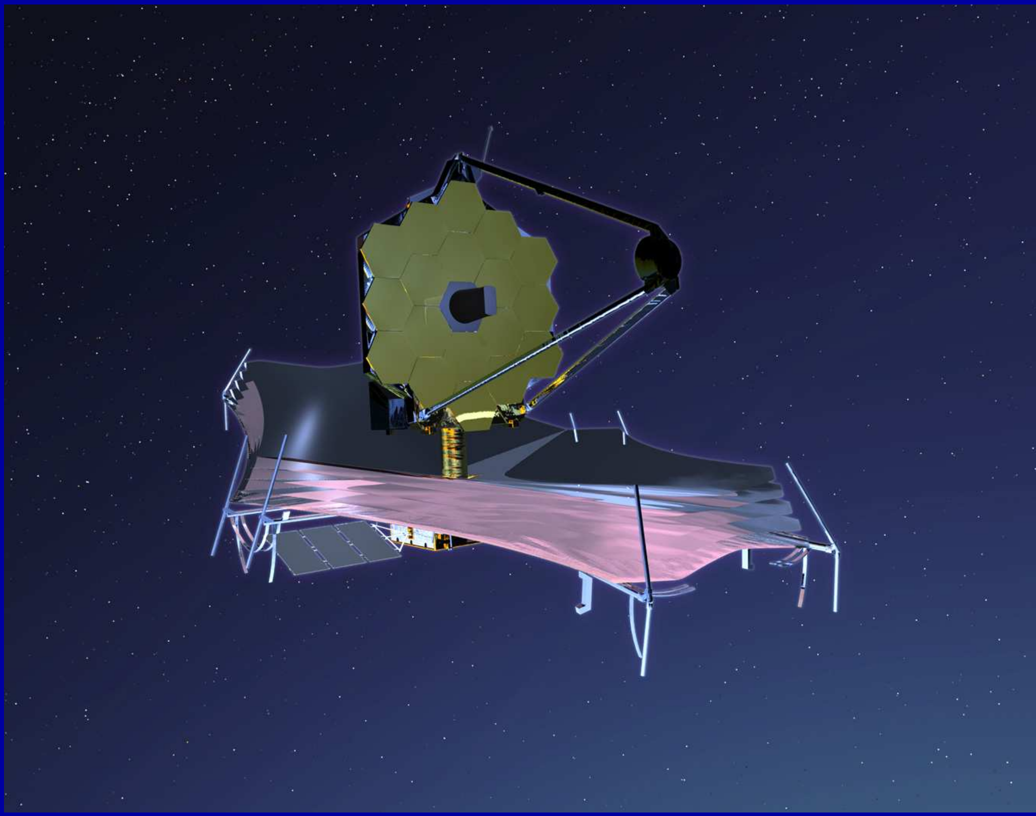
Unraveling the Distant Universe with the NASA/ESA Hubble and James Webb Space Telescopes

Rogier Windhorst (ASU) — JWST Interdisciplinary Scientist

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

& ASU (ex-) Grad Students: N. Hathi, H. Kim, R. Ryan, A. Straughn, & K. Tamura (ASU)



Public Lecture at the Royal Netherlands Embassy, Washington DC, Wednesday March 11, 2009

Outline

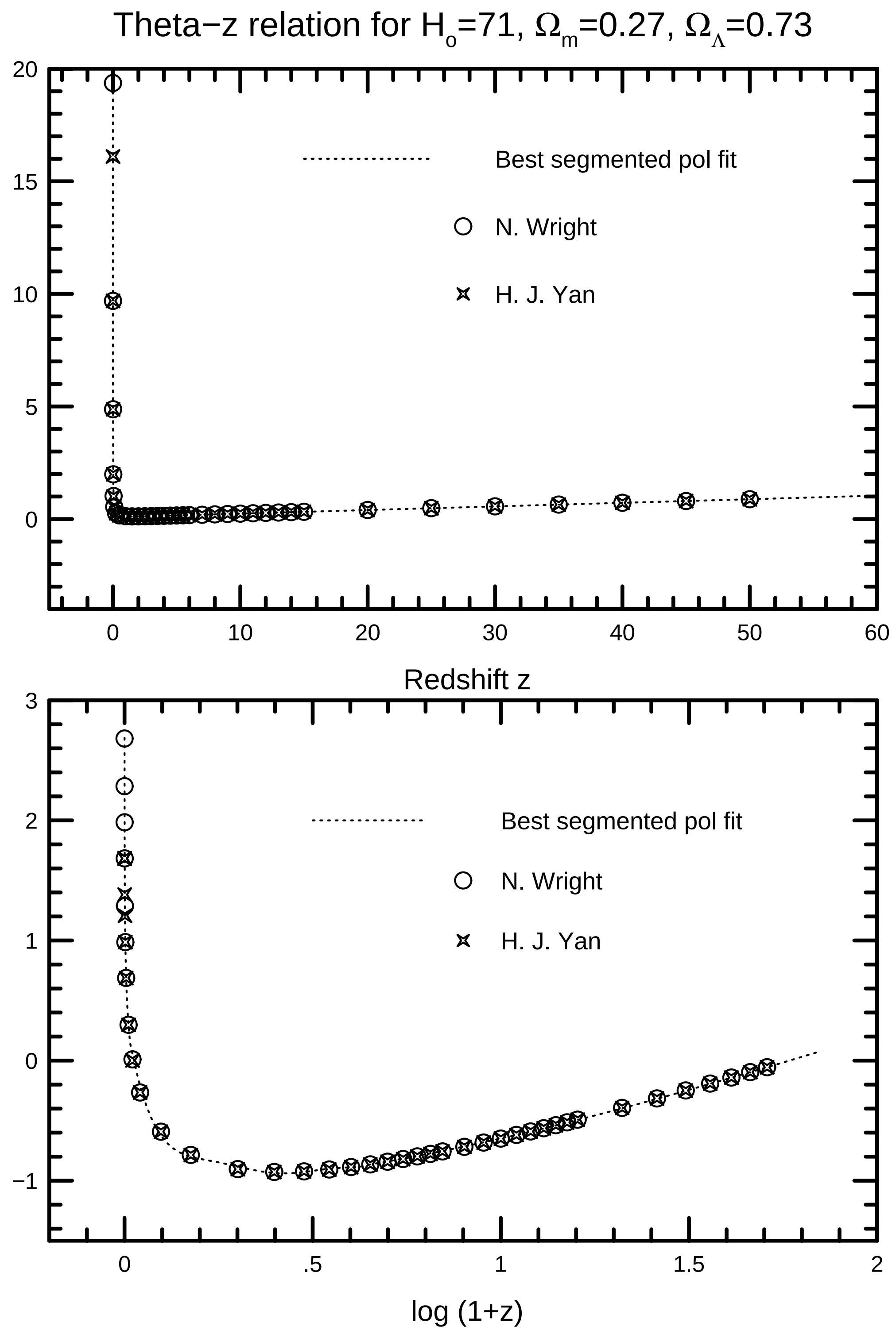
- (0) Introduction: Cosmic Expansion and Contents of the Universe
- (1) Recent key aspects of the Hubble Space Telescope (HST) project.
- (2) How has HST measured Galaxy Assembly over Cosmic Time?
- (3) What is the James Webb Space Telescope (JWST)?
- (4) How will JWST measure First Light & Reionization?
- (5) HST UV-images predict galaxy appearance for JWST at $z \simeq 1$–15.
- (6) Summary and Conclusions

Sponsored by NASA/HST & JWST

ARIZONA STATE UNIVERSITY

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

Expansion ⇒ redshift	$\lambda_{obs} = \lambda_{rest} \cdot (1+z)$
Hubble's Law:	D $\simeq$ v / $H_o \simeq (c/H_o) \cdot z = R_o \cdot z$
Cosmic Content:	inside R_0=(c/H_0)$\simeq$13.73 Glyr:
	[t_{univ} = (211 ±1 !) . (t_{dino}=65 Myr)]
Photons (light):	$N_{h\nu} \sim 10^{89}$
Baryons (atoms):	$N_b \sim 10^{80}$
η=Photons/Baryons	$\eta \sim 10^9 \Longrightarrow$ 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 (Λ):	$\Omega_\Lambda = \rho_\Lambda/\rho_{crit} \simeq 0.76$
(Supermassive) black holes:	$\rho_{smbh}/\rho_{crit} \simeq 0.0001$
Total	$\Omega_{tot}=\rho_{tot}/\rho_{crit} \simeq 1.00 \pm 0.02$



Angular size θ vs. redshift z in Lambda cosmology:

$H_0 = 73$ 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 !!

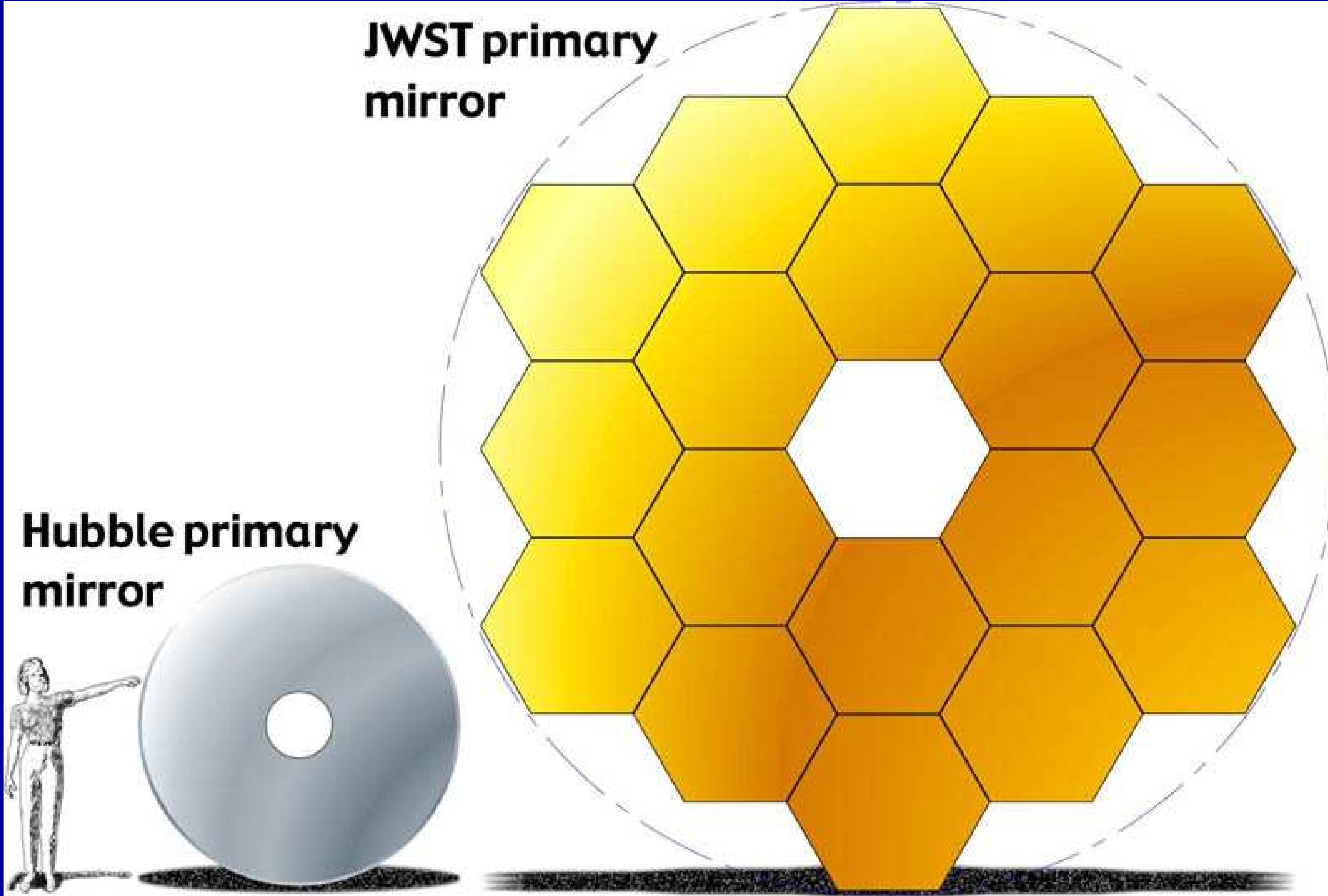
But angular sizes of rigid rods are nearly constant for all redshifts 0.5 $\lesssim$z $\lesssim$10 !

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

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

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

JWST: The infrared sequel to HST from 2013–2018 (–2025?)

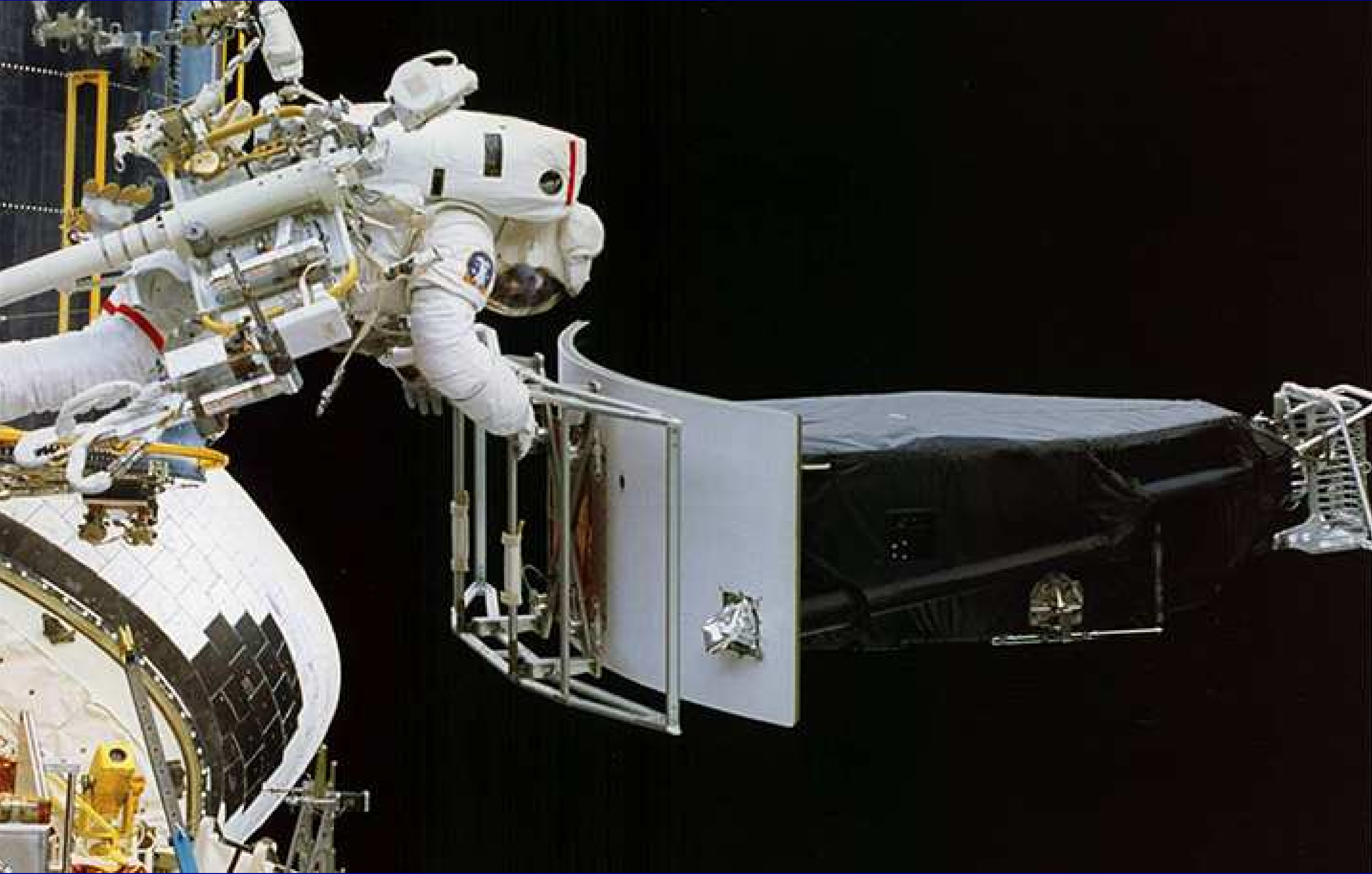


JWST $\sim 2.5\times$ larger than Hubble, so at $\sim 2.5\times$ larger wavelengths:

JWST has the same resolution in the near-IR as HST in the optical.

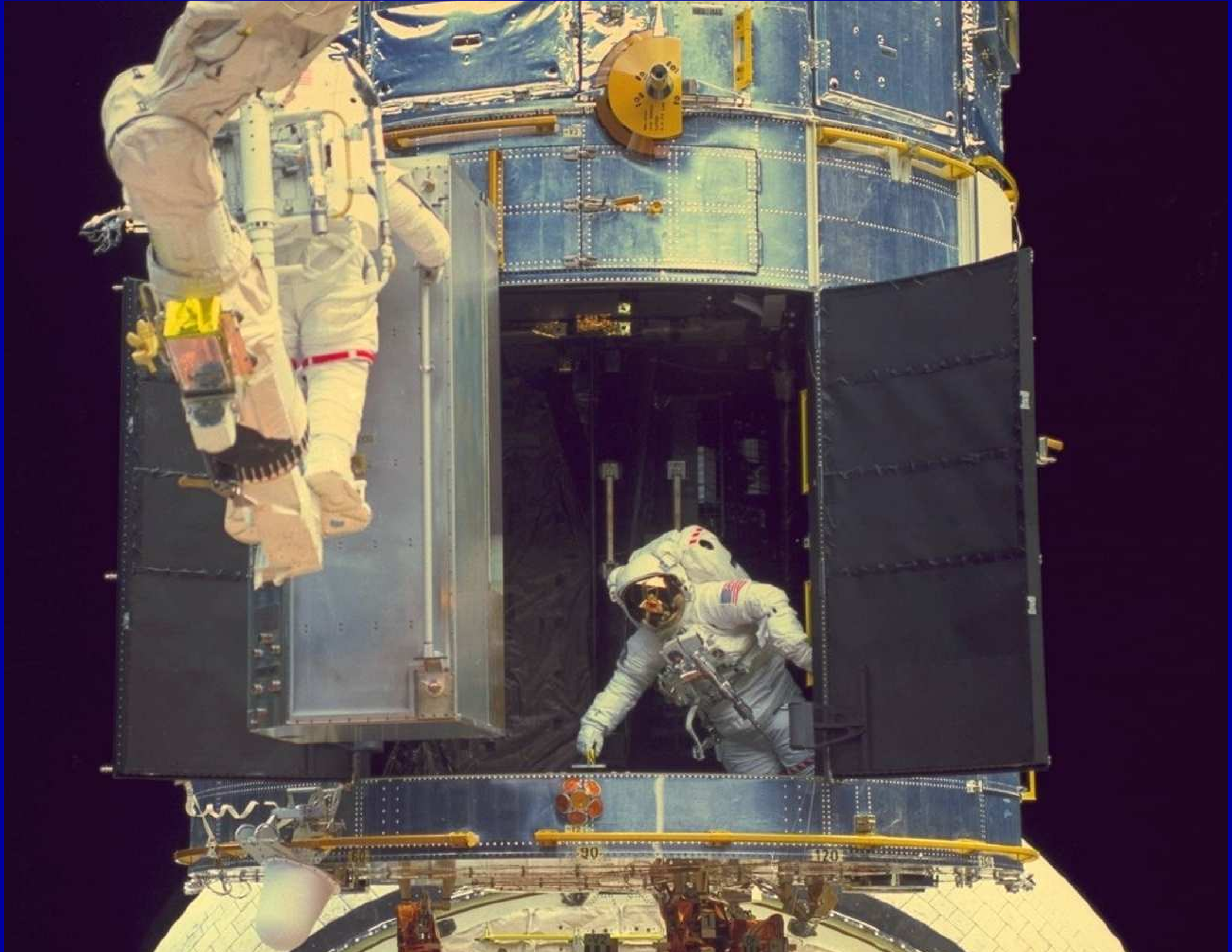
(1) Recent key aspects of the Hubble Space Telescope (HST) project

The HST Advanced Camera for Surveys (ACS) — launched 2002 (SM3B).



Installing Wide Field Camera 2 (WFPC2) during SM1 in December 1993.

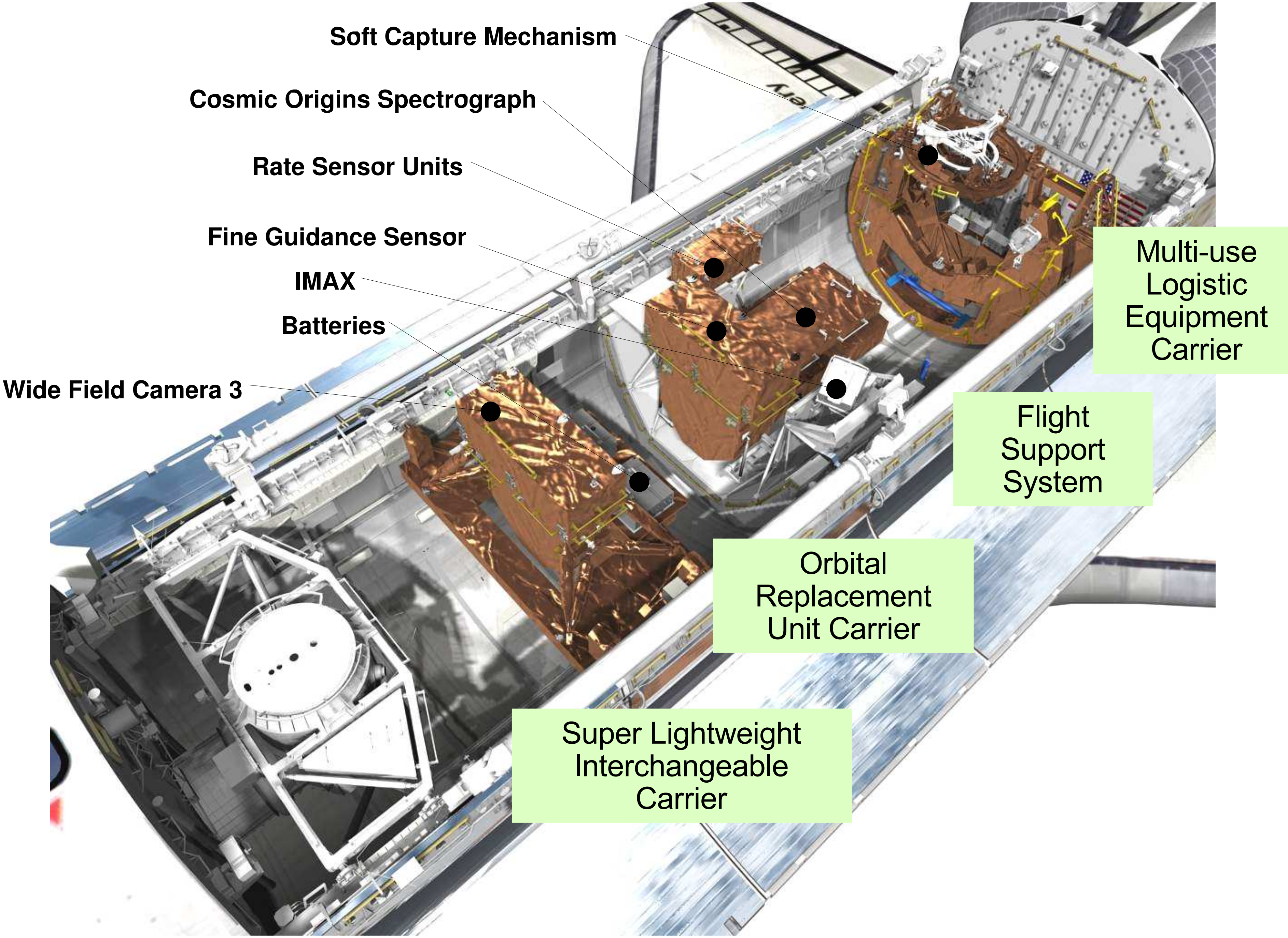
Similar to what astronauts will do with WFC3 during SM4 in May 2009.


90
120

New ESA solar panels rolling out during SM1 in December 1993

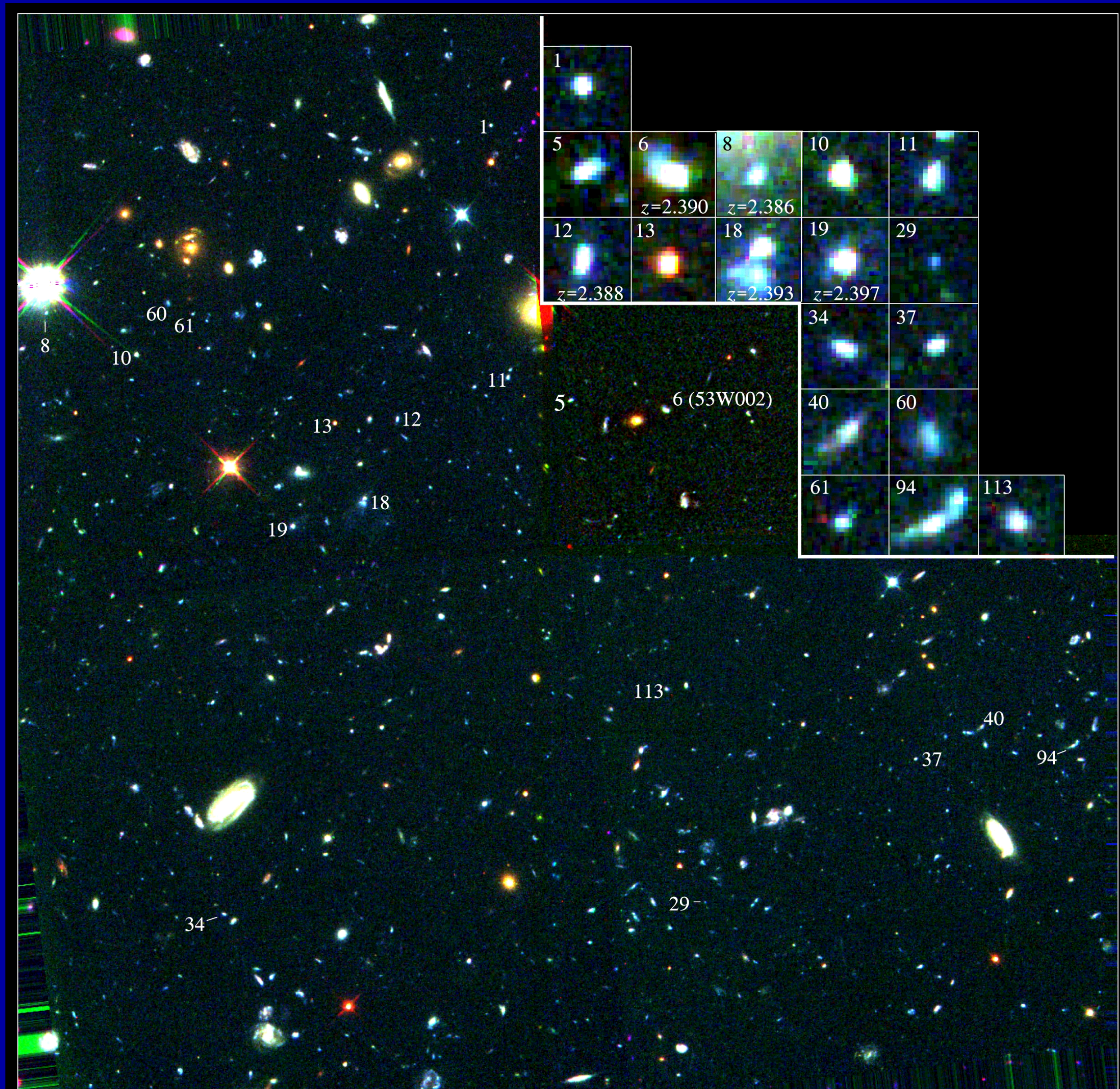
Goddard Space Flight Center

HST Servicing Mission 4 (SM4) Configuration



Wide Field Camera 3 for SM4 in 2009: More powerful HST imaging than ever.

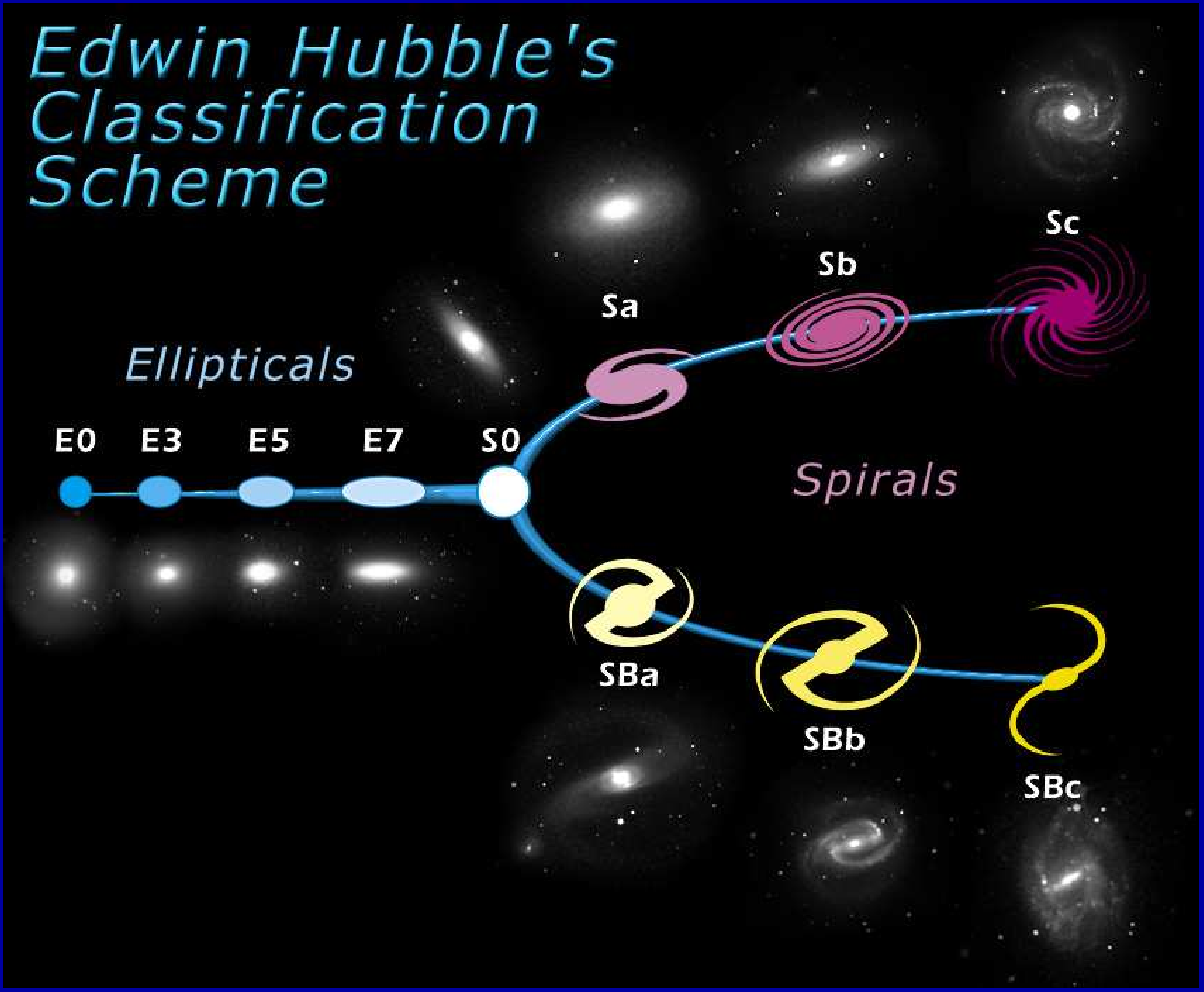
(2) How has HST measured Galaxy Assembly over Cosmic Time?



R. Windhorst (Arizona State University) and NASA

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

HST turned the classical Hubble sequence upside down!

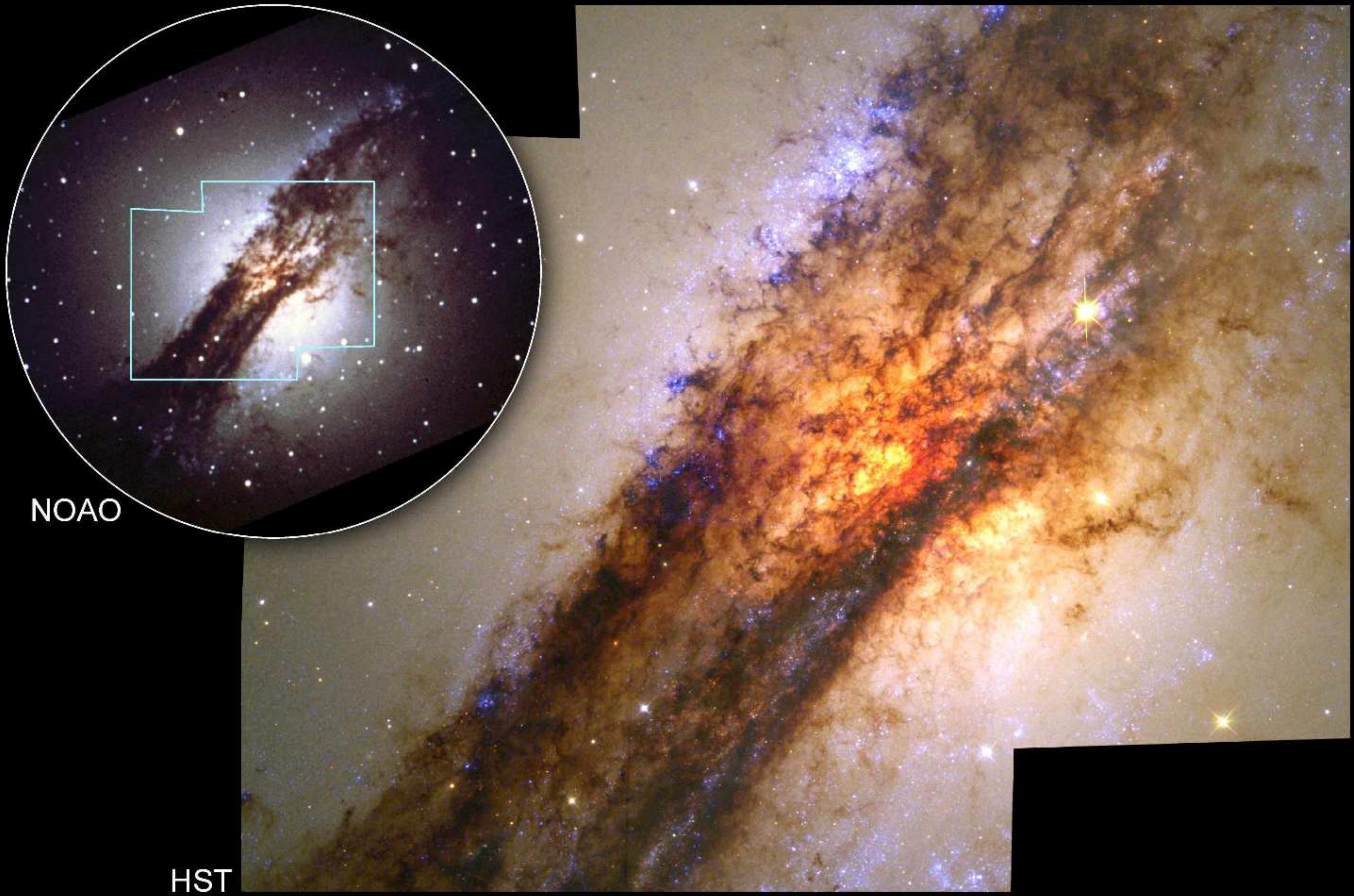


Who (when)	Cosmic Epoch	Ellipticals	Spirals	Irr's/mergers
Hubble (1920's)	z=0 (13.73 Gyr)	$\sim$40%	$\gtrsim$50%	$\lesssim$10%
HST (1990's)	z$\simeq$1–2 (3–6 Gyr)	$\lesssim$15%	$\sim$30%	$\gtrsim$55% !

Elliptical Galaxy NGC 1132

Hubble Heritage

NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration
Hubble Space Telescope ACS • STScI-PRC08-07



Active Galaxy Centaurus A

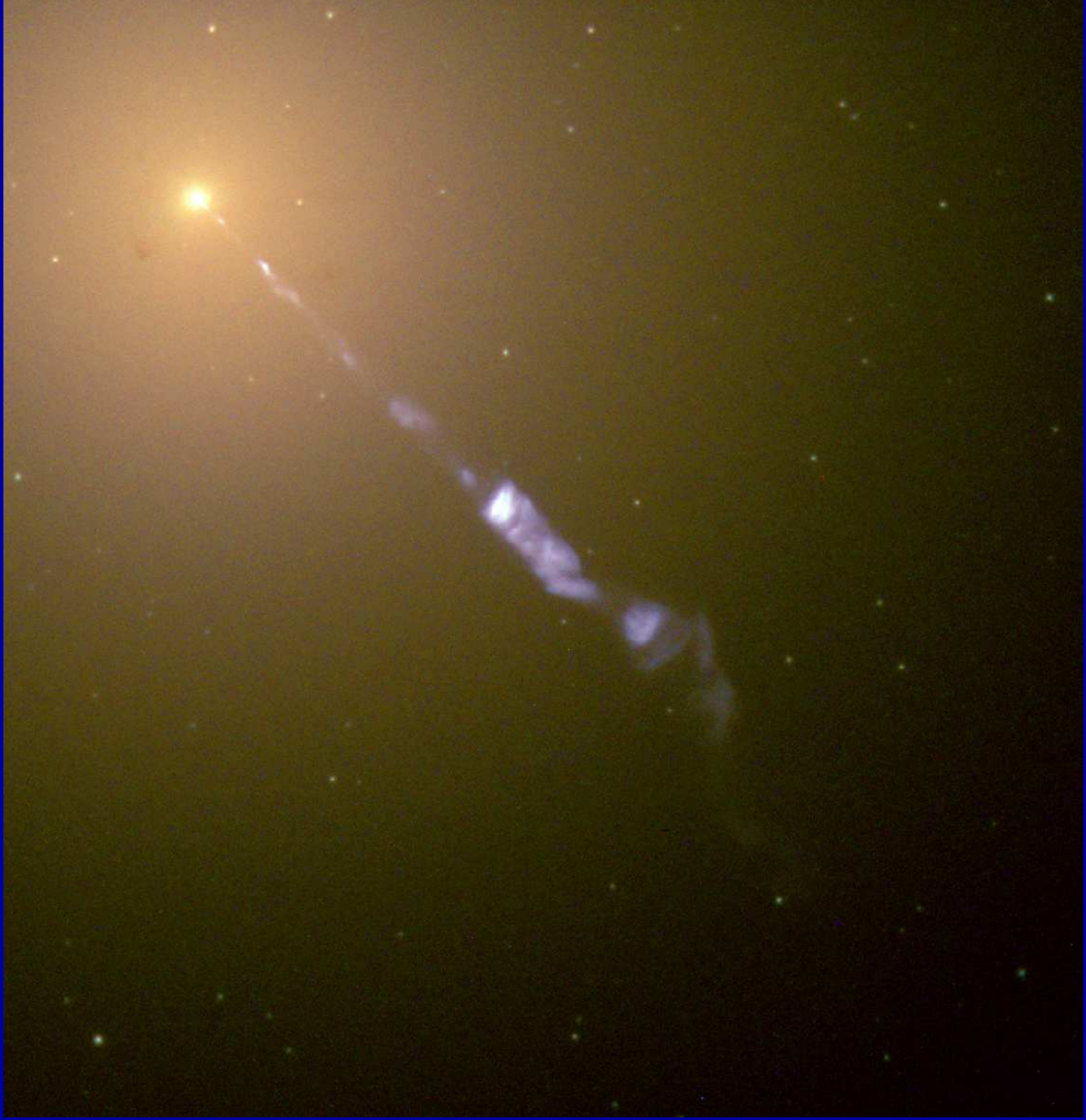
Hubble Space Telescope • Wide Field Planetary Camera 2

PRC98-14a • ST ScI OPO • May 14, 1998 • E. Schreier (ST ScI) and NASA

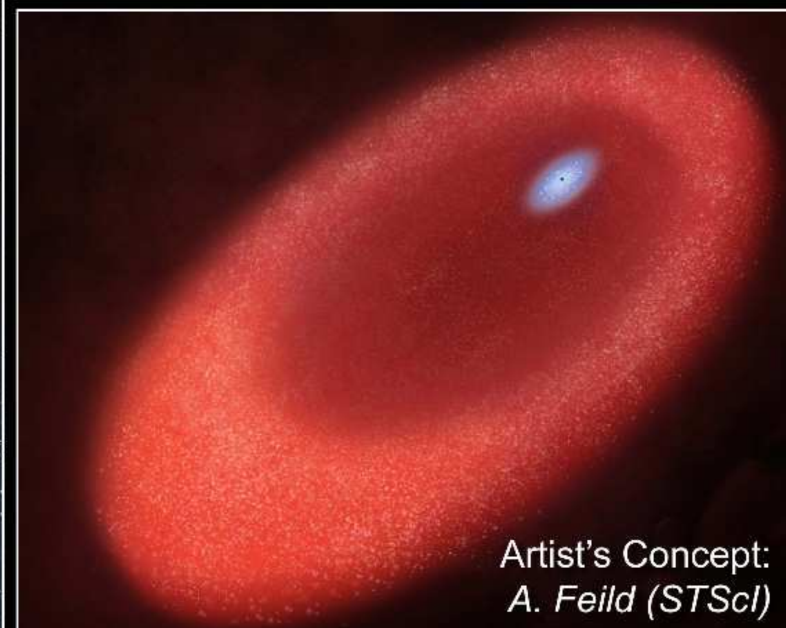
Elliptical Galaxy NGC 1316

Active Galaxy M82

NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS/WFC • STScI-PRC06-14a



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



Andromeda Galaxy Nucleus ▪ M31

Hubble Space Telescope ▪ WFPC2

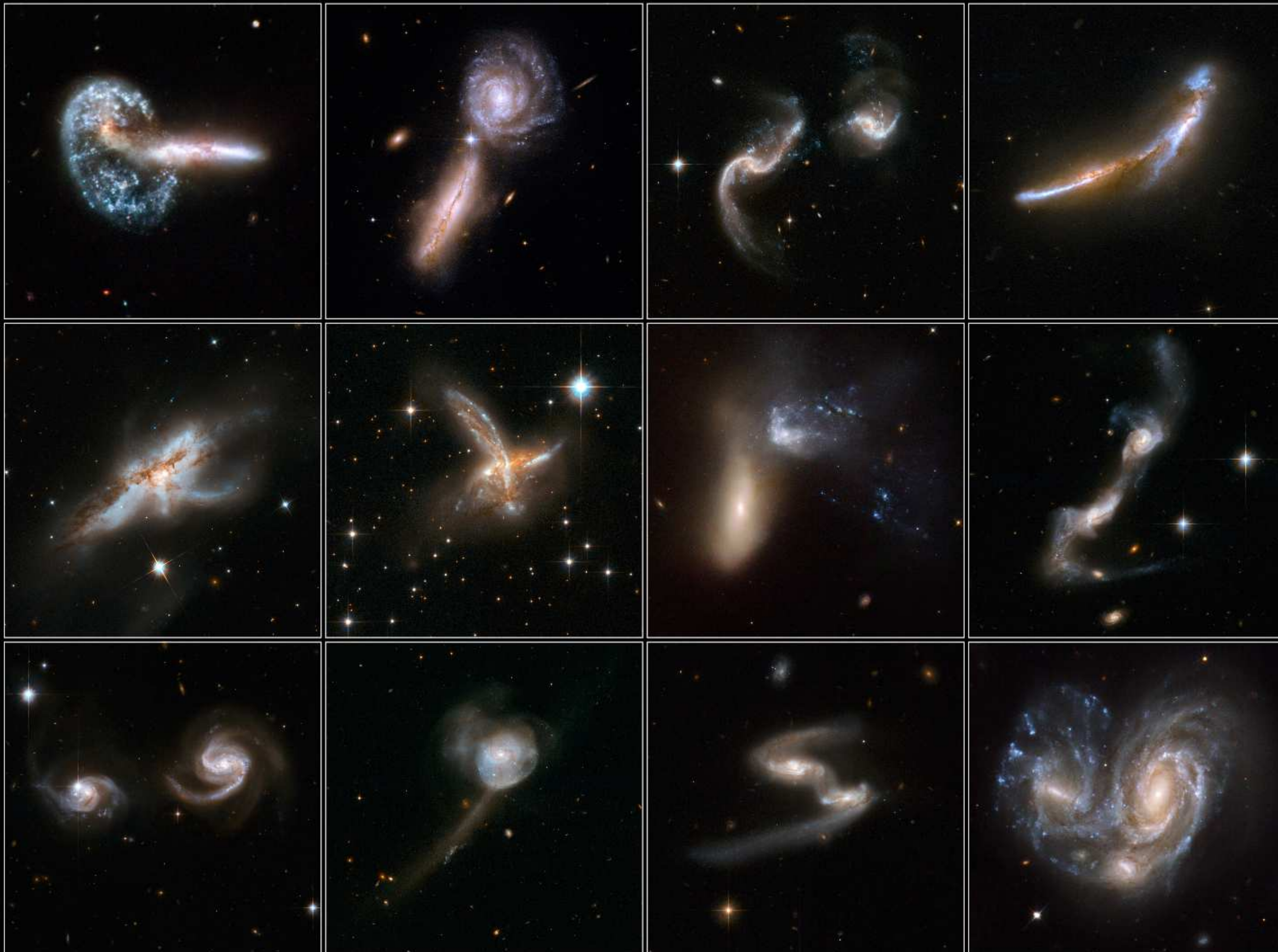
NASA, ESA, R. Gendler, T. Lauer (NOAO/AURA/NSF), and A. Feild (STScI)

STScI-PRC05-26

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

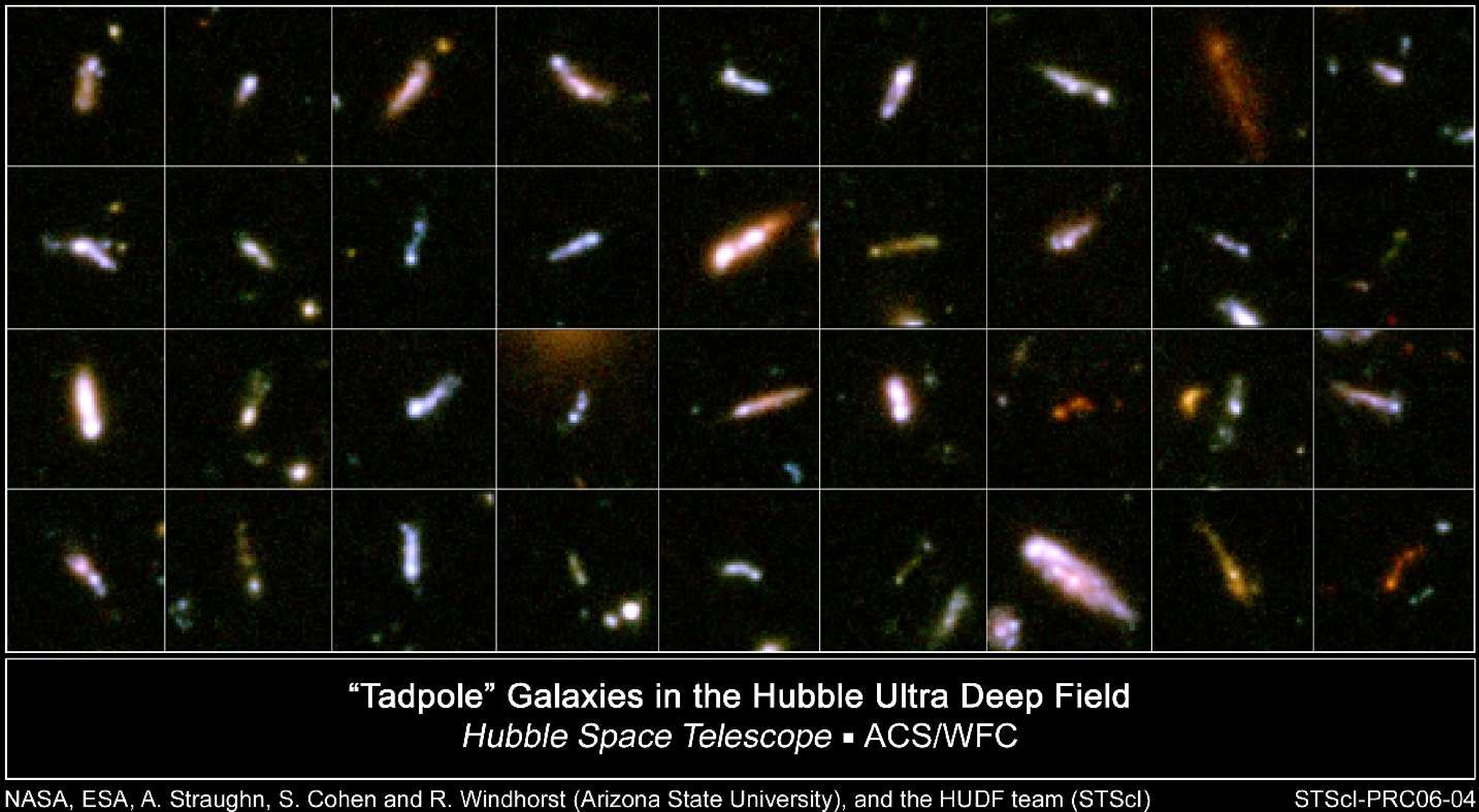
Interacting Galaxies

Hubble Space Telescope • ACS/WFC • WFPC2



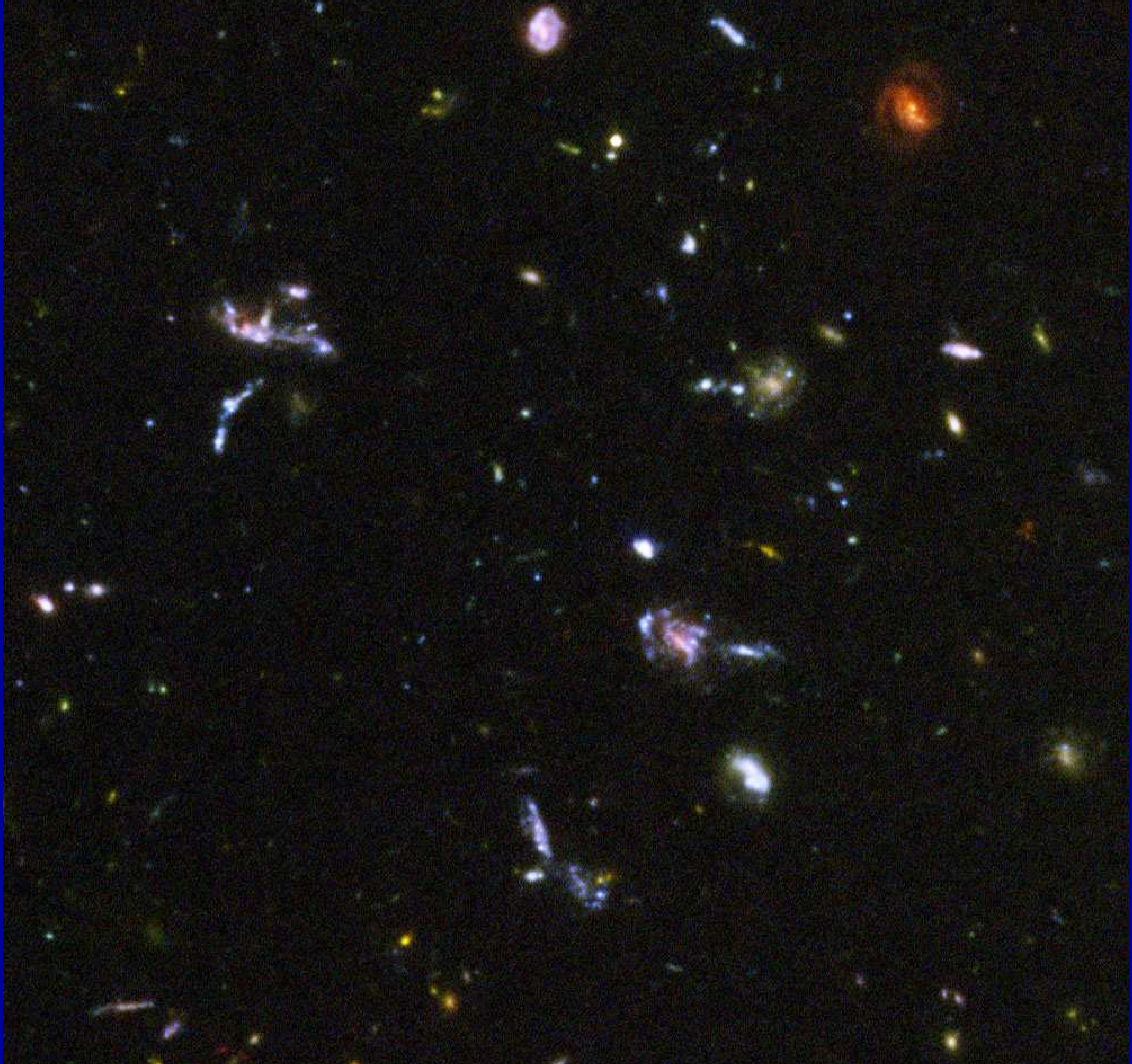
NASA, ESA, the Hubble Heritage (AURA/STScI)-ESA/Hubble Collaboration, and
A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

STScI-PRC08-16a

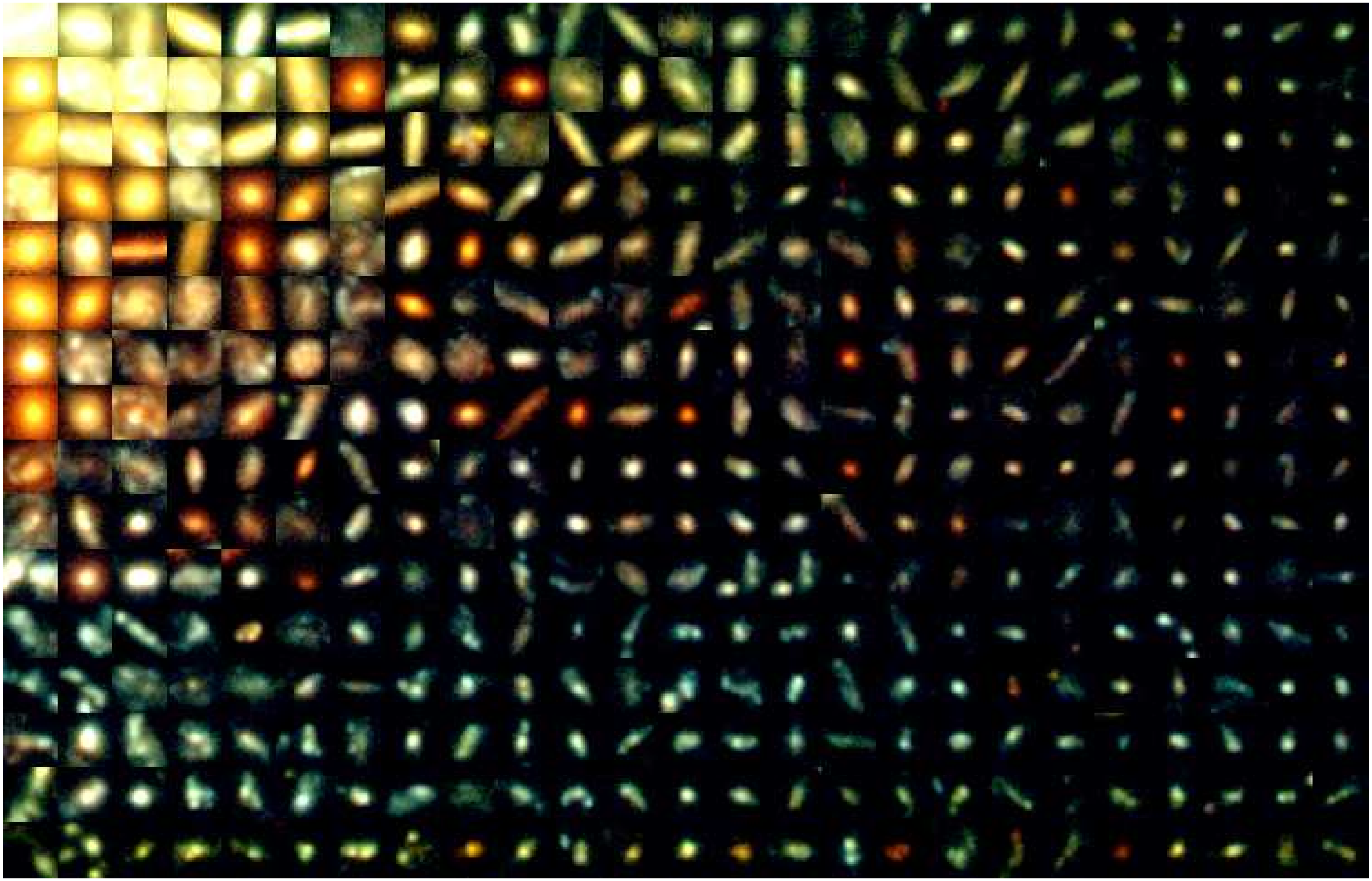


Merging galaxies constitute $\lesssim$1% of Hubble sequence today (age$\gtrsim$12.5 Gyr).

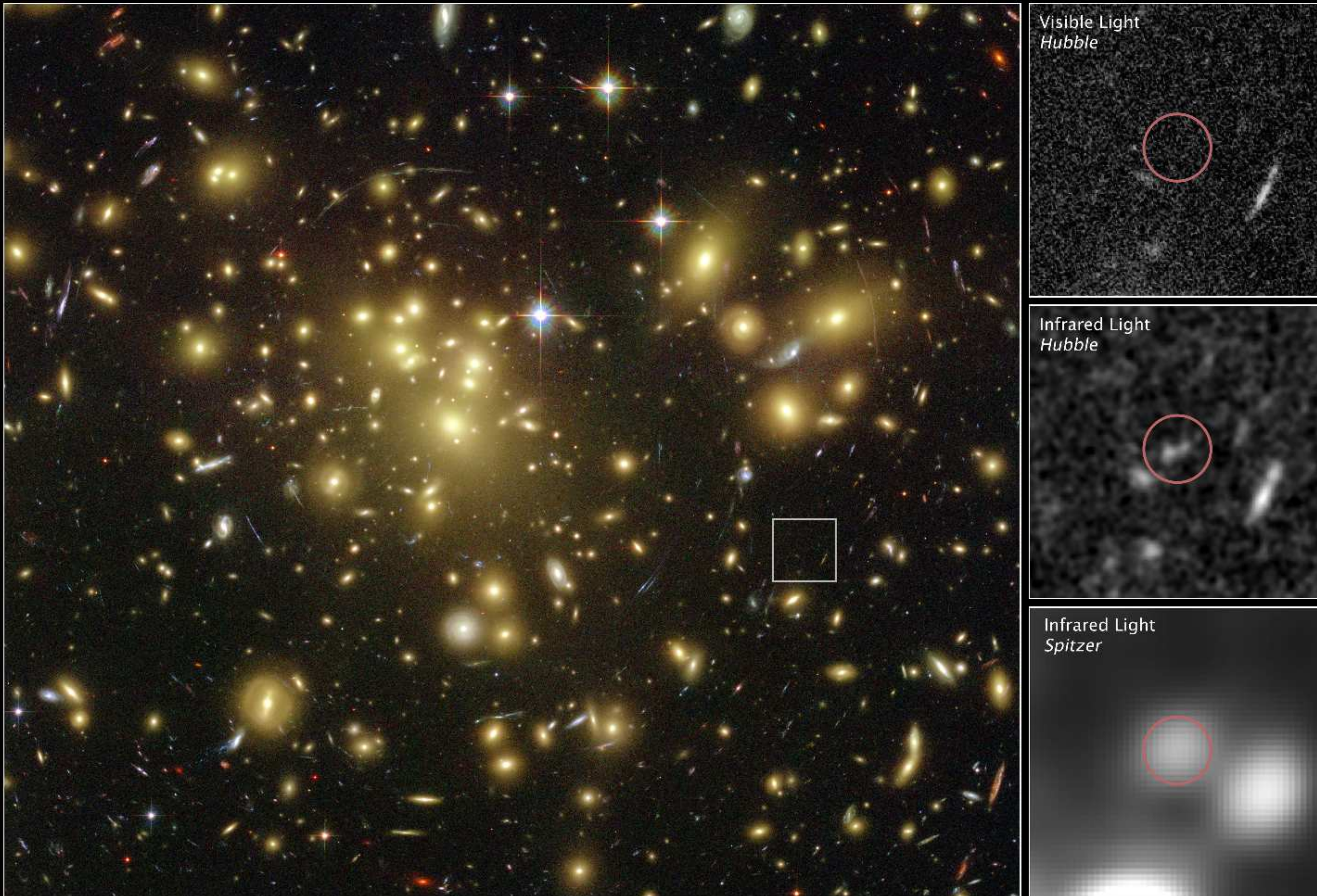
Tadpole galaxies are early stage mergers, very common at z$\gtrsim$2 (age$\lesssim$3 Gyr).



THE HUBBLE DEEP FIELD CORE SAMPLE ($I < 26.0$)

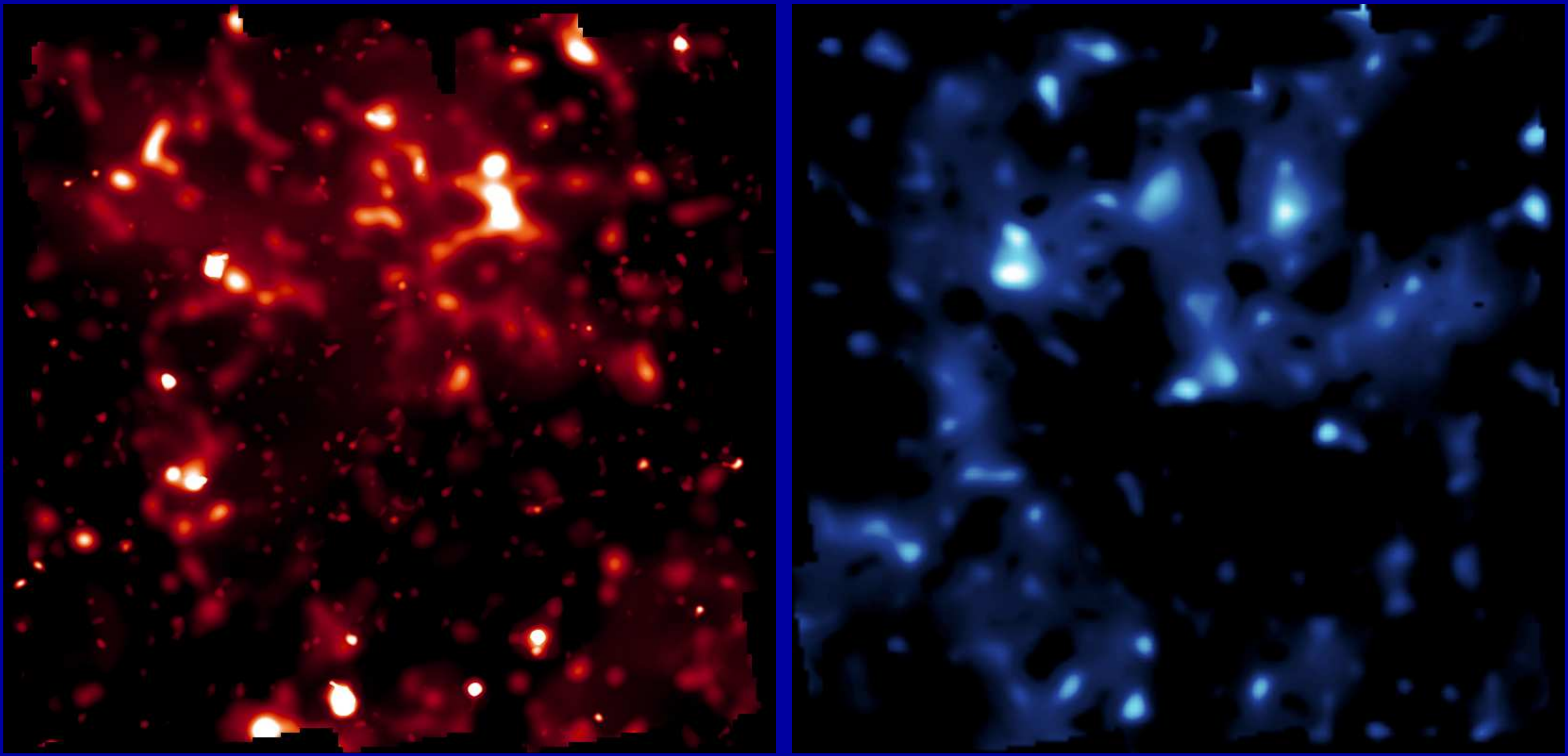


z	Age ($q_o = 0.5$)
0.19	77%
0.44	58%
0.54	52%
0.64	48%
0.74	44%
0.87	39%
0.97	36%
1.03	35%
1.14	32%
1.24	30%
1.41	27%
1.61	24%
1.76	22%
2.05	19%
2.57	15%
3.59	10%



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

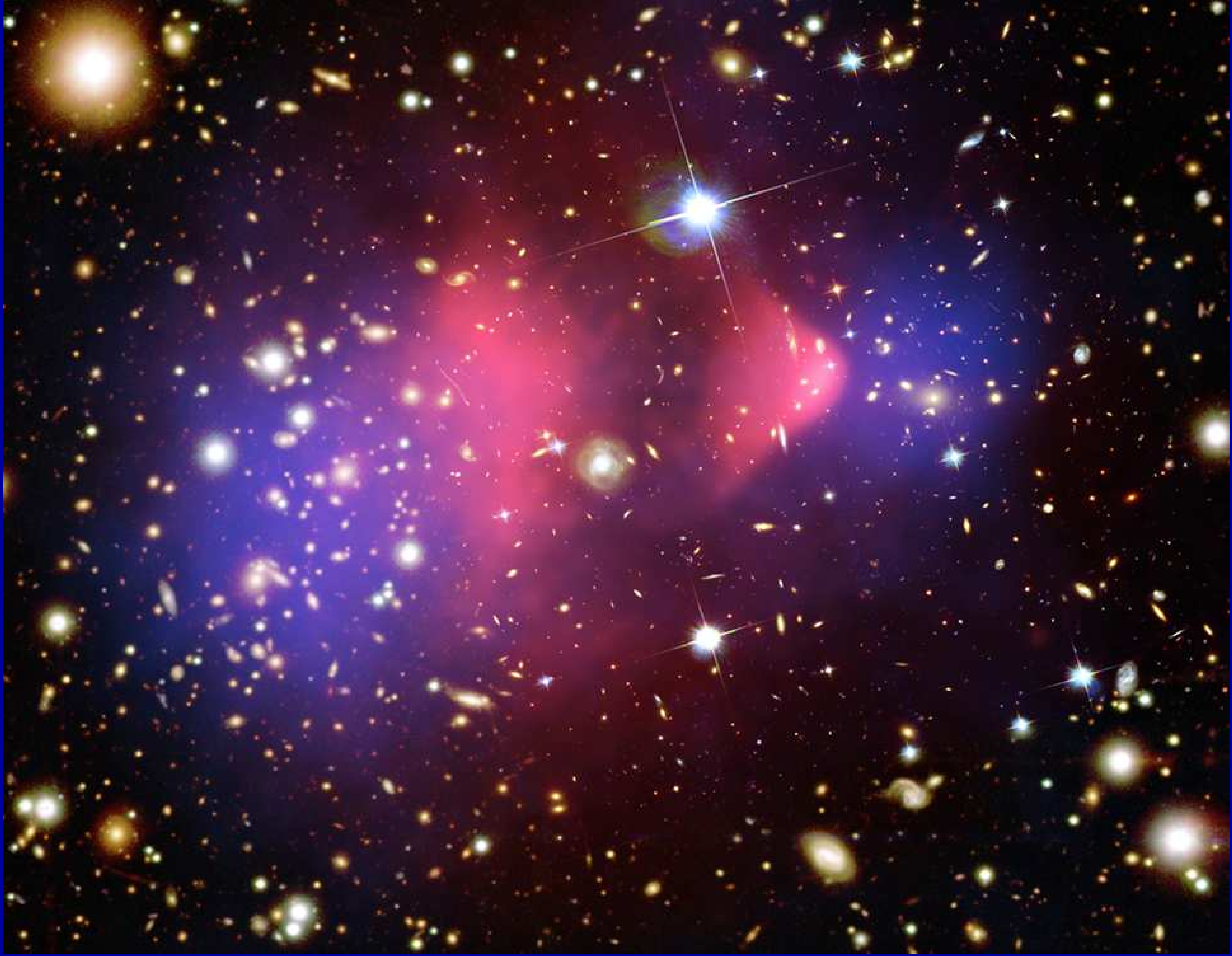
NASA, ESA, and L. Bradley (JHU), R. Bouwens (UCSC), H. Ford (JHU), and G. Illingworth (UCSC) STScI-PRC08-08a



1-degree HST/ACS mosaic of the COSMOS field:

- Visible galaxy density (red) measured by HST
- Dark Matter density (blue) measured from HST weak grav. lensing.

$\Longrightarrow$ Visible matter largely follows the Dark Matter.



Red: Chandra X-ray Observatory: hot gas ripped by cluster collision.

Blue: HST gravitational lensing: cluster Dark Matter is unaffected.

(2) How has HST measured Galaxy Assembly over Cosmic Time?

The Hubble Space Telescope has established since 1994 that:

• Galaxies of all types formed over a wide range of cosmic time, but with a notable transition around $z \simeq 1$, when the Hubble sequence formed:

(1) Subgalactic units rapidly merge from $z \simeq 7 \longrightarrow 1$ to grow bigger units.

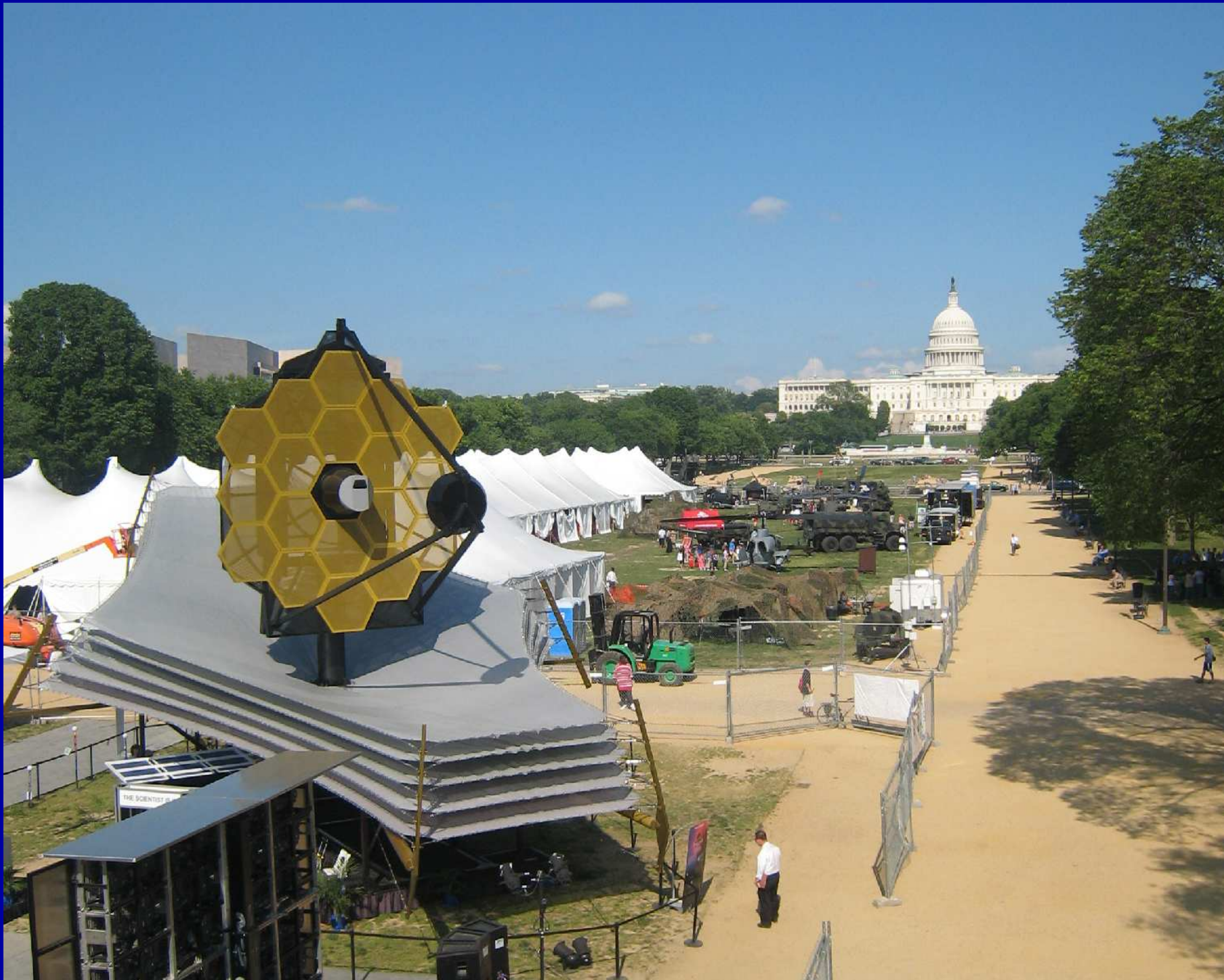
(2) Merger products start to settle as galaxies with giant bulges or large disks around $z \simeq 1$, resulting in the giant galaxies seen today.

• Through strong and weak lensing, HST measured Dark Matter in clusters and field directly. DM plays an essential stabilizing role in Galaxy Assembly.

• JWST can measure how galaxies of all types formed over a wide range of cosmic time ($z \simeq 15 \Rightarrow 0$, ages $\simeq$ 0.3–13.4 Gyr), by accurately measuring their rest-frame structure and type versus redshift or cosmic epoch.

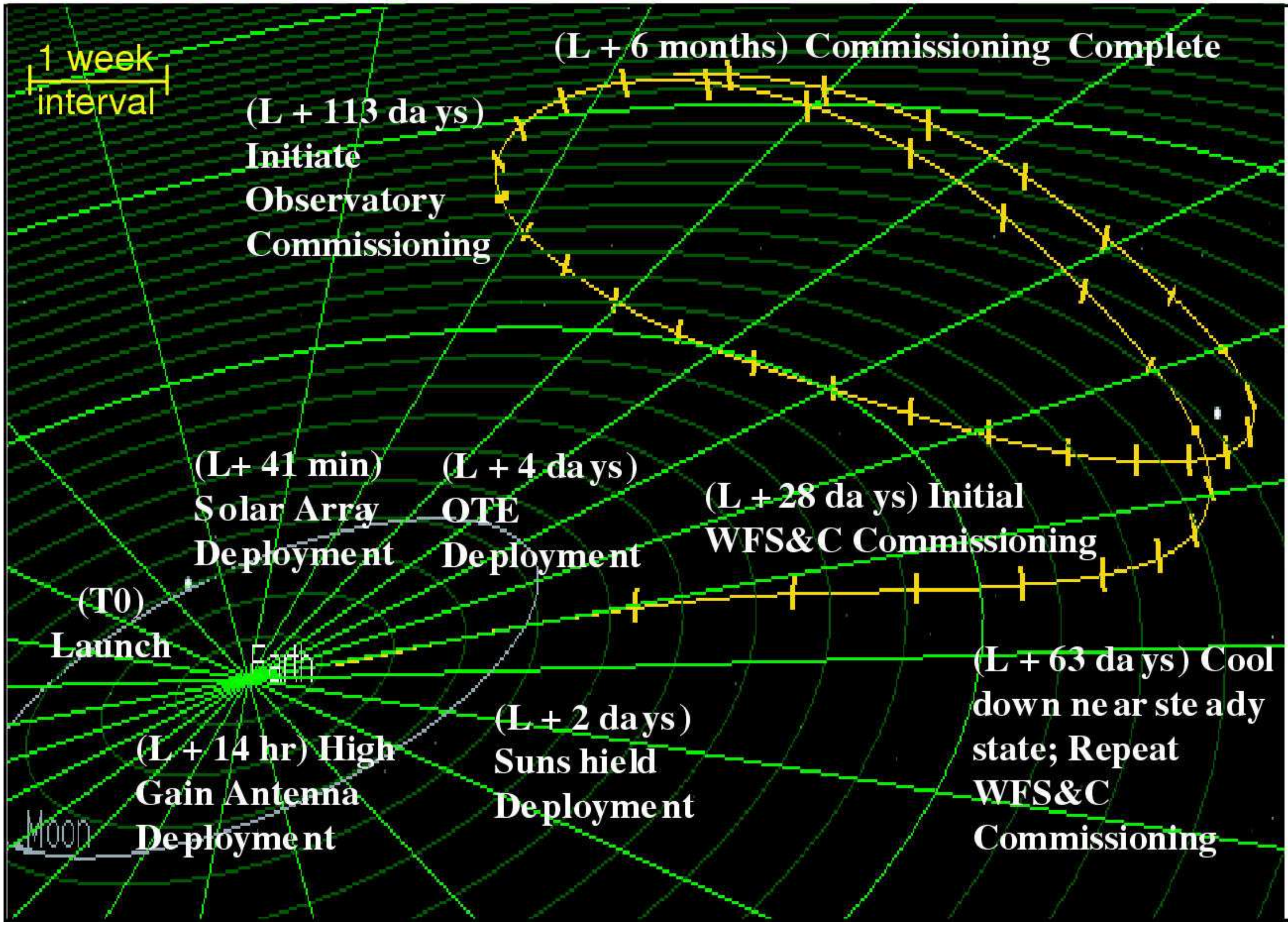
(3) What is the James Webb Space Telescope (JWST)?

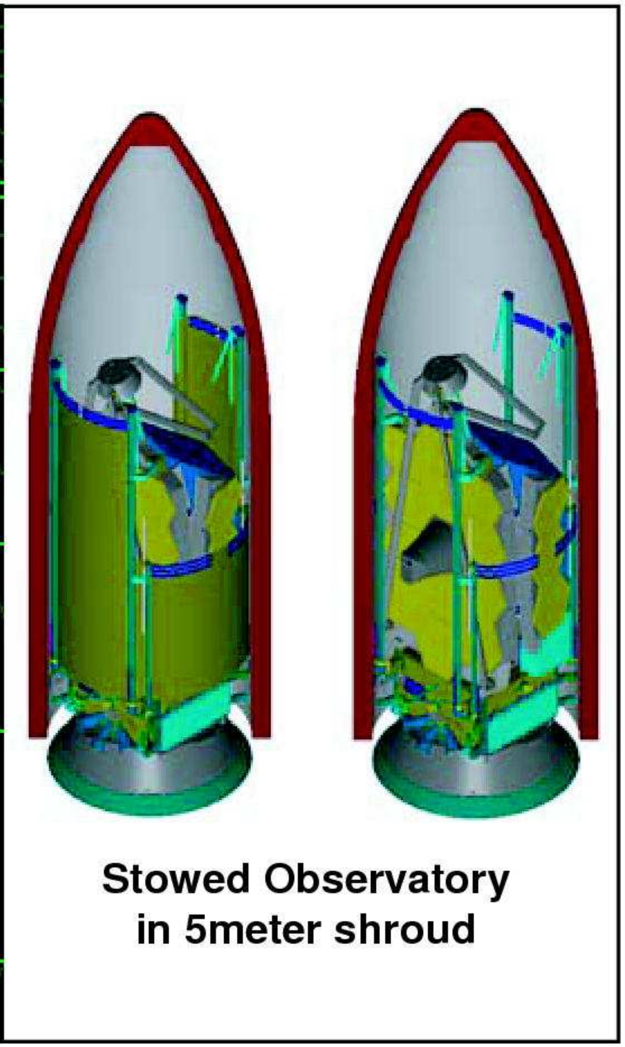
- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6 to 28 μm, to be launched in $\gtrsim$2013.
- Nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31.5) and spectroscopy (AB$\lesssim$29 mag).



Life size model of JWST on the Capitol Mall, May 2007 ...

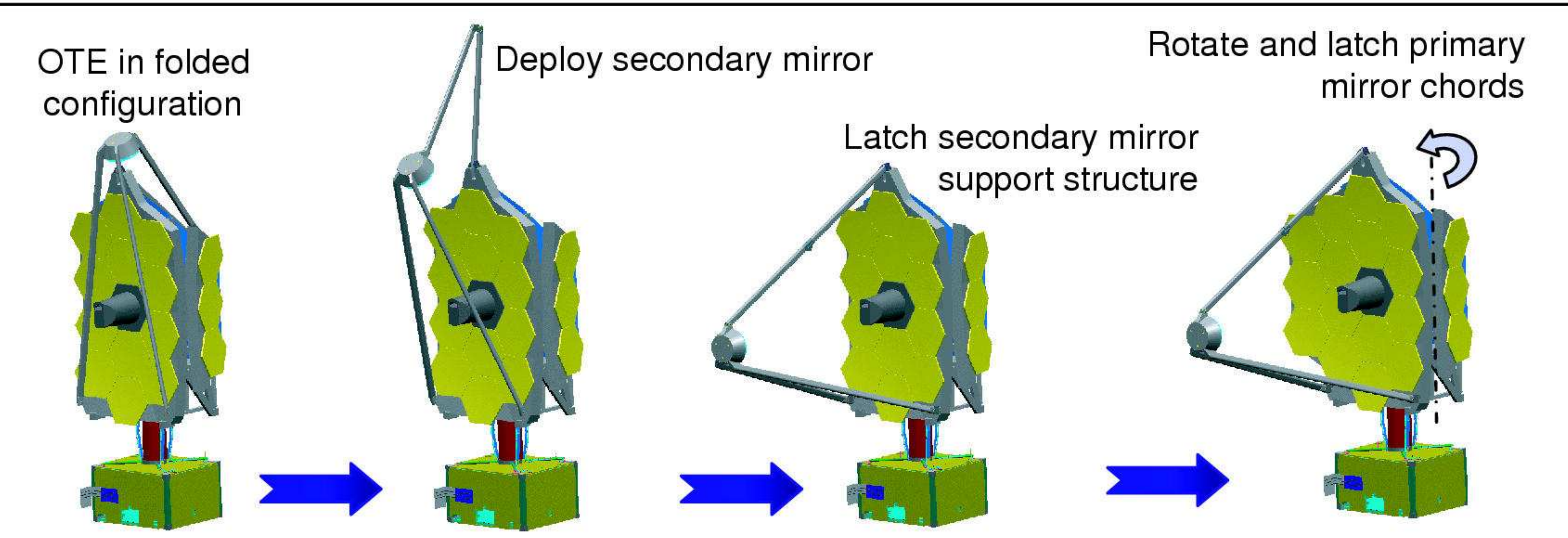
(3a) How will JWST travel to its L2 orbit?





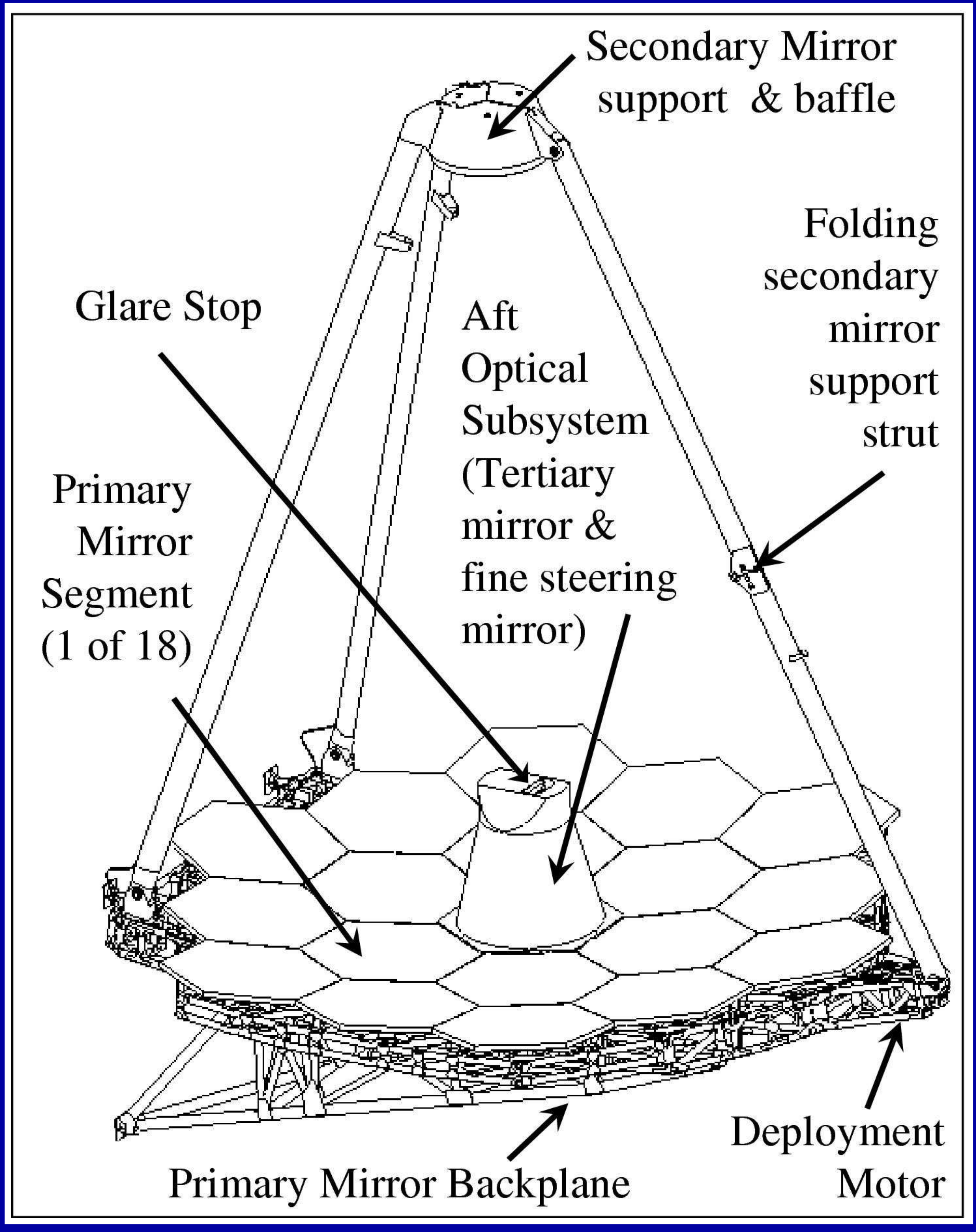
- After launch in June 2013 with an Ariane-V, JWST will orbit around the the Earth–Sun Lagrange point L2, 1.5 million km from Earth.
- JWST can cover the whole sky in segments that move along with the Earth, observe $\gtrsim$70% of the time, and send data back to Earth every day.

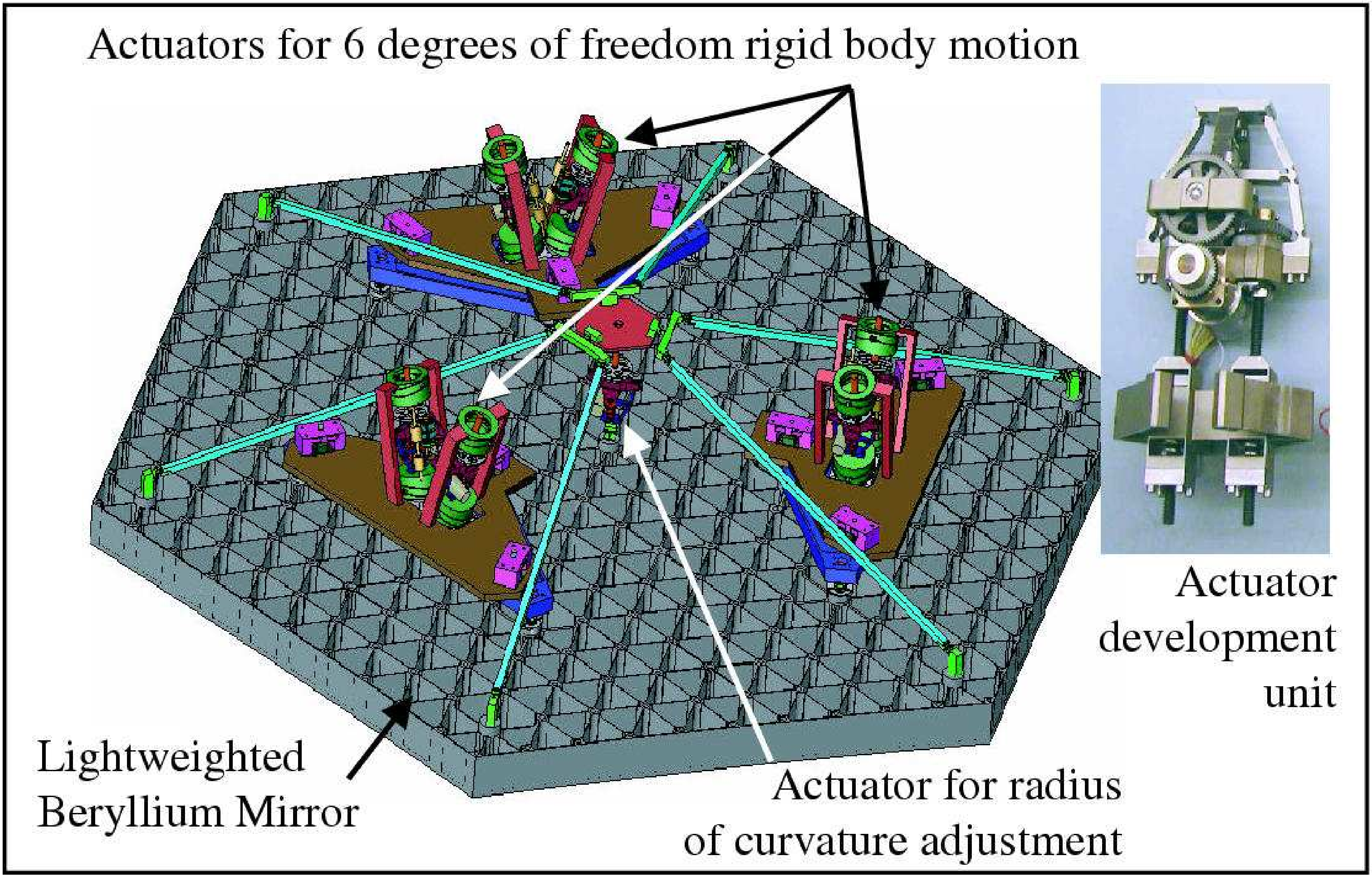
(3b) How will JWST be automatically deployed?



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

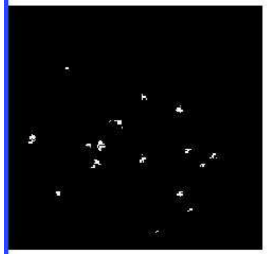
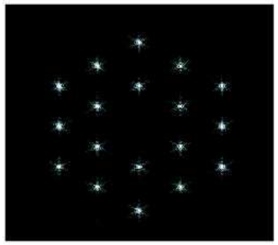
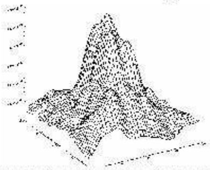
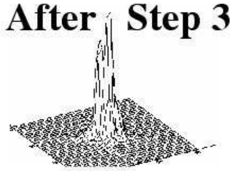
- The entire JWST deployment sequence can and will be tested several times on the ground — but only in 1-G.


Secondary Mirror support & baffle
Folding secondary mirror support strut
Glare Stop
Aft Optical Subsystem (Tertiary mirror & fine steering mirror)
Primary Mirror Segment (1 of 18)
Deployment Motor
Primary Mirror Backplane



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

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

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 Wave Front Sensing & Control similar to the Keck telescopes.

Successful 2006 demo of H/W, S/W on 6/1 scale model (Encirc. En. $\gtrsim$0.85).

Need WFS-updates every 10 days, depending on scheduling and illumination.

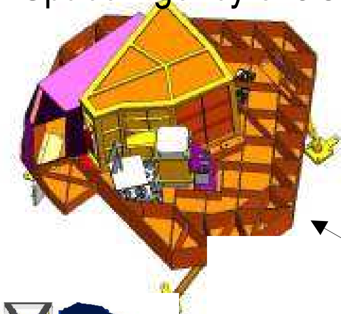
Ball 1/6-scale model: WFS produces diffraction-limited images at 2.0 μm.

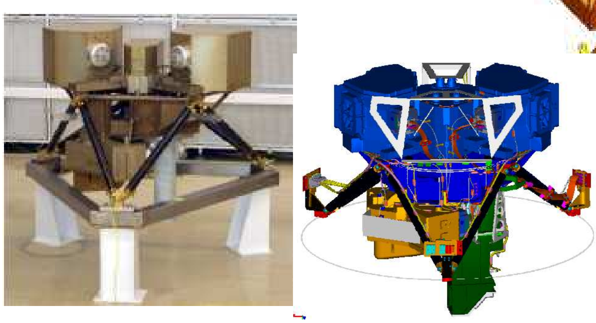
(3c) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

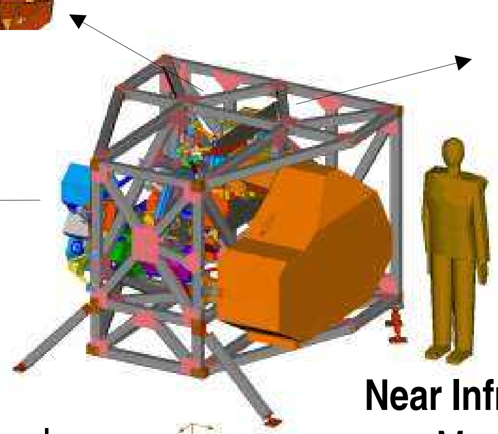
Instrument Overview

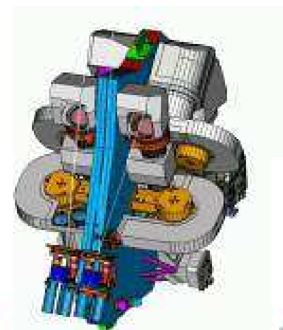
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

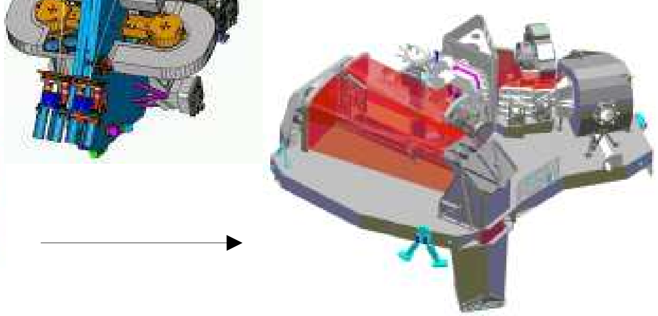
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC









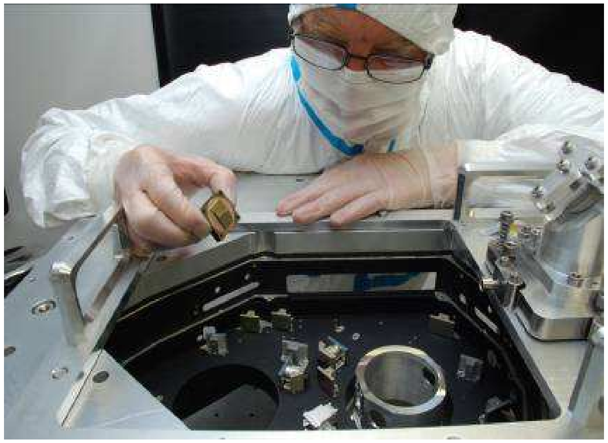


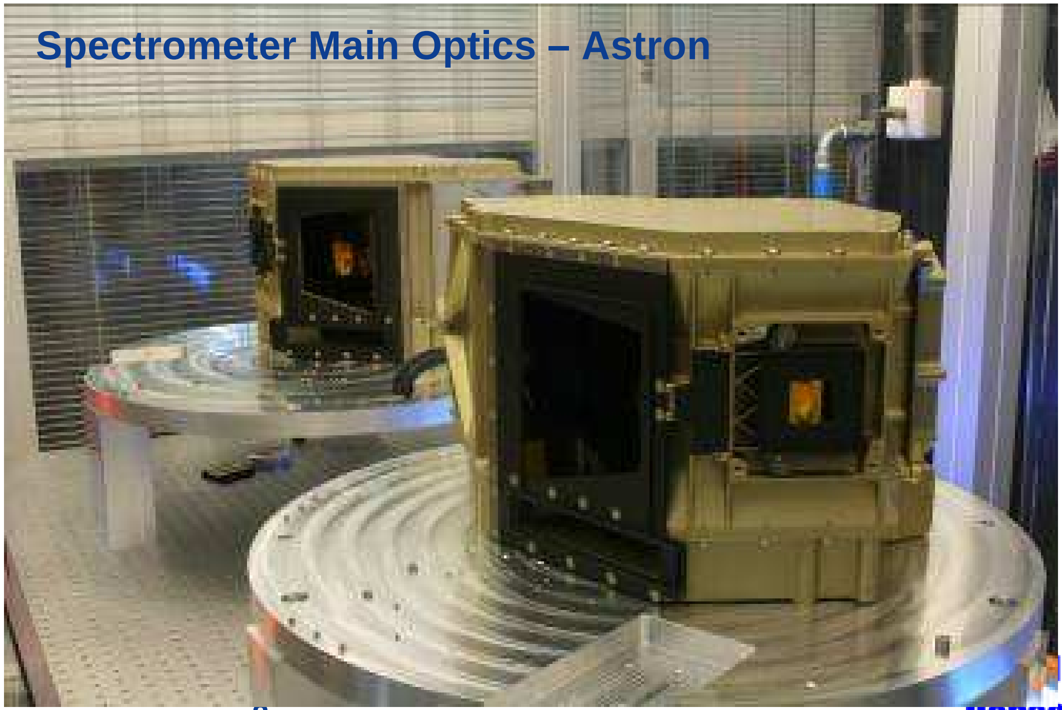
Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

Flight Model Hardware – Spectrometer

SPO – UK Astronomy Technology Centre





Spectrometer Main Optics – Astron

JPL
Jet Propulsion Laboratory
California Institute of Technology

...ropean Consortium

MIRI: The EU 5–28μm Mid-InfraRed Instrument (PI: Dr. G. Wright, UK).

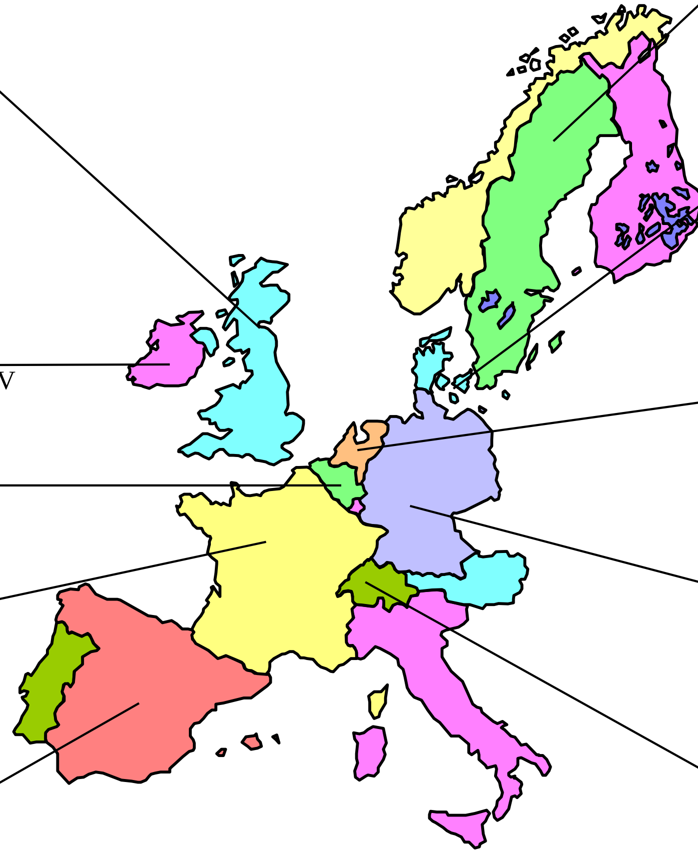
NL MIRI contributions from ASTRON (Dwingeloo), TH Delft, RU-Leiden.

European Consortium Who & Where

ATC — **Principal Investigator**
Optical Engineering
Spectrometer Pre-Optics
(SPO)
Calibration Sources
Astrium Ltd. — Consortium Management
PA Coordination
System Engineering
U. of Leicester — Mechanical Engineering
Primary Structure
MGSE
RAL — Thermal Engineering &
Hardware
Optical Bench Assembly AIV
DIAS — Filters

CSL — Input, Optics & Calibration (IOC)
Instrument Control Electronics
(ICE)
Imager Mirrors
U. of Leuven — EGSE Software Support
CEA — Imager
LESIA/LAM — Coronograph

INTA — MIRI Telescope Simulator (MTS)



U. of Stockholm — Filters and Gratings

DSRI — Hexapod

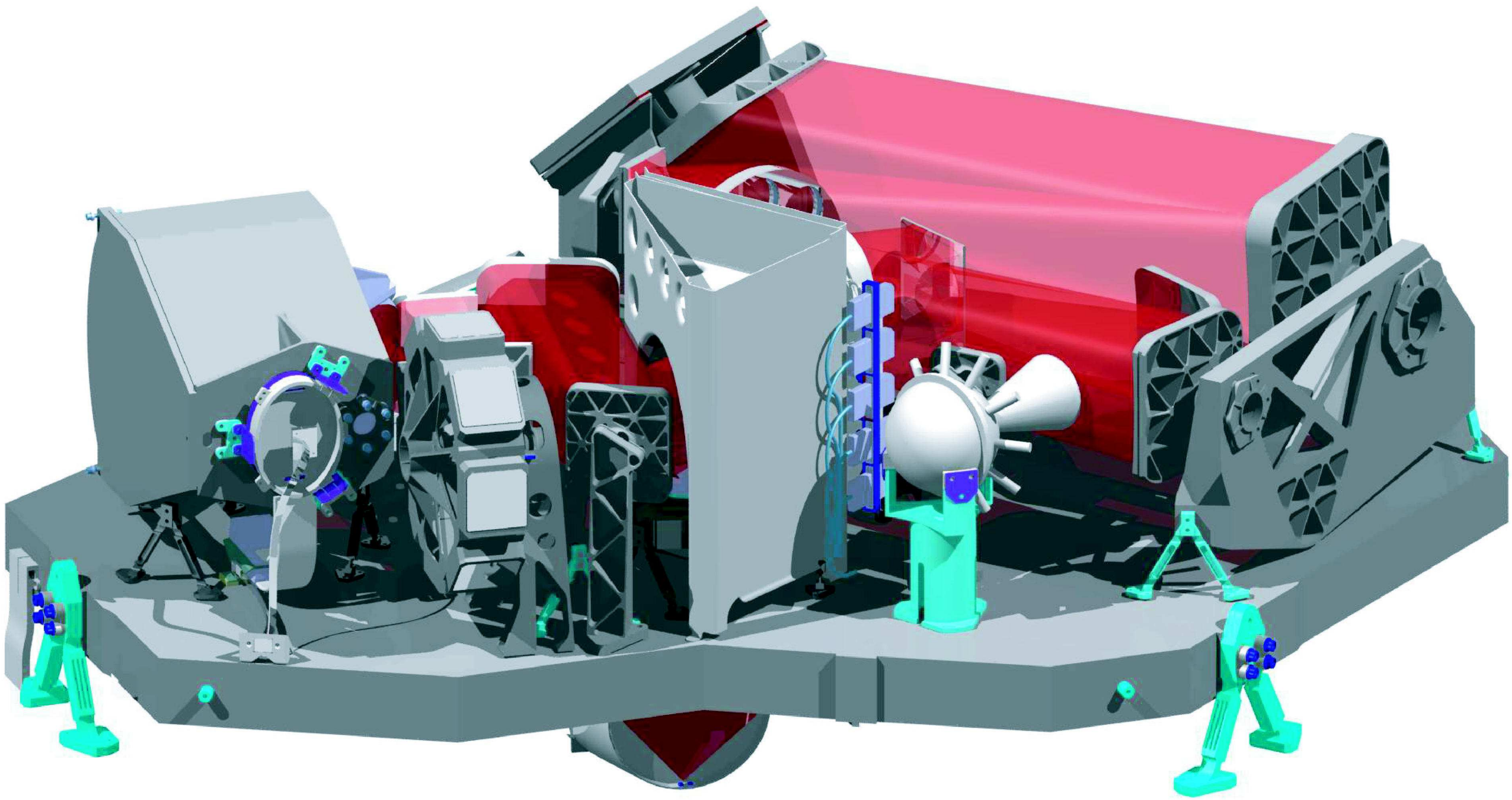
ASTRON — Spectrometer Main Optics (SMO)
U. Leiden — Spectroscopy Analysis

MPIA Heidelberg — Electrical Engineering
Cryo Mechanisms
U. of Köln — Low Resolution Spectrometer
Double Prism

PSI — Contamination Control
Cover
Cryo Harness

NASA/GSFC — JWST Project Office
Spacecraft
Integrated Science Instrument Module (ISIM)
JPL — Detector System
Flight Software
Cryo-Cooler

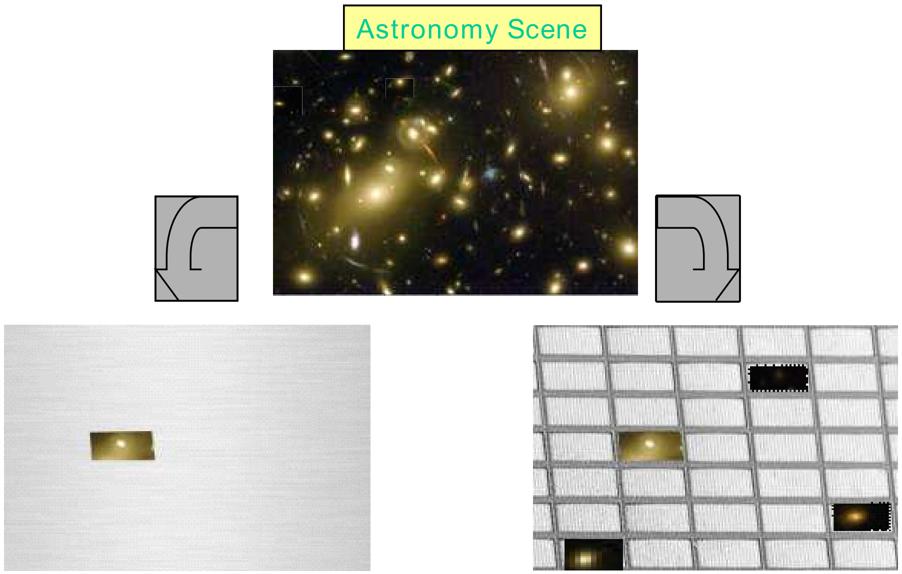
ESA/ESTEC Office — JWST Project
Prodex Office



NIRSpec: the ESA NIR-Spectrograph, made at ESTEC & Astrium/EADS

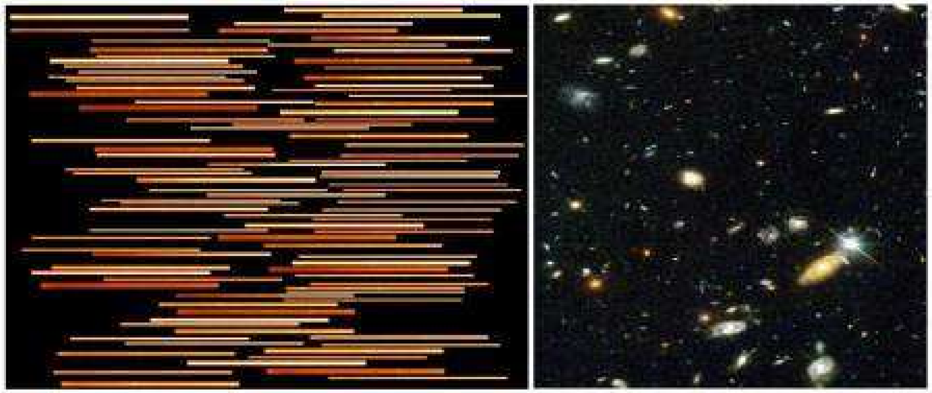
PI: Dr. Peter Jakobsen (ESTEC, Noordwijk, the Netherlands).

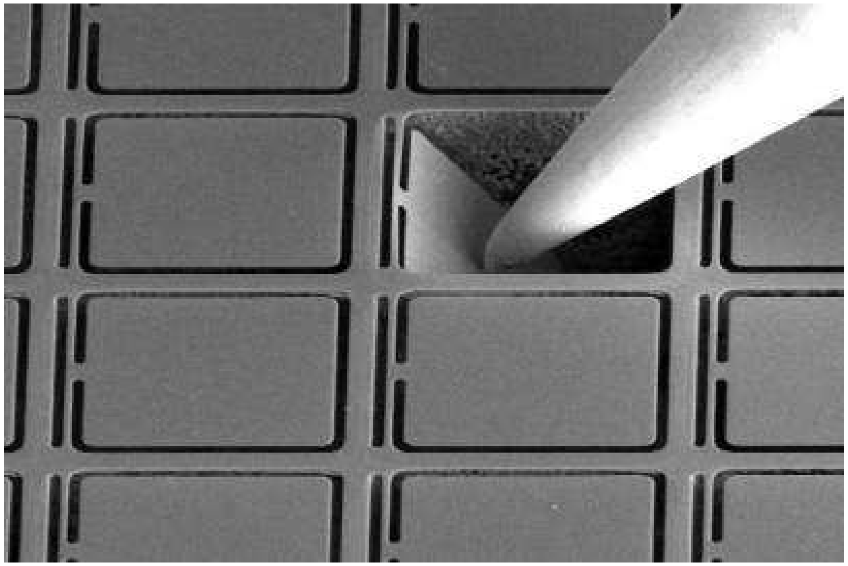
Micro Shutters

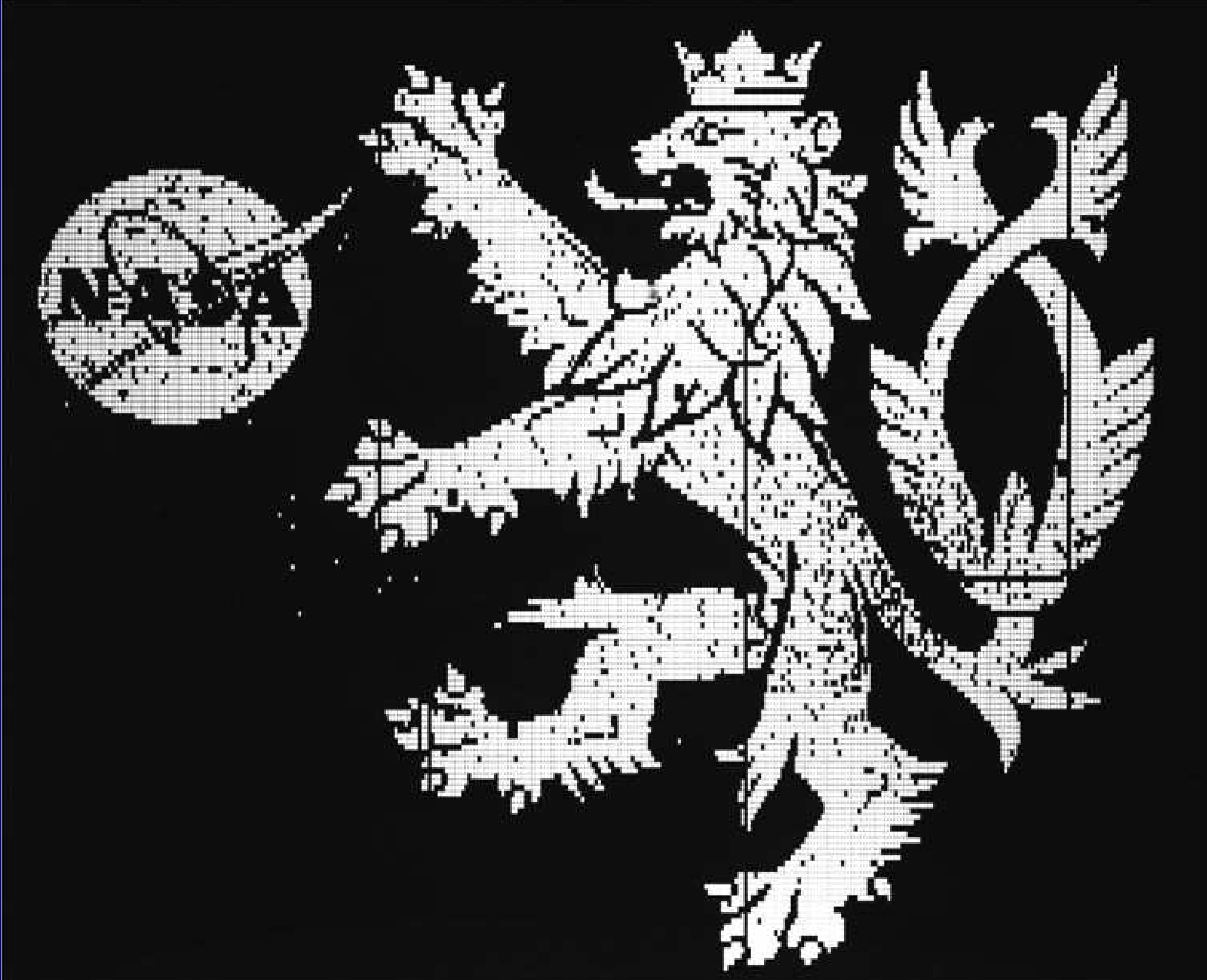


Metal Mask/Fixed Slit

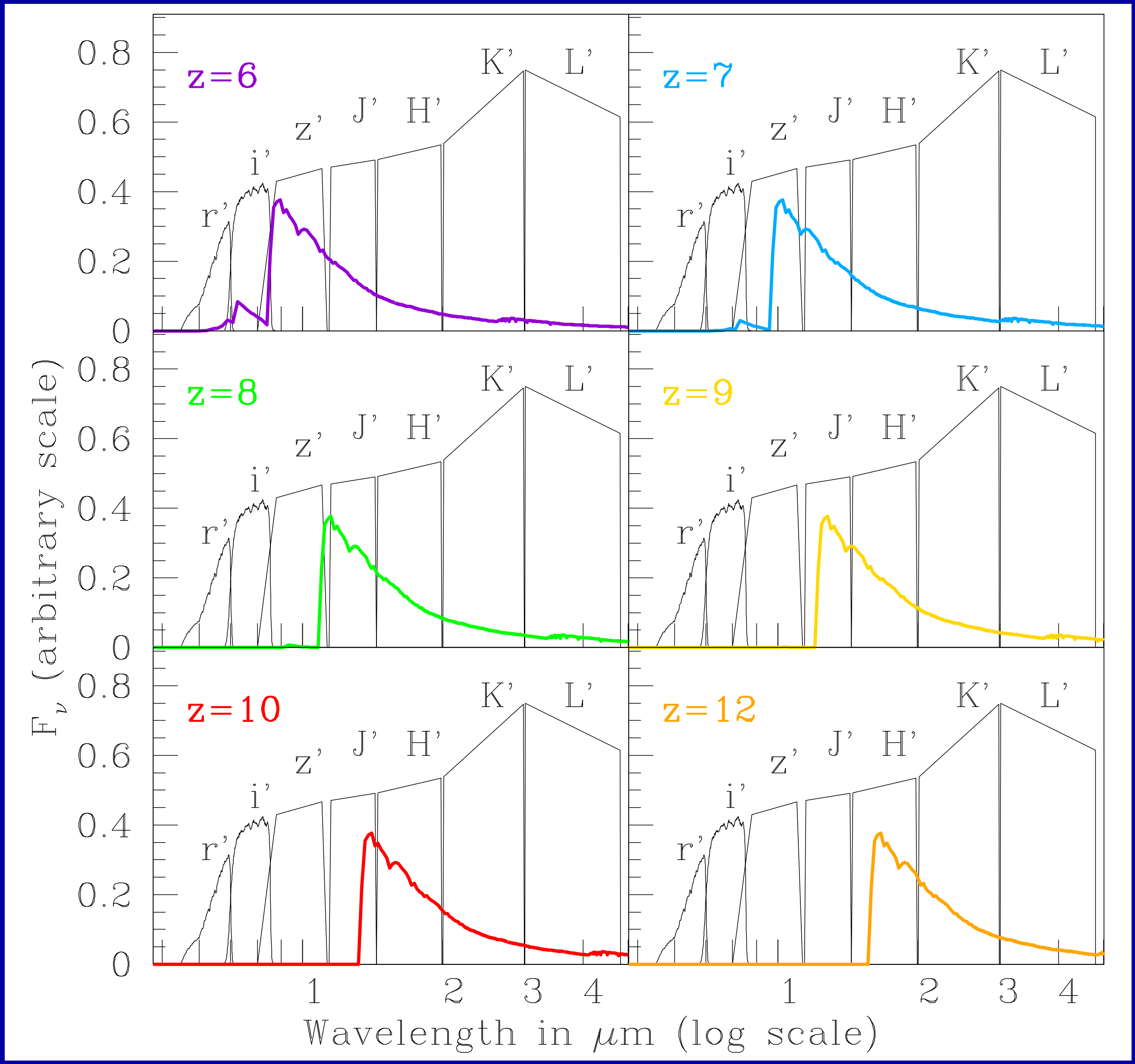
Shutter Mask






NASA

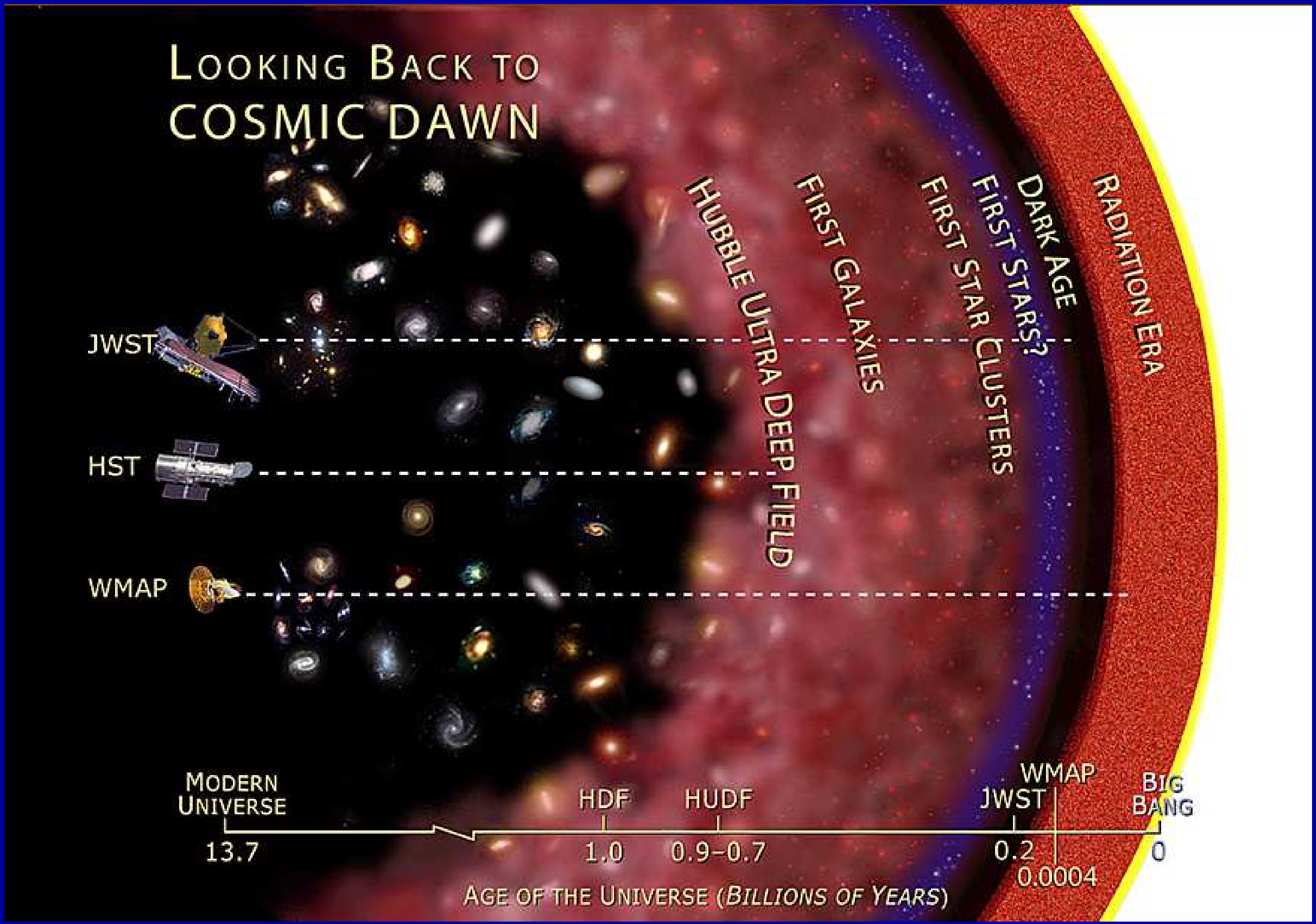
(4) How will JWST measure First Light & Reionization?



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

$\Rightarrow$ This is why JWST needs NIRCam at 0.8–5 μm and MIRI at 5–28 μm.

(4a) What is First Light and Reionization

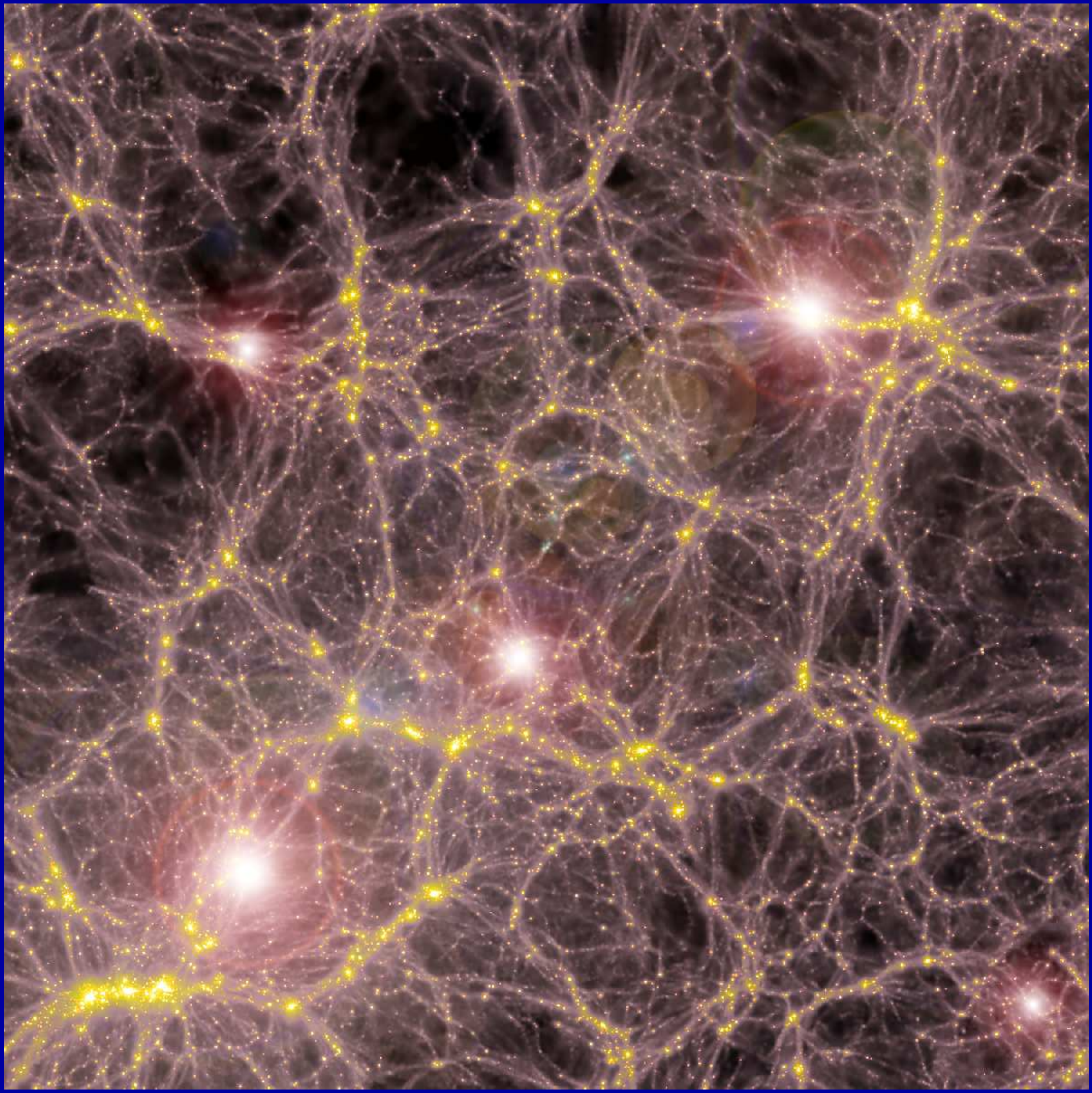


HST (+WFC3): Hubble sequence & galaxy assembly from z≃0 to z≃7–8.

JWST: First Light, Reionization, & (dwarf) galaxy assembly at z≃8–20.

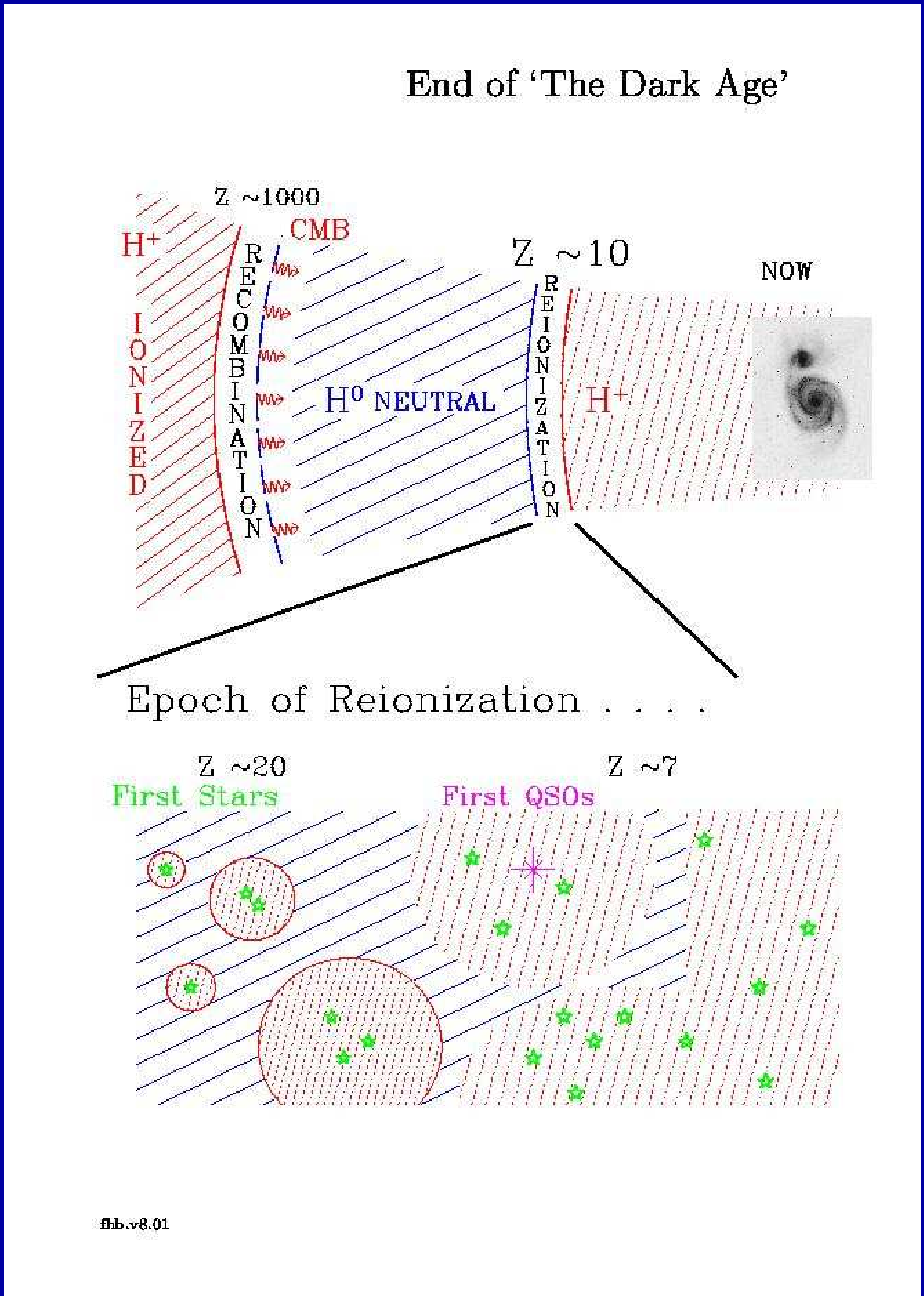
WMAP: Hydrogen Recombination at z=1091±1 (age=385,000 yrs).

(4a) What is 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 top JWST as the first massive stars and surrounding star clusters, and perhaps their extremely luminous supernovae at $z \simeq 10 \longrightarrow 30$.



WMAP: First Light may have happened as following:

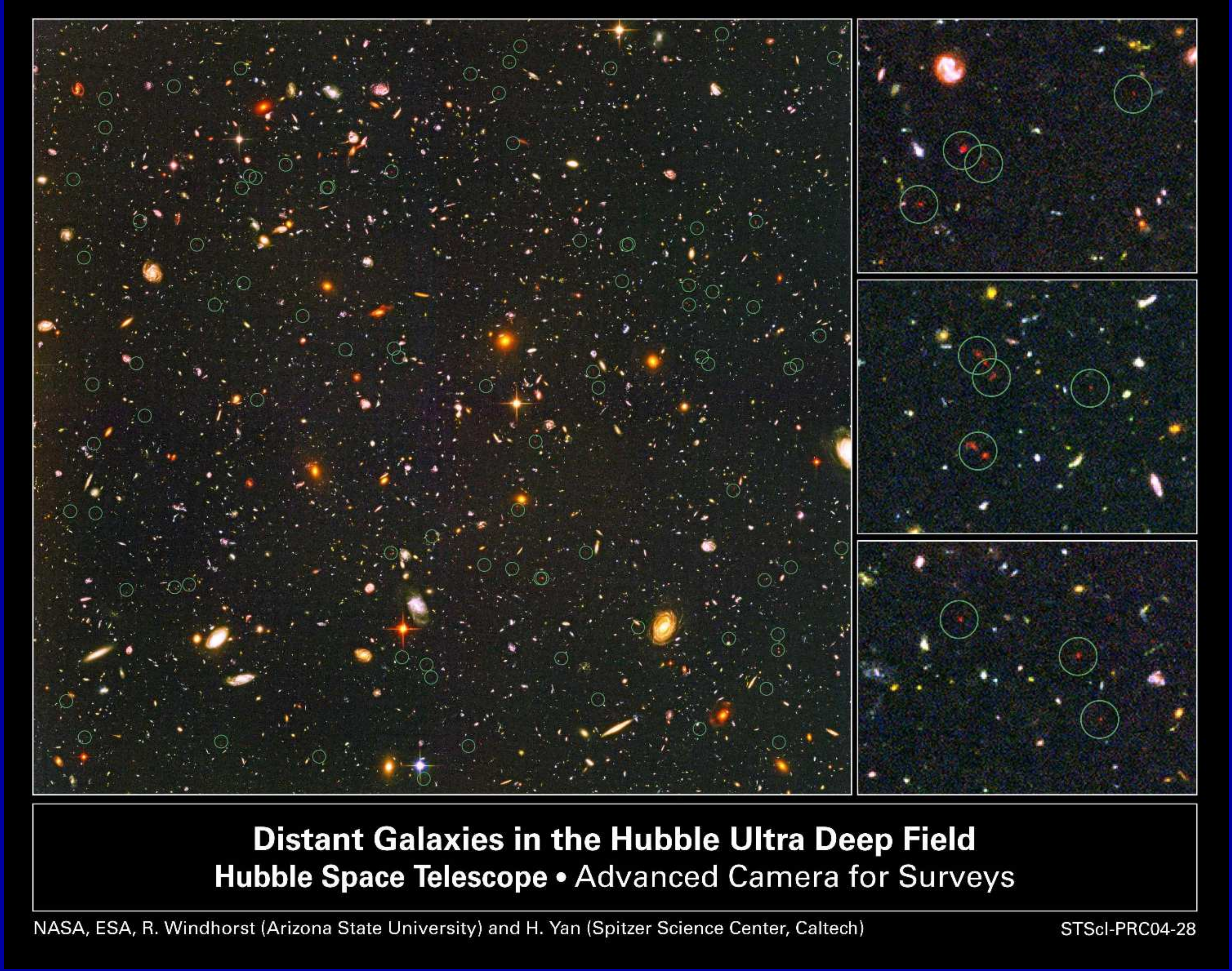
- (1) Dark Ages since recombination (z=1091) until "First Light" objects started shining (z$\gtrsim$11–20):

- (2) Pop III stars with mass$\gtrsim$100–200 $M_\odot$. Their supernovae heated Intergalactic Medium (IGM).

- (3) IGM could not cool and form Pop II halo stars until z$\simeq$9–10.

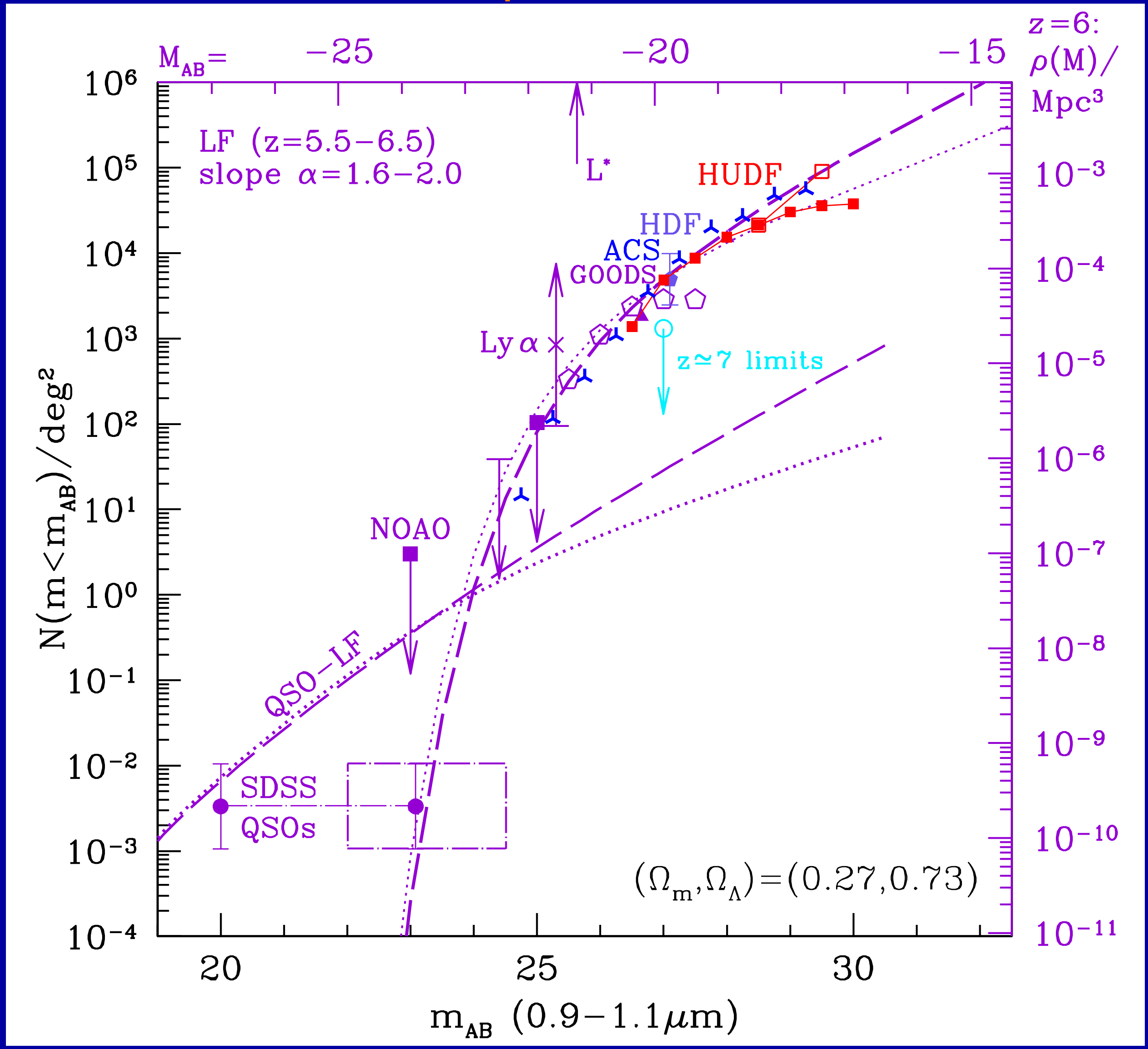
- (4) Delayed onset of Pop II stars in dwarf galaxies finished cosmic reionization at z$\simeq$6 (age$\simeq$1 Gyr).

(Fig. courtesy of Dr. F. Briggs)



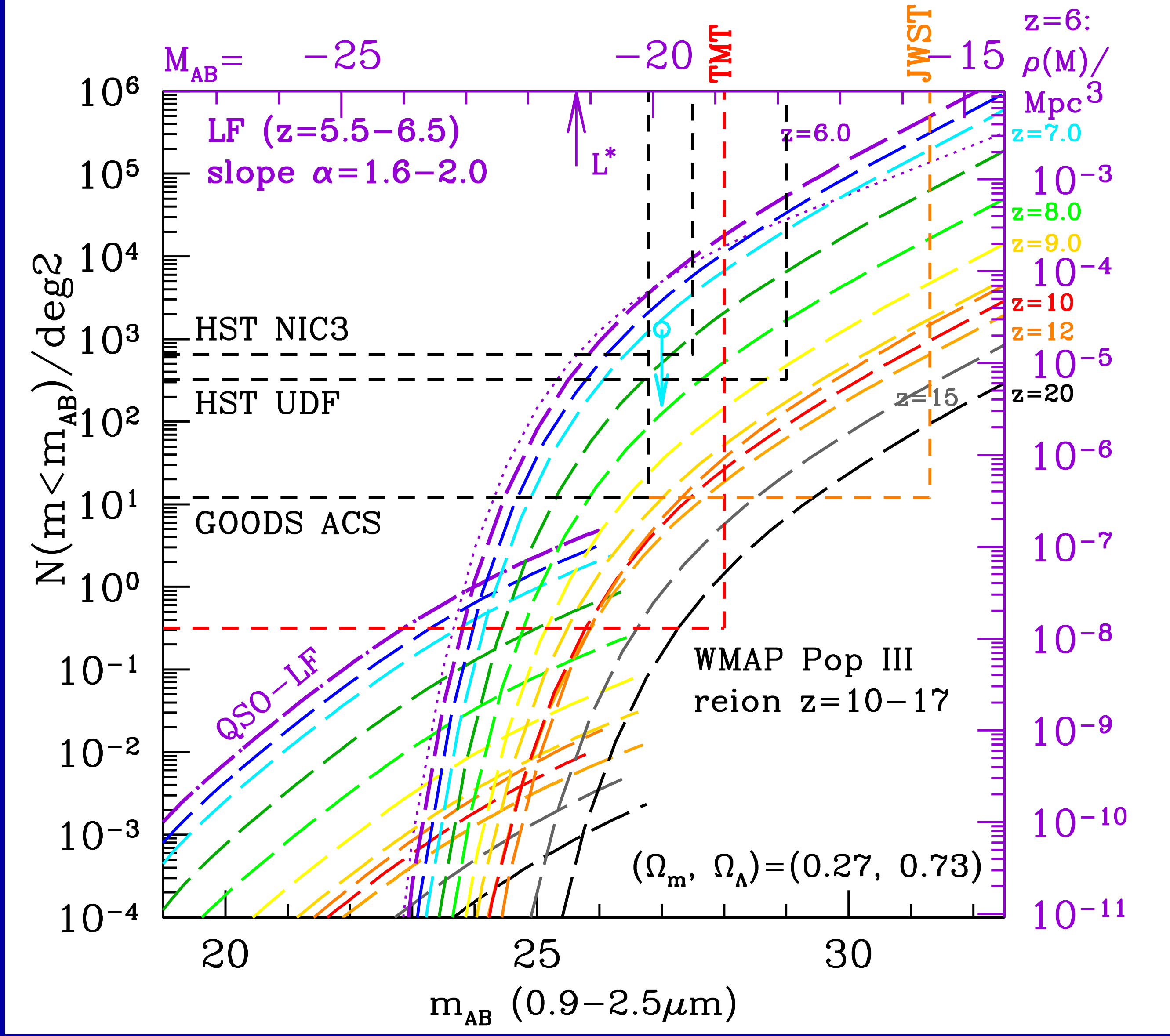
HUDF i-drops: faint galaxies at z$\simeq$6 (Yan & Windhorst 2004), most spectroscopically confirmed at z$\simeq$6 to AB$\lesssim$27.0 mag (Malhotra et al. 2005).

First Light and Reionization: Map the Cosmic Stock Market of Objects.



HUDF shows that luminosity function of z≃6 objects (Yan & Windhorst 2004a, b) may be very steep: faint-end slope $|\alpha|\lesssim 2.0$ (Olbers!).

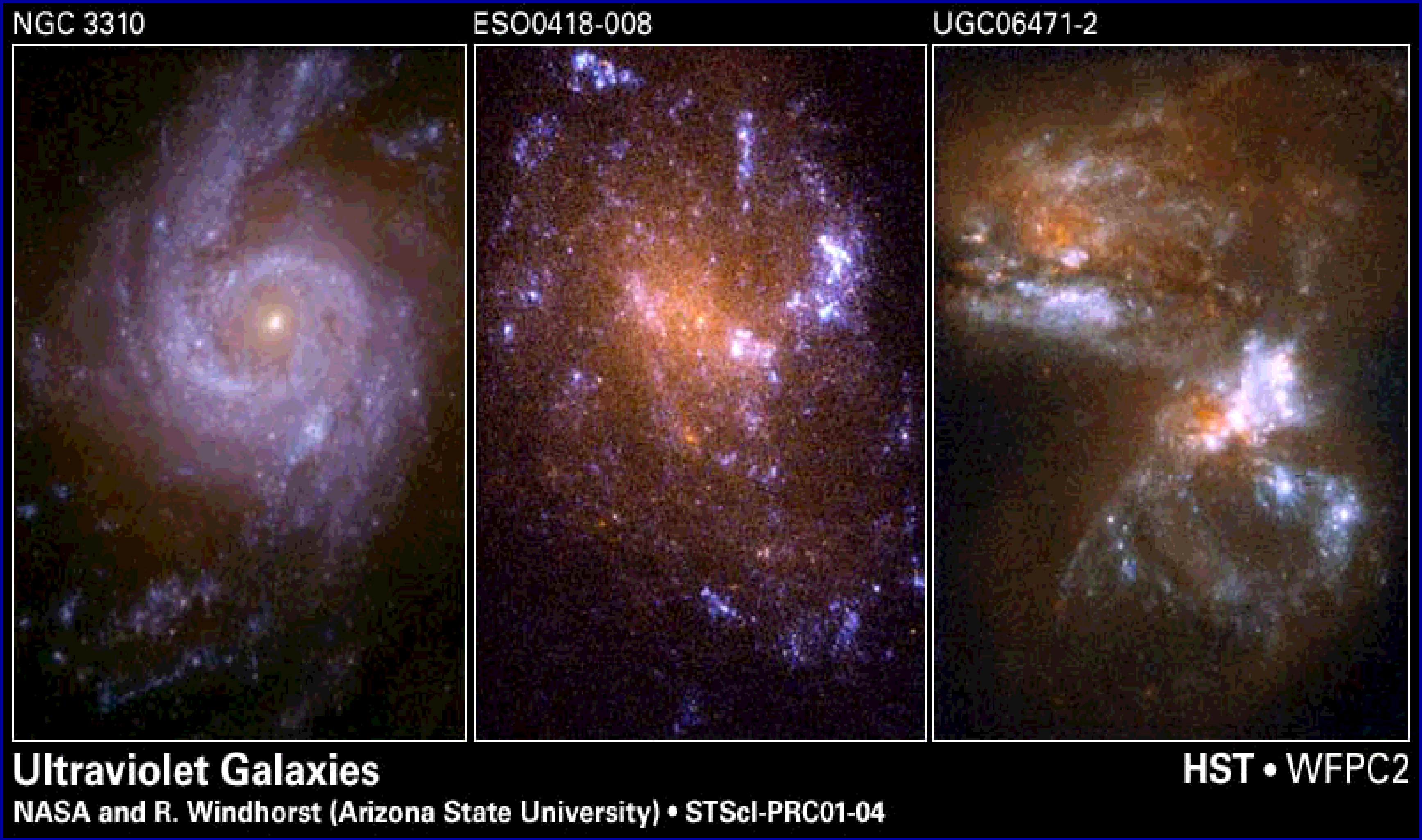
⇒ Dwarf galaxies and not quasars likely completed reionization at z≃6. This is what JWST will observe in detail for z$\gtrsim$7–20.



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

• Objects at z$\gtrsim$9 are rare, since volume/Δz is small and JWST samples brighter part of LF. JWST needs sufficient sensitivity/aperture (A), field-of-view (FOV=Ω), and λ-range (0.7-28 μm) to see "First Light".

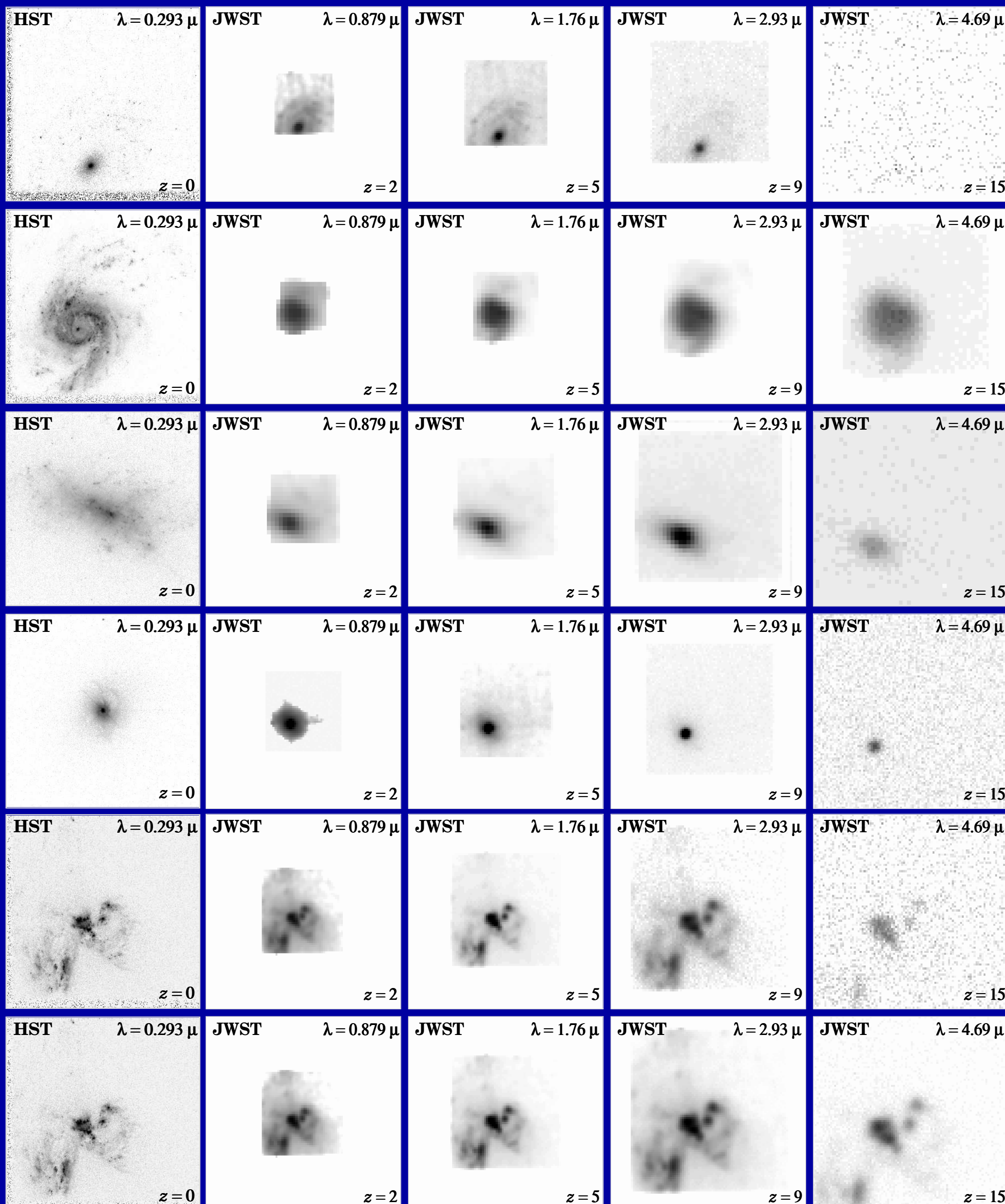
(5) HST UV-images predict galaxy appearance for JWST at z≃1–15



- The uncertain rest-frame UV-morphology of galaxies is dominated by young and hot stars, with often copious amounts of dust superimposed.
- This complicates comparison with very high-z galaxies seen by JWST. Panchromatic images will enable quantitative analysis of the restframe-wavelength dependent galaxy structure.

(5) HST UV-images predict galaxy appearance for JWST at z≃1–15.

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



Using restframe-UV images for comparison, JWST can measure evolution of galaxy structure over a wide range of cosmic time:

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

Visible to JWST at very high z are:

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

(6) Conclusions

(1) HST established how galaxies formed and evolve in the last 12.7 Gyrs:

• Galaxies of all Hubble types formed over a wide range of time, but with a notable transition around $z \simeq 1.0$ when Hubble sequence forms:

• Subgalactic units rapidly merge from $z \simeq 7 \longrightarrow 1$ to grow bigger units.

• Merger products settle as galaxies with large bulges or disks at $z \lesssim 1$.

(2) JWST passed major mission milestones in 2008. After 2013, will map the epochs of First Light, Reionization, and Galaxy Assembly in detail:

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

• Faint-end evolution: how dwarf galaxies finished reionization after 1 Gyr.

(3) JWST will have a major impact on astrophysics after 2013:

• IR sequel to HST after 2013: Training the next generation researchers.

• JWST will define the next frontier to explore: the Dark Ages at $z \gtrsim 20$.

SPARE CHARTS

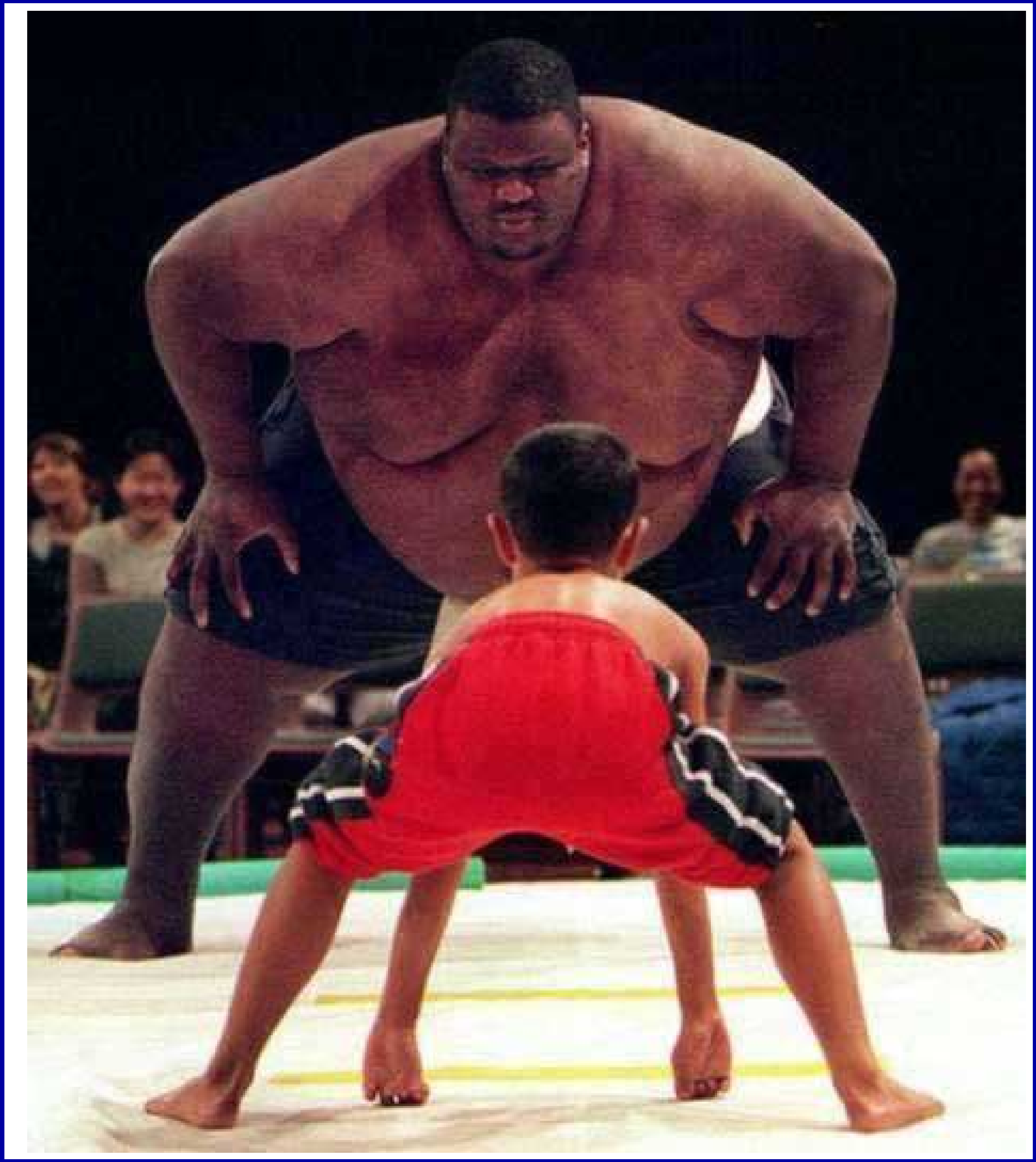
Some things are better left discussed during ...

Miller time!

Het Borrel uur!

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

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



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

What comes around, goes around ...

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/

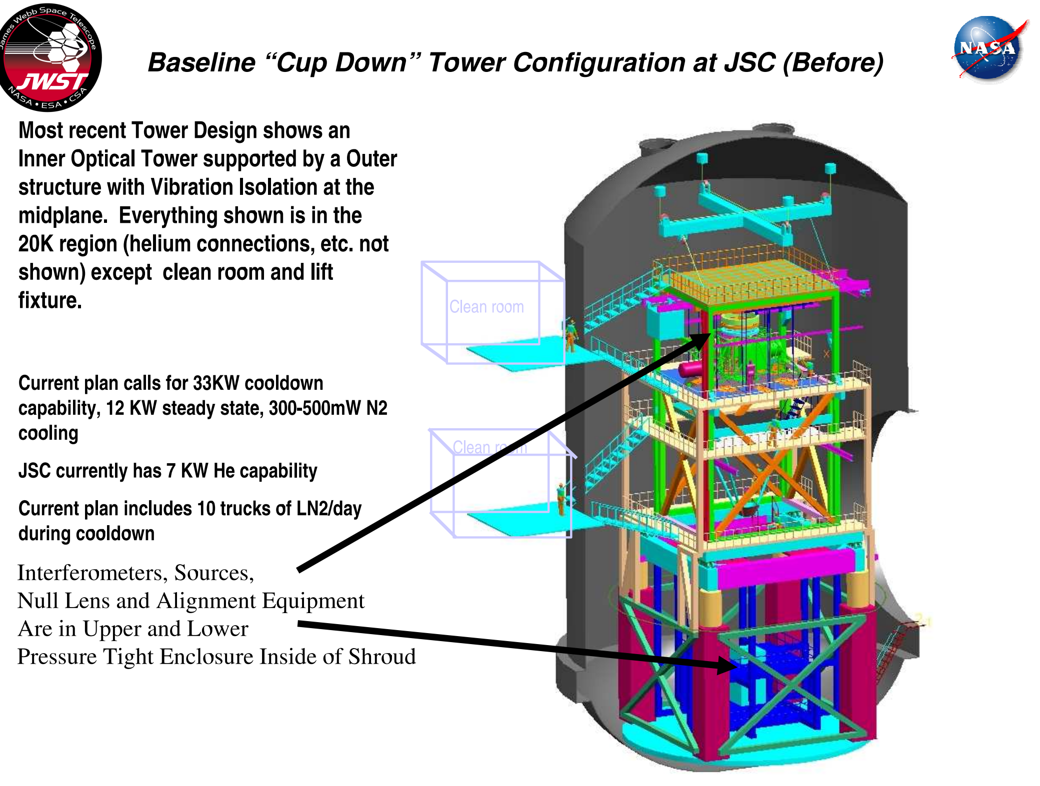
Gardner, J., Mather, J., Clampin, M., Doyon, R., Greenhouse, M., Hammel, H., Hutchings, J., Jakobsen, P., Lilly, S., Long, K., Lunine, J., McCaughrean, M., Mountain, M., Nella, J., Rieke, G., Rieke, M., Rix, H., Smith, E., Sonneborn, G., Stiavelli, M., Stockman, H., Windhorst, R., & Wright, G. 2006, Space Science Reviews, 123, 485 (astro-ph/0606175)

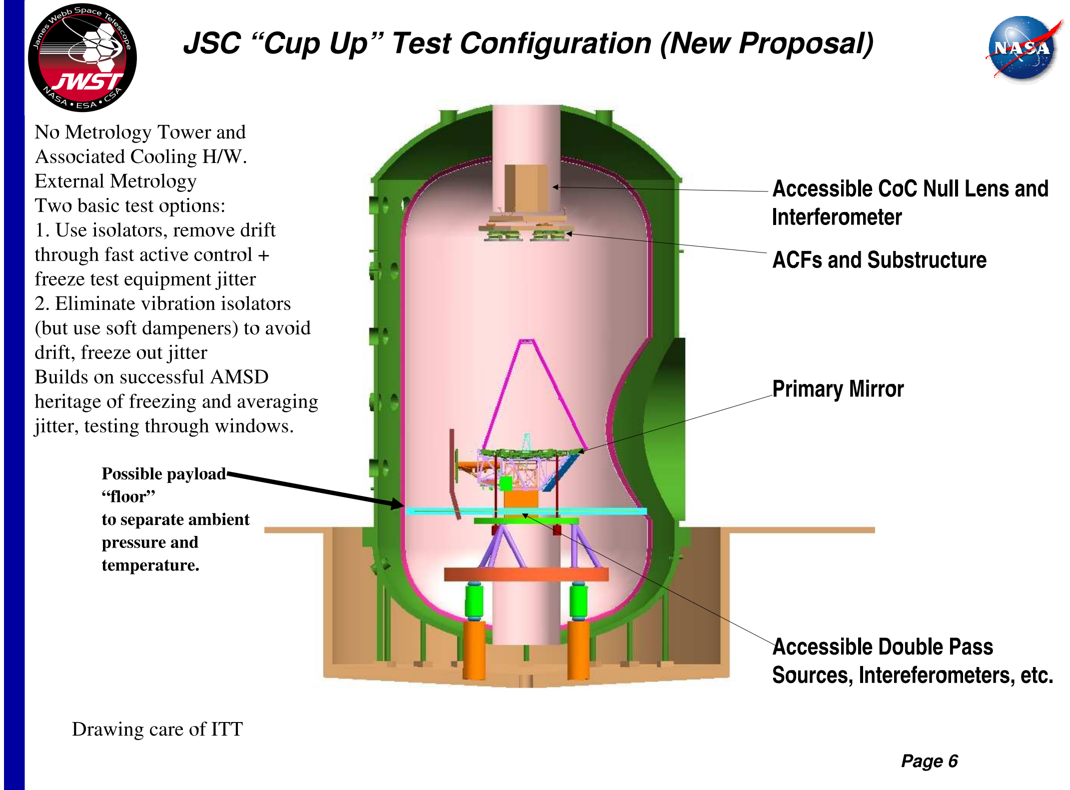
Mather, J., & Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

Windhorst, R., et al. 2007, Advances in Space Research, 42, 1–10 (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

Northrop Grumman Expertise in Space Deployable Systems

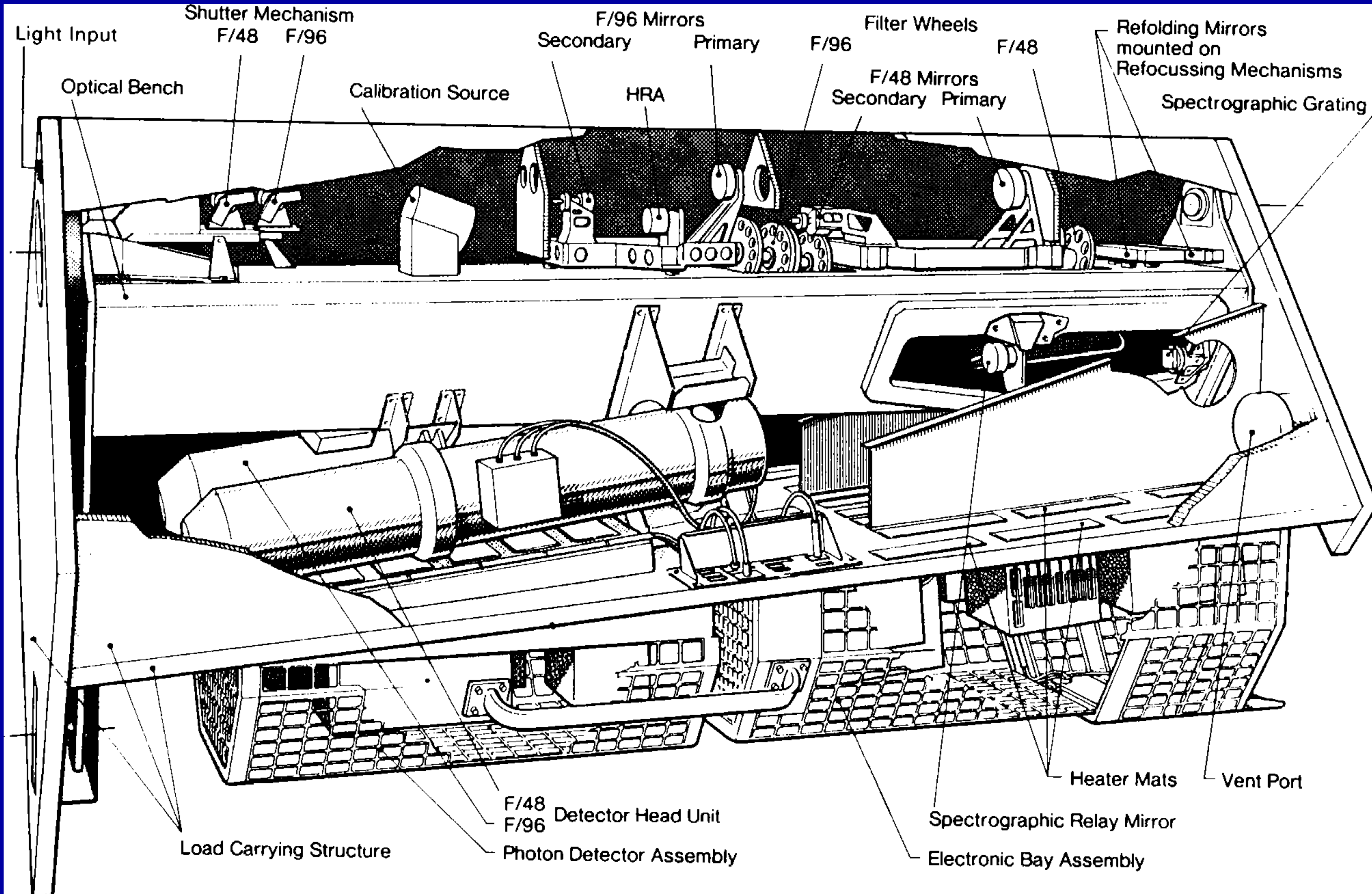
- Over 45 years experience in the design, manufacture, integration, verification and flight operation of spacecraft deployables
- 100% mission success rate, comprising over 640 deployable systems with over 2000 elements



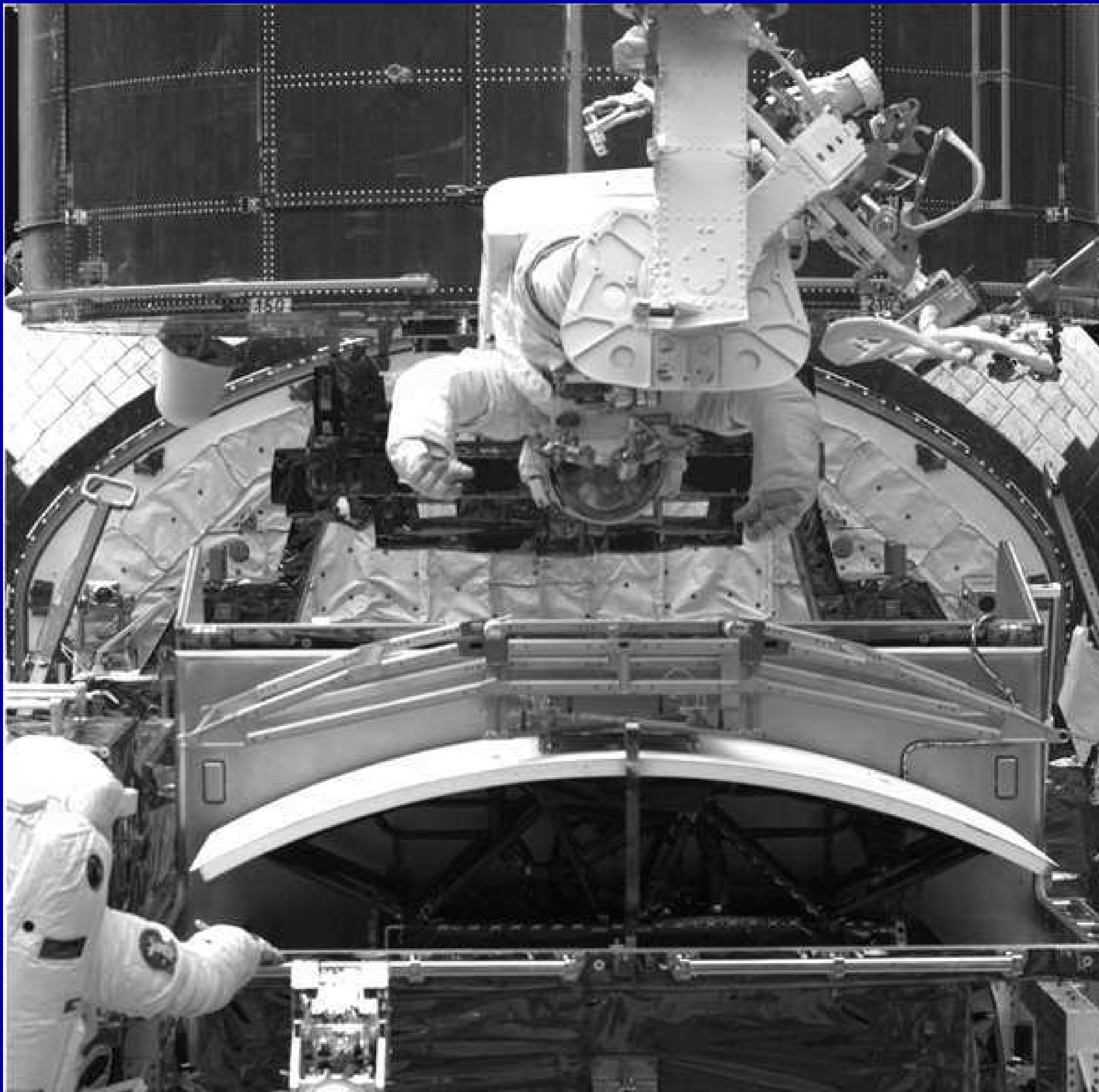


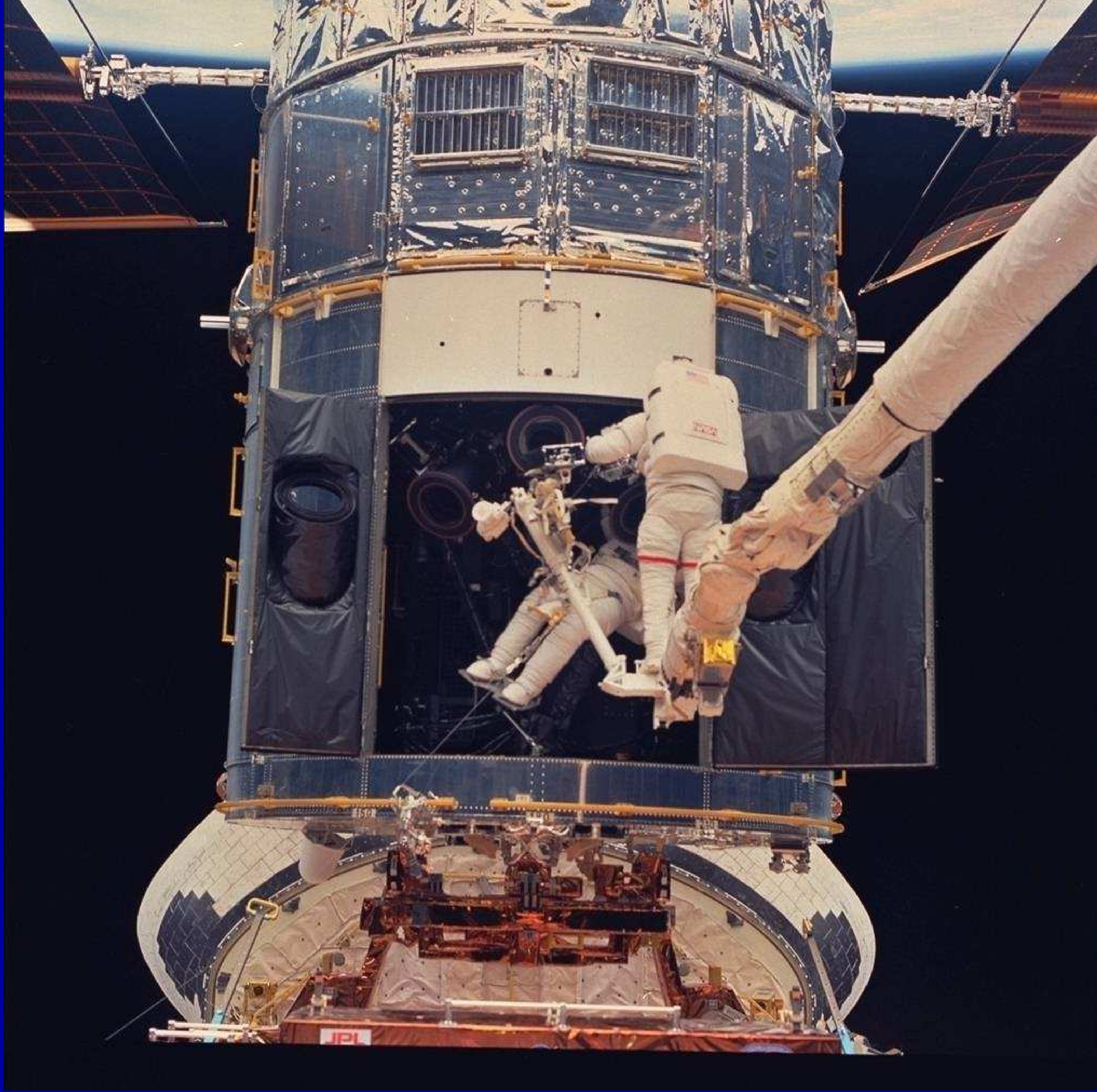
JWST underwent several significant replans and risk-reduction schemes:

- $\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.



- First ESA contribution to HST: Faint Object Camera (FOC; ESTEC)
- Concept in 1970's; Made in 1980's; Operate 1990–2002 (replaced during SM3B and returned to Earth).

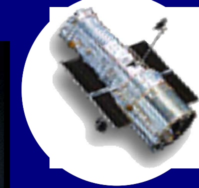




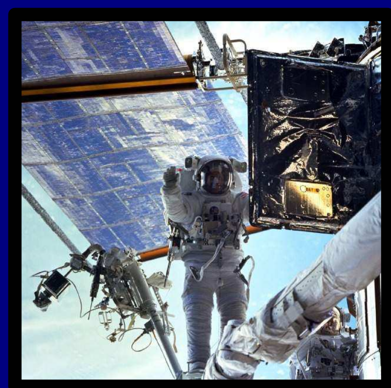

NASA

Goddard Space Flight Center

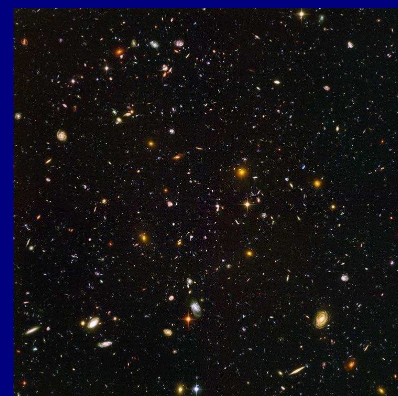
MISSION GOAL: Five working, complementary instruments for the first time since 1993; Hubble at its APEX.

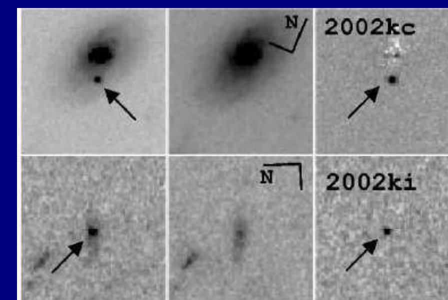


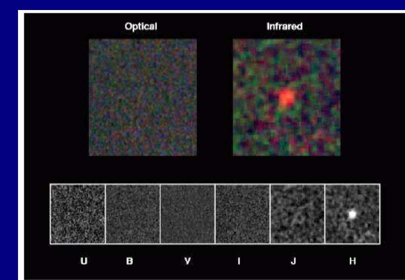
Batteries+Gyros+FGS = Sustained HST Lifetime



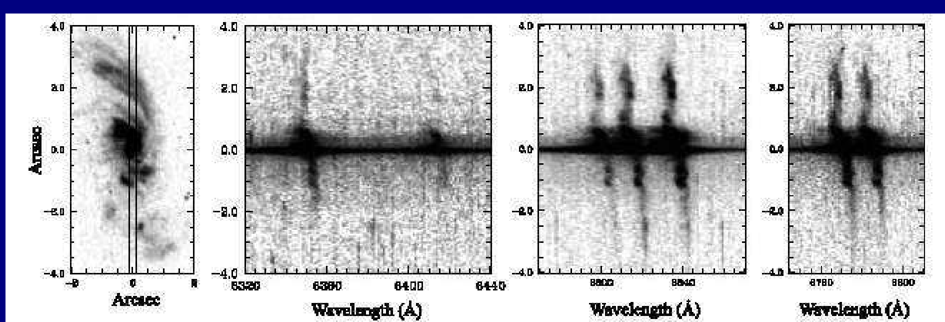
WFC3+ACS = Most powerful imaging ever

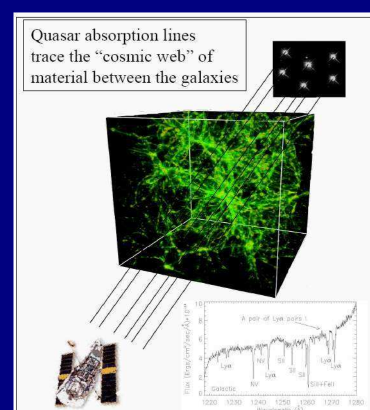


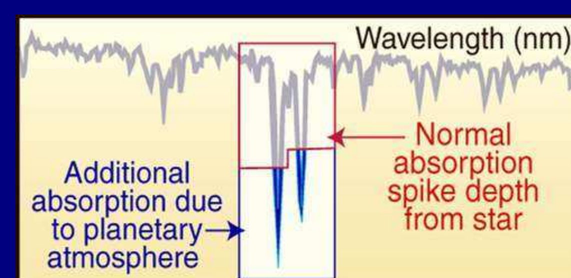




COS+STIS = Full set of tools for astrophysics

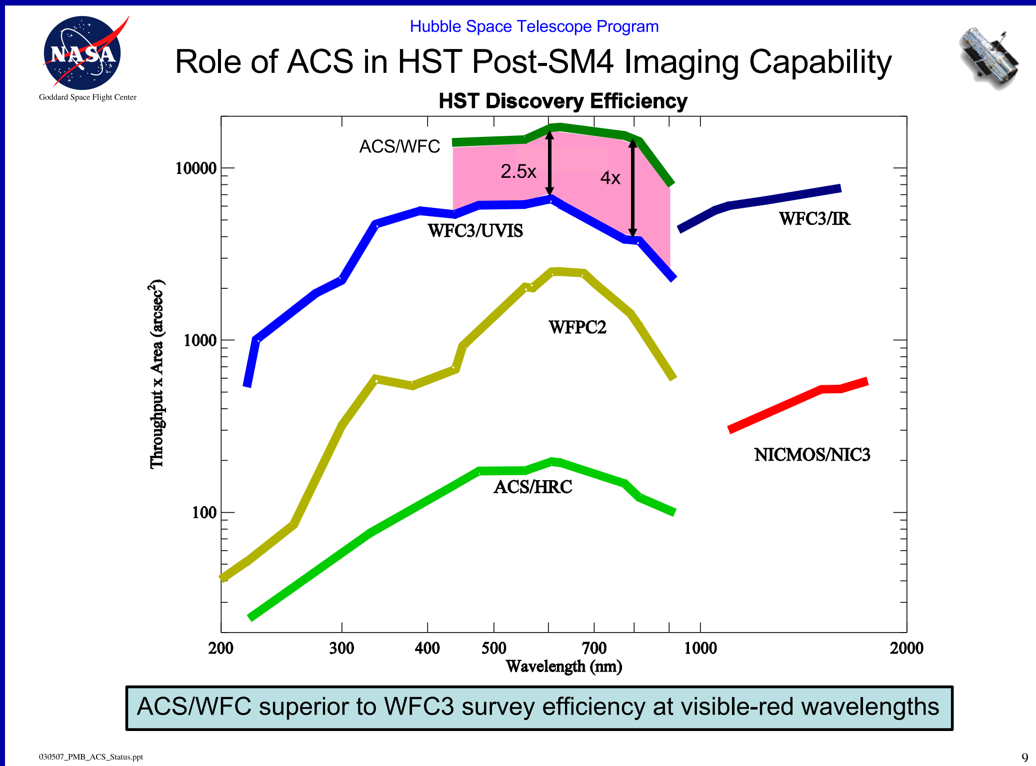


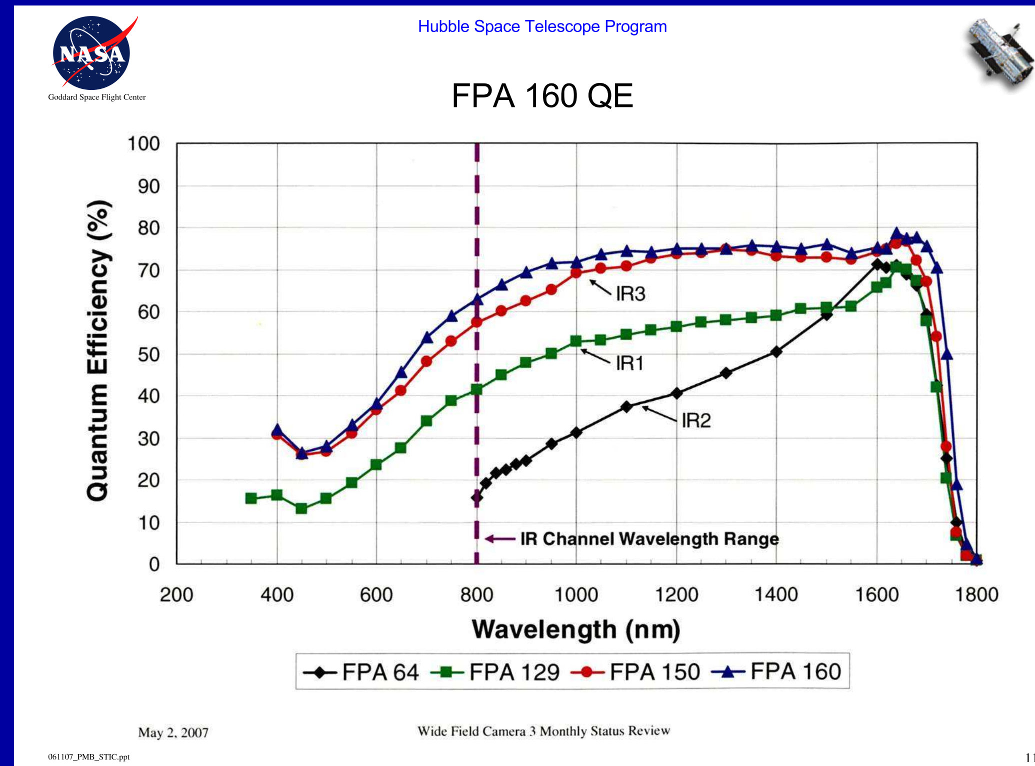




Future studies with the Hubble Wide Field Camera 3

WFC3: Hubble's new Panchromatic High-Throughput Camera





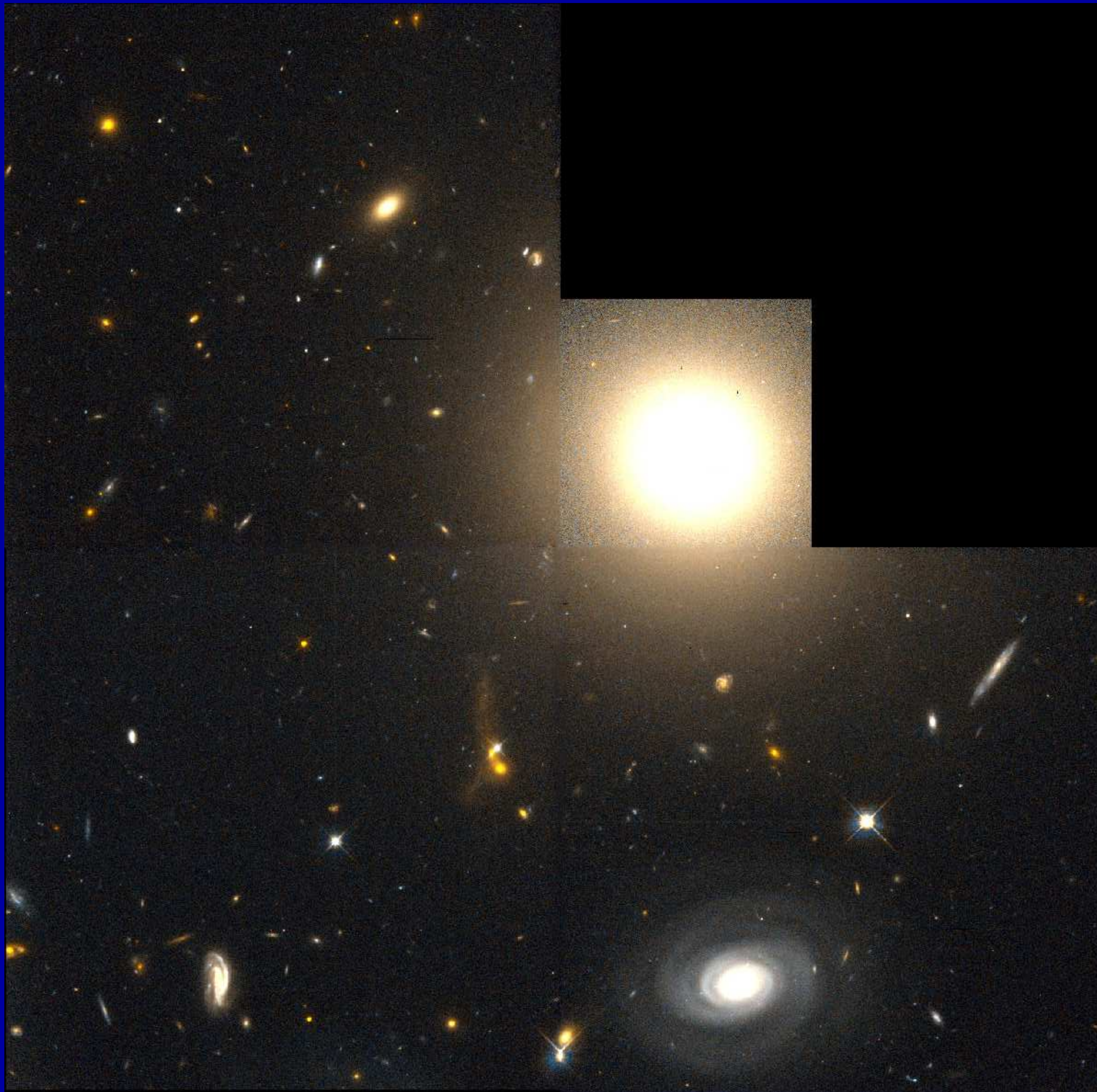
WFC3/UVIS channel has unprecedented UV–blue throughput & areal coverage:

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

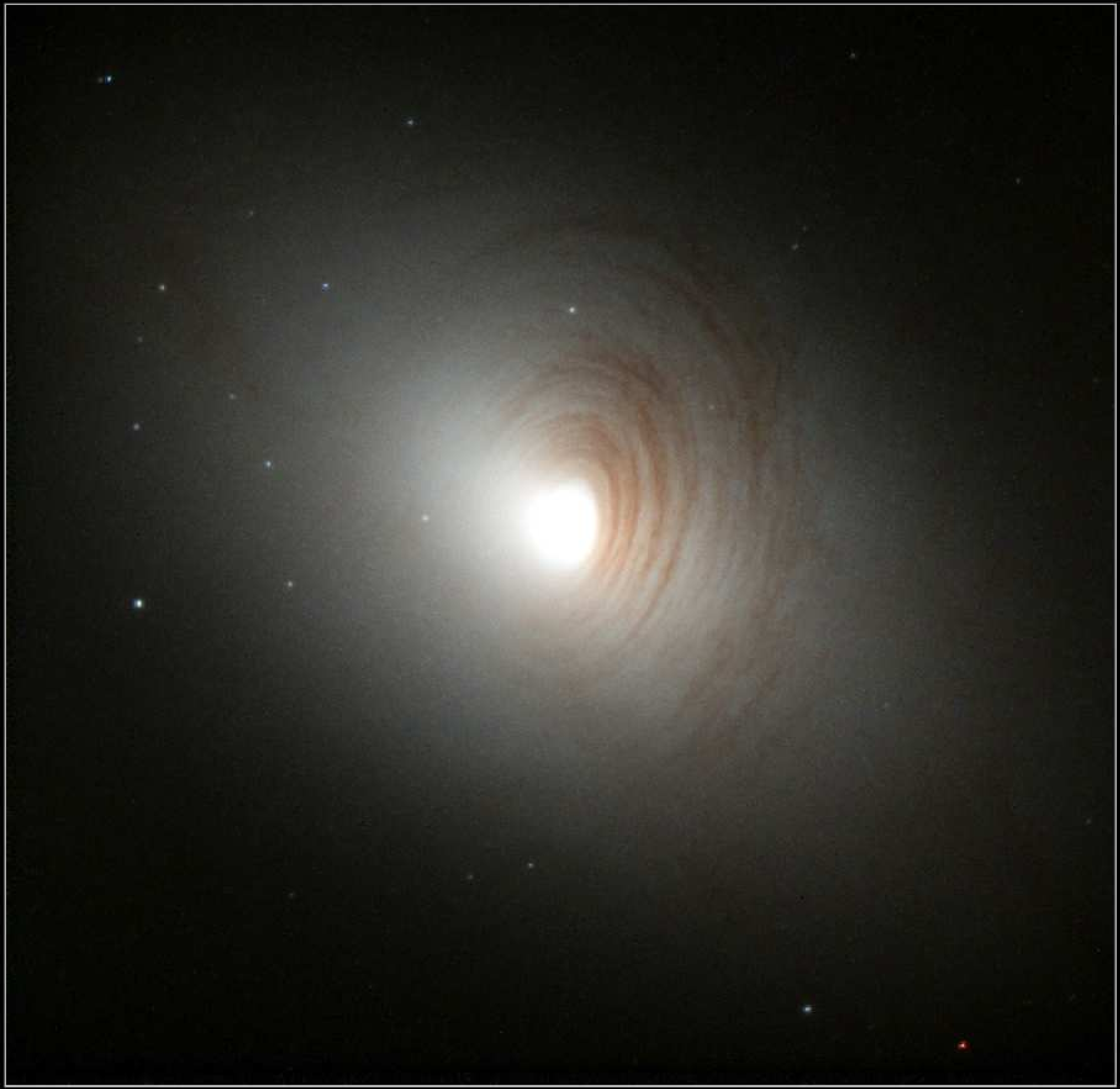
WFC3/IR channel has unprecedented near–IR throughput & areal coverage:

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

$\Longrightarrow$ WFC3 will offer major new parameter space for astrophysics in $\gtrsim$2009



Galaxy NGC 2787



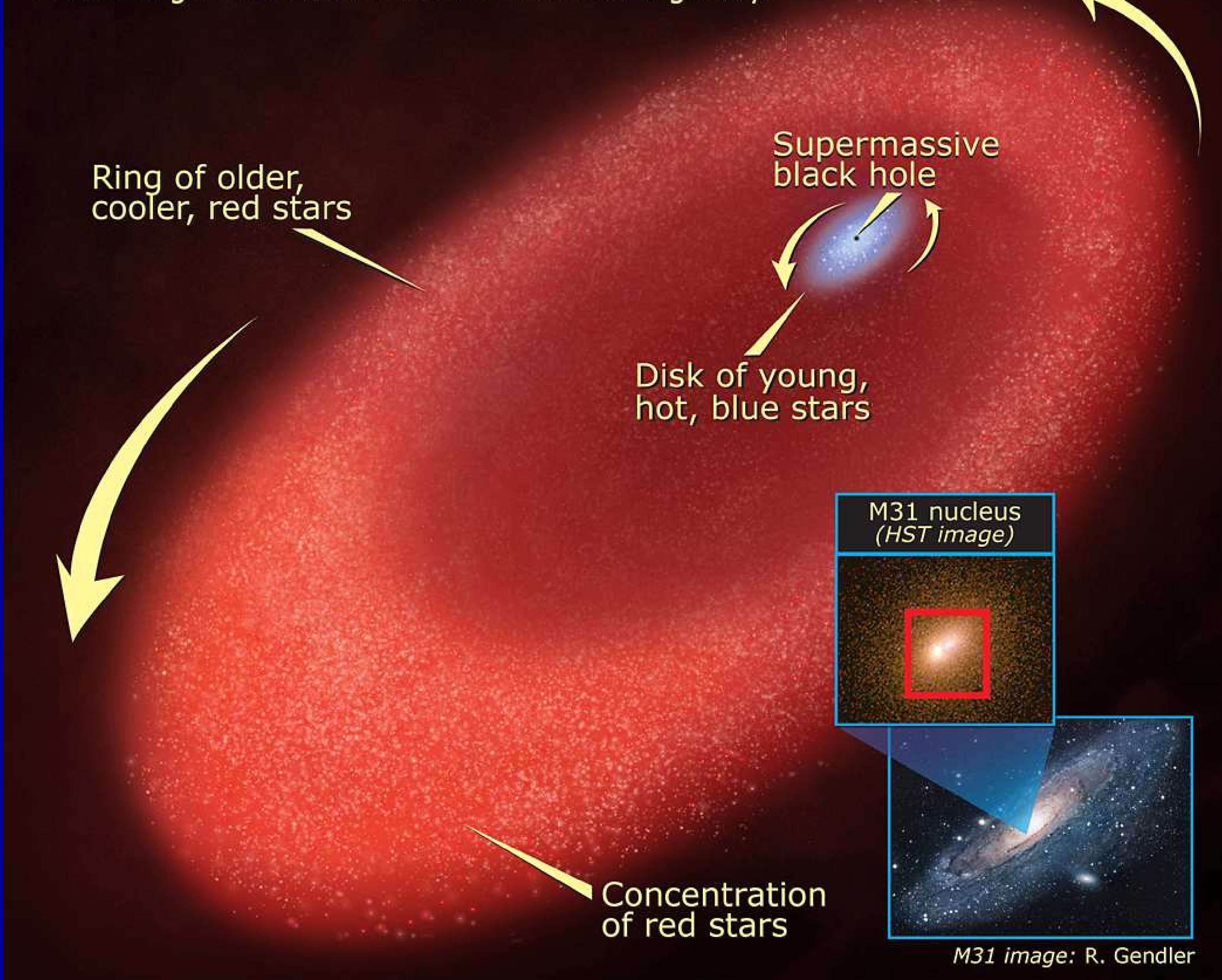
Hubble Heritage

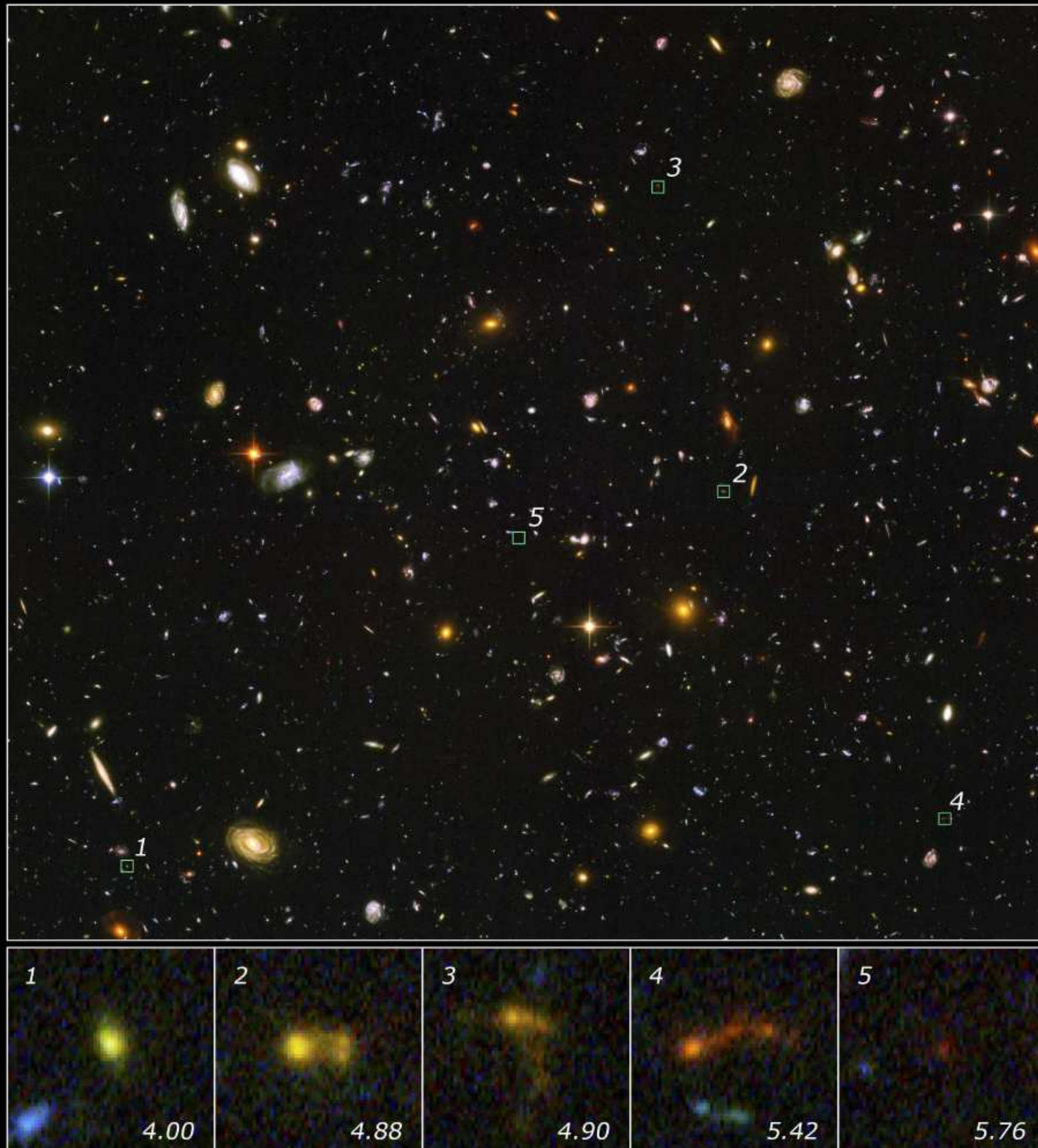
Galaxy Arp 220 *HST* ▪ ACS/HRC

NASA, ESA, and C. Wilson (McMaster University) STScI-PRC06-26

M31's intriguing nucleus

Hubble telescope observations have yielded insights into the Andromeda Galaxy's (M31's) complex nucleus. New images from Hubble uncovered a disk of young, hot, blue stars swirling around a supermassive black hole. The disk is nested inside an elliptical ring of older, cooler, red stars, seen in previous Hubble observations. The inset images show M31's bright core and a view of the entire galaxy.



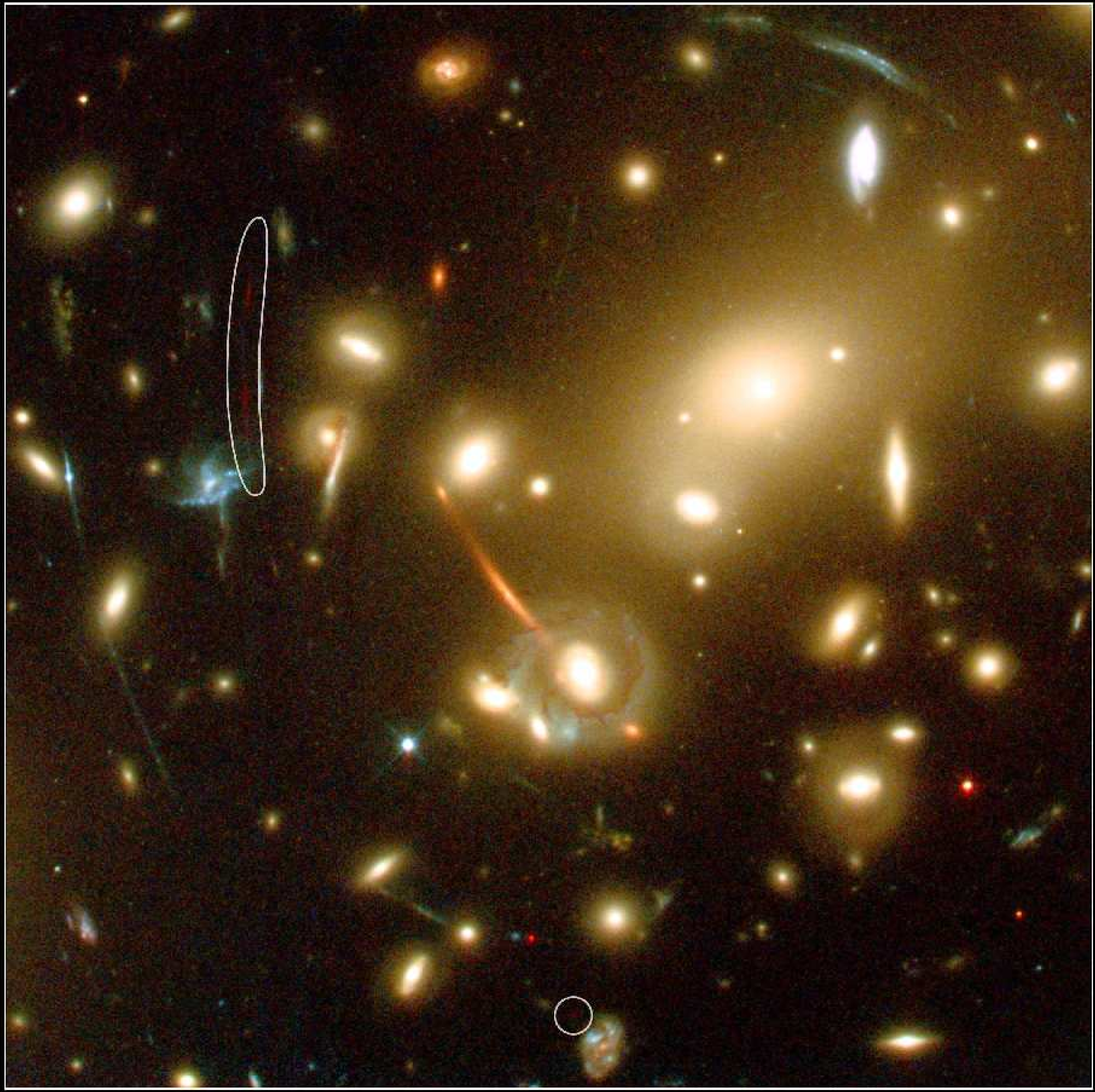


Galaxy Building Blocks in the Hubble Ultra Deep Field

Hubble Space Telescope • ACS/WFC

NASA, ESA, and N. Pirzkal (STScI/ESA)

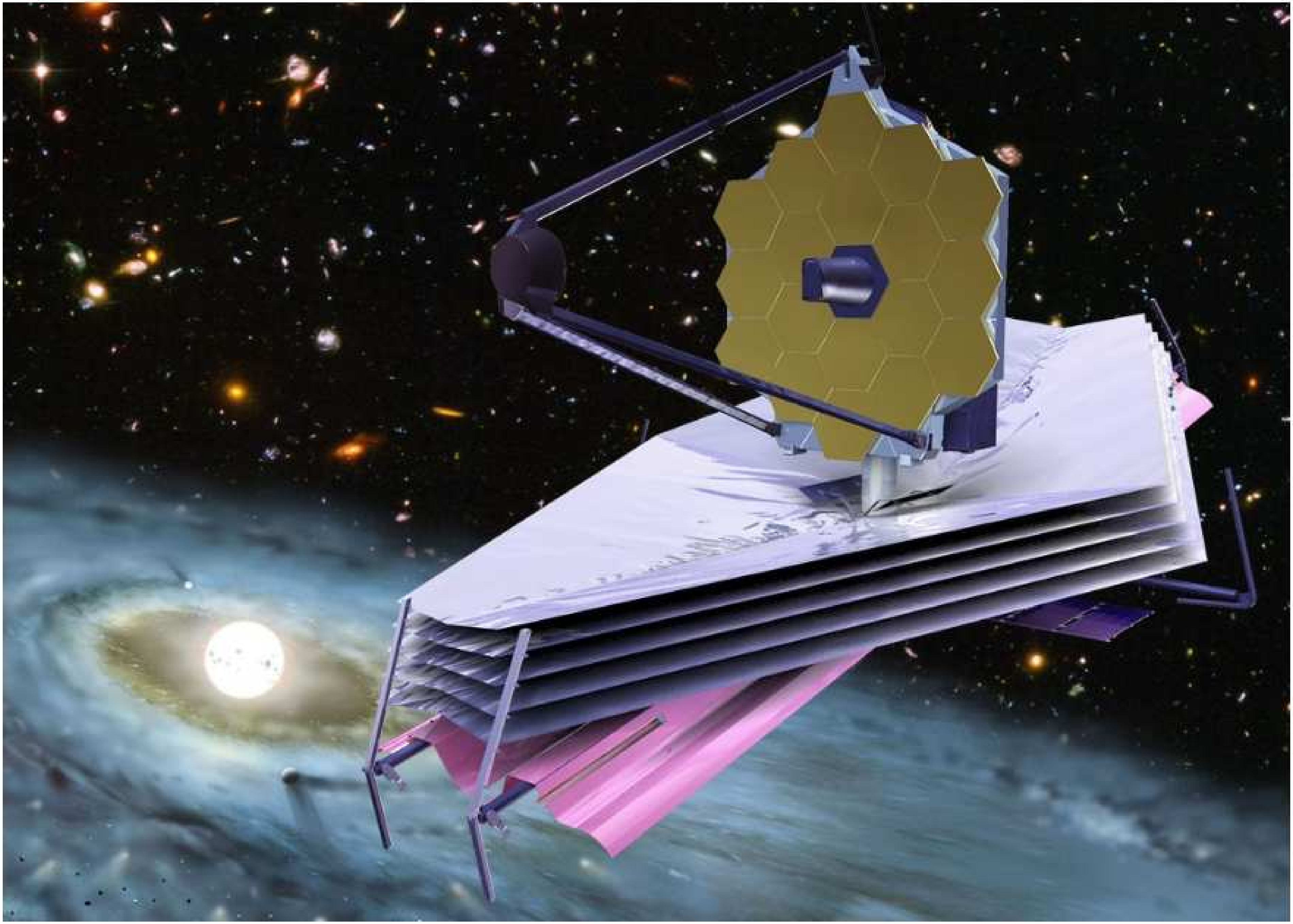
STScI-PRC07-31

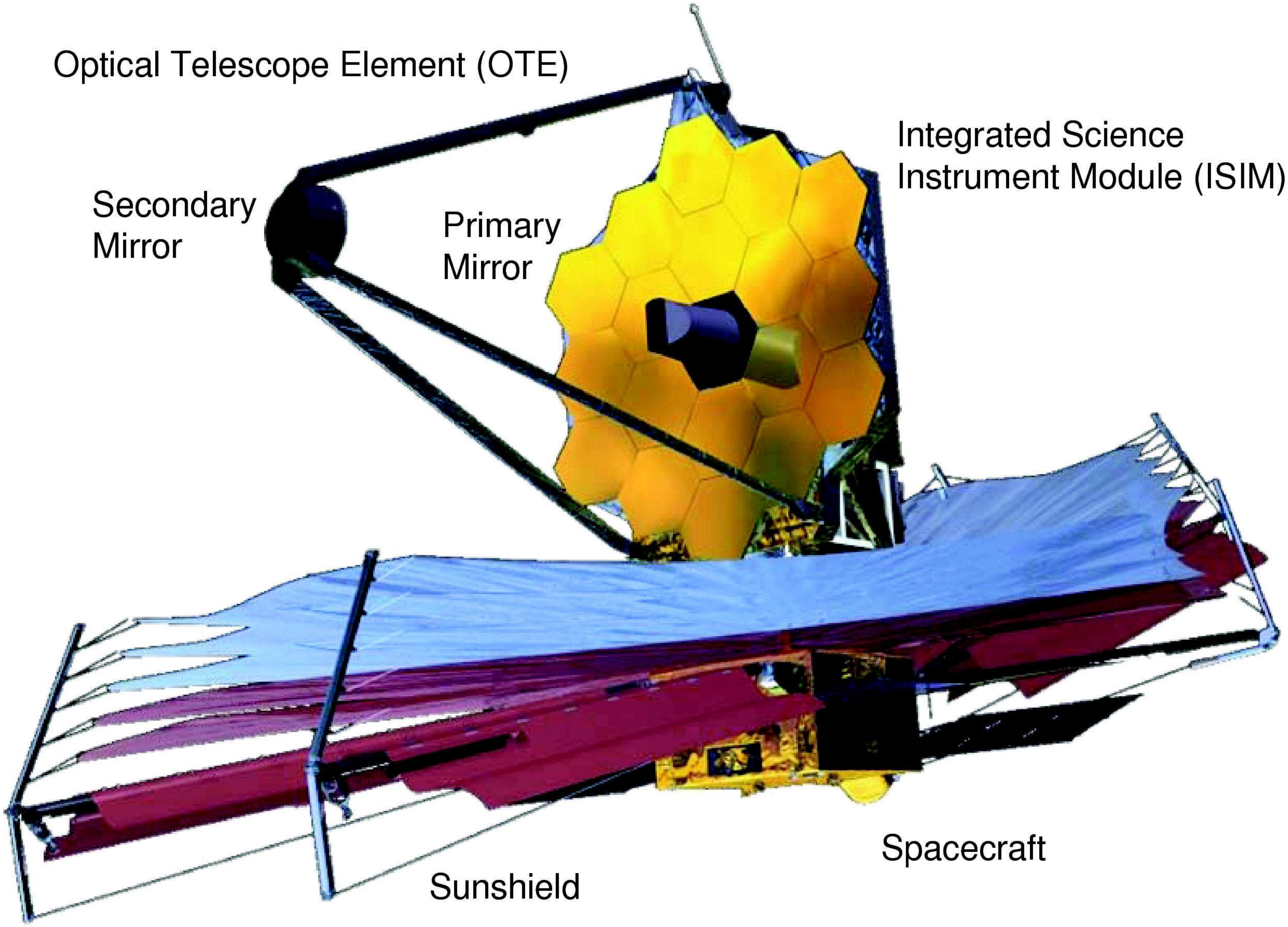


Distant Galaxy Lensed by Cluster Abell 2218
Hubble Space Telescope • WFPC2 • ACS

ESA, NASA, J.-P. Kneib (Caltech/Observatoire Midi-Pyrénées) and R. Ellis (Caltech) STScI-PRC04-08

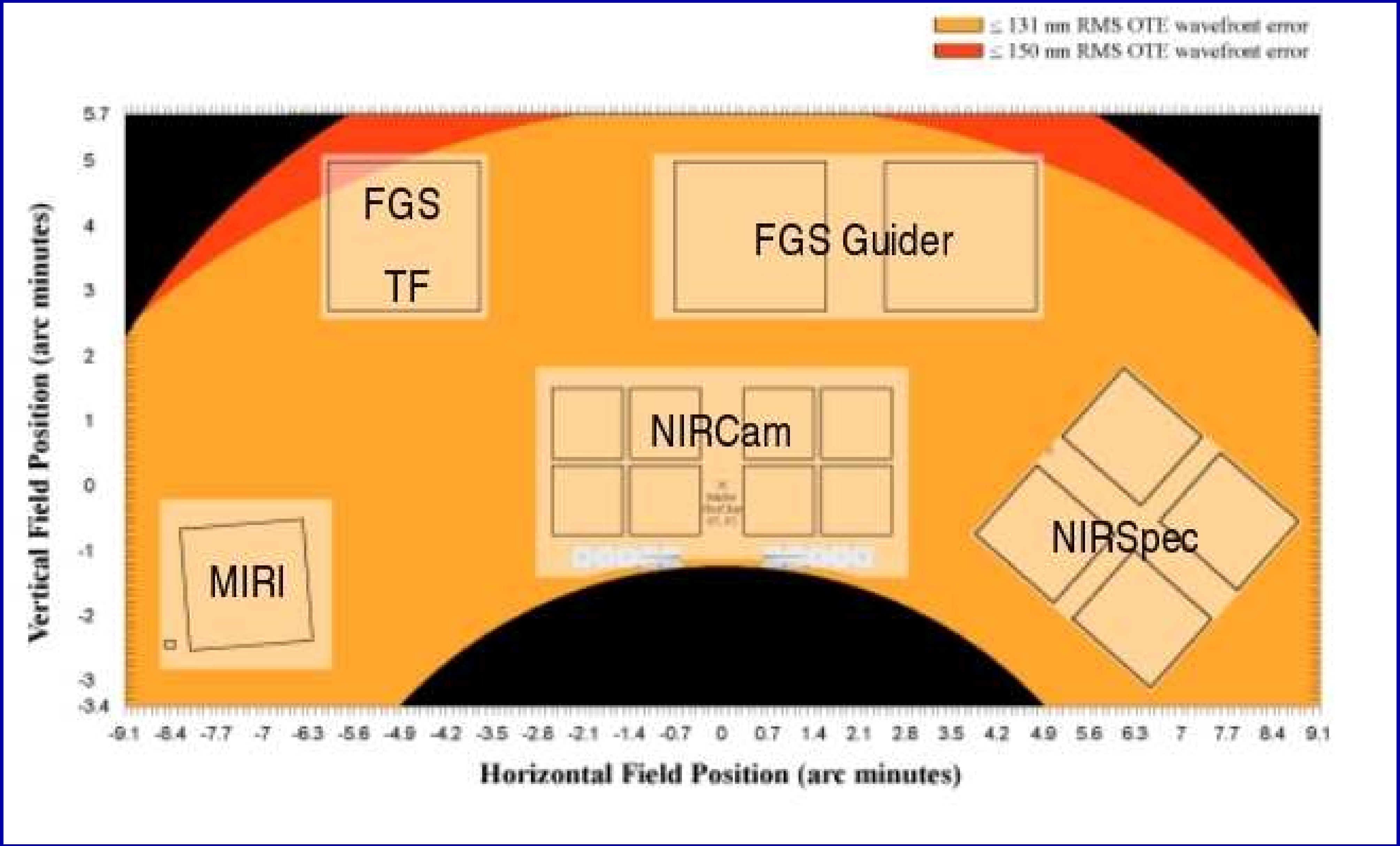
James Webb Space Telescope





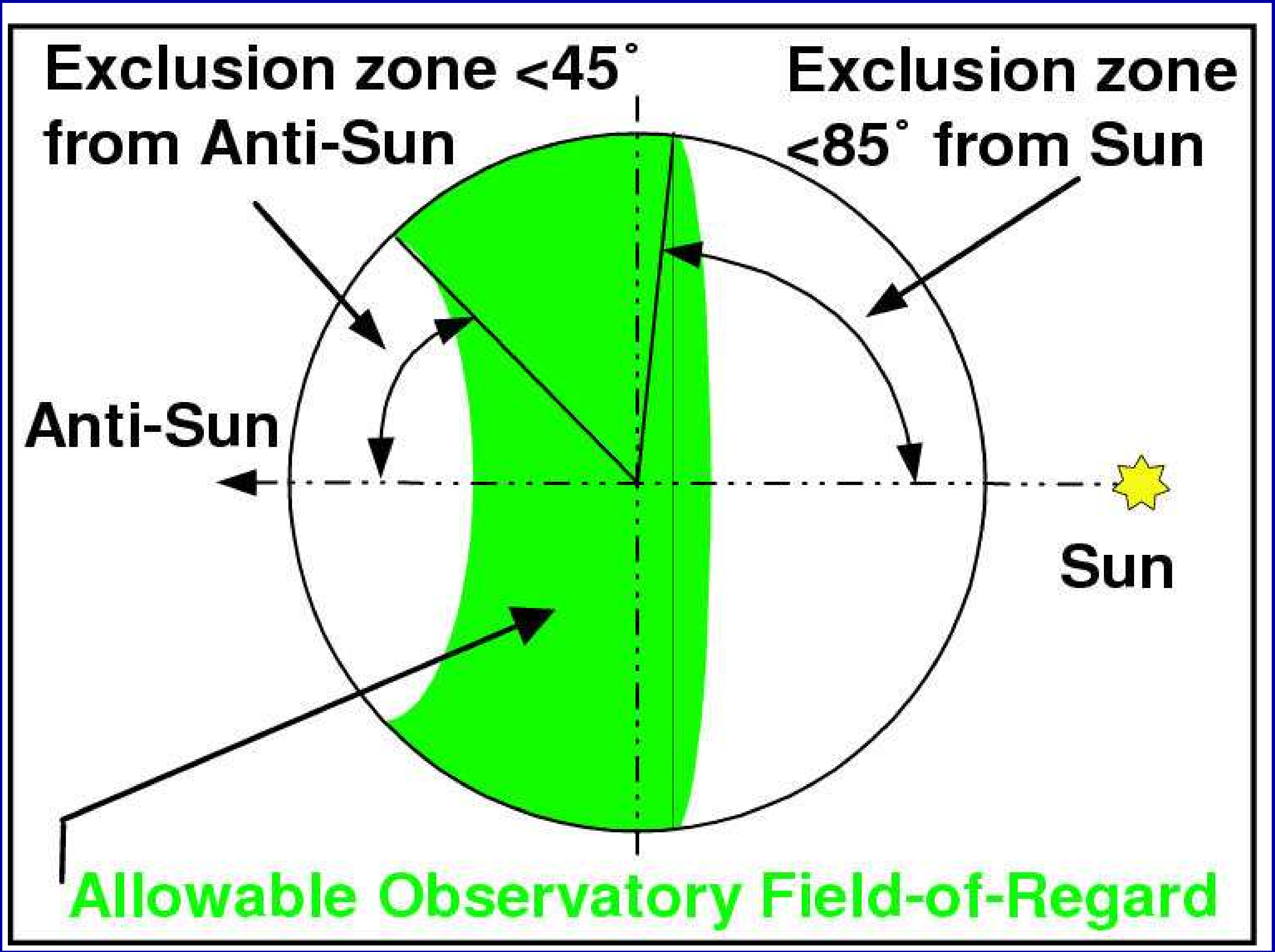
JWST mission reviewed in Gardner, J. P., Mather, J. C., et al. 2006, Space Science Reviews, Vol. 123, pg. 485–606 (astro-ph/0606175)

(3c) What instruments will JWST have?

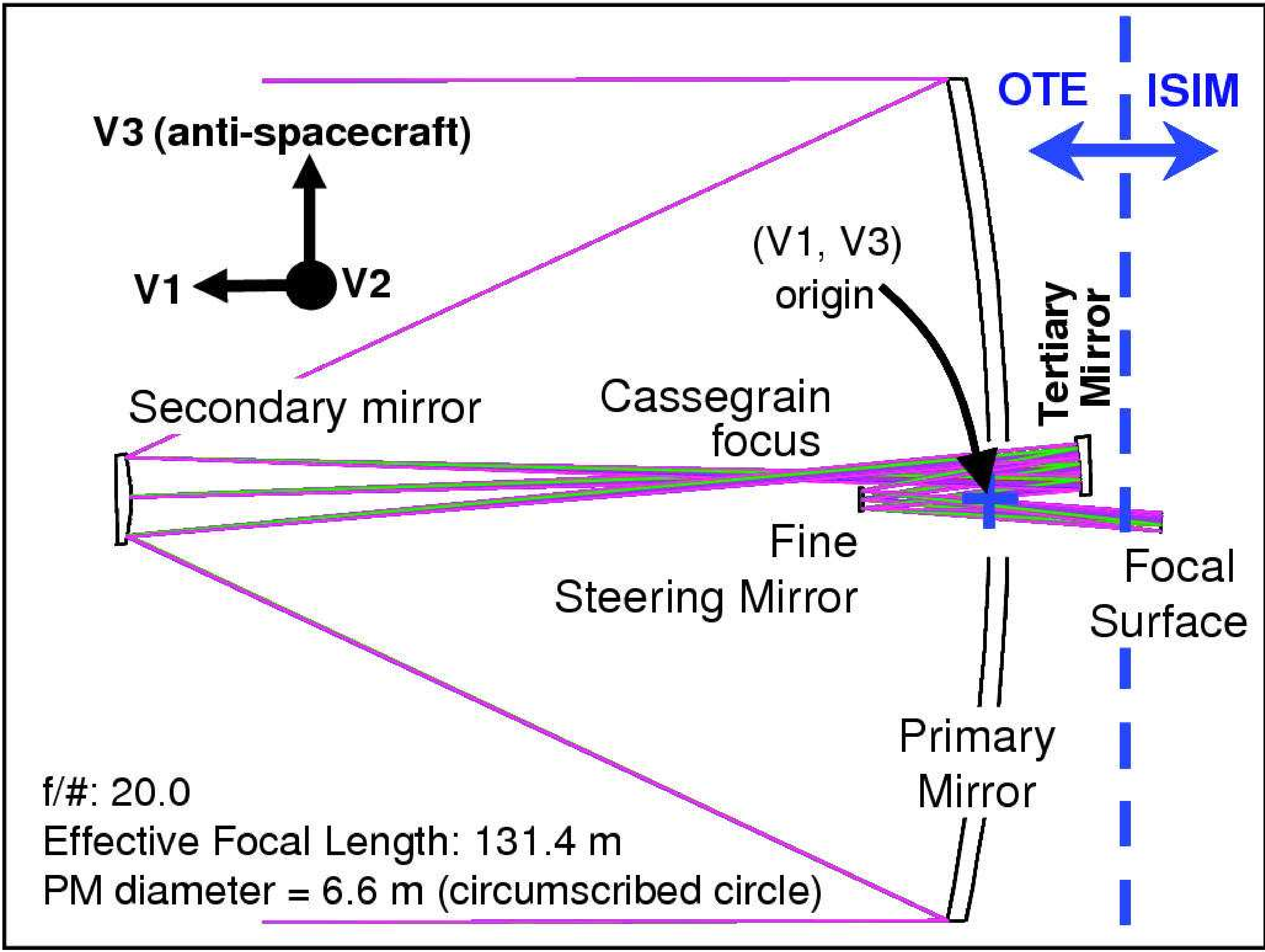


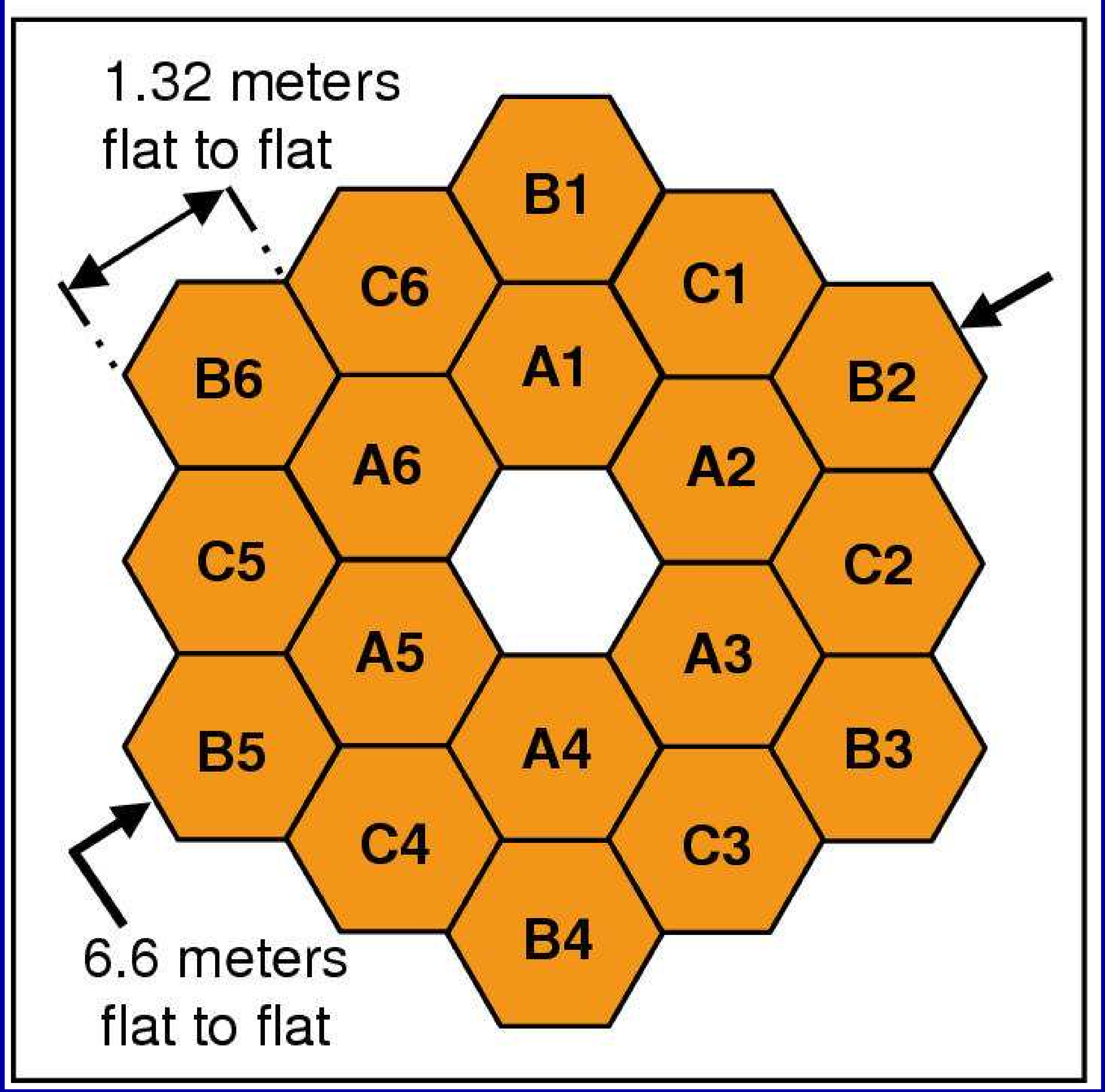
All JWST instruments can in principle be used in parallel observing mode:

- Currently only being implemented for parallel *calibrations.*



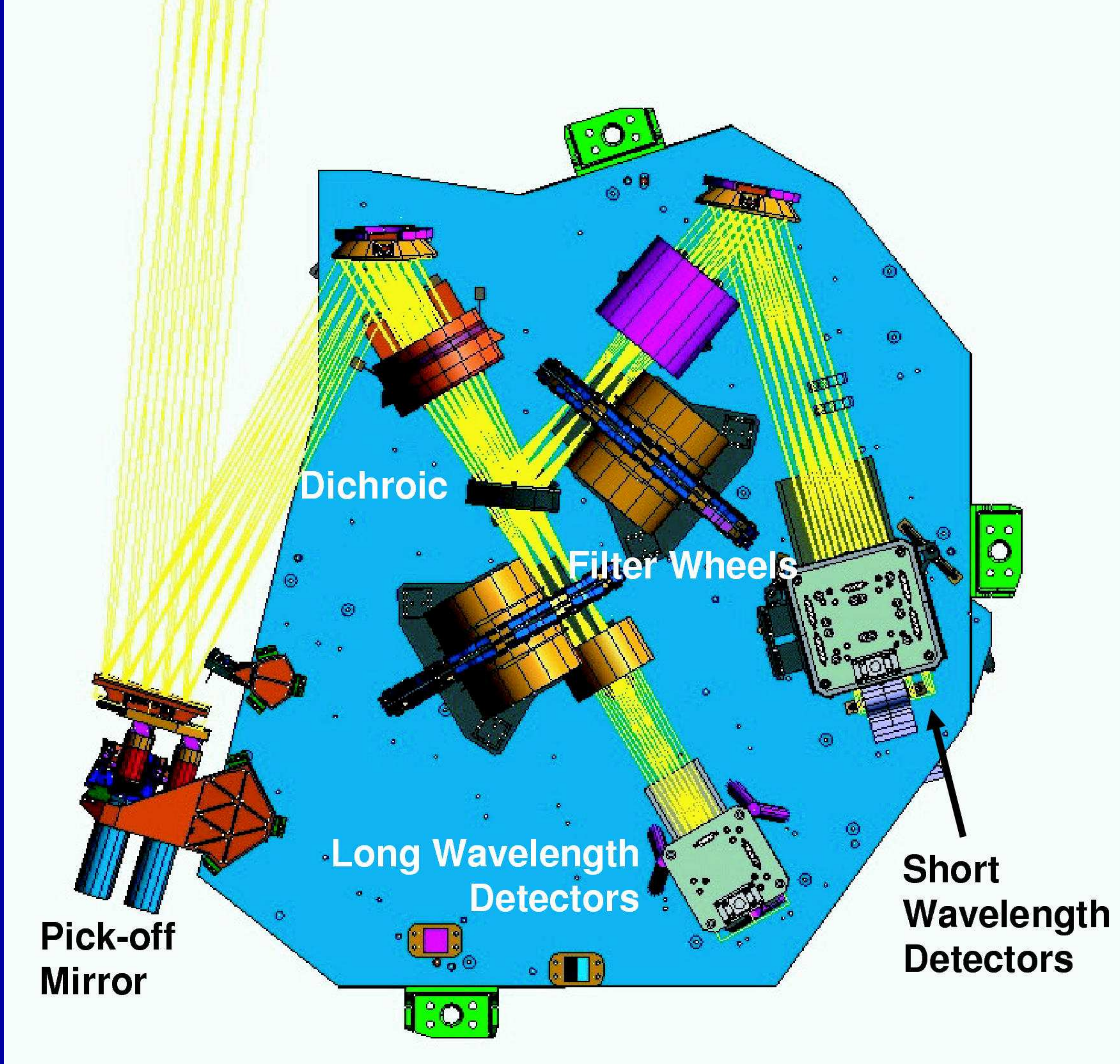
JWST can observe segments of sky that move around as it orbits the Sun.


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



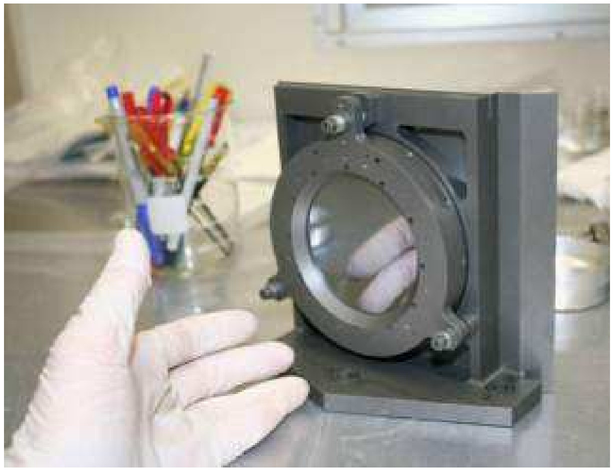
Edge-to-edge diameter is 6.60 m, but effective circular diameter is 5.85 m.

Primary mirror segments are made (AxSys). Now being polished (Tinsley).



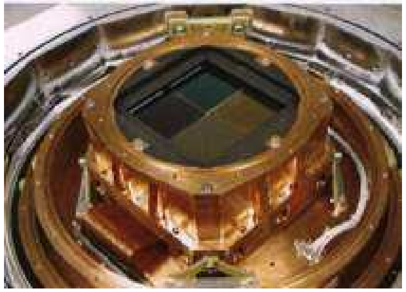
Layout of JWST NIRCam — the UofA–Lockheed NIR-Camera

Instrument Qual and ETU Model Hardware

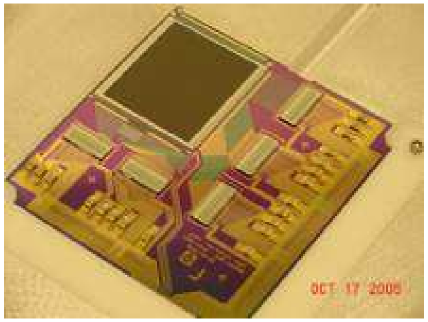


NIRCam Dichroic Beamsplitter

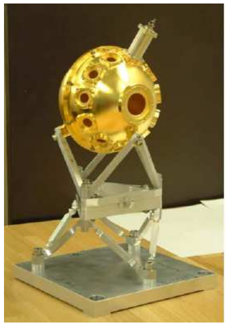
NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



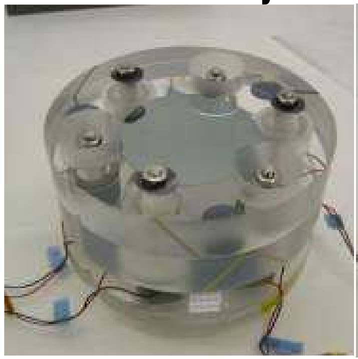
NIRSpec Calibration Assembly

NIRSpec Mirror

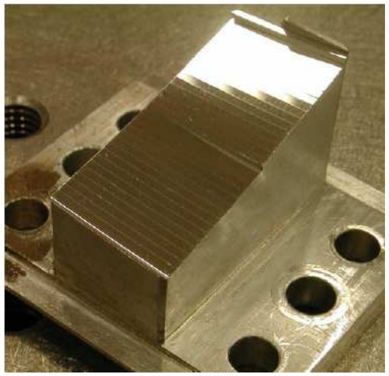
SiAs MIR Detector

MIRI Electronics

NIRSpec Fore Optics Mirror Assembly



FGS/TF Etalon Filter

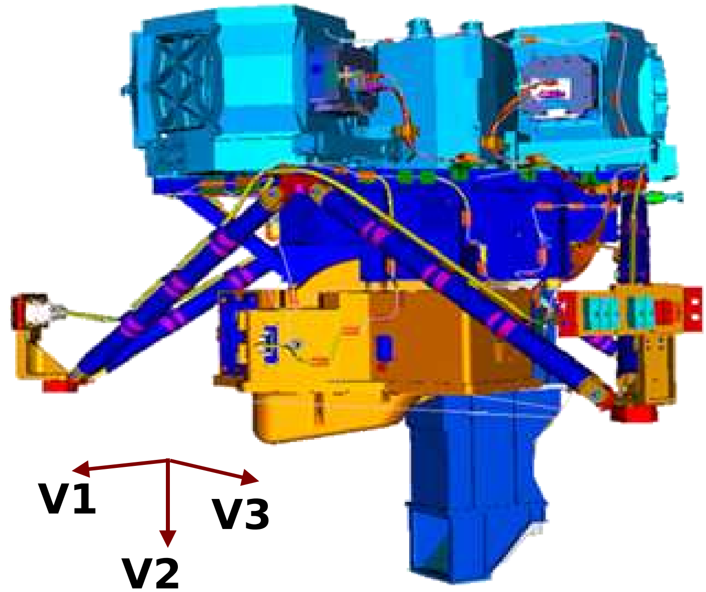


NIRSpec Image Slicer Mirror

Critical-path JWST flight hardware is being constructed as of 2006.

Introduction to MIRI

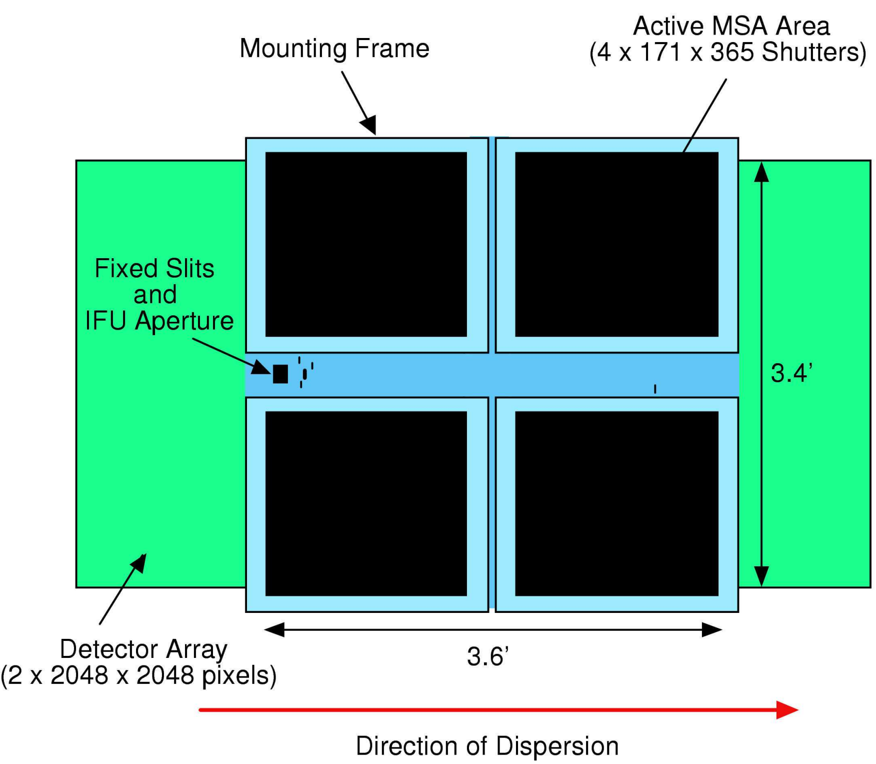
- **MIRI capabilities:**
  - Imaging from 5 – 28 microns
  - Low resolution slit Spectroscopy
  - Coronography
  - Medium resolution integral field unit spectroscopy from 5 – 28 microns
- **MIRI Partnership:**
  - European Consortium (EC) with 26 contributing Institutes in ten countries
  - Jet Propulsion Laboratory
  - European Space Agency
  - Goddard Space Flight Center
- **MIRI Optical System Passed its Critical Design Review in Feb. 2007**
- **Development since MIRI Optical System CDR**
  - Verification Model Cryo Testing –2 campaigns successfully completed
  - Unit Qualification Reviews in progress
  - FM units - several delivered and final few nearing completion

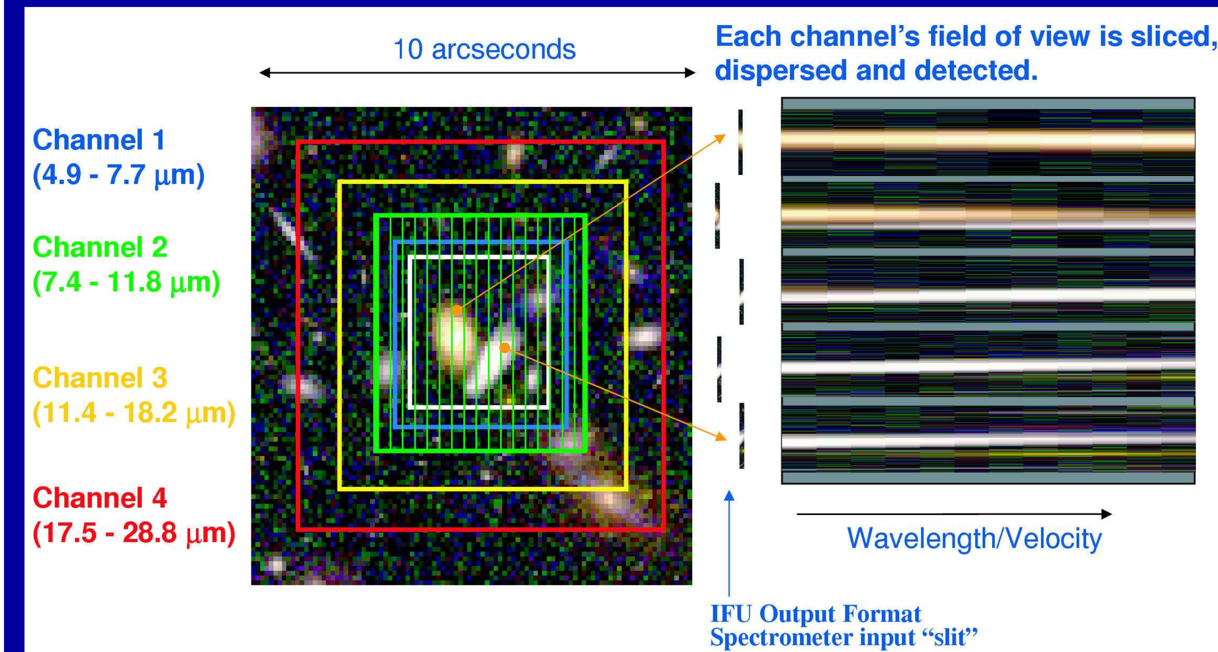


Contamination Control Cover

Engineering Model FPM

Filter Wheel Assembly





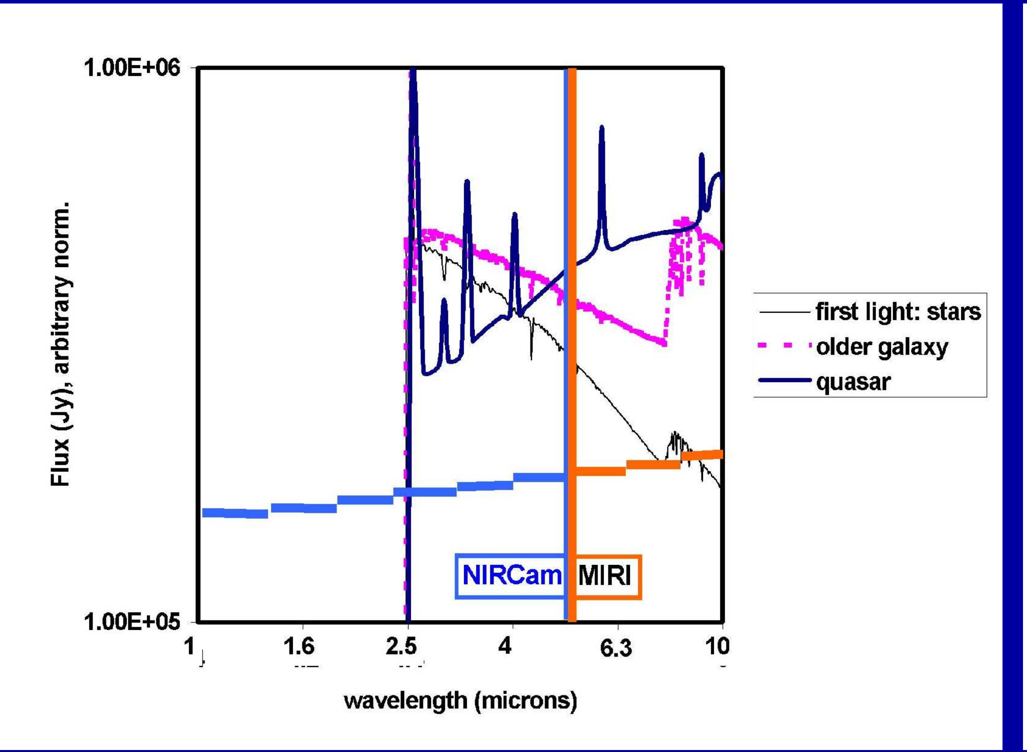
JWST offers significant multiplexing for faint object spectroscopy:

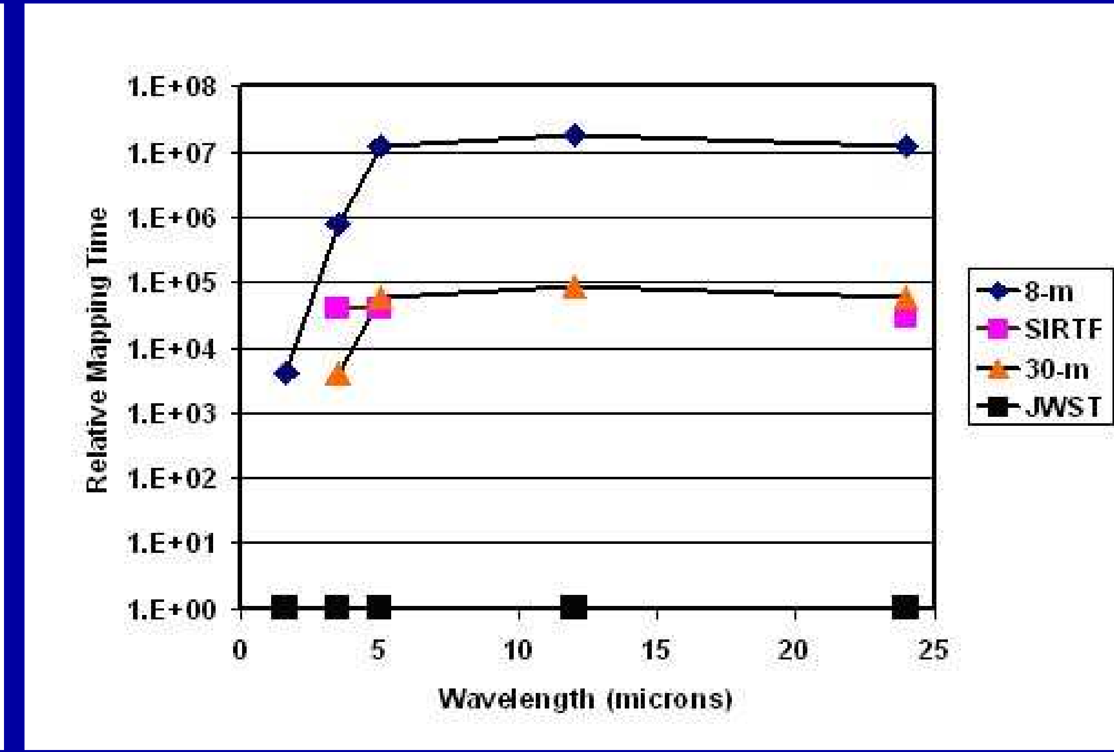
- NIRSpec/MSA with 4×62,415 independently operable micro-shutters that cover $\lambda \simeq 1$–5 μm at R$\simeq$100–1000.

- MIRI/IFU with 400 spatial pixels covering 5–28.5 μm at R$\sim$2000–4000.

- FGS/TFI that covers a $2\rlap{.}'2 \times 2\rlap{.}'2$ FOV at $\lambda \simeq 1.6$–4.9 μm at R$\simeq$100.

(3c) What sensitivity will JWST have?





The NIRCam and MIRI sensitivity complement each other, straddling 5 μm in wavelength, and together allow objects to be found to redshifts z=15–20 in $\sim 10^5$ sec (28 hrs) integration times.

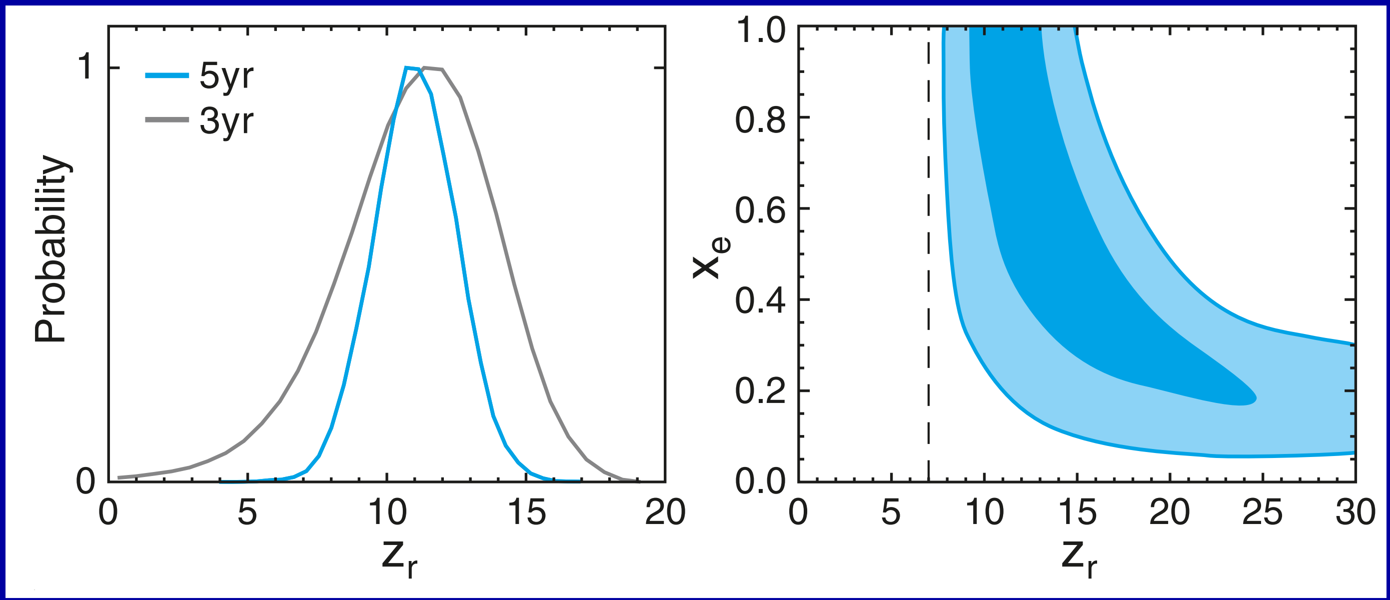
LEFT: NIRCam and MIRI broadband sensitivity to a Quasar, a "First Light" galaxy dominated by massive stars, and a 50 Myr "old" galaxy at z=20.

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

Truth≡240 hrs HUDF Vi'z'   18 hrs JWST 0.7, 0.9, 2.0 μm

Implications of the March 2008 5-year WMAP results on JWST science:

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



The year-5 WMAP data provided much better foreground removal (Dunkley ea. 2008 astro-ph/0803.0586; Komatsu ea. astro-ph/0803.0547). This implies that First Light & Reionization occurred between these extremes:

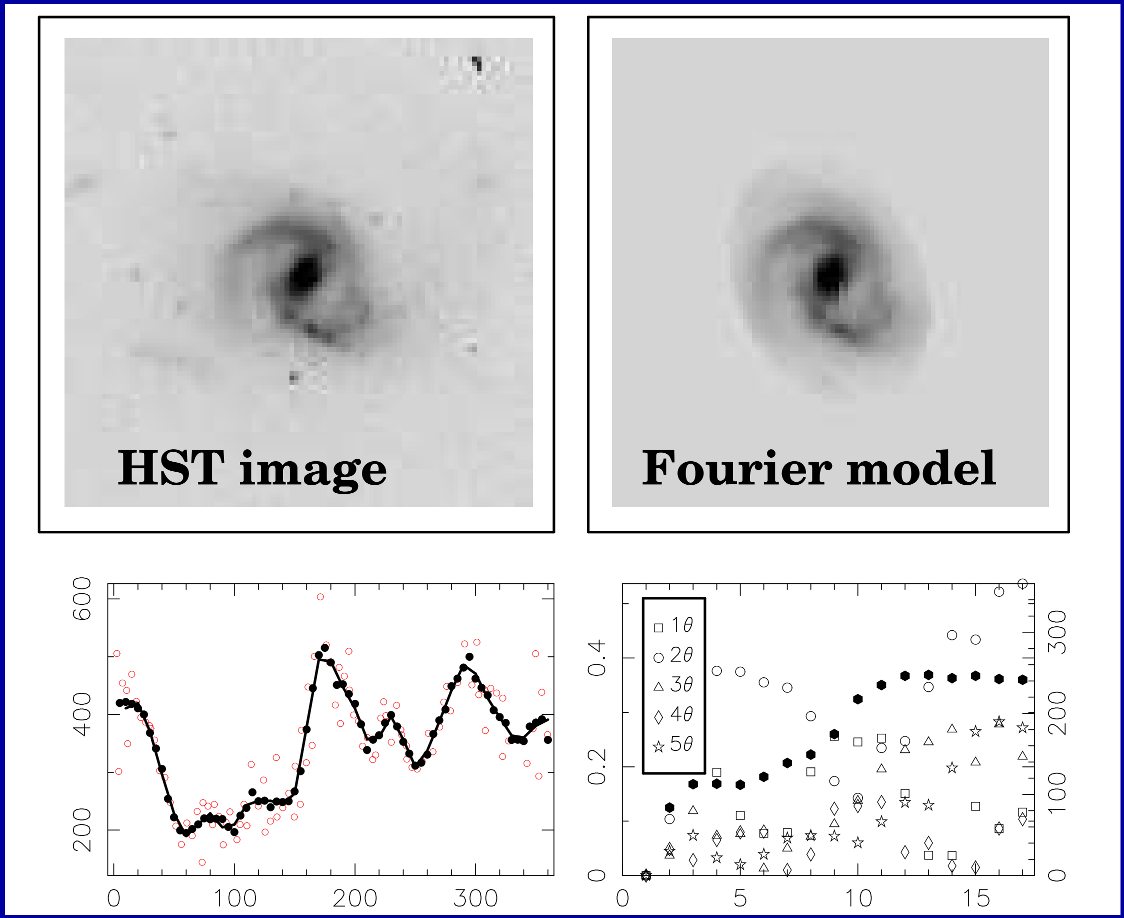
- (1) Universal & instantaneous at z$\simeq$10.8$\pm$1.4, or, much more likely:

- (2) Inhomogeneous & drawn out: starting at z$\gtrsim$20, peaking at z$\simeq$11, ending at z$\simeq$7. In both cases, the implications for HST and JWST are:

- HST has covered z$\lesssim$6 and HST/WFC3 will cover z$\lesssim$7–8.

- For First Light & Reionization, JWST must sample z$\simeq$8 to z$\simeq$15–20.

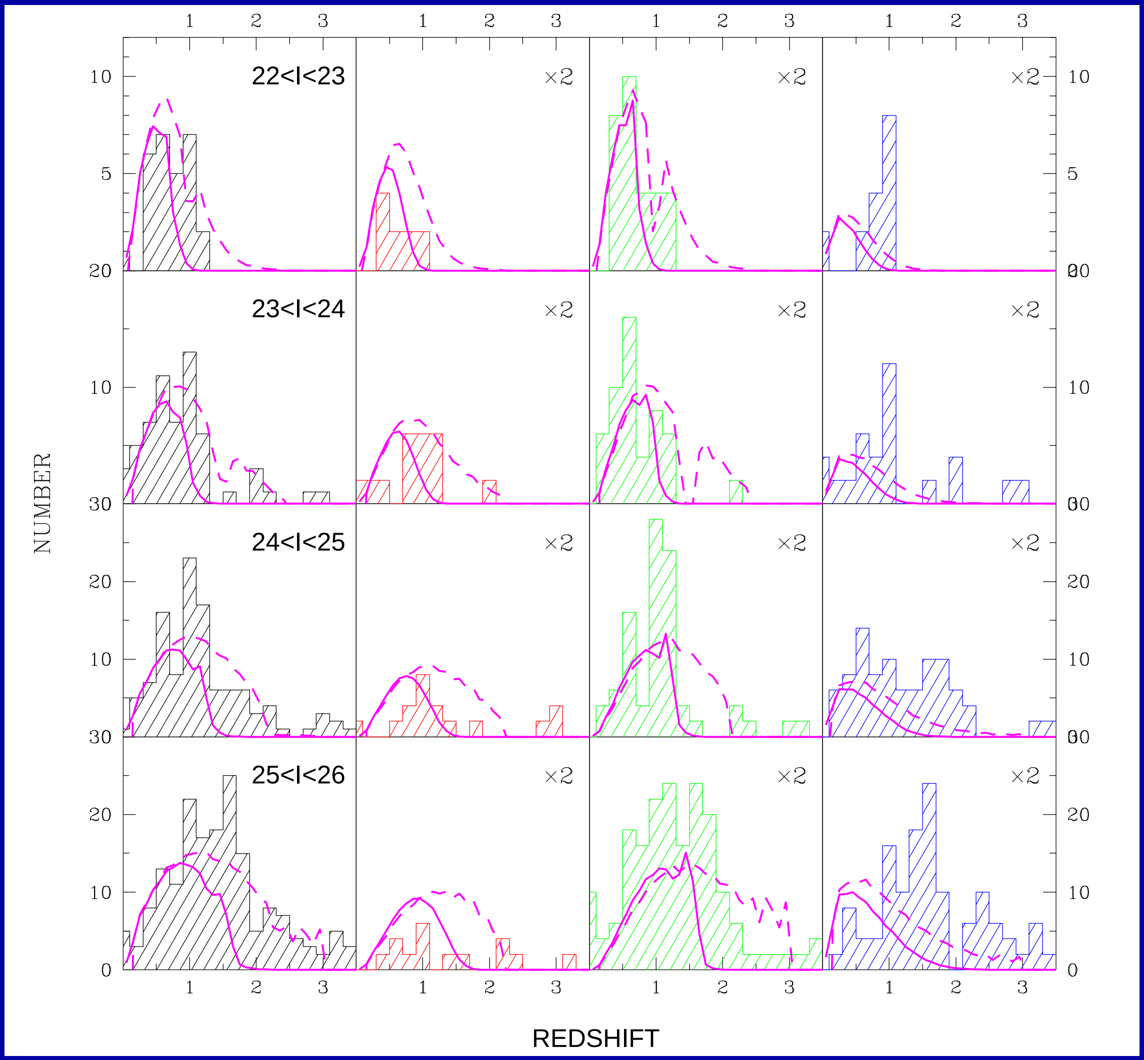
$\Rightarrow$ JWST must cover λ=0.6–28 μm, with its diffraction limit at 2.0 μm.



Fourier Decomposition is a robust way to measure galaxy morphology and structure in a quantitative way (Odewahn et al. 2002):

- (1) Fourier series are made in successive concentric annuli.
- (2) Even Fourier components indicate symmetric parts (arms, rings, bars).
- (3) Odd Fourier components indicate asymmetric parts (lopsidedness).
- (4) JWST can measure the evolution of each feature/class directly.

Total Ell/S0 Sabc Irr/Mergers



- JWST can measure how galaxies of all Hubble types formed over a wide range of cosmic time, by measuring their redshift distribution as a function of rest-frame type.
- For this, the types must be well imaged for large samples from deep, uniform and high quality multi-wavelength images, which JWST can do.

Driver et al. 1998, Astrophys. J. Letters, 496, L93