How can the James Webb Space Telescope measure First Light, Reionization, and Galaxy Assembly?

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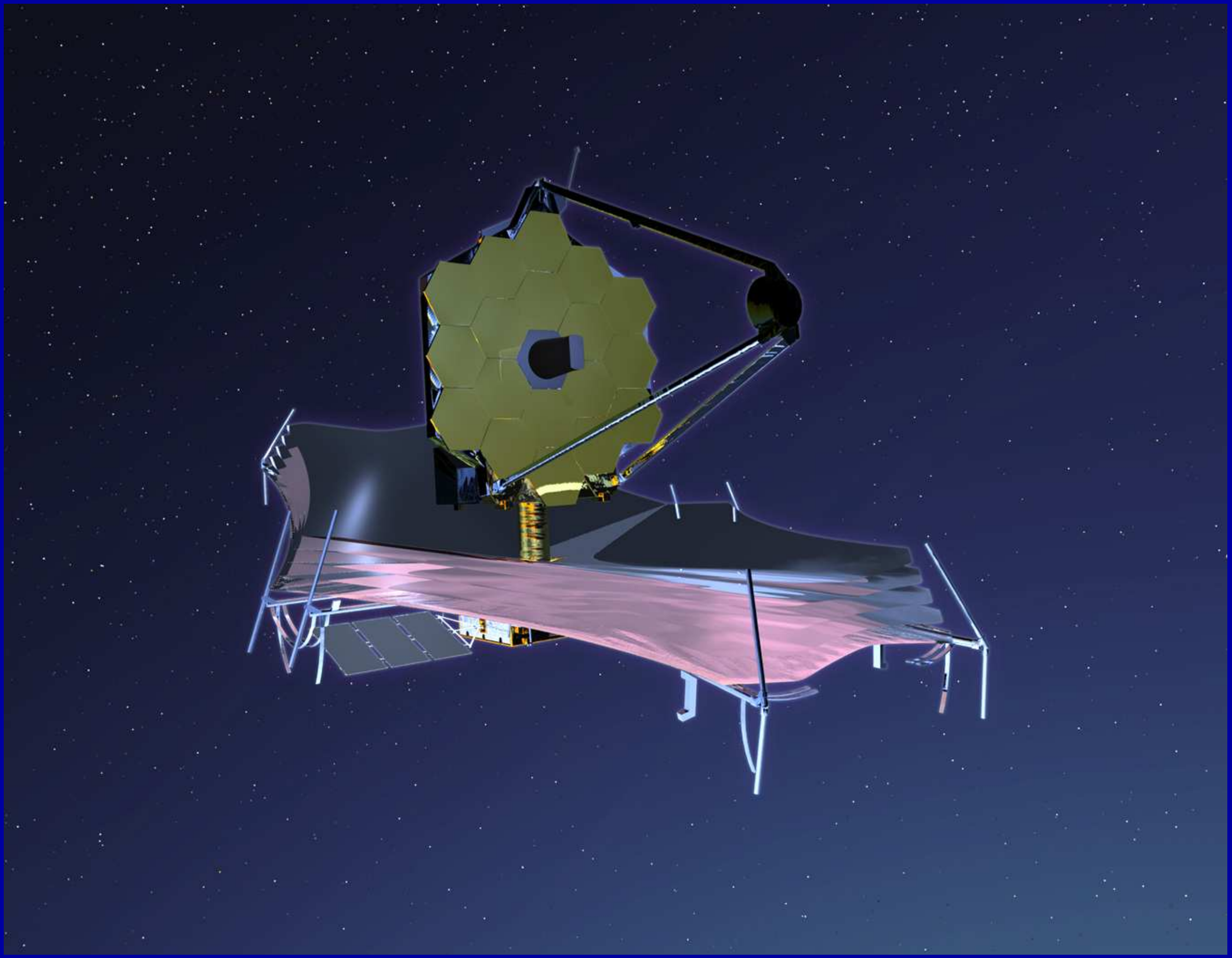
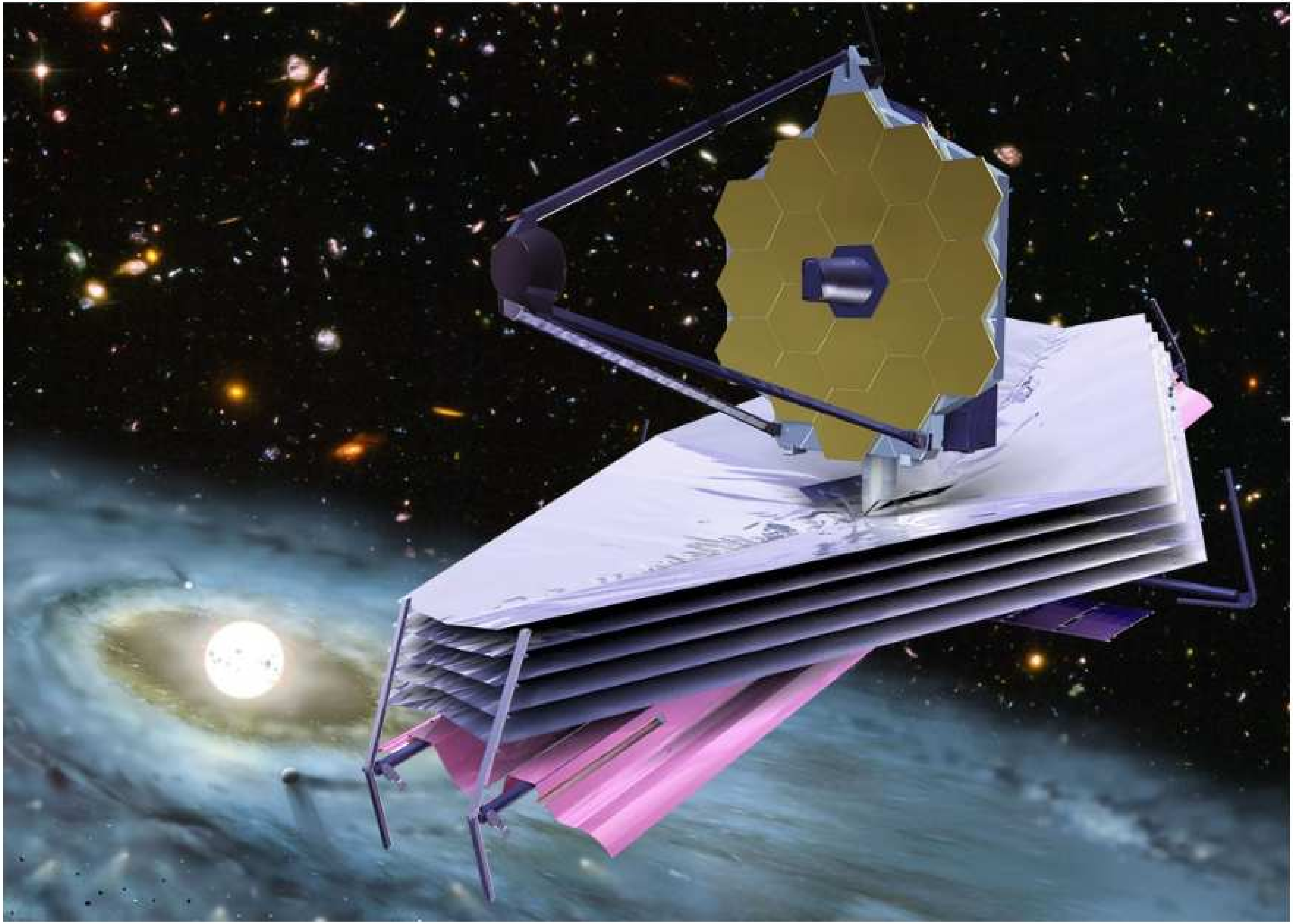
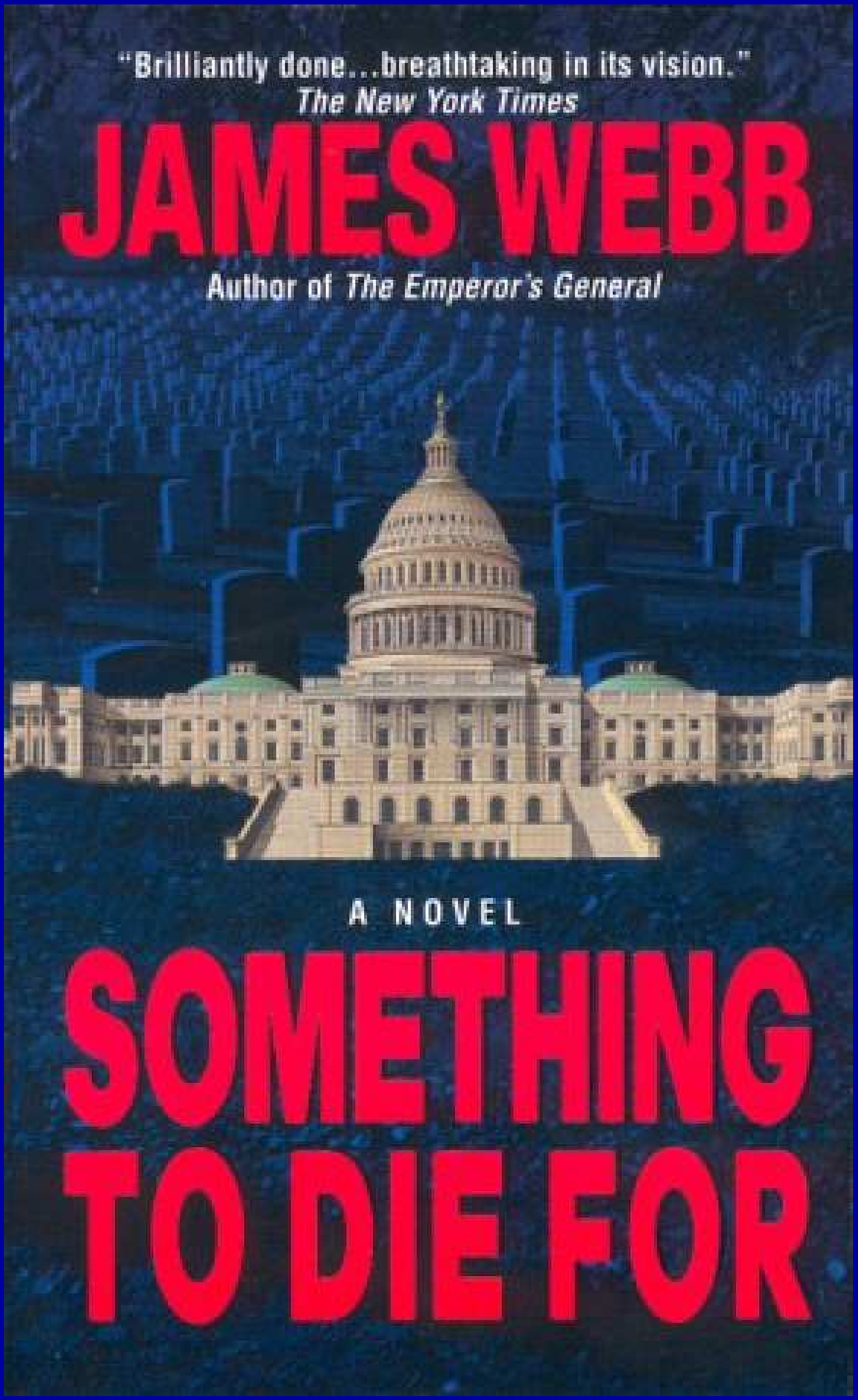


ASU Emeritus College, Wednesday October 17, 2007





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

Outline

- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) What is, and how can JWST measure First Light and Reionization?
- (4) What is, and how can JWST measure Galaxy Assembly?
- (5) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1$–15

Sponsored by NASA/JWST

ARIZONA STATE UNIVERSITY

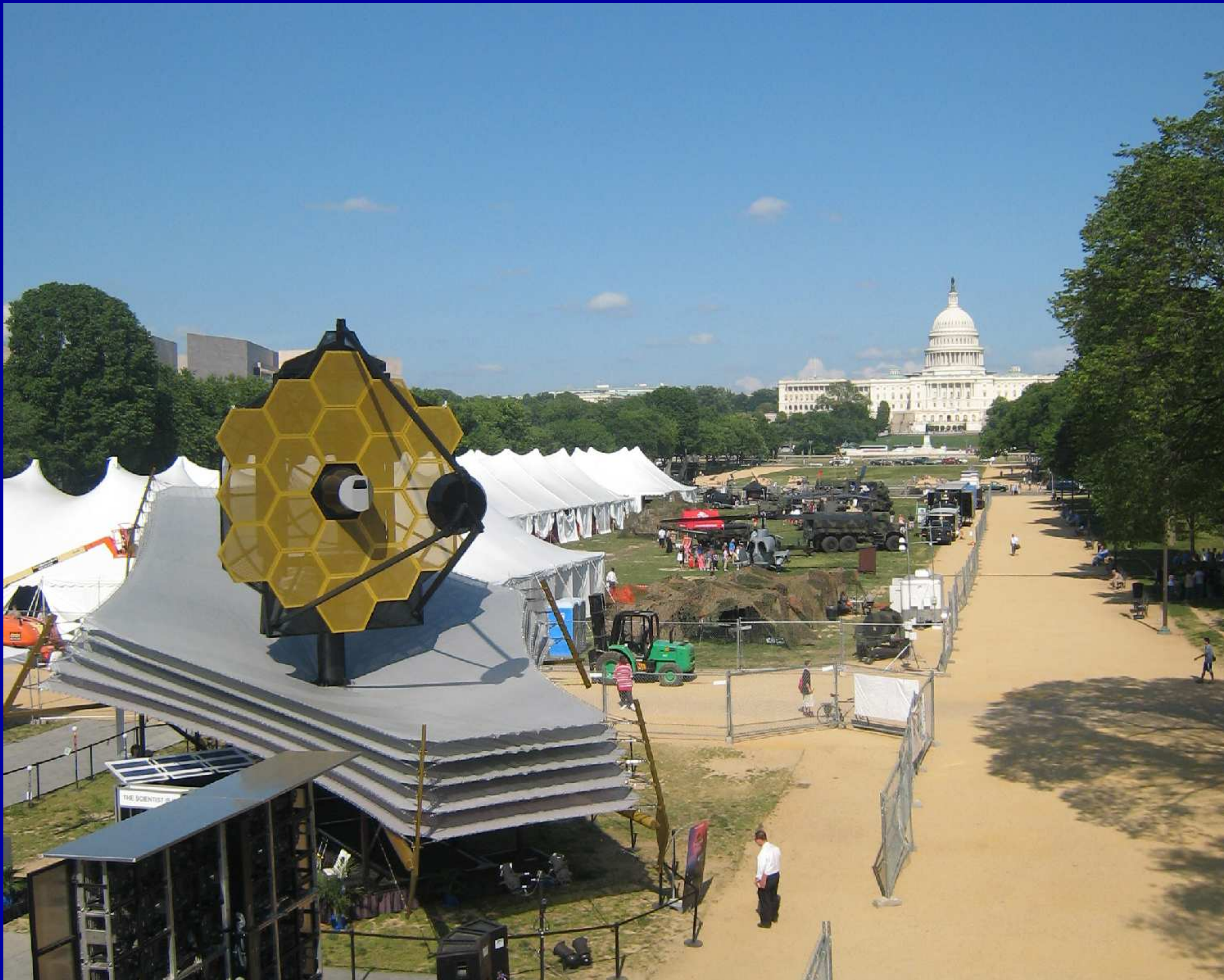
• (1) What is the James Webb Space Telescope (JWST)?

• A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6 to 28 μm, 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.

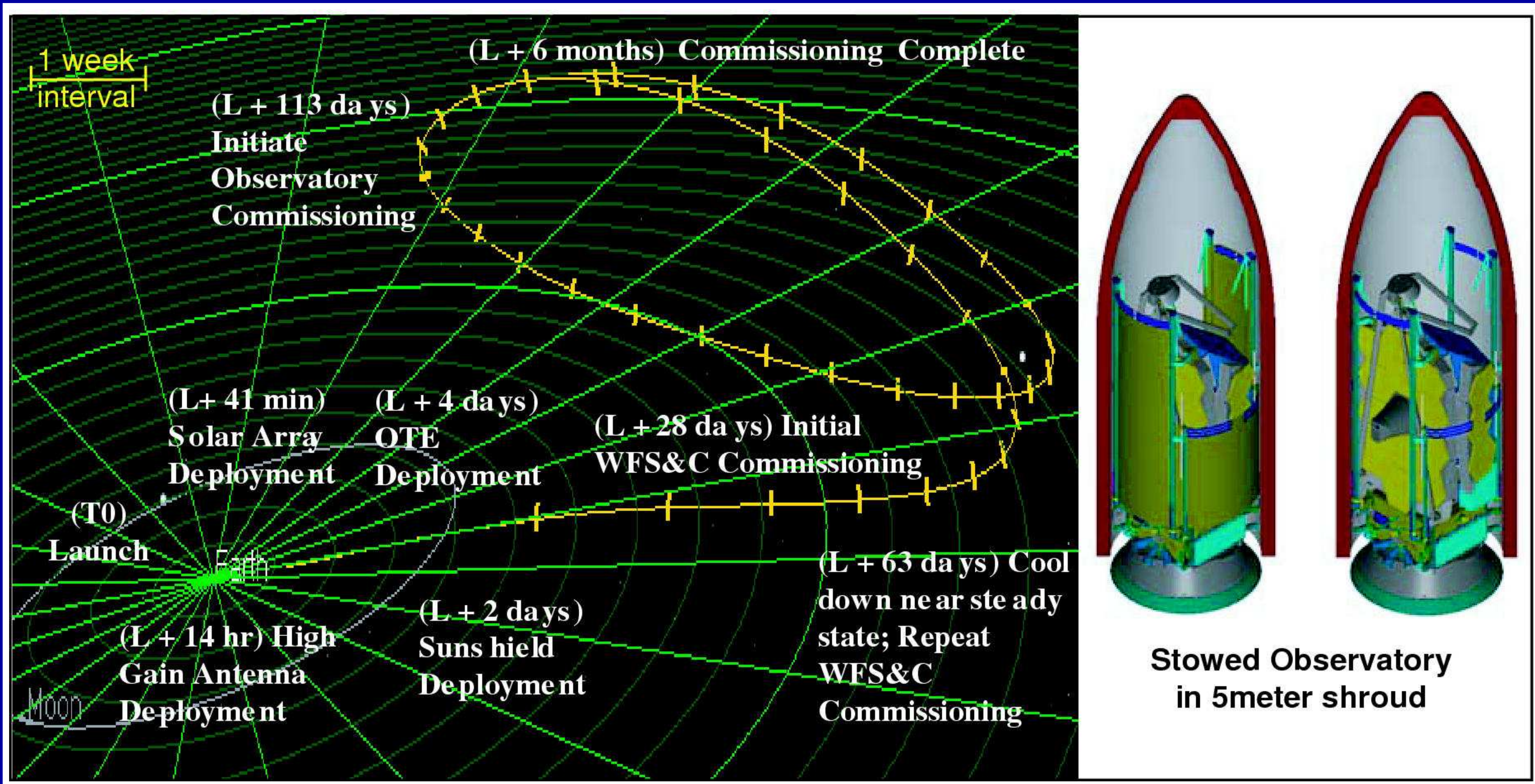
Life-sized model of JWST, used to test the deployment of its sun-shield.

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



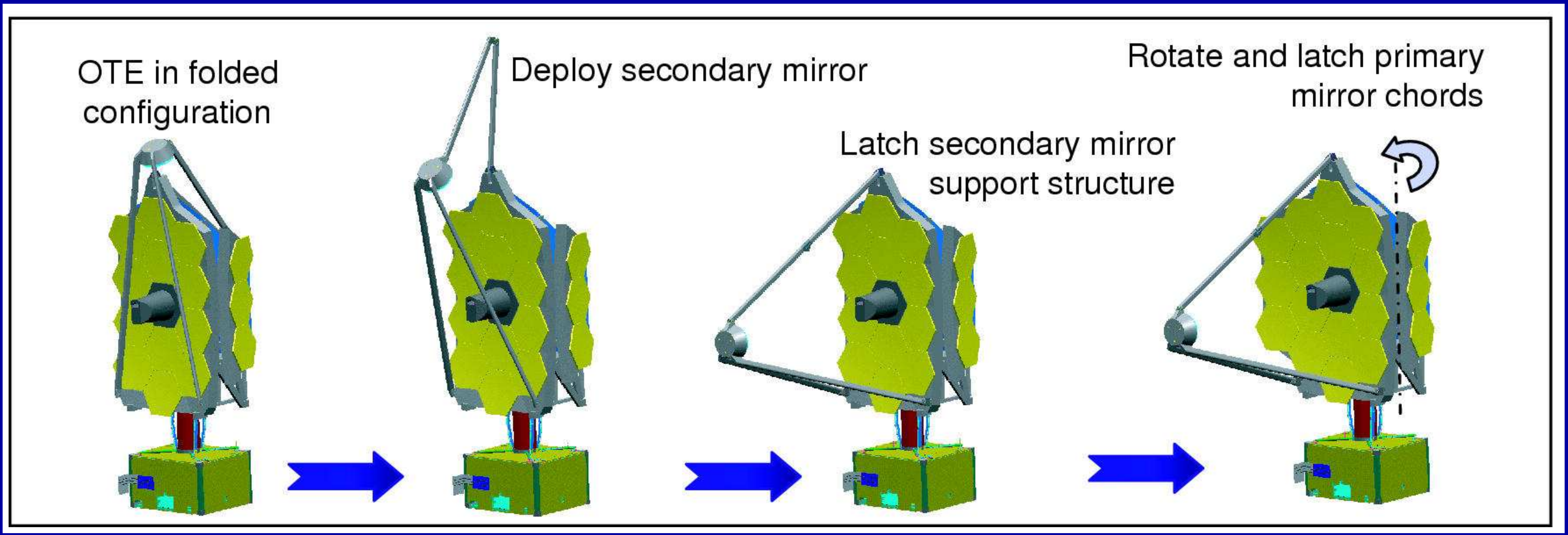
The JWST model on the Capitol Mall, May 2007 ...

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



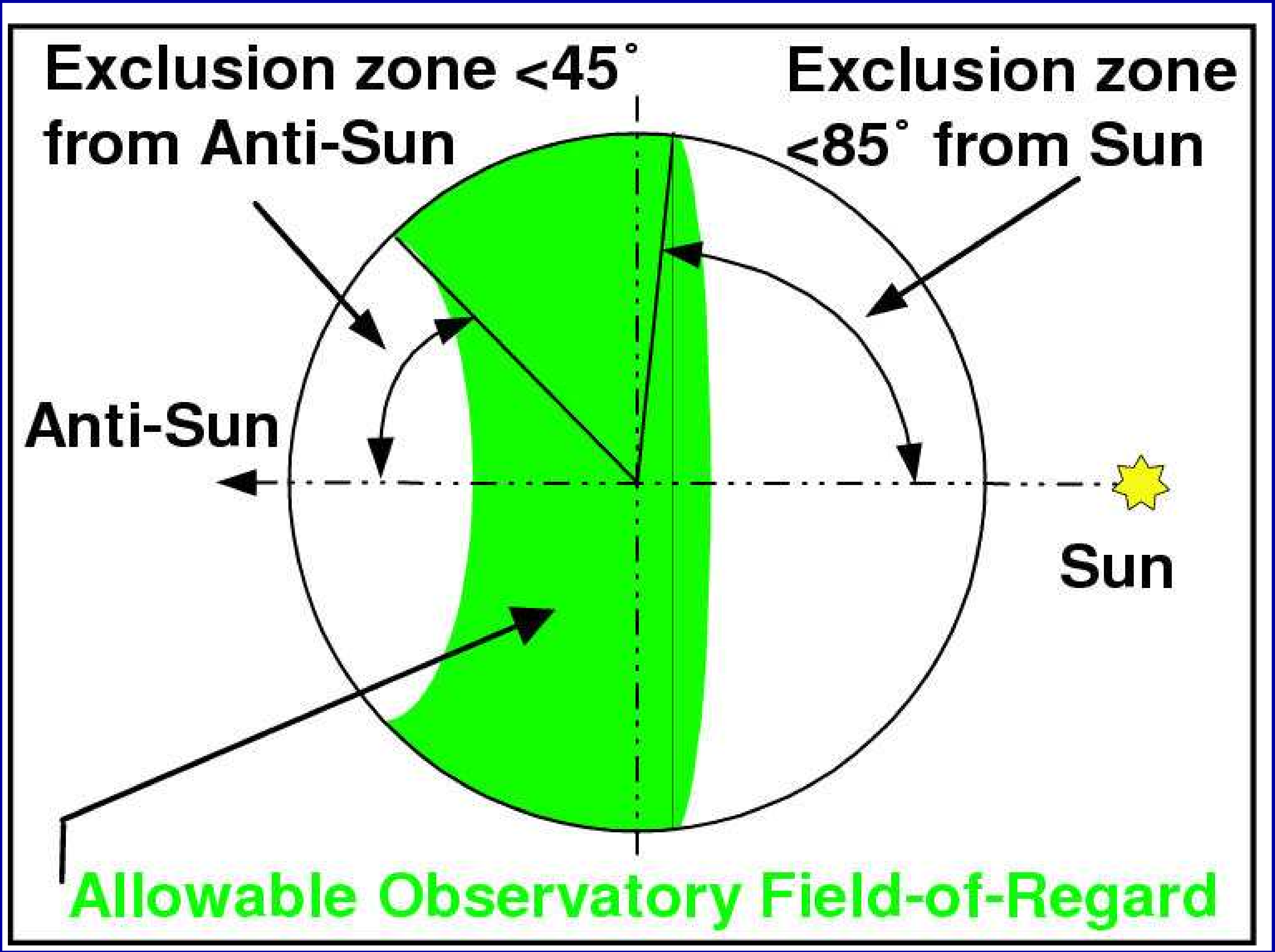
After launch in $\gtrsim$2013 with an Ariane V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

• (1) How will the JWST be automatically deployed?

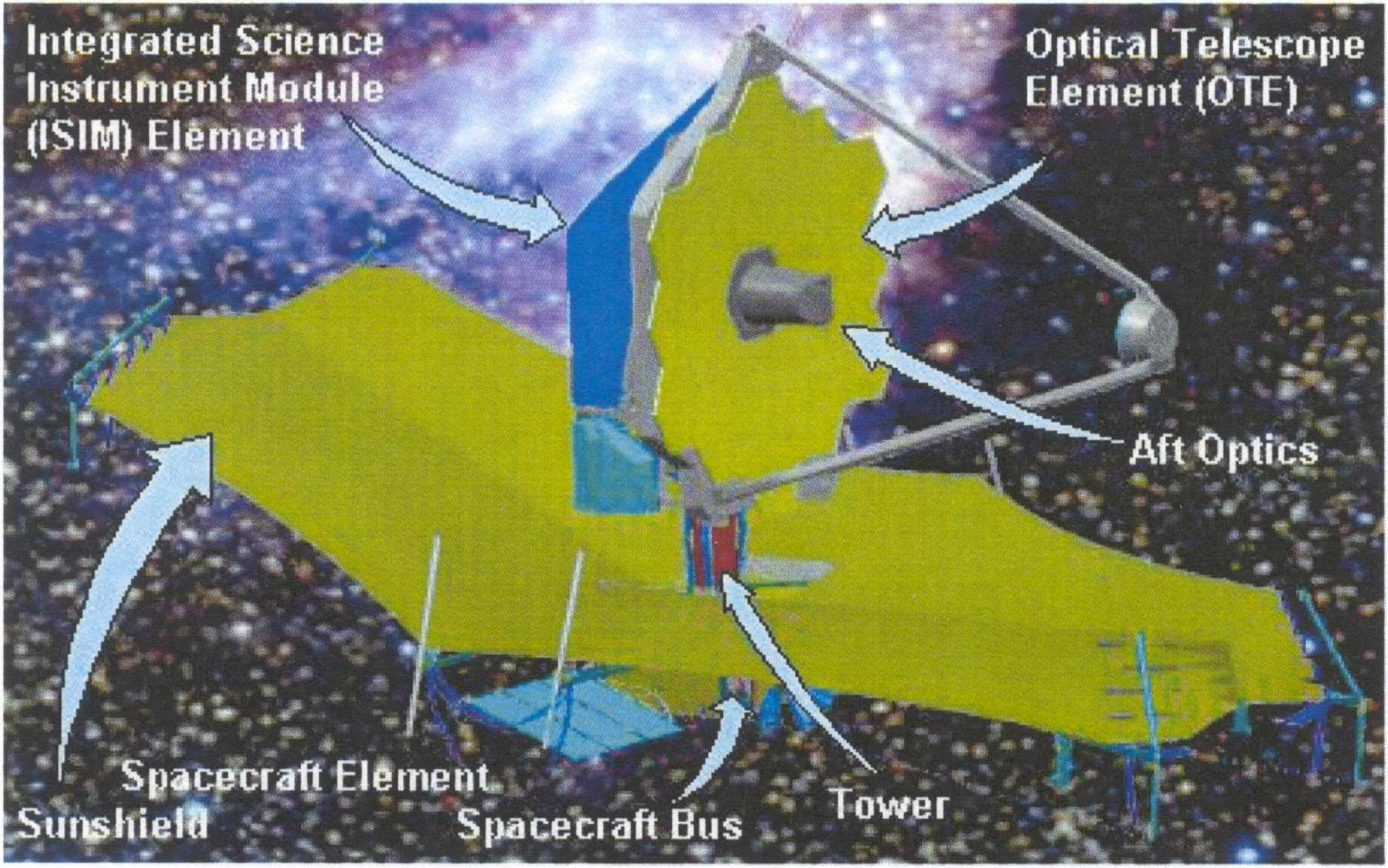


During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit.

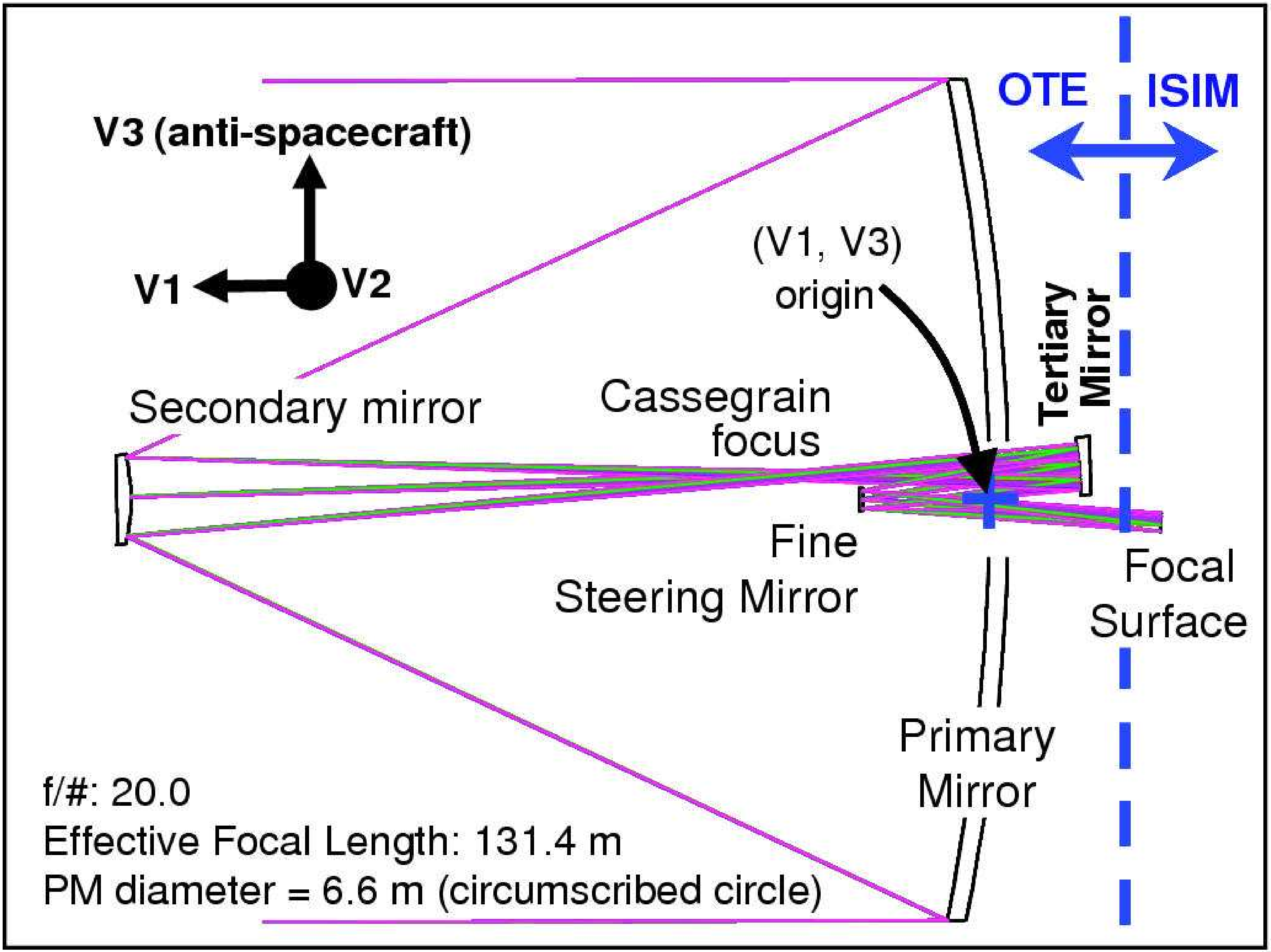
JWST mission reviewed in Gardner, J., Mather, J., et al.2006, Space Science Reviews, Vol. 123, pg. 485–606 (astro-ph/0606175).



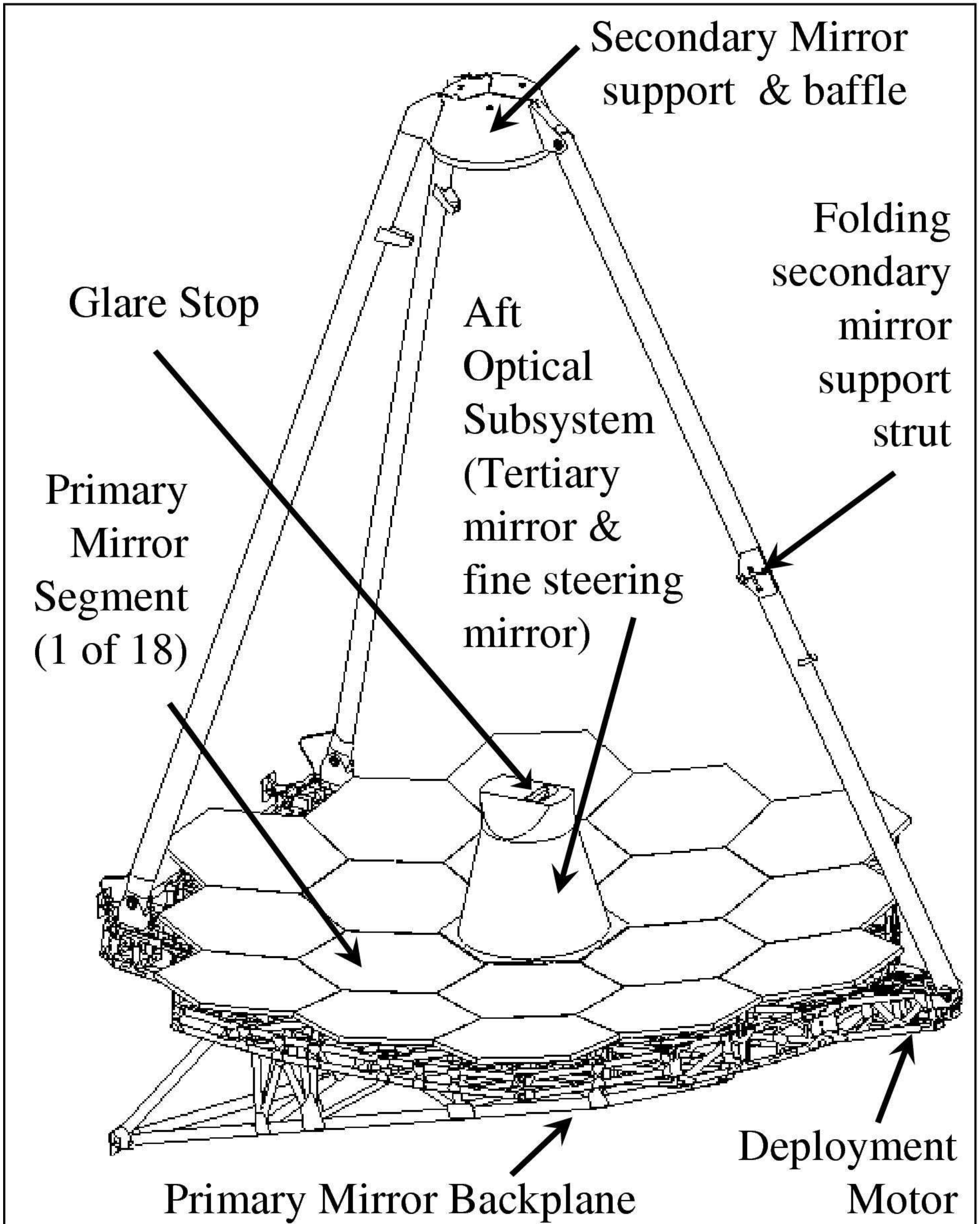
JWST can observe segments of sky that move around as it orbits the Sun.

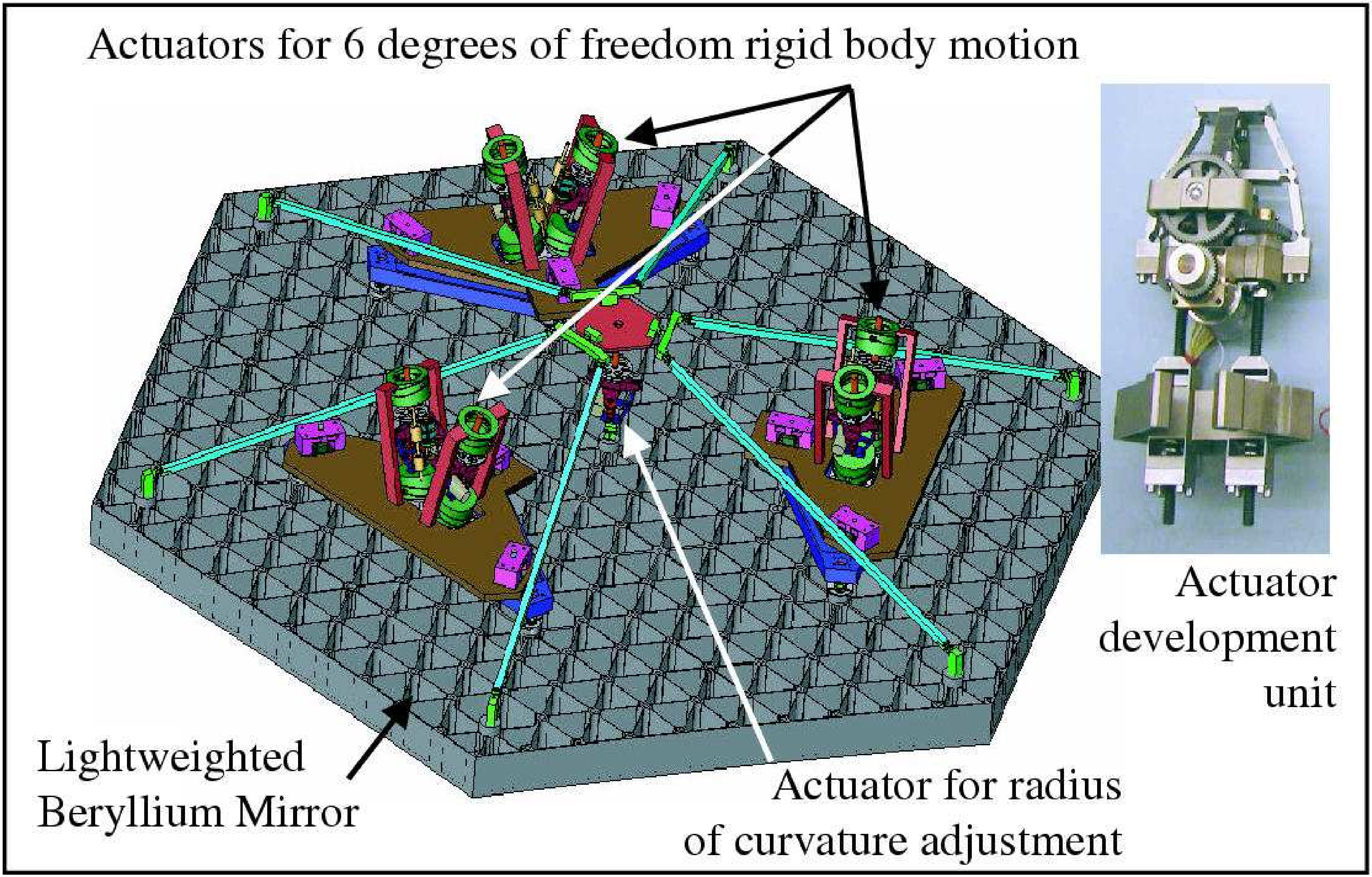


JWST mission reviewed in Gardner, J. P., et al. 2006, Space Science Reviews, Vol. 123, pg. 485–606 (lanl.arxiv.org/abs/astro-ph/0606175)

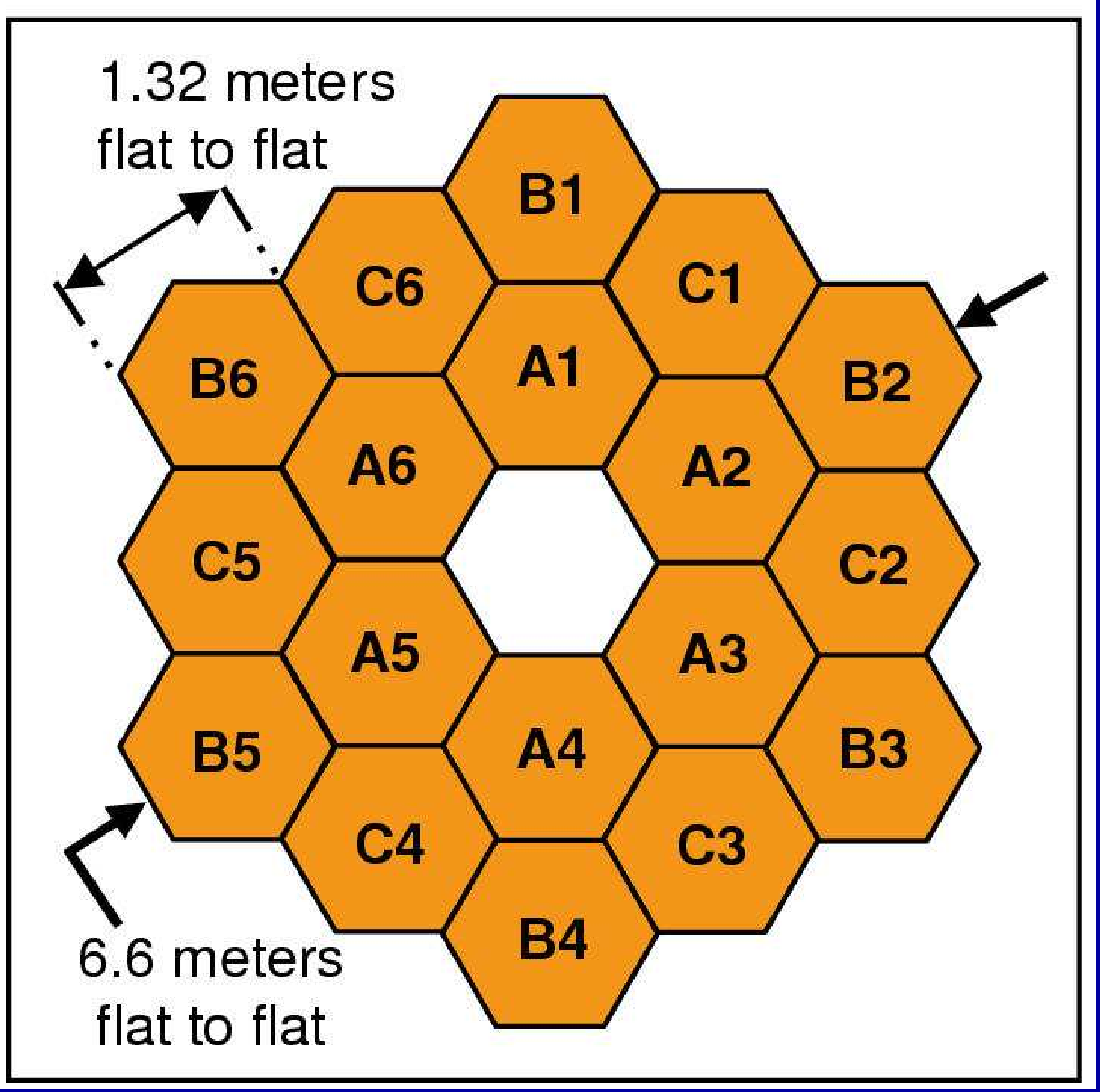


OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)


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



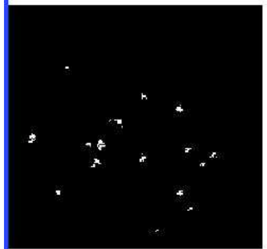
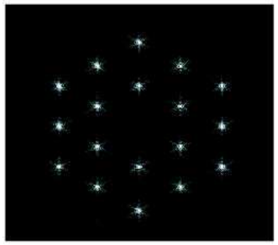
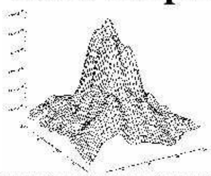
Active mirror segment support through hexapods, similar to Keck telescope.



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 telescope.

Successful 2006 demo of H/W, S/W on a 6/1 scale model at Ball Aerospace.

Need Wave Front Sensing-updates every ∼10 days, depending on scheduling.

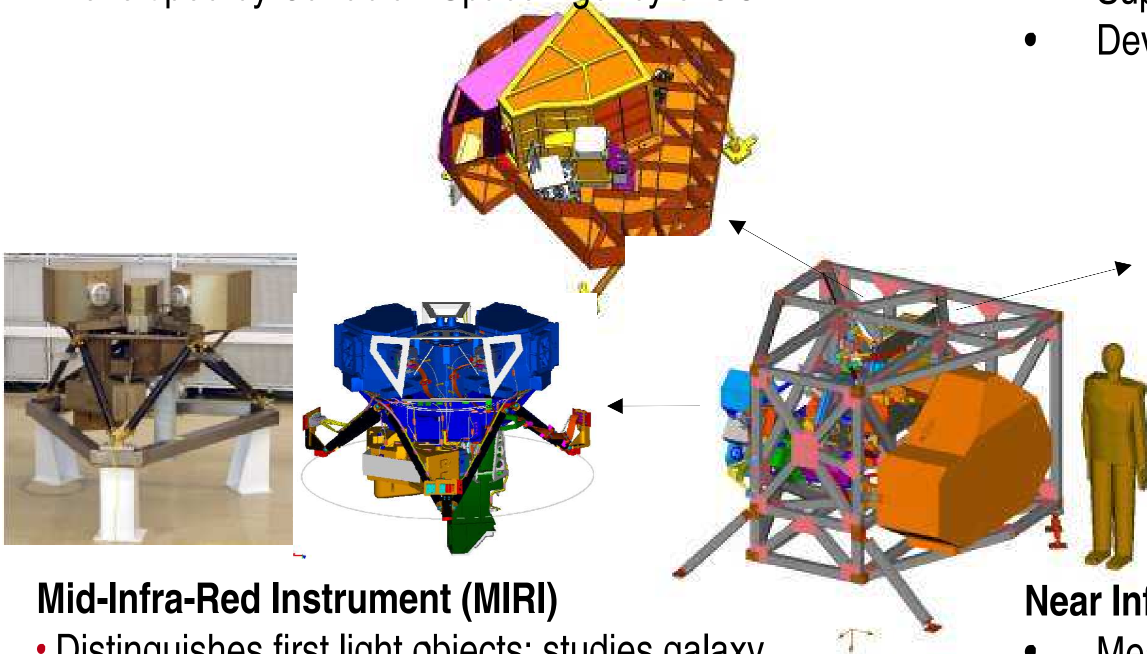
Ball 1/6-scale model: WFS produces diffraction-limited images at 2.0 μm.

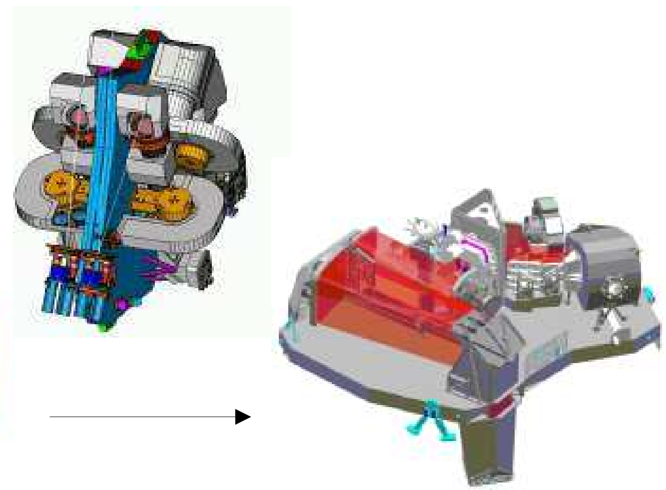
• (1) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

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

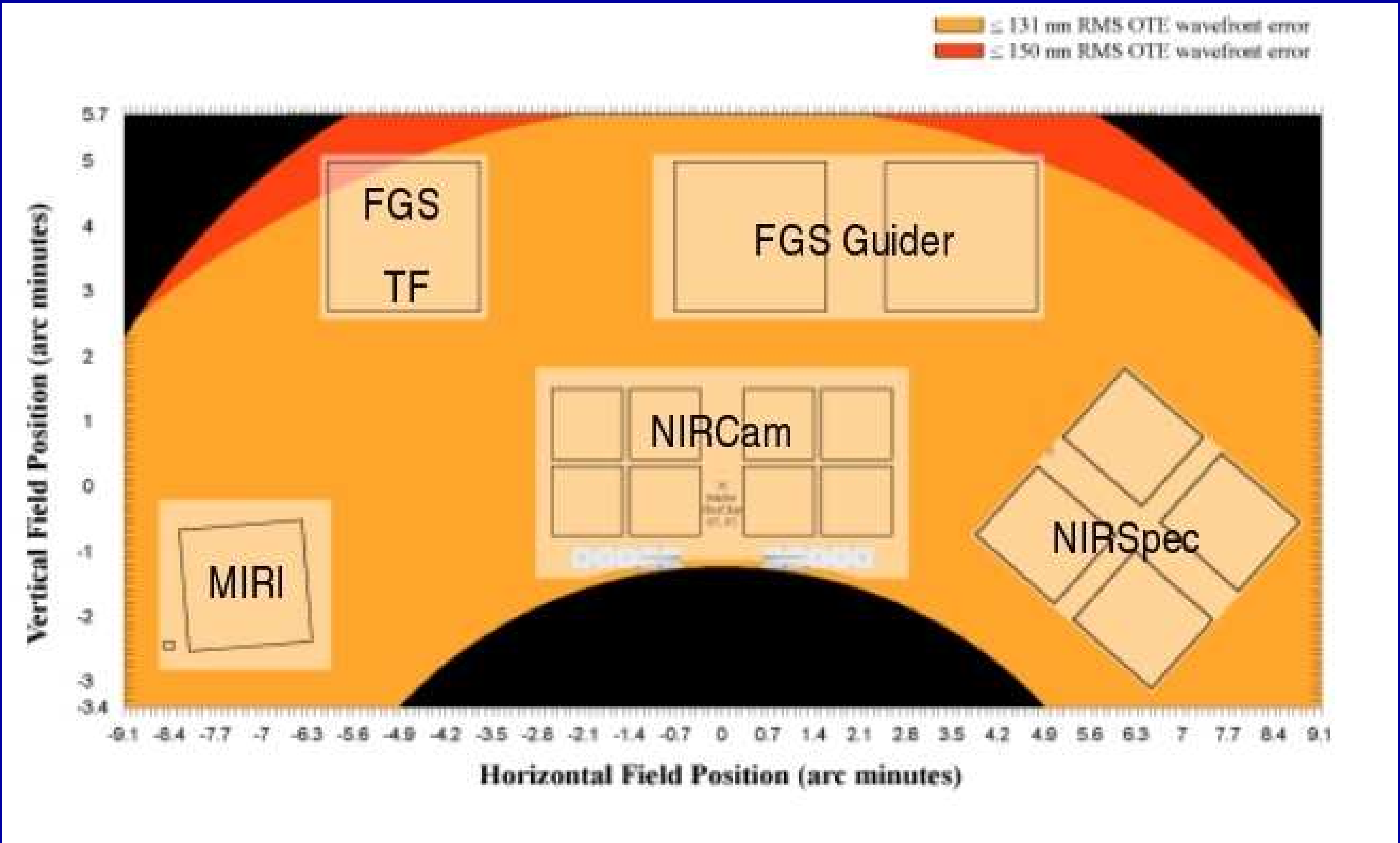




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

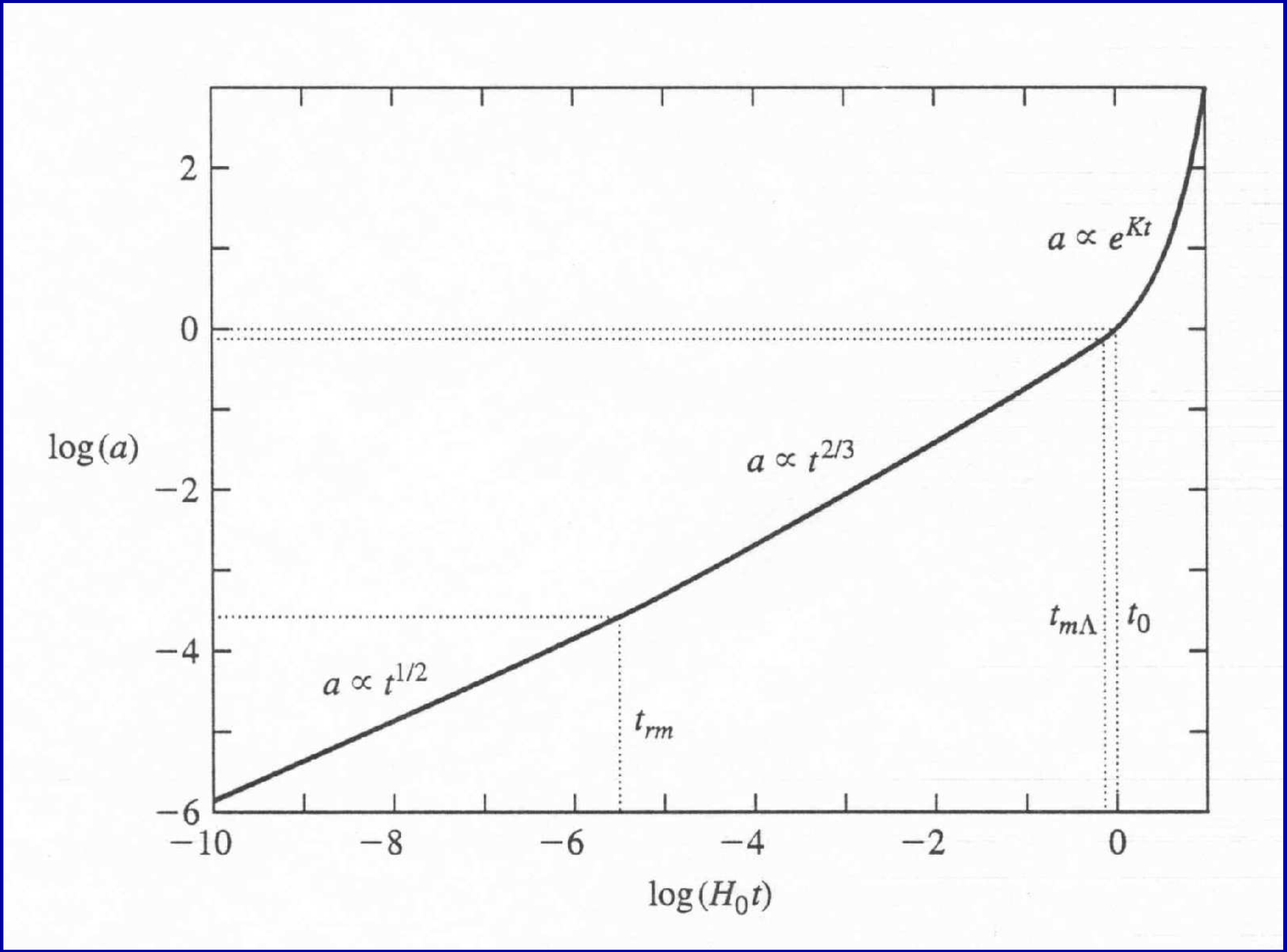
• (2) What instruments will JWST have?



The JWST instrument complement: US (UofA), ESA, and CSA.

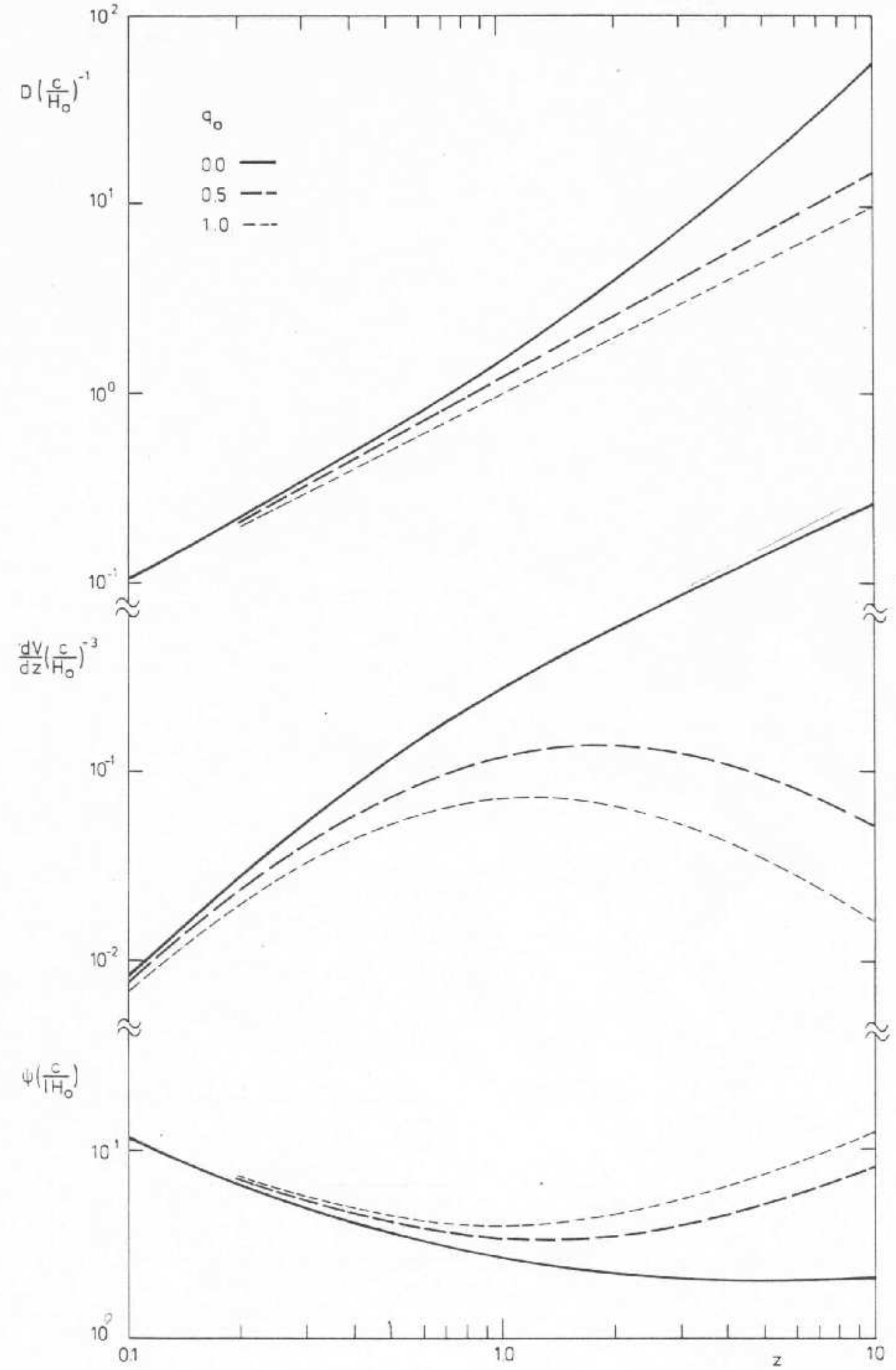
All JWST instruments are redundant, can in principle be used in parallel.

- (2) Cosmology in a nutshell: the exponentially expanding universe



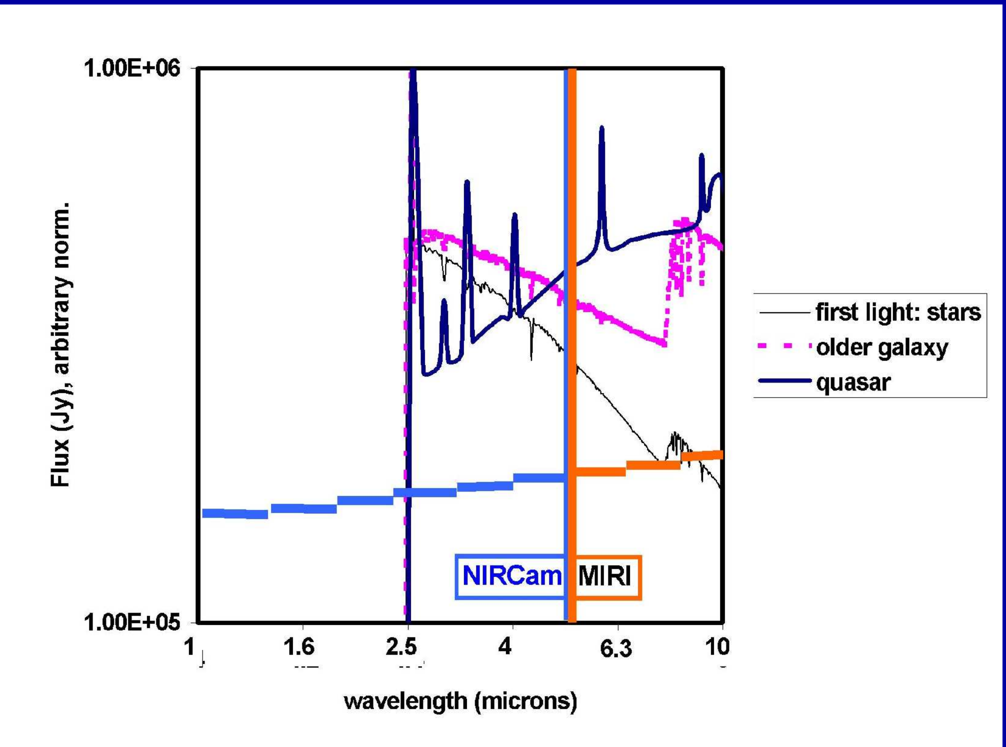
The Cosmic Stock Market: A much better and safer bet than Wall Street!

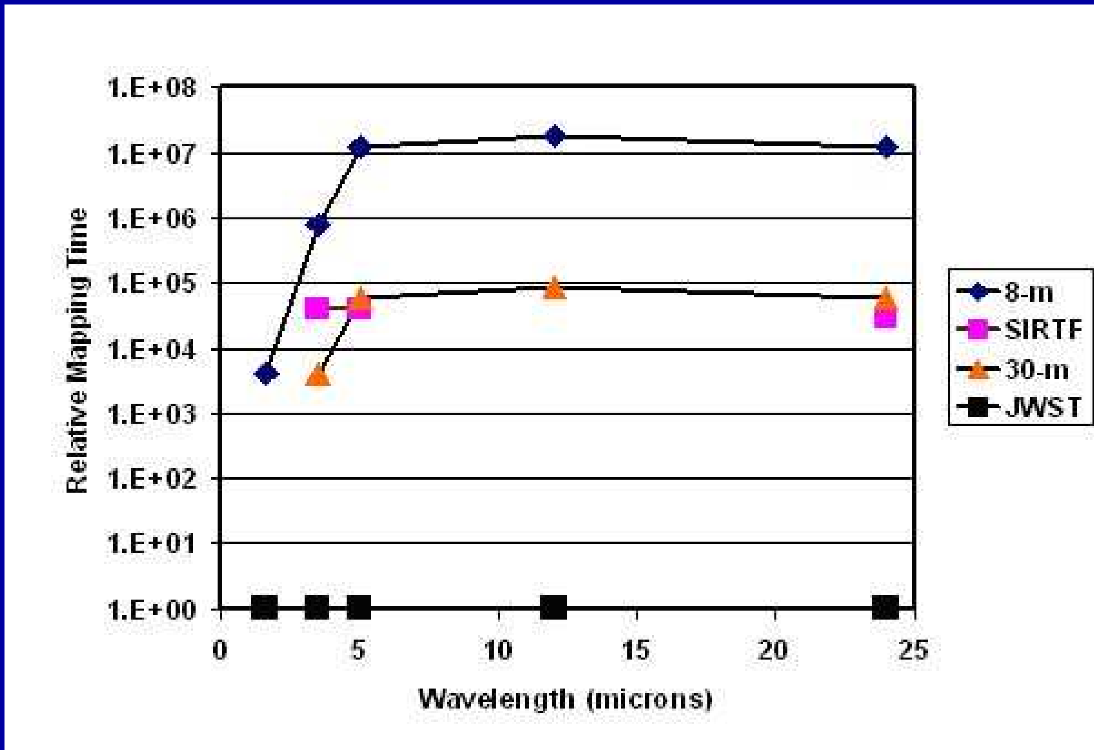
Real Expansion R $\propto$ $t^{1/2}$ (Radiation era); $t^{2/3}$ (Matter era); e^{Kt} (Λ-era)



Relativistic Distance D, Volume Element dV/dz, and Angular Size Ψ vs. z.

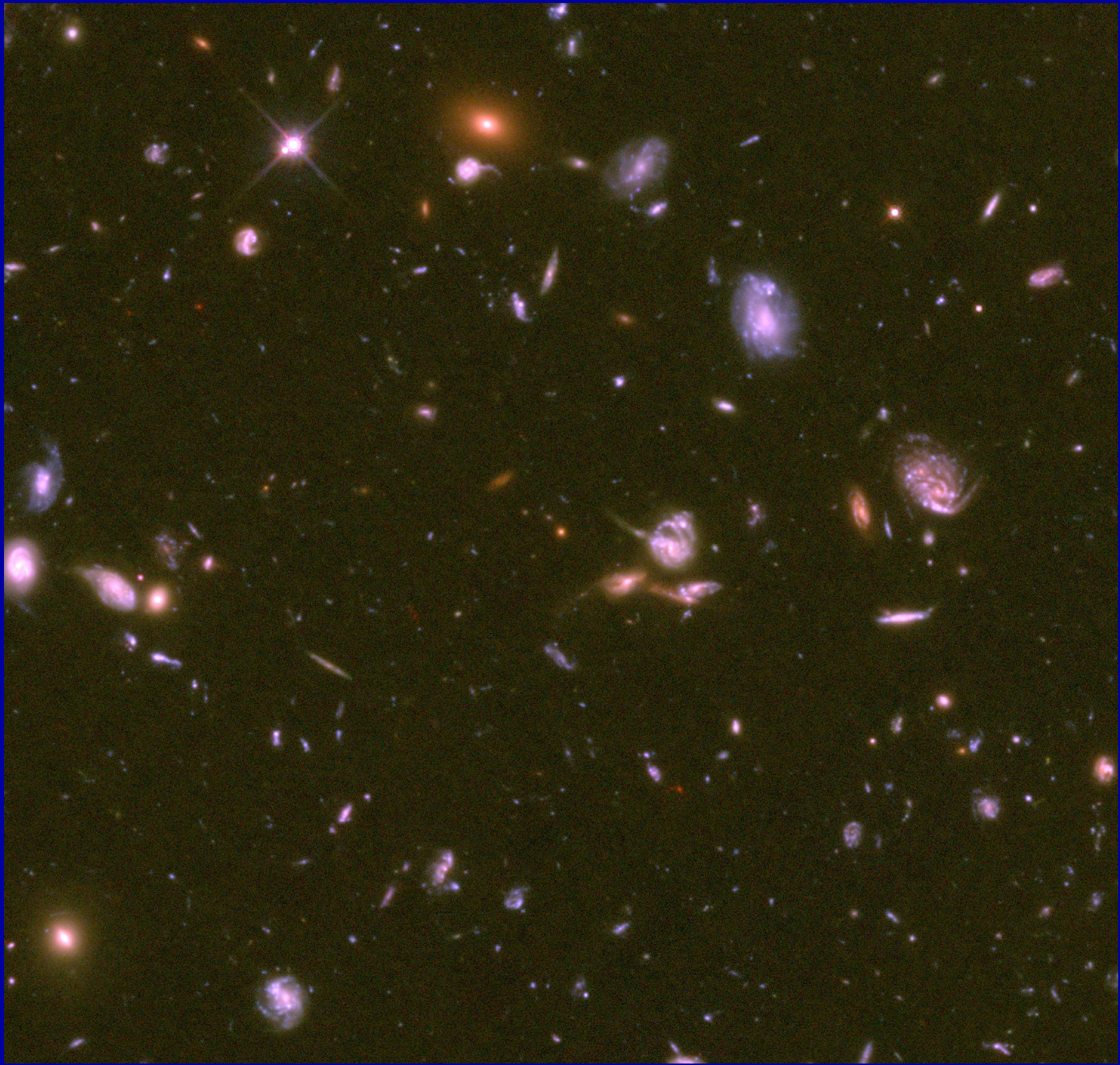
• (2) What sensitivity will JWST have?





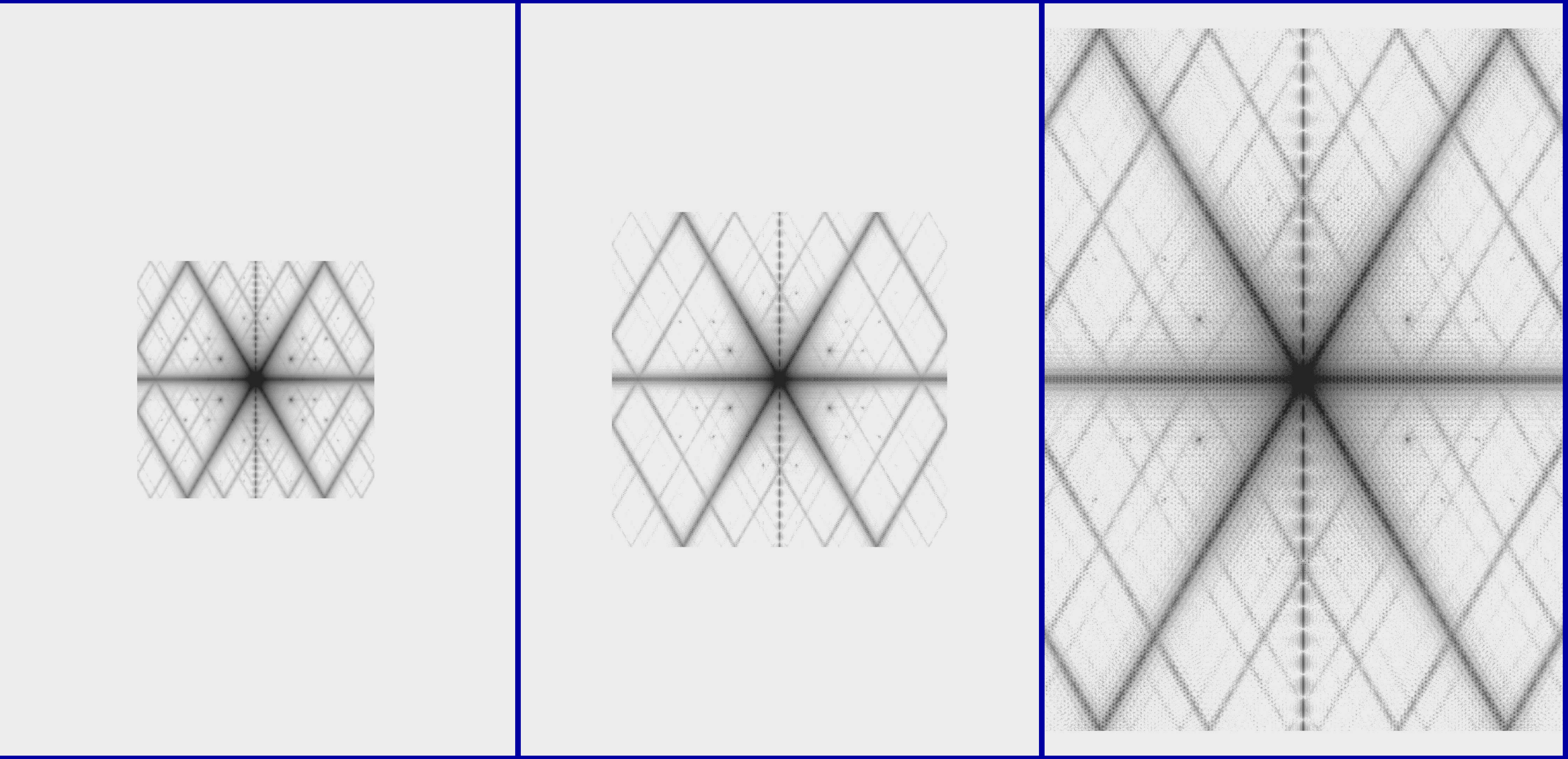
The JWST instrument sensitivity of NIRCam and MIRI complement each other, straddling 5 μm in wavelength, and together allow objects to be found to redshifts z=15–20 in $\sim 10^5$ sec (28 hrs) integration times.

The left panel shows the NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy, all at z=20. The right panel shows the relative survey time versus wavelength that SIRTF/Spitzer, a ground-based IR-optimized 8-m (Gemini) and a ground-based 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):

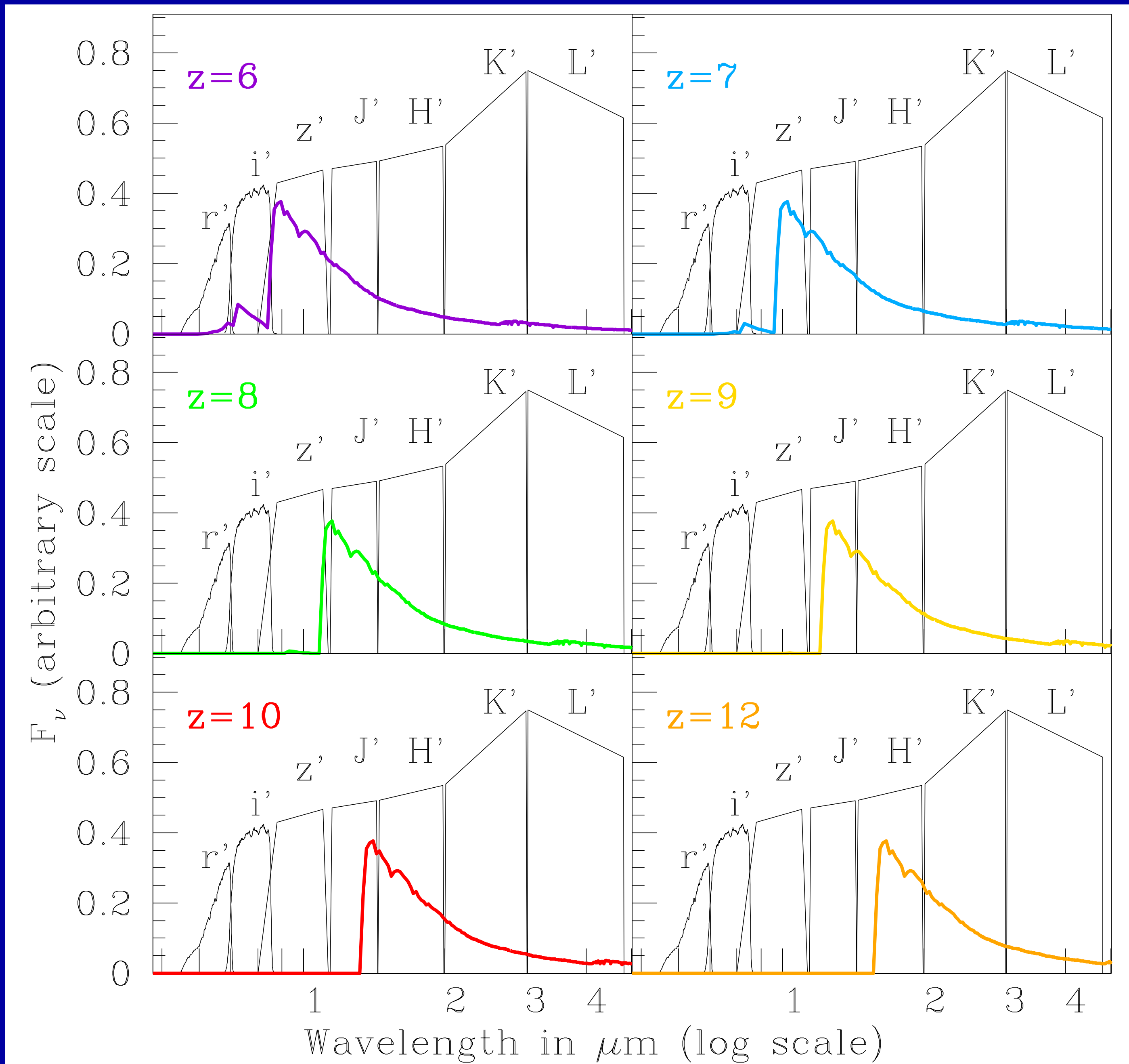


NIRCam 0.7 μm   1.0 μm (<150 nm WFE)   2.0 μm (diffr. limit)

Predicted JWST images at logarithmic greyscale: they enclose $\gtrsim$74% of the light at r$\lesssim$0.″15 at 1.0μm, and are diffraction limited at 2.0μm.

$\lesssim$20 hrs JWST NIRCam at 0.7, 0.9, 2.0 μm in the HUDF

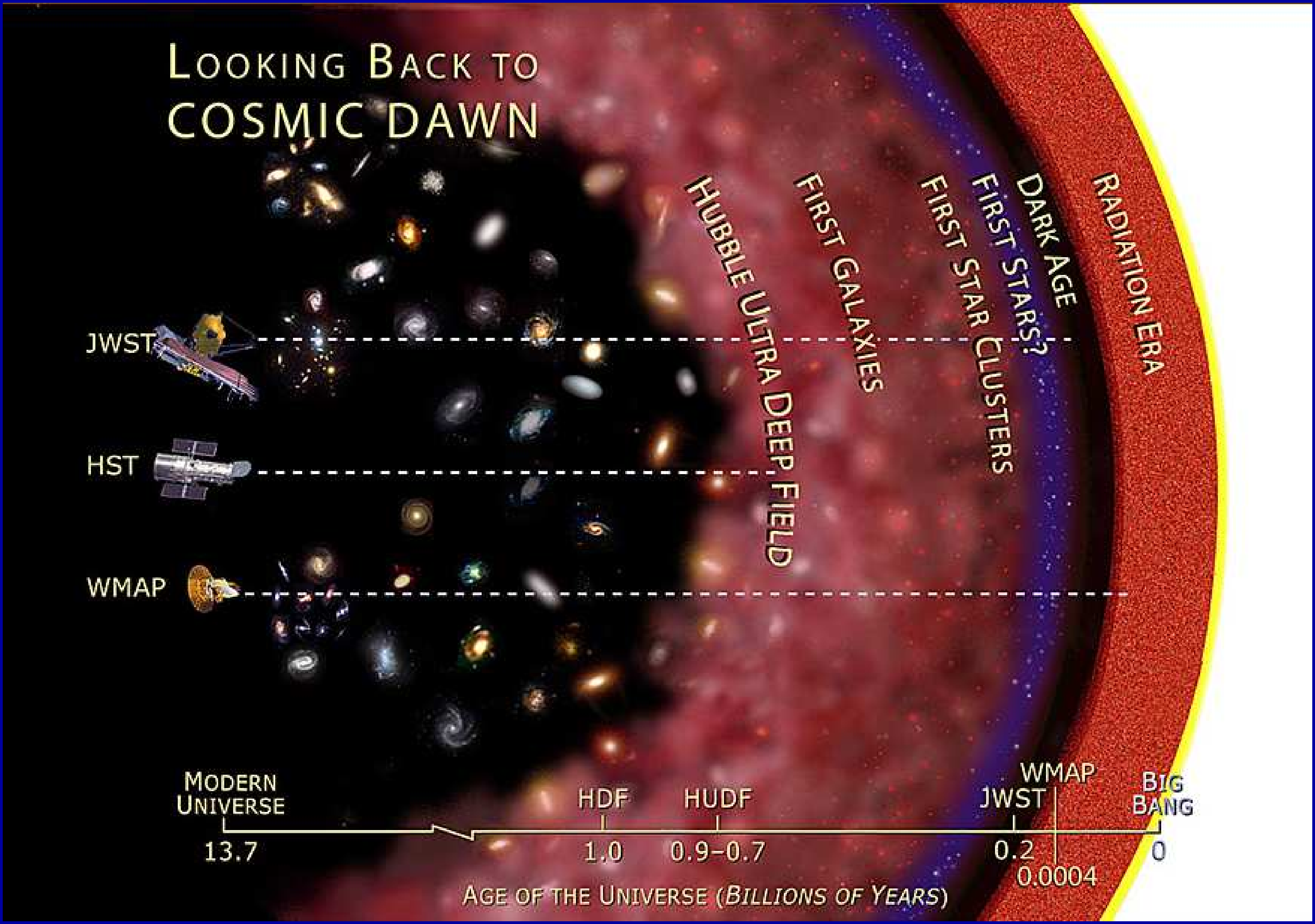
Truth$\equiv$240 hrs HUDF Vi'z' $\lesssim$20 hrs JWST 0.7, 0.9, 2.0 μm



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

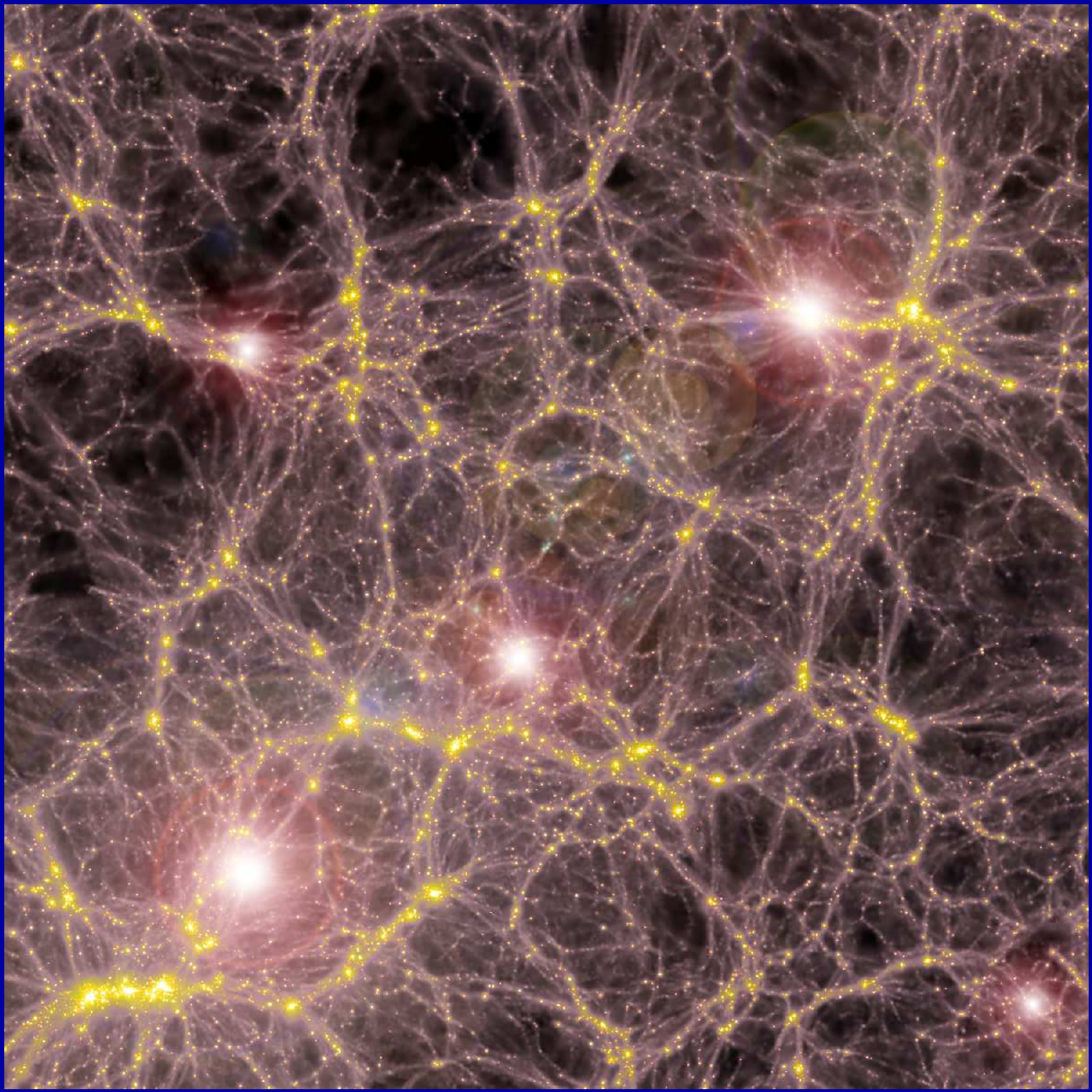
$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

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



NASA telescopes penetrating Cosmic Dawn, First Light, & Recombination

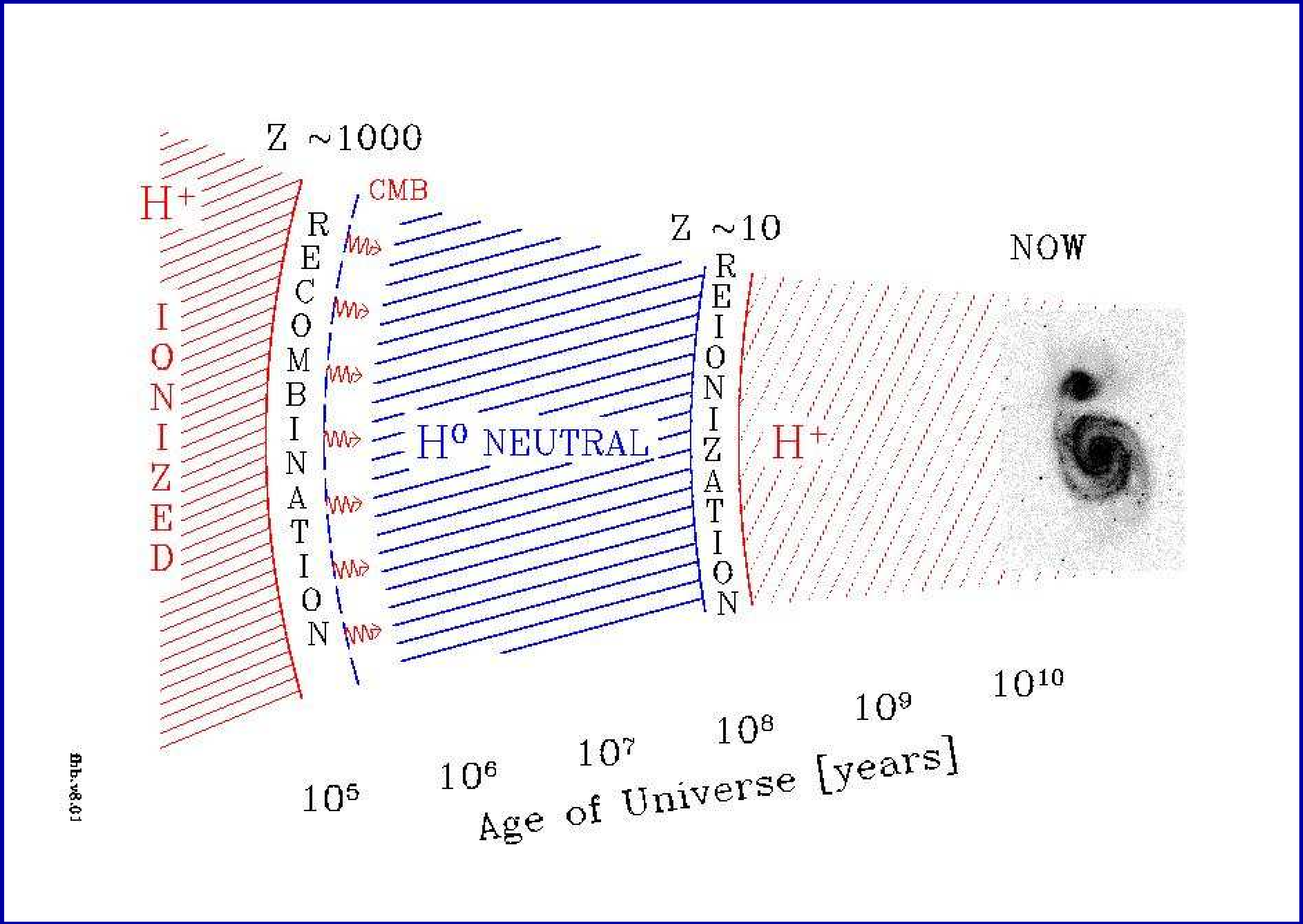
• (3a) What is First Light and Reionization?



• Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars (mass $\simeq$ 100–200 $M_{\odot}$) reionized universe for the first time at z$\lesssim$15–30 (First Light).

• Part of this could be visible to JWST as the first and extremely luminous supernovae of massive Pop III stars at redshifts z$\simeq$15$\longrightarrow$30.

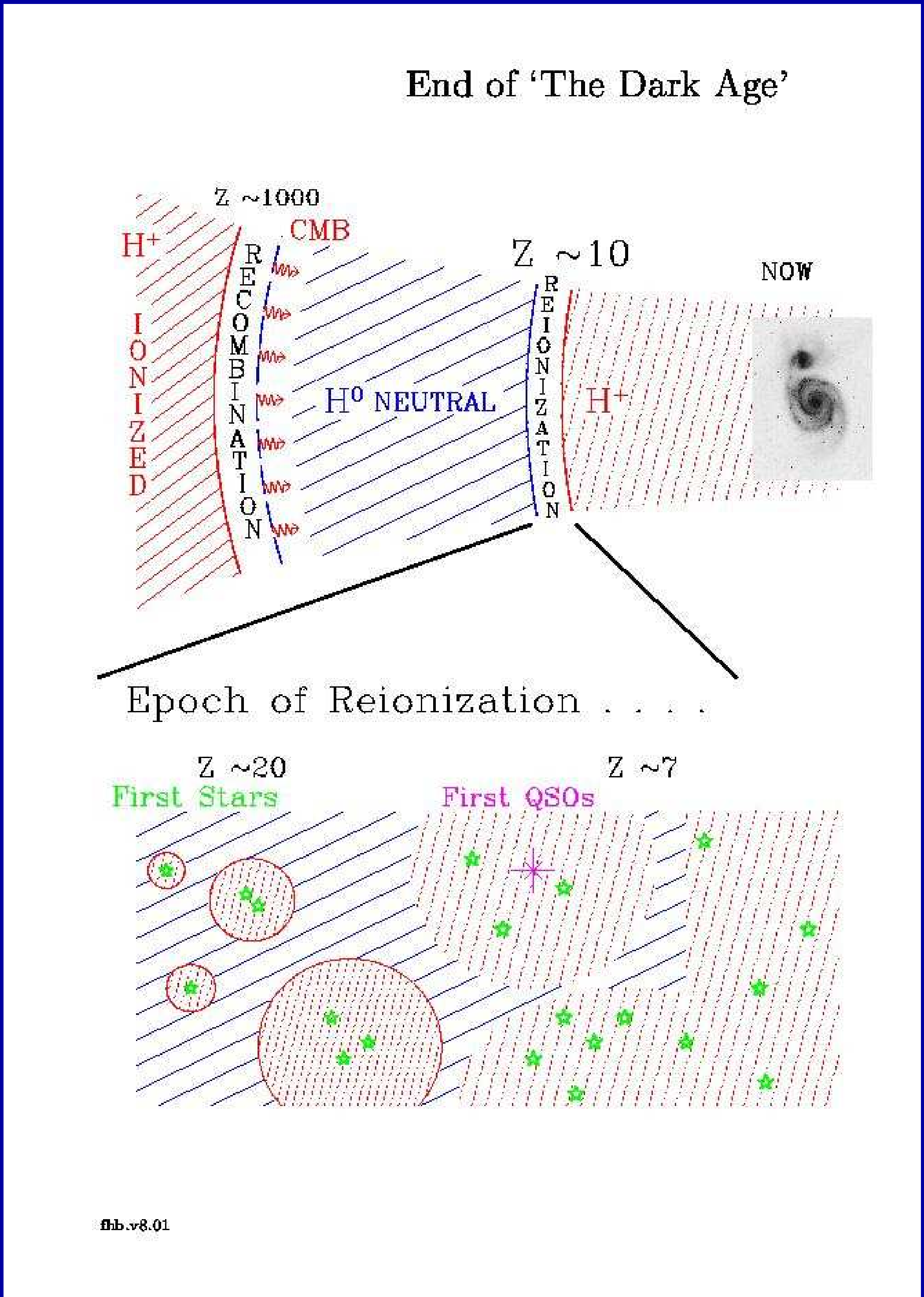
• (3a) What is First Light and Reionization?



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

- (1) Population III stars with $\gtrsim$100–200 $M_\odot$ at z$\simeq$11–20 (First Light).
- (2) First Population II stars (halo stars) form in dwarf galaxies with mass $\simeq 10^7$–10^9 $M_\odot$ at z$\simeq$6–9, which complete reionization by z$\simeq$6.

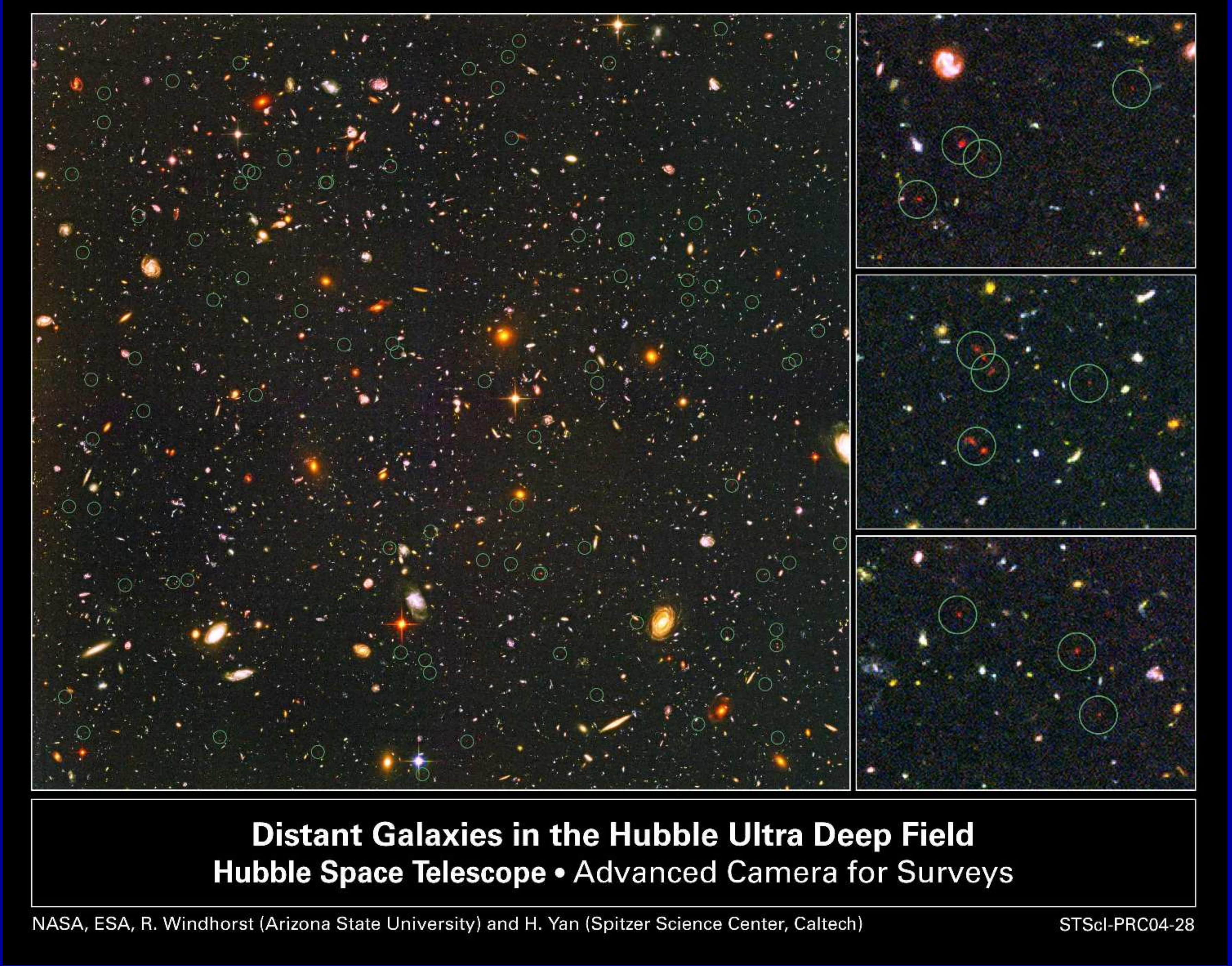
$\Rightarrow$ JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.



WMAP: First Light may have happened as following:

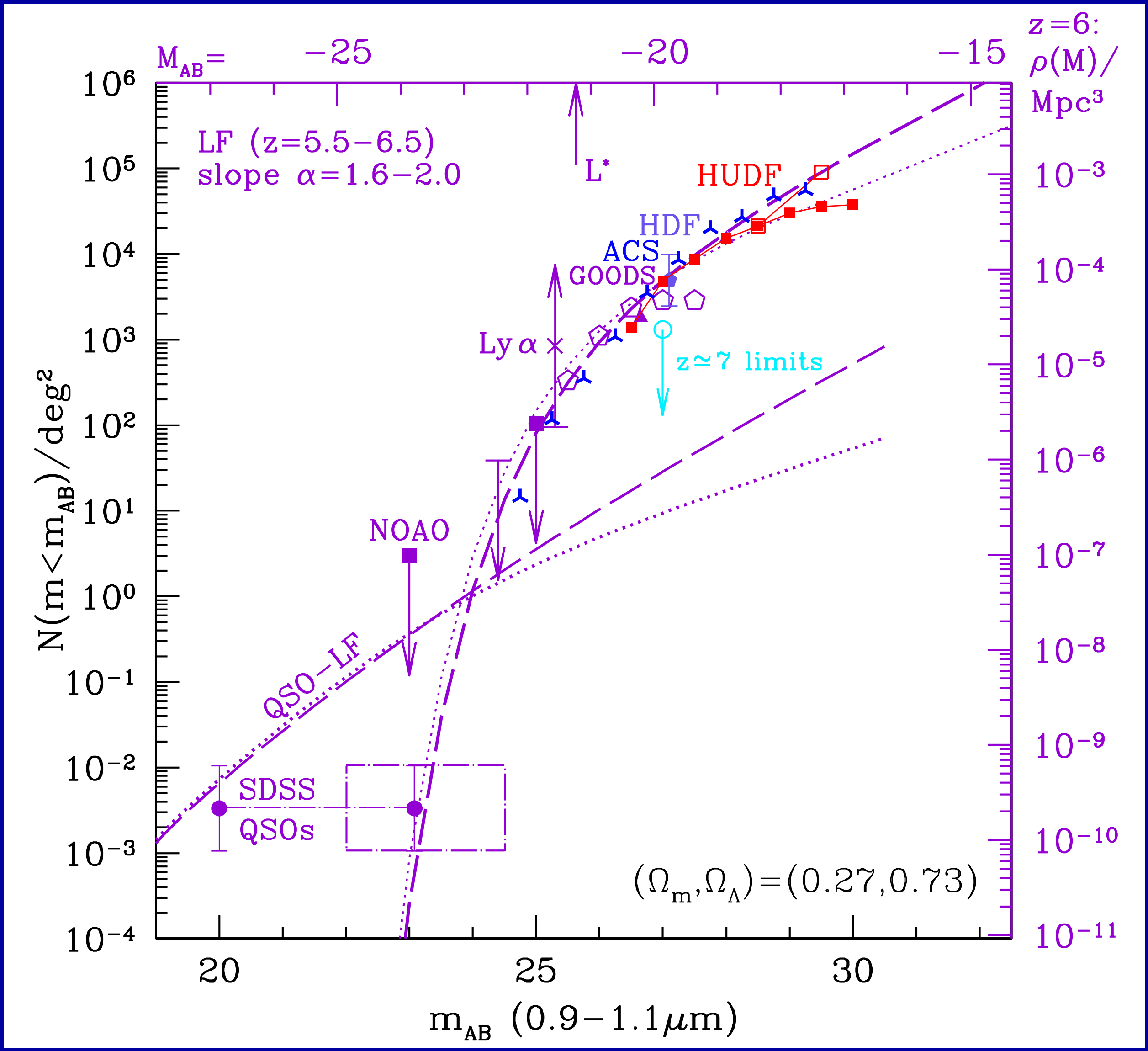
- (0) Dark Ages since recombination ($z=1089$) until First Light objects started shining ($z=11$–20).
- (1) First Light when Population III stars start shining with masses $\gtrsim 100$–$200\ M_\odot$ at $z \simeq 11$–20.
- (2) Pop III supernovae heated IGM, which could not cool and form normal Pop II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



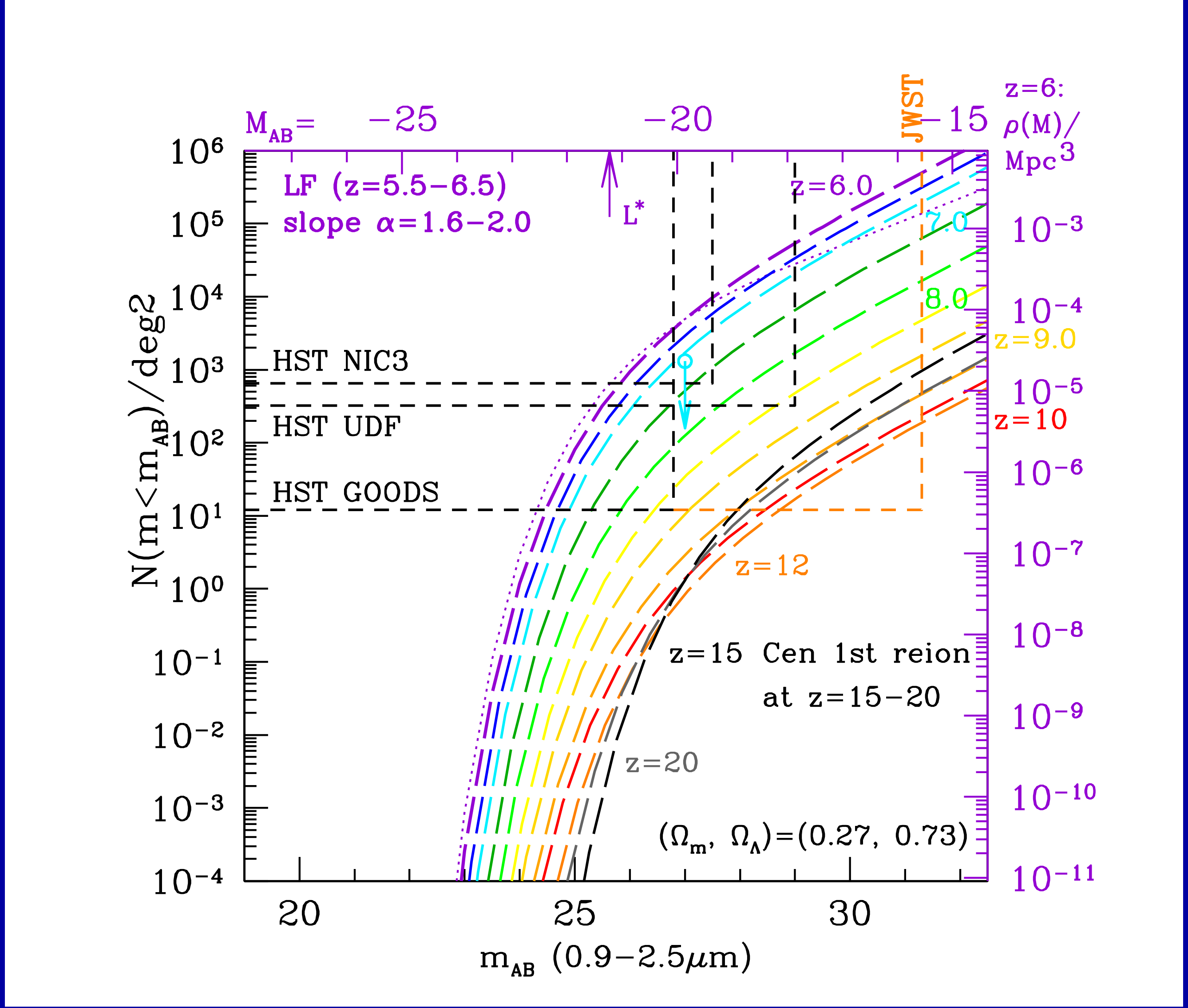
HUDF dropouts: faint galaxies at z≃6 (Yan & Windhorst 2004), most spectroscopically confirmed at z≃6 to AB≲27.0 mag (Malhotra ea. 2005)

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



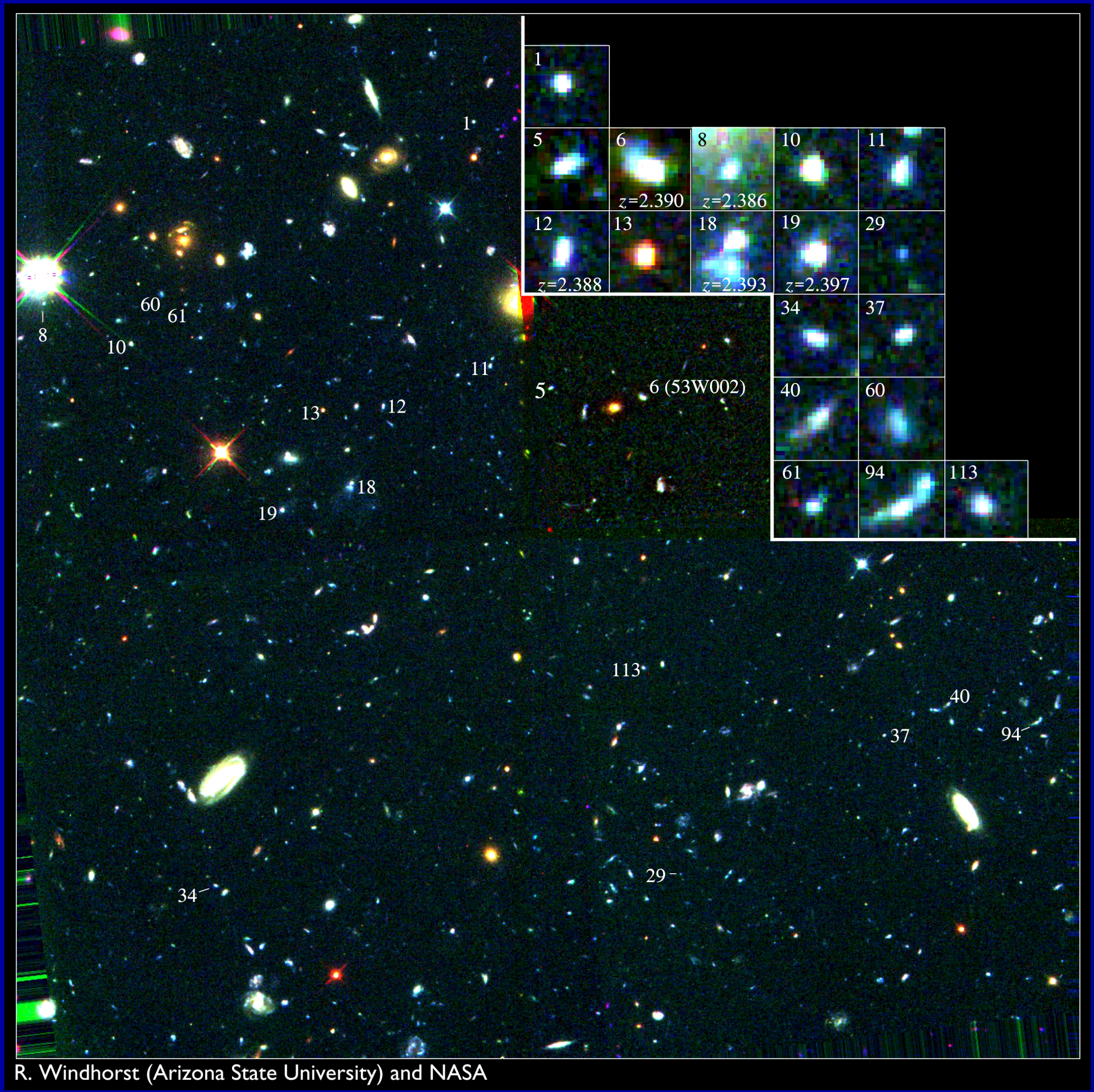
HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004a, b) may be very steep (faint-end slope $|\alpha|\gtrsim$1.8–2.0 (Olbers!).

⇒ Dwarf galaxies and not quasars likely completed the reionization epoch at z≃6. This is what JWST will observe in detail to z≳10–20.



- 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 sufficient sensitivity/aperture, field-of-view, and wavelength range (0.7-28 μm).

• (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 ($I < 26.0$)

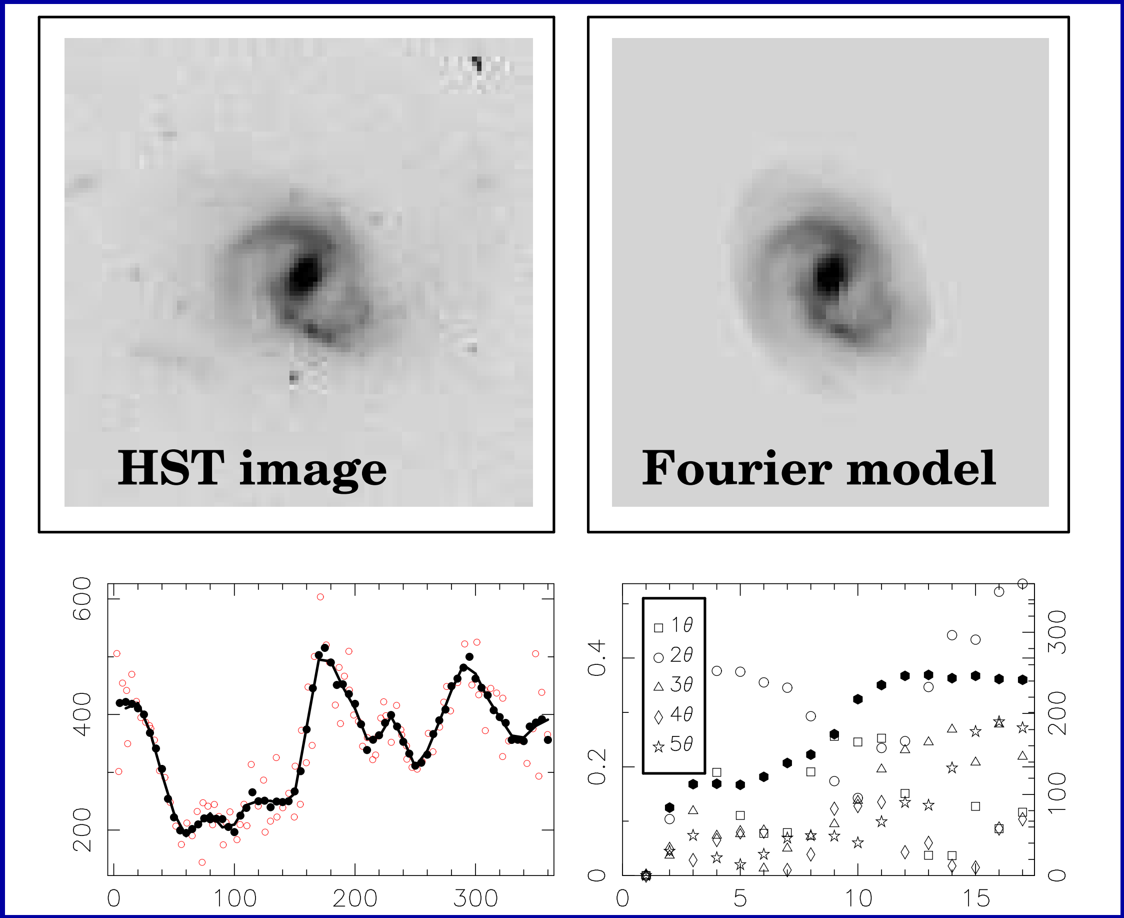
• (4) How JWST can measure Galaxy Assembly

• Galaxies of all Hubble types formed over a wide range of cosmic time, but with a notable transition around redshifts $z \simeq 0.5$–1.0:

(1) Subgalactic units rapidly merge from $z \simeq 7 \longrightarrow 1$ to grow bigger units.

(2) Merger products start to settle as galaxies with giant elliptical bulges or large spiral galaxy disks around $z \simeq 1$. These evolved mostly passively since then, resulting in the giant elliptical and spiral galaxies that we see today.

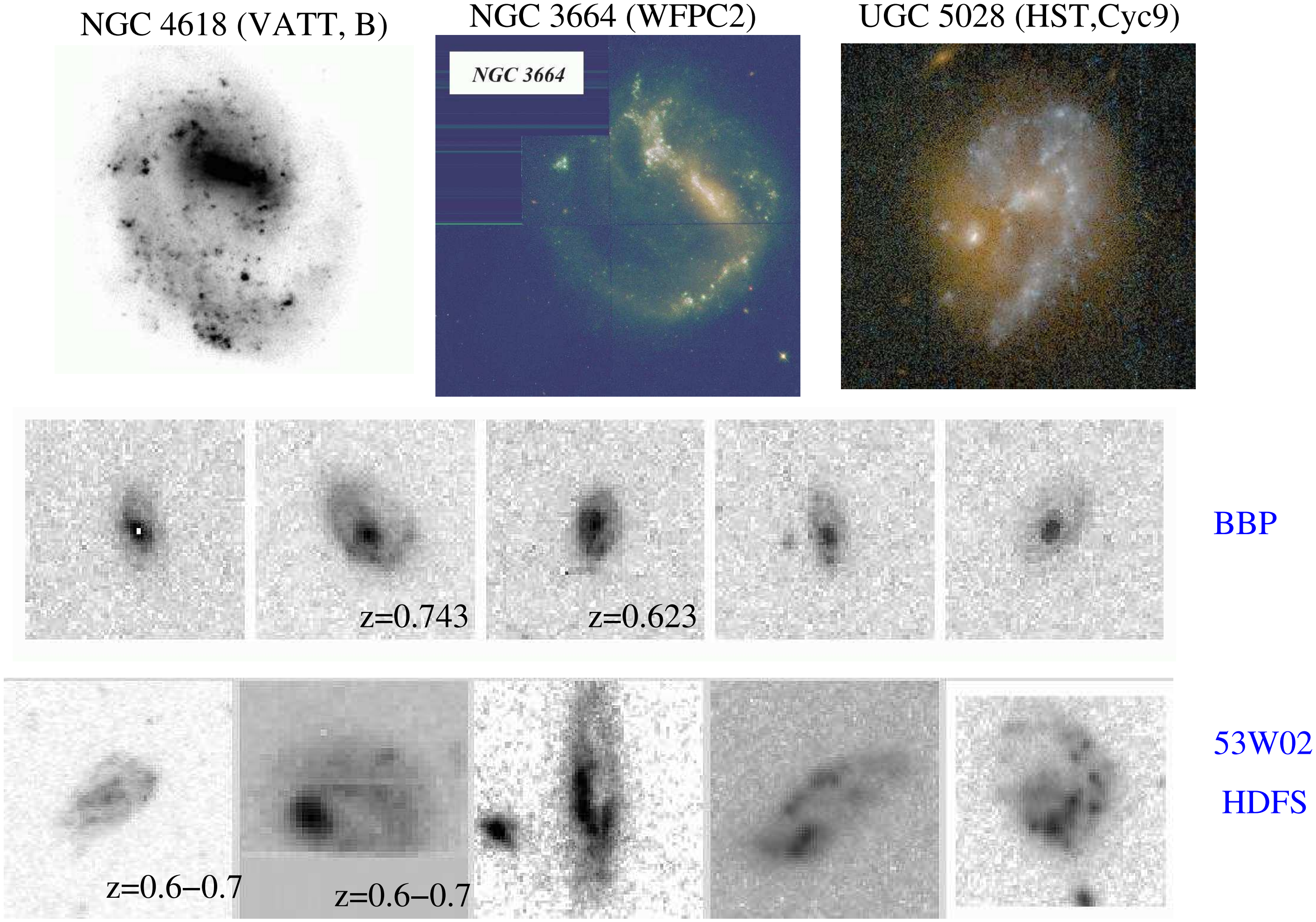
• JWST can measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their distribution over rest-frame structure and type as a function of redshift or cosmic epoch.



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

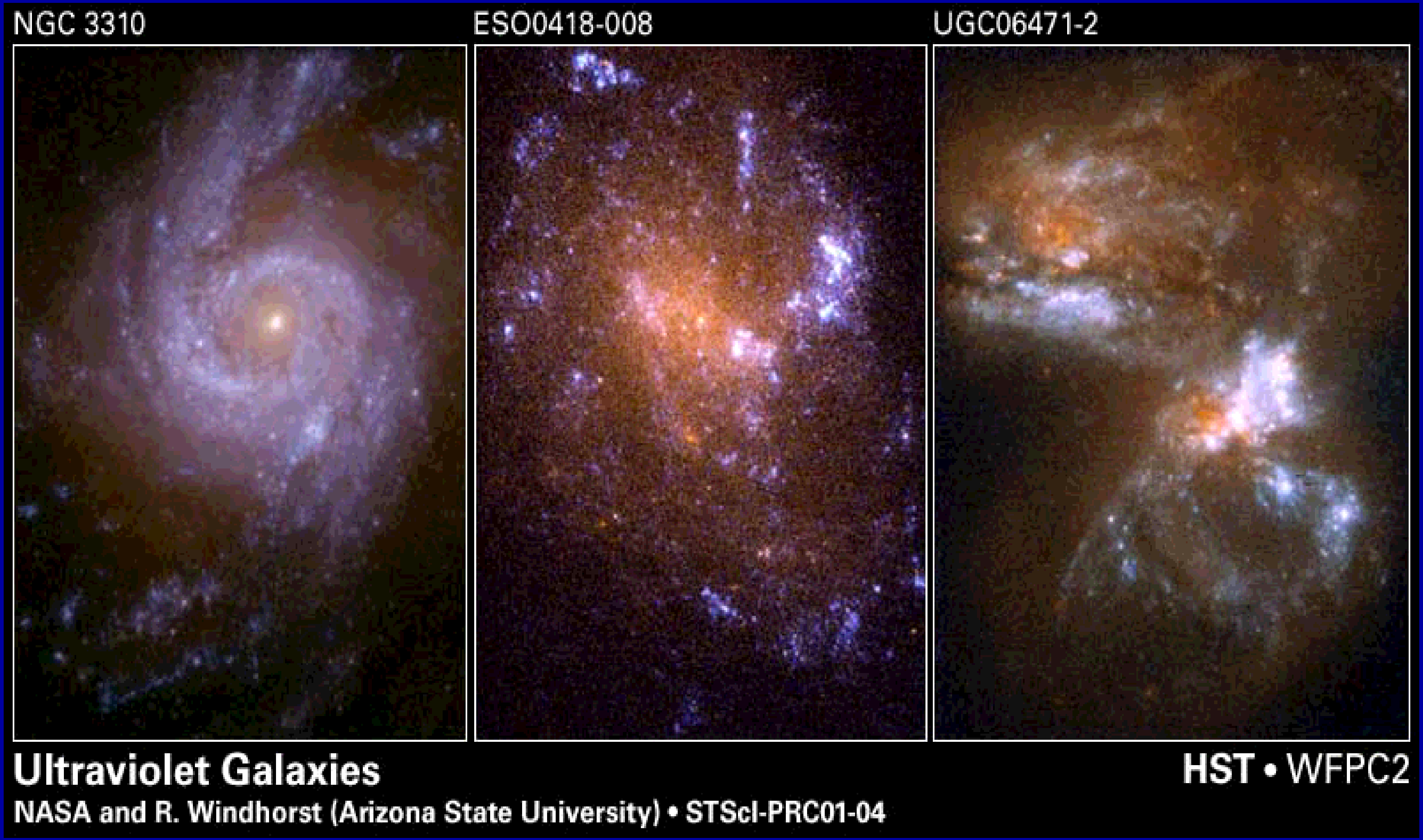
- (1) Fourier series are made in successive concentric annuli.
- (2) Even Fourier components indicate symmetric parts (arms, rings, bars).
- (3) Odd Fourier components indicate asymmetric parts (lopsidedness).
- (4) JWST can measure the evolution of each feature/class directly.

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.

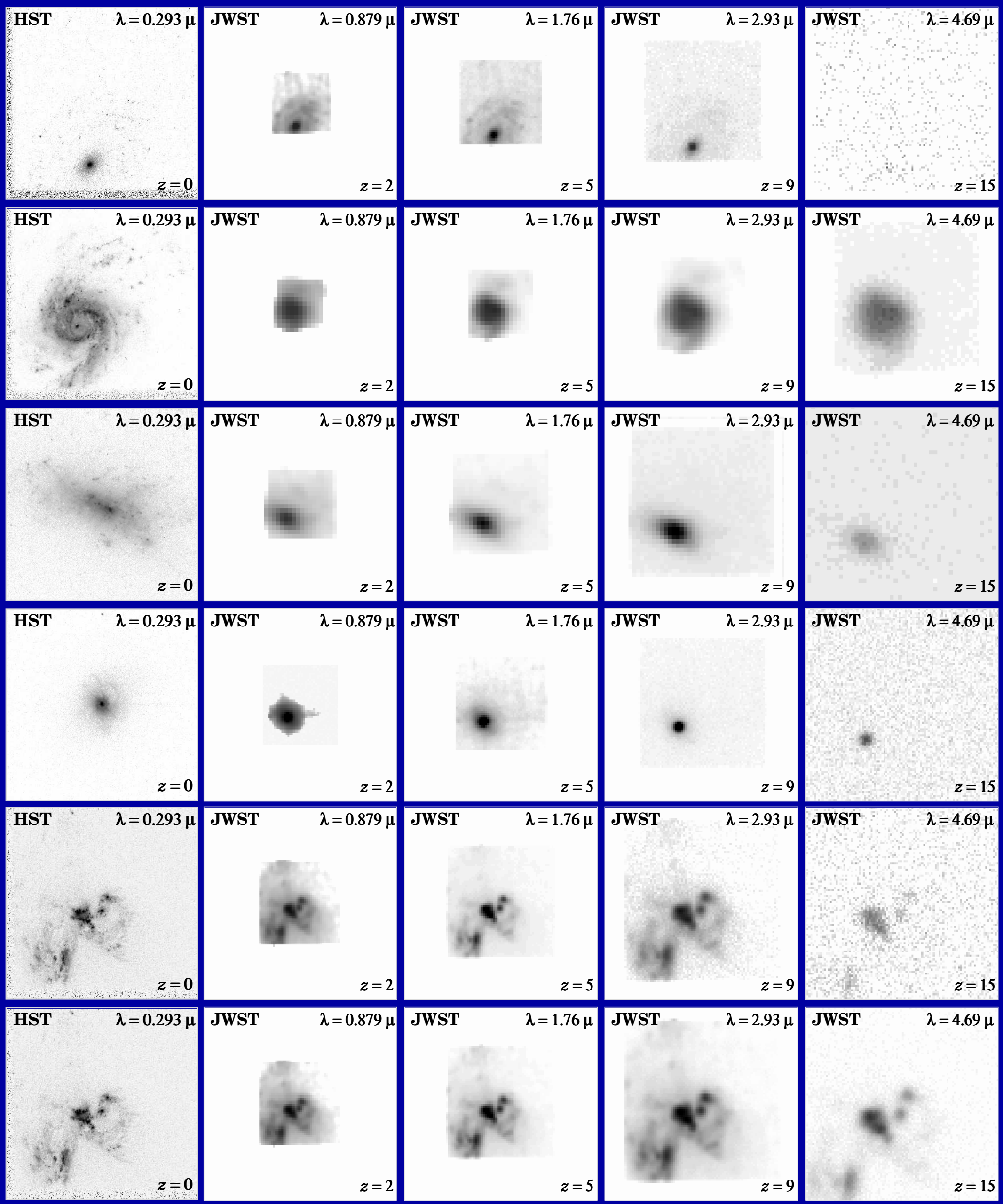
(5) Predicted Galaxy Appearance for JWST at z$\simeq$1–15



- 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≃1–15

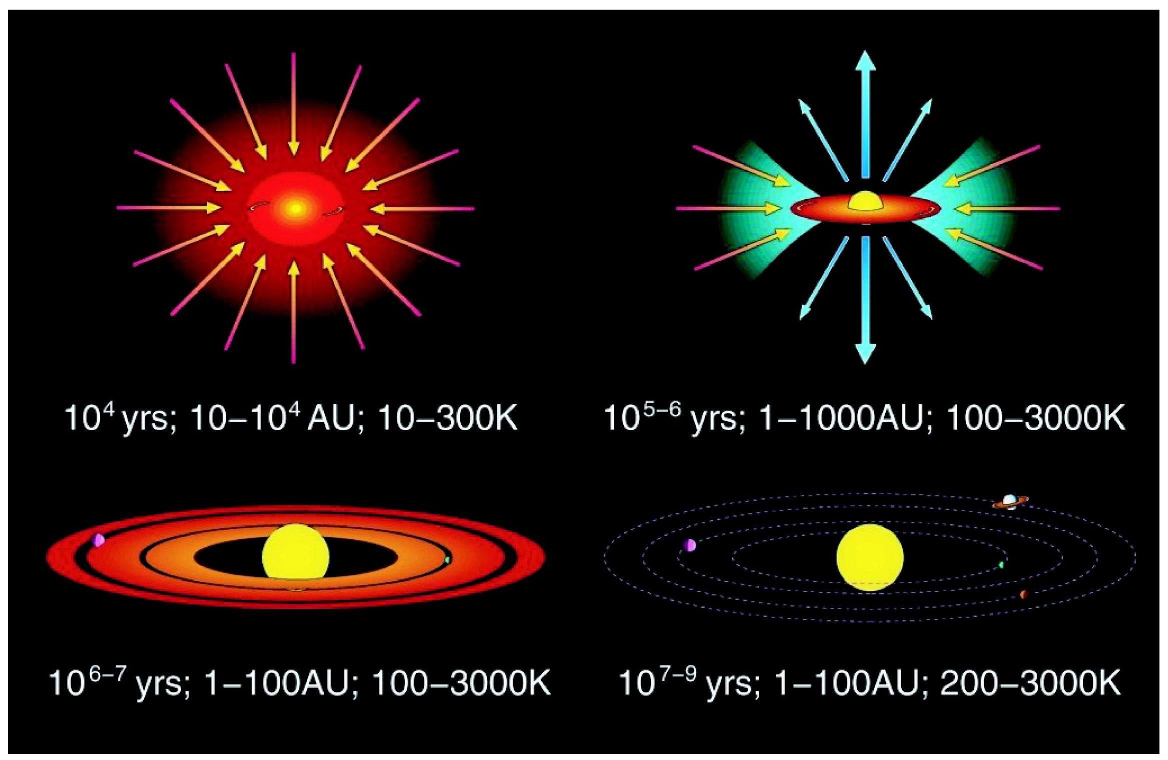
HST z=0 JWST z=2 z=5 z=9 z=15

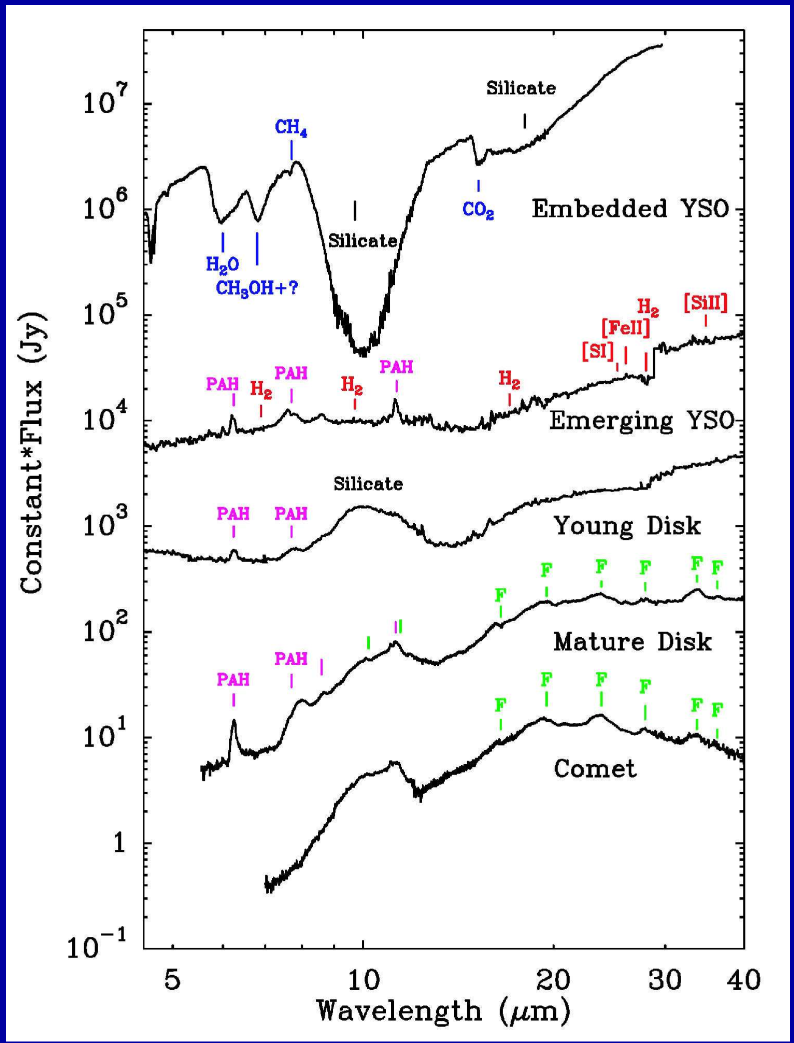


With proper restframe-UV training, JWST can quantitatively measure the evolution of galaxy morphology and structure over a wide range of cosmic time:

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

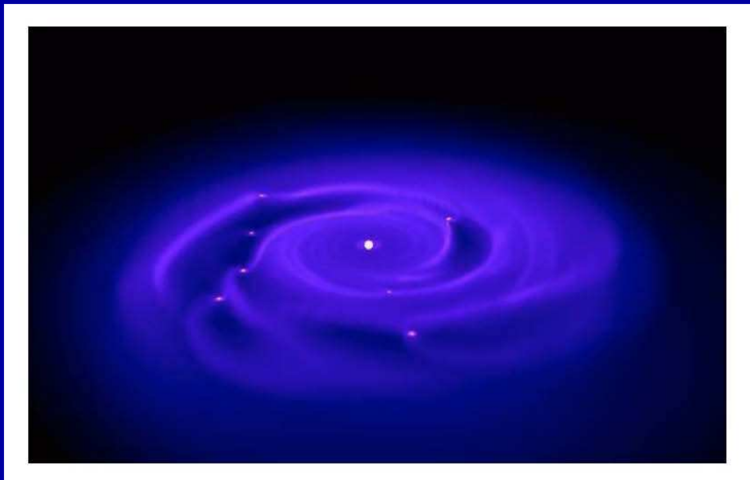
(5b) JWST breakthroughs on Star- and Planet Formation

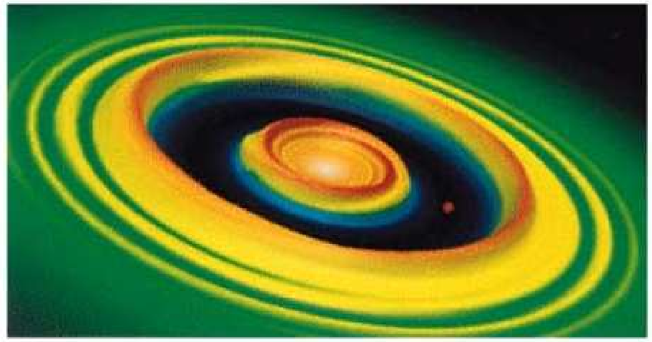


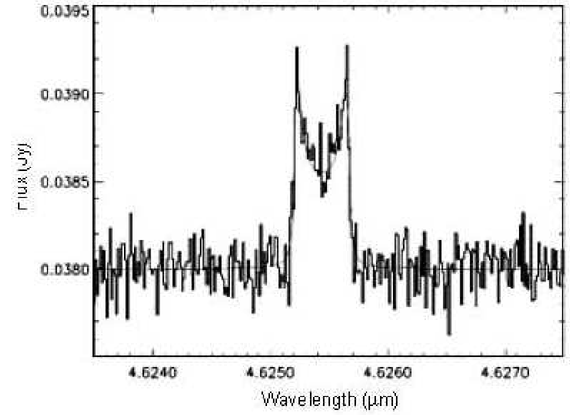


JWST will trace various stages of star-formation, young stellar objects, planetary debris-disk formation and planet-formation.

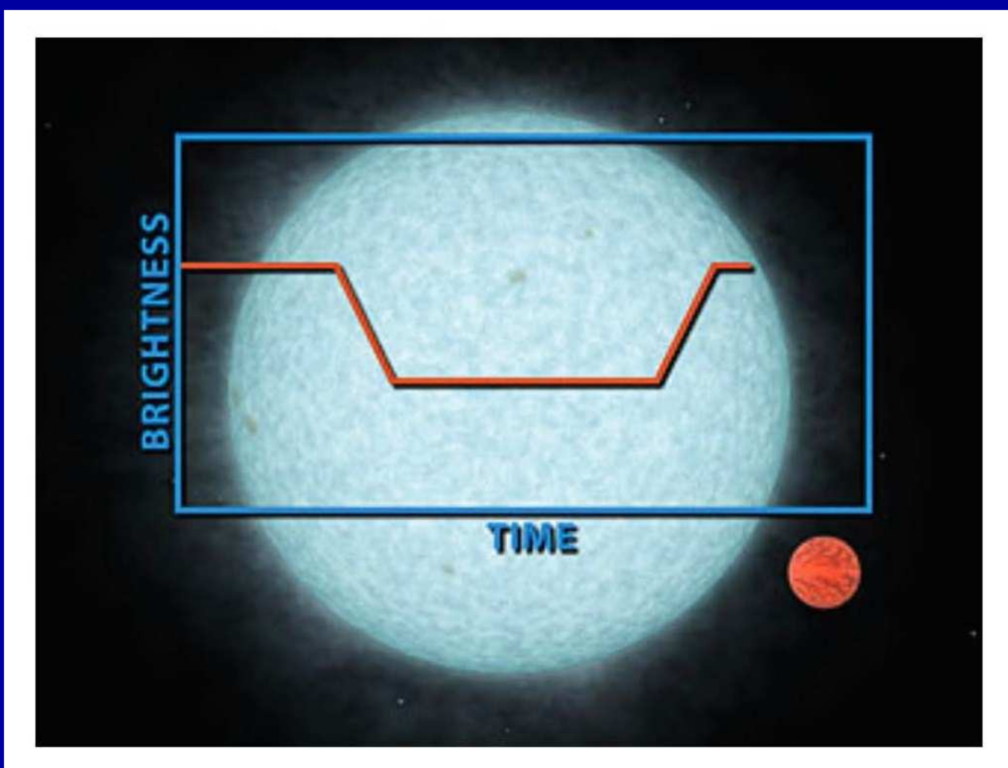
JWST provides high time-resolution photometry & coronagraphy for planet detection, and *panchromatic* low-resolution near–mid-IR spectra.

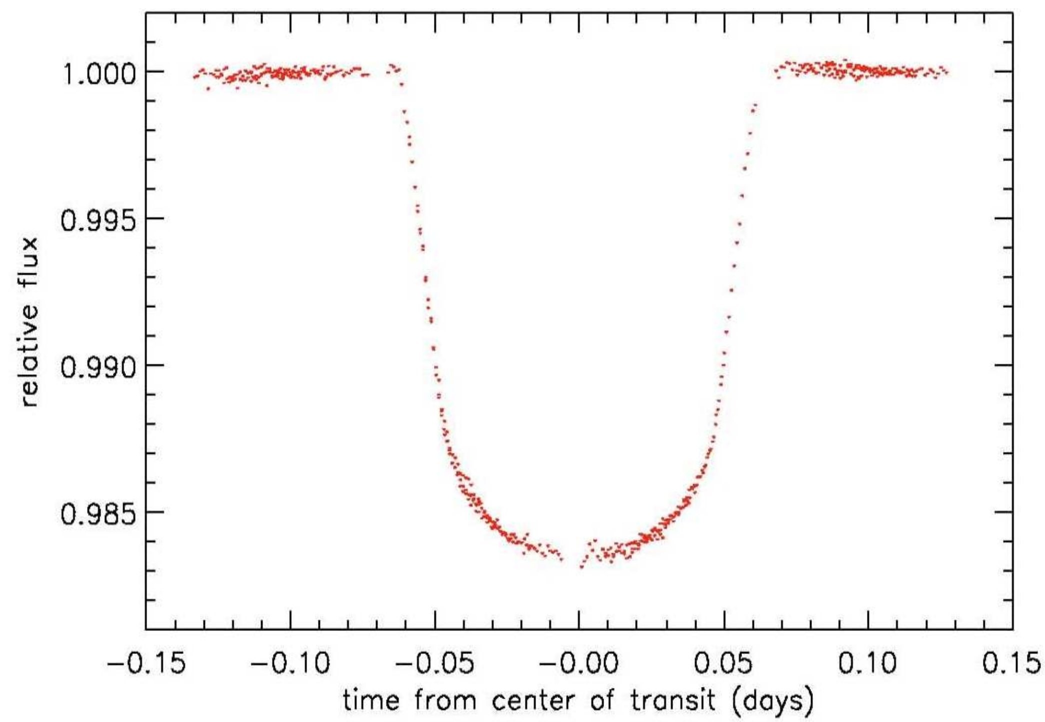






JWST: very high-resolution imaging, coronagraphy, & near–mid IR spectra.





JWST: High time-resolution photometry of (Earth-like) plantary transits.

(7) Conclusions

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

• Most items at Technical Readiness Level 6 (TRL-6) in Jan. 2007: *i.e.*, demonstration in a relevant environment — ground or space.

• Technical Non-Advocate Review done in 2007, and Mission Preliminary Design Review in March 2008 (official approval by NAS & Congress).

(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.

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

• Faint-end of luminosity function: how dwarf galaxies finished reionization.

(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

- 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://www.jwst.nasa.gov/ISIM/index.html

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/

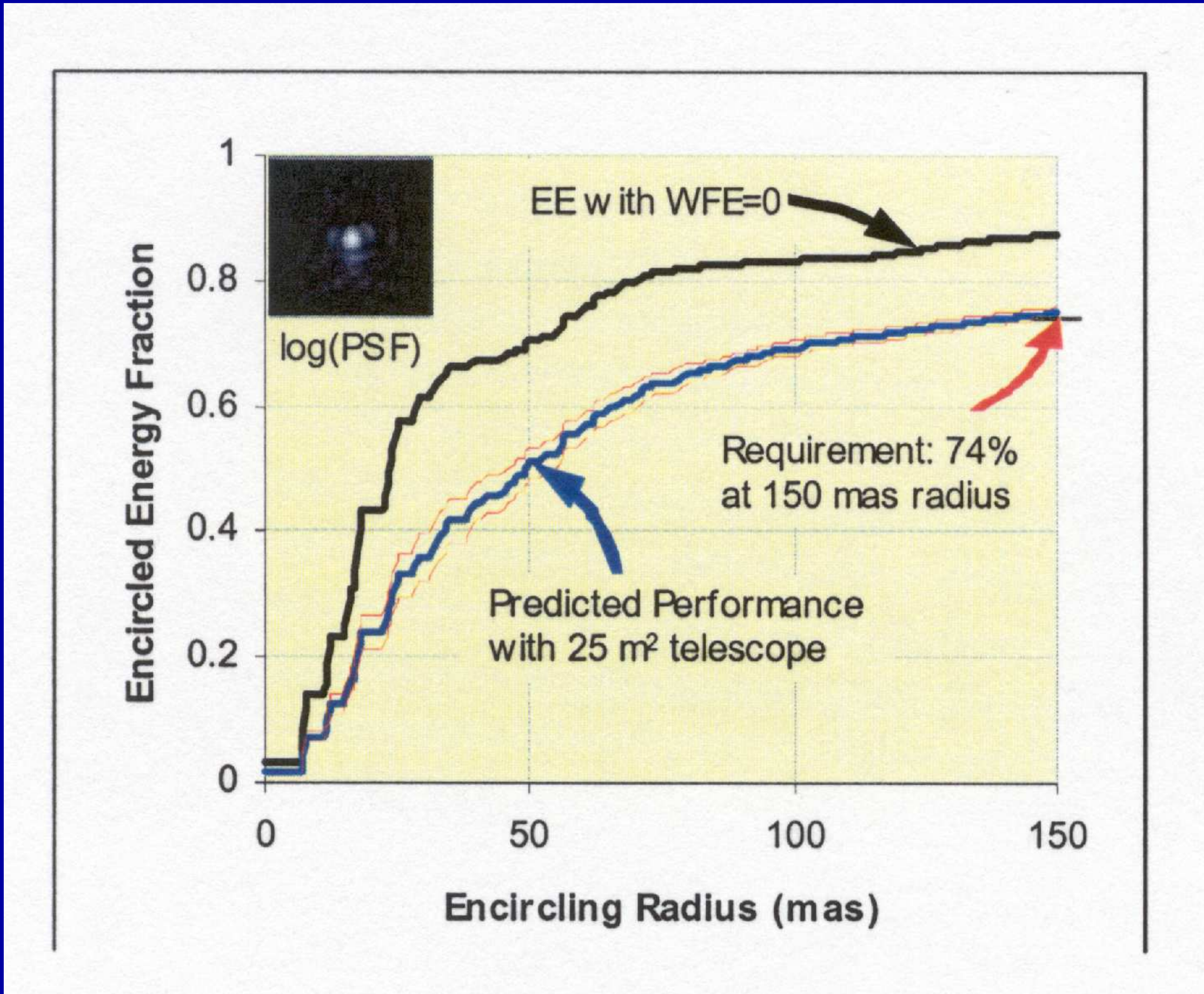
Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., Hutchings, J. B., Jakobsen, P., Lilly,S. J., Long, K. S., Lunine, J. I., McCaughrean, M. J., Mountain, M., Nella, J., Rieke, G. H., Rieke, M. J., Rix, H.-W., Smith, E. P., Sonneborn, G., Stiavelli, M., Stockman, 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, p. 2-16, in "UV, Optical, and IR Space Telescopes and Instruments", Eds. J. B. Breckinridge & P. Jakobsen (Berlin: Springer)

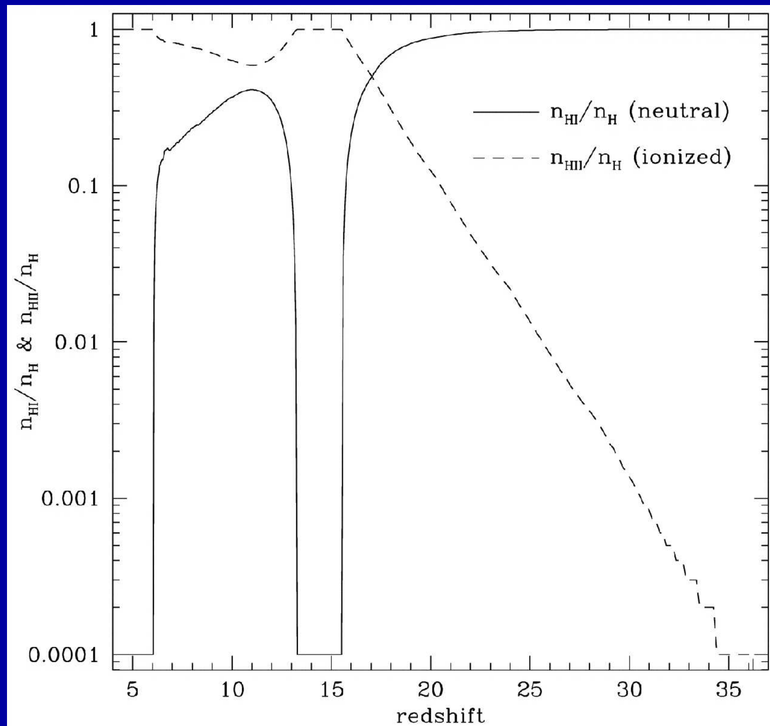
Northrop Grumman Expertise in Space Deployable Systems

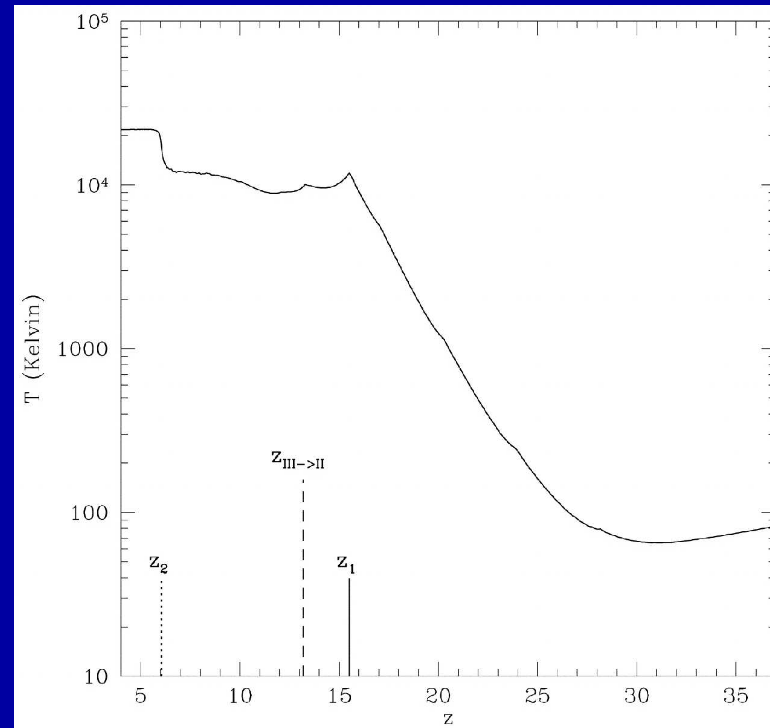
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





1/6 Scale model: system can produce diffraction limited images at 2.0μm.





WMAP and detailed Hydrodynamical models (Cen 2003) suggest that:

- (1) Population III stars caused epoch of First Light at z$\simeq$11–20.
- (2) Pop III supernovae may have caused the Second Dark Ages at z=9–11, since they heated the IGM, which could not cool until:
- (3) The first Pop II stars started forming in dwarf galaxies with 10^7–10^9 $M_\odot$ at z$\simeq$6–9.

$\Rightarrow$ This will be visible to JWST in the luminosity function (LF) of the first star-forming objects at z$\simeq$20$\longrightarrow$6.

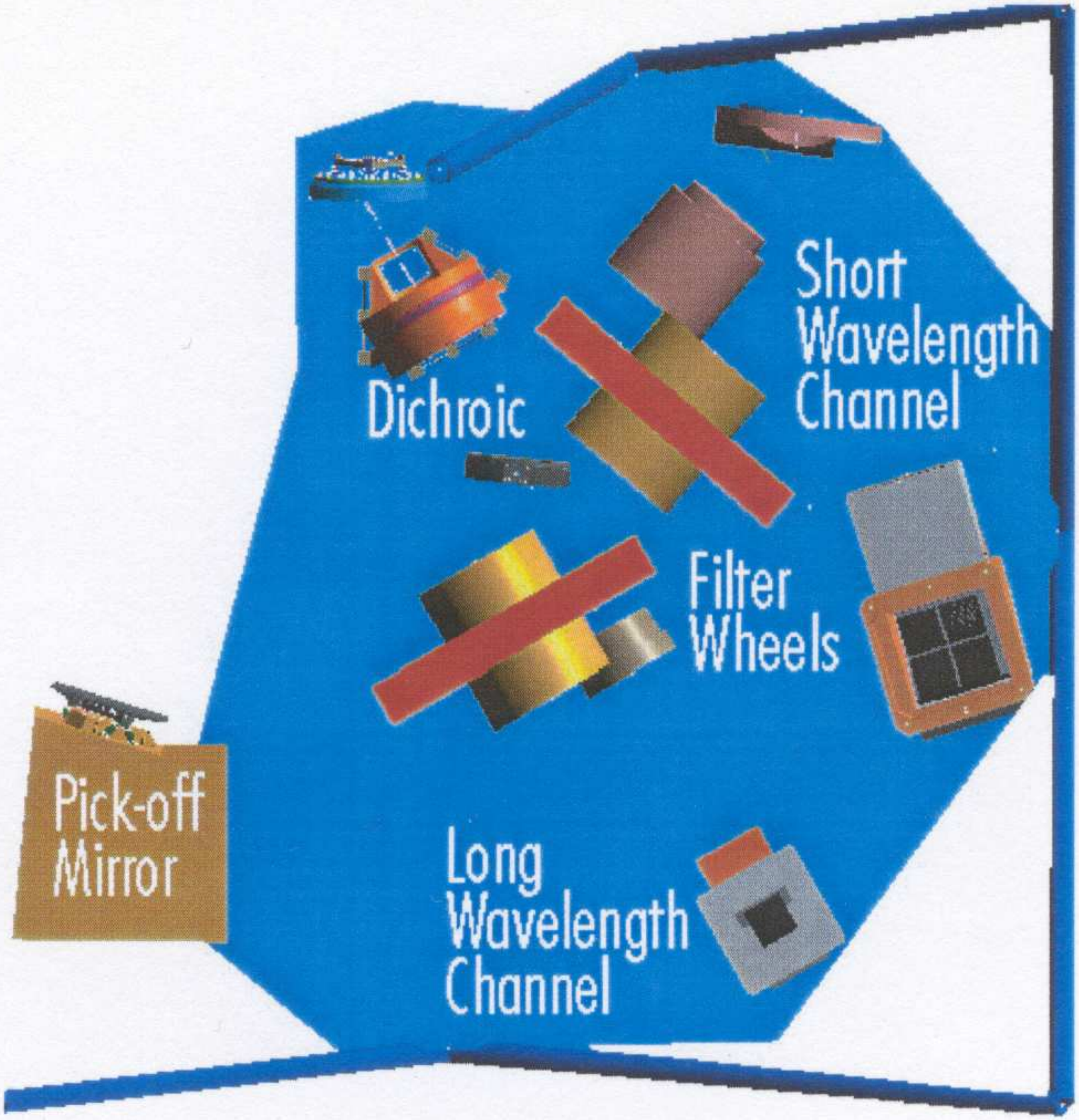


Figure 43. Optical layout of one of two NIRCam imaging modules.

• (2) What instruments will JWST have?

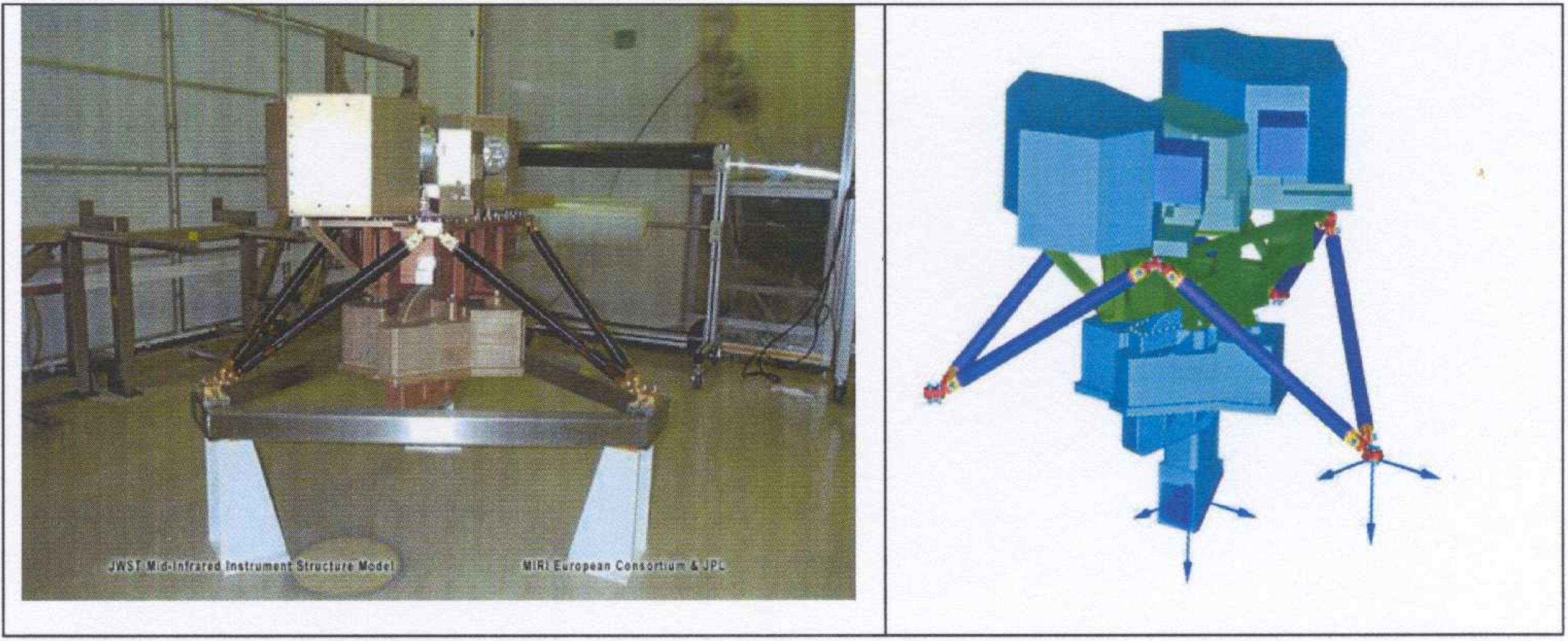


Figure 47. The MIRI structural and thermal model (left) compared to a computer design of the instrument (right).

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

MIRI IFUs fields of view

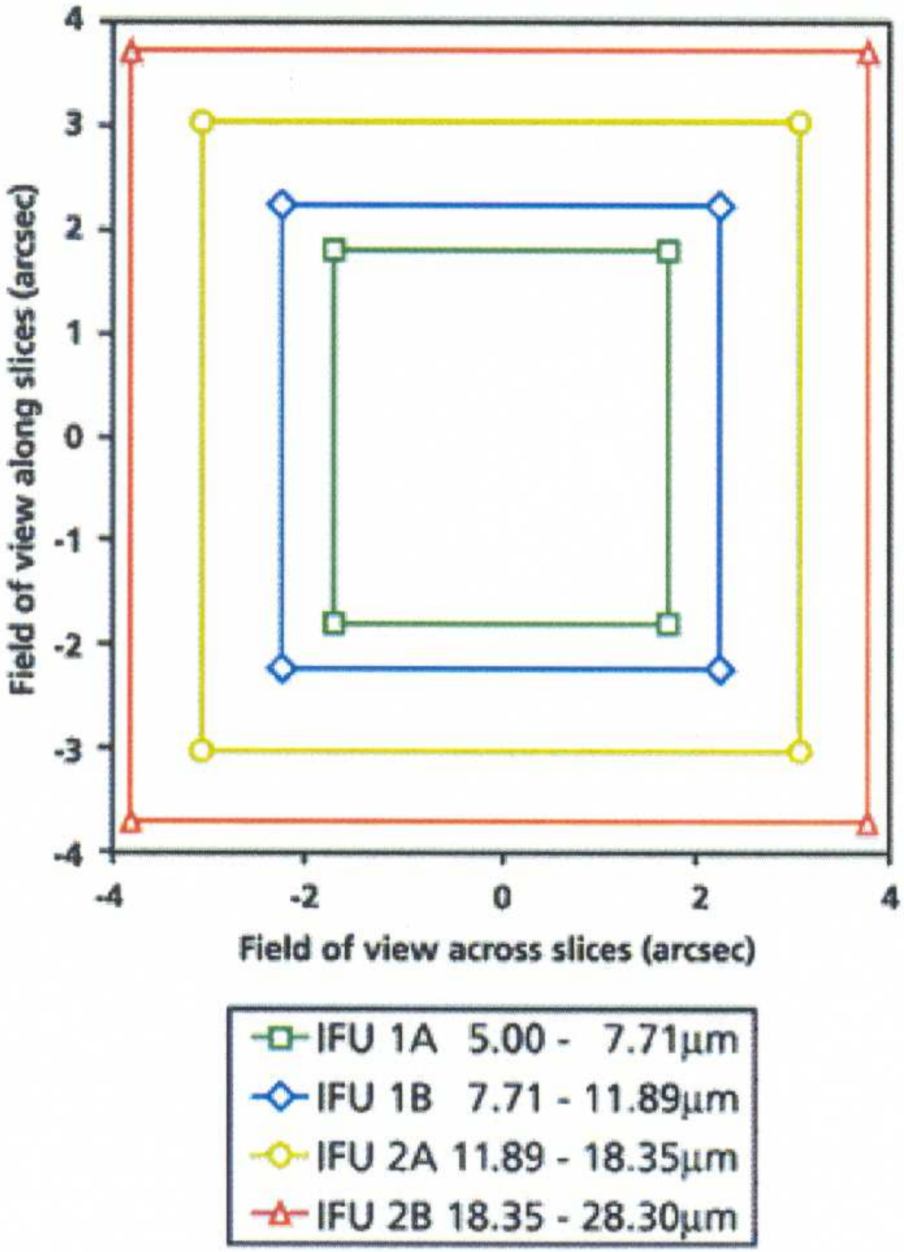


Figure 49. Fields of view of the MIRI IFU spectrograph.

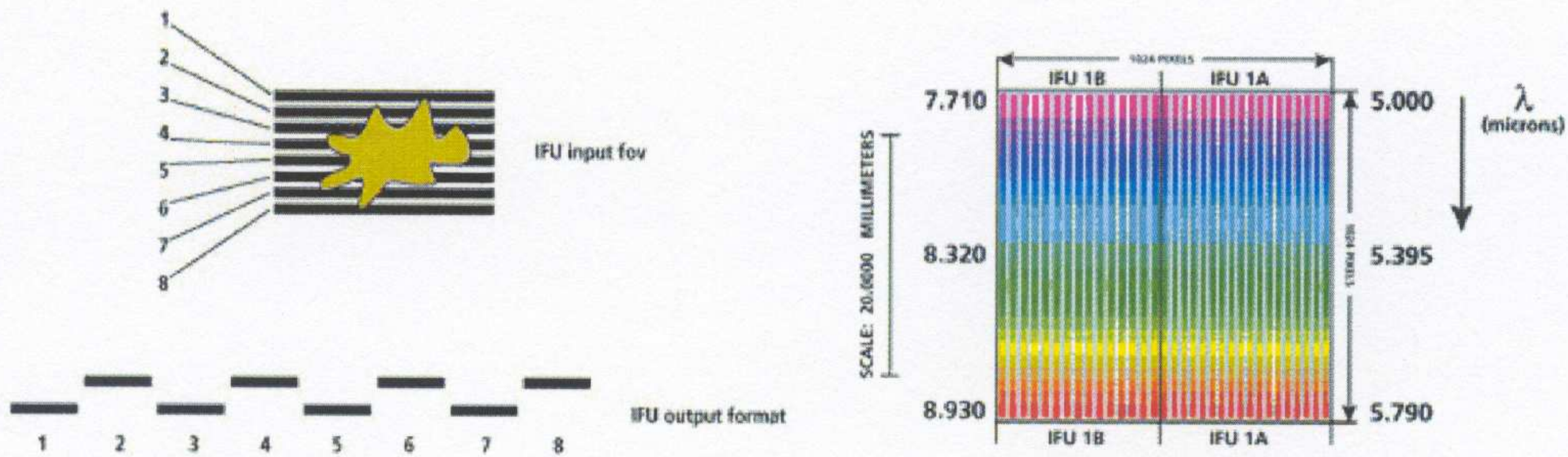


Figure 50. Schematic illustration of the MIRI IFU image slicer format (left) and dispersed spectra on detector (right)

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

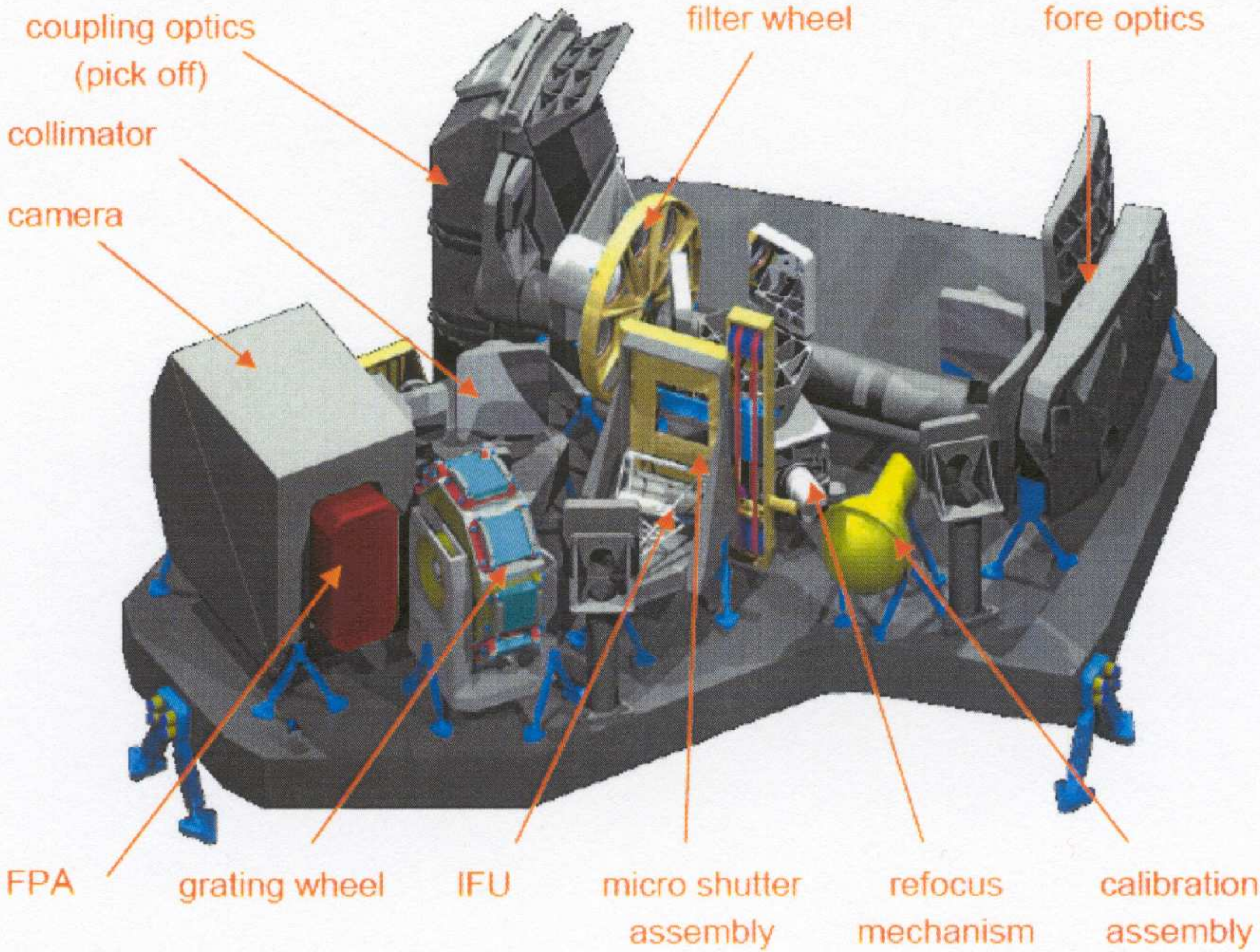
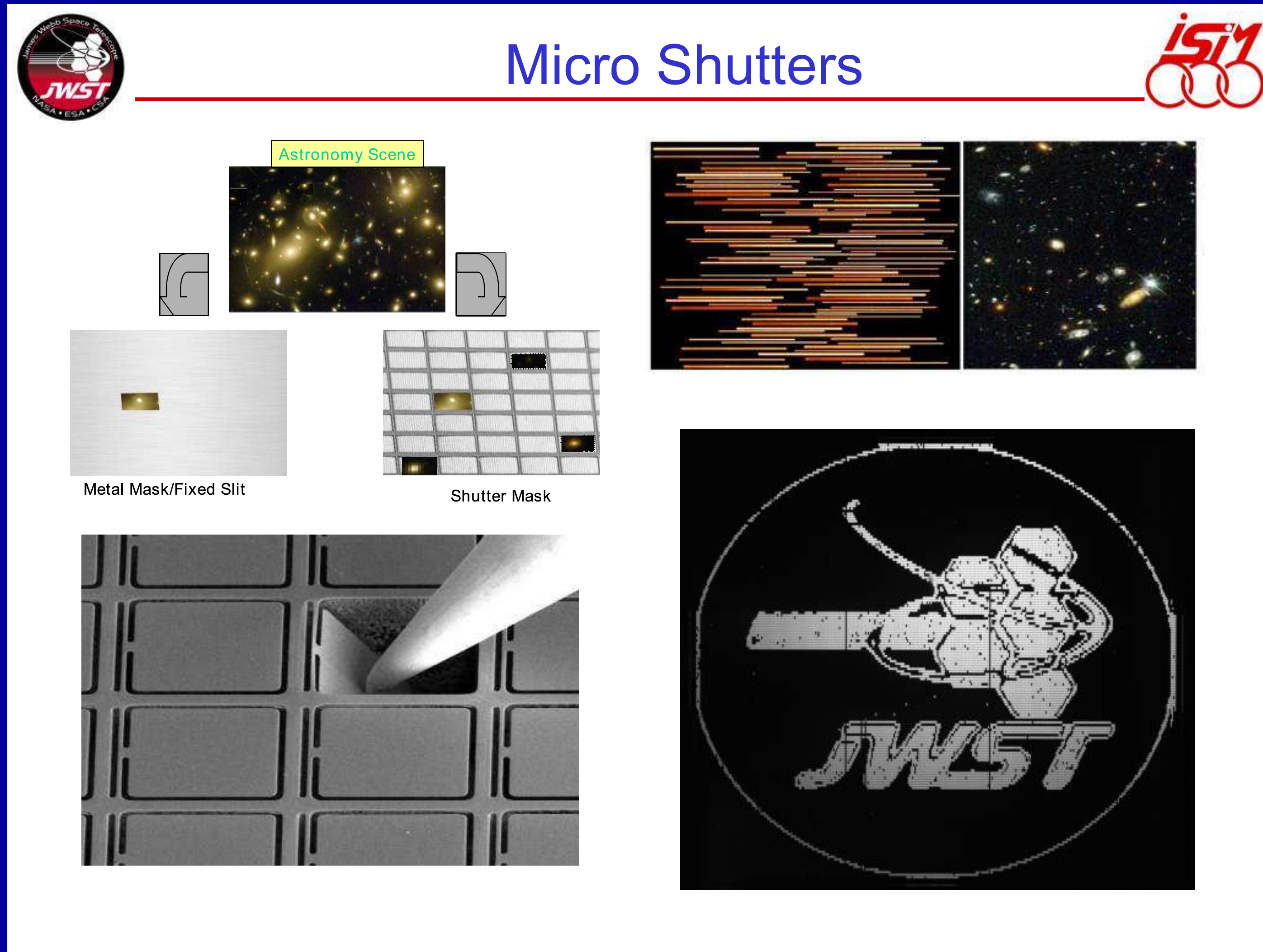


Figure 45. The NIRSpec instrument.



JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MEMS with 4$\times$62,415 independently operable micro-shutters that cover $\lambda\simeq$1–5 μm at R=100–1000.
- MIRI/IFU with 400 spatial pixels covering 5–28.5 μm at R$\sim$2000–4000.
- FGS/TFI that covers a $2\farcm2\times2\farcm2$ FOV at $\lambda\simeq$1.6–4.9 μm at R=100.

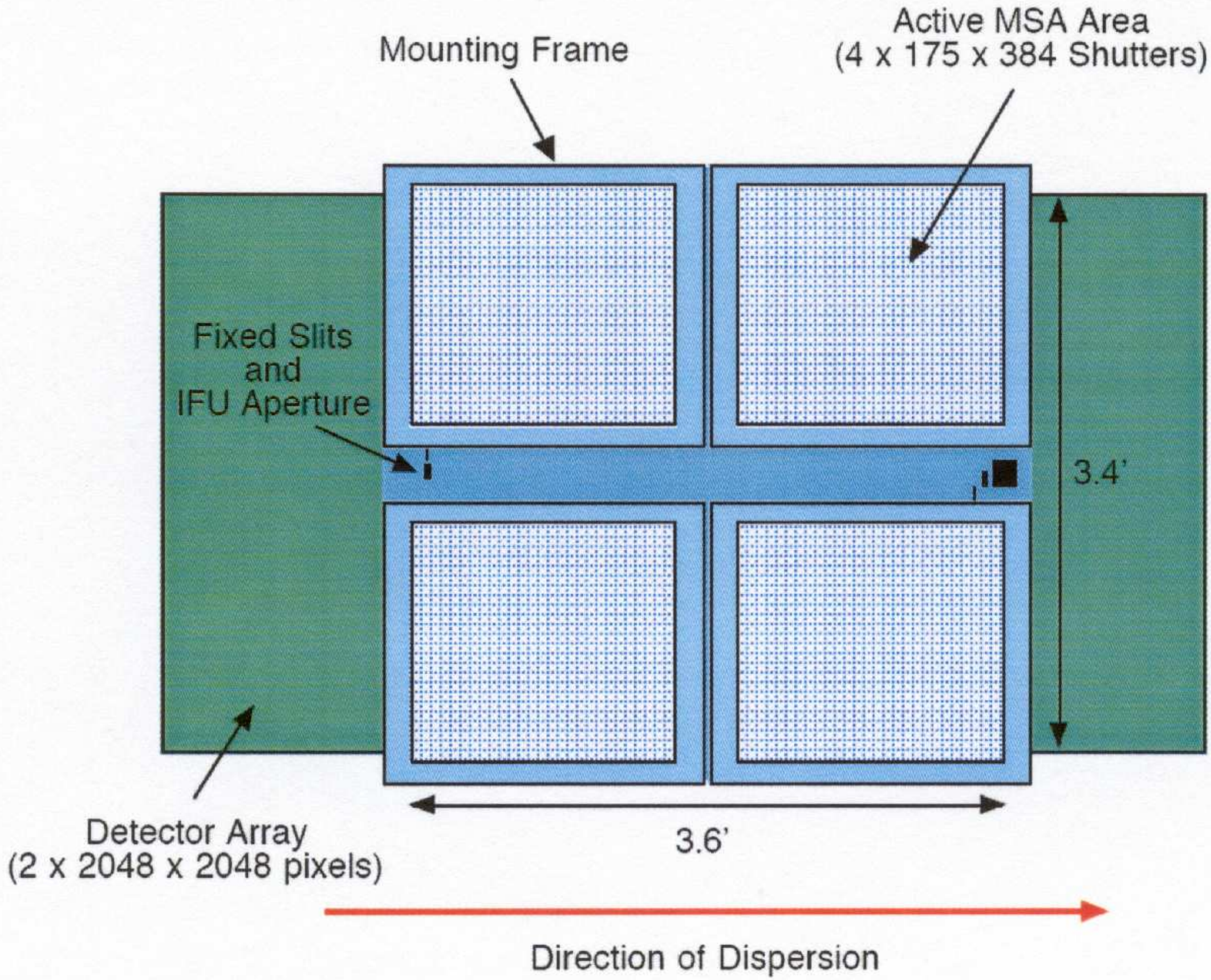
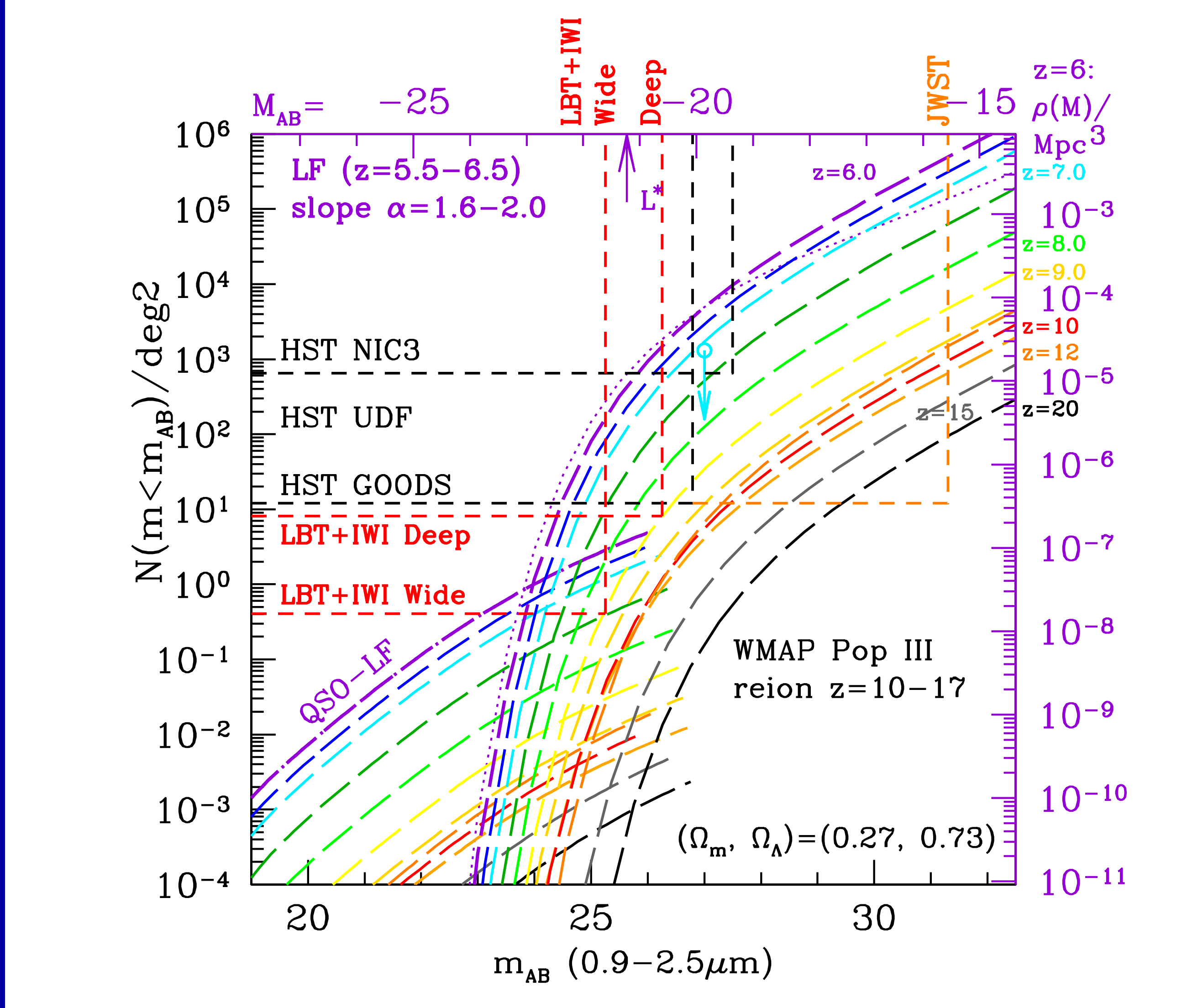
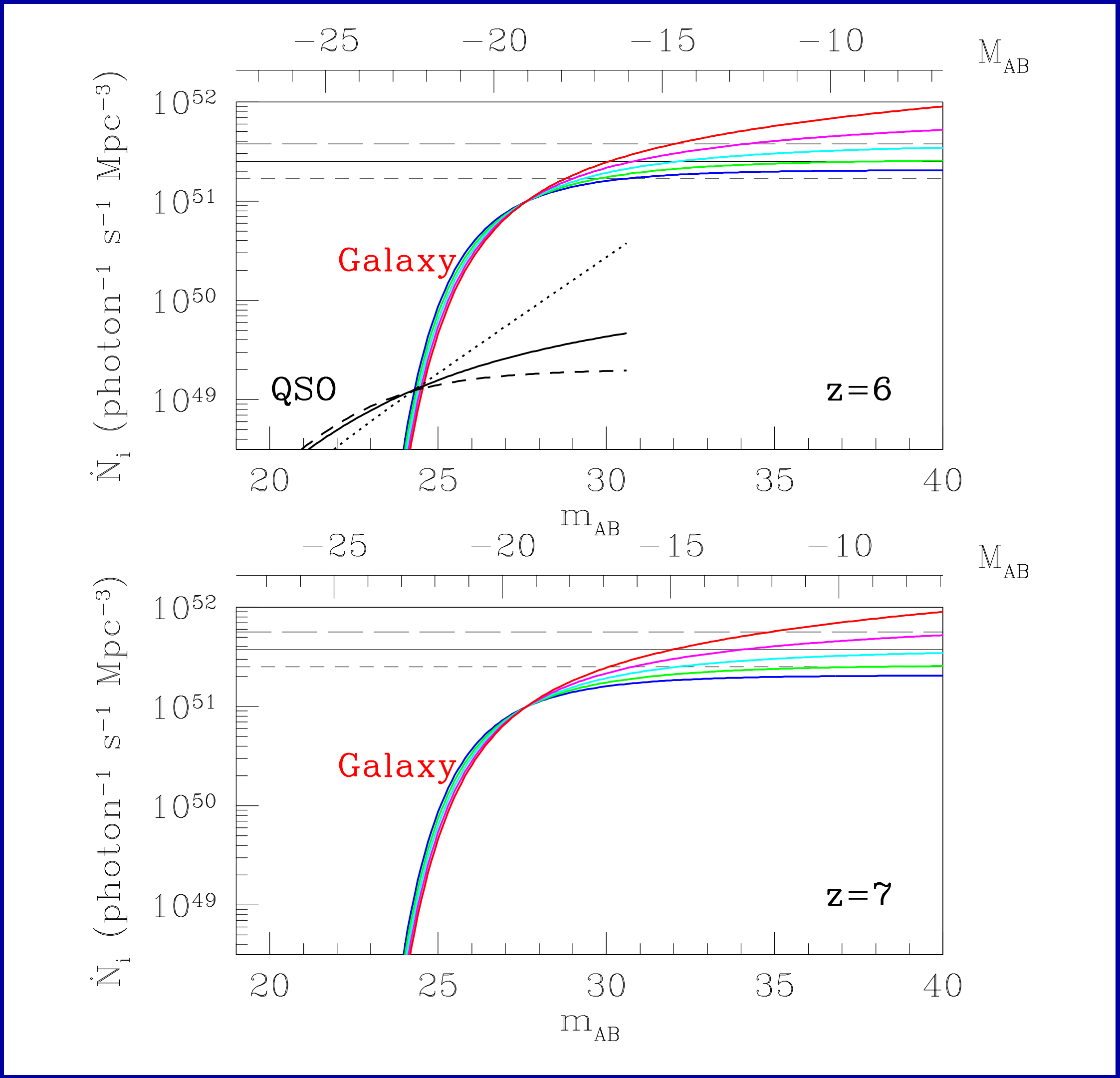


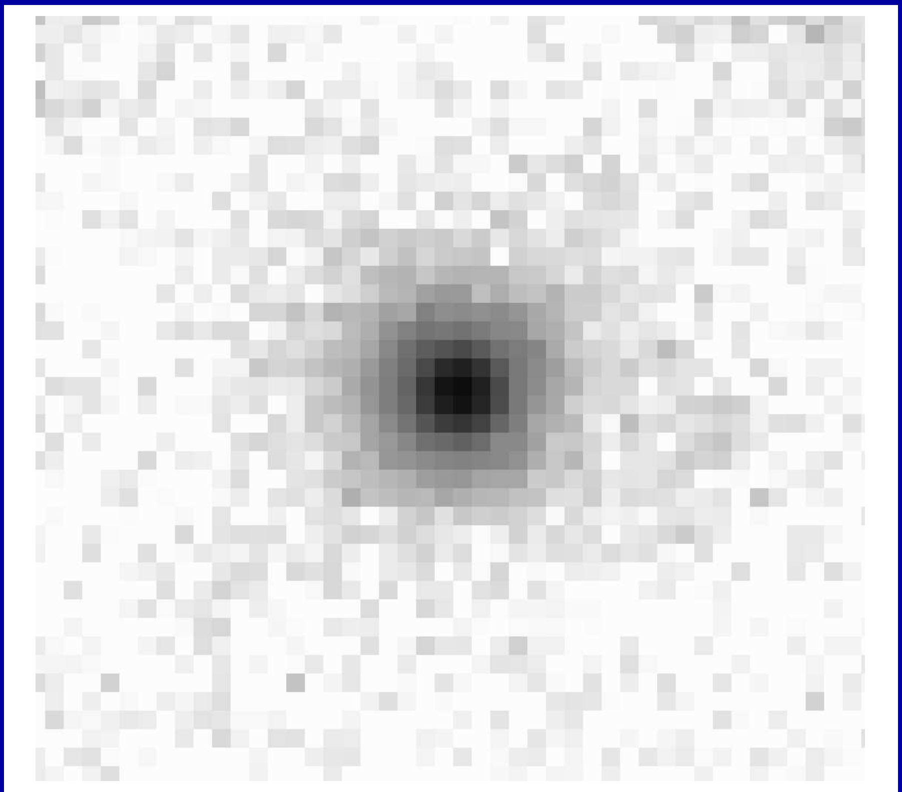
Figure 46. Schematic layout of the NIRSpec slit mask overlaid the detector array projected to the same angular scale.

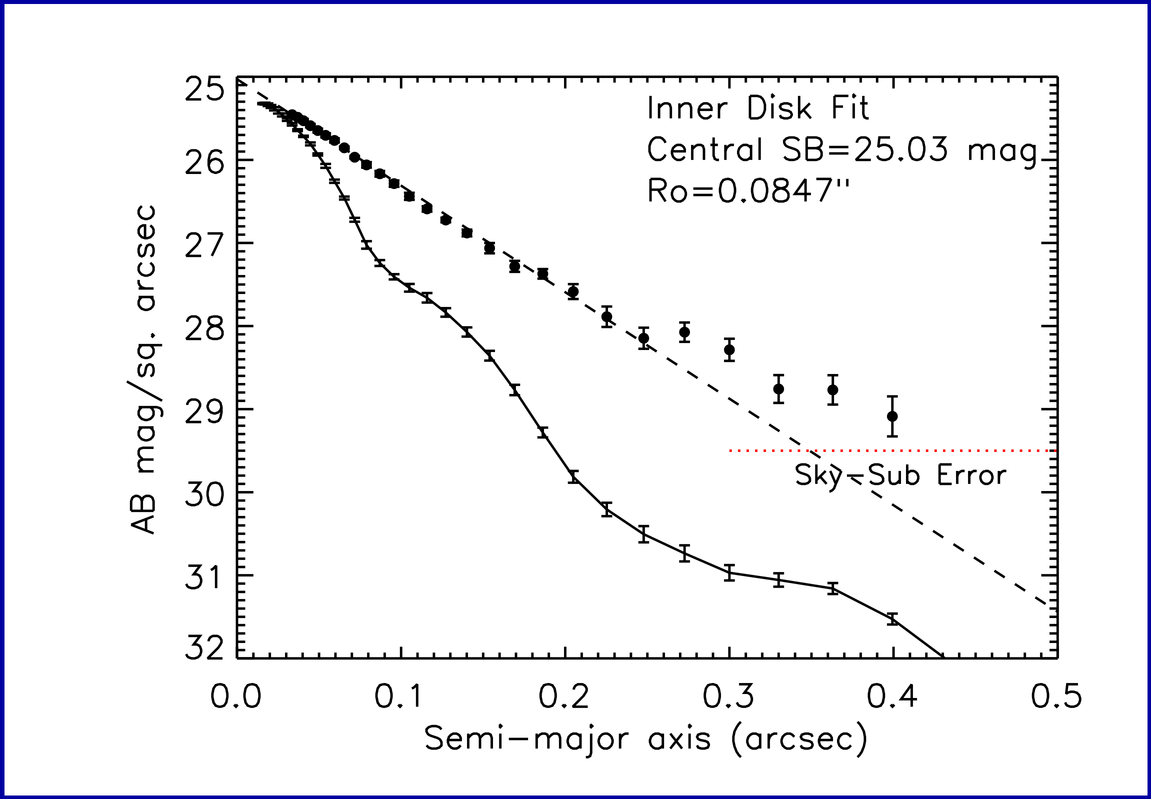


- Red boundaries indicate part of the galaxy and QSO LF that 4–10m class telescopes with WF IRCam can explore to z=10 and AB$\lesssim$25 mag.
- A ground-based wide-field near-IR survey to AB$\lesssim$25 mag z$\lesssim$10 is an essential complement to the JWST First Light studies:
- Co-evolution of supermassive black-holes and proto-bulges for z$\lesssim$10.



- 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.
- 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.





Sum of 49 isolated i-drops:
=5000 hrs HUDF z-band.
[$\simeq$ 330 hrs JWST 1 μm]

ACS light-profile, PSF and sky-error:
Deviates from exp. disk at $r_e \gtrsim 0\farcs25$
$\Rightarrow$ Dyn. age (z$\simeq$6) $\simeq$ 100-200 Myr
(*cf.* N. Hathi et al. 2006)

HST/ACS cannot accurately measure individual light-profiles at z$\simeq$6.

JWST can do this well for z$\gtrsim$6 in very long integrations.

Dynamical timescale $\simeq$ SED timescale $\Rightarrow$ Bulk of SF at $z_{form} \gtrsim$7.0??