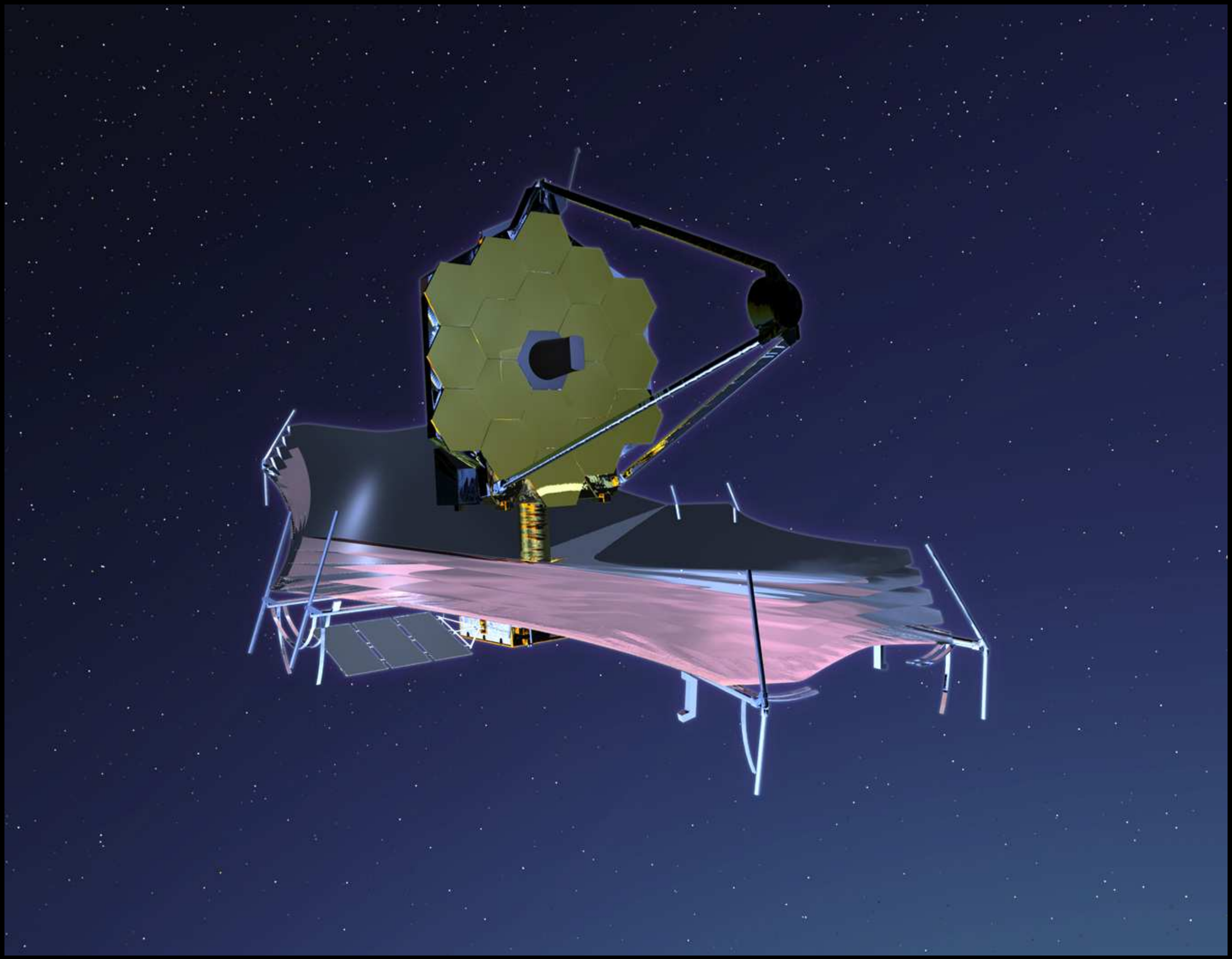
How will the Webb Space Telescope measure First Light Reionization, & Galaxy Assembly in the post WFC3 era?

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (OSU)

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



Colloquium at Ohio University, Athens, OH, Friday April 15, 2011

Outline

James Webb Space Telescope: NASA's next Flagship mission after Hubble

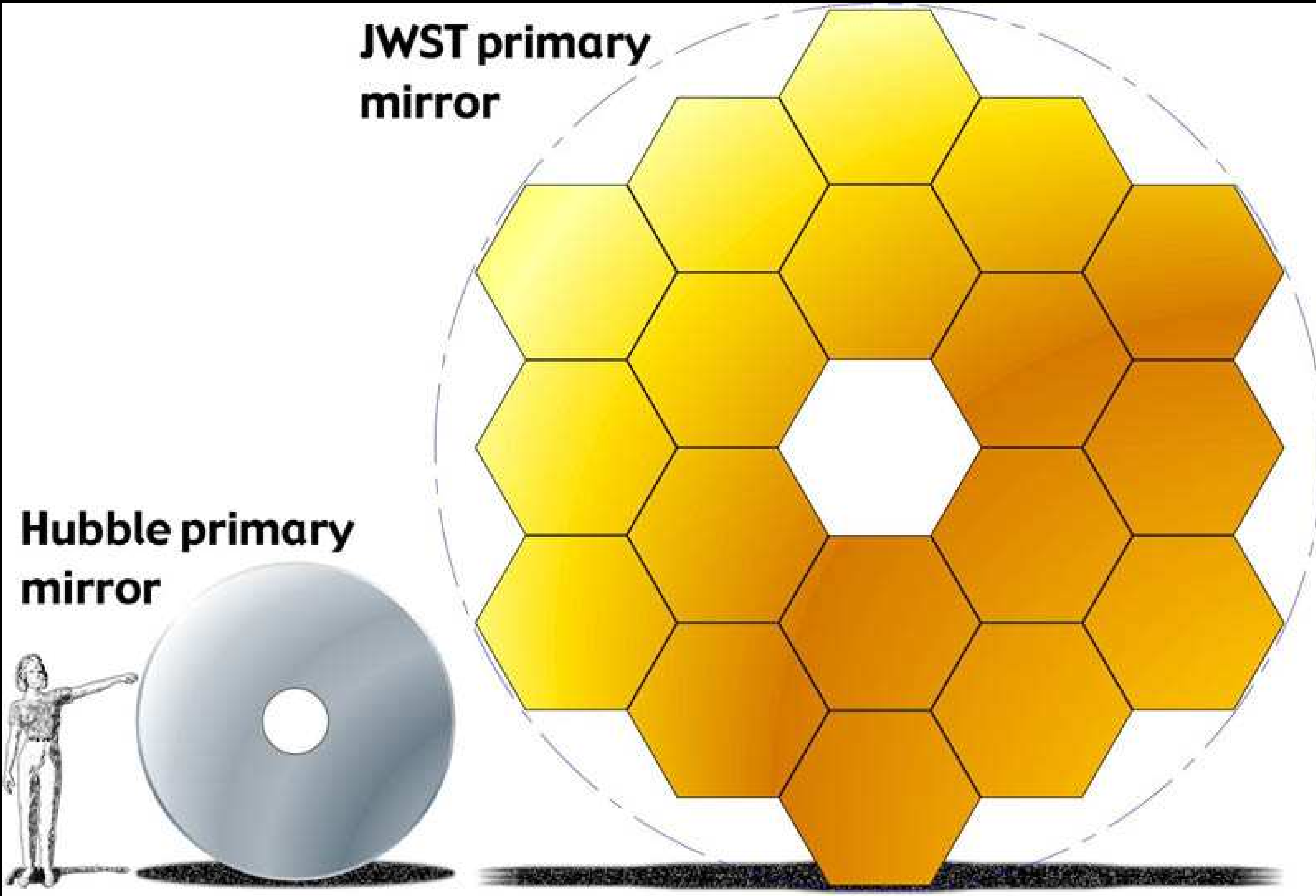
Astro 2010 Decadal Survey assumed: JWST science is done after 2015.

- (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?

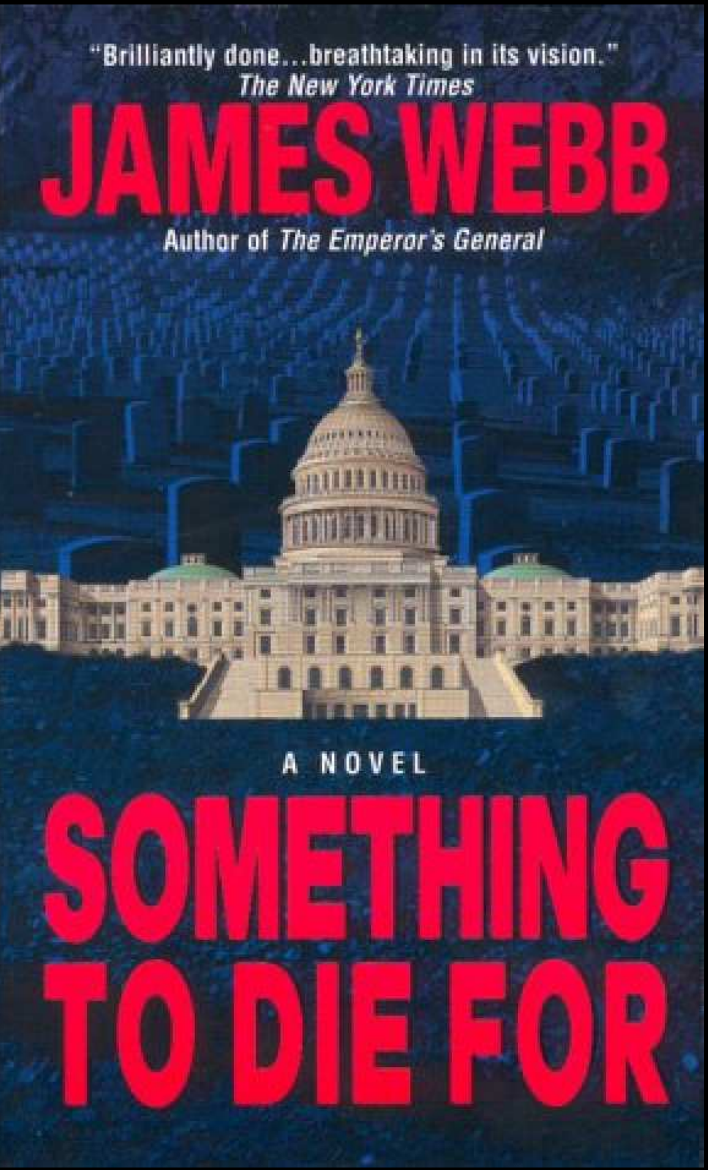
  [With some recent Hubble WFC3 results to support (3) & (4)].
- (5) Predicted Galaxy Appearance for JWST at redshifts z$\simeq$1–15.
- (6) Summary and Conclusions
- Appendix 1: Will JWST reach the Natural Confusion Limit?

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.



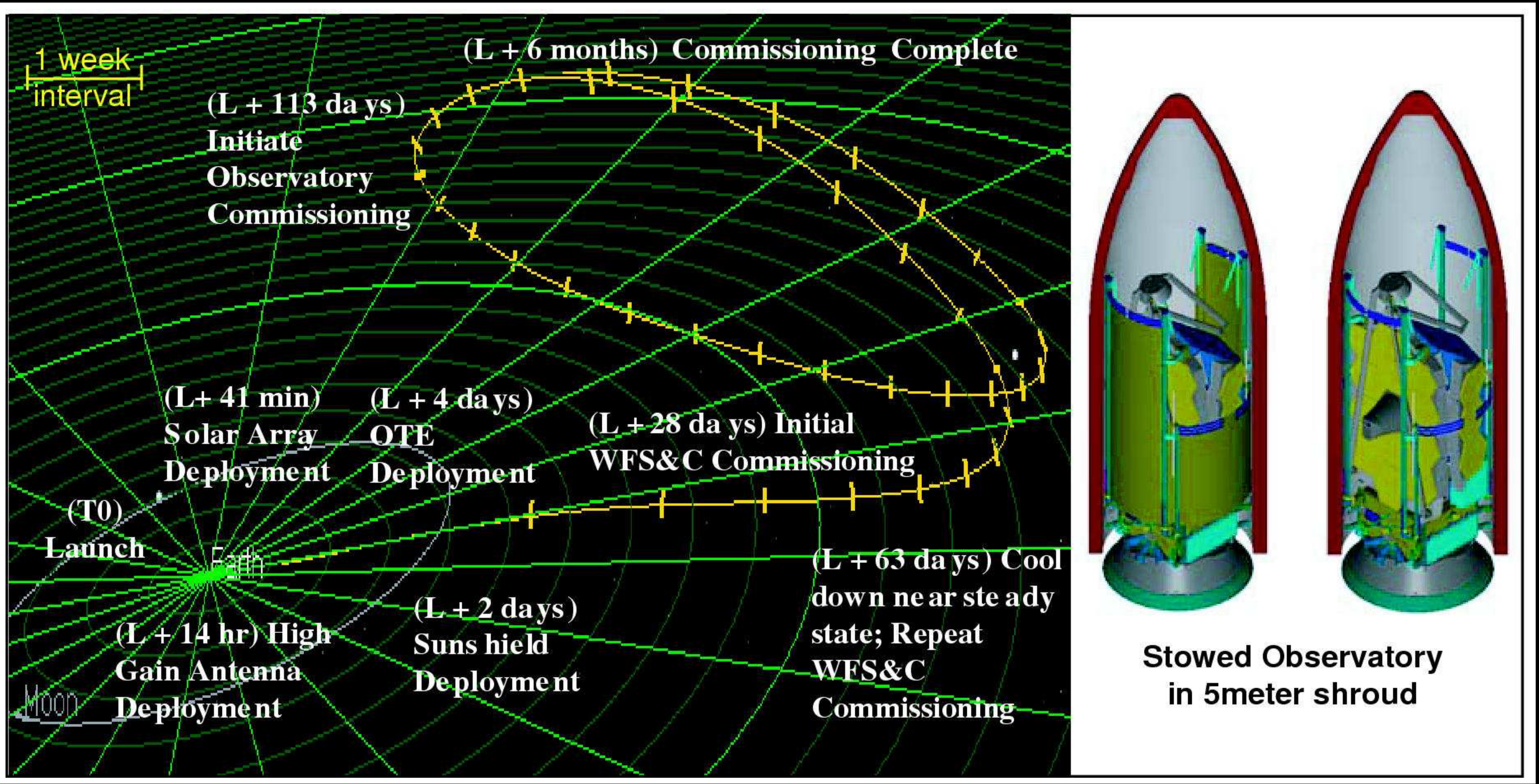
Need hard-working grad students & postdocs in $\gtrsim$2015 ... It'll be worth it!

(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$2015.
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

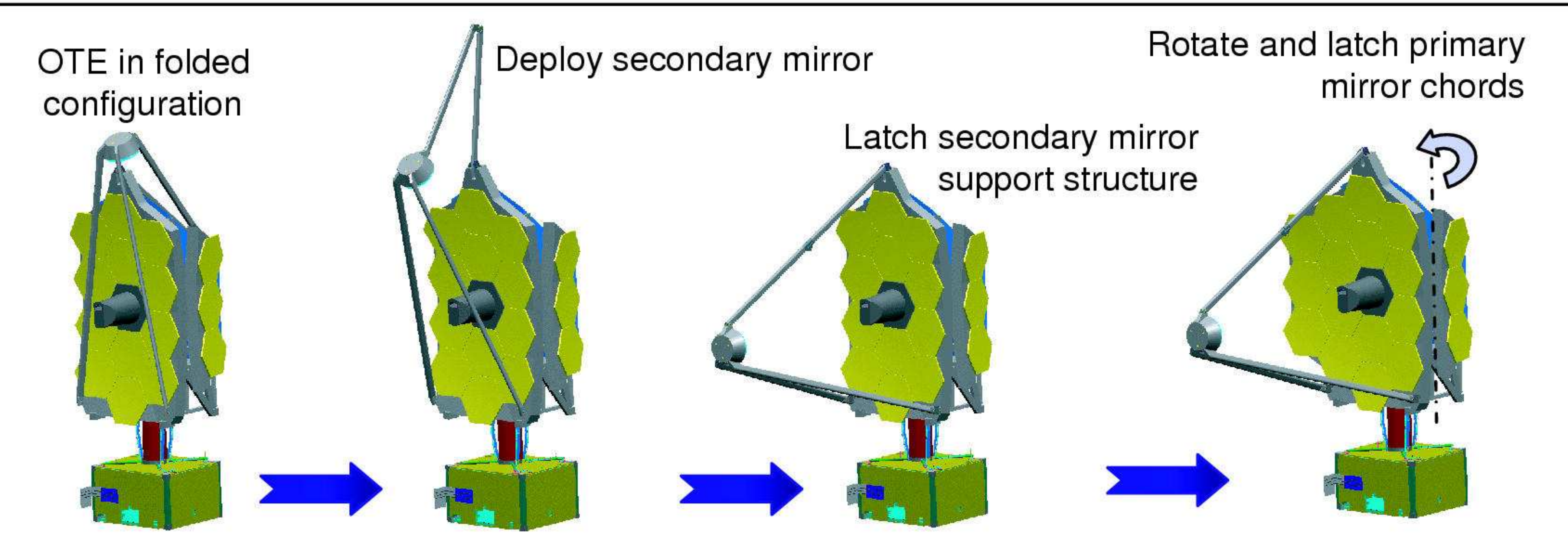
• (1) How will JWST travel to its L2 orbit?



• After launch in June 2015 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.

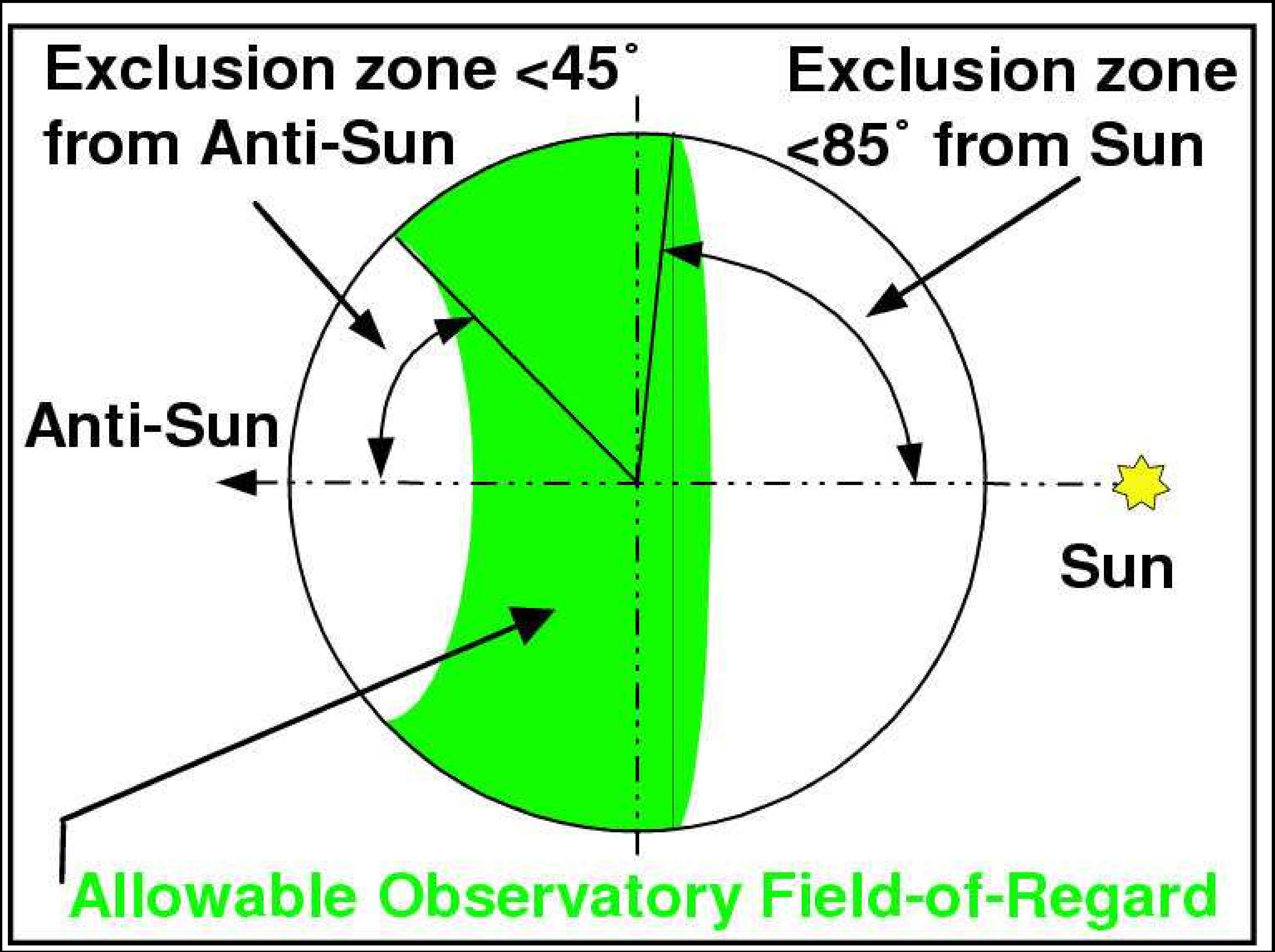
• (1) How will JWST be automatically deployed?



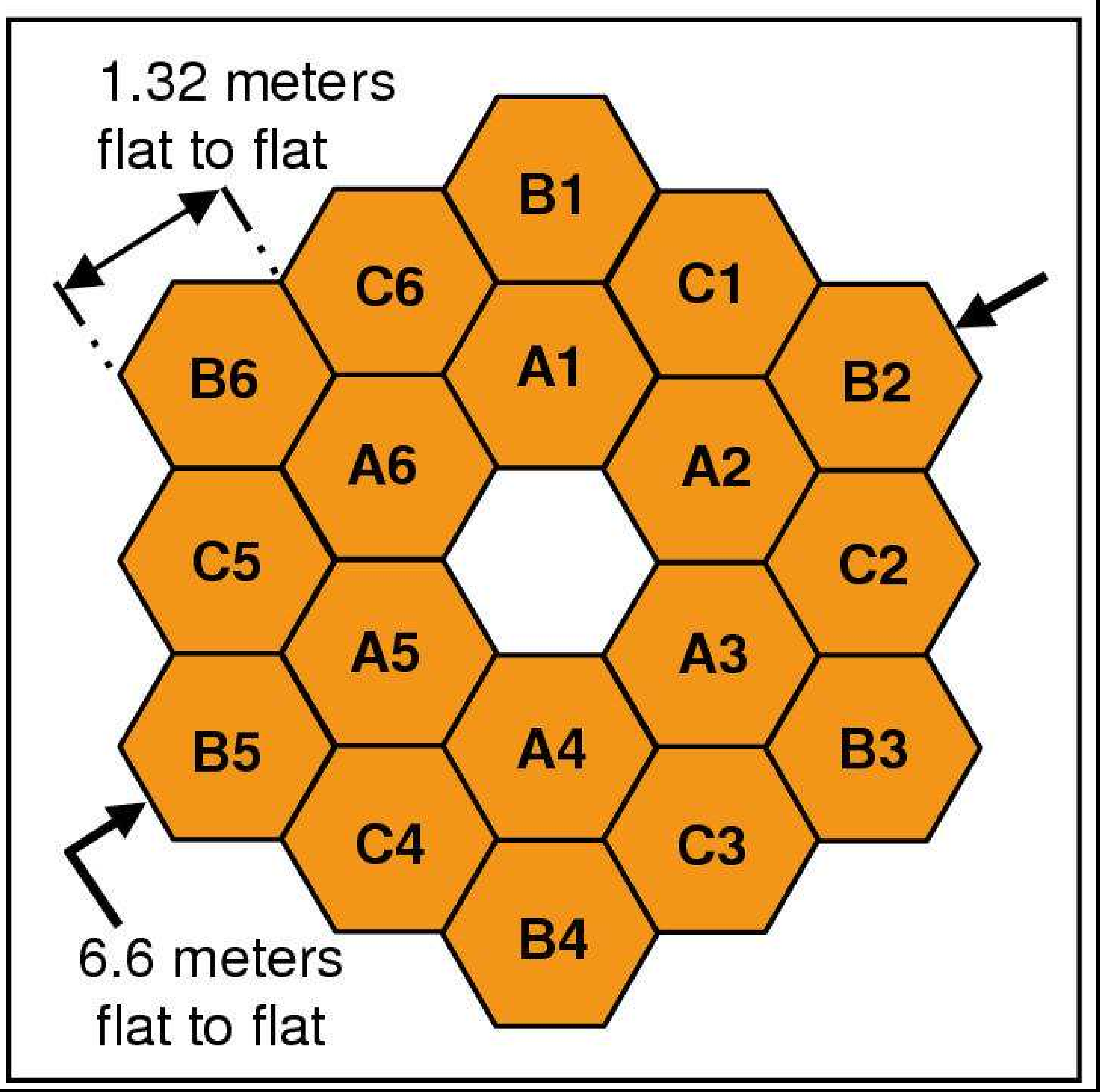
• During its several month journey to L2, JWST will be automatically deployed in phases, its instruments will be tested and calibrated, and it will then be inserted into an L2 halo orbit, 1.5 million km from Earth.

• 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!

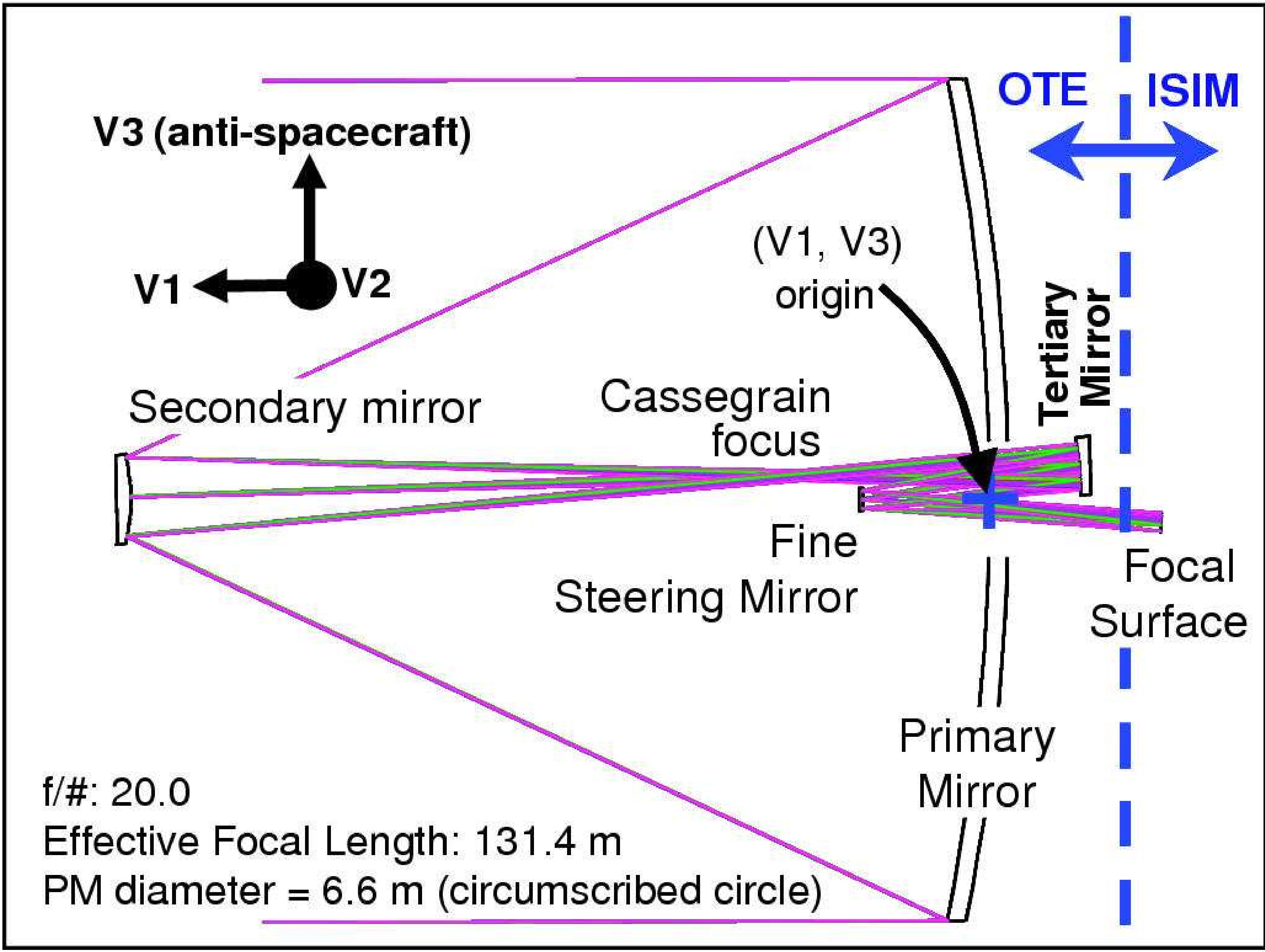


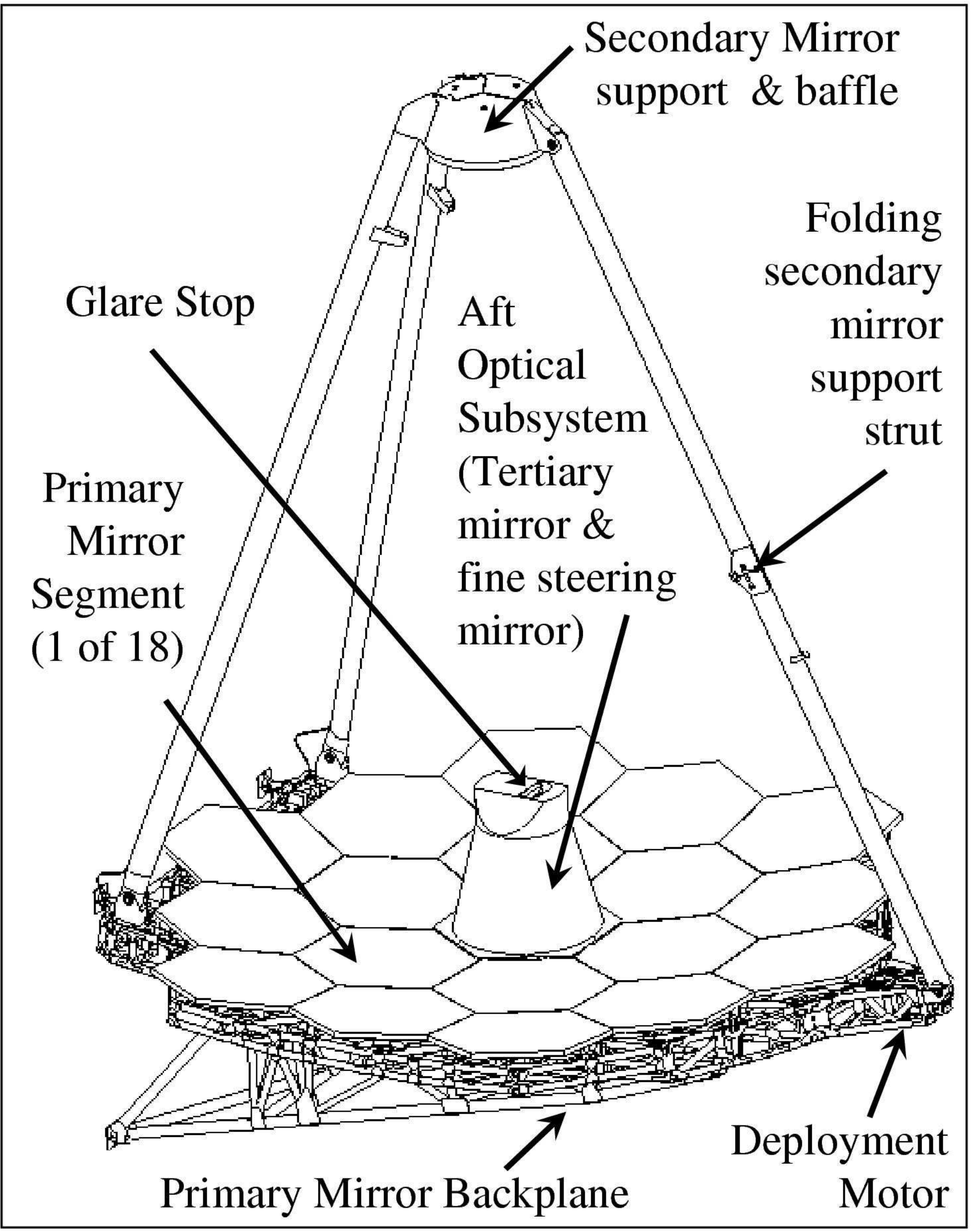
JWST can observe segments of sky that move around as it orbits the Sun.



Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m.

Primary mirror segments made (AxSys), $\geq$6/18 fully polished (Tinsley).

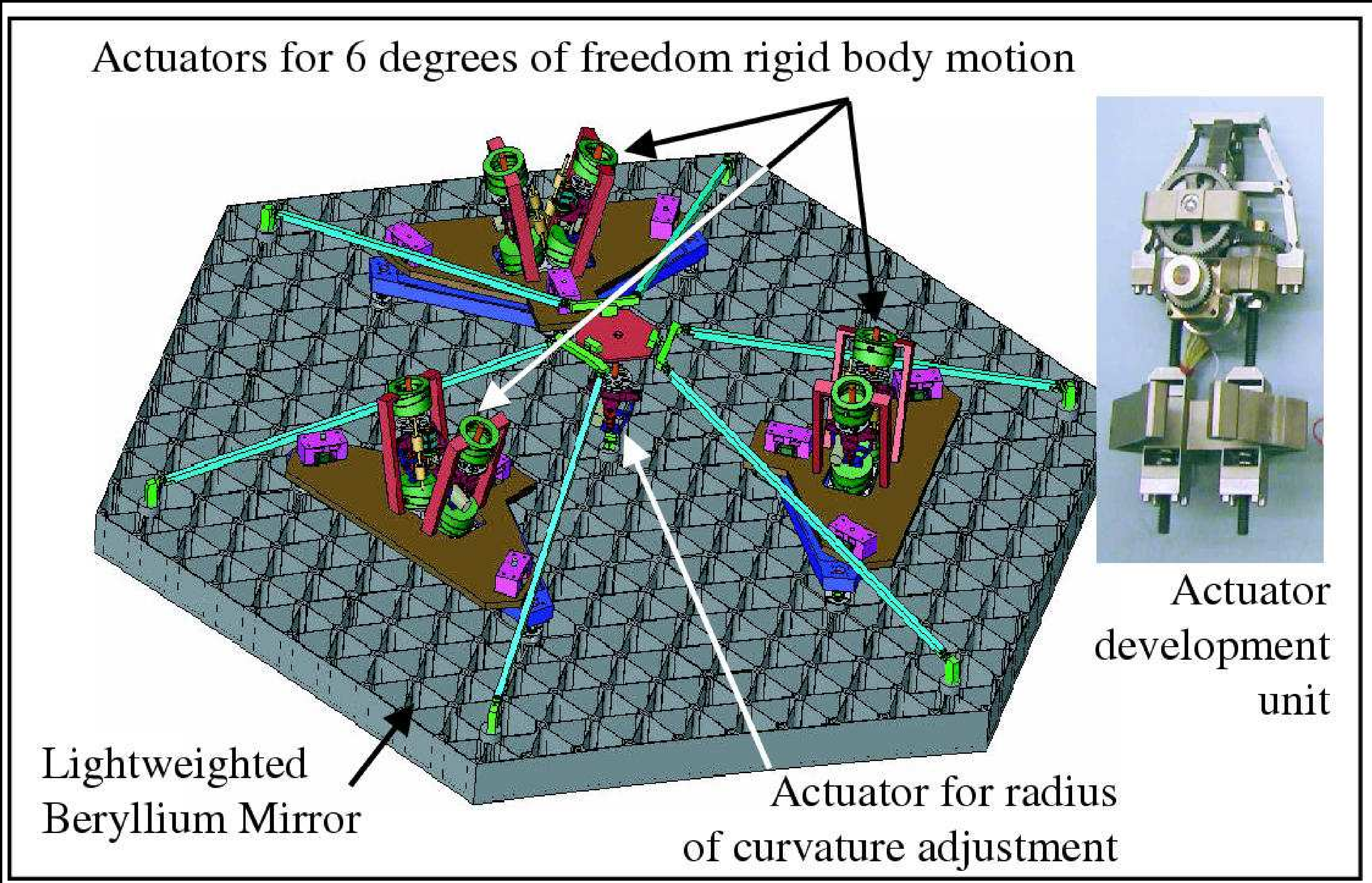

OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)



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

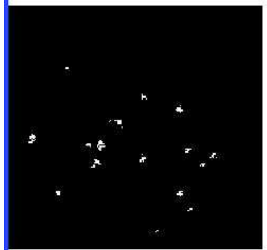
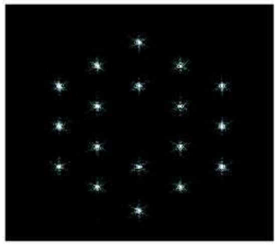
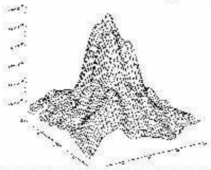
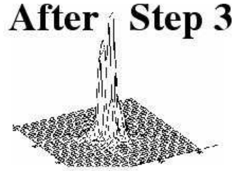
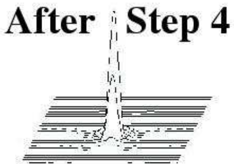
Wave-Front Sensing tested hands-off at 45 K in 1-G at JSC in 2012-2014.

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

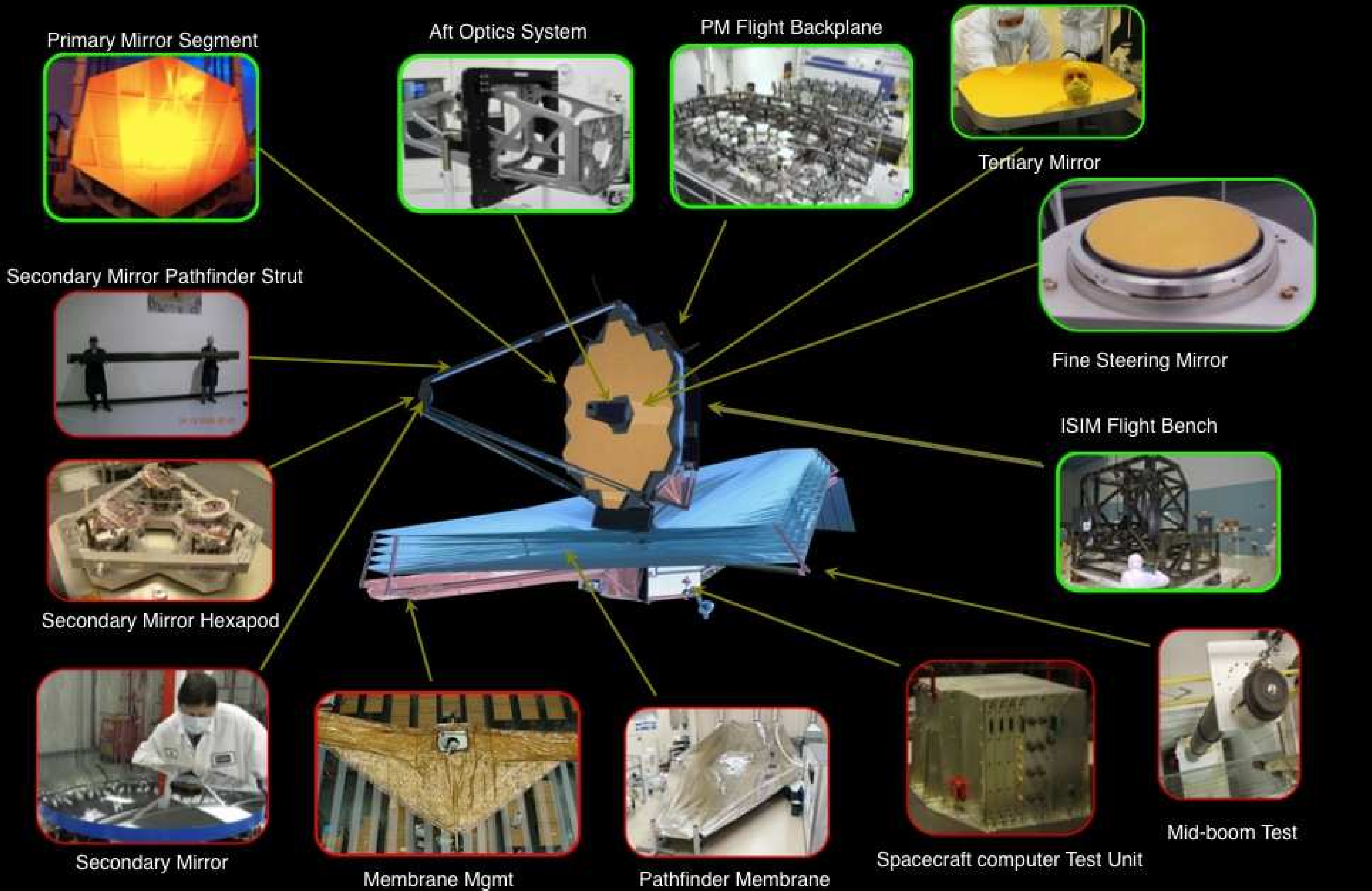
Step	After step	Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	**After Step 1** 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
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.

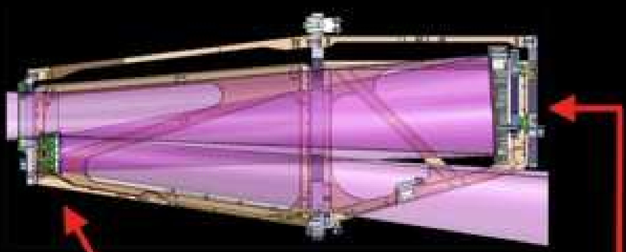
Successful WFS demo of H/W, S/W on 1/6 scale model (2 μm-Strehl$\gtrsim$0.85).

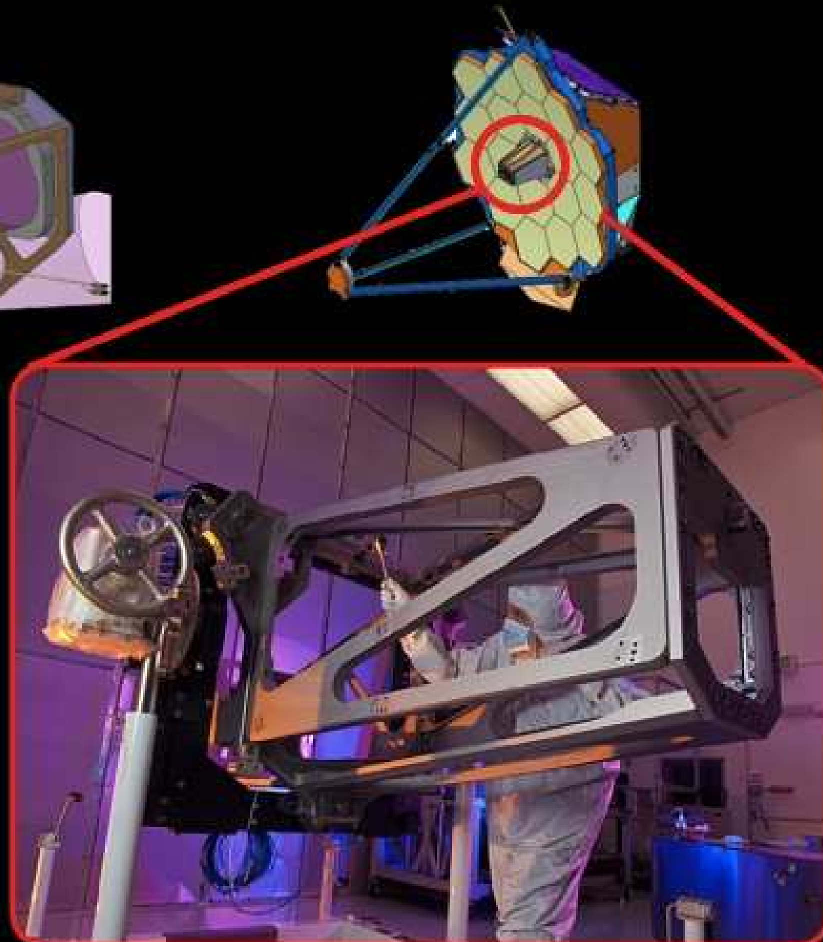
Need WFS-updates every $\sim$14 days, depending on scheduling/SC-illumination.

JWST Hardware Status



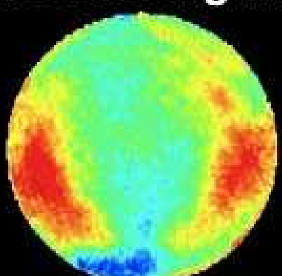
Aft-Telescope Optical System





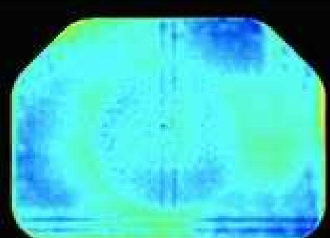
Aft optics and Aft optics bench complete

Fine Steering Mirror



3.8 nm RMS SFE

Tertiary Mirror



4.3 nm RMS SFE

AOS Bench in cryo-test

JWST: A Product of the Nation

Utah
ATK Space Systems
Space Dyamics Lab/ Utah St. U
Hexcel Corporation
Aerospace Machining

Idaho
University of Idaho

Ohio
Brush Wellman
Keithley
Lake Shore Cryotronics
Glenn Research Center

New York
Aeroflex
Indium Corp of America
ITT
University of Rochester

New Hampshire
Optical Solutions Inc
Timkin Aerospace & Super Precision

Minnesota
Minco Products, Inc.
Sheldahl CO.

Connecticut
Zygo

Massachusetts
Appli-Tec Inc
Hypertronics Corporation

Oregon
Precision Measurements & Instr.

Illinois
Boeing
Numerical Precision

Pennsylvania
Tyco Engineered Systems

New Jersey
Newark Electronics

Nevada
TRAX International Inc

Colorado
Ball Aerospace
Blue Line Engineering
CTD
Space Science Institute

California
ATK Composites Optics, Inc
Composite Optics
Glenair
Hewlett Packard
JDS Uniphase
JPL
Lockheed Martin ATC
Magna Tool
Maxwell Technologies
Moog
Newport Corporation
Northrop Grumman Space Technologies
Parsons Infrastructure & Technology
Raytheon Vision Systems
Rockwell Scientific
Sabritec
St Systems USA, Inc
SVG Tinsley Laboratories
Synopsys, Inc
Tayco Engineering, Inc
University of California
Ames Research Center

Maryland
Bechdon Company, Inc.
Boeing
Computer Science Corporation
Conceptual Analytics
Curtis Management Co.
Energy Solutions International, LLC
General Dynamics
Genesis Engineering Co., LLC
Global Science & Technology
Hammers Company
Honeywell / HTSI
Jackson & Tull Chartered Engineers
Janis Research Company
Johns Hopkins University
Litton
Lockheed Martin
Lorr Company
Mega Engineering
Microtel
NGST Electronics
Northrop Grumman
Nu-Tek
QSS Group, Inc.
Raytheon
RSTX
Science Application International Corporation
SGT
Sigma
Space Telescope Science Institute
SRS Technologies
SSAI
Swales Aerospace
University of Maryland
USRA
Wolcott Park

New Mexico
Cortez III Service Corp
DoE

Texas
Muniz Engineering
National Instruments
Texas A&M University
Johnson Space Center

Washington DC
Catholic University
Naval Research Lab

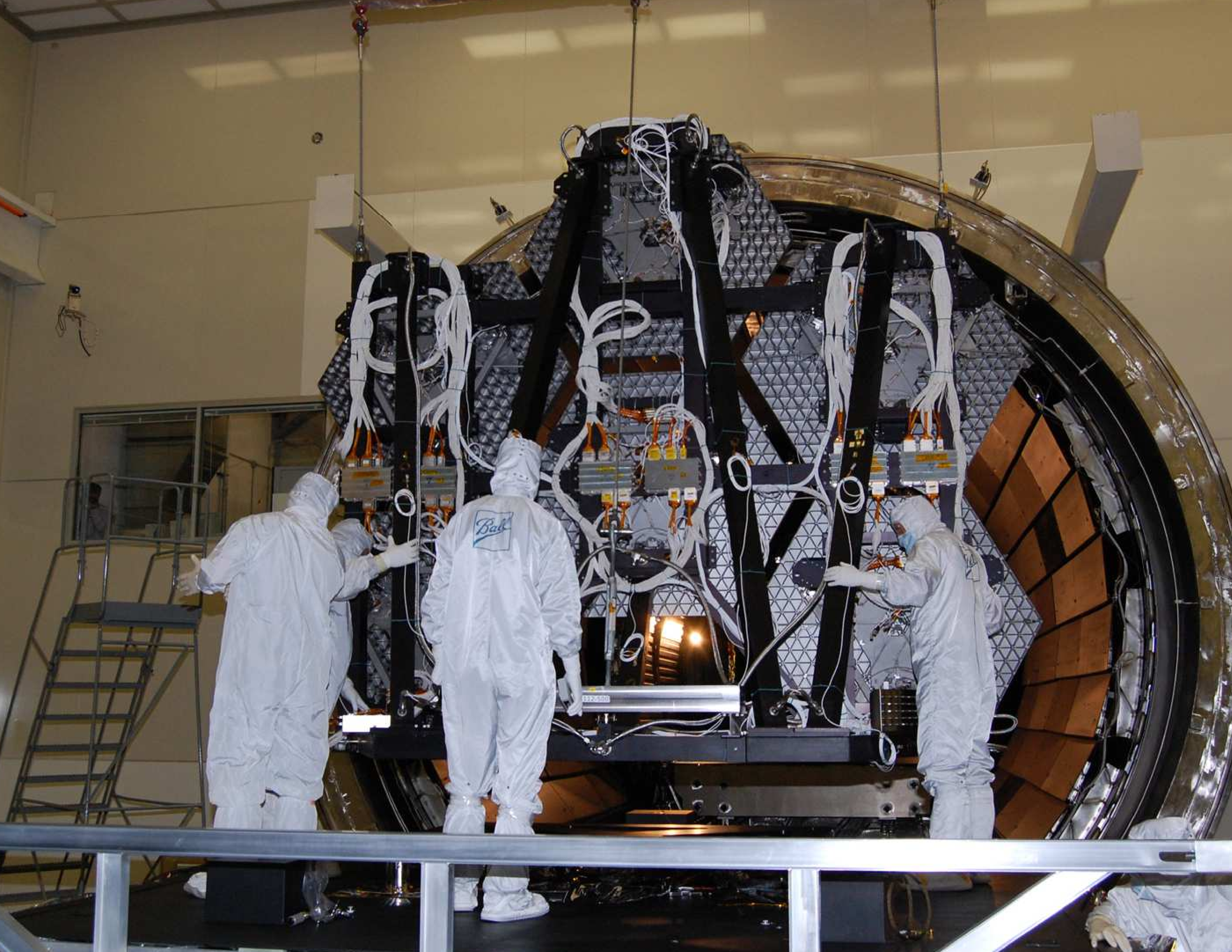
Hawaii
GL Scientific
Mauna Kea Engineering
University of Hawaii

Arizona
Dynaco
Honeywell International, Inc
Optical Device Engineering Corp
University of Arizona
Arizona State University

Alabama
Axsys Technologies
Marshall Space Flight Center
SRI

Florida
Advanced Quick Circuits
CDA InterCorp
Geodetic Services

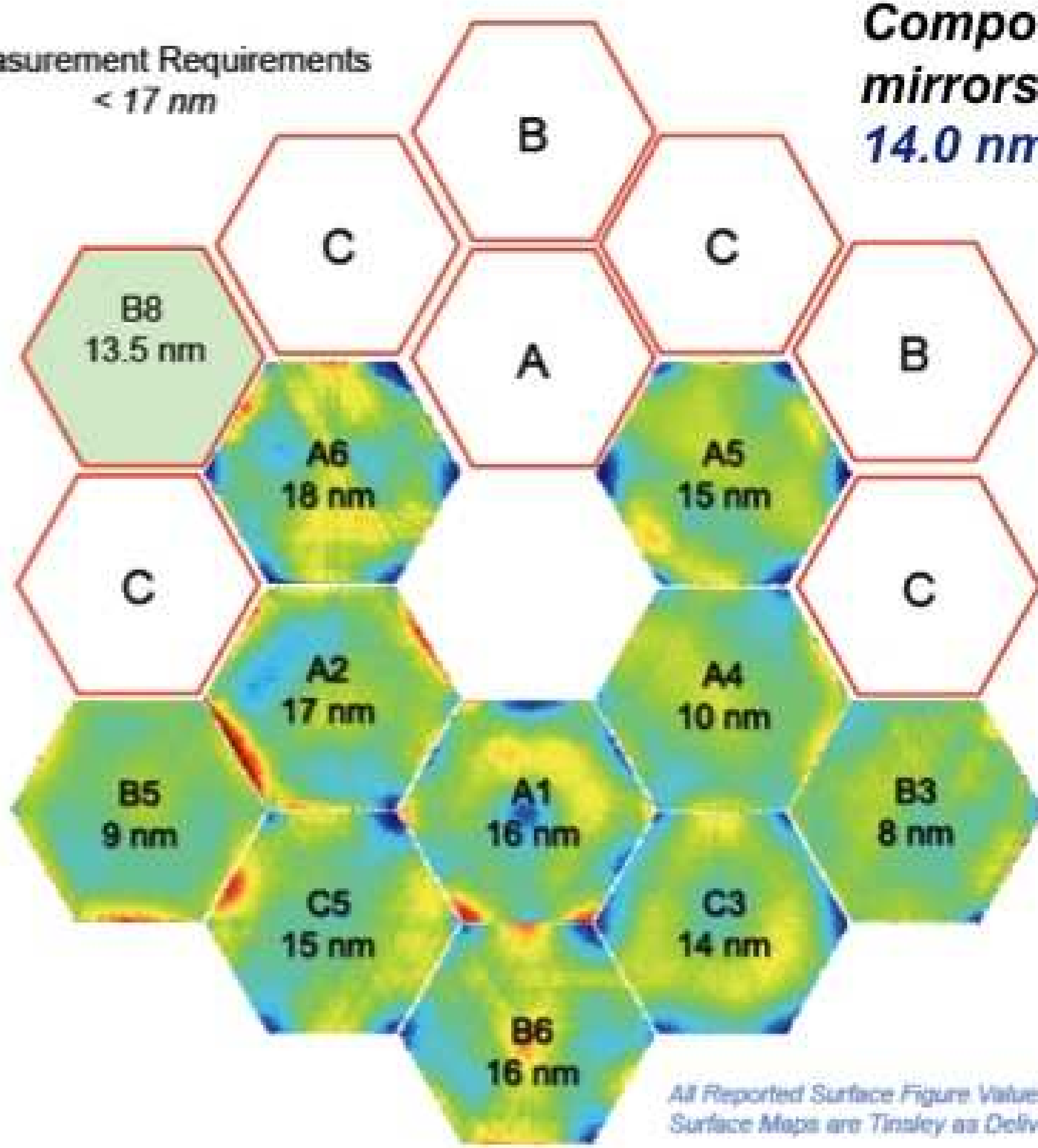
Virginia
BAE Systems
General Dynamics
Man Tech
National Research Initiatives
Orbital Sciences Corporation



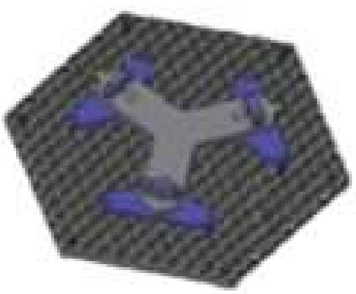
FINAL POLISHING RESULTS TO DATE

Tinsley Final Measurement Requirements
Total Figure *< 17 nm*

Composite figure of flight mirrors delivered to date:
14.0 nm RMS



All Reported Surface Figure Values in nm RMS
Surface Maps are Tinsley as Delivered Master Data Product



Mirror test configuration

3/31/11

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

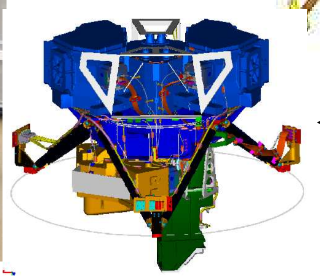
Instrument Overview

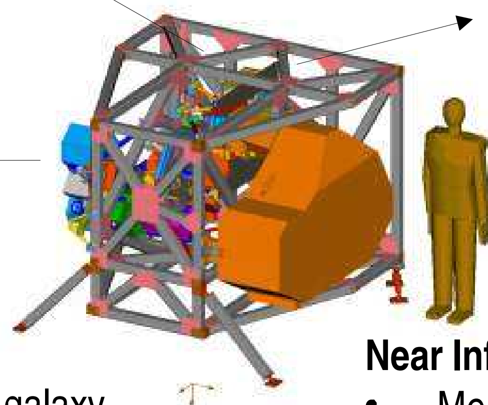
Fine Guidance Sensor (FGS)

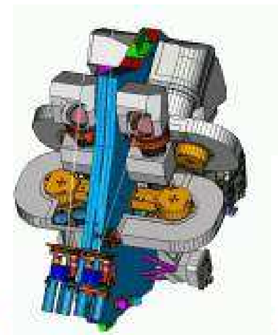
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

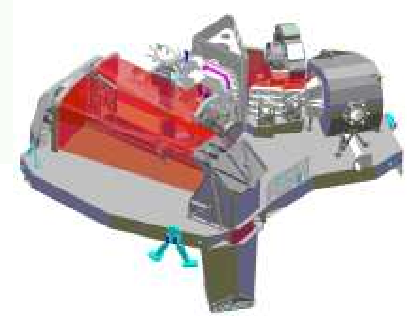
Near Infra-Red Camera (NIRCam)

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









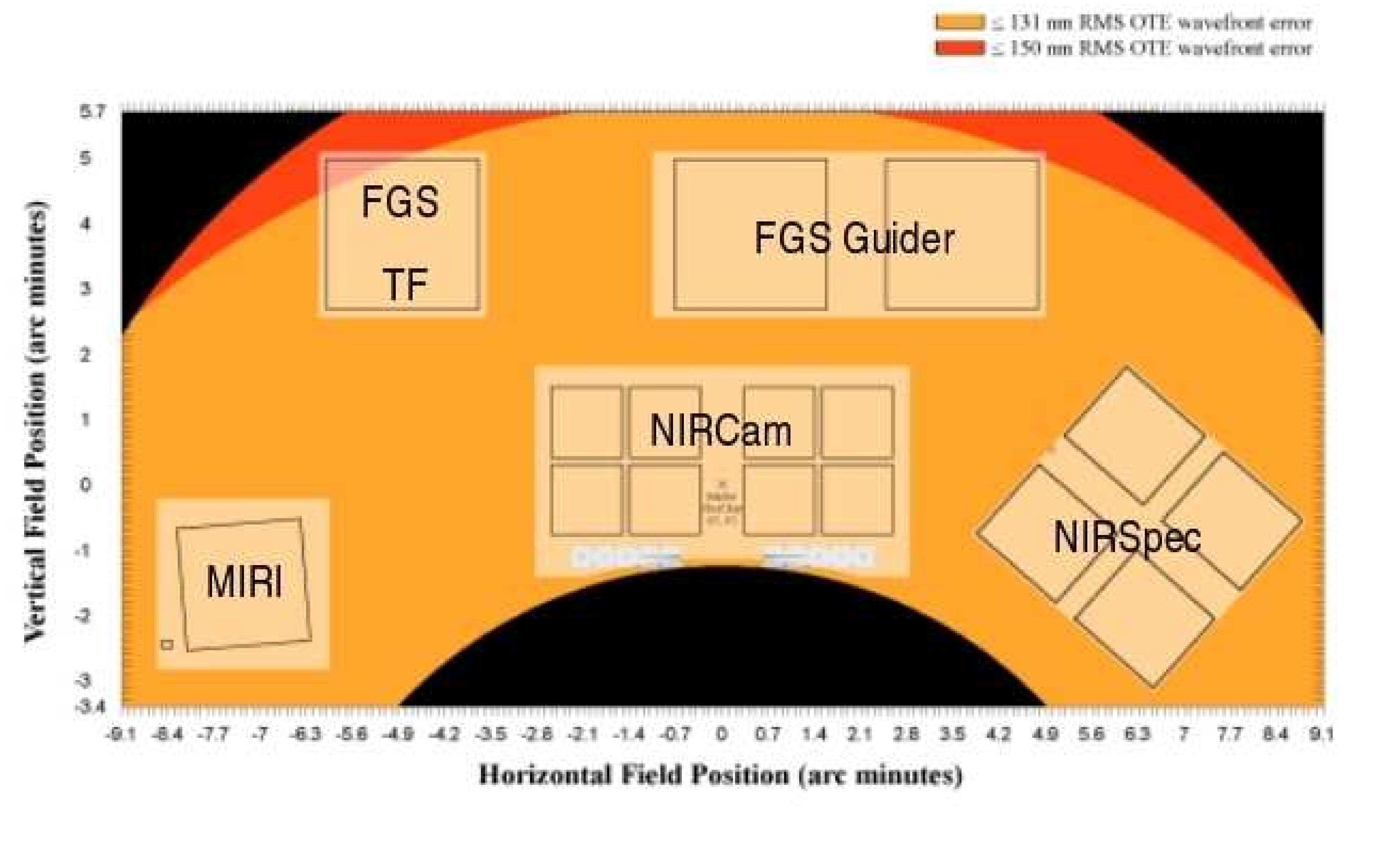
Mid-Infra-Red Instrument (MIRI)

- 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)

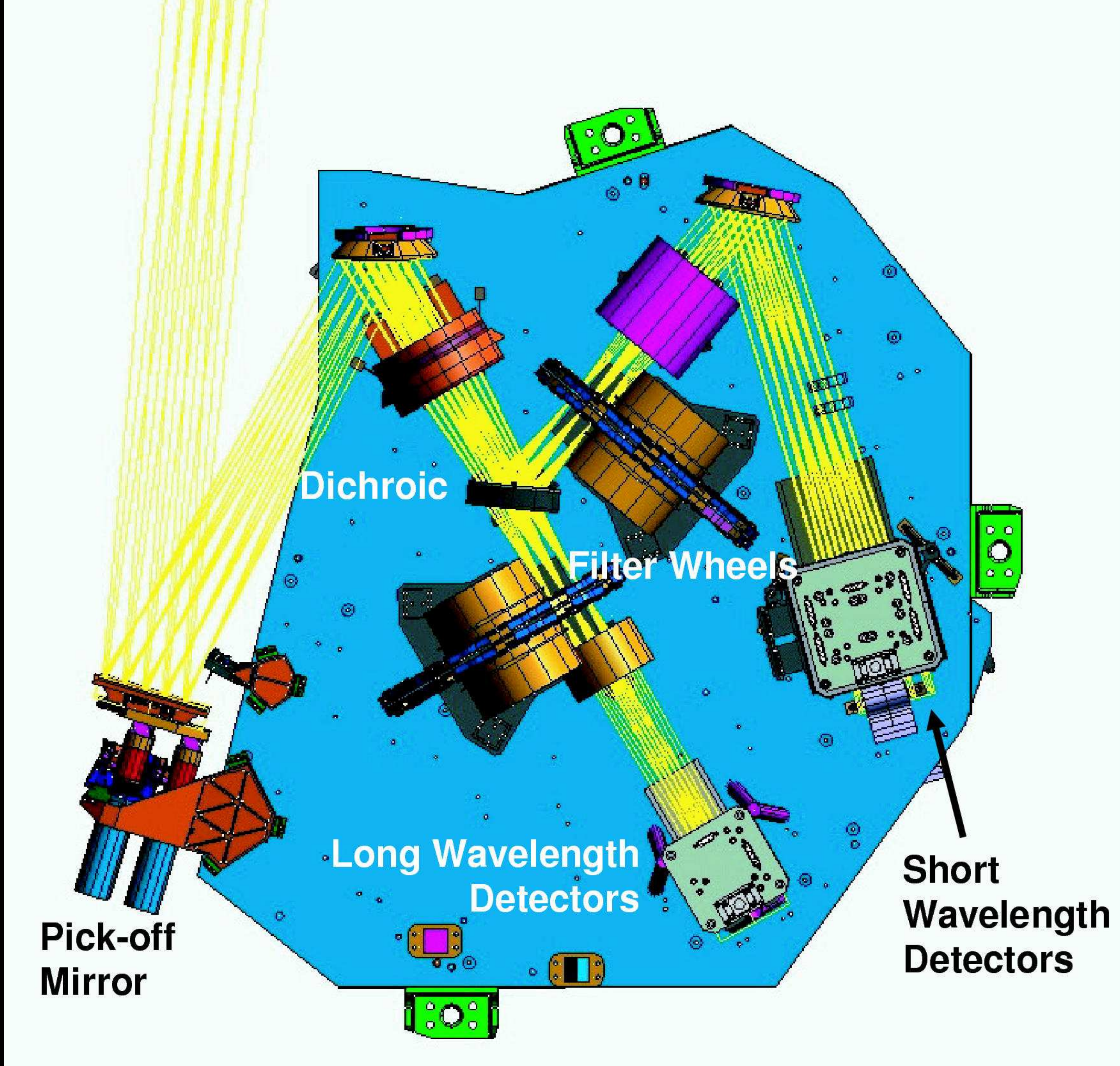
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

• (2) What instruments will JWST have?



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

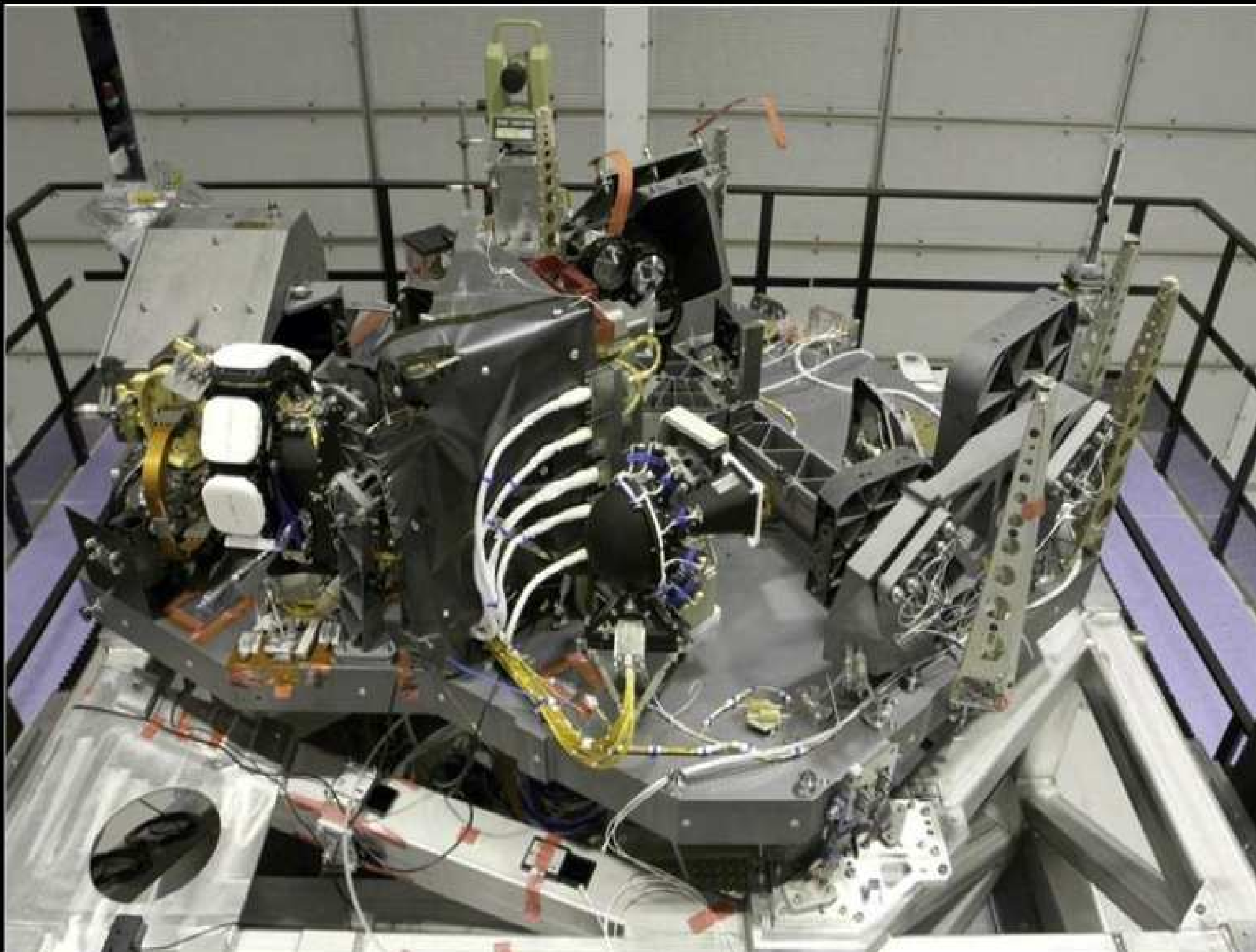
- Currently only being implemented for parallel *calibrations.*

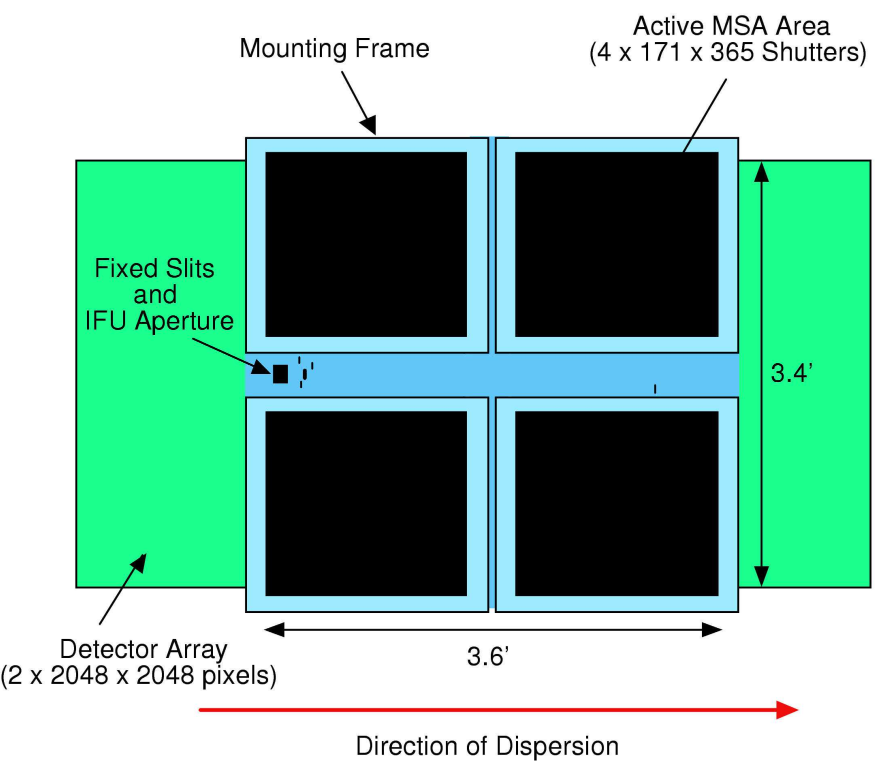


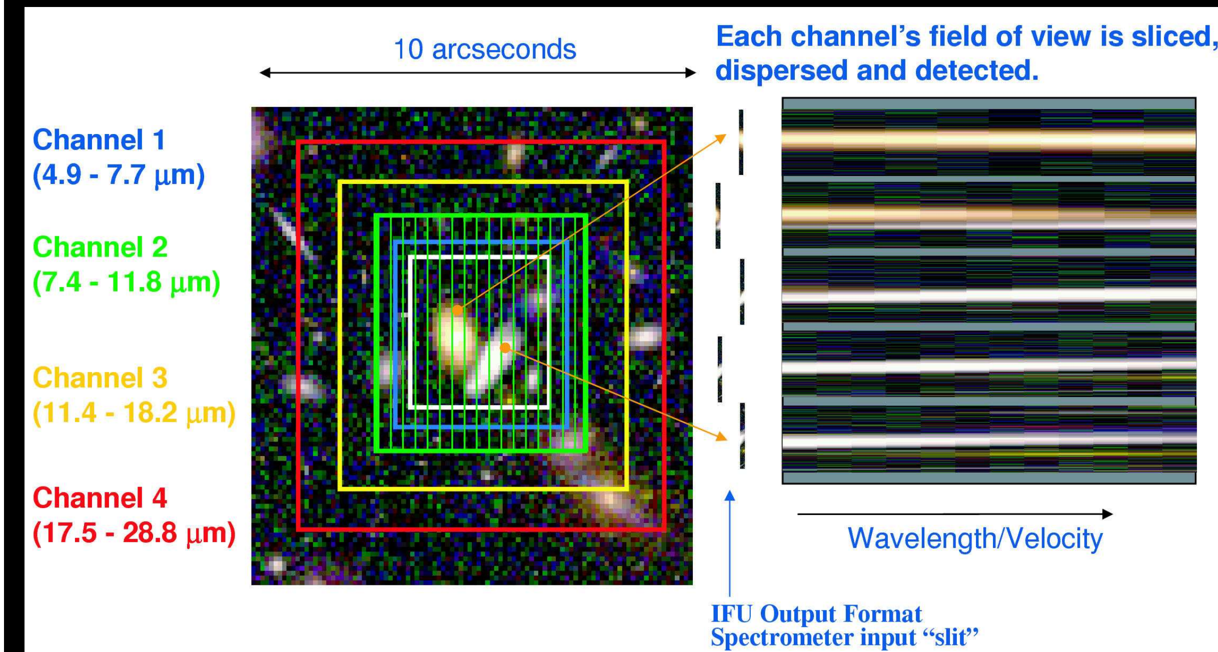
Layout of JWST NIRCam — the UofA–Lockheed NIR-Camera

ETU NIRCam

FLIGHT NIRSpec







JWST offers significant multiplexing for faint object spectroscopy:

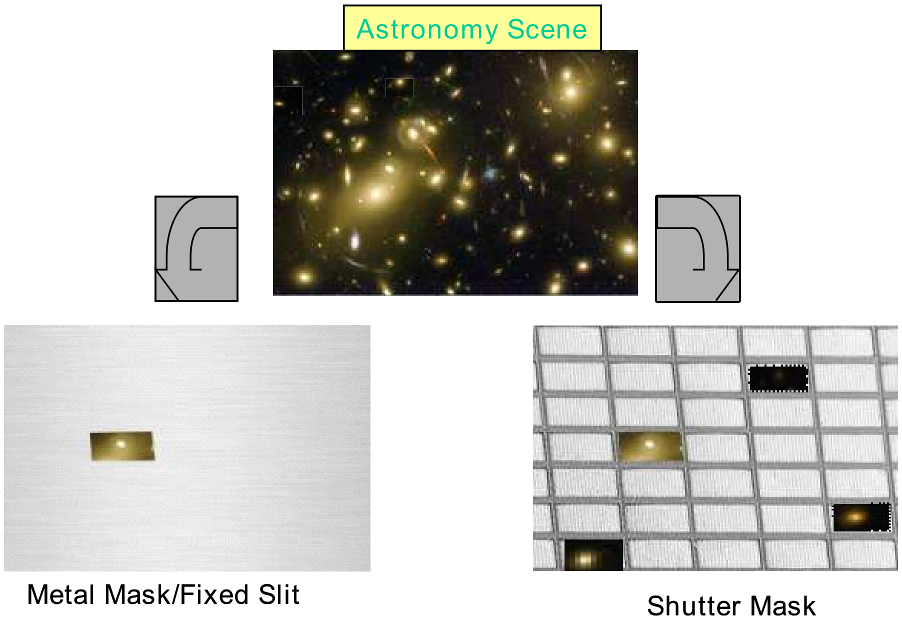
- NIRSpec/MSA with $4\times62{,}415$ independently operable micro-shutters (MEMS) that cover $\lambda\simeq1$–5 μm at R$\simeq$100–1000.

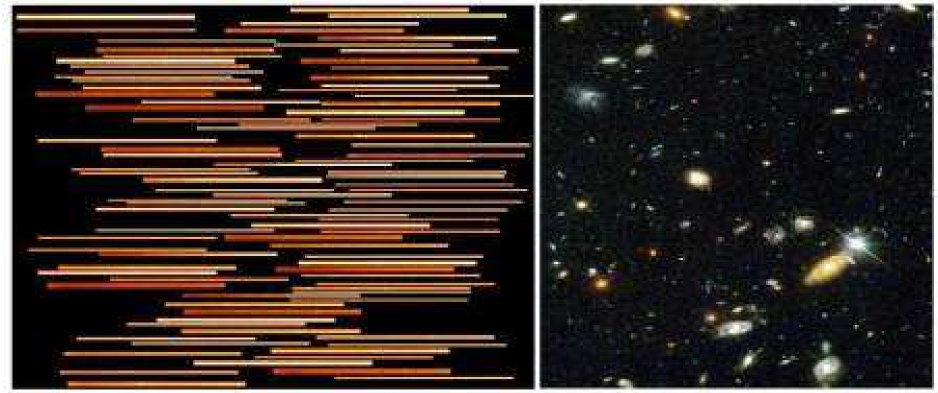
- MIRI/IFU with 400 spatial pixels covering 5–29 μm at R$\sim$2000–4000.

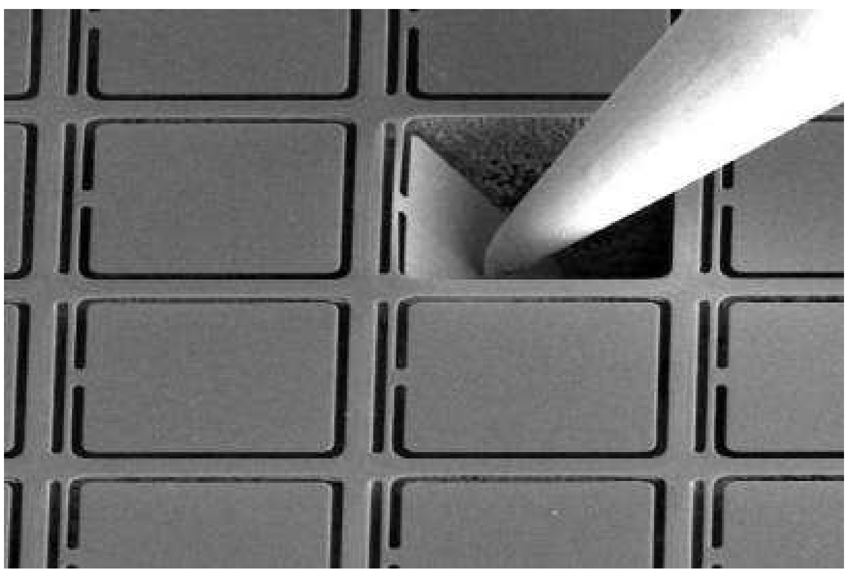
- FGS/TFI that covers a $2\farcm2\times2\farcm2$ FOV at $\lambda\simeq1.6$–4.9 μm at R$\simeq$100.

[• NIRCam offers R$\simeq$5 imaging from 0.7–5μm over two $2\farcm3\times4\farcm6$ FOV's.]

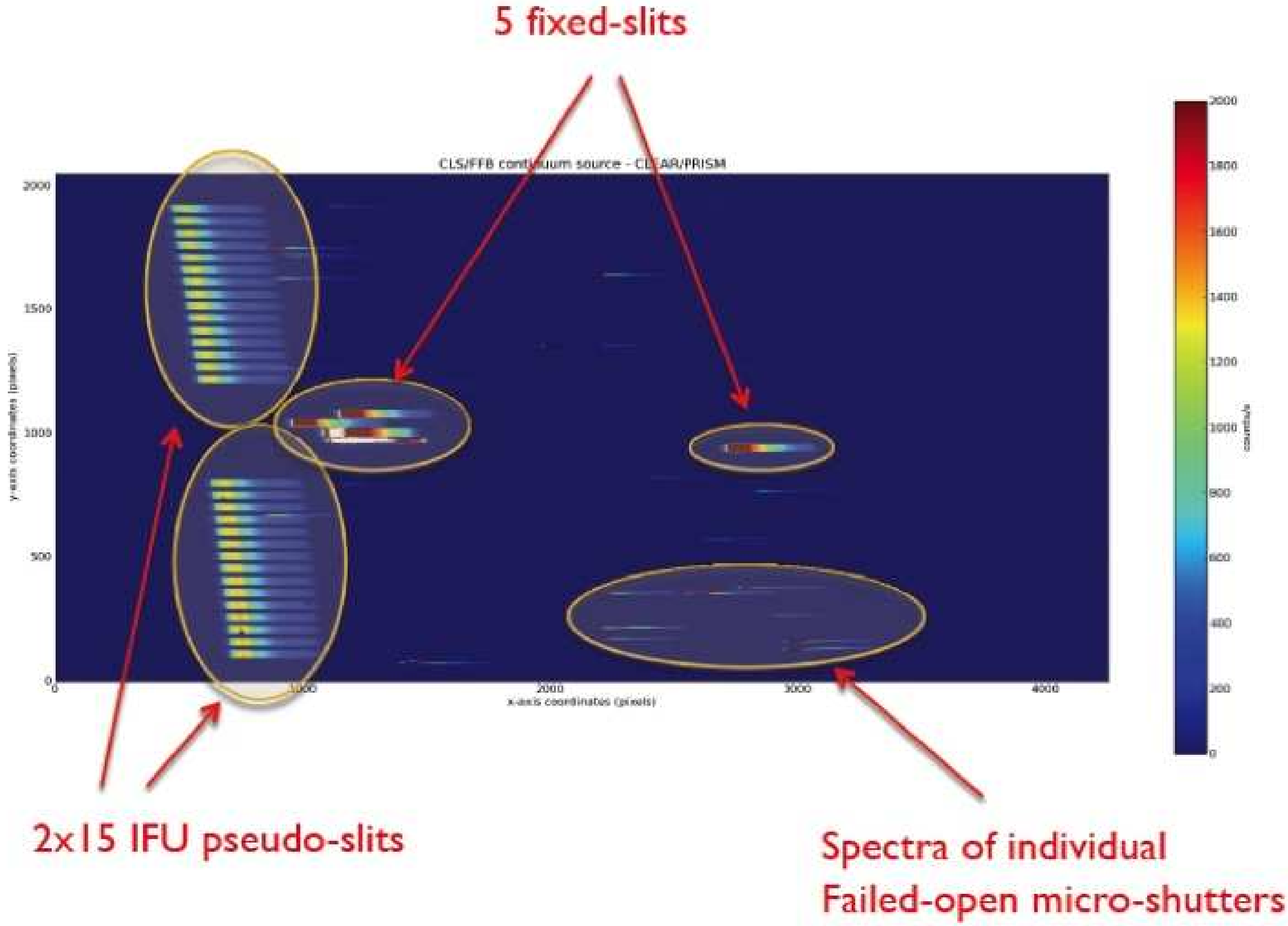
Micro Shutters







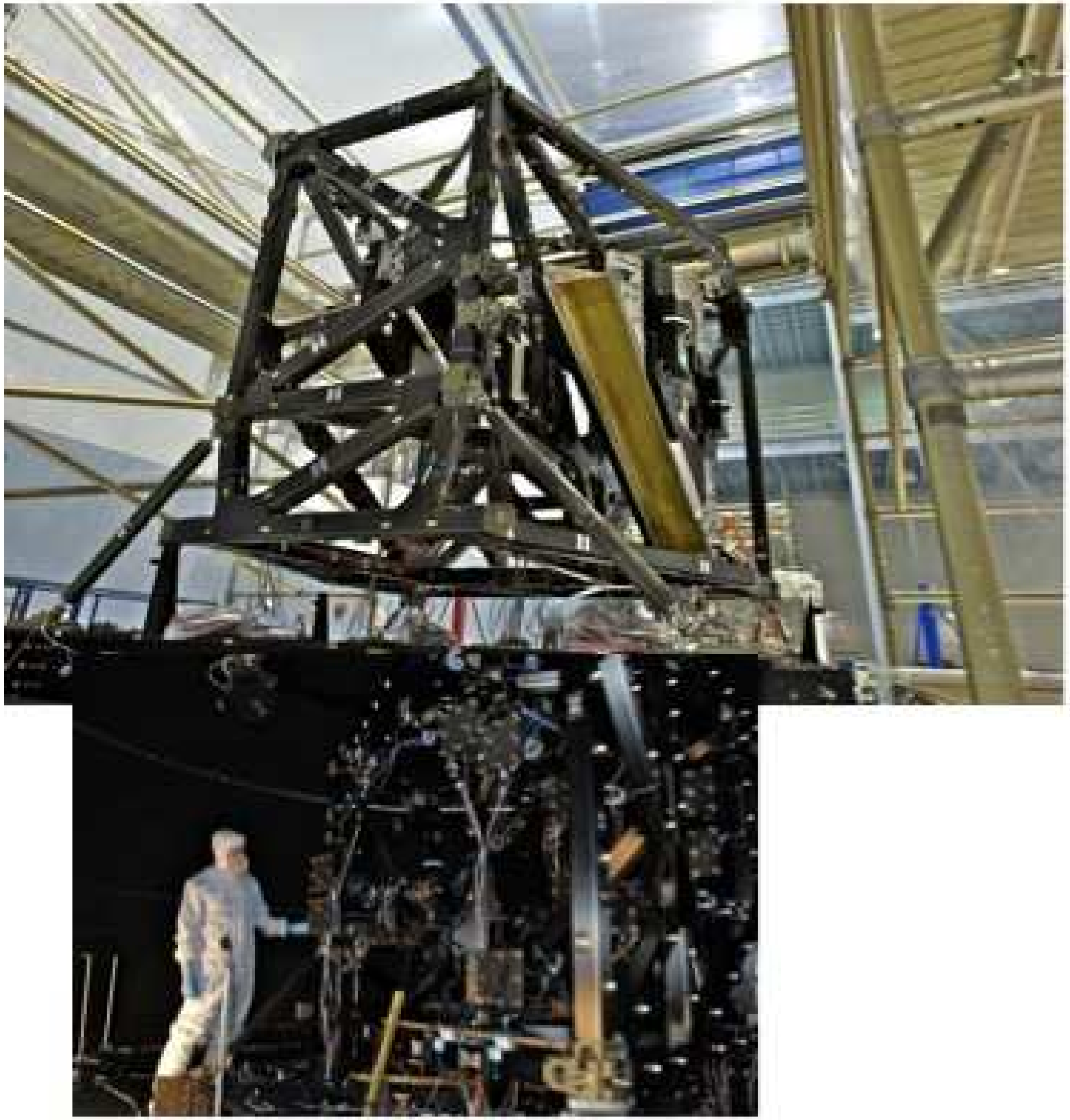
Flight NIRSpec First Light



Flight MIRI

Flight Fine Guidance Sensor

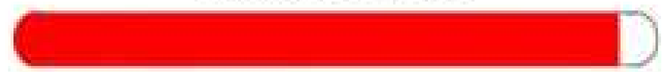
INTEGRATED SCIENCE INSTRUMENT MODULE (ISIM)



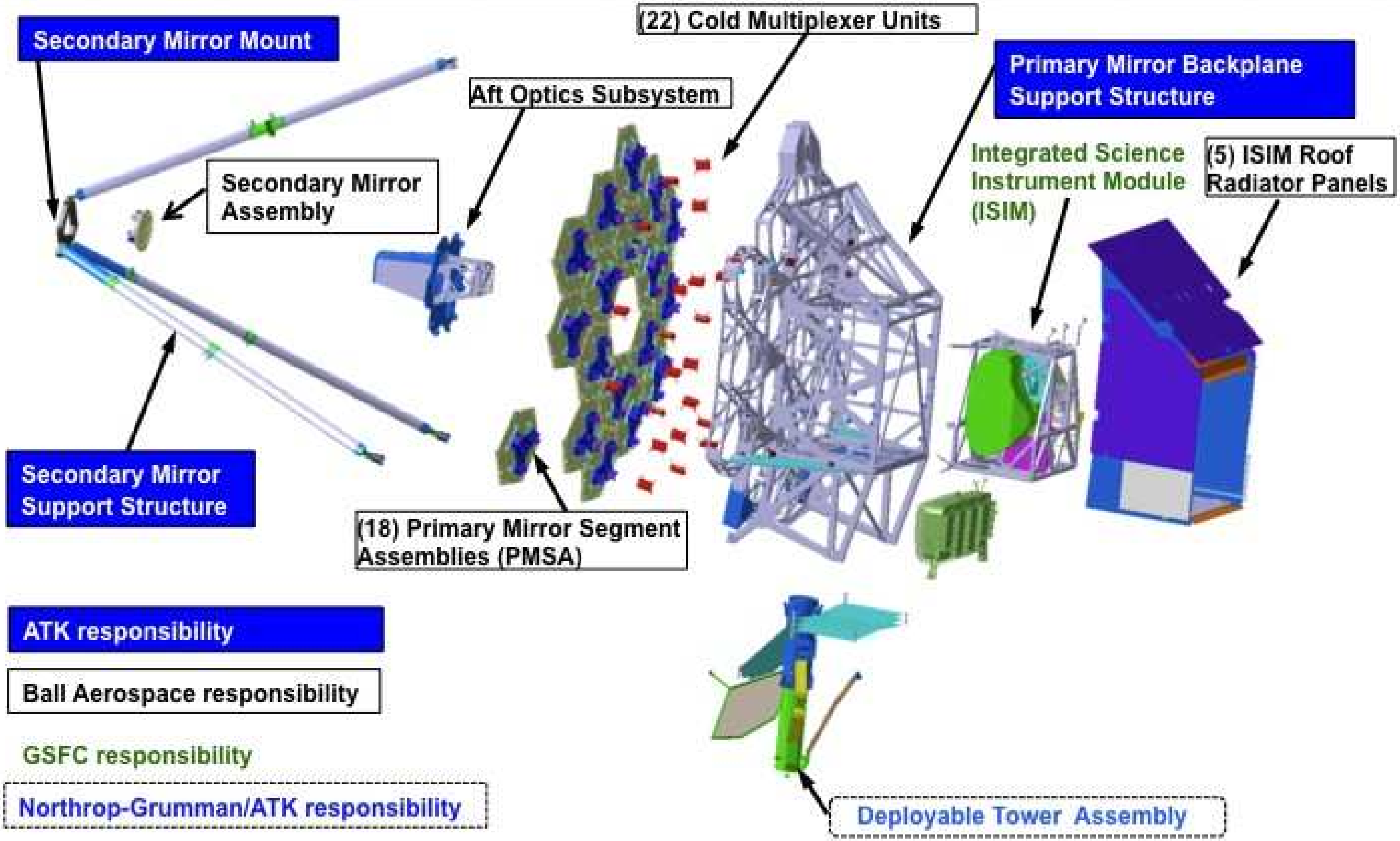
ISIM preparing for cryogenic testing

The ISIM holds the science instruments and also provides common services such a cooling and power supply to the instruments

Element Progress



TELESCOPE ARCHITECTURE



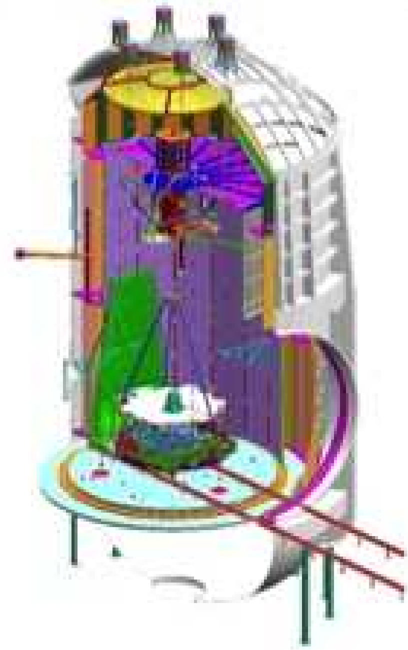
3/31/11

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

TELESCOPE TESTING CHAMBER AT JOHNSON SPACE CENTER

Notice people for scale

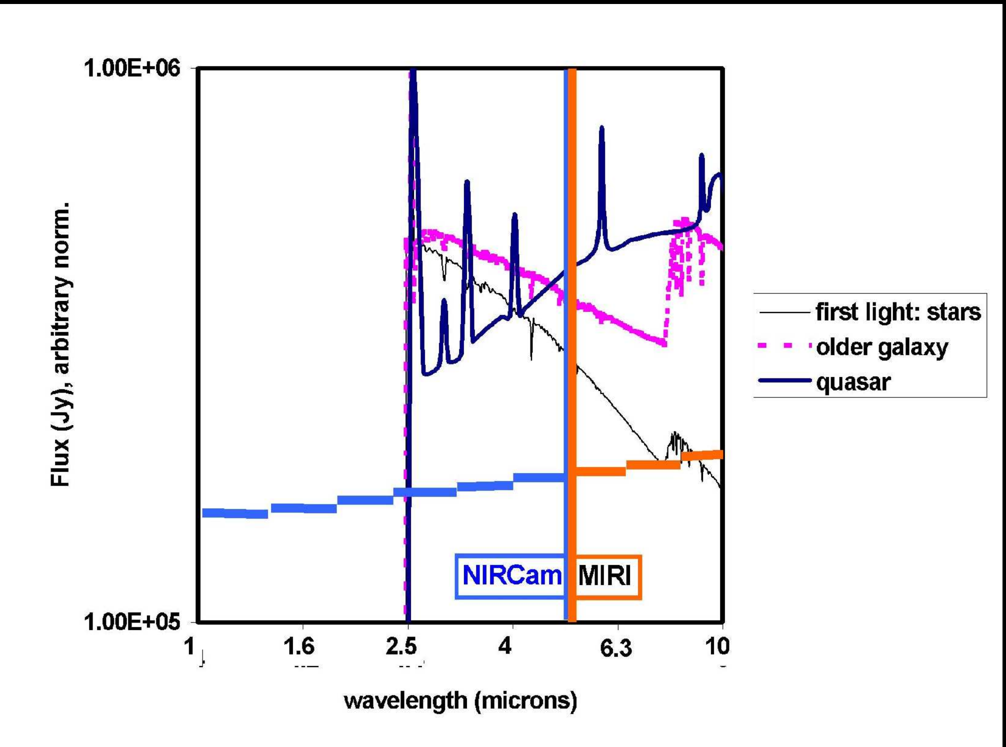
Largest simulation of deep space ever attempted will be done here

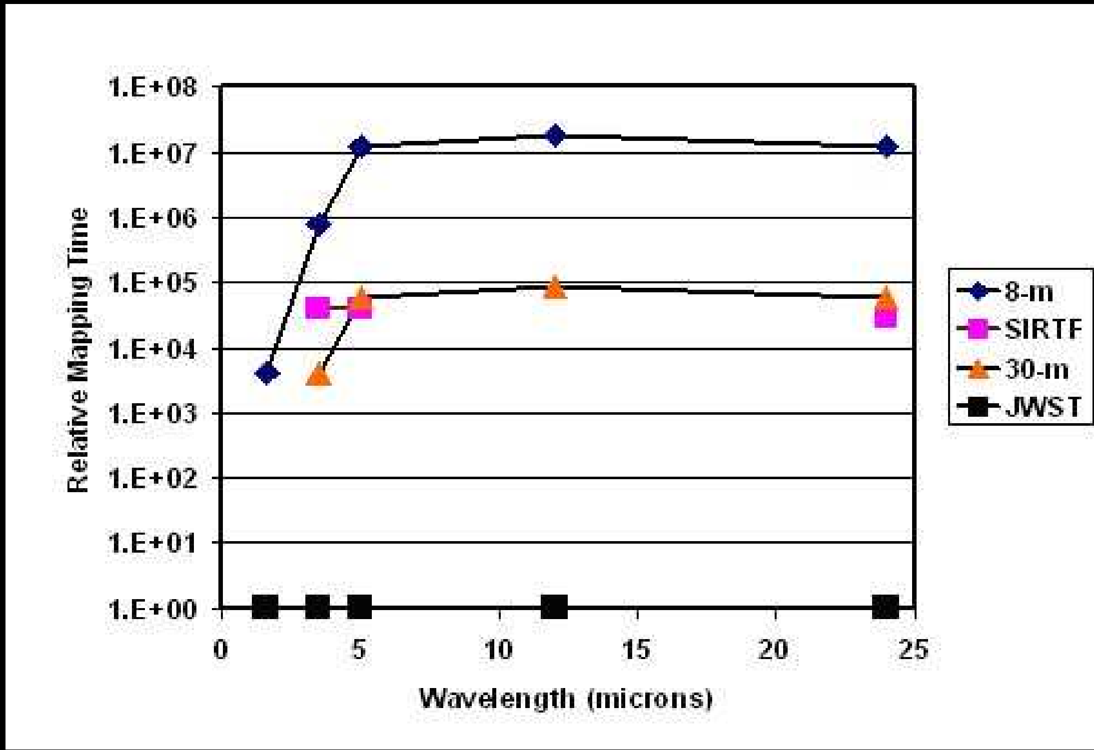


Telescope and science instruments installed in the test chamber

Element Progress

• (2) What sensitivity will JWST have?





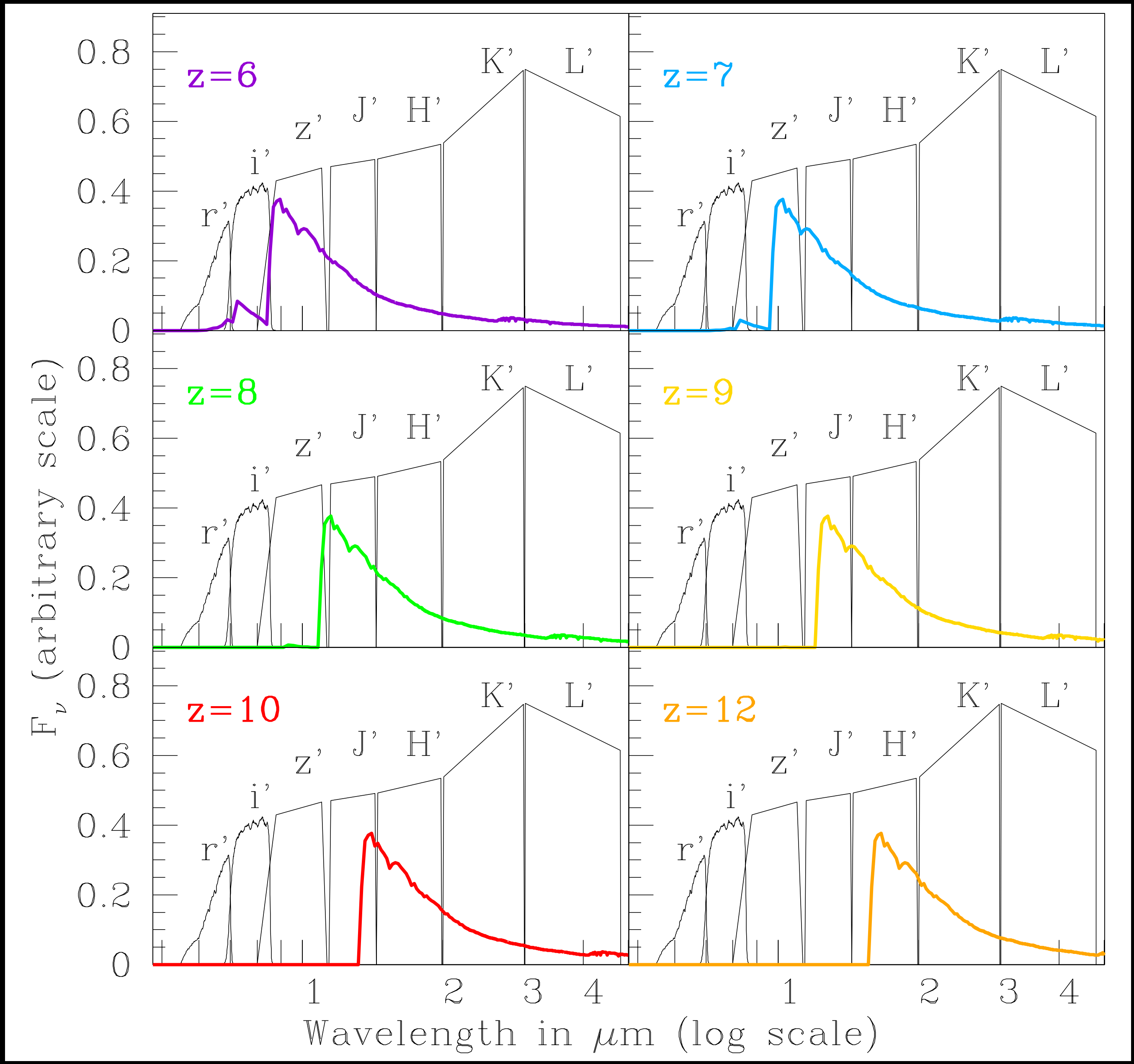
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5\ \mu$m.

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.

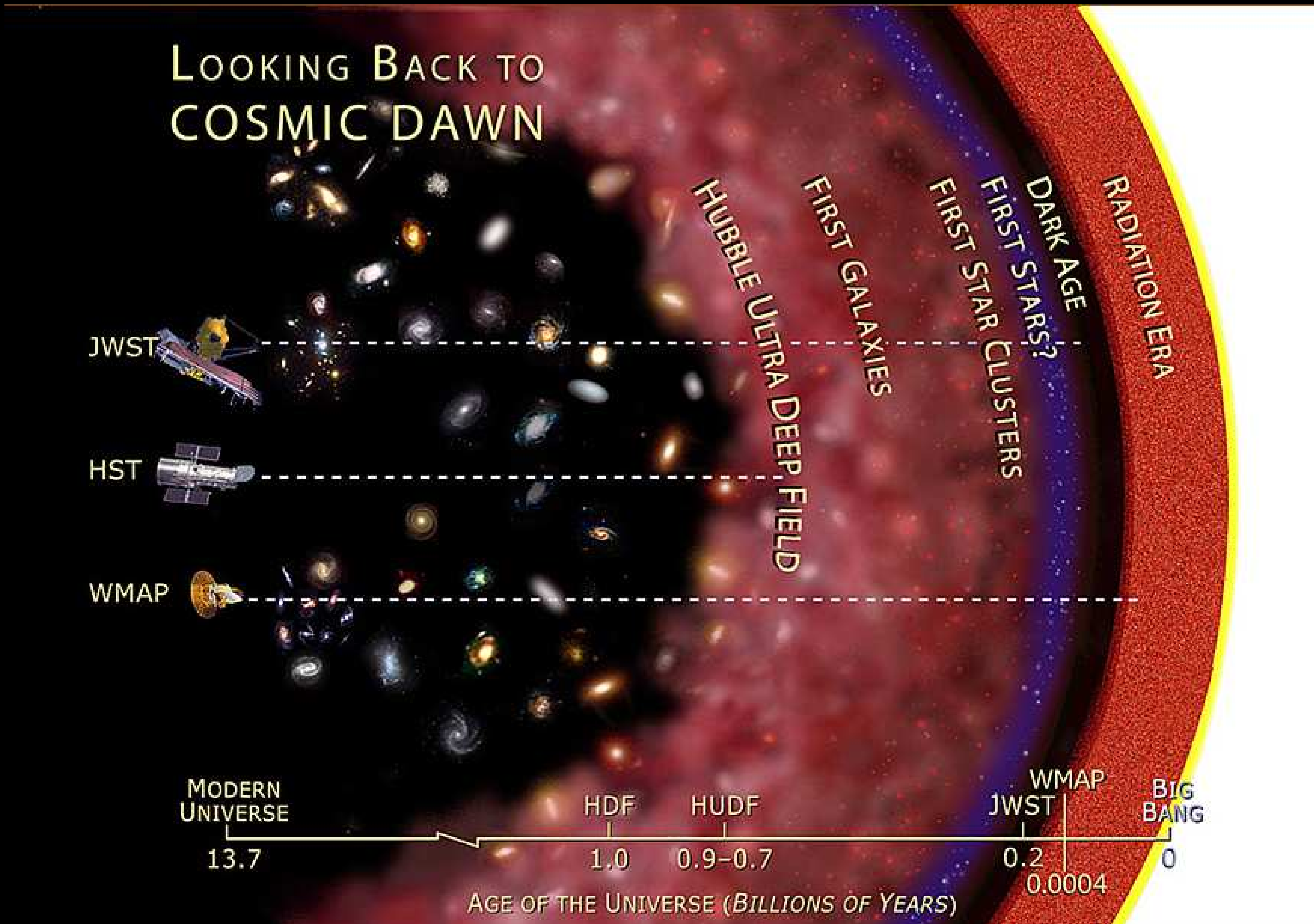
• (3) How can JWST measure First Light and Reionization?



• 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?



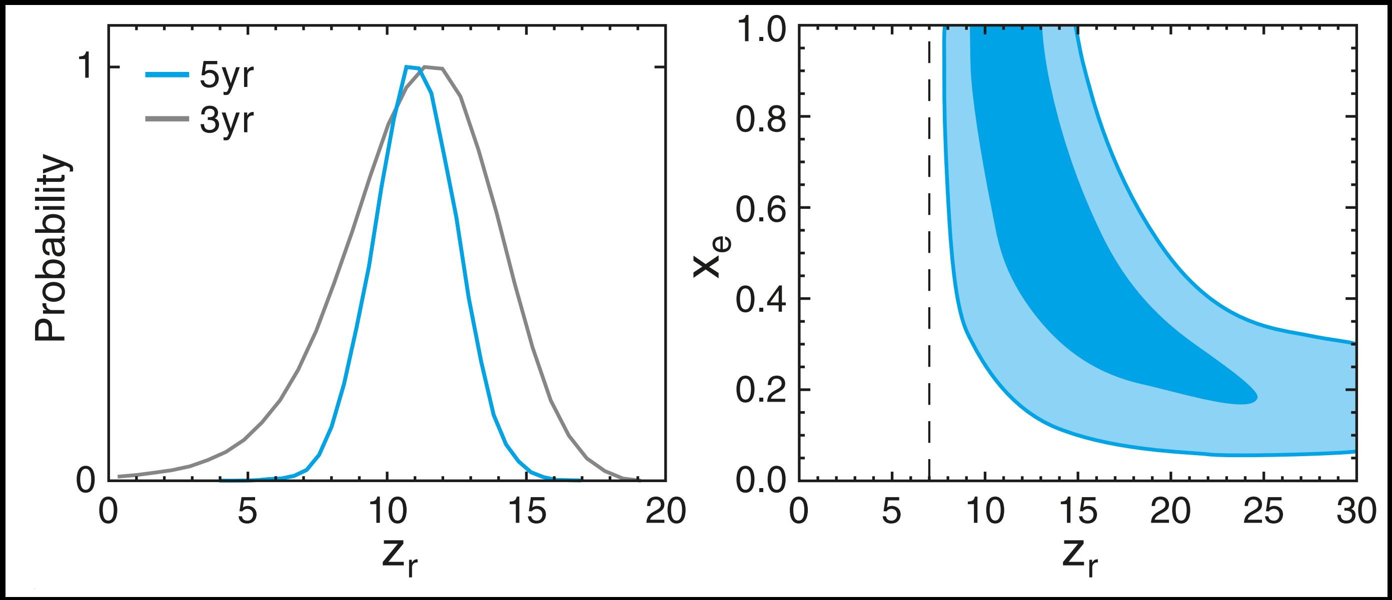
HST (+WFC3): Hubble sequence & galaxy evolution from z≃0 to z≃7–8.

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)

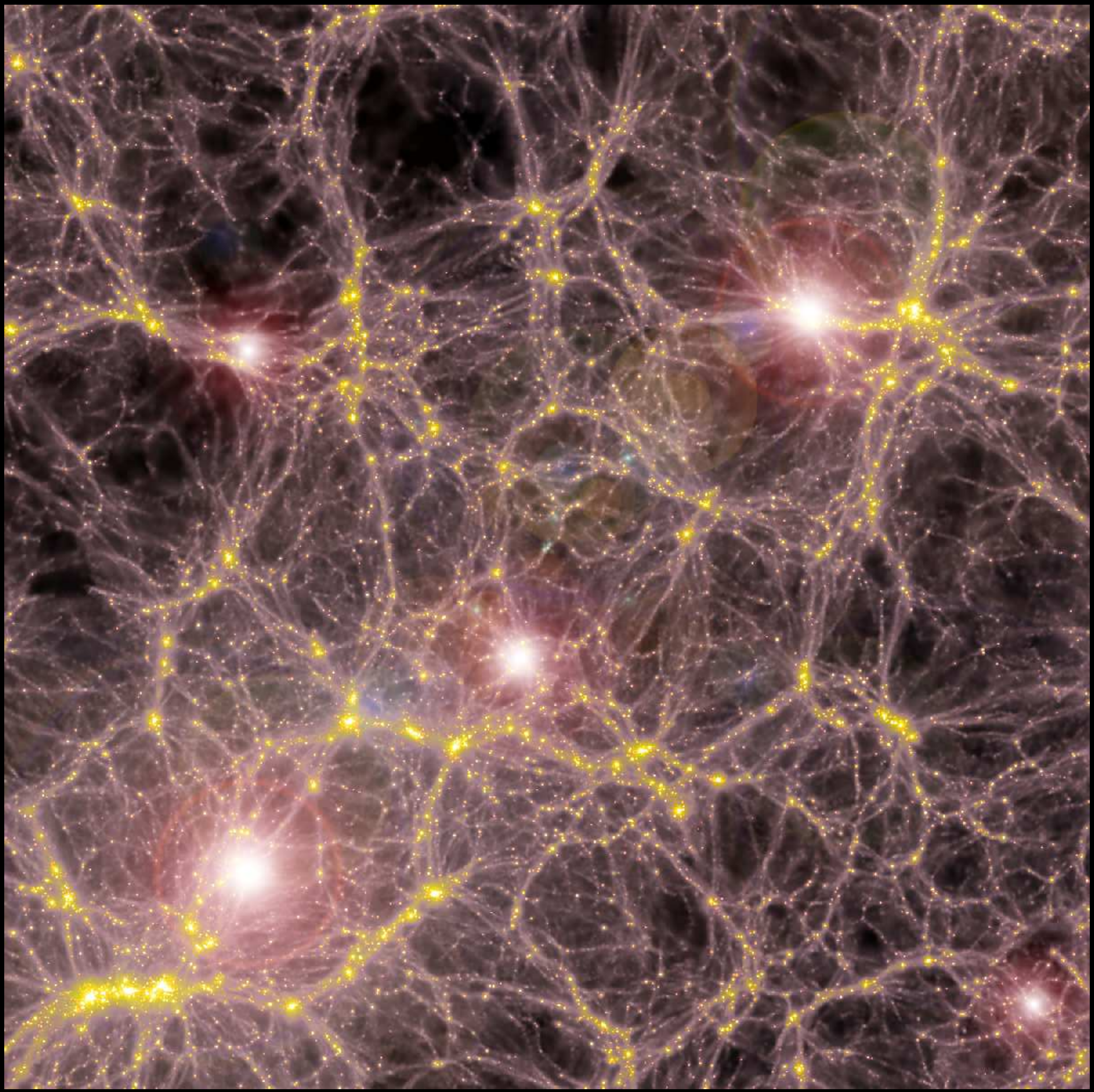
$\Longrightarrow$ First Light & Reionization occurred between these extremes:

- (1) Instantaneous at z$\simeq$10.4$\pm$1.2 (τ=0.087$\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 λ=0.7–29 μm, with its diffraction limit at 2.0 μm.

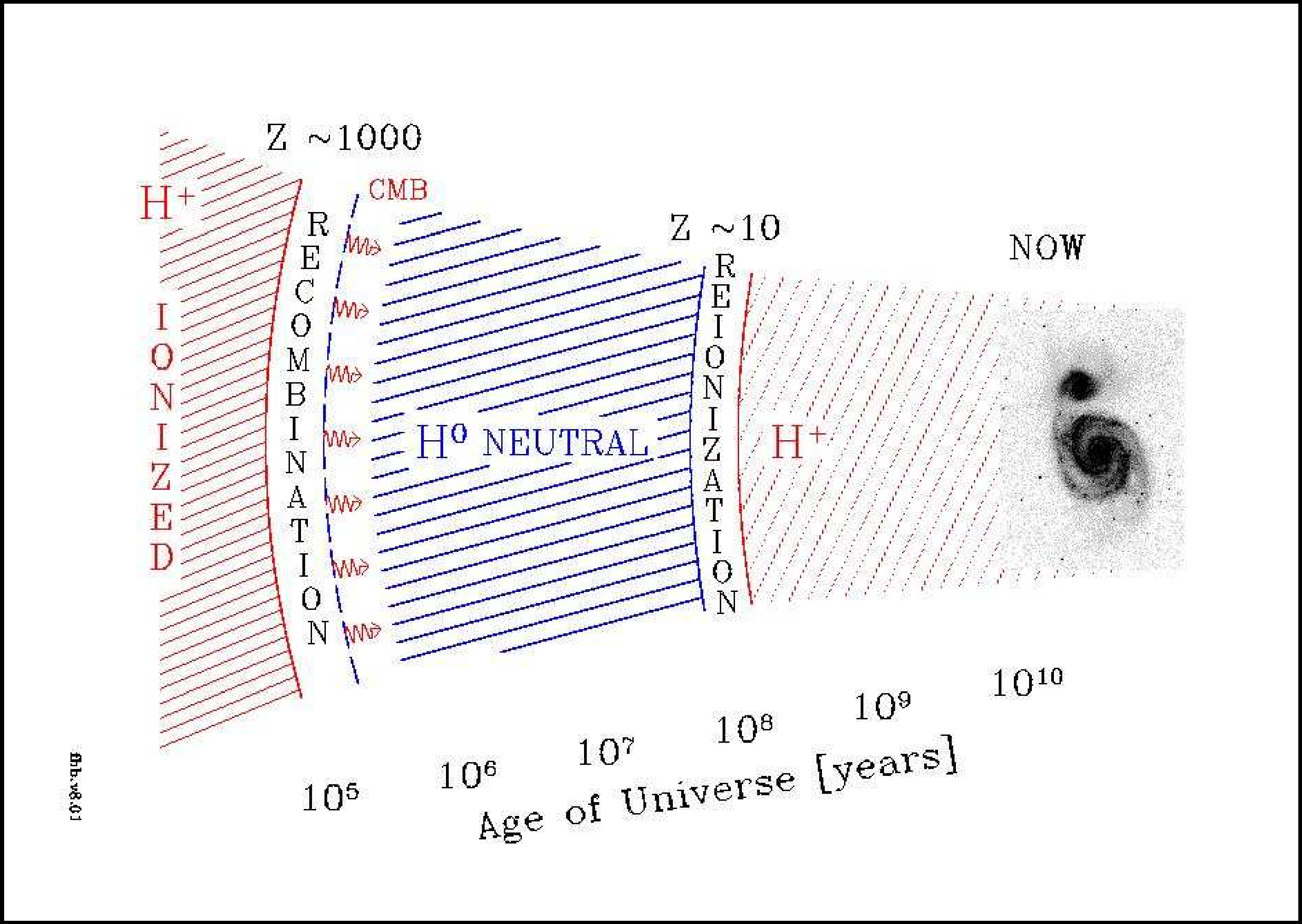
• (3) What is First Light and Reionization?



• 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?

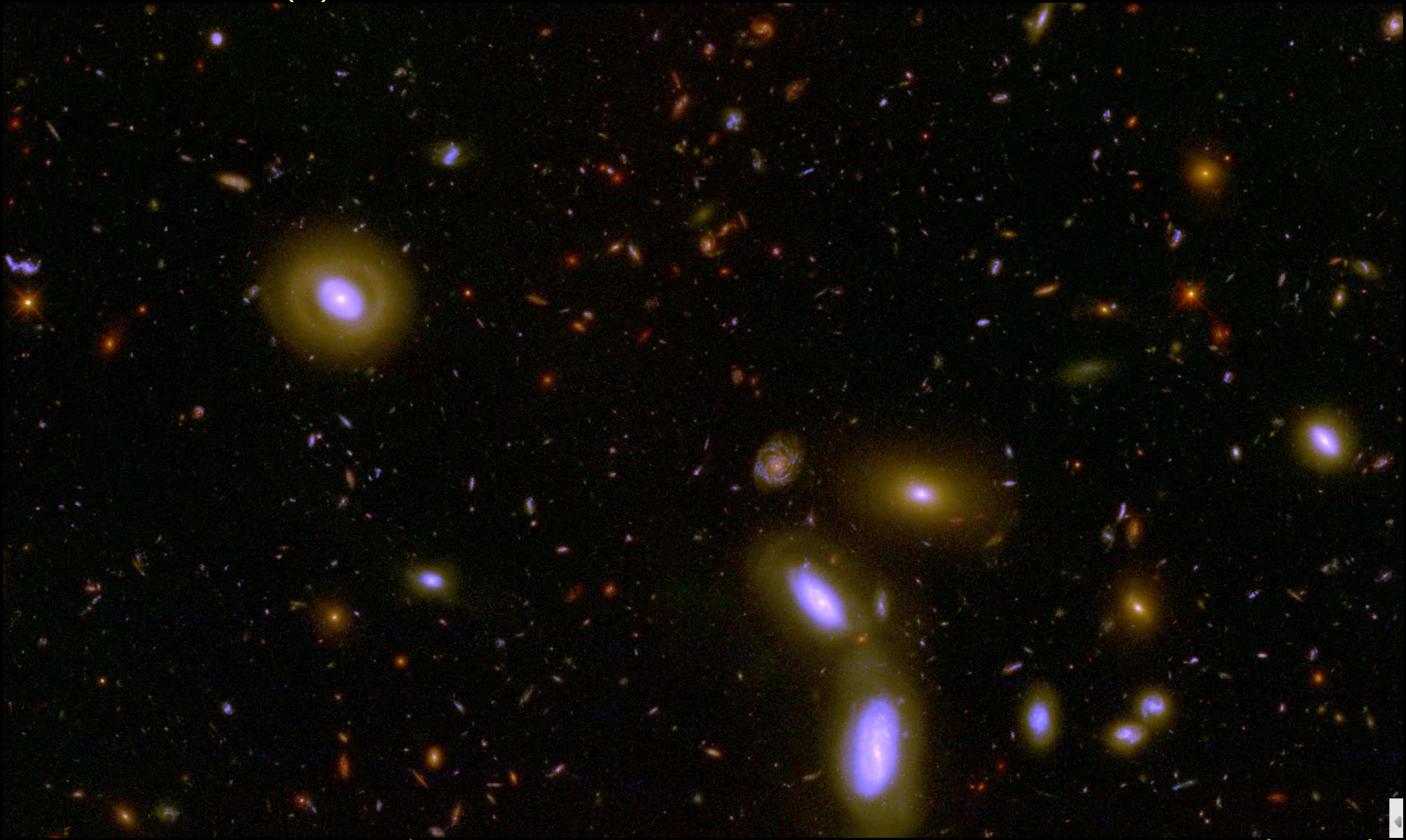


WMAP: First light may have happened as follows (Cen 2003; Spergel 2006):

- (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.

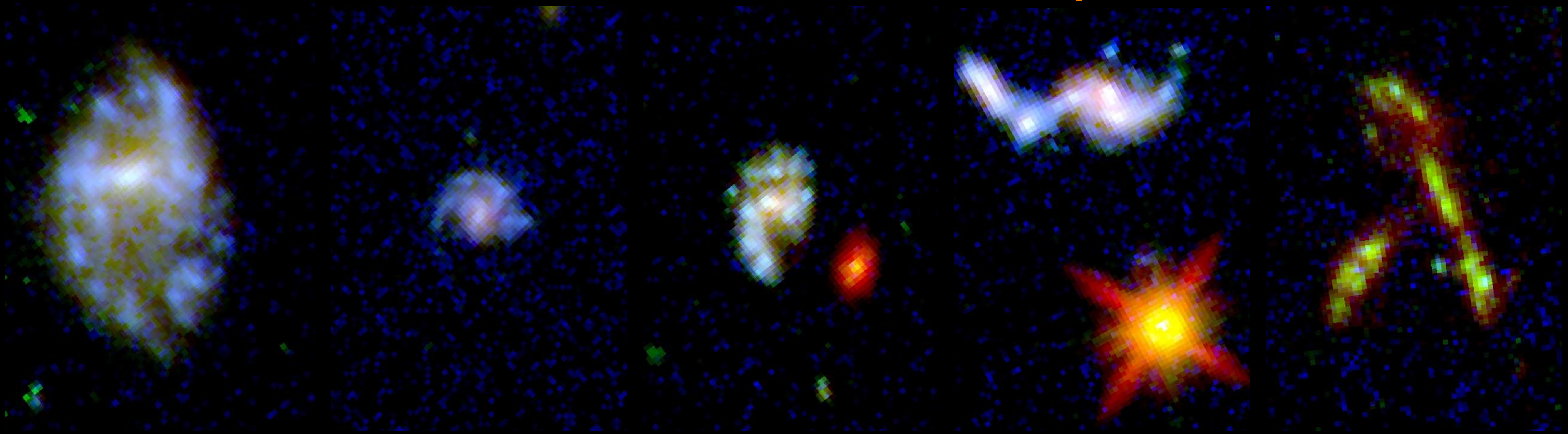
• (4) How can JWST measure Galaxy Assembly?



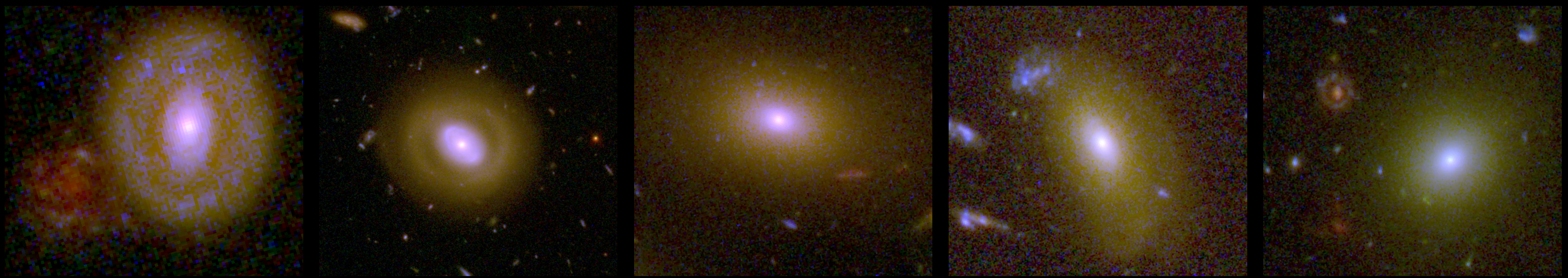
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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



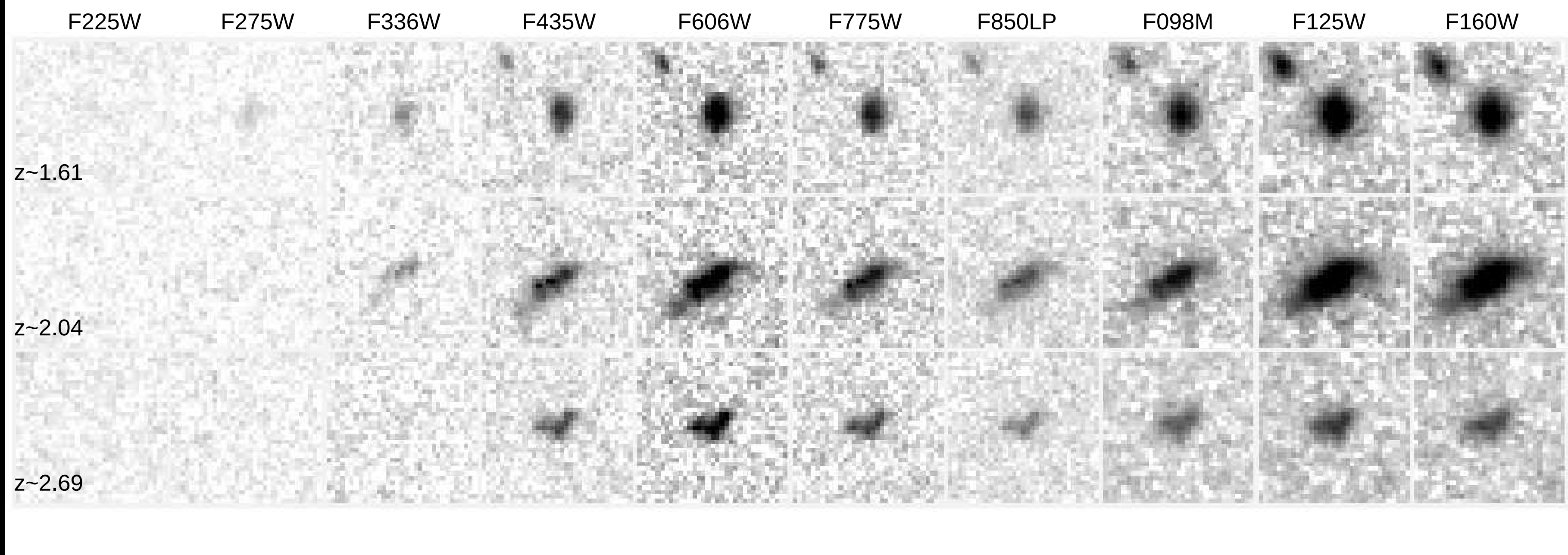
Galaxy structure at the peak of the merging epoch (z$\simeq$1–2) is very rich: some resemble the cosmological parameters H_0 , Ω, ρ_o, w, and Λ, resp.



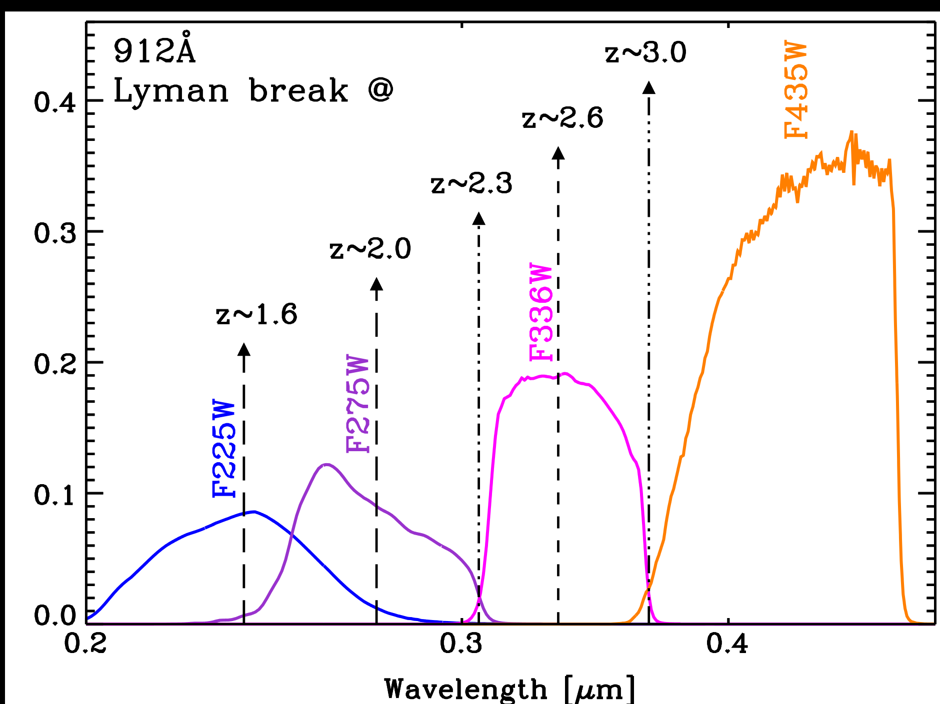
Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

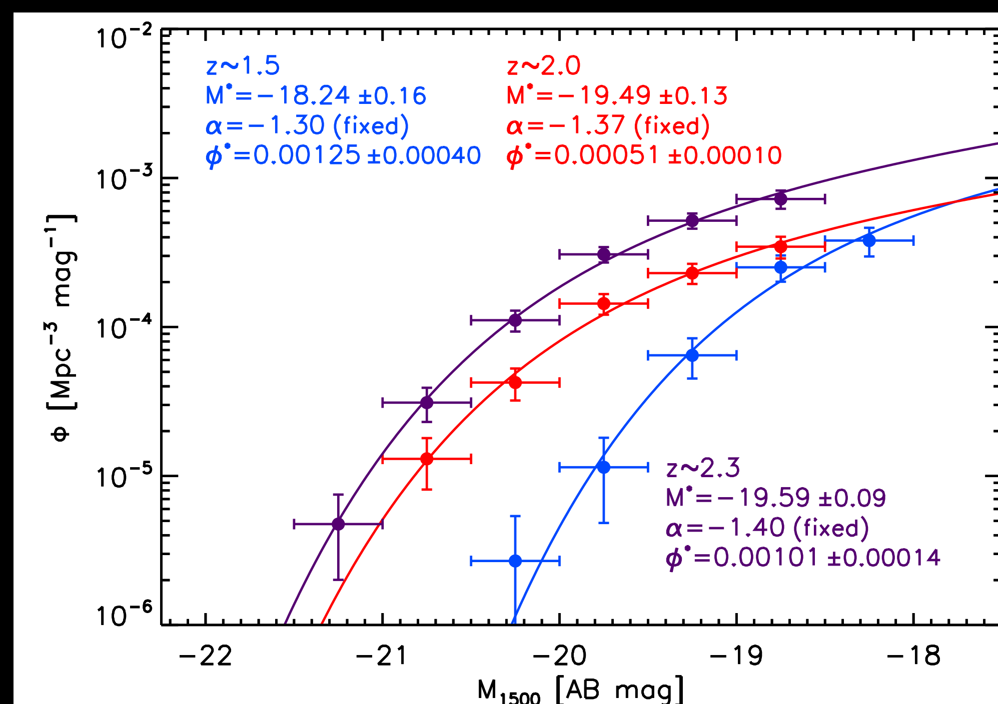
(Rutkowski et al. 2010) $\Longrightarrow$ "Red and dead" galaxies aren't dead!

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

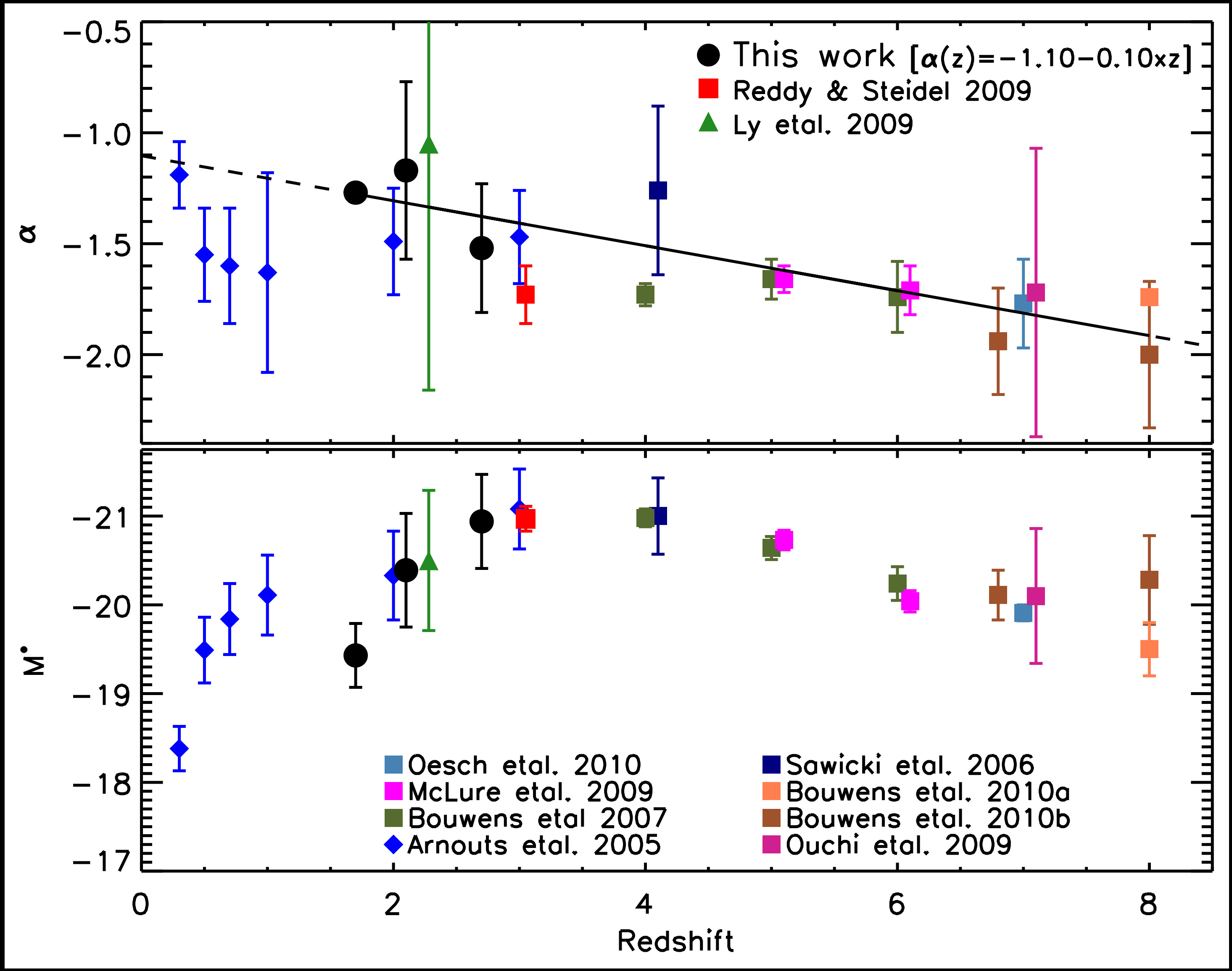


Lyman break galaxies at the peak of cosmic SF ($z\simeq1$-3; Hathi ea. 2010)



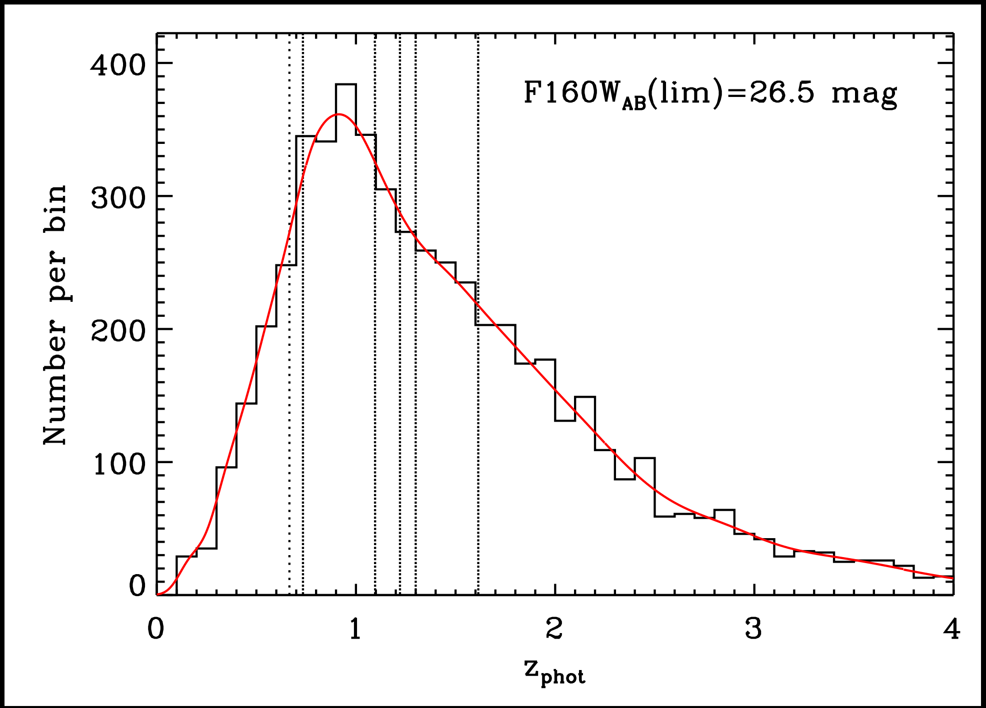


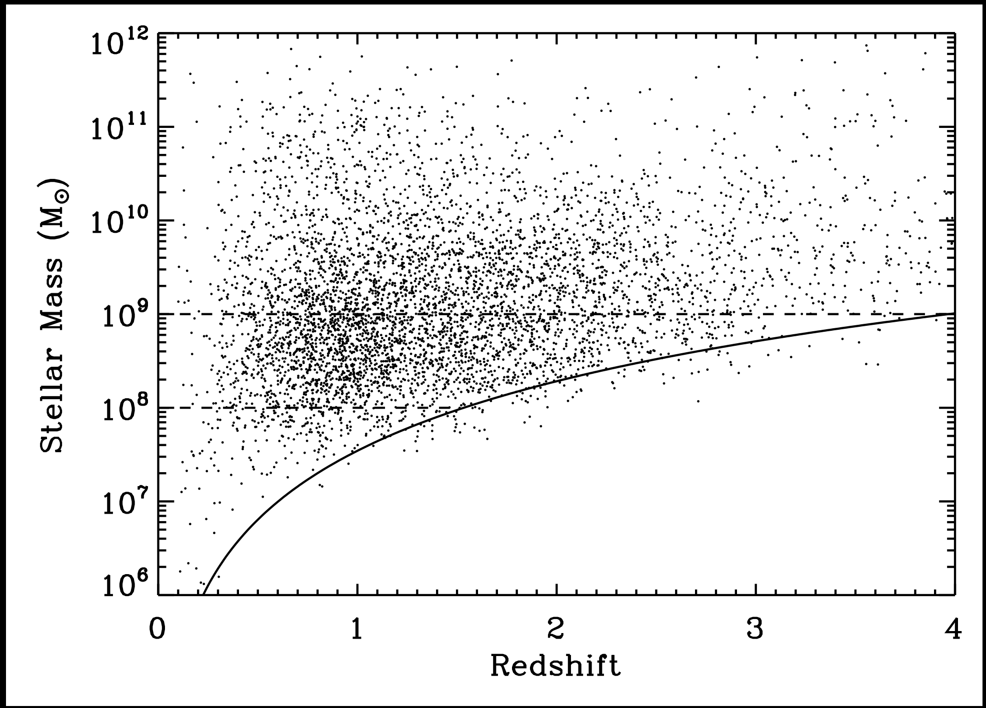
- JWST will similarly measure faint-end LF-slope evolution for $1\lesssim z\lesssim12$.



Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi et al. 2010, ApJ, 720, 1708 (arXiv:1004.5141v2).

- In the JWST regime at z$\gtrsim$8, expect faint-end LF slope $\alpha \simeq$2.0!
- In the JWST regime at z$\gtrsim$8, expect characteristic luminosity $M^* \gtrsim$–19!





WFC3 ERS 10-band redshift estimates accurate to ∼4% with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

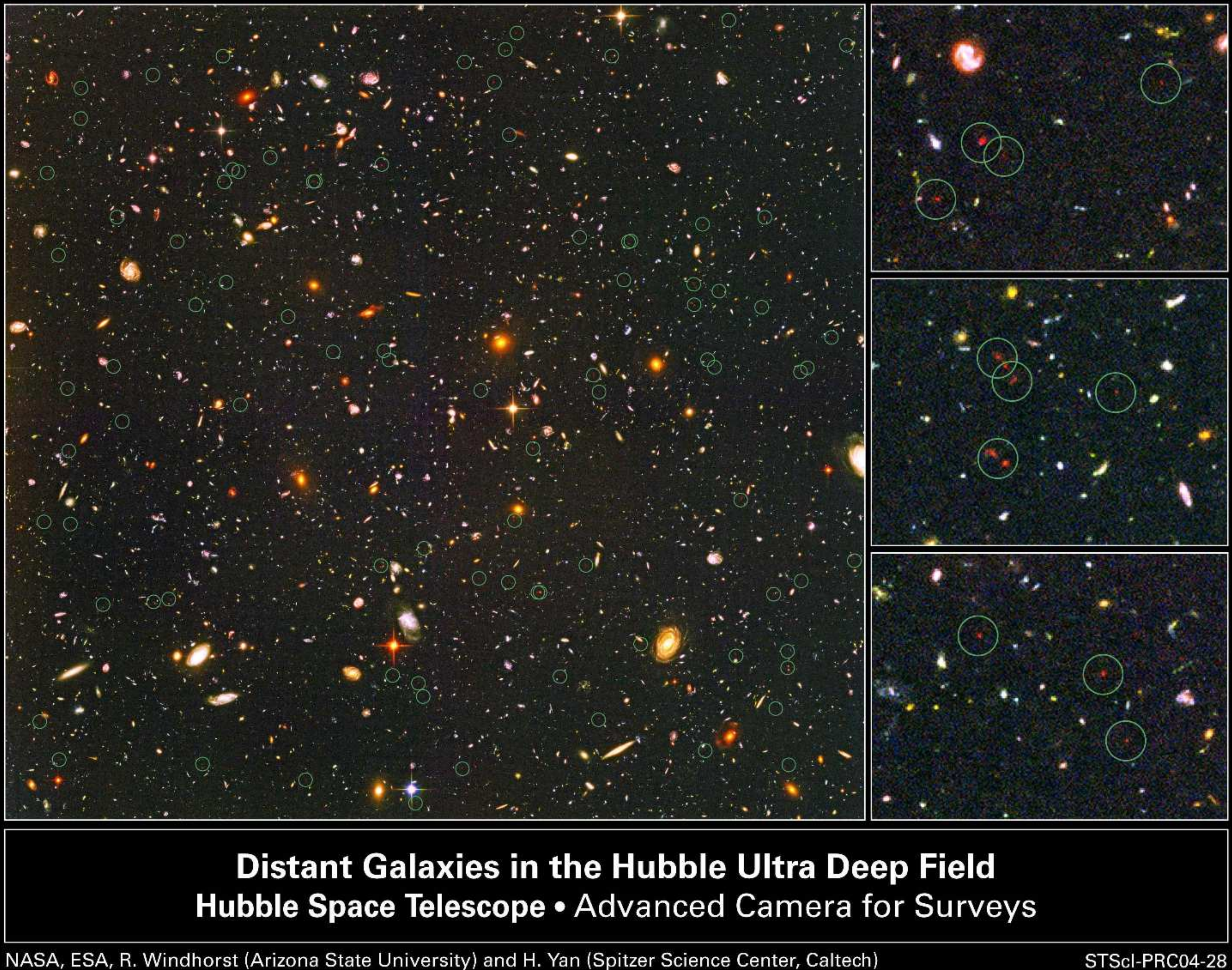
- Reliable masses of faint galaxies to AB=26.5 mag, accurately tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?)

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

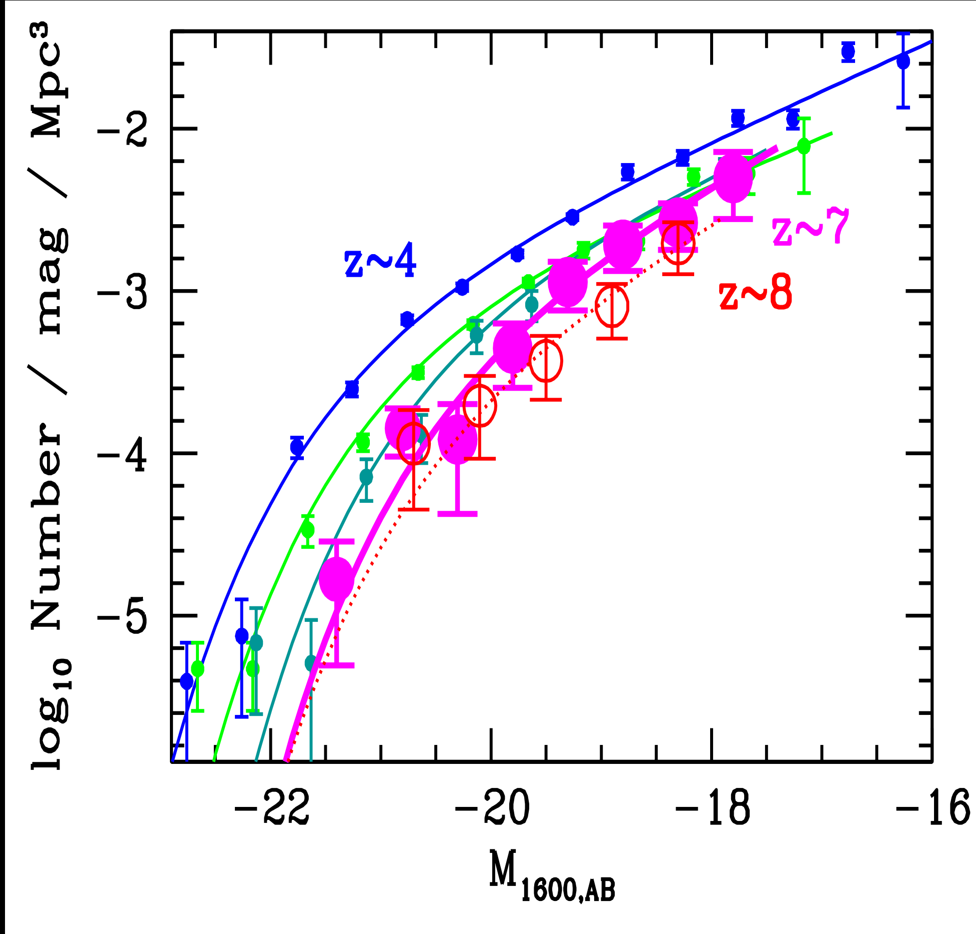
- HUDF shows WFC3 z≃7–9 capabilities (Bouwens$^+$ 2010; Yan$^+$ 2010).

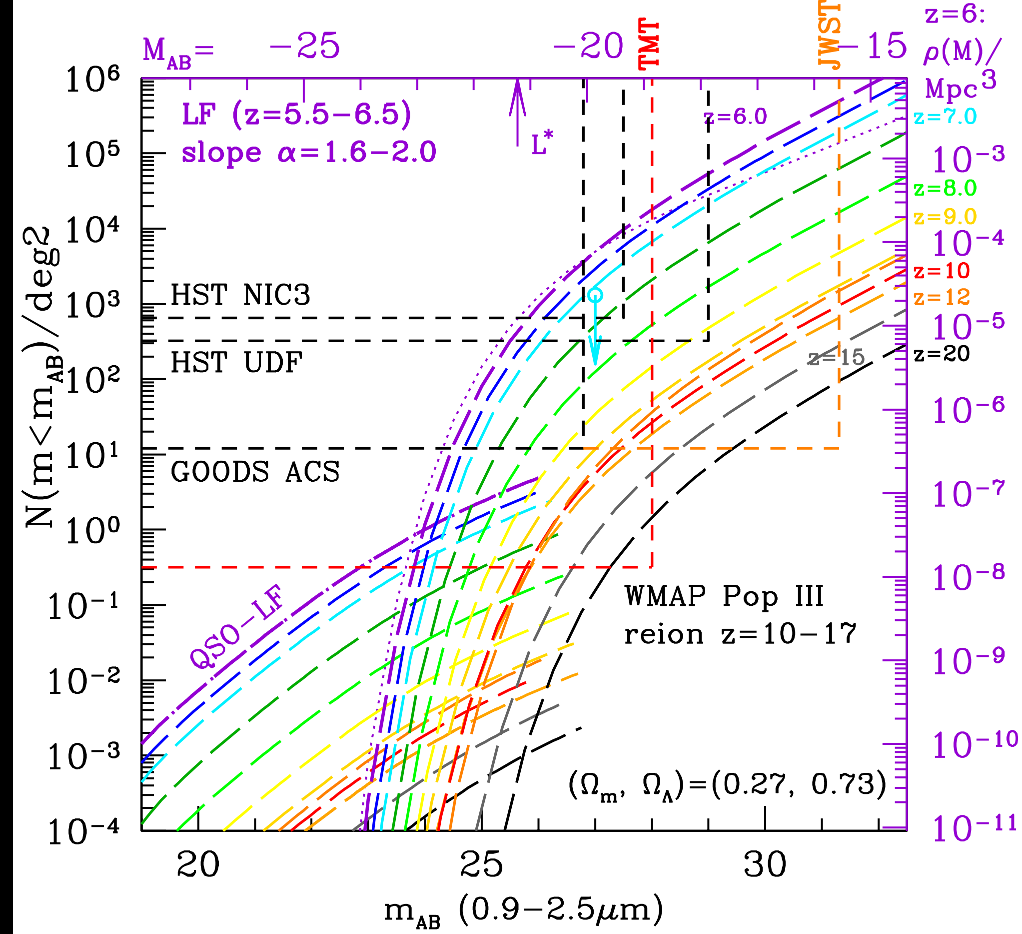
⇒ WFC3 is an essential pathfinder at z$\lesssim$8 for JWST (0.7–29 μm) at z$\gtrsim$9.

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

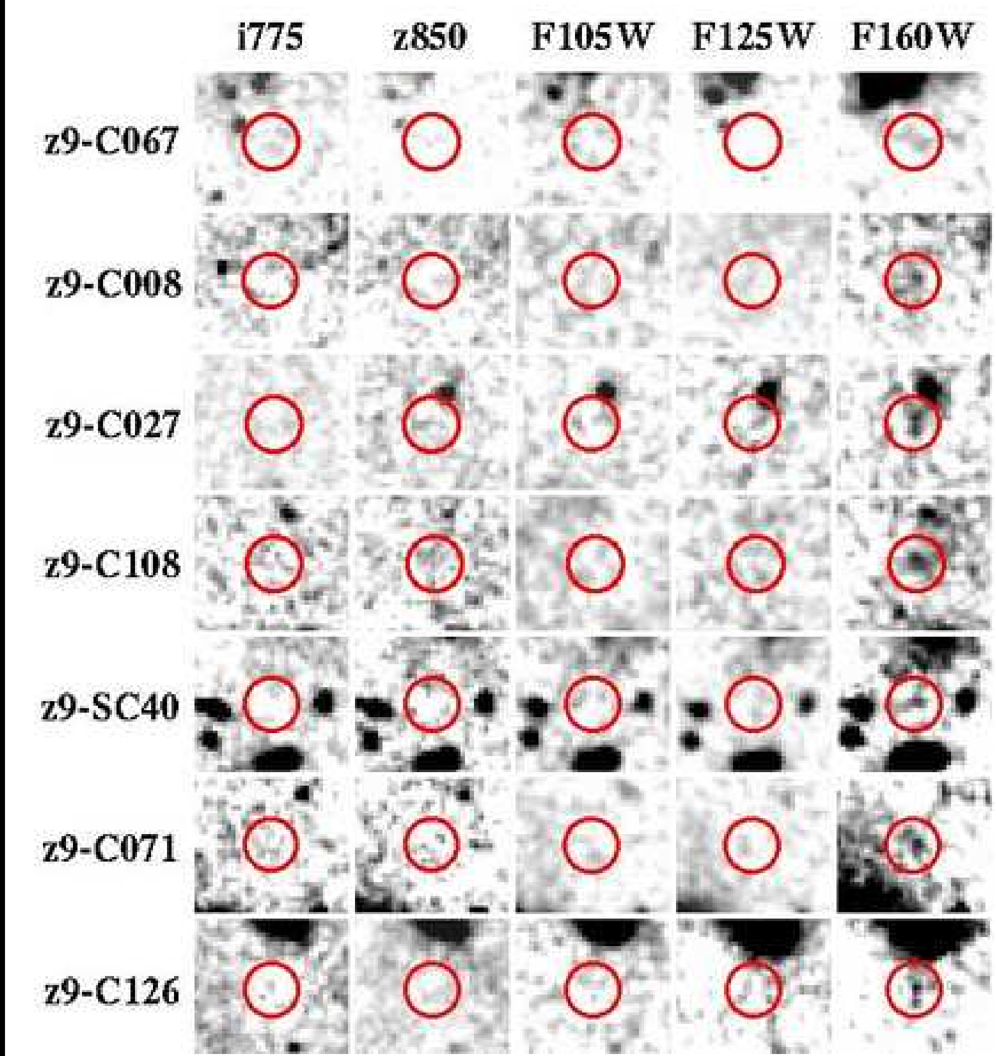


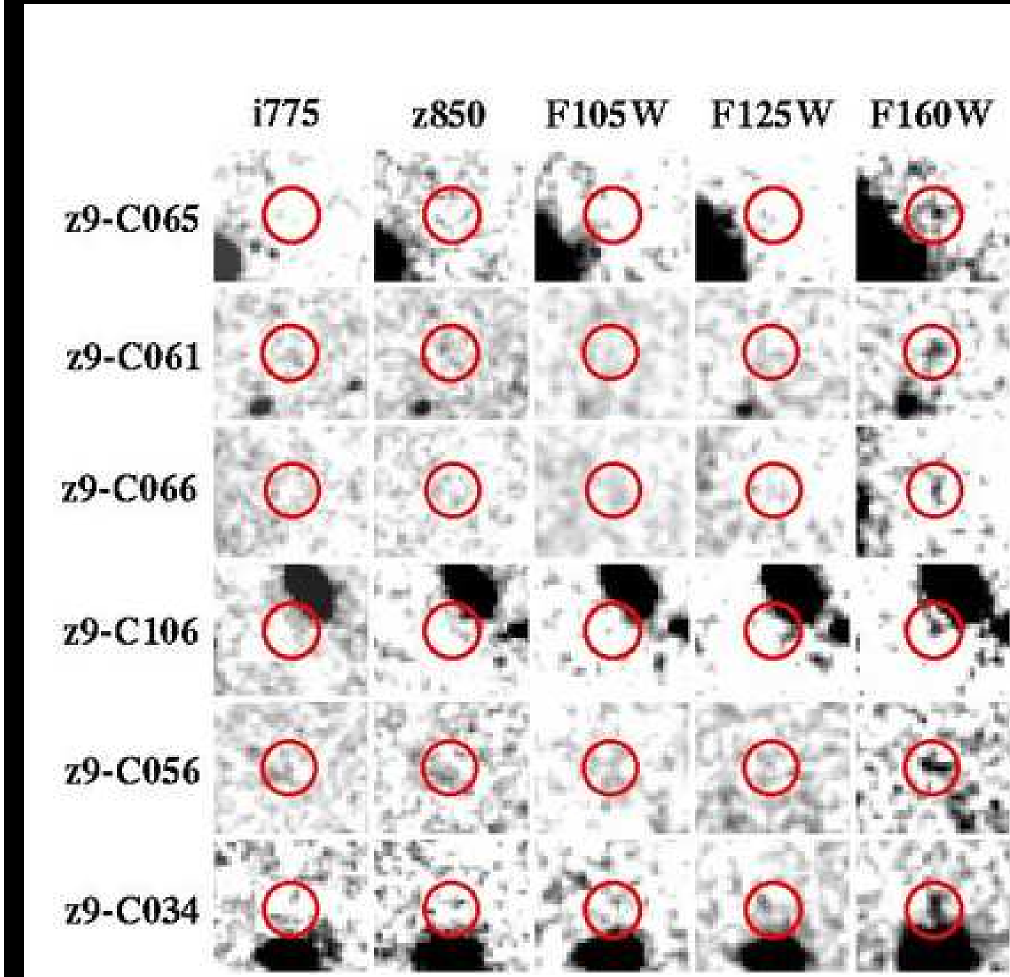
HUDF i-drops: faint galaxies at z$\simeq$6 (Yan & Windhorst 2004), most spectroscopically confirmed at z$\simeq$6 to AB$\lesssim$27.0 mag (Malhotra et al. 2005).



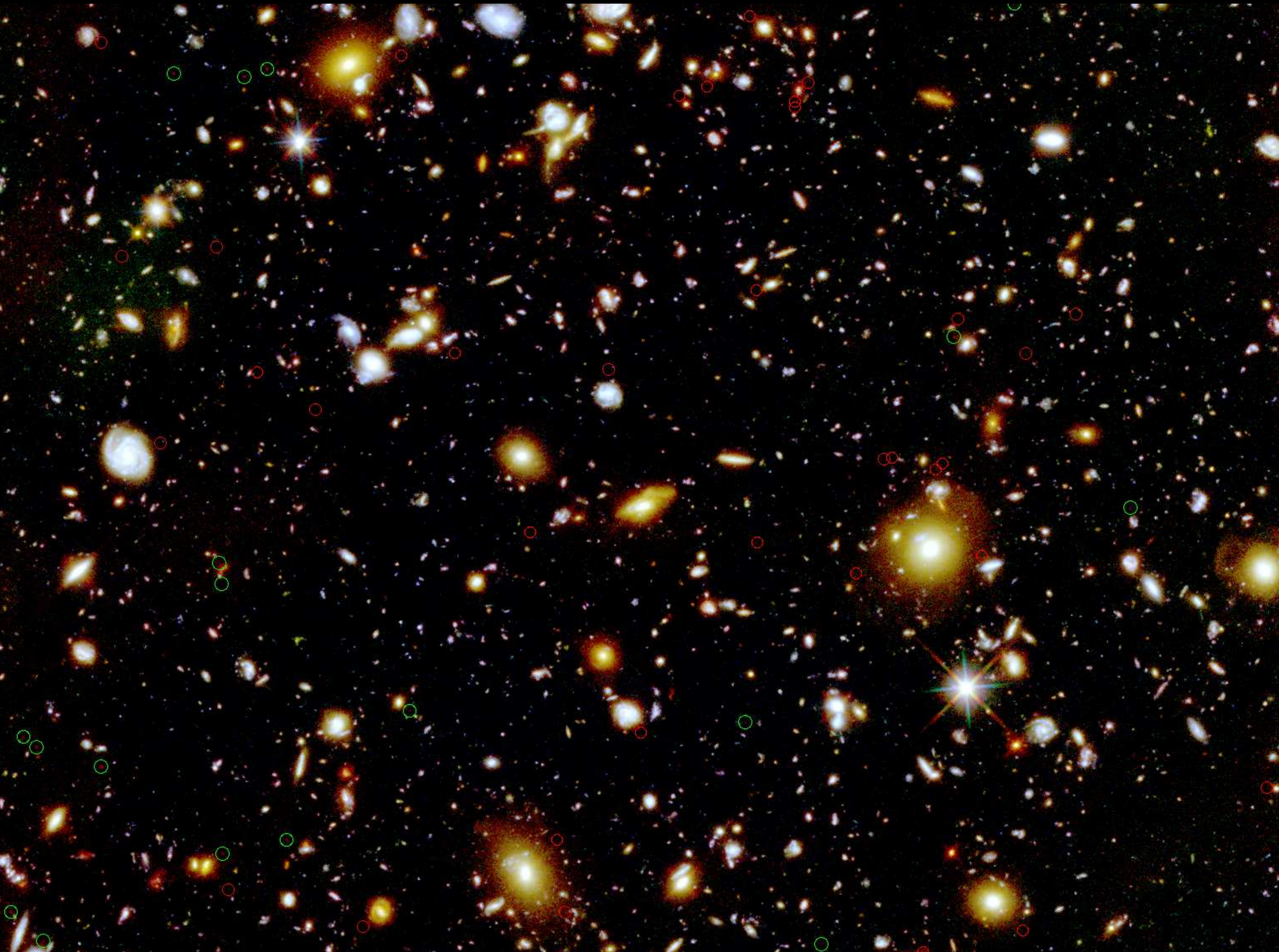


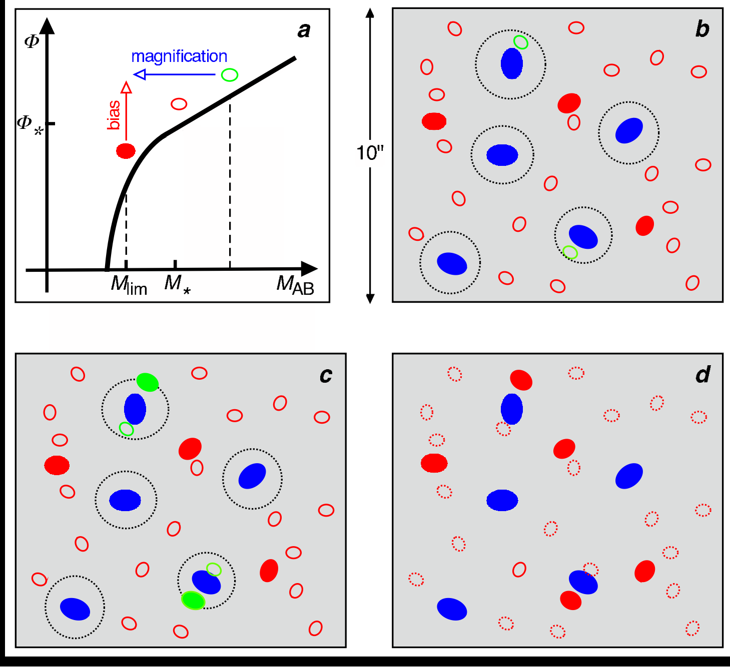
- Objects at z$\gtrsim$9 are rare (Bouwens$^+$ 2010, Yan$^+$ 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- To study co-evolution of SMBH-growth and proto-bulge assembly for z$\lesssim$10–15 requires new AGN finding techniques for JWST.

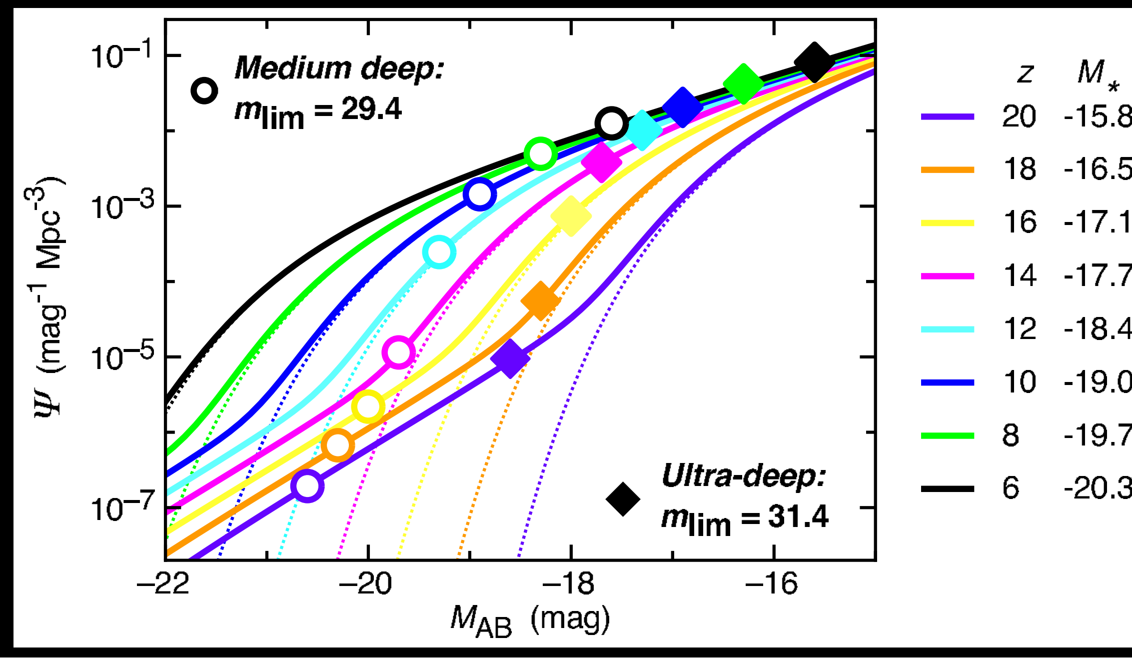


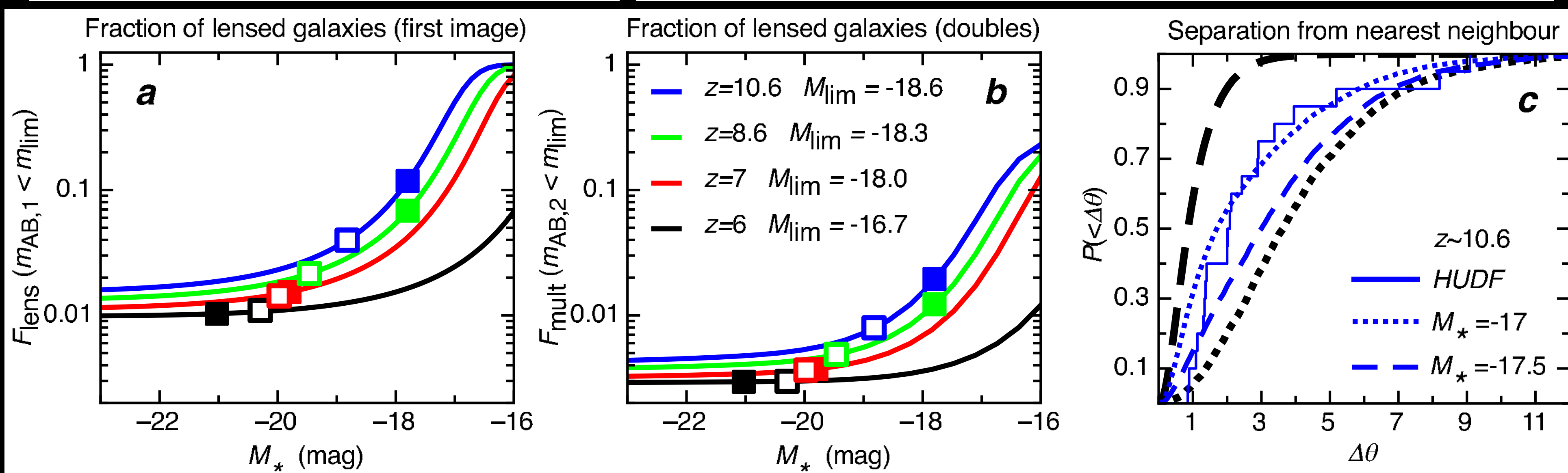


- ∼30–50% of the Y-drops and J-drops close to bright galaxies (Yan et al. 2010, Res. Astr. & Ap., 10, 867; astro.0910.0077).
- This is expected from gravitational lensing bias by galaxy dark matter halo distribution at $z \simeq 1$–2 (Wyithe et al. 2011, Nature, 469, 181.
- Need JWST to measure $z \gtrsim 9$ LF, and see if it's fundamentally different from the $z \lesssim 8$ LFs. Does a gravitational lensing bias cause power-law LF?



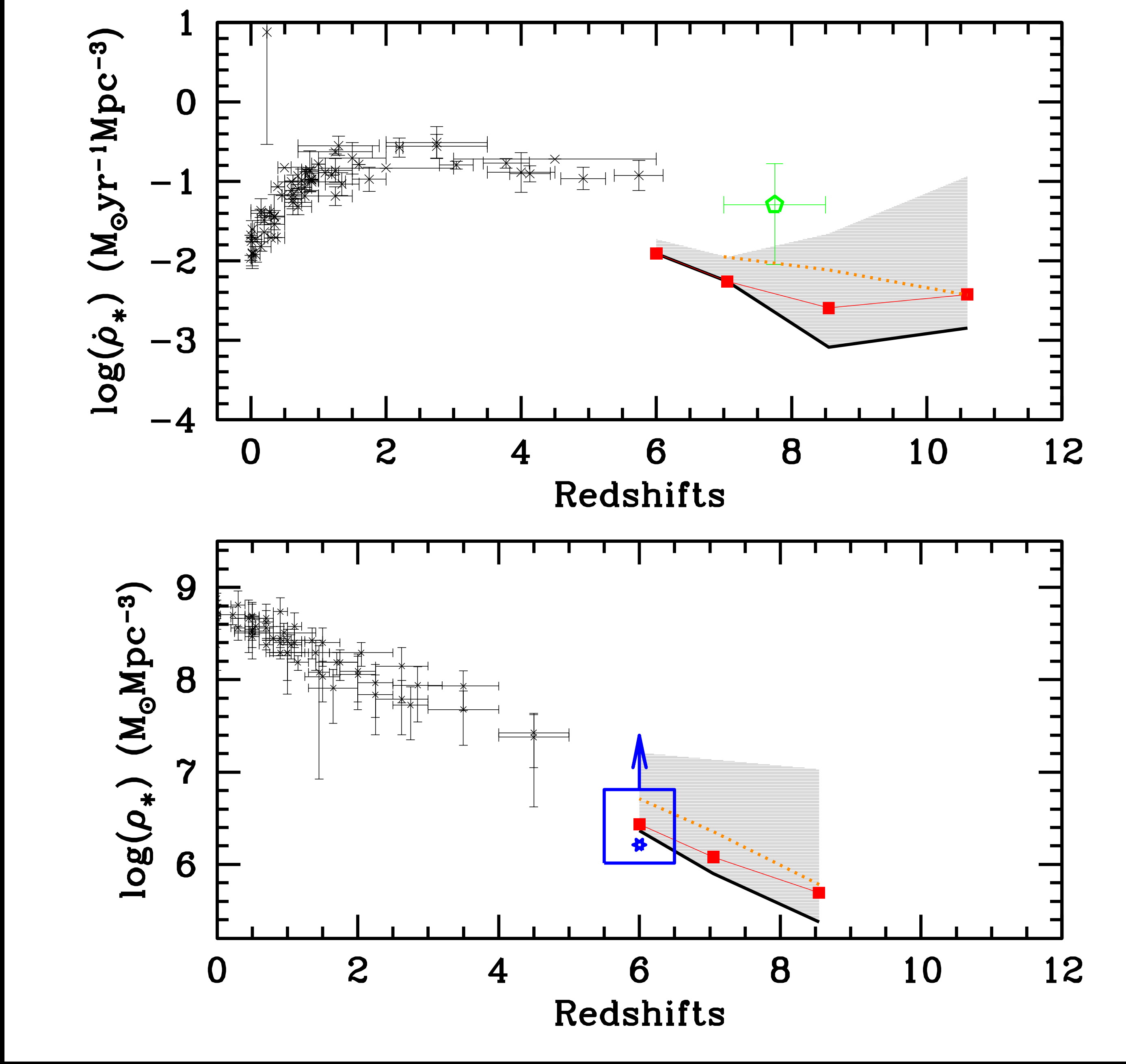






Wyithe et al. (2011, Nature, 469, 181): With a steep faint-end LF-slope $\alpha \gtrsim 2$, and a characteristic faint $M^* \gtrsim$–19 mag, foreground galaxies (at z≃1–2) may cause significant boosting by gravitational lensing at z≳8–10.

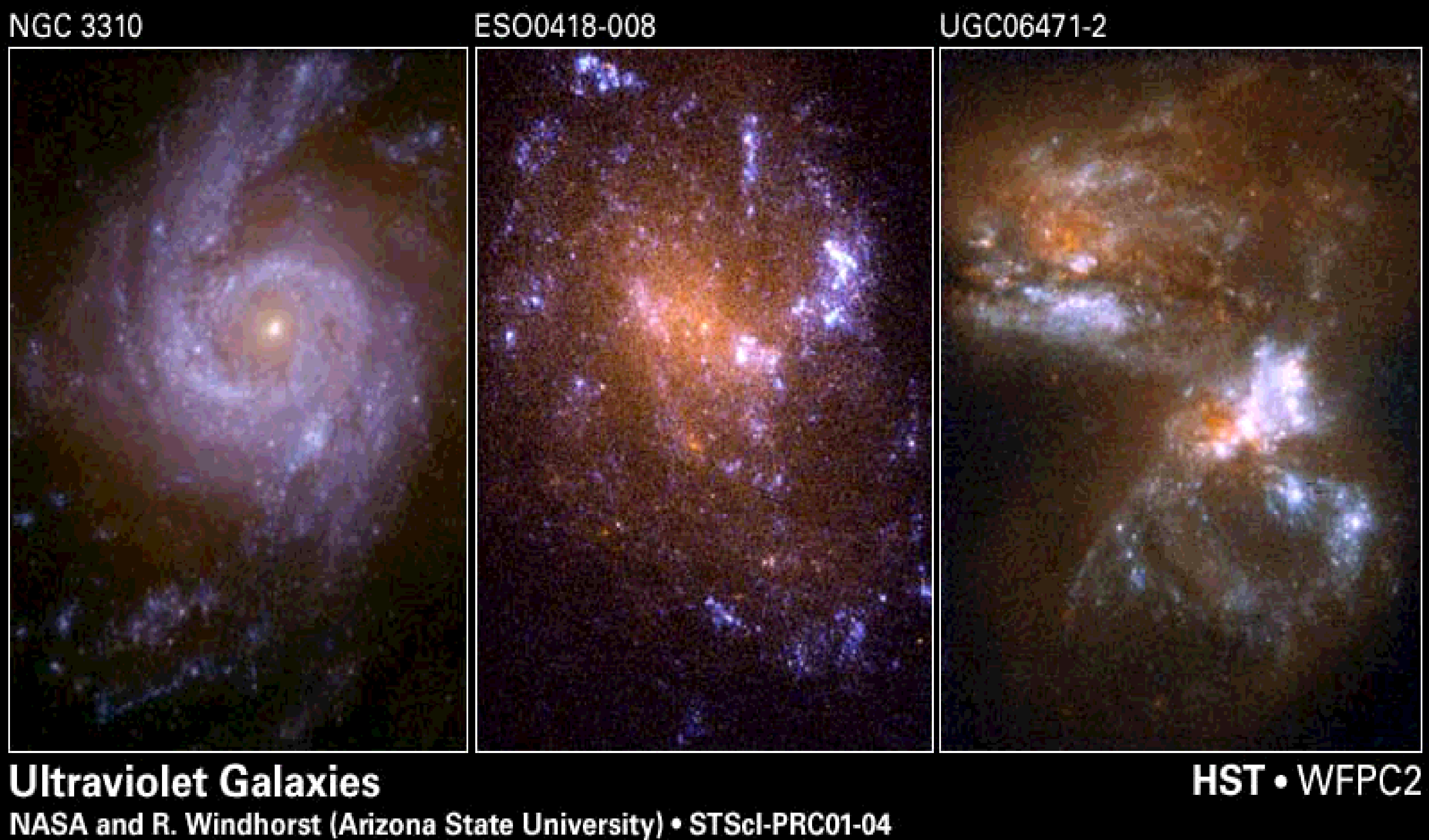
- This could change the landscape for JWST observing strategies.



The current WFC3 uncertainties on Y, J-drops large enough that at $z \gtrsim 8$, a wide range of possibilities is allowed (Yan et al. 2010, RAA, 10, 867.

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

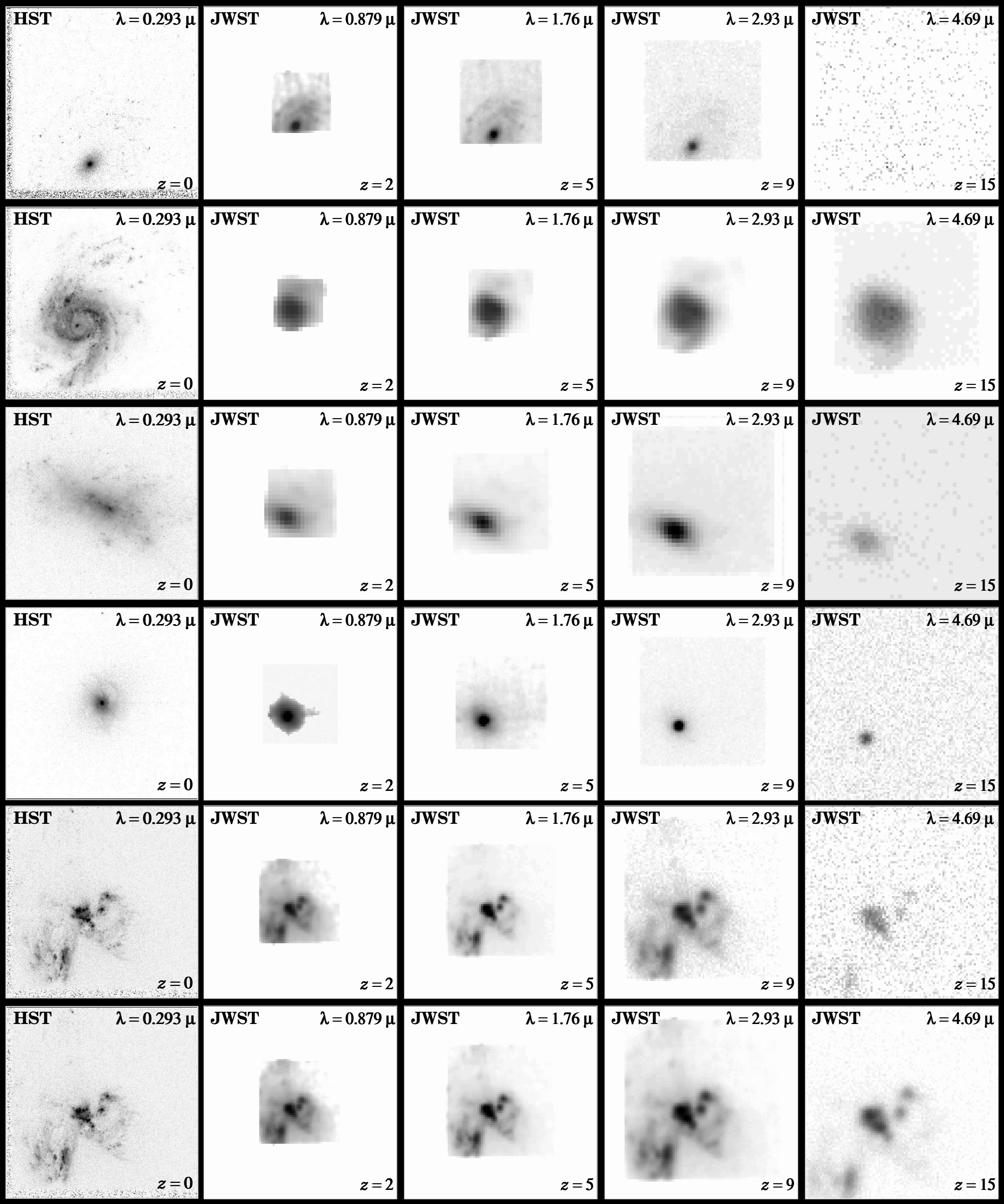
(5) Predicted Galaxy Appearance for JWST at z≃1–15



- The rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often significant dust imprinted (Mager-Taylor et al. 2005).
- 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≲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 2010. Replan in 2011.
- More than half of JWST H/W built, & meets/exceeds specs as of 02/11.

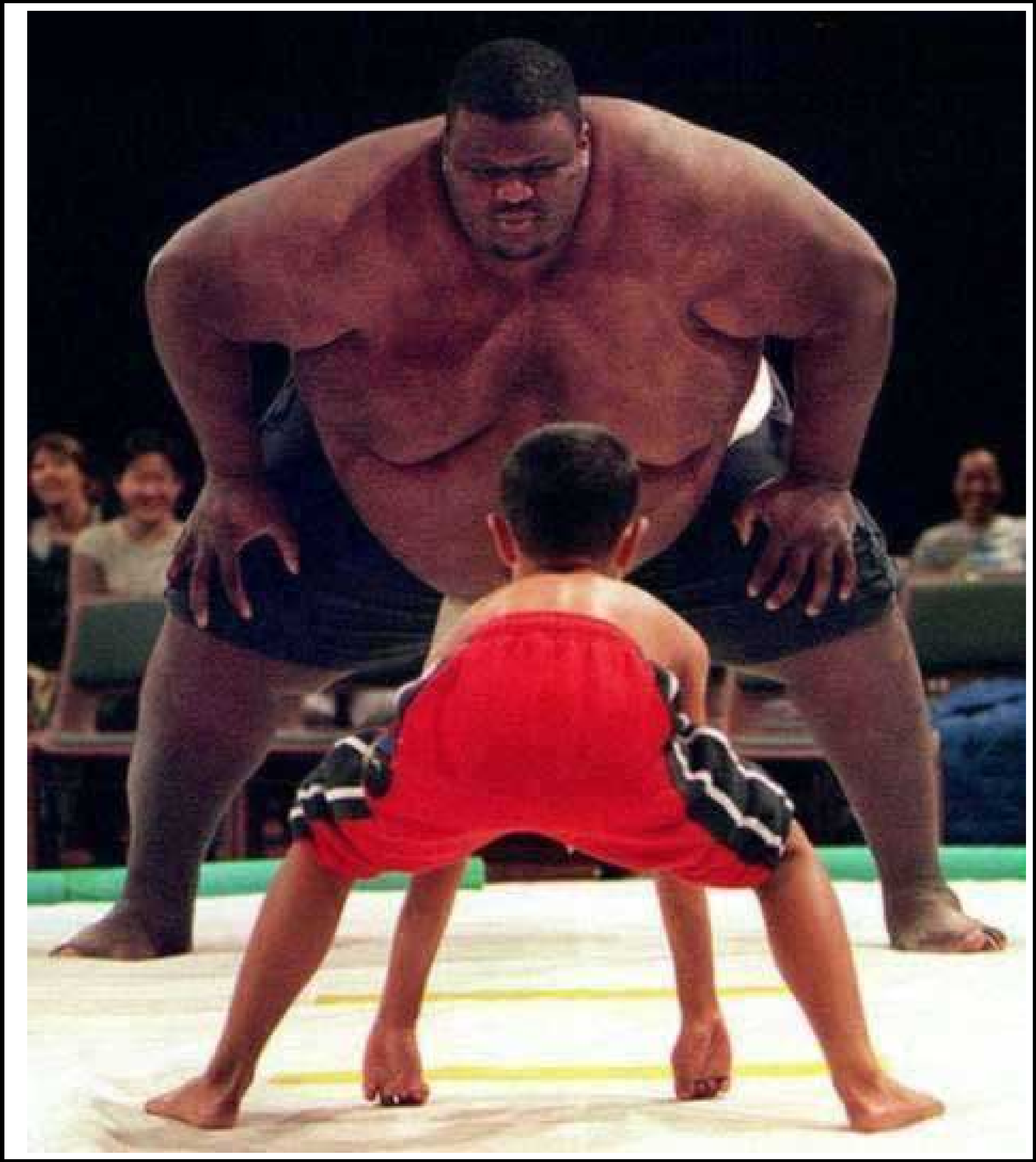
(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail. JWST will determine:

- 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.

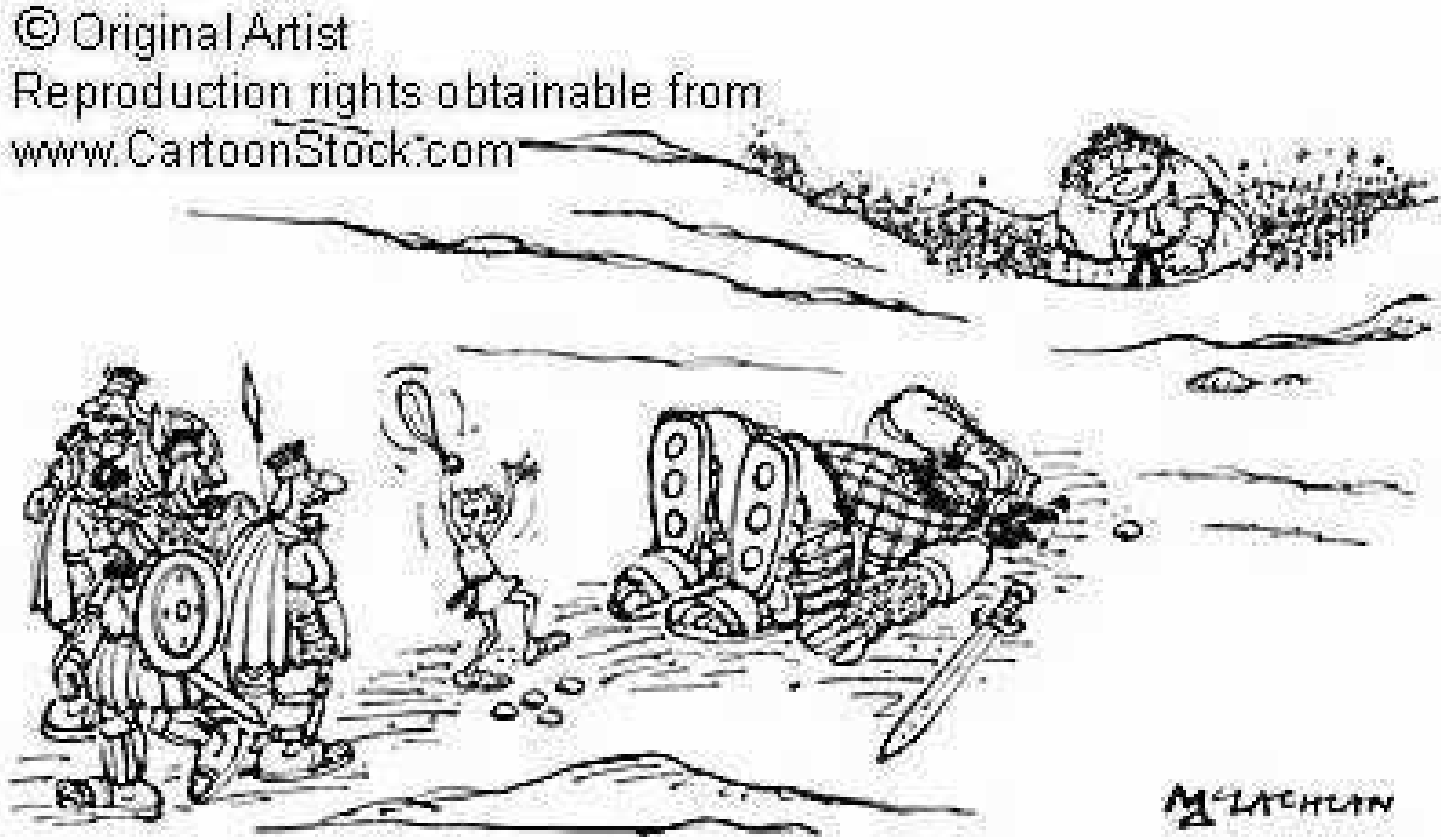
(3) JWST will have a major impact on astrophysics after 2015:

- 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



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



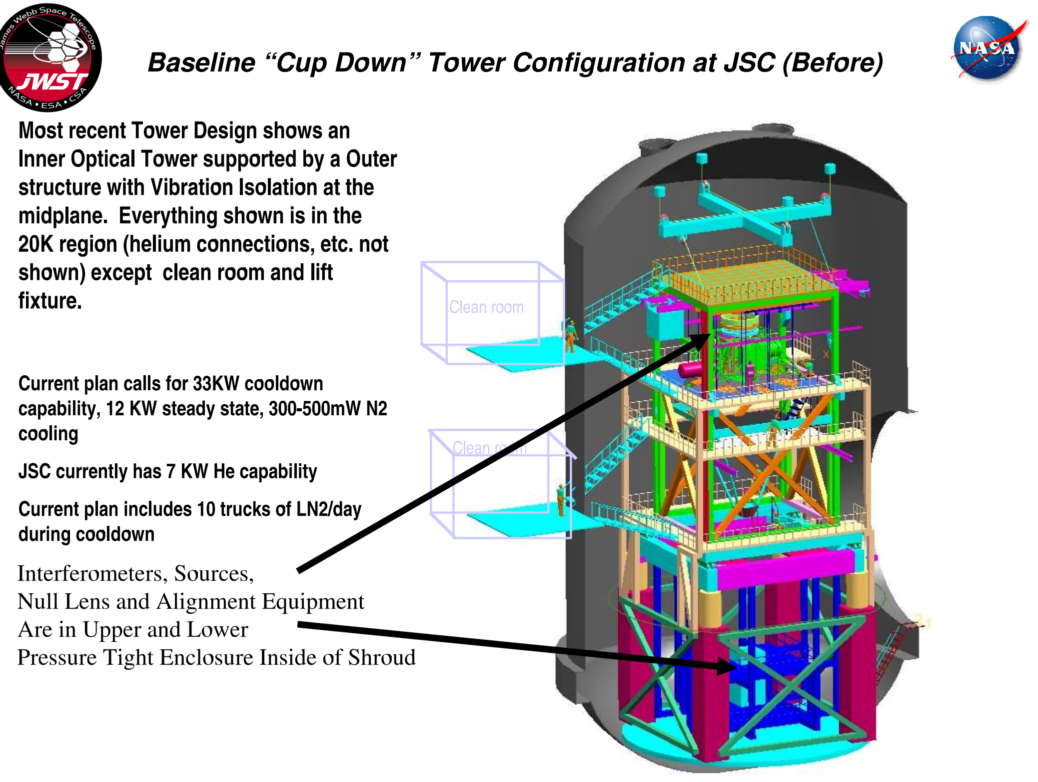
"You've done it now, David - Here comes his mother."

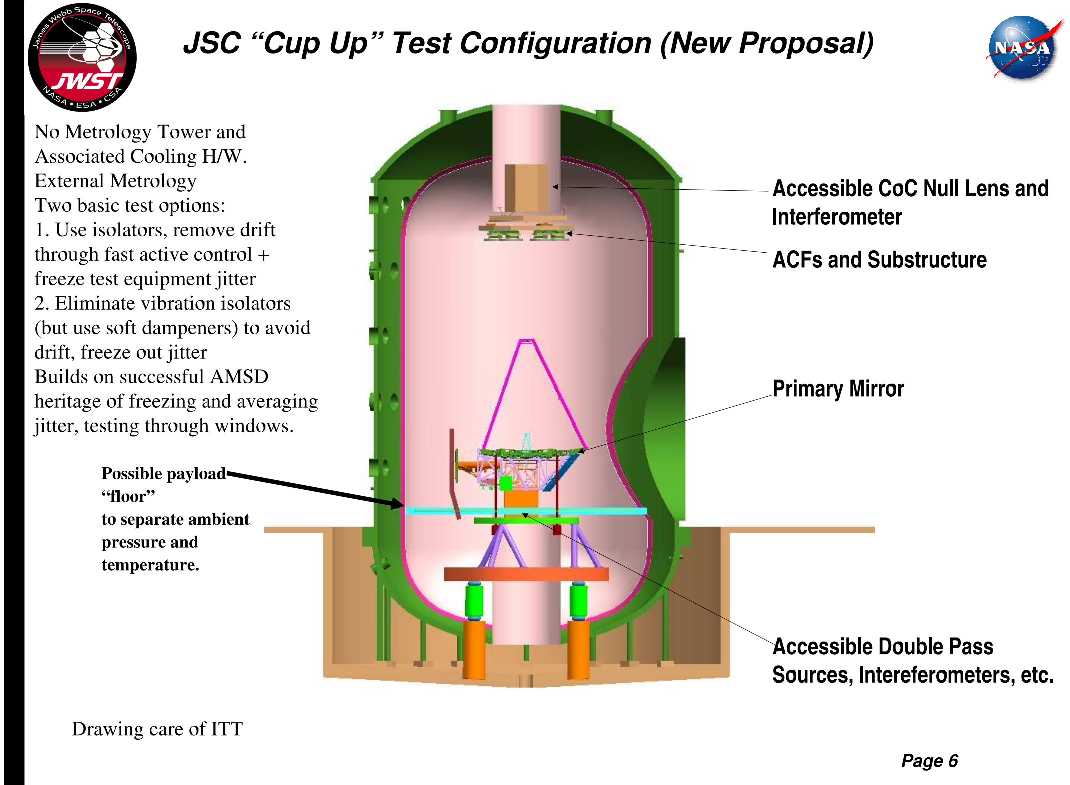
What comes around, goes around ...

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



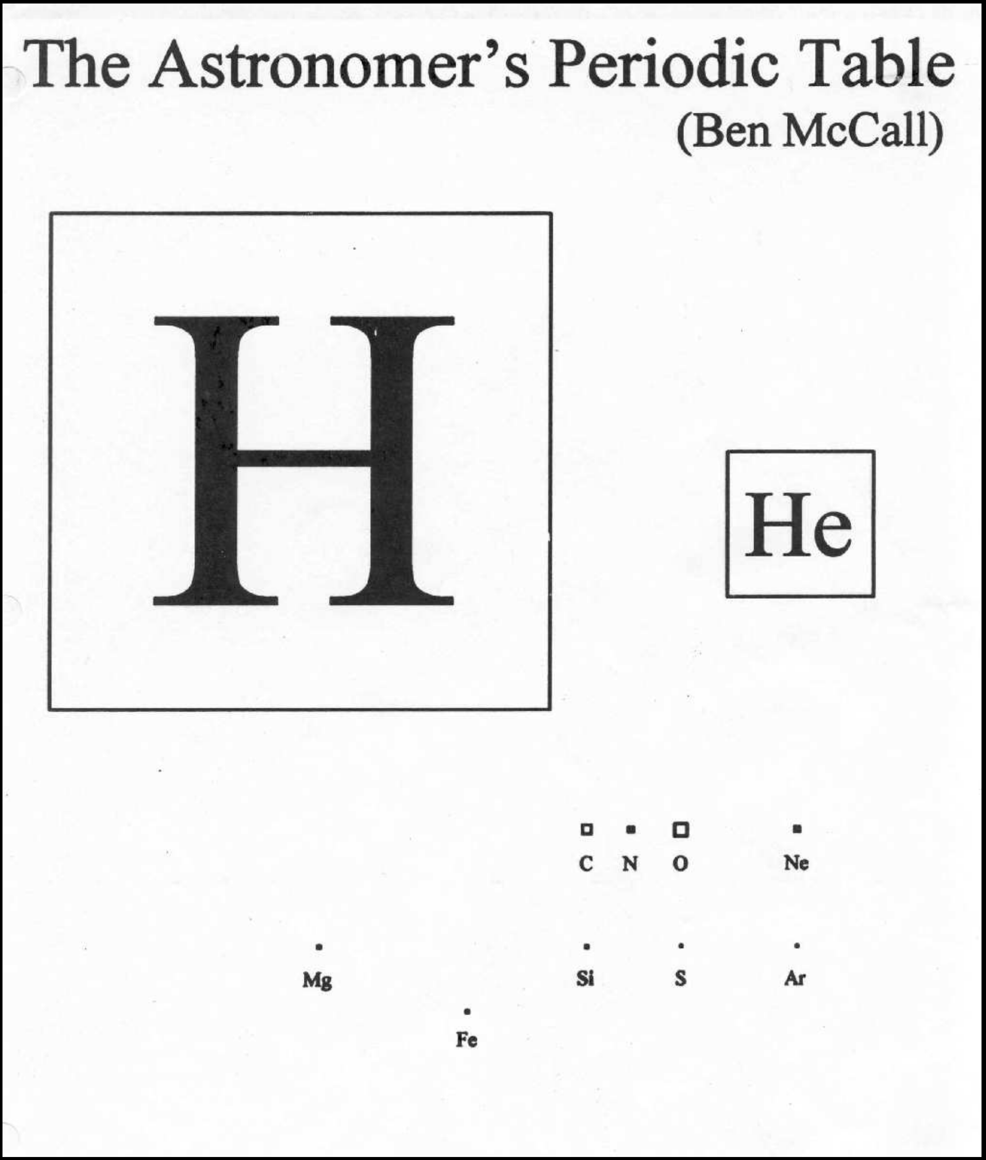




JWST underwent several significant replans and risk-reduction schemes:

- $\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).
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.
- 2010: Passes Mission Critical Design Review — Reviewing Testing.

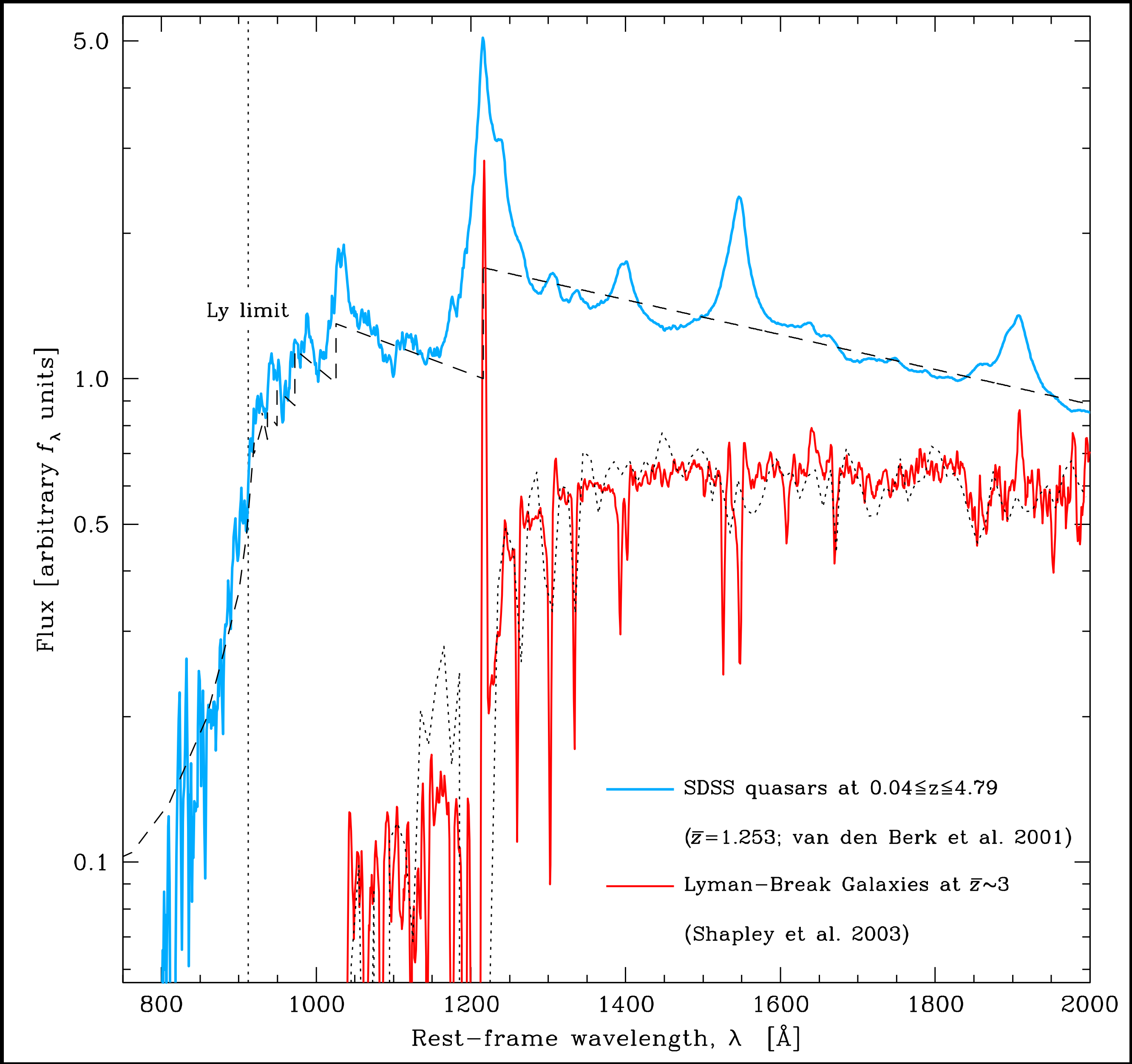
The Universe was reionized (at least) TWICE?:



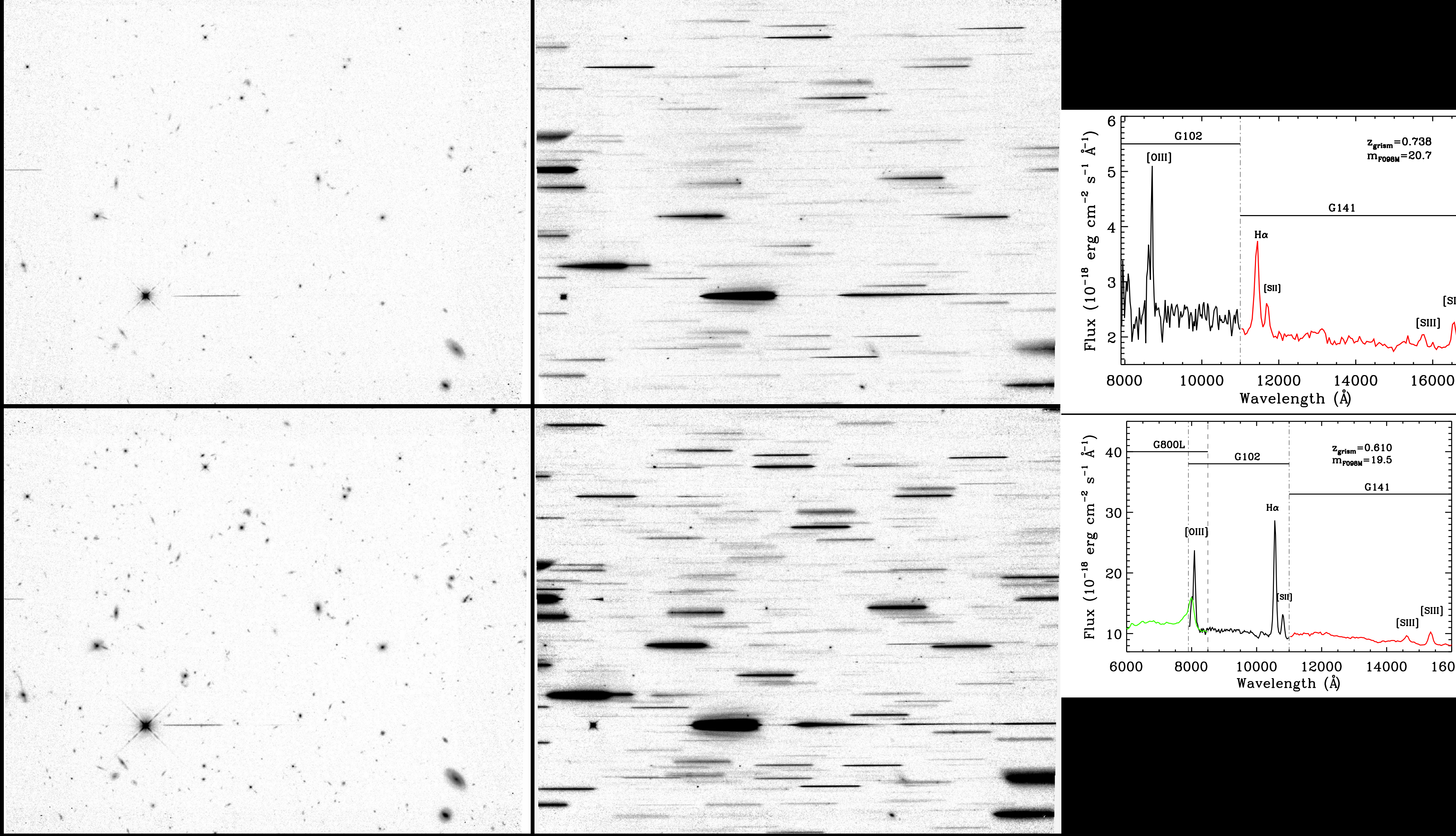
[Astronomers periodic table — with cosmic abundances included:]

- SF in dwarfs galaxies likely caused H-reionization at z$\simeq$12 $\longrightarrow$ z$\simeq$7.
- Hard-UV of QSO's and weak AGN likely caused He-reionization z$\simeq$3.

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.

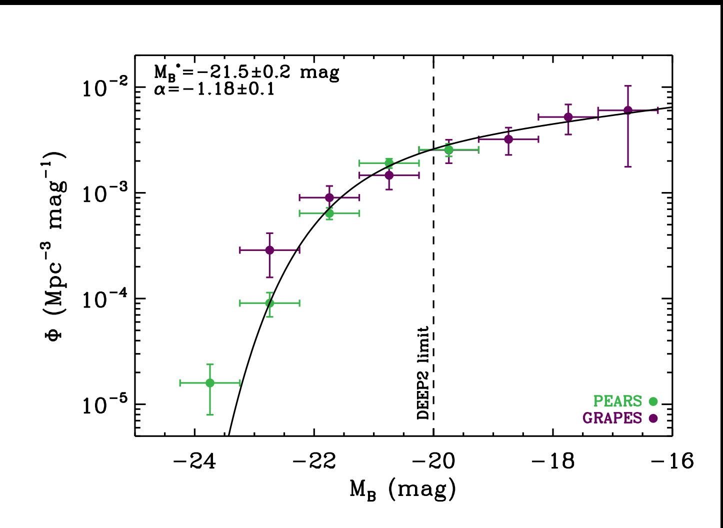


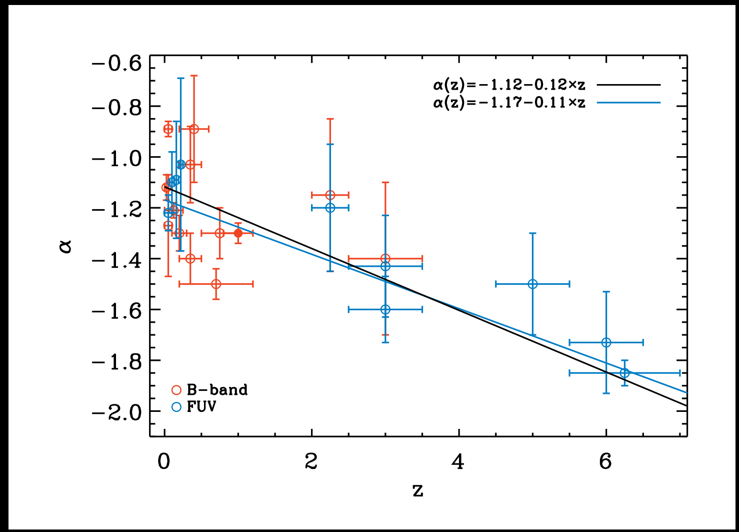
HST/WFC3 G102 & G141 grism spectra in GOODS-S ERS (Straughn+ 2010)

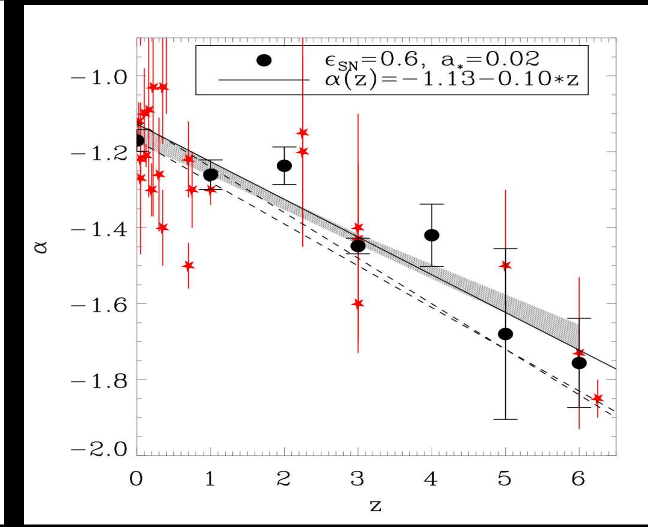
IR grism spectra from space: unprecedented new opportunities in astrophysics.

- JWST will provide near-IR grism spectra to AB$\lesssim$29 mag from 2–5.0 μm.

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.

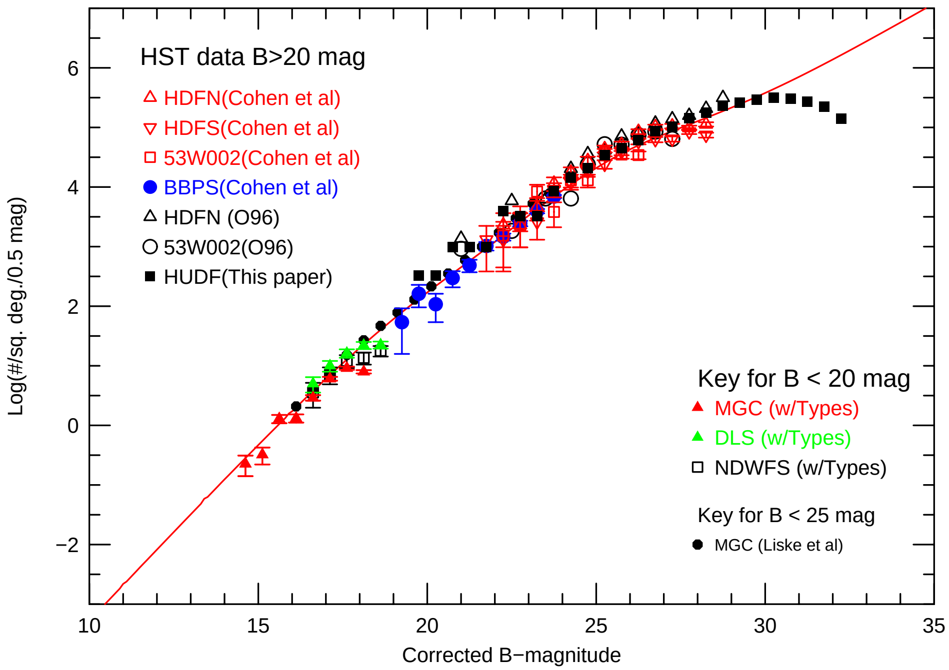
JWST is designed to observe the following re. Galaxy Assembly:

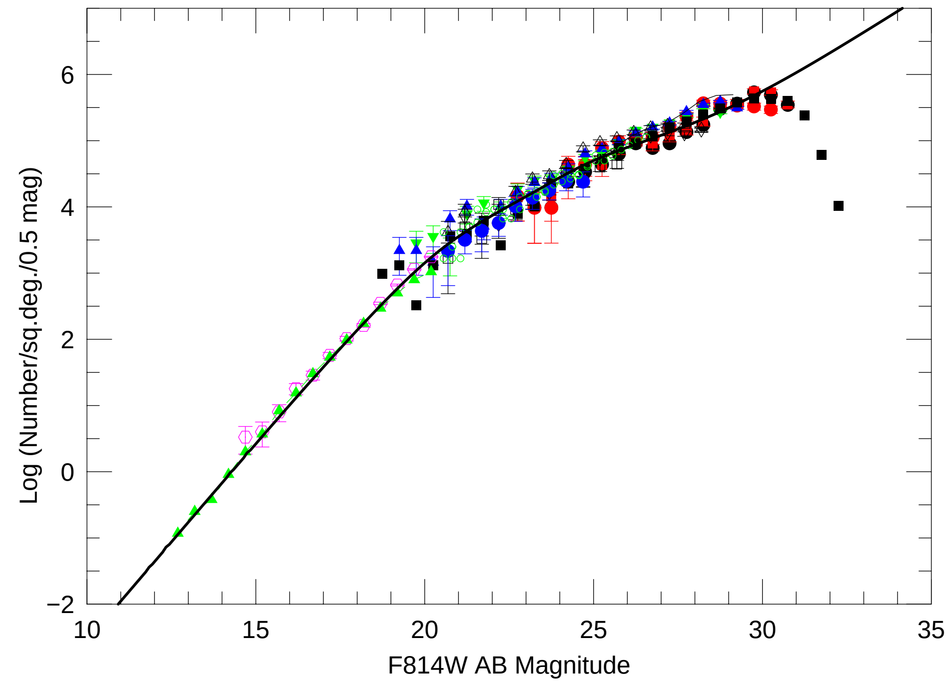
• Formation and evolution of Pop III star-clusters in the first 0.5 Gyr.

• Faint-end LF-slope evolution: (how) did dwarf galaxies finish reionization after 0.5–1 Gyr? Was there a transition to Pop-III objects?

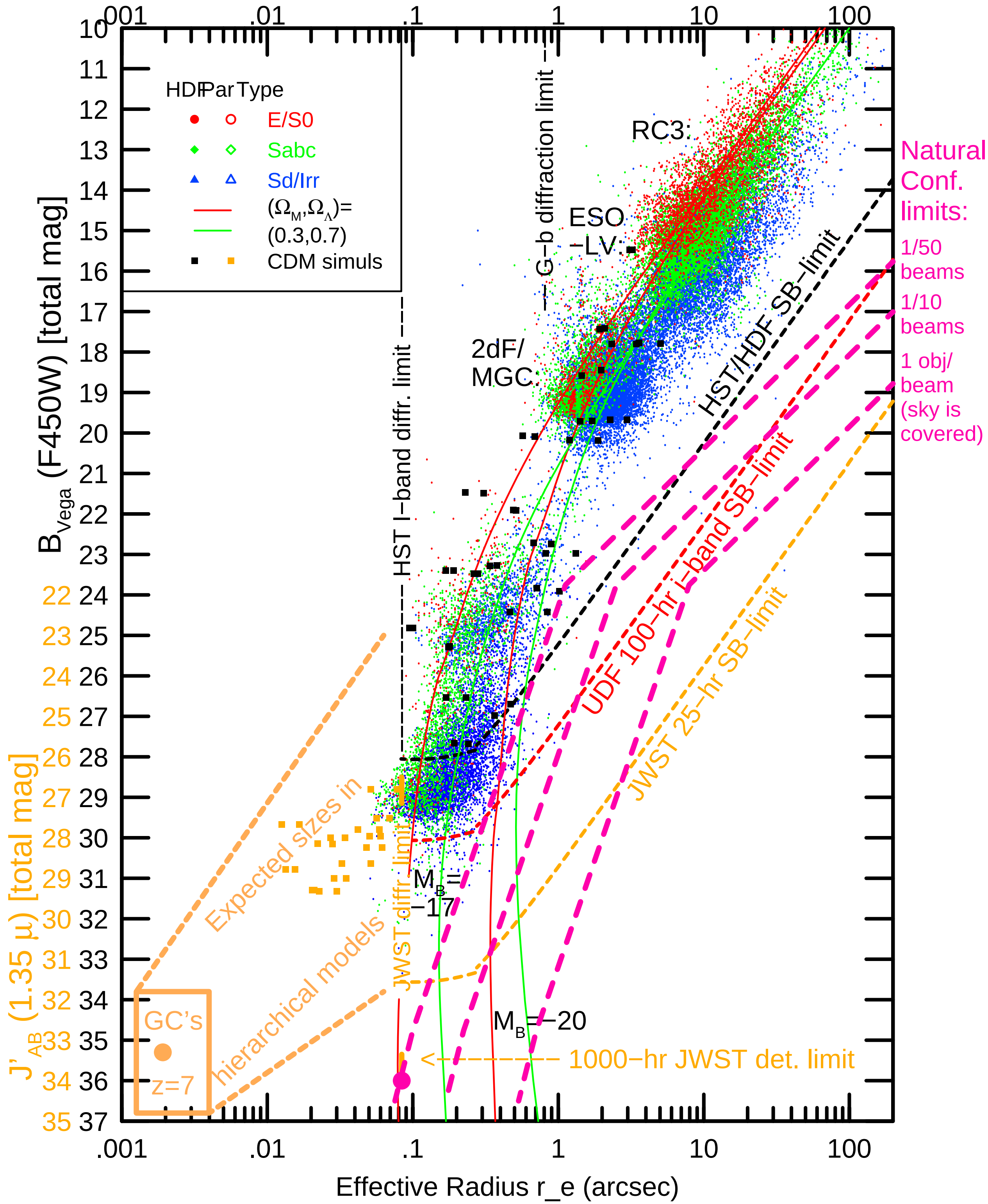
• Measure how galaxies of all types formed over a wide range of cosmic time, by accurately measuring their SF, mass, Fe/H, and dust distributions, rest-frame structure and type, etc., as function of redshift for $z{\lesssim}15$.

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

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

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

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

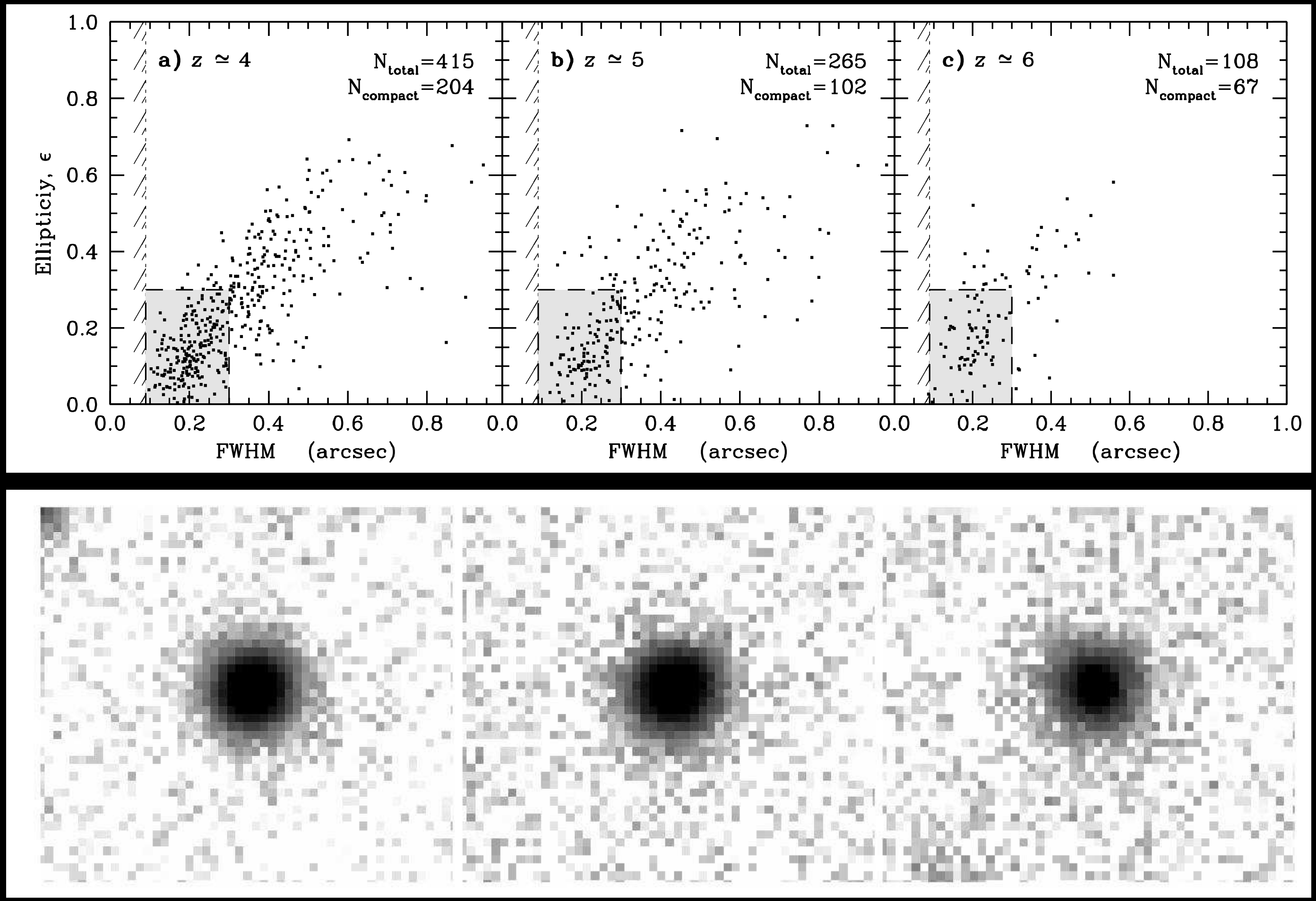
- (2a) hierarchical formation causes size evolution: $r_{hl}(z) \propto r_{hl}(0)\ (1+z)^{-1}$

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

- (3) At AB$\gtrsim$30 mag, JWST and at $\gtrsim$10 nJy, SKA will see more than 2×10^6 galaxies/deg^2. Most of these will be unresolved ($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.

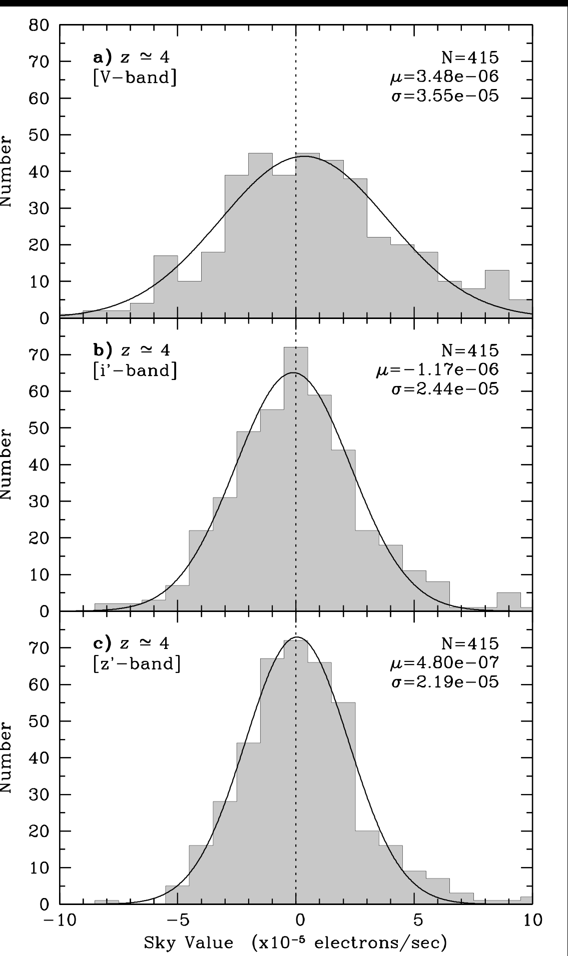
- For details, see Windhorst, R. A., et al. 2008, Advances in Space Research, Vol. 41, 1965, (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

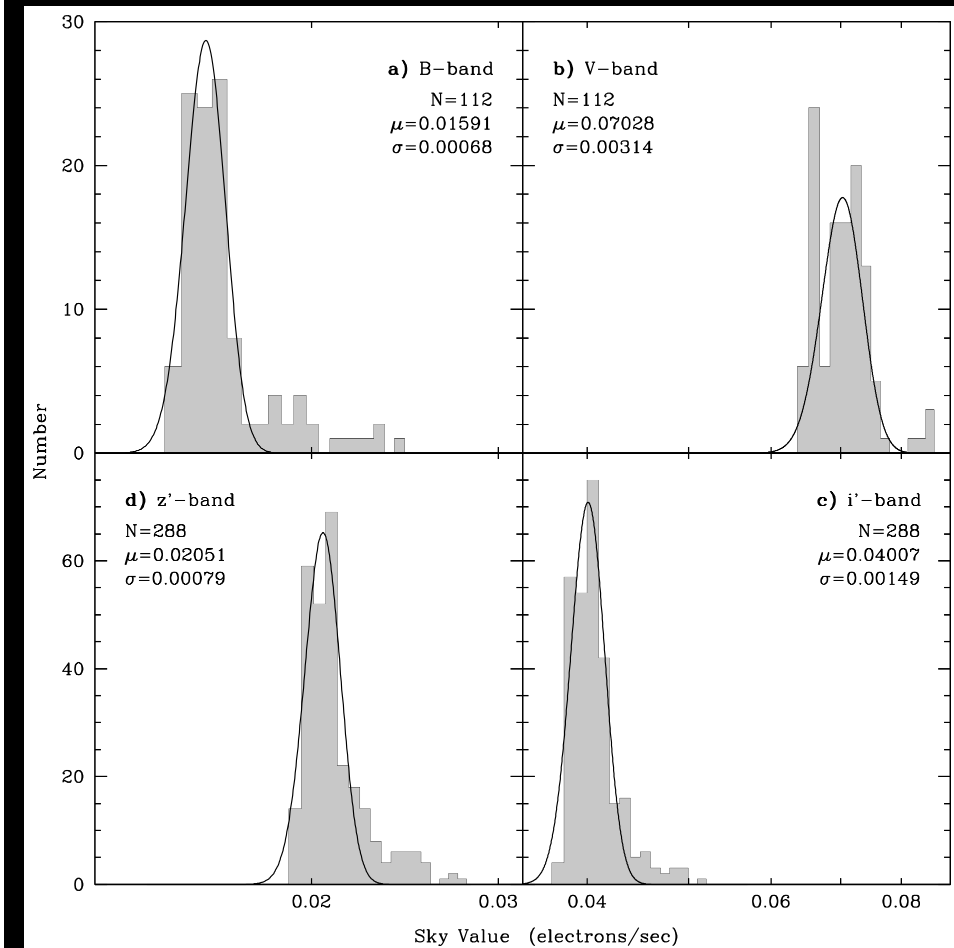
HUDF stacking: Dynamical ages of Dwarf Galaxies at z≃4–6?

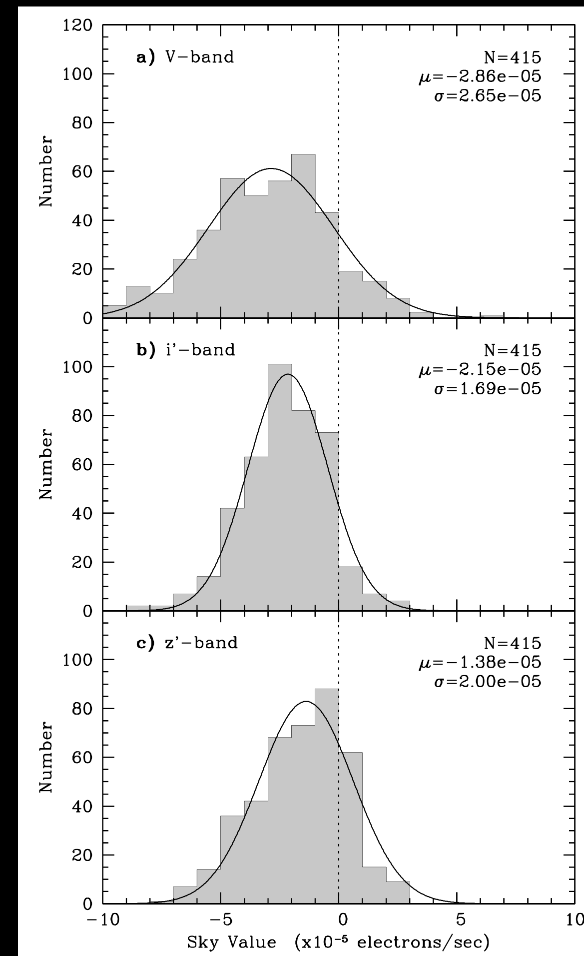


- Select all isolated, nearly unresolved ($2r_e \lesssim 0''.3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6. (Hathi et al. 2008, AJ 135, 156).
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼4300 HST orbits (≃240 JWST hrs; Hathi et al. 2008)!

Zodi BViz sky-values in HUDF to 0.2% of sky







(LEFT): Modal Viz sky-values in the Multi-Drizzled HUDF: LOCAL sky-subtraction (Hathi et al. 2008, AJ 135, 156).

(MIDDLE): Modal BViz sky-values in the HUDF: NOT sky-subtracted.

(RIGHT): Modal Viz sky's in the Multi-Drizzled HUDF: GLOBAL sky-subtr.

- HUDF sky-subtraction error≃(2–3).10^{-3} or AB≃29.0–30.2 mag/arcsec^2

Zodi BViz sky-values in HUDF to 0.2% of sky

Table 1. Measured sky values in $BVi'z'$ (filters) for the HUDF

HUDF Filter	Number of Exposures	Mean Sky Value[a] (e^-/s) and rms error[b]	Sky SB[c] (AB mag arcsec^{-2})	Sky Color[c] (AB mag)	1σ Sky-Subtraction error (AB mag arcsec^{-2})
B	112	0.015909 ± 0.000065	23.664 ± 0.003	$(B-V)_{\rm sky}$=0.800	29.85 ± 0.05
V	112	0.070276 ± 0.000297	22.864 ± 0.002	$(V-i')_{\rm sky}$=0.222	30.15 ± 0.15
i'	288	0.040075 ± 0.000088	22.642 ± 0.002	$(i'-z')_{\rm sky}$=0.065	29.77 ± 0.20
z'	288	0.020511 ± 0.000047	22.577 ± 0.003	$(V-z')_{\rm sky}$=0.287	28.95 ± 0.05

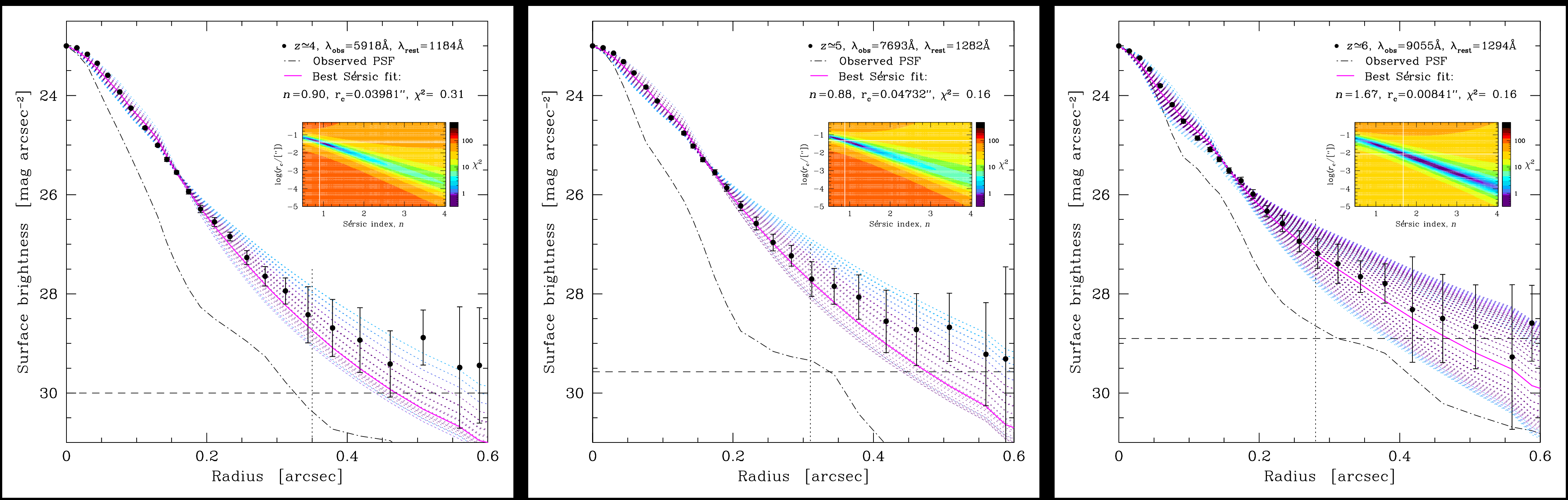
[a] From Fig. 4 in Hathi, N. P., et al. 2008, AJ, 135, 156 (astro-ph/0710.0007)

[b] Error is standard deviation of the mean ($\sigma/\sqrt{N}$)

[c] Sky surface brightness values and colors are consistent with the solar colors in AB mag of (V-i')=0.19, (V-z')=0.21 and (i'-z')=0.01 [except for bluest color (B-V)], and is dominated by the zodiacal background.

- 400 HUDF orbits in BViz (Hathi et al. 2008, AJ, 135, 156):
- HUDF sky-subtraction error$\simeq$(2–3).10^{-3} or AB$\simeq$29.0–30.2 mag/arcsec^2
- JWST can do this in 20 hrs, reaching AB$\simeq$31–32 mag/arcsec^2 in $\gtrsim$500 hrs?

HUDF stacking: Light profiles of Dwarf Galaxies at z≃4–6



Best fit Sersic profile of 1680 ACS V-band orbit stack: n=0.90 at z≃4

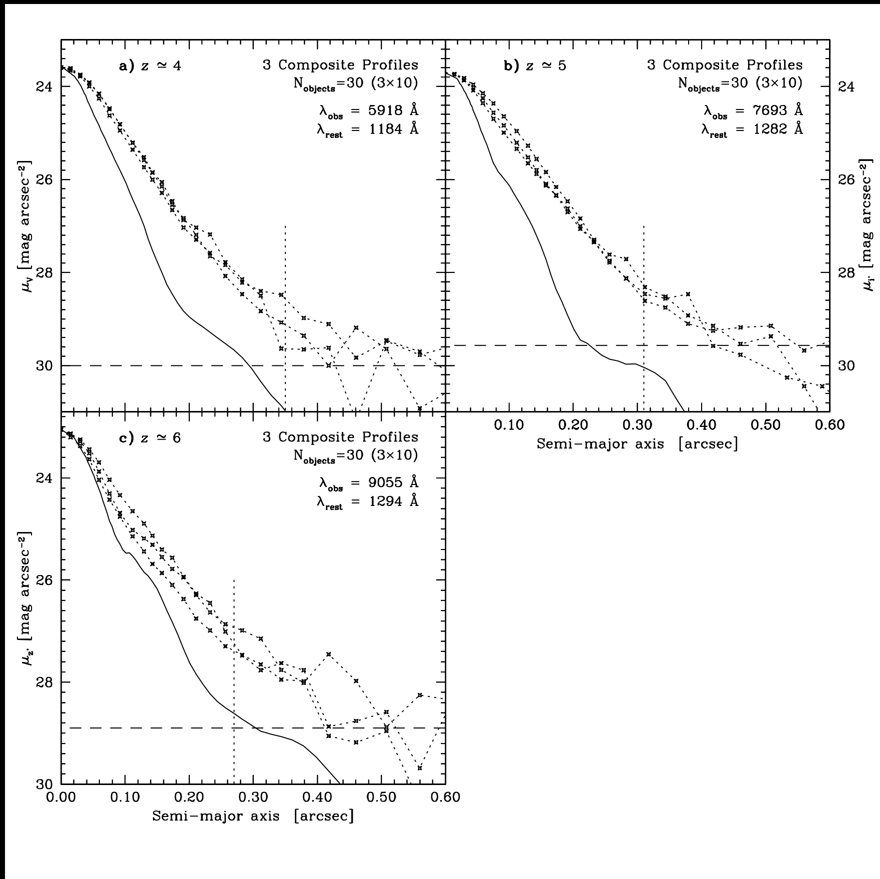
Best fit Sersic profile of 4320 ACS i-band orbit stack: n=0.88 at z≃5

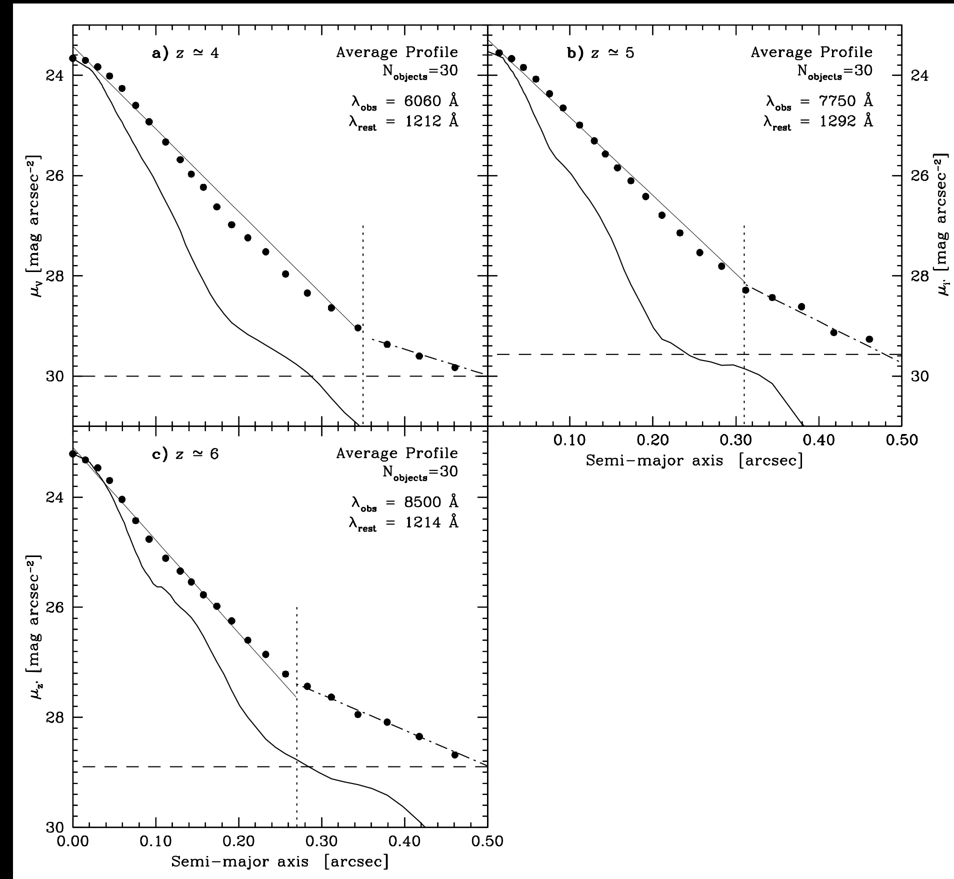
Best fit Sersic profile of 4320 ACS z-band orbit stack: n=1.67 at z≃6

⇒ Dwarf galaxies at z≃4–6 are disk dominated! (Hathi et al. 2008).

- JWST can do this to 10^{-4}, or AB≃31.0–32.0 mag/arcsec^2 to z≲15,
- *provided* that JWST straylight/rogue path is kept to a minimum: well below Zodi and only has low spatial frequencies.

HUDF stacking: Dynamical ages of Dwarf Galaxies at z≃4–6?





- HUDF sky-subtraction error is 2–3.10^{-3} or AB≃29.0–30.2 mag/arcsec^2
- Average 4300-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r≳0.″27–0.″35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of τ_{dyn}≃0.1-0.2 Gyr at z≃6–4 for the enclosed masses.

⇔ comparable to SED ages (Hathi$^+$ 2008, AJ 135, 156).

⇒ Star-formation that finished global reionization at z≃6 started at ≳7.

- 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. 2008, Advances in Space Research, 41, p. 1965 (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"