Synergy between the Thirty Meter Telescope and the James Webb Space Telescope: When 1 + 1 > 2.

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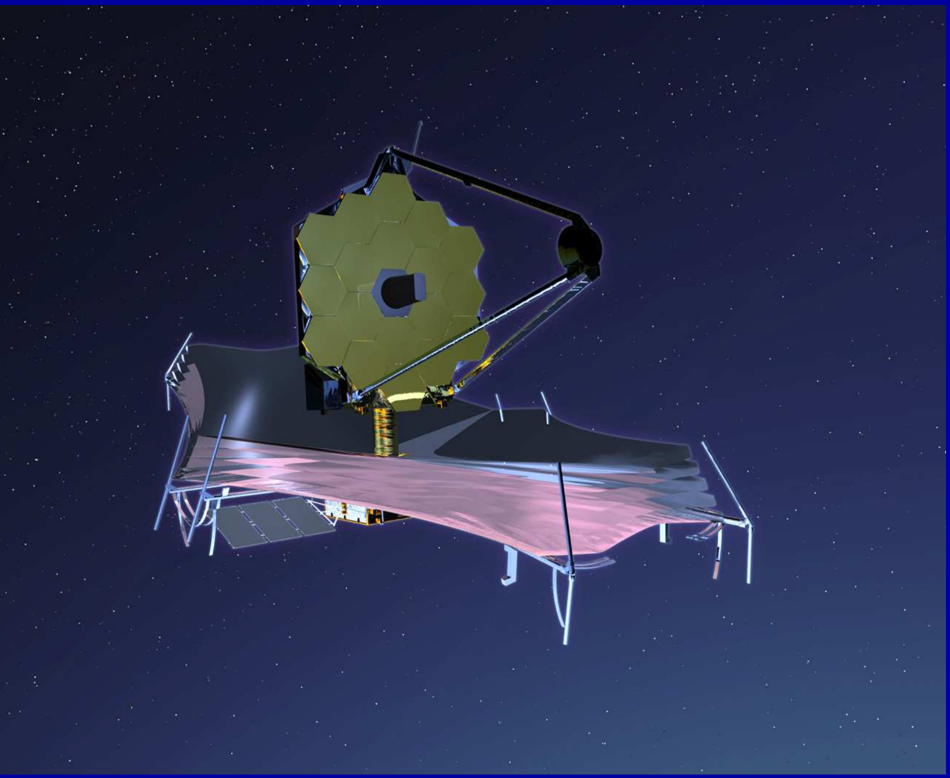
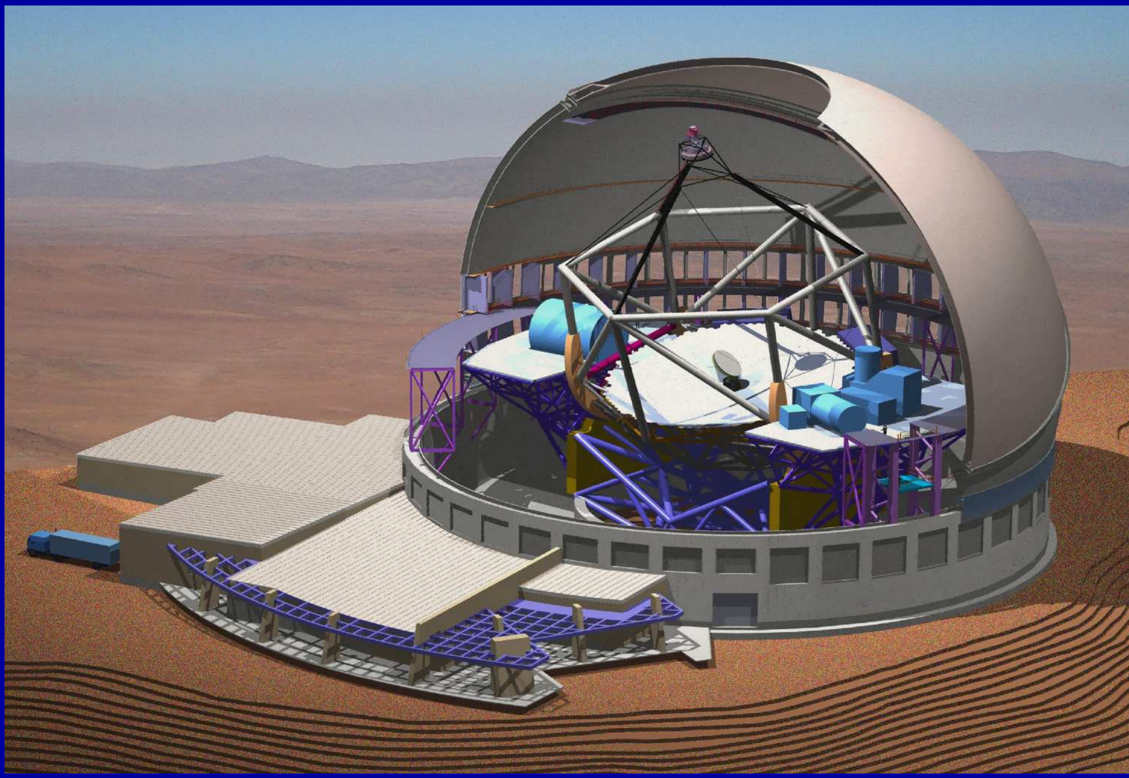
(Interdisciplinary Scientist for the JWST)



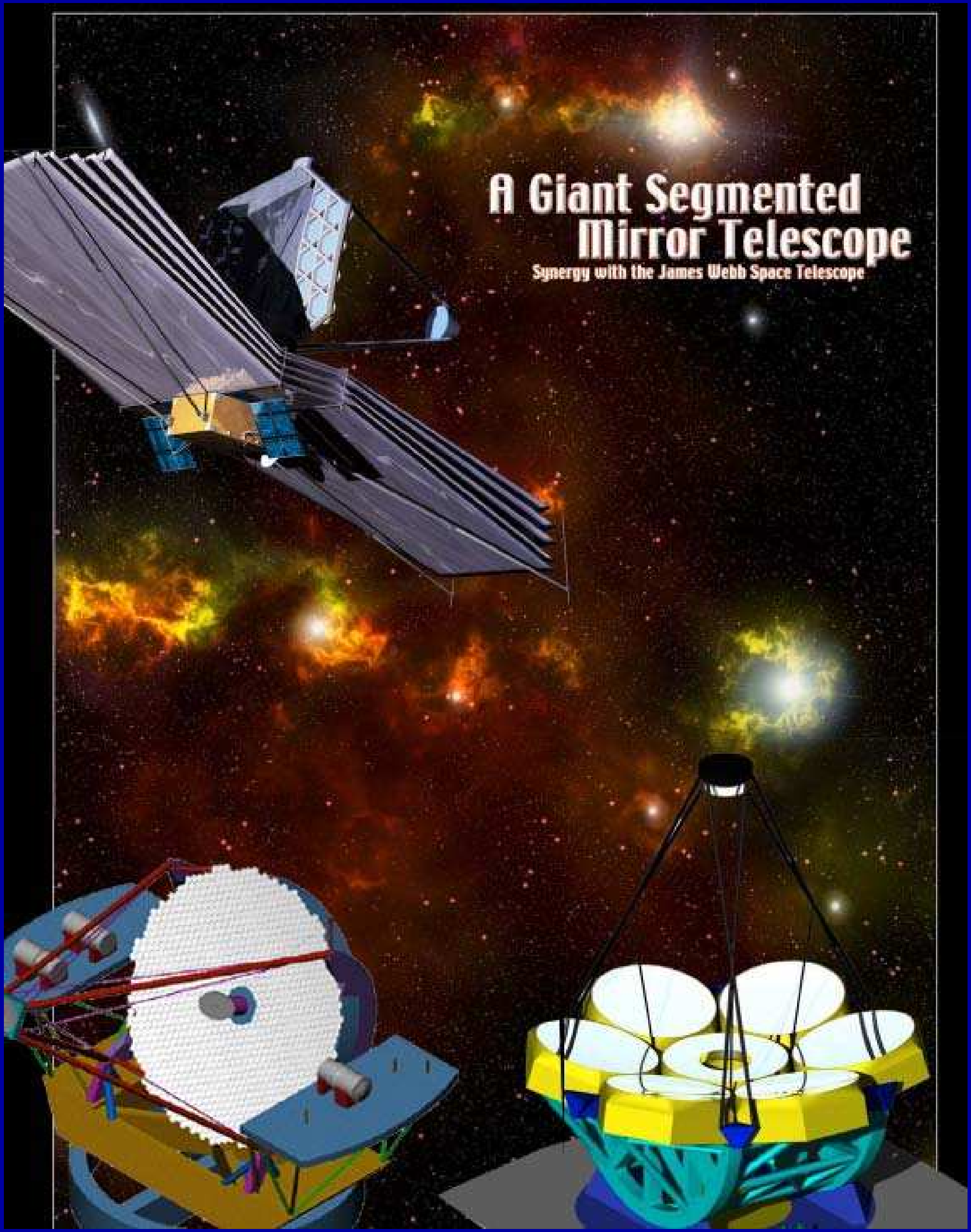


"Science in the Era of TMT" Workshop, UC Irvine, Tuesday July 24, 2007

with contributions from Jay Frogel and Rolf Kudritzki

Outline

- (1) What is JWST — deployment, instruments and sensitivity
- (2) Unique Capabilities of JWST and TMT
- (3) Synergy between TMT and JWST in First Light and Reionization
- (4) Synergy between TMT and JWST in Galaxy Assembly
- (5) Synergy between TMT and JWST in Star- and Planet Formation
- (6) Summary



TMT and JWST (Kudritzki, Frogel et al. 2005):

- (1) Are the top two priority missions of the 2001 Decadal Survey in Astronomy and Astrophysics.
- (2) Each give orders of magnitude gain in sensitivity over existing ground and space telescopes, resp.
- (3) Have complementary capabilities that open a unique new era for cosmic and planetary discovery.
- (4) Hence, maximize concurrent operation of TMT and JWST.

(2) Unique Capabilities of the 6.5 meter JWST

- (1) JWST will be in L2, above the atmosphere, so it will have:
- Continuous wavelength coverage for $0.6 \lesssim \lambda \lesssim 28.5\ \mu$m.
- Low thermal background & no OH emission $\Rightarrow$ high IR sensitivity.
- No "weather" or "daytime" $\Rightarrow$ High observing efficiency, enabling high precision and high time-resolution photometry and spectroscopy.

(2) JWST is a cold telescope ($\lesssim$40 K) $\Rightarrow$ Minimizes thermal background:

- For $\lambda \lesssim 10\ \mu$m, background limit is set by Zodi, not thermal emission.

(3) JWST will have full sky coverage in both celestial hemispheres.

(4) Diffraction limited for $\lambda \gtrsim 2.0\ \mu$m over a wide FOV ($\gtrsim 5'$), hence:

- PSF nearly constant across FOV field.
- PSF stable with time — WFS updates on time-scales of ($\sim$10) days.
- Very high dynamic range.

(2) Unique Capabilities of the TMT

(1) Sensitivity of a 30 meter mirror:

- Very high sensitivity in the optical over a wide FOV ($\gtrsim 10'$).
- High sensitivity for non-background limited IR observations and at high spectral resolution (between OH-lines), especially if diffraction limited.

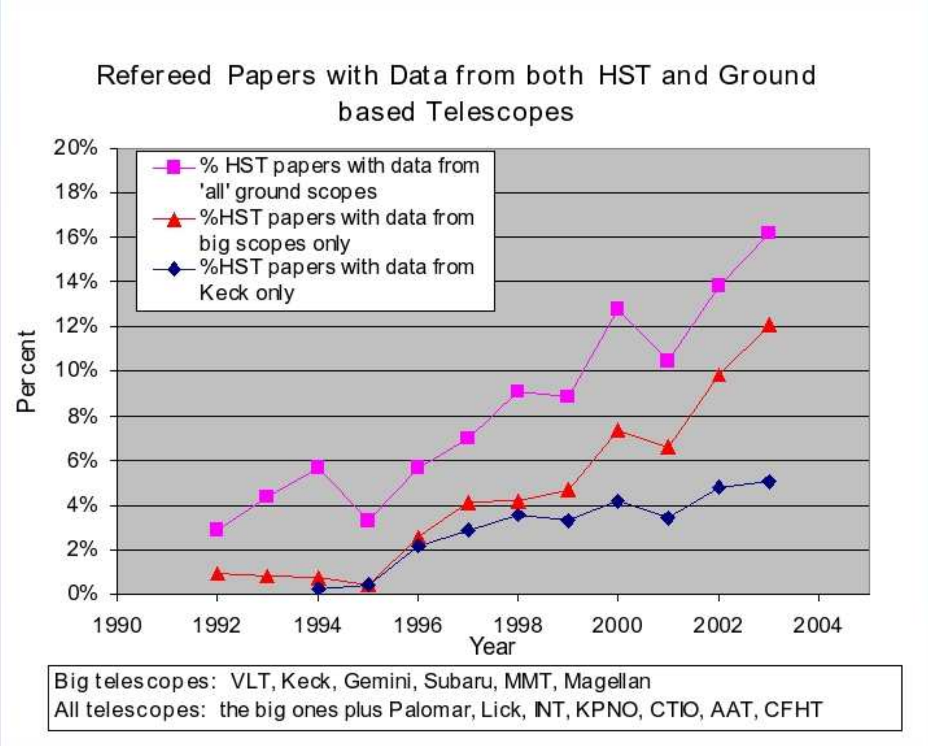
(2) Very high spatial resolution, diffraction limited imaging in mid- and near-IR — with AO gain can yield PSF = JWST's FWHM/5.

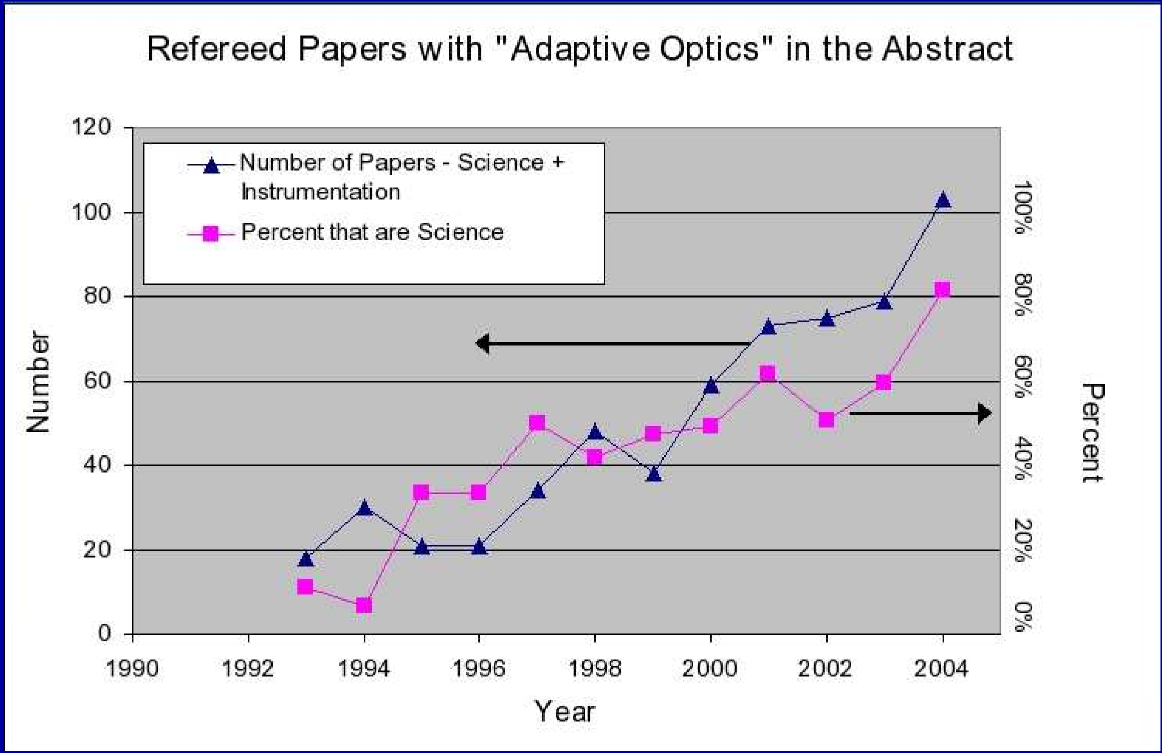
(3) Very high resolution spectroscopy in optical–mid-IR.

(4) Long lifetime — enables programs with very long time scales.

(5) Targets of Opportunity — response time of a few minutes.

(6) Flexible and upgradable — take advantage of new developments in instrumentation in the next decades.

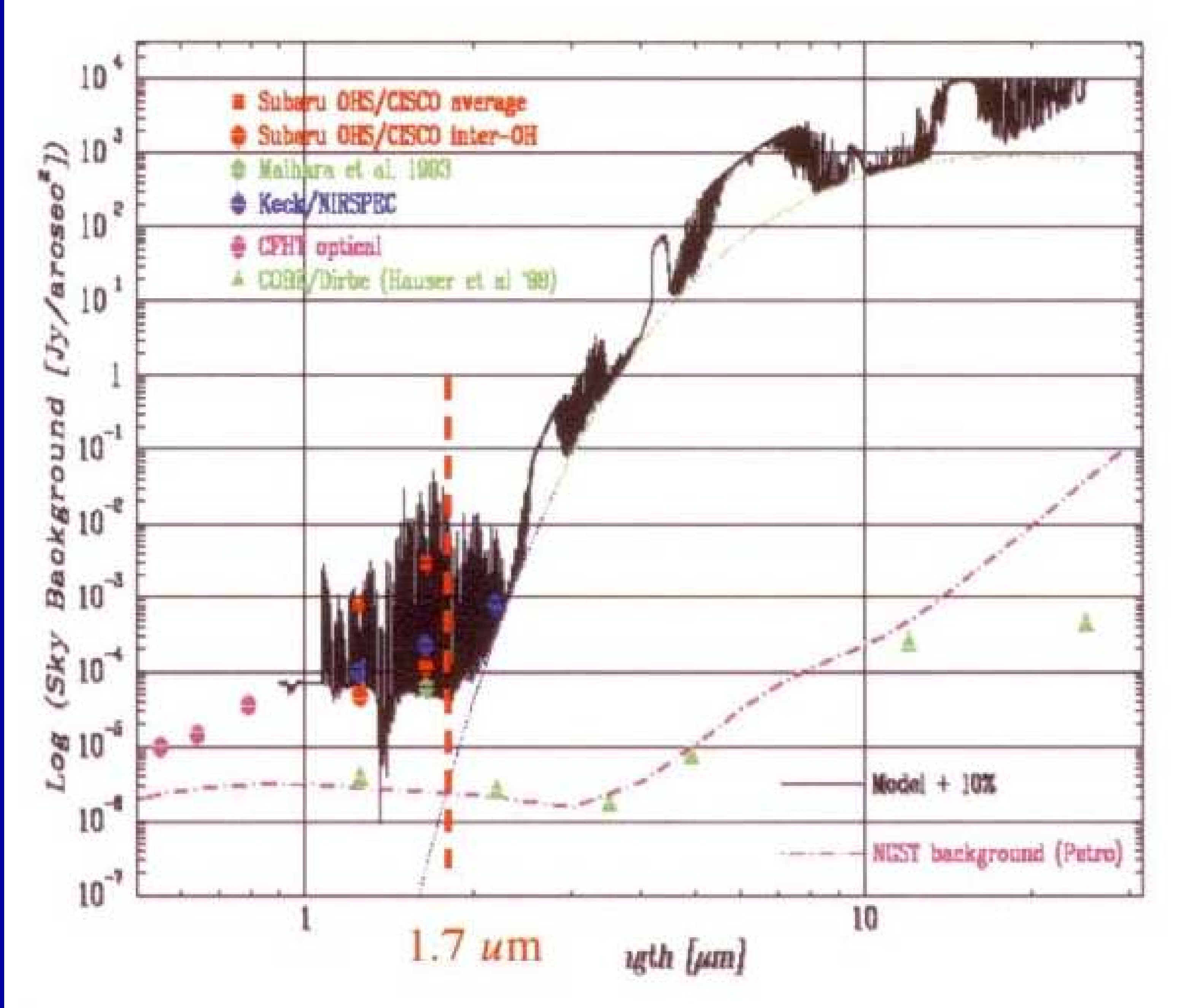




- Due to their unique capabilities, JWST and TMT will be able to significantly complement each other, thereby enhancing the science output that each would produce on their own.

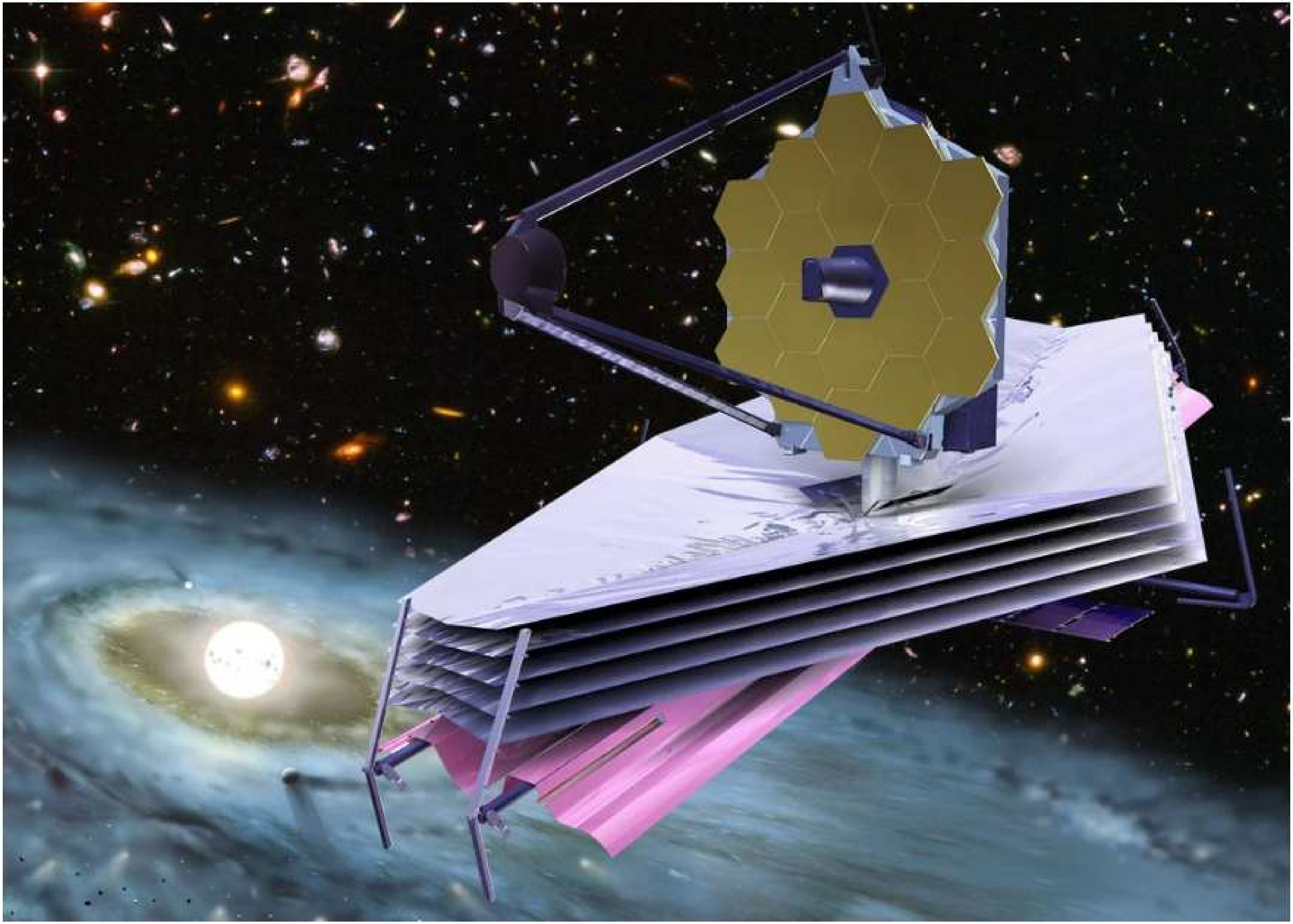
- Historically, this is demonstrated by the increase in the fraction of papers that used *both* the *current* state-of-the-art facilities: HST and 8–10 m class ground-based telescopes.

- Ground-based AO has shown a significant increase in science productivity in the last decade — HST has shown a similar increase.

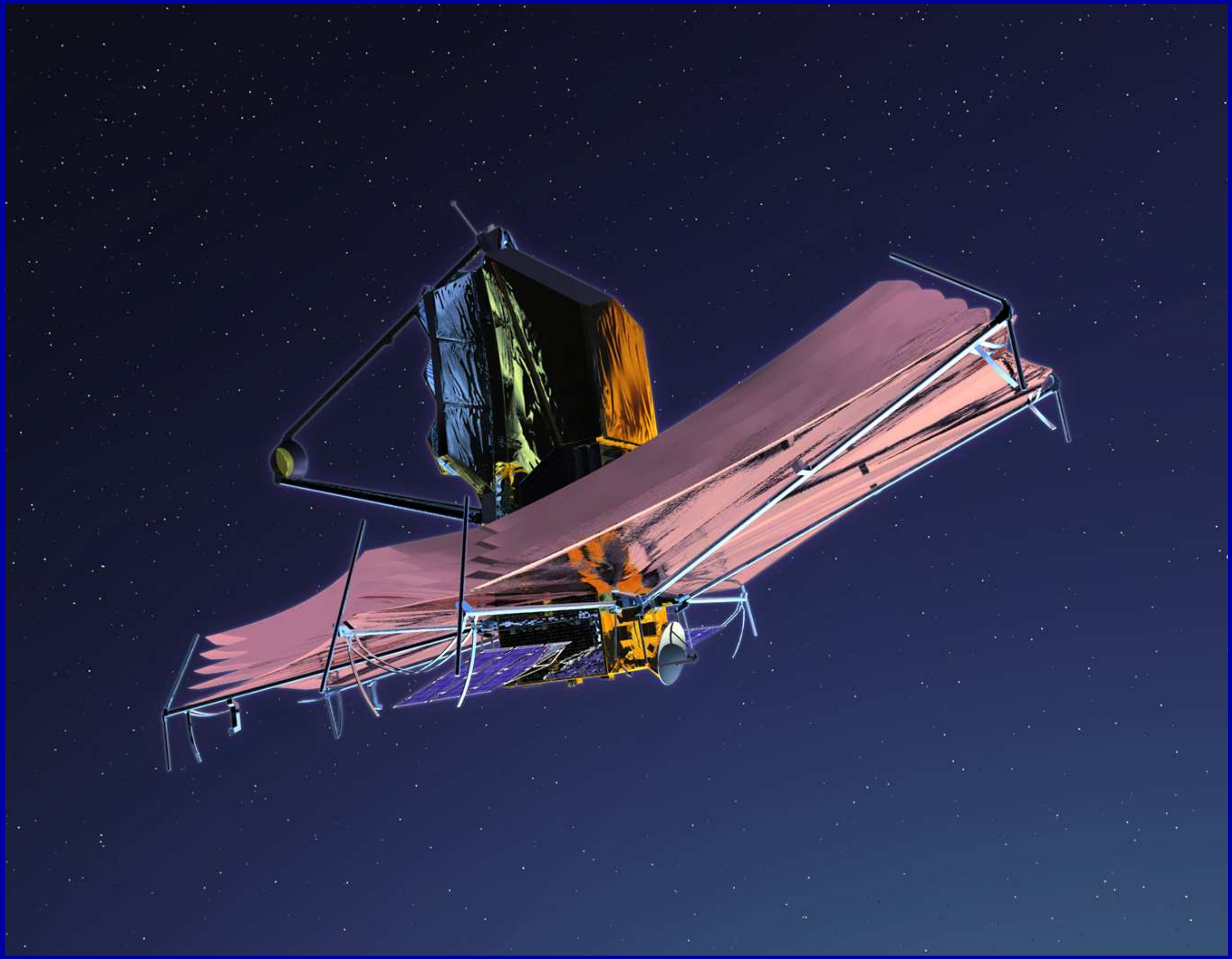


Zodiacal, atmospheric, and thermal backgrounds in the optical/IR require that systematic First Light studies (z$\gtrsim$10) be done from space.

James Webb Space Telescope

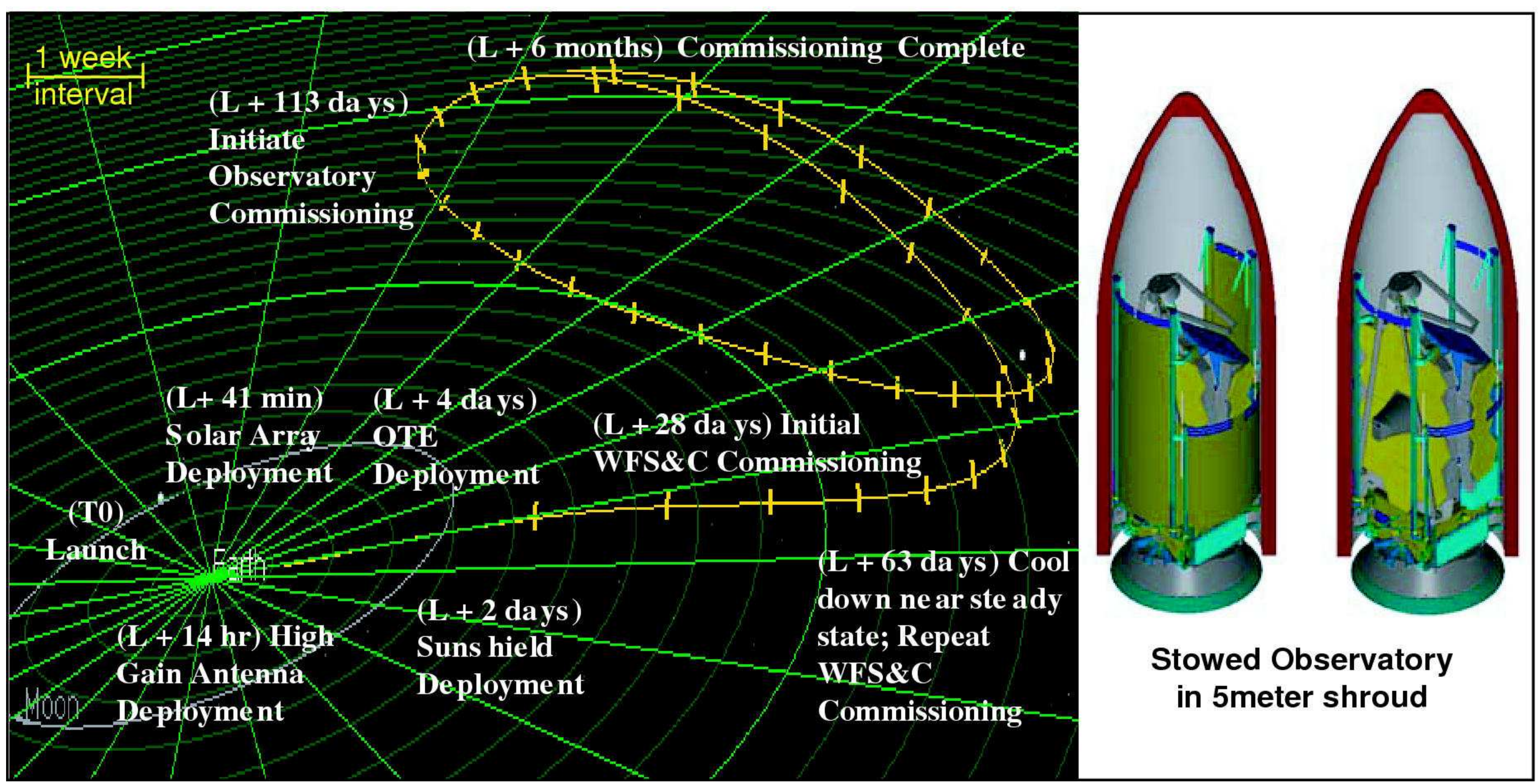


- (1) What is the James Webb Space Telescope (JWST)?



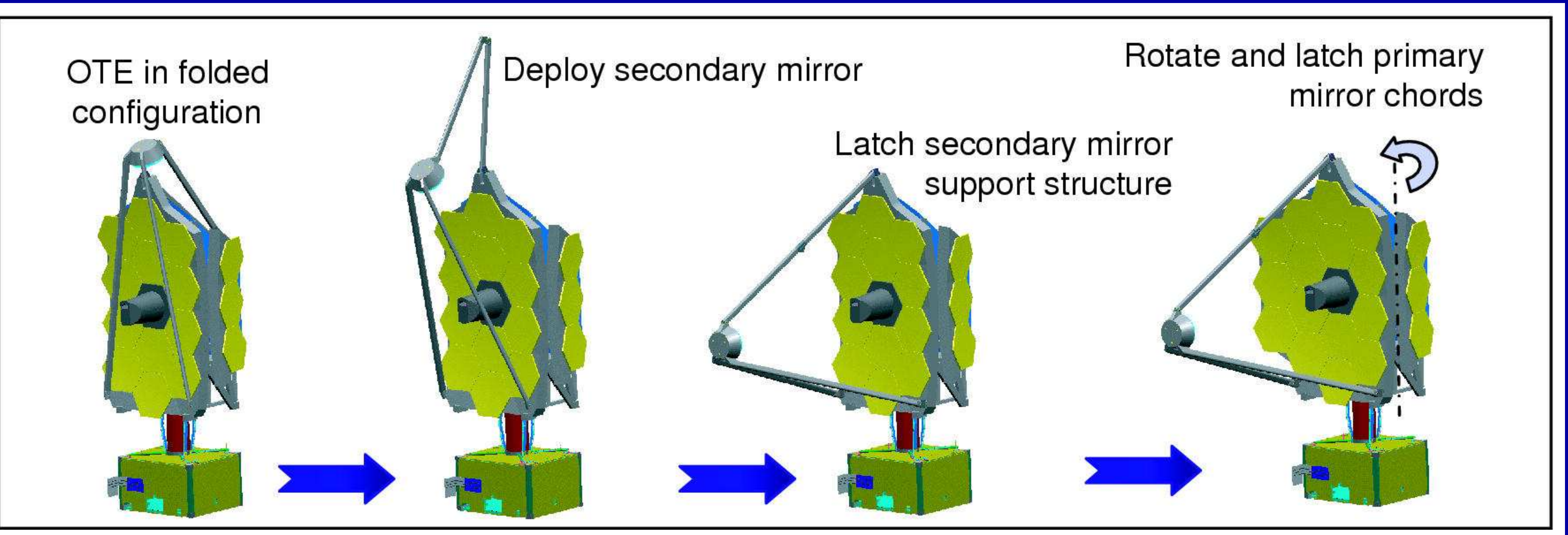
- A fully deployable 6.5 meter (25 m^2) segmented IR telescope for imaging and spectroscopy from 0.6 to 28 μm, to be launched by NASA $\gtrsim$2013. It has a nested array of sun-shields to keep its ambient temperature at 35-45 K, allowing faint imaging (AB$\lesssim$31 mag) and spectroscopy (AB$\lesssim$28 mag).

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



After launch in $\gtrsim$2013 with an Ariane V vehicle, JWST will orbit around the the Earth–Sun Lagrange point L2. From there, JWST can cover the whole sky in segments that move along in RA with the Earth, have an observing efficiency $\gtrsim$70%, and send data back to Earth every day.

• (1) How will the 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.

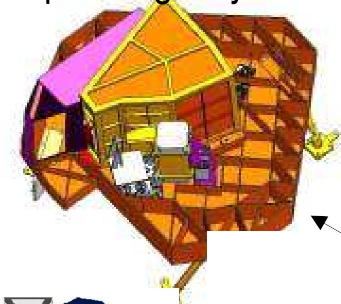
JWST mission reviewed in Gardner, J. P., et al. 2006, Space Science Reviews, Vol. 123, pg. 485–606 (astro-ph/0606175).

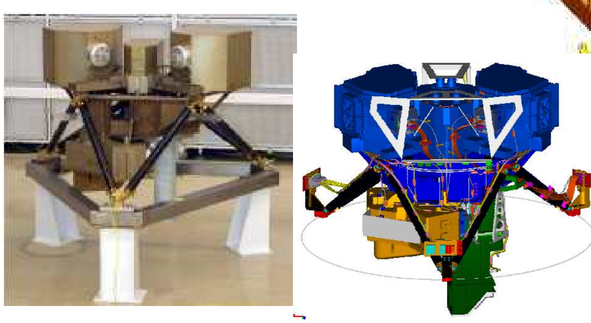
• (1) What instruments will JWST have? US (UofA, JPL), ESA, and CSA.

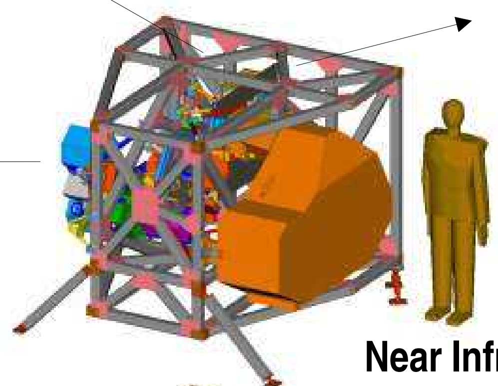
Instrument Overview

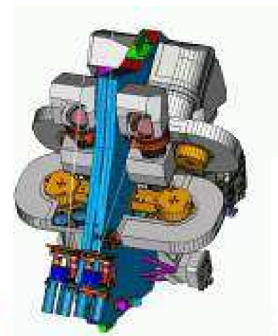
Fine Guidance Sensor (FGS)
- Ensures guide star availability with >95% probability at any point in the sky
- Includes Narrowband Imaging Tunable Filter
- Developed by Canadian Space Agency & COM DEV

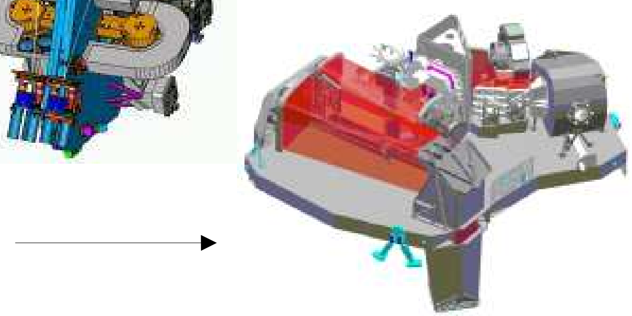
Near Infra-Red Camera (NIRCam)
- Detects first light galaxies and observes galaxy assembly sequence
- 0.6 to 5 microns
- Supports Wavefront Sensing & Control
- Developed by Univ. of AZ & LMATC







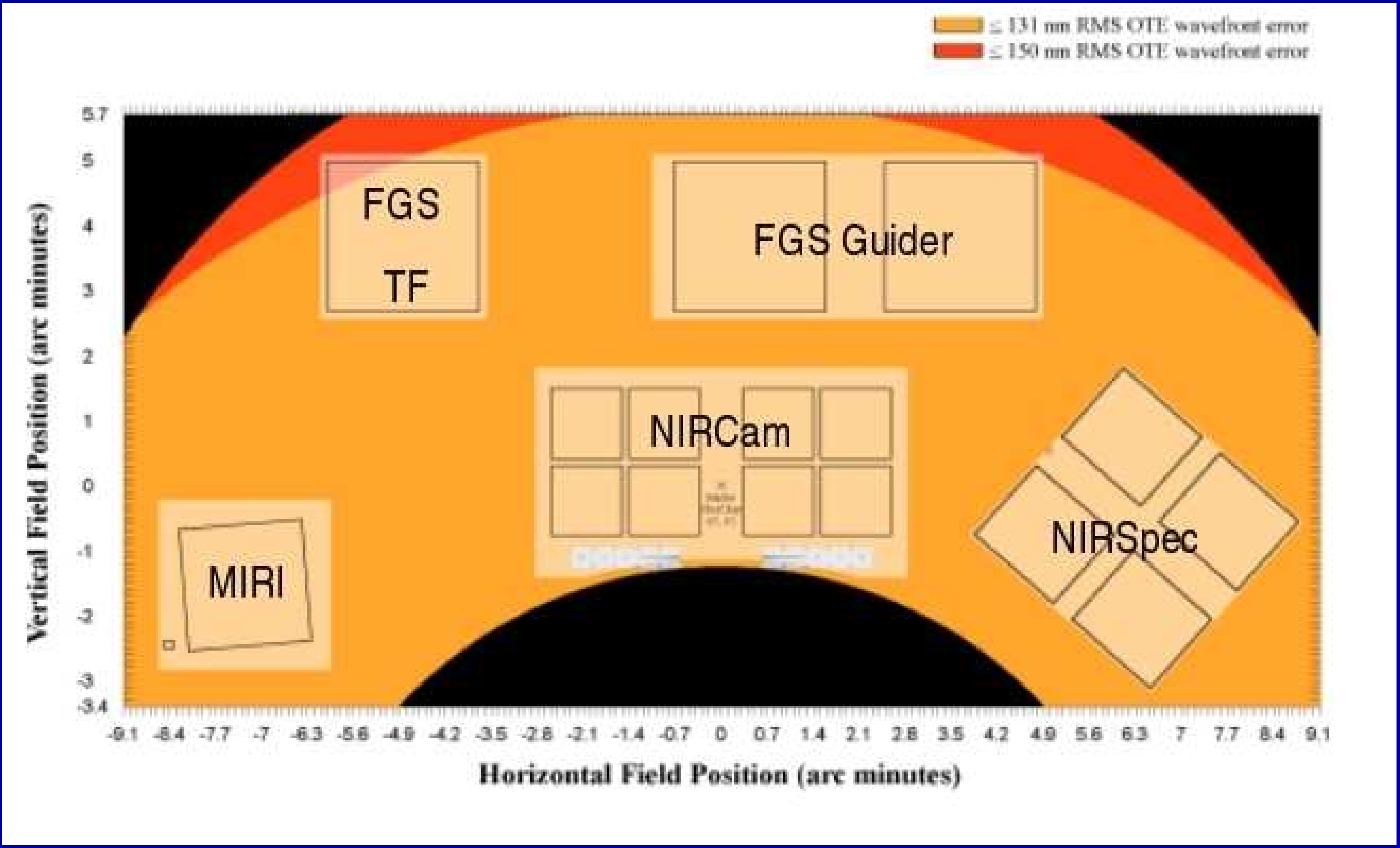




Mid-Infra-Red Instrument (MIRI)
- Distinguishes first light objects; studies galaxy evolution; explores protostars & their environs
- Imaging and spectroscopy capability
- 5 to 27 microns
- Cooled to 7K by Cyro-cooler
- Combined European Consortium/JPL development

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

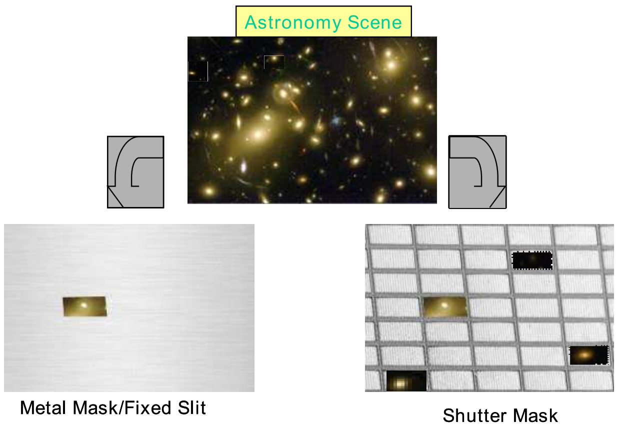
• (1) What instruments will JWST have?

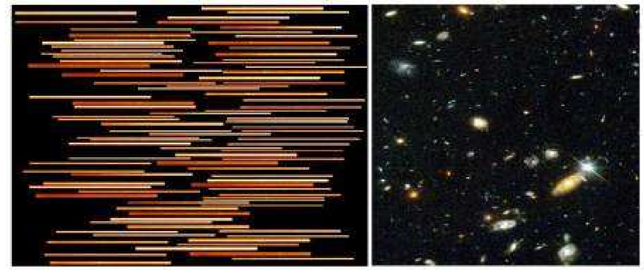


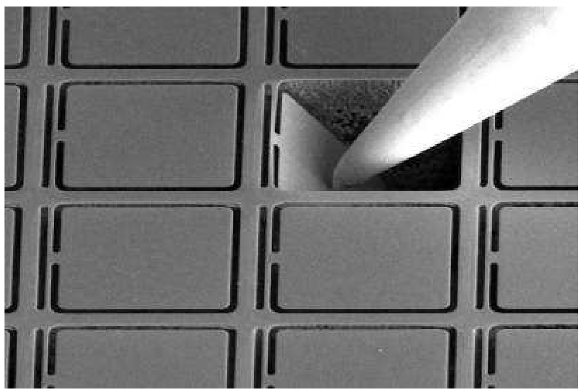
All JWST instruments can in principle be used in parallel:

• Currently only implemented for parallel calibrations.

Micro Shutters



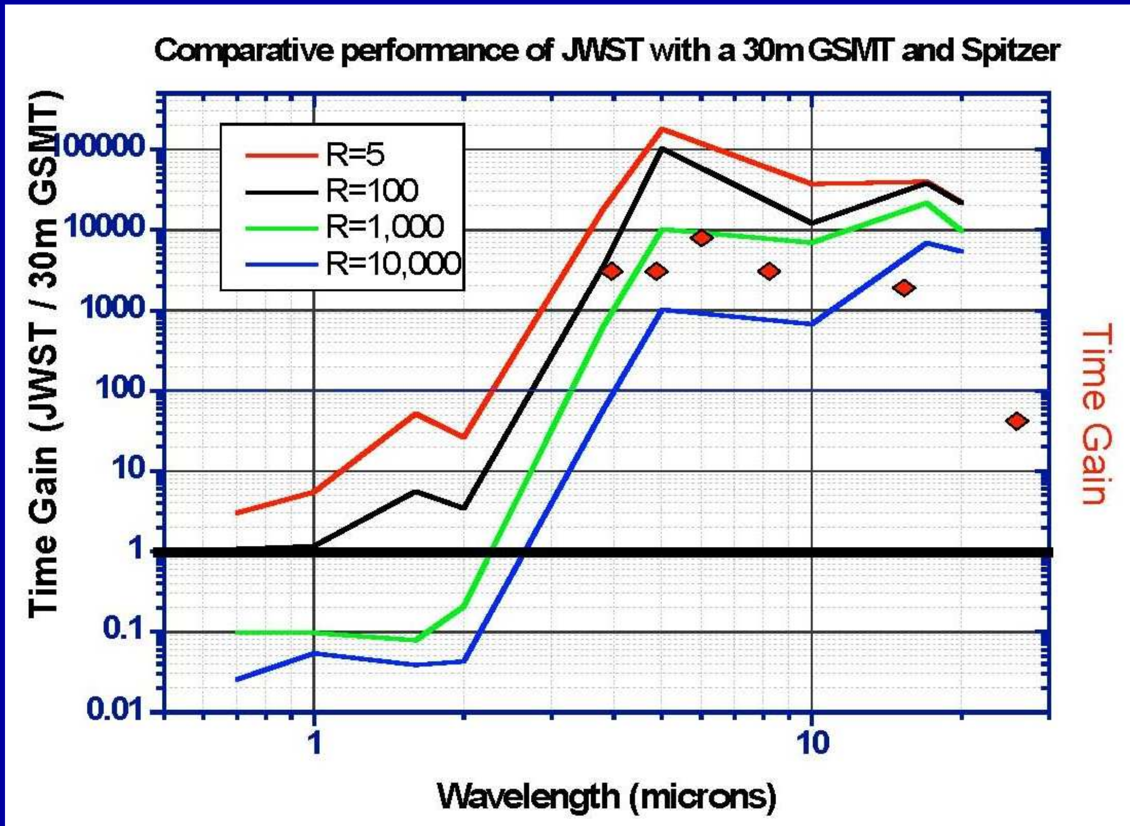


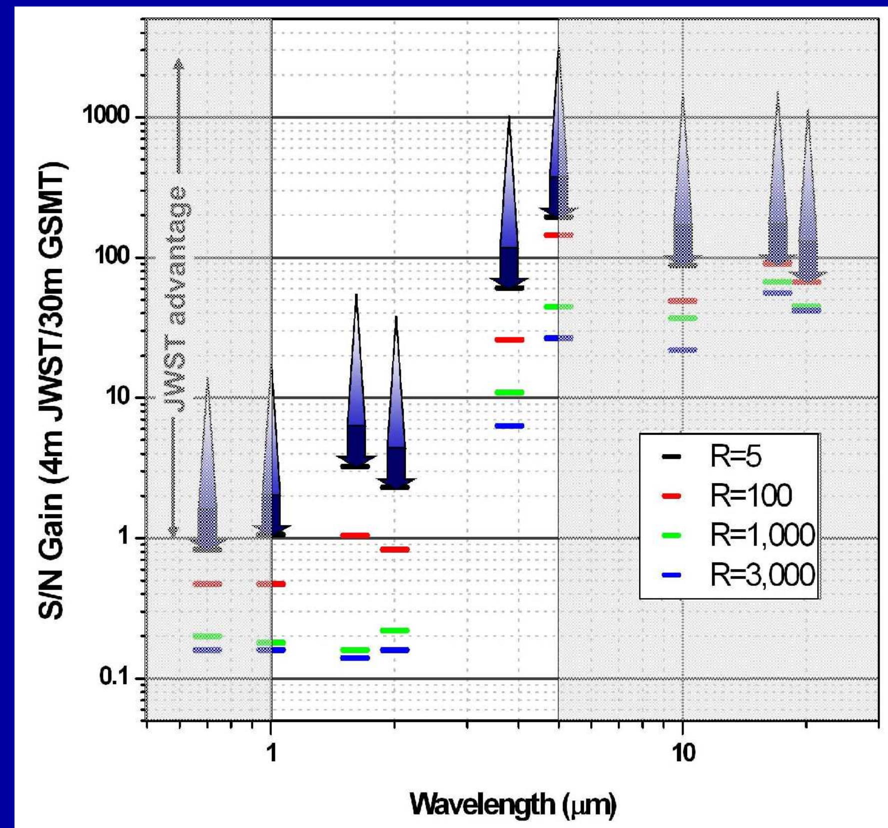


JWST offers significant multiplexing for faint object spectroscopy:

- NIRSpec/MEMS with 4$\times$62,415 independently operable micro-shutters that cover $\boldsymbol{\lambda}\simeq$1–5 μm at R=100–1000.
- MIRI/IFU with 400 spatial pixels covering 5–28.5 μm at R$\sim$2000–4000.
- FGS/TFI that covers a 2$'\!.$2$\times$2$'\!.$2 FOV at $\boldsymbol{\lambda}\simeq$1.6–4.9 μm at R=100.

(3) Synergy between the TMT and JWST





LEFT: Time-gain(λ) of JWST compared to TMT and Spitzer (diamonds).
TMT-AO competition is reason JWST no longer has specs for $\lambda \lesssim 1.7\ \mu$m.

RIGHT: S/N-gain(λ) of JWST compared to ground-based:

- Top of arrows: 6m JWST/Keck; Middle: 6m JWST/TMT; Bottom: 4m JWST/TMT.

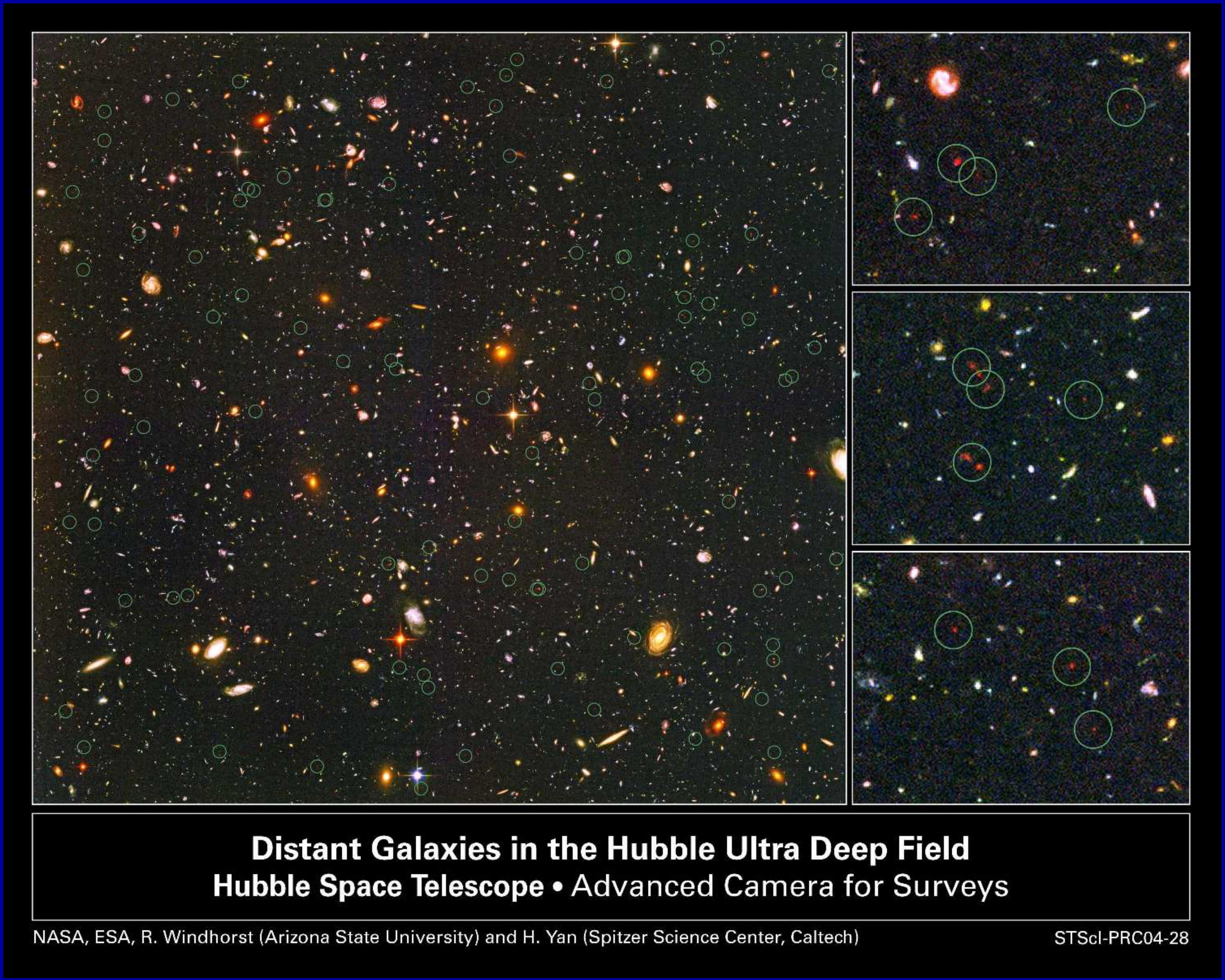
(3) Comparison of TMT and JWST — areas of unique strength

Instrument Capabilty	*Uniqueness*
Imaging 0.7-1.7 microns	20-30m MCAO will be comparable
Imaging 1.7 - 5.0 microns	JWST Unique
Imaging 5-28 microns	JWST Unique
Coronagraphy 0.7 - 2.3 microns	Extreme AO on 8-10m superior
Coronagraphy 2.4 - 5 microns	JWST Unique
Coronagraphy 5 - 28 microns	JWST in principle unique
Tunable filter 1.0 - 2.0 microns	8-10m AO & narrow band filters comparable
Tunable filter 2.4 - 5 microns	JWST in principle unique
Slit Spectroscopy 0.7-1.7 microns	20-30m MCAO superior
Slit Spectroscopy 1.6 - 5 microns	JWST Unique
MOS spectroscopy 0.7- 1.7 microns	20-30m MCAO superior
MOS spectroscopy 1.7 - 5 microns	JWST Unique
IFU spectroscopy 1.0- 1.7 microns	20-30m MCAO superior
IFU spectroscopy 1.7 - 5 microns	JWST Unique
(IFU) spectroscopy 5-28 microns	JWST Unique

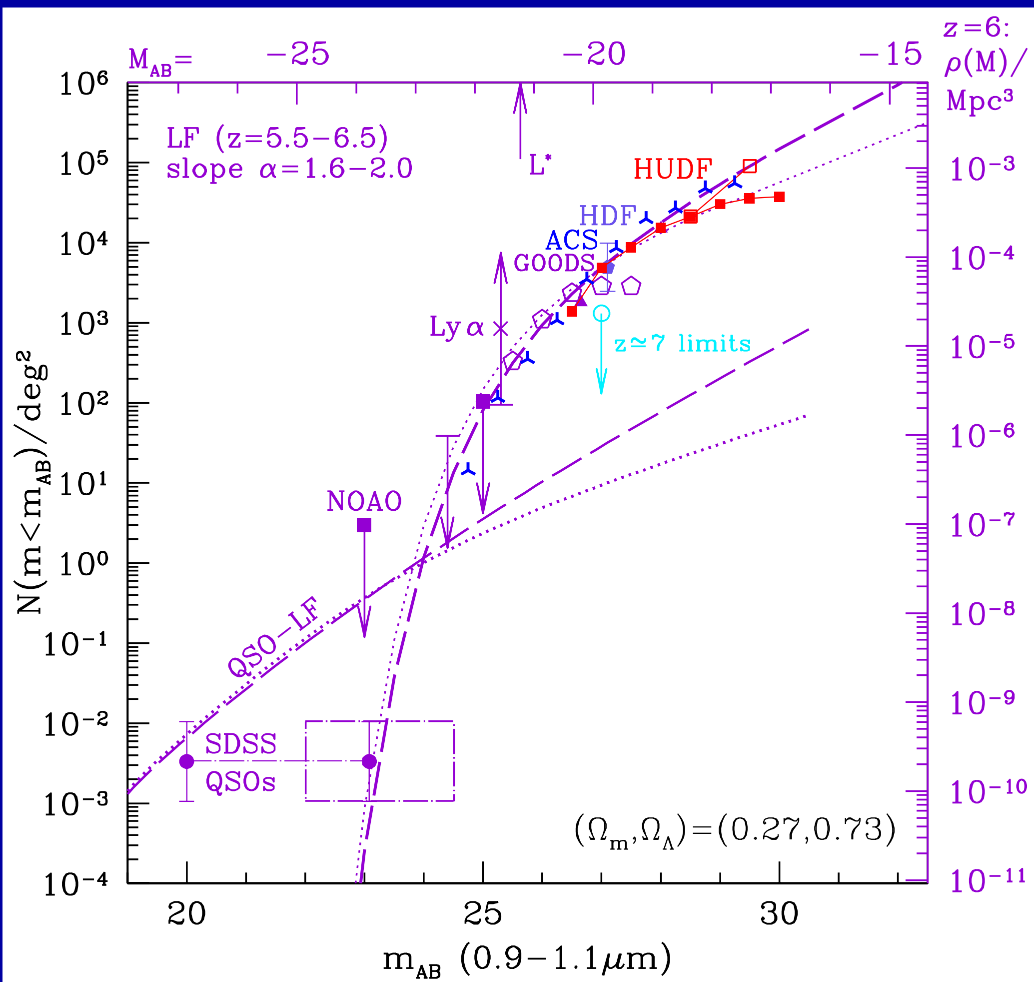
JWST: diffraction limited wide-FOV imaging and low-res spectra at $\gtrsim 2\mu$m.

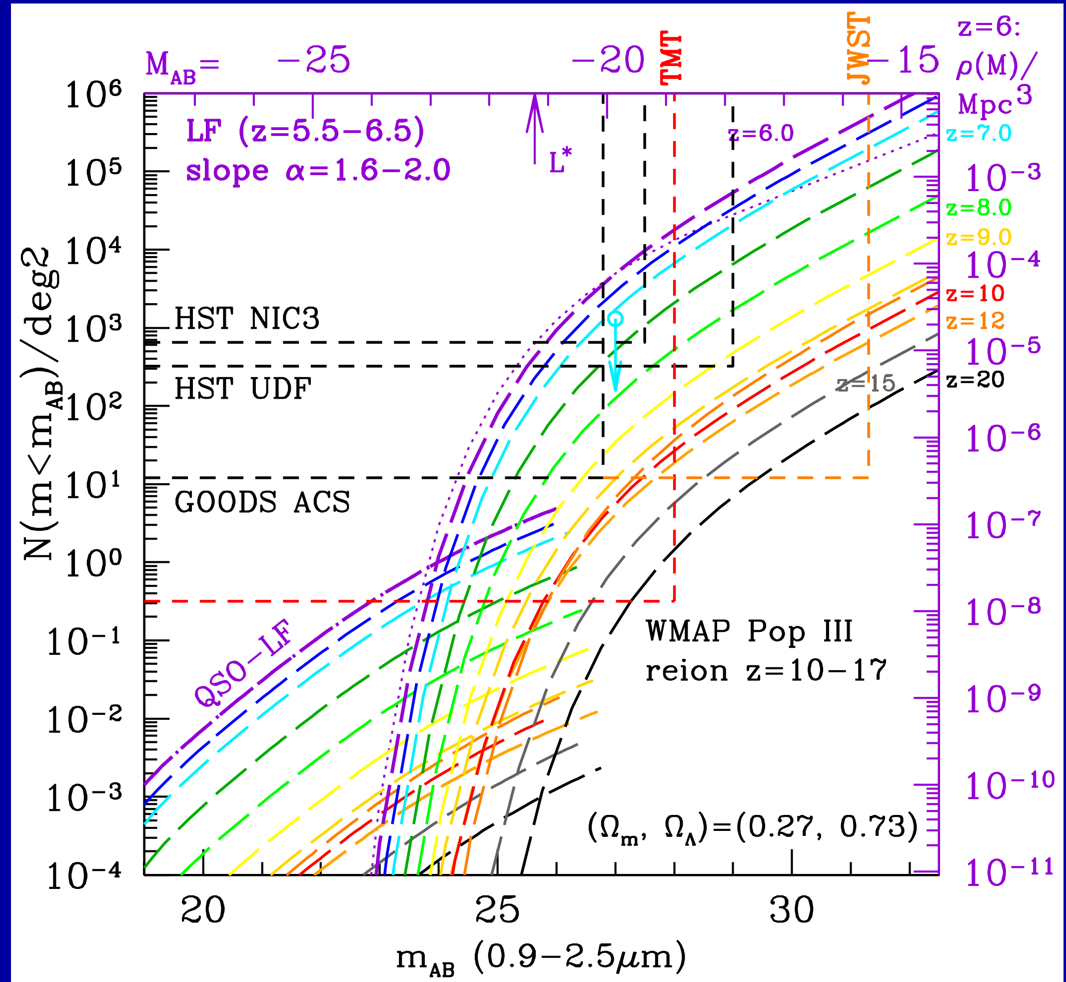
TMT: high-resolution imaging, coronagraphy, TF-imaging & IFU spectra at $\lesssim 1.7\mu$m, and high-resolution spectroscopy at $\lesssim 2\ \mu$m (with AO beyond).

(3) Synergy between TMT and JWST in First Light and Reionization



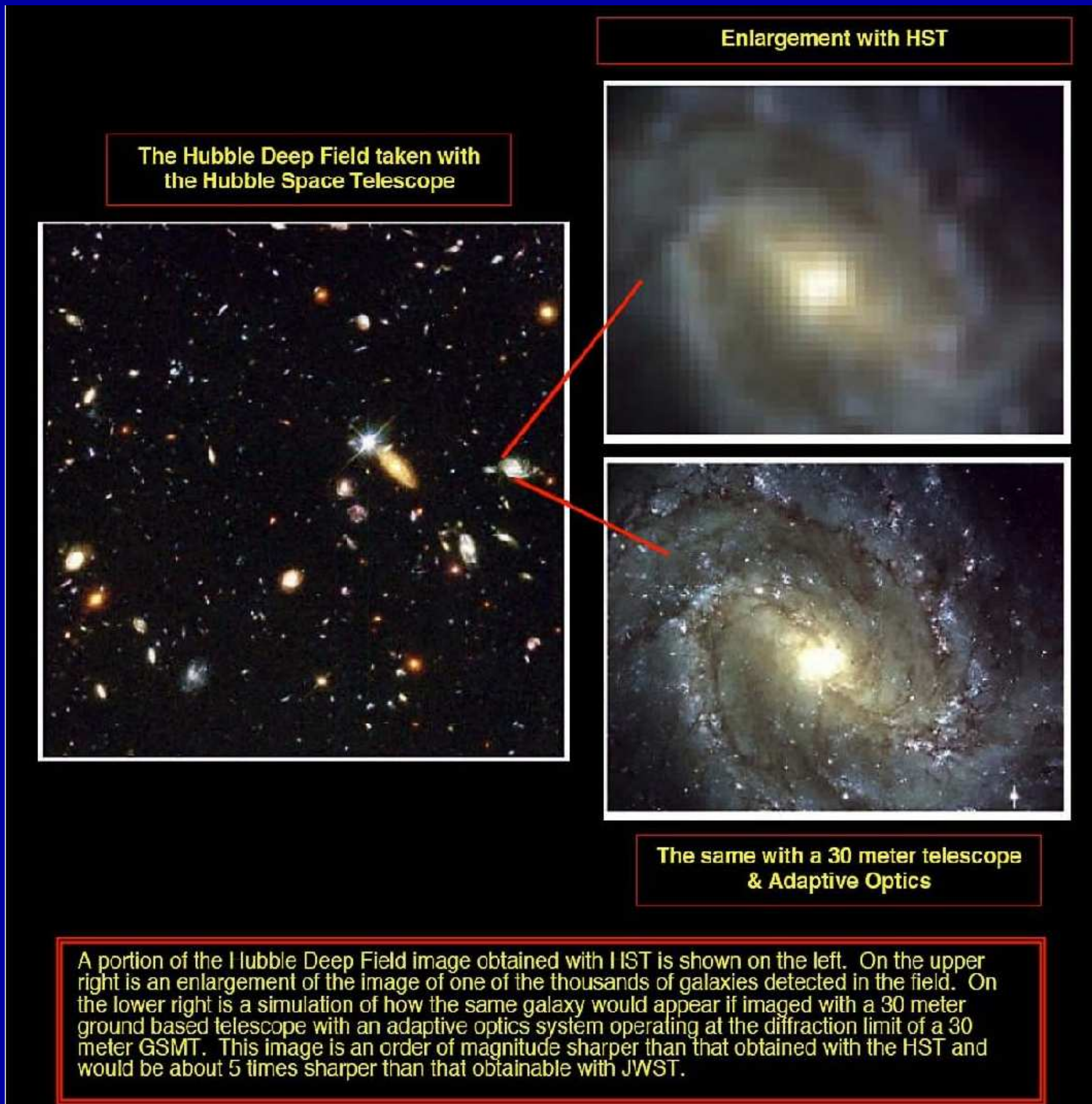
HUDF i-drops: faint galaxies at z≃6 (Yan & Windhorst 2004), most confirmed at z≃6 by ACS grism to AB≲27.0 mag (Malhotra et al. 2005).

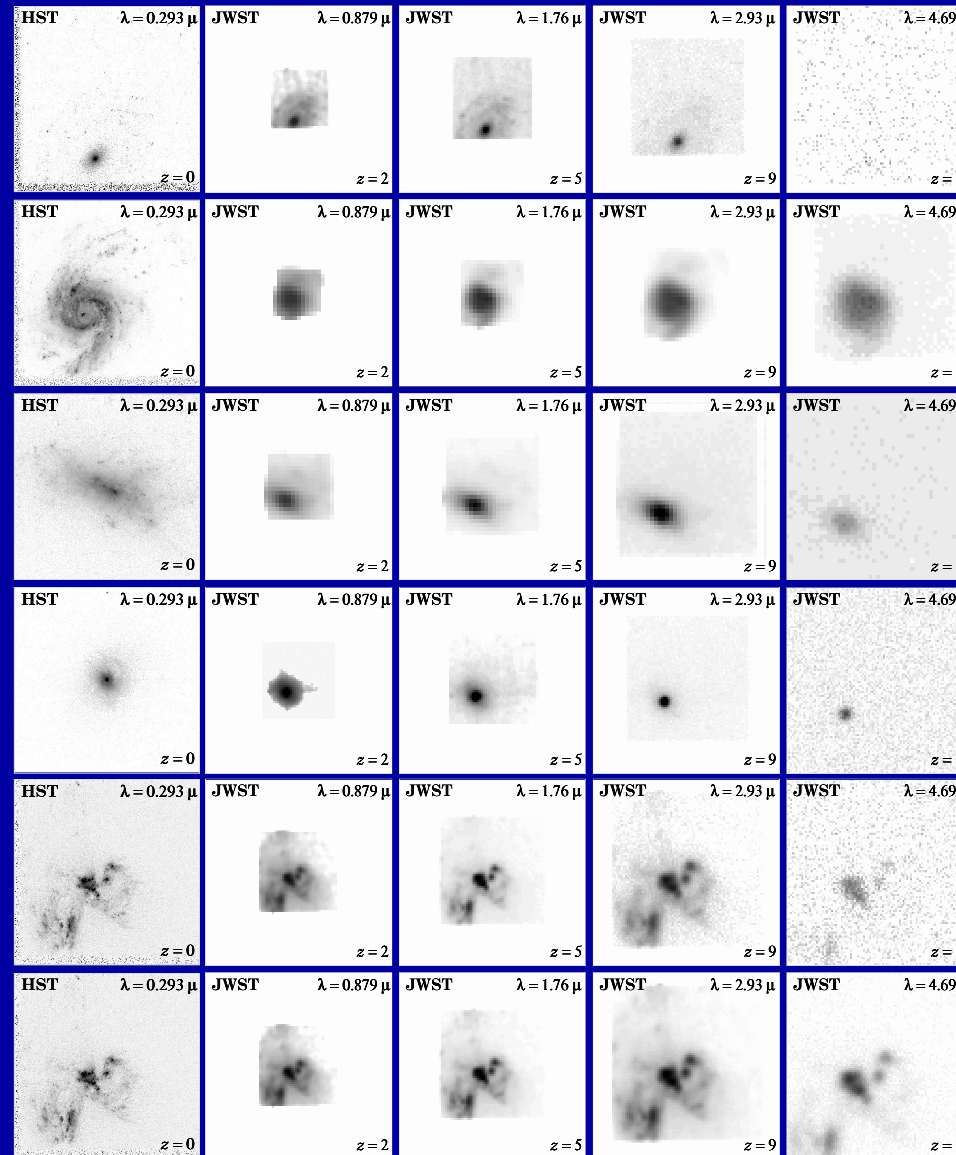




- HUDF z≃6 LF has very steep faint-end slope: $\alpha \simeq$-1.8 (Yan & Windhorst 2004). ⇒ Dwarf galaxies, not QSO's likely completed reionization at z≃6.
- With proper survey strategy (area AND depth), JWST can trace the entire reionization epoch and detect the first star-forming objects at z$\gtrsim$10.
- TMT with wide-field optical–near-IR imaging spectrograph is an essential complement to the JWST First Light survey: Galaxy and QSO LF to z∼10 & AB$\lesssim$28 mag — co-evolution of supermassive black-holes & proto-bulges.

(4) Synergy between TMT and JWST in Galaxy Assembly

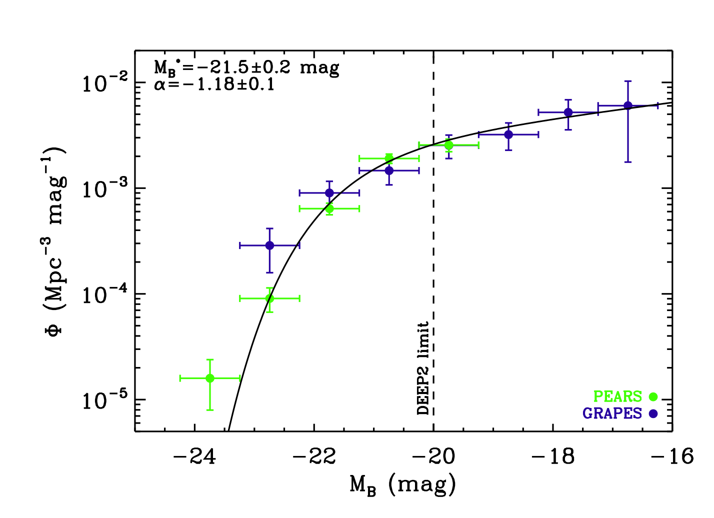


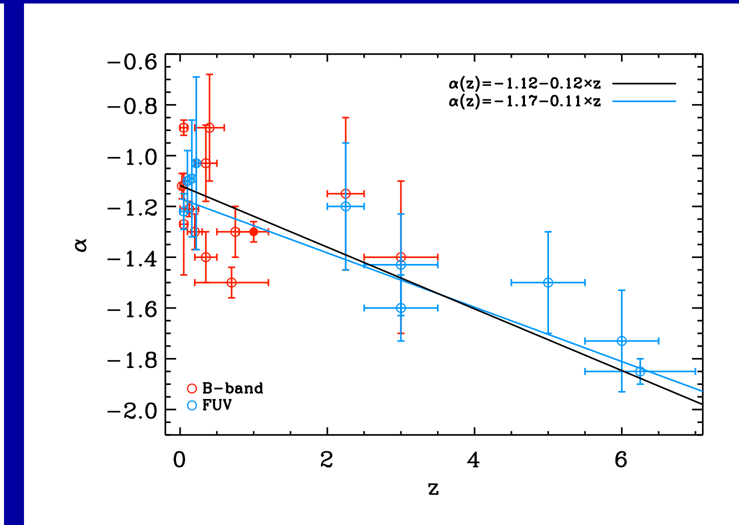


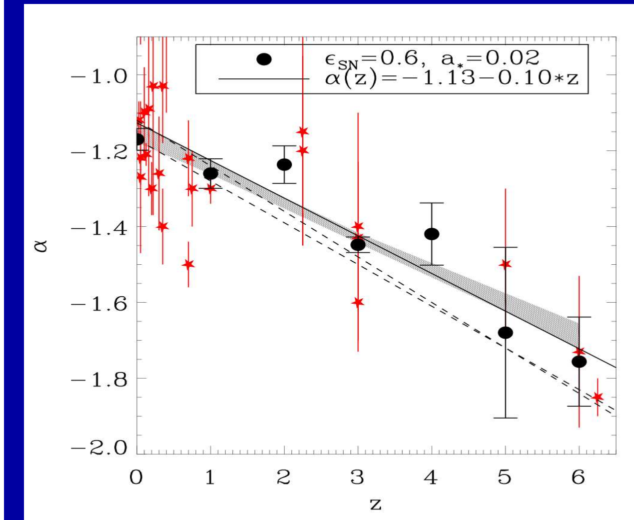
LEFT: Simulated AO image of TMT compared to Hubble Deep Field. RIGHT: Comparison of HST UV images on nearby galaxies to 1-hr JWST images of the same objects at z=2, 5, 9, 15 (bottom row = 100 hrs).

TMT strength: high resolution; JWST strength: λ/z-range & sensitivity.

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



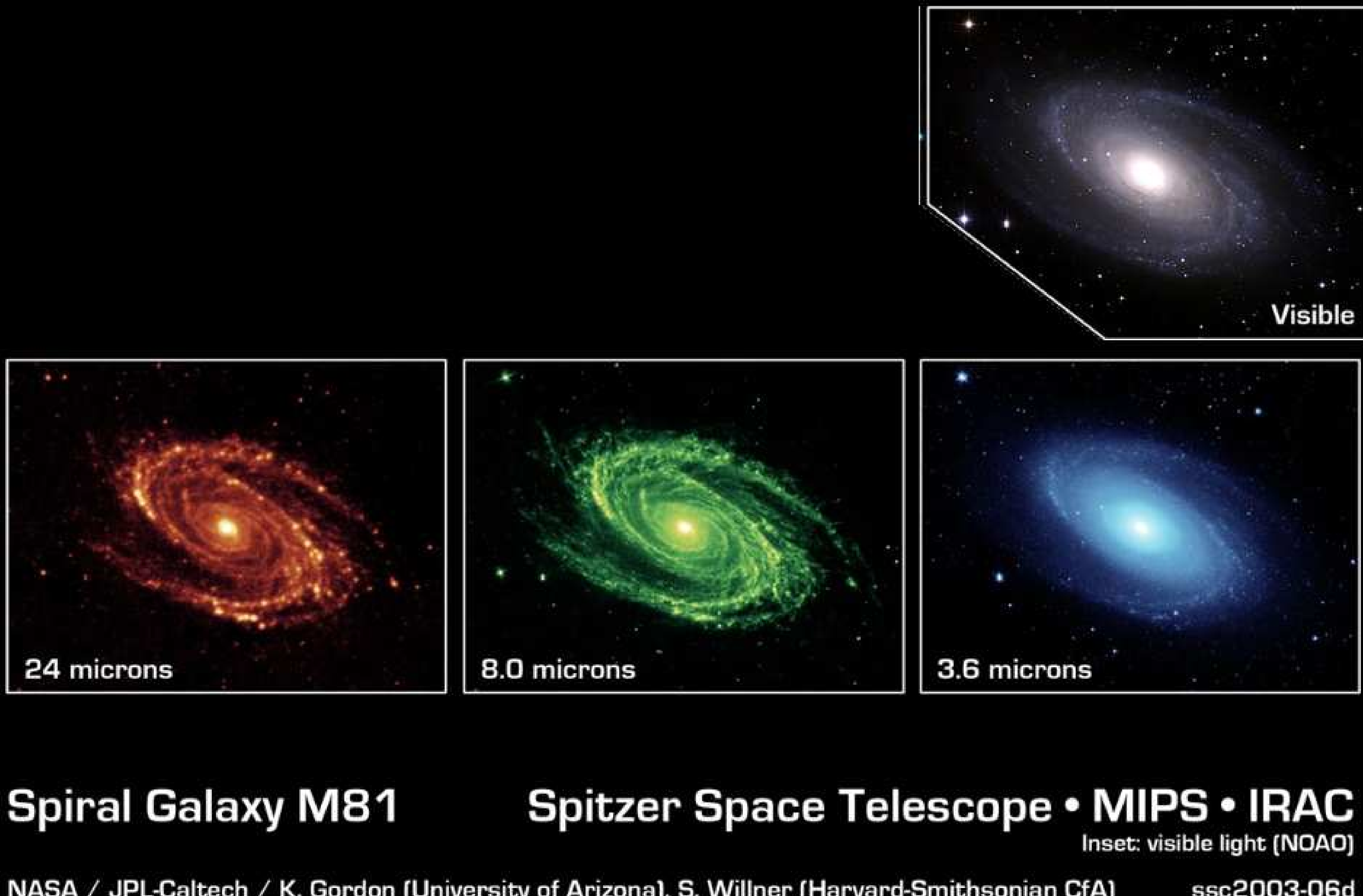




Faint-end LF-slope at z$\gtrsim$1 with accurate ACS grism z's to AB$\lesssim$27 (Cohen et al.; Ryan et al. 2007) constrains hierarchical formation theories:

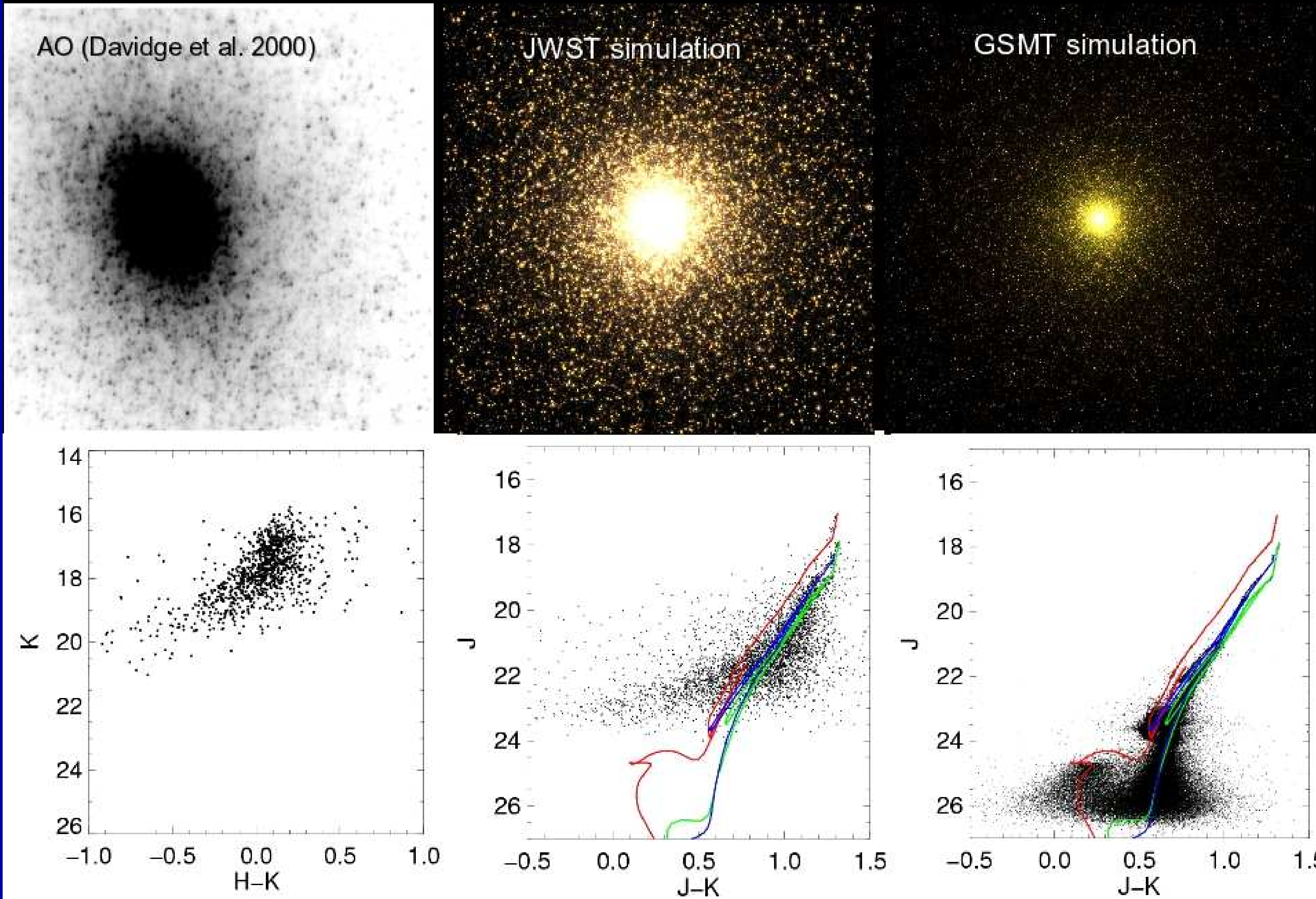
- Star-formation and SN feedback processes produce different faint-end slope-evolution: new physical constraints (Khochfar ea. astro-ph/0707.2790).
- JWST will provide fainter spectra (AB$\lesssim$29). TMT will provide much larger FOV & samples. Combination will trace α-evolution for 1$\lesssim$z$\lesssim$12.
- TMT measures environmental impact on LF faint-end slope α directly.
- Expect convergence to slope $|\alpha|\equiv$2 at z>6 before feedback starts.
- Constrain onset of Pop III SNe epoch, Type II & Type Ia SN-epochs.

Panchromatic views of Spiral Galaxies



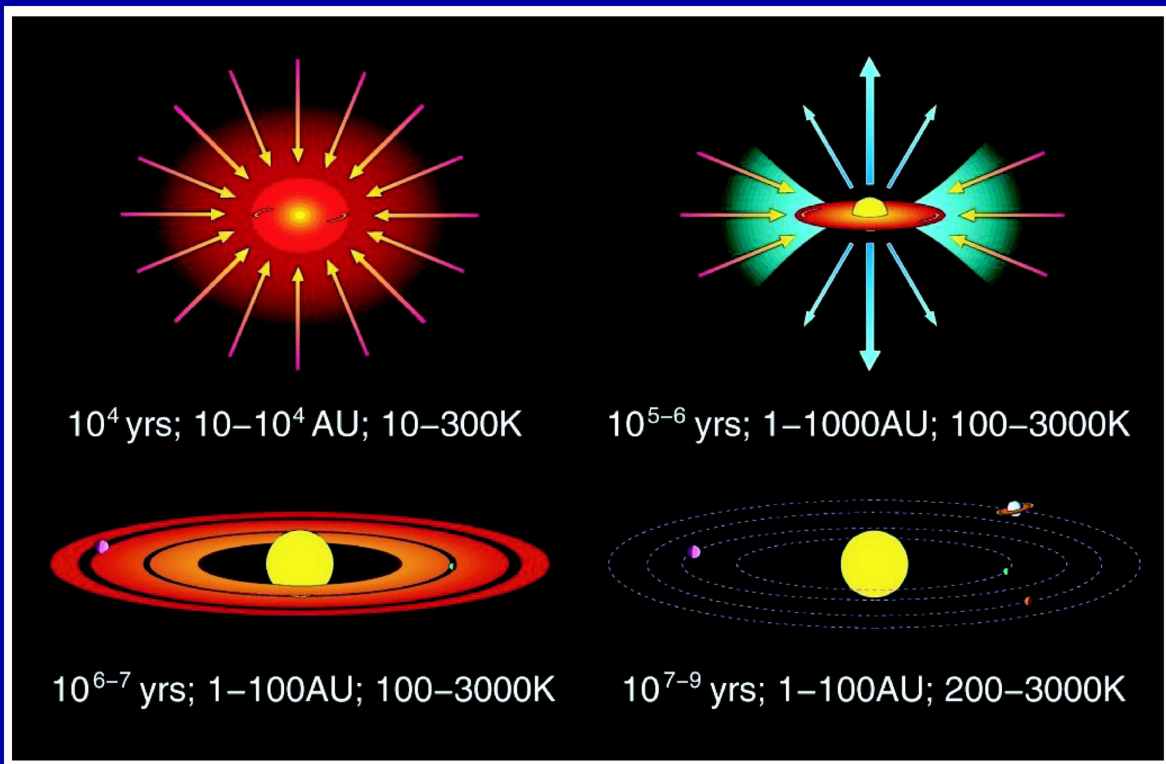
TMT strength is high resolution & sensitivity, JWST strength is λ-range.

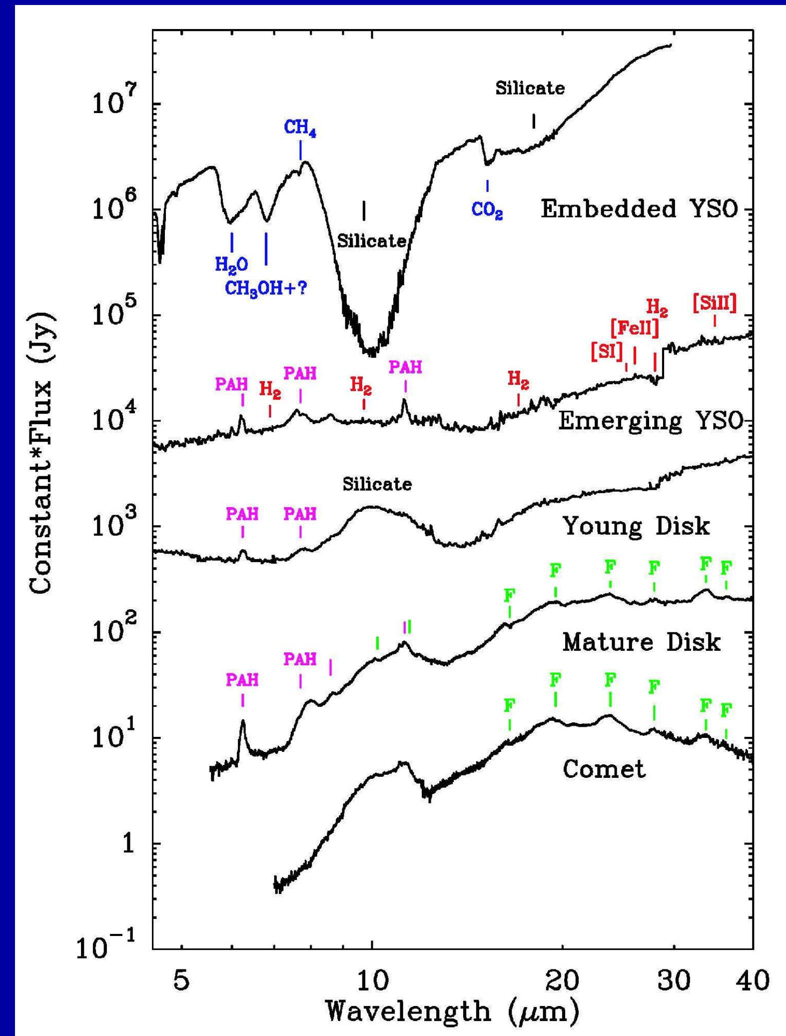
The Center of M32



TMT strength is high resolution & sensitivity, JWST strength is λ-range.

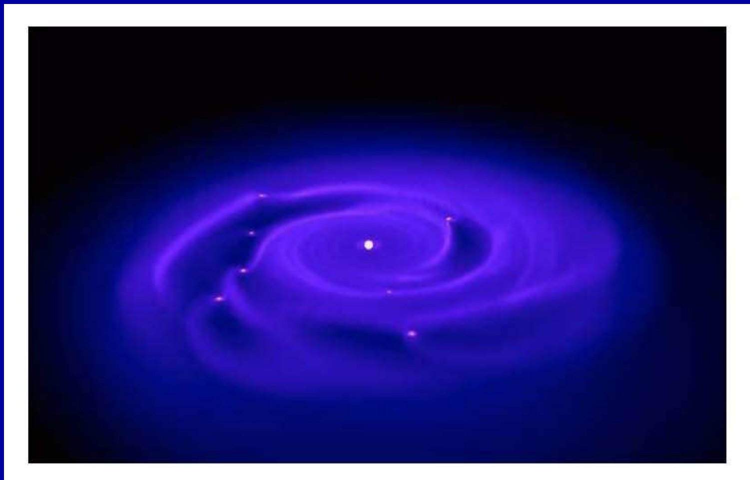
(5) Synergy between TMT and JWST in Star- and Planet Formation

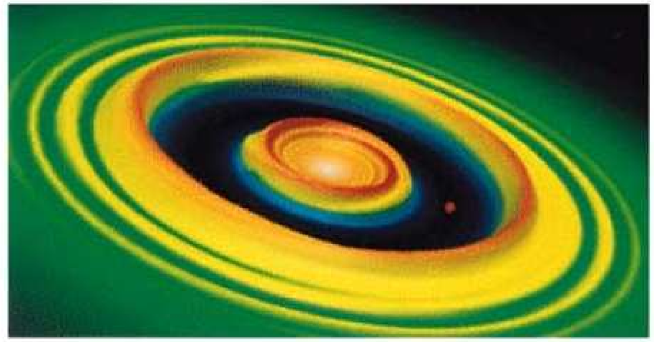


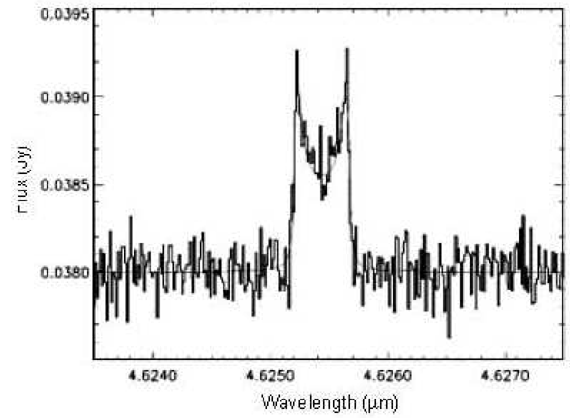


TMT will trace various stages of star-formation, YSO's, debris-disk formation and planet formation through very high-resolution imaging, coronagraphy, & high-resolution optical–IR spectra.

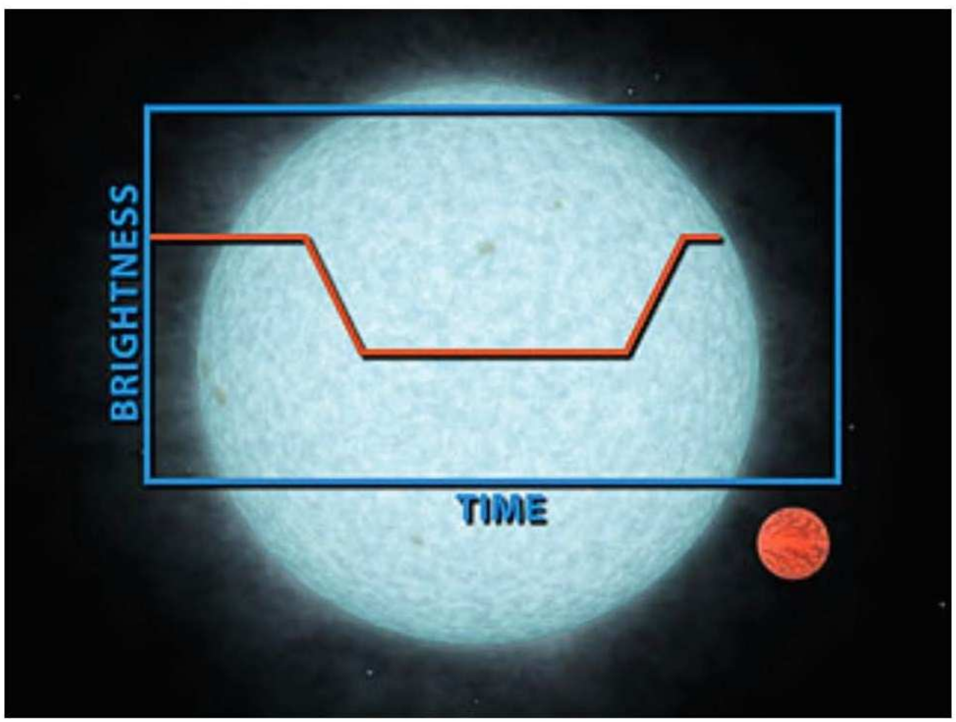
JWST provides high time-resolution photometry & coronagraphy for planet detection, and *panchromatic* low-resolution near–mid-IR spectra.

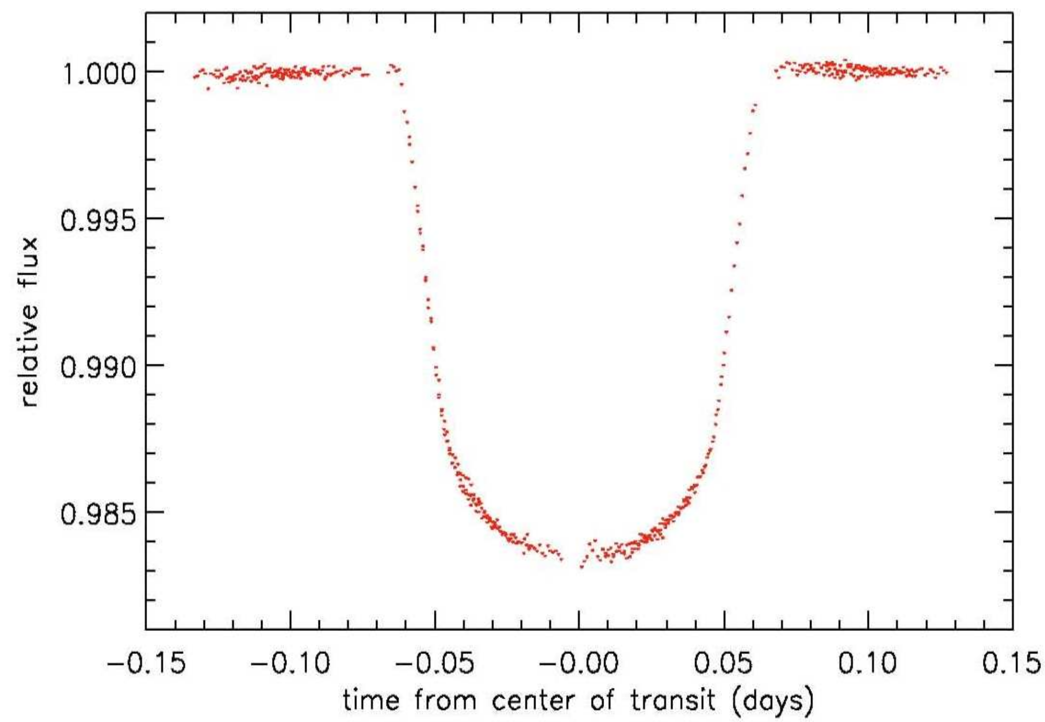






TMT: very high-res imaging, coronagraphy, & high-res optical-IR spectra.





JWST: High time-res photometry, coronagraphy, & low-res mid-IR spectra.

(6) Summary

(1) JWST will map in detail:

- (a) First Light and Reionization — from Pop III objects to dwarf galaxies.
- (b) Galaxy Assembly: hierarchical origin of the Hubble sequence.
- (c) Star-formation, planet formation and evolution.

(2) JWST provides a critical *concurrent* complement to TMT: *panchromatic near–mid-IR imaging & spectral follow-up of TMT discoveries:*

- Continuum & dust properties of First Light Lyα candidates at z$\gtrsim$8.
- Faint-end of LF around QSO's and Lyα overdensities at z$\gtrsim$8.
- JWST follow-up of rare GRB's, Pop III SNe at z$\gtrsim$8, Type II SNe at z$\gtrsim$2.
- JWST TOO's of other variable objects and moving targets: AGN, MACHO's, YSO's, novae, flare stars, KBO's, comets, etc.
- PAHs, H_2, & other molecules in Galactic and extragalactic SF-regions.
- H_2O, CH_4, NH_3, etc., in planetary debris disks and extrasolar planets.
- Expect to need JWST for the unexpected TMT discoveries !

SPARE CHARTS

- References and other sources shown:

http://www.asu.edu/clas/hst/www/jwst/ [Talk, Movie, Java-tool.]
http://www.jwst.nasa.gov/ and http://www.stsci.edu/jwst/
http://www.jwst.nasa.gov/ISIM/index.html
http://ircamera.as.arizona.edu/nircam/
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http://www.stsci.edu/jwst/instruments/guider/
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Kudritzki, R., Frogel, J. ea. 2005, A Giant Segmented Mirror Telescope: Synergy with the James Webb Space Telescope, Report to the AAAC.

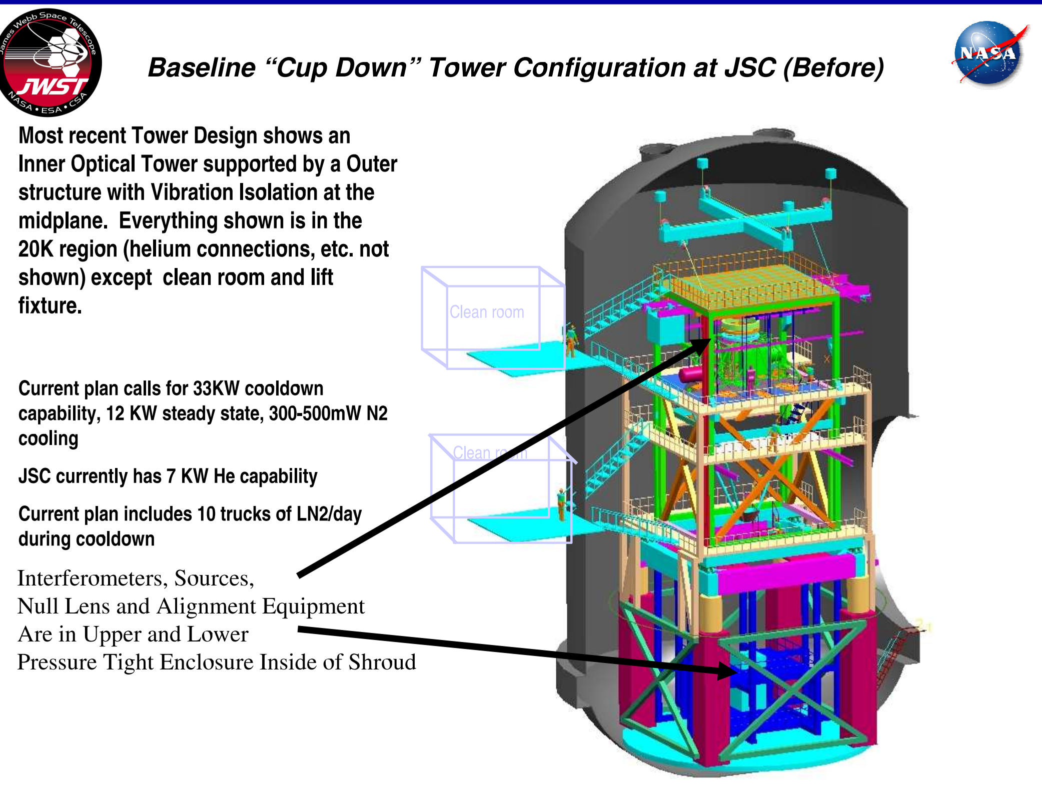
Mather, J., Stockman, H. 2000, Proc. SPIE Vol. 4013, 2

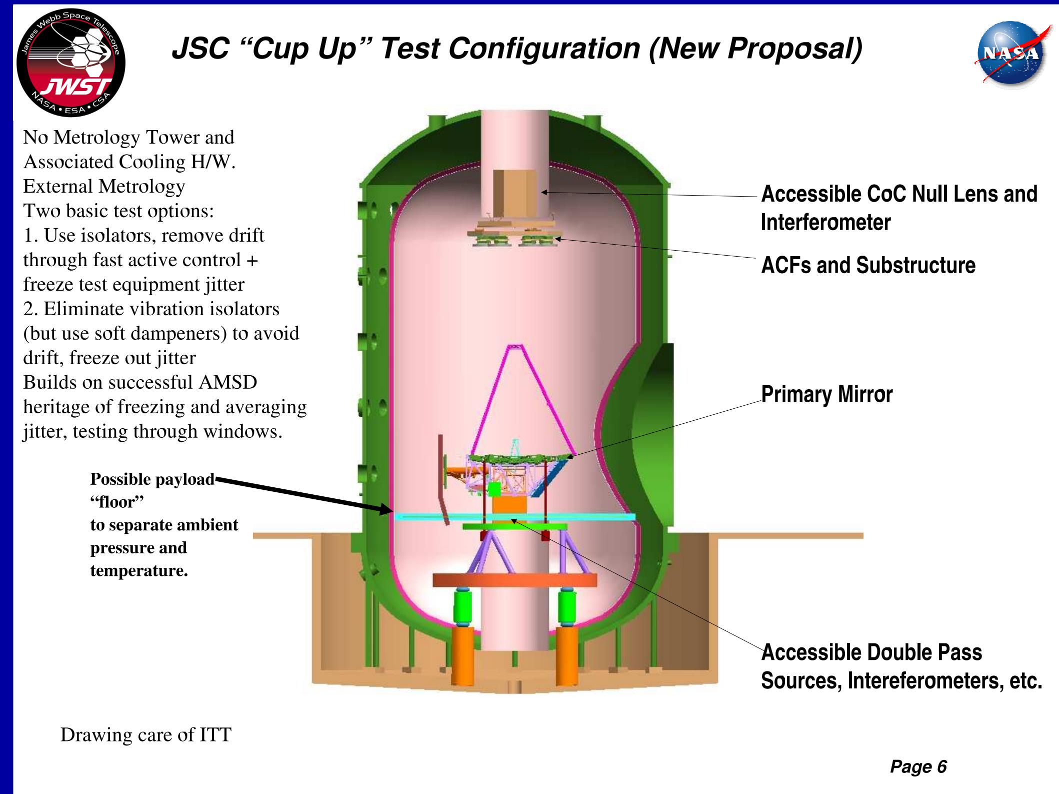
Windhorst, R. A., et al. 2007, Advances in Space Research, Vol. 9163, (astro-ph/0703171) "High Resolution Science with High Redshift Galaxies"

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

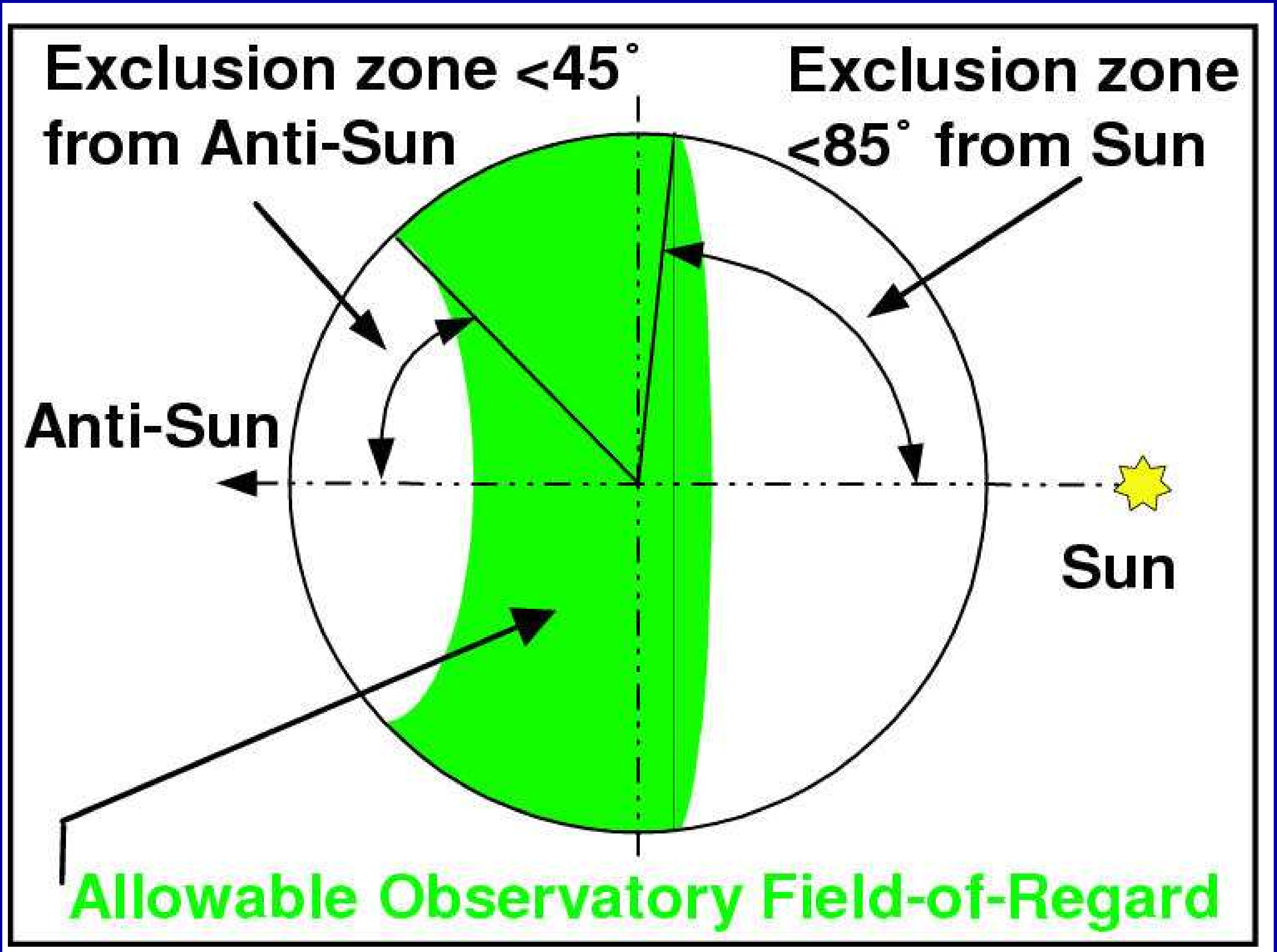




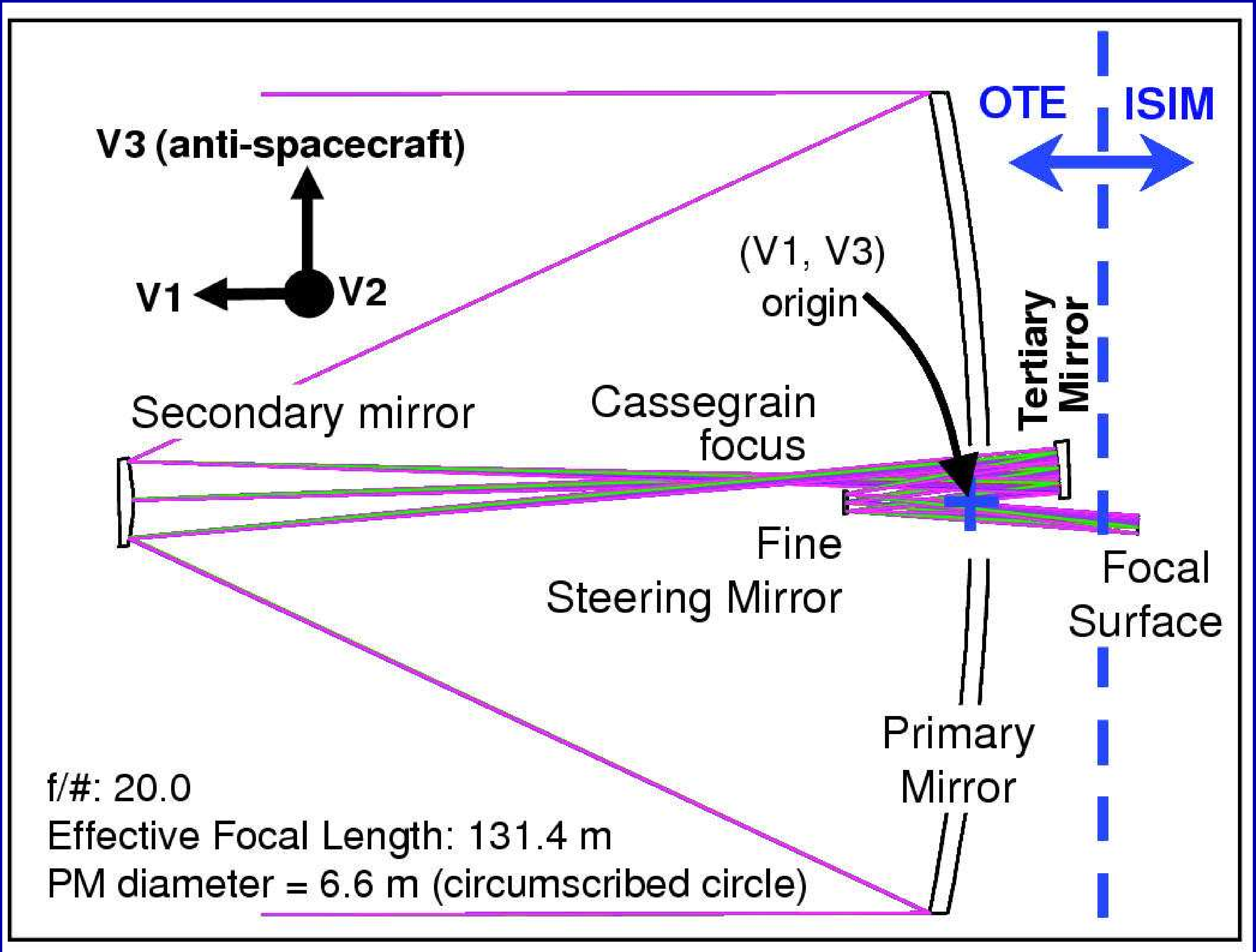


JWST underwent several significant replans and risk-reduction schemes:

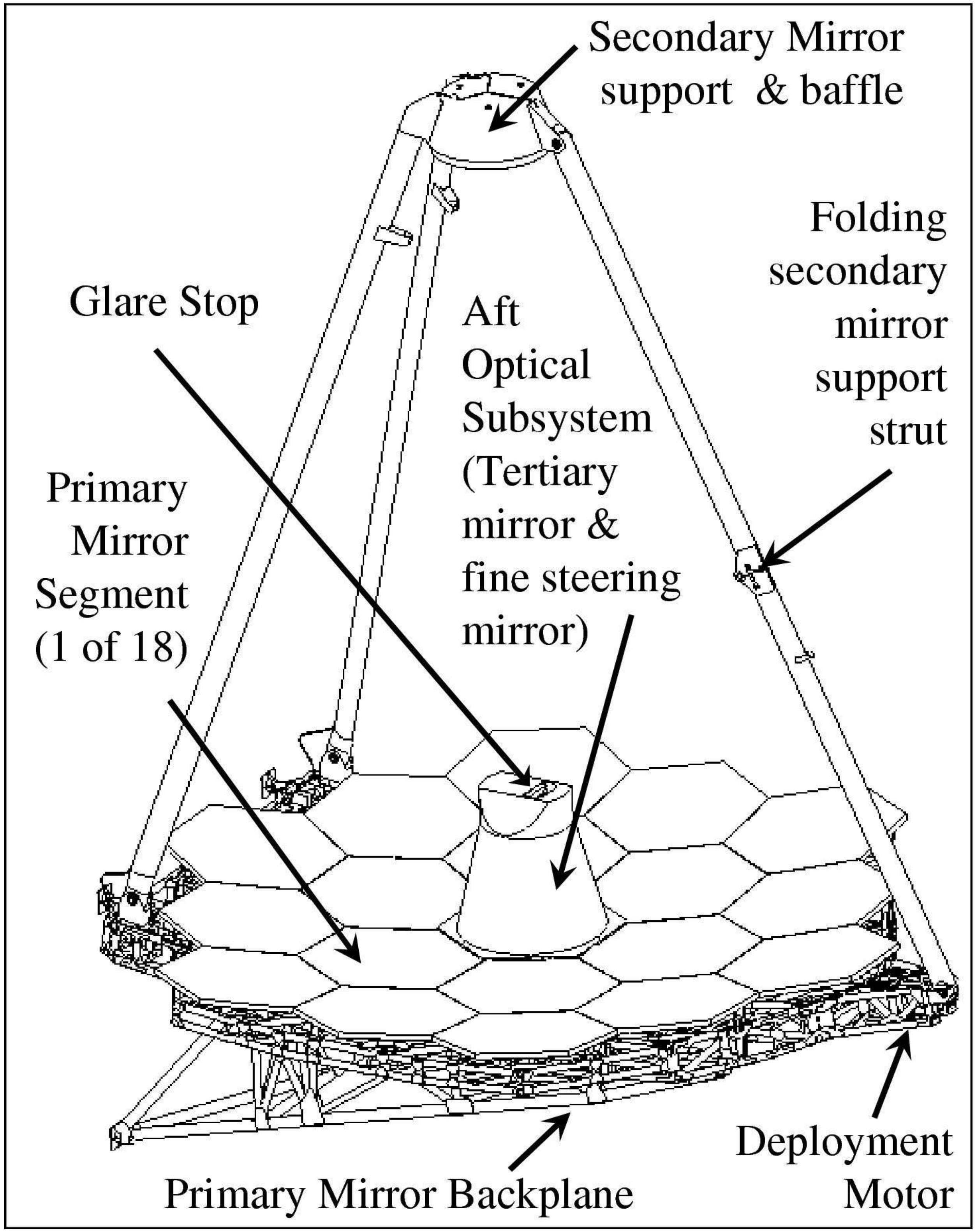
- $\lesssim$2003: Reduction from 8.0 to 7.0 to 6.5 meter. Ariane V launch vehicle.
- 2005: Eliminate costly 0.7-1.0 μm performance specs (kept 2.0 μm).
- 2005: Simplification of thermal vacuum tests: cup-up, not cup-down.
- 2006: All critical technology at Technical Readiness Level 6 (TRL-6).
- 2007: Further simplification of sun-shield and end-to-end testing.



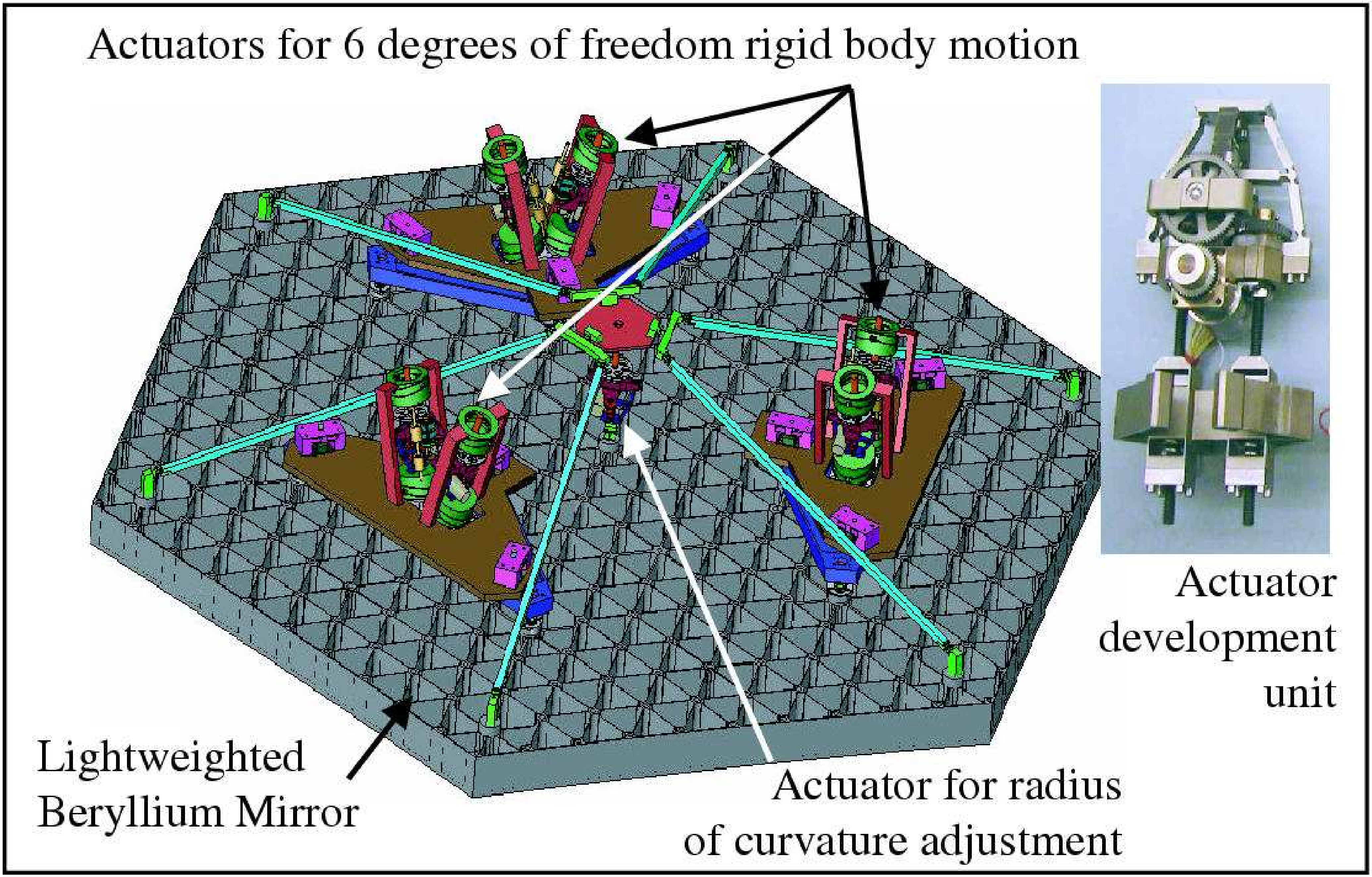
JWST can observe segments of sky that move around as it orbits the Sun.



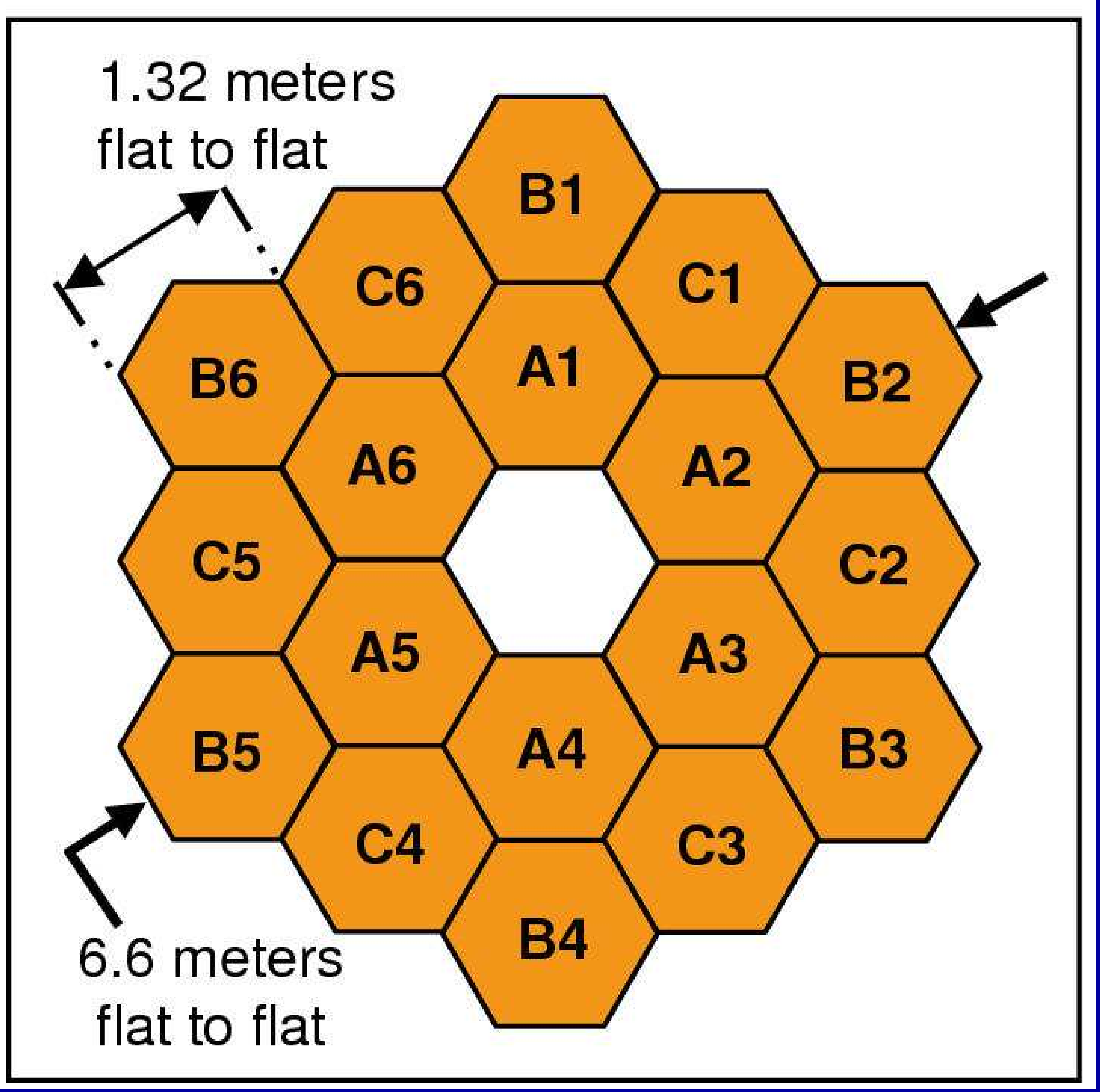
OTE
ISIM
V3 (anti-spacecraft)
V1
V2
(V1, V3)
origin
Tertiary
Mirror
Secondary mirror
Cassegrain
focus
Fine
Steering Mirror
Focal
Surface
Primary
Mirror
f/#: 20.0
Effective Focal Length: 131.4 m
PM diameter = 6.6 m (circumscribed circle)



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

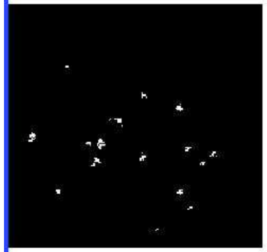
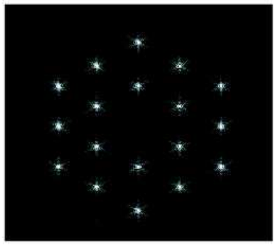
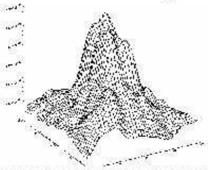


Active mirror segment support through hexapods, similar to Keck.



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).

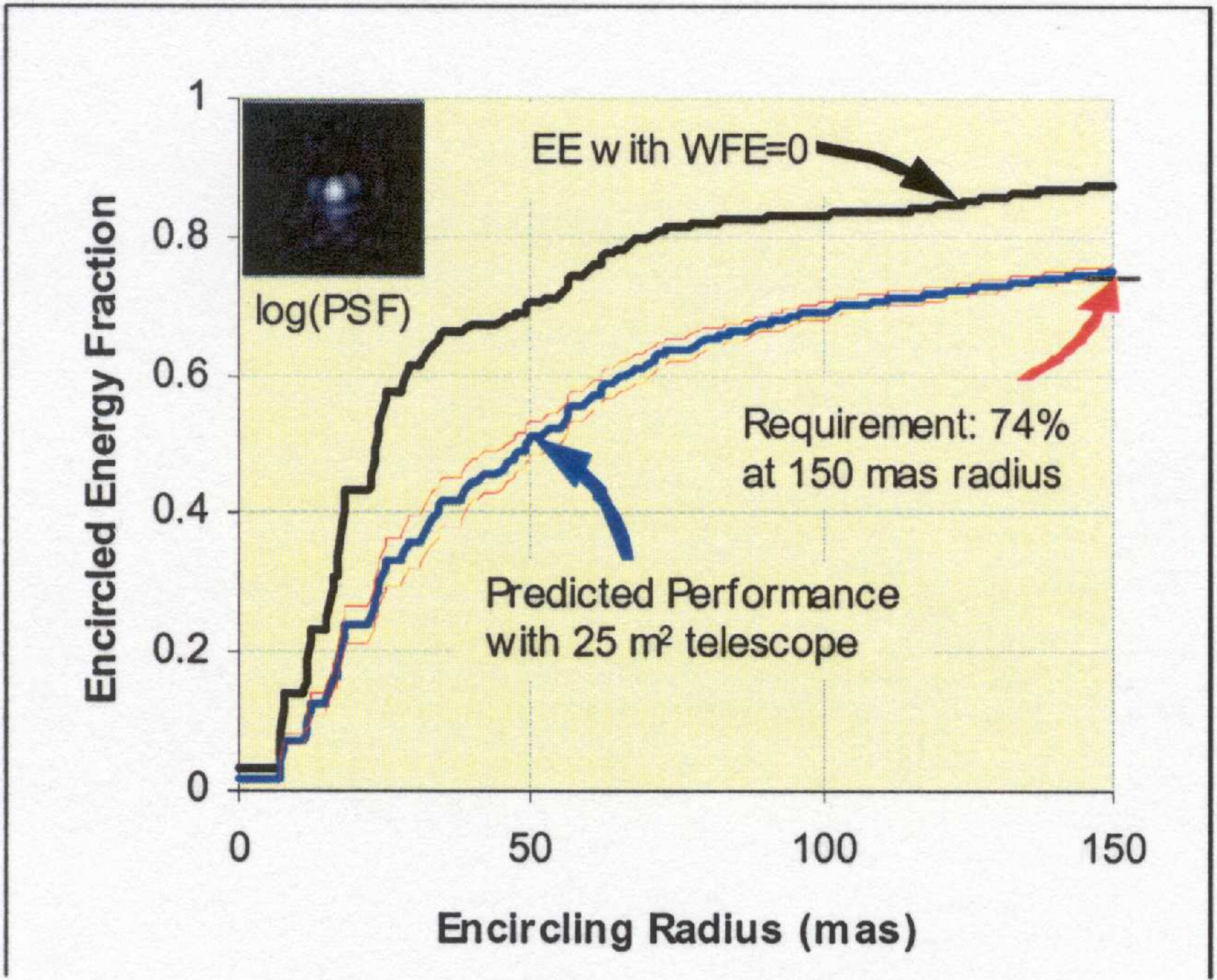
		Initial Capture	Final Condition
First light NIRCam  1. Segment Image Capture	**After Step 1** 	18 individual 1.6-m diameter aberrated sub-telescope images PM segments: < 1 mm, < 2 arcmin tilt SM: < 3 mm, < 5 arcmin tilt	PM segments: < 100 μm, < 2 arcsec tilt SM: < 3 mm, < 5 arcmin tilt
2. Coarse Alignment Secondary mirror aligned Primary RoC adjusted	**After Step 2** 	Primary Mirror segments: < 1 mm, < 10 arcsec tilt Secondary Mirror : < 3 mm, < 5 arcmin tilt	WFE < 200 μm (rms)
3. Coarse Phasing - Fine Guiding (PMSA piston)	**After Step 3** 	WFE: < 250 μm rms	WFE < 1 μm (rms)
4. Fine Phasing	**After Step 4** 	WFE: < 5 μm (rms)	WFE < 110 nm (rms)
5. Image-Based Wavefront Monitoring	**After Step 5** 	WFE: < 150 nm (rms)	WFE < 110 nm (rms)

JWST's Wave Front Sensing and Control is similar to that at Keck and HET.

Successful 2006 demo of H/W, S/W on 6/1 scale model (2 μm-Strehl$\gtrsim$0.85).

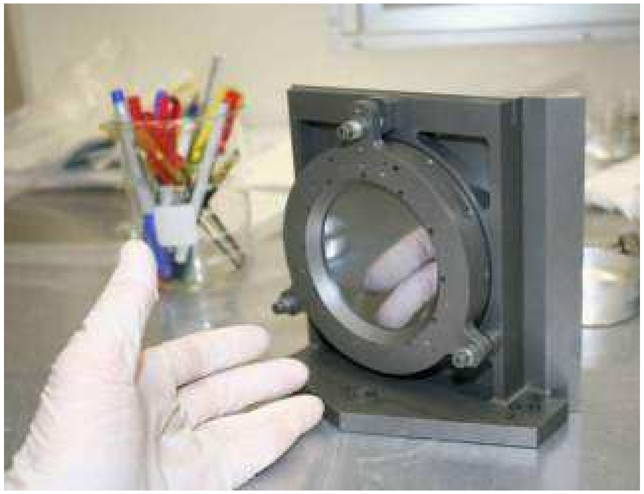
Need WFS-updates every $\sim$10 days, depending on scheduling/SC-illumination.

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



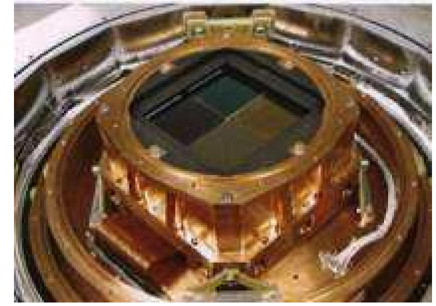
Encircled Energy Fraction
1
0.8
0.6
0.4
0.2
0
0
50
100
150
Encircling Radius (mas)
log(PSF)
EE with WFE=0
Requirement: 74%
at 150 mas radius
Predicted Performance
with 25 m² telescope

Instrument Qual and ETU Model Hardware

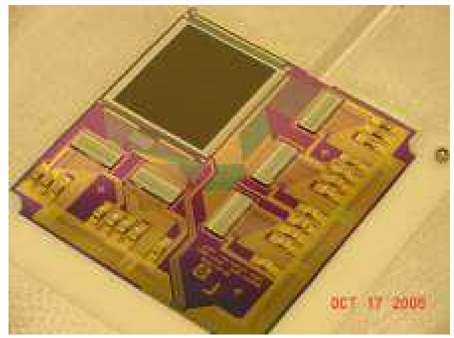


NIRCam Dichroic Beamsplitter

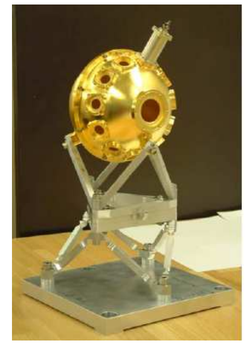
NIRCam Pupil Imaging Lens Set



NIRCam Detectors



NIRSpec Microshutter



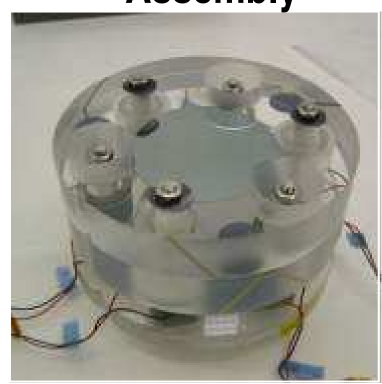
NIRSpec Calibration Assembly

NIRSpec Mirror

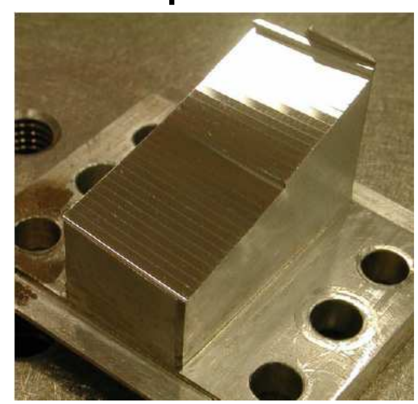
SiAs MIR Detector

MIRI Electronics

NIRSpec Fore Optics Mirror Assembly

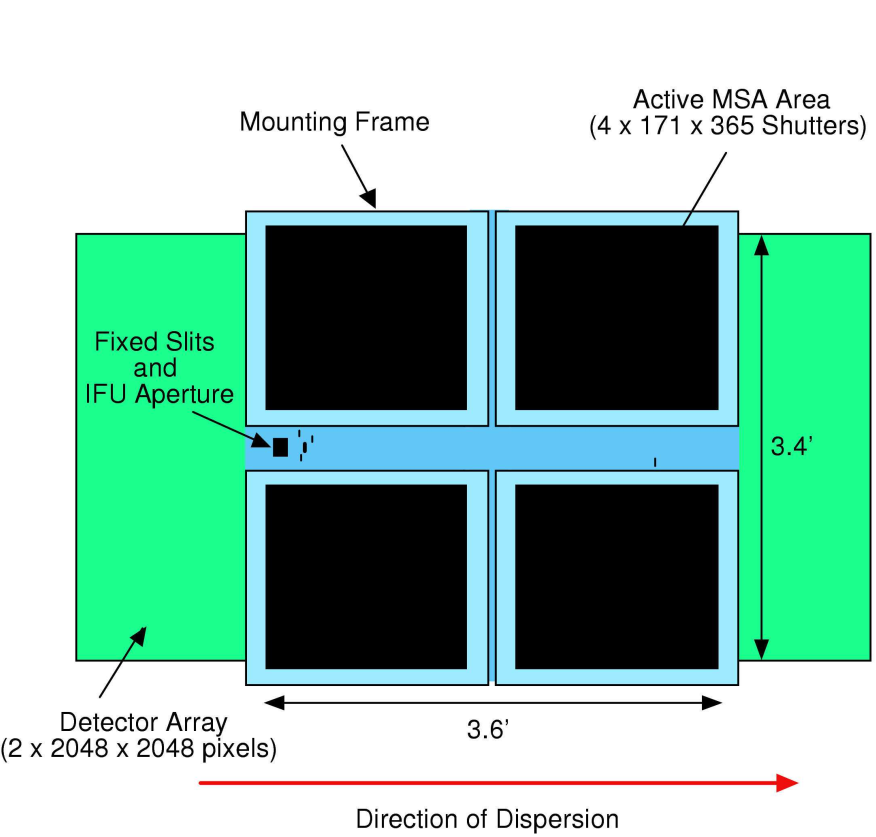


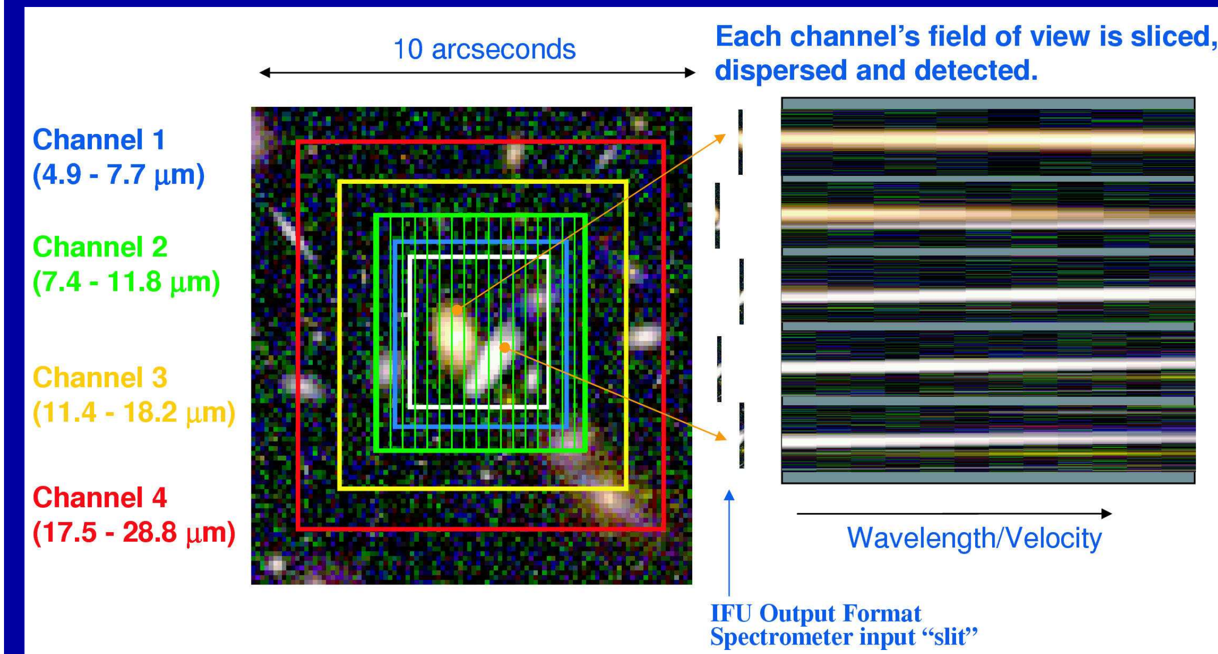
FGS/TF Etalon Filter



NIRSpec Image Slicer Mirror

MIRI Verification Model Yfirst lightZ



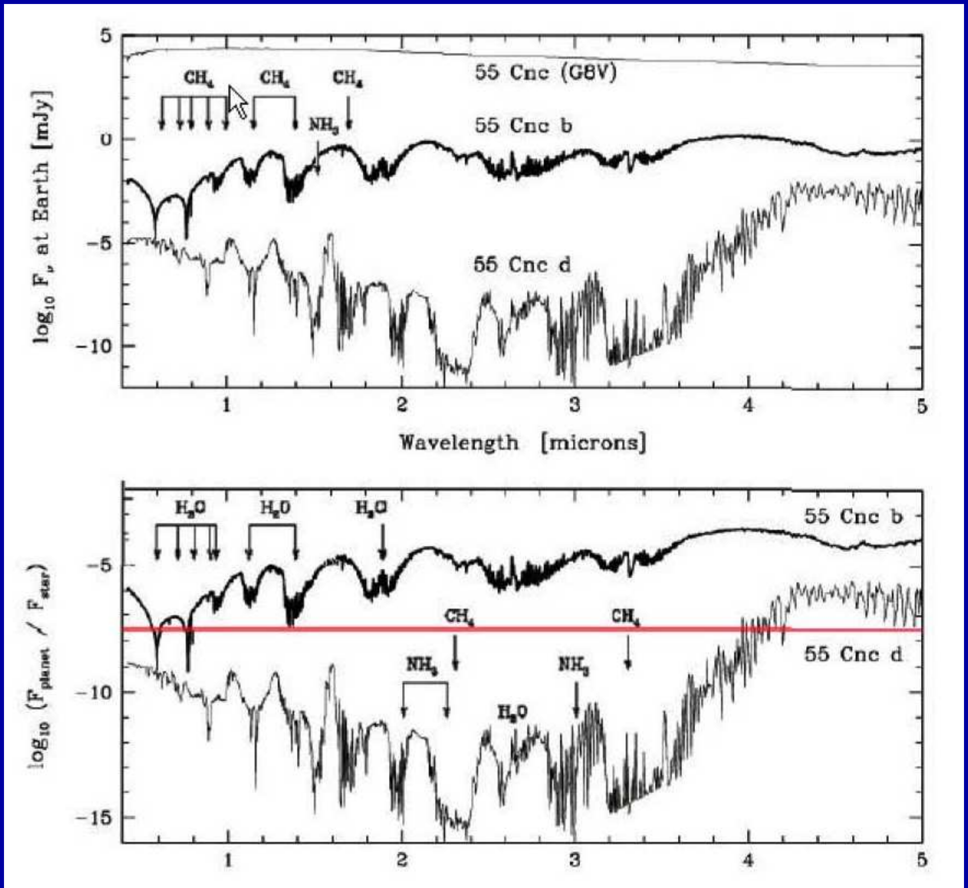


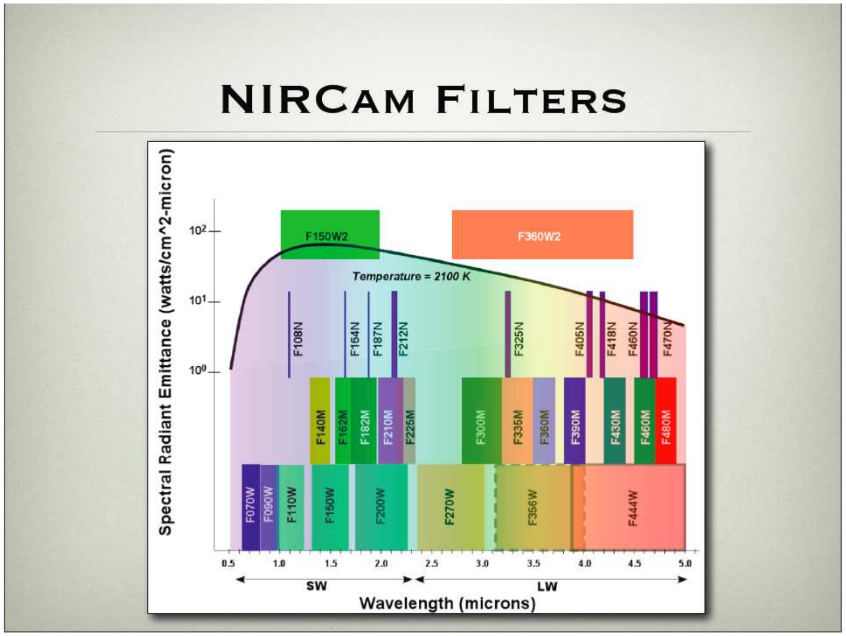
JWST offers significant multiplexing for faint object spectroscopy:

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

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

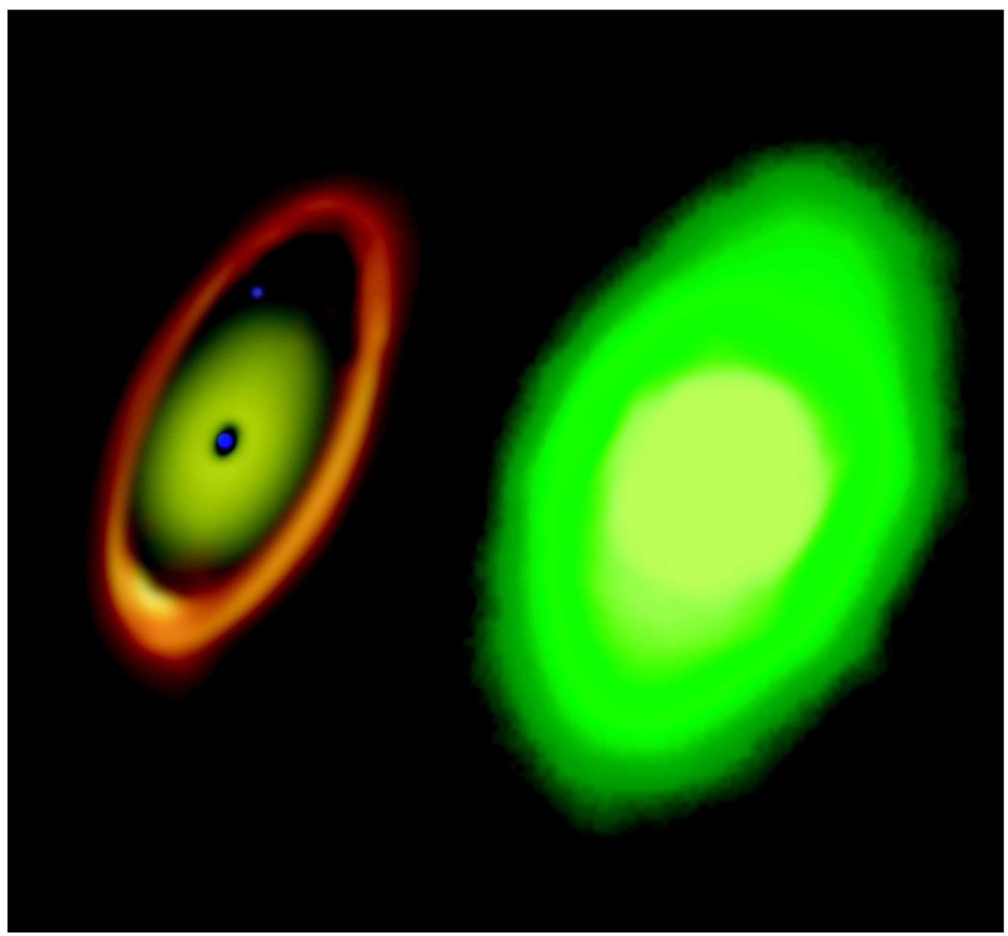
- FGS/TFI that covers a 2.'2×2.'2 FOV at $\lambda \simeq$1.6–4.9 μm at R=100.

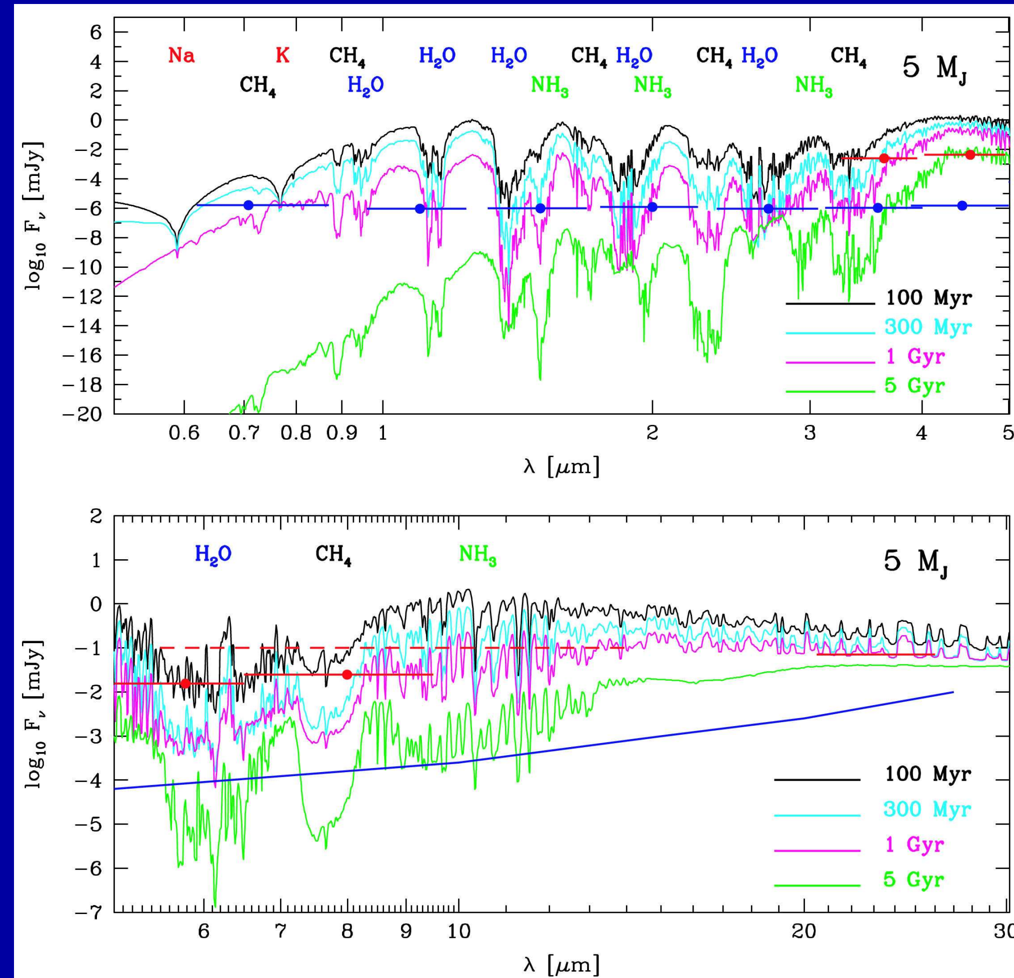




TMT will trace various stages of star-formation, YSO's, debris disk formation and planet formation through very high-resolution imaging, coronagraphy, & high-res opt-IR spectra.

JWST provides high time-resolution photometry & coronagraphy for planet detection, and *panchromatic* low-resolution near–mid-IR imaging & spectra.





Na
K
CH4
CH4
H2O
H2O
H2O
NH3
CH4
H2O
NH3
CH4
H2O
CH4
NH3
5 MJ
log10 Fν [mJy]
λ [μm]
100 Myr
300 Myr
1 Gyr
5 Gyr
H2O
CH4
NH3
5 MJ
log10 Fν [mJy]
λ [μm]
100 Myr
300 Myr
1 Gyr
5 Gyr

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