



STScI | SPACE TELESCOPE
SCIENCE INSTITUTE

EXPANDING THE FRONTIERS OF SPACE ASTRONOMY

HIGH CONTRAST IMAGING (HCI) WITH JWST

Julien H. Girard

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

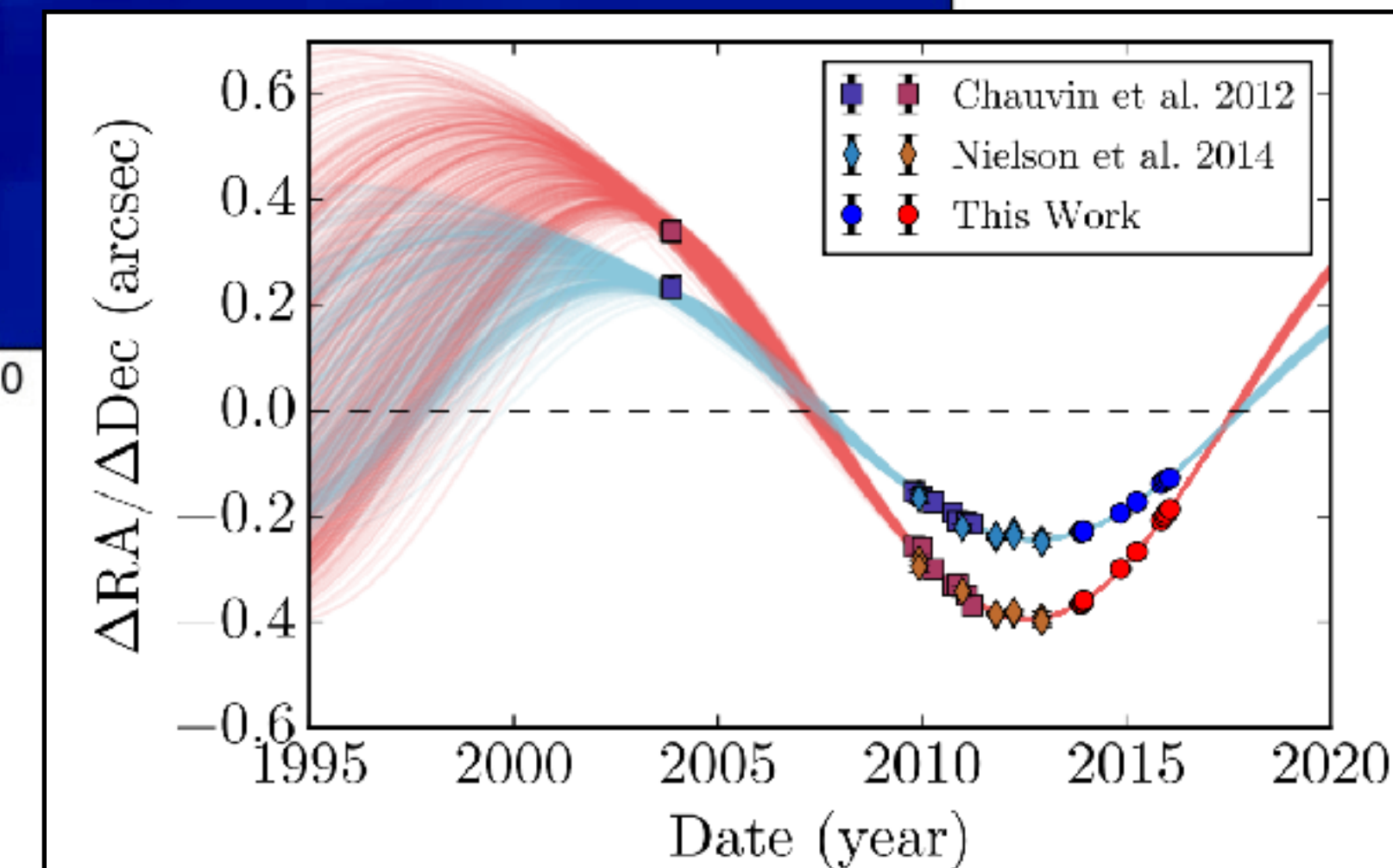
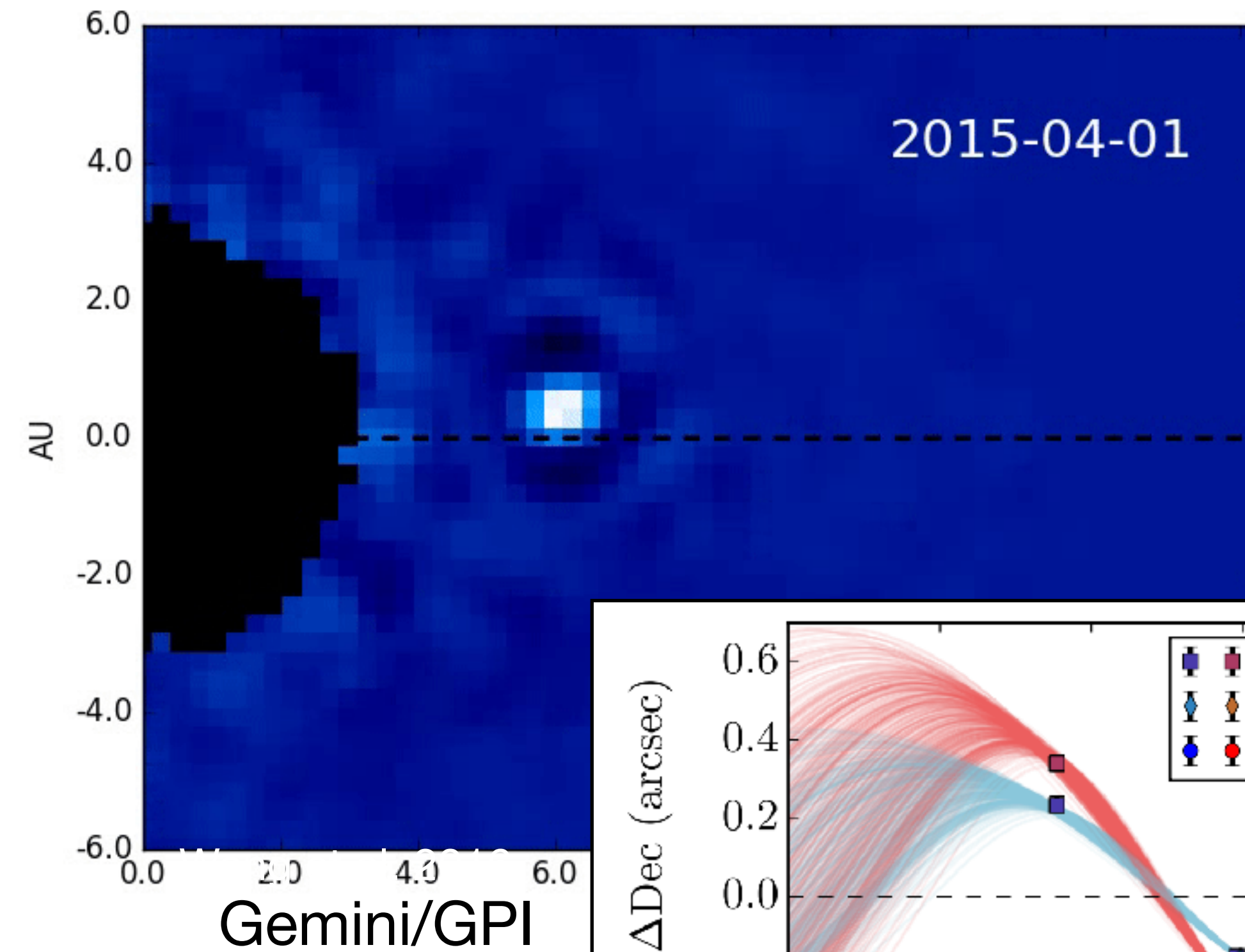
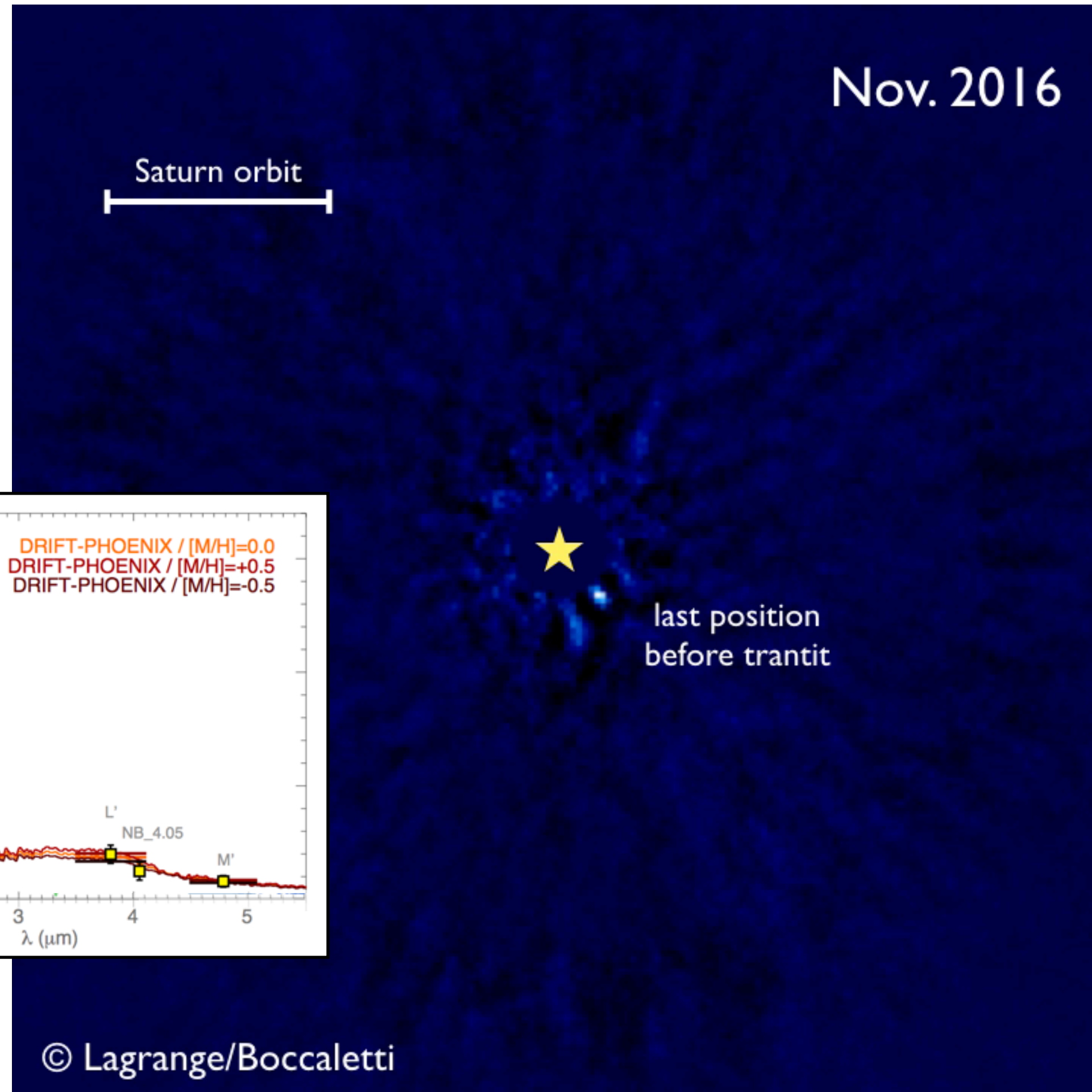
Introduction



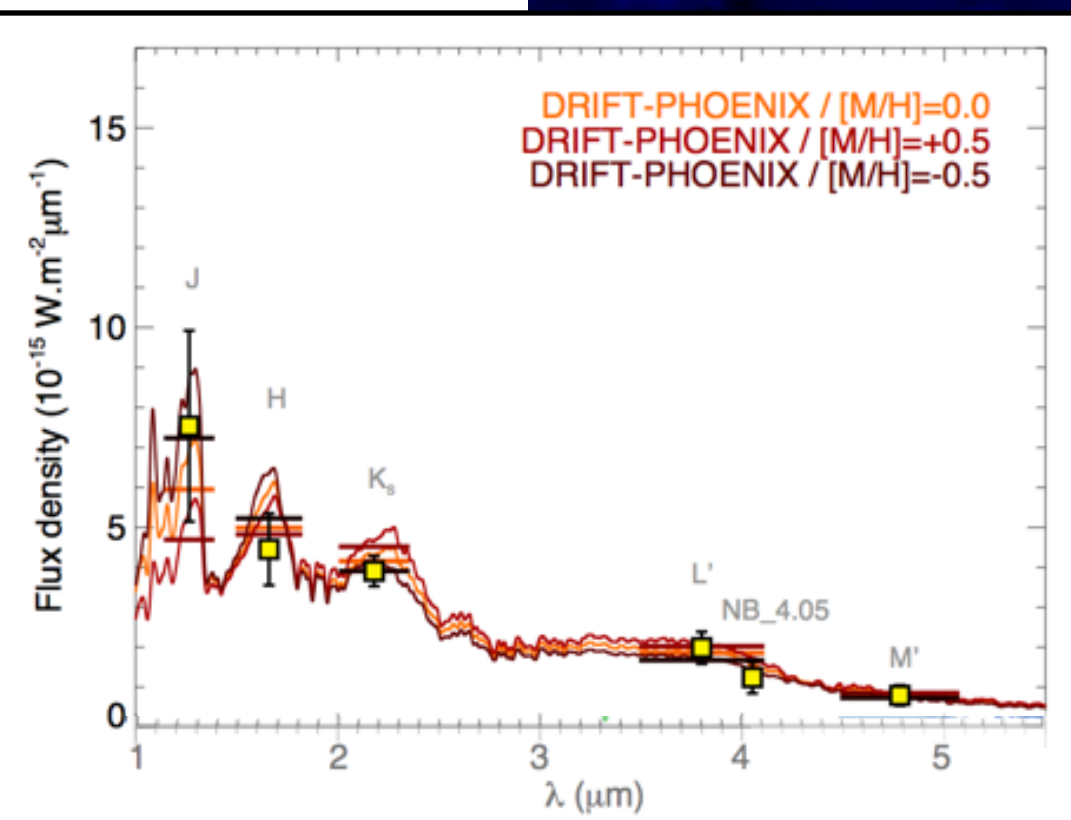


High Contrast, Direct Imaging: a powerful technique!

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



Wang et al. 2016



Bonnefoy et al. 2013

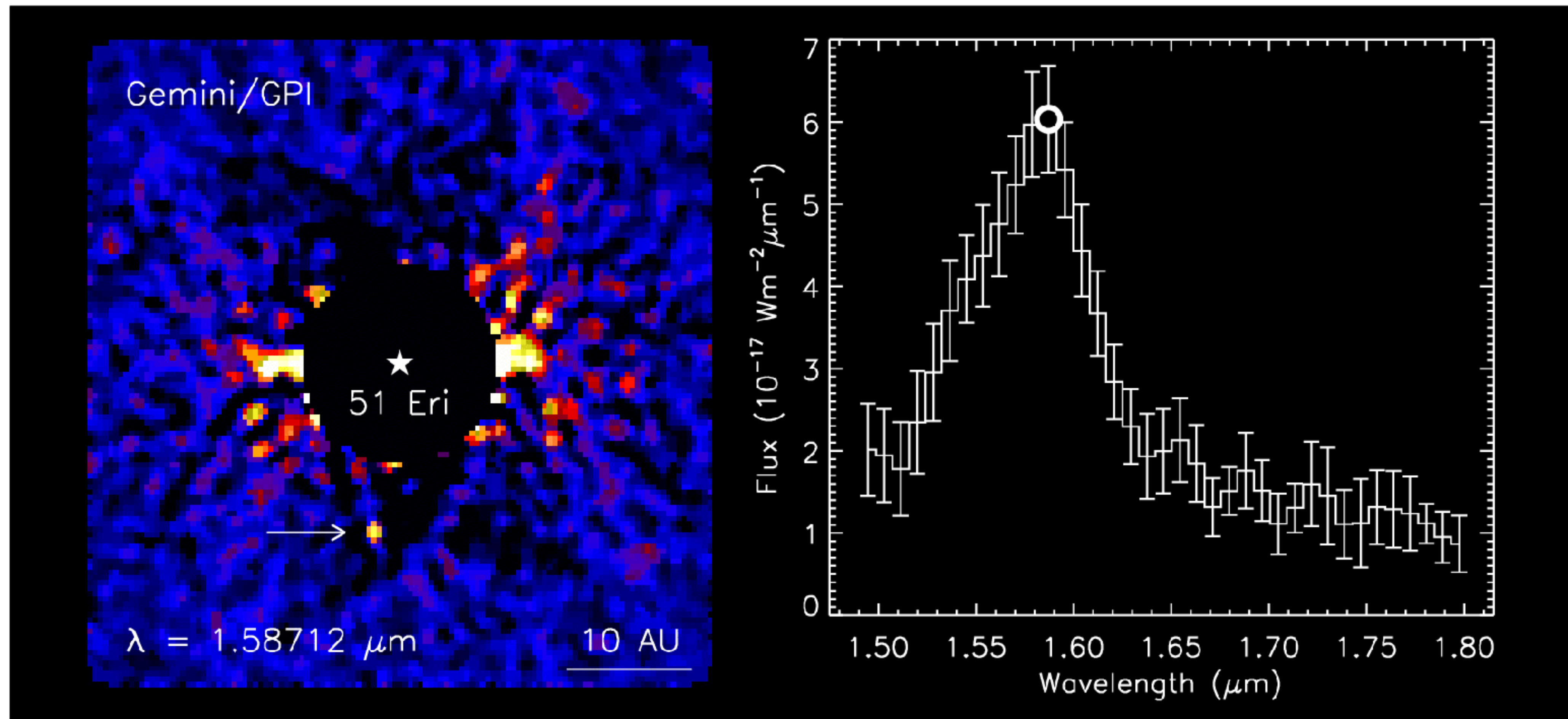
VLT/NACO & SPHERE

Lagrange et al. 2019



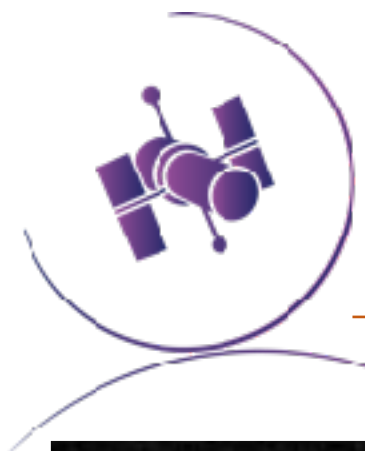
High Contrast, Direct Imaging: a powerful technique!

Low-resolution spectra: **51 Eridani b** planet $\sim 2 M_{\text{Jup}}$, $\sim 700\text{K}$



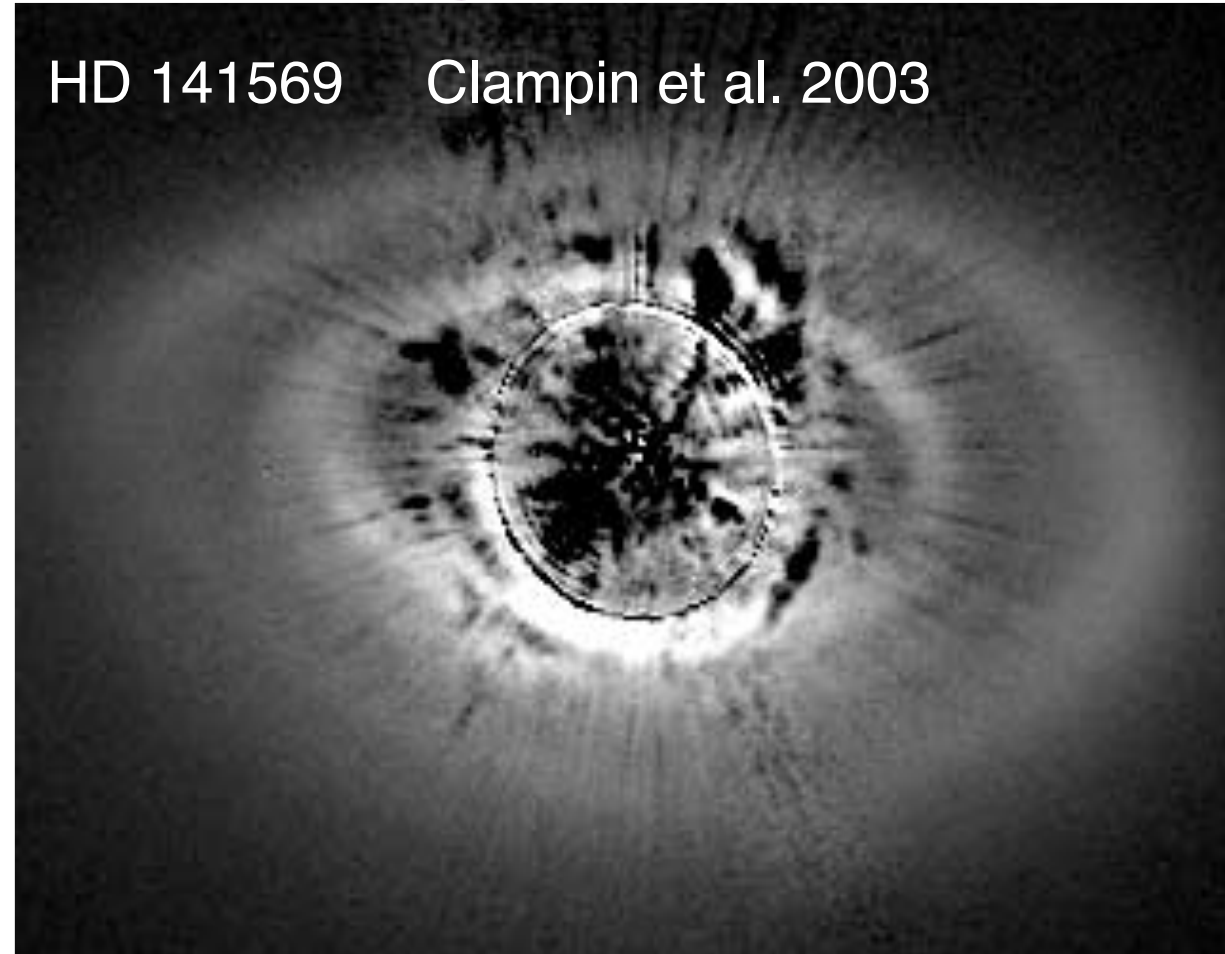
Gemini/GPI

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

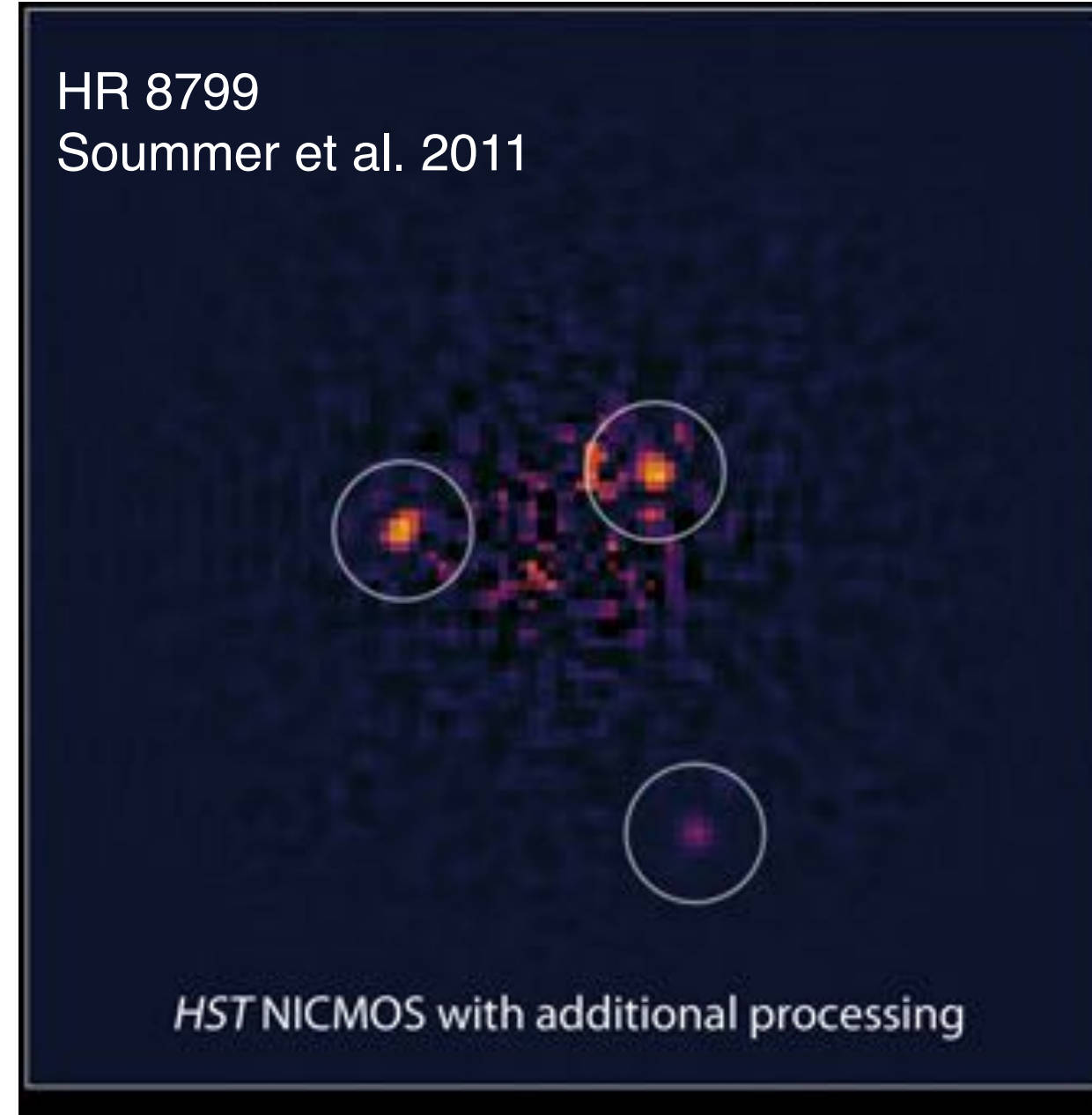


Coronagraphic studies with Hubble of exoplanets, brown dwarfs, and disks

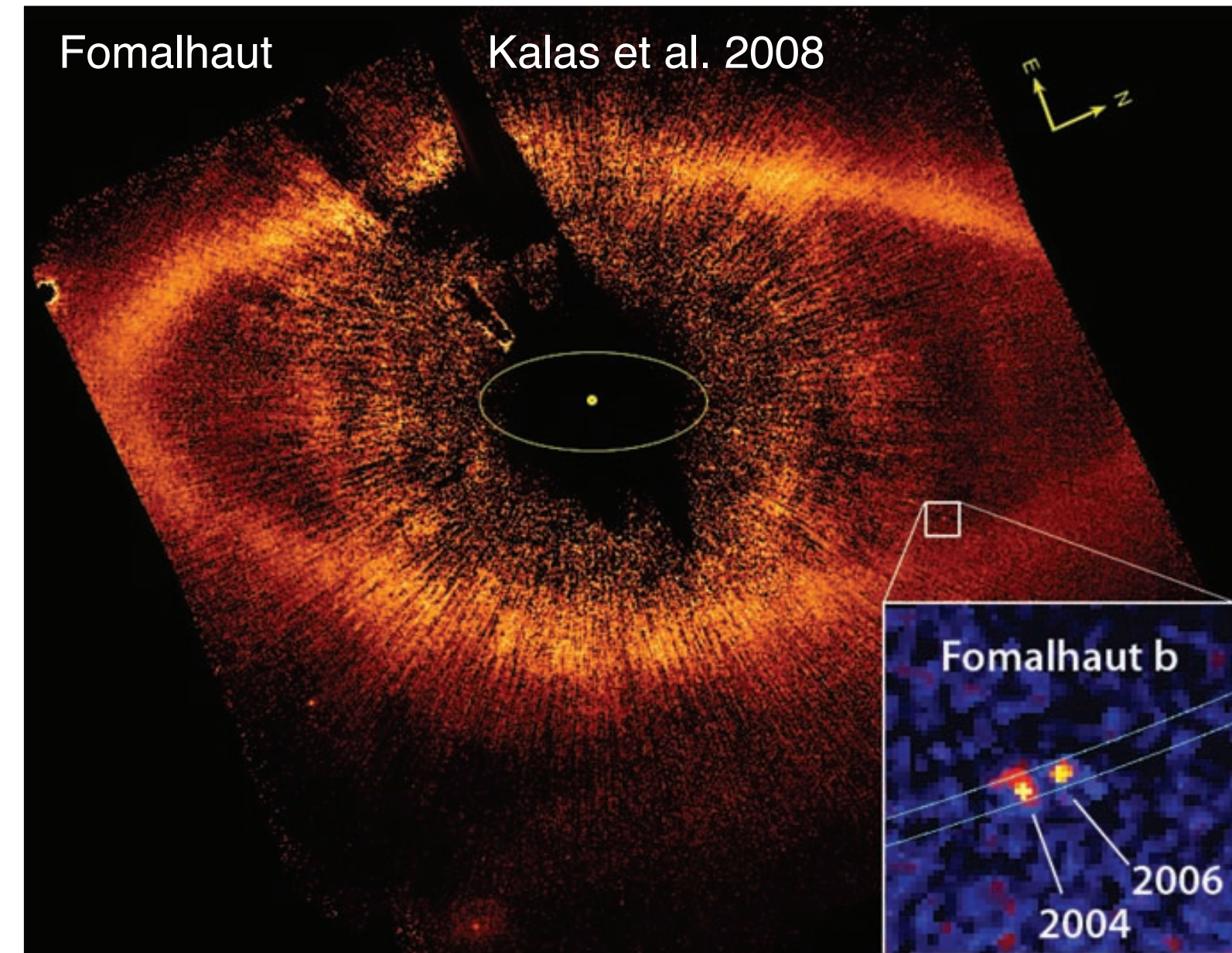
HD 141569 Clampin et al. 2003



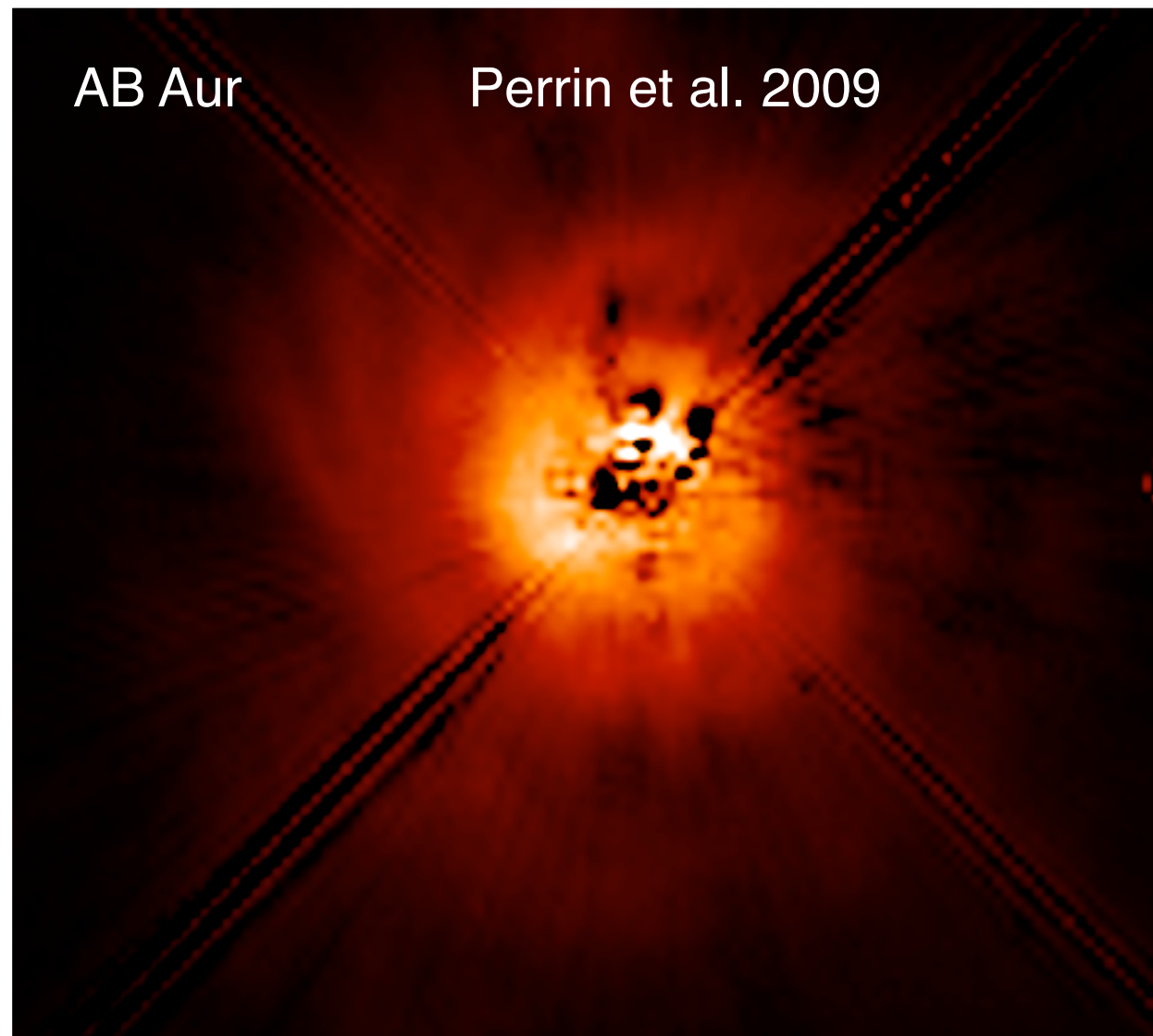
HR 8799 Soummer et al. 2011



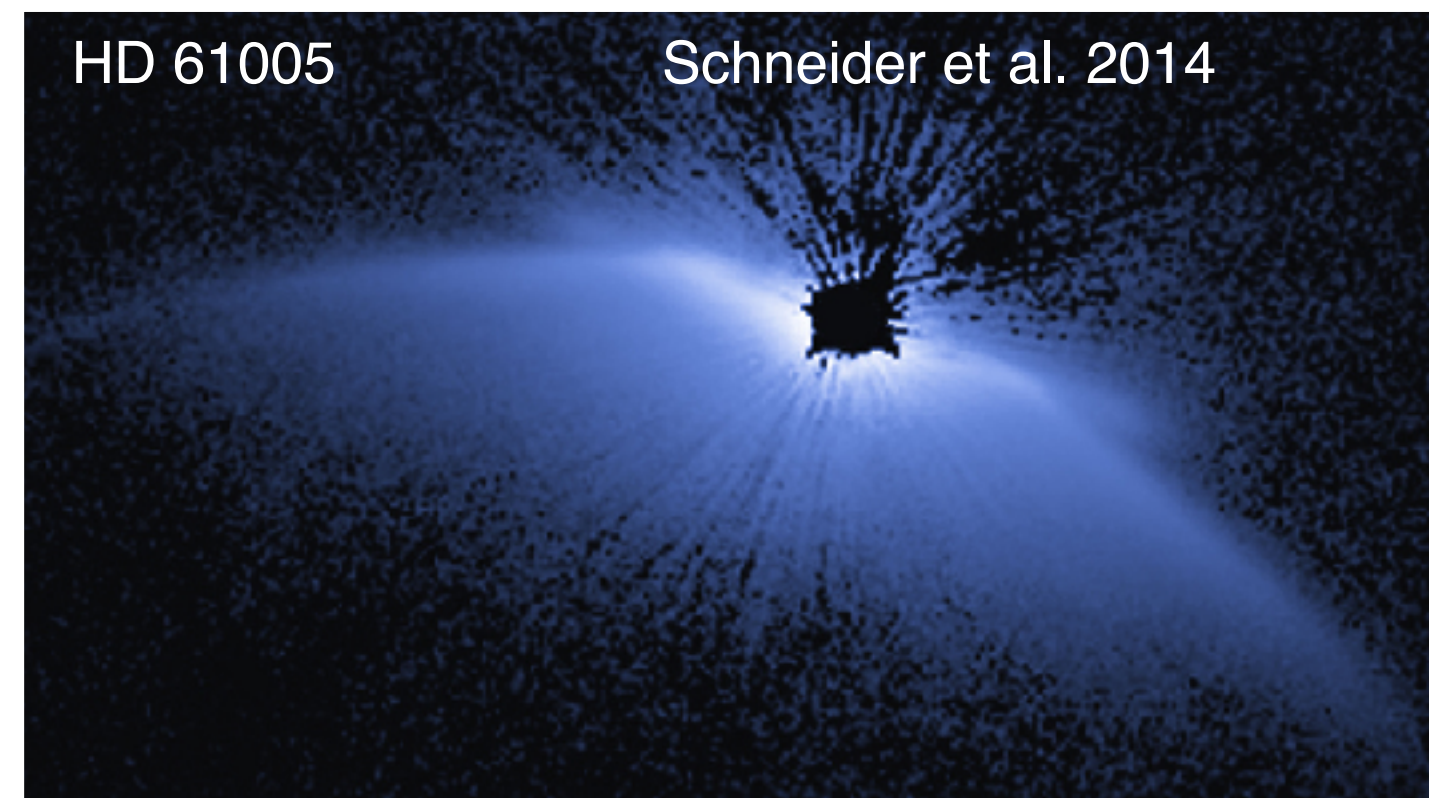
Fomalhaut Kalas et al. 2008



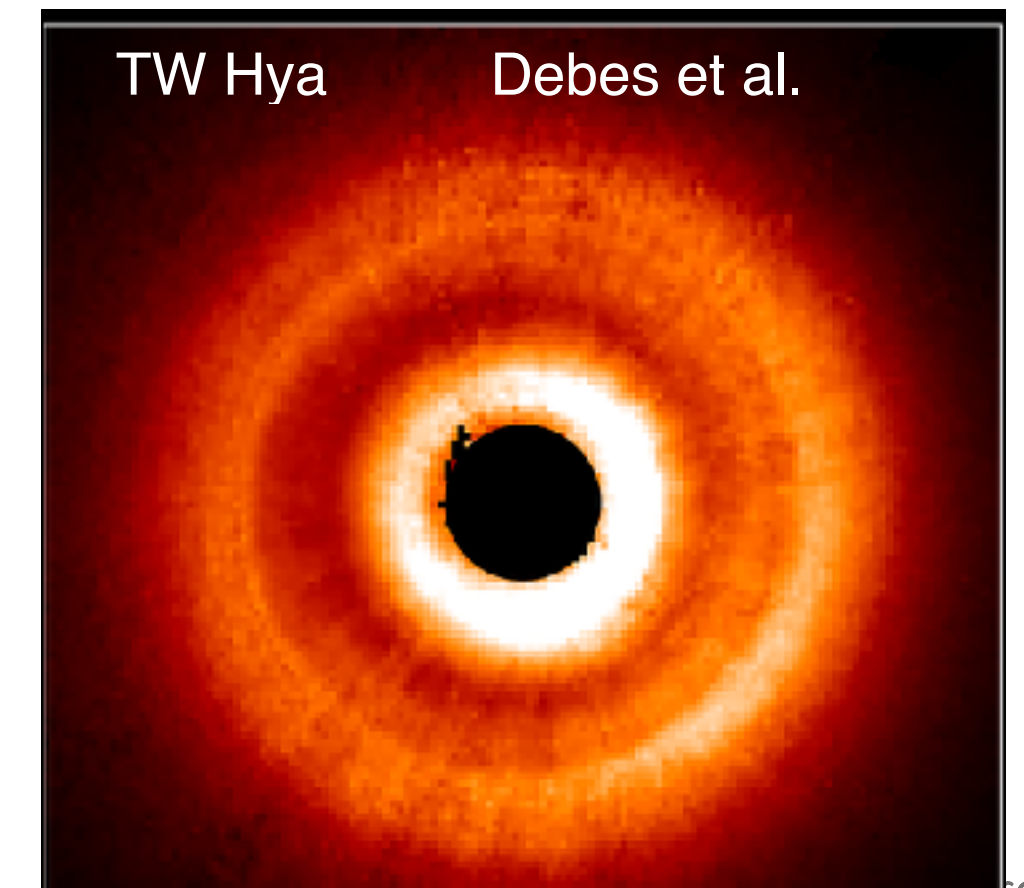
AB Aur Perrin et al. 2009



HD 61005 Schneider et al. 2014

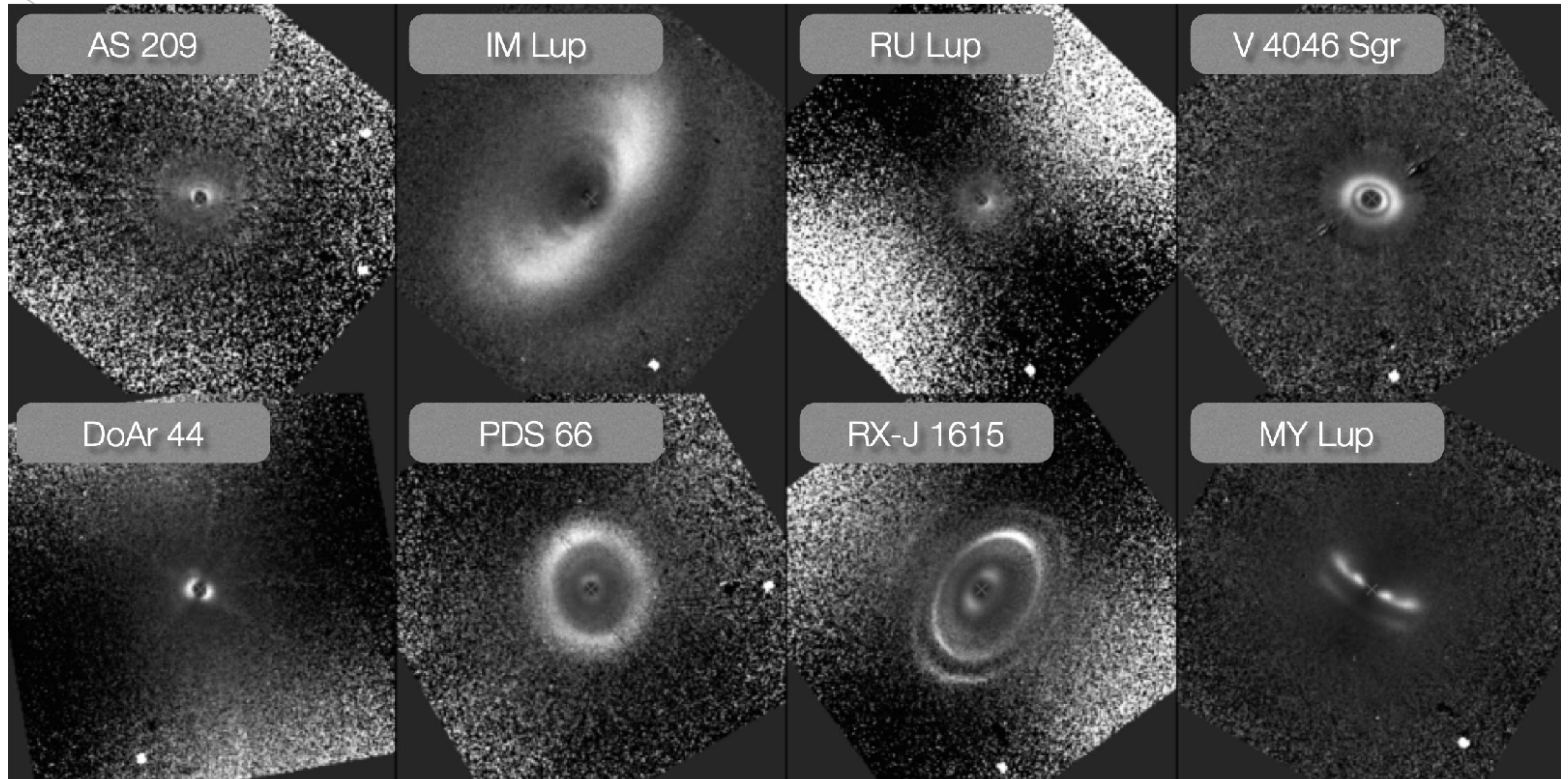


TW Hya Debes et al.





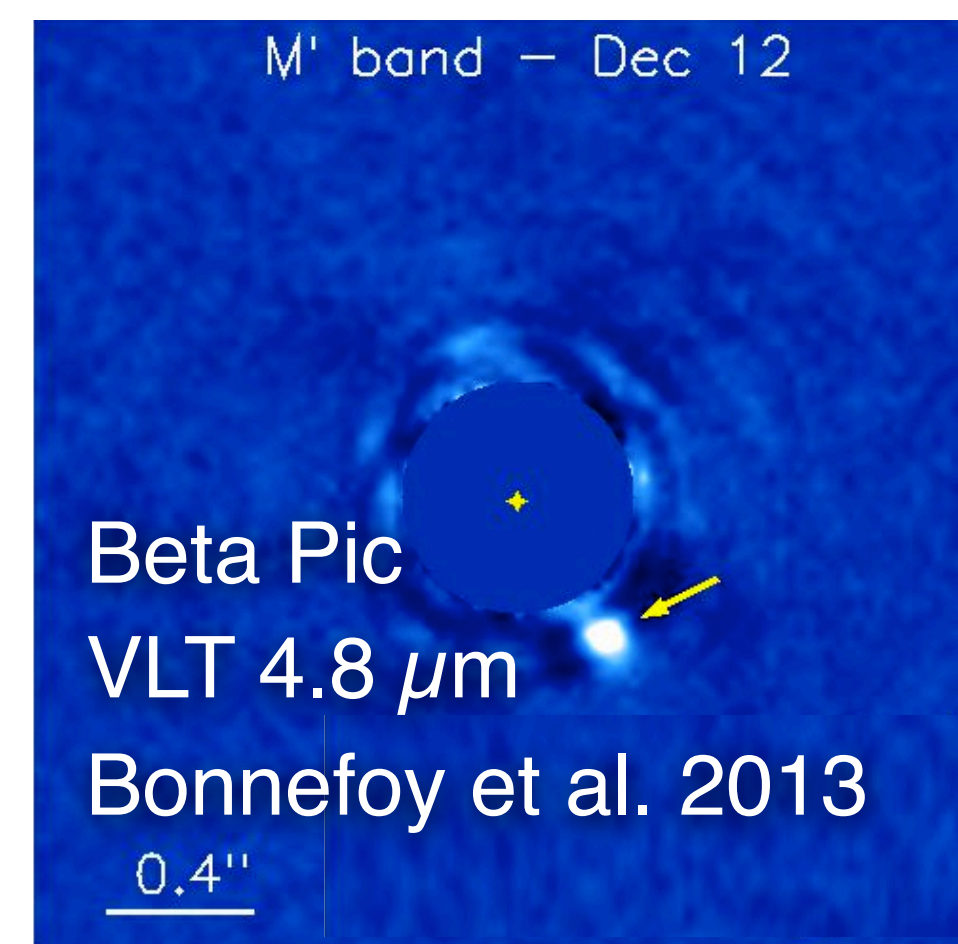
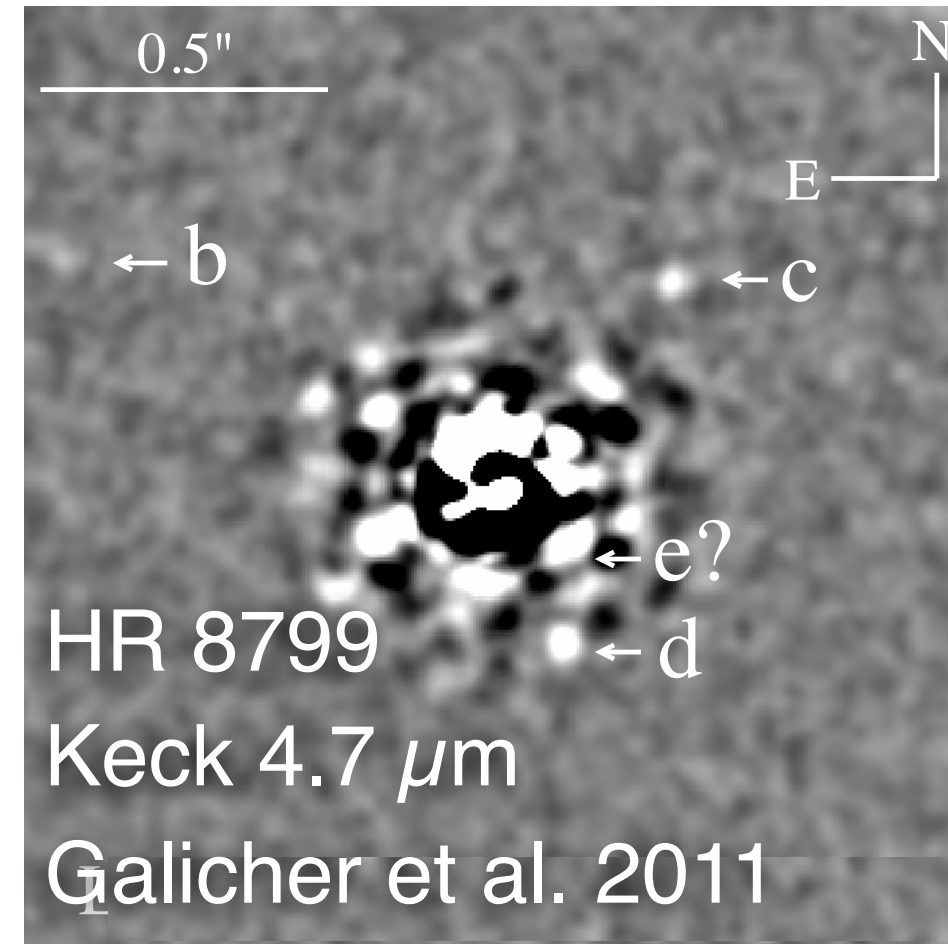
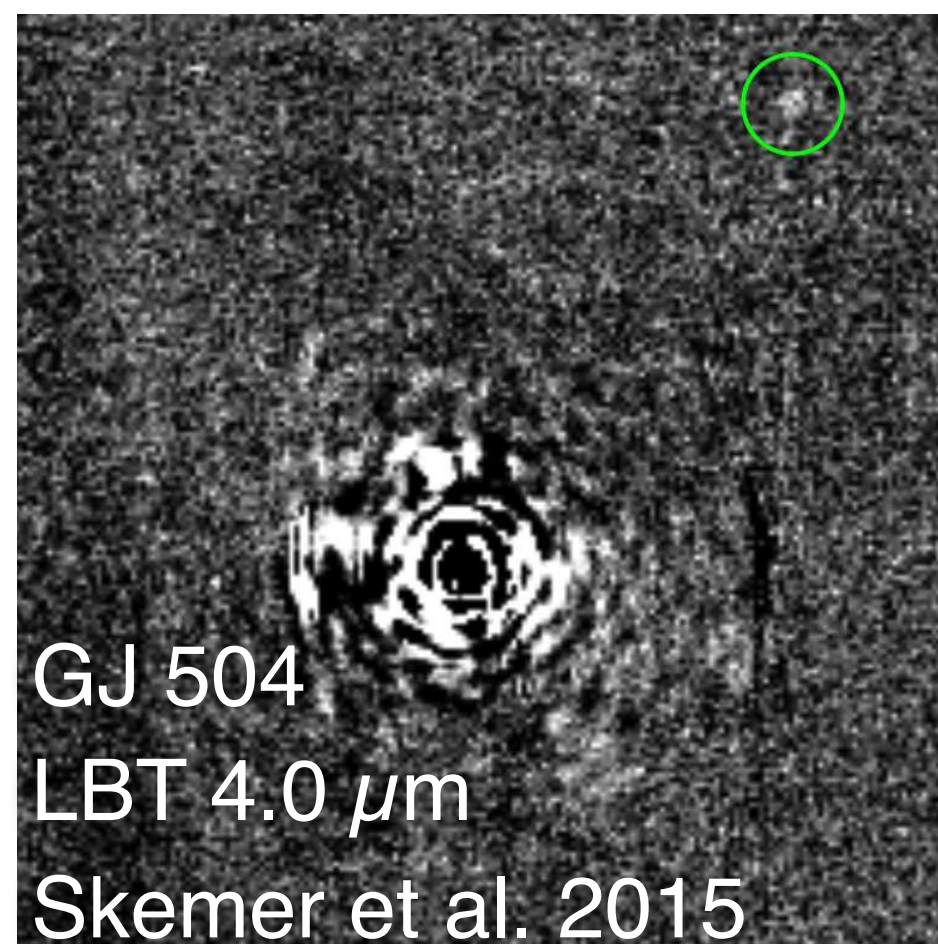
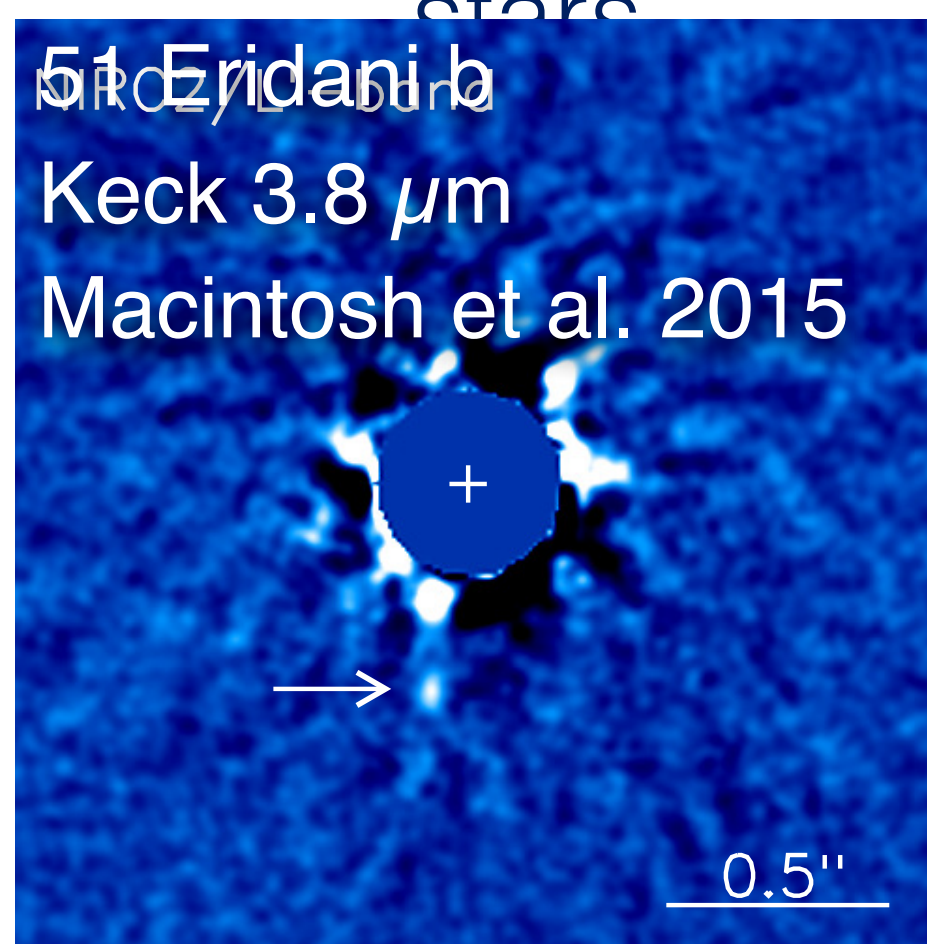
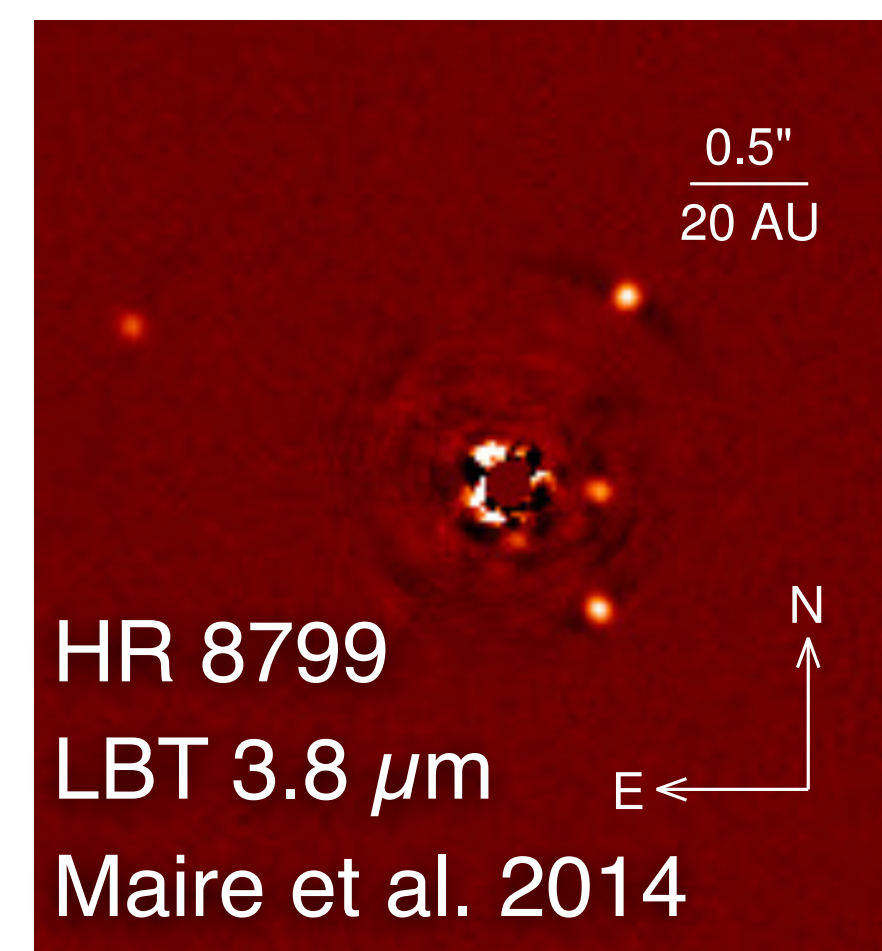
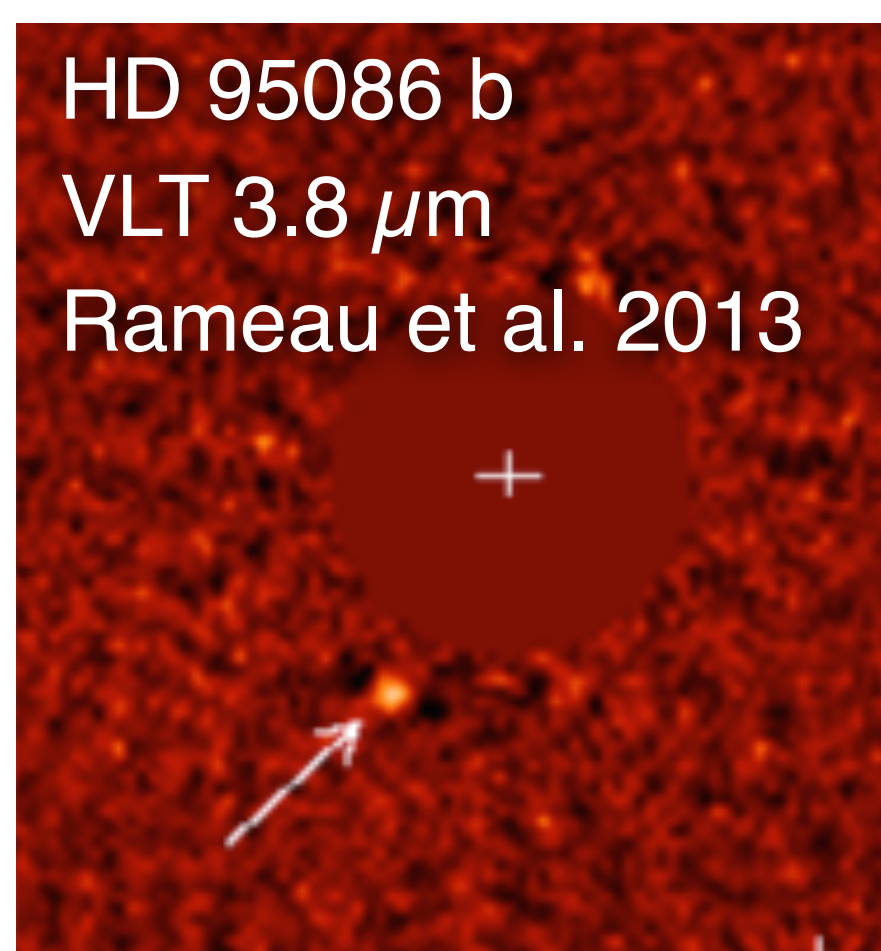
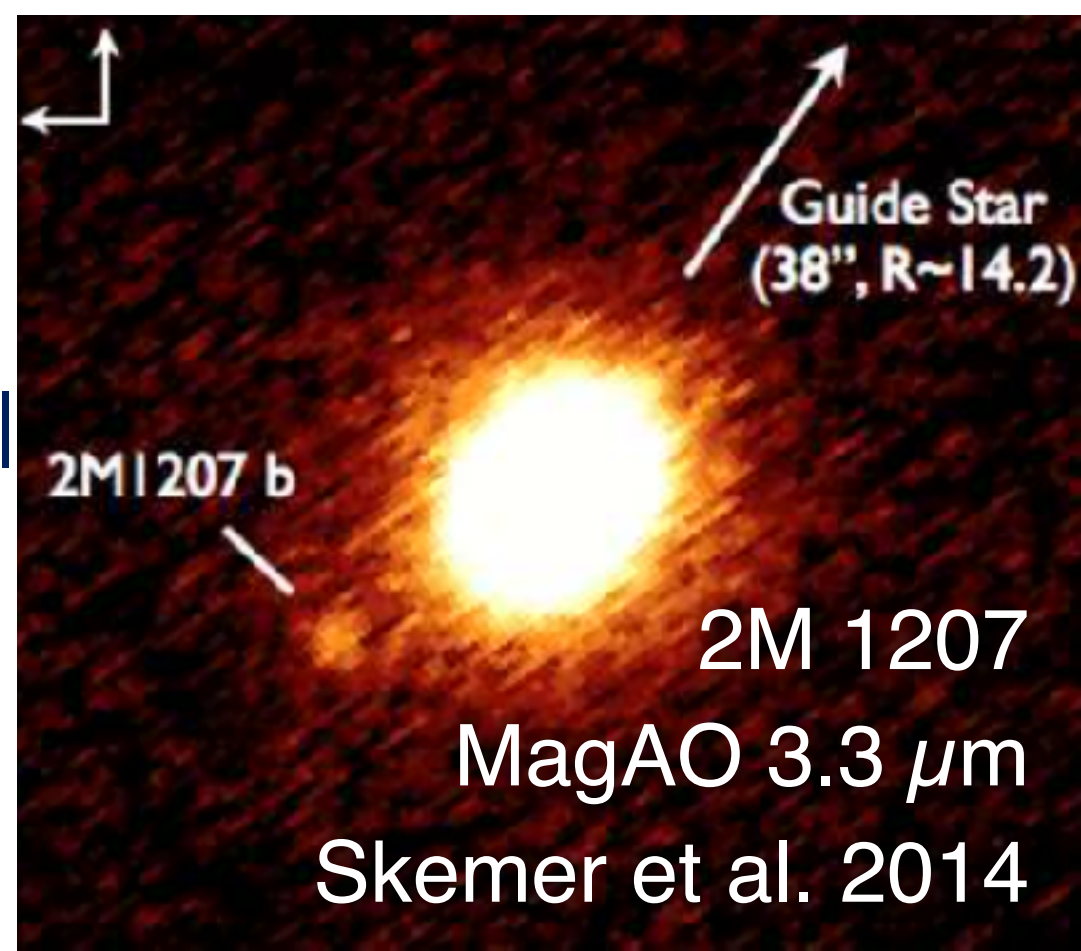
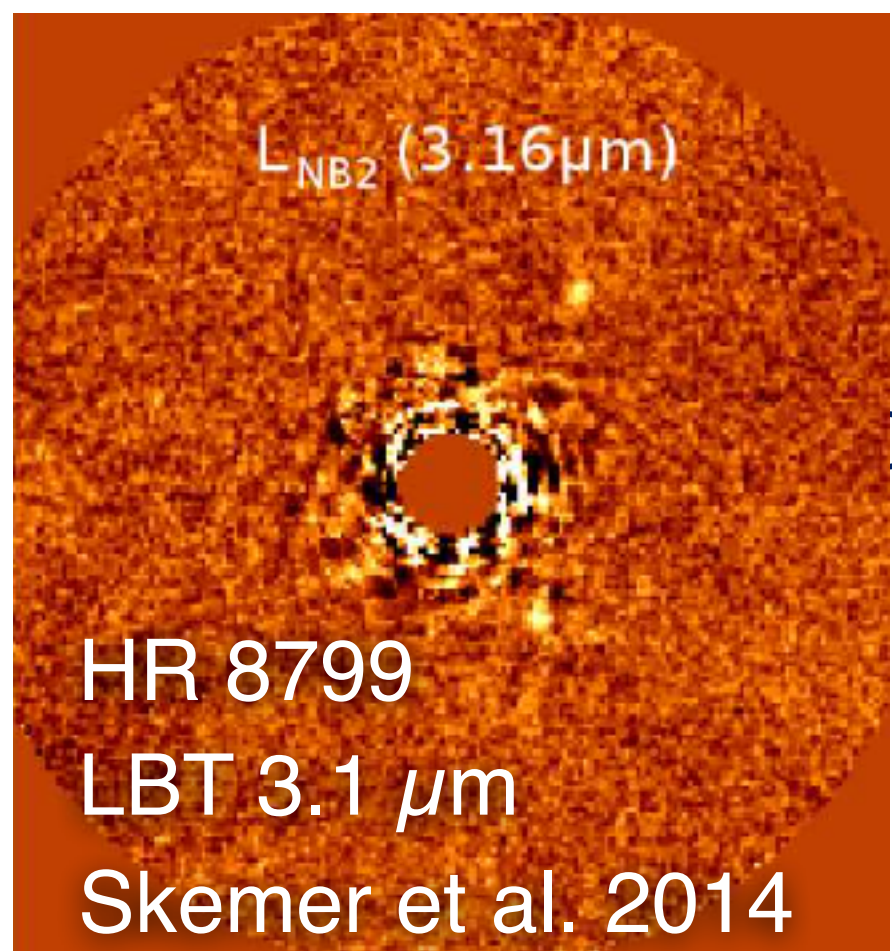
Coronagraphic images of disks in scattered light from the ground



Gallery, courtesy of H. Avenhaus (SPHERE J-band, Polarized scattered light, FWHM ~ 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, $z \sim 0.3$

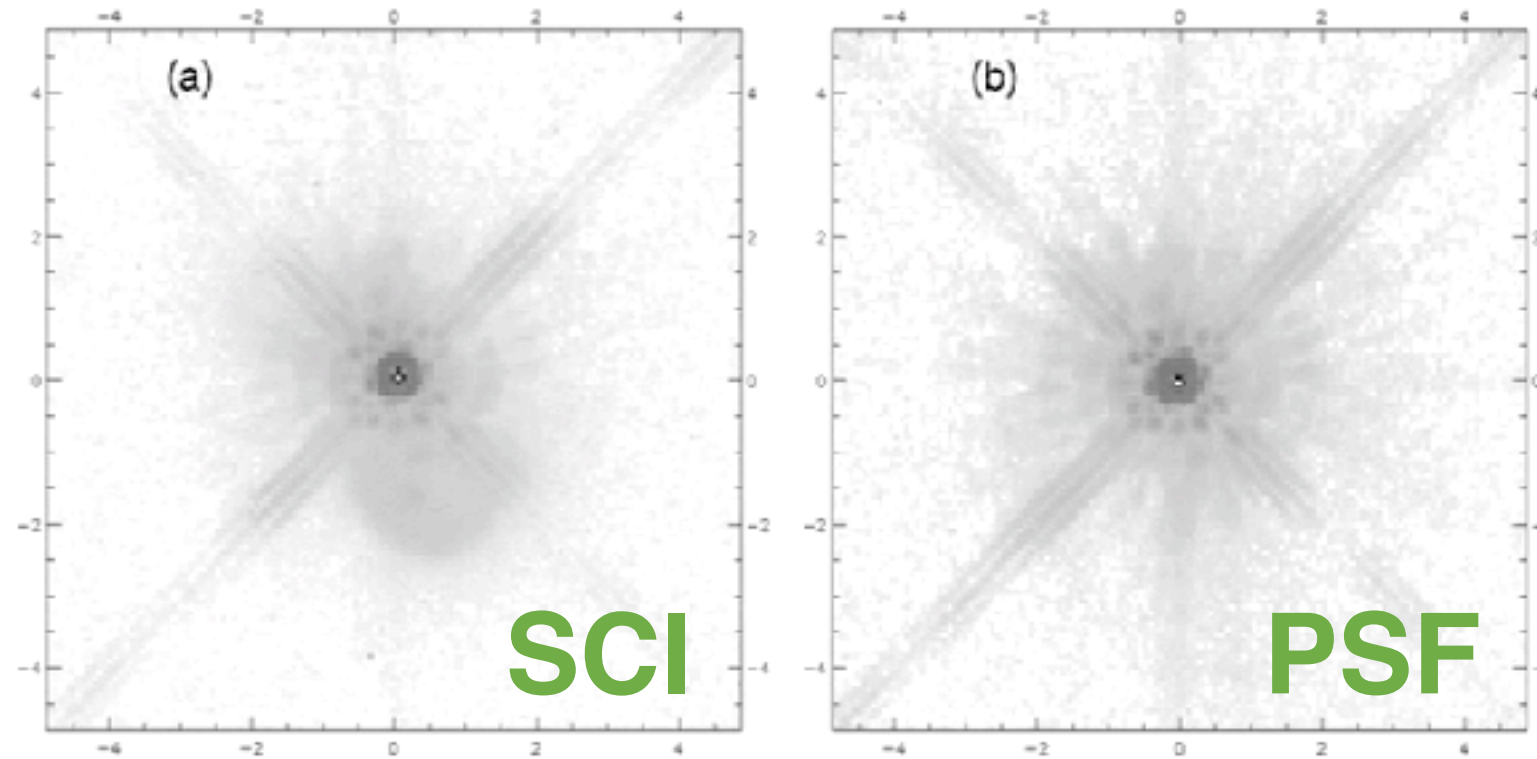
Host Galaxies & Molecular Gas

HST/NICMOS F160W (\sim H-band)

Imaging

1997

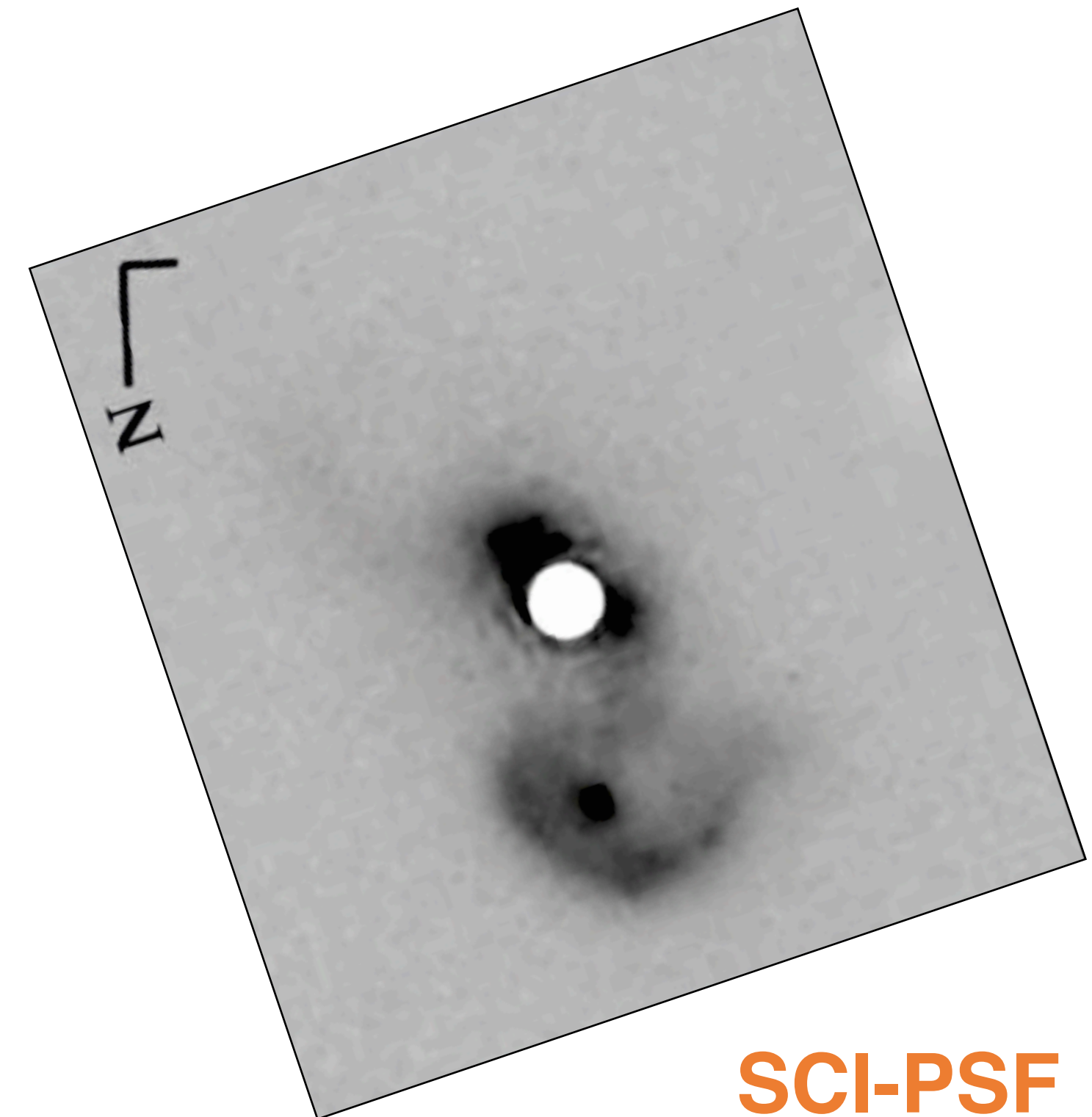
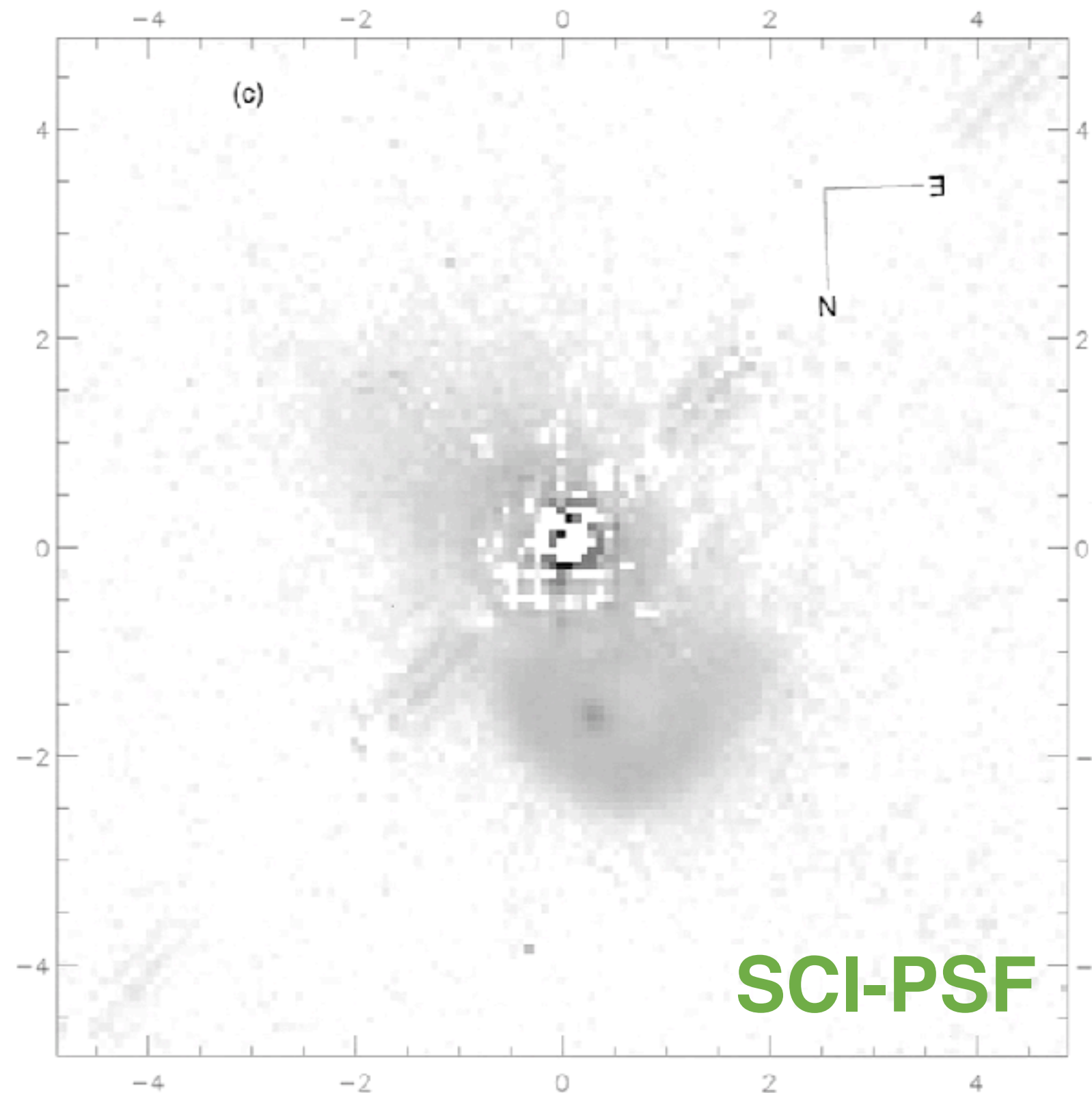
Hines et al. 1999



Coronagraphy

1998

Evans et al. 2009



SCI-PSF





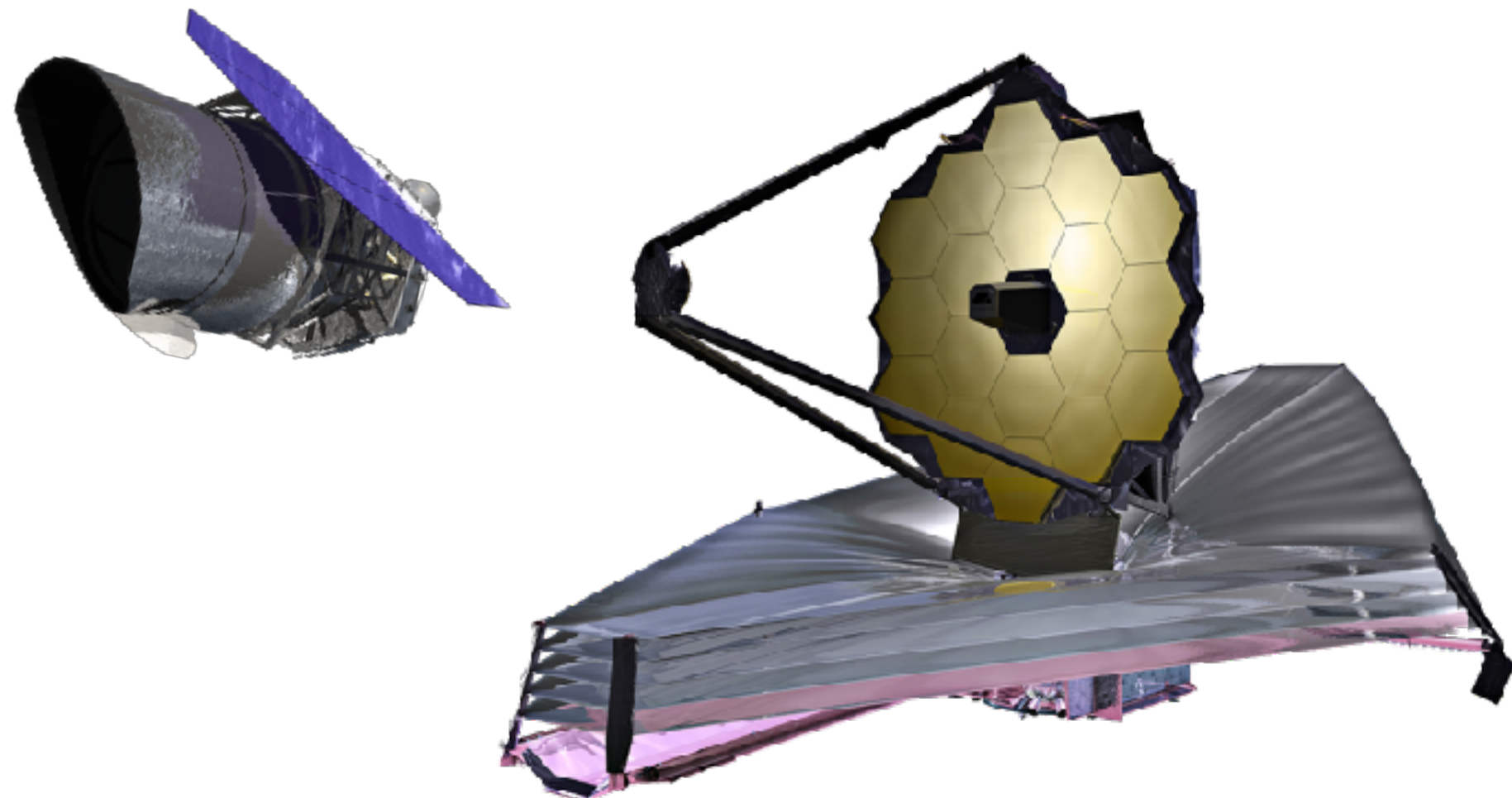
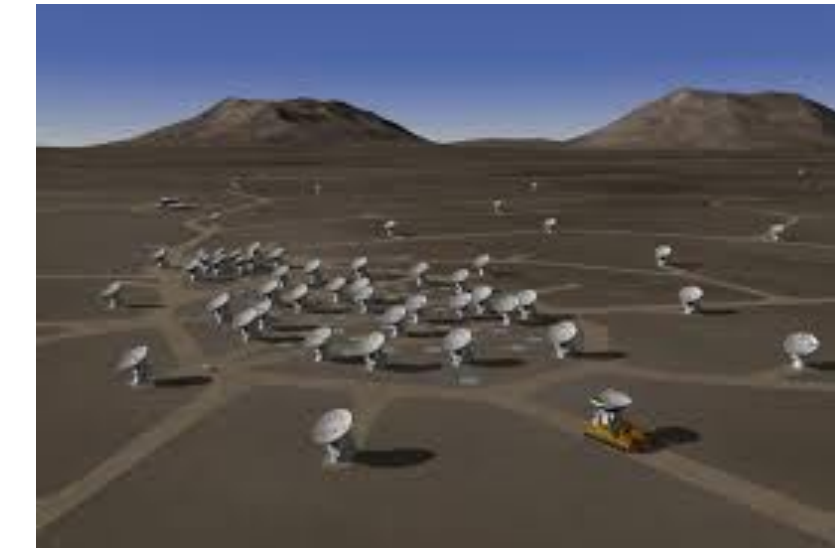
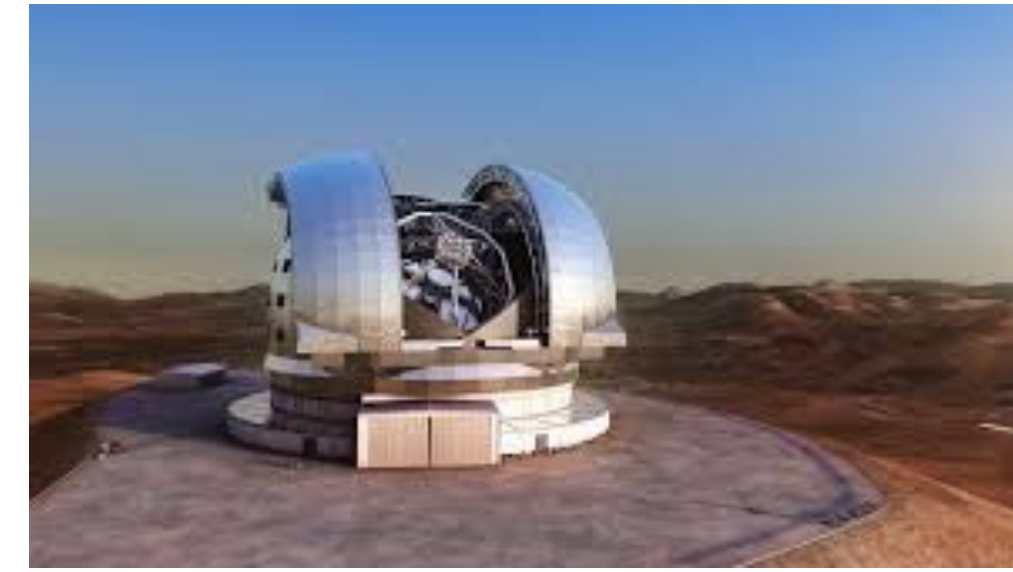
Complementarity Ground Space, great era for Direct Imaging

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)

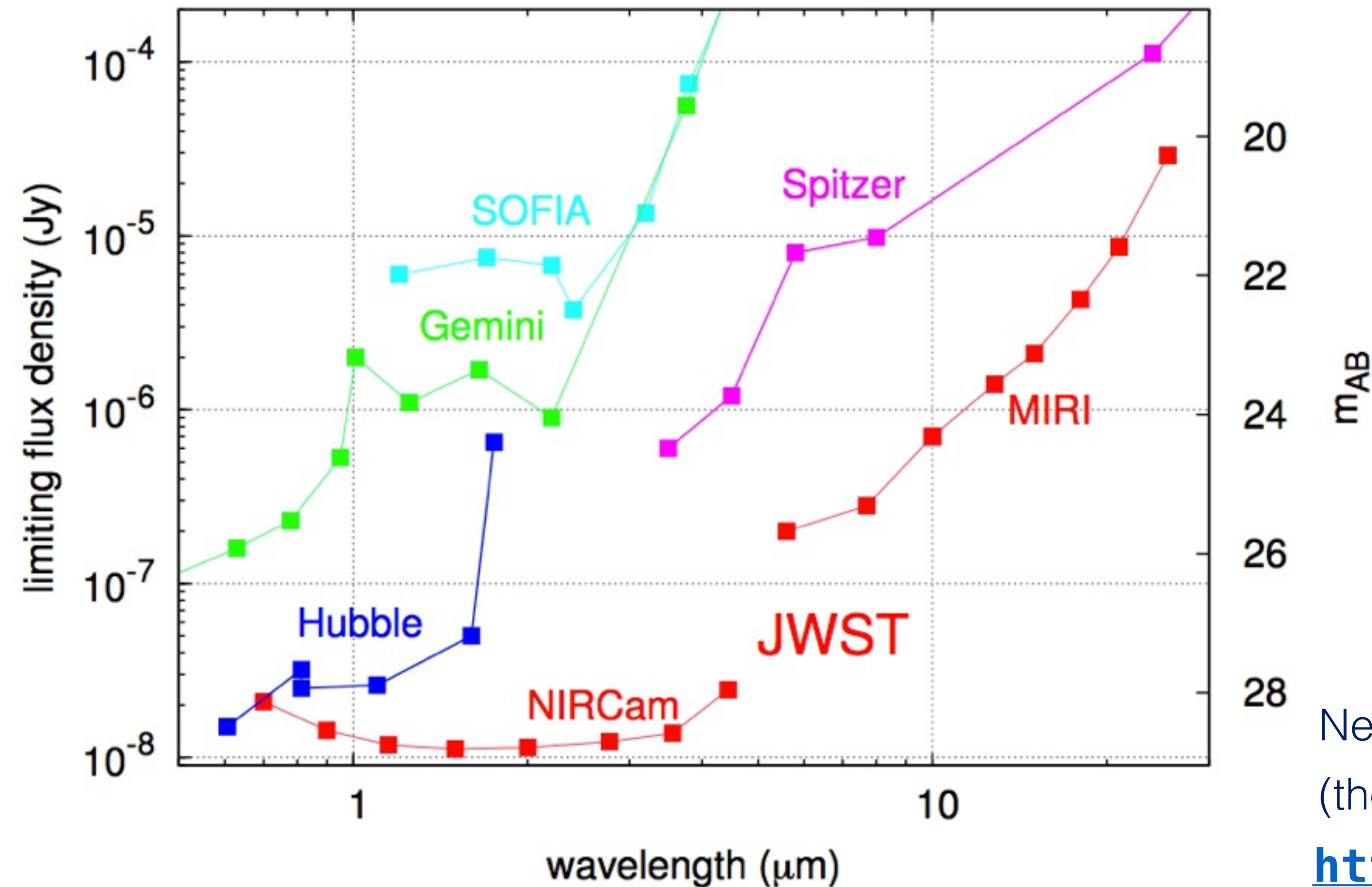
PSF homogeneity

No atmospheric bands



JWST: dramatically better sensitivity > 1.5 μm

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



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

~ 100 x more sensitive at $2 \mu\text{m}$

~ 1000 x more sensitive at $4 \mu\text{m}$

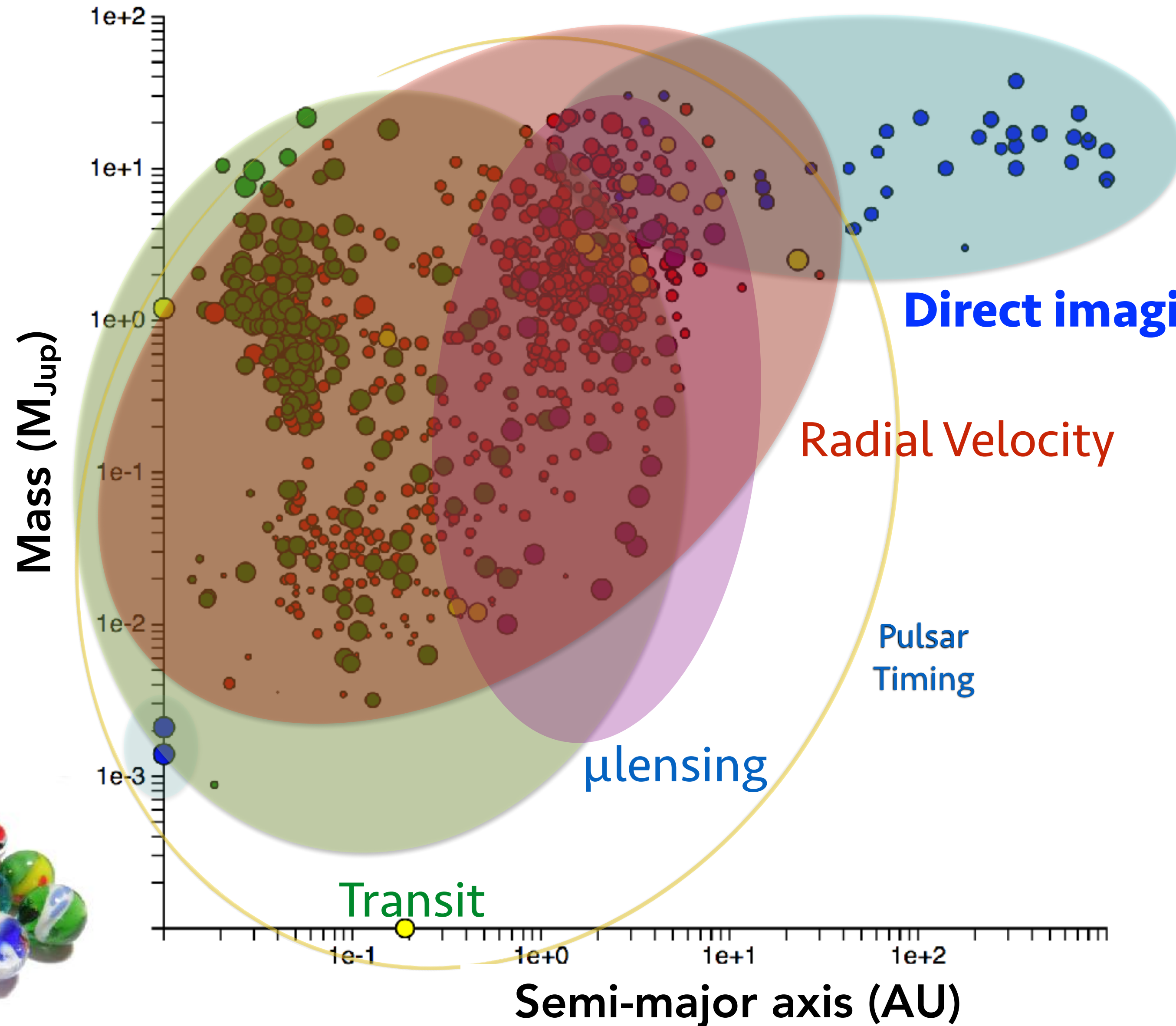
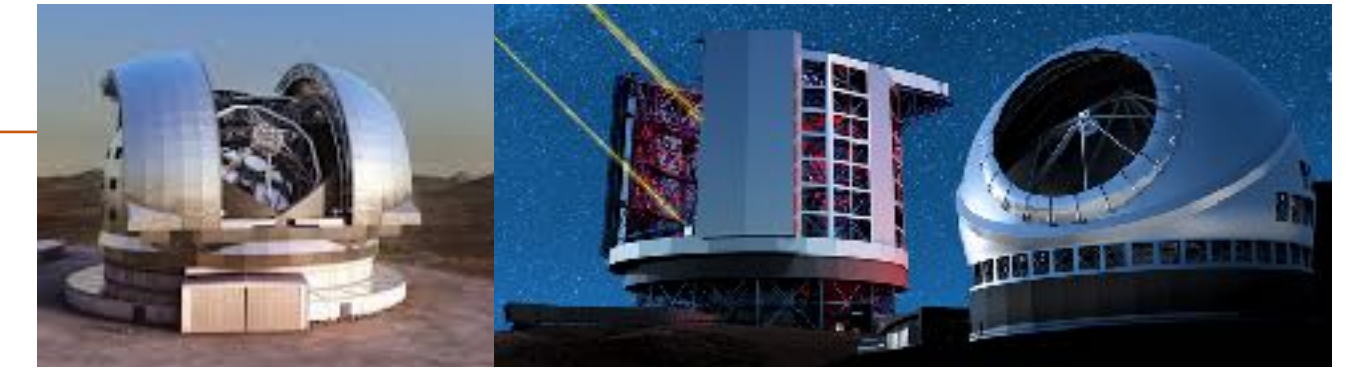
~ 30 x more sensitive than Spitzer at $10 \mu\text{m}$ and with better angular resolution

New Tool to explore sensitivity
(though no HCI)

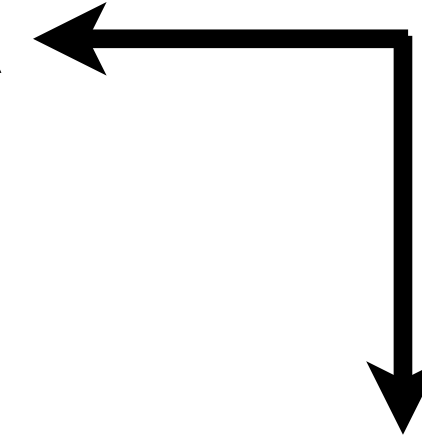
<http://jist.stsci.edu>



Exoplanet census & detection techniques



IWA



Direct imaging

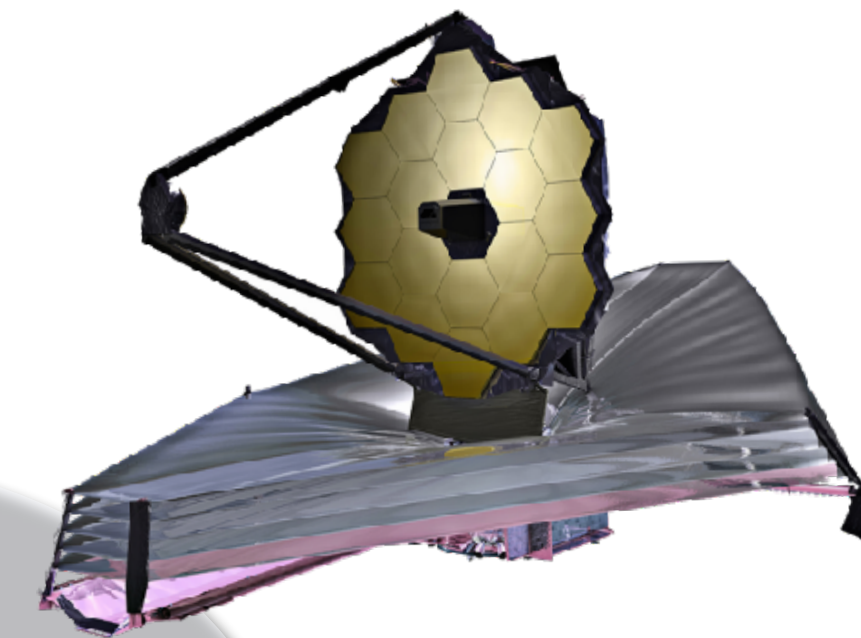
Radial Velocity

Pulsar Timing

microlensing

Transit

CONTRAST, SENSITIVITY

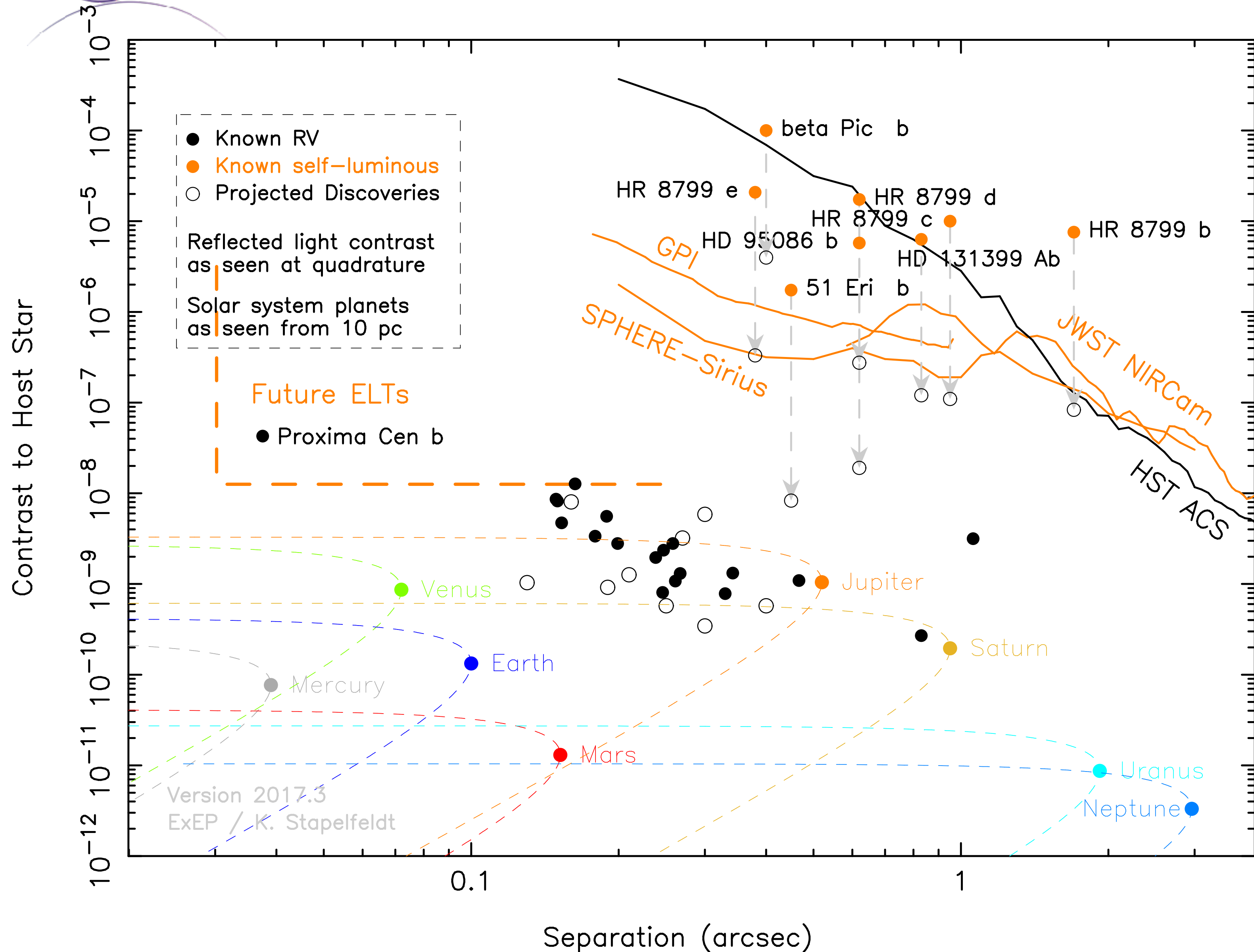


+ free floating super-jupiters



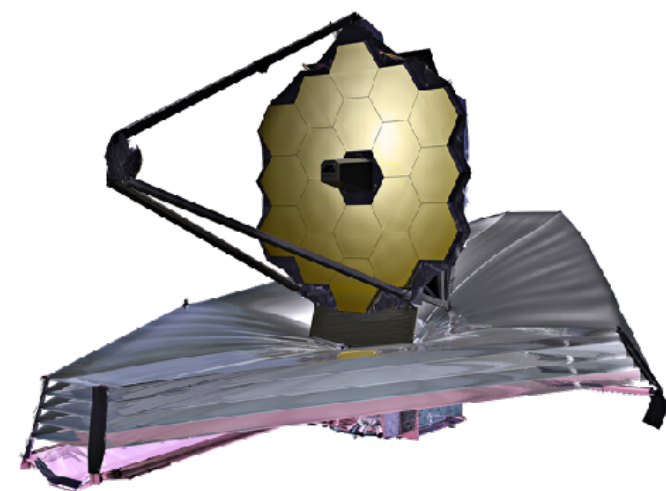


Great complementarity ground/space, great era for direct imaging



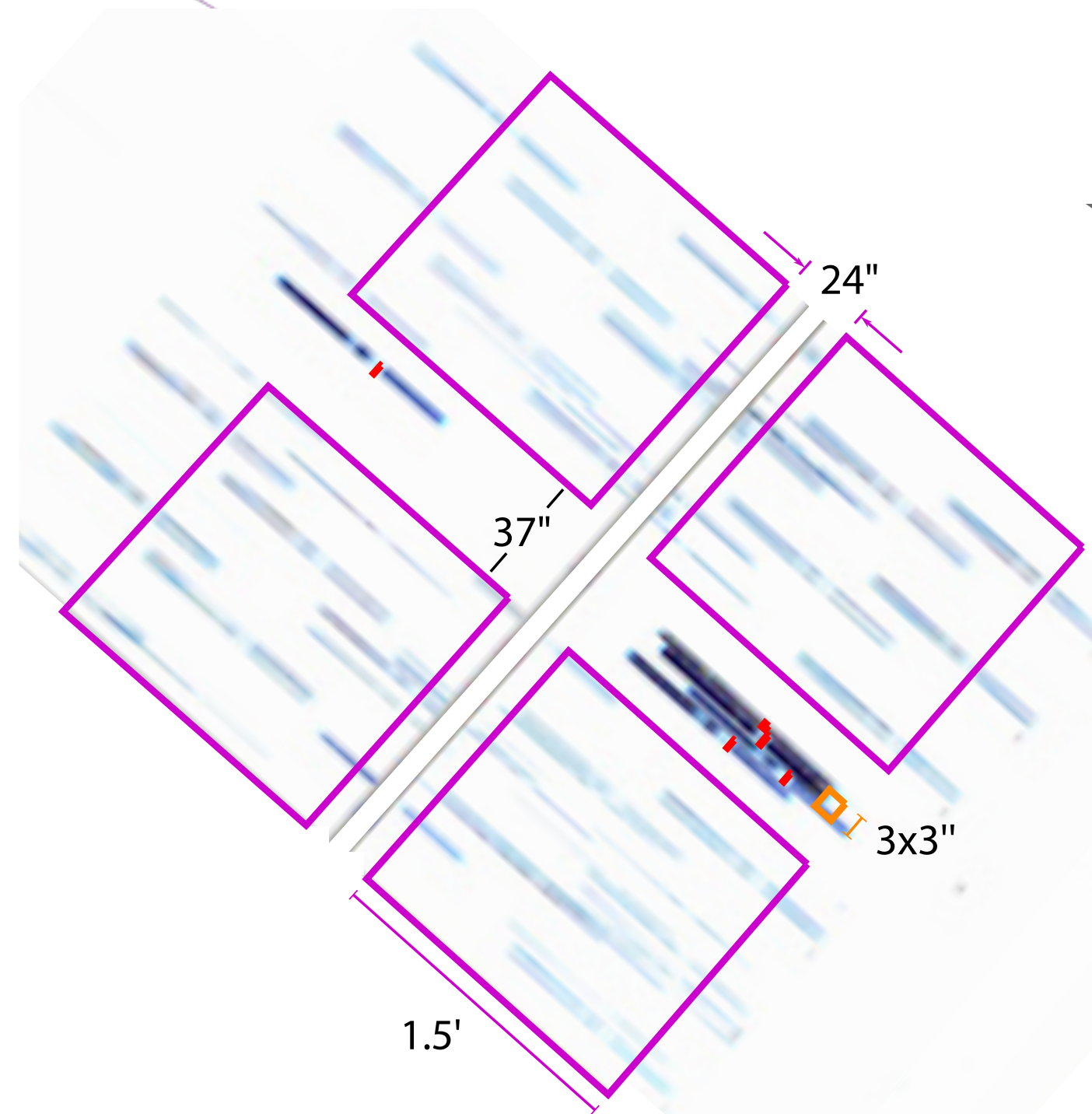
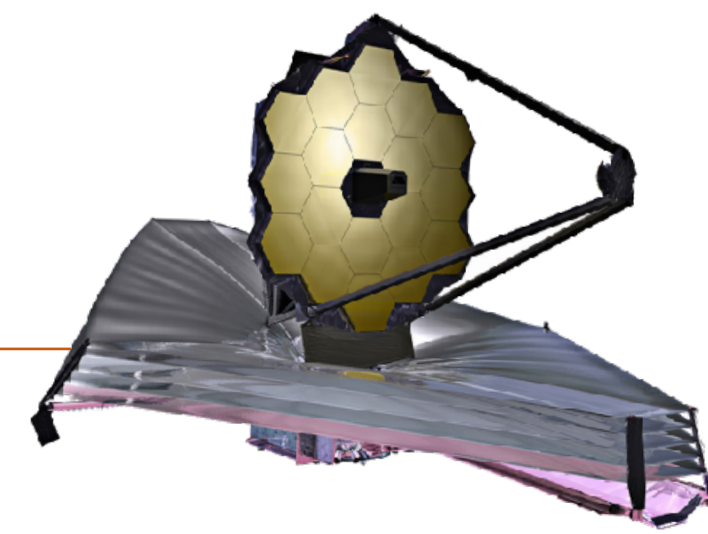
Ground with
 eXtreme Adaptive Optics:
 spatial (best IWA)
 & spectral resolutions,
 multiplexing, upgrades

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

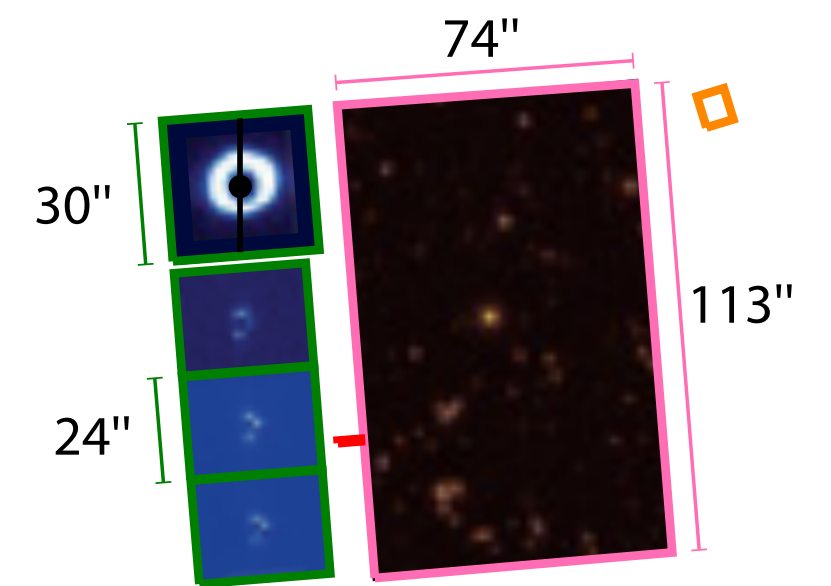
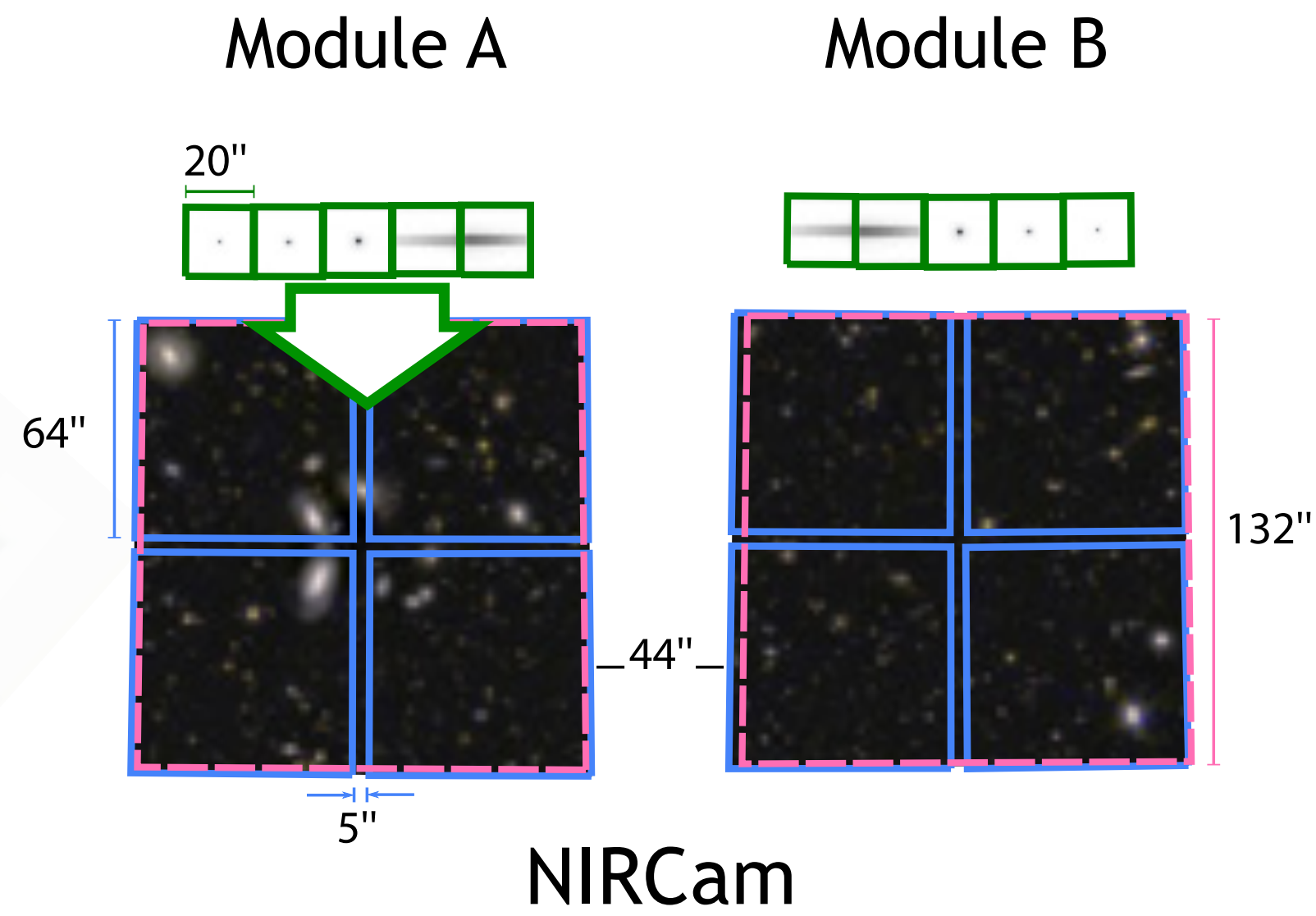




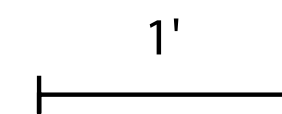
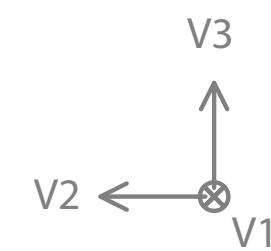
The JWST Focal Plane



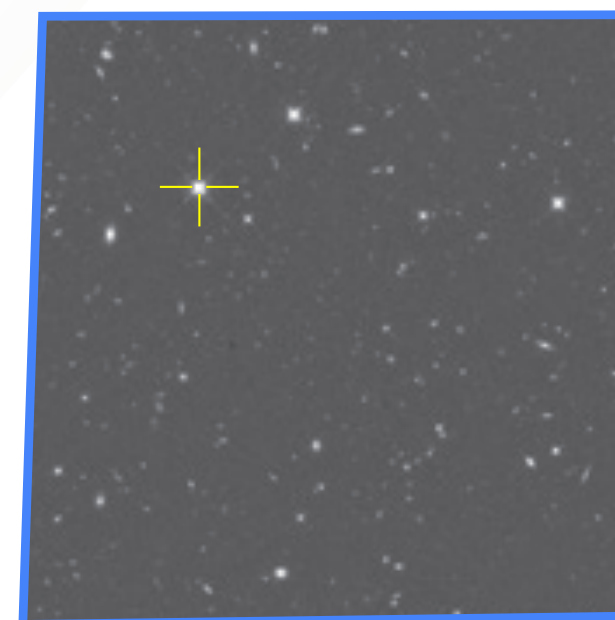
NIRSpec



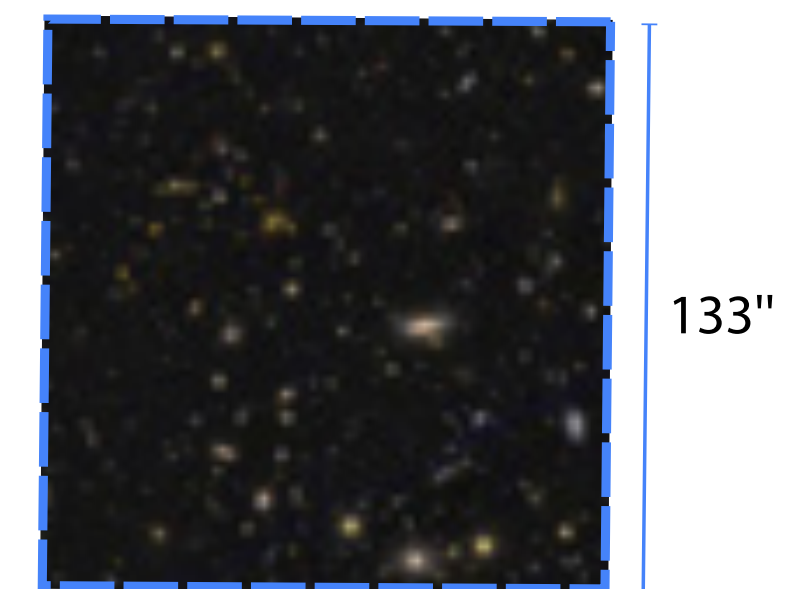
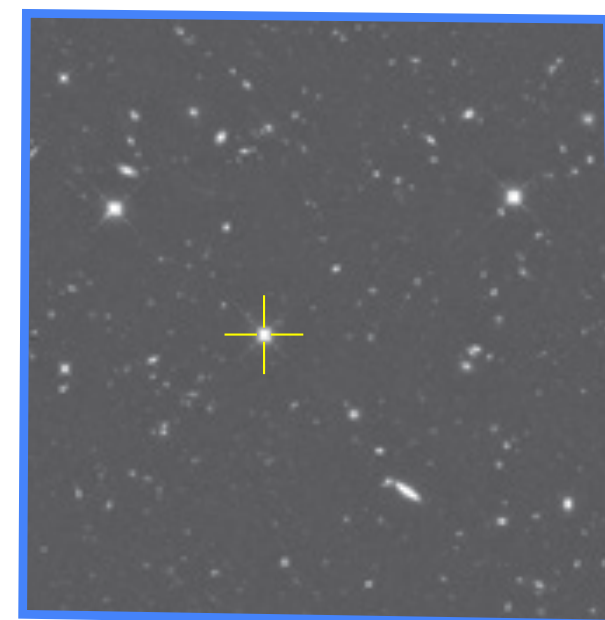
MIRI



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



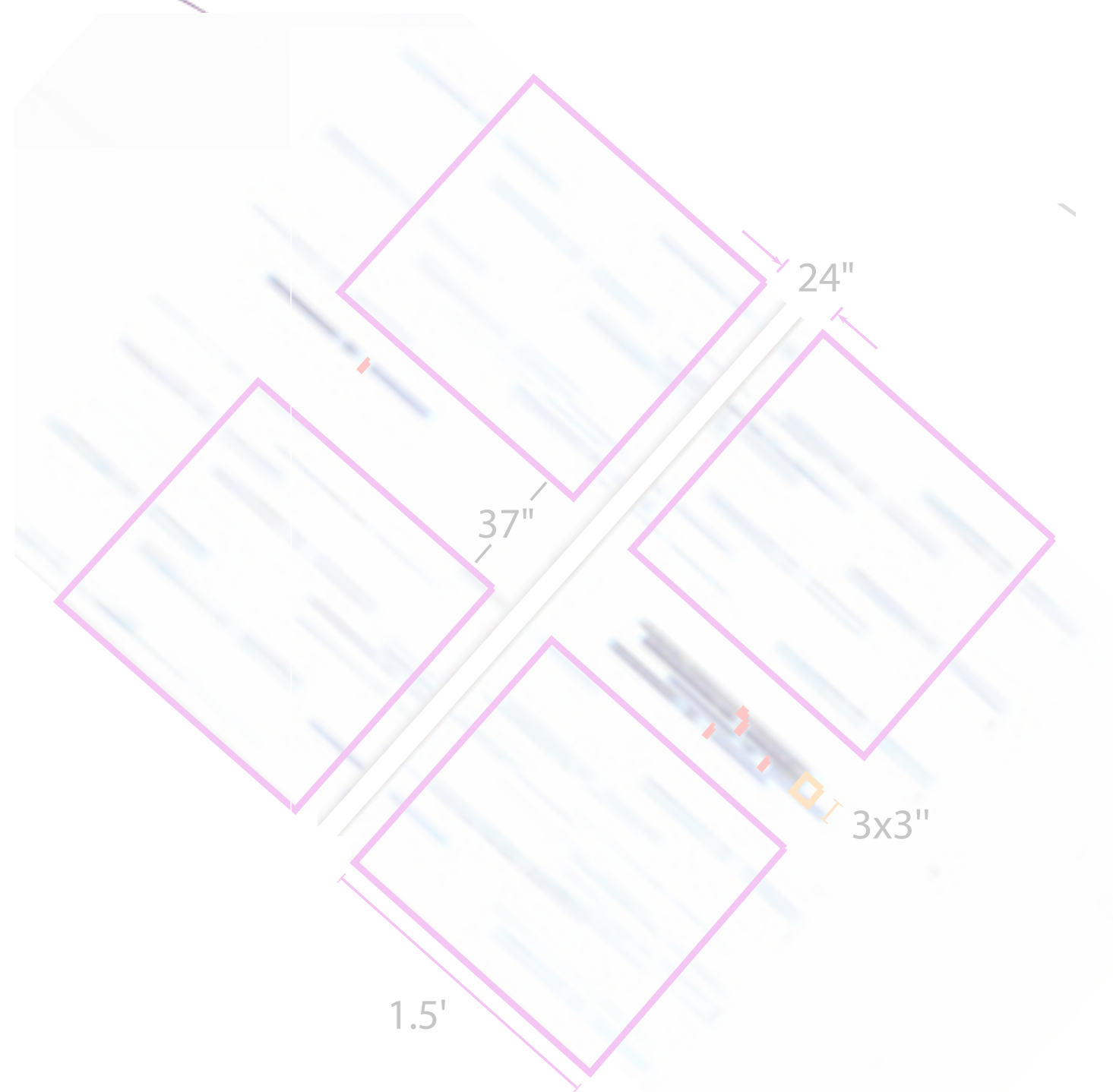
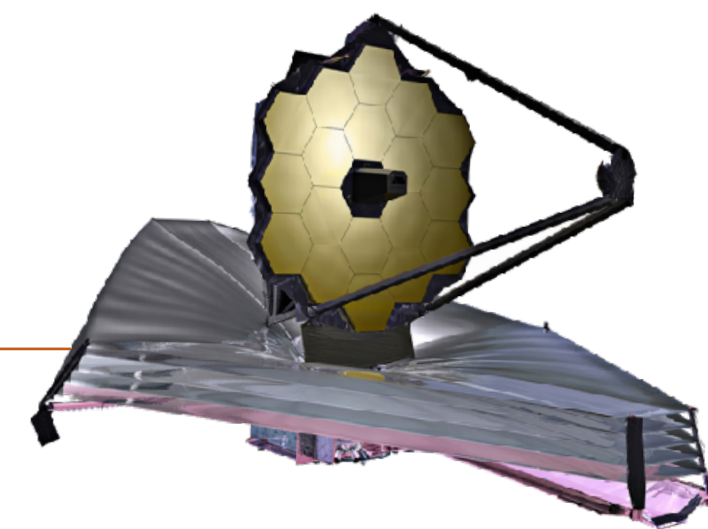
FGS



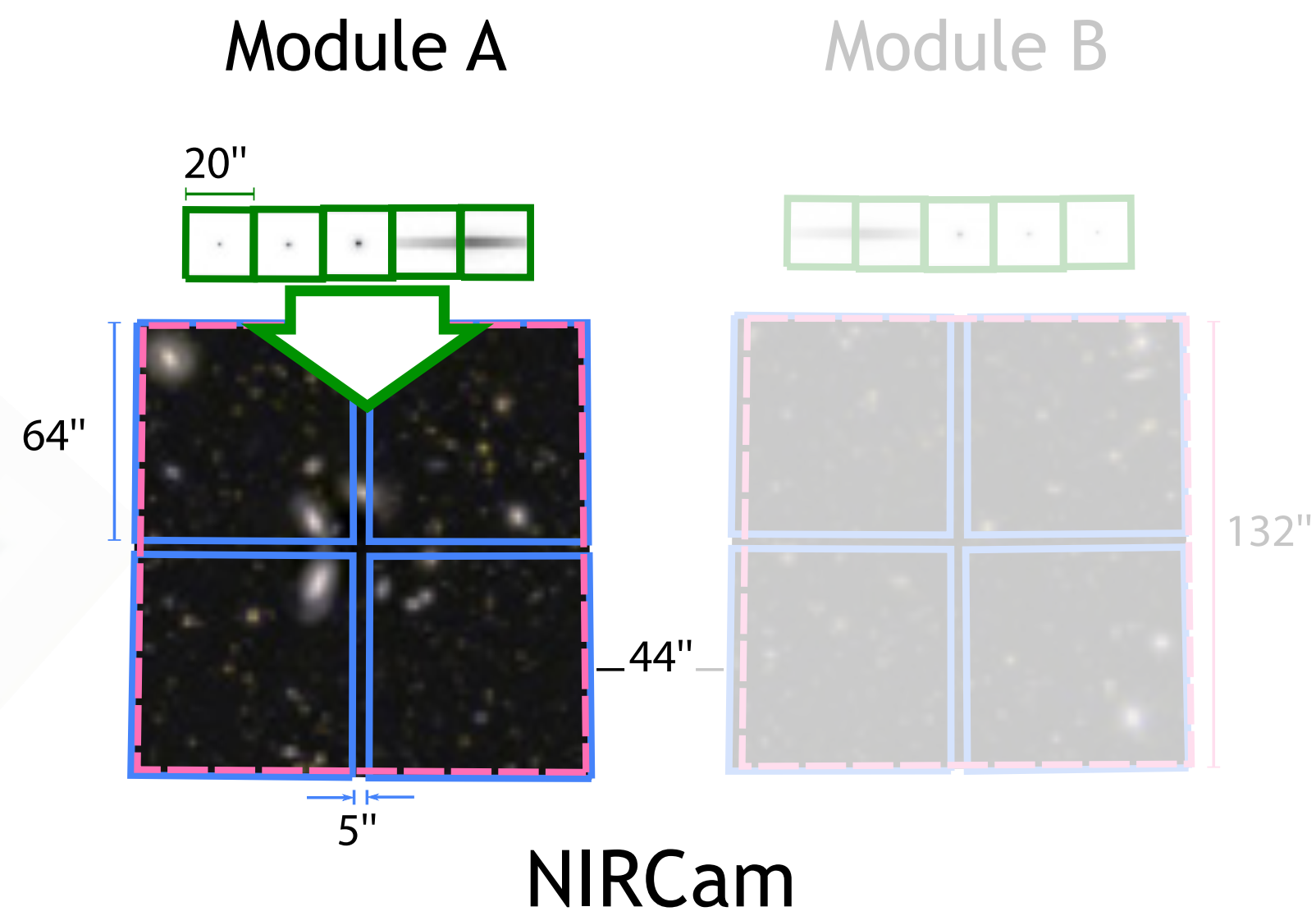
NIRISS



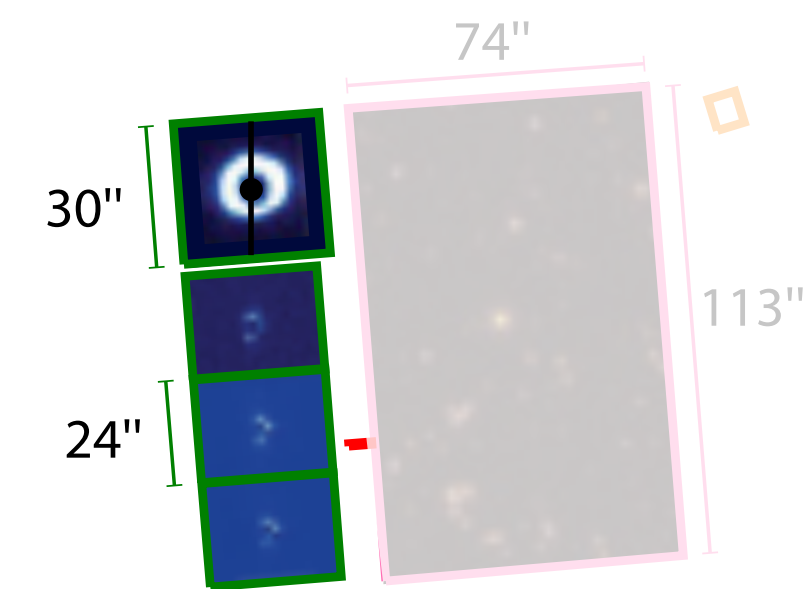
The JWST Focal Plane and main HCI instruments



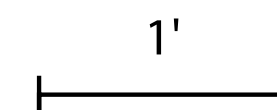
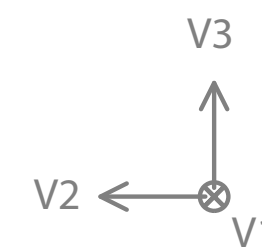
NIRSpec



NIRCam



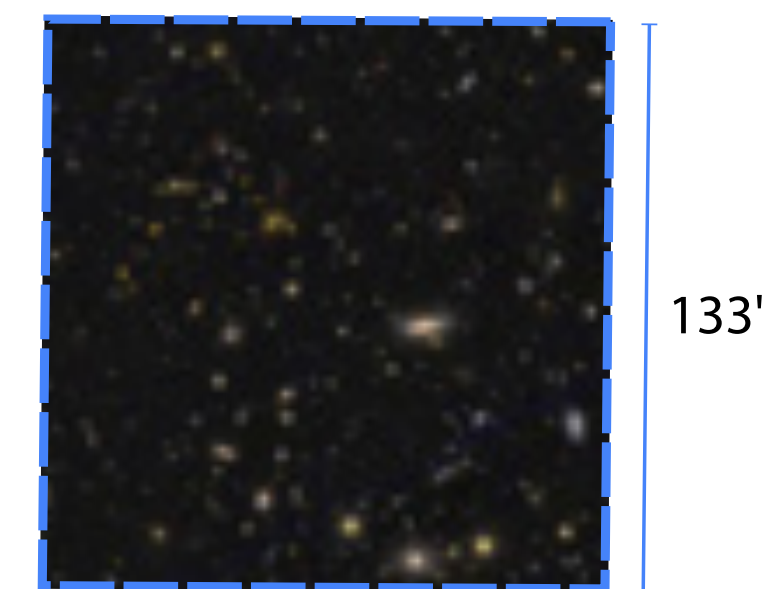
MIRI



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



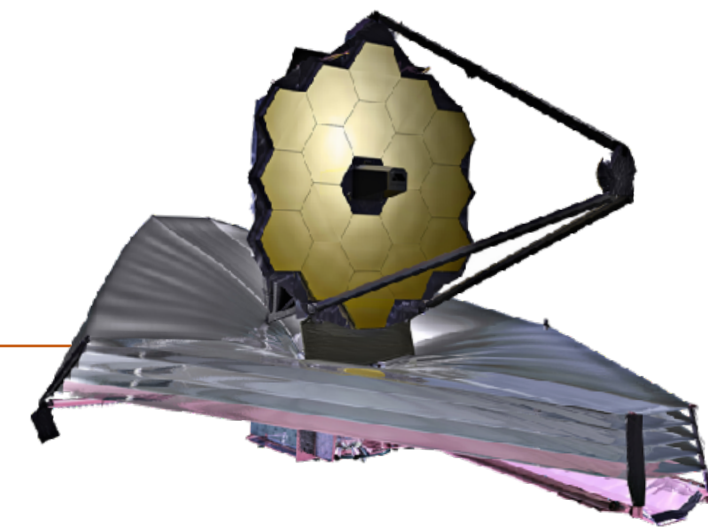
FGS



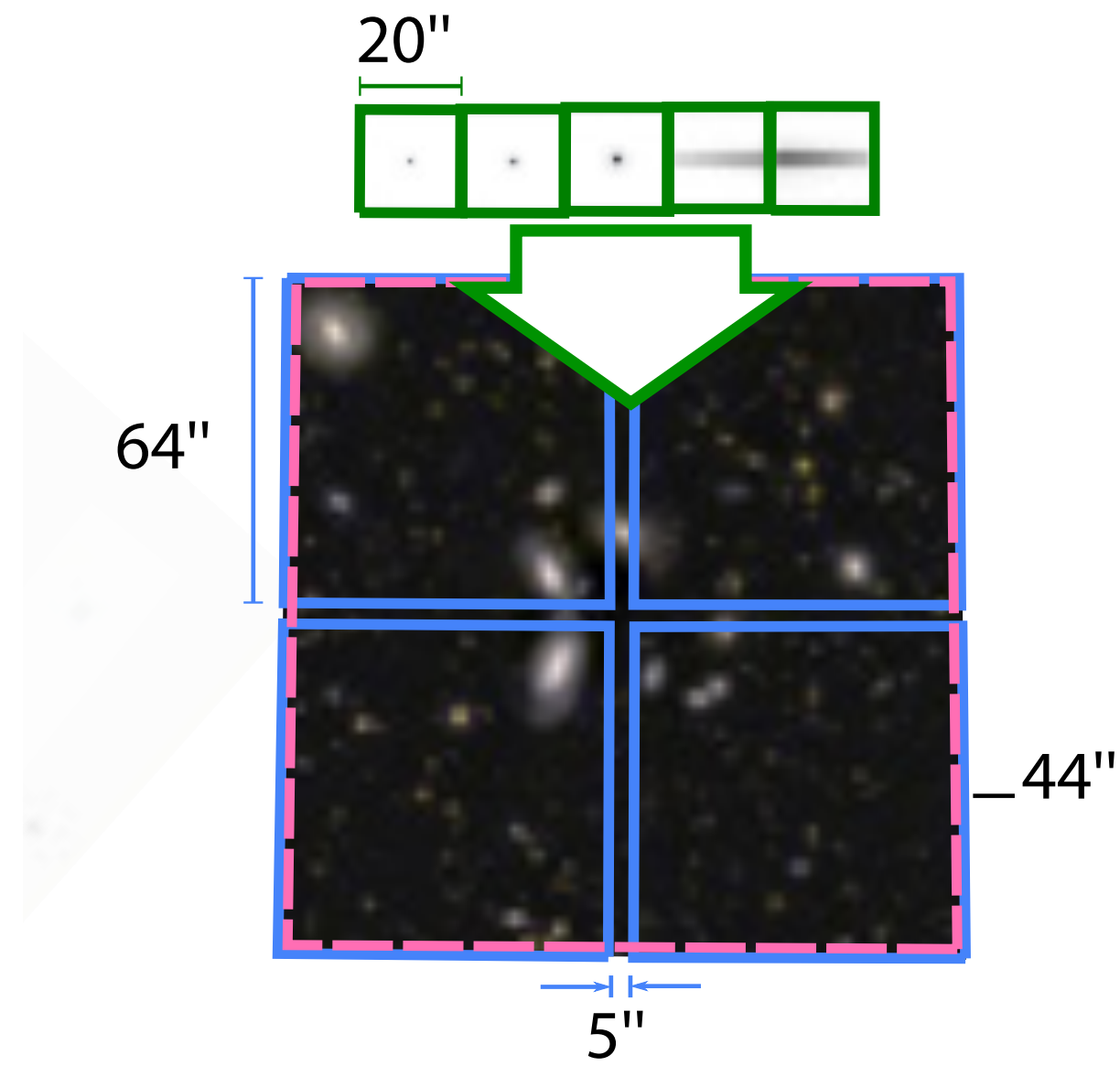
NIRISS



NIRCam & MIRI Coronagraphy in the JWST Focal Plane

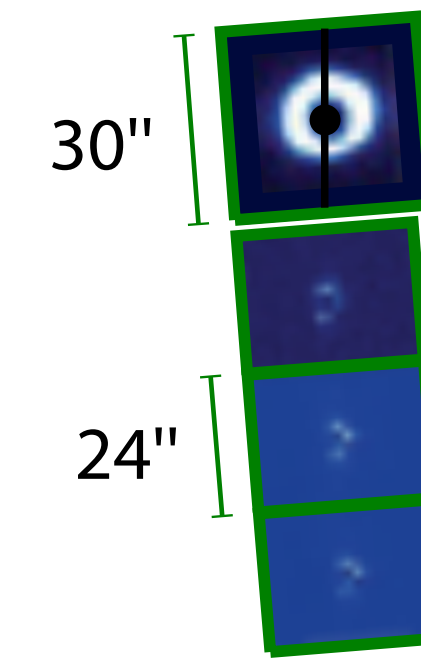


NIRCam



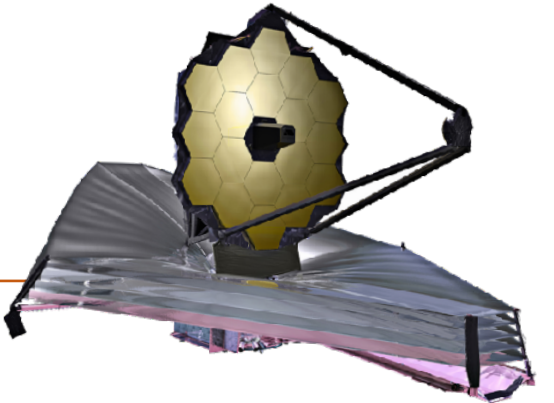
Module A

MIRI



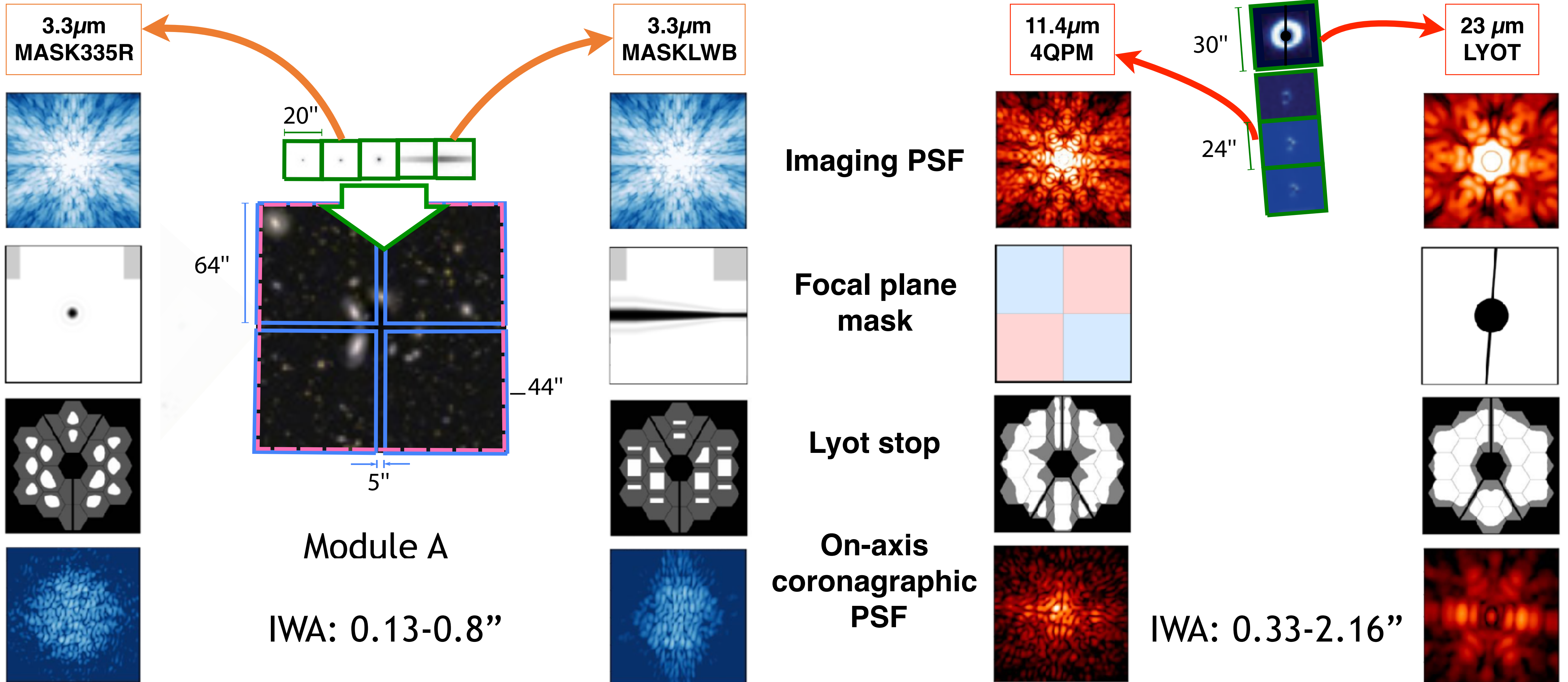


NIRCam & MIRI Coronagraphy in the JWST Focal Plane



NIRCam

MIRI

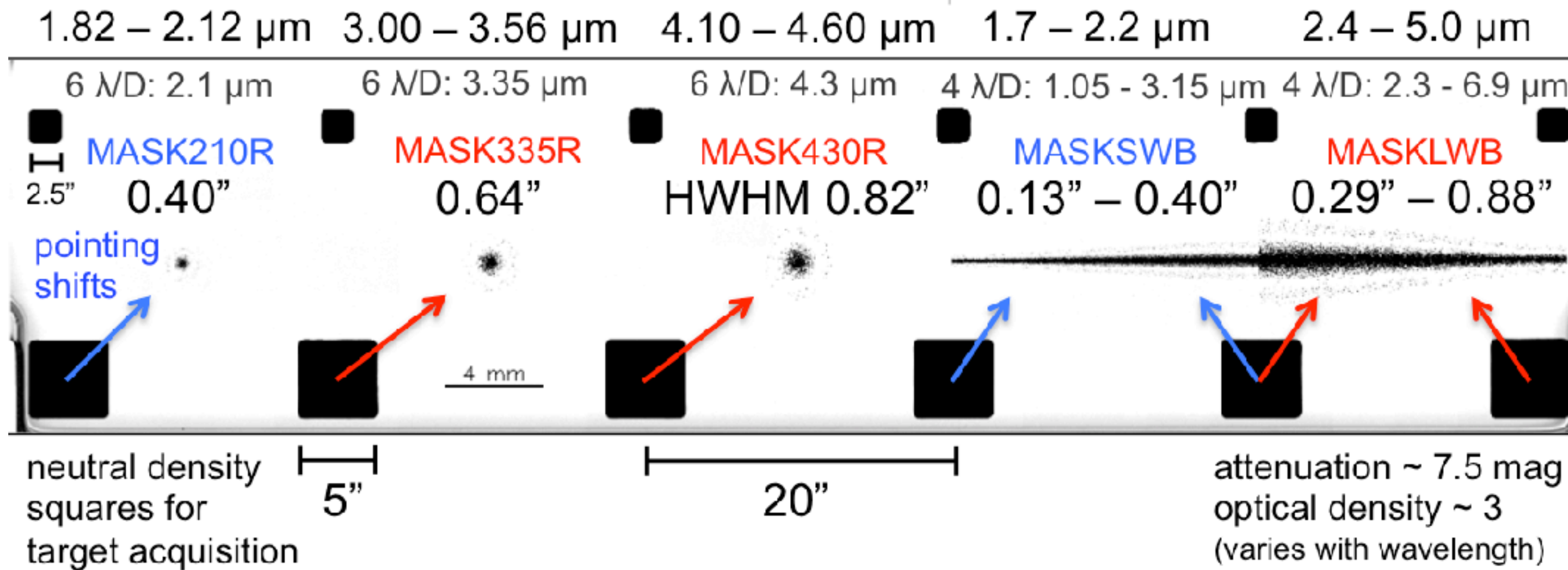




JWST NIRCam Coronagraphs

round masks

bar masks



| 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 |

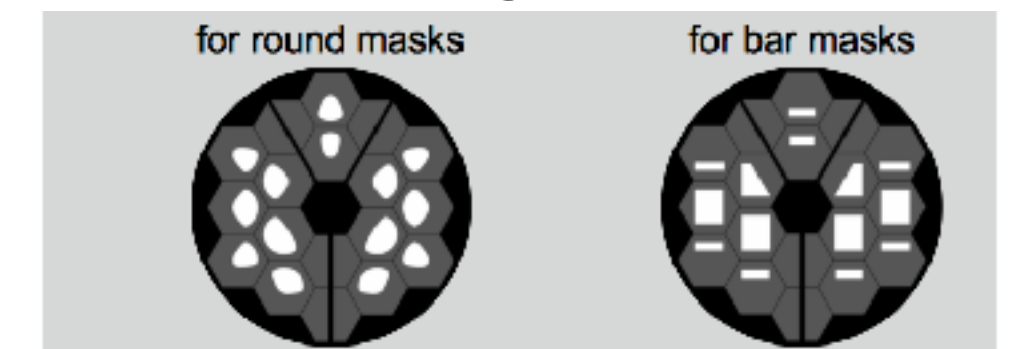
5 Lyot coronagraphs, pseudo band-limited with soft-edged grayscale occulters

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

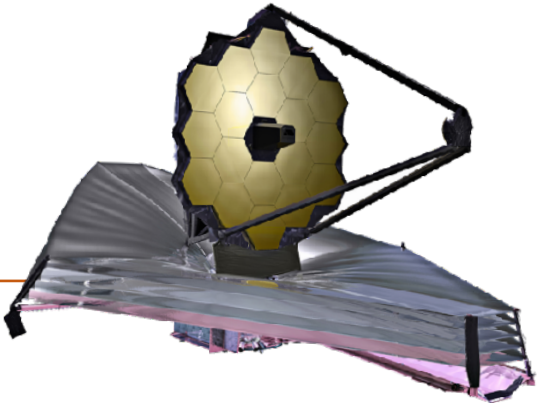
Lyot stops suppress PSF wing diffraction. Throughput = 19%



Coronagraph optics are outside the FOV during normal imaging observations

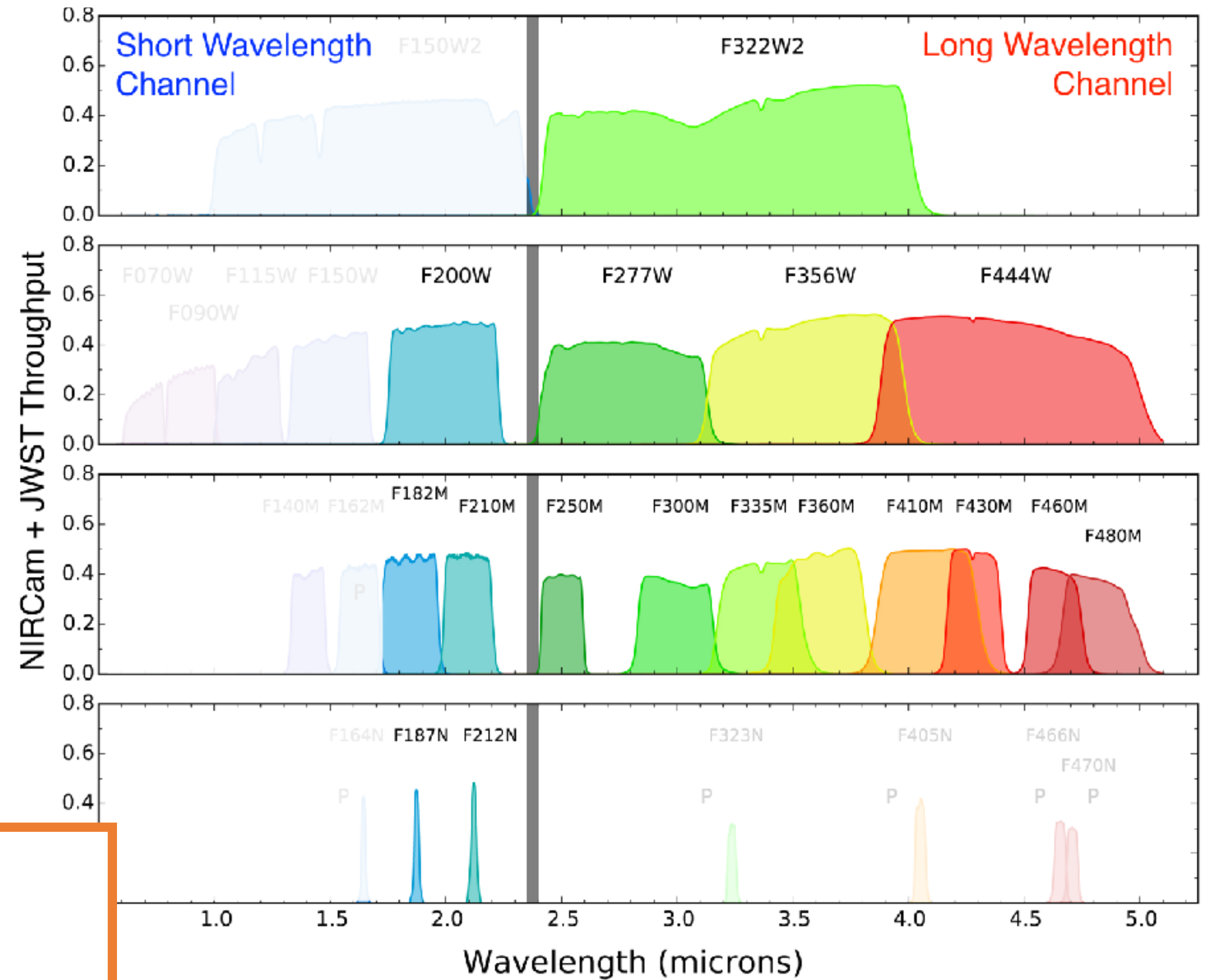
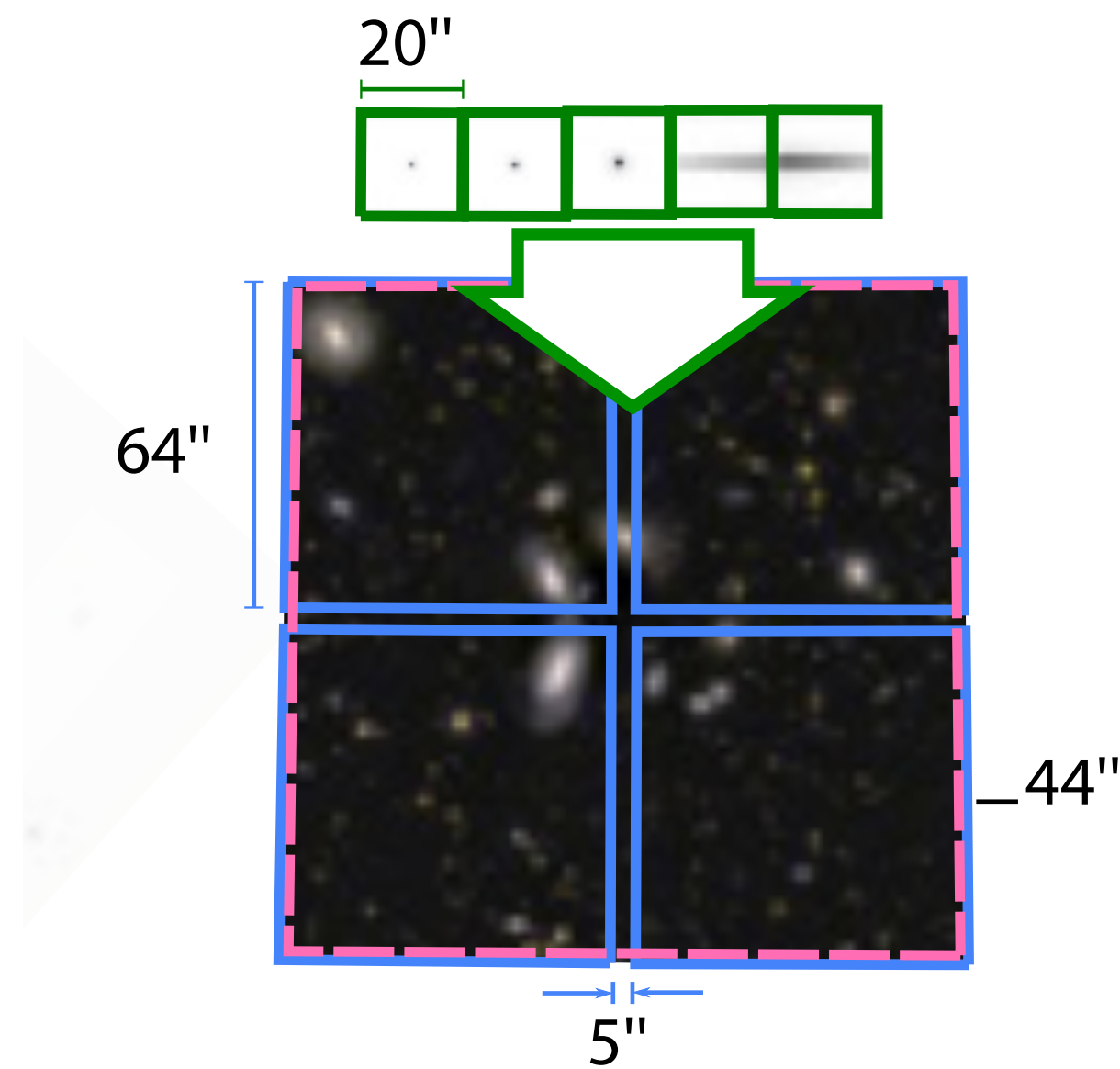


NIRCam & MIRI Coronagraphy in the JWST Focal Plane



NIRCam

Module A

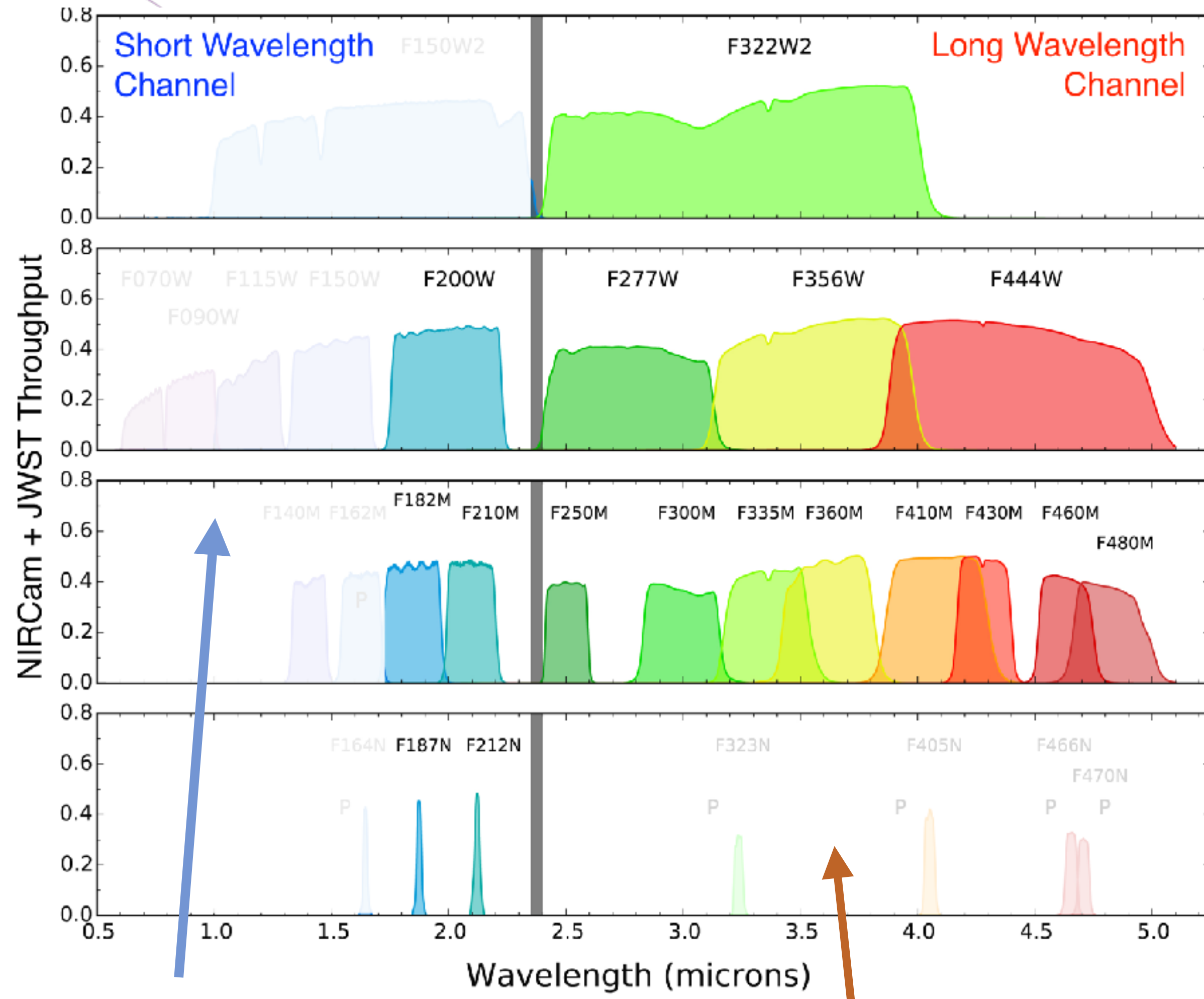


Currently SW and LW data cannot be saved simultaneously

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 $\lambda < 1.8 \mu\text{m}$

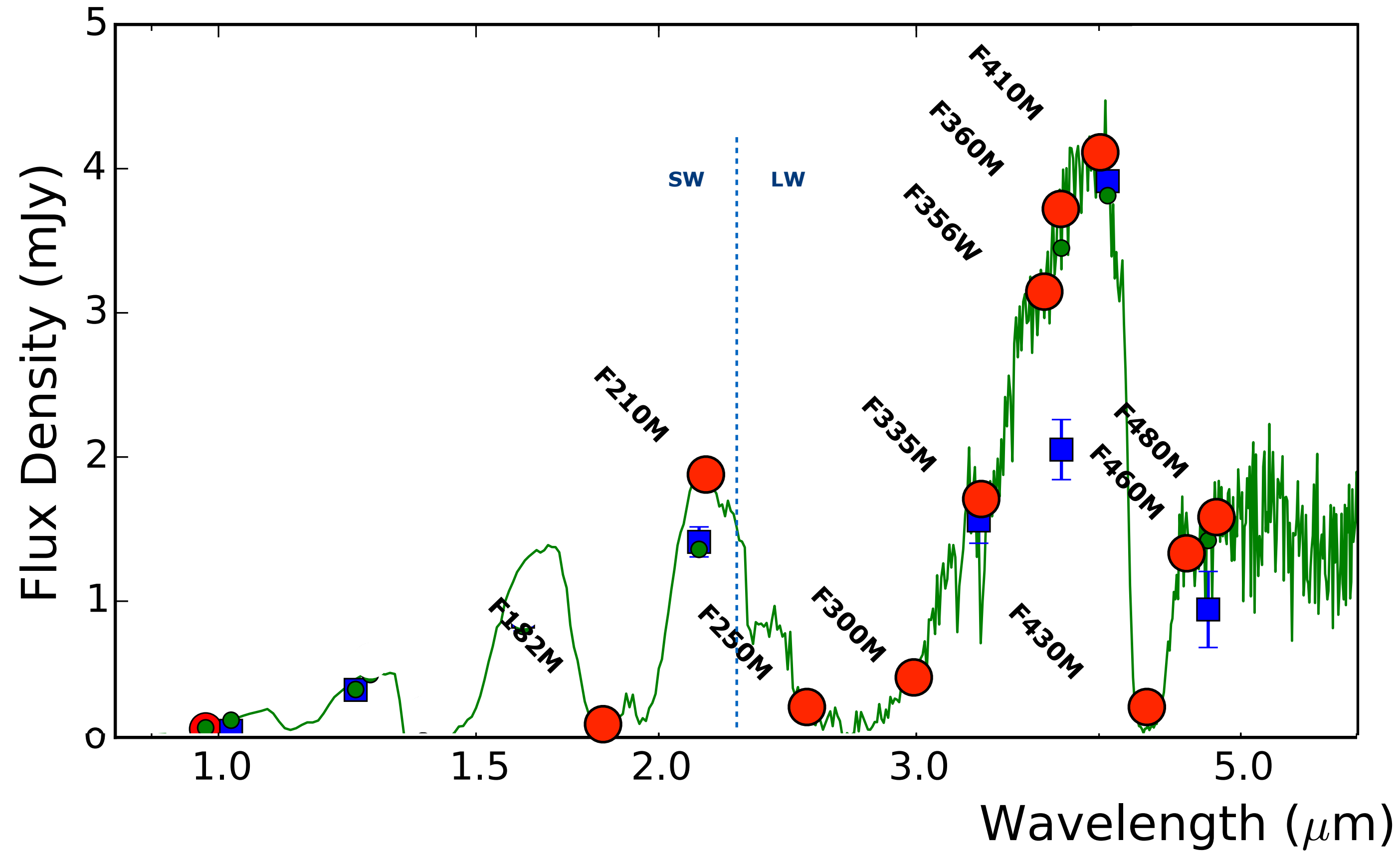
LW narrow band filters **unavailable**
 as installed in same pupil wheel
 as the coronagraph Lyot stops

| 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



Debris disk dust composition and ices

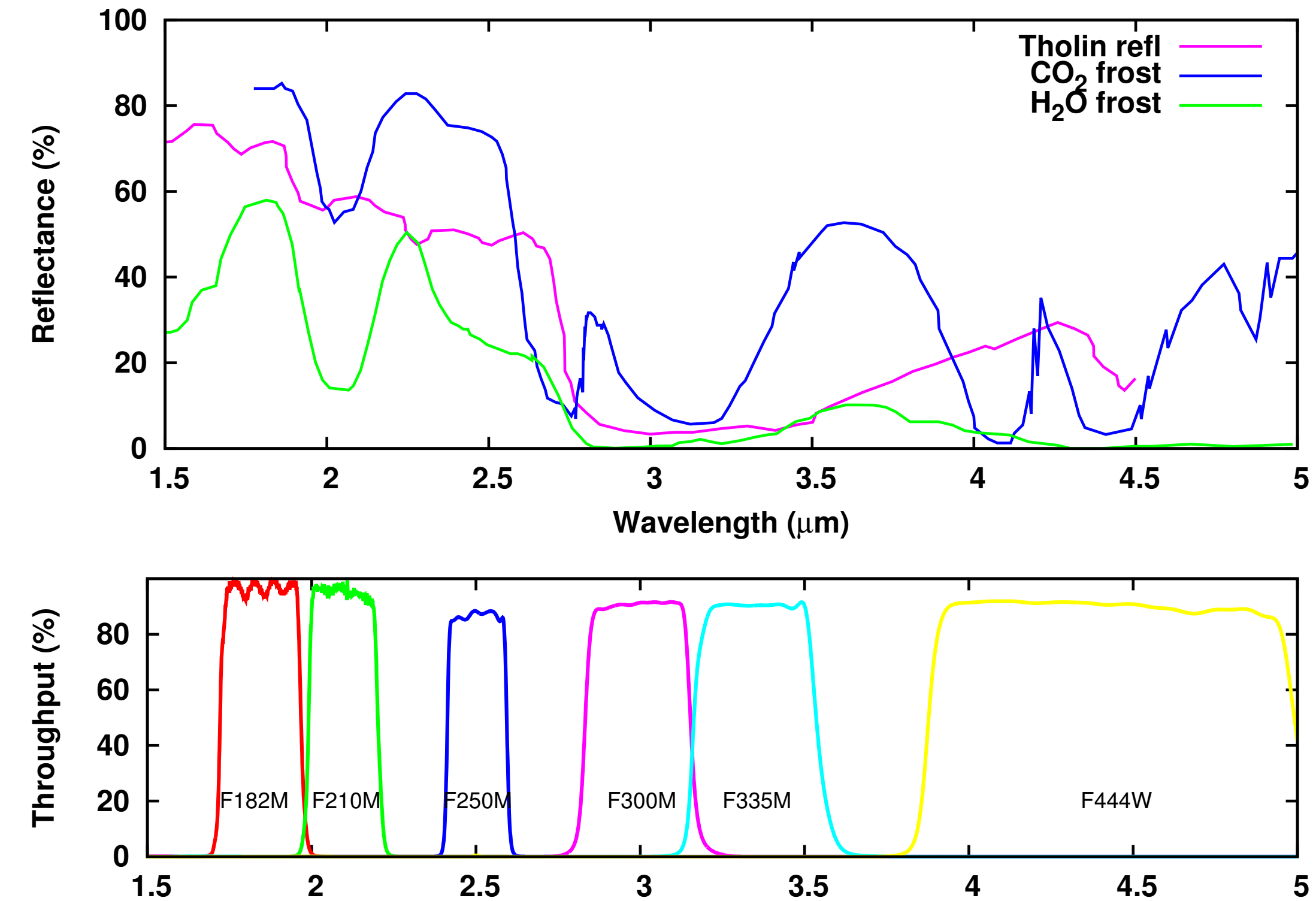
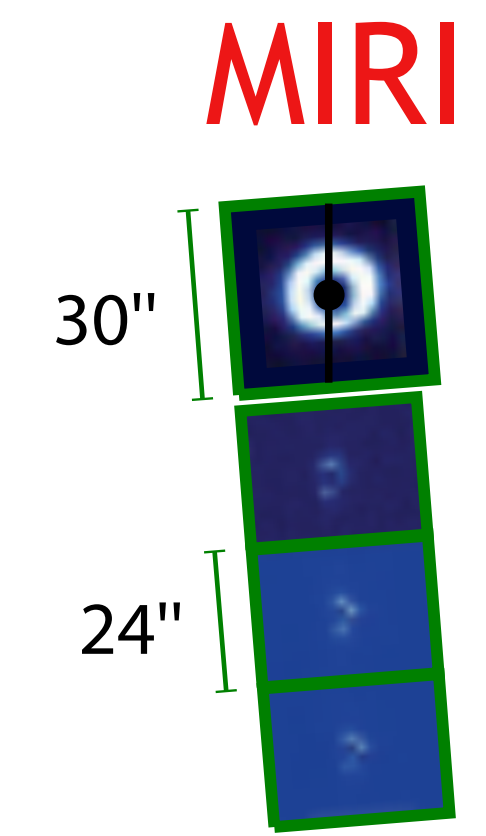
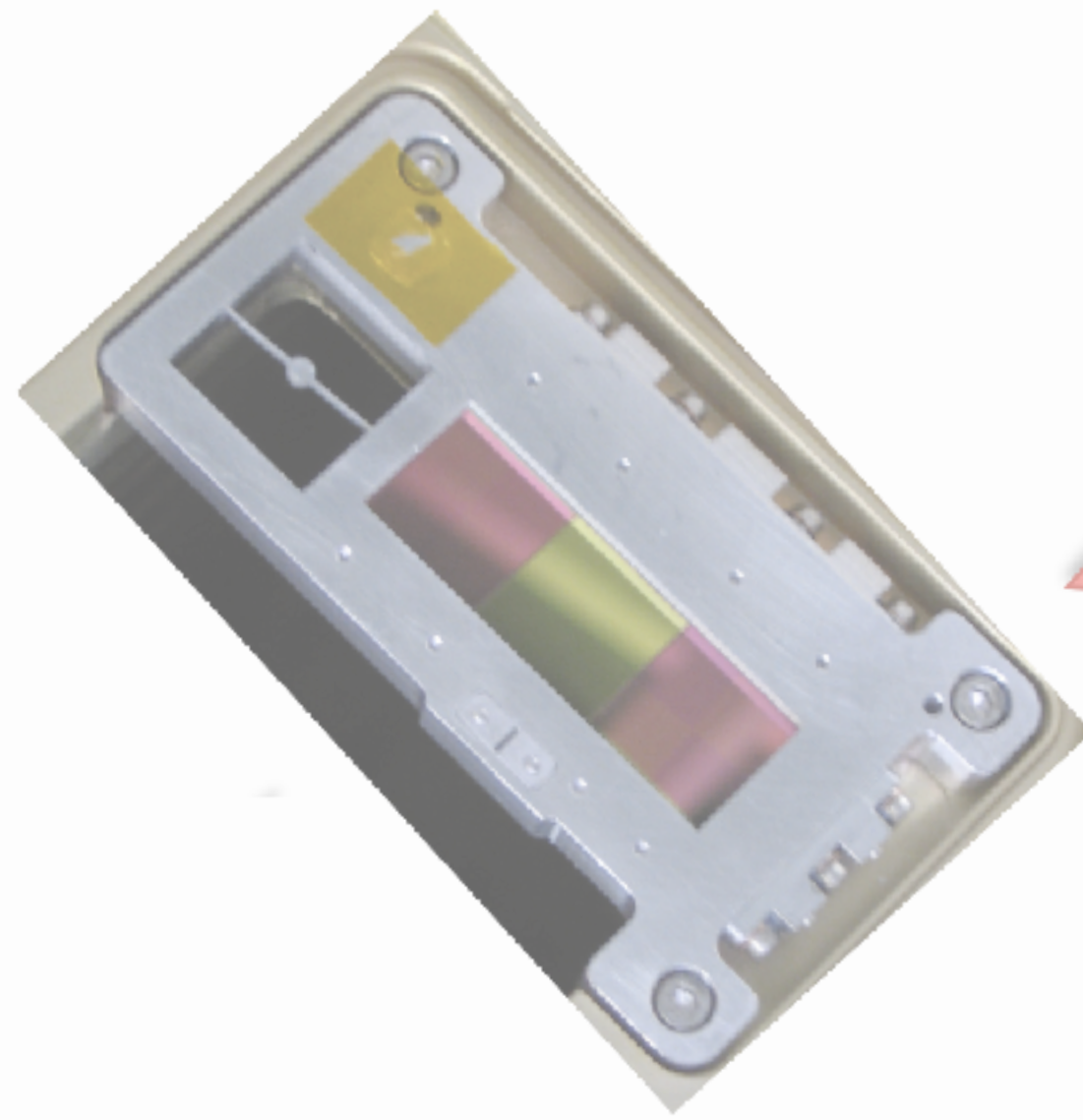
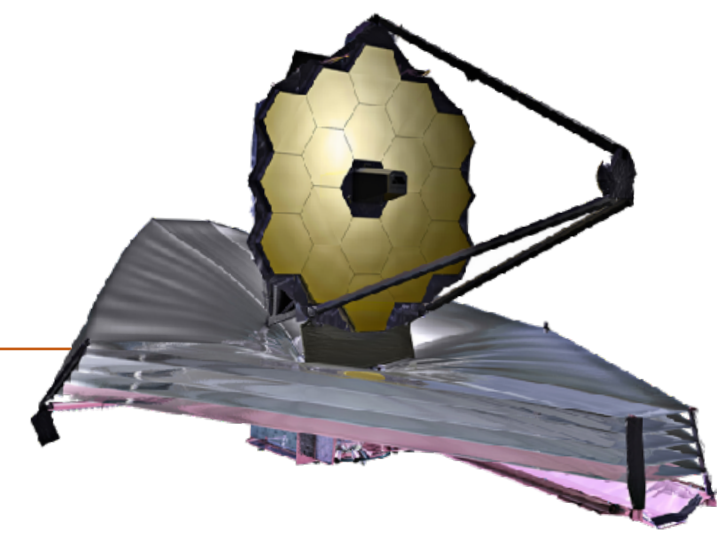


Figure courtesy Andras Gaspar et al. (NIRCam GTO)

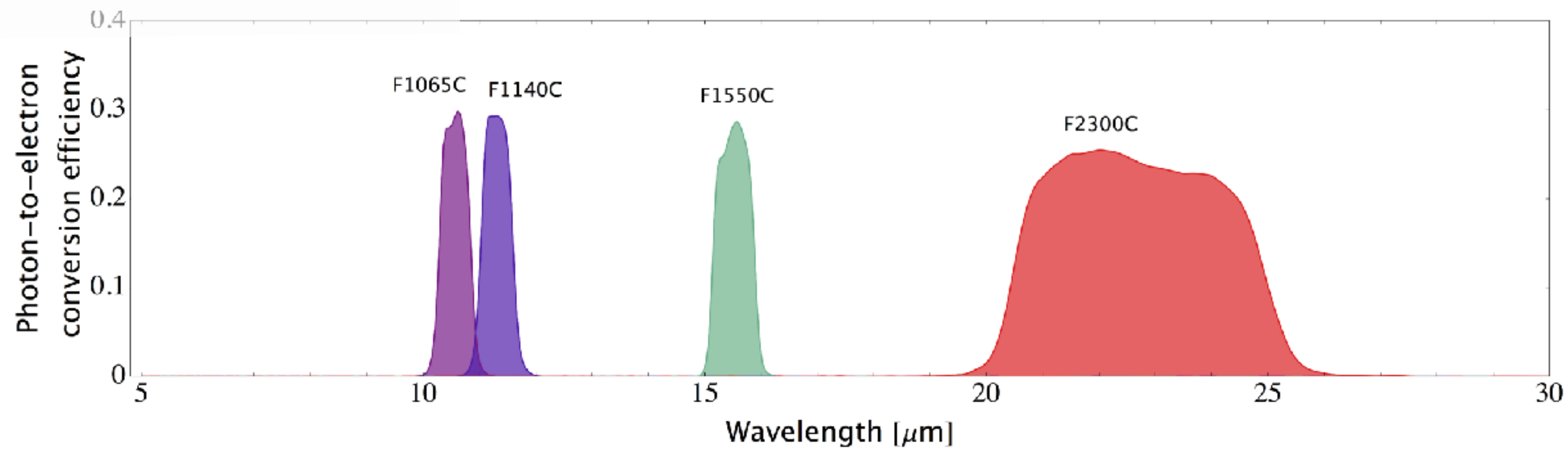
Teff = 1000 K, log(g) = 3.5 model from Barman et al.



NIRCam & MIRI Coronagraphy in the JWST Focal Plane

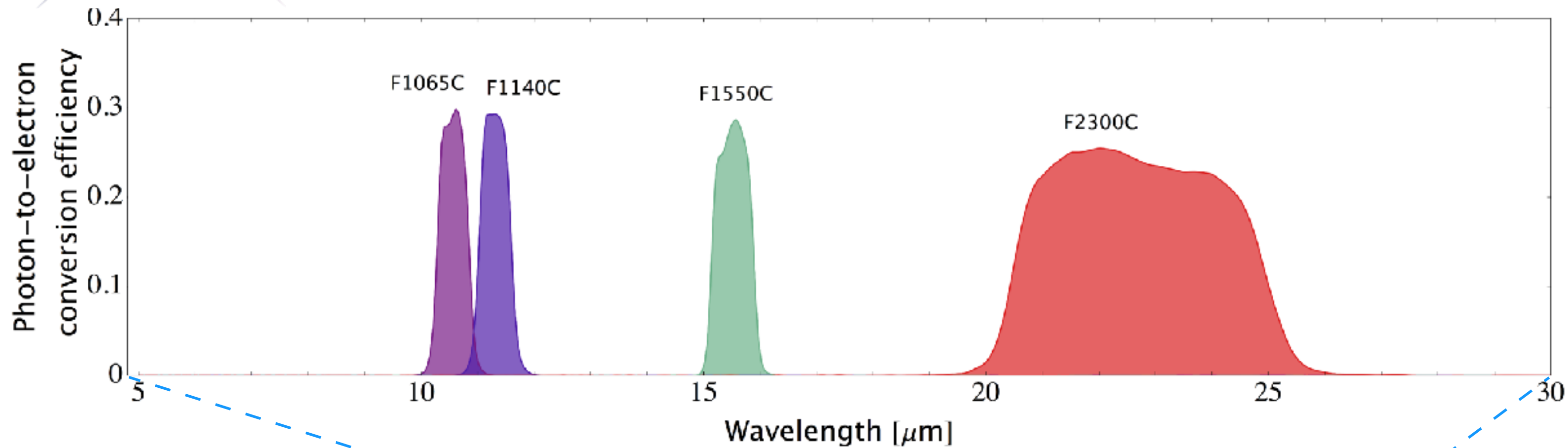


One mask, one filter

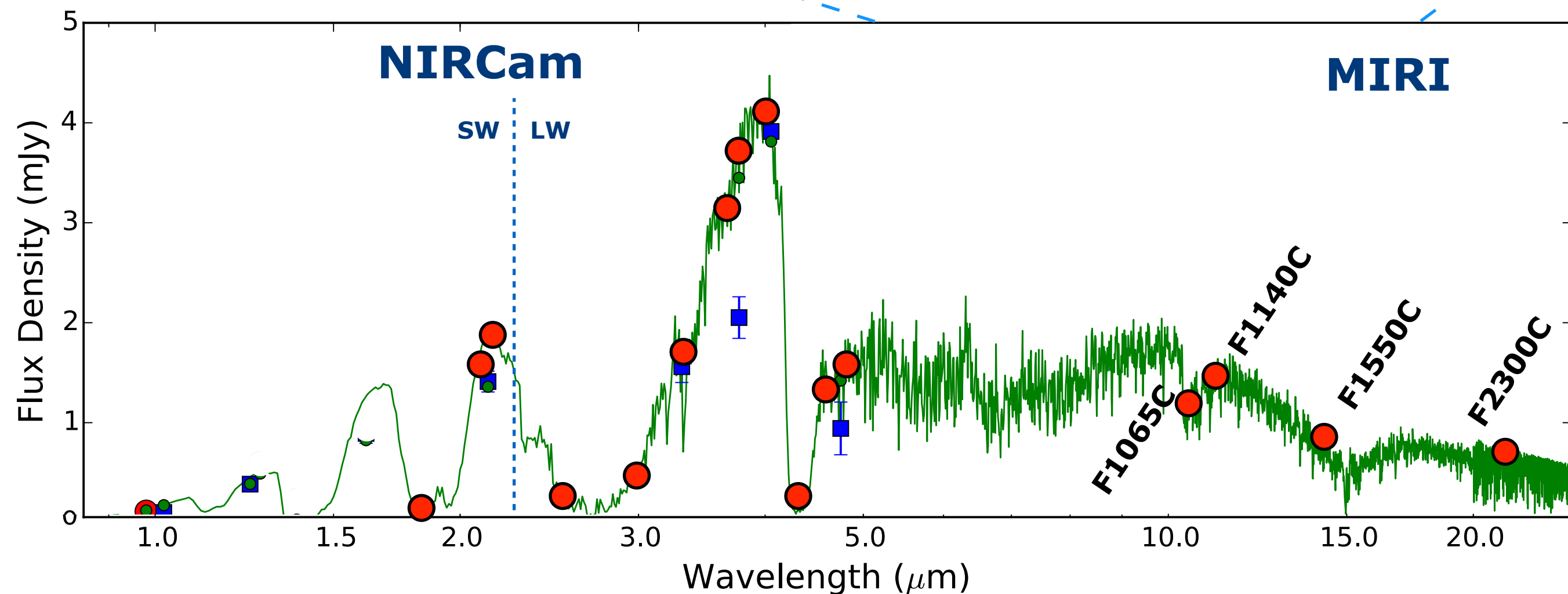




MIRI filters for coronagraphy



| Filter | |
|--------|---------------------------------------|
| F1065C | Ammonia |
| F1140C | Continuum (planets); Si, PAHs (disks) |
| F1550C | Continuum |
| C2300C | Continuum, especially for disks |



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

Continuum slope from 11.4 - 15.5 measures planet temperature.

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

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

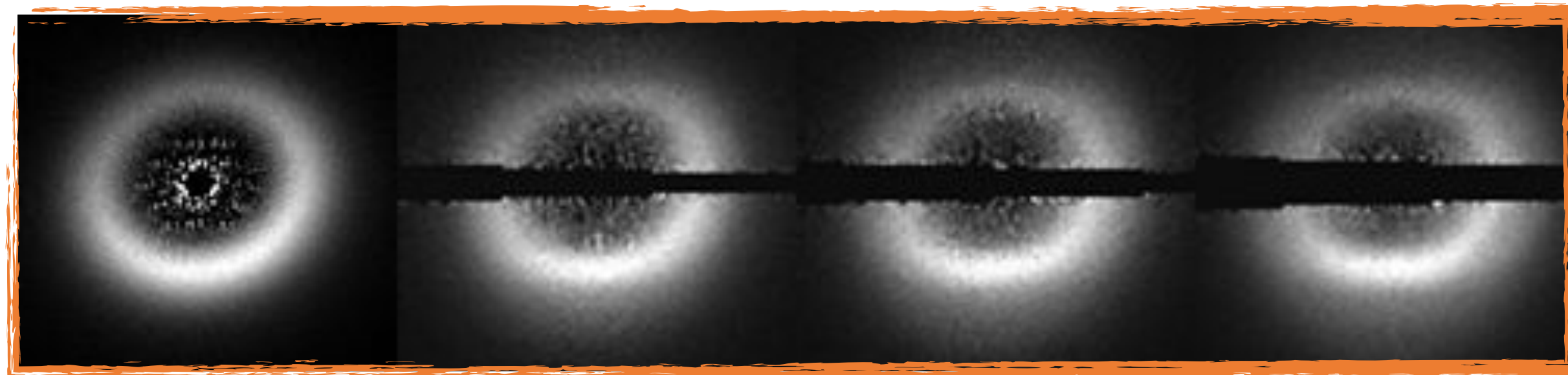


Studying Disk Compositions: Panchromatic Imaging

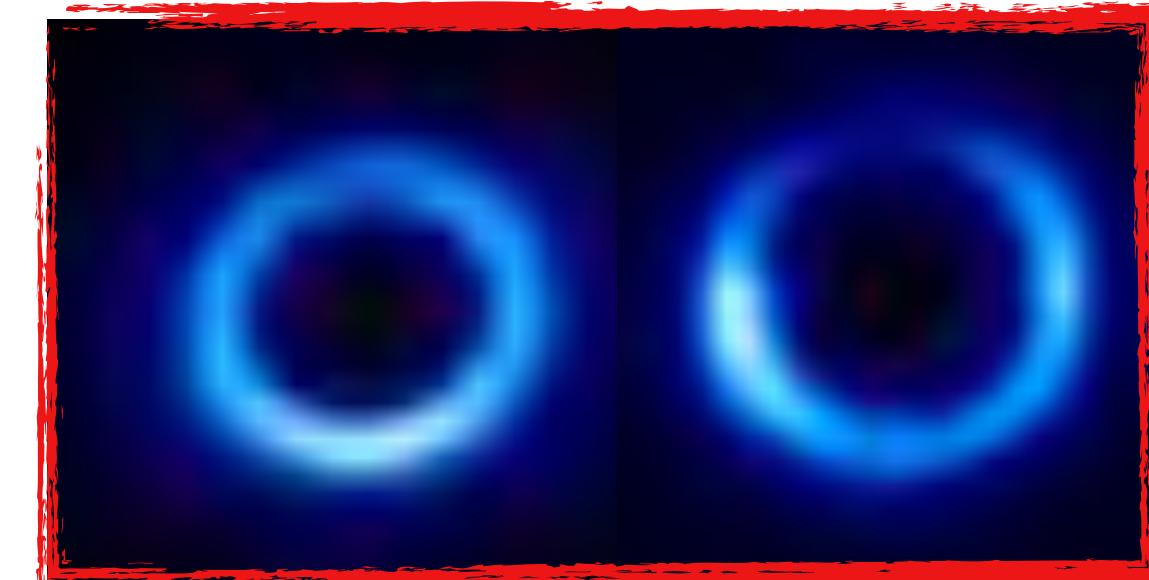
High contrast at longer wavelengths: **3-5 μm** , **10+ μm**

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

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



(Simulations by J. Lebreton)

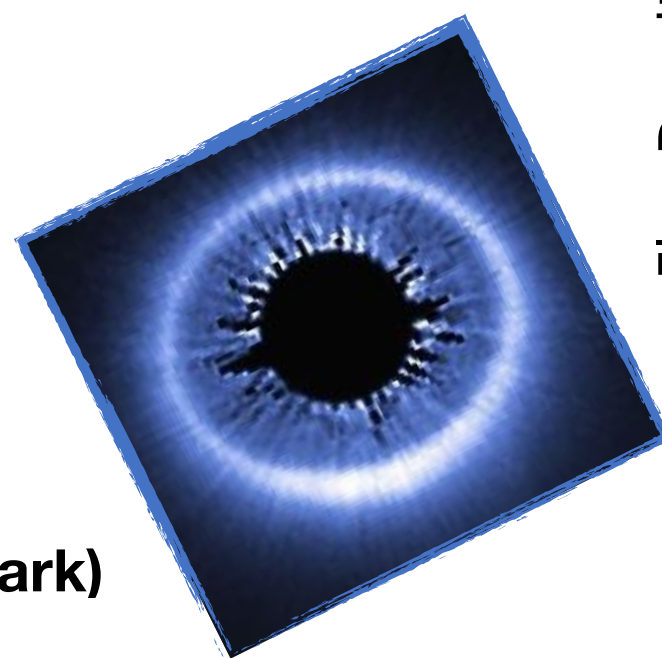


F1140 **F2300**

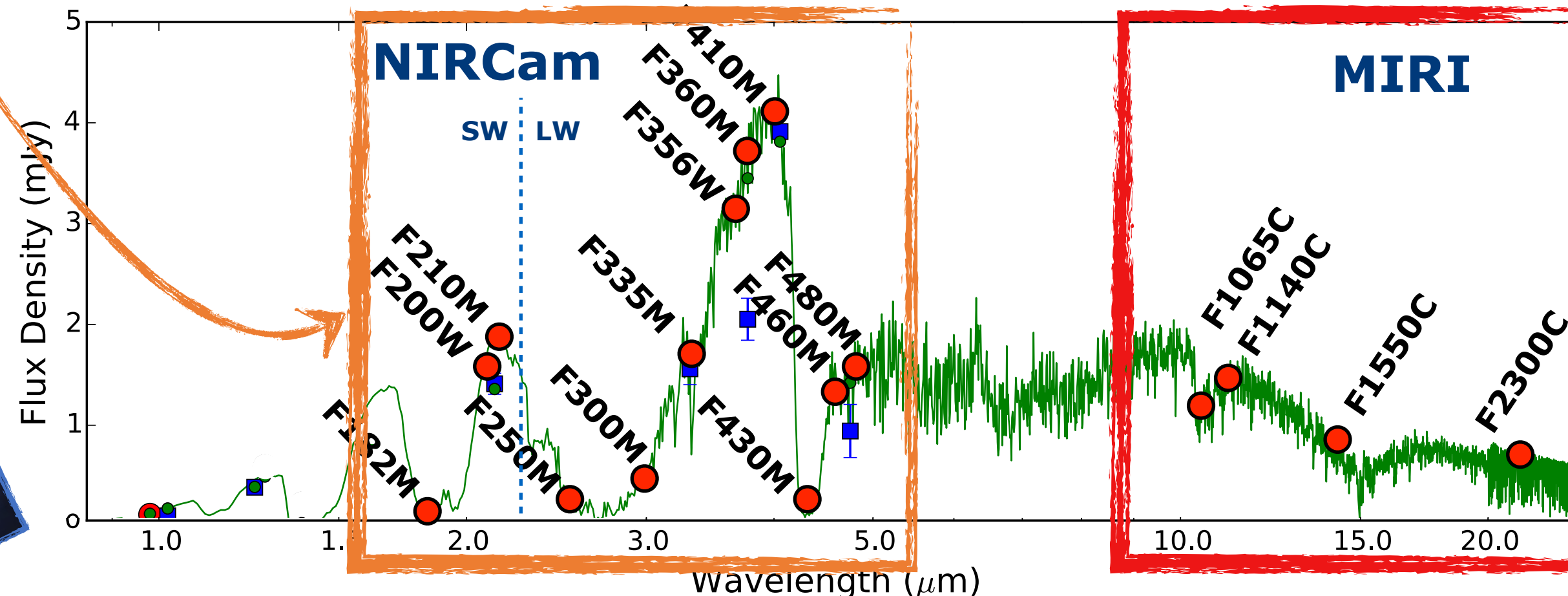
(Simulations by A. Boccaletti)

Colors, albedos, phase functions of scattering particles, Ices at 3.3 μm

E.G.: HD 181327



(HST C. Stark)

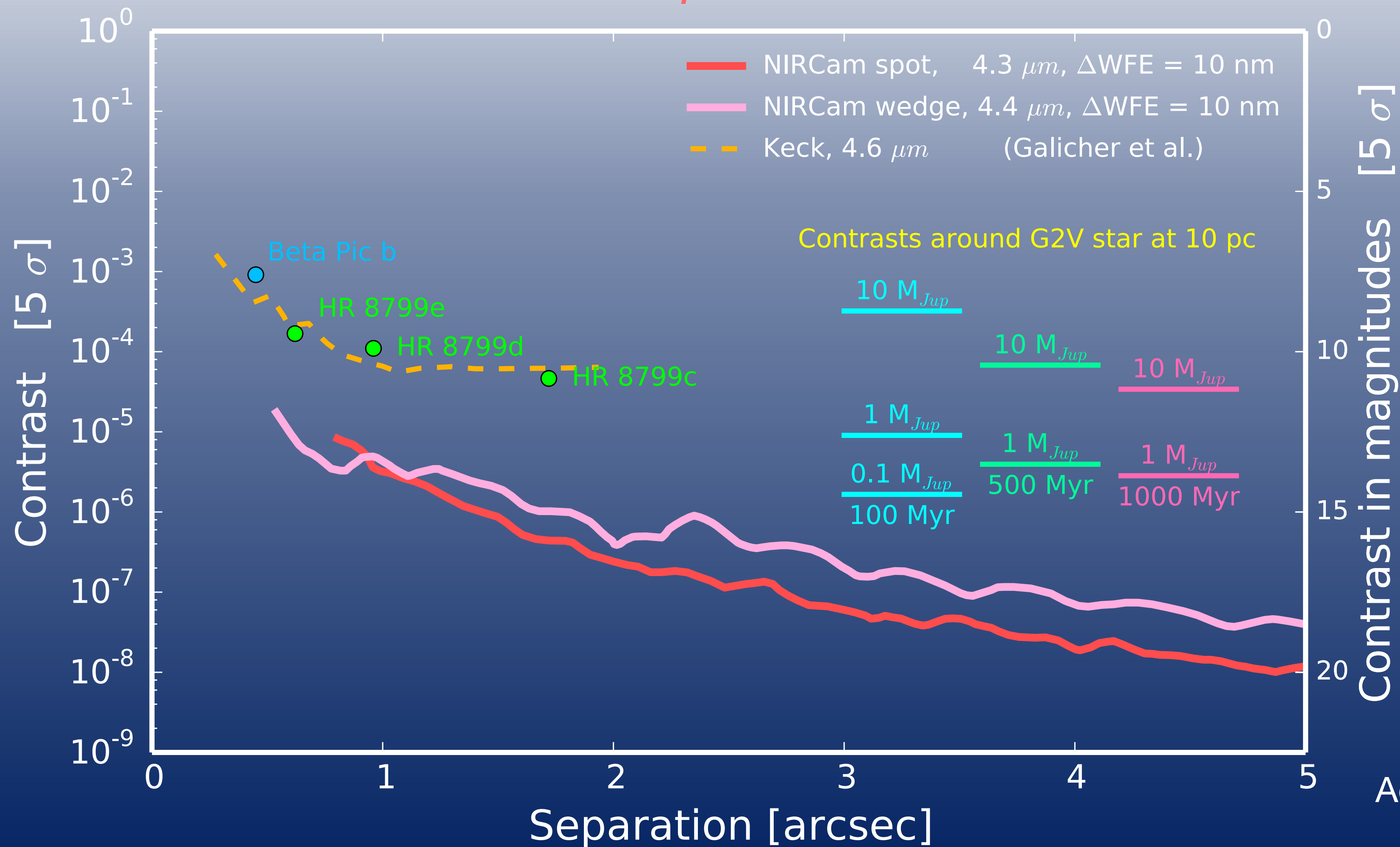


Teff = 1000 K, log(g) = 3.5 model from Barman et al.



NIRCam Coronagraphy: sensitivity!!!

4-5 μm



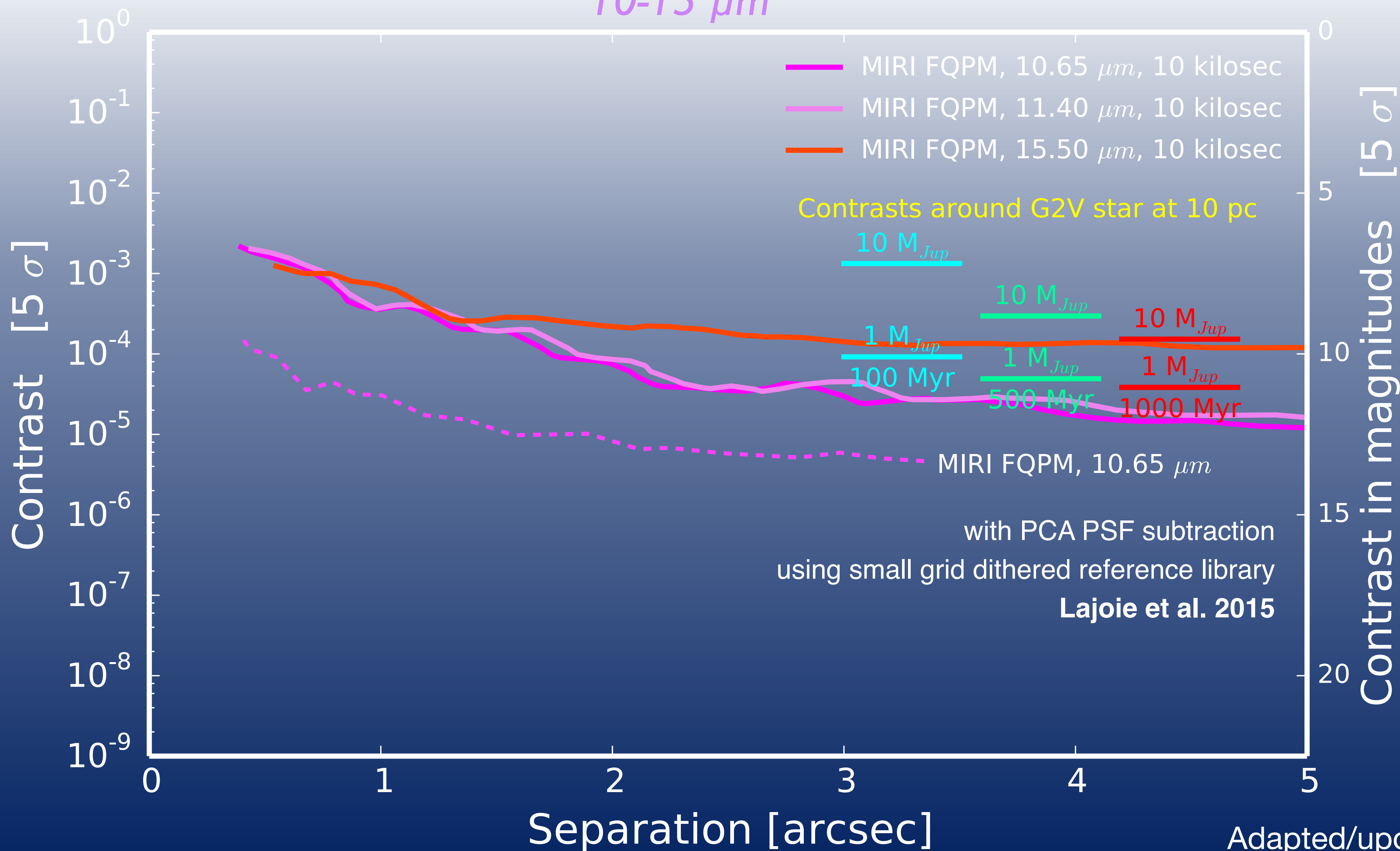
NIRCam expected contrasts:
below 10^{-5} at 1",
 10^{-7} at 4"

Adapted/updated from Beichman et al. 2010



MIRI Coronagraph: **expected contrasts**

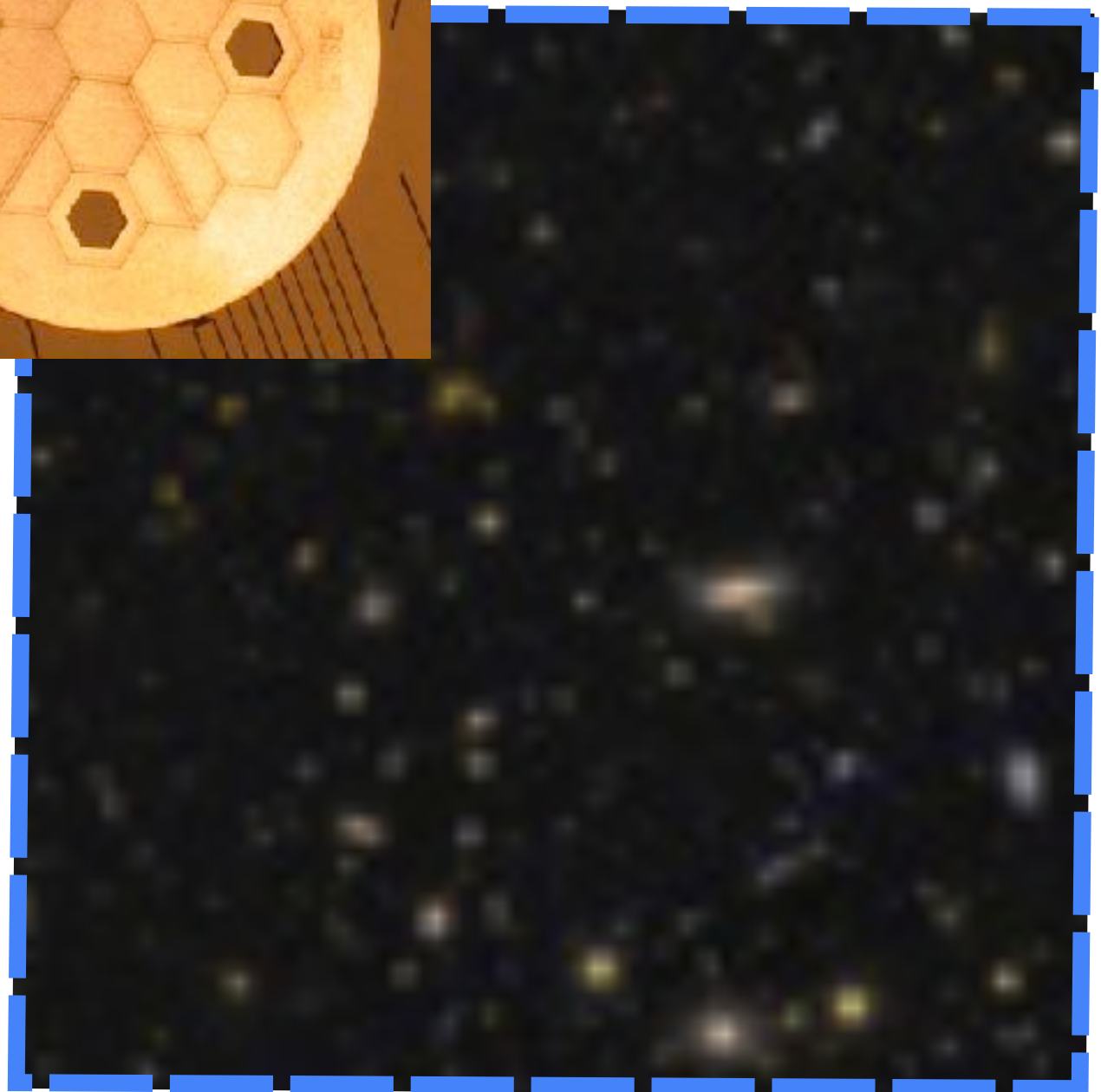
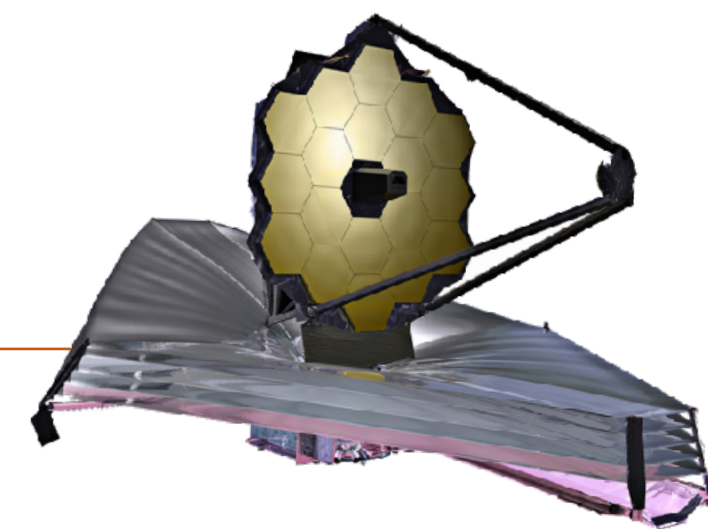
10-15 μm



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



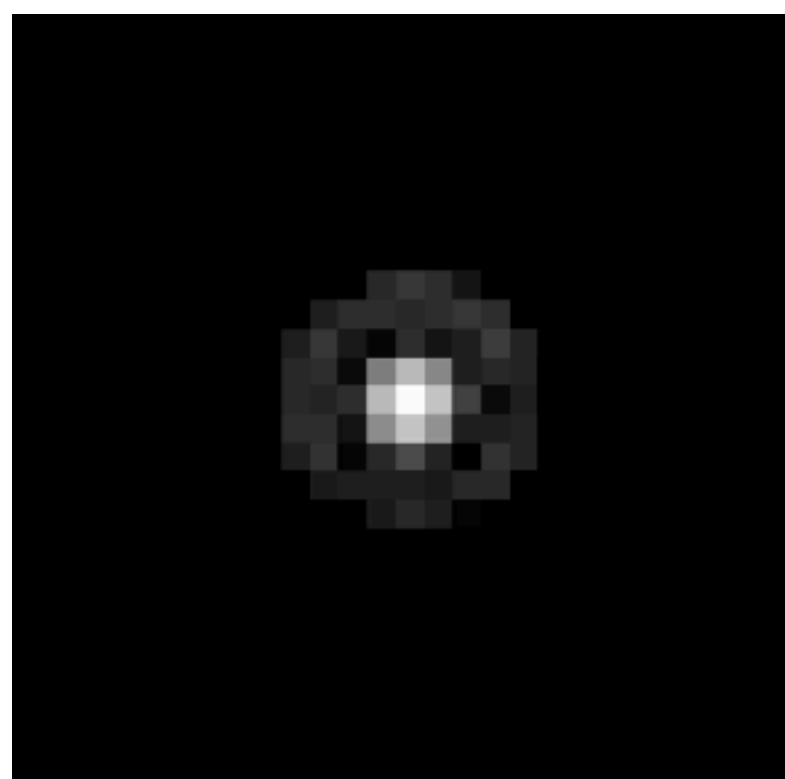
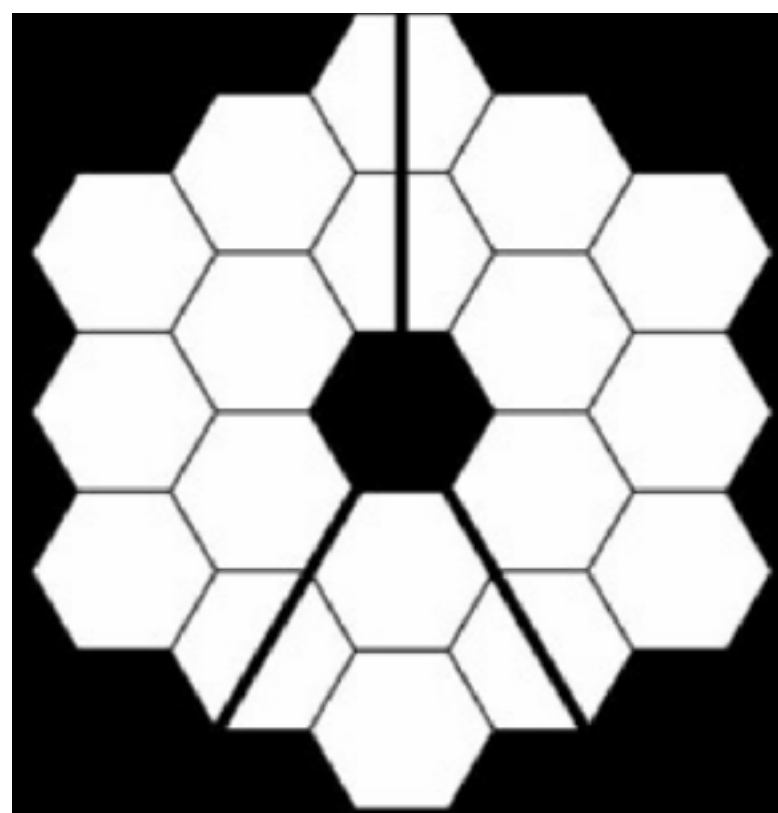
JWST/NIRISS Aperture Masking Interferometry (AMI)



NIRISS

133"

Full

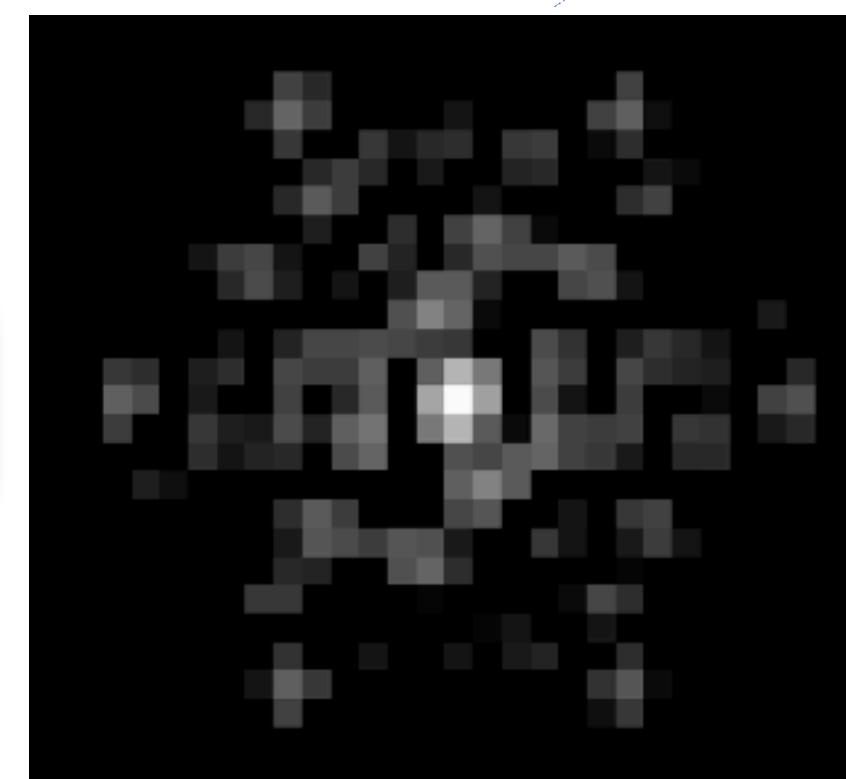


Pupil

Non Redundant Mask

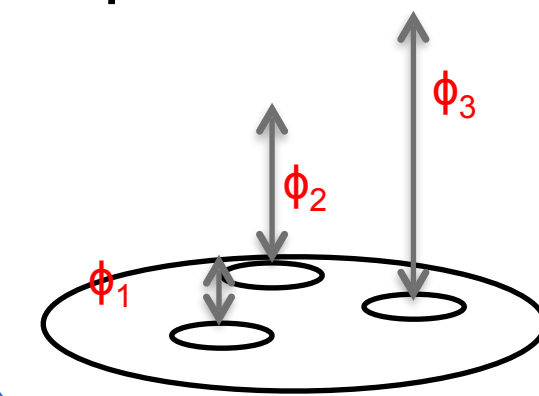


PSF

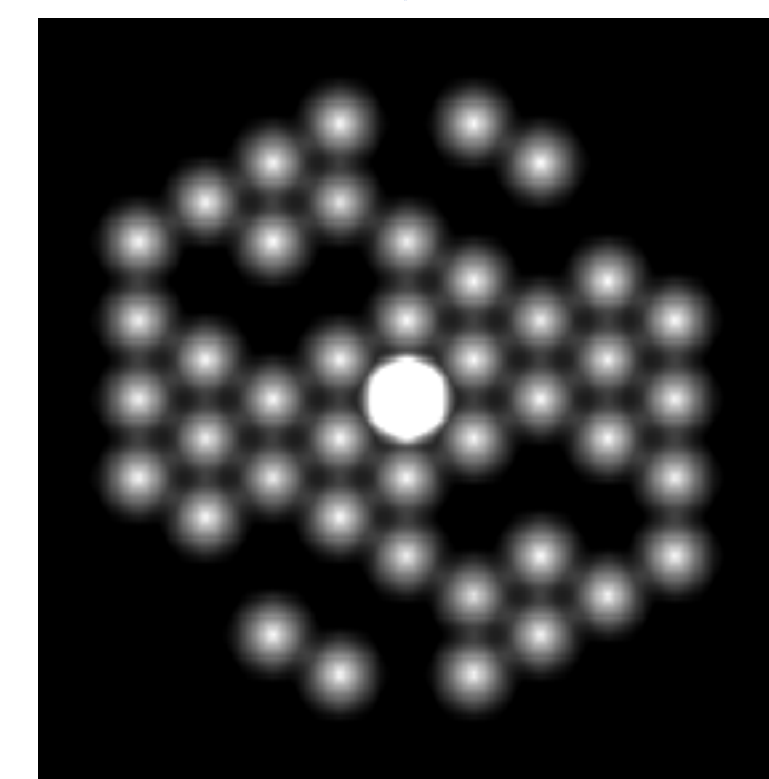


Fourier Space

- 7 holes
- 21 baselines
- Measure:
 - Fringe visibilities
 - Fourier phases



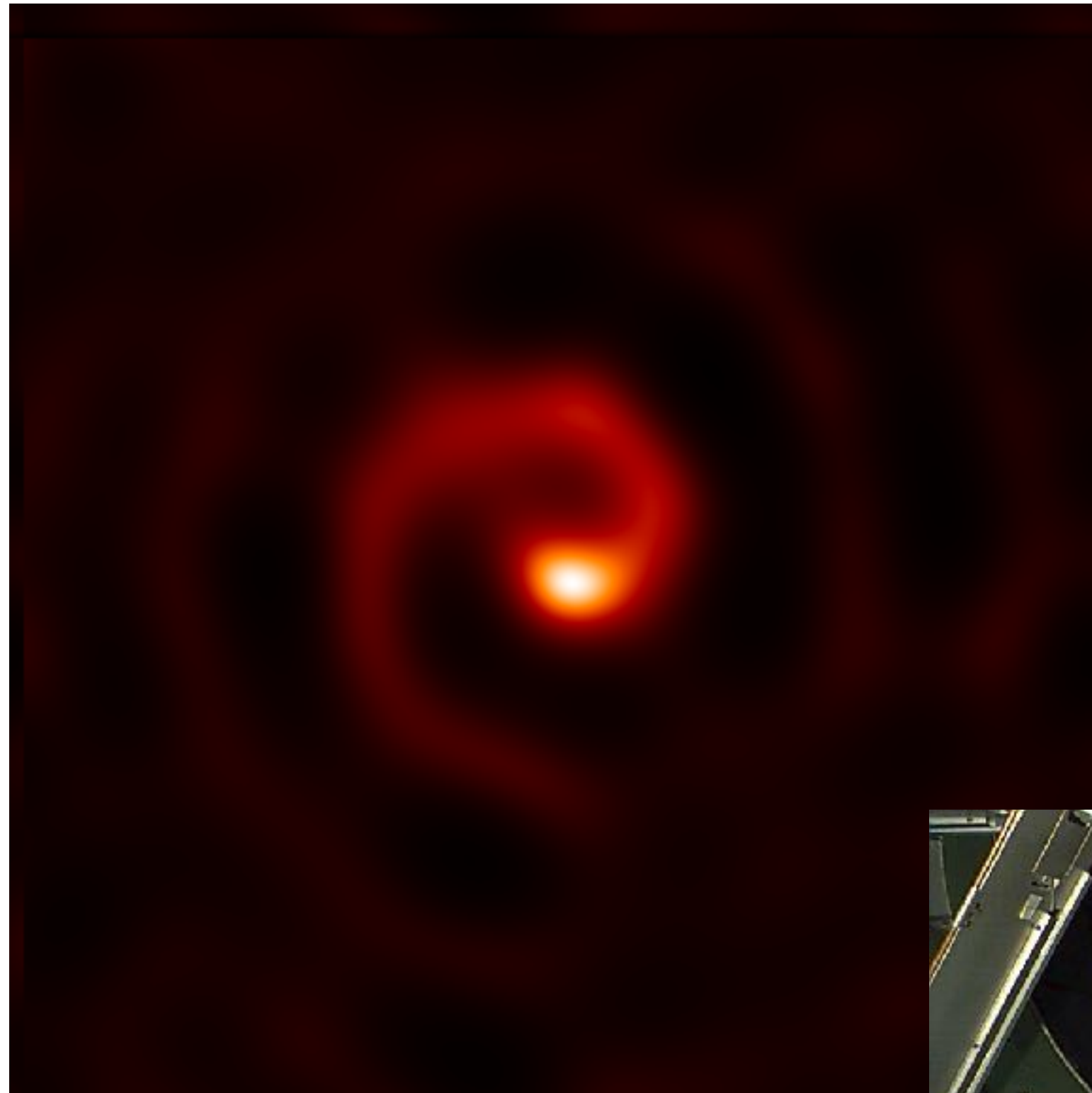
FT





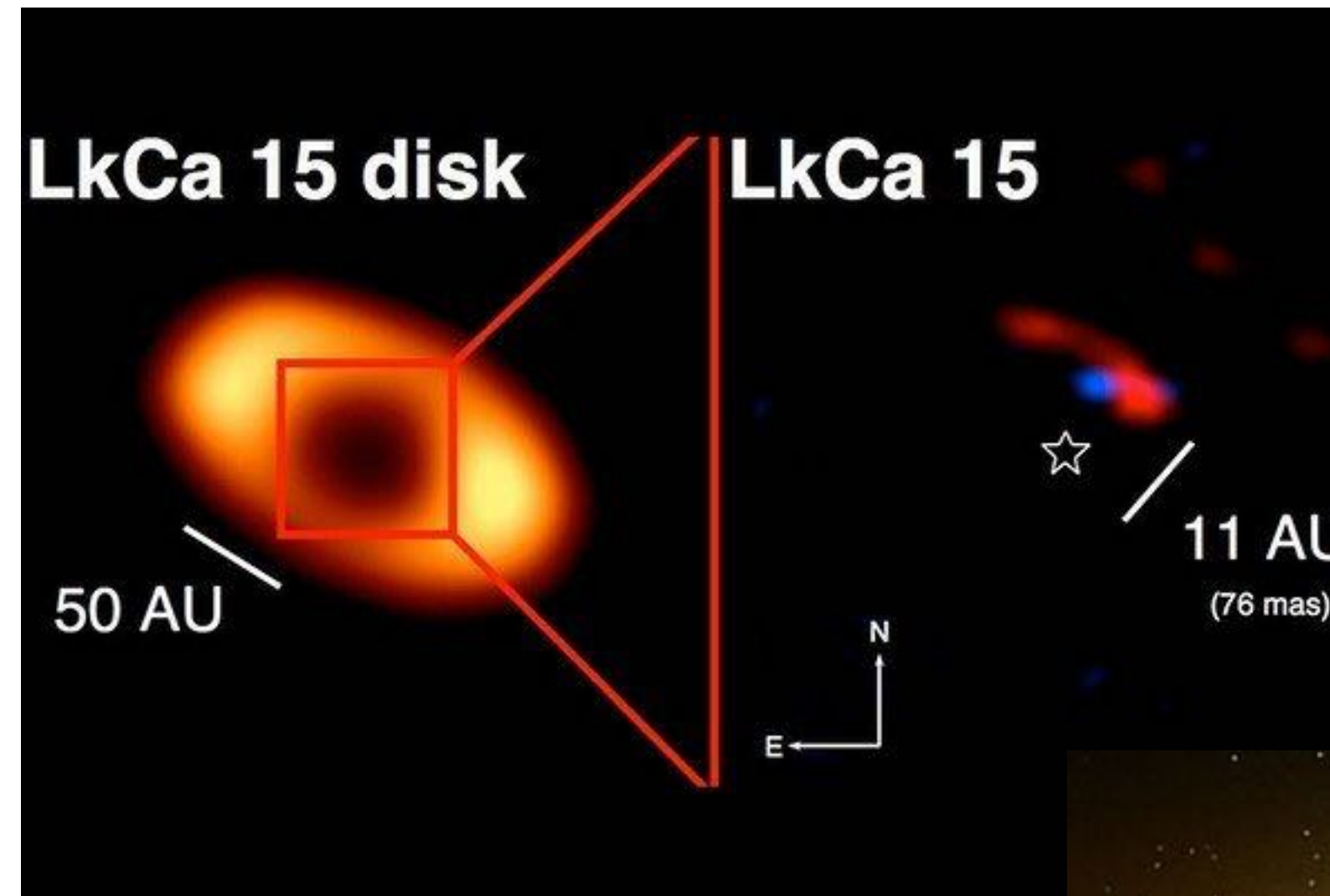
NIRISS Aperture Masking Results (Keck)

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

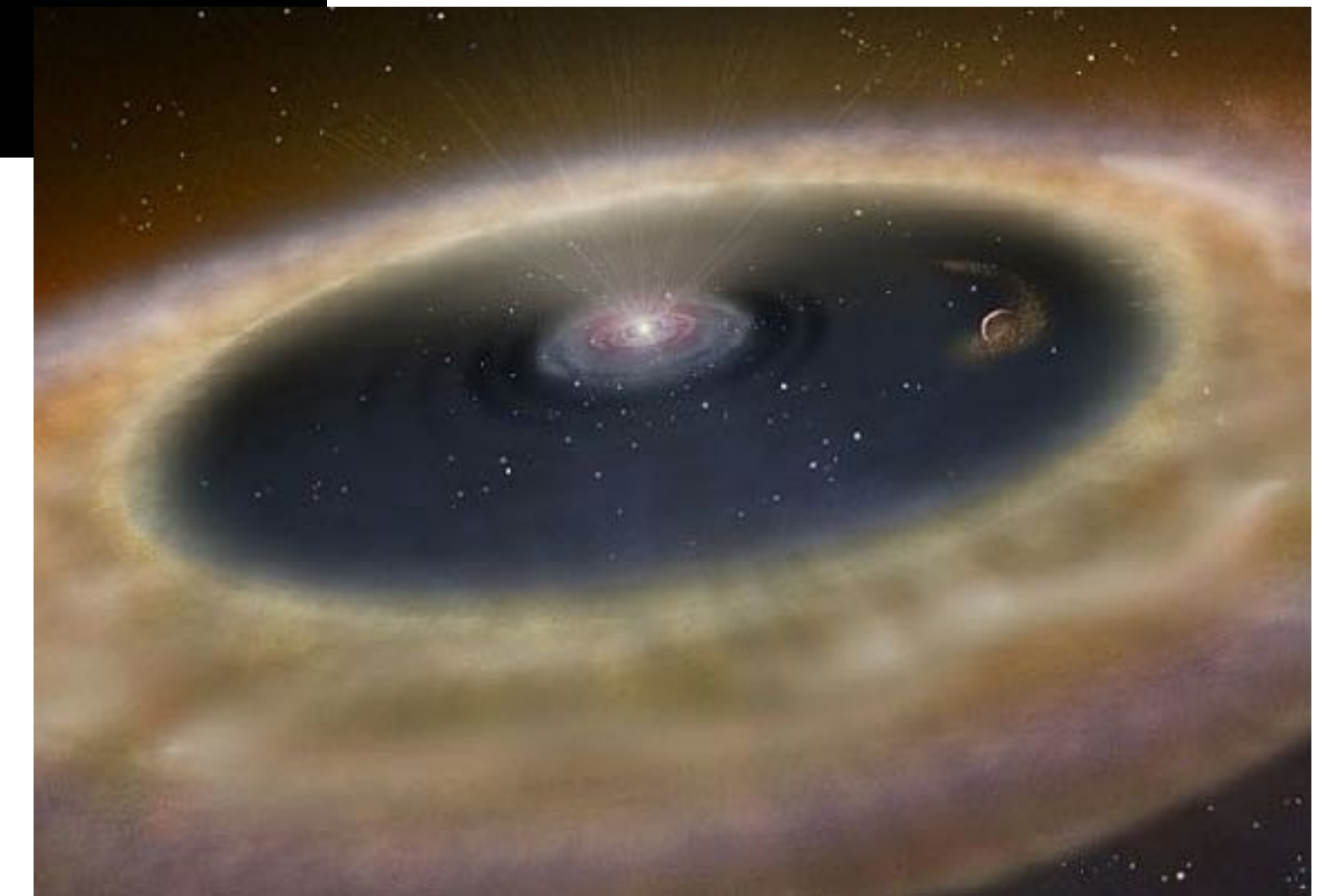


Tuthill (photo), Monnier,
Danchi 1999

Potential protoplanet LkCa 15 b

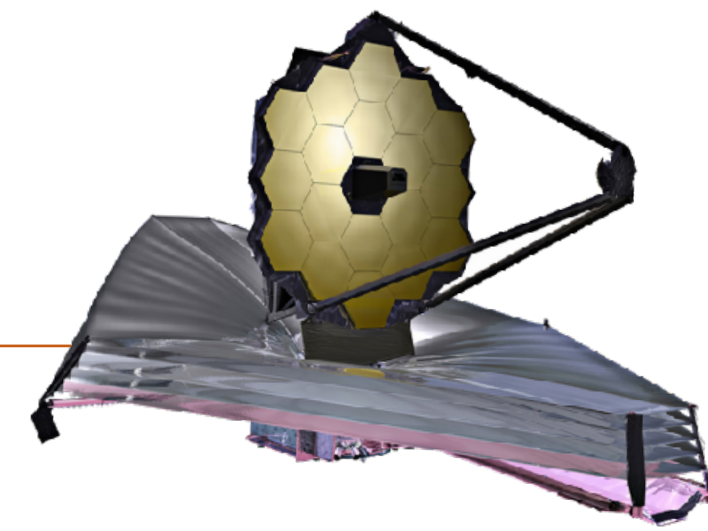


Kraus & Ireland 2012





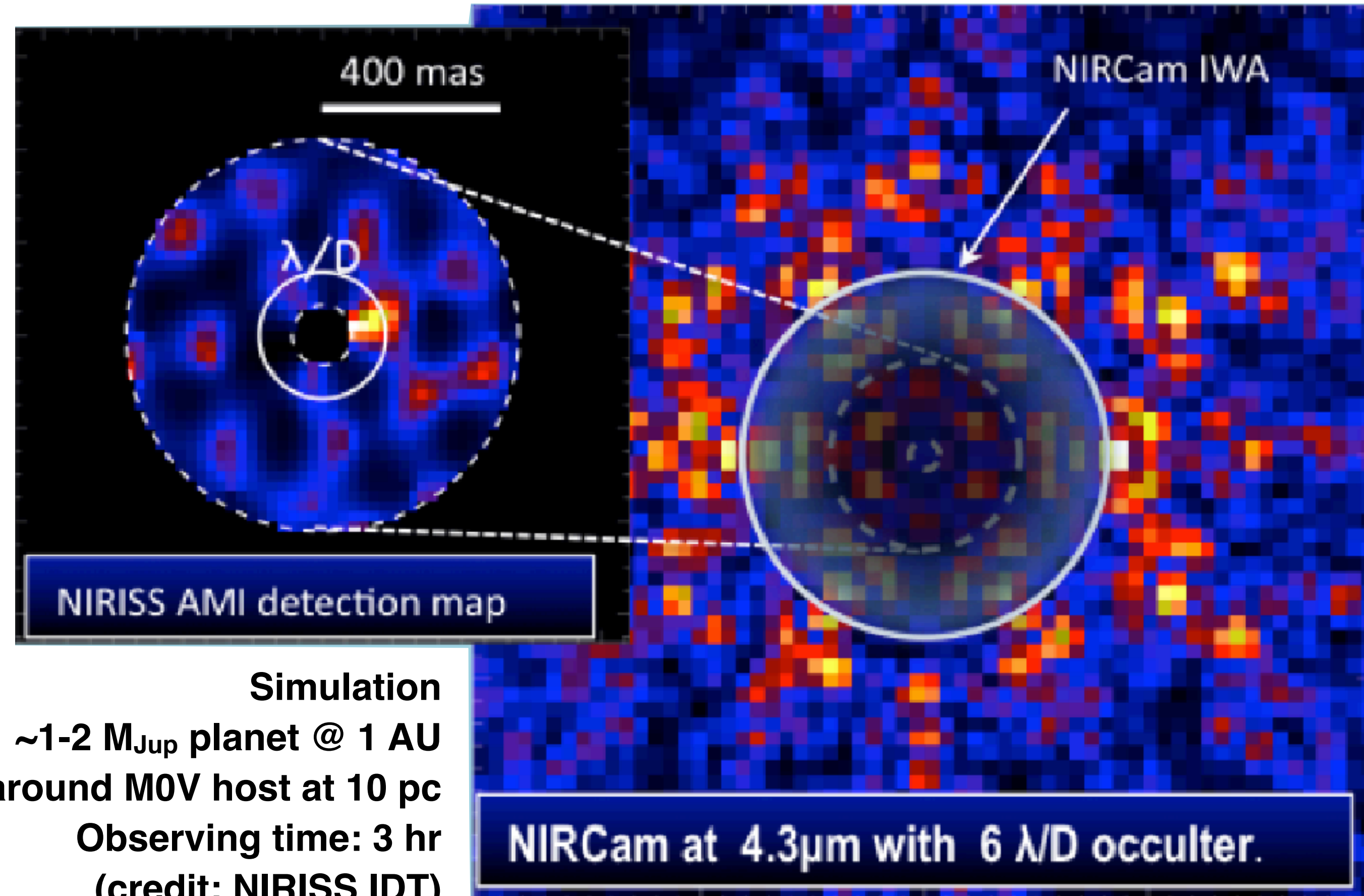
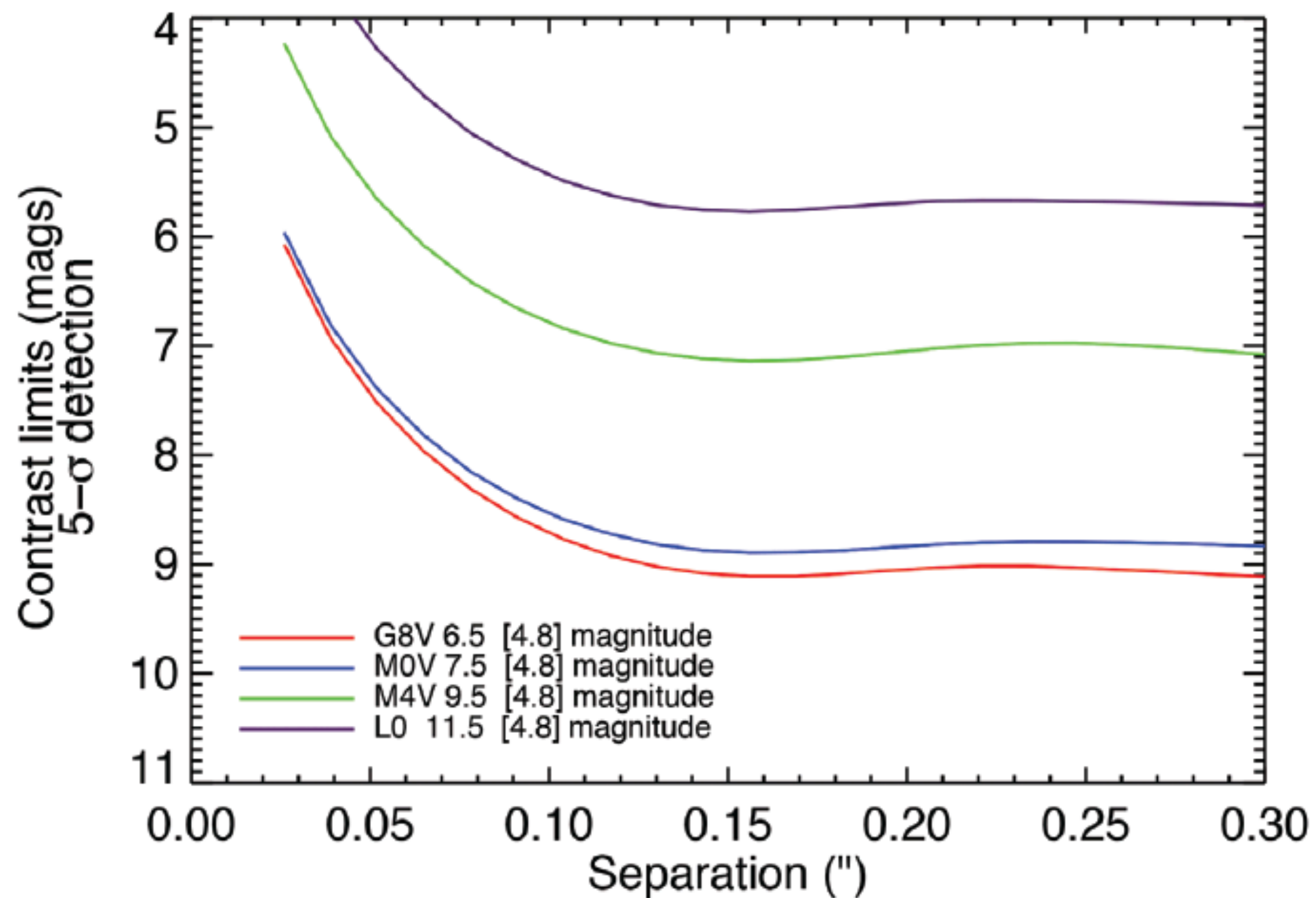
NIRISS AMI Predicted Performances



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

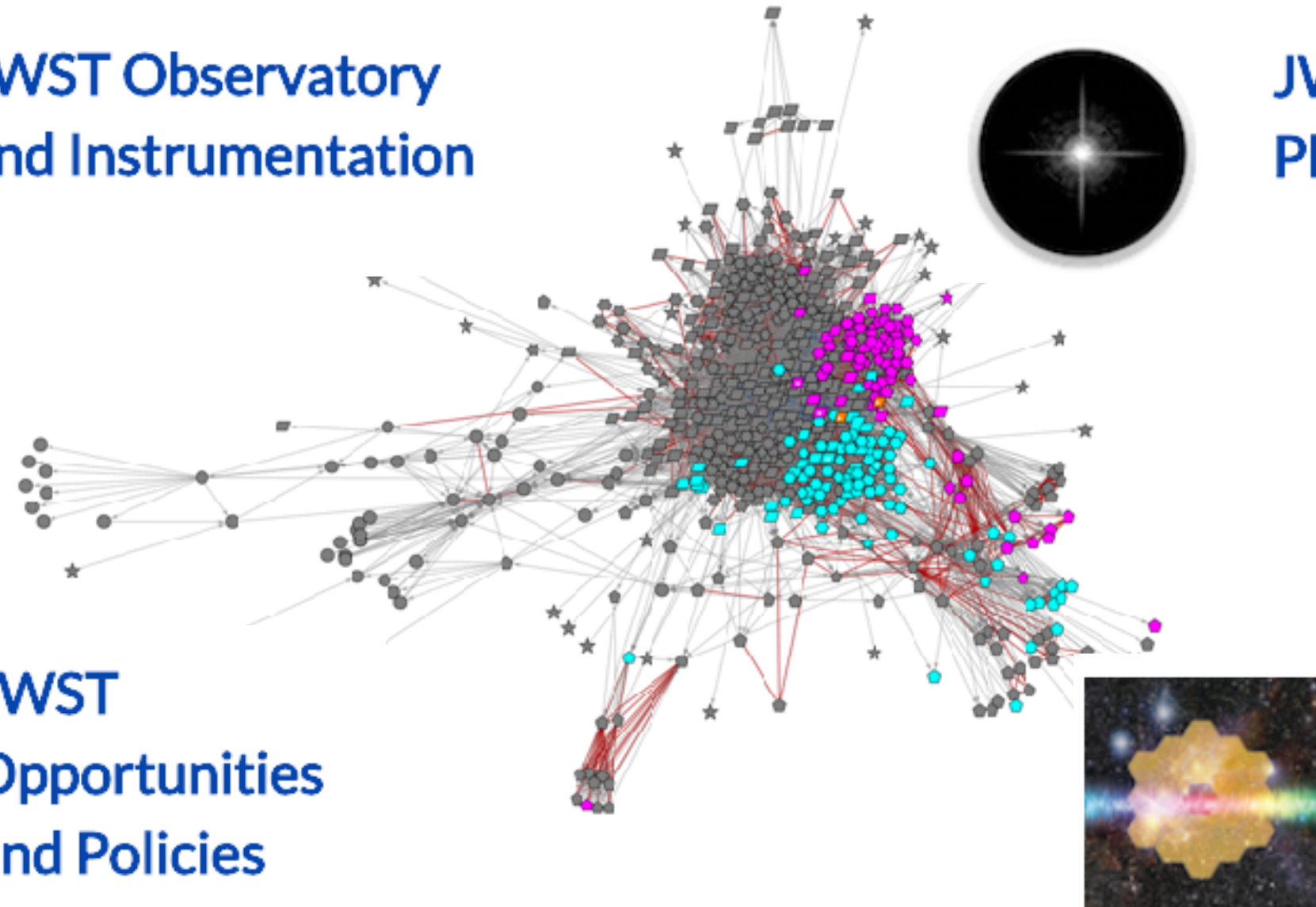




JDox: the documentation platform: web-based, agile, integrated



JWST Observatory and Instrumentation

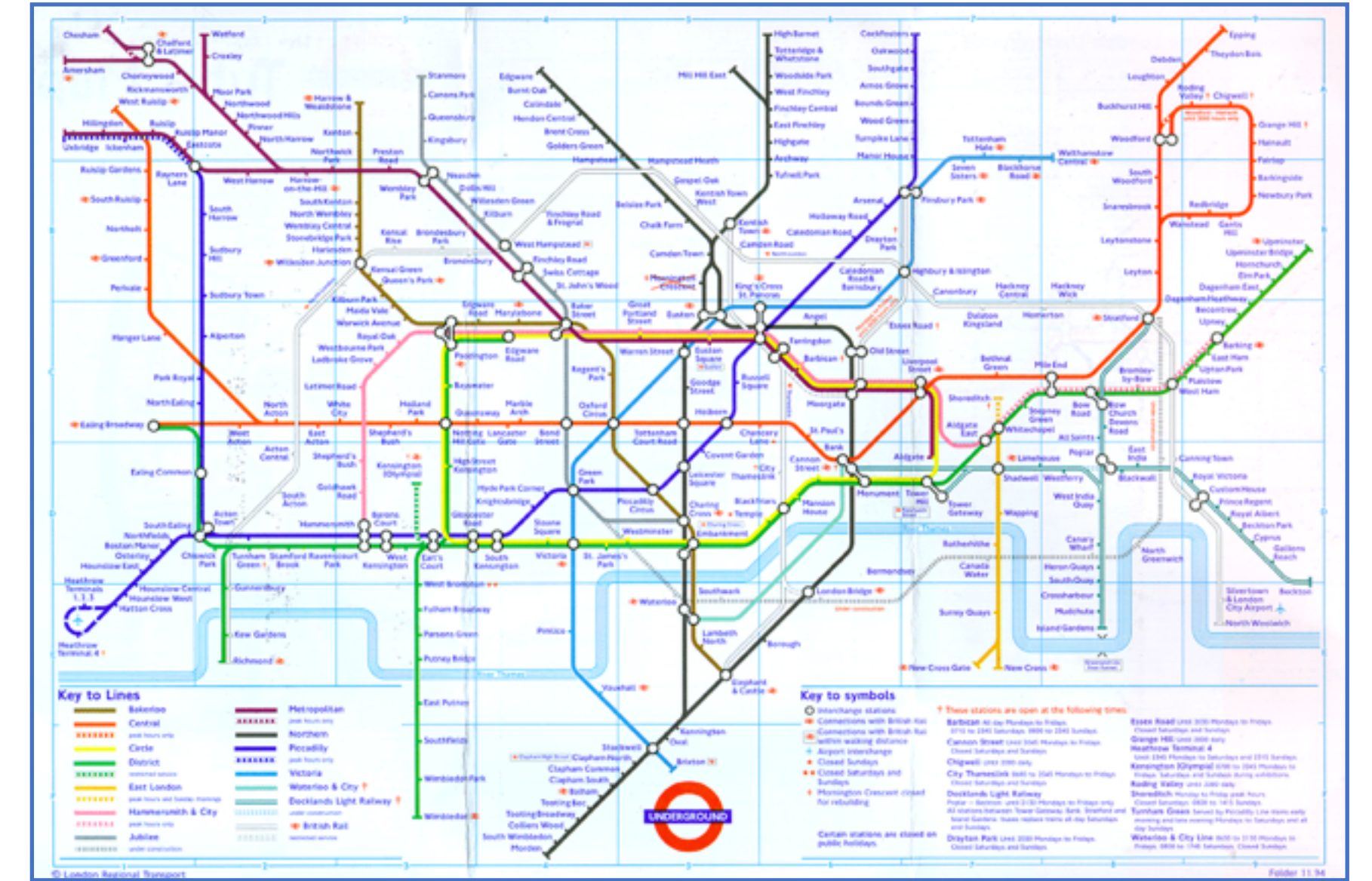


JWST Observation Planning



JWST Opportunities and Policies

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

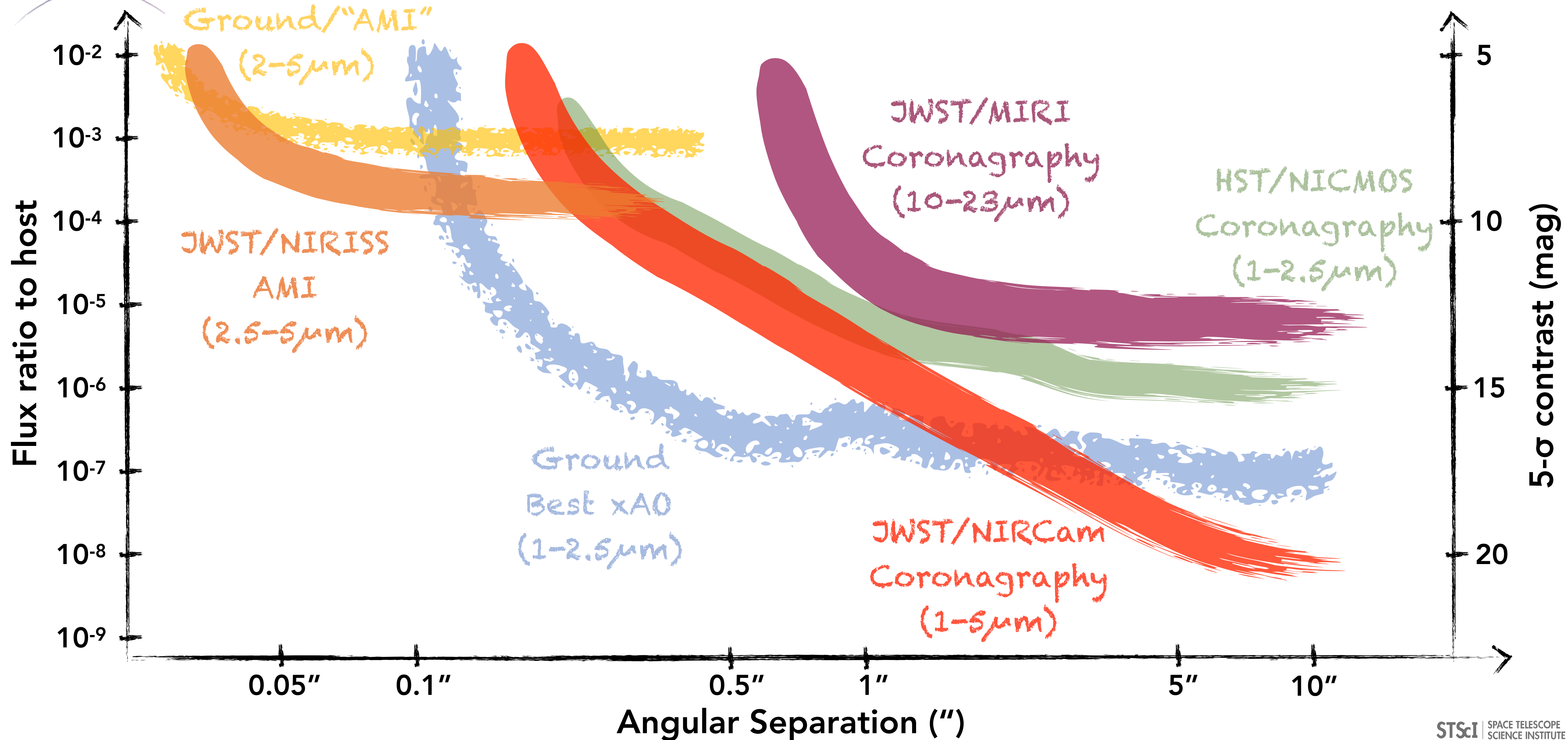
This roadmap outlines the suggested flow of planning considerations required for a High-contrast Imaging (HCI) observation with JWST and should be used in consultation with the General Proposal Planning Workflow.

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

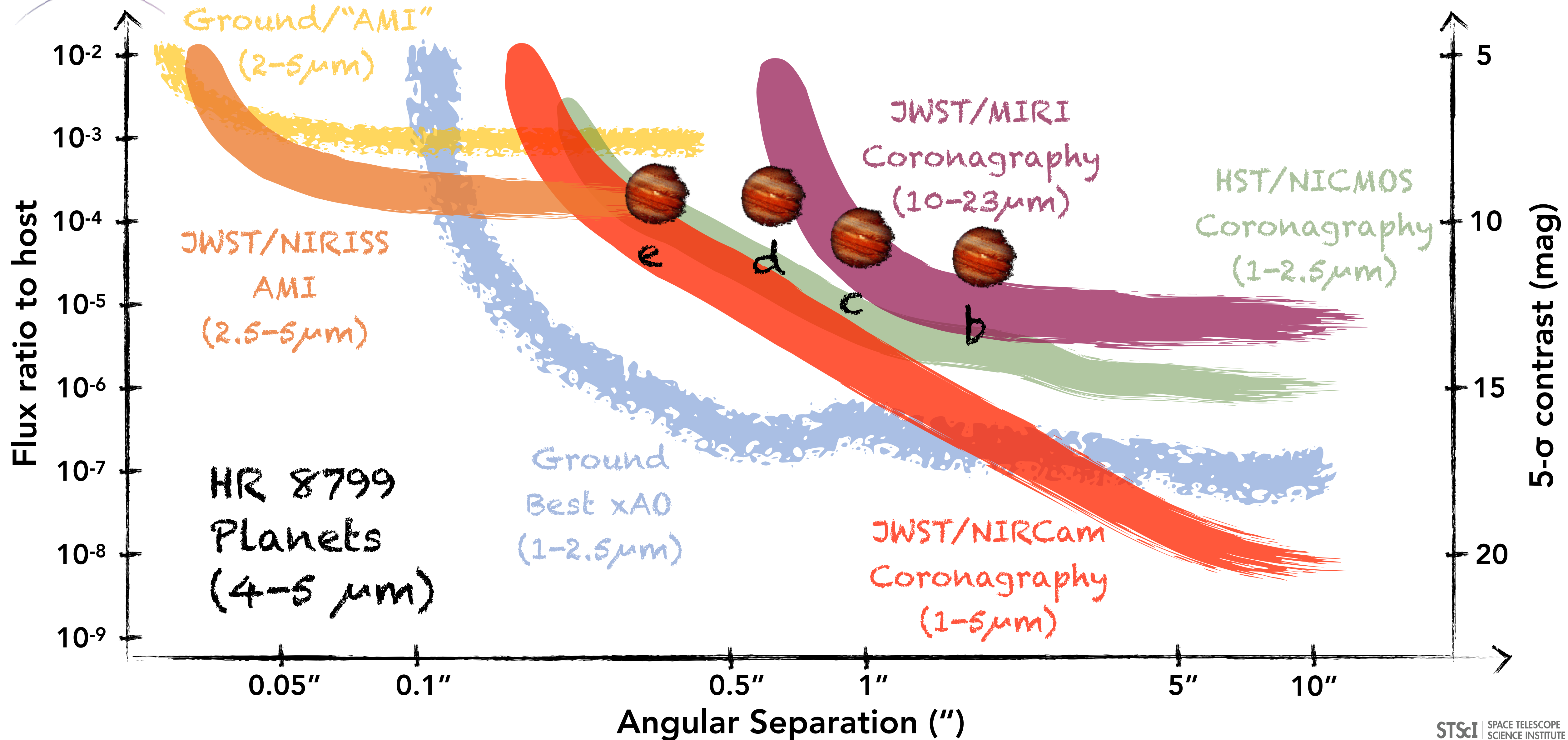


NIR to MIR Coronagraphy & Aperture Masking: Ground & Space



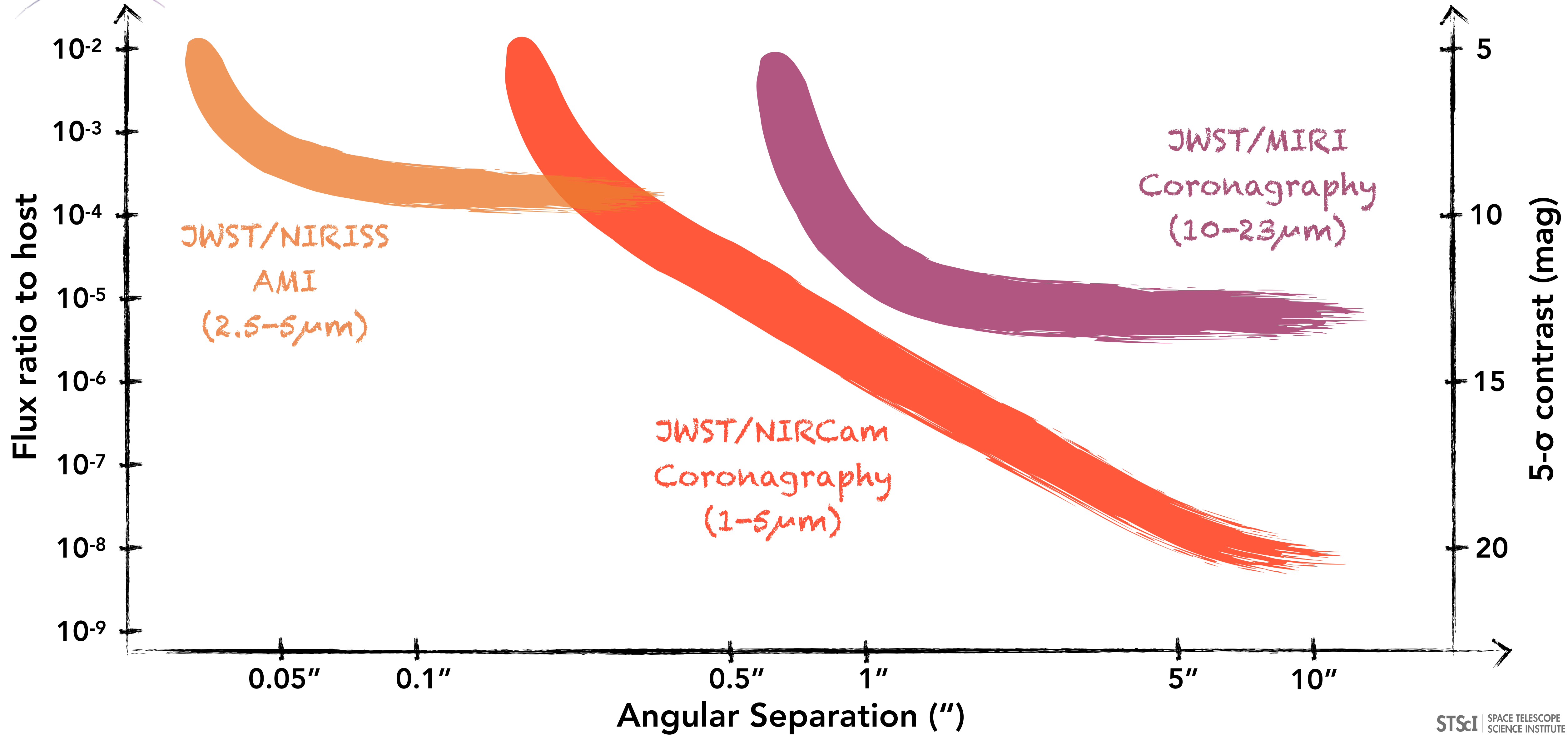


NIR to MIR Coronagraphy & Aperture Masking: Ground & Space



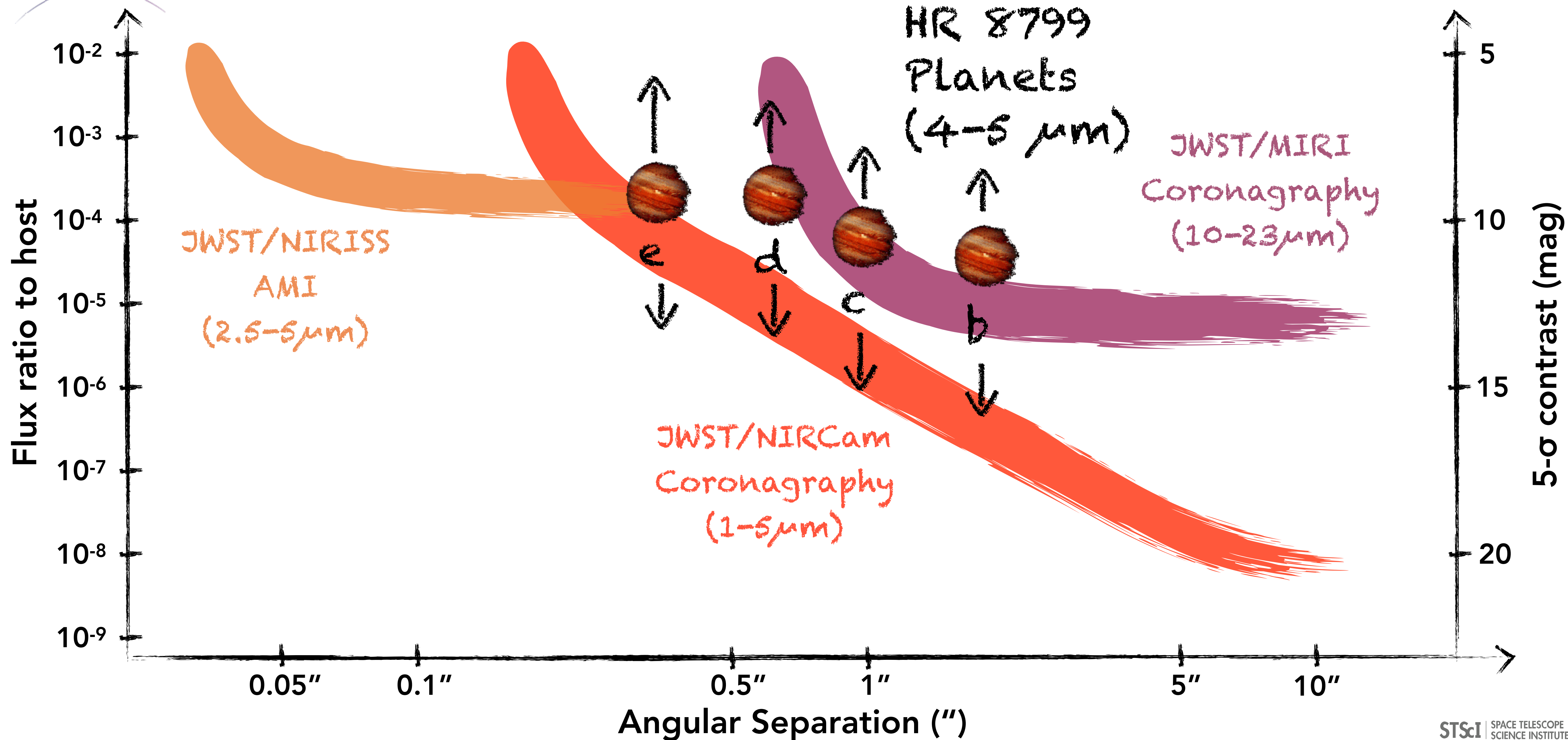


NIR to MIR Coronagraphy & Aperture Masking: Ground & Space





NIR to MIR Coronagraphy & Aperture Masking: Ground & Space

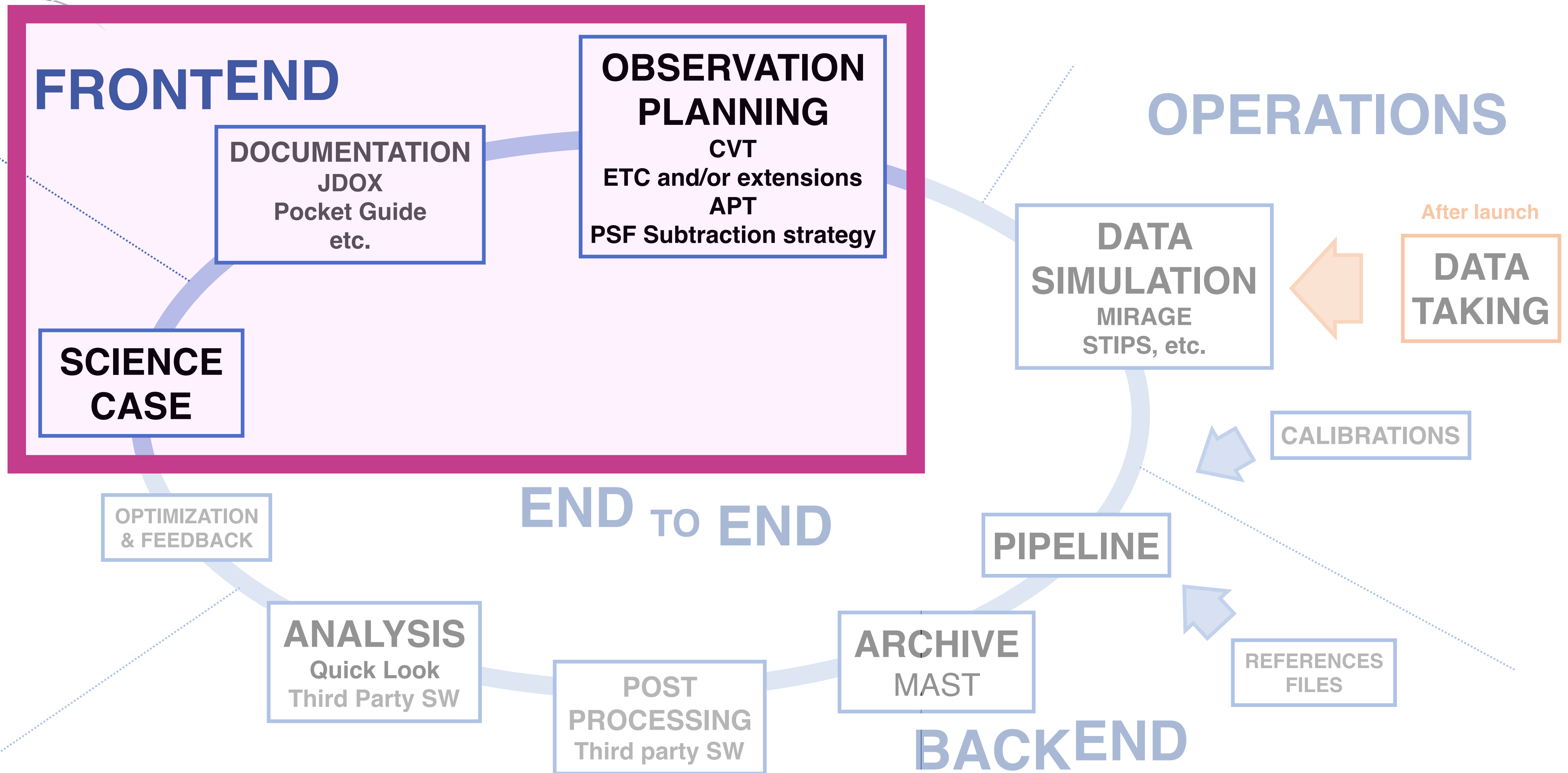


Proposal Planning Tools & HCI Resources





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)

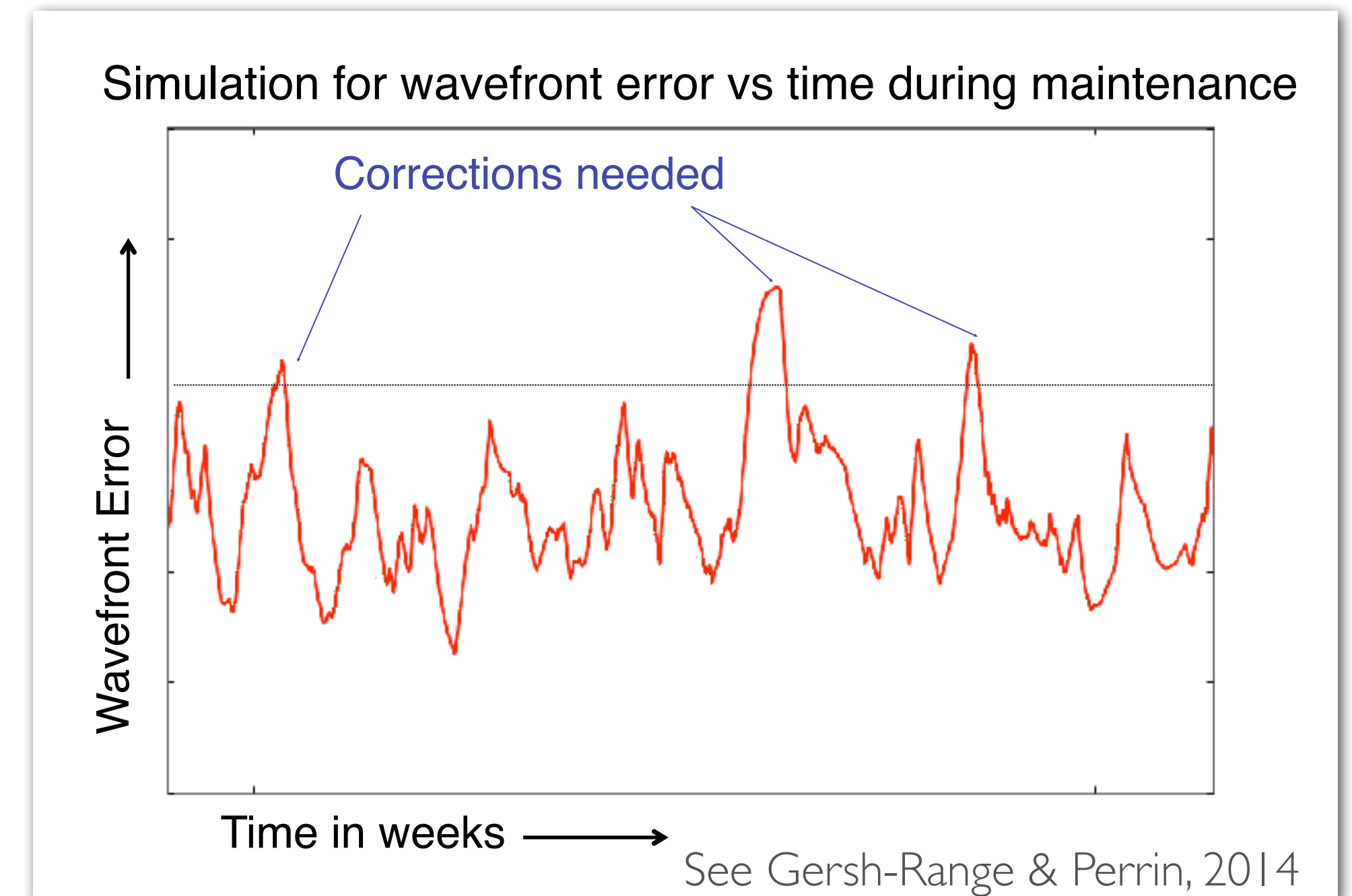
Imperfect target acquisitions

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



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:

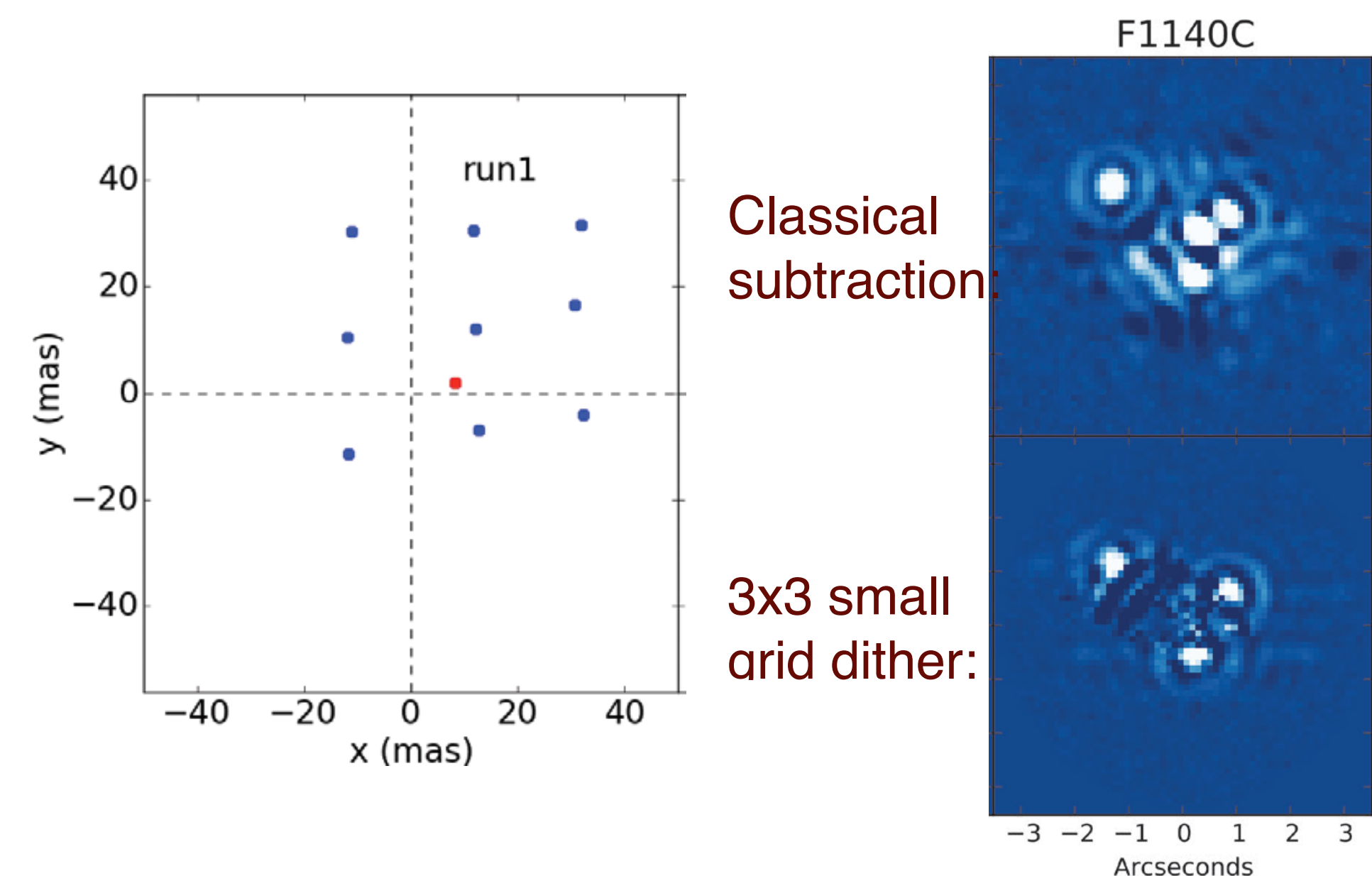
Perform sub pixel dithers of the PSF star to build mini PSF reference library, then synthesize an optimal PSF that matches the target position precisely. “Small Grid Dithers”.

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

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 NIRCcam Lyot coronas.

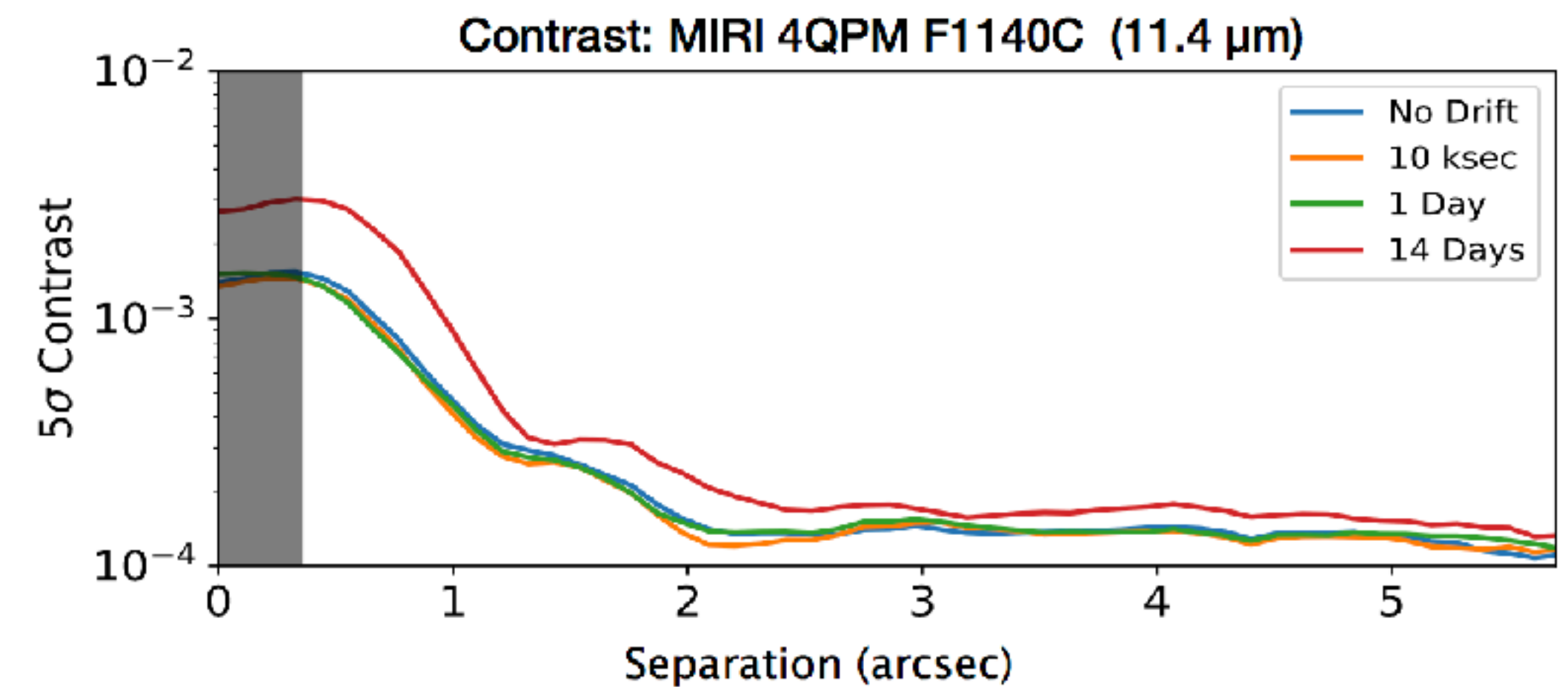
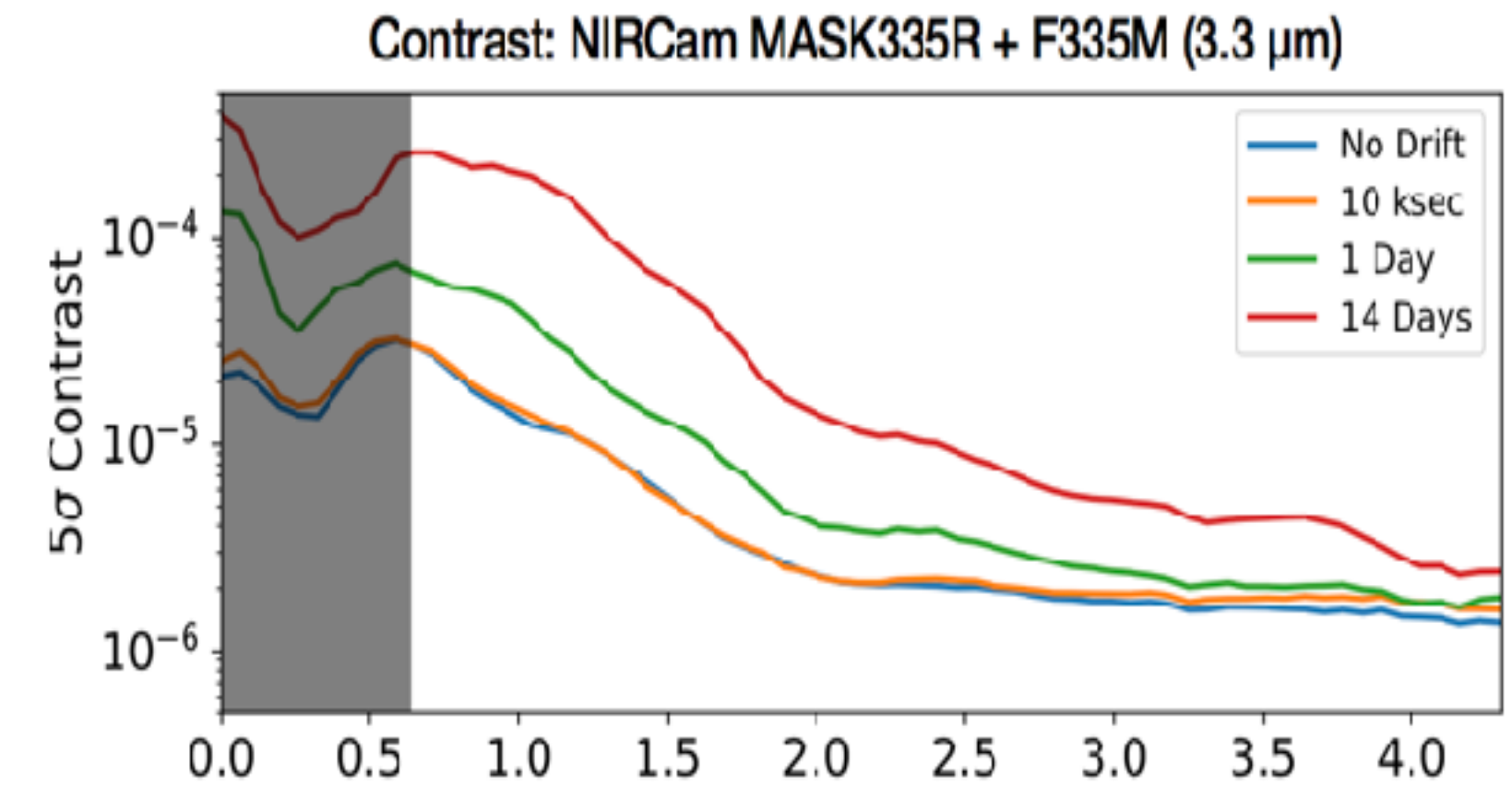
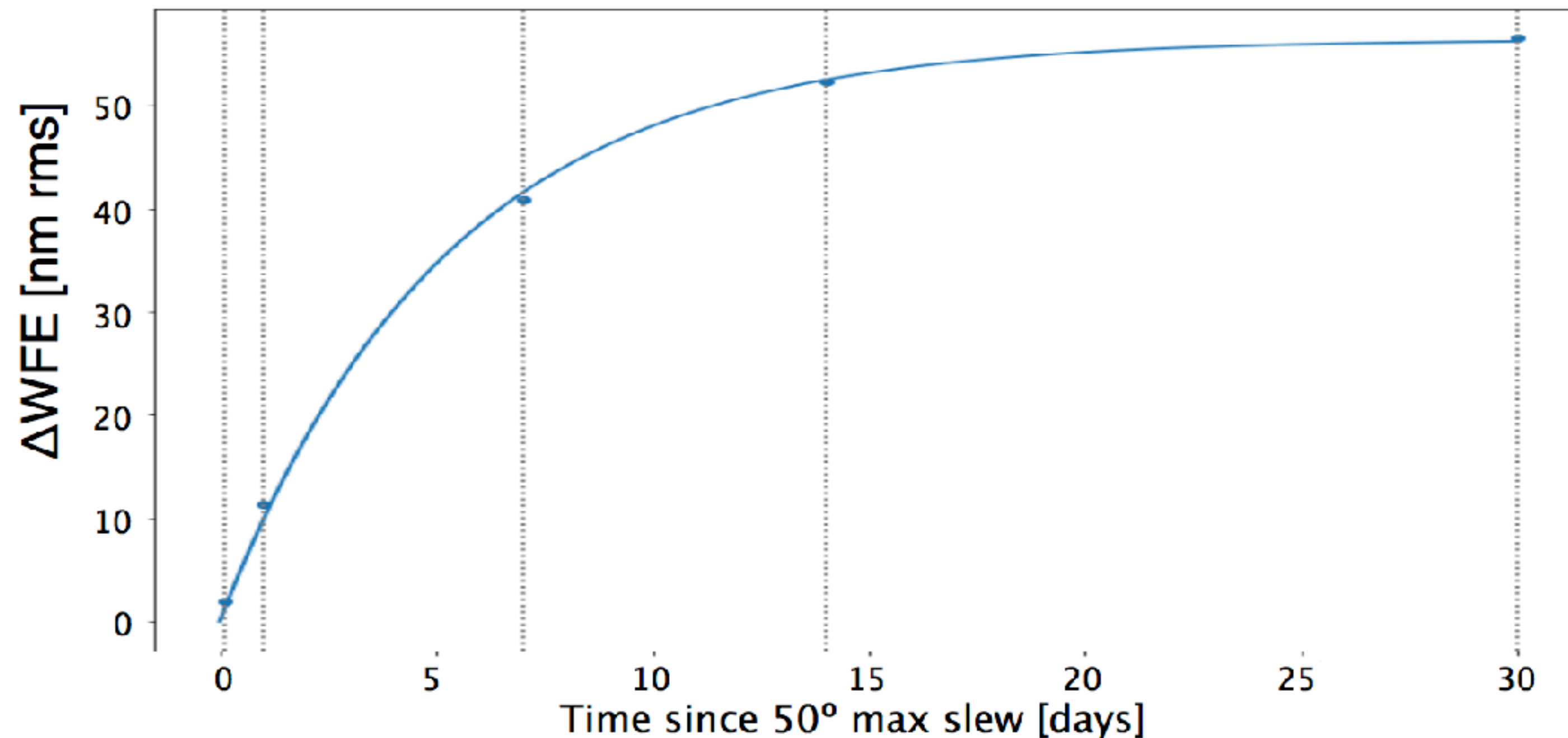


Simulated small grid dither PS subtraction
Lajoie et al. 2106



Towards the generation of realistic datasets : impact of slew

Model-predicted ΔWFE from maximum hot-to-cold slew



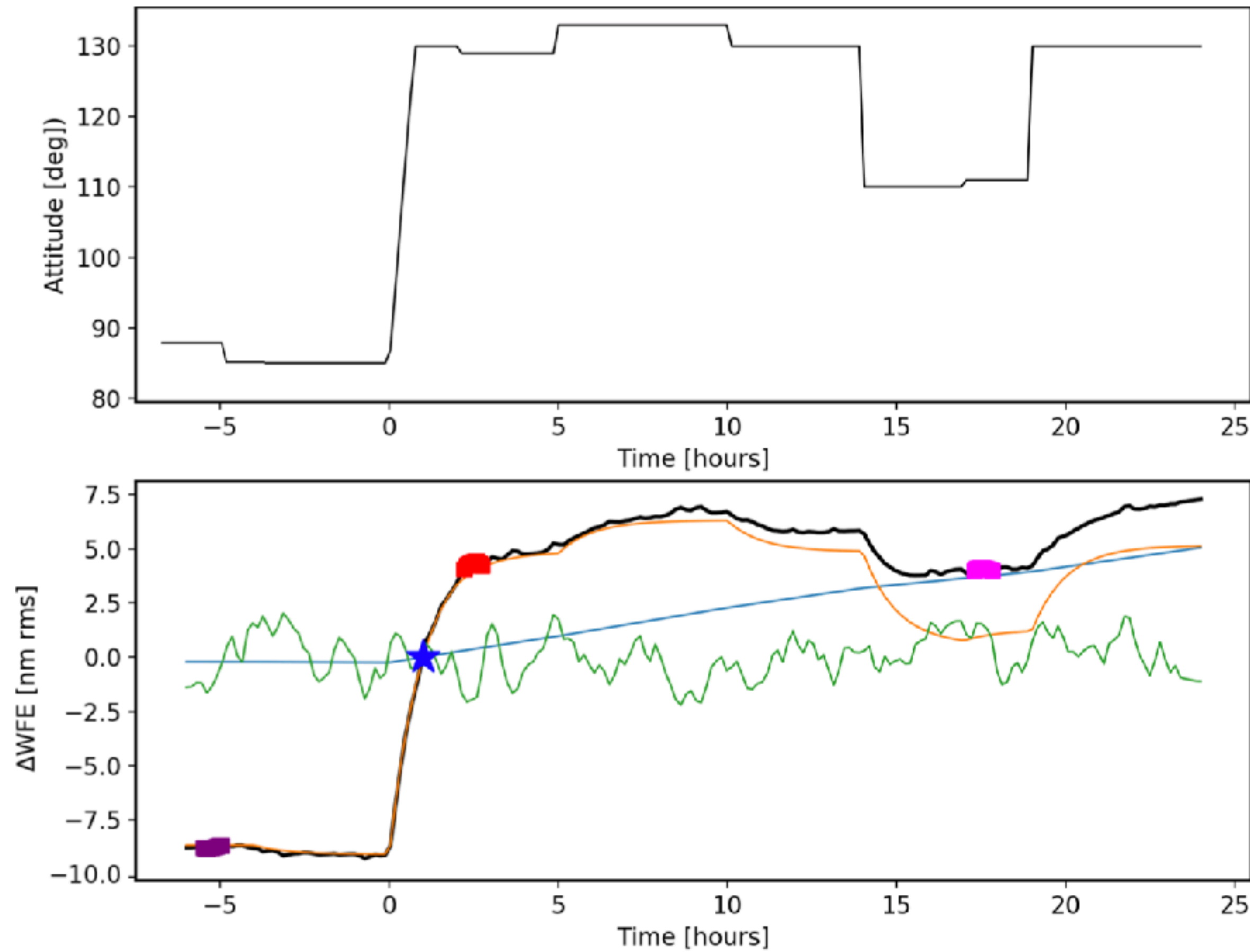
Perrin et al. SPIE 2018

Brooks et al. #AAS233

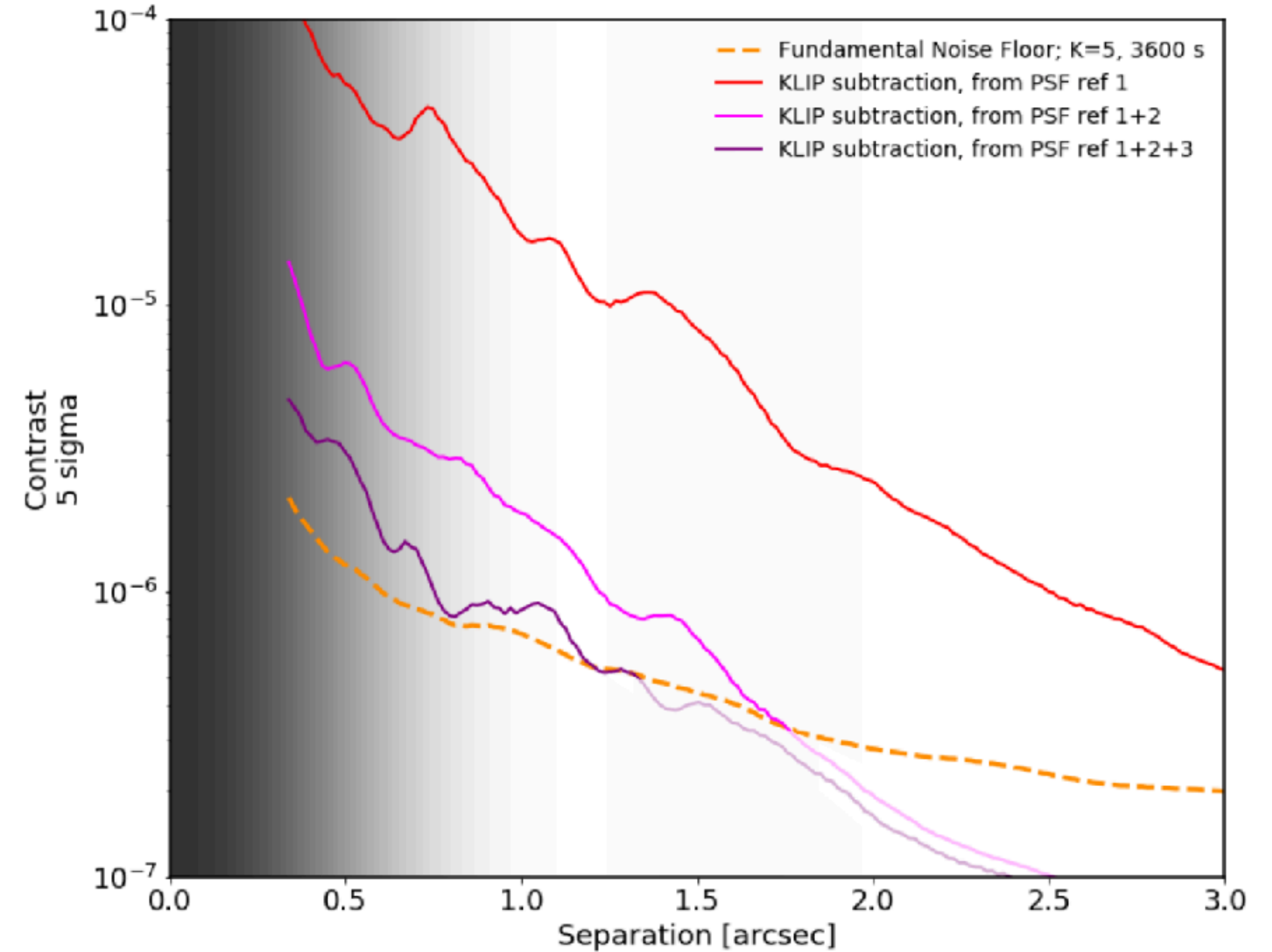


Towards the generation of realistic datasets : impact of slew

Hypothetical in-flight time series: observatory attitude and Δ WFE



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 a web browser window with the URL `jwst.etc.stsci.edu`. The page title is "Exposure Time Calculator". The main heading is "Welcome to the JWST Exposure Time Calculator". Below the heading are four buttons: "Quick Start" (green), "Create User" (white), "Login" (blue), and "Work Anonymously" (white). A light blue box contains a "News" section, which is circled in red. The news text reads: "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

Simple planet D1 case

Today is a nice day

Calculations Scores and Sources Upload Spectra Caveats and Limitations

| ID | Plot | Mode | Scene | (s) | SNR | |
|----|-------------------------------------|---------------------|-------|--------|-------|-------------------------------------|
| 11 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 409.24 | 98.74 | <input checked="" type="checkbox"/> |
| 10 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 268.06 | 93.65 | <input checked="" type="checkbox"/> |
| 9 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 306.93 | 87.94 | <input checked="" type="checkbox"/> |
| 8 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 265.77 | 81.47 | <input checked="" type="checkbox"/> |
| 7 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 204.56 | 73.97 | <input checked="" type="checkbox"/> |
| 6 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 153.46 | 65.07 | <input checked="" type="checkbox"/> |
| 5 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 102.31 | 53.99 | <input checked="" type="checkbox"/> |
| 4 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 51.15 | 38.82 | <input checked="" type="checkbox"/> |
| 3 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 51.15 | 38.82 | <input checked="" type="checkbox"/> |
| 1 | <input checked="" type="checkbox"/> | nircam target_mask | 2 | 1.88 | 37.22 | <input checked="" type="checkbox"/> |

Scene Backgrounds Instrument Setup Detector Setup Strategy

NIRCam Coronagraphy

Coronagraph: MASK335R

Filter: F335M

Calculation selected: 10, Mode: nircam coronagraphy

Final System Throughput

Images

Calculation selected: 10, Mode: nircam coronagraphy

2D SNR Detector Saturation

Plots

ApFlux ApBackground SNR SNR (time) Contrast

SNR vs On-Source Time

| Seconds | SNR |
|---------|-----|
| 0 | 38 |
| 50 | 40 |
| 100 | 55 |
| 150 | 65 |
| 200 | 75 |
| 250 | 82 |
| 300 | 88 |
| 350 | 92 |
| 400 | 98 |

Bounds/Scale: X: 25.94 436.88 Linear Clear Y: 32.46 103.66 Linear Clear Apply

Reports

Calculation selected: 10, Mode: nircam coronagraphy

Report Warnings Errors Downloads

| | |
|--|--------------|
| Instrument Filter/Diameter: | F335M/null |
| Extraction Aperture Position (arcsec): | (1.73, 0.00) |
| Wavelength of interest used to Calculate Scale Values (micrometers): | 0.35 |
| Size of Extraction Aperture (arcsec): | 0.08 |
| Total Time Required for Strategy (seconds): | 716.16 |
| Total Exposure Time (seconds): | 358.08 |
| Extracted Flux (e-/sec): | 76.73 |
| Standard Deviation in Extracted Flux (e-/sec): | 0.82 |
| Extracted Signal-to-Noise ratio: | 80.65 |
| Input Background Surface Brightness (MJy/ix): | 0.14 |
| Total Background Flux in Extraction Aperture (e-/sec): | 60.56 |
| Total Sky Background Flux in Extraction Aperture (e-/sec): | 1.20 |
| Fraction of Total Background due to Signal From Scene: | 0.86 |
| Average Number of Cosmic Rays per Frame: | 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

Simple planet D1 case

Today is a nice day

Calculations Scores and Sources Upload Spectra Constraints and Limitations

| ID | Plot | Mode | Scene | (s) | SNR |
|----|-------------------------------------|---------------------|-------|--------|-------|
| 11 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 408.24 | 98.74 |
| 10 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 268.06 | 93.65 |
| 9 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 306.93 | 87.94 |
| 8 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 266.77 | 81.47 |
| 7 | <input checked="" type="checkbox"/> | nircam coronagraphy | 2 | 204.52 | 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_mask | 2 | 1.88 | 37.22 |

Images

Calculation selected: 10, Mode: nircam coronagraphy

2D SNR Detector Saturation

Plots

ApFlux ApBackground

SNR vs On-Source Time

Instrument: Filter/Disperser: F955m/null

Extraction Aperture Position (arcsec): (1.73, 0.00)

Wavelength of Interest used to Calculate Scalar Values (microns): 3.35

Size of Extraction Aperture (arcsec): 0.08

Total Time Required for Strategy (seconds): 716.16

Total Exposure Time (seconds): 358.06

Extracted Flux (e-/sec): 76.73

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

Extracted Signal-to-Noise ratio: 80.65

Input Background Surface Brightness (MJy/ix): 0.14

Total Background Flux in Extraction Aperture (e-/sec): 60.56

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

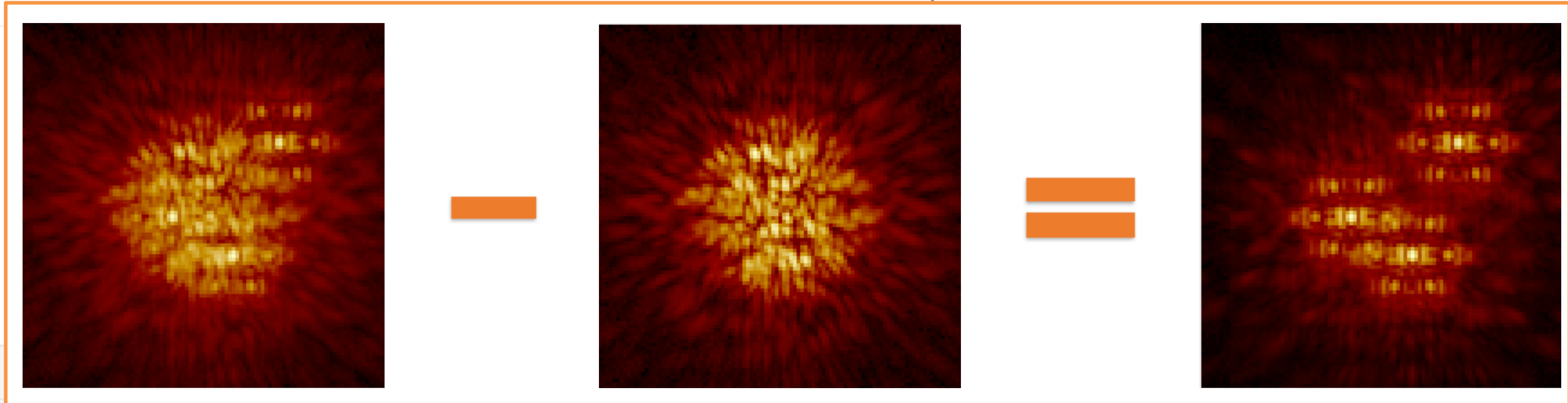
Fraction of Total Background due to Signal From Scene: 0.86

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

Radius at which Contrast is Measured (arcsec): 1.00

Azimuth at which Contrast is Measured (degrees): 0.0

Contrast: NaN



jwst.etc.stsci.edu

Example feature:
Expand SNR
through filters



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/spacetelescope/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

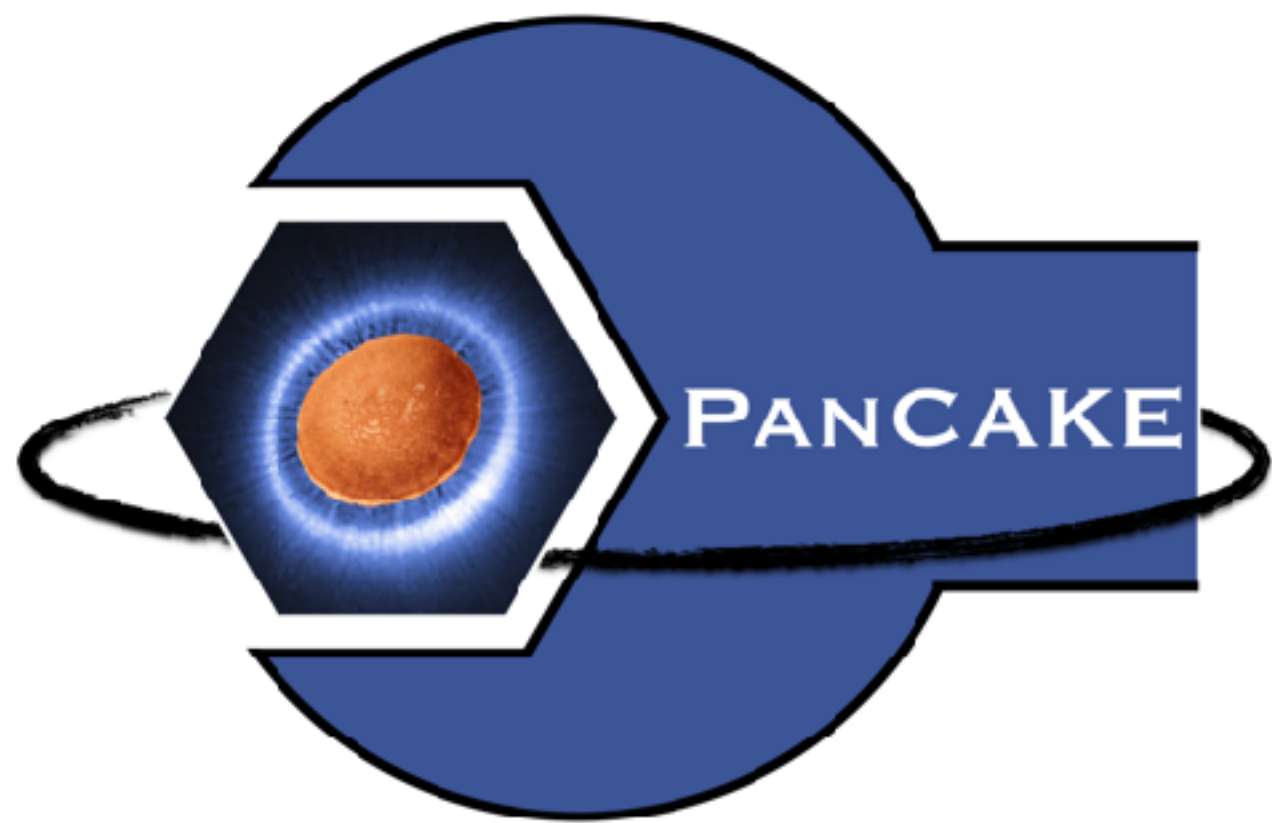
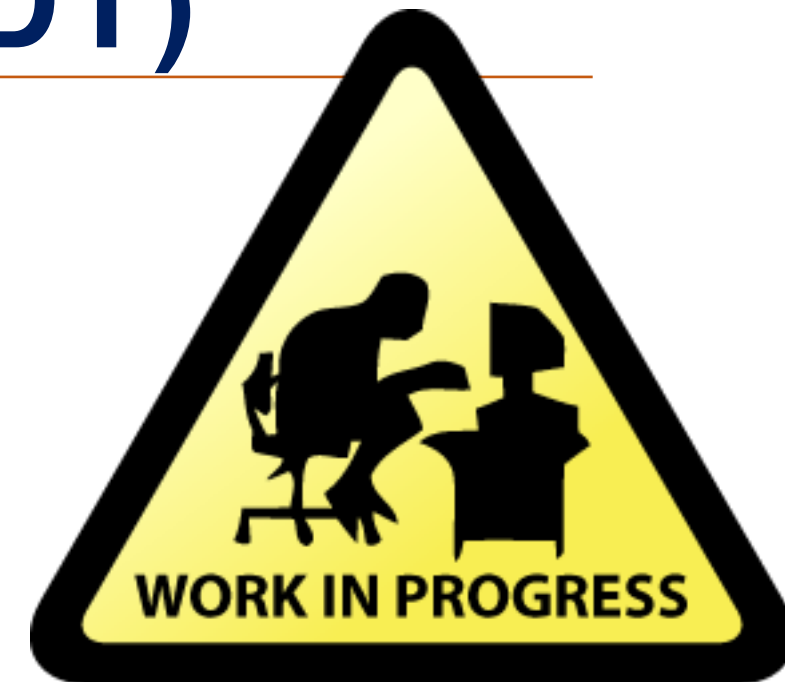
Can be done with **pyNRC** (not supported by STScI)

<https://pynrc.readthedocs.io>



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

github.com/spacetelescope/pandemia-coronagraphy



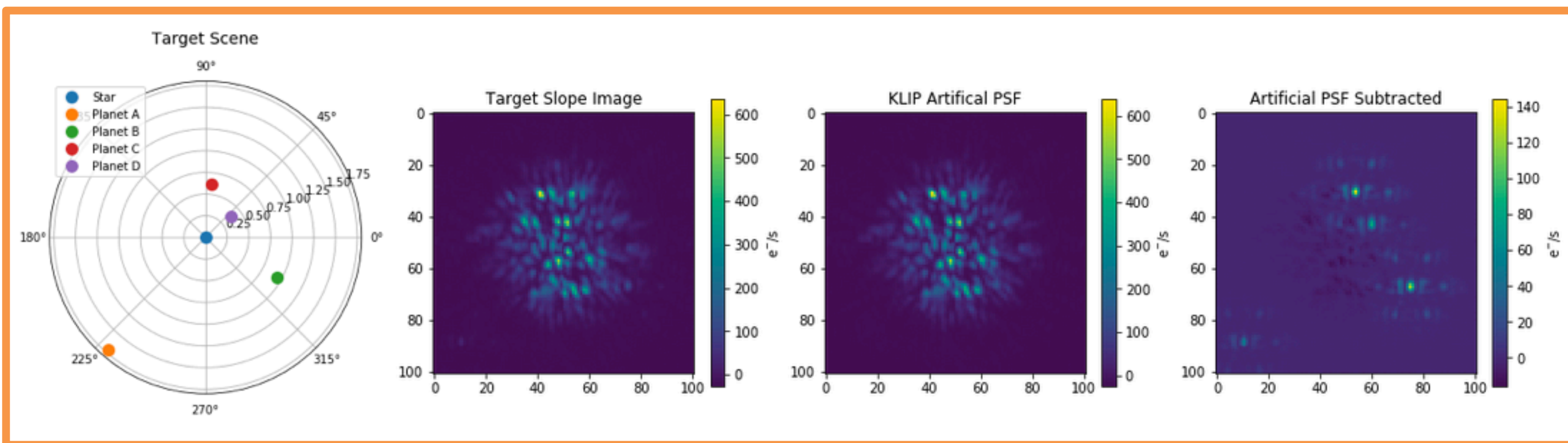
Can call WebbPSF “on the fly”

custom PSF grids/dithers, FoV, spectral sampling, more precise extractions

Several coronagraphic specific functions

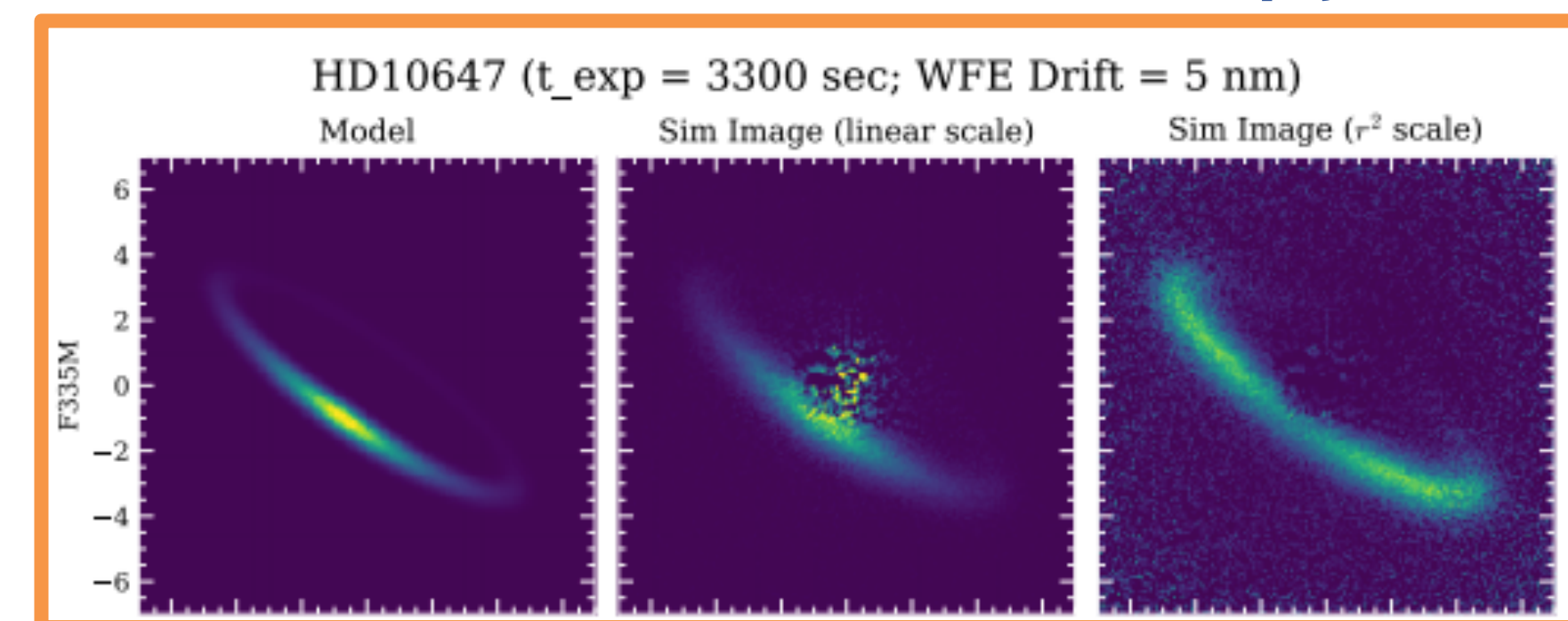
Contrast curves

Currently improving the scene compatibility with ETC UI and outputs



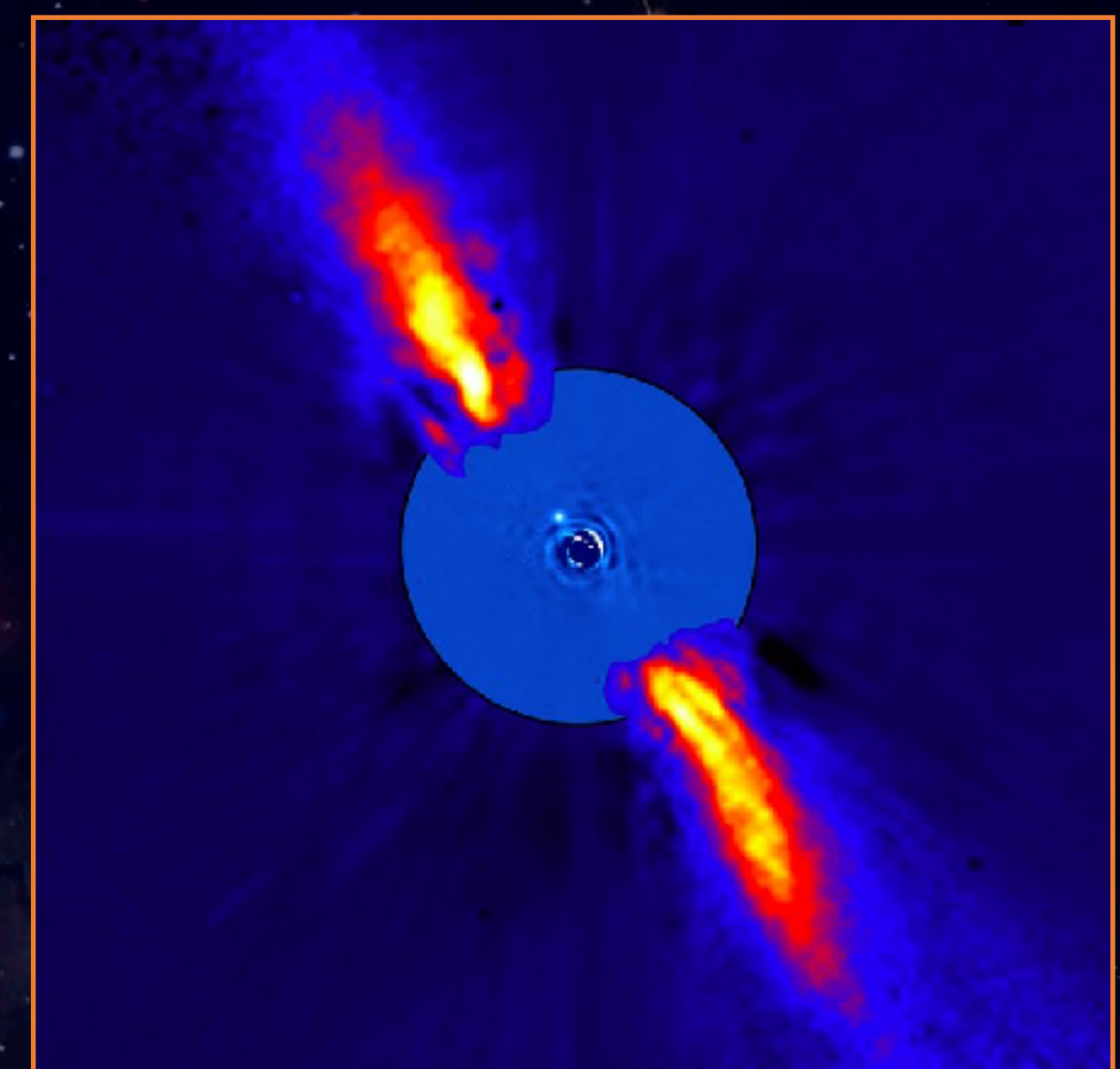
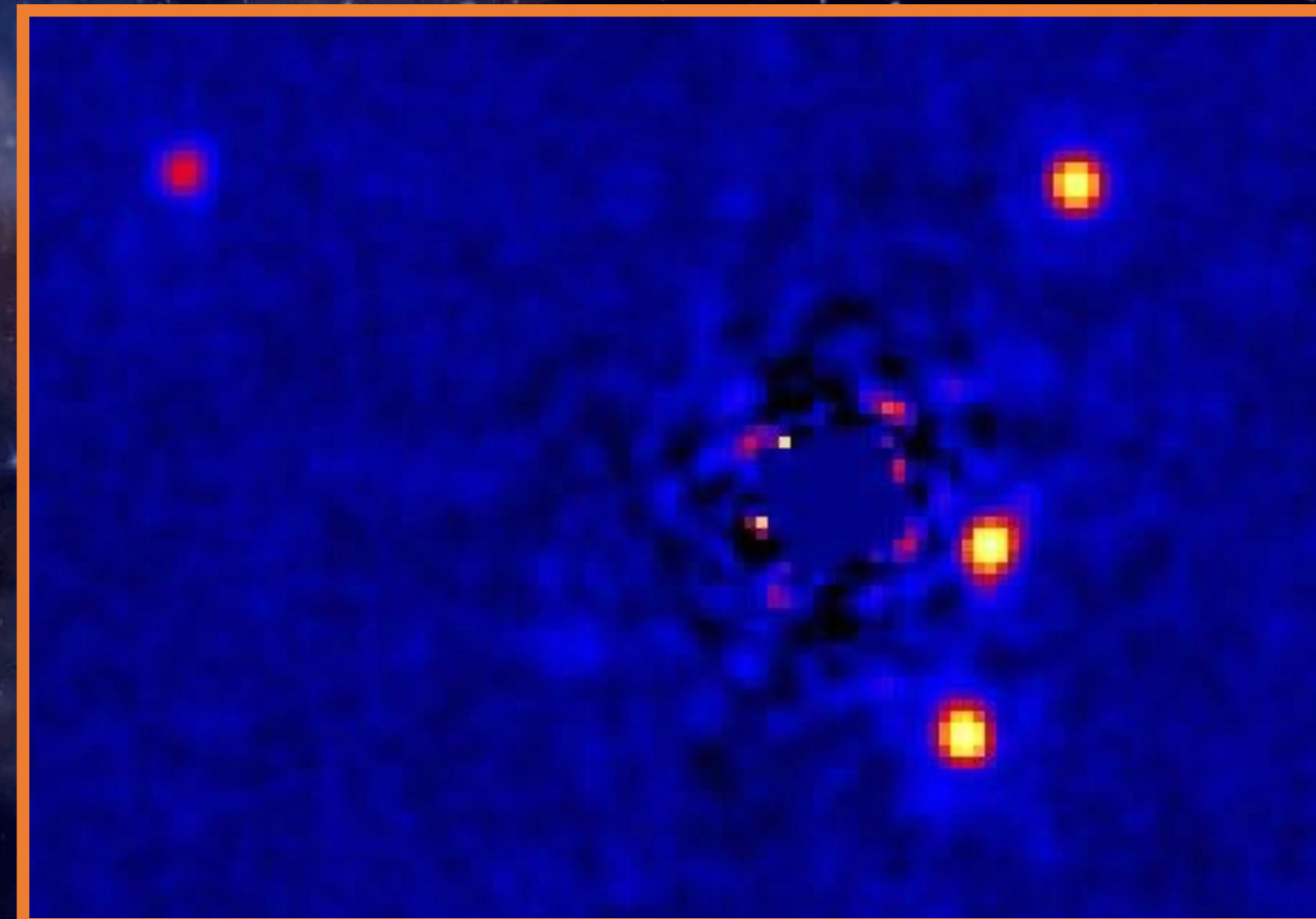
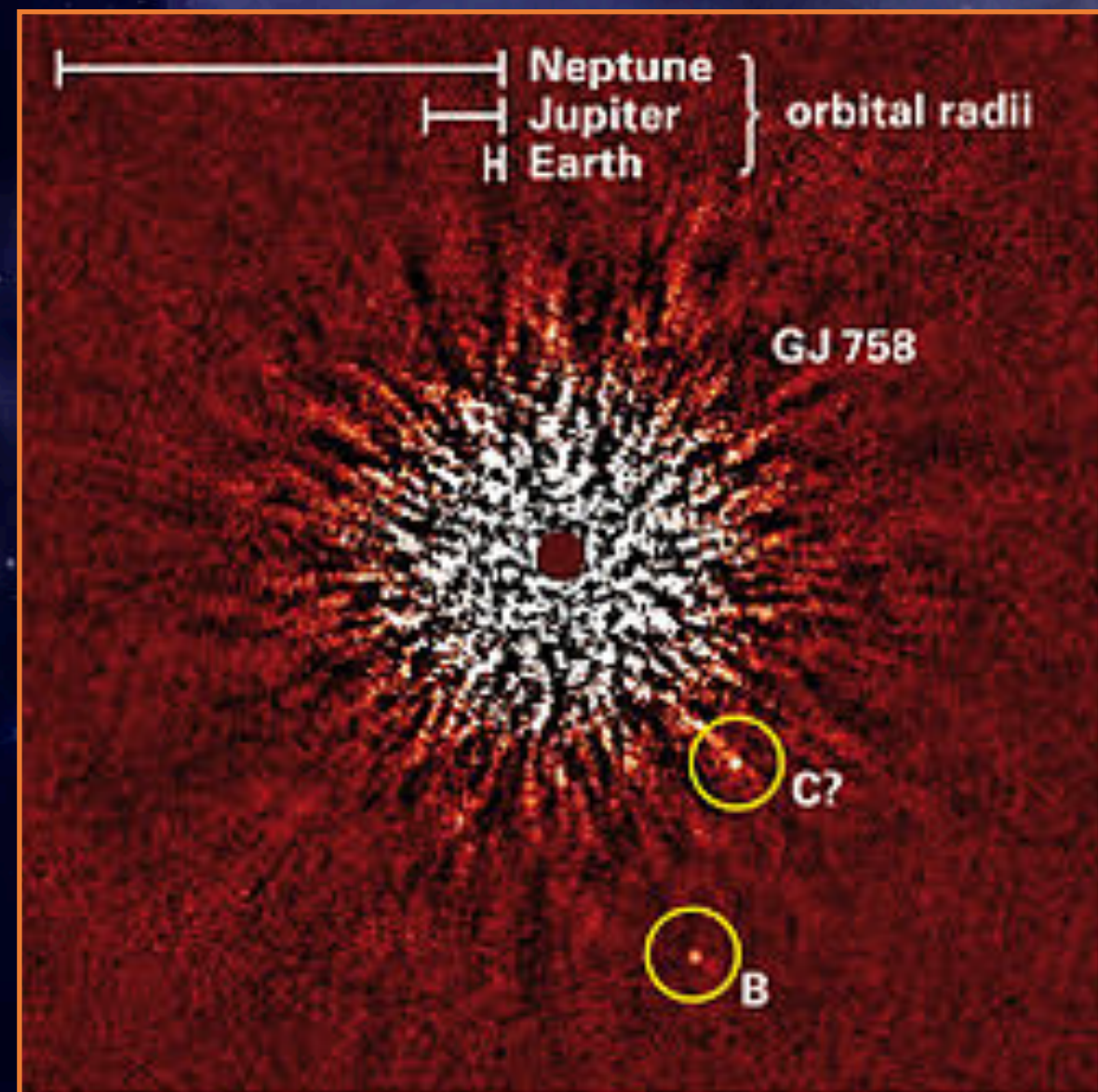
Check also (disks)!

pyNRC



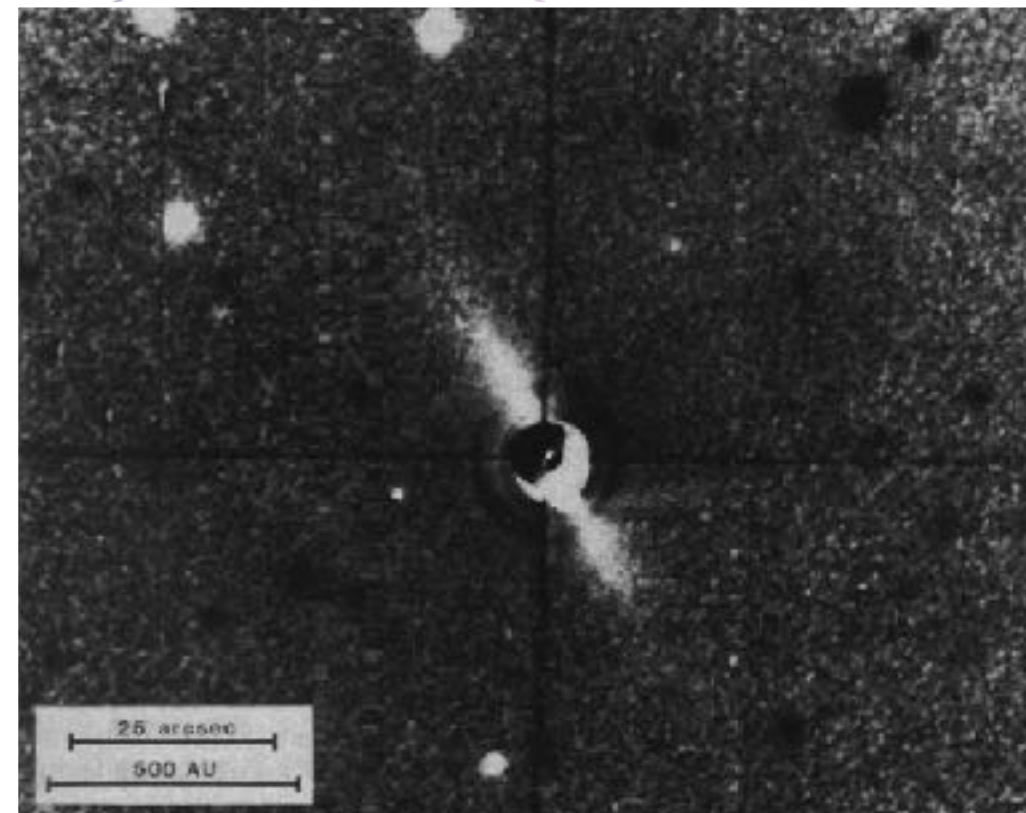
Coronagraphy

Example Science Programs

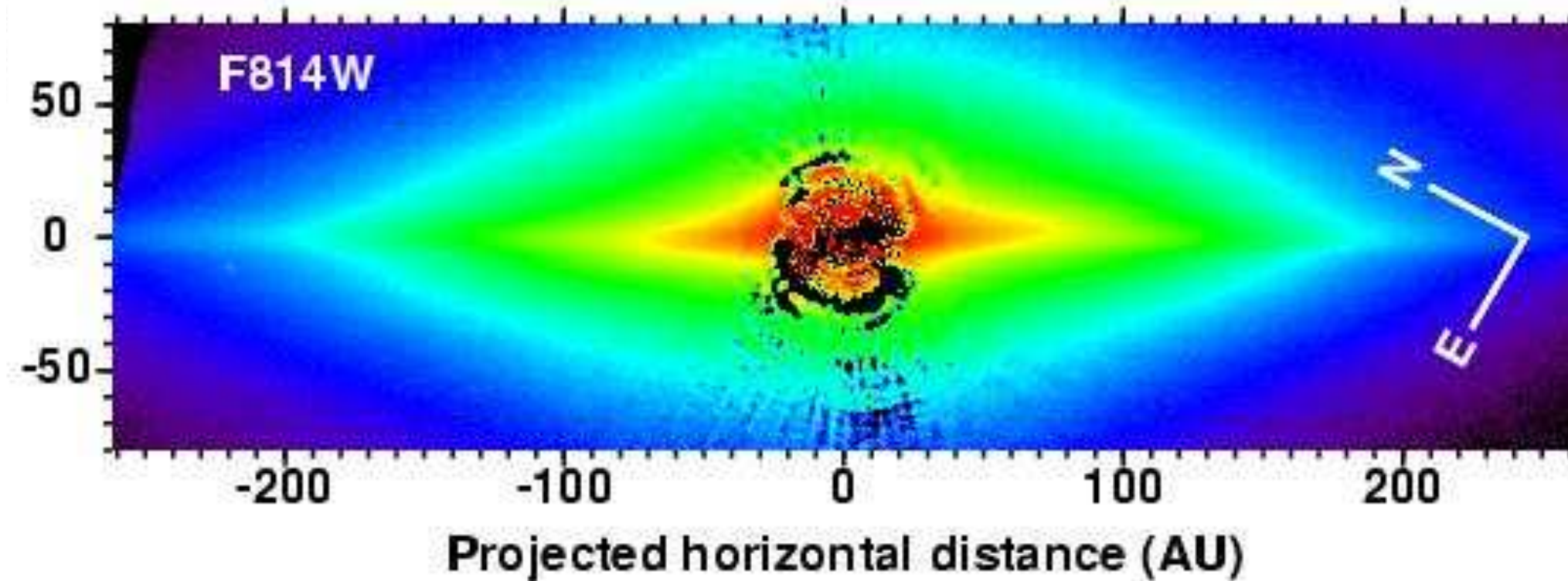




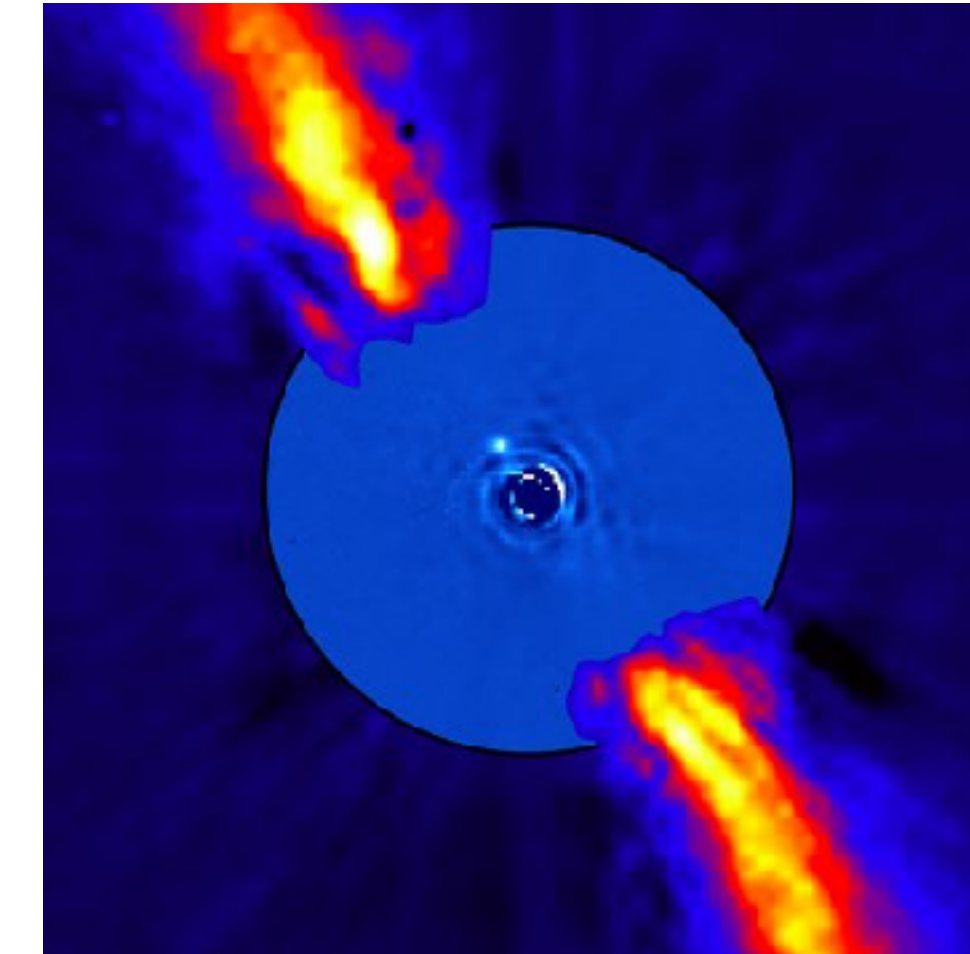
Example Science Program: deep imaging of the β Pic debris disk



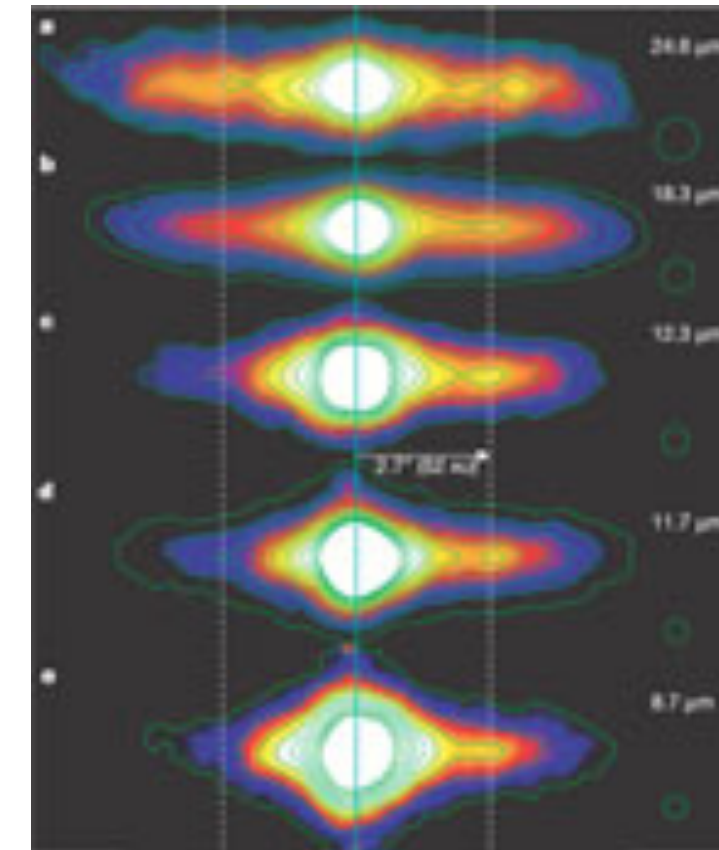
Smith & Terrile 1984



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 NIRCcam 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?

- NIRCcam, 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 NIRCcam & 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 NIRCcam; 30 minutes for MIRI.
- Note, for NIRCcam 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

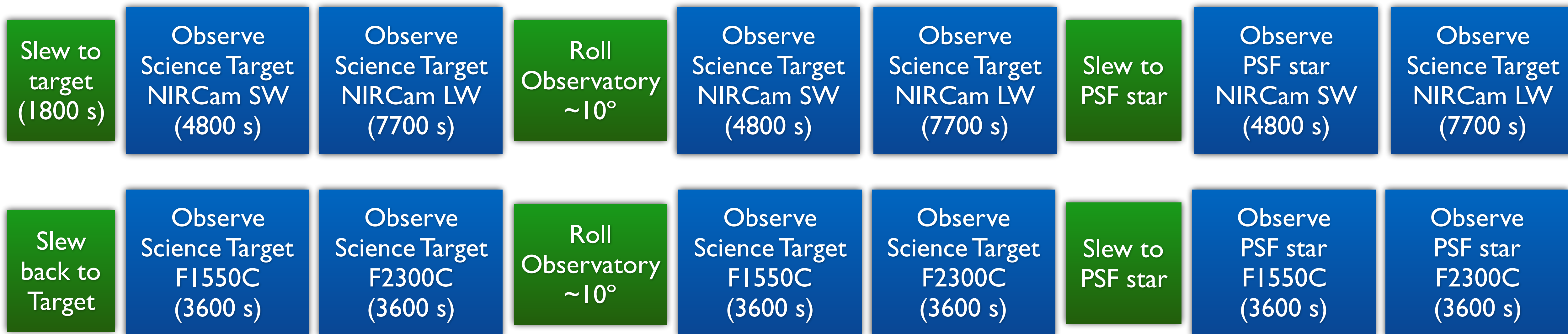
PSF reference: Alpha Pic. Spectral Type A8, K mag = 2.57. 06 48 -61 56

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



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

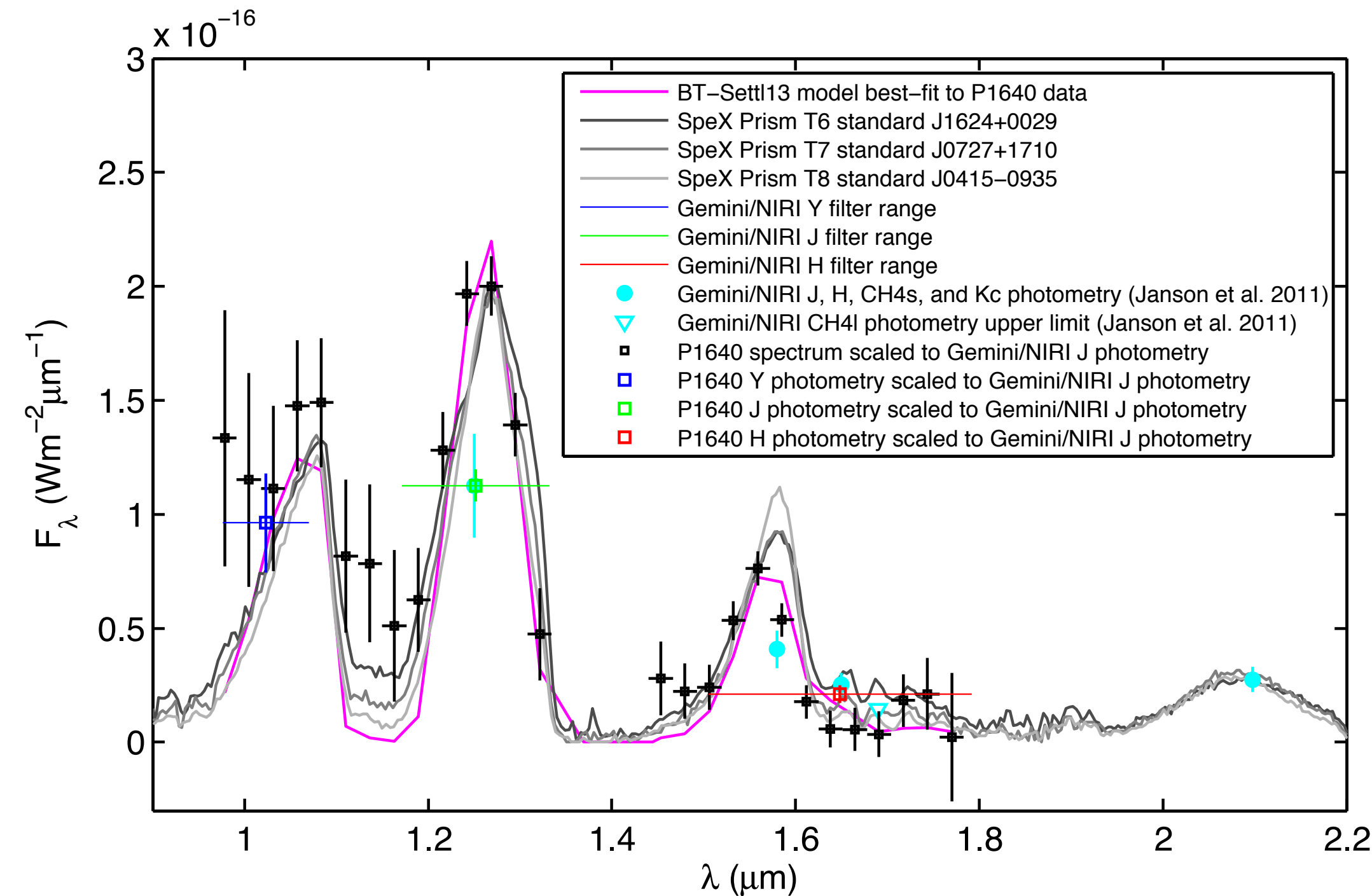
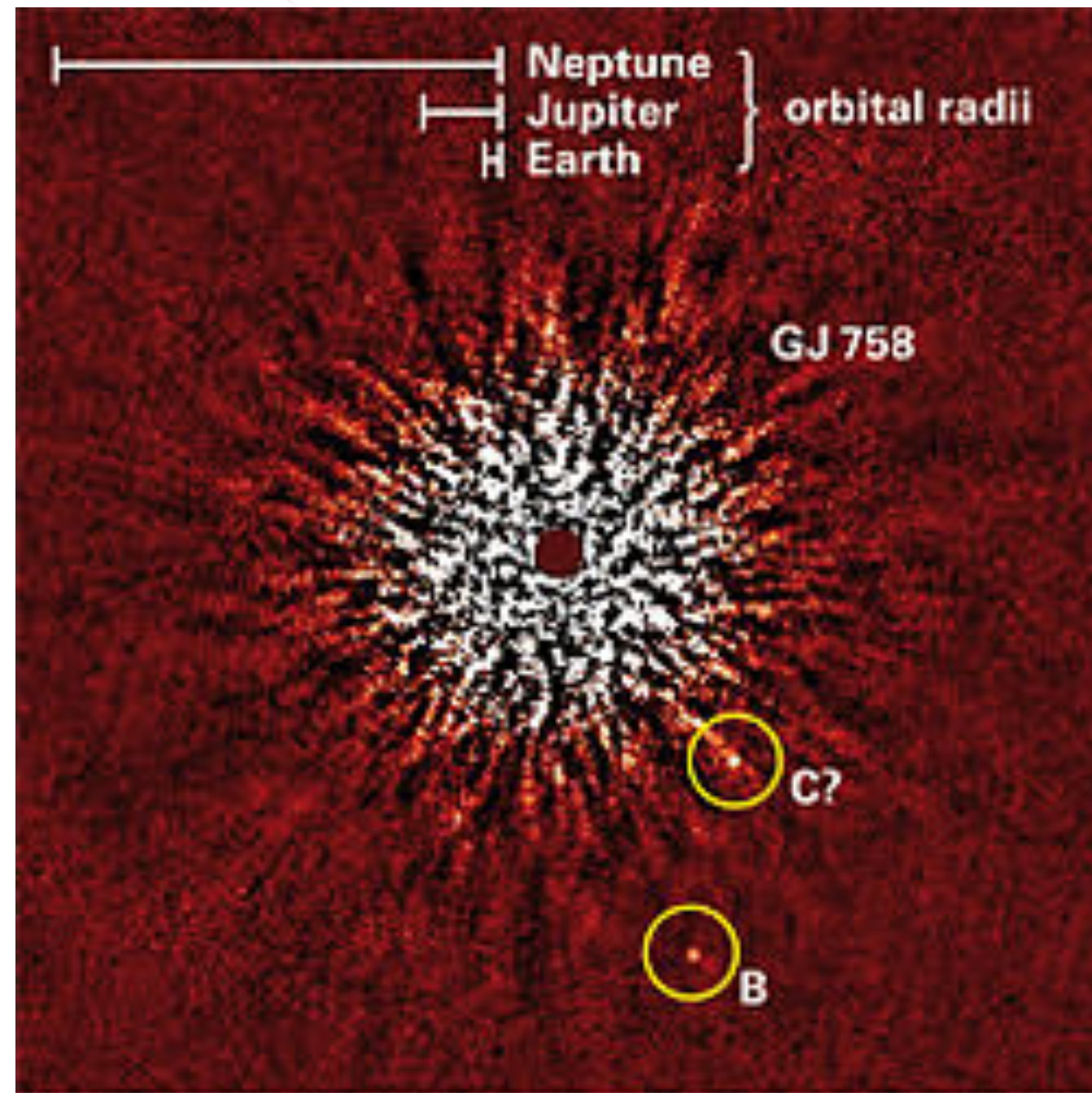
Could save a little time if we minimized slews (reorder to group all PSF star obs at end), but that would increase time delay between some science visits + their PSF reference by over 5 hrs; we opted against this trade.

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

Preferred is $\sim 45^\circ$ 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?

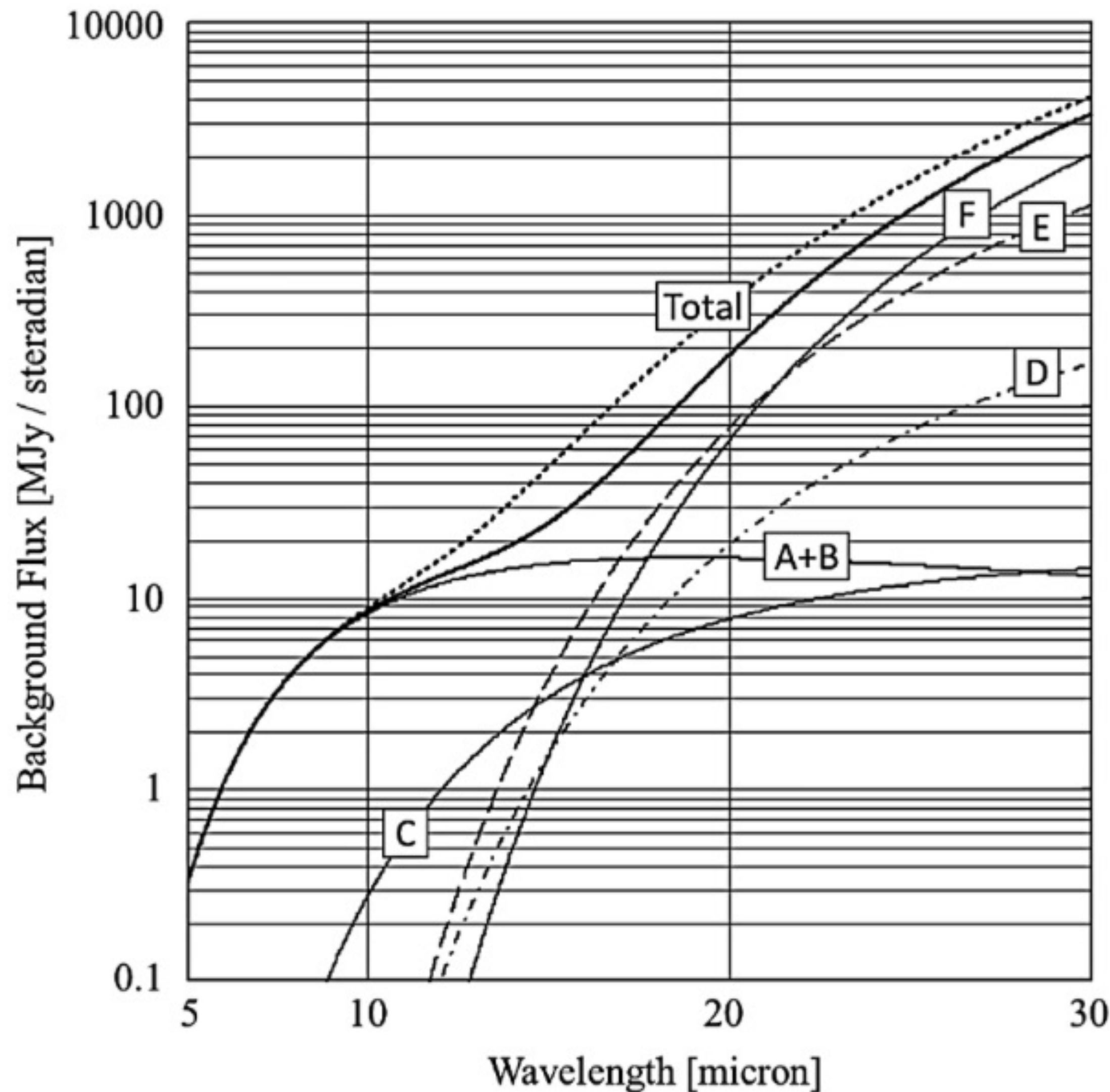
- Standard sequence, 2 rolls science + PSF star, repeat for each FQPM filter.
- Extrapolating from NIR data, companion contrast is moderate $\sim 10^{-4}$ at $10 \mu\text{m}$. But edge-on orbit will move it inward to projected separation of $1''$ by 2019.
- Therefore use small grid dither on PSF star 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 & $11.4 \mu\text{m}$. $15 \mu\text{m}$ is much harder due to increased thermal background, needs longer integration.



Thermal background matters at the longest wavelengths



Thermal background rises significantly beyond 15 μm 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

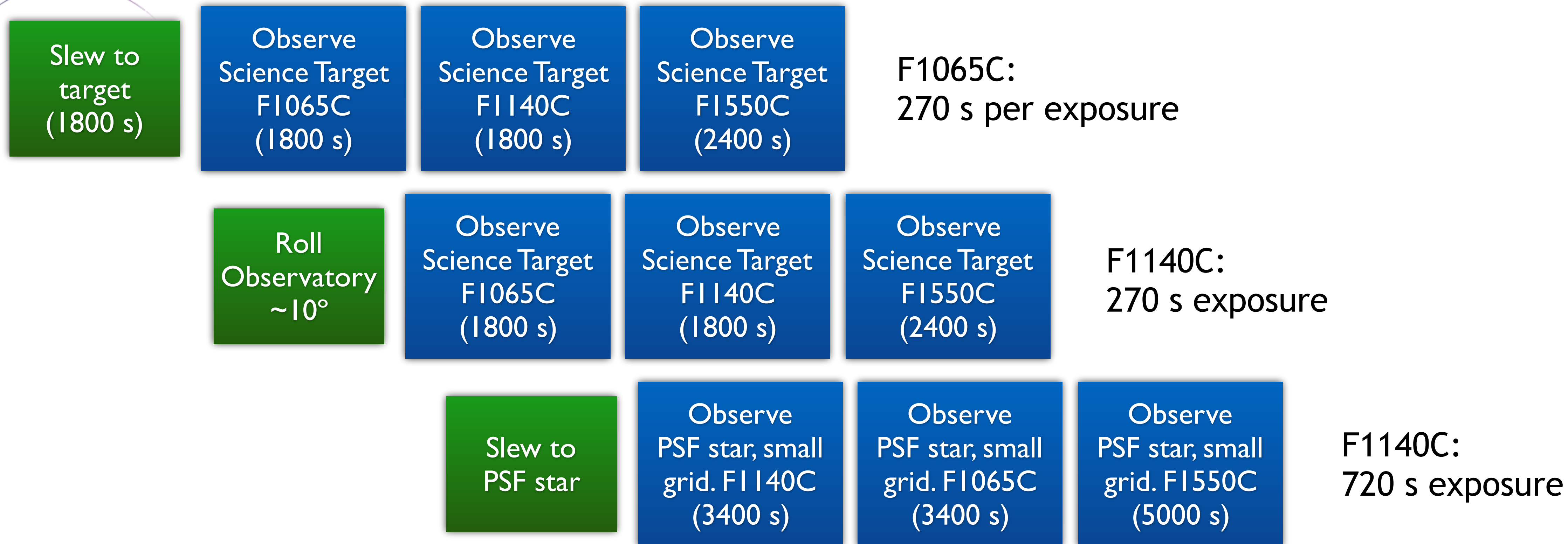
PSF reference: HD 190360. Spectral Type G7, K mag = 4.08. 20 03 + 29 53

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)

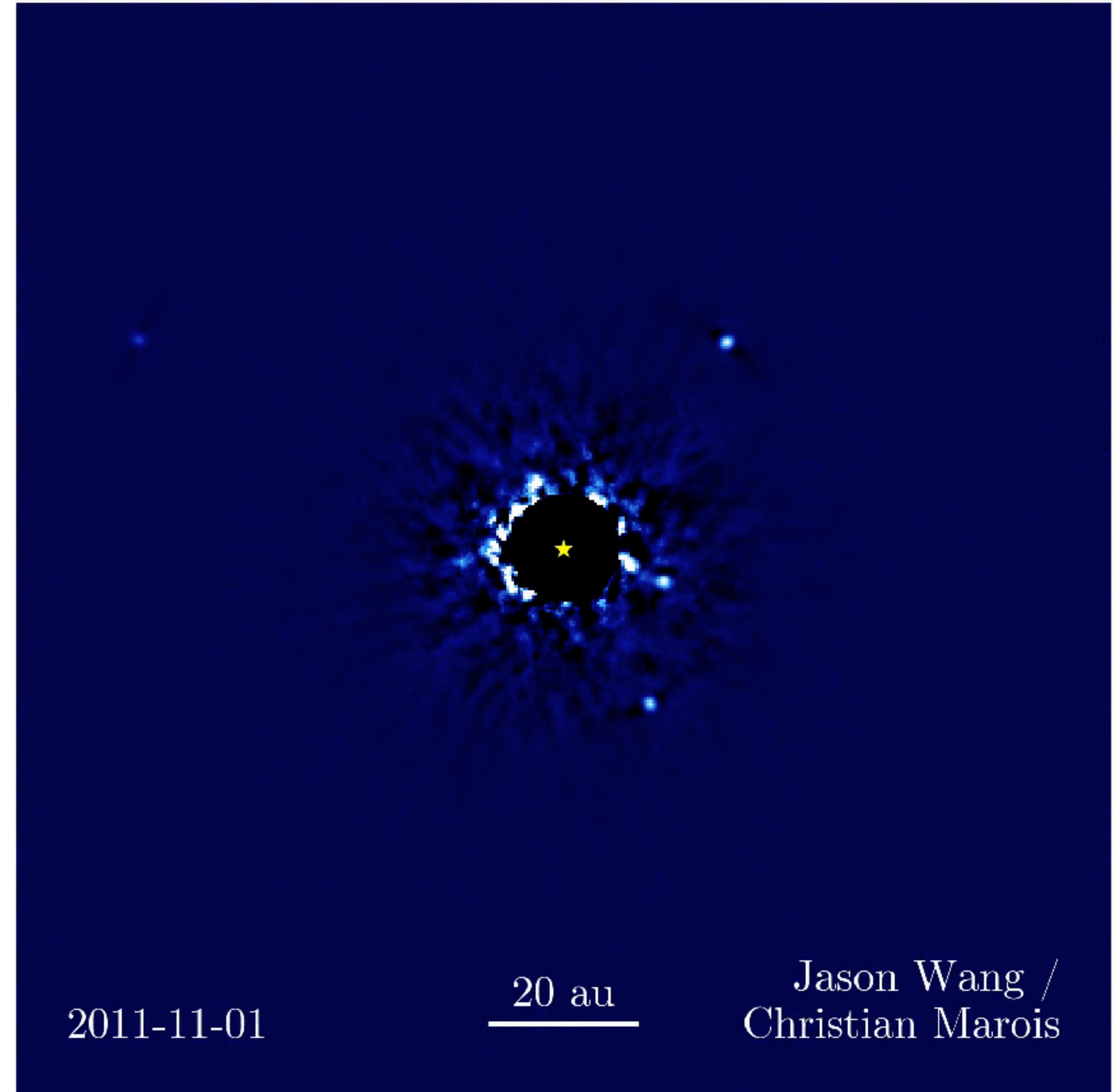
4 planets with mass $< 8 M_{\text{Jup}}$

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



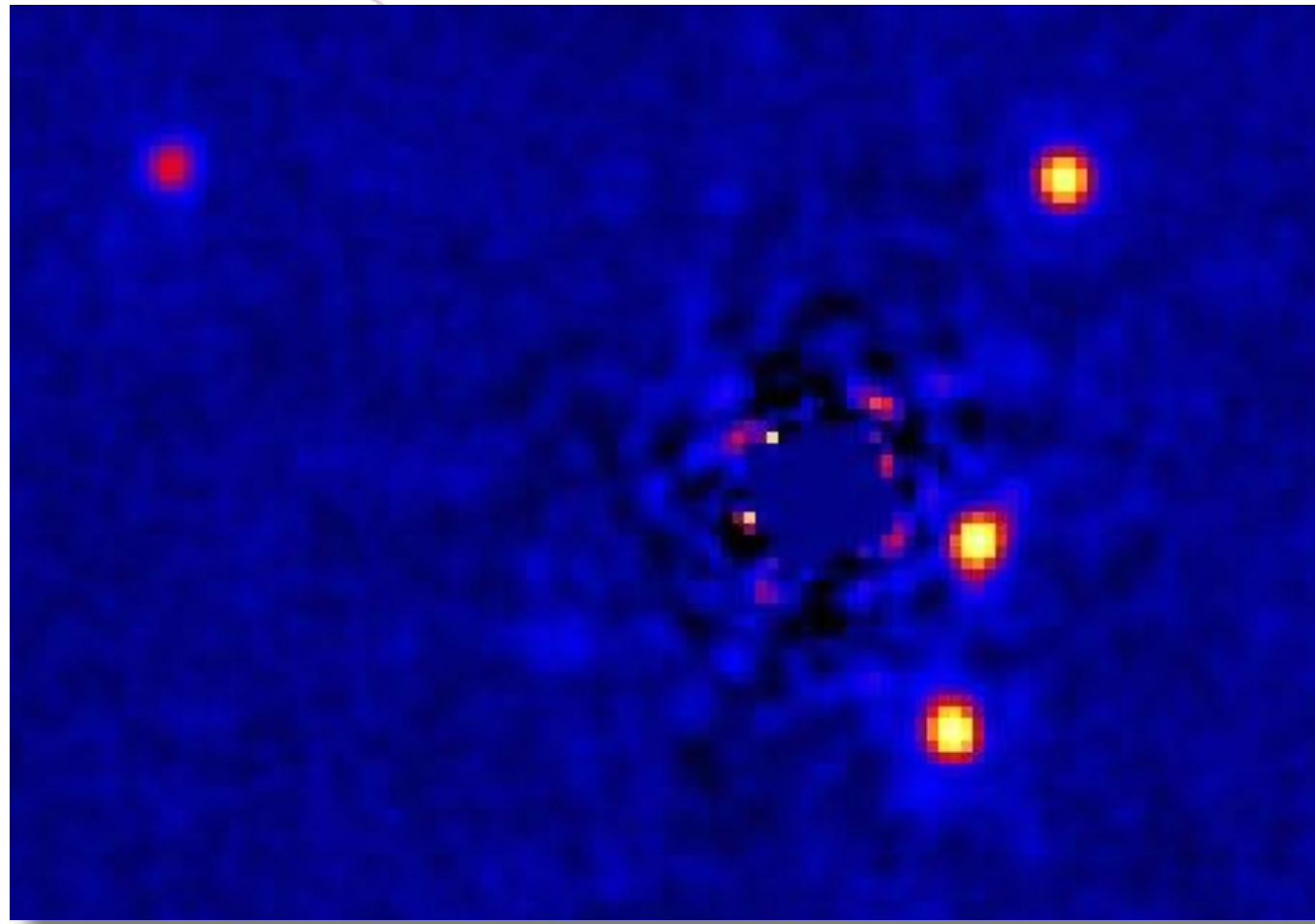
2011-11-01

20 au

Jason Wang /
Christian Marois



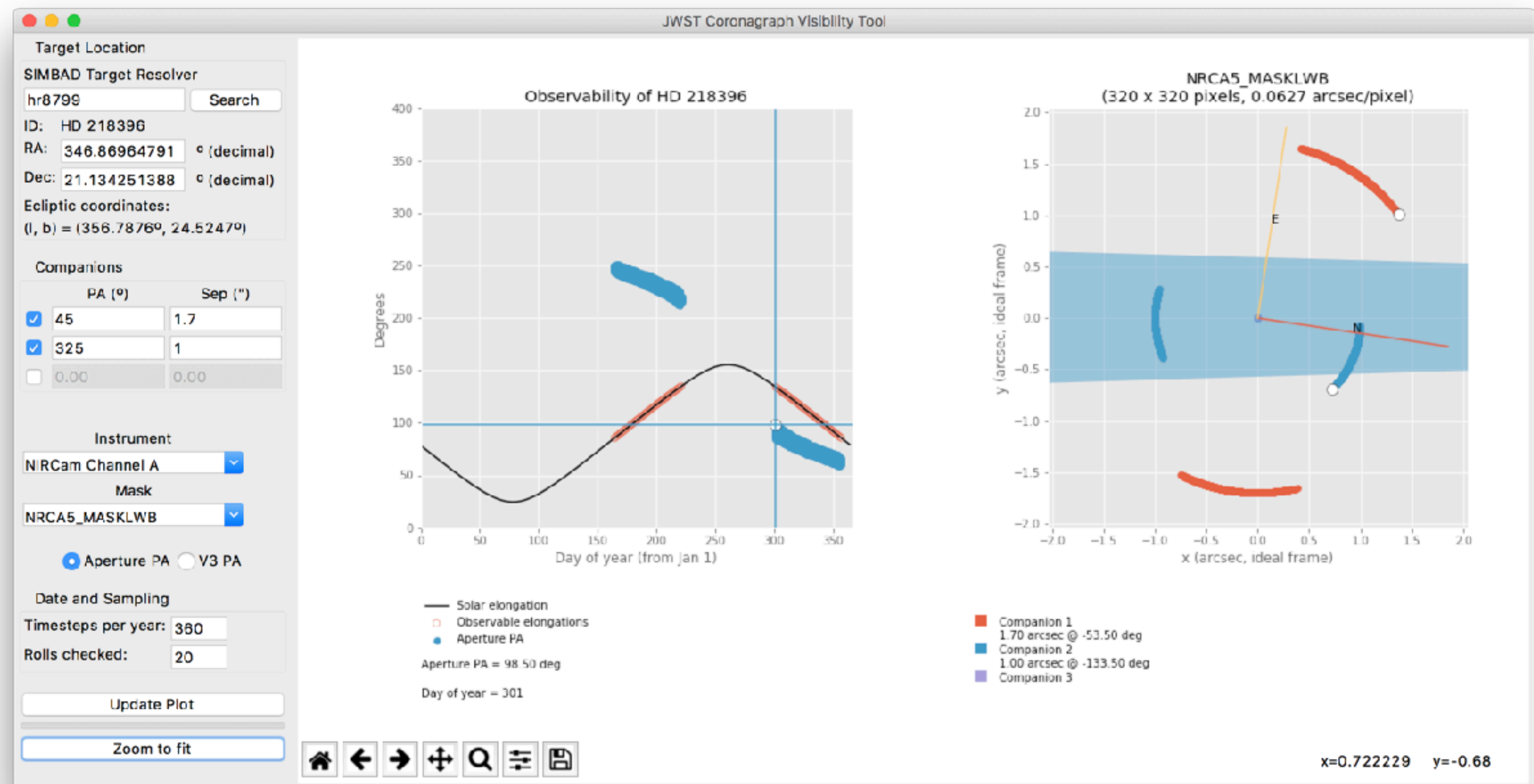
Example Science Program: the HR8799 4-planet system



discovered by Marois, here Currie et al. 2014

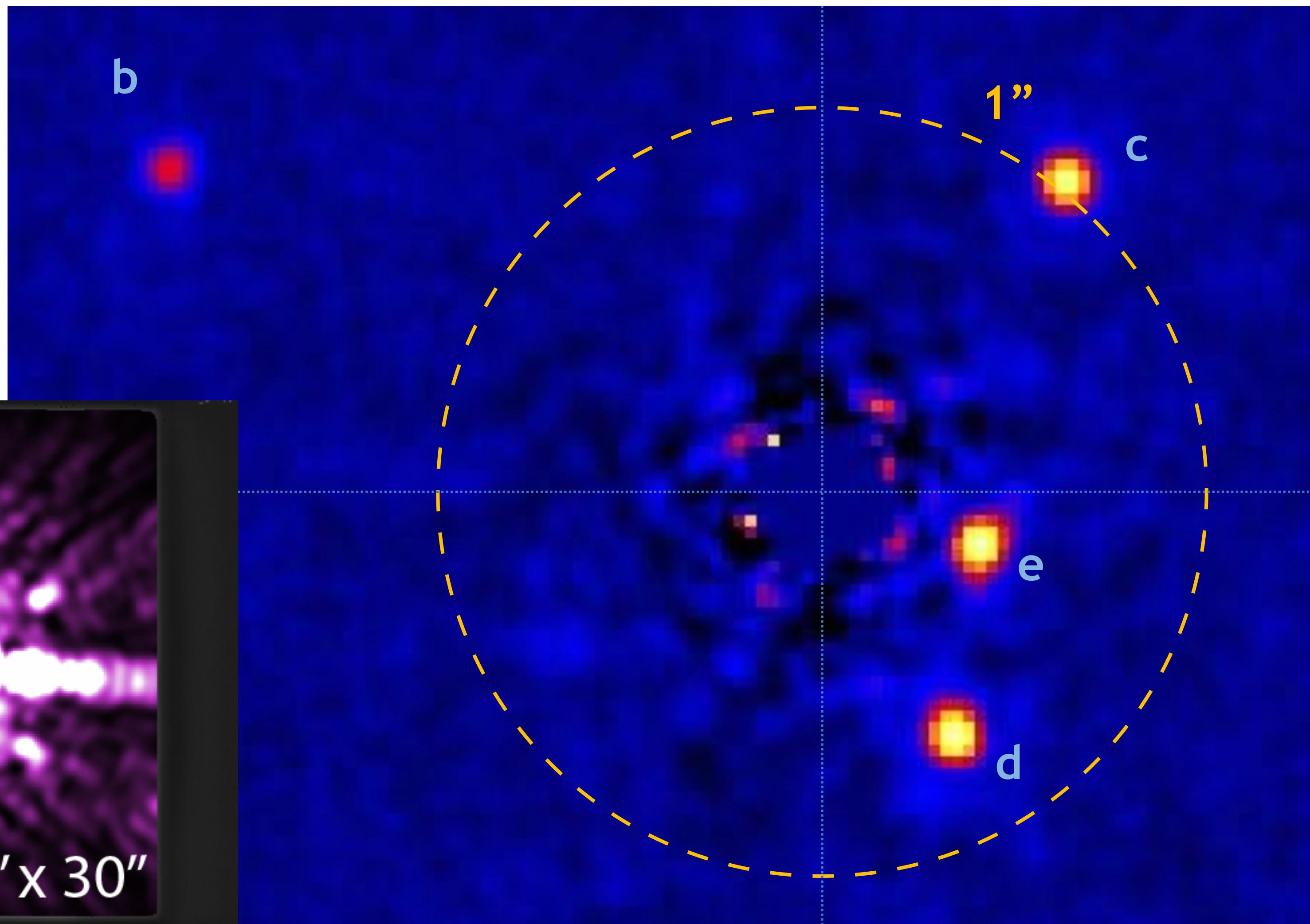
Setting special requirements for position angles

Coronagraph Visibility Tool (CVT)





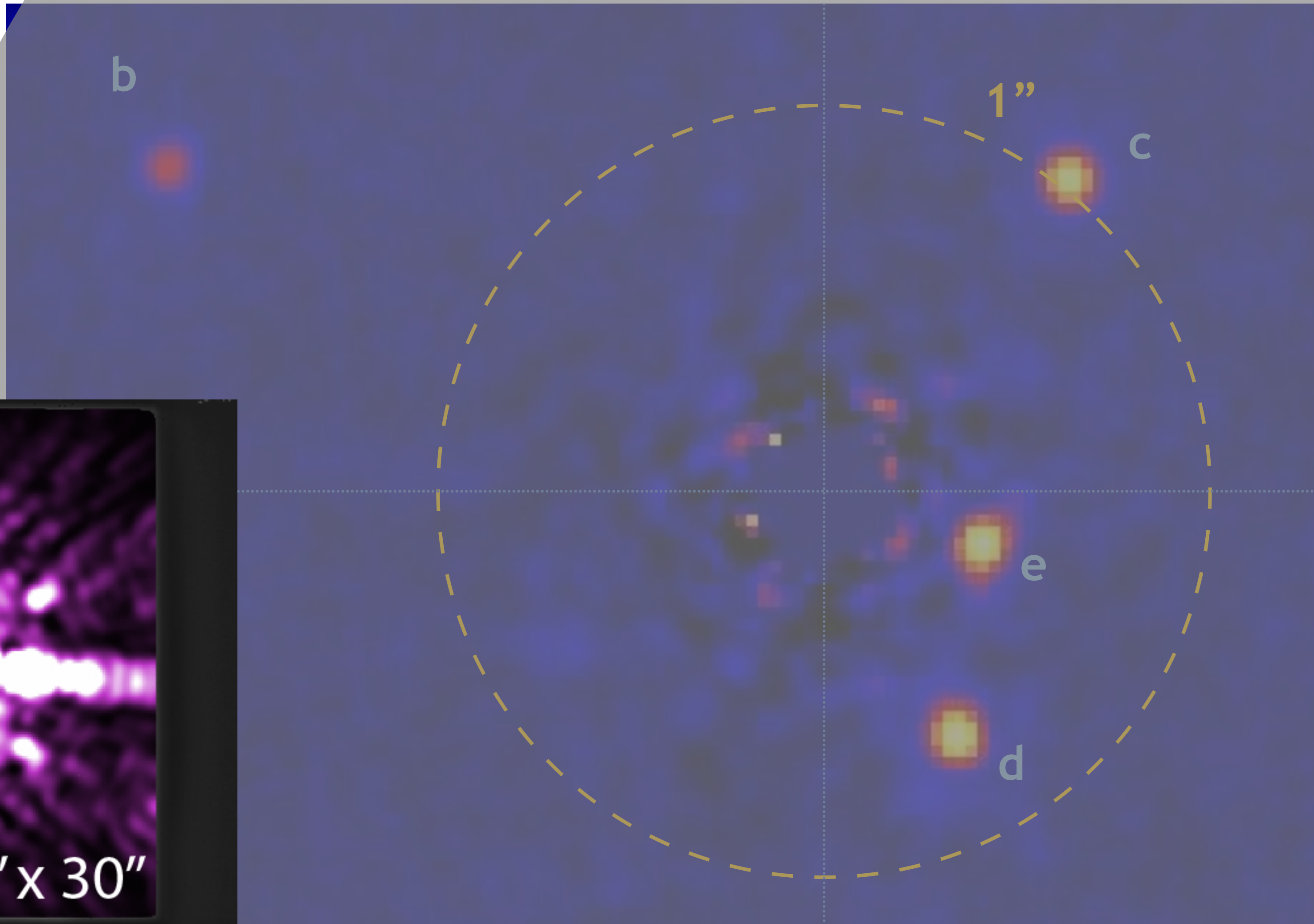
Example Science Program 1: the HR8799 4-planet system





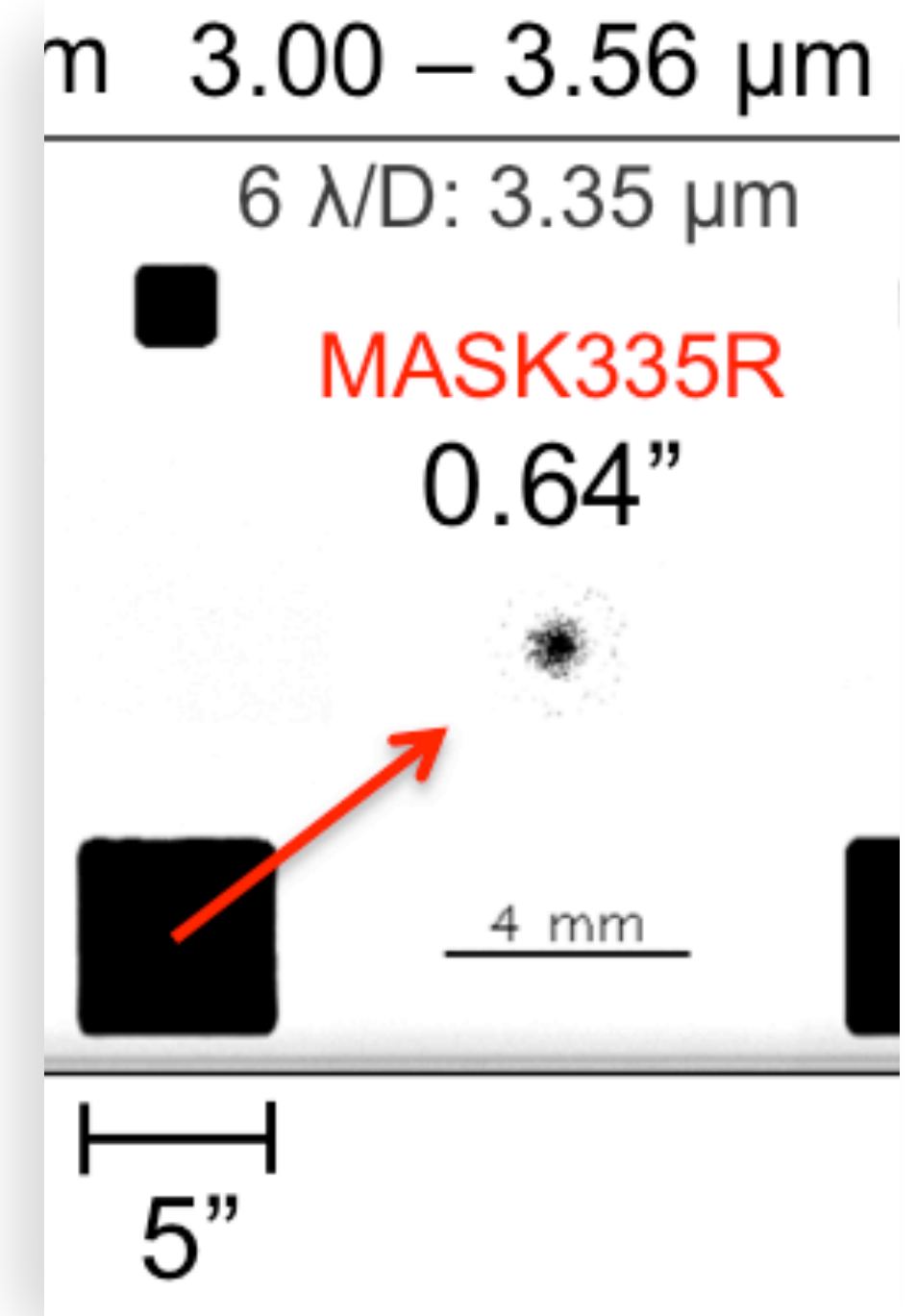
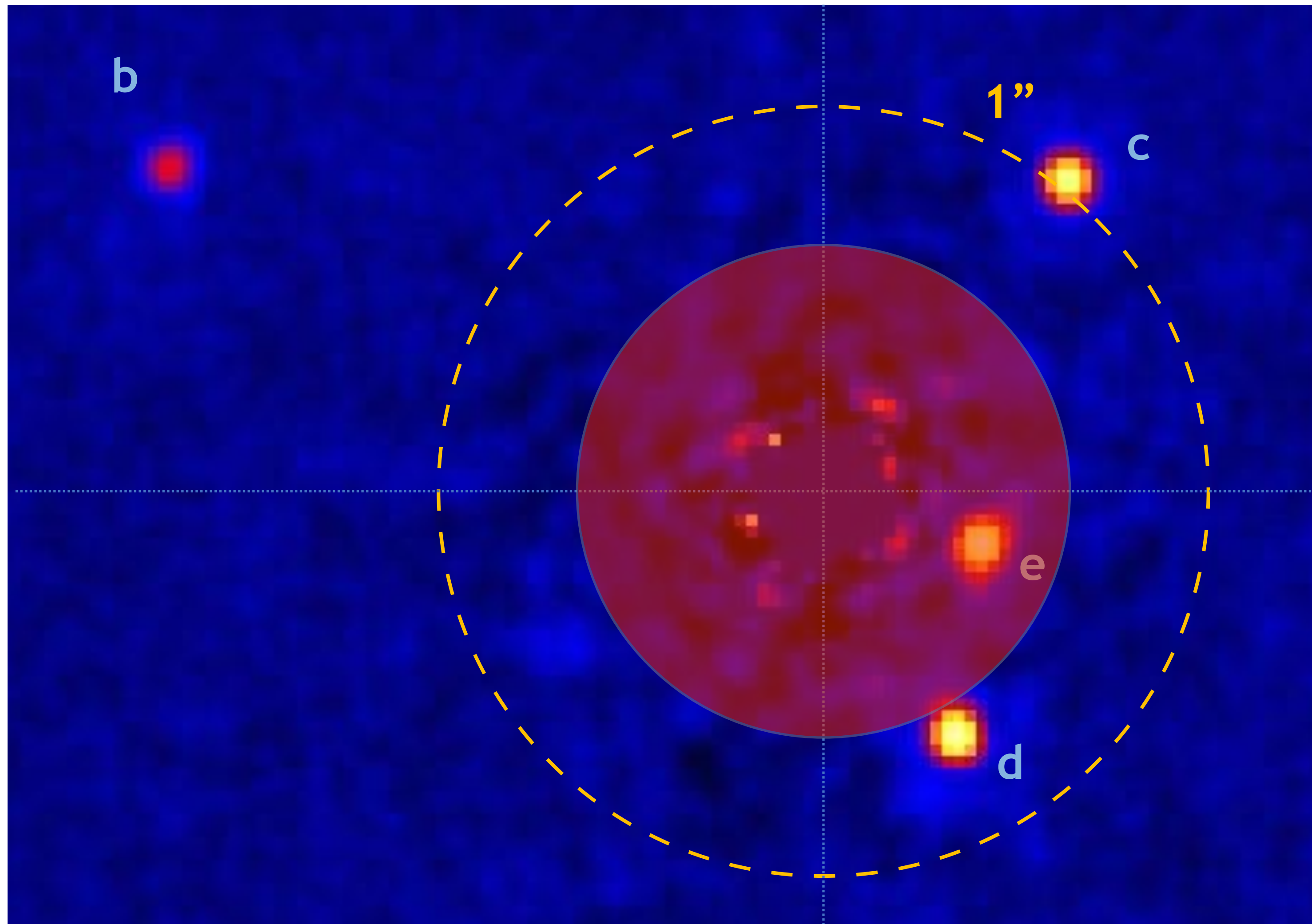
Example Science Program 1: the HR8799 4-planet system

size
2.16"!!!





Example Science Program 1: the HR8799 4-planet system

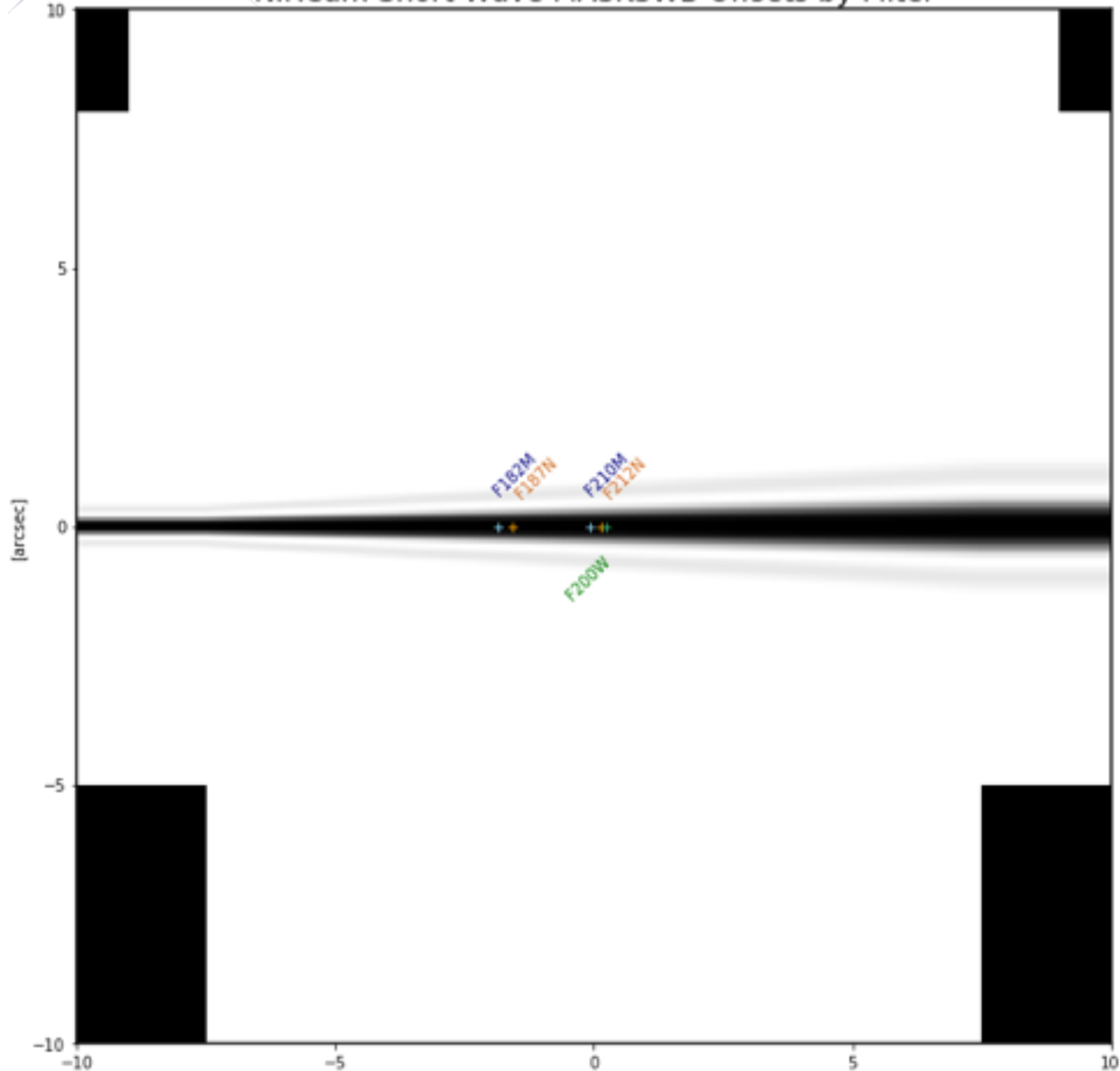


IWA ~ 0.64\"

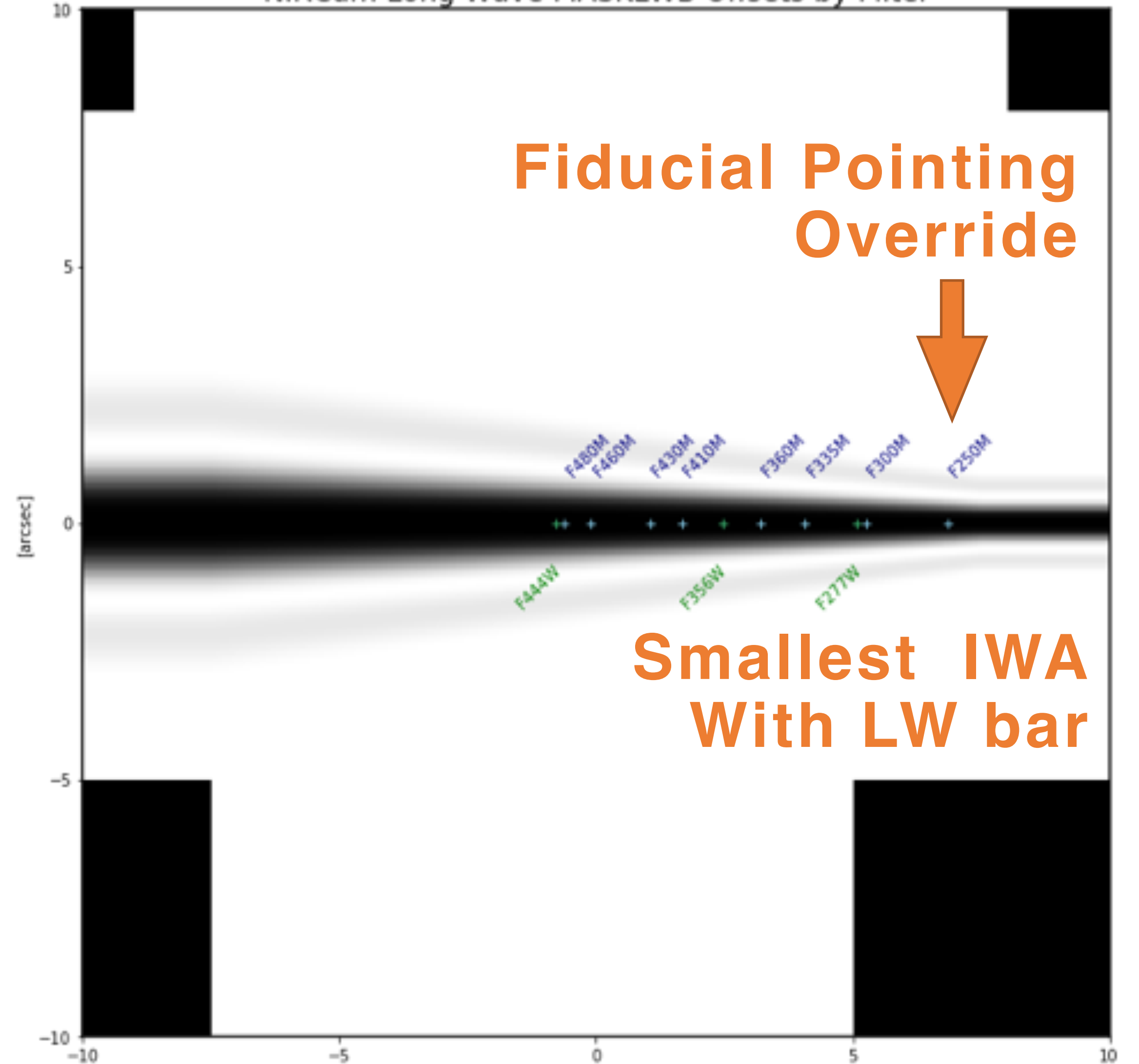


NIRCam Coronagraphy: bar coronagraphs (wedge occulters)

NIRCam Short Wave MASKSWB Offsets by Filter



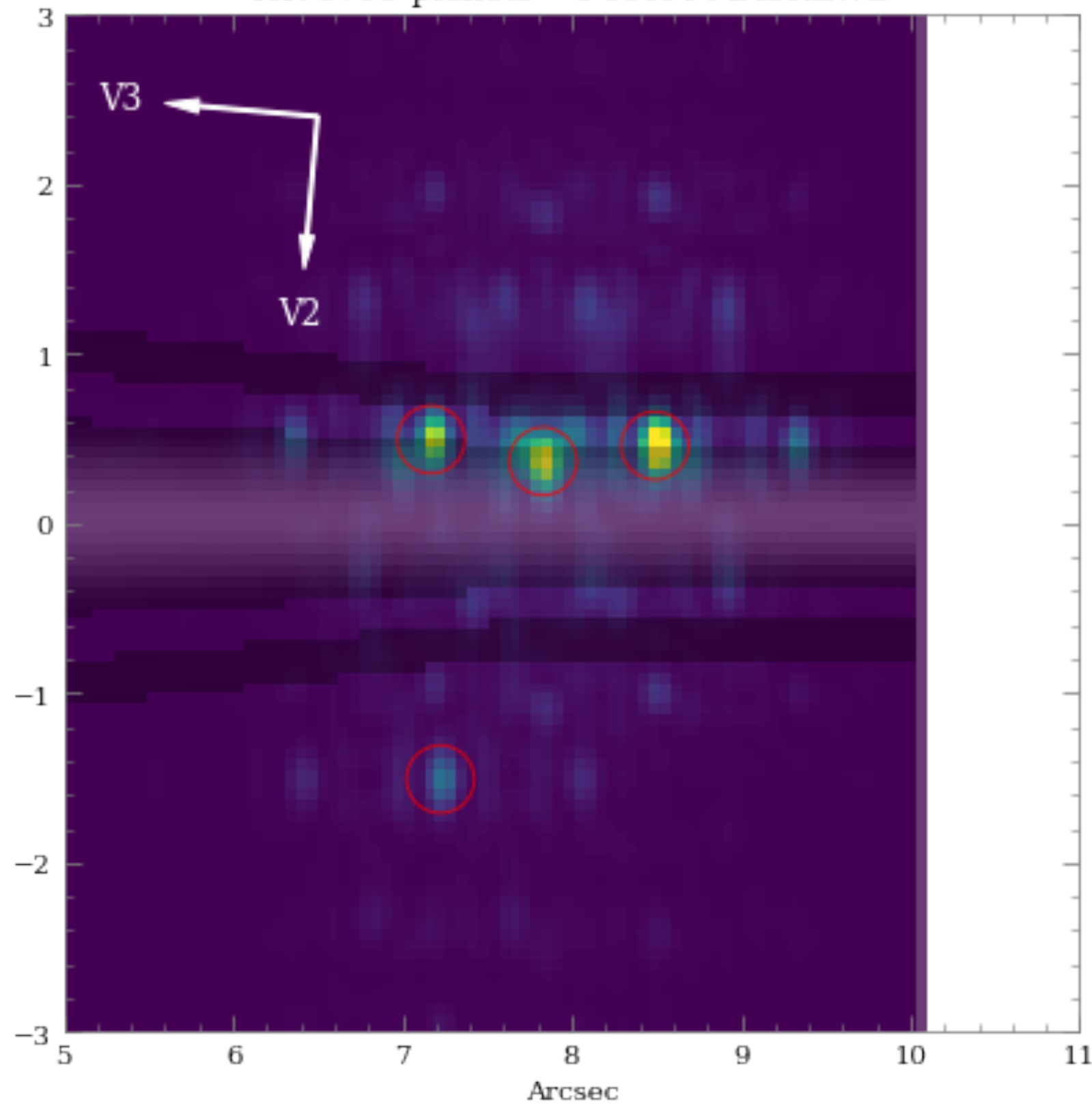
NIRCam Long Wave MASKLWB Offsets by Filter



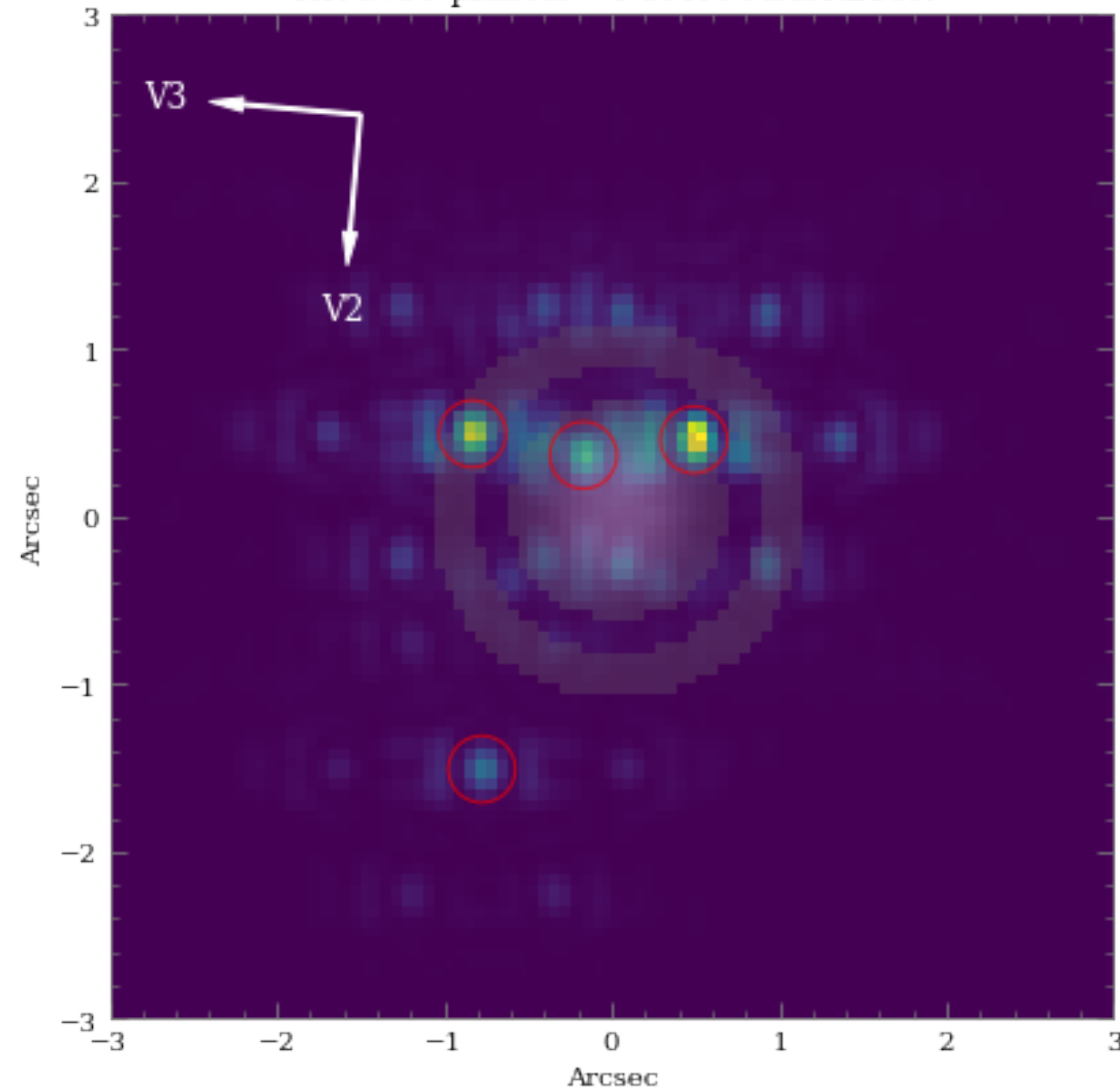


Example Science Program #36 & NIRCcam Coronagraphs

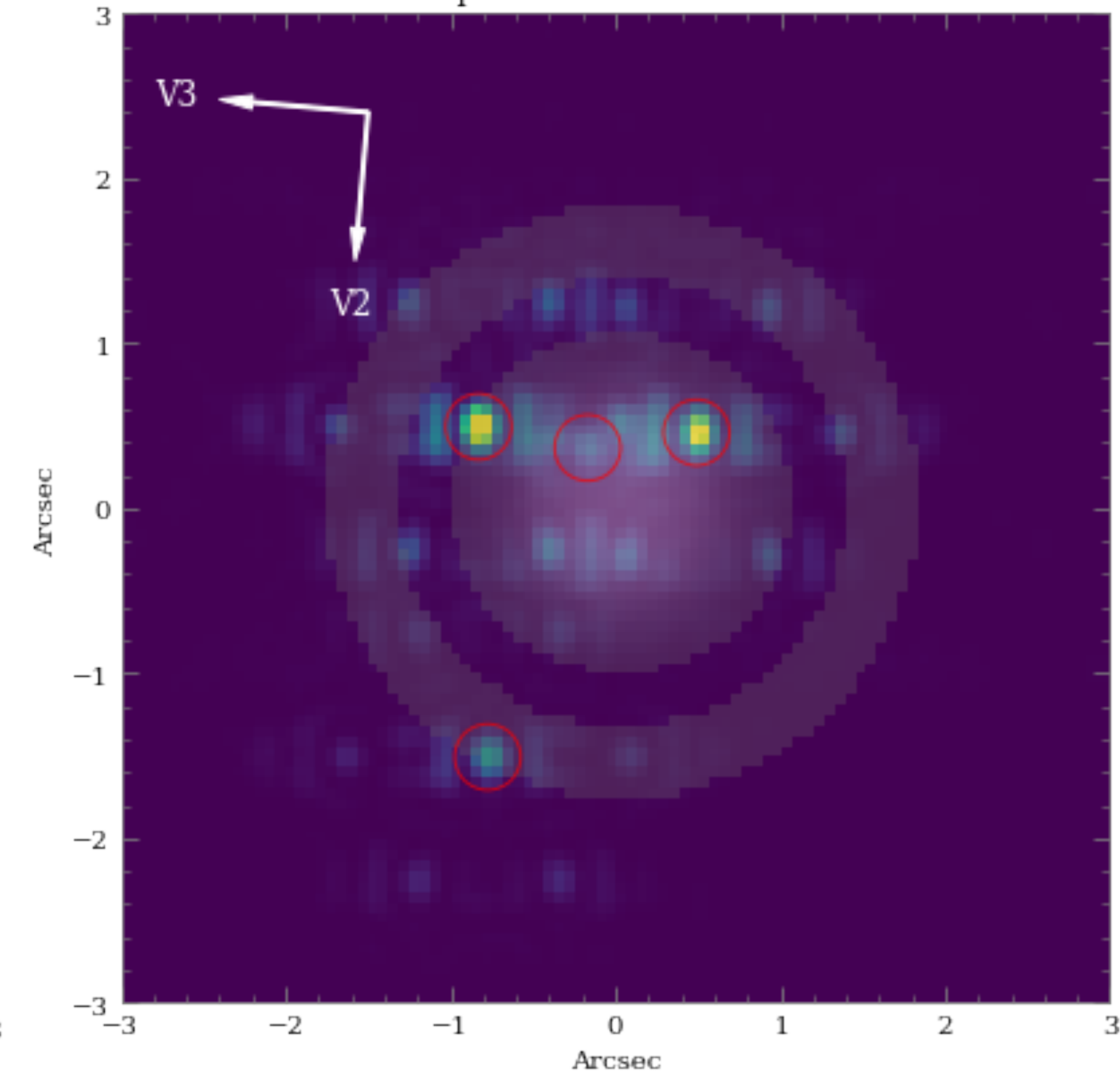
HR 8799 planets -- F460M MASKLWB



HR 8799 planets -- F460M MASK210R



HR 8799 planets -- F460M MASK335R

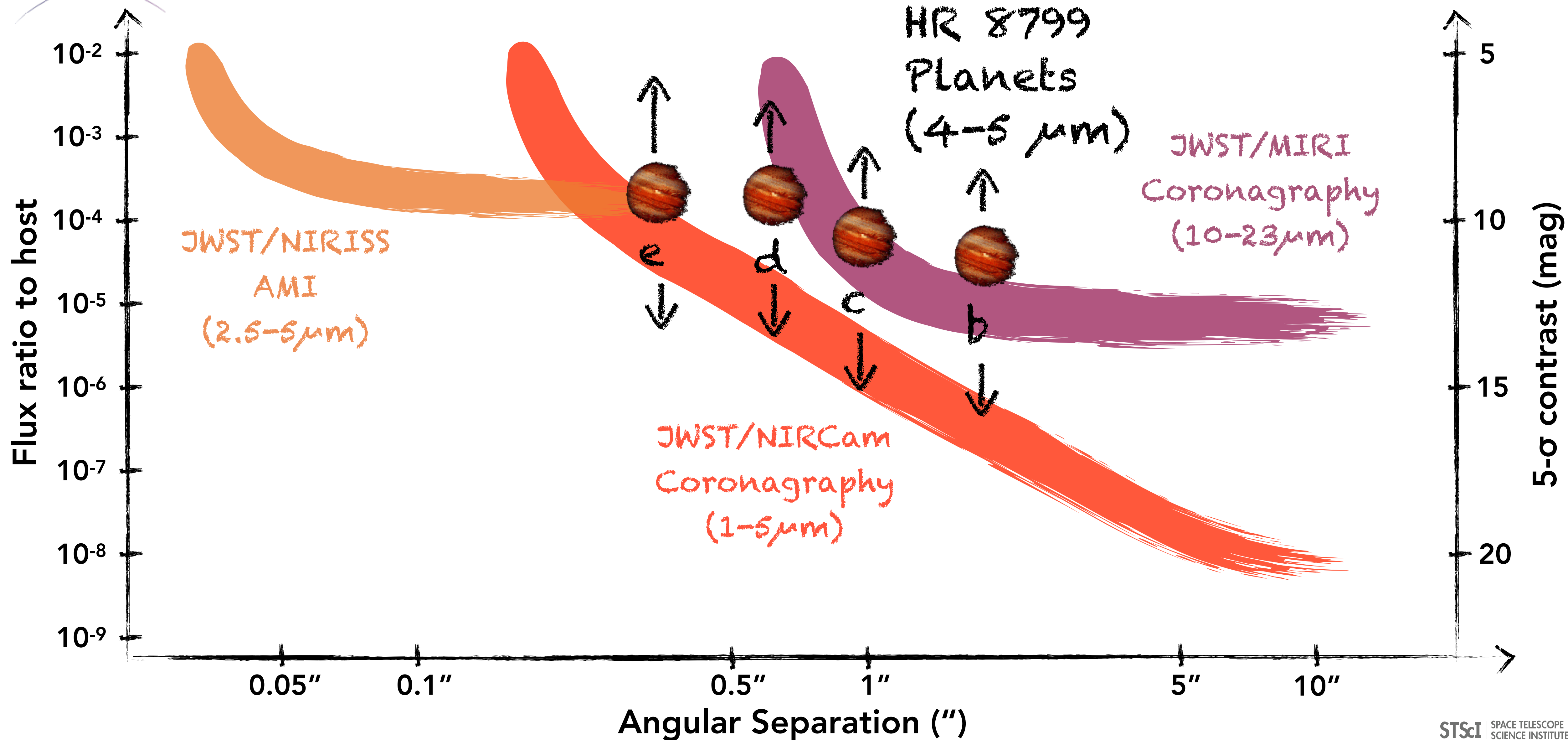


Credit: J. Leisenring (pyNRC, U. Of Arizona)

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

jwsthelphelp.stsci.edu

STScI | JWST Help Desk Knowledge

Home > Service Catalog > James Webb Help Desk > Coronagraphy

Coronagraphy

Ask about NIRCcam or MIRI coronagraphic imaging

Coronagraphy with JWST NIRCcam and MIRI

Typical requests include issues with:

- NIRCcam 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) | Constraints & Scheduling Ask questions about scheduling and observing with JWST | Coronagraphy Ask about NIRCcam or MIRI coronagraphic imaging |
| Data Analysis Tools for JWST Request assistance with STScI-developed data analysis tools | ETC Support Request assistance with the Exposure Time Calculator (ETC) | JWST Science Policies Request assistance for Science Policy Issues. |
| JWST SN Requests & Issues Submit JWST Requests and Issues related to ServiceNow | MIRI Support Request assistance with the Mid-Infrared Instrument (MIRI) | NIRCcam Support Request assistance with the Near-Infrared Camera (NIRCcam) |
| NIRISS Support Request assistance with the Near-Infrared Imager and Slitless Spectrograph (NIRISS) | NIRSpec Support Request assistance with the Near-Infrared Spectrograph (NIRSpec) | Office of Public Outreach Contact the STScI Office of Public Outreach about JWST |
| Pipeline Support Request assistance with the JWST pipeline | Solar System Observing Ask questions about proposal writing for solar system targets with JWST | Time-Series Observations Request assistance making time-series observations (e.g., transiting exoplanets) |
| WebbPSF / JWST Telescope Request assistance with the WebbPSF tool or the Telescope optical system | JWST General Support Request general JWST support for issues not covered by another category | MAST Archive Support Request general Archive support for issues not covered by another category |



Proposal Planning Workshop: material, presentations

About STScI | Archive

NASA's James Webb Space Telescope

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

PUBLIC EDUCATORS

JWST SCIENCE NEWS & EVENTS INSTRUMENTATION SCIENCE PLANNING OBSERVING PROGRAMS Q

DOCUMENTATION

NEWS & EVENTS > Events

Subscribe to Events: RSS ICS UPCOMING PAST

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

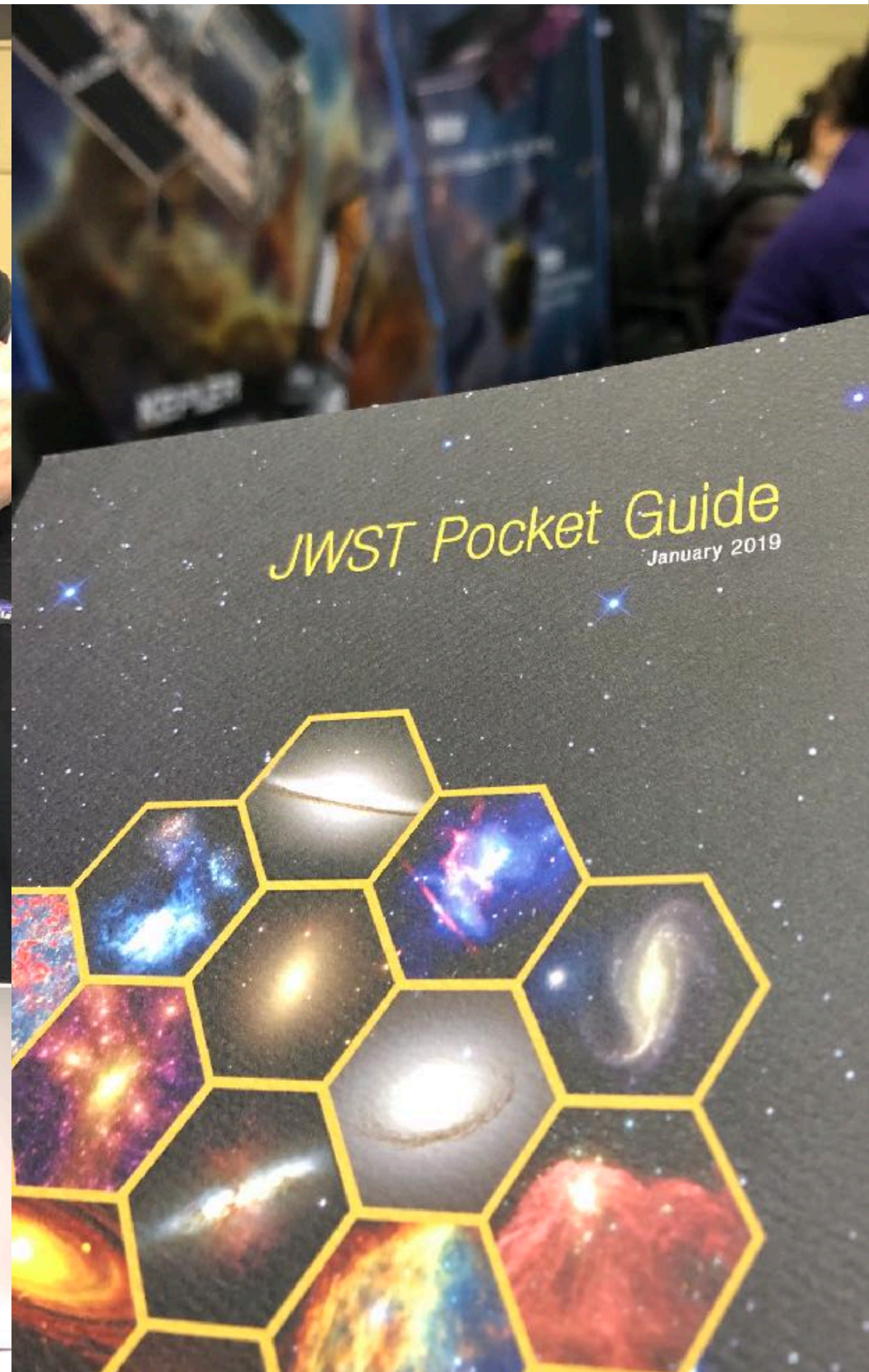
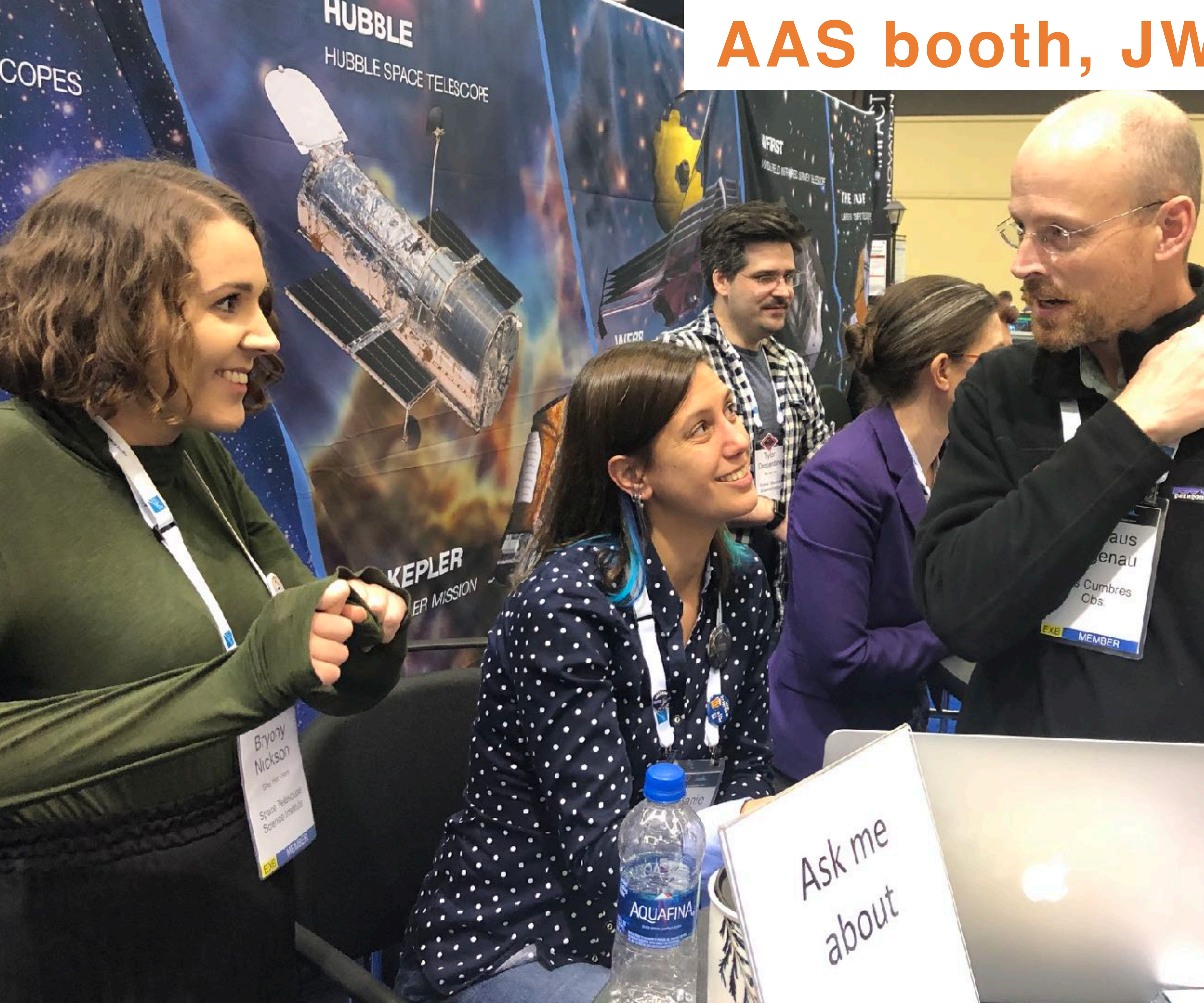
| Su | Mo | Tu | We | Th | Fr | Sa |
|----|----|----|----|----|----|----|
| 10 | 11 | 12 | 13 | 14 | 15 | 16 |

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...

AAS booth, JWST pocket Guide





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

Select a collection... MAST Observations by Object Name or RA/Dec and enter target: HIP 65426

[About Collections...](#) [Show Examples...](#) [Random Search](#) [Advanced Search](#)

[Upload Target List](#) My Download Basket: 0 files [User Manual/Help](#) | [Leave Feedback](#) | [About This Site](#)

Girard
[Login...](#)
[Account Info...](#)
[Subscriptions...](#)

<https://mast.stsci.edu>

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

Displaying 19 of 20 Total Rows HD 116434, radius: 0.20000° Footprints: All

Filters

Clear Filters Edit Filters... Help...

Keyword/Text Filter
Filter All Columns

Product Type

| Name | Quantity |
|--------------------------------|------------|
| <input type="checkbox"/> image | (19 of 19) |
| <input type="checkbox"/> cube | (0 of 1) |

Mission

| Name | Quantity |
|--|------------|
| <input checked="" type="checkbox"/> JWST | (19 of 19) |
| <input type="checkbox"/> SWIFT | (0 of 1) |

Instrument

| Name | Quantity |
|--|------------|
| <input checked="" type="checkbox"/> NIRCAM | (14 of 14) |
| <input checked="" type="checkbox"/> MIRI | (4 of 4) |
| <input checked="" type="checkbox"/> NIRISS | (1 of 1) |
| <input type="checkbox"/> UVOT | (0 of 1) |

Project

| Name | Quantity |
|-------------------------------|------------|
| <input type="checkbox"/> JWST | (19 of 19) |

| Actions | Mission | Instrument | Propos... | Principal Inv... | Filters | Target Name |
|-------------------------------------|---------|------------|----------------------|------------------|-----------|-------------|
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input type="checkbox"/> | JWST | NIRISS | 1386 | Hinkley, Sa... | F380M, | HIP-65426 |
| <input type="checkbox"/> | JWST | MIRI | 1386 | Hinkley, Sa... | F1140C, | HIP-65426 |
| <input type="checkbox"/> | JWST | MIRI | 1386 | Hinkley, Sa... | F1140C, | HIP-65426 |
| <input type="checkbox"/> | JWST | MIRI | 1386 | Hinkley, Sa... | F1550C, | HIP-65426 |
| <input type="checkbox"/> | JWST | MIRI | 1386 | Hinkley, Sa... | F1550C, | HIP-65426 |
| <input checked="" type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |
| <input checked="" type="checkbox"/> | JWST | NIRCAM | 1386 | Hinkley, Sa... | NONE, ... | HIP-65426 |

AstroView

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



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



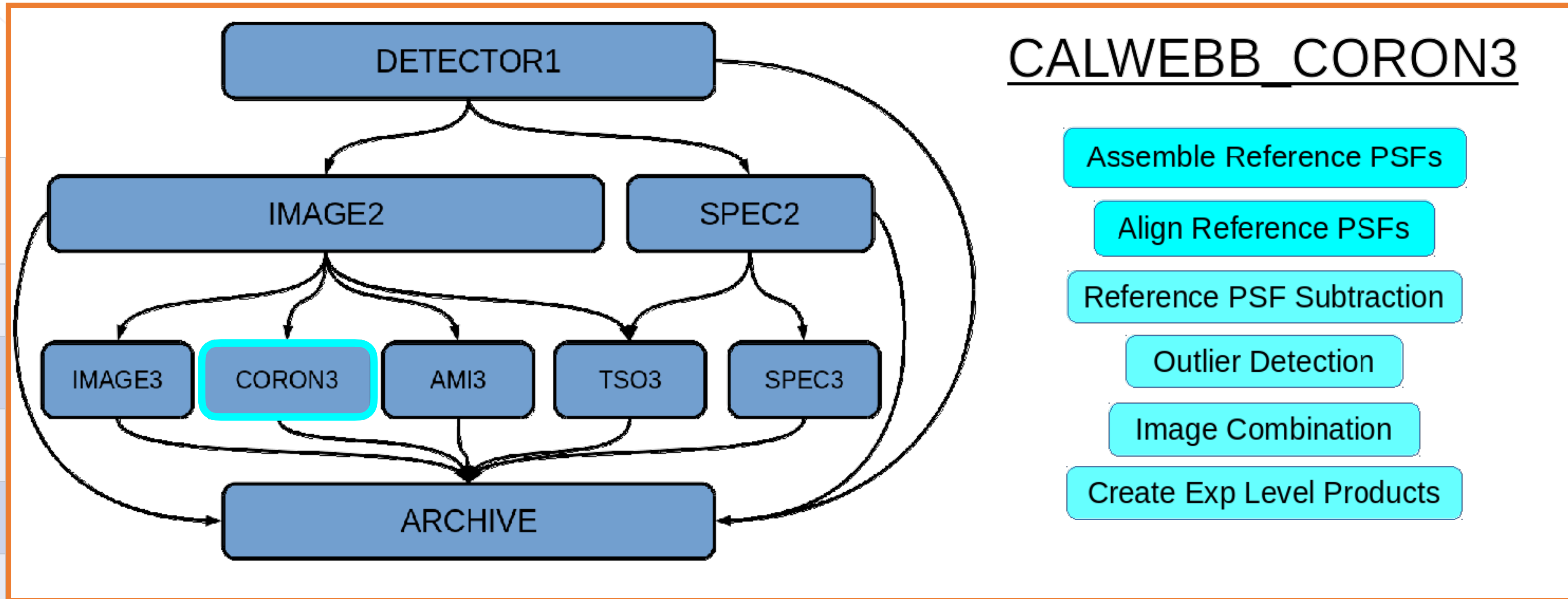
Pipeline for coronagraphy

| 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> |

jwst-docs.stsci.edu/display/JDAT/CALWEBB_CORON3



Pipeline for coronagraphy



CALWEBB_CORON3

Assemble Reference PSFs

Align Reference PSFs

Reference PSF Subtraction

Outlier Detection

Image Combination

Create Exp Level Products

Pipeline/Step

Detector1

Image2

Image3

Spec2

Spec3

tor1Pipeline

2Pipeline

3Pipeline

Pipeline

Pipeline

| | | | |
|-------------------|--|--|--|
| 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> |

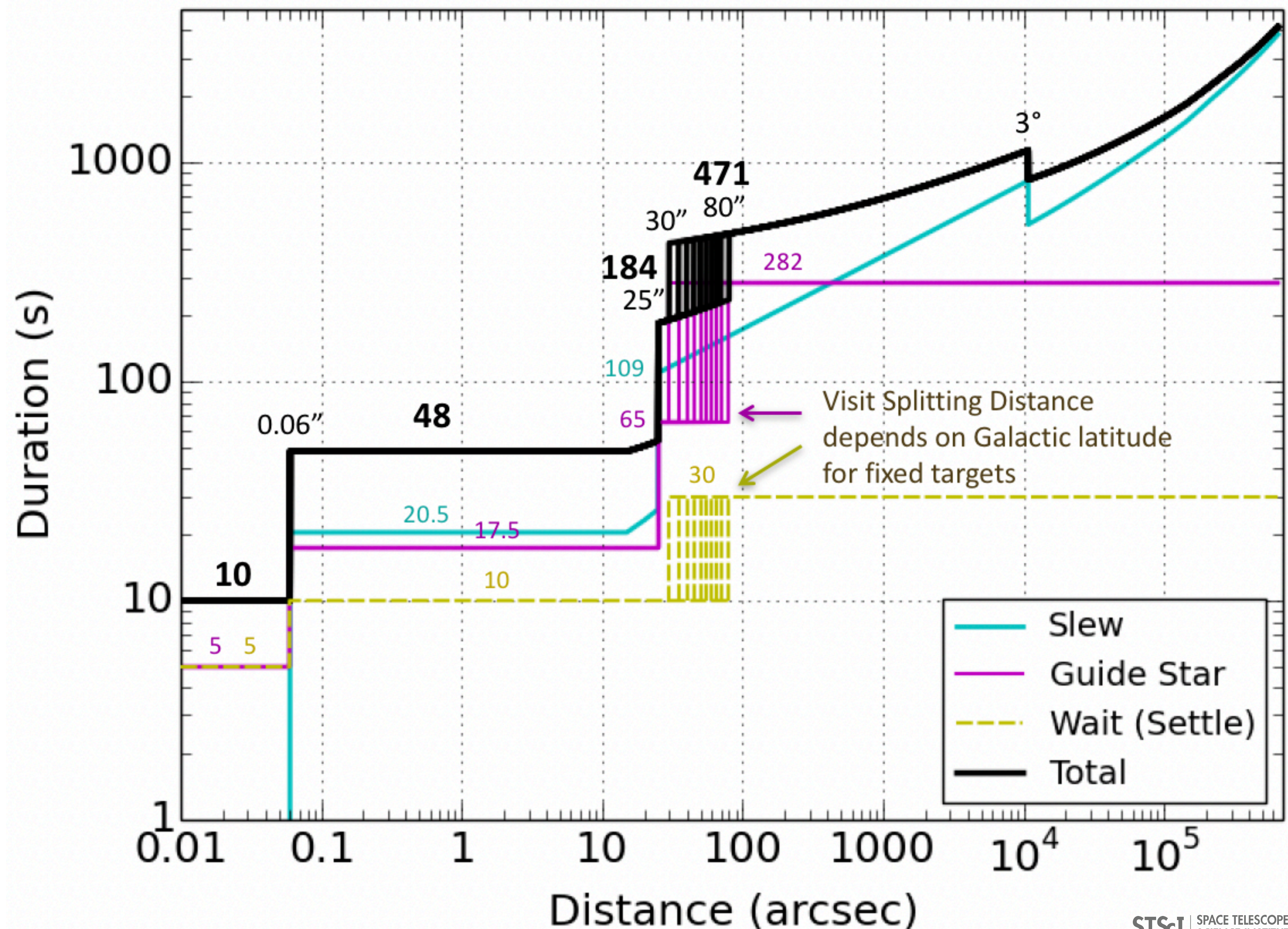
jwst-docs.stsci.edu/display/JDAT/CALWEBB_CORON3



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)

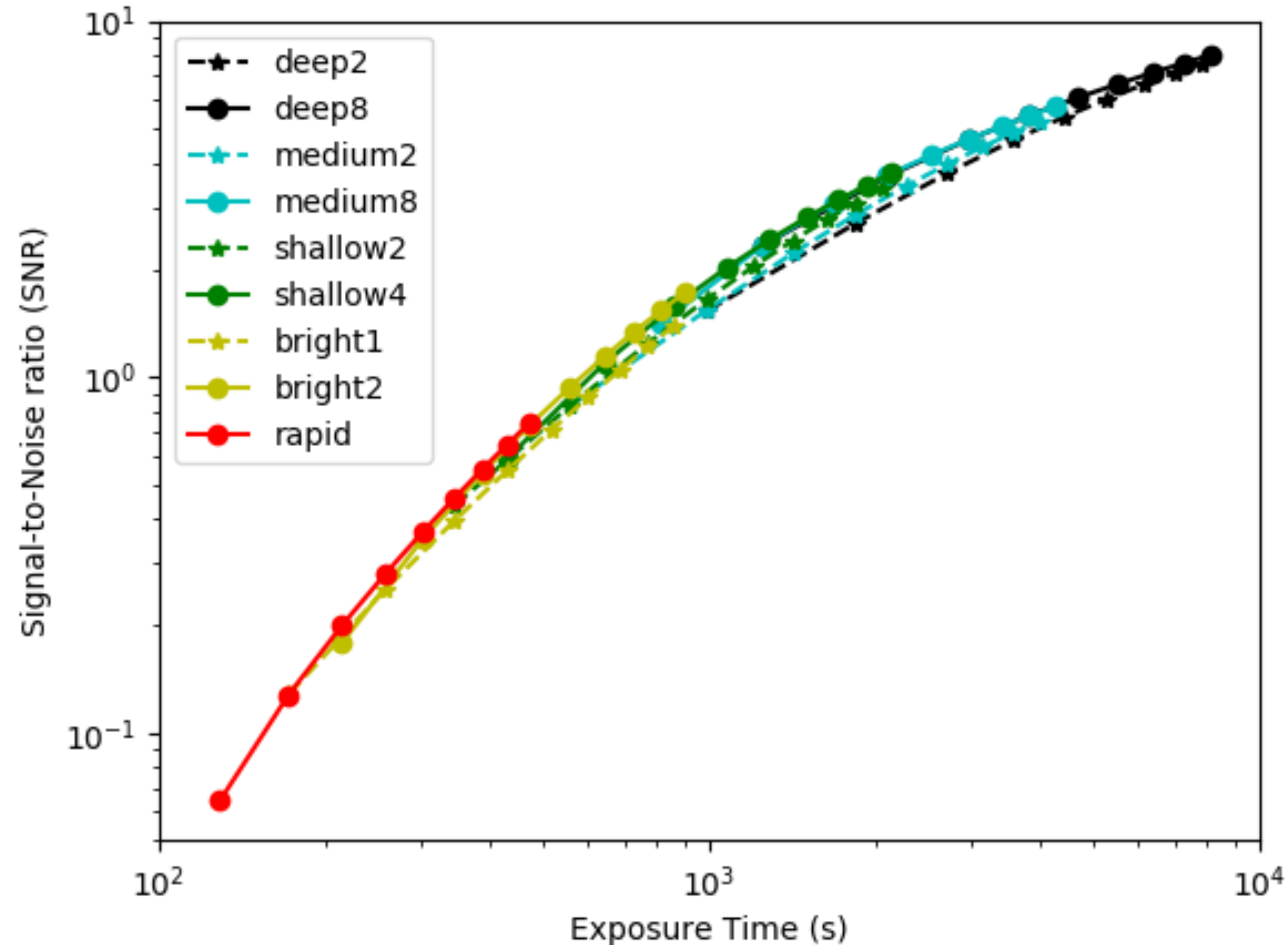




ETC: Finding the best exposure parameters

Selecting the optimal combination of readout pattern, ngroups, nints and nexps 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

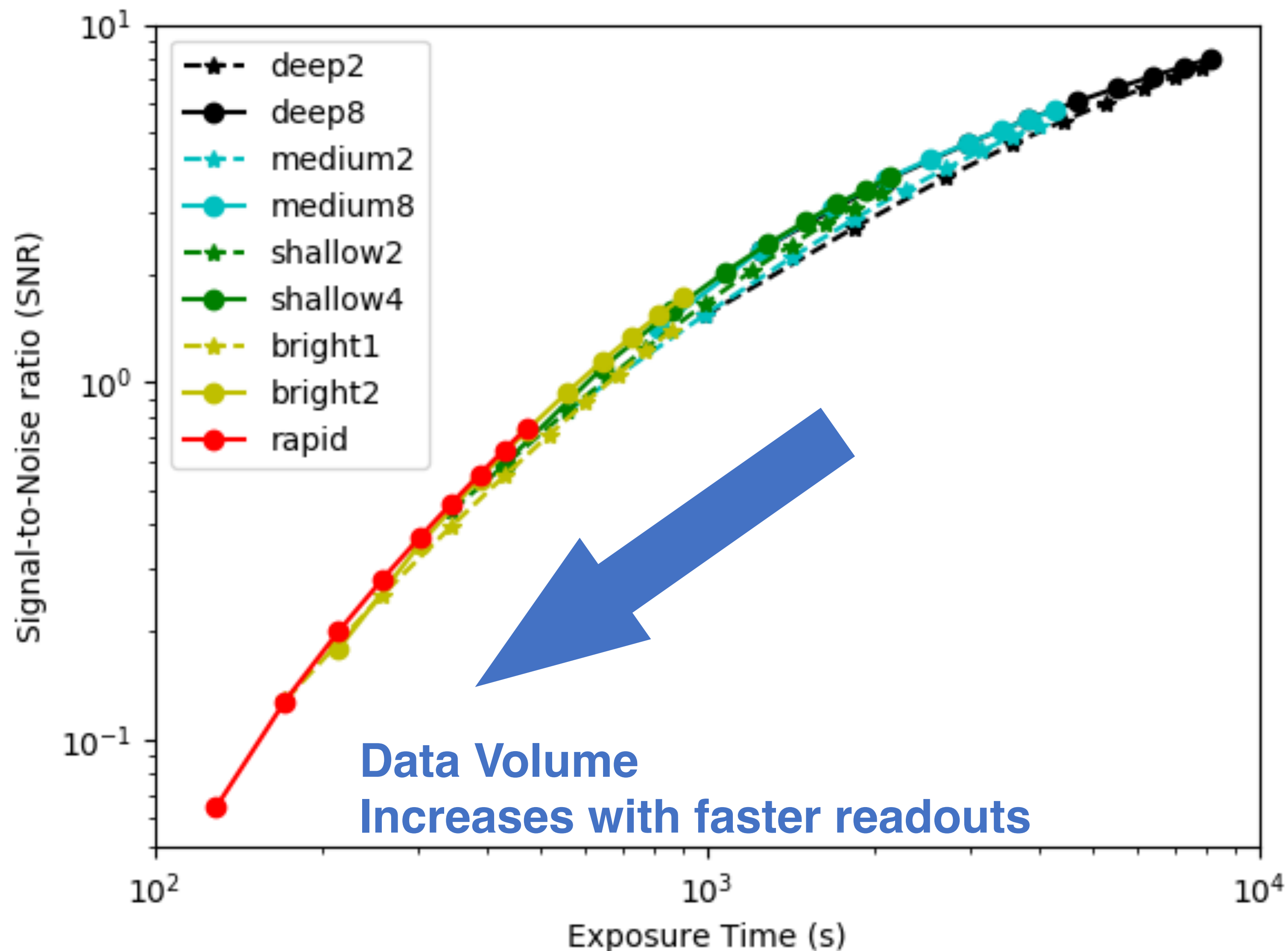




ETC: Finding the best exposure parameters

Selecting the optimal combination of readout pattern, ngroups, nints and nexps 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

STScI | SPACE TELESCOPE SCIENCE INSTITUTE

SEARCH MENU

ASTRONOMER'S PROPOSAL TOOL (APT)

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](#)

STScI | SPACE TELESCOPE SCIENCE INSTITUTE



Technical Documents / Coronagraphy, AMI

NASA's James Webb
Developed in partnership with ESA and CSA. Operated by STScI.

JWST SCIENCE NEWS & EVENTS

INSTRUMENTATION > Technical Documents

ALL CALIBRATION HIGH CONTRAST

Technical Documents

The most current versions of the technical document information in JDOx. [Click here](#) to assume JDOx is correct.

- [A PSF Library for Coronagraphy with JWST](#)
- [An APT Implementation of the JWST Coronagraph SODRM Programs](#)
- [NIRCam Filter, Weak Lens and Coronagraphic Throughputs](#)
- [Comparative Study of the Efficiency of Various JWST Coronagraph Observation Strategies](#)
- [Exposure Time Calculations for Coronagraphic Observations: Overview of User Needs](#)
- [How to Implement a JWST Coronagraphic Observation Sequence in APT](#)
- [Science Use Cases for the Preparation of Coronagraphic Operations Concepts and Policies](#)
- [The Mid-Infrared Instrument for the James Webb Space Telescope. V. Predicted Performance of the MIRI Coronagraphs](#)
- [Simulations of JWST MIRI 4QPM Coronagraphs Operations and Performances](#)
- [Simulations of MIRI Four-Quadrant Phase Mask Coronagraph \(III\): Target Acquisition and CCC Mechanism Usage](#)
- [Simulations of Target Acquisition with MIRI Four-Quadrant Phase Mask Coronagraph \(IV\): Predicted Performances Based on Slow Accuracy Estimates](#)

| 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 |

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