How will JWST measure First Light, Reionization, and Galaxy Assembly in the post WMAP-7 and WFC3 era?

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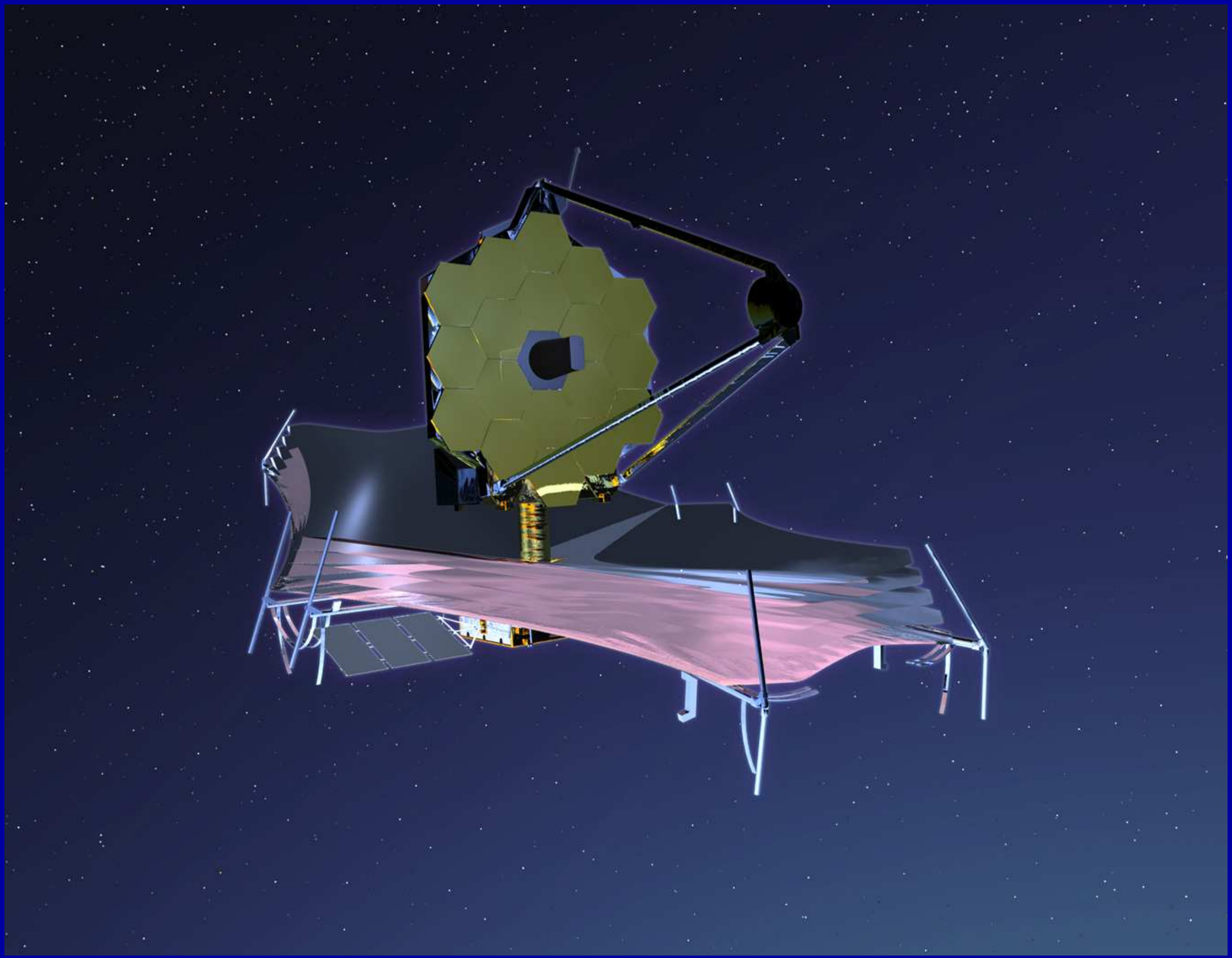


Aspen Winter conference on "The High Redshift Universe: A Multi-Wavelength view", Mo. Feb. 8, 2010

Outline

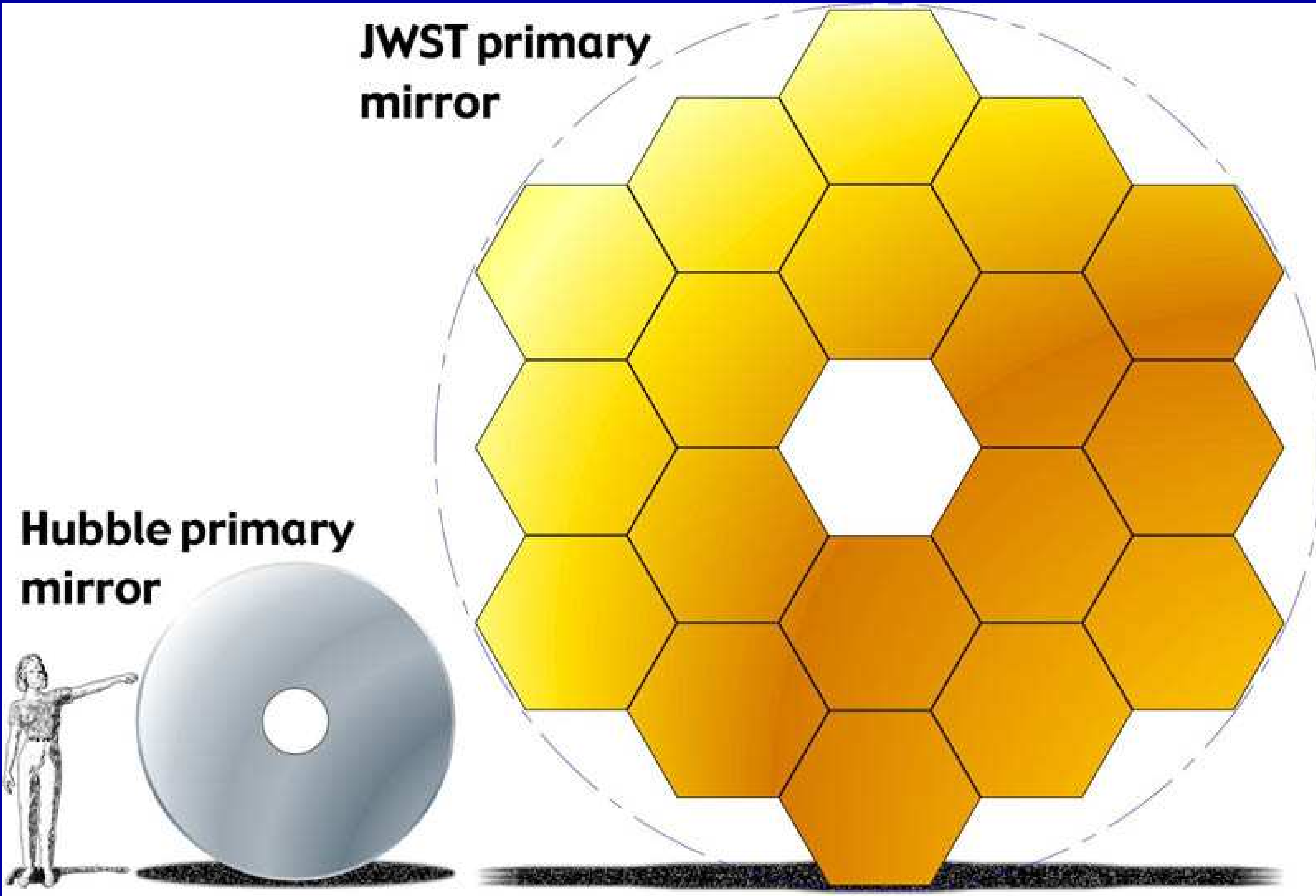
- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) How can JWST can measure First Light & Reionization?
- (4) How can JWST measure Galaxy Assembly?

  [With some recent HST WFC3 results to support (3) and (4)].

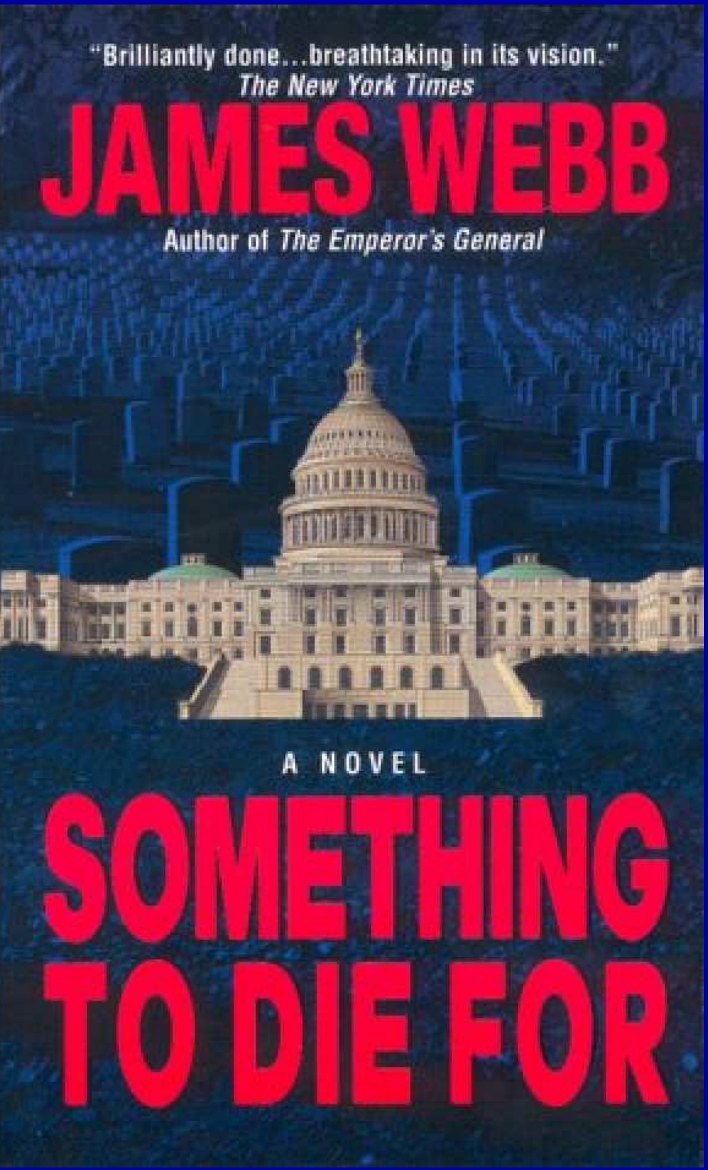
- (5) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1$–15
- (6) Summary and Conclusions
- Appendix 1: Will JWST reach the Natural Confusion Limit?

Sponsored by NASA/JWST & HST

ARIZONA STATE UNIVERSITY



JWST ~2.5× larger than Hubble, so at ~2.5× larger wavelengths:
JWST has the same resolution in the near-IR as HST in the optical.



Need hard-working grad students & postdocs in $\gtrsim$2014 ... It'll be worth it!

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

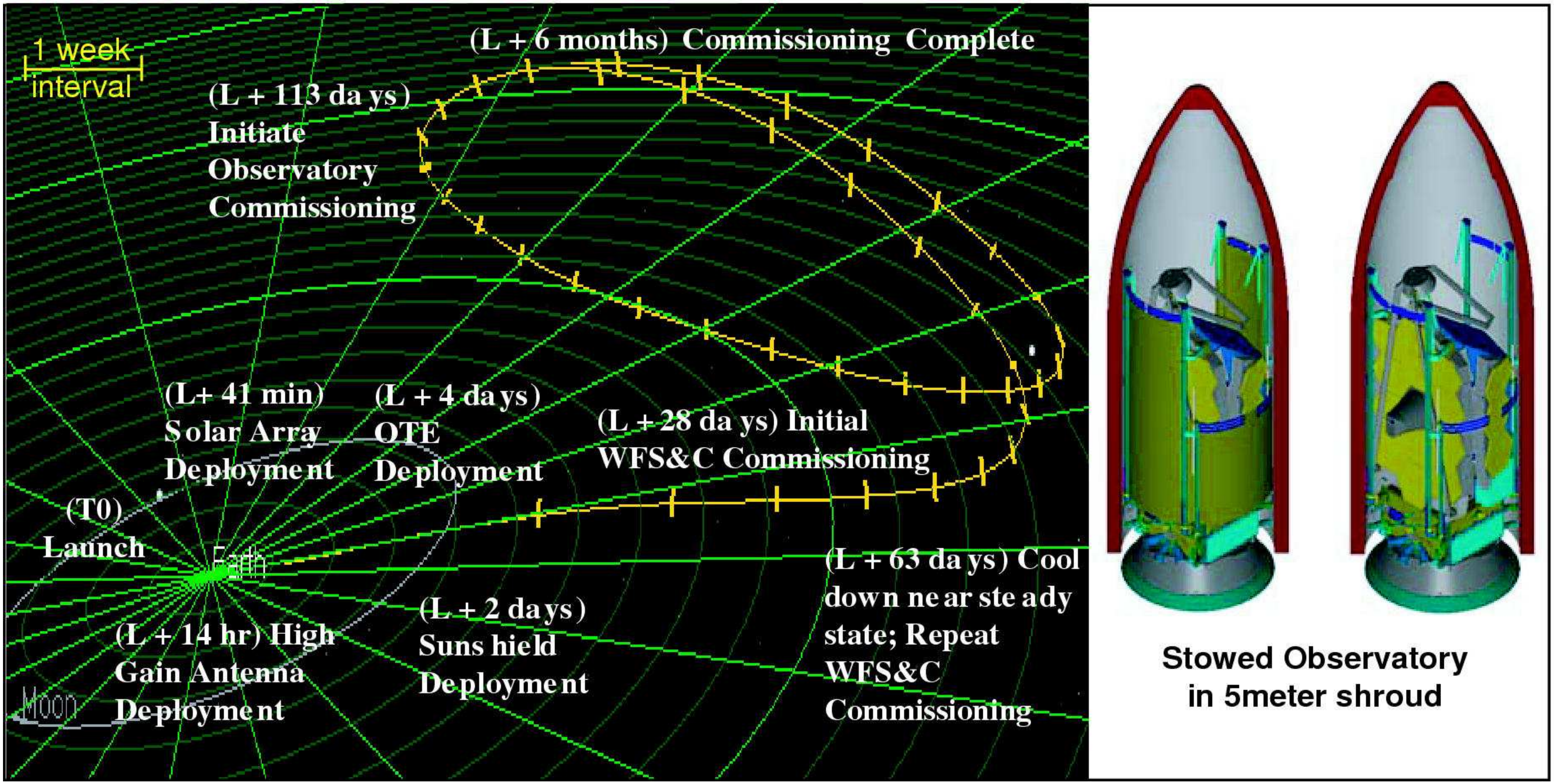
- (1) What is the James Webb Space Telescope (JWST)?

- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.7 to 29 μm, to be launched in June $\gtrsim$2014.
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

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

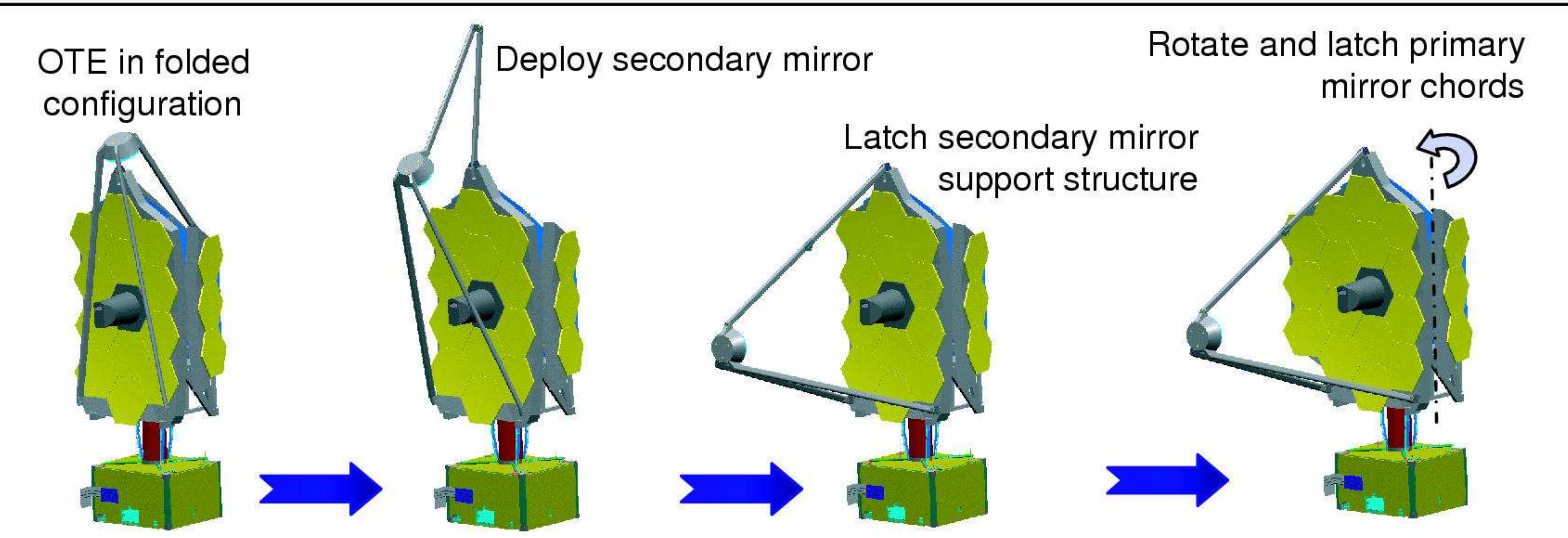
Life-sized model of JWST, at NASA/GSFC Friday afternoon after 5 pm ...

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



- After launch in June 2014 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

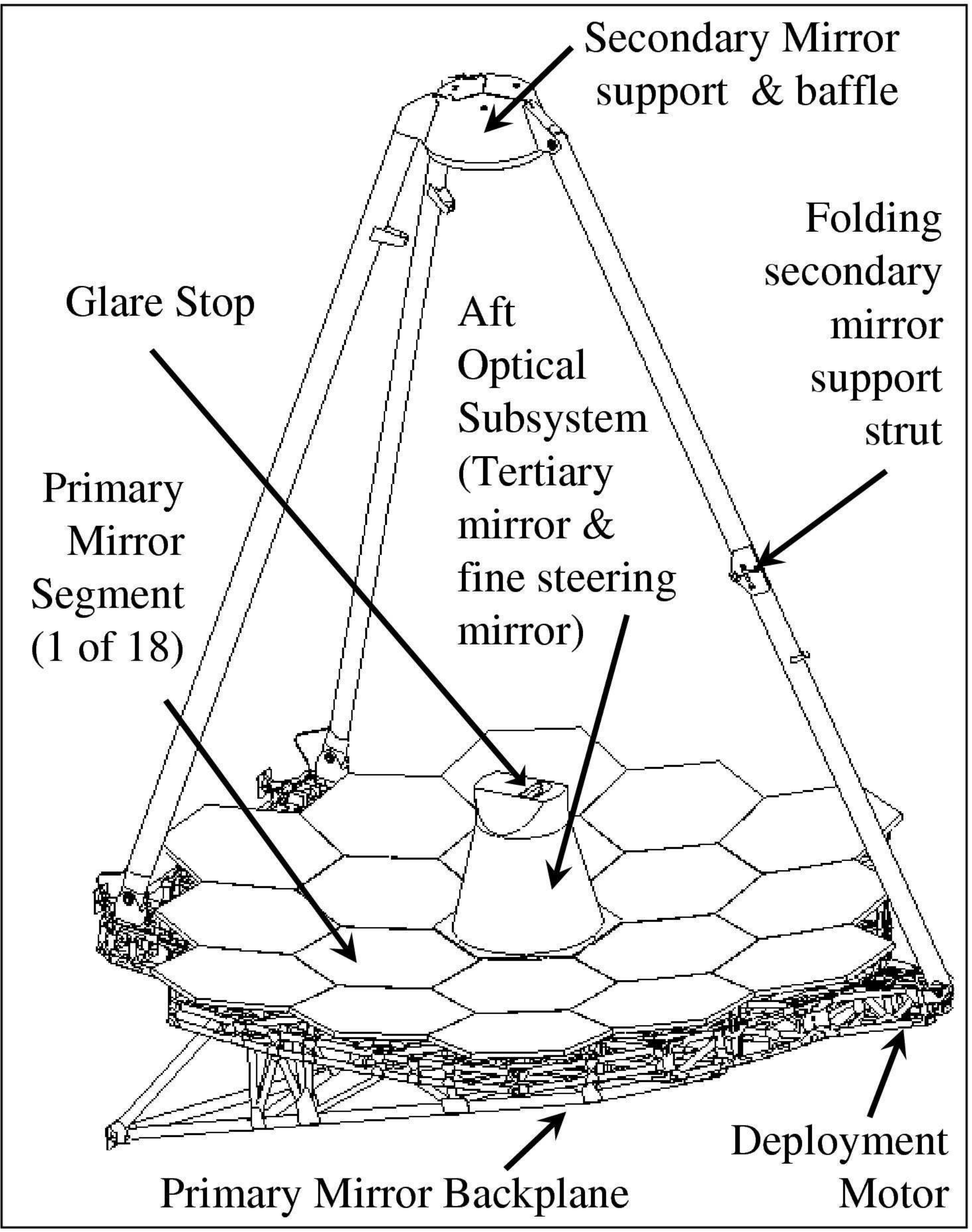
• (1) How will JWST be automatically deployed?



• During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit, 1.5 million km from Earth.

• The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: component and system tests at JSC.

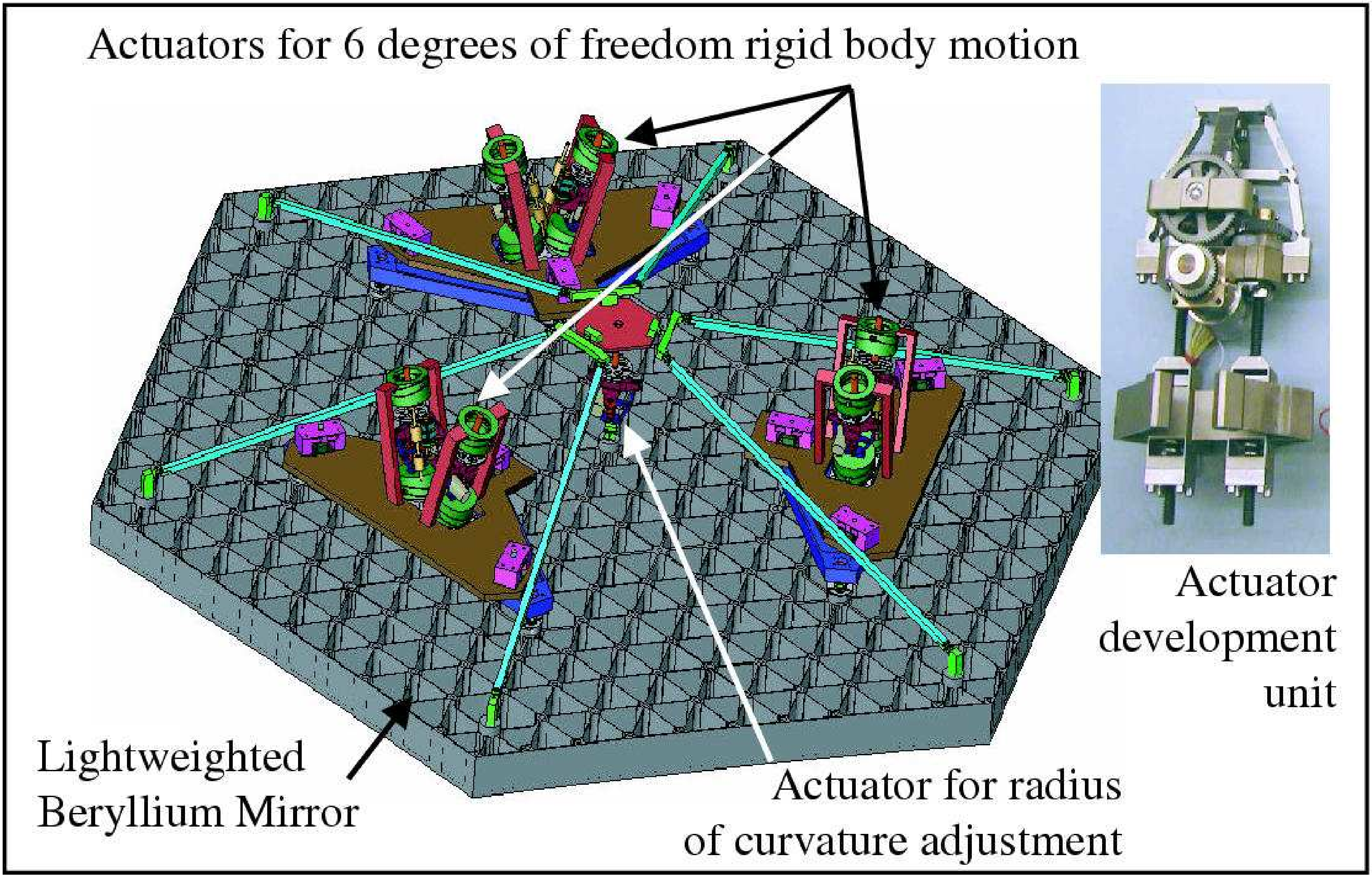
• Component fabrication, testing, & integration is on schedule: 3 out of 18 flight mirrors completely done, and at the 45K 2.0μm diffraction limit!



Ball 1/6-model for WFS: diffraction-limited 2.0 μm images (Strehl$\gtrsim$0.85).

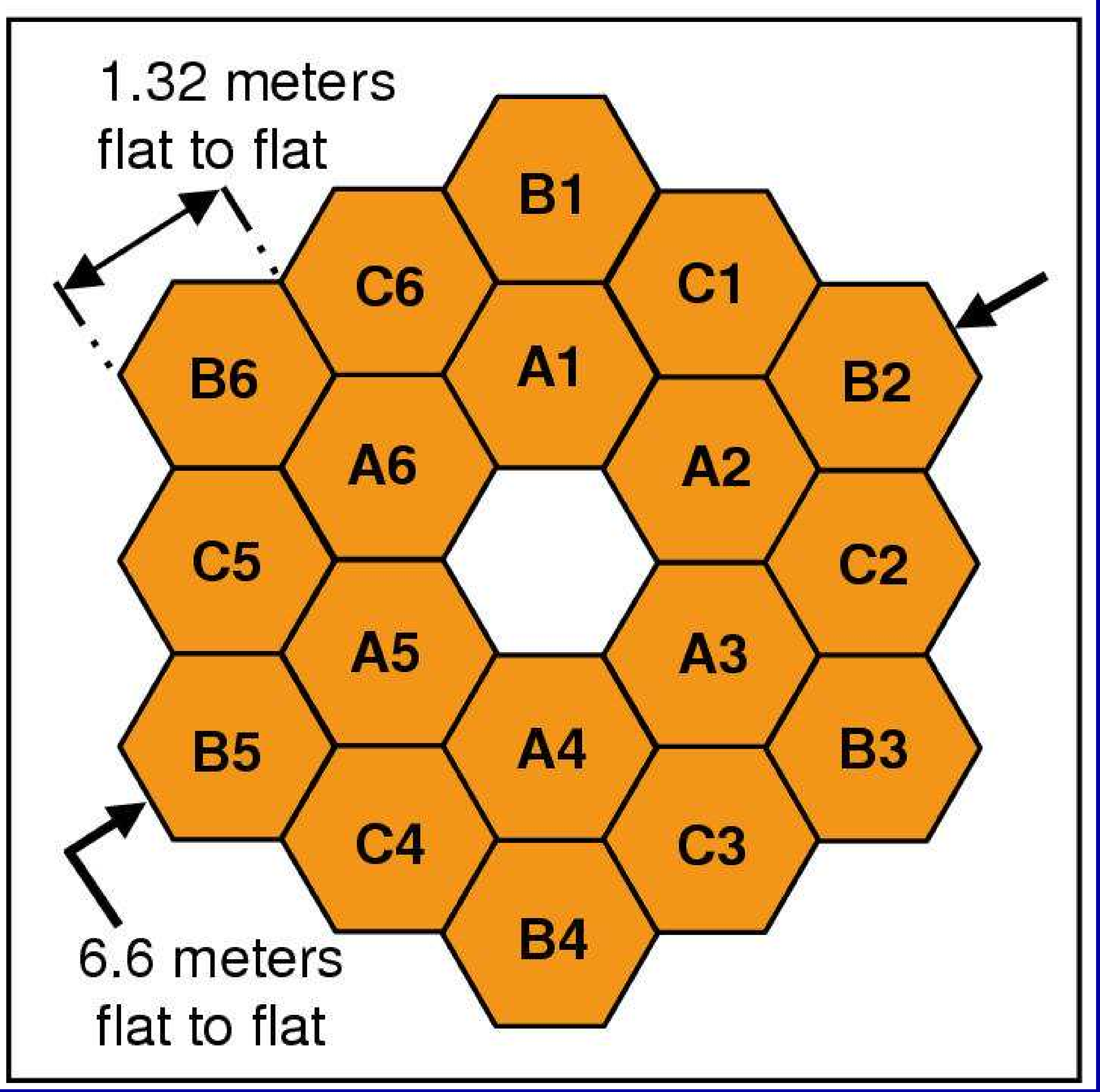
Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2011-2013.

In L2, WFS updates every 10 days depending on scheduling/SC-illumination.



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

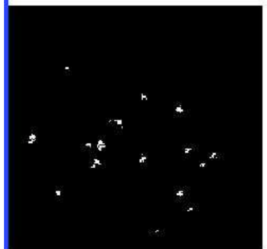
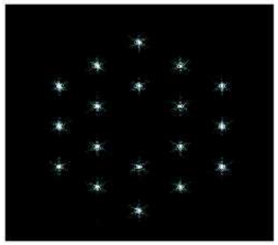
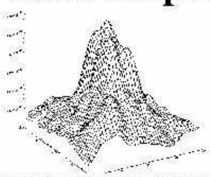
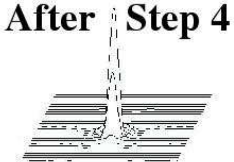
Redundant & doubly-redundant mechanisms, quite forgiving against failures



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 ...

Step		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	**After Step 1** 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 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 WFS demo of H/W, S/W on 1/6 scale model (2 μm-Strehl$\gtrsim$0.85).

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

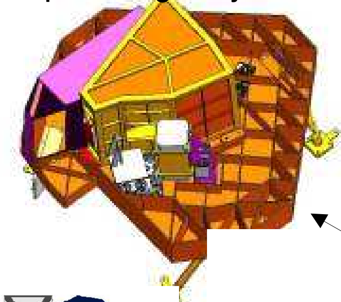
Ball 1/6-scale model: WFS produces diffraction-limited images at 2.0 μm.

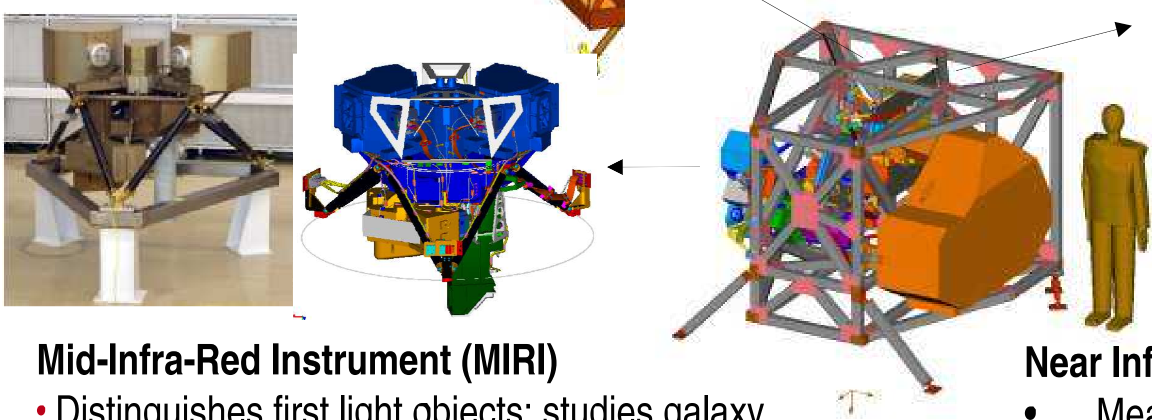
• (2) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

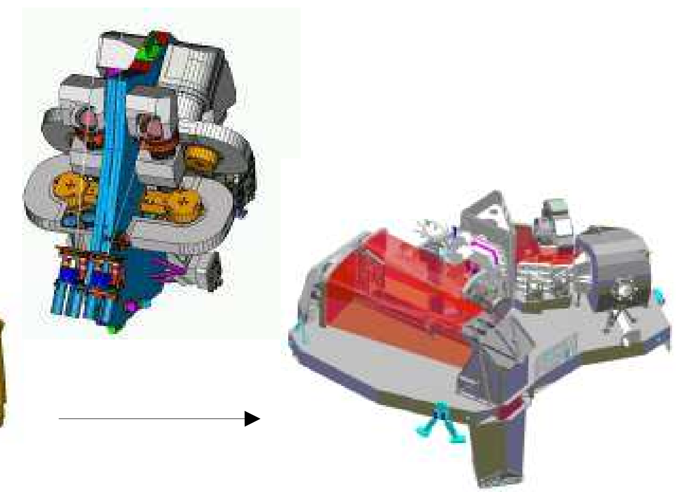
Instrument Overview

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

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



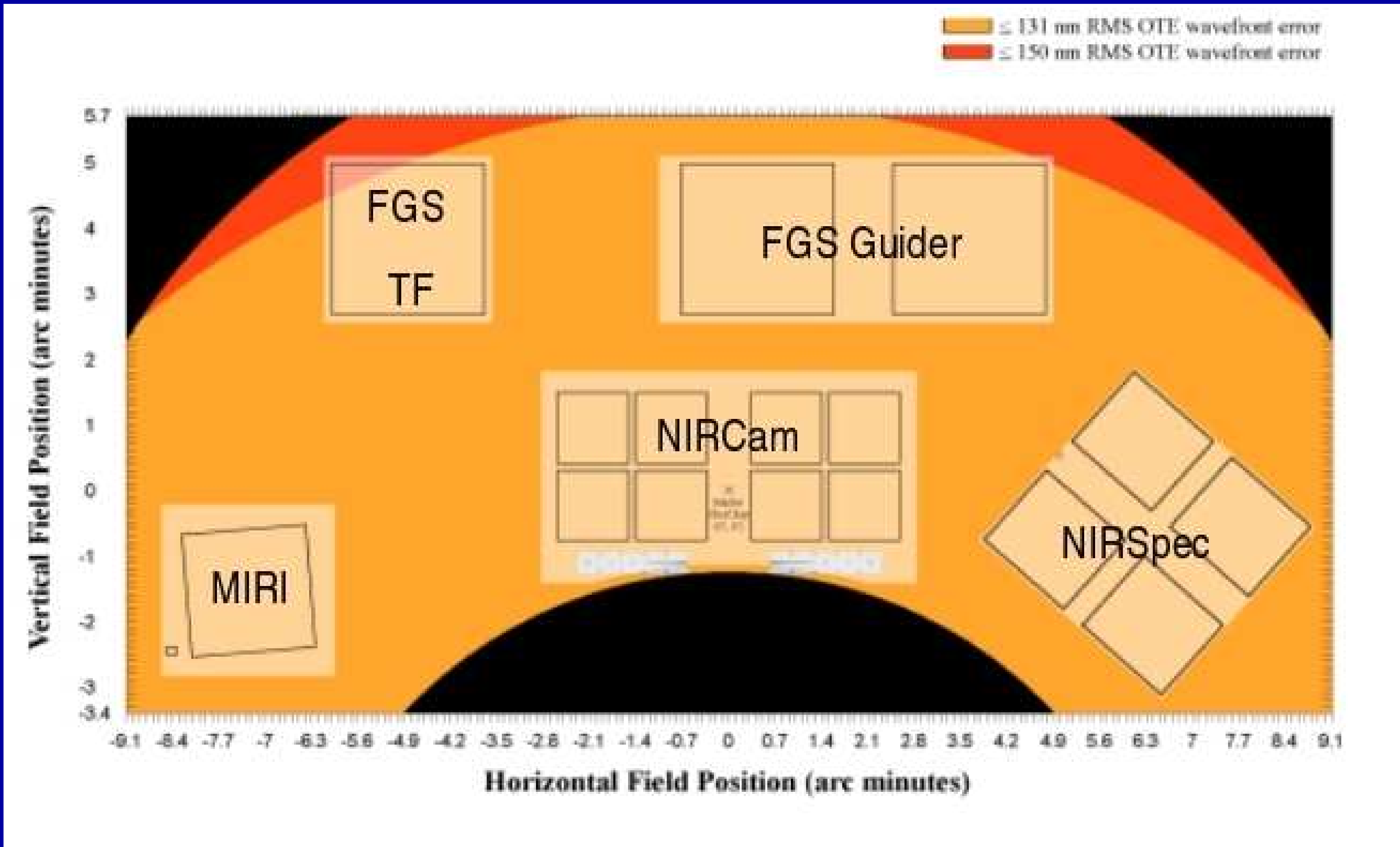




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

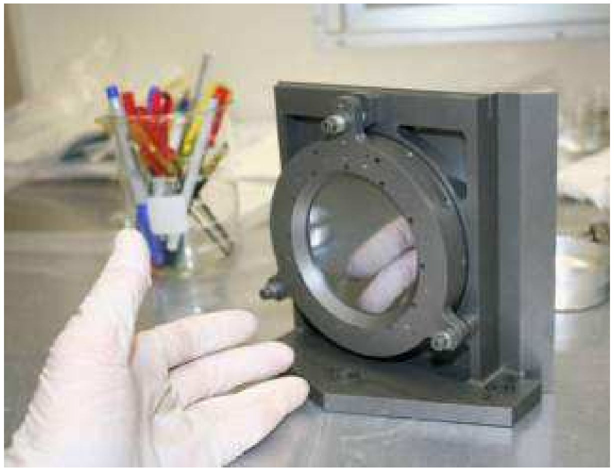
- (2) What instruments will JWST have?



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

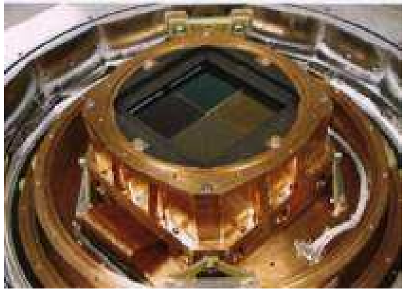
- Currently only being implemented for parallel *calibrations.*

Instrument Qual and ETU Model Hardware

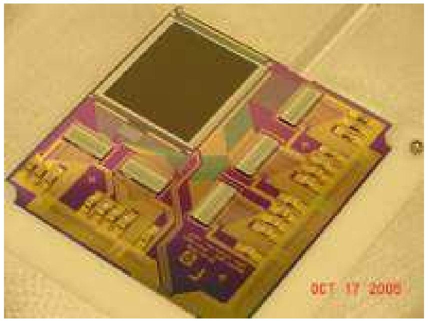


NIRCam Dichroic Beamsplitter

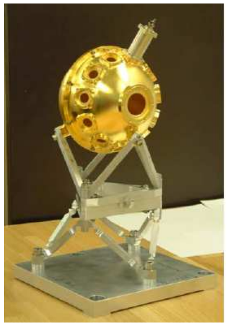
NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



NIRSpec Calibration Assembly

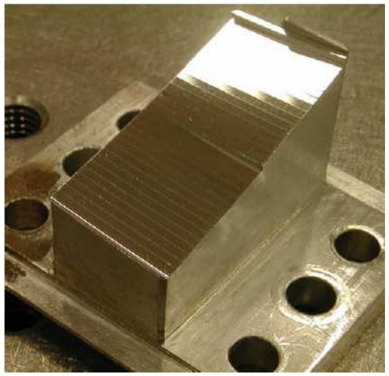
NIRSpec Mirror

SiAs MIR Detector

MIRI Electronics

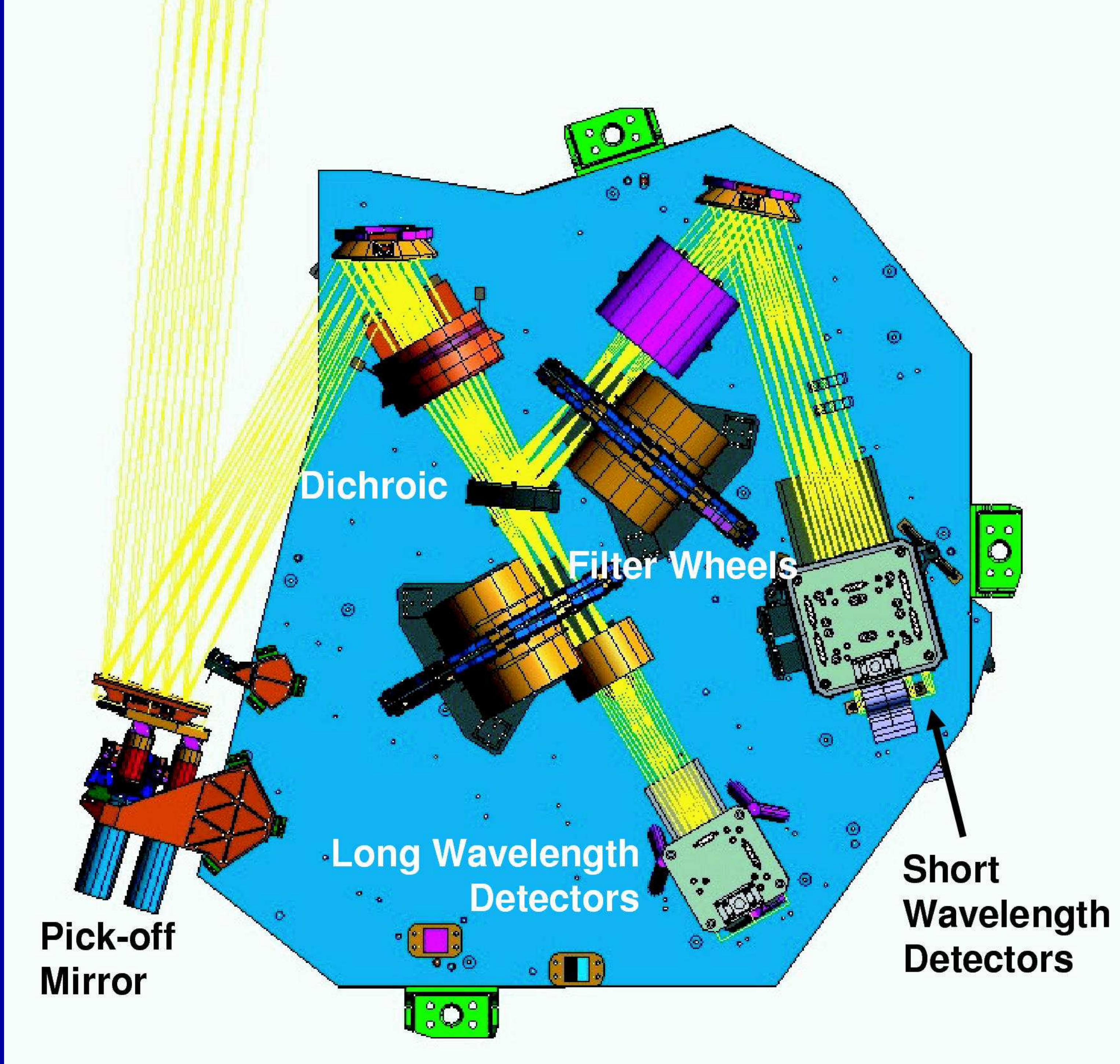
NIRSpec Fore Optics Mirror Assembly

FGS/TF Etalon Filter

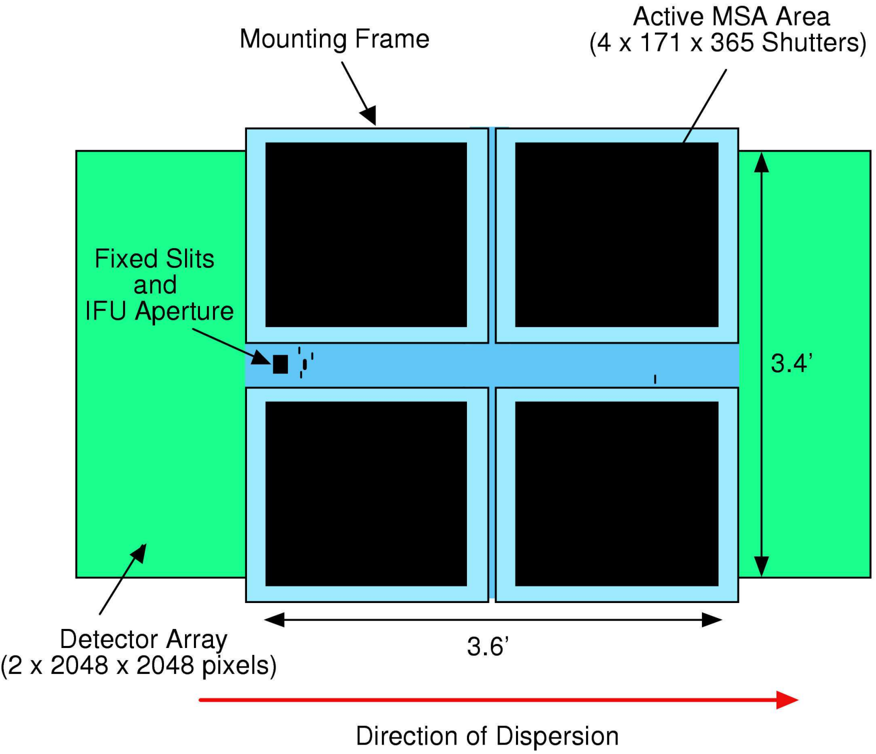


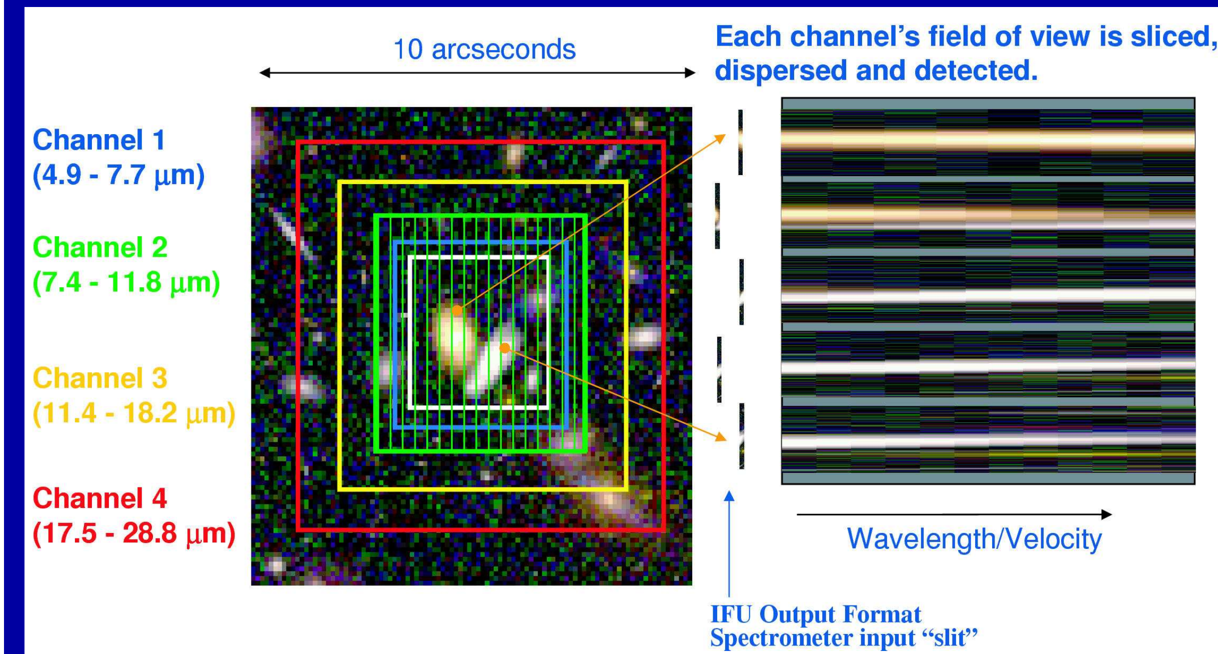
NIRSpec Image Slicer Mirror

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



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





JWST offers significant multiplexing for faint object spectroscopy:

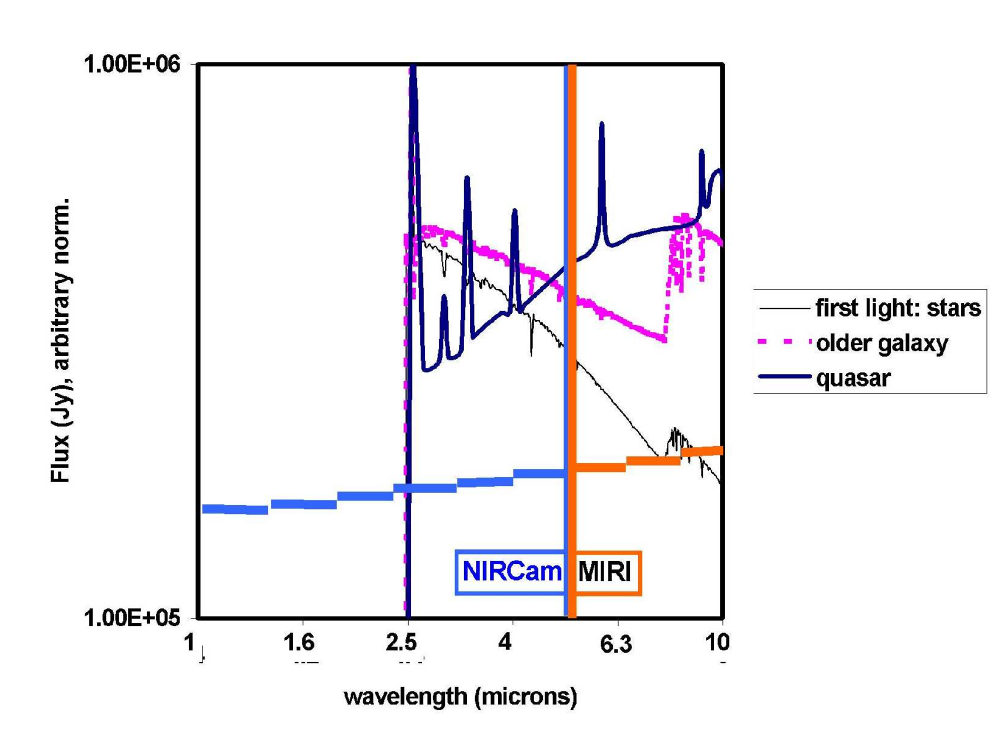
- NIRSpec/MSA with 4×62,415 independently operable micro-shutters (MEMS) that cover $\lambda \simeq 1$–$5\ \mu$m at R$\simeq$100–1000.

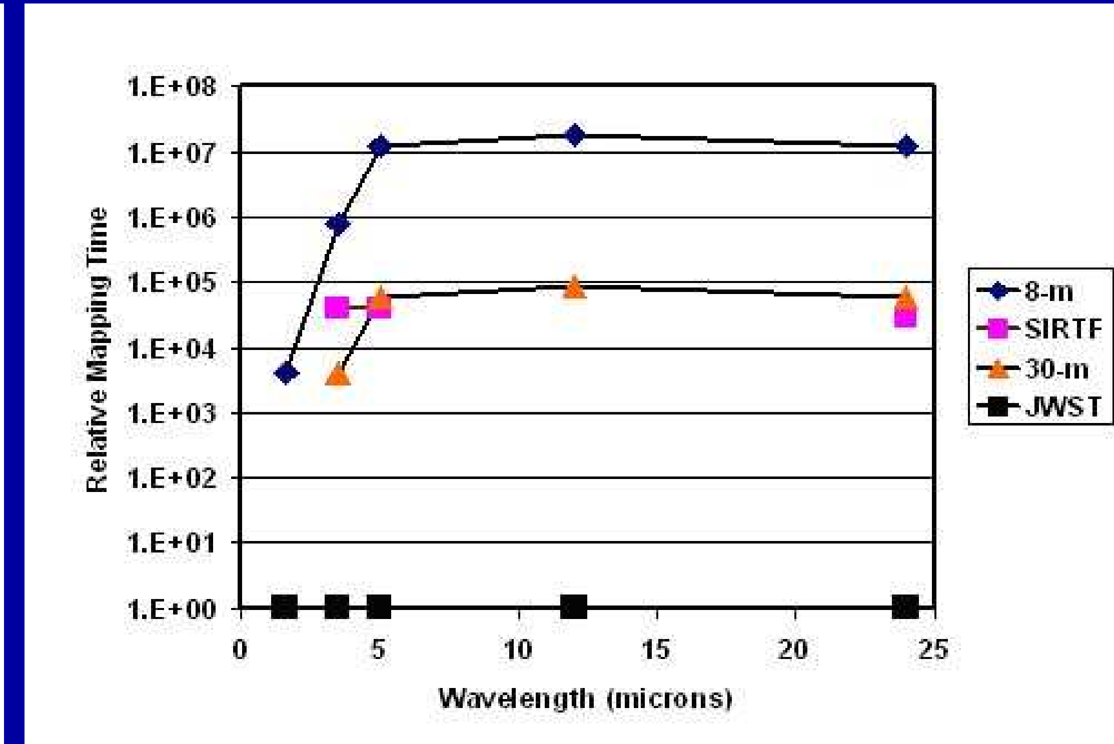
- MIRI/IFU with 400 spatial pixels covering 5–29 μm at R$\sim$2000–4000.

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

[• NIRCam offers R$\simeq$5 imaging from 0.7–5μm over two $2\farcm3 \times 4\farcm6$ FOV's.]

• (2) What sensitivity will JWST have?





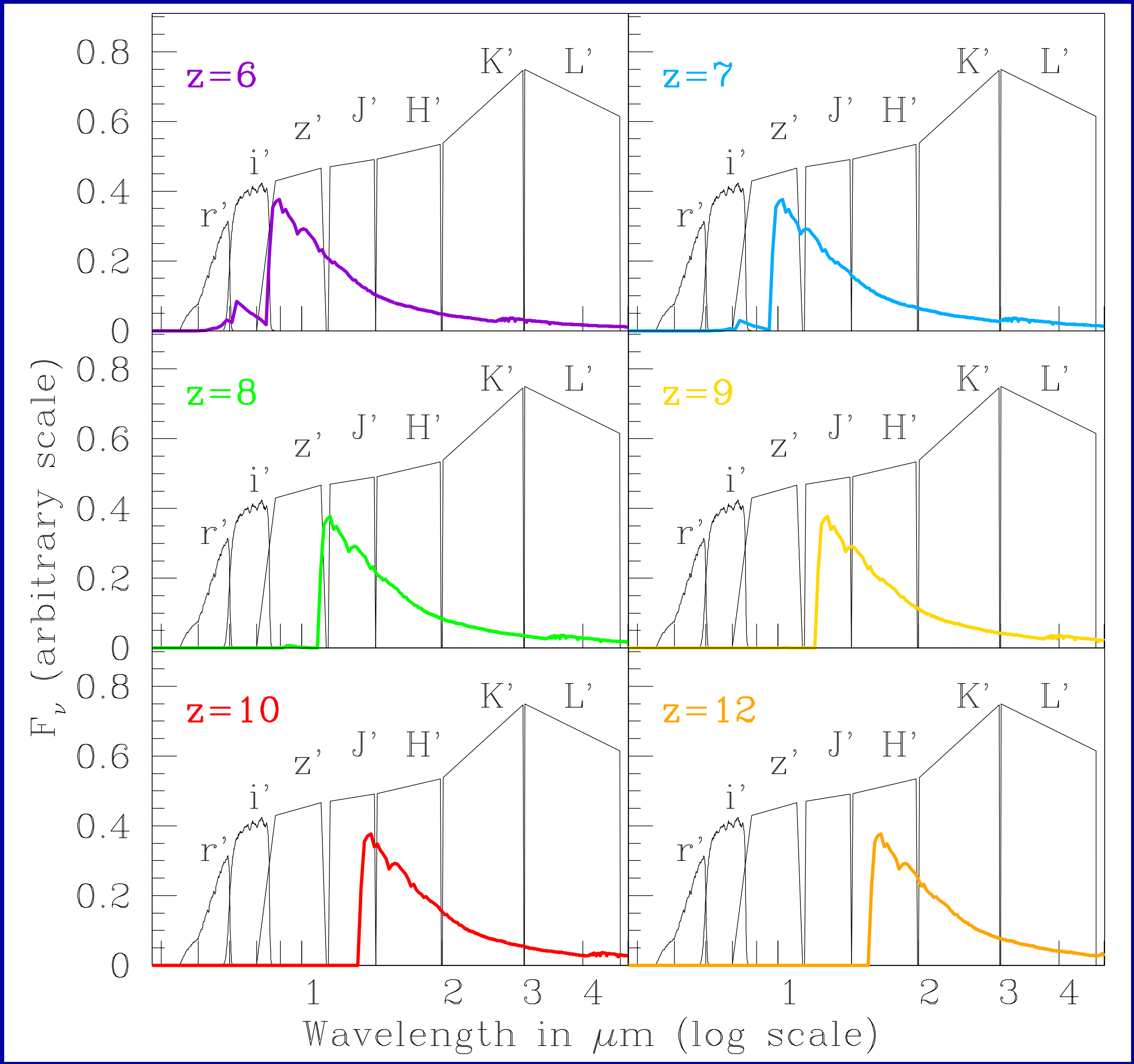
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m.

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

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

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

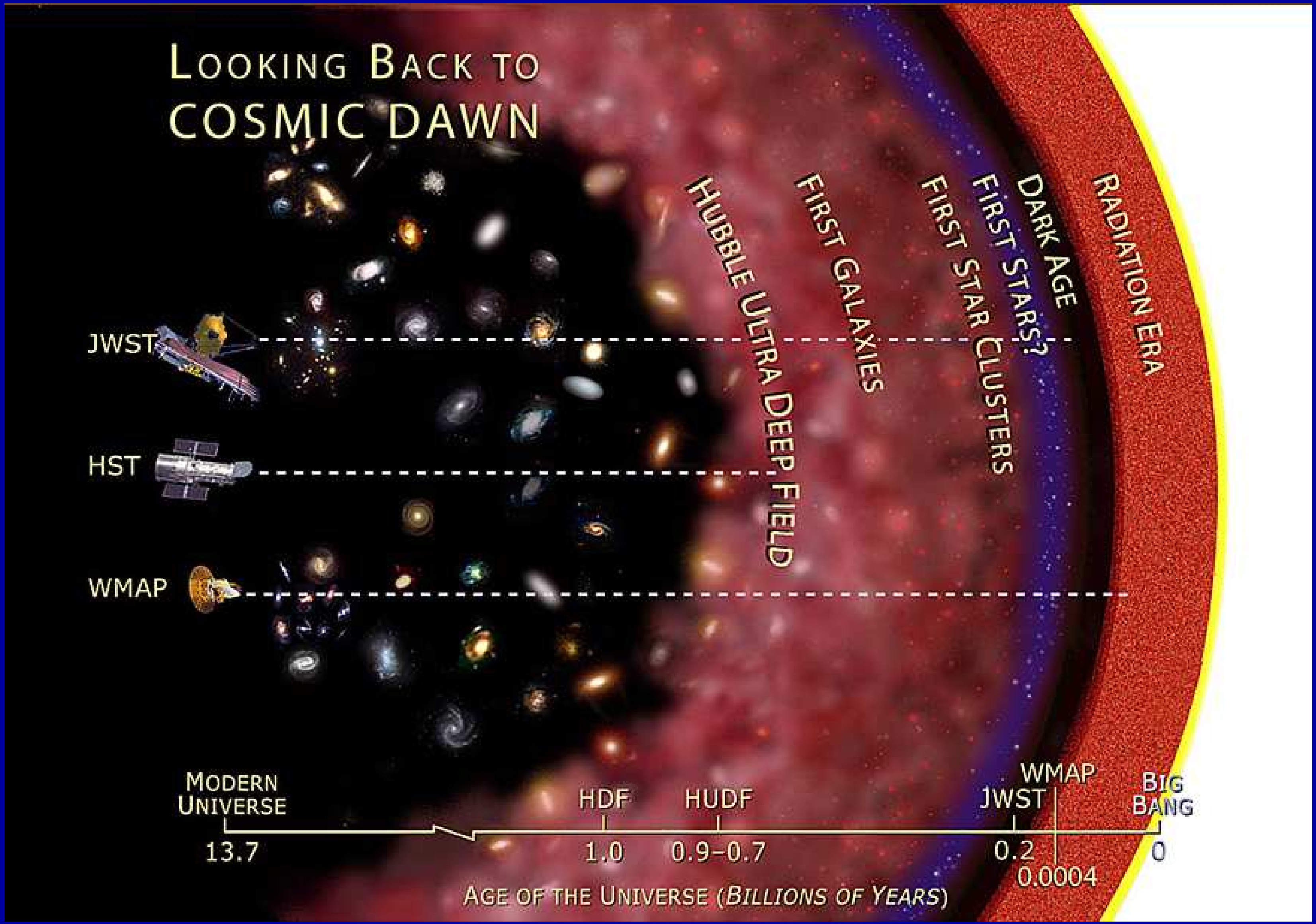
- (3) How can JWST measure First Light and Reionization?



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

$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm *and* MIRI at 5–29 μm.

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



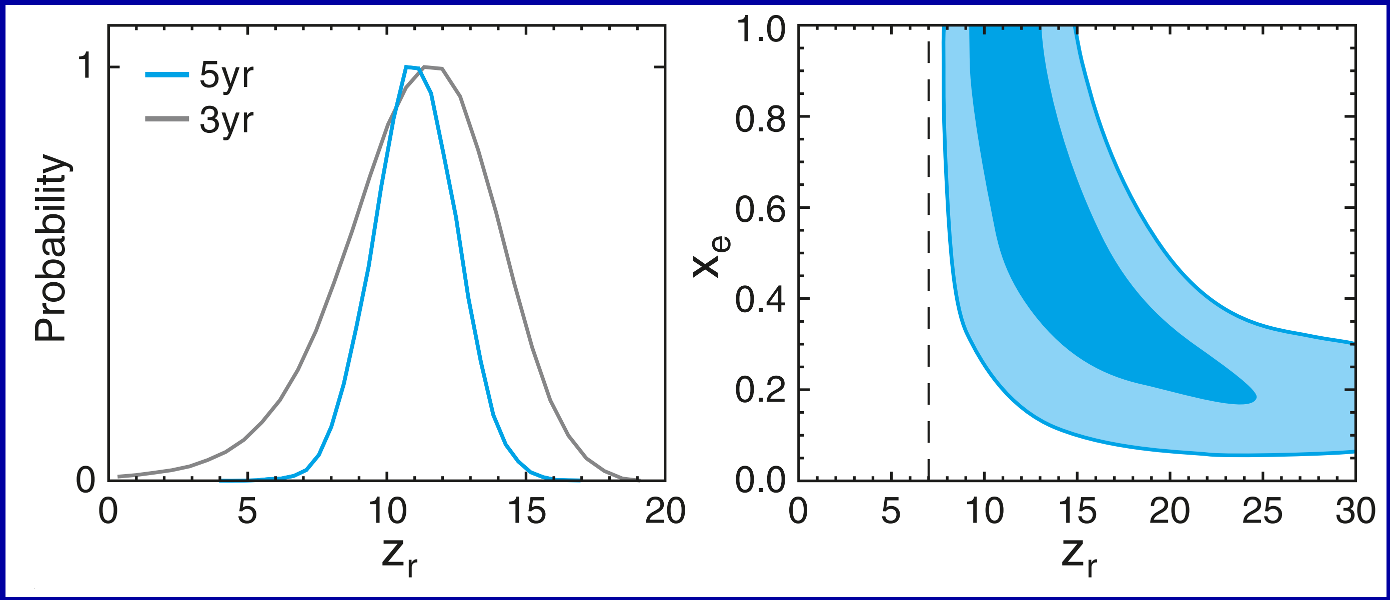
HST (+WFC3): Hubble sequence & galaxy evolution from z≃0 to z≃7–8.

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 (2010) 7-year WMAP results for JWST science:

HST/WFC3 $z \lesssim 7$–9 $\longleftarrow$ $\longrightarrow$ JWST $z \simeq 8$–25



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

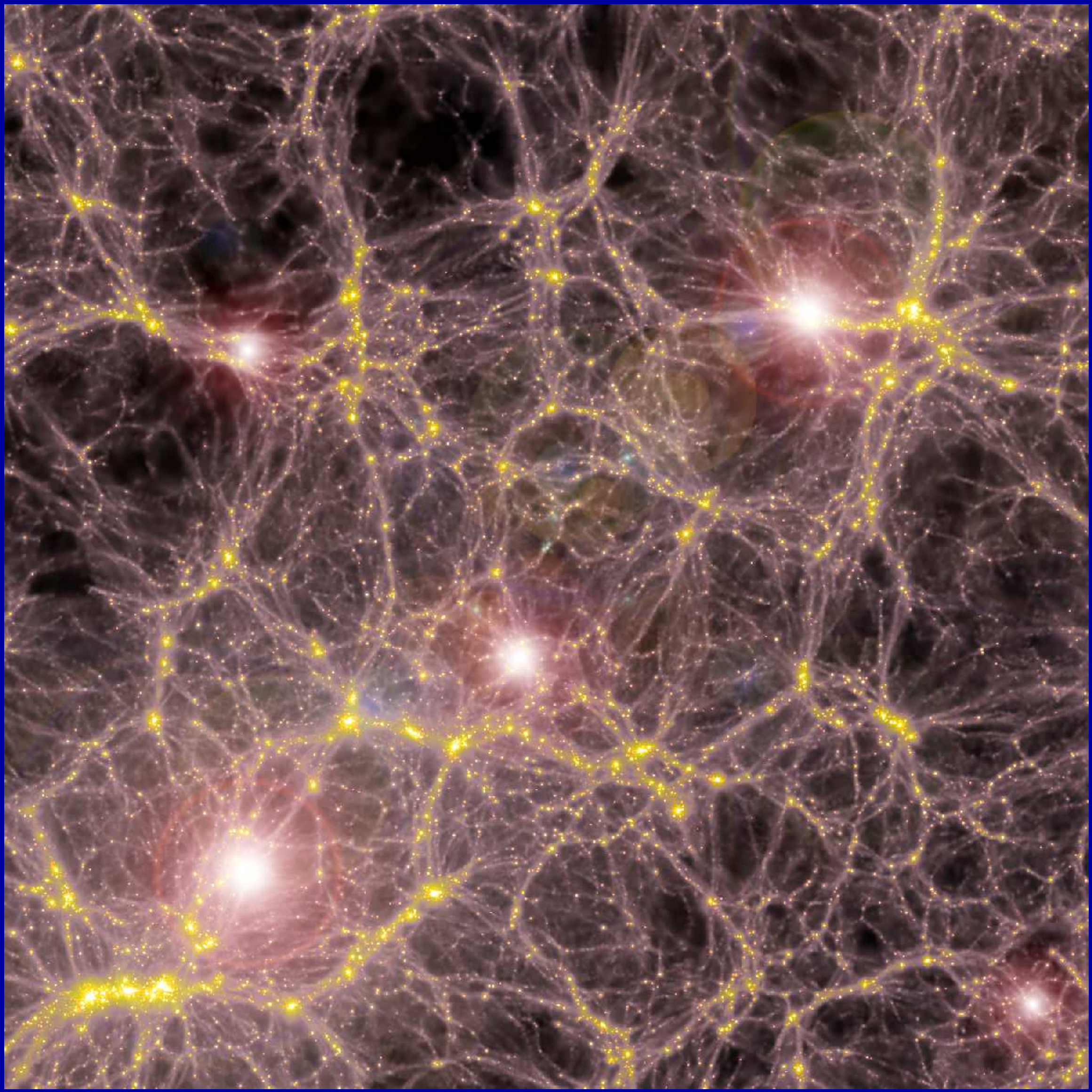
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

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

- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15$–20.

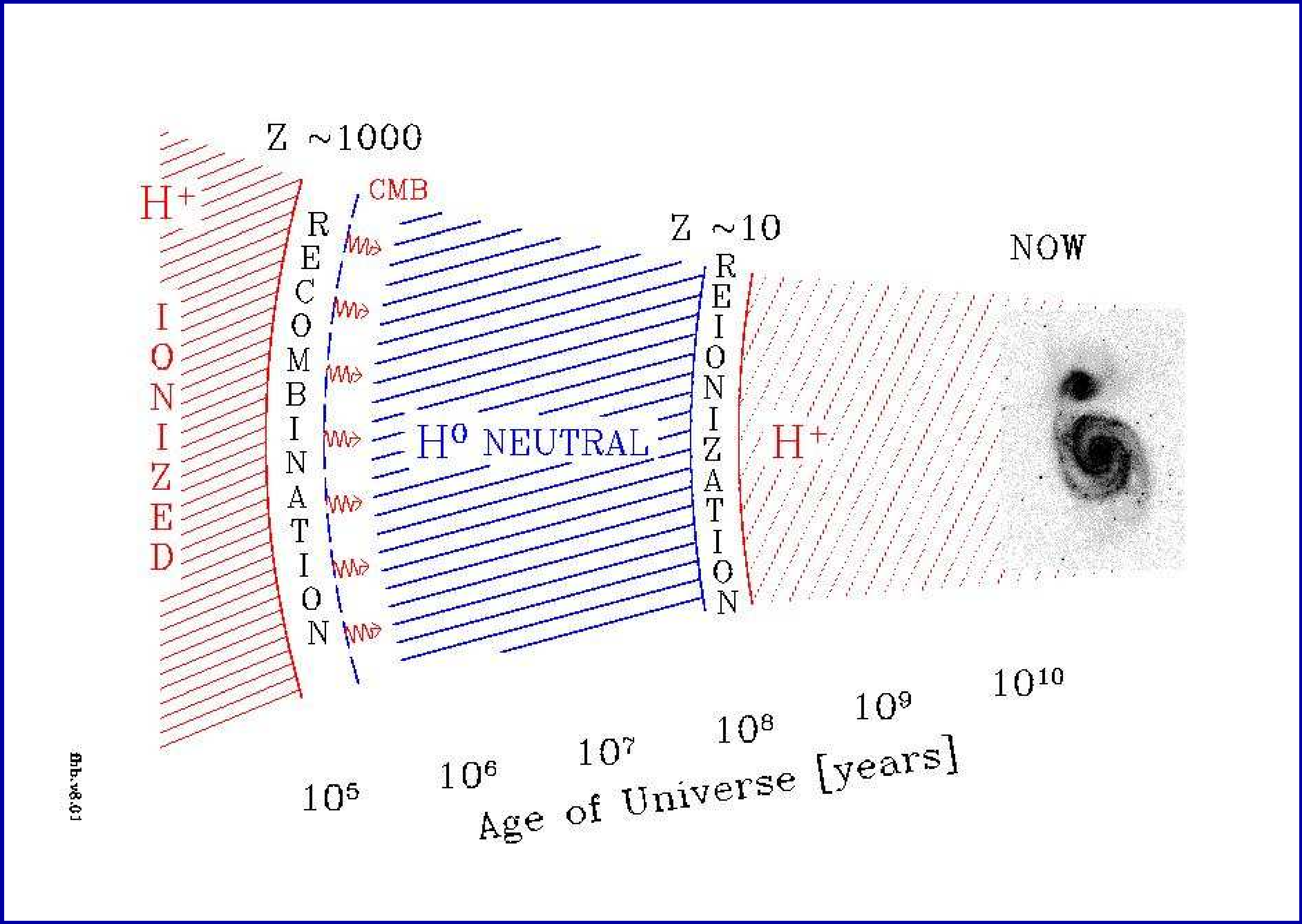
$\Rightarrow$ JWST must cover $\lambda = 0.7$–29 μm, with its diffraction limit at 2.0 μm.

• (3) 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 $z \simeq 10 \longrightarrow 30$.

• (3) What is First Light and Reionization?

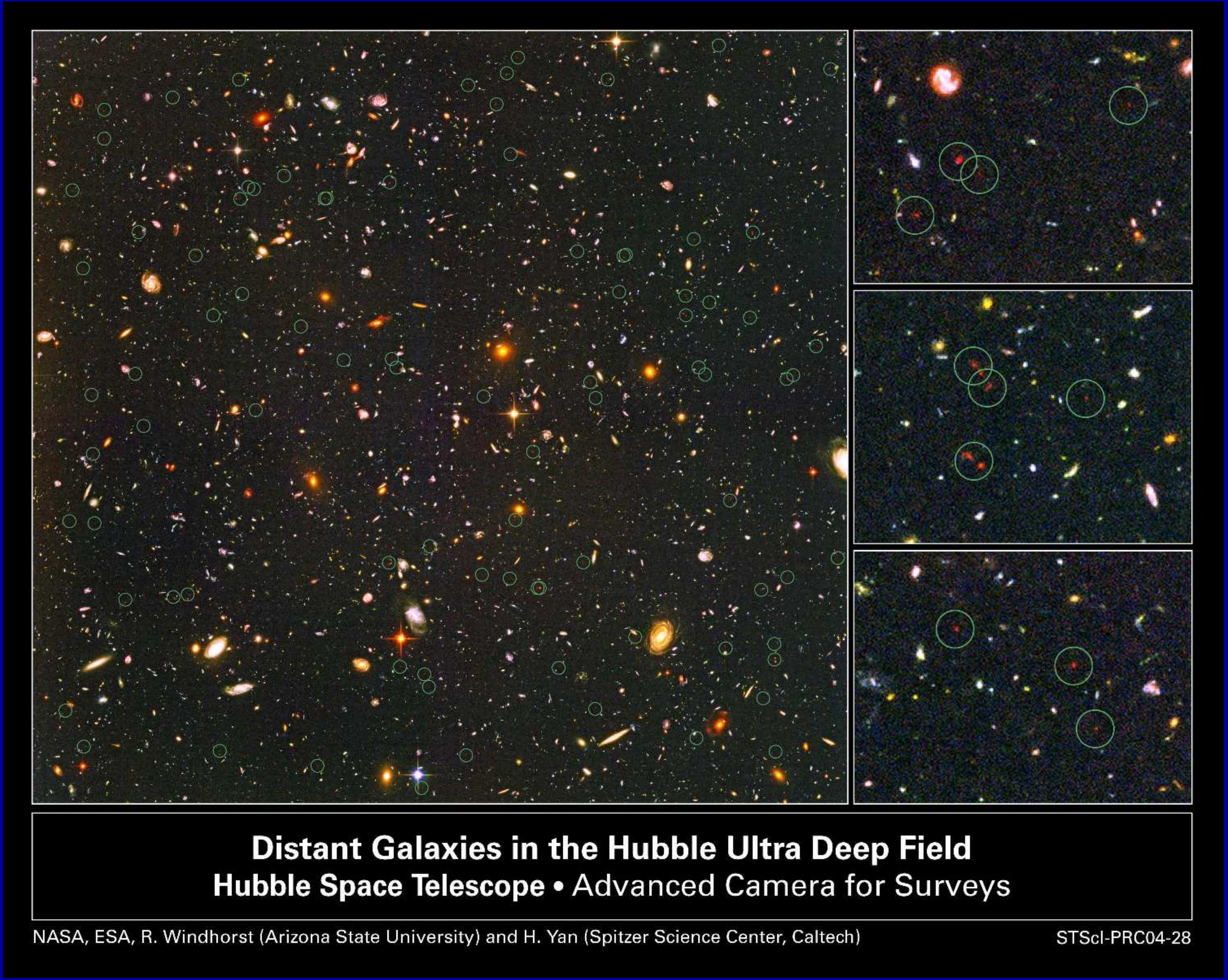


WMAP: First light may have happened as follows (Cen 2003; Spergel 2006):

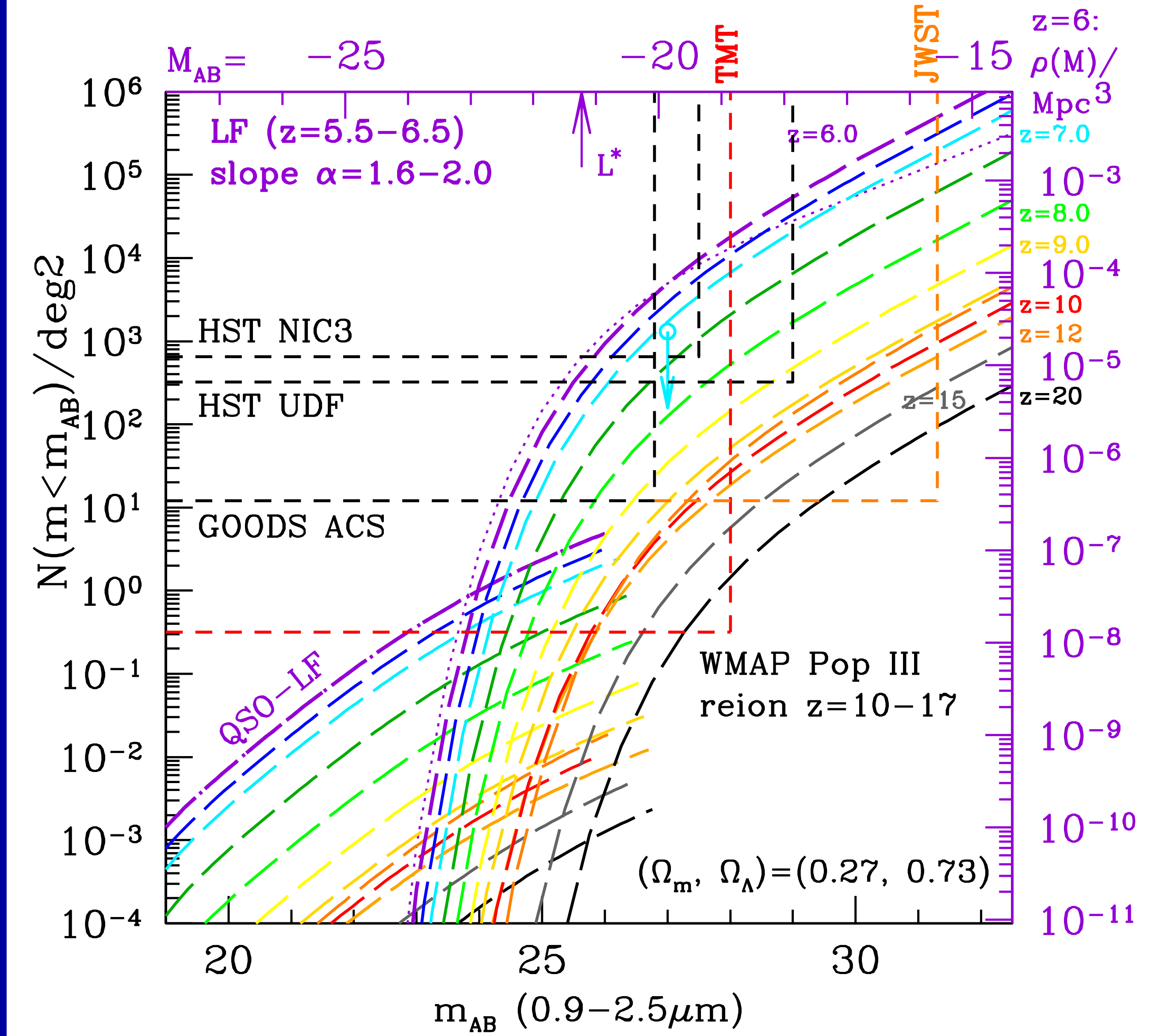
• (1) Population III stars with $\gtrsim$200 $M_\odot$ at z$\simeq$11–20 (First Light).

• (2) First Population II stars (halo stars) form in dwarf galaxies of mass$\simeq 10^7$ to 10^9 $M_\odot$ at z$\simeq$6–9, which complete reionization by z$\simeq$6.

$\Rightarrow$ JWST needs NIRCam at 0.8–5 μm and MIRI at 5–29 μm.



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).



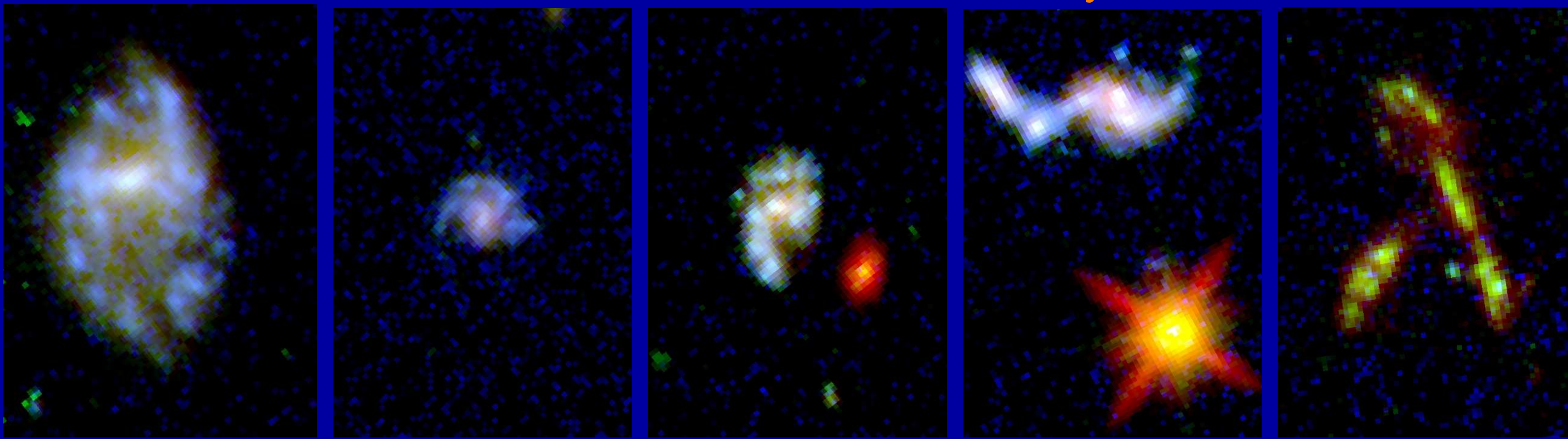
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- Objects at $z \gtrsim 9$ are rare, since volume element is small and JWST samples brighter part of LF. JWST needs the quoted sensitivity/aperture (A), field-of-view (FOV=Ω), and wavelength range (0.7-29 μm).

• (4) How can JWST measure Galaxy Assembly?

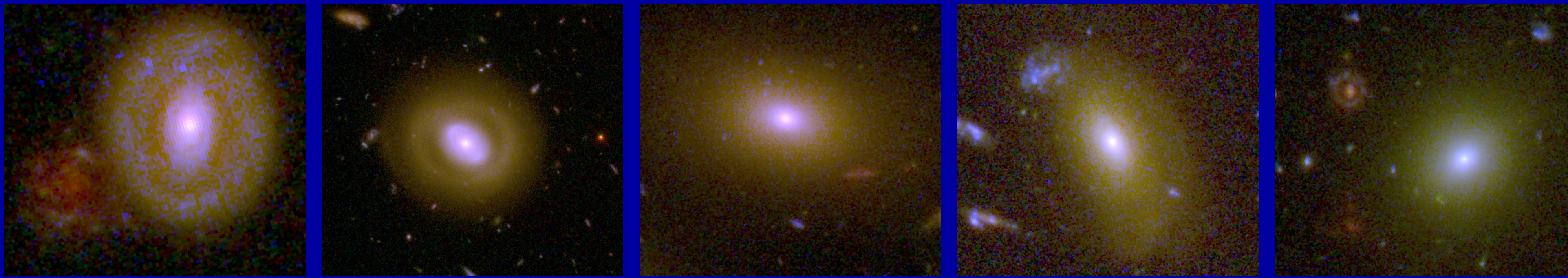
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

JWST adds 0.05–0.2" FWHM imaging to AB$\simeq$31.5 mag (1 nJy) at 1–5μm, and 0.2–1.2" FWHM at 5–29μm, tracing young+old SEDs & dust.

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



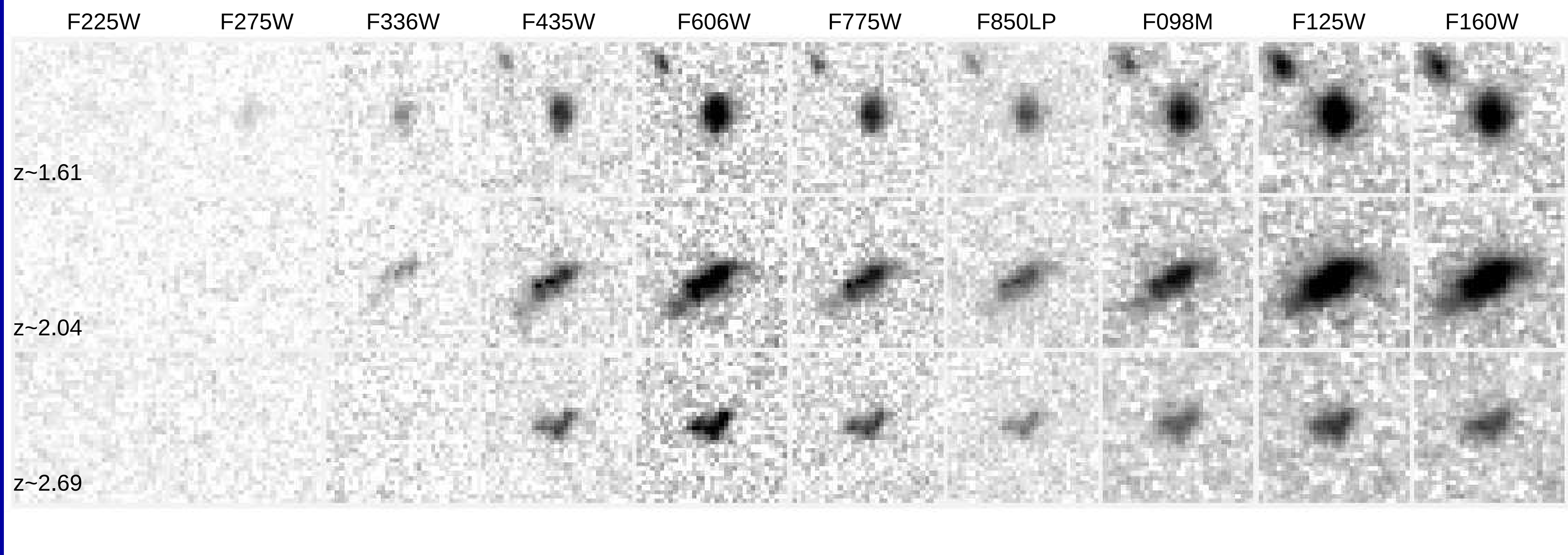
Galaxy structure at the peak of the merging epoch (z≃1–2) is very rich: some resemble the cosmological parameters $\boldsymbol{H_0}$, $\boldsymbol{\Omega}$, $\boldsymbol{\rho_o}$, $\boldsymbol{w}$, and $\boldsymbol{\Lambda}$, resp.



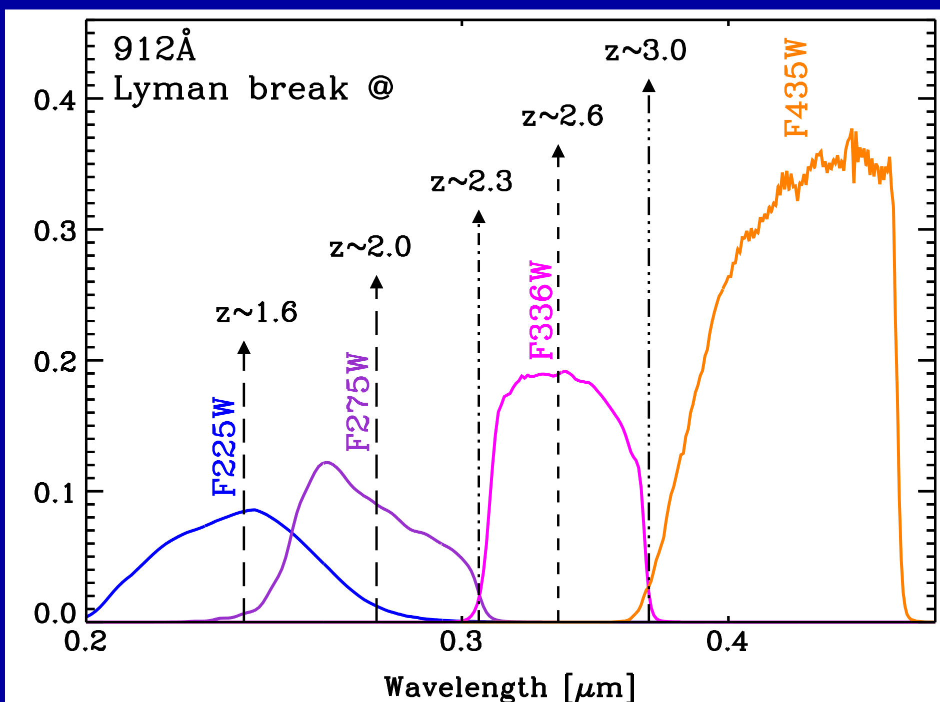
Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

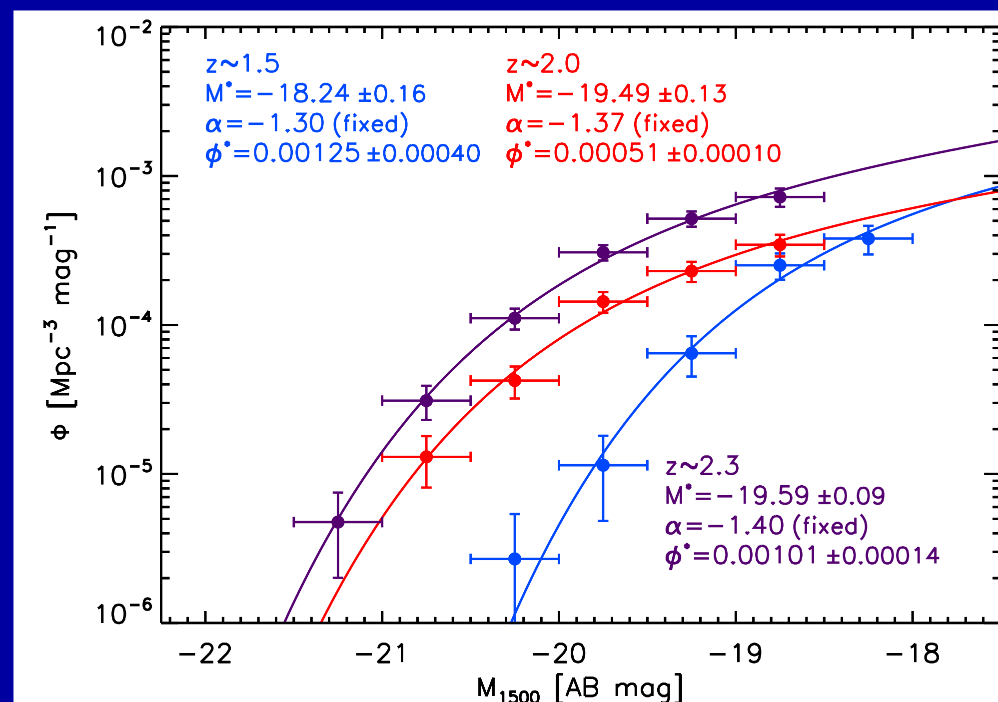
(Rutkowski et al. 2010) $\Longrightarrow$ "Red and dead" galaxies aren't dead!

- JWST will observe all such objects from 0.7–29 μm wavelength.

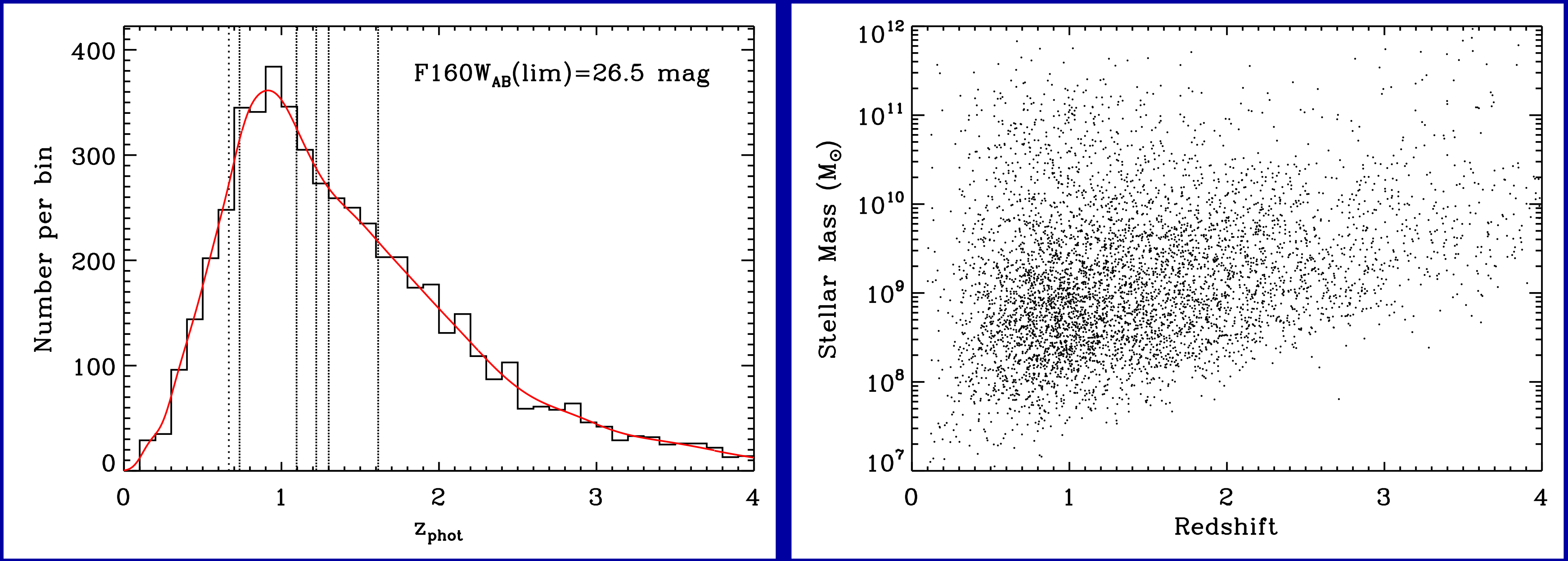


Lyman break galaxies at the peak of cosmic SF (z≃1-3; Hathi ea. 2010)





- JWST will similarly measure faint-end LF-slope evolution for 1≲z≲12.



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

- Reliable masses of faint galaxies to AB=26.5 mag, accurately tracing the process of galaxy assembly: downsizing and merging.

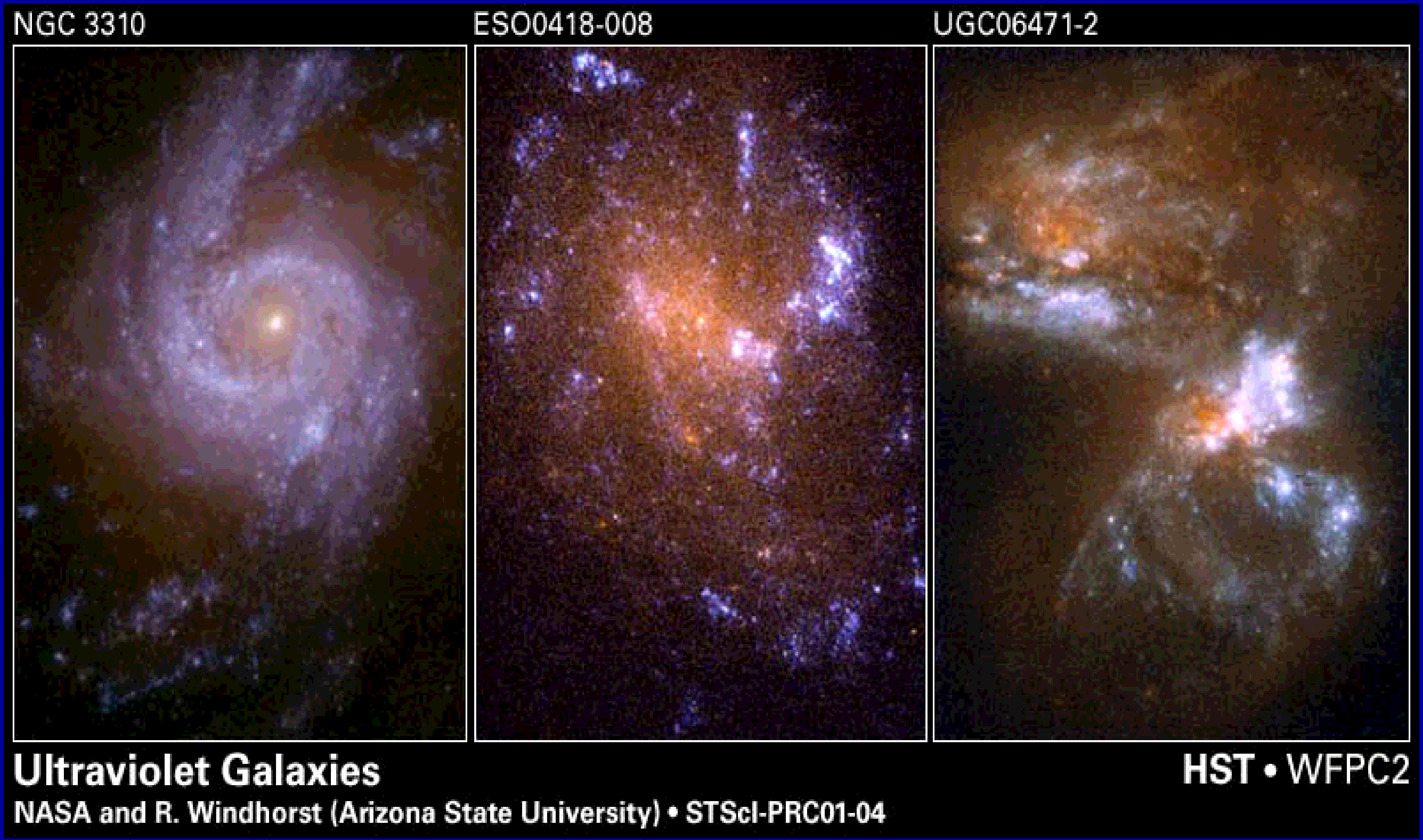
ERS shows WFC3's new panchromatic capabilities on galaxies at z≃0–7.

- The HUDF (Illingworth's talk) shows WFC3's capabilities at z≃7–9.

⇒ WFC3 is an essential pathfinder at z≲8 for JWST (0.7–29 μm) at z≳9.

- JWST will trace mass assembly and dust content 3–4 mags deeper from z≃1–12, with nanoJy sensitivity from 0.7–5μm.

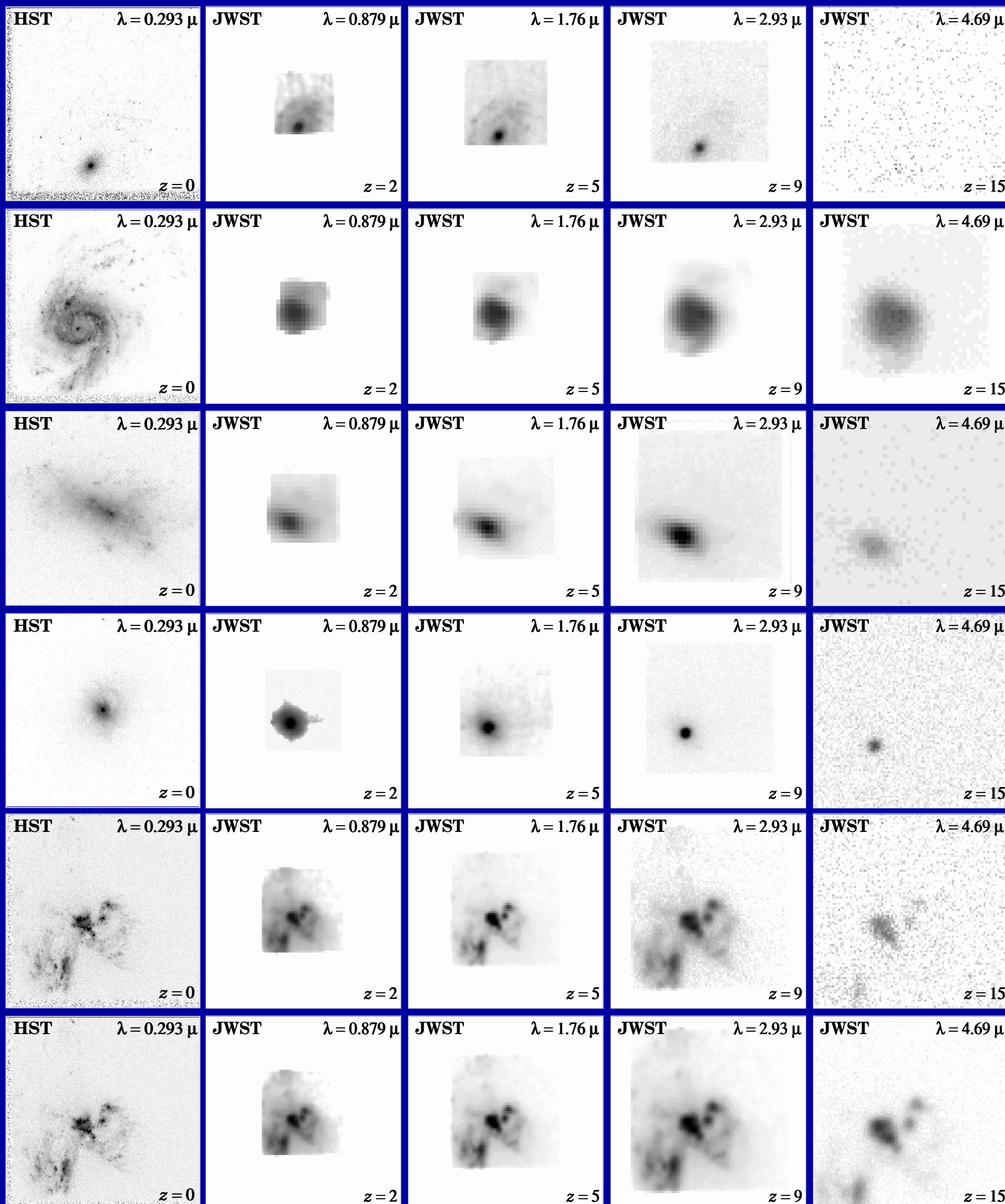
(5) Predicted Galaxy Appearance for JWST at z≃1–15



- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust imprinted.
- High-resolution HST UV images are benchmarks for comparison with very high redshift galaxies seen by JWST, enabling quantitative analysis of the restframe-λ dependent structure, B/T, CAS, SFR, mass, dust, etc.

(5) Predicted Galaxy Appearance for JWST at z≃1–15 (w/ C. Conselice)

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



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

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

(6) Conclusions

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

- Passed Non-Advocate Review (T-NAR) in 2007, and Mission Preliminary Design Review (PDR) in 2008. Mission CDR in Apr. 2010.

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

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

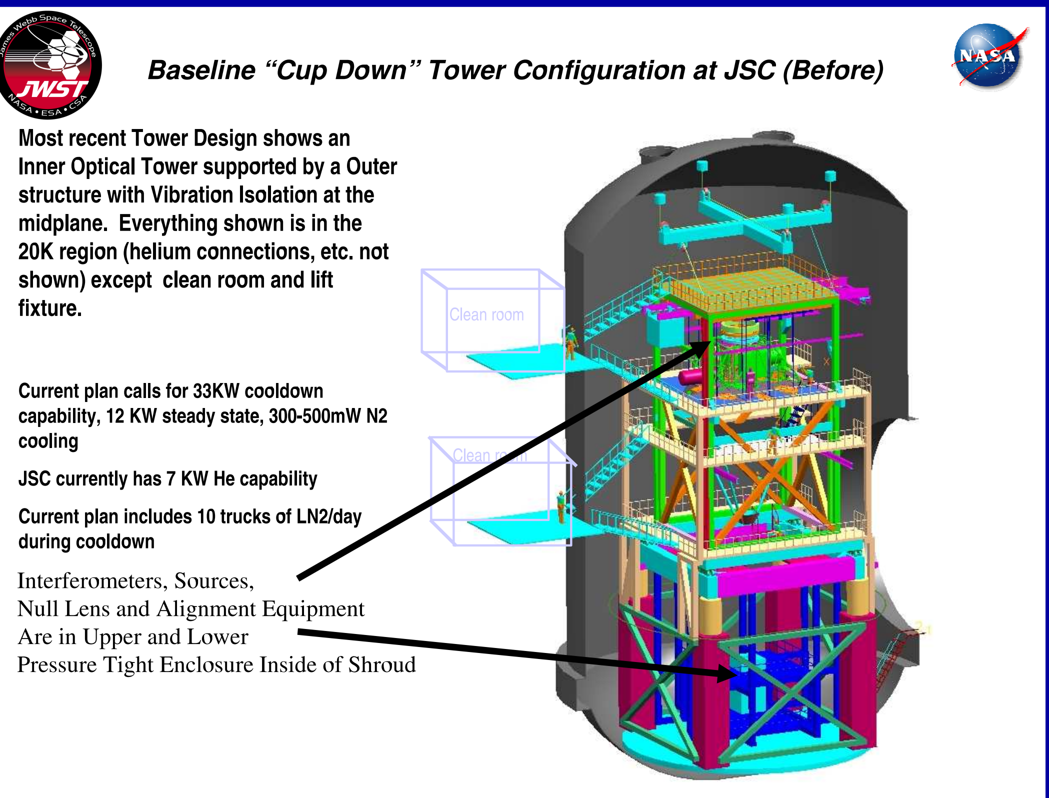
(3) JWST will have a major impact on astrophysics after 2014:

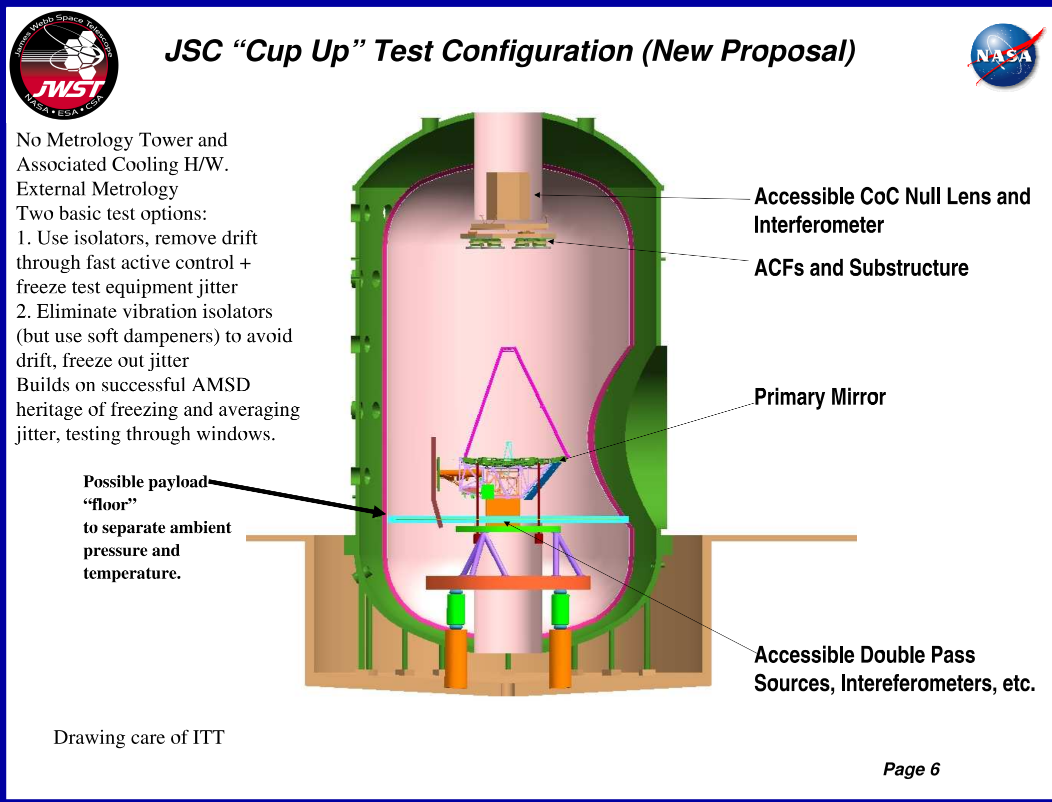
- Current generation students, postdocs will use JWST during their career
- JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS

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

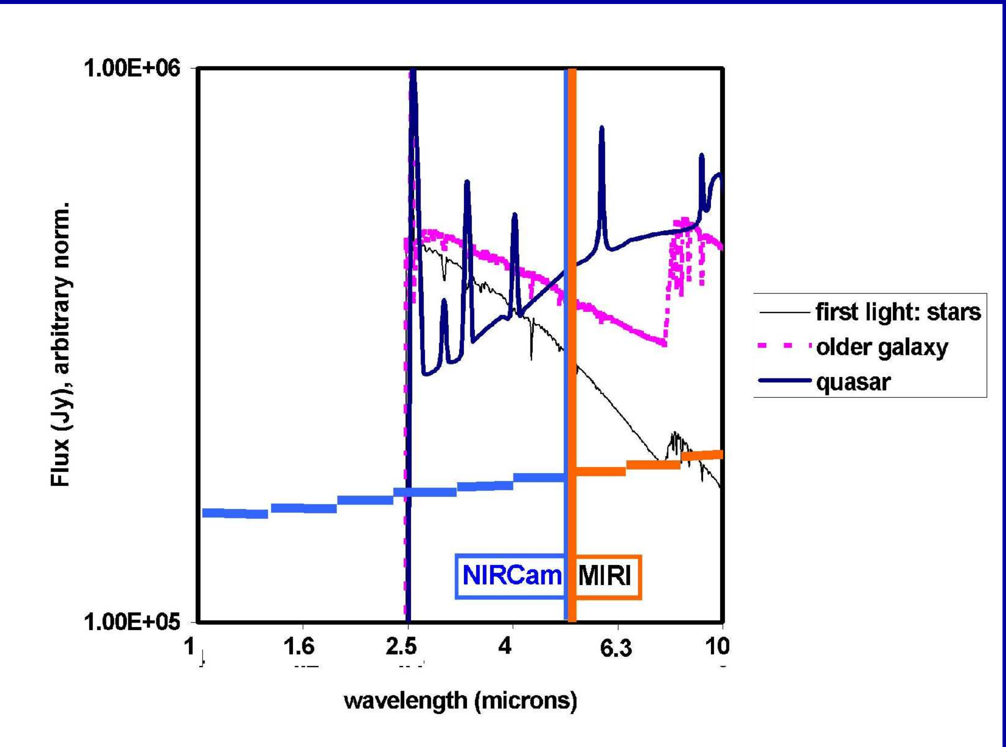


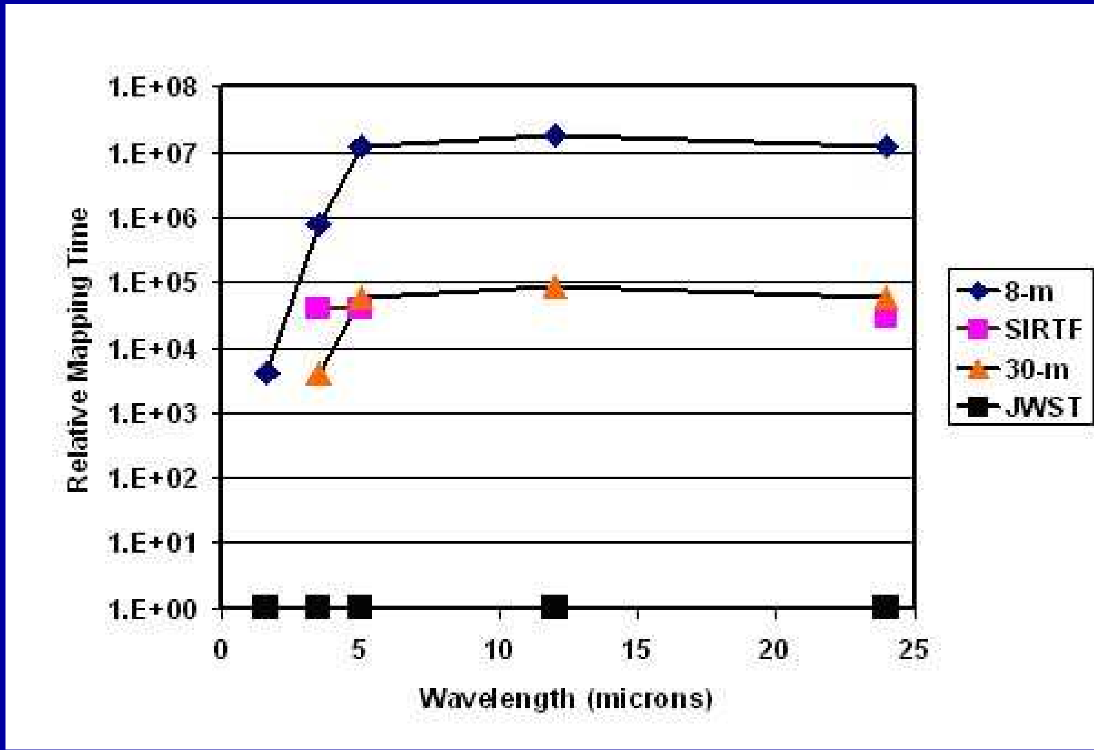


JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 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), $i.e.$, demonstration in a relevant environment — ground or space.
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.

• (2) What sensitivity will JWST have?



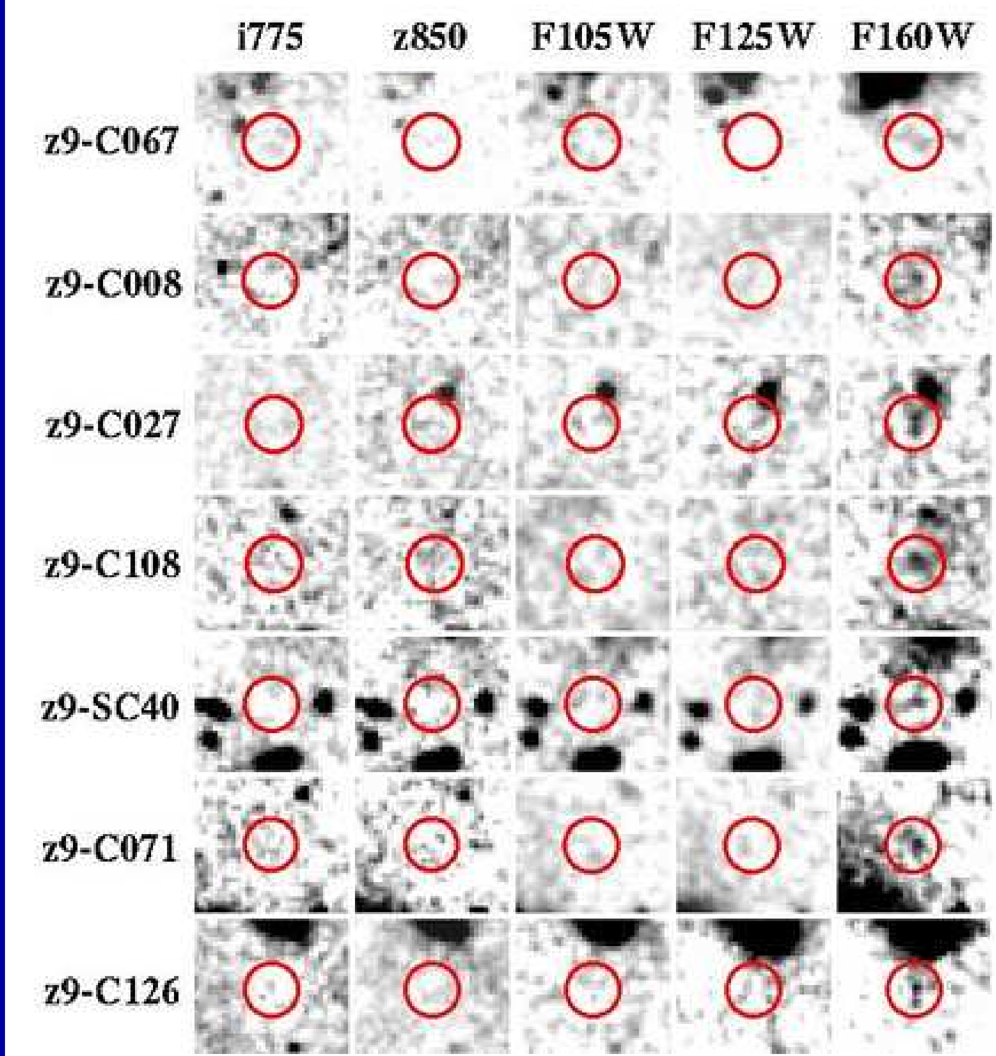


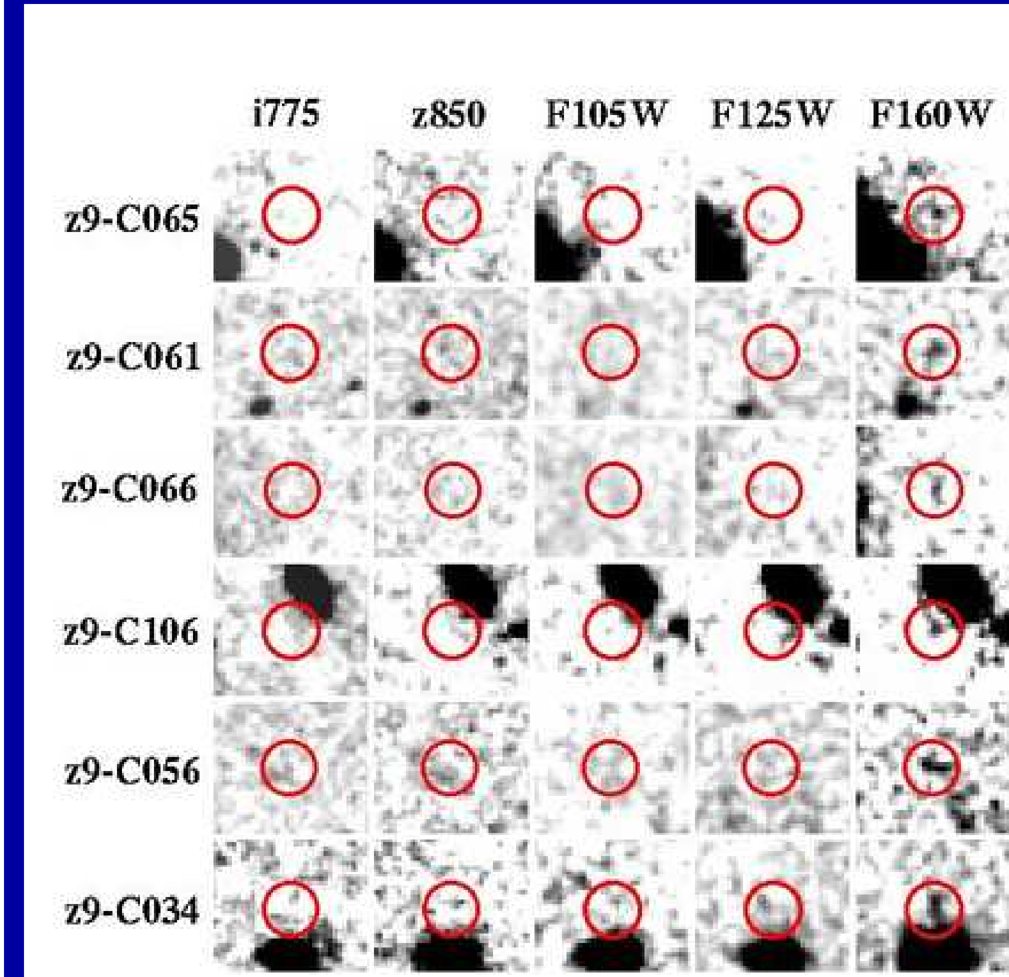
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m.

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

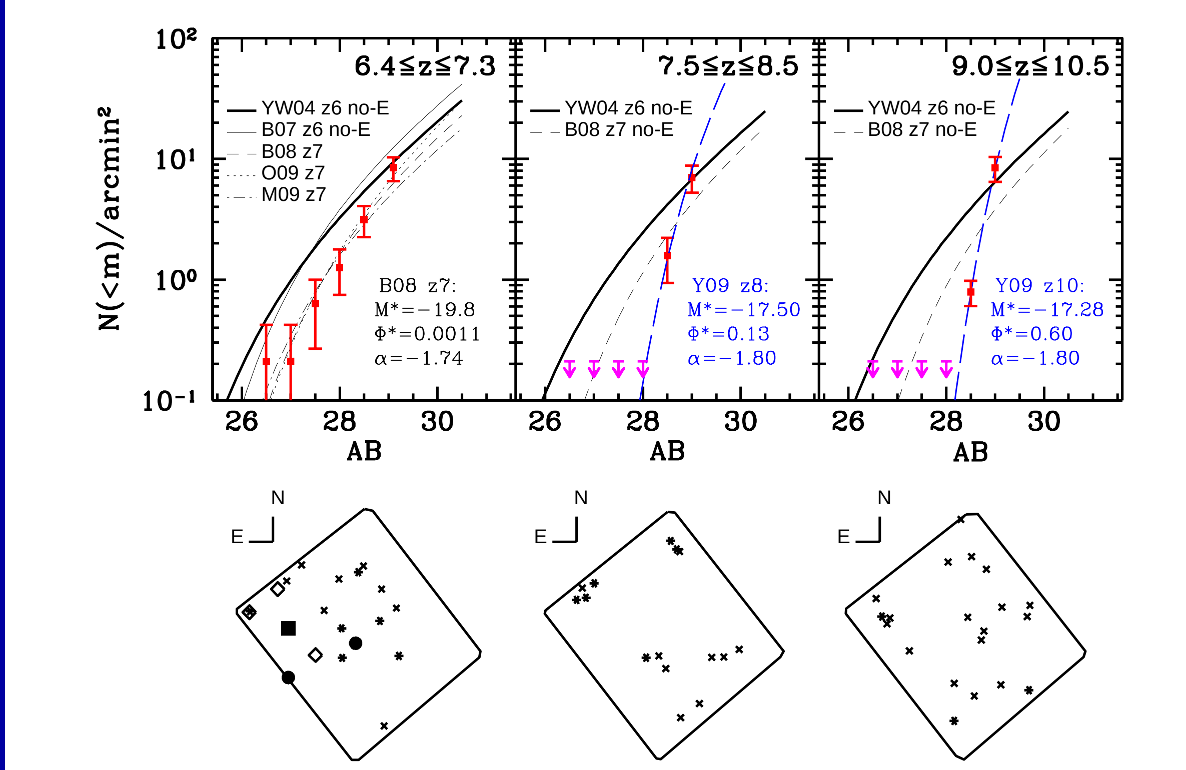
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

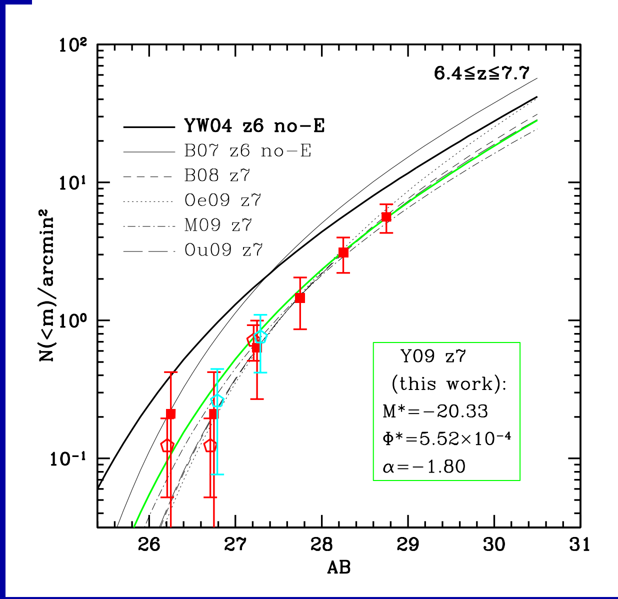
RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

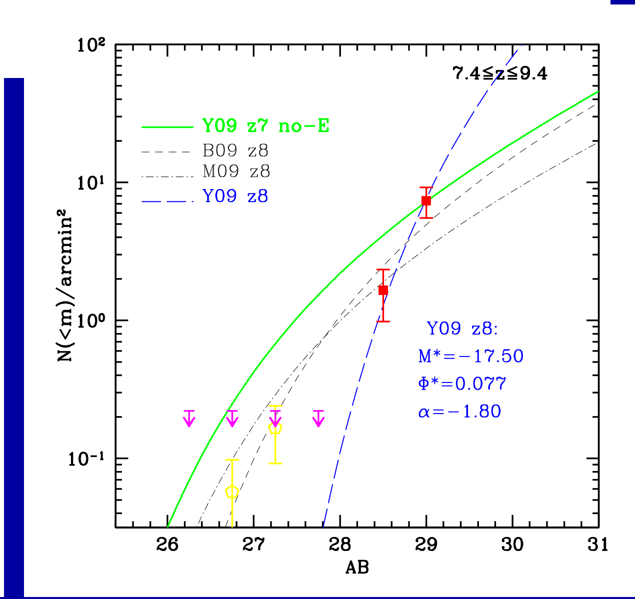




- Our simulations show that ∼50% of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at z$\gtrsim$9. Together with the HUDF and ERS upper limits to AB$\lesssim$28 mag, the z∼9 LF is still steep!
- Need JWST to measure z$\gtrsim$9 LF, and see if it's fundamentally different from the z$\lesssim$8 LFs. Does a pop-III driven IMF cause a power-law LF?

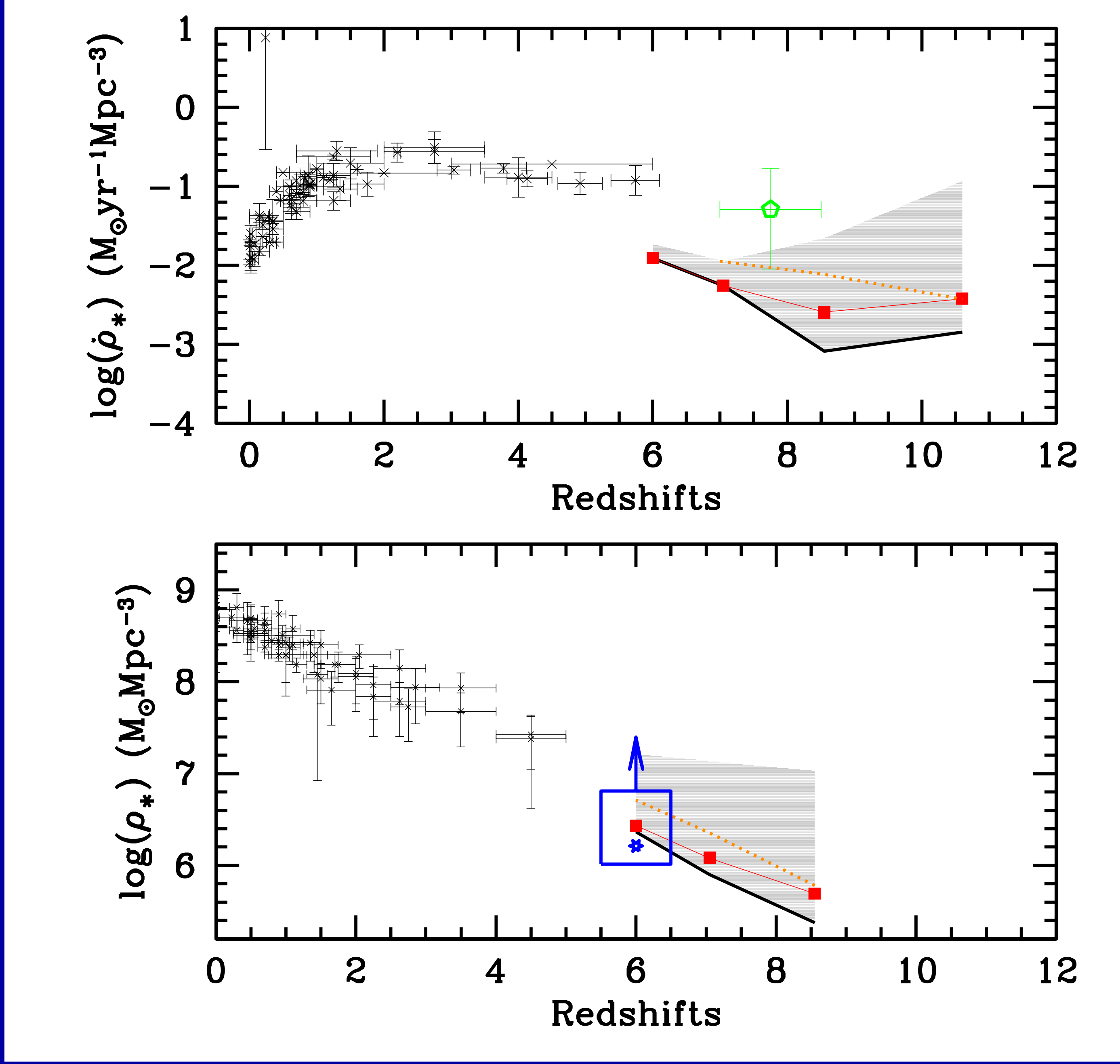






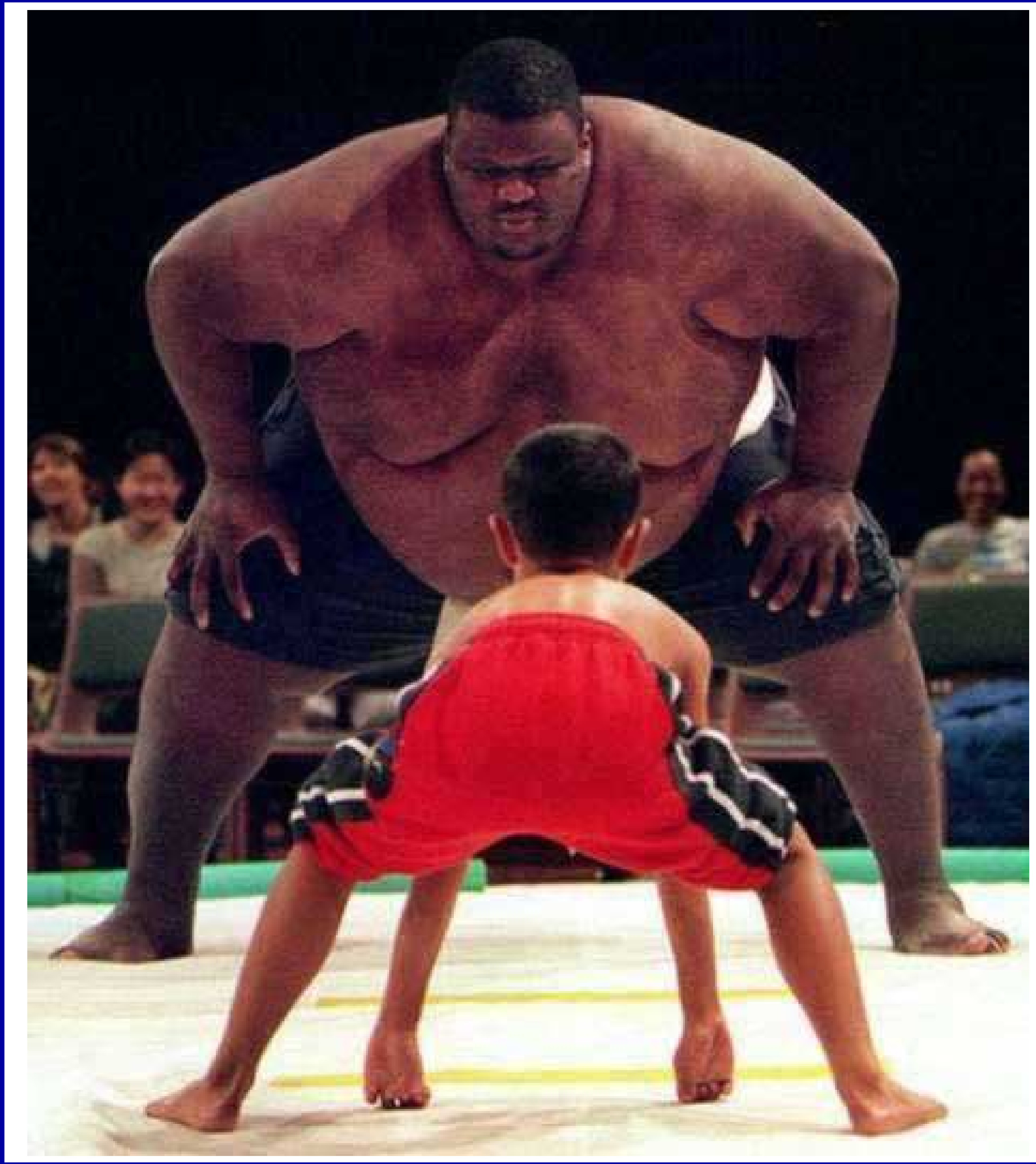
Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

- z=7 LF more firm (see Bouwens), z=8 LF refined, z=9.5 UL's still stand.



The current WFC3 uncertainties on J-drops are large enough that at z$\gtrsim$8, a wide range of possibilities is allowed (Yan et al. 2010; astro.0910.0077).

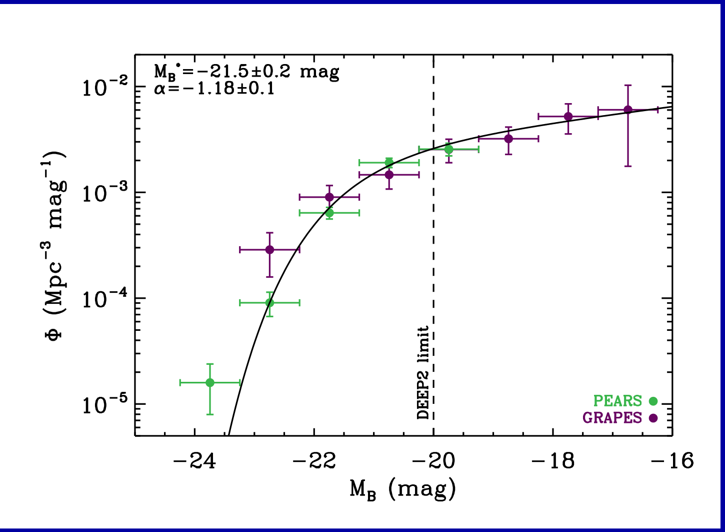
- Need JWST to fully measure the LF and SFR for 8$\lesssim$z$\lesssim$15.

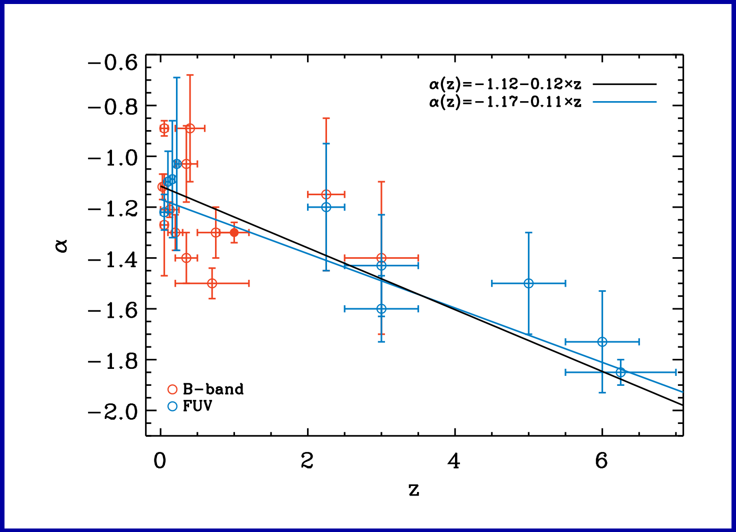


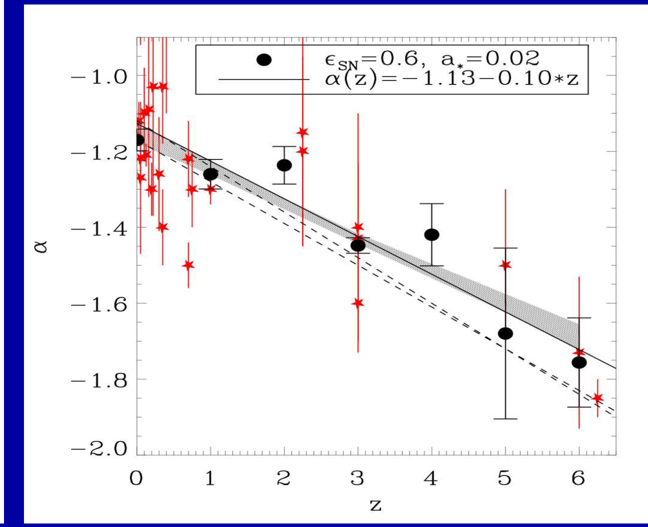
At the end of reionization, dwarfs had beaten the Giants, but ...

What comes around, goes around ...

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 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.

• (4) How can JWST measure Galaxy Assembly?

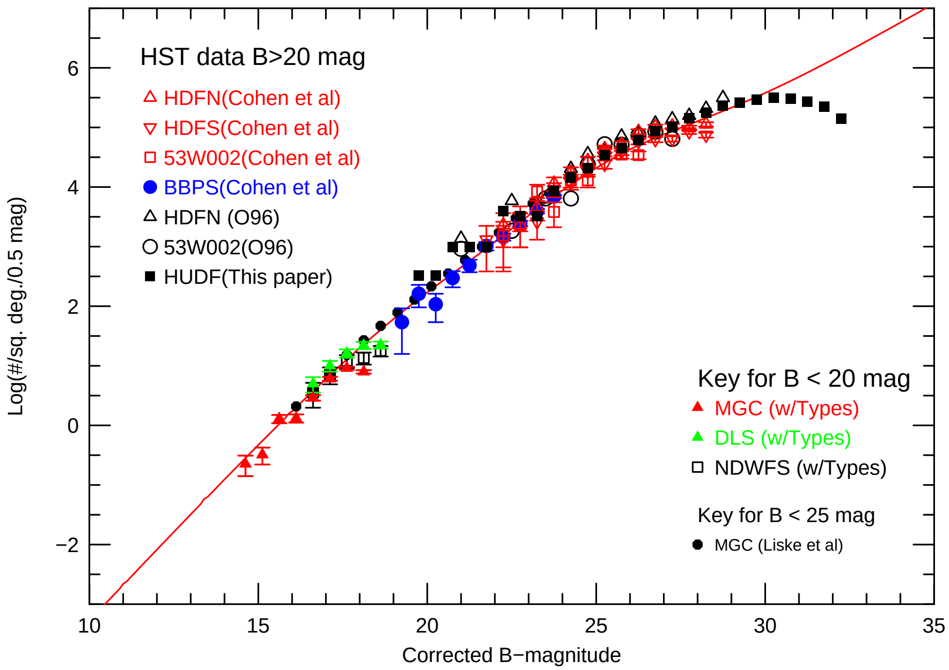
HST helped show how galaxies formed and evolved in the last 12–13 Gyrs:

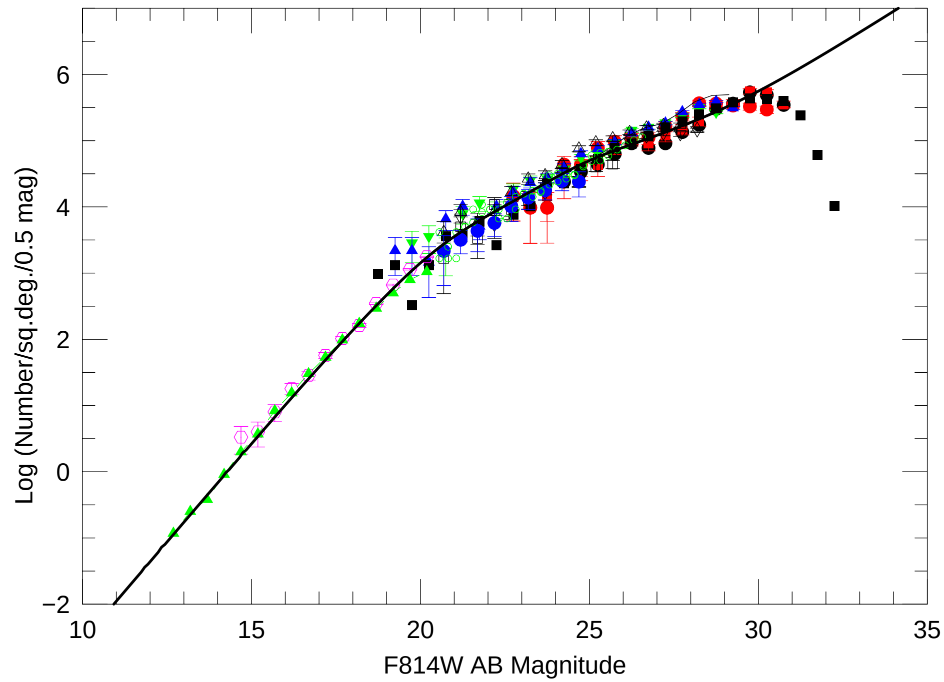
- Galaxies of all types formed over a wide range of time, but with a notable transition around $z \sim 1$–1.5, when Hubble sequence appears:
- Subgalactic units rapidly merge from $z \simeq 7 \longrightarrow 1$ to grow bigger units.
- Merger products settle as galaxies with large bulges or disks at $z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

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

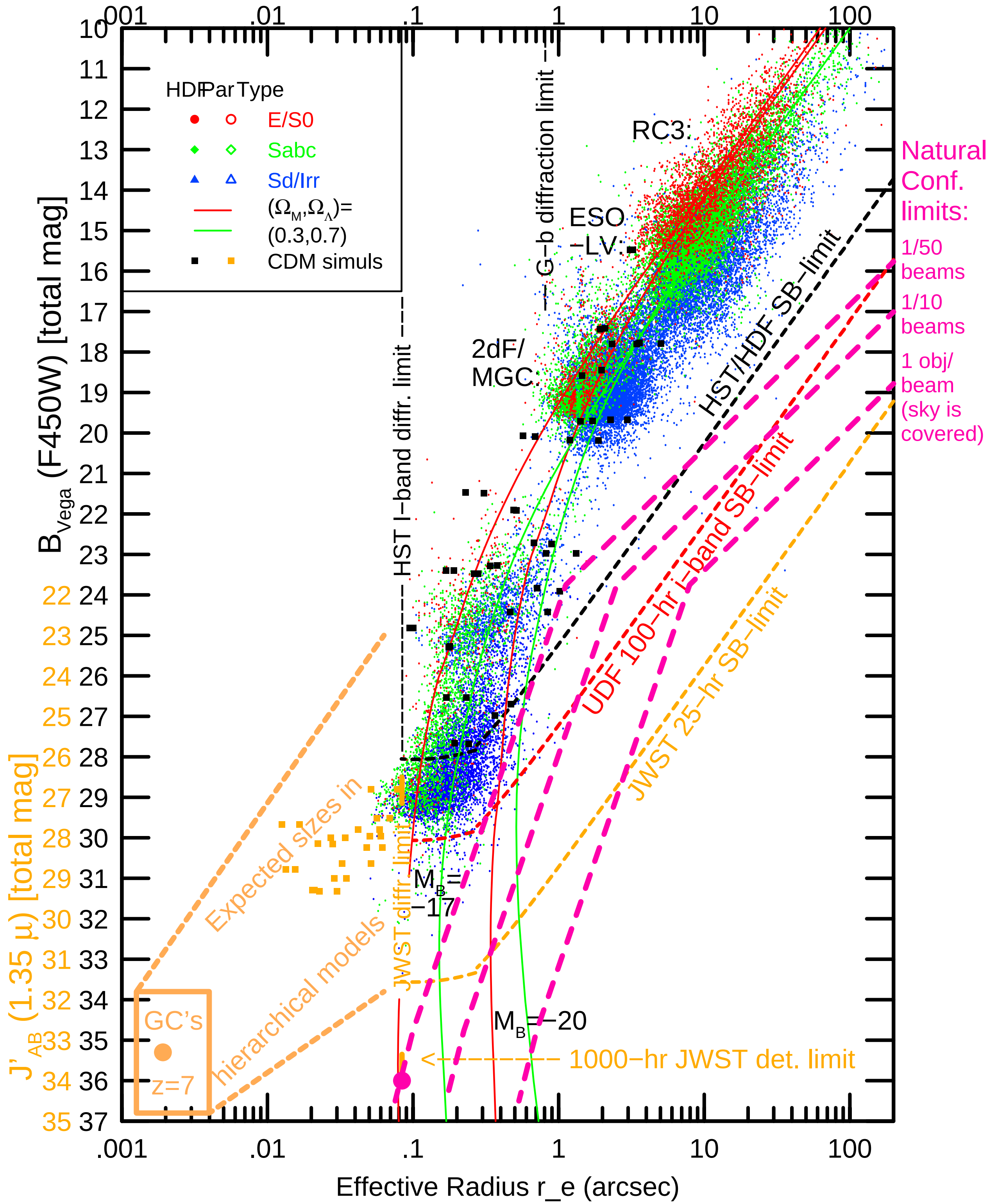
- Formation and evolution of Pop III star-clusters in the first 0.5 Gyr.
- Faint-end LF-slope evolution: (how) did dwarf galaxies finish reionization after 0.5–1 Gyr? Was there a transition to Pop-III objects?
- Measure how galaxies of all types formed over a wide range of cosmic time, by accurately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

Appendix 1: will JWST (& SKA) reach the Natural Confusion Limit?





- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2\times10^6$ 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.


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
Expected sizes in
hierarchical models
GC's
z=7
M_B=
−17
M_B=−20
<−−−−−−−−− 1000−hr JWST det. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)
B_{Vega} (F450W) [total mag]
J'_{AB} (1.35 μ) [total mag]
Effective Radius r_e (arcsec)
.001
.01
.1
1
10
100

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$10 nJy, SKA will see more than 2×10^6 galaxies/deg^2. Most of these will be unresolved ($r_{hl} \lesssim 0\farcs1$ FWHM (Kawata et al. 2006). Since $z_{med}\simeq1.5$, 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. 1965, in press (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

- 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/ [Hubble at Hyperspeed 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., et al. 2006, Space Science Reviews, 123, 485–606

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

Windhorst, R., et al. 2007, Advances in Space Research, 42, p. 1965 (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"