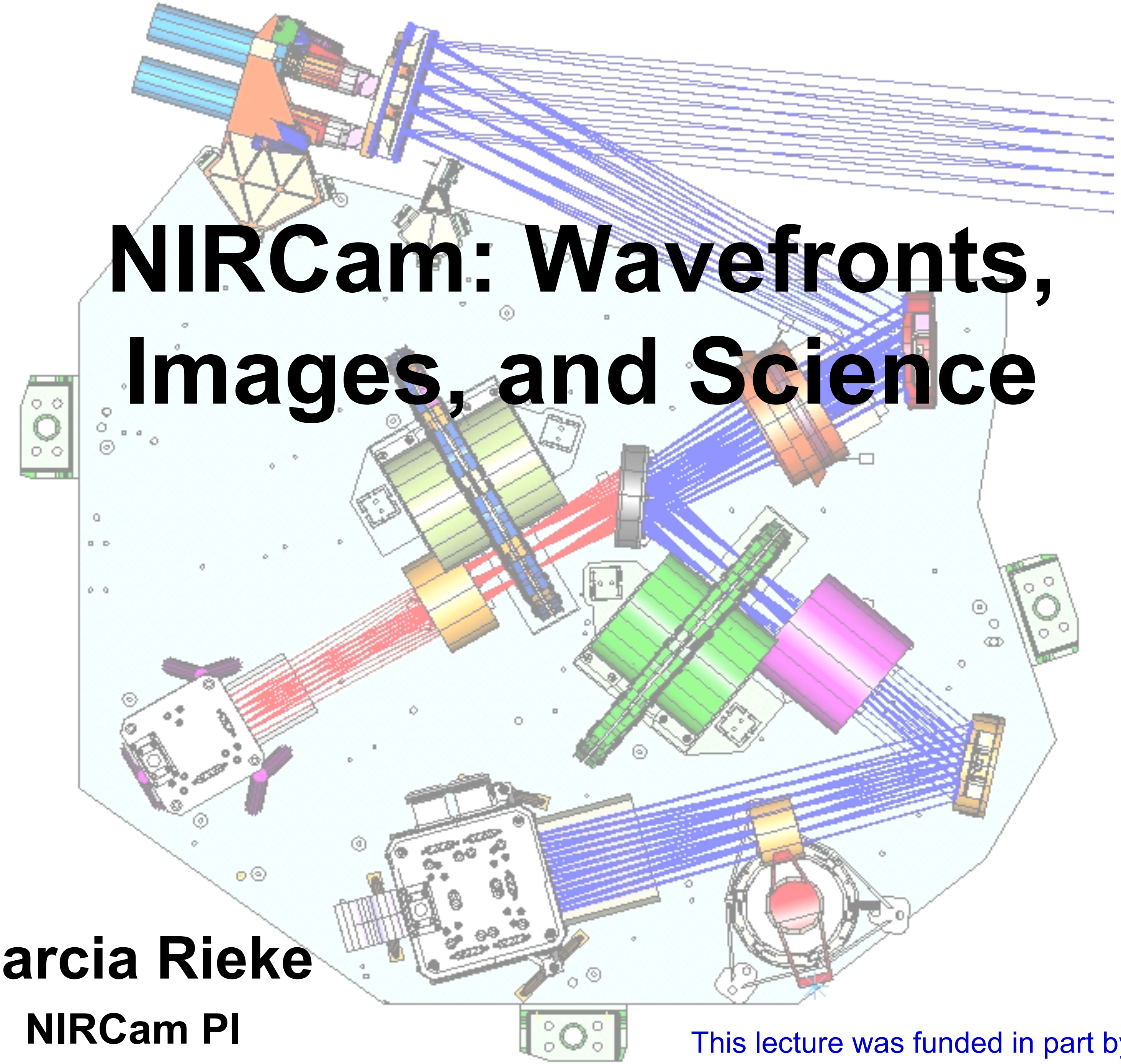

NIRCam: Wavefronts, Images, and Science

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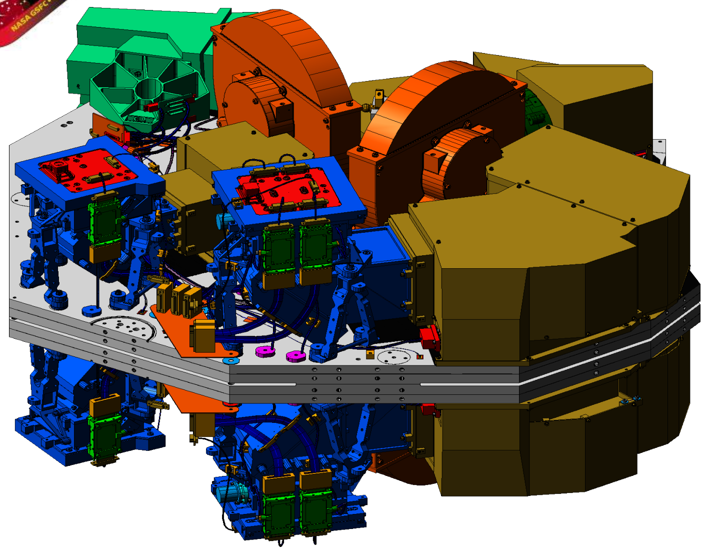
NIRCam PI

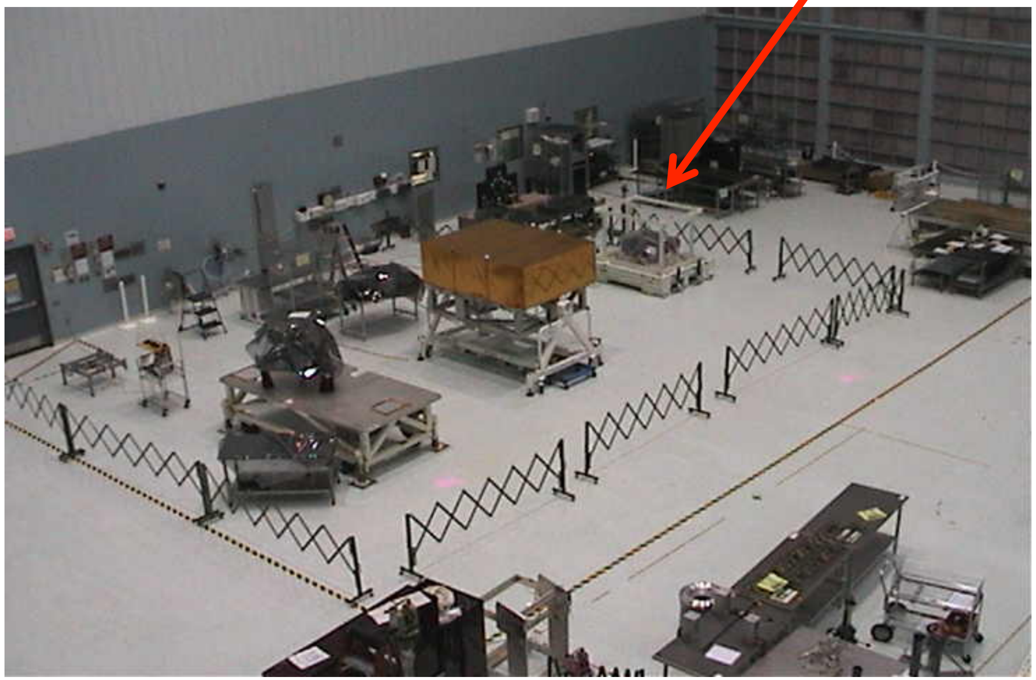
Ottobrunn, June 1-2, 2010

This lecture was funded in part by the Marie Curie Initial Training Network ELIXIR of the European Commission under contract PITN-GA-2008-214227.

What's NIRCam?



View of the Goddard clean room



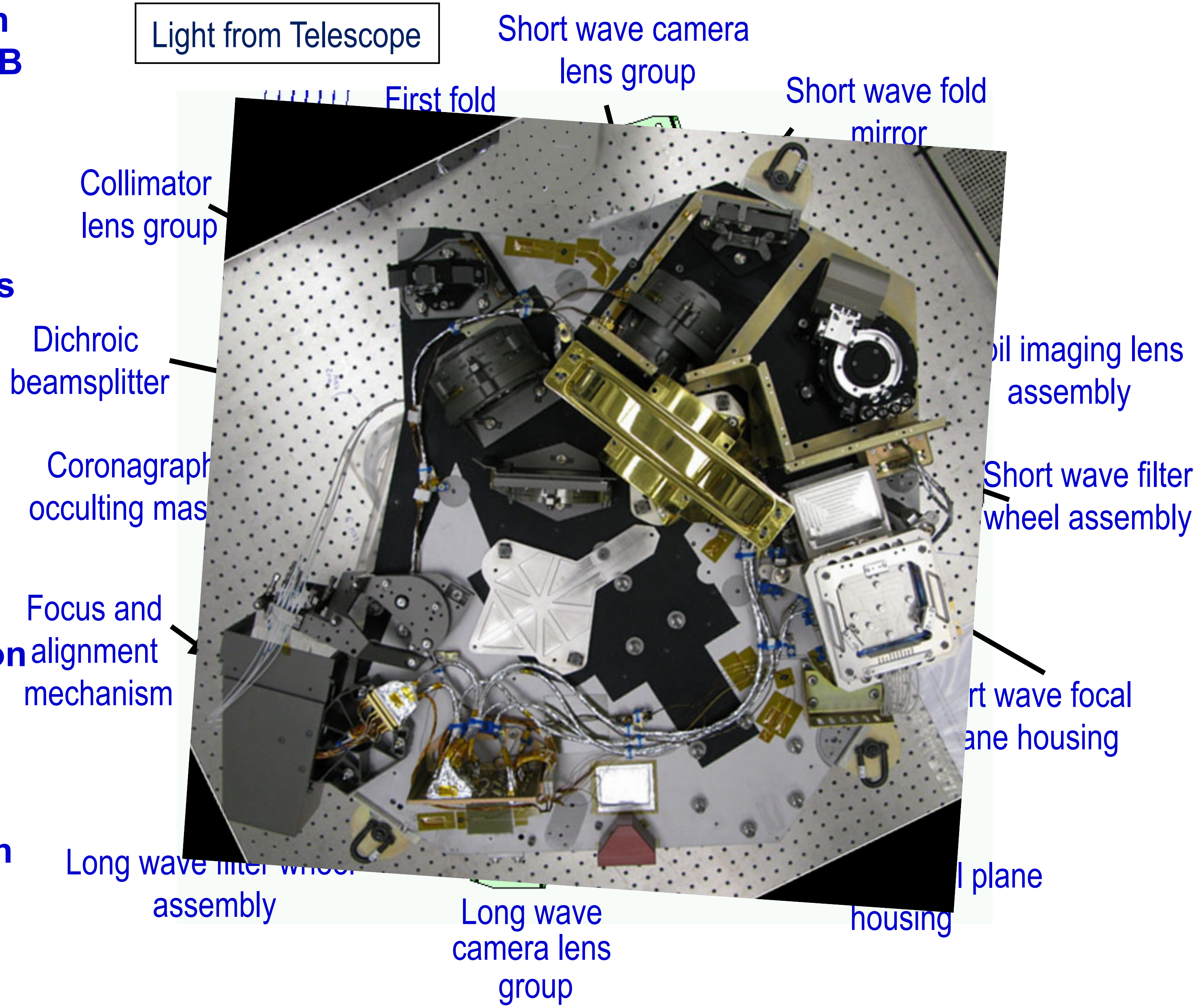
- NIRCam is the near-infrared camera (0.6-5 microns) for JWST
  - Refractive design to minimize mass and volume
  - Dichroic used to split range into short (0.6-2.3μm) and long (2.4-5μm) sections
  - Nyquist sampling at 2 and 4μm
  - 2.2 arc min x 4.4 arc min total field of view seen in two colors (40 MPixels)
  - Coronagraphic capability for both short and long wavelengths

NIRCam is the wavefront sensor

- Must be fully redundant
- Dual filter/pupil wheels to accommodate WFS hardware
- Pupil imaging lens to check optical alignment

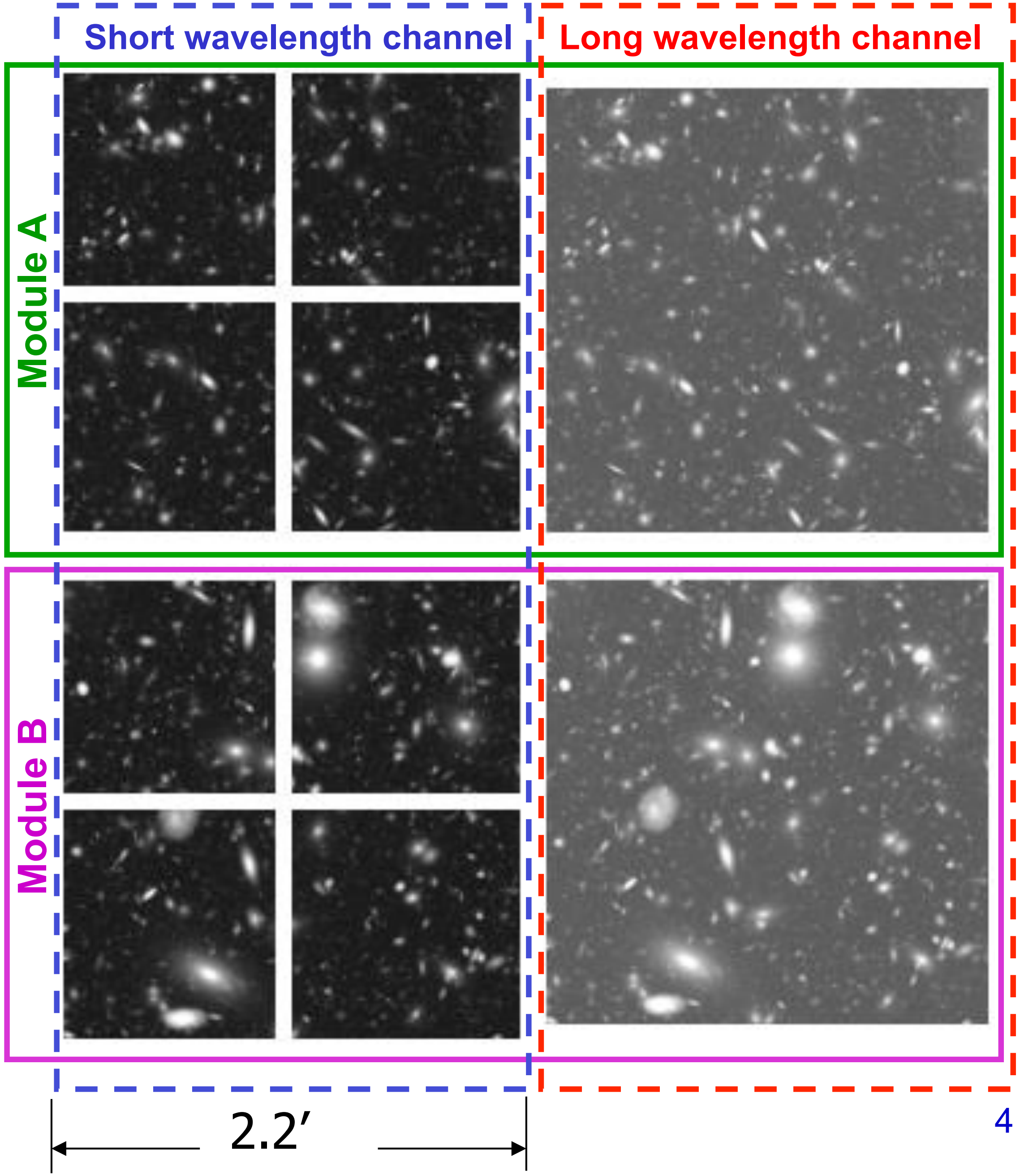
Design Overview

- **Fully redundant with mirror image A and B modules**
- **Refractive optical design**
- **Thermal design uses entire instrument as thermal ballast ; cooling straps attached to the benches**
- **SIDECAR ASICs digitize detector signals in cold region**
- **Uses two detector types – short wavelength HgCdTe and long wavelength HgCdTe (this one is same as used on NIRSpec & FGS)**

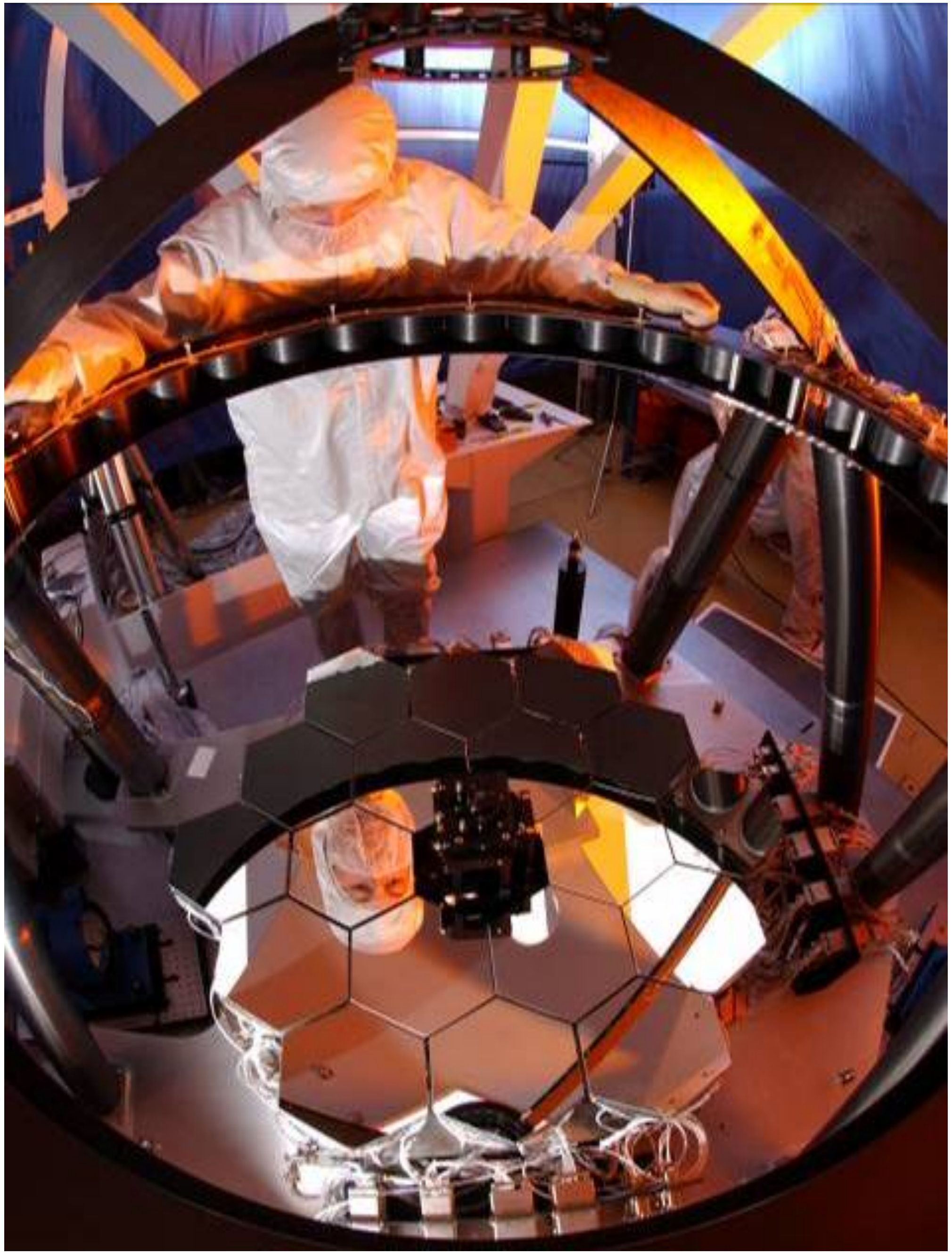


2 Channels Per Module

- Each module has two bands (0.6 microns to 2.3 microns and 2.4 microns to 5 microns)
  - Deep surveys will use ~7 wide band filters (4 SW, 3 LW, 2x time on longest filter)
  - Survey efficiency is increased by observing the same field at long and short wavelength simultaneously
- SW pixel scale is 0.032”/pix; long is 0.064”/pix



Wavefront Sensing and Control



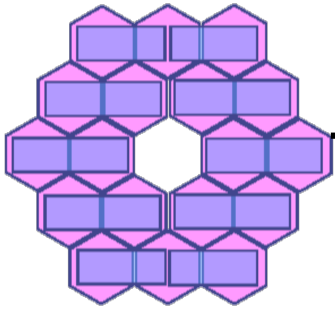
- Any telescope larger than ~3.8-meters must deploy on-orbit and hence needs an optical control system.
- Because most materials (and especially Be) have low coefficients of thermal expansion at 35K and because the L2 thermal environment is benign, wavefront updates should be needed only every two weeks.
- All steps in the process including initial capture and alignment have been tested.

The Testbed Telescope at Ball Aerospace – 1/6 scale model of JWST.

Initial Capture and Alignment

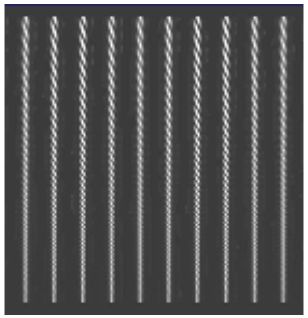
First Light

After segment capture

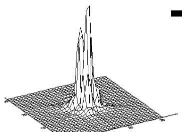


DHS at pupil

Coarse phasing w/DHS

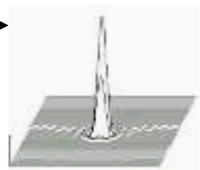


Spectra recorded by NIRCam



After coarse phasing

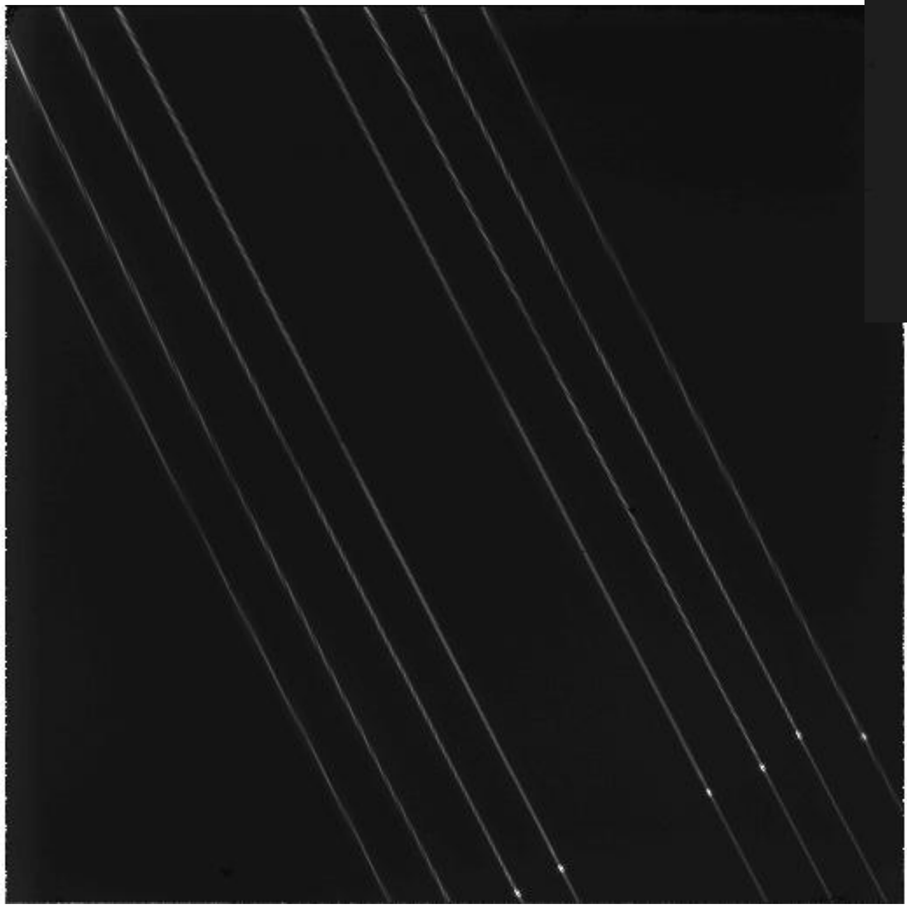
Fine phasing

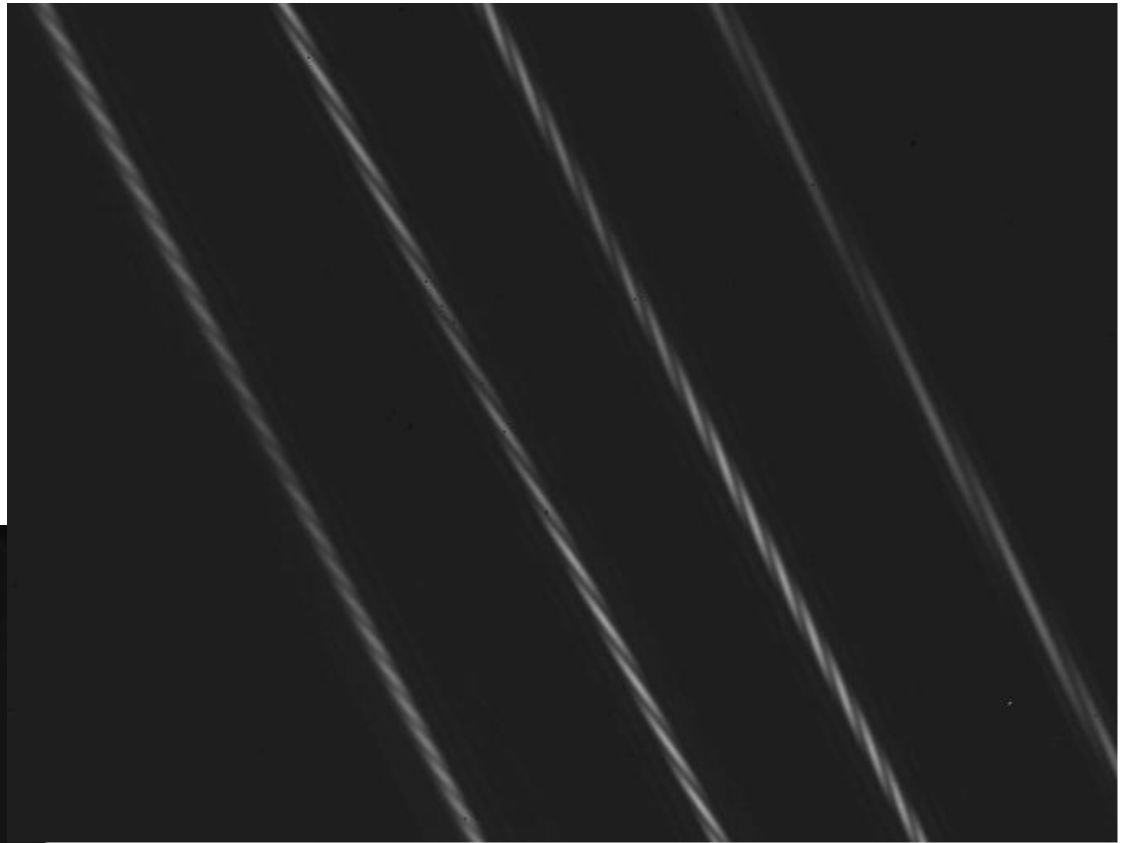


Fully aligned

- Telescope focus sweep
- Segment ID and Search
- Image array
- Global alignment
- Image stacking
- Coarse phasing
- Fine phasing uses in and out of focus images (similar to algorithms used for ground base adaptive optics)
- NIRCam provides the imaging data needed for wavefront sensing.
- Two grisms have been added to the long wavelength channel to extend the segment capture range during coarse phasing and to provide an alternative to the Dispersed Hartmann Sensor (DHS)

Real DHS Images taken with ETU NIRCam





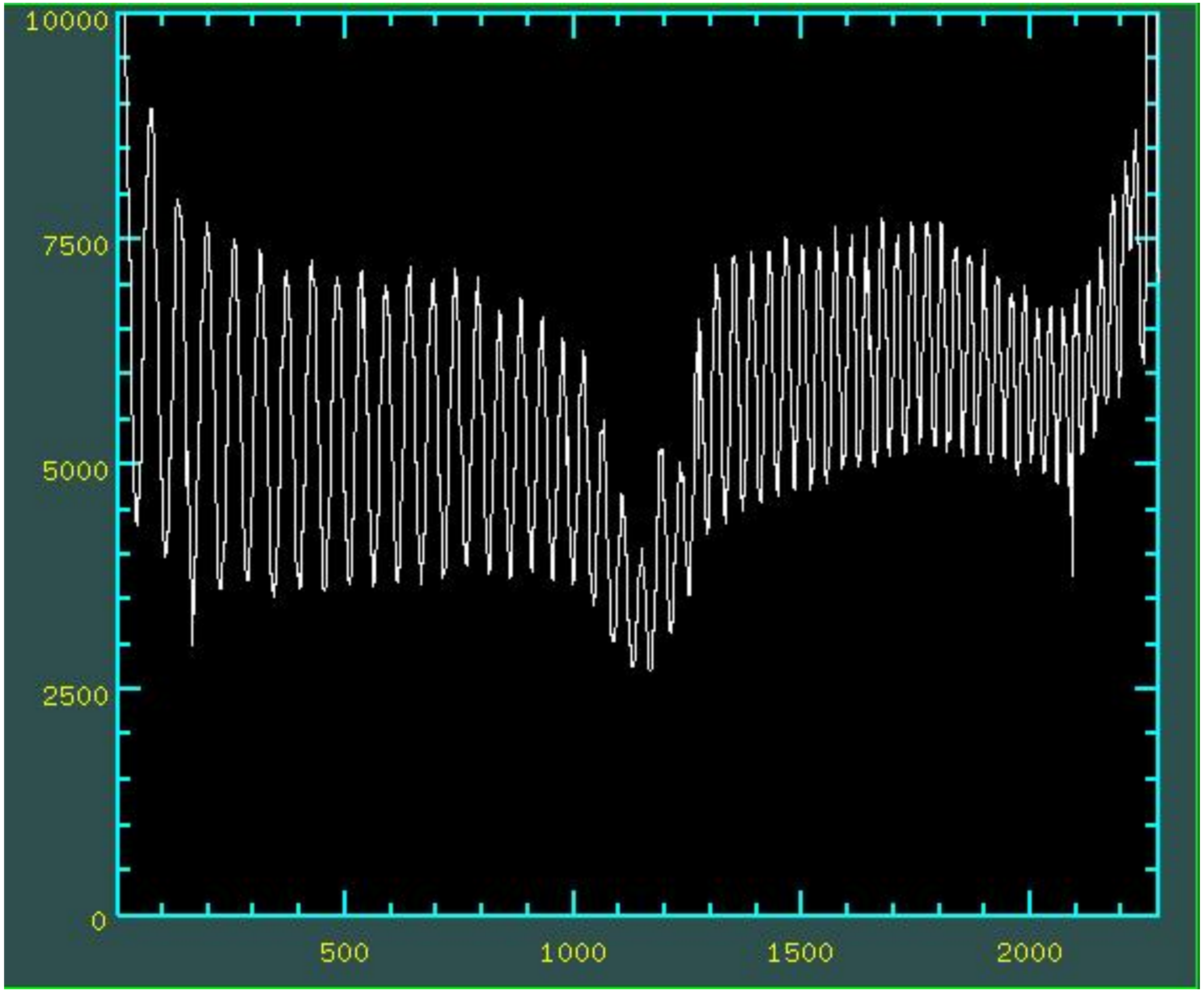
Detail from near the long wavelength end.

Bright spots are from emission lines in the super continuum source. The dimmed regions are due to OH in the fibers.

Crude DHS Spectral Extractions

Extraction of 3rd spectrum from left.

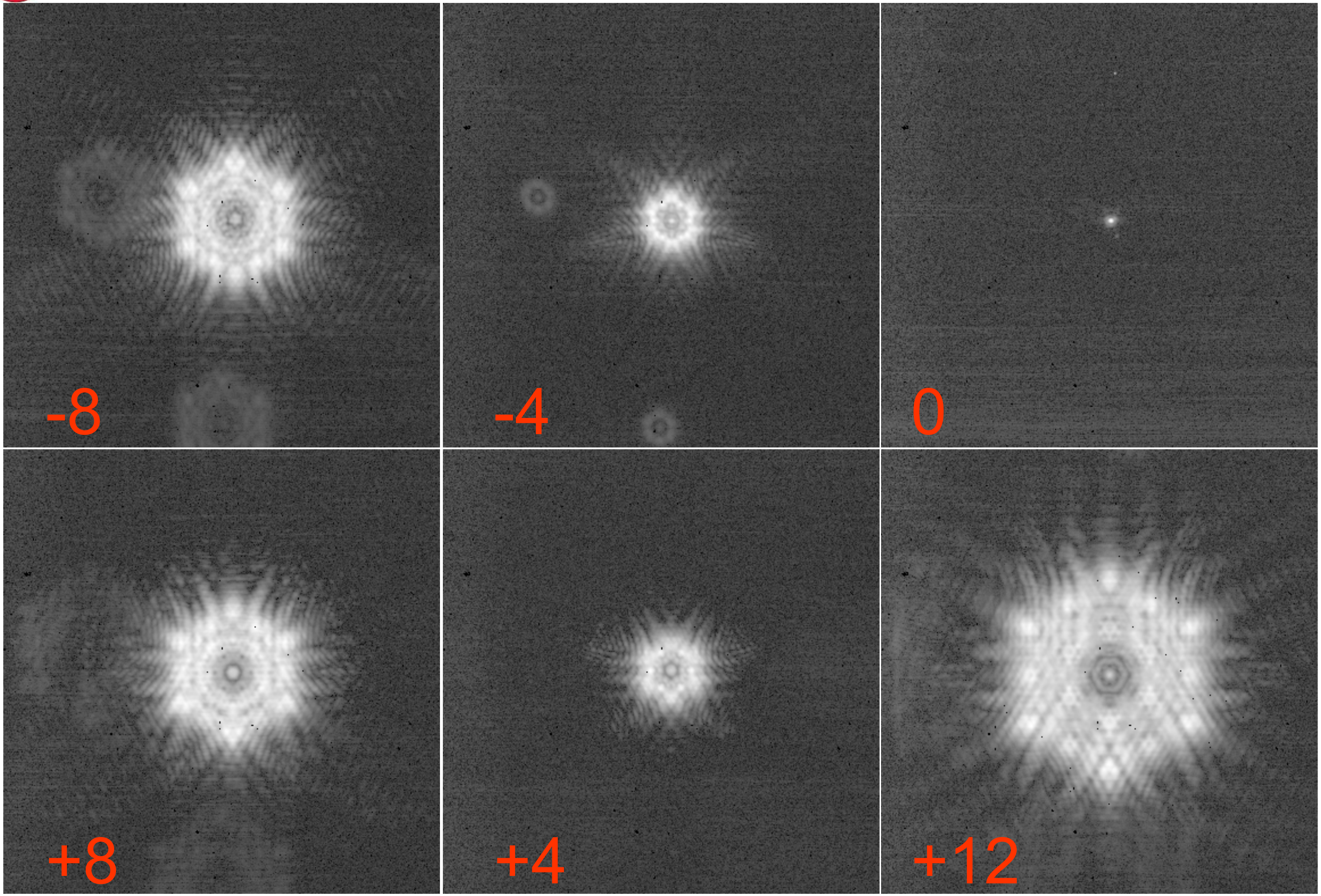
Intensity



Wavelength

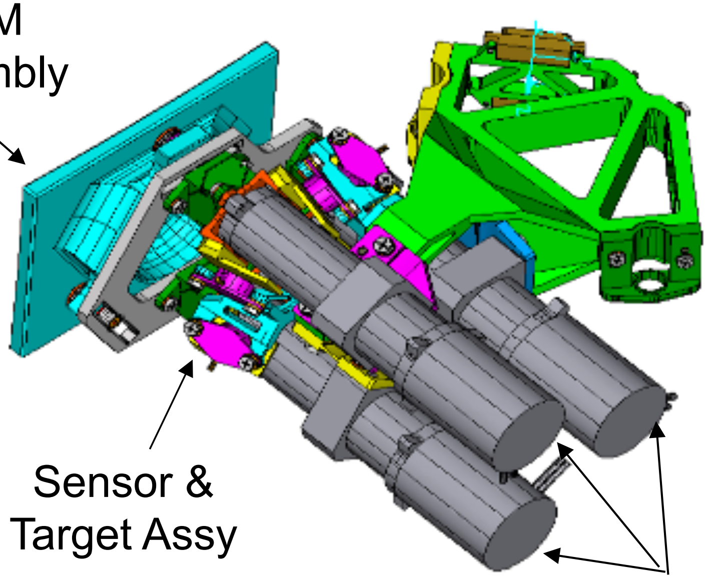
Frequency of "lines" can be analyzed to give the displacement between two mirror segments.

Fine Phasing Images from ETU



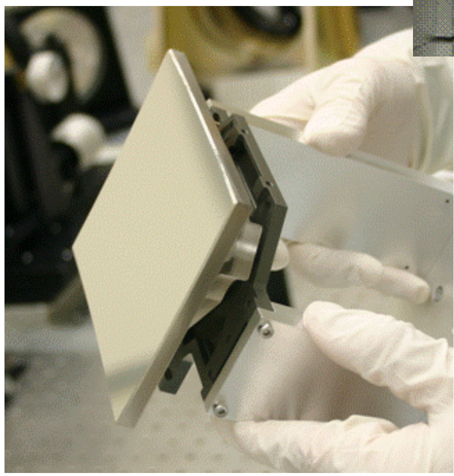
Following the Light: 1st Stop is the FAM

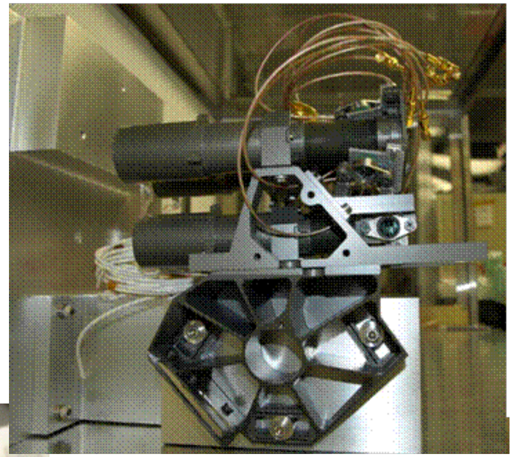
- FAM = Focus Adjust Mechanism
- Pick-off mirror (POM) is attached to the FAM; POM has some optical power to ensure that the pupil location does not move when FAM is moved
- Ensures correct mapping of NIRCam pupil onto telescope exit pupil



Prototype

↓ POM

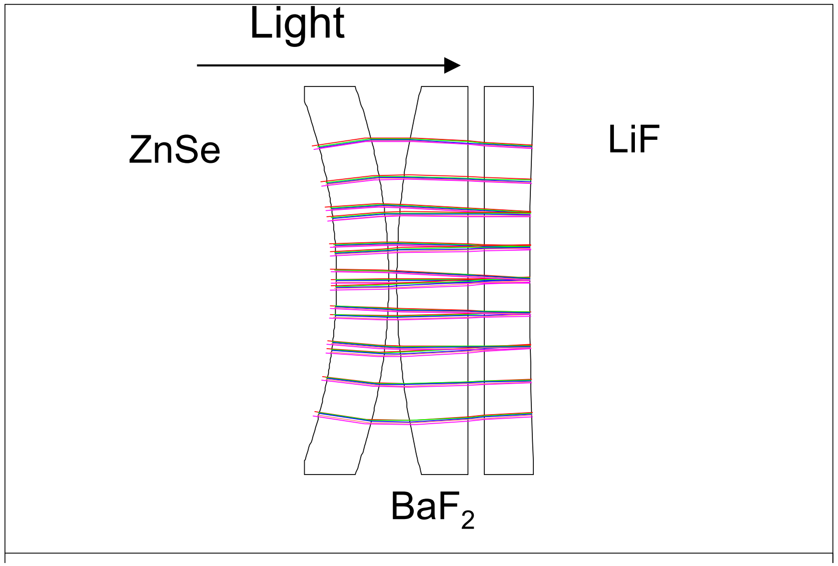


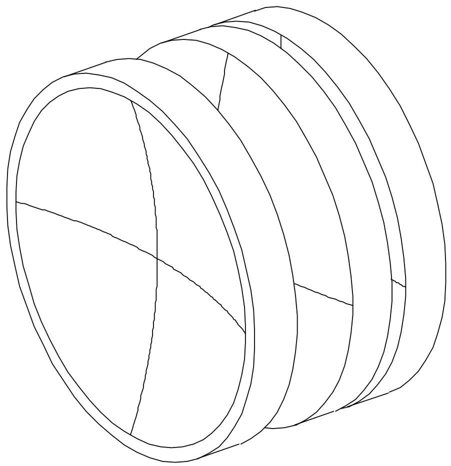


↑ ETU FAM being prepped for connector installation.

Following the Light: 2nd Stop is the Collimator

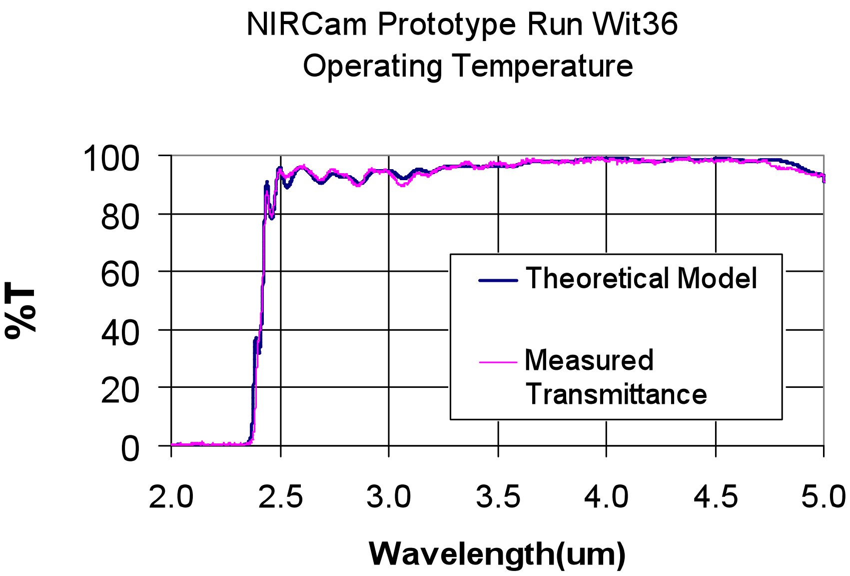
- Transmits over entire 0.6 – 5.0 micron band
- Most of the optical power is in the ZnSe lens with the other two largely providing color correction
- Excellent AR coatings available

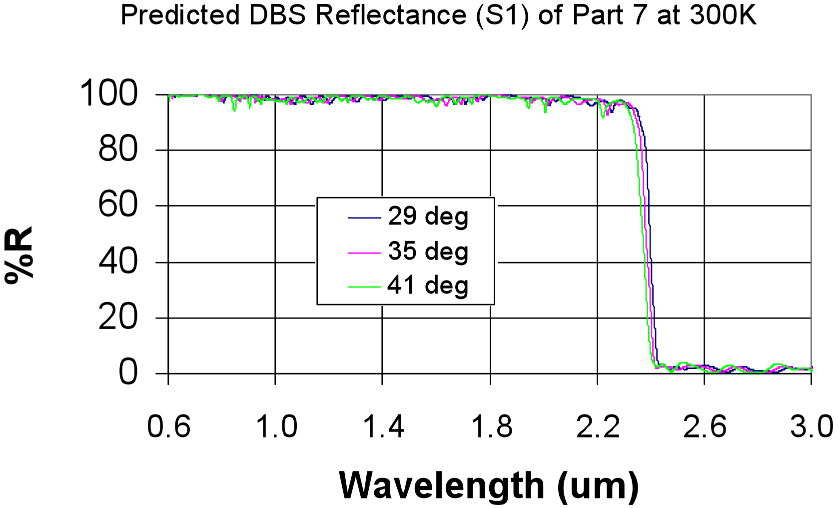


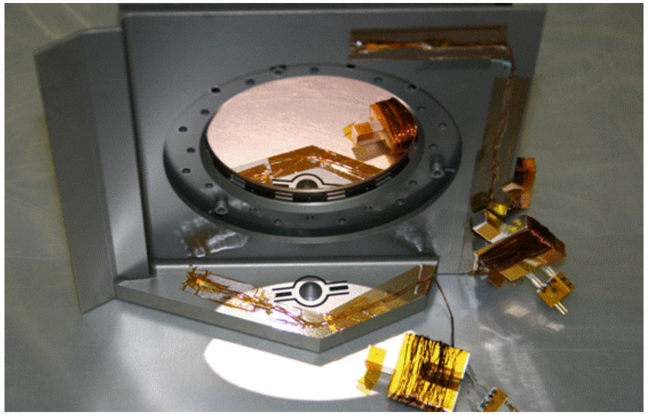


Following the Light: 3rd Stop is the Beam Splitter

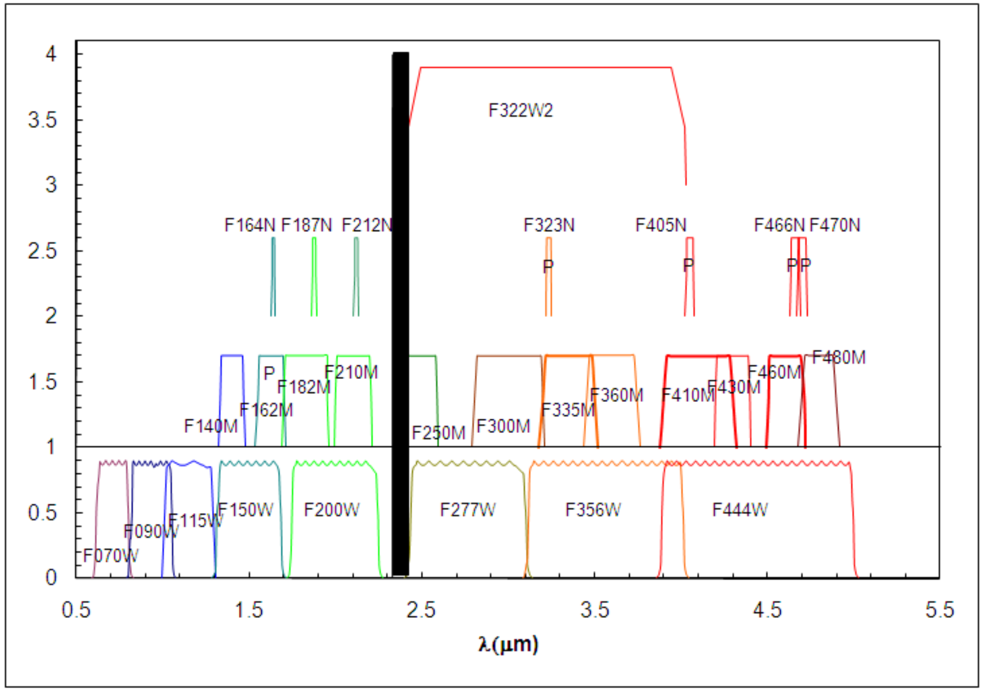
- LW beam is transmitted, SW beam is reflected
  - DBS made of Si which greatly reduces problems with short wavelength filter leaks in LW arm
- Coatings have excellent performance







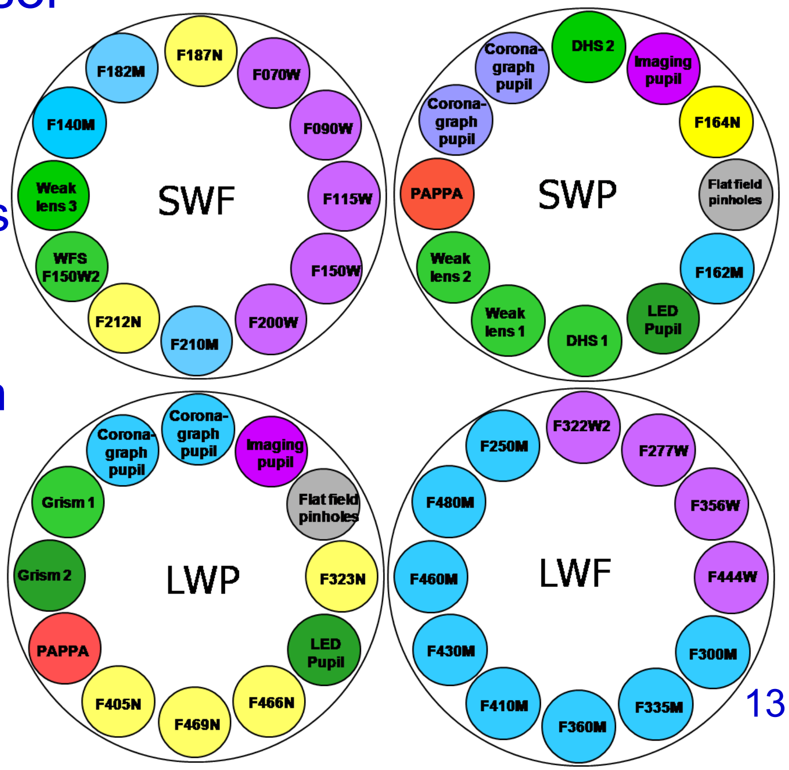
Following the Light: 4th Stop is the Filter Wheel Assembly (FWA)



- Dual wheel assembly has a pupil wheel and a filter wheel, twelve positions each, in a back-to-back arrangement
- Filters are held at 4 degree angle to minimize ghosting
- Wheels are essential for wavefront sensing as they carry the weak lenses and the dispersed Hartmann sensor

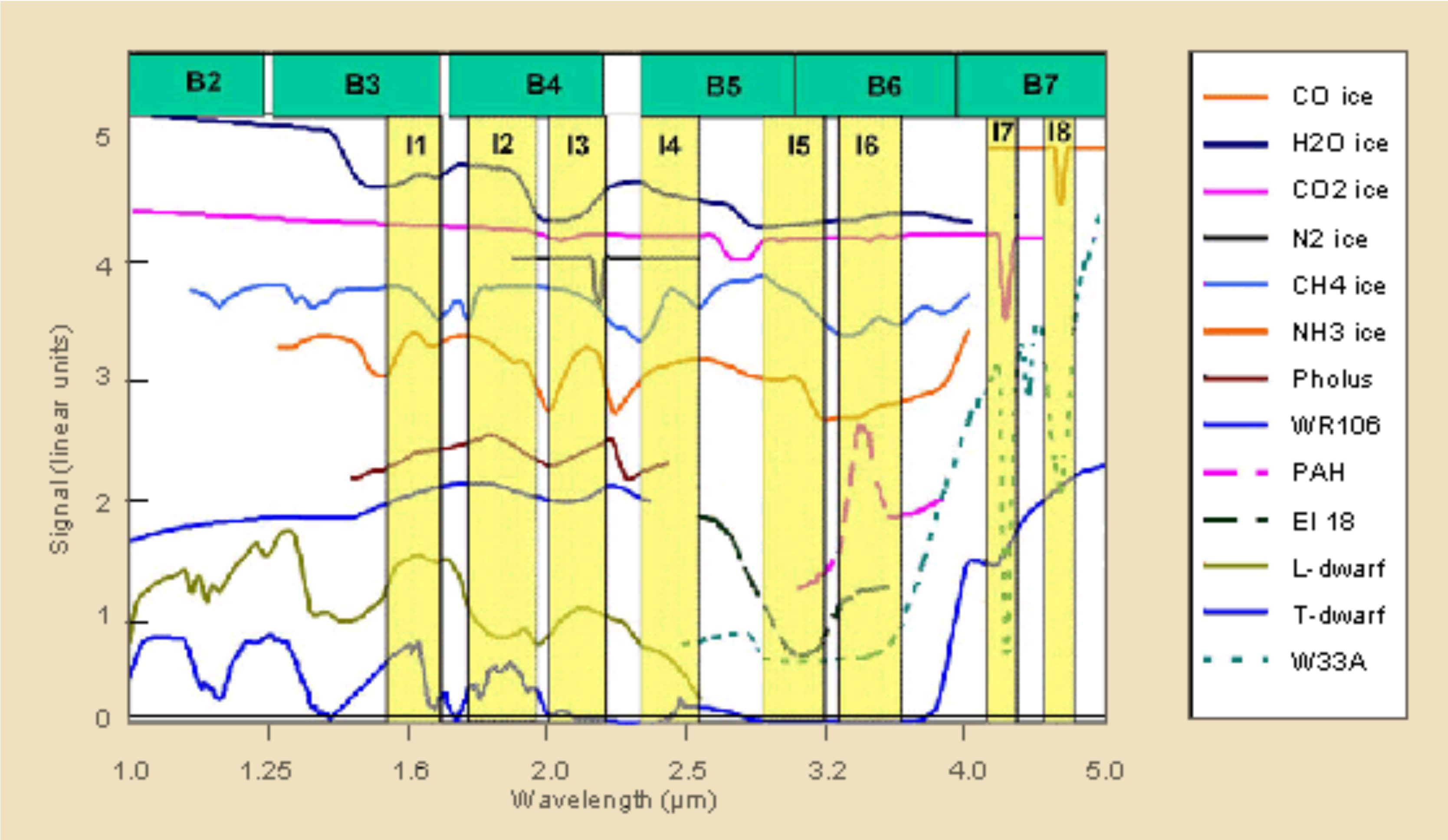
Filters have names indicating wavelength (100x microns) and width (**W**ide, **M**edium, or **N**arrow)

ETU FWA



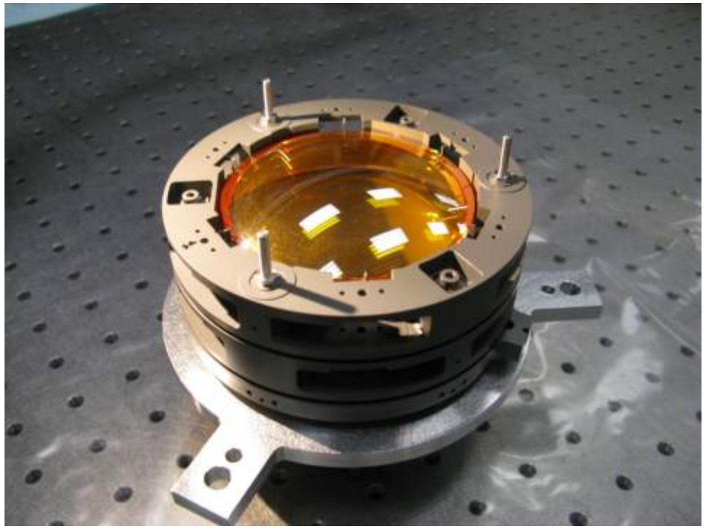
Medium & Narrow Filters Isolate Spectral Features

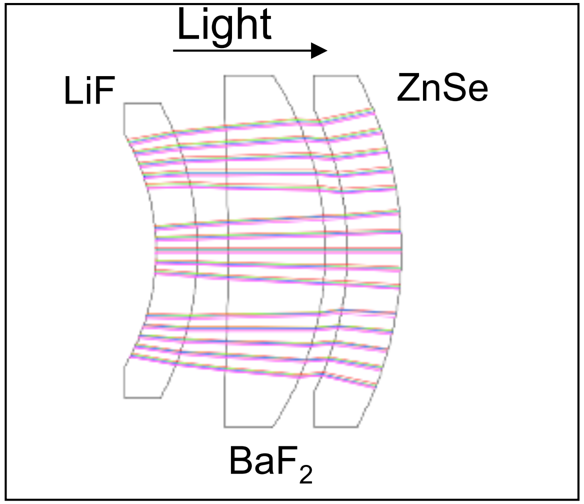
"M" filters useful for distinguishing ices, brown dwarfs.



Following the Light: 6th Stop is the Camera Triplet

- Camera triplets come in two flavors for the two arms of NIRCam
- Using same AR coatings as on collimator because they give good performance and it is cheaper to use the same coatings everywhere



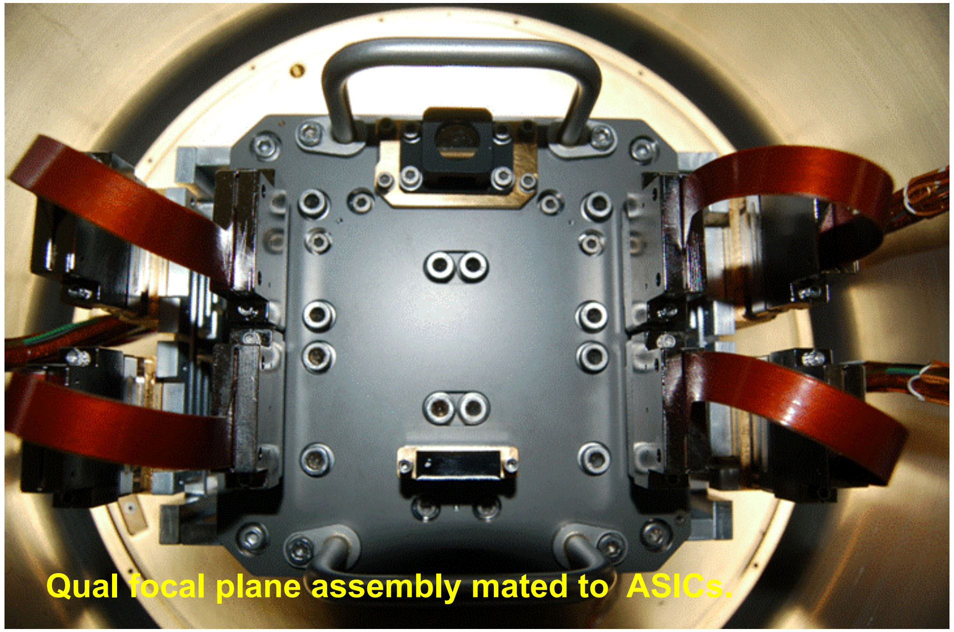


Operates over SW 0.6 – 2.3 microns

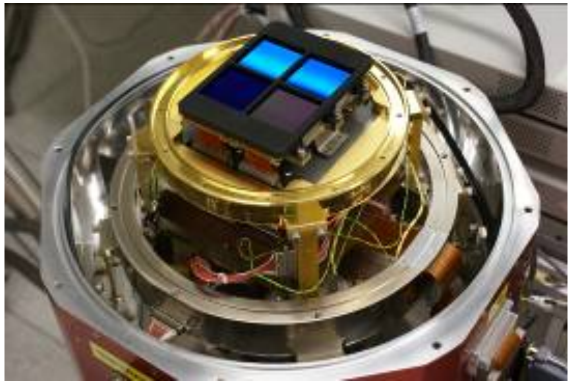
Operates over LW 2.4 – 5.0 microns

Following the Light: Last Stop is the Focal Plane Assembly (FPA)

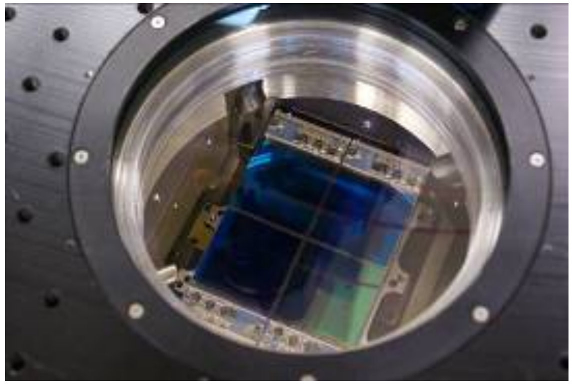
- NIRCam has two types of detectors: 2.5-μm cutoff and 5-μm cutoff HgCdTe (5-μm same as NIRSpec, FGS)
- Basic performance is excellent with read noise ~7 e- in 1000 secs, dark current < 0.01 e/sec, and QE > 80%
- Other performance factors such as latent images and linearity are excellent



Qual focal plane assembly mated to ASICs.

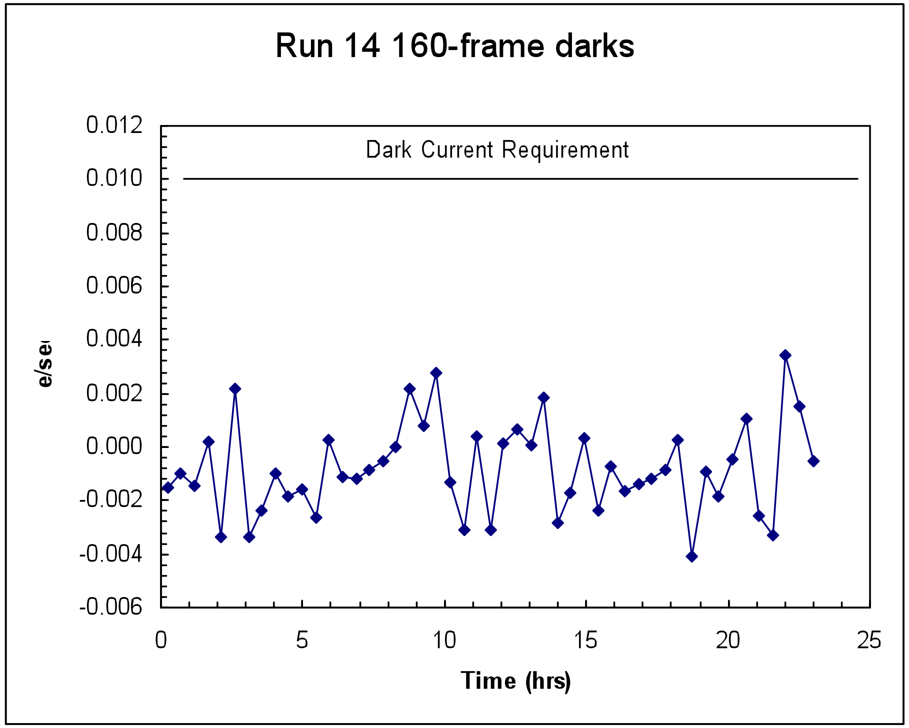


Qual SW FPA being readied for performance tests.

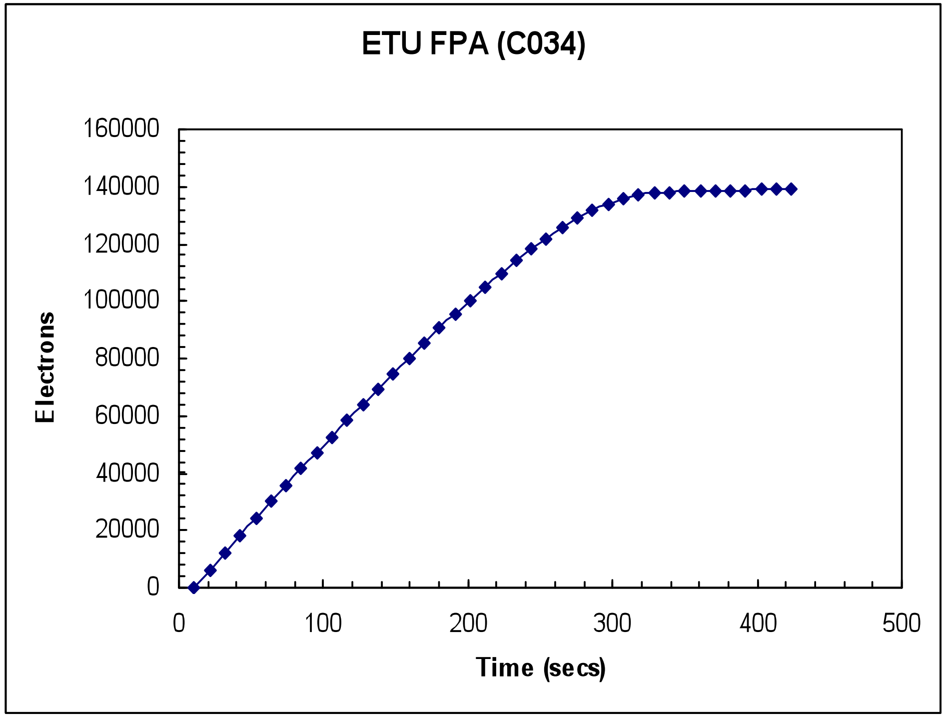


Qual SW FPA in the cryo metrology dewar.

ETU FPA Test Results



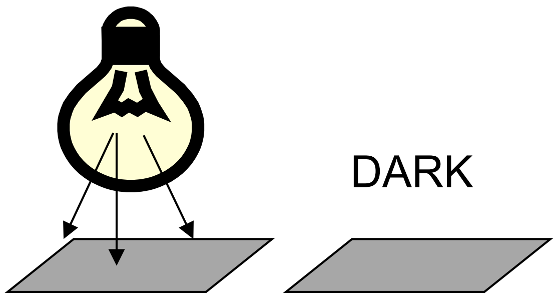
ETU FPA Dark Current (one SCA only)



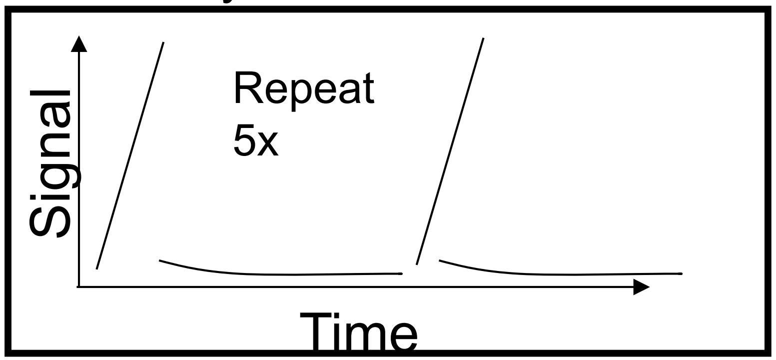
ETU FPA Linearity – Pixel 1432, 432

Latent Testing of Qual FPA

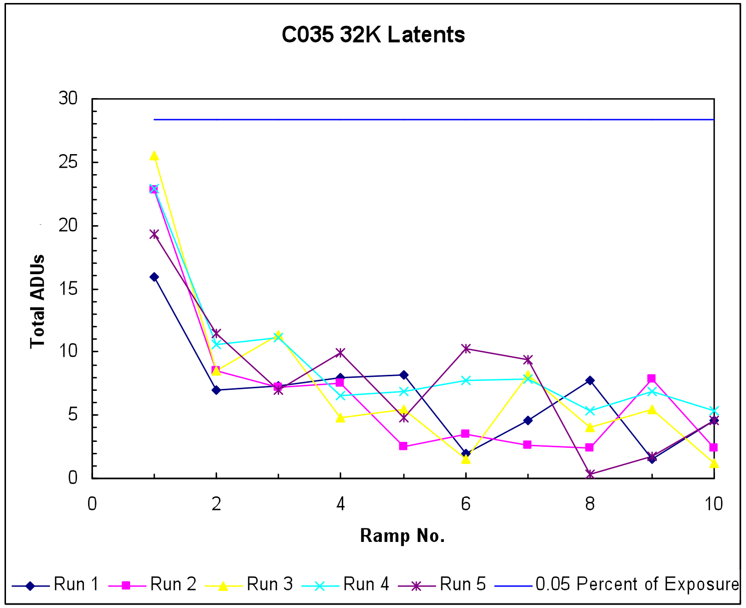
- All IR arrays suffer from latent images after exposure to light
- An issue for NIRCam because there will be an over-exposed star in every long exposure

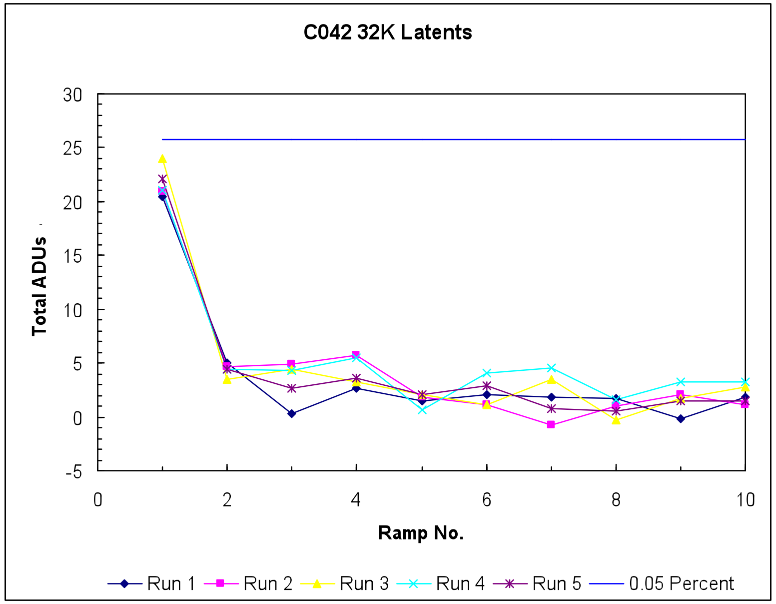


Illuminate strongly, remove illumination, reset, read non-destructively.



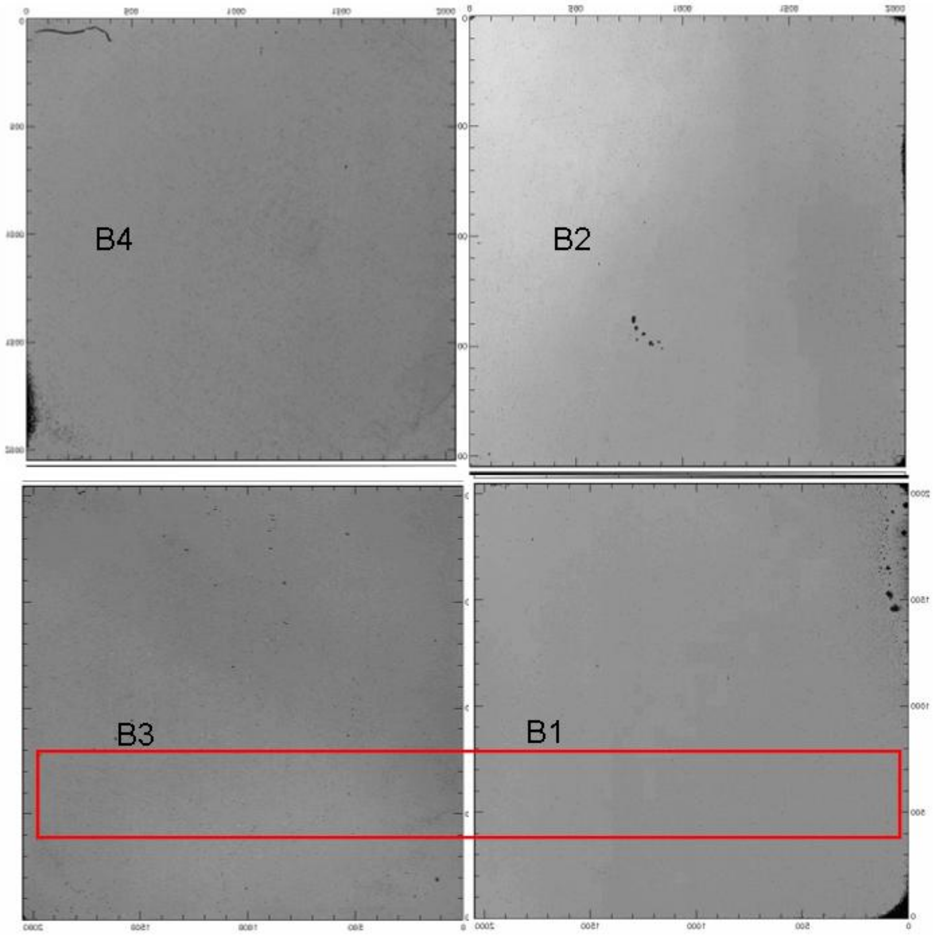
1 ADU = 4 e-



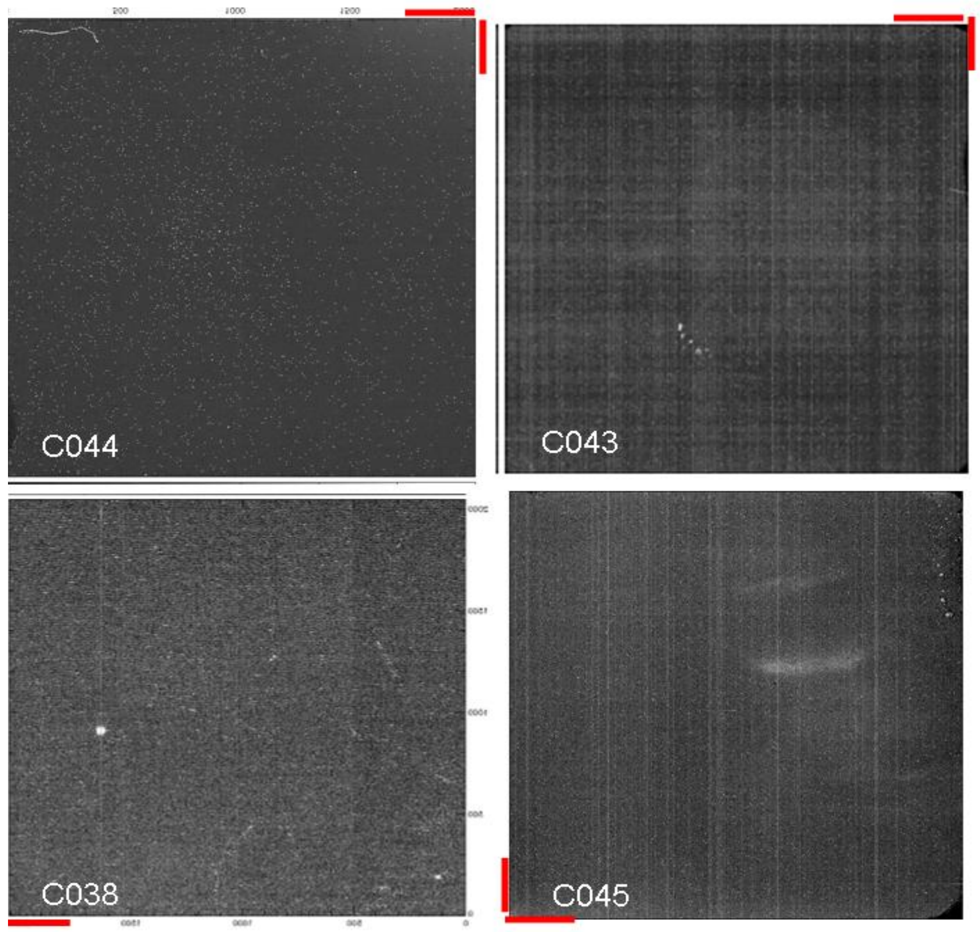


Flight FPA #1 Arrangement

Illuminated

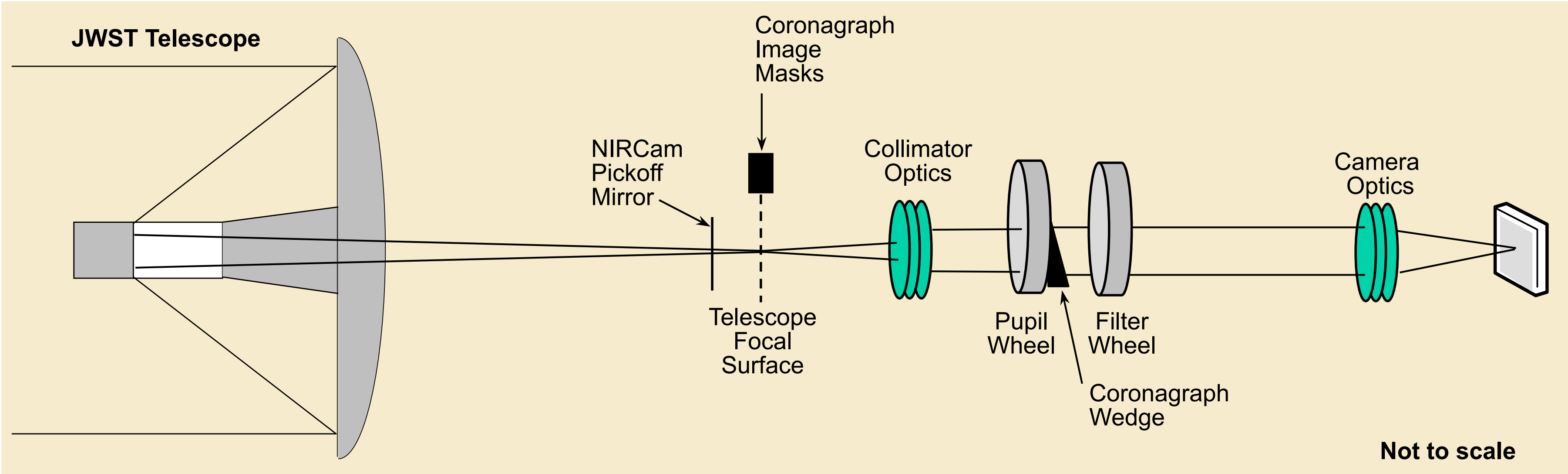


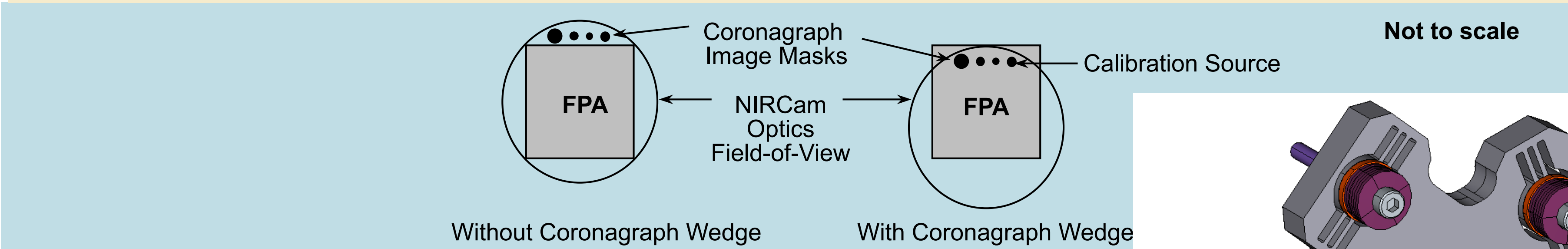
Dark



Following the Light: Optional Coronagraph

- Both SW and LW arms have coronagraphs, no extra moving parts
- No performance requirements imposed on coronagraph

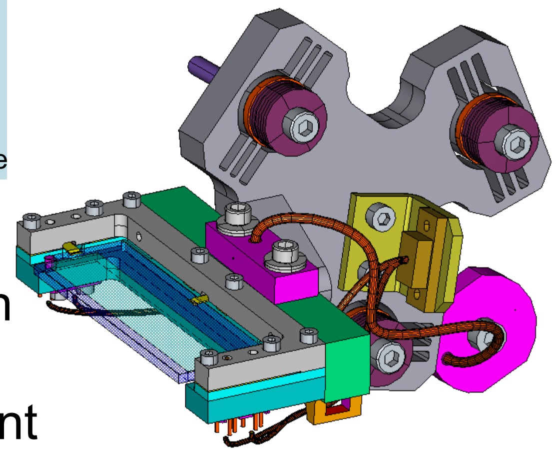




BaF_2 wedge

Sapphire mask substrate

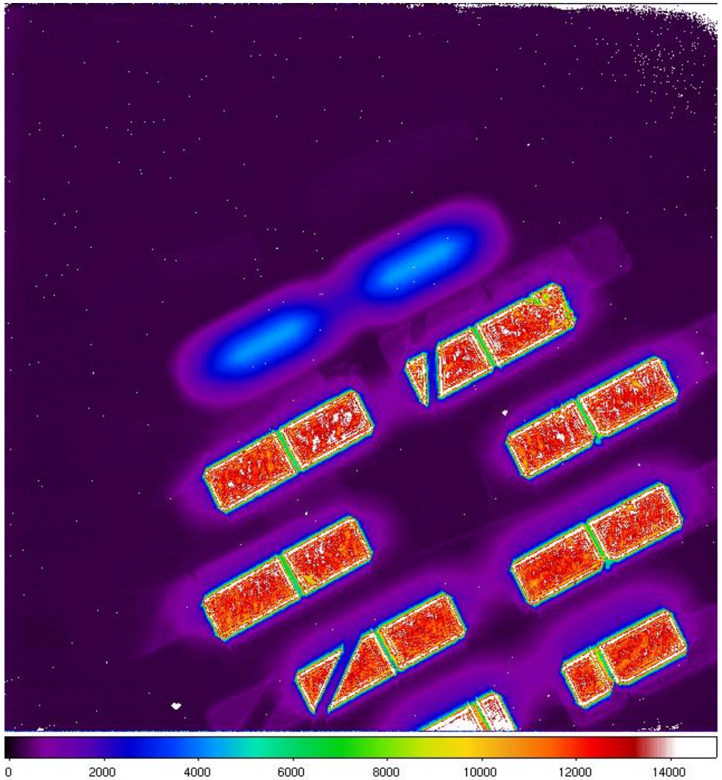
Mask with bench attachment



Following the Light: Optional Stop at the Pupil Imaging Lens (PIL)

- A pupil imaging lens was added to NIRCam SW arm at the request of the WFS Team, also helps ensure that the science imaging is not vignetted
- Mechanism has a strong spring to pull the lens out of the beam if necessary; rotary motor is the same type as is used in the filter wheel

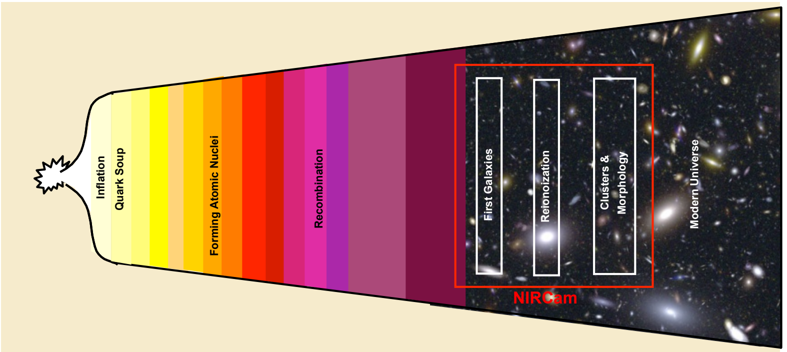
ETU PIL image of DHS.



Bench Holds it all Together

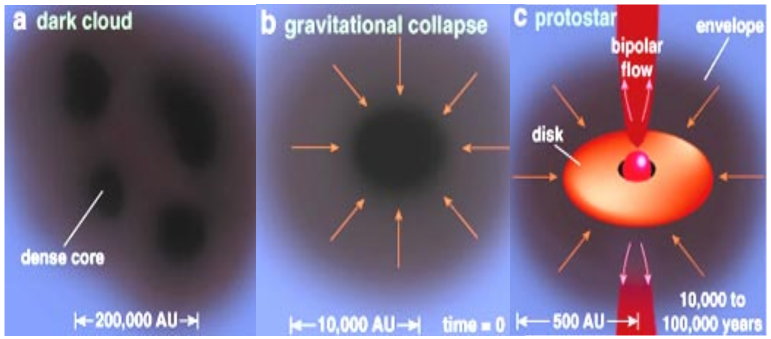
ETU bench with mass simulators ready for vibration testing.

NIRCam's Role in JWST's Science Themes



The First Light in the Universe:
Discovering the first galaxies, Reionization
NIRCam executes deep surveys to find and categorize objects.

Period of Galaxy Assembly:
Establishing the Hubble sequence, Growth of galaxy clusters
NIRCam provides details on shapes and colors of galaxies, identifies young clusters

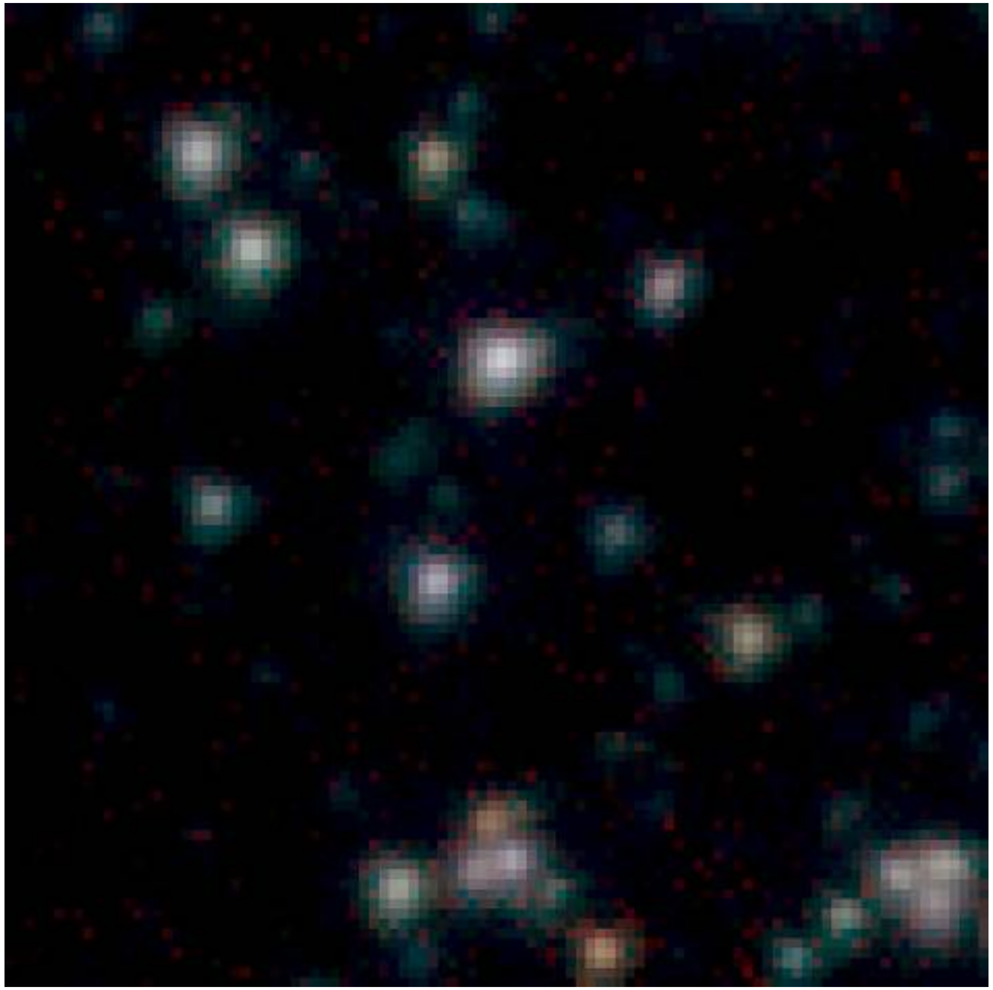


Stars and Stellar Systems: Physics of the IMF, Structure of pre-stellar cores, Emerging from the dust cocoon
NIRCam measures colors and numbers of stars in clusters, measure extinction profiles in dense clouds

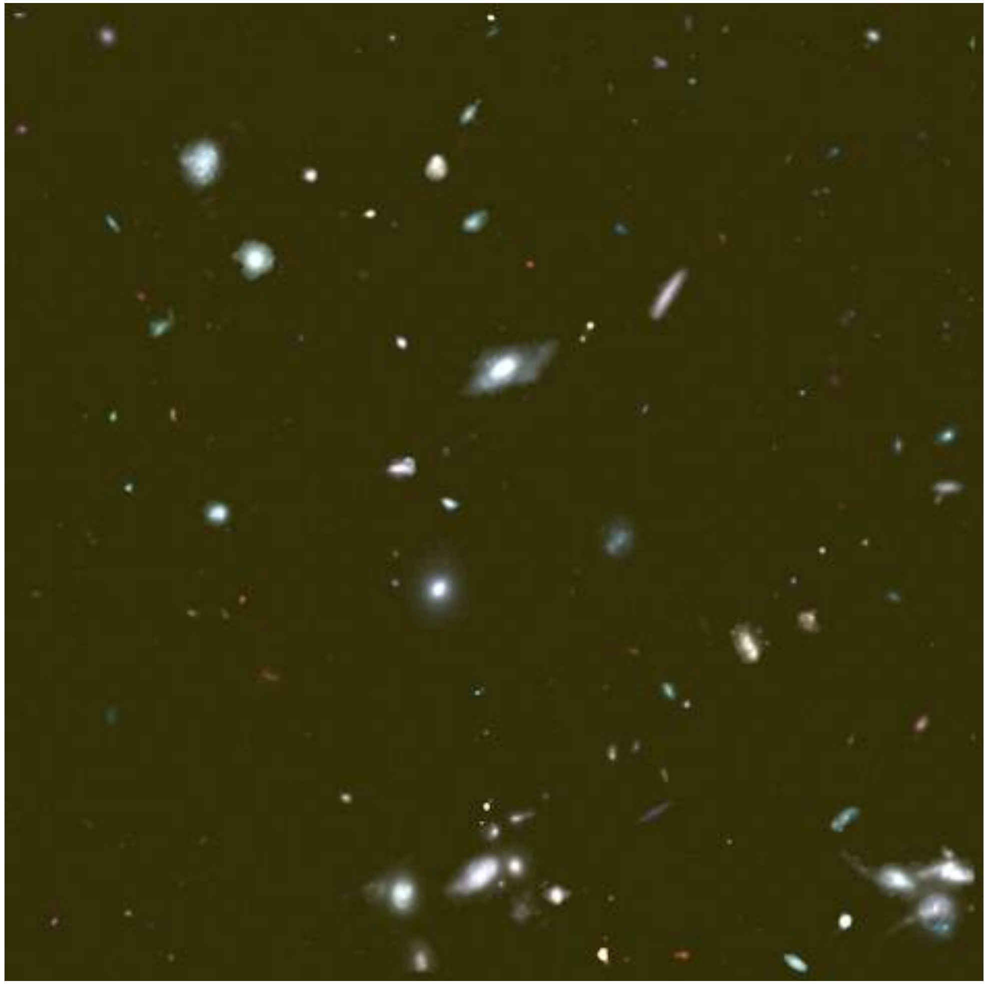
Planetary Systems and the Conditions for Life: Disks from birth to maturity, Survey of KBOs, Planets around nearby stars
NIRCam and its coronagraph image and characterize disks and planets, classifies surface properties of KBOs

JWST-Spitzer Image Comparison

1'x1' region in the UDF – 3.5 to 5.8 μm



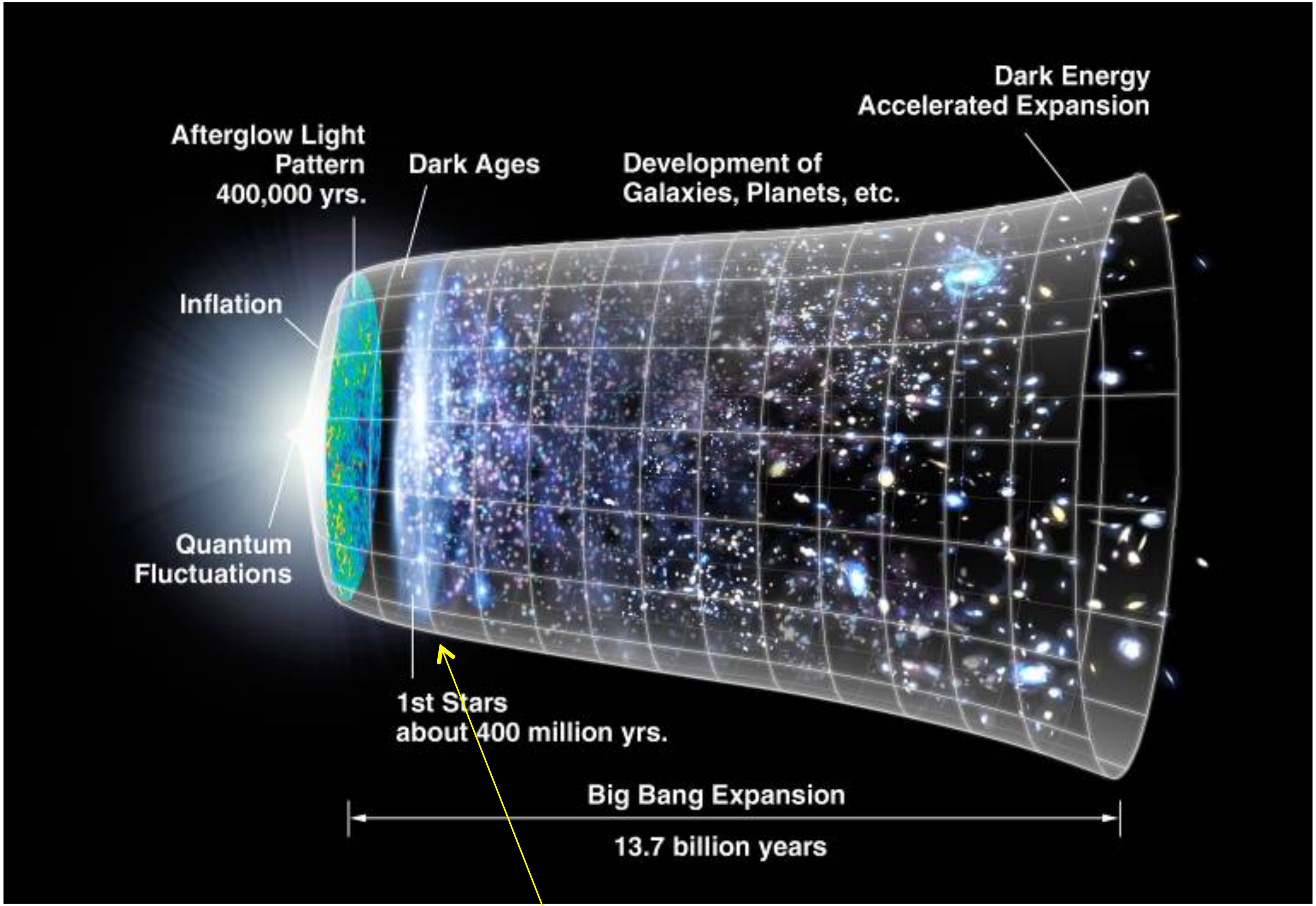
Spitzer, 25 hour per band
(GOODS collaboration)



JWST, 1000s per band (simulated)

Courtesy of M. Stiavelli

Schematic of Galaxy Development



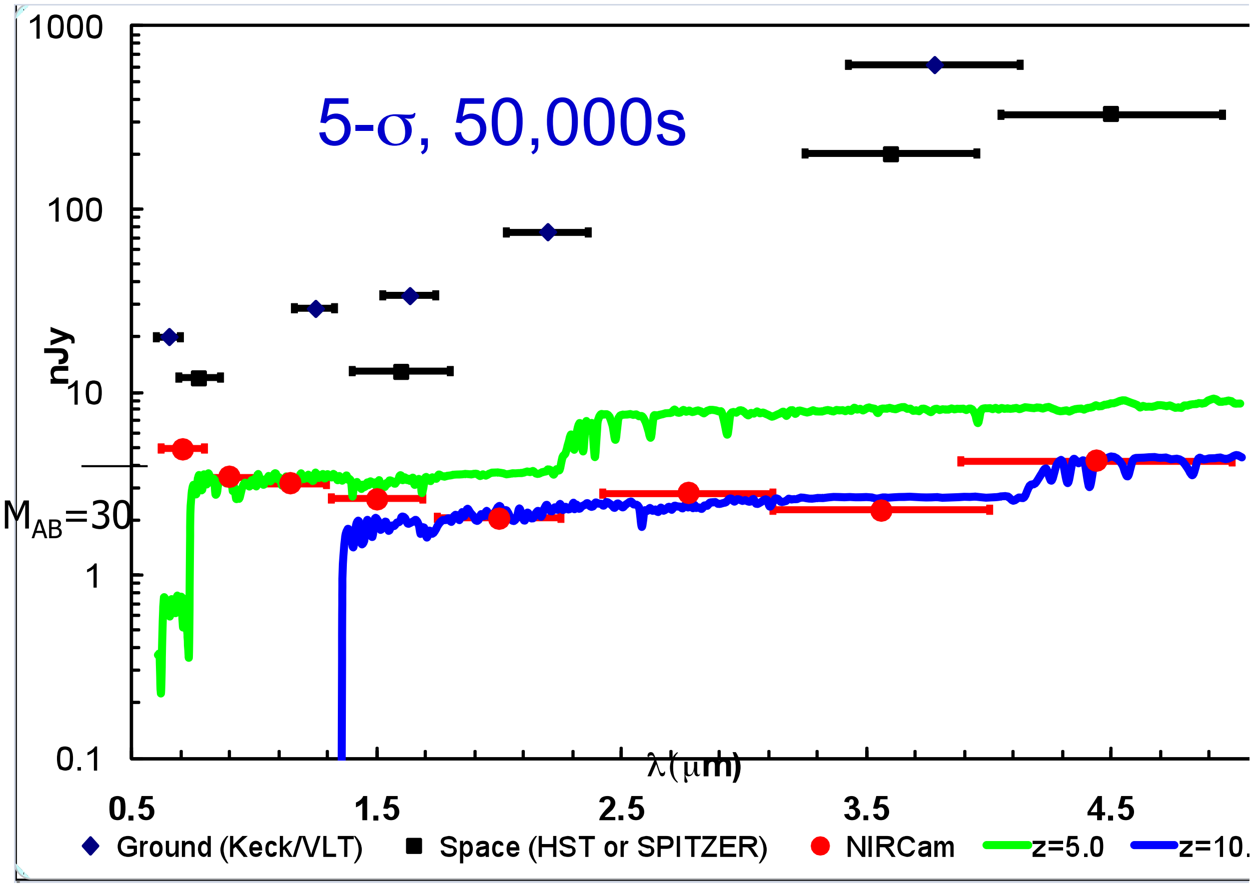
JWST's Prime Targets

How to Search for “First Light”?

- When did the first objects form – what redshift range should be searched?
- What are the characteristics of the first sources?
  - Which were most important: black holes or stars?
  - Should we base our assumptions on Super Star Clusters or dwarf galaxies or ….
  - Will the distribution of stellar types be different?
  - What will be most detectable?

High Sensitivity is Paramount

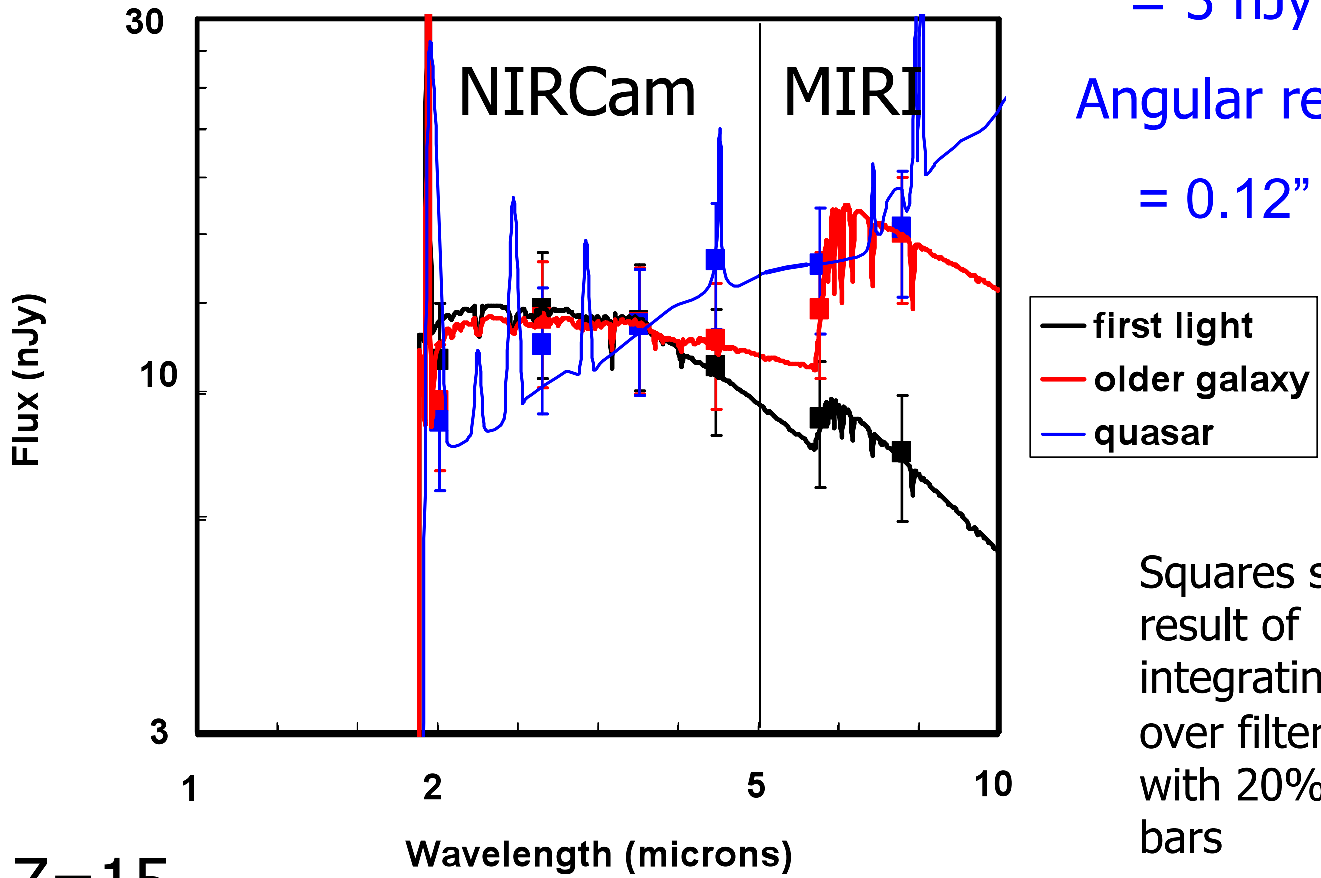
- NIRCam sensitivity is crucial for detecting "first light" objects
- At 3-5μm, NIRCam can detect objects 100x fainter than Spitzer opening up new survey possibilities



The z=10 galaxy has a mass of $4 \times 10^8 M_{Sun}$ while the mass of the z=5 galaxy is $4 \times 10^9 M_{Sun}$.

Above assumes 50,000 sec/filter with 2x time on longest wavelength

NIRCam & MIRI Provide Robust Discriminators



Z=15

Sensitivity:

5-σ in 50,000 sec

= 3 nJy at 3.6μm.

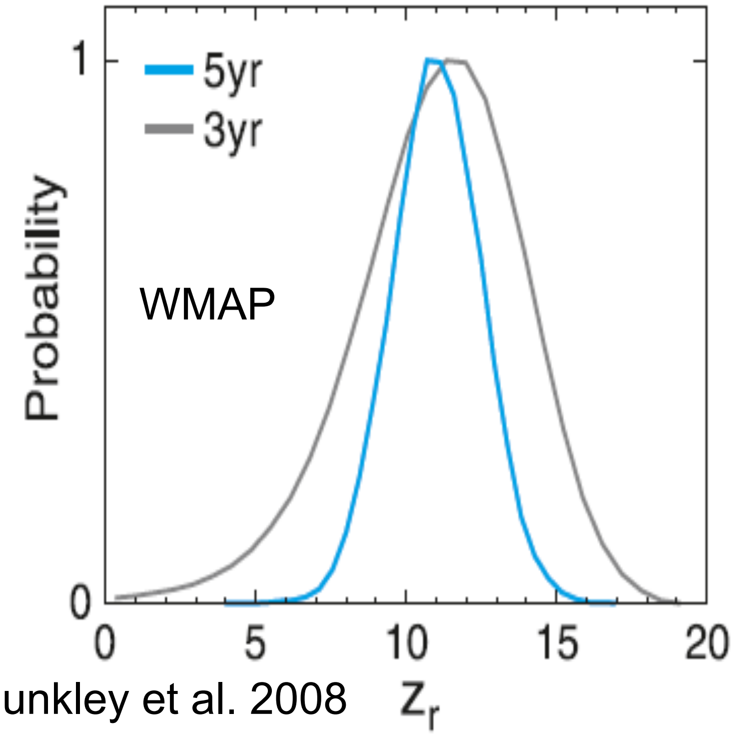
Angular resolution

= 0.12” at 4μm.

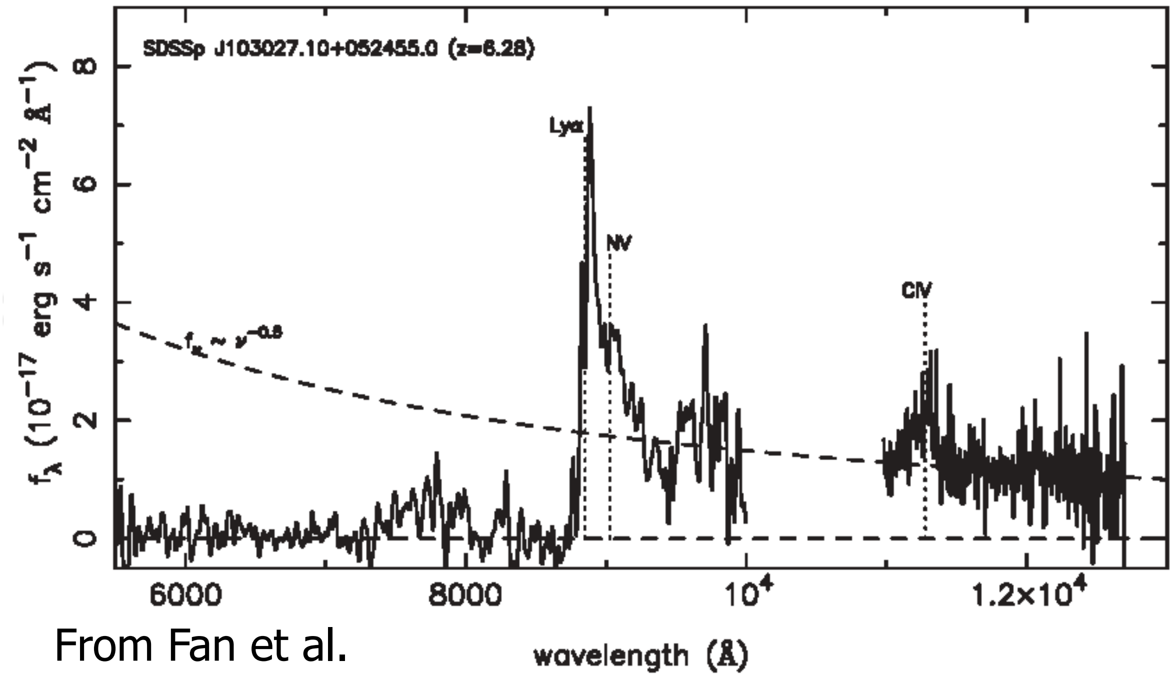
Squares show result of integrating over filters with 20% error bars

WMAP & QSO Results

- Year 5 WMAP release has reduced the uncertainties in the electron optical depth so the epoch of reionization is constrained to z~11.0 ± 1.4, equivalent to ~350Myr after Big Bang.
- Spectra of SDSS z~6 QSOs show hints that Universe was reionized at only somewhat higher z than 6.5.
- Need to search from z~7 to z~15



Dunkley et al. 2008

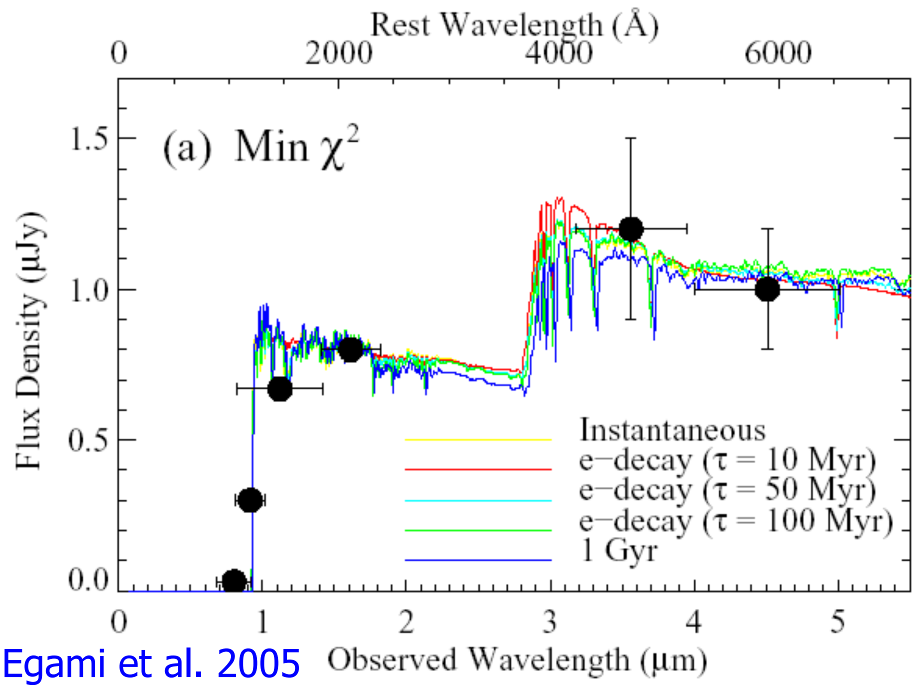


From Fan et al.

Spitzer Contributions

- The star formation rate as a function of z is much better known.
- Stellar mass assembly rate can be characterized for the first time.
- Spitzer is showing us that galaxies at z~7 formed stars as much as 200-400 million years earlier (around z~10)

➔ Epoch of first star formation now seem likely to have been around z~10-15 from combining Spitzer and WMAP results.

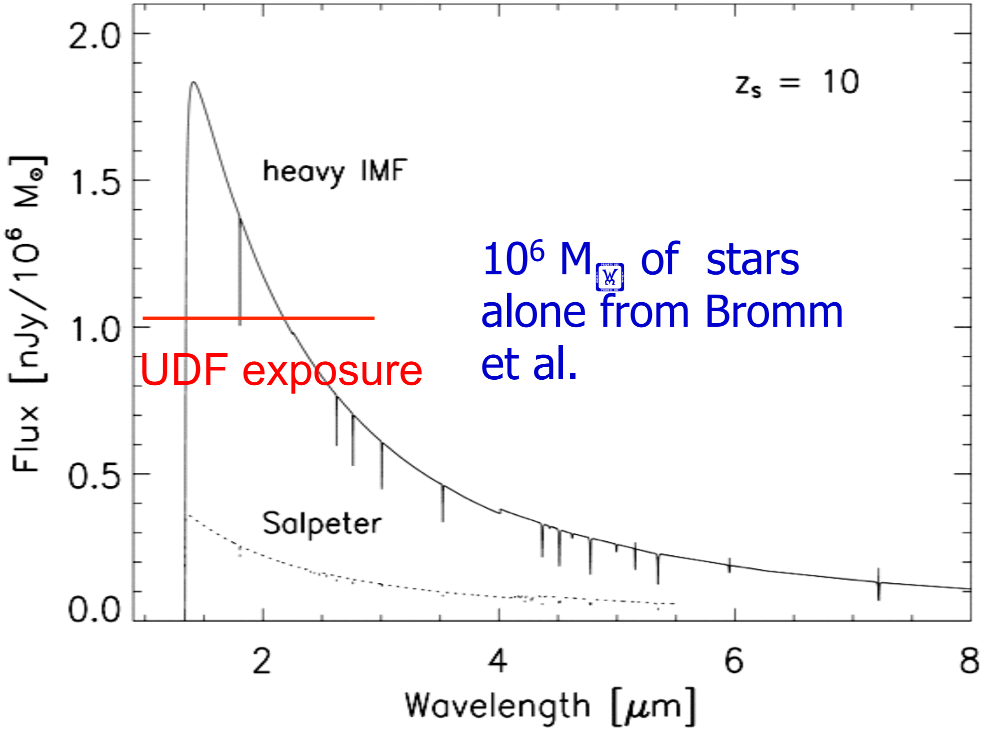


Egami et al. 2005

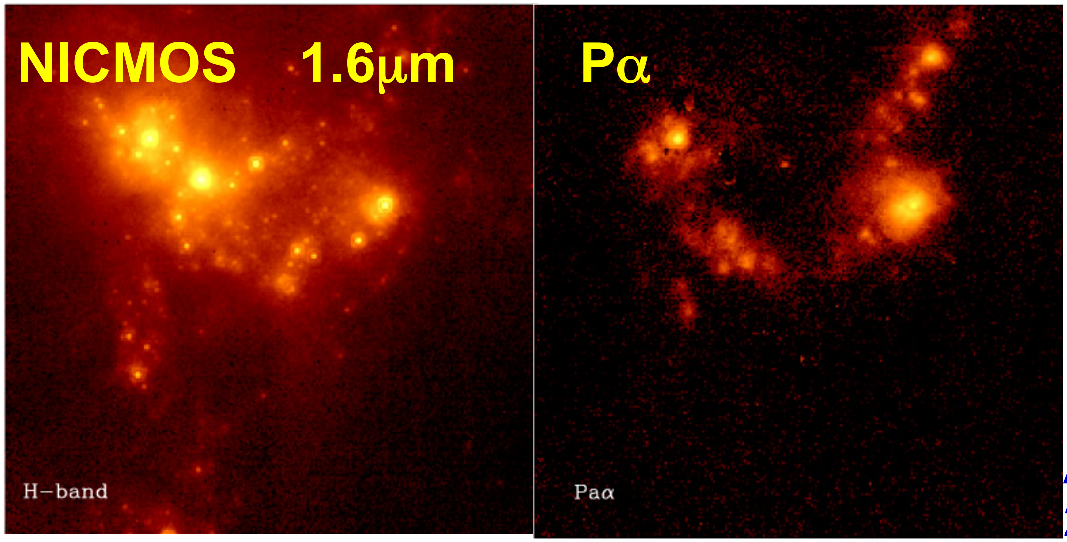
Imagine such a galaxy at 2x the redshift => z~14
- roles of NICMOS and IRAC correspond to NIRCam and MIRI on JWST.

Important to note that a number of similar galaxies have now been found by many observers

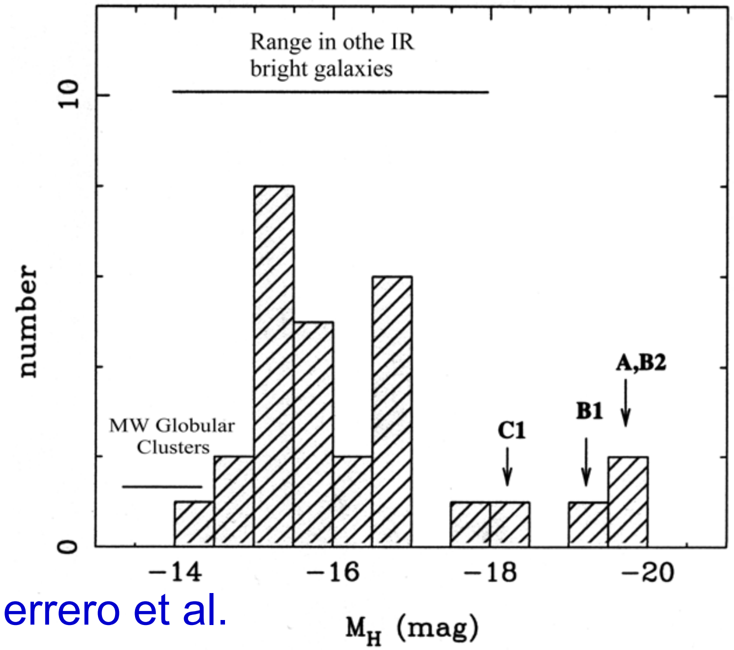
Super Star Clusters Good First Light Candidates



Super star clusters analogous to what's been found in galaxies like the Antennae or Arp 299 would be detectable at z=10 – larger clusters with M=10^7 $M_\odot$ will be readily detectable in a deep survey which spends 14 hours/filter.

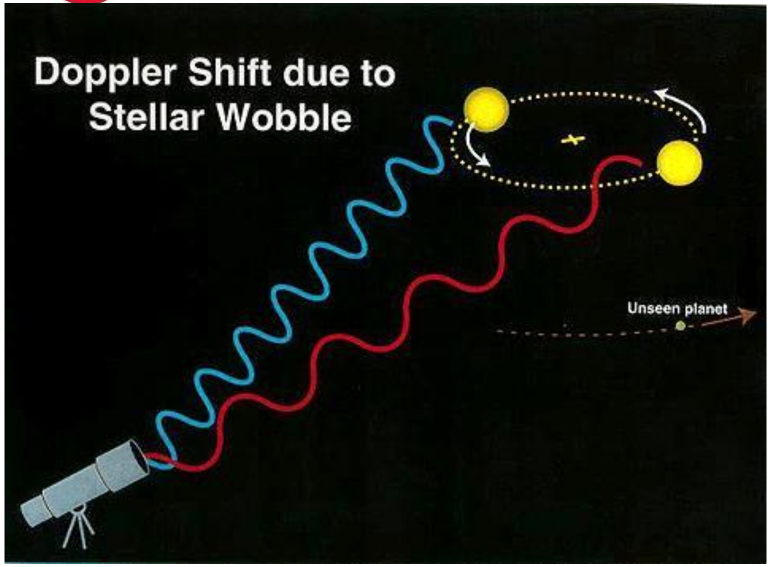


NGC 3690 =Arp 299



Alonso-Herrero et al. 2000

How to Find Planets Around Other Stars



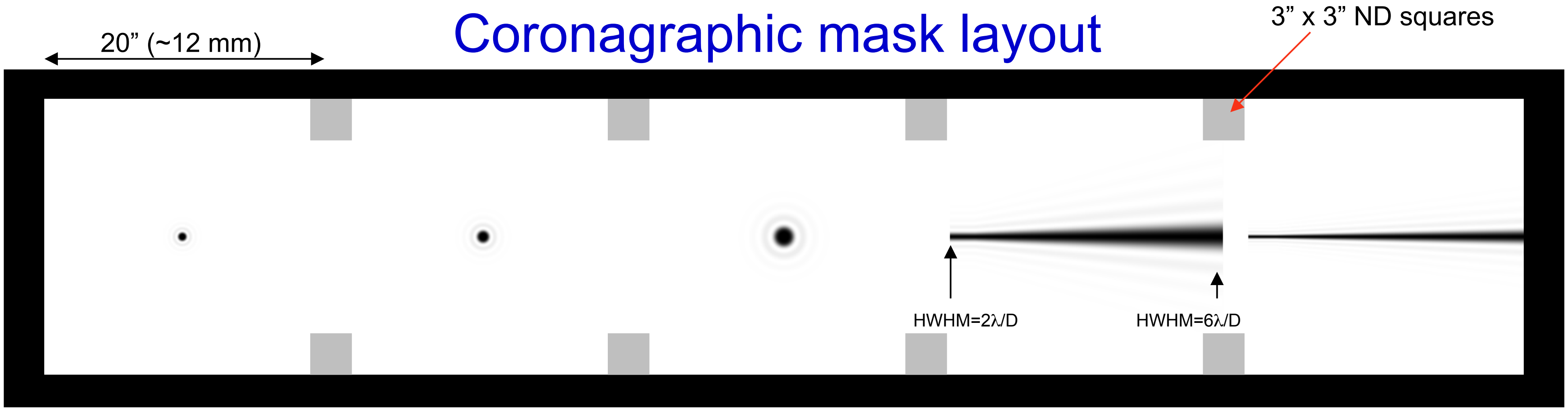
JWST will be effective at direct imaging and at transit spectroscopy.

- **By direct imaging – take a picture and see one!**
  - **Hard because planets are dim**
- By looking for varying Doppler shifts in a star's spectrum
  - Relatively easy
- **By looking for varying light output from a star due to transits (eclipses) by a planet**
  - **Not as easy as Doppler shifts but can yield more information**
- By looking for variations in a star's position
  - Very hard, mostly superceded by Doppler shifts
- By looking for gravitational lensing events
  - Relatively easy but yields only statistical information about planets

NIRCam Coronagraphy: Direct Imaging

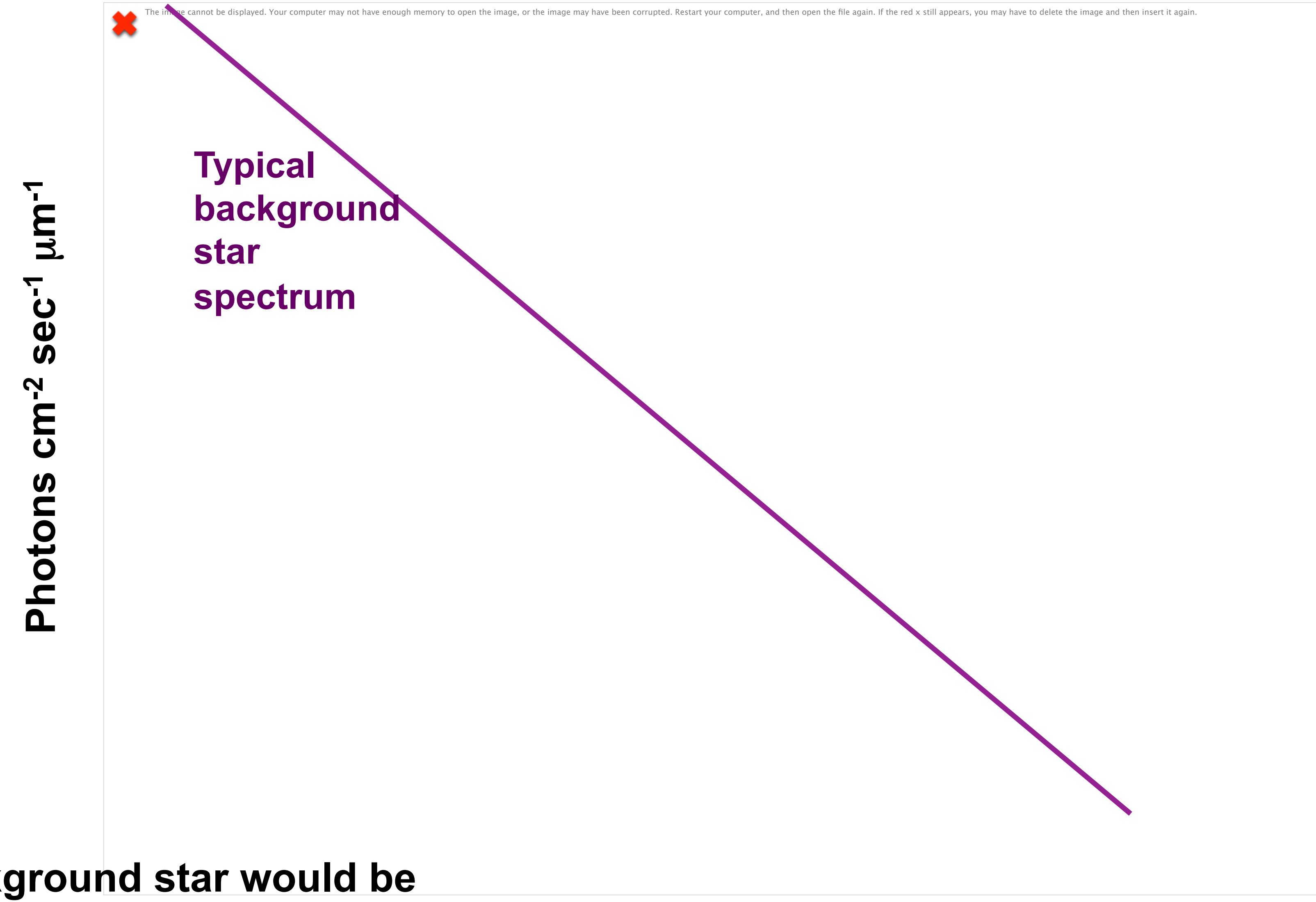
- Direct imaging using coronagraphy
  - Optimized for $\lambda \approx 4.5$ μm imaging
- Acquire star on one of the neutral density squares and then move behind the coronagraphic mask
- Diffraction from JWST's primary mirror segments will limit sensitivity but Jupiter-sized objects should be detectable.

Coronagraphic mask layout



FWHM = 0.40"	**FWHM = 0.64"**	**FWHM = 0.82"**	**$FWHM_c$ = 0.58"**	**$FWHM_c$ = 0.27"**
(6λ/D @ 2.1 μm)	**(6λ/D @ 3.35 μm)**	**(6λ/D @ 4.3 μm)**	**(4λ/D @ 4.6 μm)**	**(4λ/D @ 2.1 μm)**

100 Myr-Old, 2 M_{Jup} Planet



A background star would be brightest at F360M.

Spectrum from Burrows, Sudarsky, & Lunine (2003)

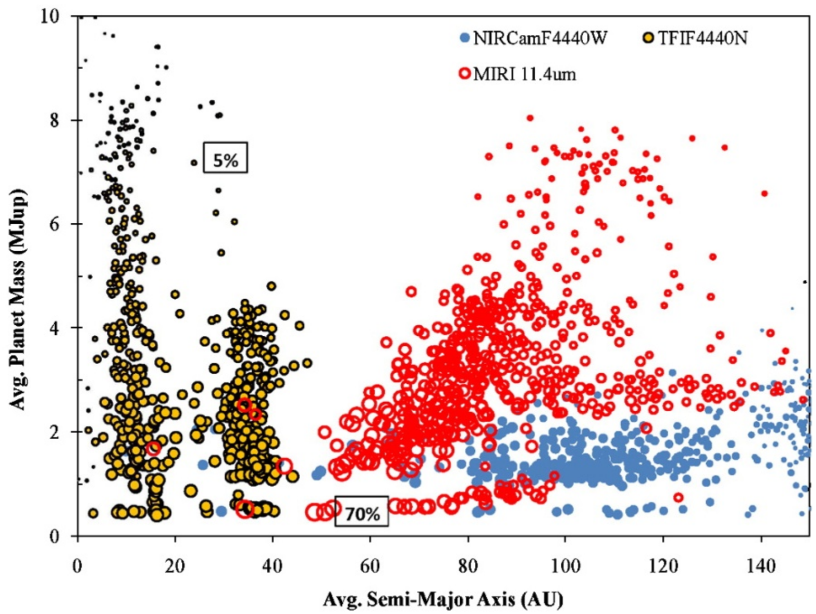
NIRCam+TFI+MIRI = Thorough Planet Census

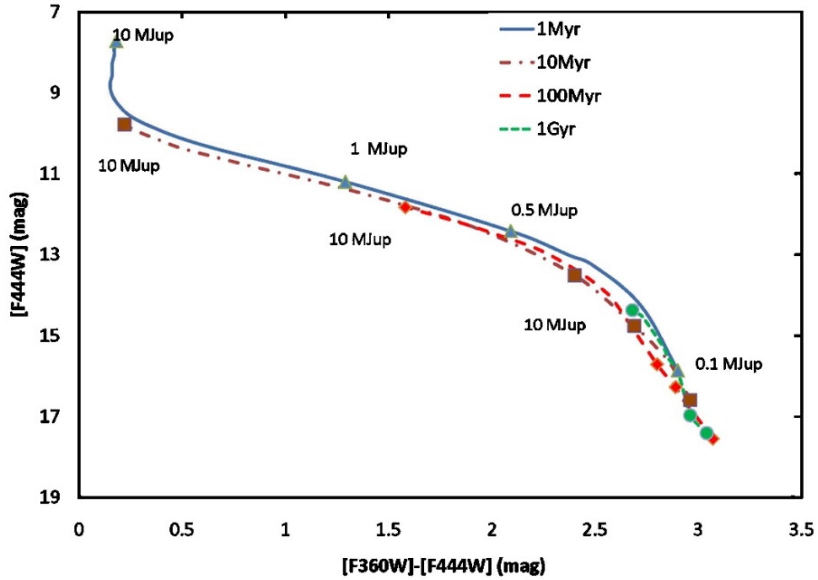
Each of the imagers has its own strengths:

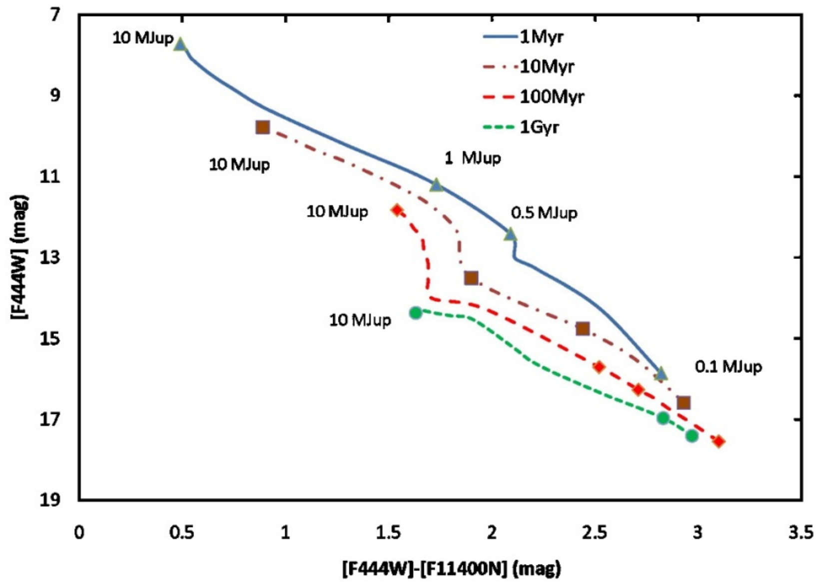
-- TFI's non-redundant mask gives excellent performance at small separations

-- NIRCam with broad filters has superior sensitivity

-- MIRI works at the best wavelengths for planet detection





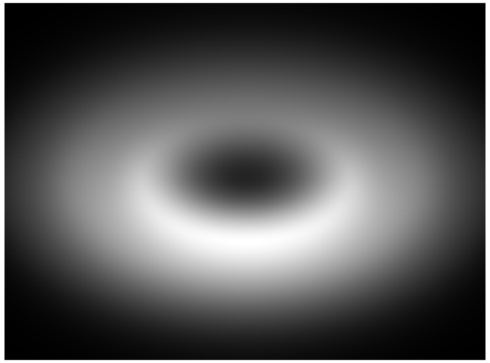


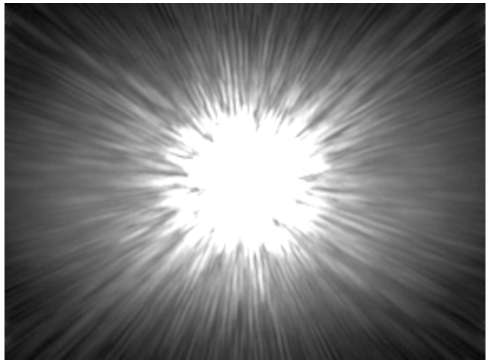
See Beichman et al. 2010 PASP

F200W Disk Imaging

A0V star @ 100 pc, r=0.4” spot occulter

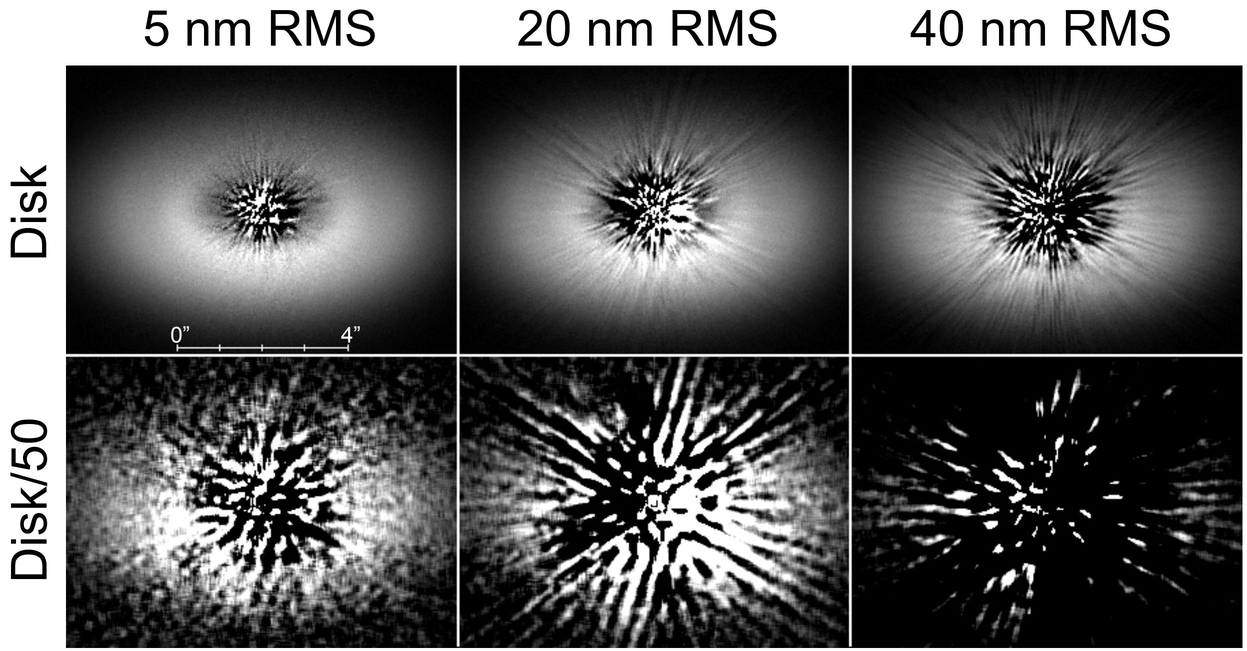
Disk Model





Disk Model +
Coronagraph

After subtraction of a similarly imaged A1V reference PSF star with the given amount of wavefront error change



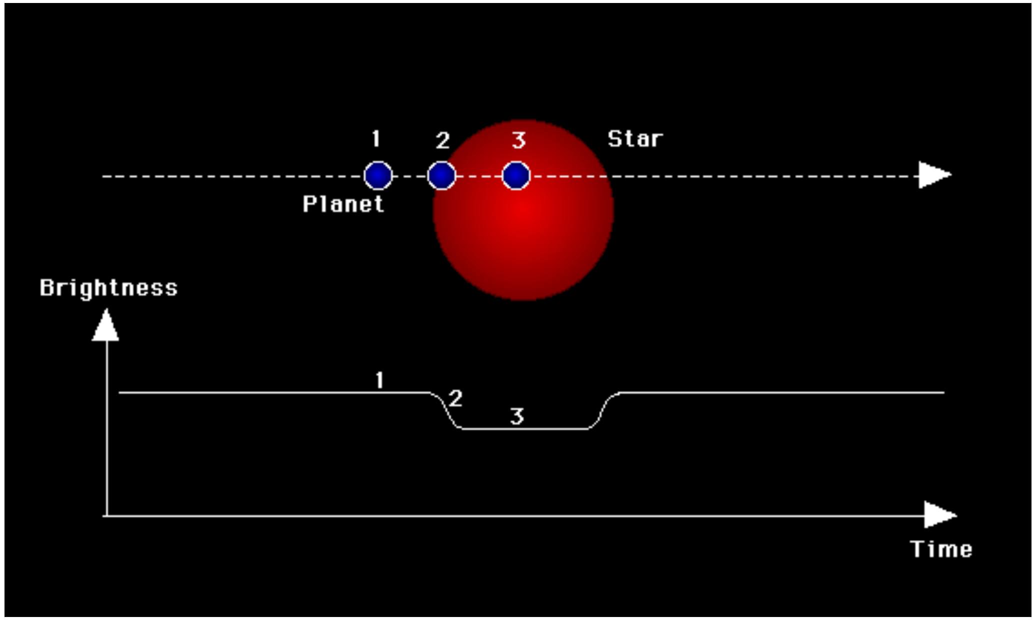
Disk is ~3x Beta Pic optical depth

Transit Detections

A transit occurs when a planet blocks some of the light from its parent star – an effect similar to an eclipse.

Only planetary systems oriented close to “edge-on” will have transits.

Planets far from the parent star are less likely to be seen in transit.



Look at a K2V star like e Eri, a star with evidence for a planet and dust around it:

Luminosity=.3xL_{Sun} = 1.17x10^{26} watts
T = 5000° K

So $$R = \sqrt{\frac{L}{4\pi\sigma T^4}} = 5.1\text{x}10^8 \text{mr the star}$$

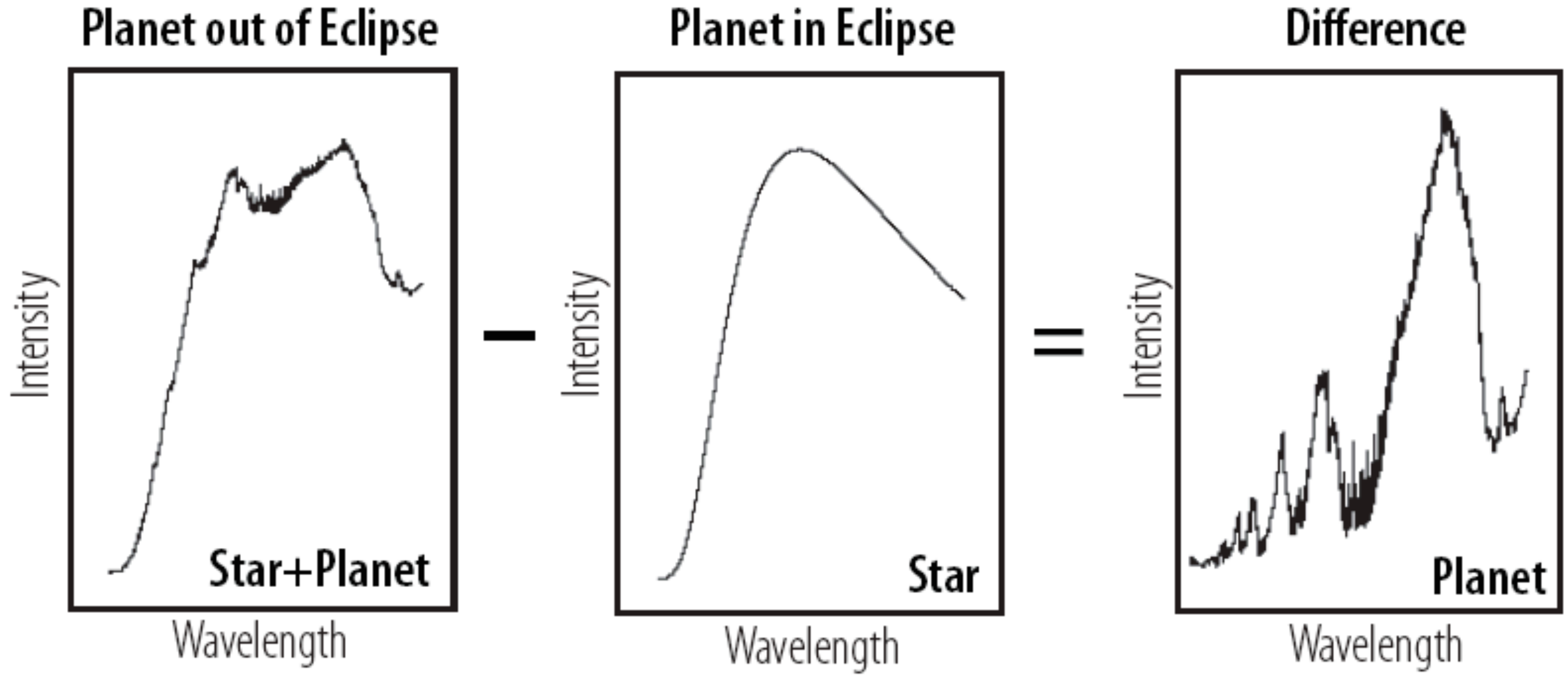
The radius of Jupiter is 3.55x10^7 m so if this star had a planet the size of Jupiter

$$\text{Fraction of light blocked} = \frac{\text{Area of planet}}{\text{Area of star}}$$

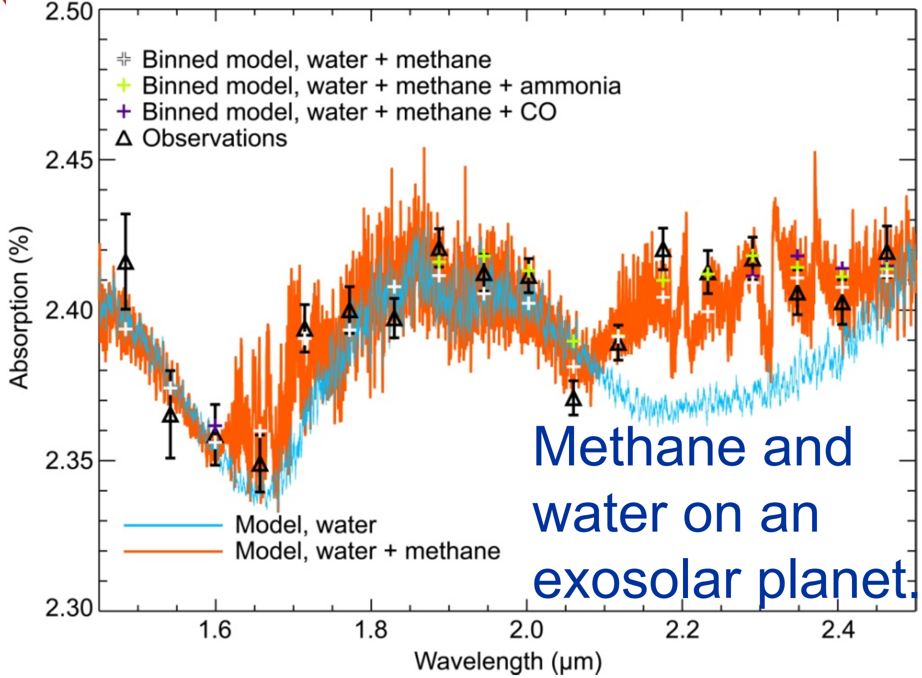
$$= \frac{\pi(3.55\text{x}10^7)^2}{\pi(5.1\text{x}10^8)^2} = .005$$

Transit Spectroscopy

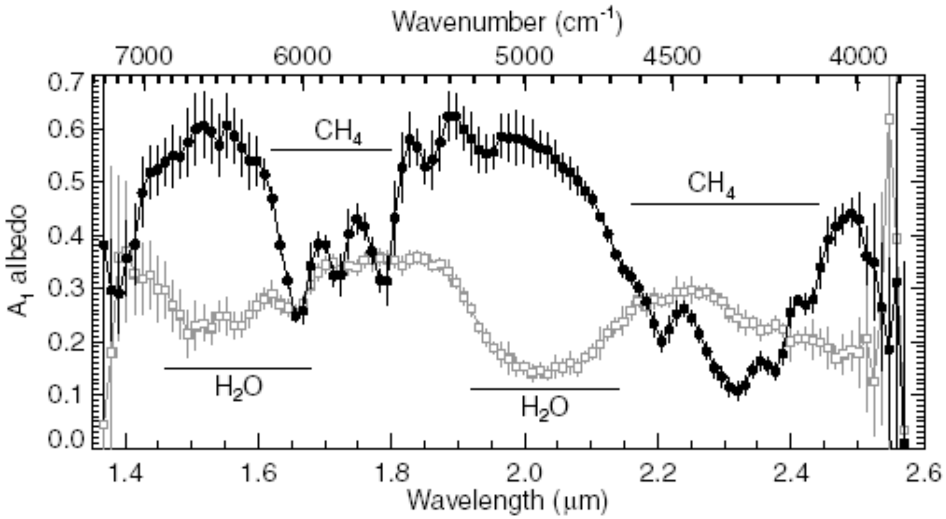
- If an instrument+telescope combination is sufficiently stable, spectra of a transiting planet's atmosphere can be obtained.
- Both emission spectra and transmission spectra can be obtained. HST and Spitzer have produced such data.
- This is likely to be a very powerful technique for JWST.
- Whether NIRSpec or NIRCam will be best will depend on systematics that may be difficult to predict



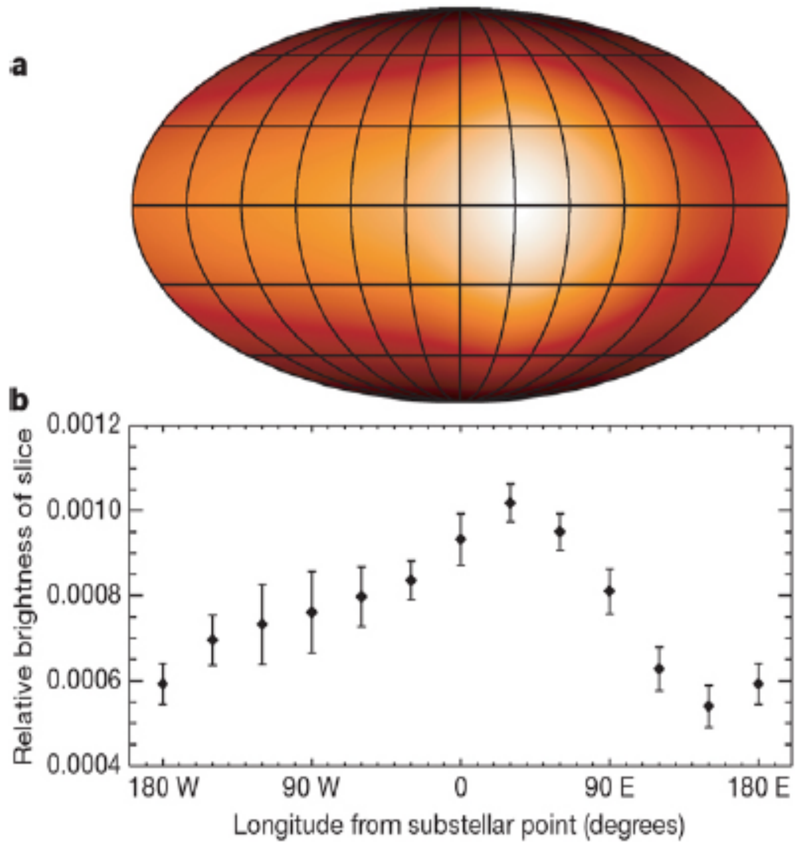
Transits Yield a Detailed View



Methane and water on an exosolar planet.



Methane on Pluto and Water on Charon.



Surface temperatures on an exosolar planet from Spitzer data.

Detailed comparisons to Solar System objects are becoming feasible!

NIRCam Opportunities

Primary and secondary transit or hot Jupiter light curves with high precision using defocused images (1-2.4 μm) and *slitless* grisms (2.4-5.0 μm).

- Short and long-lambda data obtained simultaneously
- Spectroscopy at R~ 500-2,000 at 2.5-5.0 μm where exoplanets have important spectral features.

- NIRCam may be preferred for many transit observations:
  - Immunity to initial pointing and subsequent drifts
  - High photon efficiency and stability due to *no slit losses*
  - Simultaneous long and short lamba observations
  - Monitor pointing and some drifts using other arm of NIRCam

Long-λ GRISM Spectroscopy

Filter	λ1	λ2	# pixels	# pixels/2048
F277W	2.42	3.12	696	0.34
F322W2	2.42	4.03	1600	0.78
F356W	3.12	4.01	885	0.43
F410M	3.90	4.31	408	0.20
F444W	3.89	5.00	1104	0.54

- Grism provides R~2,000 spectra
  - ➢ Spectra improve saturation limit and reduce flat field error
  - ➢ No slit losses → immune to pointing drifts
- Average over few 10^2 pixels for R~50-100 spectra

- *Spectra of (Hot) Jupiters at R~500*
- *Super Earth transit detection SNR ~ 6 in 4hr, R=20*

SNR for Primary Transit of G2V Star. R = 500; τ = 1,000 sec; T_{planet} = [illegible]K

Jupiter	M (mag)**			Earth	M (mag)	
Flat/mag	6	10	16	Flat/mag	5	10
1.0E-06	66.32	5.55	0.52	1.0E-06	0.74	0.07
1.0E-05	67.86	5.52	0.52	1.0E-06	0.73	0.07
1.0E-04	[illegible]	5.76	0.52	1.0E-04	0.46	0.07
1.0E-03	7.08	5.54	0.41	1.0E-03	[illegible]	[illegible]

SNR for Secondary Transit of G2V Star. R = 500; τ = 1,000 sec; T_{planet} = [illegible]K

Jupiter	M (mag)			Earth	M (mag)	
Flat/mag	6	10	16	Flat/mag	5	10
1.0E-06	[illegible].12	0.11	0.09	1.0E-06	[illegible]	[illegible]
1.0E-05	[illegible]	0.91	0.09	1.0E-06	0.06	0.01
1.0E-04	[illegible].71	[illegible]	0.09	1.0E-04	[illegible]	[illegible]
1.0E-03	0.76	0.57	0.09	1.0E-06	0.01	0.00

*Obtained by binning ~8 spectral channels. **Johnson magnitudes.