

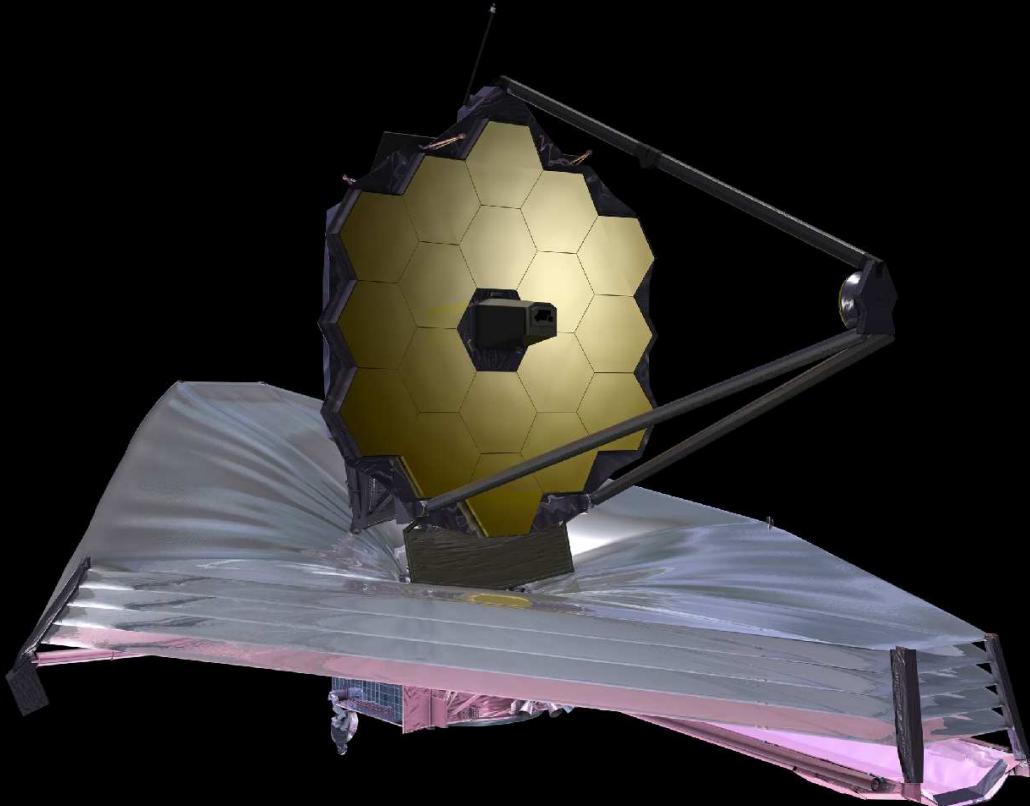
# How will JWST measure First Light, Reionization, and Galaxy Assembly: Science and Project Update as of 2012.

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Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

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

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



*AST 422 class, Arizona State University, Tempe, AZ, Tuesday April 24, 2012*

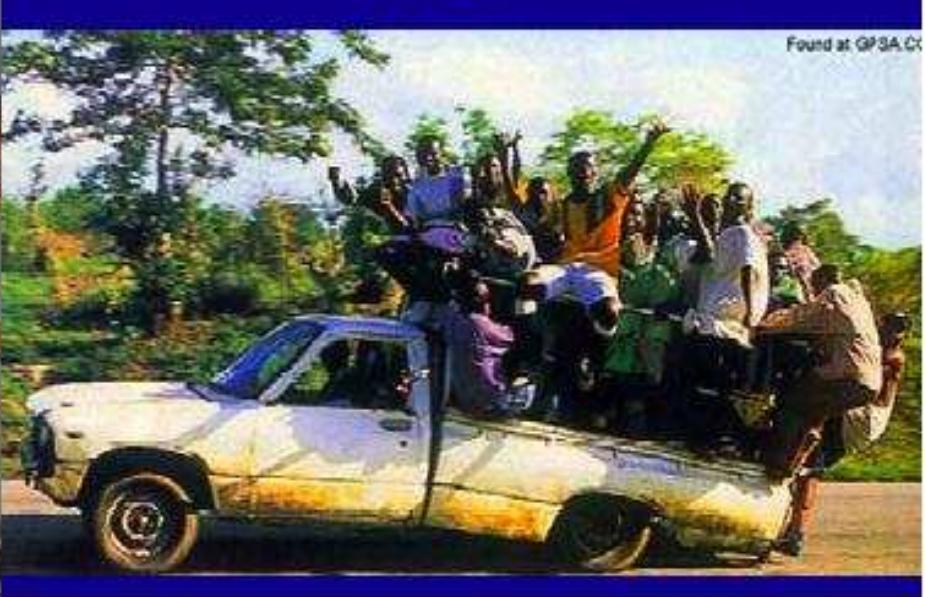
*All presented materials are ITAR-cleared. These are my opinions only, not ASU's.*

What the Scientists See:

What the Project Manager Sees:



The Happy Balance



Found at GP3A.CC

The scientist's perspective, presented to project managers and engineers ...

# Outline

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- (1) Recent key aspects of the Hubble Space Telescope (HST) project.
- (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.
- (3) What is the James Webb Space Telescope (JWST)?
- (4) How can JWST measure the Epochs of First Light & Reionization?
- (5) Summary and Conclusions.
- (6) How can JWST measure Earth-like exoplanets?
- (7) Update of JWST programatics as of 2011/2012.



Edwin P. Hubble (1889–1953) — Carnegie astronomer

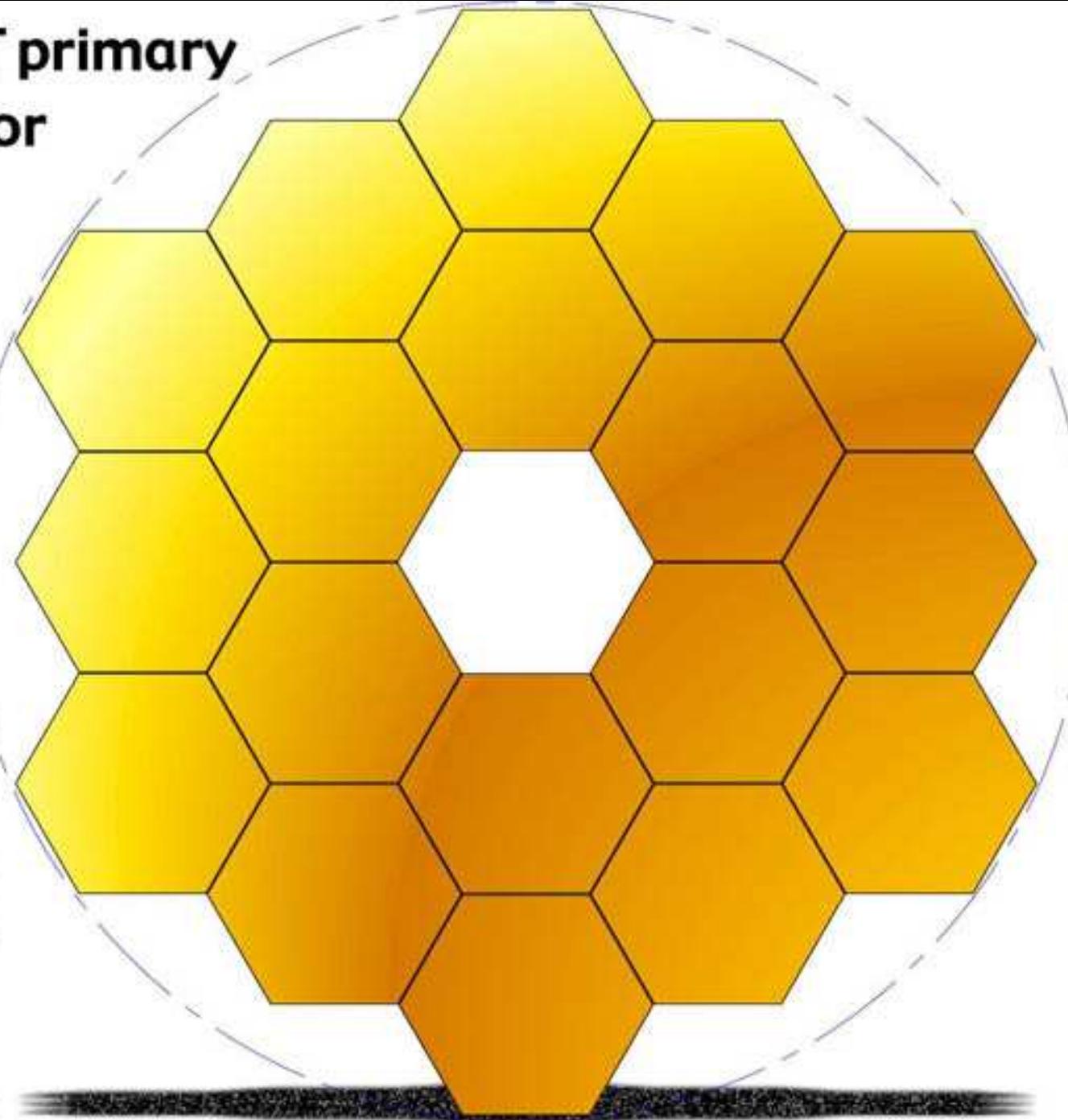


James E. Webb (1906–1992) — Second NASA Administrator

Hubble: Concept in 1970's; Made in 1980's; Operational 1990– $\gtrsim$ 2014.

JWST: The infrared sequel to Hubble from 2018–2023 (–2029?).

**JWST primary  
mirror**

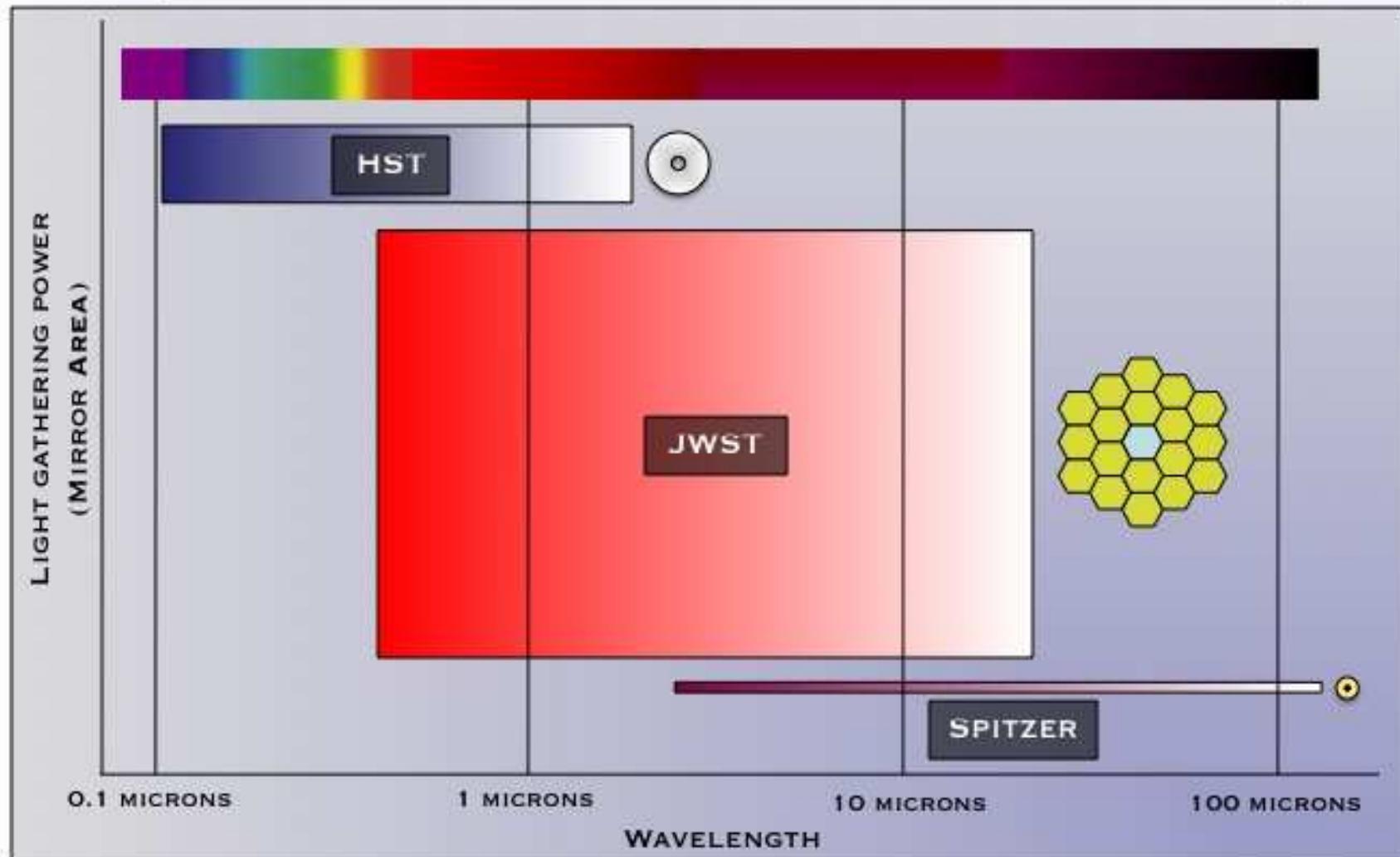


**Hubble primary  
mirror**



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

# THE JAMES WEBB SPACE TELESCOPE



## Light Gathering Power

$$\text{JWST} = 25 \text{ m}^2; \text{ Hubble} = 4.5 \text{ m}^2; \text{ Spitzer} = 0.6 \text{ m}^2$$

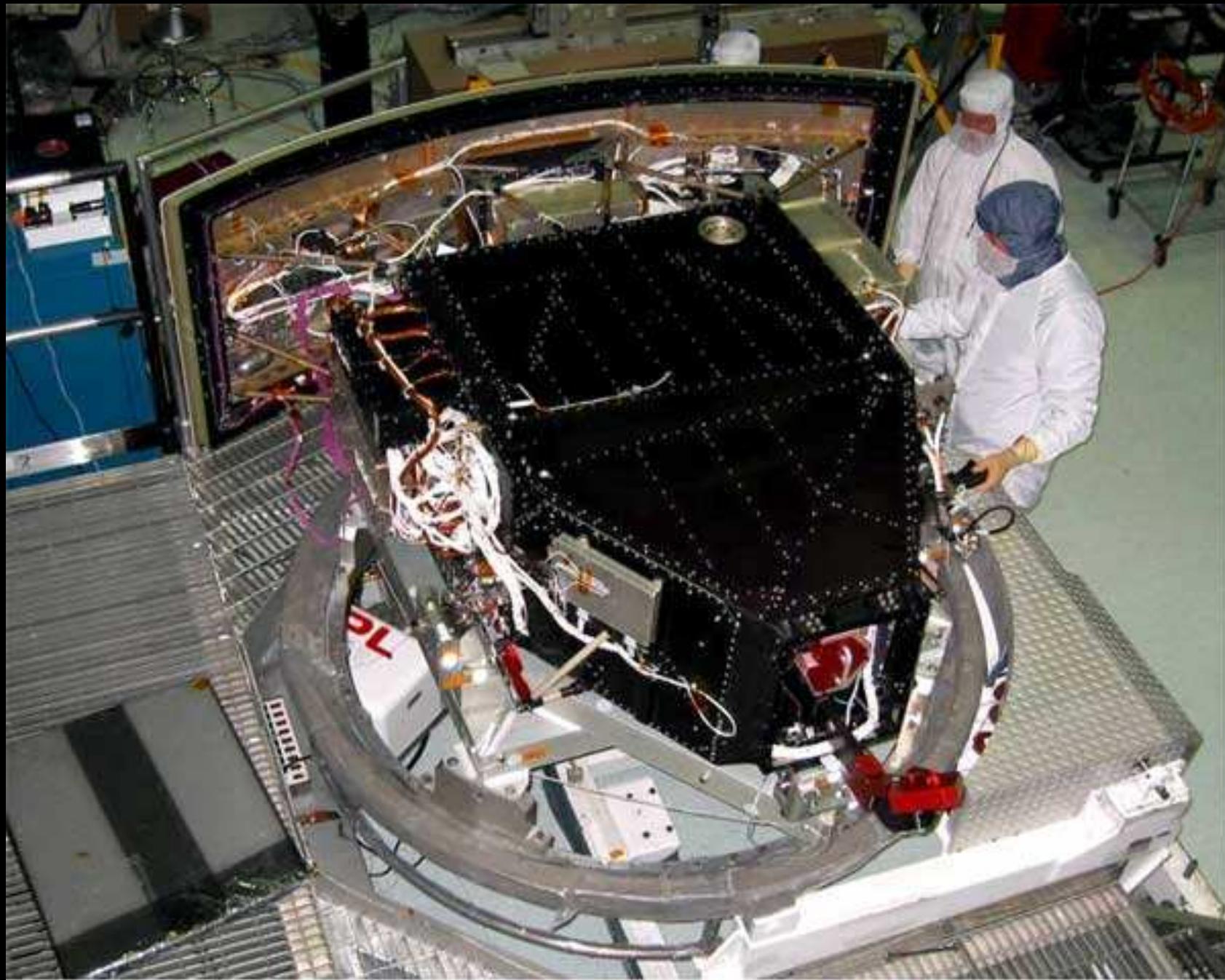
JWST is the perfect near-mid-IR sequel to HST and Spitzer:

- Vastly larger  $A \times \Omega$  than HST in UV-optical and Spitzer in mid-IR.

(1) Recent key aspects of the Hubble Space Telescope (HST) project:



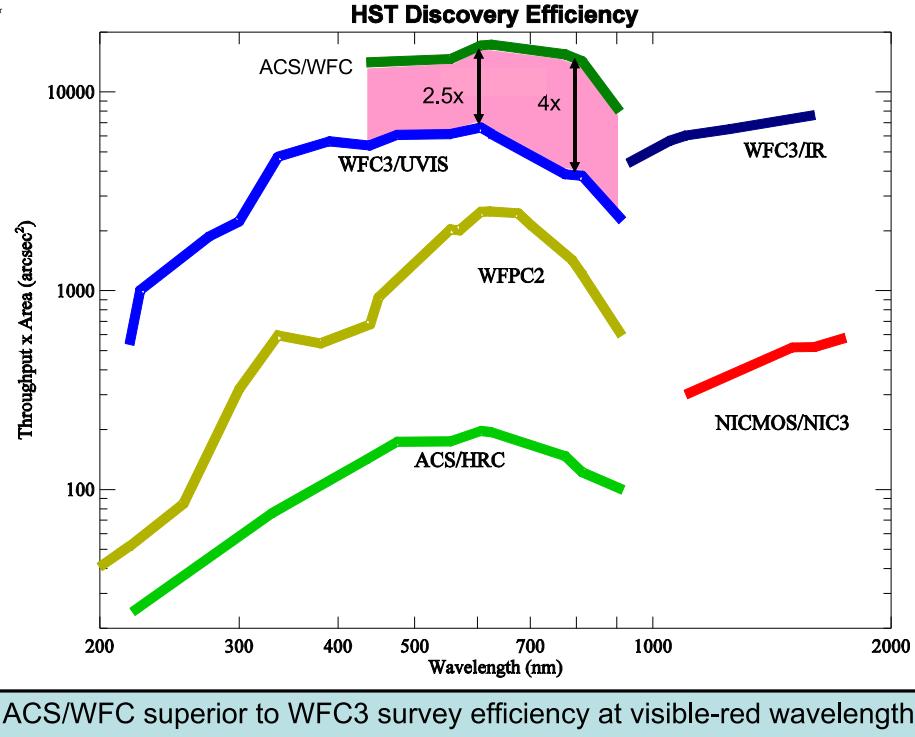
## WFC3: Hubble's new Panchromatic High-Throughput Camera



HST WFC3 and its IR channel: a critical pathfinder for JWST science.

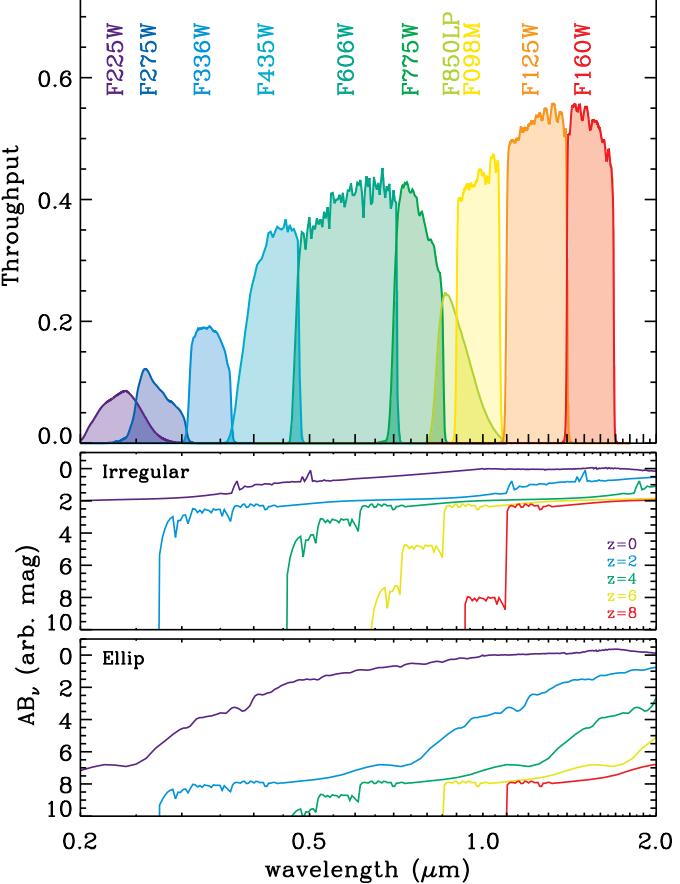


## Role of ACS in HST Post-SM4 Imaging Capability



030507\_PMB\_ACS\_Status.ppt

9



WFC3/UVIS channel unprecedented UV–blue throughput & areal coverage:

- QE  $\gtrsim 70\%$ ,  $4\text{k} \times 4\text{k}$  array of  $0''.04$  pixel, FOV  $\simeq 2''.67 \times 2''.67$ .

WFC3/IR channel unprecedented near–IR throughput & areal coverage:

- QE  $\gtrsim 70\%$ ,  $1\text{k} \times 1\text{k}$  array of  $0''.13$  pixel, FOV  $\simeq 2''.25 \times 2''.25$ .

WFC3 filters designed for star-formation and galaxy assembly at  $z \simeq 1\text{--}8$ :

- HST WFC3 and its IR channel a critical pathfinder for JWST science.

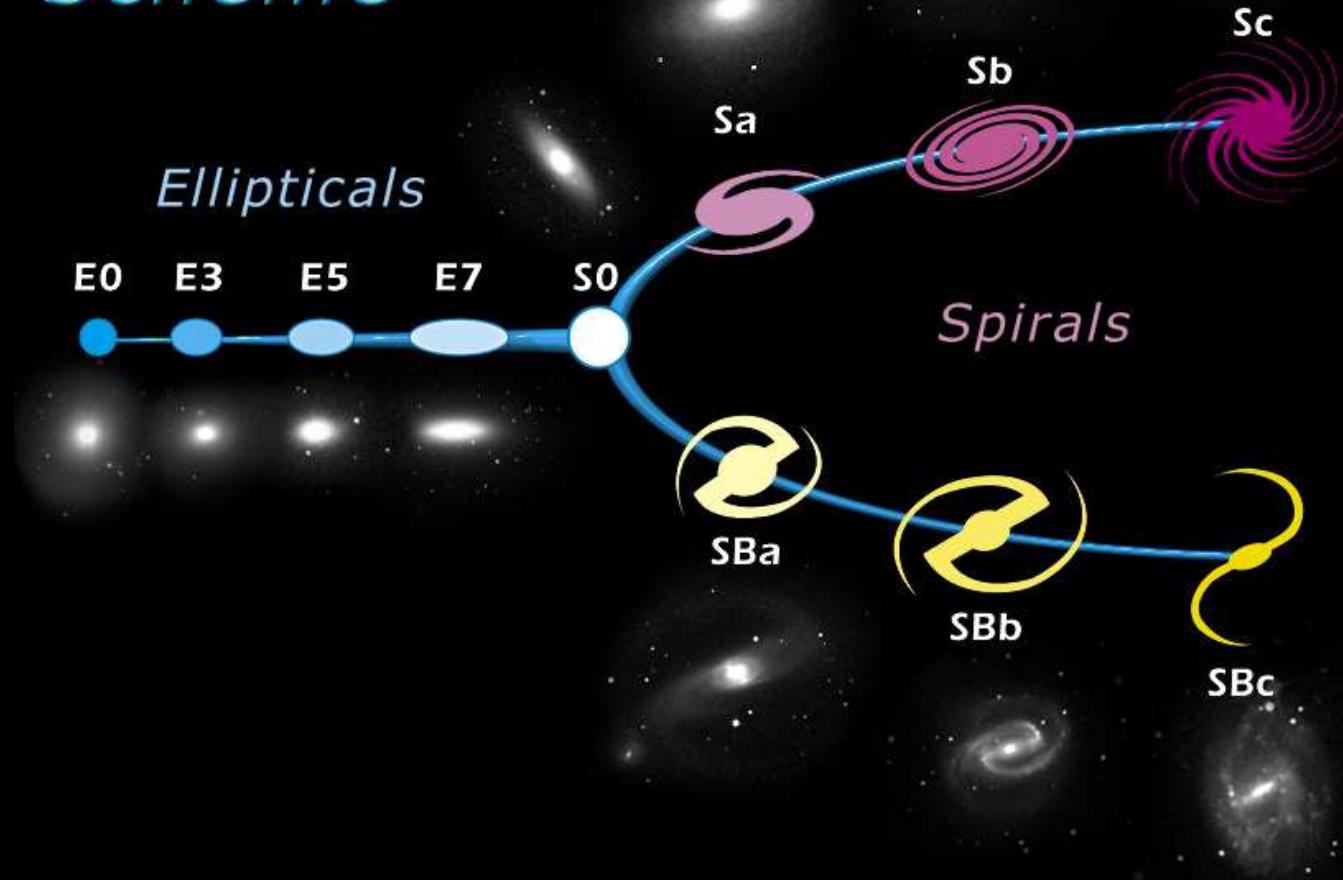
## (2) Measuring Galaxy Assembly and Supermassive Black-Hole Growth.



One of the remarkable HST discoveries was how numerous and small faint galaxies are: The building blocks of giant galaxies seen today.

(2) HST turned the classical Hubble sequence upside down!

## *Edwin Hubble's Classification Scheme*



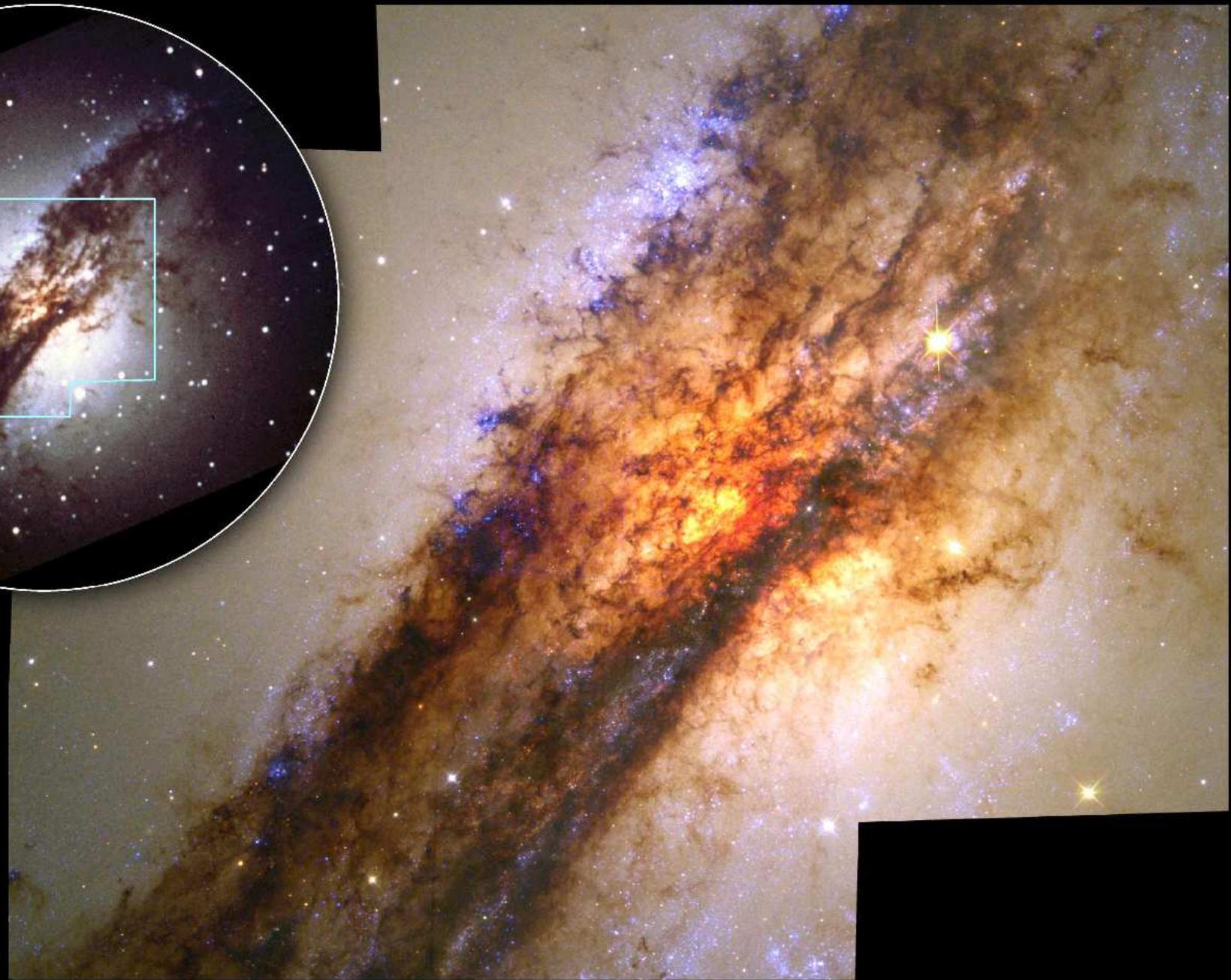
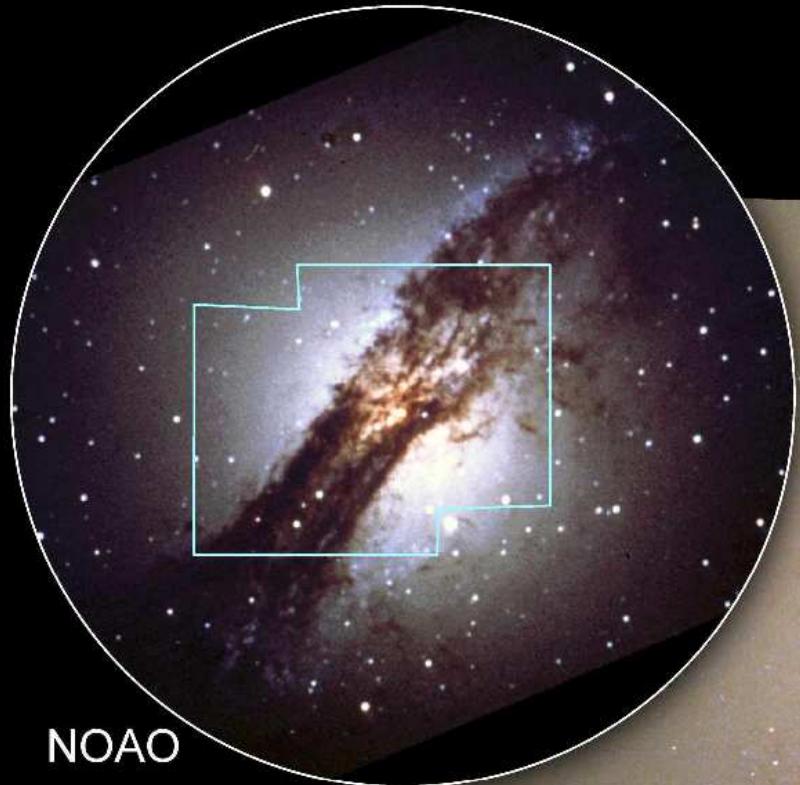
Who (when)	Cosmic Epoch	Ellipticals	Spirals	Irr's/mergers
Hubble (1920's)	$z=0$ (13.73 Gyr)	$\sim 40\%$	$\gtrsim 50\%$	$\lesssim 10\%$
HST (1990's)	$z \approx 1-2$ (3–6 Gyr)	$\lesssim 15\%$	$\sim 30\%$	$\gtrsim 55\% !$

# Elliptical Galaxy NGC 1132



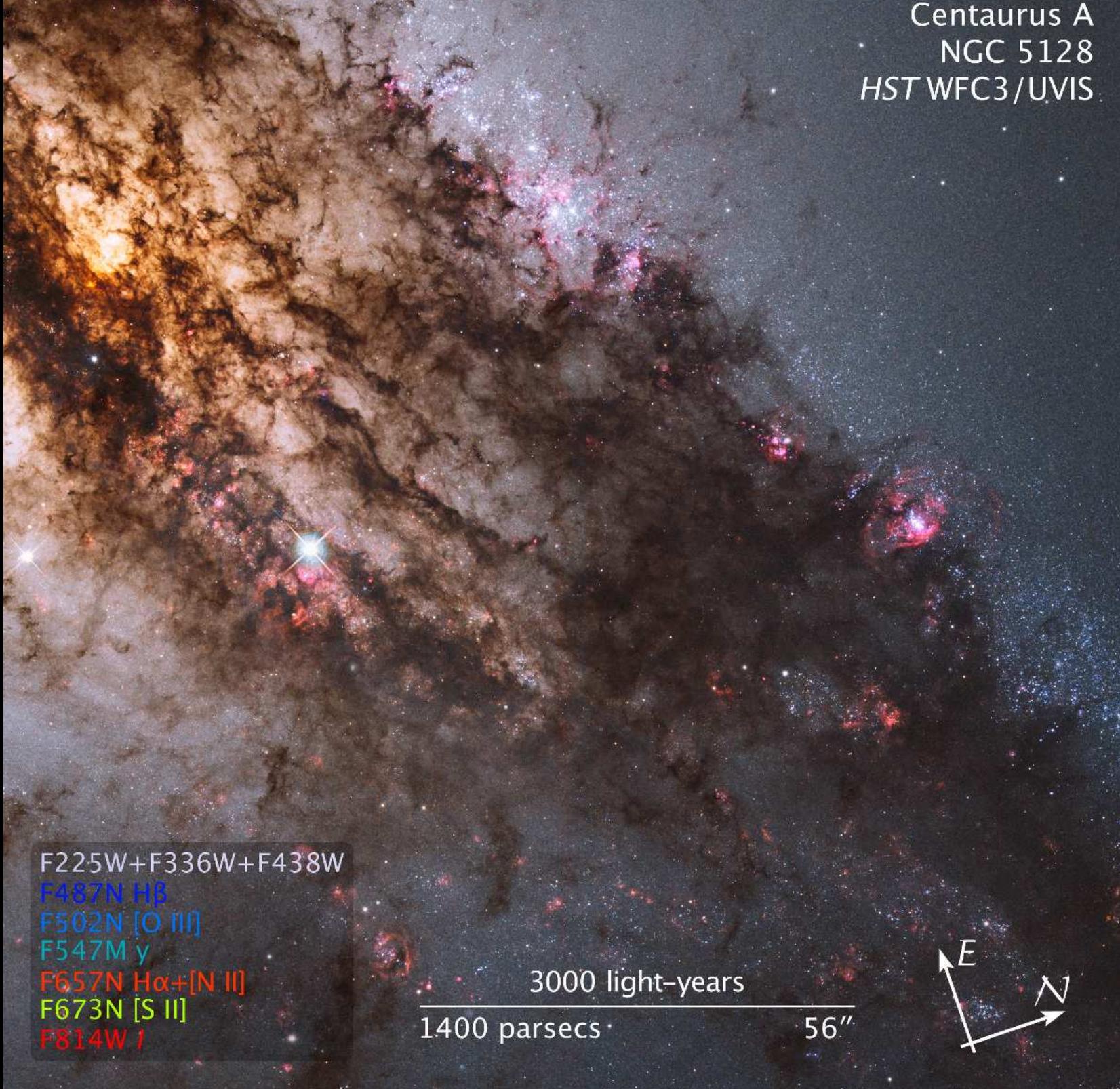
Hubble  
Heritage

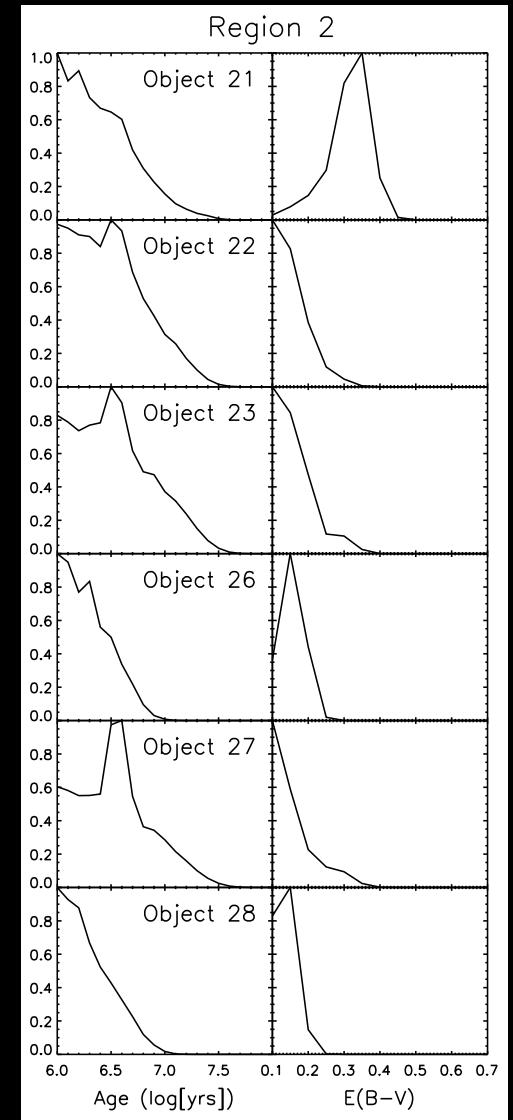
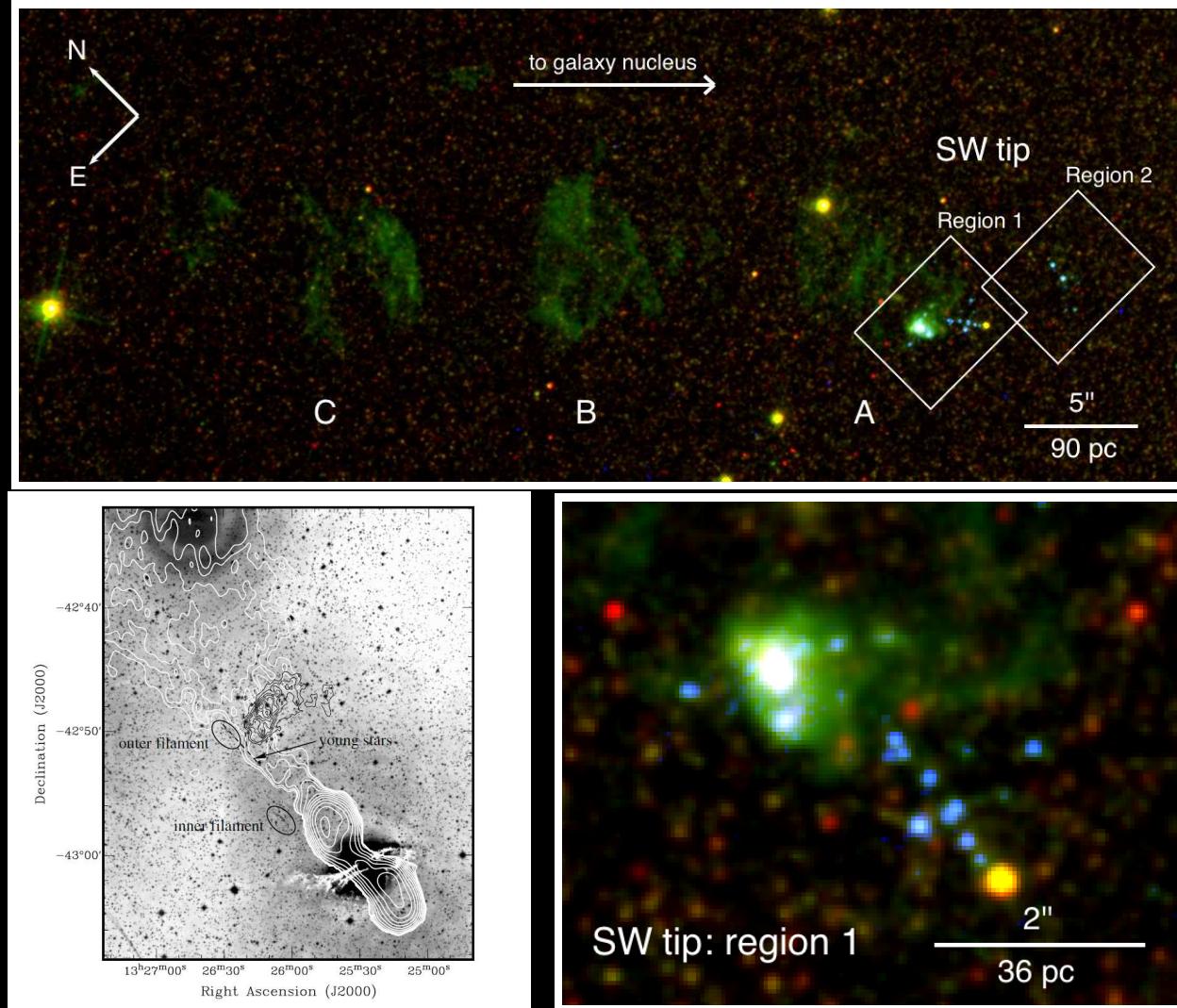
M. Rutkowski (2012, ApJS, 199, 3).



**Active Galaxy Centaurus A**  
Hubble Space Telescope • Wide Field Planetary Camera 2

Centaurus A  
NGC 5128  
*HST WFC3/UVIS*

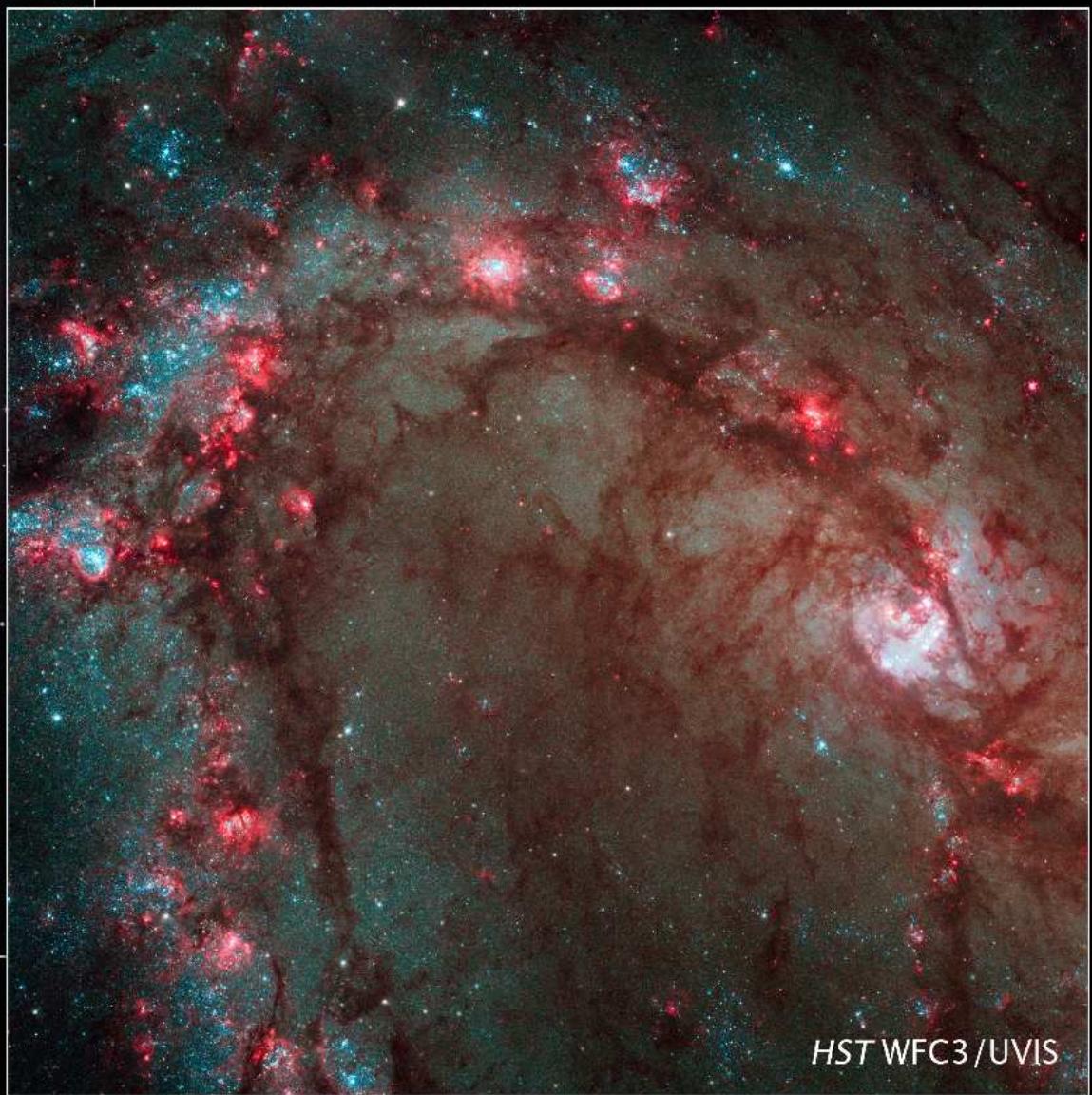




Well determined ages for young ( $\sim 2$  Myr) stars in Centaurus A jet, with star-formation in jet's wake (Crockett et al. 2012, MNRAS, 421, 1602).

JWST can do this in much dustier environments (and for older stars). We must do all we can with HST in UV-blue before JWST flies.

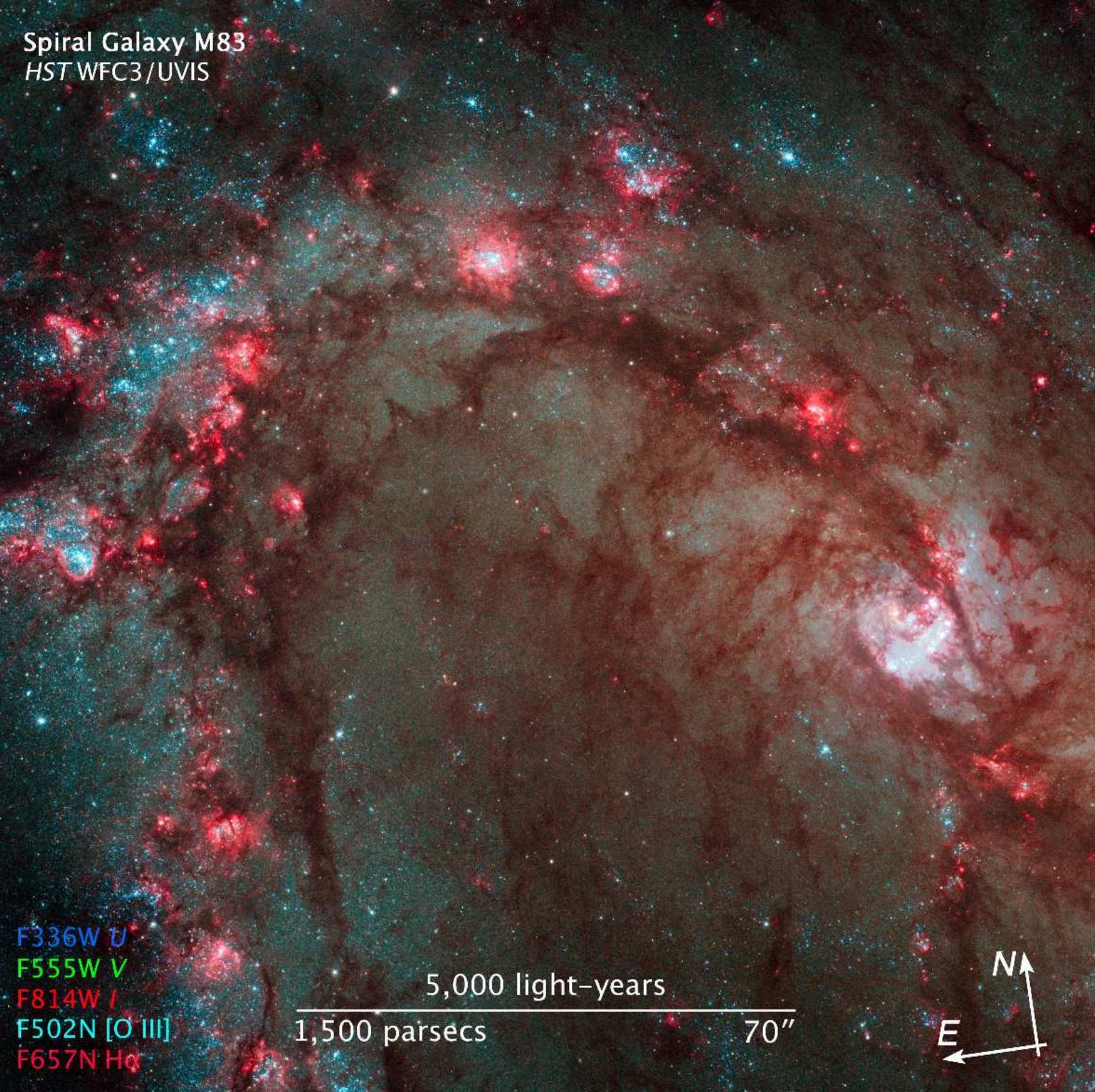
H. Kim (2012 ApJS & Dissertation)



Spiral Galaxy M83  
Hubble Space Telescope • WFC3/UVIS

# Spiral Galaxy M83

HST WFC3/UVIS



F336W *U*

F555W *V*

F814W *I*

F502N [O III]

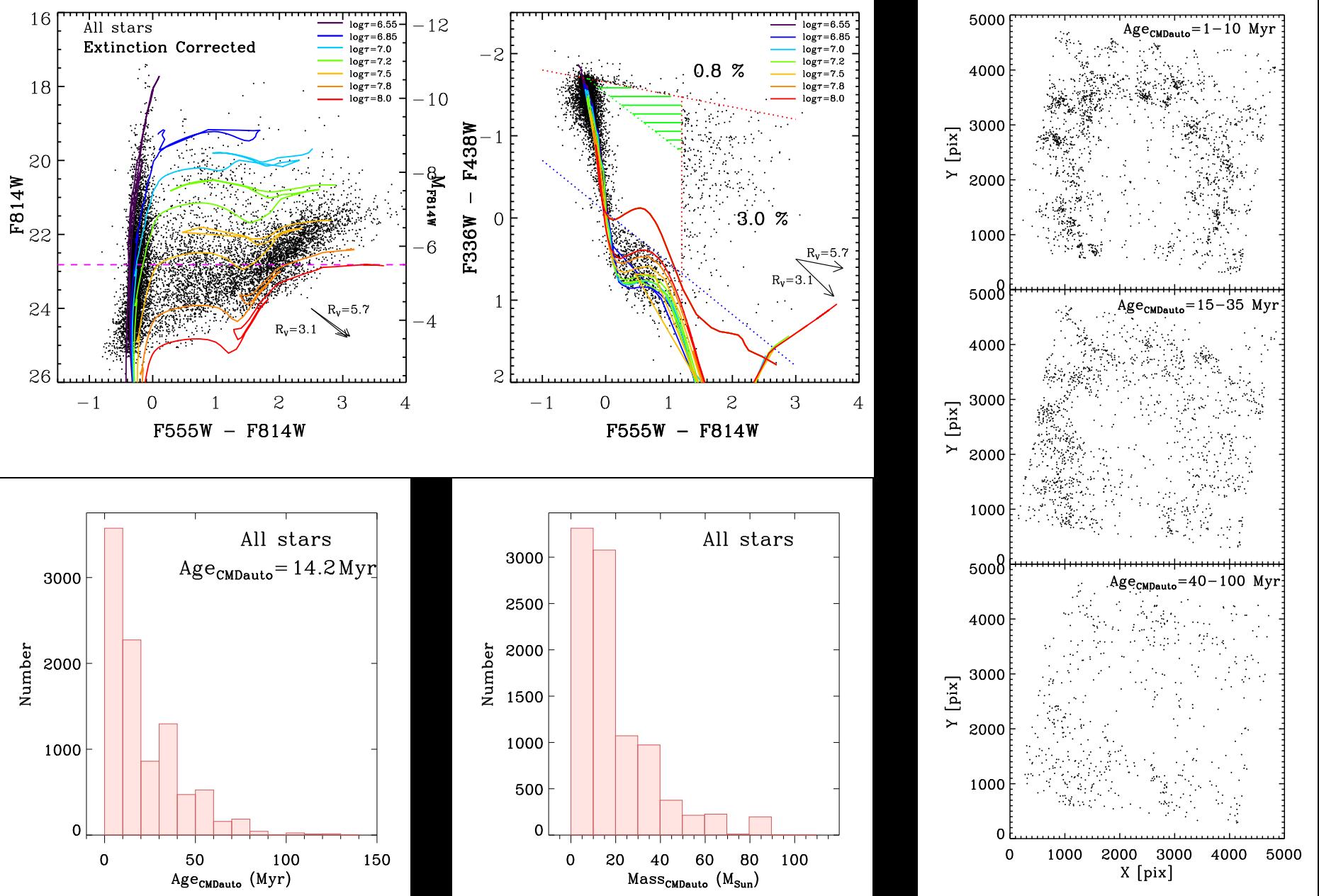
F657N H $\alpha$

5,000 light-years

1,500 parsecs

70"

N  
E



Well determined dust-corrected ages for stars in M83, with formation and dissipation along/across spiral arms (Hwihyun Kim et al. 2012, ApJS).

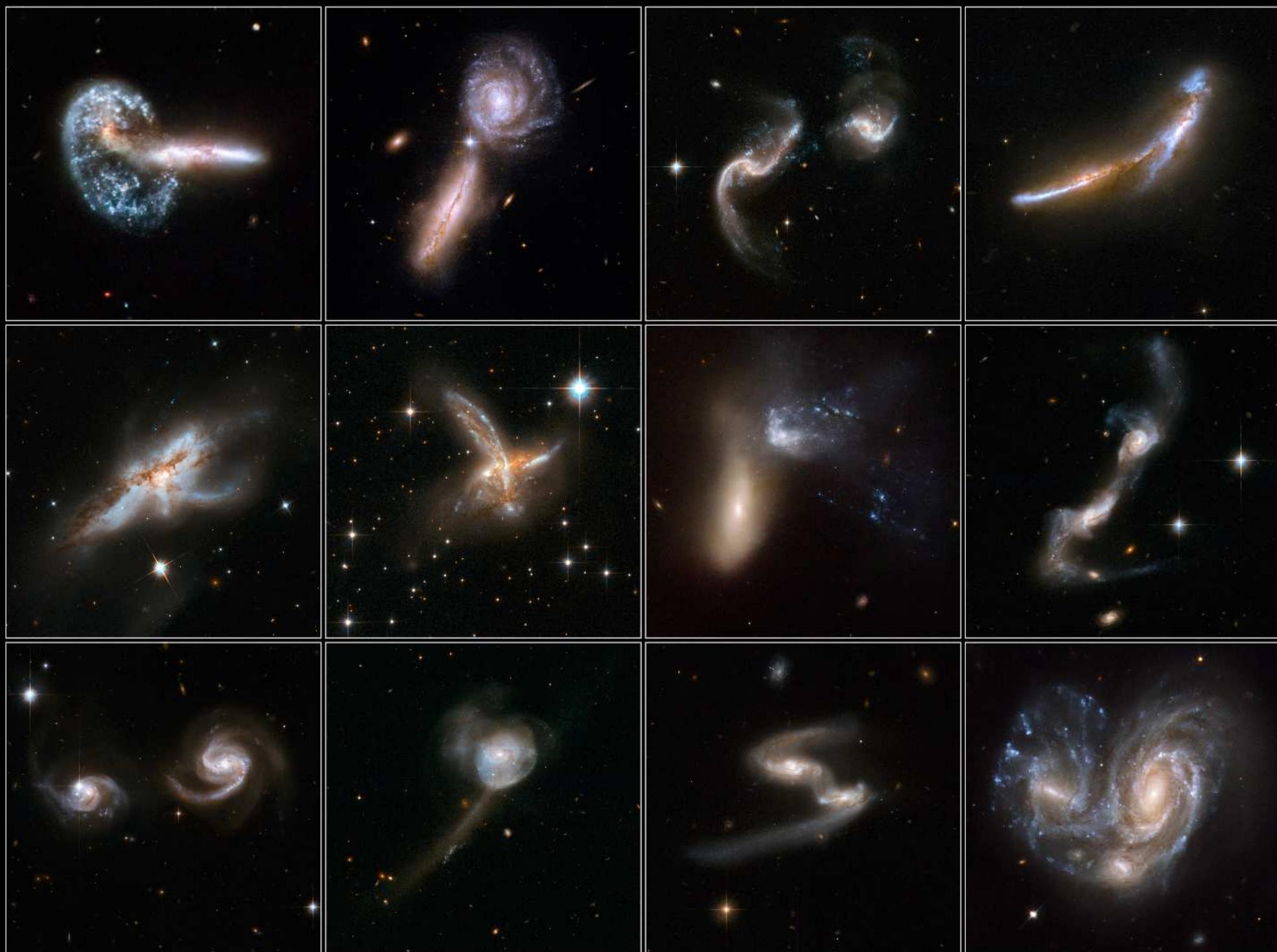
JWST can do this in much dustier environments and for older stellar populations. But must do all we can with HST in UV-blue before JWST flies!

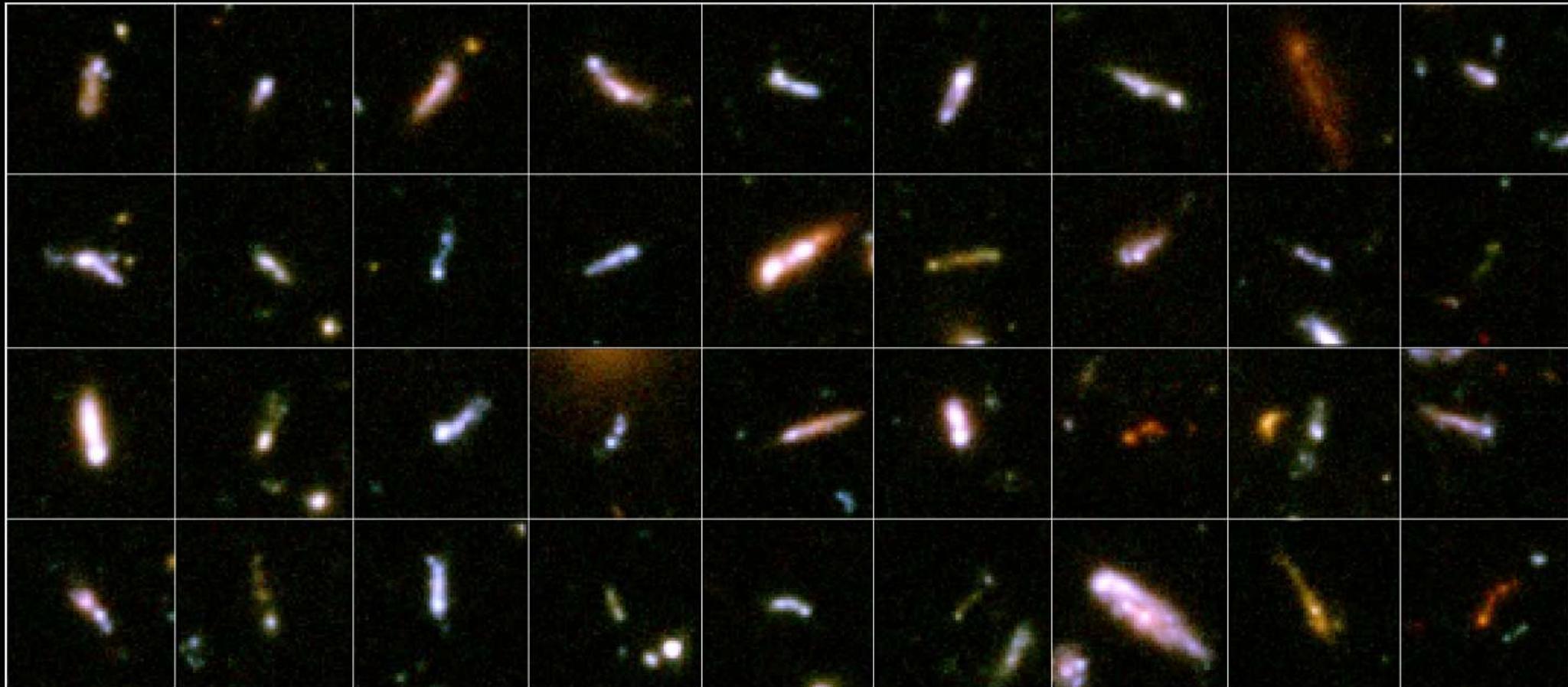


HST Antenna galaxy: Prototype of high redshift, star-forming, major merger?

# Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2





**“Tadpole” Galaxies in the Hubble Ultra Deep Field**  
*Hubble Space Telescope ■ ACS/WFC*

NASA, ESA, A. Straughn, S. Cohen and R. Windhorst (Arizona State University), and the HUDF team (STScI)

STScI-PRC06-04

Merging galaxies constitute  $\lesssim 1\%$  of Hubble sequence today (age  $\gtrsim 12.5$  Gyr).

Tadpole galaxies are early stage mergers, very common at  $z \gtrsim 2$  (age  $\lesssim 3$  Gyr).

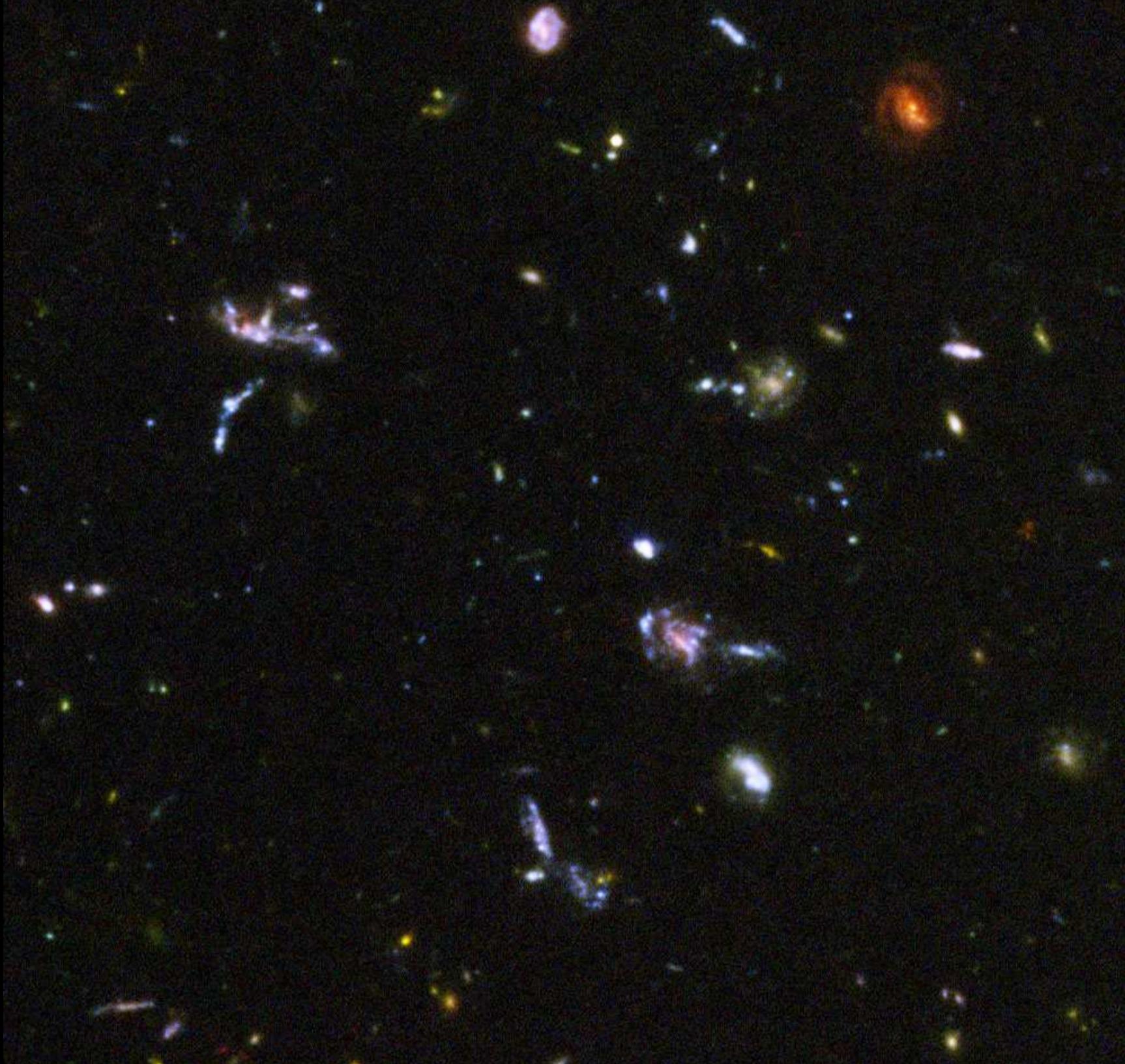
JWST will measure Galaxy Assembly to  $z \lesssim 20$  (cosmic age  $\gtrsim 0.2$  Gyr).



HST/WFC3 & ACS reach AB=26.5-27.0 mag ( $\sim$ 100 fireflies from Moon) over  $0.1 \times$ full Moon area in 10 filters from 0.2–2 $\mu$ m wavelength.

JWST has 3 $\times$ sharper imaging to AB $\simeq$ 31.5 mag ( $\sim$ 1 firefly from Moon) at 1(-29) $\mu$ m wavelengths, tracing young and old stars + dust.







Elliptical galaxy M87 with Active Galactic Nucleus (AGN) and relativistic jet.



*"For God's sake, Edwards. Put the laser pointer away."*

The danger of having Quasar-like devices too close to home ...

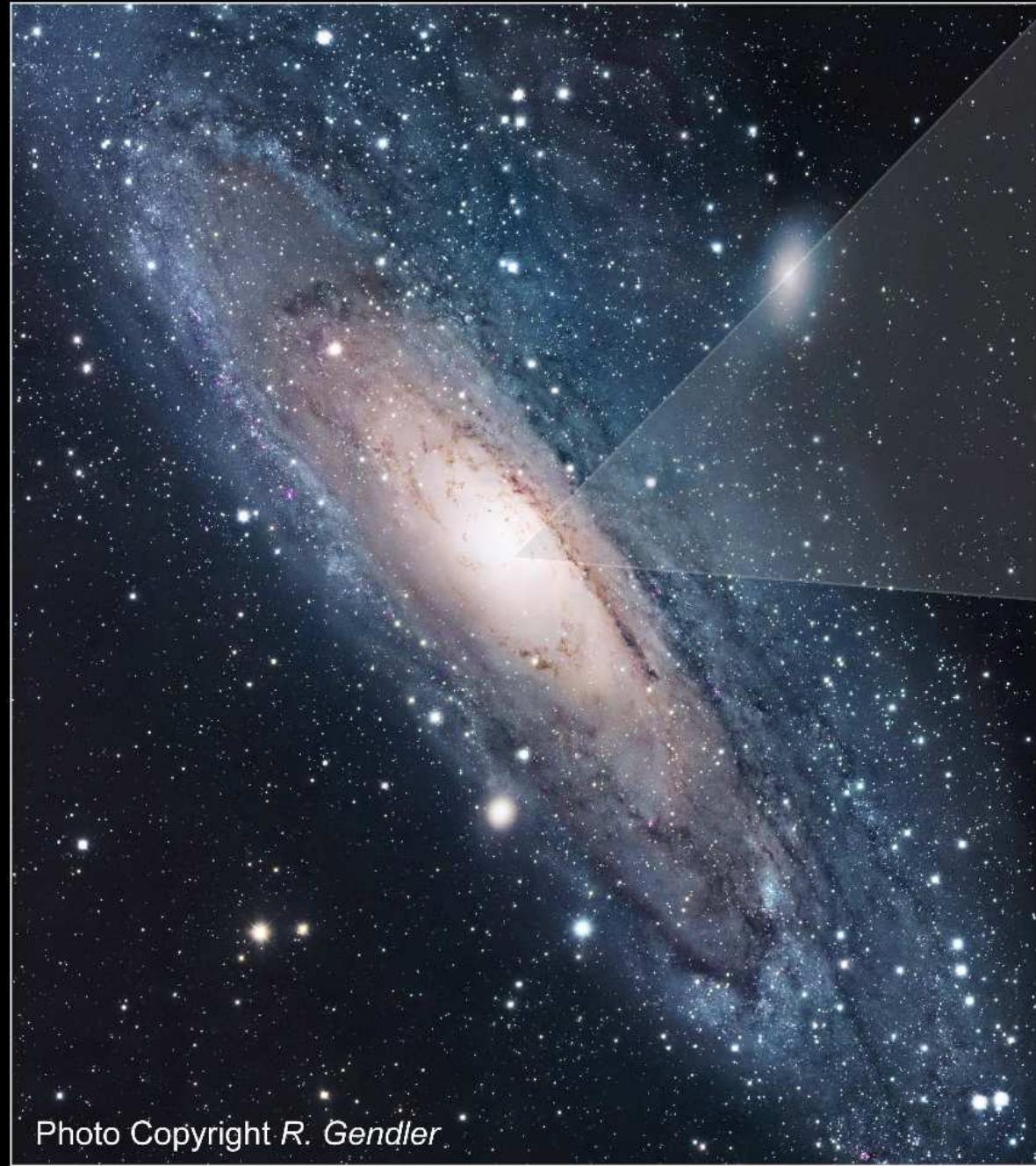
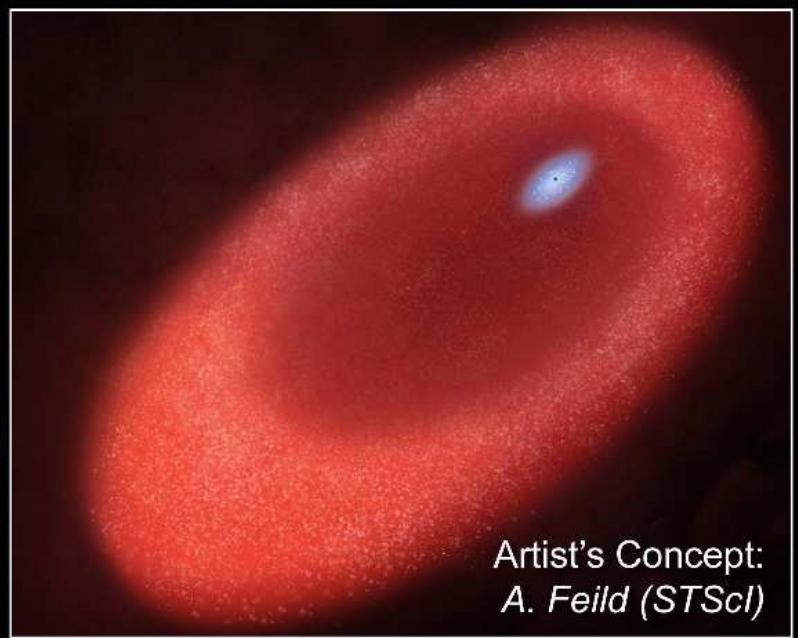


Photo Copyright R. Gendler



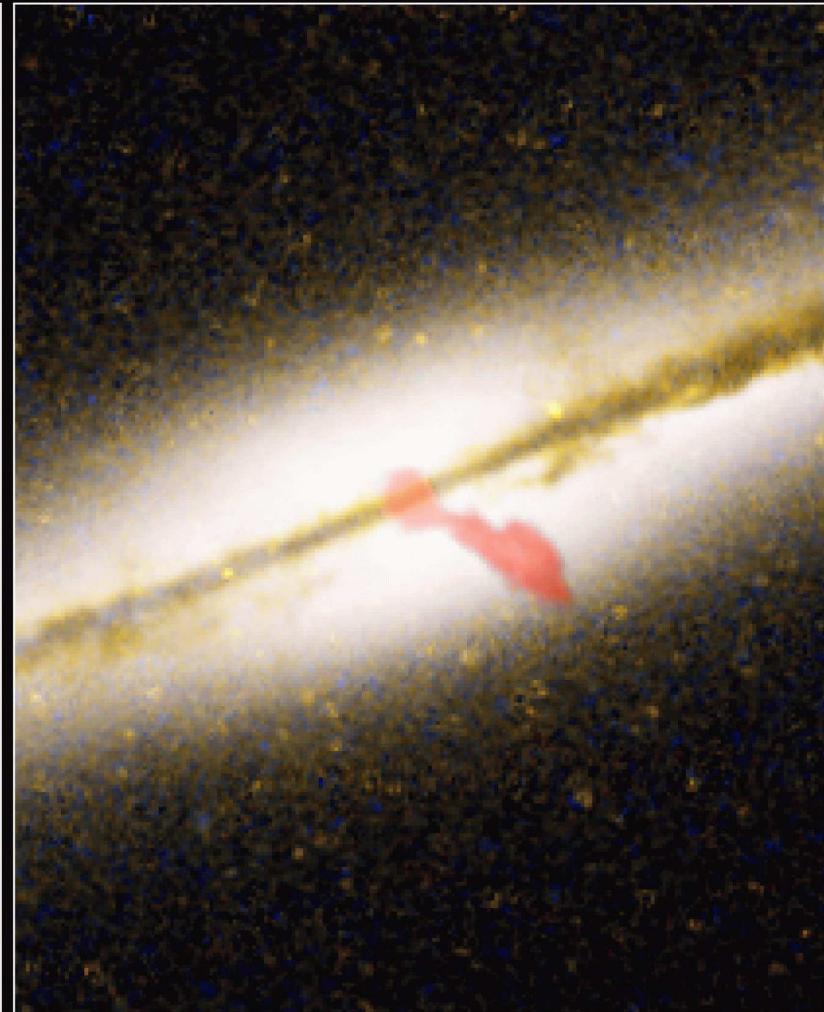
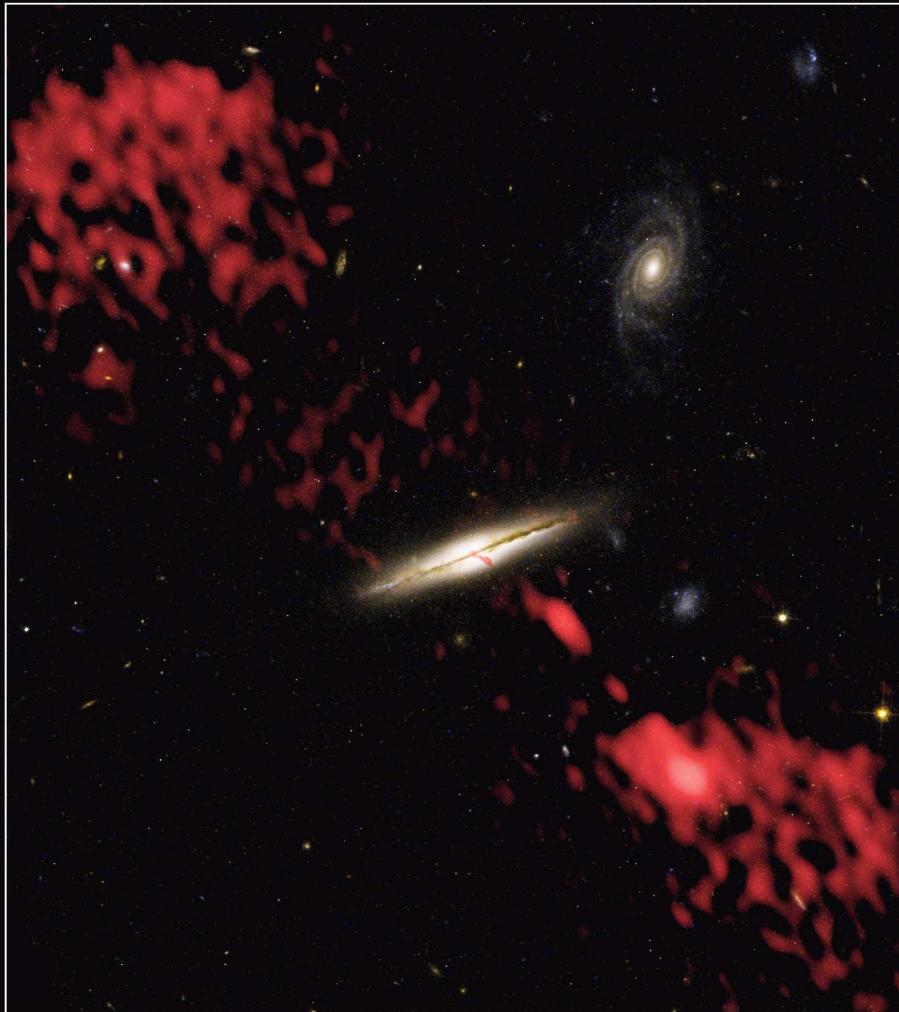
HST WFPC2 image:  
T. Lauer (NOAO/AURA/NSF)



Artist's Concept:  
A. Feild (STScI)

## Andromeda Galaxy Nucleus ▪ M31 Hubble Space Telescope ▪ WFPC2

## (2) Measuring Galaxy Assembly & Supermassive Blackhole Growth

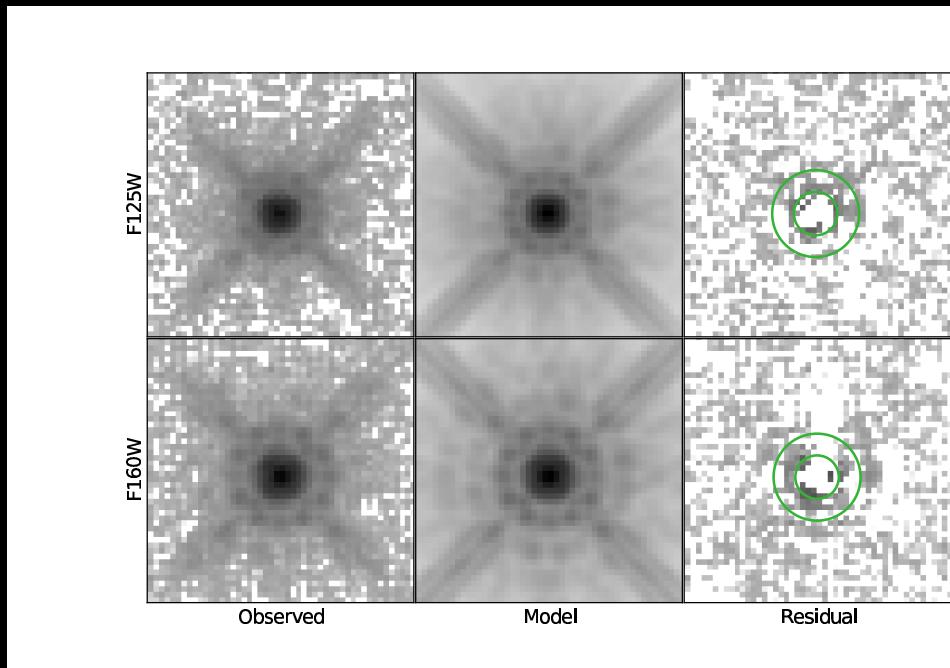
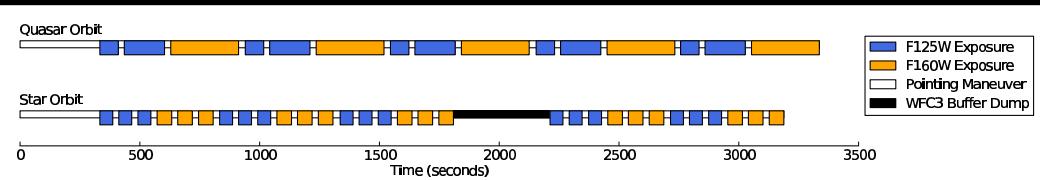


**Radio Galaxy 0313-192**  
**Hubble Space Telescope ACS WFC • Very Large Array**

NASA, NRAO/AUI/NSF and W. Keel (University of Alabama) • STScI-PRC03-04

Does galaxy assembly go hand-in-hand with supermassive blackhole growth?

# HST WFC3 observations of Quasar Host Galaxies at $z \simeq 6$ (age $\sim 1$ Gyr)

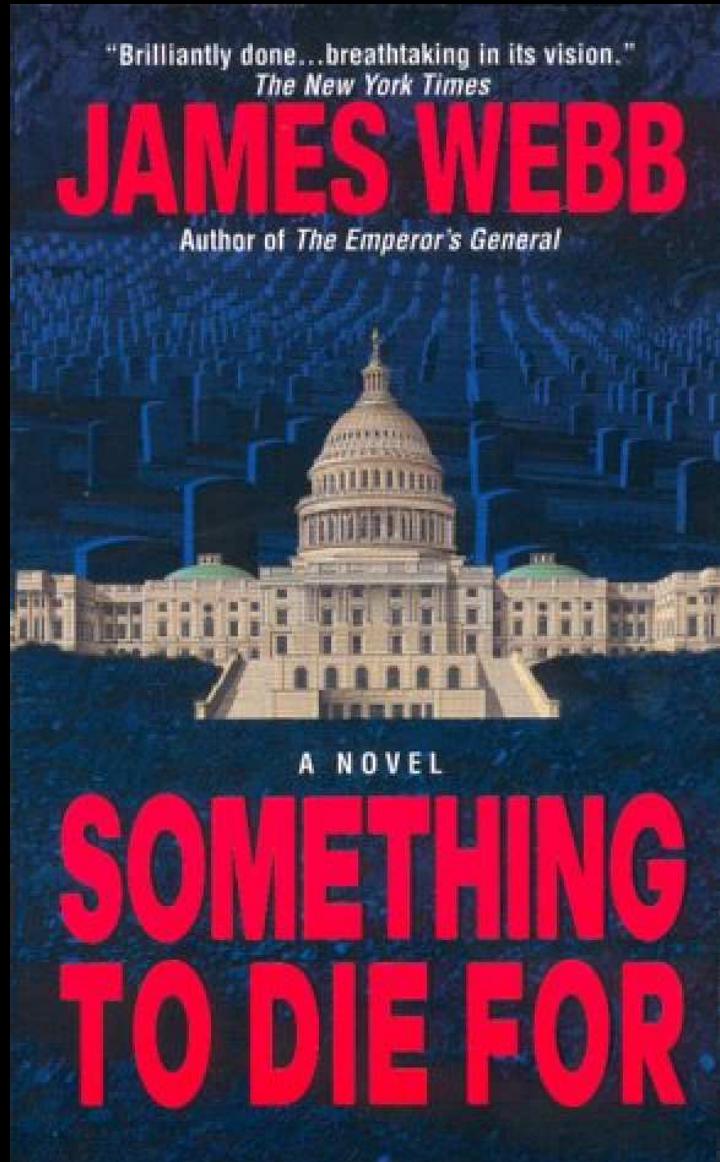


- Careful contemporaneous orbital PSF-star subtraction: Removes most of HST “OTA spacecraft breathing” effects (Mechtley et al. 2012).
- PSF-star ( $AB=15$  mag) subtracts Quasar ( $18.5$  mag) nearly to the noise limit: NO host galaxy detected  $100\times$ fainter ( $AB \gtrsim 23.5$  mag;  $r \gtrsim 0\farcs3$ ).

THE most luminous Quasars in the Universe: Are all their host galaxies faint?  $\Rightarrow$  Major implications for Galaxy Assembly–SMBH Growth!

- JWST Coronagraphs can do this  $10\text{--}100\times$  fainter (and for  $z \lesssim 20$ ) — but need JWST diffraction limit at  $2.0\mu\text{m}$  and clean PSF to do this!

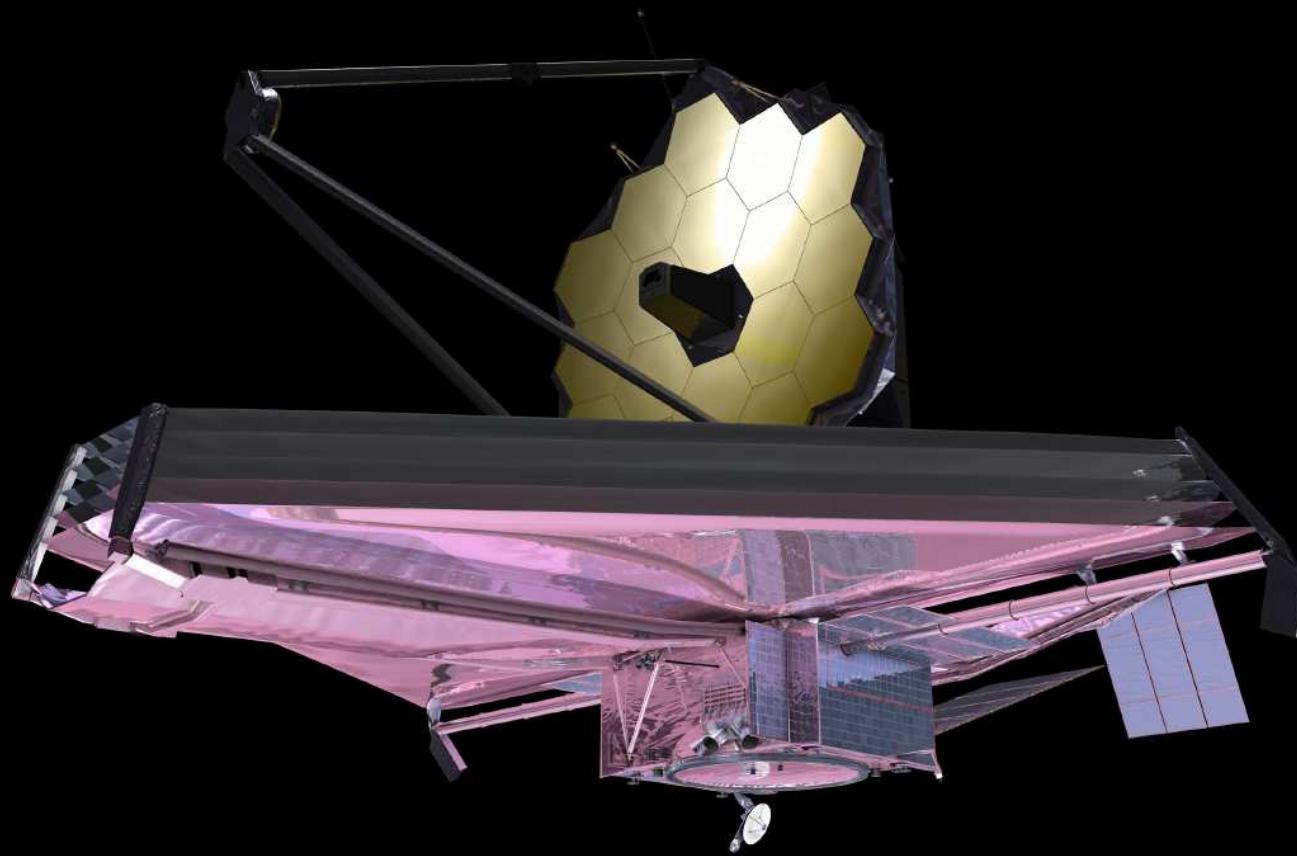
### (3) What is the James Webb Space Telescope (JWST)?



Need young generation of students & scientists after 2018 ... It'll be worth it!

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

### (3) What is the James Webb Space Telescope (JWST)?



- A fully deployable 6.5 meter ( $25 \text{ m}^2$ ) segmented IR telescope for imaging and spectroscopy at  $0.6\text{--}28 \mu\text{m}$  wavelength, to be launched in Fall 2018.
- Nested array of sun-shields to keep its ambient temperature at 40 K, allowing faint imaging (31.5 mag = firefly from Moon!) and spectroscopy.

# THE JAMES WEBB SPACE TELESCOPE

## JWST LAUNCH

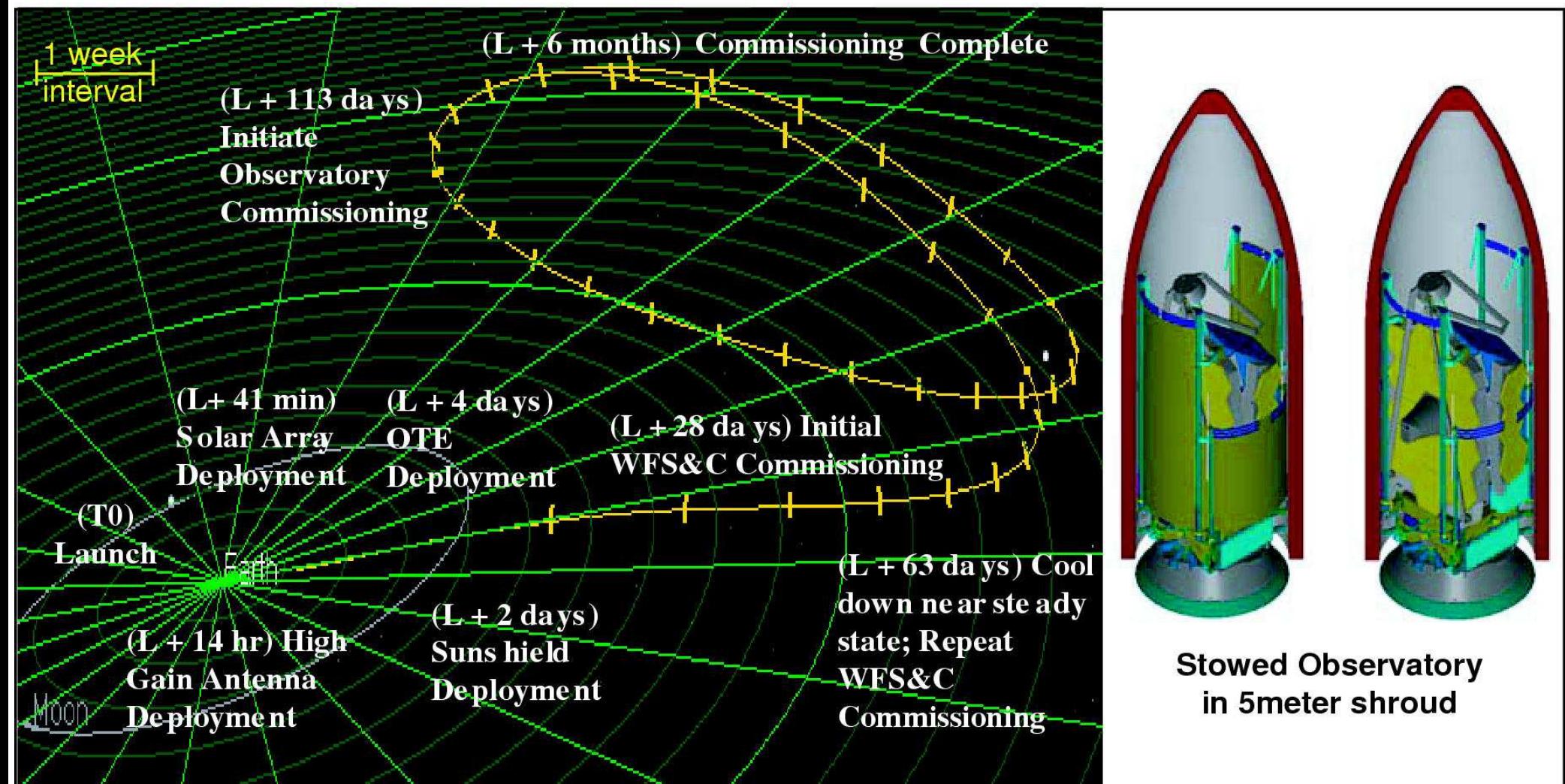
- LAUNCH VEHICLE IS AN ARIANE 5 ROCKET, SUPPLIED BY ESA
- SITE WILL BE THE ARIANESPACE'S ELA-3 LAUNCH COMPLEX NEAR KOUROU, FRENCH GUIANA



ARIANESPACE - ESA - NASA

- The JWST launch weight will be  $\lesssim 6500$  kg, and it will be launched to L2 with an ESA Ariane-V launch vehicle from Kourou in French Guiana.

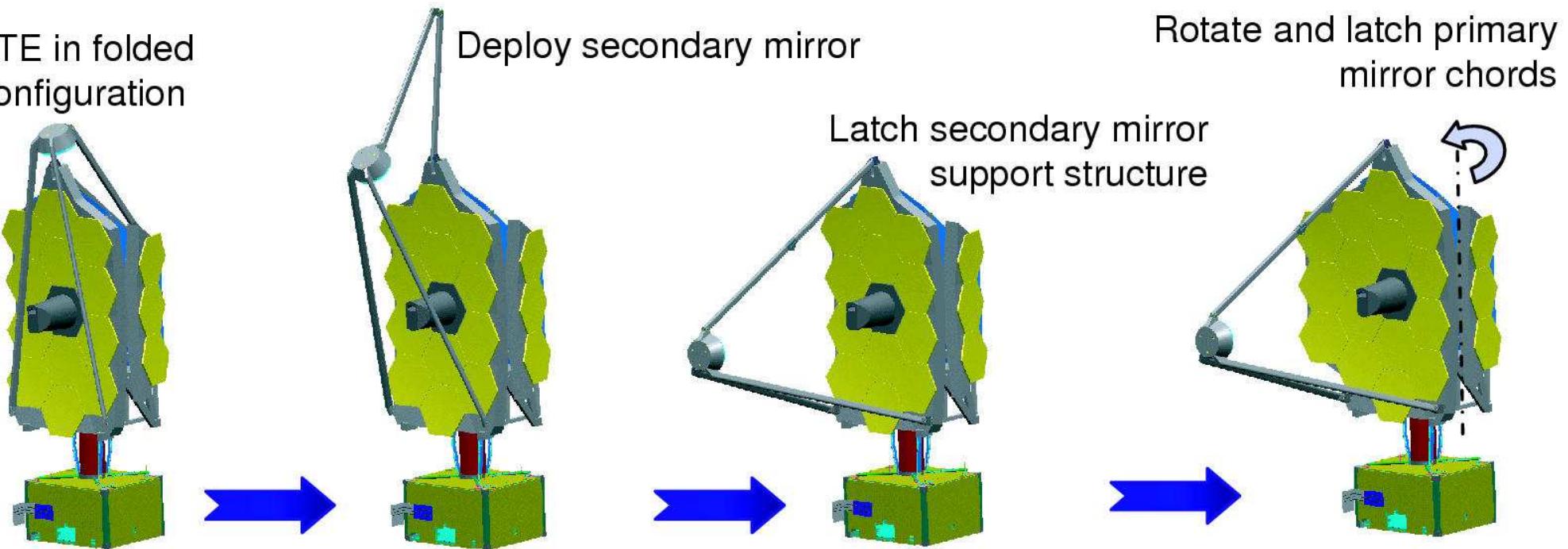
### (3a) How will JWST travel to its L2 orbit?



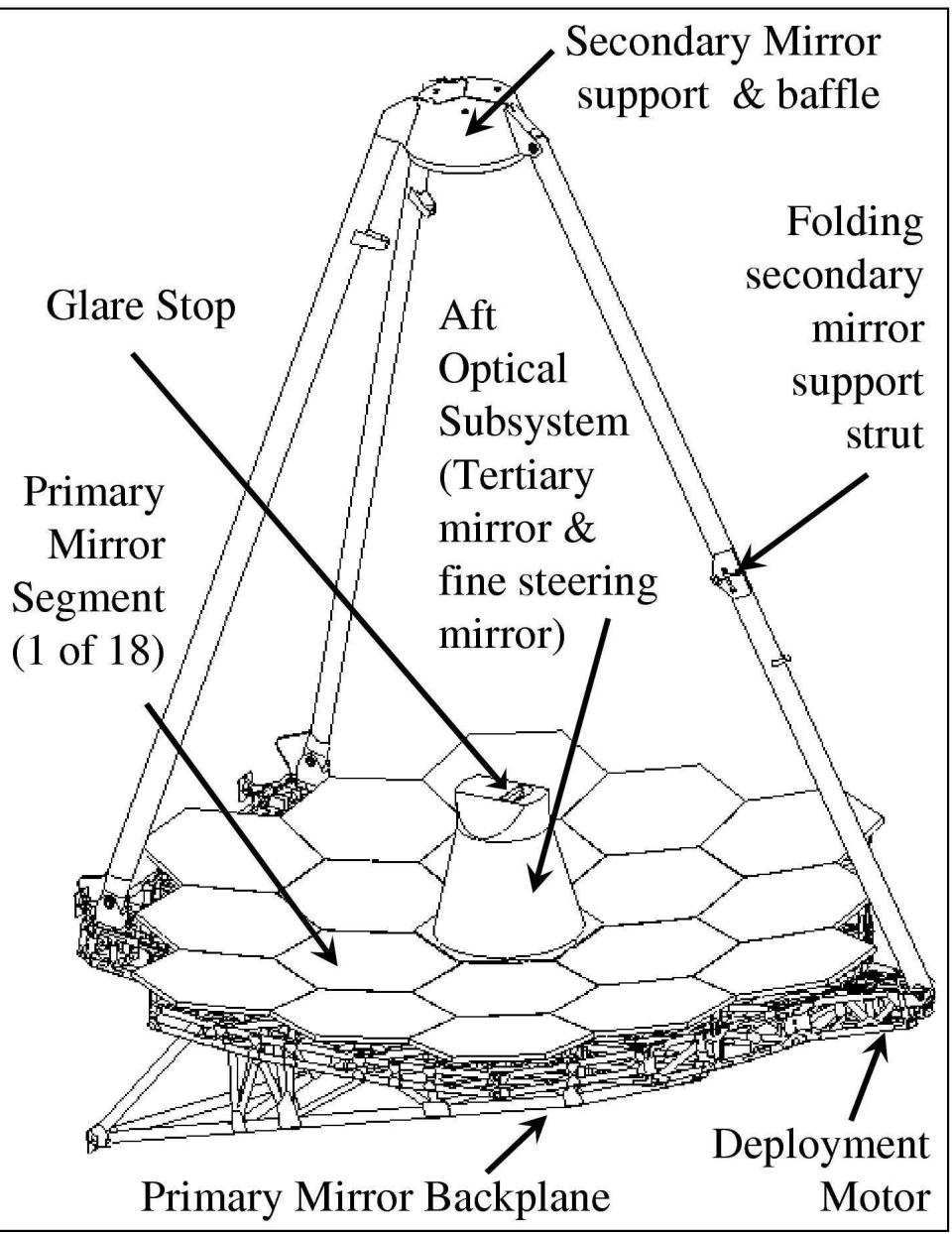
- After launch in 2018 with an ESA Ariane-V, JWST will orbit around the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe  $\gtrsim 70\%$  of the time, and send data back to Earth every day.

- (3b) How will JWST be automatically deployed?

OTE in folded configuration



- During its two month journey to L2, JWST will be automatically deployed, its instruments will be cooled, and be inserted into an L2 orbit.
- The entire JWST deployment sequence will be tested several times on the ground — but only in 1-G: Component and system tests in Houston.
- Component fabrication, testing, & integration is on schedule: 18 out of 18 flight mirrors completely done, and meet the 40K specifications!



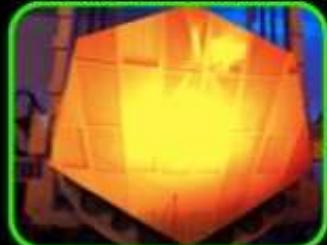
Wave-Front Sensing tested hands-off at 40 K in 1-G at JSC in 2015-2016.

Ball 1/6 scale-model for WFS: produces diffraction-limited 2.0  $\mu\text{m}$  images.

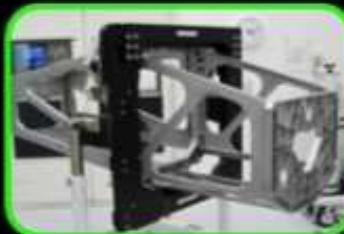


# JWST Hardware Status

Primary Mirror Segment



Aft Optics System



PM Flight Backplane



Tertiary Mirror

Secondary Mirror Pathfinder Strut



Fine Steering Mirror



ISIM Flight Bench



Secondary Mirror Hexapod



Secondary Mirror



Membrane Mgmt



Pathfinder Membrane



Mid-boom Test

Spacecraft computer Test Unit

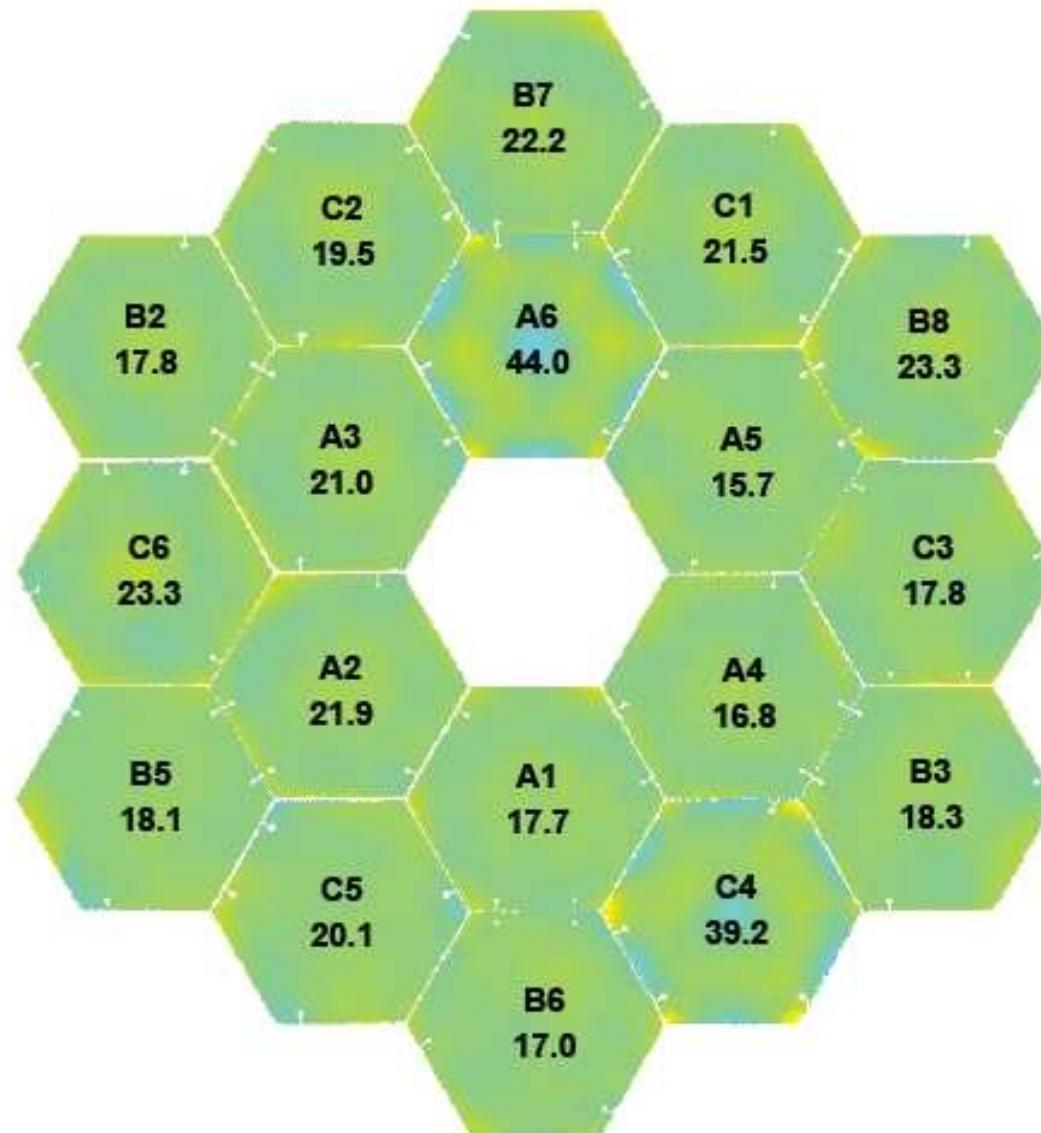
# Mirror Acceptance Testing





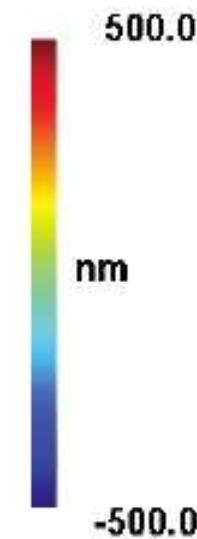


# Primary Mirror Composite



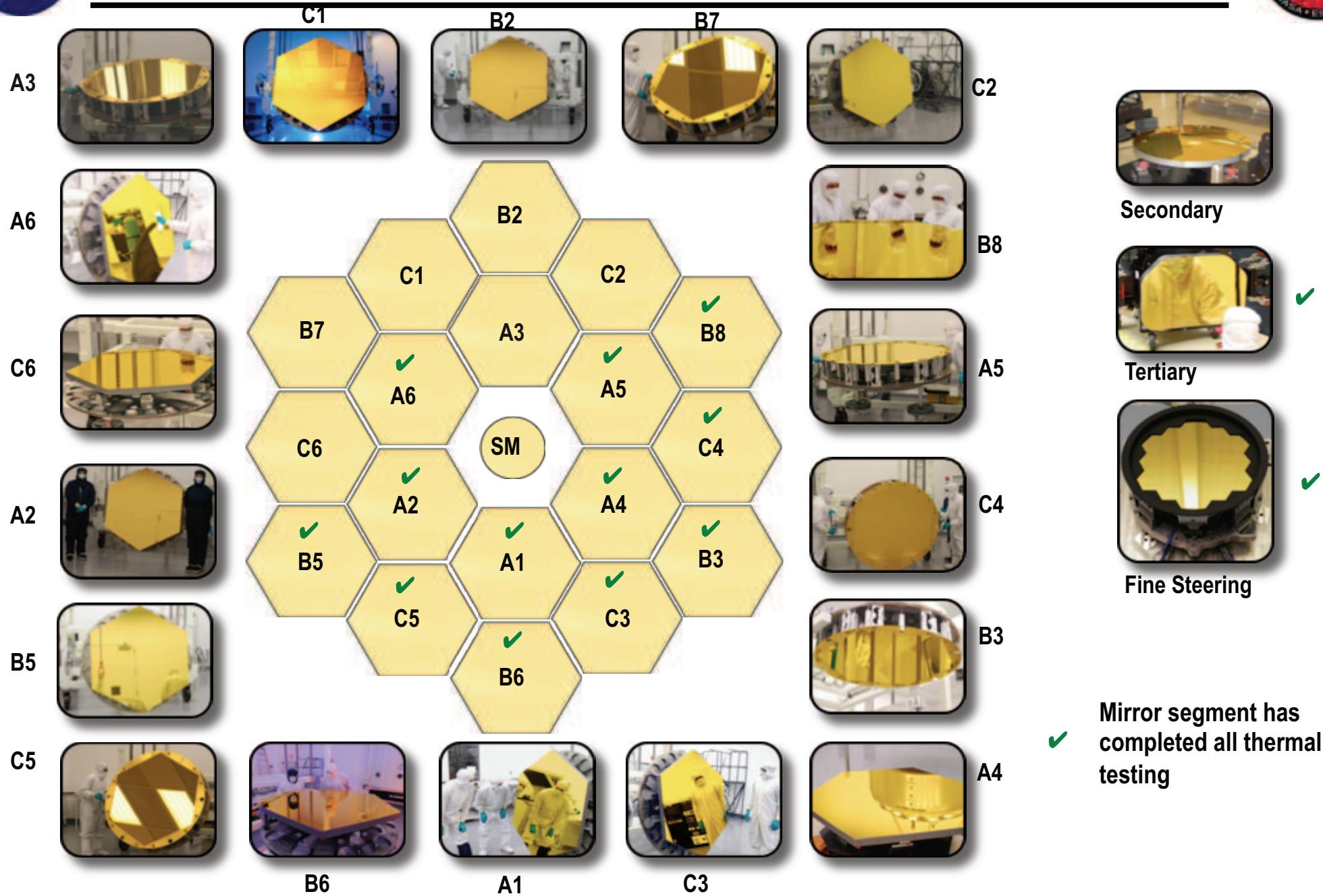
RMS:  
**23.2 nm**

PV:  
**515.5 nm**





# Family Portrait





# Sunshield



- **Template membrane build to flight-like requirements for verification of:**
  - Shape under tension to verify gradients and light line locations
  - Hole punching & hole alignment for membrane restraint devices (MRD)
  - Verification of folding/packing concept on full scale mockup
  - Layer 3 shape measurements completed



←Layer-3 template membrane under tension for 3-D shape measurements at Mantech

Full-scale JWST mockup with sunshield pallette



# Telescope Assembly Ground Support Equipment



Hardware has been installed at GSFC approximately 8 weeks ahead of schedule



# (3b) JWST instrument update: US (UofA, JPL), ESA, & CSA.

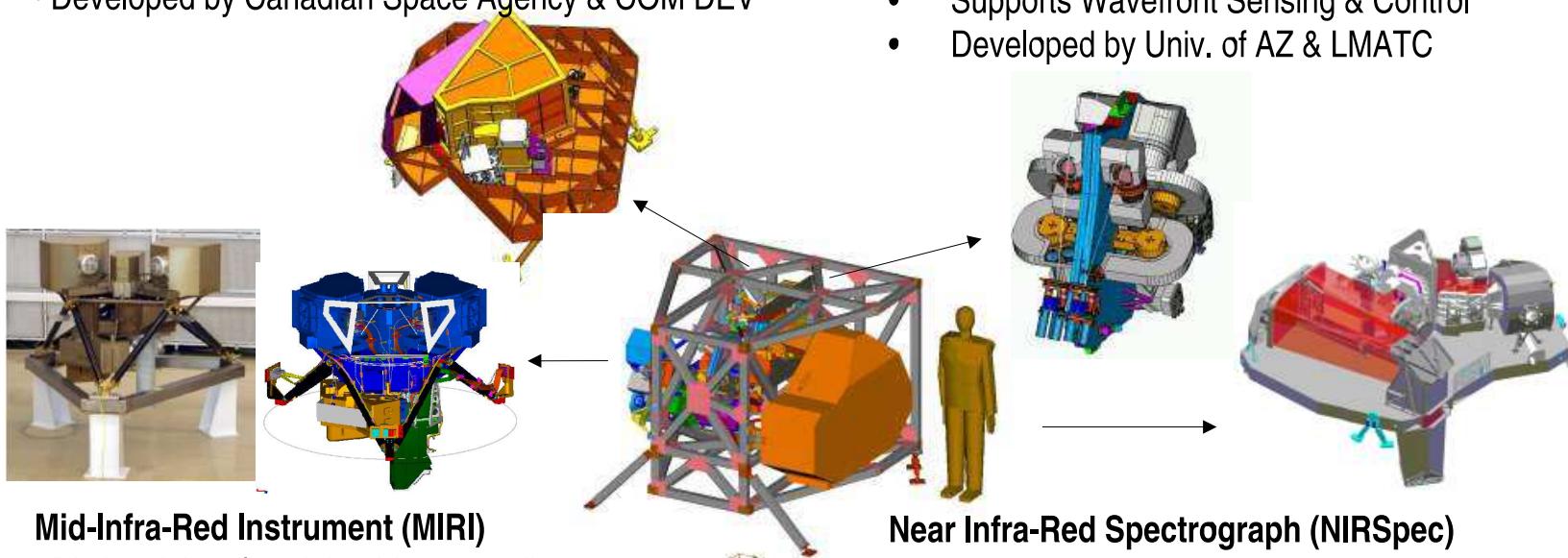


## Instrument Overview



### 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



### 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)

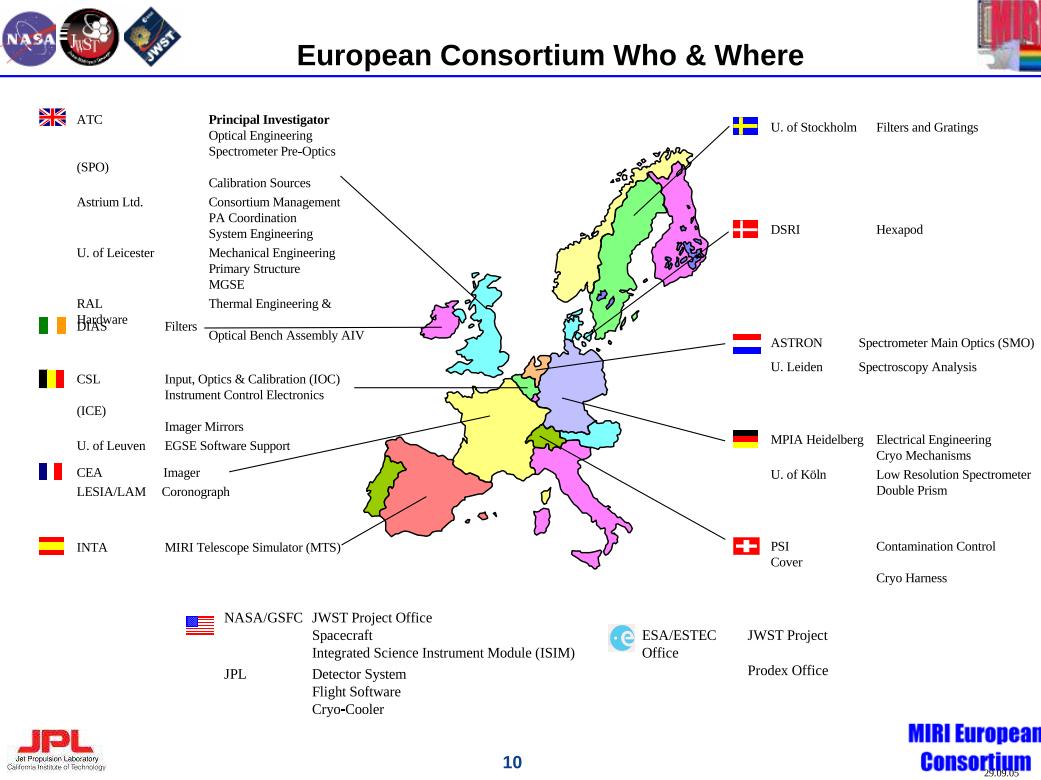
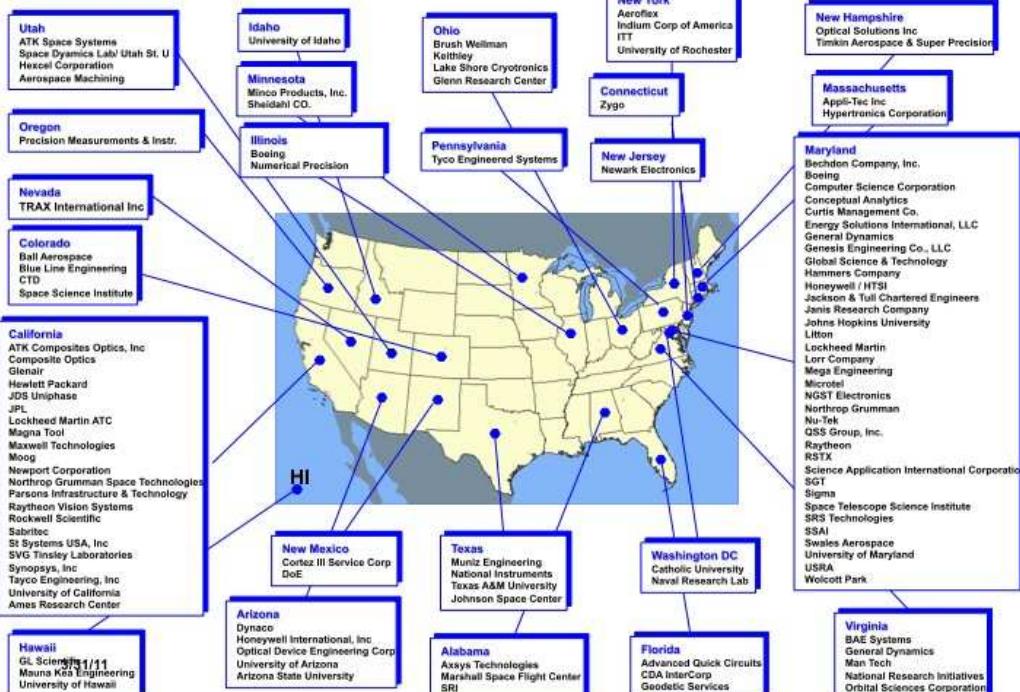
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC

### 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

MIRI delivery 05/12; NIRCam 09/12; NIRSpec & FGS early 2013.

# JWST: A Product of the Nation

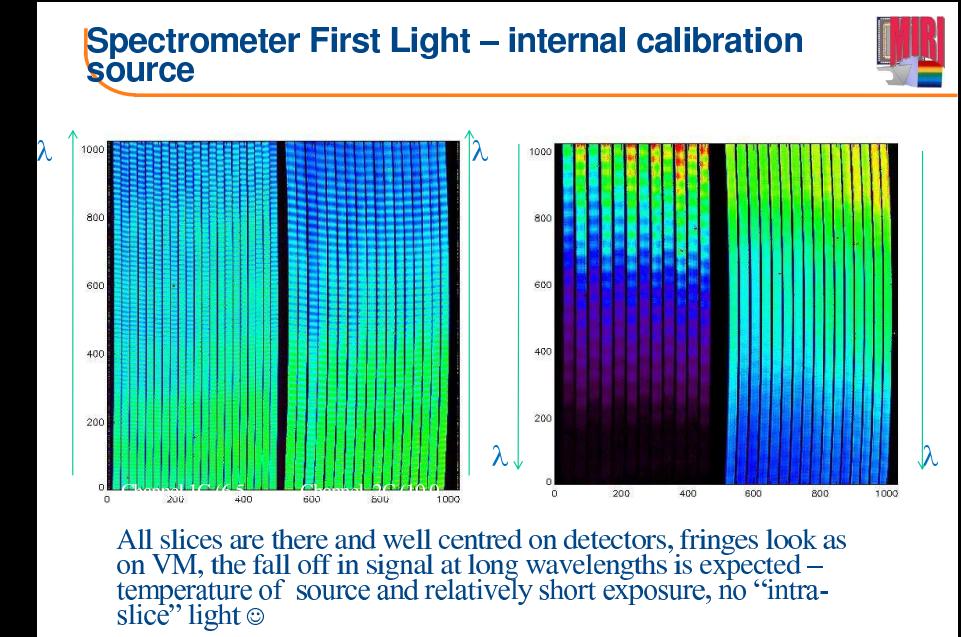


- JWST hardware made in 27 US States:  $\gtrsim 75\%$  of launch-mass finished.
- Ariane V Launch & NIRSpec provided by ESA; & MIRI by ESA & JPL.
- JWST Fine Guider Sensor + NIRISS provided by Canadian Space Agency.
- JWST NIRCam made by UofA and Lockheed.





# Flight MIRI



JWST's mid-infrared ( $5\text{--}29\mu\text{m}$ ) camera and spectrograph:

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

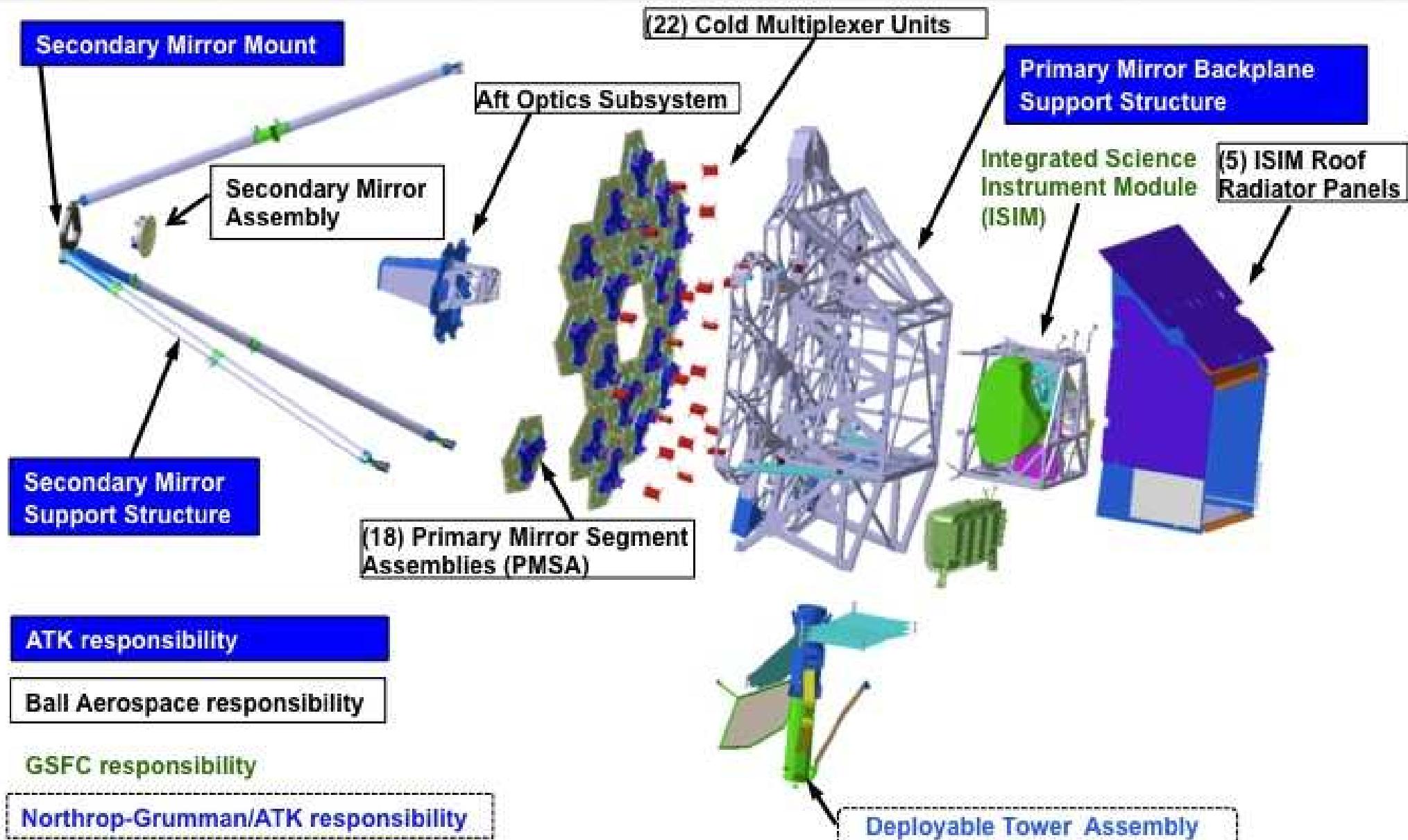
Final MIRI delivery to NASA/GSFC in early May 2012.



11-Apr-2012: Here is where your MIRI inside ISIM will be tested soon!

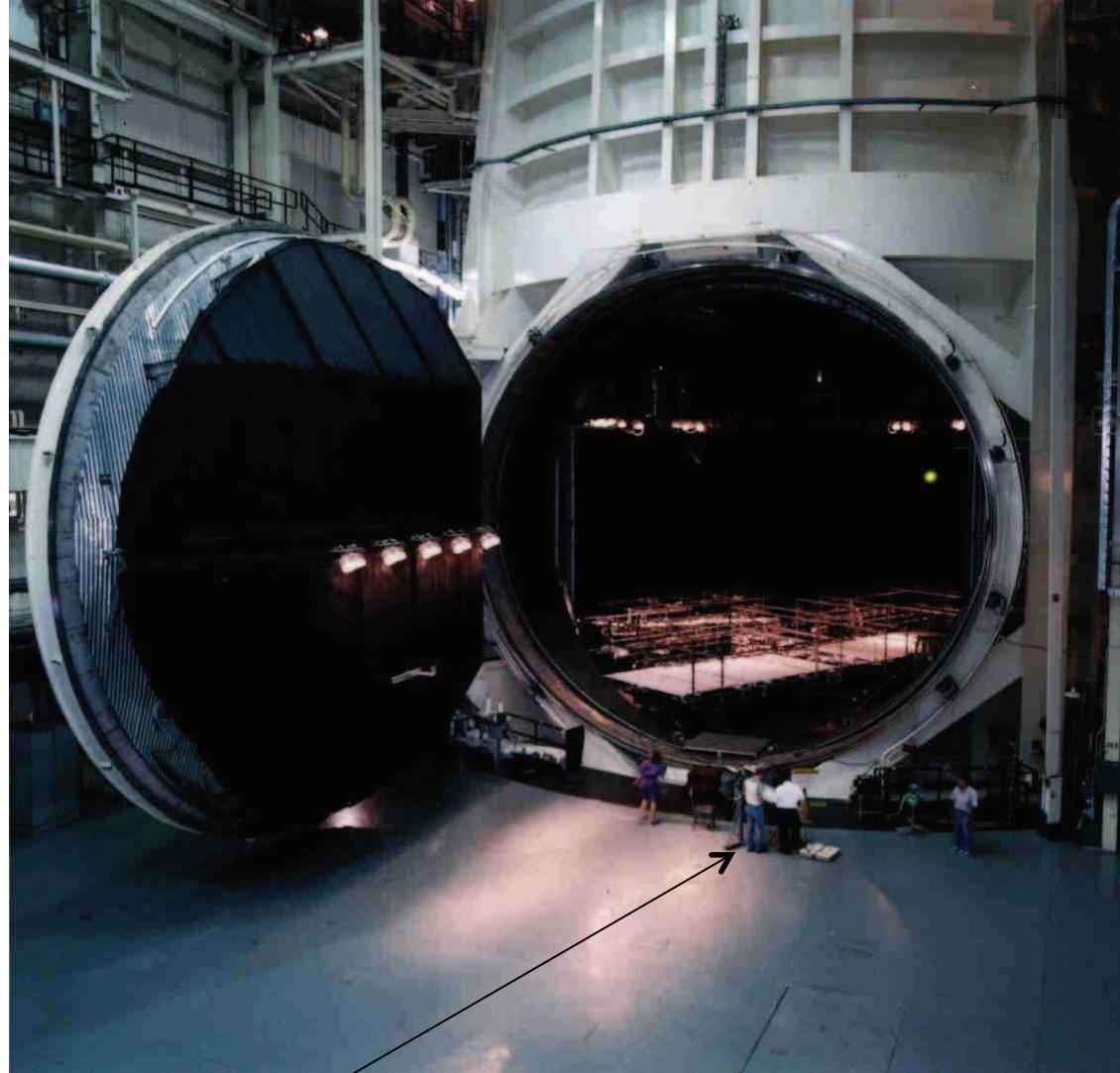


# TELESCOPE ARCHITECTURE



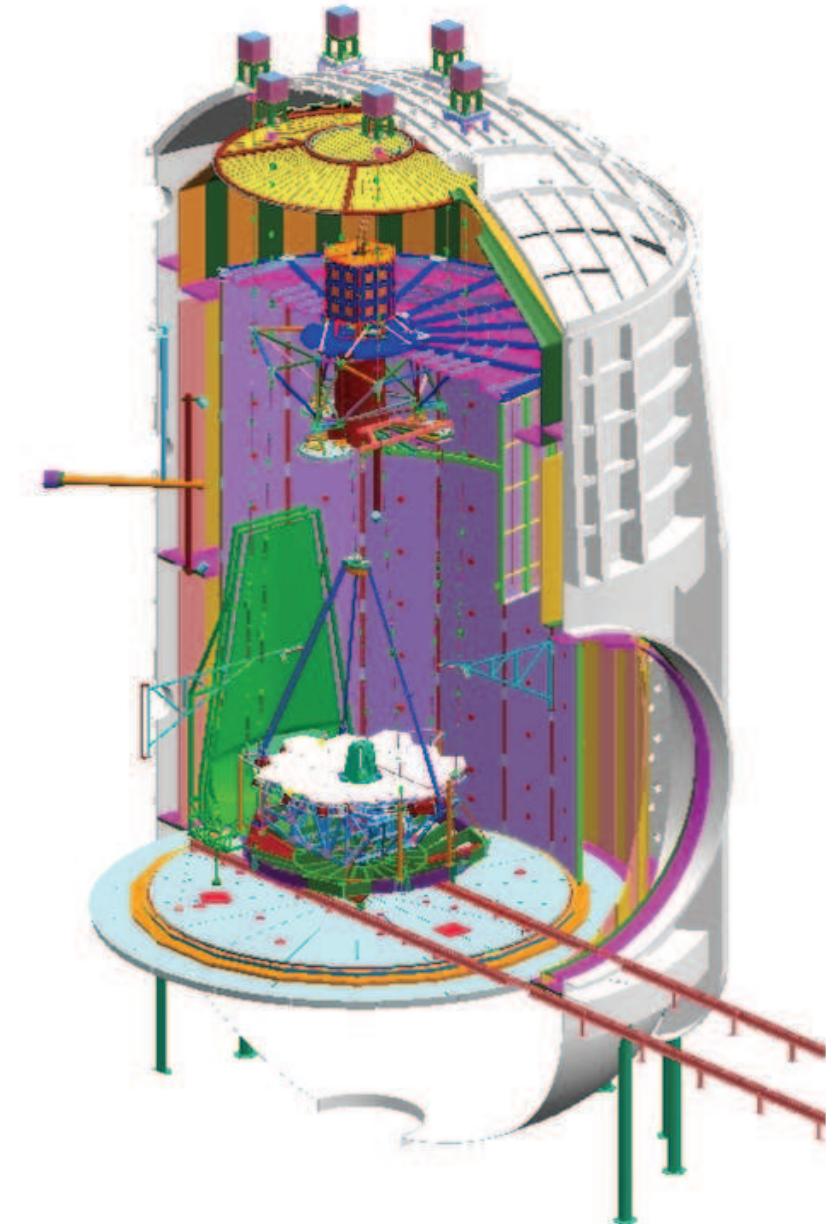


# OTE Testing – Chamber A at JSC

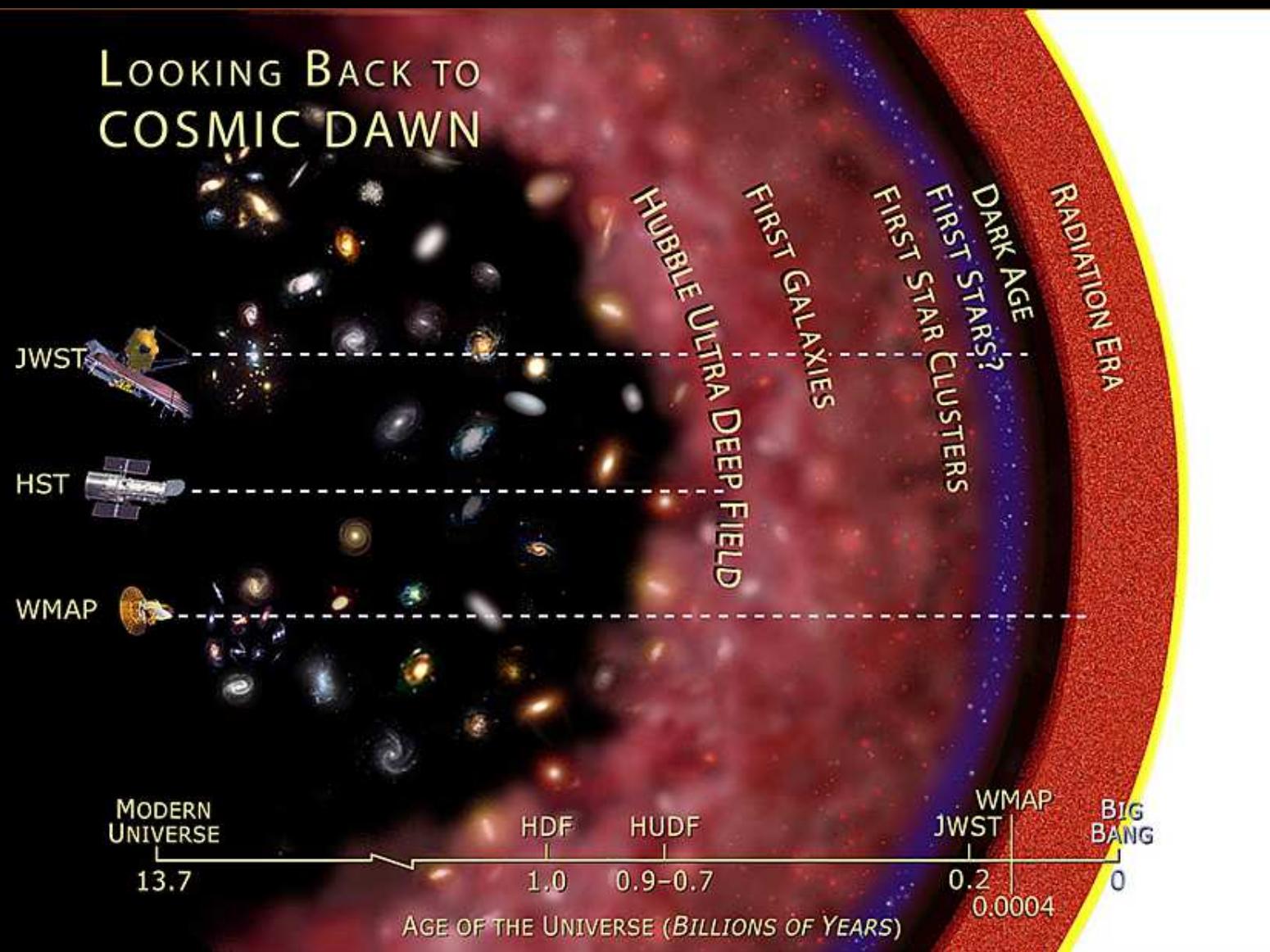


Notice people for scale

Will be the largest cryo vacuum test chamber in the world



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

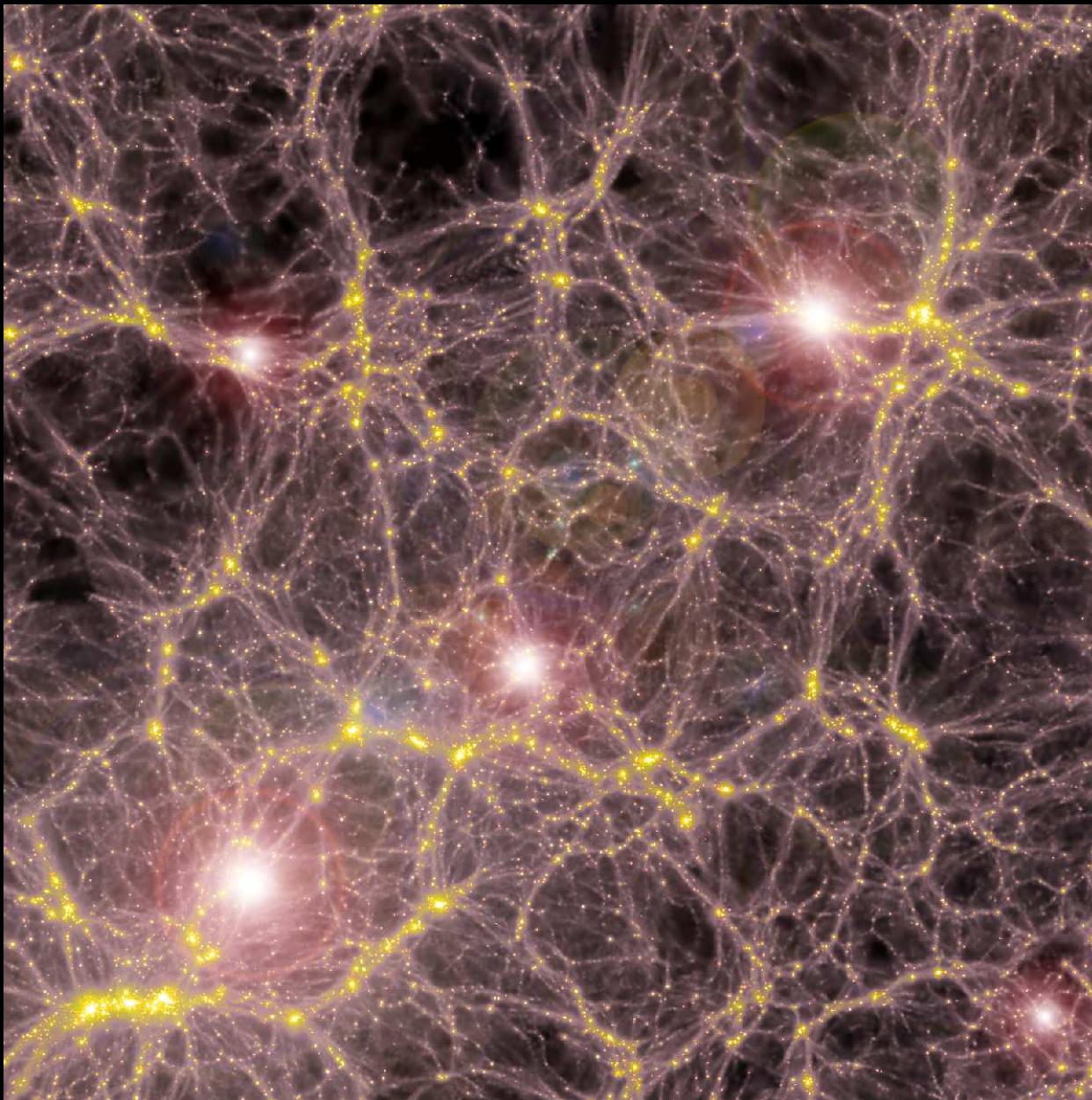


HST: Hubble sequence & galaxy evolution at  $z \lesssim 7-8$  (age  $\gtrsim 0.7$  Gyr).

JWST: First Light, Reionization, & Galaxy Assembly  $z \gtrsim 8-20$  (0.2-0.7 Gyr).

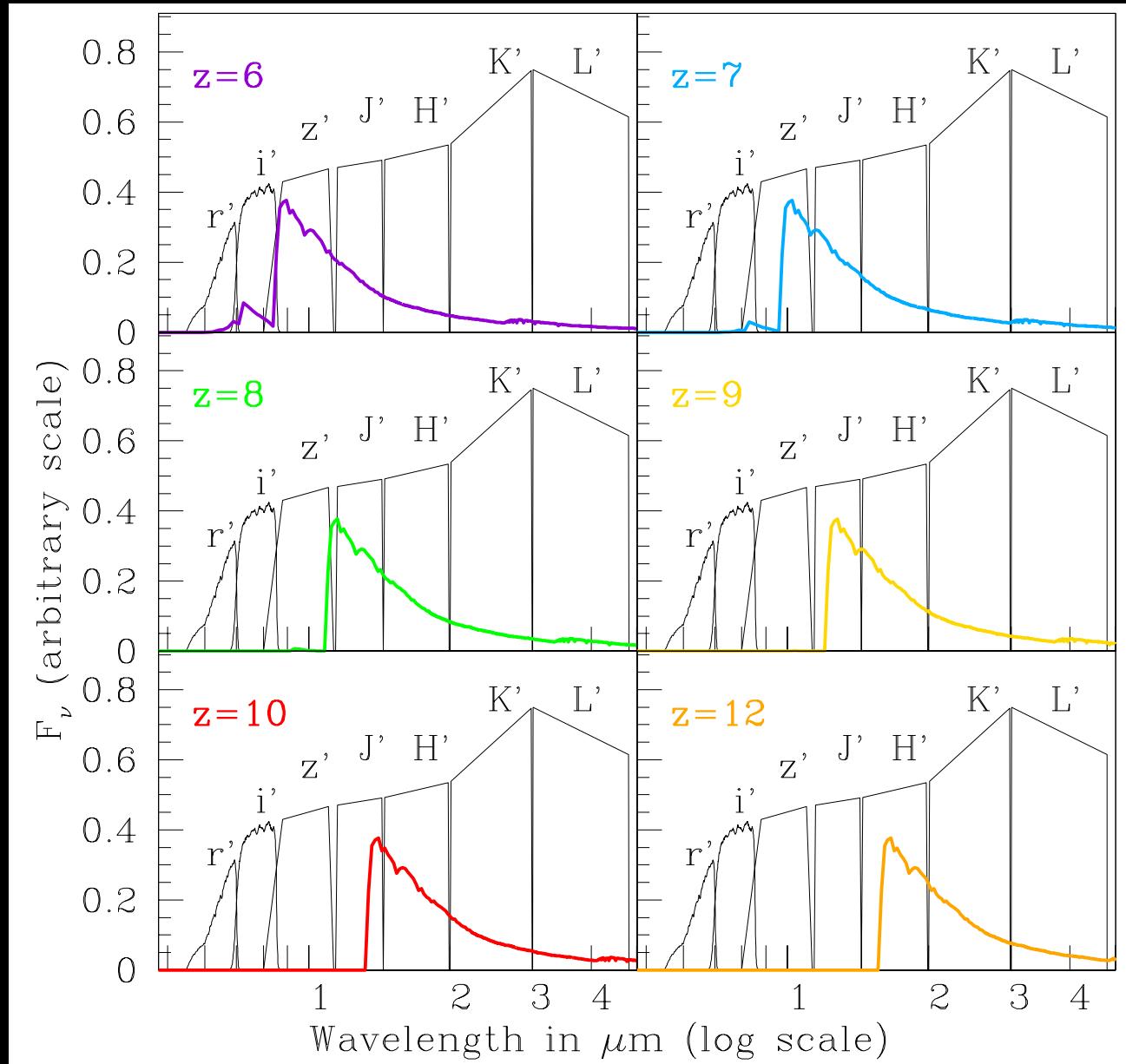
WMAP: Neutral Hydrogen first forms at  $z = 1090$  (cosmic age  $\approx 0.38$  Myr).

## (4a) How will JWST Observe First Light and Reionization?



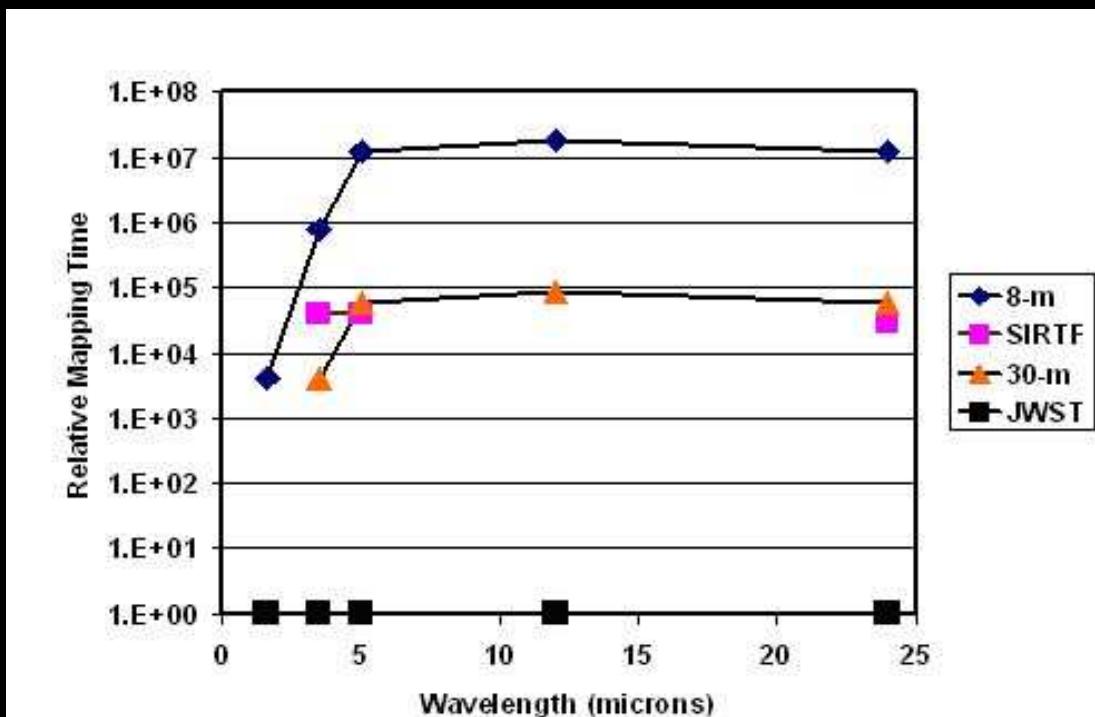
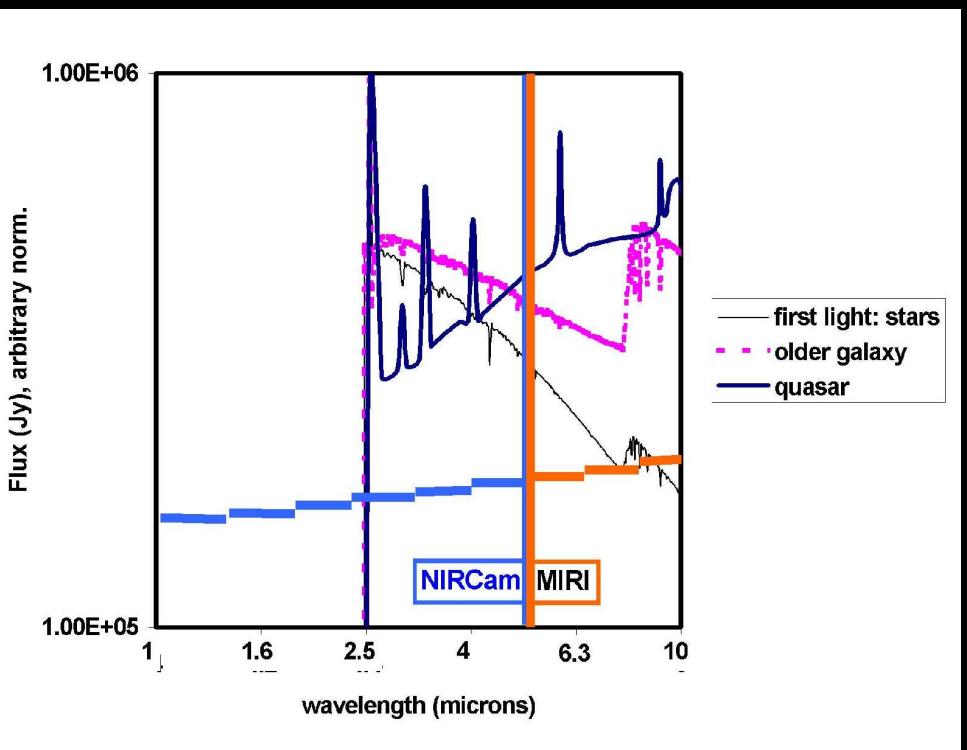
- Detailed hierarchical models (Dr. V. Bromm) show that formation of Pop III stars reionized universe for the first time at  $z \simeq 10-30$  (First Light, age  $\simeq 500-100$  Myr).
- This should be visible to JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at  $z \simeq 10-30$ .

## (4) How will JWST measure First Light & Reionization?



- Can't beat redshift: to see First Light, must observe near–mid IR.  
⇒ This is why JWST needs NIRCam at 0.8–5  $\mu\text{m}$  and MIRI at 5–28  $\mu\text{m}$ .

- (4) What sensitivity will JWST have?

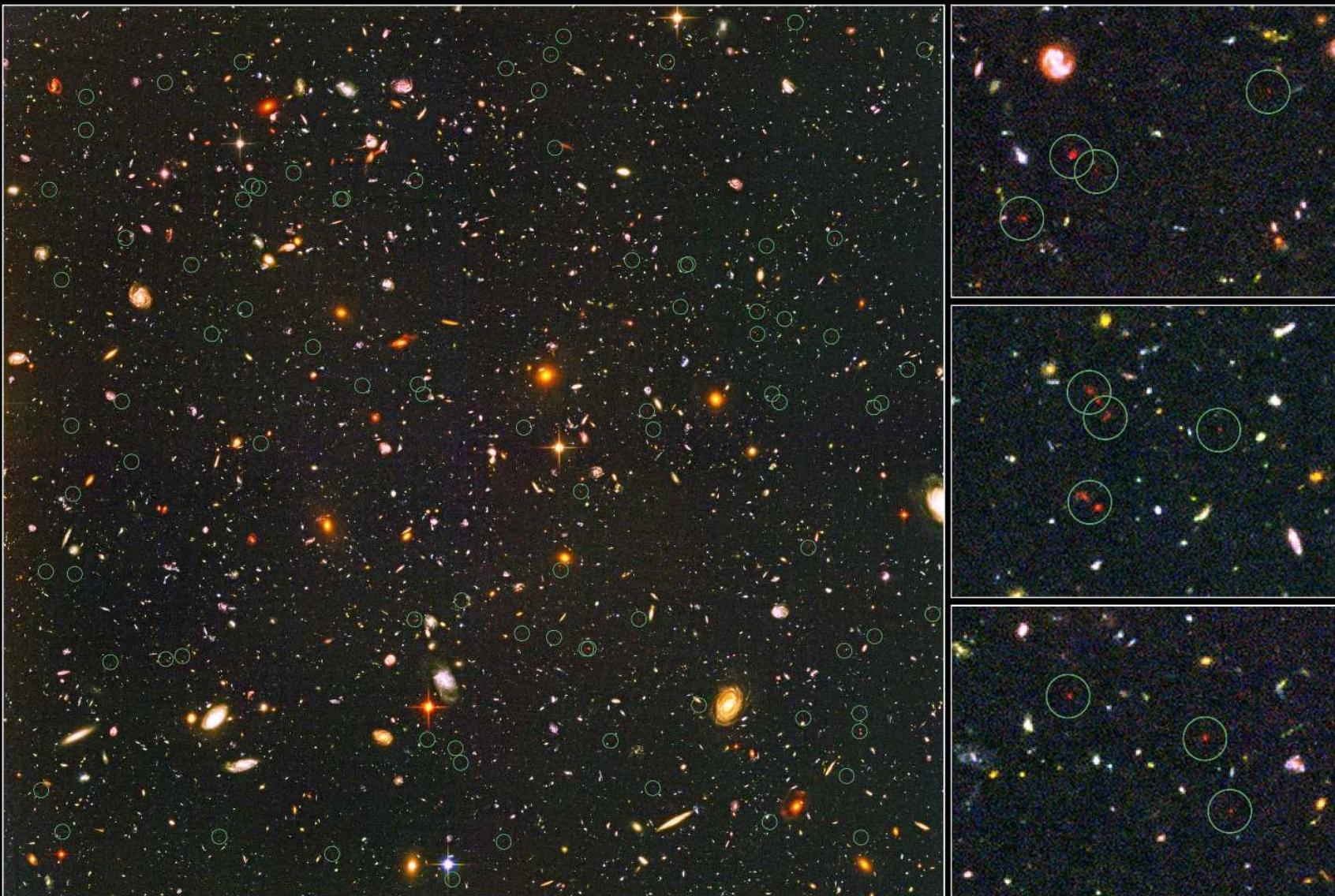


NIRCam and MIRI sensitivity complement each other, straddling  $\lambda \simeq 5 \mu\text{m}$ .

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.  $\lambda$  that Spitzer, a ground-based IR-optimized 8-m, and a 30-m telescope would need to match JWST.

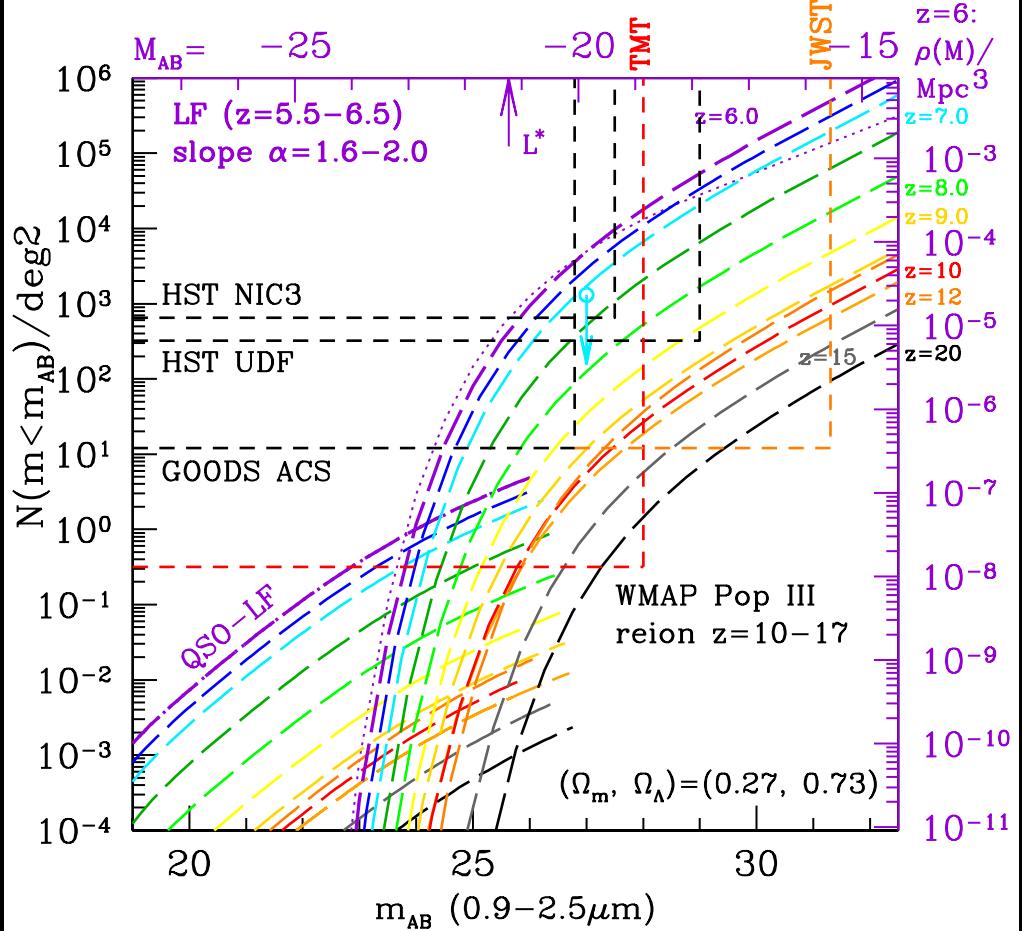
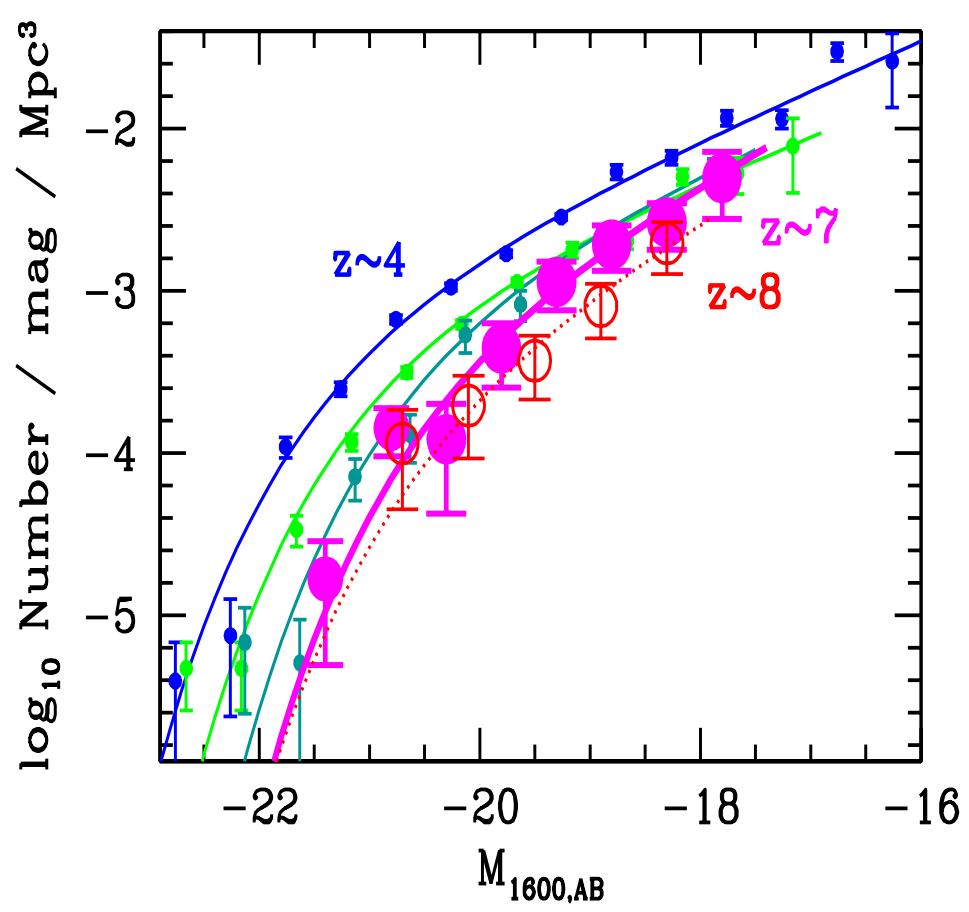


**Distant Galaxies in the Hubble Ultra Deep Field**  
Hubble Space Telescope • Advanced Camera for Surveys

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

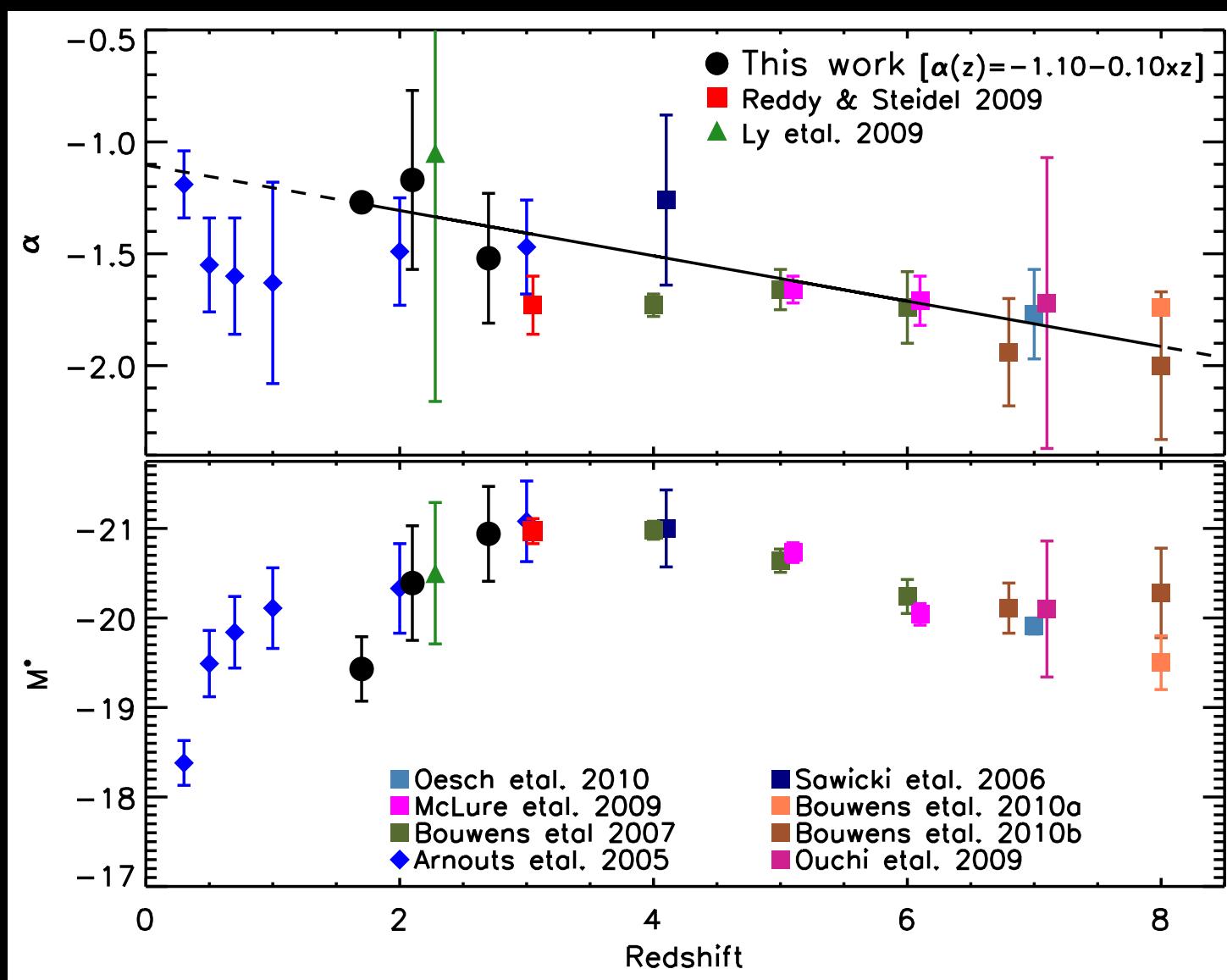
STScI-PRC04-28

Hubble UltraDeep Field: Dwarf galaxies at  $z \simeq 6$  (age  $\simeq 1$  Gyr; Yan & Windhorst 2004), many confirmed by spectra at  $z \simeq 6$  (Malhotra et al. 2005).



The “Cosmic Stock Market chart of galaxies: Very few big bright objects in the first Gyr, but lots of dwarf galaxies at  $z \gtrsim 6$  (age  $\lesssim 1$  Gyr).

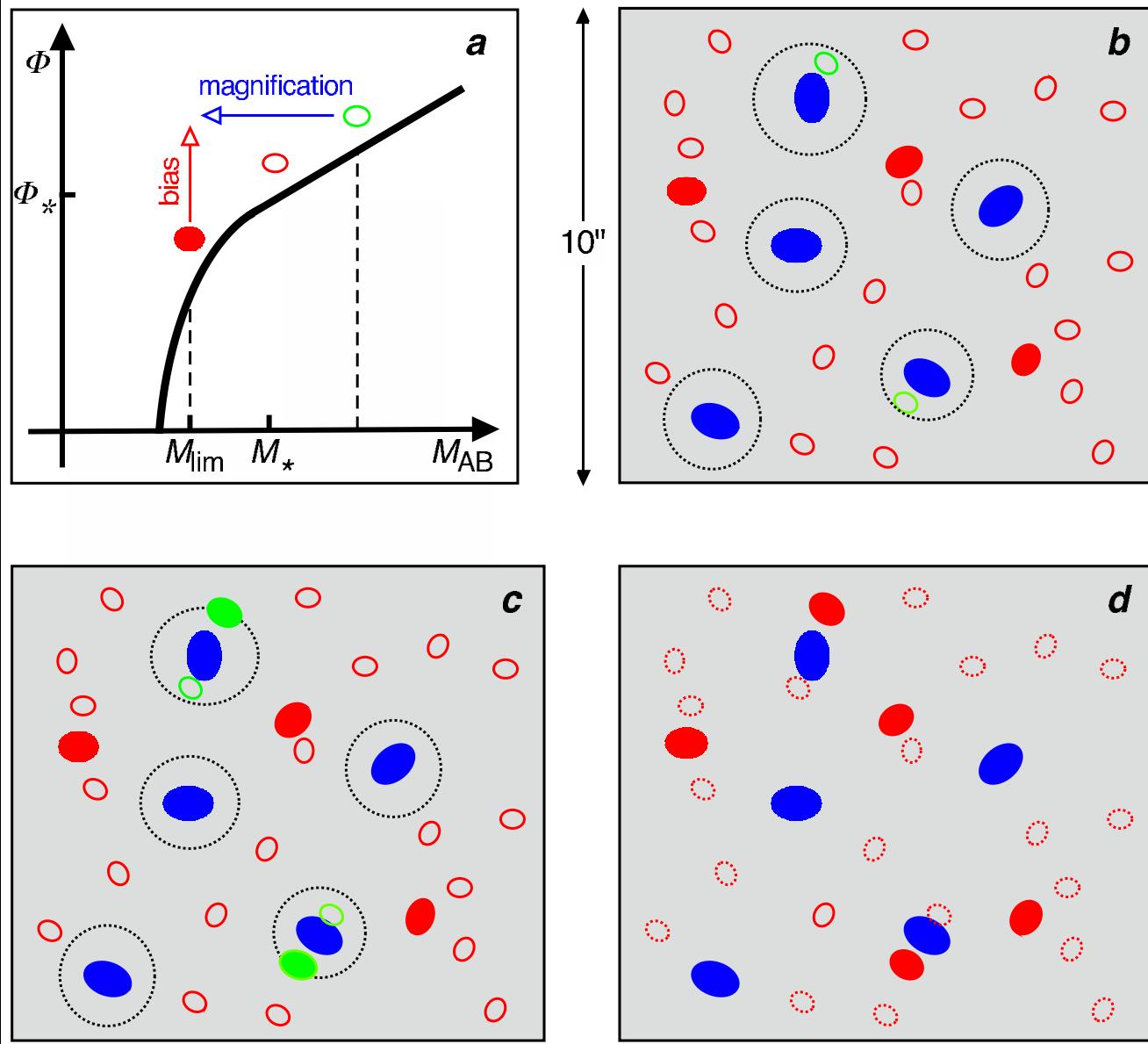
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects.
- JWST Coronagraphs can also trace Super-Massive Black Holes as faint Quasars in young galaxies: JWST needs  $2.0\mu\text{m}$  diffraction limit for this!



Measured faint-end LF slope evolution (top) and characteristic luminosity evolution (bottom) from Hathi<sup>+</sup> 2010, ApJ, 720, 1708 (arXiv:1004.5141v2).

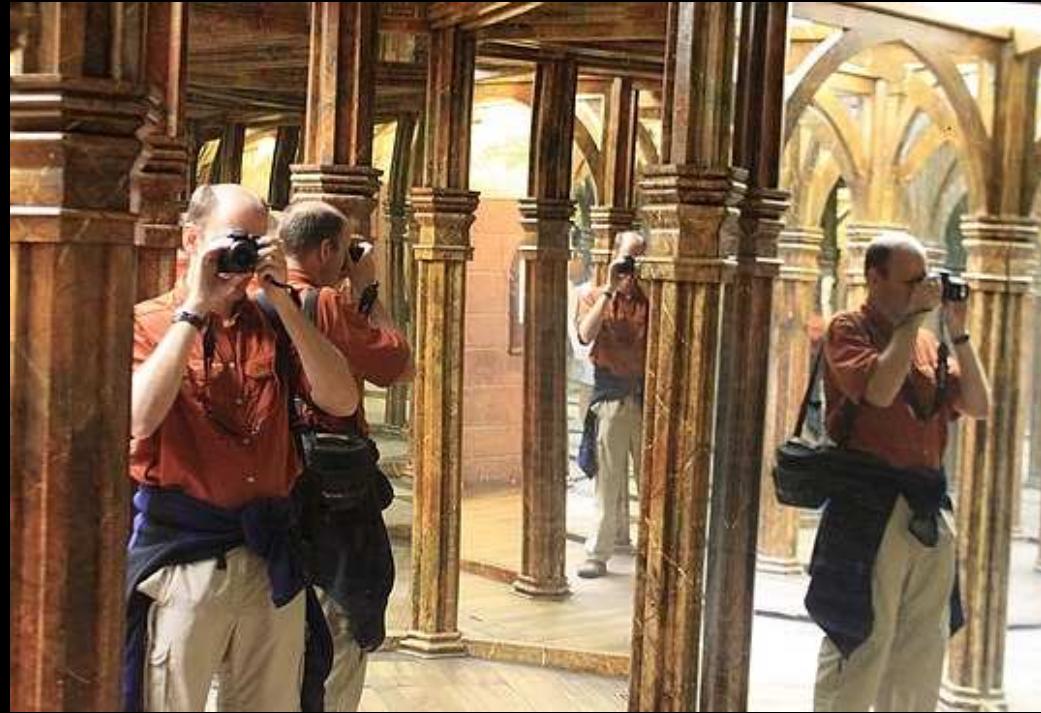
- In the JWST regime at  $z \gtrsim 8$ , expect faint-end LF slope  $\alpha \simeq 2.0$ !
- In the JWST regime at  $z \gtrsim 8$ , expect characteristic luminosity  $M^* \gtrsim -19$ !





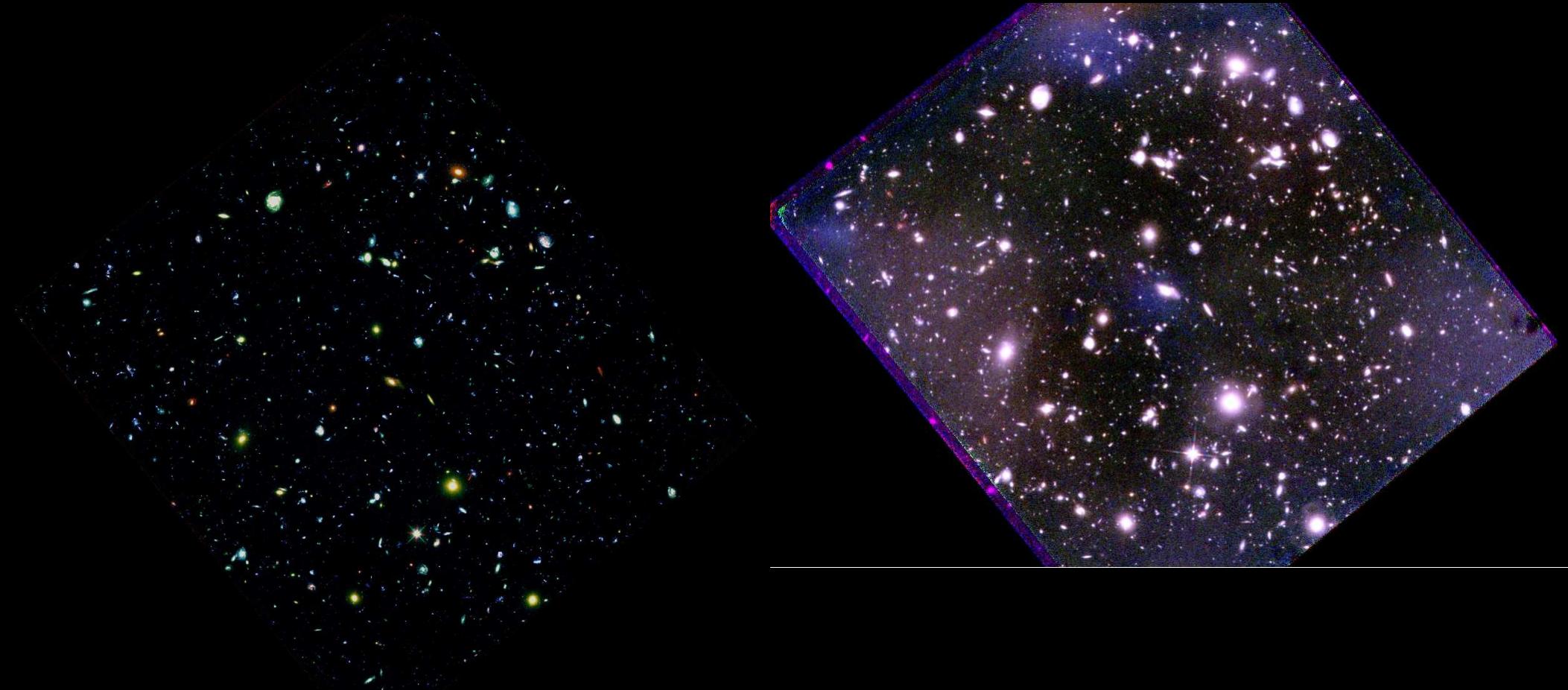
Hard to see the forest for the trees in the first 0.5 Gyrs?:

- Foreground galaxies ( $z \simeq 1-2$  or age  $\simeq 3-6$  Gyr) may gravitationally lens or amplify galaxies at  $z \gtrsim 8-10$  (cosmic age  $\lesssim 0.5$  Gyr; Wyithe et al. 2011).
- This could change the landscape for JWST observing strategies.



Two fundamental limitations determine ultimate JWST image depth:

- (1) Cannot-see-the-forest-for-the-trees effect: Background objects blend into foreground neighbors  $\Rightarrow$  Need multi- $\lambda$  deblending algorithms!
  - (2) House-of-mirrors effect: (Many?) First Light objects can be gravitationally lensed by foreground galaxies  $\Rightarrow$  Must model/correct for this!
- Proper JWST 2.0 $\mu\text{m}$  PSF and straylight specs essential to handle this!



(Left) 100-hr HST/WFC3 IR-mosaic in HUDF at  $1\text{--}1.6\mu\text{m}$  (YJH filters; Bouwens et al 2010; Yan et al. 2010).

(Right) Same WFC3 IR-mosaic, but stretched to  $\lesssim 10^{-3}$  of Zodical 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 very good baffling and rogue path mitigation to do ultradeep JWST fields (JUDF's) to  $10^{-4}$  of sky.

## (5) Conclusions

(1) HST set stage to measure galaxy assembly in the last 12.7-13.0 Gyrs.

- Today's Hubble sequence formed 7–10 Gyrs ago.

(2) JWST passed Preliminary & Critical Design Reviews in 2008 & 2010.

Replan in 2011. No technical showstoppers: your MIRI work is paying off!

- More than 75% of JWST H/W built or in fab, & meets/exceeds specs.

(3) JWST is designed to map the epochs of First Light, Reionization, and Galaxy Assembly & SMBH-growth in detail. JWST will determine:

- Formation and evolution of the first star-clusters after 0.2 Gyr.
- How dwarf galaxies formed and reionized the Universe after 1 Gyr.
- How to find water and CO<sub>2</sub> in transiting Earth-like exoplanets.

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

- IR sequel to HST after 2018: Training the next generation researchers.

# SPARE CHARTS

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- References and other sources of material shown:

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

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

<http://www.asu.edu/clas/hst/www/jwst/clickonHUDF/> [Clickable HUDF map]

<http://www.jwst.nasa.gov/> & <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/fgs>

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, 1965

Windhorst, R., et al., 2011, *ApJS*, 193, 27 ([astro-ph/1005.2776](#))

## (4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1-15$

NGC 3310



ESO0418-008



UGC06471-2



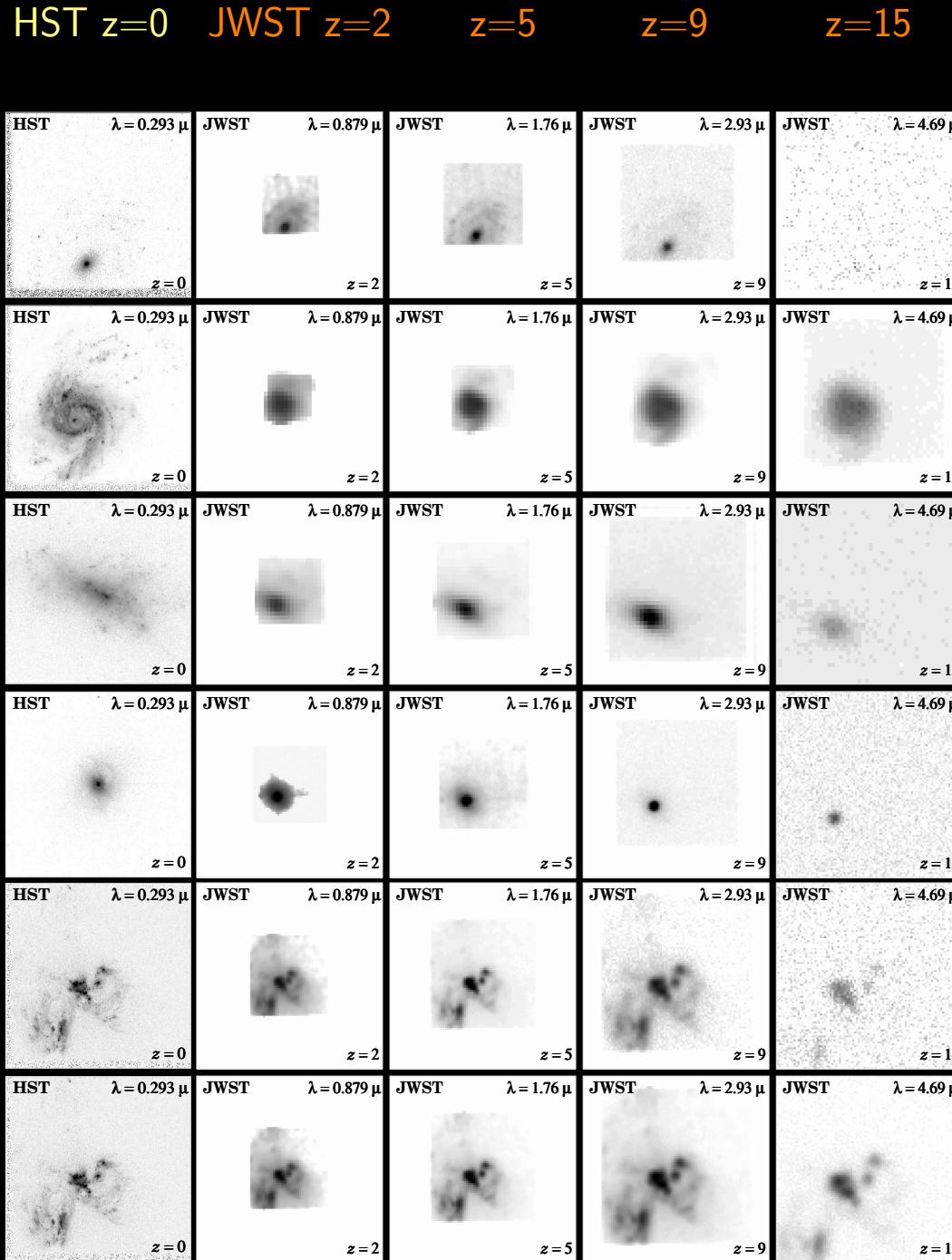
### Ultraviolet Galaxies

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 significant dust imprinted (Mager-Taylor et al. 2005).
- High-resolution HST ultraviolet images are benchmarks for comparison with very high redshift galaxies seen by JWST.

## (4b) Predicted Galaxy Appearance for JWST at redshifts $z \simeq 1$ –15



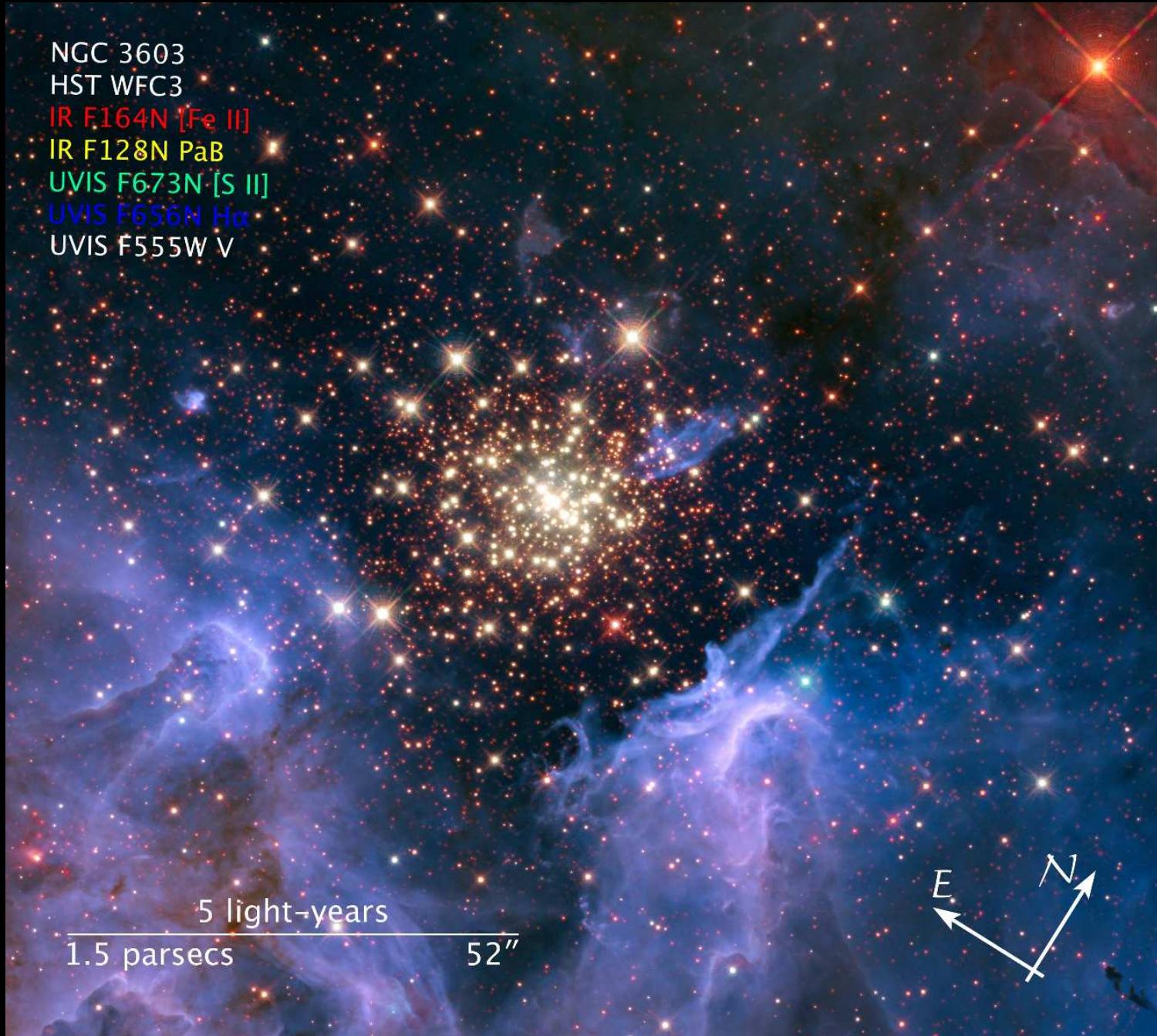
With Hubble UV-optical images as benchmarks, JWST can measure the evolution of galaxy structure & physical properties over a wide range of cosmic time:

- (1) Most spiral disks will dim away at high redshift, but most formed at  $z \lesssim 1$ –2.

Visible to JWST at very high  $z$  are:

- (2) Compact star-forming objects (dwarf galaxies).
- (3) Point sources (QSOs).
- (4) Compact mergers & train-wrecks.

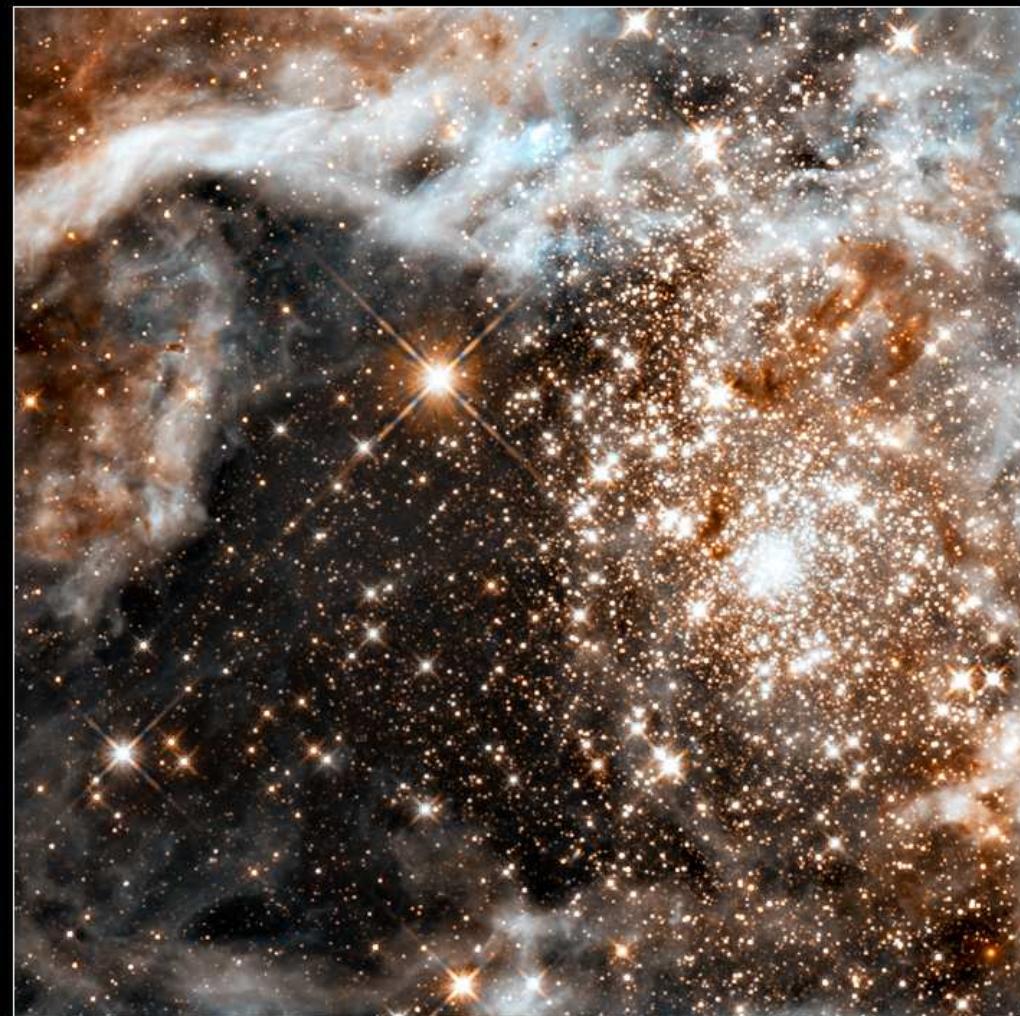
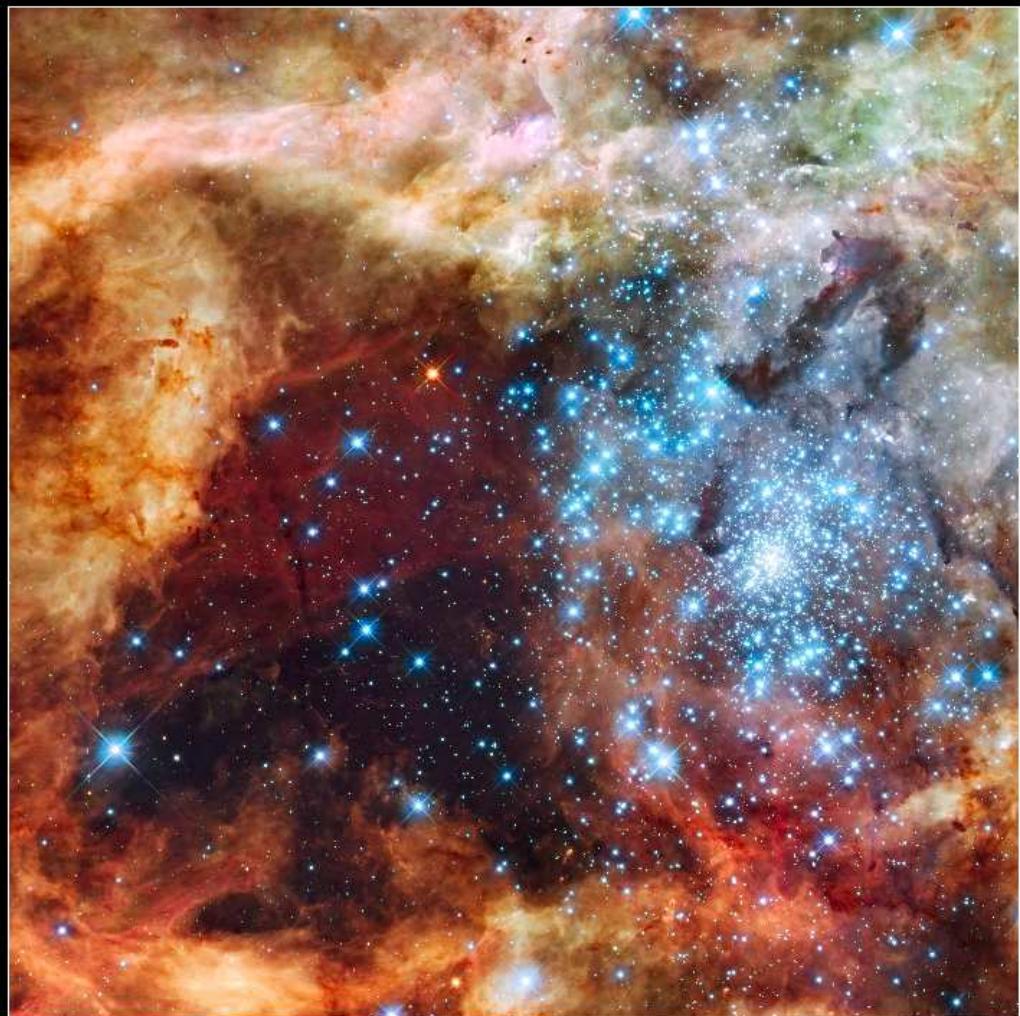
## (6) How can JWST measure Earth-like exoplanets?



NGC 3603: Young star-cluster triggering star-birth in “Pillars of Creation”

Visible

Infrared



## 30 Doradus Nebula and Star Cluster

*Hubble Space Telescope • WFC3/UVIS/IR*

NASA, ESA, F. Paresce (INAF-IASF, Italy), and the WFC3 Science Oversight Committee

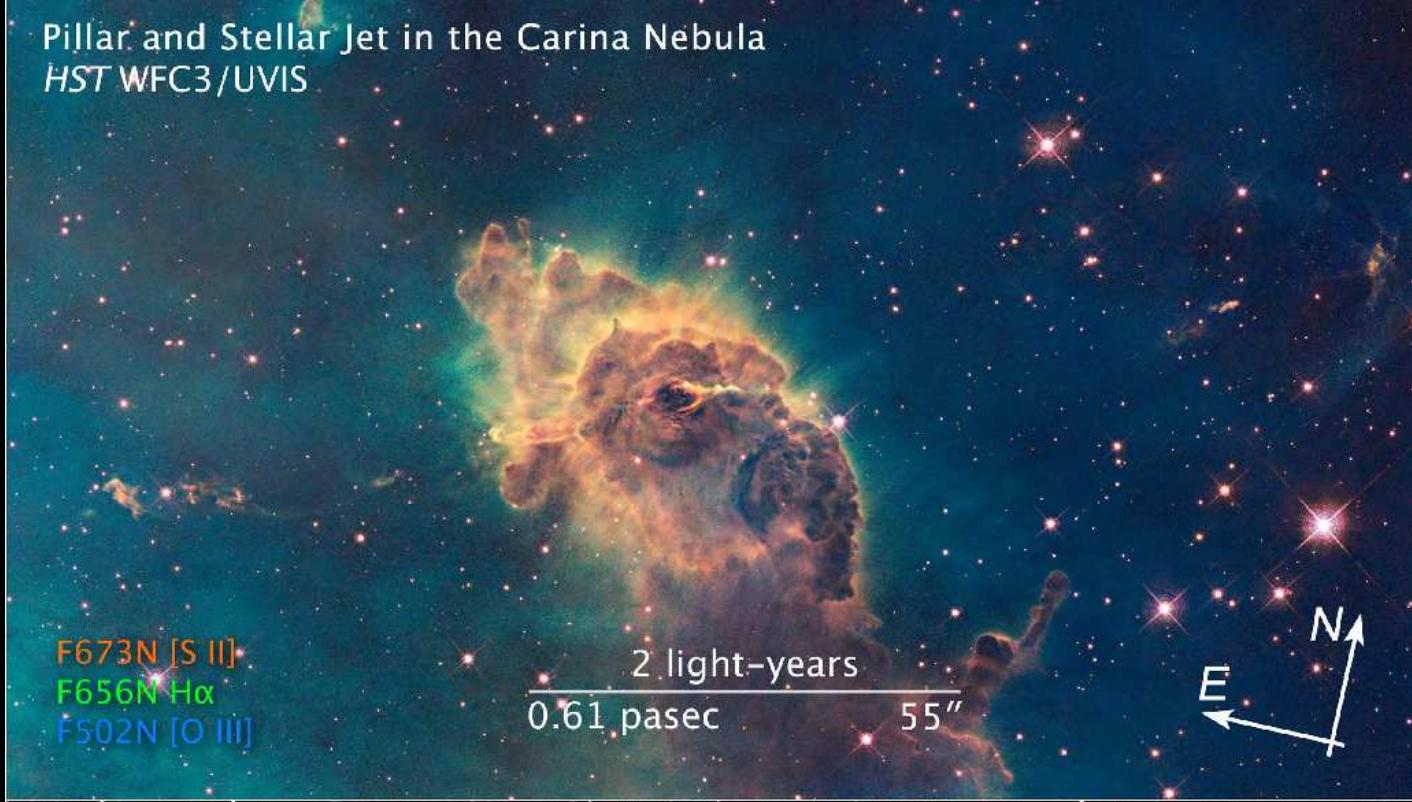
STScI-PRC09-32b

30 Doradus: Giant young star-cluster in Large Magellanic Cloud (150,000 ly), triggering birth of Sun-like stars (and surrounding debris disks).

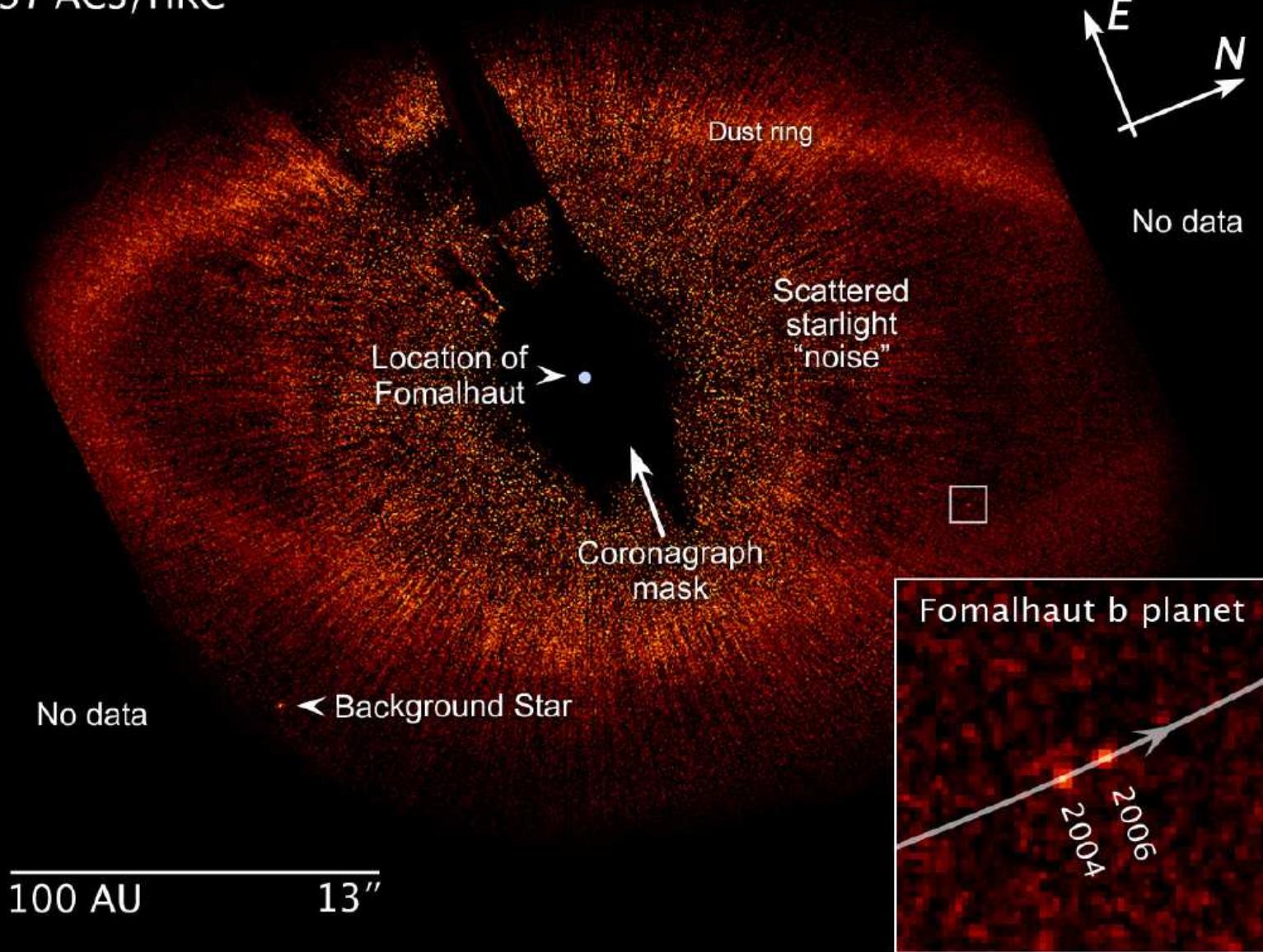




Pillar and Stellar Jet in the Carina Nebula  
HST WFC3/UVIS

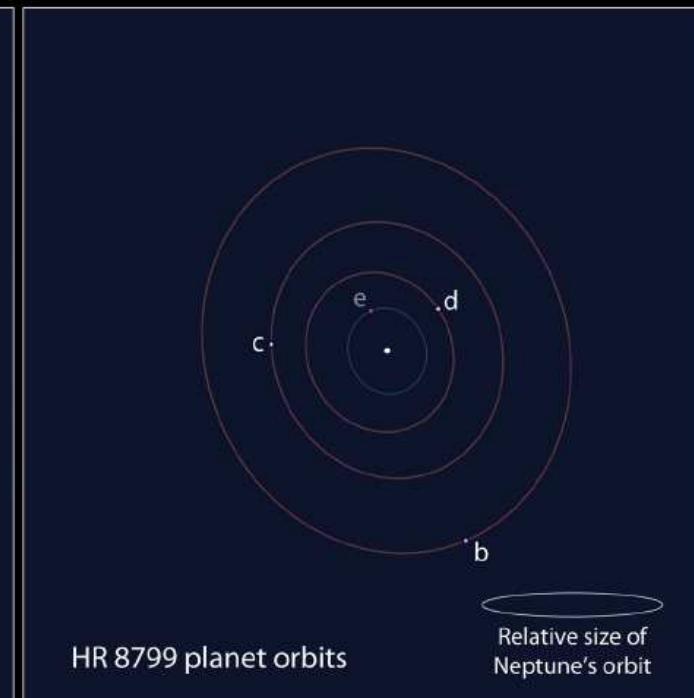
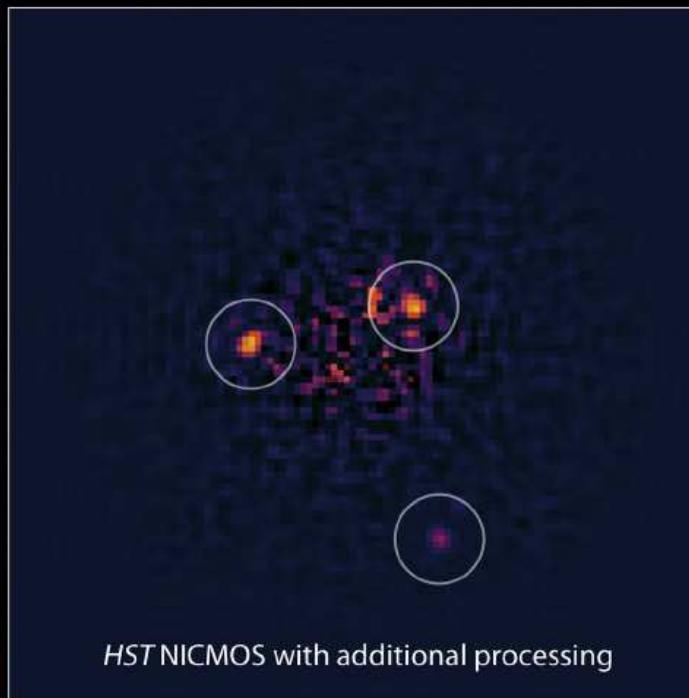
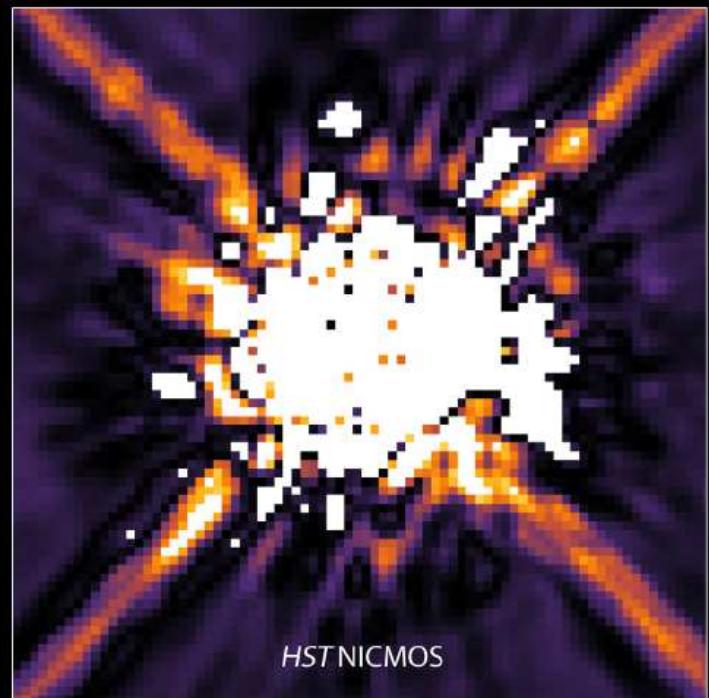


Fomalhaut  
HST ACS/HRC



HST/ACS Coronagraph imaging of planetary debris disk around Fomalhaut:  
First direct imaging of a moving planet forming around a nearby star!  
JWST can find such planets much closer in for much farther stars.

## Exoplanet HR 8799 System



NASA, ESA, and R. Soummer (STScI)

STScI-PRC11-29

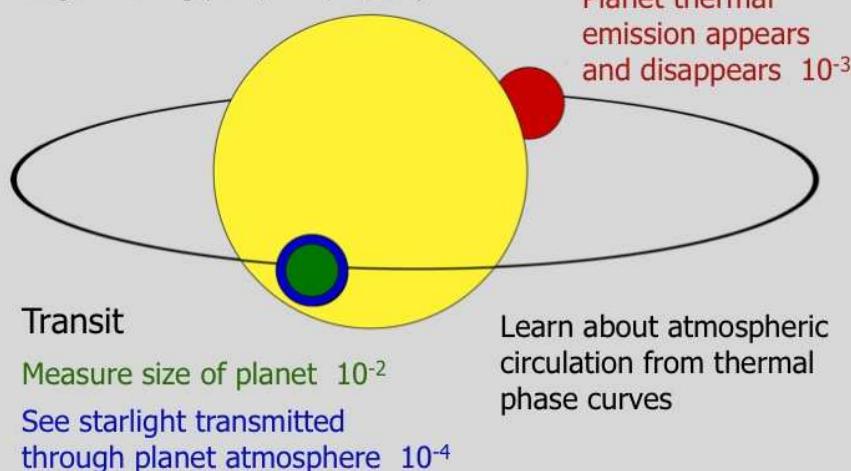
HST/NICMOS imaging of planetary system around the (carefully subtracted) star HR 8799: Direct imaging of planets around a nearby star!

Press release: <http://hubblesite.org/newscenter/archive/releases/2011/29/>

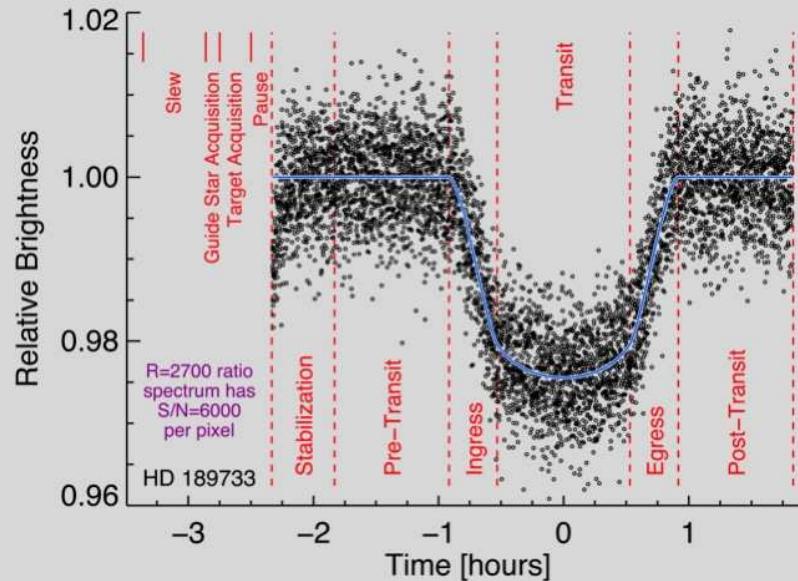
JWST can find such planets much closer in for much farther-away stars!

## Schematic of Transit and Eclipse Science

Seager & Deming (2010, ARAA, 48, 631)



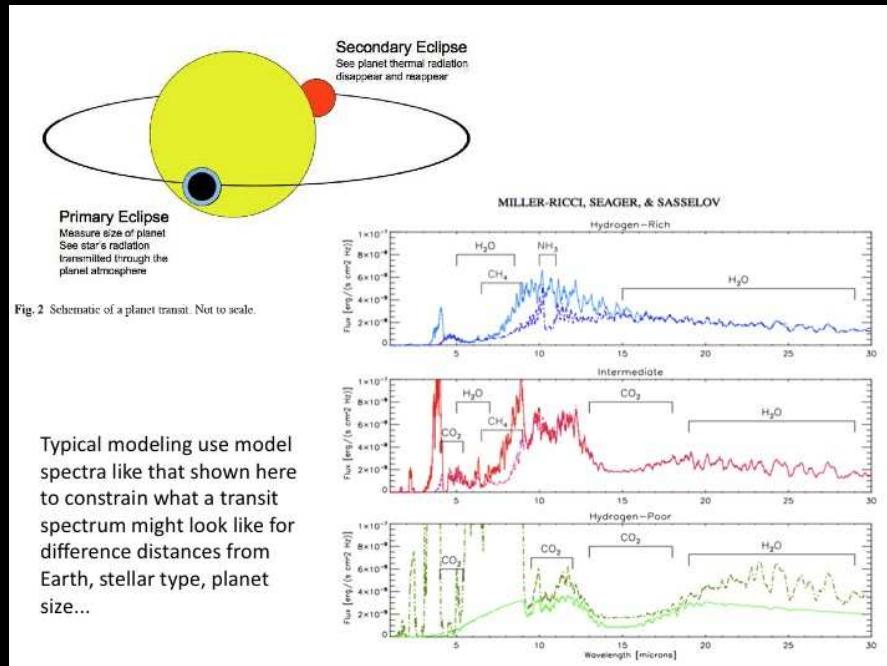
## Timeline of a Transit Observation



6

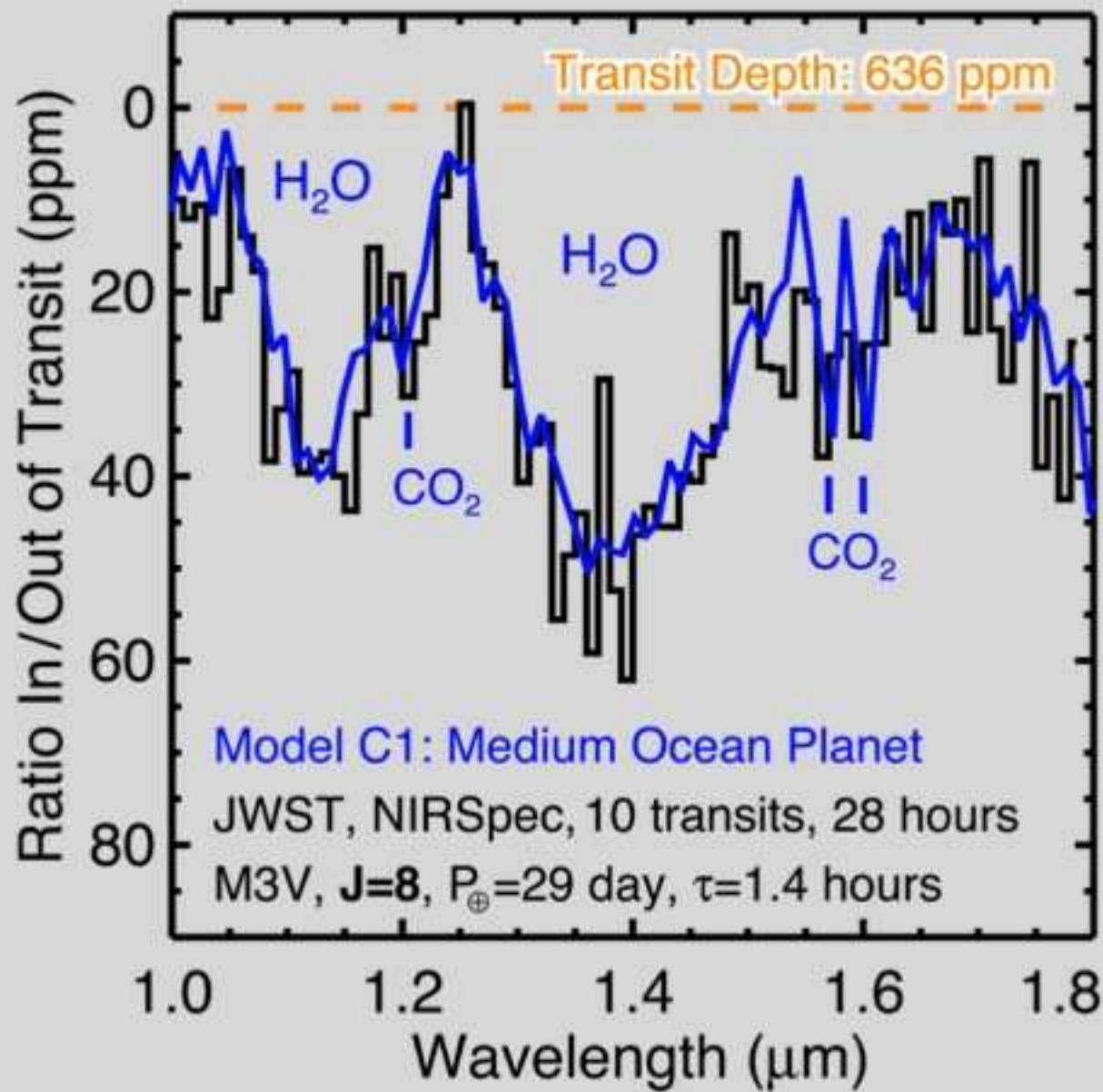
13

JWST can do very precise photometry of transiting Earth-like exoplanets.



JWST IR spectra can find water and  $\text{CO}_2$  in (super-)Earth-like exoplanets.

# Transit Spectrum of Habitable “Ocean Planet”



17

JWST IR spectra can find water and CO<sub>2</sub> in transiting Earth-like exoplanets.

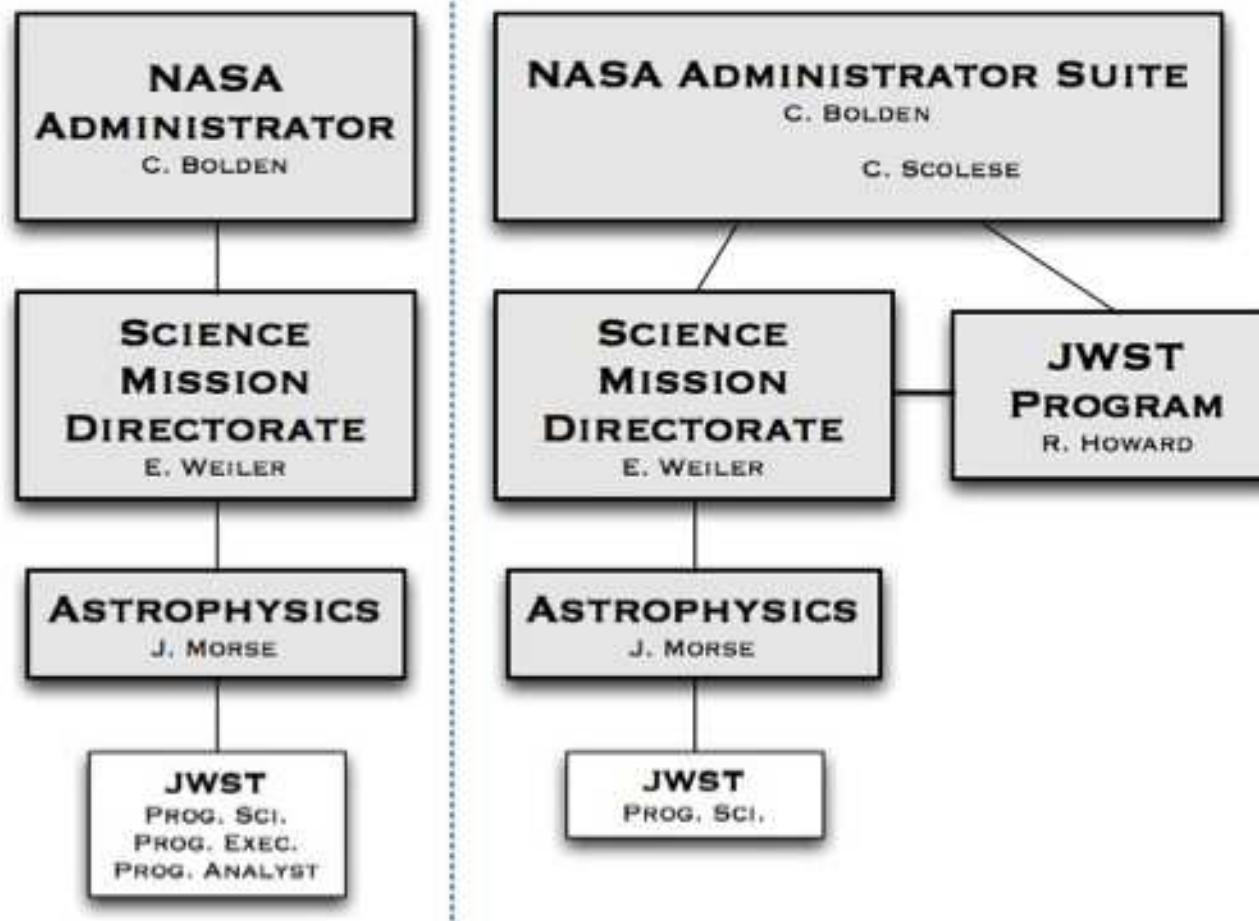
(7) Update of JWST programmaticas as of 2011/2012:



# JWST moved out of Astrophysics Division

WAS

IS

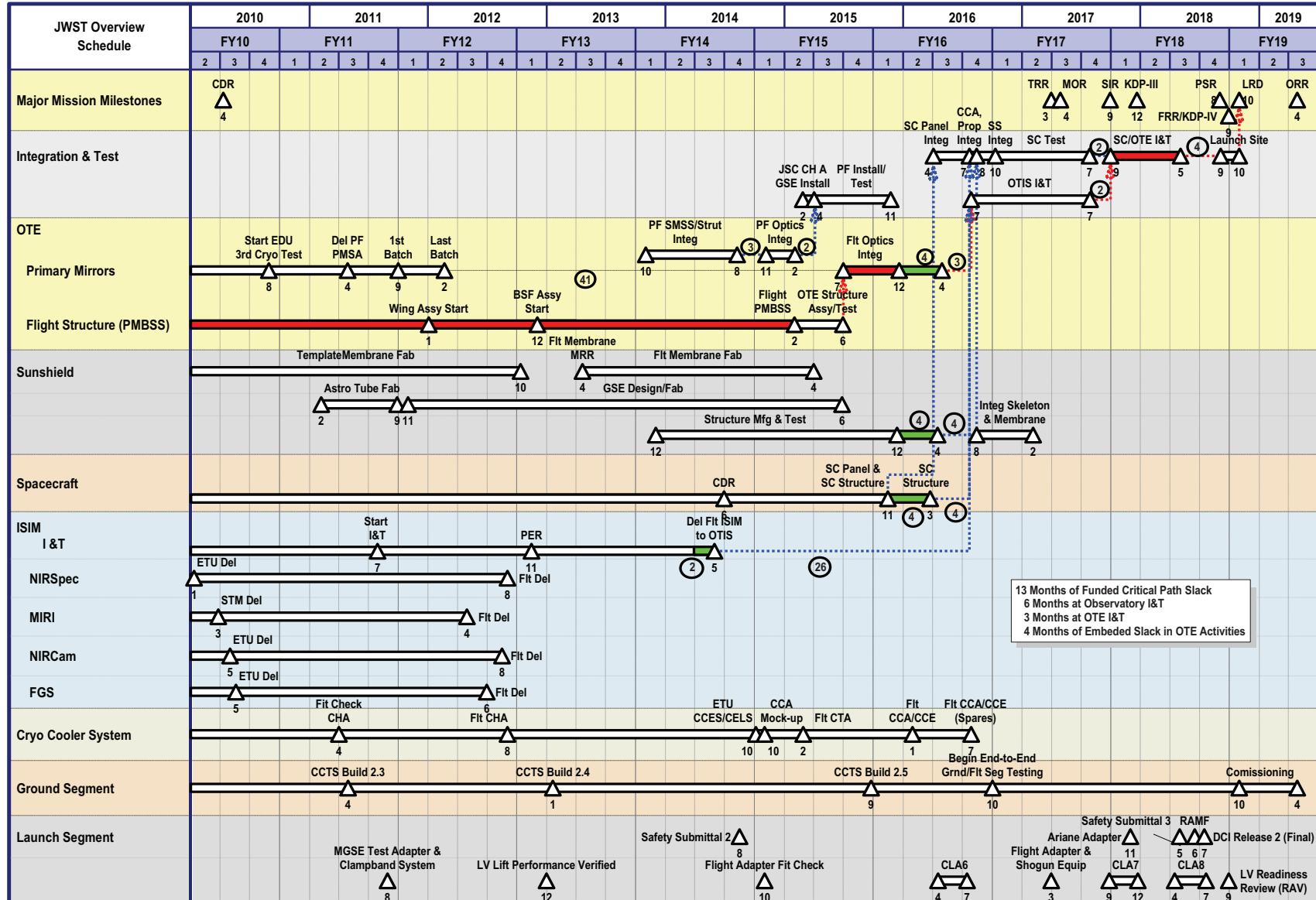


NASA HQ Reorg: JWST budget no longer comes directly from SMD/Ap.

# (7) Update of JWST programmaticas as of 2011/2012:



## JWST Master Schedule

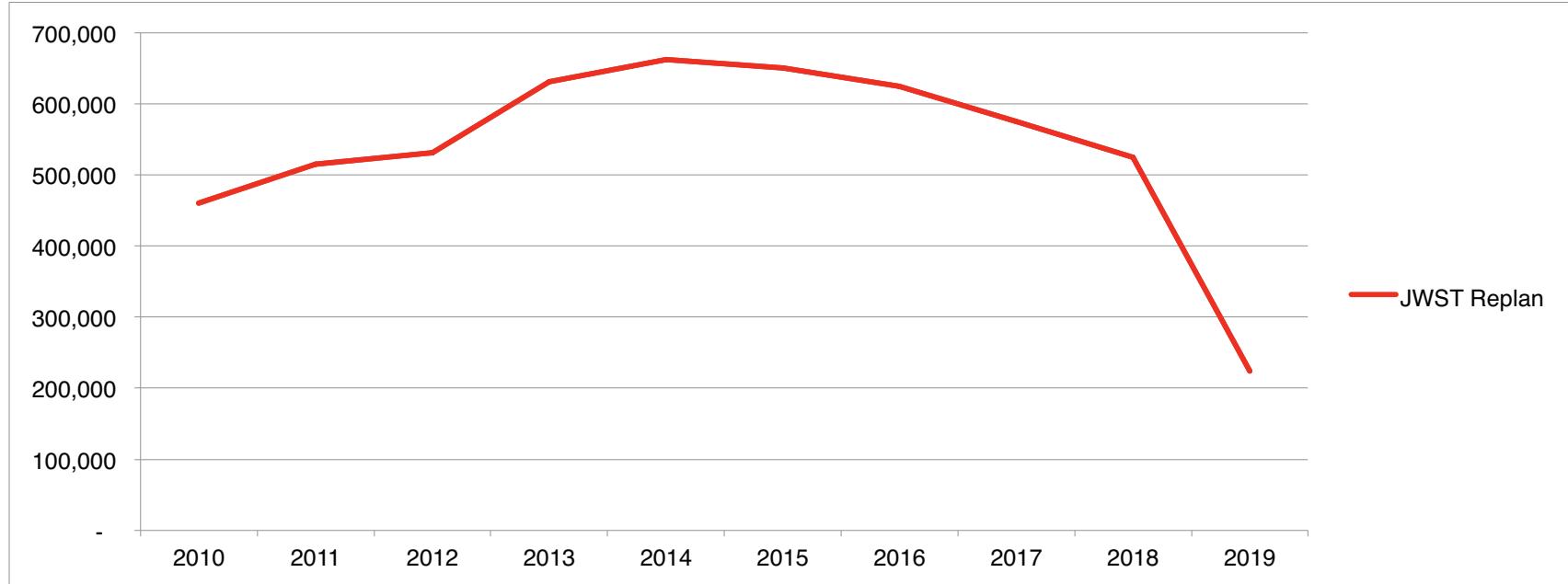


JWST schedule replan for FY12–18 as of 2011 (W. Ochs; NASA GSFC).

## (7) Update of JWST programmaticas as of 2011/2012:

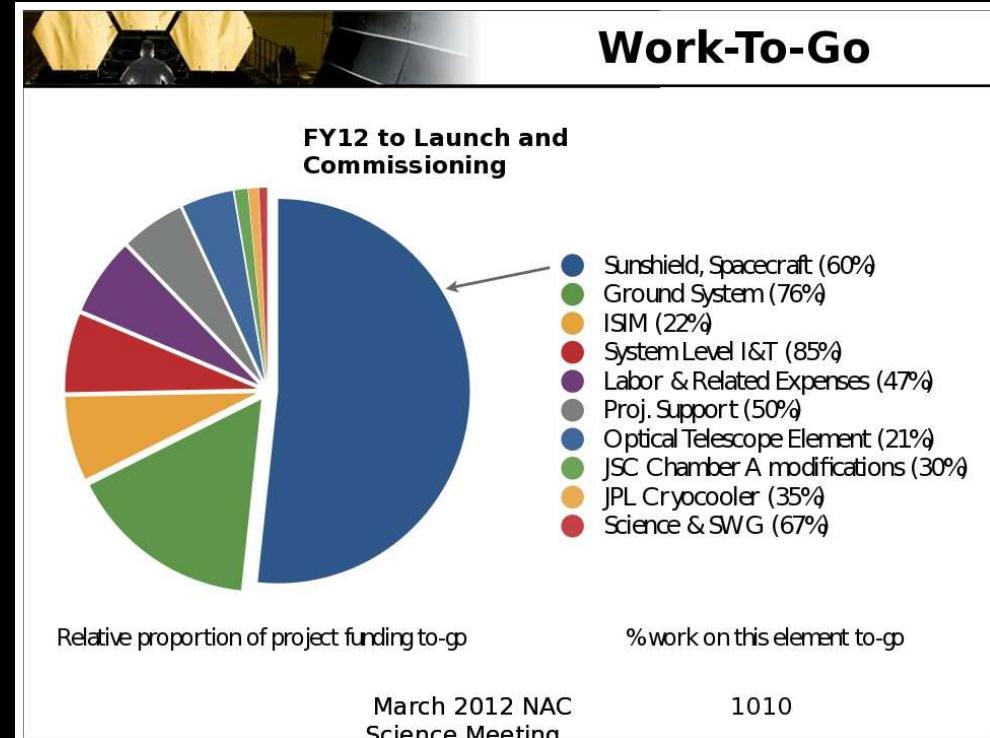
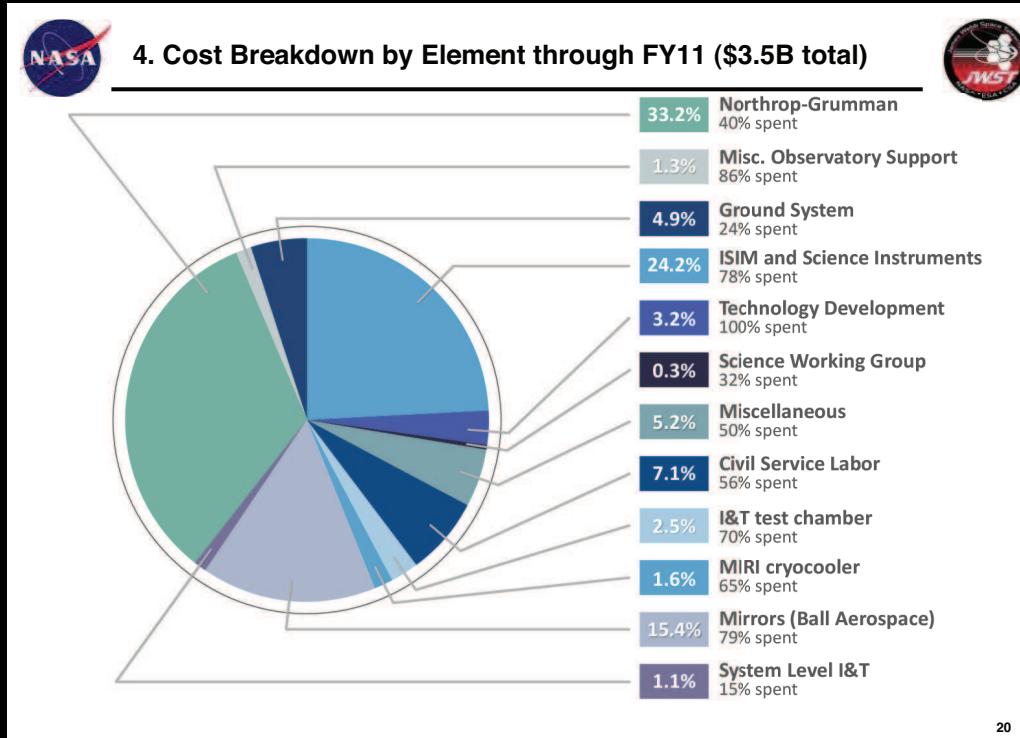


### JWST Budget Profile (July 2011)



- **The replan addresses the findings of the SRB and the ICRP report**
  - Avoids making the mistakes identified by ICRP by providing adequate funding in early years
  - Provides a profile that can retire risk earlier by accelerating critical activities

## (7) Update of JWST programmaticas as of 2011/2012:



Outcome of 2010 TAT & ICRP reviews and 2011 Project replan (JCL):

(Left) Cost breakdown through FY $\leq$ 11 on each element (as fraction of total Project cost + part thereof spent as of FY11);

(Right) Work-to-go: FY12–FY19 work replanned for each element (as fraction of total cost of each element over length of Project).

- After its 2011 replan, JWST now has a viable path to its 2018 launch.

# 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)



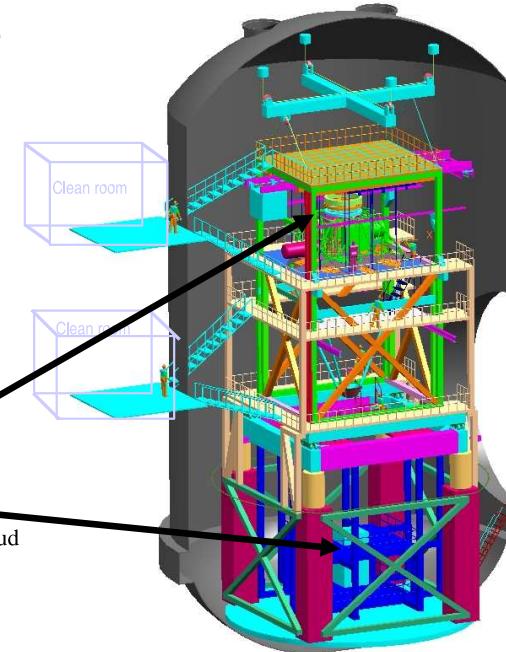
Most recent Tower Design shows an Inner Optical Tower supported by a Outer structure with Vibration Isolation at the midplane. Everything shown is in the 20K region (helium connections, etc. not shown) except clean room and lift fixture.

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)

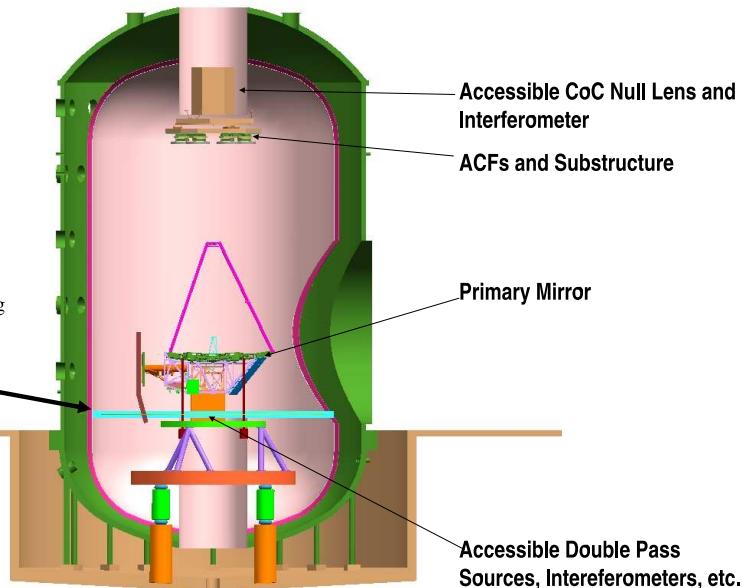


No Metrology Tower and Associated Cooling H/W. External Metrology

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  $\mu\text{m}$  performance specs (kept 2.0  $\mu\text{m}$ ).
- 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 — Replan Int. & Testing.



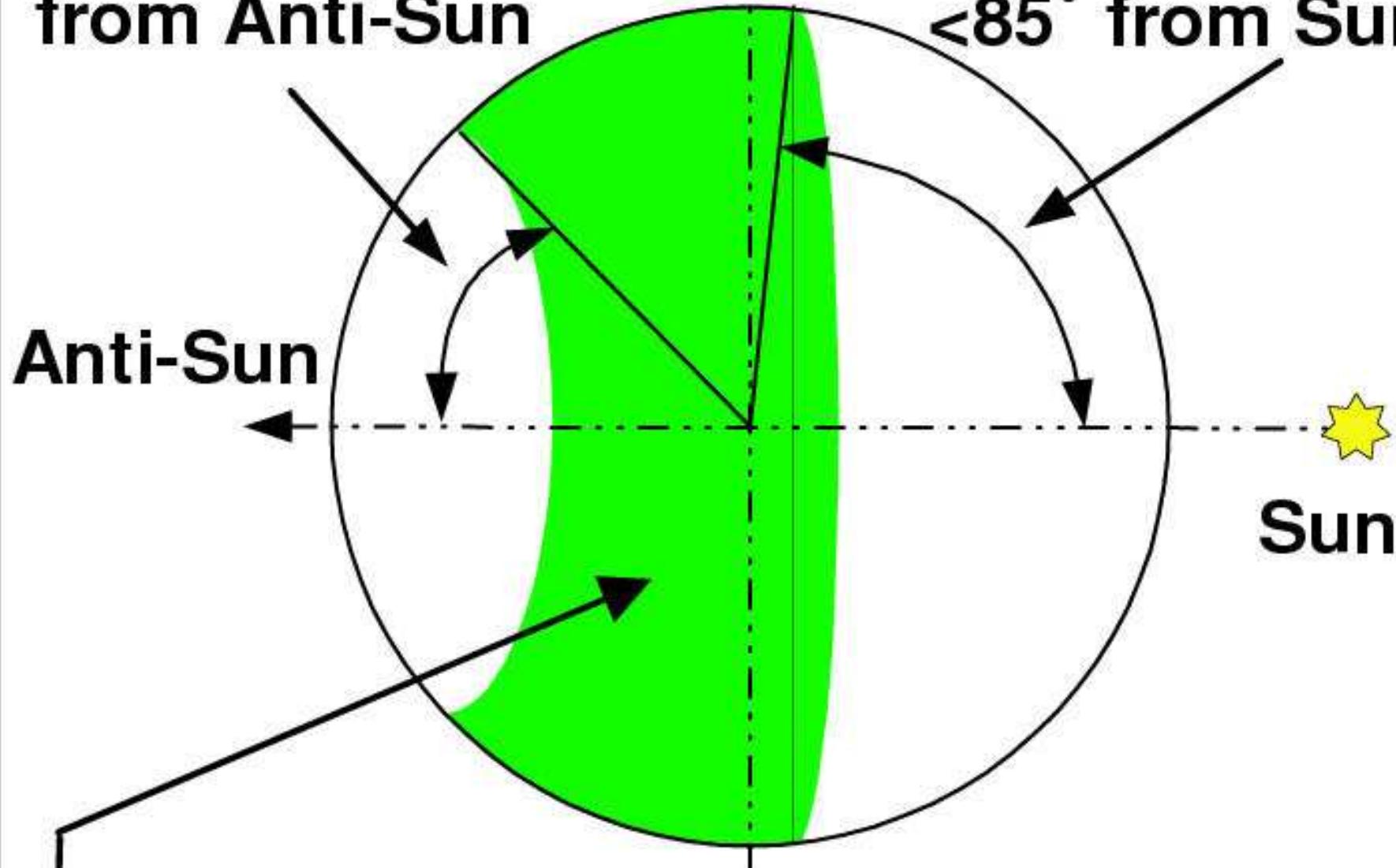
Life-sized JWST model, at NASA/GSFC with the whole JWST Project ...



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

**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.

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)

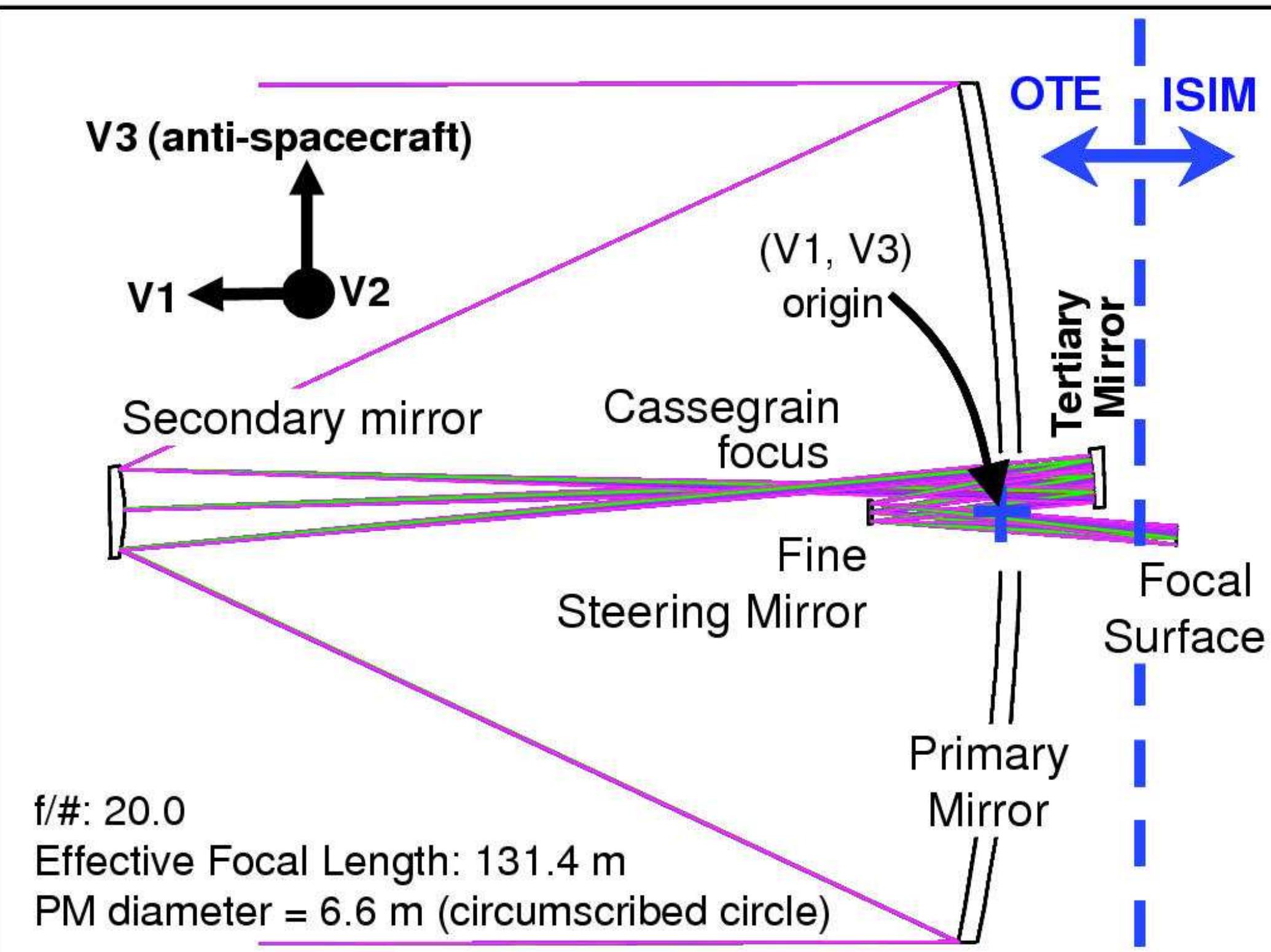
(V1, V3)  
origin

OTE  
ISIM

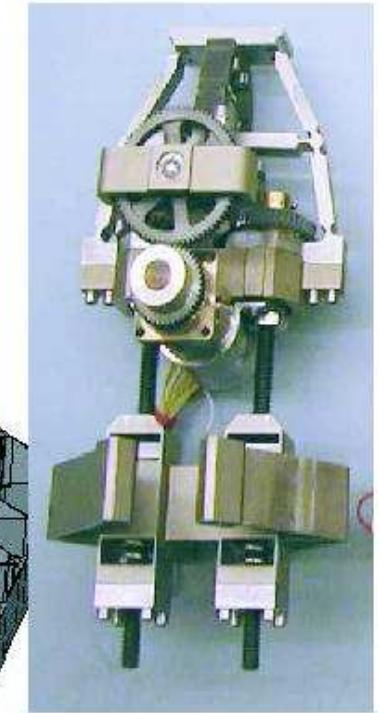
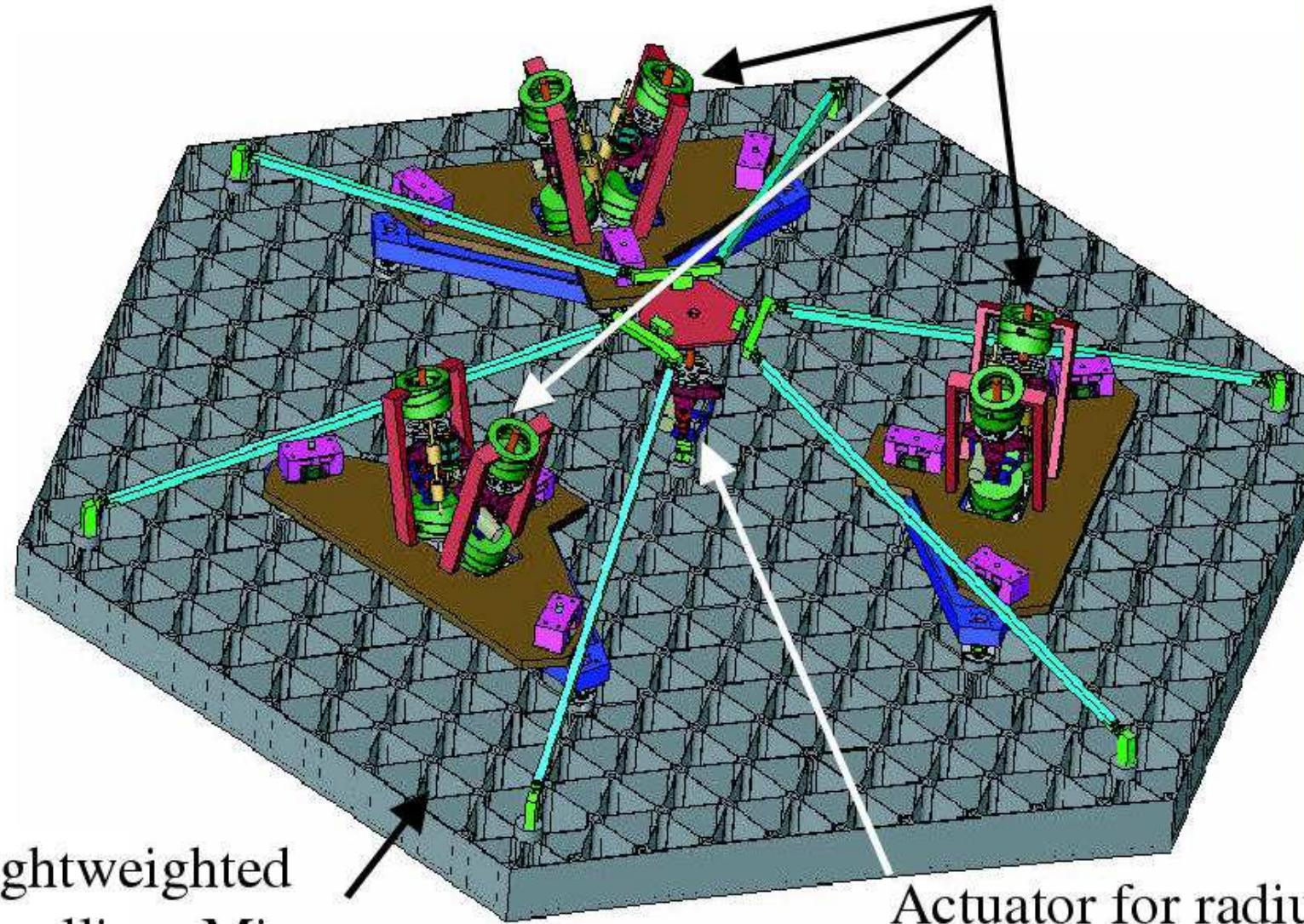
Tertiary  
Mirror

Focal  
Surface

Primary  
Mirror



## Actuators for 6 degrees of freedom rigid body motion



Actuator development unit

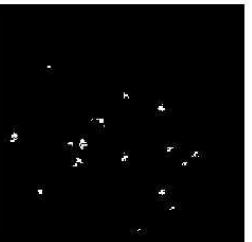
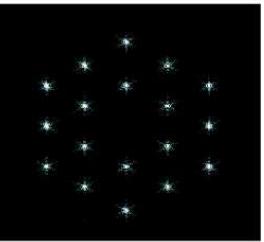
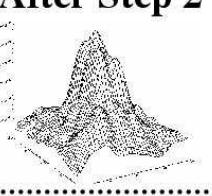
Lightweighted  
Beryllium Mirror

Actuator for radius  
of curvature adjustment

Active mirror segment support through “hexapods”, similar to Keck.

Redundant & doubly-redundant mechanisms, quite forgiving against failures.

*First light  
NIRCam*

After Step 1	Initial Capture	Final Condition
 <b>1.</b> 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
<b>2. Coarse Alignment</b> 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)
<b>3. Coarse Phasing - Fine Guiding (PMSA piston)</b>	 WFE: < 250 μm rms	WFE < 1 μm (rms)
<b>4. Fine Phasing</b>	 WFE: < 5 μm (rms)	WFE < 110 nm (rms)
<b>5. Image-Based Wavefront Monitoring</b>	 WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to the Keck telescope.

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



## ETU NIRCam



## Flight Fine Guidance Sensor

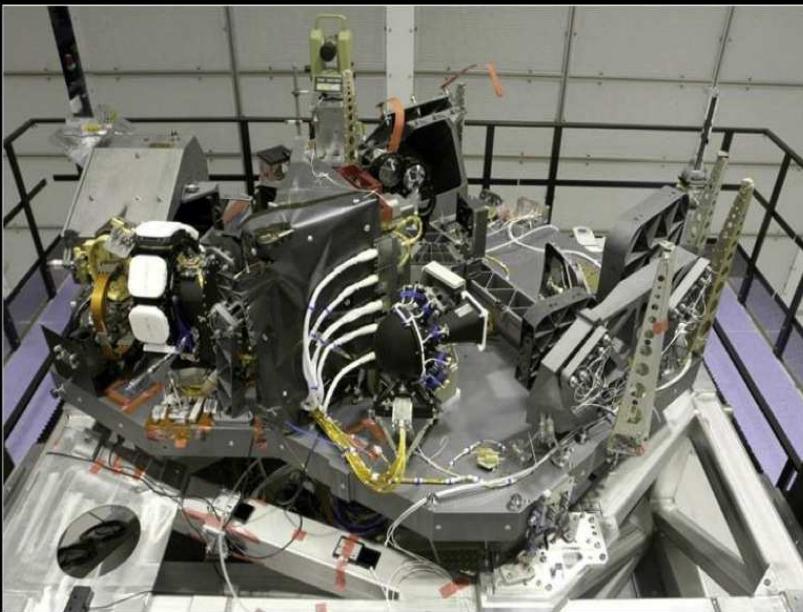


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) imagers:

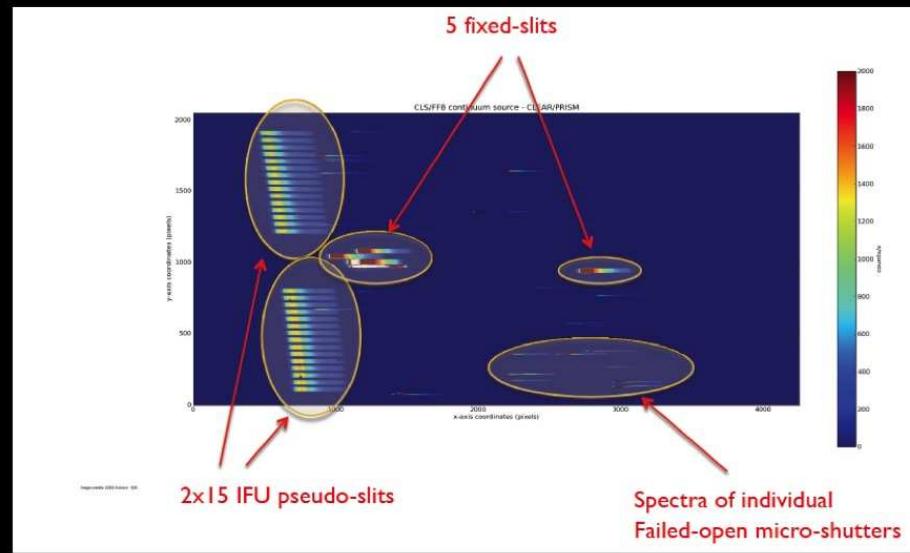
- NIRCam — built by UofA (AZ) and Lockheed (CA).
- Fine Guidance Sensor (&  $1\text{--}5\mu\text{m}$  grisms) — built by CSA (Montreal).
- NIRCam scheduled for delivery to GSFC Fall 2011, FGS early 2013.



## FLIGHT NIRSpec



## Flight NIRSpec First Light

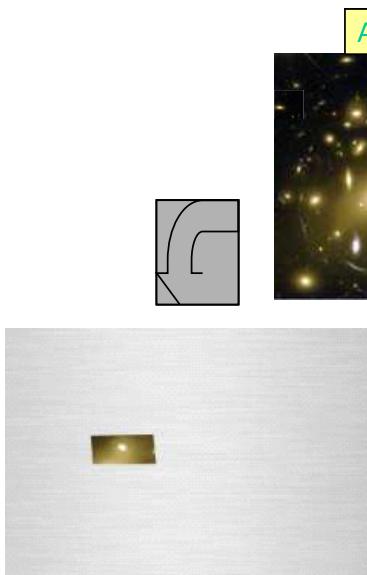


JWST's short-wavelength ( $0.6\text{--}5.0\mu\text{m}$ ) spectrograph:

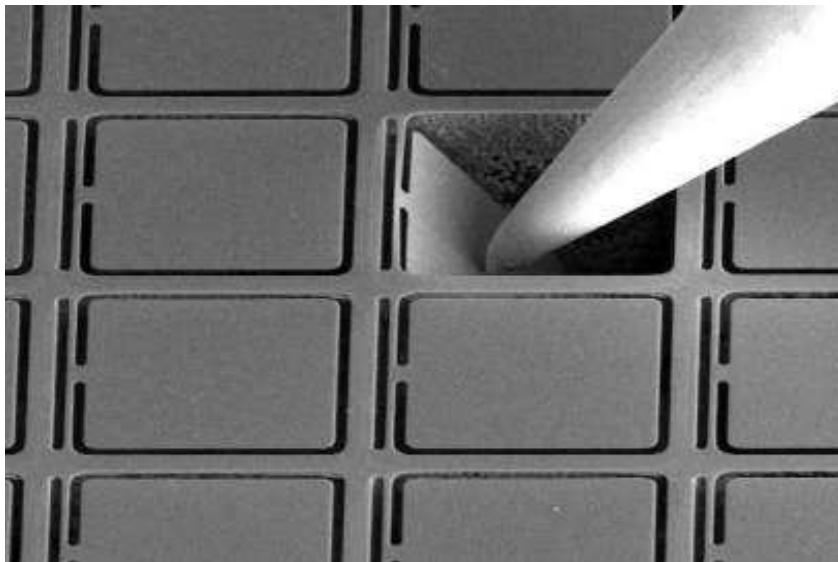
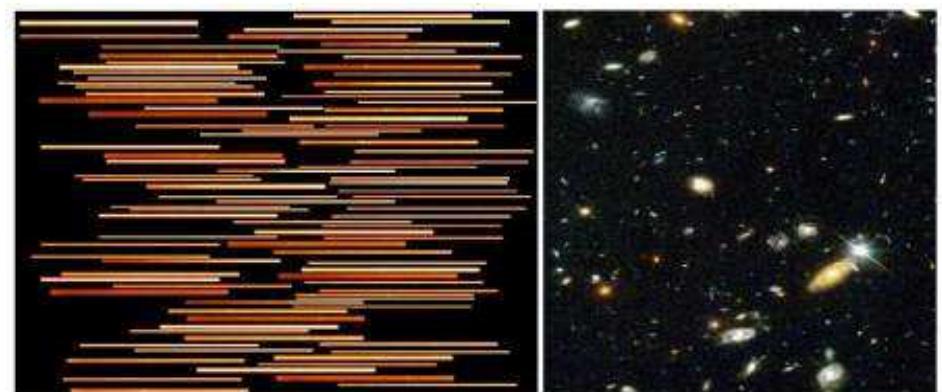
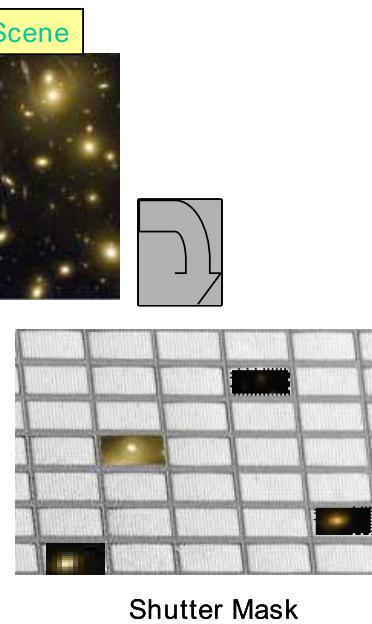
- NIRSpec — built by ESA/ESTEC and Astrium (Munich).
- Flight build completed and tested with First Light in Spring 2011.

Final NIRSpec delivery to NASA/GSFC in early 2013.

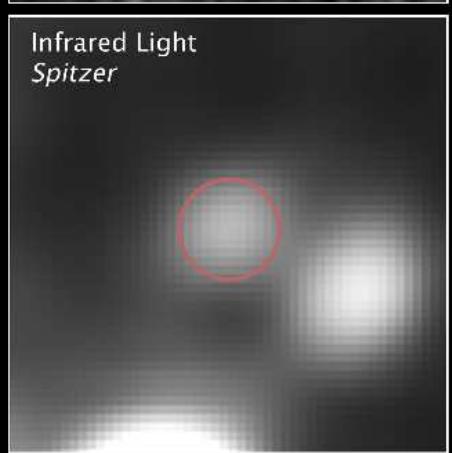
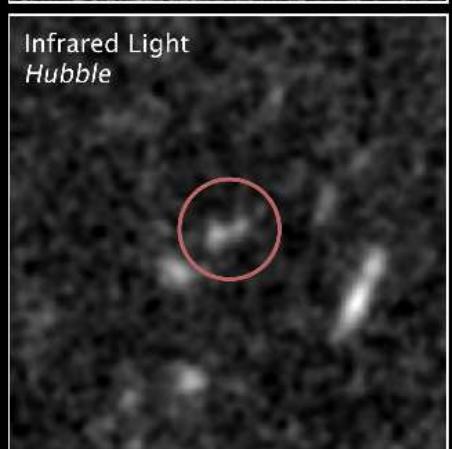
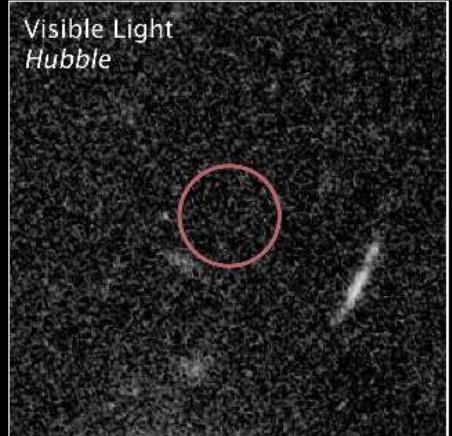
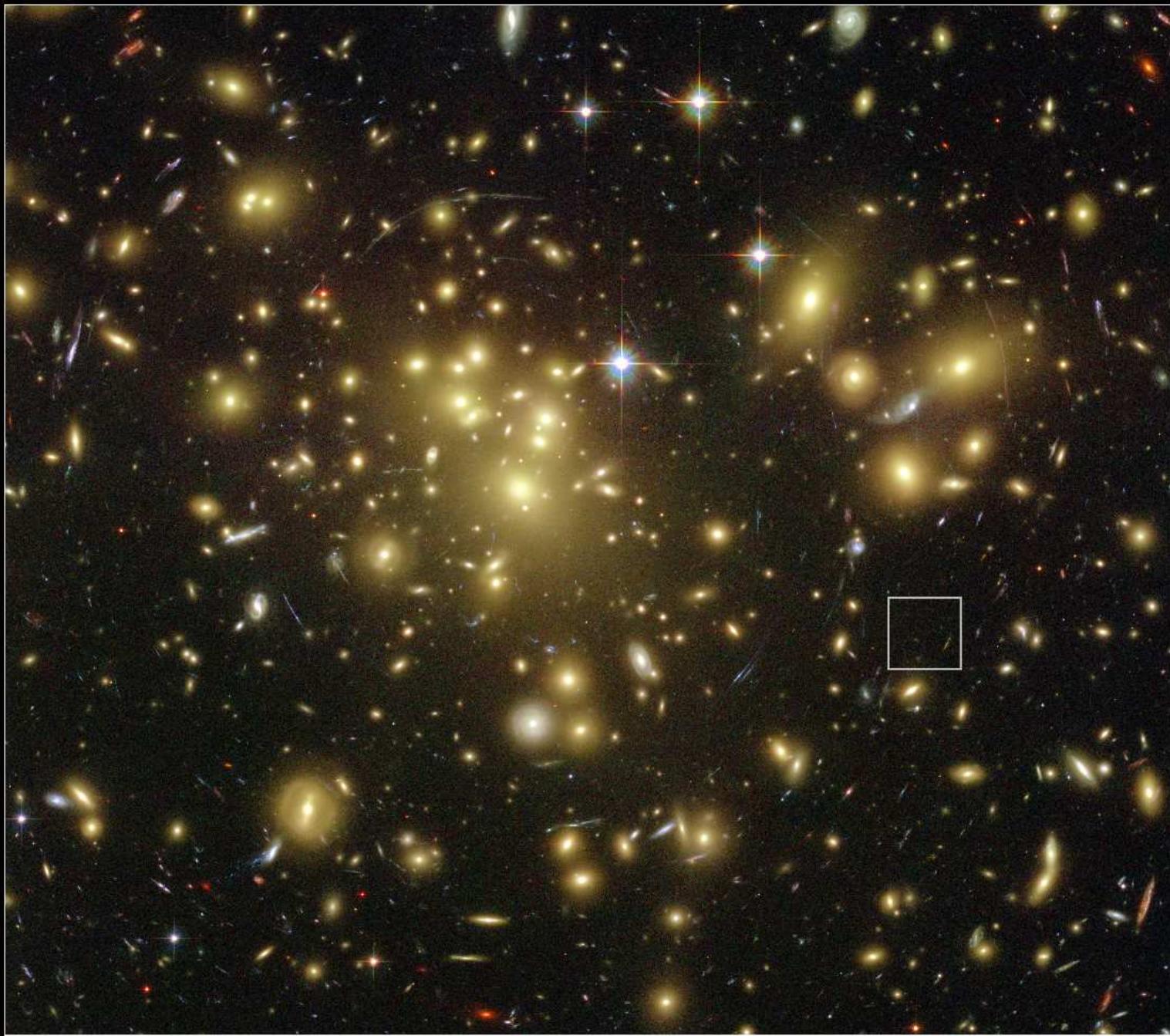
# Micro Shutters



Metal Mask/Fixed Slit







Distant Gravitationally Lensed Galaxy ■ Galaxy Cluster Abell 1689  
*Hubble Space Telescope ■ ACS/WFC NICMOS*

# (0) Intro: Cosmic Expansion and Contents of the Universe

---

Expansion  $\Rightarrow$  redshift

$$\lambda_{obs} = \lambda_{rest} \cdot (1+z)$$

Hubble's Law:

$$D \simeq v / H_0 \simeq (c/H_0) \cdot z = R_0 \cdot z$$

Cosmic Content:

inside  $R_0 = (c/H_0) \simeq 13.73$  Gyr:

$$[ t_{univ} = (211 \pm 1 !) \cdot (t_{dino} = 65 \text{ Myr}) ]$$

Photons (light):

$$N_{h\nu} \sim 10^{89}$$

Baryons (atoms):

$$N_b \sim 10^{80}$$

$\eta = \text{Photons/Baryons}$

$$\eta \sim 10^9 \Rightarrow \text{He/H ratio} = 0.235$$

Energy Density:

as fraction of critical closure density:

Baryons (atoms):

$$\Omega_b = \rho_b / \rho_{crit} \simeq 0.042$$

Dark Matter:

$$\Omega_d = \rho_d / \rho_{crit} \simeq 0.20$$

Dark Energy ( $\Lambda$ ):

$$\Omega_\Lambda = \rho_\Lambda / \rho_{crit} \simeq 0.76$$

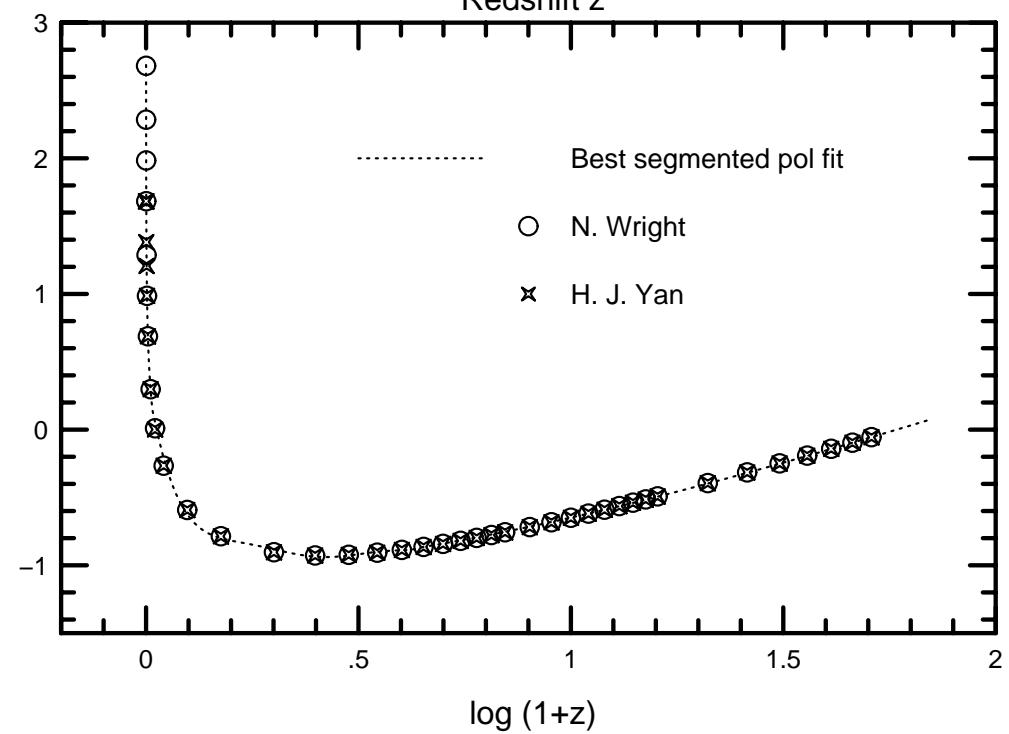
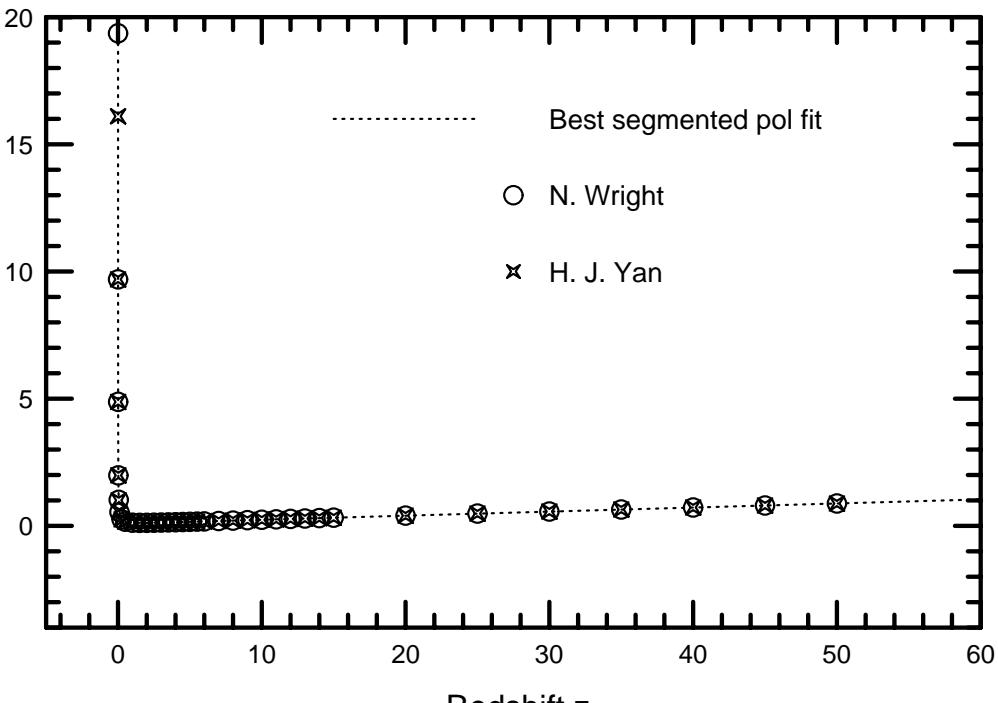
(Supermassive) black holes:

$$\rho_{smbh} / \rho_{crit} \simeq 0.0001$$

Total

$$\Omega_{tot} = \rho_{tot} / \rho_{crit} \simeq 1.00 \pm 0.02$$

Theta-z relation for  $H_0=71$ ,  $\Omega_m=0.27$ ,  $\Omega_\Lambda=0.73$



Angular size  $\theta$  vs. redshift  $z$  in Lambda cosmology:

$H_0 = 73 \text{ km/s/Mpc}$ ,  
 $\Omega_m = 0.24$ ,  $\Omega_\Lambda = 0.76$ .

- $\theta \propto 1/z$  for  $z \lesssim 0.05$   
 (small angle approximation).

- $\theta \propto z$  for  $z \gtrsim 3$  !!
- Objects appear larger with redshift for  $z \gtrsim 1.65$  !!

But angular sizes of rigid rods are nearly constant for all redshifts  $0.5 \lesssim z \lesssim 10$  !

## JWST — Web-links:

<http://capwiz.com/supportjwst/home/>

<http://www.whitehouse.gov/contact>

<http://www.facebook.com/SaveJWST>

<http://twitter.com/#!/saveJWST> or <http://goo.gl/iAR4I>

<http://savethistelescope.blogspot.com/>

<http://www.change.org/petitions/do-not-cancel-funding-for-the-james-webb-space-telescope>

## General JWST Information:

<http://www.aura-astronomy.org/news/news.asp?newsID=264>

<http://www.jwst.nasa.gov/> & <http://www.stsci.edu/jwst/>

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

Thank you for your time and hard work!