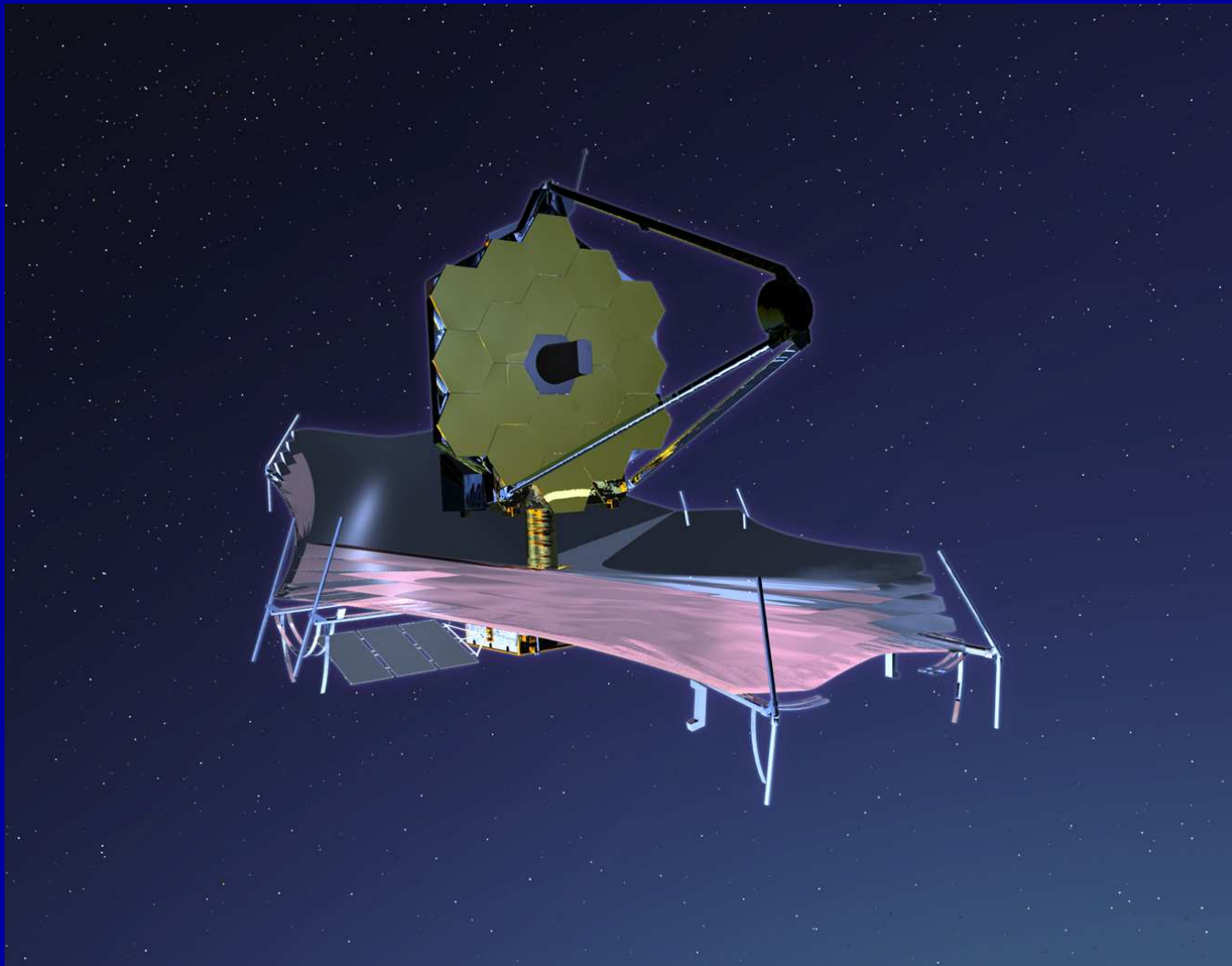


How can the James Webb Space Telescope Measure First Light, Reionization, & Galaxy Assembly?

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

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



Review at the Kavli Workshop on "Cosmic Reionization", Beijing, China; Friday July 12, 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; all charts ITAR cleared

"Brilliantly done...breathtaking in its vision."
The New York Times

JAMES WEBB

Author of *The Emperor's General*



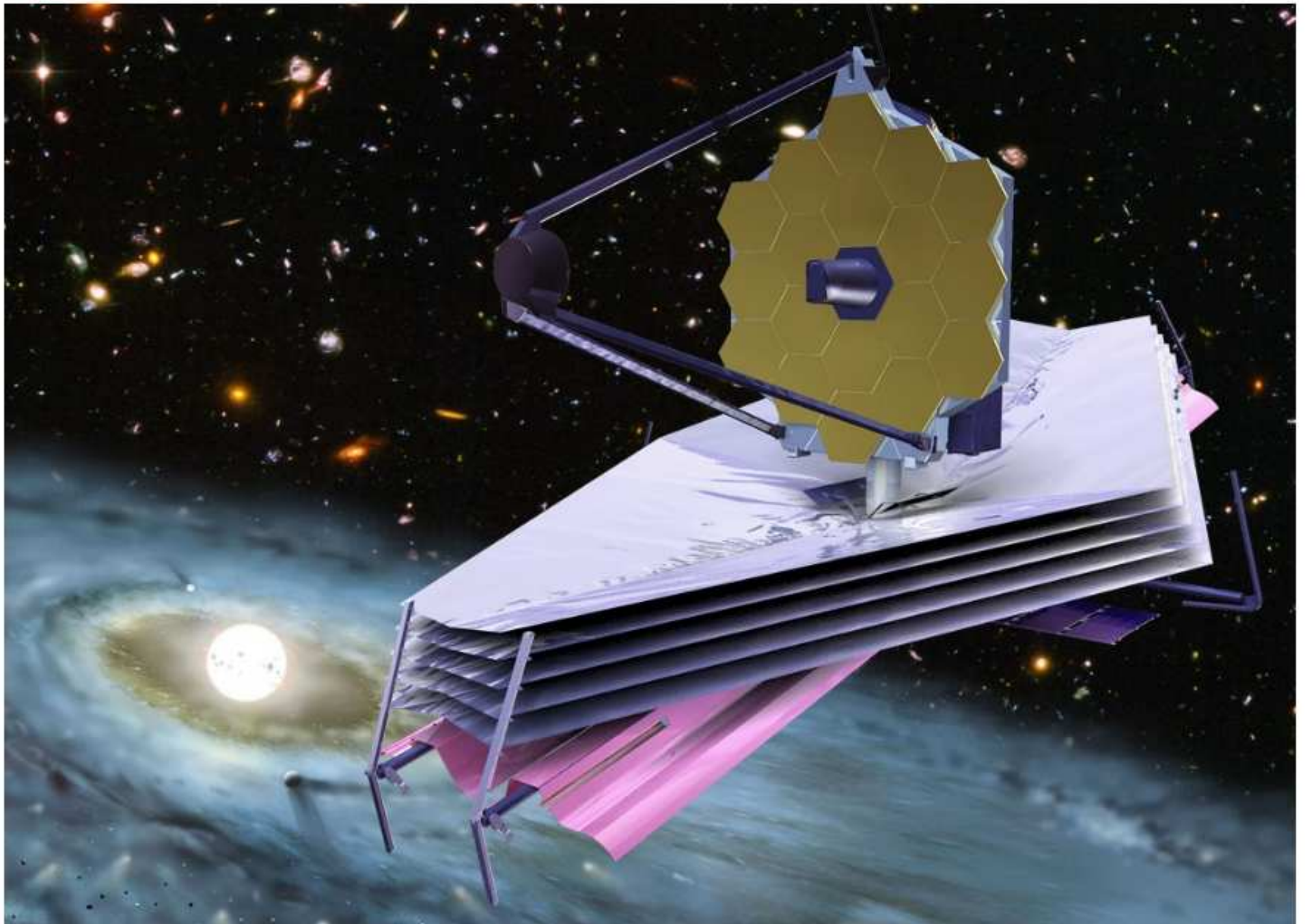
A NOVEL

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)?

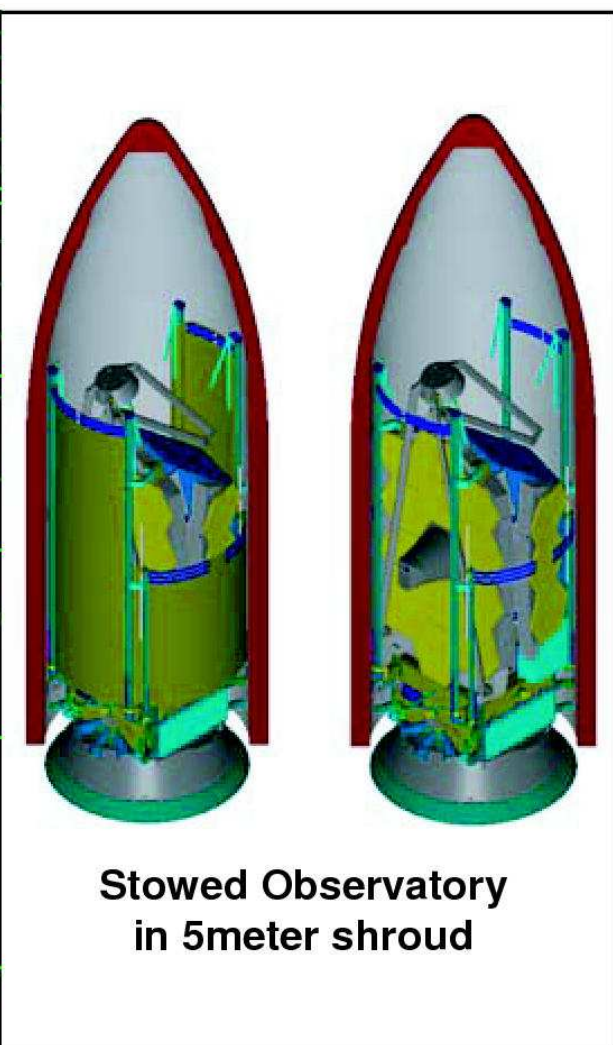
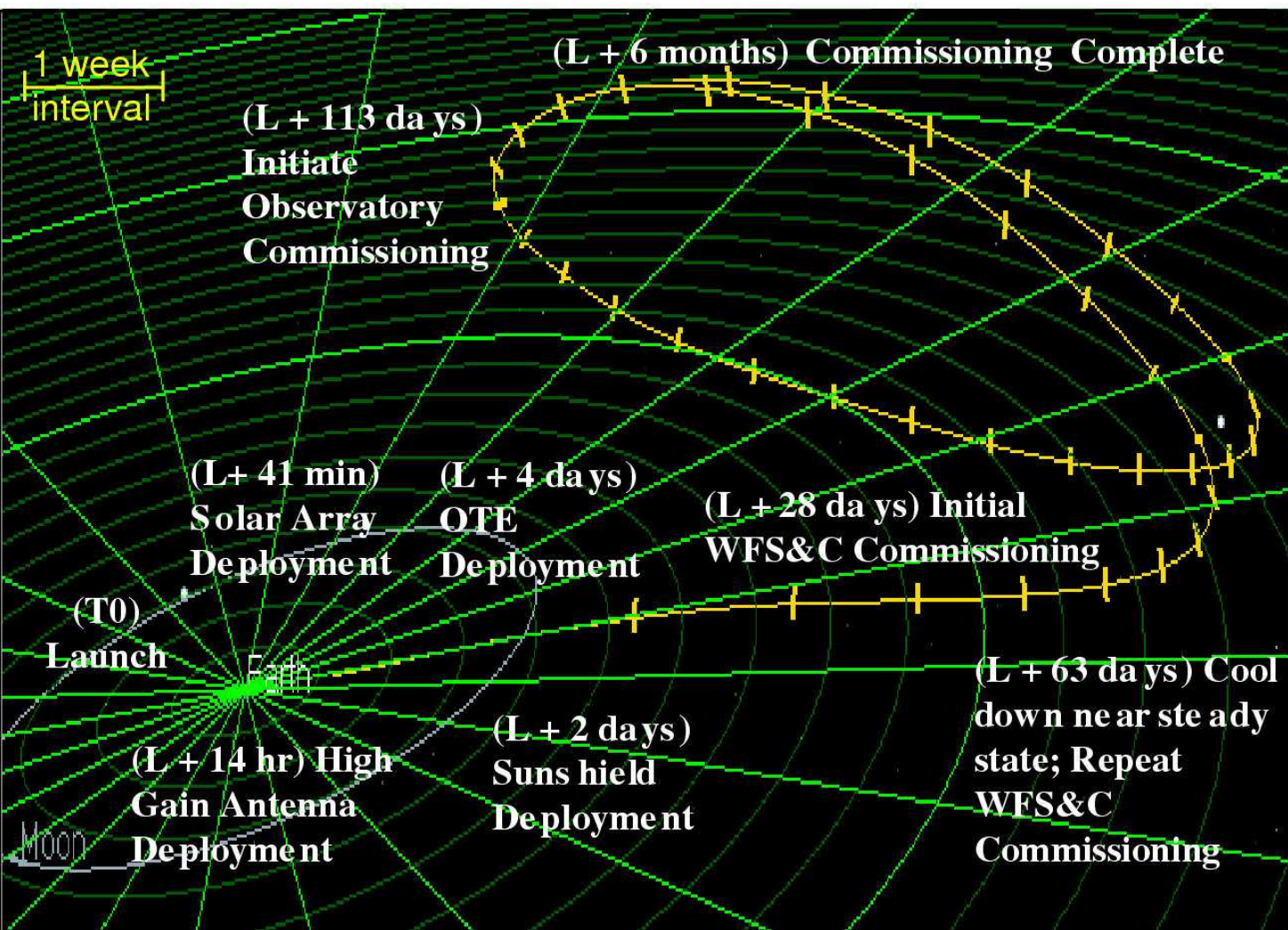


- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6 to $28 \mu\text{m}$, to be launched by NASA $\gtrsim 2013$. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging ($AB \lesssim 31.5$) and spectroscopy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



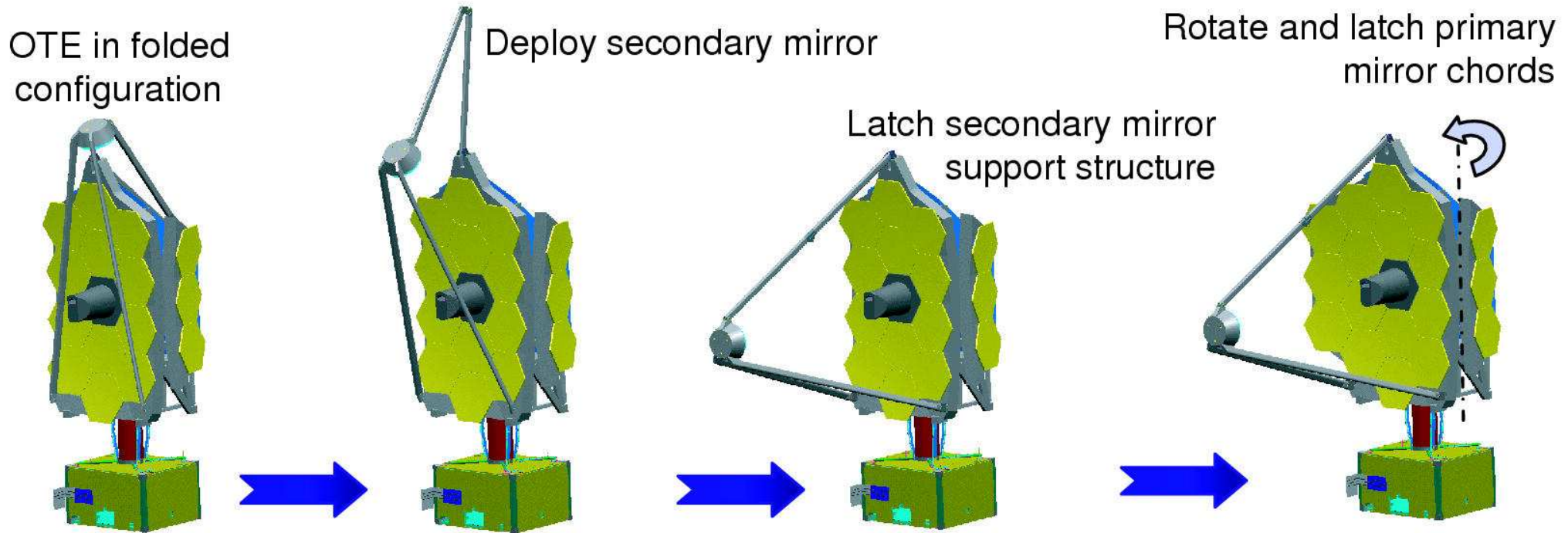
Life size model of JWST: displayed at the Jan. 2007 AAS mtg in Seattle.

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



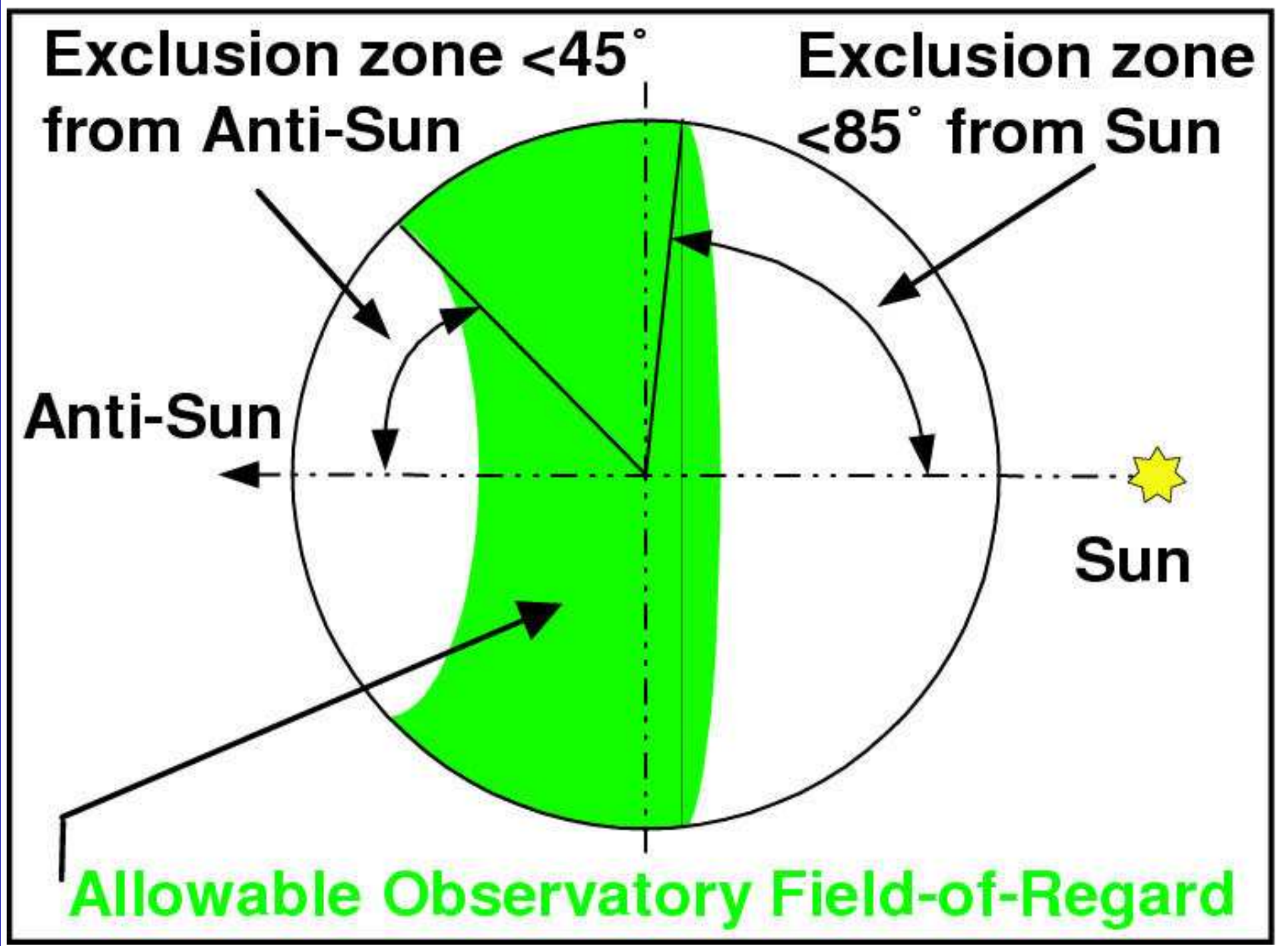
After launch in June 2013 with an Ariane-V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim 70\%$, and send data back to Earth every day.

- (1) How will JWST be automatically deployed?

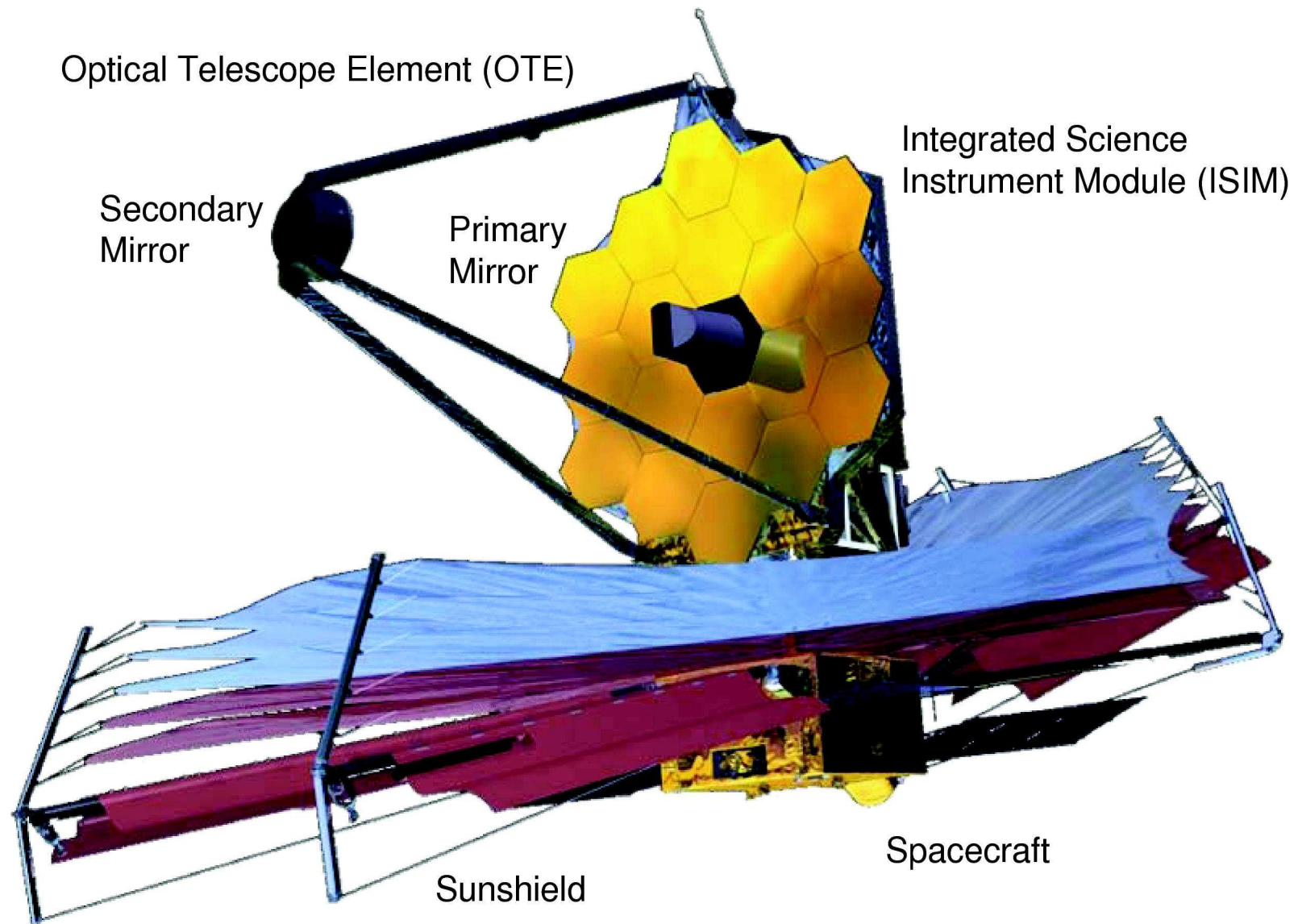


During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit.

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

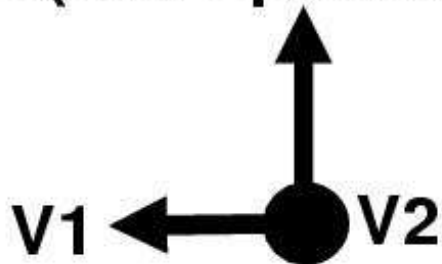


JWST can observe segments of sky that move around as it orbits the Sun.



JWST mission reviewed in Gardner, J. P., et al. 2006, *Space Science Reviews*, Vol. 123, pg. 485–606 ([astro-ph/0606175](https://arxiv.org/abs/astro-ph/0606175))

V3 (anti-spacecraft)



OTE ISIM



(V1, V3)
origin

Tertiary
Mirror

Secondary mirror

Cassegrain
focus

Fine
Steering Mirror

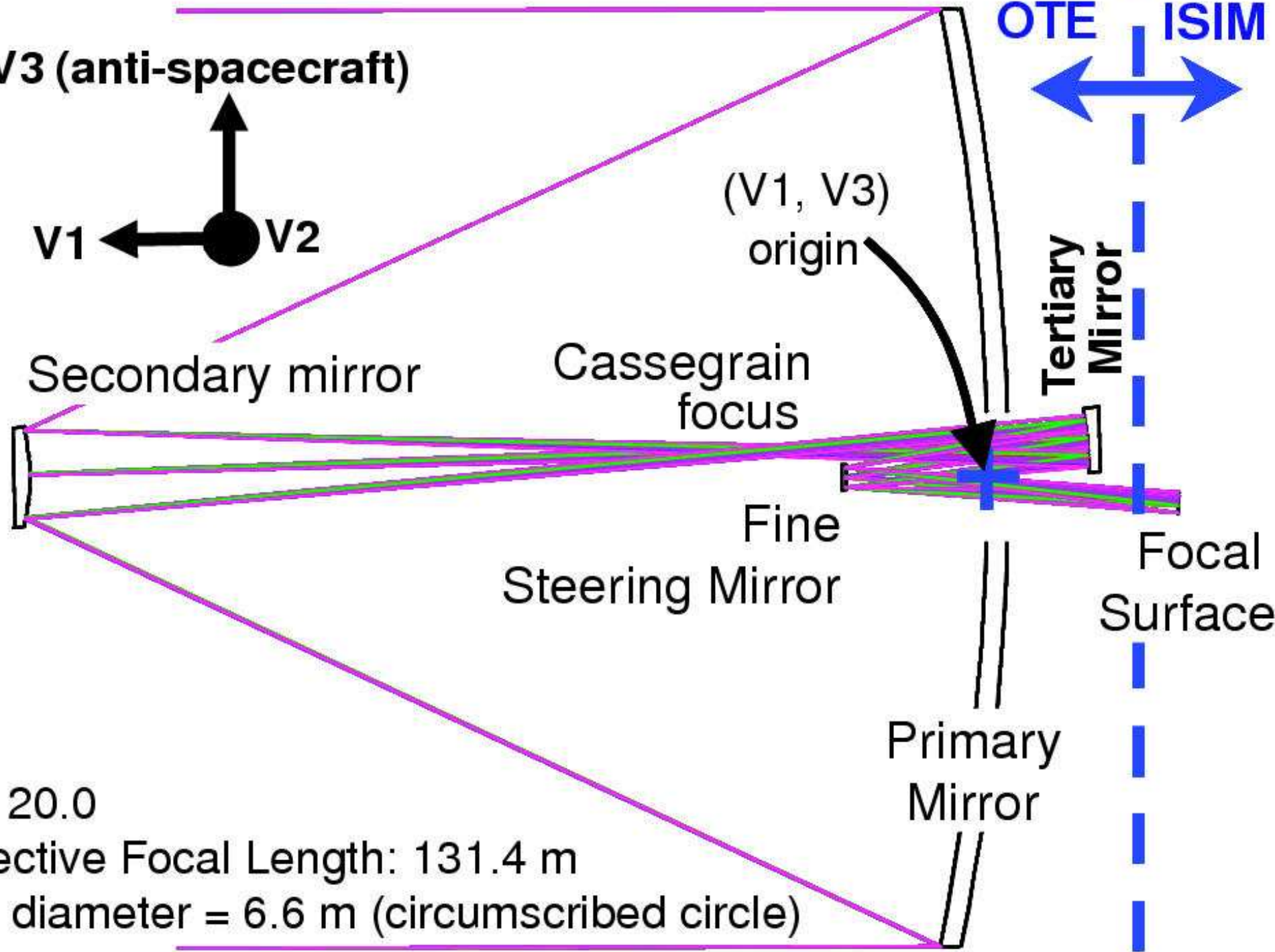
Focal
Surface

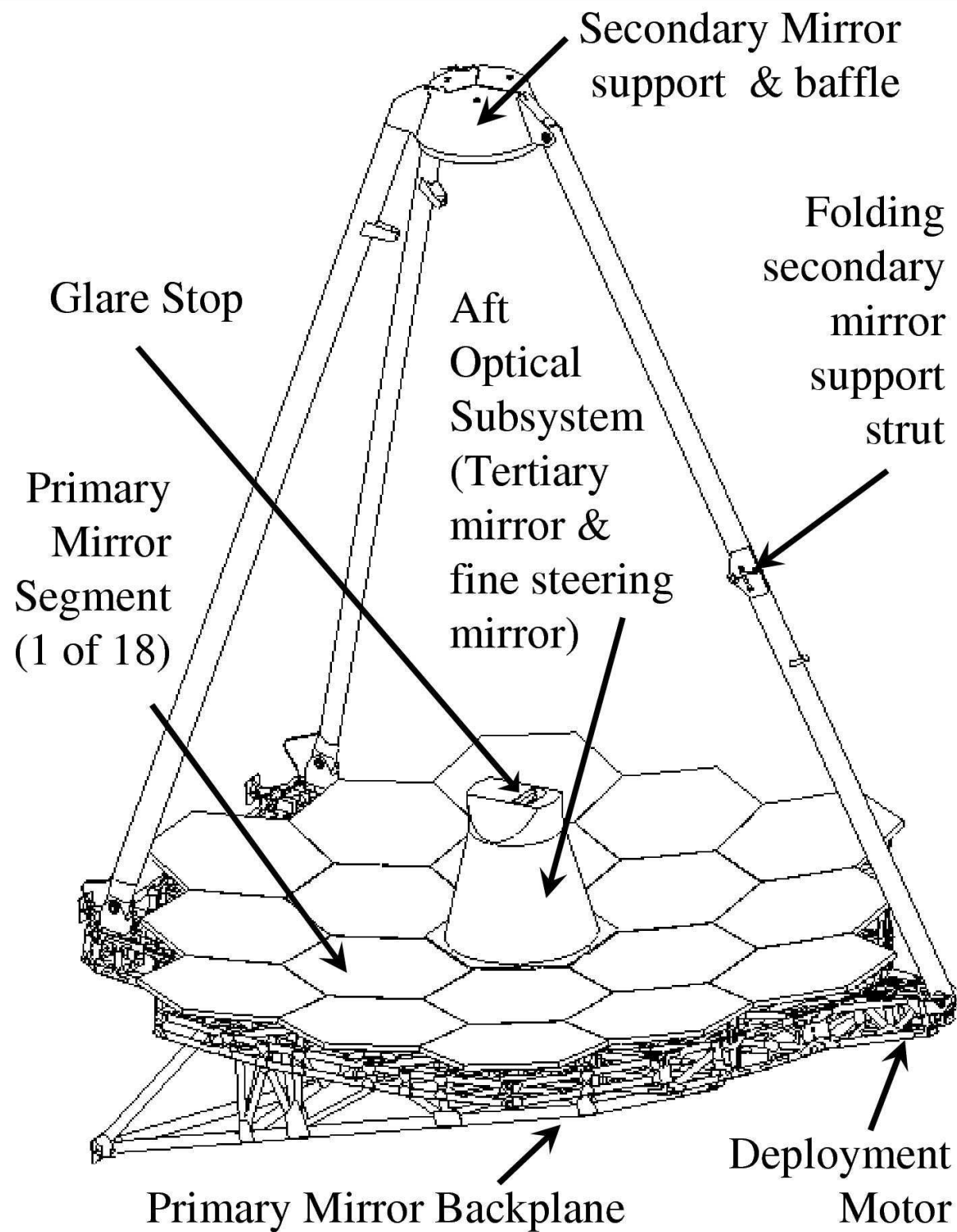
Primary
Mirror

f/#: 20.0

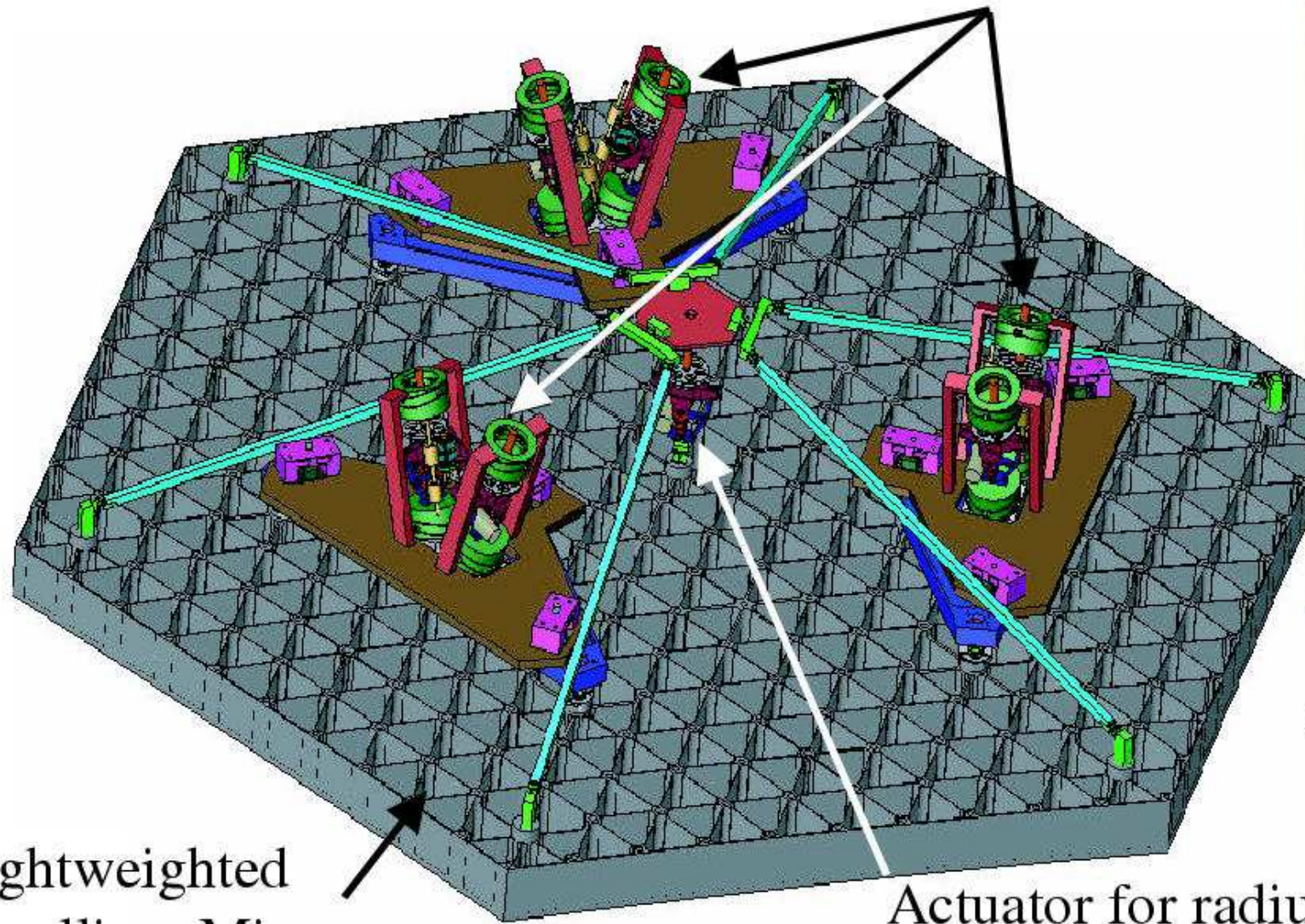
Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)



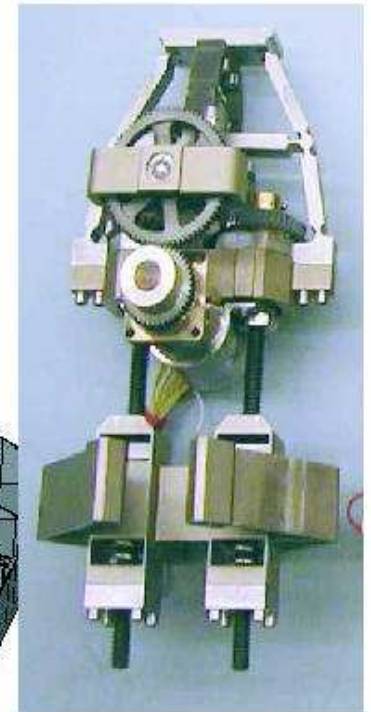


Actuators for 6 degrees of freedom rigid body motion



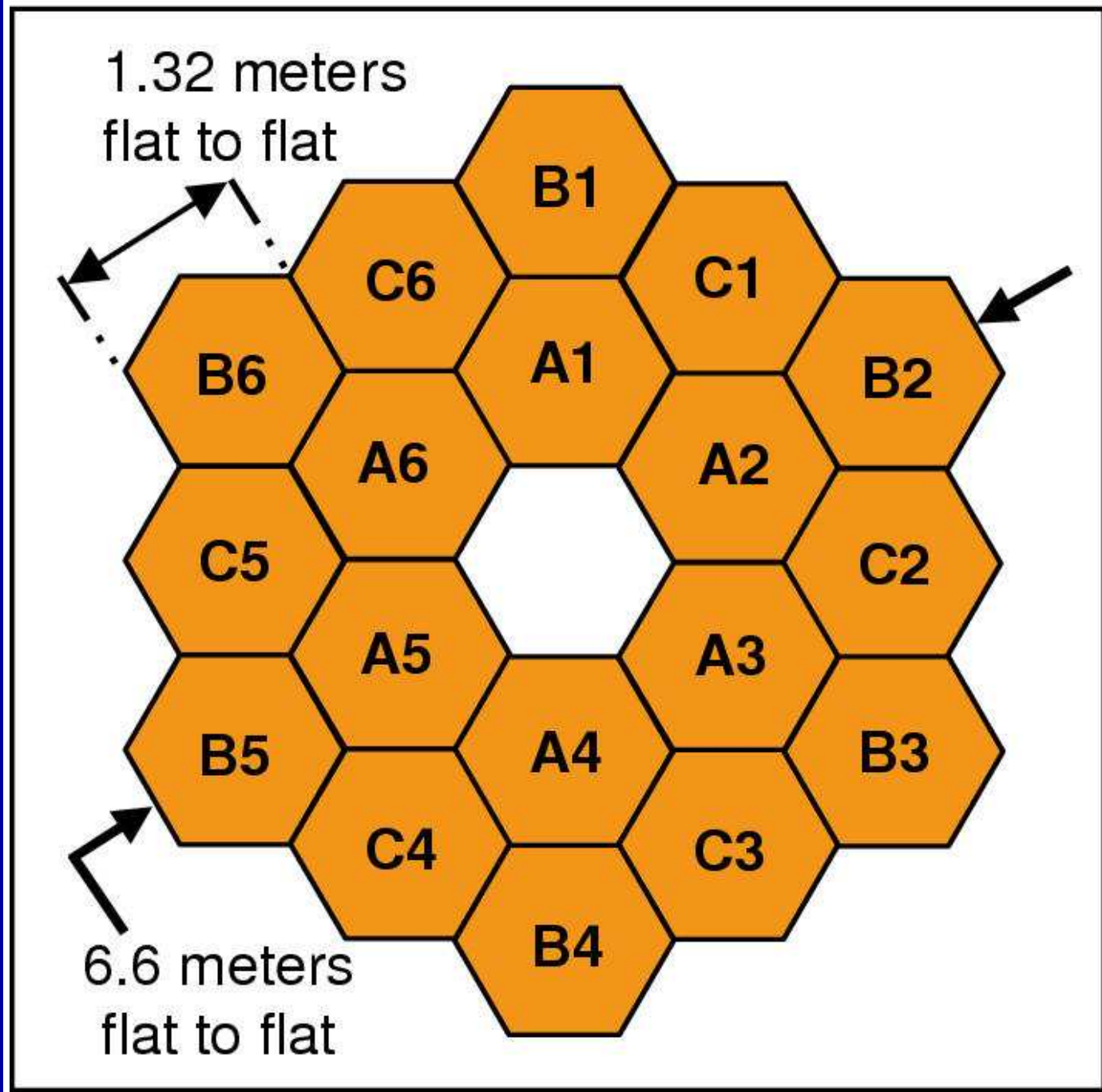
Lightweighted
Beryllium Mirror

Actuator for radius
of curvature adjustment



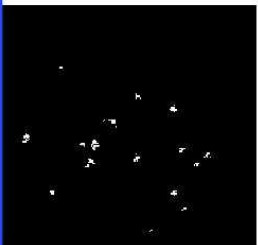
Actuator
development
unit

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



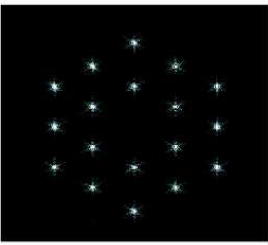
Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m.
 Primary mirror segments are made (AxSys). Now being polished (Tinsley).

**First light
NIRCam**



1.
Segment
Image
Capture

After Step 1



Initial Capture

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

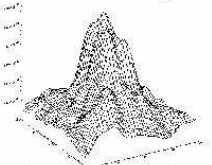
Final Condition

PM segments:
 < 100 μm ,
 < 2 arcsec tilt
 SM: < 3 mm,
 < 5 arcmin tilt

2. Coarse Alignment

Secondary mirror aligned
 Primary RoC adjusted

After Step 2

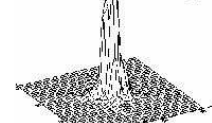


Primary Mirror segments:
 < 1 mm, < 10 arcsec tilt
 Secondary Mirror :
 < 3 mm, < 5 arcmin tilt

WFE < 200 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 ($2 \mu\text{m}$ -Strehl $\gtrsim 0.8$).

Need WFS-updates every ~ 14 days, depending on scheduling/SC-illumination.

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



Instrument Overview

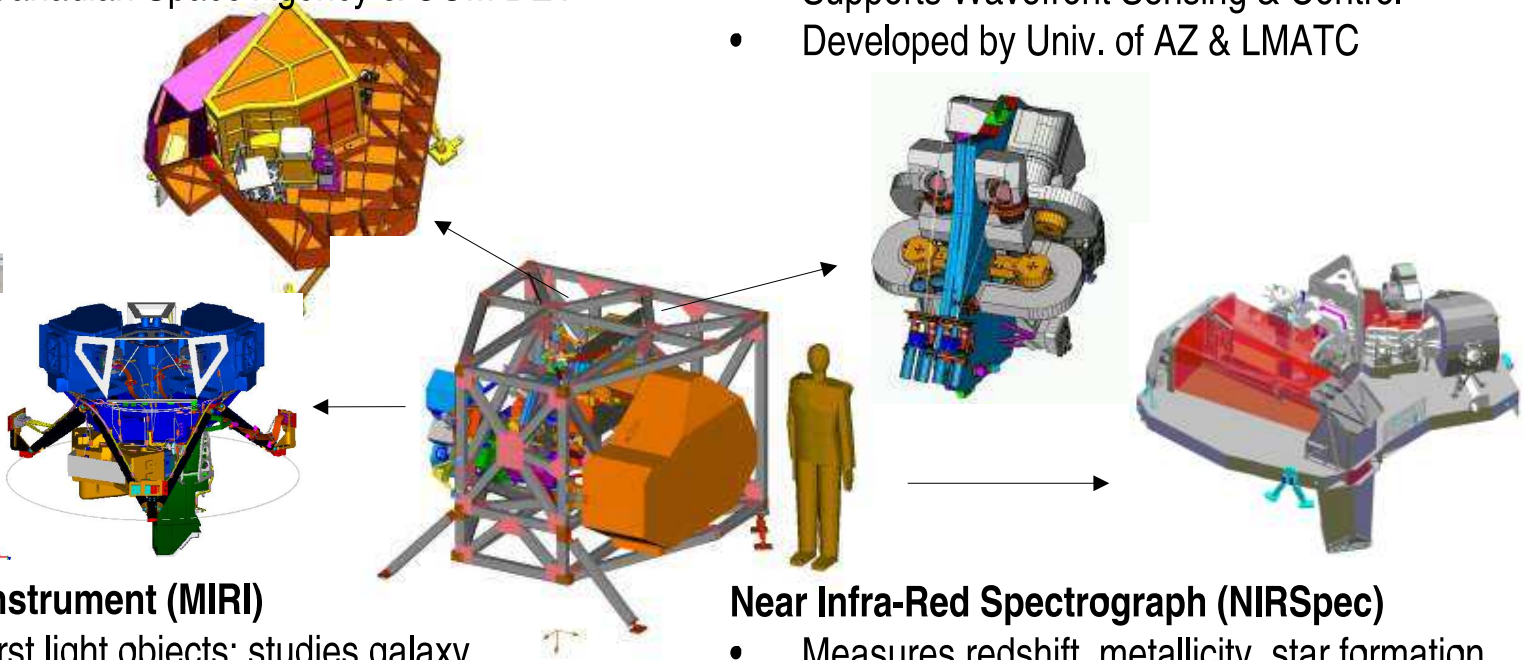


Fine Guidance Sensor (FGS)

- 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



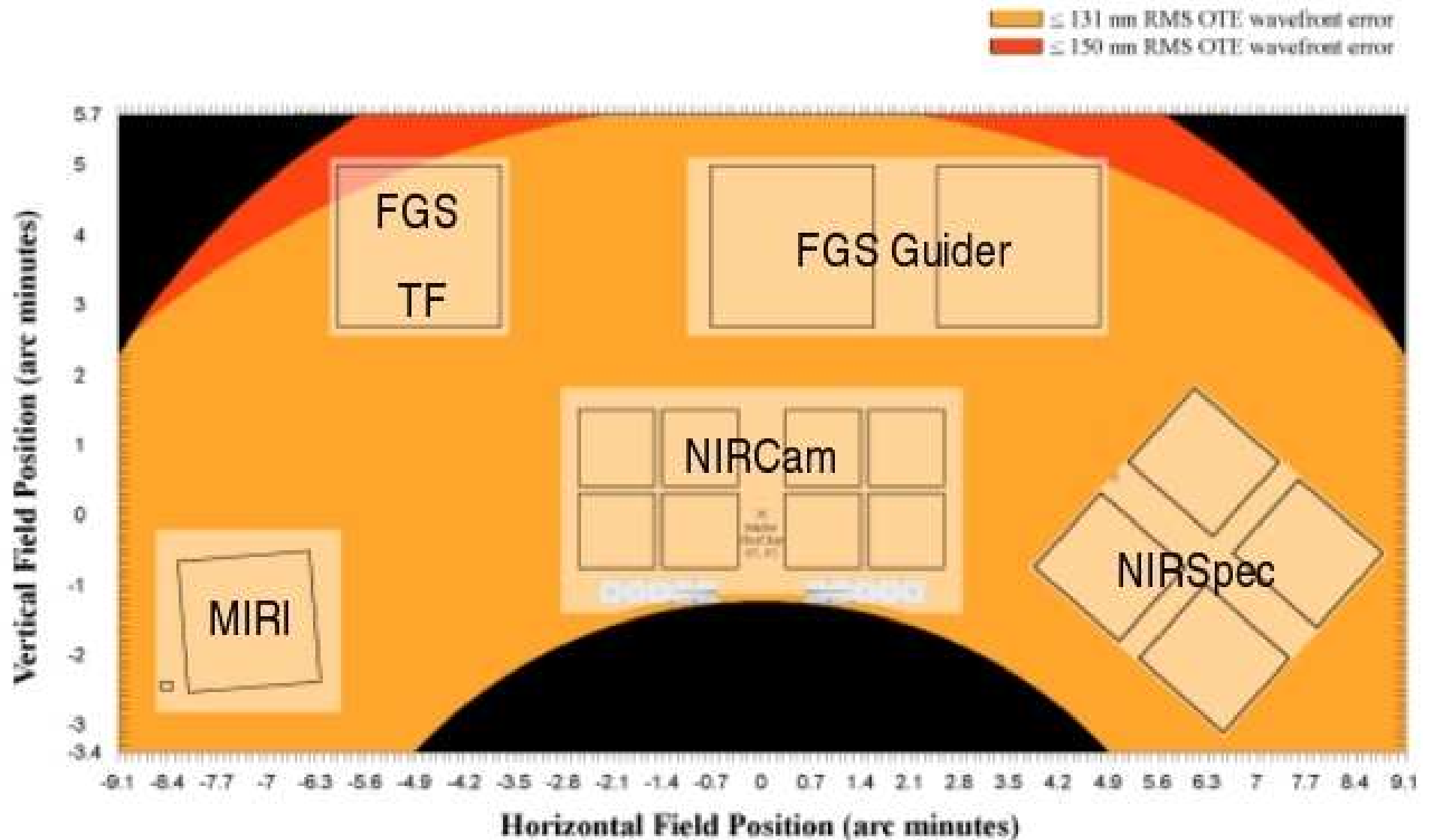
Mid-Infra-Red Instrument (MIRI)

- 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)

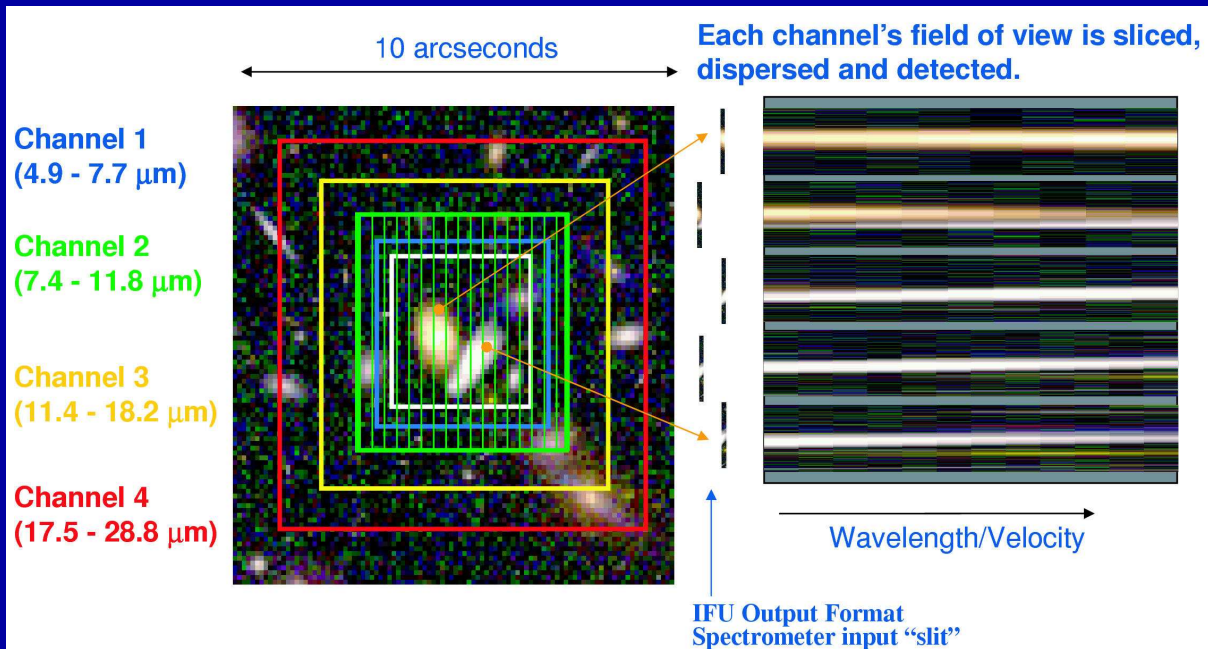
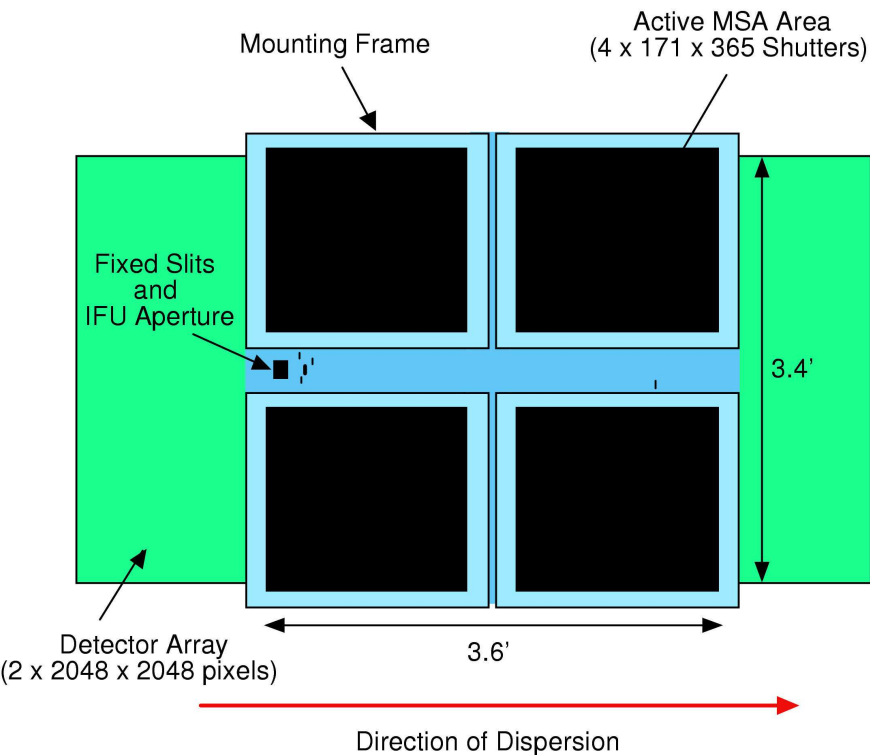
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/ GSFC Detector & Microshutter Subsystems

- (2) What instruments will JWST have?



All JWST instruments can in principle be used in parallel:

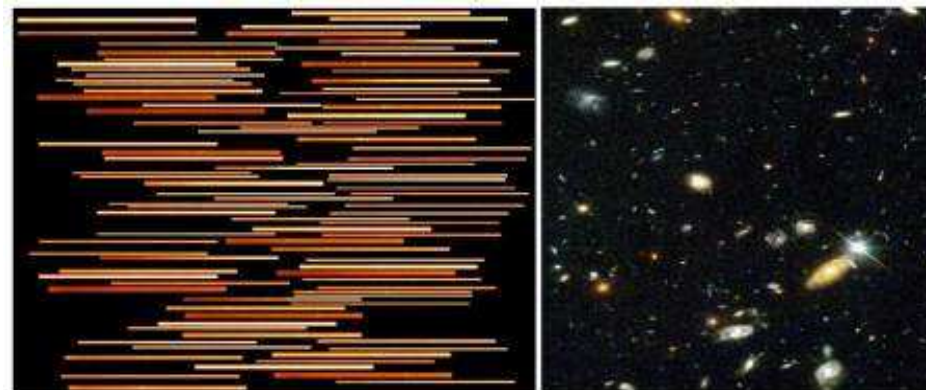
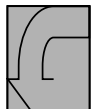
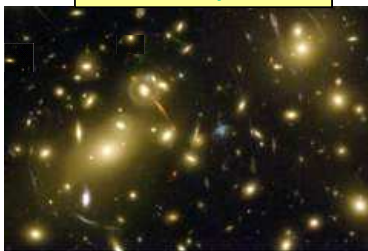
- Currently only being implemented for parallel *calibrations*.



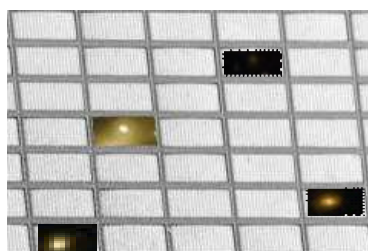
JWST/NIRSpec offers significant multiplexing for faint object spectroscopy:

- 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 $R=100$.

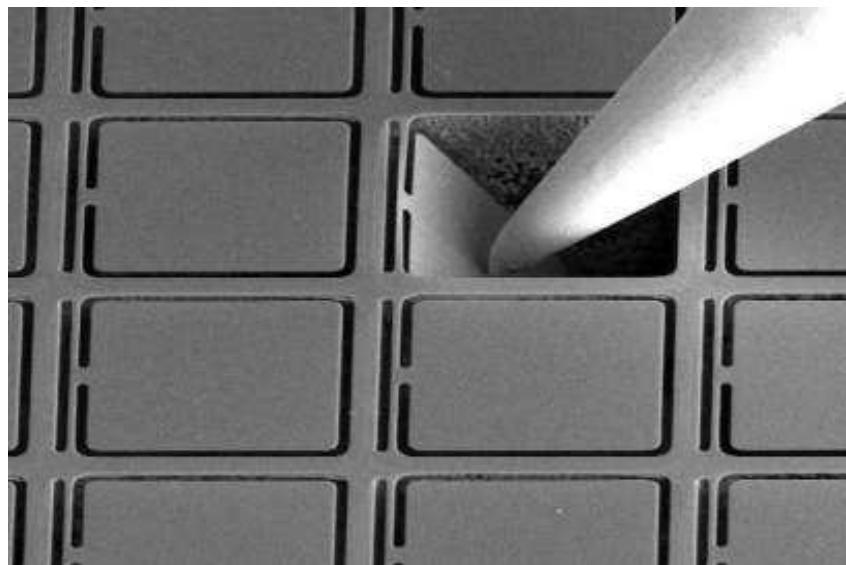
Astronomy Scene



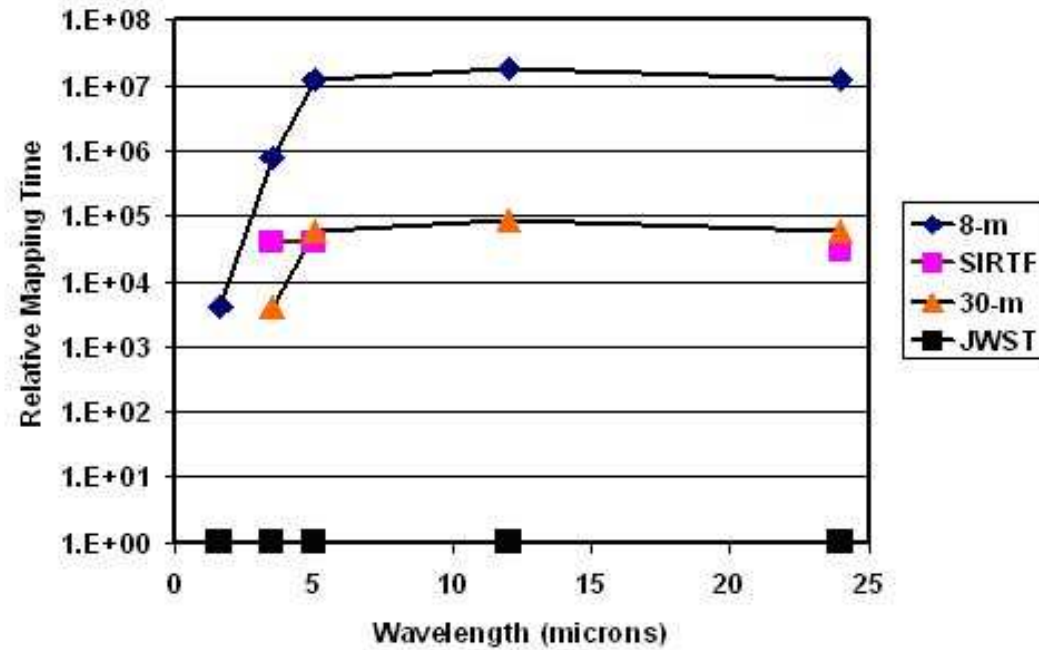
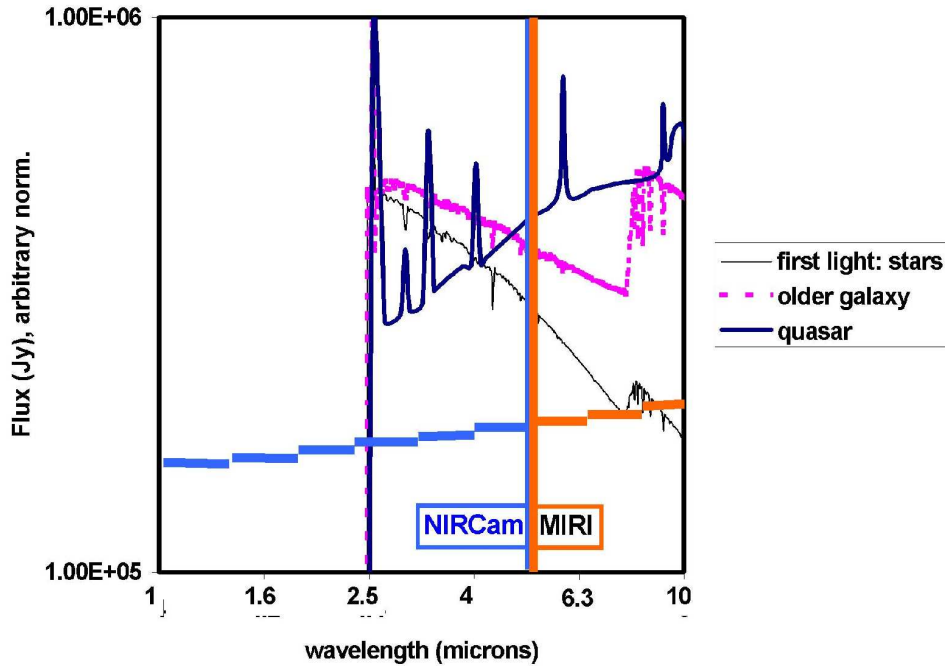
Metal Mask/Fixed Slit



Shutter Mask



- (2) What sensitivity will JWST have?



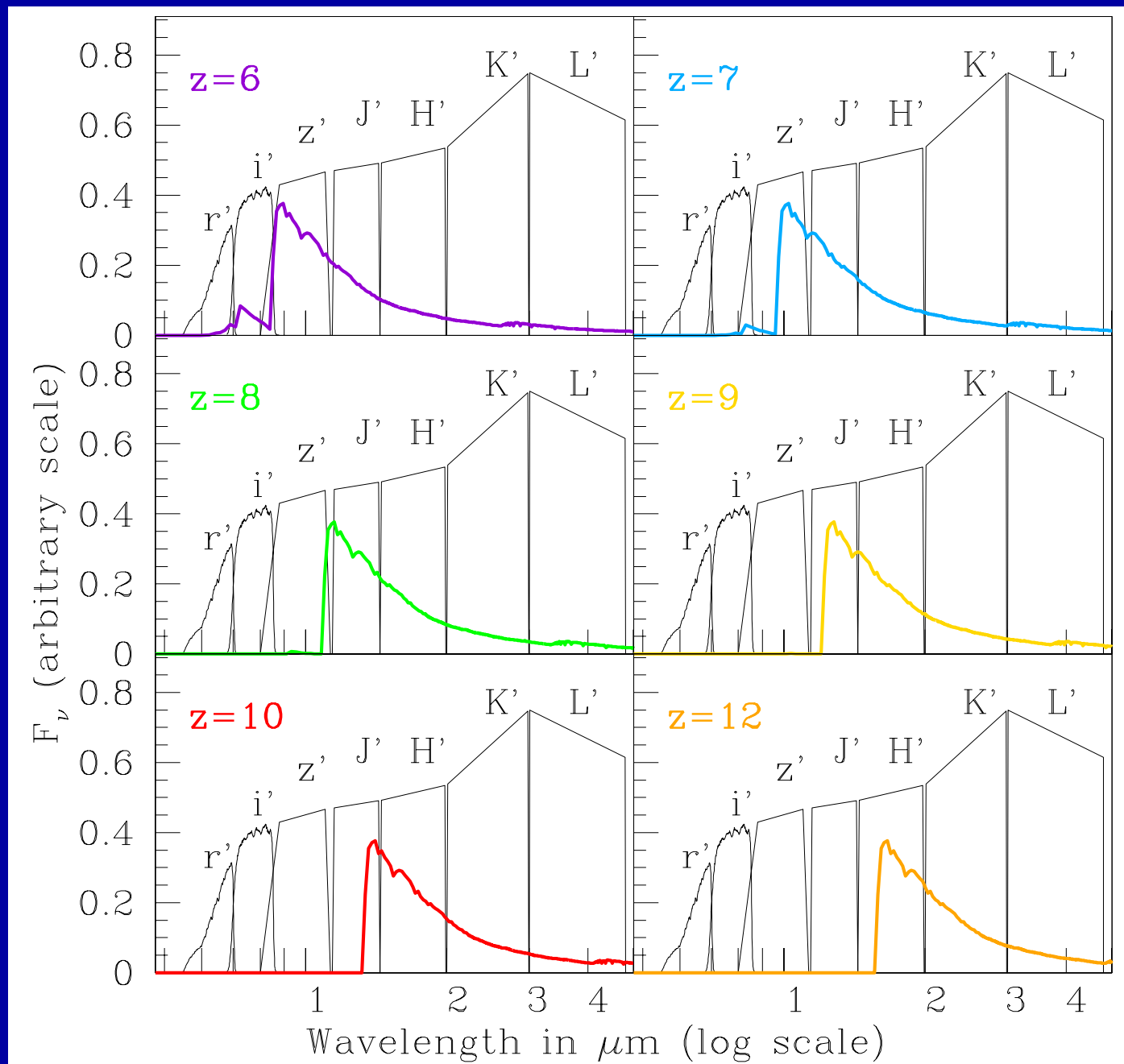
The NIRCam and MIRI sensitivity complement each other, straddling $5 \mu\text{m}$ in wavelength, and together allow objects to be found to redshifts $z=15-20$ in $\sim 10^5$ sec (28 hrs) integration times.

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. λ that Spitzer, a ground-based IR-optimized 8-m (Gemini) and 30-m telescope would need to match JWST.



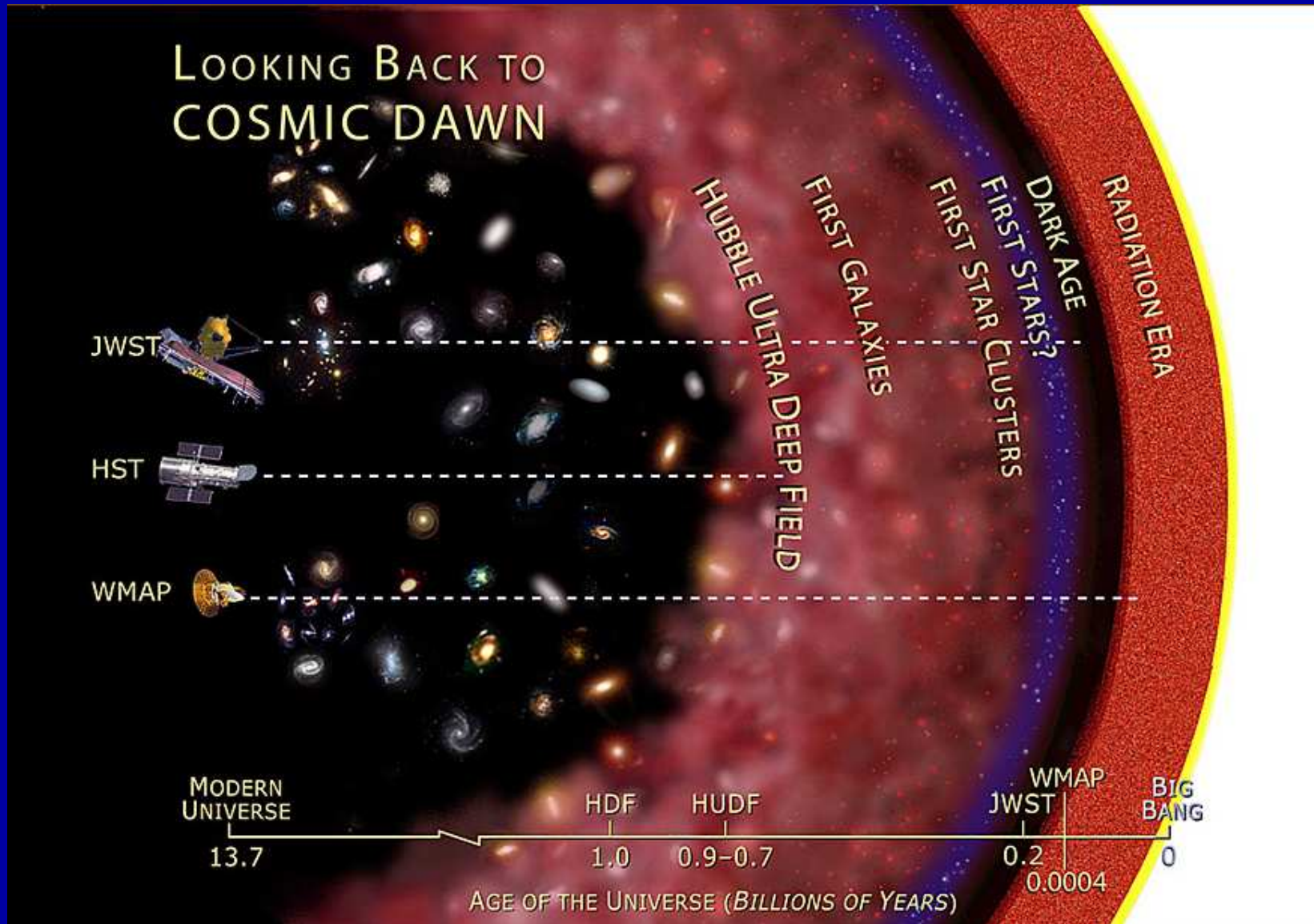
Truth \equiv 240 hrs HUDF $V_i z'$ 18 hrs JWST 0.7, 0.9, 2.0 μm



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

⇒ This is why JWST needs NIRC*am* at 0.8–5 μm and MIRI at 5–28 μm .

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



HST (+WFC3): Hubble sequence & galaxy evolution from $z \simeq 0$ to $z \simeq 7-8$.

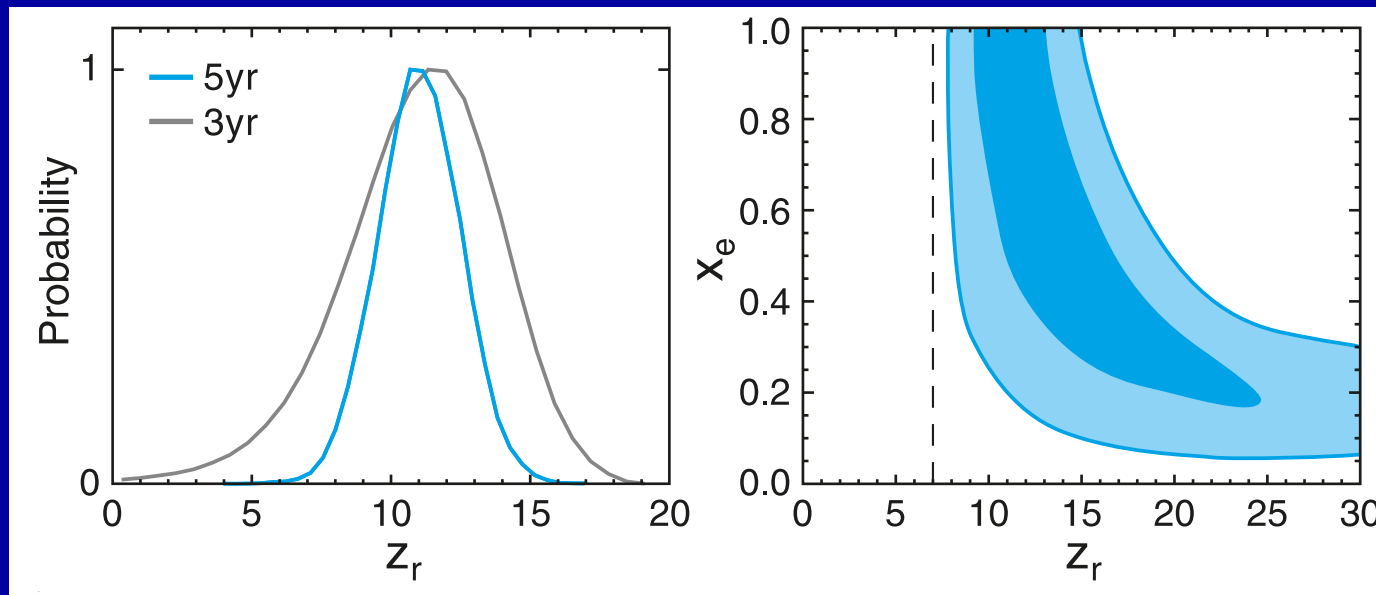
JWST: First Light, Reionization, & (dwarf) Galaxy Assembly at $z \simeq 8-20$.

WMAP: H-Recombination at $z = 1091 \pm 1$. Imprints of all foregrounds.

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

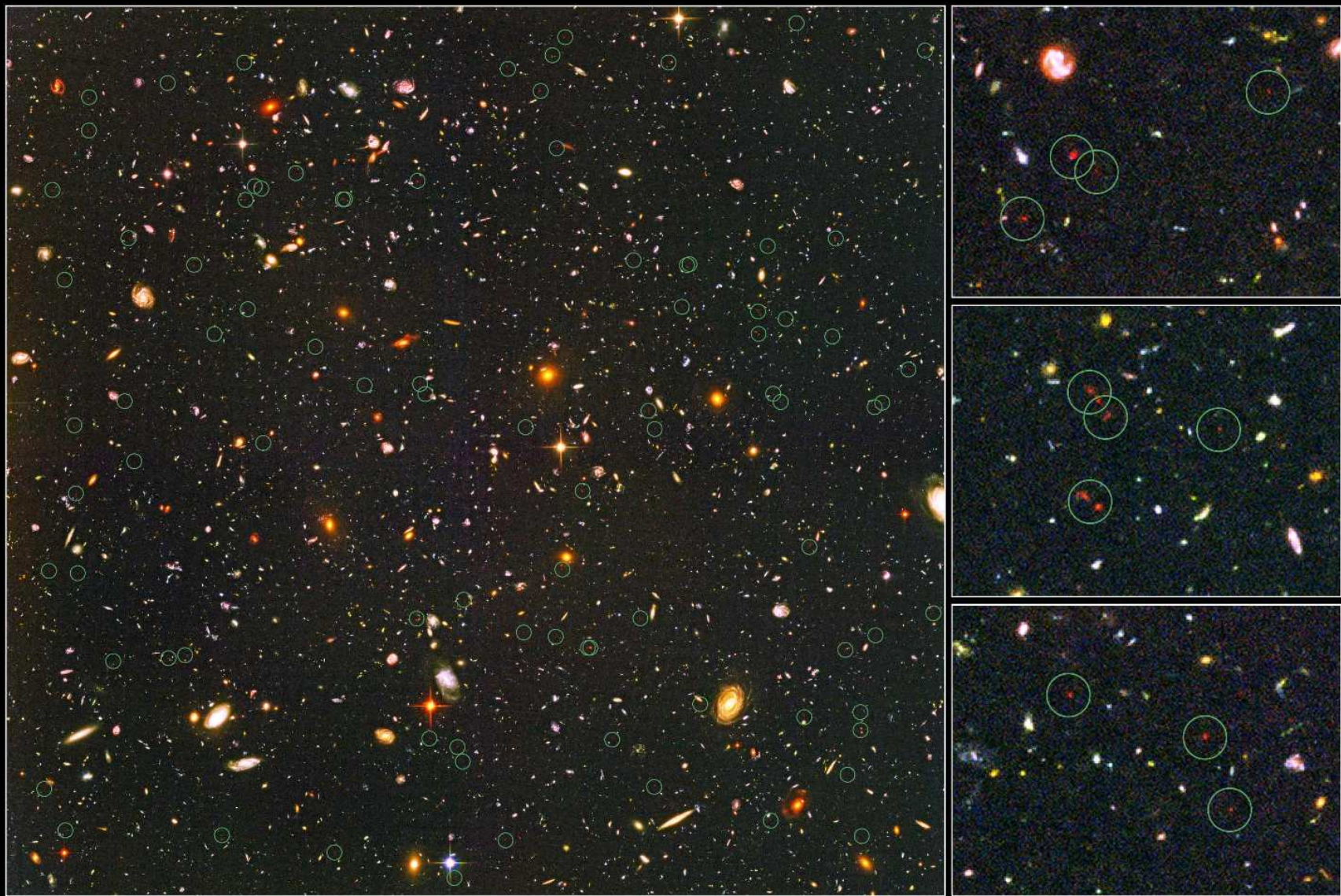
HST/WFC3 $z \lesssim 7-8$ ←

→ 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 $z \simeq 15-20$.
- ⇒ JWST must cover $\lambda = 0.6-28 \mu\text{m}$, with its diffraction limit at $2.0 \mu\text{m}$.



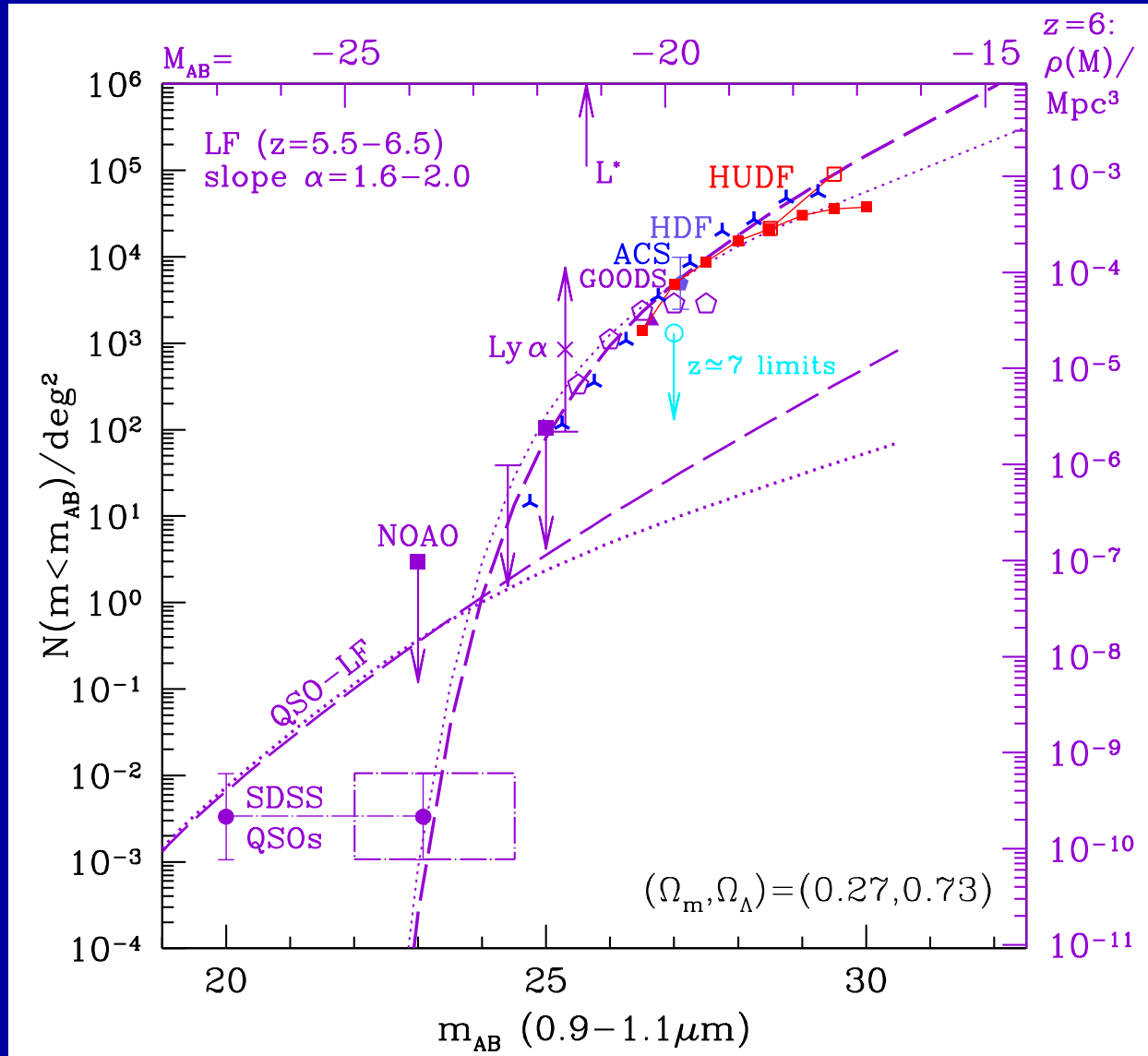
Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

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

STScI-PRC04-28

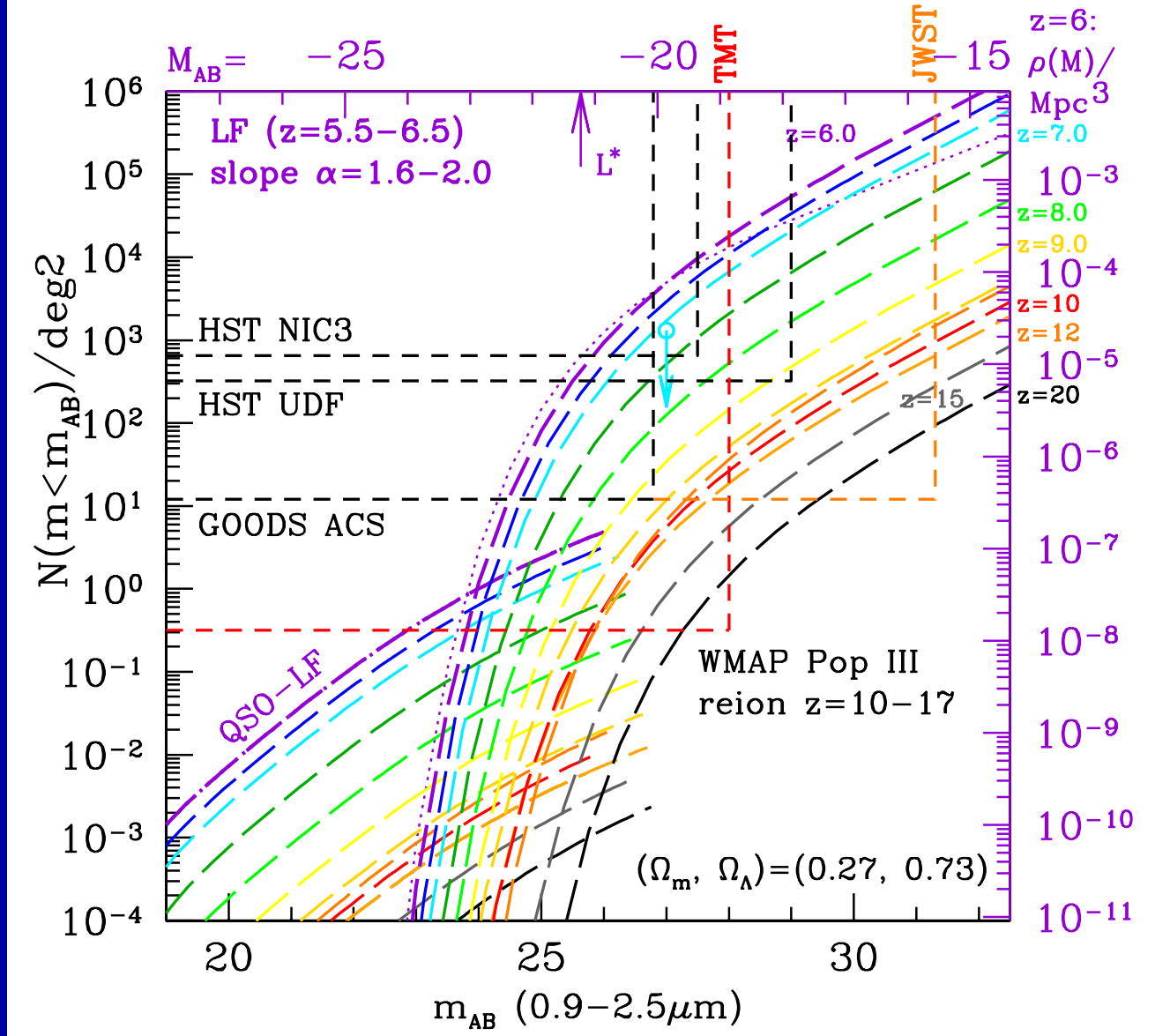
HUDF i-drops: faint galaxies at $z \simeq 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \simeq 6$ to $AB \lesssim 27.0$ mag (Malhotra et al. 2005).

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



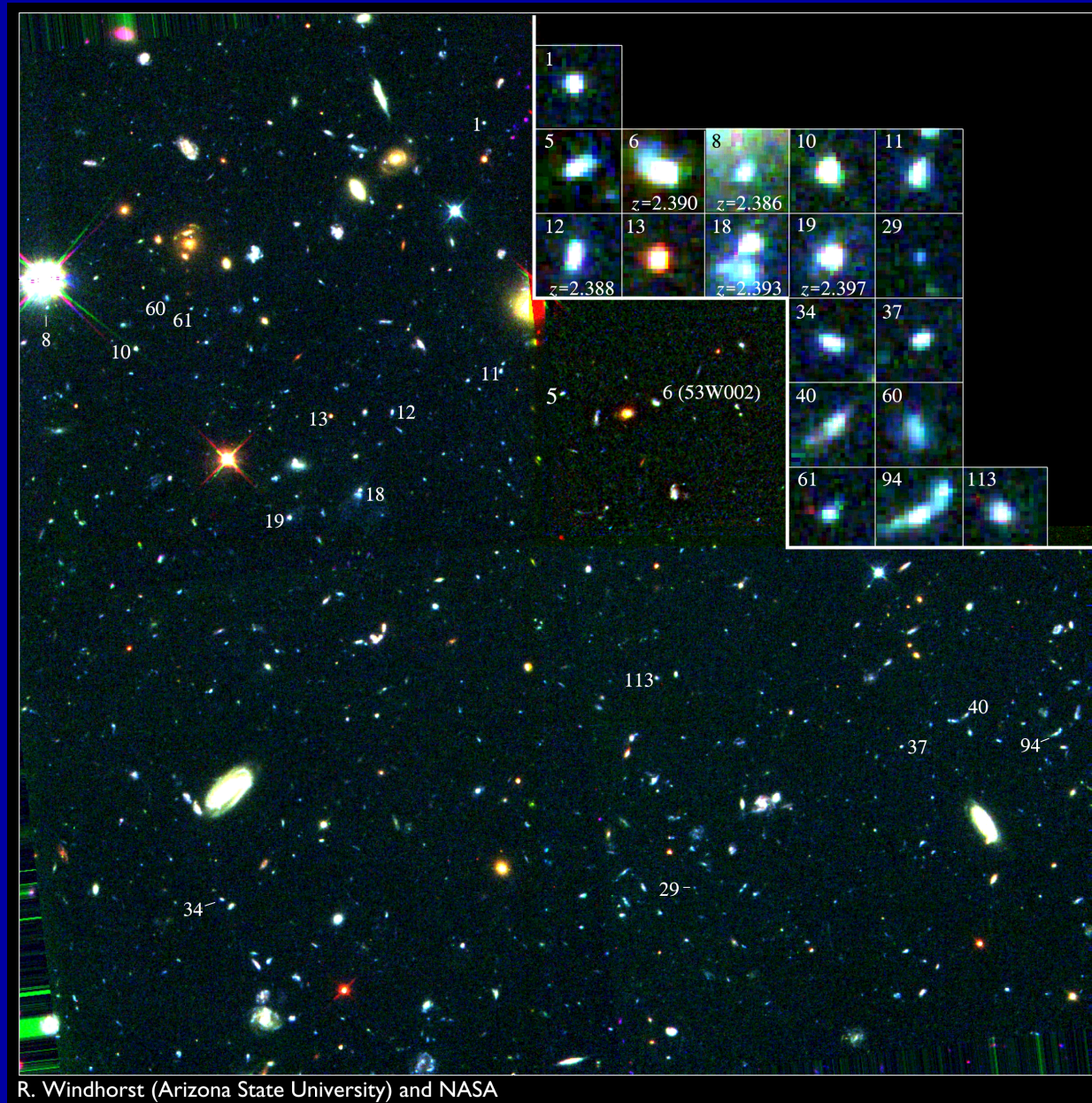
HUDF shows that luminosity function of $z \simeq 6$ objects (Yan & Windhorst 2004a, b) is very steep: faint-end Schechter slope $|\alpha| \simeq 1.6-2.0$.

\Rightarrow Dwarf galaxies and not quasars likely completed the reionization epoch at $z \simeq 6$. This is what JWST will observe in detail for $z \gtrsim 7-20$.



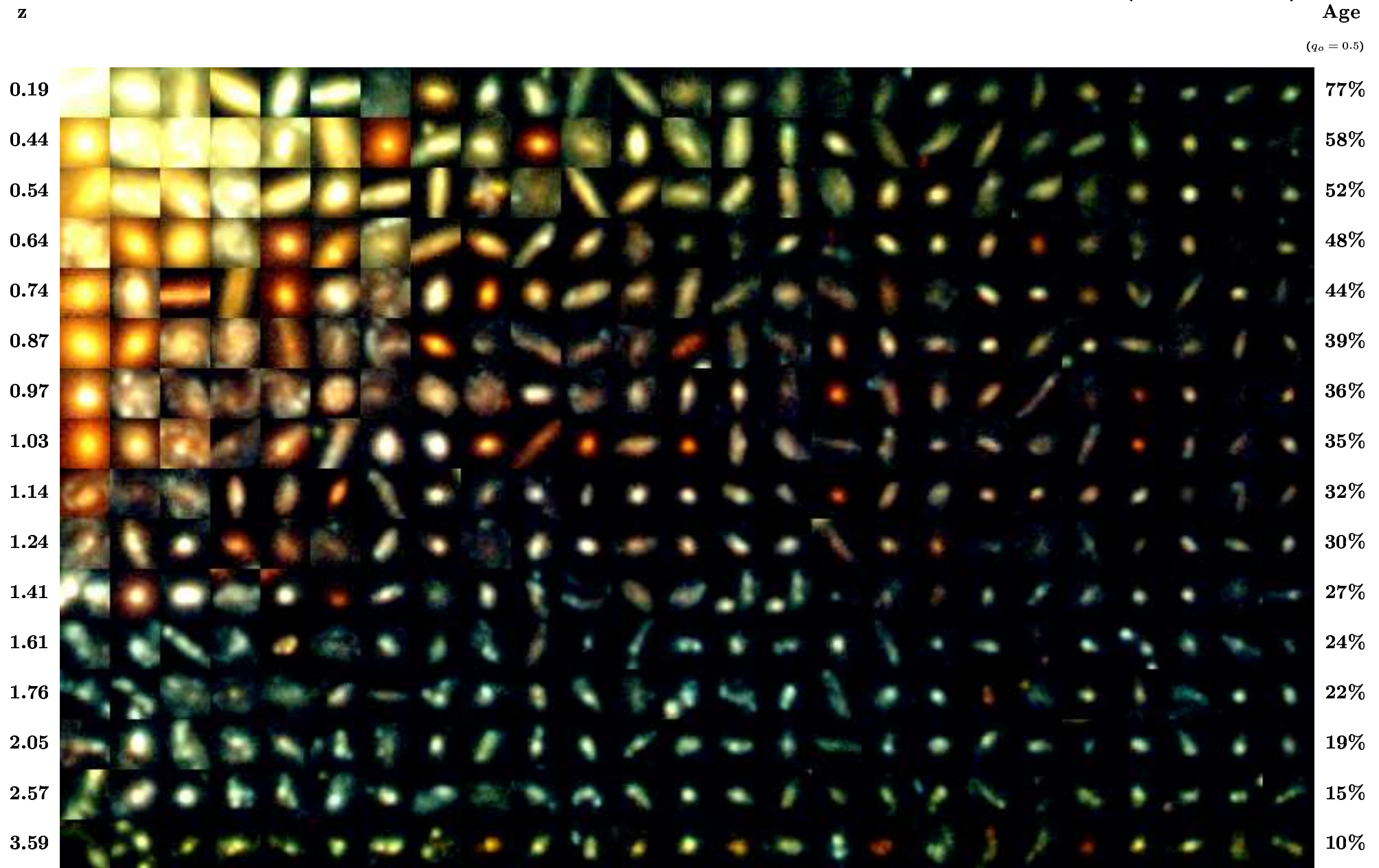
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- Objects at $z \gtrsim 8$ are rare, since volume element is small and JWST samples brighter part of LF. JWST needs the quoted sensitivity/aperture (A), field-of-view ($FOV = \Omega$), and wavelength range ($0.7-28 \mu m$).

- (4) How JWST can measure Galaxy Assembly



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 ($I < 26.0$)



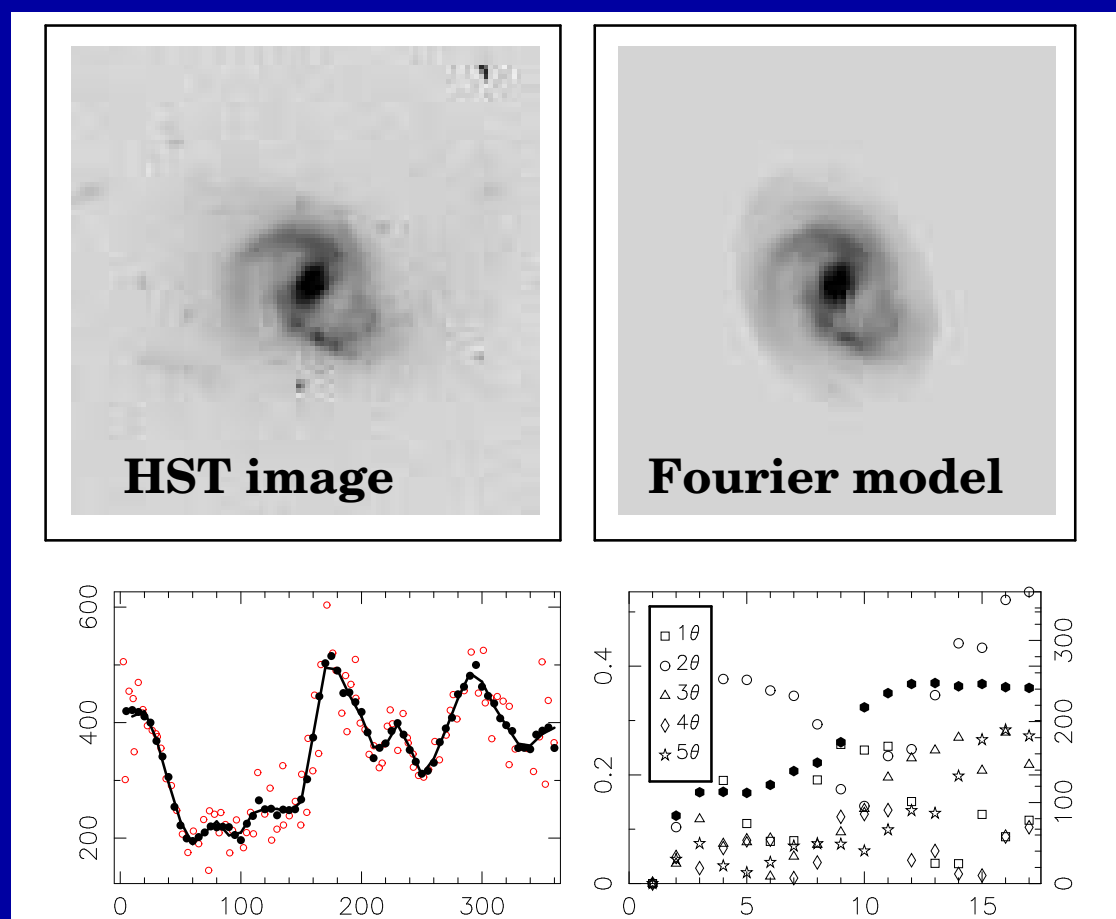
- (4) How JWST can measure Galaxy Assembly

- Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable 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.

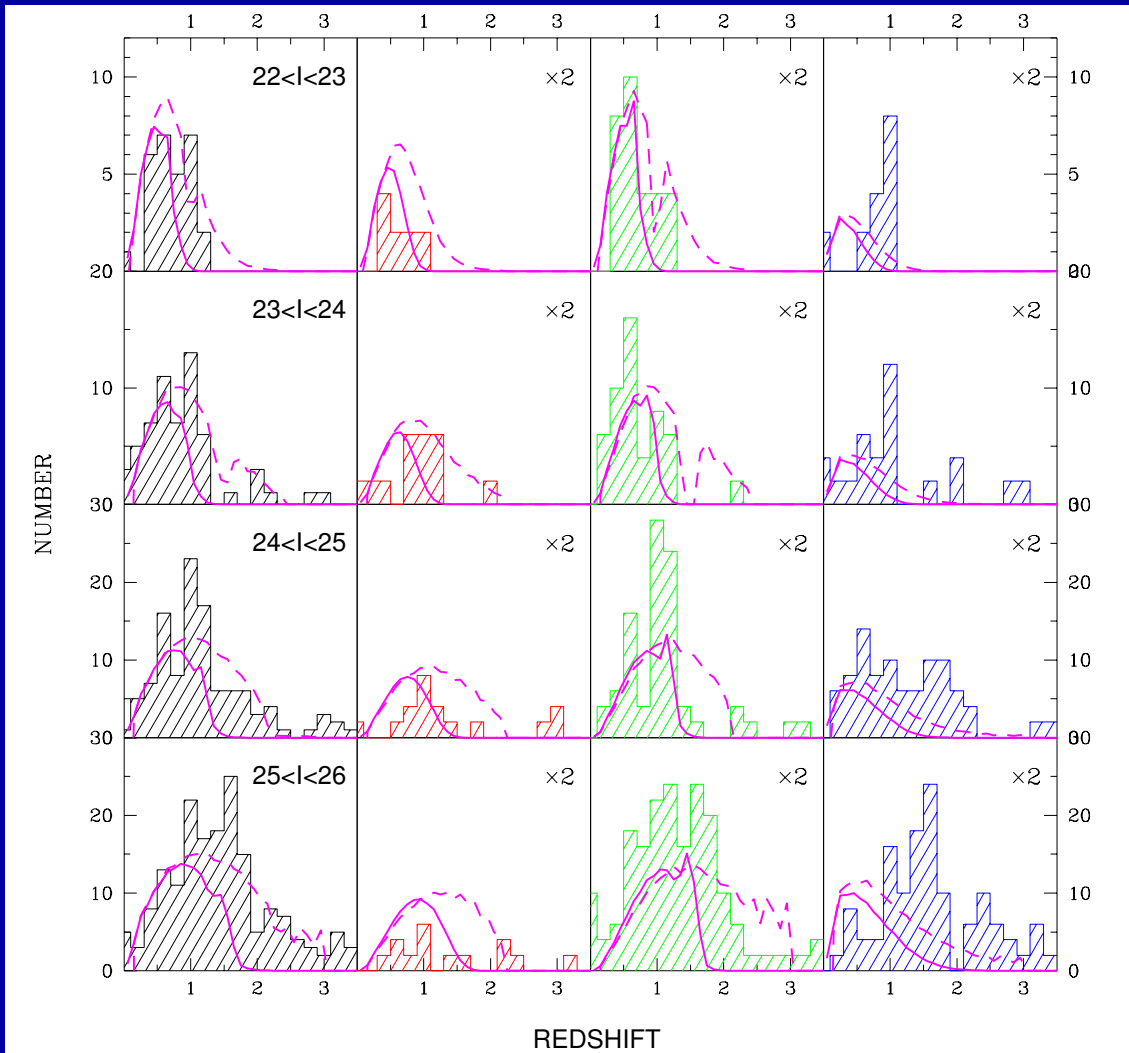
- JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame structure and type as a function of redshift or cosmic epoch.



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

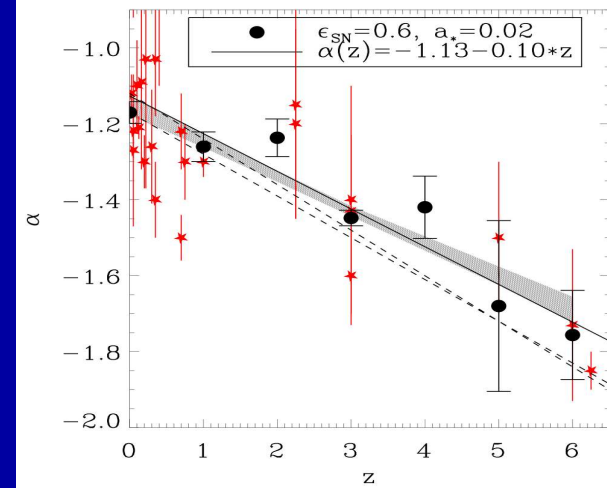
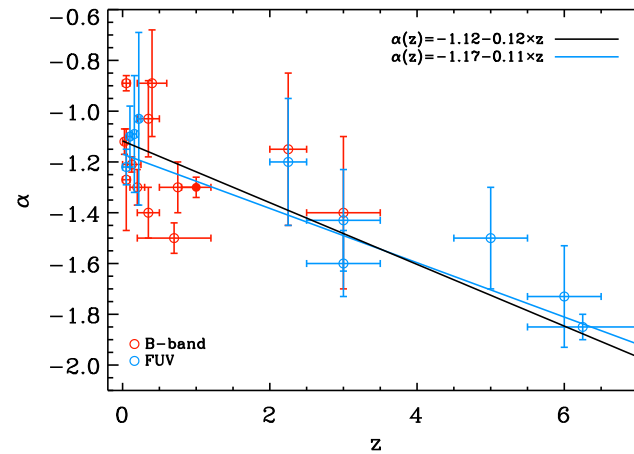
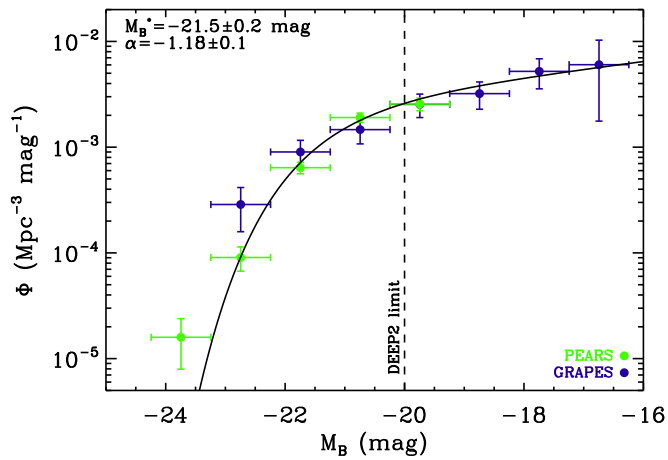
- (1) Fourier series are made in successive concentric annuli.
- (2) Even Fourier components indicate symmetric parts (arms, rings, bars).
- (3) Odd Fourier components indicate asymmetric parts (lopsidedness).
- (4) JWST can measure the evolution of each feature/class directly.

Total EII/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.

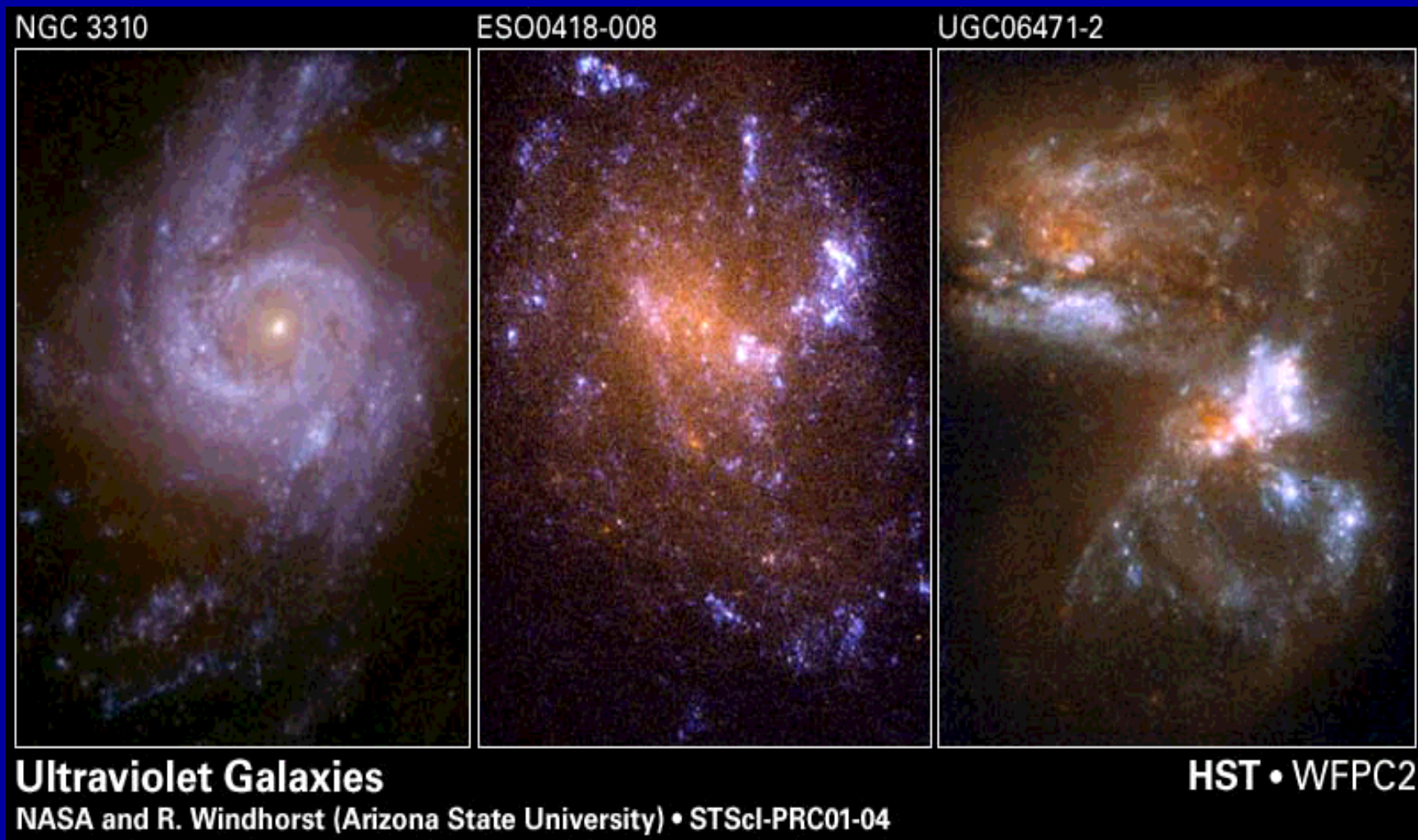
Faint-end LF-Slope Evolution (fundamental, like local IMF)



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 et al. 2007, ApJL, 668, L115).
- JWST will provide fainter spectra ($AB \lesssim 29$) and spectro-photometric redshifts to much higher z ($\lesssim 20$). JWST will trace α -evolution for $z \lesssim 12$.
- Can measure environmental impact on faint-end LF-slope α 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.

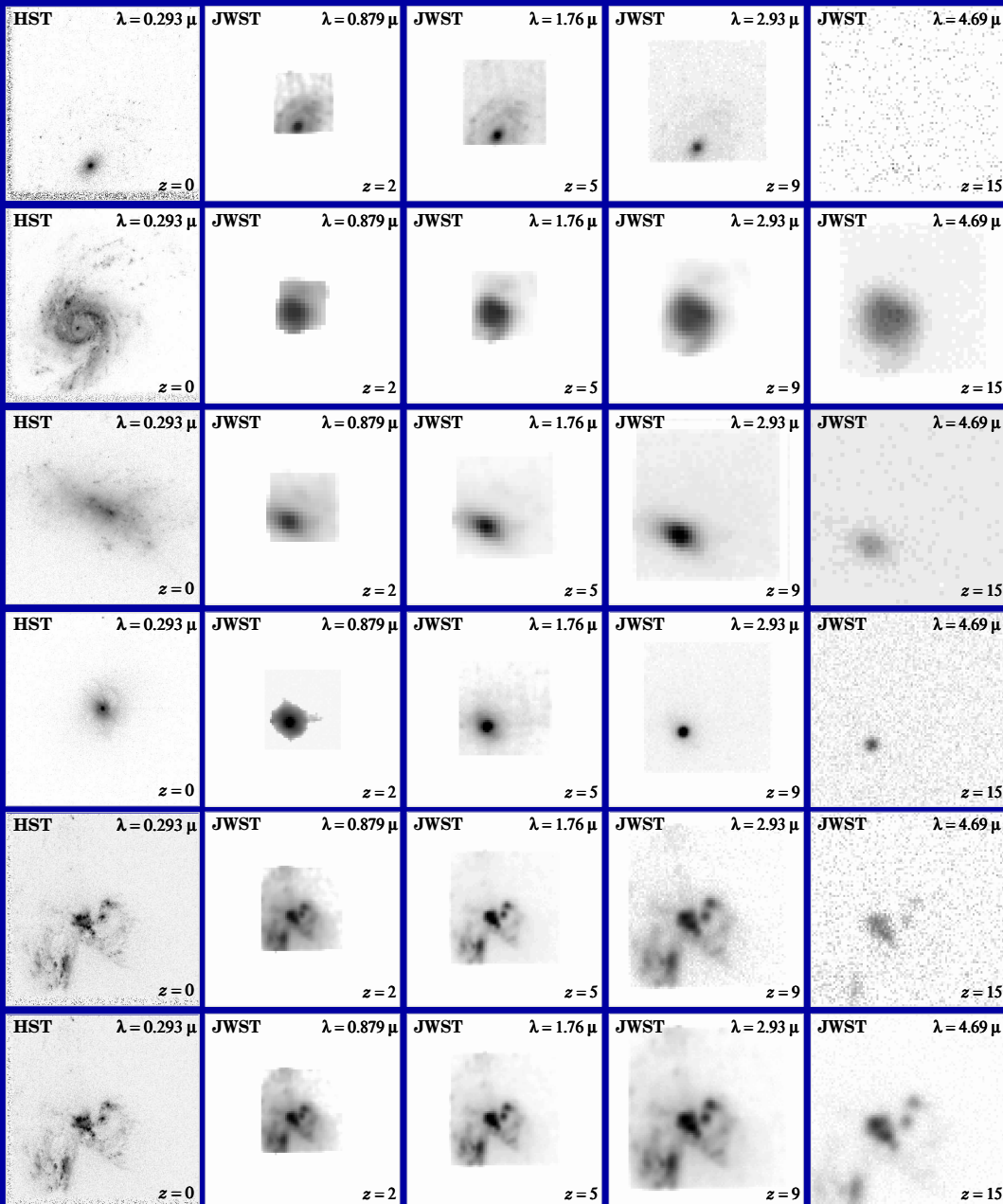
(5) Predicted Galaxy Appearance for JWST at $z \simeq 1-15$



- 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 Mission Preliminary Design Review (PDR) in spring 2008 \implies Phase C/D.

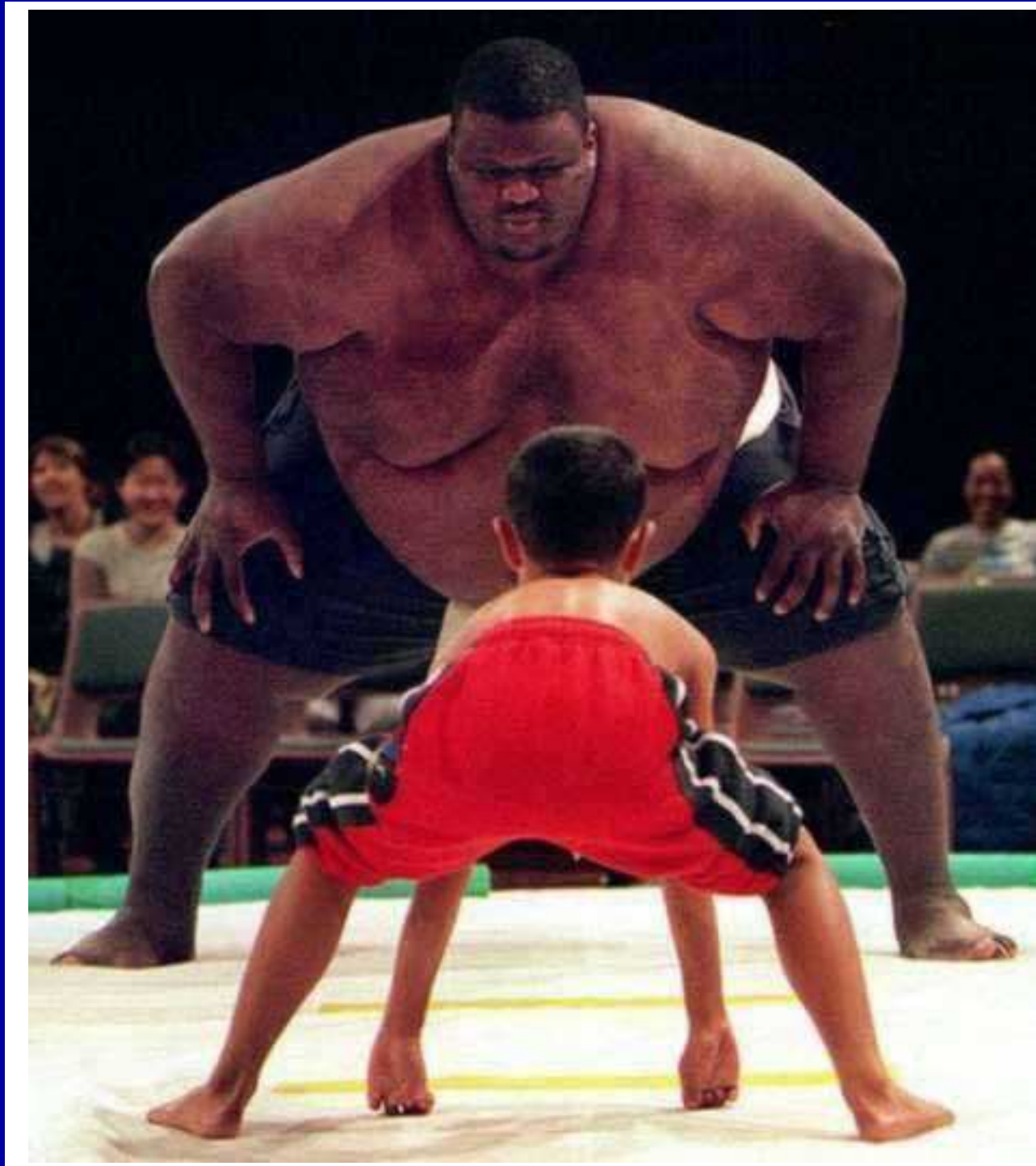
(2) JWST will map the epochs of First Light, Reionization, and Galaxy Assembly in detail. It will determine:

- 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:

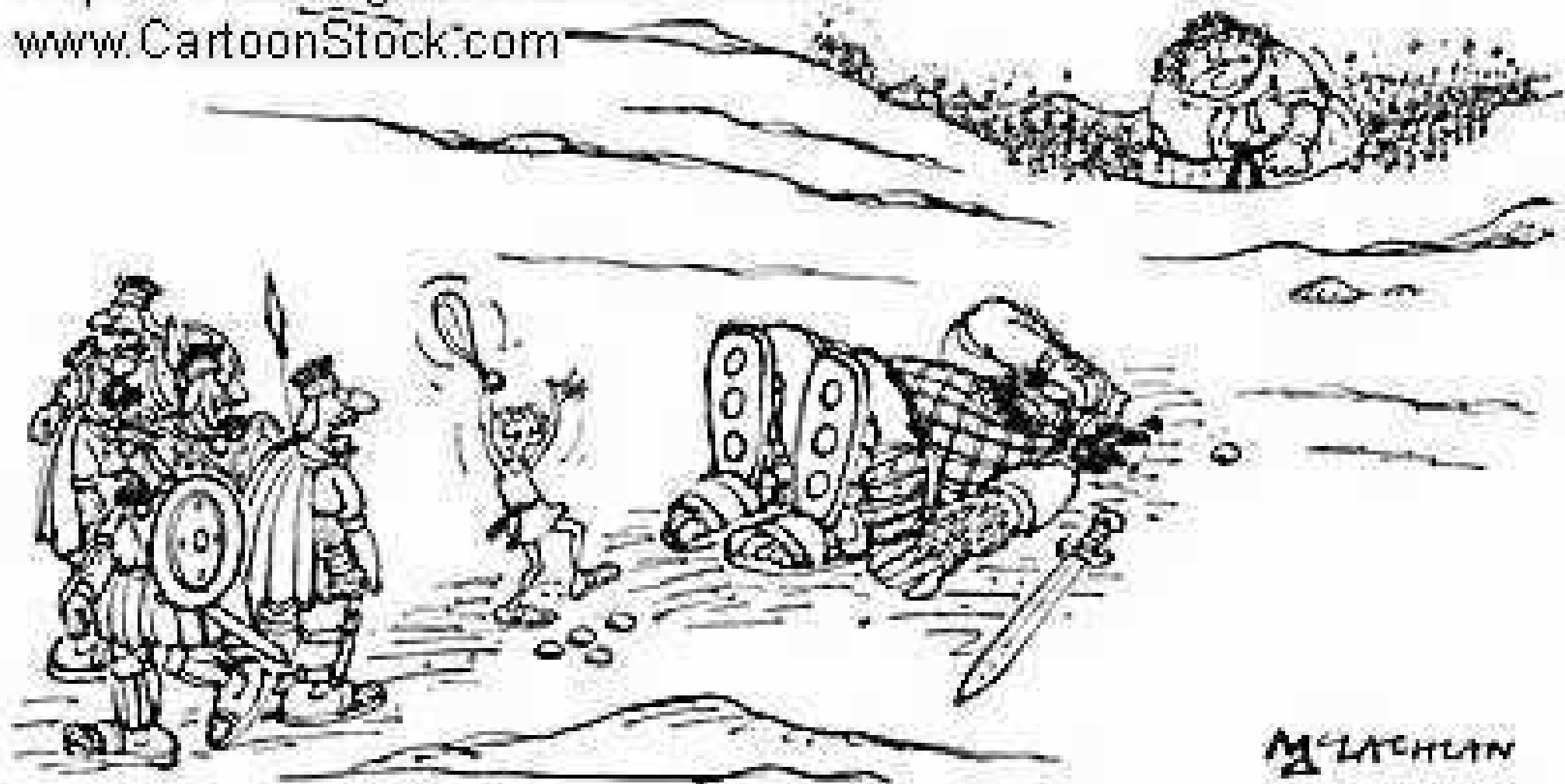
- Current generation of graduate students and postdocs will be using JWST during their professional careers.
- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS



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

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"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]

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. 2008, *J. Adv. Space Res.*, Vol. 41, 1965 (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





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



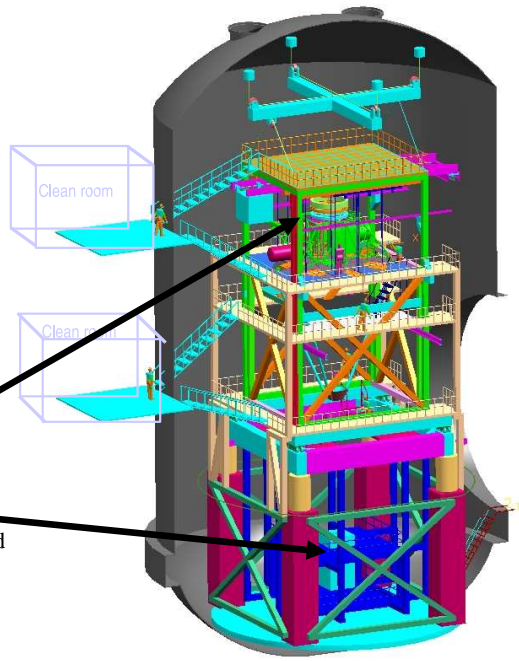
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

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

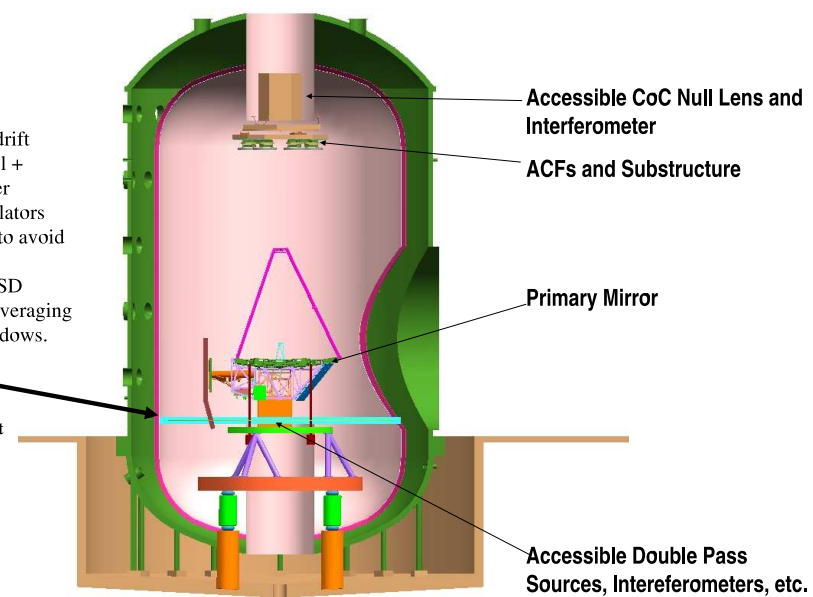


JSC "Cup Up" Test Configuration (New Proposal)



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

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

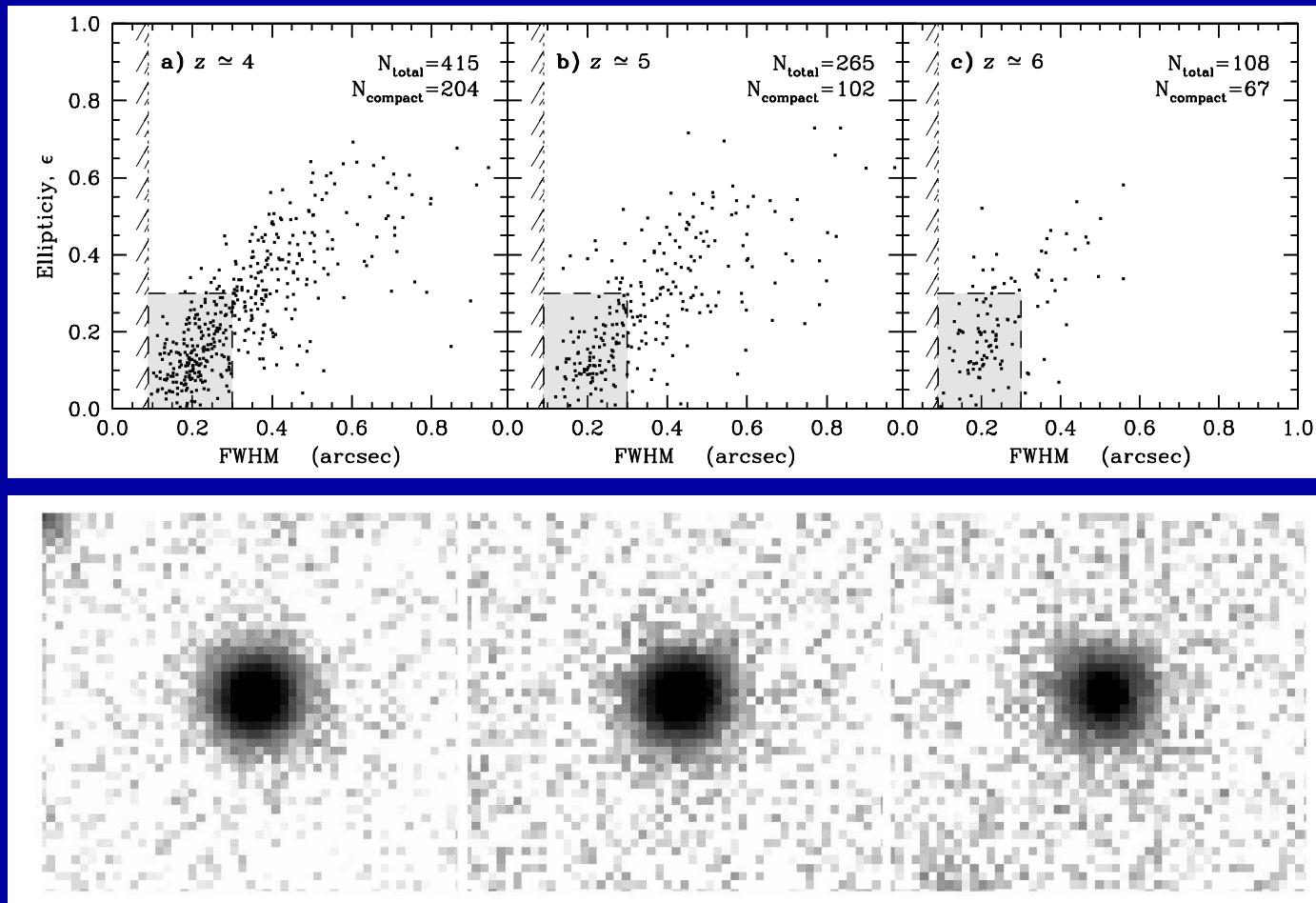


Drawing care of ITT

JWST underwent several significant replans and risk-reduction schemes:

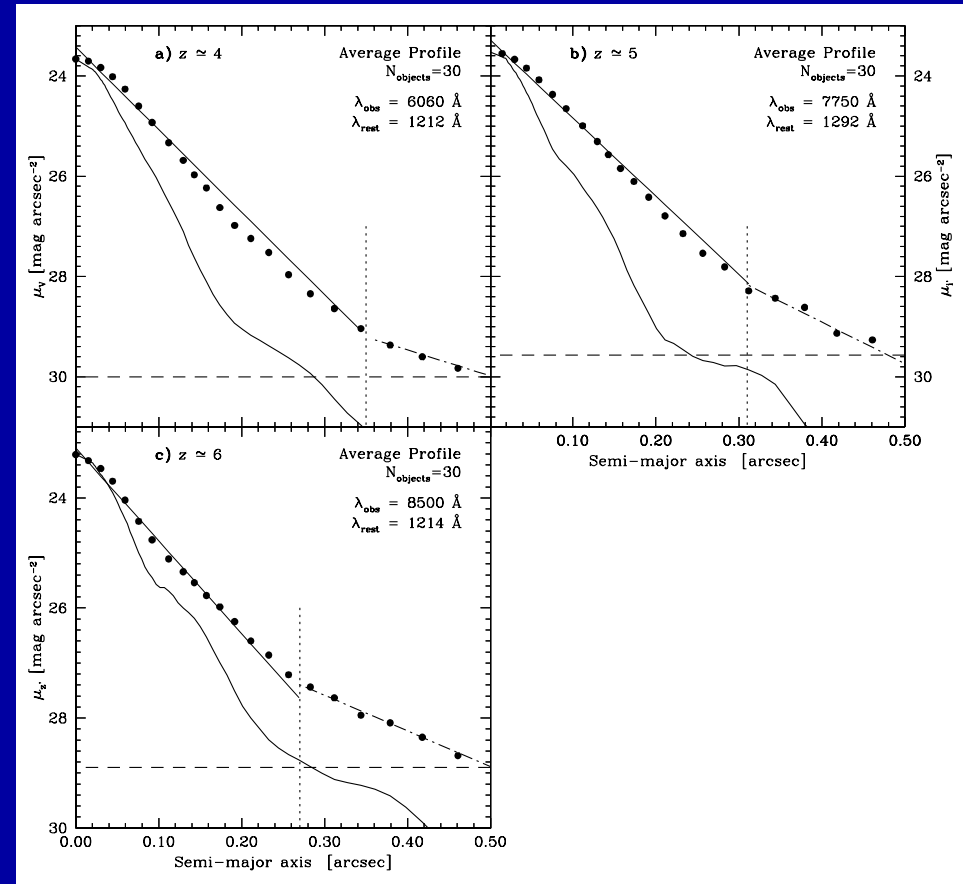
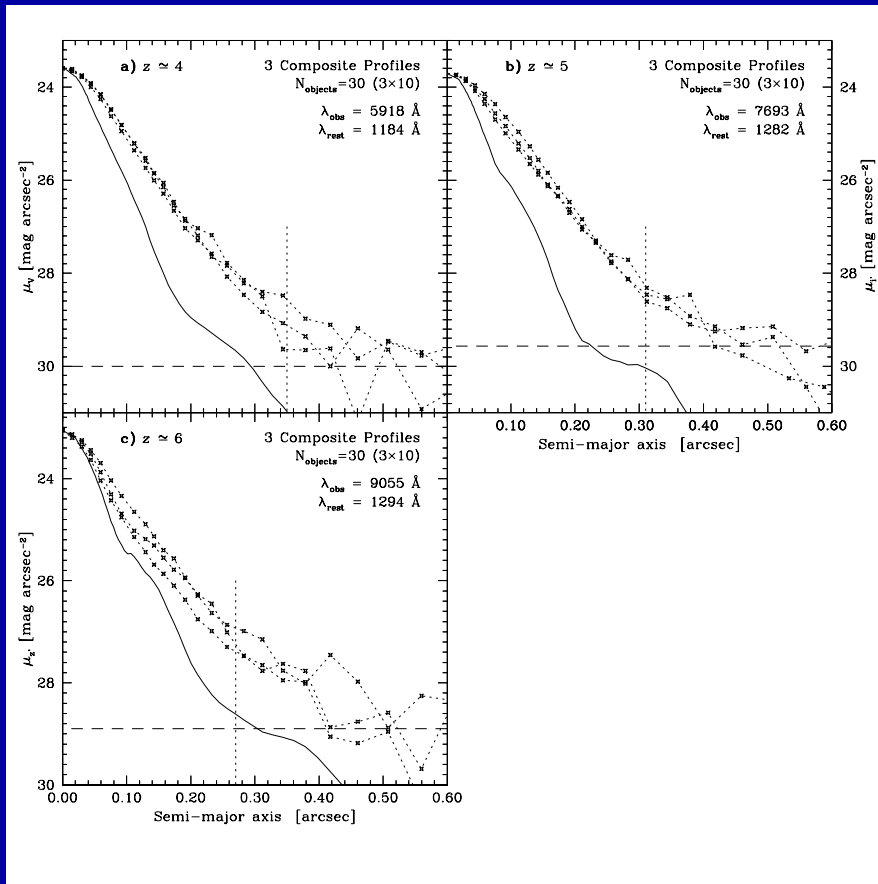
- $\lesssim 2003$: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6)
- 2007: Simplification of sun-shield & end-to-end testing; passed T-NAR.
- 2008: Passed Mission PDR & Non-Advocate Review \implies Phase C/D.

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 ~ 5000 HST orbits ($\simeq 300$ JWST hrs; Hathi et al. 2008 AJ).

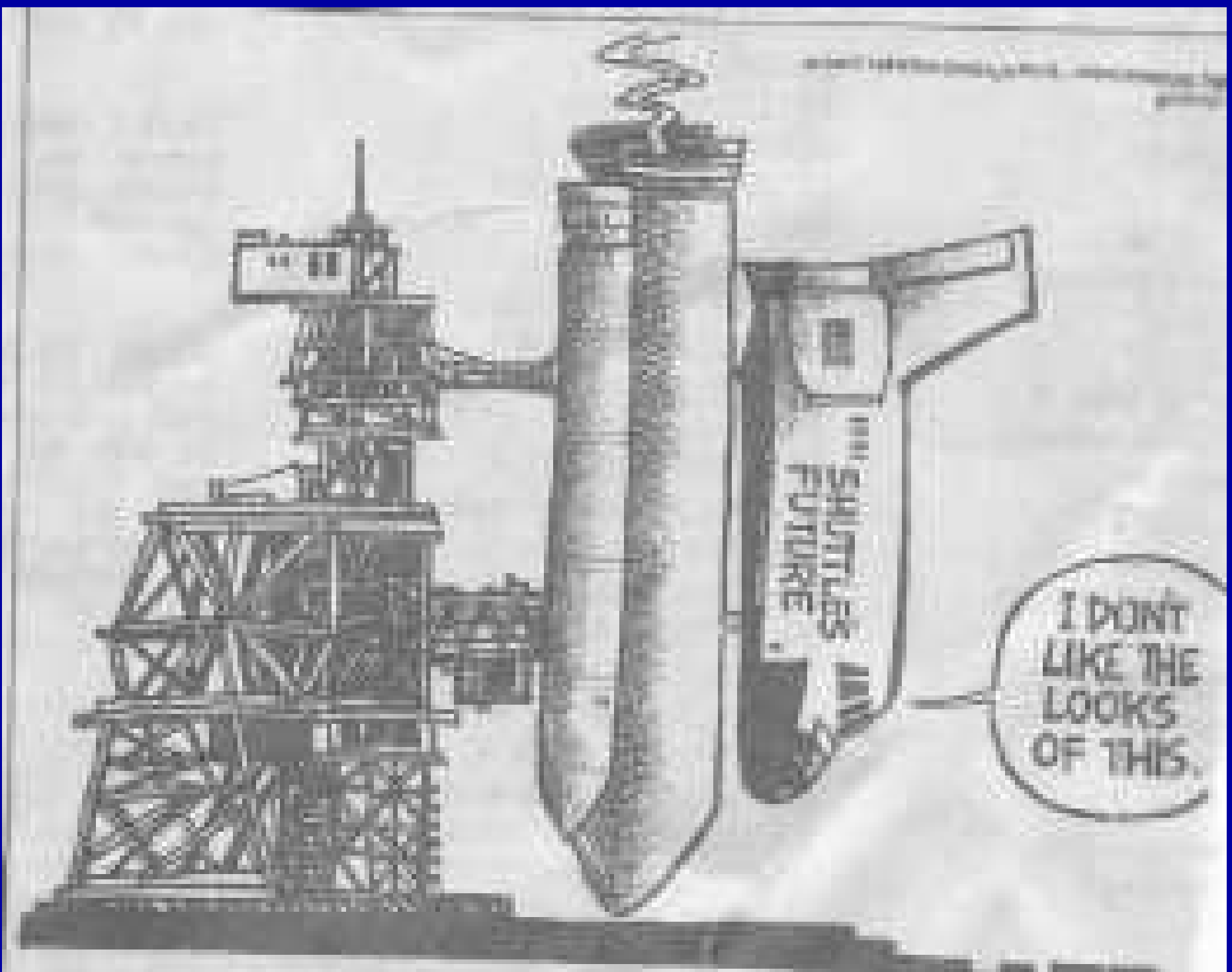
Dynamical ages of Dwarf Galaxies at $z \simeq 4-6$?



- HUDF sky-subtraction error is $2-3 \cdot 10^{-3}$ or $AB \simeq 29.0-30.0$ mag/arcsec²
- 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 $\tau_{dyn} \simeq 0.1-0.2$ 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 $z \simeq 6.6$?

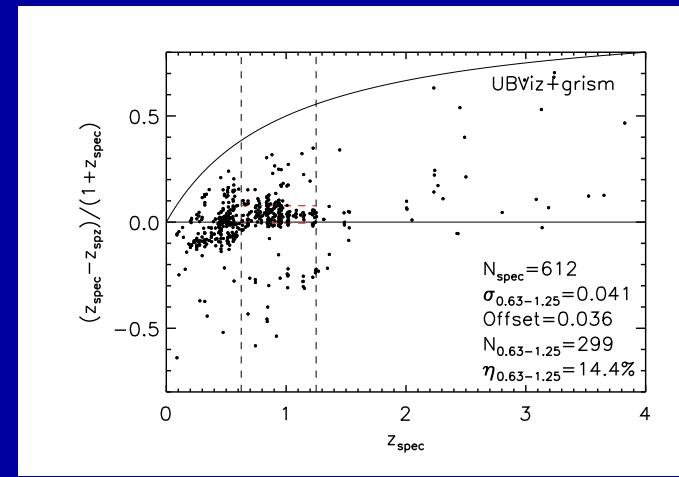
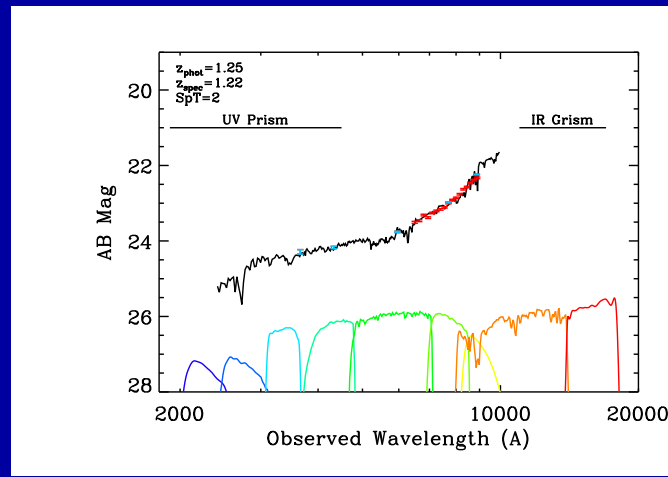
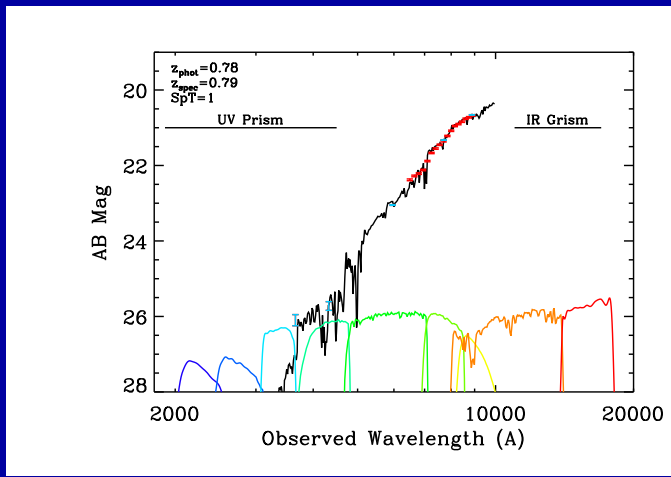
Appendix 1: Complementary studies with the Hubble Wide Field Camera 3





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

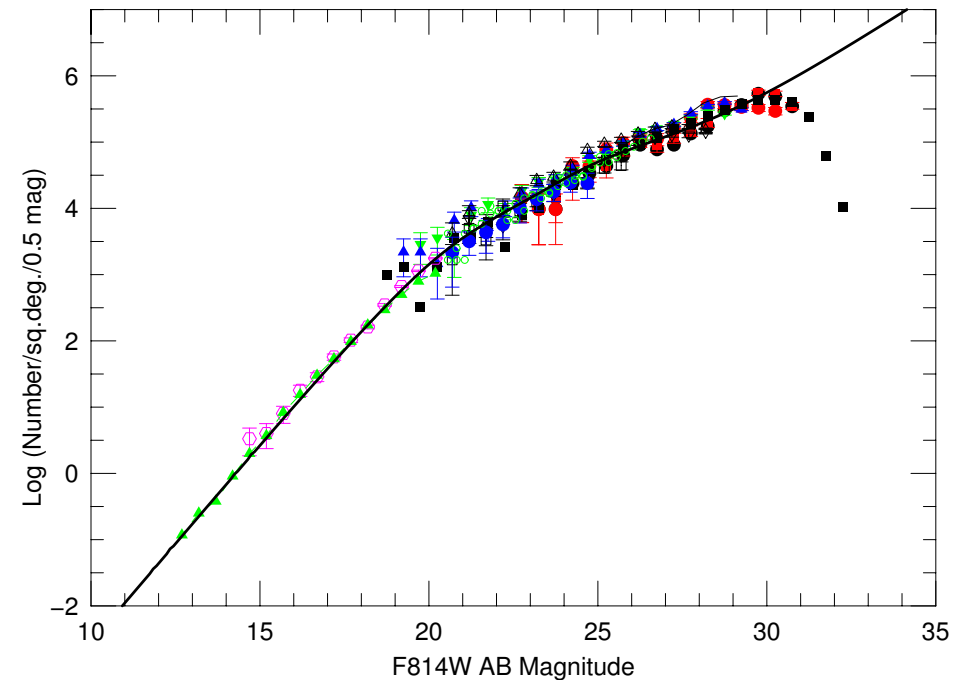
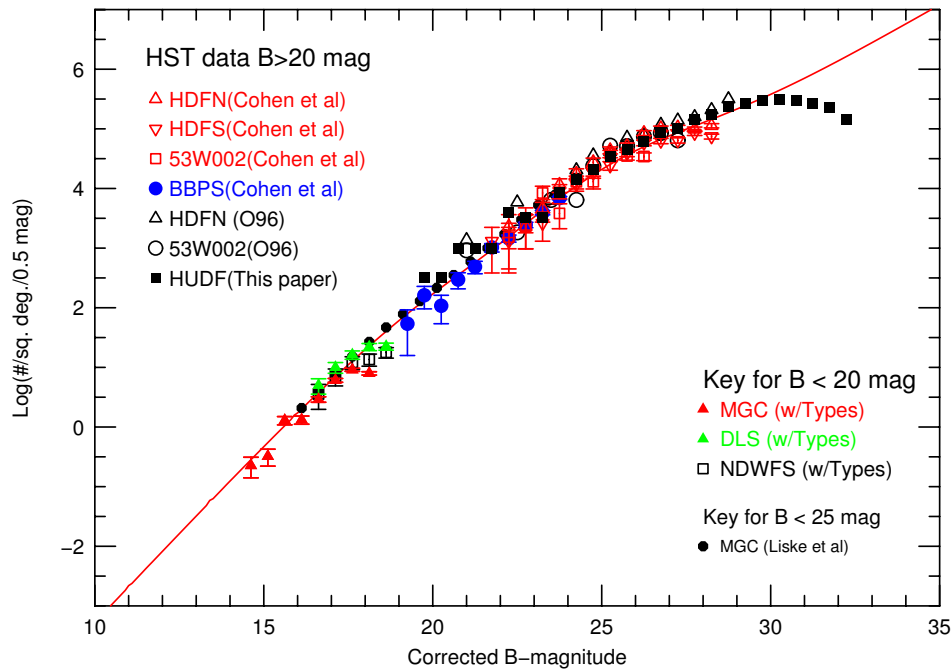
Power of combination of Grism and Broadband for WFC3



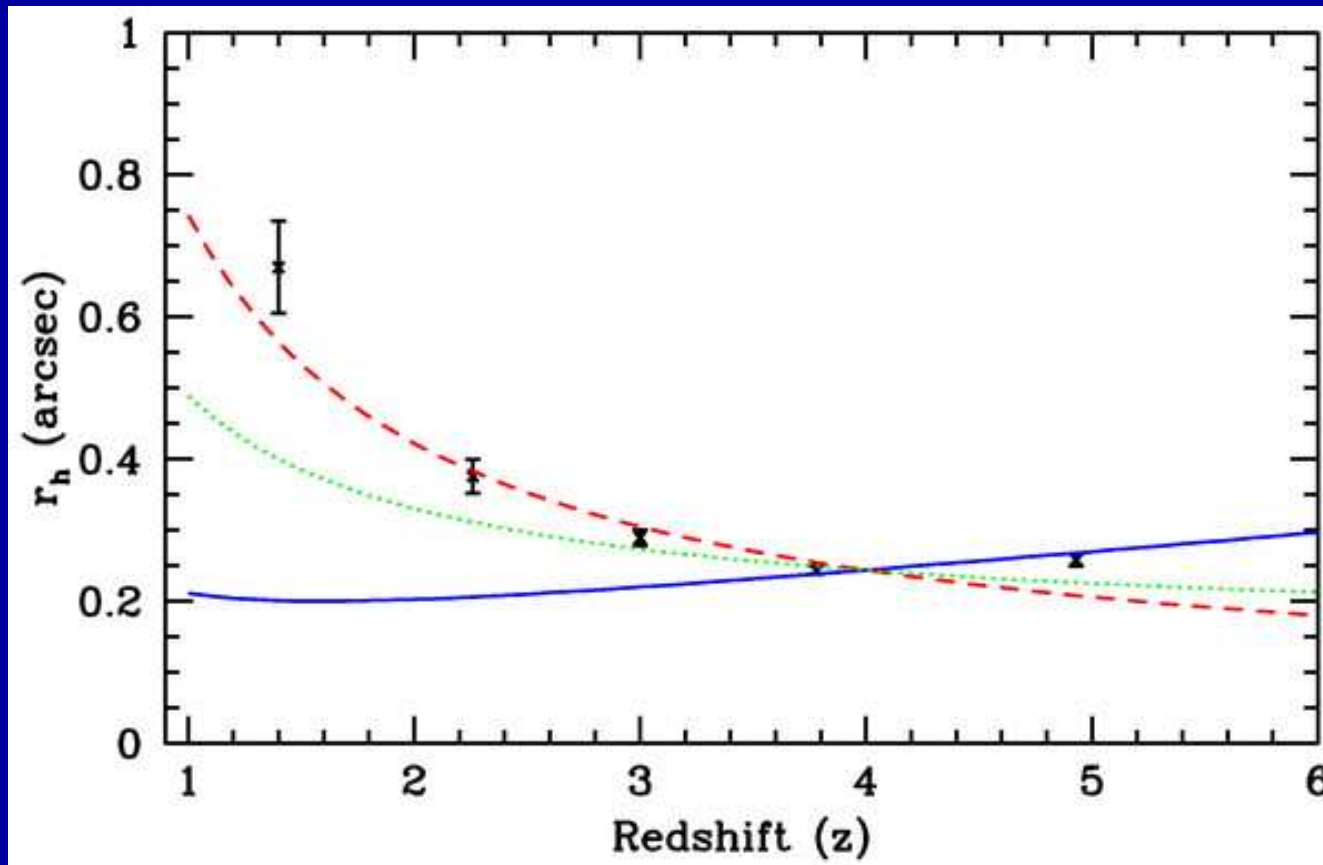
Lessons from the Hubble ACS grism surveys “GRAPES” and “PEARS” (Malhotra et al. 2005; Cohen et al. 2007; Ryan et al. 2007, ApJ, 668, 839):

- (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 $0.2-1.7 \mu\text{m}$, permitting high accuracy photo-z’s for faint galaxies of all types to $AB \simeq 27.0-29.0$ mag (10σ for $\sim 2-80$ orbits/filter).

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

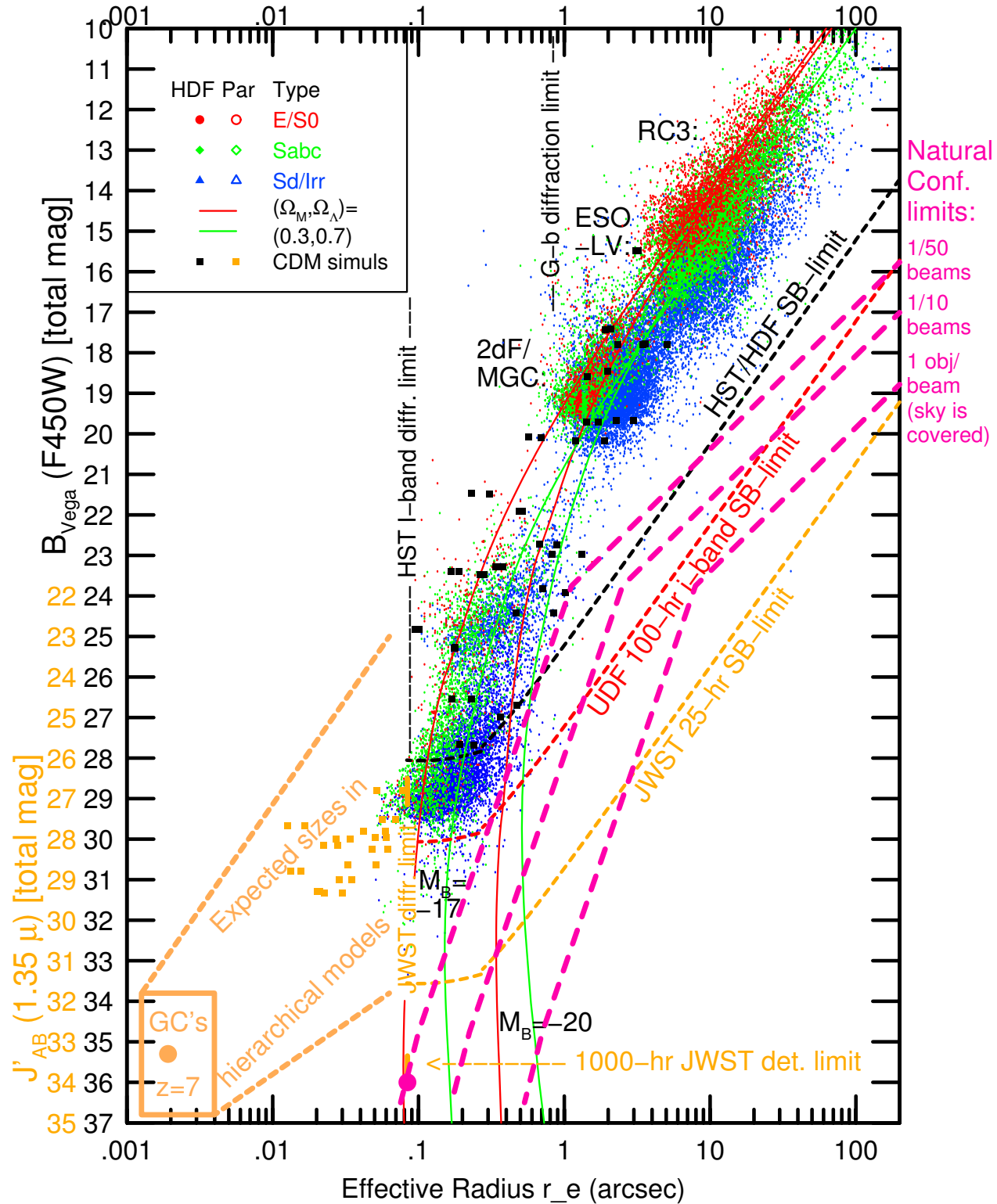


- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2 \times 10^6$ galaxies/deg² to AB=31.5 mag ($\simeq 1$ nJy at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq 1$ and 10 nJy, resp.
- \Rightarrow Must carry out JWST and SKA nJy-surveys with sufficient 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 Θ - z relation that minimizes at $z \simeq 1.6$ for Λ -cosmology.
- Evidence of intrinsic size evolution: $r_{hl}(z) \propto r_{hl}(0) \cdot (1+z)^{-s}$, $s \simeq 1$.
- 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.

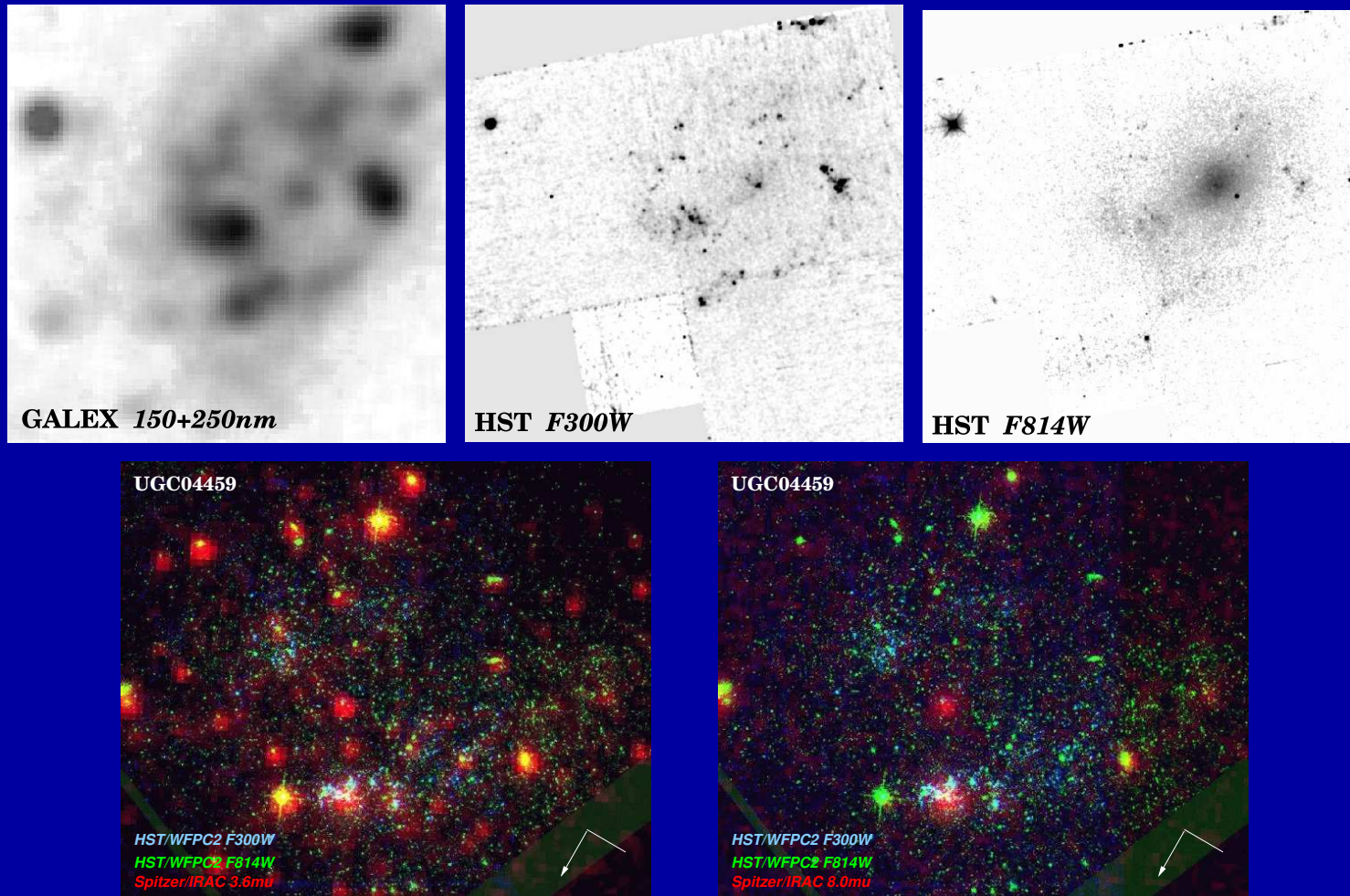


Combination of ground-based and space-based HST surveys show:

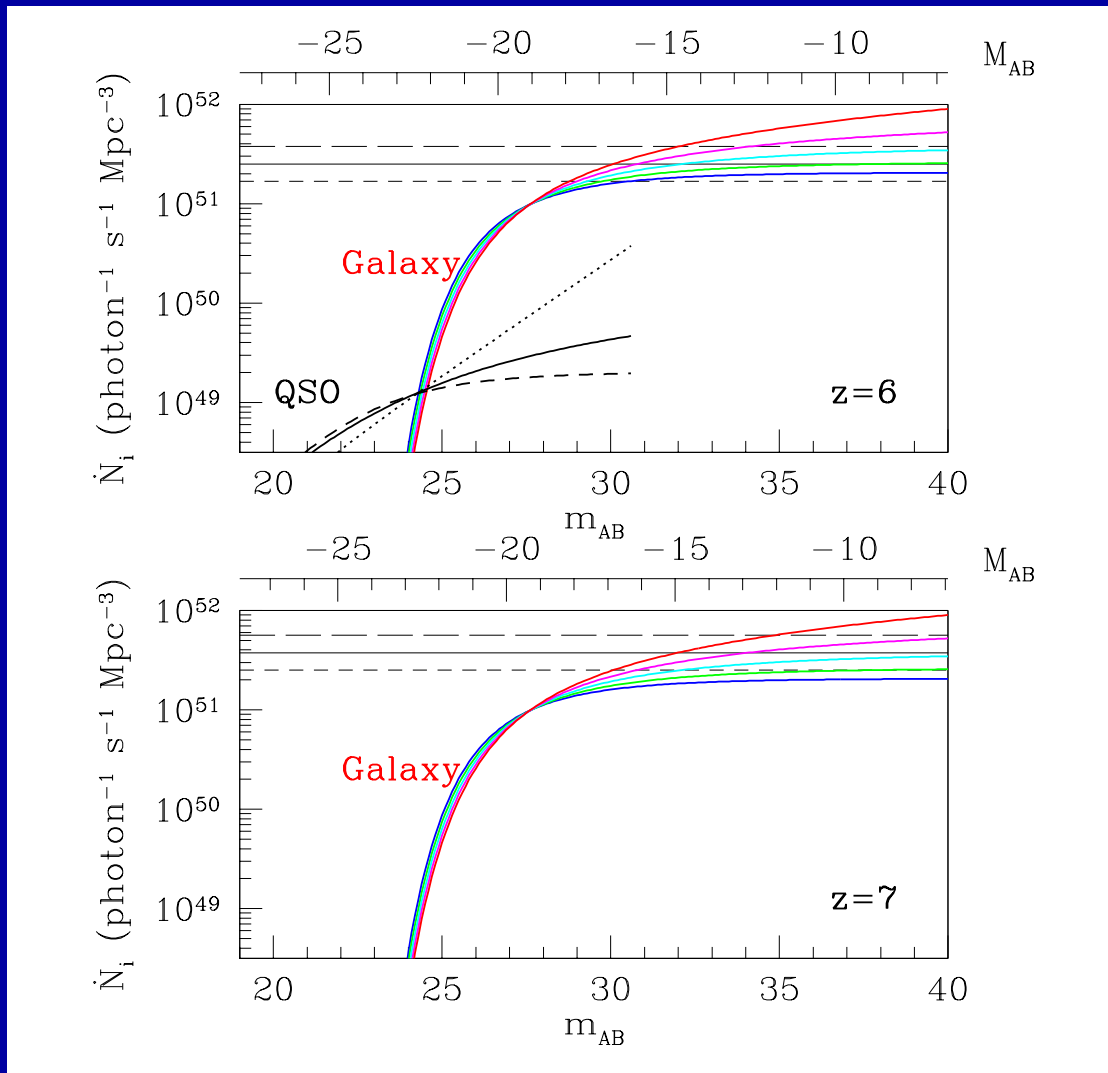
- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:
- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$ -dimming), but also due to:
 - (2a) hierarchical formation causes size evolution: $r_{hl}(z) \propto r_{hl}(0) (1+z)^{-1}$
 - (2b) 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 2×10^6 galaxies/deg². 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. 2008, J. Adv. Space Res., Vol. 41, 1965 (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.

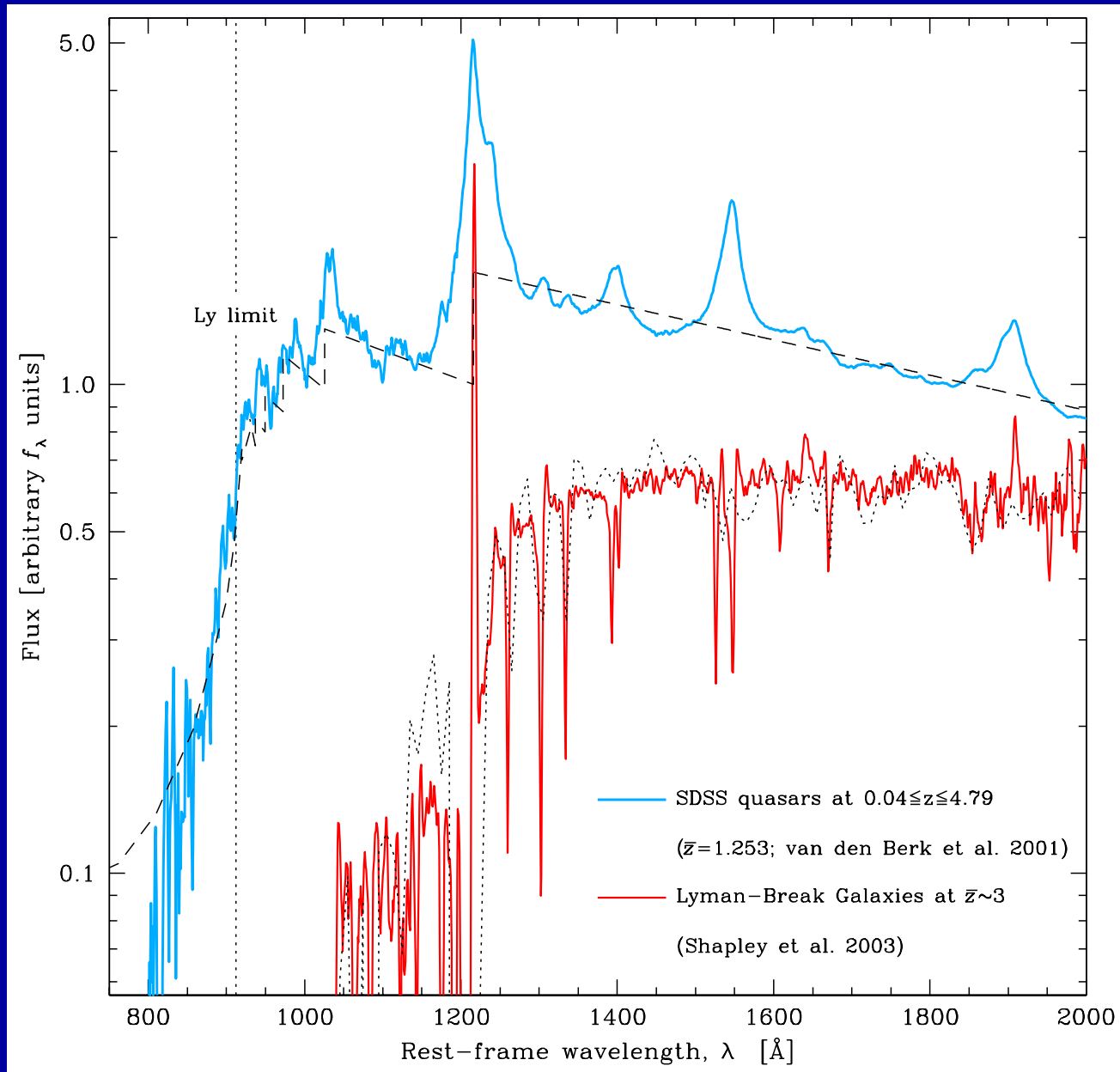


- A steep LF of $z \simeq 6$ objects (Yan & Windhorst 2004a, ApJL, 600, L1) could provide enough UV-photons to complete the reionization epoch at $z \simeq 6$ (if $f_{esc} \gtrsim 10\%$).

- Pop II dwarf galaxies may not have started shining *per-vasively* 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.