Ferguson et al. 2004 ApJL):

- Median galaxy sizes decline steadily at higher redshifts, despite the cosmological $\Theta$–z relation that minimizes at z$\simeq$1.6 for $\Lambda$-cosmology.
- Evidence of intrinsic size evolution: $r_{hl}(z) \propto r_{hl}(0) \,.\, (1+z)^{-s}$, $s \simeq 1$.
- Caused by hierarchical formation of galaxies, leading to intrinsically smaller galaxies at higher redshifts, where fewer mergers have occurred.
- JWST & SKA must anticipate the small $\lesssim$0$''\!\!.$15 sizes of faint galaxies.


HDF Par Type
E/S0
Sabc
Sd/Irr
$(\Omega_M,\Omega_\Lambda)$=
(0.3,0.7)
CDM simuls
RC3:
ESO
–LV:
2dF/
MGC:
G–b diffraction limit
HST I–band diffr. limit
HST/HDF SB–limit
UDF 100–hr i–band SB–limit
JWST 25–hr SB–limit
JWST diffr. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)
Expected sizes in
hierarchical models
GC's
z=7
$M_B$=
–17
$M_B$=–20
1000–hr JWST det. limit
$B_{Vega}$ (F450W) [total mag]
$J'_{AB}$ (1.35 μ) [total mag]
Effective Radius r_e (arcsec)

Combination of ground-based and space-based HST surveys show:

- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:

- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$-dimming), but also due to:

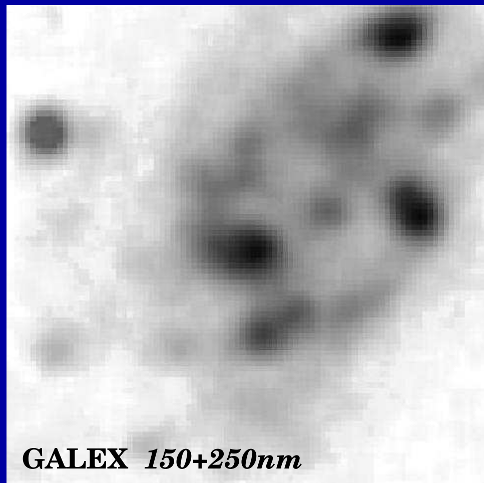
- (2a) hierarchical formation causes size evolution: $r_{hl}(z) \propto r_{hl}(0)\,(1+z)^{-1}$

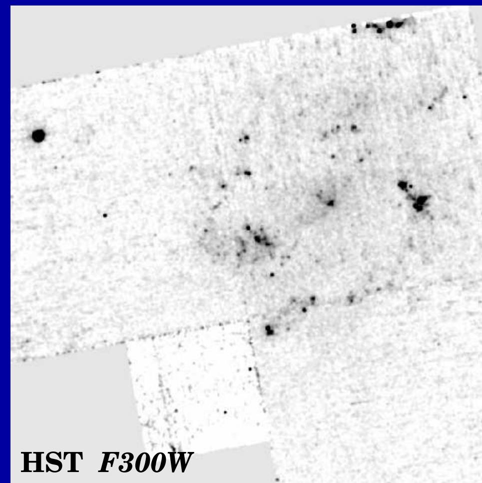
- (2b) increasing inability of object detection algorithms to deblend galaxies at faint mags ("natural" confusion $\neq$ "instrumental" confusion).

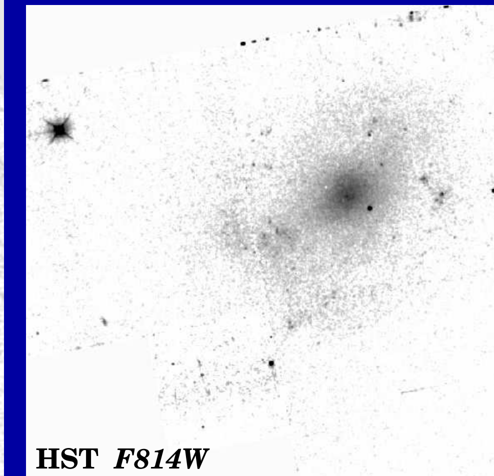
- (3) At AB$\gtrsim$30 mag, JWST and at $\gtrsim$10 nJy, SKA will see more than $2\times10^6$ galaxies/deg$^2$. Most of these will be unresolved ($r_{hl} \lesssim 0''.1$ FWHM (Kawata et al. 2006). Since $z_{med}\simeq 1.5$, this influences the balance of how $(1+z)^4$-dimming & object overlap affects the catalog completeness.

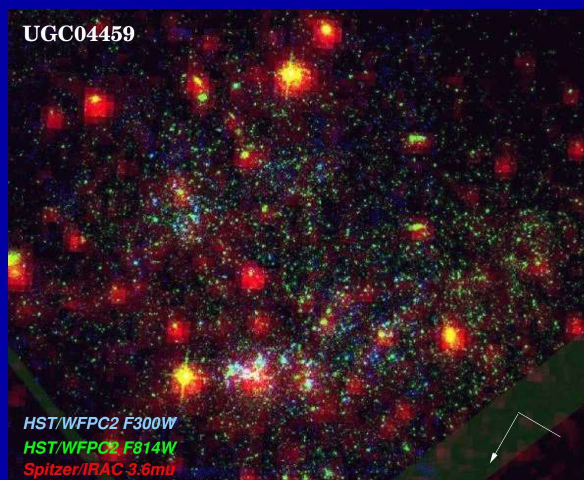
- For details, see Windhorst, R. A., et al. 2007, Advances in Space Research, Vol. 42, p. 1–10, in press (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

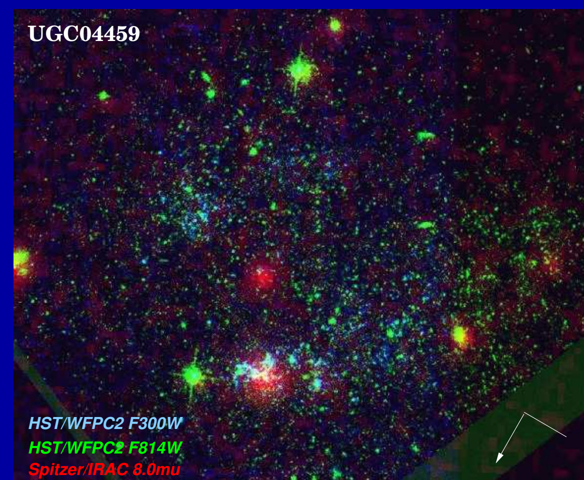
# App. 3: The Lyman continuum escape fraction $f_{esc}(z)$ of dwarf galaxies



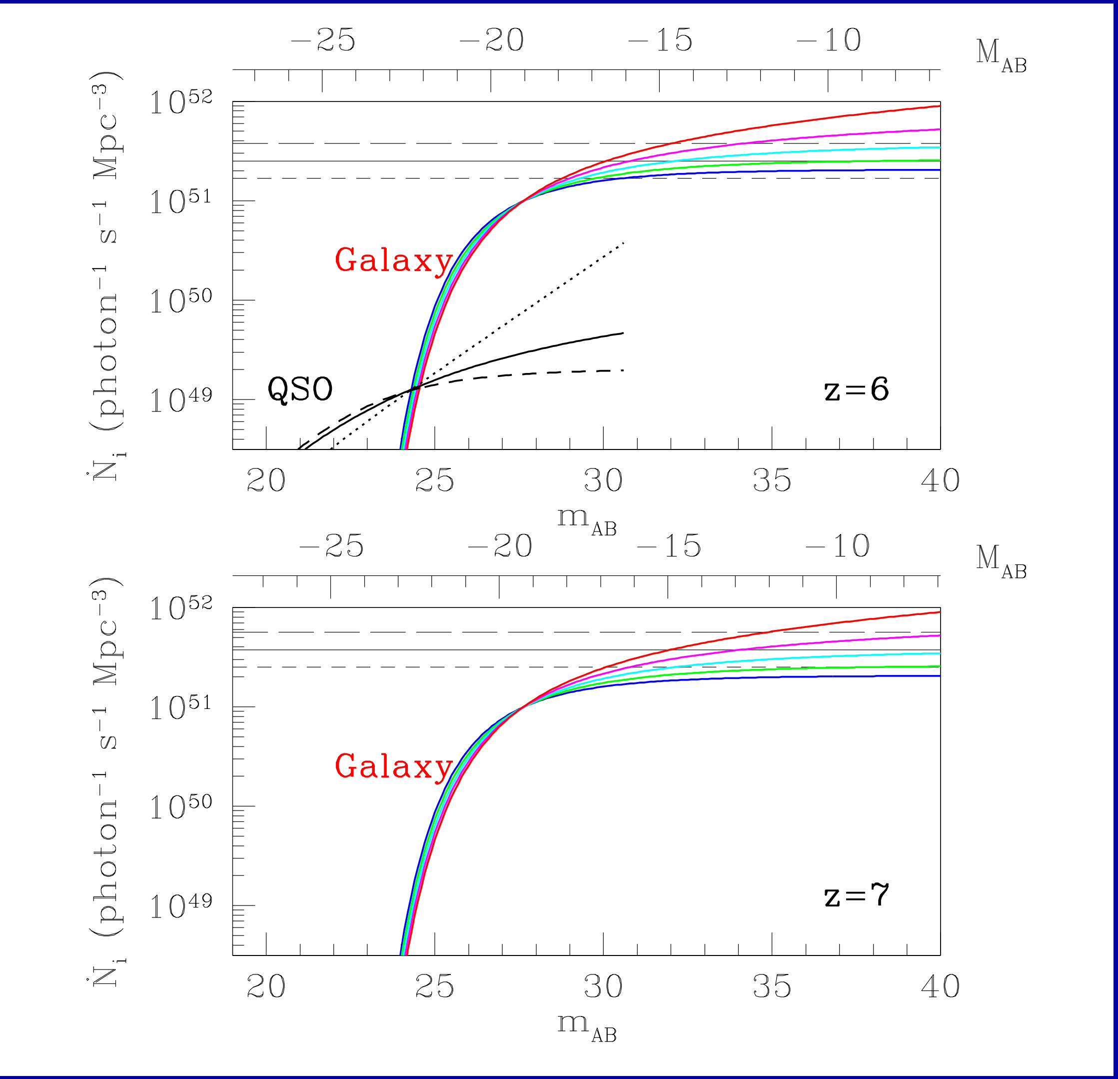




- GALEX, HST/UV and Spitzer IRAC images of nearby late-type dwarf galaxies suggests enough (SN-driven?) holes between their dust that UV-photons can escape: covering factors $\gtrsim$20% ($\propto f_{esc}$ ? $\leftrightarrow$ HI).
- Steidel et al. (2001): z$\simeq$3 LBG's have UV-escape fraction $f_{esc}$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

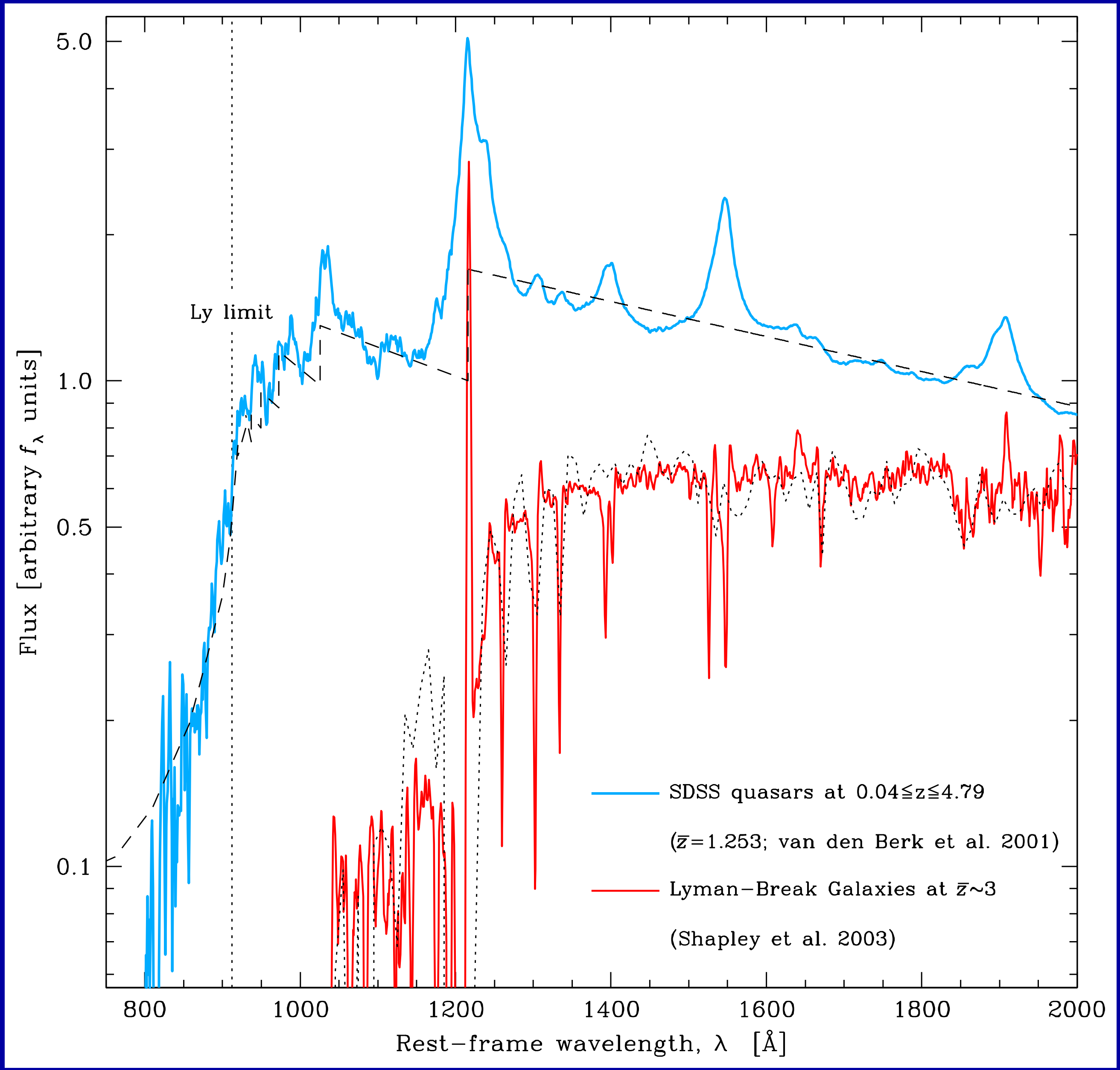



- A steep LF of z≃6 objects (Yan & Windhorst 2004a, ApJL, 600, L1) could provide enough UV-photons to complete the reionization epoch at z≃6 (if $f_{esc} \gtrsim 10\%$).

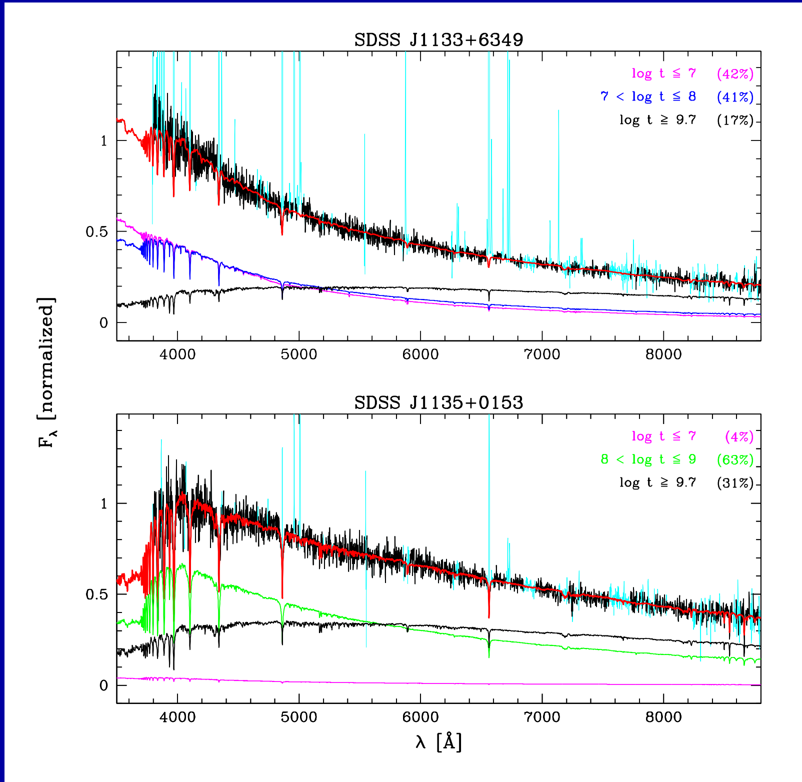
- Pop II dwarf galaxies may not have started shining *pervasively* much before z≃7–8, or no H-I would be seen in the foreground of z≳6 quasars.

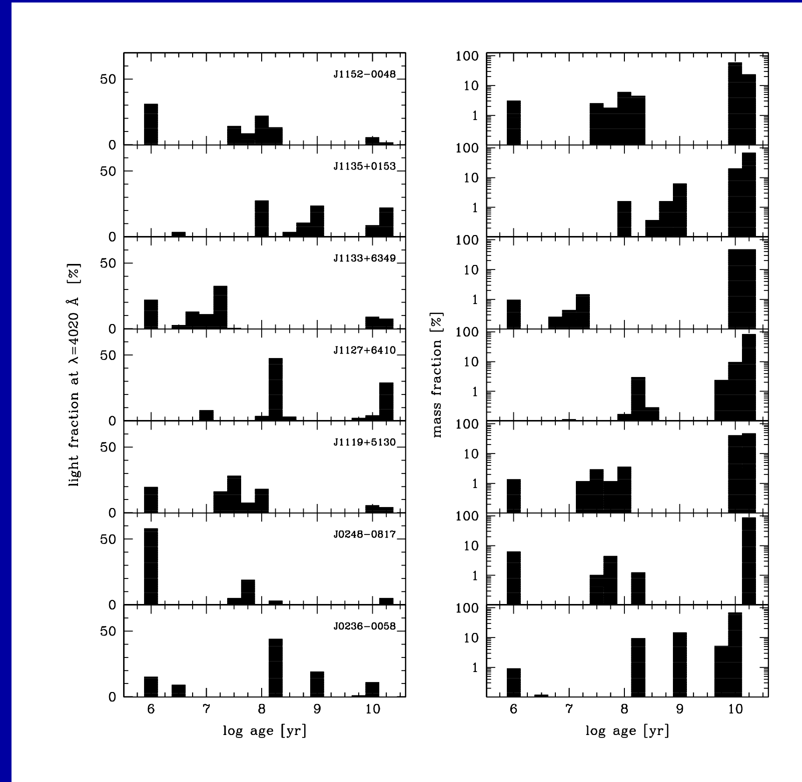
- JWST will measure this numerous population of dwarf galaxies from the end of the reionization epoch at z≃6 into the epoch of First Light (Pop III stars) at z≳10.

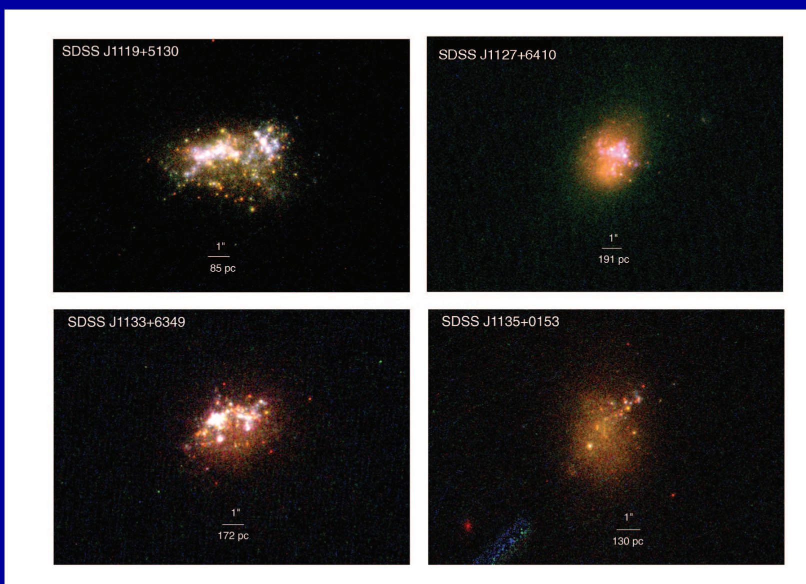
# Caveat: Can the Hard-UV of weak AGN outshine Dwarf Galaxies?




- 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.



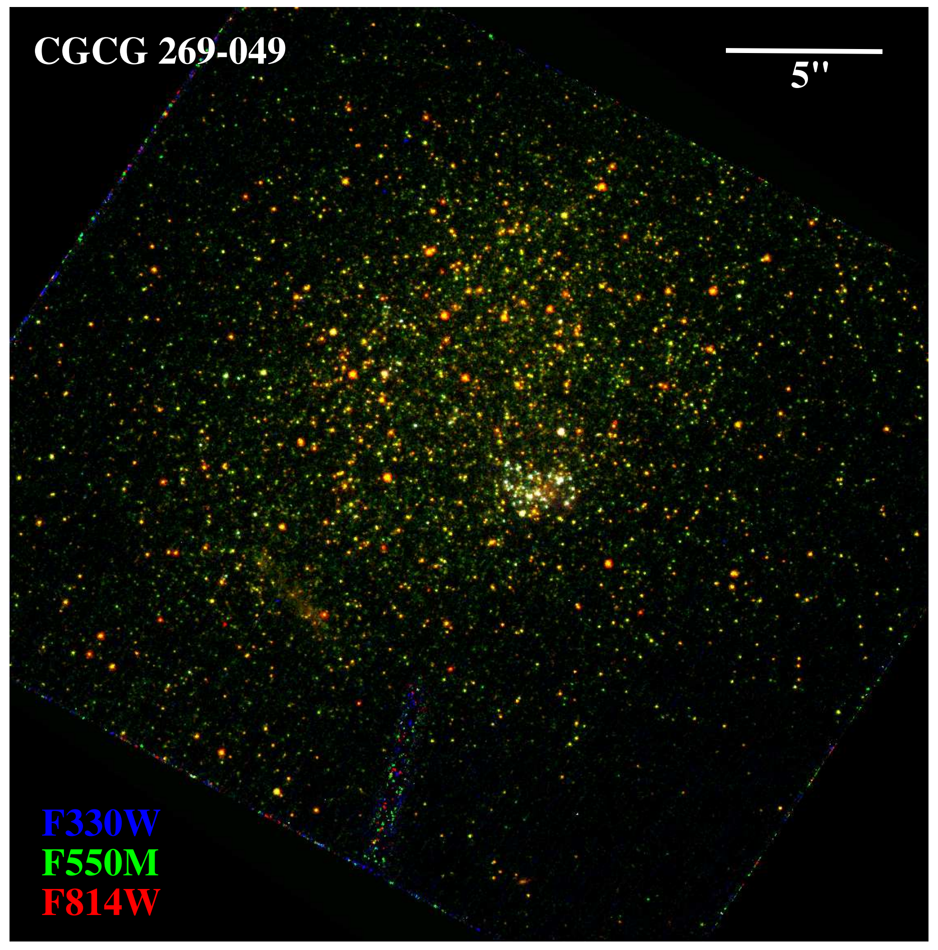

Possible local analogs for dwarf galaxies that finished reionization at z$\gtrsim$6?:

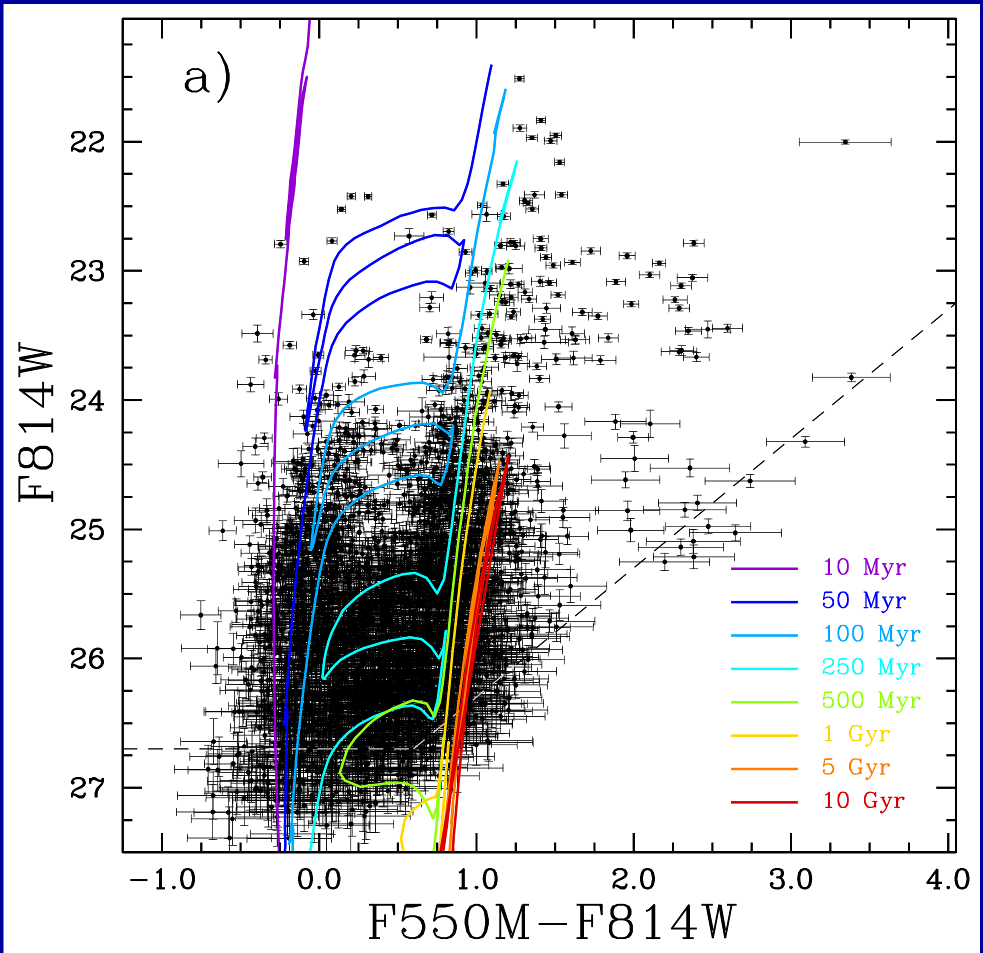
- Low metallicity Ultra-Blue Compact Dwarf galaxies in voids (Corbin et al. 2006, 2007).

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 $f_{esc}$.



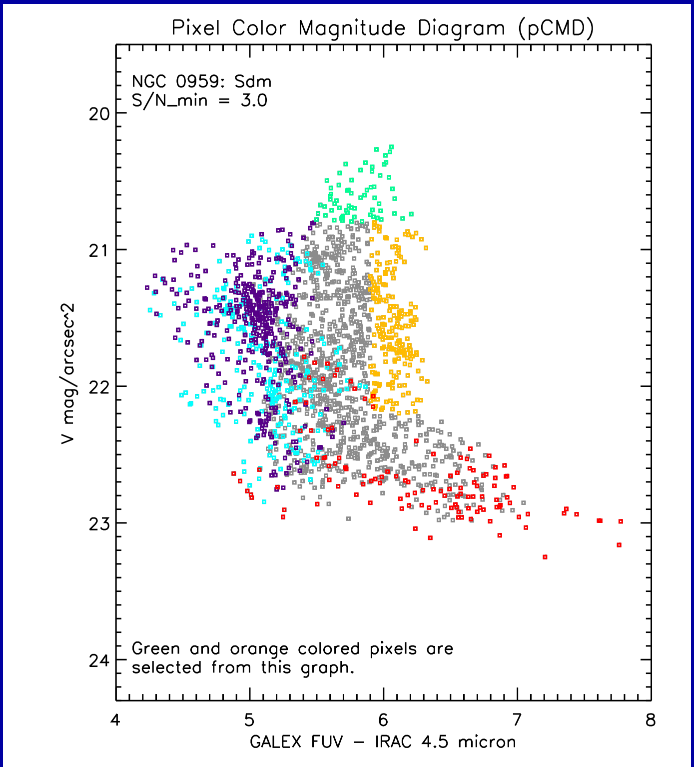



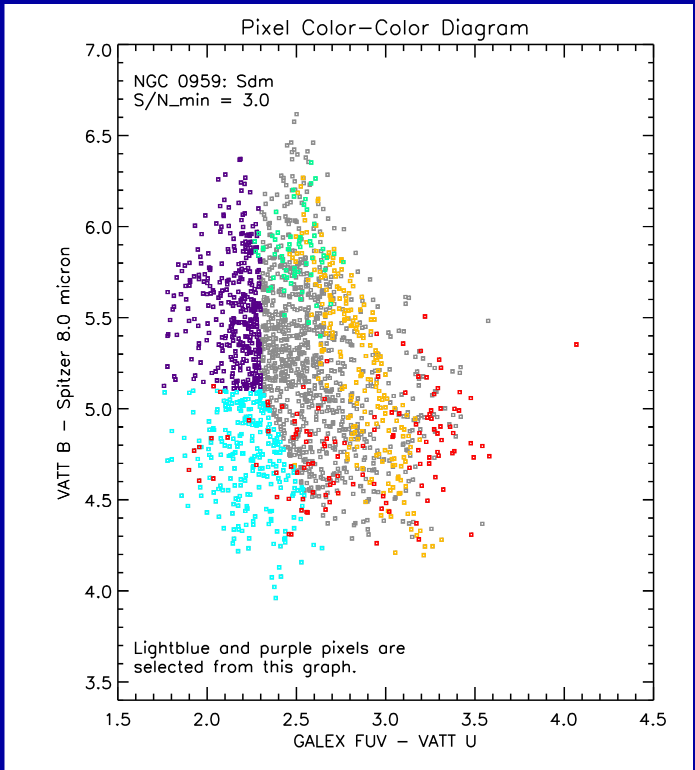

Possible local analogs for dwarf galaxies that finished reionization at $z \gtrsim 6$?:

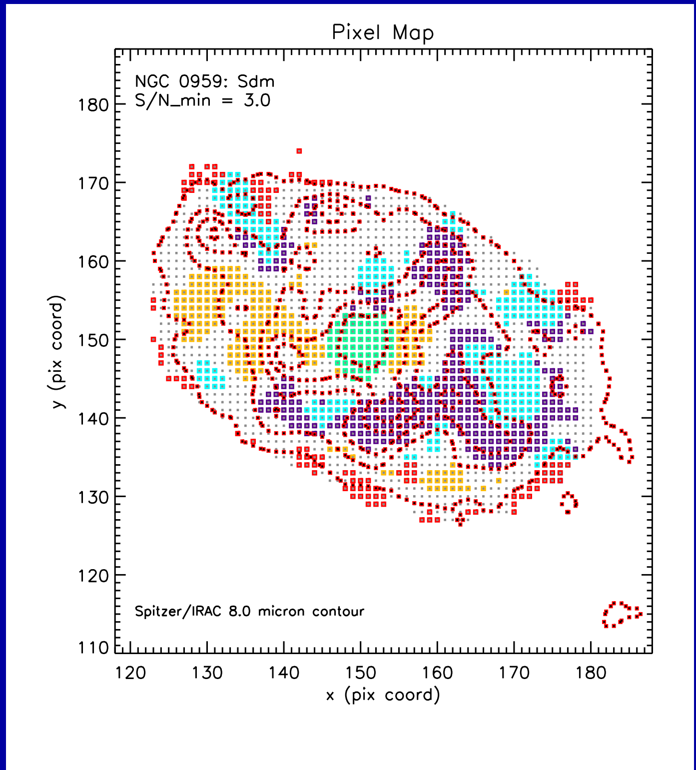
- Low metallicity Ultra-Blue Compact Dwarf galaxies in voids (Corbin et al. 2006, 2007).

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).

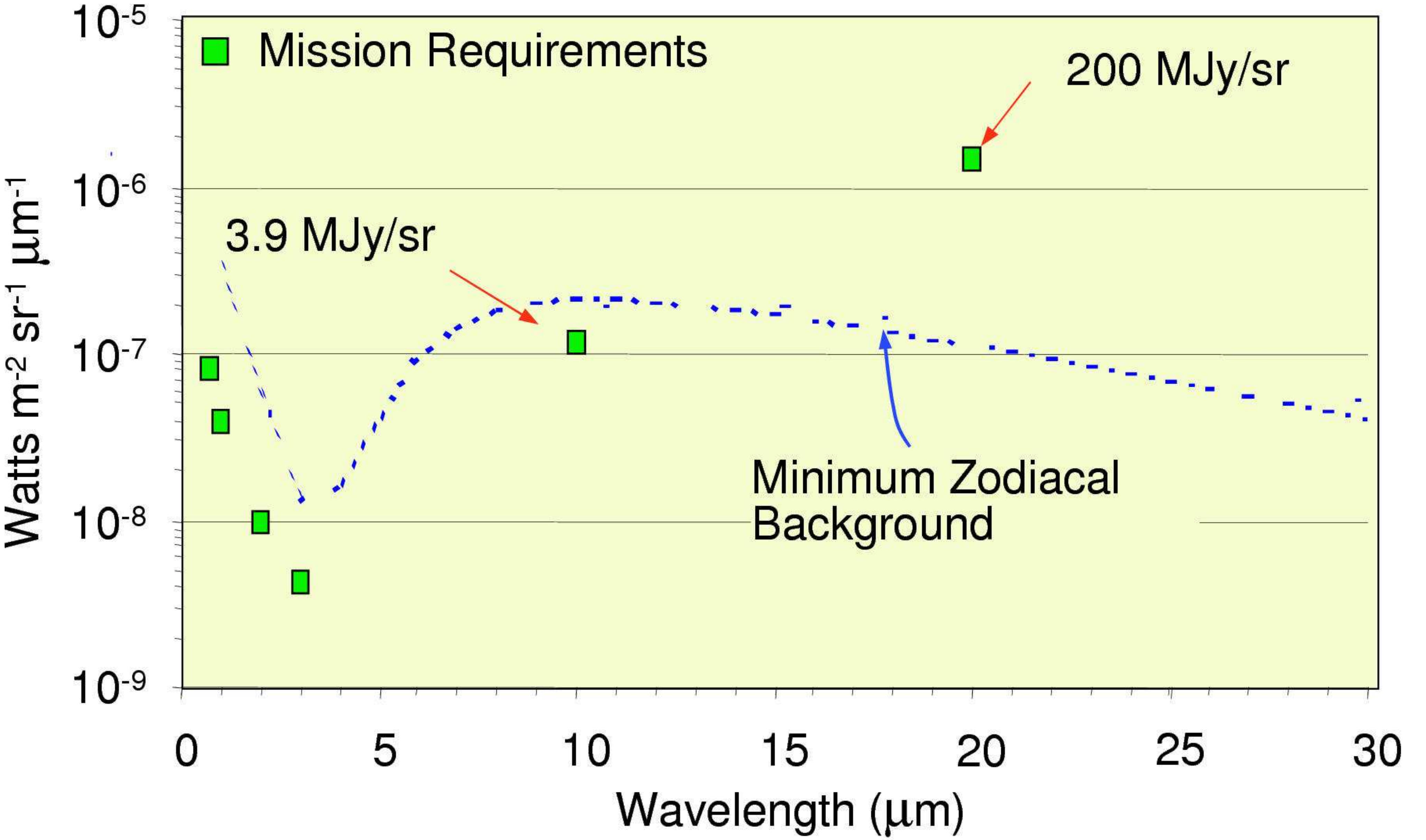
- Combination of GALEX FUV+NUV, HST-mid-UV, ground-based UBVRI, & Spitzer IRAC on local late-types/Irr's shows:

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

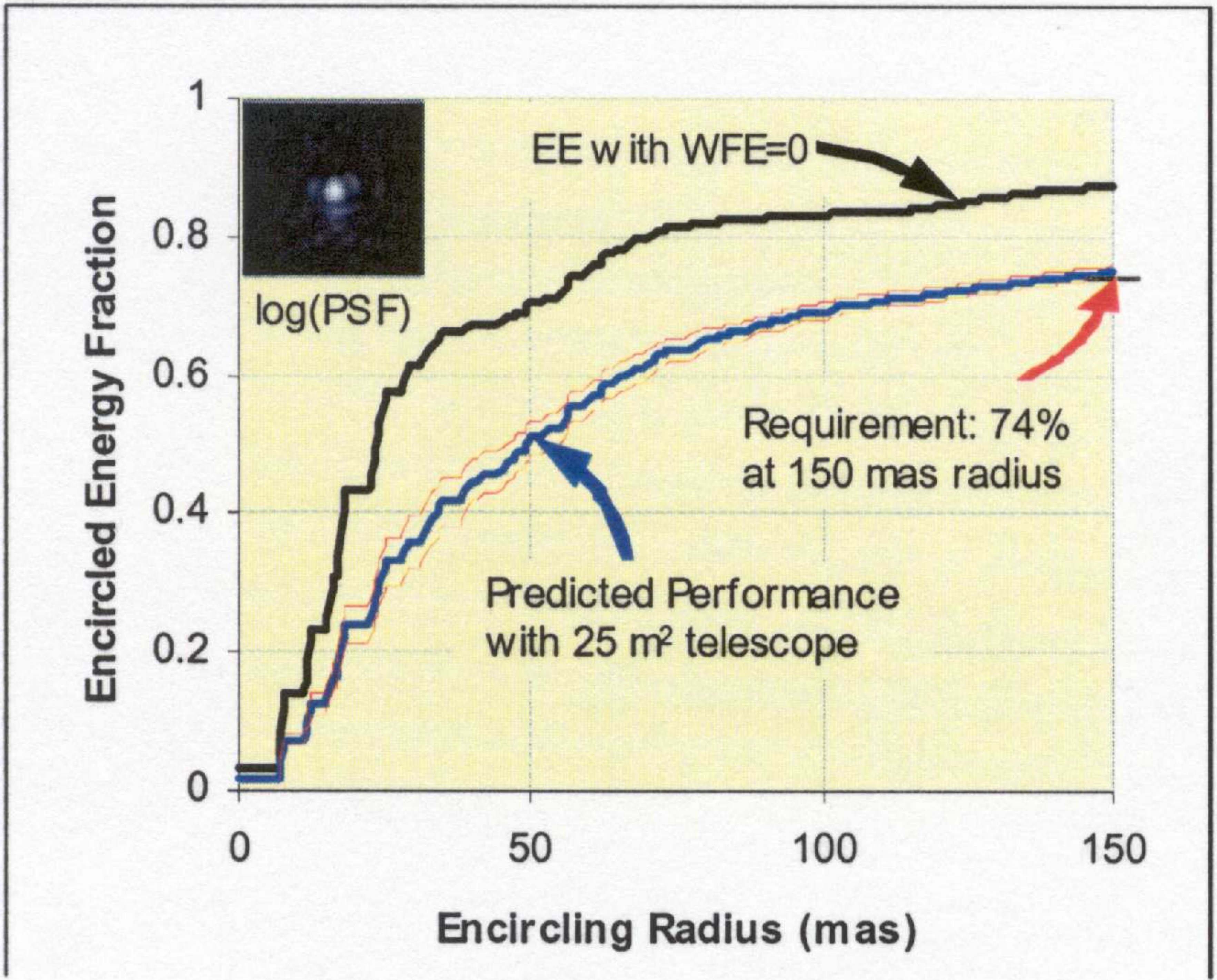
- Measure Lyman continuum escape fraction and its geometry with a dedicated FUV space mission (Lyman).

# Table 10. Predicted Performance of the JWST Observatory

| Parameter | Capability |
|---|---|
| **Wavelength** | 0.6 to 29 μm. Reflective gold coatings |
| **Sensitivity** | SNR=10, integration time = $\tau_i$, R=λ/Δ λ and Zodiacal of 1.2 times that at north ecliptic pole |
| NIRCam | 12 nJy (1.1μm, $\tau_i$=10,000s, and λ/Δ λ = 4) |
| NIRCam | 10.4 nJy (2.0μm, $\tau_i$=10,000s, and λ/Δ λ = 4) |
| TFI | 368 nJy (3.5μm, $\tau_i$=10,000s, and λ/Δ λ = 100) |
| NIRSpec | 120 nJy (3.0μm, $\tau_i$=10,000s, and λ/Δ λ = 100) |
| NIRSpec | 560 nJy (10μm, $\tau_i$=10,000s, and λ/Δ λ = 5) |
| MIRI | 5000 nJy (21μm, $\tau_i$=10,000s, and λ/Δ λ = 4.2) |
| NIRSpec Med | $5.2 \times 10^{-22}$ $Wm^{-2}$ (2 μm, $\tau_i$=100,000s, R= 1000) |
| MIRI Spec | $3.4 \times 10^{-21}$ $Wm^{-2}$ (9.2 μm, $\tau_i$=10,000s, R= 2400) |
| MIRI Spec | $3.1 \times 10^{-20}$ $Wm^{-2}$ (22.5 μm, $\tau_i$=10,000s, R= 1200) |
| **Spatial Resolution & Stability** | Encircled Energy of 75% at 1 μm for 150mas radius<br>Strehl ratio of ~ 0.86 at 2 μm.<br>PSF stability better than 1% |

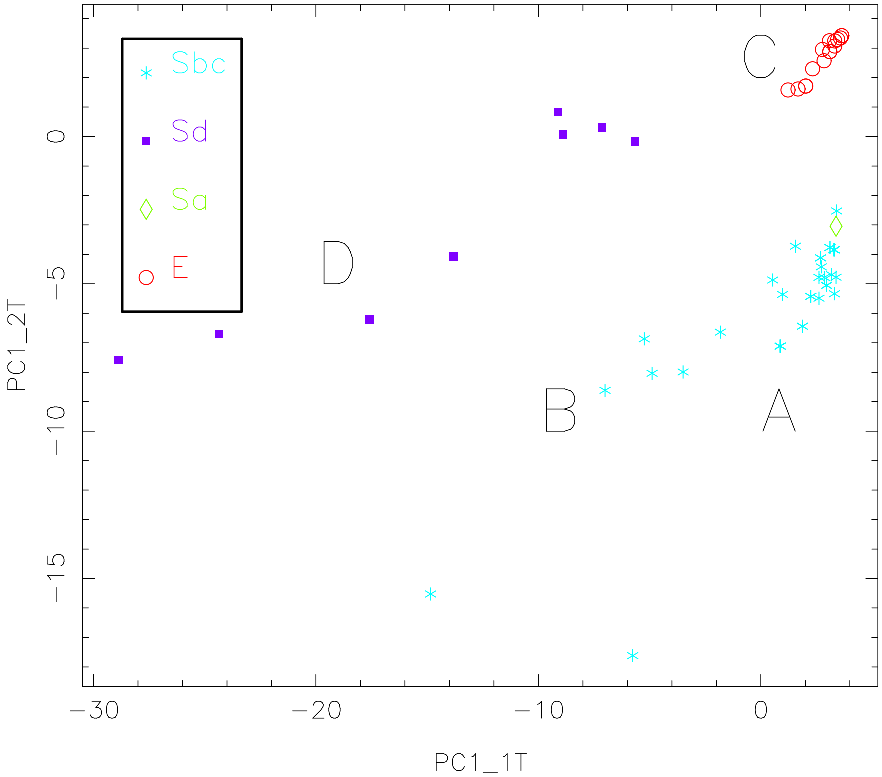


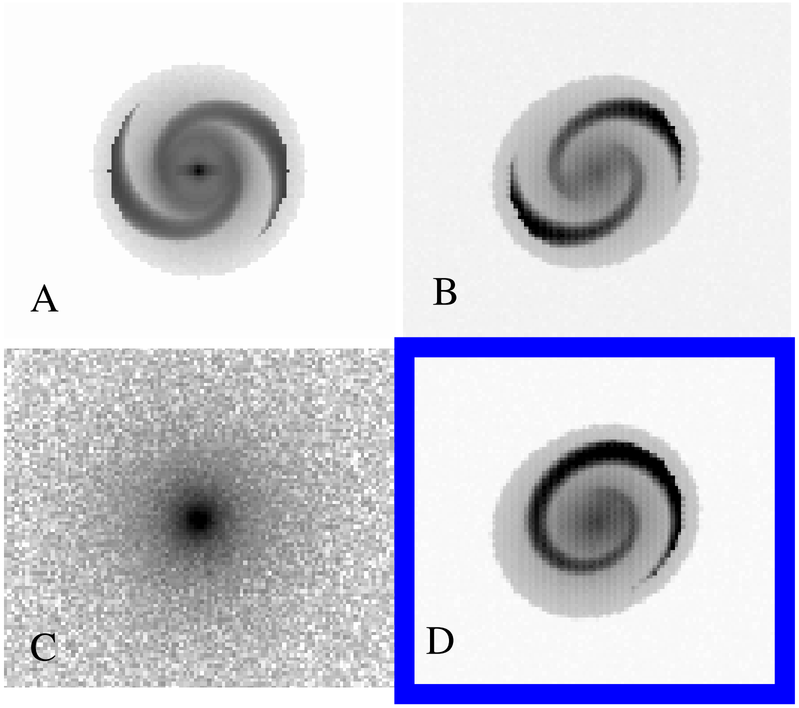

JWST L2 sky minimizes $\lambda \simeq 3\ \mu$m: $\gtrsim 10^4\times$ fainter than ground-based sky.



1
0.8
0.6
0.4
0.2
0
Encircled Energy Fraction
log(PSF)
EE w ith WFE=0
Requirement: 74%
at 150 mas radius
Predicted Performance
with 25 m² telescope
0
50
100
150
Encircling Radius (mas)

# Quantitative Morphology – We can numerically describe and identify m=1 galaxies!

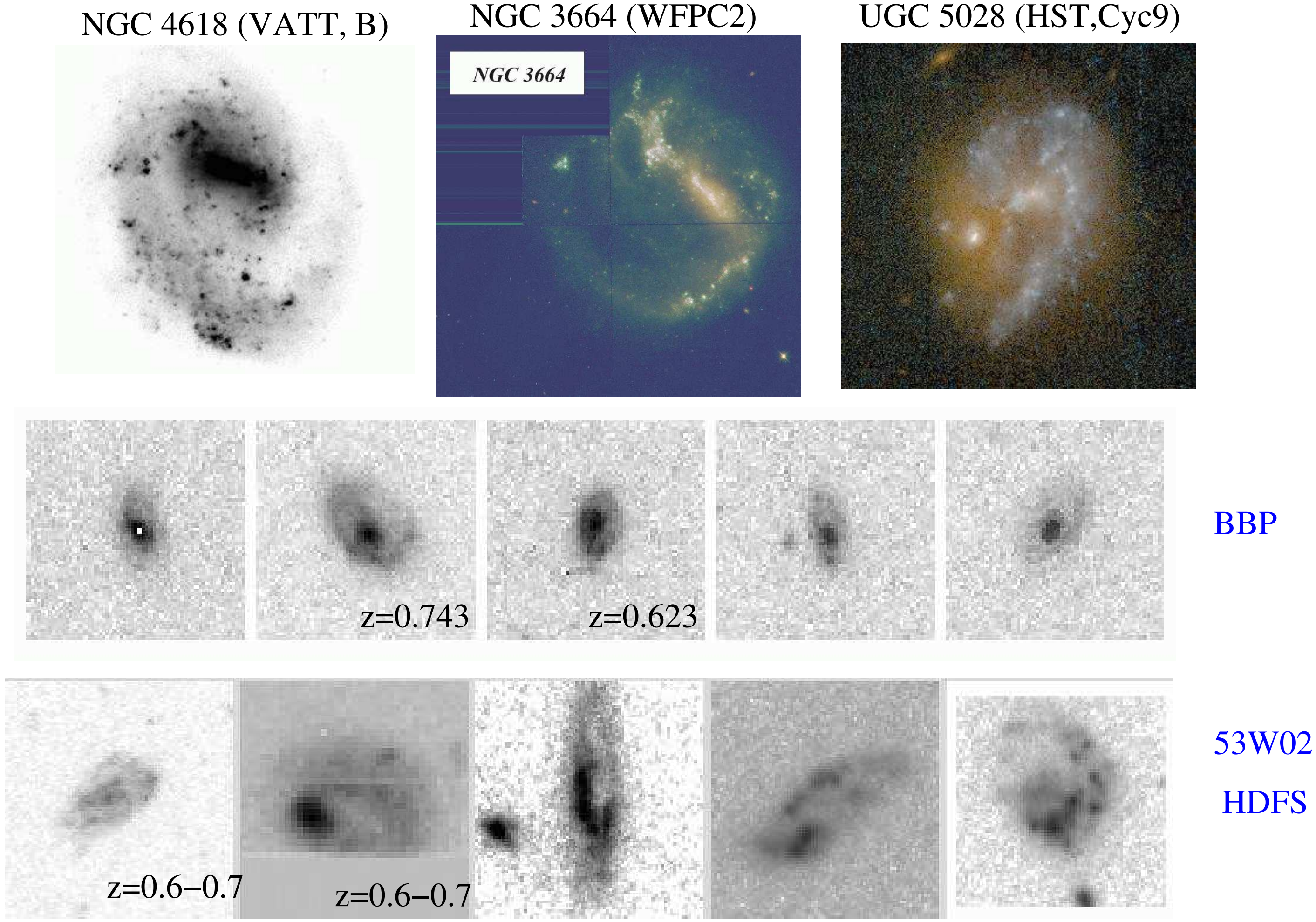



Odewahn et.al. 2002 ApJ, 568, 539

Fourier Decomposition is remarkably good in distinguishing and quantifying bars and (1-armed, 2-armed) spiral structure. JWST will be able to do this out to z=5 at least, hence enabling to quantitatively trace galaxy assembly.

# Massive Star Formation: Near and Far




Fourier Decomposition of nearby and distant galaxies in JWST images will directly trace the evolution of bars, rings, spiral arms, and other structural features. This measures the detailed history of galaxy assembly in the epoch $z\simeq 1$–$3$ when most of today's giant galaxies were made.

# SPARE CHARTS ON JWST IMAGE SIMULATIONS

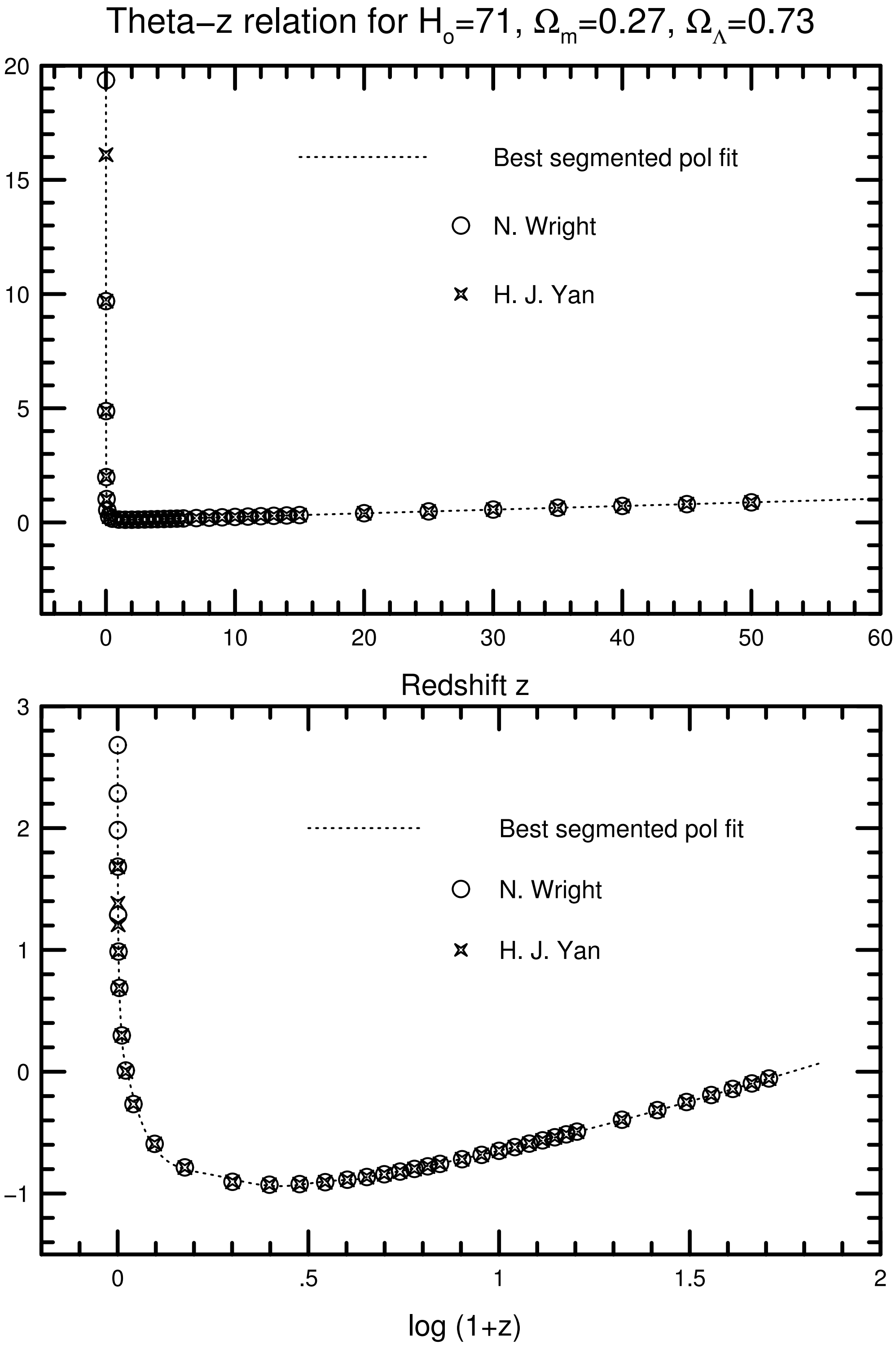
## (5) Details on JWST image simulations:

- All based on HST/WFPC2 F300W images from the HST mid-UV survey of nearby galaxies (Windhorst et al. 2002, ApJ Suppl. 143, 113).

- WMAP COSMOLOGY: $H_0$=73 km/s/Mpc, $\Omega_m$=0.24, $\Omega_\Lambda$=0.76.

- INSTRUMENT: 6.0 m effective aperture, diffraction-limited at $\lambda \gtrsim 2.0 \mu$m, JWST/NIRCam, $0\farcs034$/pix, read-noise=5.0 $e^-$, dark-current=0.02 $e^-$/s, NEP-Sky(1.6 $\mu$m)=21.7 mag/($''^2$) in L2, Zodi spectrum, $t_{exp}$=4×900s.

| Row | Telesc. | Redshift | $\lambda$ ($\mu$m) | FWHM ($''$) |
|---|---|---|---|---|
| 1 | HST | z∼0 | 0.293$\mu$m | $0\farcs04$ |
| | JWST | z=1.0 | 0.586$\mu$m | $0\farcs084$ |
| | JWST | z=2.0 | 0.879$\mu$m | $0\farcs084$ |
| 2 | JWST | z=3.0 | 1.17 $\mu$m | $0\farcs084$ |
| | JWST | z=5.0 | 1.76 $\mu$m | $0\farcs084$ |
| | JWST | z=7.0 | 2.34 $\mu$m | $0\farcs098$ |
| 3 | JWST | z=09.0 | 2.93 $\mu$m | $0\farcs122$ |
| | JWST | z=12.0 | 3.81 $\mu$m | $0\farcs160$ |
| | JWST | z=15.0 | 4.69 $\mu$m | $0\farcs197$ |




Angular size vs. redshift relation in a Lambda dominated cosmology of $H_0$ =73 $km\ s^{-1}\ Mpc^{-1}$ , $\Omega_m$=0.24, $\Omega_\Lambda$=0.76.

In the top panel the relation is nearly linear in 1/z for z$\lesssim$0.05 (the small angle approximation) and linear in z for z$\gtrsim$3 (the Lambda dominated universe).

All curvature occurs in the range 0.05$\lesssim$z$\lesssim$3, which is coded up in the IRAF script that does the JWST simulations.

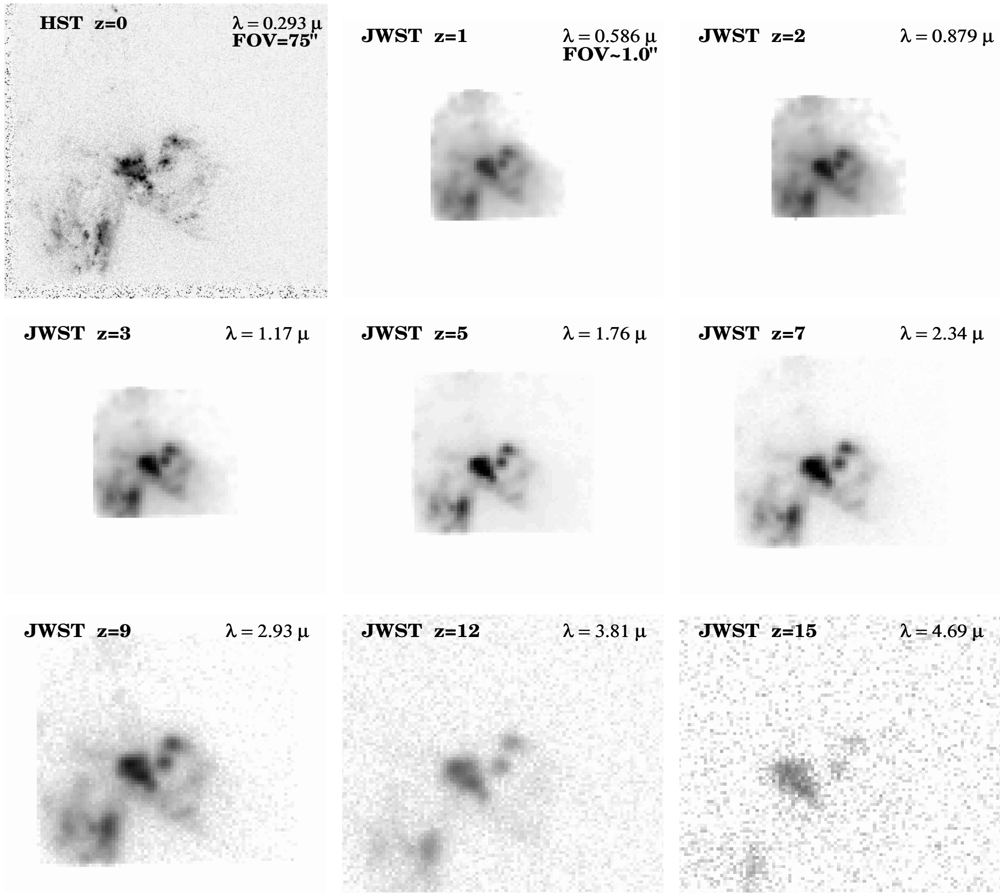



**Fig. 4.06.a.** JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). Note that the two unresolved star-bursting knots in the center remain visible until z∼12, beyond which the SB-dimming also kills their flux. This is the NOMINAL JWST [= (GOALS+REQUIREMENTS)/2 ].

ASSUMPTIONS: COSMOLOGY: $H_0$=71 km/s/Mpc, $\Omega_m$=0.27, and $\Omega_\Lambda$=0.73.

INSTRUMENT: 6.0 m effective aperture, JWST/NIRCam, 0.034″ /pix, RN=5.0 $e^-$, Dark=0.020 $e^-$/sec, NEP H-band Sky=21.7 mag/arcsec$^2$ in L2, Zodiacal spectrum, $t_{exp}$=1.0 hrs, read-out every 900 sec ("NOMINAL").

**Row 1:** z=0.0 (HST $\lambda$=0.293$\mu$m, FWHM=0.04″ ), z=1.0 (JWST $\lambda$=0.586$\mu$m, FWHM=0.084″ ), and z=2.0 (JWST $\lambda$=0.879$\mu$m, FWHM=0.084″ ). **Row 2:** z=3.0 (JWST $\lambda$=1.17$\mu$m, FWHM=0.084″ ), z=5.0 (JWST $\lambda$=1.76$\mu$m, FWHM=0.084″ ), and z=7.0 (JWST $\lambda$=2.34$\mu$m, FWHM=0.098″ ). **Row 3:** z=9.0 (JWST $\lambda$=2.93$\mu$m, FWHM=0.122″ ), z=12.0 (JWST $\lambda$=3.81$\mu$m, FWHM=0.160″ ), and z=15.0 (JWST $\lambda$=4.69$\mu$m, FWHM=0.197″ )

The galaxy merger UGC06471-2 (z=0.0104) is a major and very dusty collision of two massive disk galaxies.

It shows two bright unresolved star-bursting knots to the upper-right of the center, which remain visible until z≃12, beyond which the cosmic SB-dimming kills their flux. These are more typical for the small star-forming objects expected at z≃10–15.

This is the NOMINAL JWST = (GOALS+REQUIREMENTS)/2.

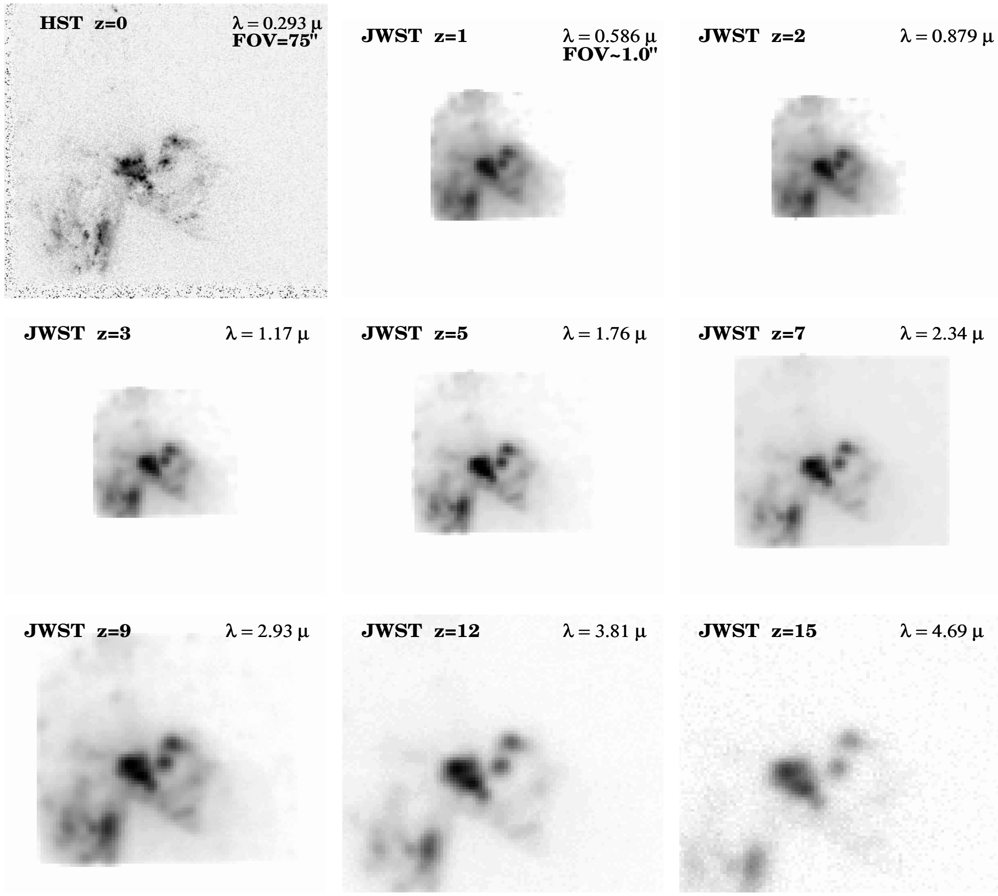



**Fig. 4.06.c.** JWST simulations based on HST/WFPC2 F300W images of the merger UGC06471-2 (z=0.0104). This is the BEST CASE JWST [meeting all GOALS, and $t_{exp}$=100 hrs]. The object is recognizable to z$\simeq$15.

ASSUMPTIONS: COSMOLOGY: $H_0$=71 km/s/Mpc, $\Omega_m$=0.27, and $\Omega_\Lambda$=0.73.

INSTRUMENT: 6.0 m effective aperture, JWST/NIR camera, 0.034″ /pix, RN=3.0 $e^-$, Dark=0.010 $e^-$/sec, NEP H-band Sky=21.7 mag/arcsec$^2$ in L2, Zodi spectrum, $t_{exp}$=100.0 hrs, read-out every 900 sec ("GOALS").

**Row 1:** z=0.0 (HST $\lambda$=0.293$\mu$m, FWHM=0.04″ ), z=1.0 (JWST $\lambda$=0.586$\mu$m, FWHM=0.084″ ), and z=2.0 (JWST $\lambda$=0.879$\mu$m, FWHM=0.084″ ). **Row 2:** z=3.0 (JWST $\lambda$=1.17$\mu$m, FWHM=0.084″ ), z=5.0 (JWST $\lambda$=1.76$\mu$m, FWHM=0.084″ ), and z=7.0 (JWST $\lambda$=2.34$\mu$m, FWHM=0.098″ ). **Row 3:** z=9.0 (JWST $\lambda$=2.93$\mu$m, FWHM=0.122″ ), z=12.0 (JWST $\lambda$=3.81$\mu$m, FWHM=0.160″ ), and z=15.0 (JWST $\lambda$=4.69$\mu$m, FWHM=0.197″ )

The galaxy merger UGC06471-2 (z=0.0104).

This is the BEST CASE JWST. It assumes that all GOALS are met, and that $t_{exp}$=100 hrs. The whole object (including the two star-forming knots) is recognizable to z$\simeq$15.

This does not imply that observing galaxies at z=15 with JWST will be easy. On the contrary, since galaxies formed through hierarchical merging, many objects at z$\simeq$10–15 will be $10^1$–$10^4\times$ less luminous, requiring to push JWST to its limits.