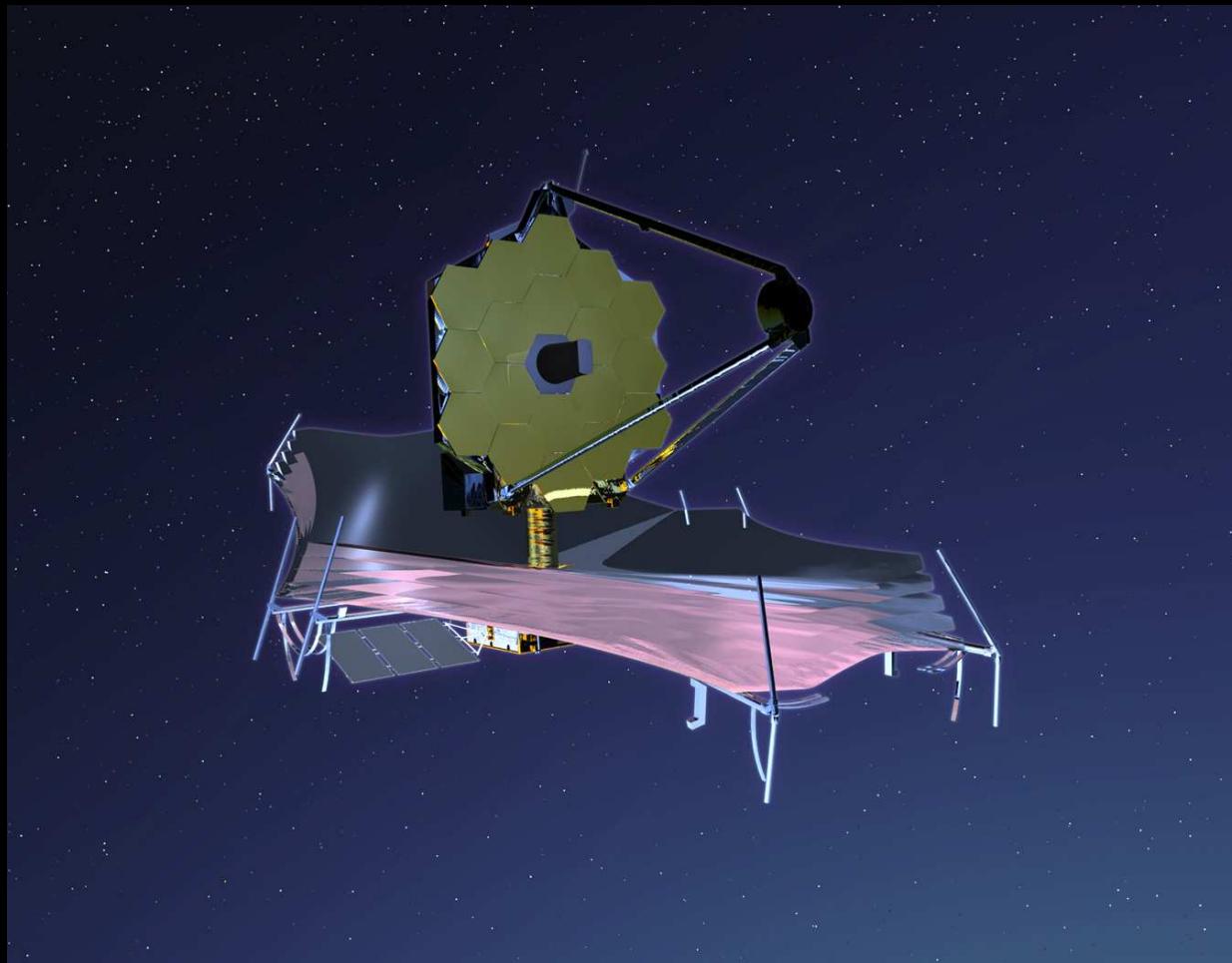


How will the Webb Space Telescope measure First Light Reionization, & Galaxy Assembly in the post WFC3 era?

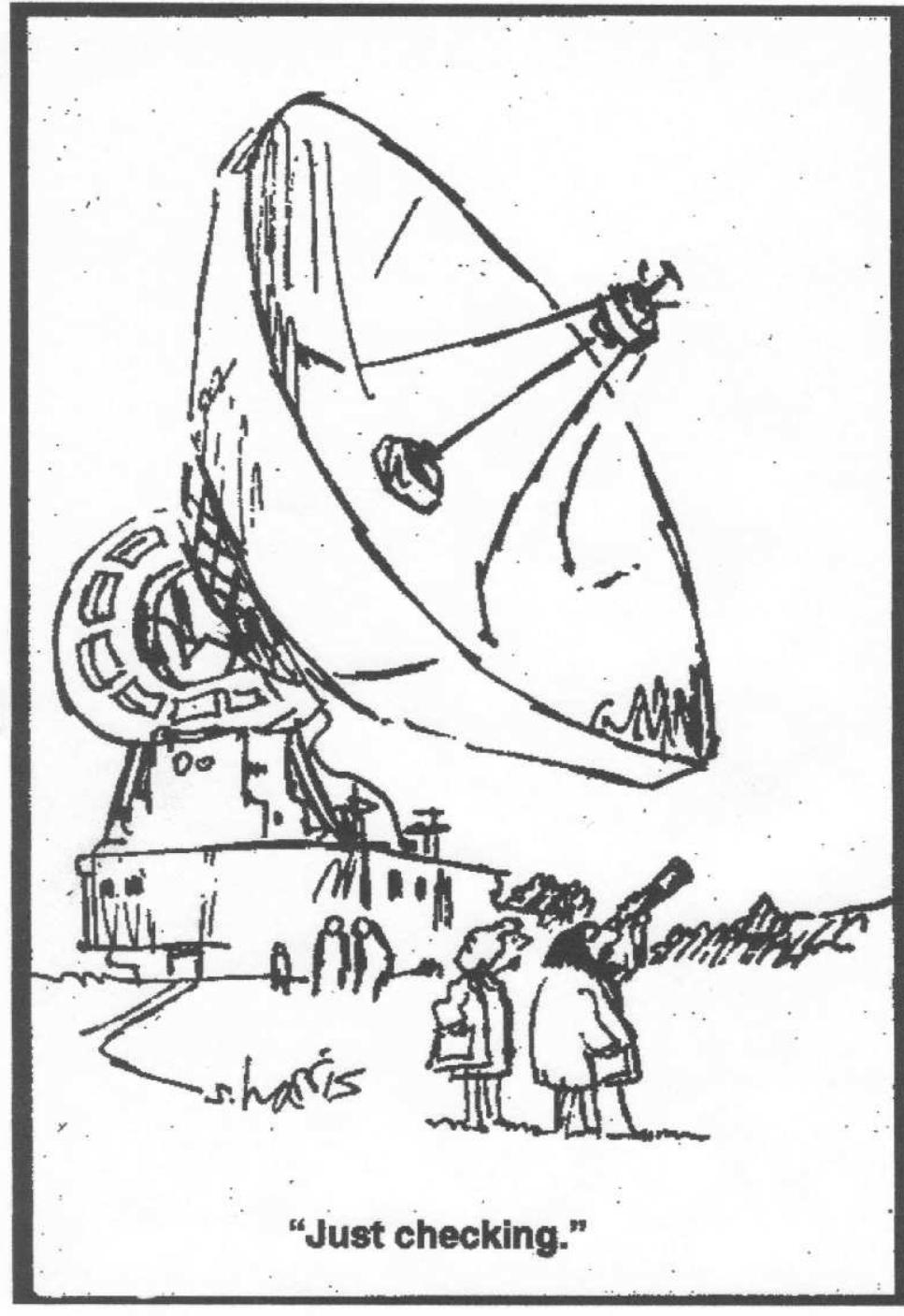
Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

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 UC Berkeley, California, Thursday December 2, 2010



HST and JWST changed the career of this radio astronomer ...

Outline

James Webb Space Telescope: NASA's next Flagship mission after Hubble
Astro 2010 Decadal Survey assumed: JWST science is done after 2014.

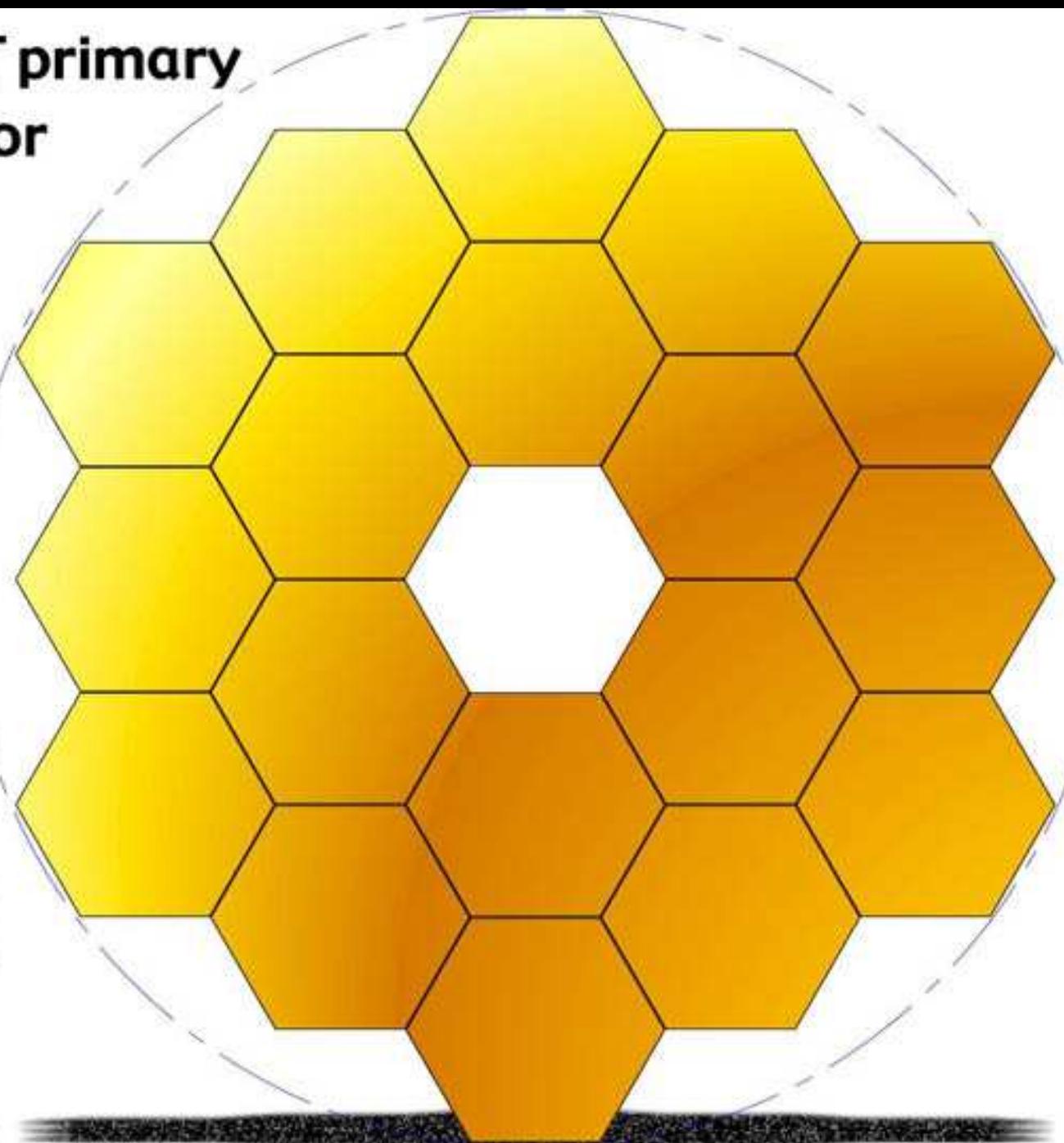
- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) How can JWST measure First Light & Reionization?
- (4) How can JWST measure Galaxy Assembly?

[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

**JWST primary
mirror**



**Hubble primary
mirror**

JWST $\sim 2.5 \times$ larger than Hubble, so at $\sim 2.5 \times$ larger wavelengths:
JWST has the same resolution in the near-IR as HST in the optical.

"Brilliantly done...breathtaking in its vision."

The New York Times

JAMES WEBB

Author of *The Emperor's General*



A NOVEL

SOMETHING TO DIE FOR



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

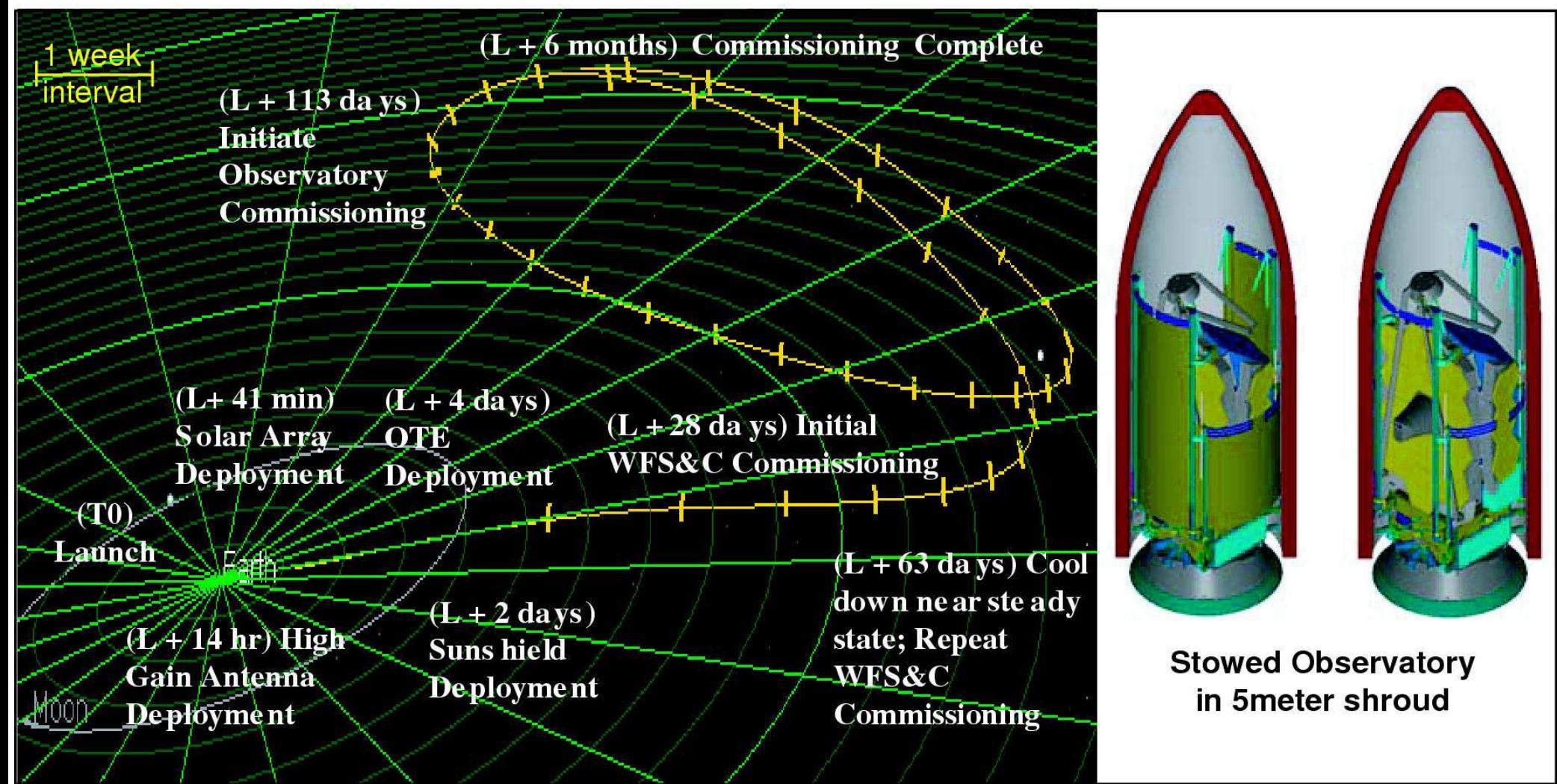
(RIGHT) Life-size JWST prototype on the Capitol Mall, May 2007 ...

- (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 $29 \mu\text{m}$, to be launched in June $\gtrsim 2014$.
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging ($\text{AB} \lesssim 31.5$) and spectroscopy ($\text{AB} \lesssim 29$ mag).

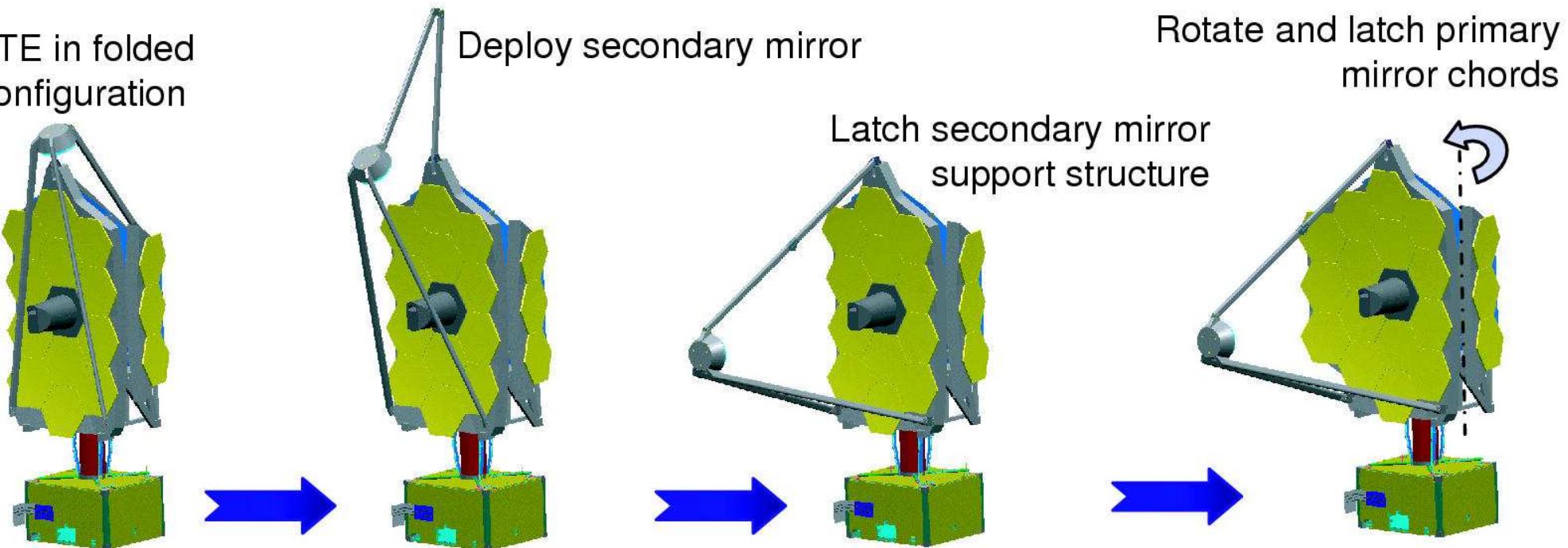
- (1) How will JWST travel to its L2 orbit?



- After launch in June 2014 with an Ariane-V, JWST will orbit around 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?

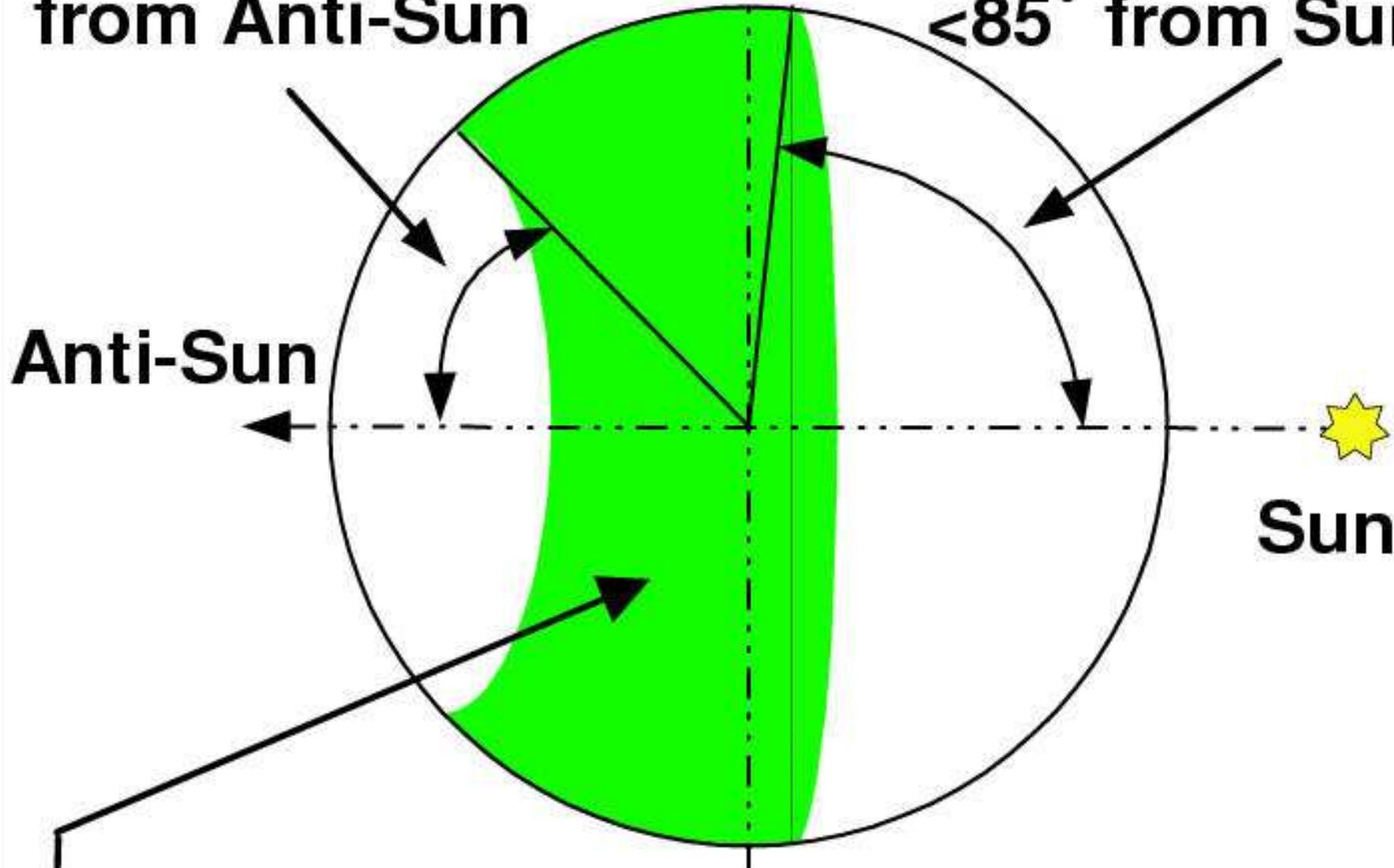
OTE in folded configuration



- 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 $2.0\mu\text{m}$ diffraction limit!

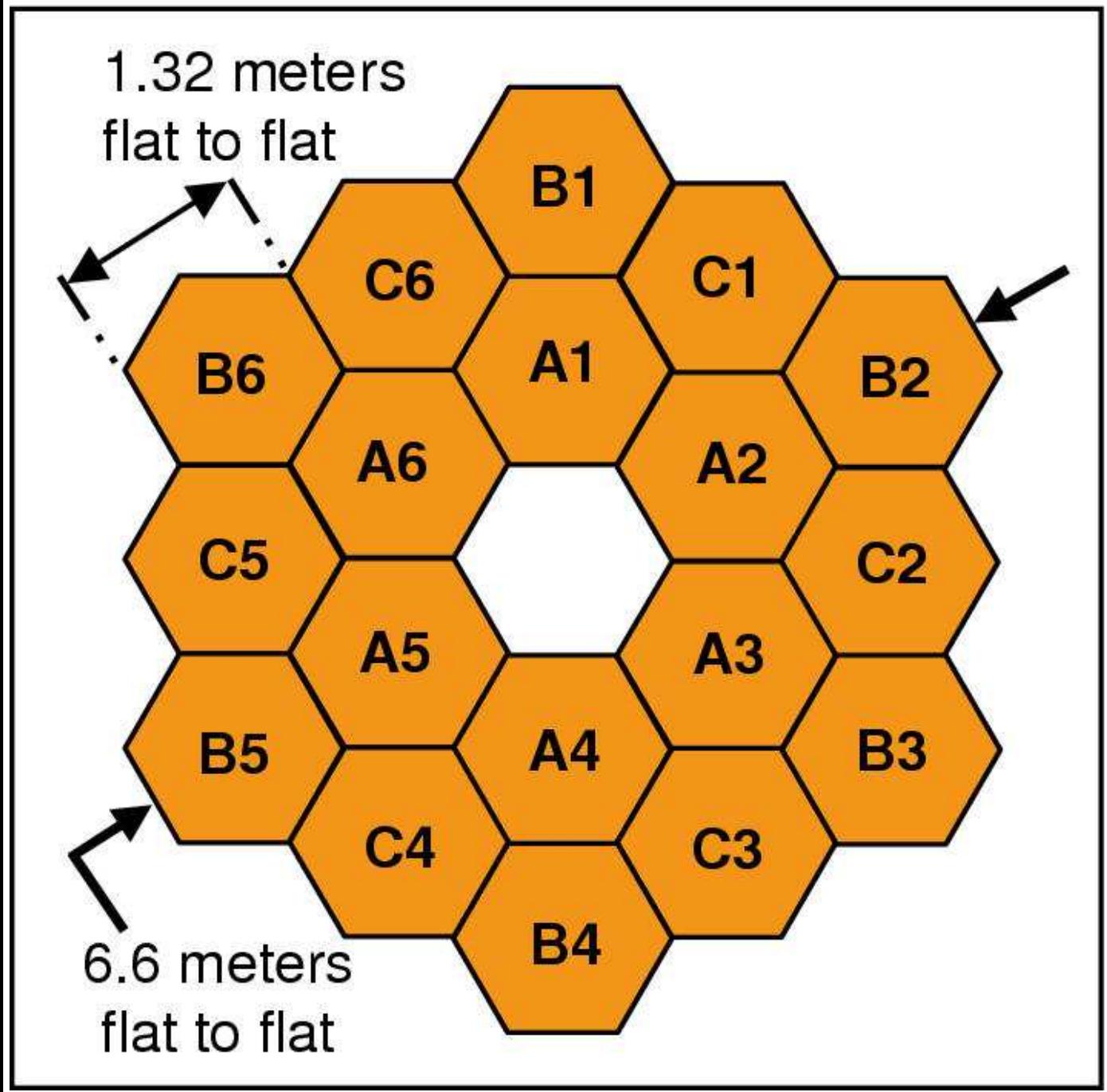
Exclusion zone <45° from Anti-Sun

Exclusion zone <85° from Sun



Allowable Observatory Field-of-Regard

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).

V3 (anti-spacecraft)

V1
V2

Secondary mirror

Cassegrain focus

Fine Steering Mirror

f/#: 20.0

Effective Focal Length: 131.4 m

PM diameter = 6.6 m (circumscribed circle)

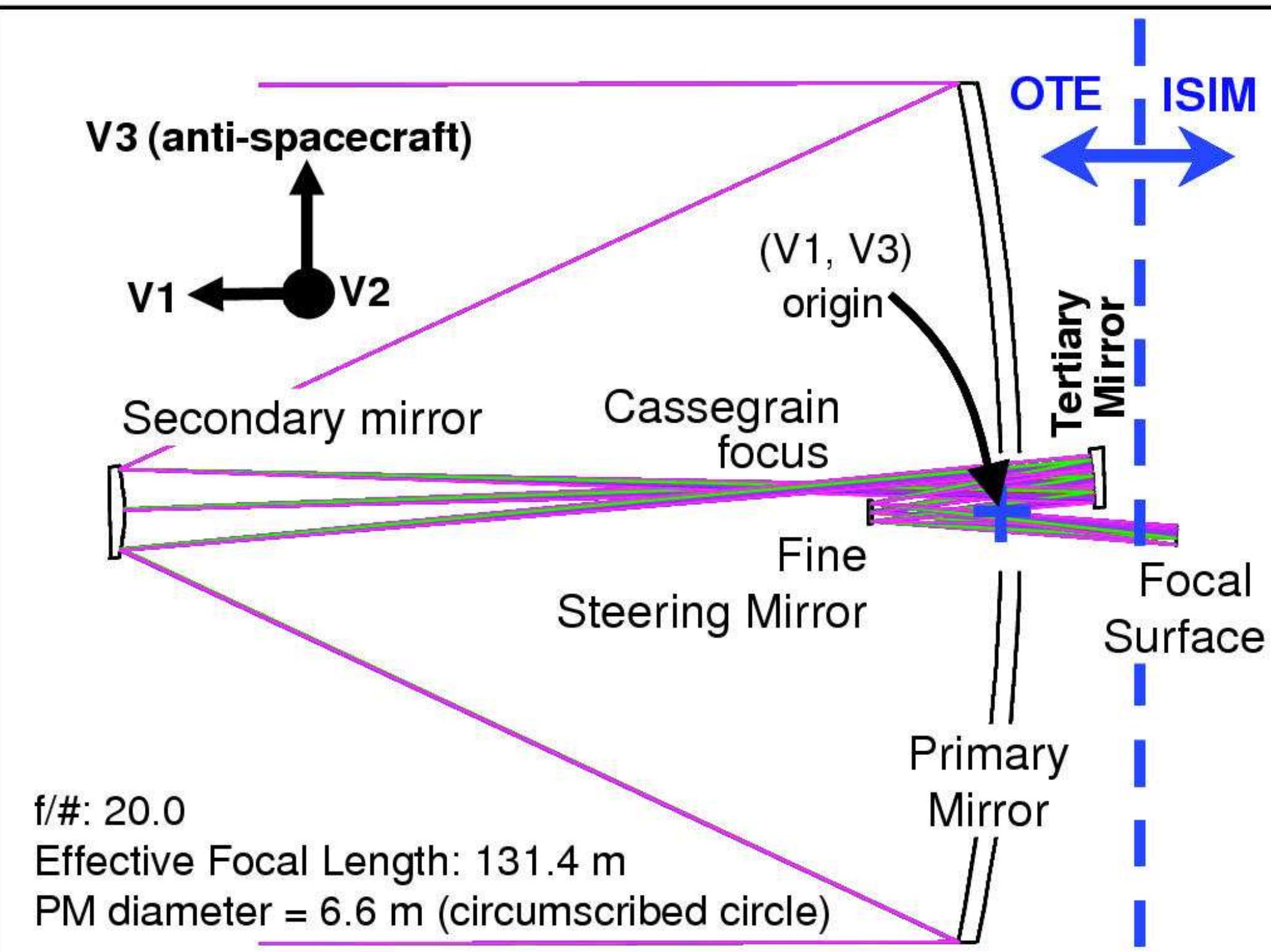
(V1, V3)
origin

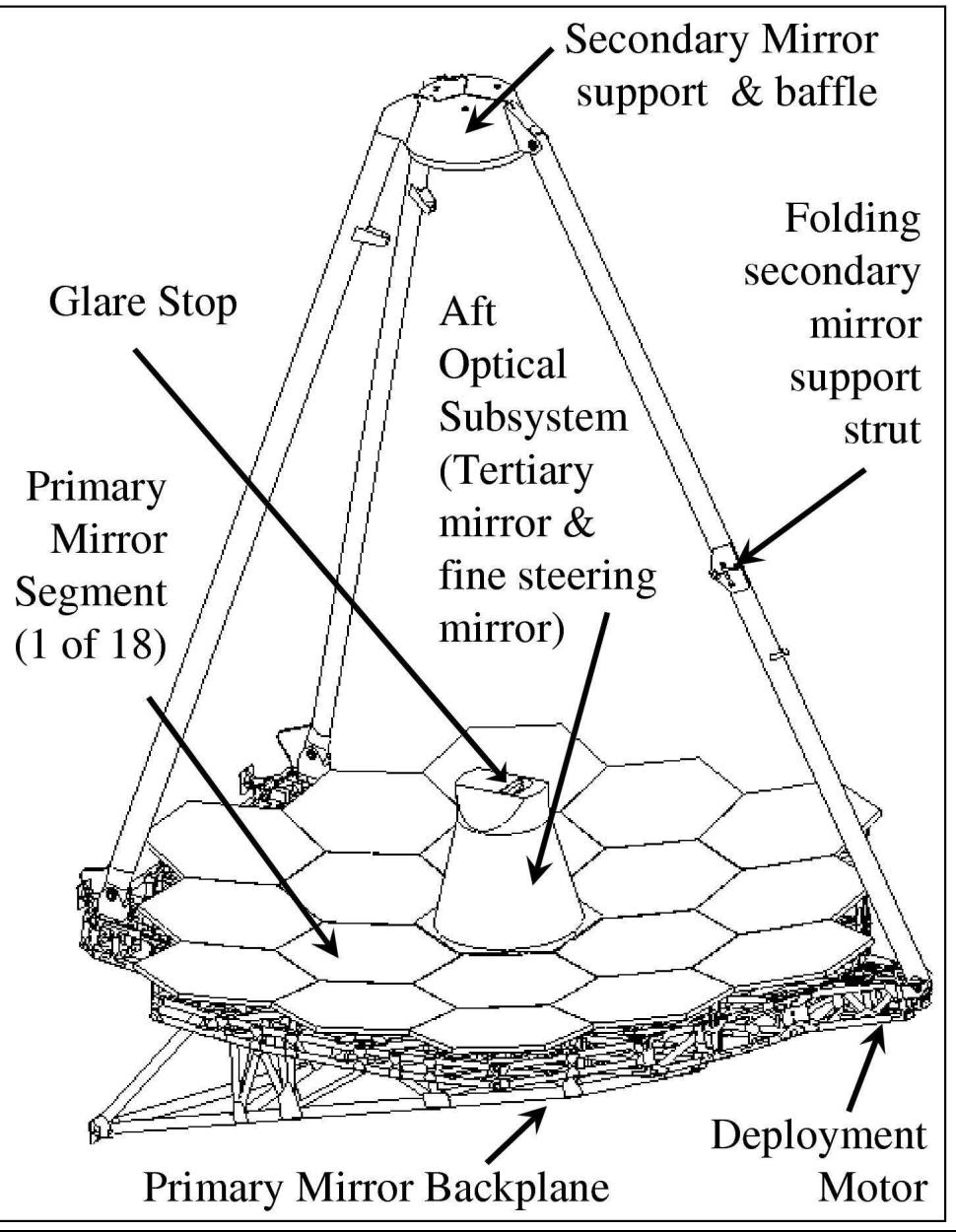
OTE
ISIM

Tertiary
Mirror

Focal
Surface

Primary
Mirror



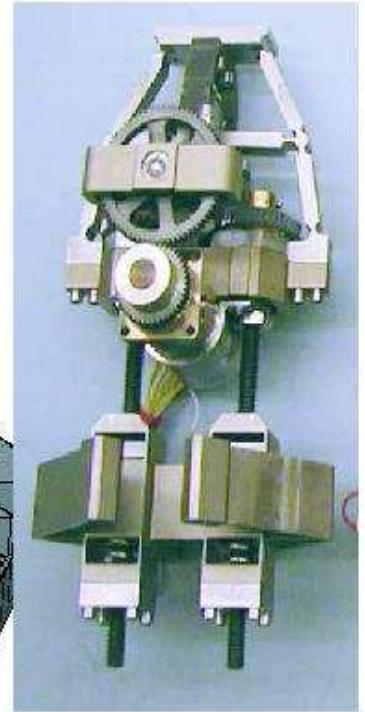
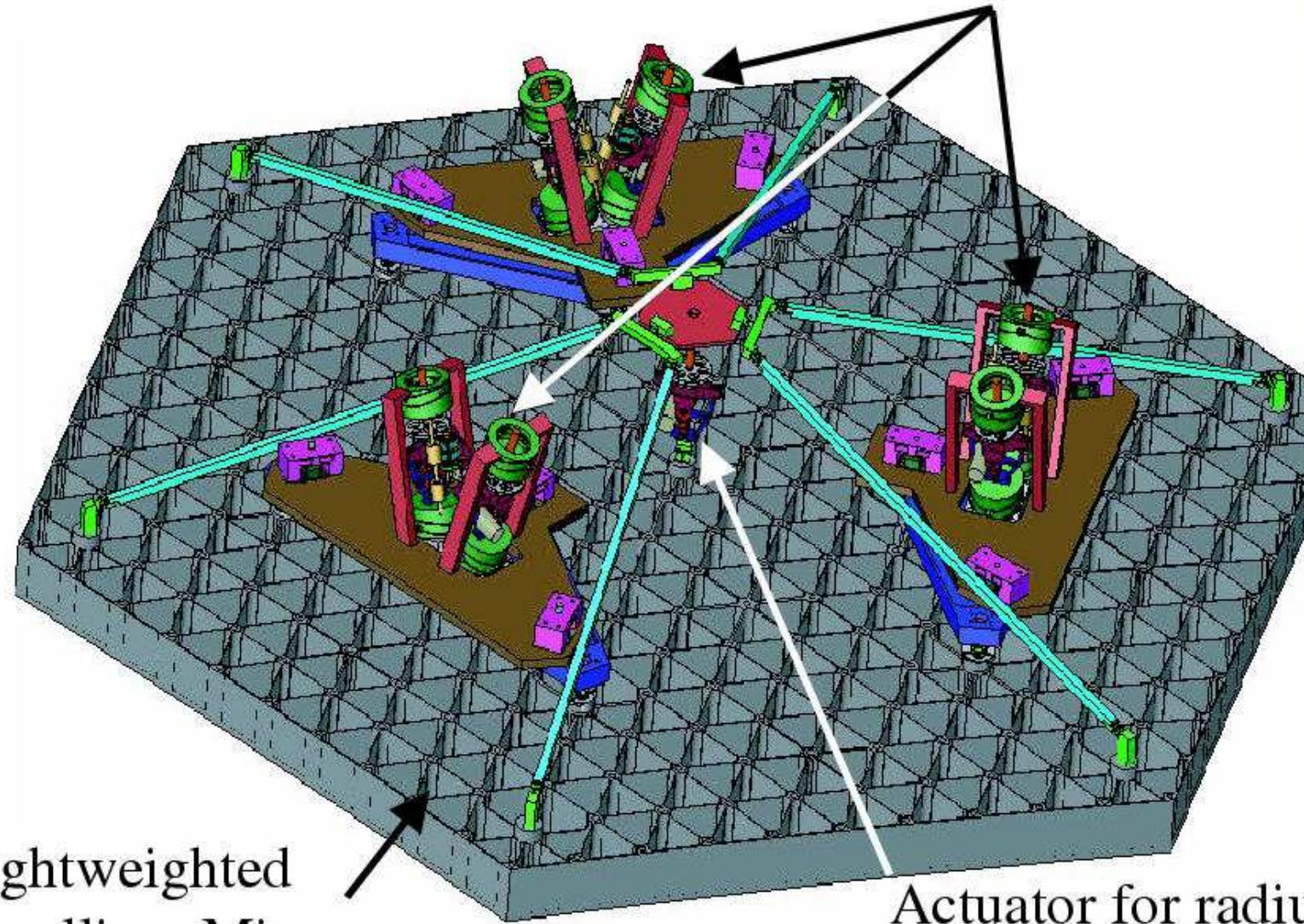


Ball 1/6-model for WFS: diffraction-limited $2.0 \mu\text{m}$ images (Strehl $\gtrsim 0.85$).

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.

Actuators for 6 degrees of freedom rigid body motion

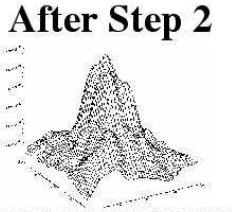


Actuator
development
unit

Lightweighted
Beryllium Mirror

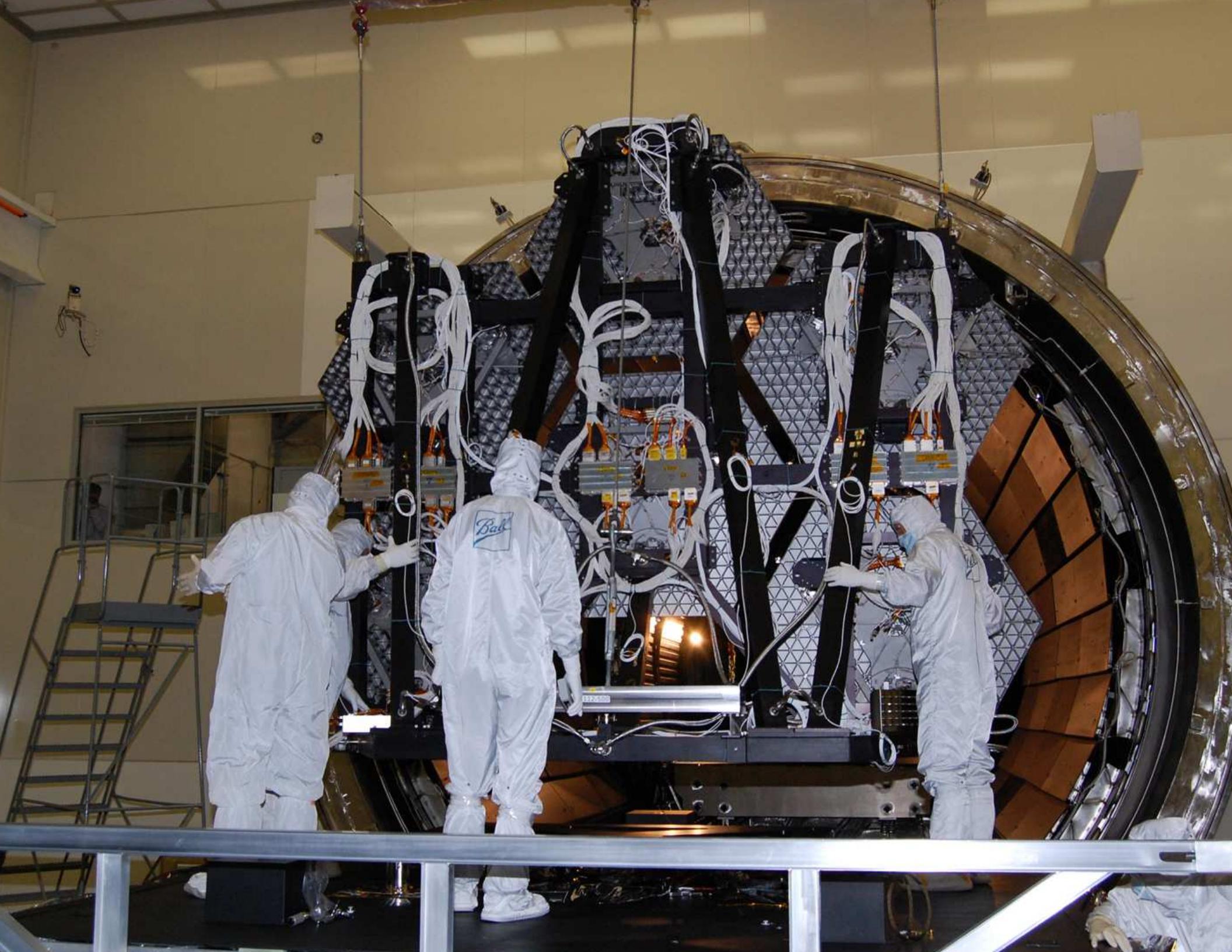
Actuator for radius
of curvature adjustment

Active mirror segment support through hexapods (7 d.o.f.), similar to Keck.
Redundant & doubly-redundant mechanisms, quite forgiving against failures

First light NIRCam	After Step 1	Initial Capture	Final Condition
1. Segment Image Capture		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		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)		WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing		WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring		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 ($2 \mu\text{m}$ -Strehl $\gtrsim 0.85$). Need WFS-updates every ~ 14 days, depending on scheduling/SC-illumination.









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

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

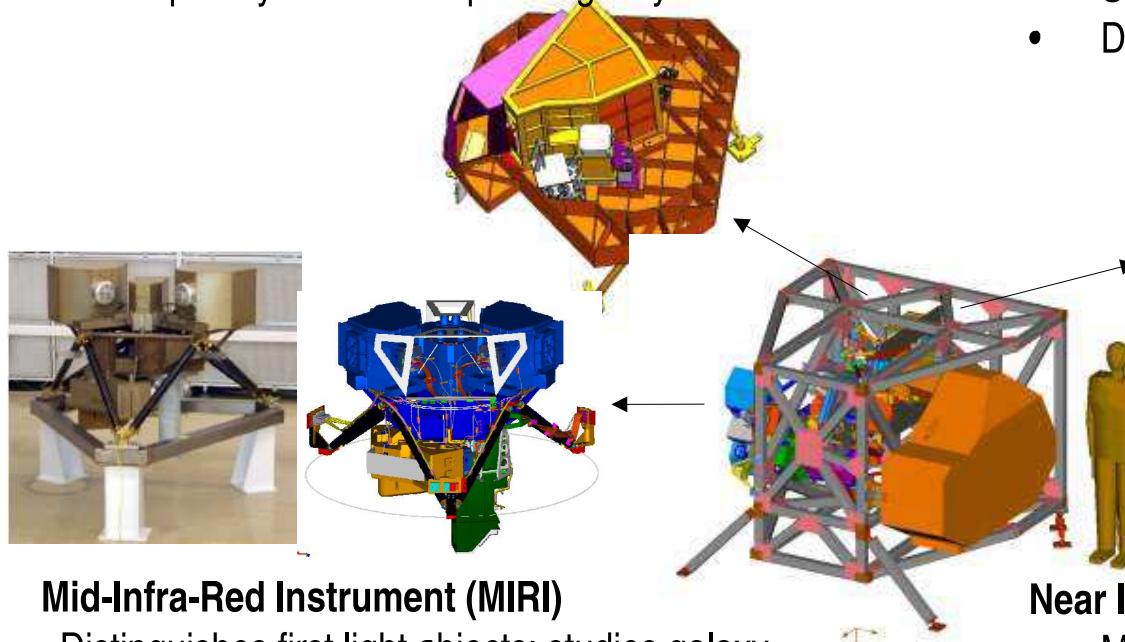


Instrument Overview



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

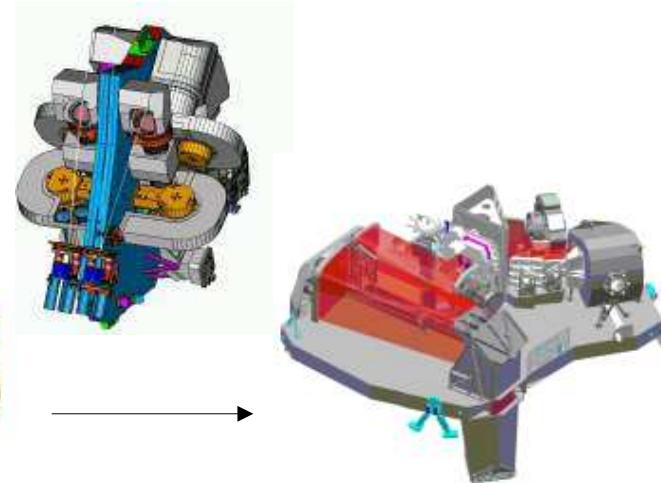


Mid-Infra-Red Instrument (MIRI)

- 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 Camera (NIRCam)

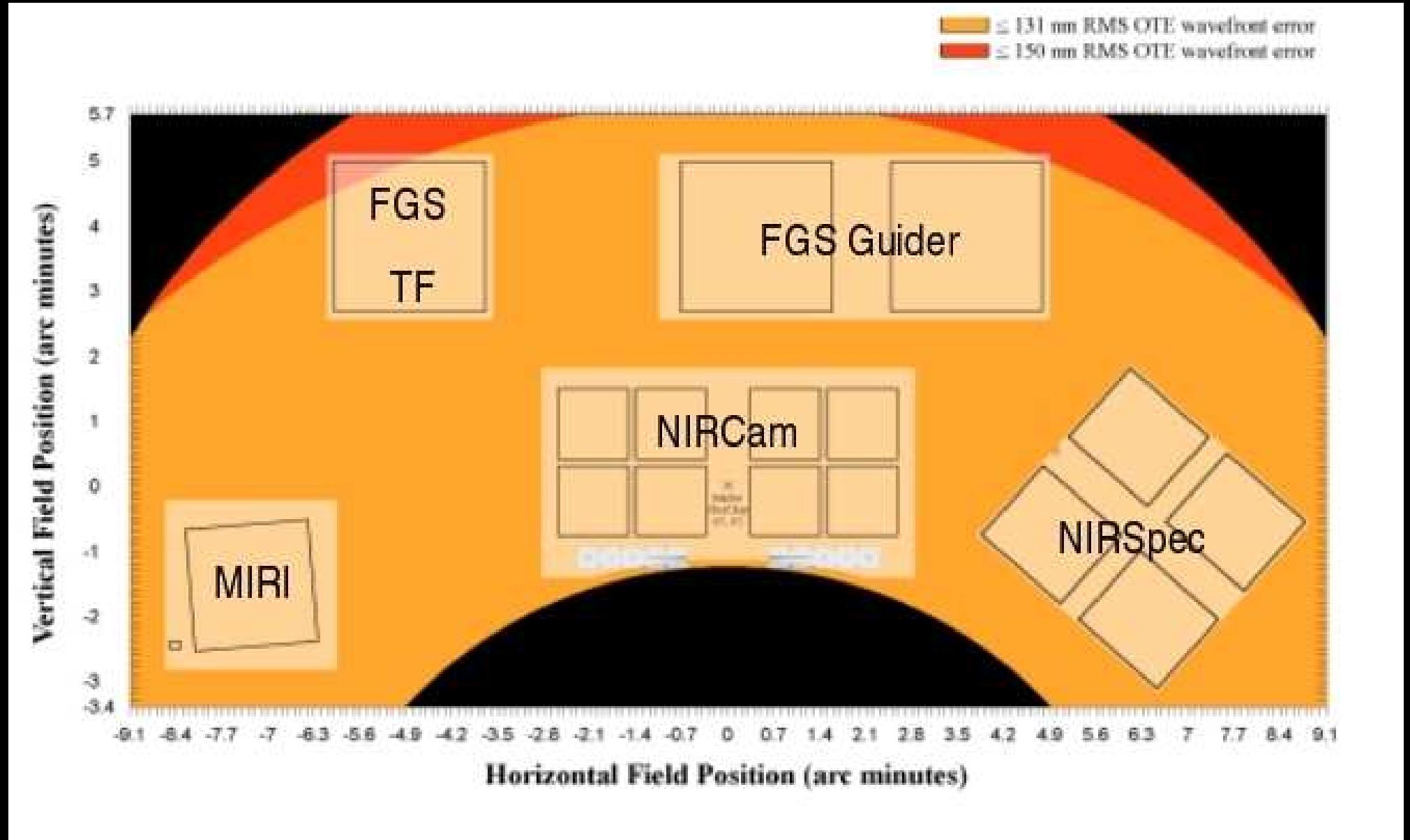
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC



Near Infra-Red Spectrograph (NIRSpec)

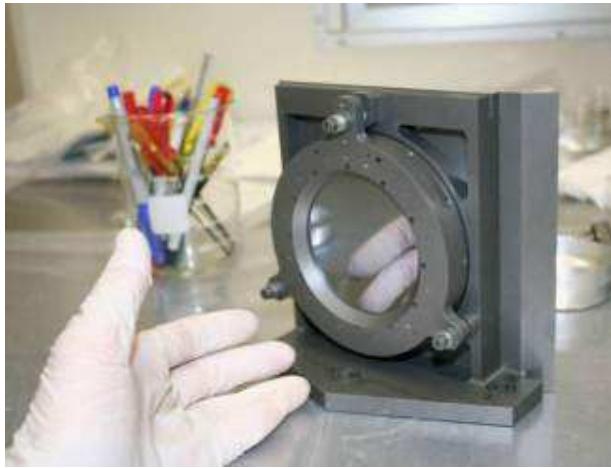
- Measures redshift, metallicity, star formation rate in first light galaxies
- 0.6 to 5 microns
- Simultaneous spectra of >100 objects
- Developed by ESA & EADS with NASA/GSFC Detector & Microshutter Subsystems

- (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*.

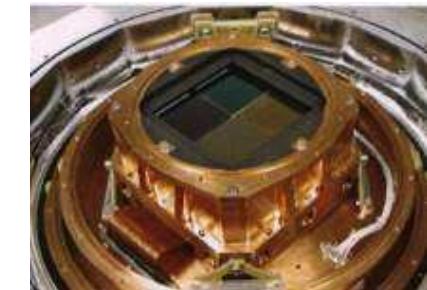
Instrument Qual and ETU Model Hardware



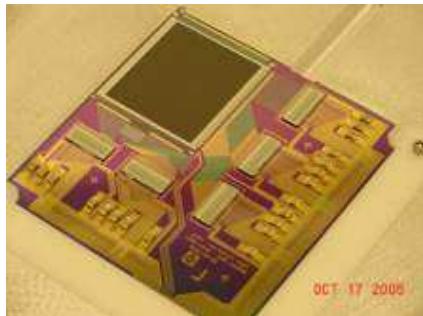
NIRCam Dichroic Beamsplitter



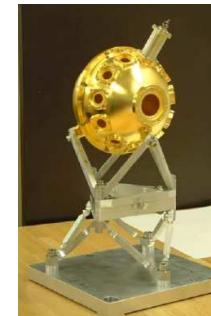
NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



NIRSpec
Calibration
Assembly



NIRSpec Mirror



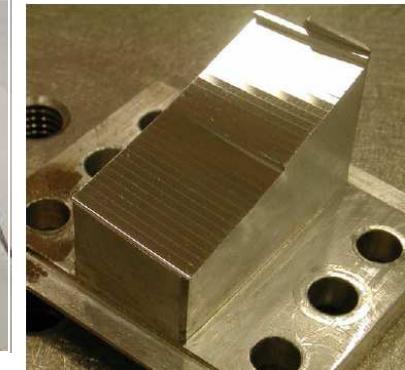
SiAs MIR Detector



NIRSpec Fore Optics Mirror Assembly

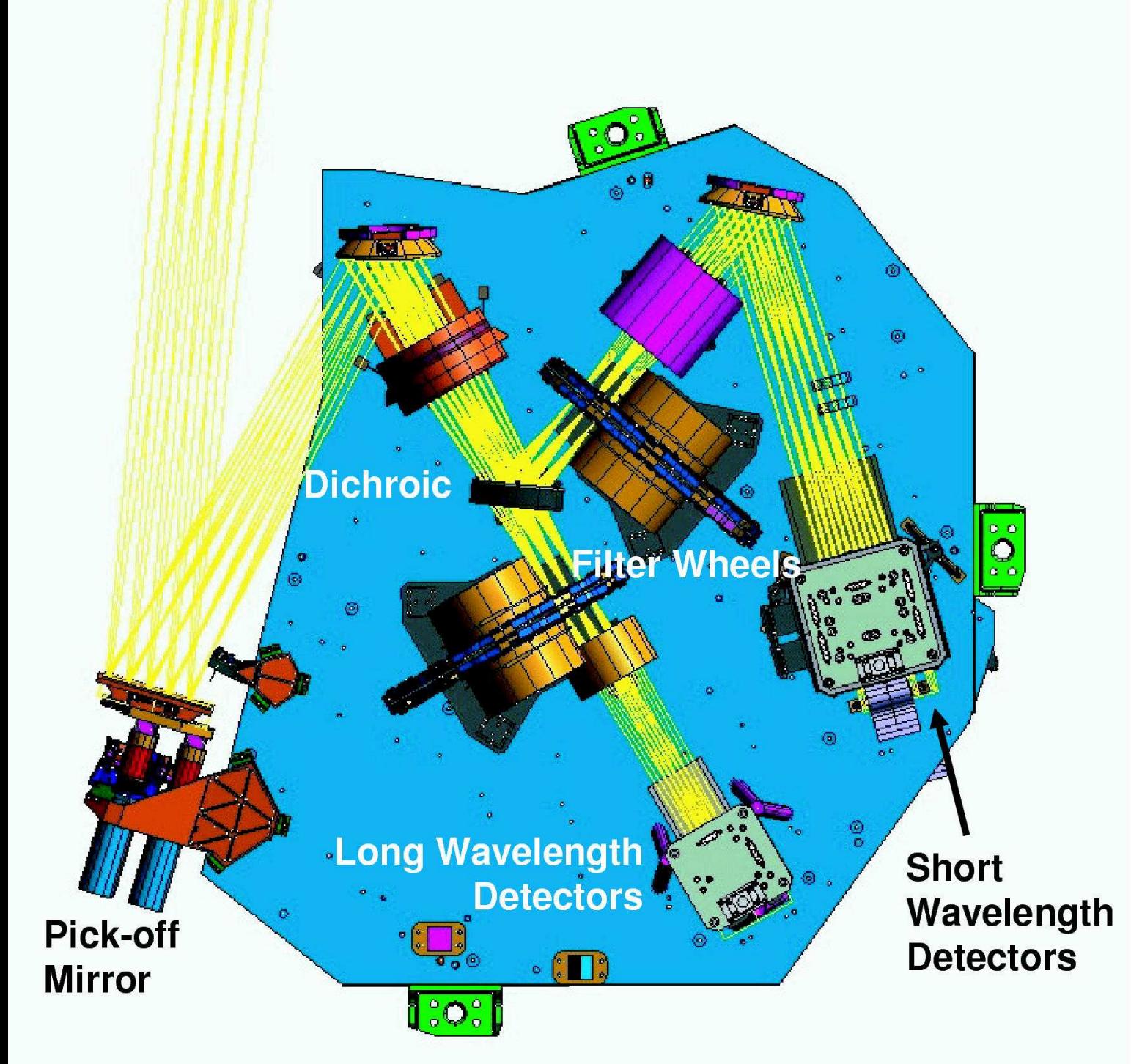


FGS/TF Etalon Filter

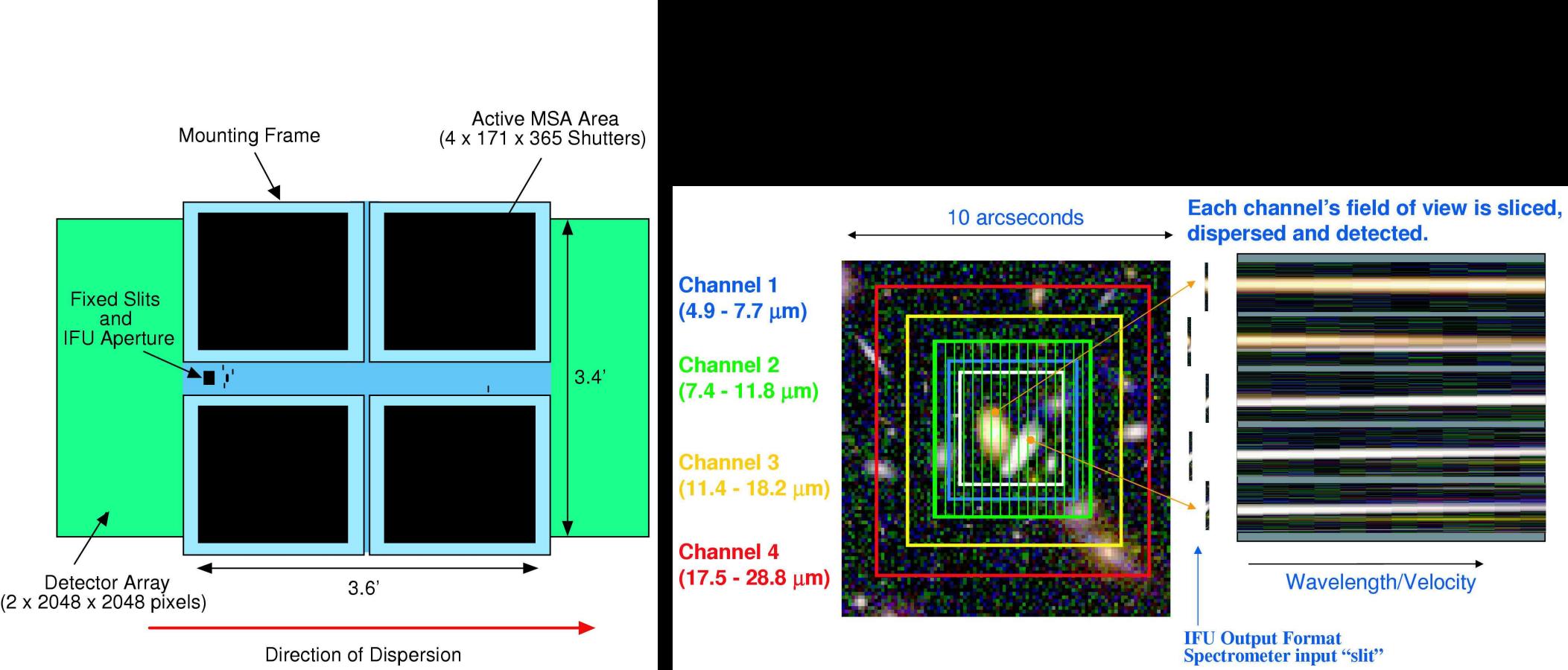


NIRSpec Image
Slicer Mirror

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



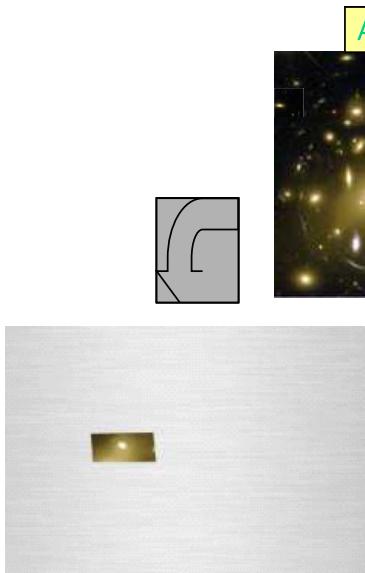
Layout of JWST NIRCam — the UofA-Lockheed NIR-Camera



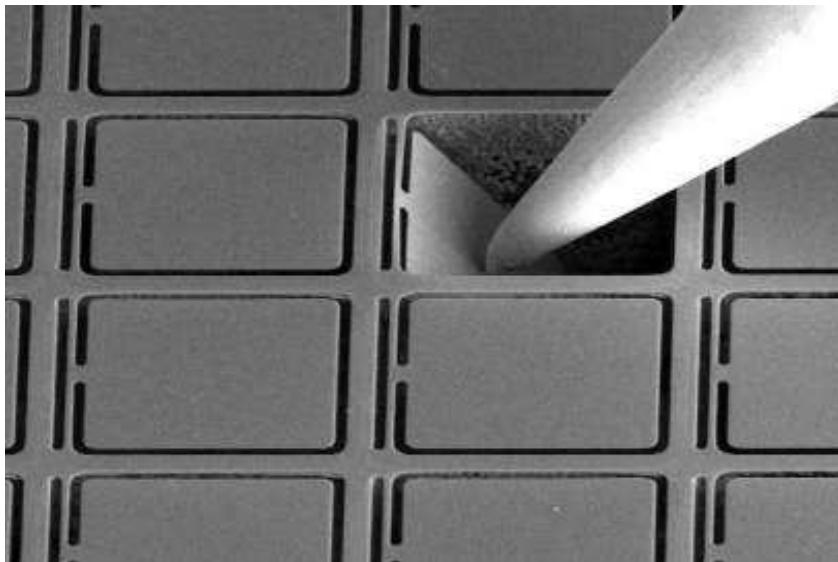
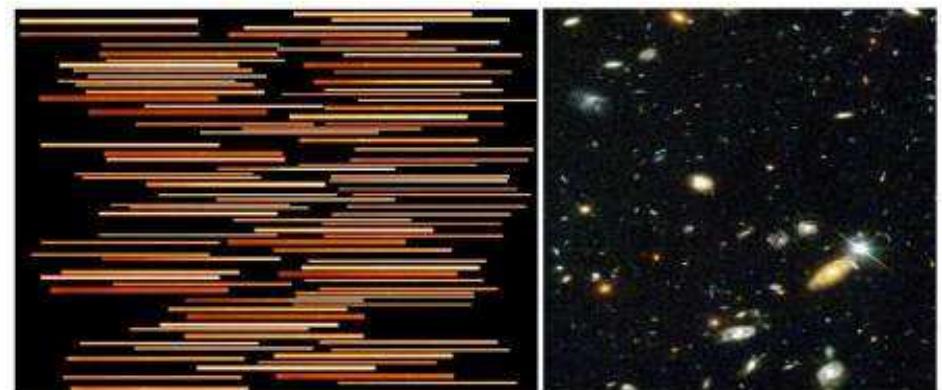
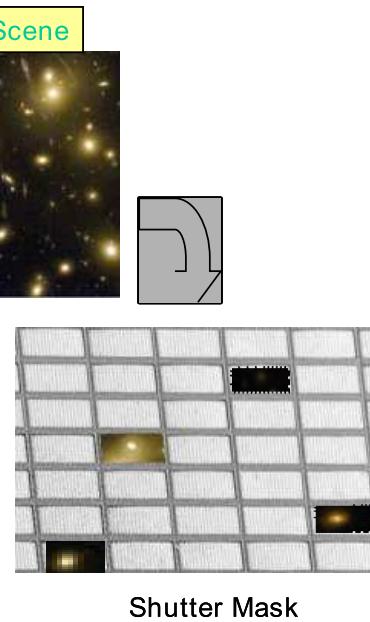
JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MSA with $4 \times 62,415$ independently operable micro-shutters (MEMS) that cover $\lambda \simeq 1\text{--}5 \mu\text{m}$ at $R \simeq 100\text{--}1000$.
- MIRI/IFU with 400 spatial pixels covering $5\text{--}29 \mu\text{m}$ at $R \sim 2000\text{--}4000$.
- FGS/TFI that covers a $2!2 \times 2!2$ FOV at $\lambda \simeq 1.6\text{--}4.9 \mu\text{m}$ at $R \simeq 100$.
- [● NIRCam offers $R \simeq 5$ imaging from $0.7\text{--}5 \mu\text{m}$ over two $2!3 \times 4!6$ FOV's.]

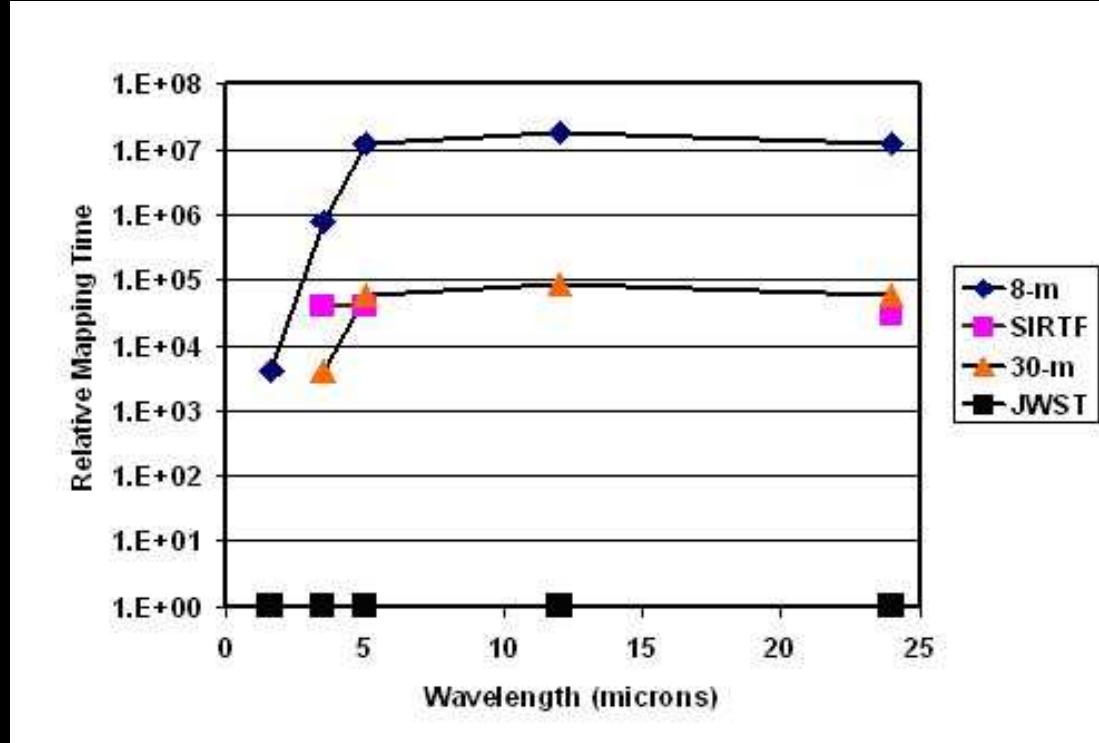
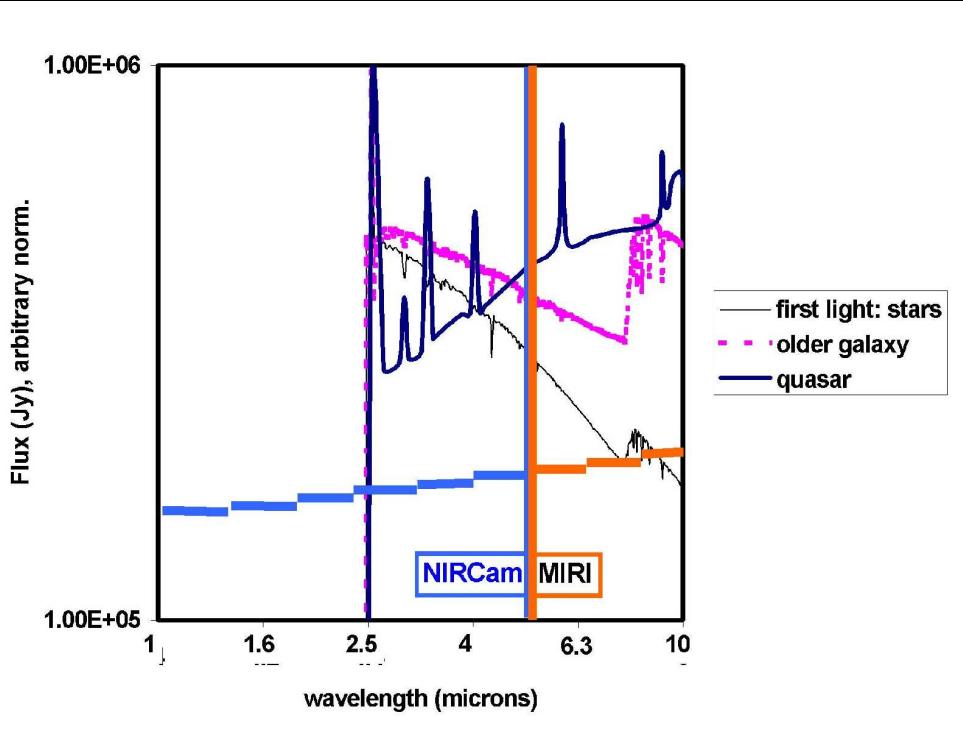
Micro Shutters



Metal Mask/Fixed Slit



- (2) What sensitivity will JWST have?



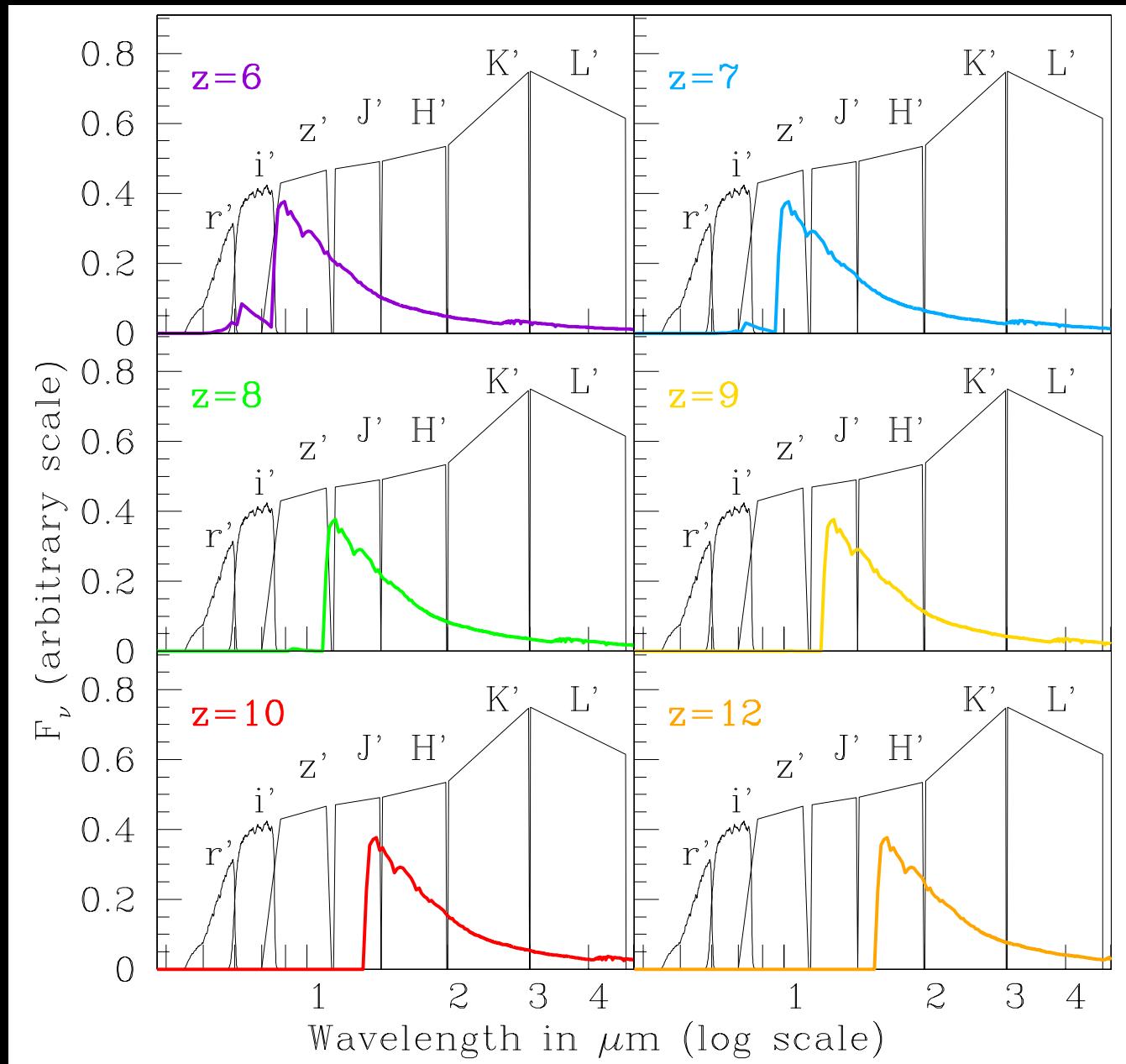
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5 \mu\text{m}$.

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 $z=20$.

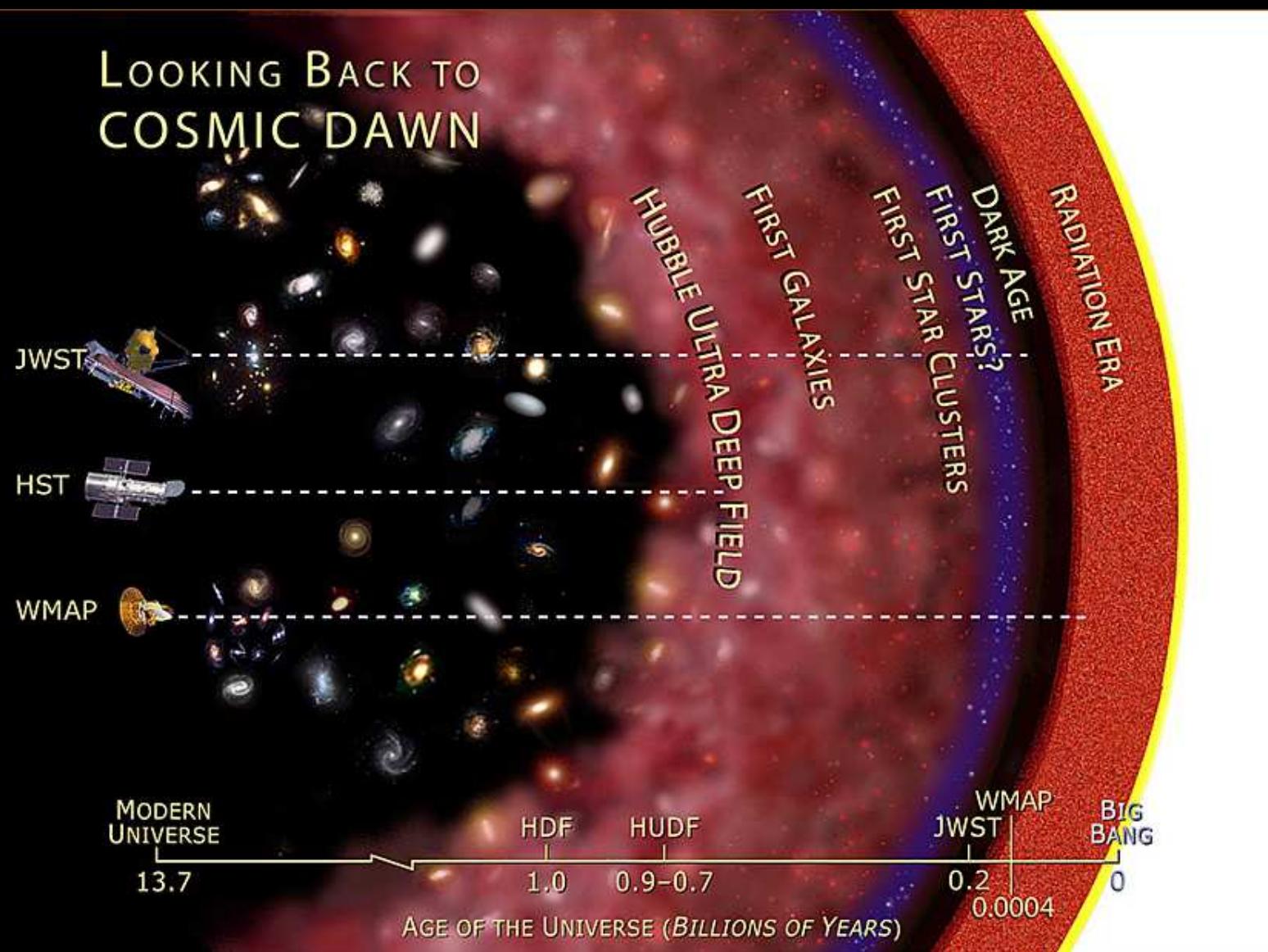
RIGHT: Relative survey time vs. λ that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

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



- Can't beat redshift: to see First Light, must observe near-mid IR.
⇒ This is why JWST needs NIRCam at $0.8\text{--}5 \mu\text{m}$ and MIRI at $5\text{--}29 \mu\text{m}$.

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



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

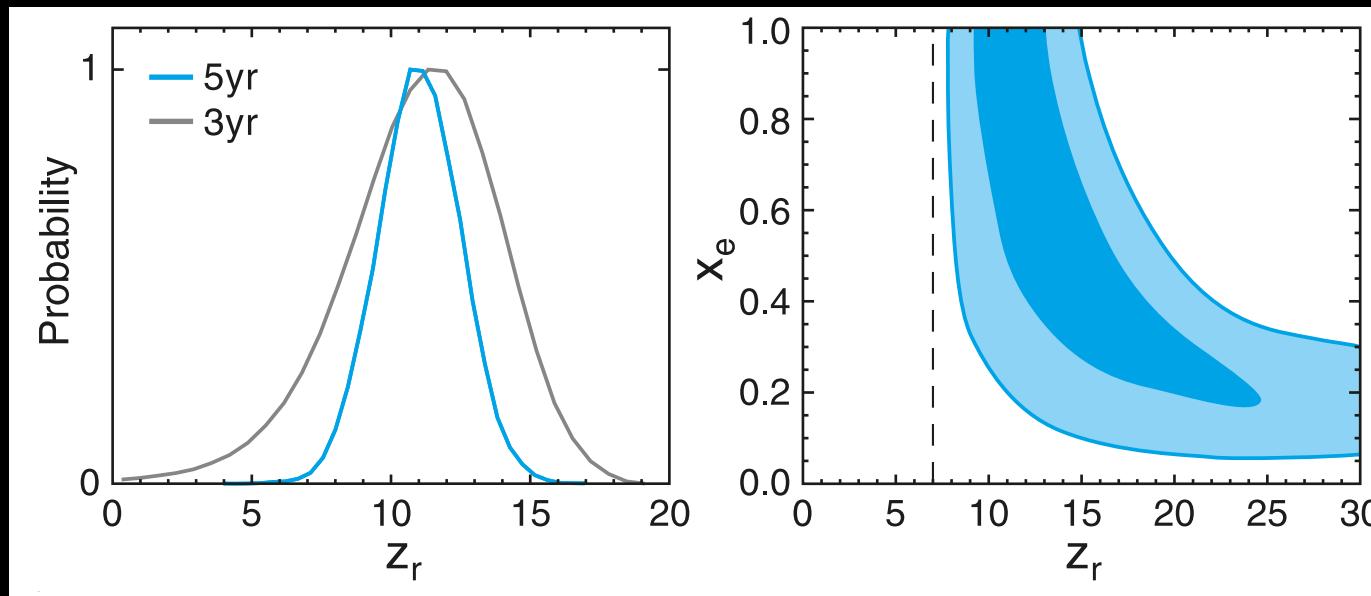
JWST: First Light, Reionization, & (dwarf) Galaxy Assembly at $z \approx 8-20$.

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

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

HST/WFC3 $z \lesssim 7\text{--}9 \leftarrow$

\longrightarrow JWST $z \simeq 8\text{--}25$

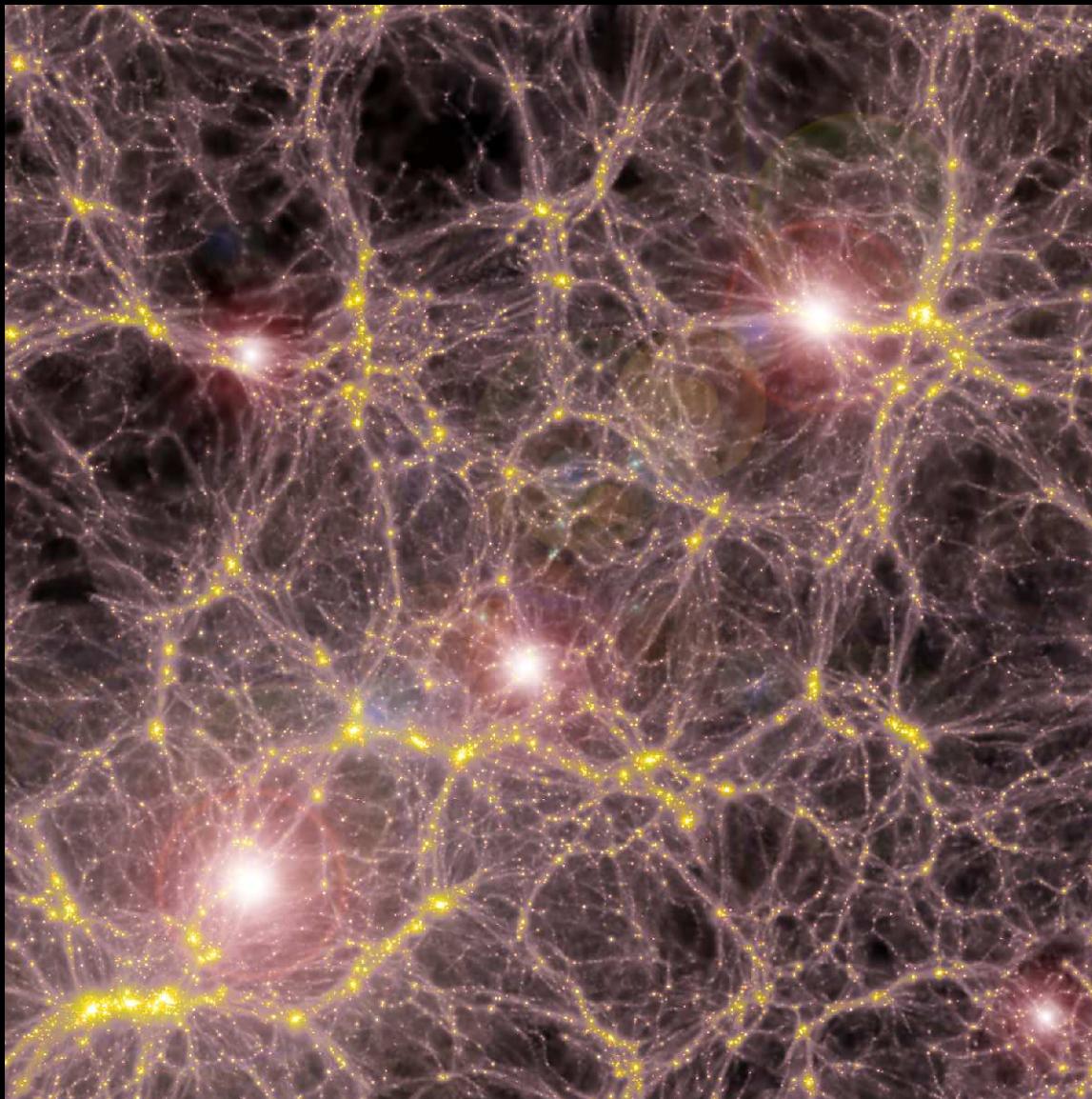


The year-7 WMAP data provided much better foreground removal
 (Dunkley et al. 2009; Komatsu et al. 2009, 2010; astro-ph/1001.4538)

\implies First Light & Reionization occurred between these extremes:

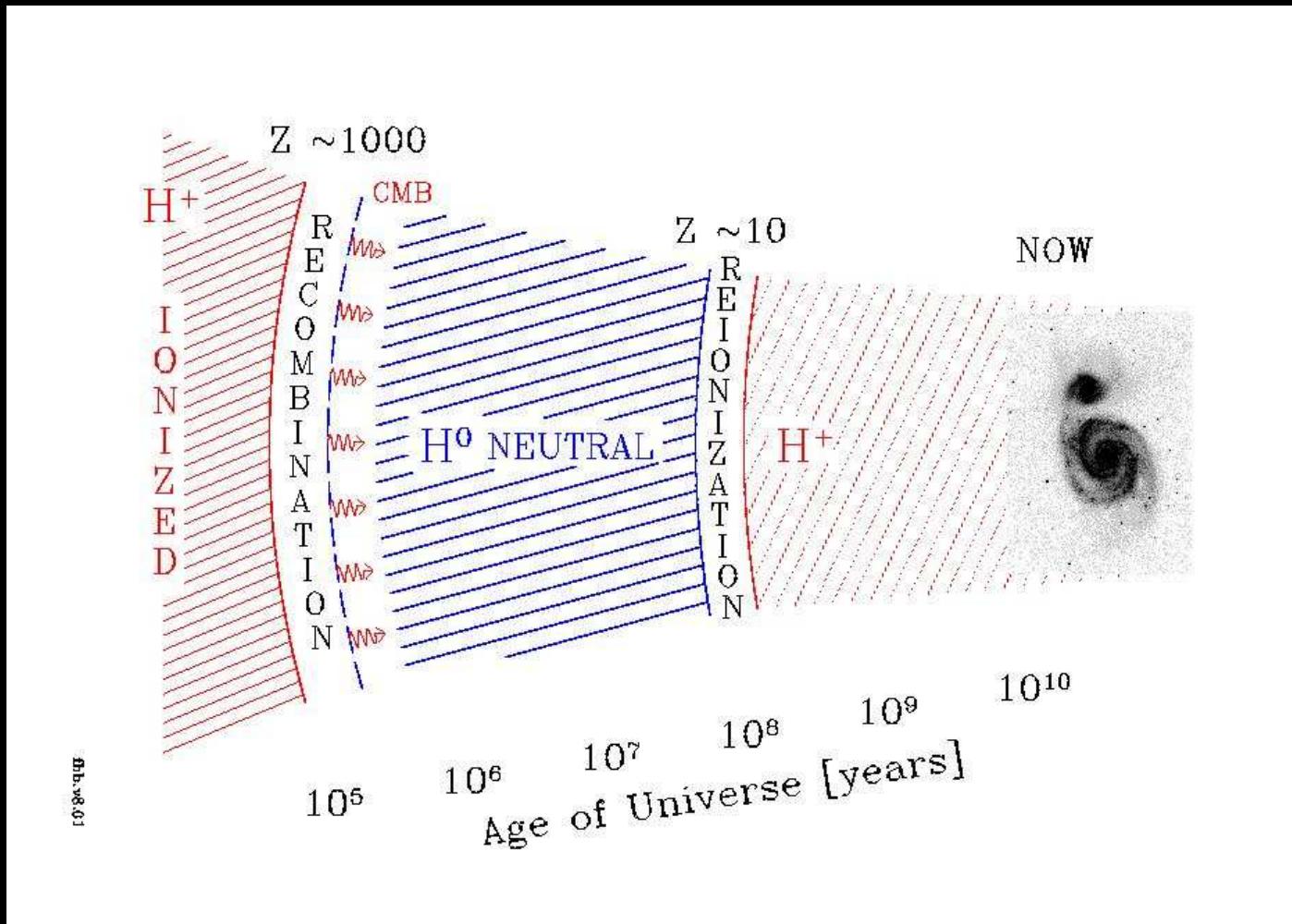
- (1) Instantaneous at $z \simeq 10.4 \pm 1.2$ ($\tau = 0.087 \pm 0.014$), or, more likely:
 - (2) Inhomogeneous & drawn out: starting at $z \gtrsim 20$, peaking at $z \simeq 11$, ending at $z \simeq 7$. The implications for HST and JWST are:
 - HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7\text{--}9$.
 - For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15\text{--}20$.
- \Rightarrow JWST must cover $\lambda = 0.7\text{--}29 \mu\text{m}$, with its diffraction limit at $2.0 \mu\text{m}$.

- (3) What is First Light and Reionization?



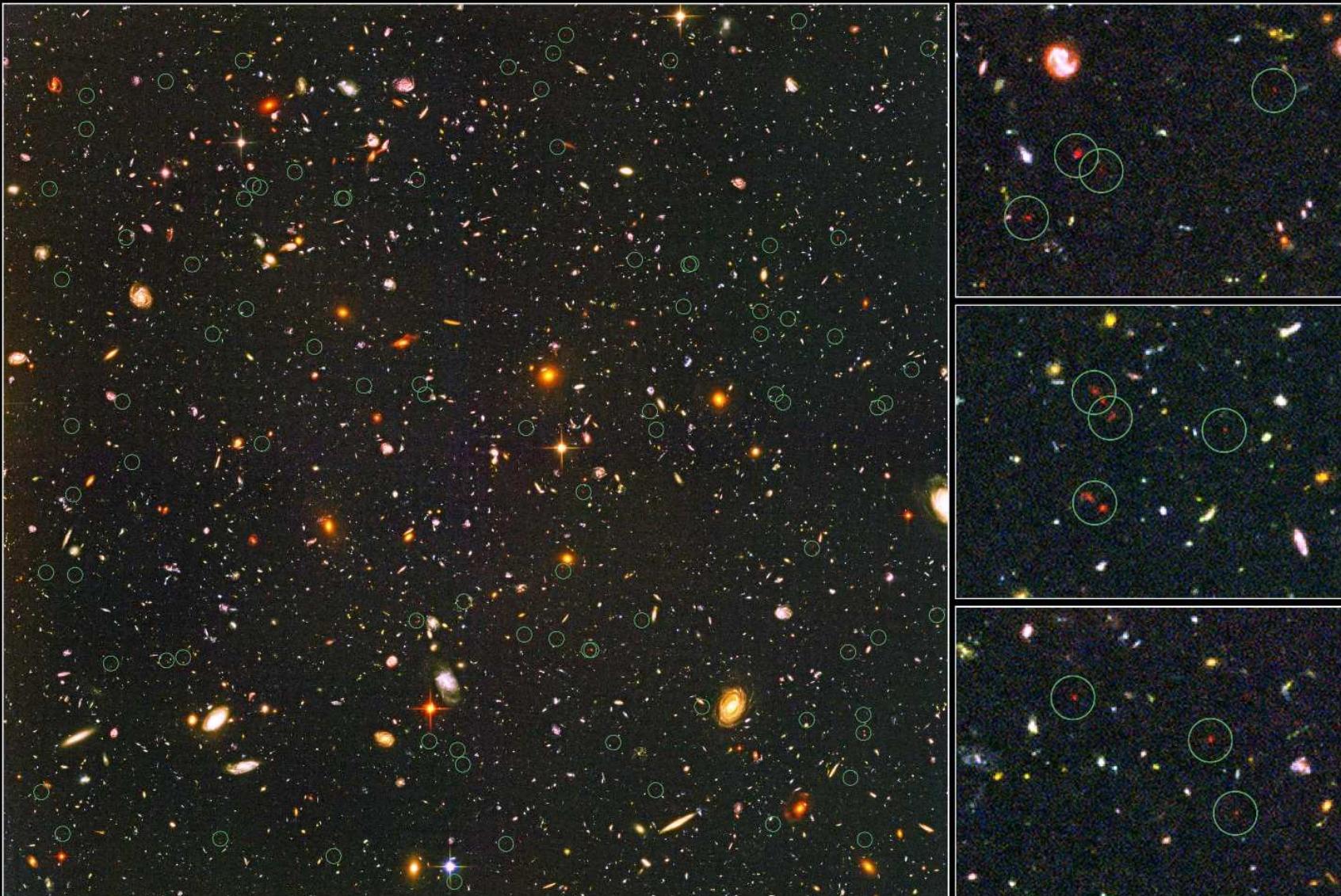
- Detailed Hydrodynamical models (V. Bromm) show that formation of Pop III stars reionized universe for the first time at $z \lesssim 10-30$ (First Light).
- A this should be visible to JWST as the first Pop III stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10-30$.

- (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 $z \approx 11-20$ (First Light).
 - (2) First Population II stars (halo stars) form in dwarf galaxies of mass $\approx 10^7$ to $10^9 M_{\odot}$ at $z \approx 6-9$, which complete reionization by $z \approx 6$.
- ⇒ JWST needs NIRCam at 0.8–5 μm and MIRI at 5–29 μm .

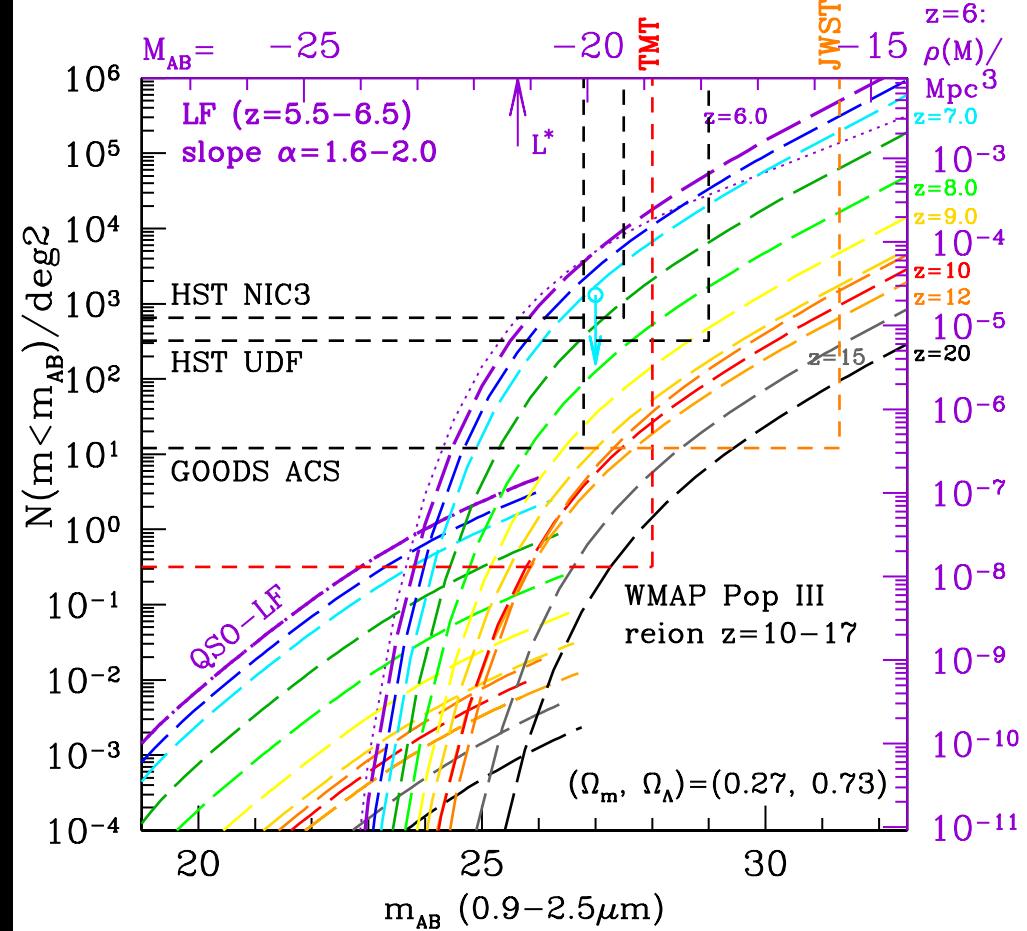
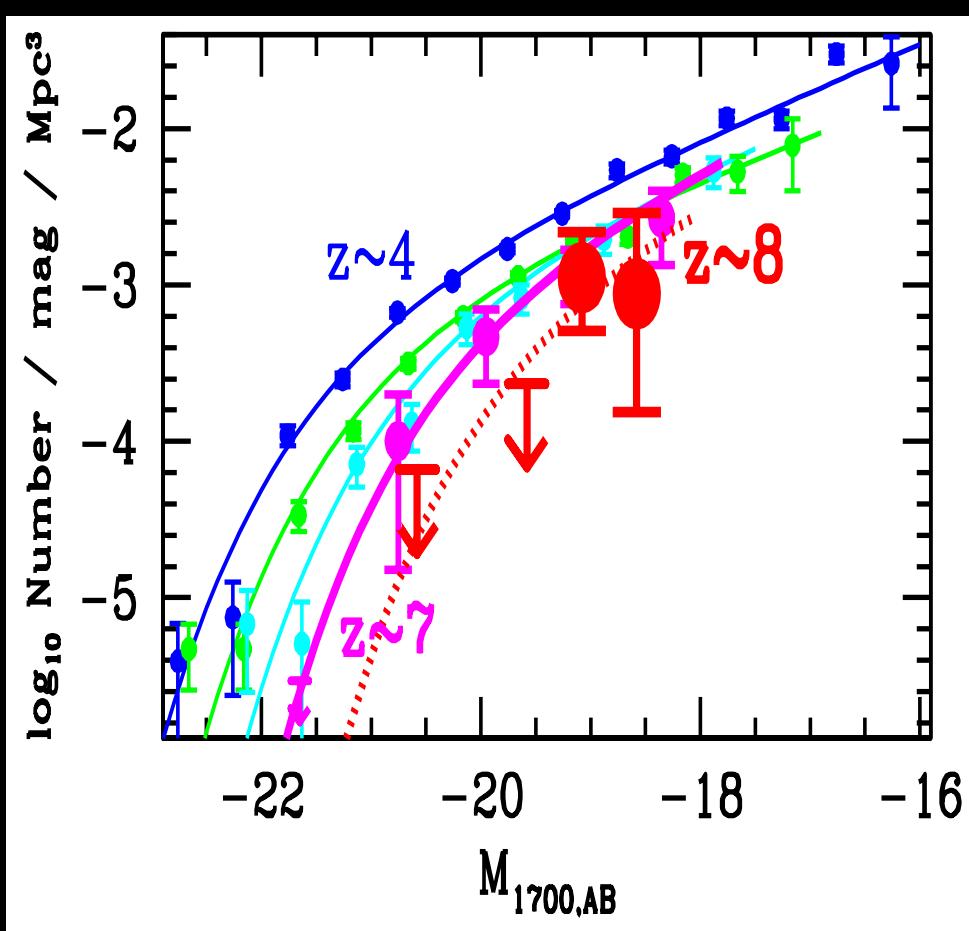


Distant Galaxies in the Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

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

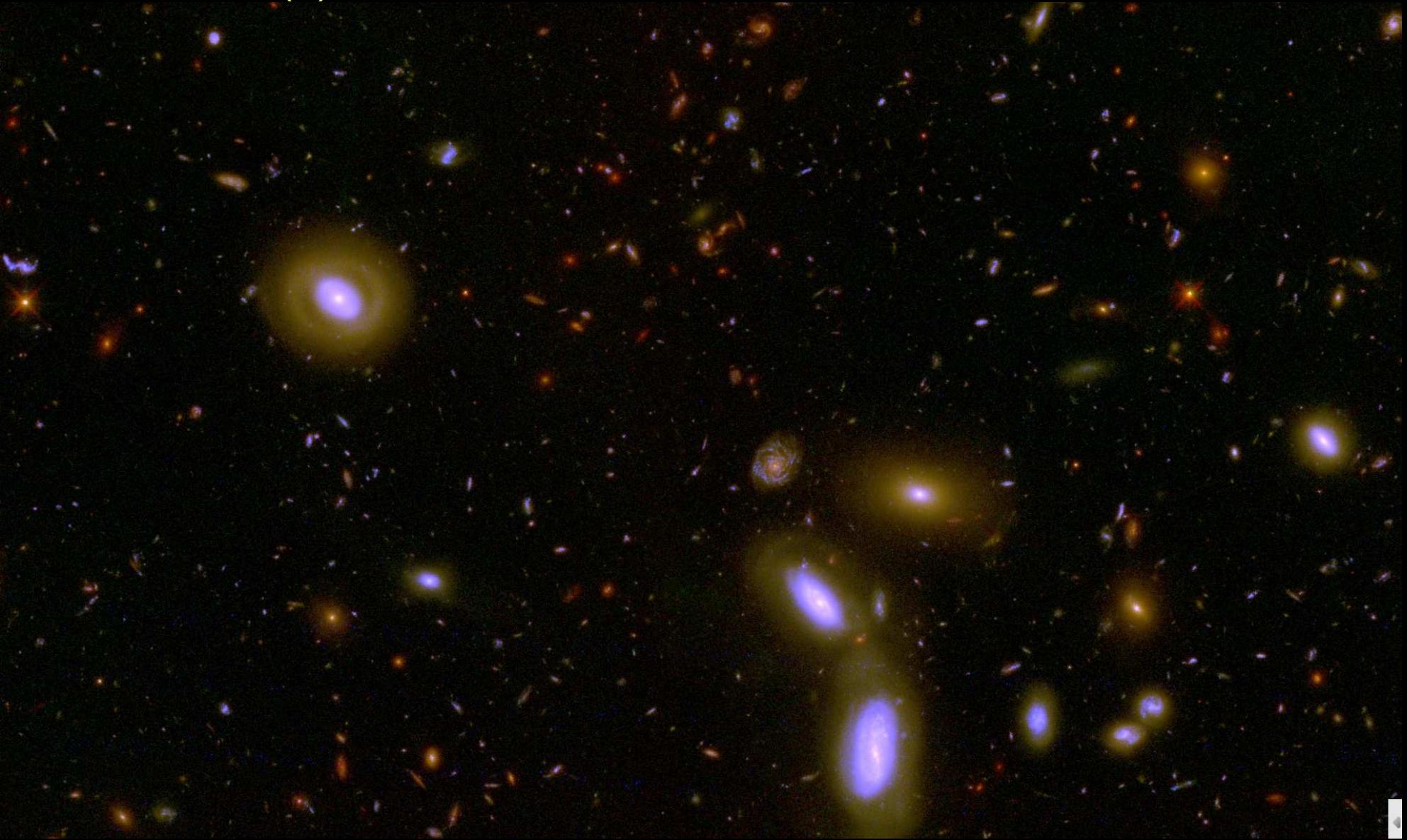
STScI-PRC04-28

HUDF i-drops: faint galaxies at $z \approx 6$ (Yan & Windhorst 2004), most spectroscopically confirmed at $z \approx 6$ 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 ($0.7-29 \mu m$).
- 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.

- (4) How can JWST measure Galaxy Assembly?



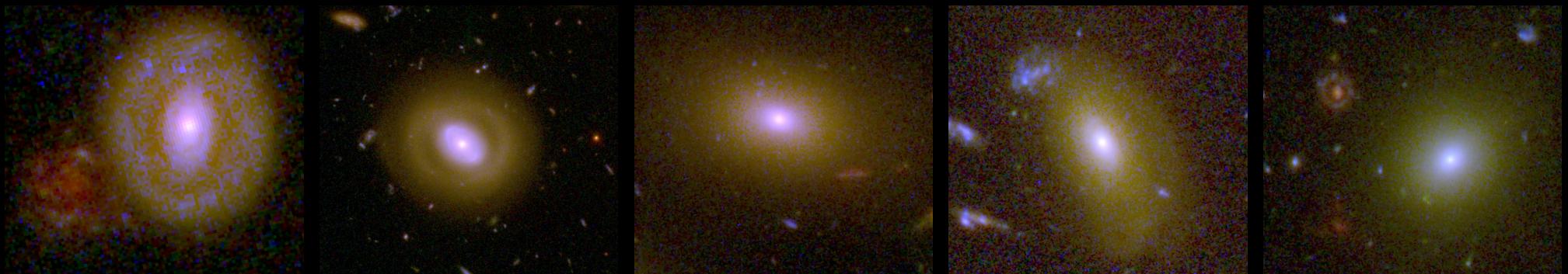
10 filters with HST/WFC3 & ACS reaching AB=26.5–27.0 mag (10- σ) over 40 arcmin² at 0.07–0.15" FWHM from 0.2–1.7 μ m (UVUBVizYJH).

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

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



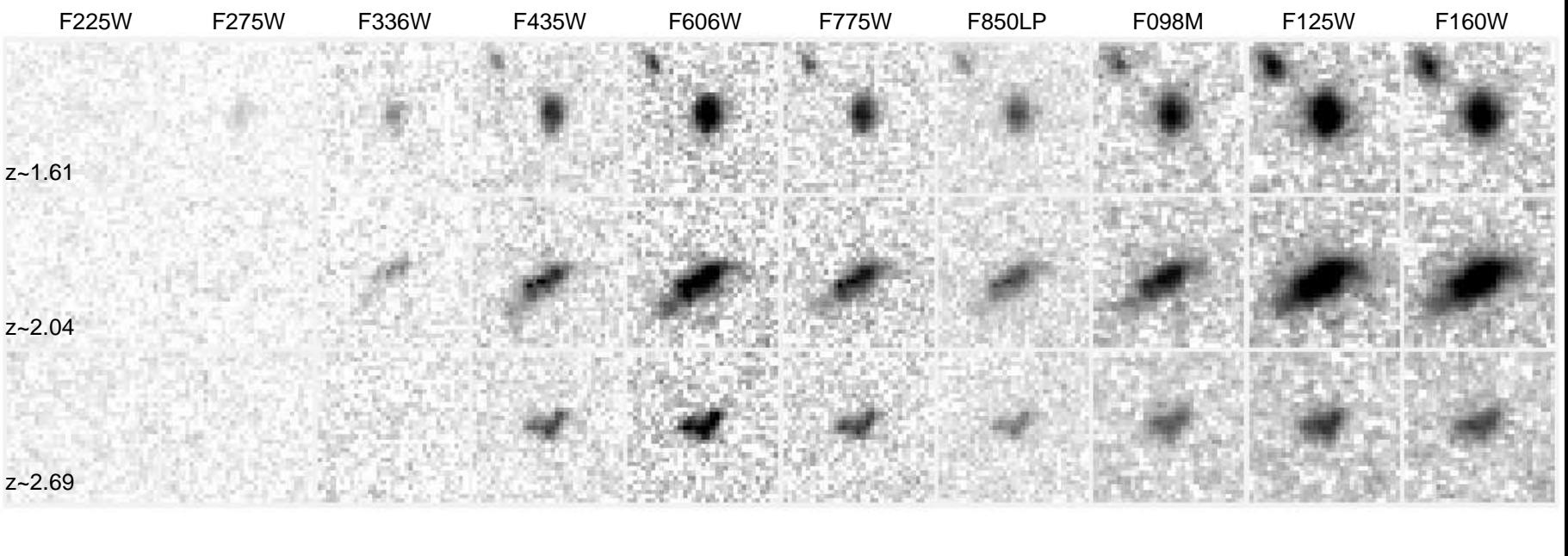
Galaxy structure at the peak of the merging epoch ($z \approx 1-2$) is very rich: some resemble the cosmological parameters H_0 , Ω , ρ_O , w , and Λ , resp.



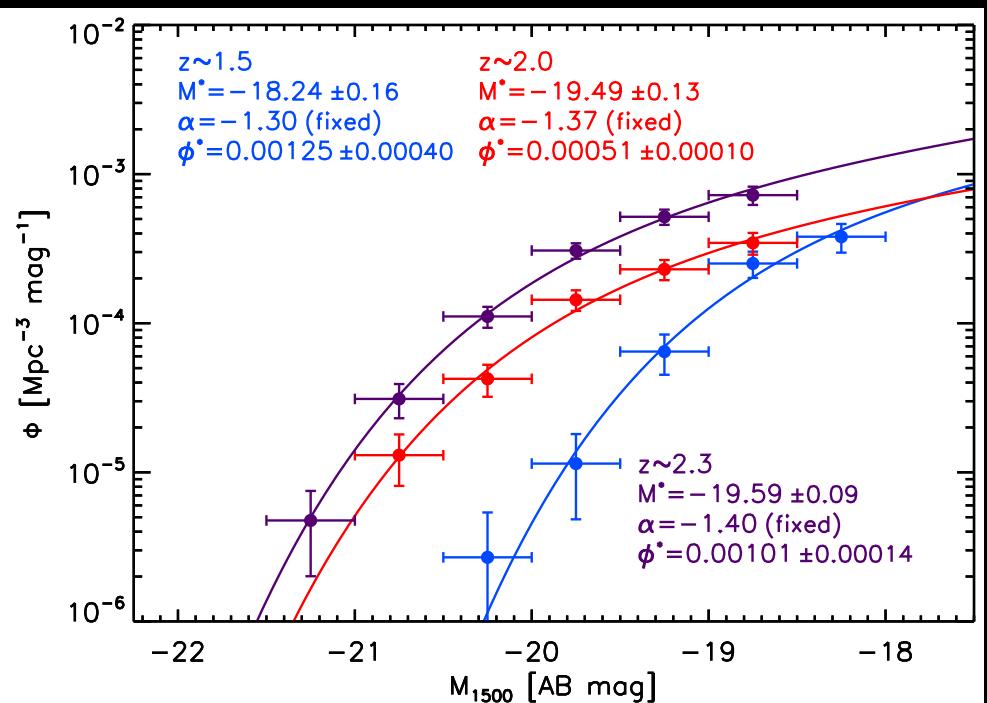
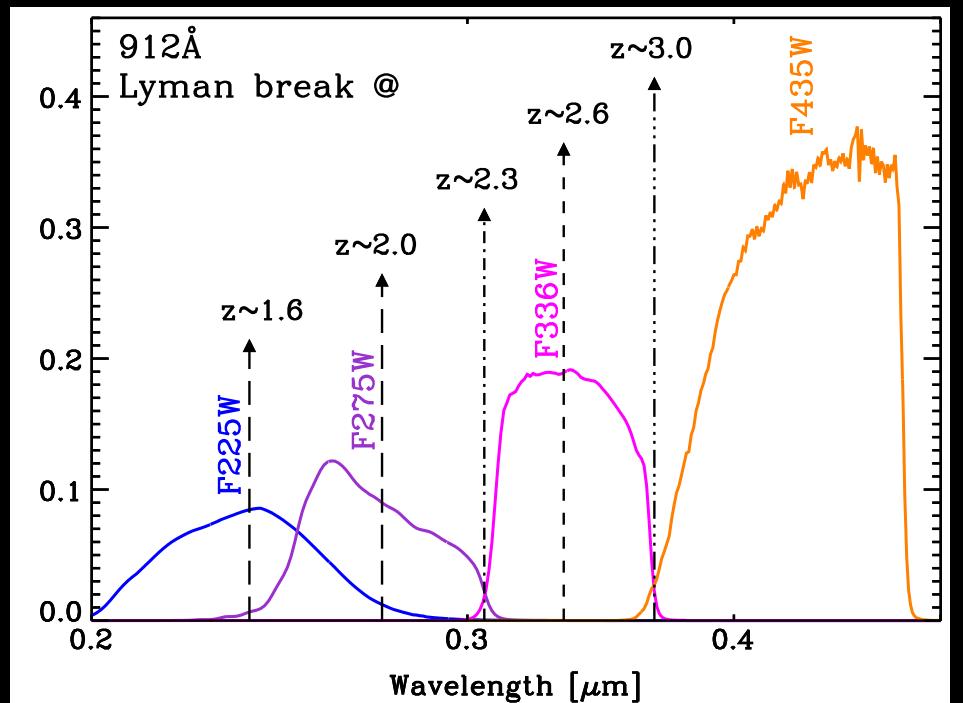
Panchromatic WFC3 ERS images of early-type galaxies with nuclear star-forming rings, bars, weak AGN, or other interesting nuclear structure.

(Rutkowski et al. 2010) \Longrightarrow “Red and dead” galaxies aren’t dead!

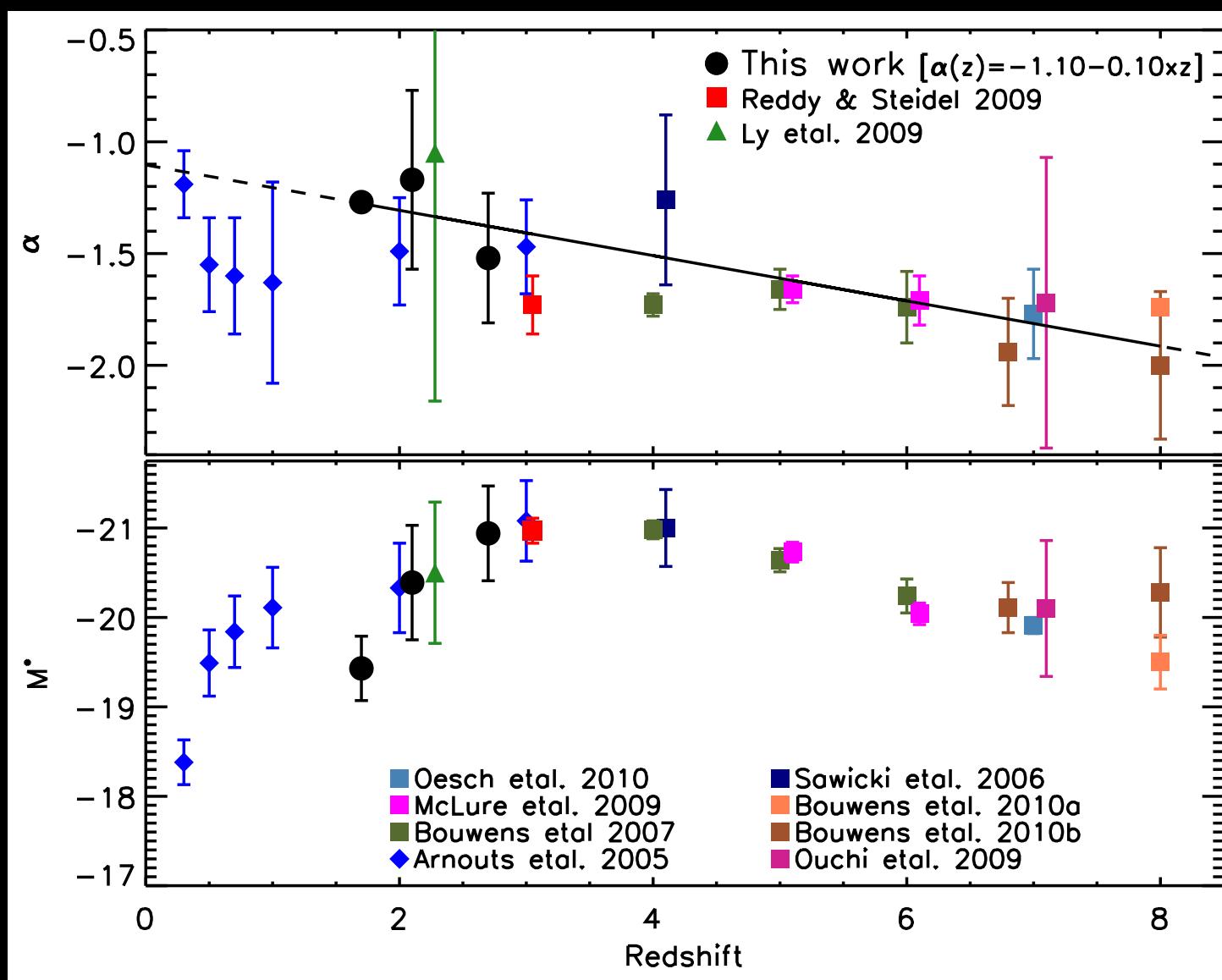
- JWST will observe all such objects from 0.7–29 μm wavelength.



Lyman break galaxies at the peak of cosmic SF ($z \approx 1-3$; Hathi et al. 2010)

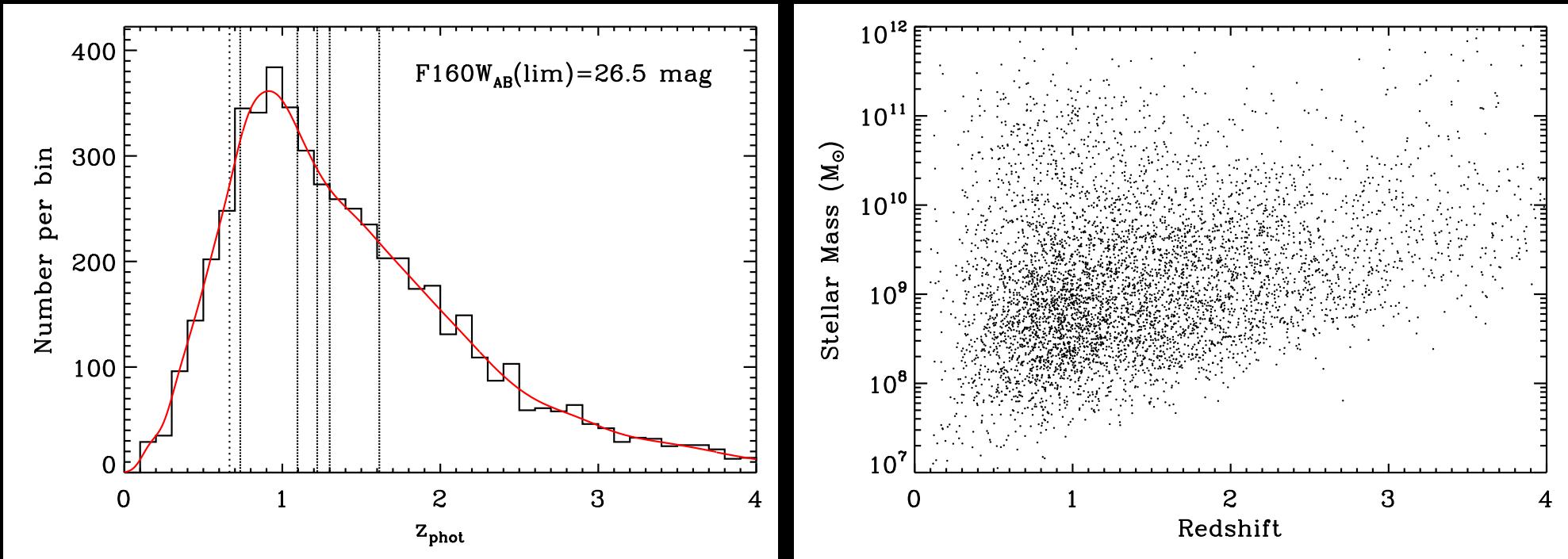


- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.



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 $M^* \gtrsim -19$!

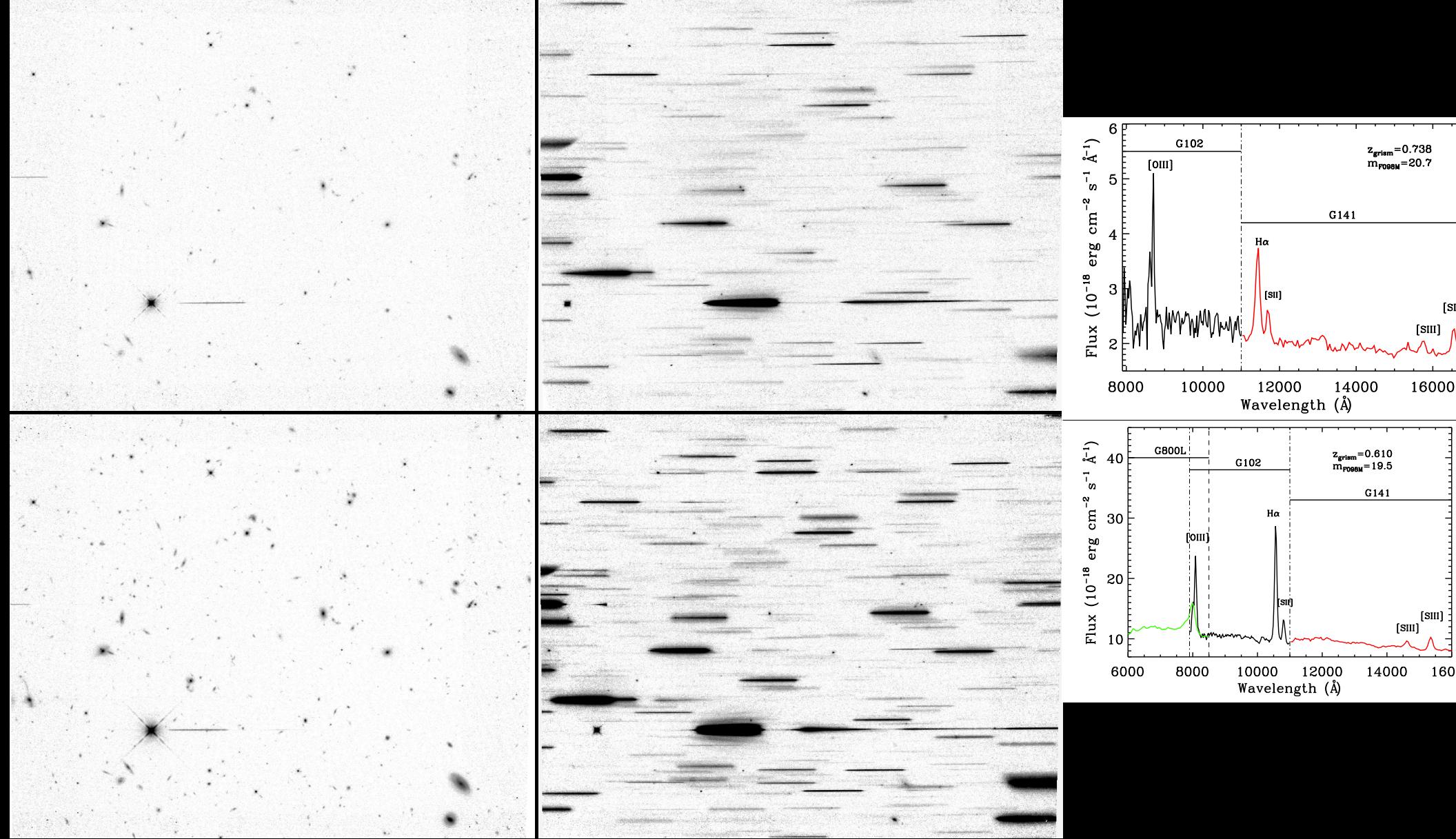


ERS 10-band redshift estimates accurate to $\sim 4\%$ with small systematic errors (Cohen et al. 2010), resulting in a reliable redshift distribution.

- 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 $z \simeq 0-7$.

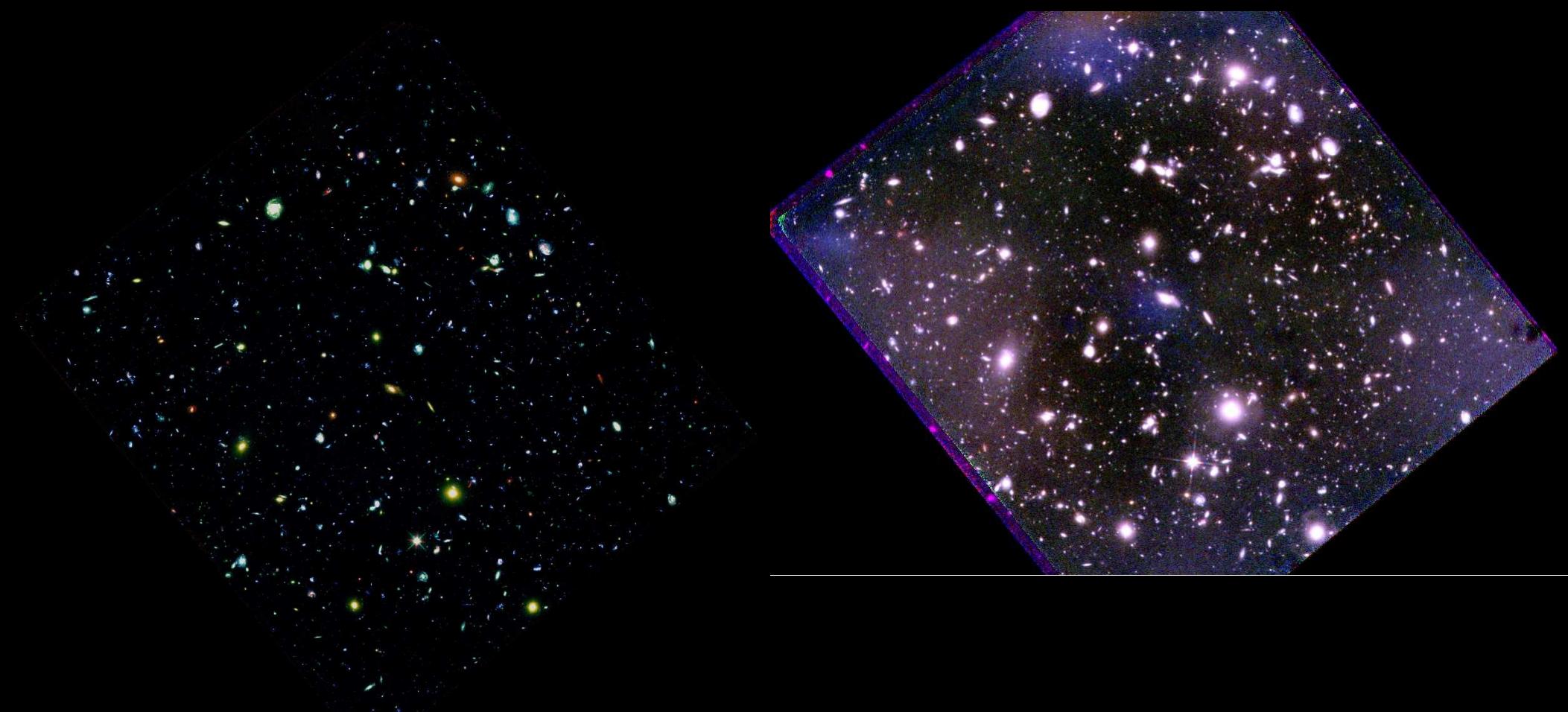
- The HUDF (Illingworth's talk) shows WFC3's capabilities at $z \simeq 7-9$.
- \Rightarrow WFC3 is an essential pathfinder at $z \lesssim 8$ for JWST (0.7–29 μm) at $z \gtrsim 9$.
- JWST will trace mass assembly and dust content 3–4 mags deeper from $z \simeq 1-12$, with nanoJy sensitivity from 0.7–5 μm .



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

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

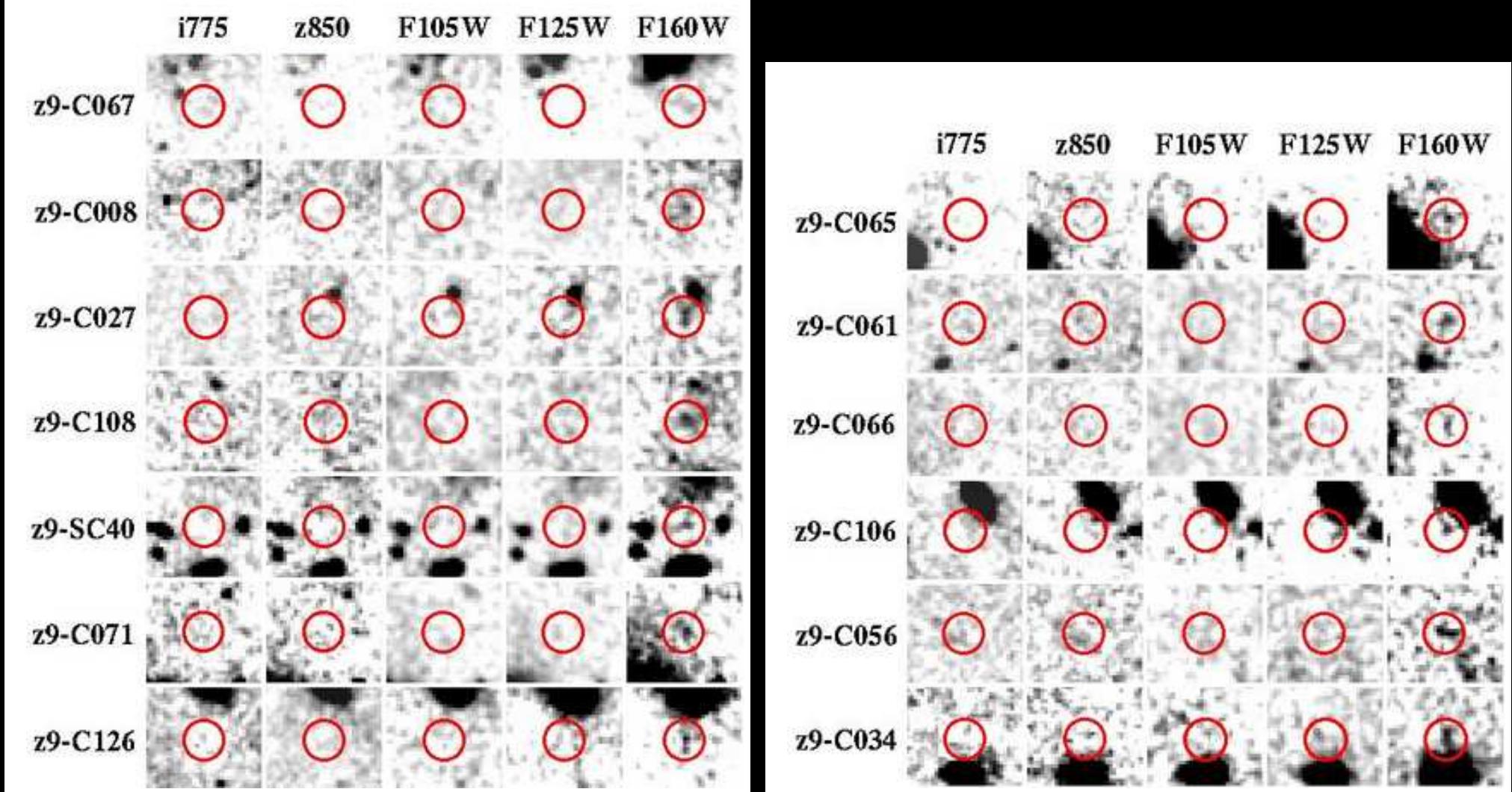
JWST will provide near-IR grism spectra to AB \lesssim 29 mag from 2–5.0 μ m.



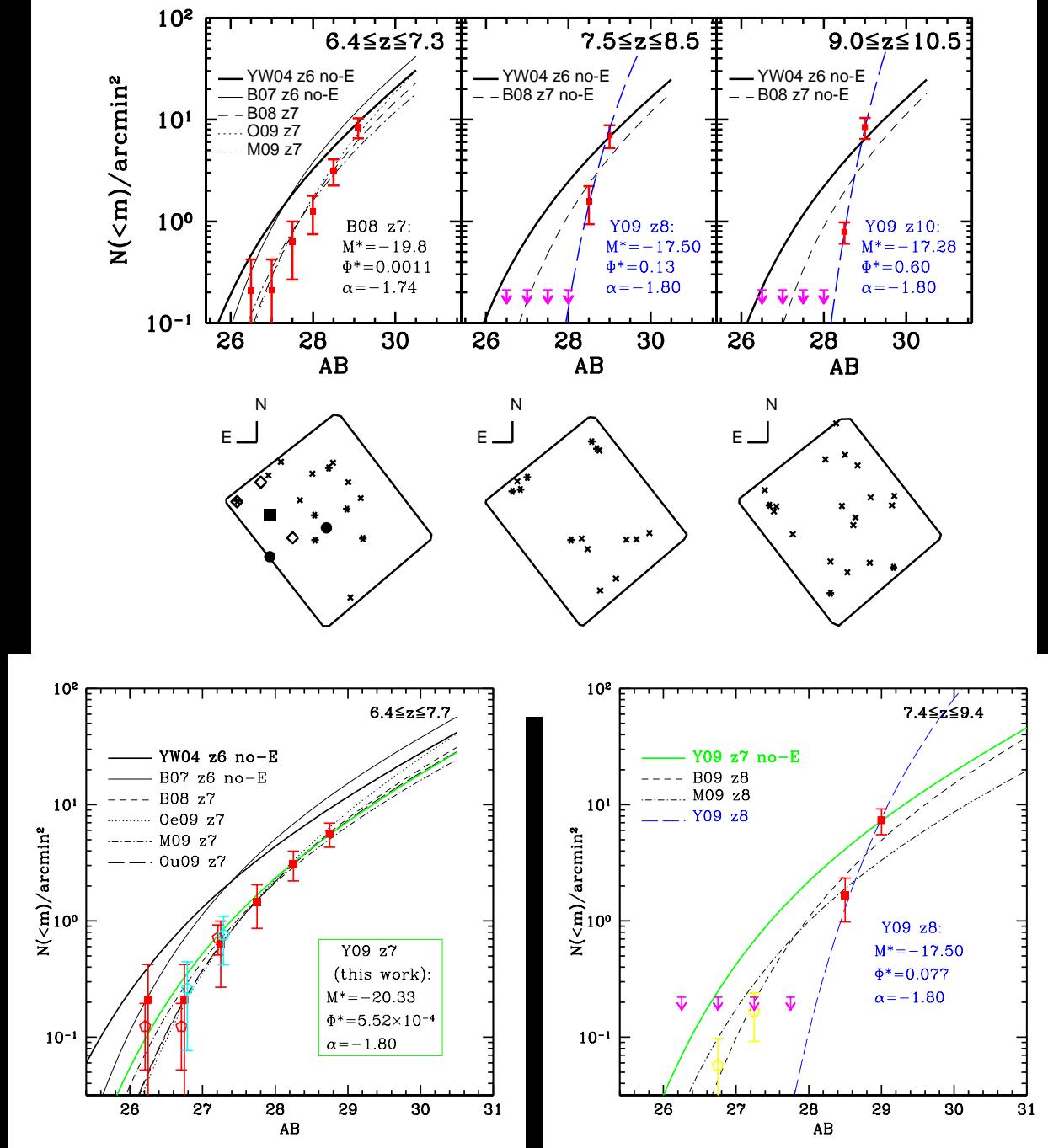
(Left) HST/WFC3 IR-mosaic in YJH in the HUDF: Bouwens et al (2010), Yan et al. (2009; astro-ph/0910.0077).

(Right) Same WFC3 IR-mosaic, but stretched to $\lesssim 10^{-3}$ of Zodi sky!!

- The CLOSED-TUBE HST has residual low-level systematics: imperfect removal of detector artifacts, flat-fielding errors, and/or faint straylight.
- The open JWST architecture needs perfect baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.

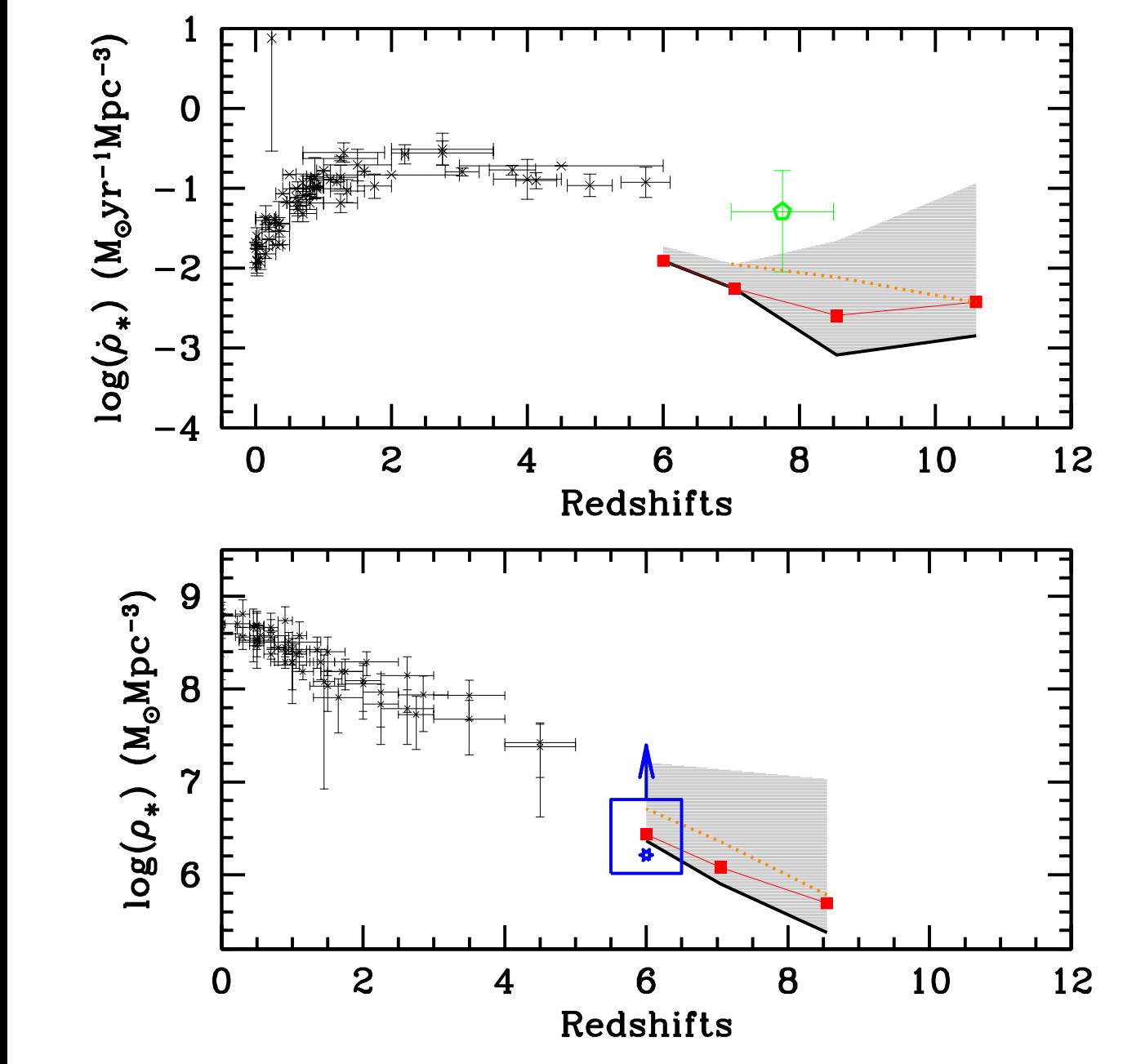


- Our simulations show that $\sim 50\%$ of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at $z \gtrsim 9$. Together with the HUDF and ERS upper limits to $AB \lesssim 28$ mag, the $z \sim 9$ LF is 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?



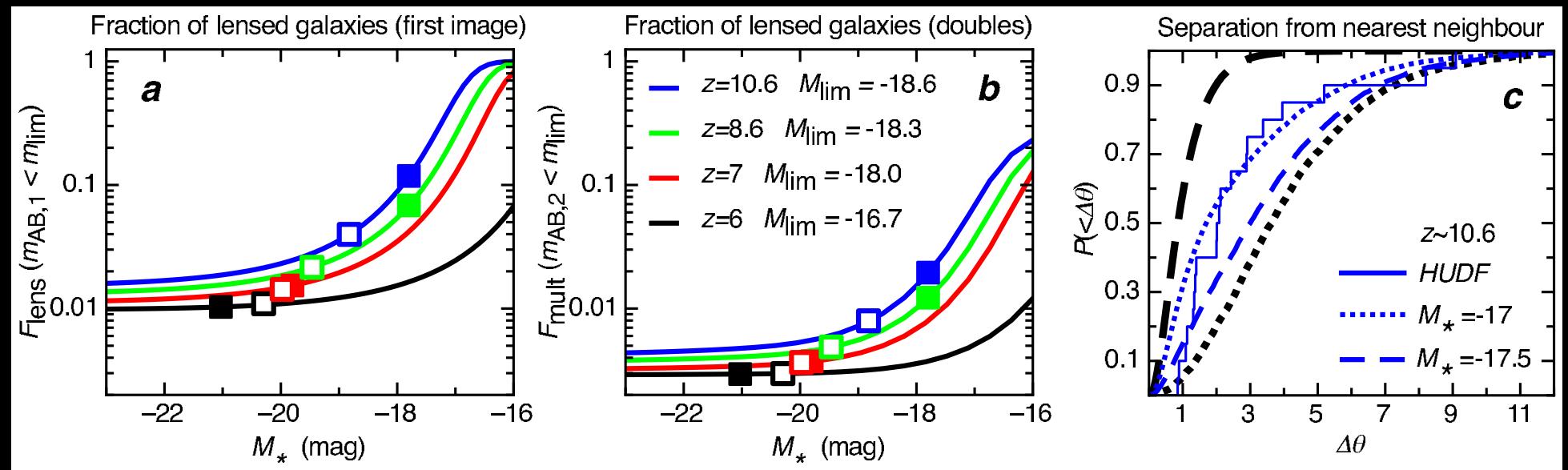
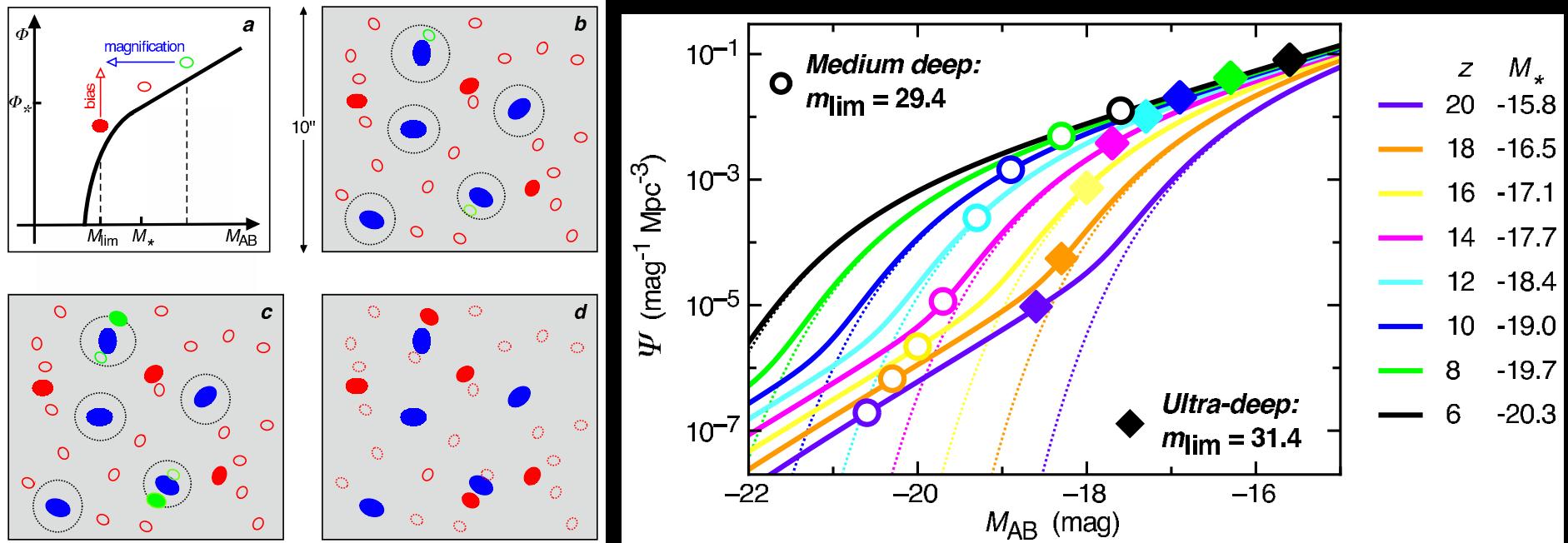
Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

- 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 $8 \lesssim z \lesssim 15$.



Wyithe et al. (2010, Nature, in press): With a steep faint-end LF-slope $\alpha \gtrsim 2$, and a characteristic faint $M^* \gtrsim -19$ mag, foreground galaxies (at $z \approx 1-2$) may cause significant boosting by gravitational lensing at $z \gtrsim 8-10$.

- This could change the landscape for JWST observing strategies.

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

NGC 3310



ESO0418-008



UGC06471-2



Ultraviolet Galaxies

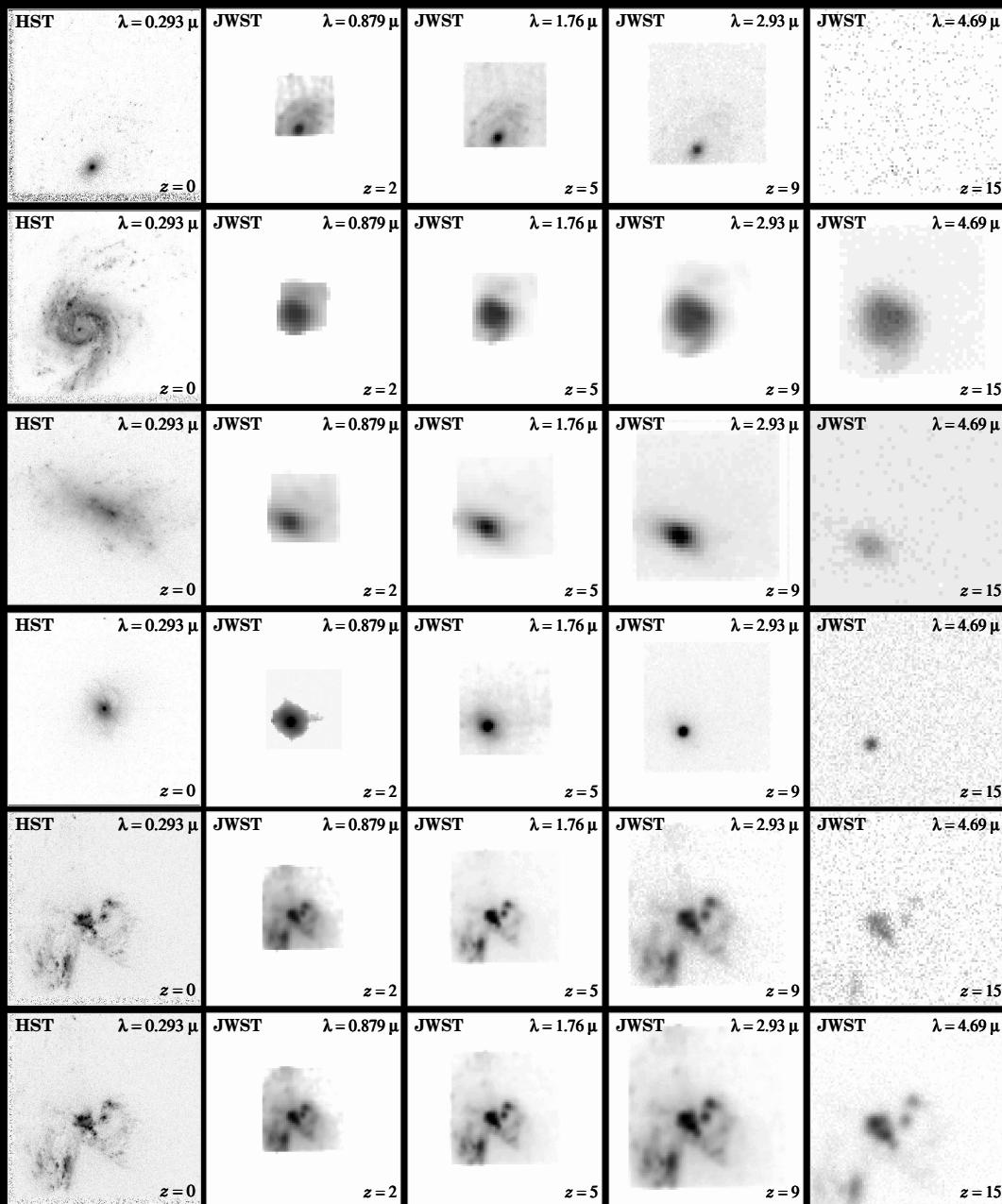
NASA and R. Windhorst (Arizona State University) • STScI-PRC01-04

HST • WFPC2

- 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 $z \simeq 1-15$ (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.

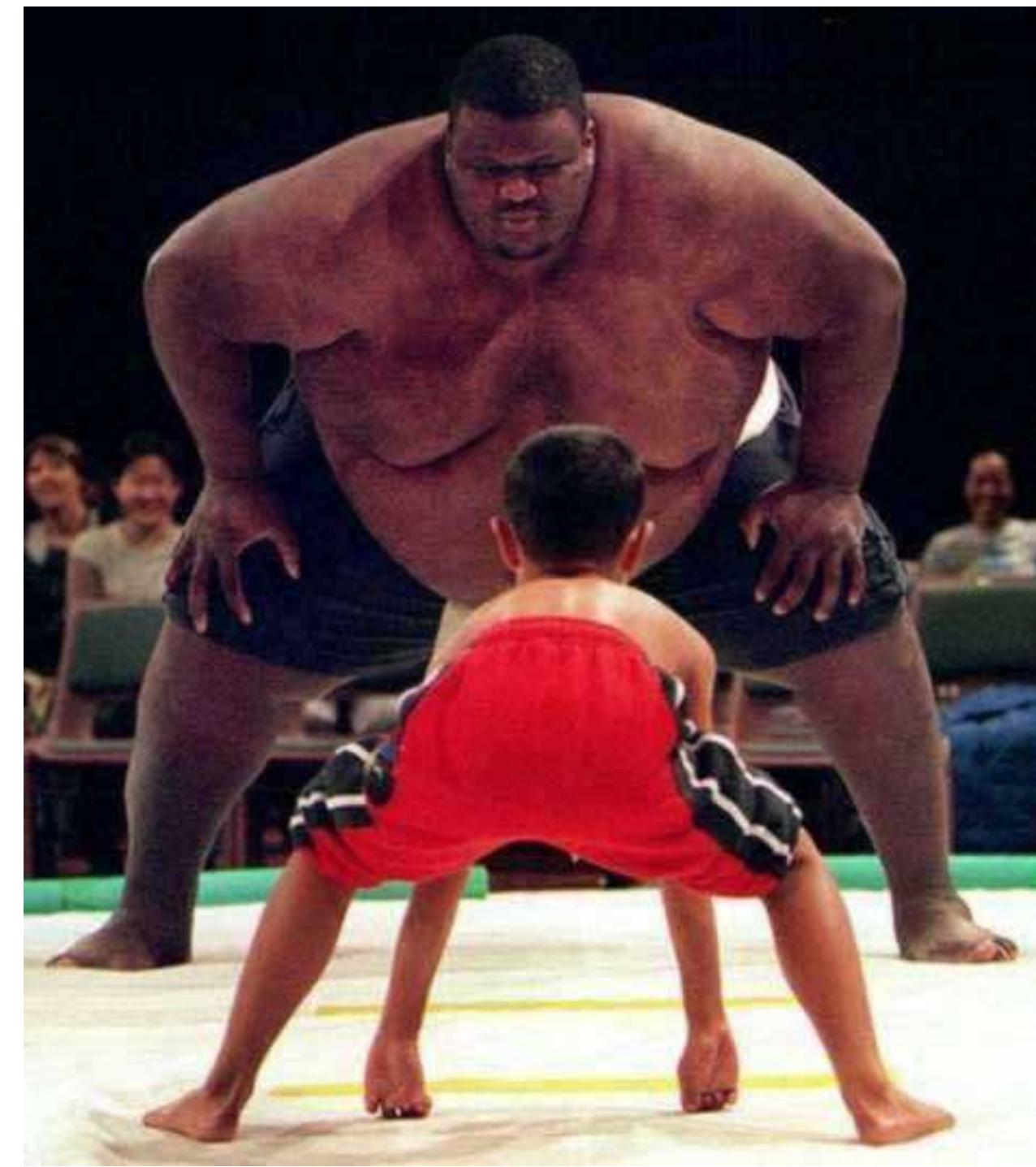
(2) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail. JWST will determine:

- 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

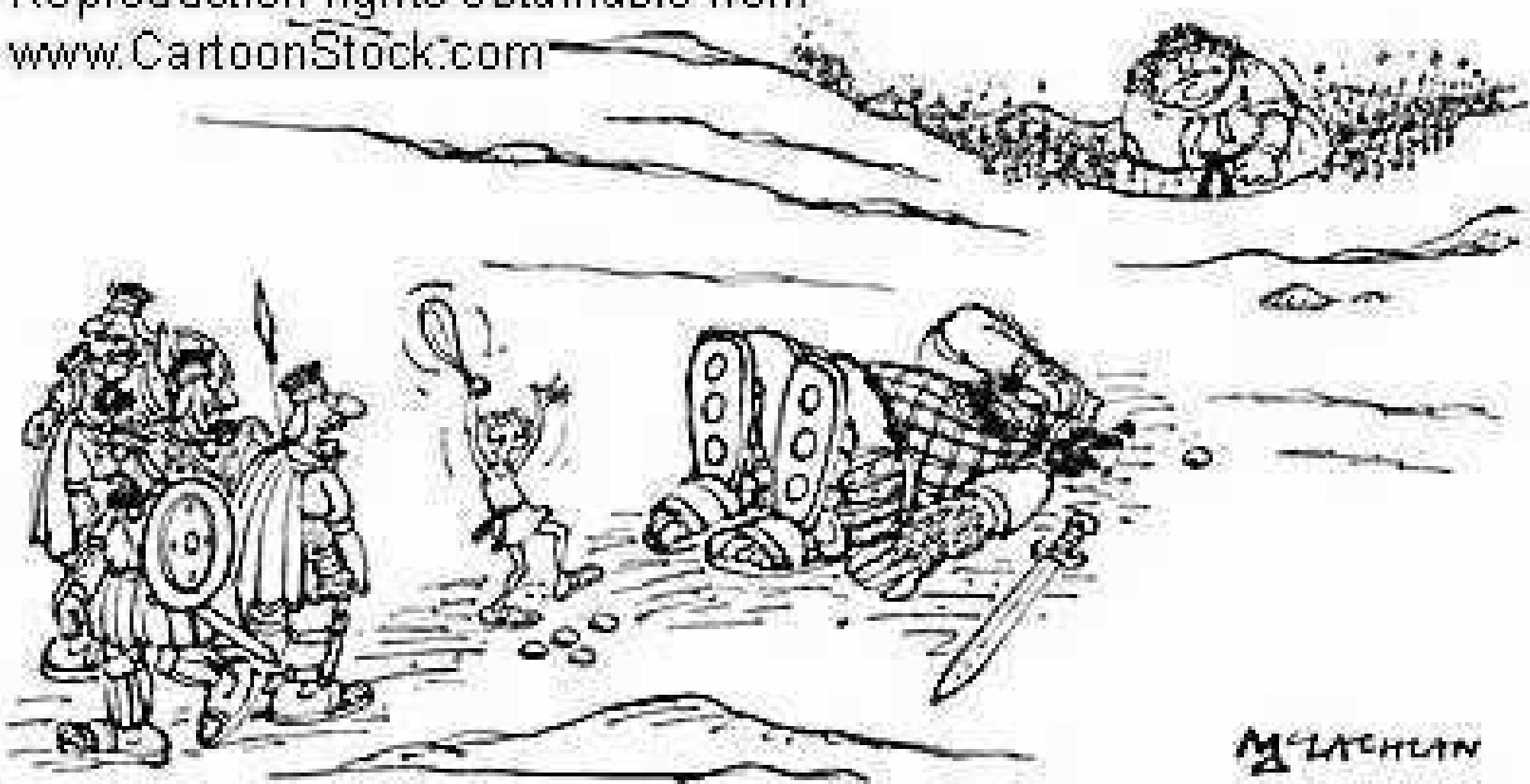


At the end of reionization, dwarfs had beaten the Giants, but ...

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

What comes around, goes around ...

Northrop Grumman Expertise in Space Deployable Systems

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



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



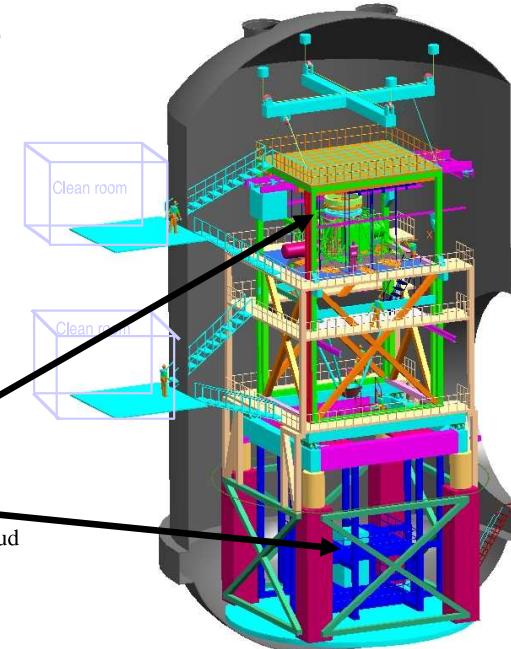
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

Current plan includes 10 trucks of LN2/day during cooldown

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



JSC "Cup Up" Test Configuration (New Proposal)

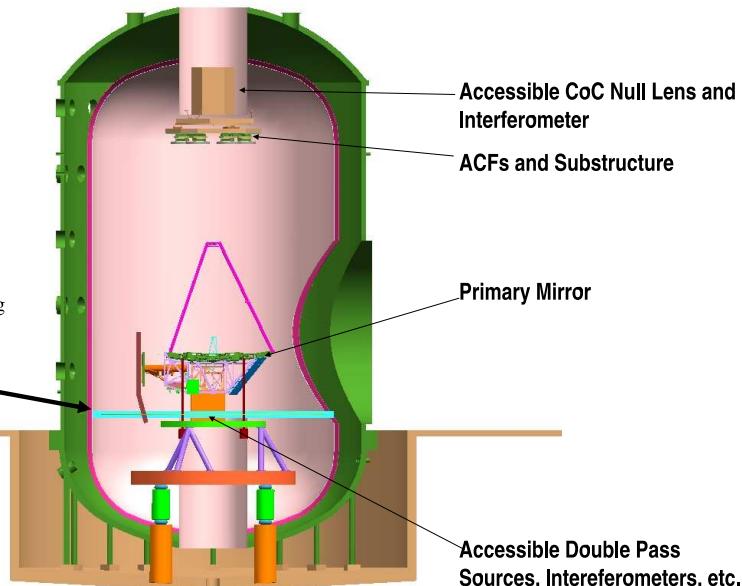


No Metrology Tower and Associated Cooling H/W. External Metrology

Two basic test options:

1. Use isolators, remove drift through fast active control + freeze test equipment jitter
 2. Eliminate vibration isolators (but use soft dampeners) to avoid drift, freeze out jitter
- Builds on successful AMSD heritage of freezing and averaging jitter, testing through windows.

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



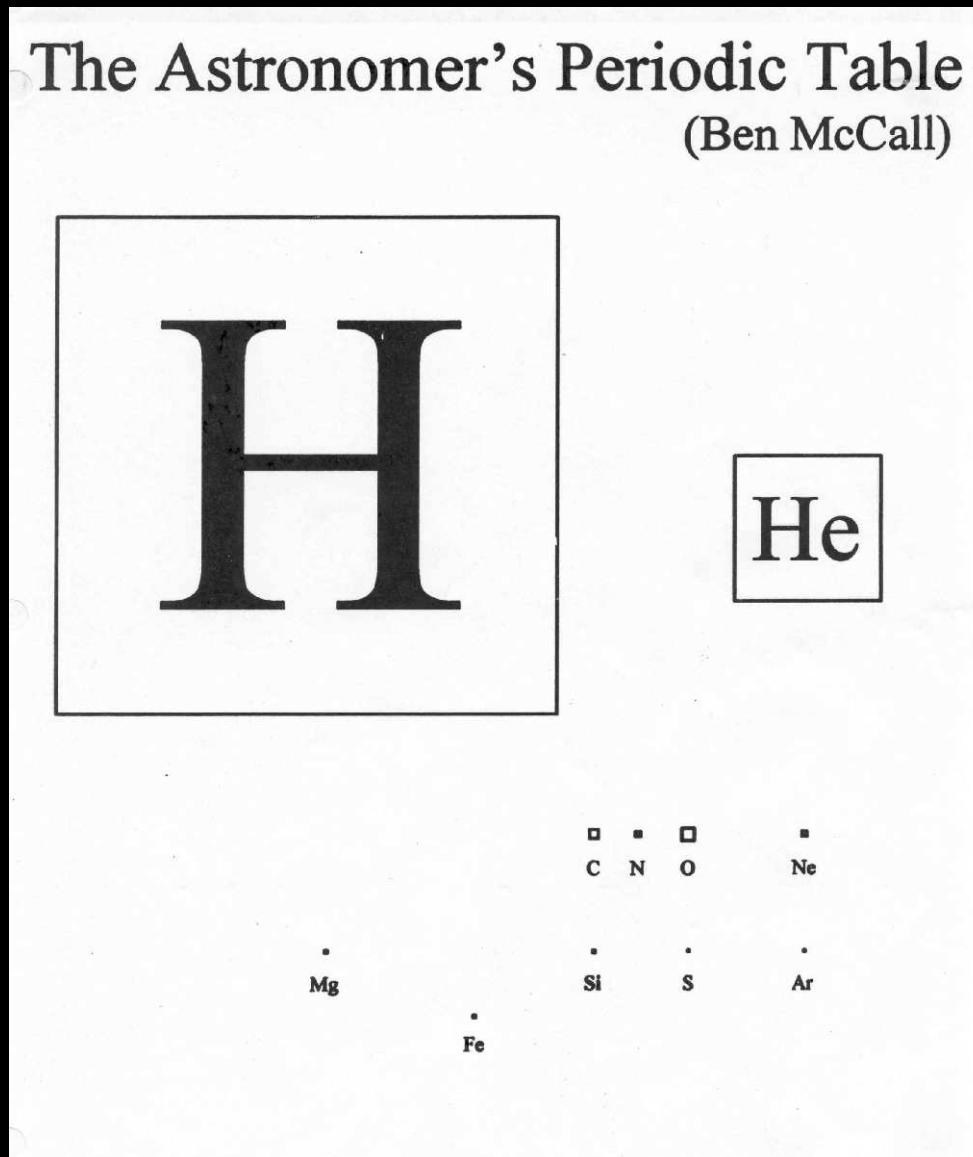
Drawing care of ITT

Page 6

JWST underwent several significant replans and risk-reduction schemes:

- ≈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.

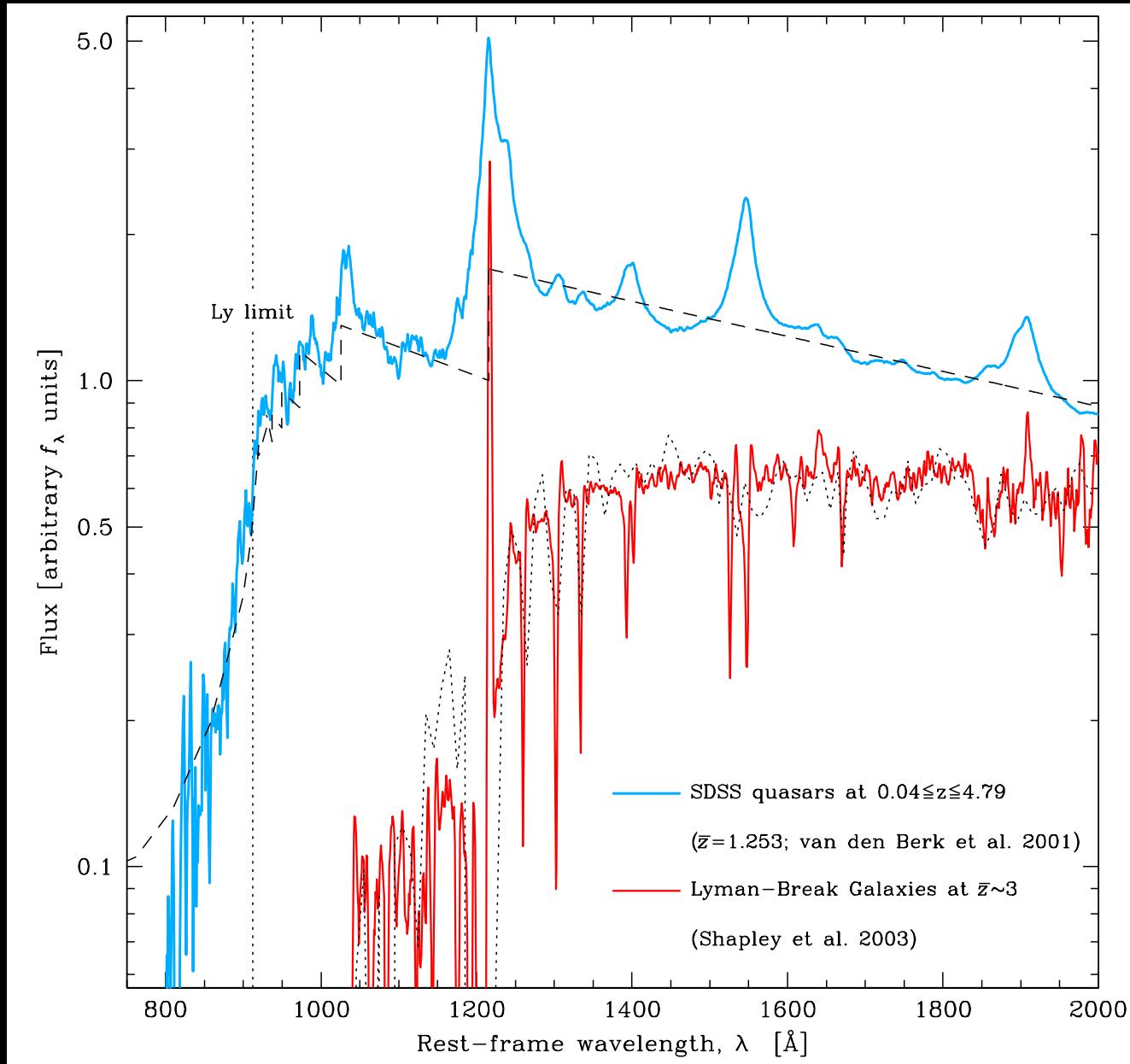
The Universe was reionized (at least) TWICE?:



[Astronomers periodic table — with cosmic abundances included:]

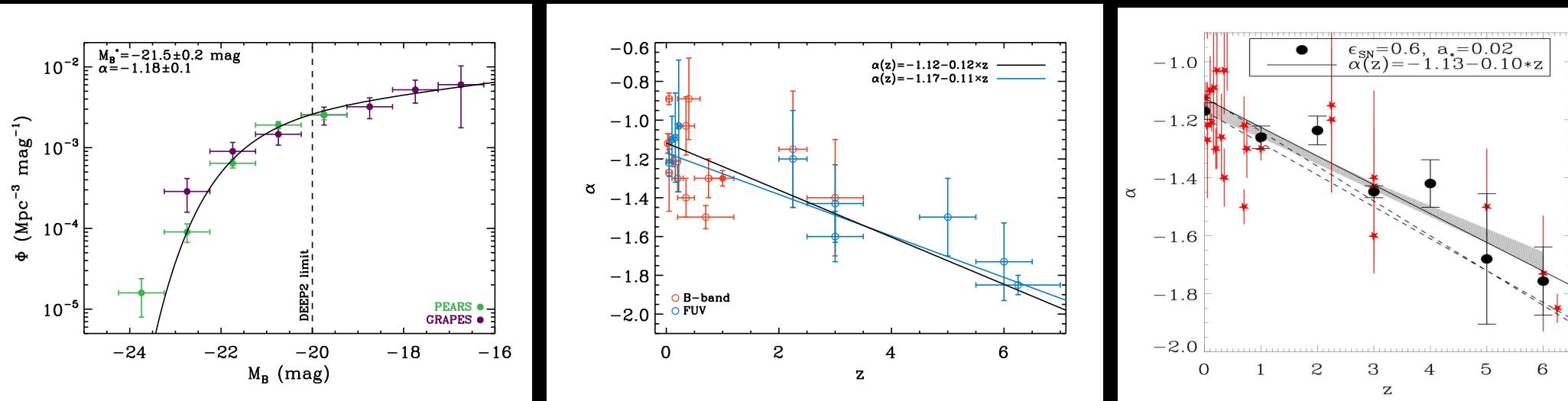
- SF in dwarf galaxies likely caused H-reionization at $z \simeq 12 \rightarrow z \simeq 7$.
- Hard-UV of QSO's and weak AGN likely caused He-reionization $z \simeq 3$.

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.

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?

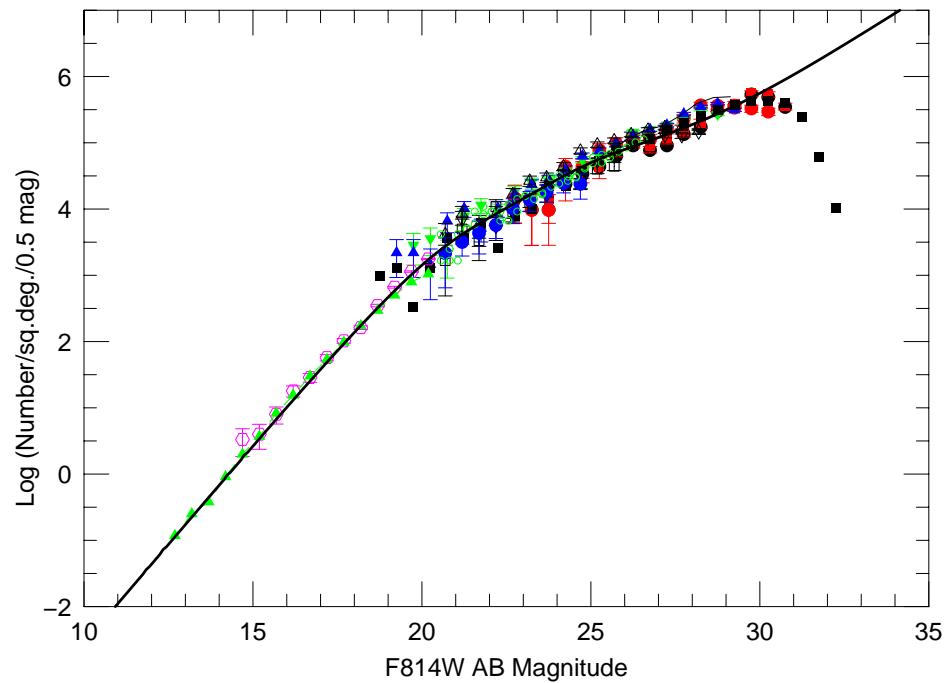
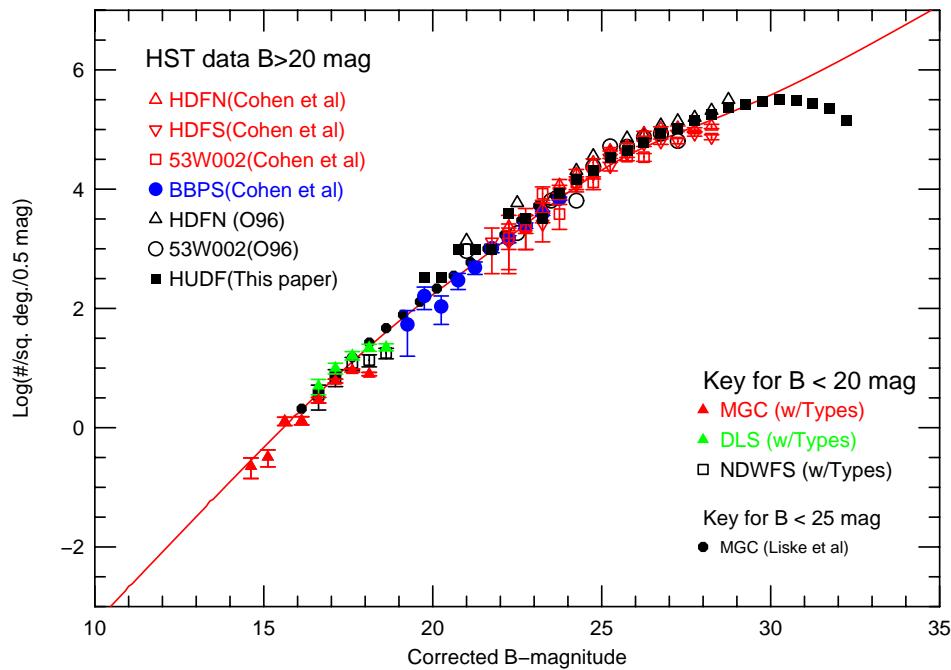
HST helped show how galaxies formed and evolved in the last 12–13 Gyrs:

- 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 $z \simeq 7 \rightarrow 1$ 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.

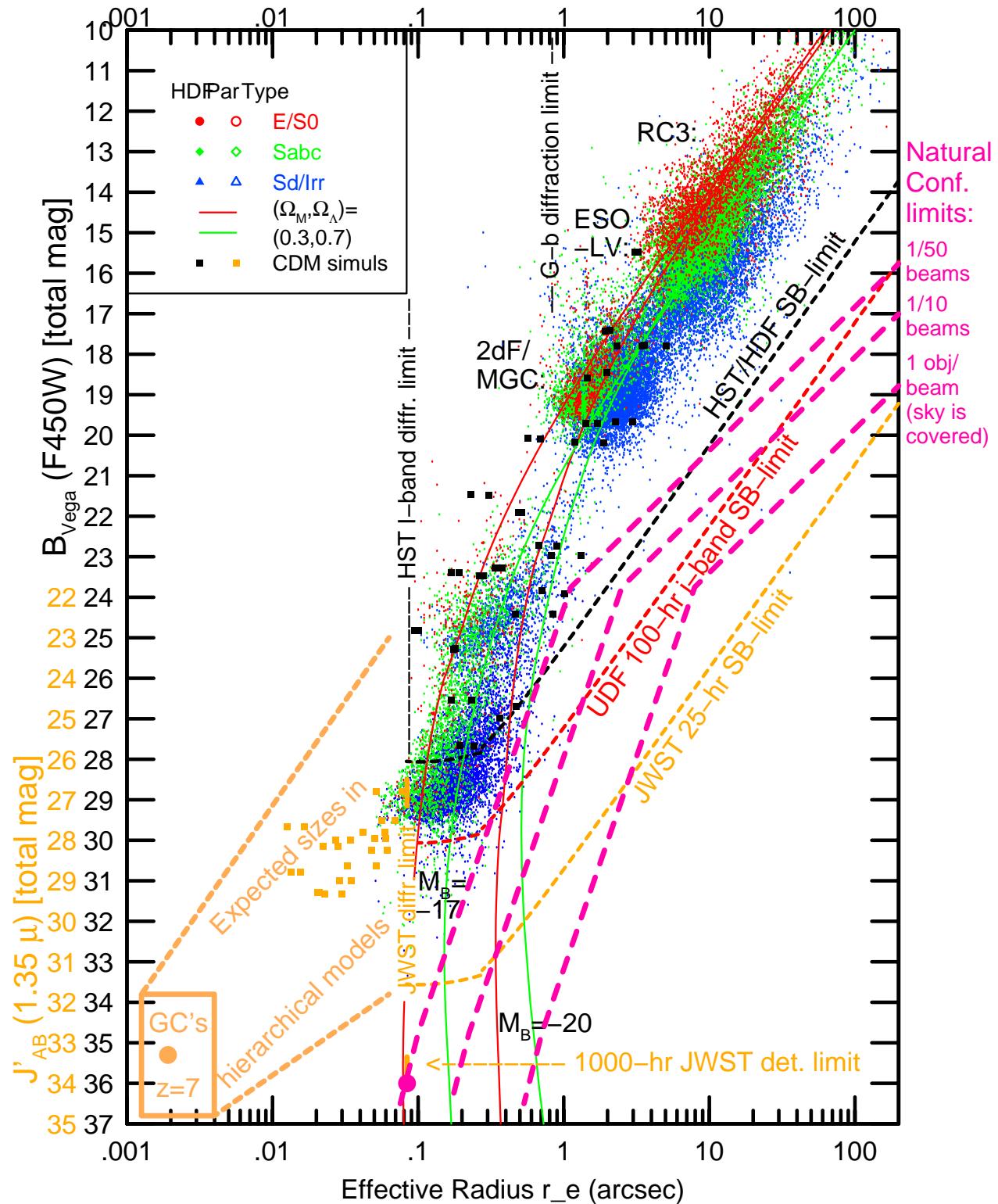
JWST is designed to observe the following re. Galaxy Assembly:

- 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?



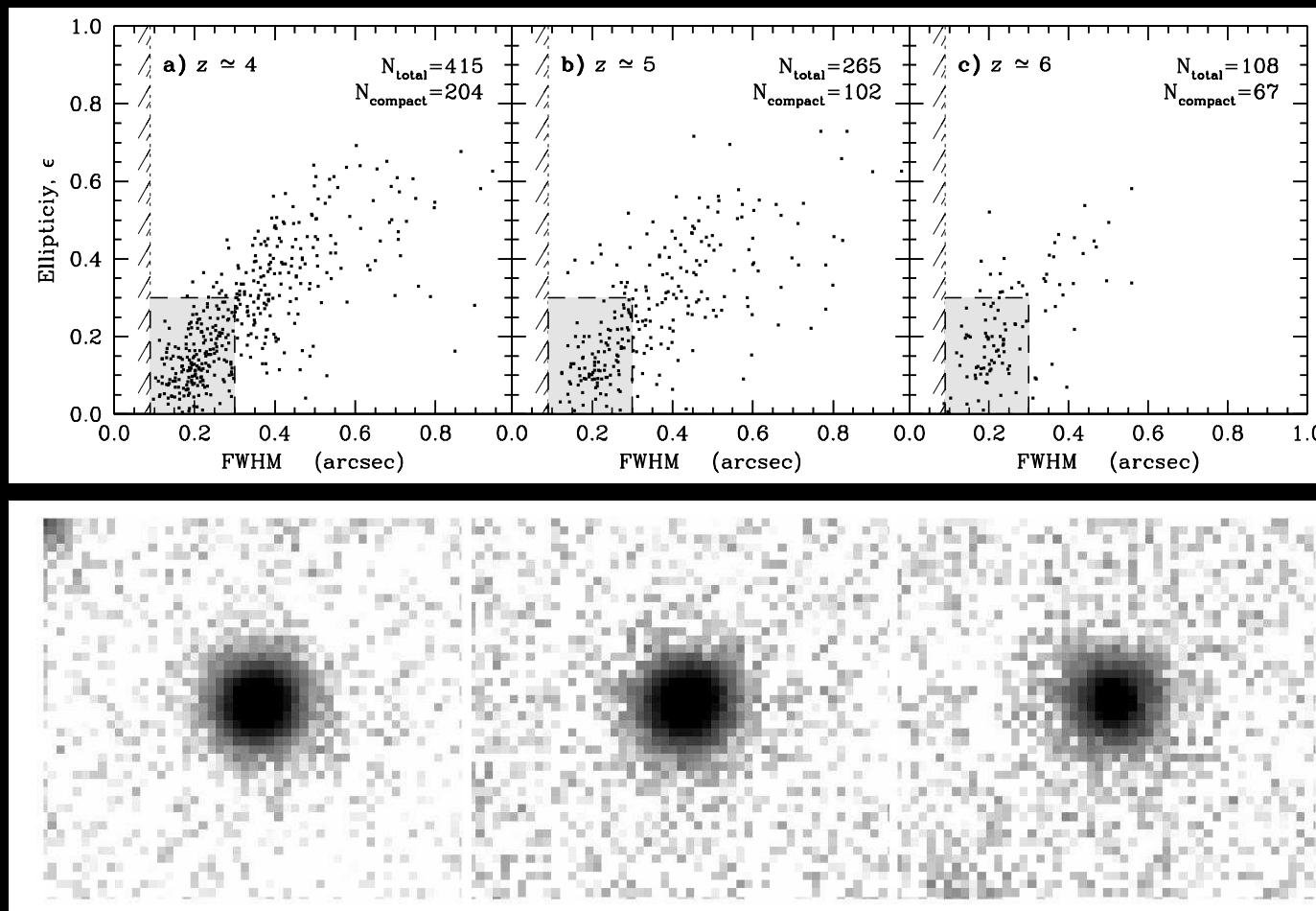
- HUDF galaxy counts (Cohen et al. 2006): expect an integral of $\gtrsim 2 \times 10^6$ galaxies/ deg^2 to AB=31.5 mag ($\simeq 1 \text{ nJy}$ at optical wavelengths). JWST and SKA will see similar surface densities to $\simeq 1$ and 10 nJy , resp.
- ⇒ Must carry out JWST and SKA nJy-surveys with sufficient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



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

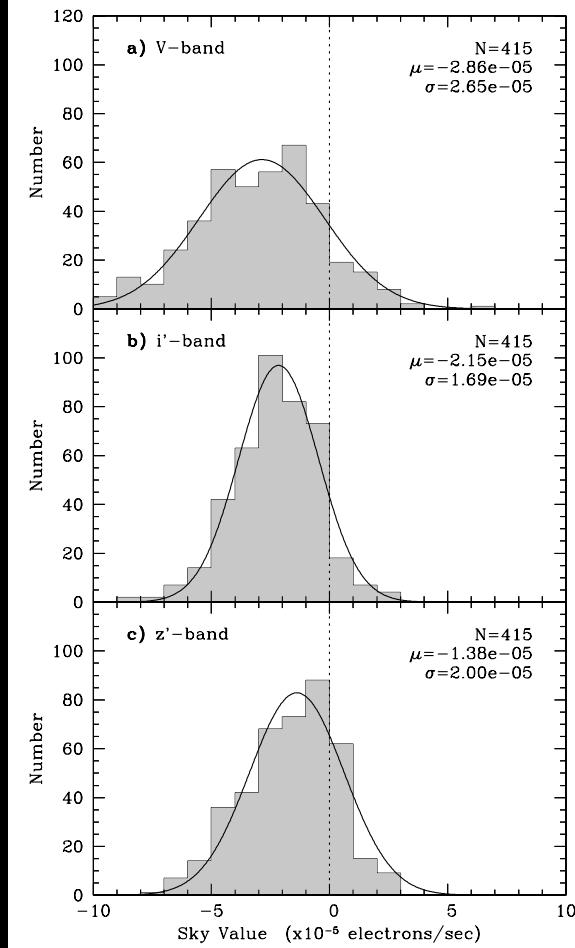
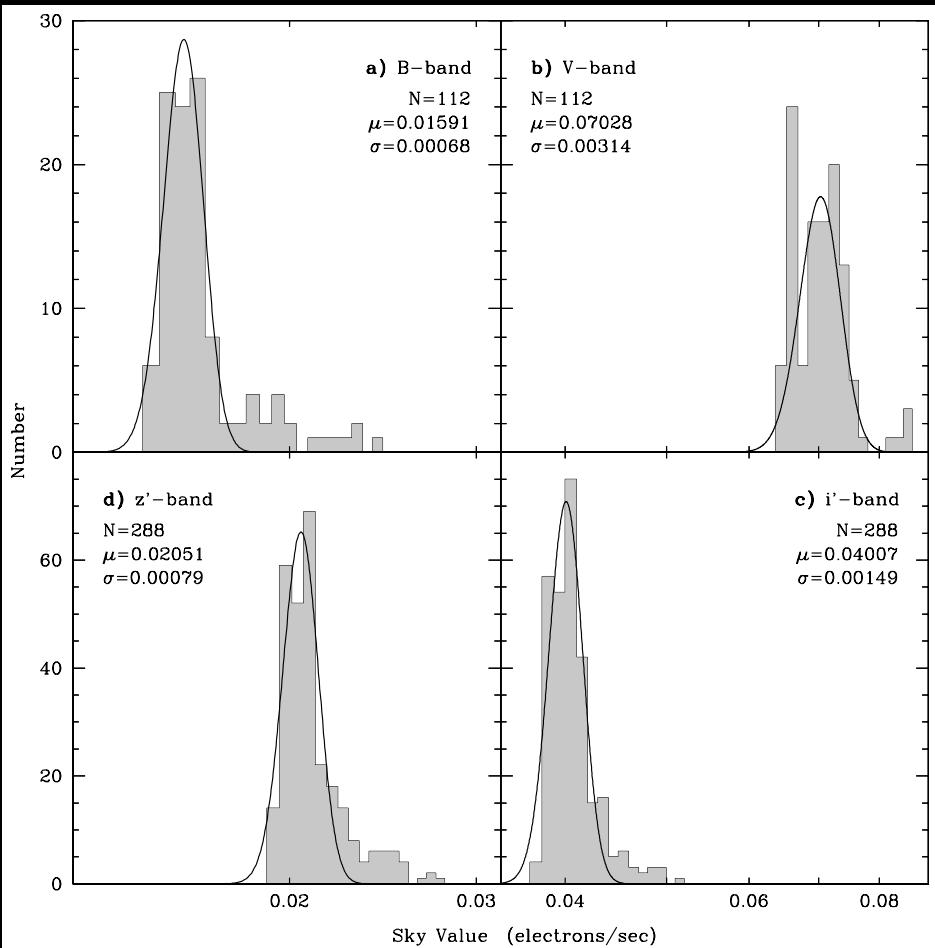
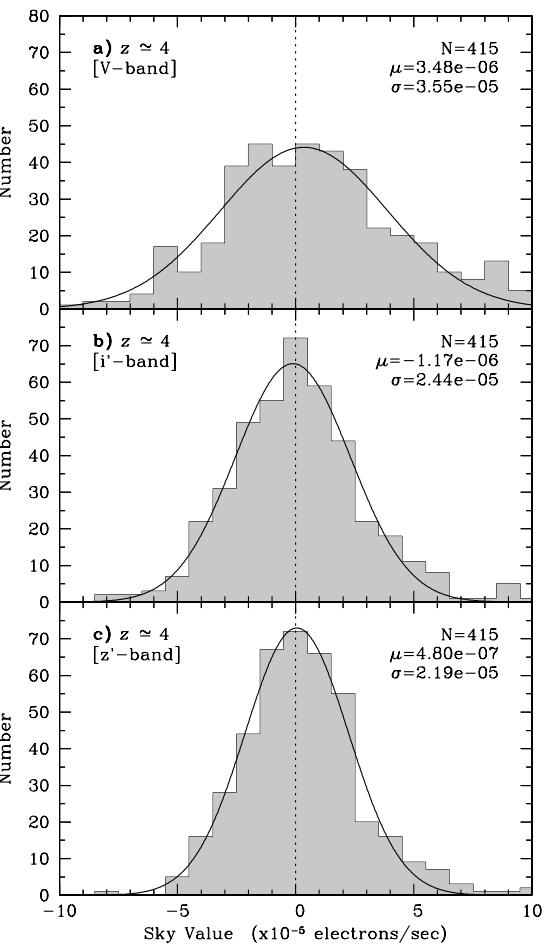
- (1) Apparent galaxy sizes decline from the RC3 to the HUDF limits:
- (2) At the HDF/HUDF limits, this is *not* only due to SB-selection effects (cosmological $(1+z)^4$ -dimming), but also due to:
 - (2a) hierarchical formation causes size evolution:
 $r_{hl}(z) \propto r_{hl}(0) (1+z)^{-1}$
 - (2b) 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 $z_{med} \simeq 1.5$, this influences the balance of how $(1+z)^4$ -dimming & object overlap affects the catalog completeness.
- For details, see Windhorst, R. A., et al. 2008, 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 $z \simeq 4-6$?



- Select all isolated, nearly unresolved ($2r_e \lesssim 0''.3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at $z \simeq 4$, $z \simeq 5$, and $z \simeq 6$. (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 ($\simeq 240$ 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 $\simeq (2-3) \cdot 10^{-3}$ or AB $\simeq 29.0-30.2$ 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	$(B - V)_{\text{sky}} = 0.800$	29.85 ± 0.05
V	112	0.070276 ± 0.000297	22.864 ± 0.002	$(V - i')_{\text{sky}} = 0.222$	30.15 ± 0.15
i'	288	0.040075 ± 0.000088	22.642 ± 0.002	$(i' - z')_{\text{sky}} = 0.065$	29.77 ± 0.20
z'	288	0.020511 ± 0.000047	22.577 ± 0.003	$(V - z')_{\text{sky}} = 0.287$	28.95 ± 0.05

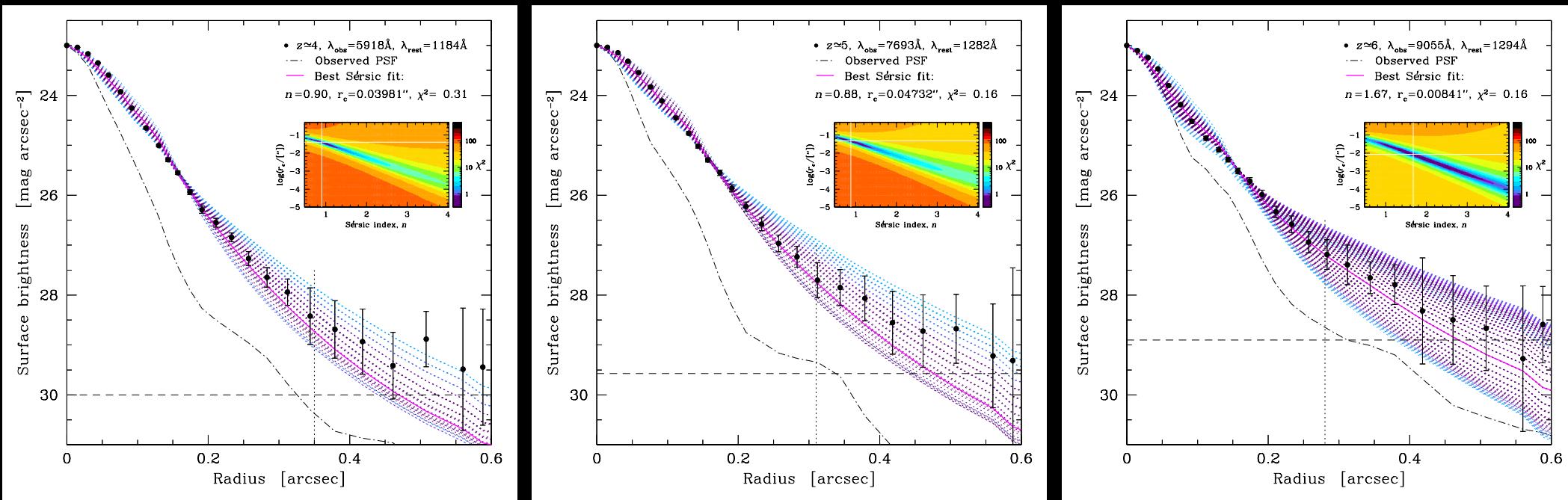
^aFrom Fig. 4 in Hathi, N. P., et al. 2008, AJ, 135, 156 (astro-ph/0710.0007)

^bError is standard deviation of the mean (σ/\sqrt{N})

^cSky 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 $z \simeq 4-6$



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

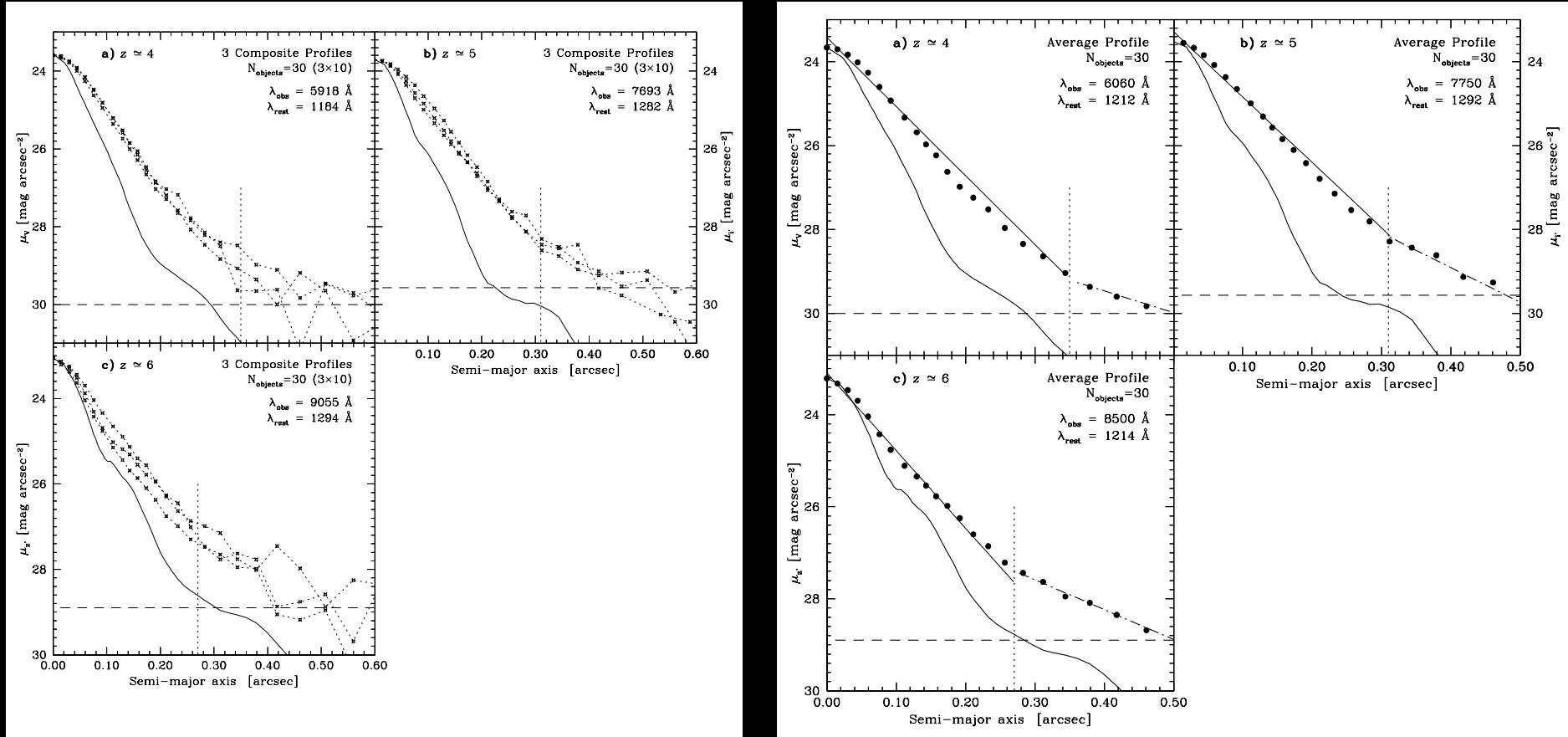
Best fit Sersic profile of 4320 ACS i-band orbit stack: $n=0.88$ at $z \simeq 5$

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

⇒ Dwarf galaxies at $z \simeq 4-6$ are disk dominated! (Hathi et al. 2008).

- JWST can do this to 10^{-4} , or $\text{AB} \simeq 31.0-32.0 \text{ mag/arcsec}^2$ to $z \lesssim 15$,
- *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 $z \simeq 4-6$?



- HUDF sky-subtraction error is $2-3 \cdot 10^{-3}$ or $AB \simeq 29.0-30.2$ mag/arcsec 2
- Average 4300-orbit compact, round dwarf galaxy light-profile at $z \simeq 6-4$ deviates from best fit Sersic $n \simeq 1.0$ law (incl. PSF) at $r \gtrsim 0''27-0''35$.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of $\tau_{\text{dyn}} \simeq 0.1-0.2$ Gyr at $z \simeq 6-4$ for the enclosed masses.
 ⇔ comparable to SED ages (Hathi+ 2008, AJ 135, 156).
- ⇒ Star-formation that finished global reionization at $z \simeq 6$ started at $\gtrsim 7$.

- 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”