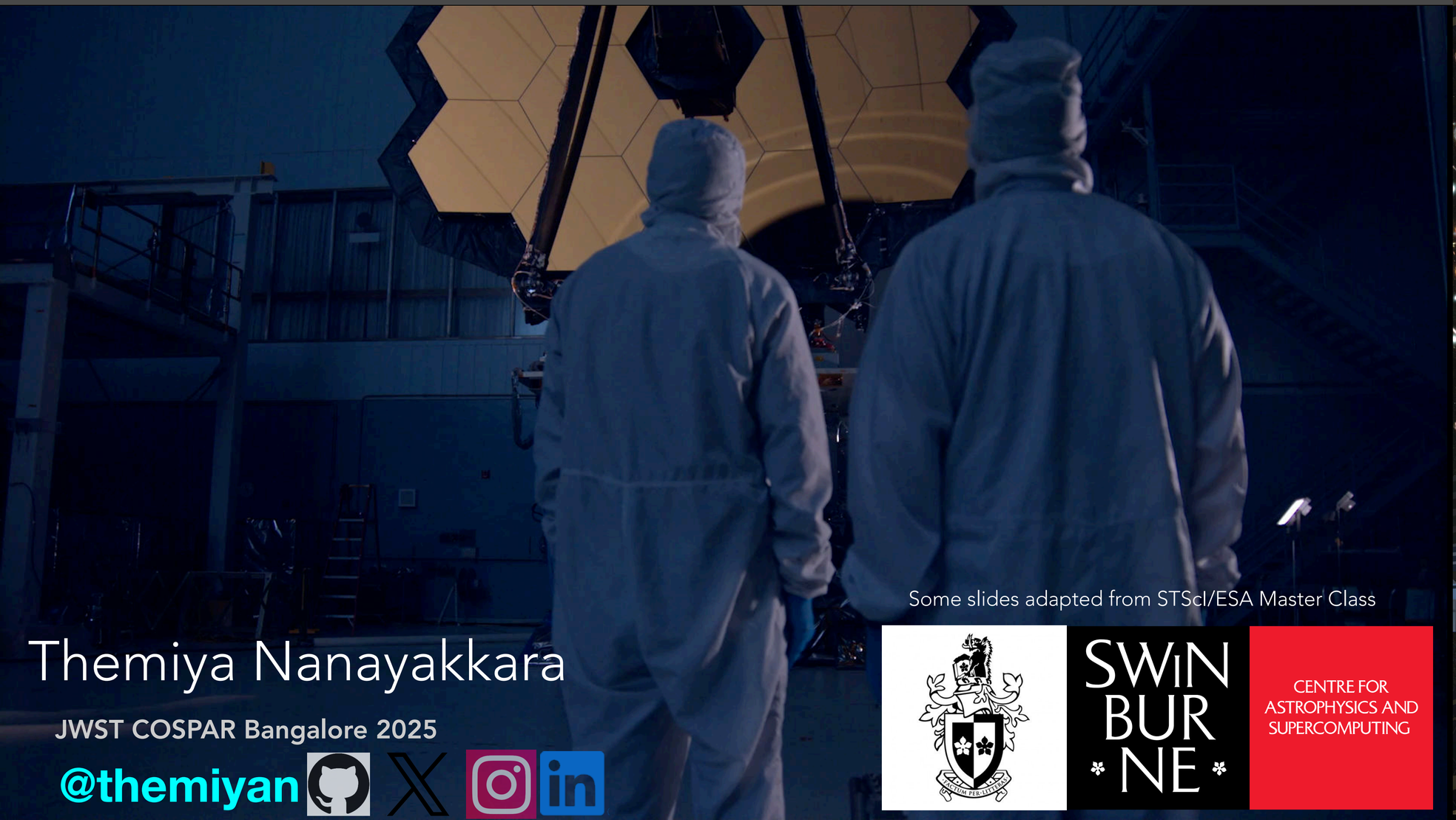
The James Webb space telescope



Some slides adapted from STScI/ESA Master Class

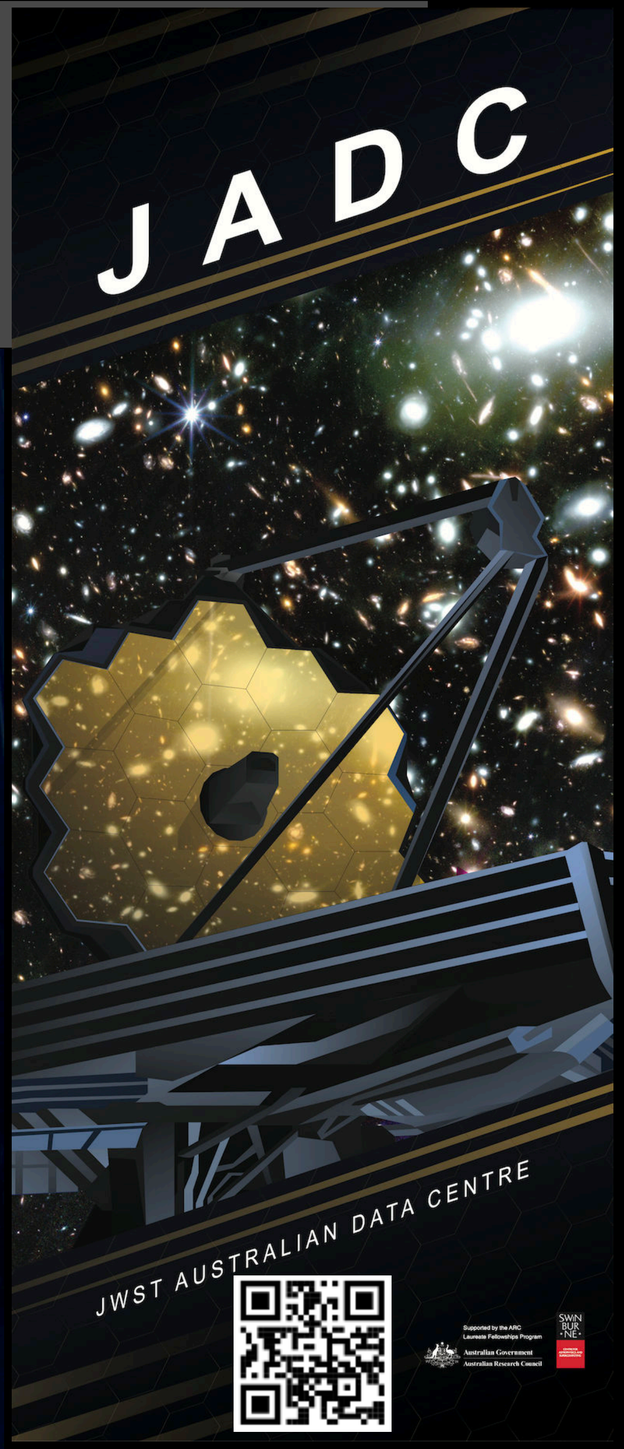
Themiya Nanayakkara

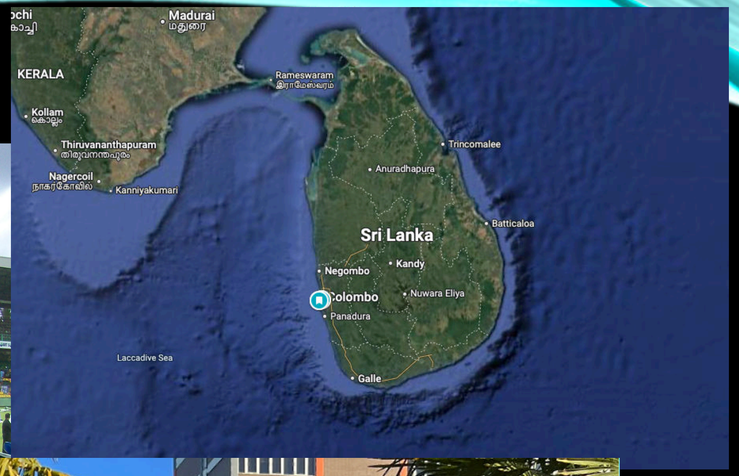
JWST COSPAR Bangalore 2025

@themiyan

SWINBURNE

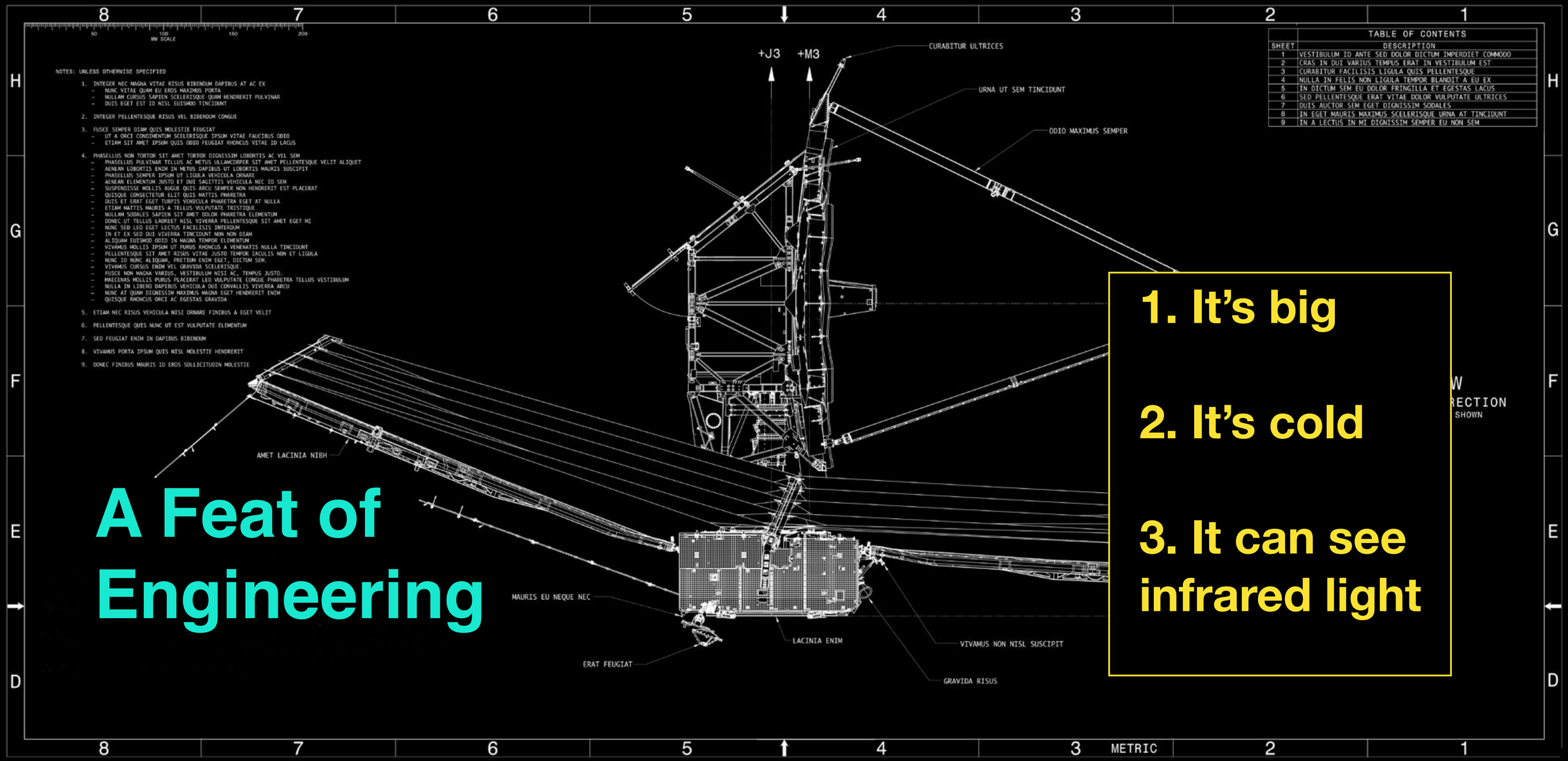
CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING




Madurai
KERALA
Rameswaram
Kollam
Thiruvananthapuram
Nagercoil
Kanniyakumari
Trincomalee
Anuradhapura
Batticaloa
Sri Lanka
Kandy
Negombo
Colombo
Nuwara Eliya
Panadura
Laccadive Sea
Galle

JADC
JWST AUSTRALIAN DATA CENTRE
NEW YORK

A Feat of Engineering



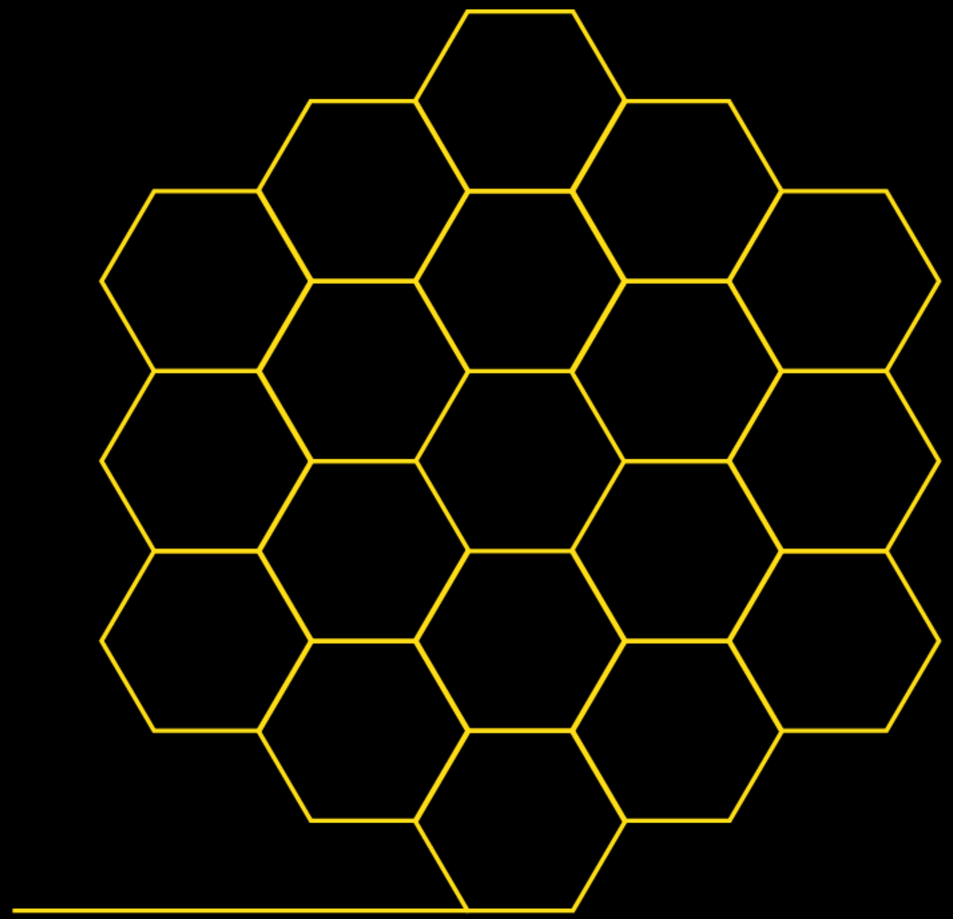
1. It’s big

2. It’s cold

3. It can see infrared light

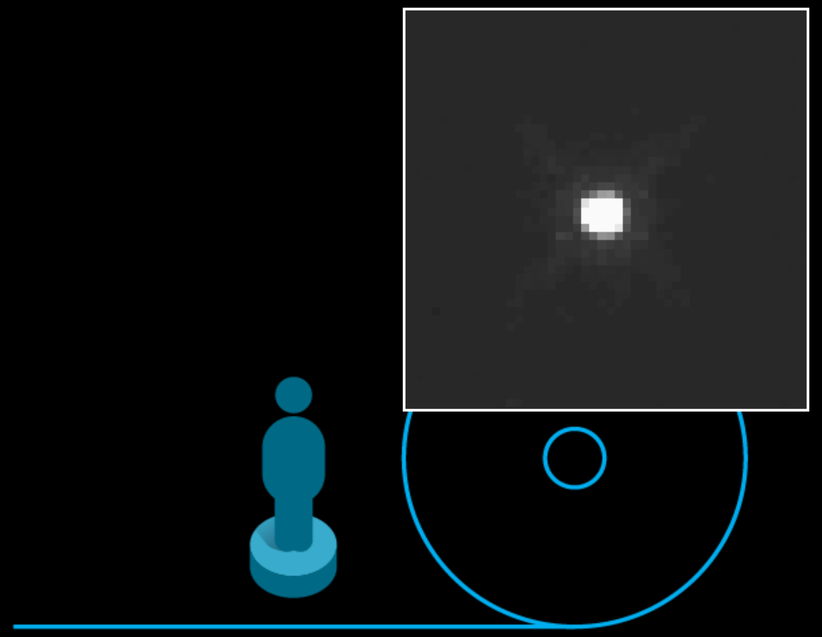
Capturing Faint, Infrared Light

Hubble's PRIMARY MIRROR

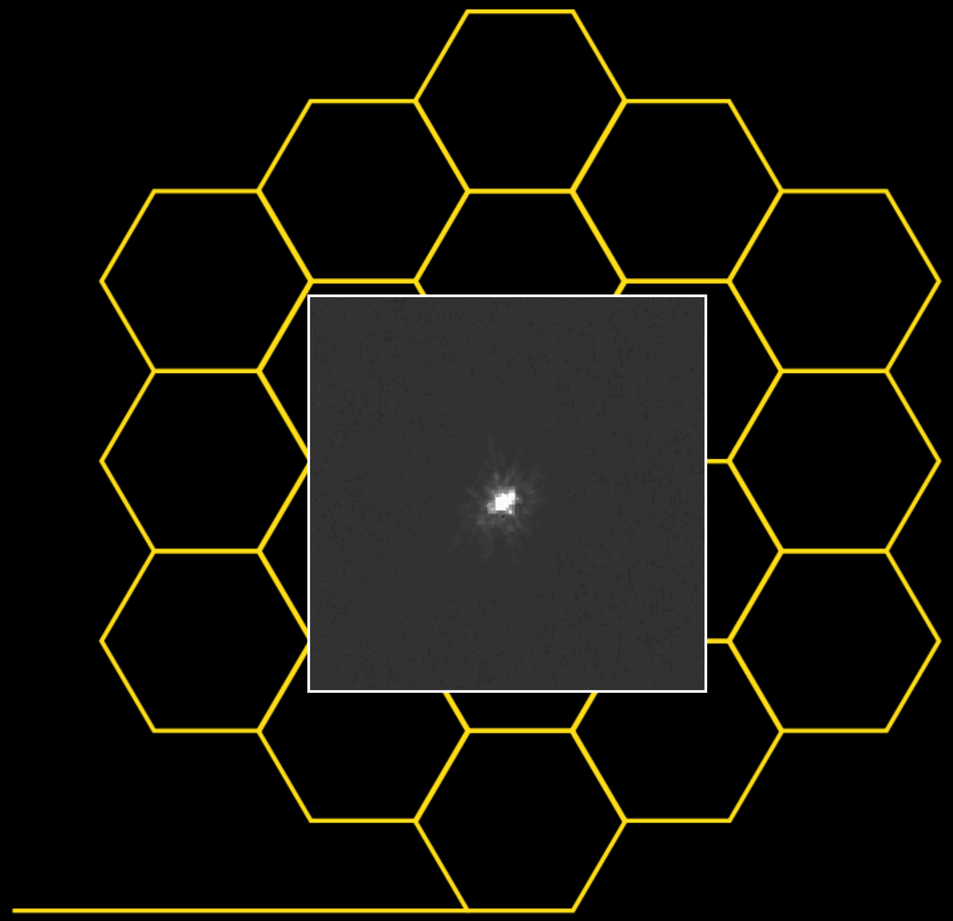


Webb's PRIMARY MIRROR

Capturing Faint, Infrared Light

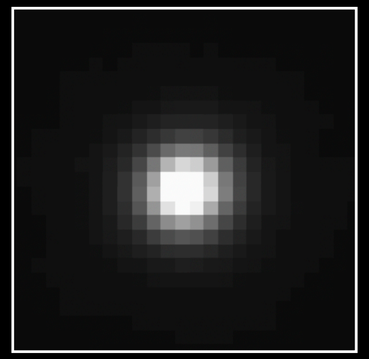


Hubble's PRIMARY MIRROR

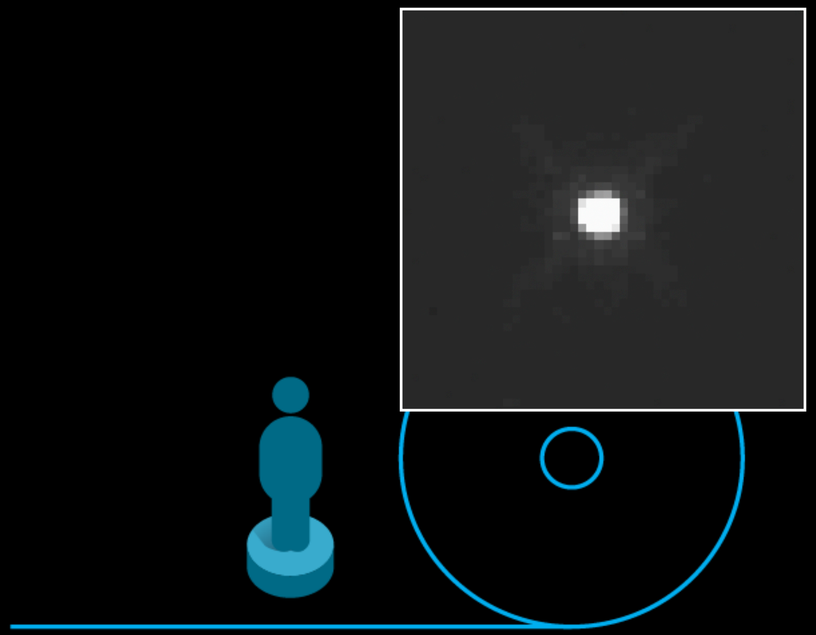


Webb's PRIMARY MIRROR

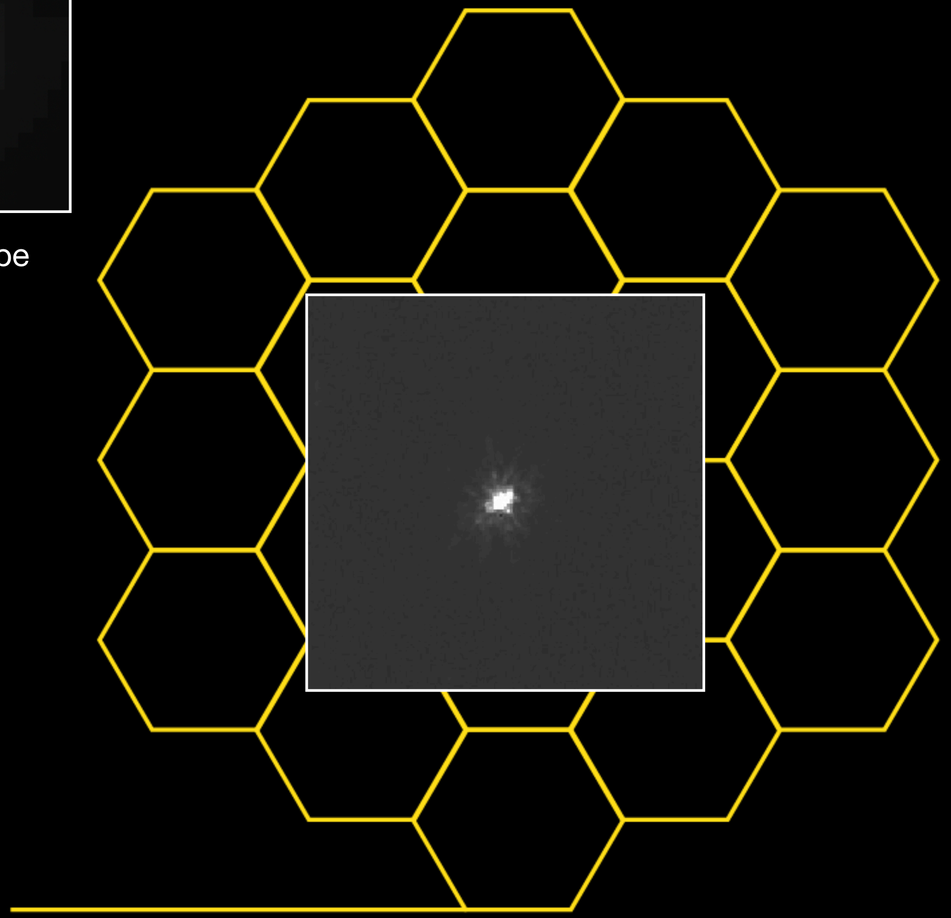
Capturing Faint, Infrared Light



Ground Telescope



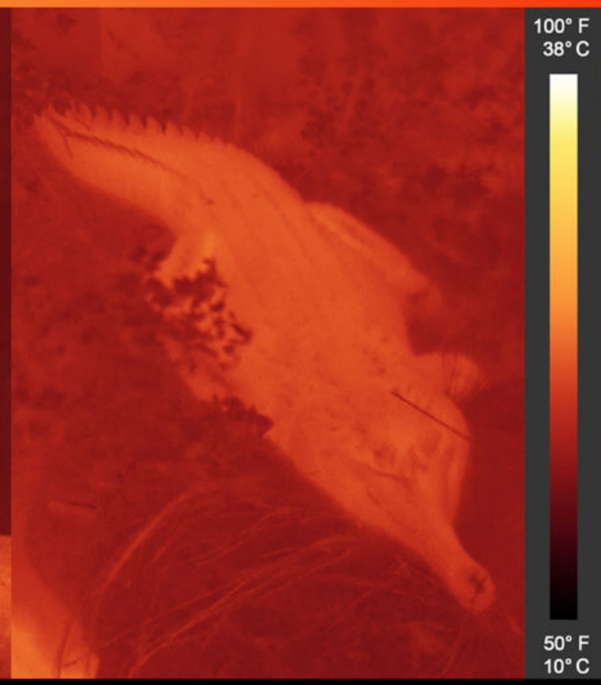
Hubble's PRIMARY MIRROR



Webb's PRIMARY MIRROR

Why Study Infrared Light?

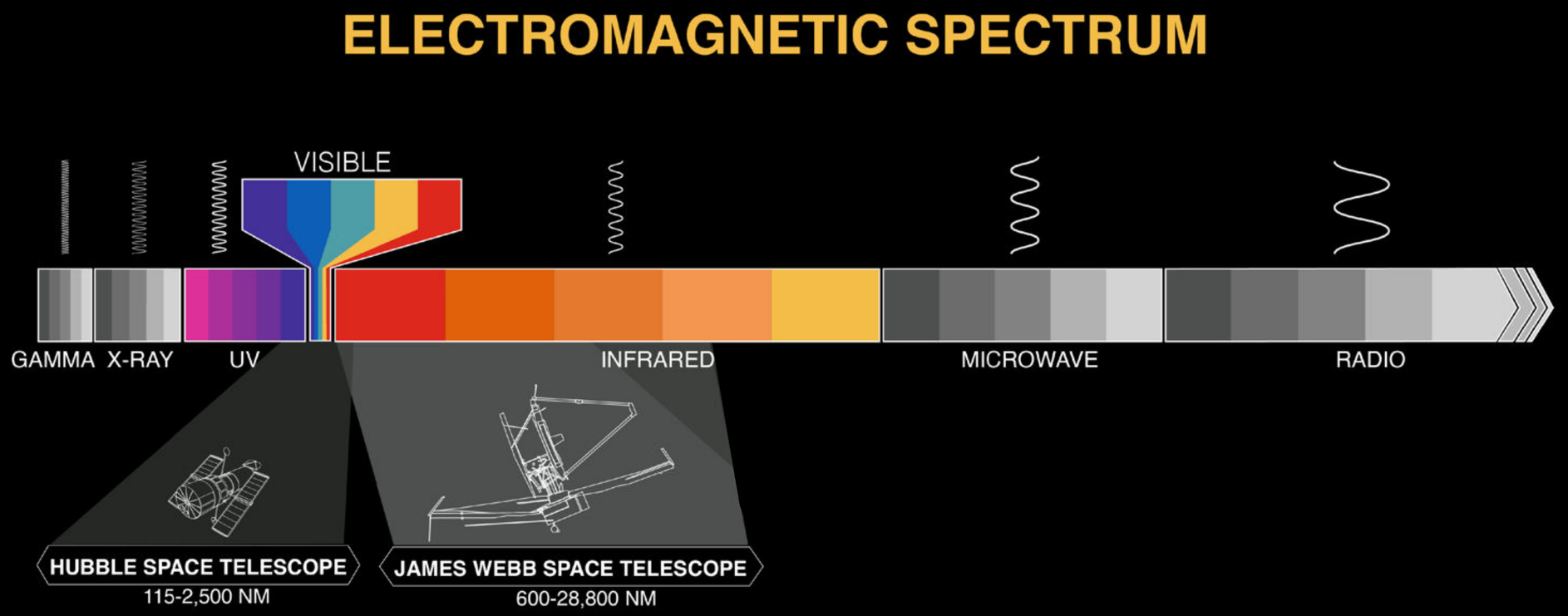
Visible vs. Infrared Light



Meerkats

Freshwater crocodile

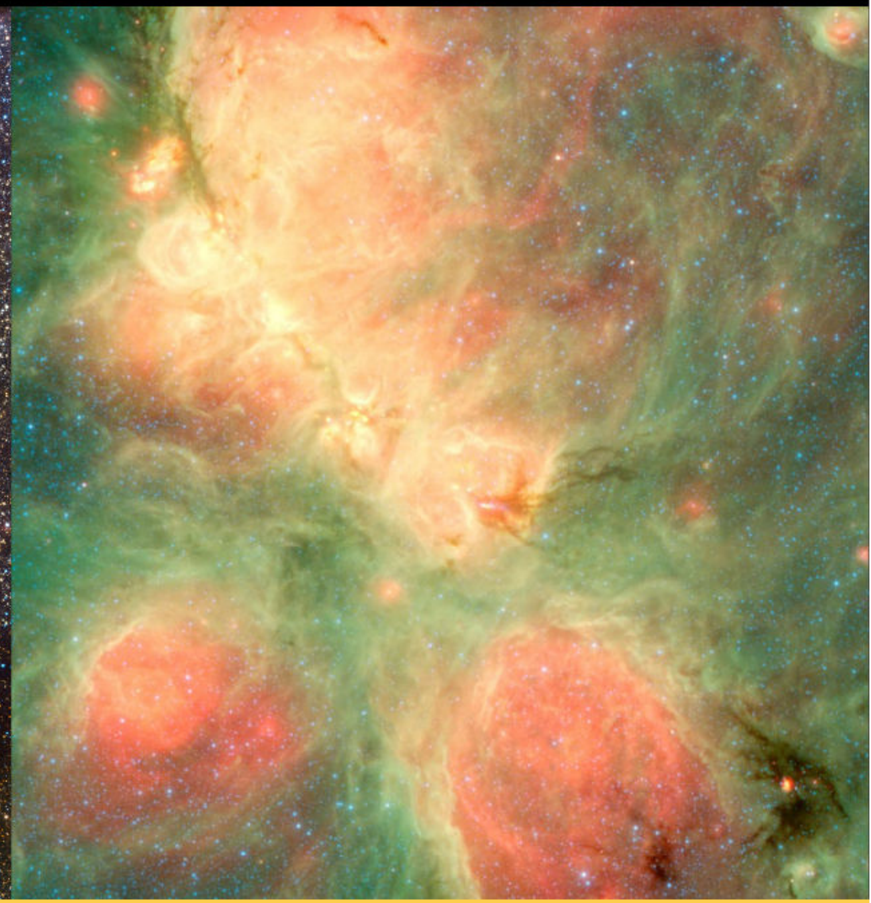
Webb’s Specialization in Infrared Light



Webb Can Peer Through *and* Examine Dust

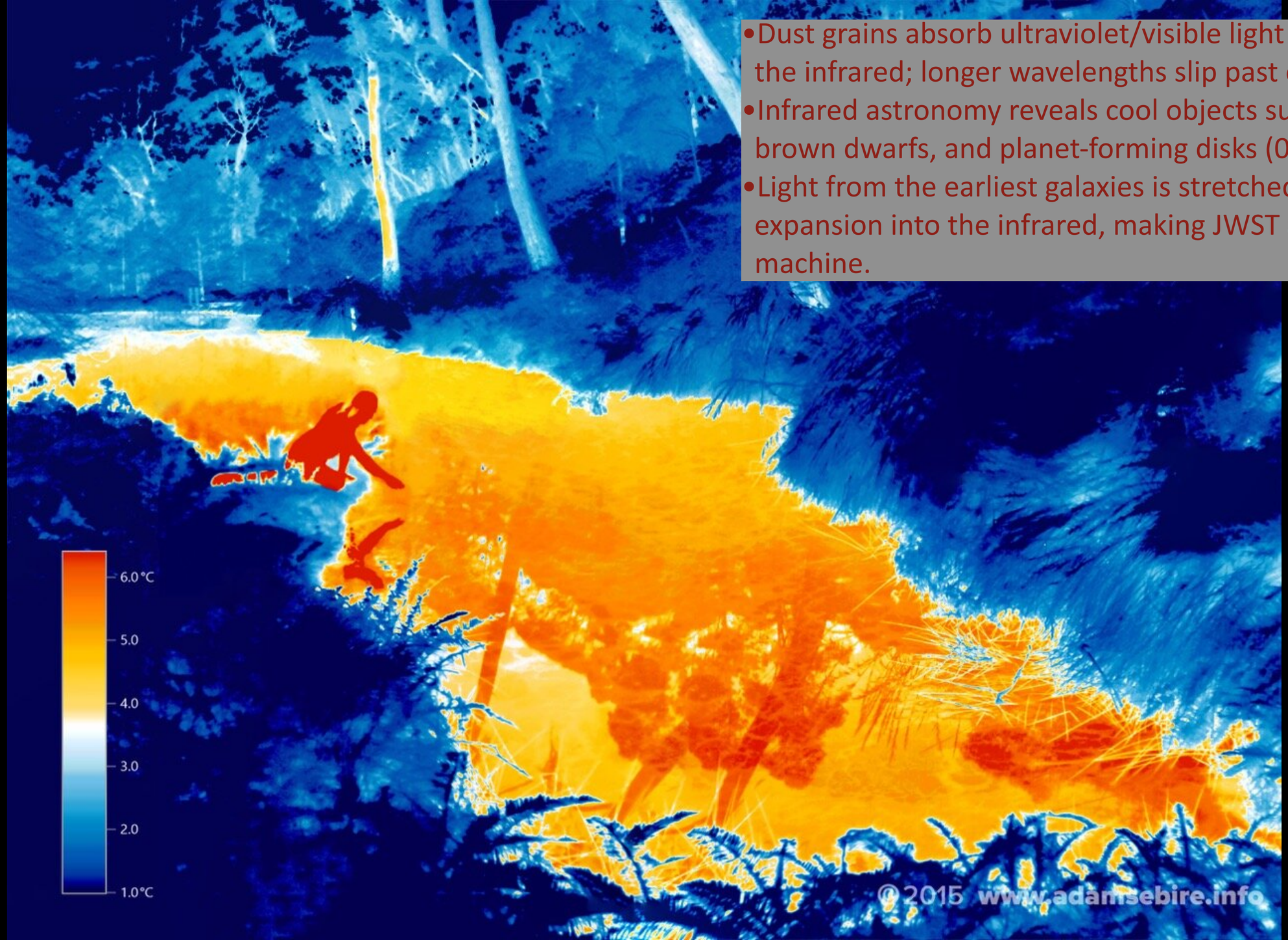
Visible Light (ESO)

Near-Infrared Light (ESO)

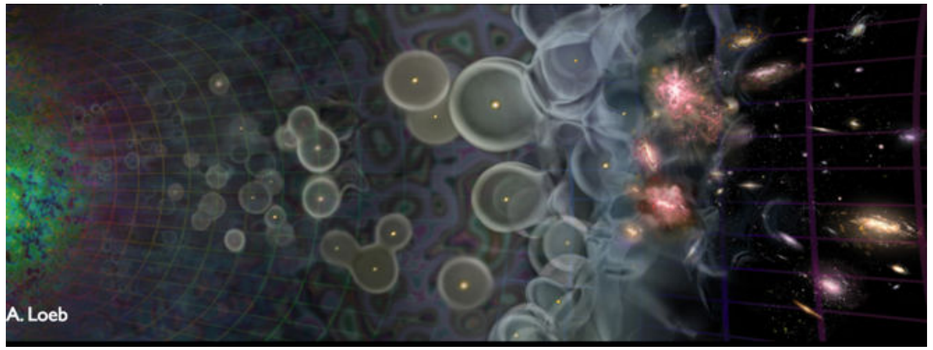


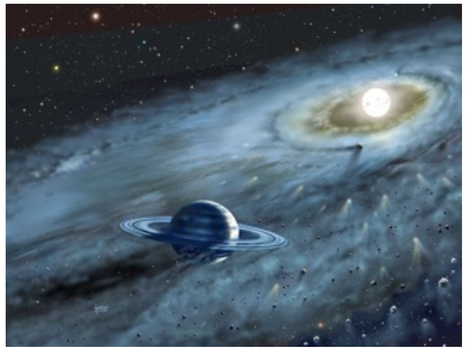
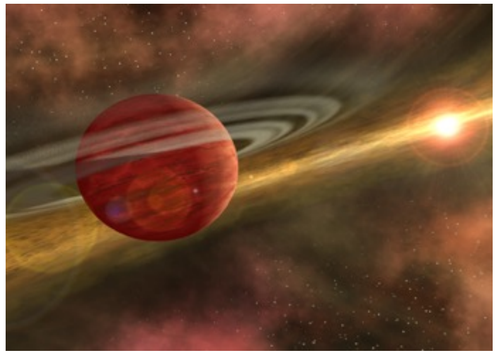
Mid-Infrared Light (Spitzer)

- Dust grains absorb ultraviolet/visible light and re-emit it in the infrared; longer wavelengths slip past obscuring clouds.
- Infrared astronomy reveals cool objects such as protostars, brown dwarfs, and planet-forming disks (0.6–28 μm).
- Light from the earliest galaxies is stretched by cosmic expansion into the infrared, making JWST a cosmic time machine.



JWST – the mission in a few sentences



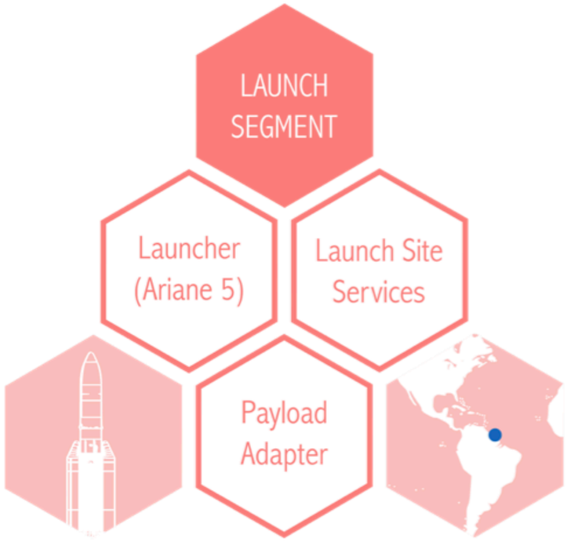



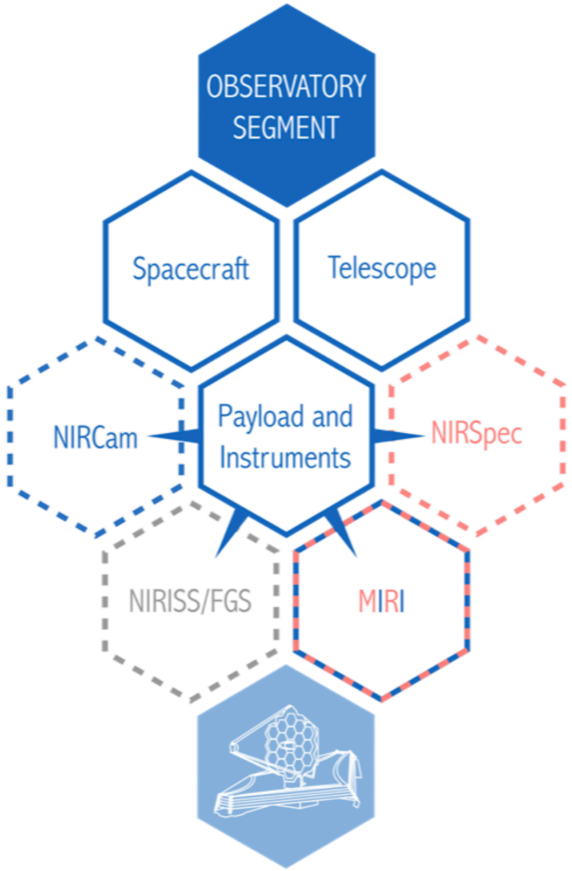
High-sensitivity, low-background, imaging, spectroscopic and coronagraphic capabilities over the 0.6-29 micron wavelength range.

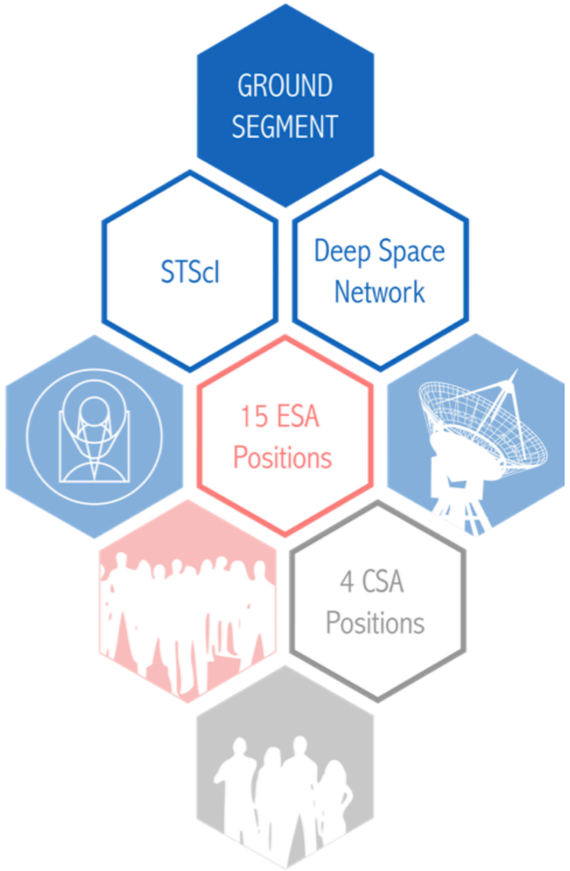
Very powerful and versatile observatory with broad science goals.

From the first galaxies to our Solar system.

JWST – an international collaboration







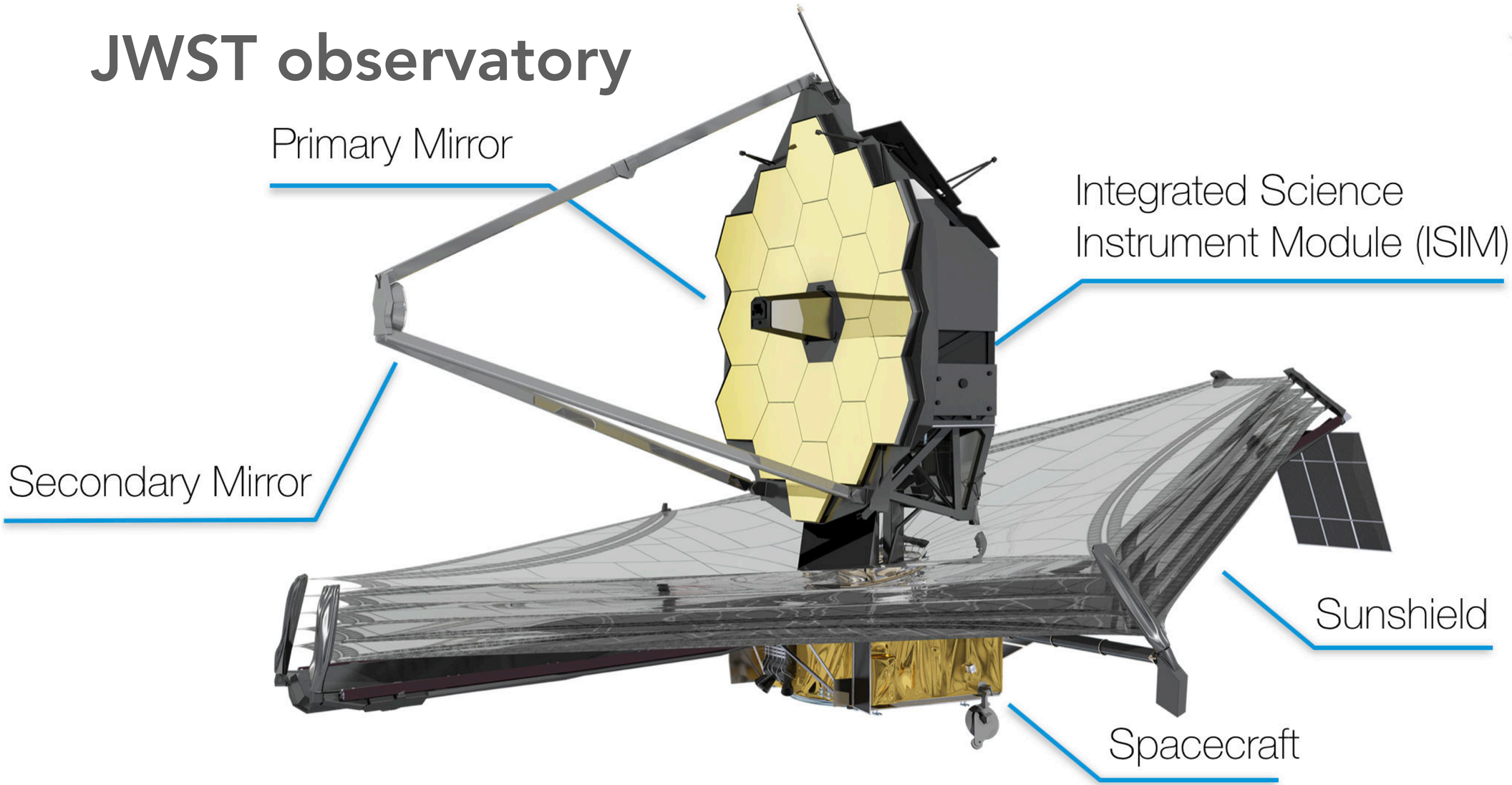
Provided by NASA

Provided by ESA/Europe

Provided by CSA

JWST – Main building blocks

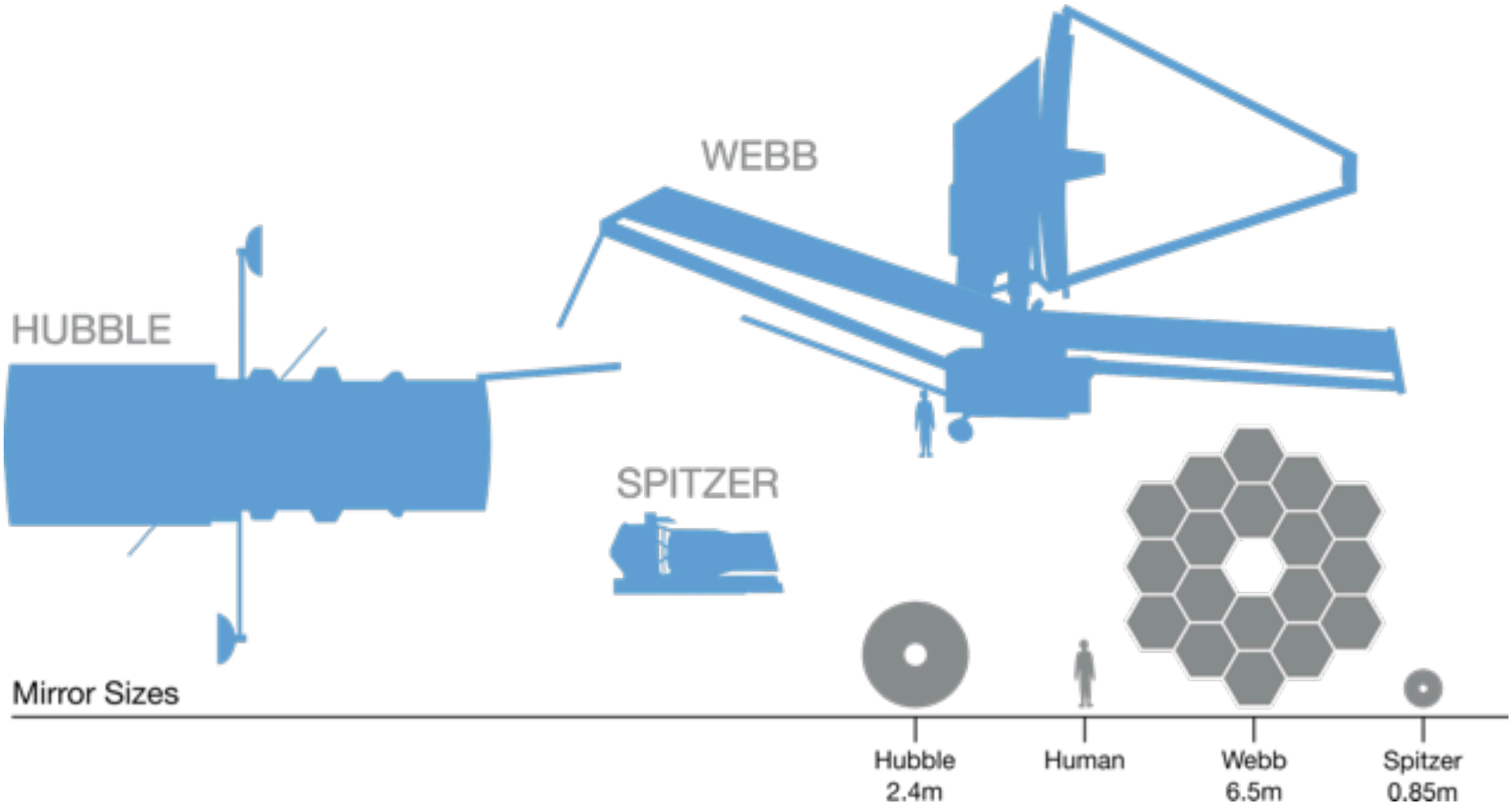
JWST observatory



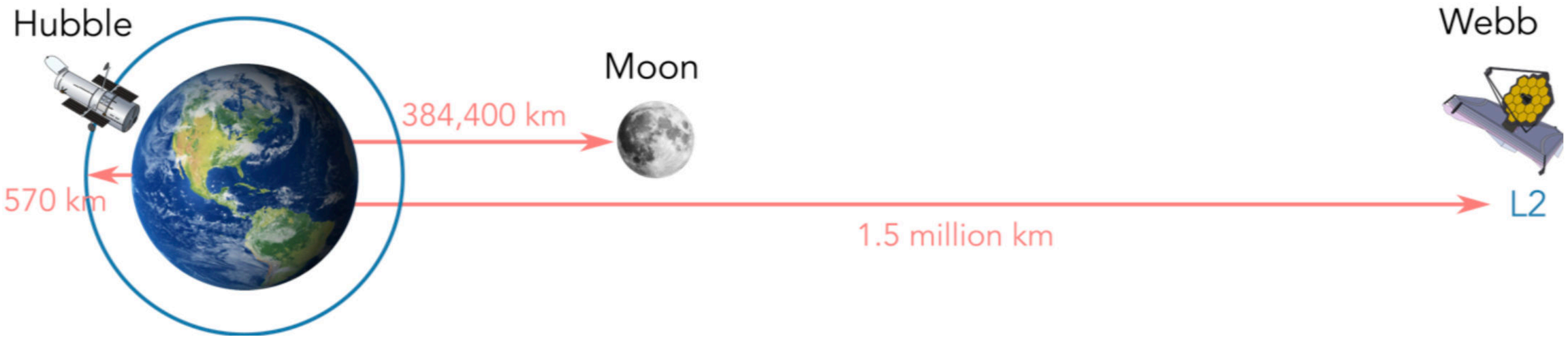
SCE = spacecraft + sunshield

OTIS = telescope + instruments

JWST – Main building blocks

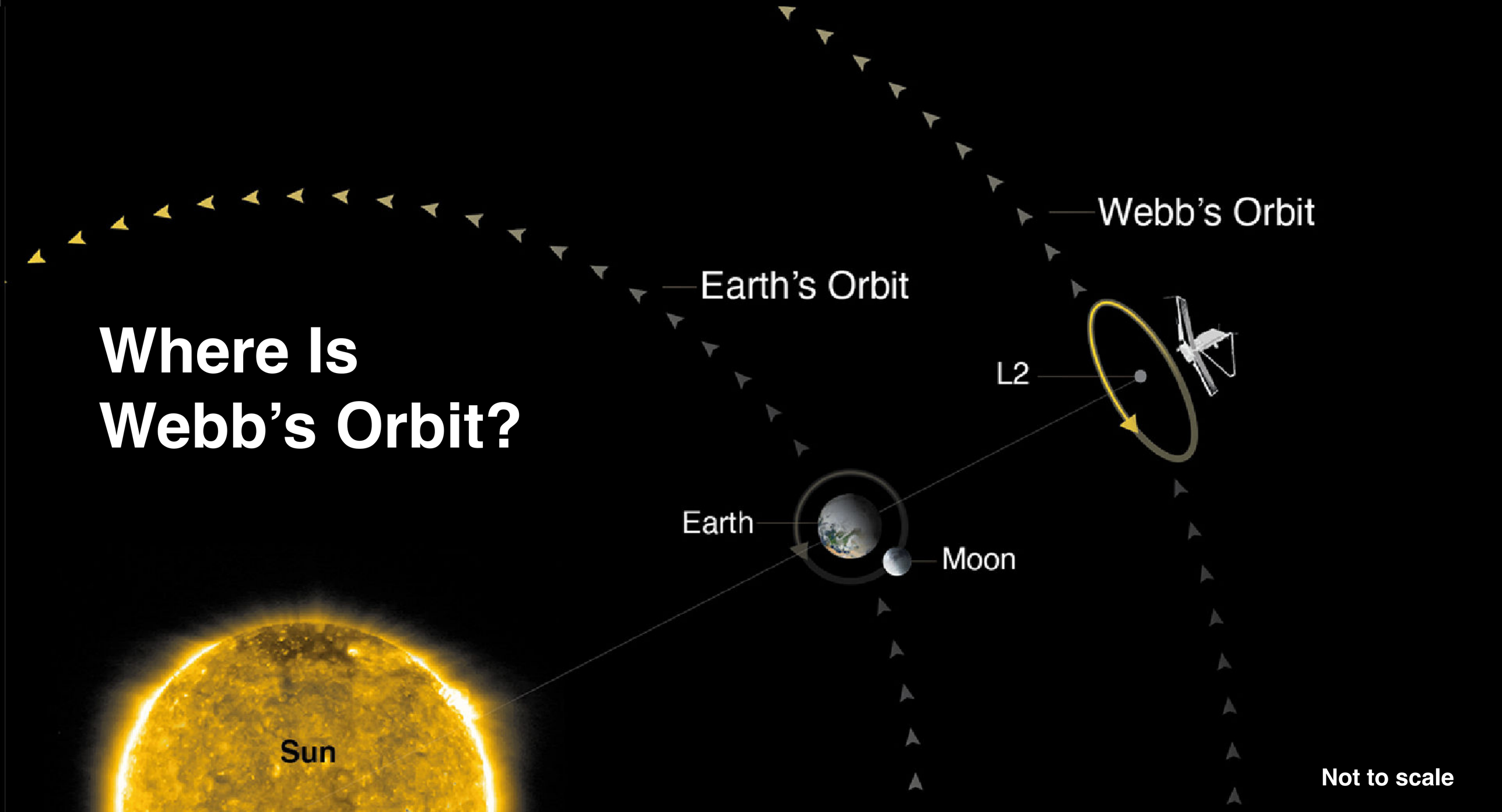


JWST – a deployable observatory



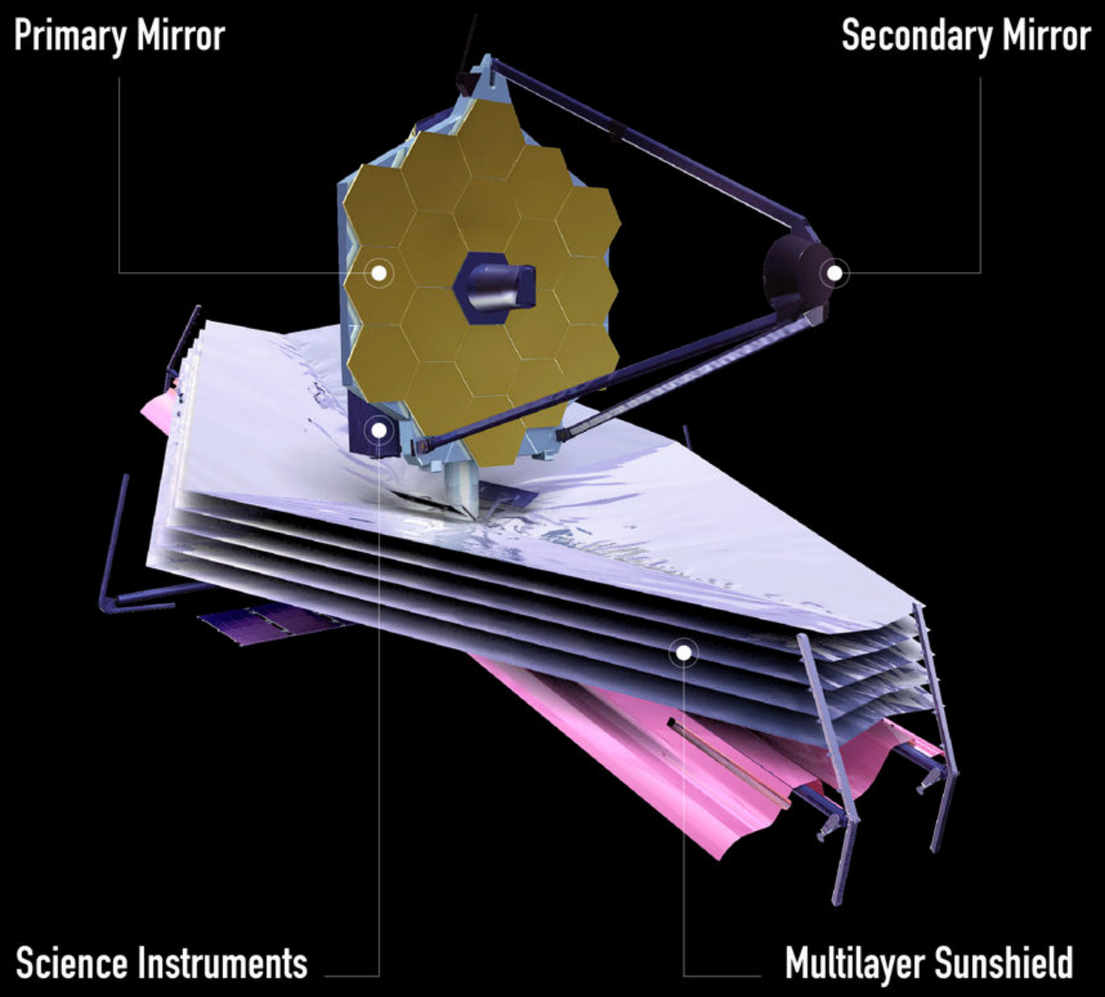
esa
ariane

Where Is Webb's Orbit?

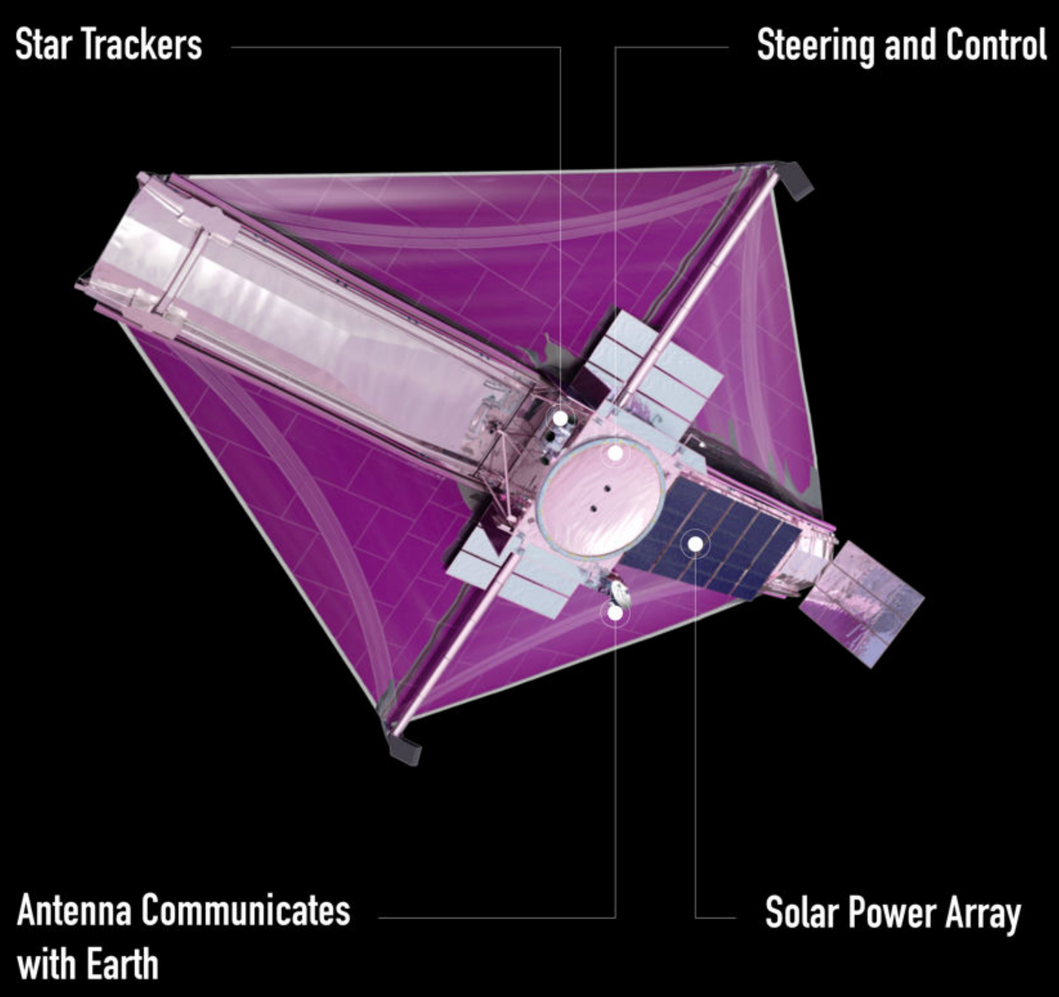


Not to scale

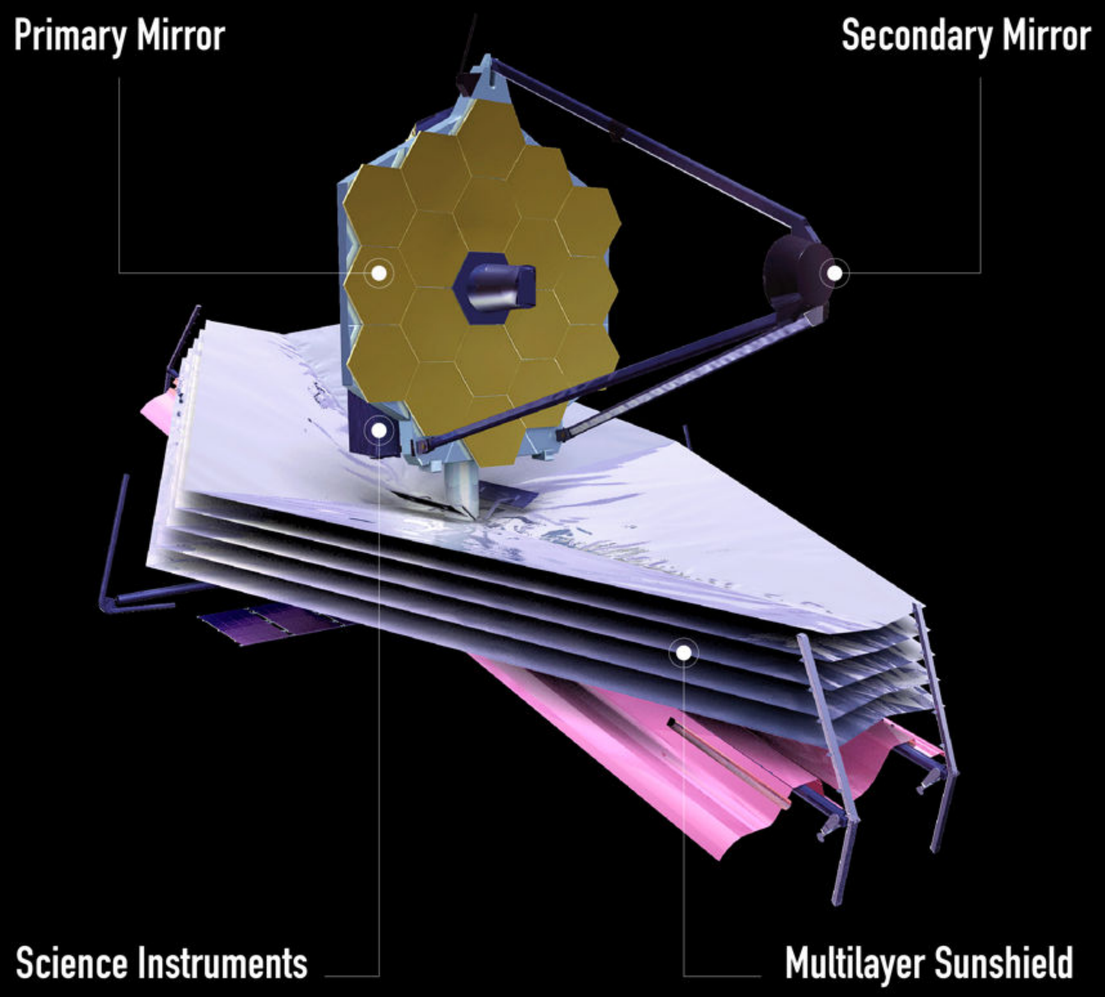
Observing Side



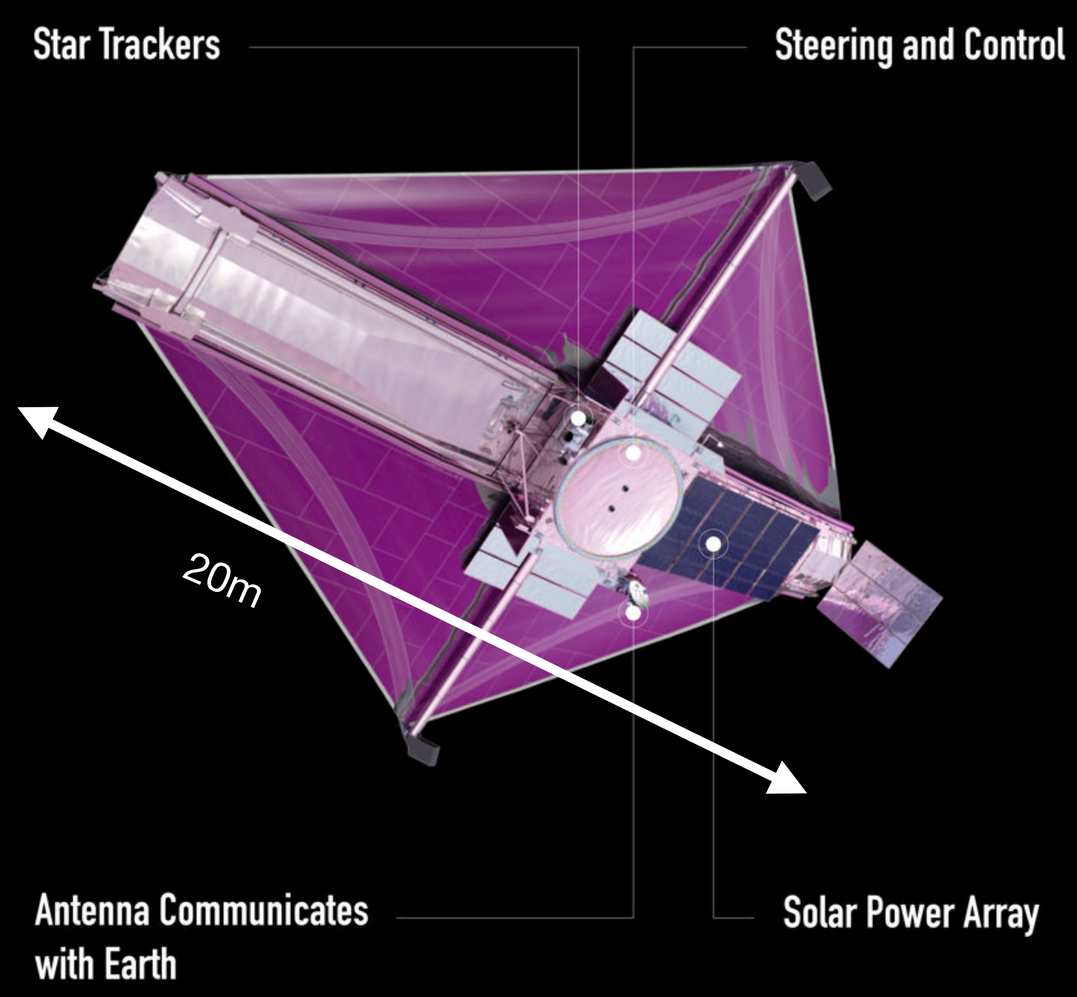
Sun-Facing Side



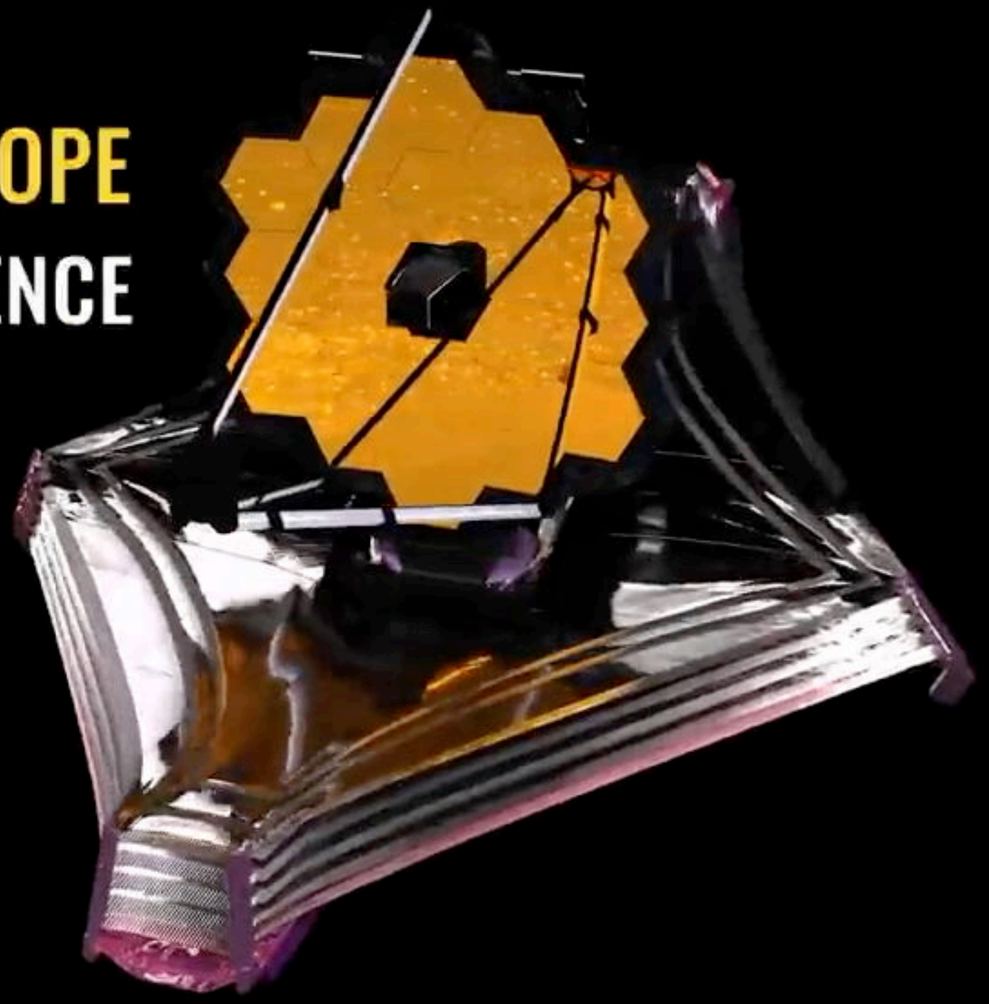
Observing Side

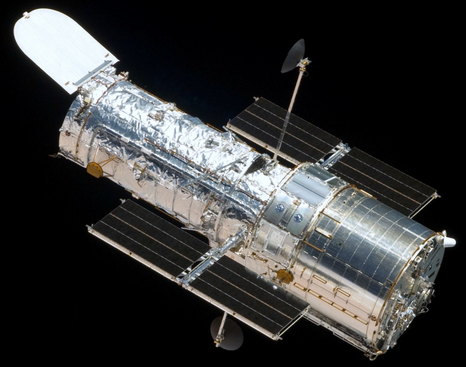


Sun-Facing Side

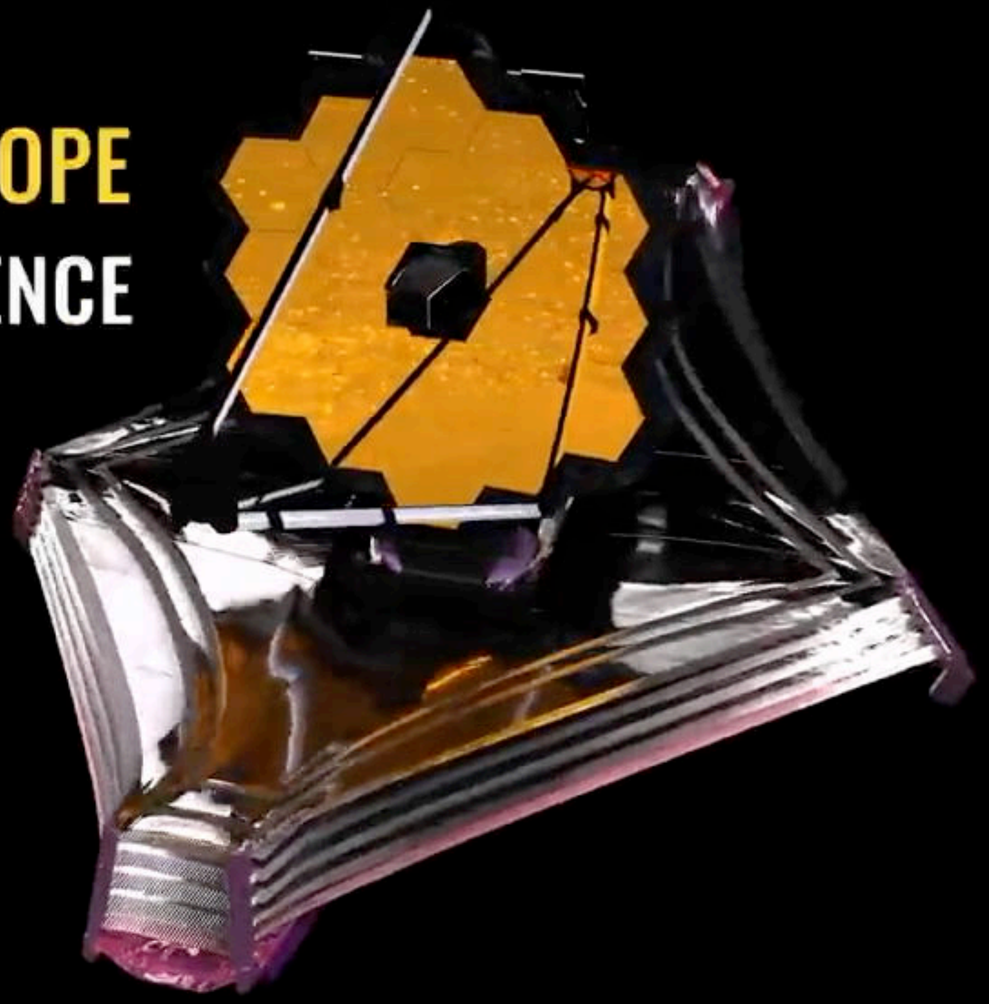


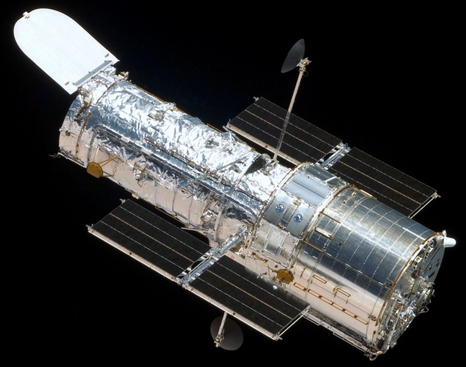
Post-Launch Deployment Sequence

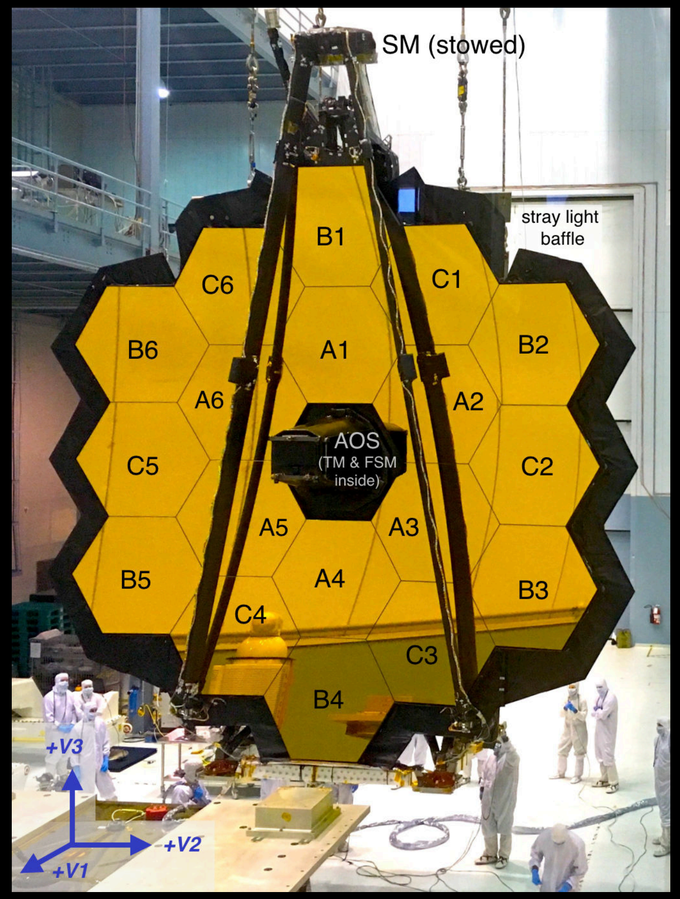


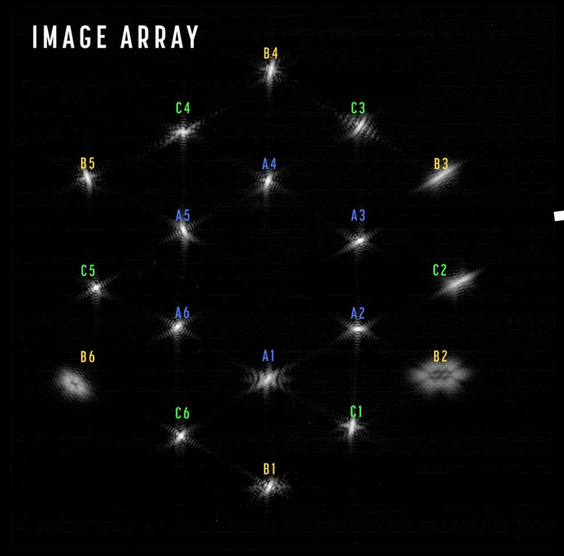


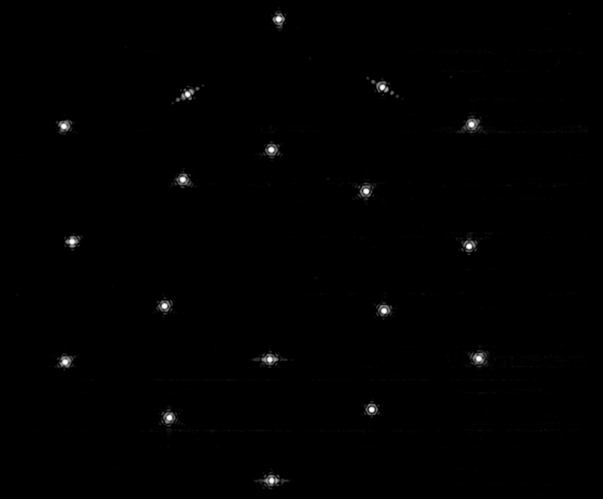
Post-Launch Deployment Sequence

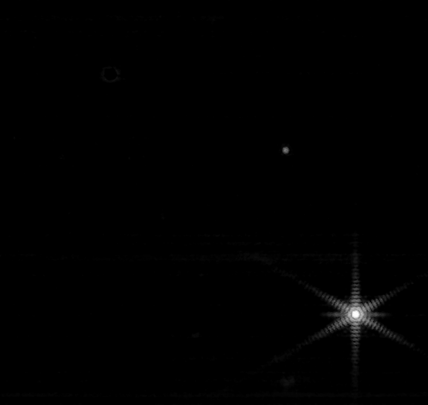


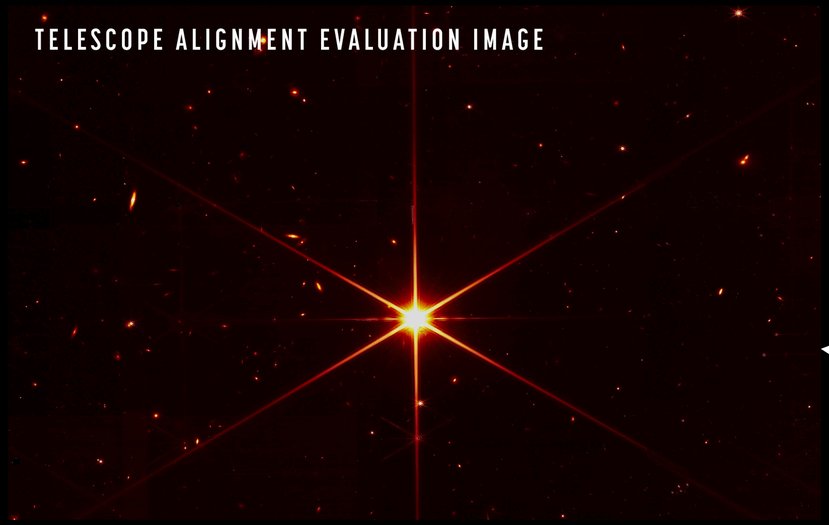




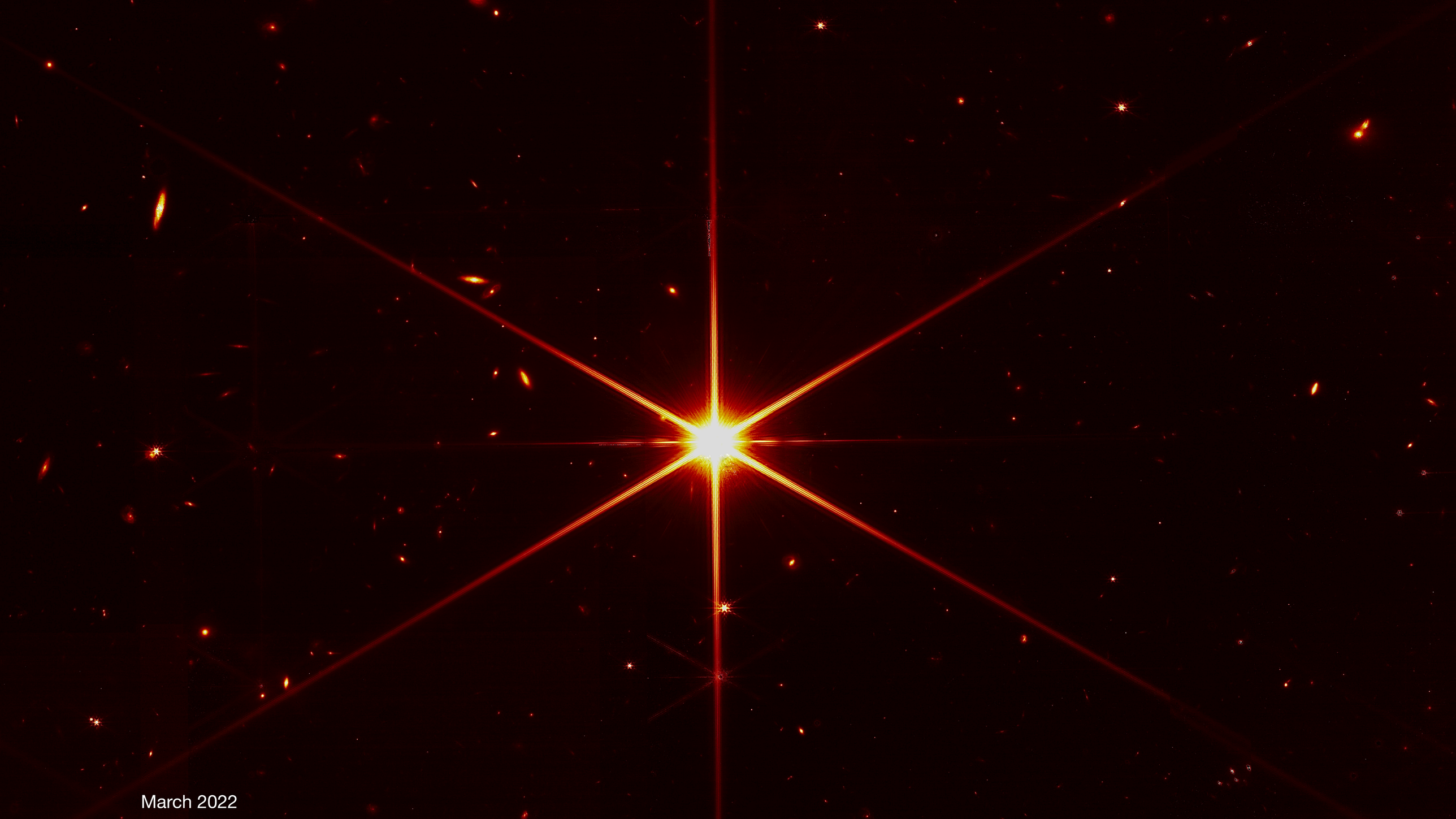








- 18 hexagonal beryllium segments combine into a 6.5 m mirror; actuators align them with nanometre precision.
- Gold coatings optimise infrared reflectivity while keeping mass low.
- A five-layer Kapton sunshield unfolds to ~21×14 m; layers thinner than a human hair block heat and light.
- Passive cooling at L2 lowers instruments to ~40 K, reducing >200 kW of solar energy to a fraction of a watt.


March 2022

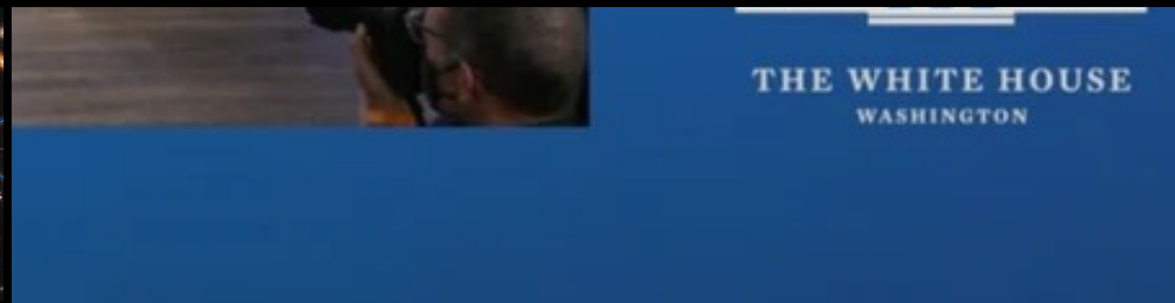
THE WHITE HOUSE
WASHINGTON

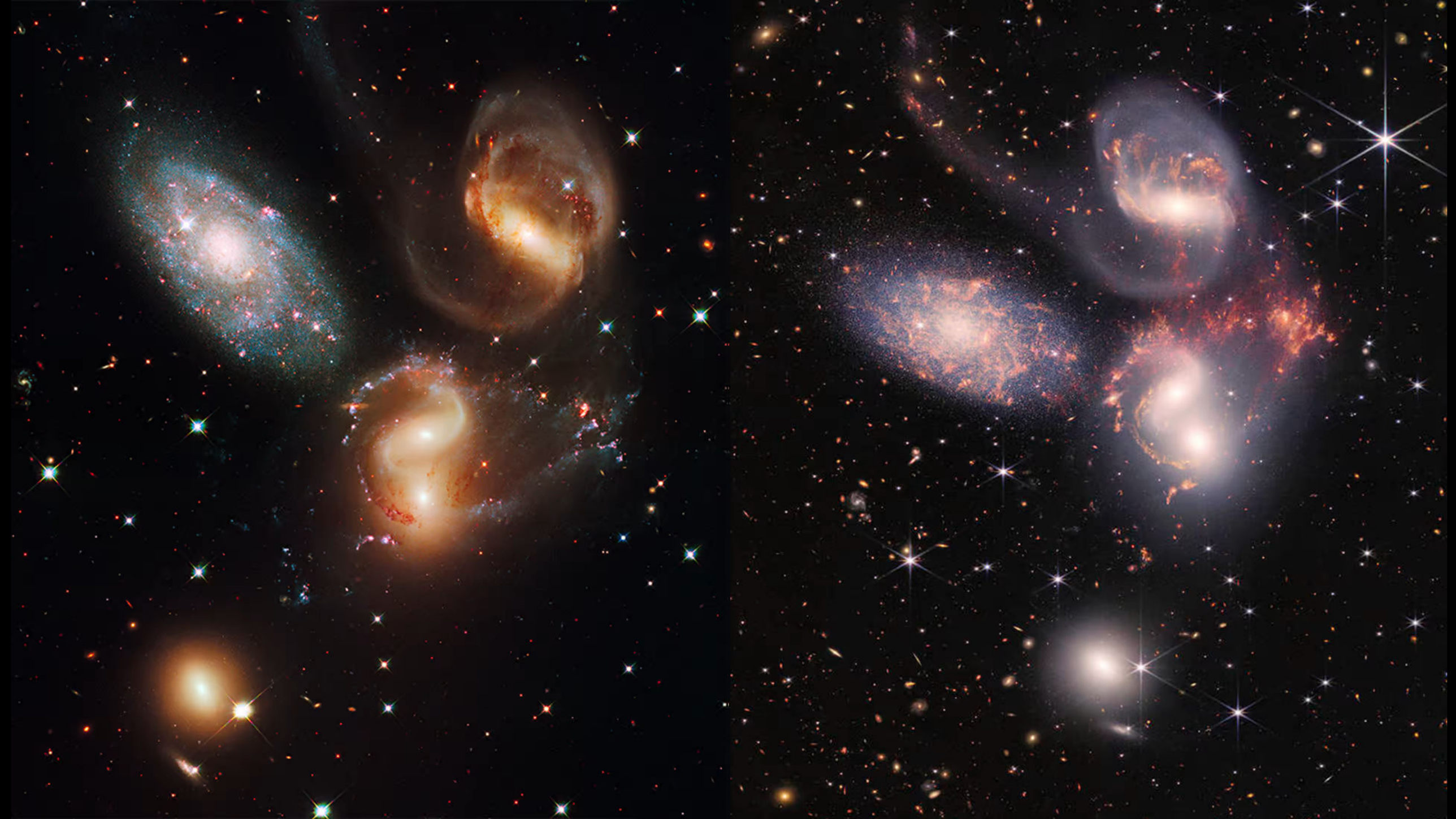
WHITEHOUSE.GOV

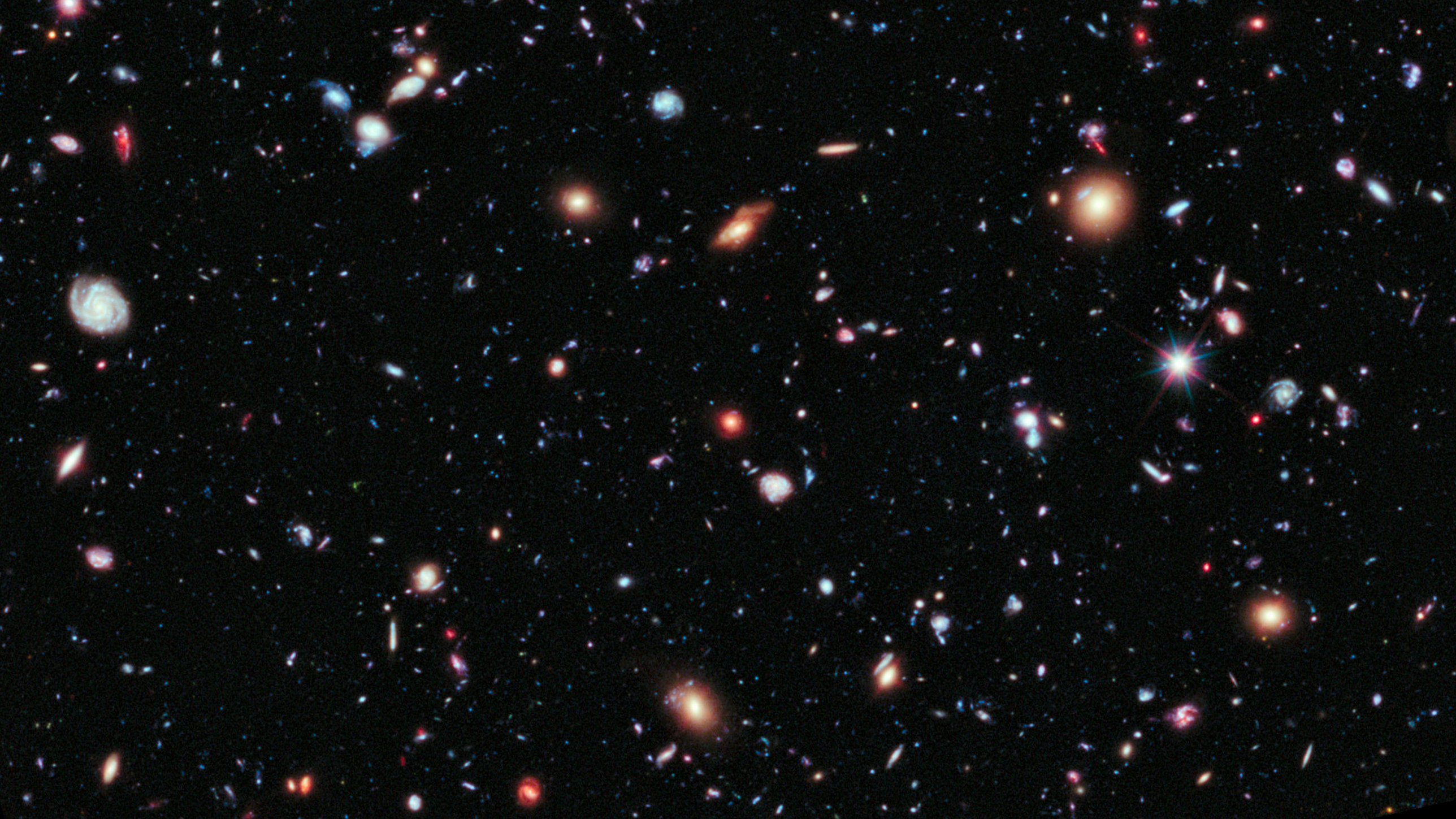
11th July 2022

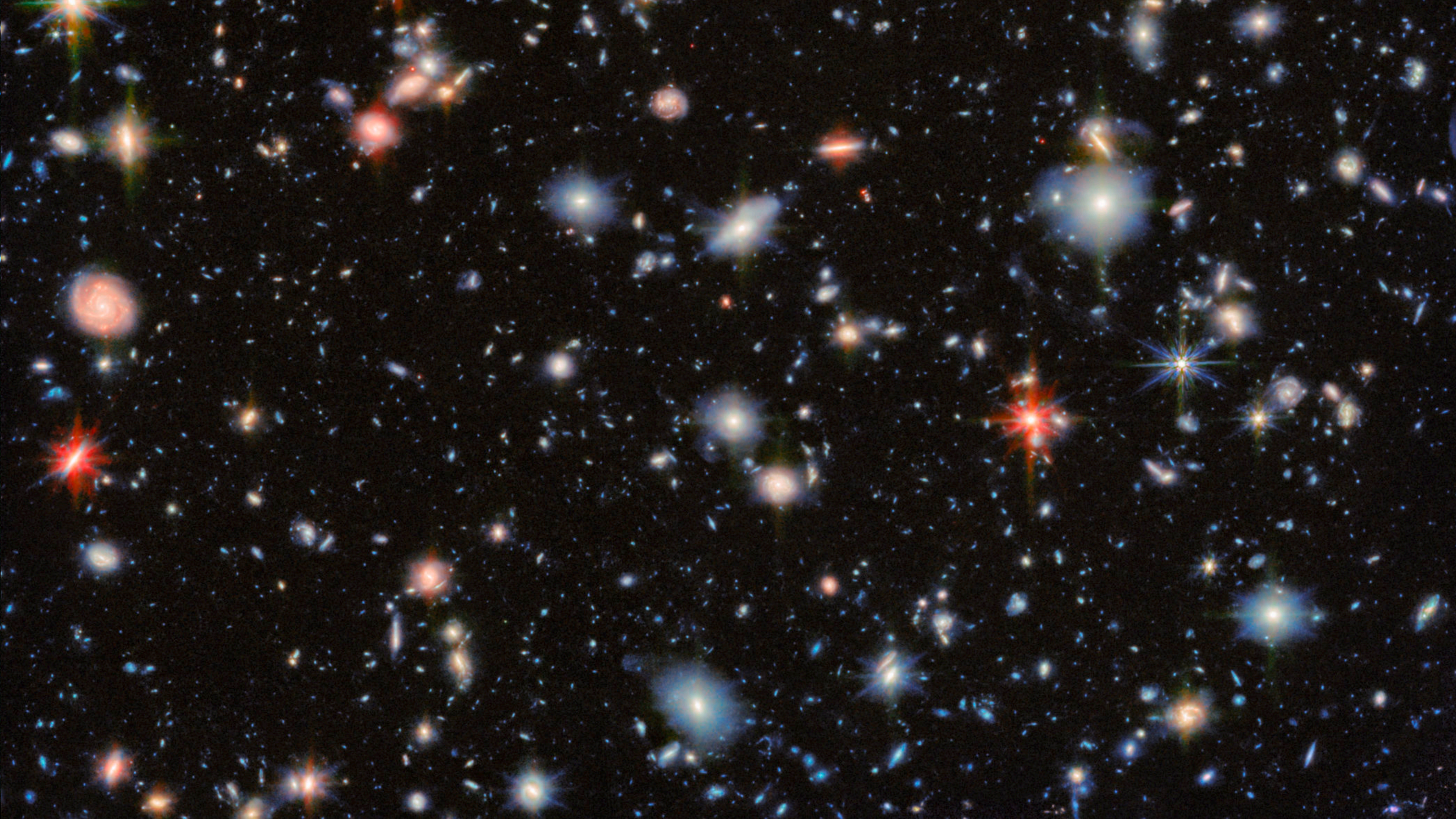
E PLURIBUS UNUM

THE WHITE HOUSE
WASHINGTON

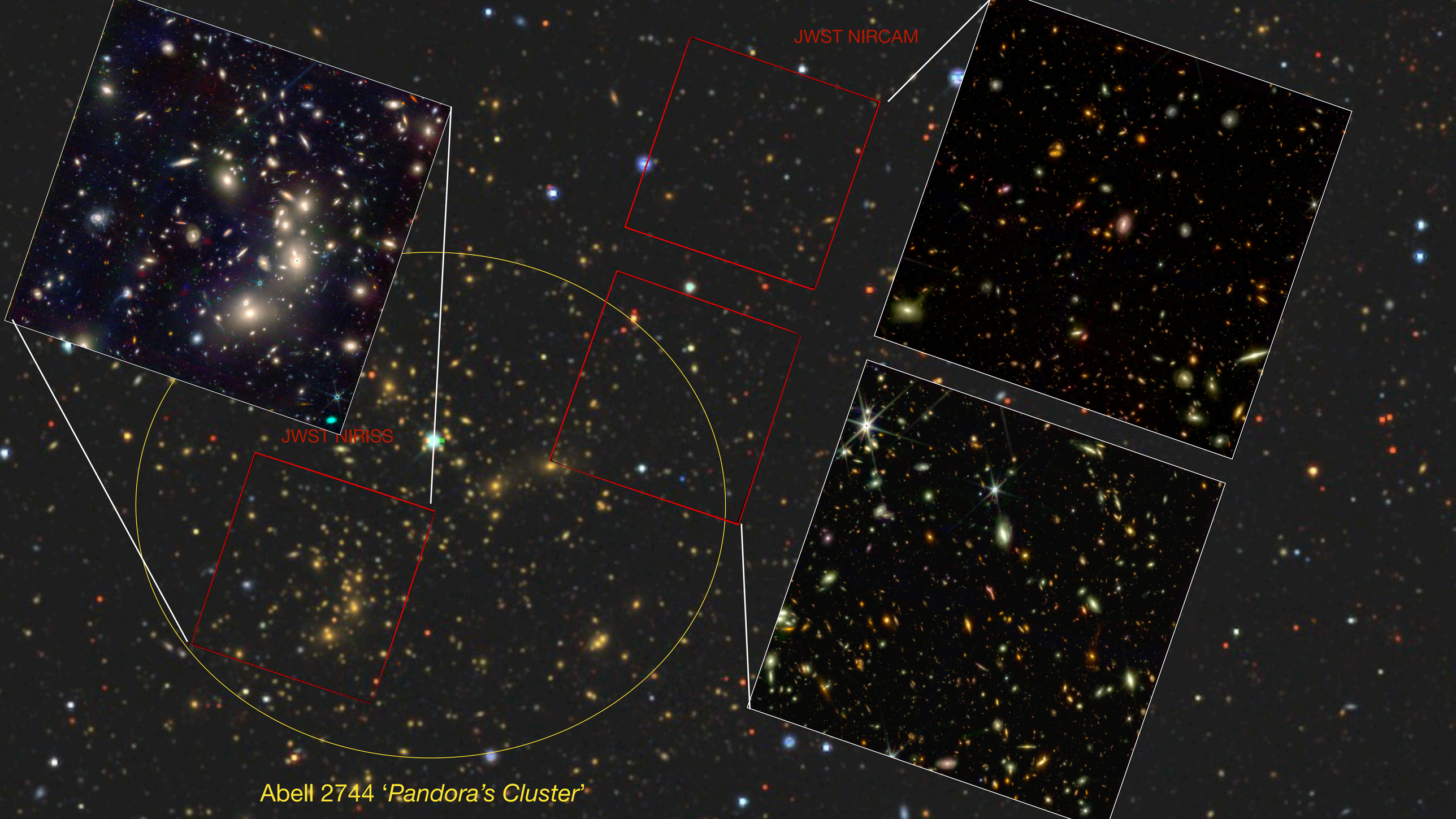

THE WHITE HOUSE
WASHINGTON





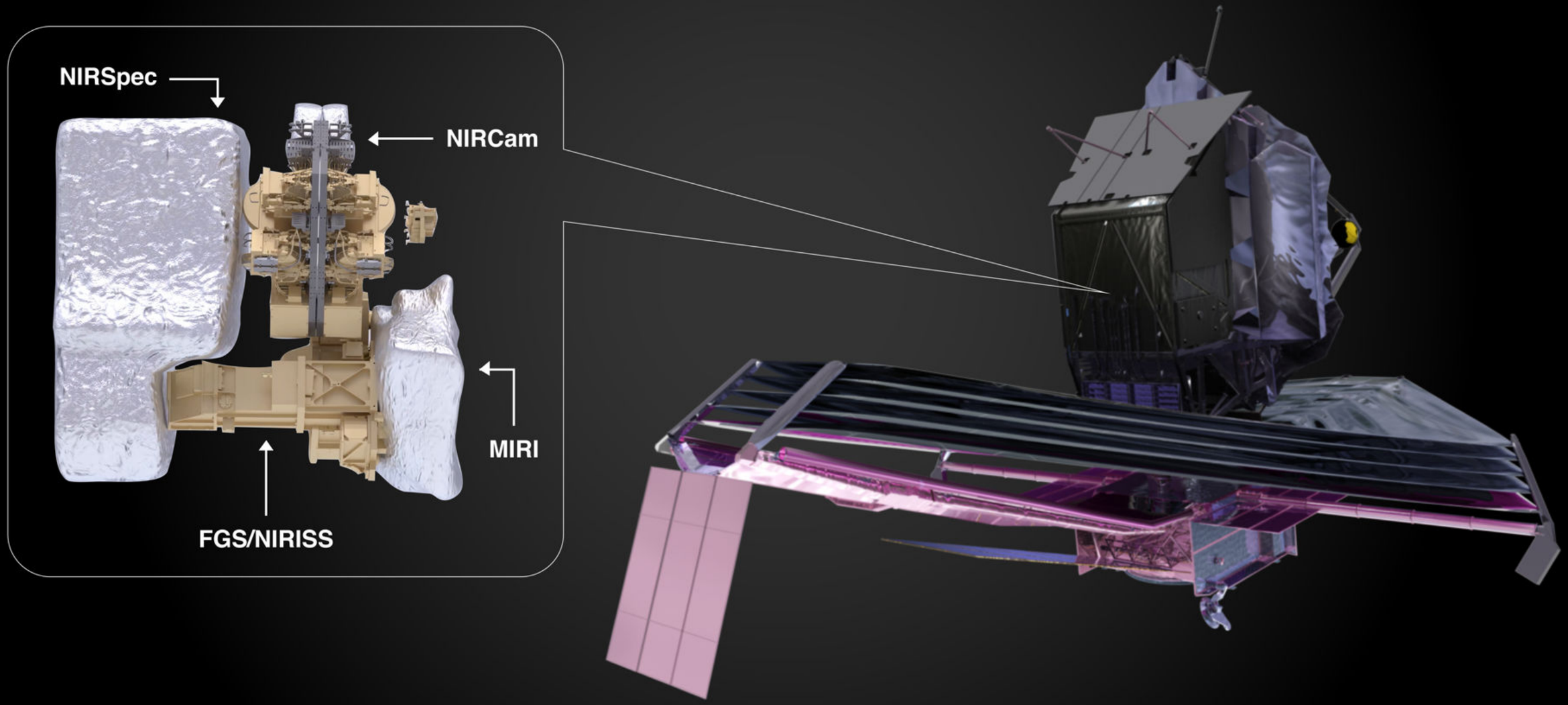


Abell 2744 ‘*Pandora’s Cluster*’

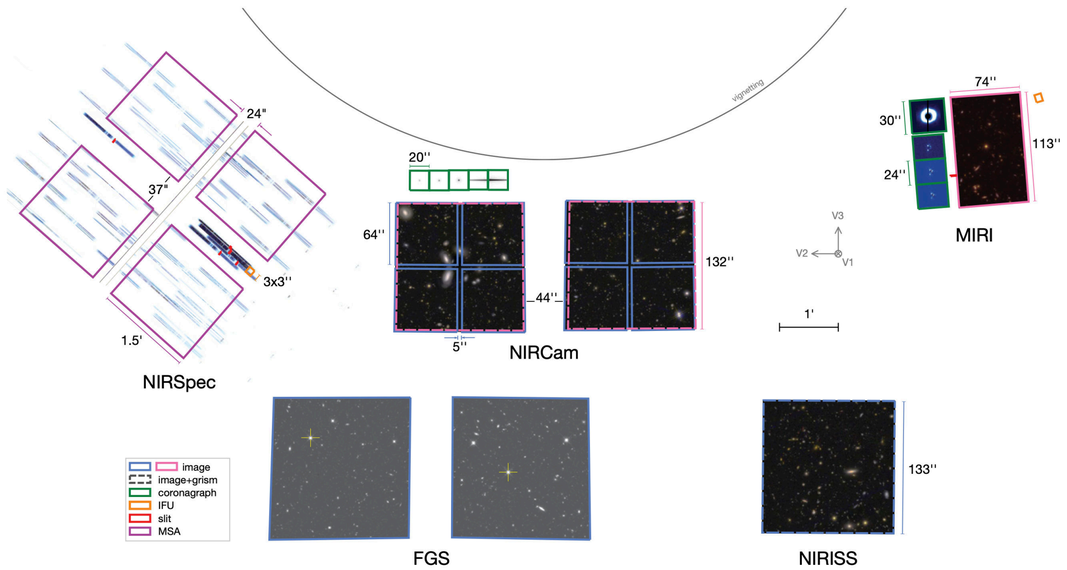

JWST NIRCAM
JWST NIRISS
Abell 2744 ‘*Pandora’s Cluster*’

JWST Instruments

Webb’s Infrared Instruments



Instruments on Board



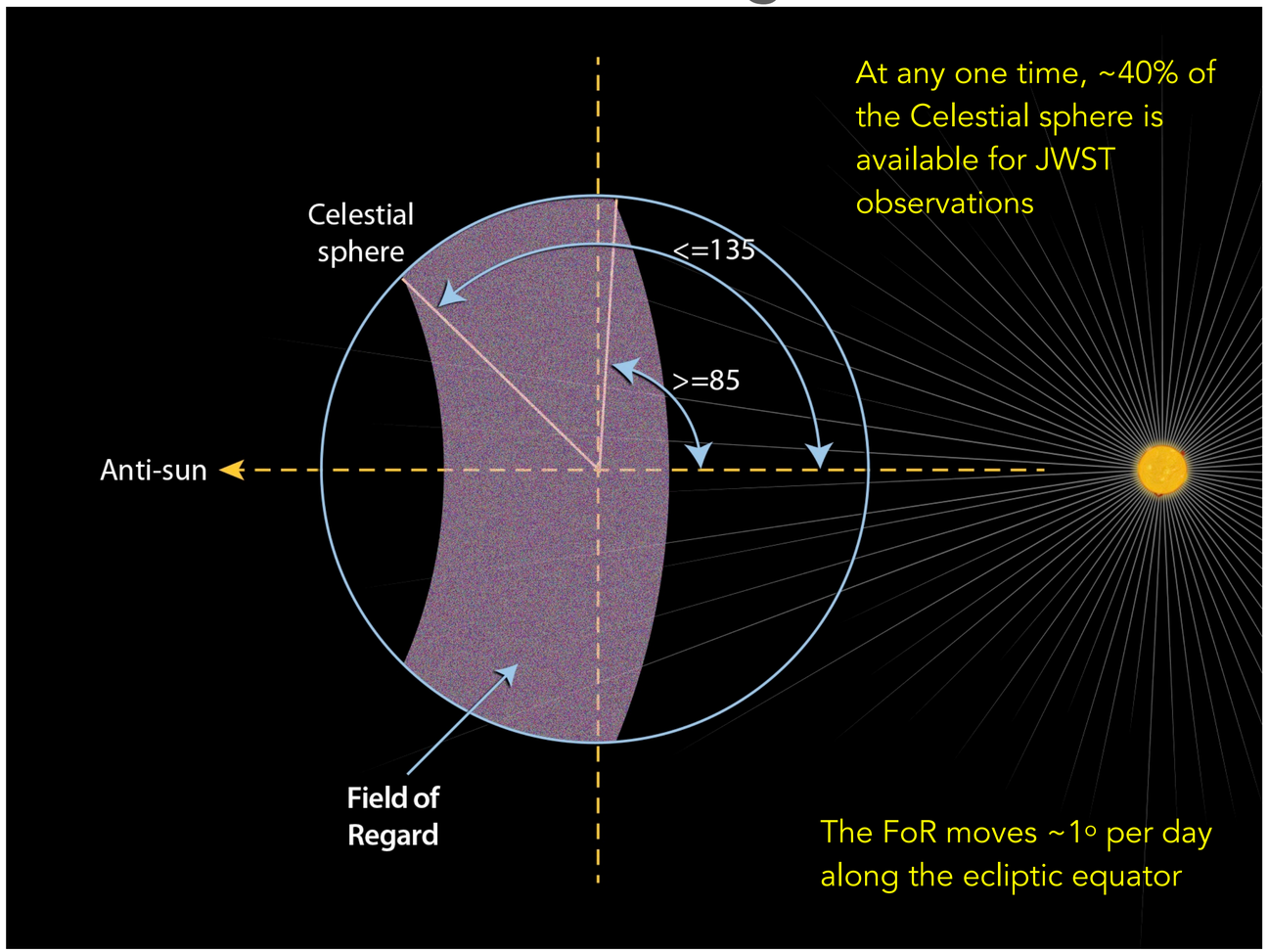
- Four instruments span 0.6–28 µm, delivering high-resolution imaging, spectroscopy and precision pointing.
- NIRCam & MIRI cameras capture stunning images and use coronagraphs to block starlight.
- NIRSpec's microshutter array enables spectra of dozens of galaxies simultaneously.
- NIRISS & FGS combine slitless spectroscopy with fine guidance for ultra-steady pointing.

Instrument	Wavelength (µm)	Primary Roles
NIRCam	0.6–5	Imaging, wavefront sensing, coronagraphy
NIRSpec	0.6–5.3	Slit, multi-object & integral-field spectroscopy
NIRISS/FGS	0.6–5	Slitless spectroscopy, interferometry & guidance
MIRI	4.9–27.9	Mid-IR imaging, spectroscopy & coronagraphs

Where can JWST point?

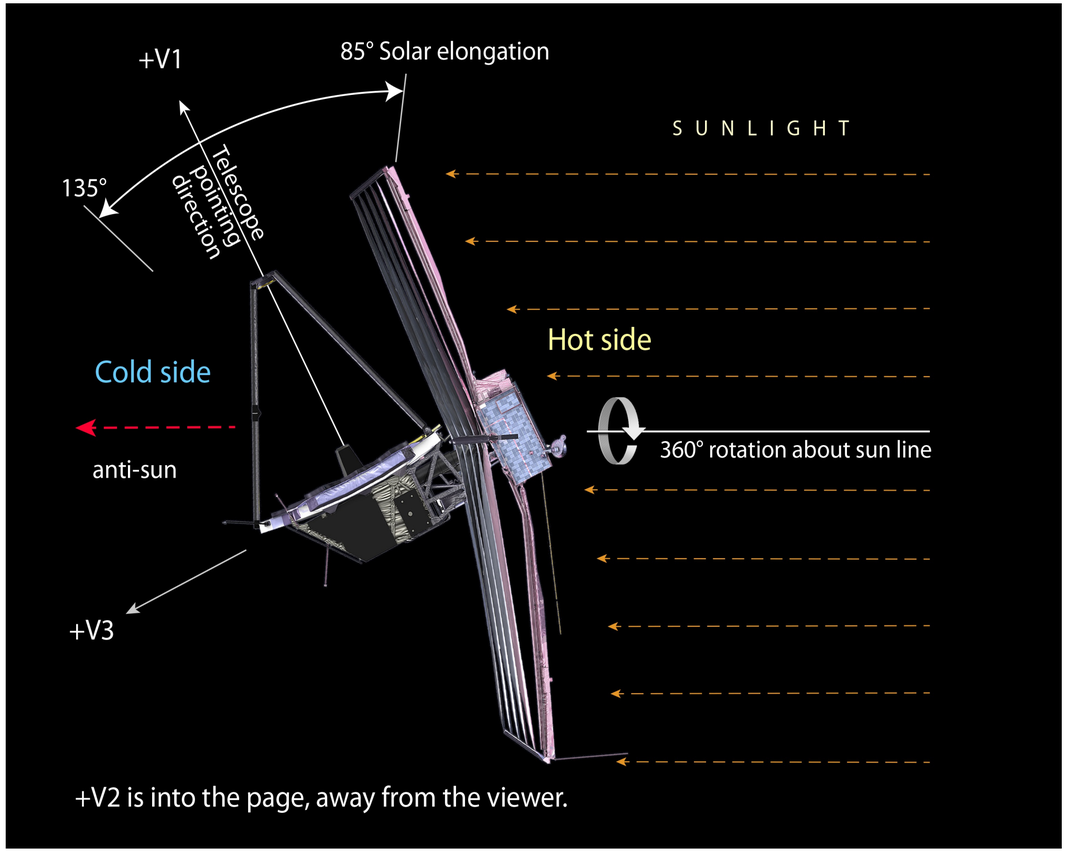
- JWST can observe the entire sky; just not all at the same time!
- If your science targets have no timing or position angle constraints, you probably don't need to concern yourself with the target visibility tools.
- However, if timing and/or position angle is important, there are special tools you need to use to compute the visibility.

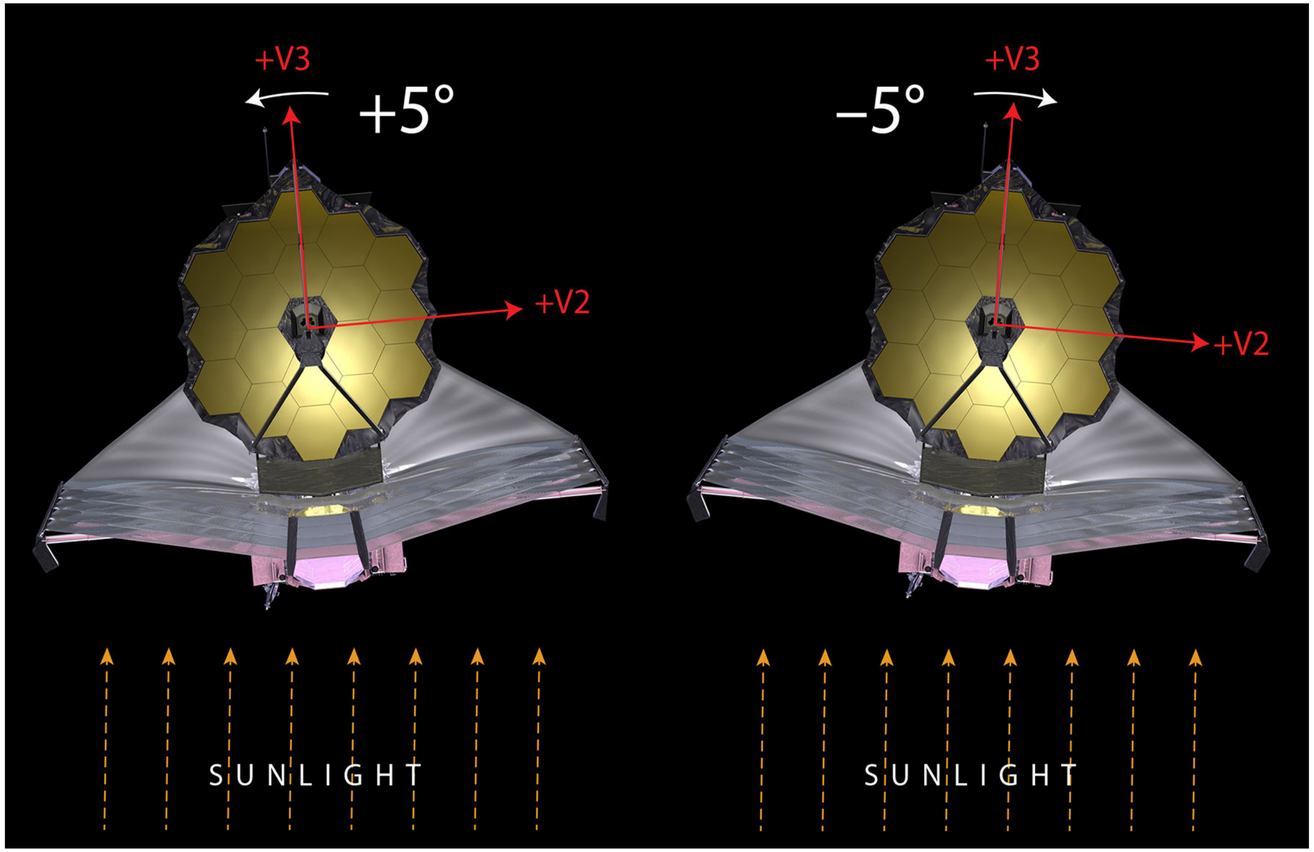
The JWST Field of Regard (FoR)



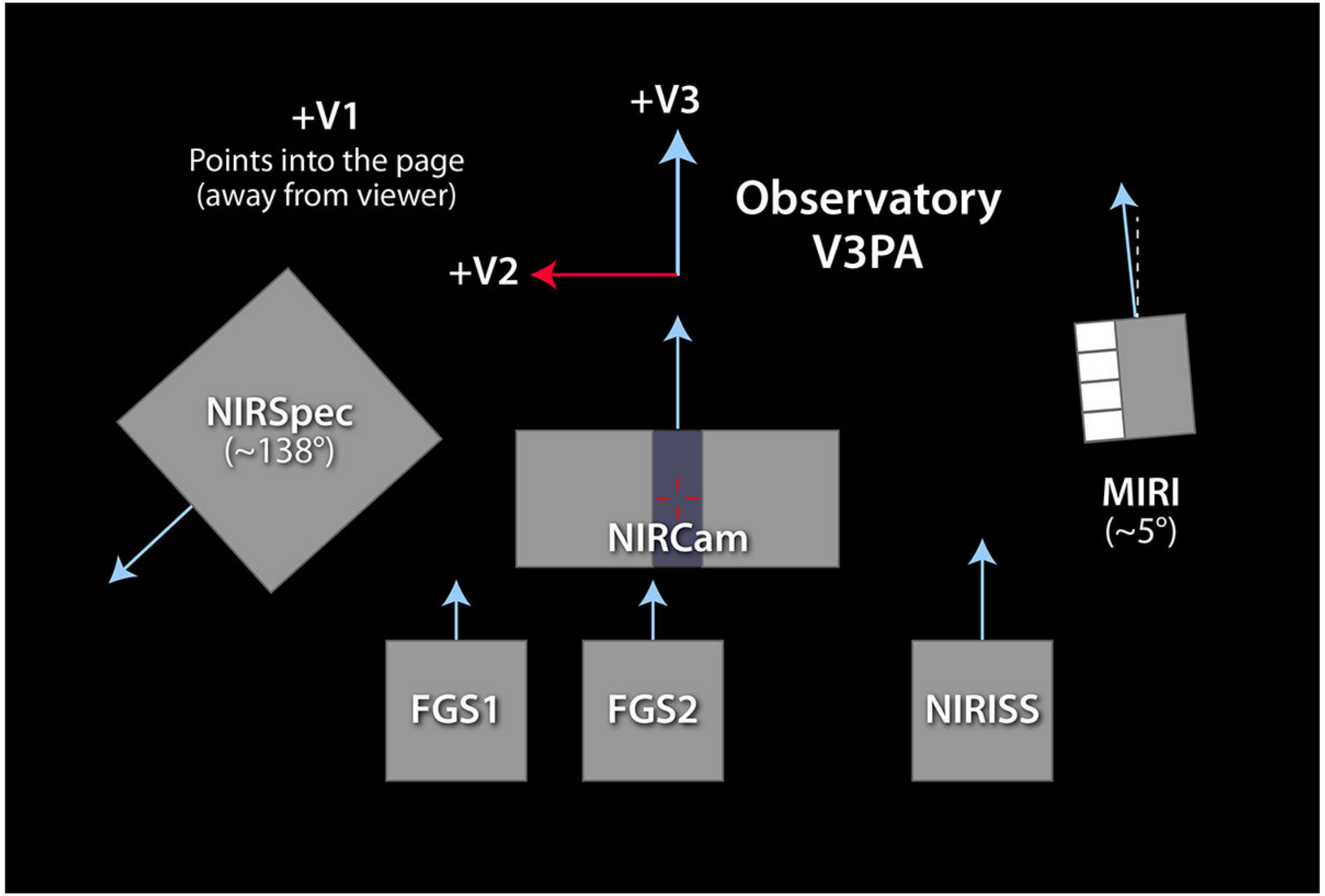
JWST Pointing Restrictions

- JWST can rotate 360° about the sun line, but can only roll about the bore sight by ~5°.
- This impacts the orientation of the JWST field of view on the sky, as well as target visibility.





JWST Position Angles

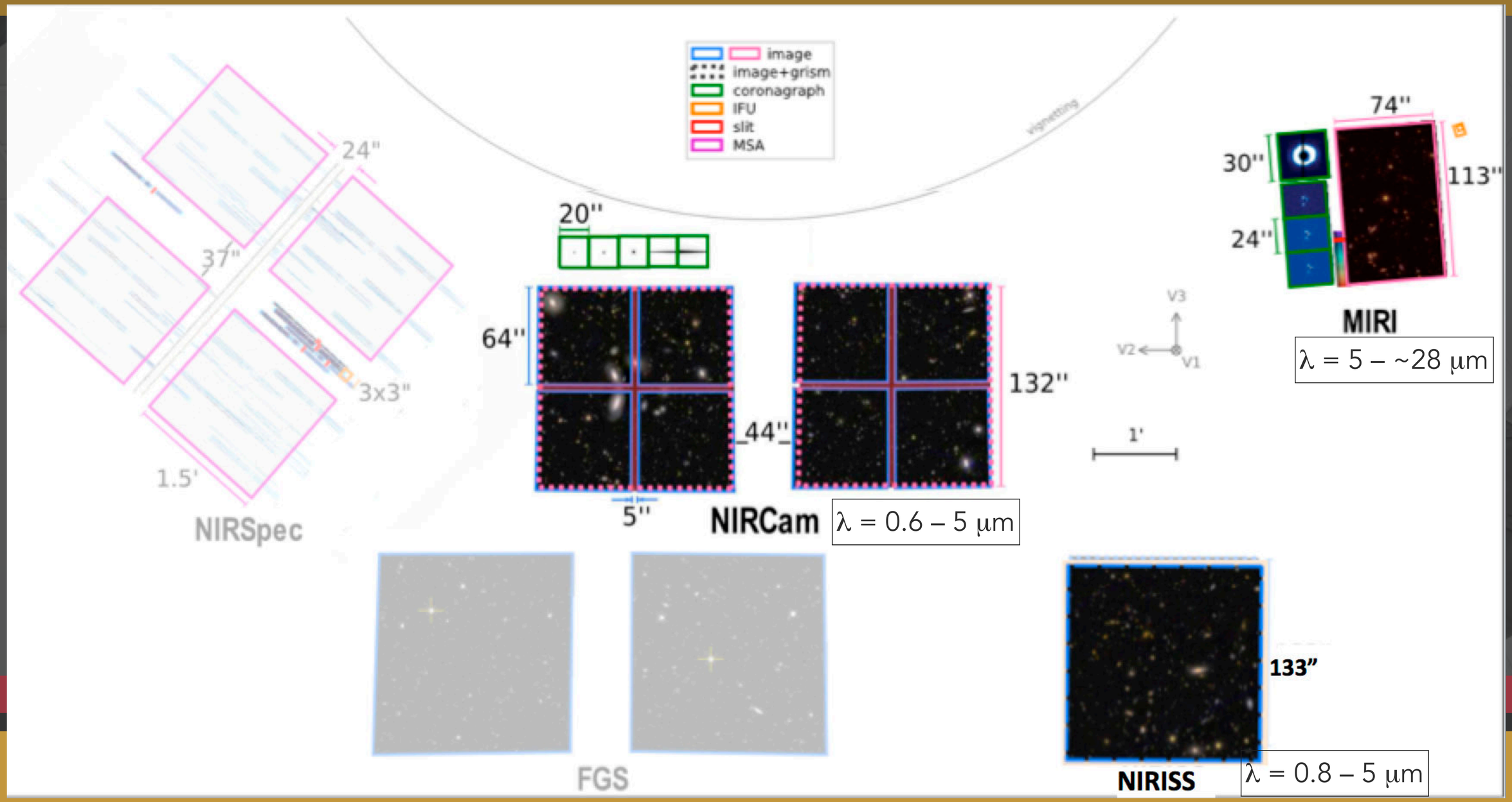


V3PA is the position angle of the V3 observatory axis when Projected on the sky (measured 'east of north').

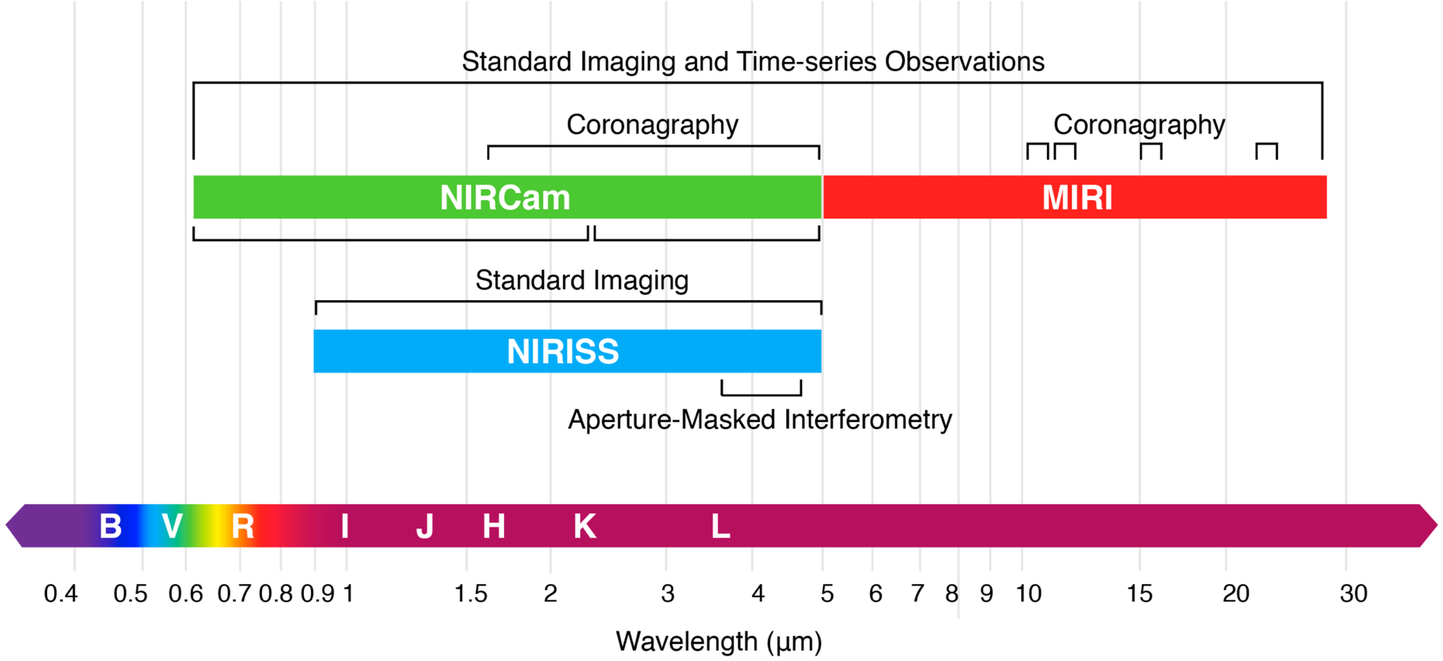
The reference axes of all SIs except NIRSpec are closely aligned with the V3 axis.

Imaging with JWST

JWST Imaging Instruments



JWST Imaging Summary

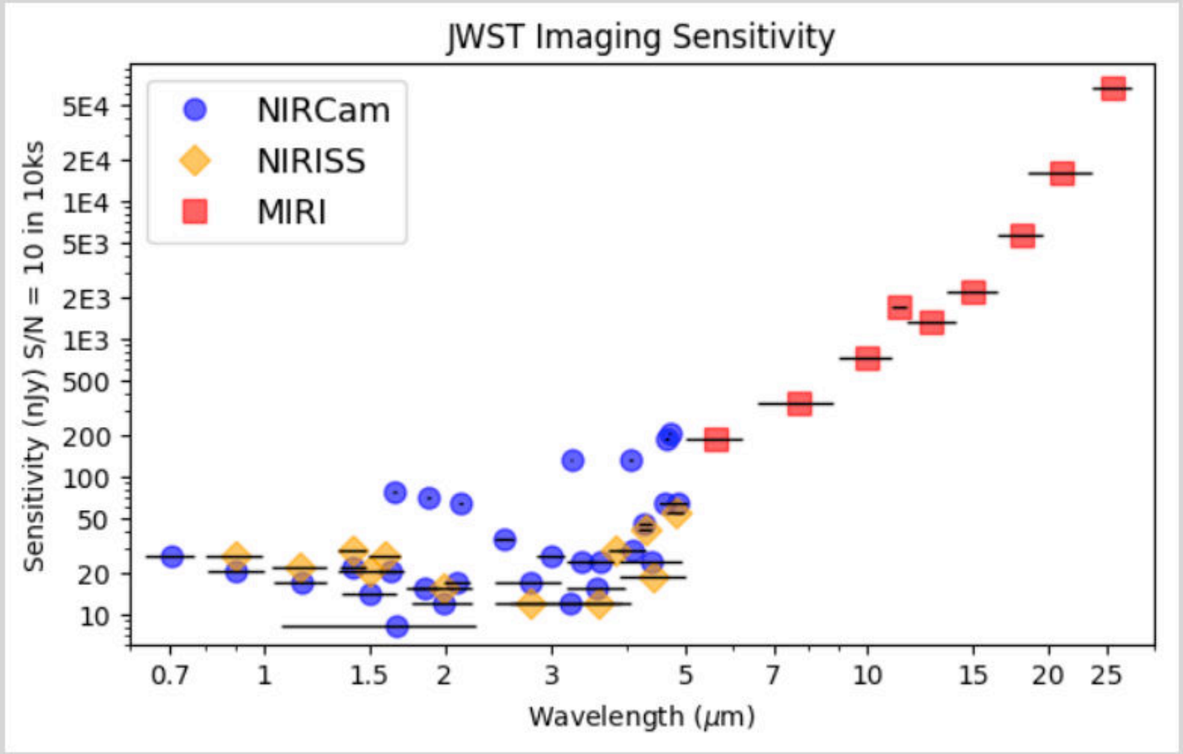


Instrument	Wavelength range	Mode of use	
NIRCam	0.6 μm < λ < 5 μm	Primary or parallel	Standard, time-series, and coronagraphic imaging
MIRI	5.6 μm < λ < 25.5 μm	Primary or parallel	Standard, time-series, and coronagraphic imaging
NIRISS	0.8 μm < λ < 5 μm	Parallel only	Standard and high resolution (AMI) imaging

NIRCam must be prime for NIRISS standard imaging

See https://jwst-docs.stsci.edu/methods-and-roadmaps/jwst-imaging

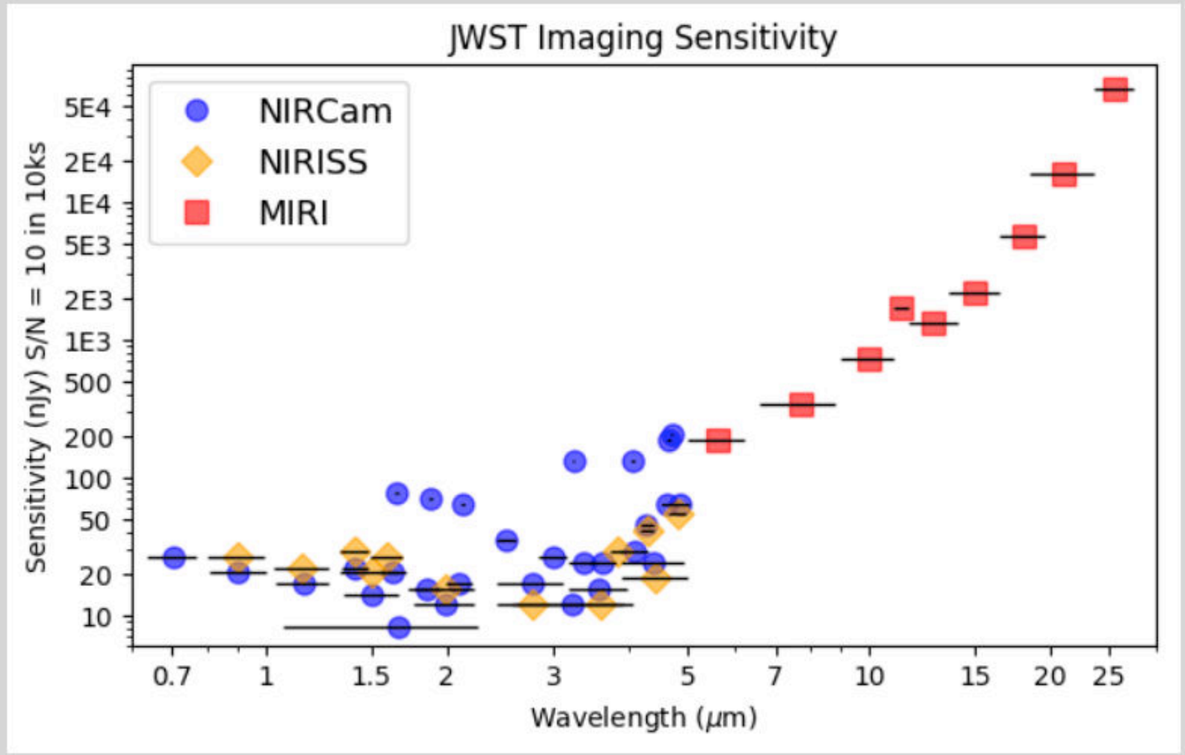
JWST Imaging Summary



The S/N = 10 detection limits of JWST's imaging instruments in 10 ks, shown for every available filter. The horizontal error bars represent the width of the filter. Sources are assumed to have a flat spectrum in nJy and a benchmark background, as described on the JWST Background Model article. Please use the JWST Exposure Time Calculator (ETC) to calculate sensitivity estimates for your specific proposed observations.

See https://jwst-docs.stsci.edu/methods-and-roadmaps/jwst-imaging

JWST Imaging Summary



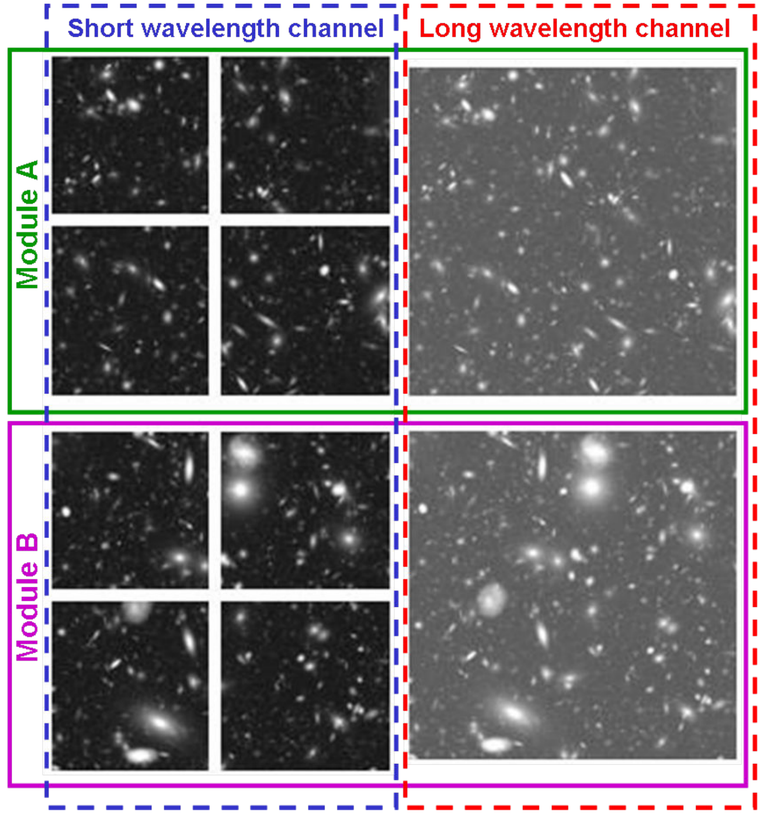
The S/N = 10 detection limits of JWST's imaging instruments in 10 ks, shown for every available filter. The horizontal error bars represent the width of the filter. Sources are assumed to have a flat spectrum in nJy and a benchmark background, as described on the JWST Background Model article. Please use the JWST Exposure Time Calculator (ETC) to calculate sensitivity estimates for your specific proposed observations.

	PSF FWHM (pix)	Plate scale	Nyquist sampled
NIRCam	0.987–2.341 (SW) 1.340–2.574 (LW)	0.031 (SW) 0.063 (LW)	>2 μm (SW) >4 μm (LW)
NIRISS	2 pix @ 3.4 μm	0.066	>3.4 μm
MIRI	1.00–7.45	0.11	>6 μm

See https://jwst-docs.stsci.edu/methods-and-roadmaps/jwst-imaging

NIRCam

- Imaging filter centers from λ = 0.7 – 4.8 μm
- Two identical modules with adjacent fields of view: 2.’2 x 4.’4 total
  - SW Camera: 0.032 "/pix < 2.4 μm
  - LW Camera: 0.065 "/pix > 2.4 μm
  - SW and LW can observe simultaneously
- Coronagraphic capability
- R~1700 grisms for 2.4 - 5 μm slitless spectroscopy
- Also serves as the observatory wavefront sensor



NIRCam Modules, Fields of View, Channels

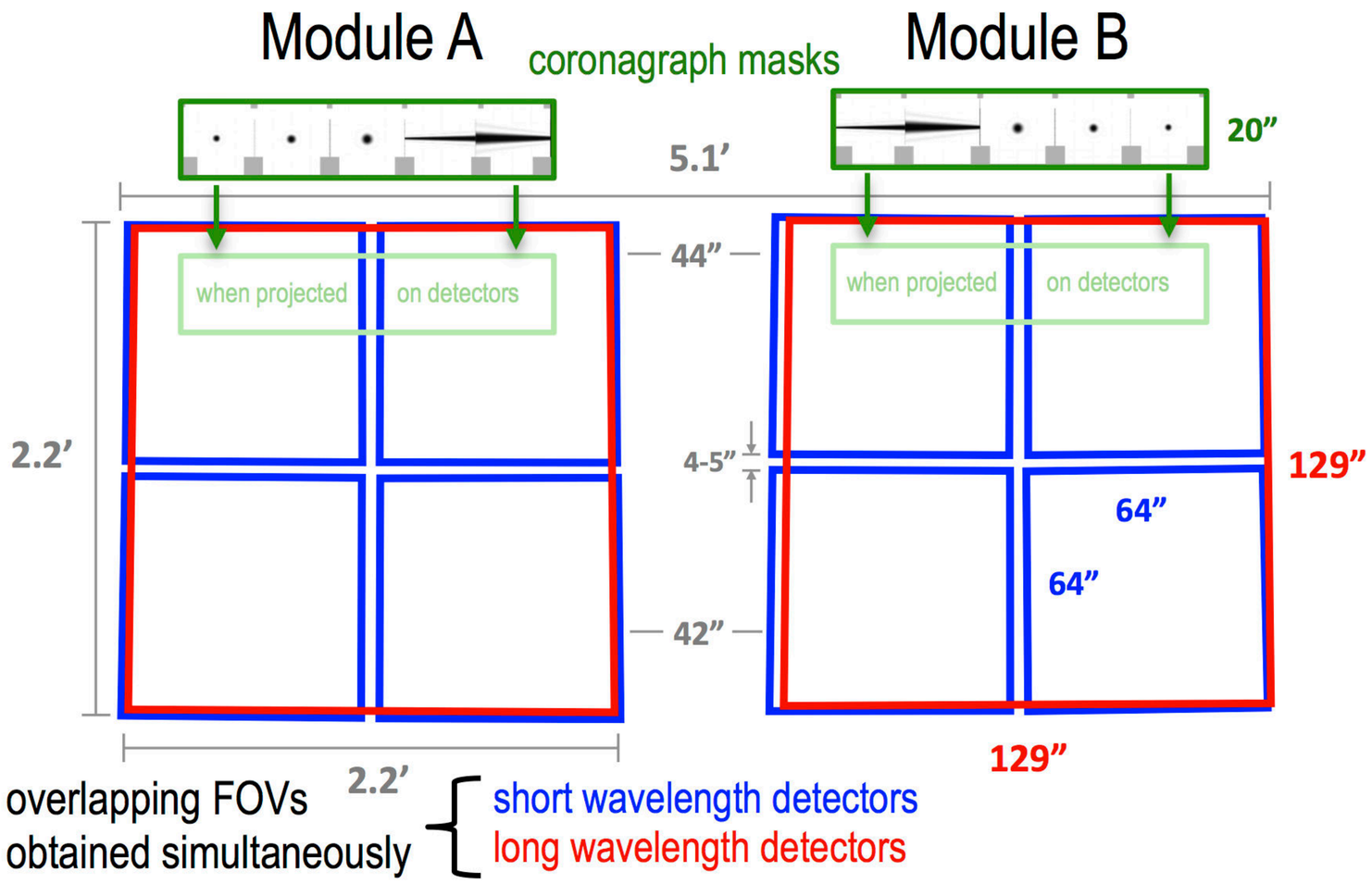
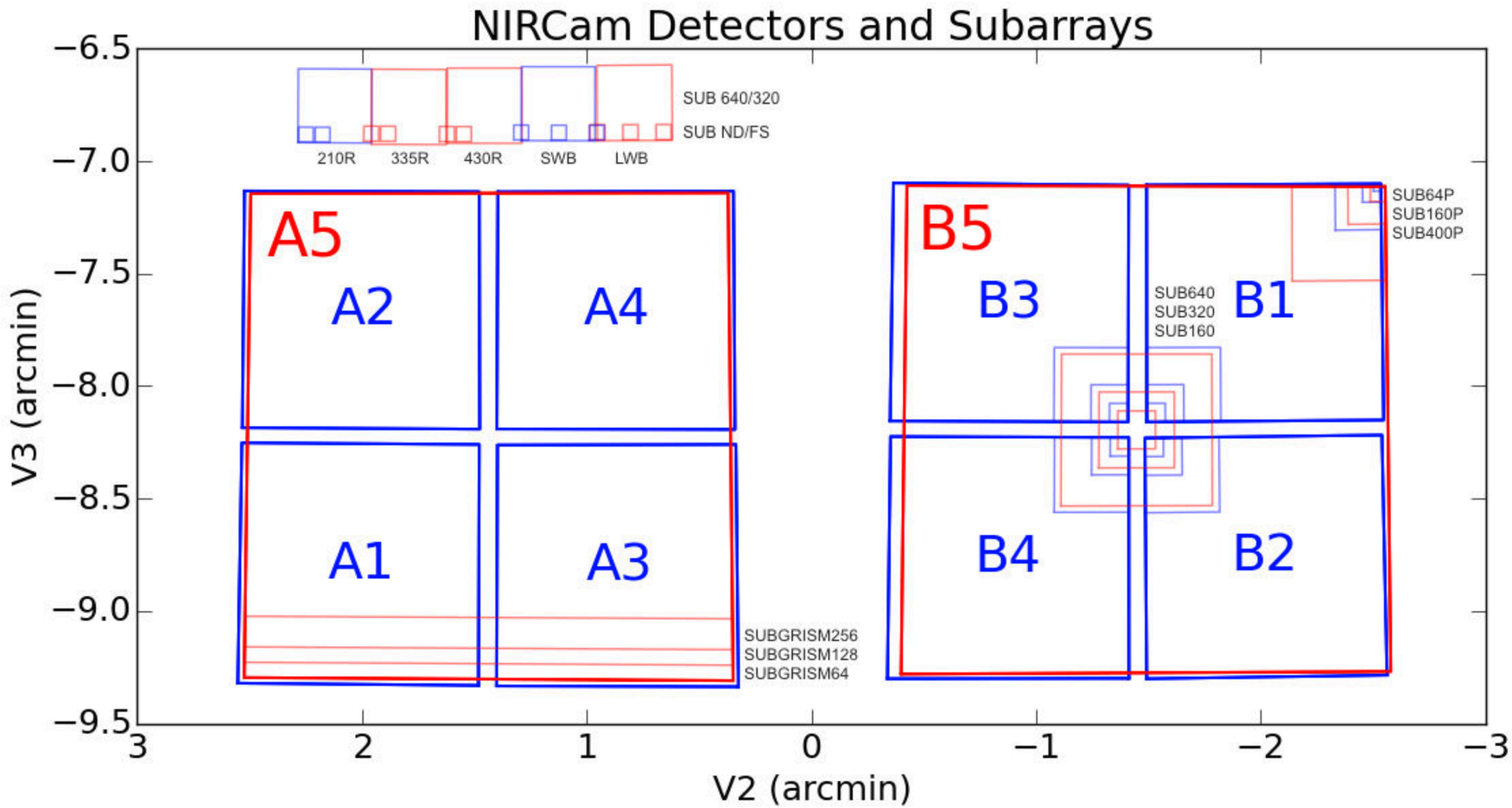


Table 1. Properties of NIRCam short and long wavelength channels

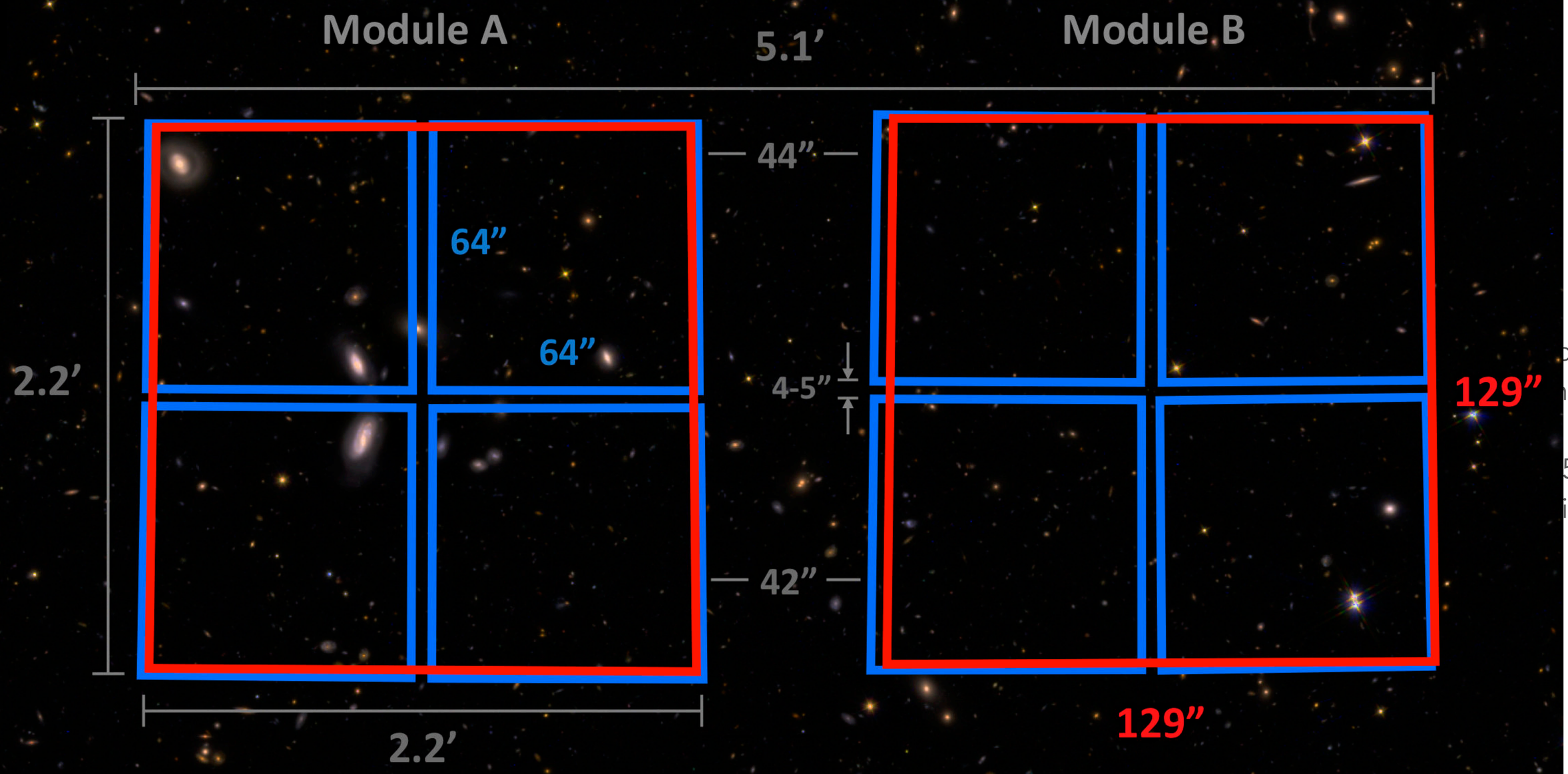
	Short wavelength channel	Long wavelength channel
Wavelength range	0.6–2.3 μm	2.4–5.0 μm
Nyquist wavelength[1]	2.0 μm	4.0 μm
Fields of view	2 × 2.2′ × 2.2′ (with 4"–5" gaps)	2 × 2.2′ × 2.2′
Imaging pixels	8 × 2040 × 2040 pixels	2 × 2040 × 2040 pixels
Pixel scale	0.031 ″/pixel	0.063 ″/pixel

[1] PSF FWHM ~ 2 pixels; undersampled at shorter wavelengths

NIRCam Detectors and Subarrays



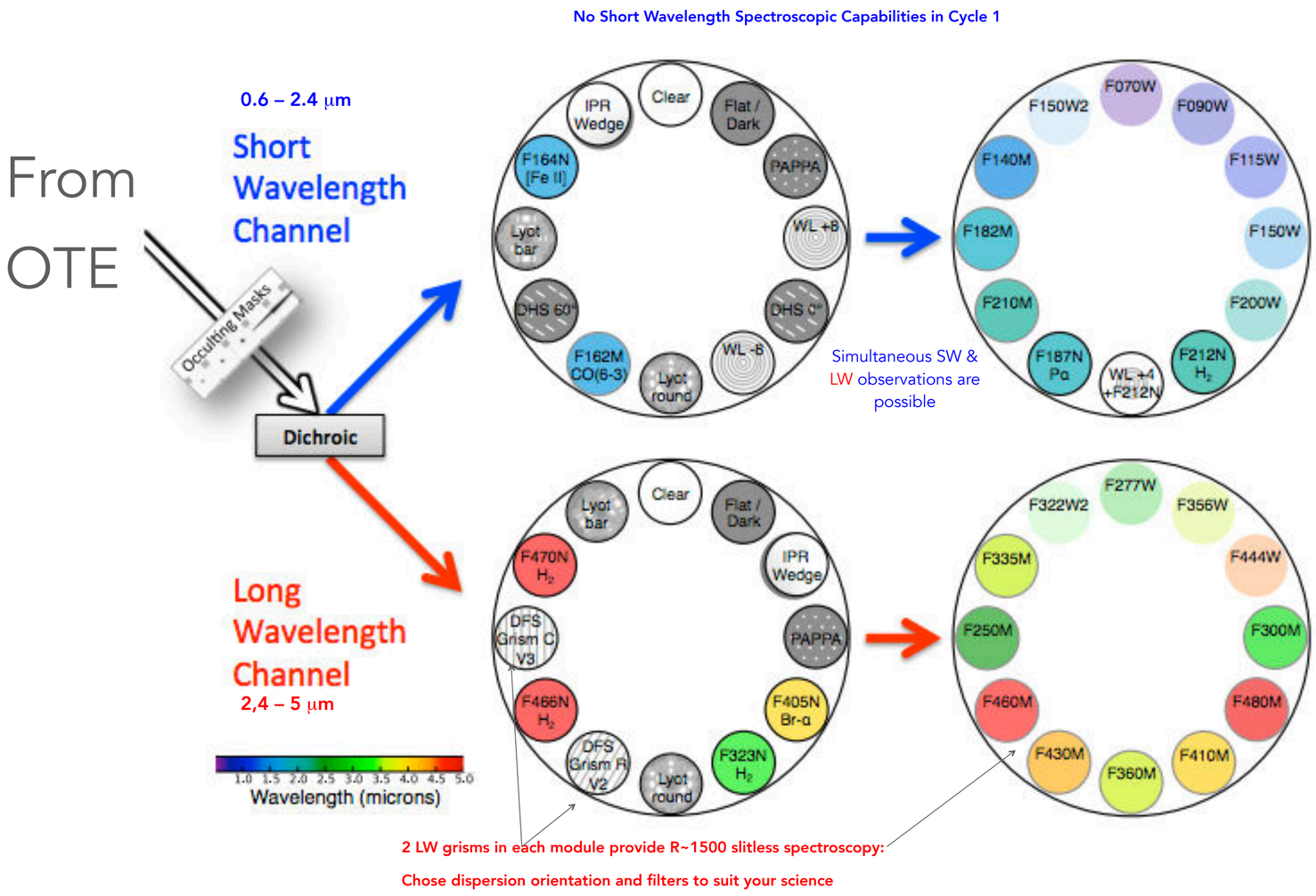
Blue and red correspond to the short and long wavelength channels, respectively. The 10 NIRCam detectors (A1–5 and B1–5) are labeled within each module (from Jdox).



Short Wavelength Channel (0.6 – 2.3 microns) 8 x 2040 x 2040 0.031”/pix

Long Wavelength Channel (2.4 – 5.0 microns) 2 x 2040 x 2040 0.063”/pix

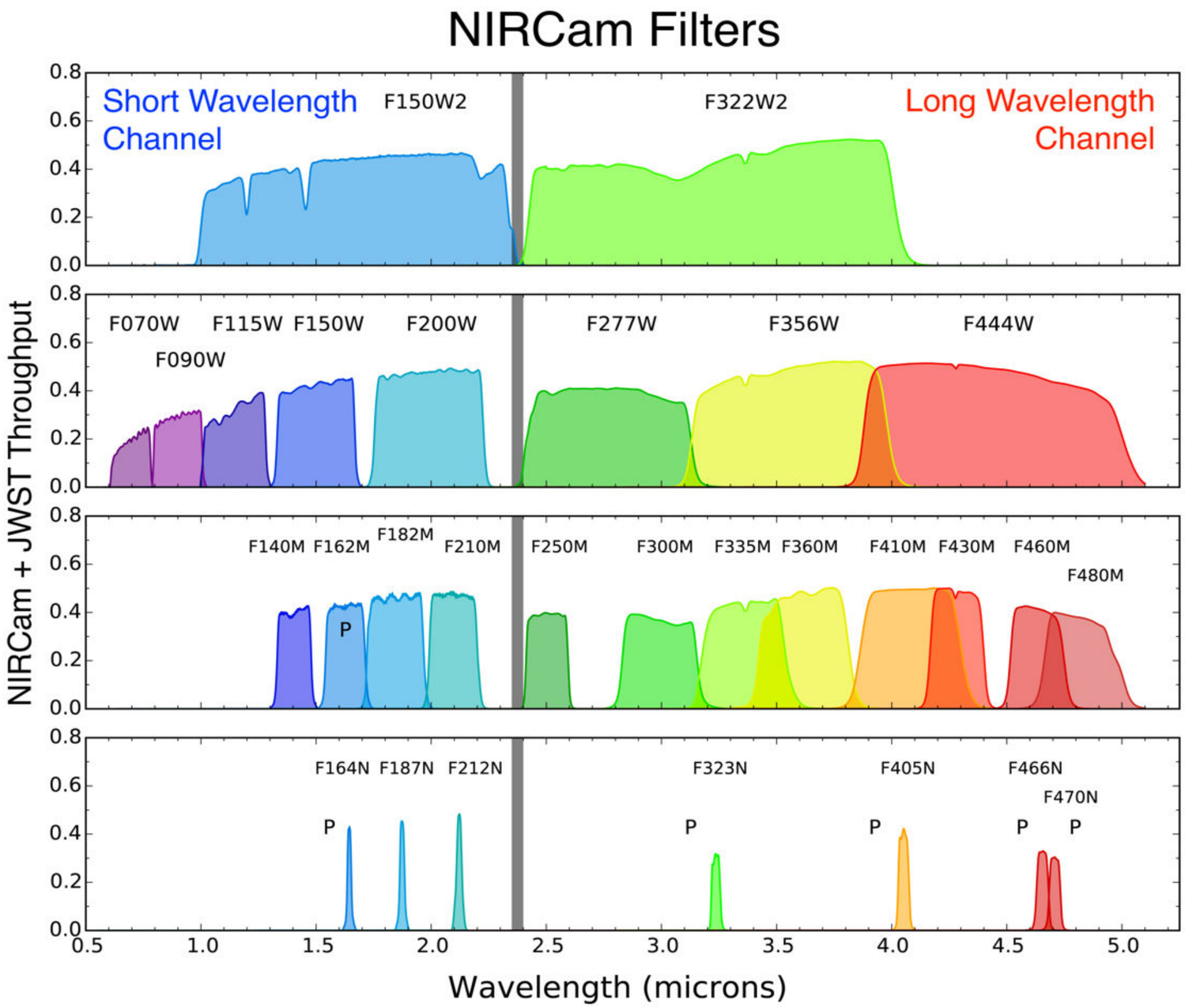
NIRCam Modes: Selectable with wheels



NIRC

F

C

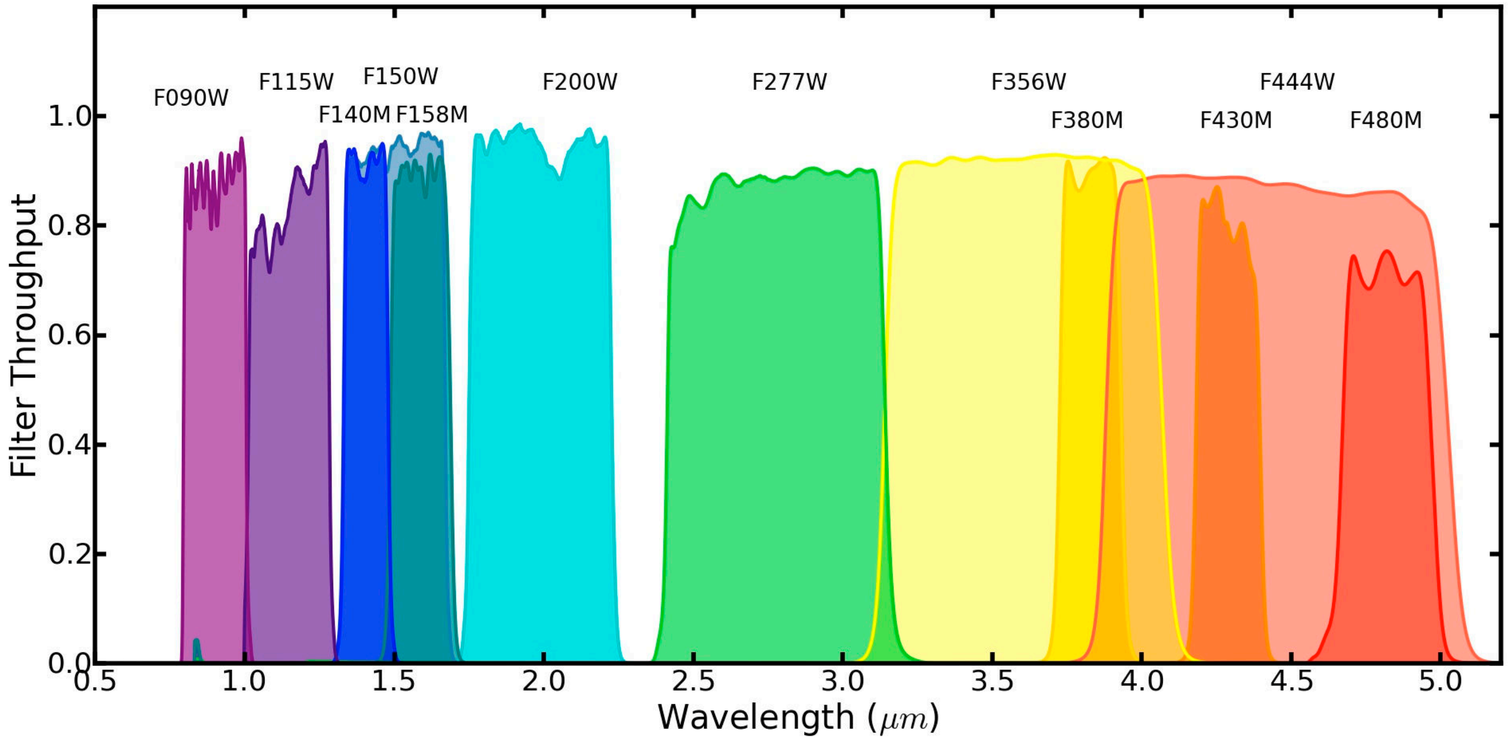

NIRCam Filters
Short Wavelength Channel
Long Wavelength Channel
F150W2
F322W2
F070W
F090W
F115W
F150W
F200W
F277W
F356W
F444W
F140M
F162M
F182M
F210M
F250M
F300M
F335M
F360M
F410M
F430M
F460M
F480M
P
F164N
F187N
F212N
F323N
F405N
F466N
F470N
NIRCam + JWST Throughput
Wavelength (microns)
0.0
0.2
0.4
0.6
0.8
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0

NIRISS Imaging

- Imaging from λ = 0.6 – 5 μm with a single HAWAII-2RG detector
- Similar to a single NIRCam module with a reduced filter set
- 0.065 "/pix scale for all filters
- Imaging in parallell with NIRCam only
- Also capable of WFSS and SOSS spectrpscopy (L. Albert)

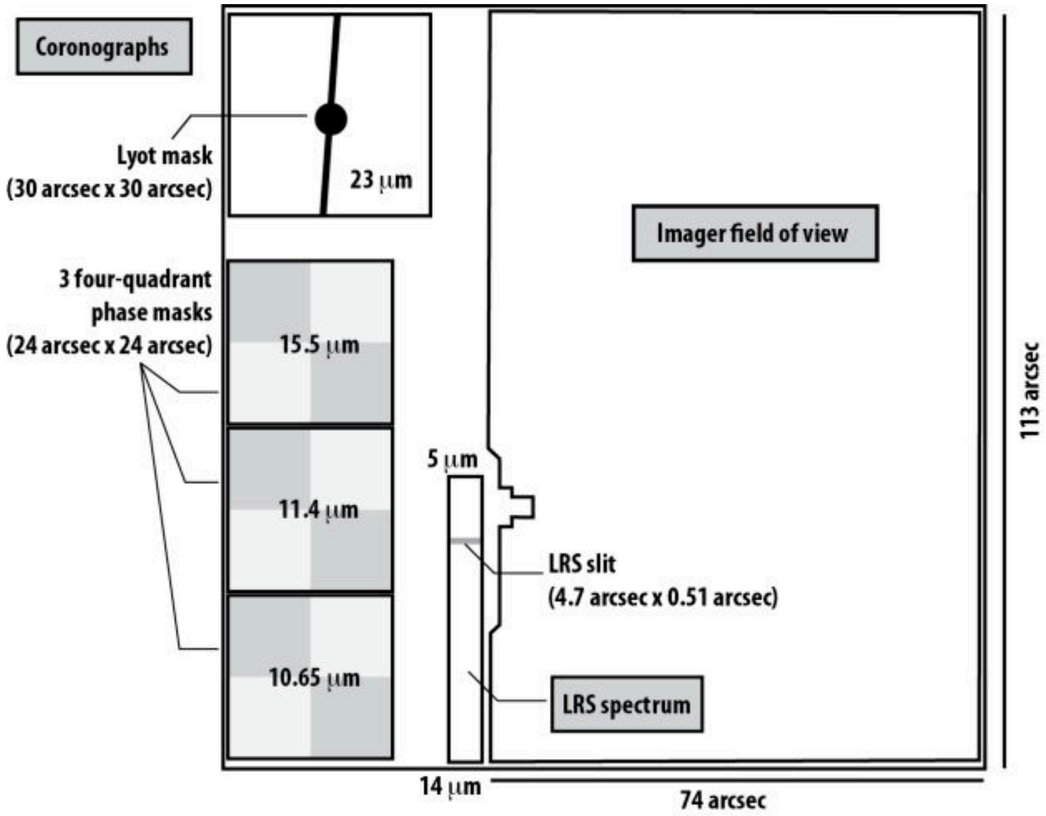
NIRISS Imaging

- Imaging from λ = 0.6 – 5 μm with a single HAWAII-2RG detector
- Similar to a single NIRCam module with a reduced filter set
- 0.065 "/pix scale for all filters
- Imaging in parallell w
- Also capable of WFS



MIRI

- Imaging filter centers from λ = 5.6 – 25.5 μm
- MIRI Imager Module has different regions:
  - Imager: 74″ x 113″
  - Low-res spectrograph slit + spectrum
  - Coronagraphs: 3 x 4QPMS + 1 Lyot
- Pixel scale is 110 mas for all imager regions
  - Single detector, Nyquist sampled at λ = 7 μm
- Separate aperture for medium-resolution spectrograph (MRS)



See https://jwst-docs.stsci.edu/mid-infrared-instrument/miri-observing-modes/miri-imaging

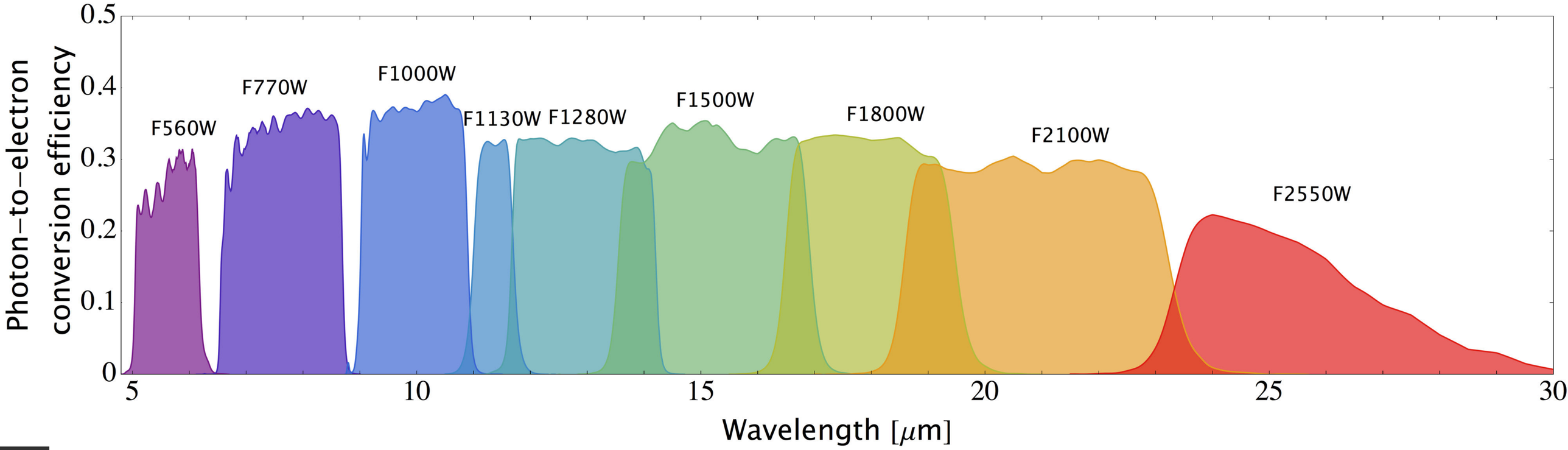
MIRI Filters

Filter name	λ_0 (μm)	$\Delta\lambda$ (μm)	FWHM (arcsec)	Point source detection limit (μJy)	Extended source detection limit † (μJy arcsec^{-2})	Comment
F560W[1]	5.6	1.2	0.22	0.182	0.22	Broadband Imaging
F770W	7.7	2.2	0.25	0.276	0.26	PAH, broadband imaging
F1000W	10.0	2.0	0.32	0.592	0.53	Silicate, broadband imaging
F1130W	11.3	0.7	0.36	1.465	1.2	PAH, broadband imaging
F1280W	12.8	2.4	0.41	0.945	0.83	Broadband imaging
F1500W	15.0	3.0	0.48	1.618	0.93	Broadband imaging
F1800W	18.0	3.0	0.58	3.881	1.9	Silicate, broadband imaging
F2100W	21.0	5.0	0.67	7.550	3.3	Broadband imaging
F2550W	25.5	4.0	0.82	26.959	9.1	Broadband imaging

† Signal/noise = 10 for 10^4 s on-source integration time

MIRI Filters

Filter name	λ_0 (μm)	$\Delta\lambda$ (μm)	FWHM (arcsec)	Point source detection limit (μJy)	Extended source detection limit † (μJy arcsec^{-2})	Comment
F560W[1]	5.6	1.2	0.22	0.182	0.22	Broadband Imaging
F770W	7.7	2.2	0.25	0.276	0.26	PAH, broadband imaging
F1000W	10.0	2.0	0.32	0.592	0.53	Silicate, broadband imaging



High Contrast Imaging with JWST

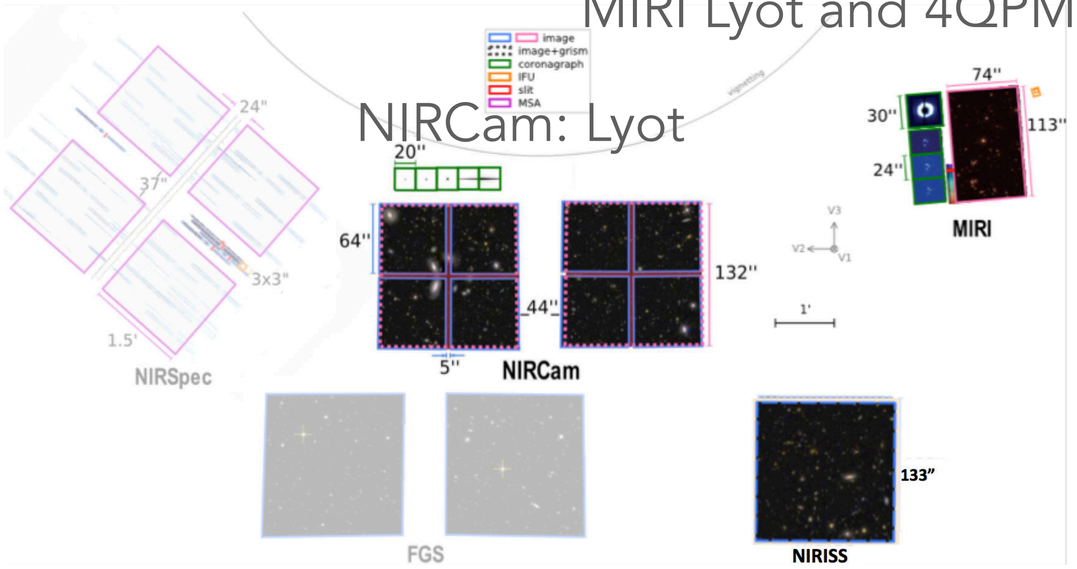
High Contrast Imaging allows observing

High Contrast Imaging with JWST

Three JWST instruments are equipped for HCI

- MIRI using a coronagraph and a Four-Quadrant Phase Mask (4QPM)
- NIRCam coronagraph
- NIRISS Aperture Masking Interferometer (see hands-on exercise by Loic Albert)

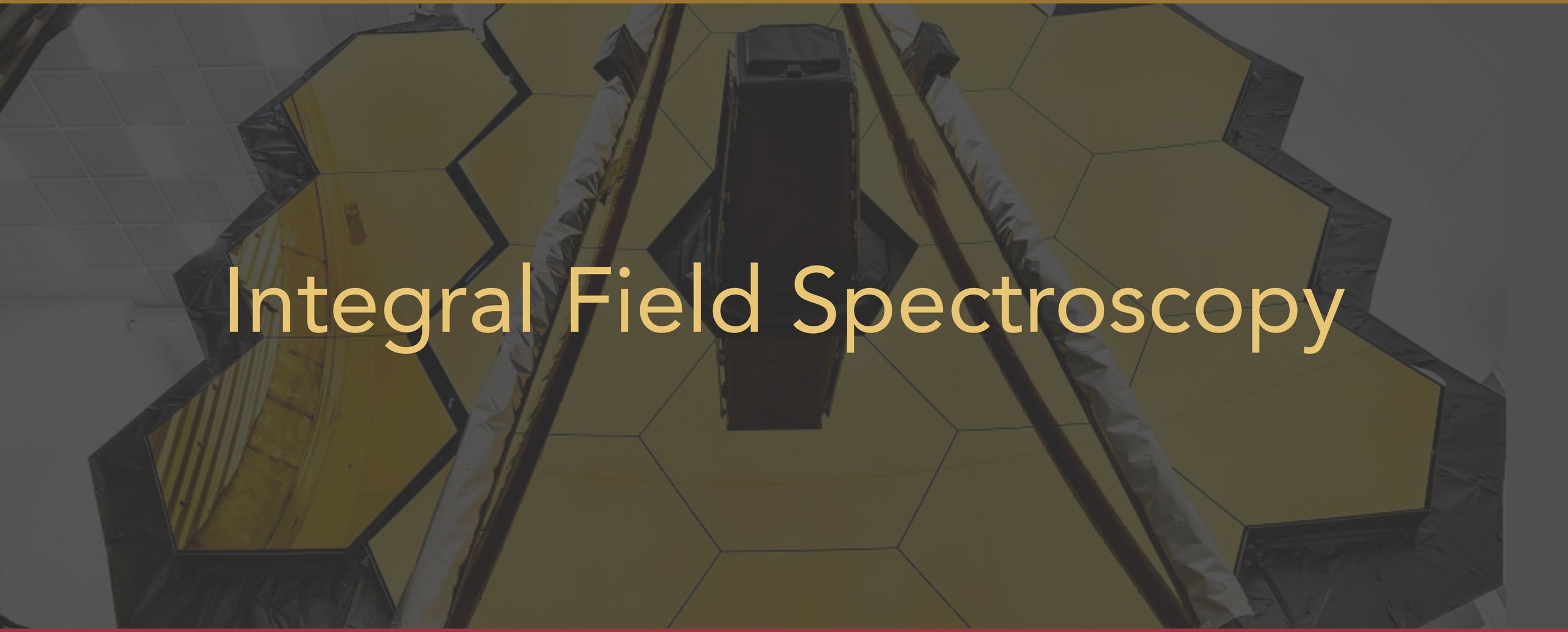
MIRI Lyot and 4QPM



NIRCam: Lyot

NIRISS : AMI

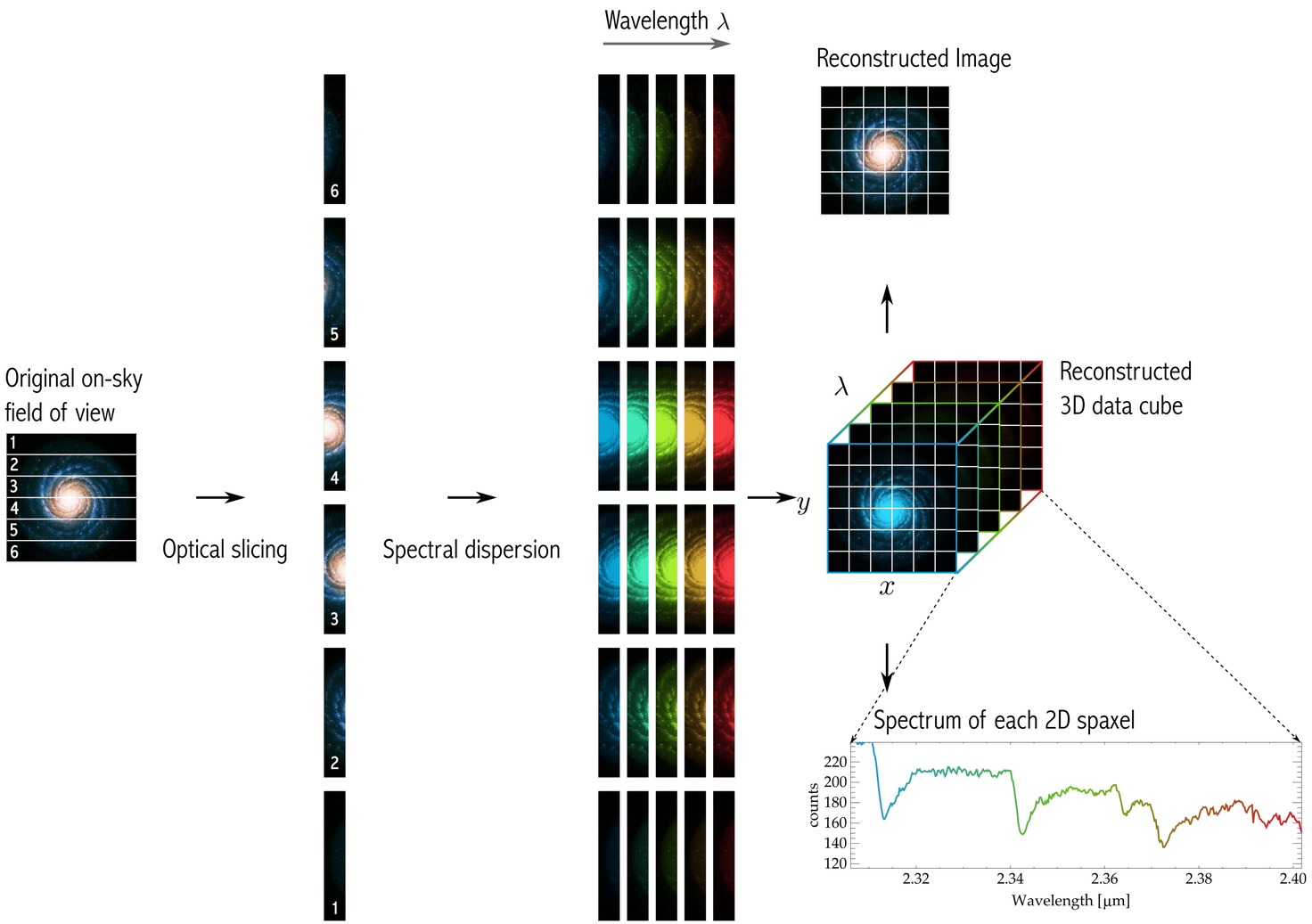
https://jwst-docs.stsci.edu/methods-and-roadmaps/jwst-imaging



Integral Field Spectroscopy

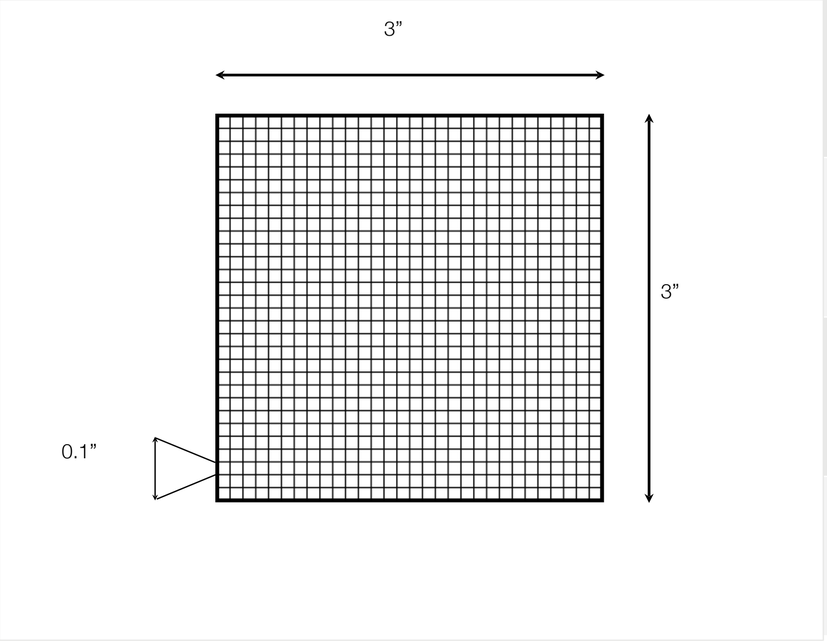
Concept

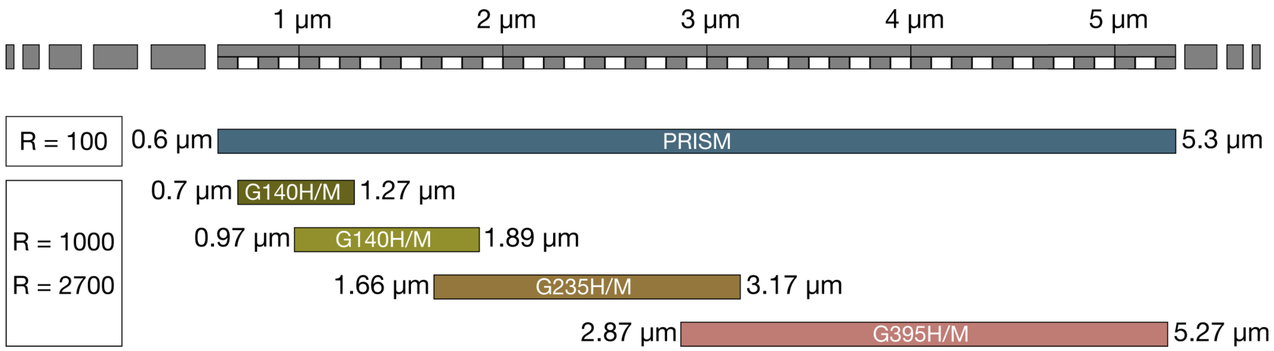
- MIRI and NIRSpec use Image Slicer IFUs
- Slices are dispersed in wavelength
- Signal Recorded on detector
- Pipeline constructs cubes from slices



NIRSpec: IFU Overview

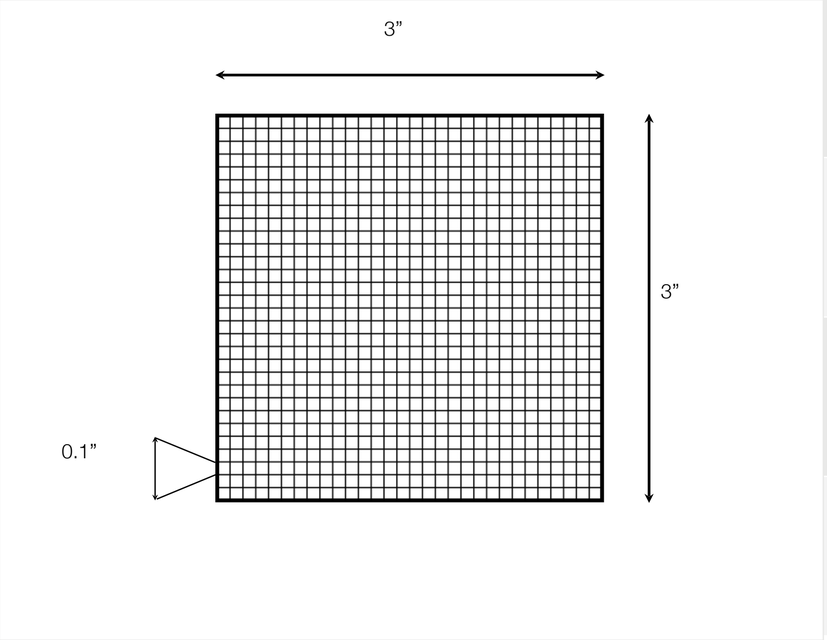
Concept	Advanced Image Slicer Module
Number of Slices	30
Field of View	3″ x 3″
Spaxel Size	0.1″ x 0.1″
Configurations	

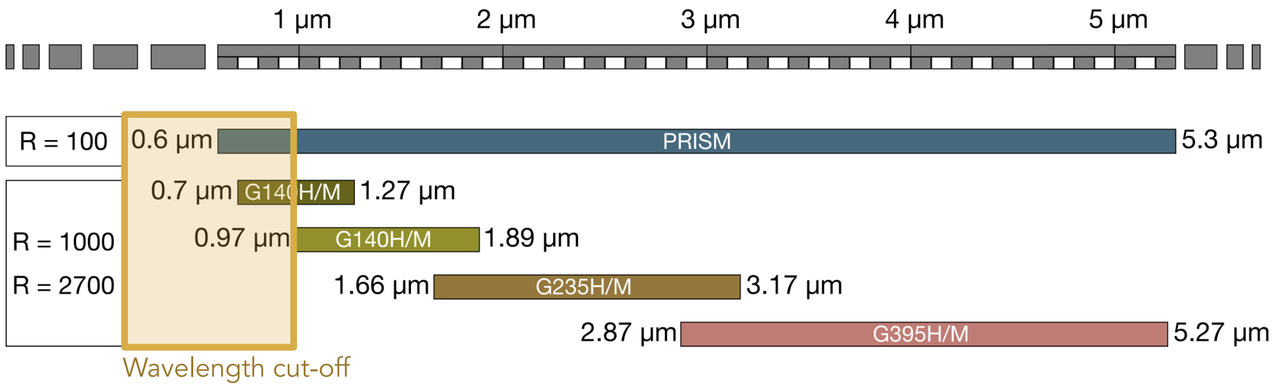




NIRSpec: IFU Overview

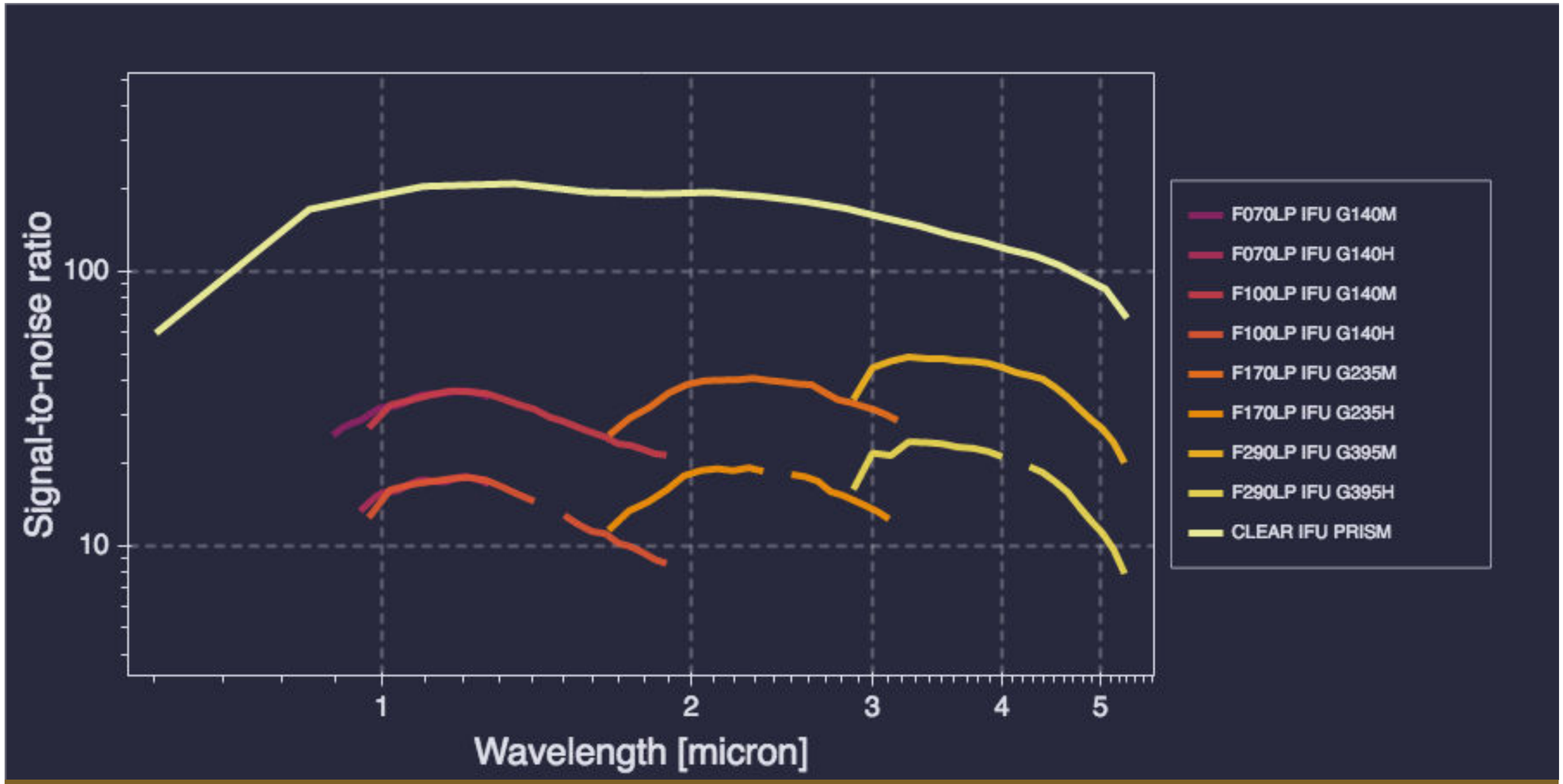
Concept	Advanced Image Slicer Module
Number of Slices	30
Field of View	3″ x 3″
Spaxel Size	0.1″ x 0.1″
Configurations	





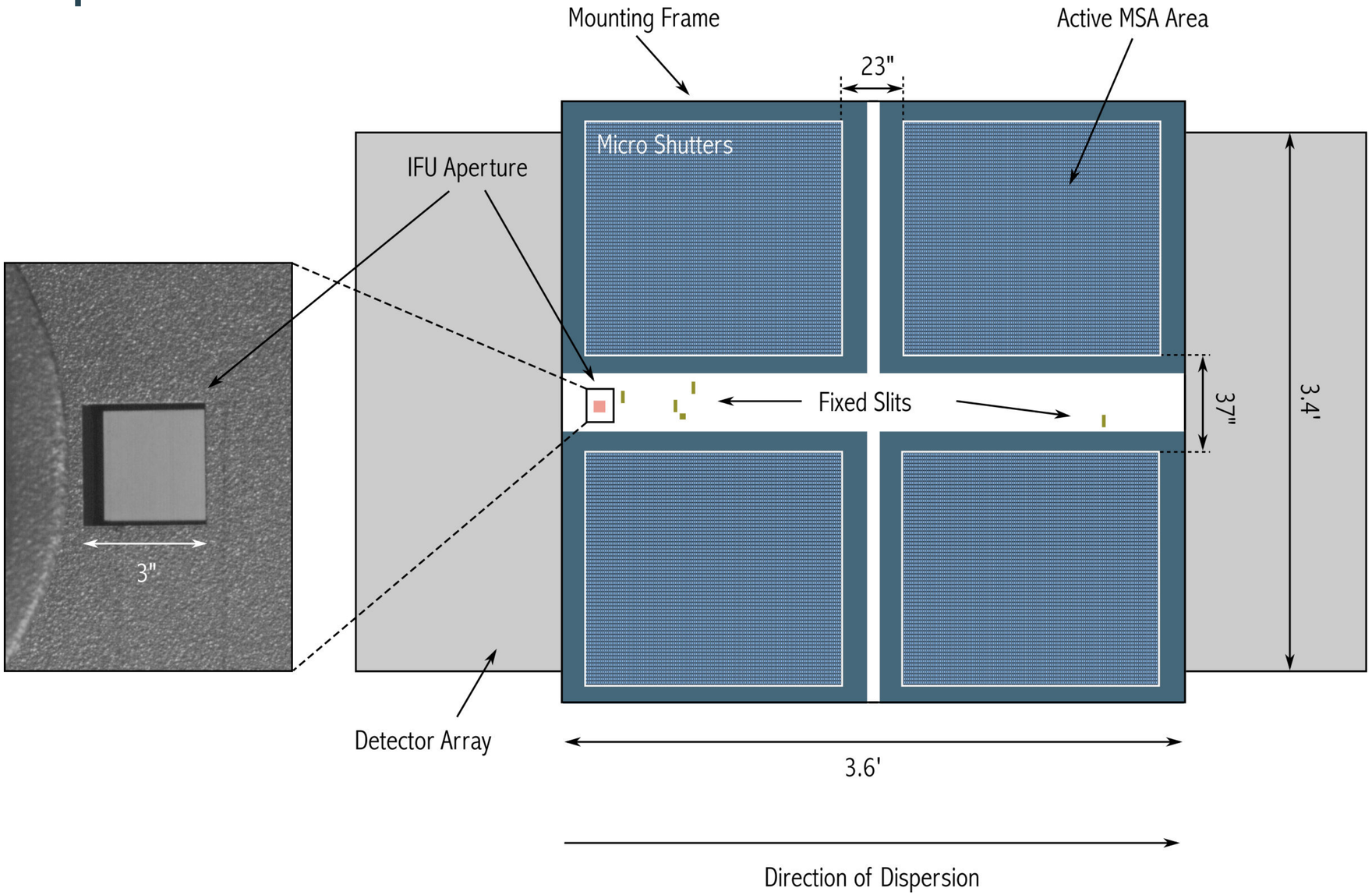
NIRSpec IFS: Sensitivity

PS, 18 ABmag, 300s

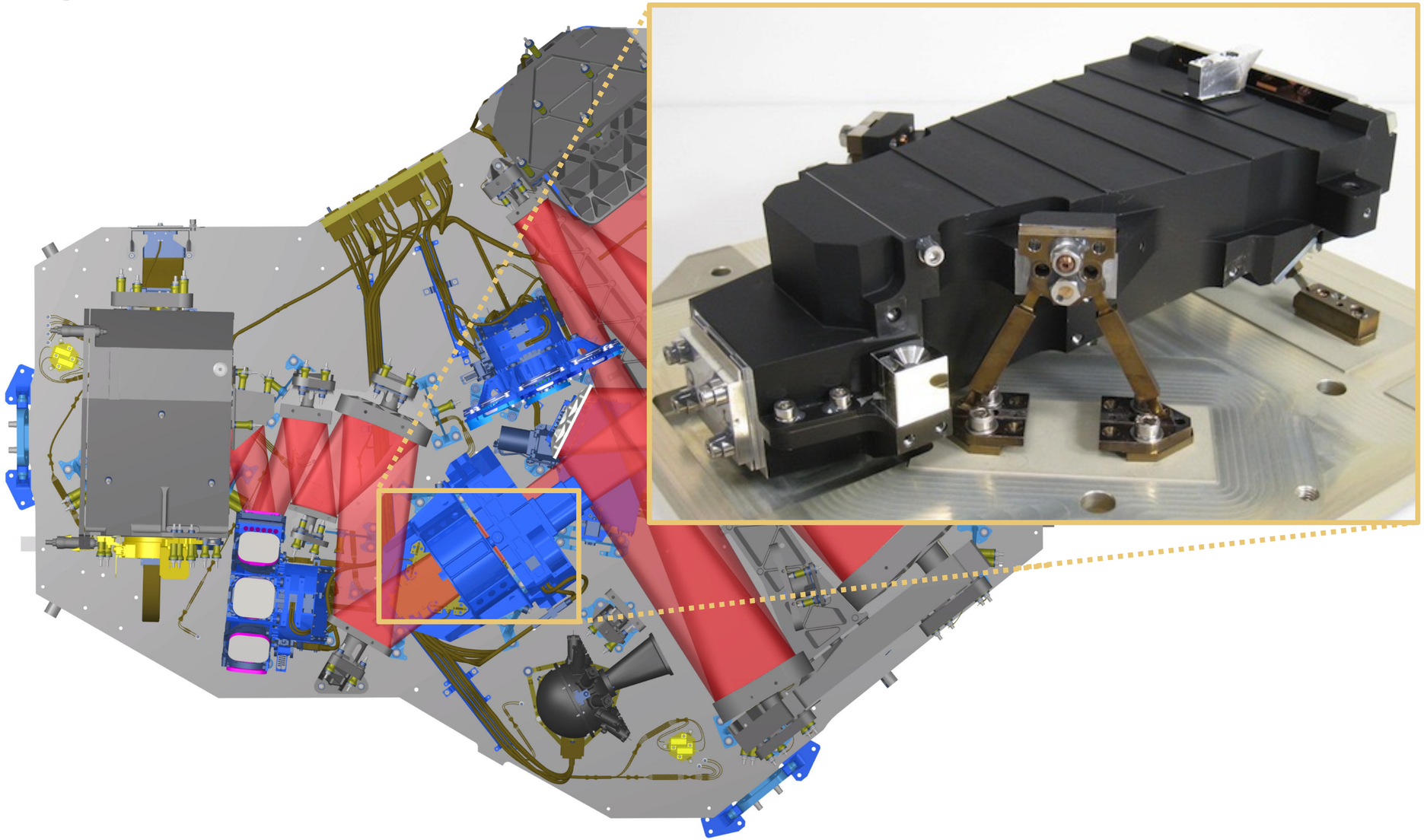


DISCLAIMER: Data taken from https://jist.stsci.edu/jist, will likely change with new ETC release

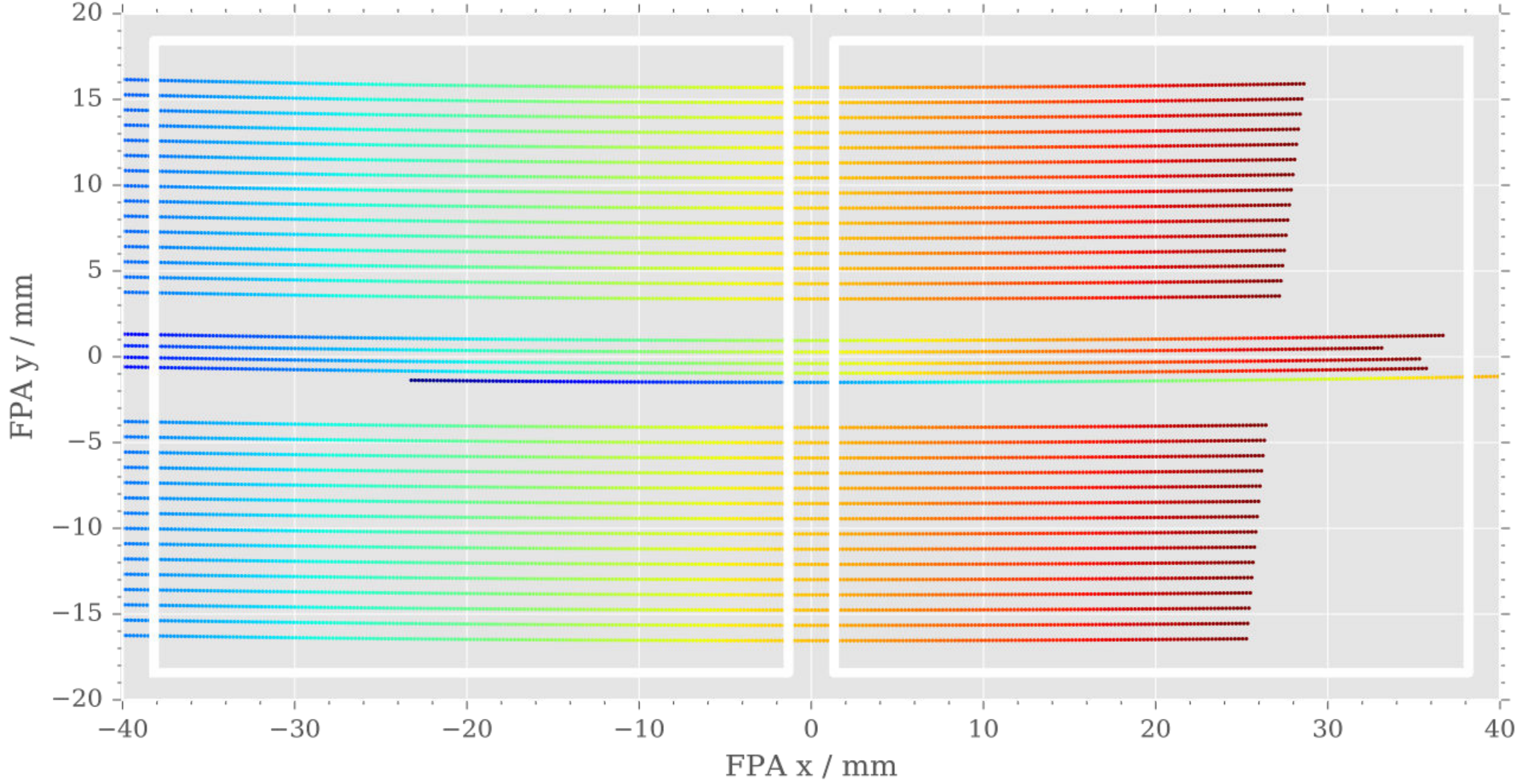
NIRSpec: Hardware



NIRSpec: Hardware

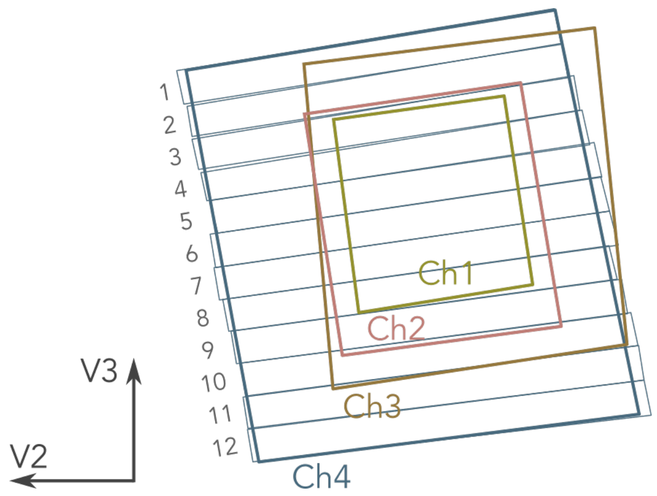


NIRSpec: Dispersed

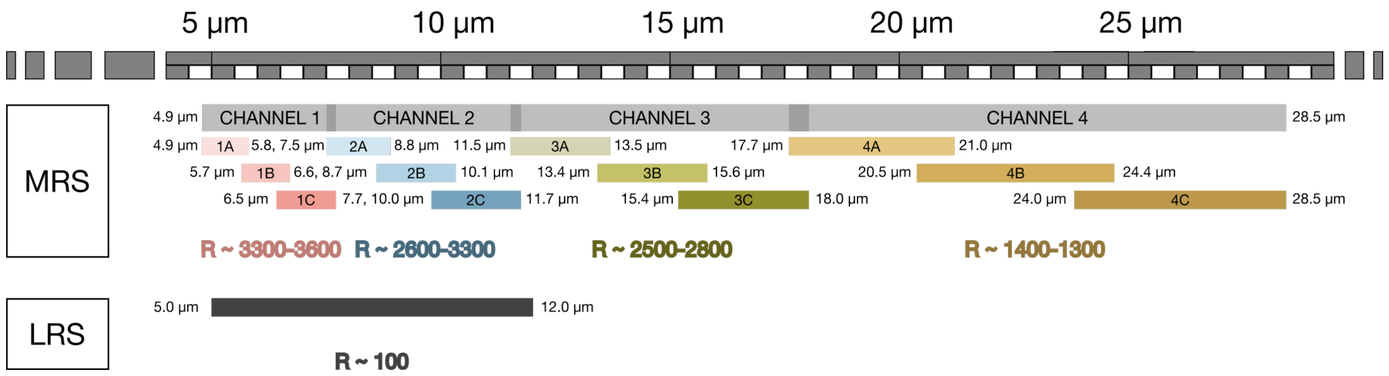


MIRI: MRS Overview

Concept	Advanced Image Slicer Module			
	CH1	CH2	CH3	CH4
Number of Slices	21	17	16	12
Field of View	3.3″ × 3.7″	4.2″ × 4.8″	5.6″ × 6.2″	7.2″ × 7.9″
Slice Size	0.176″	0.277″	0.387″	0.645″



Configurations



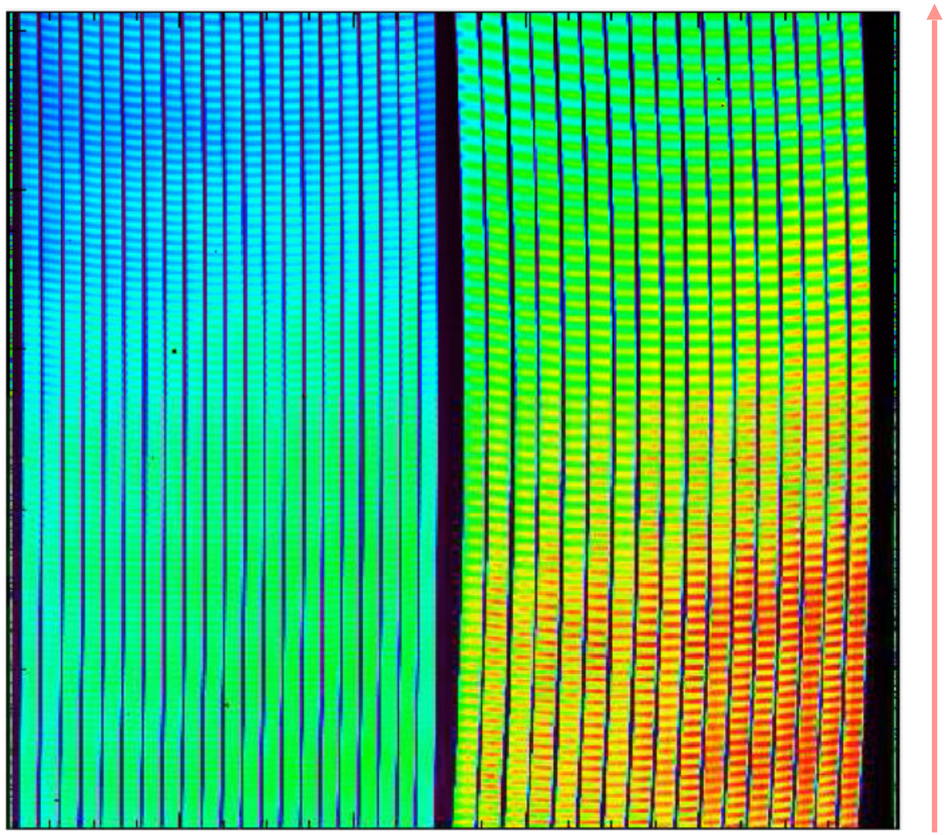
MIRI: MRS Overview

	Channel	Band	Nr. slices	Wavelength Range [μm]	Spectral Resolution	FoV [arcsec]
IFUSHORT	1	1A		4.88 - 5.77		3.46 x 3.72
		1B	21	5.64 - 6.67	~3500	3.46 x 3.72
		1C		6.50 - 7.70		3.41 x 3.72
	2	2A		7.47 - 8.83		4.16 x 4.76
		2B	17	8.63 - 10.19	~3000	4.16 x 4.76
		2C		9.96 - 11.77		4.12 x 4.76
IFULONG	3	3A		11.49 - 13.55		6.00 x 6.24
		3B	16	13.28 - 15.66	~2600	5.96 x 6.24
		3C		15.34 - 18.09		5.91 x 6.24
	4	4A		17.60 - 21.00		7.14 x 7.87
		4B	12	20.51 - 24.48	~1600	7.06 x 7.87
		4C		23.92 - 28.55		6.99 x 7.87

→ 3 exposures needed to obtain an entire spectra

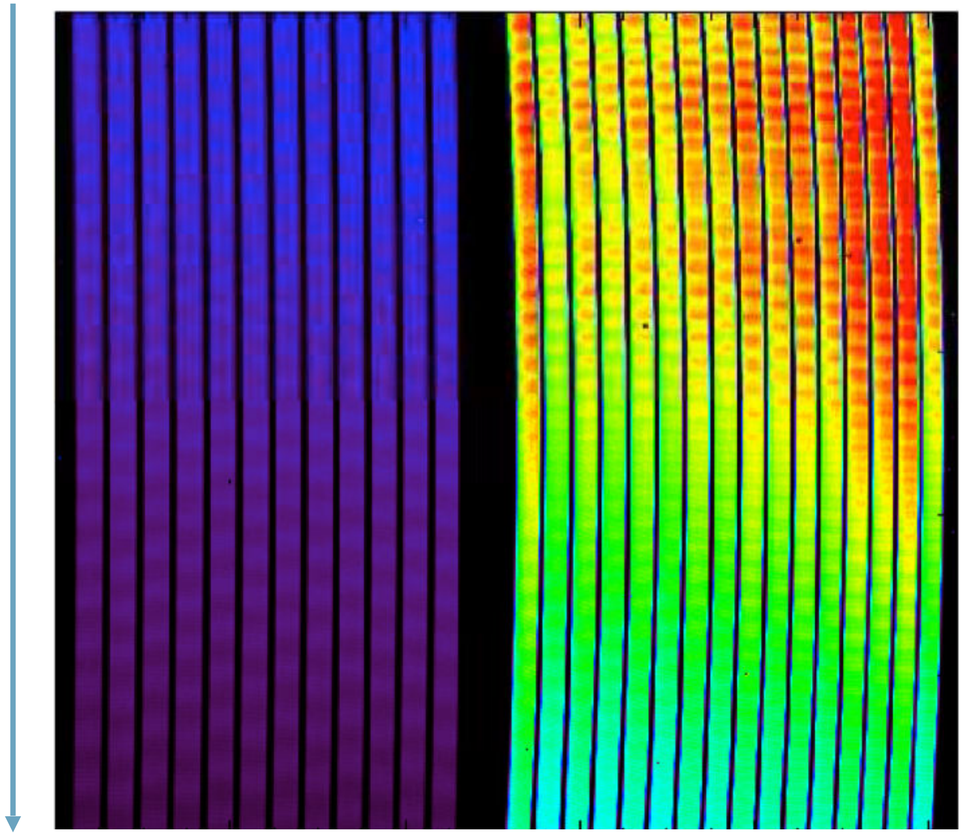
MIRI MRS: Dispersed

6.7 CHANNEL 1 & 2 10.2



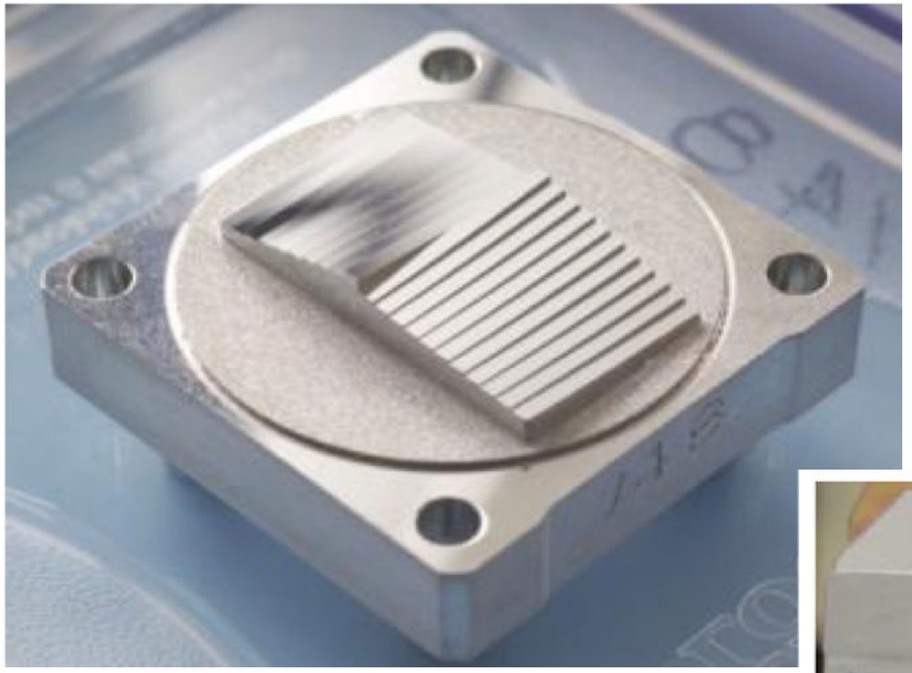
5.6 IFUSHORT 8.6

20.5 CHANNEL 4 & 3 13.3



24.5 IFULONG 15.7

MIRI: Hardware

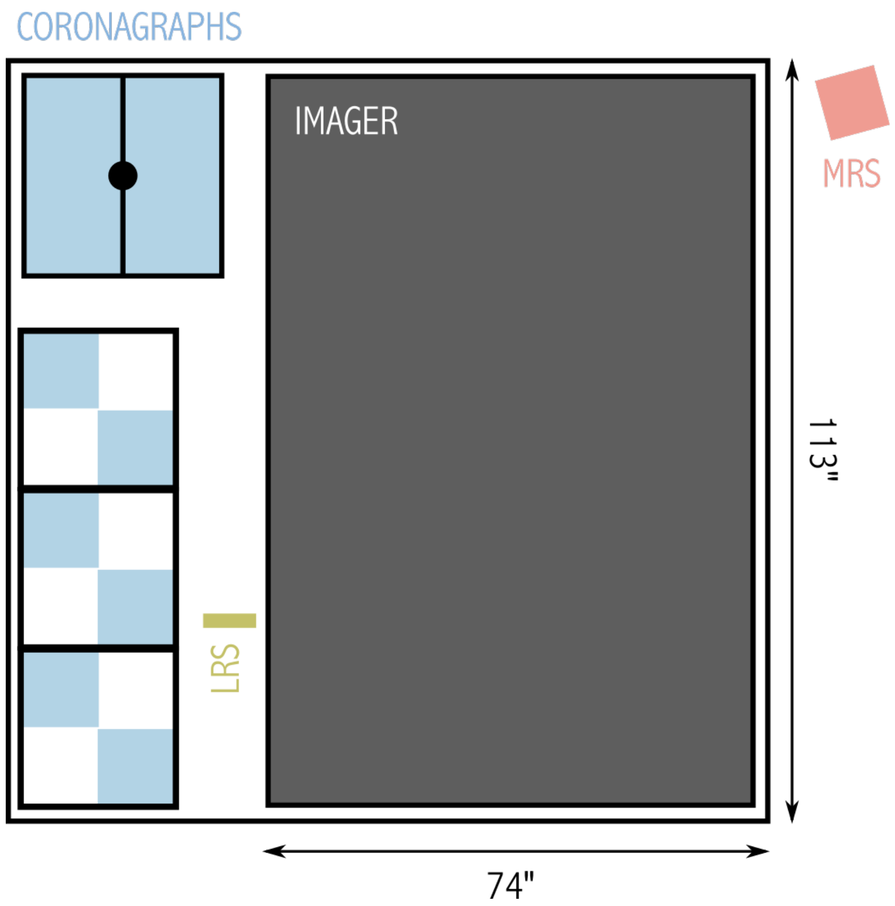


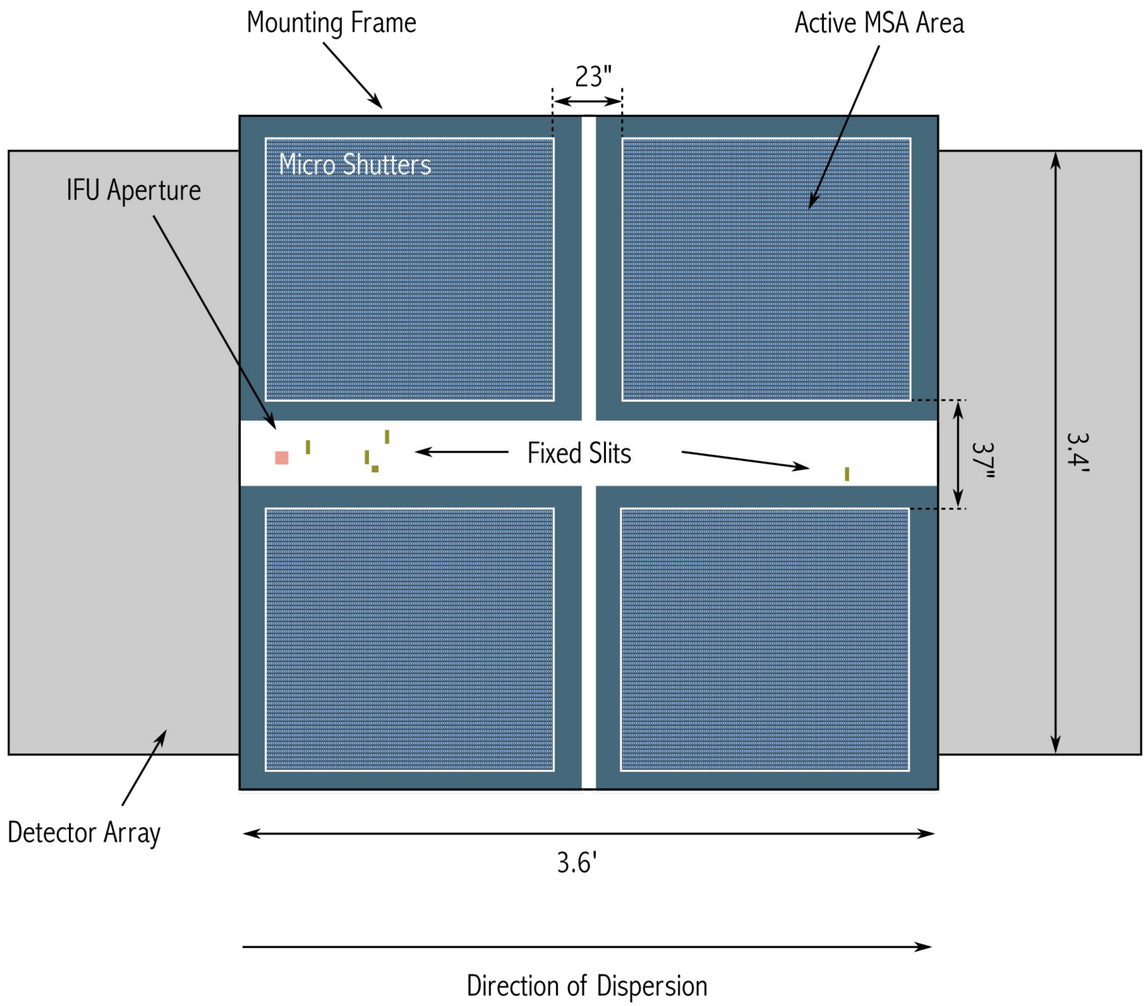
Slicer

Exit Slits

Fixed Slits

The FS of MIRI and NIRSpec

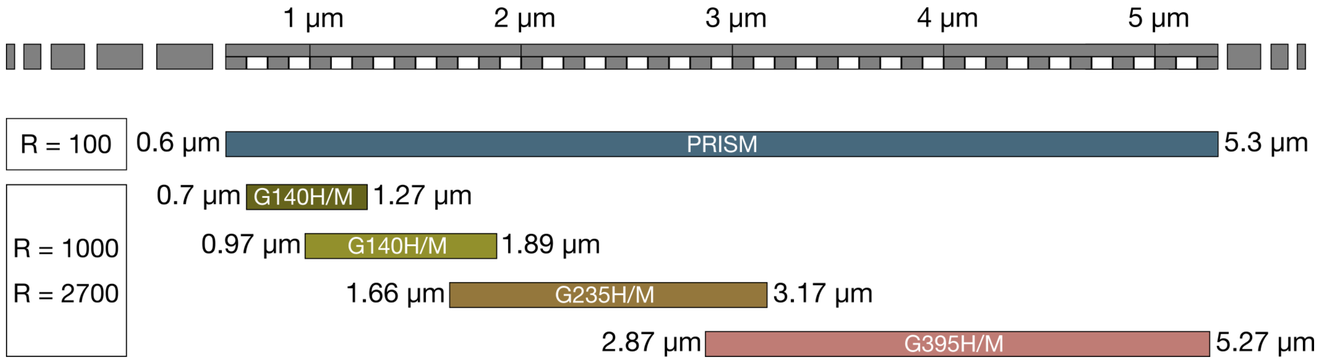


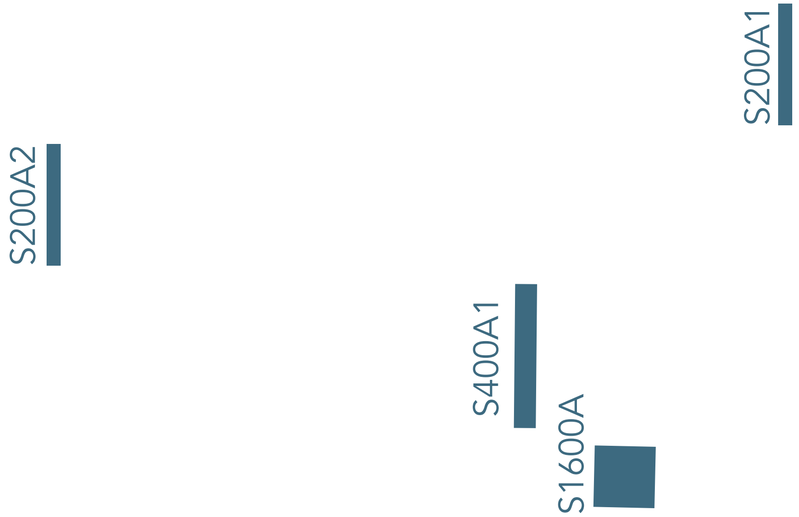


NIRSpec FS Basics and Design

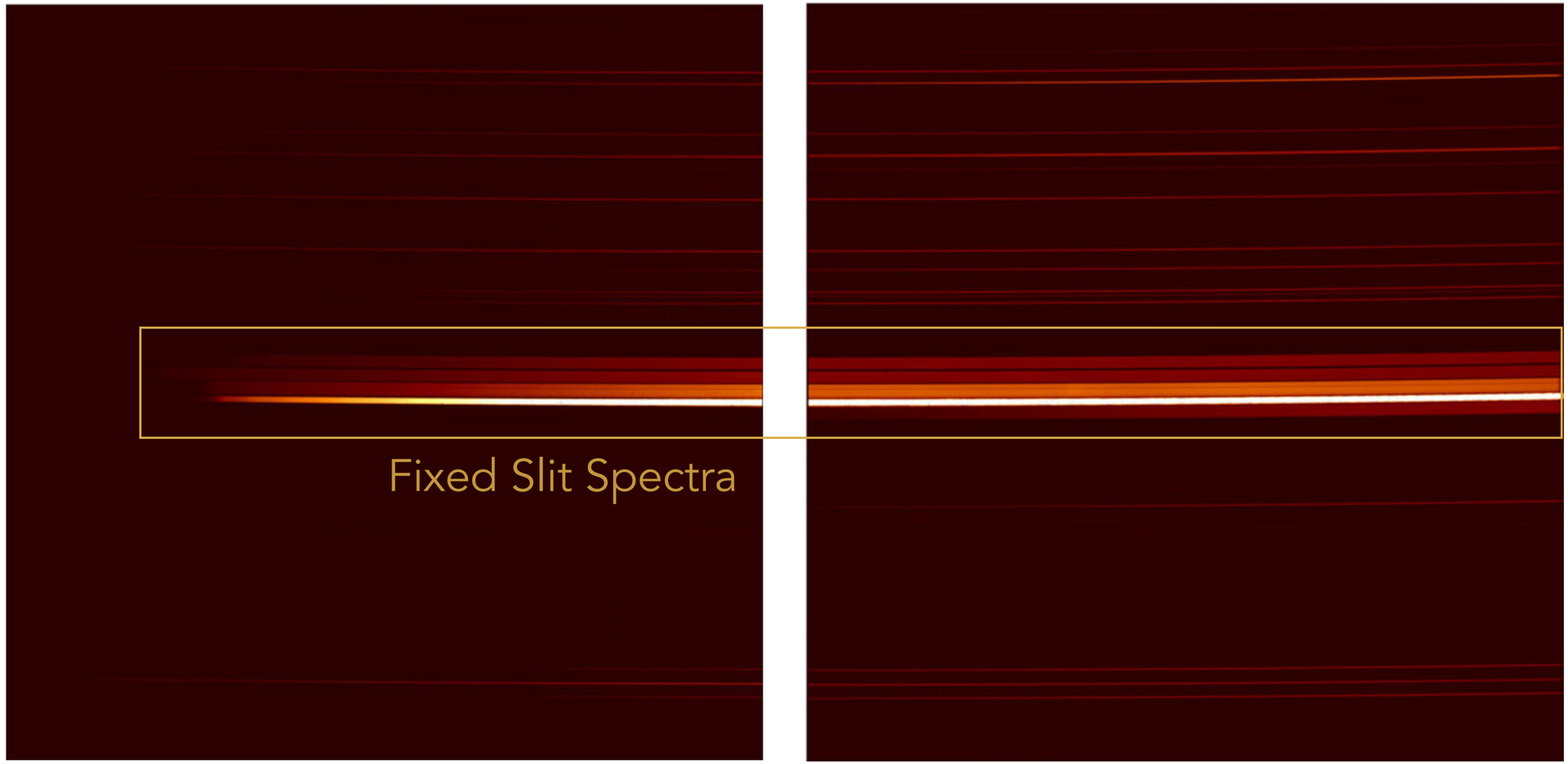
FIXED SLIT SPECTROSCOPY	Single (compact) object (high contrast)	0.2″ x 3.2″ slits (3) 0.4″ x 3.65″ slit 1.6″ x 1.6″ aperture
BRIGHT OBJECT TIME SERIES	e.g. Transit/eclipse spectroscopy	1.6″ x 1.6″ aperture

Six gratings and one prism available as dispersers (full wavelength range)



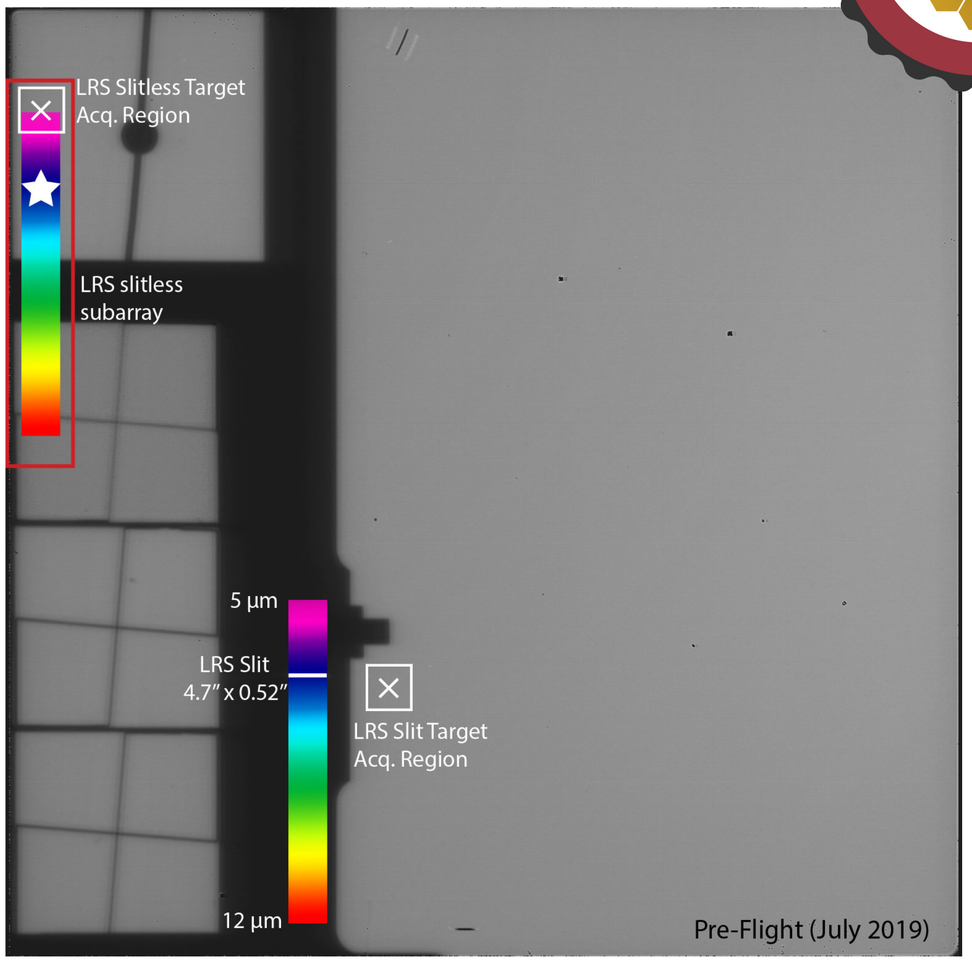


NIRSpec FS Basics and Design



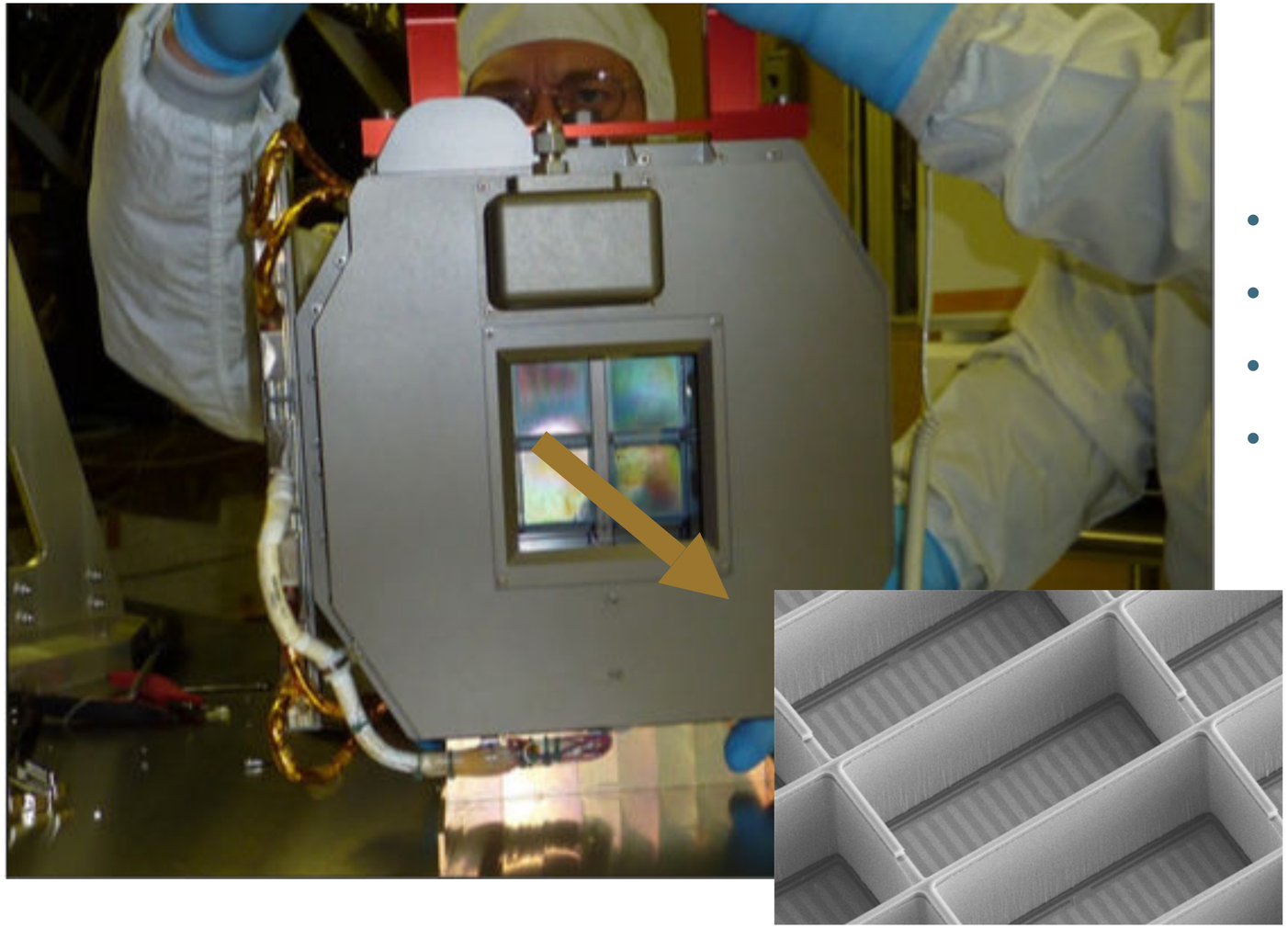
MIRI LRS Basics and Design

- R ~ 100 spectroscopy of compact source from 5-12 μm (~40 to 160 over the 5-10 μm range)
- Can be operated slitted (4.7 x 0.52″) or slitless mode
- Shares focal plane with imager & coronagraph modes
- Dispersion via double prism in filter wheel



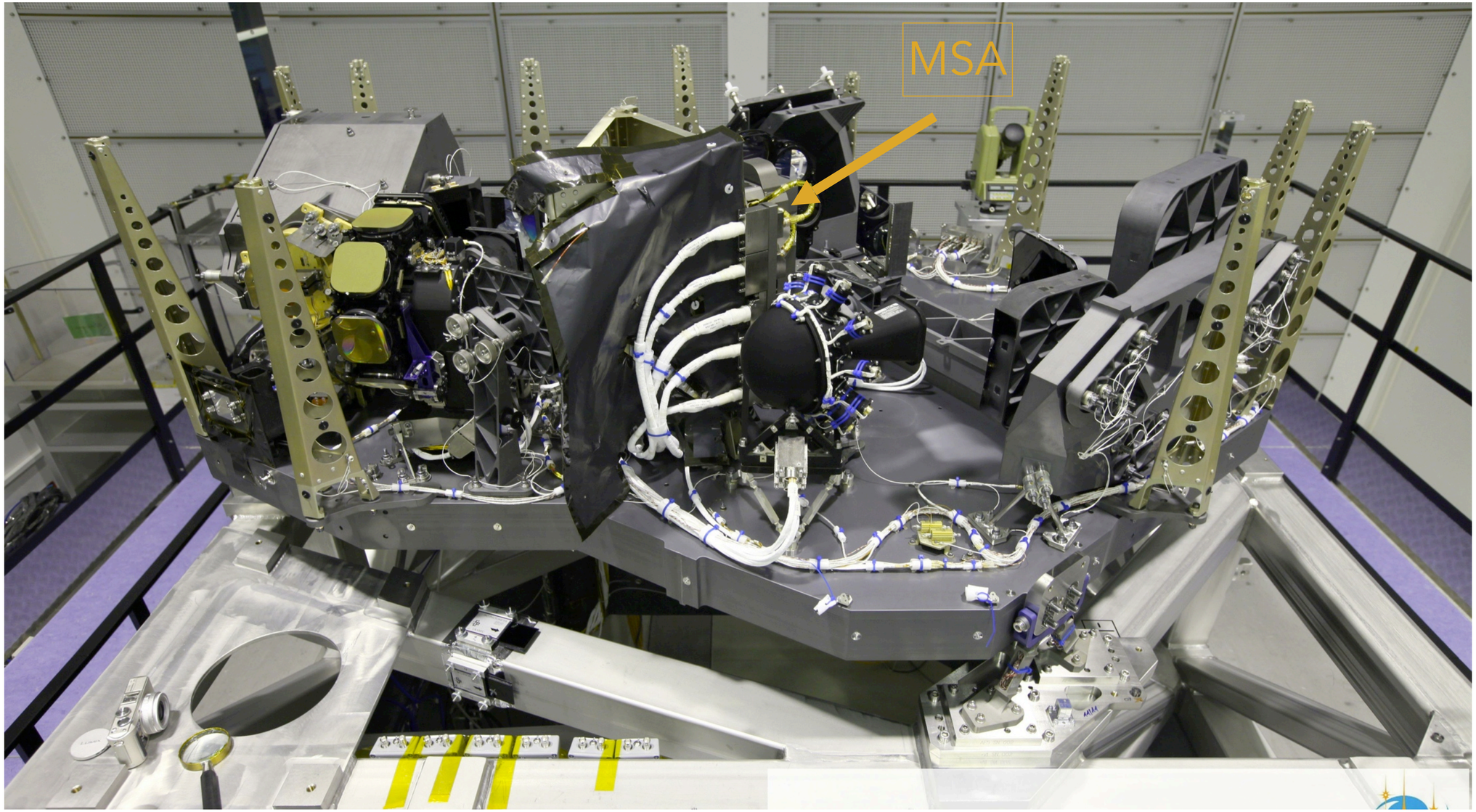
Multi Object Spectroscopy

The Micro Shutter Assembly (MSA)

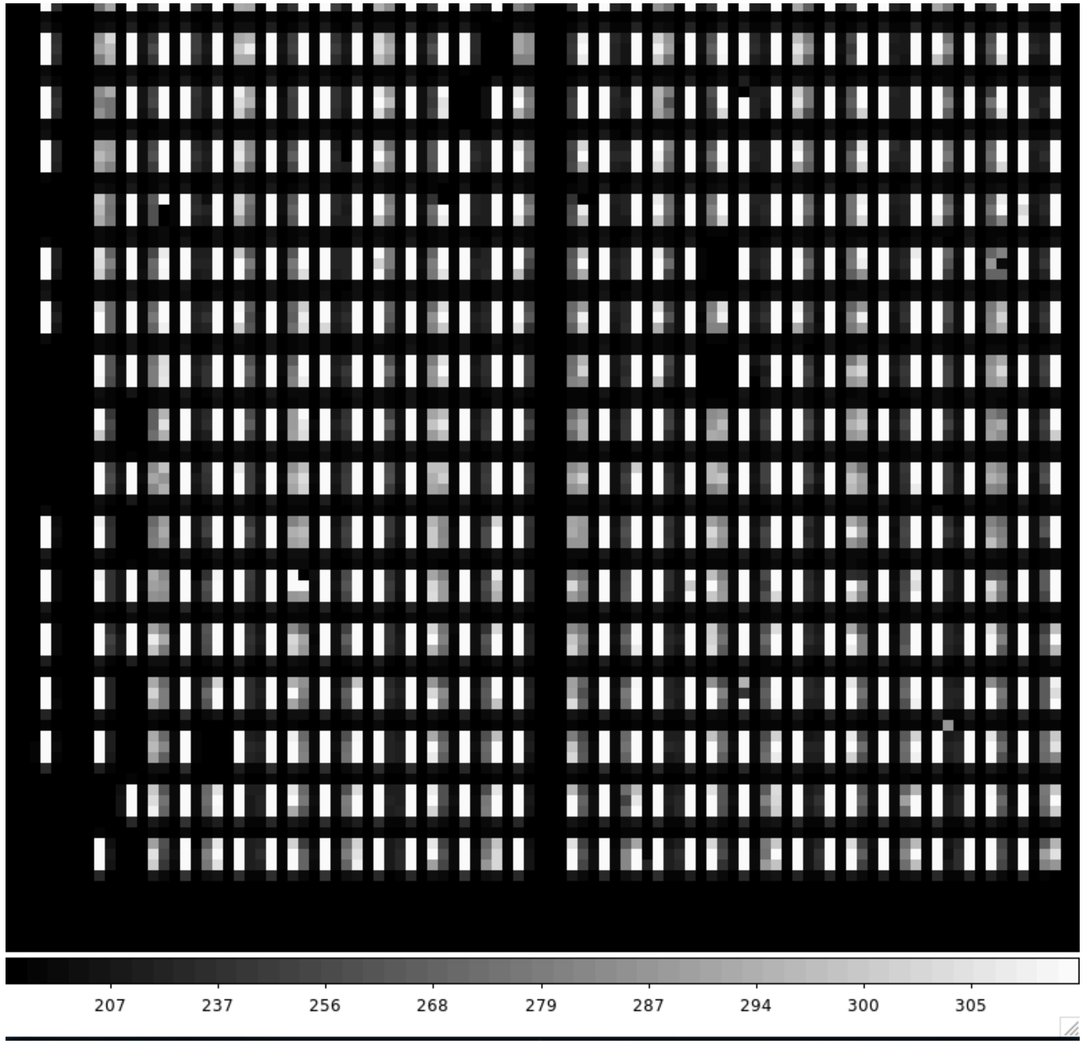


- 4 arrays of 365x171 micro-shutters
- 250,000 individually addressable shutters
- 3.6′x3.4′ field-of-view ~ 9 arcmin^2
- Each shutter 0.20"×0.46"
  (width in the dispersion direction
  × height)

NIRSpec

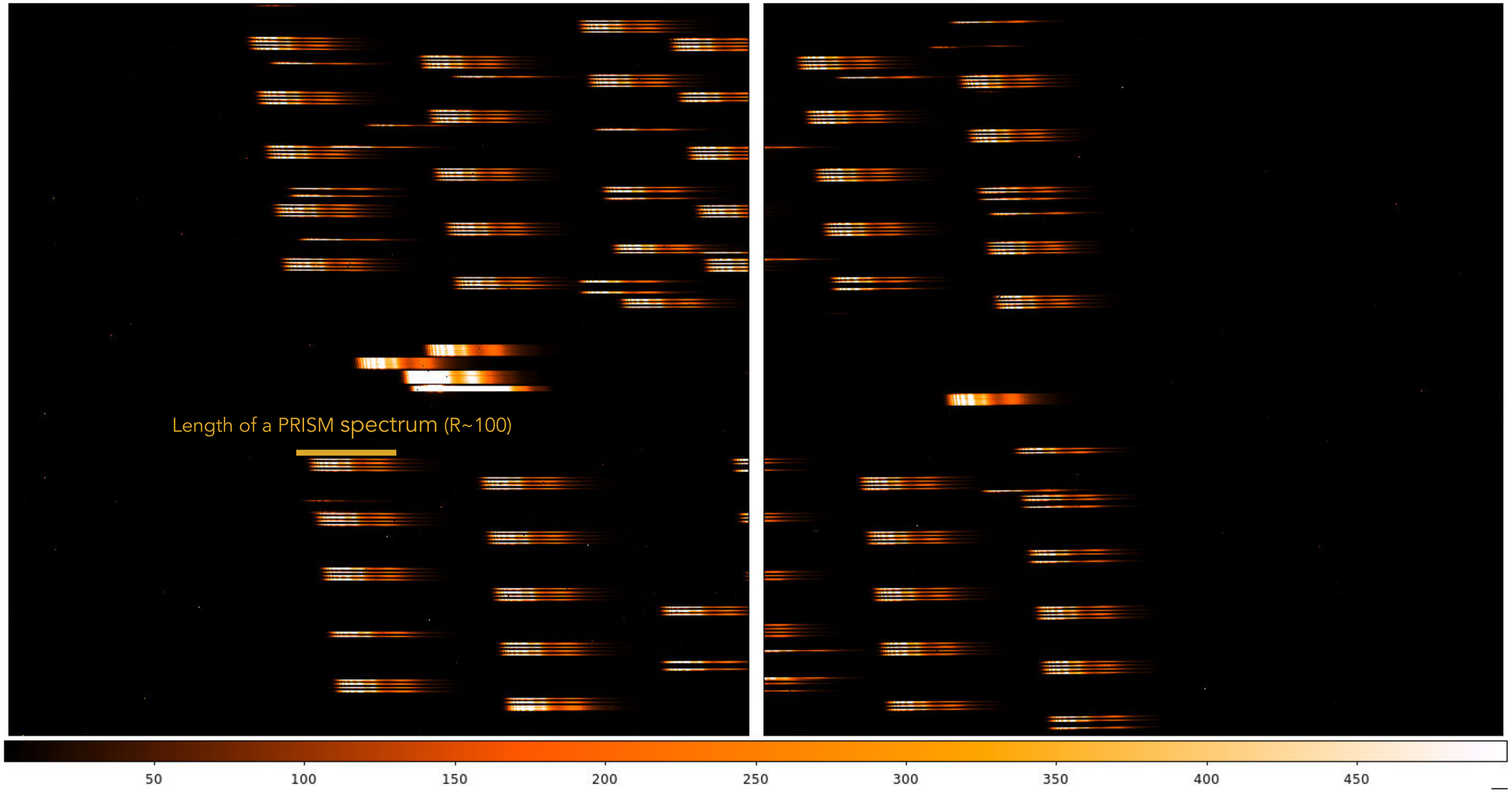


The MSA is a fixed grid

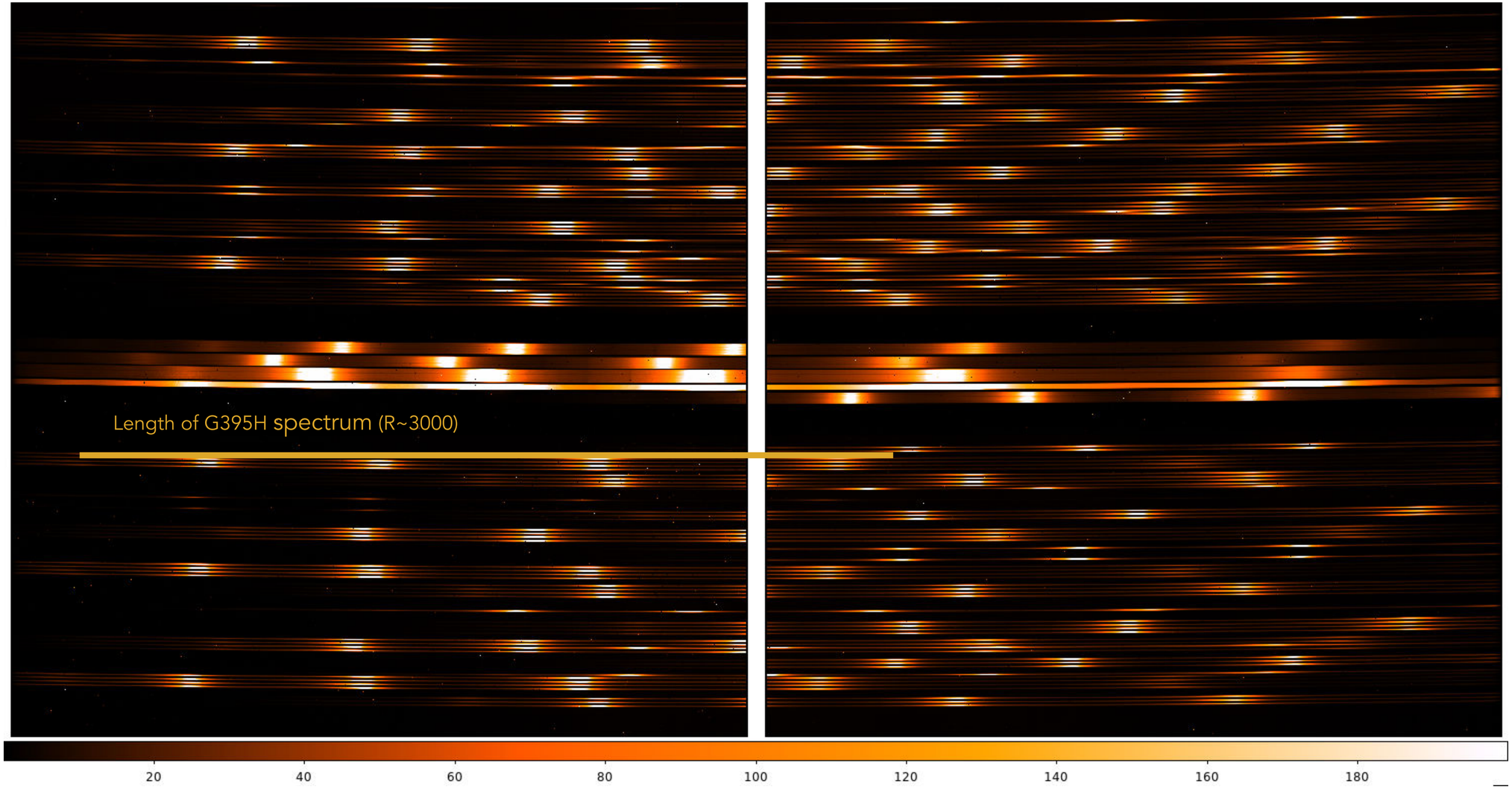


- Shutter bars vignette light from an extended sources
- Gap between the 2 detectors that leads to a gap in wavelength coverage
- In general sources will not be centered in the aperture
- Positioning sources in MSA require knowledge of optical distortions/ velocity aberrations

Spectra on the detector have different length: PRISM

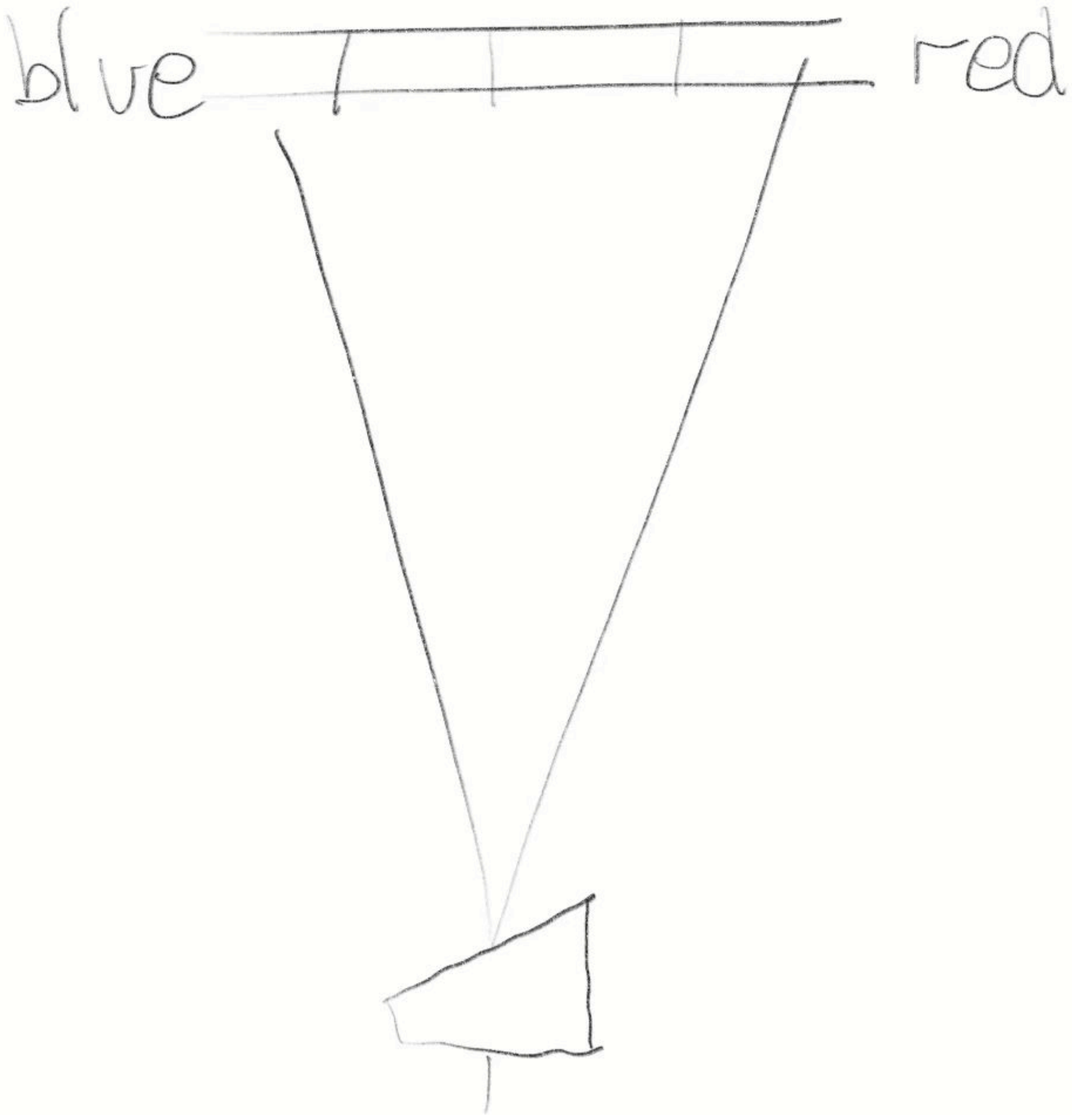


Spectra on the detector have different length: G395H

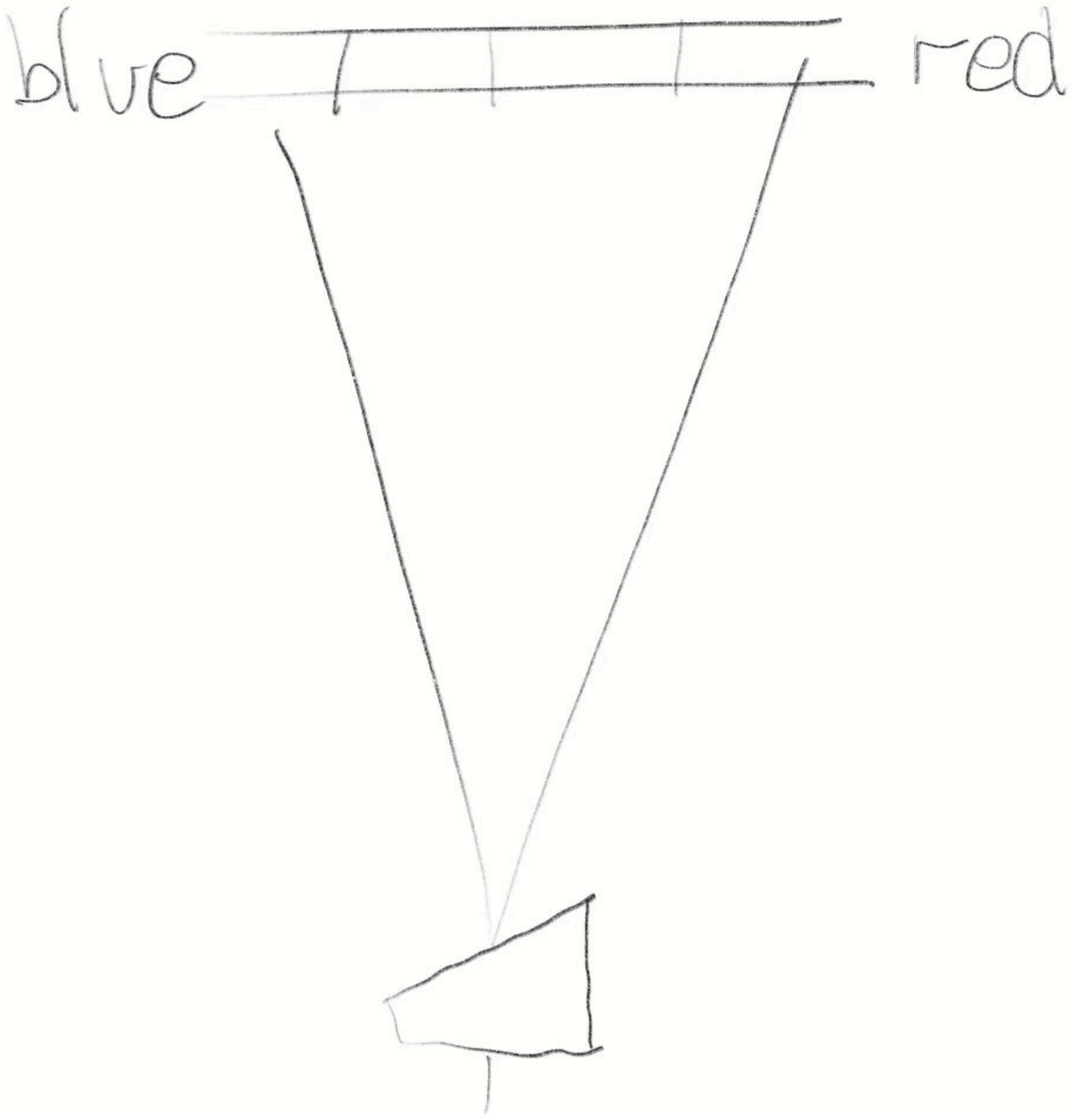


Wide Field Slitless Spectroscopy

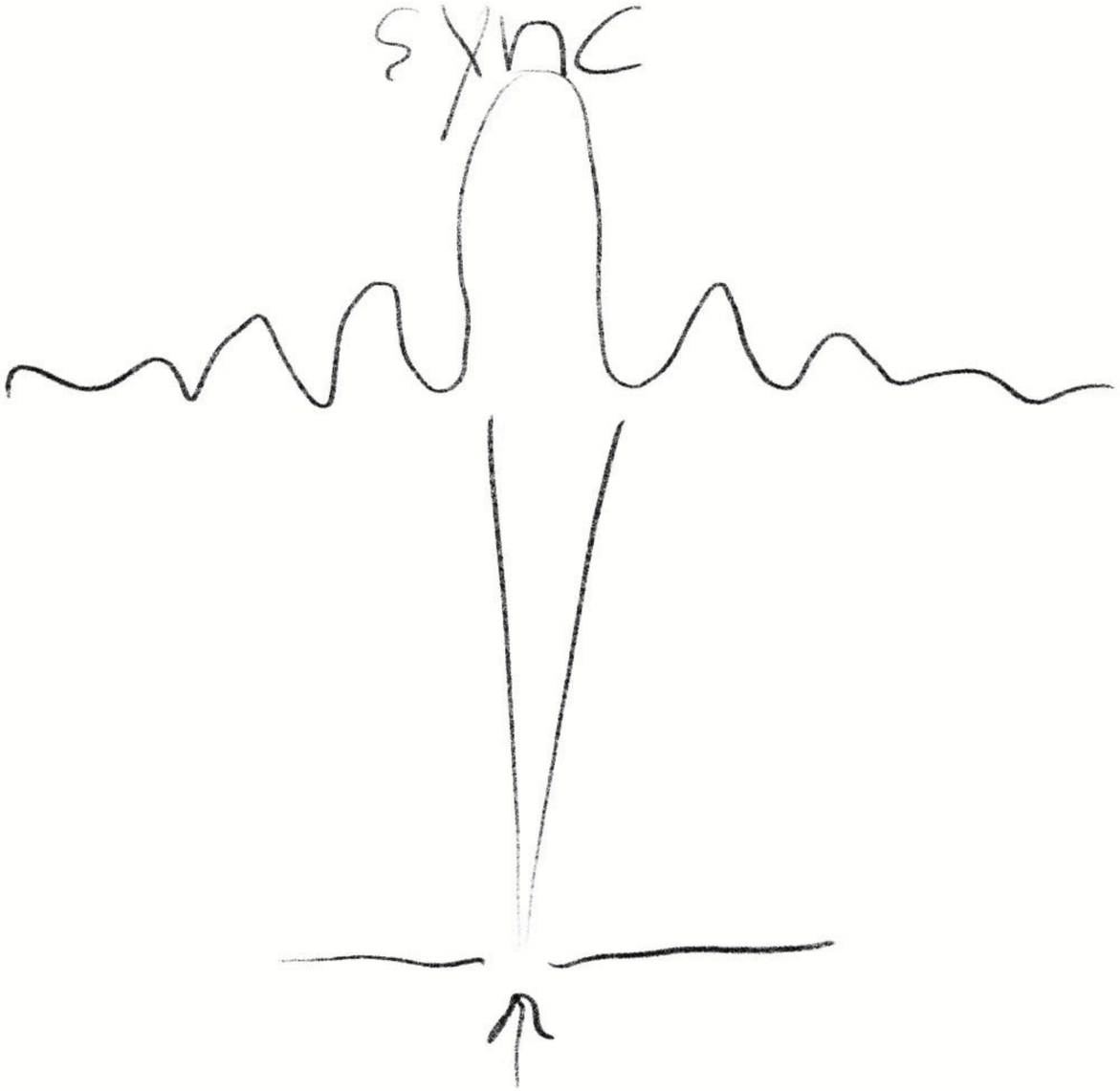
Dispersion by a Prism



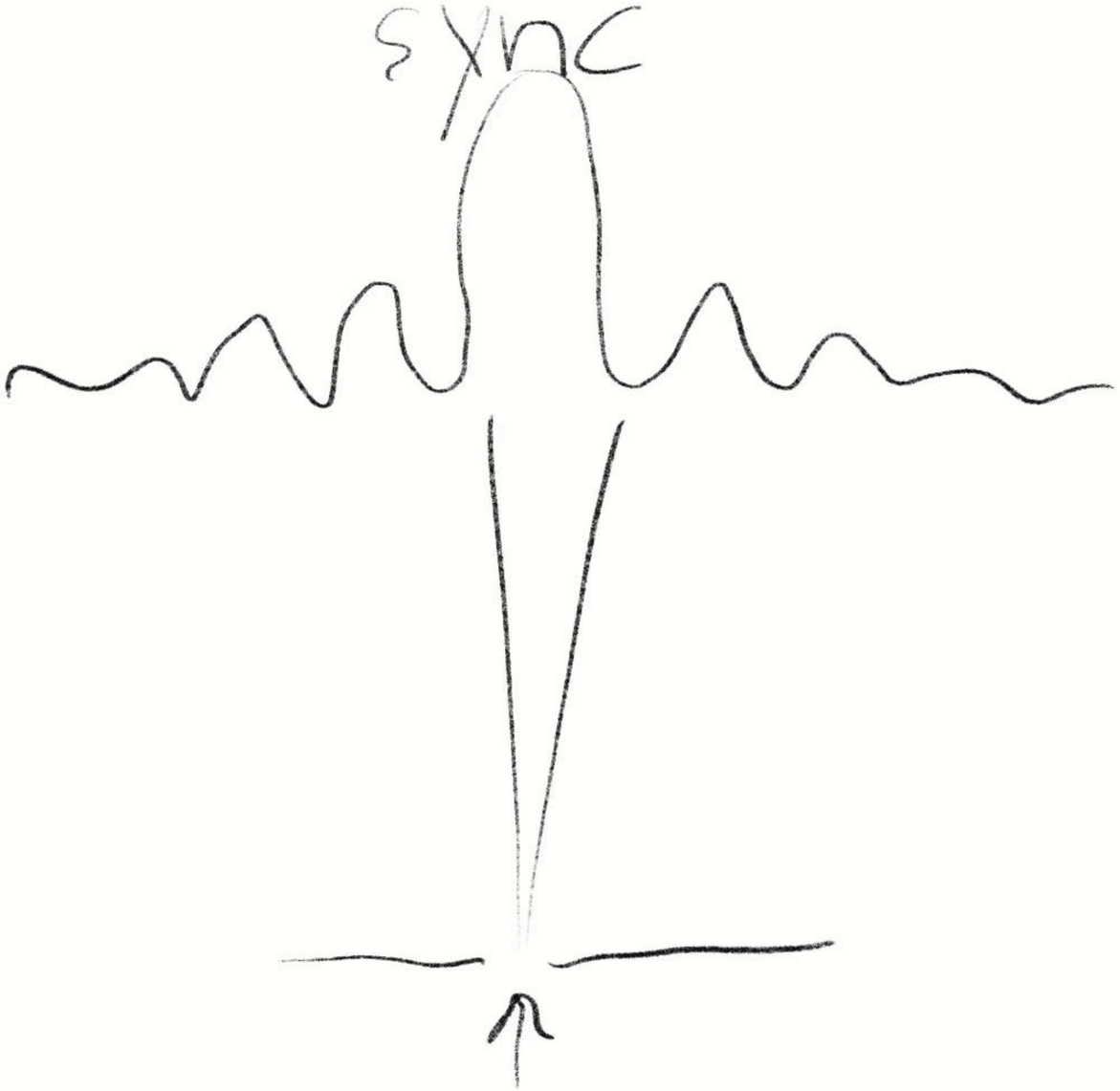
Dispersion by a Prism



Diffraction of a Point Source



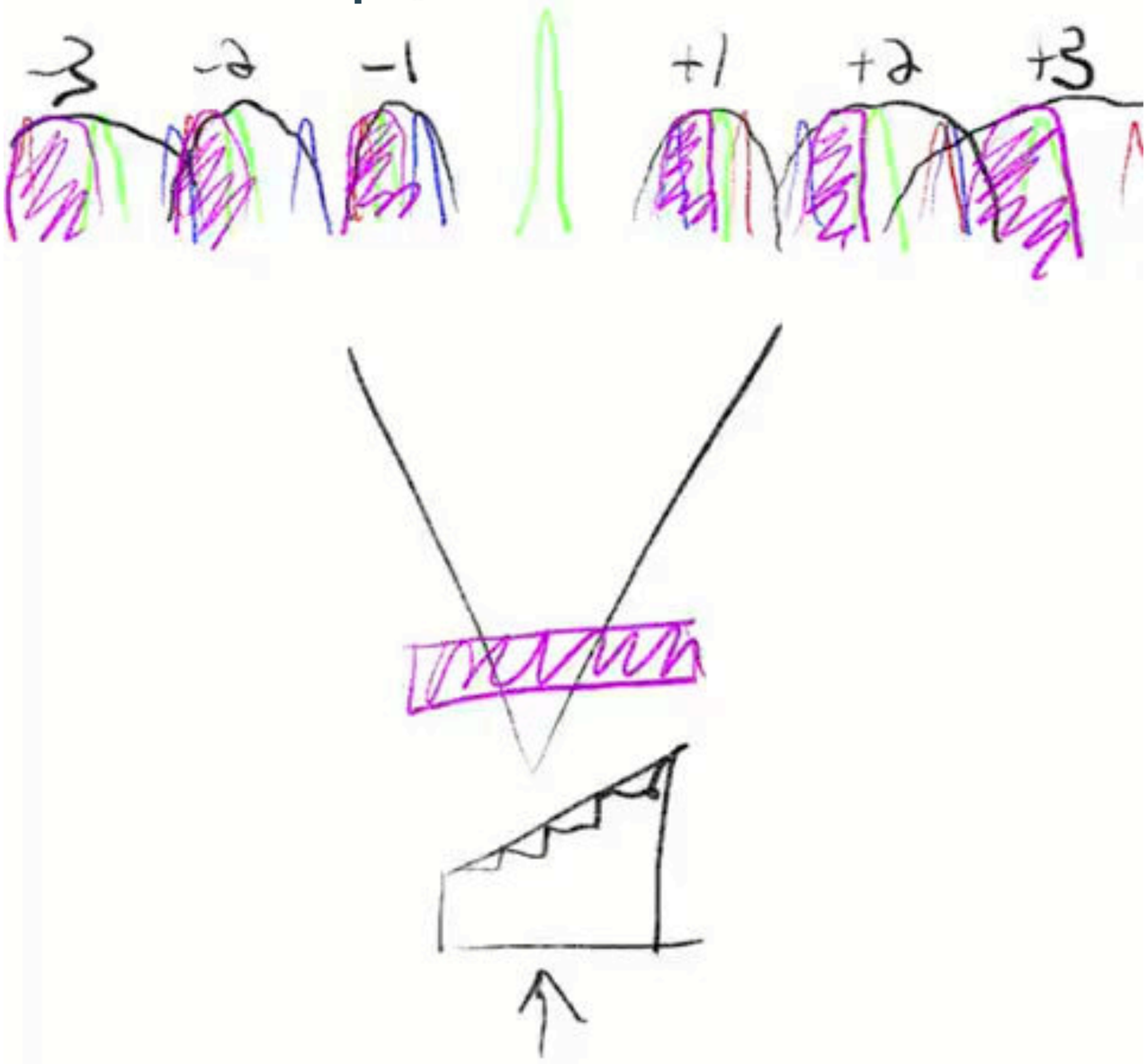
Diffraction of a Point Source



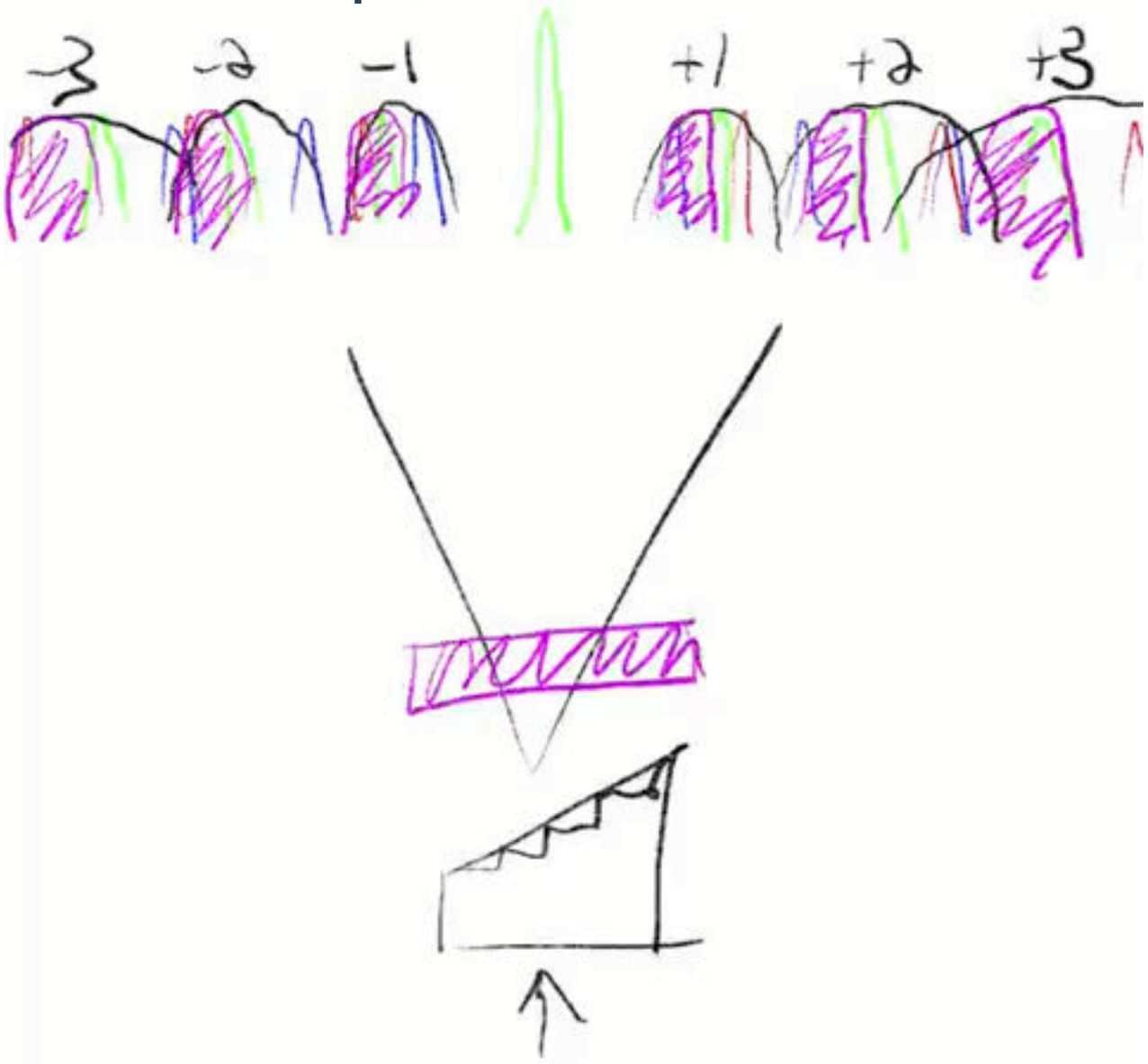
Grism Diffraction - Monochromatic Light

Grism Diffraction - Monochromatic Light

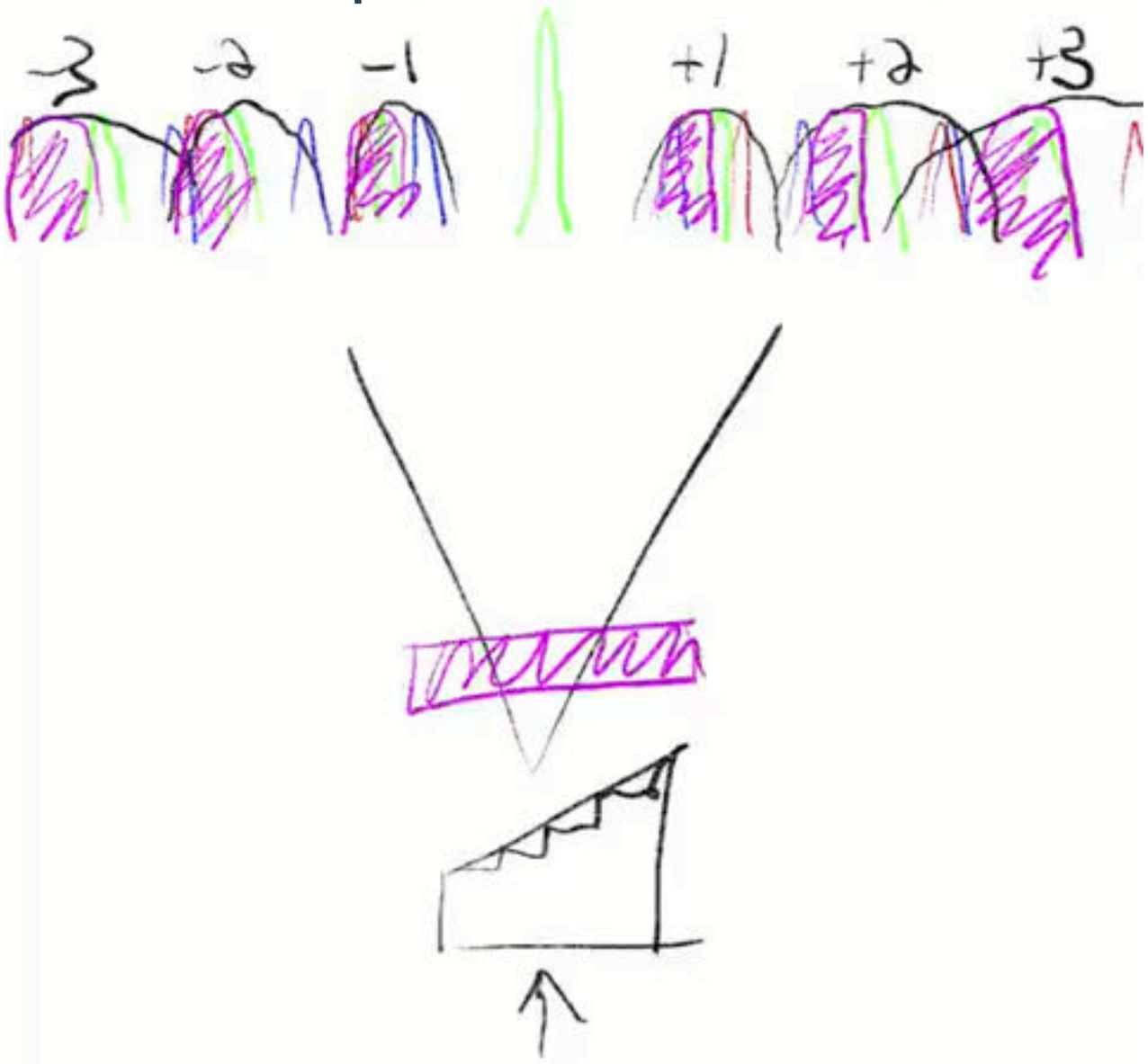
Grism Spectroscopy



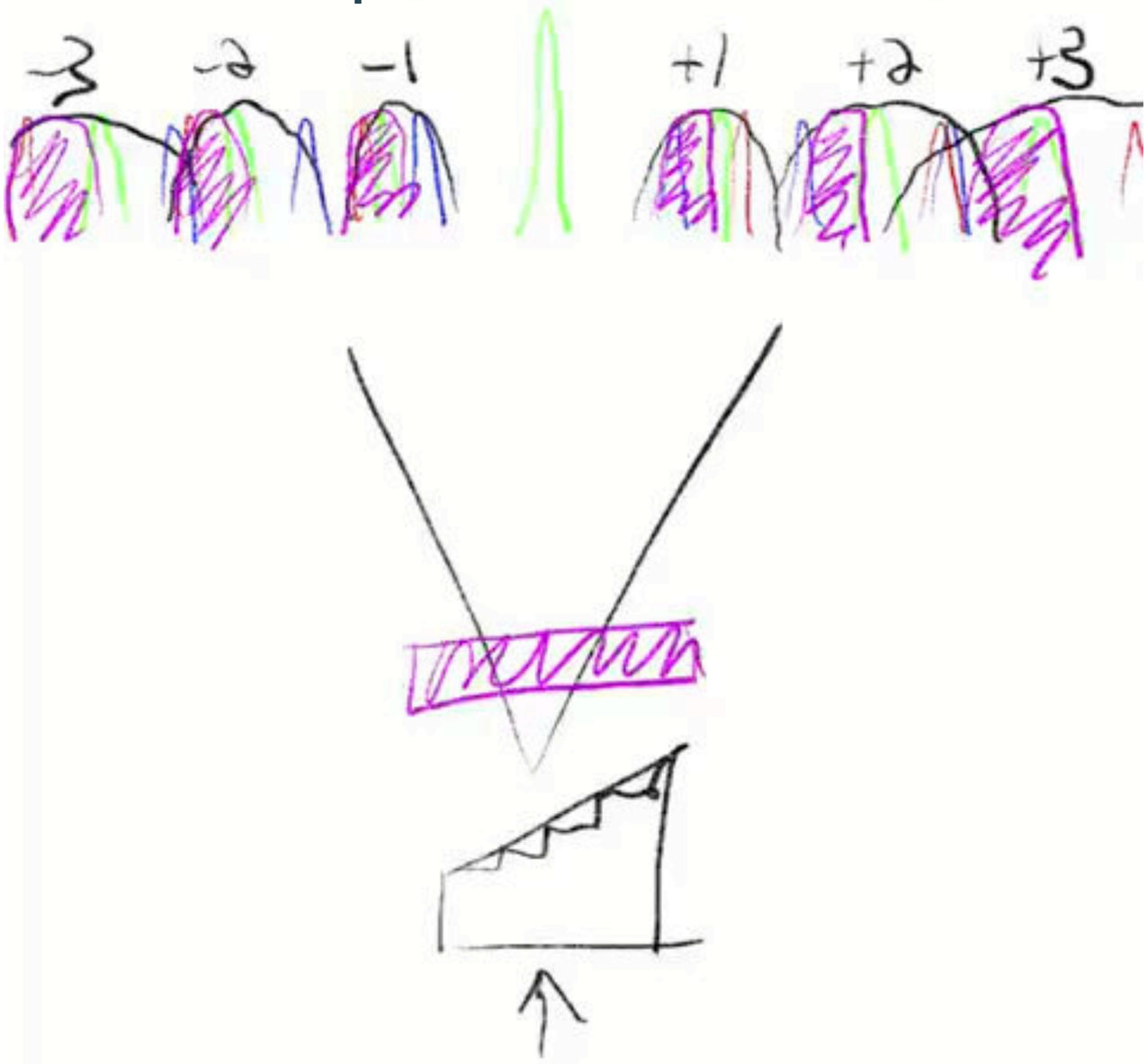
Grism Spectroscopy



Grism Spectroscopy + Blocking Filter

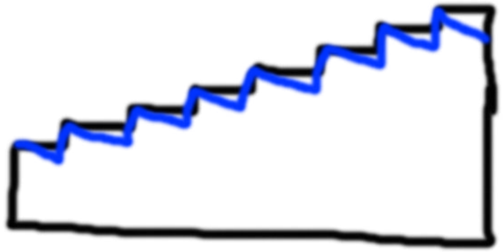


Grism Spectroscopy + Blocking Filter



Blaze Wavelength and Undeviated Wavelength

- The angles of the prism faces determine the diffracted beam deviation sideways.
- The angle of the grating facets determine the blaze wavelength, i.e. where most of the power is directed.

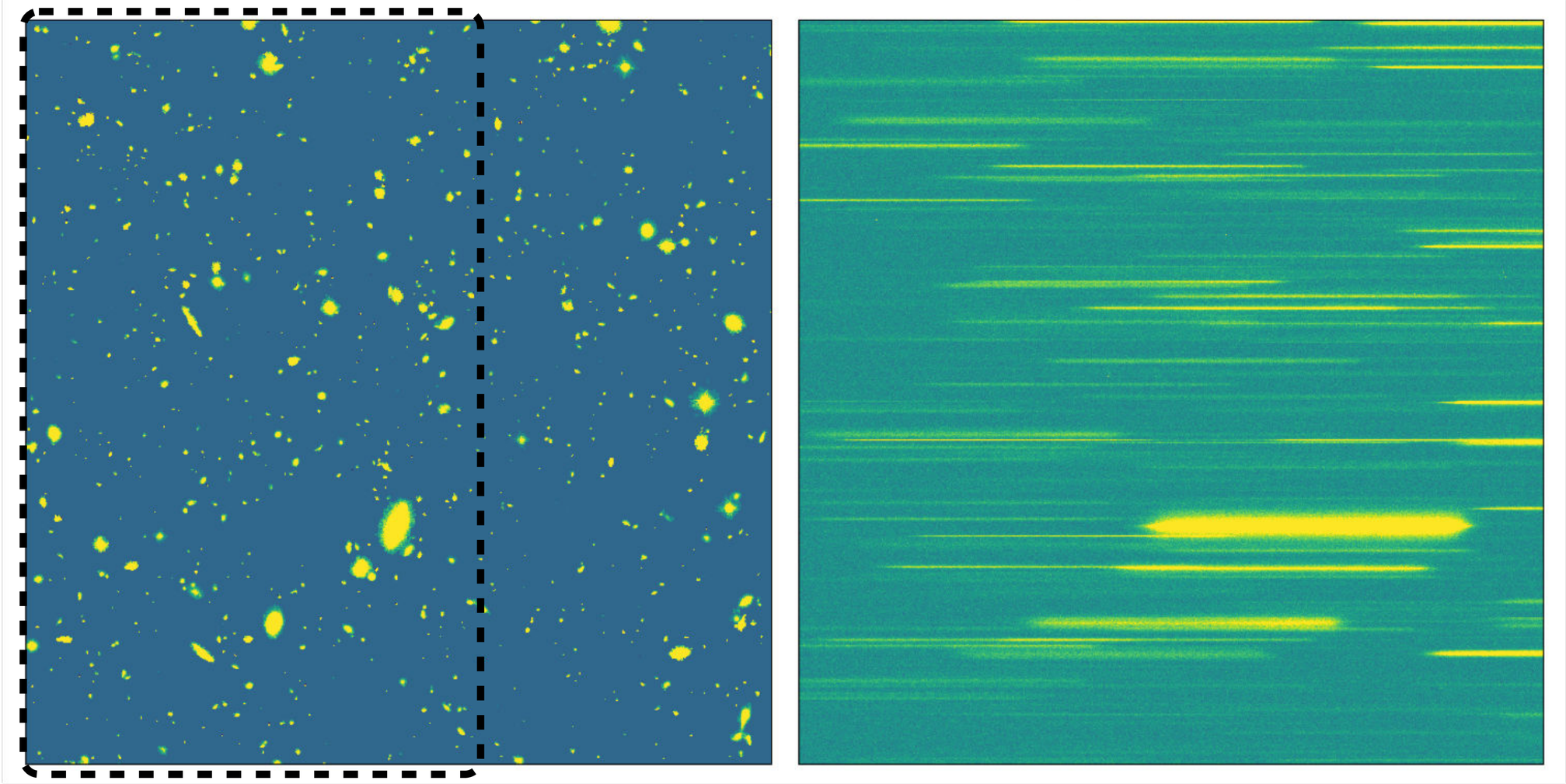


NIR WFSS Side-by-Side Specs

NIRISS	Instrument	NIRCam
~150	R	1200-1600
0.8-2.2 microns	Wavelength Coverage	2.4-5.0 microns
A little less than 2.2′x2.2′ FOV	Full Spectrum FOV	• Depends on the filter • ~1/3 of 2.2′x2.2′ FOV • 2 Modules simultaneously!
F090W, F115W, F140M, F150W, F158M, F200W	Filter	F250M, F277W, F300M, F322W2, F335M, F356W, F360M, F410M, F430M, F444W, F460M, F480M
Low Background	Background	For many filters, need background subtraction
NIRCam Imaging or MIRI Imaging	Coordinated Parallel	MIRI Imaging or NIRISS Imaging. Plus, get simultaneous NIRCam imaging in shortwave channel

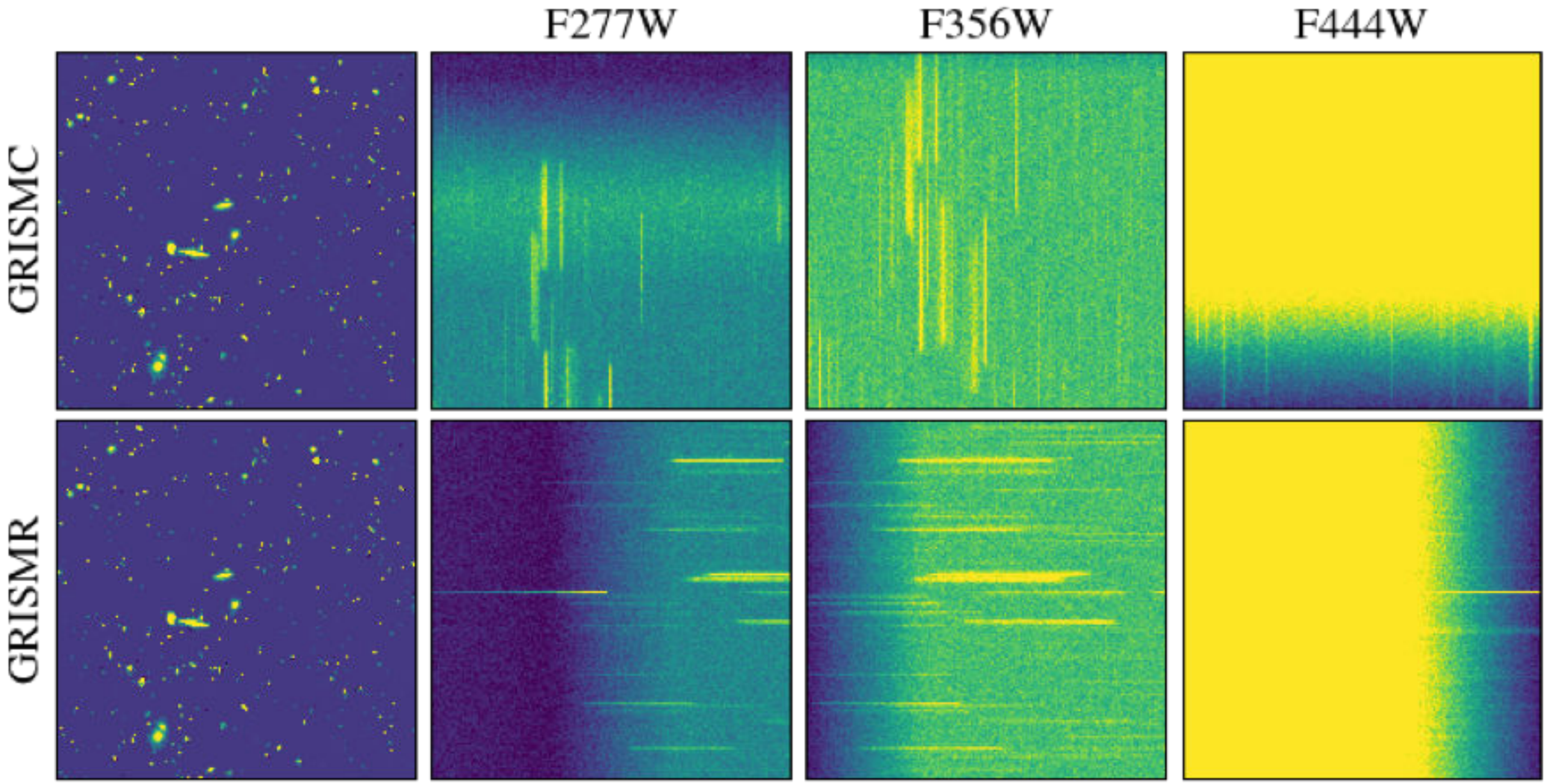
MIR WFSS

NIRCam WFSS Traces Example



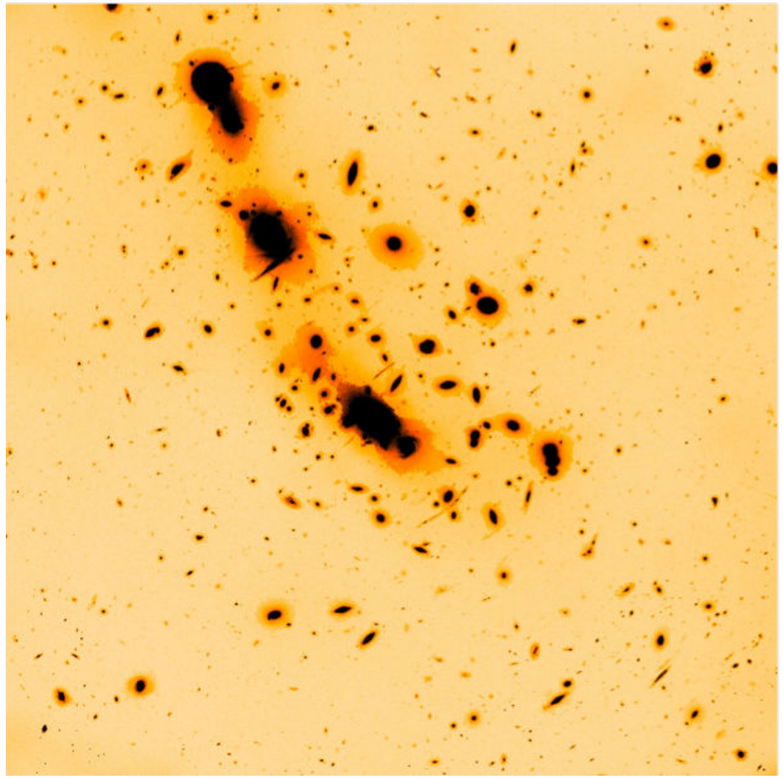
NIRCam WFSS simulations of the GOODS ERS field, with 2hr exposures for the direct image in F356W and grism image in F356W+GrismR. The F356W background has been subtracted from the simulated grism image on the right.

2 Orthogonal Grisms to Mitigate Contamination

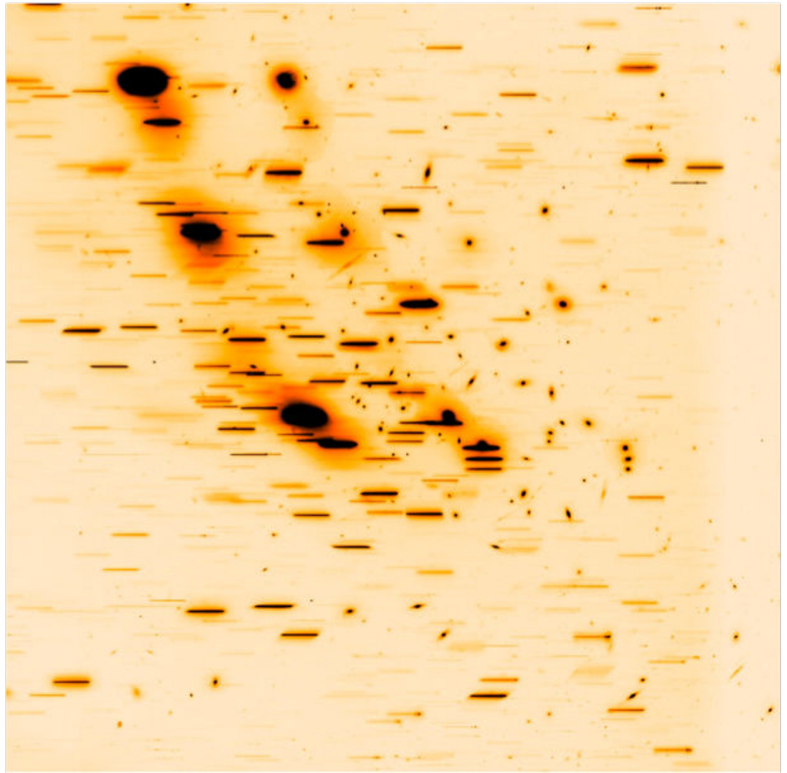


Same for NIRISS

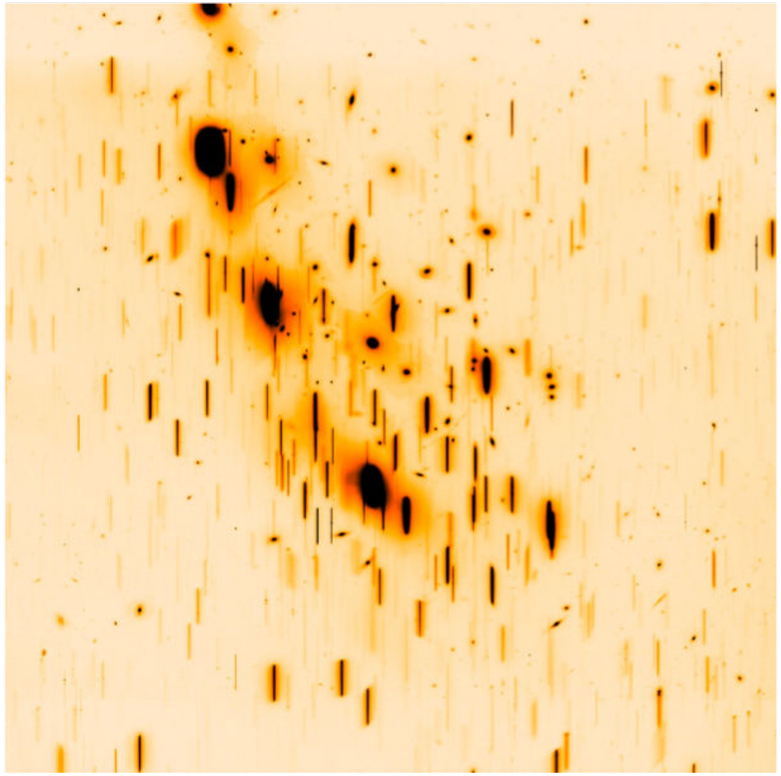
Direct image F200W



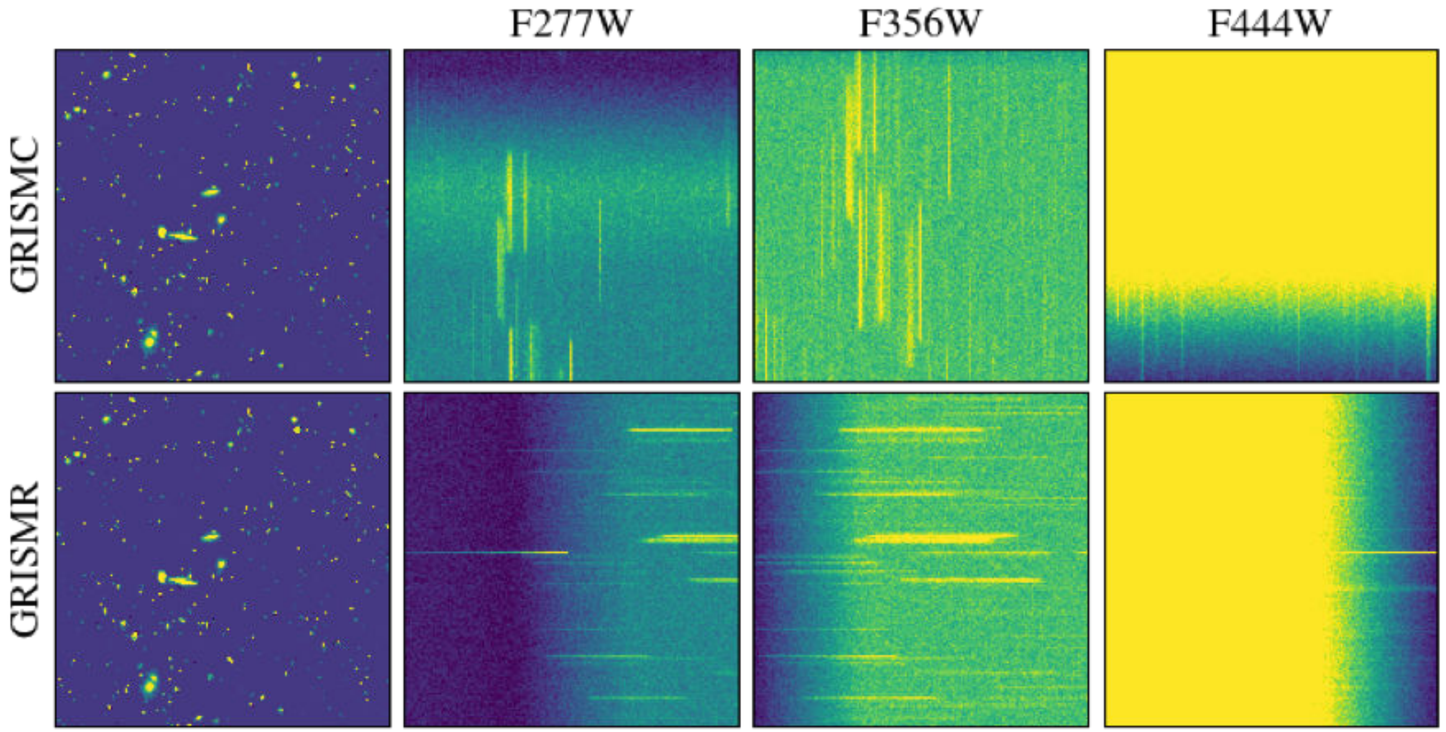
Dispersed image F200W+GR150C



Dispersed image F200W+GR150R



A Word About Background



- NIRCam WFSS benefits from many dithers to construct and subtract a “background” image.

WFSS Strengths and Weaknesses (Compared with MOS/Slit Spectroscopy) - Operation-Wise

- WFSS has no slit so the whole FOV contributes to the background —
- No slit loss +
- No need for a pre-imaging survey. Can do a blind survey of whole FOV +
- Wavelength calibration requires direct images co-observations —
- Constraints on field position angle is loose (facililates mosaics) +
- Wavelength range is limited to the width of a blocking filter —

WFSS Strengths and Weaknesses (Compared with MOS/Slit Spectroscopy) - Science-Wise

- WFSS is ideally suited for blind emission-line surveys and detection of continuum breaks in high-z galaxies +
- Ideally suited for detection of high redshift galaxies : for example, Lyα emission line at z > 5.6 - 17 with NIRISS, and Lyα at z > 18 and optical Hα emission lines at z =2.8 – 6.6 with NIRCam +
- Spatial resolution allows to map emission lines on physical scales of few kpc across redshifits (z>2) +
- For an extragalactic blank field, there are ~ 3000 faint galaxies with < 28 AB magnitude +/—
- Can use Coordinated **PARALLEL** NIRCam Imaging or MIRI Imaging +

JWST Data Calibration Pipeline

From Photons to Science

- JWST collects faint infrared photons and records them as raw digital numbers (DN) on its detectors.
- Raw exposures carry instrumental signatures (noise, bias, cosmic rays) that obscure the astrophysical signal.
- Calibration transforms raw data into science-ready products with accurate fluxes, wavelengths and astrometry.
- Rigorous calibration is essential for reliable photometry, spectroscopy and reproducibility of JWST science results.

Science in Action & Philosophy

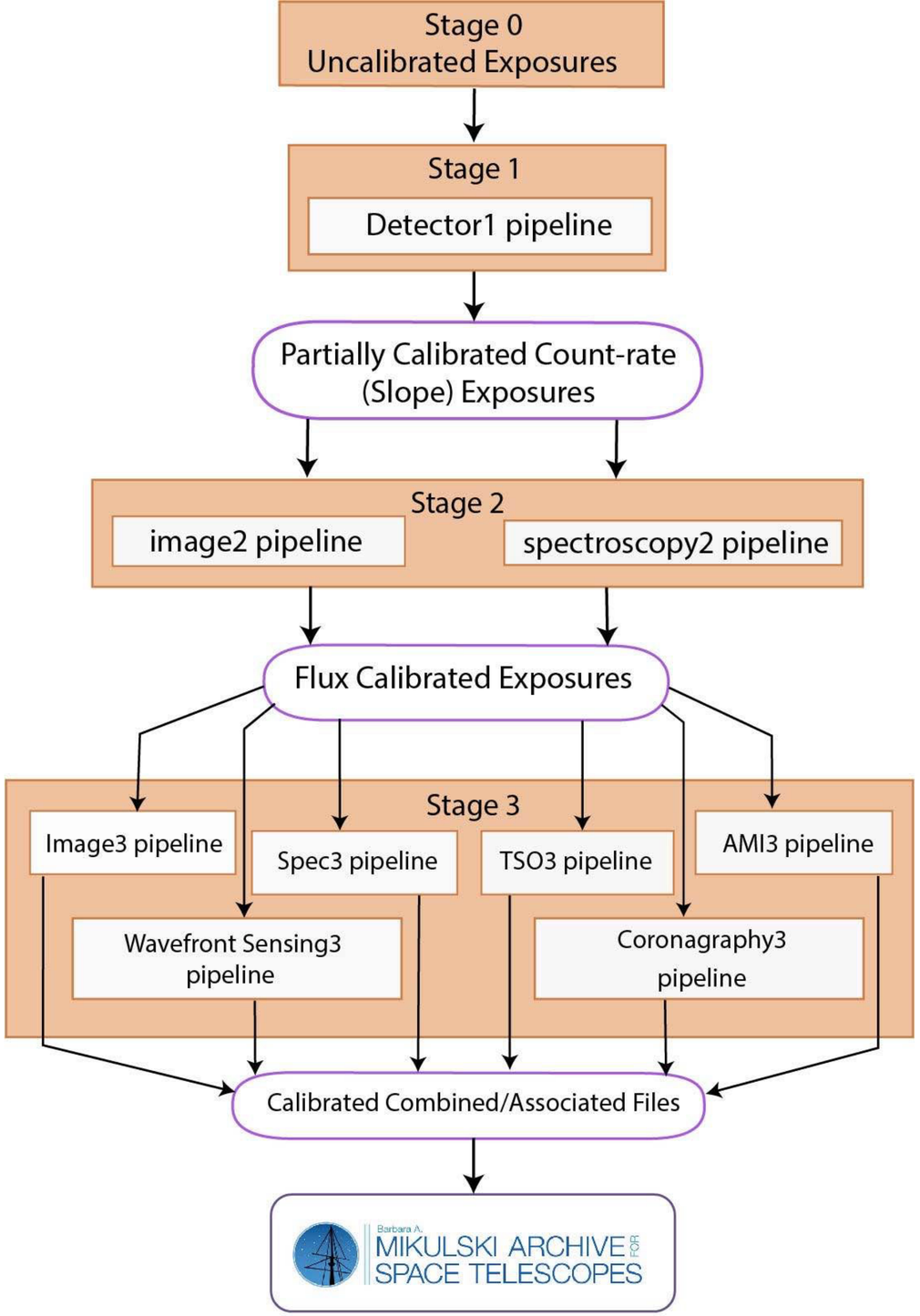
- Calibrated JWST data have enabled discoveries: the earliest galaxies, exoplanet atmospheres and stunning nebulae all rely on precise calibration.
- Transparent, open-source code and version-controlled reference files foster reproducibility and community trust.
- Unified & Modular: JWST uses a single, modular pipeline applicable to all instruments, ensuring shared detector corrections and consistent data models across imaging and spectroscopy.
- Mode-Centric Architecture: Pipeline stages branch by observing mode class (imaging vs spectroscopy), allowing each instrument to plug in specifics without altering the core calibration logic.
- Reference File-Driven: Calibration details are governed by metadata-selected CRDS reference files, keeping algorithms broadly applicable yet finely tuned per mode.
- Association-Based Processing: The pipeline groups exposures based on proposal metadata into associations, enabling consistent data combination (mosaics, cubes, spectra) regardless of instrument.
- Reproducible & Scalable: Steps are configurable, fully documented, and provenance-rich, providing consistent, science-ready products, streamlined maintenance, and future-proof scalability.

Anatomy of JWST Data

- Stage 0 delivers uncalibrated exposures (_uncal.fits) in units of total DN from the detectors.
- Raw files include science frames plus metadata: detector readouts, timing, subarray configuration and housekeeping telemetry.
- Pipeline processing produces a hierarchy of products: count-rate images (_rate), calibrated exposures (_cal), mosaics (_i2d), spectral cubes (_s3d) and catalogs (_cat).
- Each product is accompanied by descriptive headers and data quality arrays for downstream analysis.

Pipeline Architecture

- Stage 1 applies detector-level corrections and converts ramps into slope images (_rate)
- Stage 2 performs instrumental calibration on each exposure: flat-fielding, wavelength, flux and astrometric calibration (_cal)
- Stage 3 combines multiple exposures into mosaics and cubes, and extracts spectra and catalogs (_i2d, _s3d, _cat)



Stage 1: Detector Corrections

- Data Quality (DQ) initialization flags saturated pixels, bad pixels and instrument anomalies.
- Superbias and reference-pixel subtraction remove detector bias patterns.
- Jump detection identifies cosmic rays; non-linearity and persistence corrections linearize ramps.
- Dark current subtraction removes instrument thermal signal; ramp fitting produces count-rate images (_rate).

Stage 2: Building Calibrated Exposures

- Flat-fielding corrects pixel-to-pixel sensitivity variations across the detector.
- Wavelength calibration constructs the World Coordinate System (WCS) and maps pixels to spectral/sky coordinates.
- Flux calibration scales data into physical units (Jy or erg s^{-1} cm^{-2} $Å^{-1}$) using standard stars and instrument response.
- Background subtraction removes stray light and residual dark signal; output calibrated exposures carry suffix _cal and spectral products _s2d/_x1d.

Stage 3: Combining & Extracting Products

- Align and resample calibrated exposures onto a common astrometric grid using drizzle and 3D cube algorithms.
- Produce flux-calibrated mosaics (_i2d) and spectral cubes (_s3d) combining information from multiple dither positions.
- Extract one-dimensional spectra from cubes (_x1d) and generate segmentation maps (_segm) and source catalogs (_cat).
- Stage 3 algorithms account for astrometric distortions, flux conservation and noise propagation.

CRDS & Reference Files

- Calibration relies on version-controlled reference and parameter files (ASDF) describing darks, flats, linearity and distortion corrections.
- Instrument teams periodically update these files; they are ingested into the Calibration Reference Data System (CRDS).
- CRDS uses dataset metadata (instrument, filter, observation date, pipeline version) to select the correct reference files.
- When the pipeline runs, CRDS automatically downloads the appropriate files into a local cache and logs the context for reproducibility.

Working with Calibrated Data & Tools

- Data products progress from _uncal to _rate, _cal, _i2d/_s2d/_s3d and _cat; filenames embed processing stage and instrument information.
- The Python jwst package provides DataModel classes to read, modify and write JWST FITS files and run individual steps.
- Pipelines and steps are modules that can be imported and configured; the .call() method executes them while CRDS picks reference files.
- Jupyter notebooks, STScI tutorials and command-line interfaces make it easy to reprocess data or explore individual calibration steps.

What's Next?

- JWST offers 18 distinct science observing modes, too many to comprehensively cover within this workshop. We'll concentrate on three core areas:
  - Imaging
  - Spectroscopy (2D and 3D)
  - Coronagraphy
- Project work (Week 2) Please discuss your specific science interests with the lecturers early on. We'll tailor support to best match your goals and help you successfully use JWST data in your projects.
- This focused approach ensures you'll gain a strong foundation in key JWST data-analysis skills while allowing flexibility to explore individual scientific objectives in depth.