



STScI | SPACE TELESCOPE
SCIENCE INSTITUTE

EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

HIGH CONTRAST IMAGING (HCI) WITH JWST

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JWST Coronagraphs Working Group Lead

Master Class - Level 2 - Nov 19th & 20th 2019 - STScI



JWST High Contrast Imaging (HCI) Level 2 Master Class: Outline

Introduction

- ◆ **High Contrast, Direct Imaging**, a powerful technique!
- ◆ JWST's incredible combination of inner-working angle & sensitivity in the IR, synergy with the ground
- ◆ JWST **Coronagraphy**: **NIRCam** & **MIRI**
- ◆ JWST **Aperture Masking Interferometry** (AMI): **NIRISS**

HCI Roadmap Walk-Through

- ◆ **Parameter & detectability space** of JWST HCI modes
- ◆ **Example Science Programs**
- ◆ The **HR 8799** exoplanetary system, an **ideal use case** for the Master Class

Proposal Planning Tools & HCI Resources

- ◆ STScI supported: JDox, ETC, APT, CVT...
- ◆ ETC Limitations & high(er) fidelity calculations

Hands-on session & NIRISS/AMI

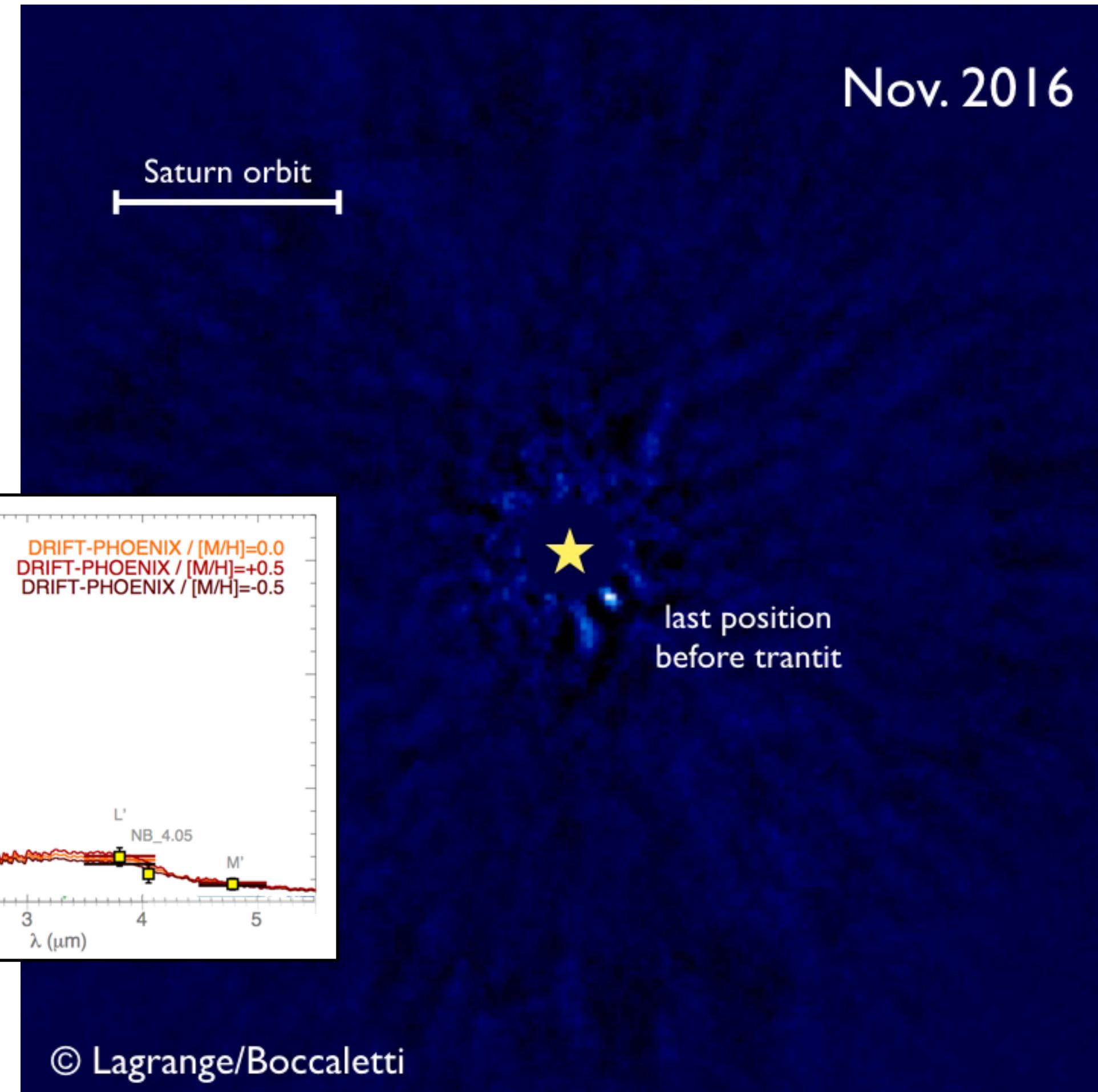


Introduction



High Contrast, Direct Imaging: a powerful technique!

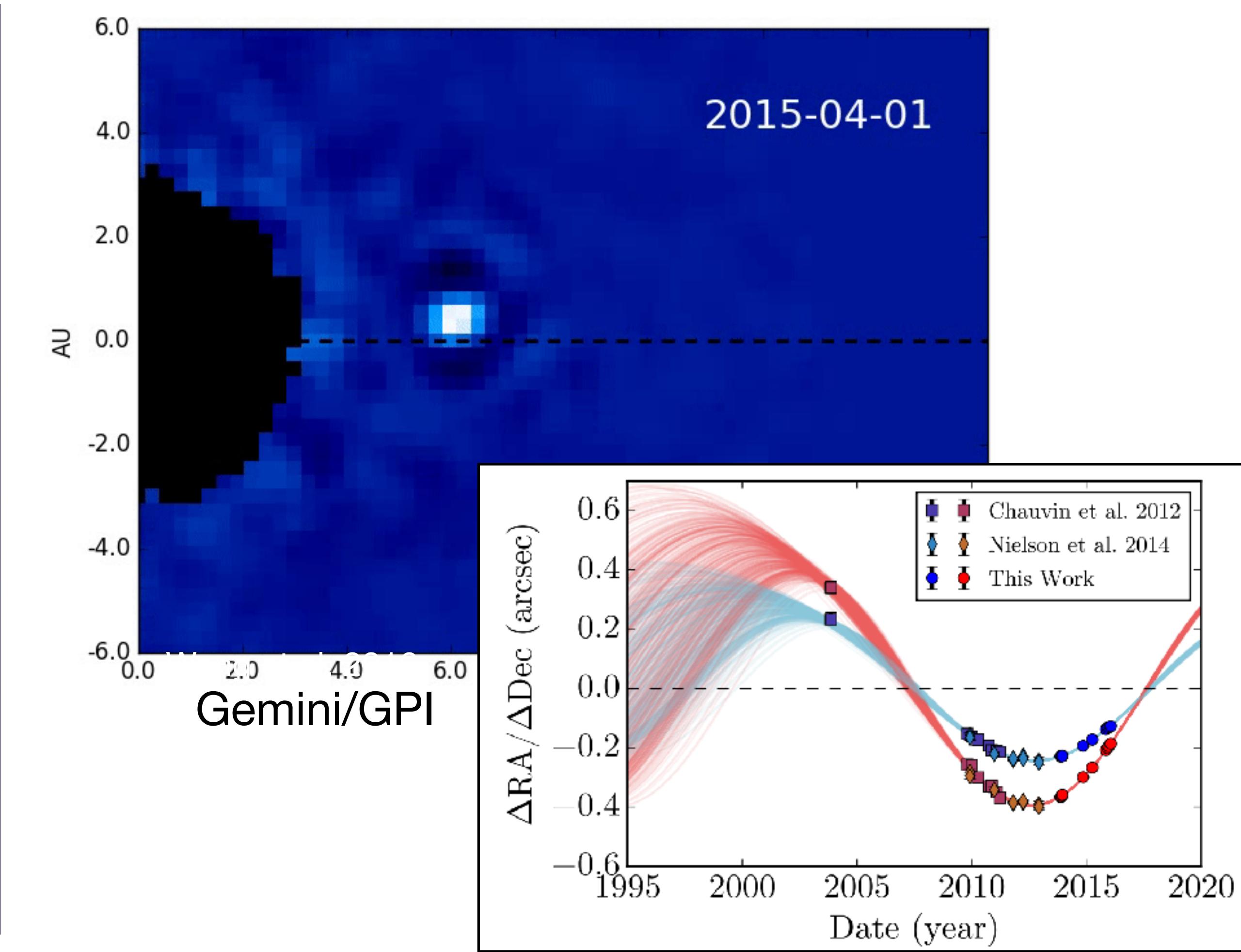
Direct measurement, orbital motion, colors: the **β Pictoris** debris disk & **\sim 10-12 M_{Jup} planet**



Bonnefoy et al.
2013

VLT/NACO & SPHERE

Lagrange et al.
2019

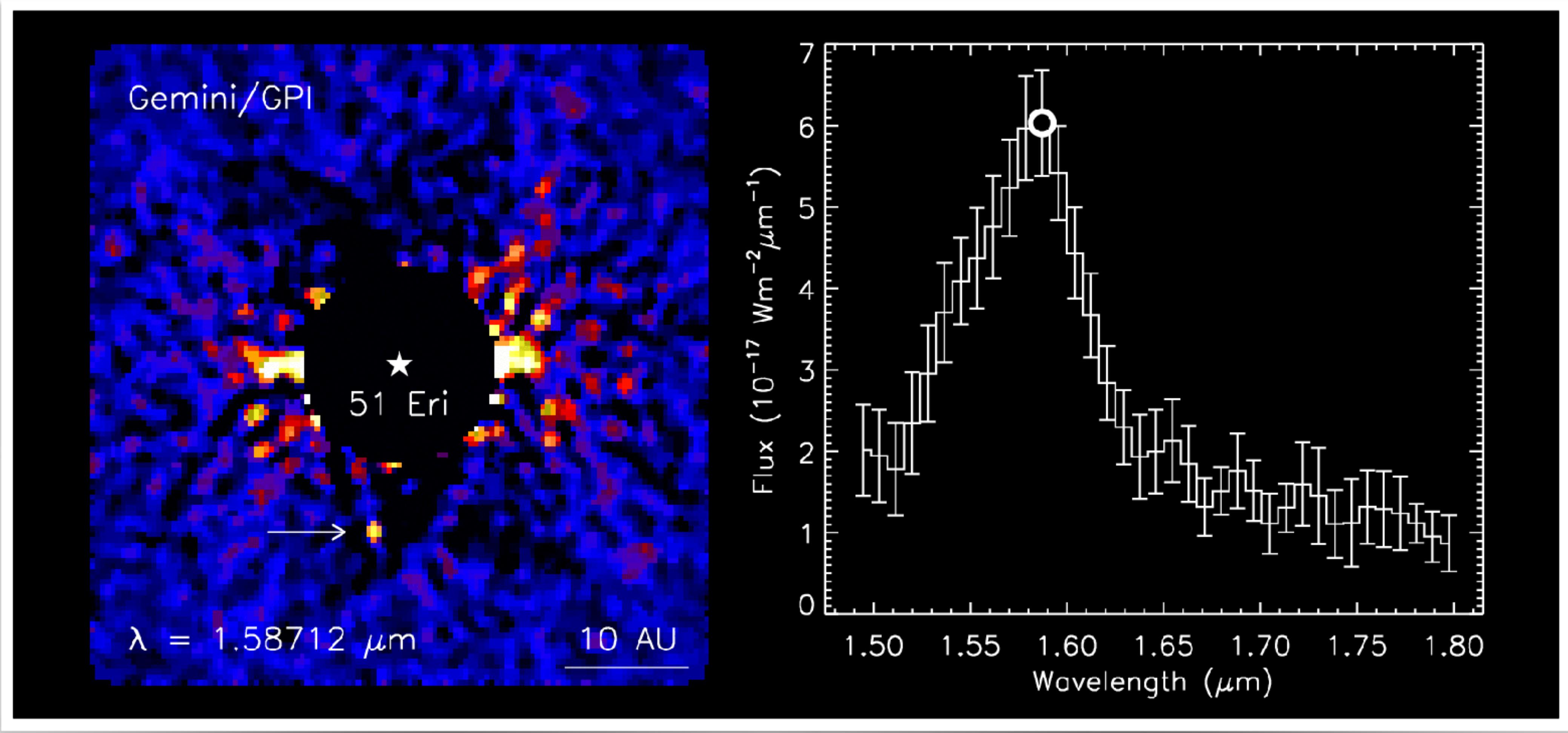


Wang et al. 2016



High Contrast, Direct Imaging: a powerful technique!

Low-resolution spectra: **51 Eridani b** planet ~ 2 M_{Jup}, ~ 700 K

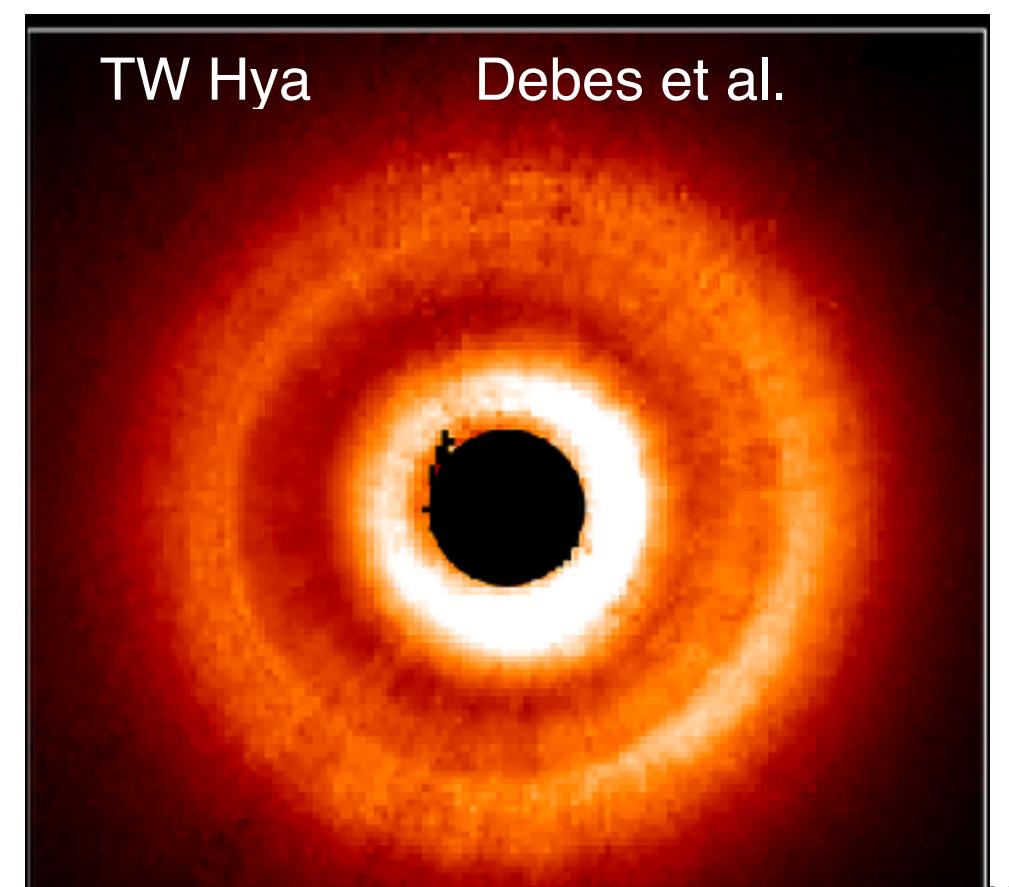
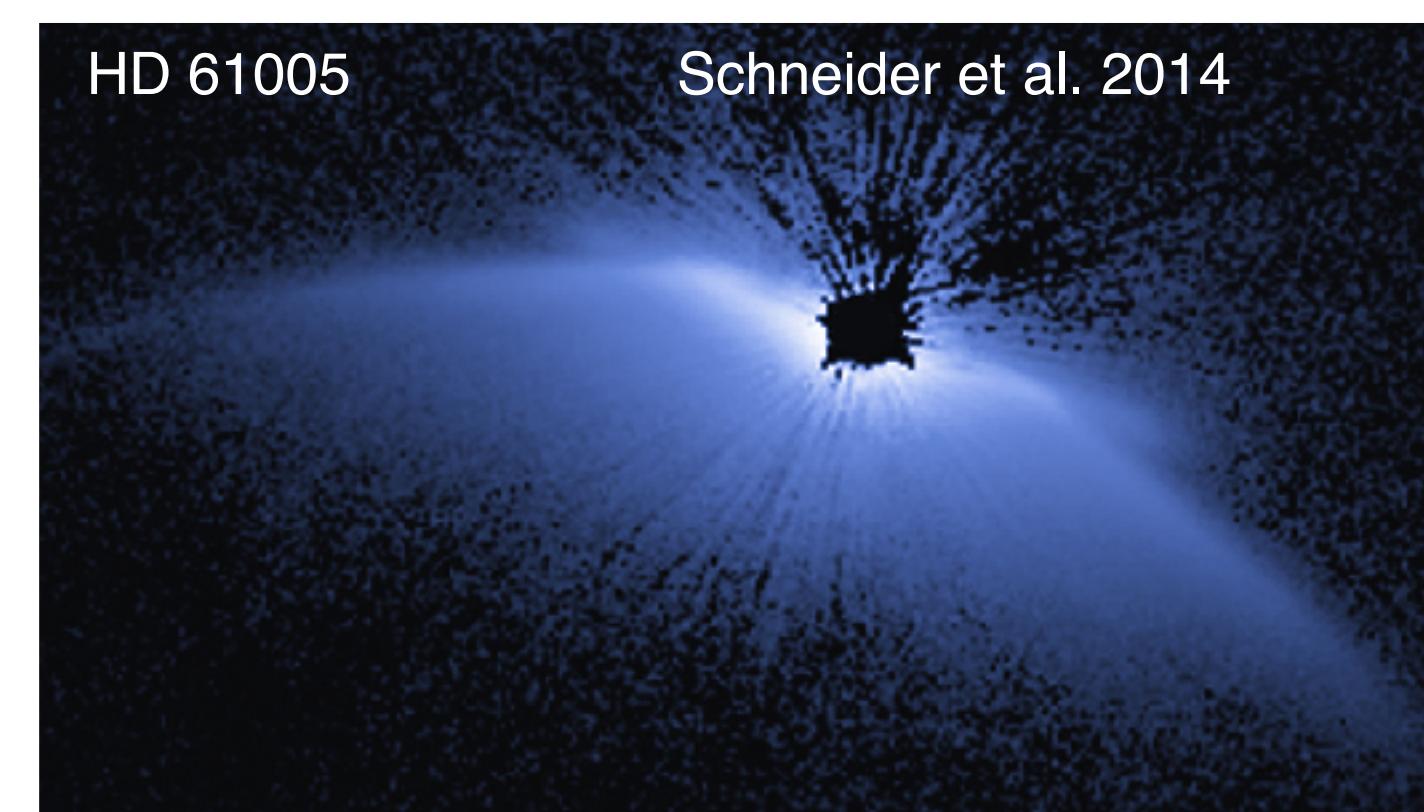
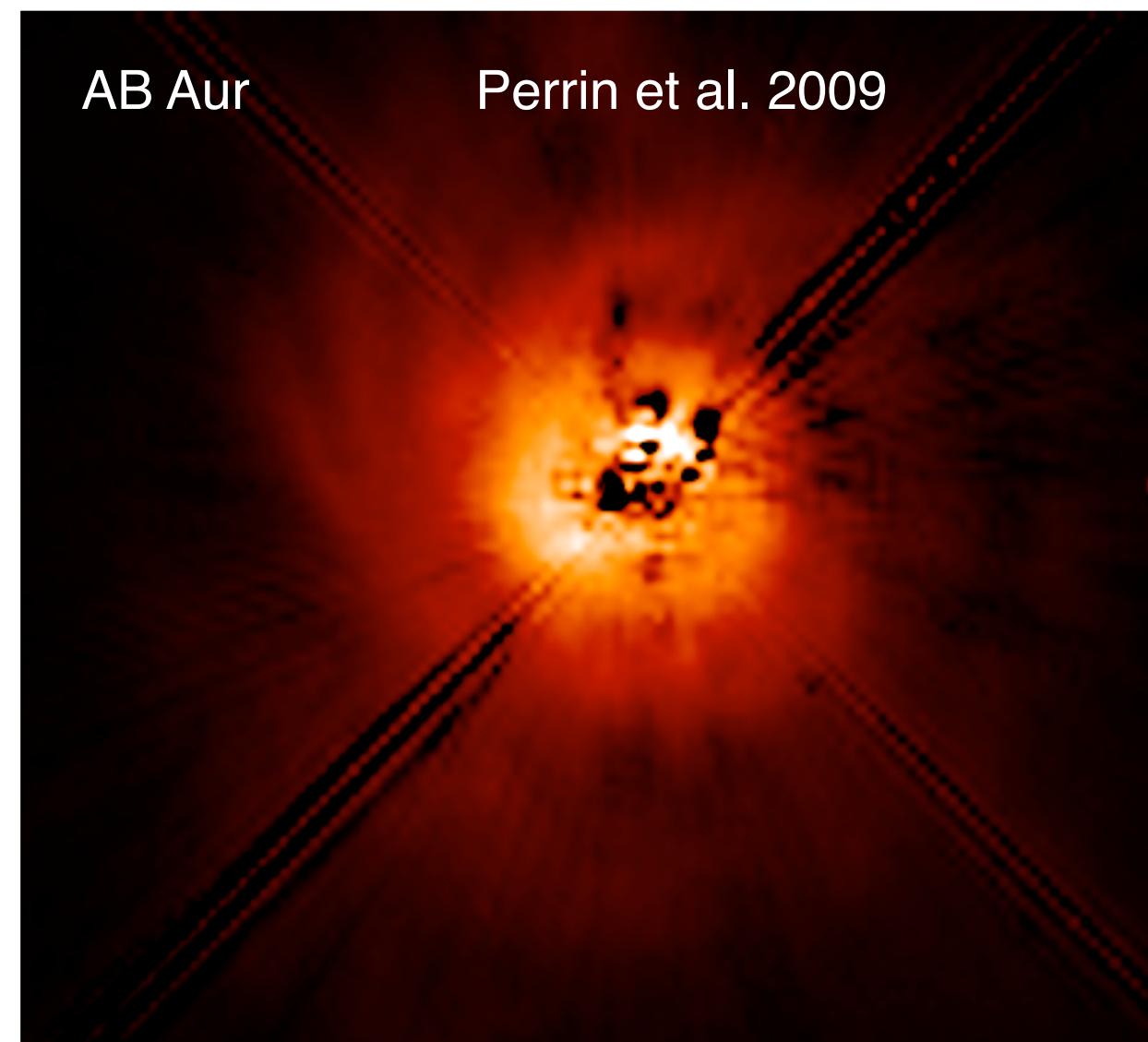
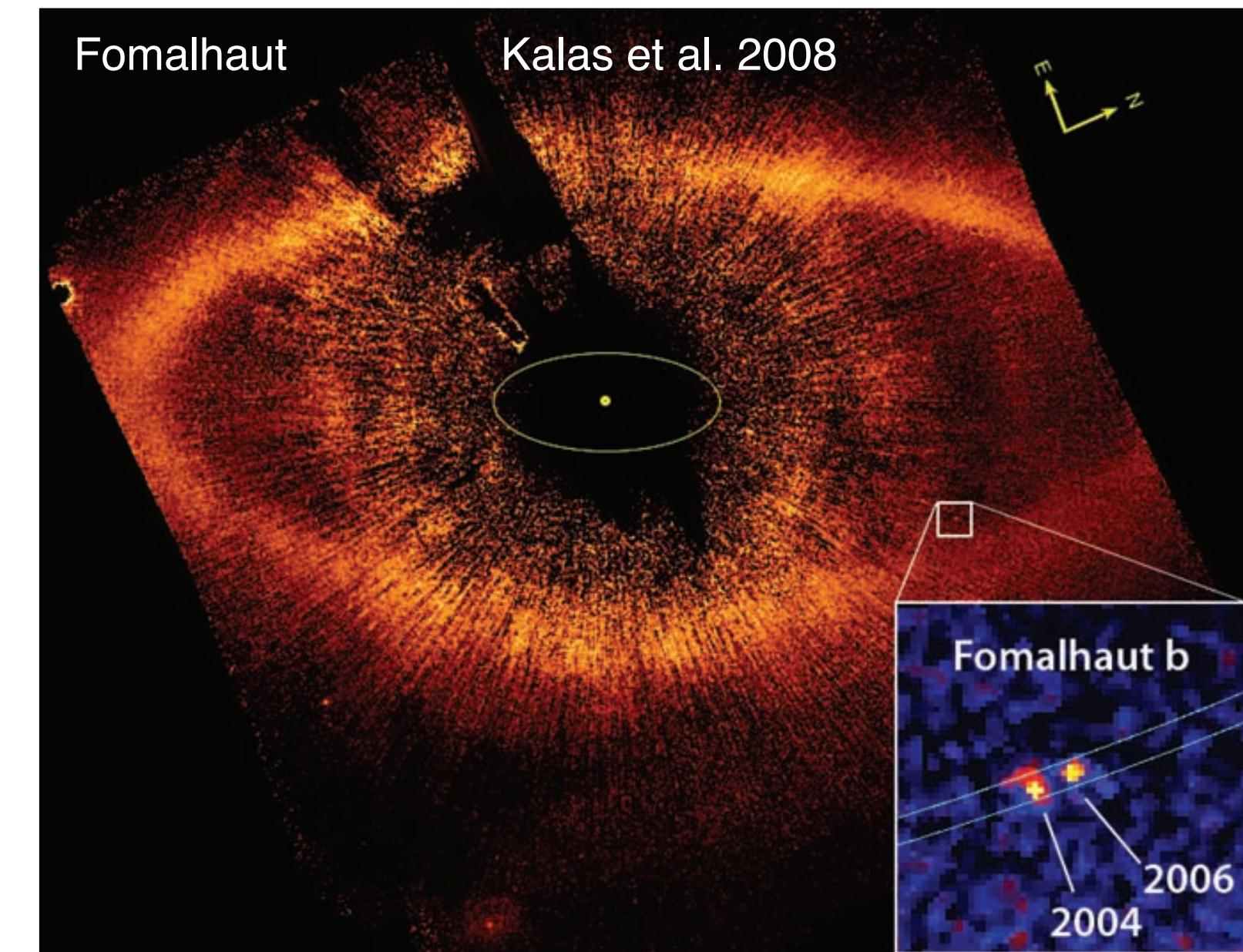
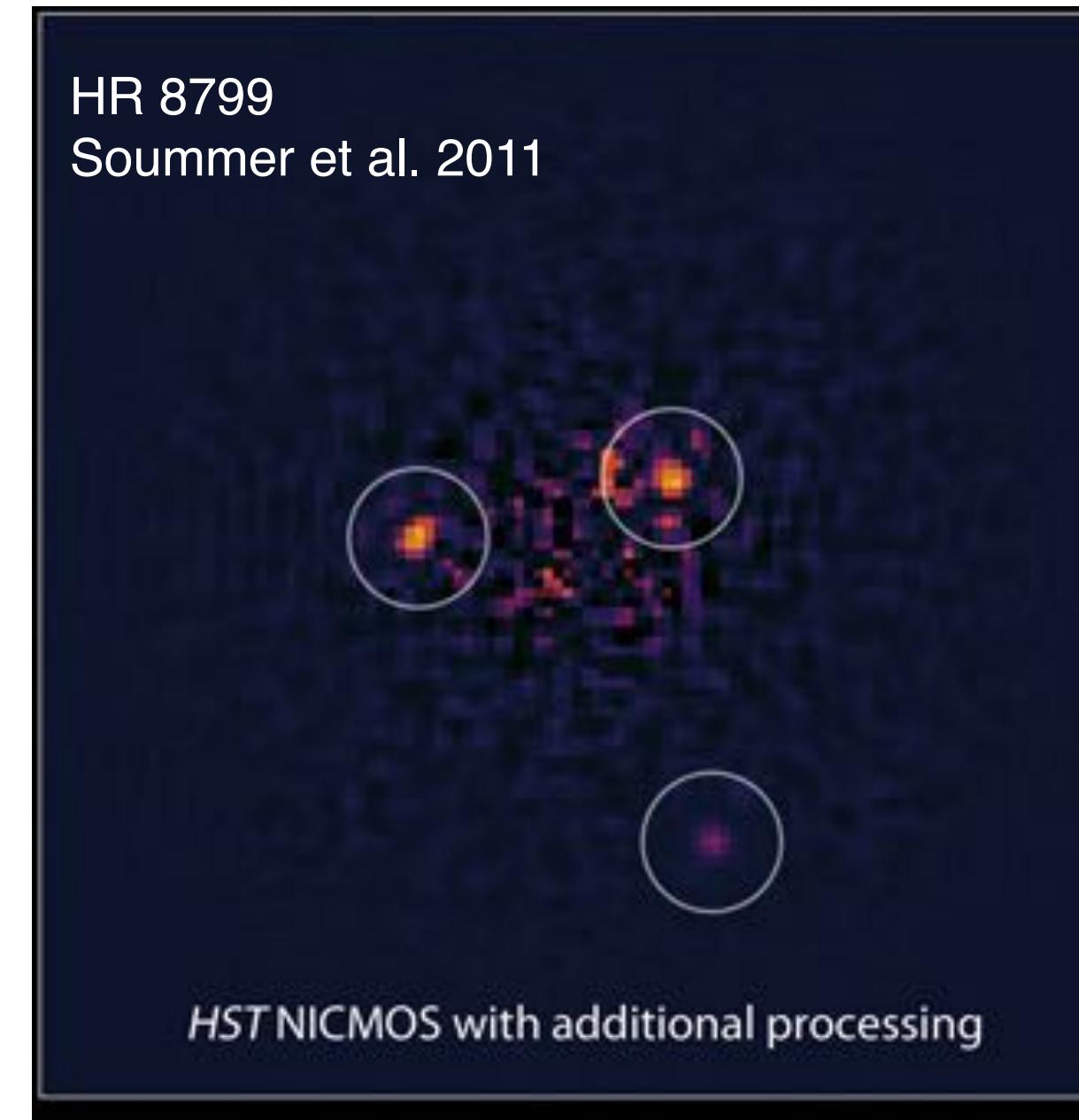
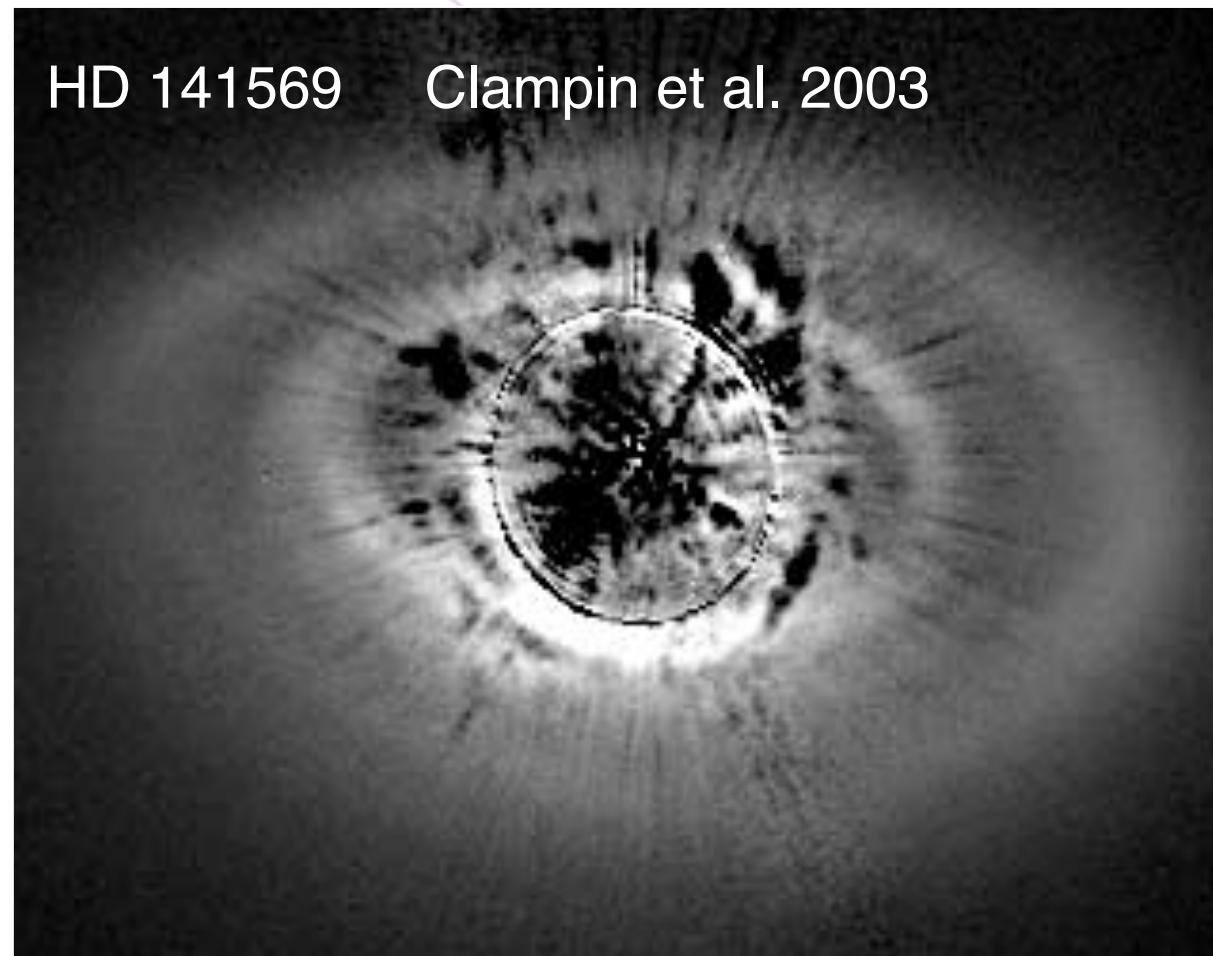


Gemini/GPI

Macintosh et al. 2015, Rosa, R et al. 2015, Rajan et al. 2017

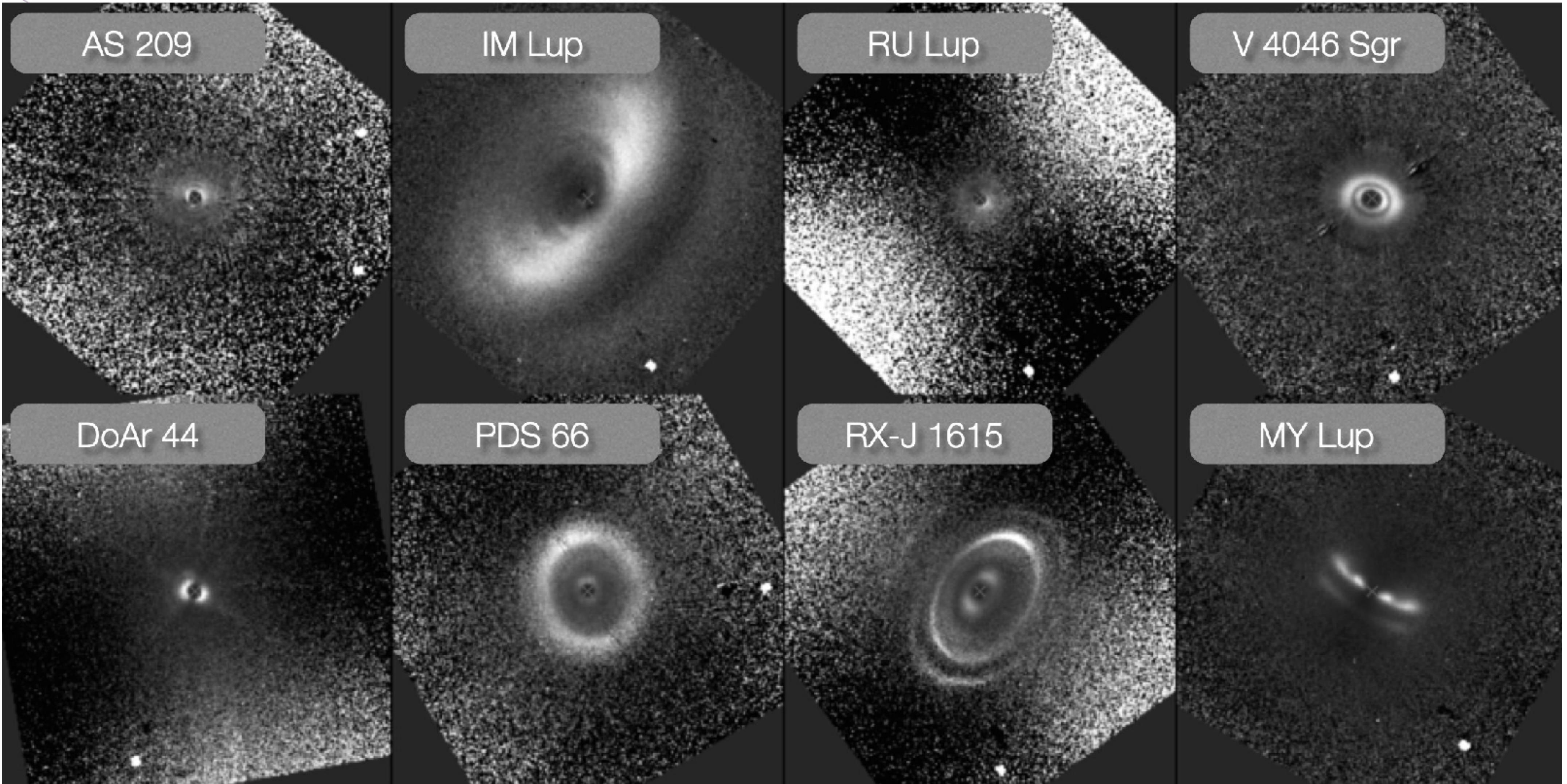


Coronagraphic studies with Hubble of exoplanets, brown dwarfs, and disks





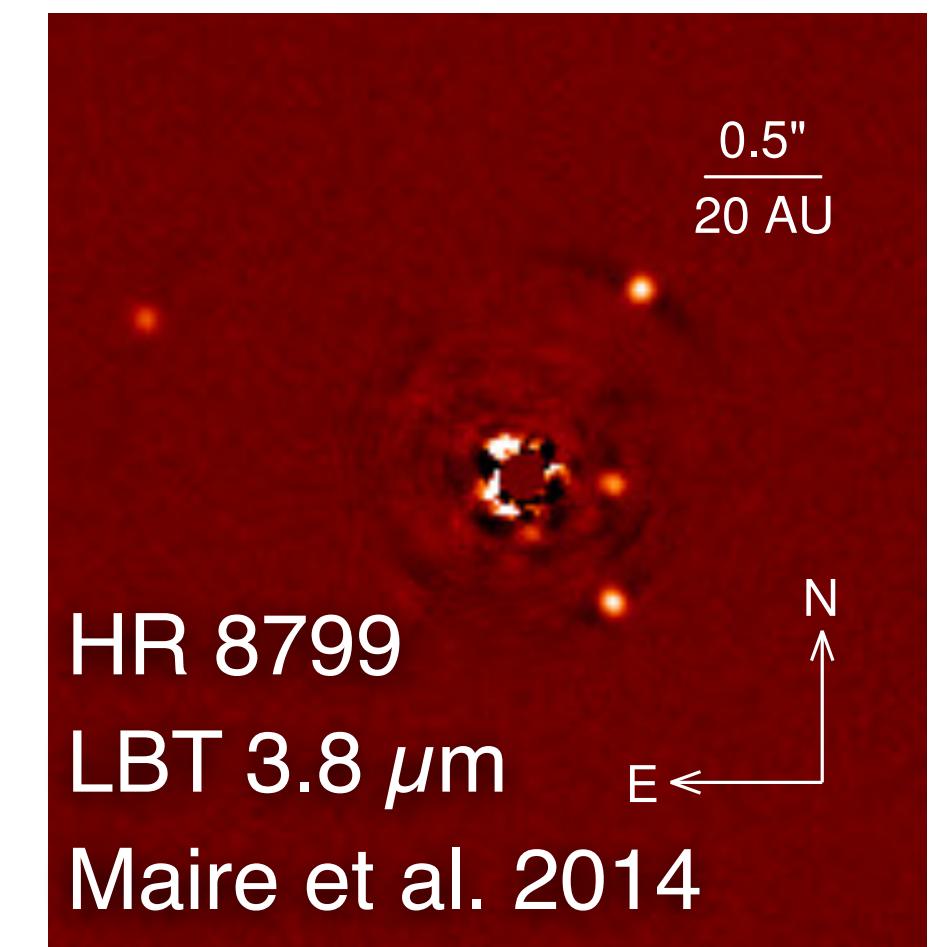
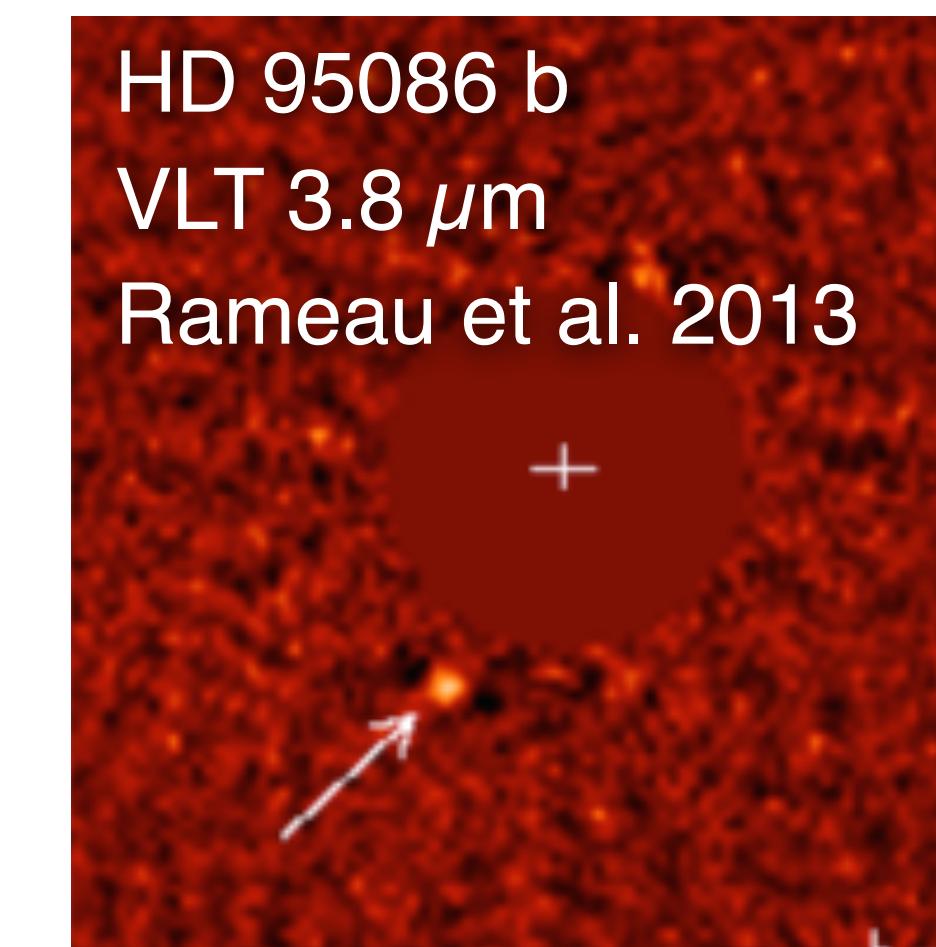
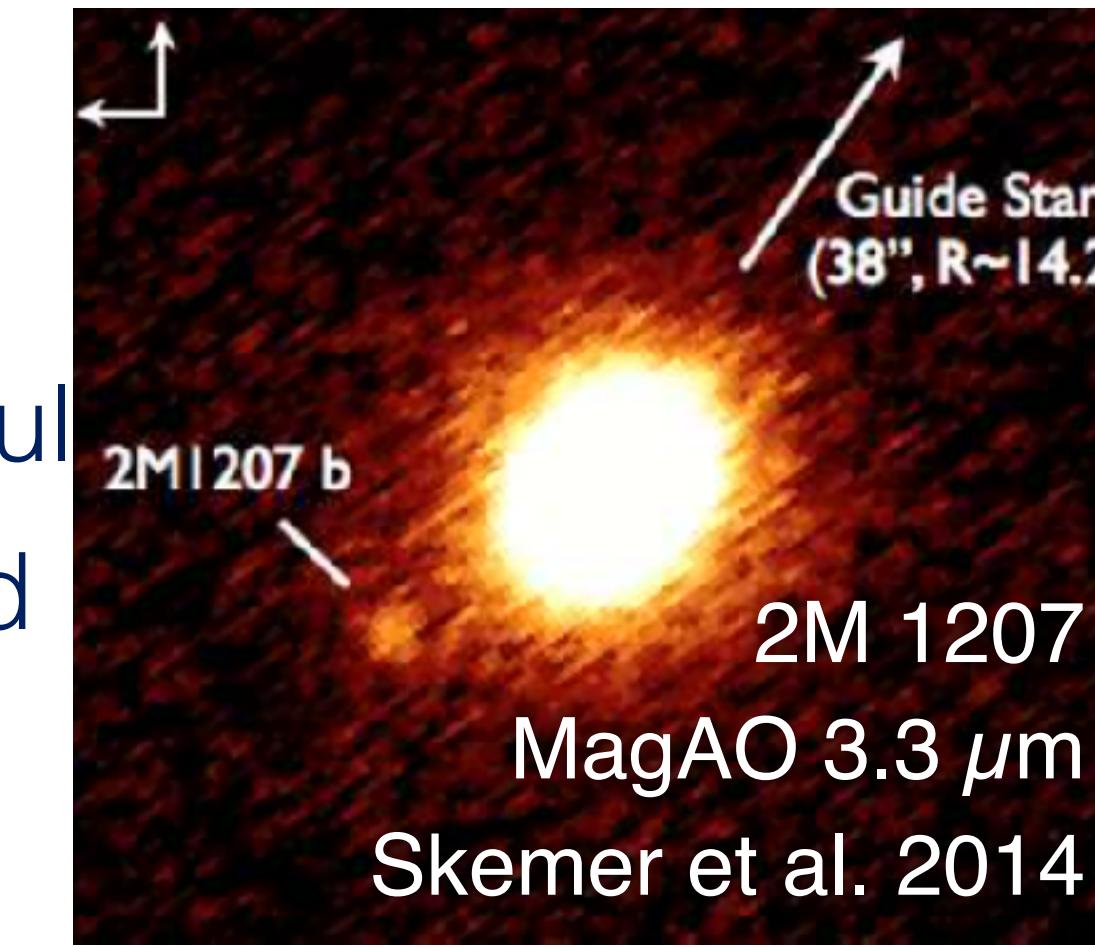
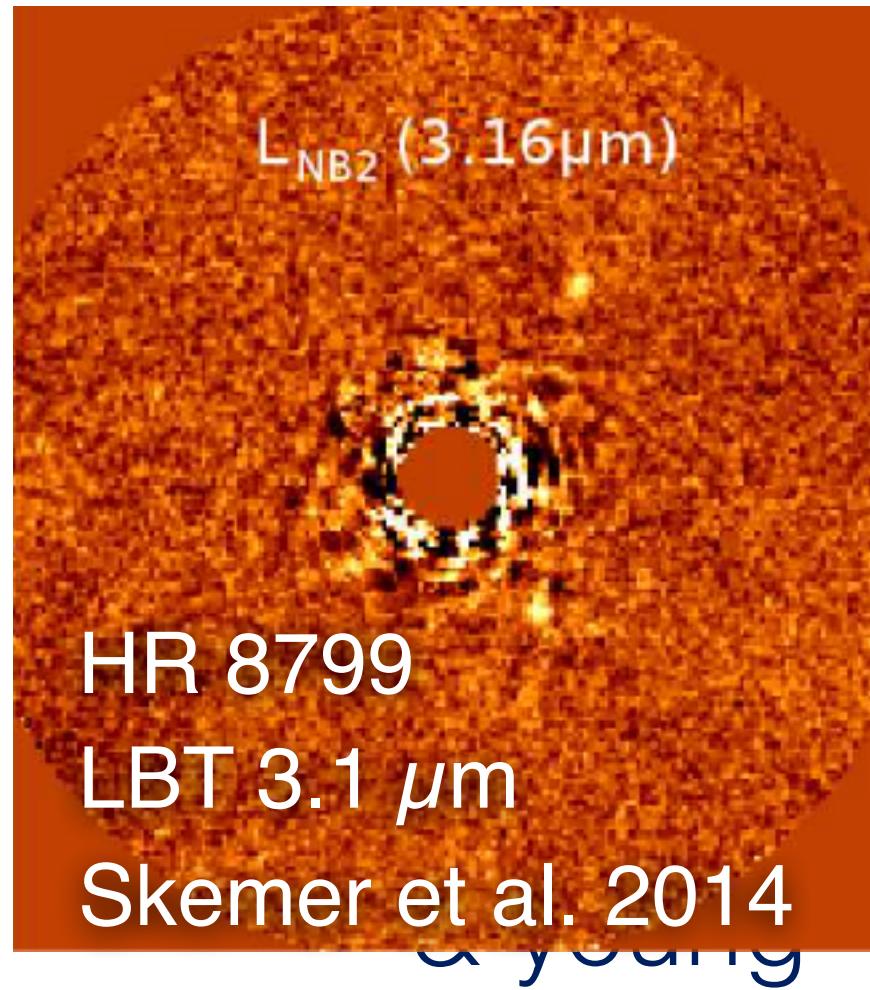
Coronagraphic images of disks in scattered light from the ground



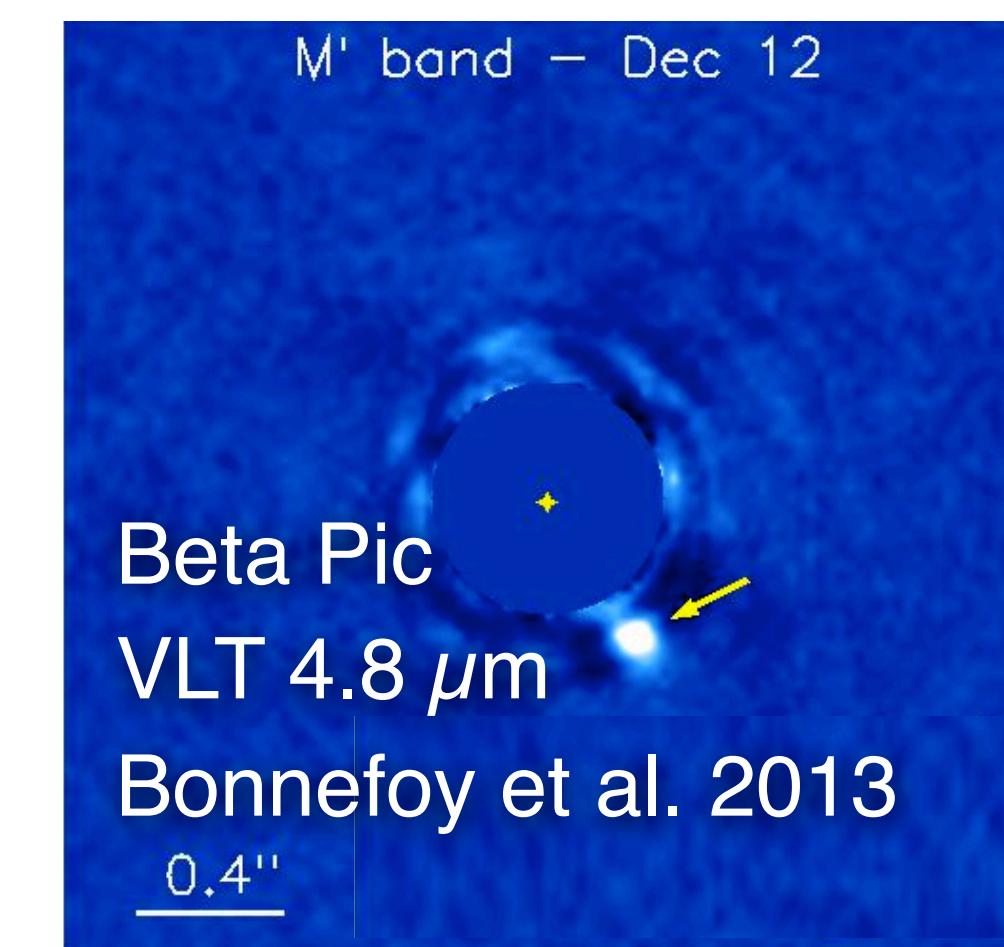
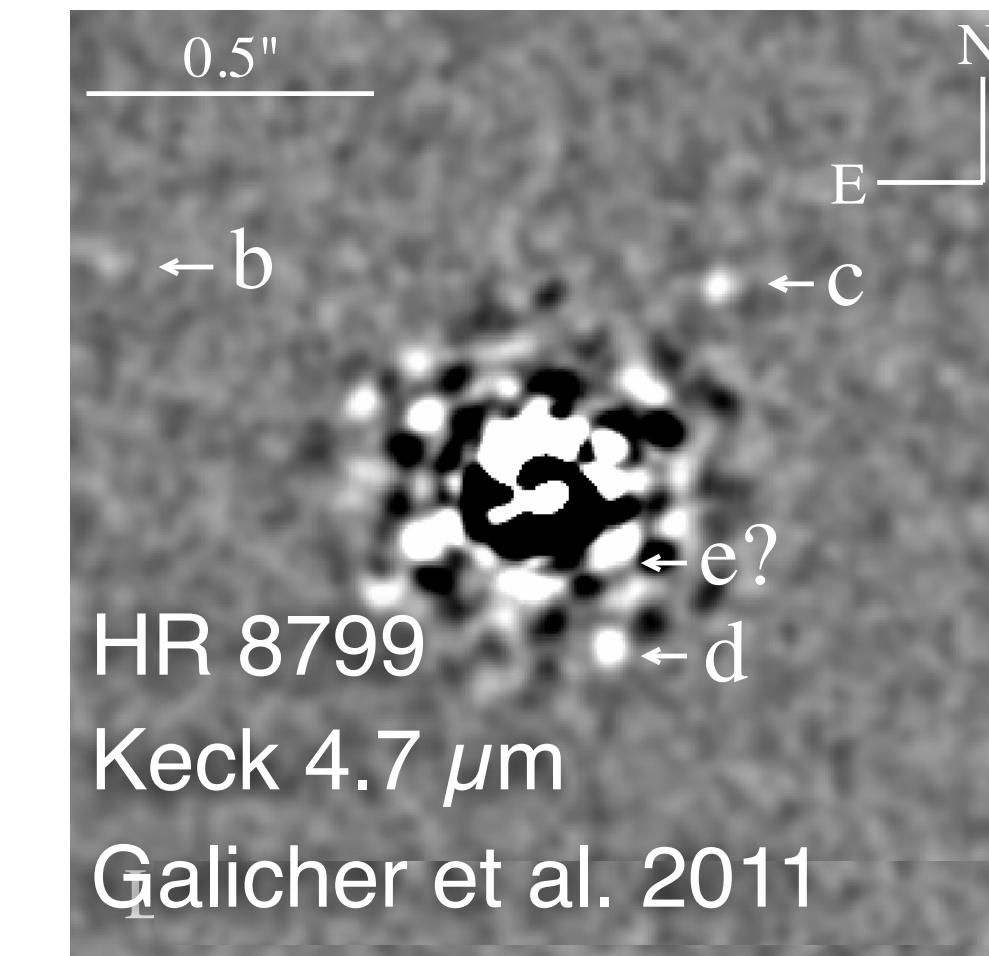
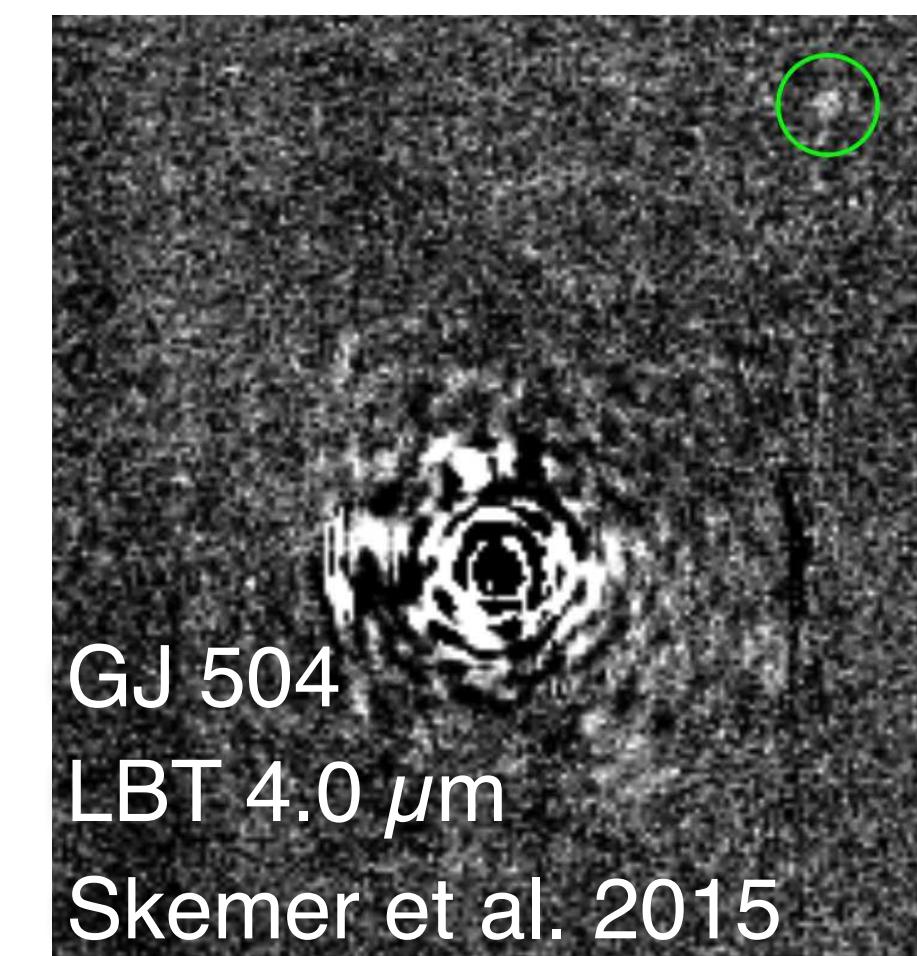
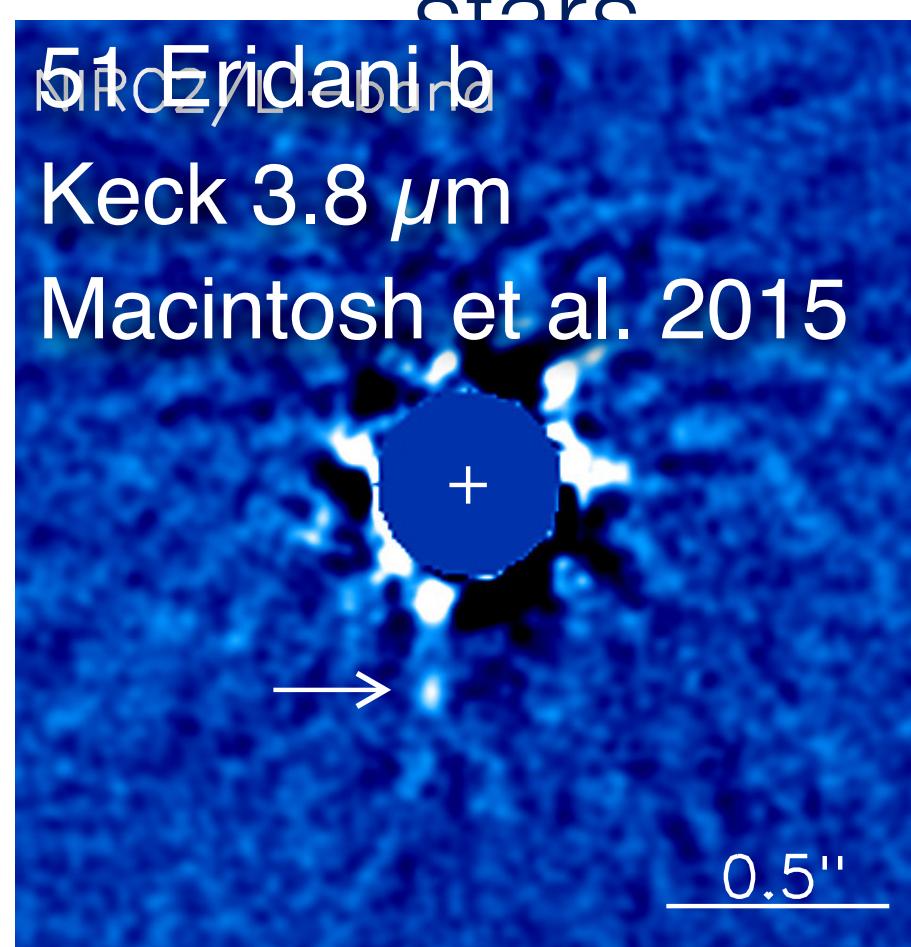
Gallery, courtesy of H. Avenhaus (SPHERE J-band, Polarized scattered light, FWHM \sim 35-50 mas)



examples of 3 to 5 μm exoplanet imaging from the ground



Possible
but with
great difficulty
and around
very bright
& young
stars





i.e Coronagraphy & High Contrast Imaging of QSOs

PG 1700+518

QSO, $z \sim 0.3$

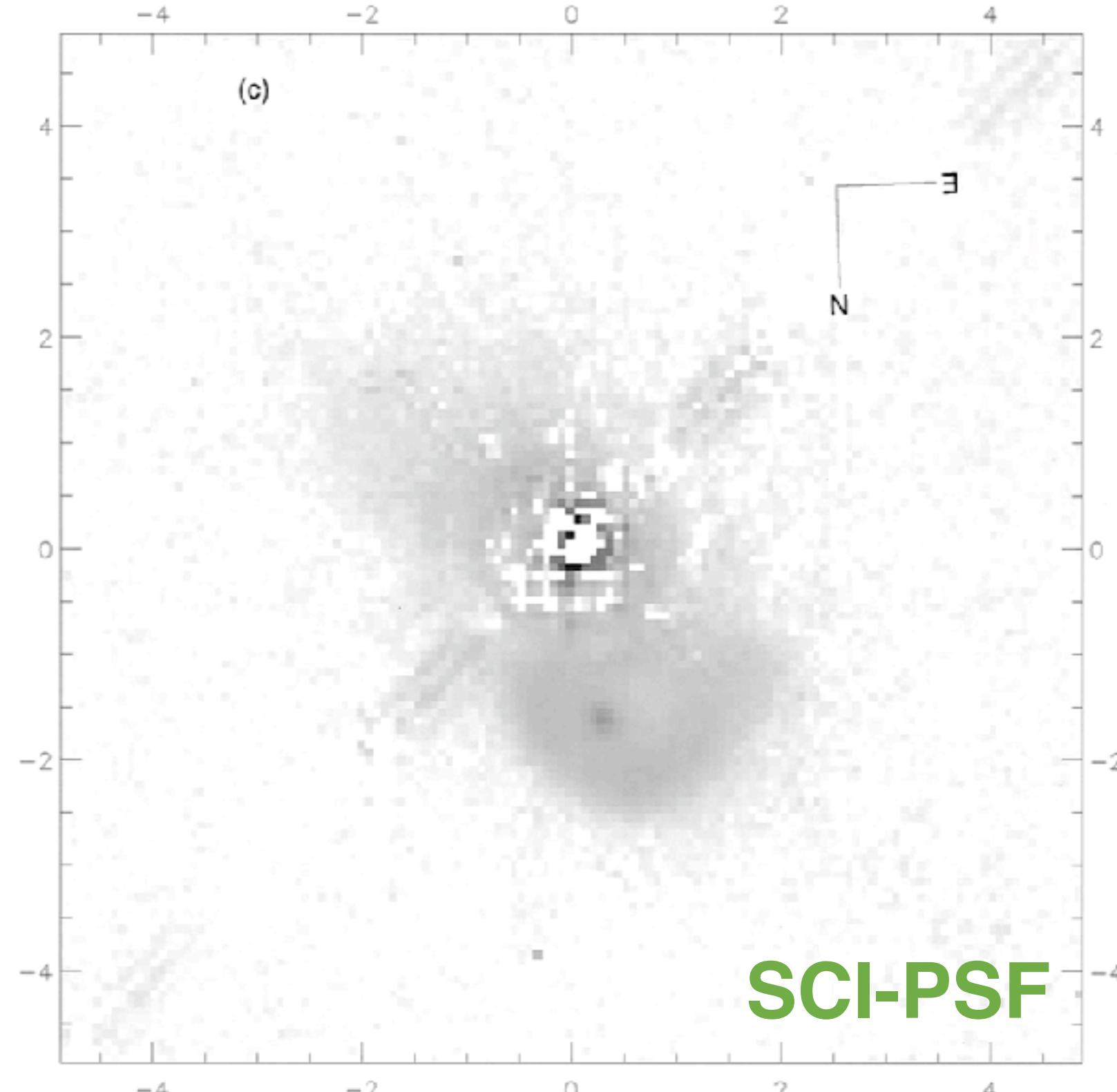
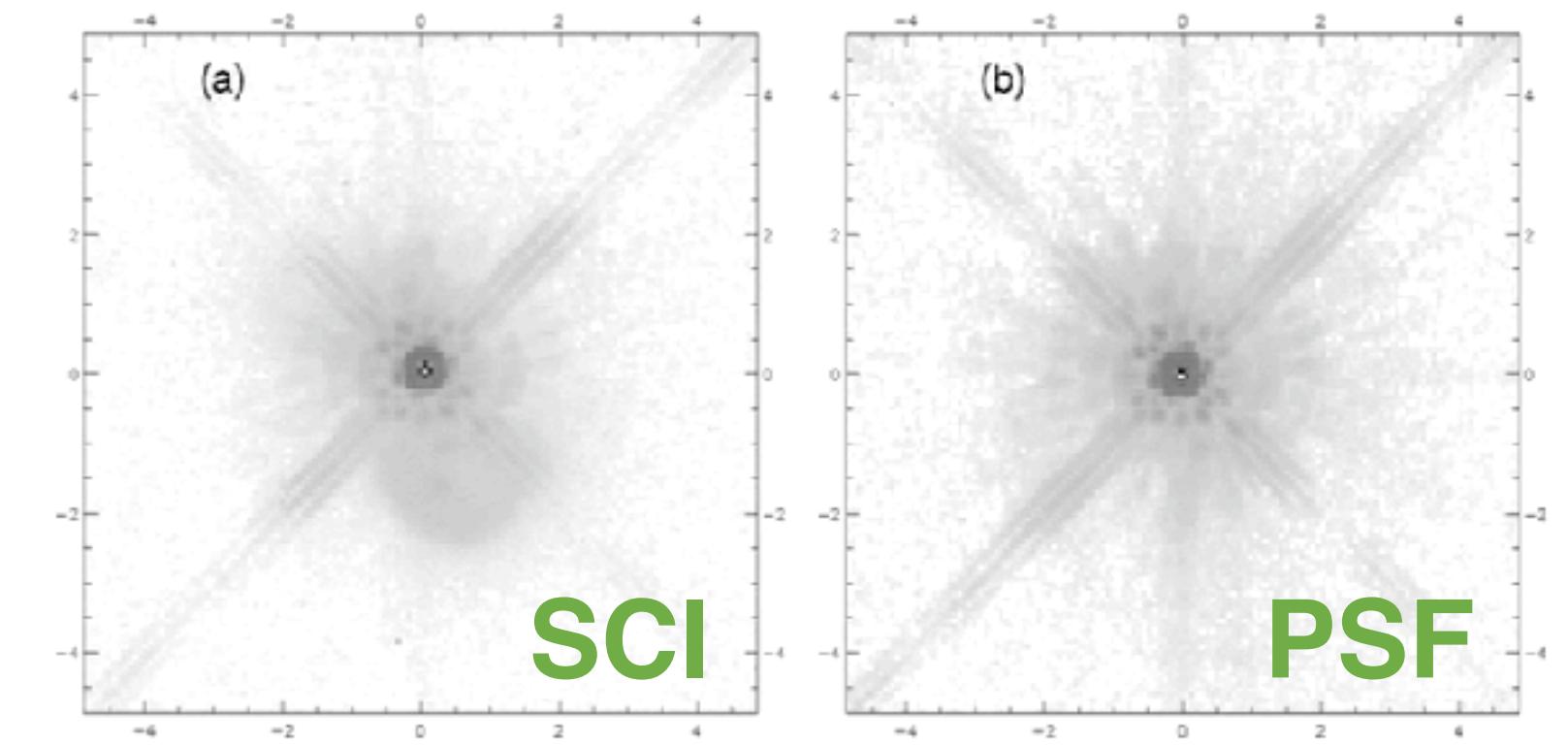
Host Galaxies & Molecular Gas

HST/NICMOS F160W (\sim H-band)

Imaging

1997

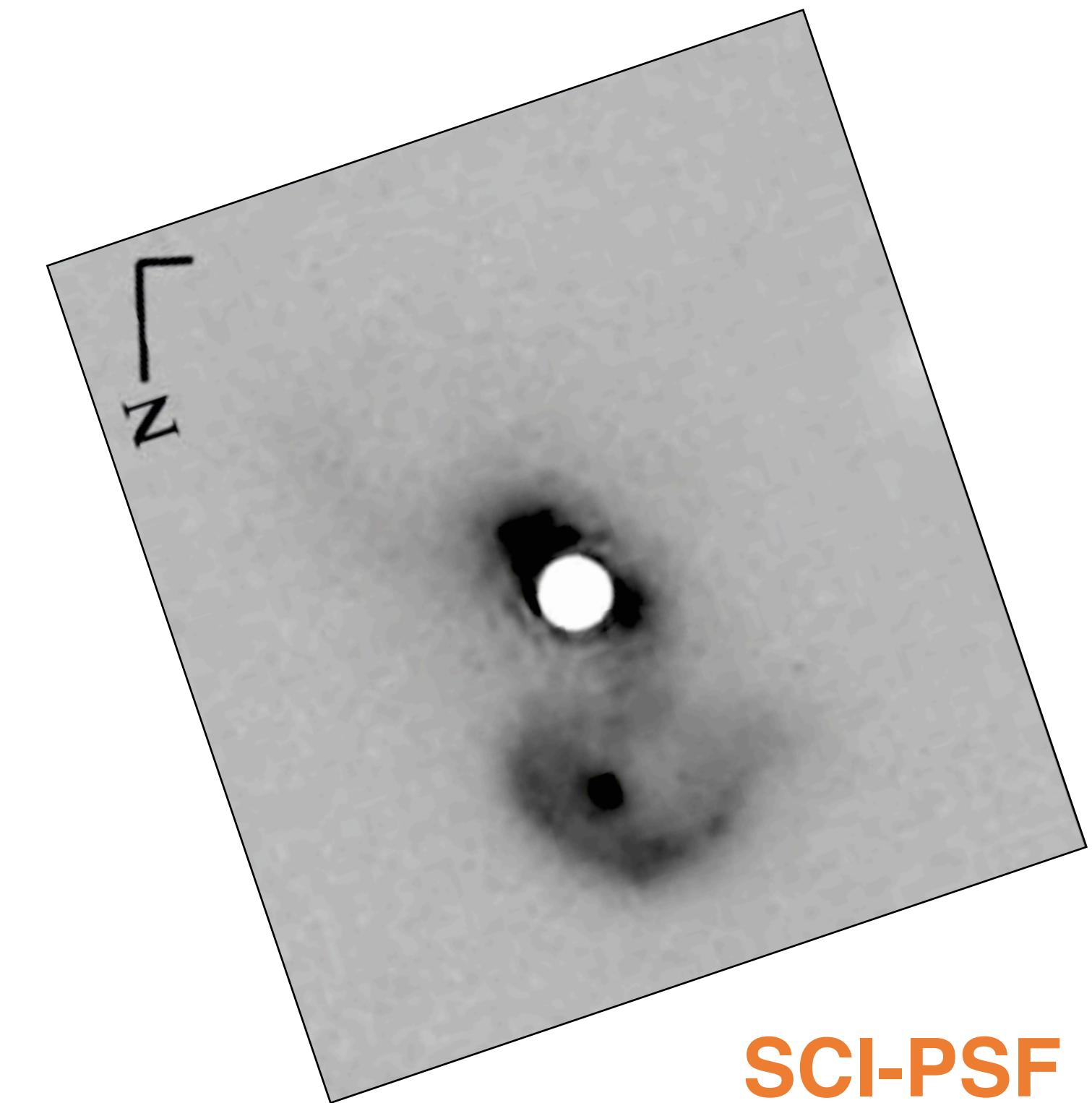
Hines et al. 1999



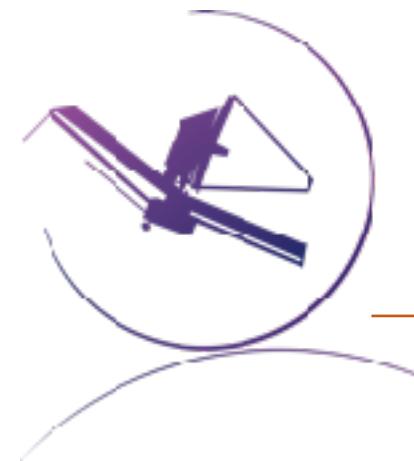
Coronagraphy

1998

Evans et al. 2009

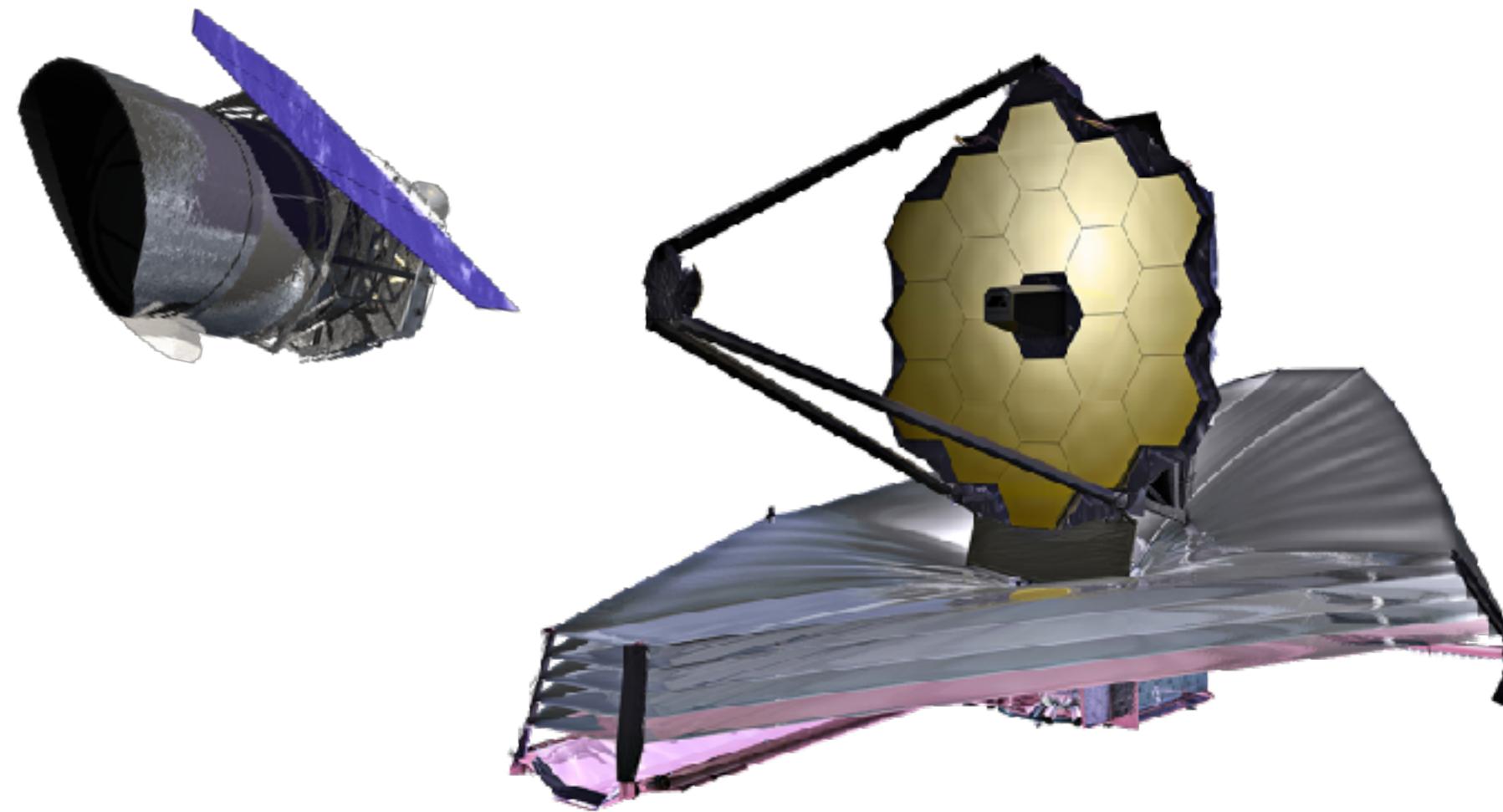
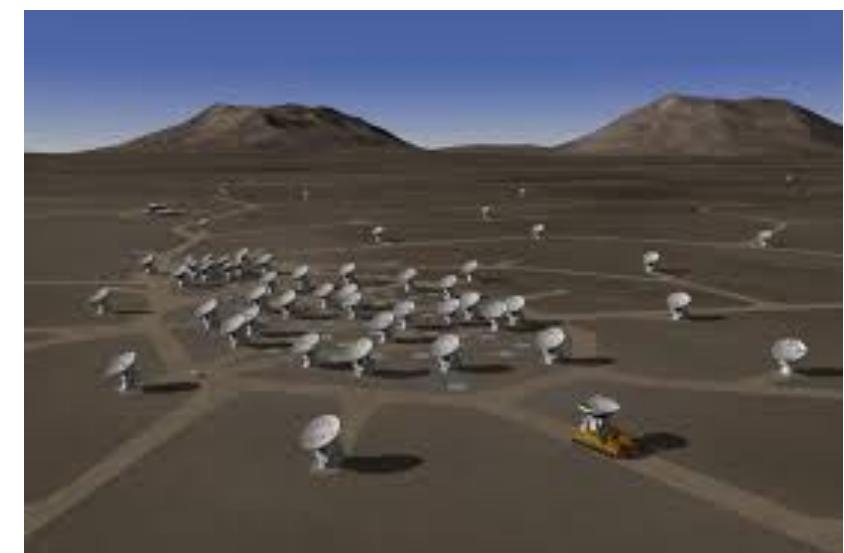
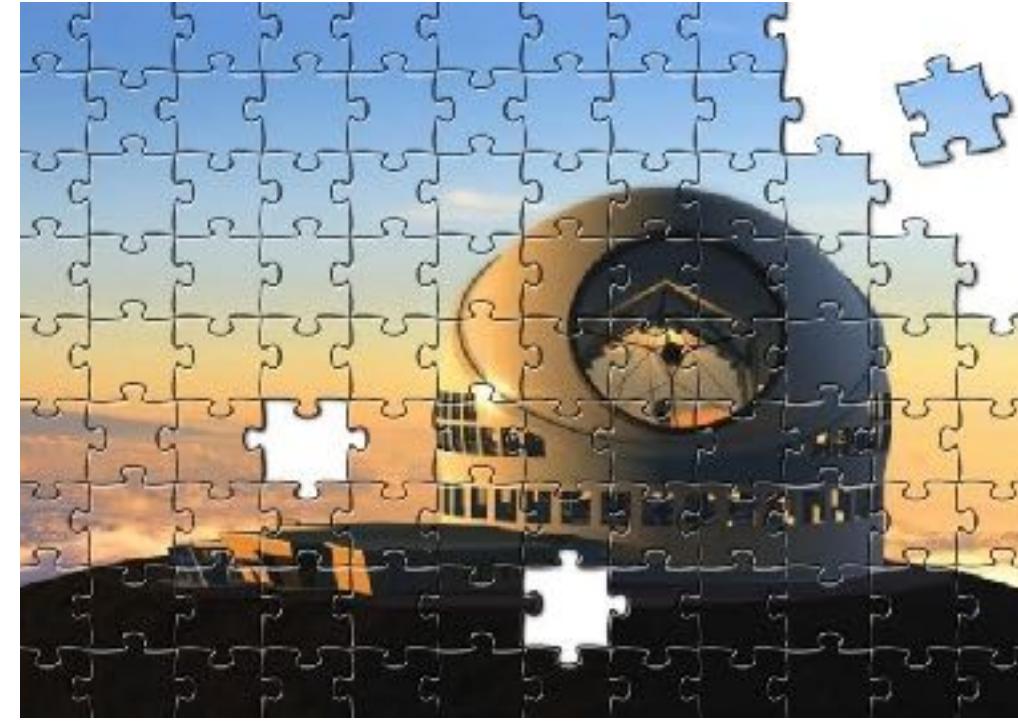
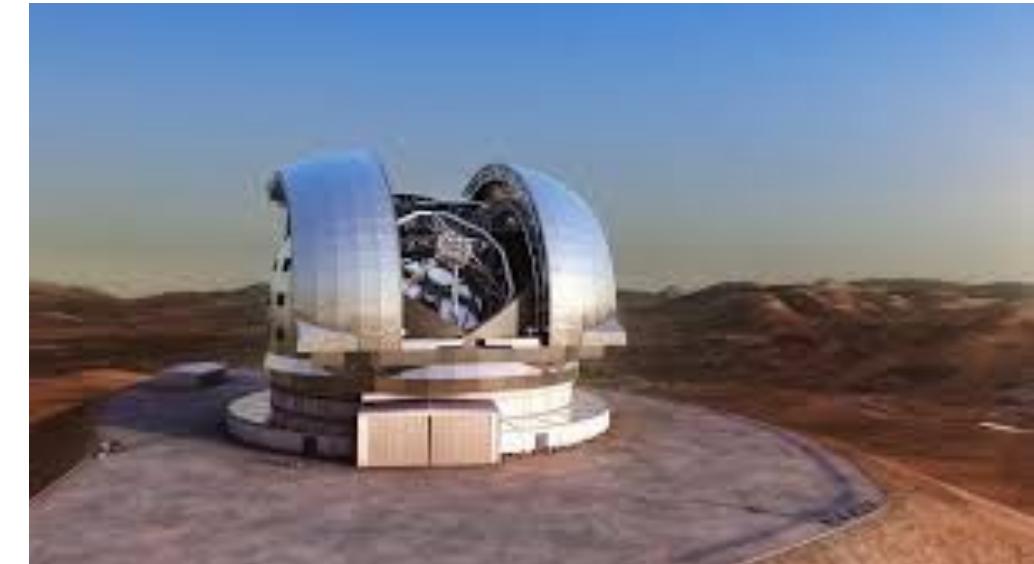


SCI-PSF



Complementarity Ground Space, great era for Direct Imaging

Ground with eXtreme Adaptive Optics:
spatial resolution (best IWA)
& spectral resolutions (huge instruments)
multiplexing, upgrades, Imaging, Interferometry
ELTs, ALMA (sub-mm), VLTI & CHARA (0.7 - 5 μ m)

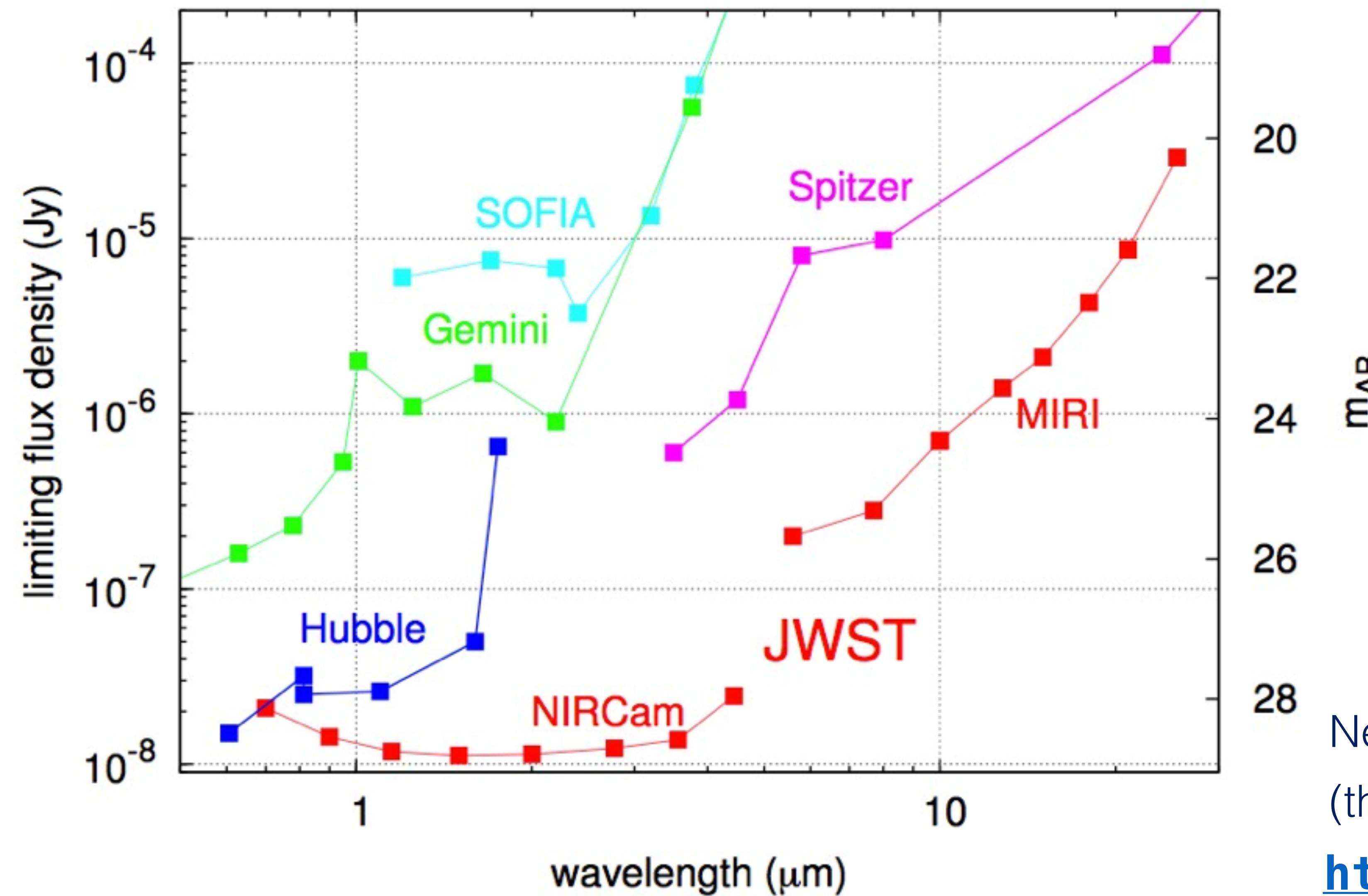


Space with HST, **JWST**, WFIRST
Incomparable **sensitivity & stability**,
field of view (@diffraction limit)
PSF homogeneity
No atmospheric bands



JWST: dramatically better sensitivity $> 1.5 \mu\text{m}$

photometric performance, point source, SNR=10 in 10^4 s



In background limited regime
(i.e beyond $\sim 1''$)

~ 100 x more sensitive at 2 μm

~1000 x more sensitive at 4 μm

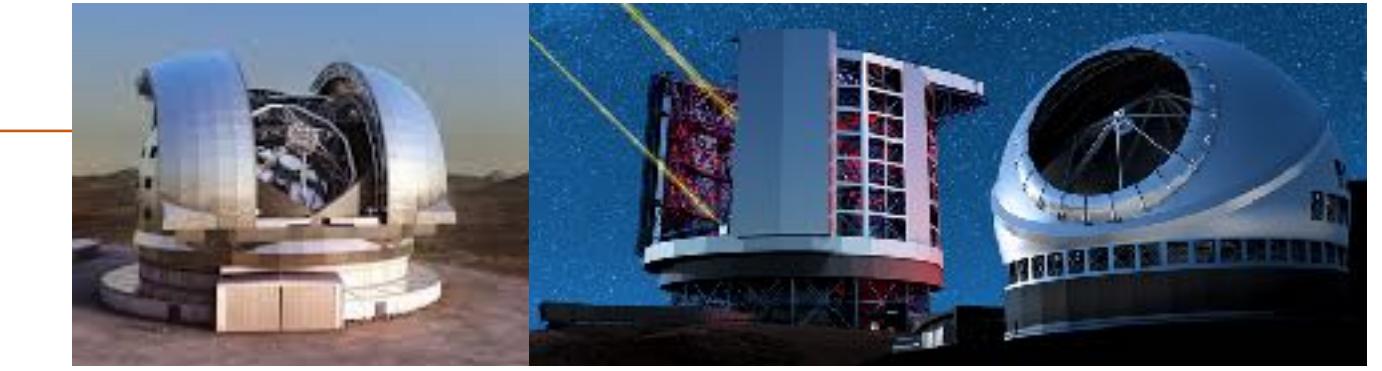
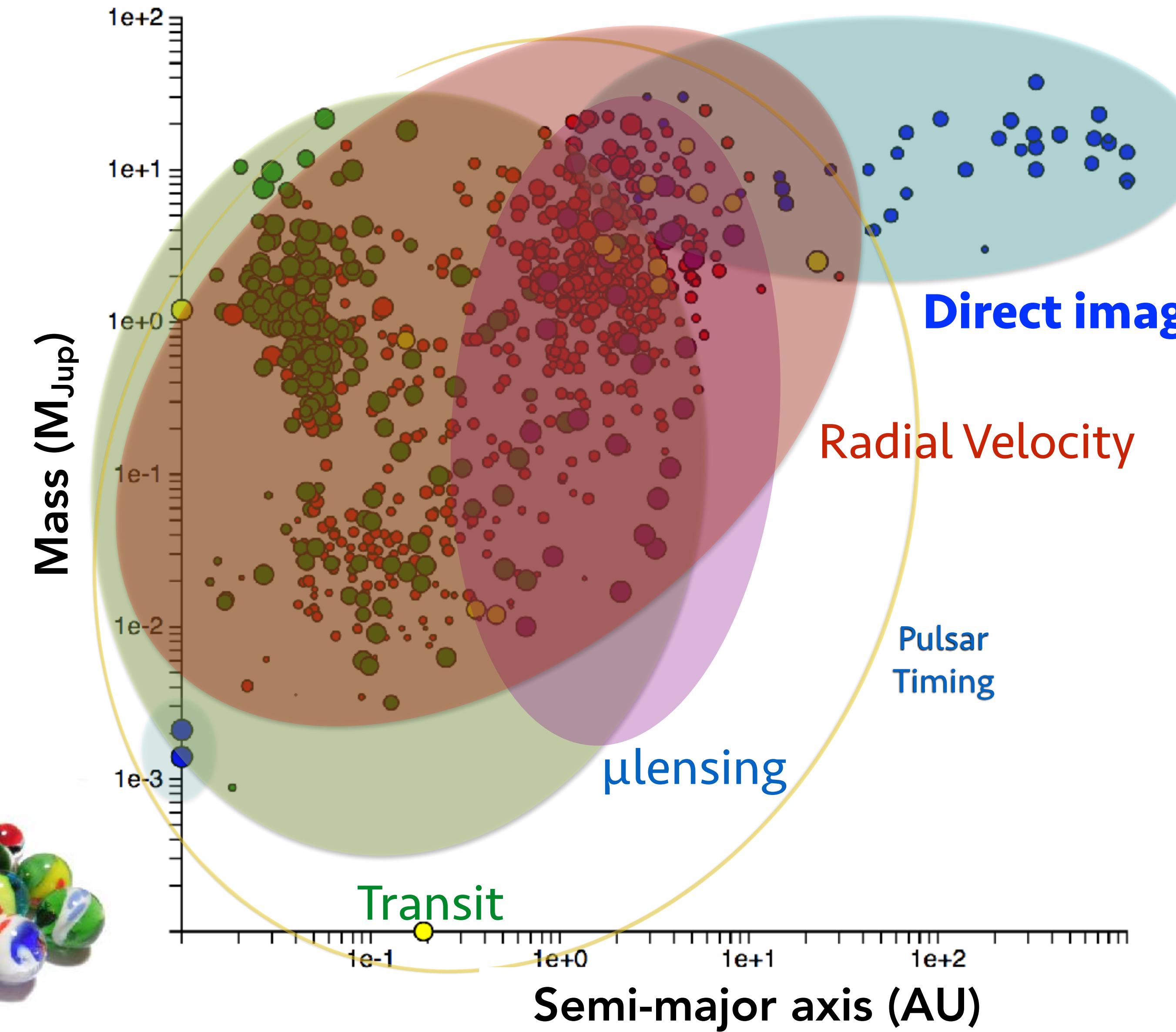
**~ 30 x more sensitive than
Spitzer at 10 μm
and with better angular
resolution**

New Tool to explore sensitivity
(though no HCI)

<http://jist.stsci.edu>

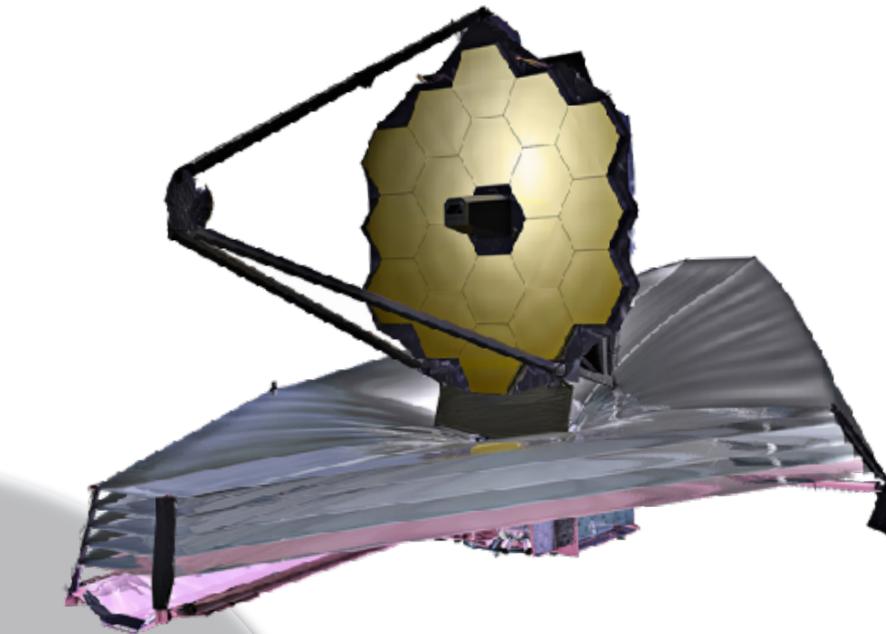


Exoplanet census & detection techniques



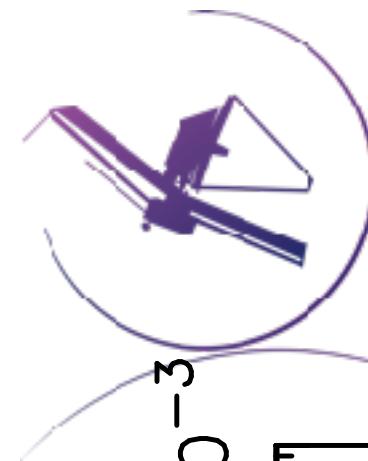
IWA ←
↓

CONTRAST, SENSITIVITY

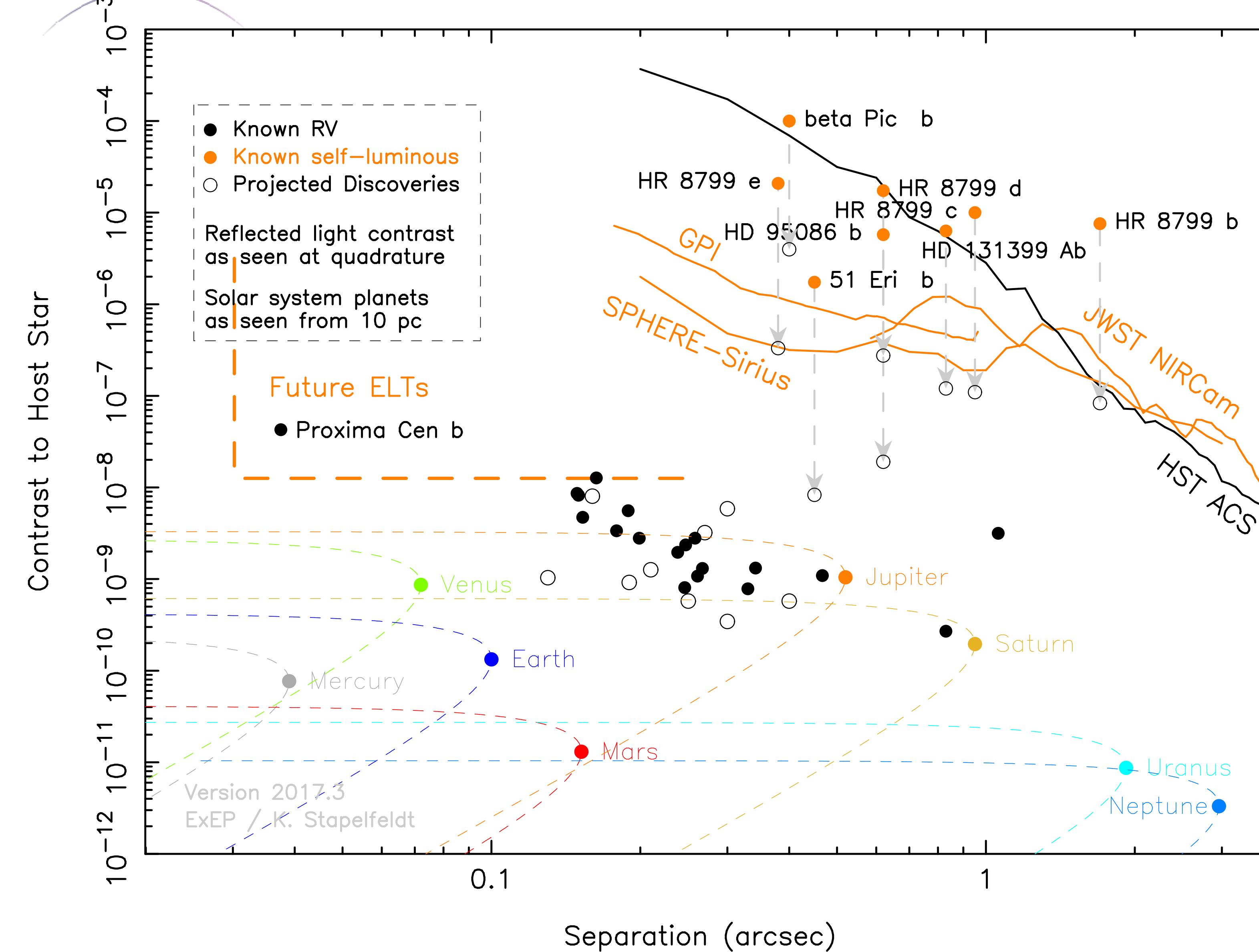


+ free floating
super-jupiters



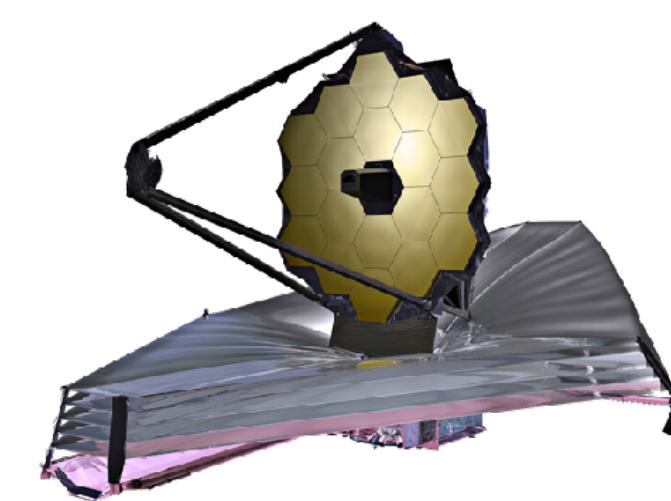


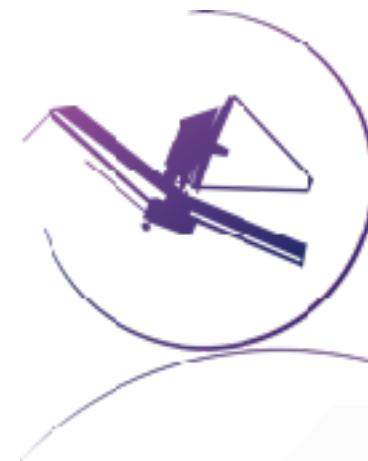
Great complementarity ground/space, great era for direct imaging



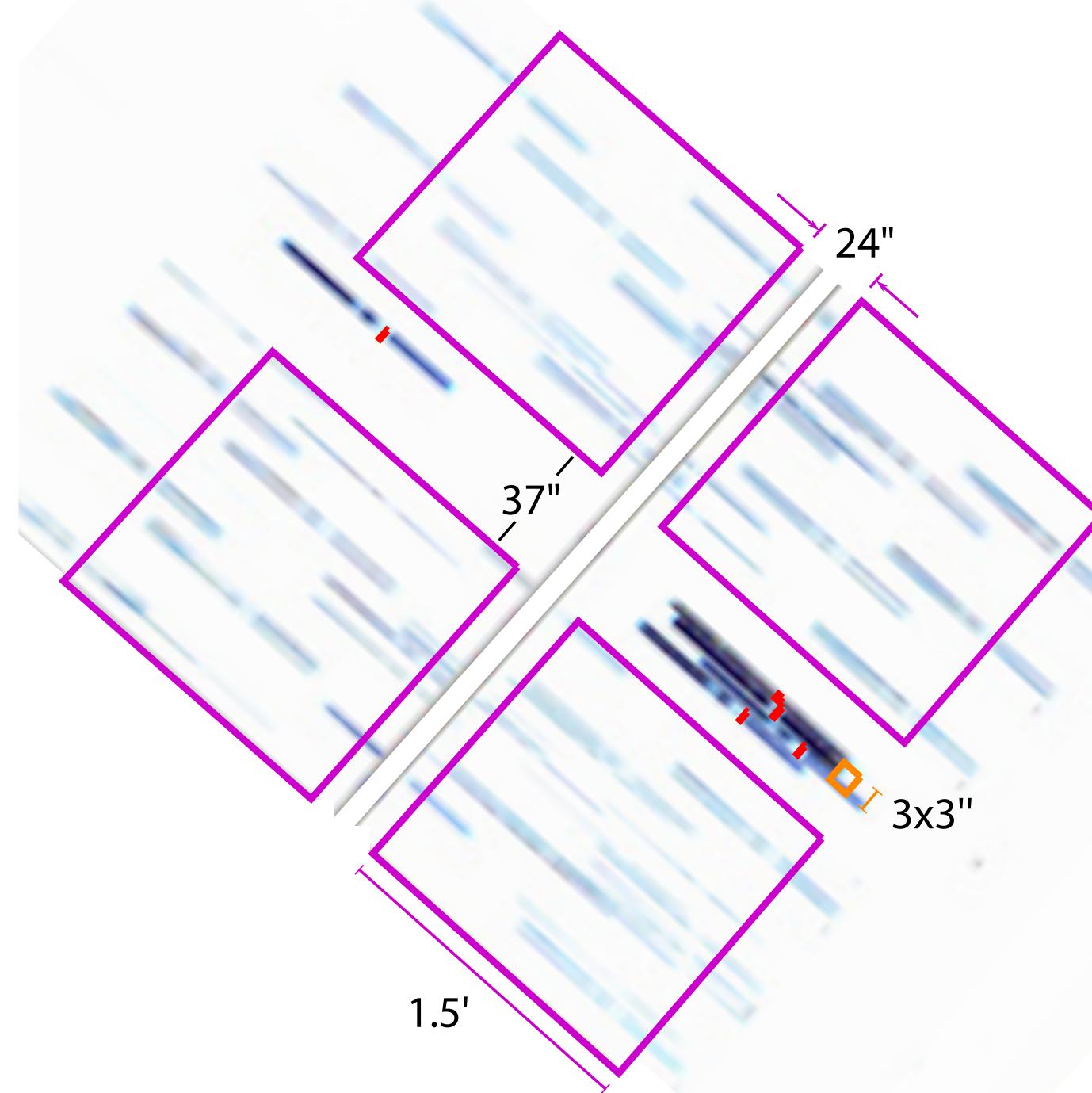
Ground with
eXtreme Adaptive Optics:
spatial (best IWA)
& spectral resolutions,
multiplexing, upgrades

Space
Incomparable **sensitivity**,
& **stability**,
field of view
PSF homogeneity
No atmospheric bands



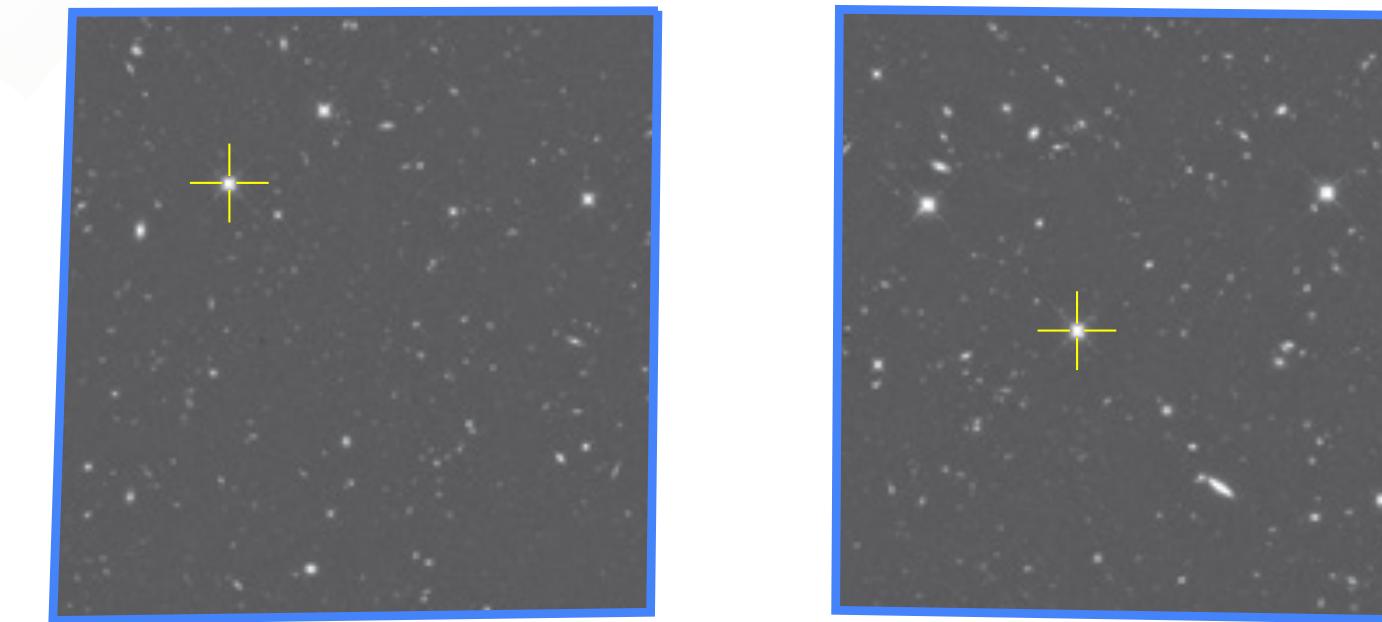


The JWST Focal Plane

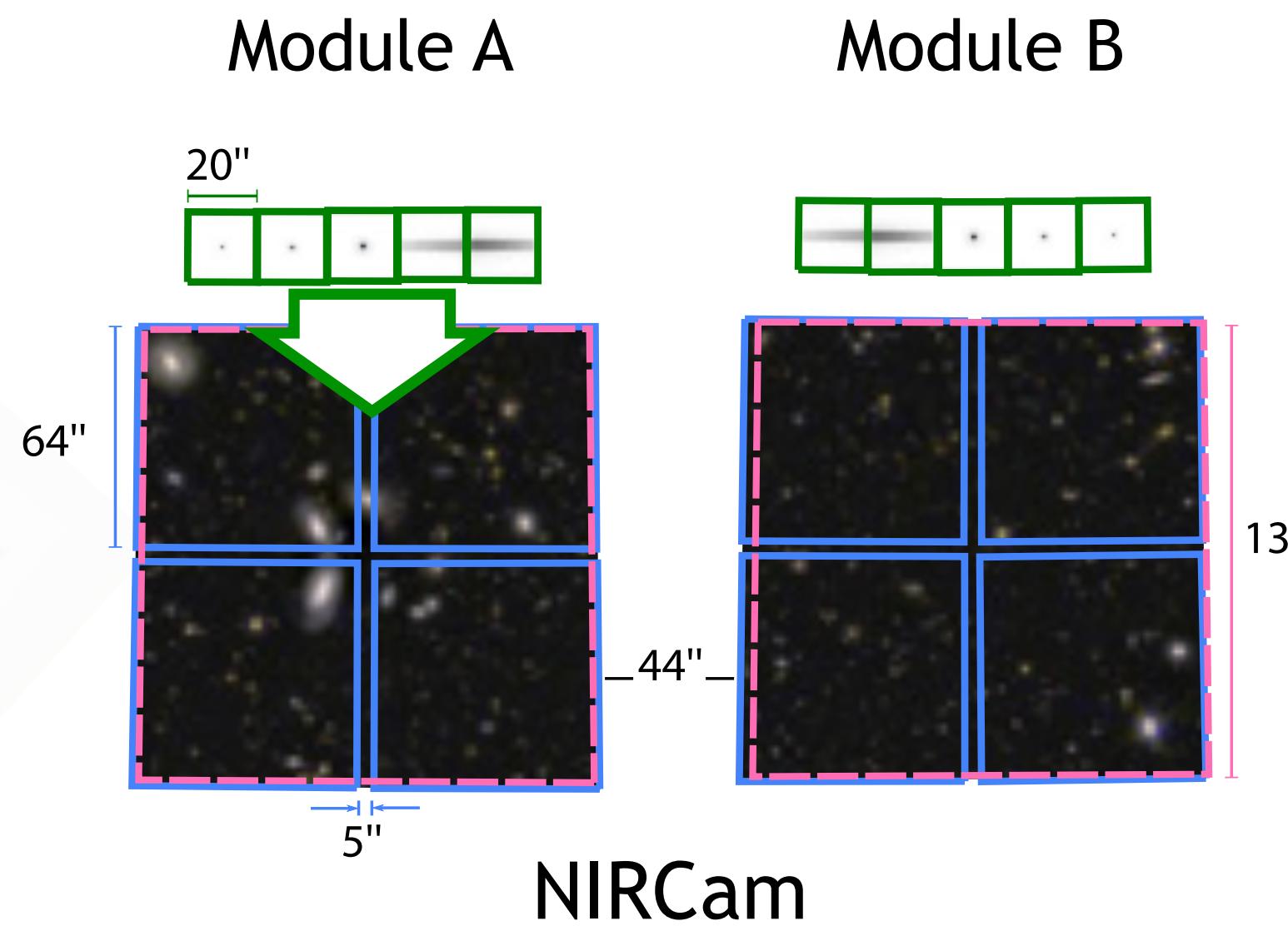


NIRSpec

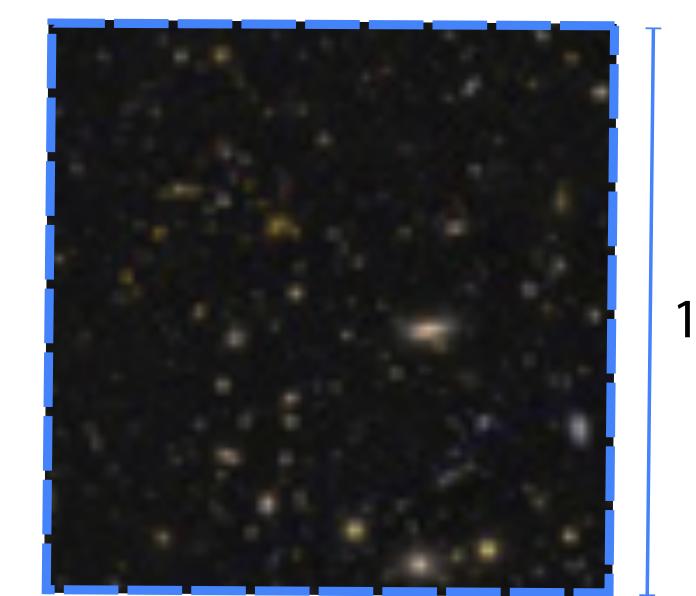
- [Blue Box] image
- [Dashed Box] image+grism
- [Green Box] coronagraph
- [Orange Box] IFU
- [Red Box] slit
- [Purple Box] MSA



FGS

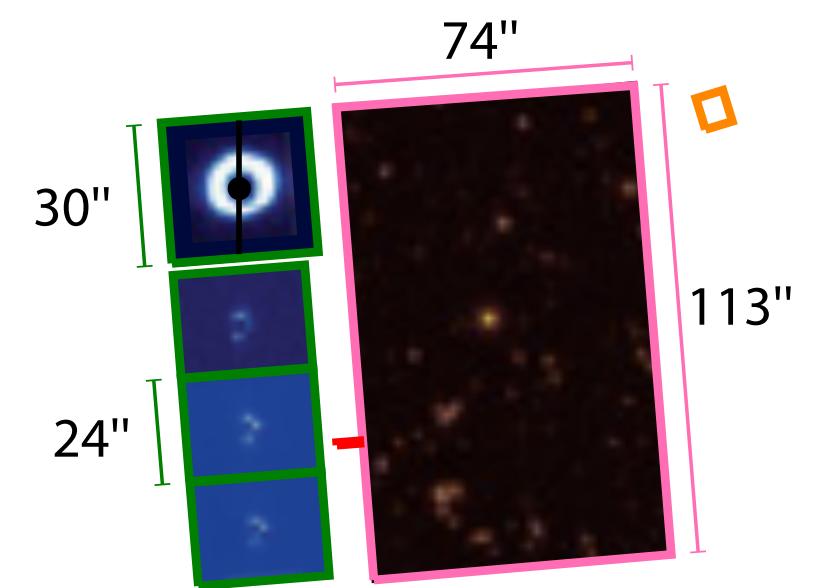


NIRCam

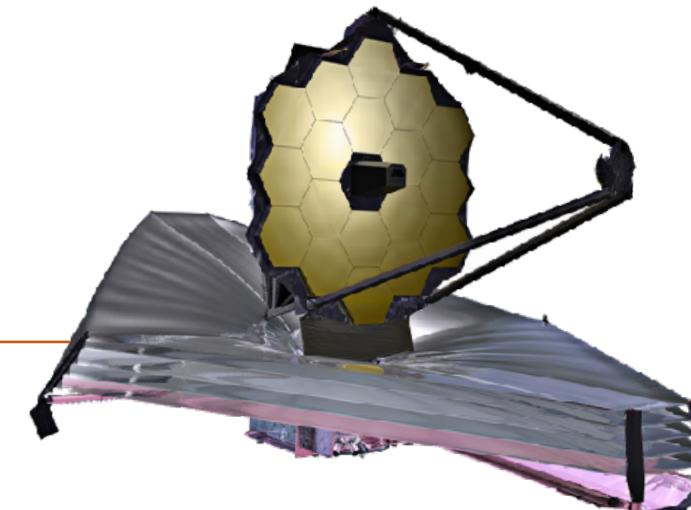


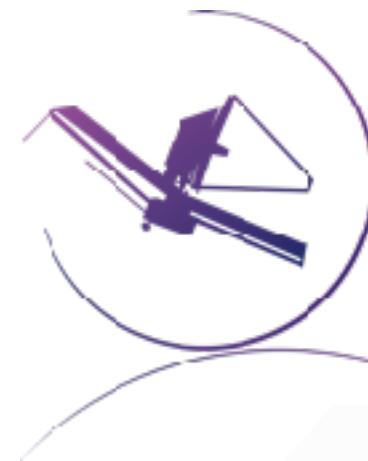
NIRISS

V3
V2 ←
V1

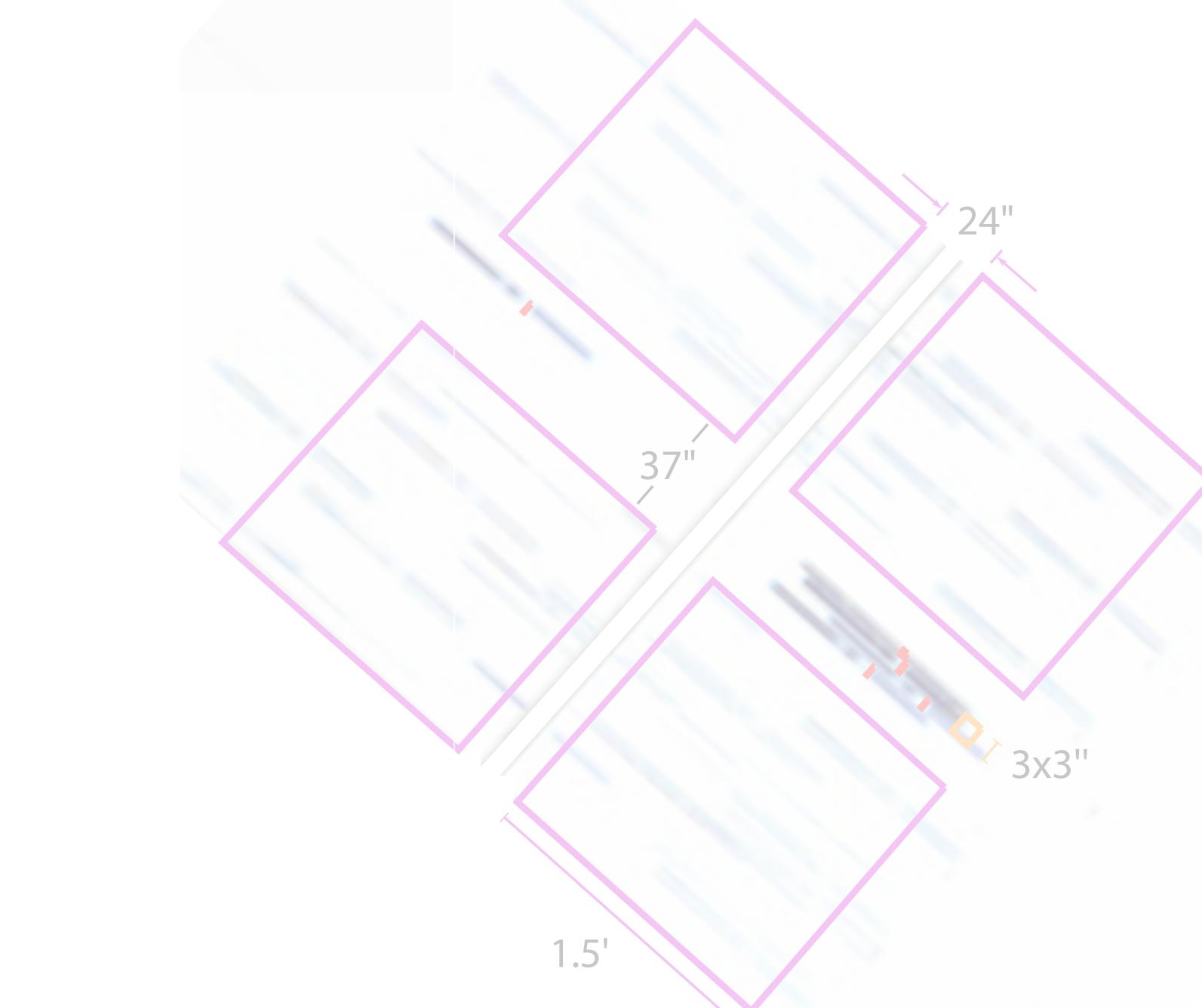
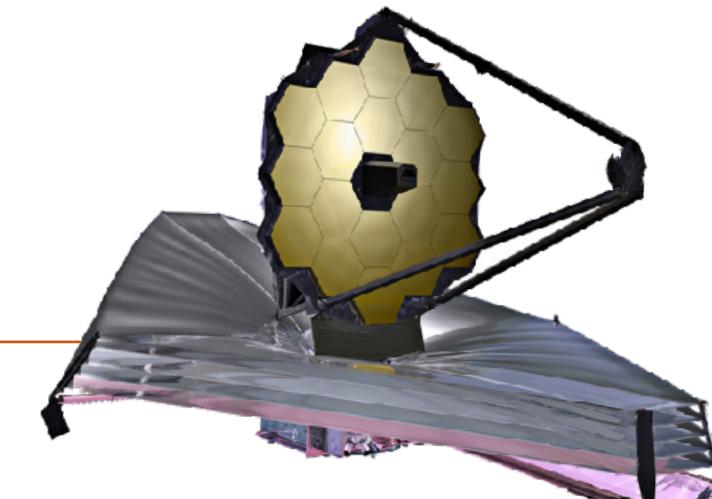


MIRI



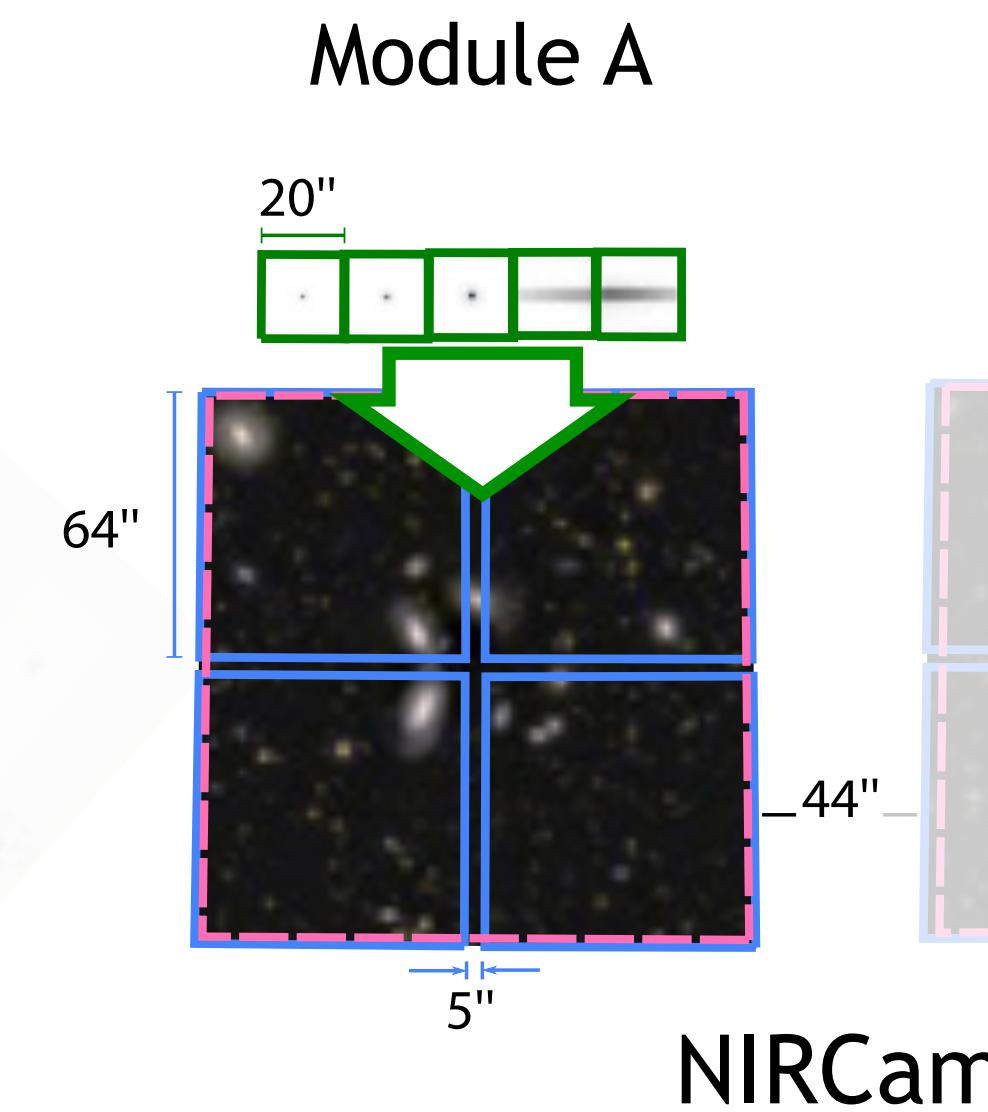


The JWST Focal Plane and main HCI instruments

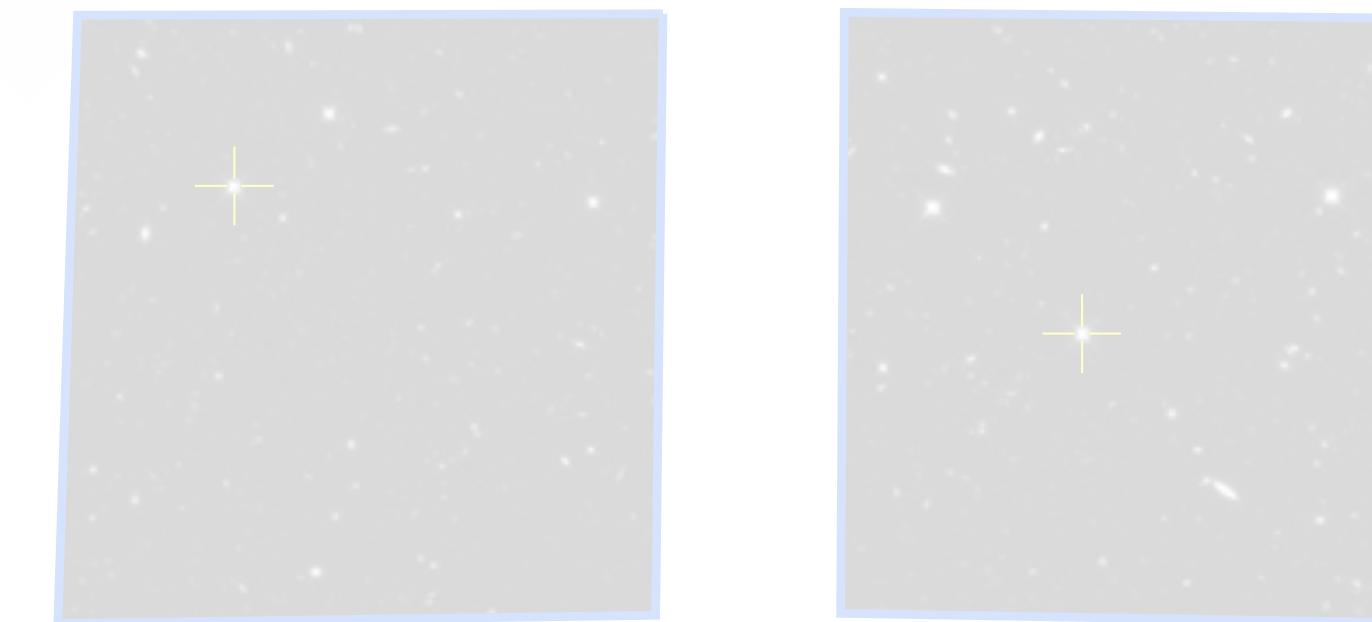


NIRSpec

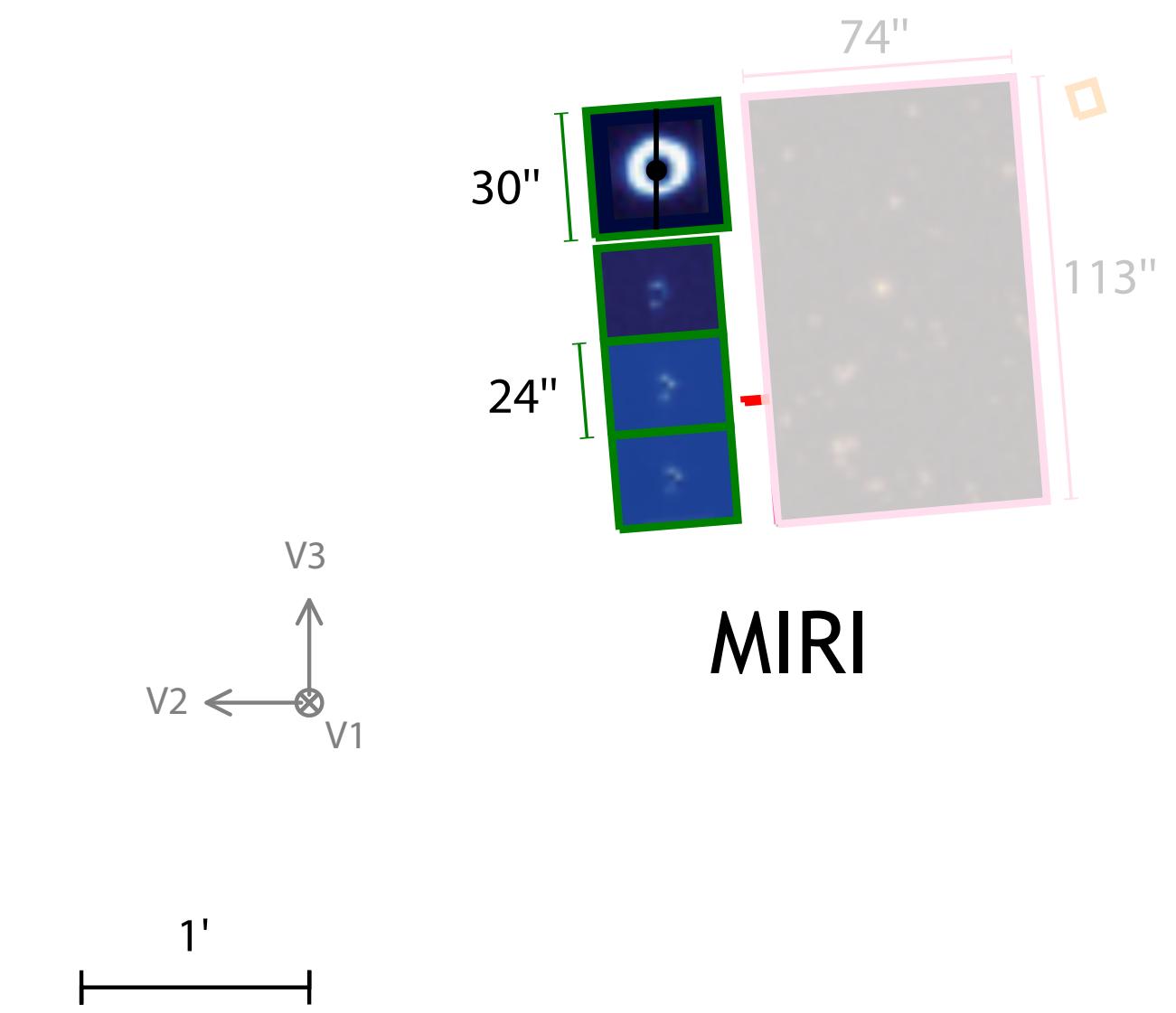
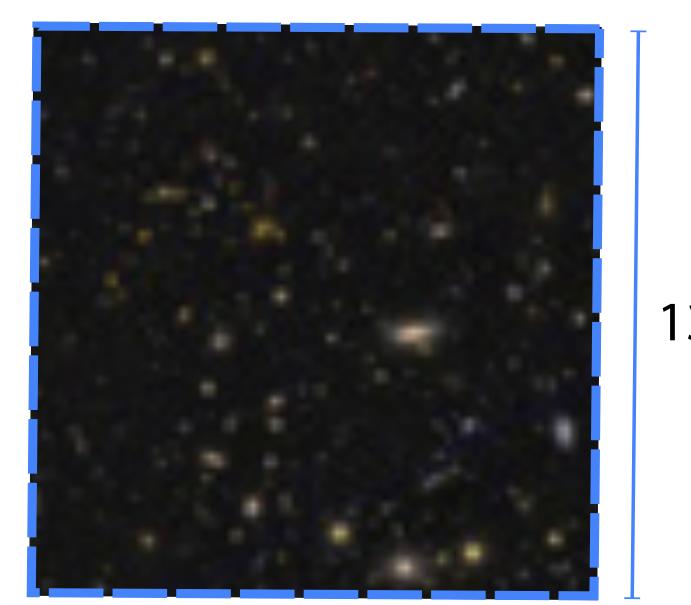
- image
- image+grism
- coronagraph
- IFU
- slit
- MSA



FGS



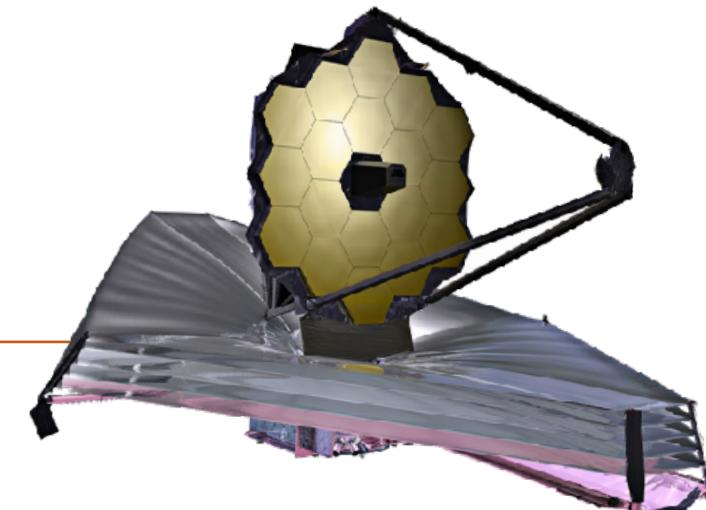
NIRISS



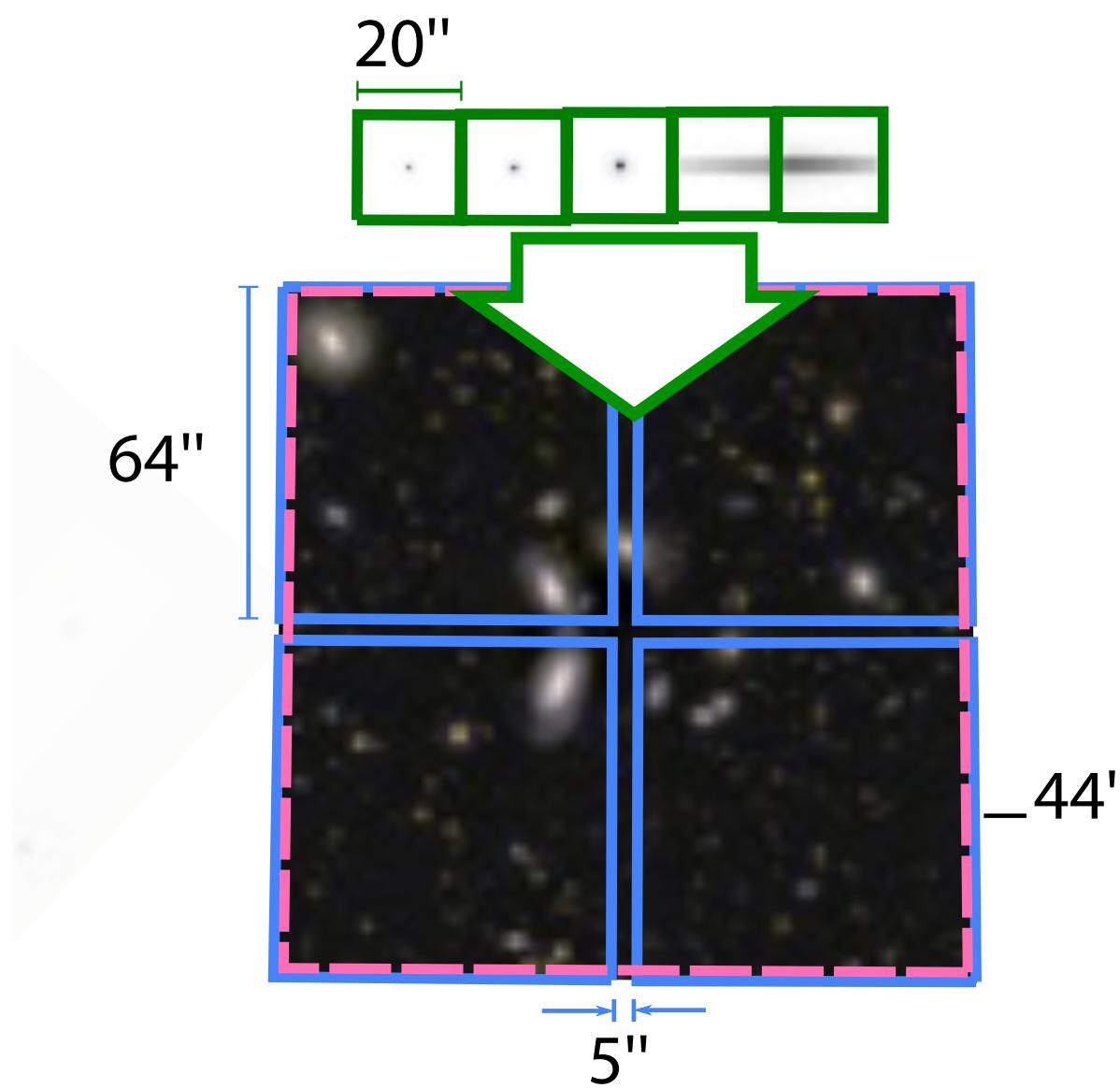
MIRI



NIRCam & MIRI Coronagraphy in the JWST Focal Plane

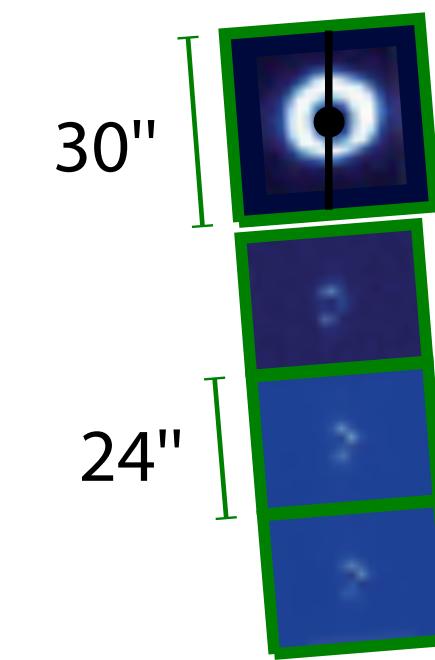


NIRCam



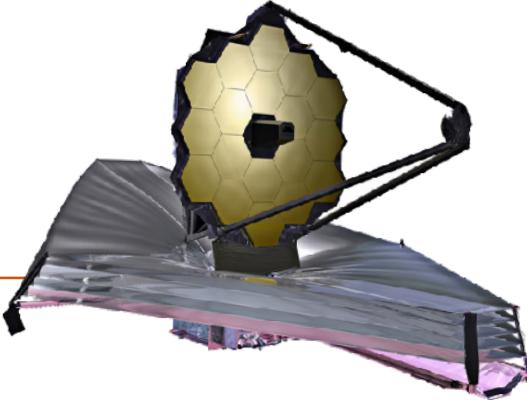
Module A

MIRI

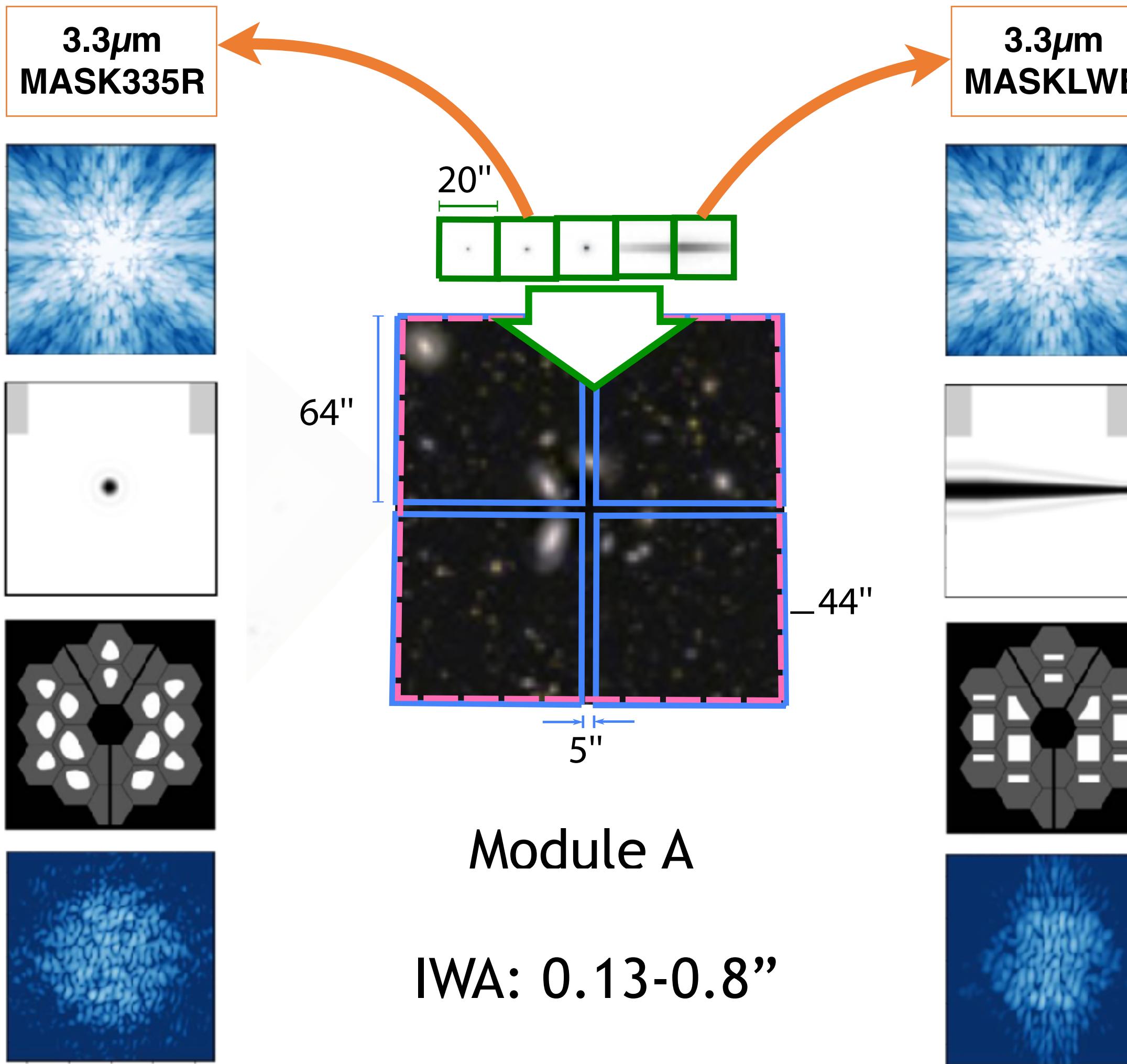




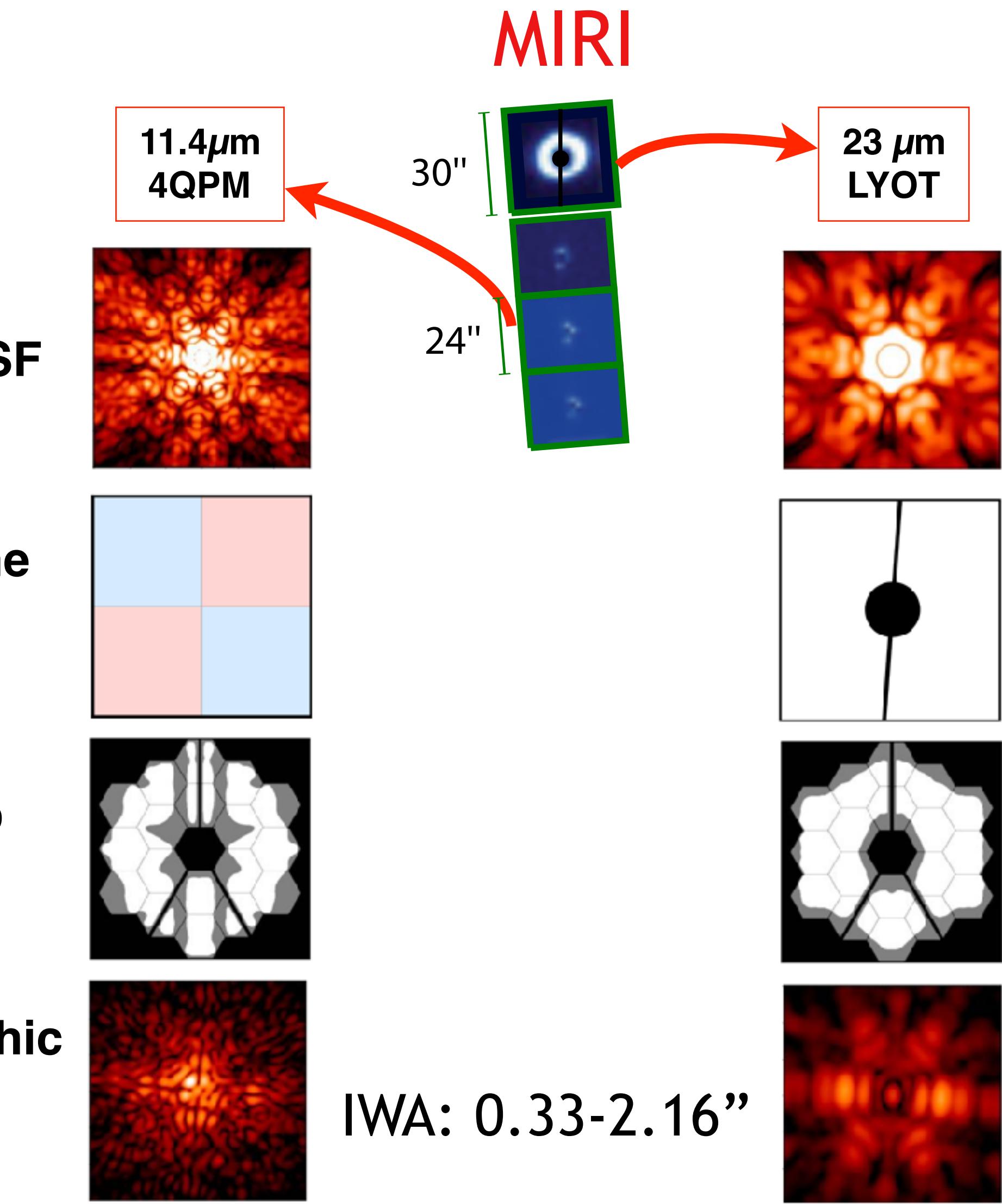
NIRCam & MIRI Coronagraphy in the JWST Focal Plane



NIRCam

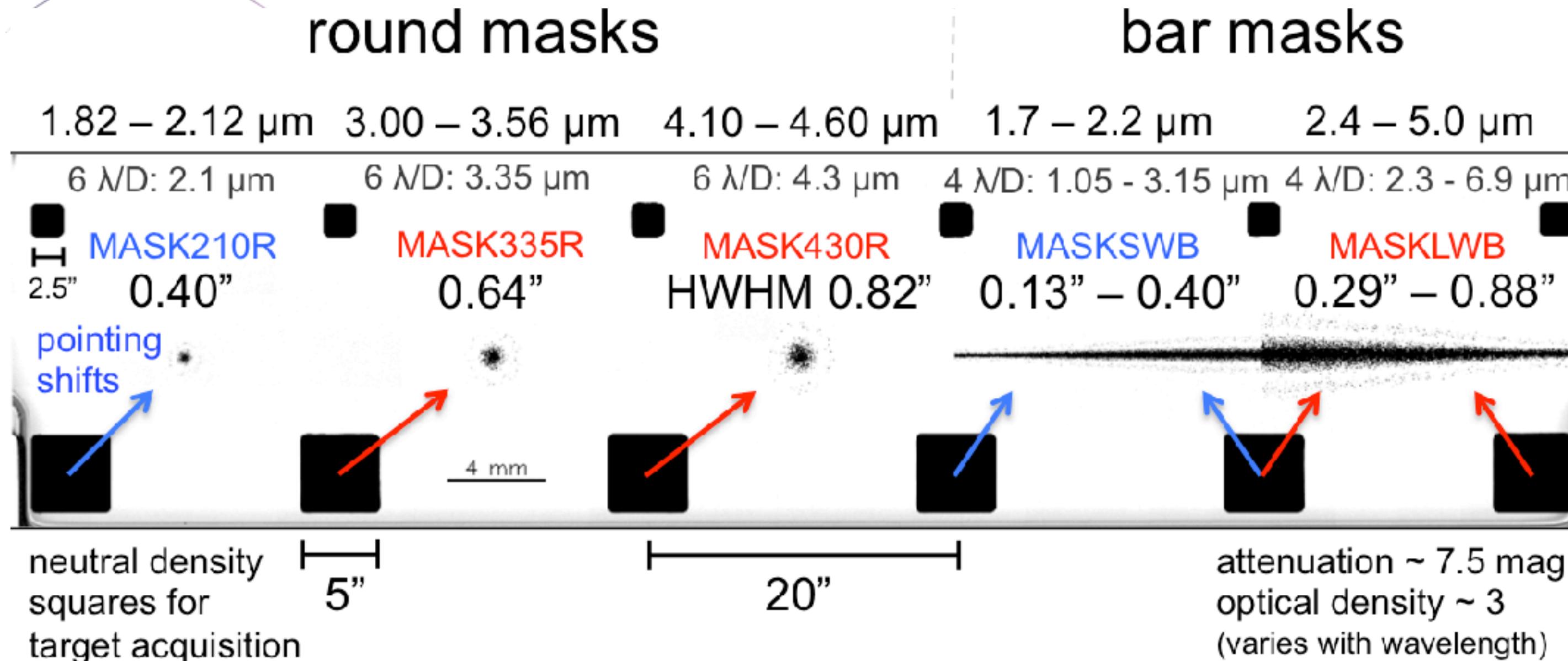


Imaging PSF





JWST NIRCam Coronagraphs



Name	Shape	Inner Working Angle	Wavelength Range
MASK210R	round	0.40"	1.8 - 2.2 μm
MASKSWB	bar	0.13 - 0.40"	1.8 - 2.2 μm
MASK335R	round	0.63"	2.5 - 4.1 μm
MASK430R	round	0.81"	2.5 - 4.6 μm
MASKLWB	bar	0.29 - 0.88"	2.5 - 4.8 μm

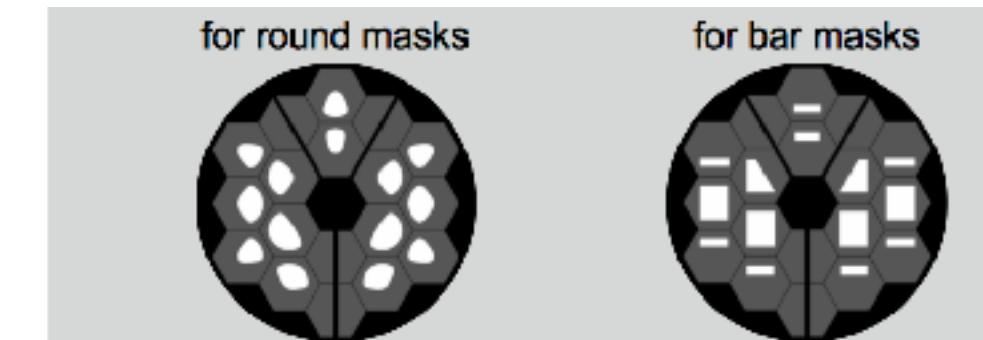
5 Lyot coronagraphs, pseudo band-limited with soft-edged grayscale occulters

Round occulters provide 360° azimuthal coverage for disk observations and planet searches

Relatively large (HWHM = 0.4-0.8"'): optimized for 6 λ/D at $\lambda= 2.1, 3.3, 4.3$

Bar occulters provide allow selection of inner working angle to match wavelength. Optimized for 4 λ/D . Each filter has its own location along the wedge

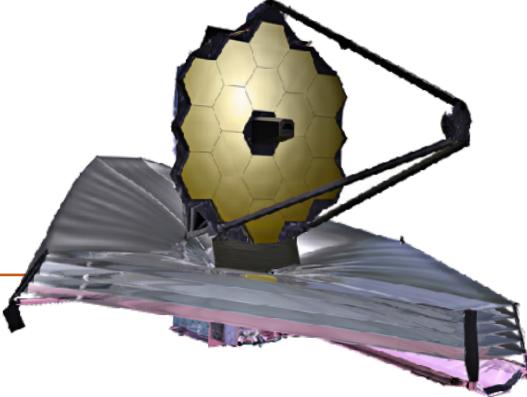
Lyot stops suppress PSF wing diffraction. Throughput = 19%



Coronagraph optics are outside the FOV during normal imaging observations

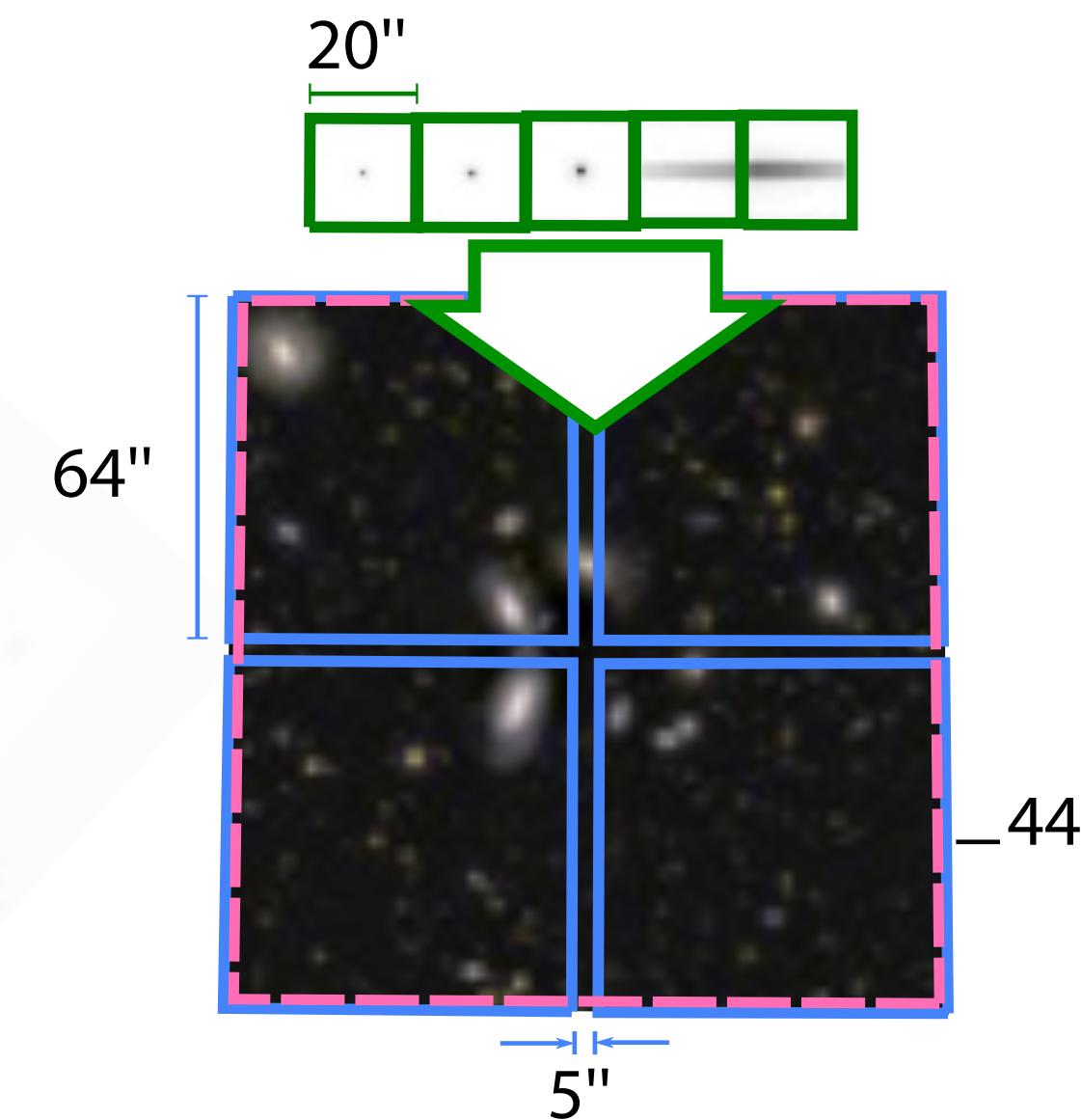


NIRCam & MIRI Coronagraphy in the JWST Focal Plane



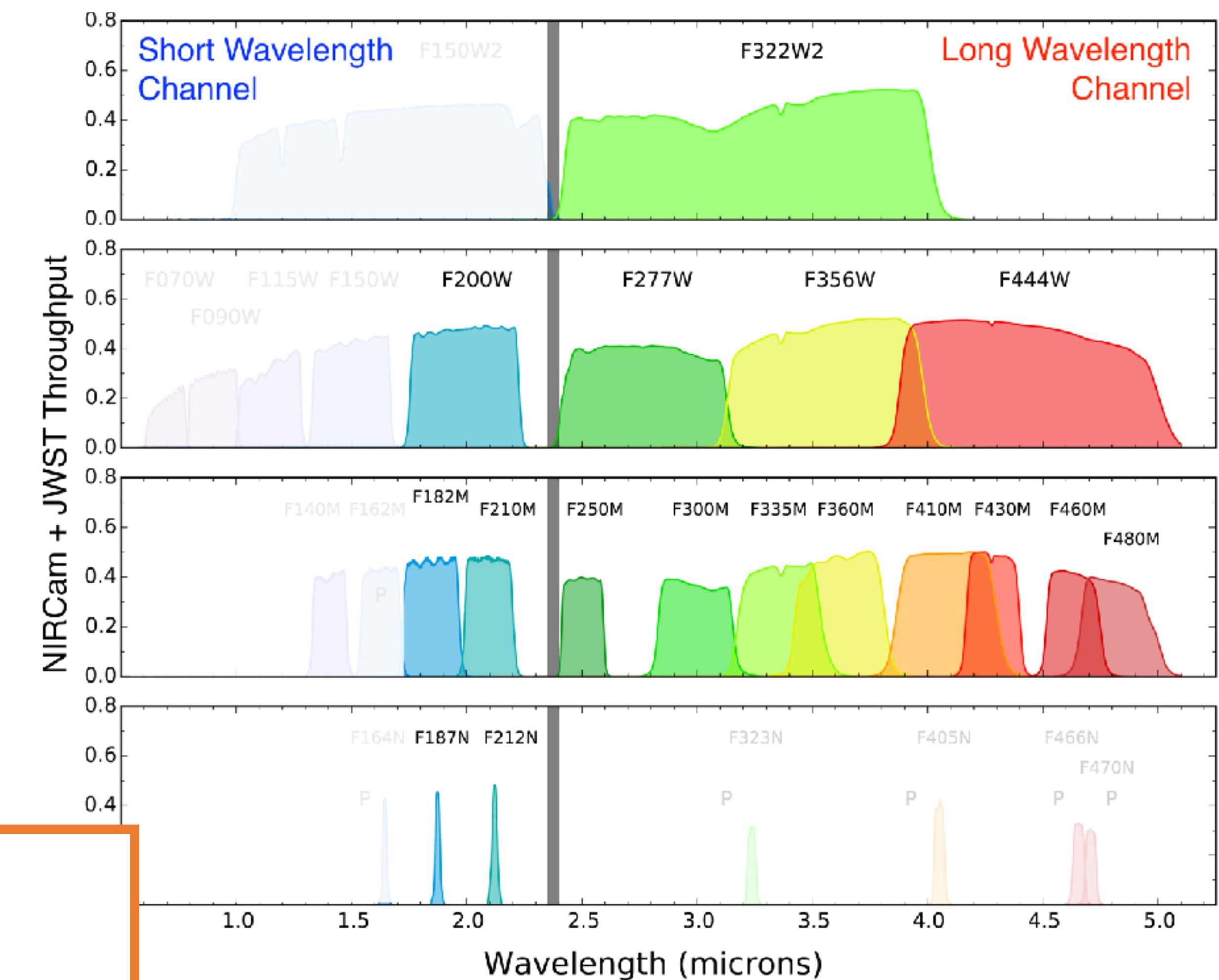
NIRCam

Module A



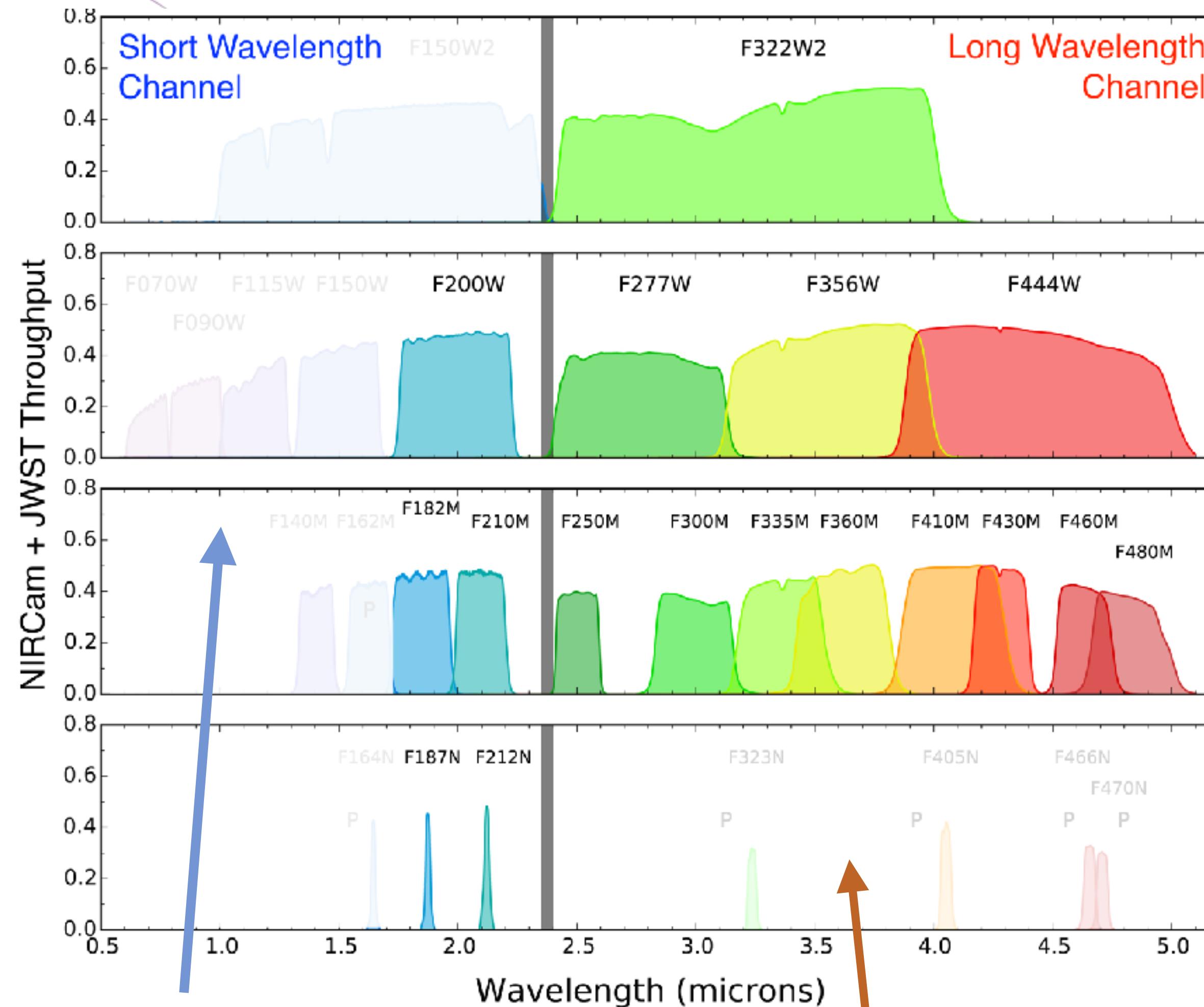
Currently SW and LW data cannot be saved simultaneously

It may change in later cycles





Most NIRCam filters are available for coronagraphy



SW filters below 1.8 μm **unavailable**
Coronagraph mask anti-reflection coating
has low throughput for $\lambda < 1.8 \mu\text{m}$

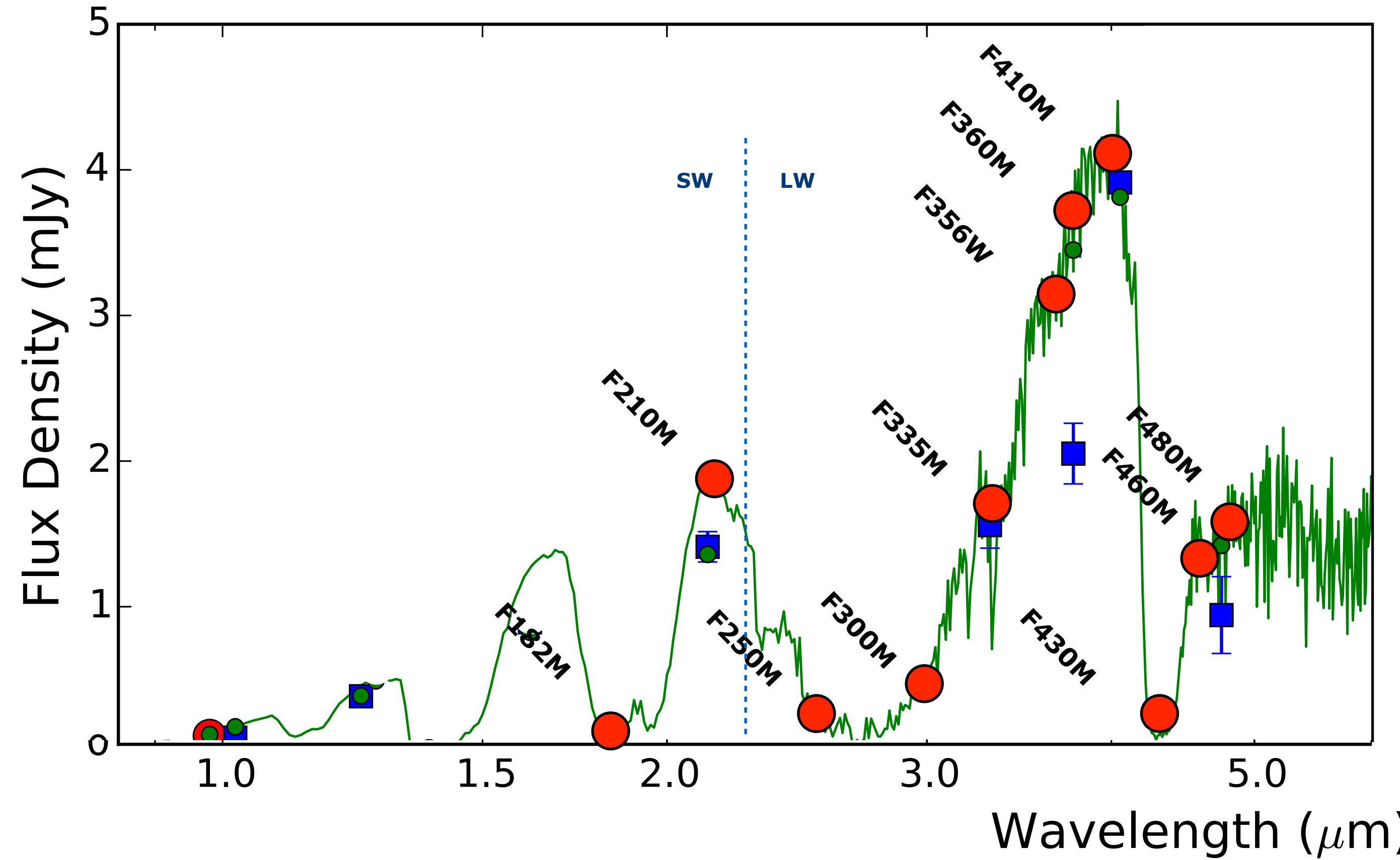
LW narrow band filters **unavailable**
as installed in same pupil wheel
as the coronagraph Lyot stops

Filter	
F182M	H ₂ O, CH ₄
F187N	Paschen Alpha
F200W	continuum
F210M	H ₂ O, CH ₄
F212N	H ₂
F250M	continuum, CH ₄
F277W	continuum
F300M	H ₂ O ice
F322W2	double-wide, max sensitivity
F335M	PAH, CH ₄
F360M	continuum
F410M	continuum
F430M	CO ₂ , N ₂
F444W	continuum
F460M	CO
F480M	CO



NIRCam is well suited for characterizing substellar companions & disks

Exoplanet and brown dwarf atmospheres



$T_{\text{eff}} = 1000 \text{ K}$, $\log(g) = 3.5$ model from Barman et al.

Debris disk dust composition and ices

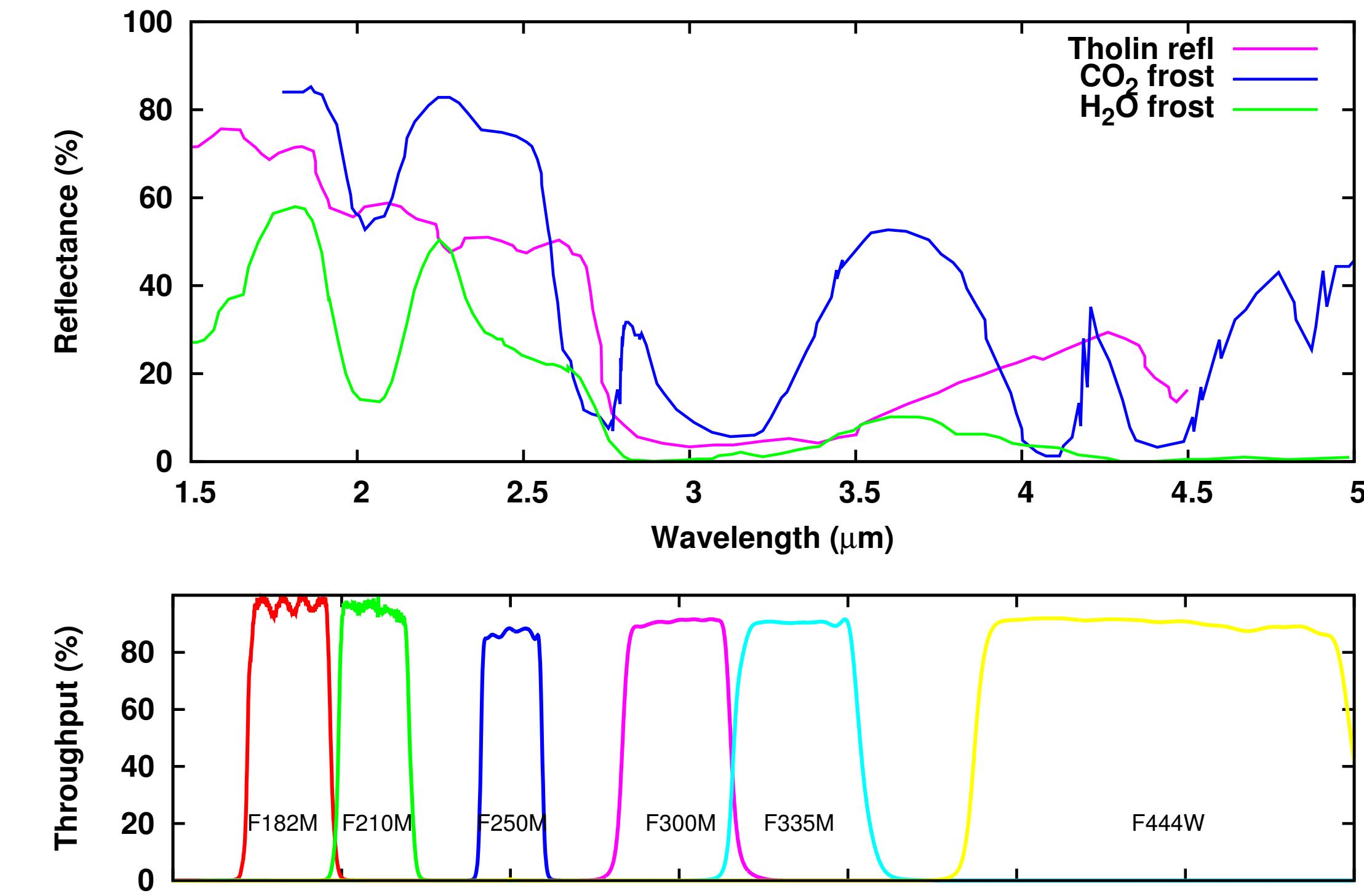
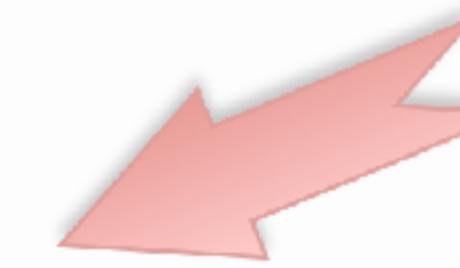
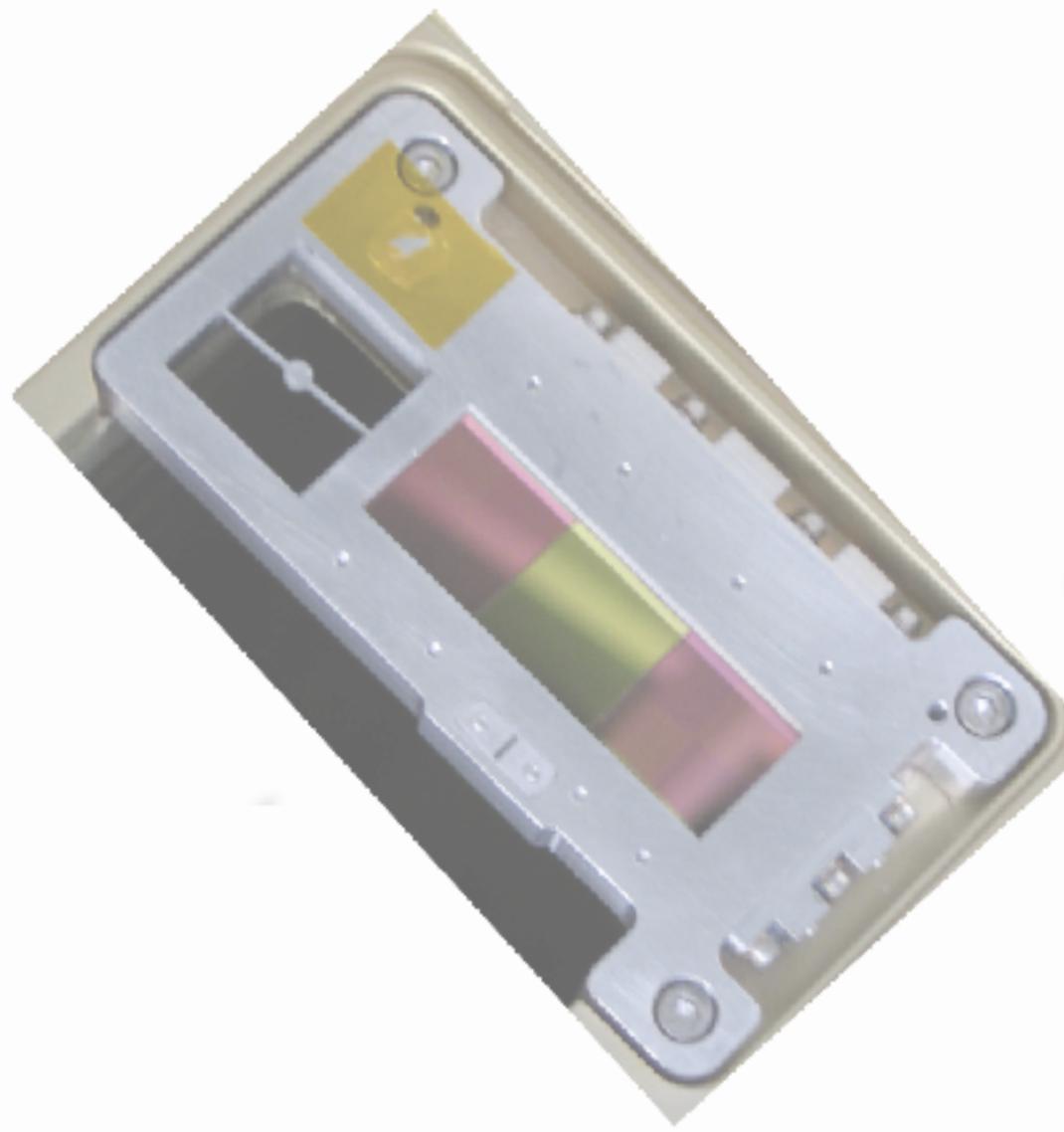
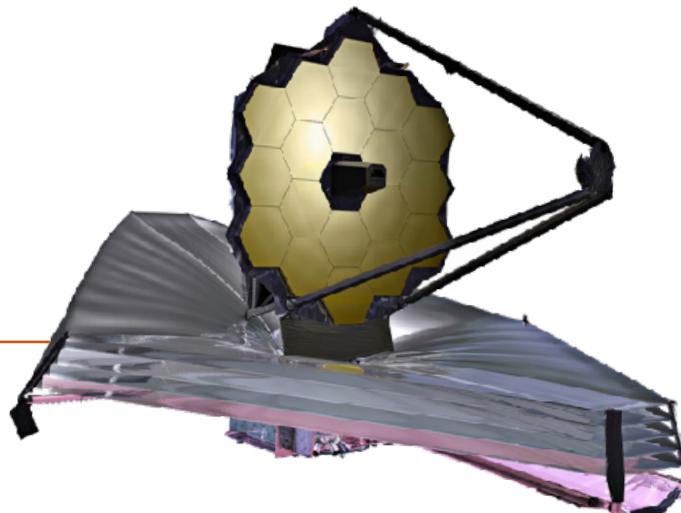


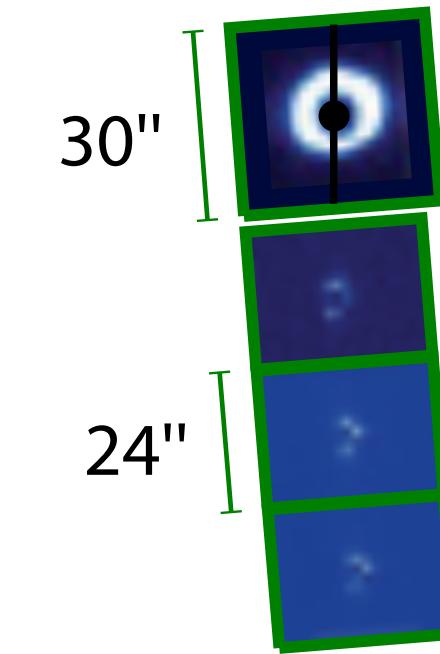
Figure courtesy Andras Gaspar et al. (NIRCam GTO)



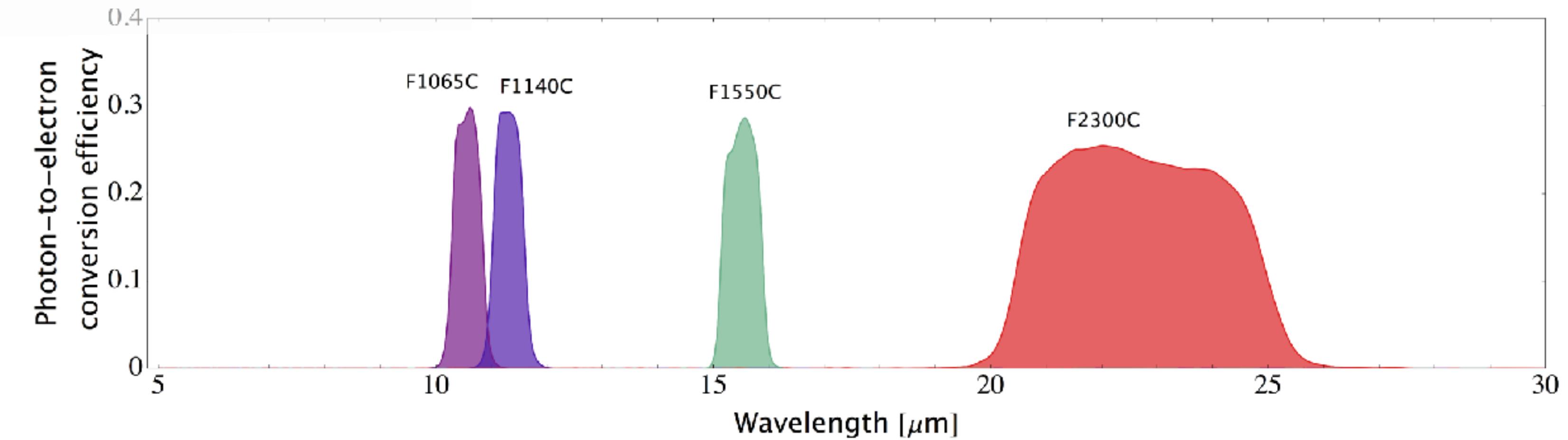
NIRCam & MIRI Coronagraphy in the JWST Focal Plane



MIRI

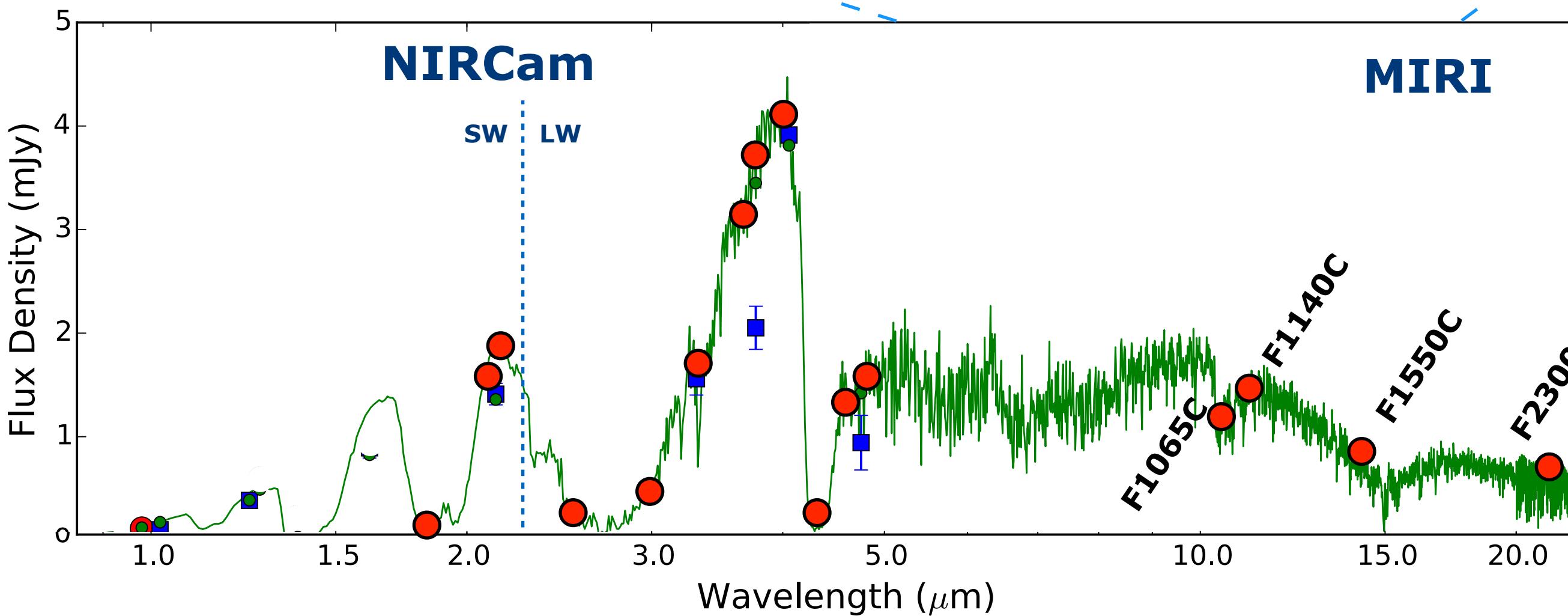
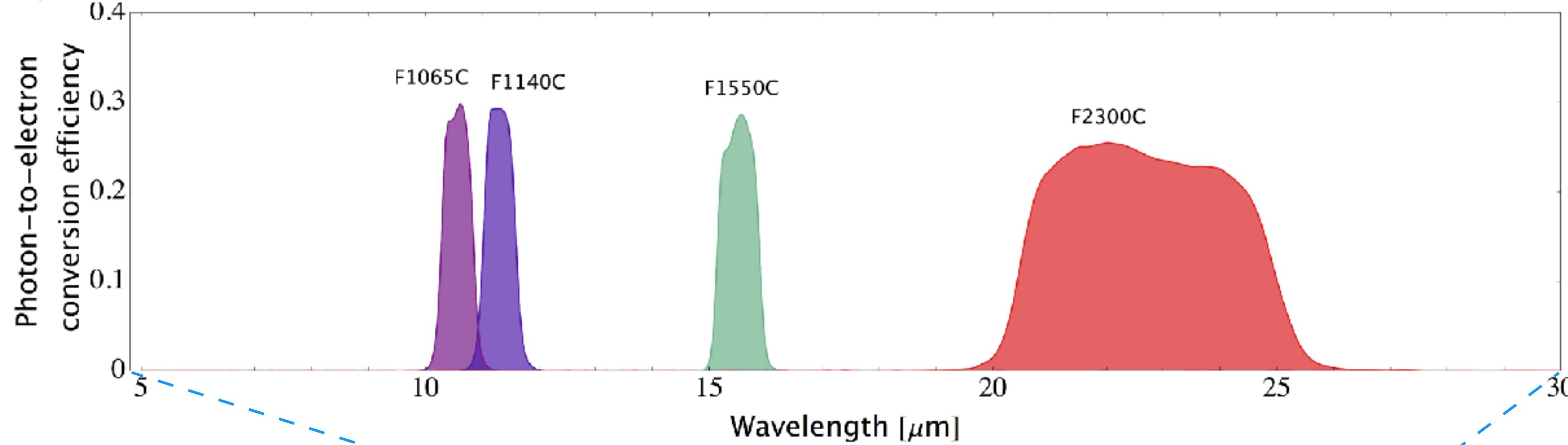


One mask, one filter





MIRI filters for coronagraphy



Teff = 1000 K, log(g) = 3.5 model from Barman et al.

Ammonia feature at $10.65 \mu\text{m}$ is main spectral feature at $5-20 \mu\text{m}$ for cool exoplanet atmospheres ($T \sim 200-500 \text{ K}$).

Continuum slope from $11.4 - 15.5$ measures planet temperature.

These filters also suitable for studies of circumstellar disks and AGN.

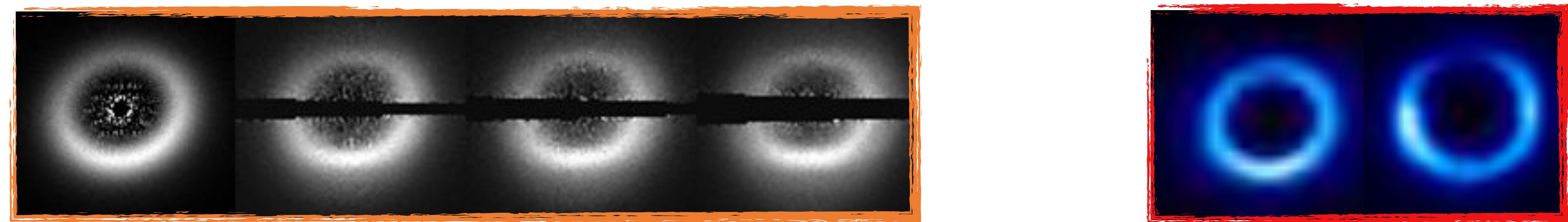


Studying Disk Compositions: Panchromatic Imaging

High contrast at longer wavelengths: $3\text{-}5 \mu\text{m}$, $10\text{+} \mu\text{m}$

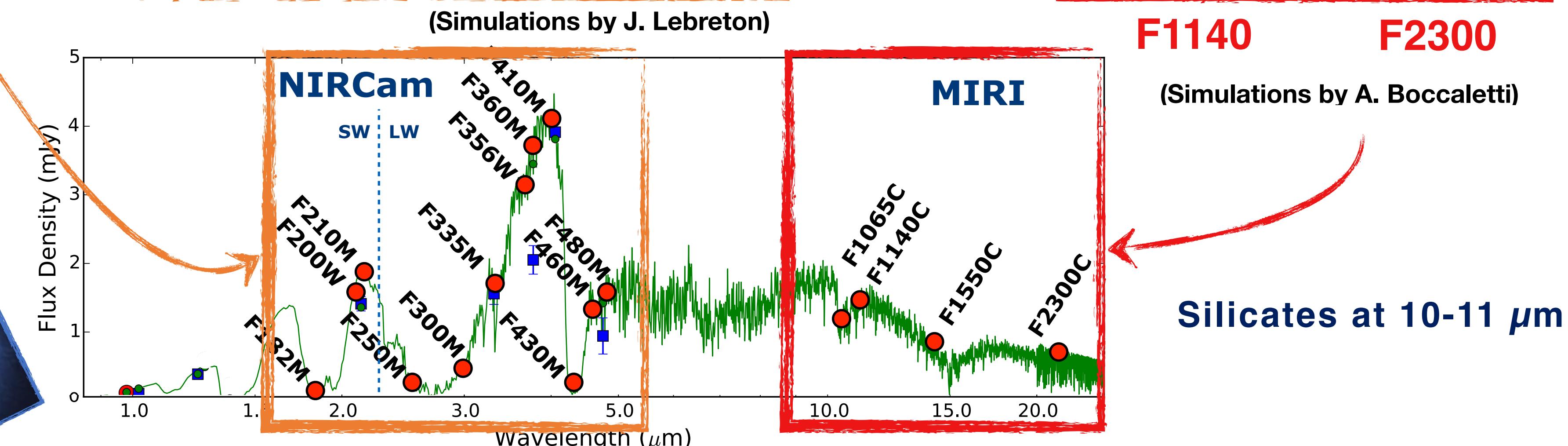
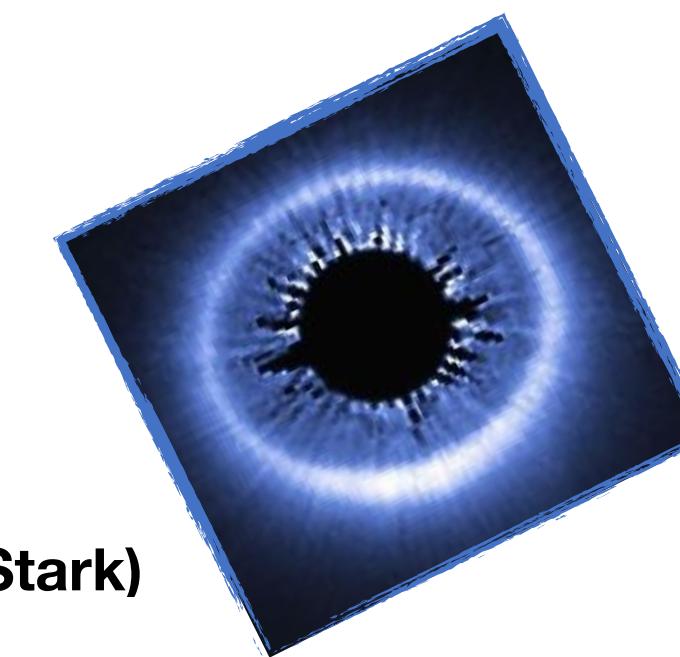
Much deeper sensitivity & wider field of view than AO, superb optical stability

Options: **NIRCam** & **MIRI** coronagraphs, **NIRISS AMI**, **NON-coronagraphic PSF subtraction!**



Colors, albedos, phase functions of scattering particles, Ices at $3.3 \mu\text{m}$

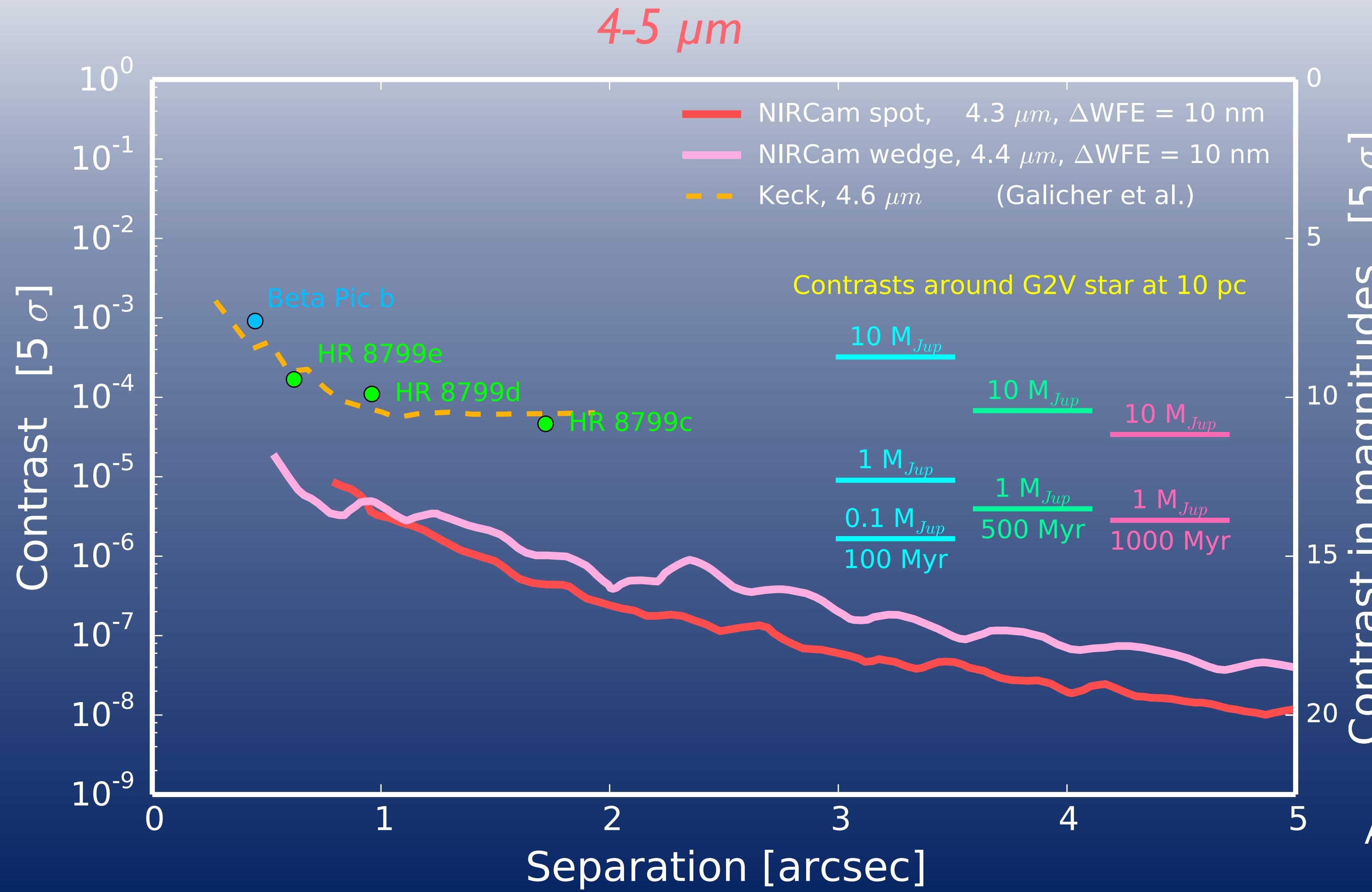
E.G.: HD 181327



Teff = 1000 K, log(g) = 3.5 model from Barman et al.



NIRCam Coronagraphy: sensitivity!!!

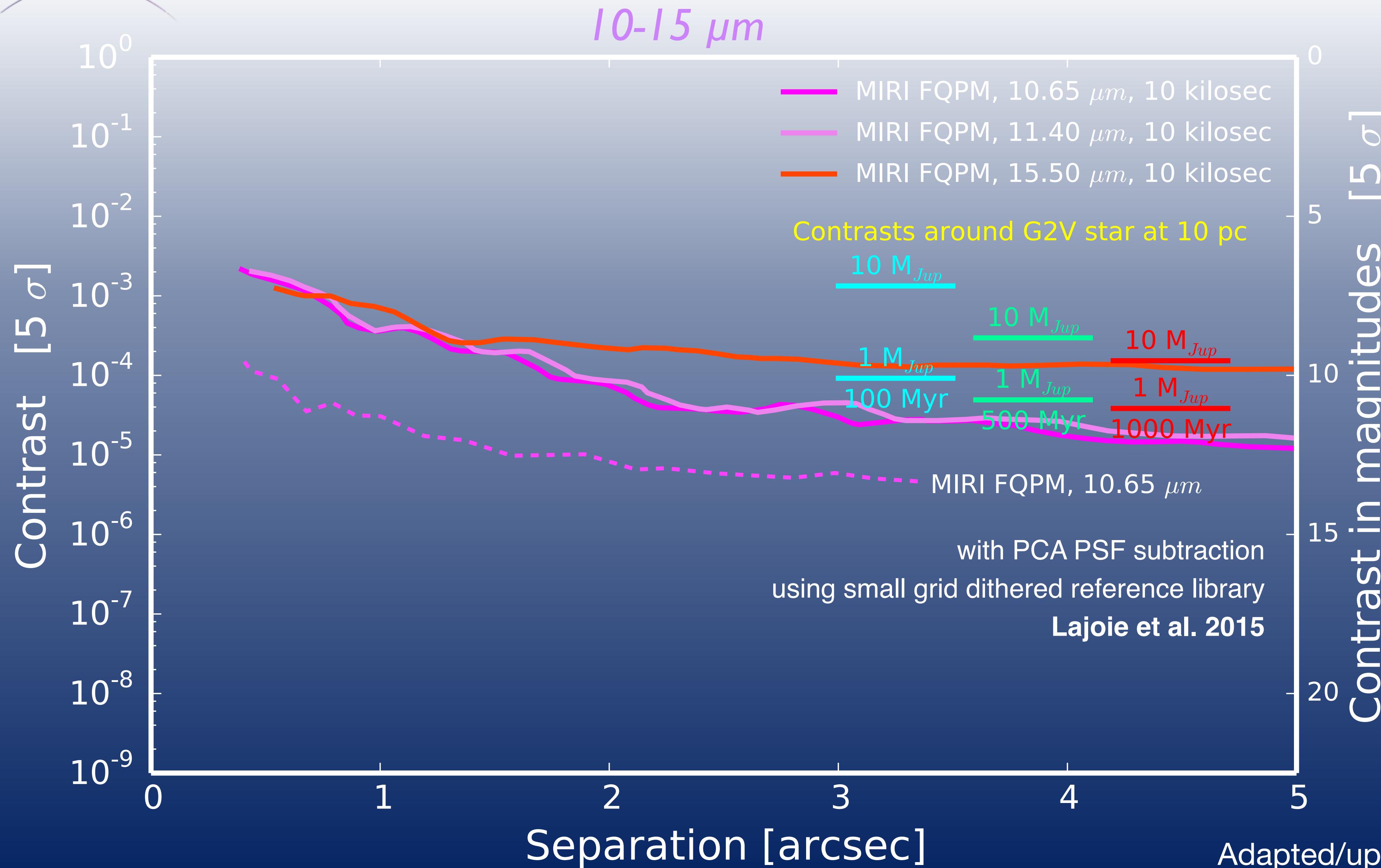


**NIRCam expected
contrasts:
below 10^{-5} at 1'',
 10^{-7} at 4''**

Adapted/updated from Beichman et al. 2010



MIRI Coronagraphy: expected contrasts

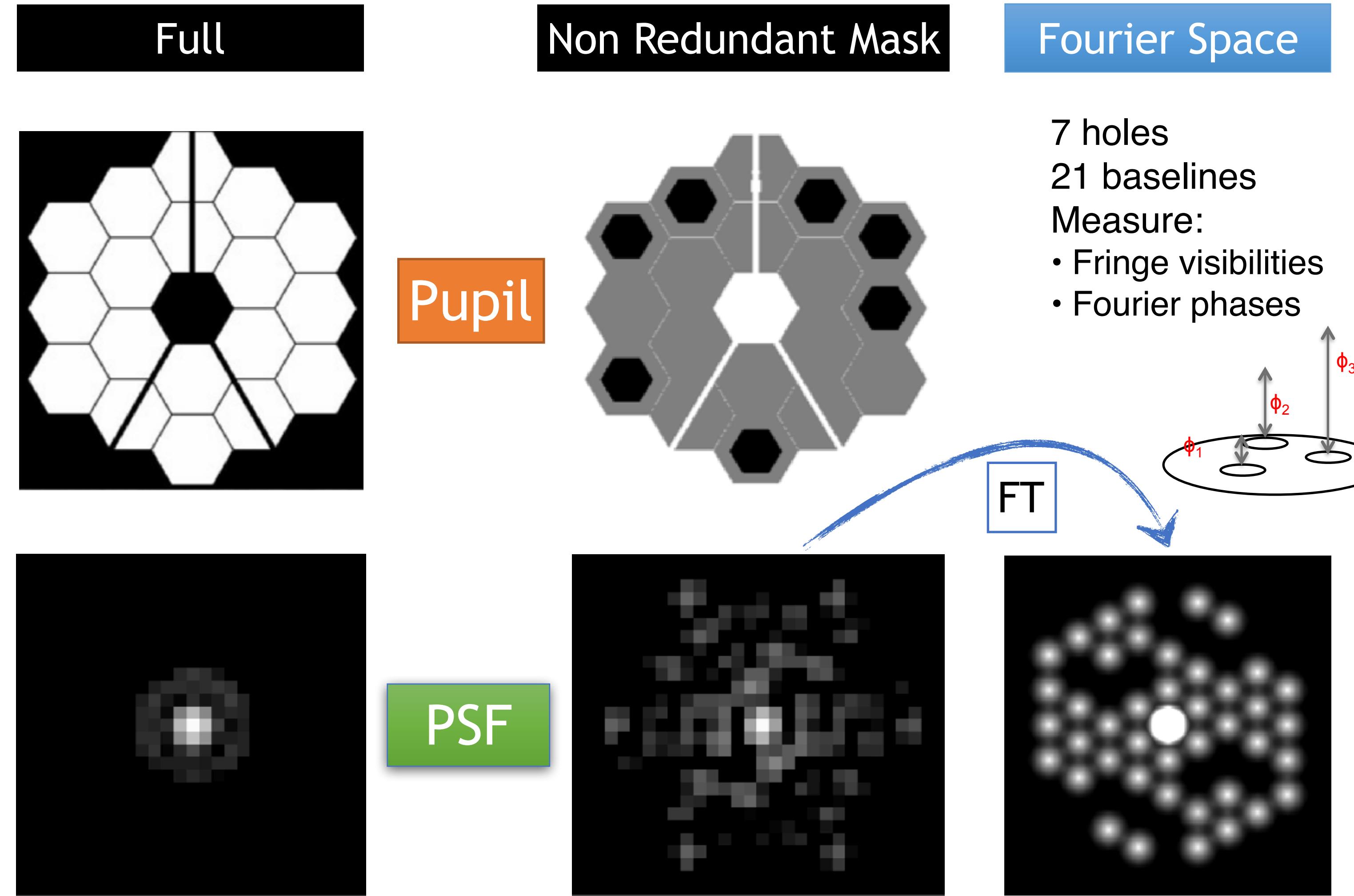
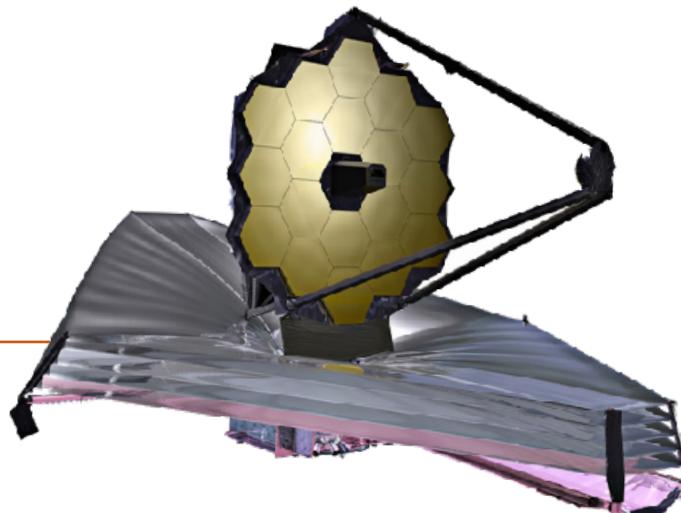


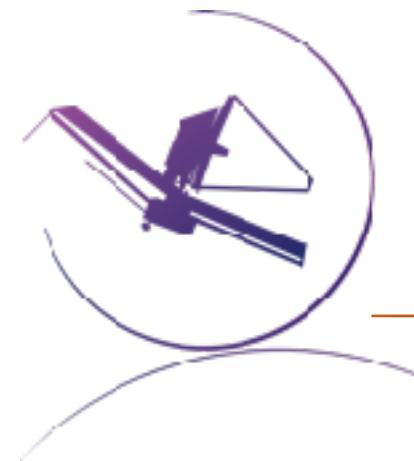
MIRI contrasts:
10⁻⁴ to 10⁻⁵
for $r > 1''$

Adapted/updated from Beichman et al. 2010



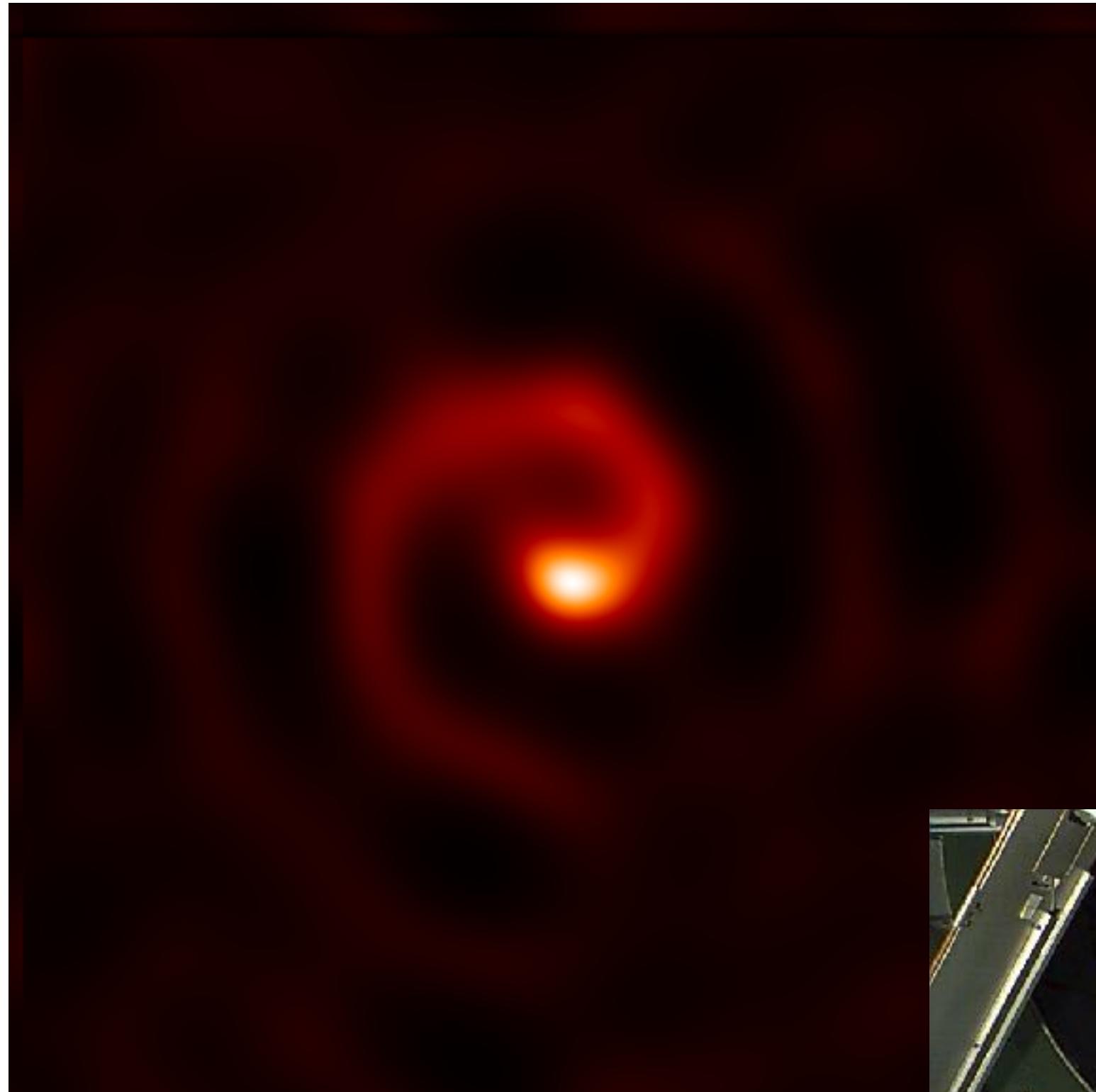
JWST/NIRISS Aperture Masking Interferometry (AMI)





NIRISS Aperture Masking Results (Keck)

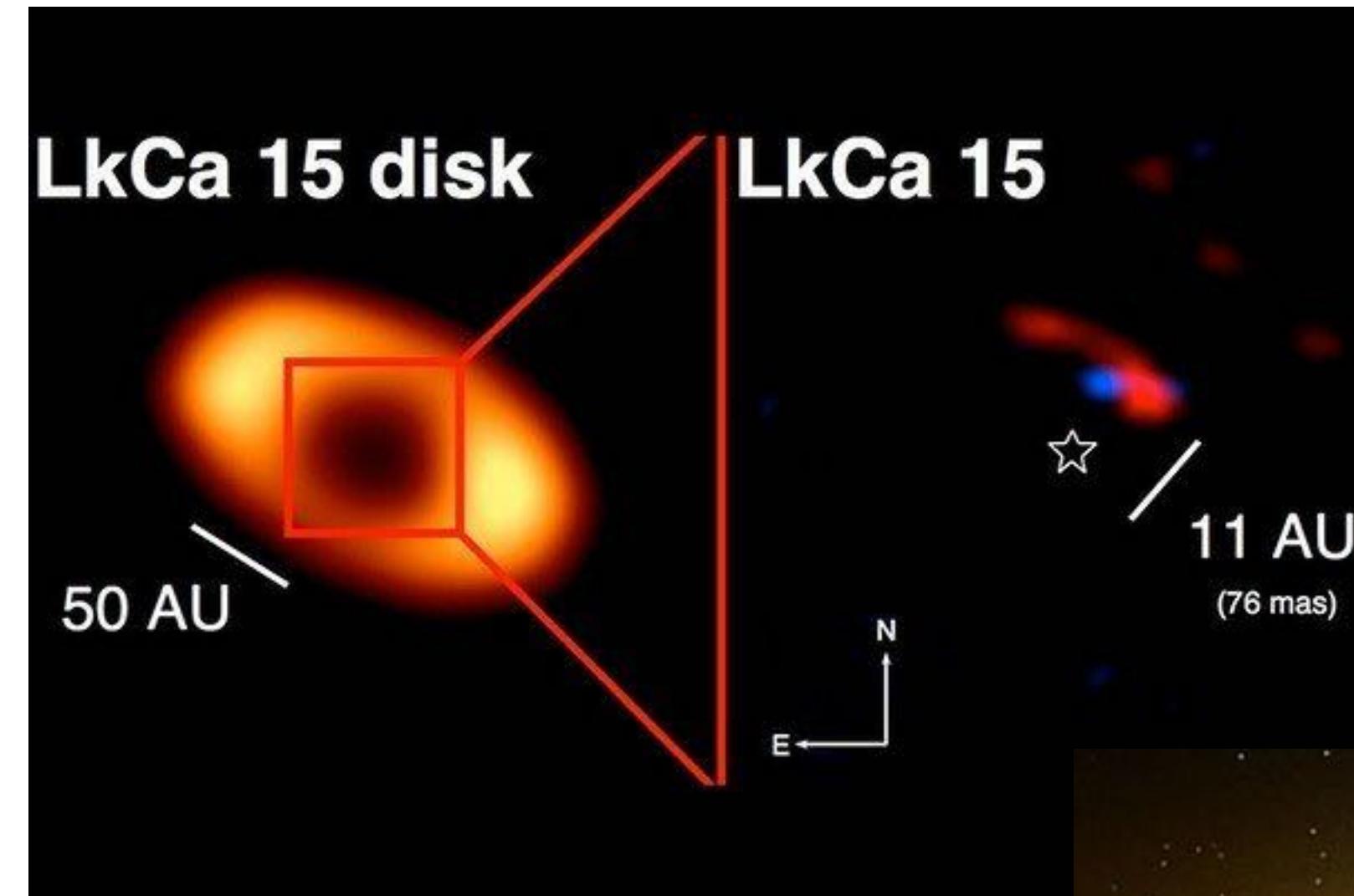
Wolf Rayet 104 or “Pinwheel Nebula”
Reconstructed images over > 6 years



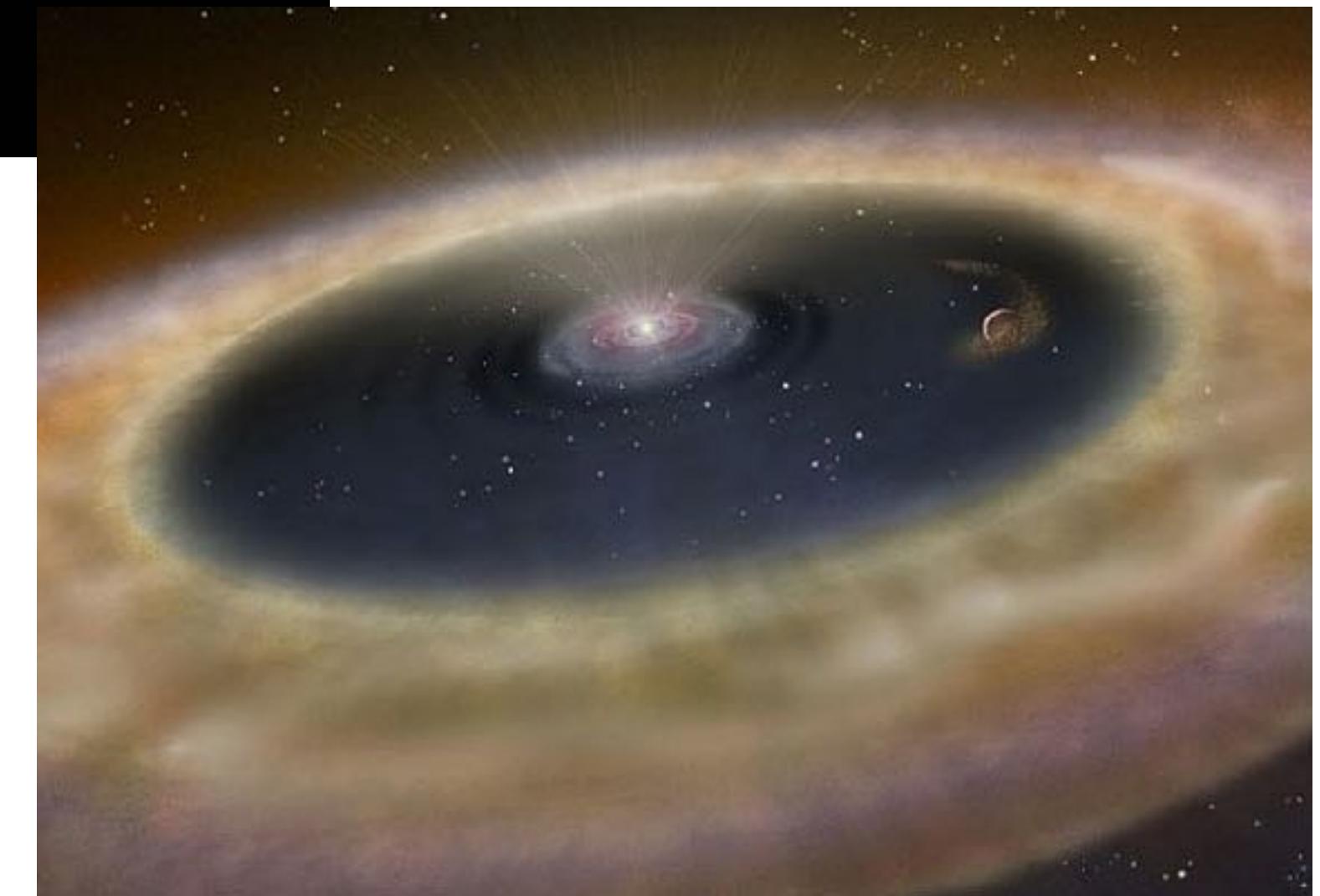
Tuthill (photo), Monnier,
Danchi 1999



Potential protoplanet LkCa 15 b

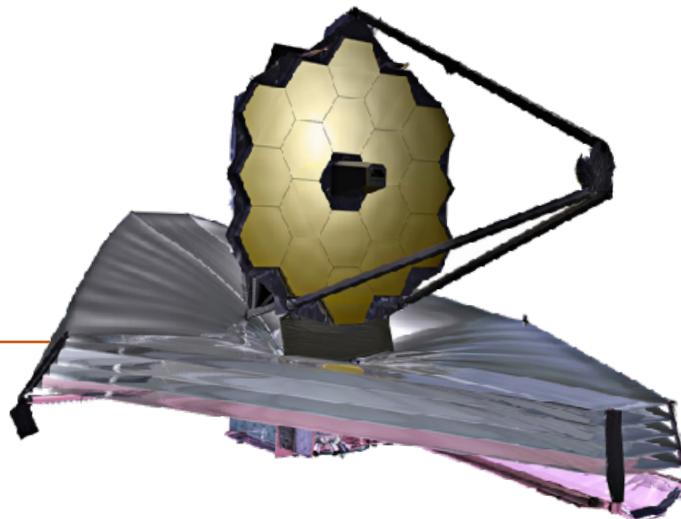


Kraus & Ireland 2012





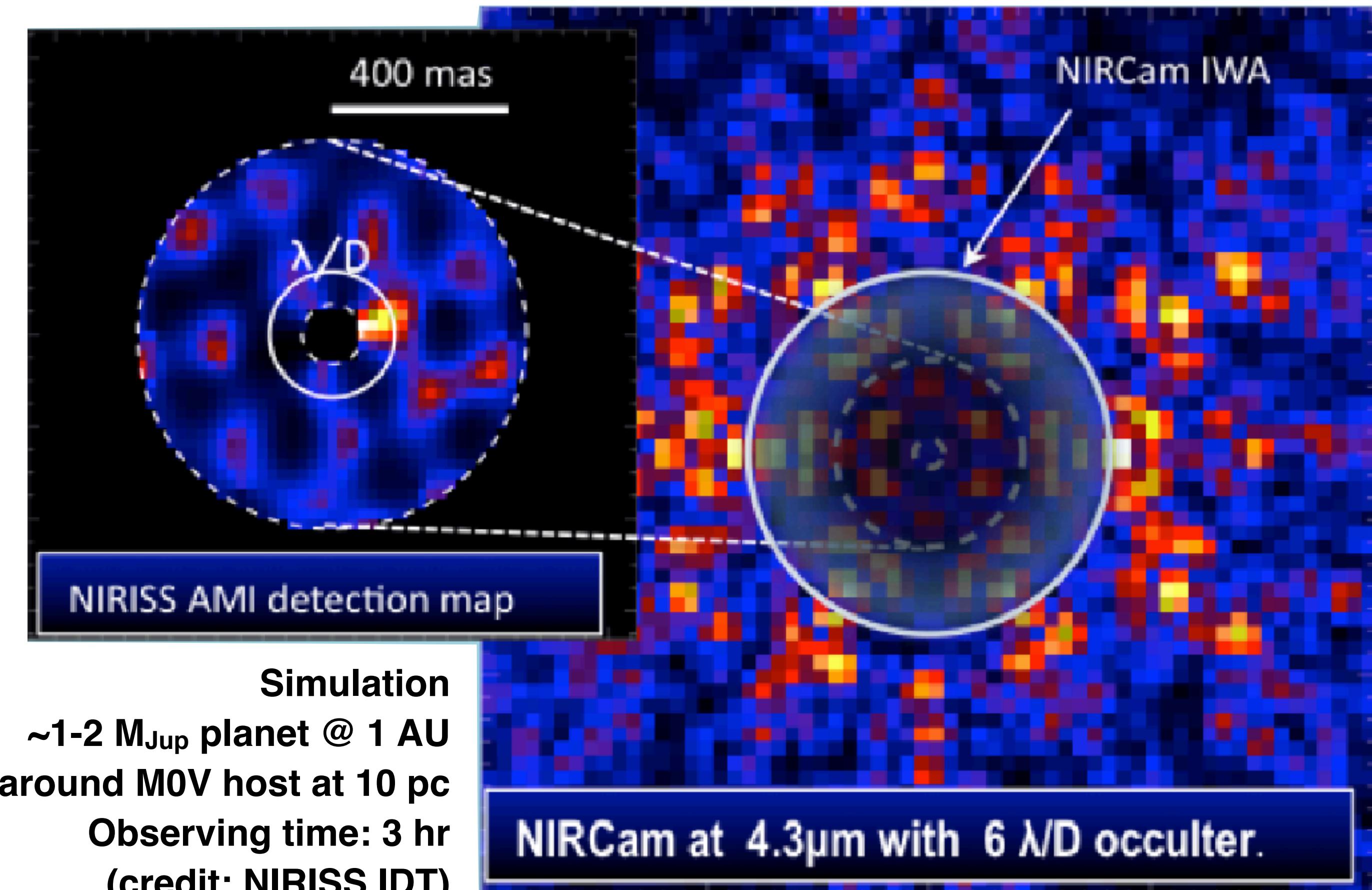
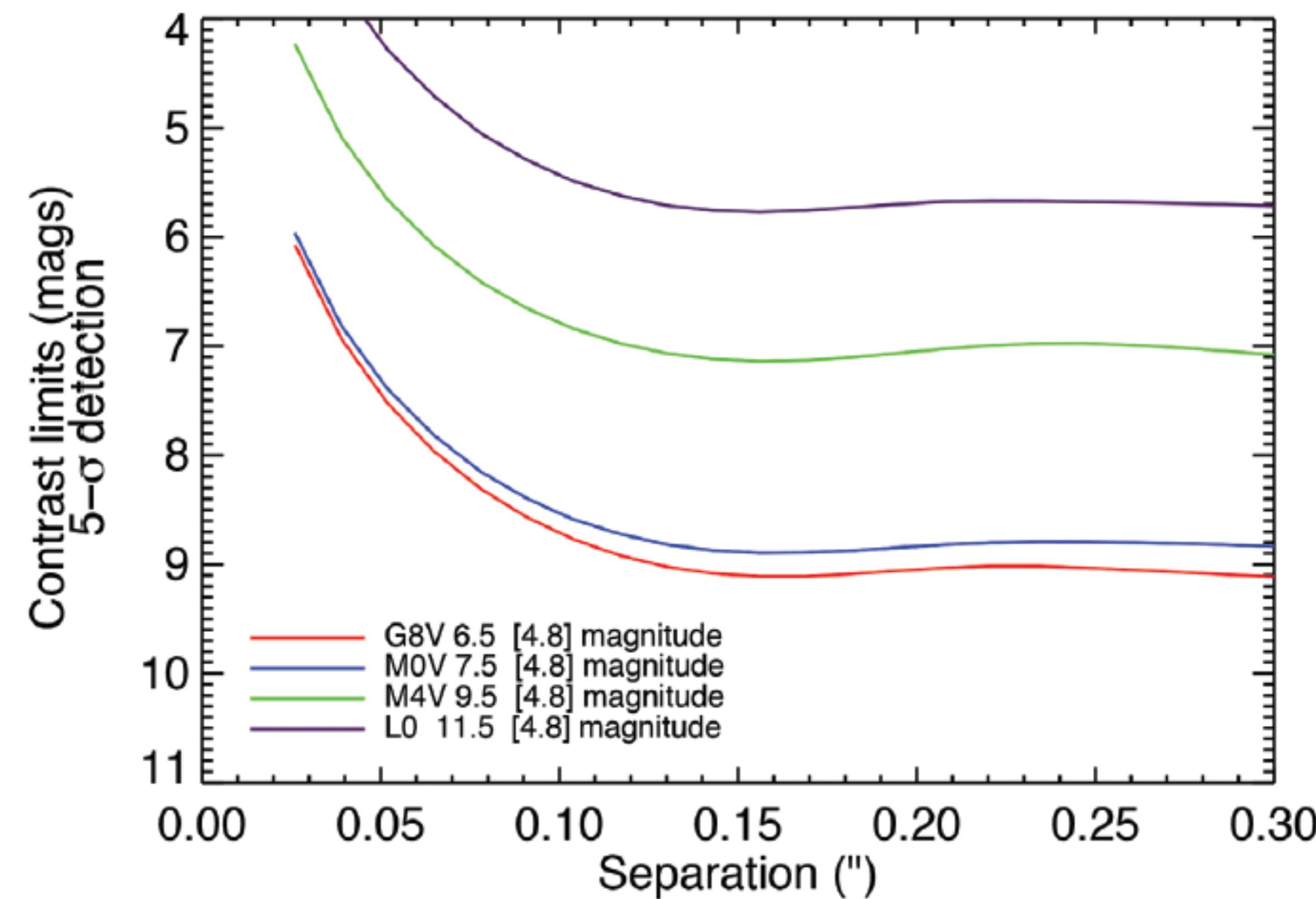
NIRISS AMI Predicted Performances



Probe separations of ~40 to 400 mas

At contrast of up to 9 mag

Filters: F380M, F430M, F480M, (and F277W)



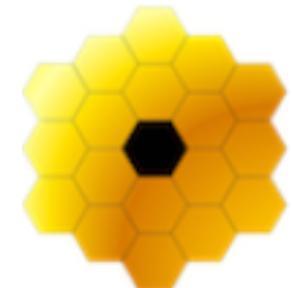
AMI Talk and exercises led by Deepashri Thatte later in this session



HCI Roadmap Walkthrough

JDox: the documentation platform: web-based, agile, integrated

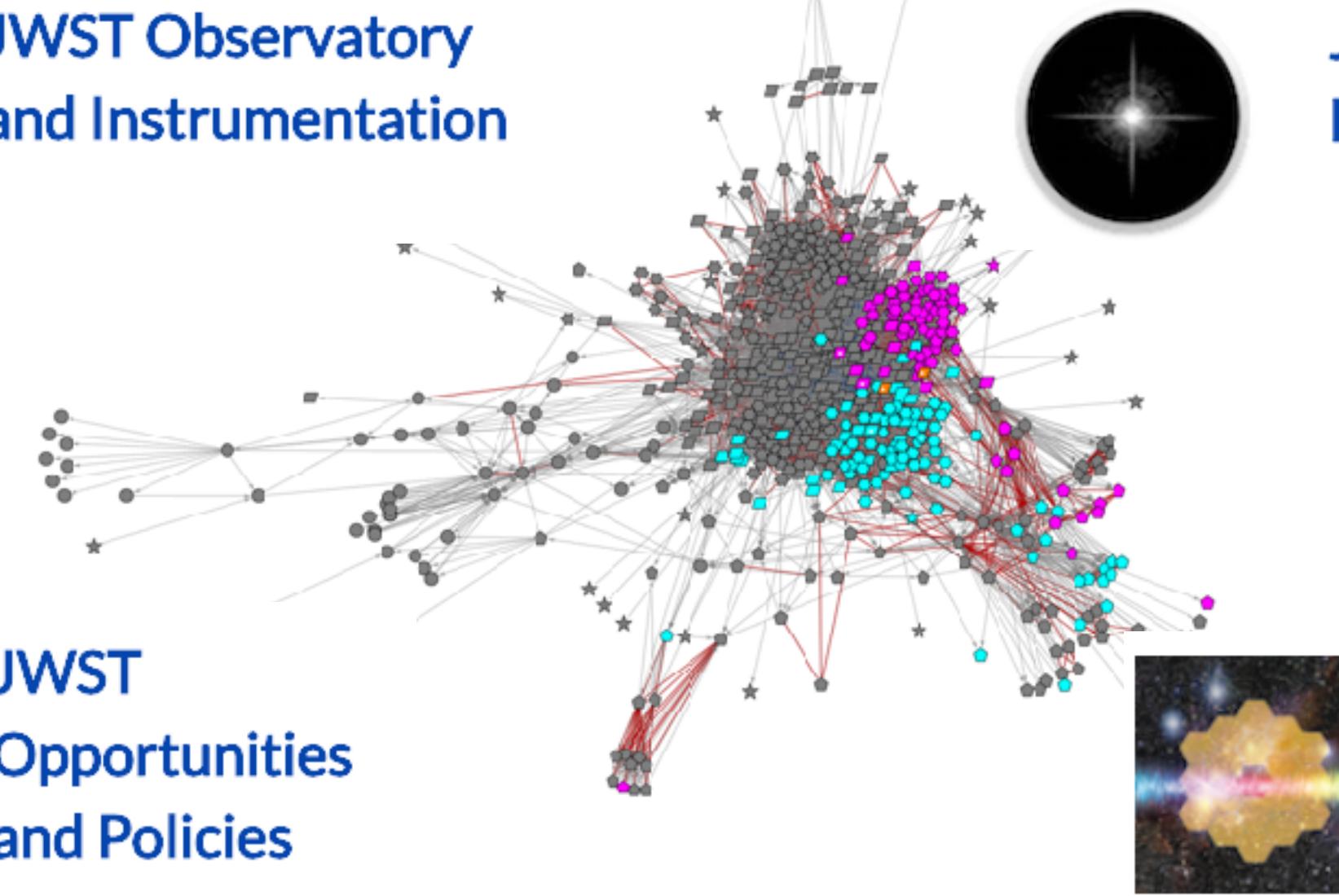
JWST Observatory and Instrumentation



JWST Opportunities and Policies



JWST Observation Planning



JWST Data Calibration and Analysis



jwst-docs.stsci.edu

James Webb Space Telescope User Documentation

HOME

INSTRUMENTS ▾

PLANNING ▾

CALL FOR PROPOSALS ▾

DATA ▾

Search





The HCI Roadmap article

jwst-docs.stsci.edu/methods-and-roadmaps/jwst-high-contrast-imaging/jwst-high-contrast-imaging-roadmap

OPEN

Proposing Opportunities

- › JWST Cycle 1 Proposal Opportunities
- › JWST General Science Policies

Proposal Preparation

- General Proposal Planning Workflow
- Understanding Exposure Times
- Methods and Roadmaps
 - › Imaging
 - › Wide Field Slitless Spectroscopy
 - High-Contrast Imaging
 - High Contrast Imaging Roadmap

[Home](#) / [Methods and Roadmaps](#) / [JWST High-Contrast Imaging](#) / [JWST High Contrast Imaging Roadmap](#)

JWST High Contrast Imaging Roadmap



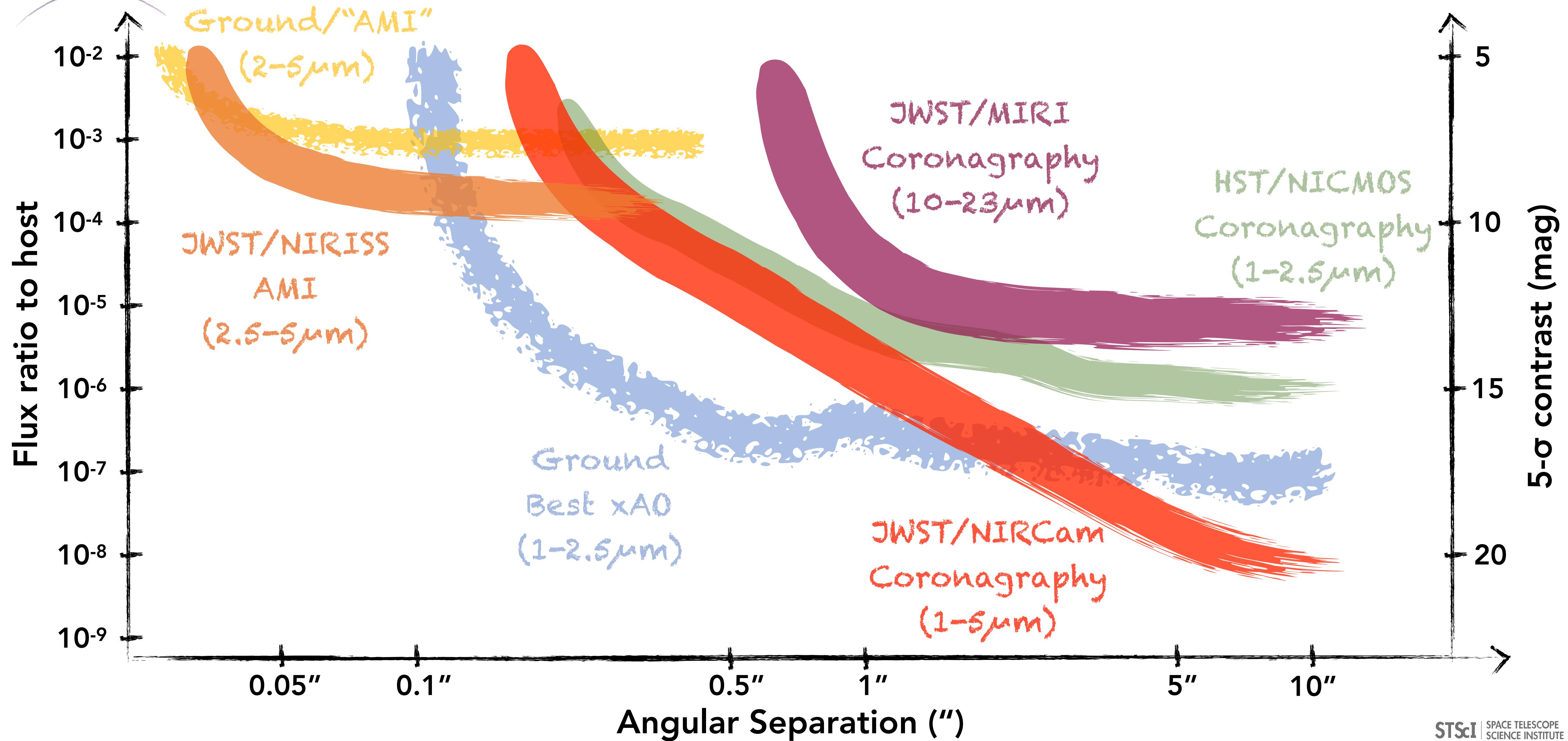
This roadmap outlines the suggested flow of planning considerations required for a High-contrast Imaging (HCI) observation with JWST and should be used in consultation with the General Proposal Planning Workflow.

On this page

- Stage 1 – Becoming familiar with the HCI capabilities and instrument-specific modes of JWST
- Stage 2 – Comparing your parameter space to the performance limits and capabilities of the HCI observing modes.
- Stage 3 – Selecting a PSF calibration strategy
- Stage 4 – Assessing target visibilities and allowed position angles
- Stage 5 – Using the Exposure Time Calculator (ETC)
- Stage 6 – Selecting a suitable PSF calibrator
- Stage 7 – Finalizing your observing strategy
- Stage 8 – Using the Astronomer's Proposal Tool (APT)
- References

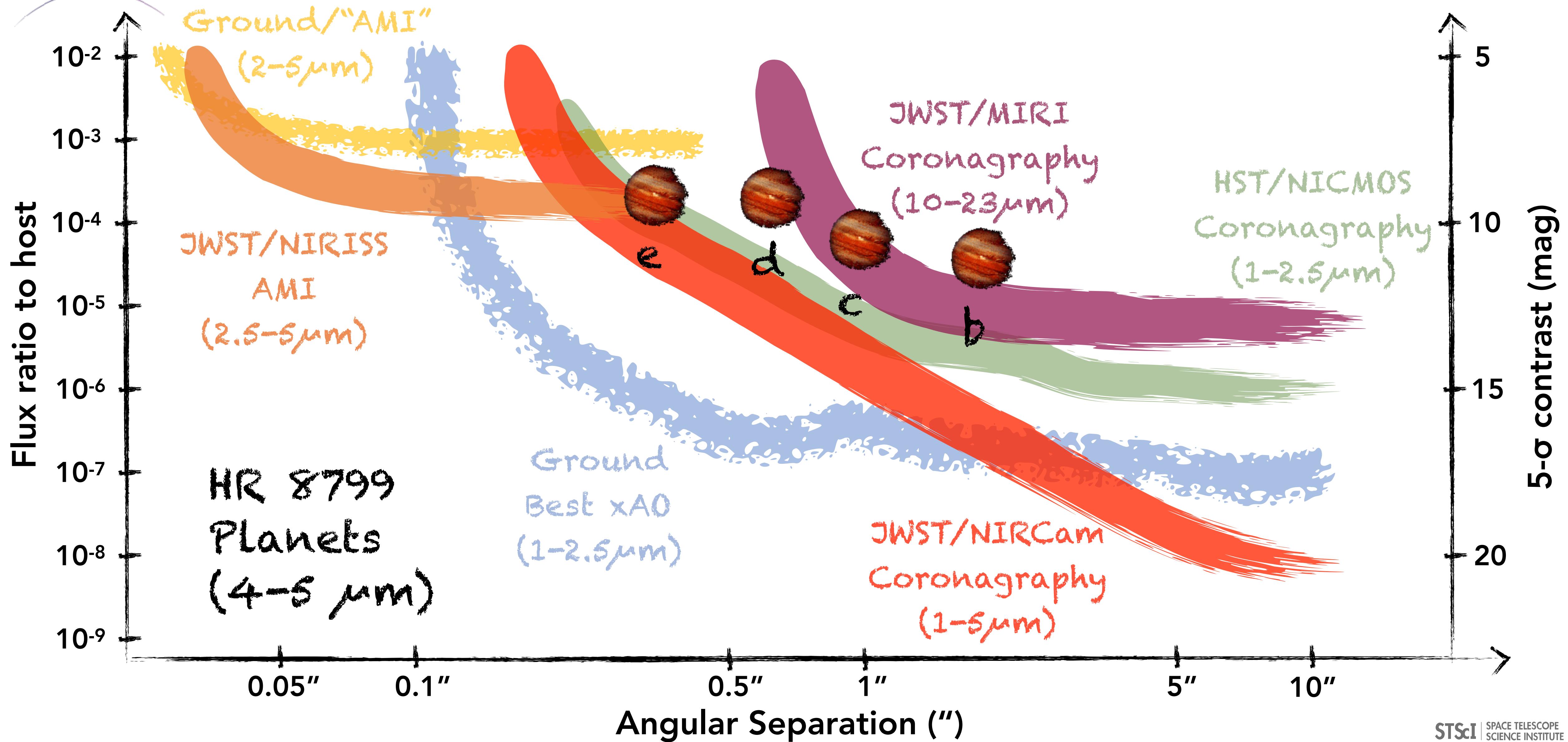


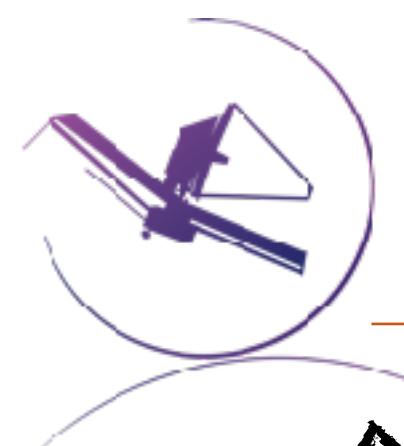
NIR to MIR Coronagraphy & Aperture Masking: Ground & Space



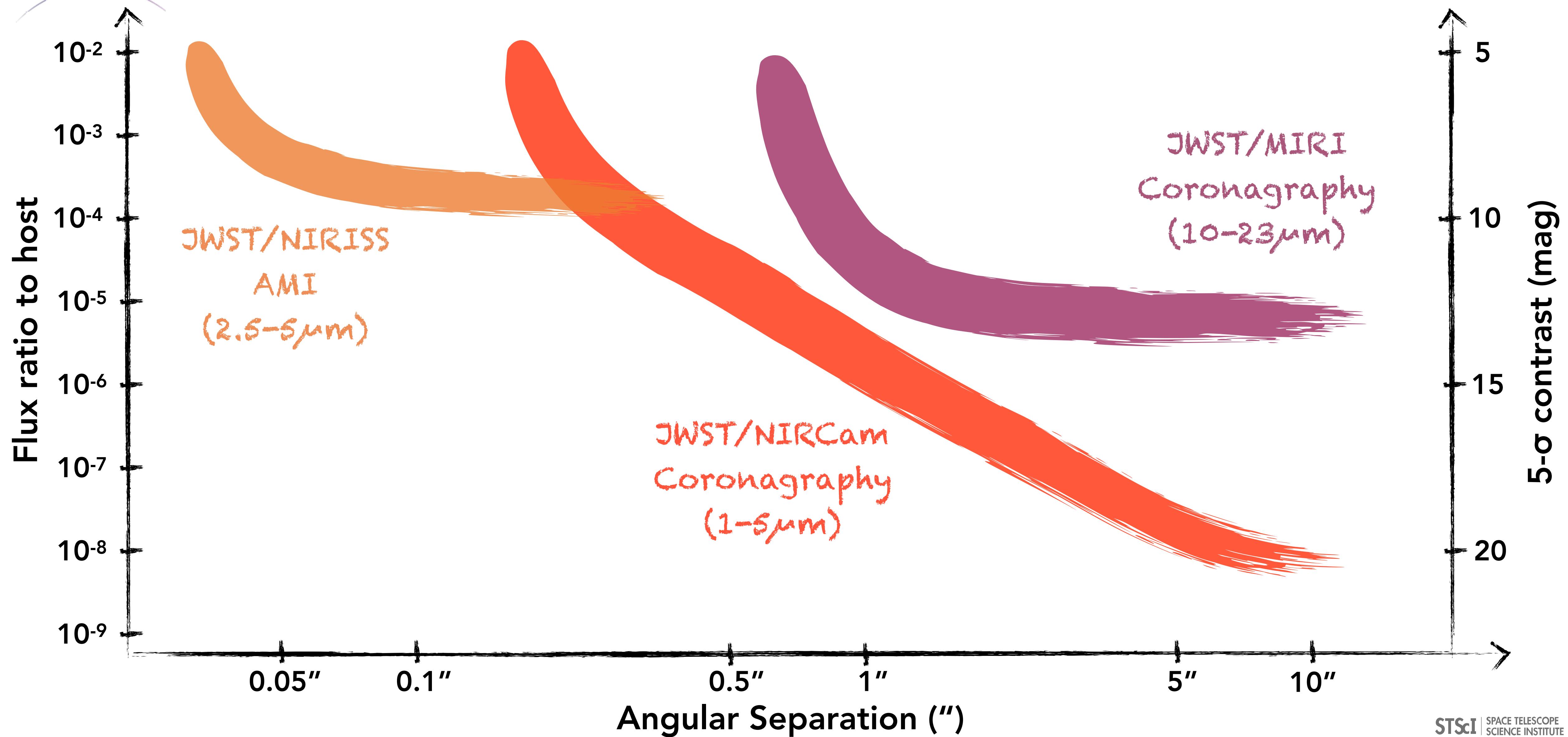


NIR to MIR Coronagraphy & Aperture Masking: Ground & Space



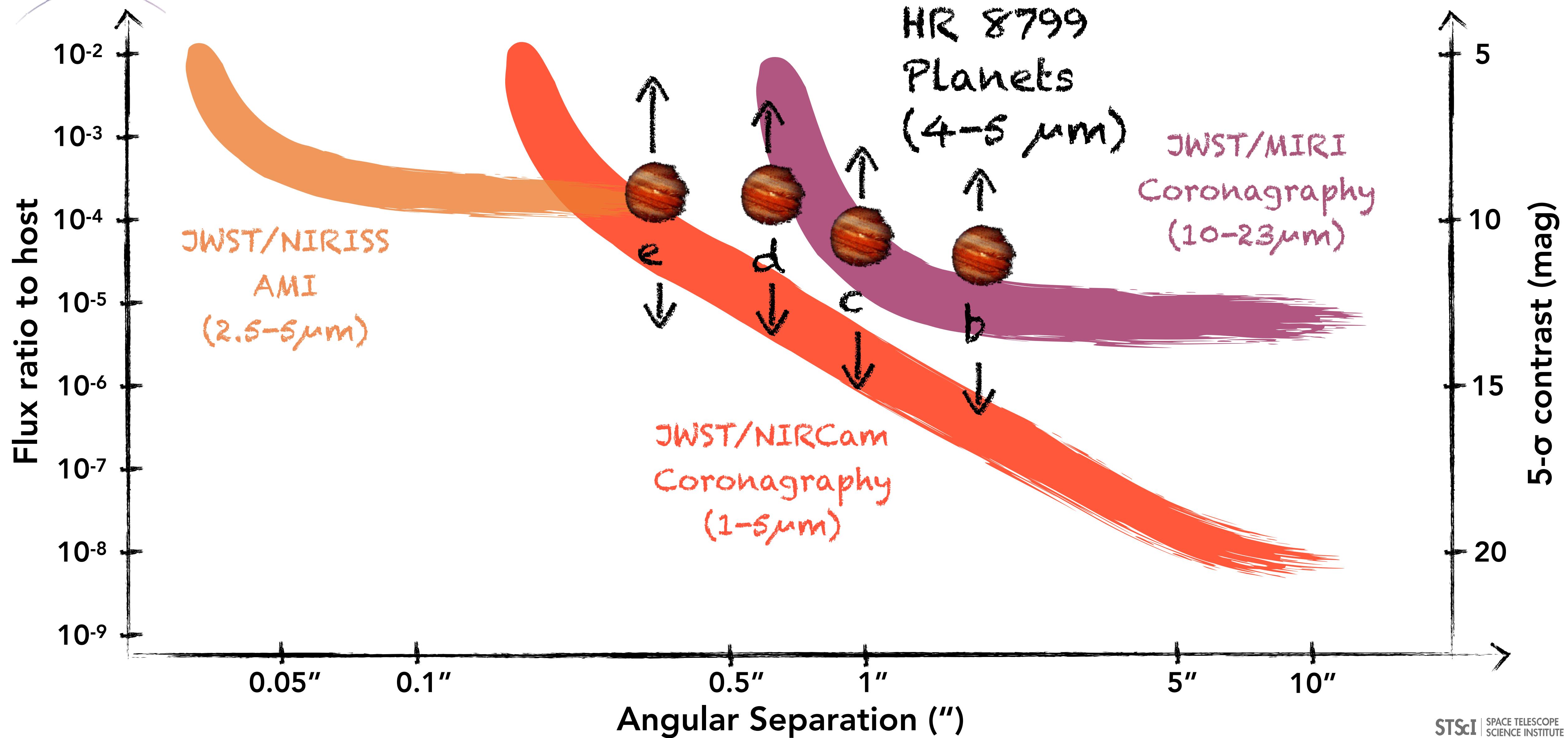


NIR to MIR Coronagraphy & Aperture Masking: Ground & Space





NIR to MIR Coronagraphy & Aperture Masking: Ground & Space

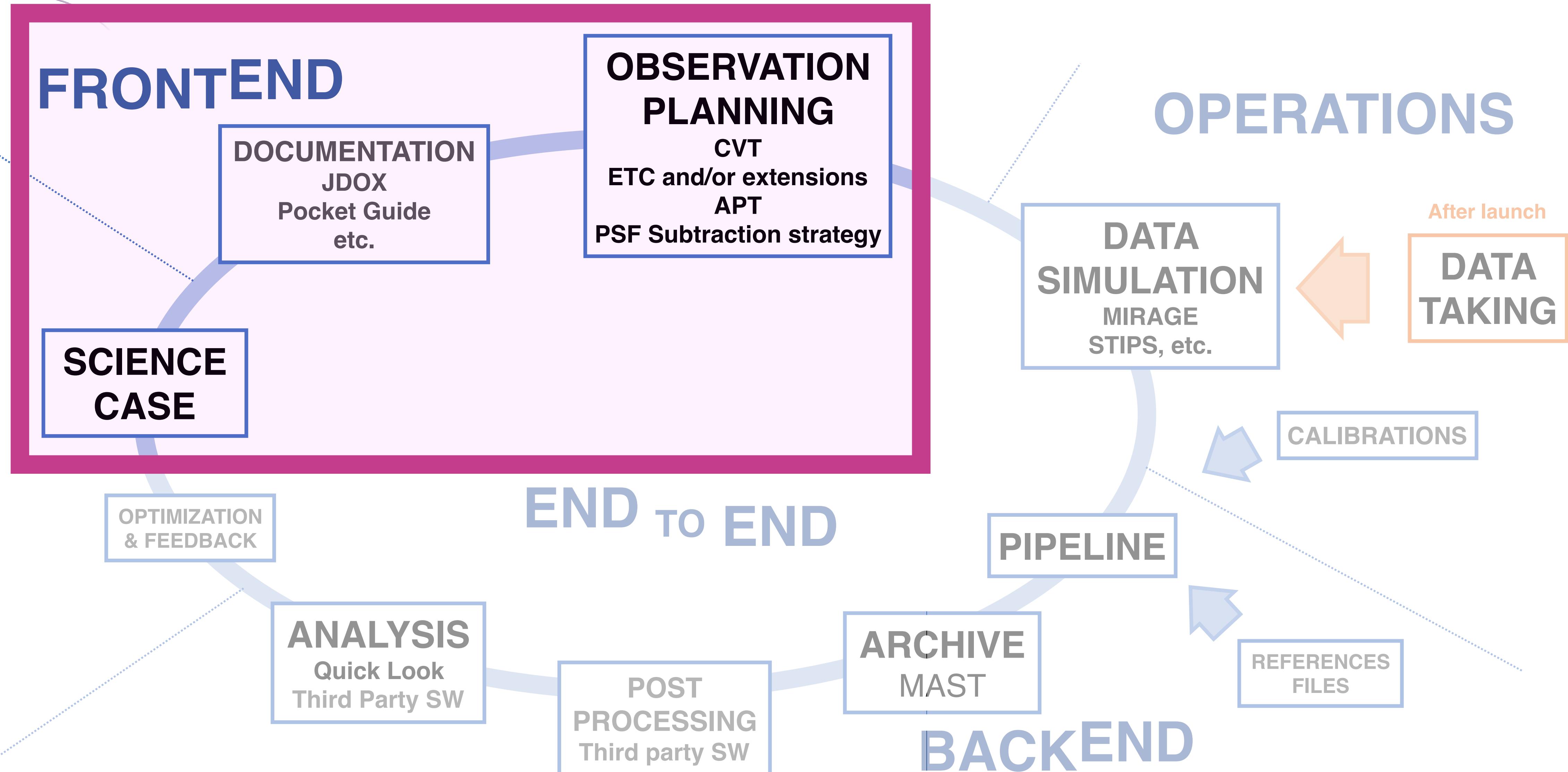




Proposal Planning Tools & HCI Resources



From an astrophysical idea to a result





Why do we recommend two rolls plus a PSF calibrator?

Factors degrading PSF calibration and subtraction

Wavefront drifts of the observatory

PSF star color differences

Self-subtraction biases (esp. for disks)

Imperfect target acquisitions

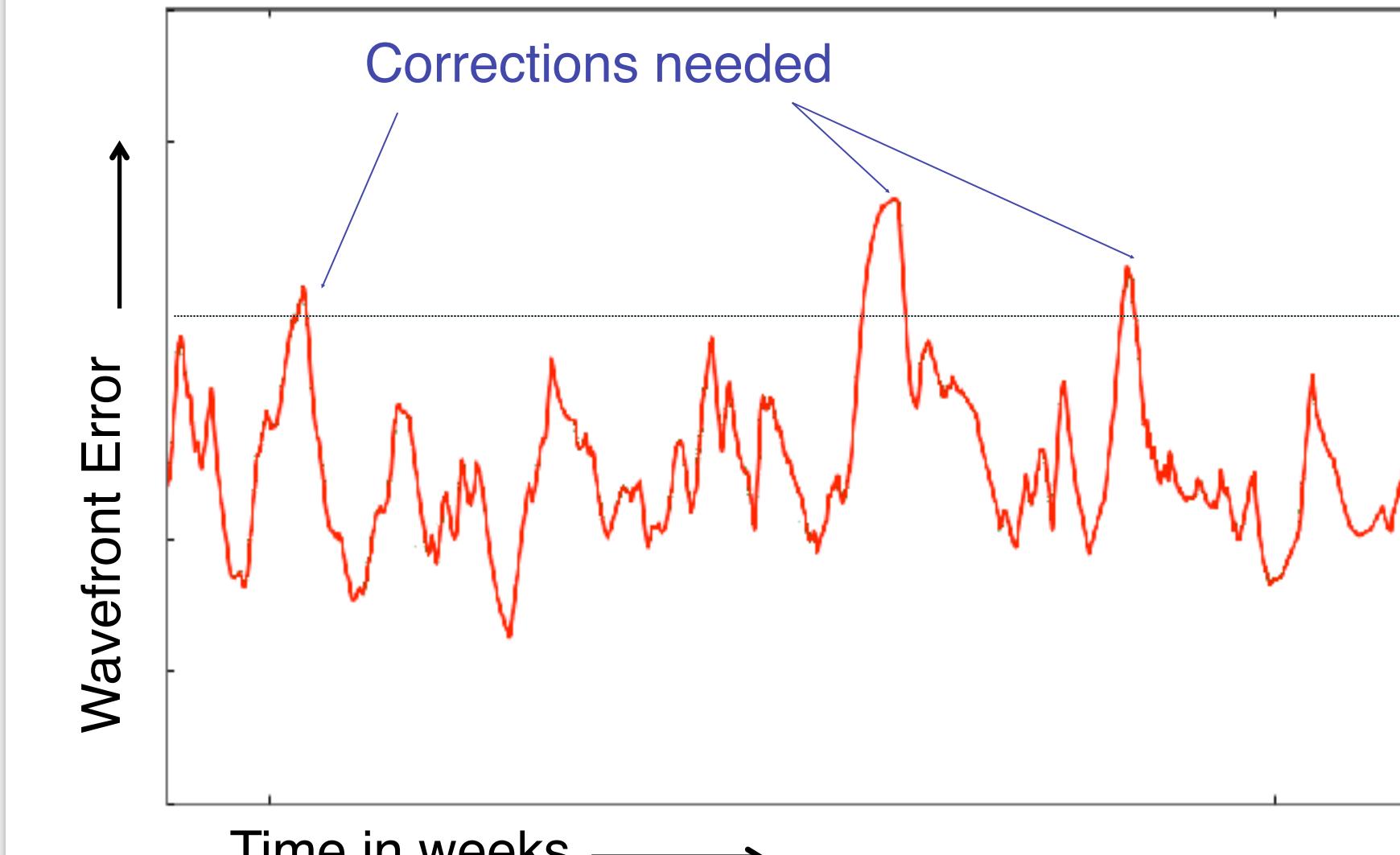
Line-of-sight jitter and dynamic wavefront error

By scheduling science and PSF calibration observations back-to-back, wavefront drifts should be minimized. (predicted to be negligible; sub-nm).

Performance and stability will not truly be known until measurements in flight.

Expect Hubble-like stability:
small wavefront changes driven by temperature drifts

Simulation for wavefront error vs time during maintenance



See Gersh-Range & Perrin, 2014

Changes in sun pitch angle will cause small changes in OTE temperature (< 1 K), but very slowly (predicted time constant ~ 5 to 9 days).



Why do we recommend two rolls plus a PSF calibrator?

Factors degrading PSF calibration and subtraction

Wavefront drifts of the observatory

PSF star color differences

Self-subtraction biases (esp. for disks)

Imperfect target acquisitions

Line-of-sight jitter and dynamic wavefront error

Observing science target at 2 rolls has proven highly effective with HST. Allows PSF subtraction at nearly same spacecraft attitude (for wavefront stability), eliminates stellar color mismatch terms, increases efficiency (PSF calibrator is also more science data), and helps mitigate detector artifacts.

However, this comes at the cost of introducing self-subtraction biases, especially given the limited available roll ($\sim 10^\circ$ max) of JWST.

For robustness, we conservatively advocate PSF calibration via both ADI+RDI.



Why do we recommend two rolls plus a PSF calibrator?

Factors degrading PSF calibration and subtraction

Wavefront drifts of the observatory

PSF star color differences

Self-subtraction biases (esp. for disks)

Imperfect target acquisitions

Line-of-sight jitter and dynamic wavefront error

Optional:

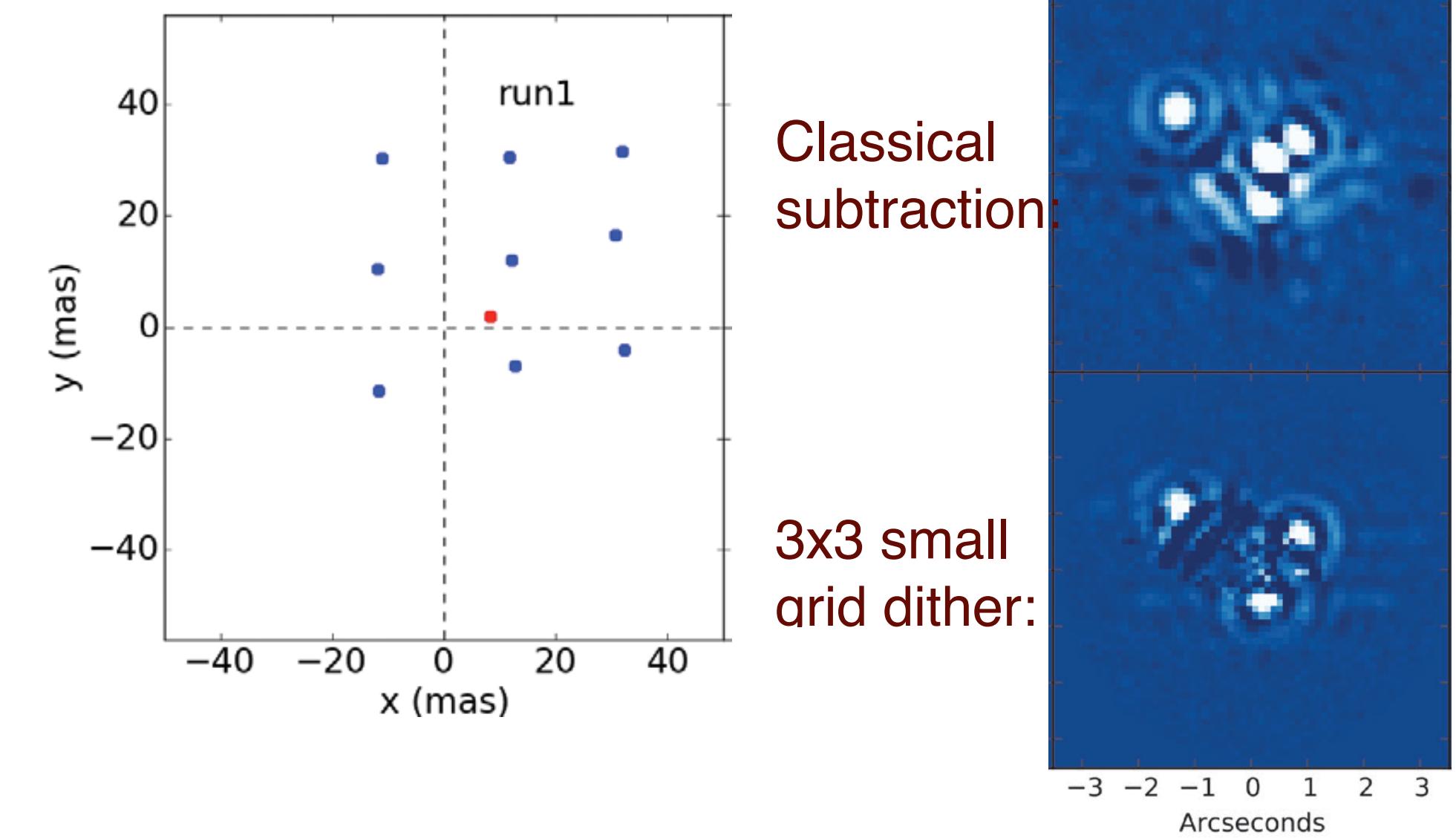
Perform sub pixel dithers of the PSF star to build mini PSF reference library, then synthesize an optimal PSF that matches the target position precisely. “Small Grid Dithers”.

>10x contrast improvement for MIRI,
3-5x improvement for NIRCam.

Cost: 5-9x longer PSF star exposure times.

Target acq is required for all coronagraphy.
Expected precision is very good (~ few mas)
but residuals still matter.

All coronagraphs are sensitive to misalignments;
MIRI FQPMs more sensitive than NIRCam Lyot corons.

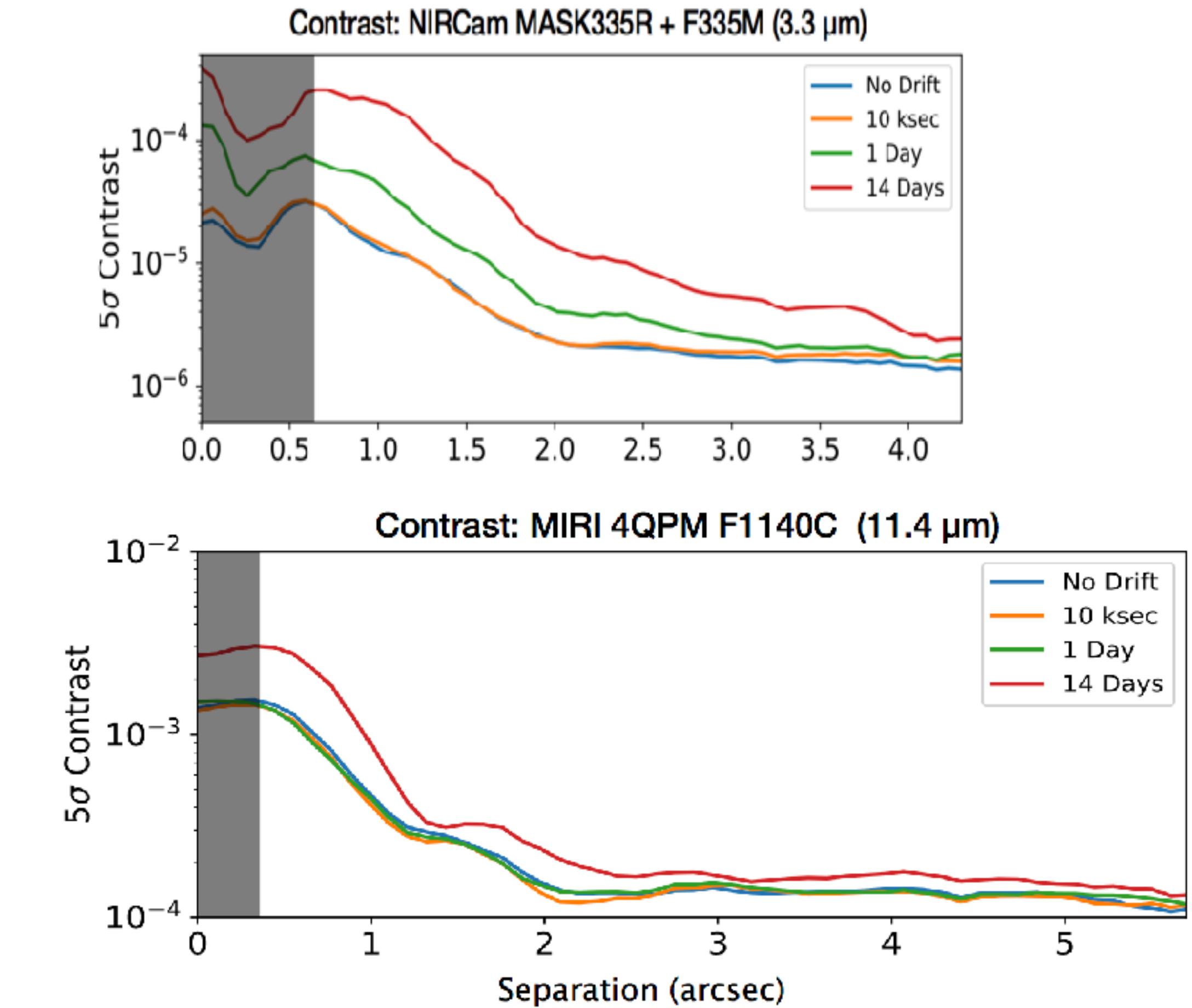
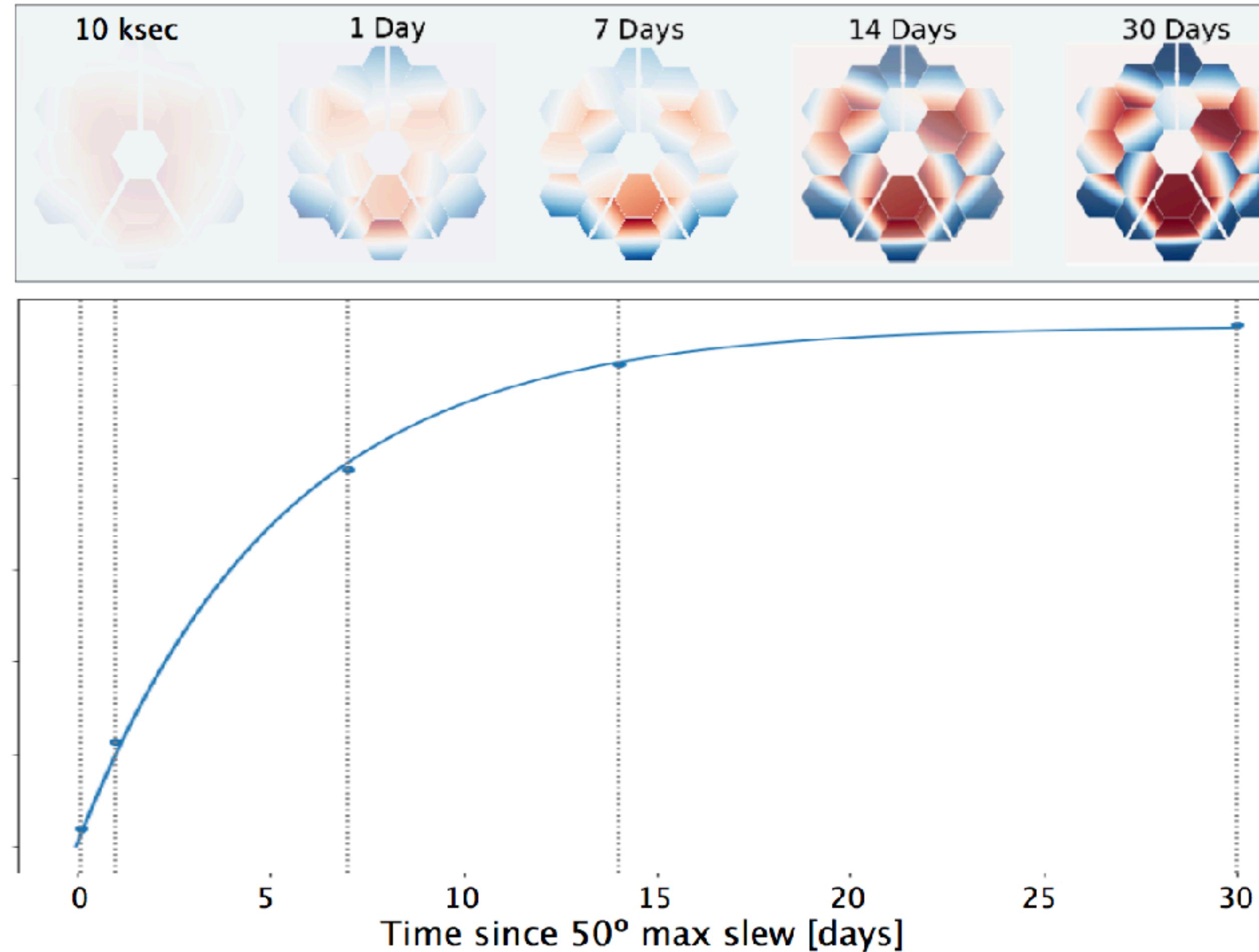


Simulated small grid dither PS subtraction
Lajoie et al. 2106



Towards the generation of realistic datasets : impact of slew

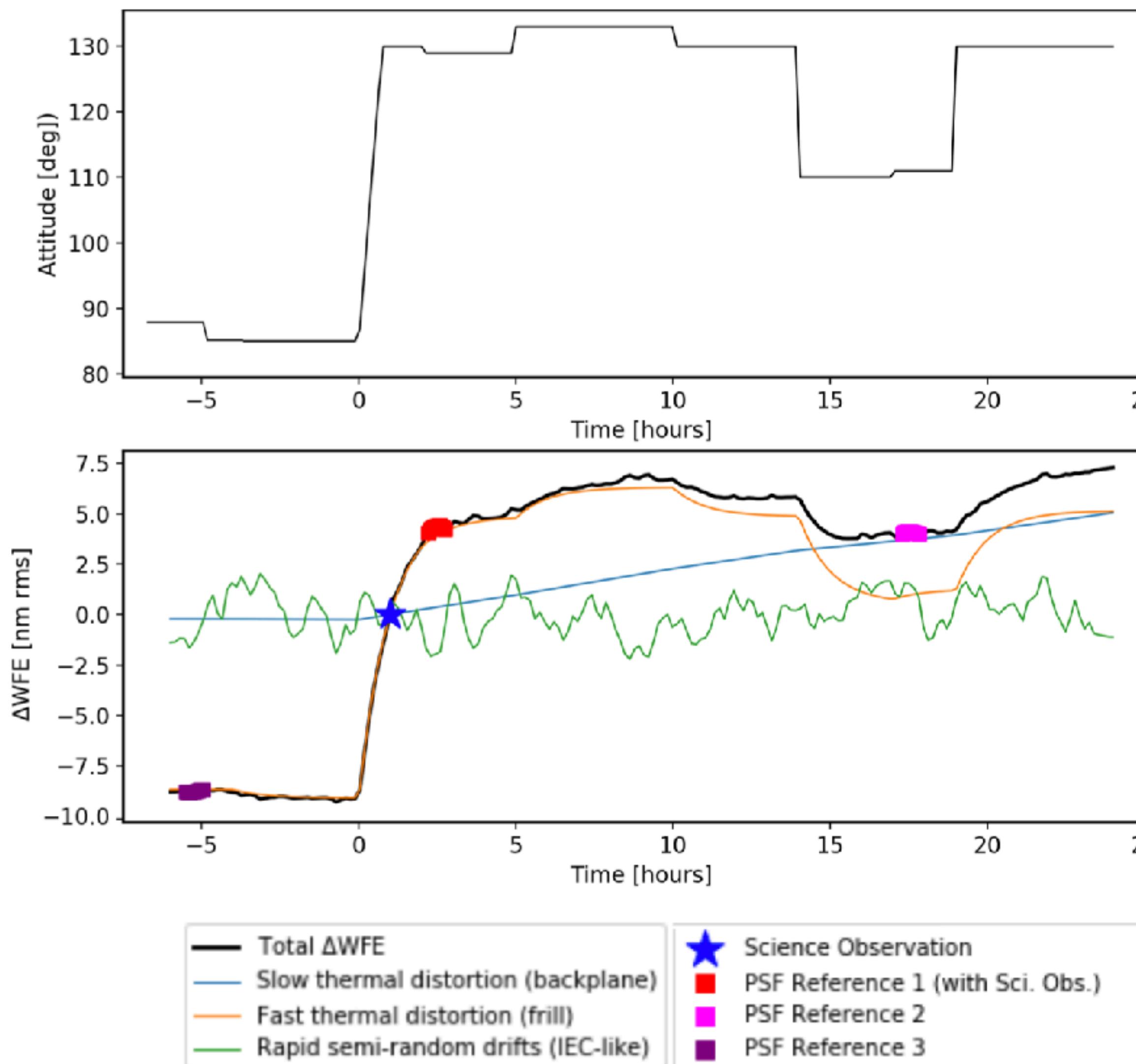
Model-predicted Δ WFE from maximum hot-to-cold slew



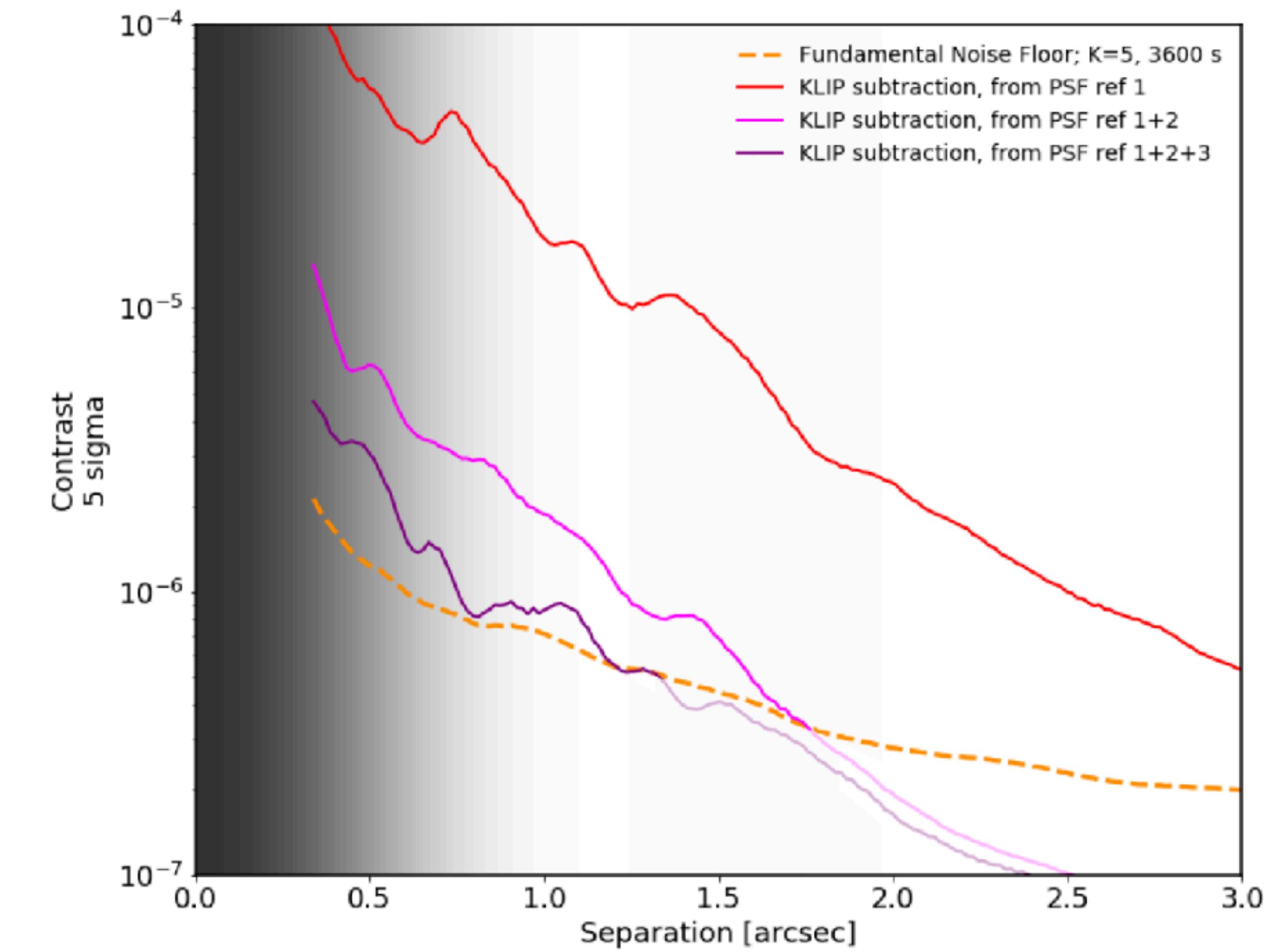


Towards the generation of realistic datasets : impact of slew

Hypothetical in-flight time series: observatory attitude and ΔWFE



Modeled Contrast after KLIP PSF subtraction



Perrin et al. SPIE 2018

Brooks et al. #AAS233



ETC: Exposure Time Calculator: now at v1.5 (soon 1.6)

<https://jwst.etc.stsci.edu/>

The screenshot shows the homepage of the JWST ETC. At the top, there is a navigation bar with icons for back, forward, search, and other browser functions. The URL 'jwst.etc.stsci.edu' is visible in the address bar. Below the header, the page title 'Exposure Time Calculator' is partially visible. The main content area features a large heading 'Welcome to the JWST Exposure Time Calculator'. Below this are four buttons: 'Quick Start' (green), 'Create User' (white), 'Login' (blue), and 'Work Anonymously' (white). A red oval highlights a section titled 'News' which contains a welcome message and release notes. A list of bullet points provides information about logging in to version 1.5.

Welcome to the JWST Exposure Time Calculator

Quick Start Create User Login Work Anonymously

News

Welcome to version 1.5 of the JWST ETC!

This release features new instrument modes, accuracy improvements, usability enhancements, and more: see the [Release Notes](#) for details, and be sure to review the [Known Issues](#) for this release.

When you log in to the 1.5 ETC, your old workbooks will be marked "Out of Date":

- When you load them, they will open in Read-Only mode: this ensures that your previous results are not overwritten and remain available to you for reference.
- If you copy an out of date workbook, and load the copy, all its calculations will be automatically updated for you with the current version of the software.
- For more information, see [ETC Releases and Out-of-Date Workbooks](#).



ETC for Coronagraphy: PSF subtraction from a reference star

Exposure Time Calculator Edit - Expand - Julien Girard - Help -

Today is a nice day!

Calculations Scenes and Sources Uploaded Spectra Coverages and Limitations

MIRI ✓ NIRCam ✓ NIRISS ✓ NIRPSpec ✓

ID	Plot	Mode	Scene	(s)	SNR	Δ
11	<input checked="" type="checkbox"/> nircam coronagraphy	2		408.34	98.74	
10	<input checked="" type="checkbox"/> nircam coronagraphy	2		388.06	93.65	
9	<input checked="" type="checkbox"/> nircam coronagraphy	2		306.93	87.94	
8	<input checked="" type="checkbox"/> nircam coronagraphy	2		286.77	81.47	
7	<input checked="" type="checkbox"/> nircam coronagraphy	2		204.82	73.97	
6	<input checked="" type="checkbox"/> nircam coronagraphy	2		153.46	65.07	
5	<input checked="" type="checkbox"/> nircam coronagraphy	2		102.31	53.99	
4	<input checked="" type="checkbox"/> nircam coronagraphy	2		51.15	38.82	
3	<input checked="" type="checkbox"/> nircam coronagraphy	2		51.15	38.82	
1	<input checked="" type="checkbox"/> nircam target_star	2		1.88	37.27	

Scenes ★ Backgrounds Instrument Setup Detector Setup Strategy

NIRCam Coronagraphy

Coronagraph: MASK335R

Filter: F335M

Calculation selected: 10, Mode: nircam coronagraphy

Total System Throughput

NIRCAM CORONOGRAPHY MASK335R F335M

Pres. Calculate

Images

Calculation selected: 10, Mode: nircam coronagraphy

2D SNR Detector Saturation

SNR vs On-Source Time

SNR

Seconds

SNR vs On-Source Time

SNR

Seconds

Bounds/Scale:

X: -25.91 436.96 Linear Clear

Y: 32.46 103.68 Linear Clear

Apply

Reports

Calculation selected: 10, Mode: nircam coronagraphy

Report Warnings Errors Downloads

Instrument Filter/Dispenser: F335M/Null

Extraction Aperture Position (arcsec): [1.72, 0.00]

Wavelength of interest used to Calculate Scale Values (micron): 3.35

Size of Extraction Aperture (arcsec): 0.08

Total Time Required for Strategy (seconds): 716.16

Total Exposure Time (seconds): 388.06

Extracted Flux (e-/sec): 76.73

Standard Deviation in Extracted Flux (e-/sec): 0.82

Extracted Signal-to-Noise ratio: 93.65

Input Background Surface Brightness (Mjy/s): 0.14

Total Background Flux in Extraction Aperture (e-/sec): 0.06

Total Sky Background Flux in Extraction Aperture (e-/sec): 1.20

Fraction of Total Background due to Signal From Scene: 0.98

Average Number of Cosmic Rays per Ramp: 4.0e-3

Radius at which Contrast is Measured (arcsec): 1.00

Azimuth at which Contrast is Measured (degrees): 0.0

Contrast: NaN

Example feature:
Expand SNR
through filters

jwst.etc.stsci.
.edu



ETC for Coronagraphy: PSF subtraction from a reference star

Exposure Time Calculator Edit - Expand - Julien Girard - Help -

Today is a nice day!

Simple planet DI case

Calculations Scenes and Sources Uploaded Spectra Coverts and Limitations

MIR MIRCam NIRISS NIRSpec

ID	Plot	Mode	Scene	(s)	SNR	Δ
11	<input checked="" type="checkbox"/>	nircam coronagraphy	2	408.34	98.74	
10	<input checked="" type="checkbox"/>	nircam coronagraphy	2	388.06	93.65	
9	<input checked="" type="checkbox"/>	nircam coronagraphy	2	306.03	87.94	
8	<input checked="" type="checkbox"/>	nircam coronagraphy	2	286.77	81.47	
7	<input checked="" type="checkbox"/>	nircam coronagraphy	2	204.82	73.97	
6	<input checked="" type="checkbox"/>	nircam coronagraphy	2	153.46	65.07	
5	<input checked="" type="checkbox"/>	nircam coronagraphy	2	102.31	53.99	
4	<input checked="" type="checkbox"/>	nircam coronagraphy	2	51.15	38.82	
3	<input checked="" type="checkbox"/>	nircam coronagraphy	2	51.15	38.82	
1	<input checked="" type="checkbox"/>	nircam target_star	2	1.88	37.27	
-	-	-	-	--	--	-

Images

Calculation selected: 10, Mode: nircam coronagraphy

2D SNR Detector Saturation

SNR vs On-Source Time

Instrument Filter/Dispenser: F935W/Null

Extraction Aperture Position (arcsec): [1.72, 0.00]

Wavelength of interest used to Calculate Scales Values (micron): 3.35

Size of Extraction Aperture (arcsec): 0.08

Total Time Required for Strategy (seconds): 716.16

Total Exposure Time (seconds): 388.06

Extracted Flux (e-/sec): 76.73

Standard Deviation in Extracted Flux (e-/sec): 0.82

Extracted Signal-to-Noise ratio: 93.65

Input Background Surface Brightness (Mjy/s): 0.14

Total Background Flux in Extraction Aperture (e-/sec): 0.06

Total Sky Background Flux in Extraction Aperture (e-/sec): 1.20

Fraction of Total Background due to Signal From Scene: 0.98

Average Number of Cosmic Rays per Ramp: 4.0e-3

Radius at which Contrast is Measured (arcsec): 1.00

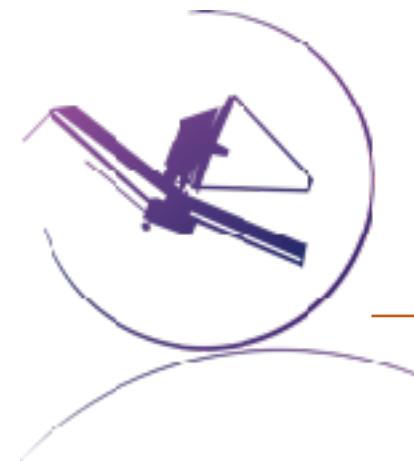
Azimuthal at which Contrast is Measured (degrees): 0.0

Contrast: NaN

Example feature:
Expand SNR
through filters

The screenshot displays the JWST ETC software interface. At the top, there's a navigation bar with 'Exposure Time Calculator', 'Edit', 'Expand', 'Julien Girard', and 'Help'. Below it is a message 'Today is a nice day!' and a note 'Simple planet DI case'. The main area has tabs for 'Calculations', 'Scenes and Sources', 'Uploaded Spectra', and 'Coverts and Limitations'. A table lists calculations with columns for ID, Plot, Mode, Scene, time (s), SNR, and a delta column. The 'Scenes and Sources' tab is active, showing a list of 11 entries, with the 10th entry highlighted in yellow. The 'Scenes' column shows icons for 'nircam coronagraphy' and 'nircam target_star'. The 'Sources' column shows numerical values. The 'Coverts and Limitations' tab is also visible. To the right of the table are three panels showing 2D images of a star with a coronagraphic mask, each with an orange color bar. Below the table is a 'Plots' section with a '2D SNR' plot showing a blue heatmap of signal-to-noise ratio across a field of view from -3.15 to 3.15 arcsec on both axes. A color bar at the bottom ranges from 0 to 60. To the right of the heatmap is a scatter plot titled 'SNR vs On-Source Time' with 'Seconds' on the x-axis (0 to 400) and 'SNR' on the y-axis (40 to 100). Data points are colored by filter: blue (0s), green (50s), orange (100s), red (150s), purple (200s), blue (250s), green (300s), red (350s), and yellow (400s). Below the scatter plot are 'Bounds/Scale' controls for X and Y axes. To the right of the scatter plot is a large panel containing detailed parameters for the calculation, such as instrument filter, extraction aperture position, wavelength, total exposure time, extracted flux, and contrast.

jwst.etc.stsci.edu



ETC for Coronagraphy: Limitations for High Contrast Imaging

Pre-computed PSF library from WebbPSF with a discrete number of angular separations (sparse spatial sampling)

→ Calculations can be **inaccurate in the speckle limited regime** (close to the coronagraphs, typically at separations $< 1''$)

ETC does not account for spectral mismatch (only photometrically) of the PSF reference star

ETC supposes a perfect centering (target acquisition) of all stars

→ Calculations can be **optimistic**

PSF calculations “on the fly” are time consuming: can be done in command line with Pandeia engine or with PanCAKE (not yet fully supported)

- ◆ Custom small grid dithers and positioning
- ◆ Custom spectral sampling
- ◆ Custom field of view

[https://github.com/spacetlescope/
pandeia-coronagraphy](https://github.com/spacetlescope/pandeia-coronagraphy)

The ETC PSF subtraction strategies assume the same detector readout parameters for all stars in a workbook

→ If one wants to use a brighter reference star, several ETC workbooks are needed

The ETC cannot inject ring like features or disks

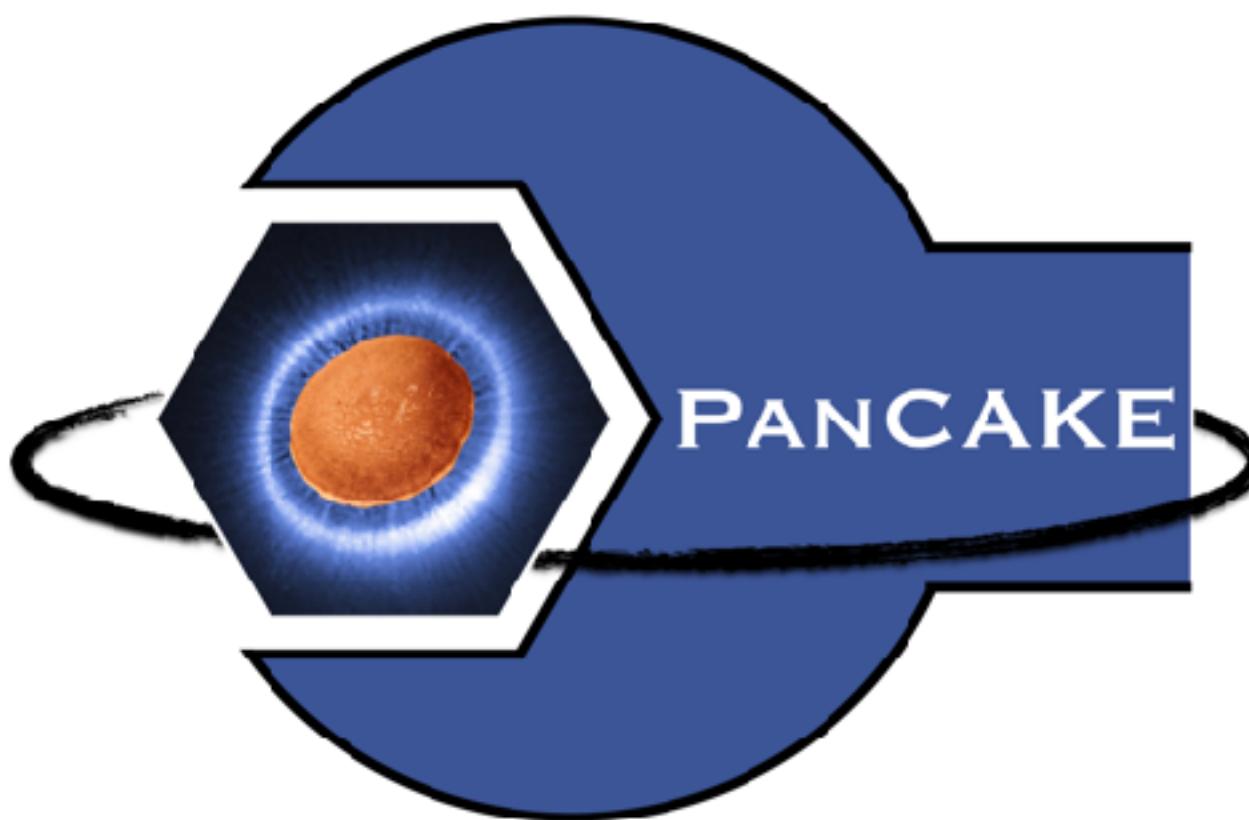
Can be done with pyNRC (not supported by STScI)

<https://pynrc.readthedocs.io>

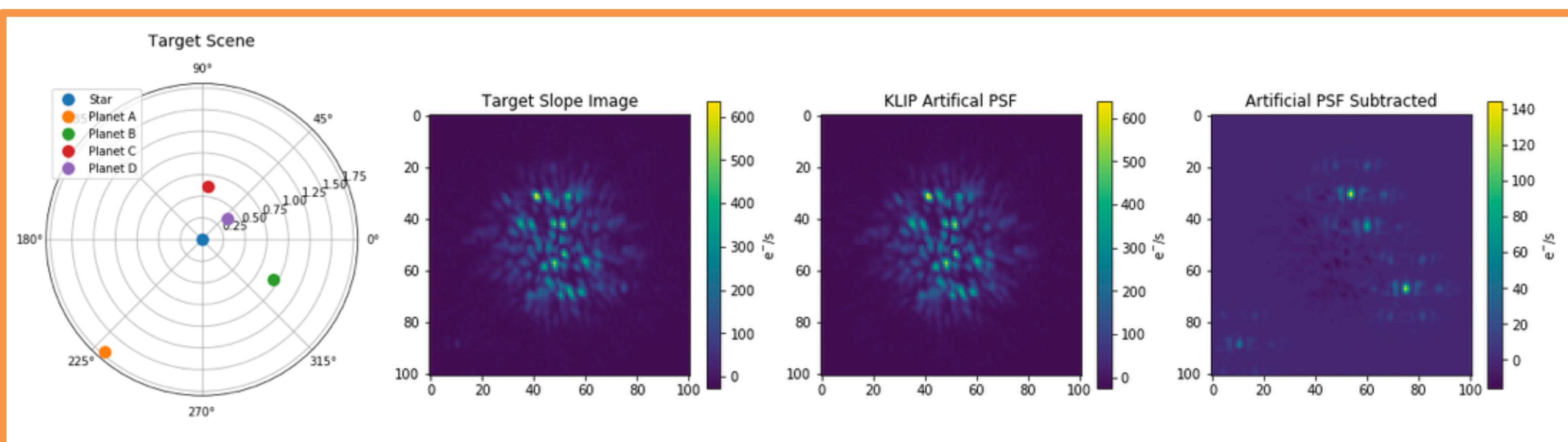


ETC extensions: PanCAKE (STScI) & pyNRC (NIRCam IDT)

github.com/spacetlescope/pandeia-coronagraphy

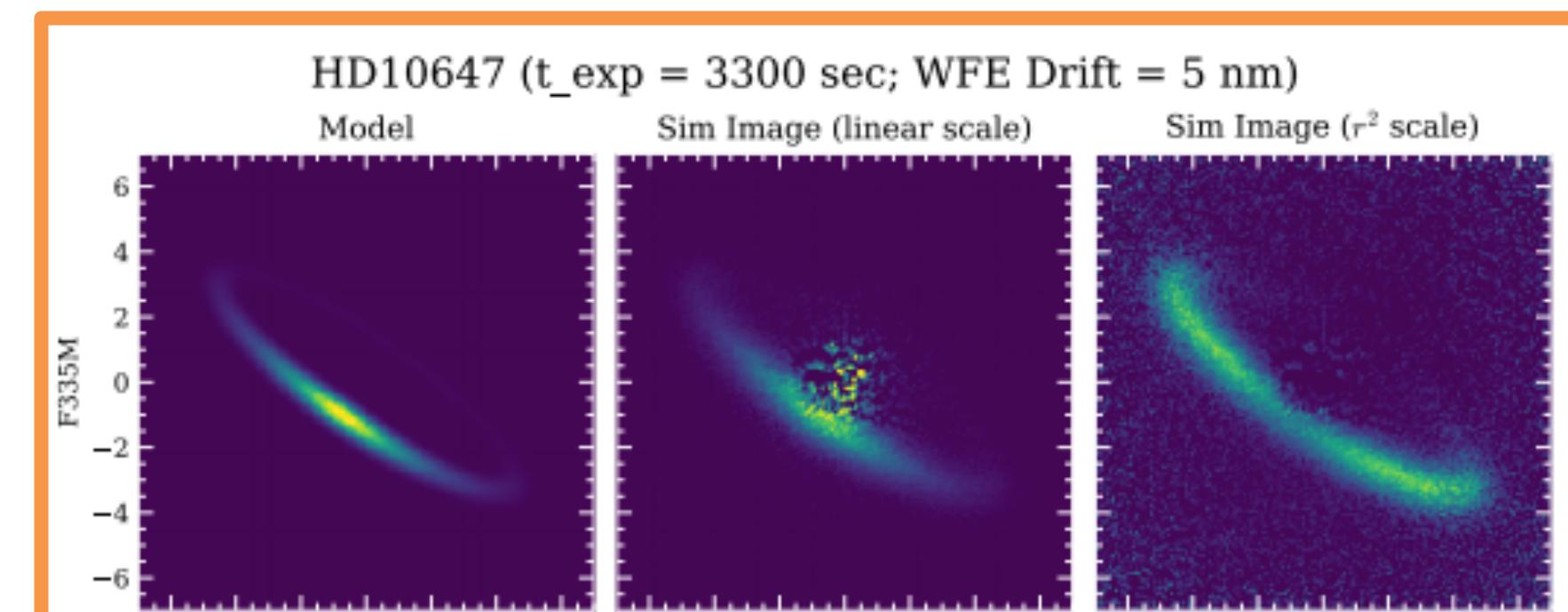


- Can call WebbPSF “on the fly”
 - custom PSF grids/dithers, FoV, spectral sampling
- Several coronagraphic specific functions
 - Contrast curves
- Currently improving the scene compatibility



Check also (disks)!

pyNRC

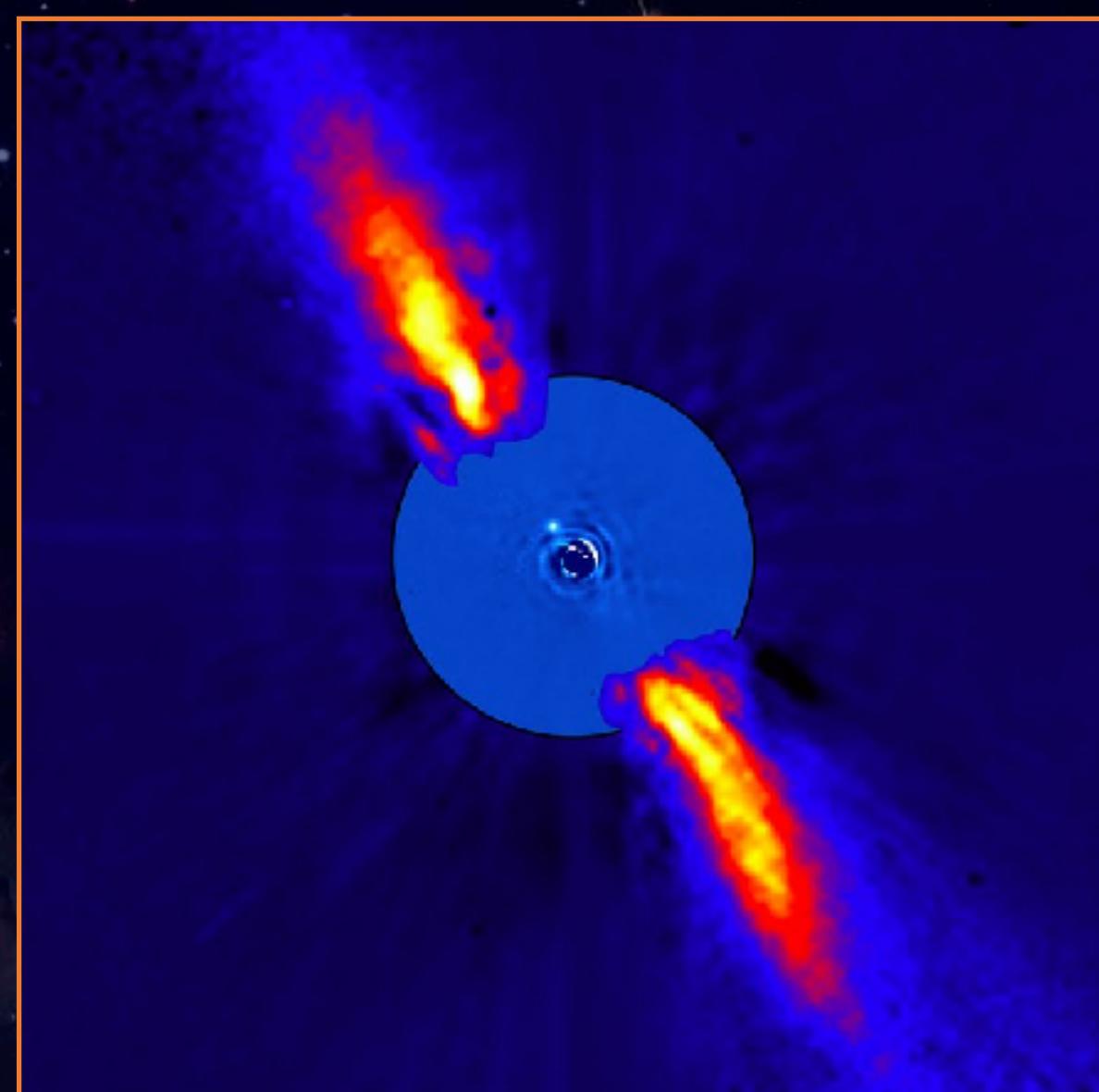
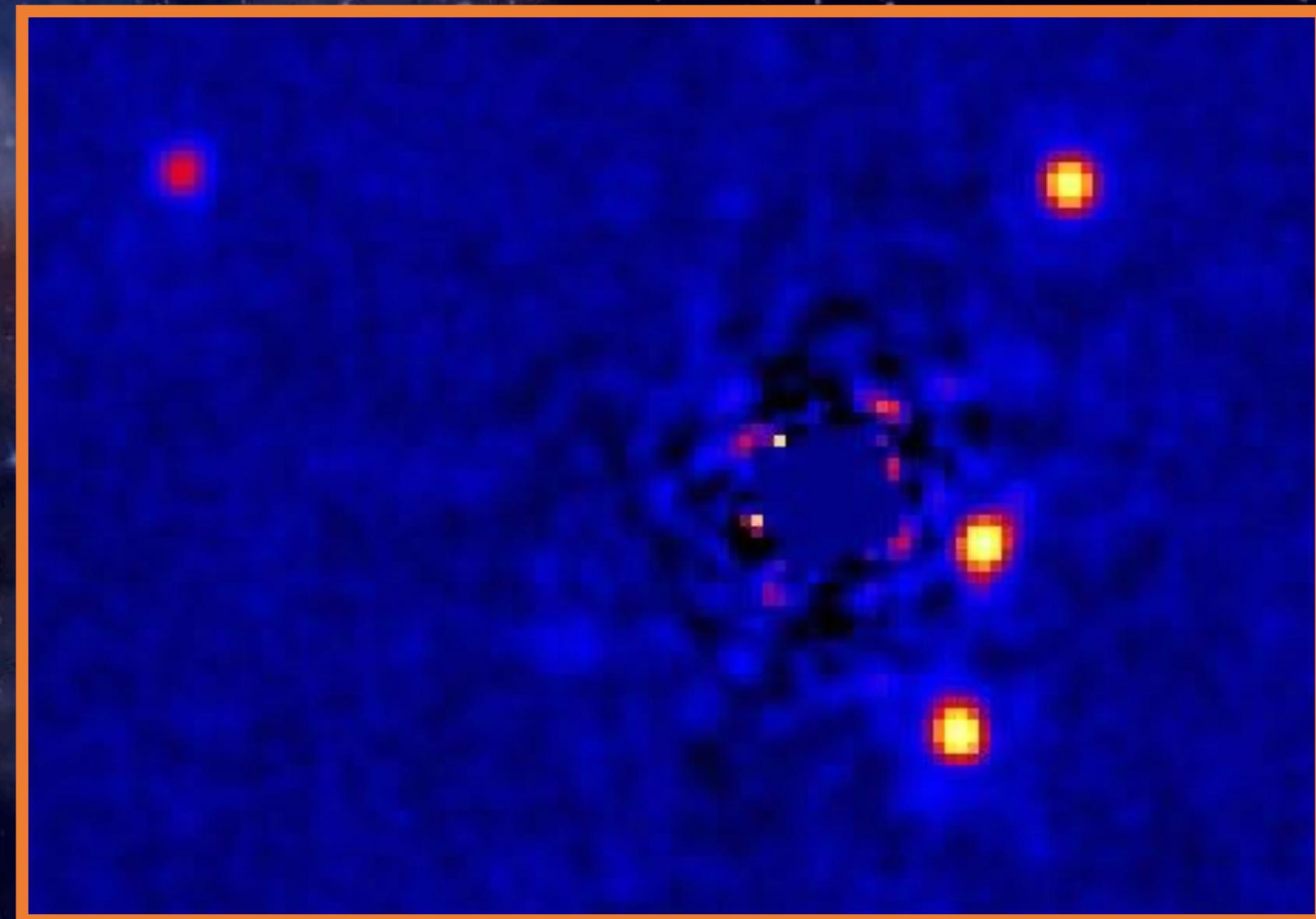
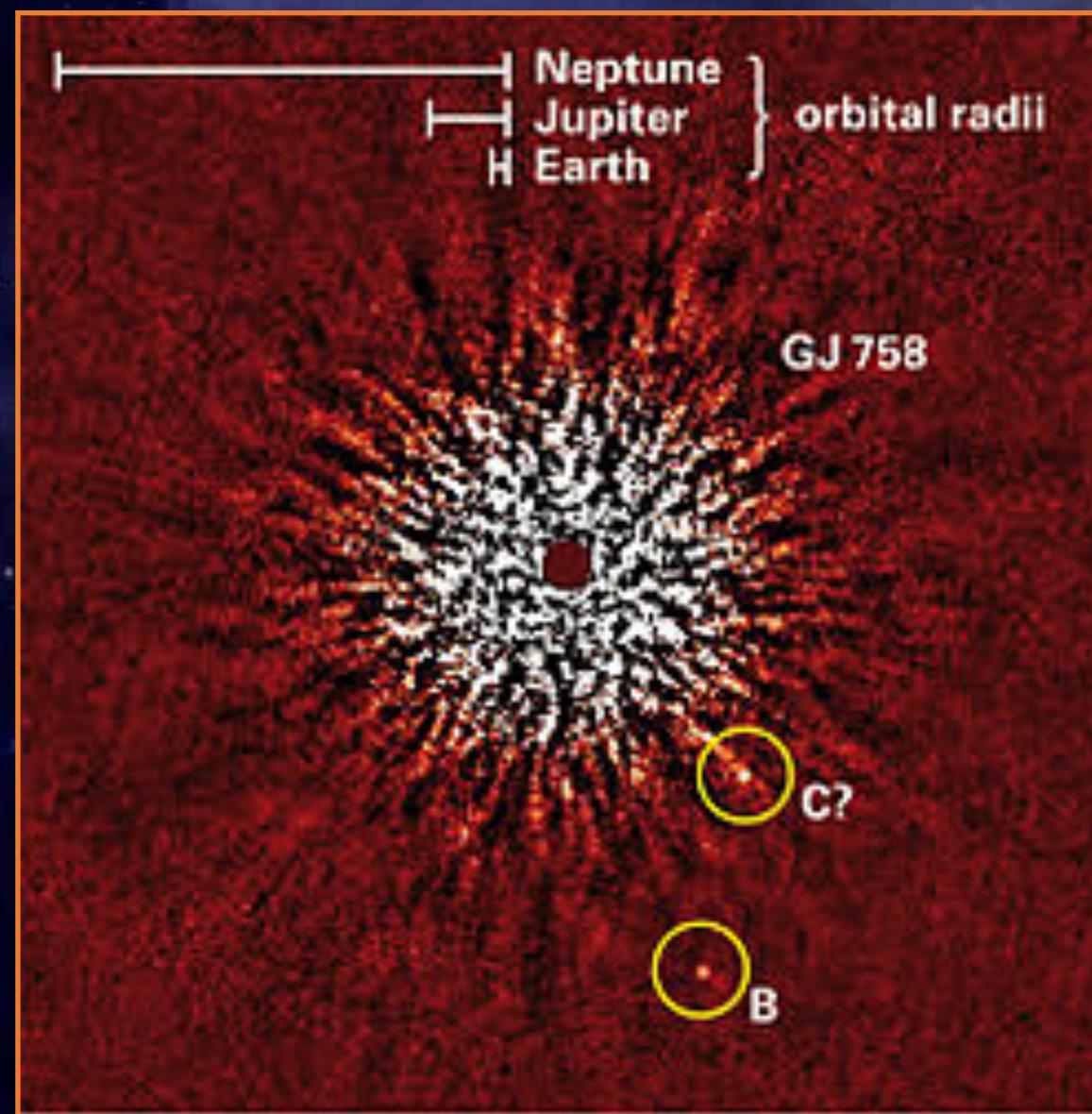


Van Gorkom, York, Perrin, Girard

Leisenring

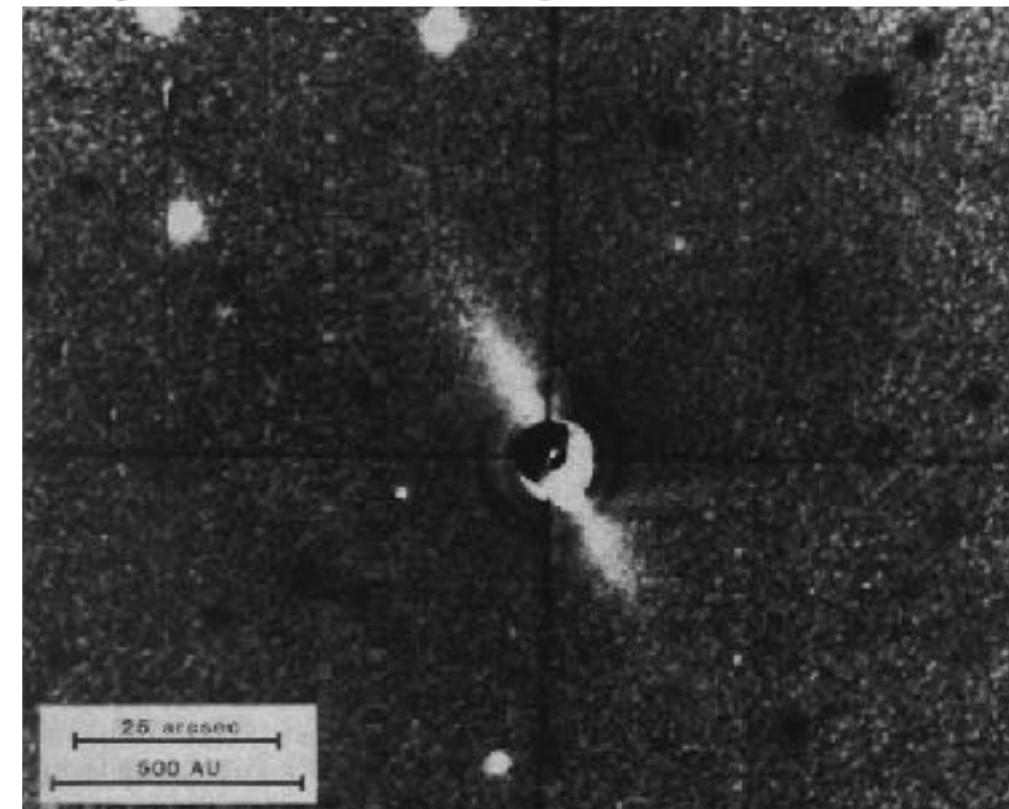
Coronagraphy

Example Science Programs

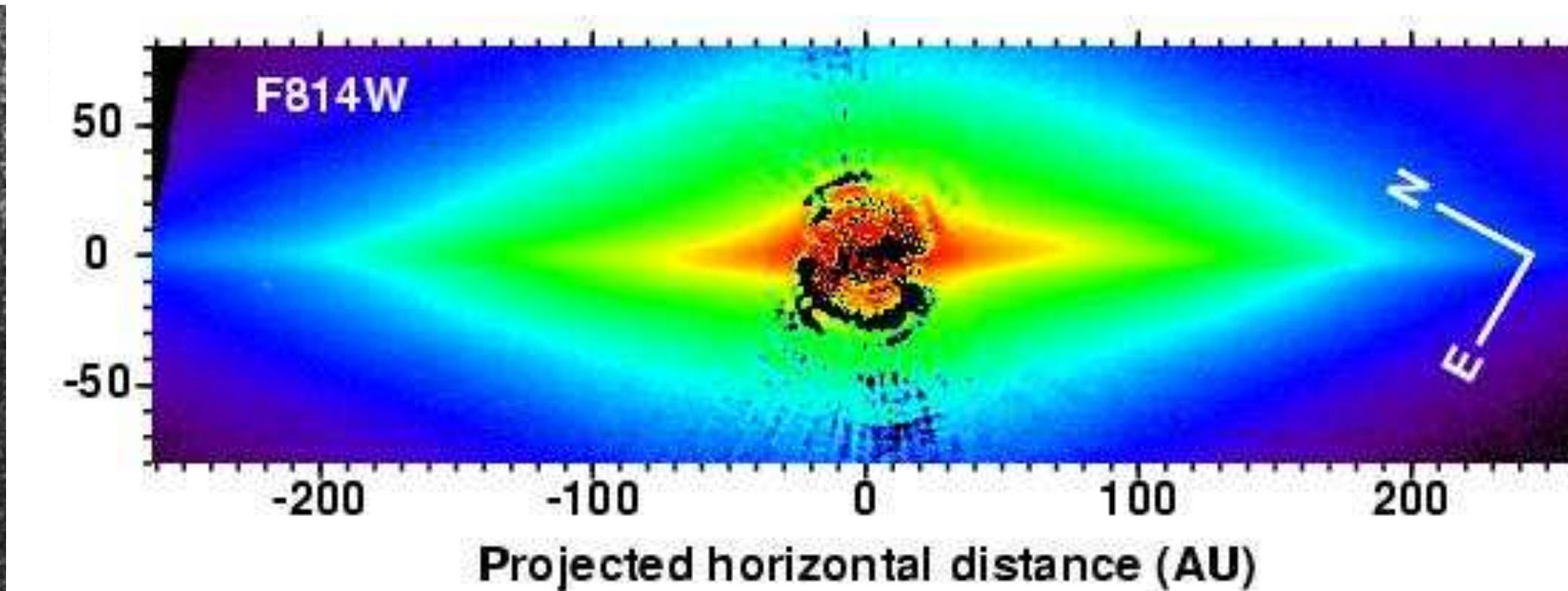




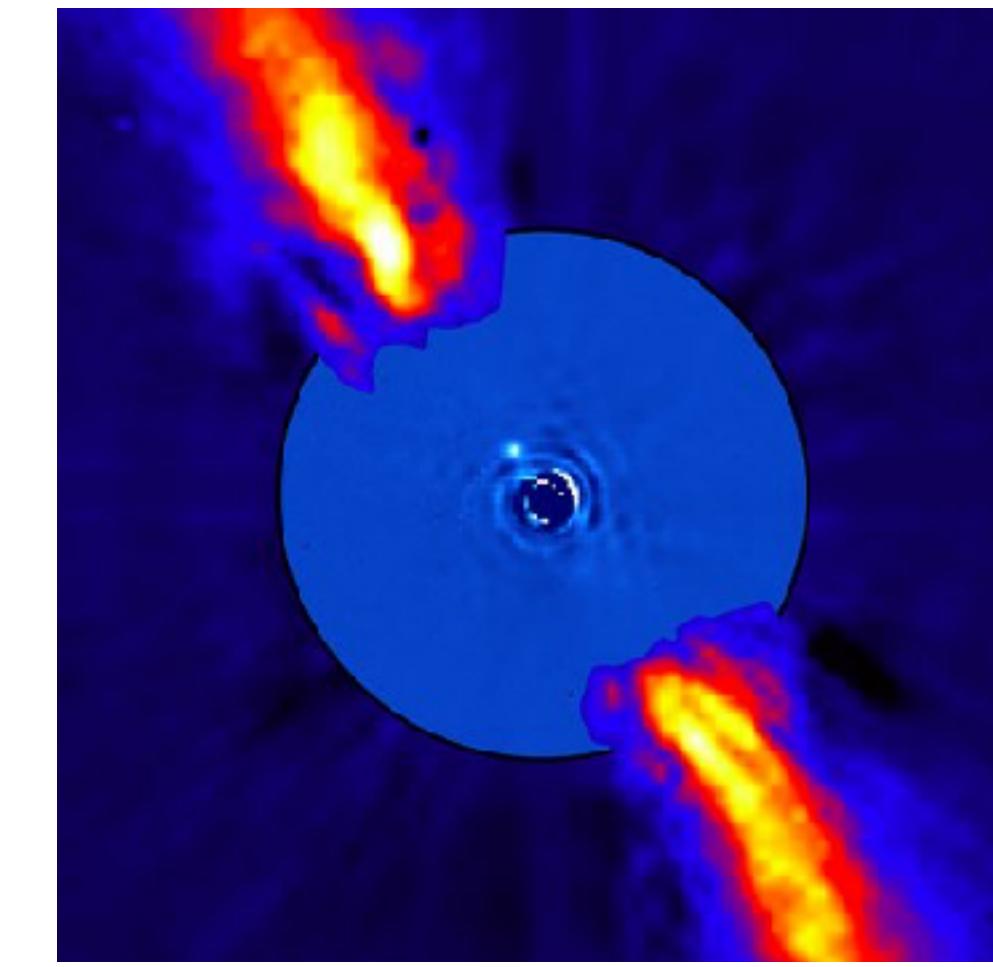
Example Science Program: deep imaging of the β Pic debris disk



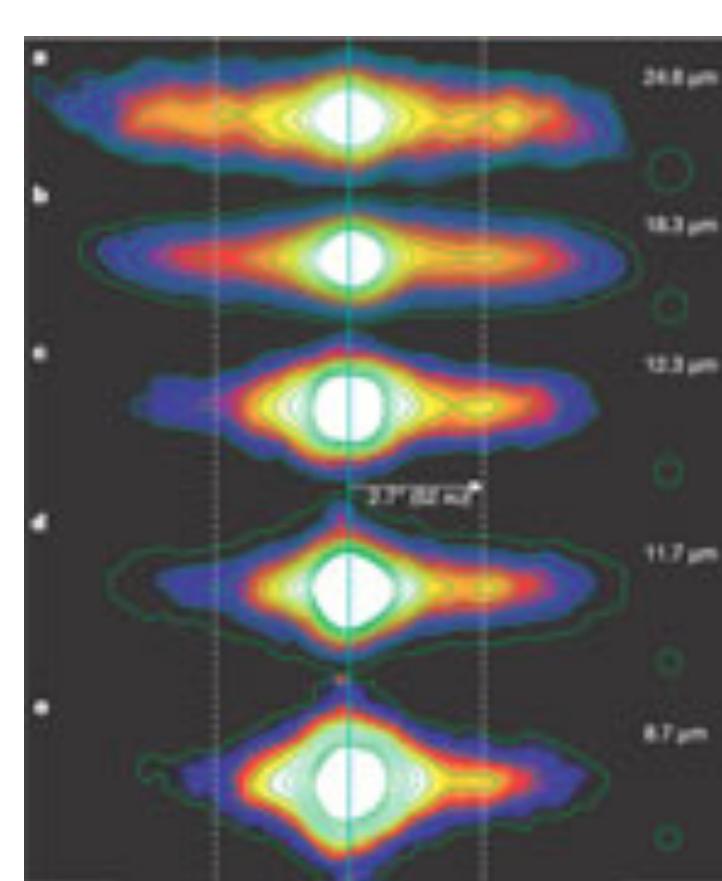
Smith & Terrile 1984



Golimowski et al. 2006



Lagrange et al. 2009, 2010



Telesco et al. 2005

Goals: Characterize the archetypal debris disk around Beta Pic with deep imaging in multiple filters across JWST's entire wavelength range.

Measure disk structure, composition, and interactions with planets. Test for presence of water and CO₂ ices, and of organic tholins (like on Titan). Measure color variations and asymmetries across the disk. Probe thermal emission from both the warm inner belt and outer cooler main disk. Obtain a comprehensive legacy dataset on this target, for analysis alongside similar data on several other debris disks from the NIRCam and MIRI GTO programs. (note, observing the known planet Beta Pic b is not a goal of this program given its projected separation in 2019.)



Example Science Program: Beta Pictoris debris disk

Which coronagraphs and filters?

- NIRCam, 6 medium band filters for disk composition: 1.82, 2.10 in SW; 2.5, 3.0, 3.3, 4.1 in LW.
Use round coronagraphs for full azimuthal coverage (MASK210R and MASK335R).
- MIRI, F1550C (for warm inner disk) and F2300C (for cooler outer disk).

Observing strategy and PSF subtraction?

- Standard sequence, ADI+RDI.
- One of the brightest disks in the sky; a relatively easy target. Does not need small grid dithers.

Exposure times?

- Obtain consistent dataset with NIRCam & MIRI GTO observations of several other disks;
therefore adopted fixed deep exposures per filter list rather than optimizing to source specifics.
- 20 minutes per filter per roll for NIRCam; 30 minutes for MIRI.
- Note, for NIRCam can take multiple filters on same coronagraph after one target acq;
MIRI needs to switch coronagraph and do target acq for every filter change.



Choosing a PSF star for Beta Pic

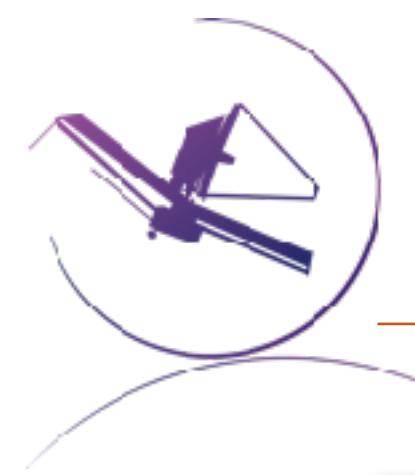
- This time we can take a shortcut for picking a PSF calibrator star:

Science target: Beta Pic. **Spectral Type A6, K mag = 3.48.** **05 47 -51 03**

PSF reference: Alpha Pic. **Spectral Type A8, K mag = 2.57.** **06 48 -61 56**

Why did we pick Alpha Pic?

- Successfully used as PSF reference in many HST observations.
- Close match in spectral type, nearby, 1 mag brighter, known single star.



Beta Pic observing program overall

Slew to target (1800 s)

Observe Science Target NIRCam SW (4800 s)

Observe Science Target NIRCam LW (7700 s)

Roll Observatory ~10°

Observe Science Target NIRCam SW (4800 s)

Observe Science Target NIRCam LW (7700 s)

Slew to PSF star

Observe PSF star NIRCam SW (4800 s)

Observe Science Target NIRCam LW (7700 s)

Slew back to Target

Observe Science Target F1550C (3600 s)

Observe Science Target F2300C (3600 s)

Roll Observatory ~10°

Observe Science Target F1550C (3600 s)

Observe Science Target F2300C (3600 s)

Slew to PSF star

Observe PSF star F1550C (3600 s)

Observe PSF star F2300C (3600 s)

Program total time is dominated by overheads. (8.7 hr science time, 18.5 hr total charged).

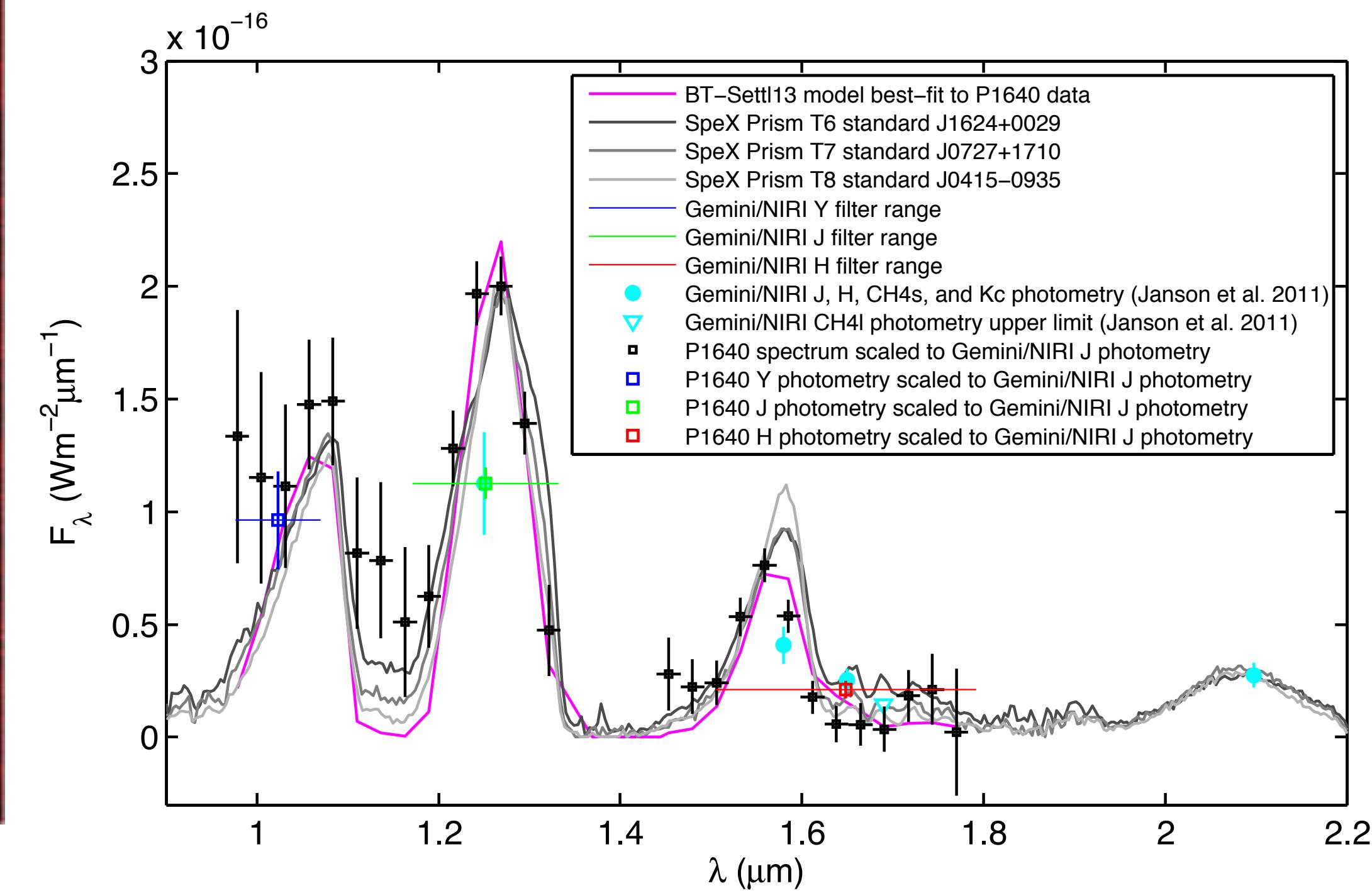
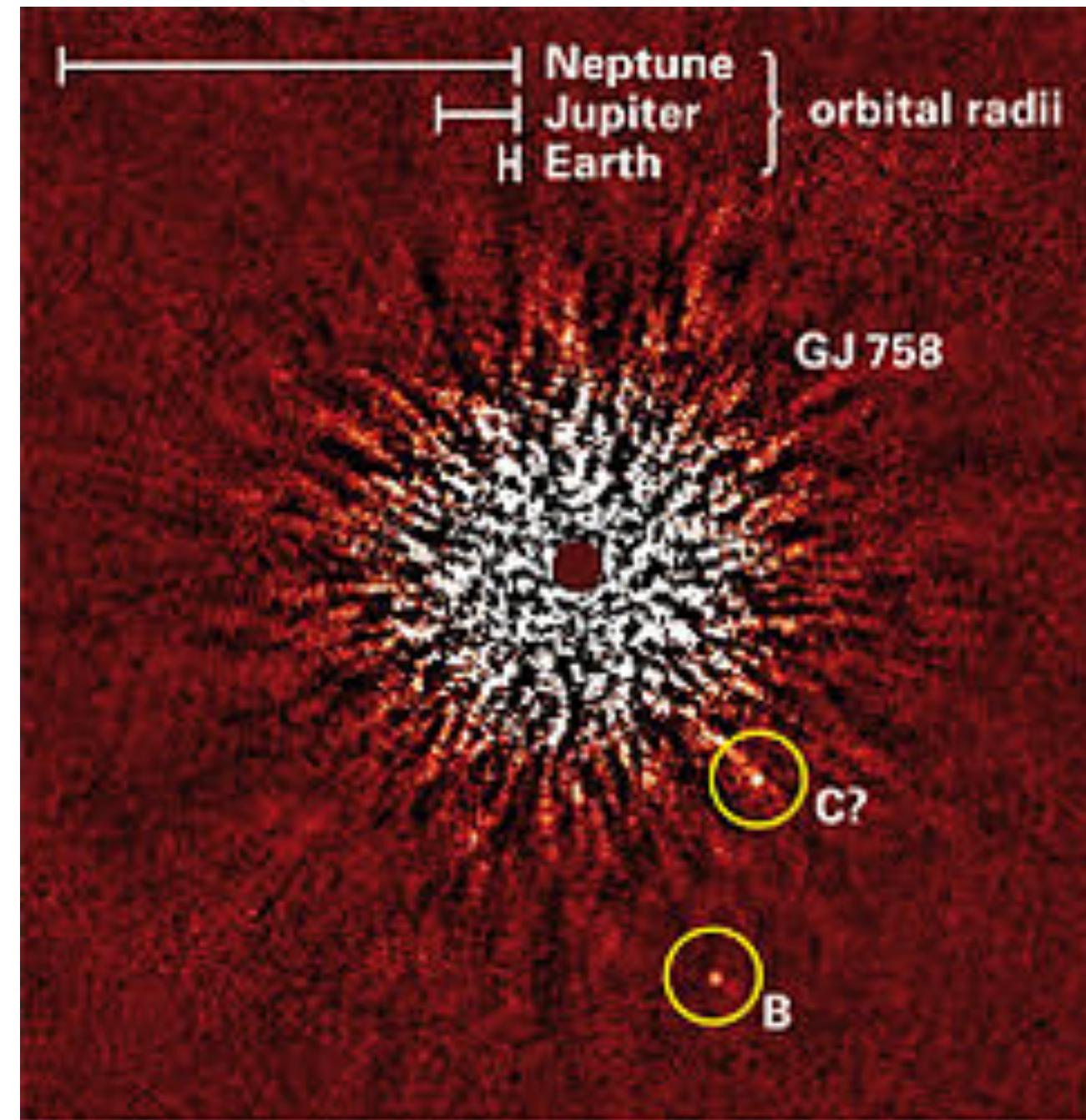
Could save a little time if we minimized slews (reorder to group all PSF star obs at end), but that would increase time delay between some science visits + their PSF reference by over 5 hrs; we opted against this trade.

Notes, need to set orientation constraints to avoid the disk major axis landing along any FQPM quadrant boundaries.

Preferred is ~ 45° relative to the MIRI FQPM axes (loose tolerance).



Example Science Program: Characterizing the Brown Dwarf GJ758



~700 K, methane-rich brown dwarf.
Nearly edge-on orbit.
Radial velocity trends will yield dynamical mass.
Host star is G9, 19 pc distant.

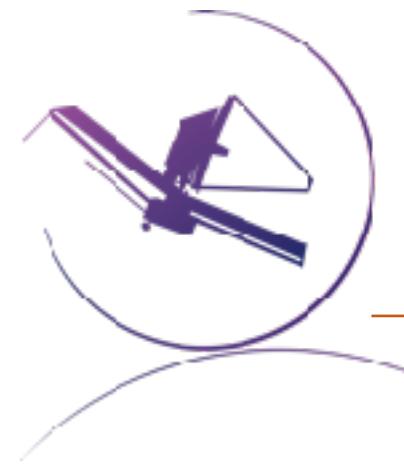
See:
Thalmann et al. 2009
Currie et al. 2010
Jansson et al. 2011
Nilsson et al. 2017

Program goals:

Characterize the atmosphere of this cool benchmark brown dwarf at long wavelengths.

Measure effective temperature and atmospheric ammonia absorption.

Compare to atmospheres of field brown dwarfs. Combine with existing shorter wavelength data to retrieve atmospheric properties in detail.



Example Science Program: Characterizing the Brown Dwarf GJ

Which coronagraphs?

- MIRI, all 3 FQPMs. To get continuum fluxes, temperature, and ammonia absorption.

Observing strategy and PSF subtraction?

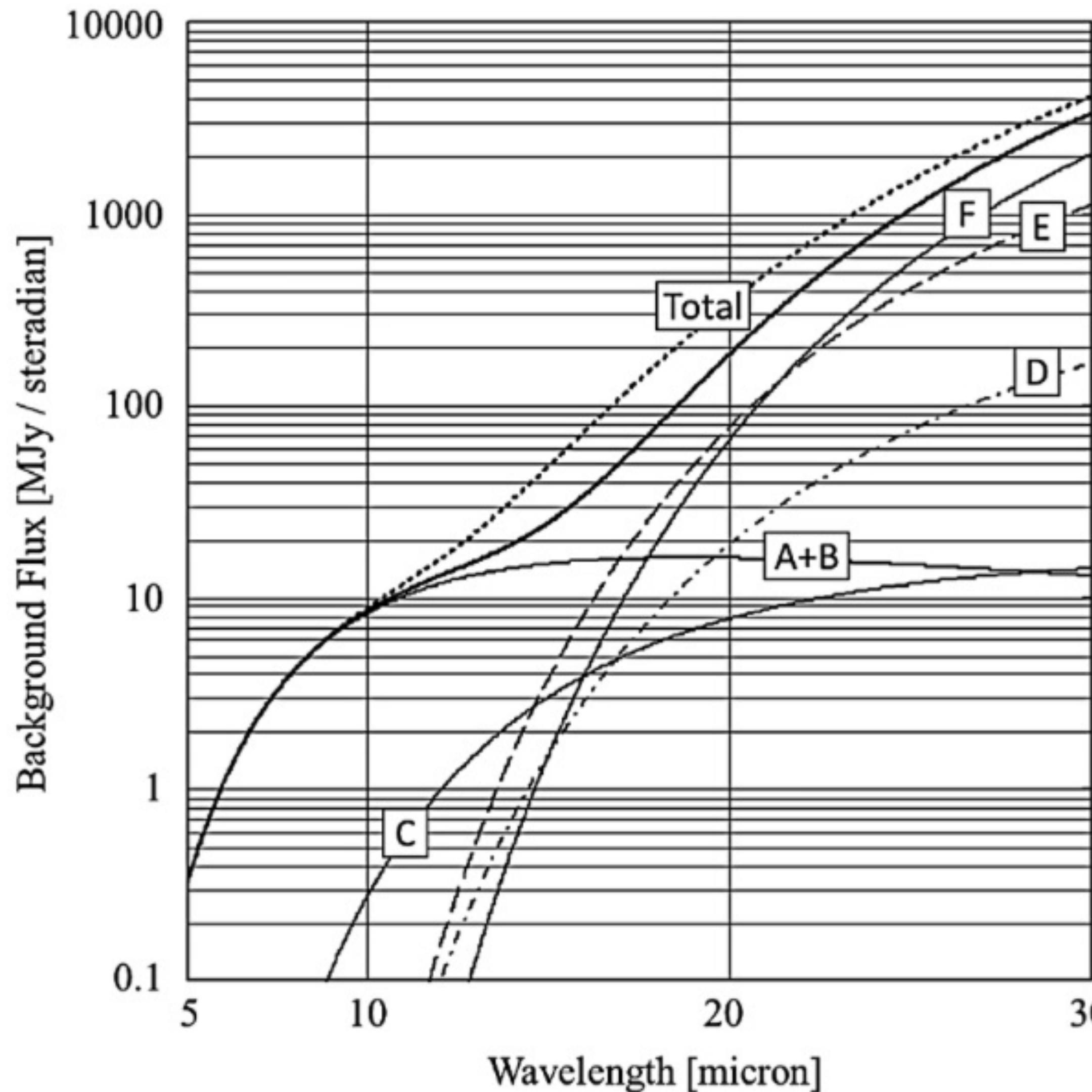
- Standard sequence, 2 rolls science + PSF star, repeat for each FQPM filter.
- Extrapolating from NIR data, companion contrast is moderate $\sim 10^{-4}$ at 10 μm . But edge-on orbit will move it inward to projected separation of 1" by 2019.
- Therefore use small grid dither on PSF star to optimize contrast close to the star.

Exposure times?

- Upload to ETC a model spectrum fit to NIR data; normalize to available K band photometry.
- Setup ETC scene with target star, companion, reference star. Calculate exposure times. See splinter session for details!
- Calculated that just a few hundred s yields very high SNR at 10.6 & 11.4 μm . 15 μm is much harder due to increased thermal background, needs longer integration.



Thermal background matters at the longest wavelengths



Thermal background rises significantly beyond $15\ \mu\text{m}$ from primary mirror & sunshield thermal emission.

Limiting factor for MIRI F1550C and F2300C coronagraphy; less significant for all other filters.

This is included in the background model used by the JWST ETC.



Choosing a PSF REFERENCE star for GJ 758

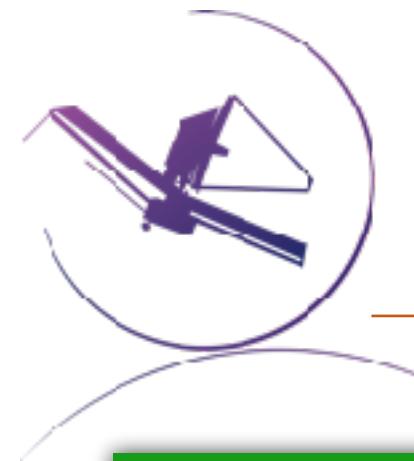
- Science target is quite bright; needs similarly bright PSF reference for comparable exposure times.
- Relatively few 4th mag stars, hence small set to choose from. Here's what we picked:

Science target: GJ 758. Spectral Type G9, K mag = 4.49. 19 23 + 33 13

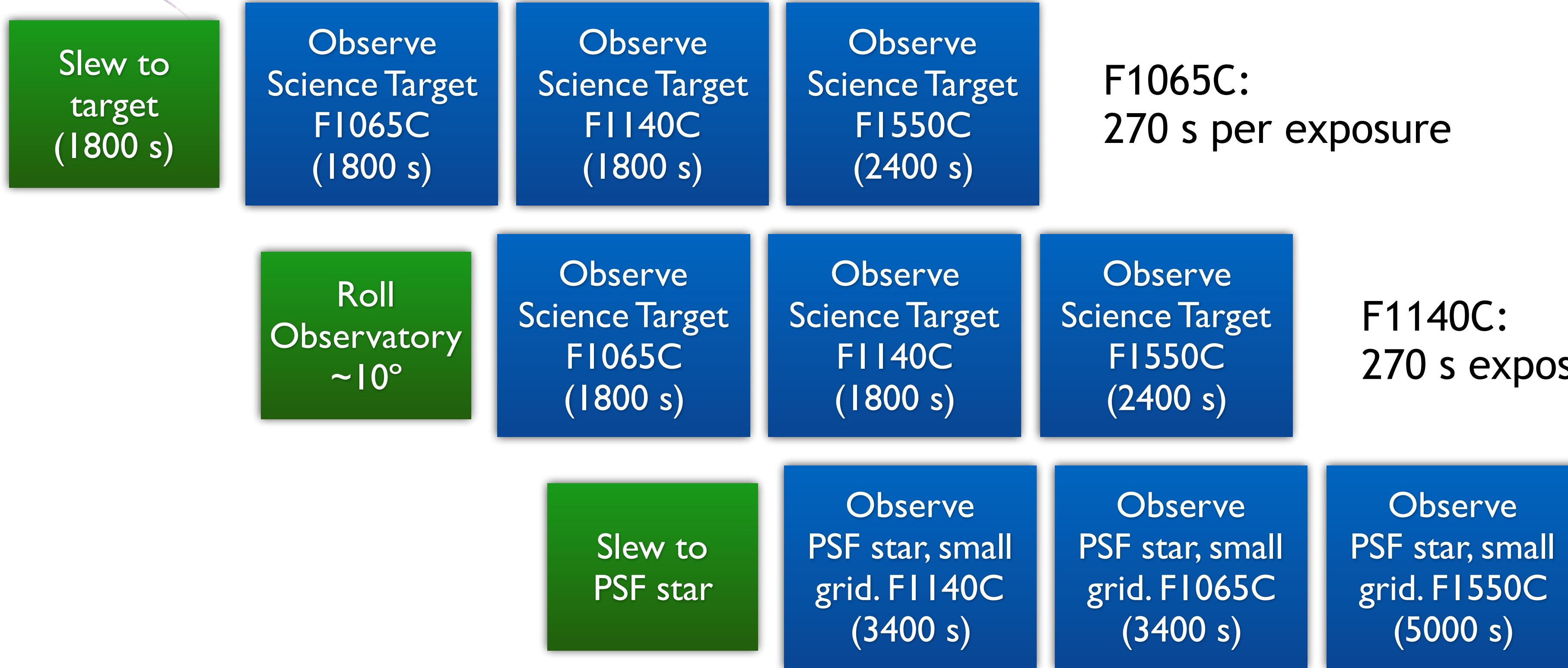
PSF reference: HD 190360. Spectral Type G7, K mag = 4.08. 20 03 + 29 53

Why did we pick HD 190360?

- Relatively near by (~9 deg separation.)
- Close match in spectral type (not as critical at MIRI wavelengths but still good to have)
- 0.4 mag brighter (allows shorter exposure time on PSF star, which helps reduce cost of taking PSF observation 9x in small grid dither pattern.)
- We're 100% certain it's not a binary. (known RV planet host star with extensive observations that rule out binarity).



GJ 758 b observing program overall



Program total time is dominated by overheads: slews, target acqs, etc. (2 hr science time, 7.25 hr total charged).

Reordering visits can (slightly) trade efficiency against closeness in time of PSF calibrators; how this is handled by APT's "Smart Accounting" is still in flux.

Notes, need to set orientation constraints to avoid the companion landing along any FQPM quadrant boundaries.



The HR 8799 Science Use Case

Face on system (faint debris disk)

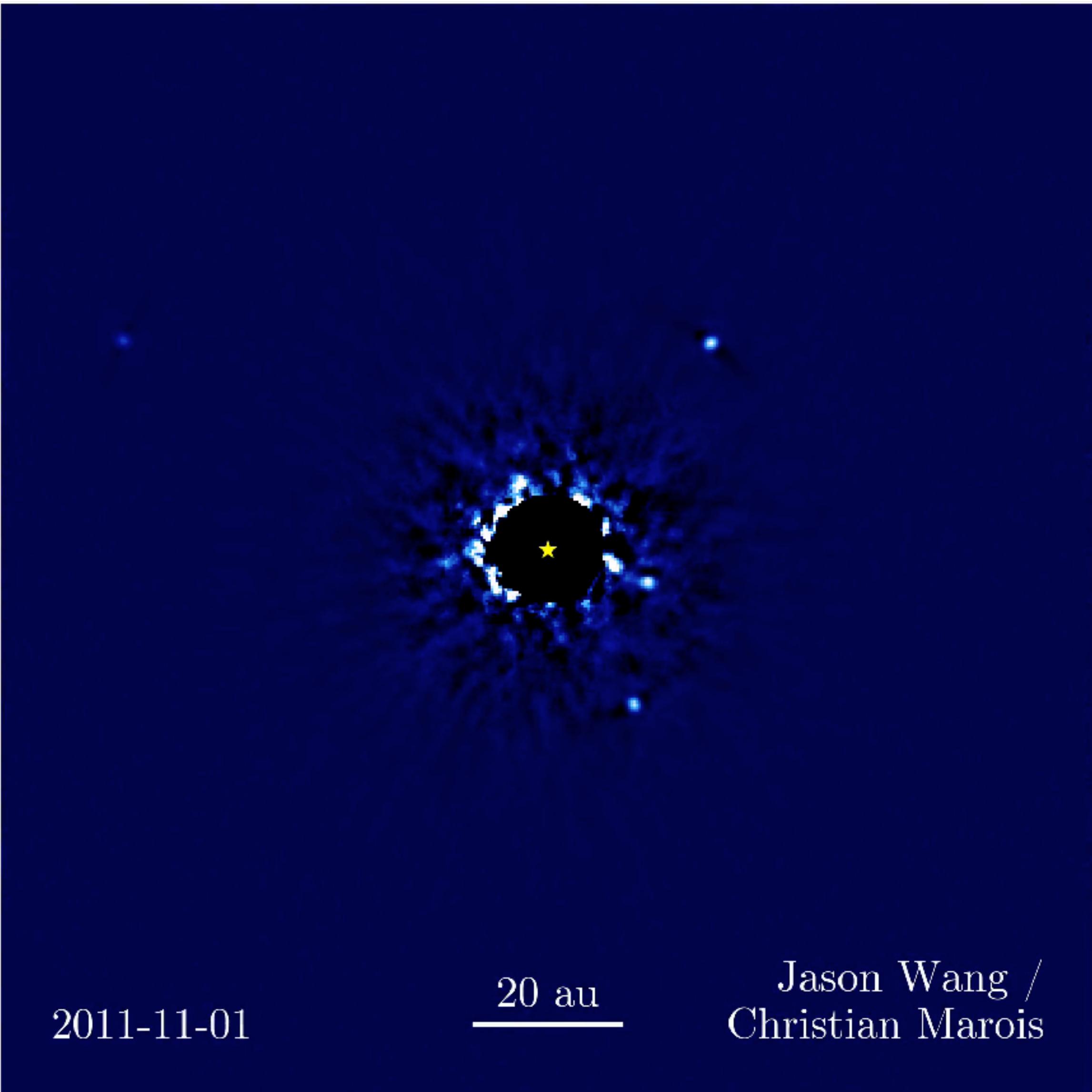
4 planets with mass $< 8 M_{Jup}$

b at 1.7" is the faintest

b c d e are all doable with NIRCam
Coronagraphy

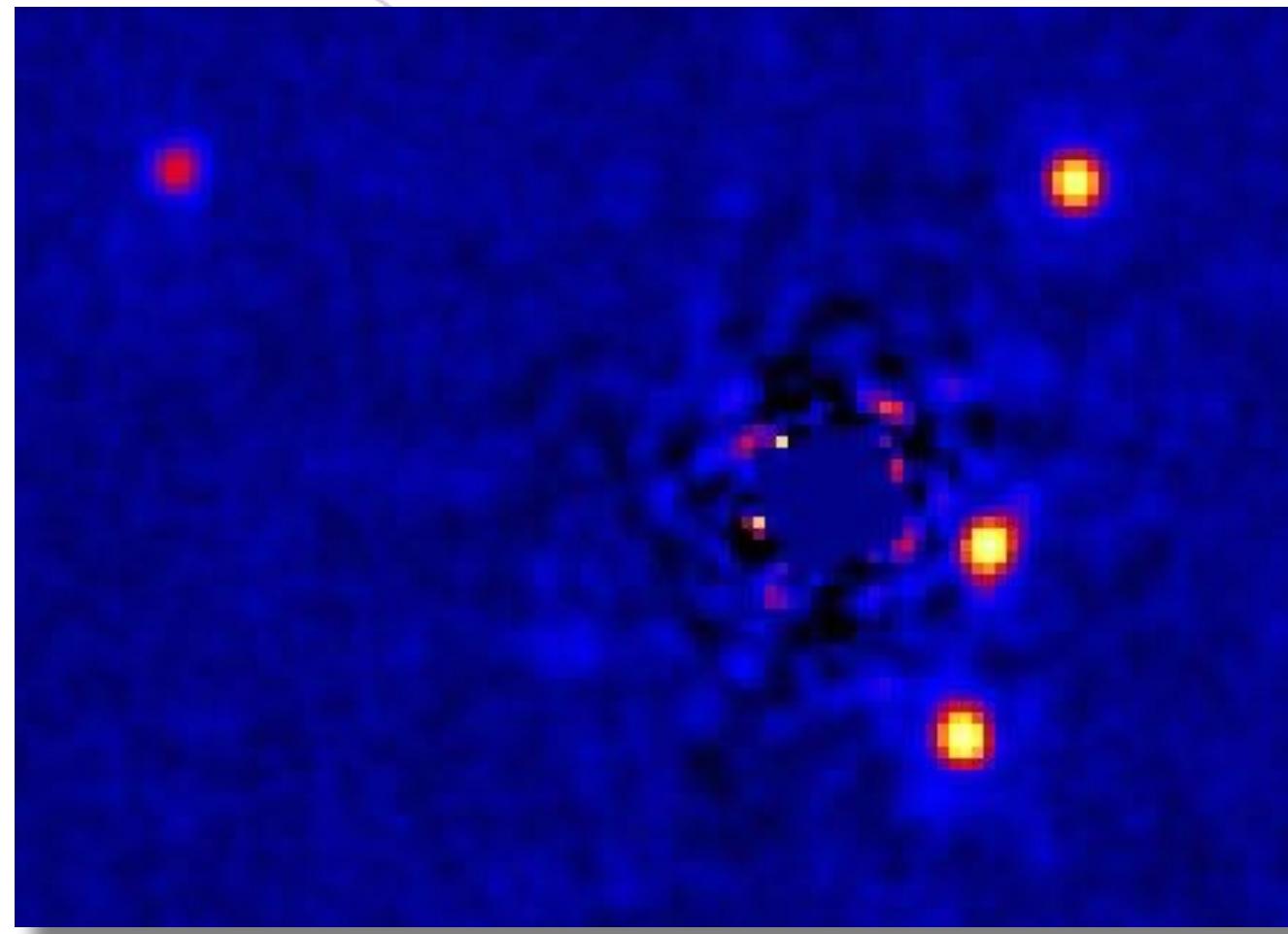
b & c can be done with MIRI 4QFM
coronagraph

e can be attempted with NIRISS/AMI



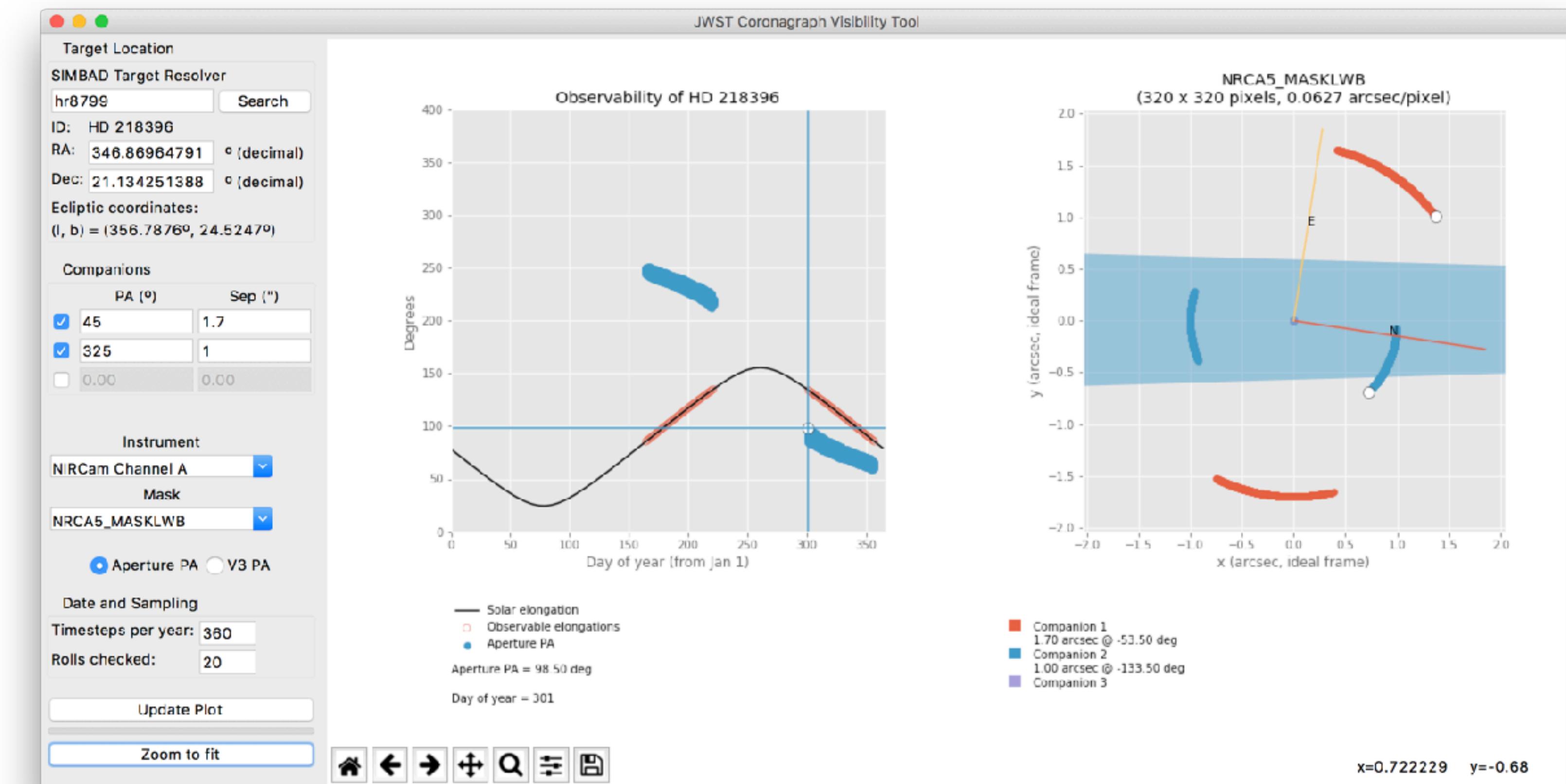


Example Science Program: the HR8799 4-planet system



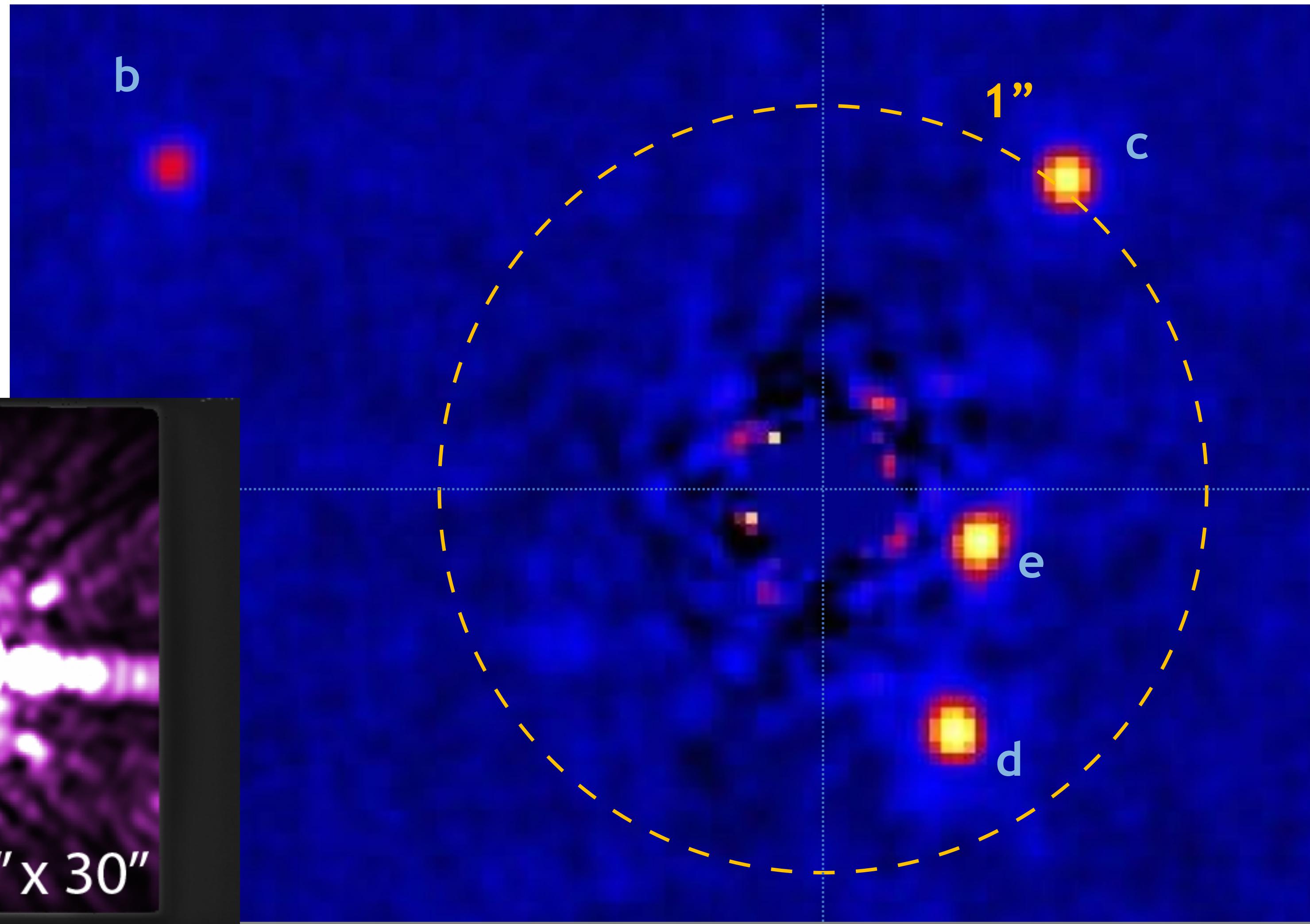
discovered by Marois, here Currie et al. 2014

Setting special requirements
for position angles





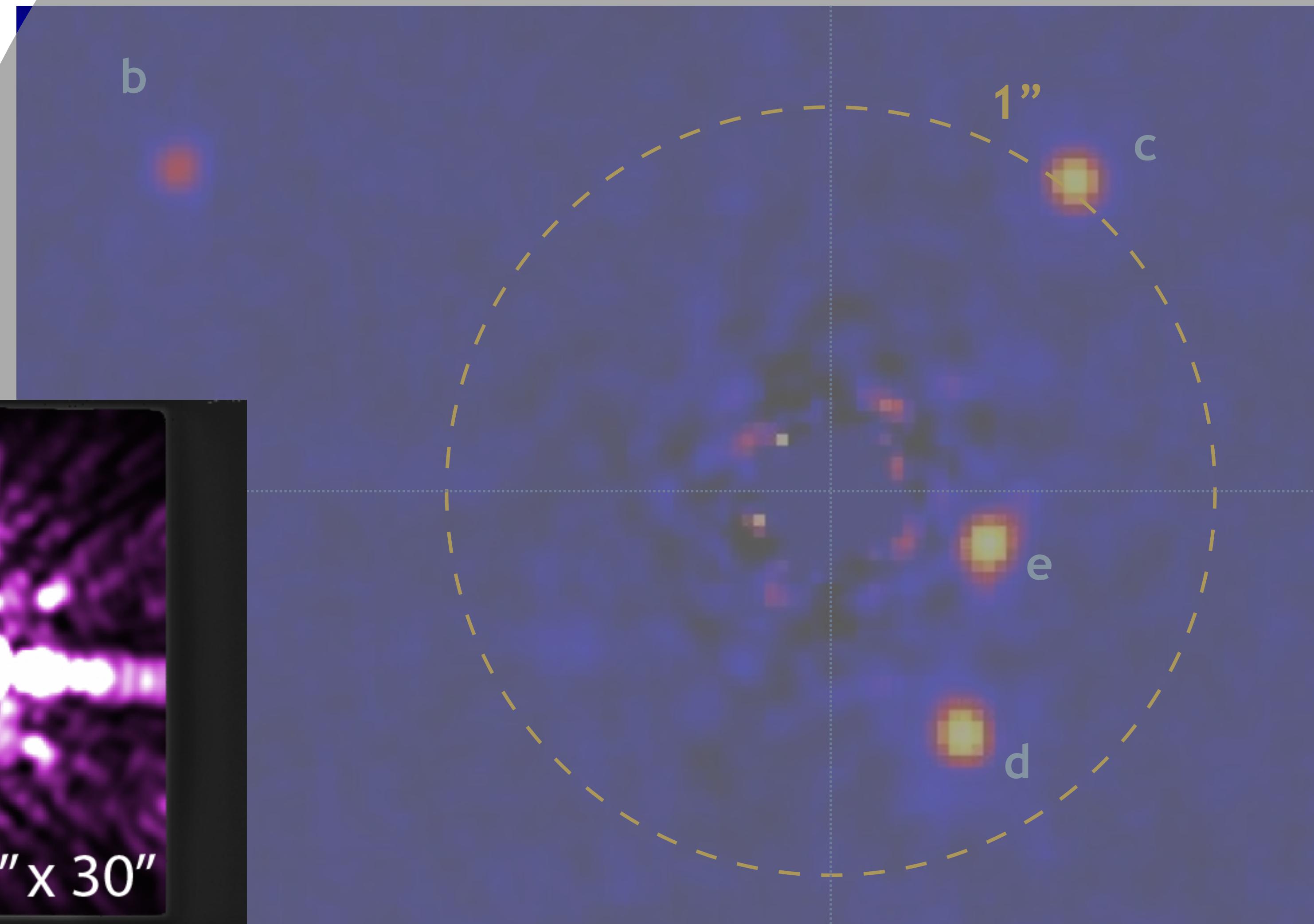
Example Science Program 1: the HR8799 4-planet system





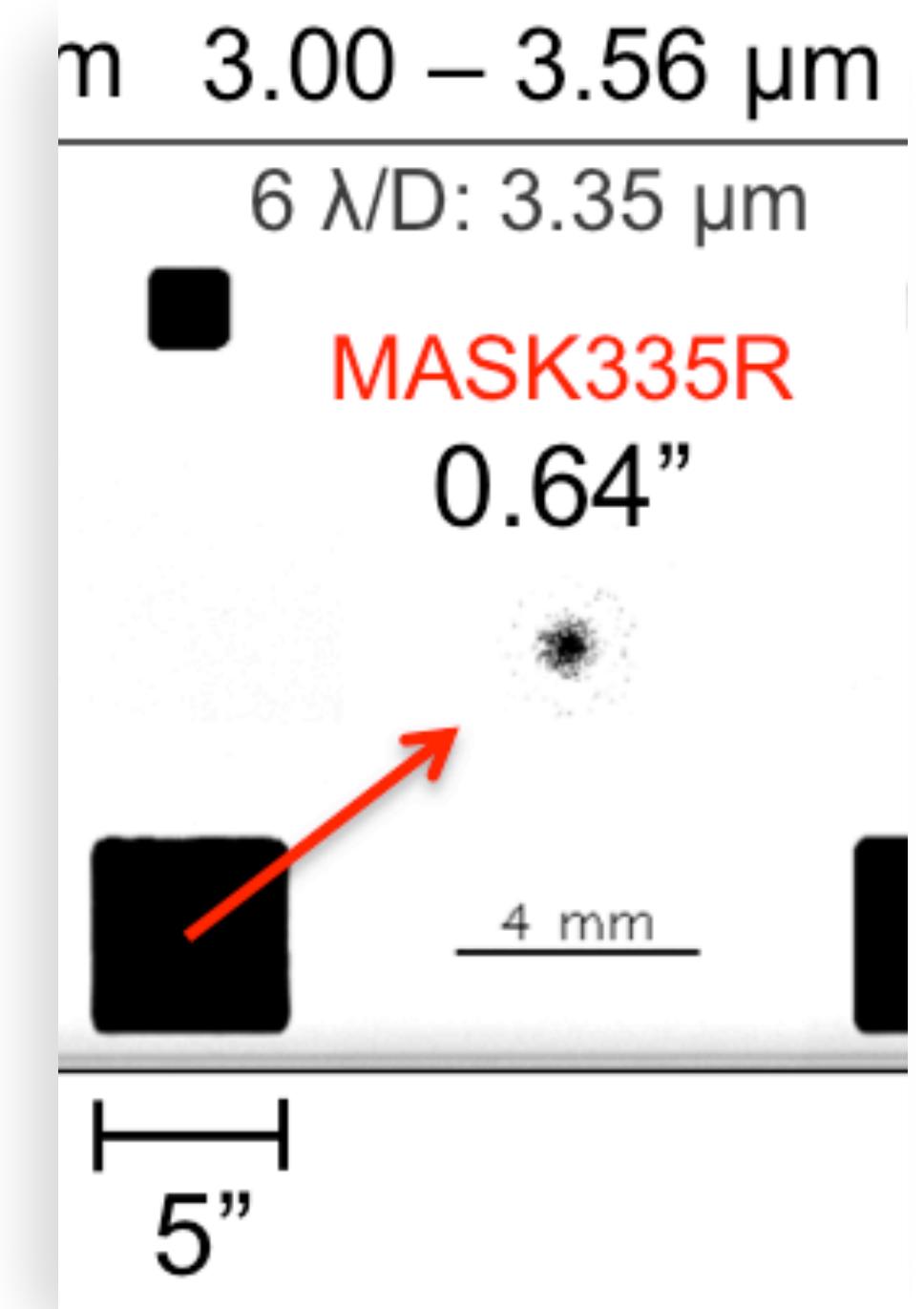
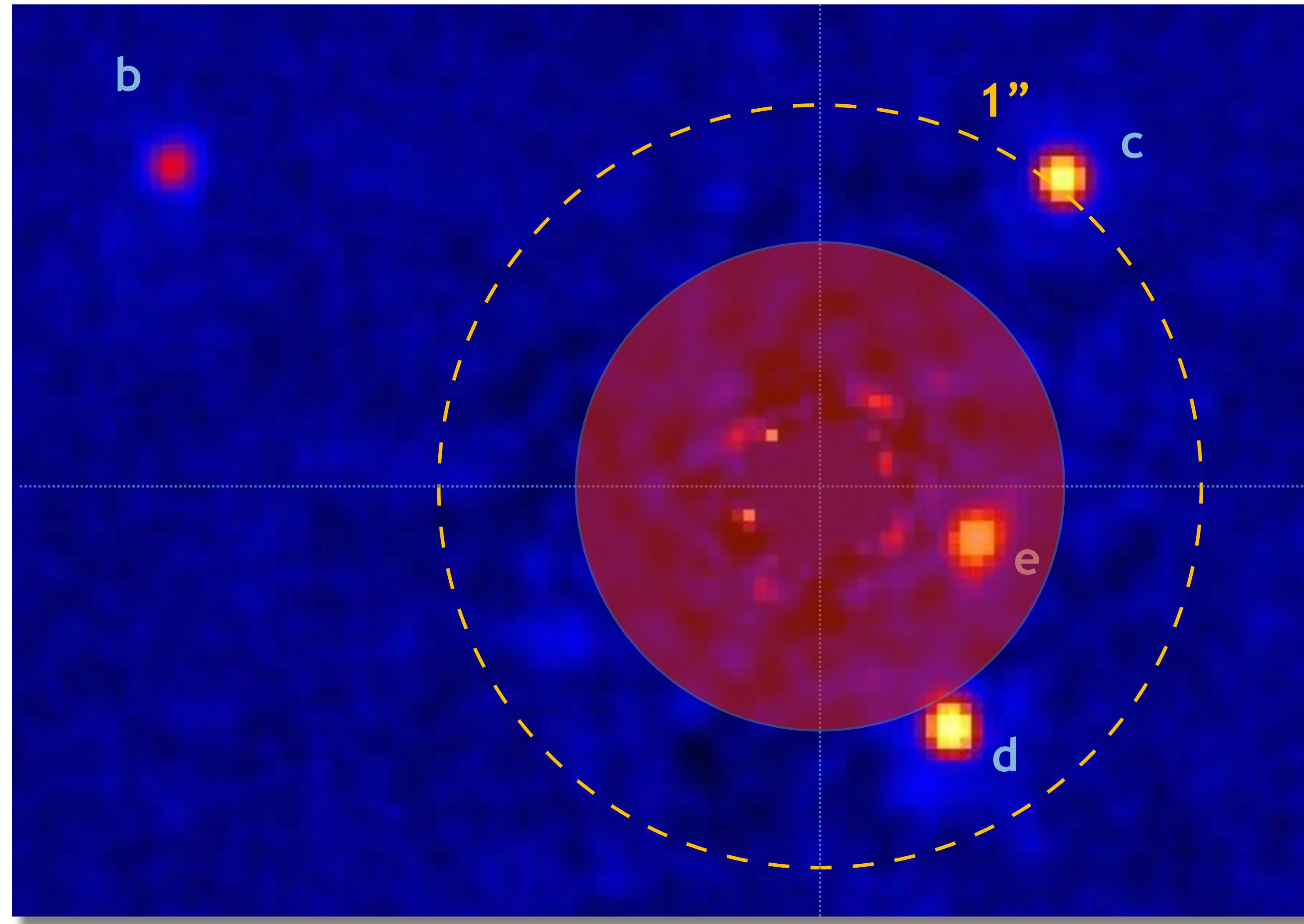
Example Science Program 1: the HR8799 4-planet system

**size
2.16''!!!**





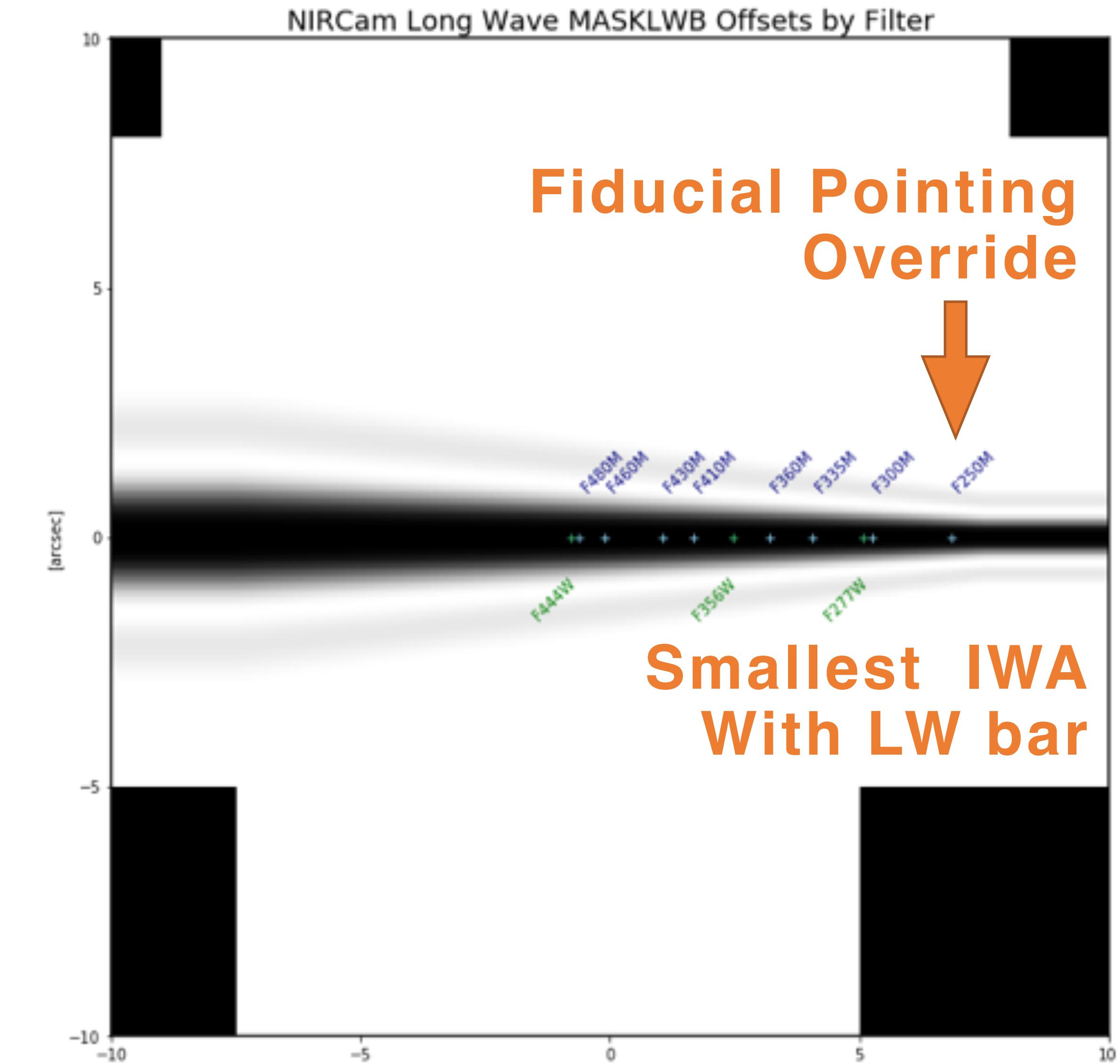
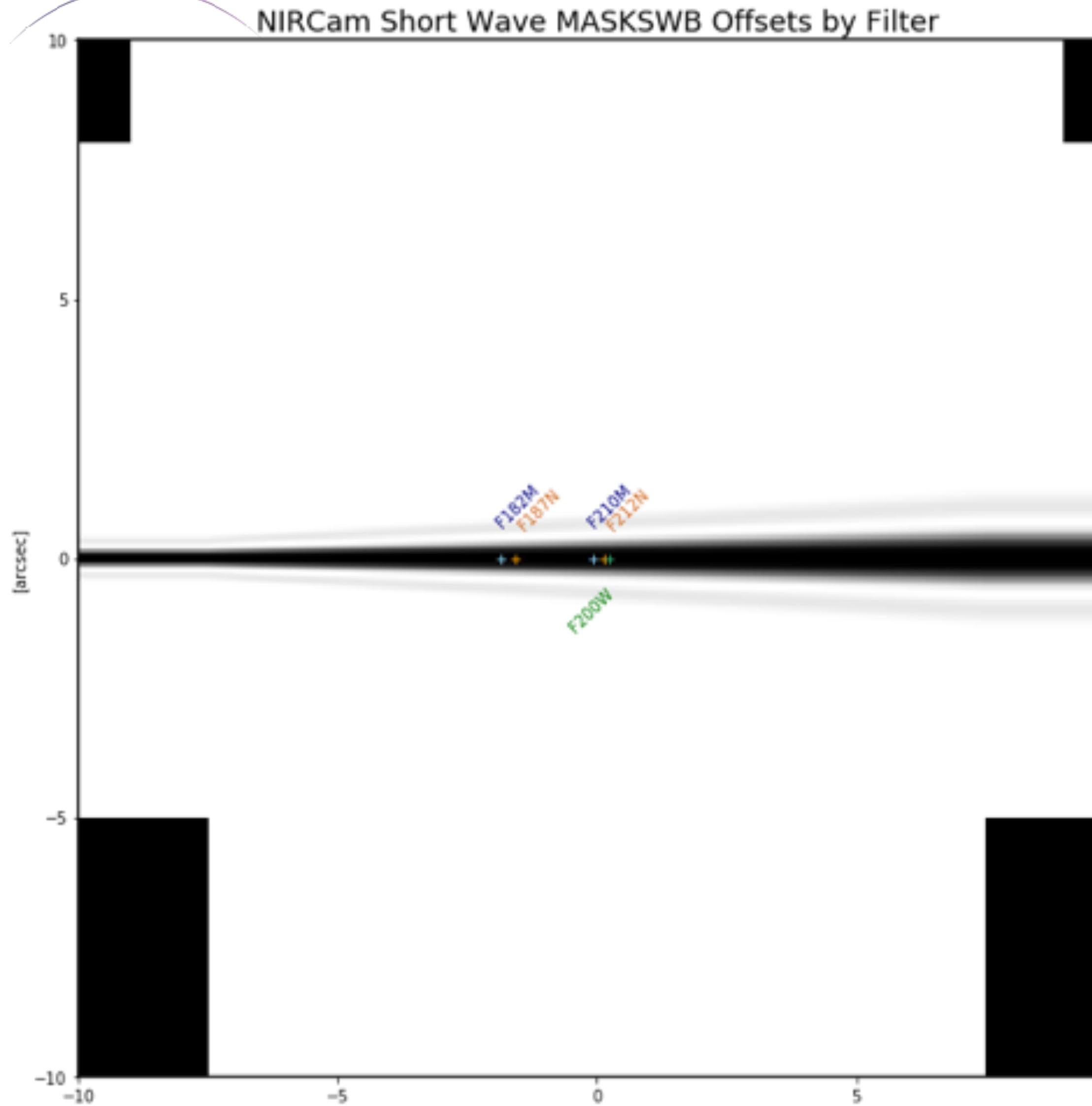
Example Science Program 1: the HR8799 4-planet system



IWA~0.64''

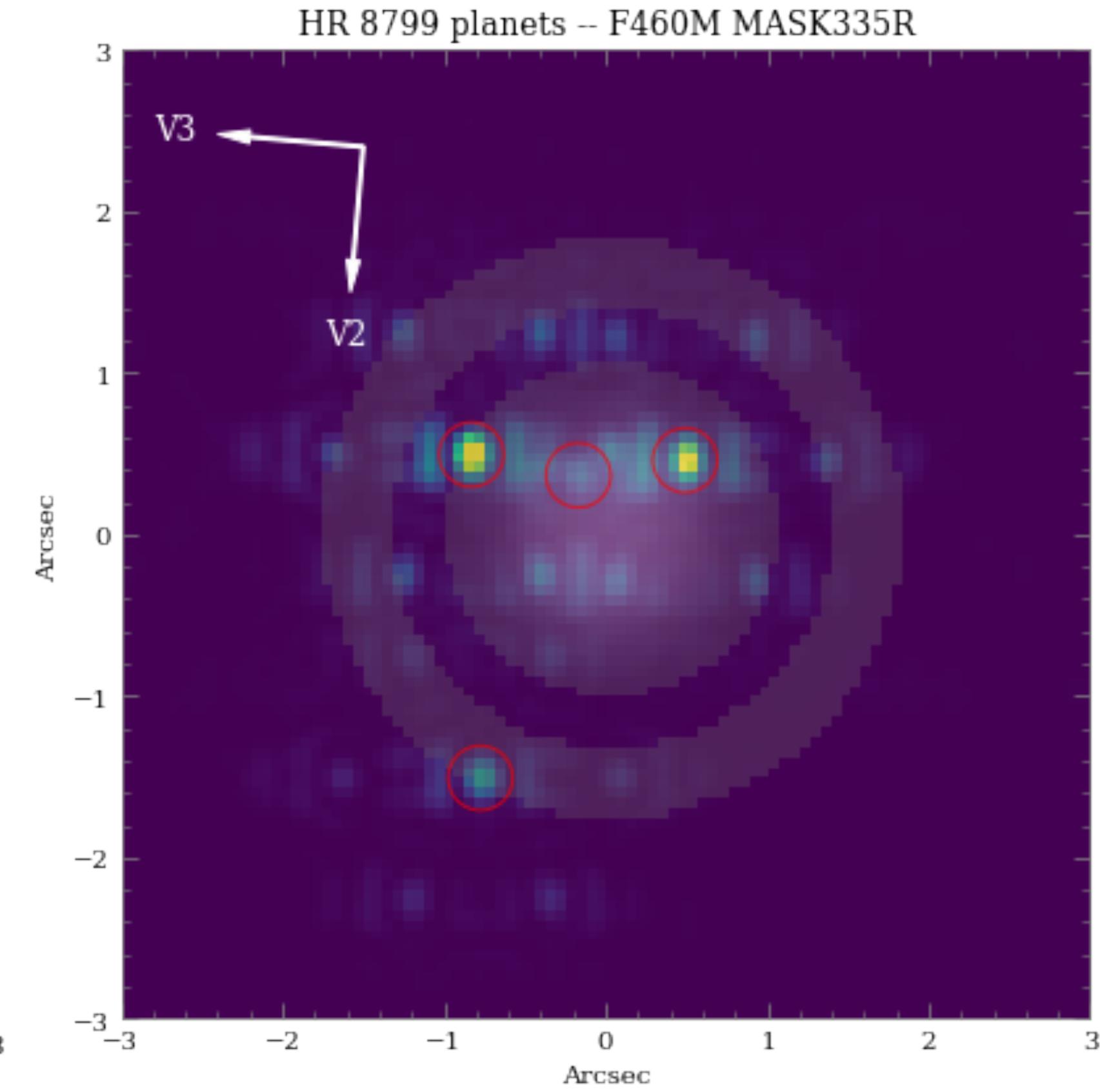
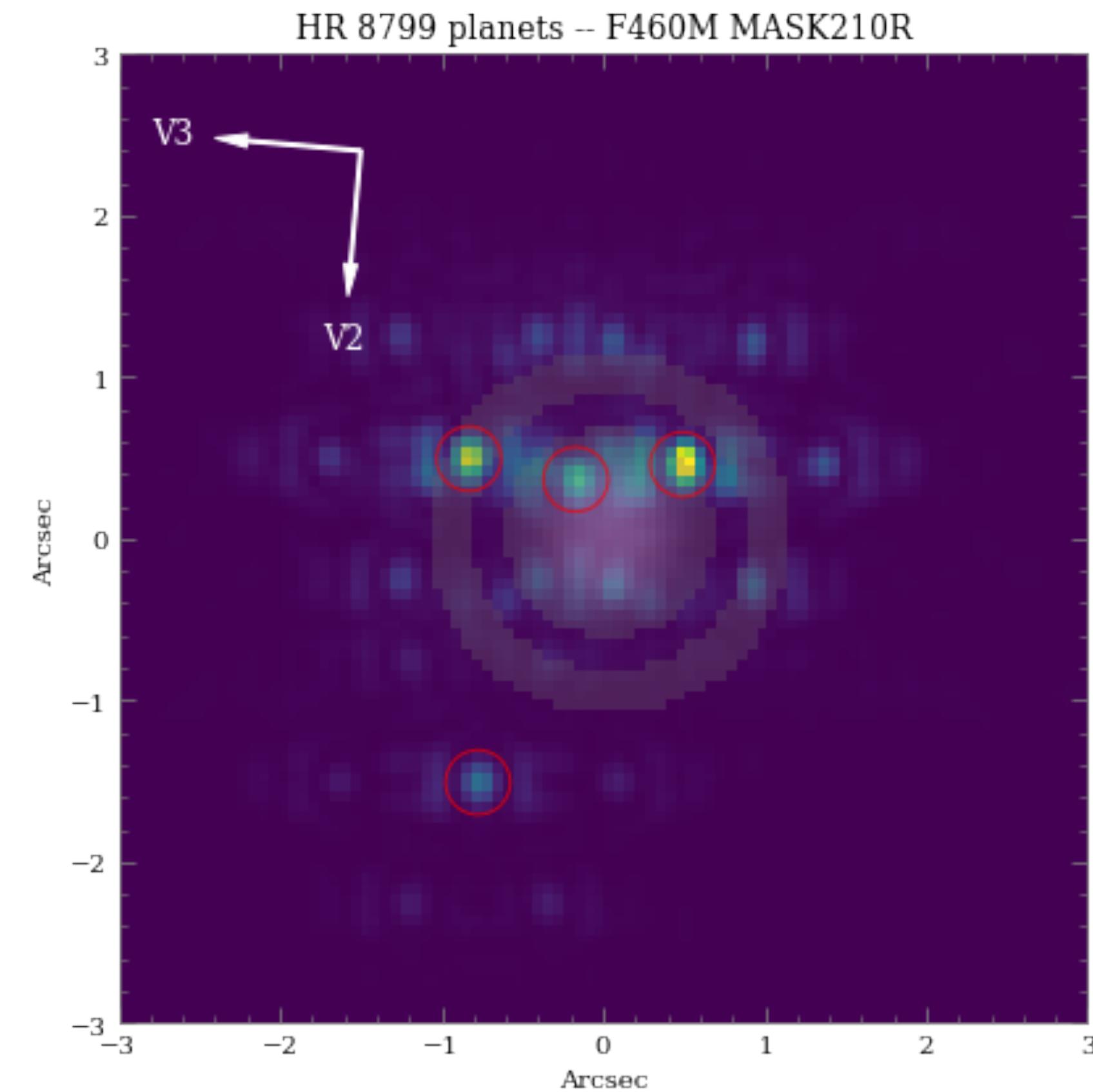
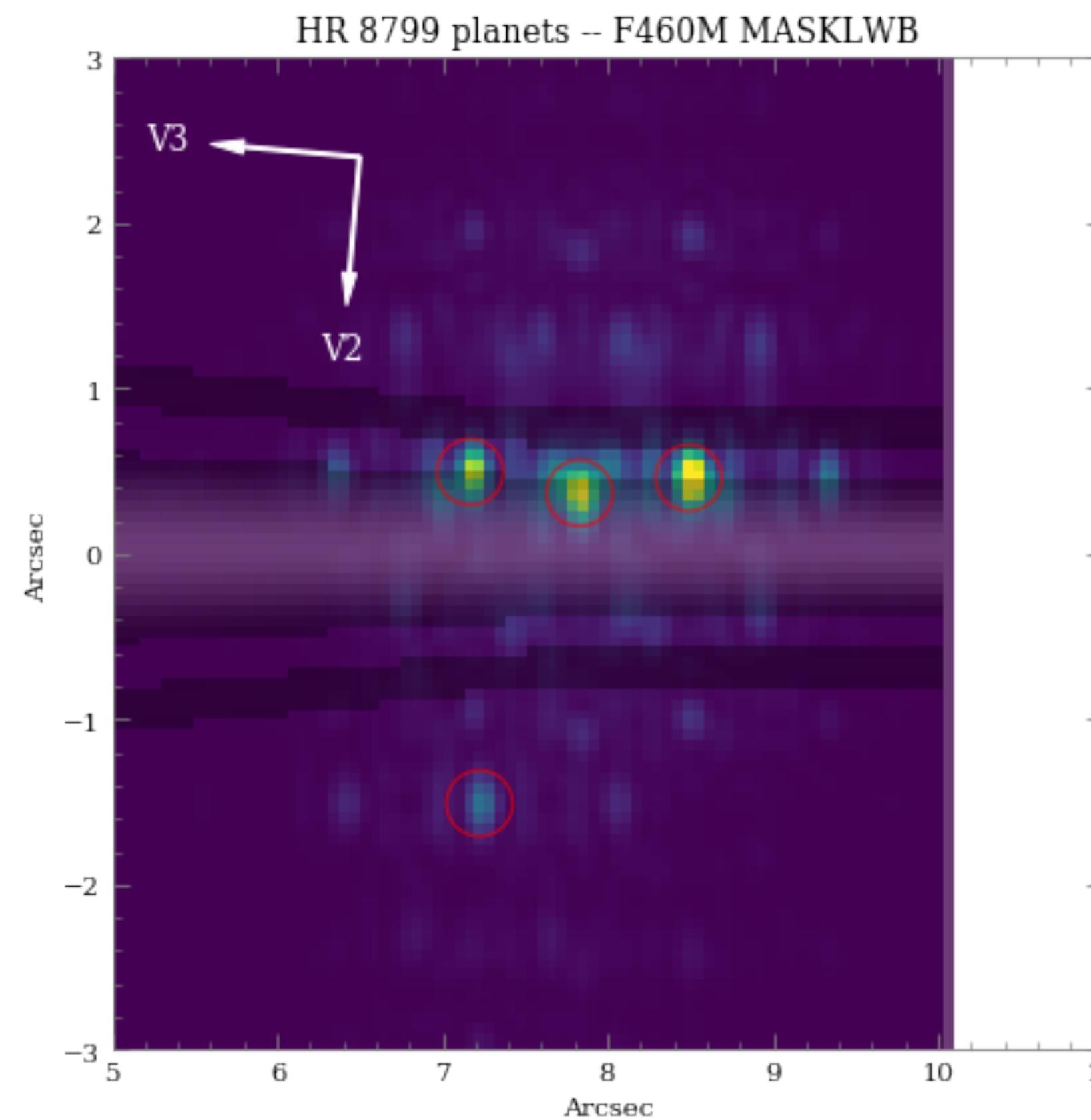


NIRCam Coronagraphy: bar coronagraphs (wedge occulters)





Example Science Program #36 & NIRCam Coronagraphs

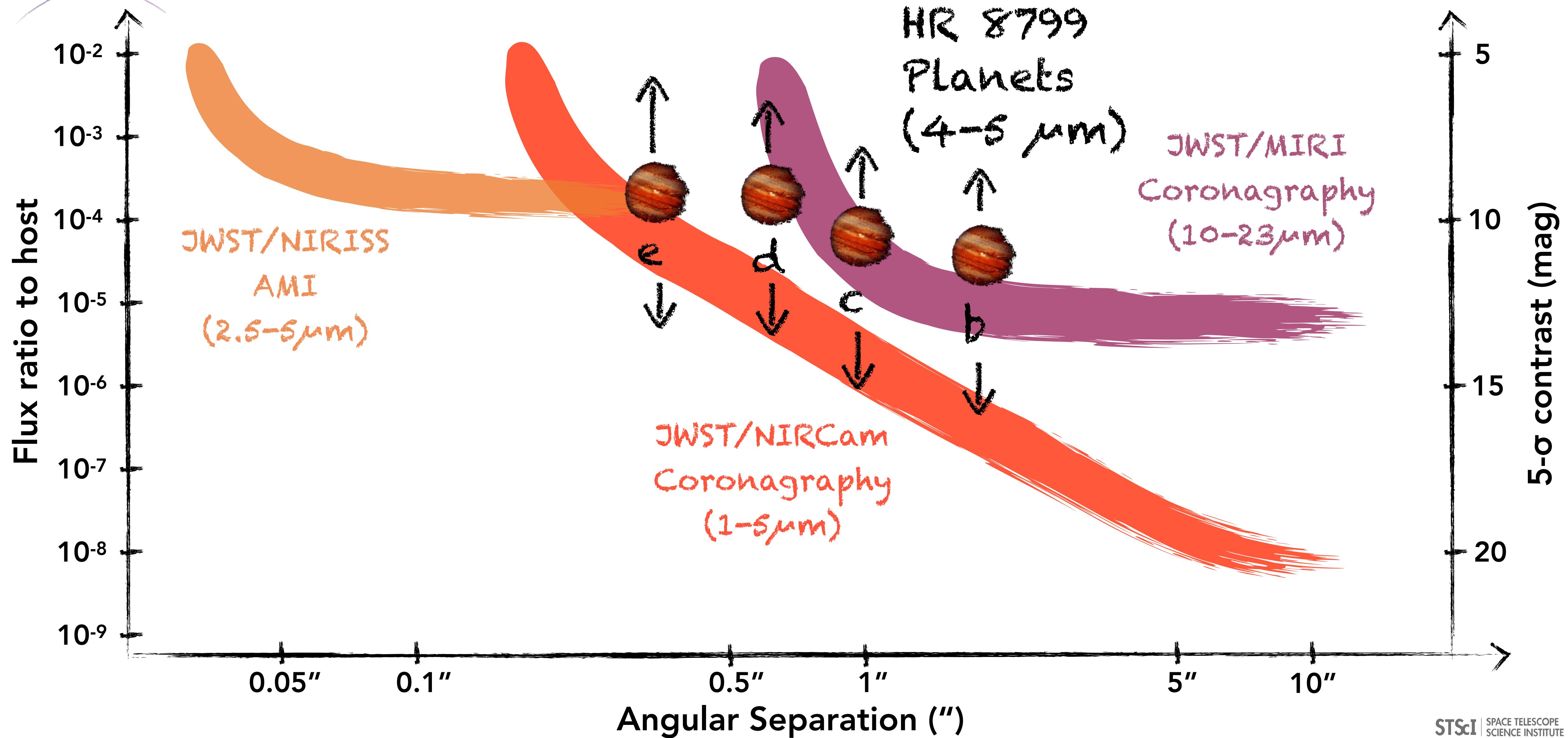


Credit: J. Leisenring (pyNRC, U. Of Arizona)

Note: All compass axes should be (N, E) not (V3, V2)



NIR to MIR Coronagraphy & Aperture Masking: Ground & Space





Extra Slides, Extra Resources



Help Desk

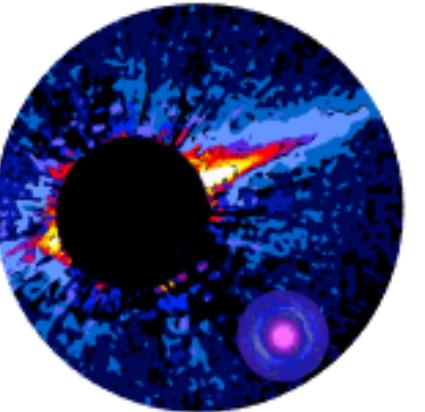
jwsthelp.stsci.edu

STScI | JWST Help Desk

Home > Service Catalog > James Webb Help Desk > Coronography

Coronagraphy

Ask about NIRCam or MIRI coronagraphic imaging



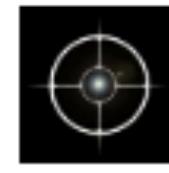
Coronagraphy with JWST NIRCam and MIRI

Typical requests include issues with:

- NIRCam Lyot, MIRI Lyot, and MIRI 4-quadrant phase-mask (4QPM) coronagraphy
- Exposure Time Calculator (ETC) estimates
- Designing observations with APT and adopting the best possible PSF subtraction strategy
- The Coronagraphic Visibility Tool (CVT)

For faster resolution, please attach draft APT files, ETC workbook numbers, and/or screenshots.

James Webb Help Desk
Your JWST gateway. Report issues and submit requests.

APT Support
Request assistance with the Astronomer's Proposal Tool (APT)

[View Details](#)

Constraints & Schedulability
Ask questions about schedulability and observing with JWST

[View Details](#)

Coronagraphy
Ask about NIRCam or MIRI coronagraphic imaging

[View Details](#)

Data Analysis Tools for JWST
Request assistance with STScI-developed data analysis tools

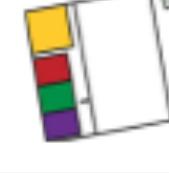
[View Details](#)

ETC Support
Request assistance with the Exposure Time Calculator (ETC)

[View Details](#)

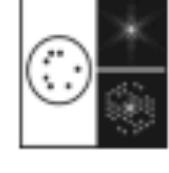
JWST Science Policies
Request assistance for Science Policy Issues.

[View Details](#)

MIRI Support
Request assistance with the Mid-Infrared Instrument (MIRI)

[View Details](#)

NIRCam Support
Request assistance with the Near-Infrared Camera (NIRCam)

[View Details](#)

NIRISS Support
Request assistance with the Near-Infrared Imager and Slitless Spectrograph (NIRISS)

[View Details](#)

NIRSpec Support
Request assistance with the Near-Infrared Spectrograph (NIRSpec)

[View Details](#)

Office of Public Outreach
Contact the STScI Office of Public Outreach about JWST

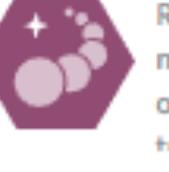
[View Details](#)

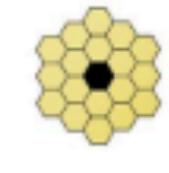
Pipeline Support
Request assistance with the JWST pipeline

[View Details](#)

Solar System Observing
Ask questions about proposal writing for solar system targets with IM2ST

[View Details](#)

Time-Series Observations
Request assistance making time-series observations (e.g., transiting exoplanets)

[View Details](#)

WebbPSF / JWST Telescope
Request assistance with the WebbPSF tool or the Telescope optical system

[View Details](#)

JWST General Support
Request general JWST support for issues not covered by another category

[View Details](#)

MAST Archive Support
Request general Archive support for issues not covered by another category

[View Details](#)



Proposal Planning Workshop: material, presentations

 STScI

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NASA's James Webb Space Telescope

Developed in partnership with ESA and CSA. Operated by AURA's Space Telescope Science Institute

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Past Events

13
Dec 2017

Su	Mo	Tu	We	Th	Fr	Sa
10	11	12	13	14	15	16

Planning Solar System Observations with JWST - ESTEC venue

Science Meeting • December 13 - 15, 2017 • Noordwijk, Netherlands ESTEC

This 2.5-day workshop will include a mixture of presentations about the promise of JWST for solar system science, specifics on observer planning tools and observatory capabilities, and hands-on training and Q&A with the planning tools. Observations of solar system targets approved for guaranteed-time observers (GTOs) and through the Early Release Science (ERS) program will be summarized. The workshop...

11
Dec 2017

Su	Mo	Tu	We	Th	Fr	Sa
10	11	12	13	14	15	16

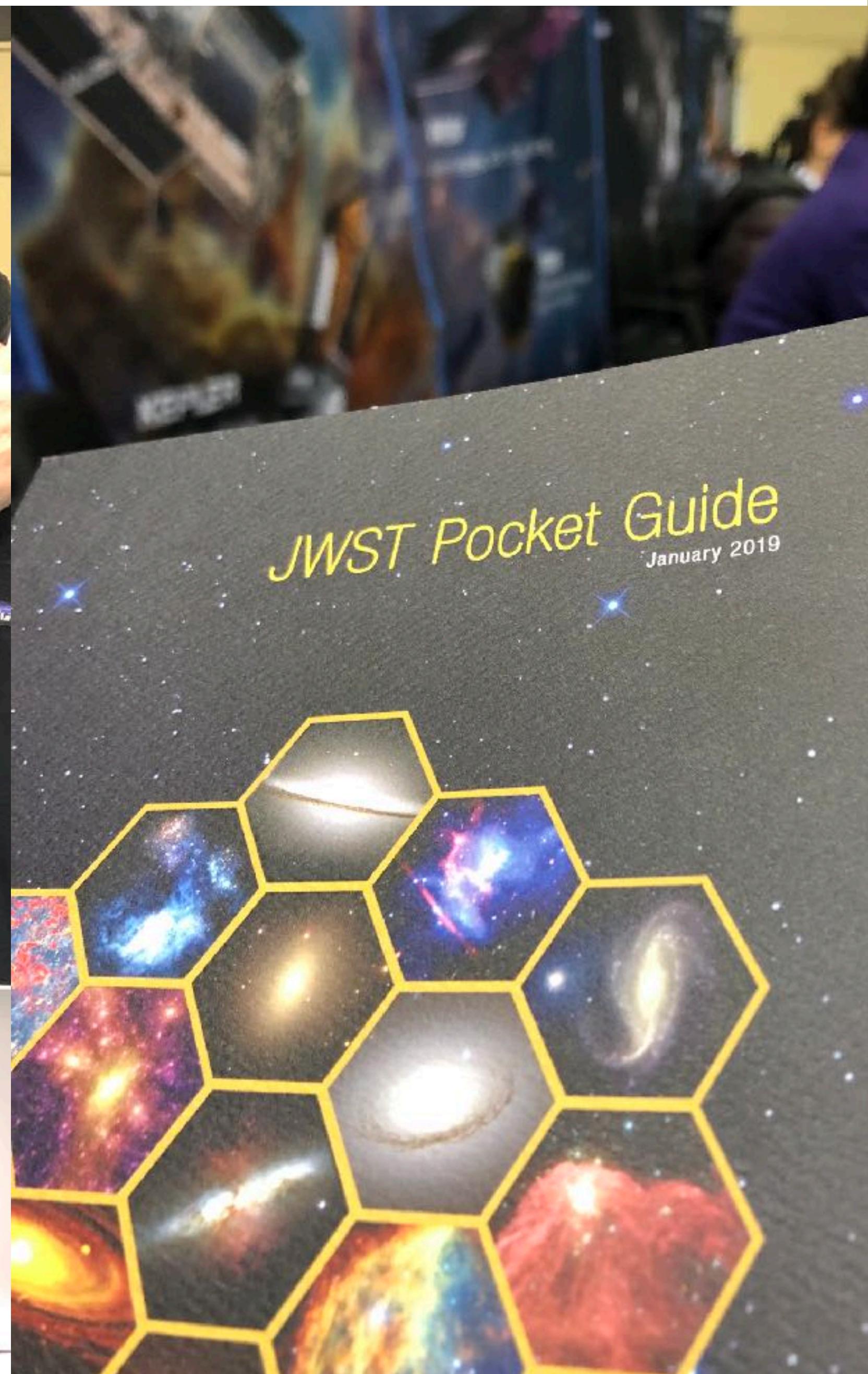
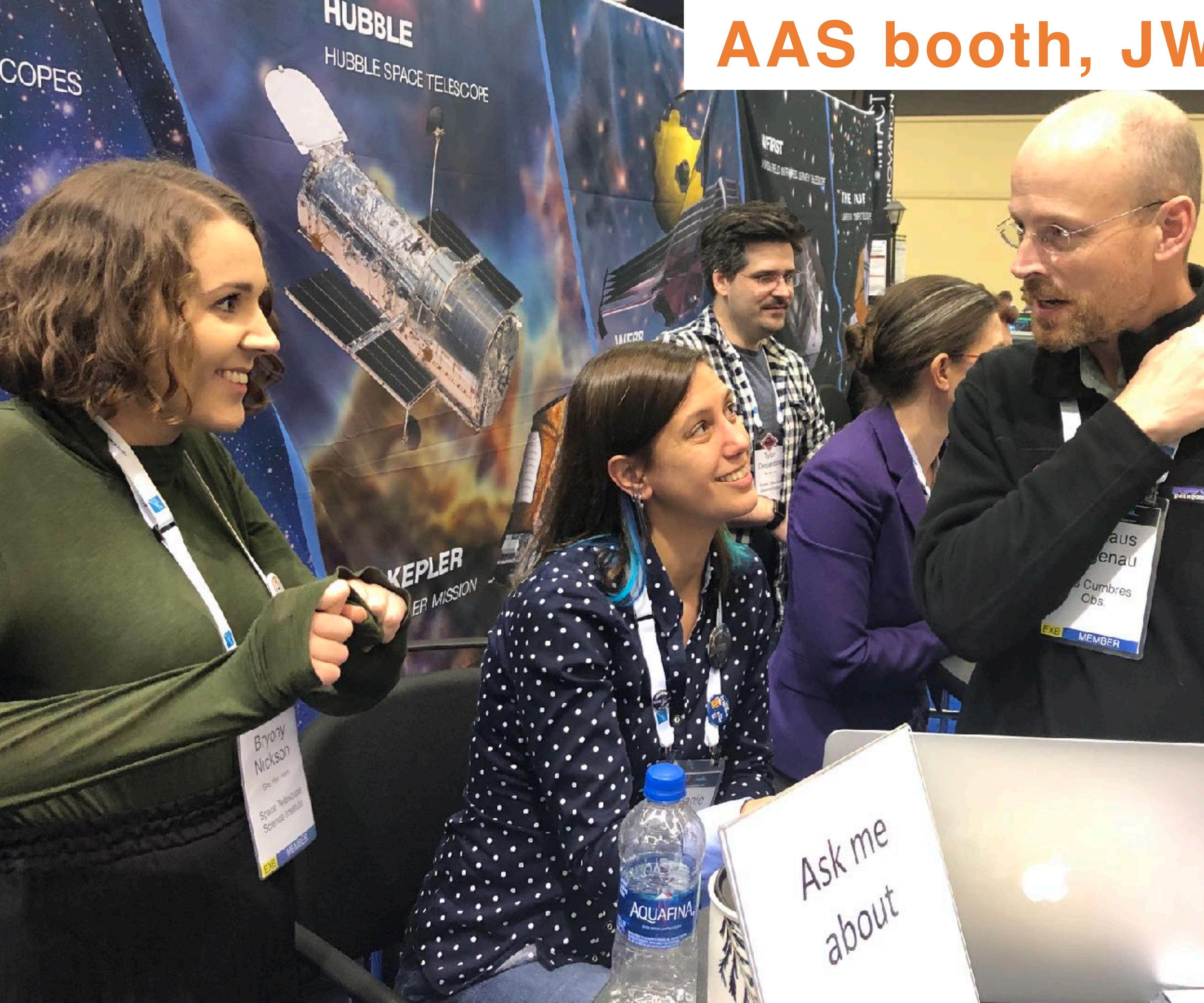
JWST Proposal Planning Workshop

Training Workshop • December 11 - 14, 2017 • Caltech, Pasadena, CA

This workshop will take place shortly after the announcement of the programs selected under the first JWST open call for proposals (the Directory Discretionary Early Release Science Programs), and shortly before their observing files (meant to serve as models for the general observer community) become public. Therefore, the workshop will coincide with active proposal preparation for the next open...

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AAS booth, JWST pocket Guide





Approved programs on MAST: example of ERS #1386 (Hinkley)

Select a collection... and enter target: **HIP 65426** Search

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Home Page MAST: HR8799 MAST: HR8799 MAST: HR8799 MAST: HIP 65426

Displaying 19 of 20 Total Rows

HD 116434, radius: 0.20000°

List View Album View

Edit Columns... Table Display: All Show Preview: Show Cutout:

Filters

Clear Filters Edit Filters... Help...

Keyword/Text Filter
Filter All Columns

Product Type
Name Quantity
 image (19 of 19)
 cube (0 of 1)

Mission
Name Quantity
 JWST (19 of 19)
 SWIFT (0 of 1)

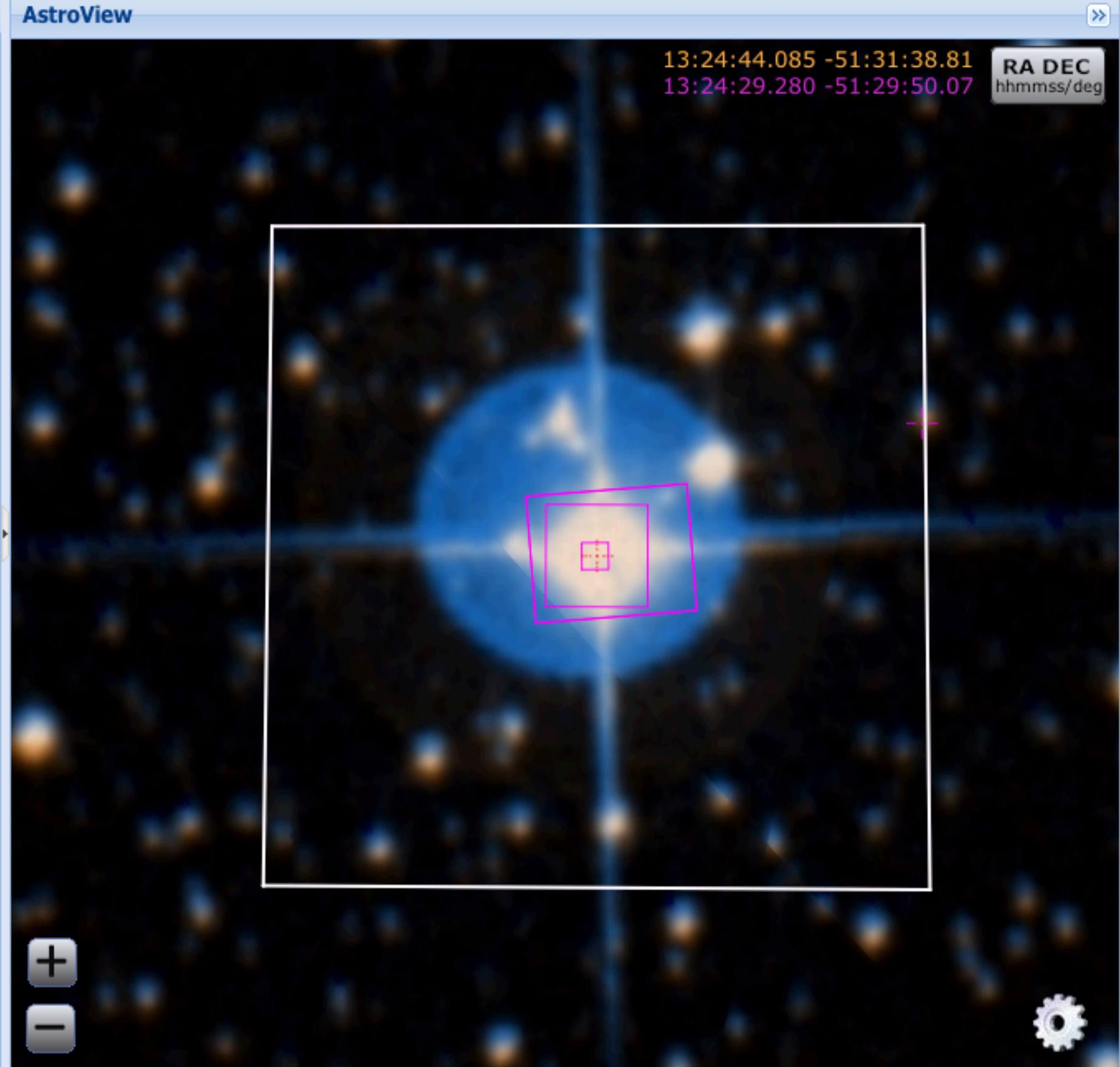
Instrument
Name Quantity
 NIRCAM (14 of 14)
 MIRI (4 of 4)
 NIRISS (1 of 1)
 UVOT (0 of 1)

Project
Name Quantity
 JWST (19 of 19)

	Actions	Mission	Instrument	Propos...	Principal Inv...	Filters	Target Name
<input type="checkbox"/>		JWST	NIRCAM	1386	Hinkley, Sa...	NONE, ...	HIP-65426
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AstroView

13:24:44.085 -51:31:38.81
13:24:29.280 -51:29:50.07 RA DEC
hhmmss/deg



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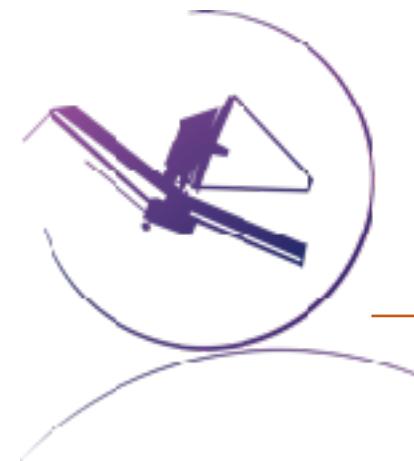
4 Ideas which aren't always true

Coronagraphy is the **only way** to **perform & achieve high contrast imaging**

Coronagraphy & high contrast imaging **do not** concern **extragalactic science**

Images from **space** are **sharper**

Coronagraphic observing strategies & data (post-)processing are **for experts**



4 “Take Home” from this talk!

Coronagraphy is **NOT** the **only way** to **perform & achieve high contrast imaging**

Moderate to high contrasts can be achieved with other techniques (Imaging, IFU, AMI)

Coronagraphy & high contrast imaging **do not** concern **extragalactic science**

Images from **space** are **sharper, in general (HST “trademark”)**

6.5 to 40-meter class ground based facilities with (x)AO can provide better FWHM in some cases (rather bright objects) but with a limited FoV, stability & sensitivity, unlike NIRCam

Coronagraphic observing strategies & data (post-)processing are **not just for experts**

At STScI , the CWG works in synergy with other working groups & divisions, the IDTs and the general community to provide the best possible support

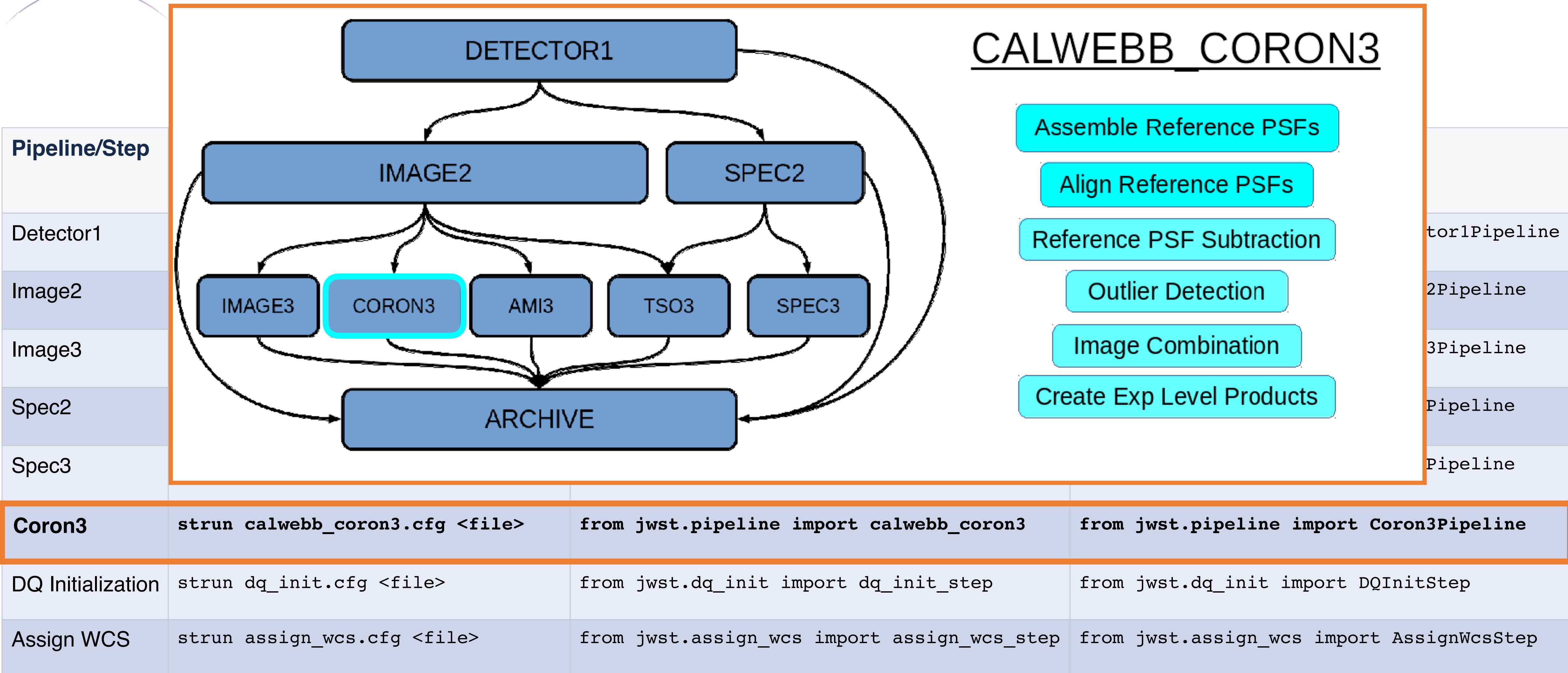


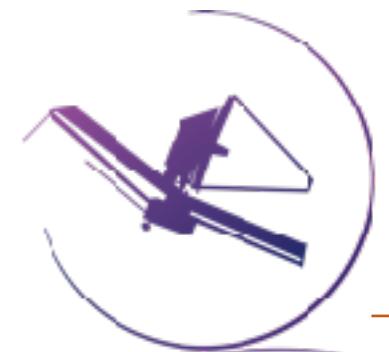
Pipeline for coronagraphy

Pipeline/Step	Command line	iPython + modules (run method)	iPython + classes (call method)
Detector1	<code>strun calwebb_detector1.cfg <file></code>	<code>from jwst.pipeline import calwebb_detector1</code>	<code>from jwst.pipeline import Detector1Pipeline</code>
Image2	<code>strun calwebb_image2.cfg <file></code>	<code>from jwst.pipeline import calwebb_image2</code>	<code>from jwst.pipeline import Image2Pipeline</code>
Image3	<code>strun calwebb_image3.cfg <file></code>	<code>from jwst.pipeline import calwebb_image3</code>	<code>from jwst.pipeline import Image3Pipeline</code>
Spec2	<code>strun calwebb_spec2.cfg <file></code>	<code>from jwst.pipeline import calwebb_spec2</code>	<code>from jwst.pipeline import Spec2Pipeline</code>
Spec3	<code>strun calwebb_spec3.cfg <file></code>	<code>from jwst.pipeline import calwebb_spec3</code>	<code>from jwst.pipeline import Spec3Pipeline</code>
Coron3	<code>strun calwebb_coron3.cfg <file></code>	<code>from jwst.pipeline import calwebb_coron3</code>	<code>from jwst.pipeline import Coron3Pipeline</code>
DQ Initialization	<code>strun dq_init.cfg <file></code>	<code>from jwst.dq_init import dq_init_step</code>	<code>from jwst.dq_init import DQInitStep</code>
Assign WCS	<code>strun assign_wcs.cfg <file></code>	<code>from jwst.assign_wcs import assign_wcs_step</code>	<code>from jwst.assign_wcs import AssignWcsStep</code>



Pipeline for coronagraphy

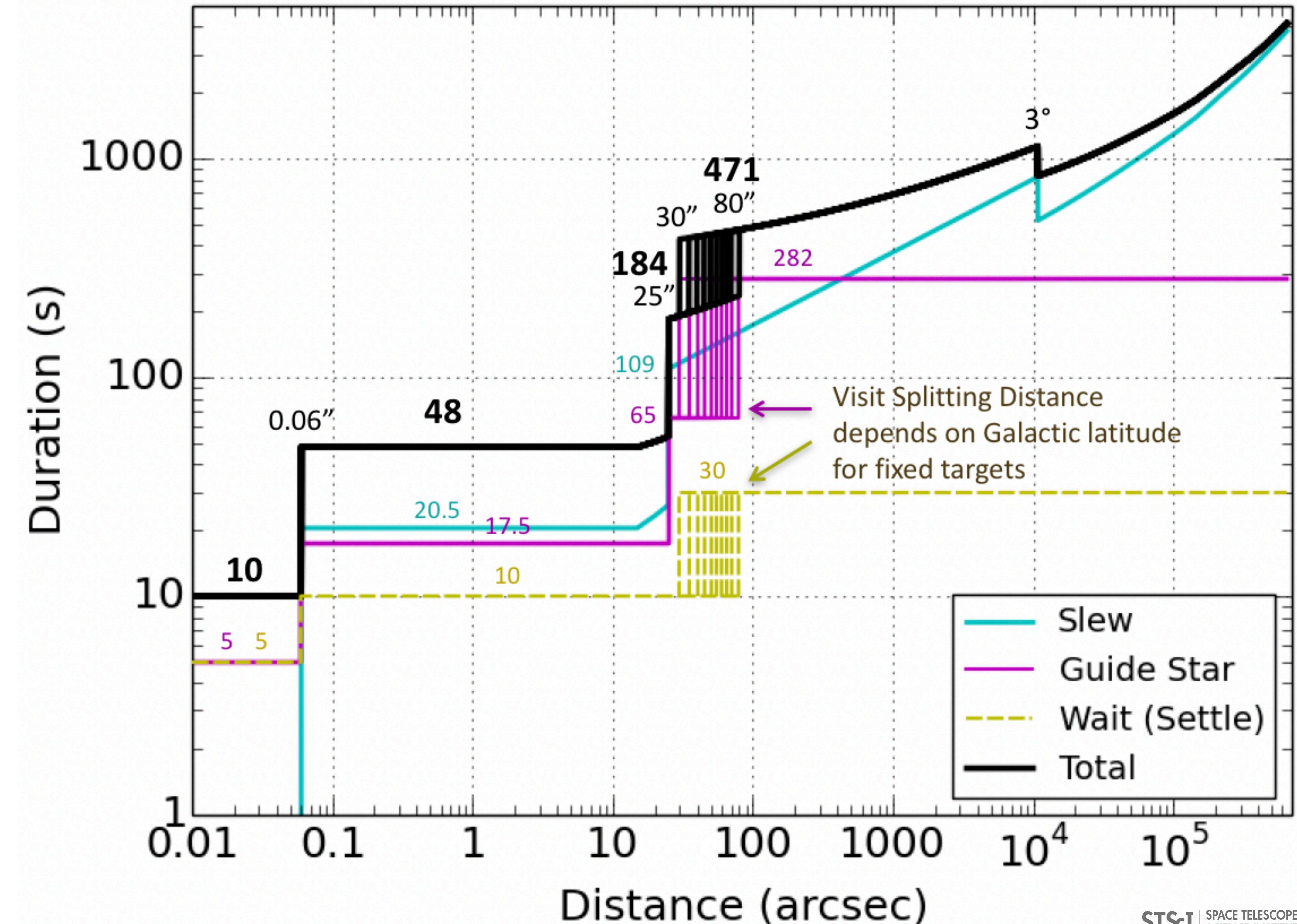




Reference star & overheads: slew, settle, reacquire guide star

Changing attitude

1. Update observatory pointing and roll
2. Let disturbances settle
3. Reacquire guide star
 - ♦ Fine guide (always)
 - ♦ Track ($>0.06''$)
 - ♦ Acquisition ($>25''$)
 - ♦ Identification (new visit)

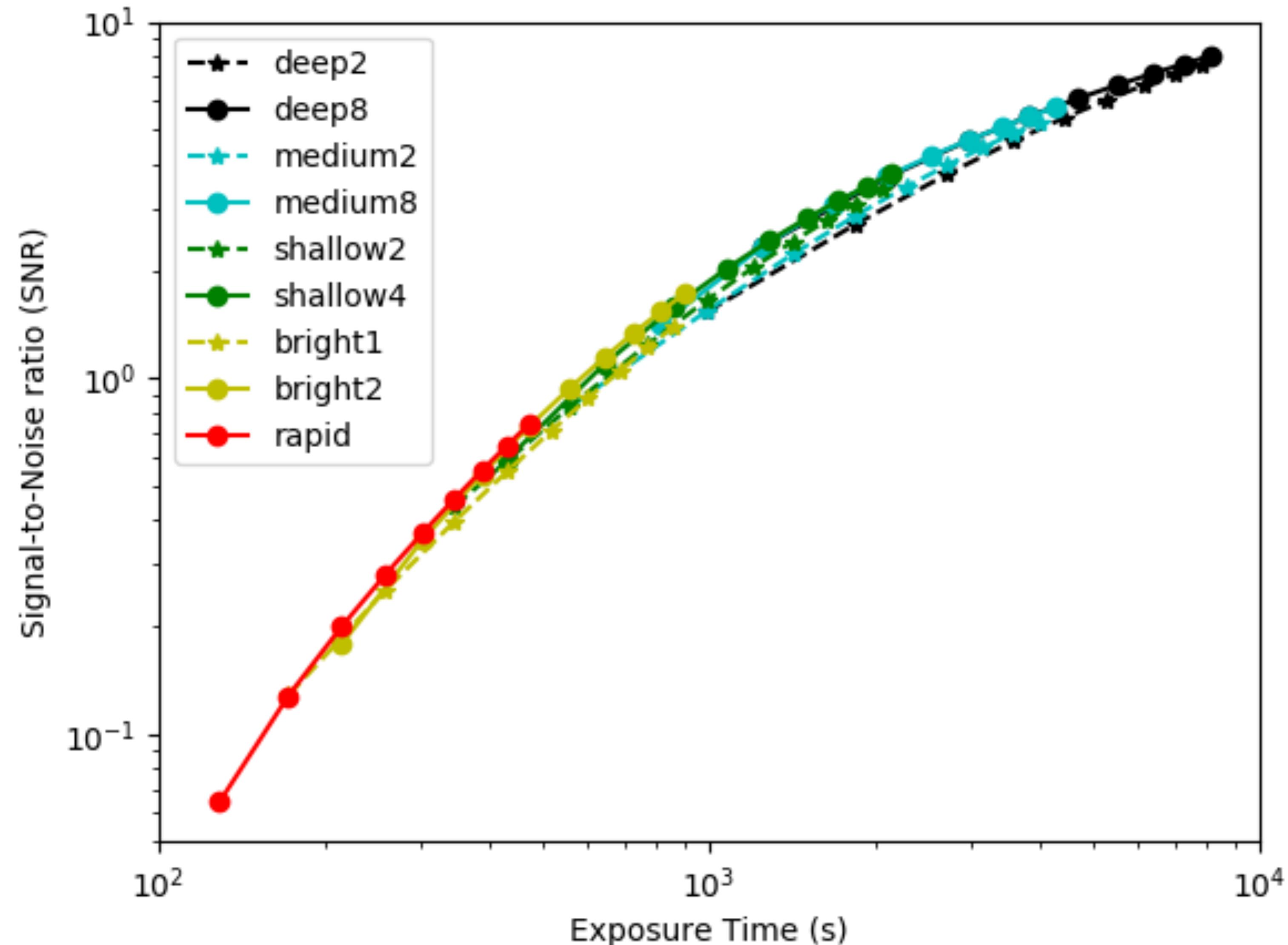




ETC: Finding the best exposure parameters

Selecting the optimal combination of readout pattern, ngroups, nints and nexp is a trade-off

- ♦ More frames decreases read noise
- ♦ Shorter groups increases data volume
- ♦ Longer groups increases the chance of a cosmic ray hit during the group
- ♦ Shorter integrations make ramp fits more uncertain in the presence of non-linearity
- ♦ More dithered exposures decreases flat field errors (not currently modeled by ETC!)
- ♦ Patterns that skip a lot of frames have higher read noise, but have slightly better duty cycle

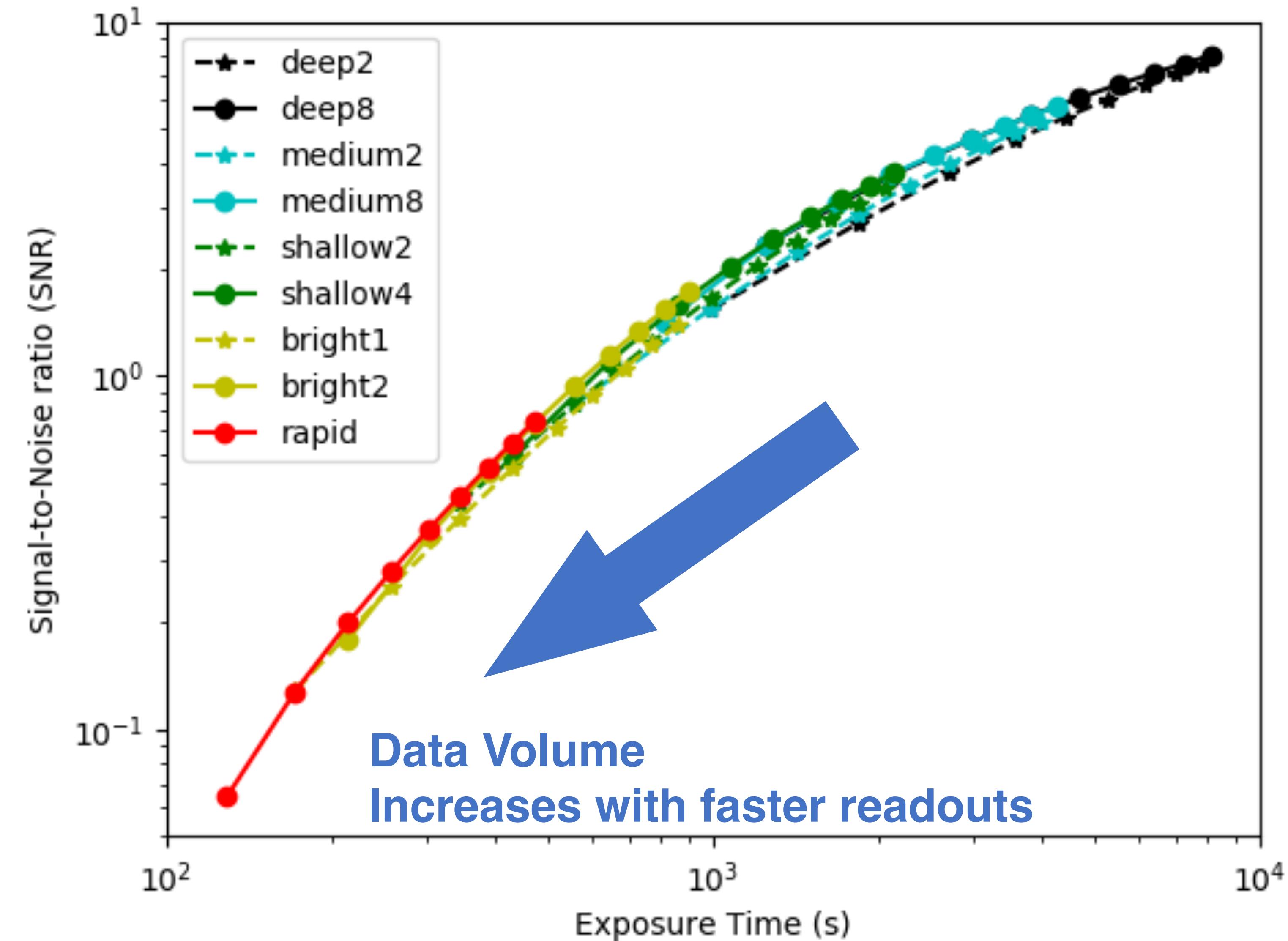




ETC: Finding the best exposure parameters

Selecting the optimal combination of readout pattern, ngroups, nints and nexp is a trade-off

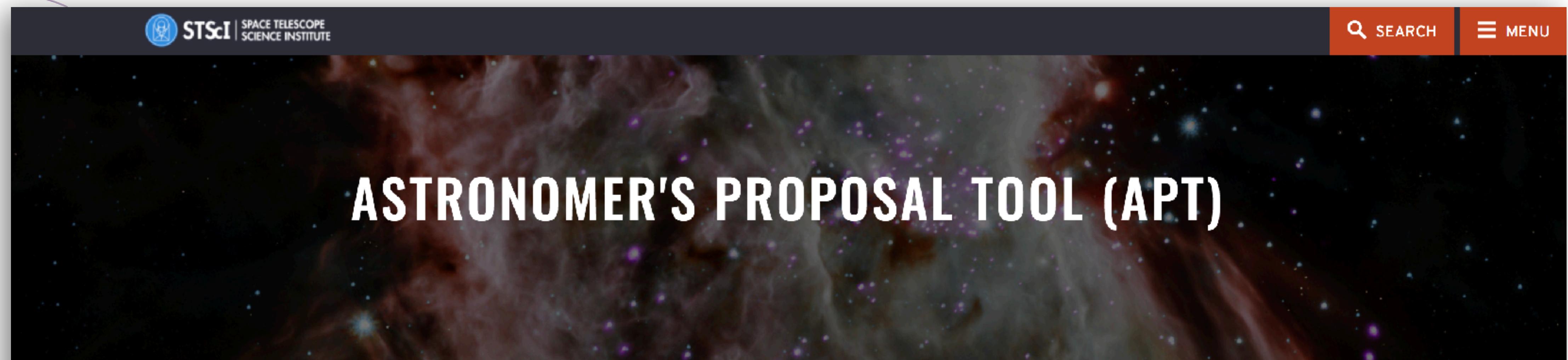
- ♦ More frames decreases read noise
- ♦ Shorter groups increases data volume
- ♦ Longer groups increases the chance of a cosmic ray hit during the group
- ♦ Shorter integrations make ramp fits more uncertain in the presence of non-linearity
- ♦ More dithered exposures decreases flat field errors (not currently modeled by ETC!)
- ♦ Patterns that skip a lot of frames have higher read noise, but have slightly better duty cycle





APT 27.3

[www.stsci.edu/scientific-community/software/
astronomers-proposal-tool-apt](http://www.stsci.edu/scientific-community/software/astronomers-proposal-tool-apt)



The page features a dark background image of a nebula with stars. At the top, there's a navigation bar with the STScI logo, a search bar, and a menu icon. The main title "ASTRONOMER'S PROPOSAL TOOL (APT)" is displayed prominently in white text against the nebula background.

[Home](#) > [Scientific Community](#) > [Software](#)

What is APT?

The Astronomer's Proposal Tool (APT) is used to write, validate, and submit proposals for the Hubble Space Telescope and the James Webb Space Telescope.

Download and Installation Instructions

[Linux](#) [Mac OSX](#) [Windows](#)

Current Release: 27.3

Released: September 16, 2019

This upgrade is not required for HST Proposers.

This upgrade is recommended for people working on JWST programs. [Read more](#)

[Previous Release Information](#)



Technical Documents / Coronagraphy, AMI

The screenshot shows a web browser displaying the NASA's James Webb Space Telescope's Technical Documents page. The URL is <https://jwst.stsci.edu/instrumentation/technical-documents>. A search bar at the top right contains the text "Coro". The main content area is a table listing technical documents related to Coronagraphy, sorted by Title, Author, and Year.

Title	Author	Year
A PSF Library for Coronagraphy with JWST	Stark, C., Pueyo, L. & the JWST Coronagraphs Working Group	2017
An APT Implementation of the JWST Coronagraph SODRM Programs	Stark, C. & Van Gorkom, K.	2017
NIRCam Filter, Weak Lens and Coronagraphic Throughputs	Hilbert, B. & Stansberry, J.	2017
Comparative Study of the Efficiency of Various JWST Coronagraph Observation Strategies	Pueyo, L., Soummer, R. & the JWST Coronagraphs Working Group	2016
Exposure Time Calculations for Coronagraphic Observations: Overview of User Needs	Pueyo, L., Soummer, R. & the JWST Coronagraphs Working Group	2016
How to Implement a JWST Coronagraphic Observation Sequence in APT	Stark, C. & Van Gorkom, K.	2016
Science Use-Cases for the Preparation of Coronagraphic Operations Concepts and Policies	Soummer, R., et al.	2015
The Mid-Infrared Instrument for the James Webb Space Telescope. V. Predicted Performance of the MIRI Coronagraph	Boccalotti, A., et al.	2015
Simulations of JWST MIRI 4QPM Coronagraph Operations and Performances	Lajoie, C-P., Soummer, R., Hines, D. & Rieke, G.	2014
Simulations of MIRI Four-Quadrant Phase Mask Coronagraph (III): Target Acquisition and CCC Mechanism Usage	Lajoie, C-P., Hines, D., Soummer, R. & the JWST Coronagraphs Working Group	2014
Simulations of Target Acquisition with MIRI Four-Quadrant Phase Mask Coronagraph (IV): Predicted Performances Based on Slow Accuracy Estimates	Lajoie, C-P., Soummer, R., Hines, D. & the JWST Coronagraphs Working Group	2014

<https://jwst.stsci.edu/instrumentation/technical-documents>