

Koo-1 Panchromatic Astronomy: Past, Present, and Future

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

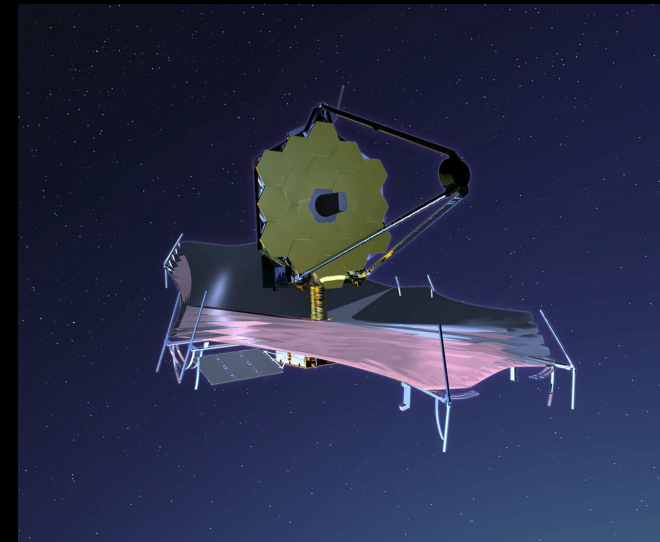
Collaborators: S. Cohen, R. Jansen (ASU), C. Conselice, S. Driver (UK), & H. Yan (OSU) & (Ex) ASU Grads: N. Hathi, H. Kim, M. Mechtley, R. Ryan, M. Rutkowski, A. Straughn, & K. Tamura



KPNO 1970's-1980's



HST \gtrsim 2002-2009



JWST \gtrsim 201?

Review at the UC Galaxy Workshop "Koo-fest 2011", UC Santa Cruz, Monday Aug. 8, 2011

Outline: Koo-1 Panchromatic Astronomy: Past, Present, & Future

PAST: David Koo's multi-band KPNO 4m work in the 1980's.

PRESENT: Recent panchromatic imaging with the HST WFC3.

New tools to measure Galaxy Assembly from $z \simeq 8-10$ to $z \simeq 0$.

[See also talks by S. Faber, G. Illingworth, and many others here.]

FUTURE: Panchromatic near-mid-IR imaging with JWST:

- (1) JWST update: $\gtrsim 75\%$ of hardware procured or completed.
- (2) How JWST can measure First Light ($z=10-20$) & Reionization.
- (3) Conclusions
- Appendix 1: Predicted Galaxy Appearance for JWST at $z \simeq 1-15$.

Sponsored by NASA/JWST & HST

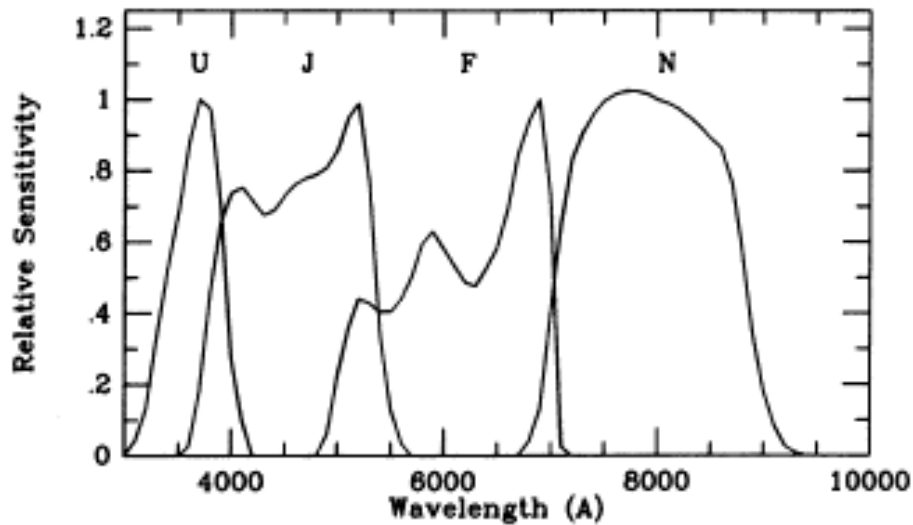
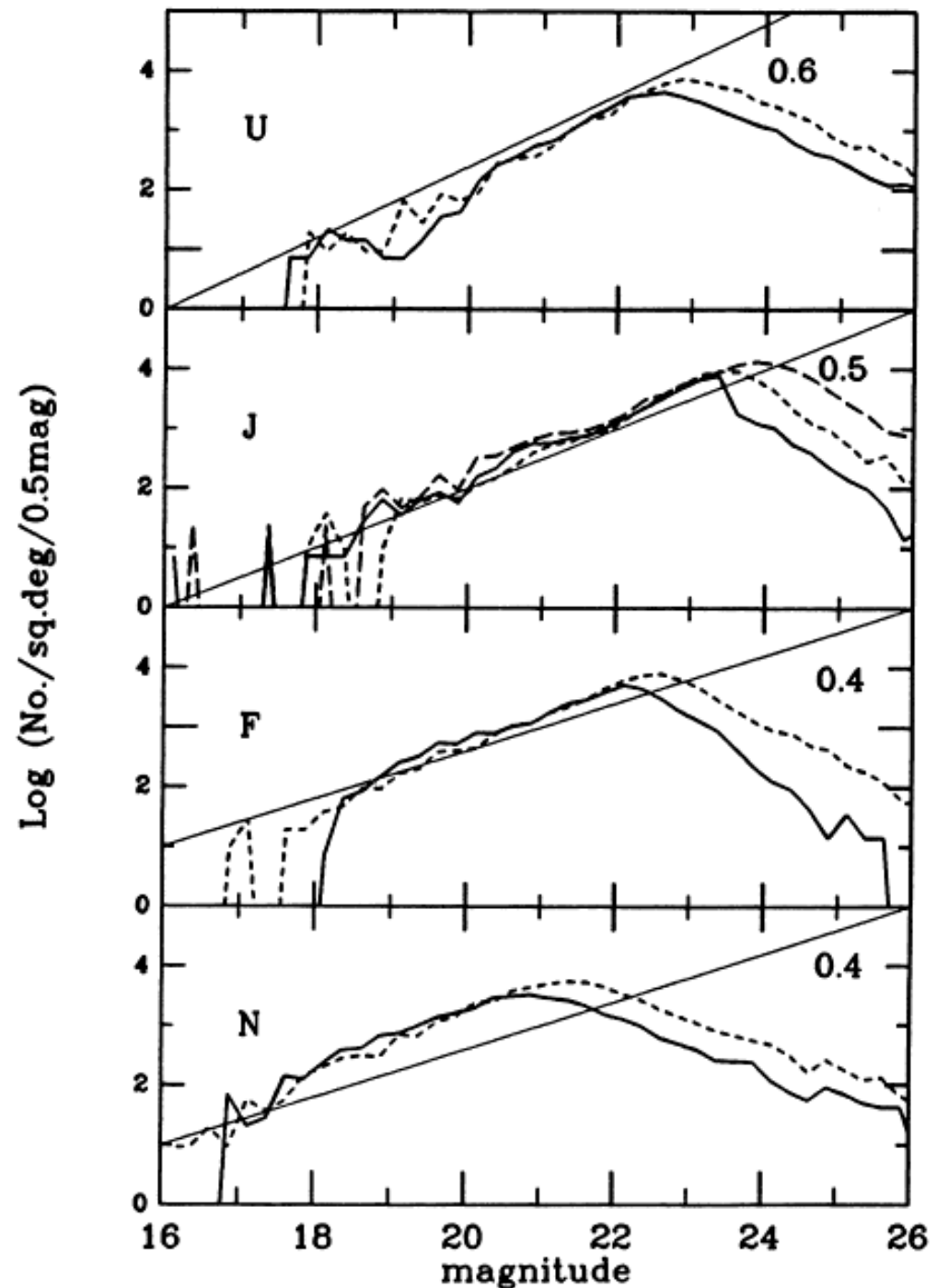


FIG. 1.—Response functions for bandpasses *U*, *J*, *F*, and *N*. See § III for a description of the derivation of the *U* and *N* bands. See Kron (1980a) for the *J* and *F* bands.

Koo 1985, AJ, 90, 418 &
Koo 1986, ApJ, 311, 651

4m Mayall plates with
with four filters: UJ^+FN ,
reaching $UJ^+ \sim 24$ mag,
and $FN \sim 23-22$ mag.



Panchromatic galaxy counts understood as changing type mix vs. epoch.

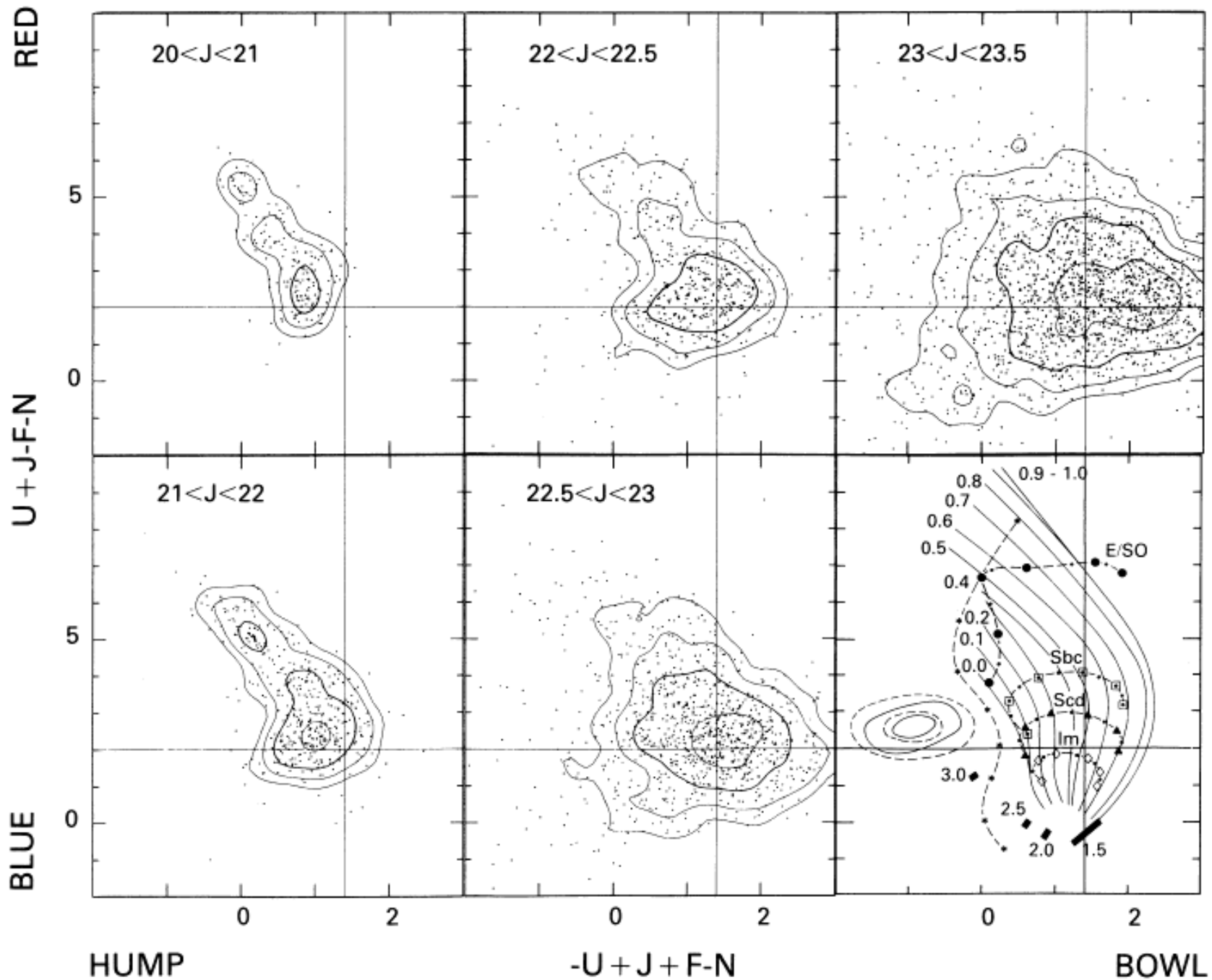


FIG. 9c

Koo (1985, 1986): UJ^+FN can disentangle SED-type and redshift for $z \simeq 0-1$.

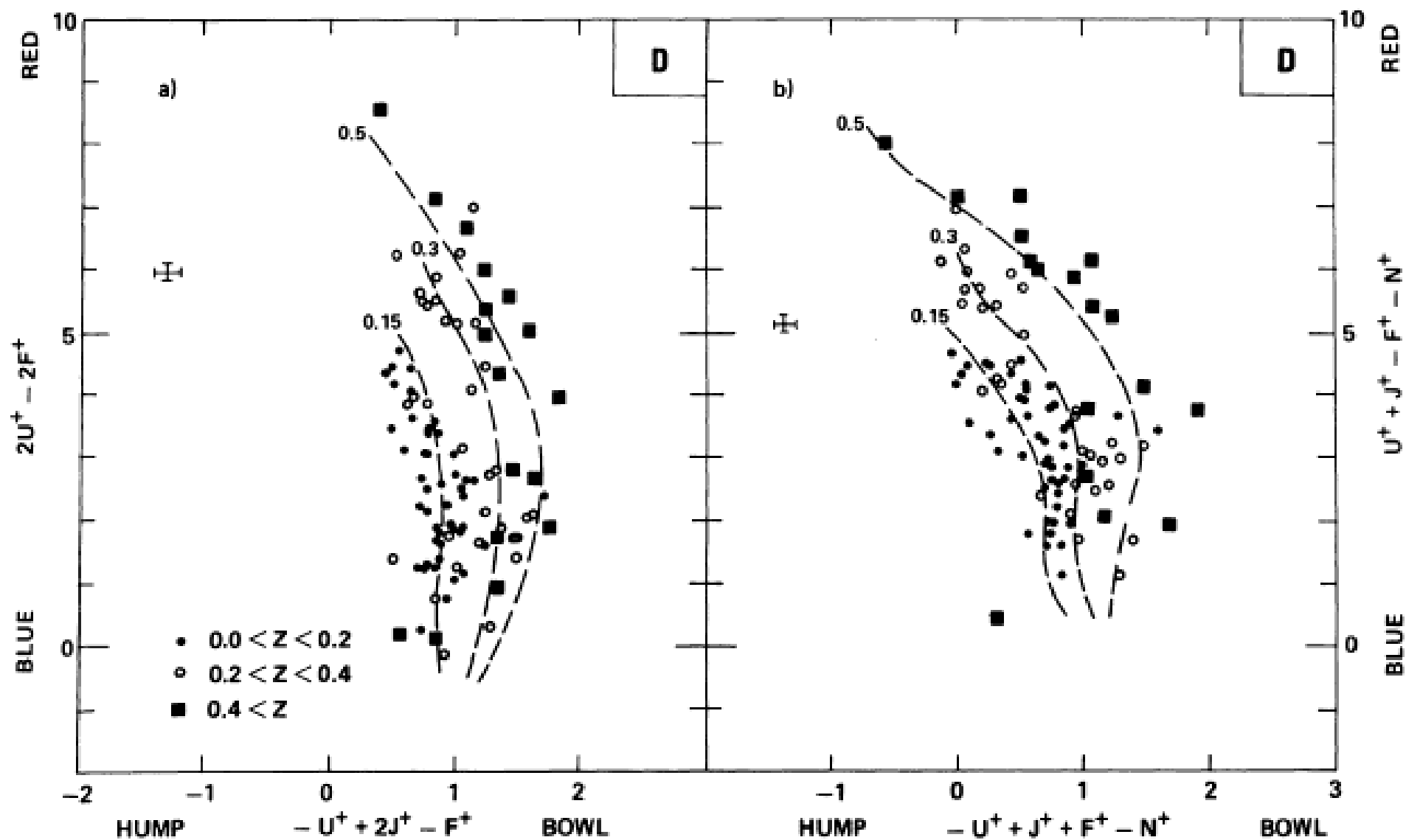


FIG. 5. Color-shape plots [UF for (a) and $UJFN$ for (b)] showing positions of all galaxies in Table IV with redshifts measured from low-resolution spectra. The data are divided into three redshift intervals, dark dots for redshifts z less than 0.20, light circles for redshifts z between 0.2 and 0.4, and dark squares for larger redshifts, to demonstrate the segregation of galaxies of different redshifts in these color-color plots. Dashed lines marked with the redshift are the predictions from the no-evolution model D. Error bars show typical errors of the data of 0.1 mag in each of the axes.

Koo (1985, 1986): UJ^+FN actually disentangles SED-type and z for $z \lesssim 0.5$.

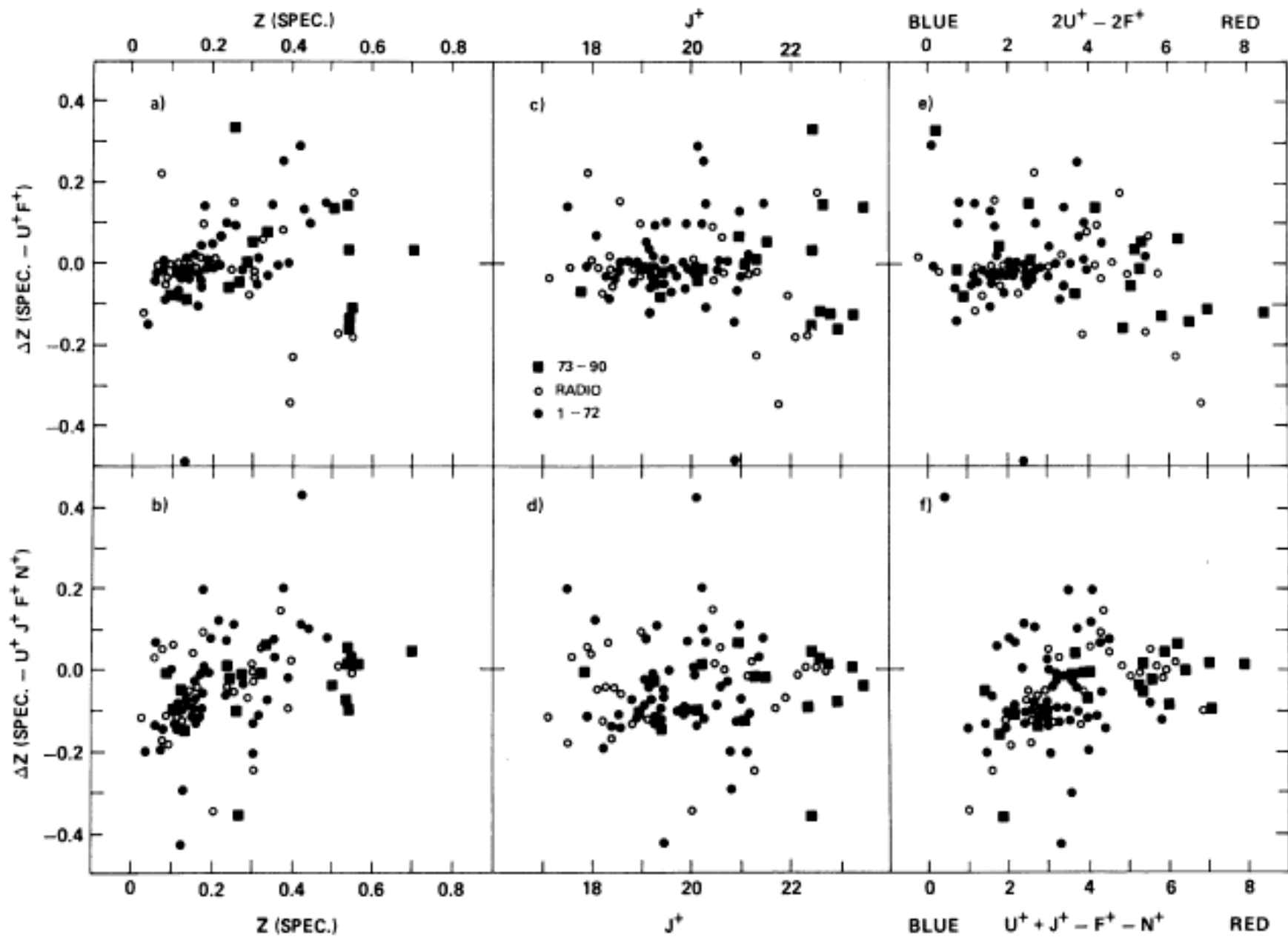
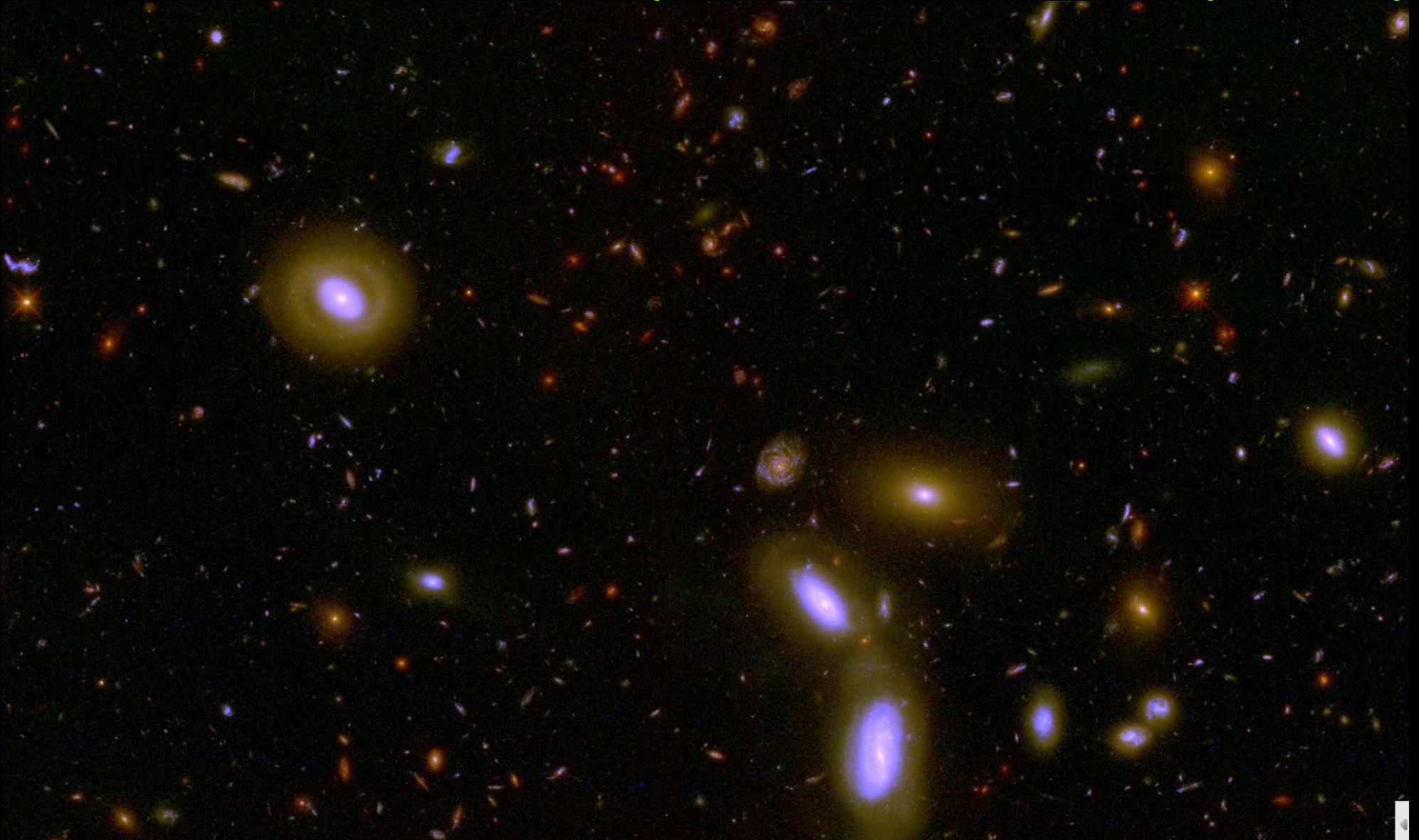


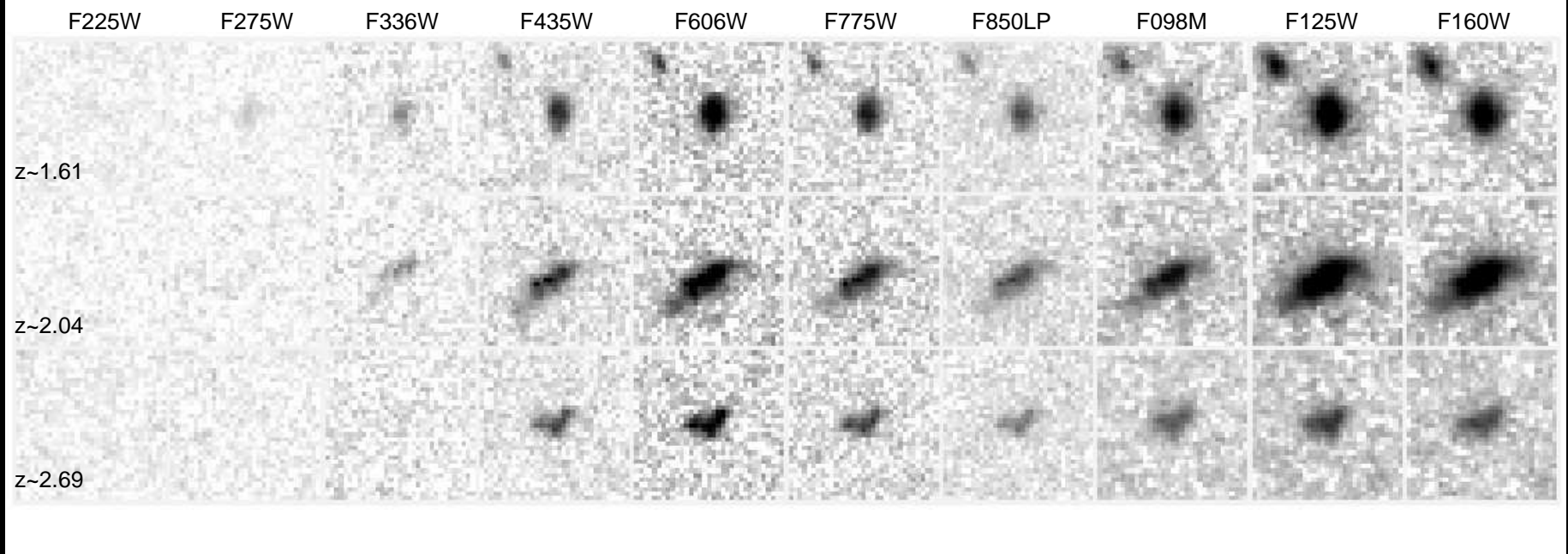
FIG. 7. Differences between spectroscopic redshifts and those estimated from broadband colors (as determined from either the UF or the $UJFN$ color-shape diagrams) are plotted against the spectroscopic redshifts (a,b), apparent blue magnitudes J^+ (c,d), and colors (e,f). Dark dots are for galaxies with spectroscopic redshifts from Turner, Gunn, and Sargent (1981); light circles are for radio galaxies from Kron, Koo, and Windhorst (1984) or Windhorst *et al.* (1985); dark squares are for galaxies with redshifts measured by H. Spinrad, R. Kron, and the author.

Koo (1985, 1986): first believable photoz's with $\sigma(\Delta z)/(1+z) \lesssim 0.05$.

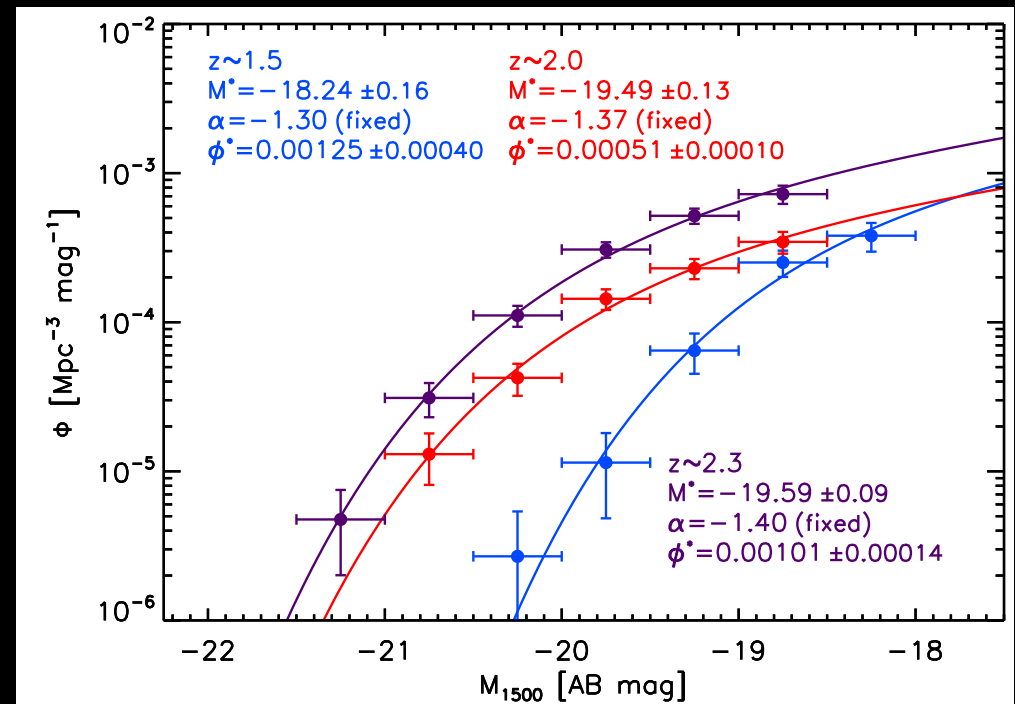
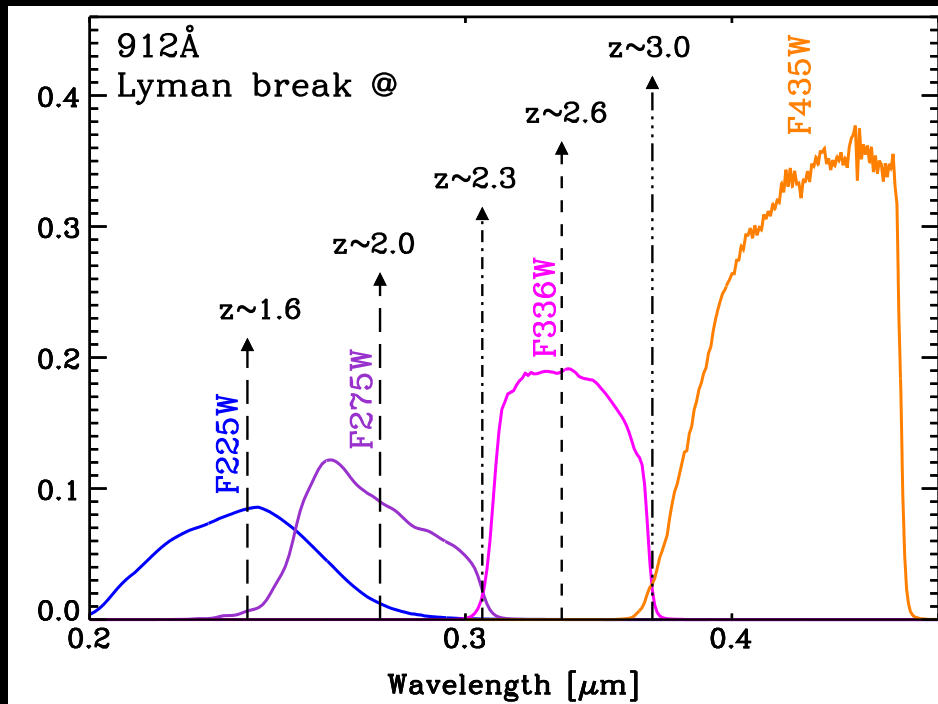
PRESENT: Panchromatic Astronomy with the HST WFC3: Galaxy Assembly



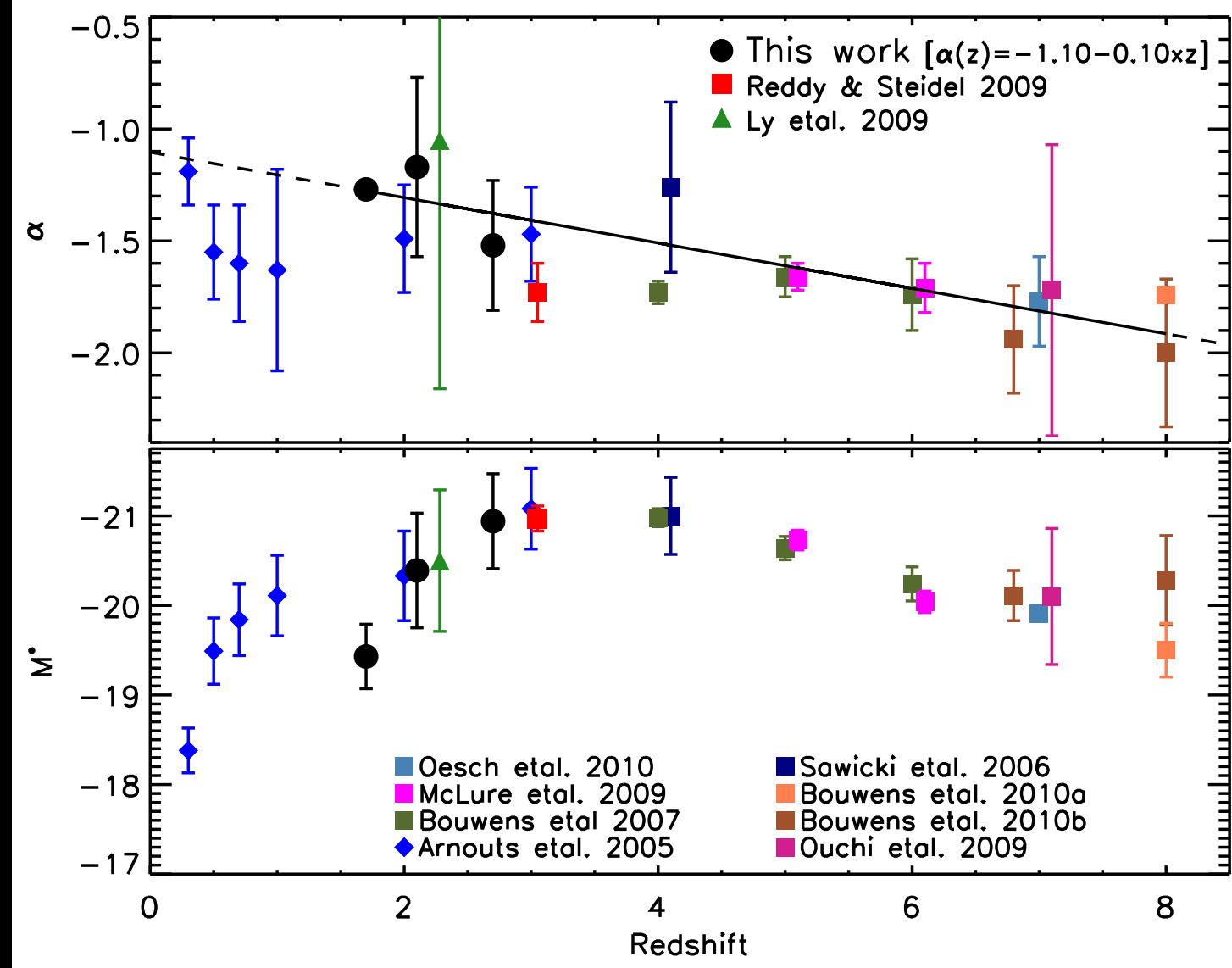
10 filters with HST/WFC3 & ACS reaching $AB=26.5-27.0$ mag ($10-\sigma$) over 40 arcmin^2 at $0.07-0.15''$ FWHM from $0.2-1.7 \mu\text{m}$ (UVUBVizYJH). JWST adds $0.05-0.2''$ FWHM imaging to $AB \simeq 31.5$ mag (1 nJy) at $1-5 \mu\text{m}$, and $0.2-1.2''$ FWHM at $5-29 \mu\text{m}$, tracing young+old SEDs & dust.



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



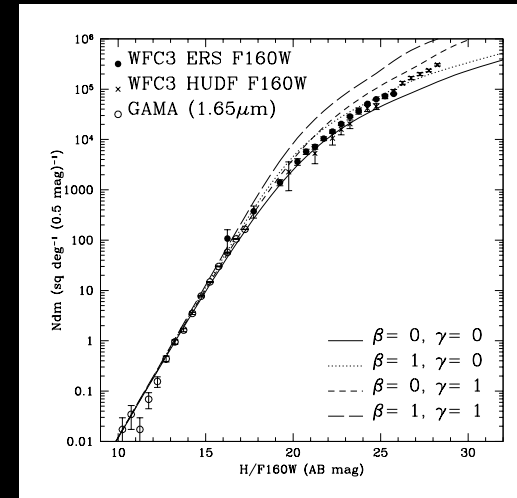
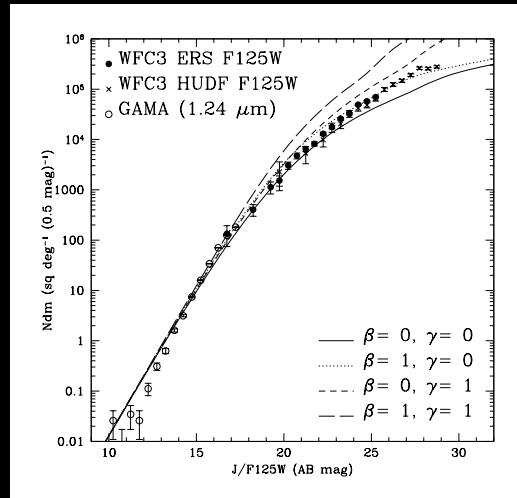
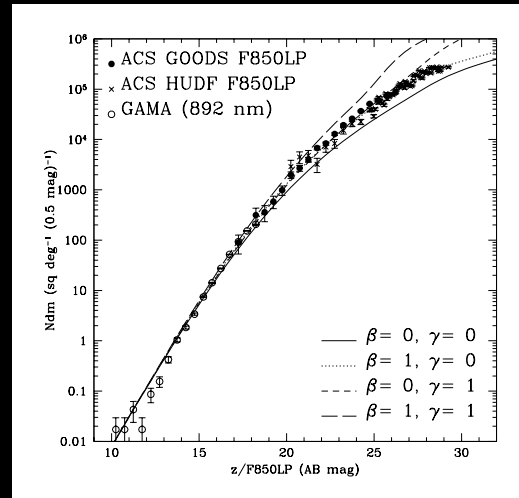
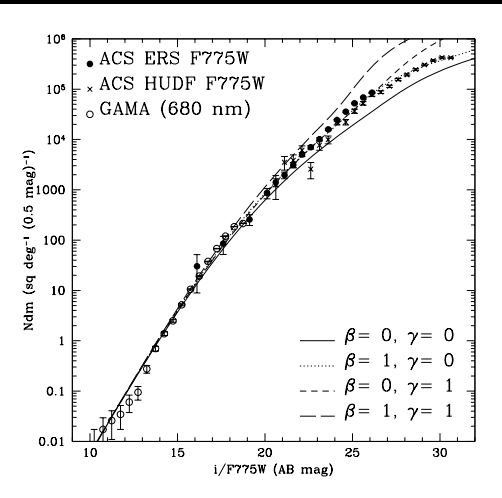
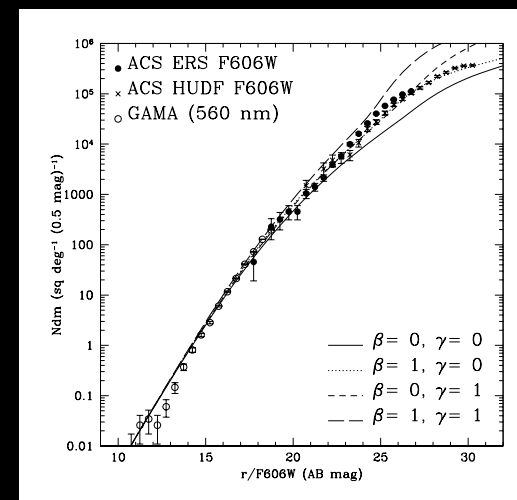
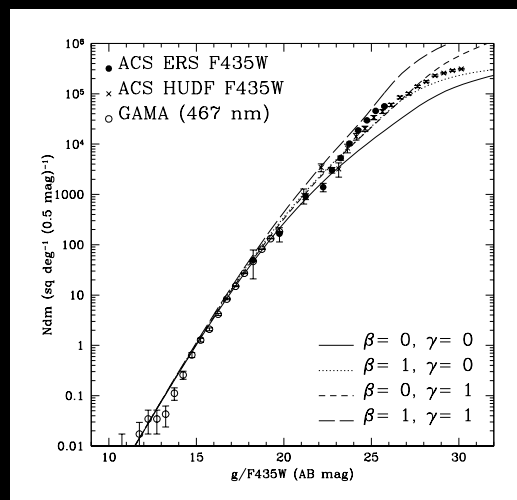
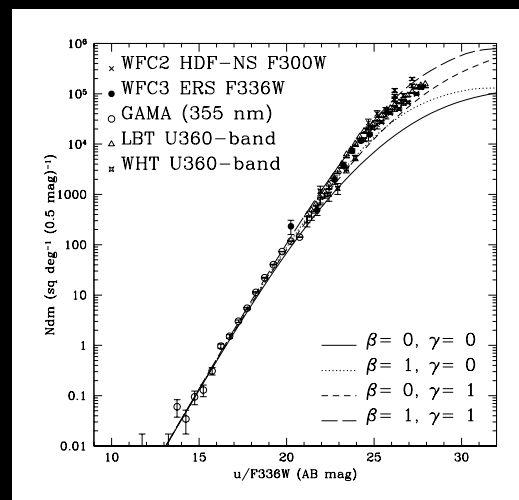
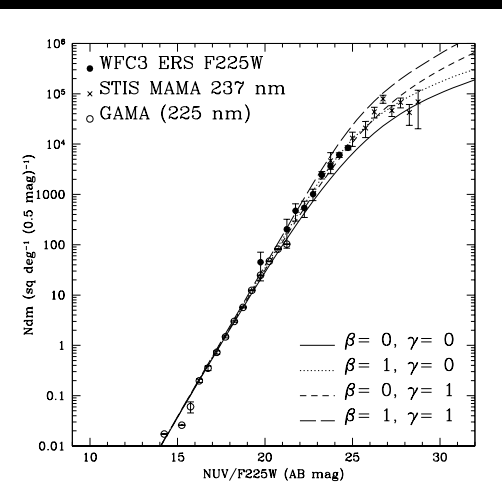
- JWST will similarly measure faint-end LF-slope evolution for $1 \lesssim z \lesssim 12$.



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

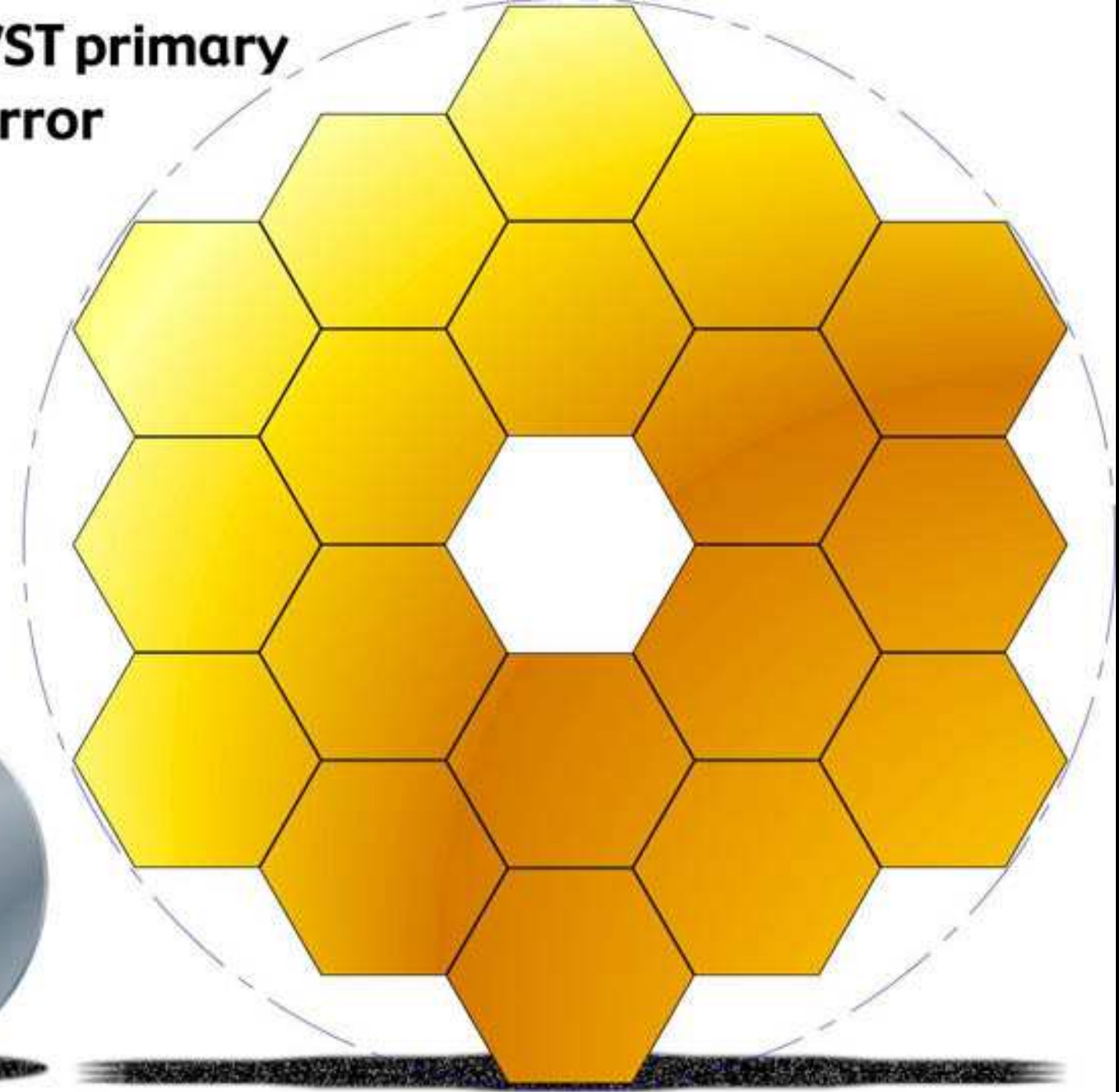
- In the JWST regime at $z \gtrsim 8$, expect faint-end LF slope $\alpha \simeq -2.0$.
 - In the JWST regime at $z \gtrsim 8$, maybe characteristic luminosity $M^* \gtrsim -19$?
- \Rightarrow Could have critical consequences for gravitational lensing bias at $z \gtrsim 10$.

Panchromatic Galaxy Counts from $\lambda \simeq 0.2\text{--}2\mu\text{m}$ for $AB \simeq 10\text{--}30$ mag

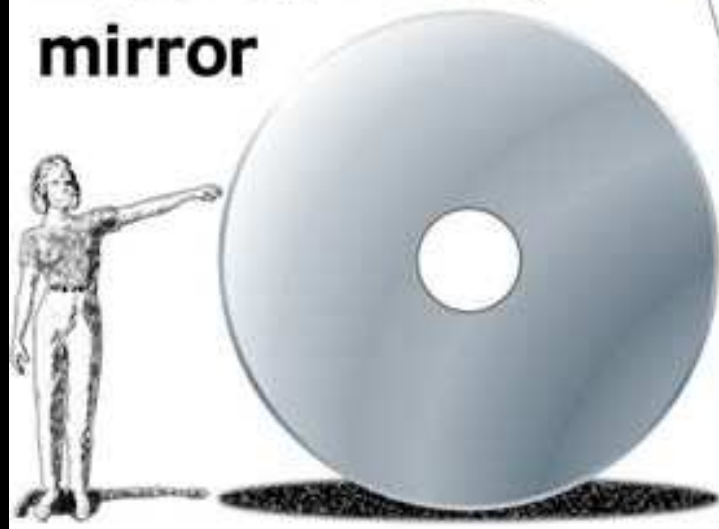


- Data: GALEX, ground-based GAMA, HST ERS ACS+WFC3 + HUDF ACS+WFC3 (*e.g.*, Windhorst et al. 2011, ApJS 193, 27):
- Filters: F225W, F275W, F336W, F435W, F606W, F775W, F850LP, F098M/F105W, F125W, F160W.
- No single Lum.+Dens evol model fits over 1 dex in λ and 8 dex in flux.

**JWST primary
mirror**

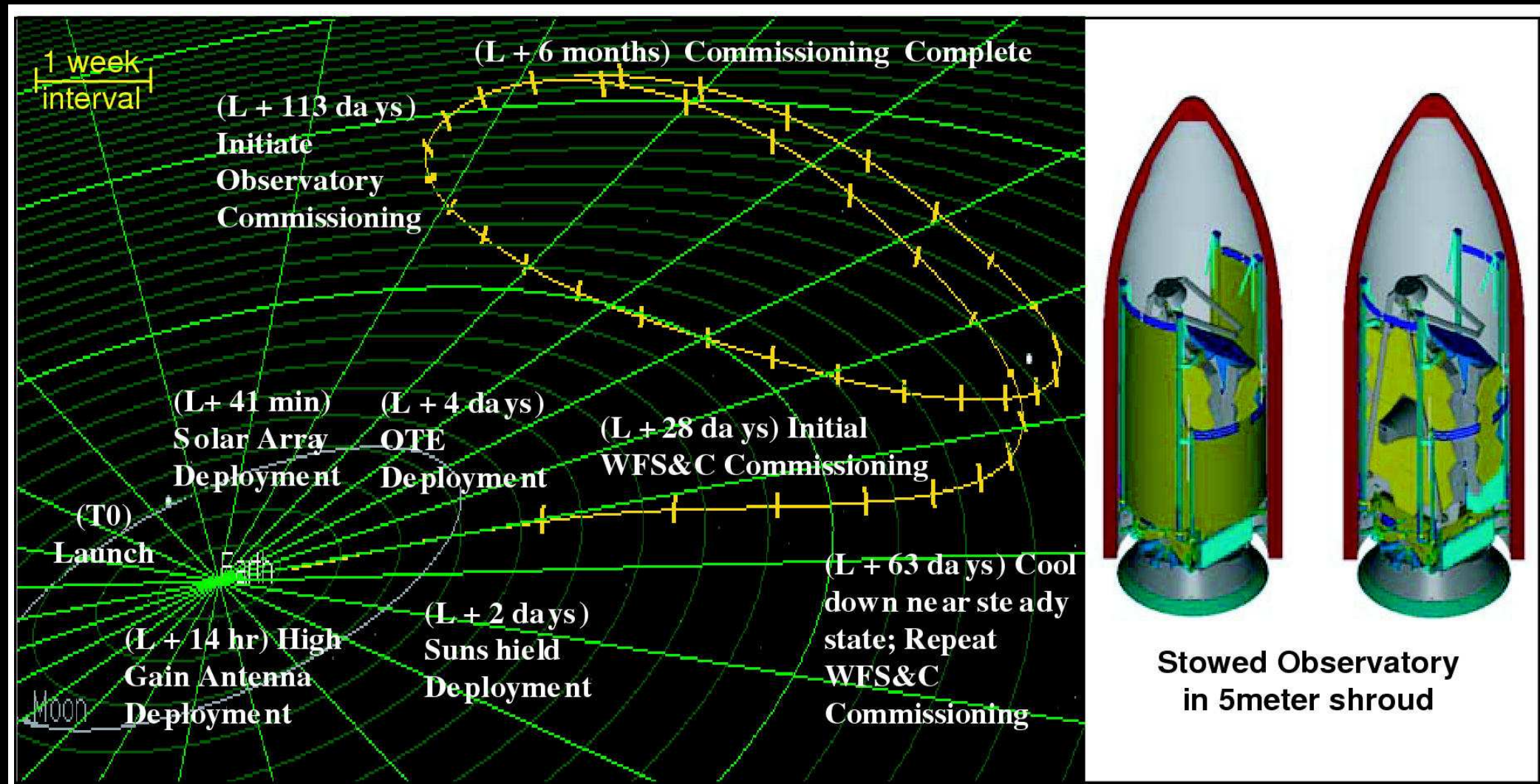


**Hubble primary
mirror**

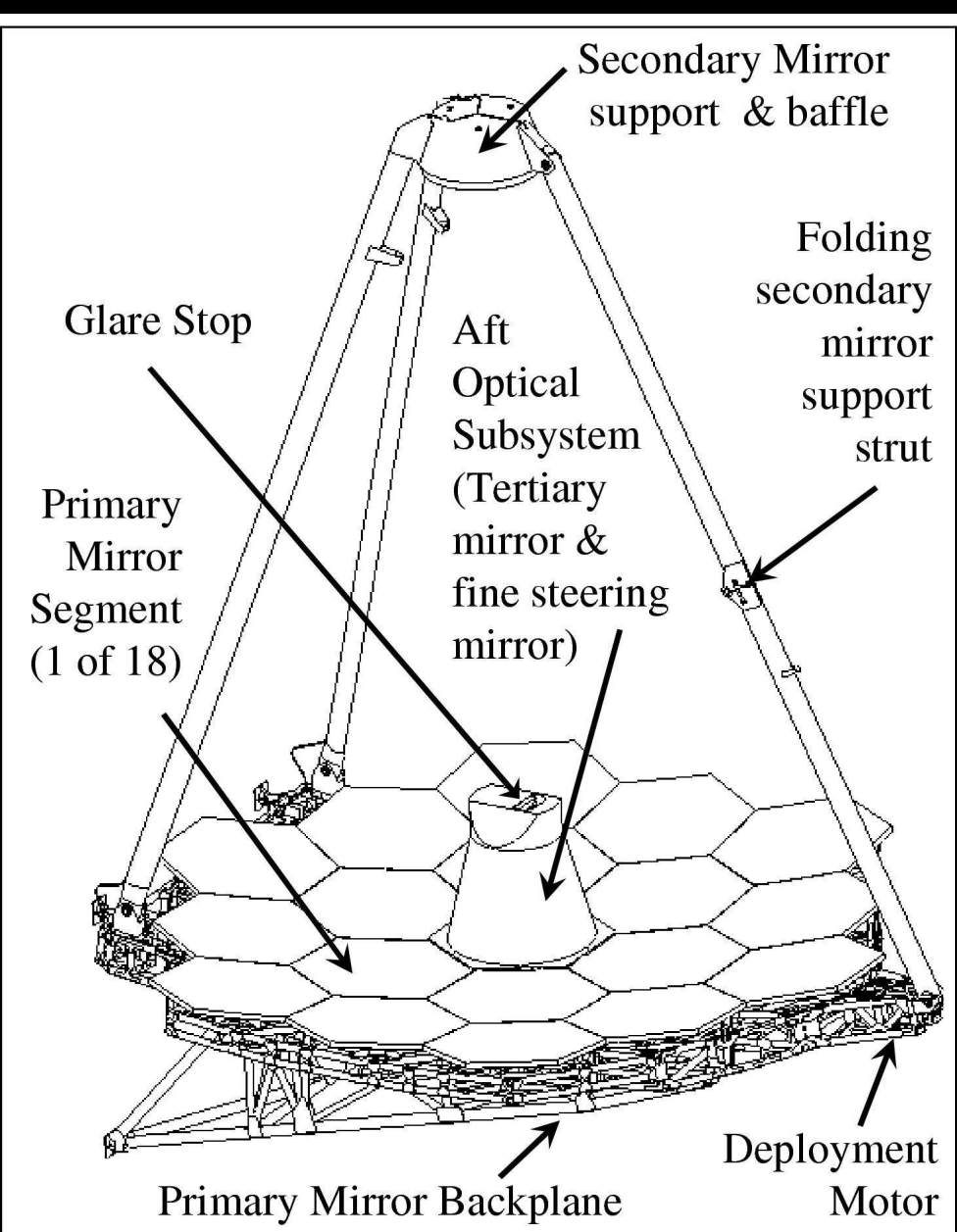


JWST $\sim 2.5\times$ larger than Hubble, so at $\sim 2.5\times$ larger wavelengths:
JWST has the same resolution in the near-IR as HST in the optical.

(1) JWST update: $\gtrsim 75\%$ of hardware procured or completed as of 8/11.



- After launch in June 201? with the 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.



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



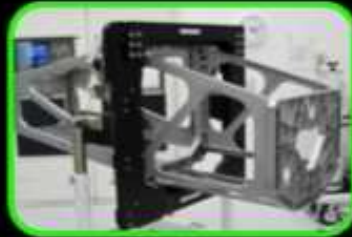
JWST Hardware Status



Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror



Fine Steering Mirror

ISIM Flight Bench



Secondary Mirror Pathfinder Strut



Secondary Mirror Hexapod



Secondary Mirror



Membrane Mgmt



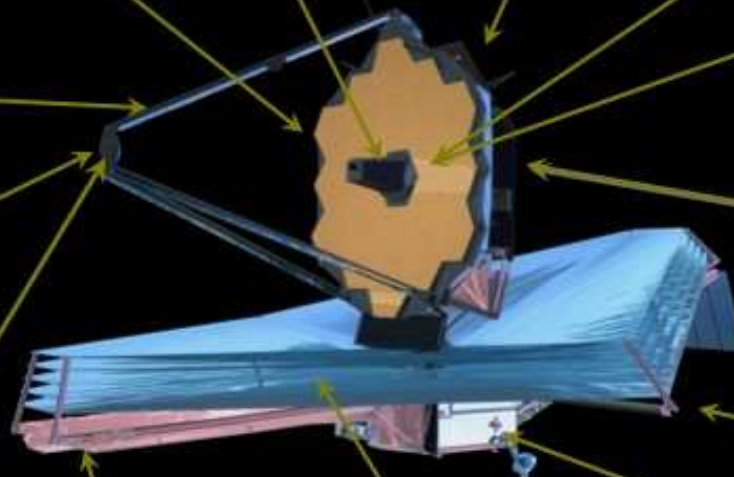
Pathfinder Membrane



Spacecraft computer Test Unit

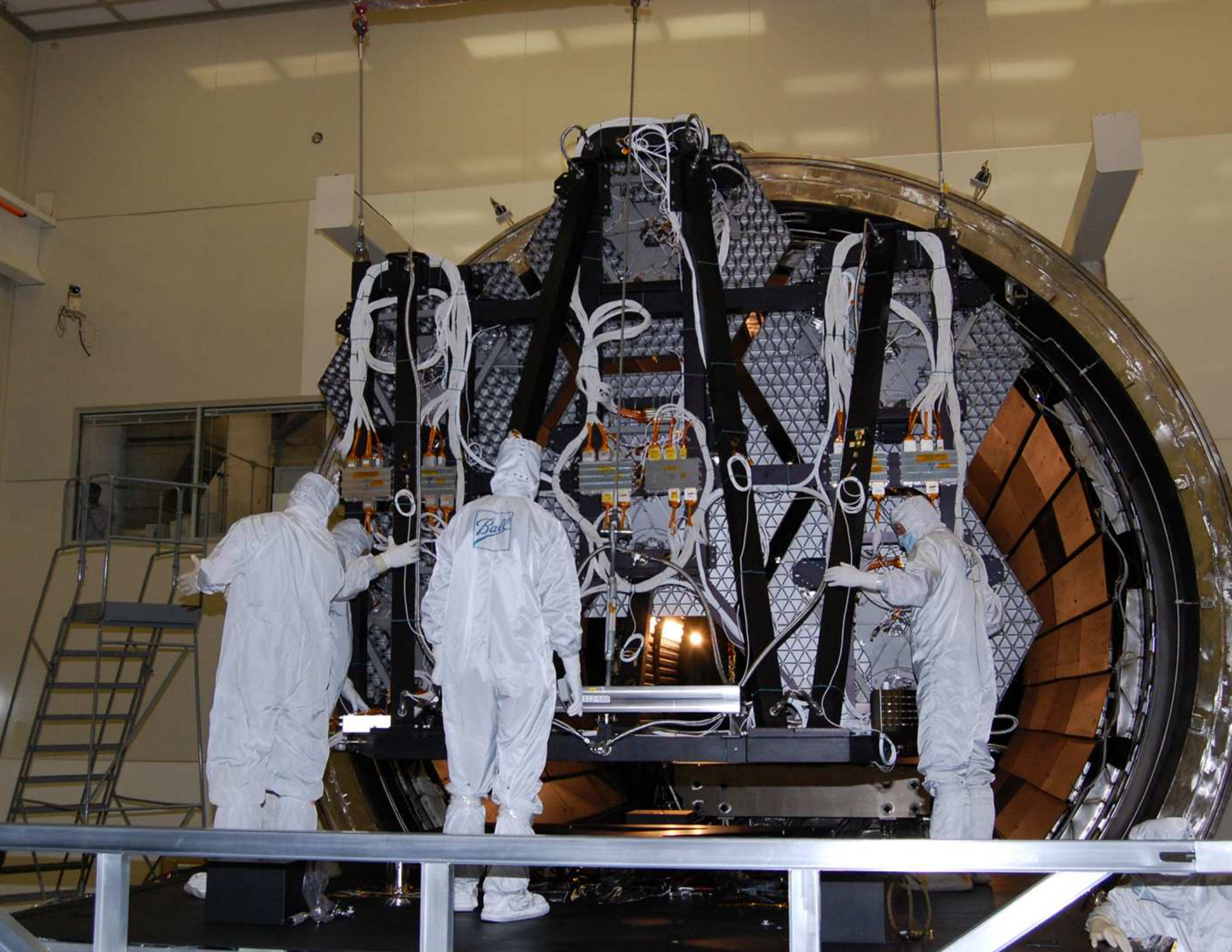


Mid-boom Test



Mirror Acceptance Testing







JWST Flight Mirrors Have Completed Polishing



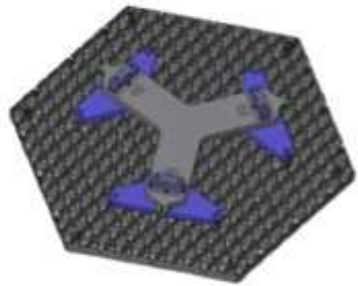
Tinsley Final Measurement Requirements
Total Figure < 17 nm

FLIGHT COMPOSITE RMS:

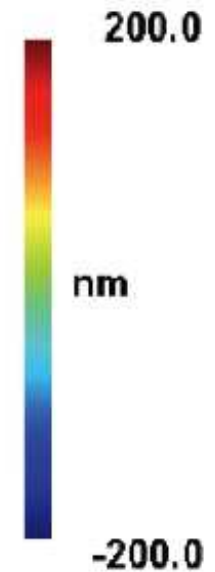
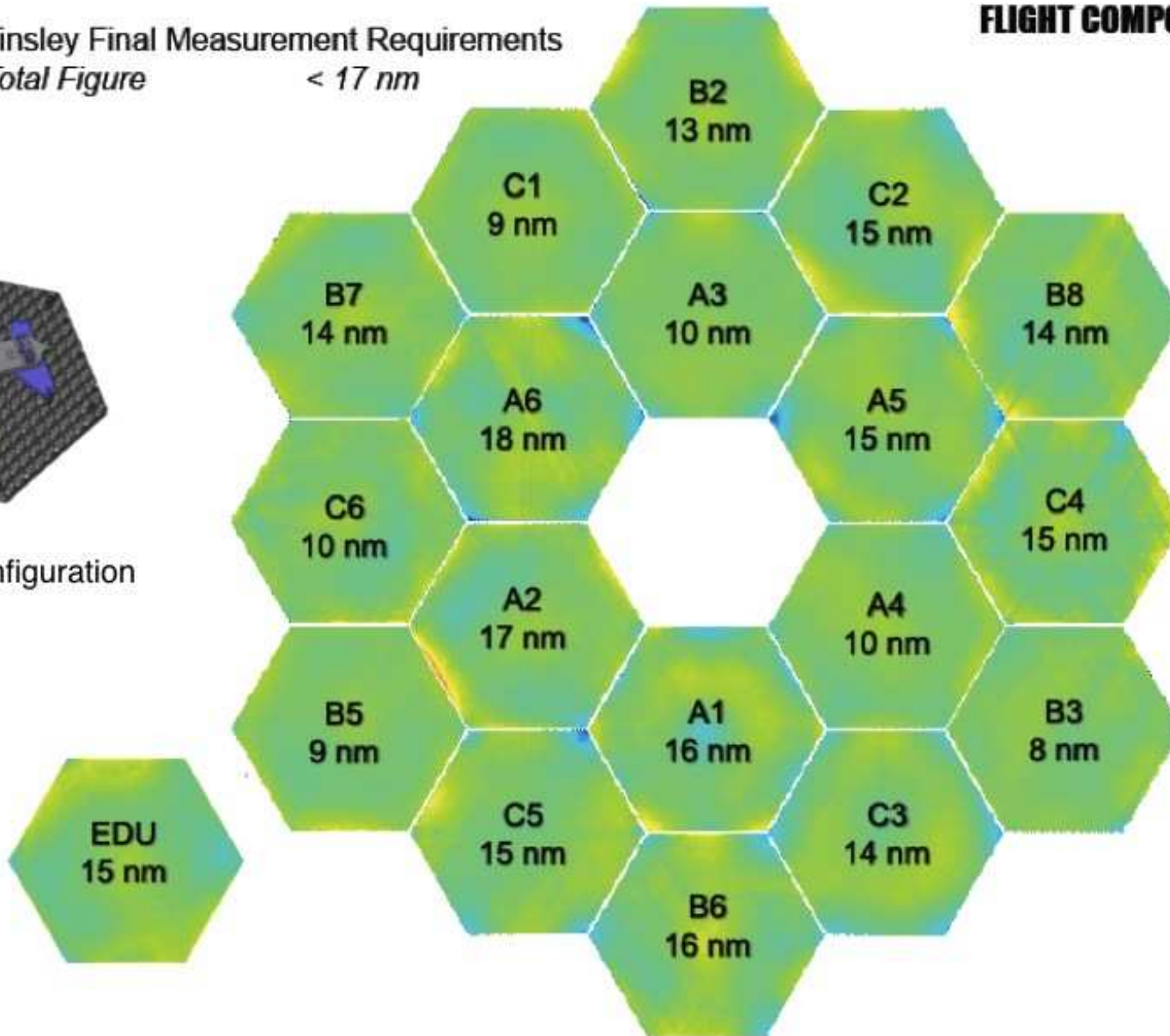
13.3 nm

PV:

976.4 nm



Mirror test configuration



(1b) JWST instrument update: US (UofA, JPL), ESA, & CSA.



Instrument Overview

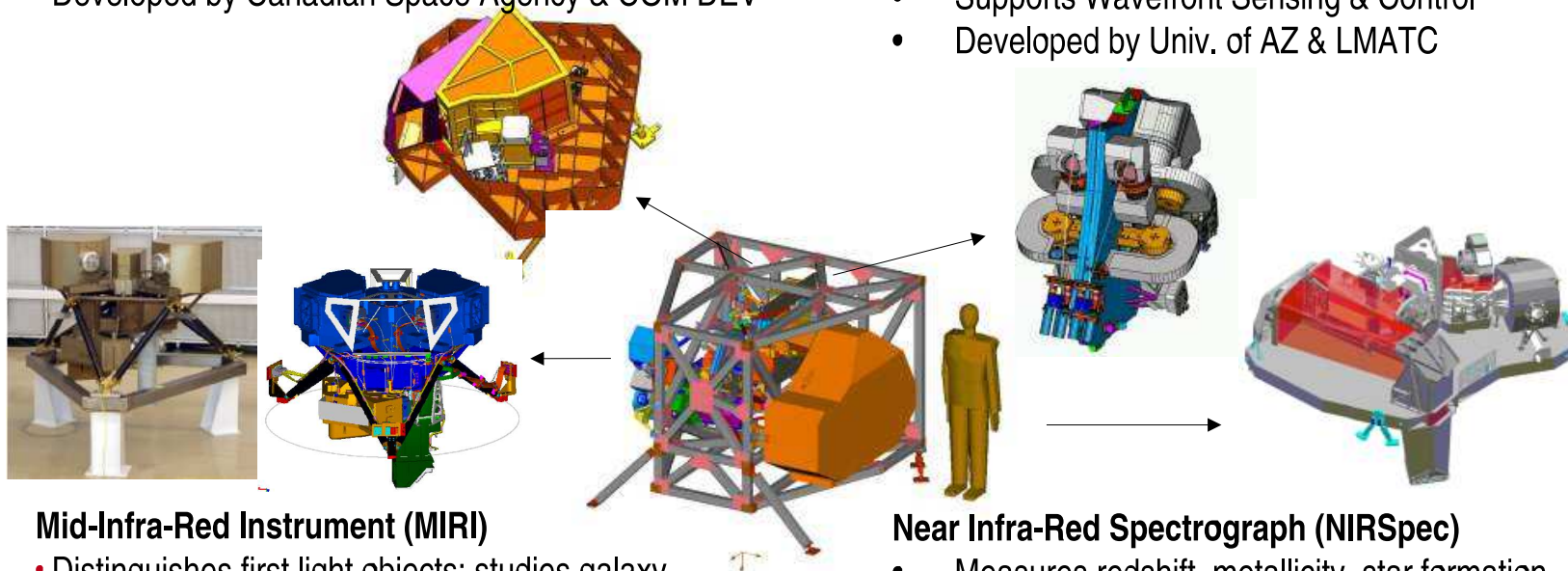


Fine Guidance Sensor (FGS)

- 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

MIRI & NIRSpec completed 8/11; NIRCam & FGS delivery to GSFC 12/11.



ETU NIRCcam



Flight Fine Guidance Sensor



JWST's short-wavelength ($0.6\text{--}5.0\mu\text{m}$) imagers:

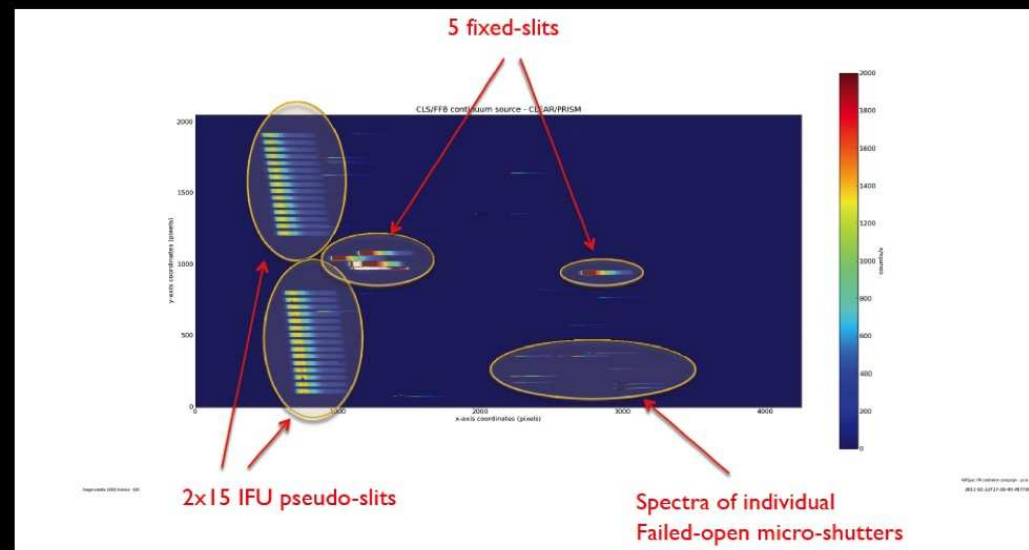
- NIRCcam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (& $1\text{--}5\ \mu\text{m}$ grisms) — built by CSA (Montreal).
- Both to be delivered to GSFC late Fall 2011.



FLIGHT NIRSpec



Flight NIRSpec First Light



JWST's short-wavelength ($0.6\text{--}5.0\mu\text{m}$) spectrograph:

- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

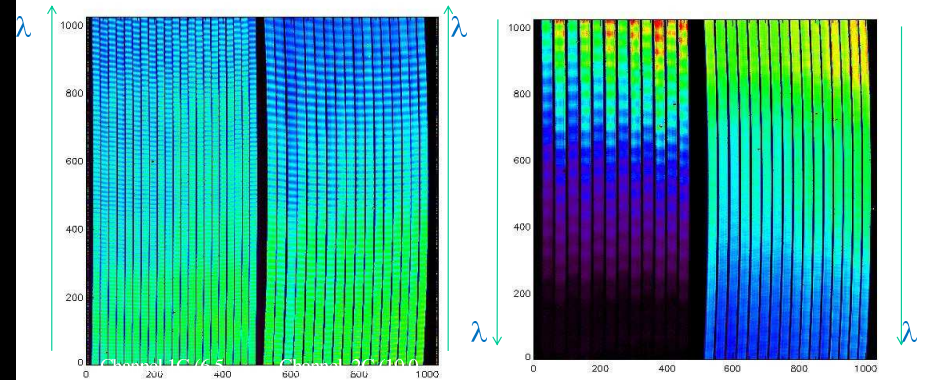
Final delivery to NASA/GSFC in early Fall 2011.



Flight MIRI



Spectrometer First Light – internal calibration source



All slices are there and well centred on detectors, fringes look as on VM, the fall off in signal at long wavelengths is expected – temperature of source and relatively short exposure, no “intra-slice” light ☺

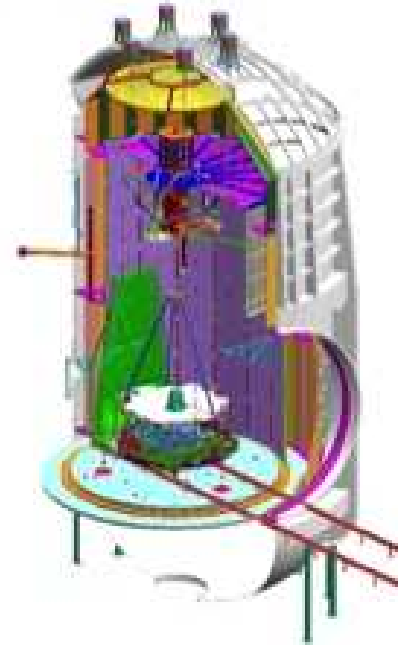
JWST's mid-infrared (5–29 μm) camera and spectrograph:

- MIRI — built by ESA consortium of 10 EU countries (ROE-lead) & JPL.
- Flight build completed and tested with First Light in July 2011.

Final delivery to NASA/GSFC in early Fall 2011.



TELESCOPE TESTING CHAMBER AT JOHNSON SPACE CENTER



Telescope and science instruments installed in the test chamber

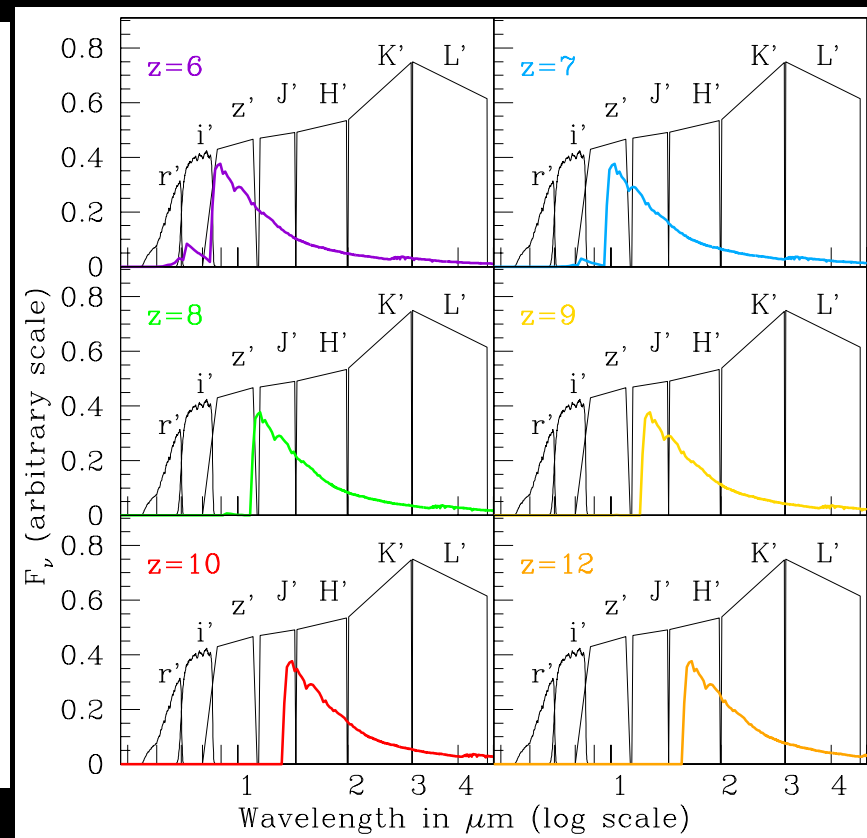
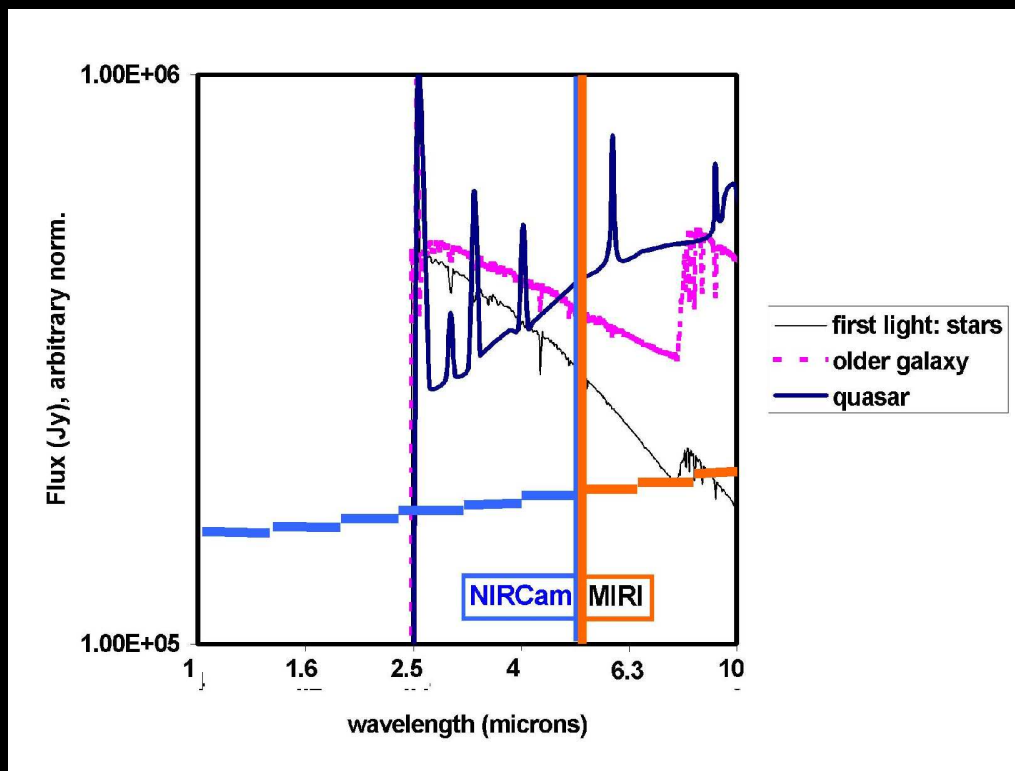
Element Progress



Notice people for scale

Largest simulation of deep space ever attempted will be done here

(2) How can JWST measure First Light and Reionization?



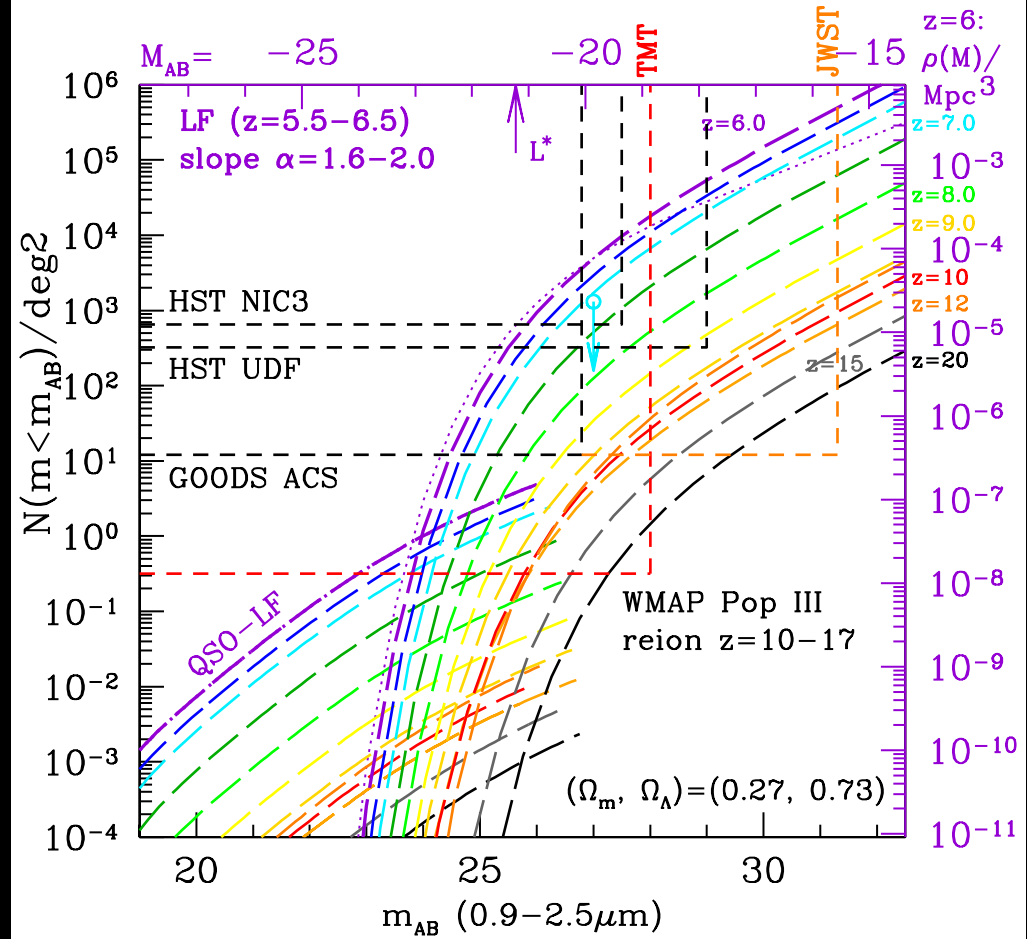
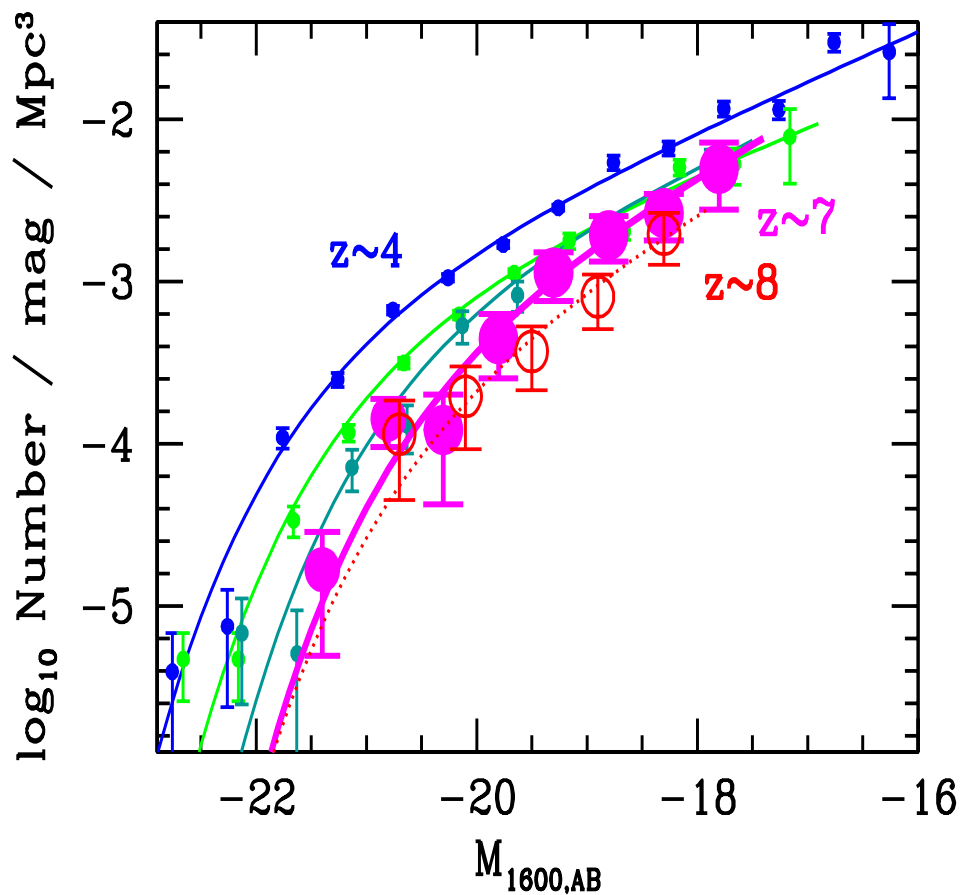
NIRCam and MIRI sensitivity complement each other, straddling $\lambda \simeq 5 \mu\text{m}$.

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

\Rightarrow JWST needs NIRCam at $0.8-5 \mu\text{m}$ and MIRI at $5-29 \mu\text{m}$.

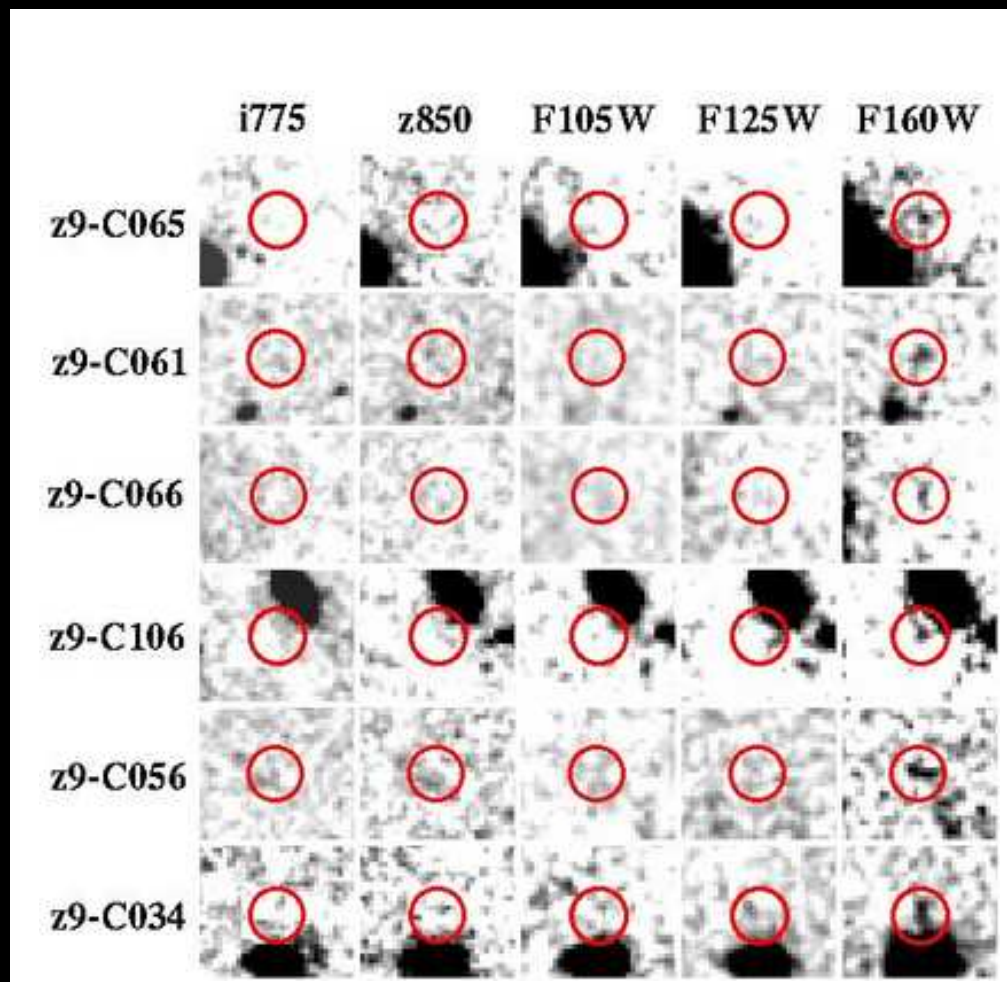
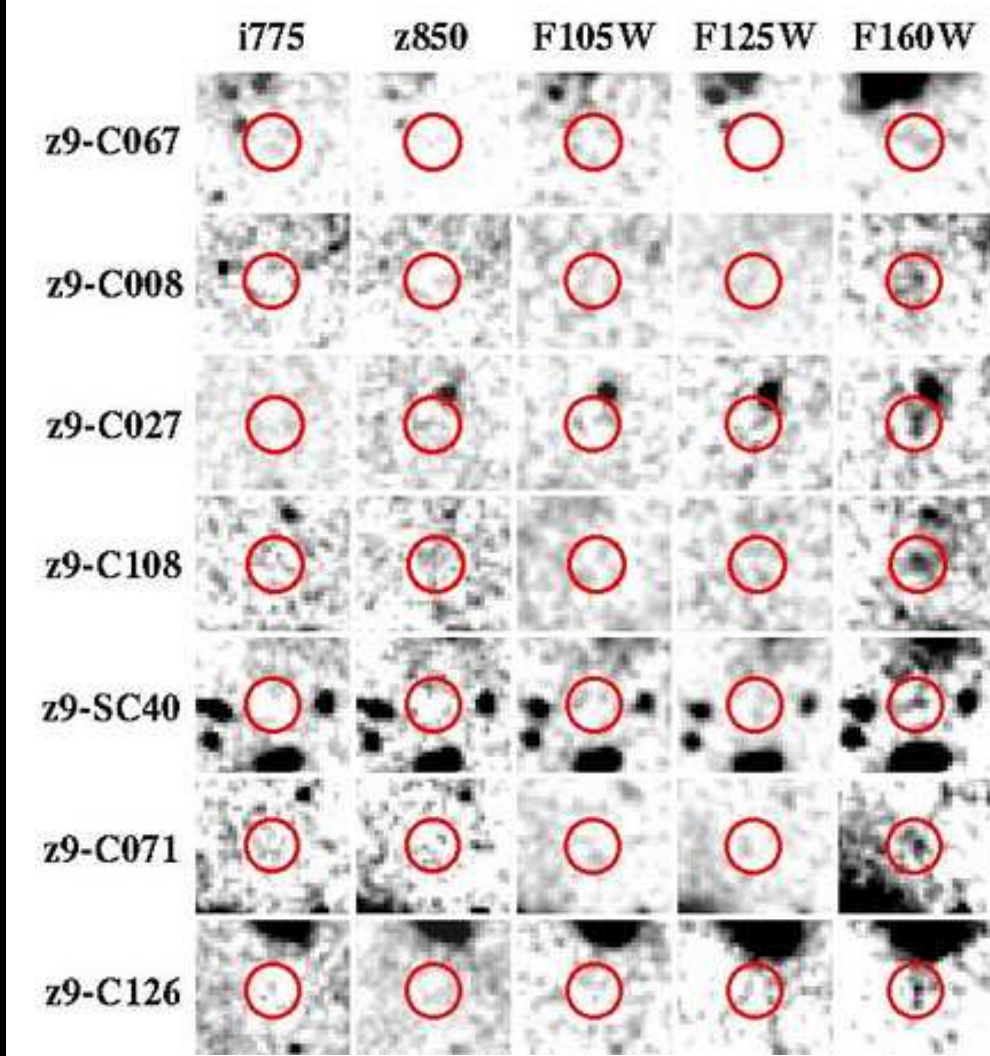


- Objects at $z \gtrsim 9$ are rare (Bouwens⁺ 10; Trenti,⁺ 10; Yan⁺ 10), since volume elt is small, and JWST samples brighter part of LF.

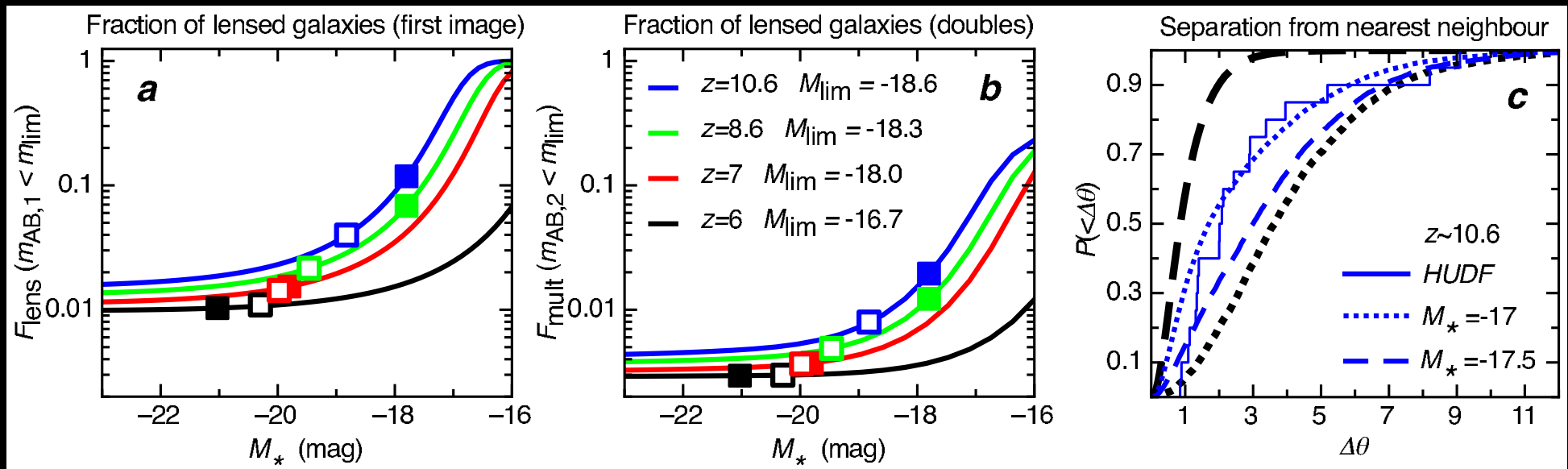
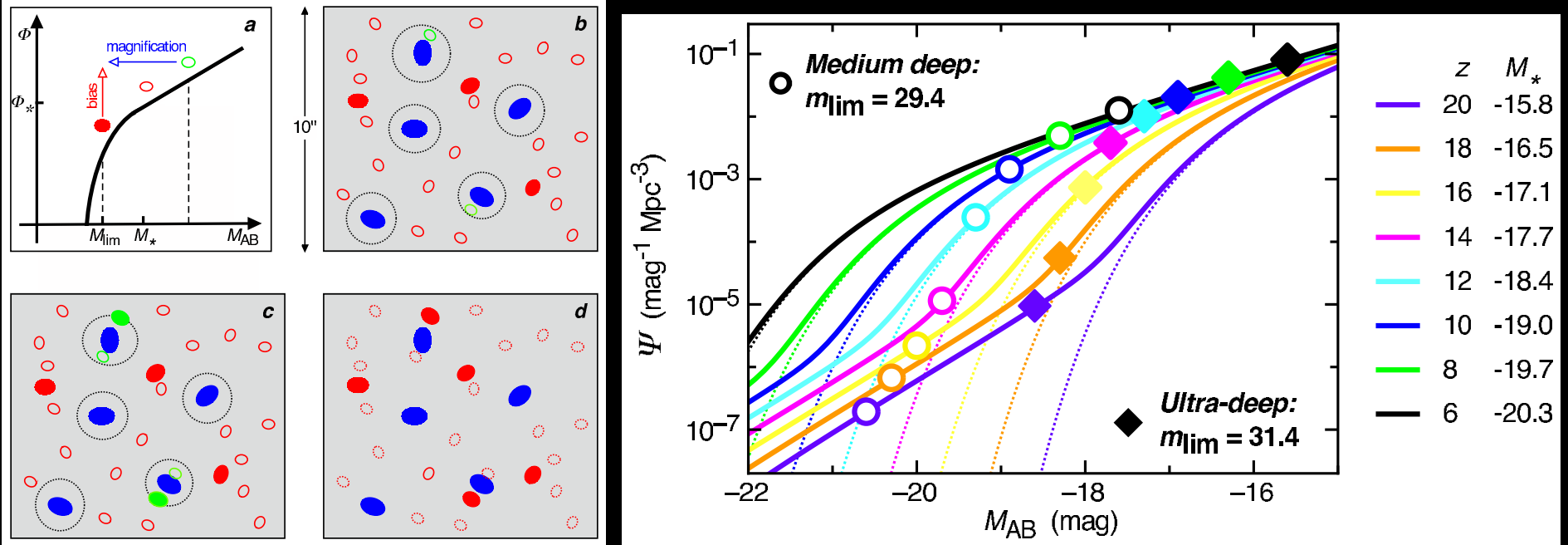
⇒ JWST needs its sensitivity/aperture (A), field-of-view (Ω), and λ -range (0.7-29 μm). [See Garth's talk, this conf.]

- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.





- $\sim 10\text{--}40\%$ of Y-drops and J-drops appear close to bright galaxies (Yan et al. 2010, Res. Astr. & Ap., 10, 867).
- Expected from gravitational lensing bias by galaxy dark matter halo distribution at $z \simeq 1\text{--}2$ (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 gravitational lensing bias cause power-law LF?



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

- This could change the landscape for JWST observing strategies.

Conclusions

(1) David Koo's work in the 1980's: First real panchromatic astronomy.

(2) HST ACS+WFC3: panchromatic work at $\lambda \simeq 0.2\text{-}2\mu\text{m}$ to $AB \lesssim 30$.

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

- Passed Mission Preliminary Design Review (PDR) in 2008, & Mission CDR in 2010. No technical showstoppers. Management replan in 2011.
- More than 75% of JWST H/W built, & meets/exceeds specs as of 08/11.
- JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly in detail.

(4) JWST will have a major impact on astrophysics later this decade:

- 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

we do not want this to
happen to U.S. astrophysics



Risk ending up like SSC (left). Canceled project funds never returns!

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)



JSC "Cup Up" Test Configuration (New Proposal)



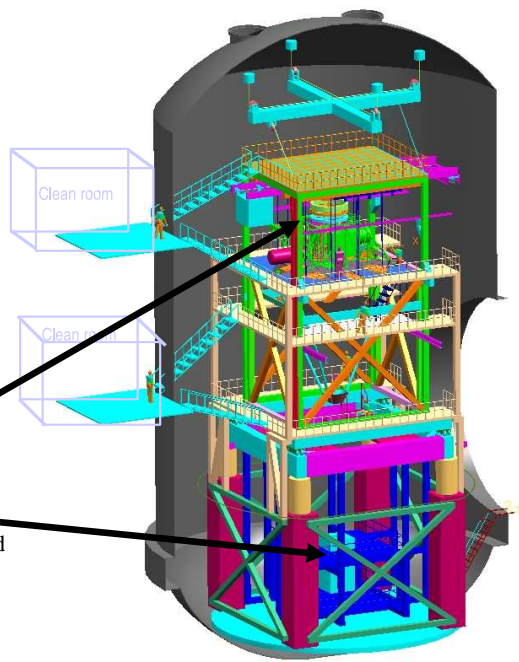
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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

JSC currently has 7 KW He capability

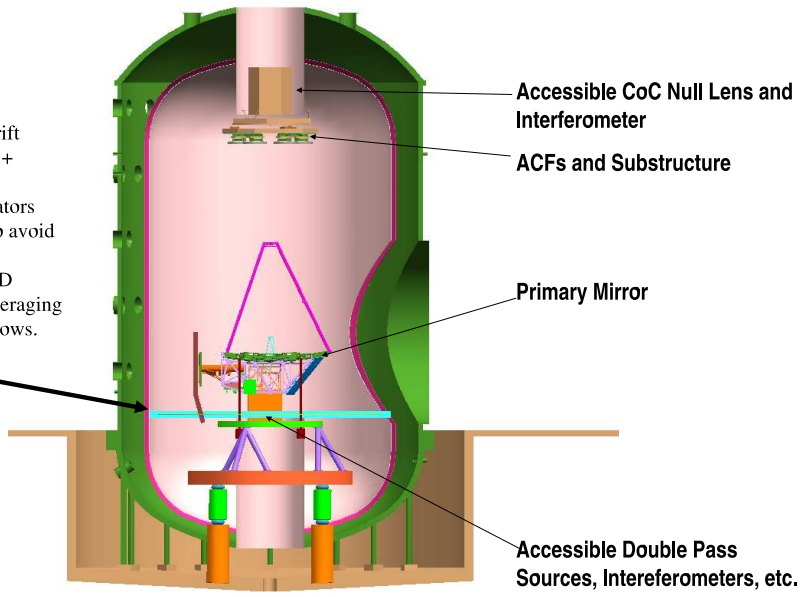
Current plan includes 10 trucks of LN2/day during cooldown

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



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.



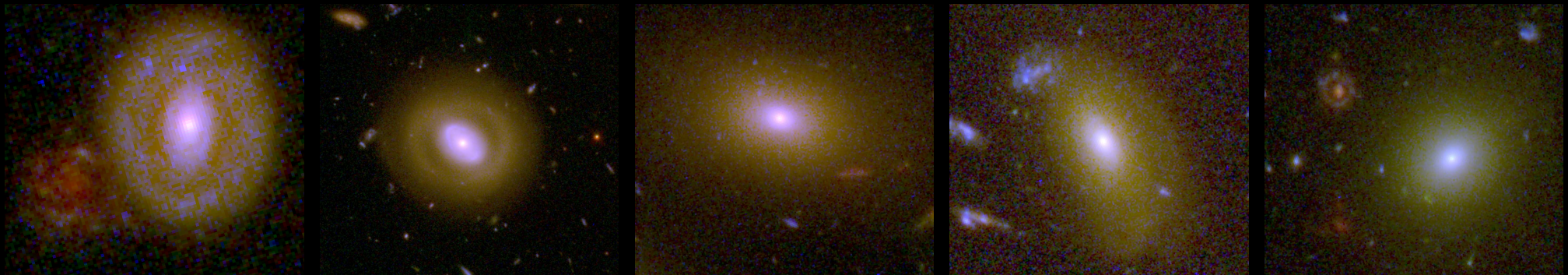
Drawing care of ITT

- 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.

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



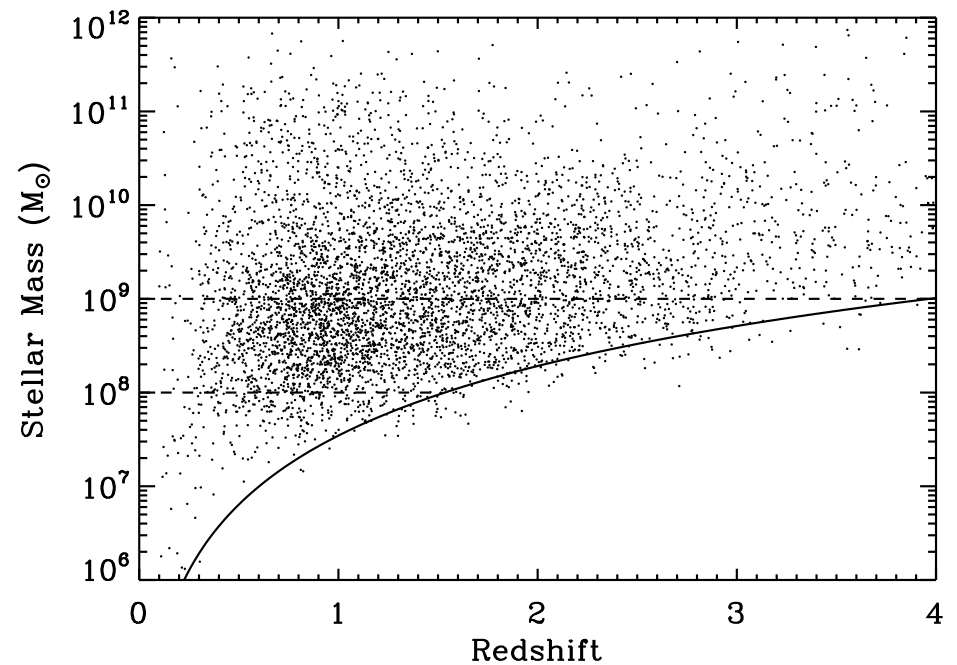
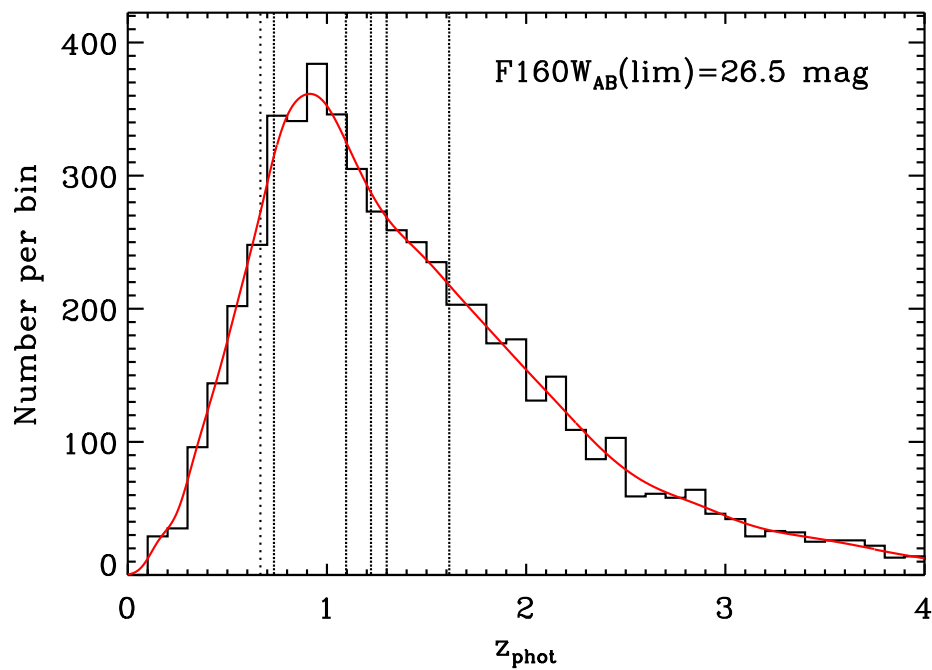
Galaxy structure at the peak of the merging epoch ($z \simeq 1-2$) is very rich: some resemble the cosmological parameters H_0 , Ω , ρ_0 , w , and Λ , resp.



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

(Rutkowski et al. 2011) \implies “Red and dead” galaxies aren’t dead!

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



WFC3 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 $AB=26.5 \text{ mag}$, accurately tracing the process of galaxy assembly: downsizing, merging, (& weak AGN growth?)

ERS shows WFC3's new panchromatic capabilities on galaxies at $z \simeq 0-8$.

- HUDF shows WFC3 $z \simeq 7-9$ capabilities (Bouwens⁺ 2010; Yan⁺ 2010).

\Rightarrow WFC3 is an essential pathfinder at $z \lesssim 8$ for JWST ($0.7-29 \mu\text{m}$) at $z \gtrsim 9$.

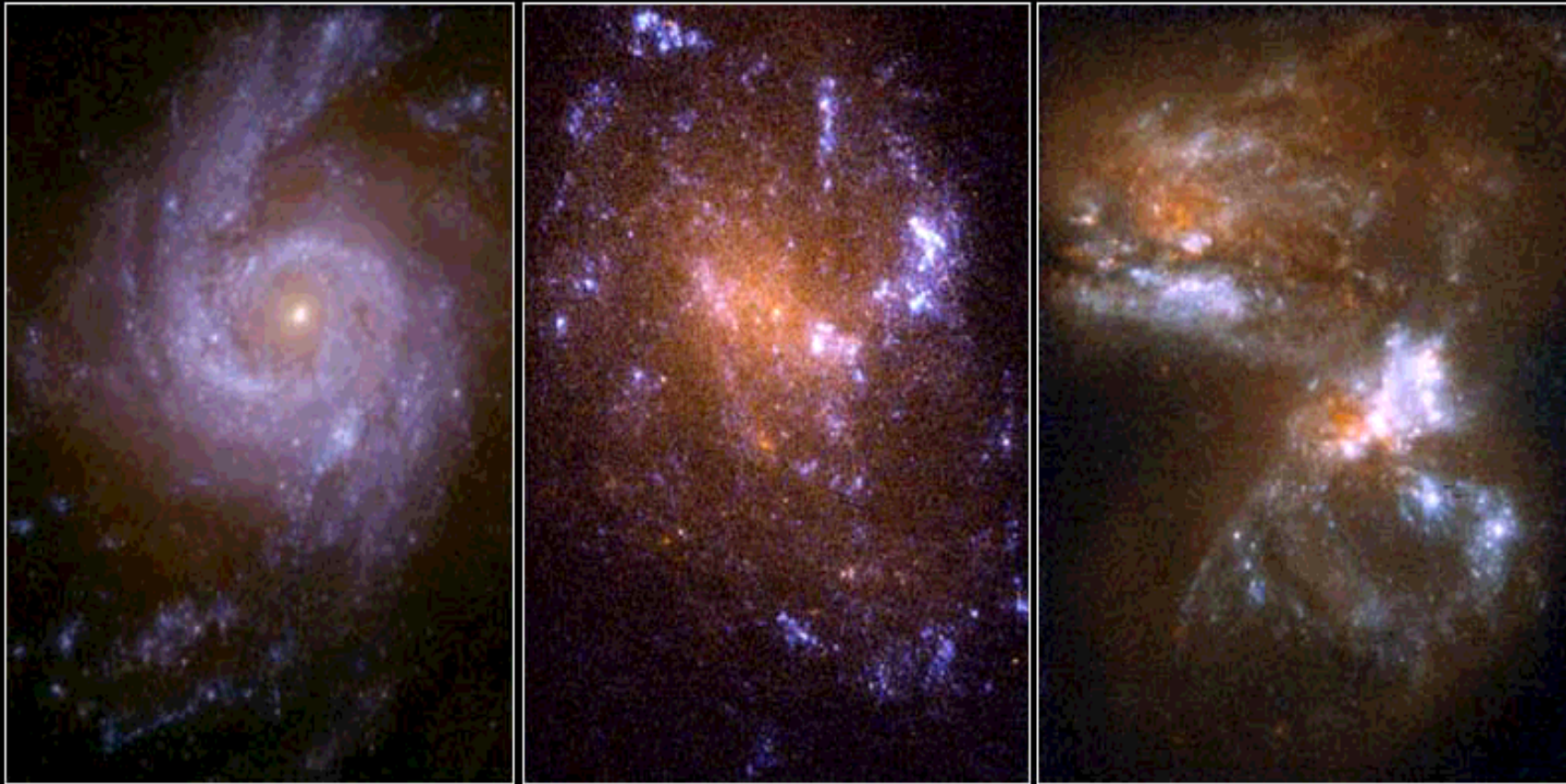
- JWST will trace mass assembly and dust content 3-4 mags deeper from $z \simeq 1-12$, with nanoJy sensitivity from $0.7-5 \mu\text{m}$.

Appendix 1: Predicted Galaxy Appearance for JWST at $z \simeq 1-15$

NGC 3310

ESO0418-008

UGC06471-2



Ultraviolet Galaxies

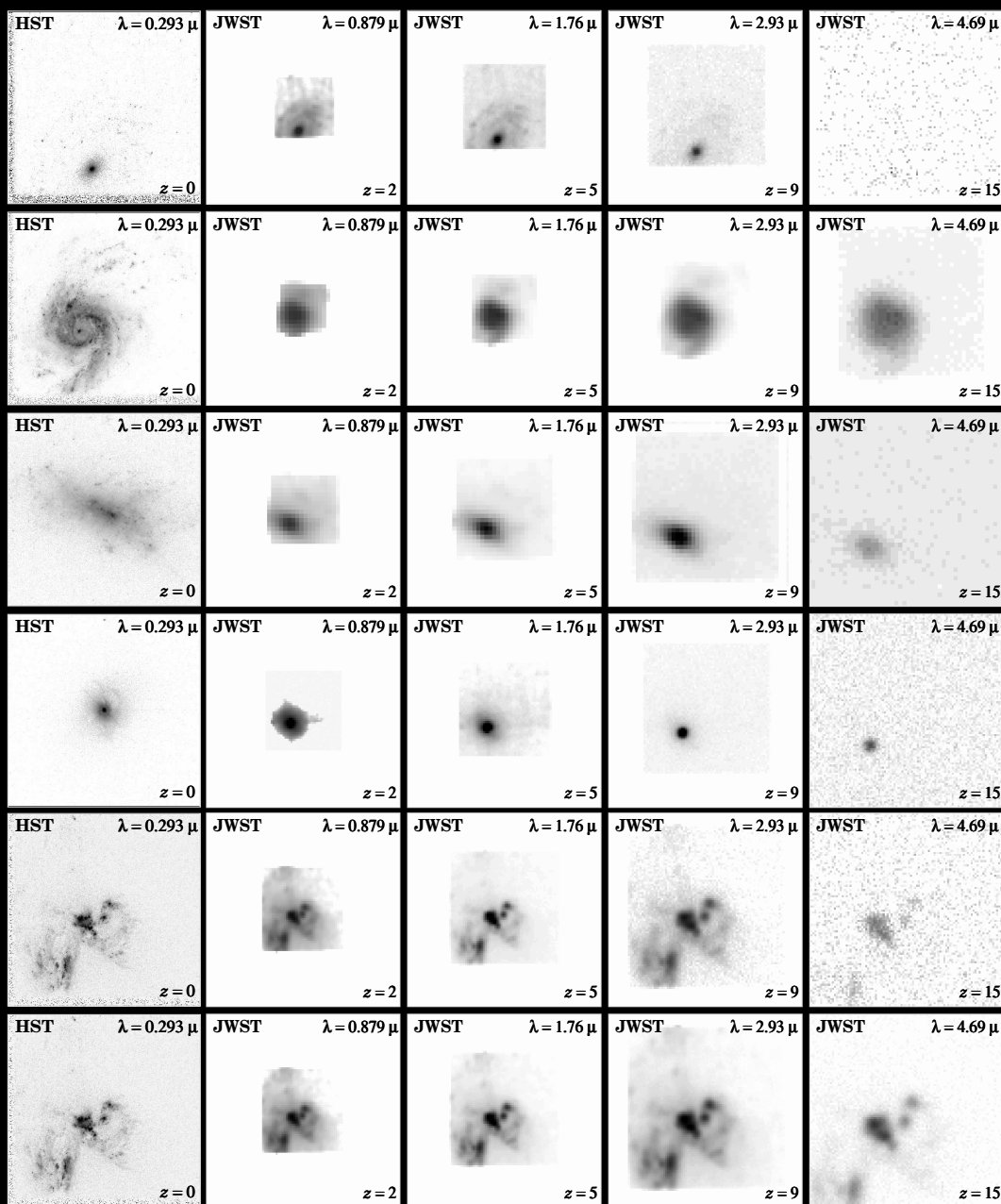
HST • WFPC2

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

- 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.

App. 1. Predicted Galaxy Appearance for JWST at $z \simeq 1-15$ (w/ Conselice)

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

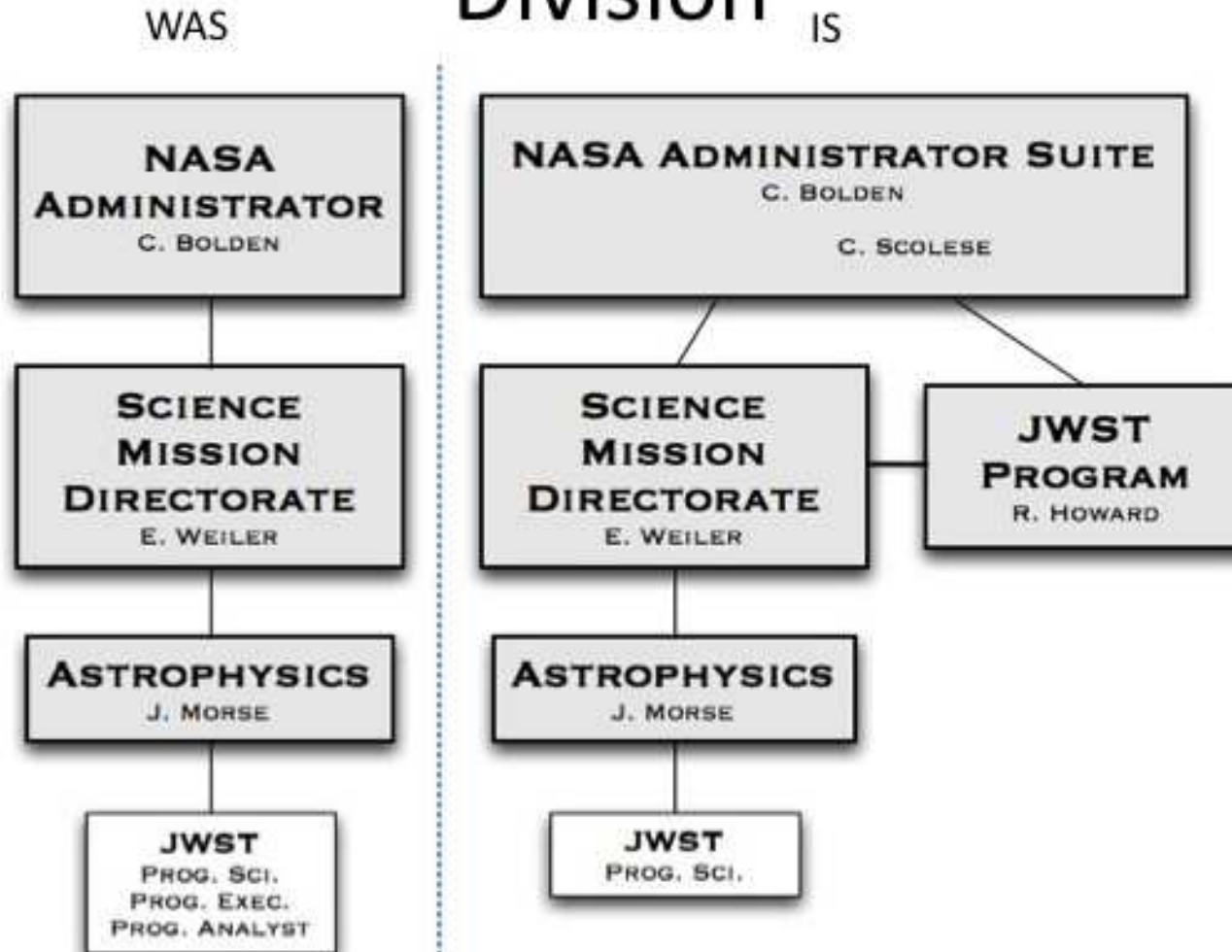


With proper restframe UV-optical benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (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 .

(4) How to launch JWST while minimizing impact on NASA Space Science?

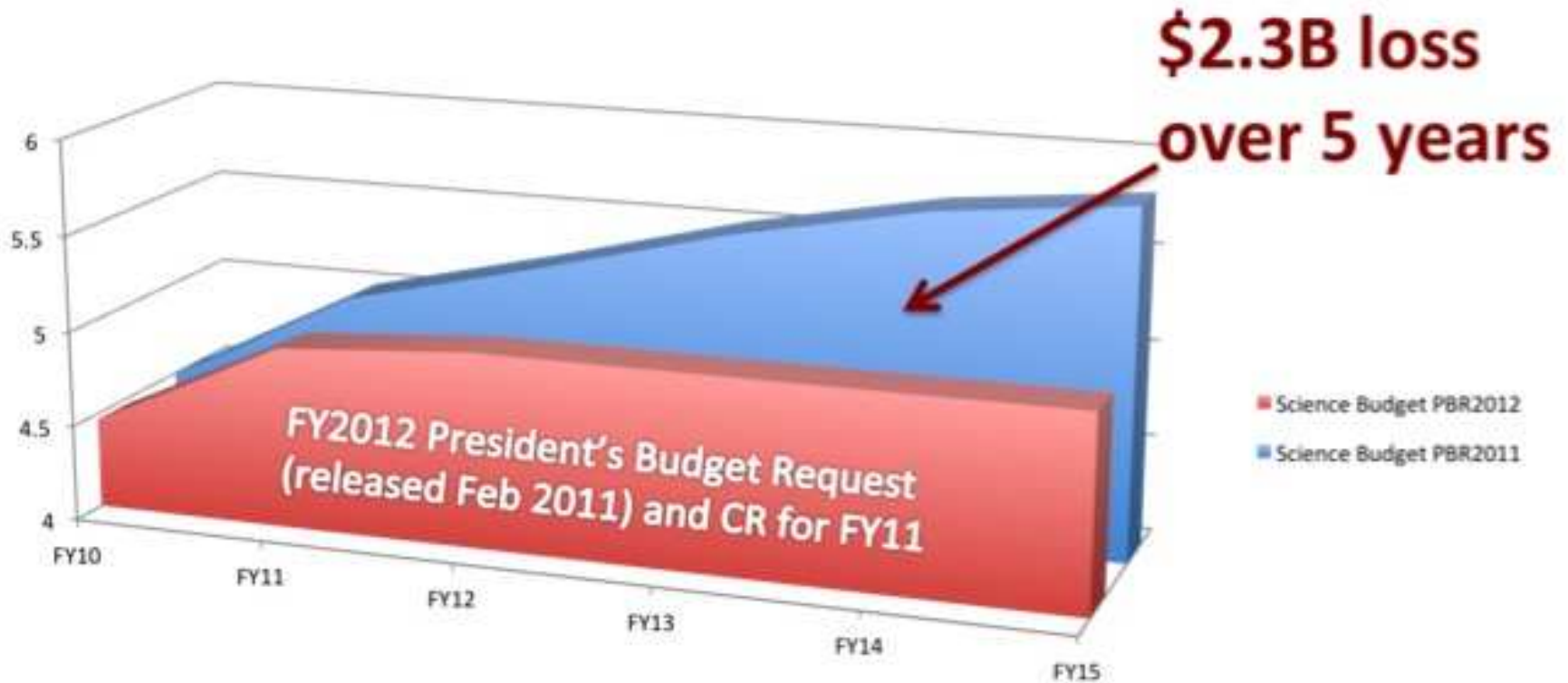
JWST moved out of Astrophysics



NASA HQ Reorg: JWST budget no longer comes directly from SMD/Ap.

NASA Science shrinks 8% relative to 2011 President's Budget Request

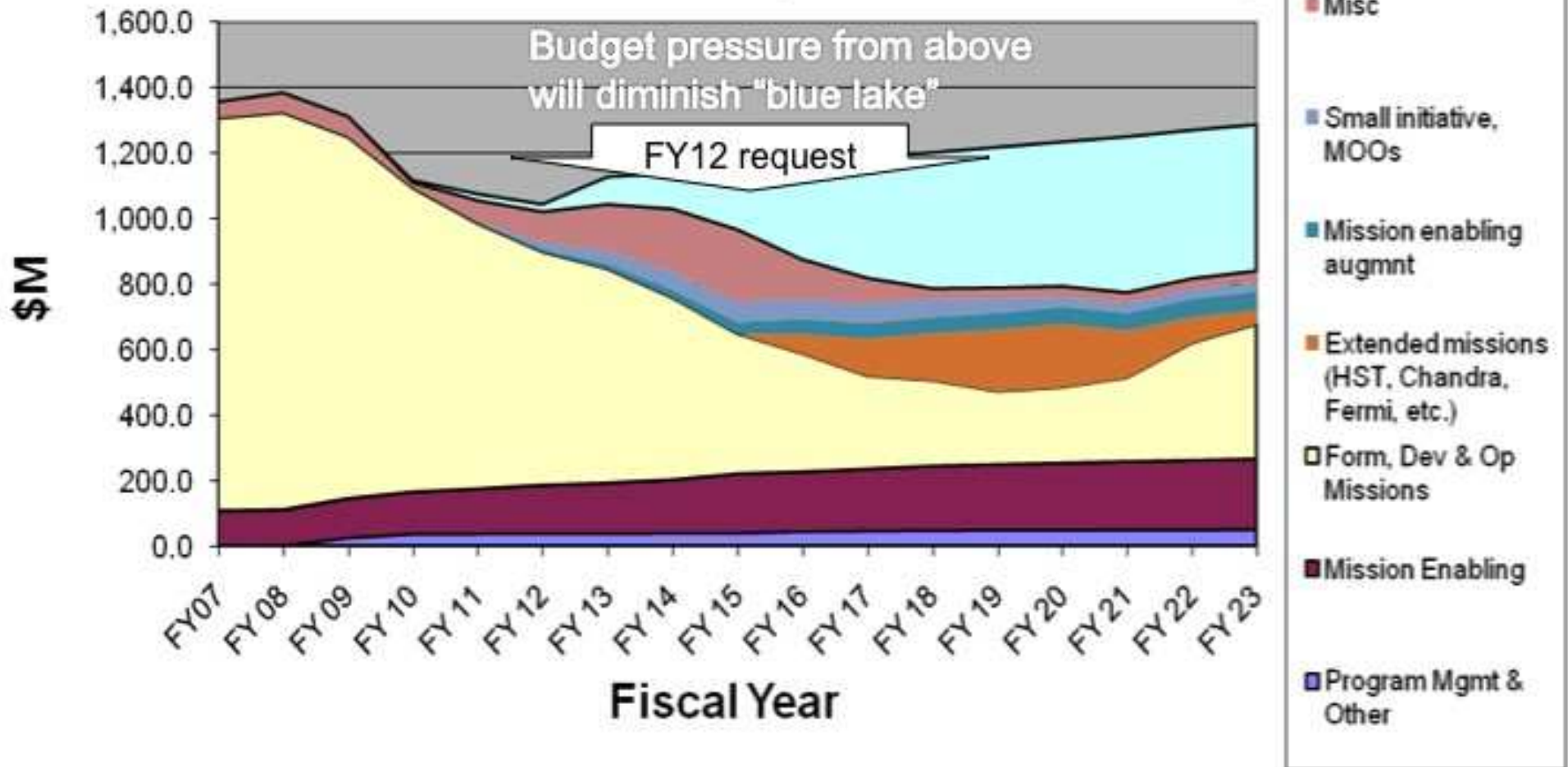
Science Budget Picture as seen in 2011 vs 2010



NASA science Budget flat beginning 2012

NASA Space Science has external budget pressures independent of JWST.

Astrophysics FY2010 President's Budget and Estimates for 2011 - 2023 (with notional offsets)



Launching JWST as early as possible helps keep "blue lake" bottom intact.

NASA's Great Observatories Impact

The Impact of GO Funding on US Astronomy

GALEX

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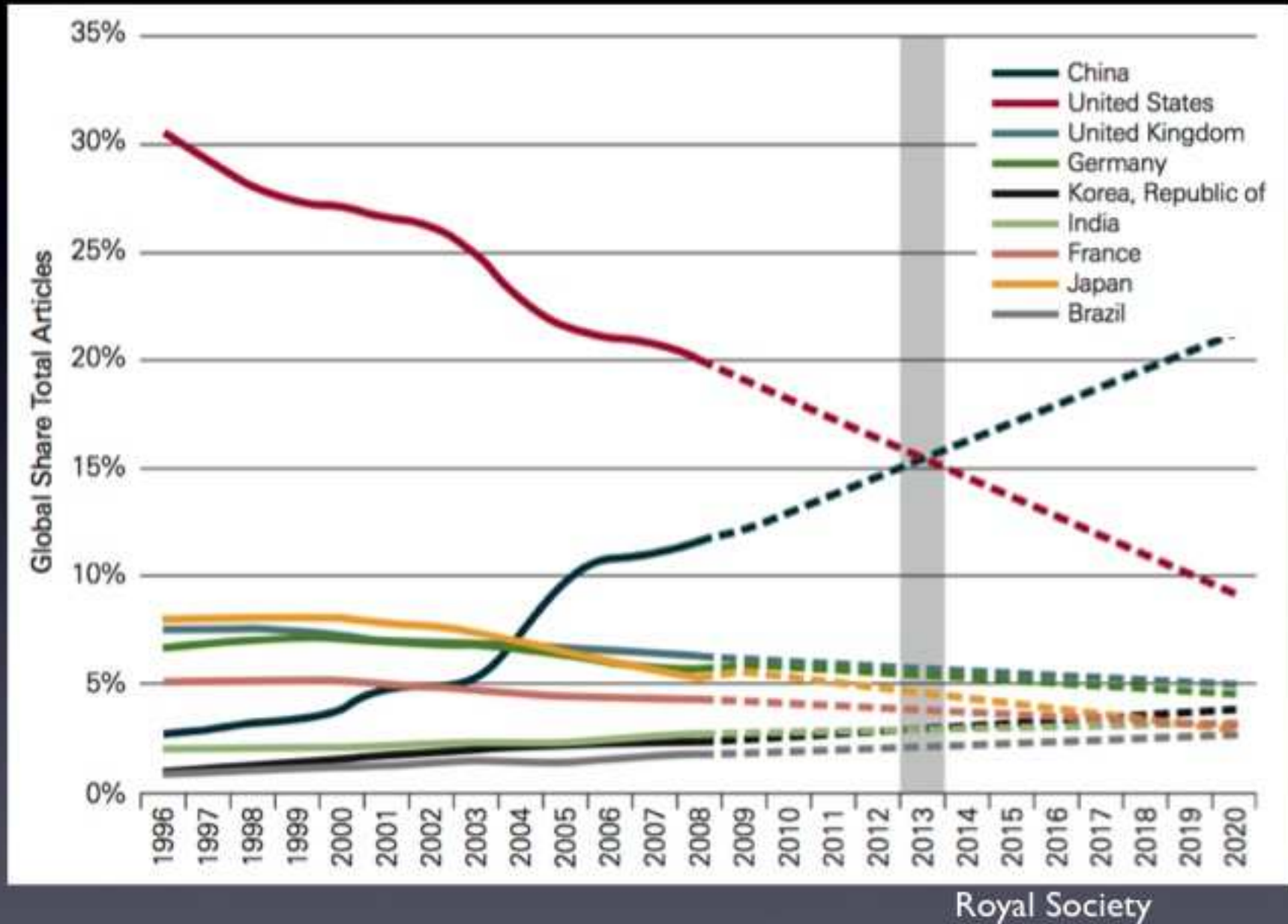
- HST has produced over 9400 refereed publications, which is about 1.25 per day over the 21-year life of the mission.
- And the rate is increasing - nearly 2/day last year. (719 papers in 2010)
- HST papers have gleaned over 340,000 citations, or an average of more than 40 citations per day.
- HST is in demand around the world.
- Approved HST programs have had more than 5000 unique investigators

2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 - 2015* 2016 - 2020

*MINIMUM PROJECTION: ASSUMES FLAT HST FUNDING AT \$30M / YEAR

NASA Great Observatories had enormous impacts last two decades:
NASA must keep a healthy mix of big, medium and small space missions.

Projected growth in scientific literature



US and NASA must have major future facilities to remain competitive.

- 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”