The Era of JWST: Measuring First Light, Reionization, and Galaxy Assembly from the L2 Zodi Environment

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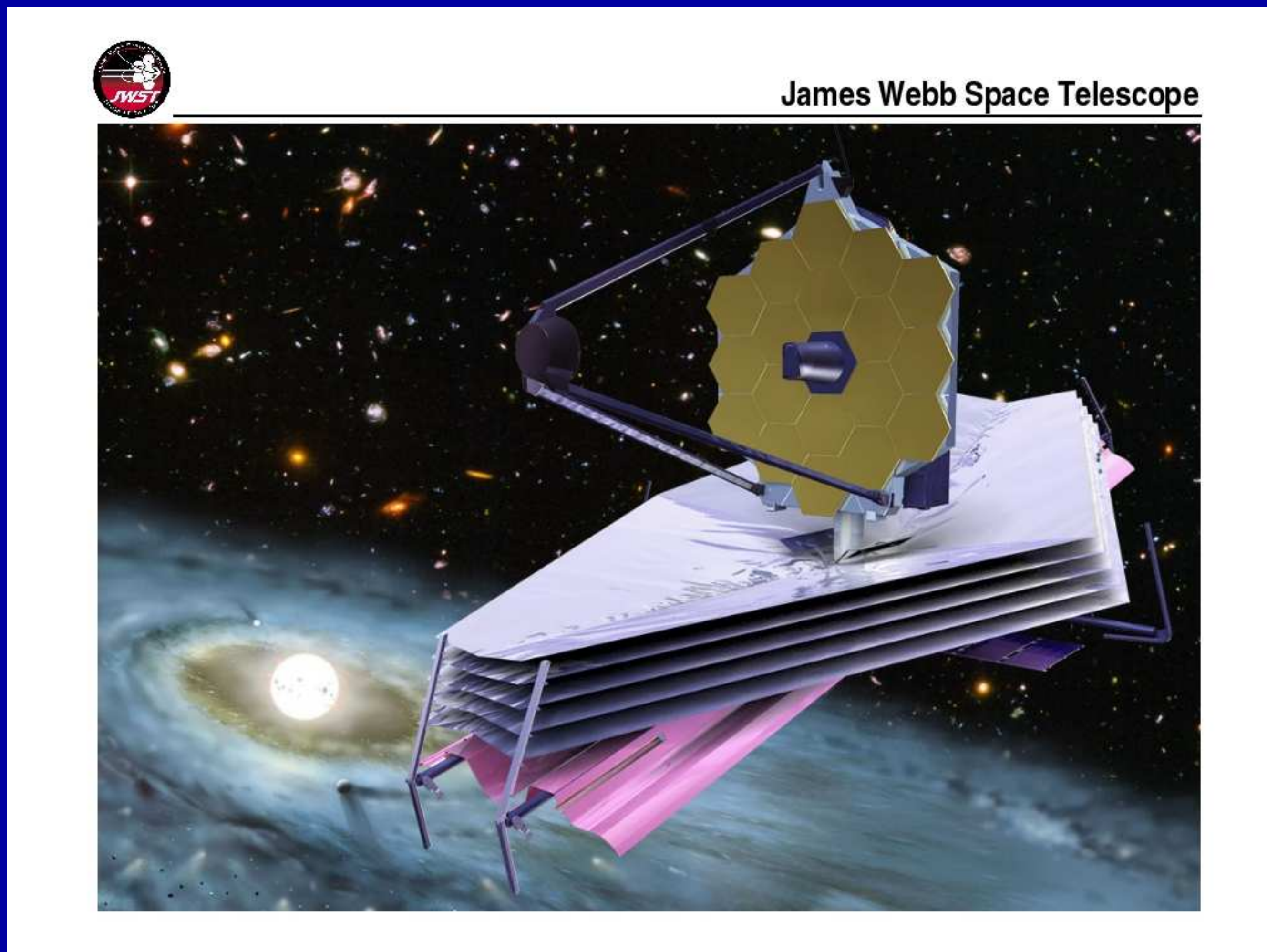

UC Irvine Workshop on: "The View from 5 AU", Th. Mar 25, 2010

Outline

- (1) What is JWST and how will it be deployed?
- (2) What instruments and sensitivity will JWST have?
- (3) Measuring the All Sky Zodi in VI with HST/WFPC2 to few %
- (4) Measuring the HUDF Zodi in BViz with HST/ACS to 0.2%
- (5) How JWST will measure First Light & Reionization, & Galaxy Assembly from the L2 Zodi Environment
- (6) Summary and Conclusions
- Appendix 1: Will JWST reach the Natural Confusion Limit?

Sponsored by NASA/JWST & HST

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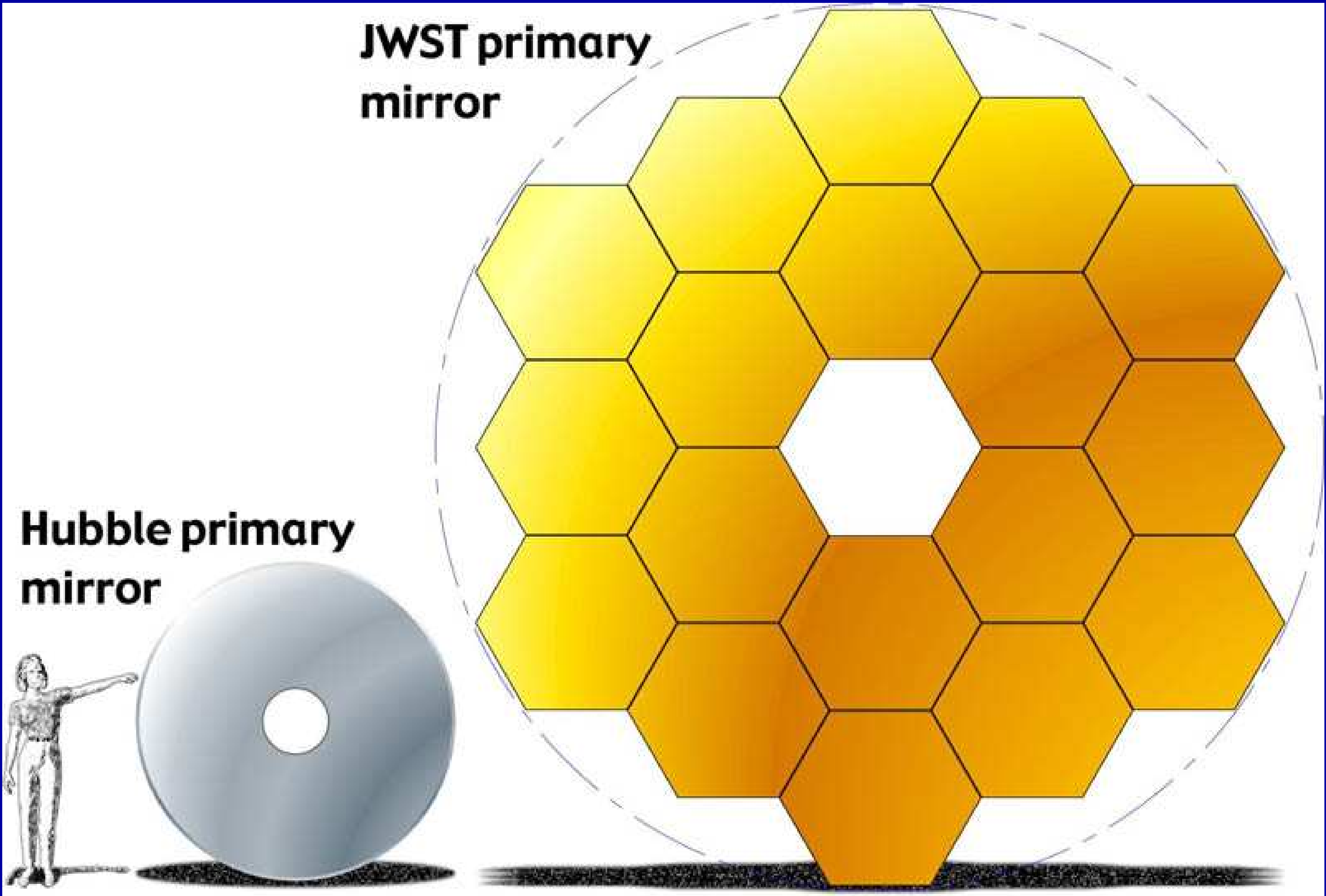
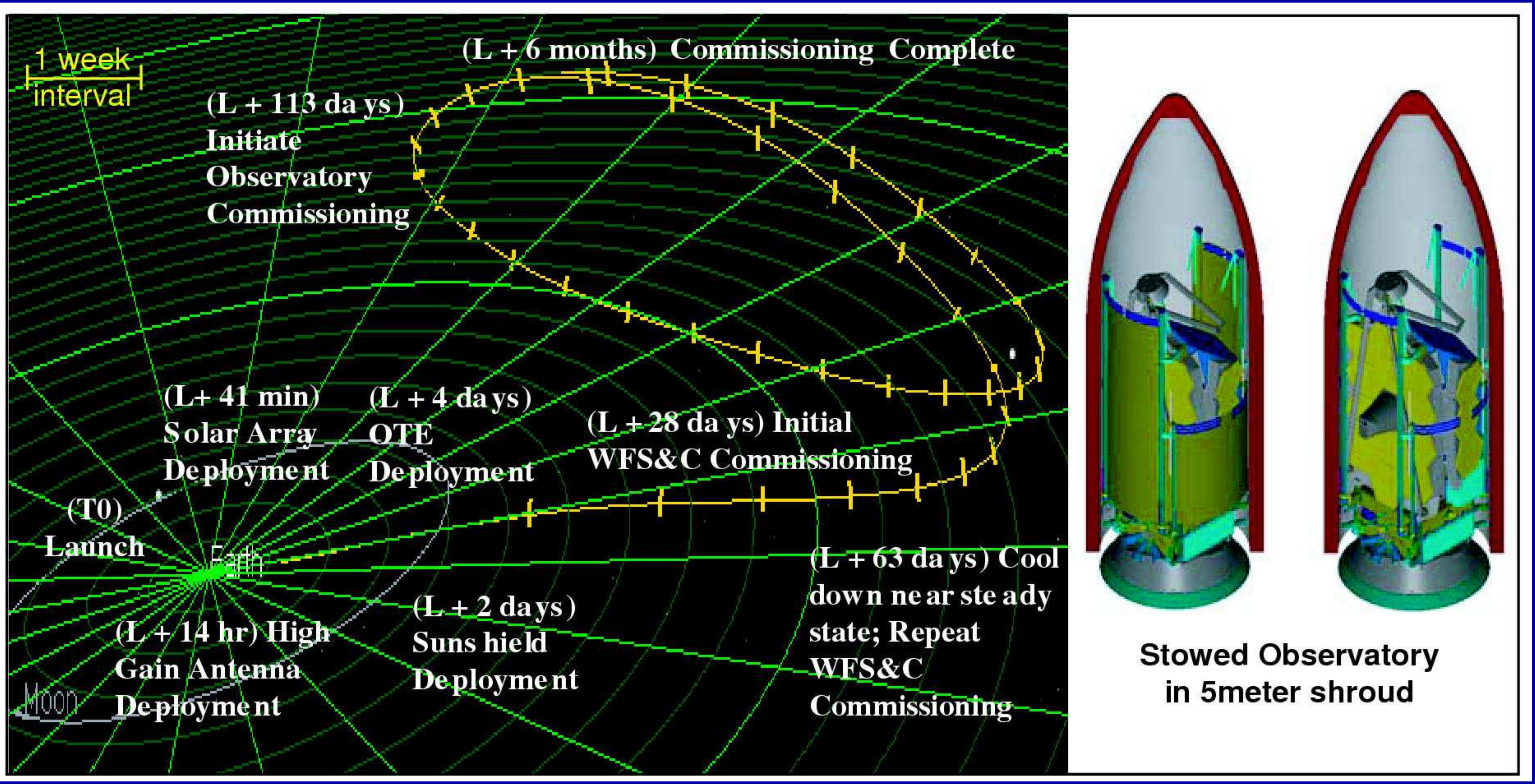


JWST ∼2.5× larger than Hubble, so at ∼2.5× larger wavelengths:
JWST has the same resolution in the near-IR as HST in the optical.

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

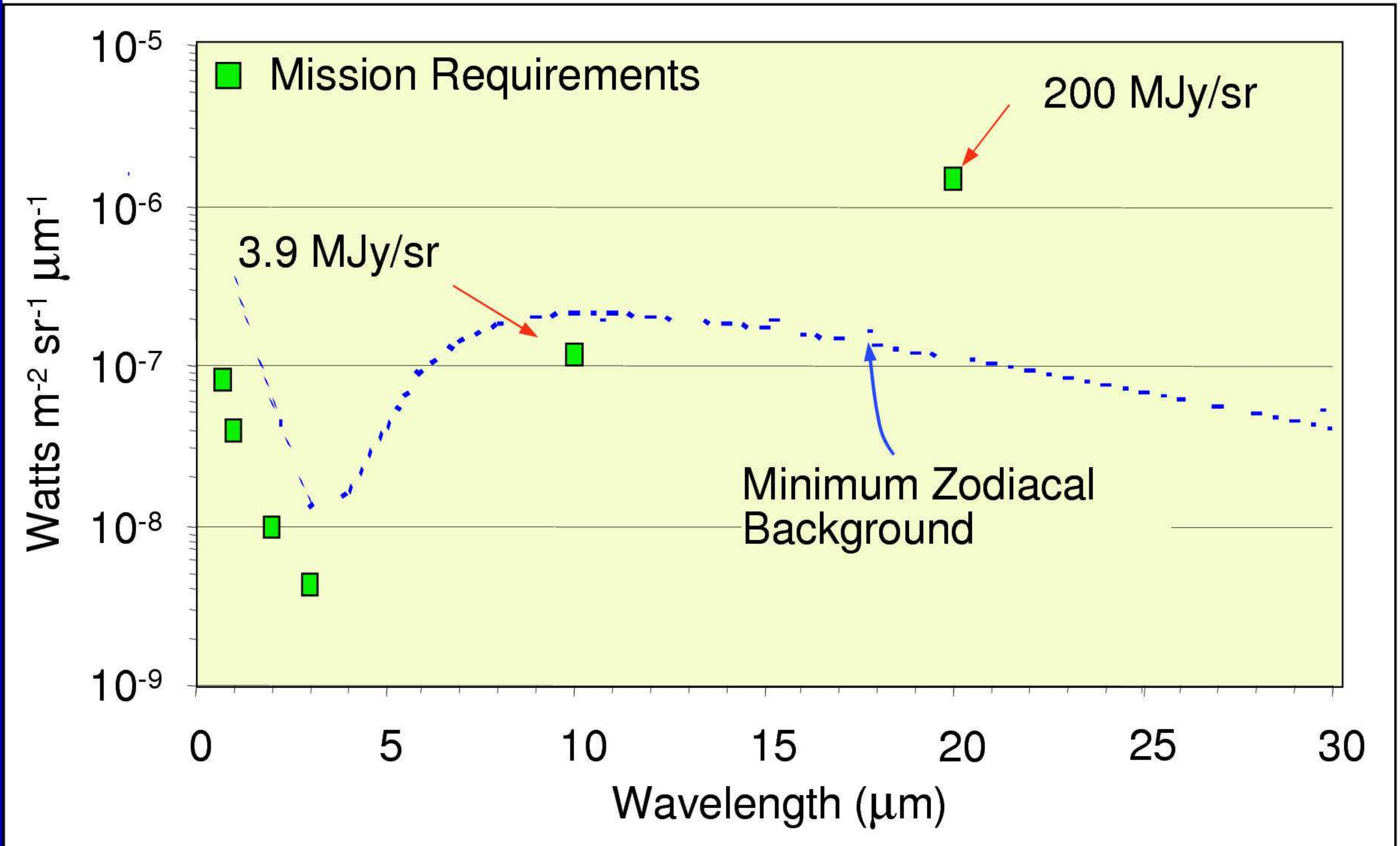
- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.7 to 29 μm, to be launched in June $\gtrsim$2014.
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).

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

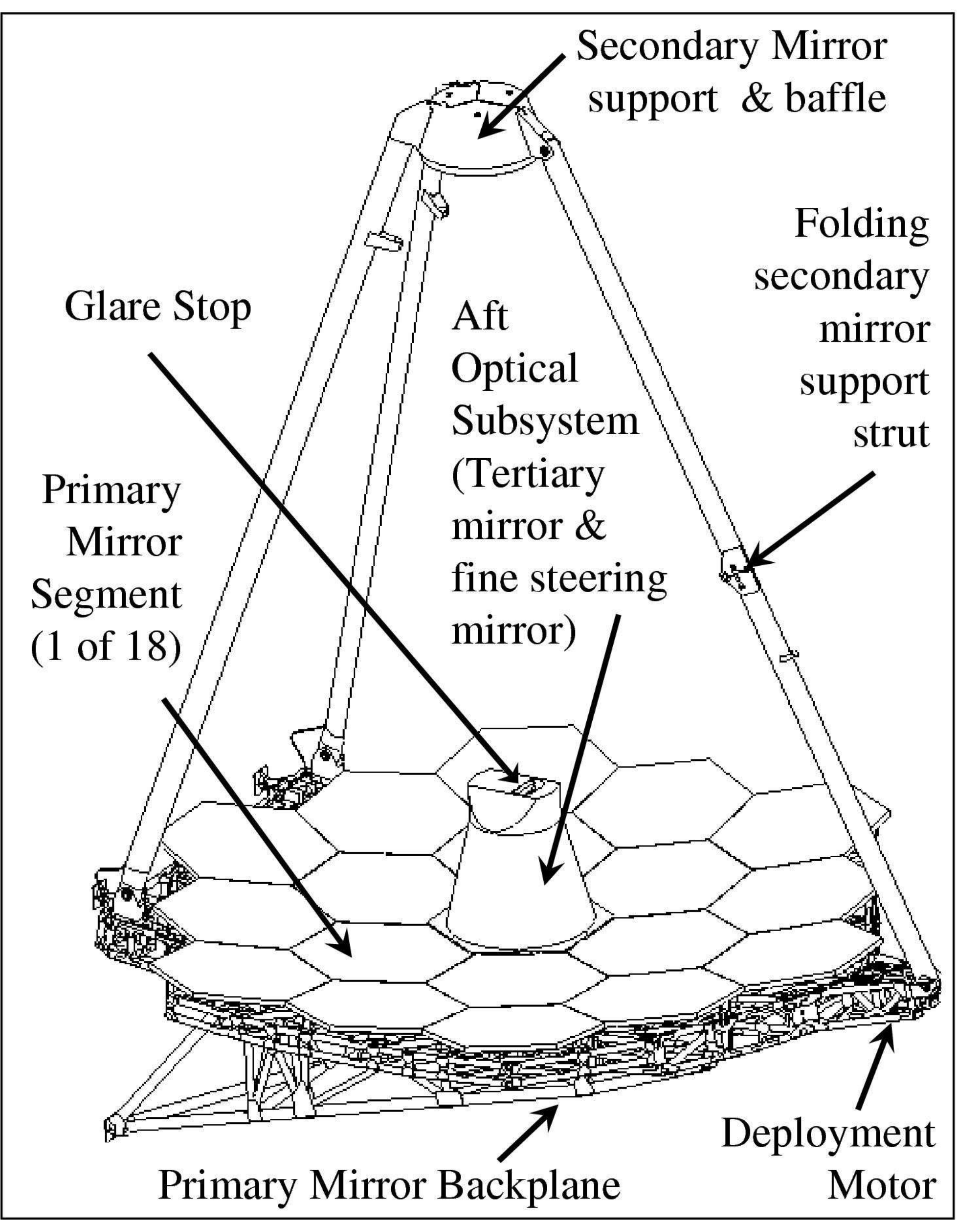


• After launch in June 2014 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.

• JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.



- JWST L2-sky minimizes $\lambda \simeq 3\mu$m: $\sim 10^4 \times$ fainter than ground-based sky.
- Faintest observable JWST objects have AB=31.5 mag $\simeq$ 1 nanoJy
- Need JWST-UDF systematics and sky-subtr 10 mag fainter than Zodi!



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

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

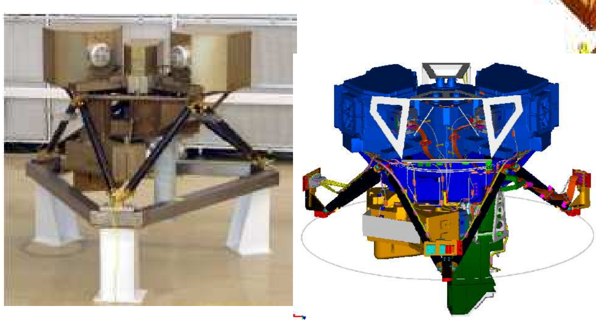
In L2, WFS updates every 10 days depending on scheduling/SC-illumination.

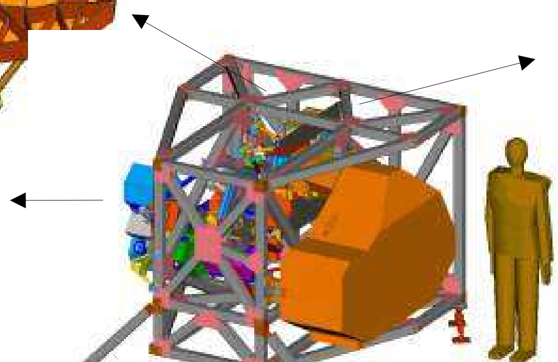
- (2) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

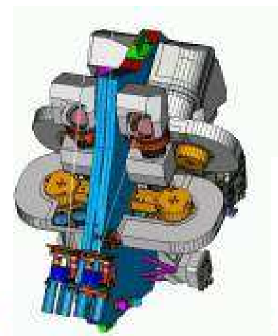
Instrument Overview

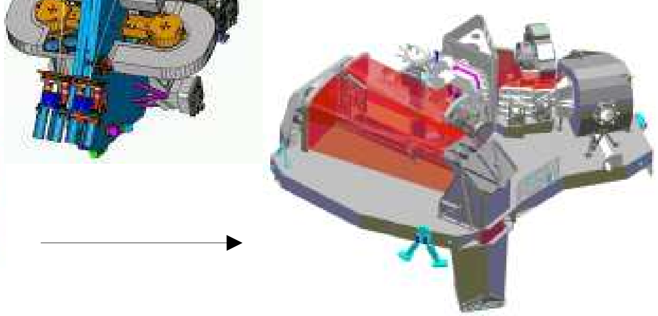
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

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





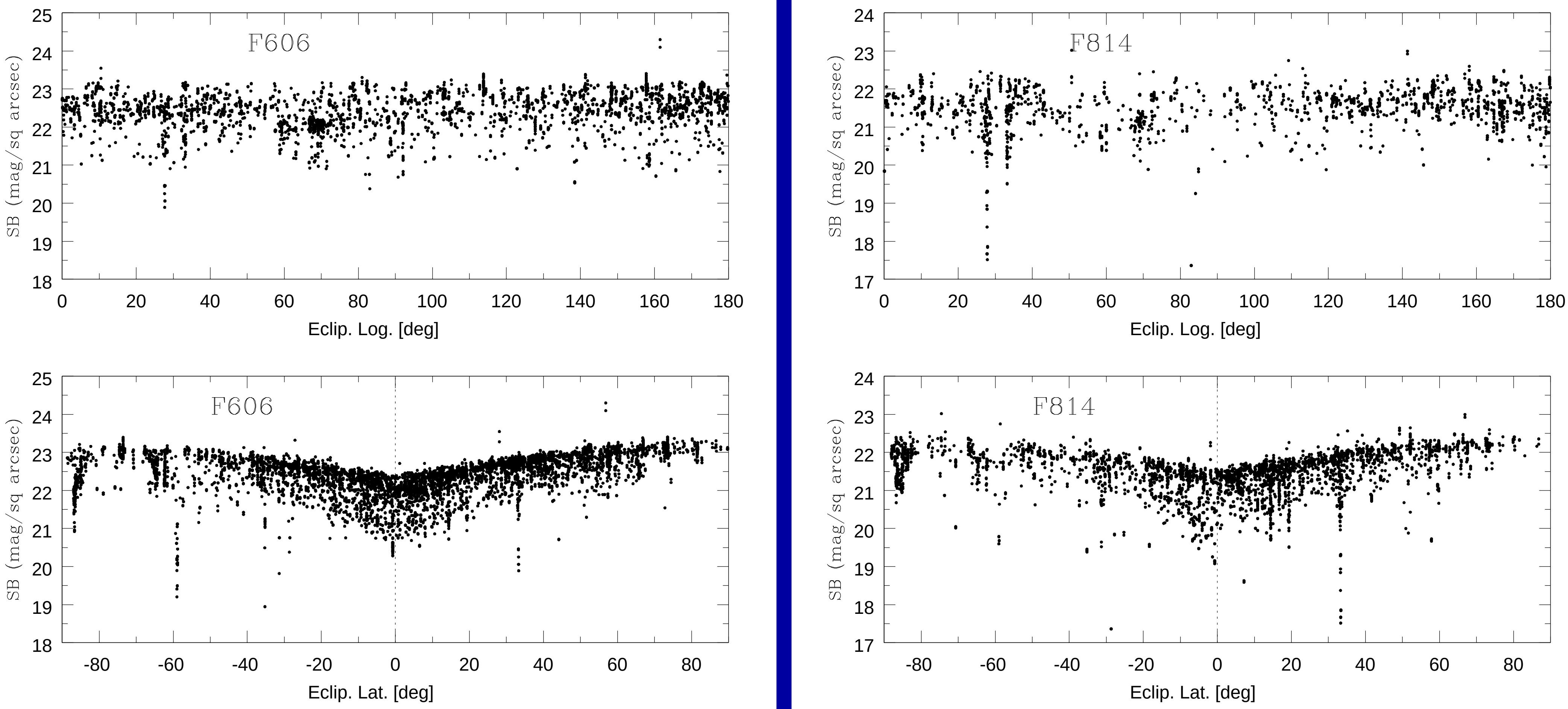




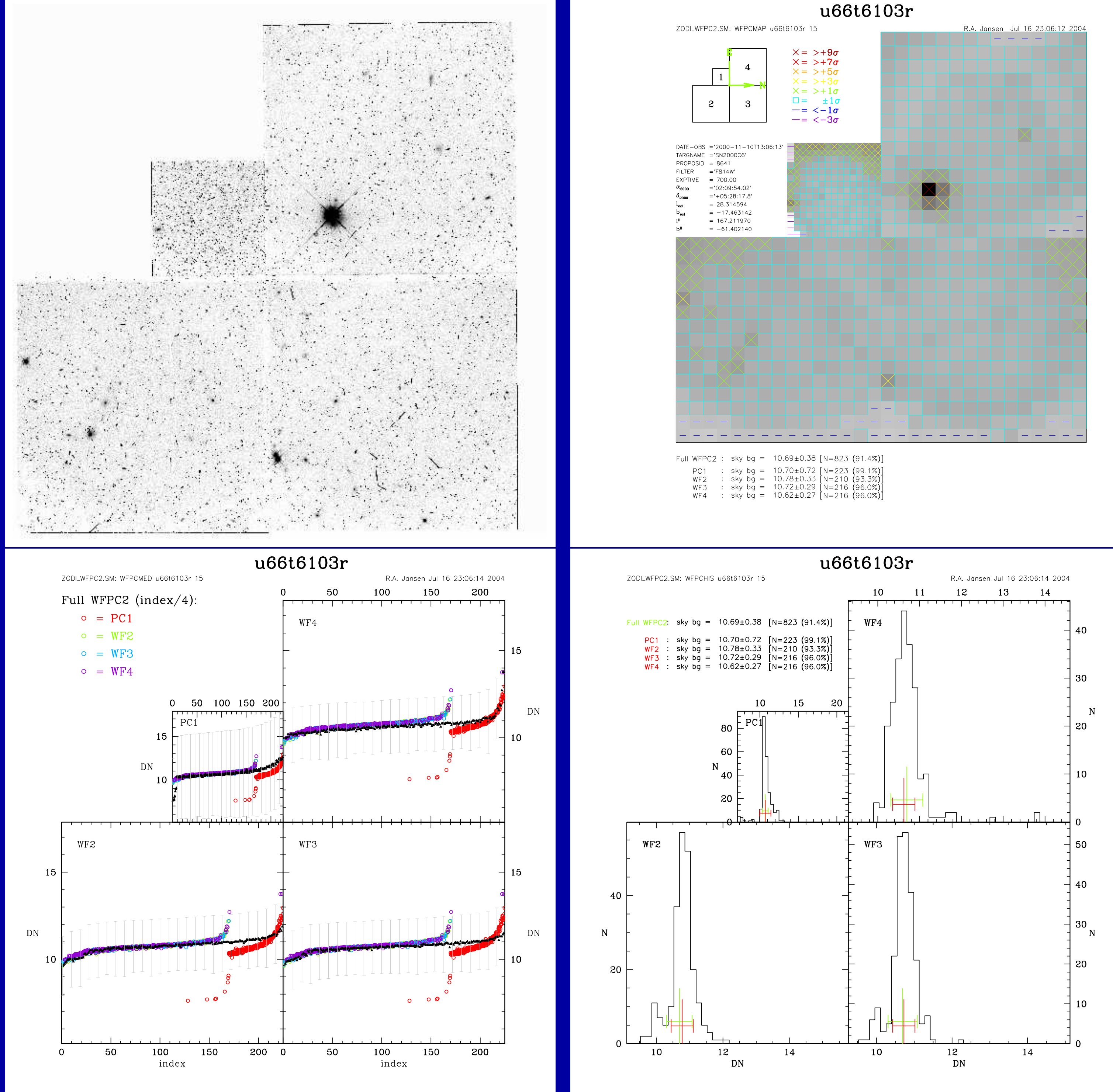
Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

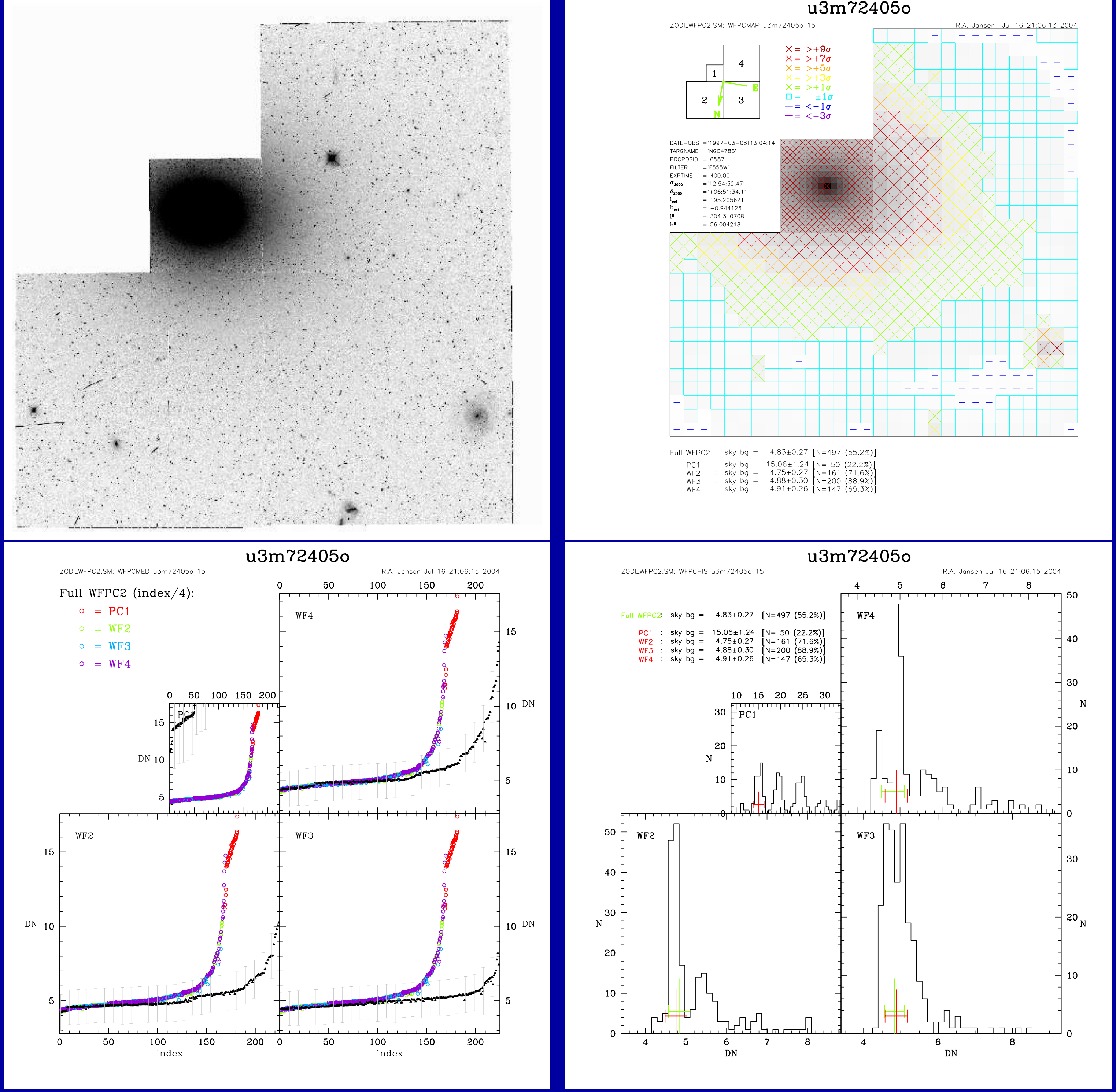
(3) Zodi BVI Sky-values in entire HST/WFPC2 data base



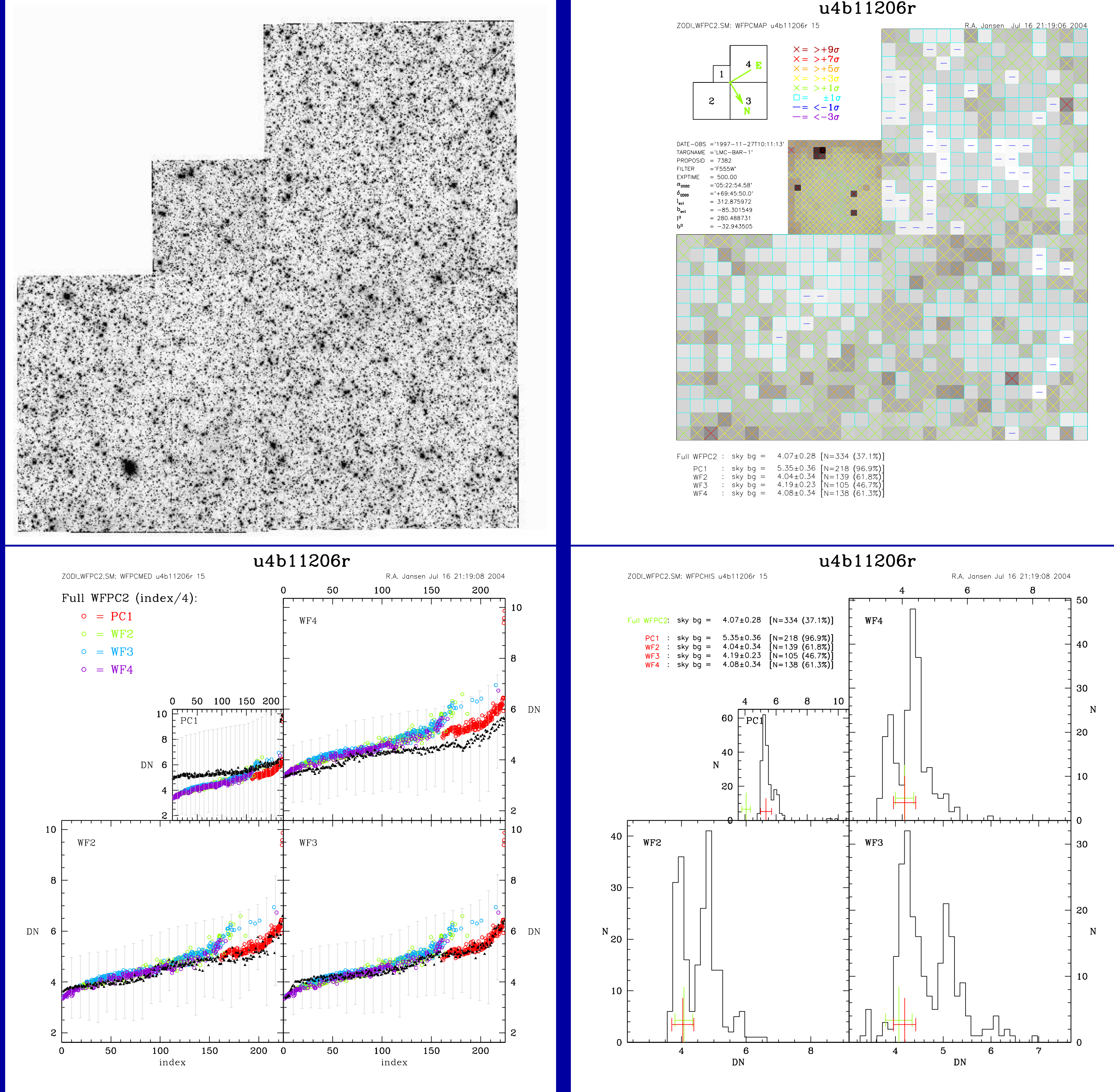
- WFPC2 NEP/SEP Zodi sky is $V_{AB} \simeq 23.20$ mag/arcsec^2
- WFPC2 NEP/SEP Zodi sky is $I_{AB} \simeq 22.45$ mag/arcsec^2



UL: Blank field; UR: 32^2 modes; LL: sorted; LR: 1-sided mode-fit

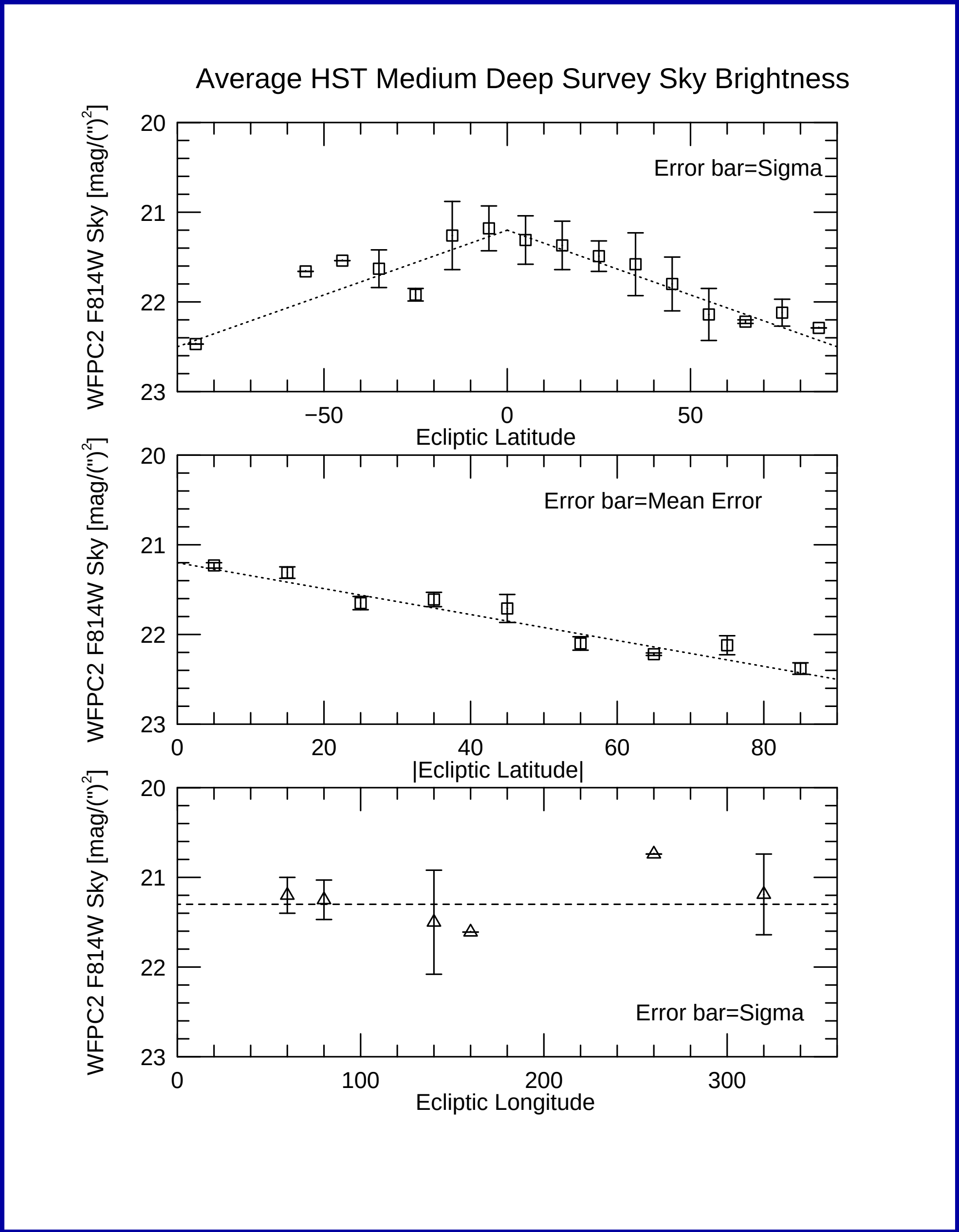


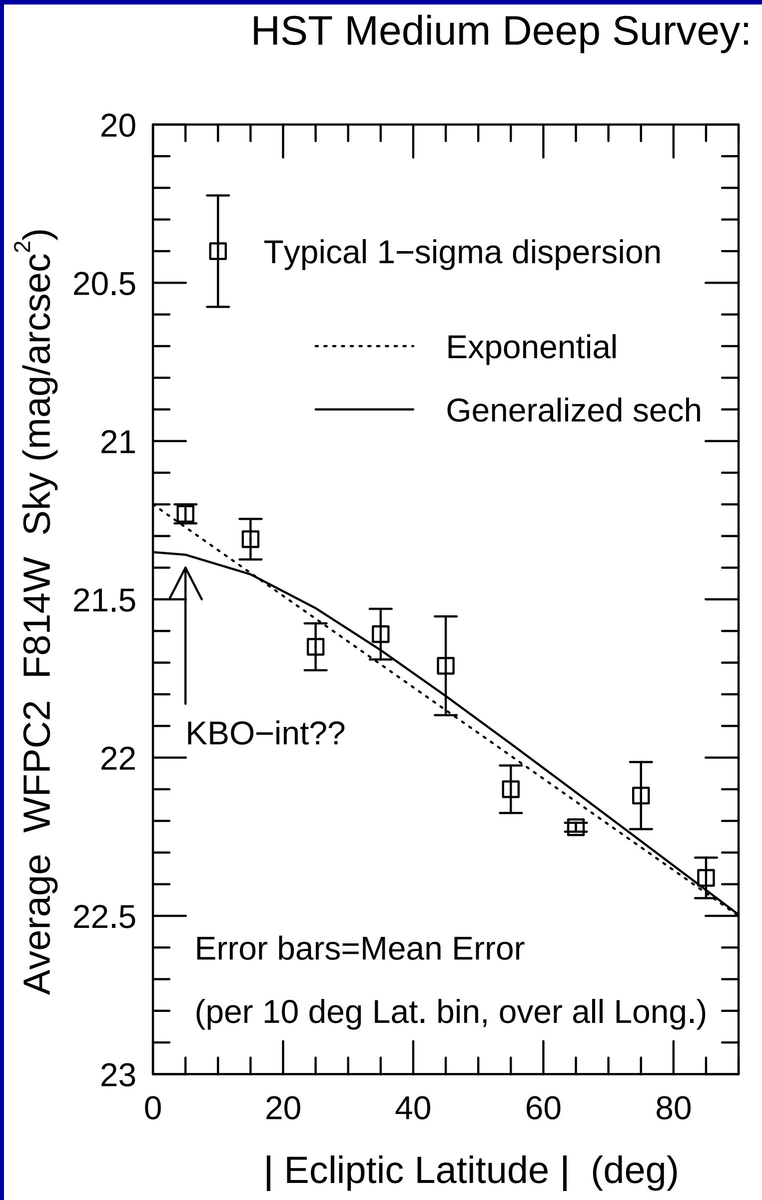
UL: Galaxy; UR: 32^2 modes; LL: sorted; LR: 1-sided mode-fit



UL: Starfield; UR: 32^2 modes; LL: sorted; LR: 1-sided mode-fit

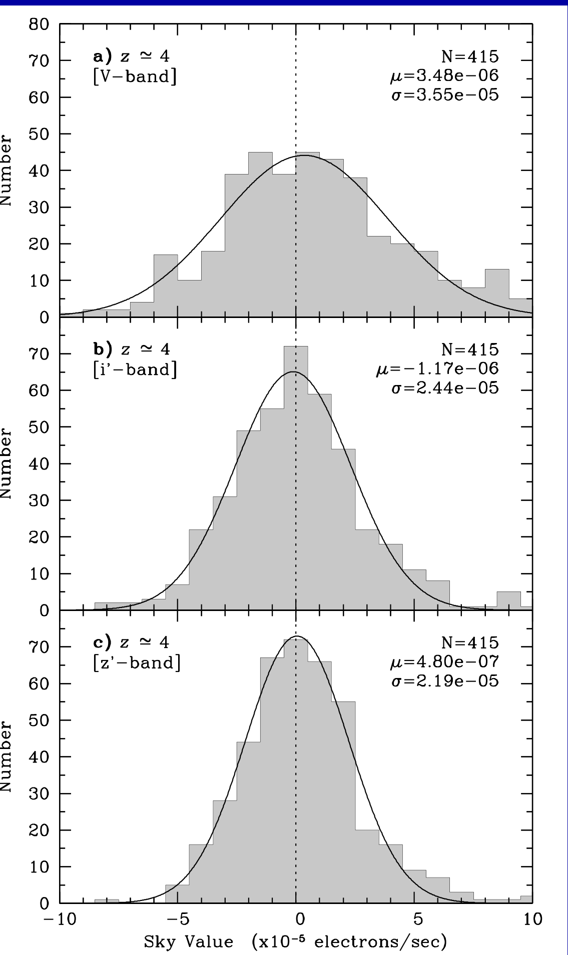
(3) Zodi BVI Sky-values in entire HST/WFPC2 data base

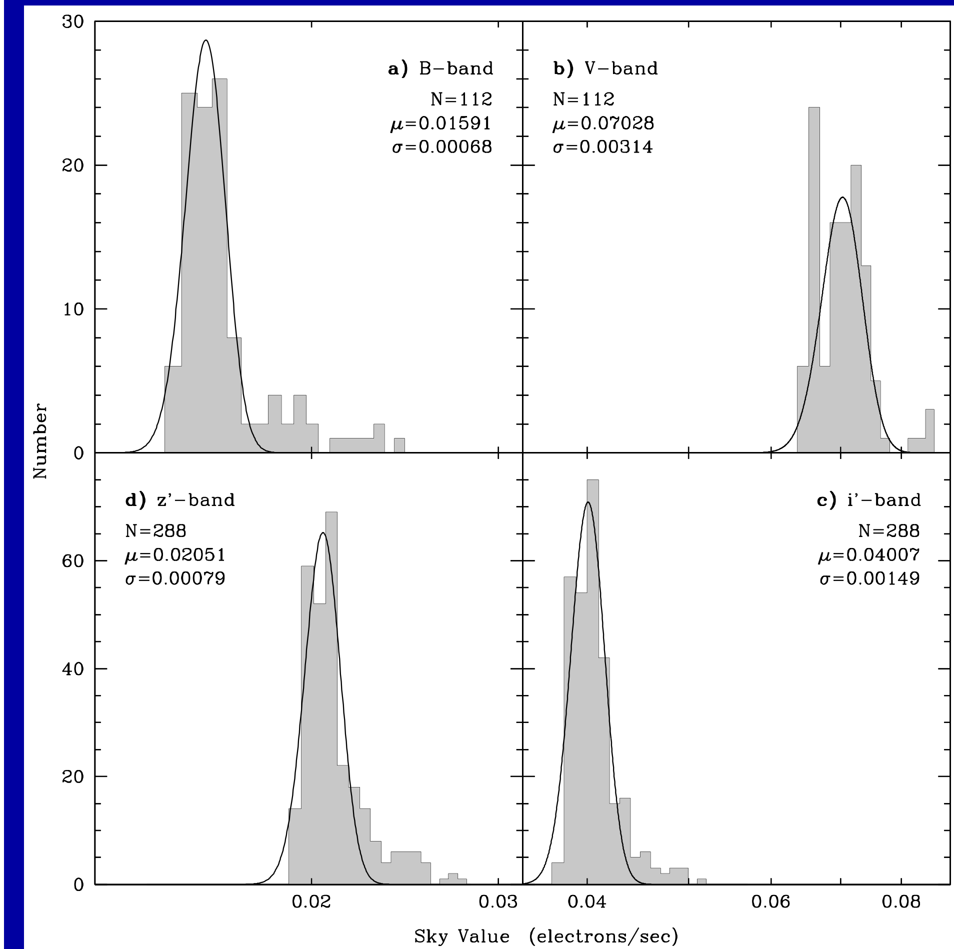


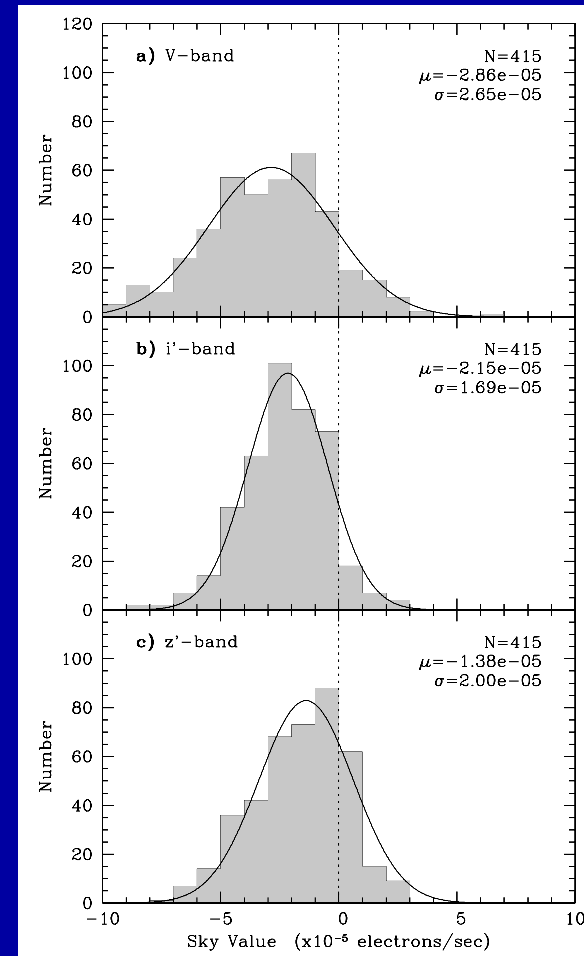


- WFPC2 NEP/SEP Zodi sky is $I_{AB} \simeq 22.45$ mag/arcsec^2

(4) 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[+] 2008, AJ, 135, 156; astro-ph/0710.0007)

(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).$\mathbf{10^{-3}}$ or AB≃29.0–30.2 mag/arcsec^2

(4) 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

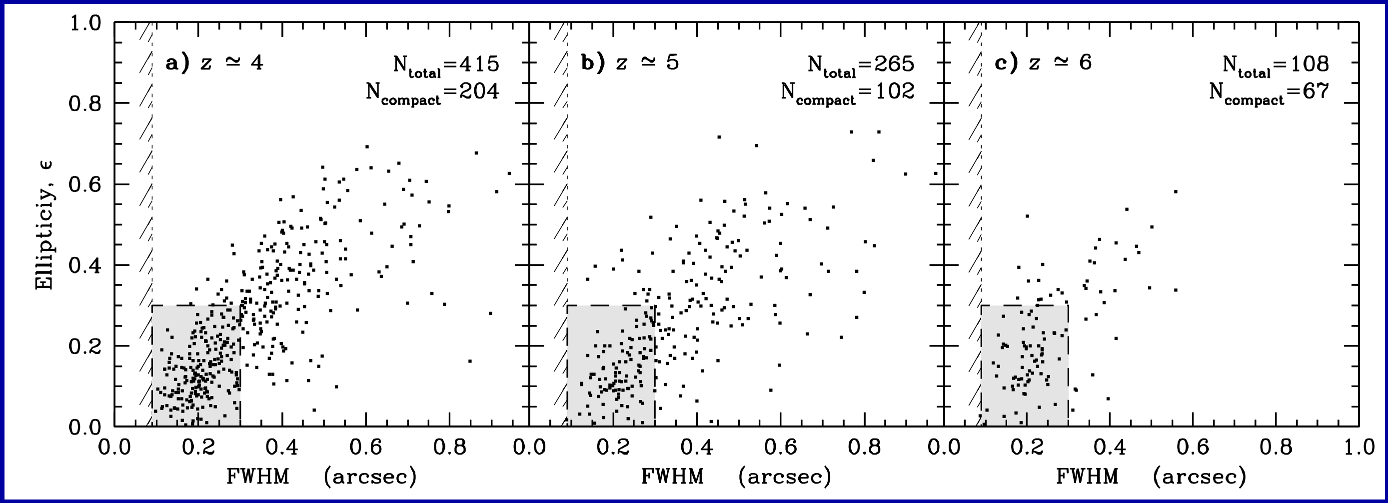
[a]From Fig. 4 in Hathi, N. P., et al. 2008, AJ, 135, 156 (astro-ph/0710.0007)

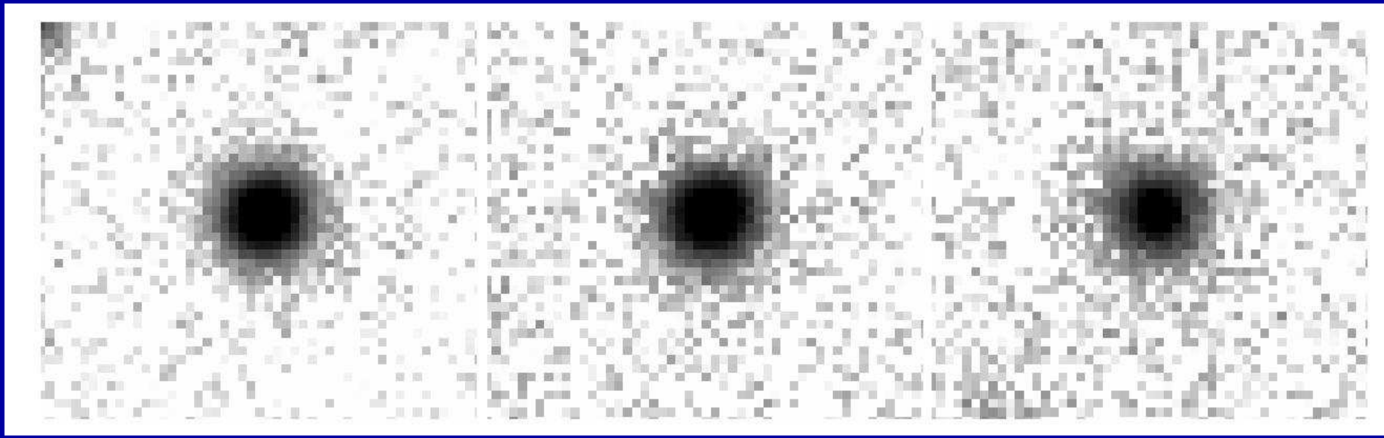
[b]Error is standard deviation of the mean ($\sigma/\sqrt{N}$)

[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.

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

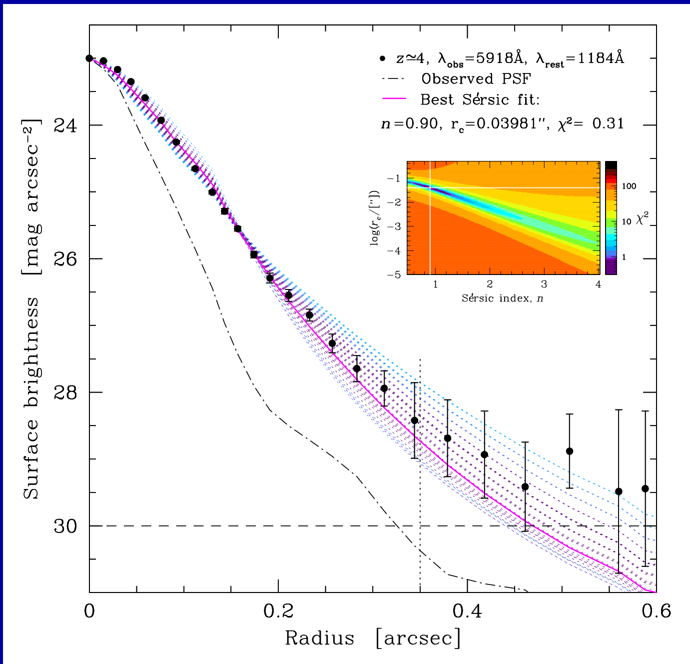
HUDF Zodi: Dynamical ages of Dwarf Galaxies at z≃4–6?

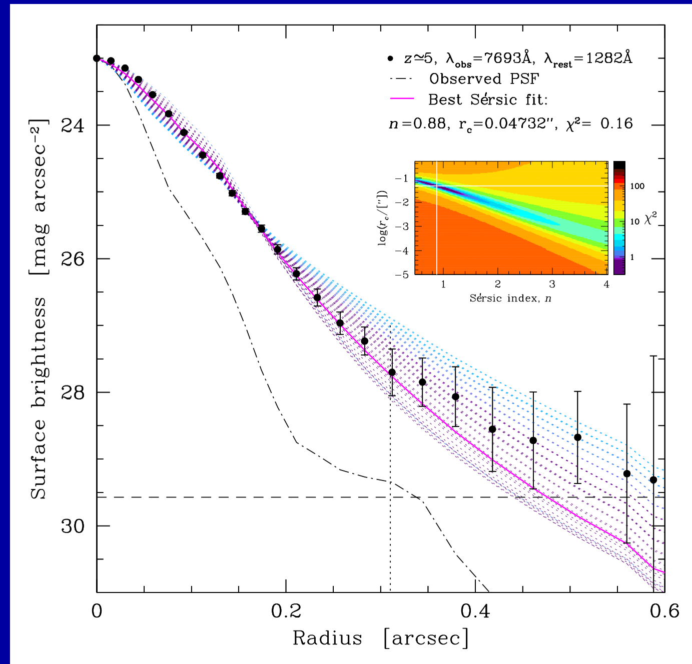


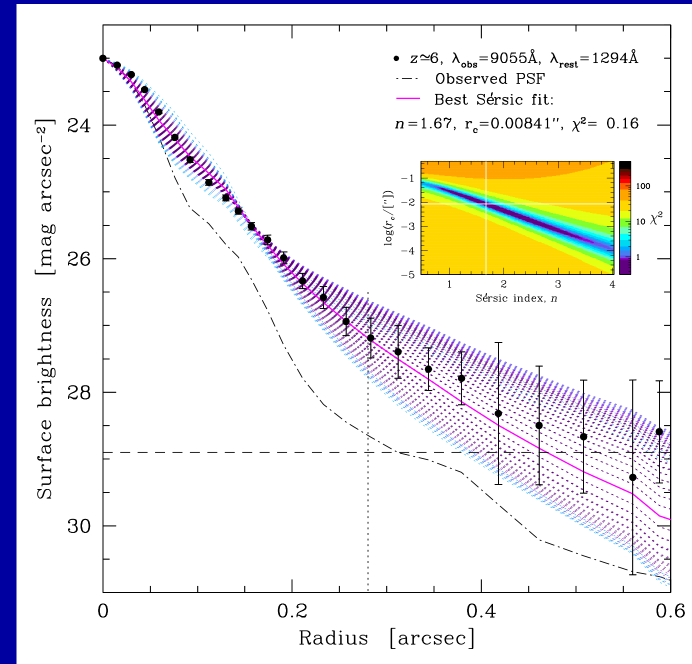


- Select all isolated, nearly unresolved ($2r_e \lesssim 0\farcs3$), round ($1-b/a \lesssim 0.3$) HUDF B-drops, V-drops, and i-drops. to AB=29.0 mag
- Construct average image stack and light-profiles of these dwarf galaxies at z≃4, z≃5, and z≃6.
- If these compact, round objects are intrinsically comparable, each stack has the S/N of ∼4300 HST orbits (≃300 JWST hrs; Hathi et al. 2008)!

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







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

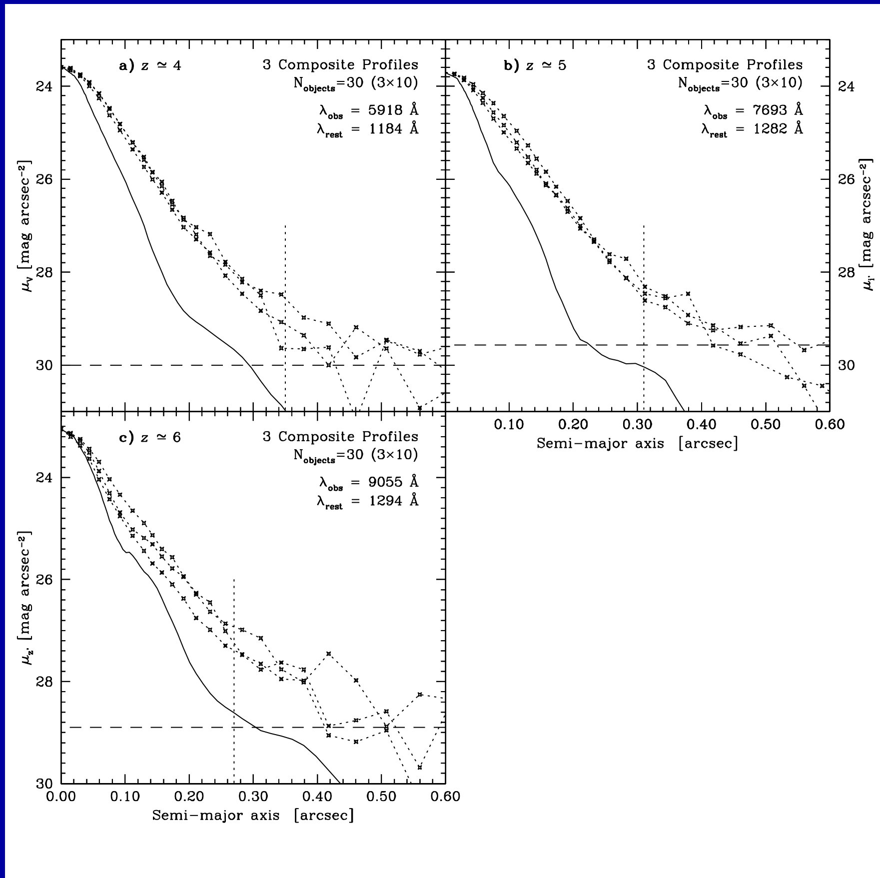
Best fit Sersic profile of 4320 ACS i-band orbit stack: n=0.88

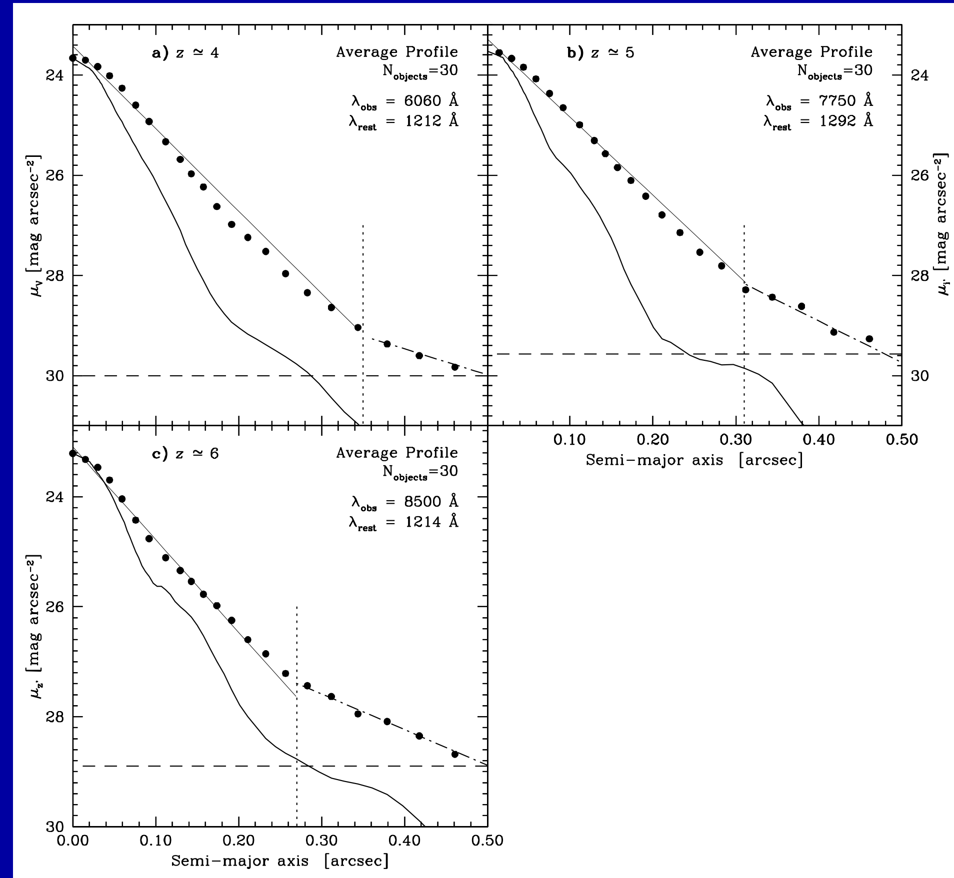
Best fit Sersic profile of 4320 ACS z-band orbit stack: n=1.67

⇒ Dwarf galaxies at z≃4–5 are disk dominated!

- 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 at low spatial frequencies.

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



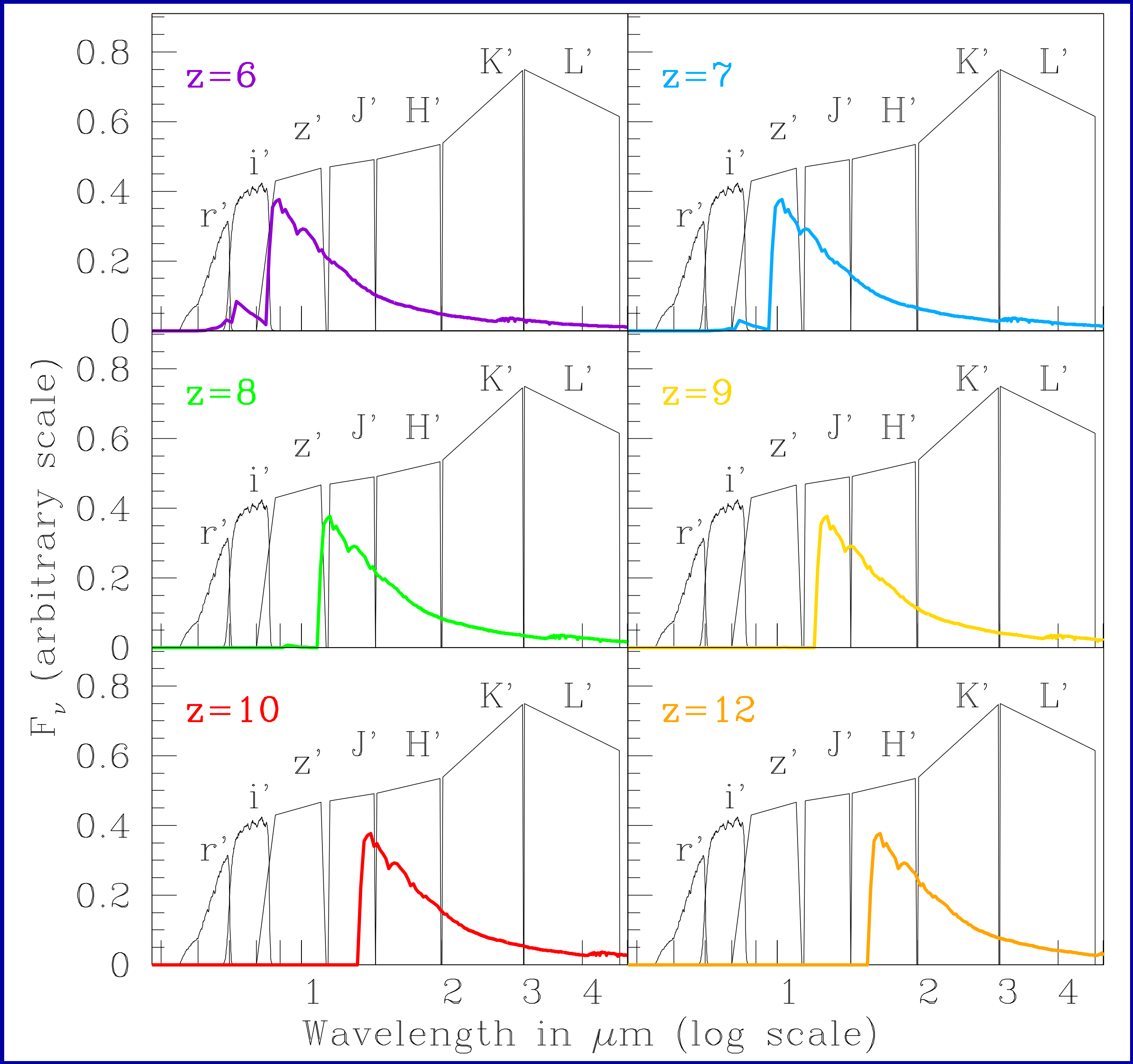


- HUDF sky-subtraction error is 2–3.10^{-3} or AB≃29.0–30.2 mag/arcsec^2
- Average 4300-orbit compact, round dwarf galaxy light-profile at z≃6–4 deviates from best fit Sersic n≃1.0 law (incl. PSF) at r≳0.″27–0.″35.
- If interpreted as virial radii in hierarchical growth, these imply dynamical ages of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

⇔ comparable to SED ages (Hathi$^+$ 2008, AJ 135, 156; astro-ph/0710.0007)

⇒ Global starburst that finished reionization at z≃6 started at z≃6.6?

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



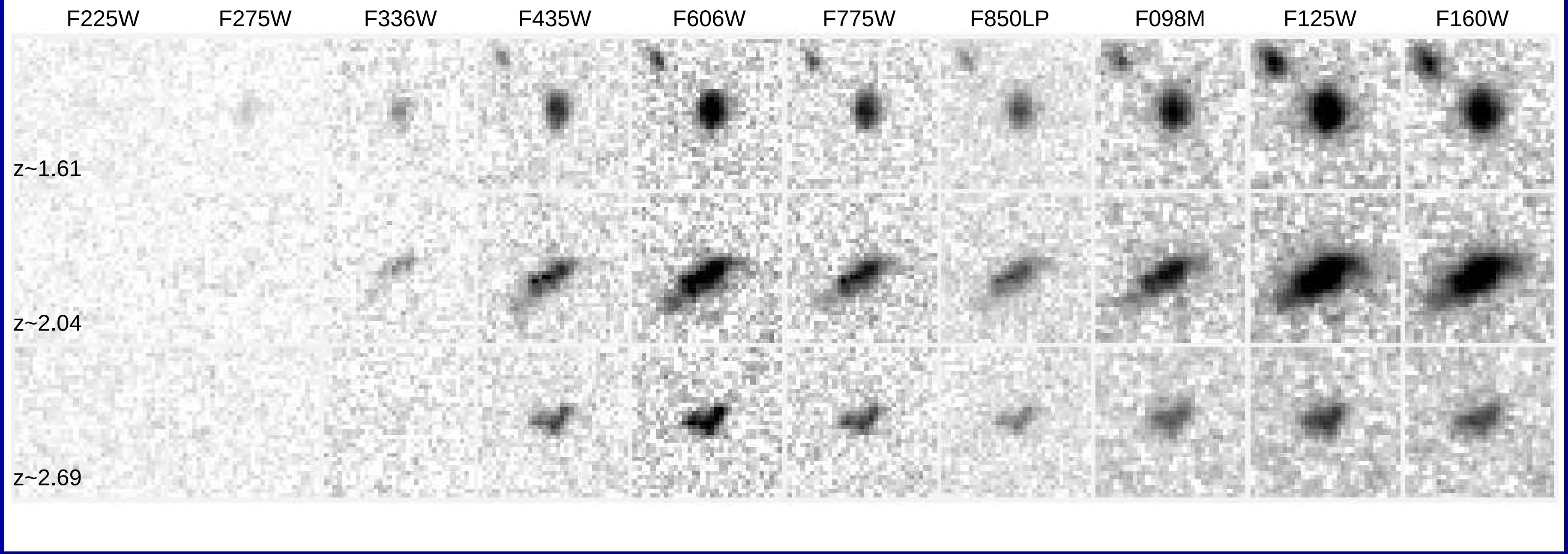
- Can't beat redshift: to see First Light, must observe near–mid IR.

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

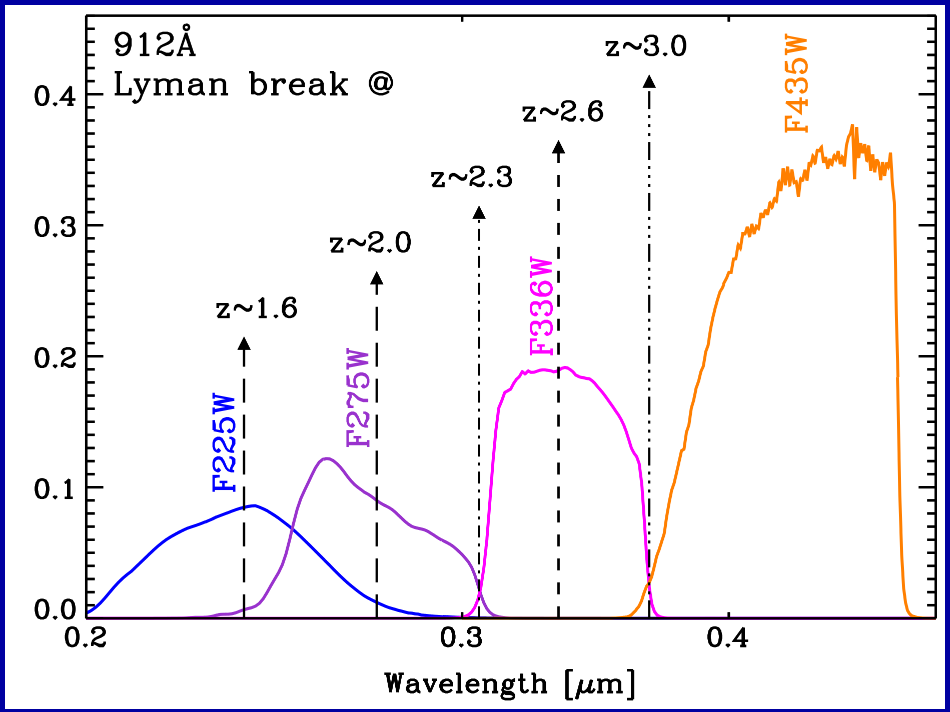
• (5) How to measure First Light and Reionization with JWST

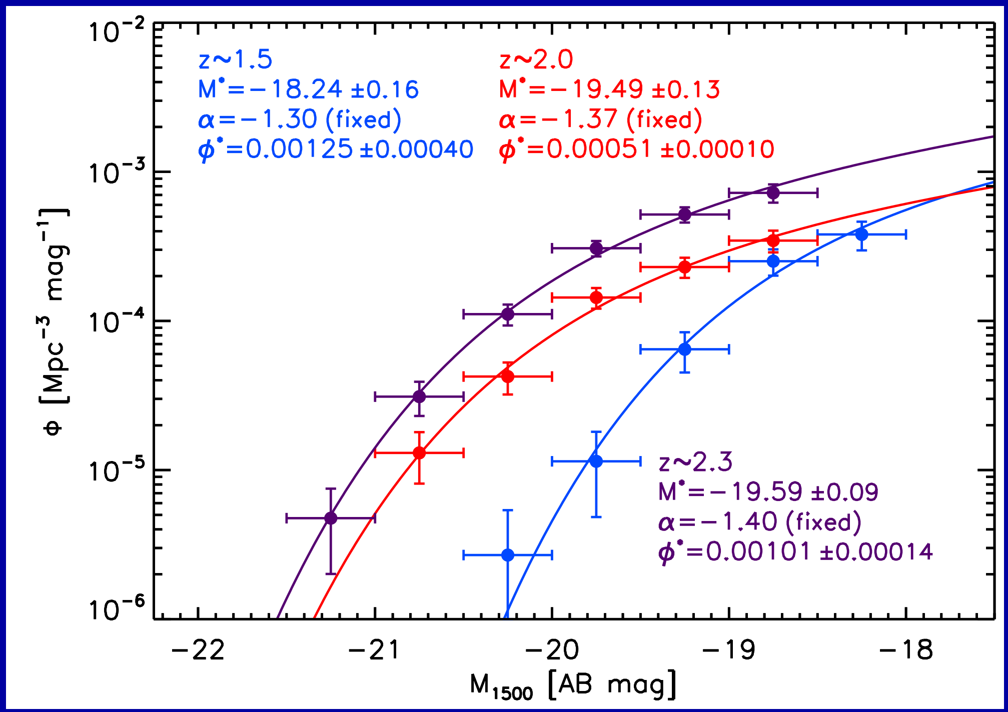
10 filters with HST/WFC3 & ACS reaching AB=26.5-27.0 mag (10-σ) over 40 arcmin^2 at 0.07–0.15" FWHM from 0.2–1.7μm (UVUBVizYJH).

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.



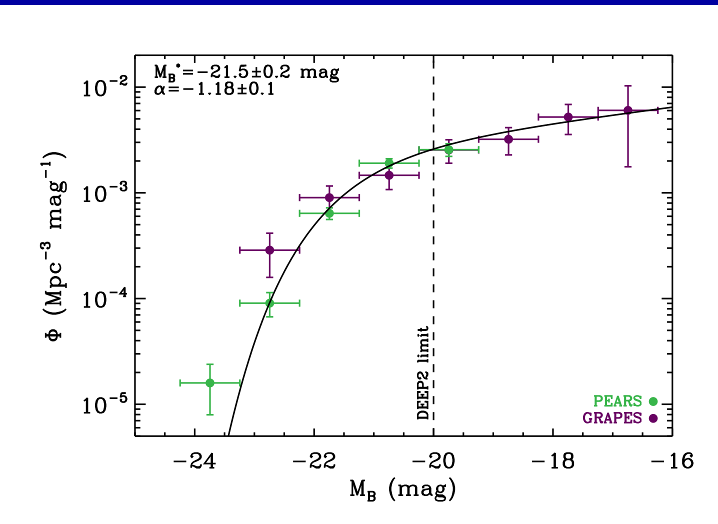
WFC3 Lyman break galaxies at the peak of cosmic SF (z≃1-3; Hathi+ 2010)

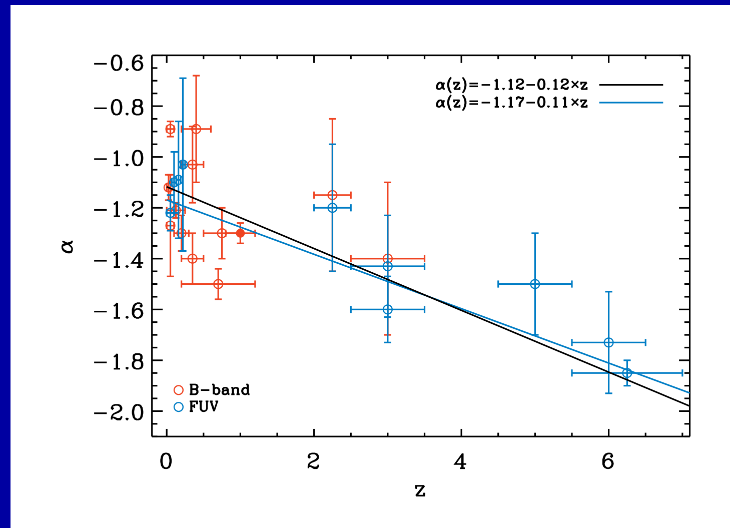


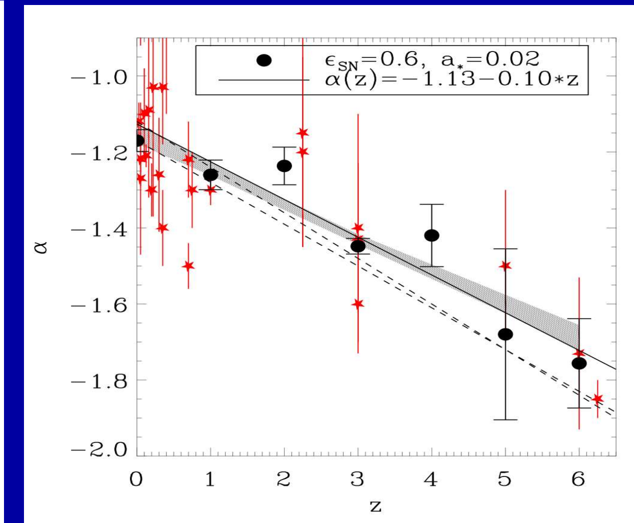


• JWST will similarly measure faint-end LF-slope evolution for 1≲z≲12.

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

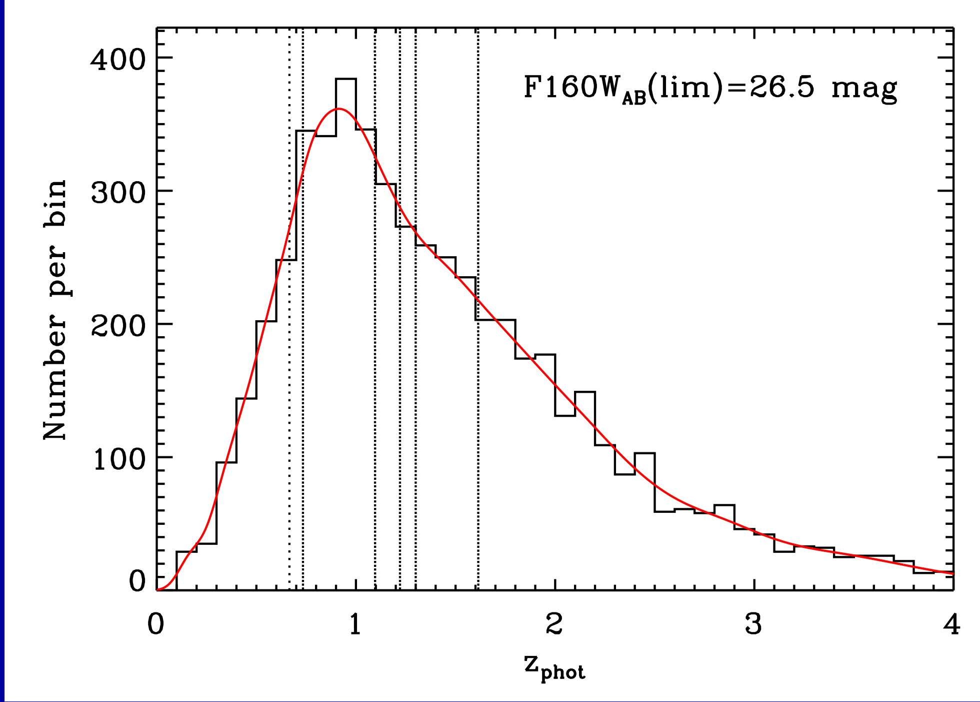


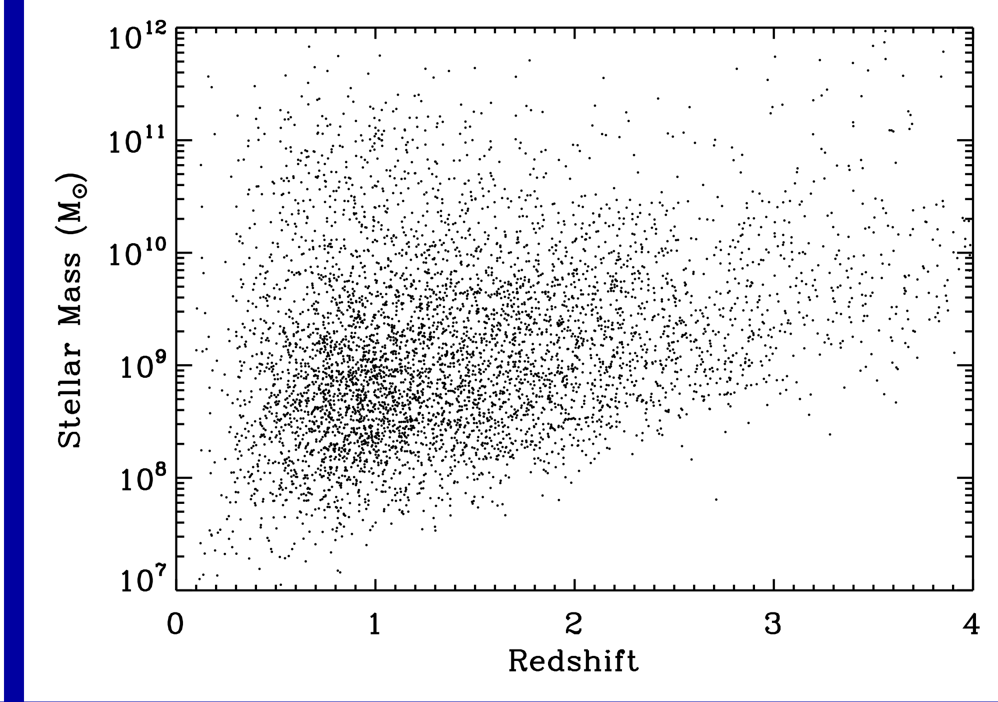




Faint-end LF-slope at $z \gtrsim 1$ with accurate ACS grism z's to AB$\lesssim$27 (Cohen et al.; Ryan et al. 2007, ApJ, 668, 839) constrains hierarchical formation:

- 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.





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

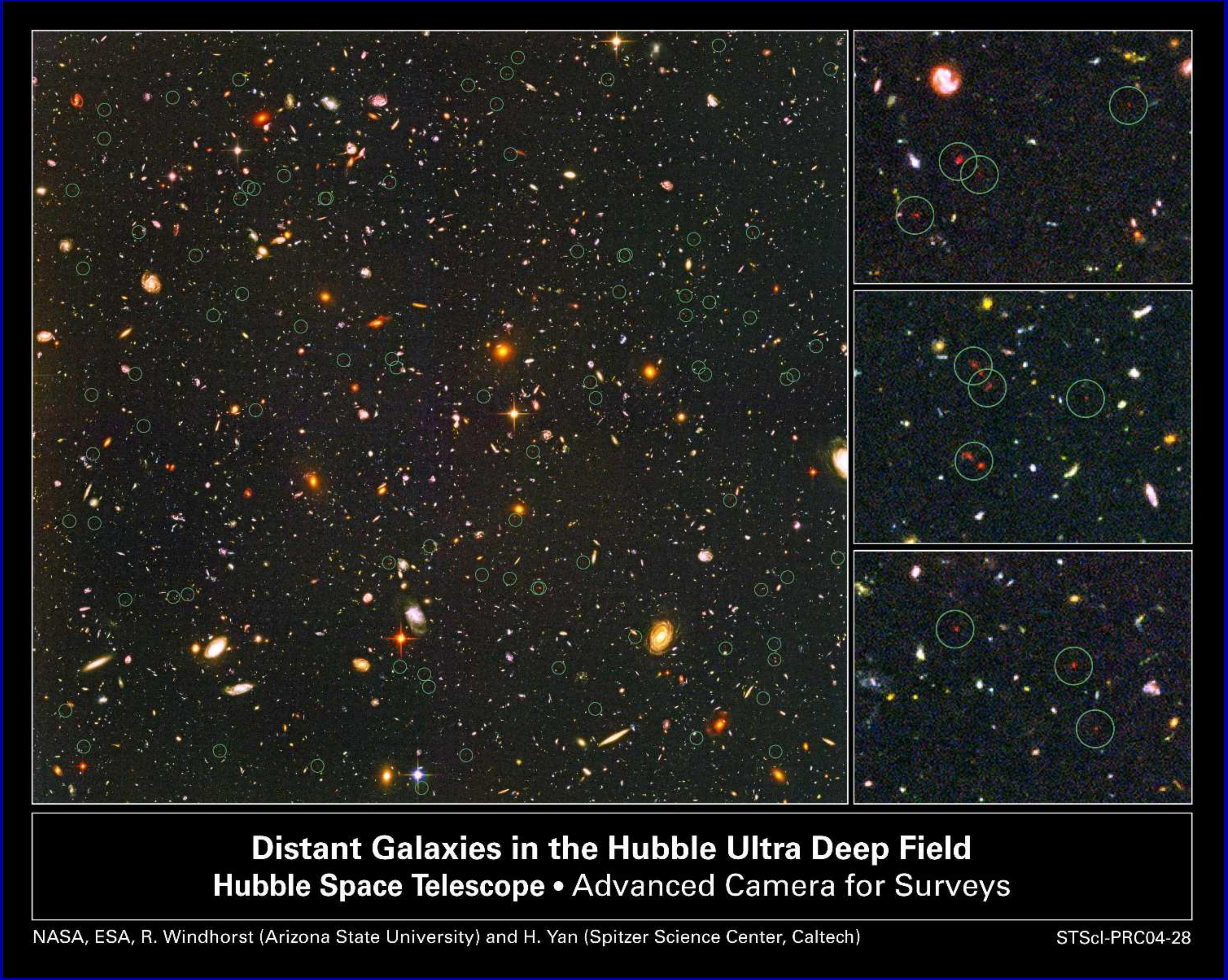
- Reliable masses of faint galaxies to AB=26.5 mag, accurately tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?)

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

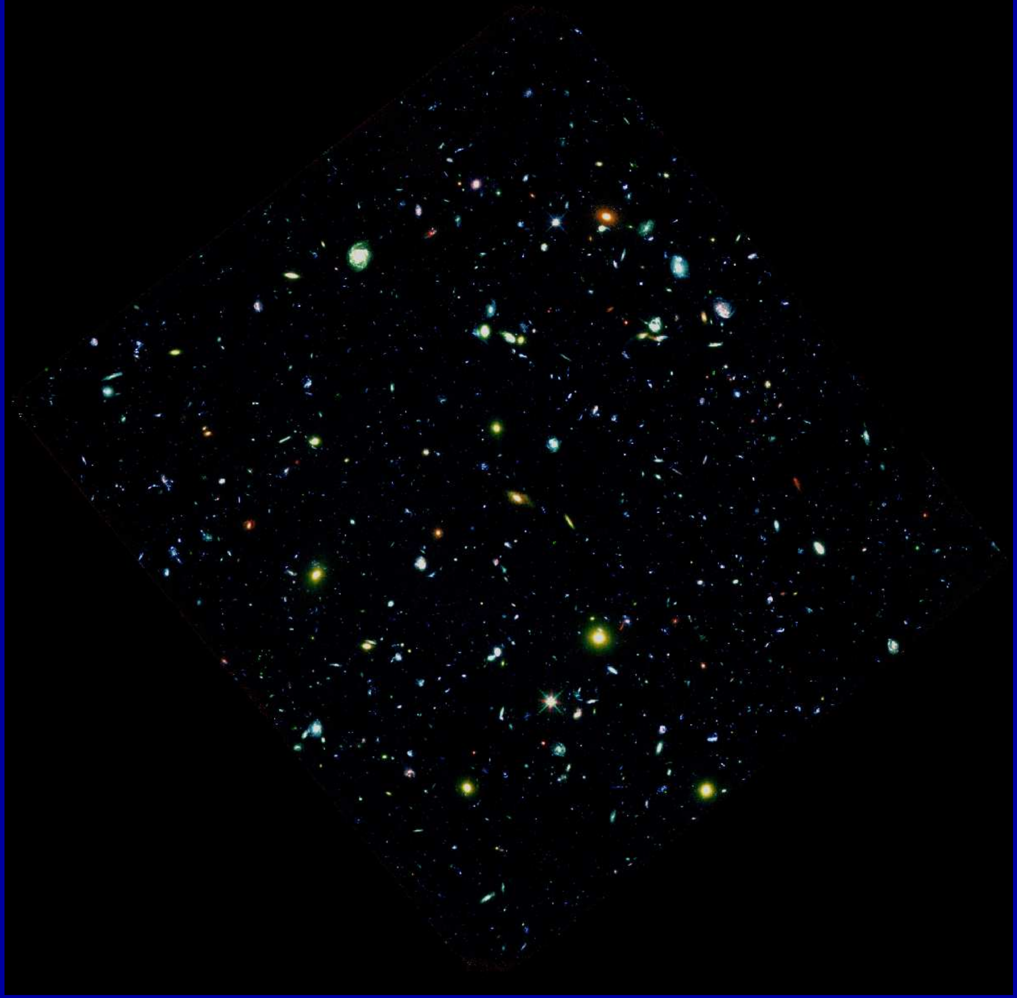
- The HUDF shows WFC3 IR's capabilities at $z \simeq 7$–9.

⇒ 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 0.7–5μm.



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).

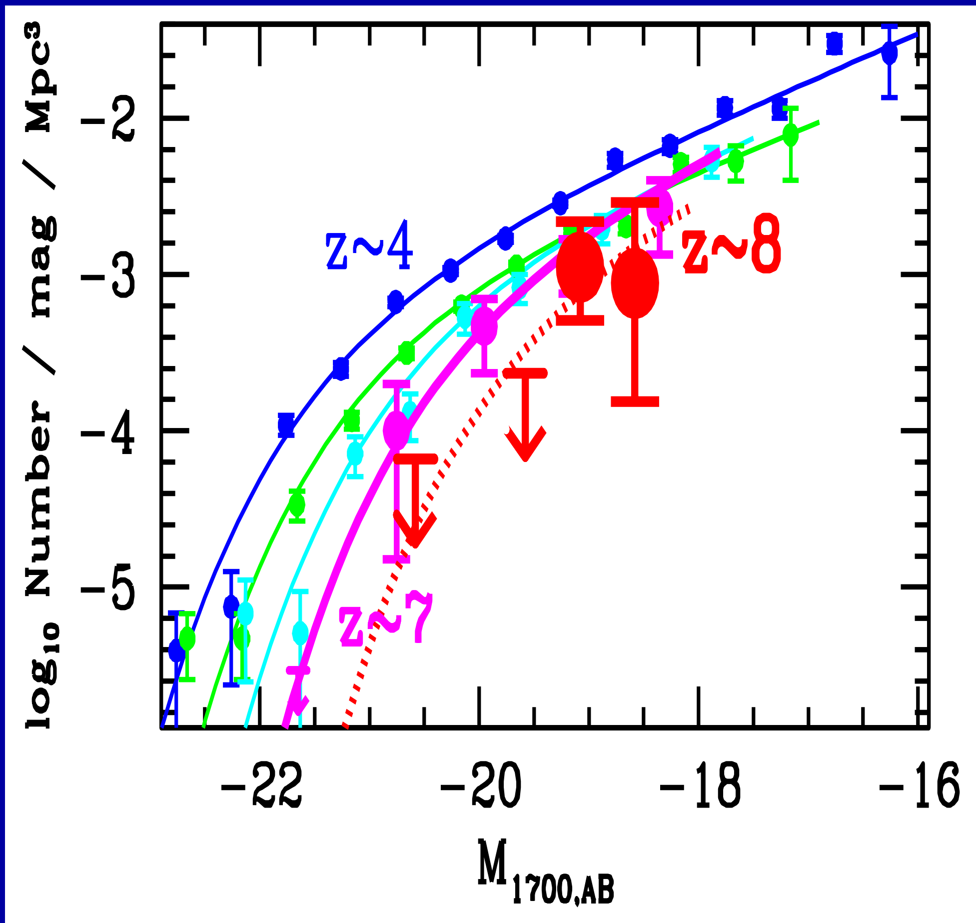


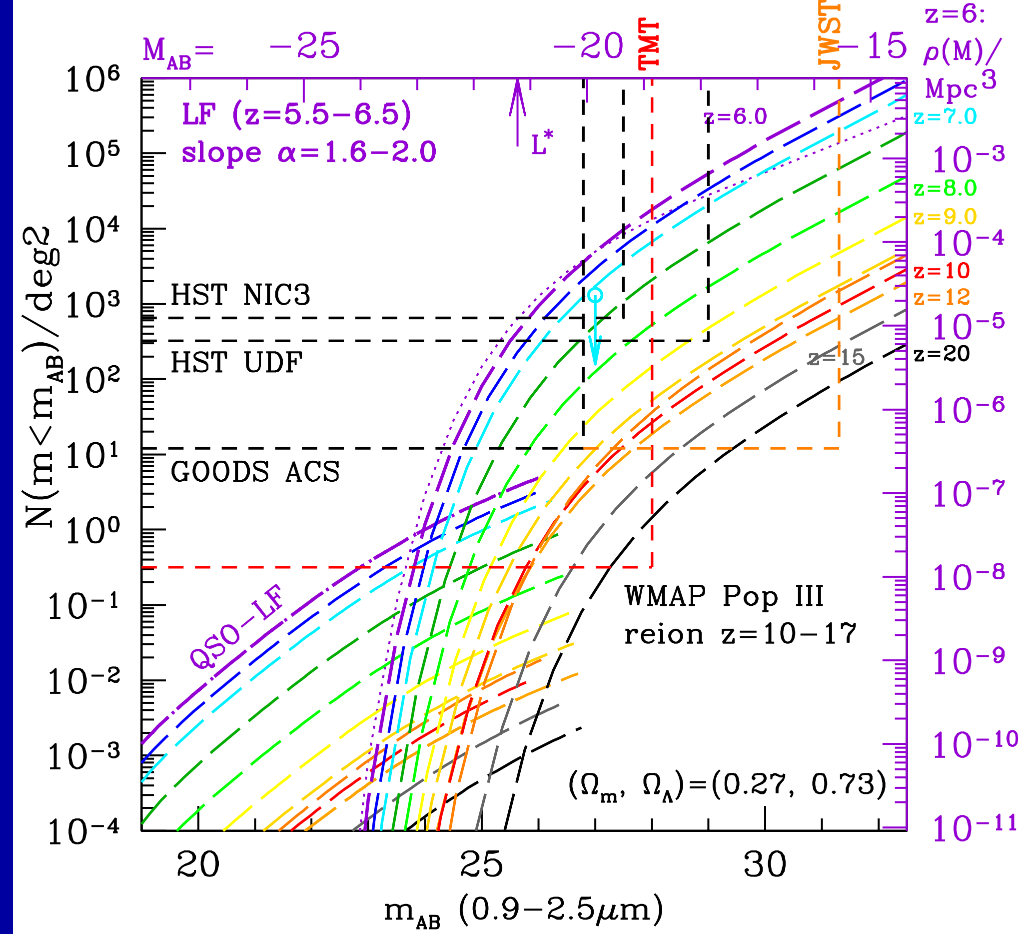
(LEFT) HST/WFC3 IR-mosaic in YJH in the HUDF: Bouwens et al (2010), Yan et al. (2009; astro-ph/0910.0077).

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

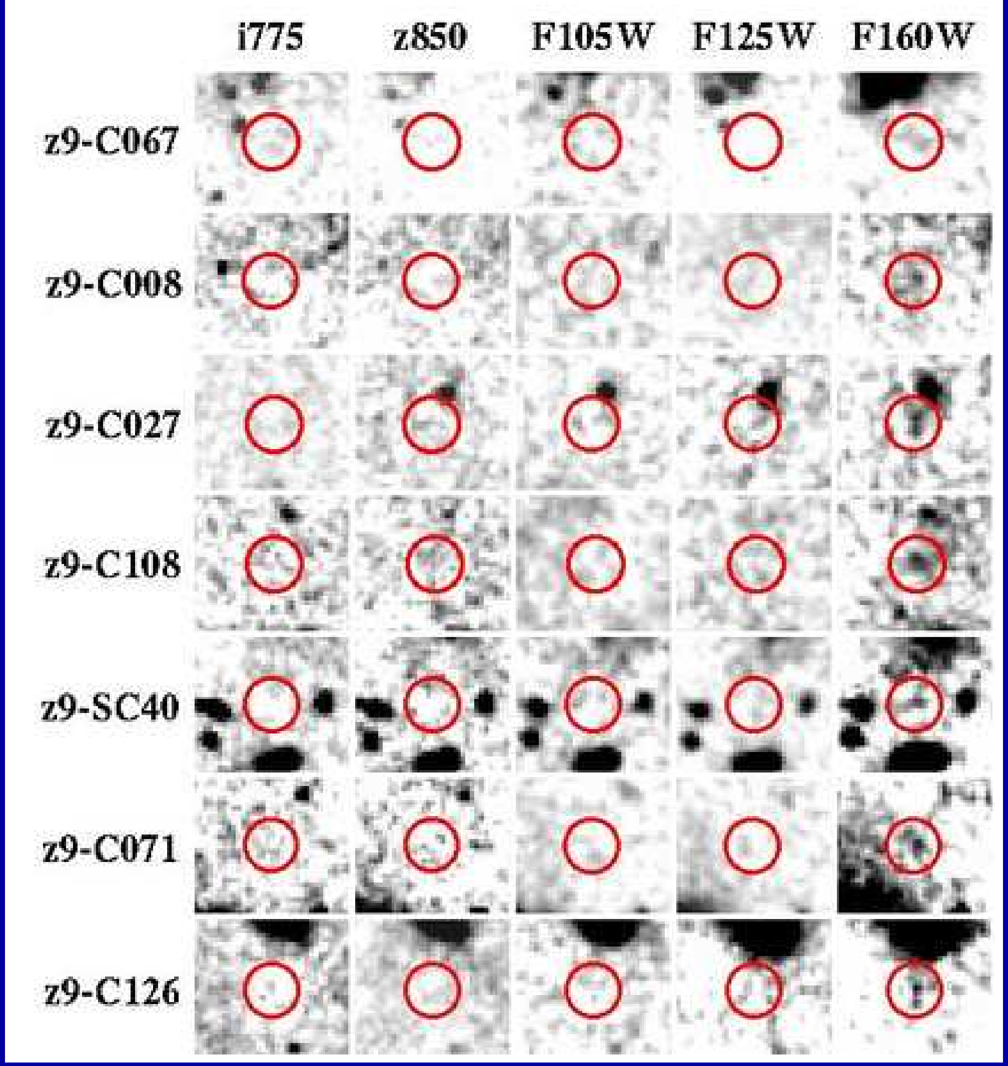
The CLOSED-TUBE HST has residual low-level systematics: imperfect removal of detector artifacts, flat-fielding, and faint straylight.

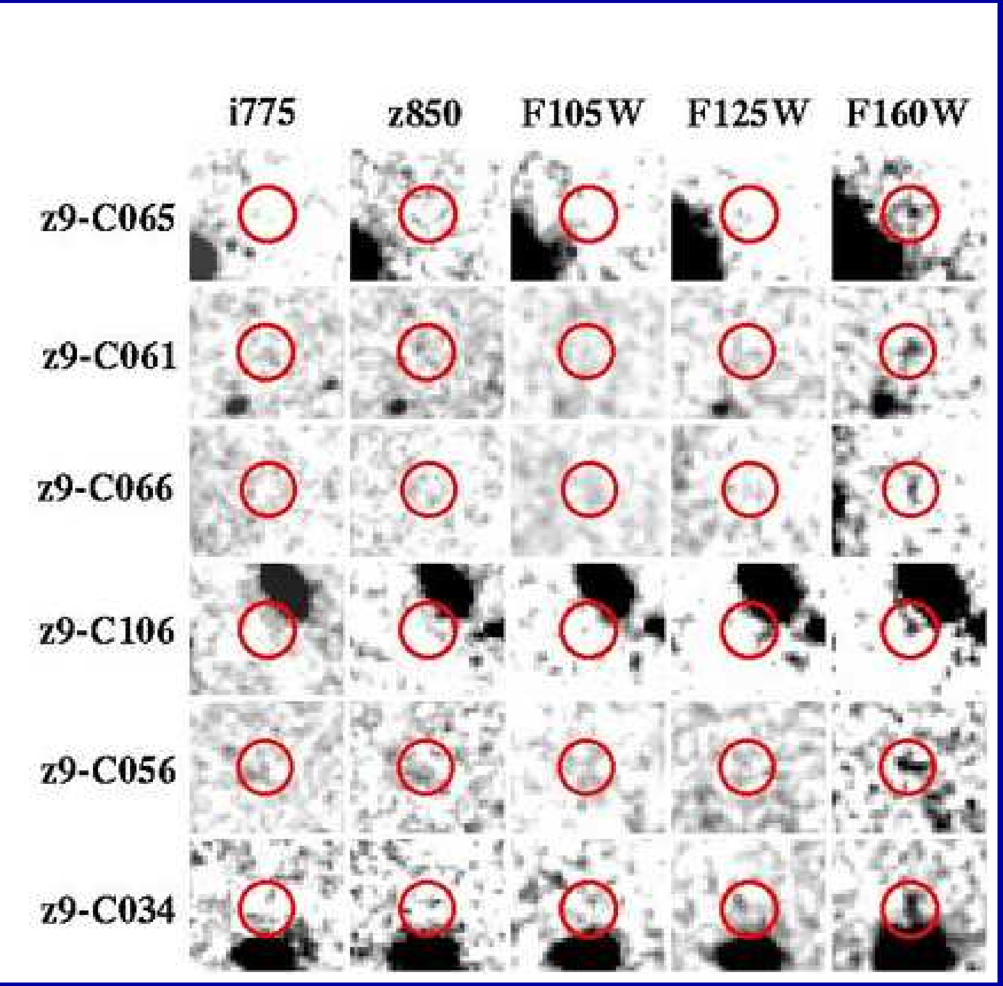
The open JWST architecture need perfect baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to 10^{-4} of sky.



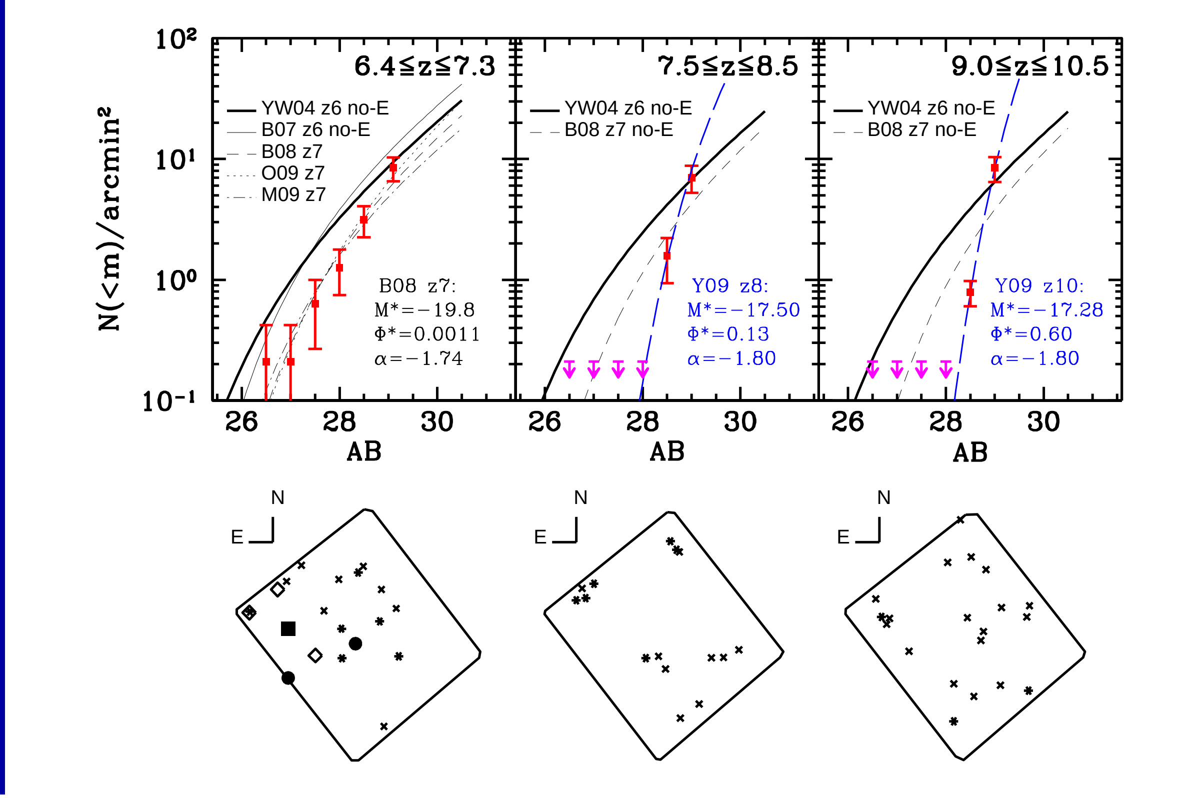


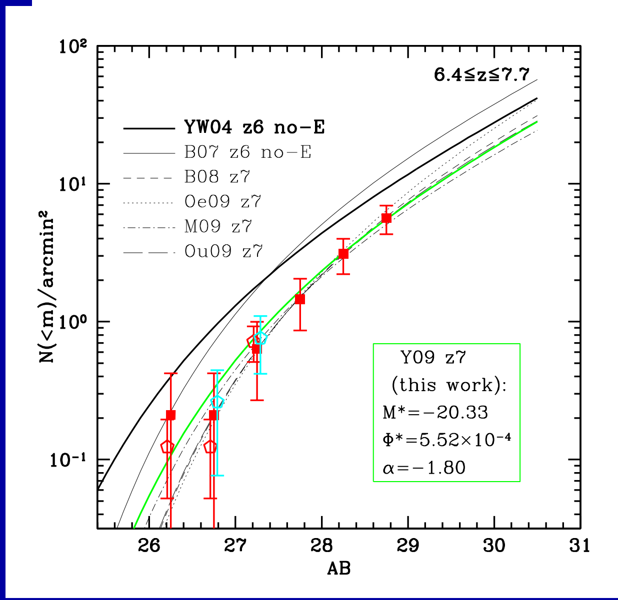
- Objects at z$\gtrsim$9 are rare (Bouwens^{+} 2010, Yan^{+} 2010), since volume element is small and JWST samples brighter part of LF. JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ-range (0.7-29 μm).
- With proper survey strategy (area AND depth), JWST can trace the entire reionization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

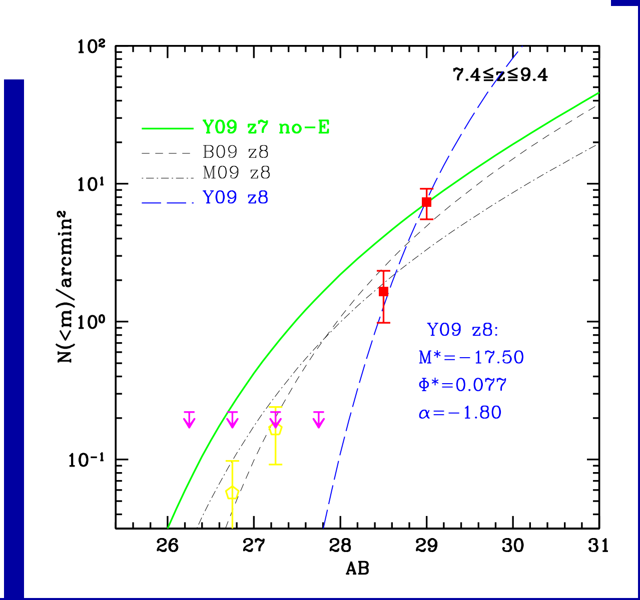




- Our simulations show that ∼50% of the J-drops close to bright galaxies are real (unlike Bouwens 2010), see Yan et al. 2010 (astro.0910.0077).
- Assume only 33% of J-drops are real *and* at z$\gtrsim$9. Together with the HUDF and ERS upper limits to AB$\lesssim$28 mag, the z∼9 LF is still steep!
- Need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

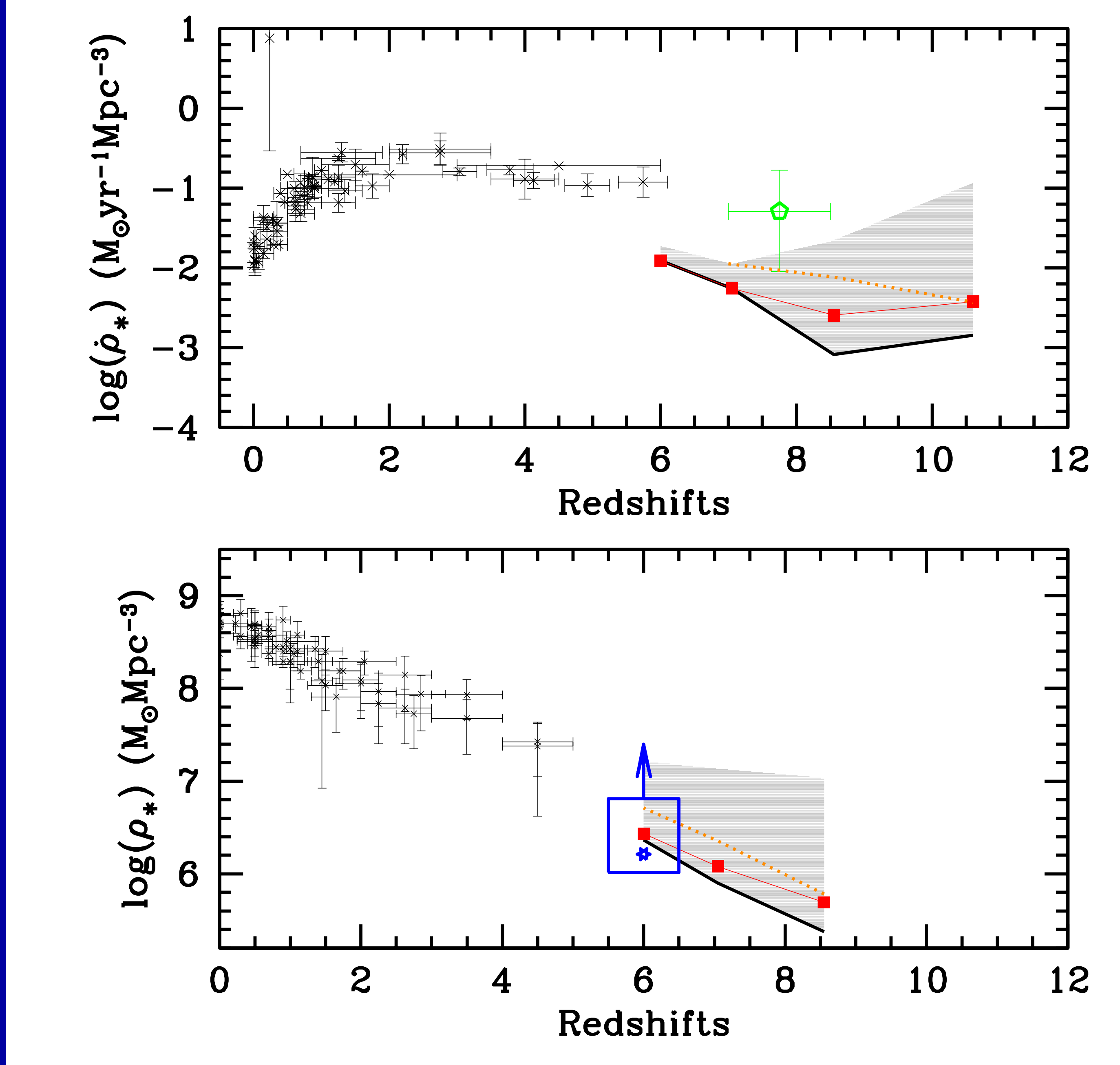






Update of Yan et al. 2009 (astro.0910.0077) HUDF with WFC3 ERS data:

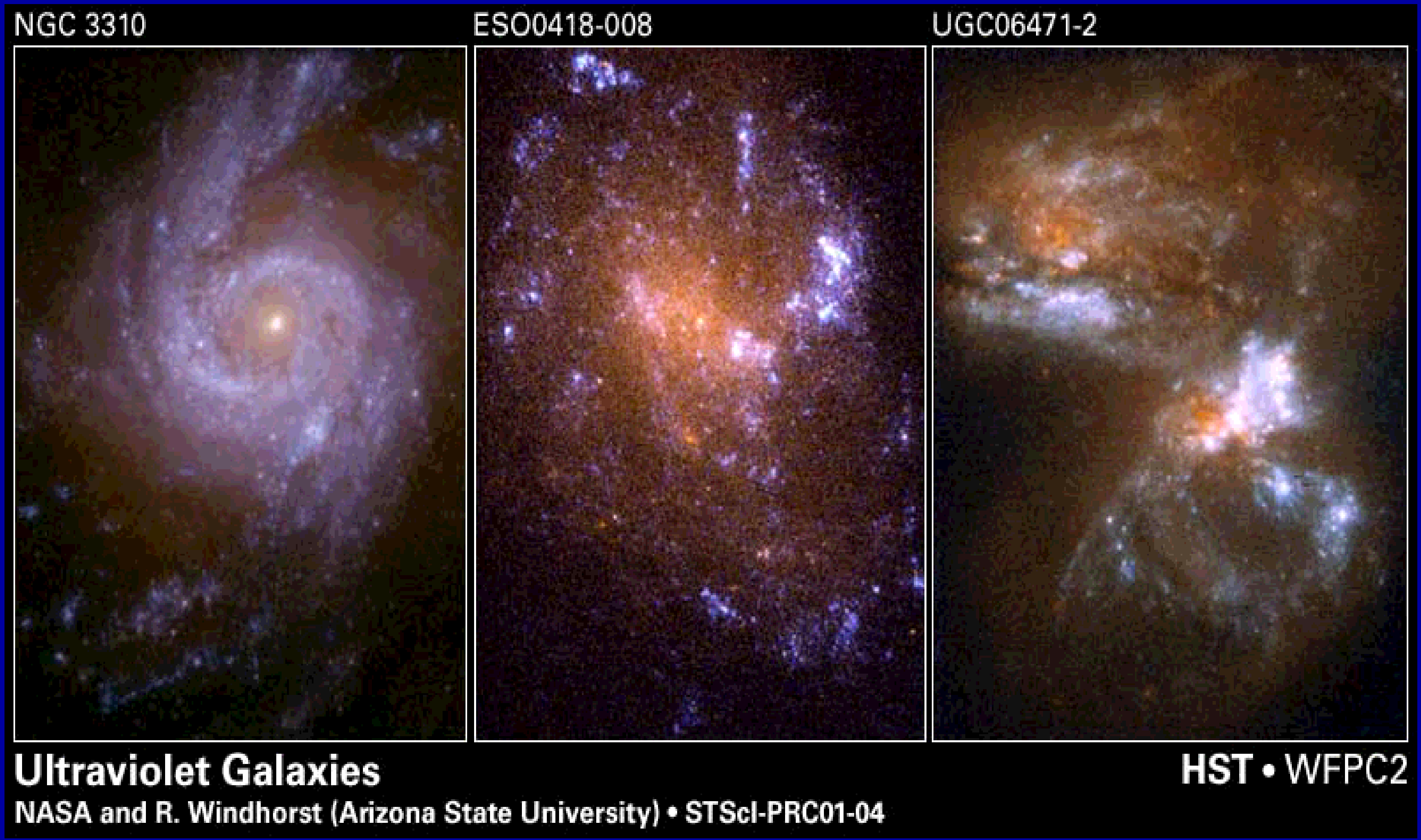
- z=7 LF more firm (see Bouwens), z=8 LF refined, z=9.5 UL's still stand.



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

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

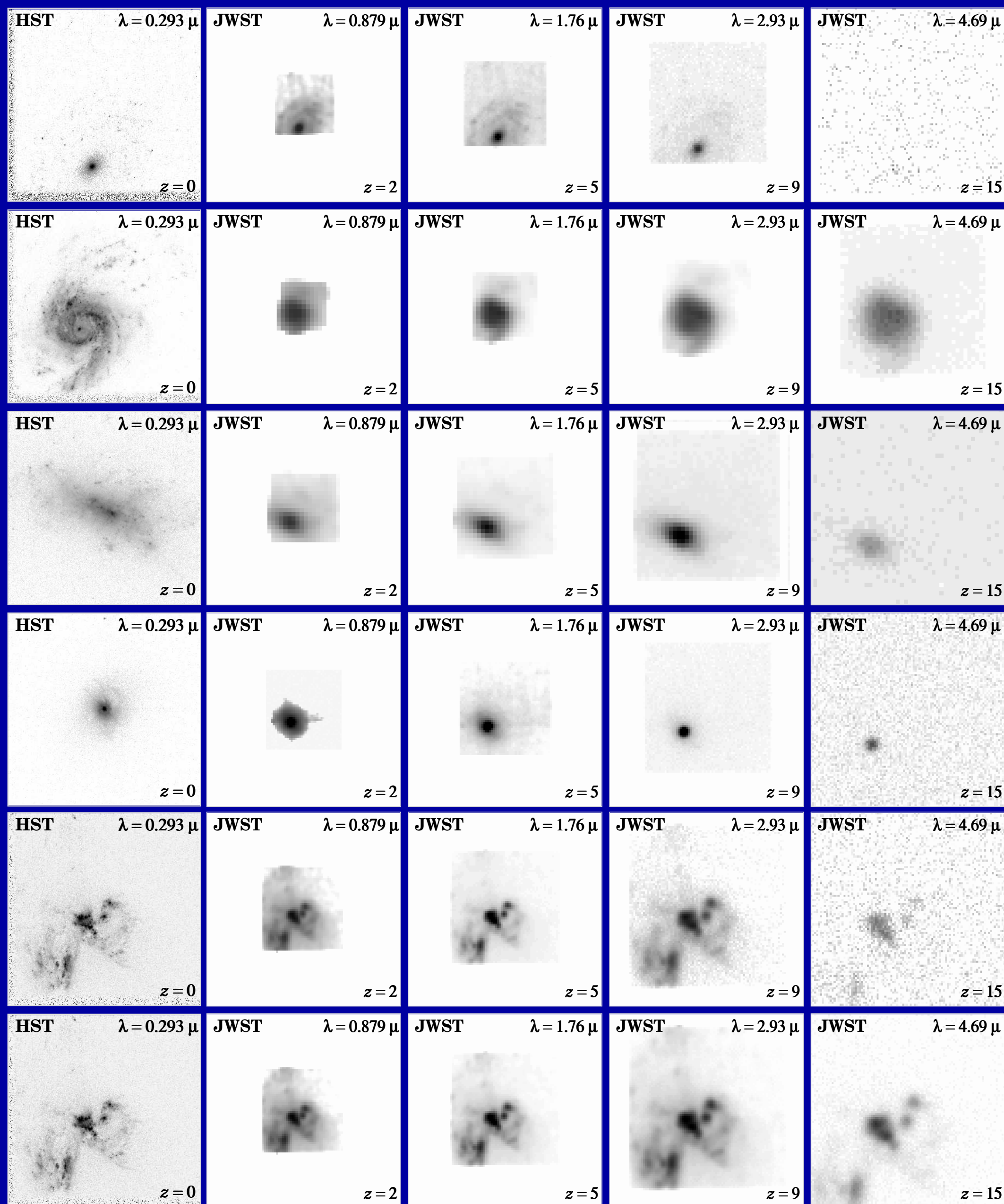
(5) Predicted Galaxy Appearance for JWST at z≃1–15



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

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

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



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

- (1) Most disks will SB-dim away at high z, but most formed at z≲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 to be held 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 must learn all lessons from HST ACS, NICMOS & WFC3:

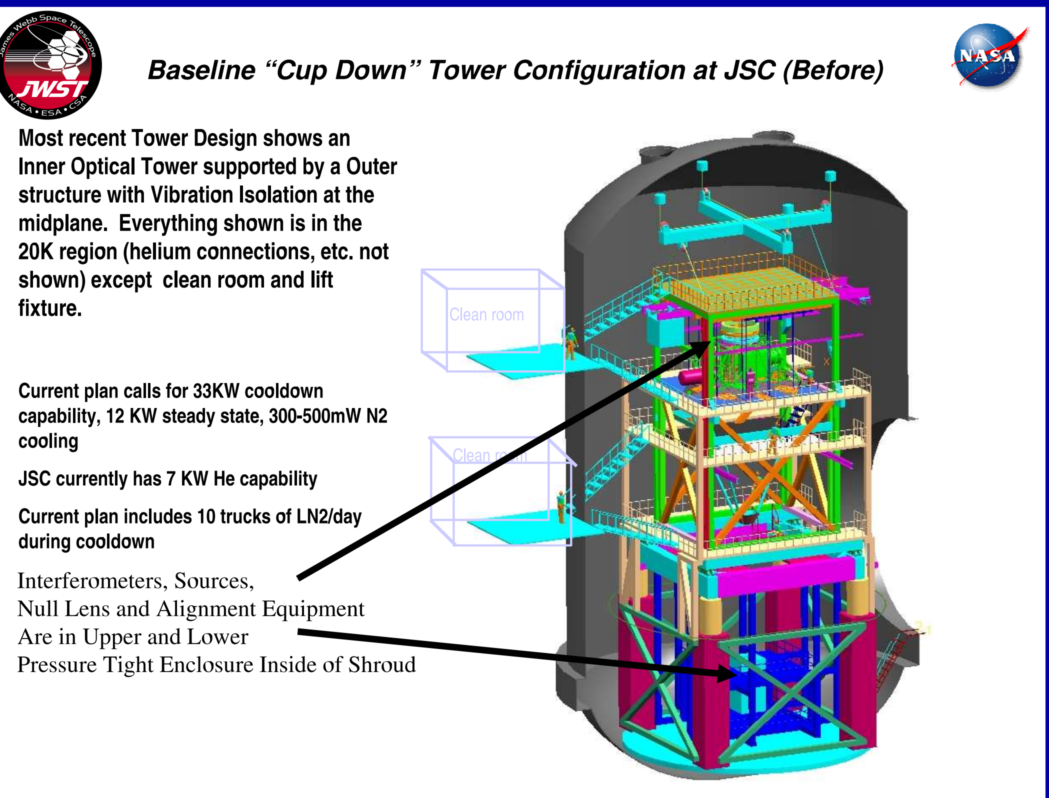
- Keep straylight/rogue path to an absolute minimum, and out-of-focus.
- Making sky-superflats (MDS mode) will be critical for a 500^{+} hr JUDF!

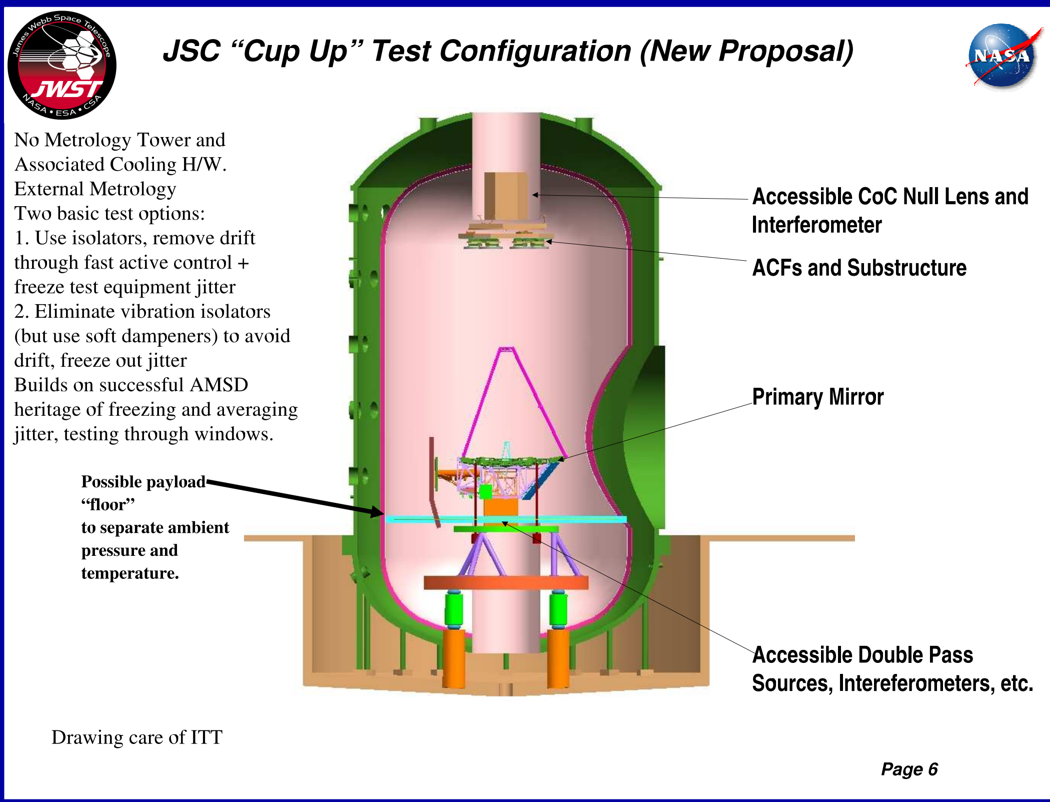
SPARE CHARTS

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

Northrop Grumman Expertise in Space Deployable Systems

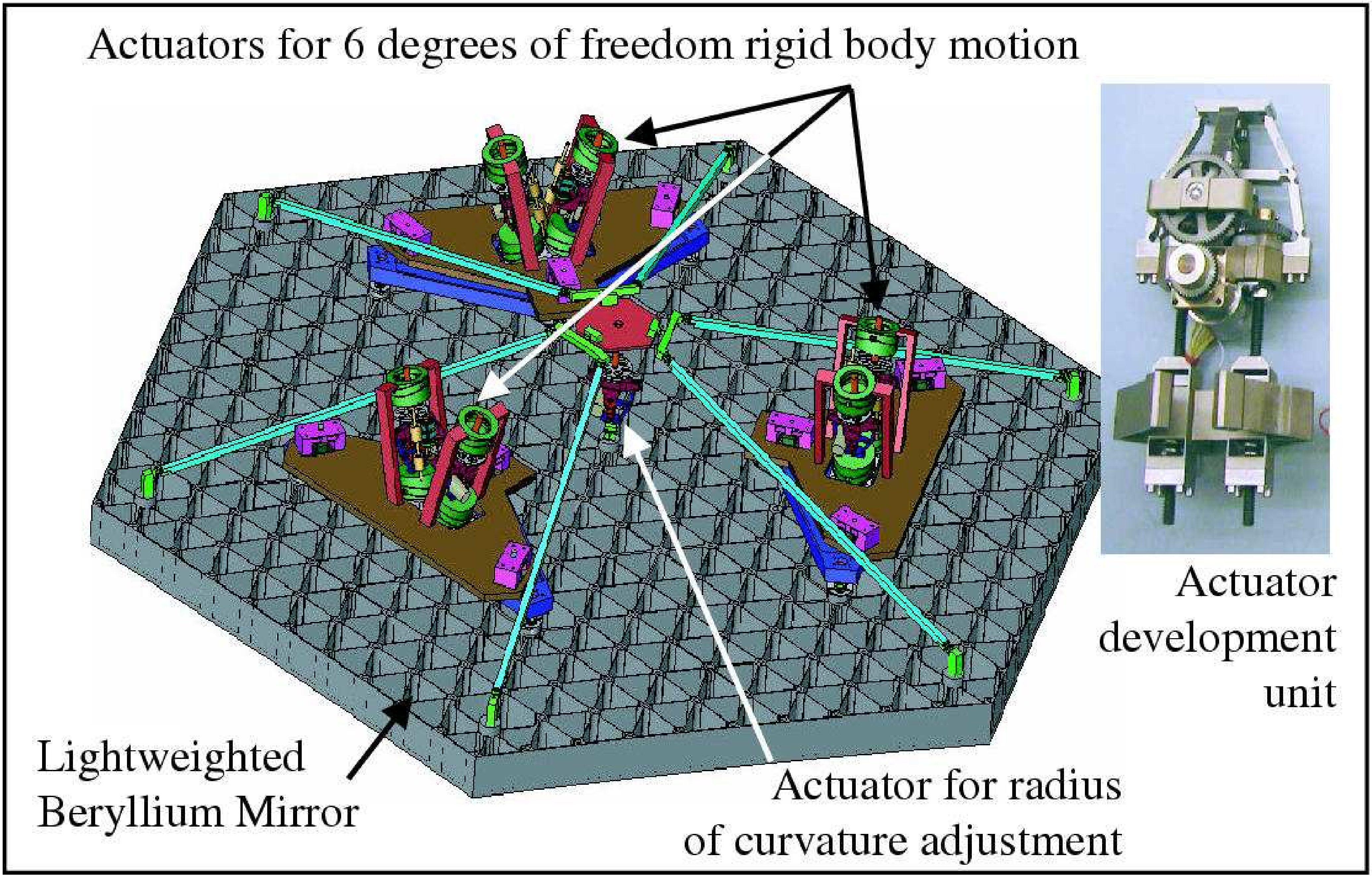
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements





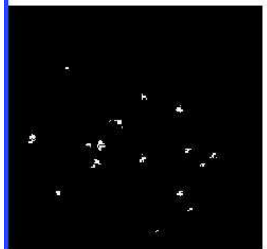
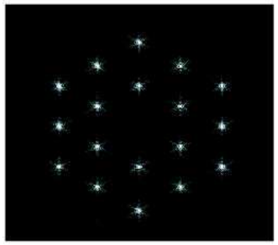
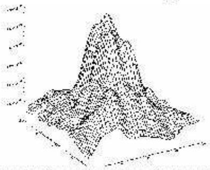
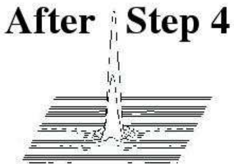
JWST underwent several significant replans and risk-reduction schemes:

- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane-V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6), *i.e.*, demonstration in a relevant environment — ground or space.
- 2007: Further simplification of sun-shield and end-to-end testing.
- 2008: Passes Mission Preliminary Design & Non-advocate Reviews.



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

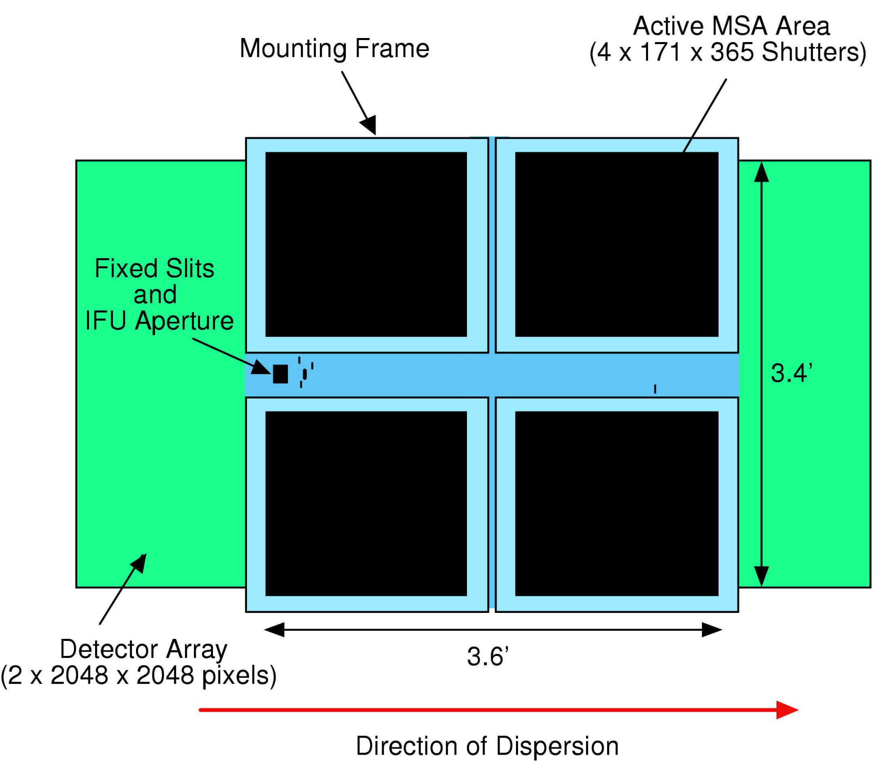
Redundant & doubly-redundant mechanisms, quite forgiving against failures

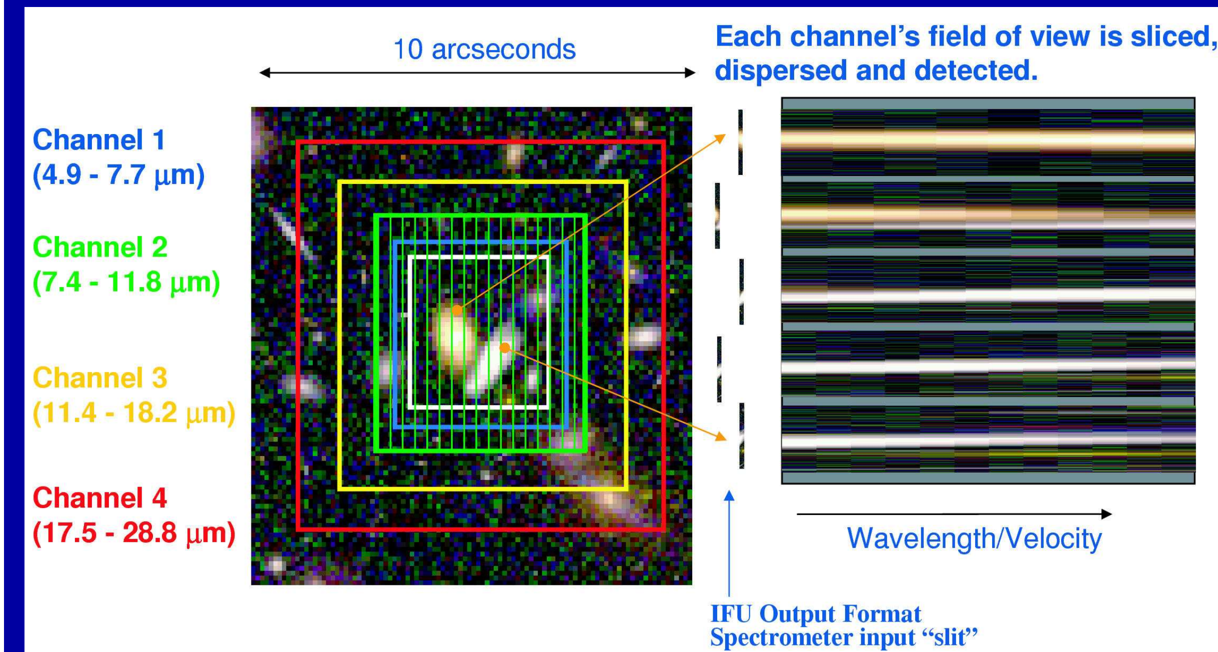
Step		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	After Step 1 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment 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$10 days, depending on scheduling/SC-illumination.





JWST offers significant multiplexing for faint object spectroscopy:

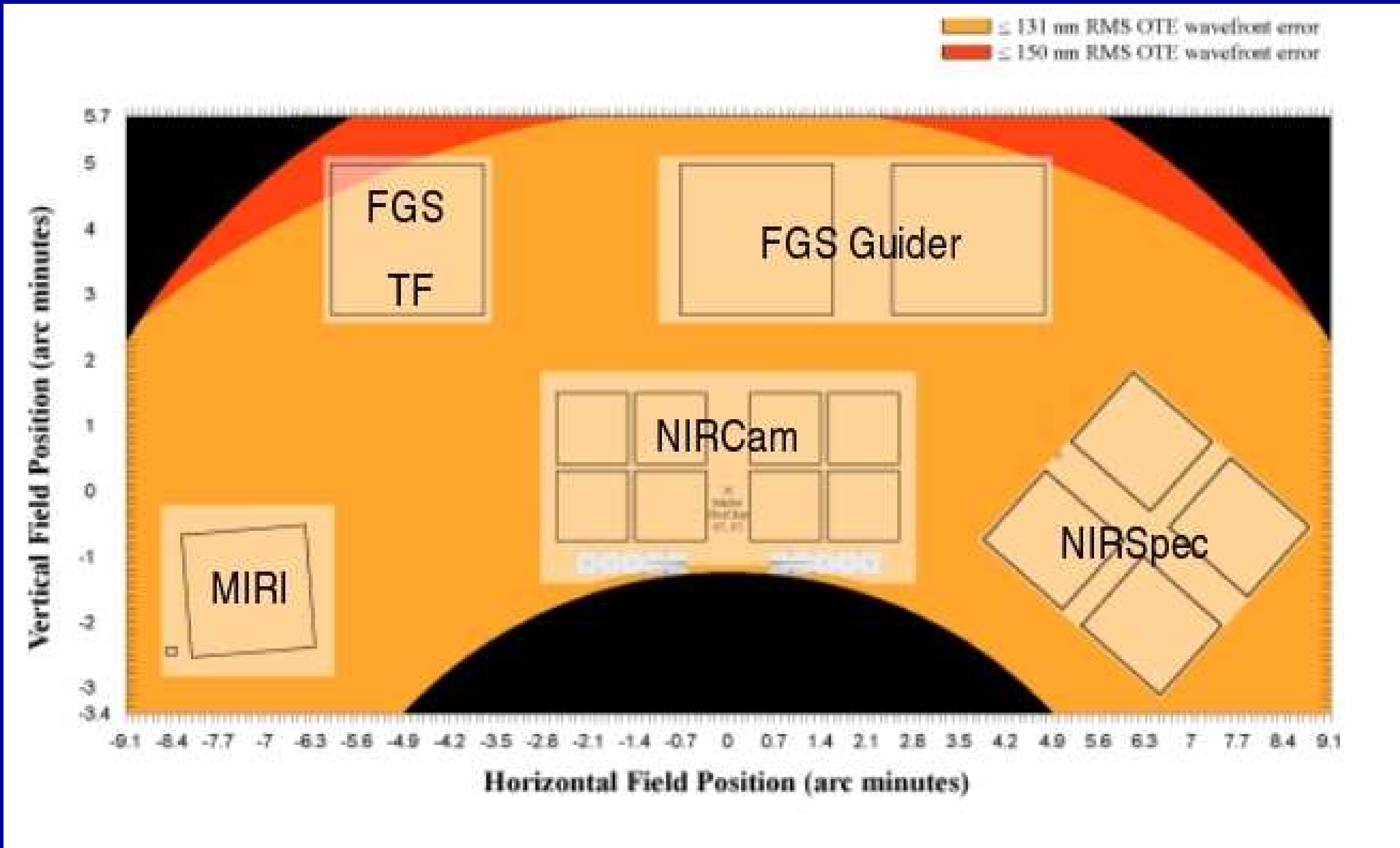
- NIRSpec/MSA with 4×62,415 independently operable micro-shutters (MEMS) that cover $\lambda\simeq$1–5 μm at R$\simeq$100–1000.

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

- FGS/TFI that covers a 2$'\!.$2×2$'\!.$2 FOV at $\lambda\simeq$1.6–4.9 μm at R$\simeq$100.

[• NIRCam offers R$\simeq$5 imaging from 0.7–5μm over two 2$'\!.$3×4$'\!.$6 FOV's.]

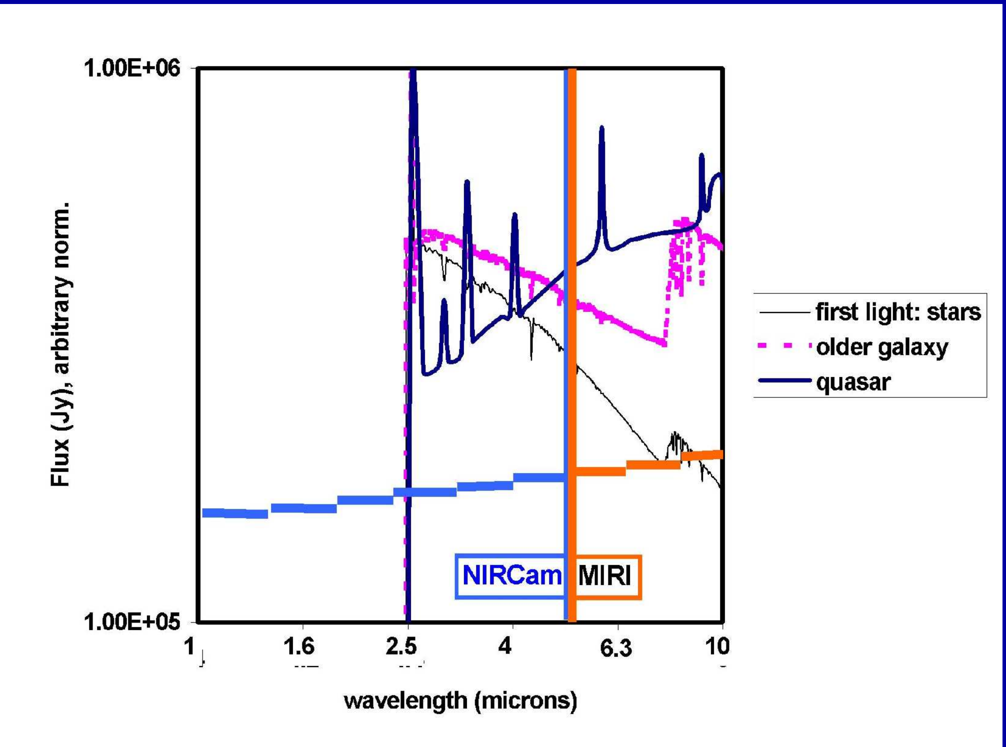
• (2) What instruments will JWST have?

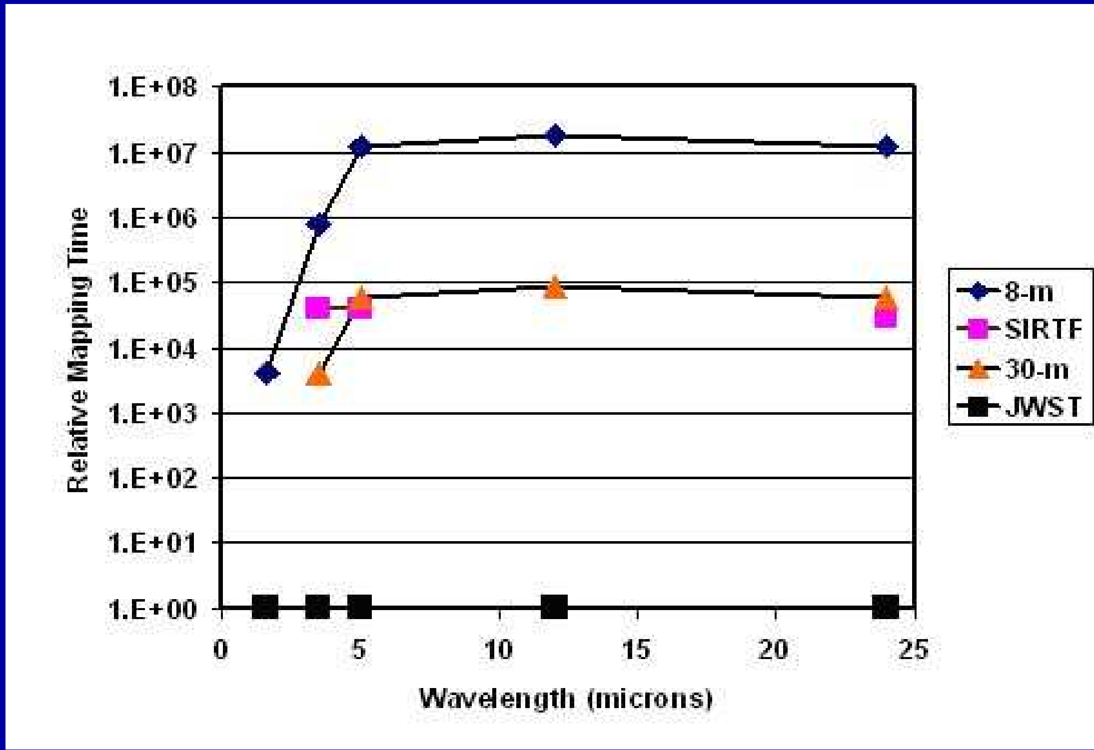


All JWST instruments can in principle be used in parallel observing mode:

• Currently only being implemented for parallel *calibrations.*

• (2) What sensitivity will JWST have?





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

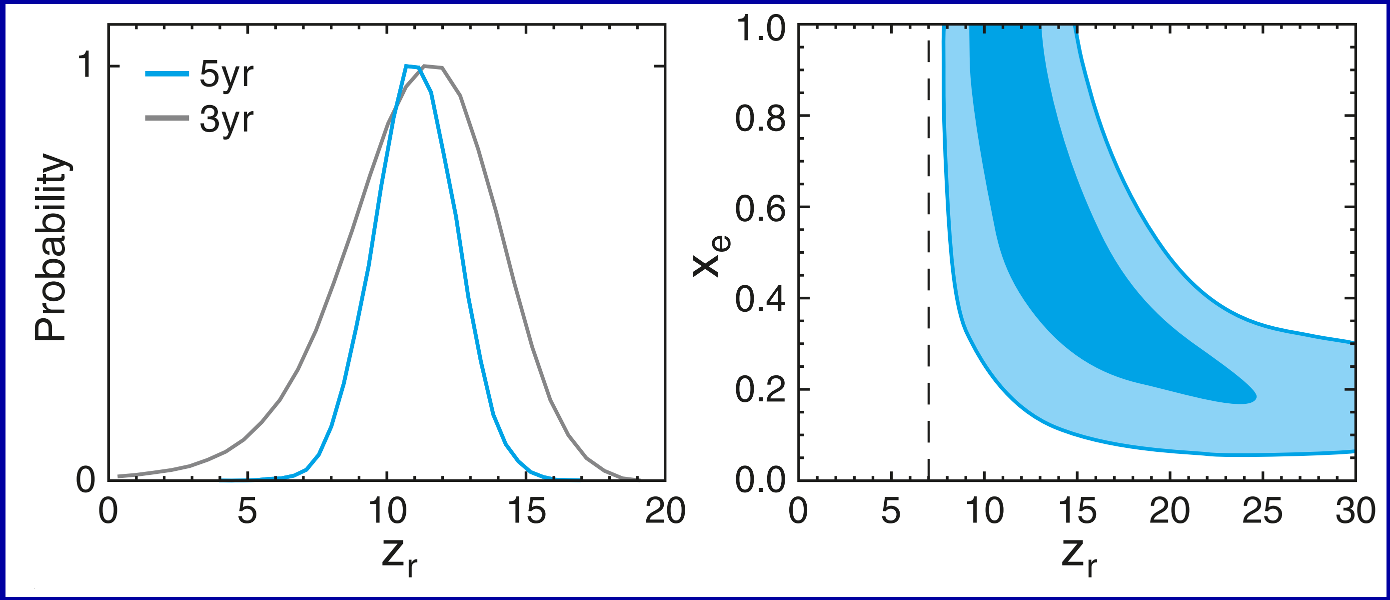
Together, they allow objects to be found to z=15–20 in $\sim 10^5$ sec (28 hrs).

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.

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

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



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

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

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

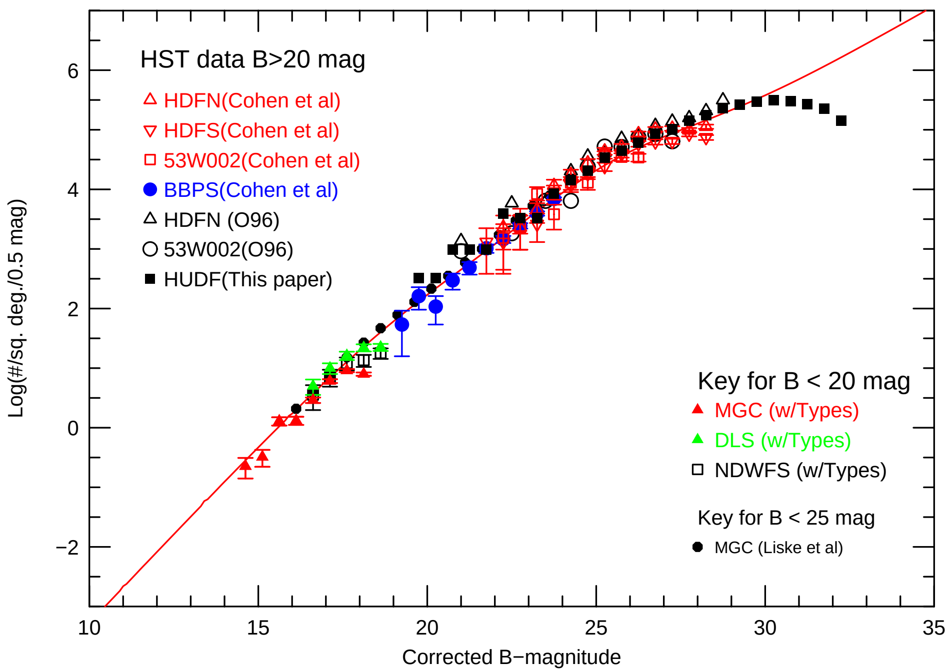
- HST/ACS has covered $z \lesssim 6$, and WFC3 is now covering $z \lesssim 7$–9.
- For First Light & Reionization, JWST must sample $z \simeq 8$ to $z \simeq 15$–20.

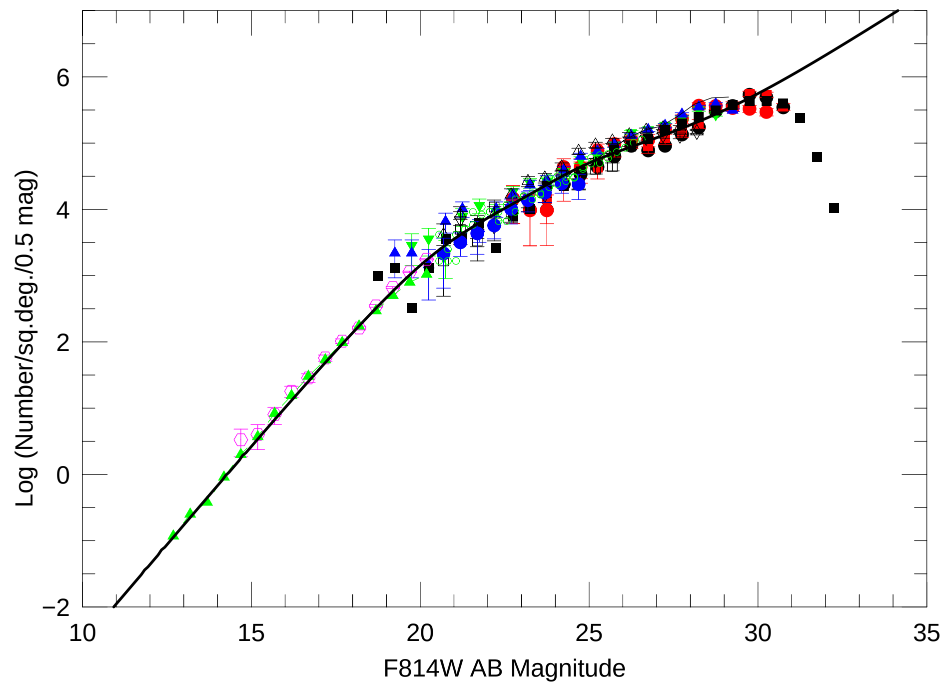
$\Rightarrow$ JWST must cover $\lambda = 0.7$–29 μm, with its diffraction limit at 2.0 μm.

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

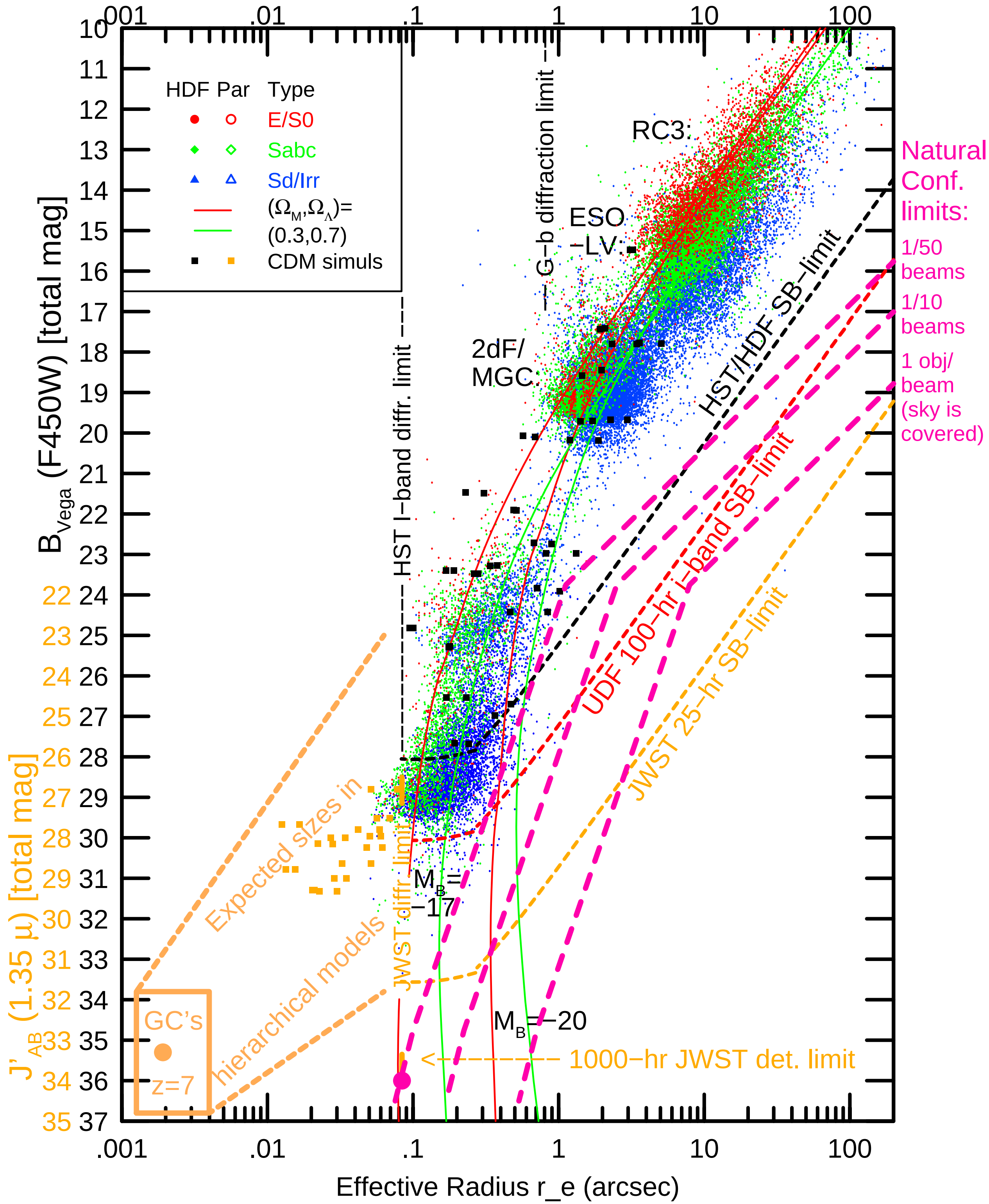
What comes around, goes around ...

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.



.001 .01 .1 1 10 100
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
22 23 24 25 26 27 28 29 30 31 32 33 34 35
HDF Par Type
E/S0
Sabc
Sd/Irr
(Ω_M,Ω_Λ)=
(0.3,0.7)
CDM simuls
B_Vega (F450W) [total mag]
J'_AB (1.35 μ) [total mag]
Effective Radius r_e (arcsec)
RC3
ESO
−LV
2dF/
MGC
G−b diffraction limit
HST I−band diffr. limit
HST/HDF SB−limit
UDF 100−hr I−band SB−limit
JWST 25−hr SB−limit
JWST diffr. limit
Expected sizes in
hierarchical models
GC's
z=7
M_B=
−17
M_B=−20
<−−−−−−−−−− 1000−hr JWST det. limit
Natural
Conf.
limits:
1/50
beams
1/10
beams
1 obj/
beam
(sky is
covered)

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$0$''$.1 FWHM (Kawata et al. 2006). Since $z_{med}\simeq$1.5, this influences the balance of how $(1+z)^4$-dimming & object overlap affects the catalog completeness.

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

- References and other sources of material shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool]

www.asu.edu/clas/hst/www/ahah/ [Hubble at Hyperspeed Java–tool]

http://wwwgrapes.dyndns.org/udf_map/index.html [Clickable HUDF map]

http://www.jwst.nasa.gov/ and http://www.stsci.edu/jwst/

http://ircamera.as.arizona.edu/nircam/

http://ircamera.as.arizona.edu/MIRI/

http://www.stsci.edu/jwst/instruments/nirspec/

http://www.stsci.edu/jwst/instruments/guider/

Gardner, J. P., et al. 2006, Space Science Reviews, 123, 485–606

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

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