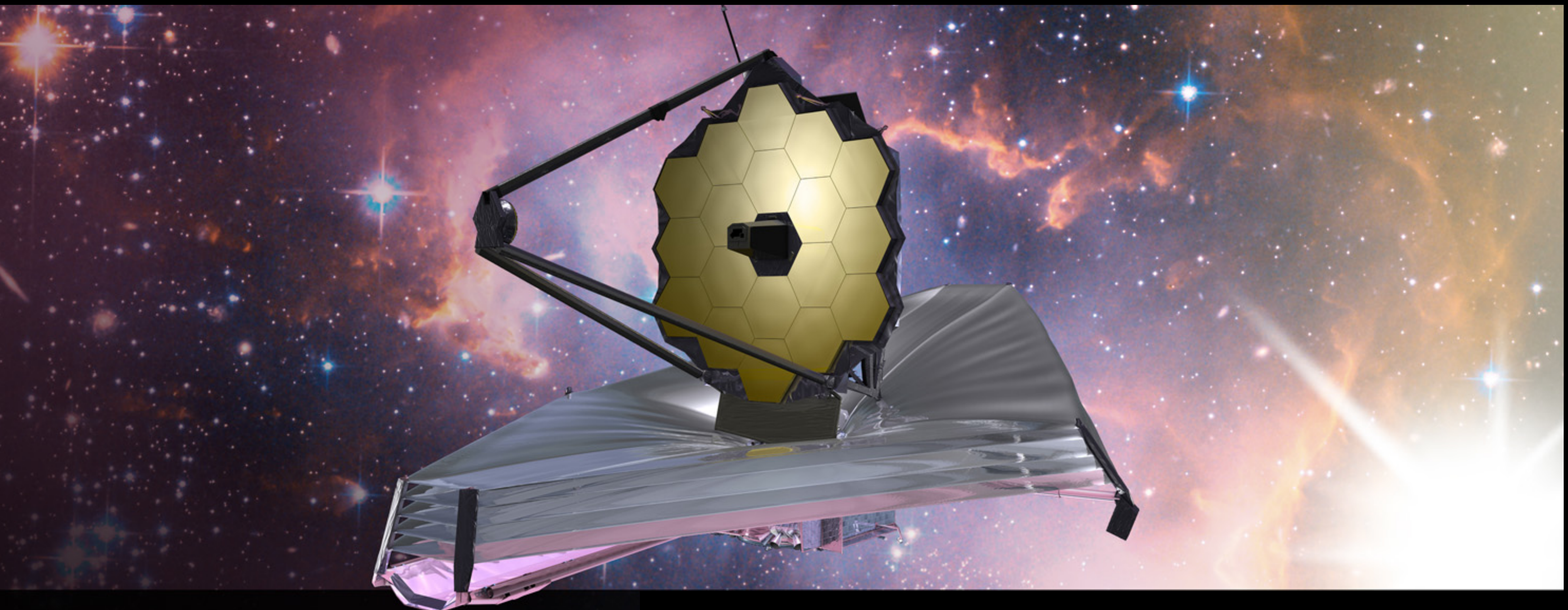
The next step: Coronagraphy with JWST



Marshall Perrin
Space Telescope Science Institute
Telescope Optics Group
JWST Coronagraphs Working Group

Based on work by *many* people across the JWST Project international collaboration: NASA, ESA, CSA & many more

Exoplanet Science Questions for JWST

What are the properties of giant planets in terms of atmospheres, composition, temperature, radius? Formation histories?

What are the compositions of circumstellar disks?
How common are ices?

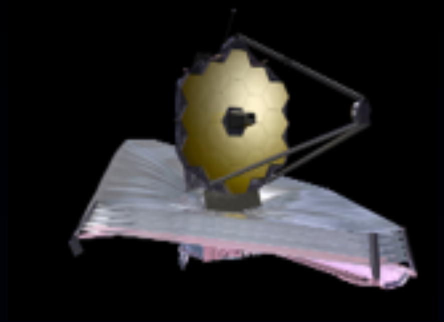
How common are lower mass planets on wide orbits? (sub-Jupiter mass)

Tests of planet formation mechanisms?
Hot start vs cold star,t, core accretion vs instability.

What are the characteristics of sub-Neptunes and super-Earths?

What about free floating planets?

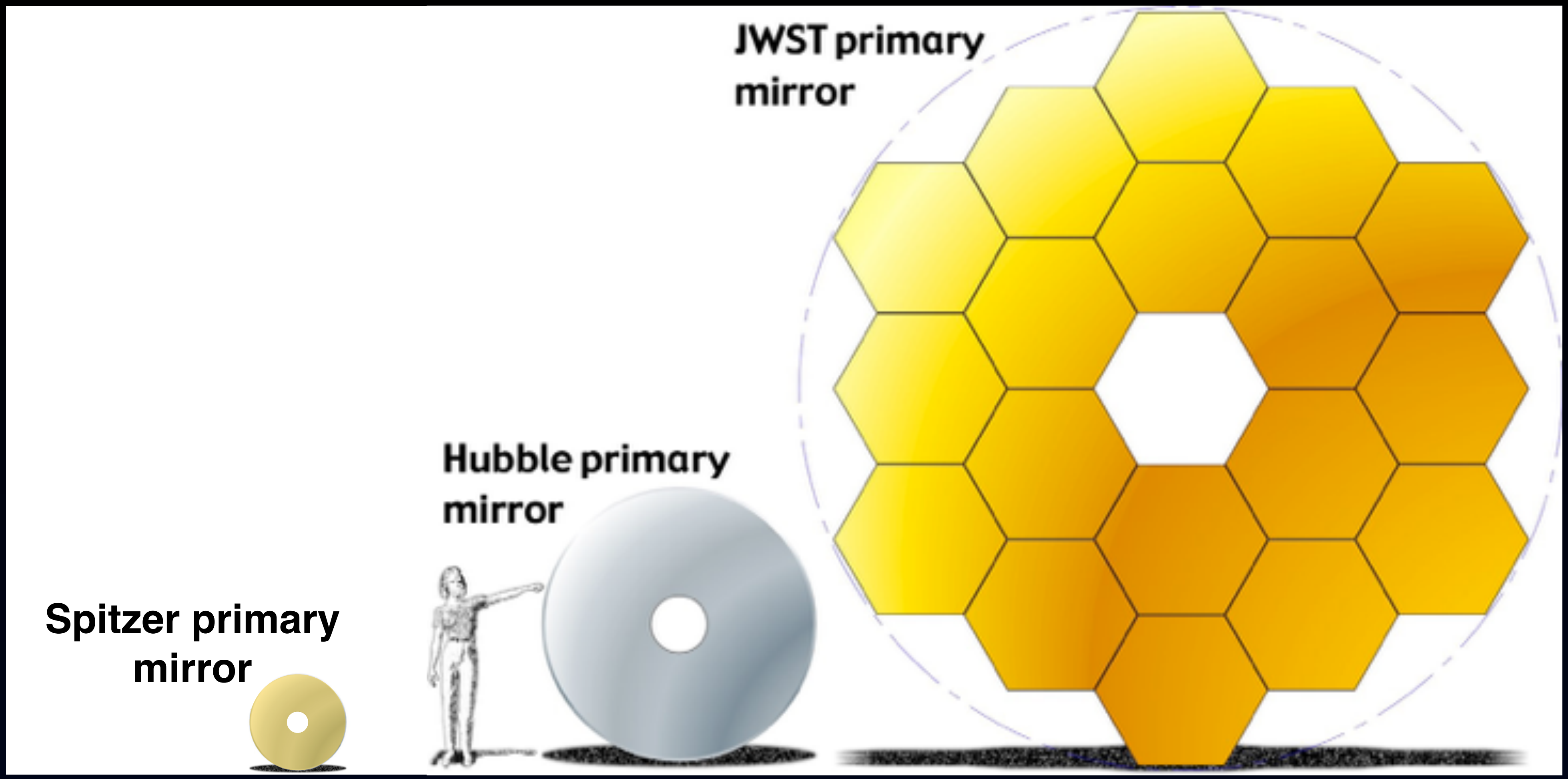
How do planets and debris disks interact?



Outline

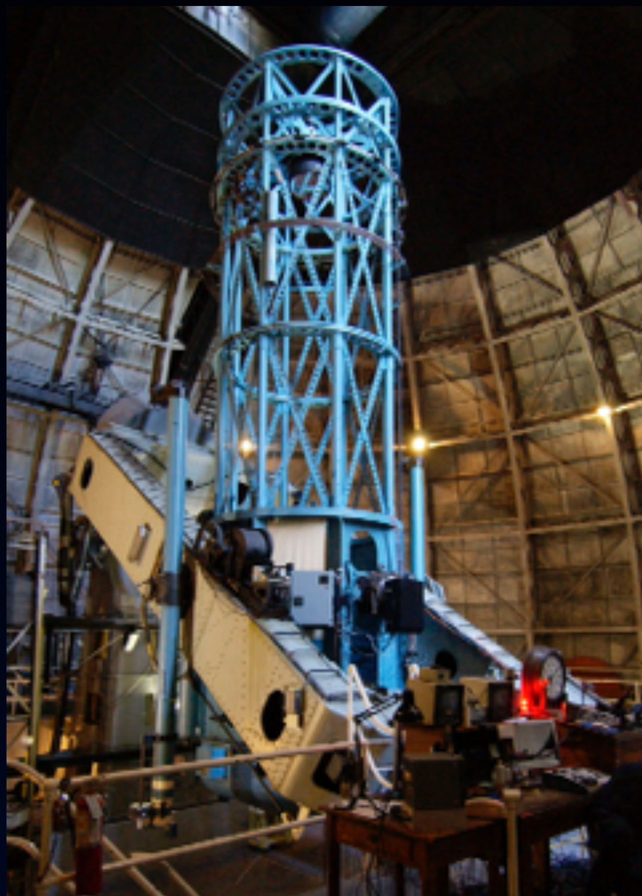
- JWST:
  - *Telescope Design*
  - *Project Status*
- Exoplanet Imaging with JWST:
  - *Stability and active wavefront control in space*
  - *NIRCam coronagraphs*
  - *MIRI coronagraphs*
  - *NIRISS aperture masking interferometry*

JWST as a **telescope**



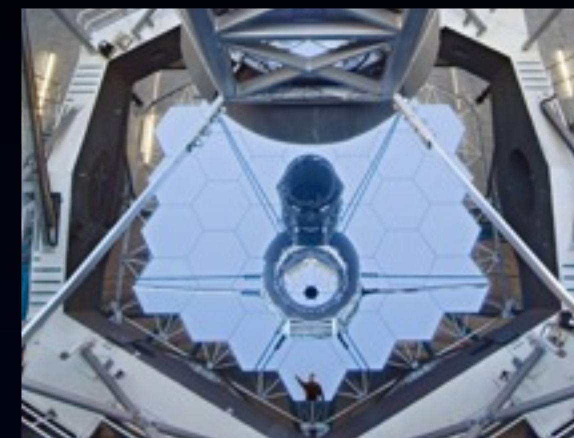
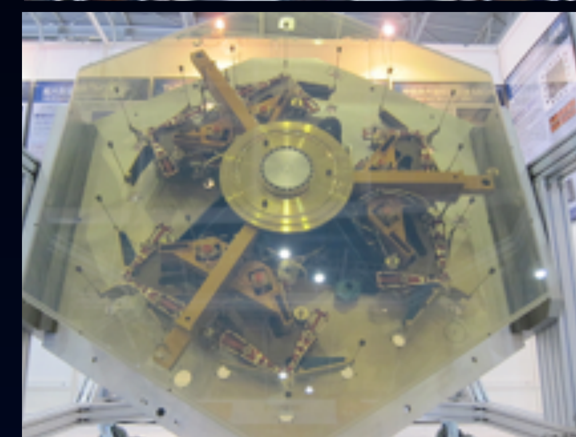
	Hubble	Spitzer	JWST
Primary diameter	2.4	0.85	6.6
Collecting Area (m	4.24	0.5	26.3
Observatory Mass (kg)	11,000	860	6,300
Observatory Volume, when stowed (m	190	13	155
Orbit Location	LEO	Earth-trailing solar	Sun-Earth L2

“Pre-1980” telescopes



- Thick mirrors (100s of kg/m^2)
- Passive stability
- Slow optics (> f/3)
- Equatorial mounts

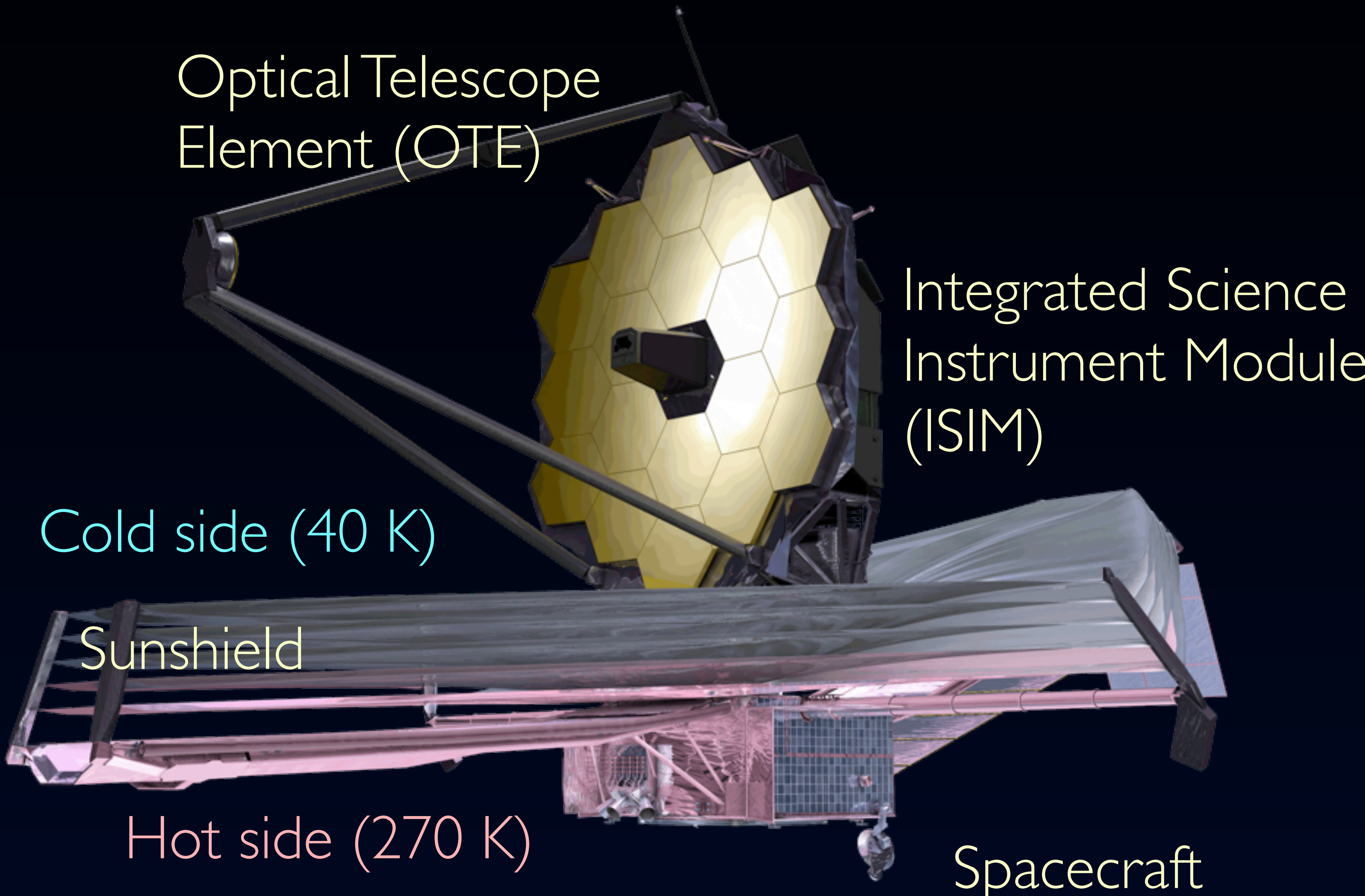
“Modern” telescopes

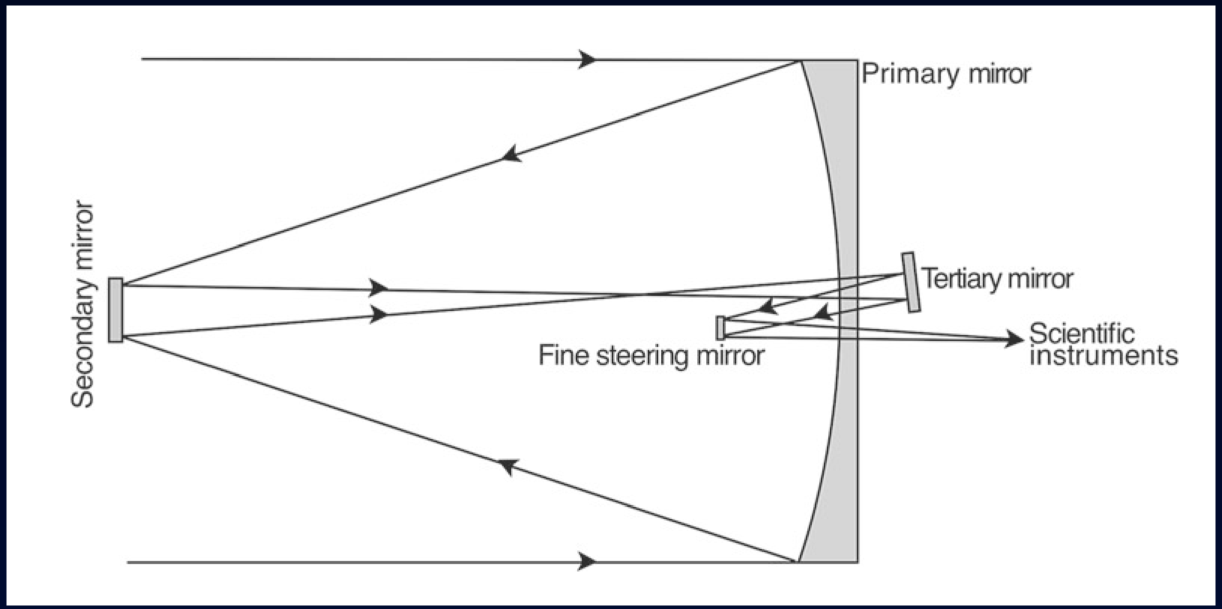




- Lightweight mirrors (10s of kg/m^2)
- Active & adaptive wavefront control
- Fast optics (< f/3)
- Altitude-azimuth mounts
- Frequently segmented

1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
Mt Wilson 100", 1917
Palomar 48" Schmidt, 1948
Keck, 1990
Lick 3 m with AO, 1994
Gemini with extreme AO
HST
Kepler
JWST
WFIRST/AFTA
ATLAST?

JWST Observatory Design





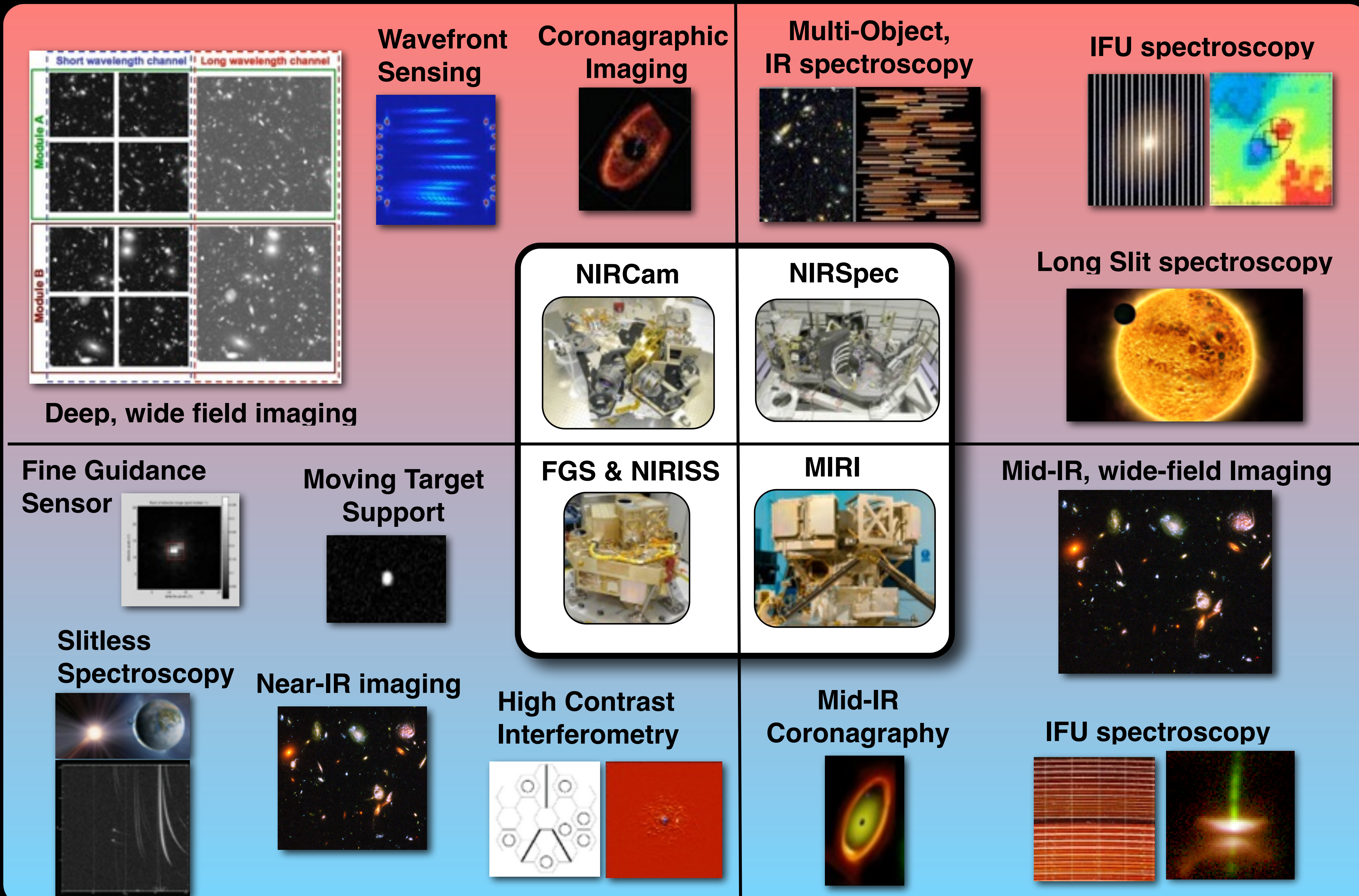
- Passively cooled, open telescope
- Beryllium optics, gold coated

  Lightweight and stiff, very low CTE
- Three Mirror Anastigmat

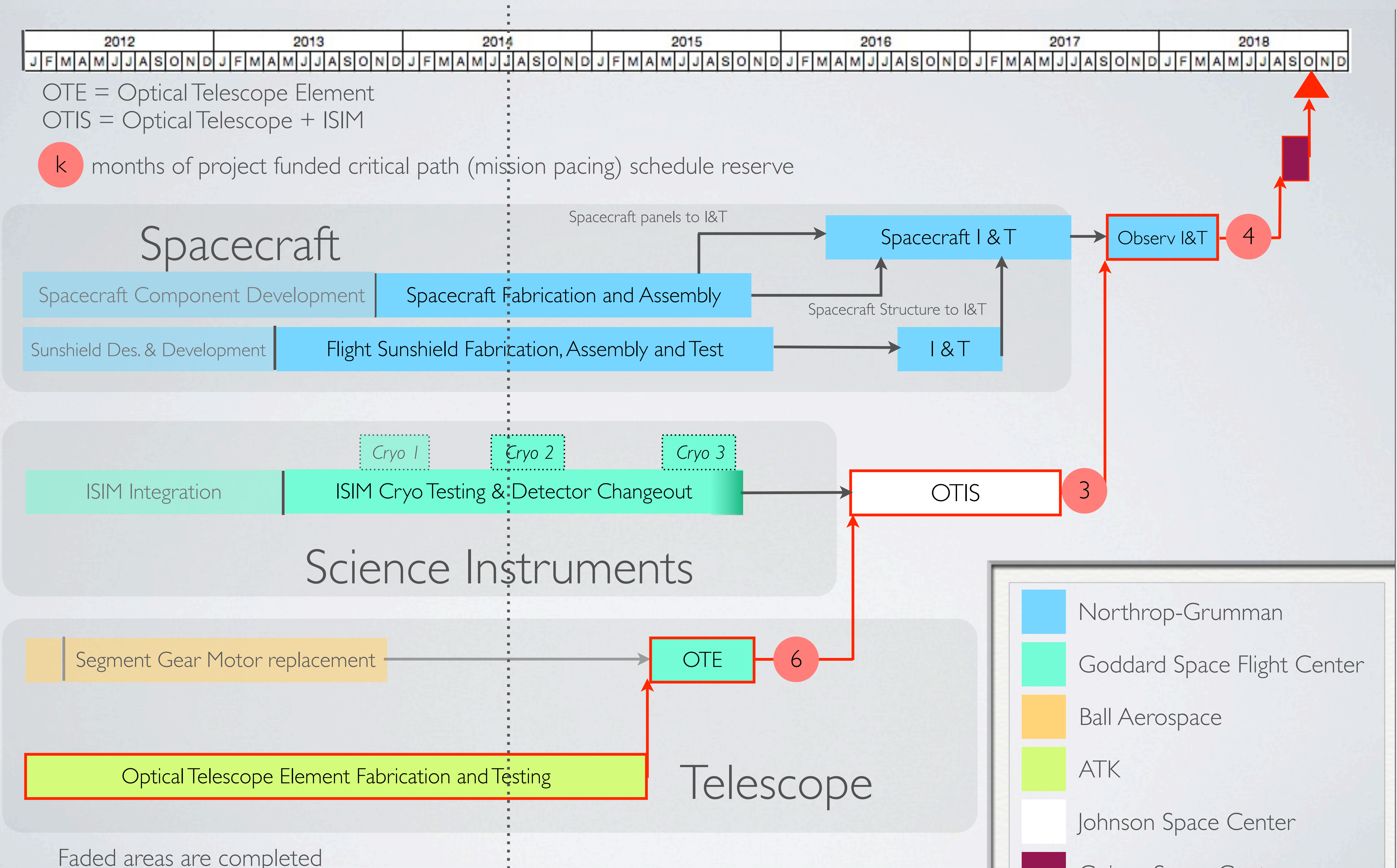
  Relatively wide field diffraction limited performance.
- Fine steering mirror driven by FGS at 15 Hz

  7 mas rms pointing control
- Baffles for stray light at intermediate image and focal planes.

JWST's Science Instruments

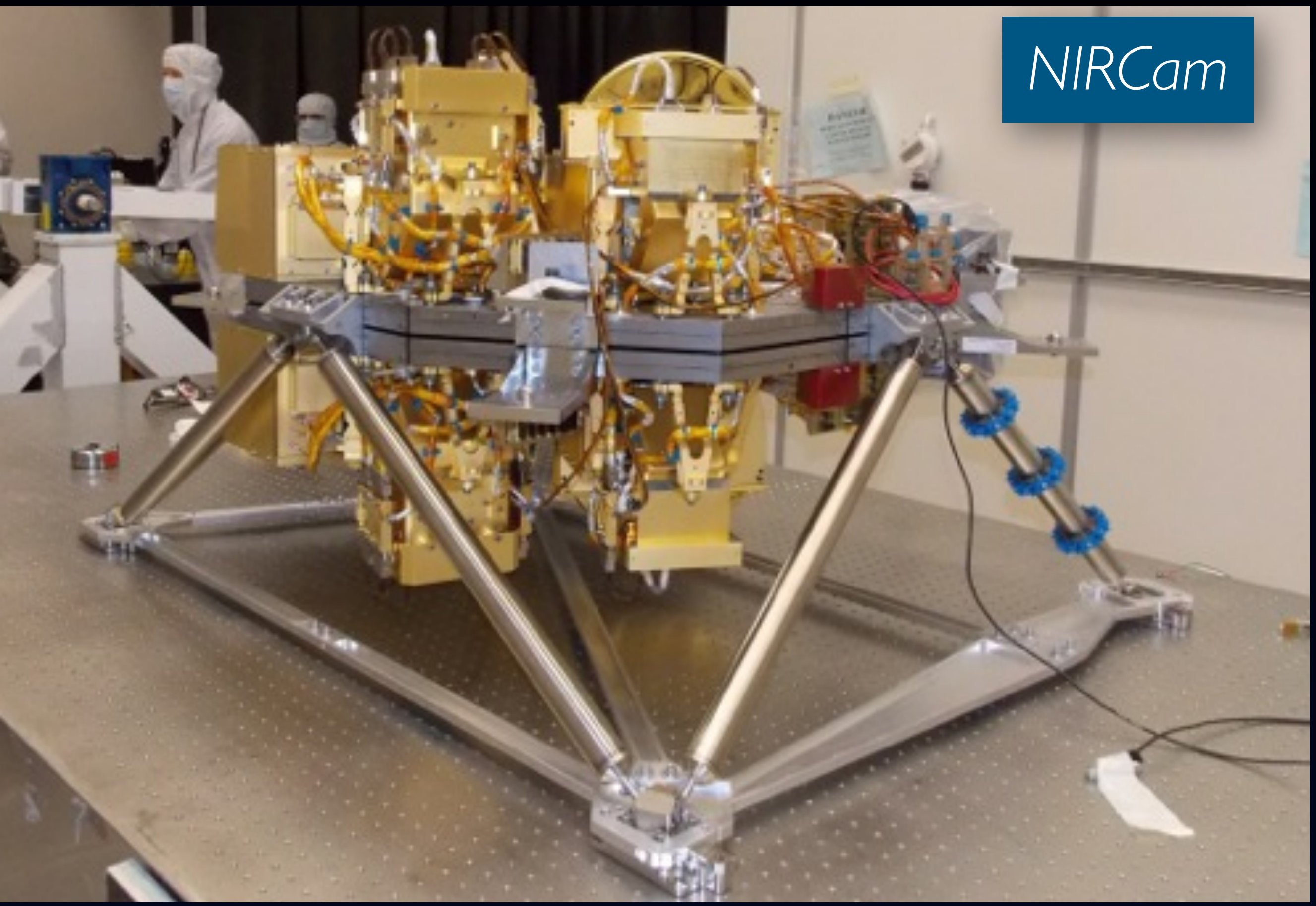


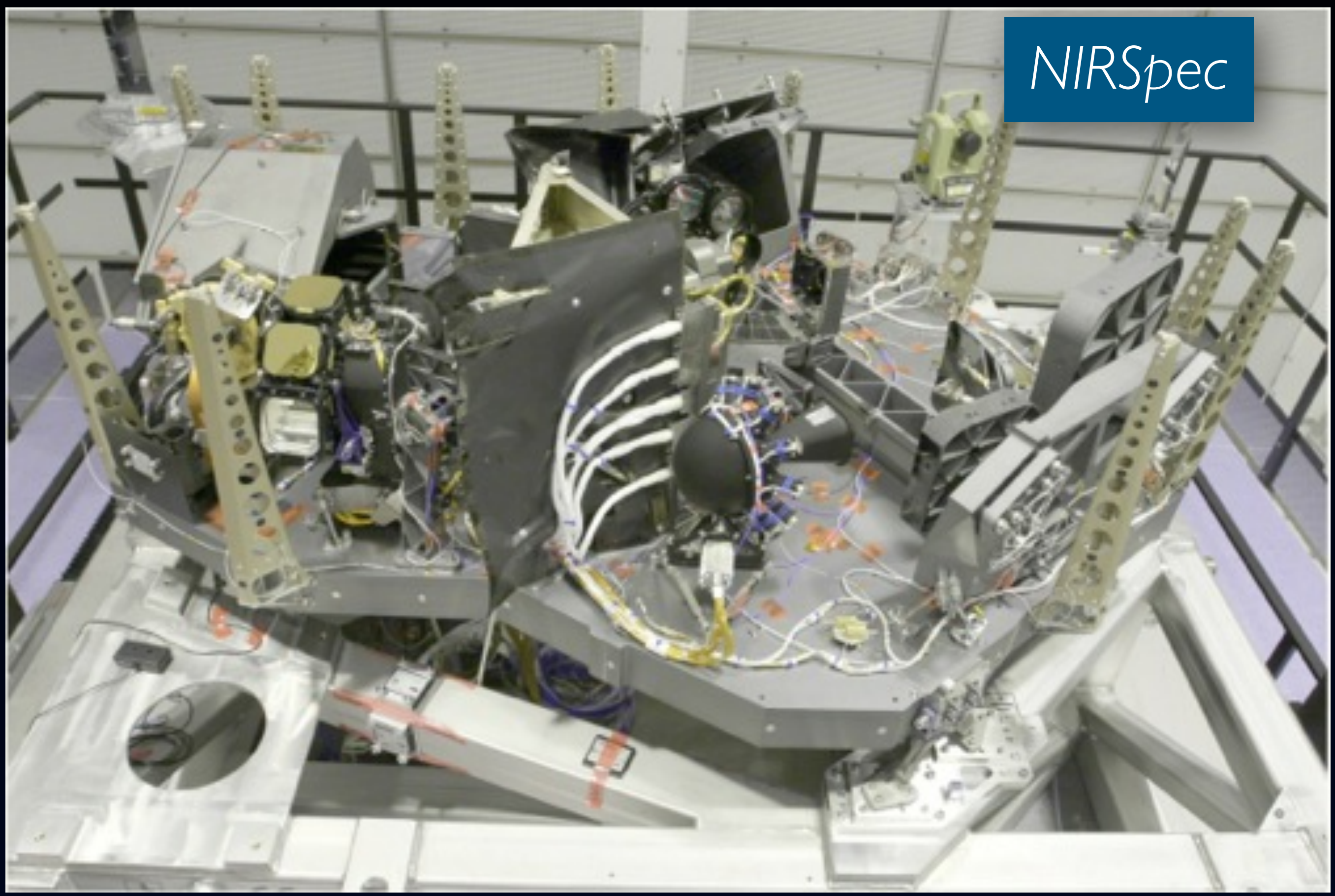
JWST Schedule

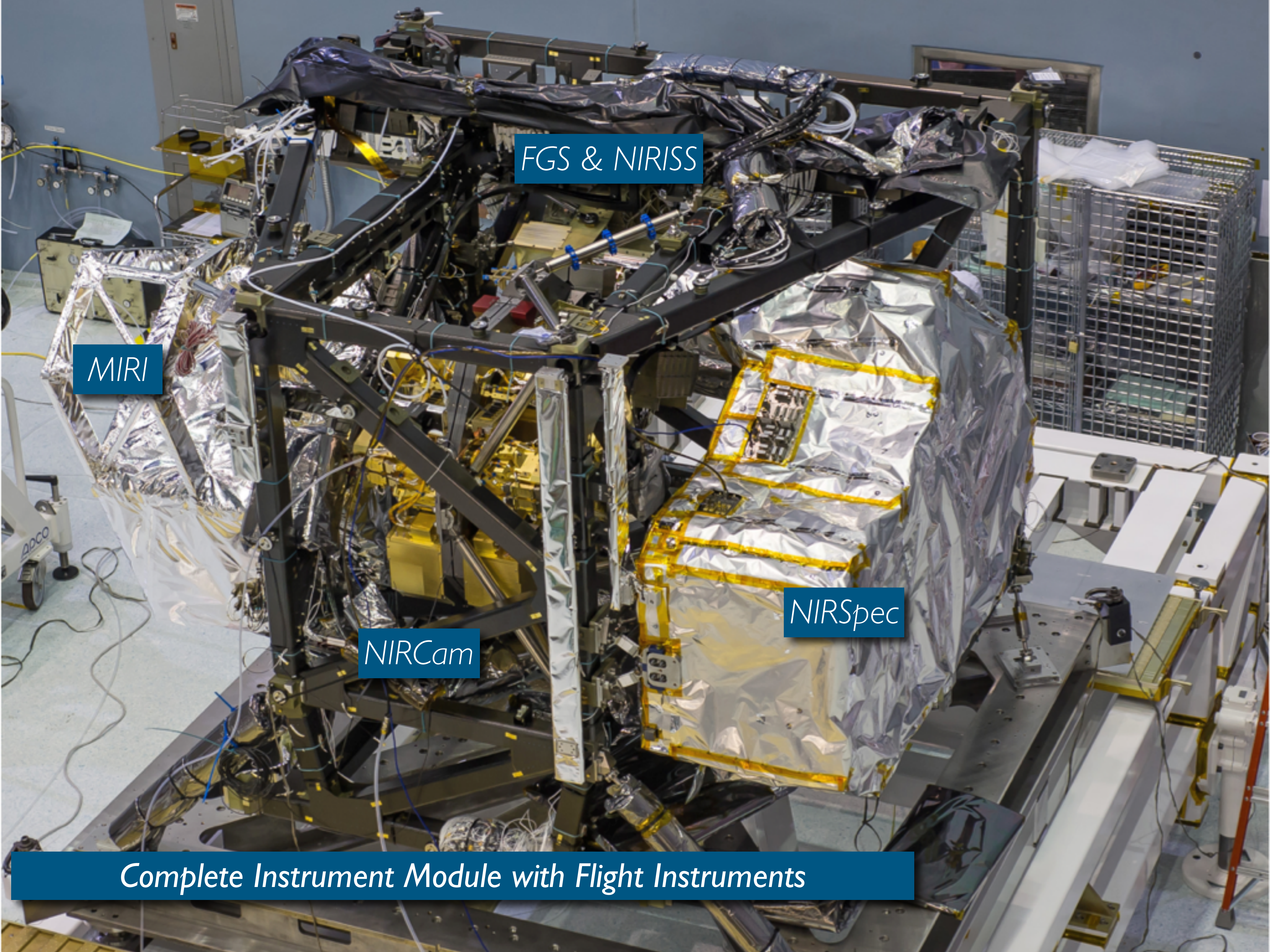


slide adapted from Eric Smith, JWST town Hall, Jan '14

Flight Instruments Delivered

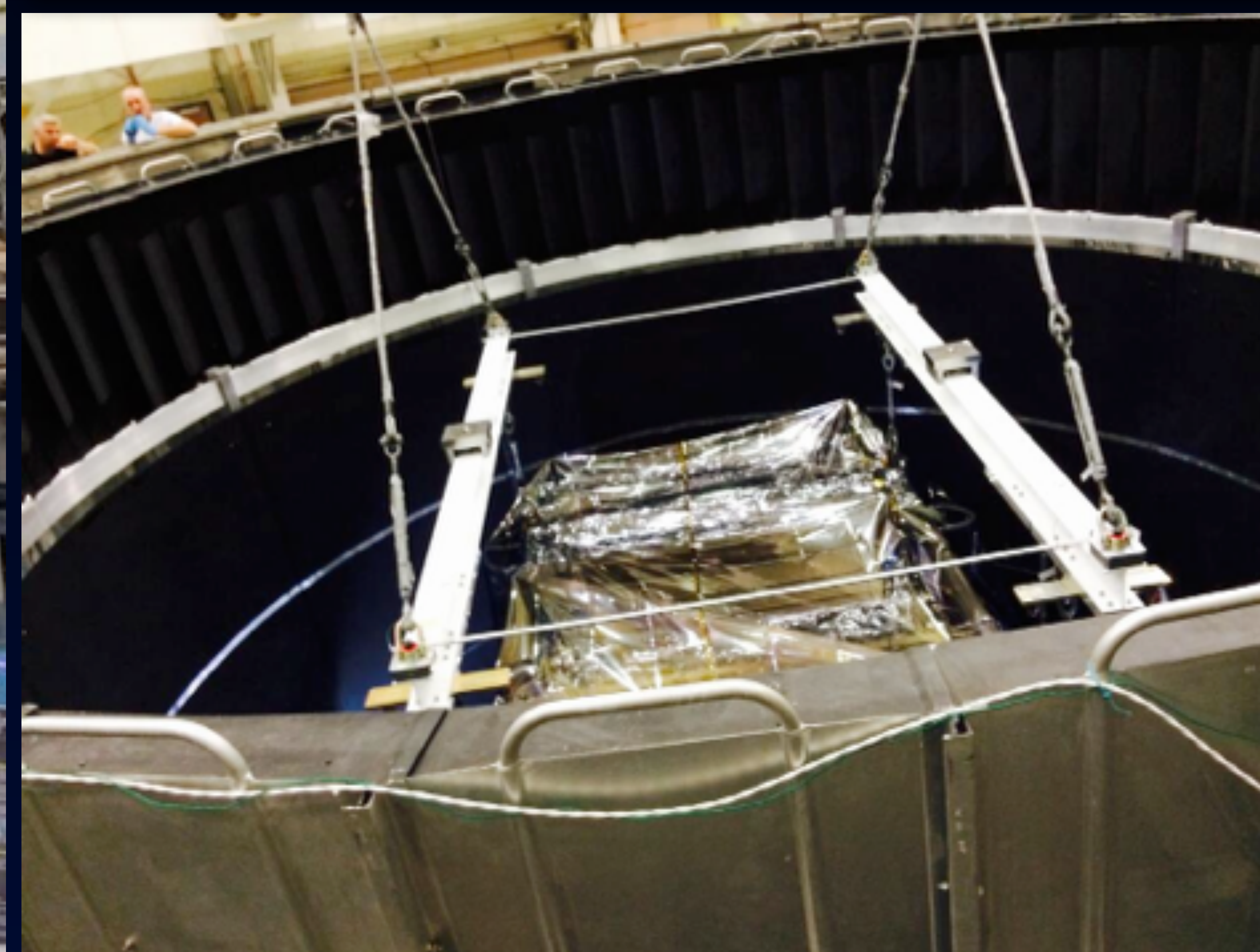






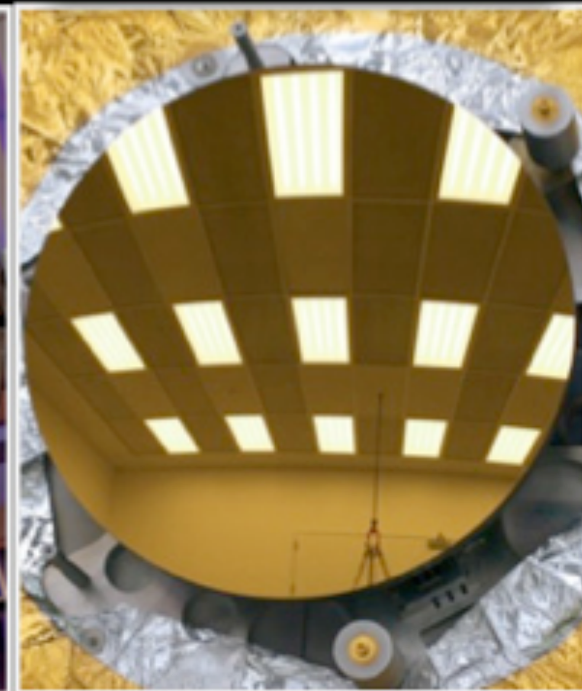
Complete Instrument Module with Flight Instruments

ISIM into Space Environment Simulator for ongoing cryovac tests (June-Sept)

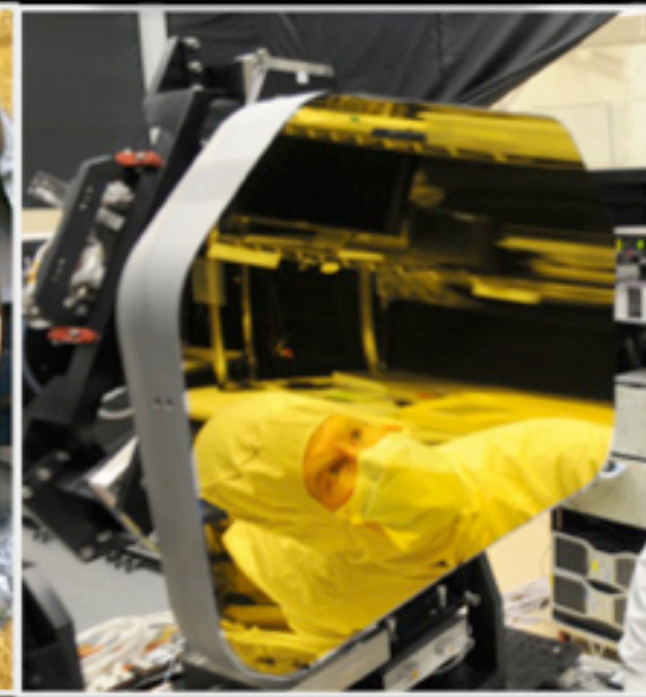


Primary Mirror Segment

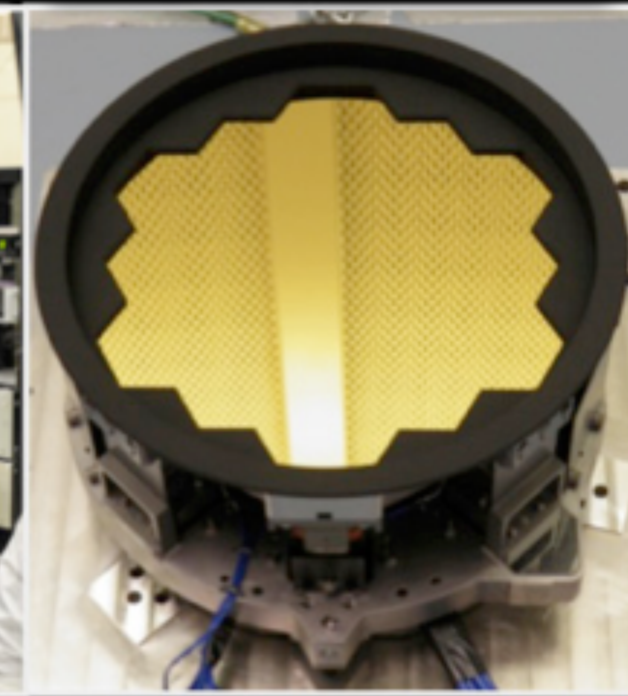
Secondary Mirror



Tertiary Mirror

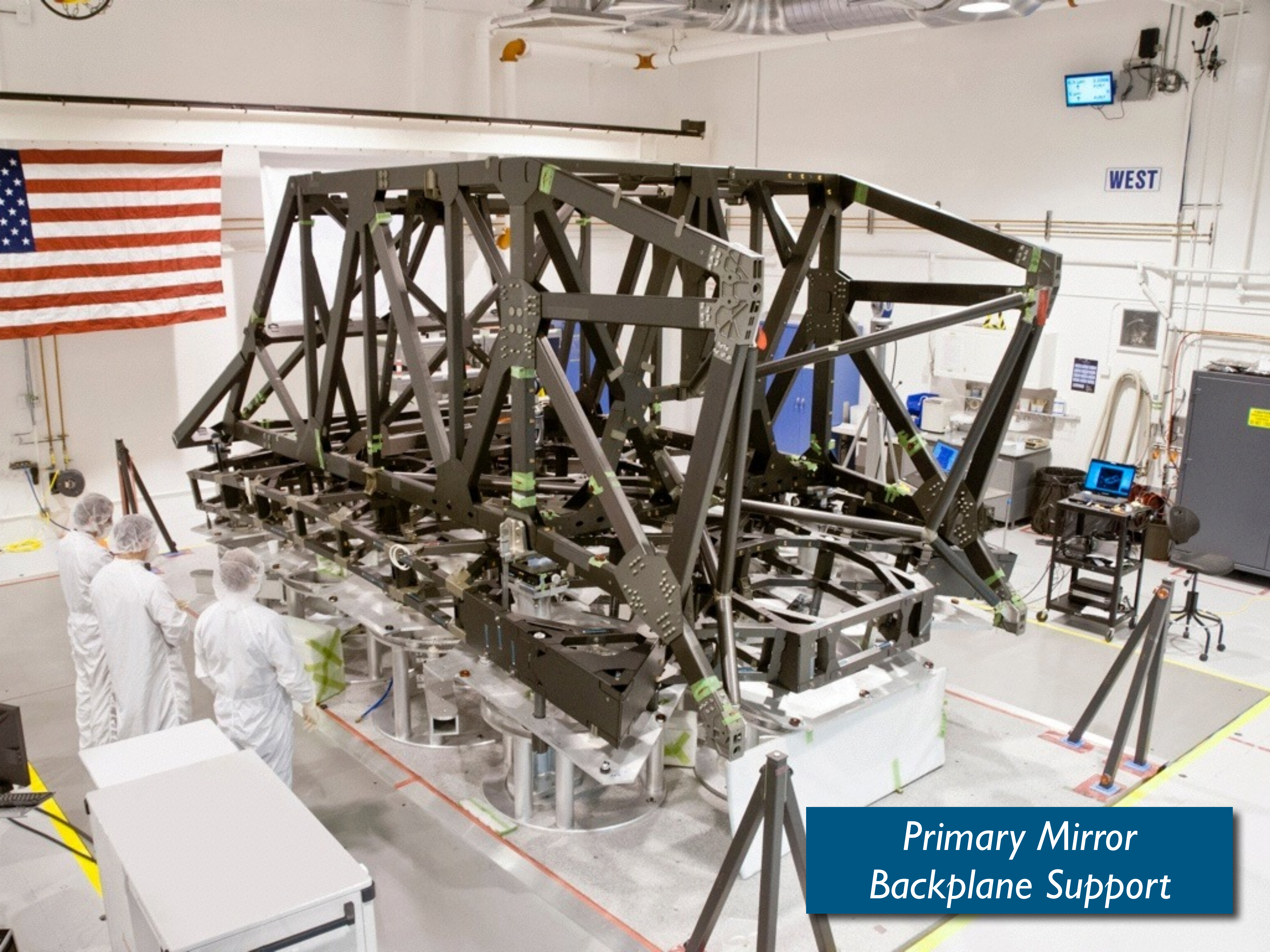


Fine Steering Mirror

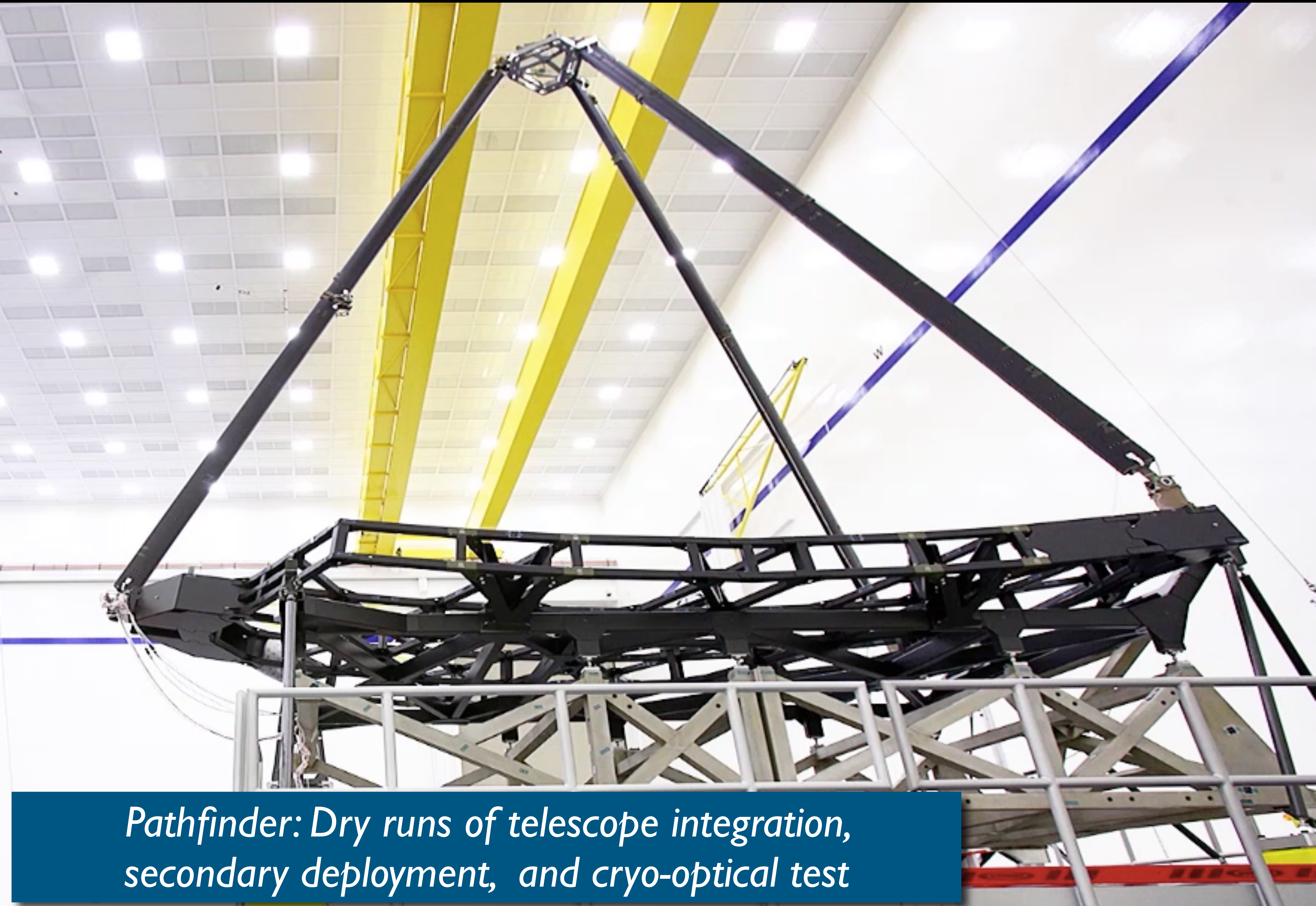


All flight mirrors complete 2011

Mirrors in storage for now



Primary Mirror
Backplane Support



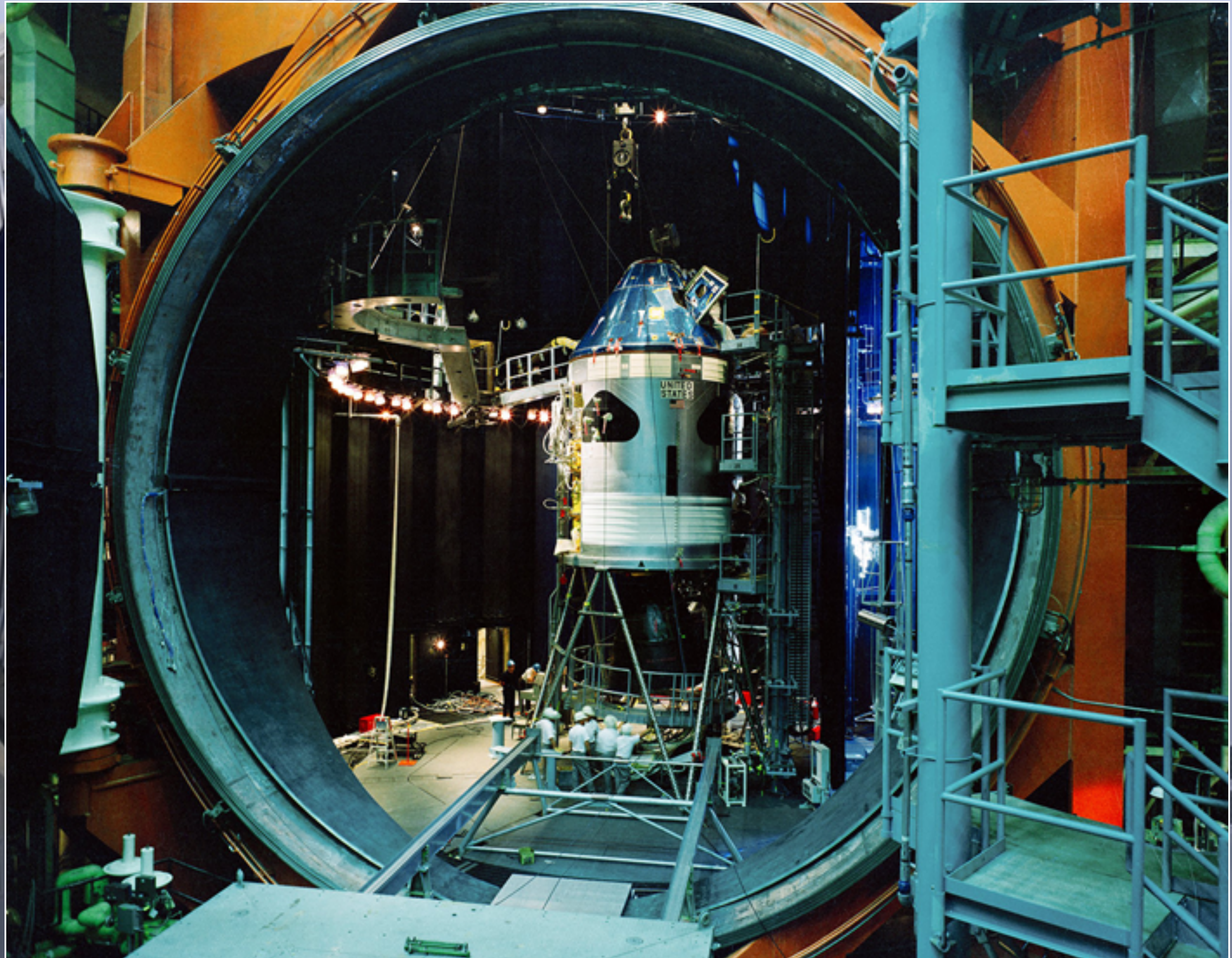
Pathfinder: Dry runs of telescope integration, secondary deployment, and cryo-optical test

Trial Assembly with Flight Spare Segment & Backplate Test Article

Spacecraft test unit


Sunshield full size test membrane

First 5 layer deployment test
2 weeks ago, here in Los Angeles

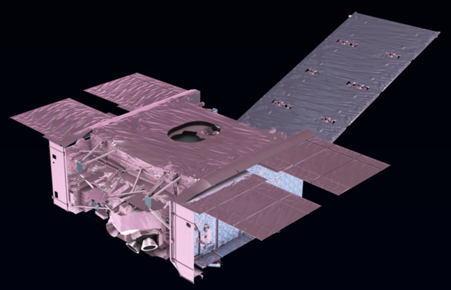


Apollo Program in Chamber-A

Refurbished Chamber-A test facility, NASA Johnson Space Center

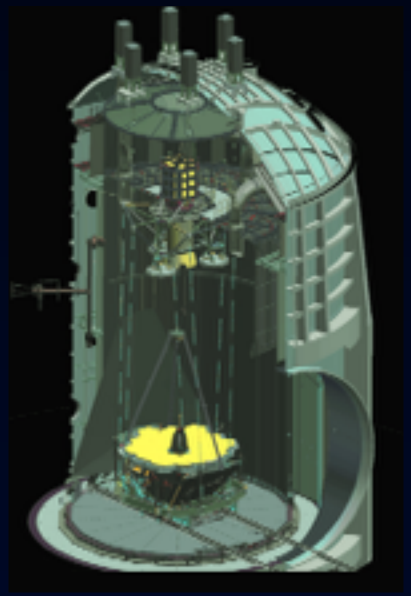
Project Milestones

- 2014: Manufacturing the spacecraft, & testing the instruments



- 2015: Telescope Integration

- 2016: Observatory assembly



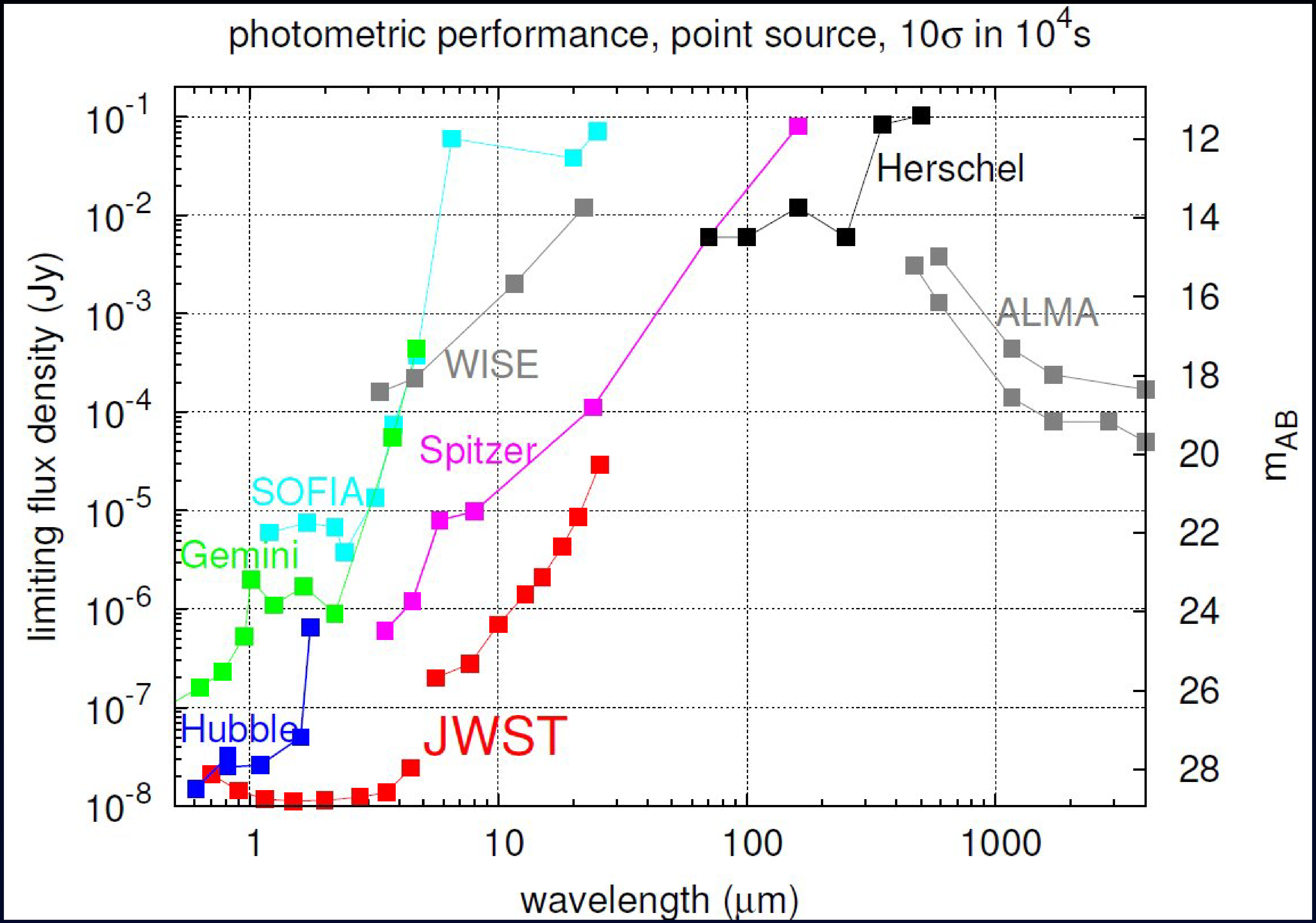
- 2017: Observatory Testing

Cycle 1 proposals due November 2017

- 2018: Observatory Test ⇒ Launch

Factors affecting JWST coronagraphy

JWST will have exquisite sensitivity



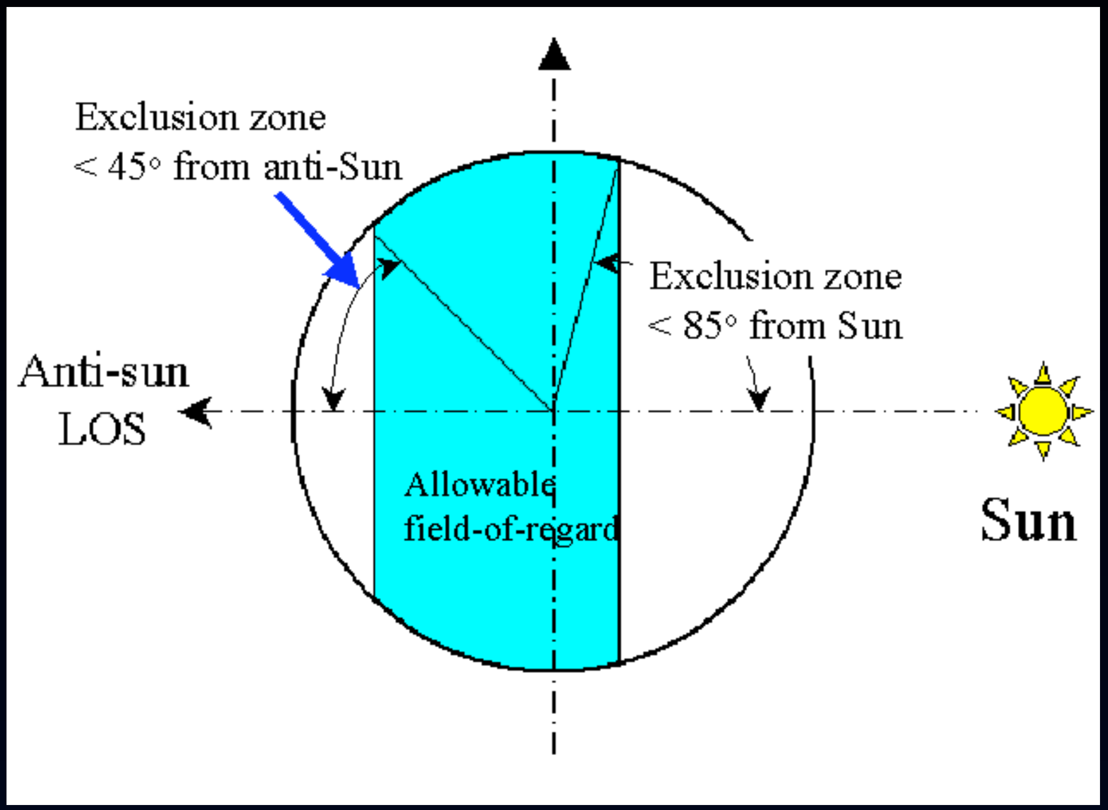
100x Gemini at 2 μm

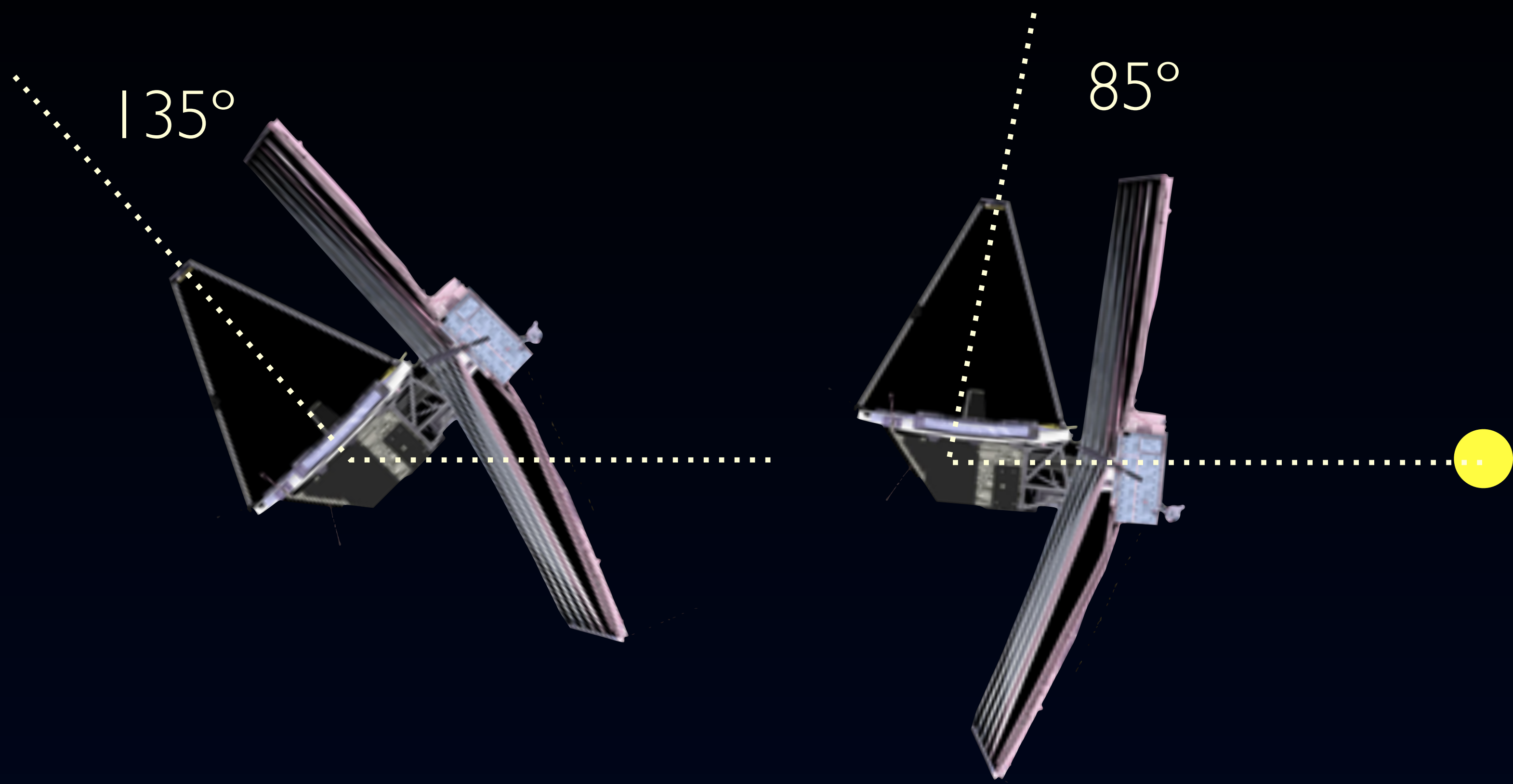
Low infrared background in space

50x Spitzer at 8 μm

Large aperture cryogenic telescope

Field of Regard and Orientation are constrained

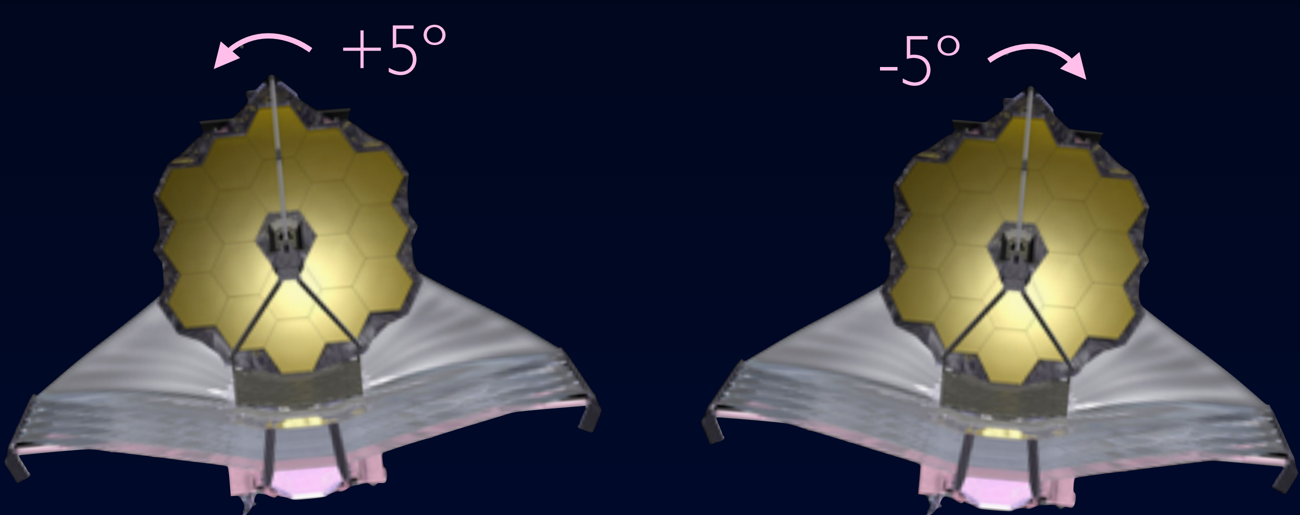




49.8% of the sky at a time

Pitch: 85°-135° from the sun

Continuous Viewing Zone
above ±85° at ecliptic poles

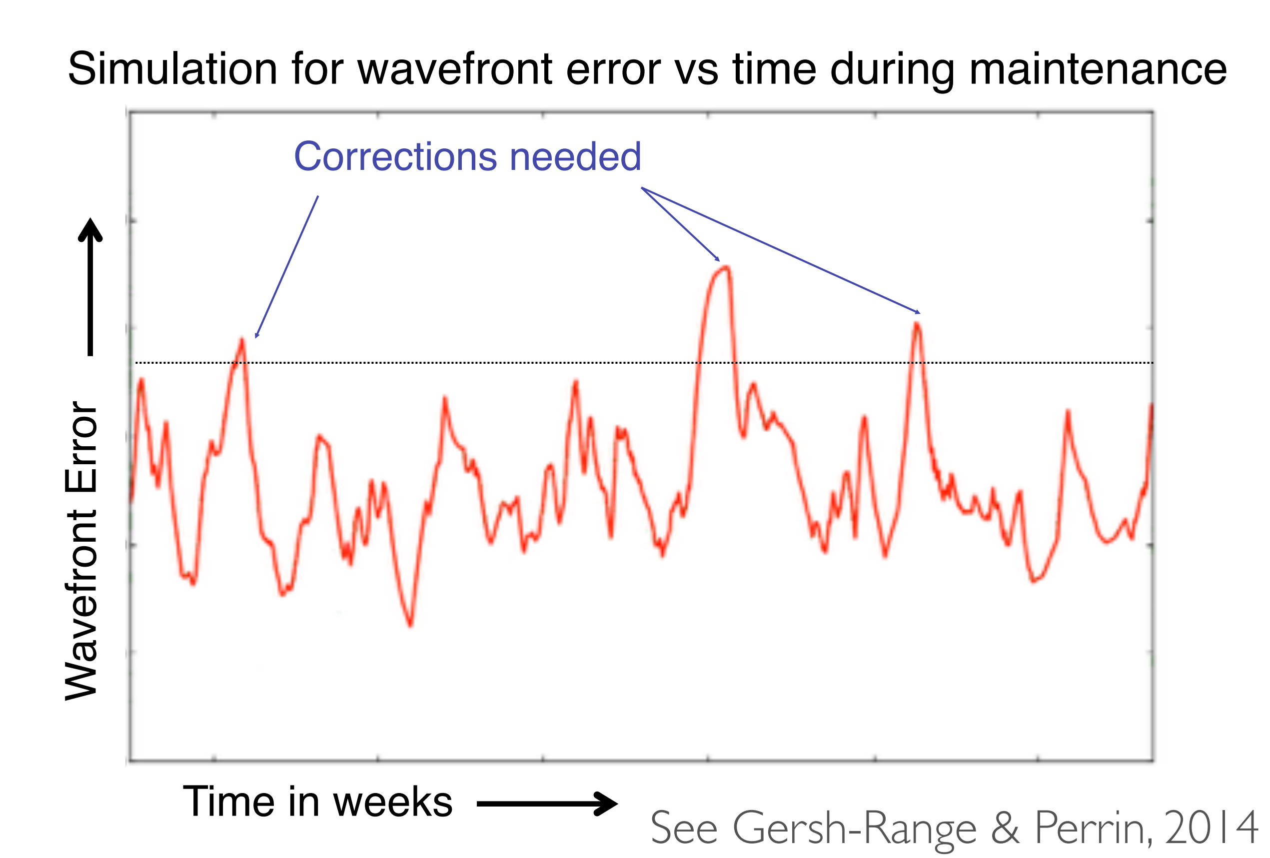


Roll: Only ±5° at any one time

non-instantaneous roll depends on ecliptic latitude.
0-360 range at poles; only 0 &180 at equator.

The telescope will be actively aligned

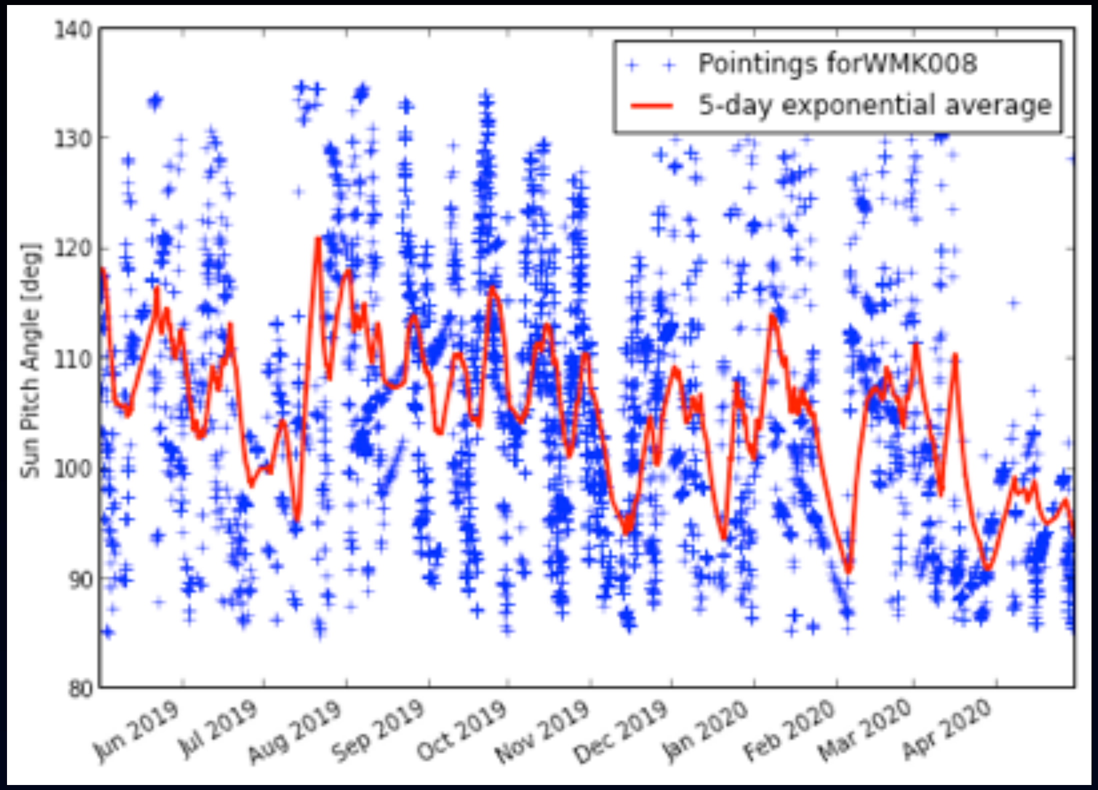
- Commissioning
  - Post Launch Deployments
  - Converging from millimeters to nanometers of misalignment
  - Approx. from 40 to 120 days after launch

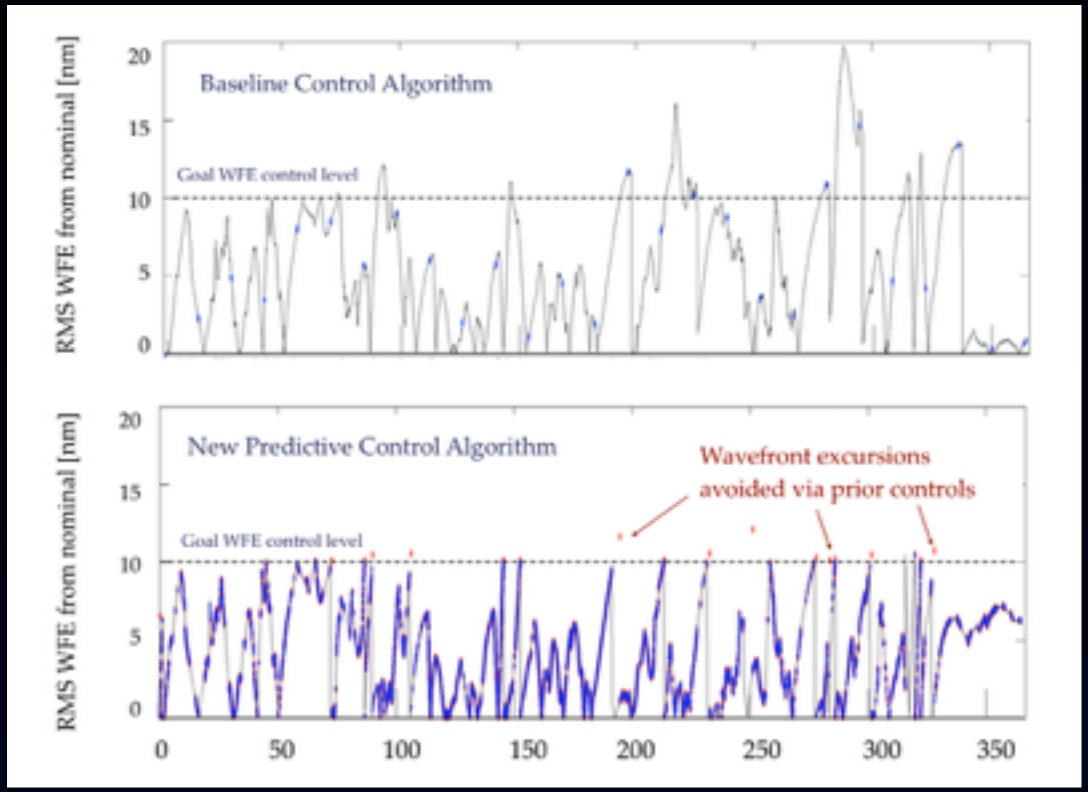


See Gersh-Range & Perrin, 2014

- Maintenance
  - Thermal perturbations are primary driver on long time scales. (hours to weeks) Dynamic effects, vibration on short time scales (seconds to hours)
  - Thermal e-folding time constant ~ 5 days; JWST is *never* in thermal equilibrium, but it's a slow drift.
  - Planned sensing cadence is every 2 days.

We're developing control strategies to maximize stability





- Study using semianalytic model (derived from results of detailed finite element modeling) to estimate temperature and WFE evolution for SODRM-derived schedules.
- Method 1: Add weighting function to schedule generation to minimize thermal drifts. Tradeoffs vs. added scheduling complexity.
- Method 2: Predictive thermal+optical model could estimate corrections in advance. Appears promising even with model uncertainties.

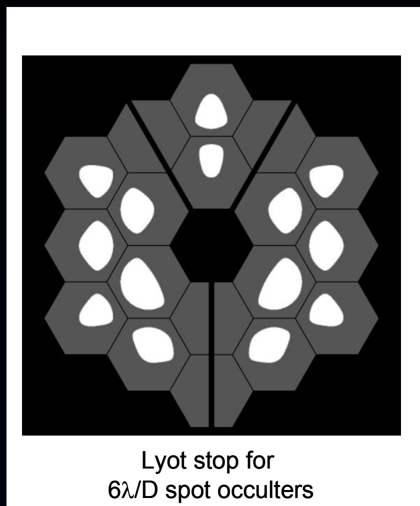
Jessica Gersh-Range & Perrin 2014, JATIS, in press.

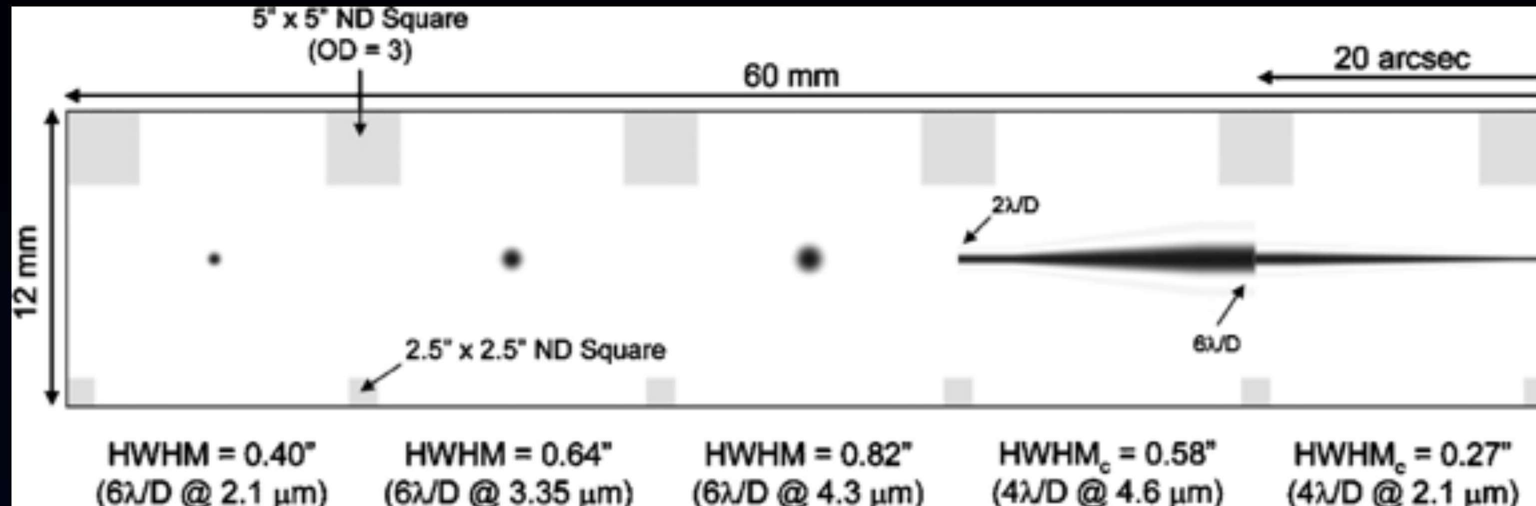
So how stable will the telescope be?

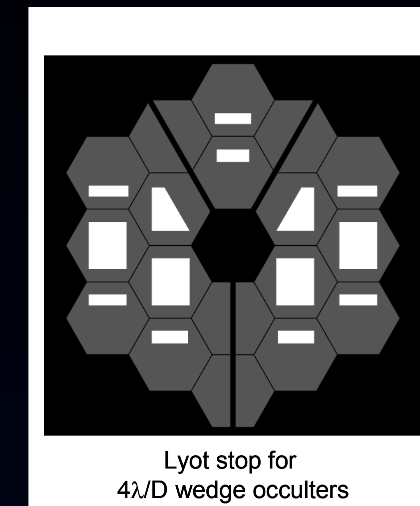
- Benefits both exoplanet imaging & transit spectrophotometry, & lots more...
- JWST requirement is < 54 nm WFE stability over 2 weeks for the maximum possible attitude change *before* applying wavefront control.
- High fidelity integrated finite element modeling has not yet been completed for realistic coronagraphic science cases.
- But based on simplified models and latest (2014) optical performance budget, it appears not unreasonable to expect...
    - <20 nm delta wavefront error on arbitrarily long timescales after active control, limited by sensing precision & control model accuracy.
    - 2-3 nanometer delta wavefront error over 12 hours, with mid-spatial frequency WFE mostly from vibration.
    - *sub-nanometer* stability for back-to-back PSF star observations.

JWST Coronagraph Science

NIRCam coronagraphs: Band Limited Lyot

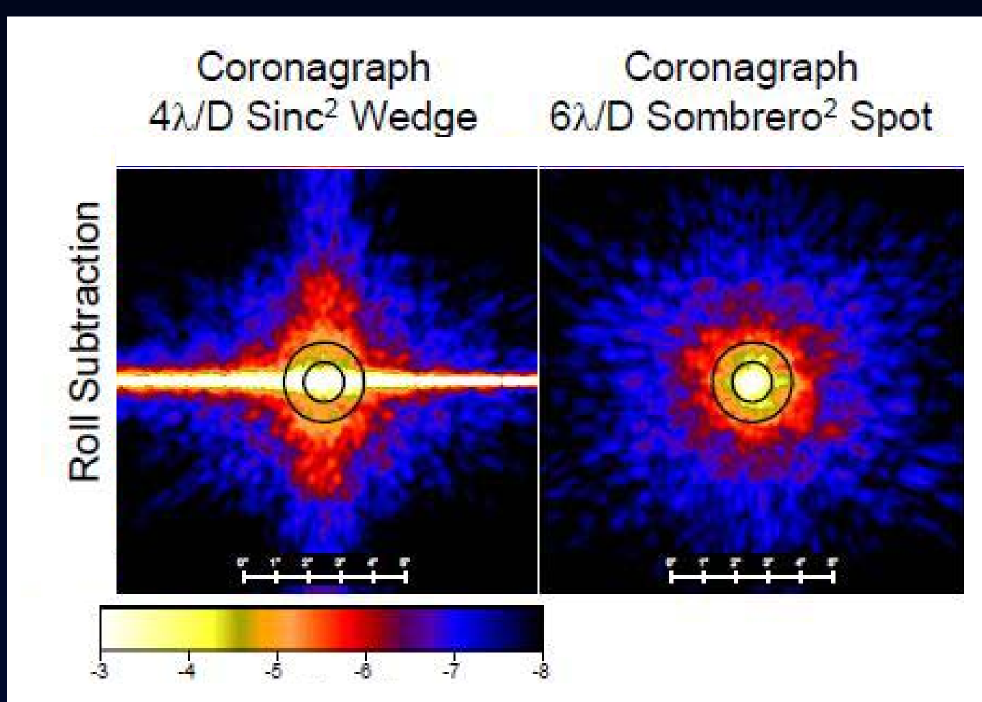






1-5 μm

5 Band-limited coron.
3 circular, 2 wedge



Circles above are 0.6 and 1.4 arcsec
(4 and 8 lam/D)

- Optimized for 2.1 - 4.6 μm.
  22 wide, medium, narrow filters from 0.7-4.8 μm
- Spot occulters provide 360° azimuthal coverage for disk observations and planet search.
- Wedge occulters provide better diffraction suppression at small separations for characterization of known planets, and allow selection of inner working angle.
- Inner working angles ~ 4-6 lam/D
- See Krist et al. 2007, 2010; Beichman et al. 2010.

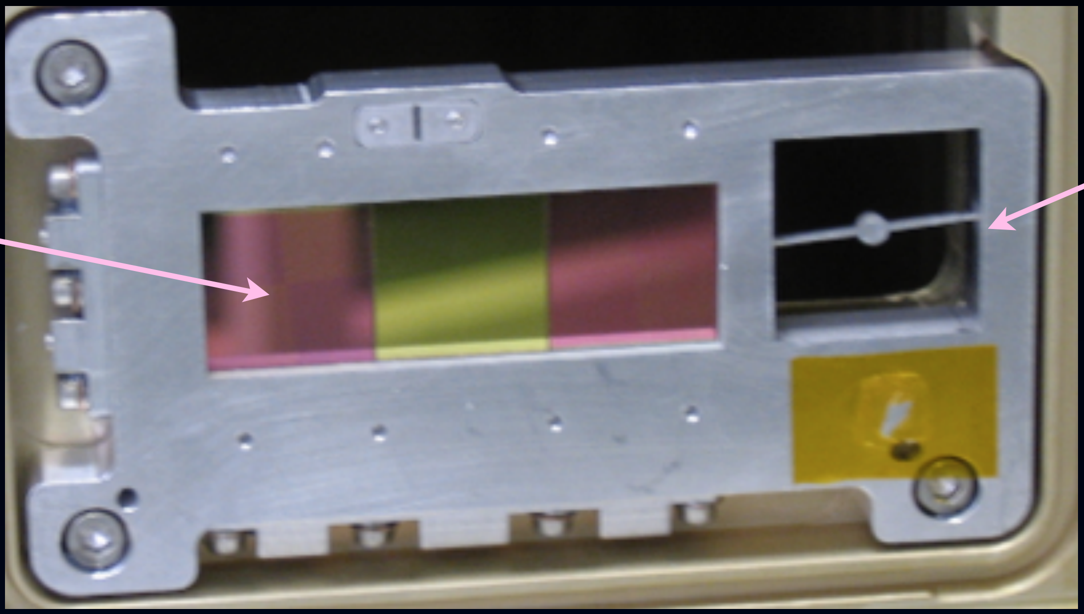
MIRI Coronagraphs: Quad Phase Masks + Lyot

5-25 μm

3x 4 quadrant phase masks
at 10.65, 11.4, 15.5 μm

to get NH_3 abundances
and continuum slope

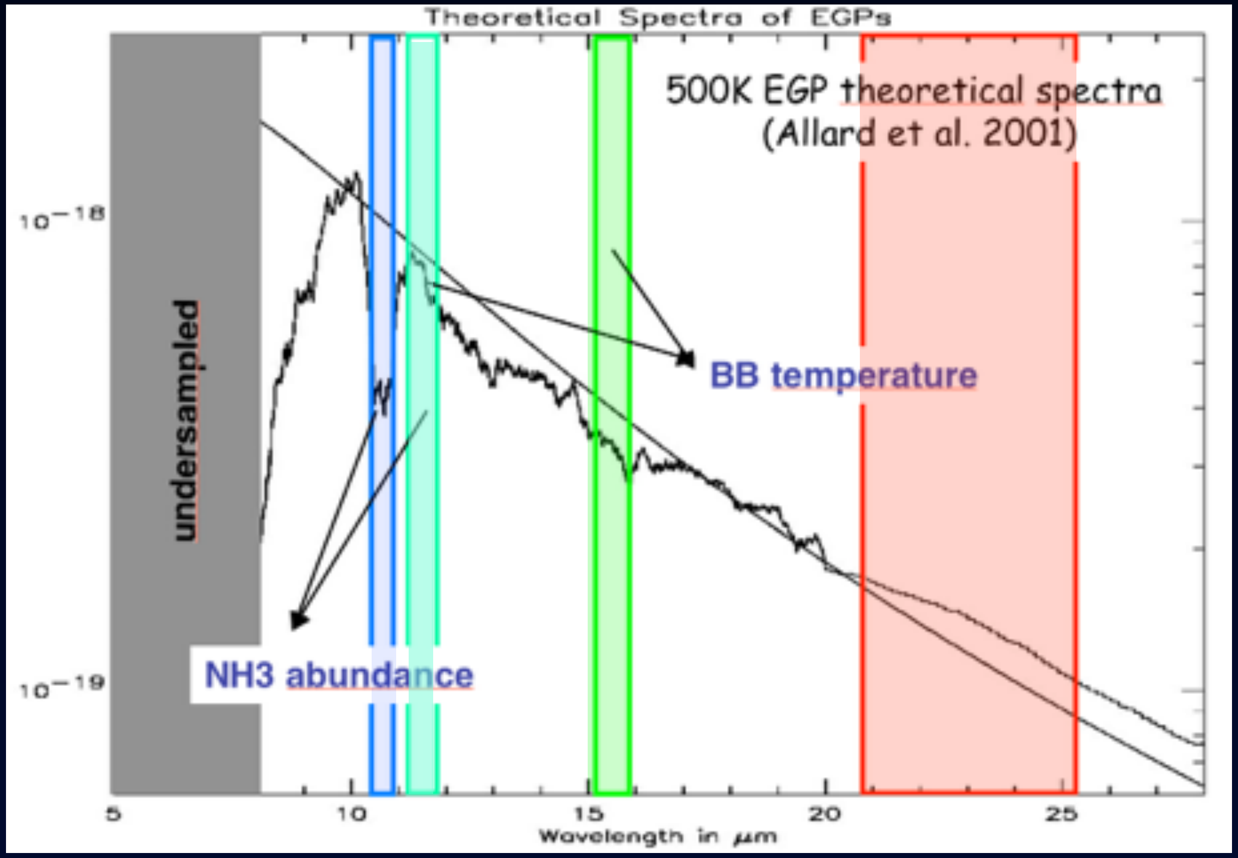
Inner working angle ~ 1 lam/D



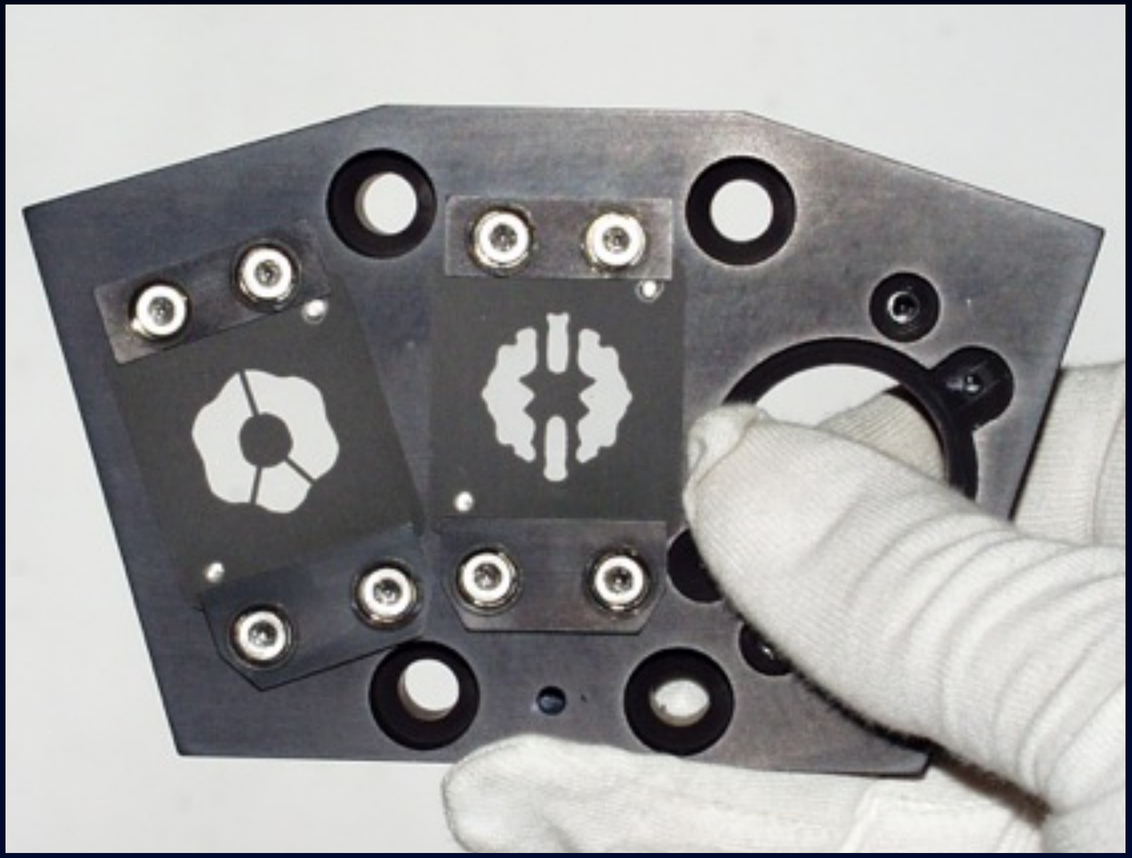
Classical Lyot coron
for 23 μm

Inner working angle
= 2.1 arcsec

Also: imaging with any other NIRCam filter, using the spot or its narrow support bar but no matching Lyot stops

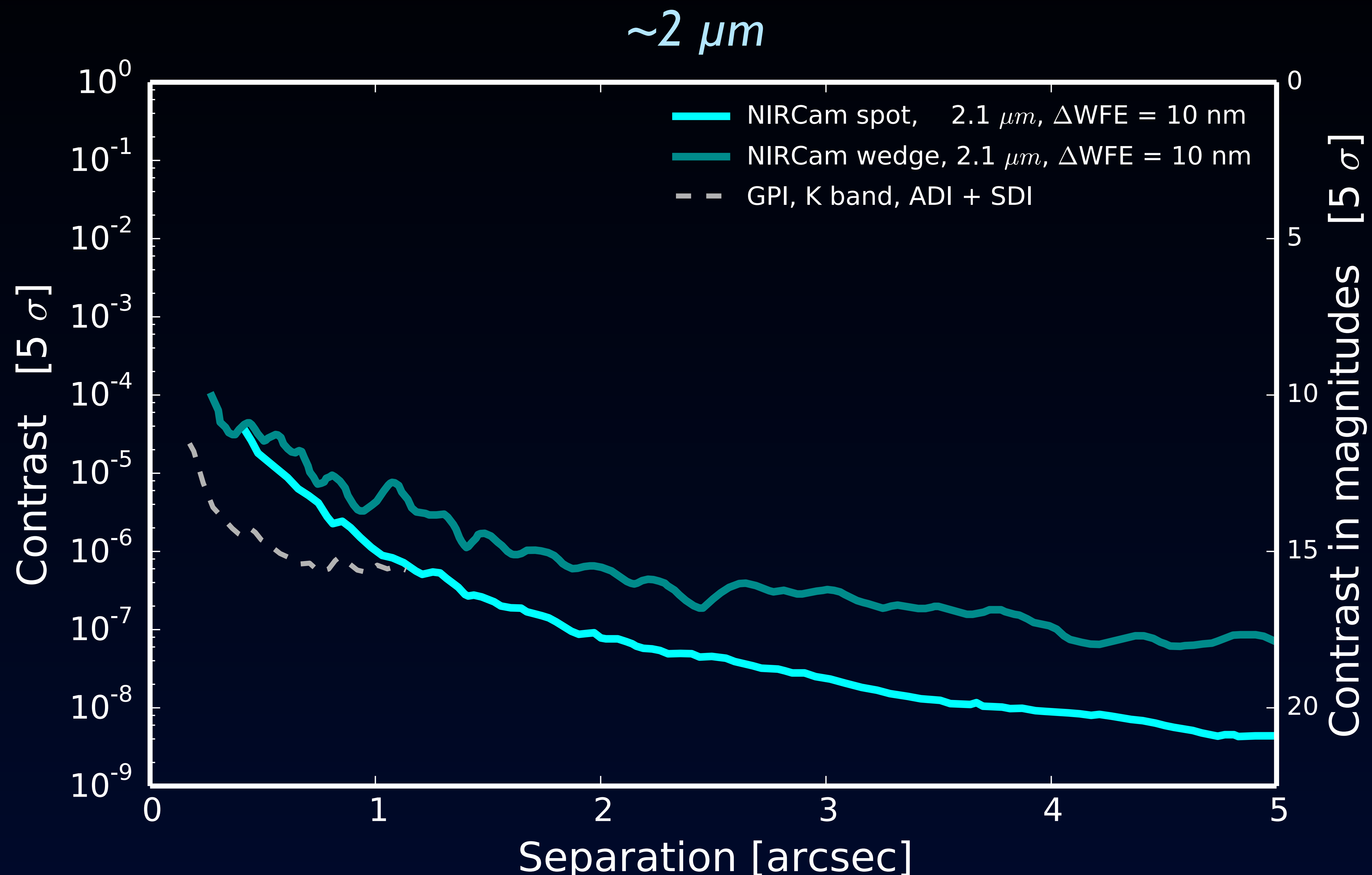


MIRI coronagraph filters

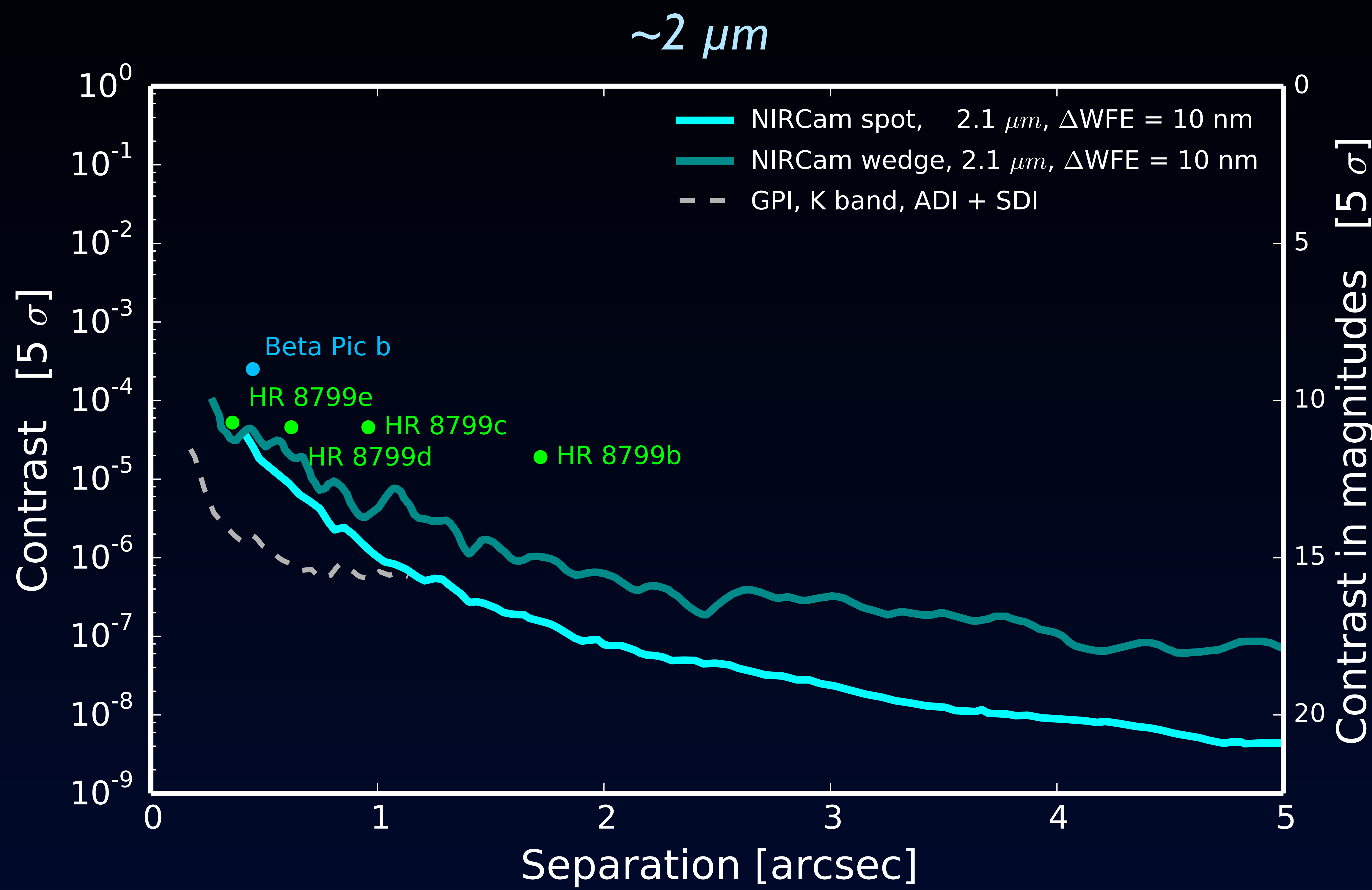


MIRI Lyot masks

Observing planets with NIRCam & MIRI

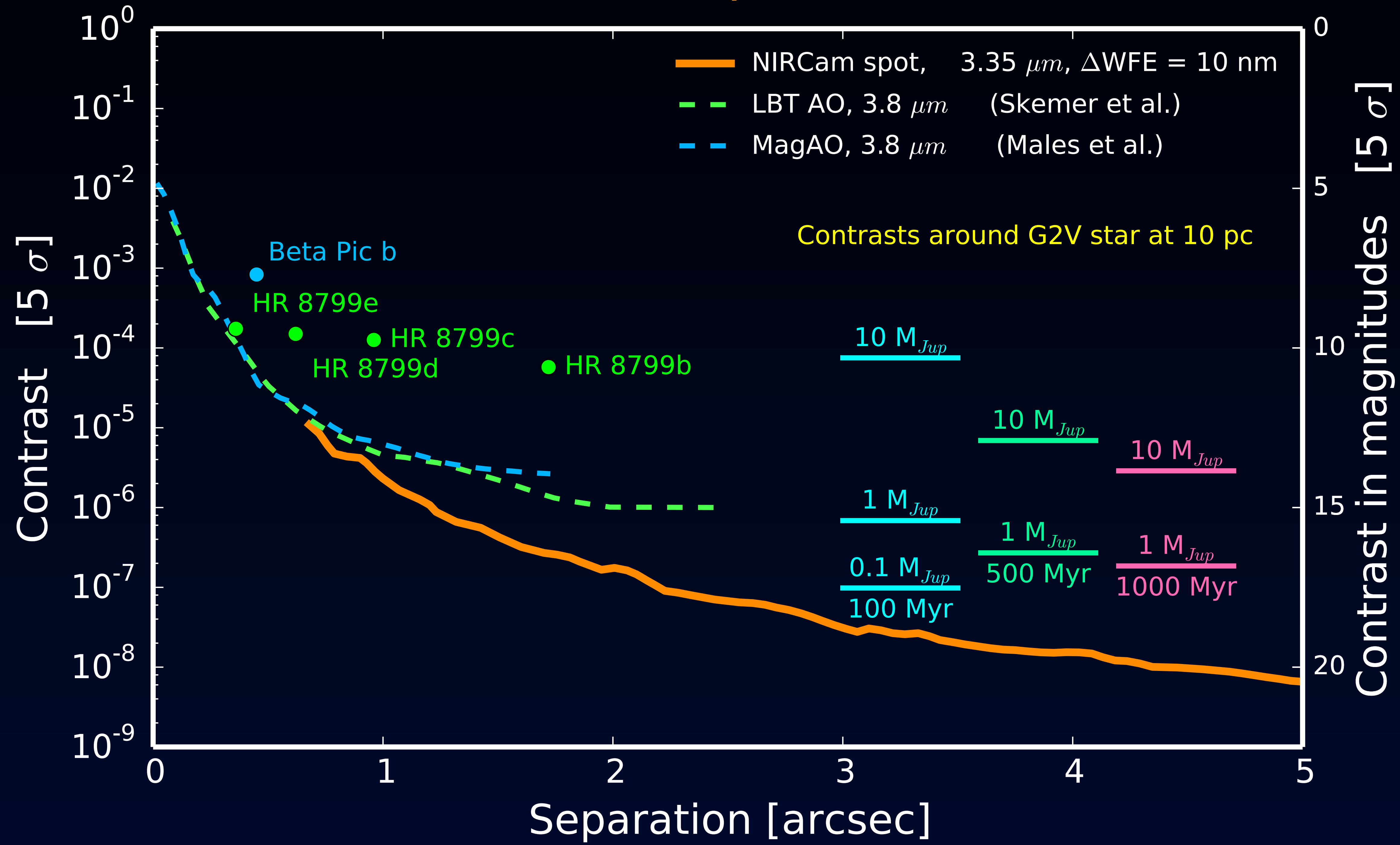


Observing planets with NIRCam & MIRI



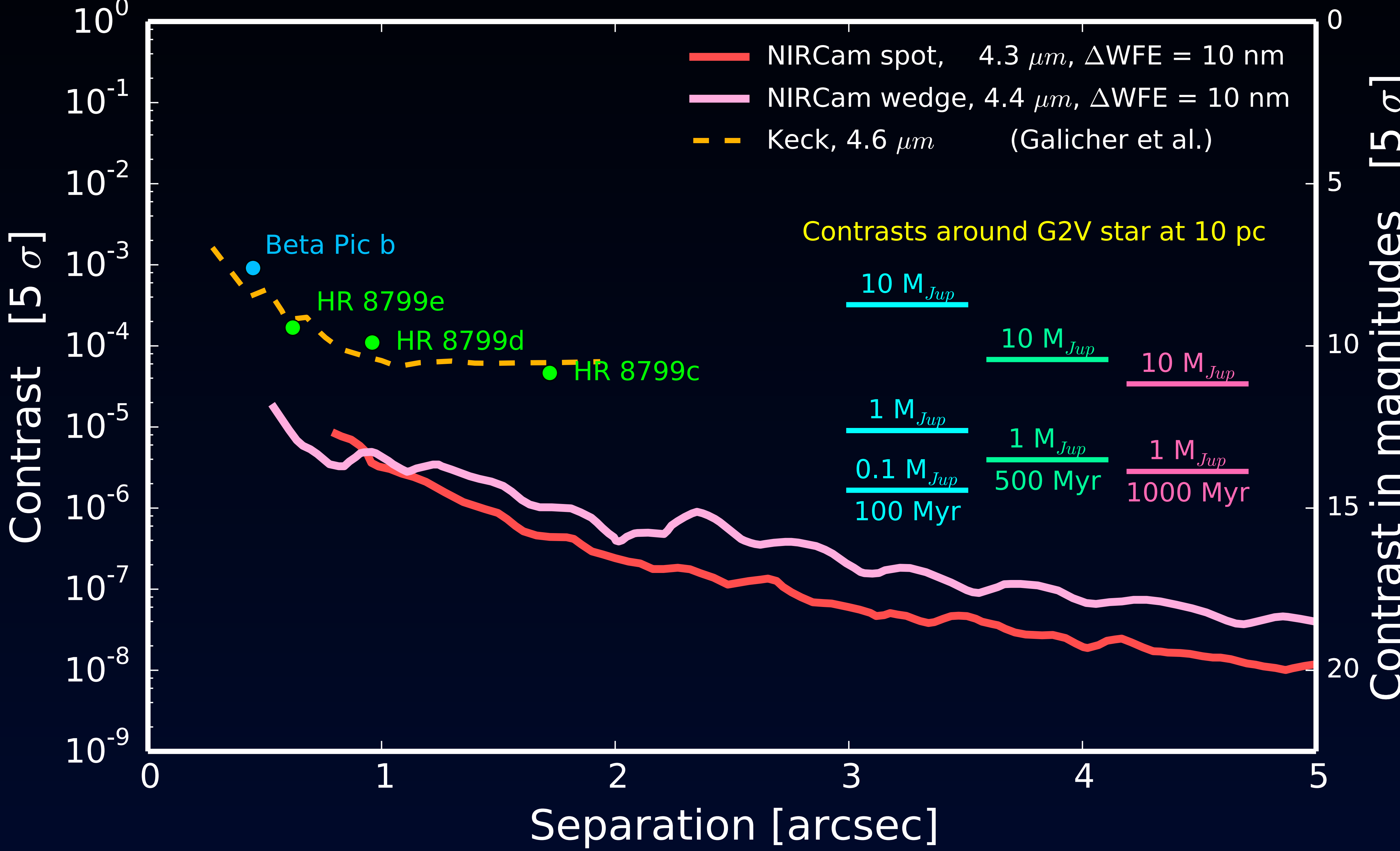
Observing planets with NIRCam & MIRI

~3.5 μm



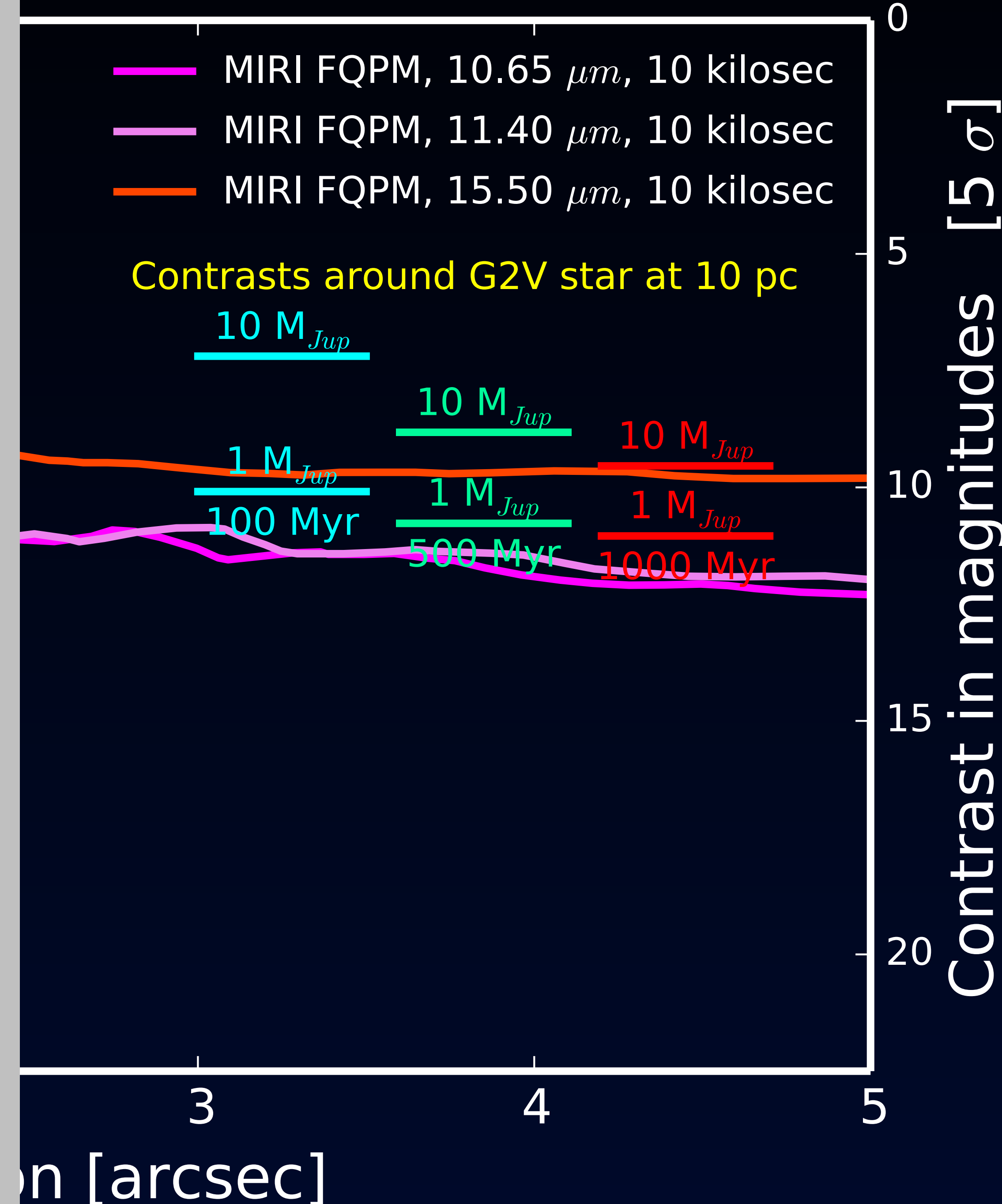
Observing planets with NIRCam & MIRI

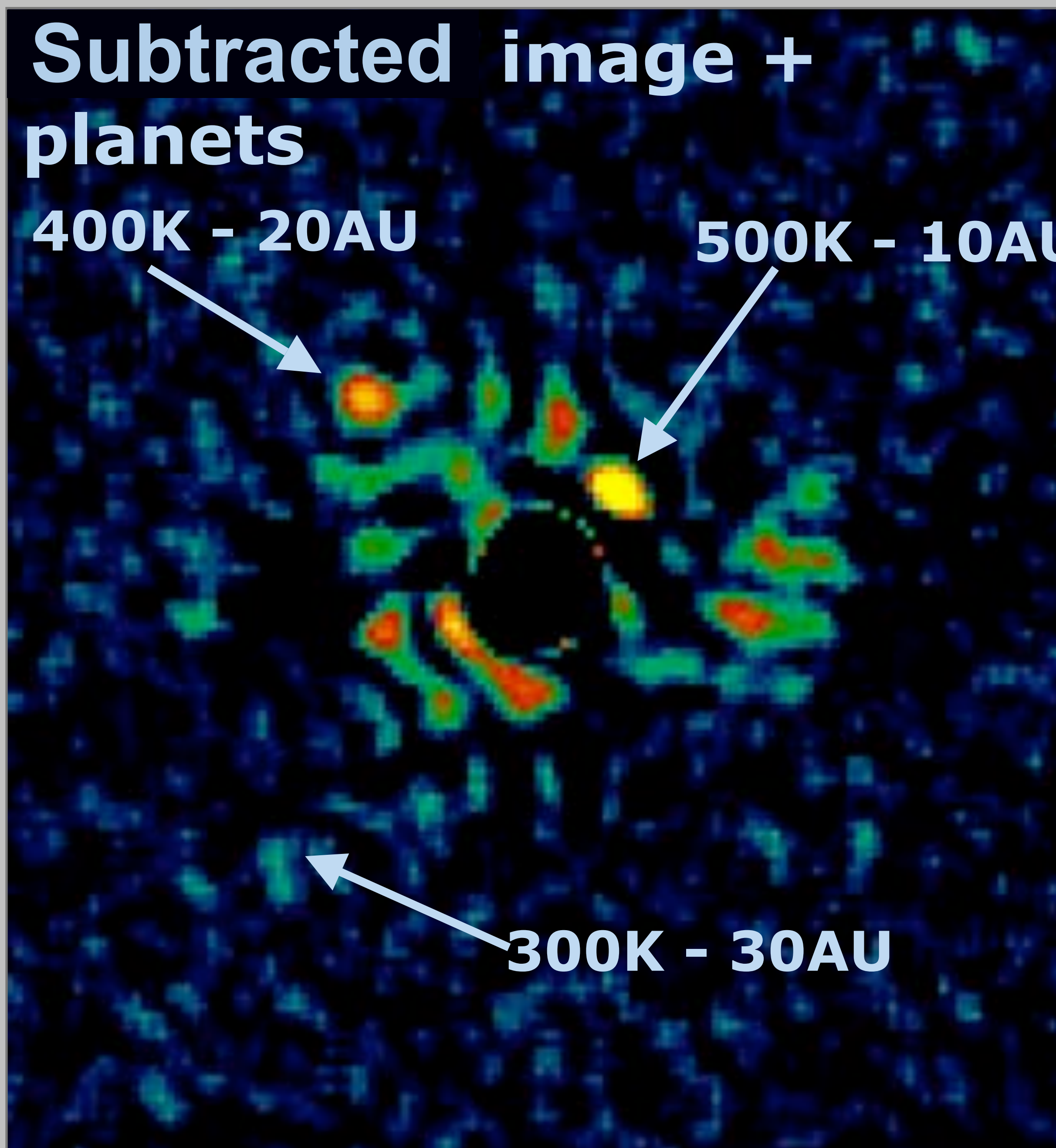
~4.5 μm



Observing planets with NIRCam & MIRI

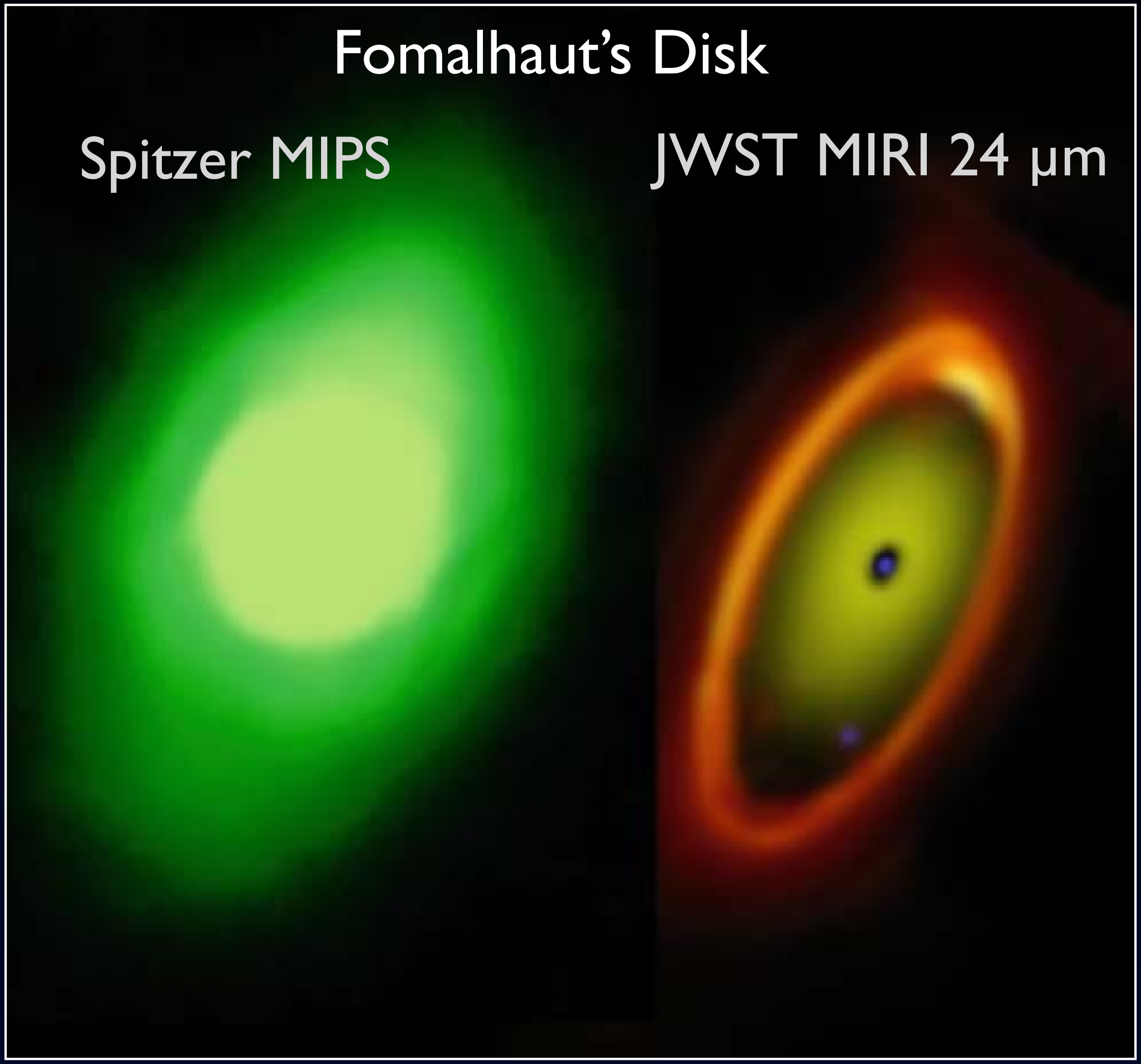
10-15 μm





M2V @10 pc Rouan et al. 2007

What about disks?

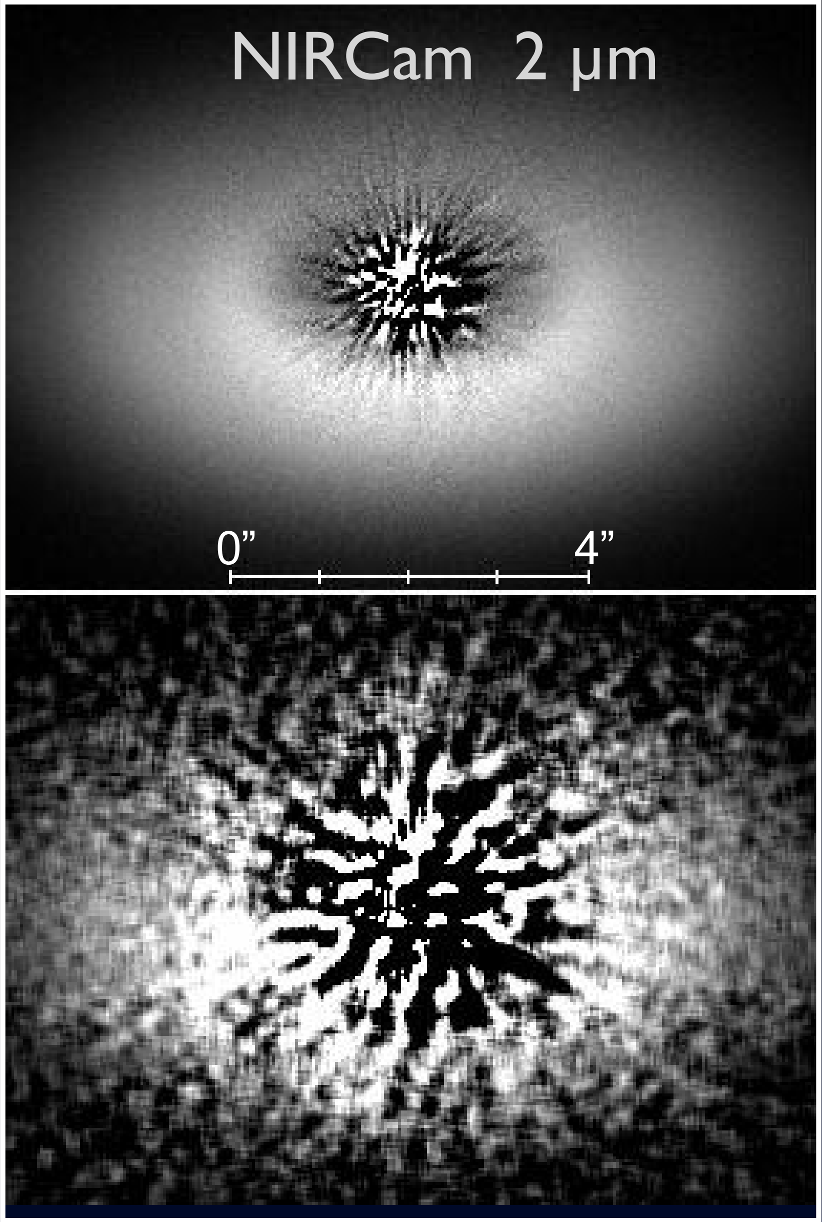


Stapelfeldt et al. 2004

Model disk based on HD 141569

optical depth= 8e-3

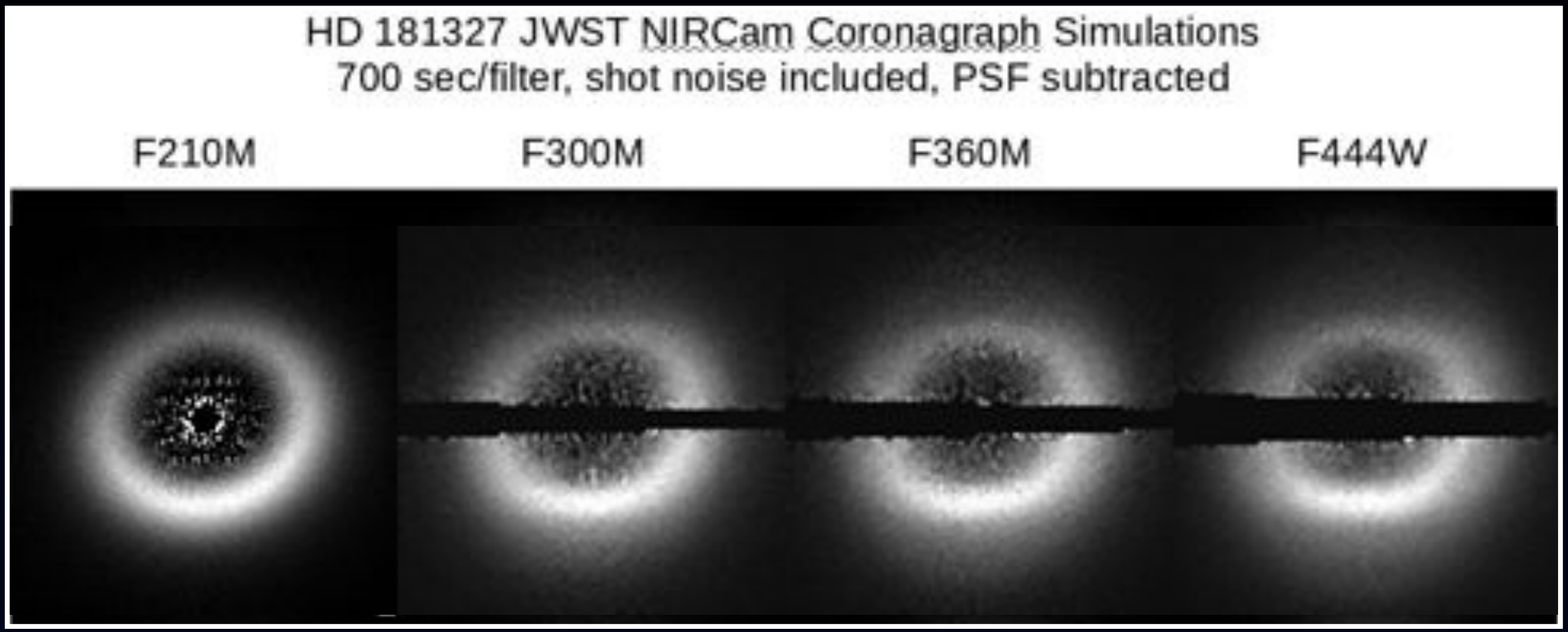
optical depth 50x lower



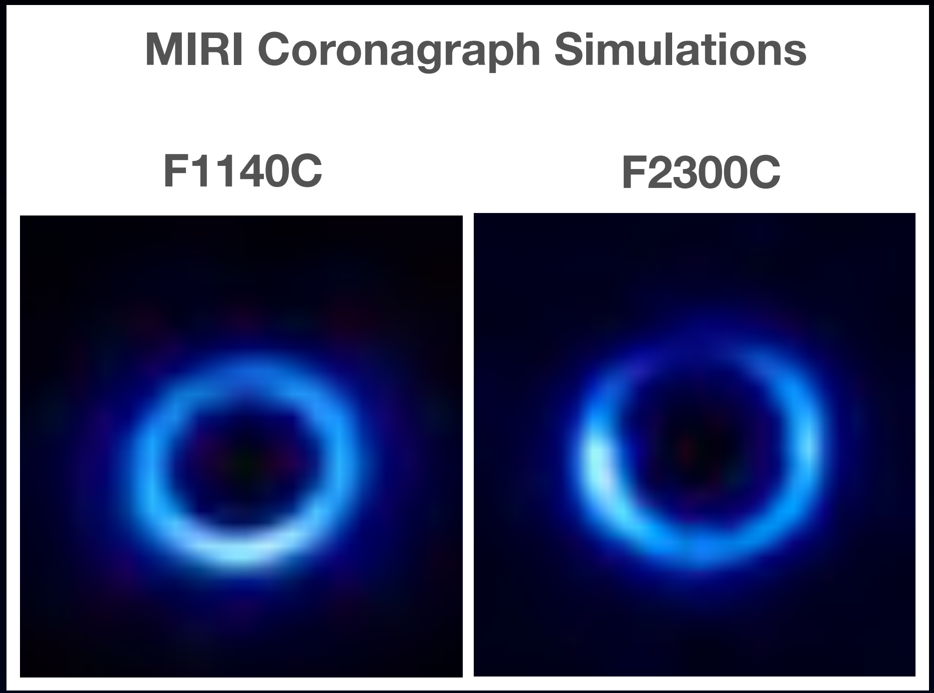
PSF subtractions assuming 5 nm rms delta WFE

Krist et al. 2007

Studying Disk Compositions through Imaging



from J. Lebreton



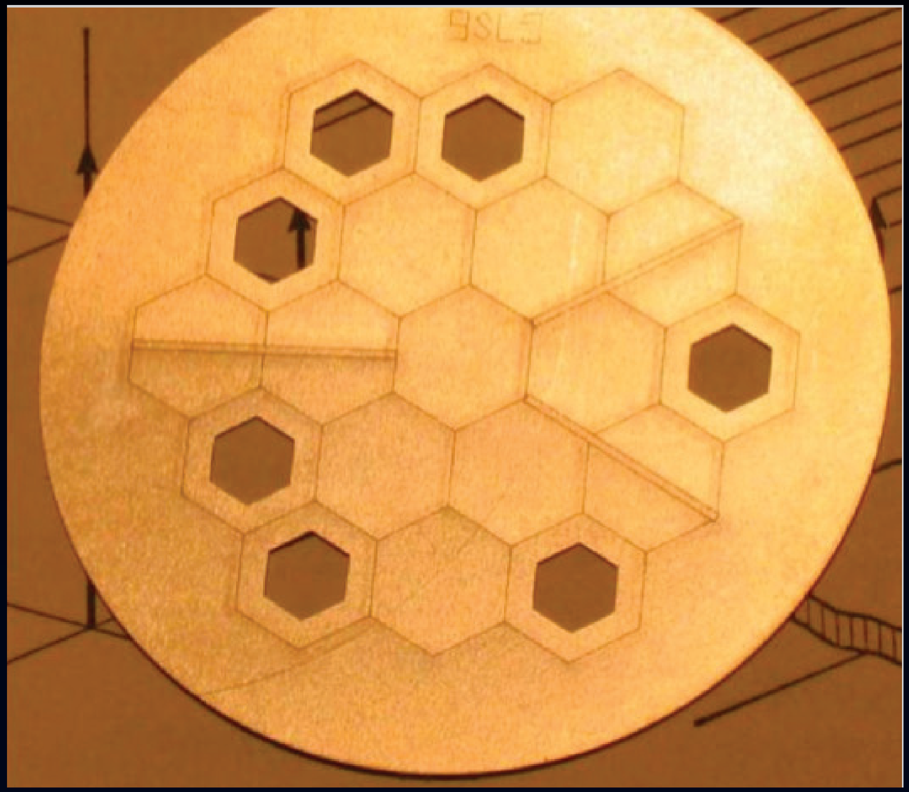
from A. Boccaletti

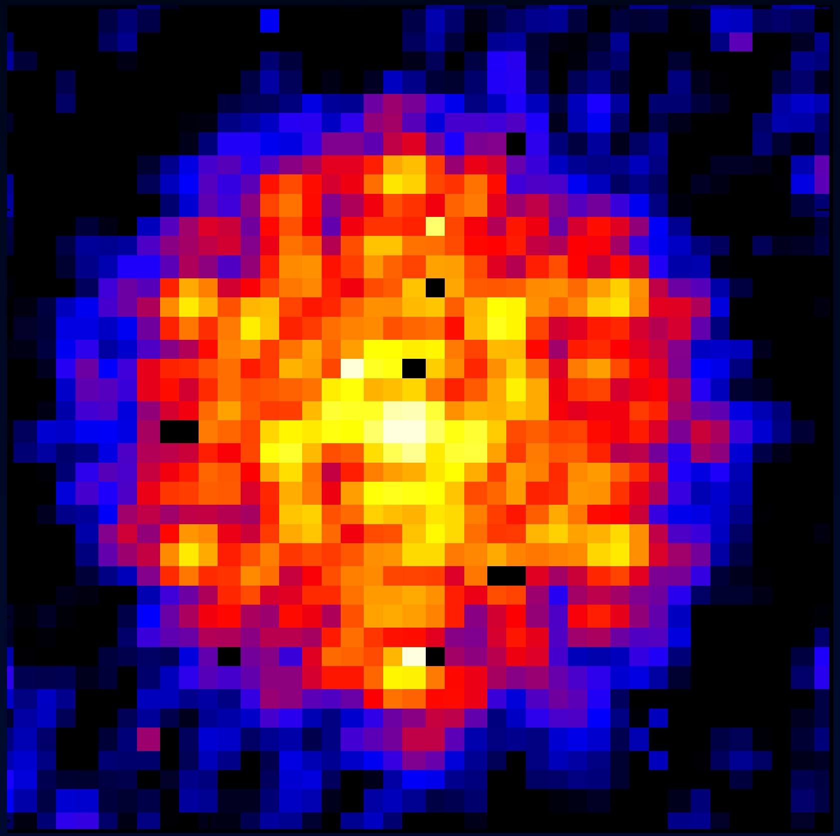
Colors, albedos, phase functions of scattering particles
Ices at 3.3 μm
Silicates at 10-11 μm

NIRCam & MIRI Integral Field Spectrographs.

R~700 - 2700, from 0.7 to 27 μm.
How much can we do with PSF subtraction with these image slicers?

NIRISS Aperture Masking Interferometry



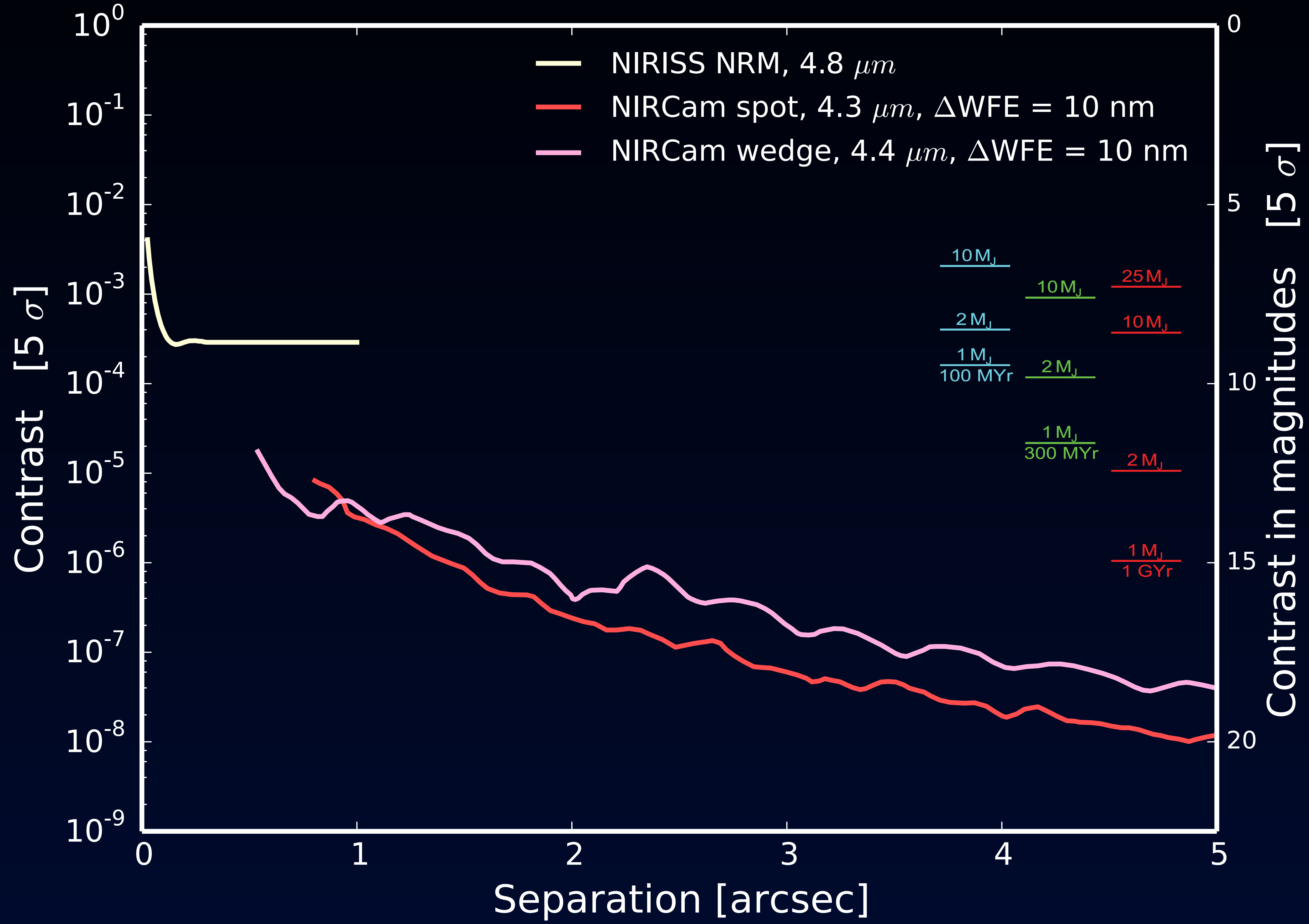


NIRISS cryovac test data, Oct 2013

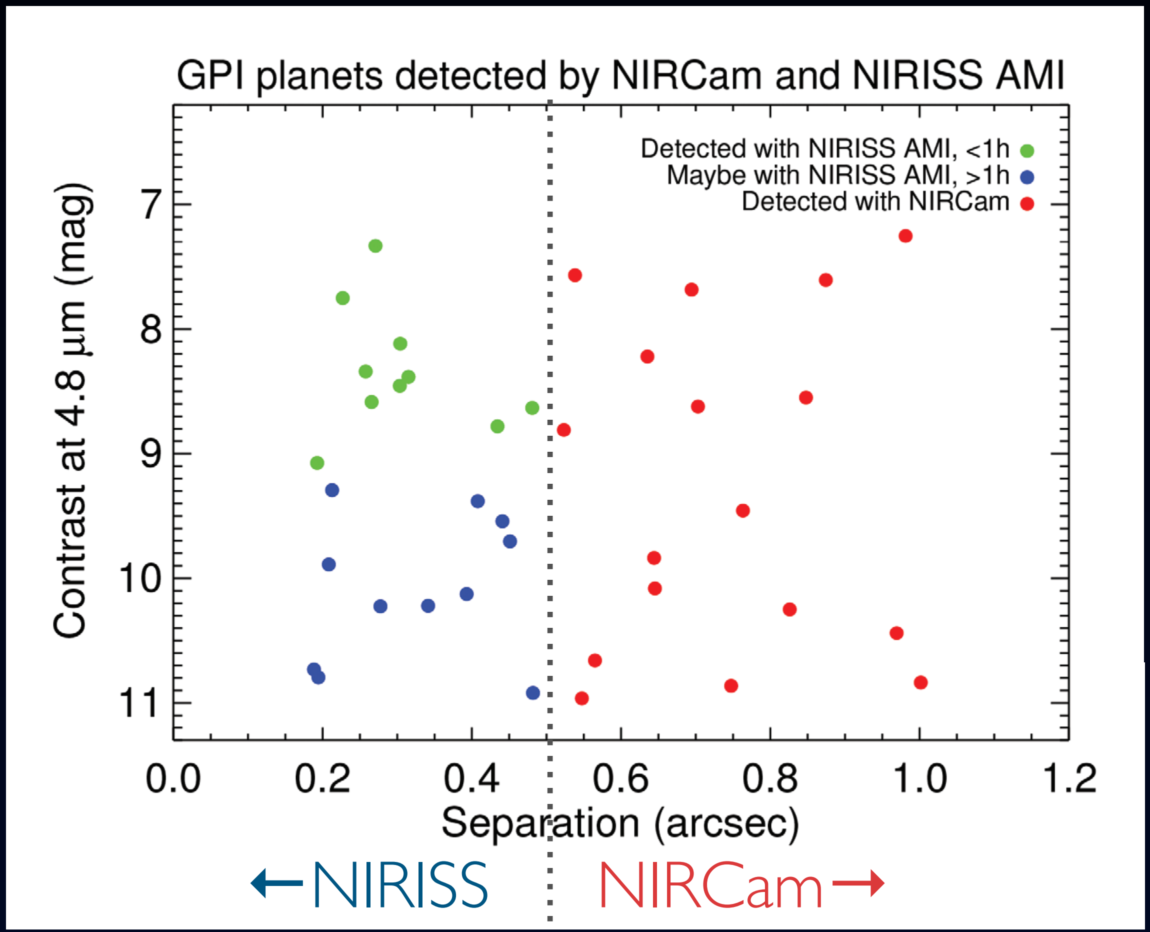
- 7 hole nonredundant mask in NIRISS pupil wheel. 21 baselines.
- Inner working angle about 70 mas
- 5% filters at 3.8, 4.3, 4.8 µm
- 25% filter at 2.7 µm
  (undersampled but image plane forward model algorithms enable model fitting.)

Sivaramakrishnan et al. 2009, 2010, 2012,
Ford et al. 2014,
Greenbaum et al. in prep.

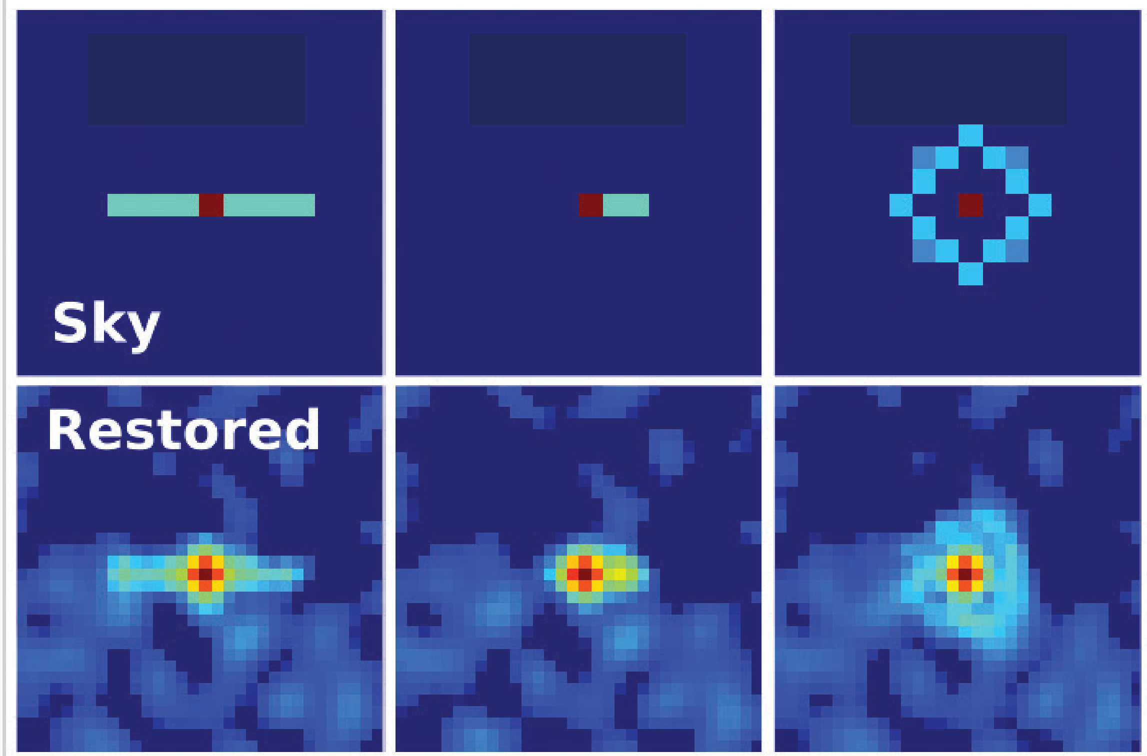
NIRISS Aperture Masking Interferometry



Followup to small separation planets



Imaging disks, AGN, quasar hosts...



1 arcsec FOV = 50 pc at 10 Mpc distance
Imaging at 100:1 contrast at subarcsec scales at 4.8 μm

Figures from Sivaramakrishnan & Artigau 2014
(article in next month's STScI newsletter)

Transits, transits, transits...

- JWST will *excel* at transit and eclipse spectrophotometry.
  - Photon noise limited SNR ~ 3-8x better than HST or Spitzer
  - Exquisite spectra of gas giants from 0.7 to beyond 10 μm.
  - But not transiting Earth twins.
- Wide spectral range & various resolutions -
  - NIRISS: 0.6-2.4 μm, R ~700, entire range simultaneously, slitless, and cross-dispersion defocused for enhanced dynamic range
  - NIRSpec: 0.7-2.5 μm, R~100, 1000, 2700, square 1.6'' aperture,
  - NIRCam: can be defocused w/ weak lenses for very bright star photometry
    2.5-5 μm, R~1700 slitless spectroscopy
  - MIRI: 5-12+ μm, R~70, slitless spectroscopy
- TESS & JWST synergy. PLATO beyond 2024.

Complimentary strengths for exoplanet imaging in the 2020s

High Contrast AO	JWST
Jovian planet detection	Planet spectroscopy & characterization
Disk imaging in the near-IR	Disk imaging & spectroscopy in the mid-IR
Higher angular resolution	Greater sensitivity
Smaller inner working angles	Larger field of view
Polarimetry	Total intensity with fewer subtraction biases
Young Jupiter twins	Young Saturn twins
Some results in visible light	Fainter (younger/farther) science targets

Backup Slides

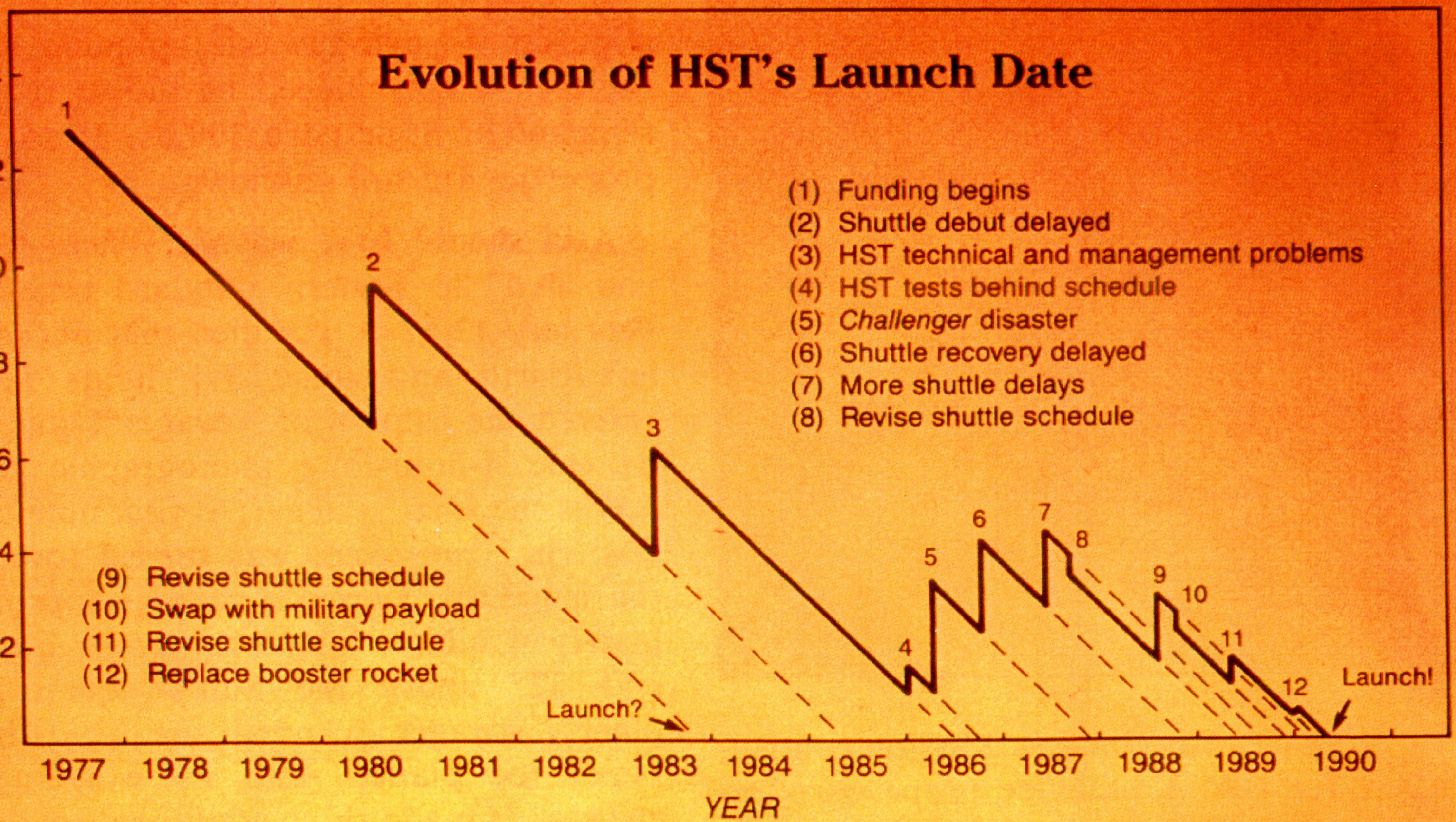
The bottom line

- Active and adaptive optics are essential for extending our vision with future large telescopes, from both Earth and space.

- JWST is "Keck 1990 in space": Active, but not adaptive, optics enable a giant leap in aperture above Hubble's "Mt Wilson 100 inch in space."

- Future high contrast imaging missions will use "Extreme AO in space" to spectroscopically characterize nearby worlds.
  AFTA Coronagraph: Jovian & Neptunian planets
  ATLAST: Terrestrial planets in habitable zones

- Whatever we do, it will take a decade or two per mission, and cost "one great observatory quantum"; Bringing such missions into reality will take both technological *boldness* and management *discipline*.

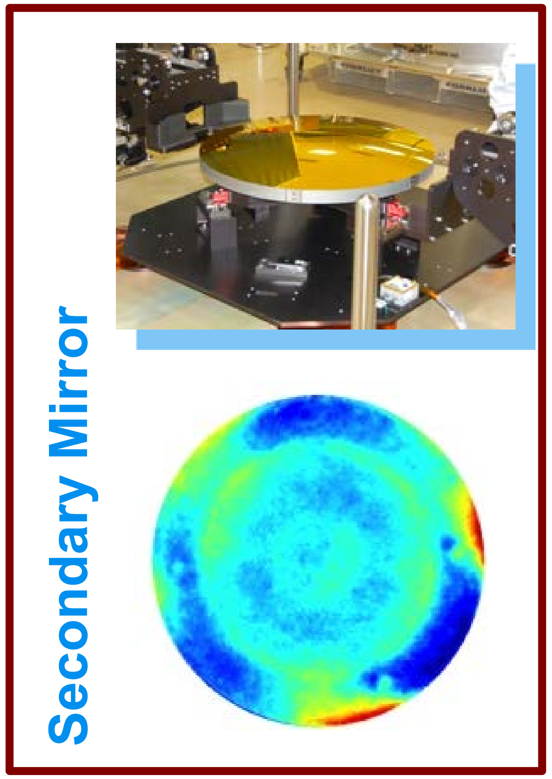


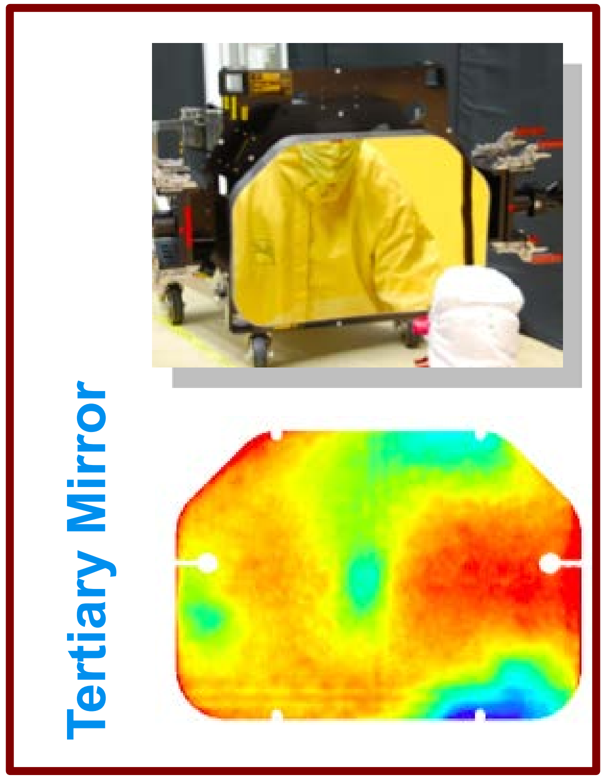
The Hubble Space Telescope's road to space has been both long and rocky. Problems within the project itself and with the Space Shuttle have forced numerous launch delays. As a result, HST's development took more than twice as much time and money as originally intended.

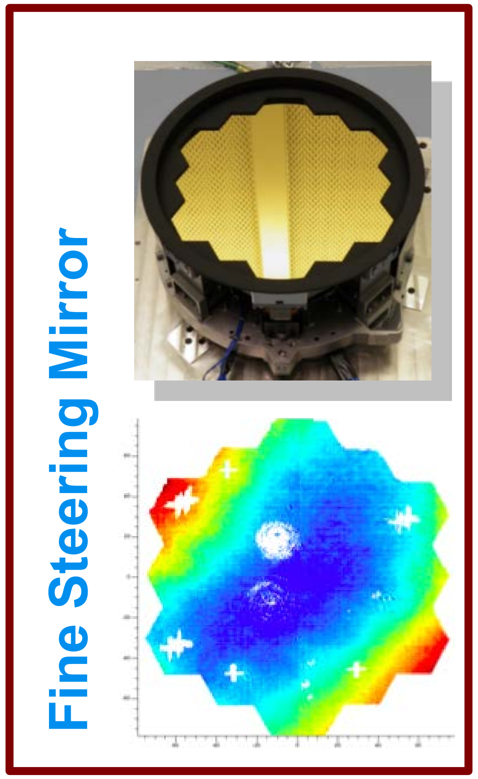
Courtesy of Duccio Machetta,
shown at "20 years of HST" meeting in Venice 2010

JWST Mirrors Completed in 2011

Mirror	Measured (nm rms SFE)	Uncertainty (nm rms SFE)	Total (nm rms SFE)	Req (nm rms SFE)	Margin (nm rms SFE)
Primary Mirror (18 mirror composite)	23.6	8.1	**25.0**	25.8	6.4
Secondary Mirror	14.7	13.2	**19.8**	23.5	12.7
Tertiary Mirror	18.1	9.5	**20.5**	23.2	10.9
Fine Steering Mirror	13.9	4.9	**14.7**	18.7	11.6

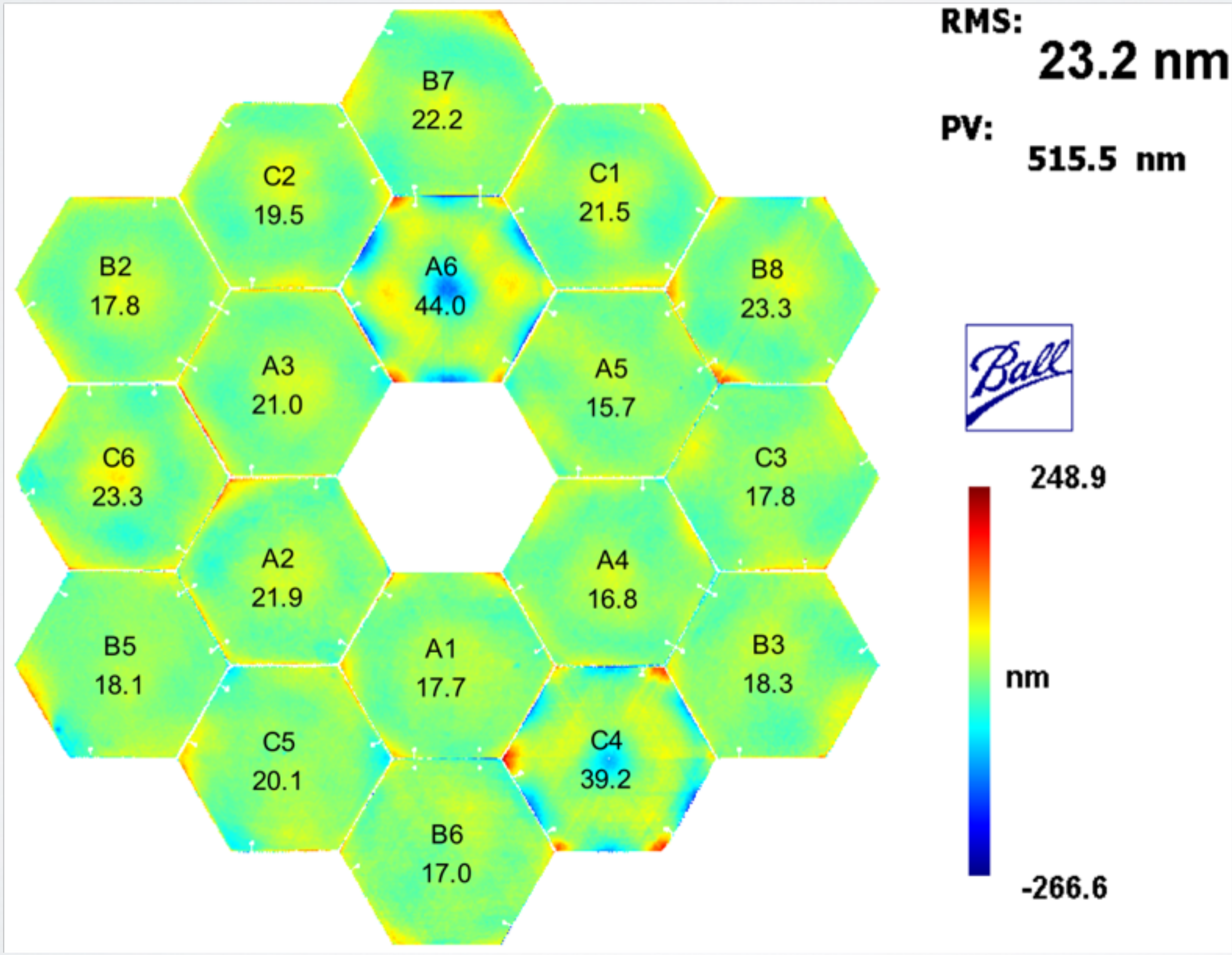




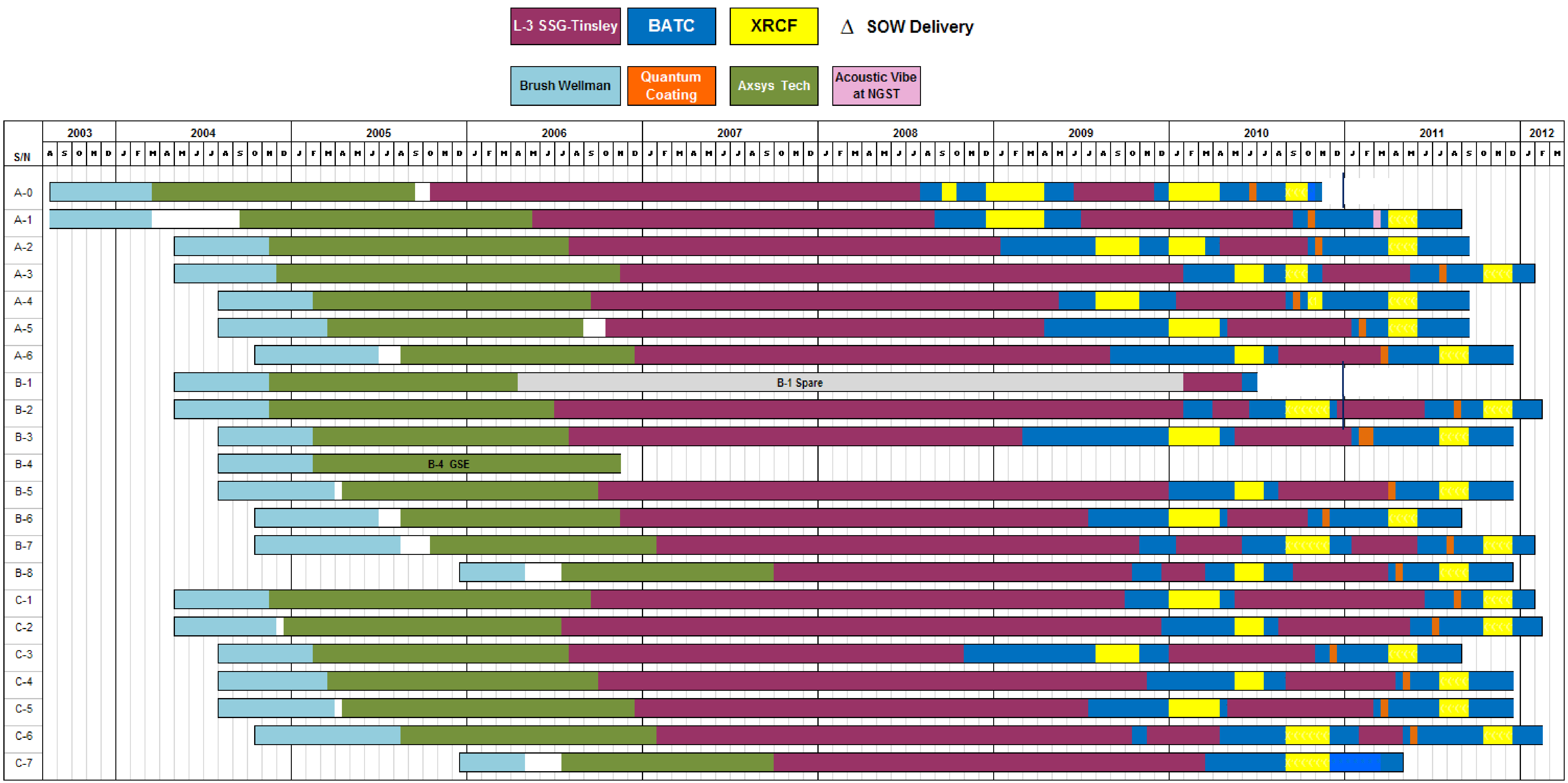


Slide from Lee Feinberg

Requirement	=	25.8 nm rms
Total Measurement + Uncertainty	=	25.0 nm rms

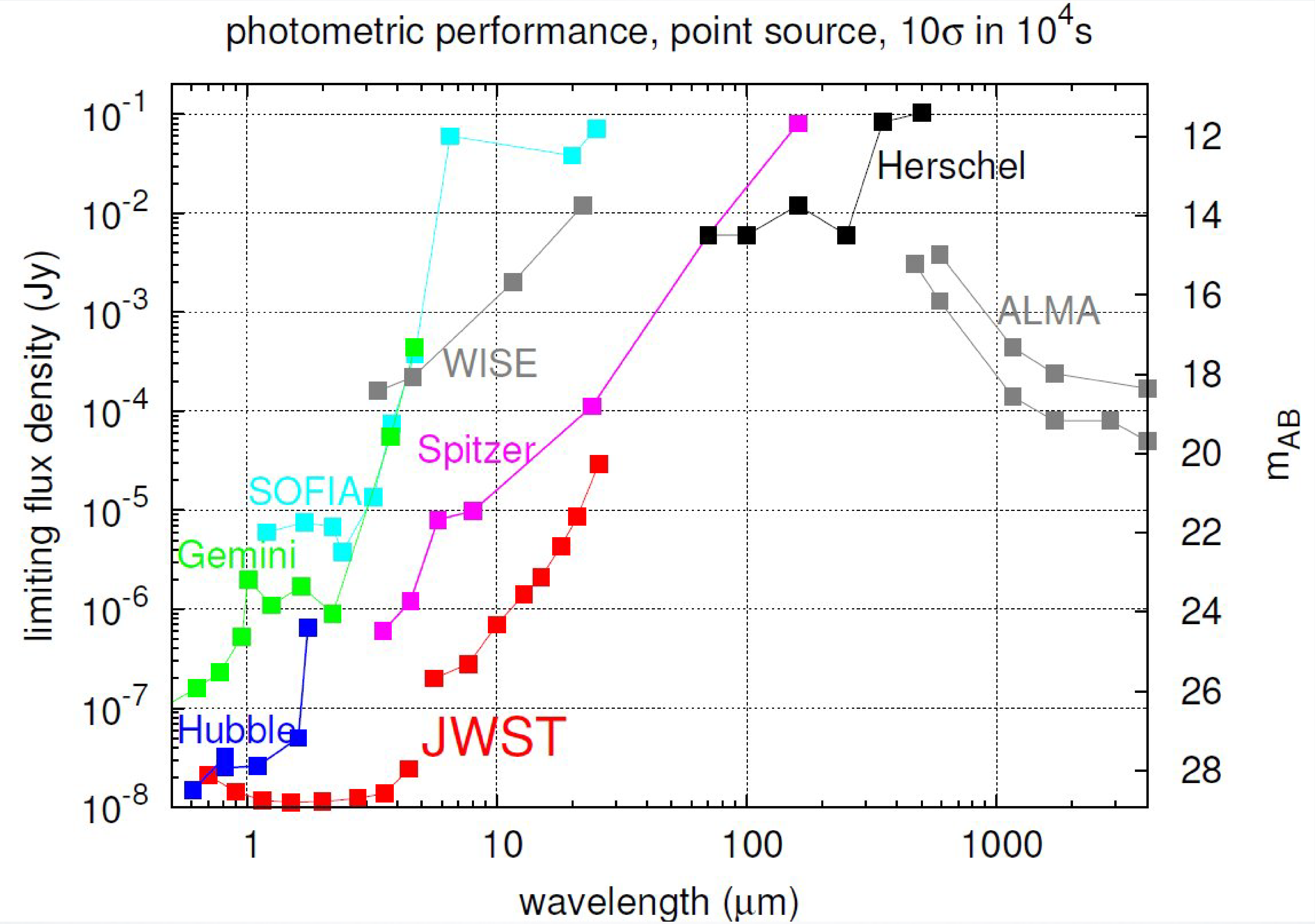


Mirror Fabrication and Test Now Complete (As Run Schedule)

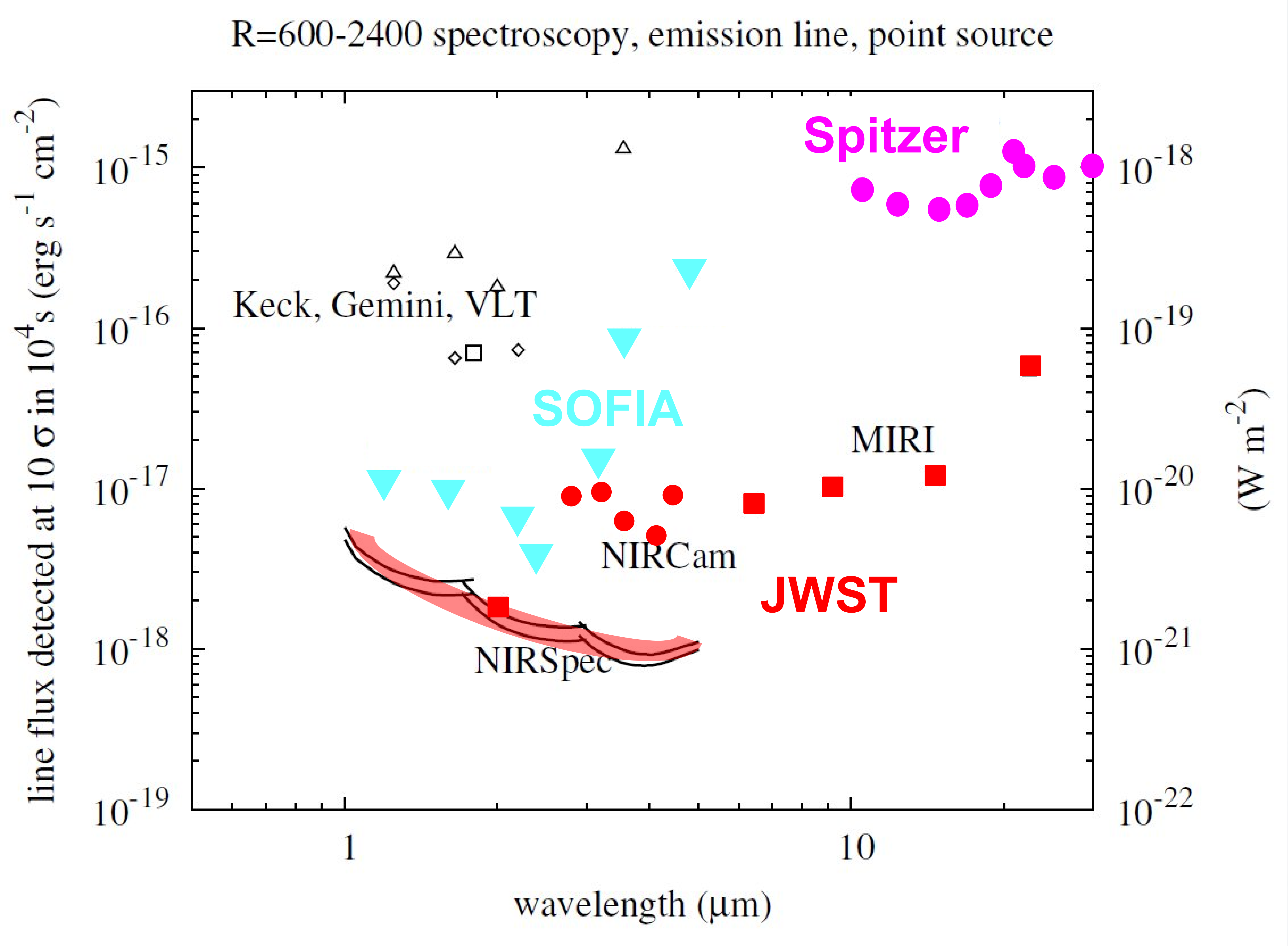


Slide from Lee Feinberg

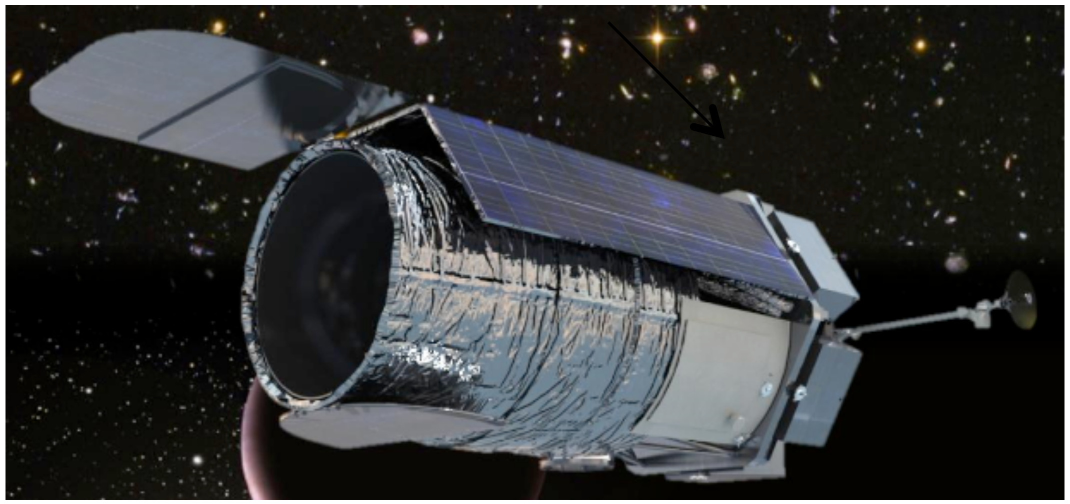
JWST Imaging Sensitivity

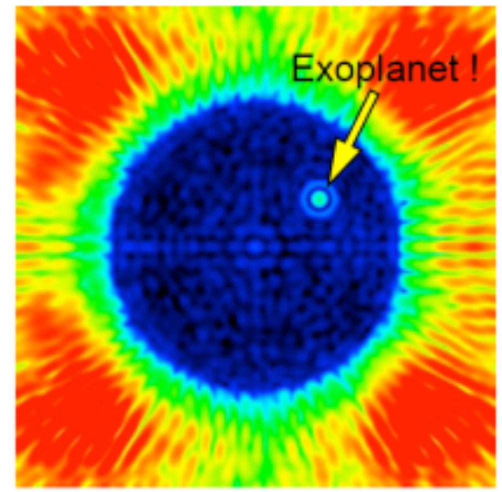


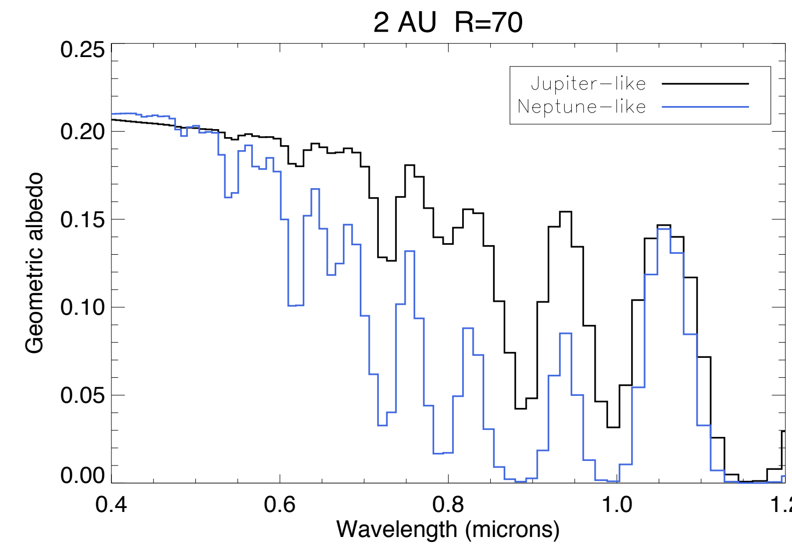
JWST Spectroscopic Sensitivity



WFIRST-AFTA Coronagraph Capability







Coronagraph Architecture:
Primary: Occulting Mask (OMC)
Backup: Phase Induced Amplitude Apodization (PIAA)

Exoplanet Direct Imaging

Exoplanet Spectroscopy

Bandpass	400 – 1000 nm	Measured sequentially in five ~10% bands
Inner working angle	100 – 250 mas	~3λ/D
Outer working angle	0.75 – 1.8 arcsec	By 48x48 DM
Detection Limit	Contrast ≤ 10^{-9} (after post processing)	Cold Jupiters, Neptunes, and icy planets down to ~2 RE
Spectral Resolution	~70	With IFS, R~70 across 600 – 980 nm
Spatial Sampling	17 mas	Nyquist for λ~430nm