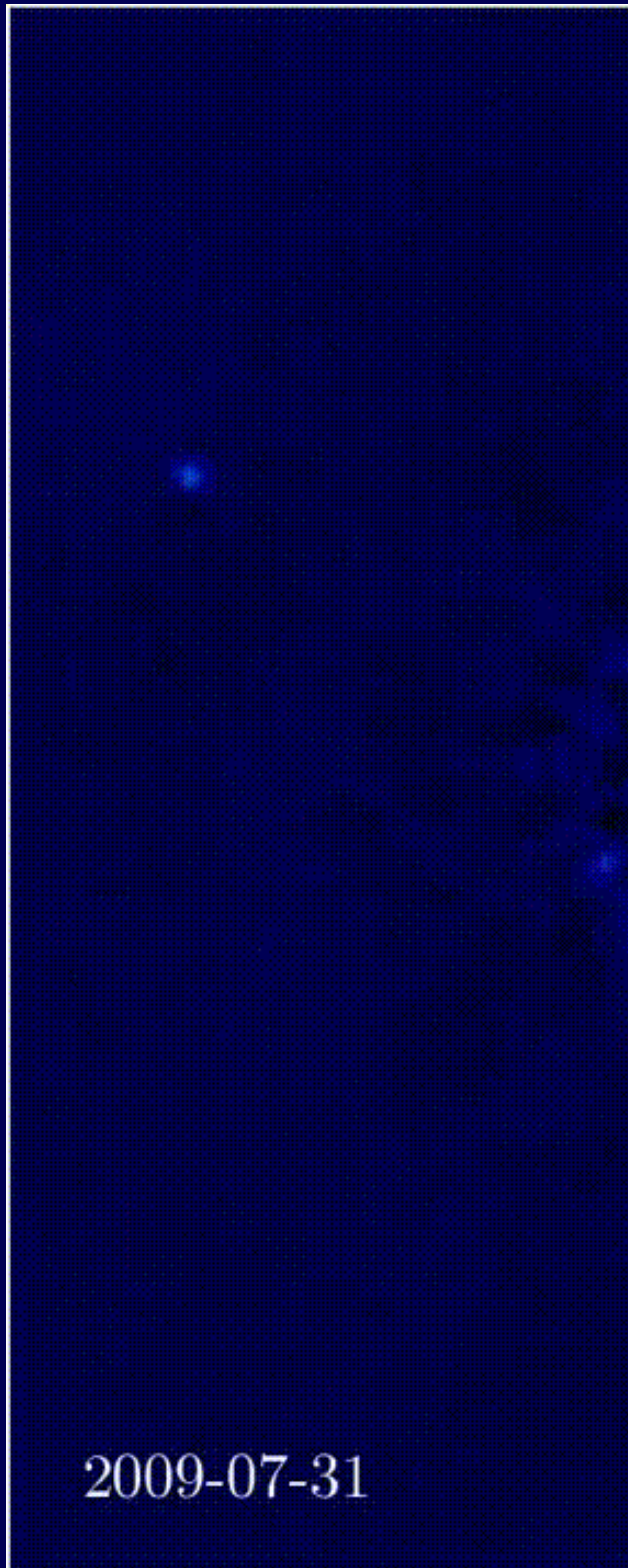
Calibrating High-contrast Imaging Data

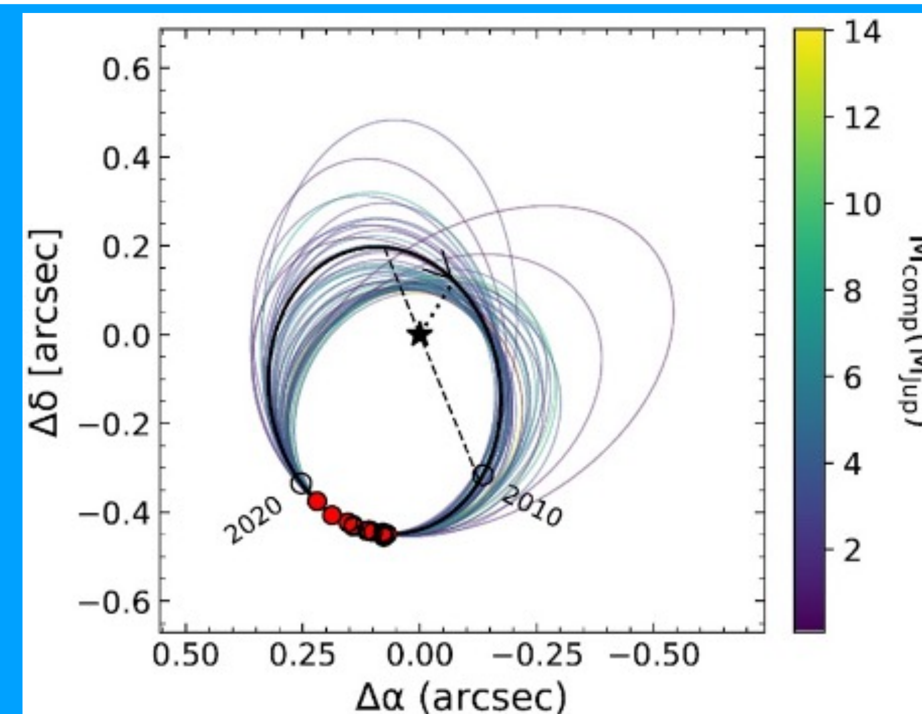
Robert De Rosa, European Southern Observatory

2024 Sagan Summer Workshop — Advances in Direct Imaging: From Young Jupiters to Habitable Earths

What do we want to measure?

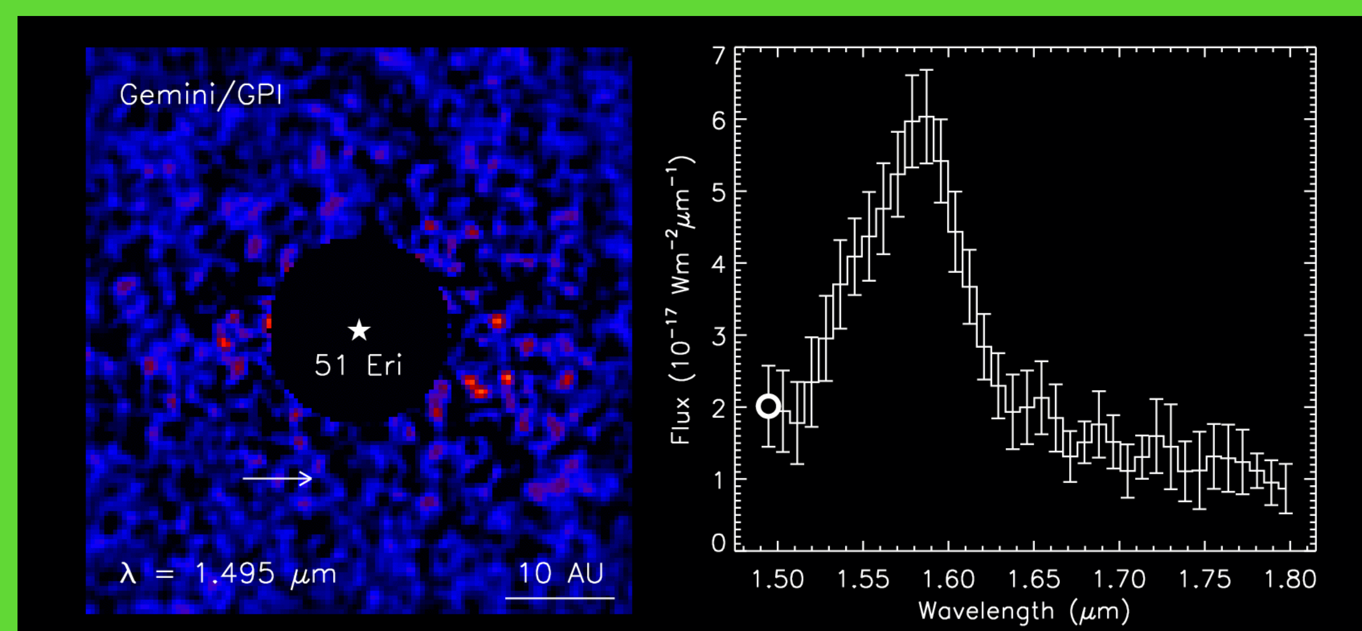


Astrometry



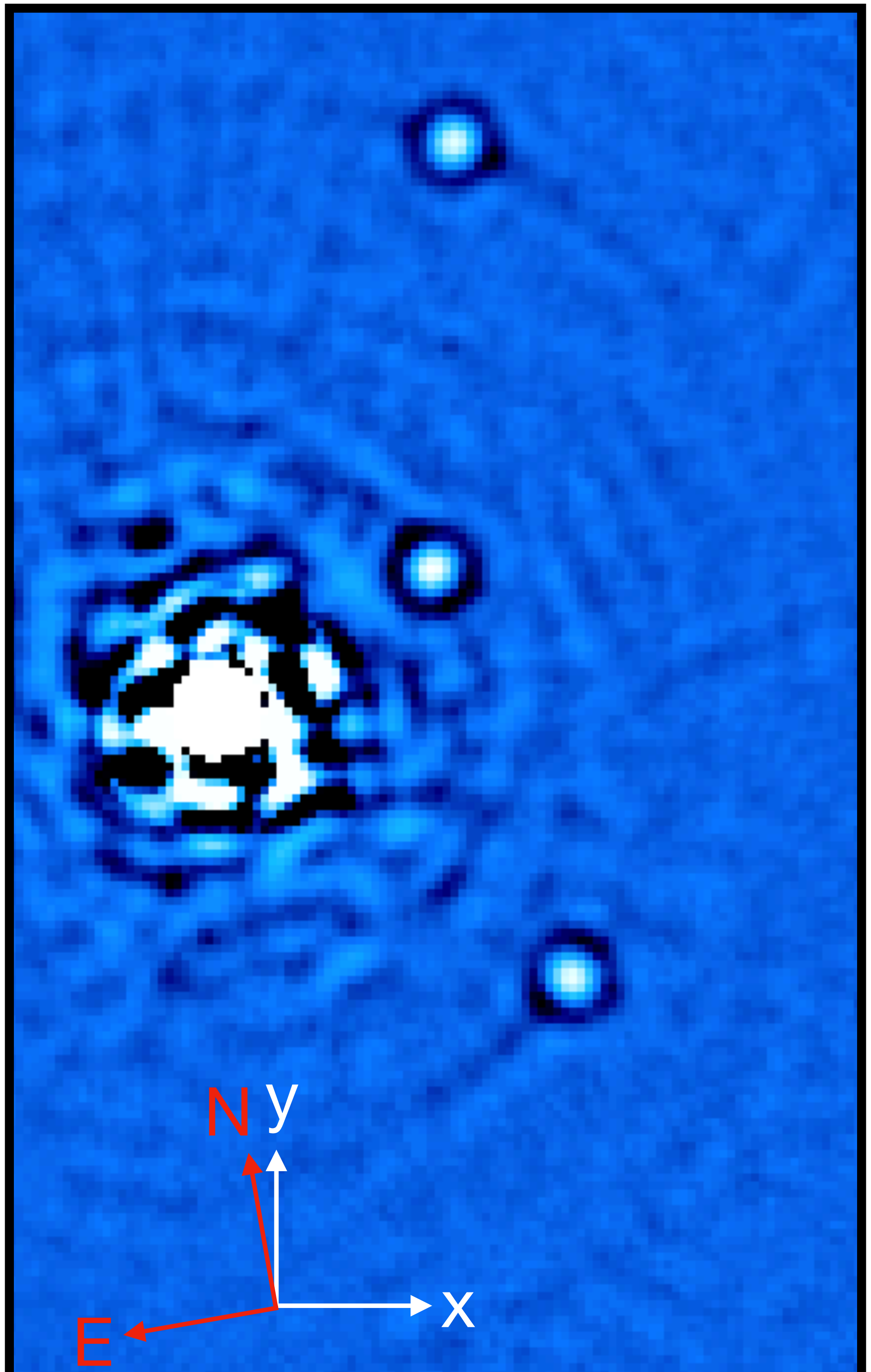
51 Eri b (Dupuy et al. 2022)

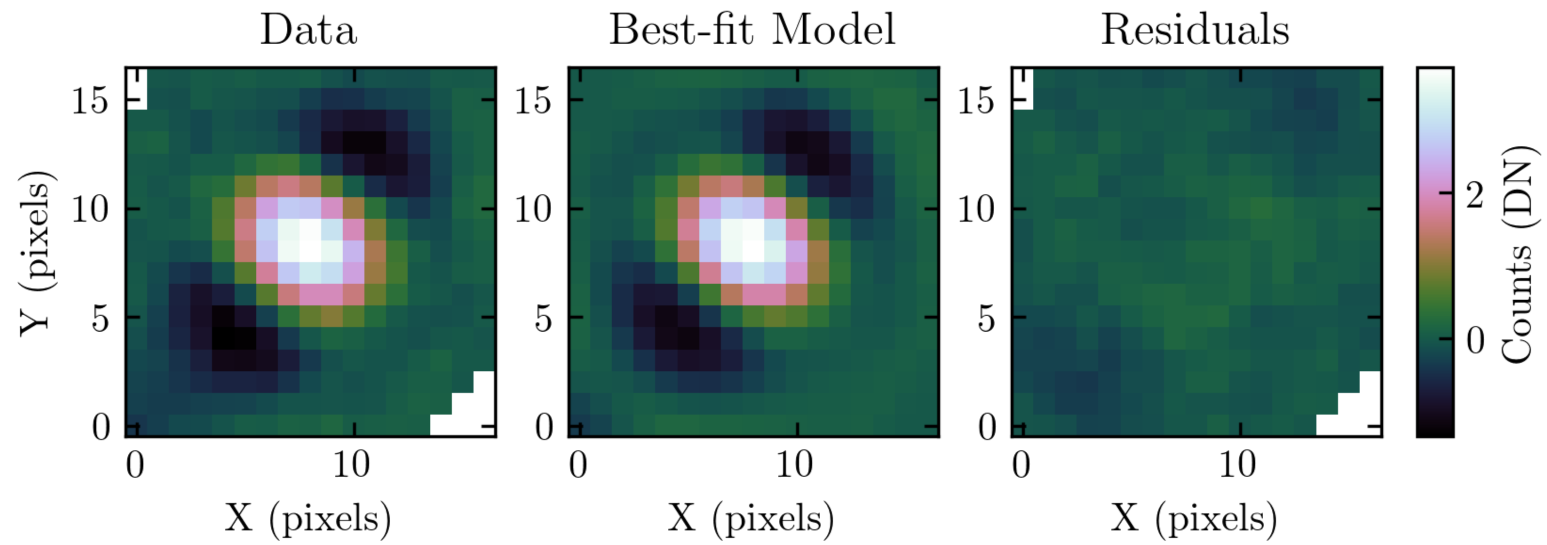
Photometry/Spectroscopy



51 Eri b (Macintosh et al. 2015)

Astrometry





$$x_{\mathrm{pl}} = 154.77 \pm 0.04\,\mathrm{px}$$

$$y_{\mathrm{pl}} = 76.24 \pm 0.03\,\mathrm{px}$$

- But where is the star?
- How do we transform from detector offsets to on-sky angular separations?

Astrometry

$$x_{\rm pl} = 154.77 \pm 0.04\,{\rm px}$$
$$y_{\rm pl} = 76.24 \pm 0.03\,{\rm px}$$

Detector plate scale

$$\begin{bmatrix} \Delta {\rm R.A} \\ \Delta {\rm Dec.} \end{bmatrix} = \begin{bmatrix} -\cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \left(x_{\rm pl} - x_{\rm star}\right) p_x \\ \left(y_{\rm pl} - y_{\rm star}\right) p_y \end{bmatrix}$$

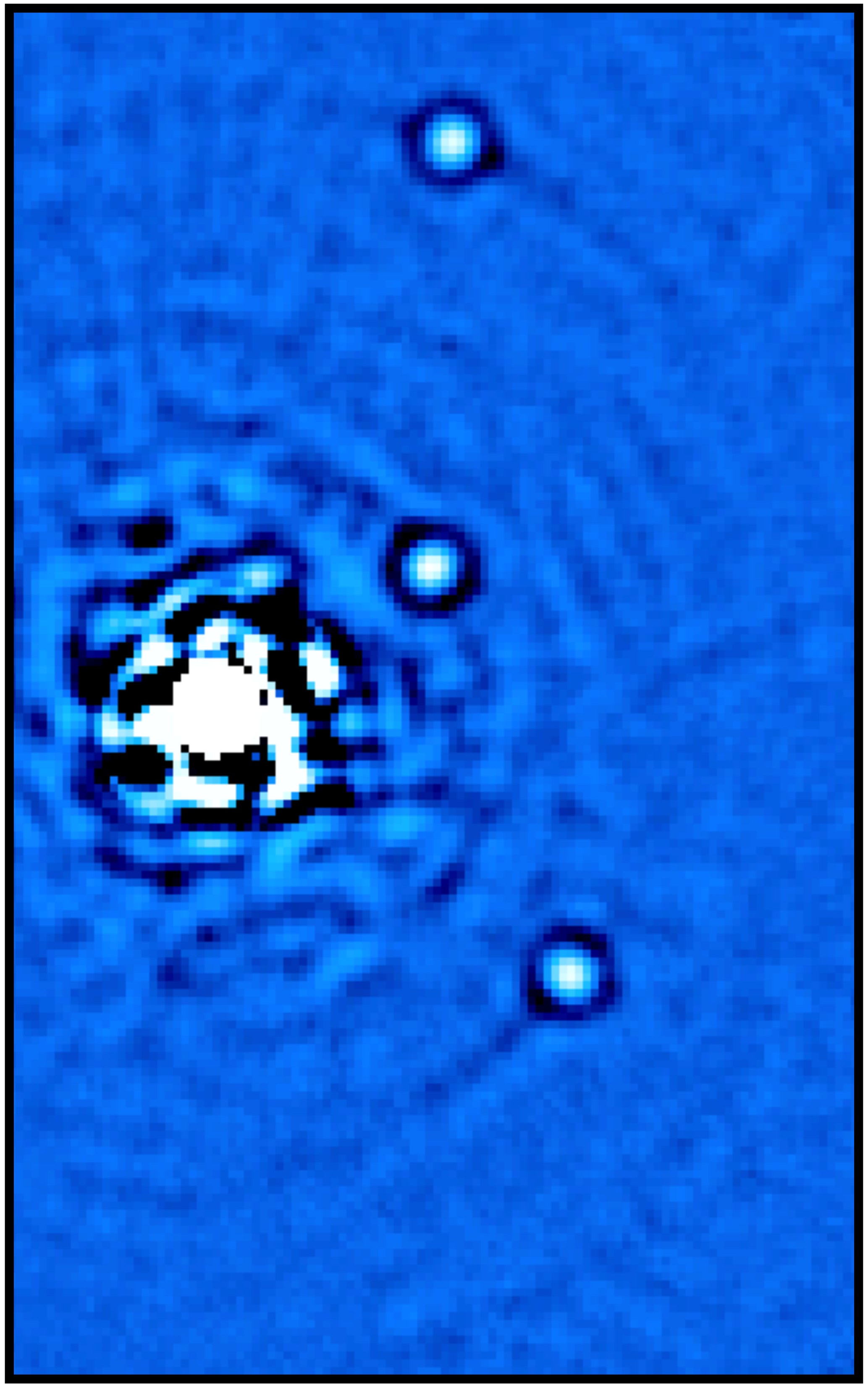
On-sky angular separation

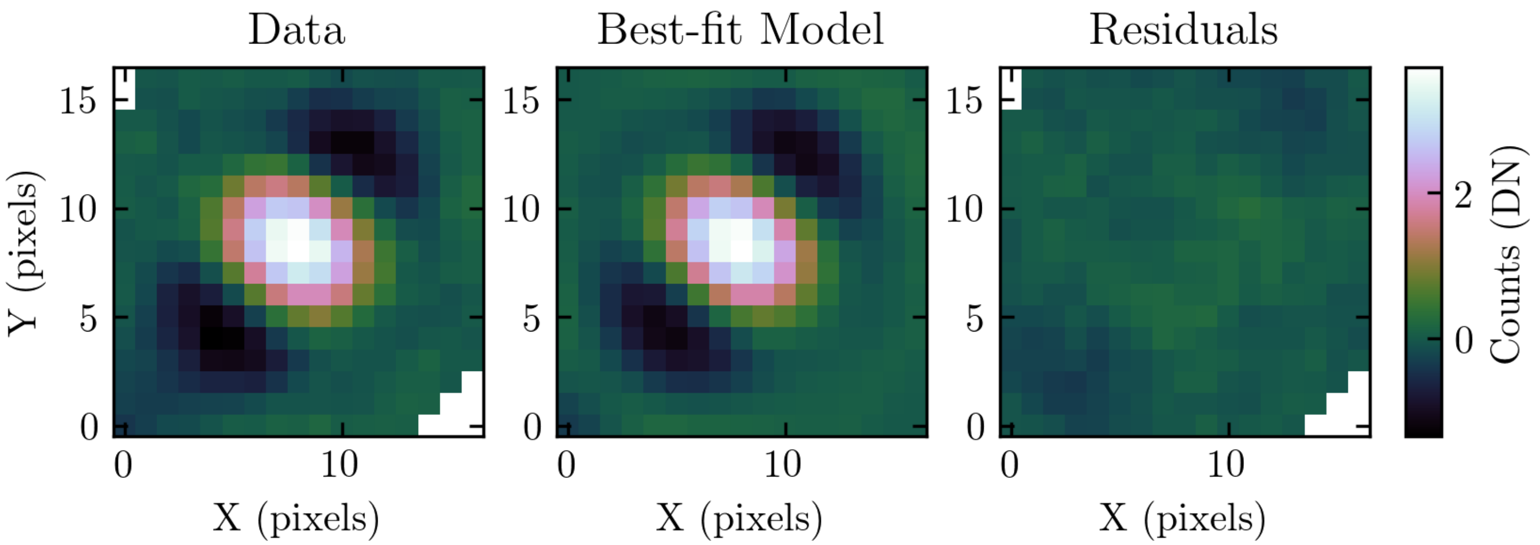
Rotation matrix to align with celestial North

Pixel position of star

*Assumes higher-order optical distortion removed

Photometry





$$f_{\rm pl} \sim 4\,{\rm ADU}$$

- How bright is the star?
- How do we convert from flux ratio to absolute flux?

Photometry

Flux of the planet in image

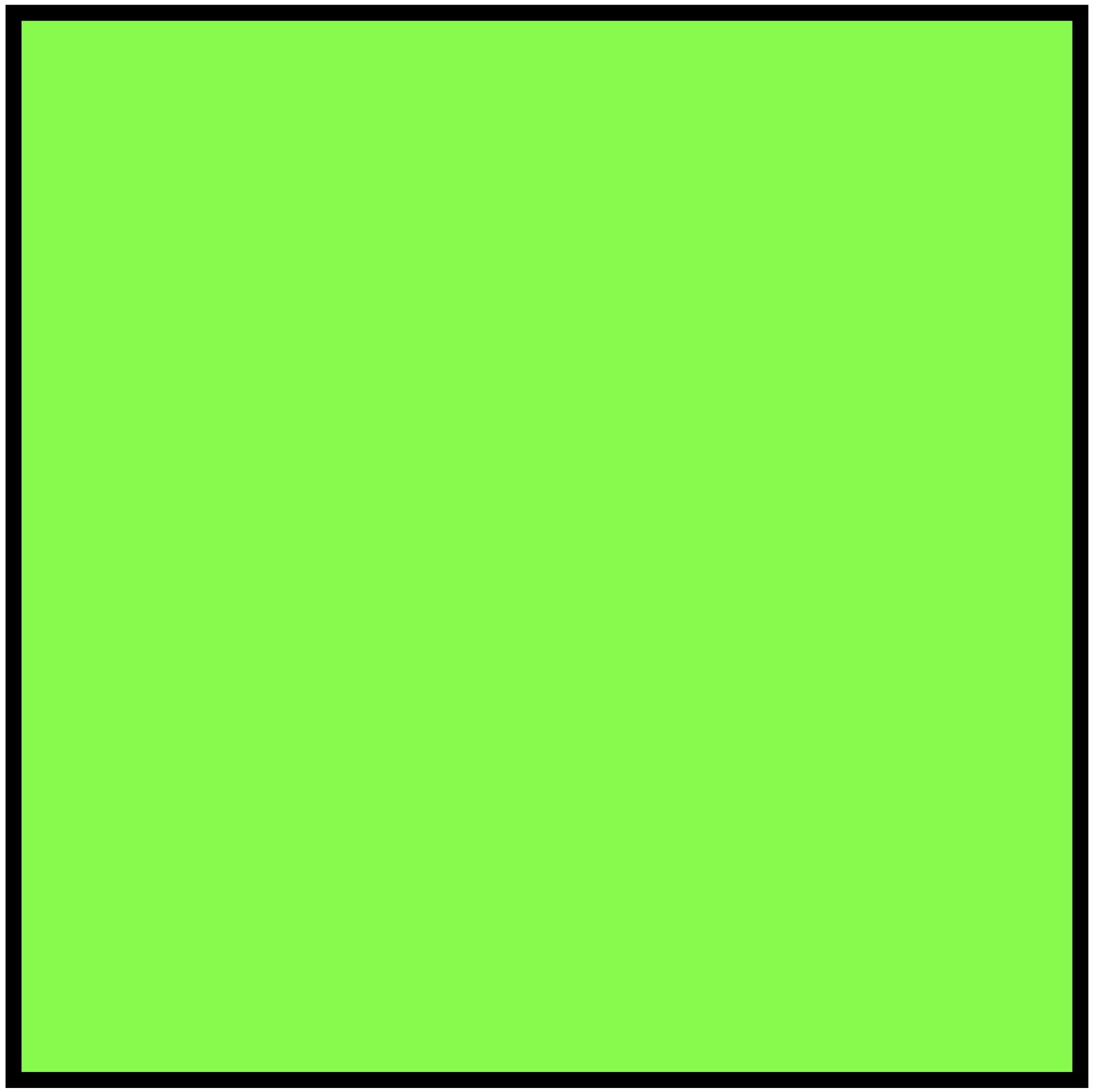
Absolute flux of the star

$$F_{\lambda,\mathrm{pl}}(\lambda) = \frac{f_{\mathrm{pl}}(\lambda)}{f_{\mathrm{star}}(\lambda)} F_{\lambda,\mathrm{star}}(\lambda)$$

Absolute flux of the planet

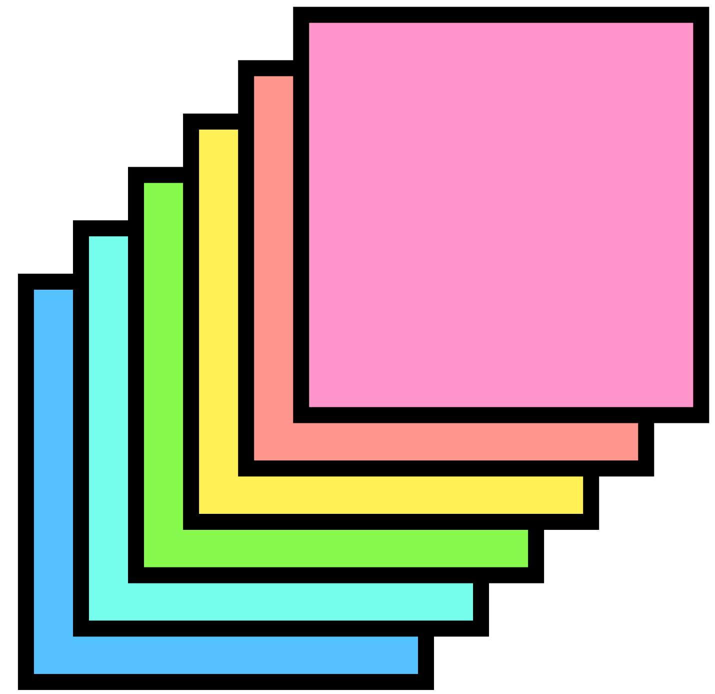
Flux of the star in the same image

First, data reduction



Imaging

Single filter (narrow/ broadband)



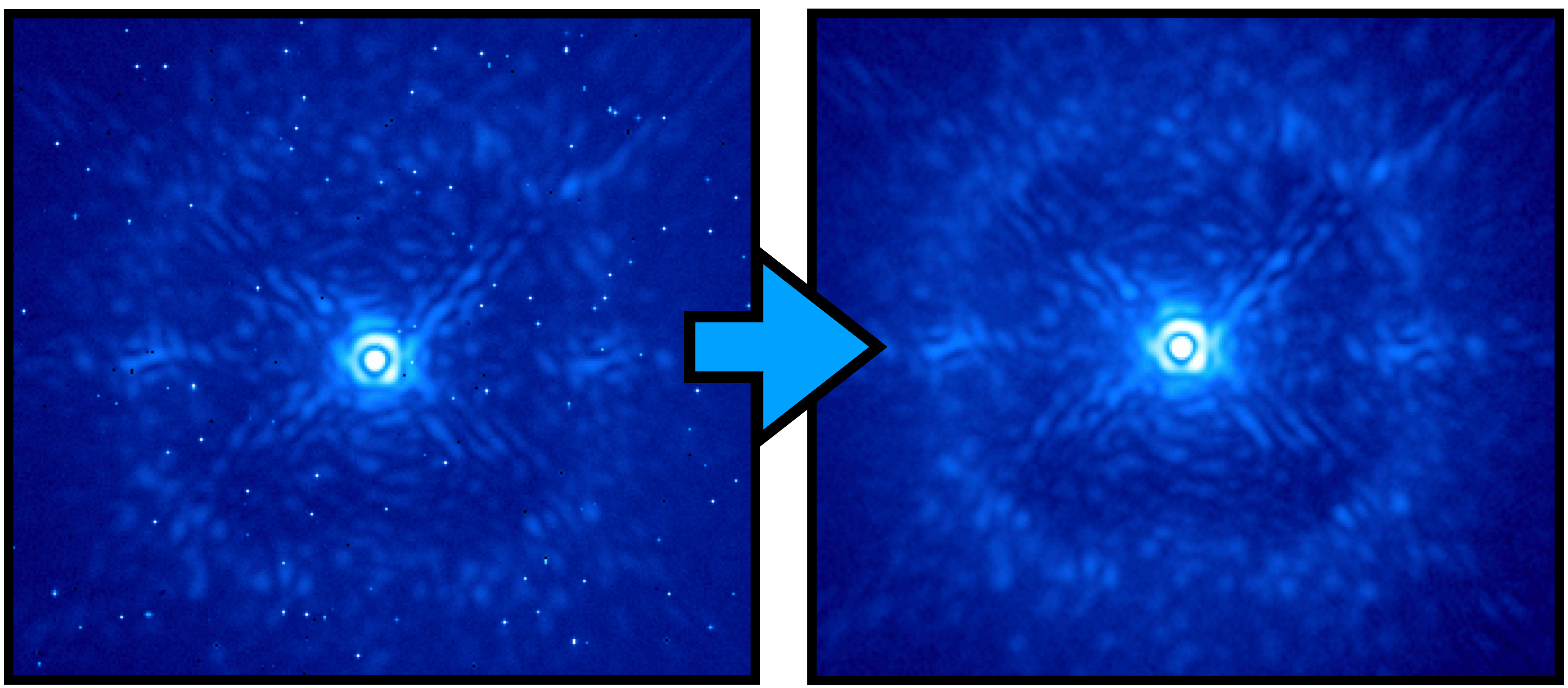
Integral field spectroscopy

Low/medium resolution

Imaging

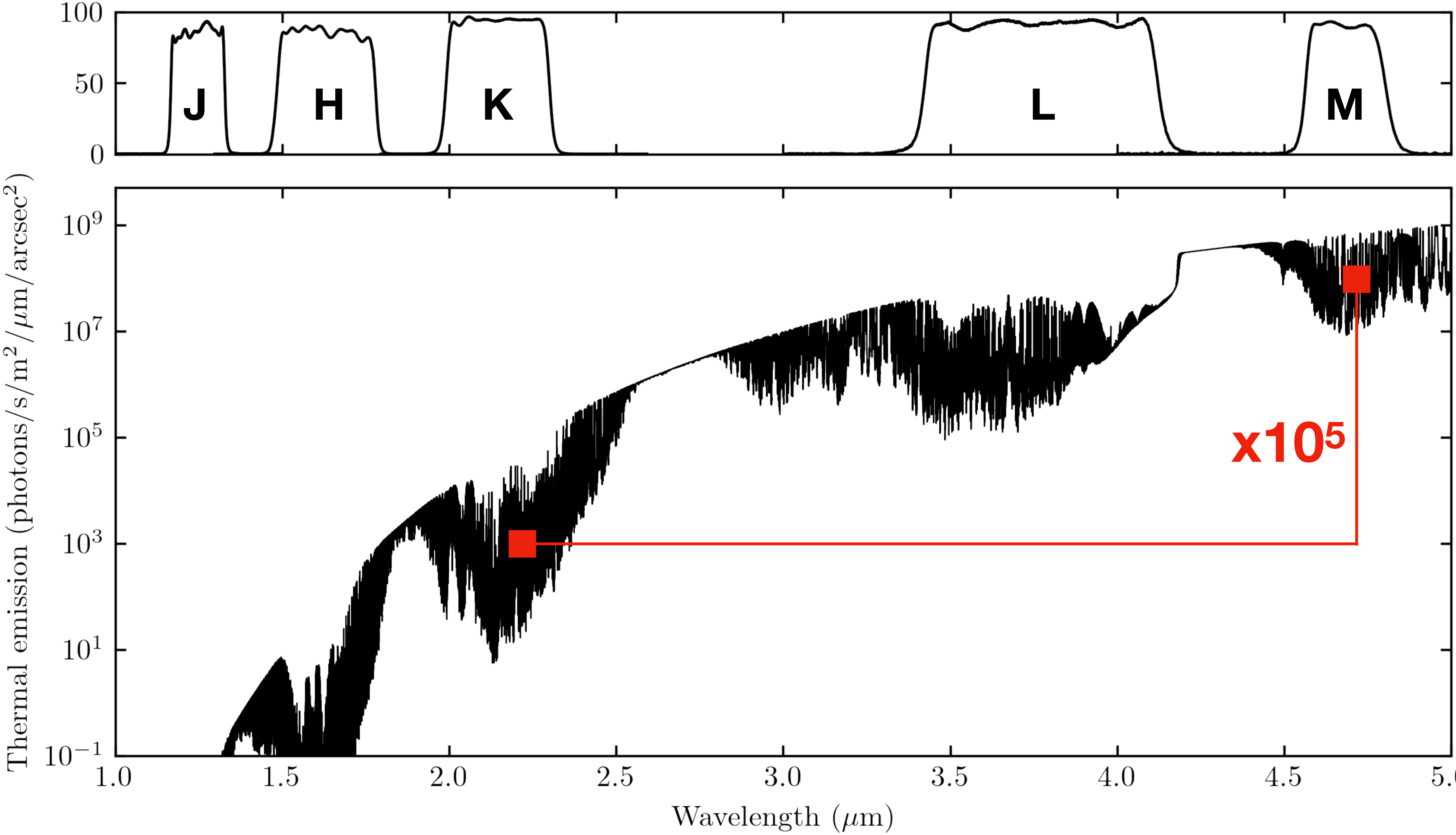
- Typical near-IR data reduction:
  dark subtraction, flat fielding, bad pixel fixing, etc.

- Instrument-specific pipelines:
  - Maintained by observatories, consortia, and/or the community.
  - Often not handled by your favorite PSF subtraction package.



Imaging — long wavelength

- Sky background is more problematic at longer wavelengths.



Imaging — long wavelength

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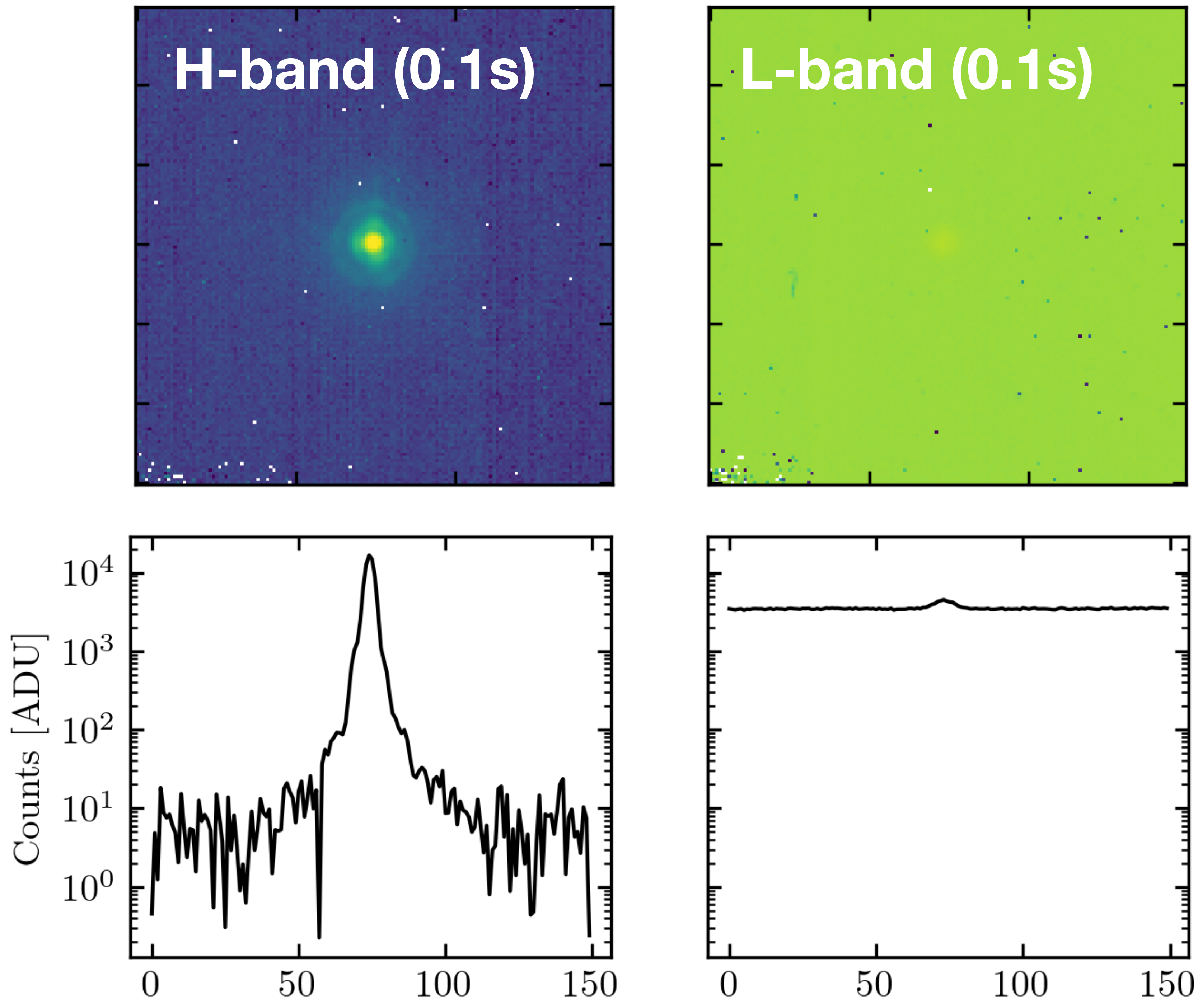
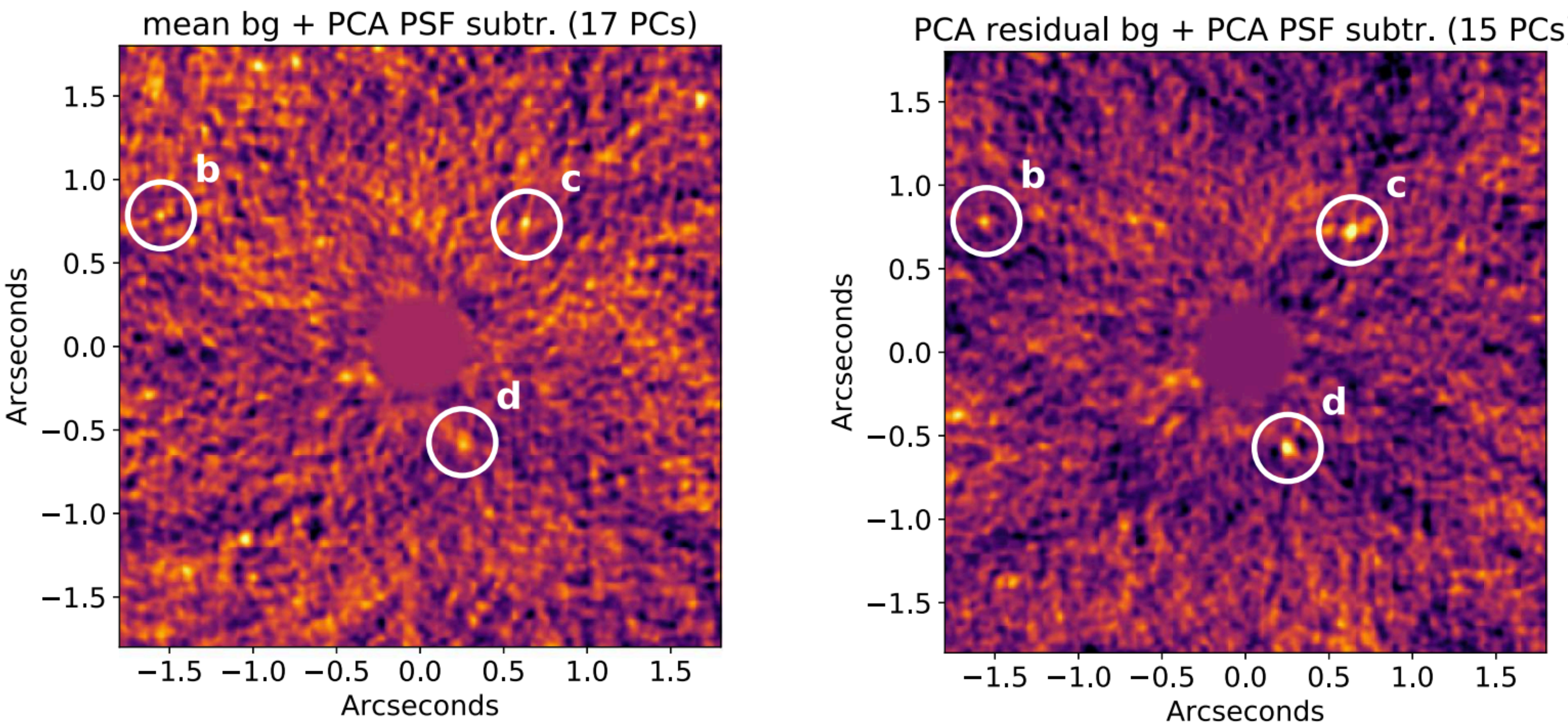


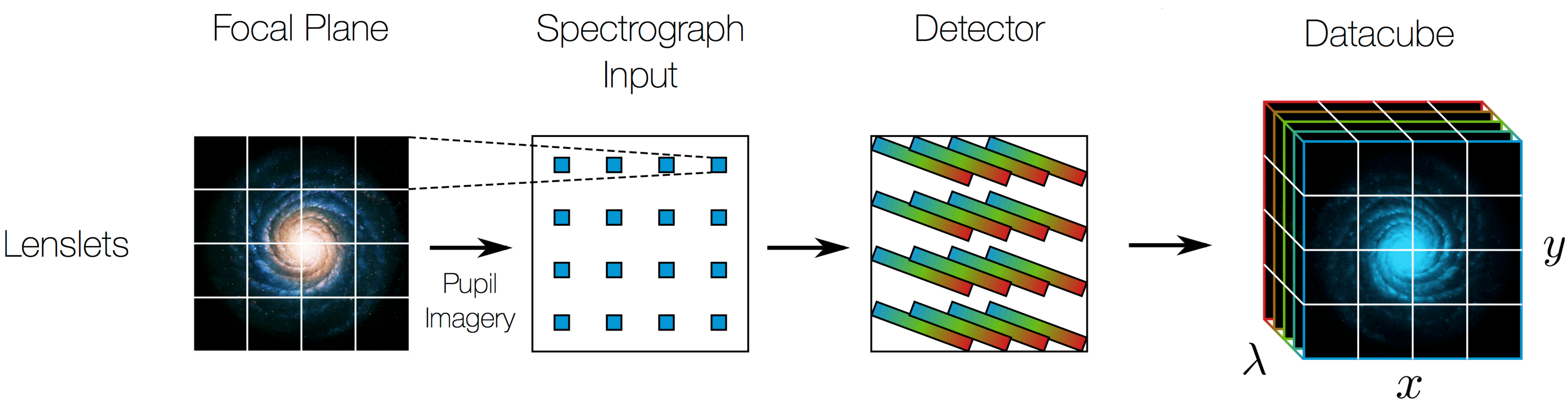
Imaging — long wavelength

- PCA-based sky subtraction can help, depending on conditions.
  e.g., [Hunziker et al. (2018)] applied to M-band NaCo data

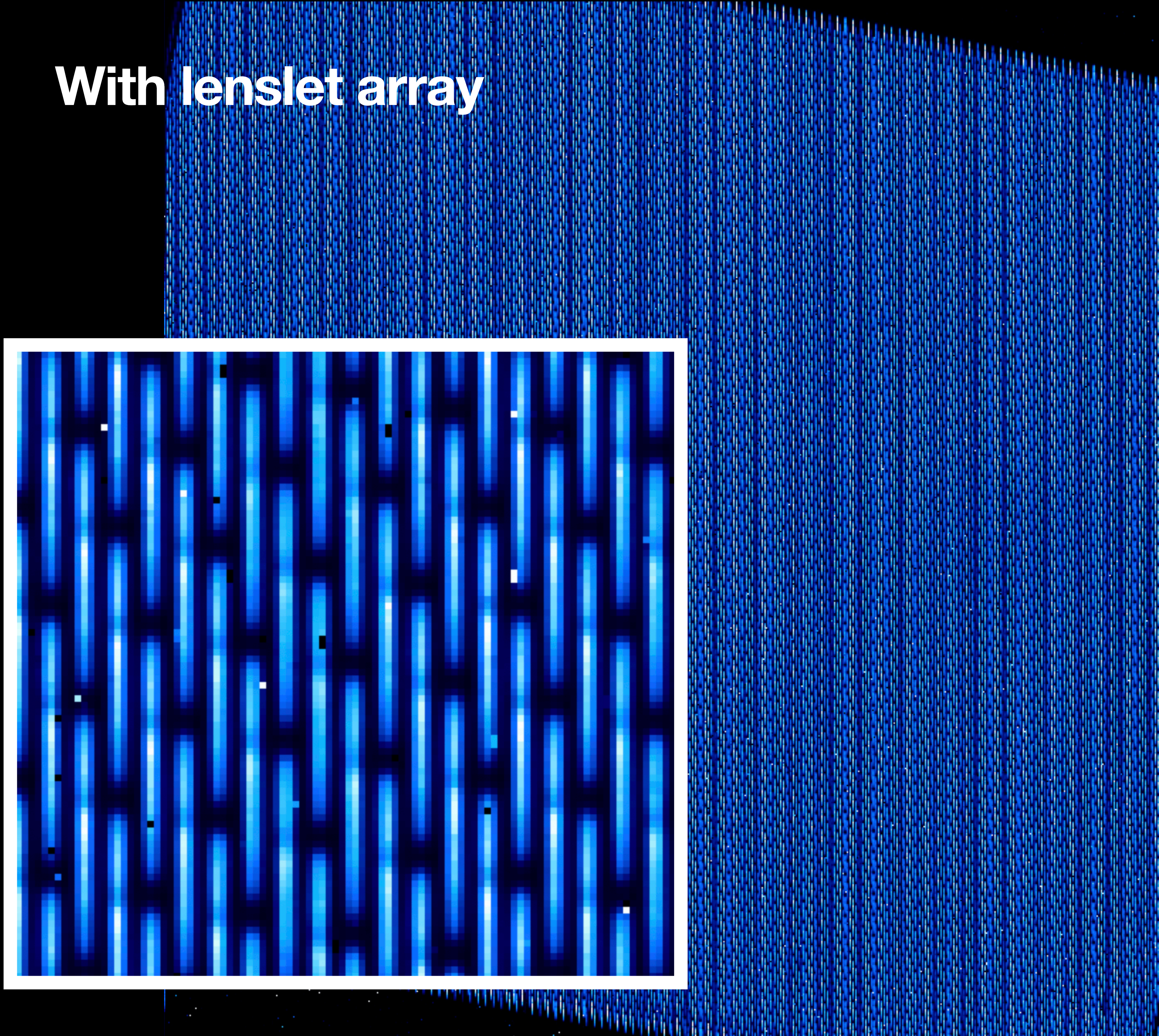


Integral Field Spectroscopy

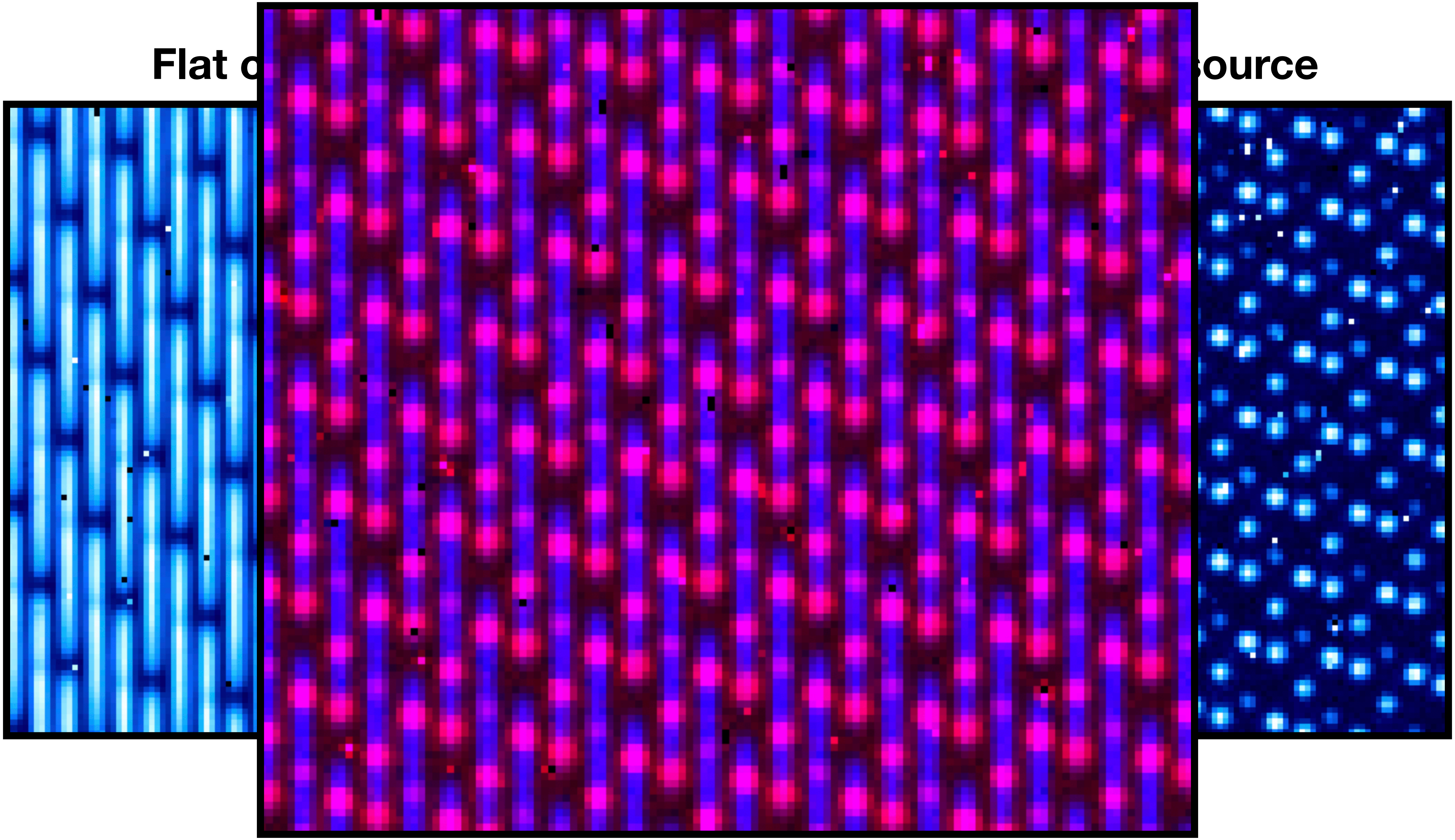
- Low/medium-resolution spectroscopy at each pixel in your FoV.



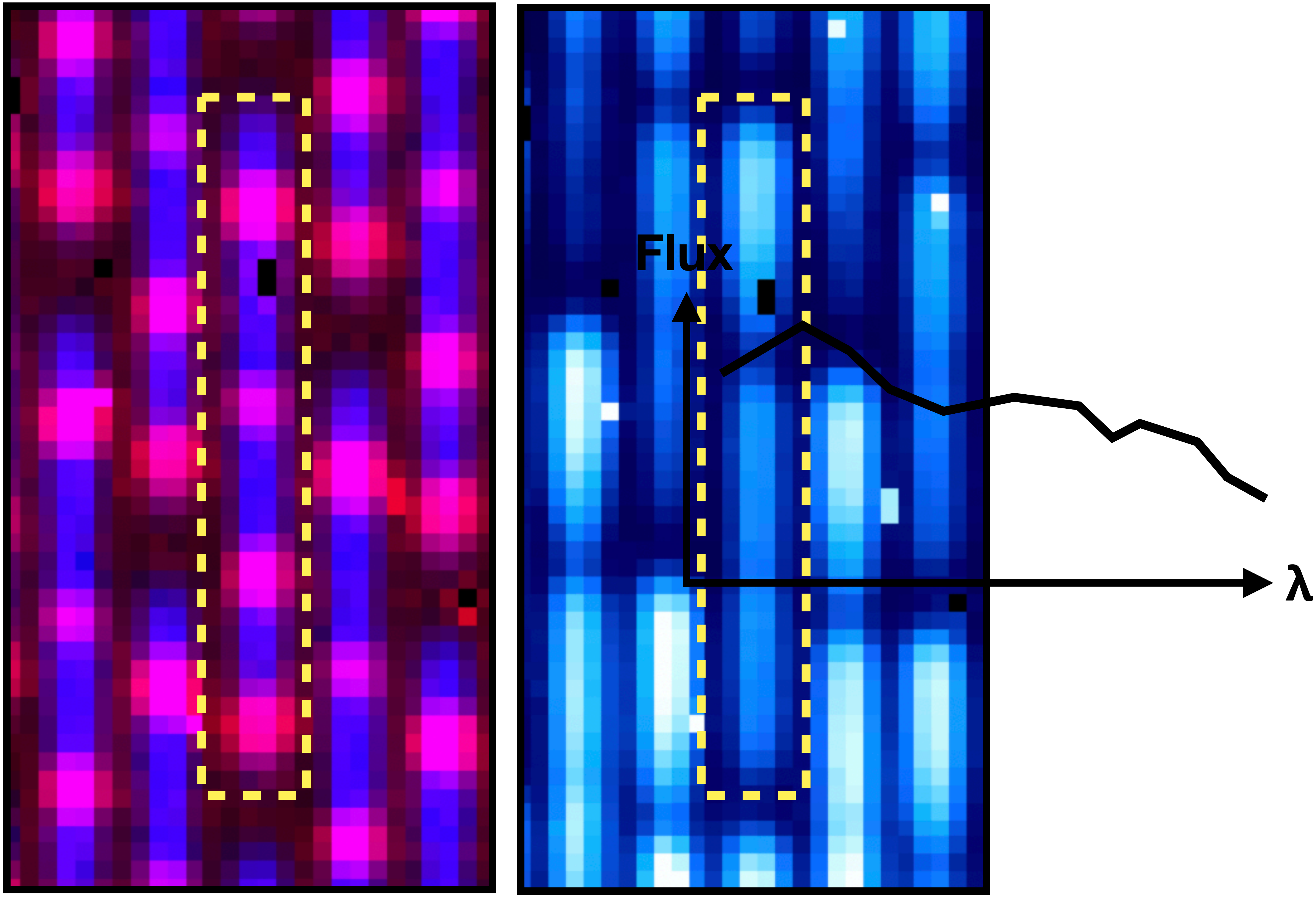
With lenslet array



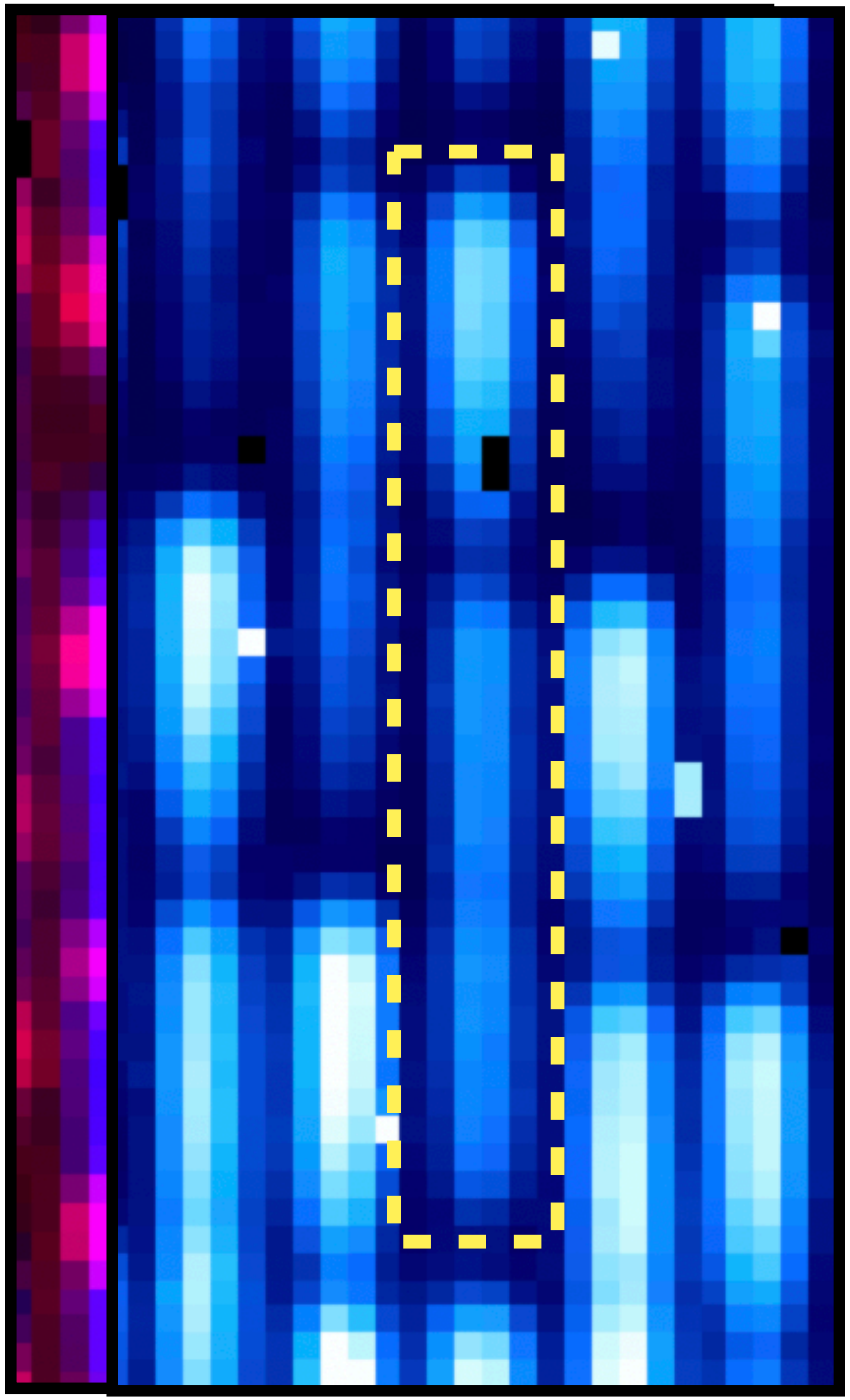
Integral Field Spectroscopy



Integral Field Spectroscopy



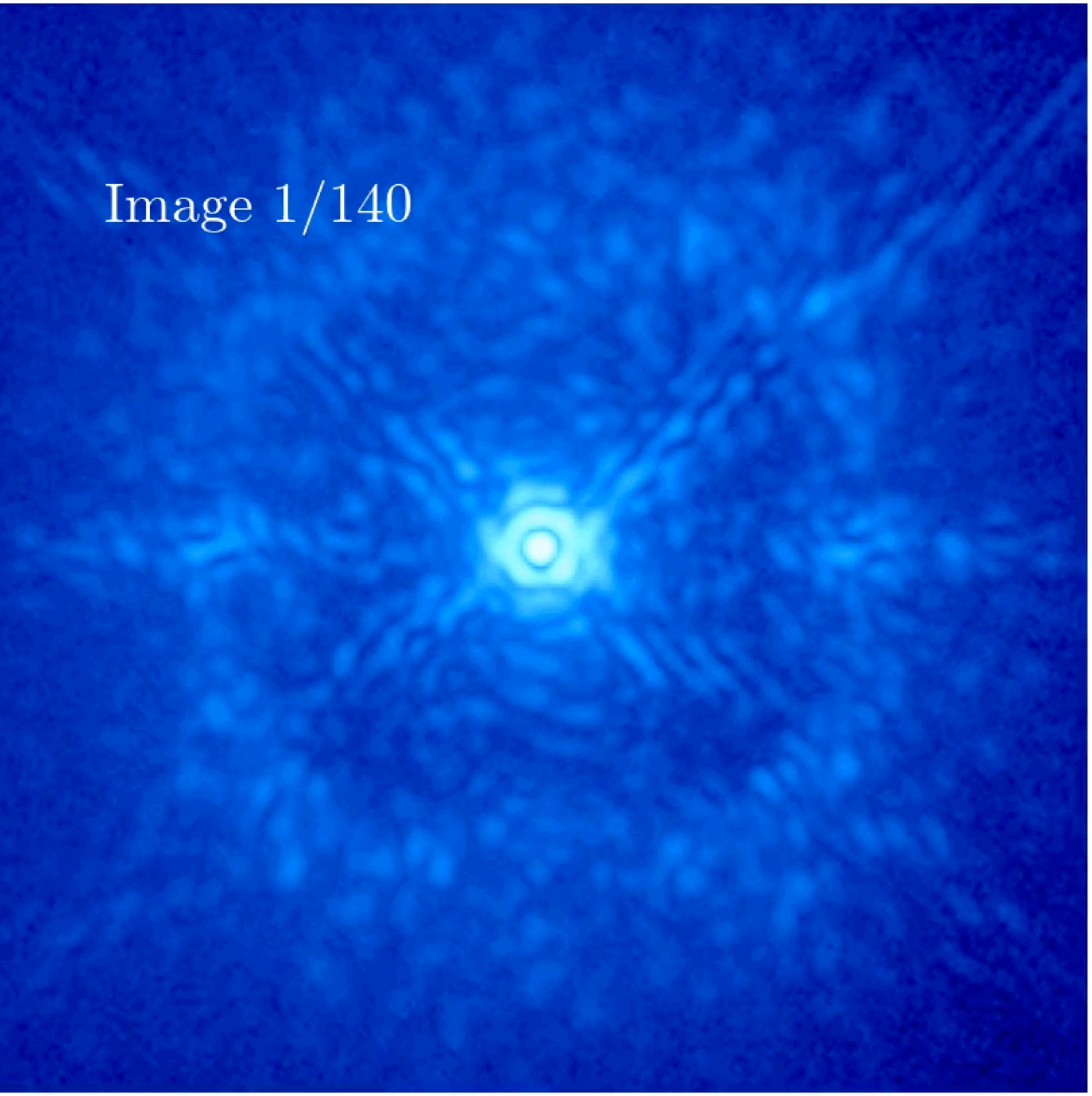
Integral Field Spectroscopy



Micro-spectra extraction:

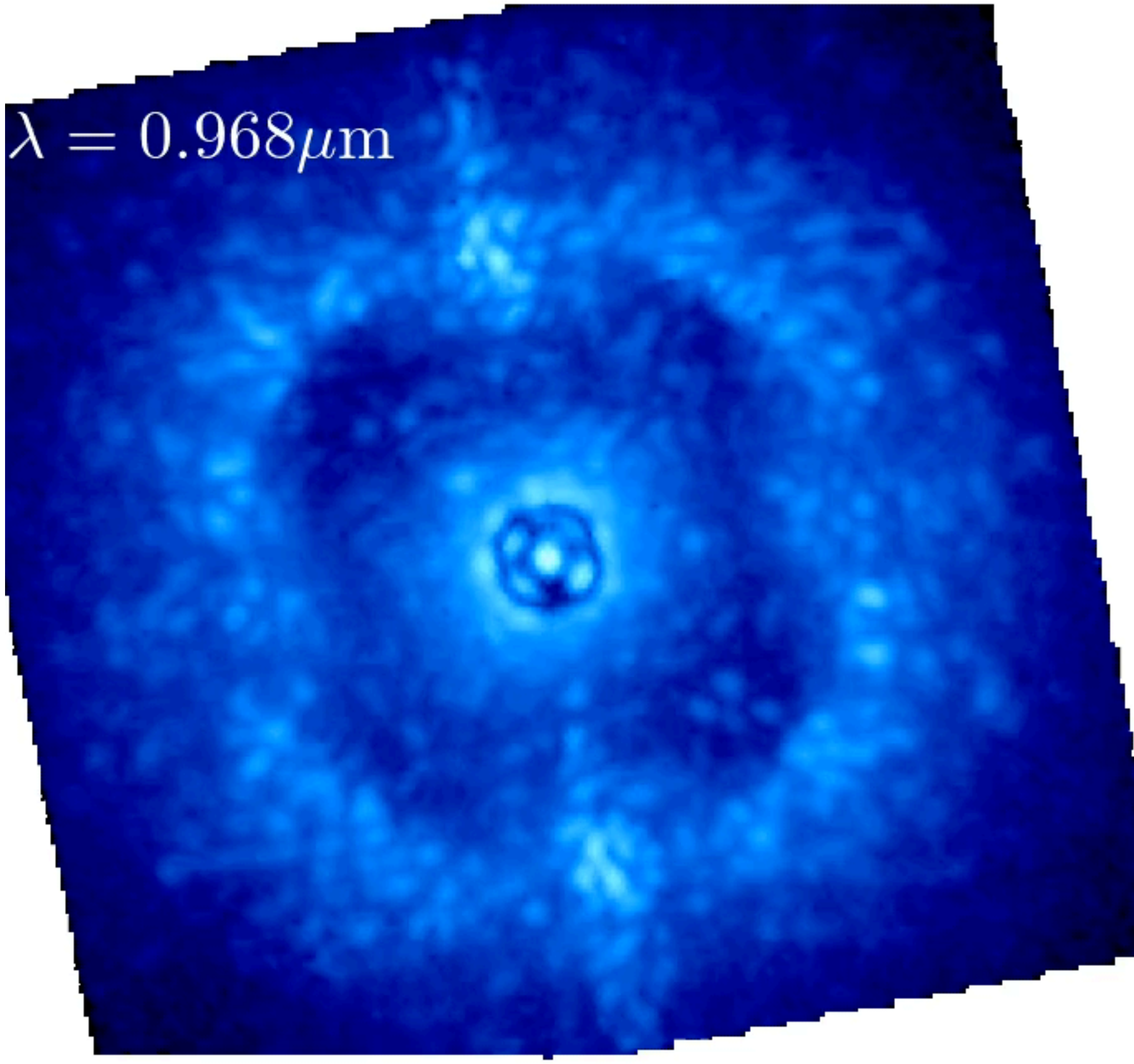
- Aperture photometry perpendicular to dispersion direction

- Forward-modeling with model/empirical lenslet PSFs (e.g. Samland et al. 2022)



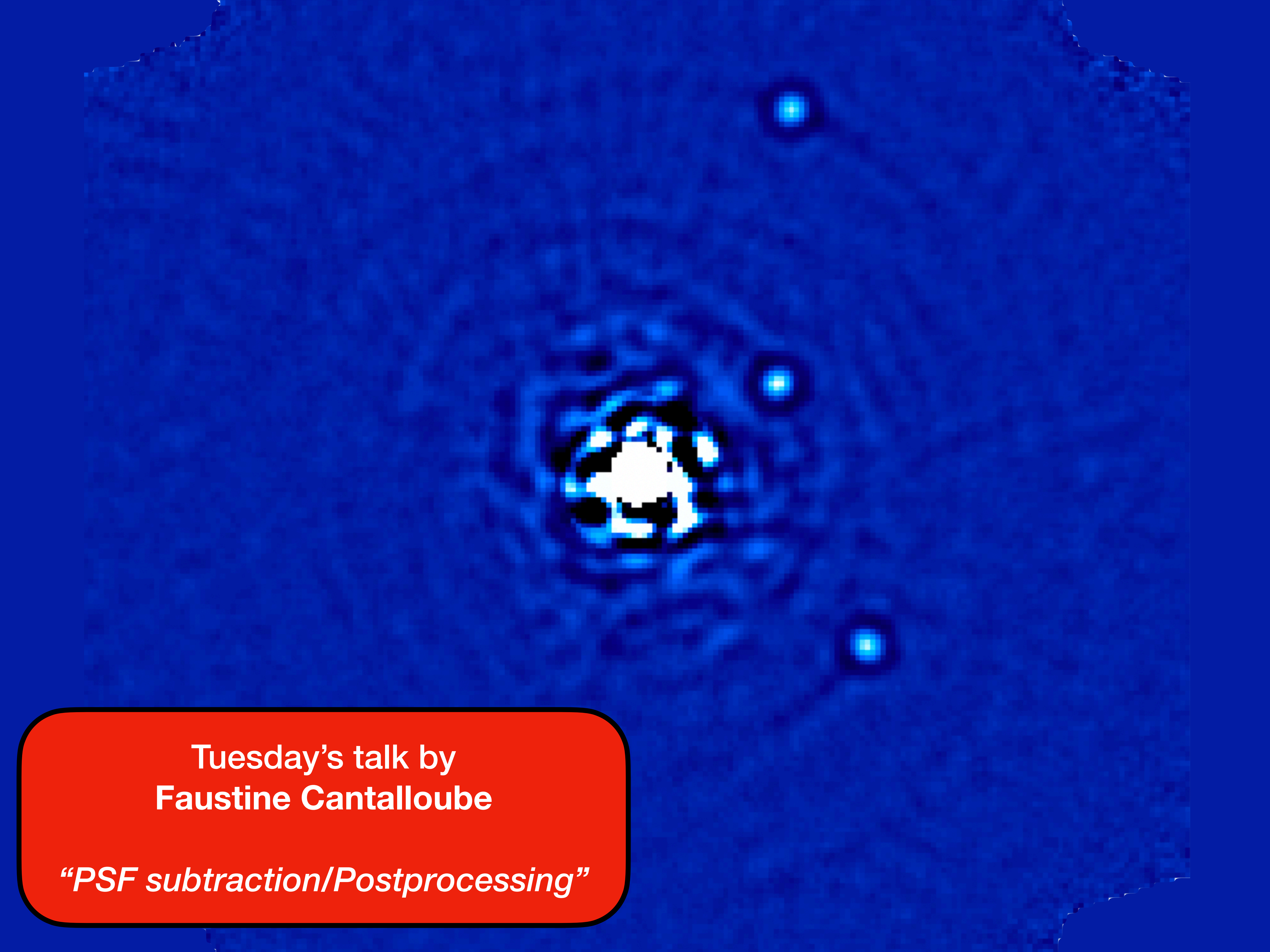
Imaging

Single filter (narrow/ broadband)



Integral field spectroscopy

Low/medium resolution

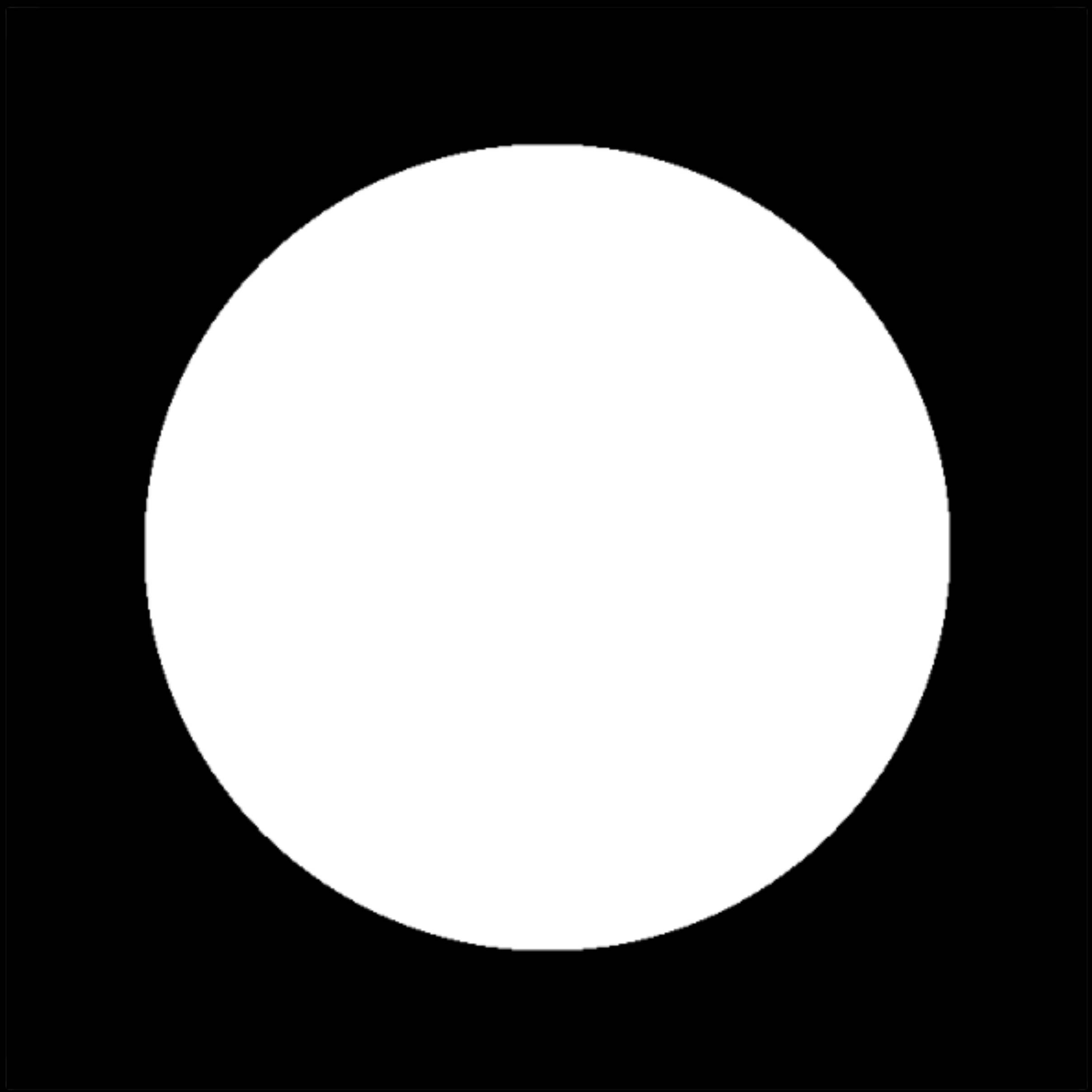


Tuesday’s talk by
Faustine Cantalloube

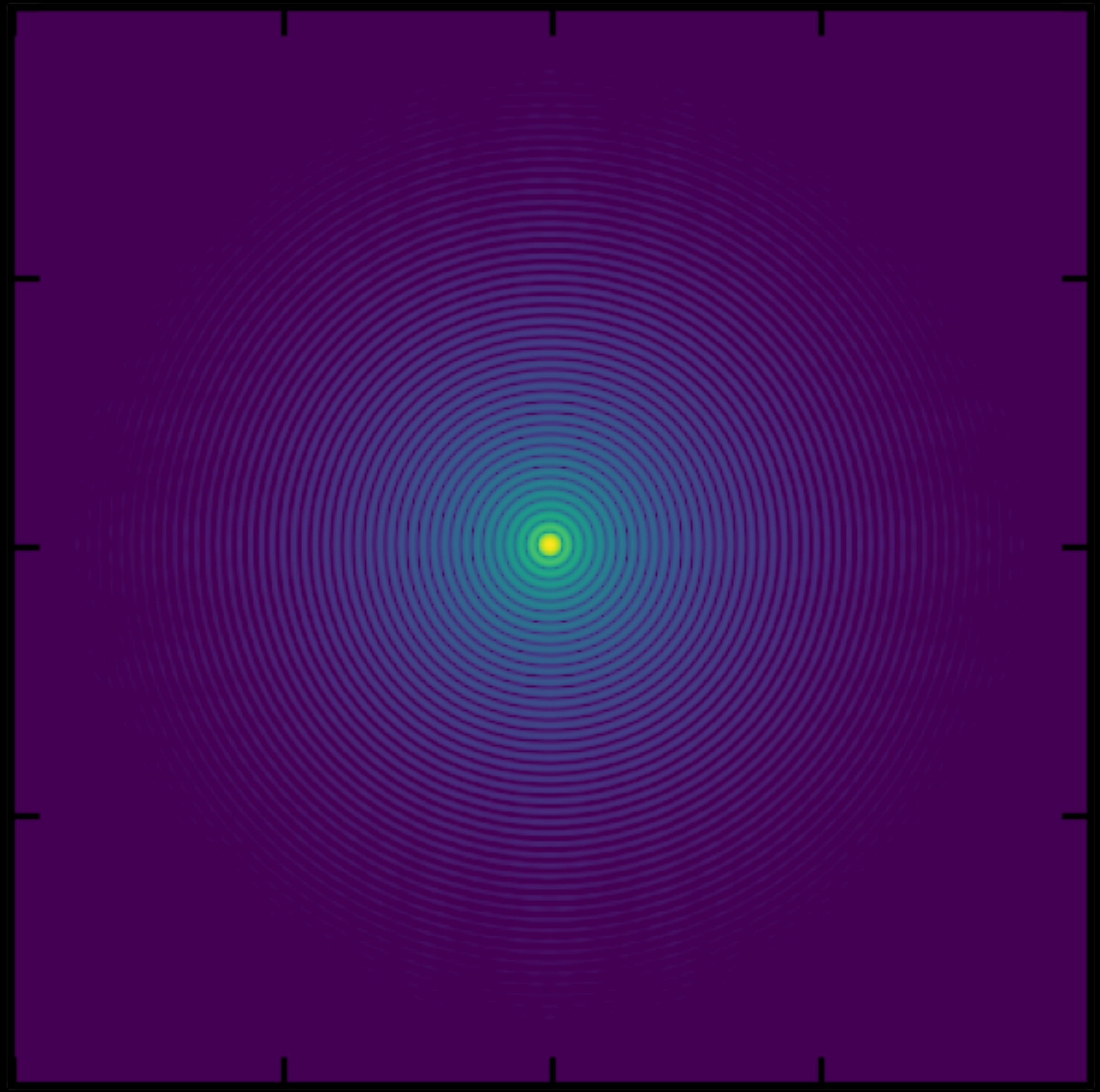
“PSF subtraction/Postprocessing”


Where is the star?

Open pupil



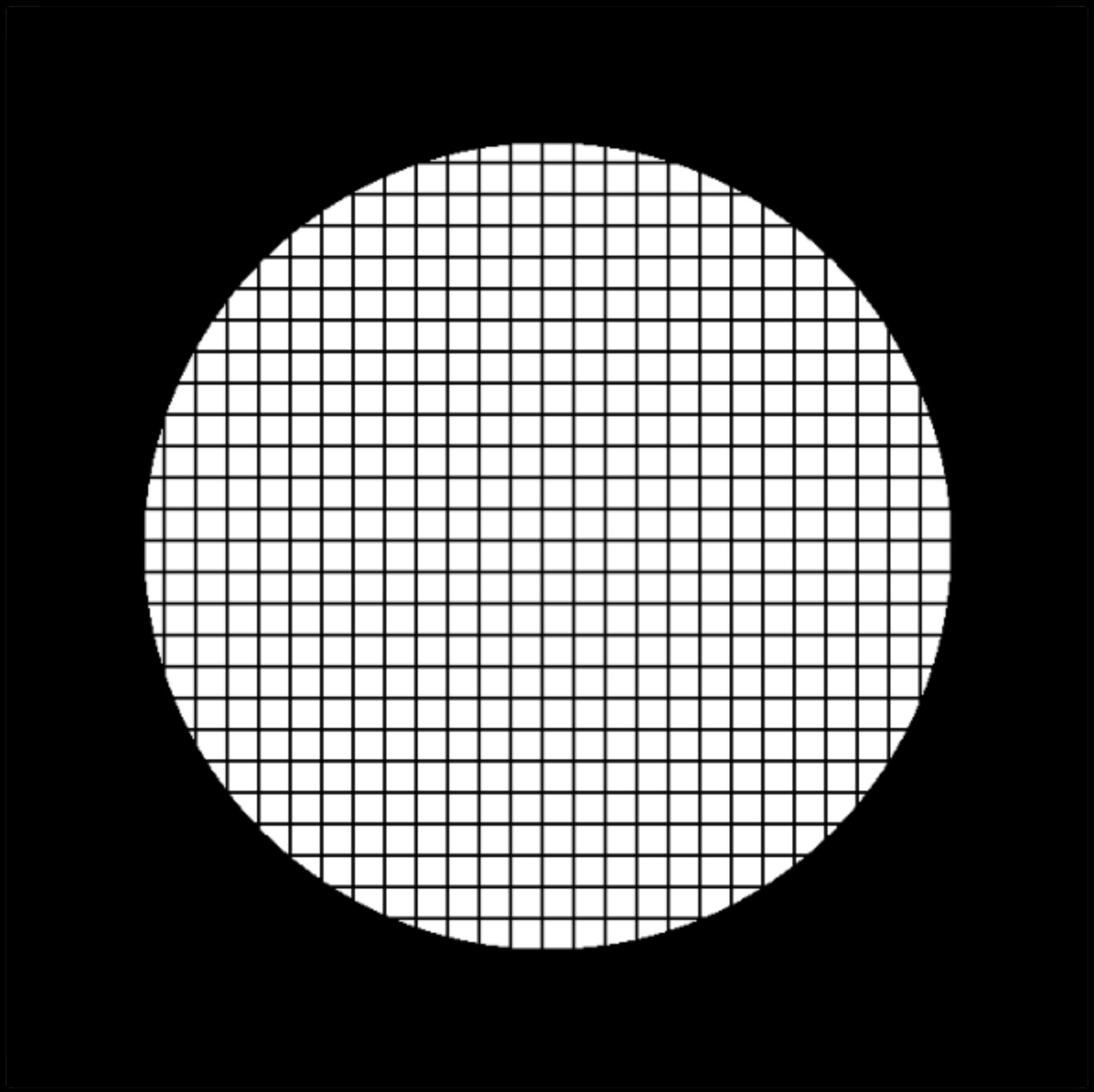
Pupil plane



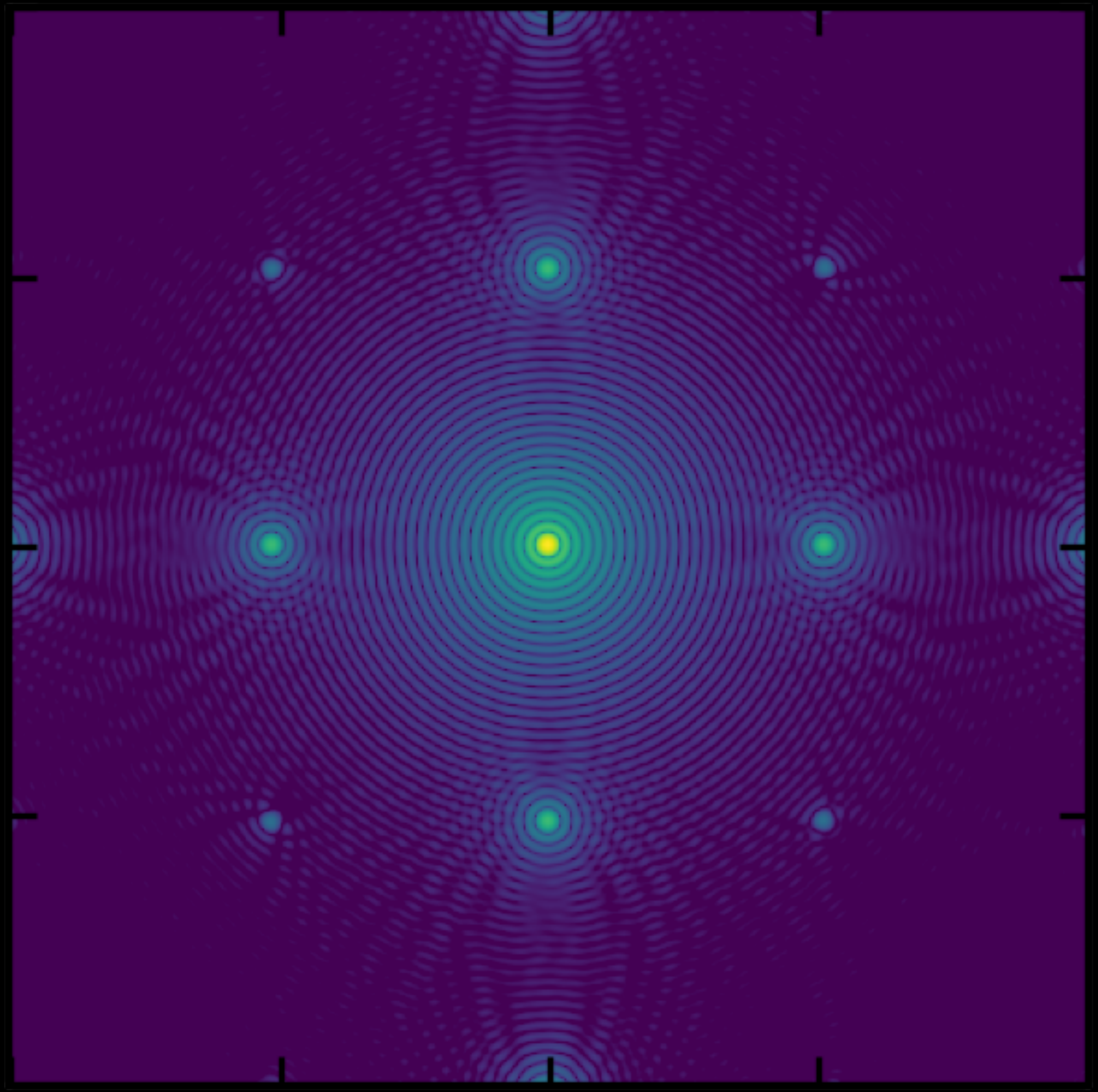
Focal plane

*Monochromatic simulation

Reticulate pupil mask



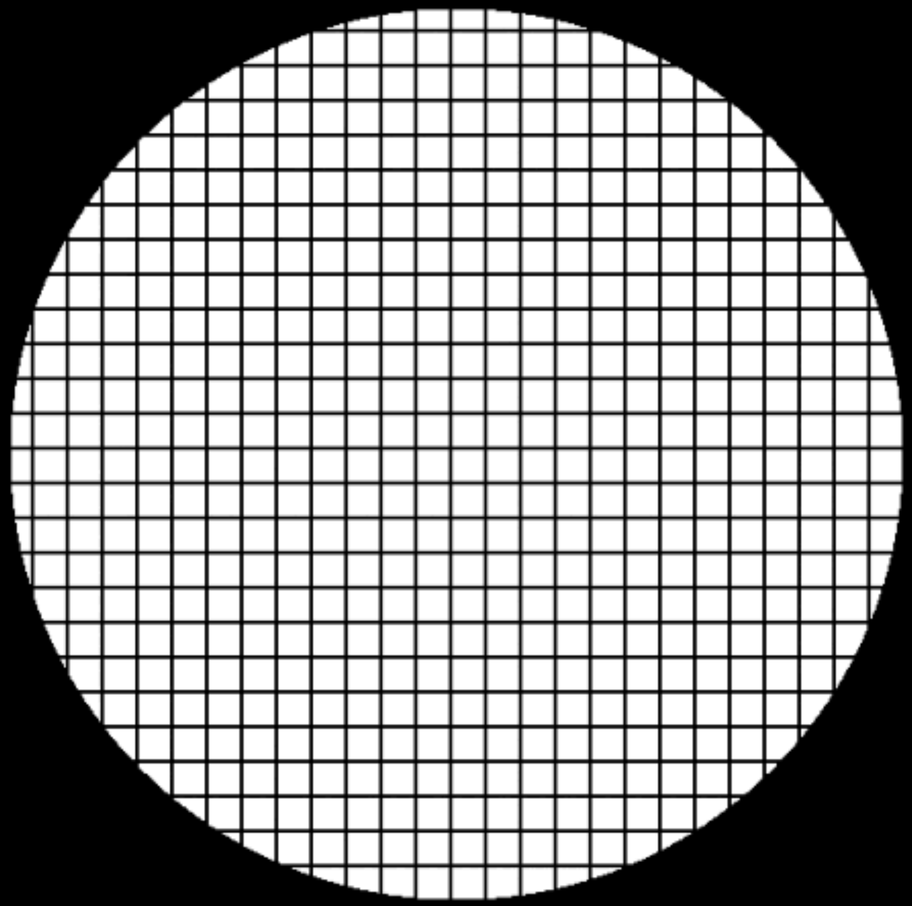
Pupil plane



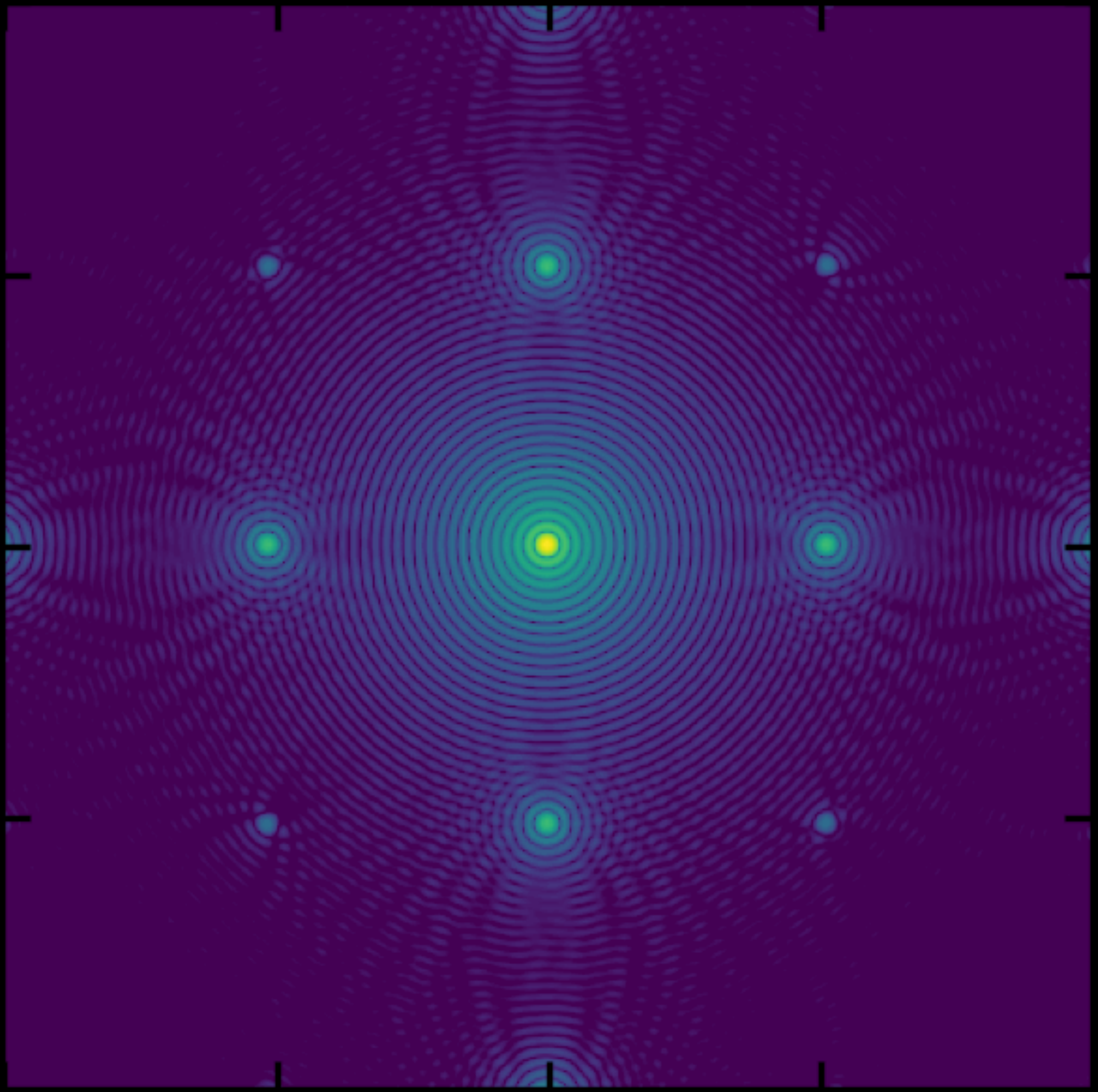
Focal plane

*Monochromatic simulation

Varying angle



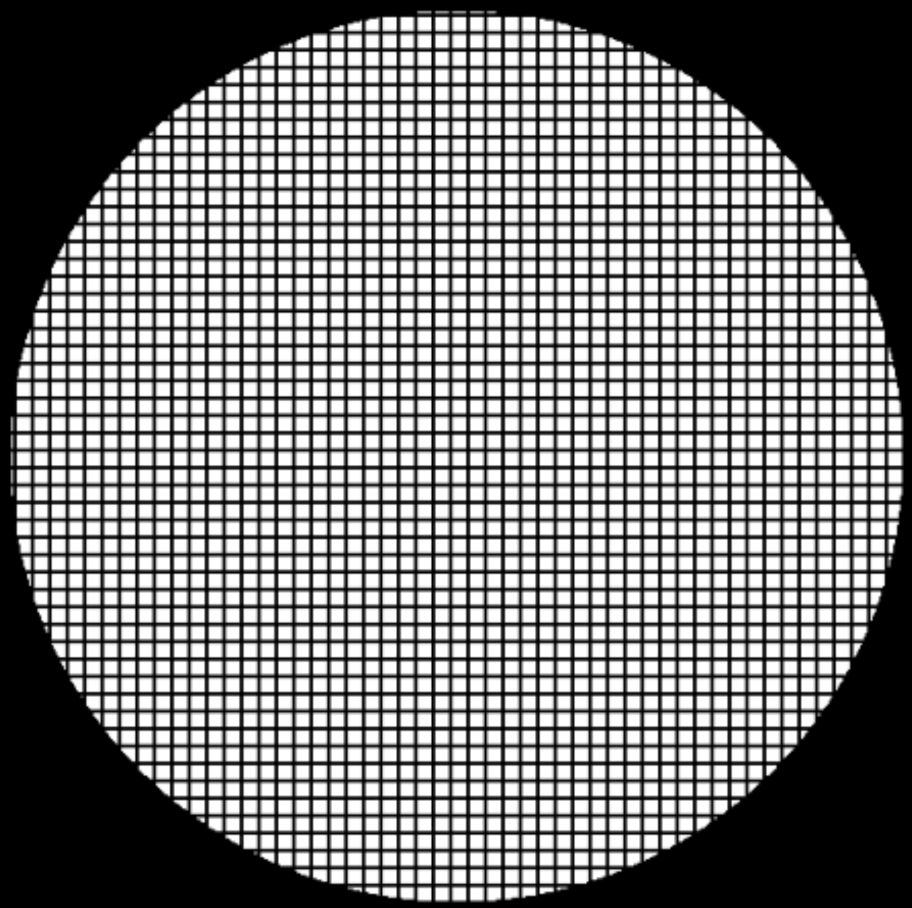
Pupil plane



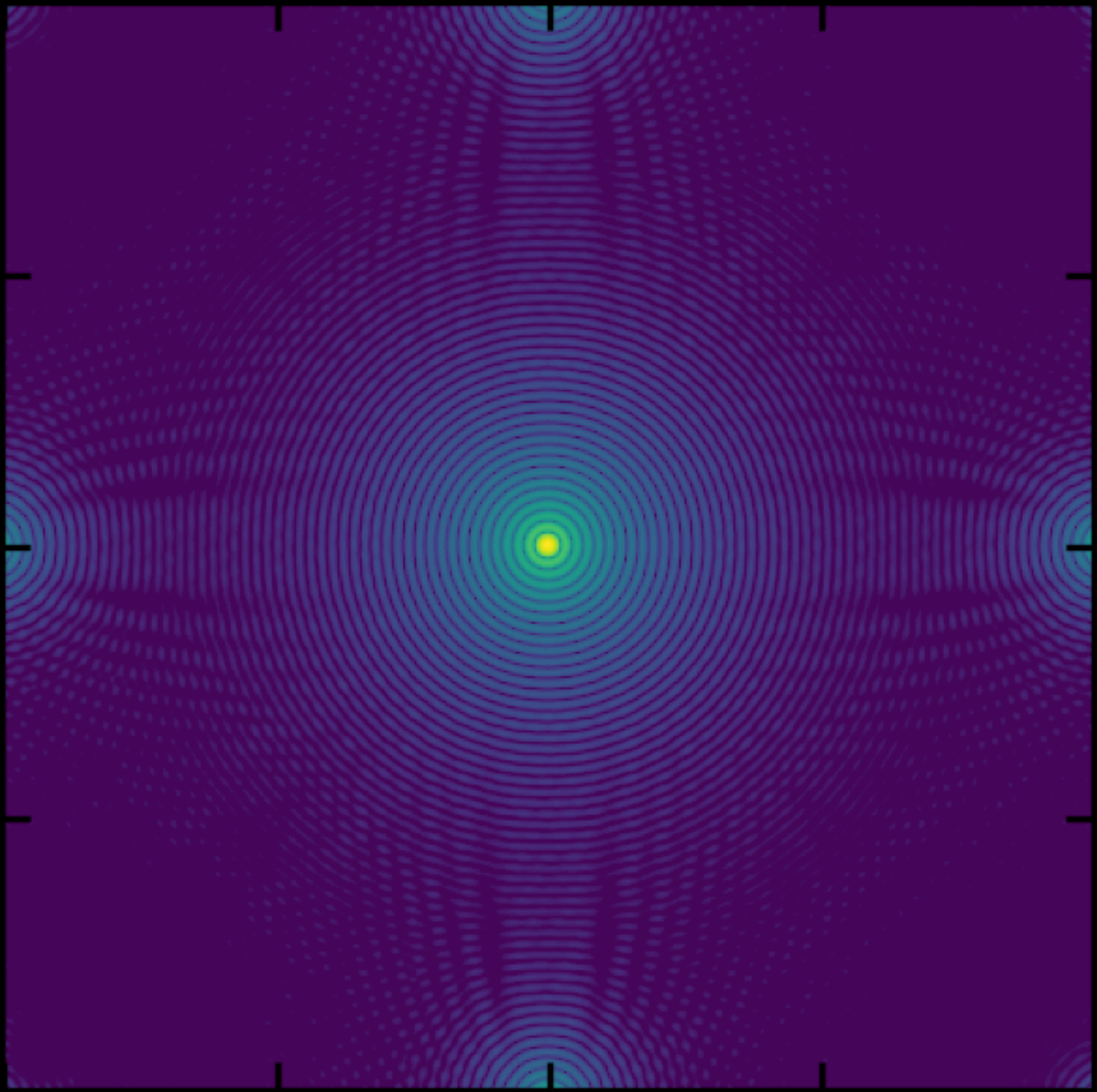
Focal plane

*Monochromatic simulation

Varying spacing



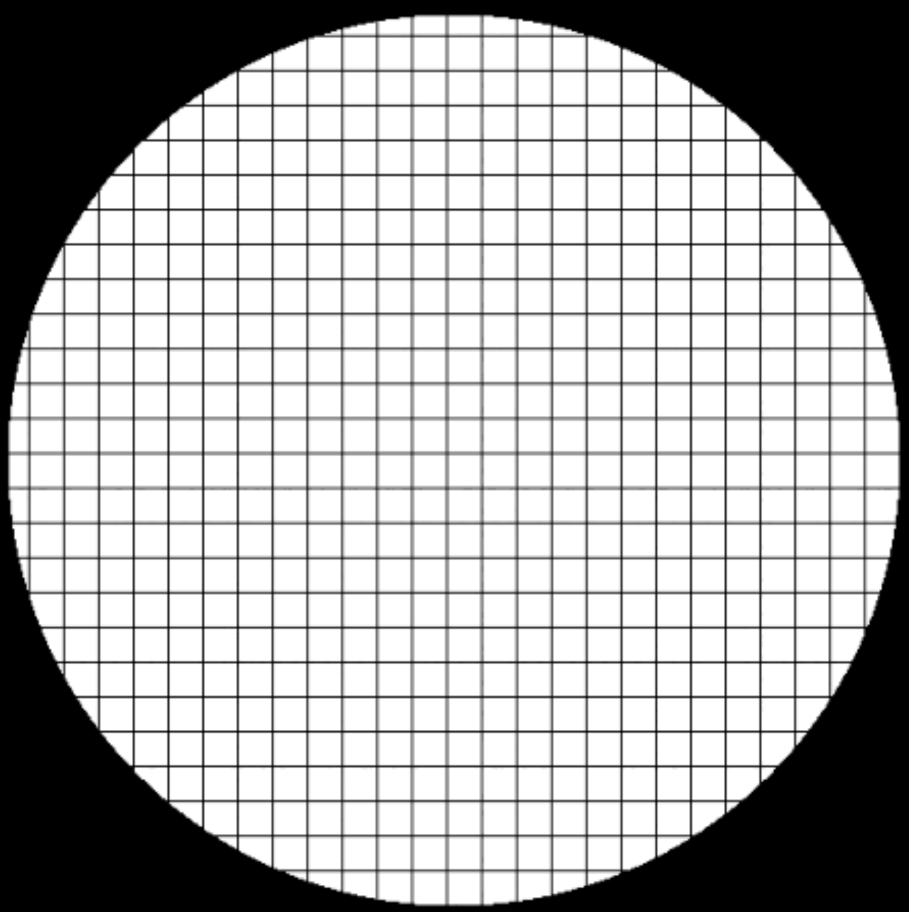
Pupil plane



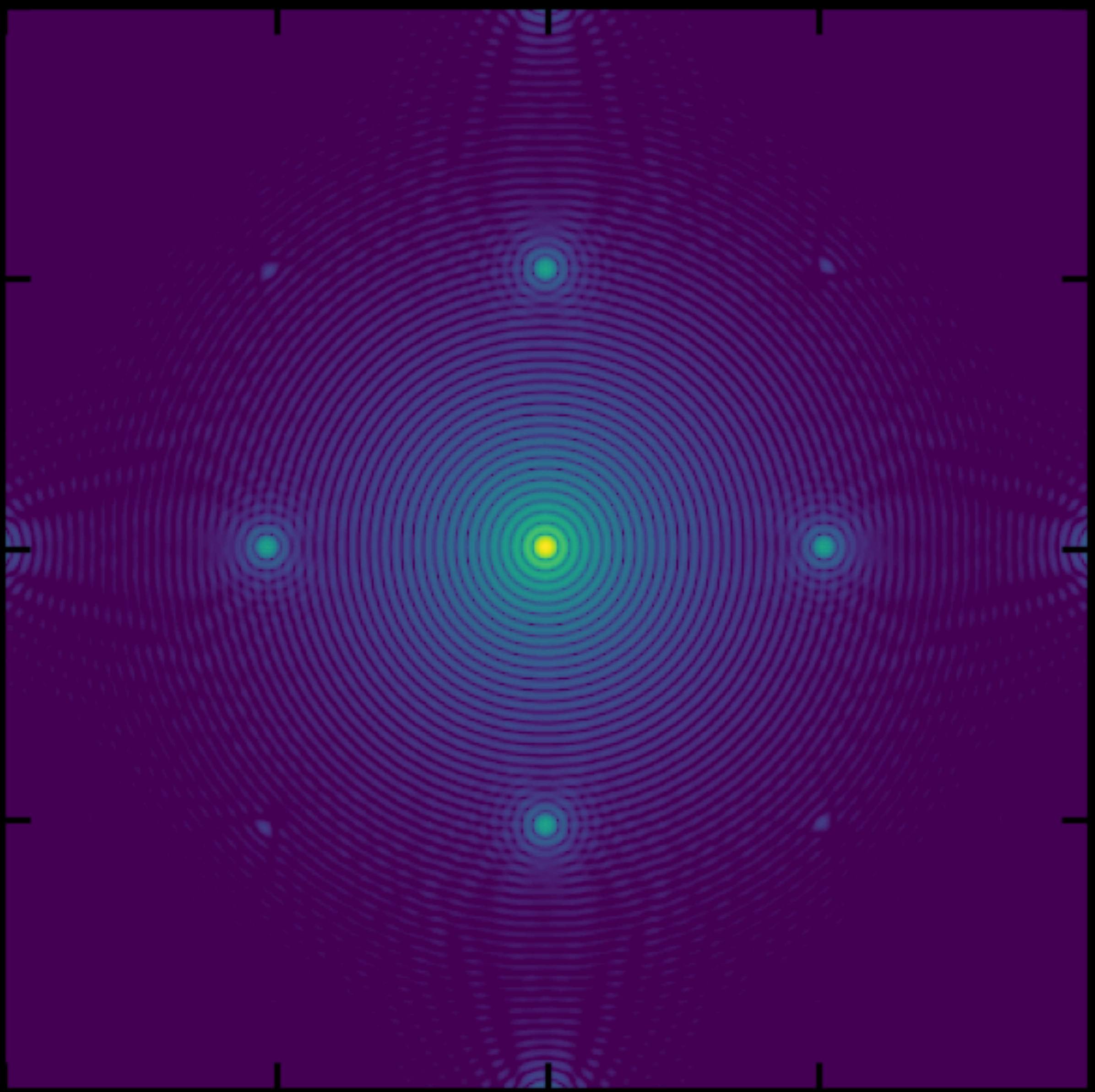
Focal plane

*Monochromatic simulation

Varying thickness

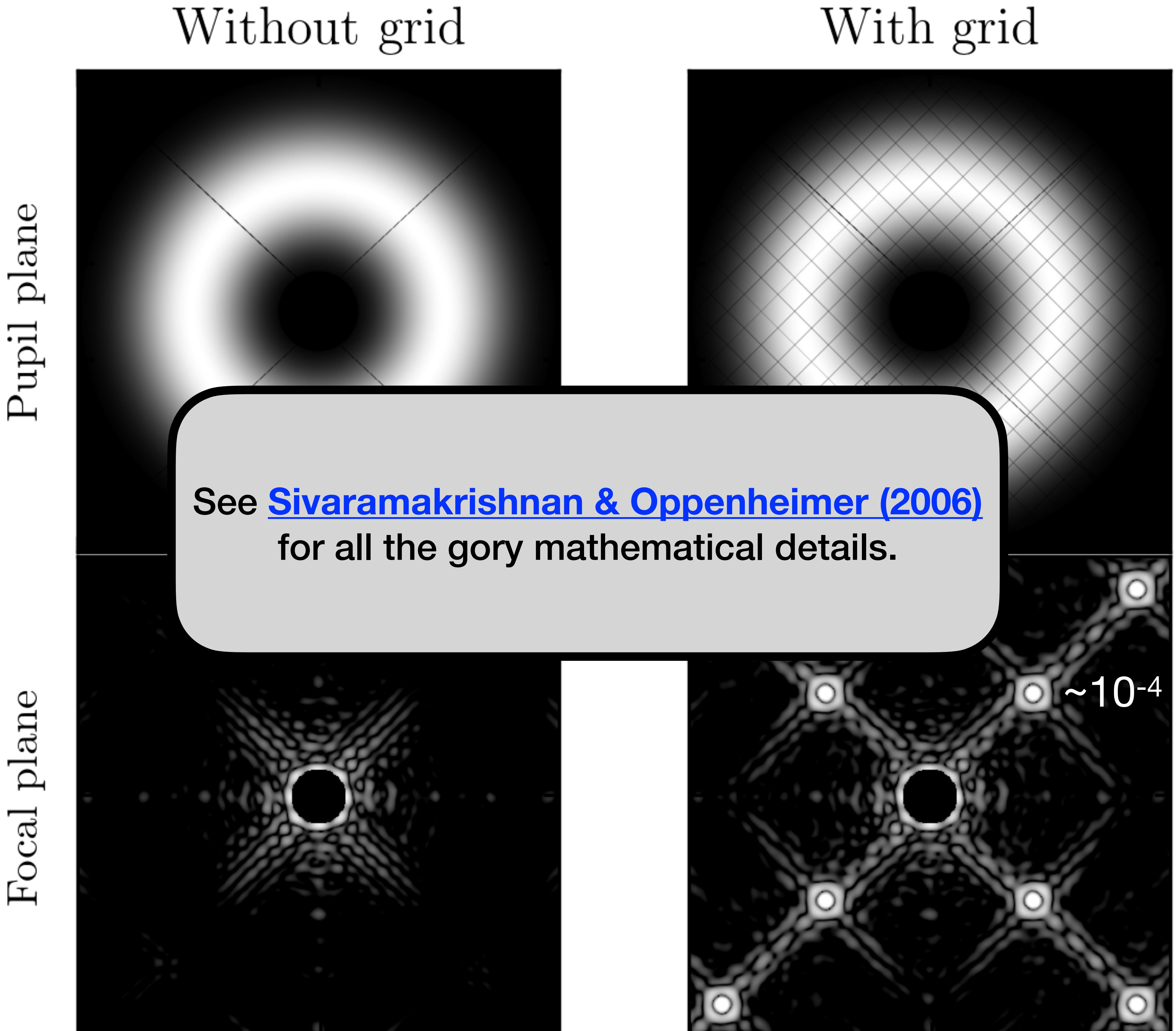


Pupil plane



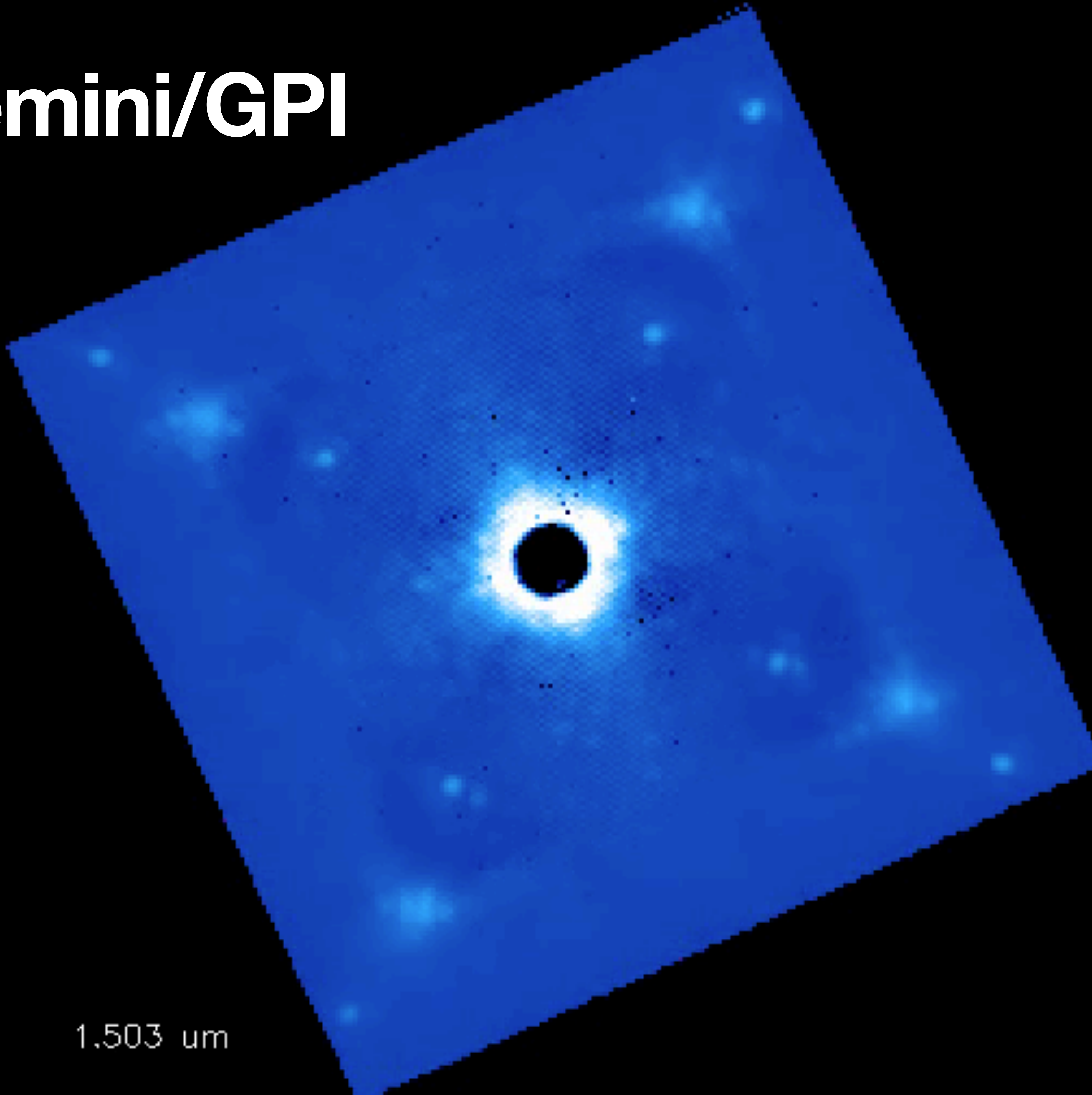
Focal plane

*Monochromatic simulation



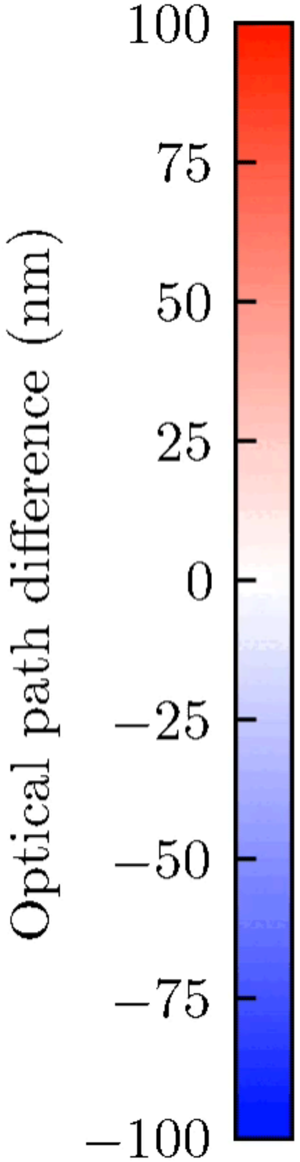
See Sivaramakrishnan & Oppenheimer (2006) for all the gory mathematical details.

Gemini/GPI

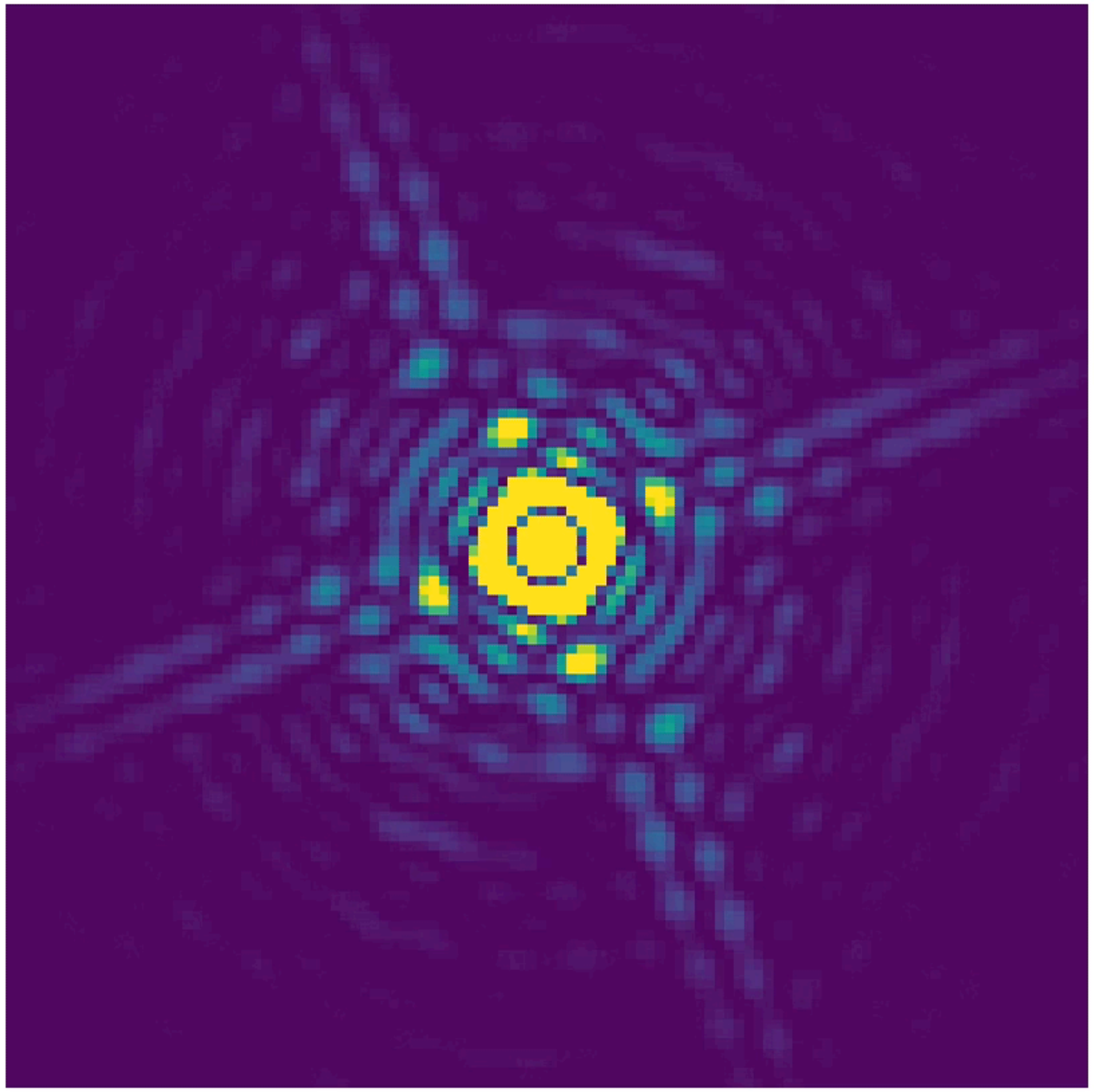


Phase vs. amplitude

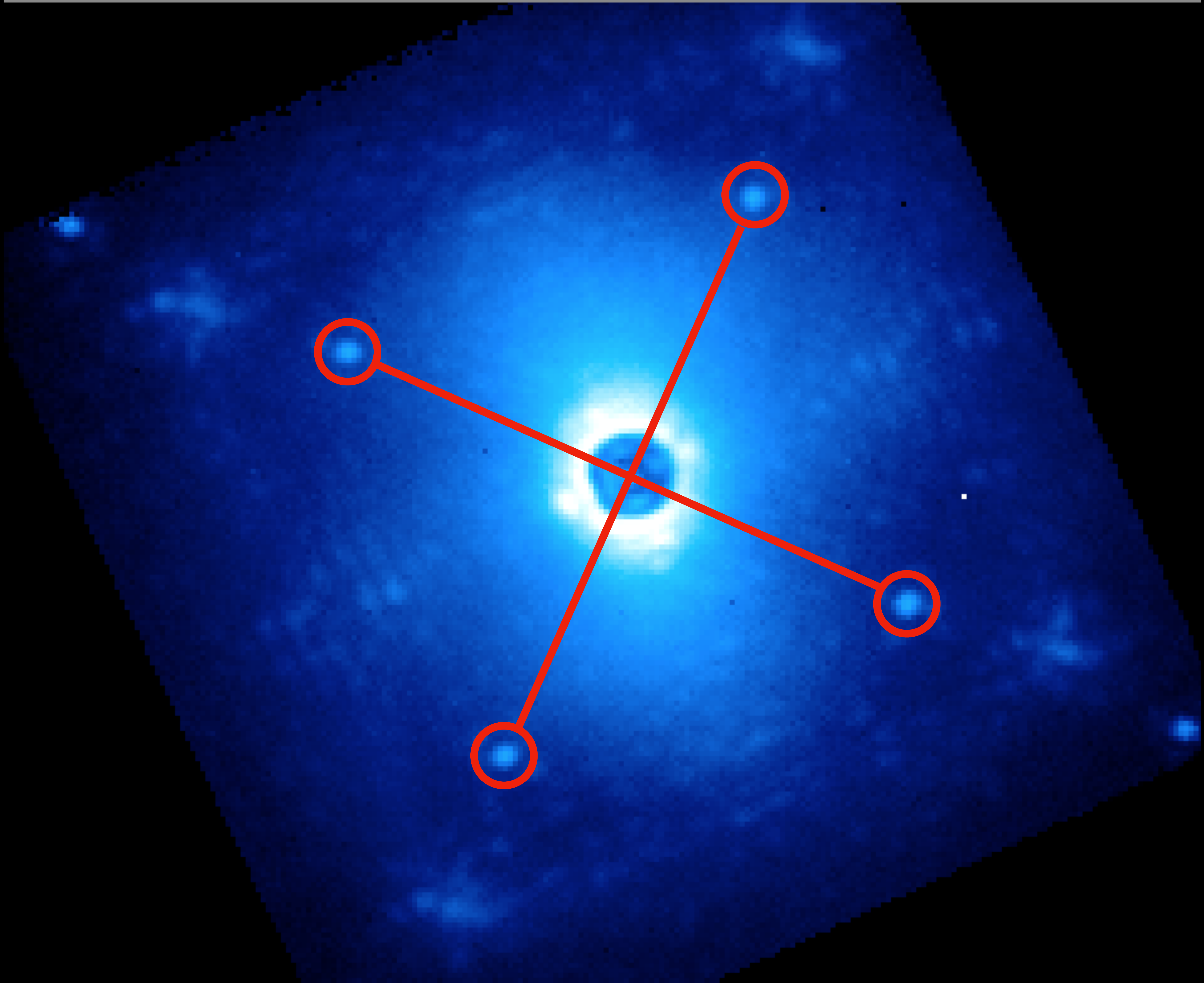
Pupil plane (DM)



Focal plane

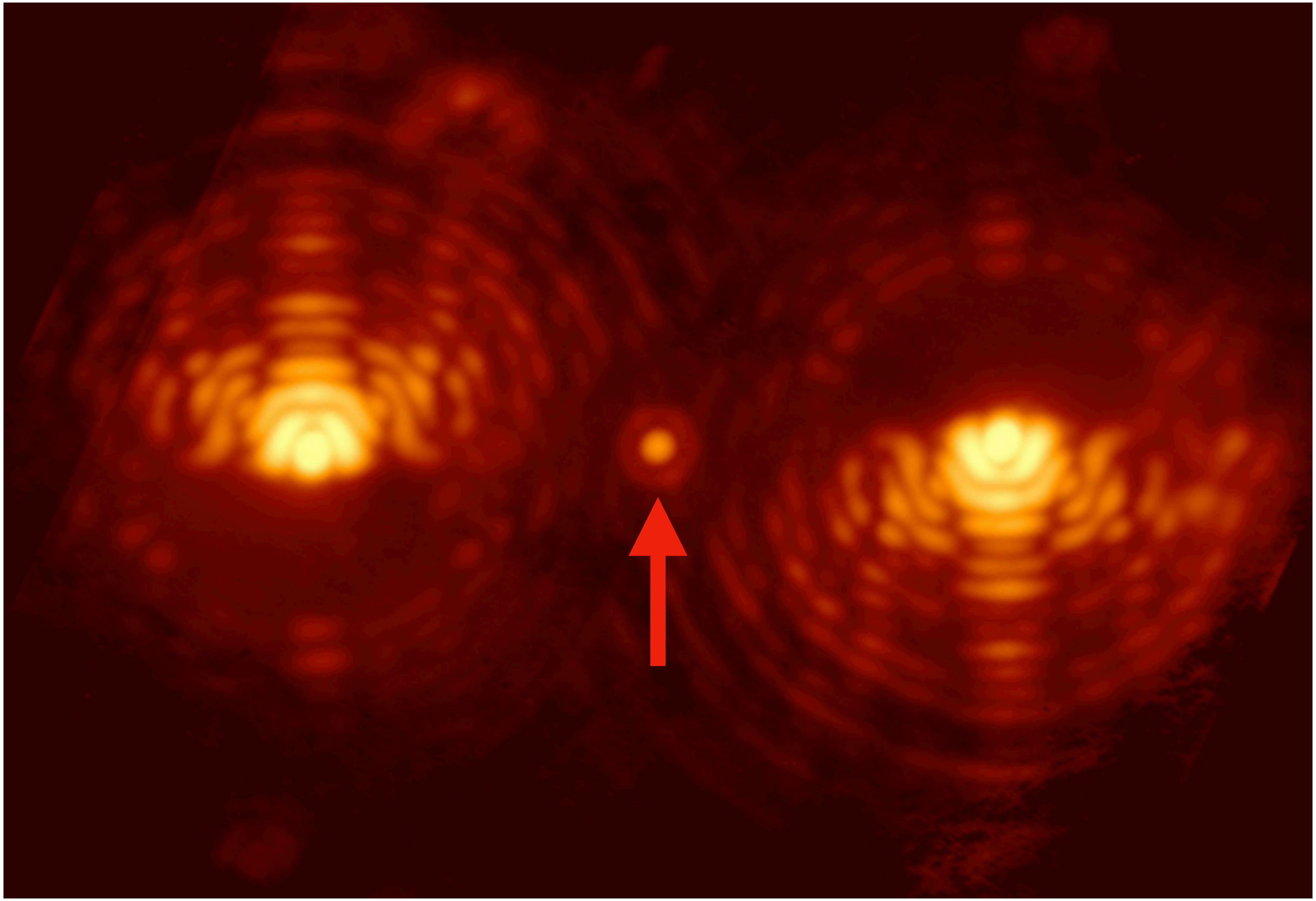


Sahoo et al. 2020, Jovanovic et al. 2021 for rigorous on-sky implementation



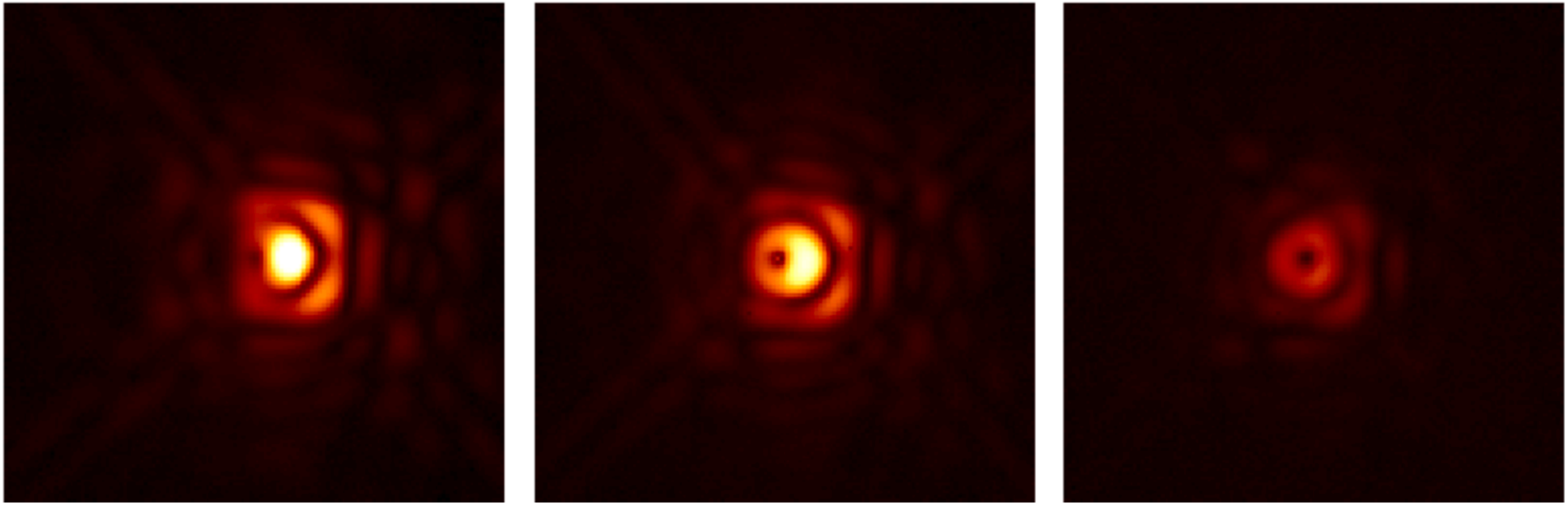
Other types of coronagraphs (I)

Pupil plane: Apodizing Phase Plate (Otten et al. 2014)

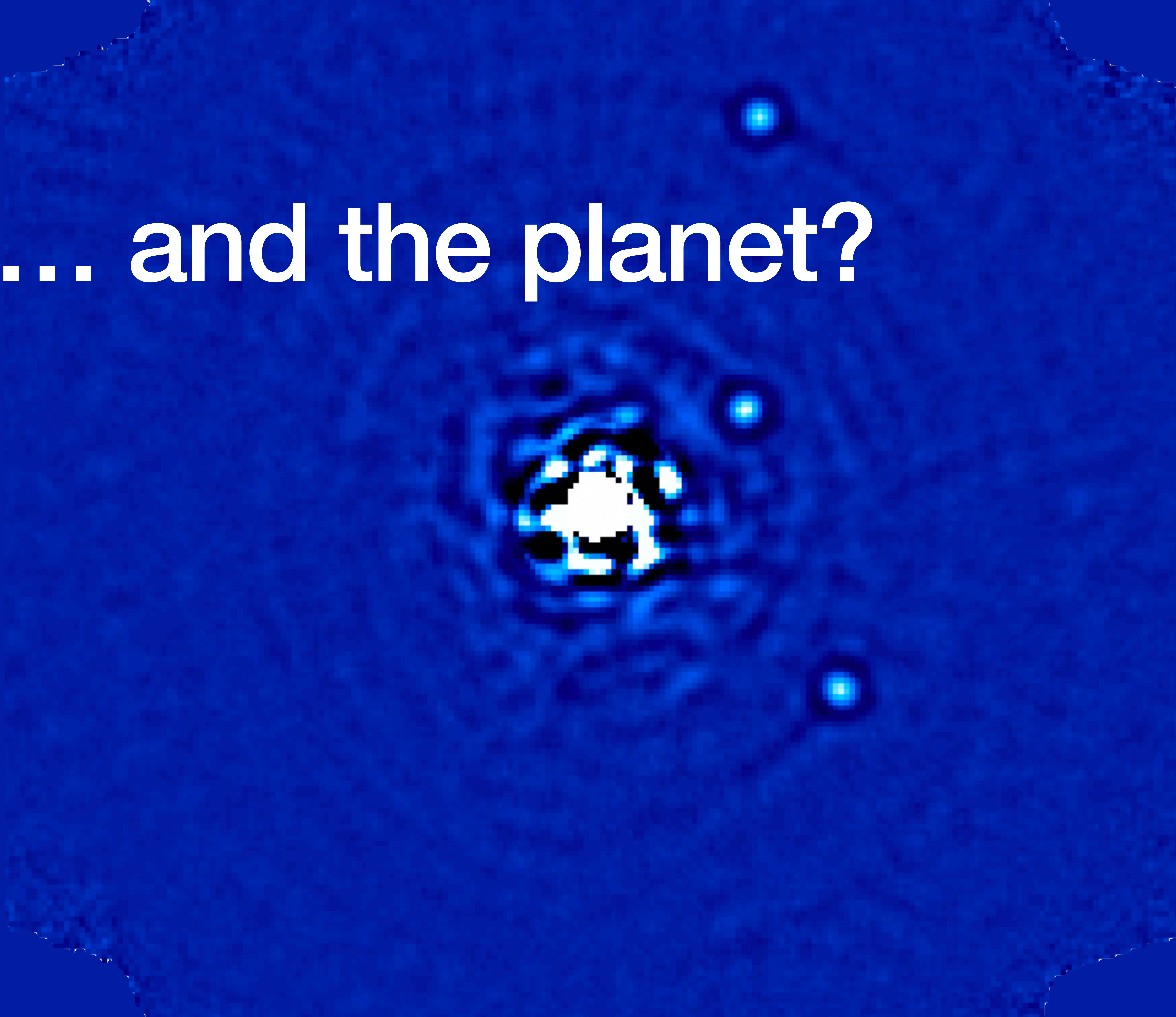


Other types of coronagraphs (II)

Focal plane: Annular Groove Phase Mask "Vortex" Coronagraph (Mawet et al. 2005)

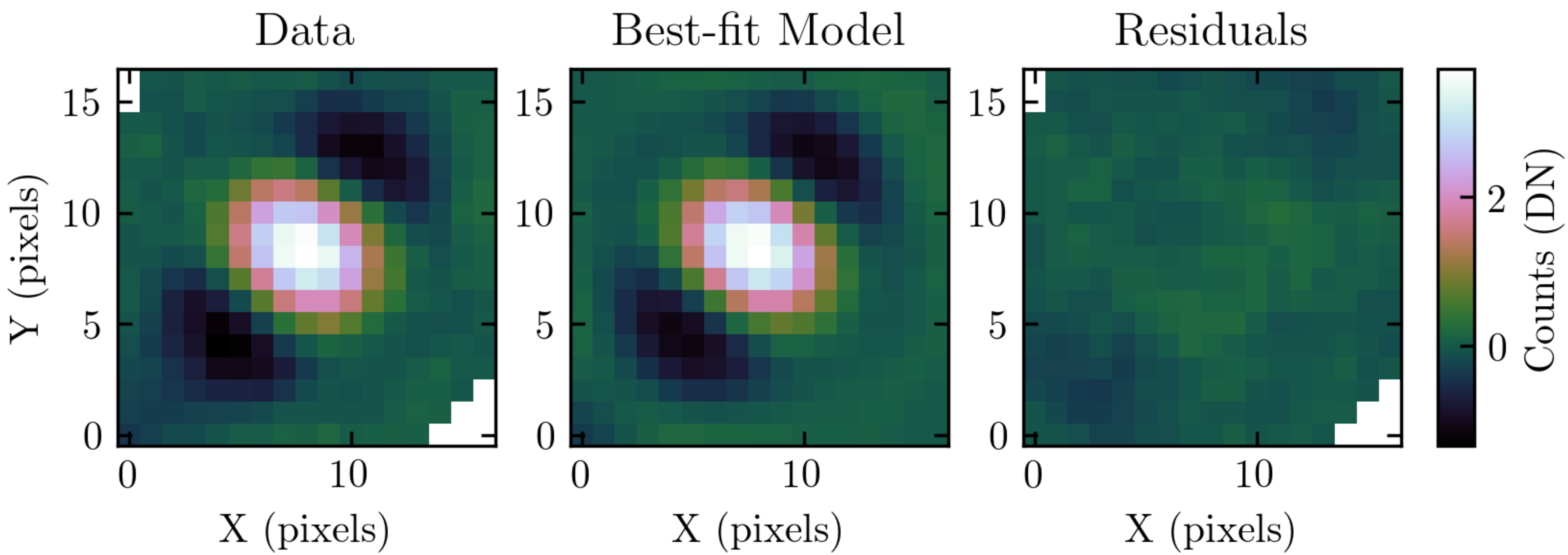


Misaligned → Aligned


… and the planet?

Planet astrometry

- Typically done using **forward modeling** or **negative planet injection** techniques.



Relative astrometry

Detector plate scale

$$\begin{bmatrix} \Delta \mathrm{R.A} \\ \Delta \mathrm{Dec.} \end{bmatrix} = \begin{bmatrix} -\cos\theta & \sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} \left(x_{\mathrm{pl}} - x_{\mathrm{star}}\right) p_x \\ \left(y_{\mathrm{pl}} - y_{\mathrm{star}}\right) p_y \end{bmatrix}$$

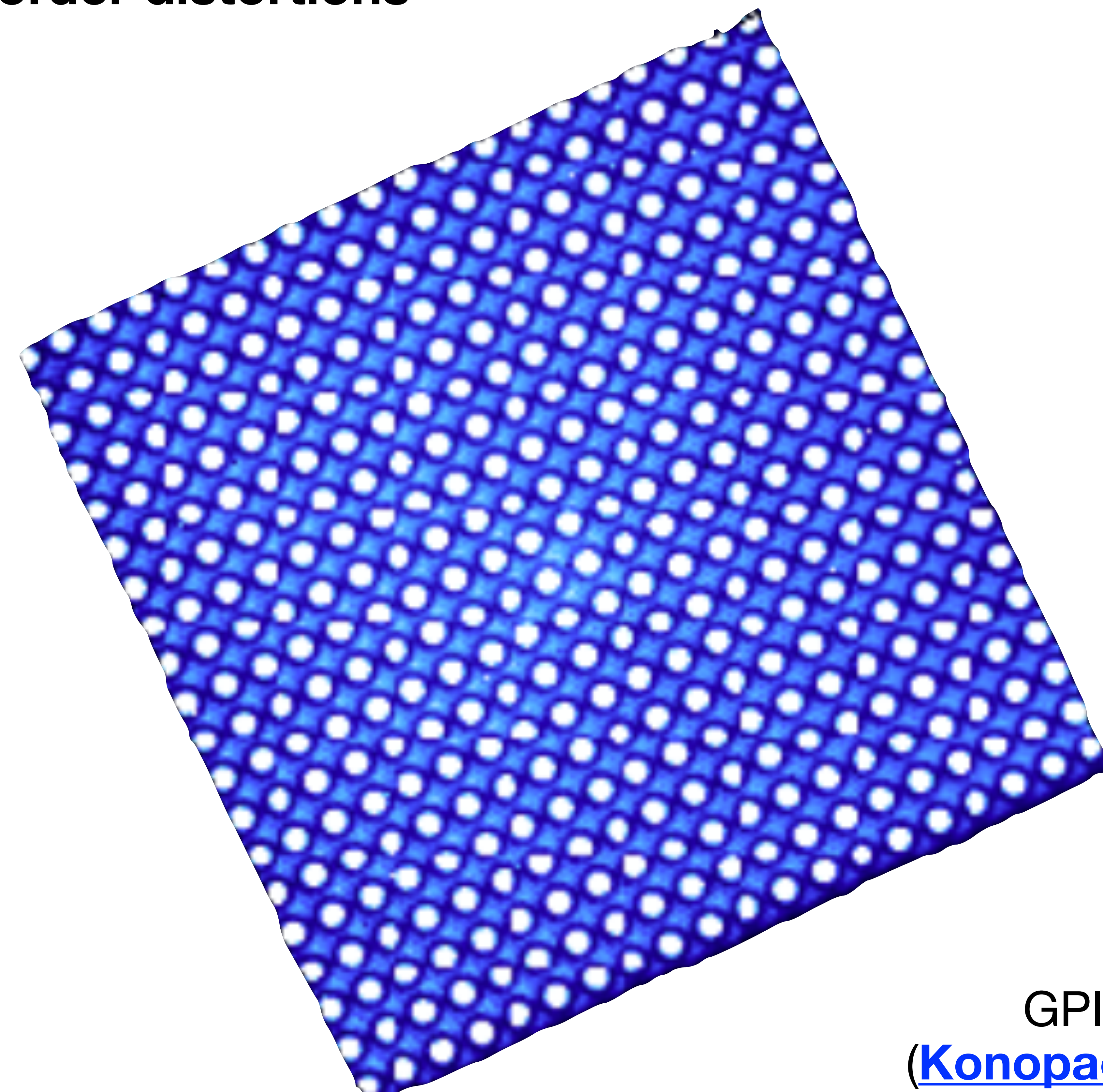
On-sky angular separation

Rotation matrix to align with celestial North

*Assumes higher-order optical distortion removed

Astrometric calibration

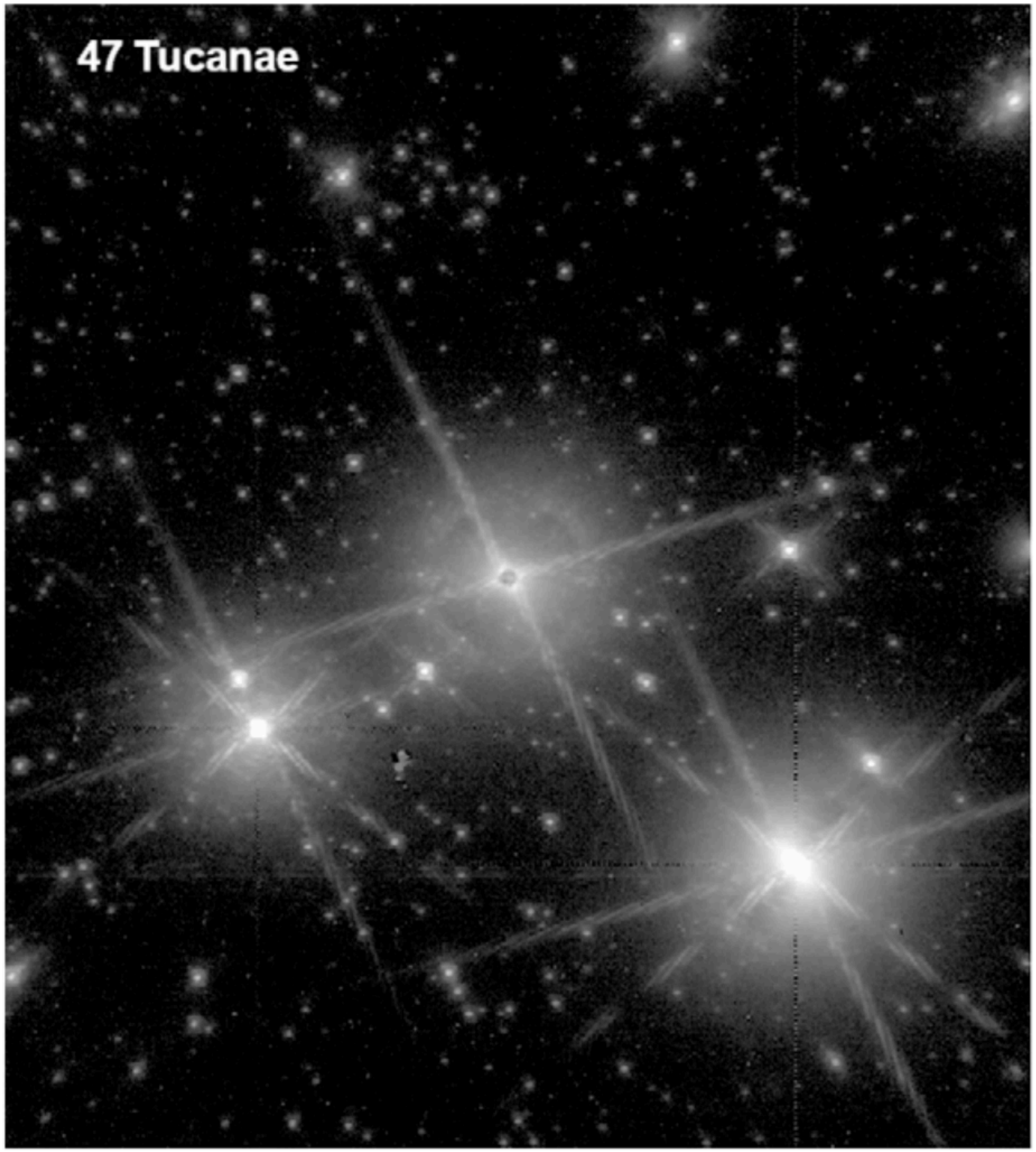
Higher-order distortions



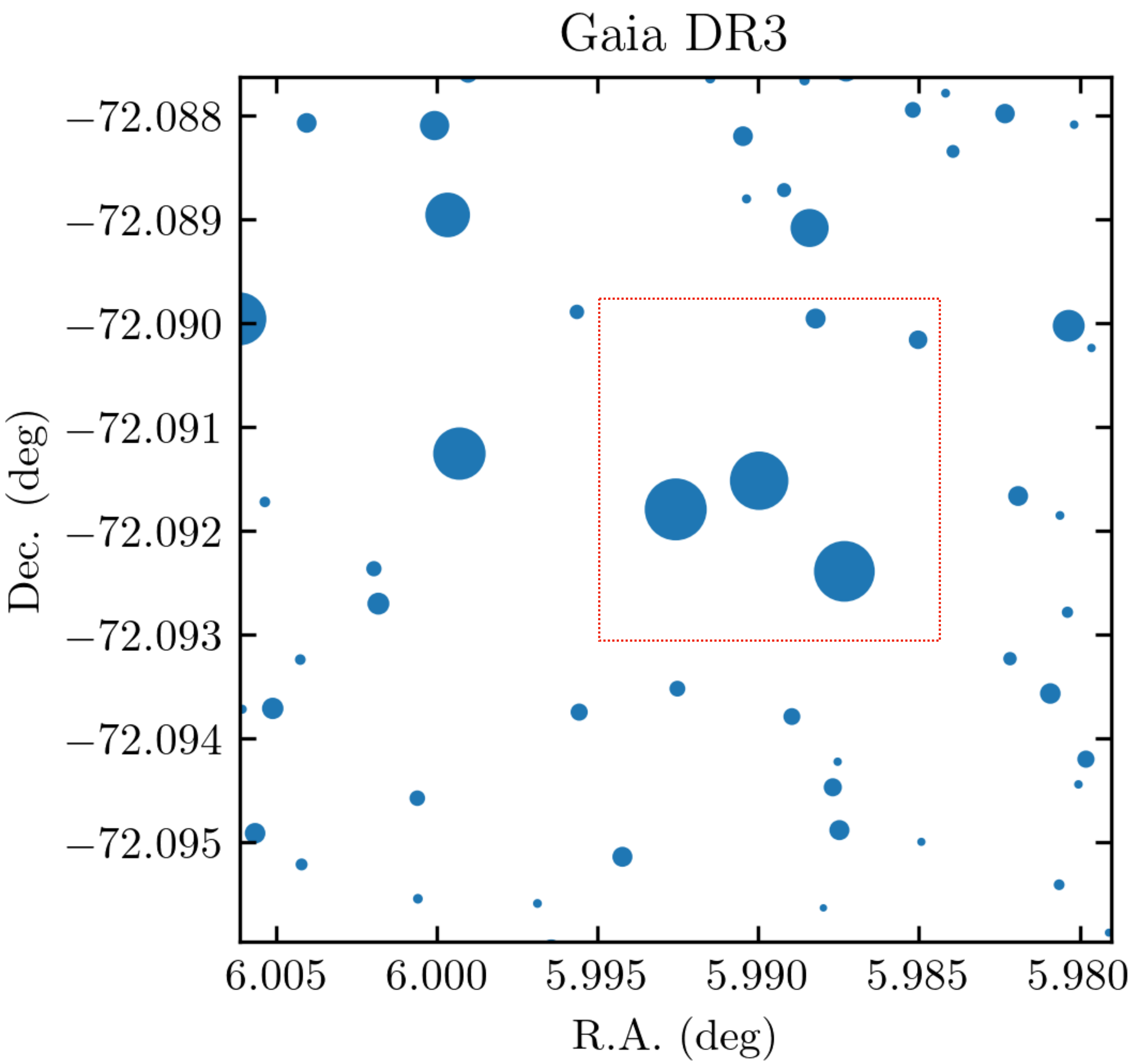
GPI's pinhole mask
(Konopacky et al. 2014)

Astrometric calibration

Absolute calibration



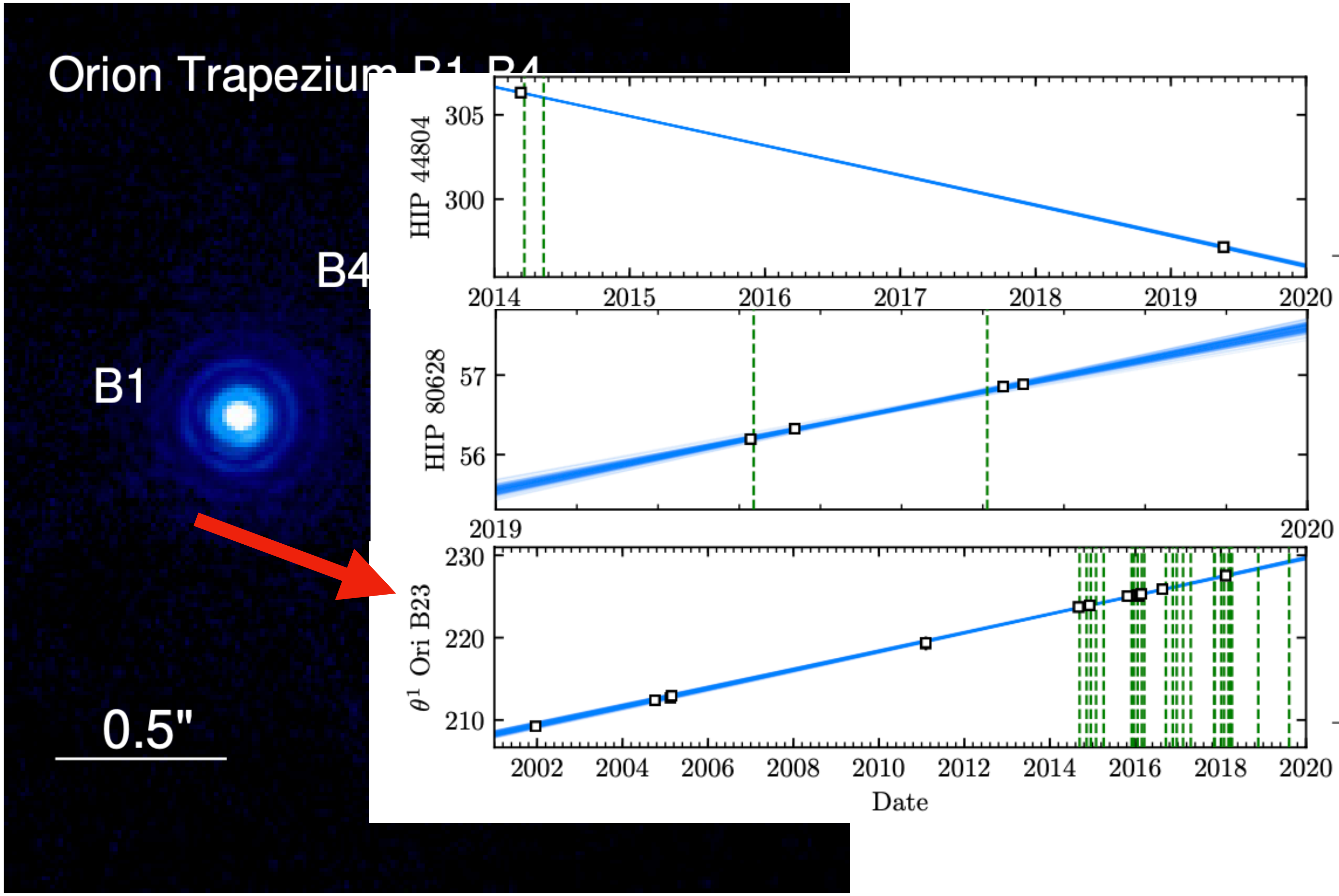
SPHERE/IRDIS
(Maire et al. 2021)



… and also *HST*

Astrometric calibration

Absolute calibration



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On-sky angular separation

Rotation matrix to align with celestial North

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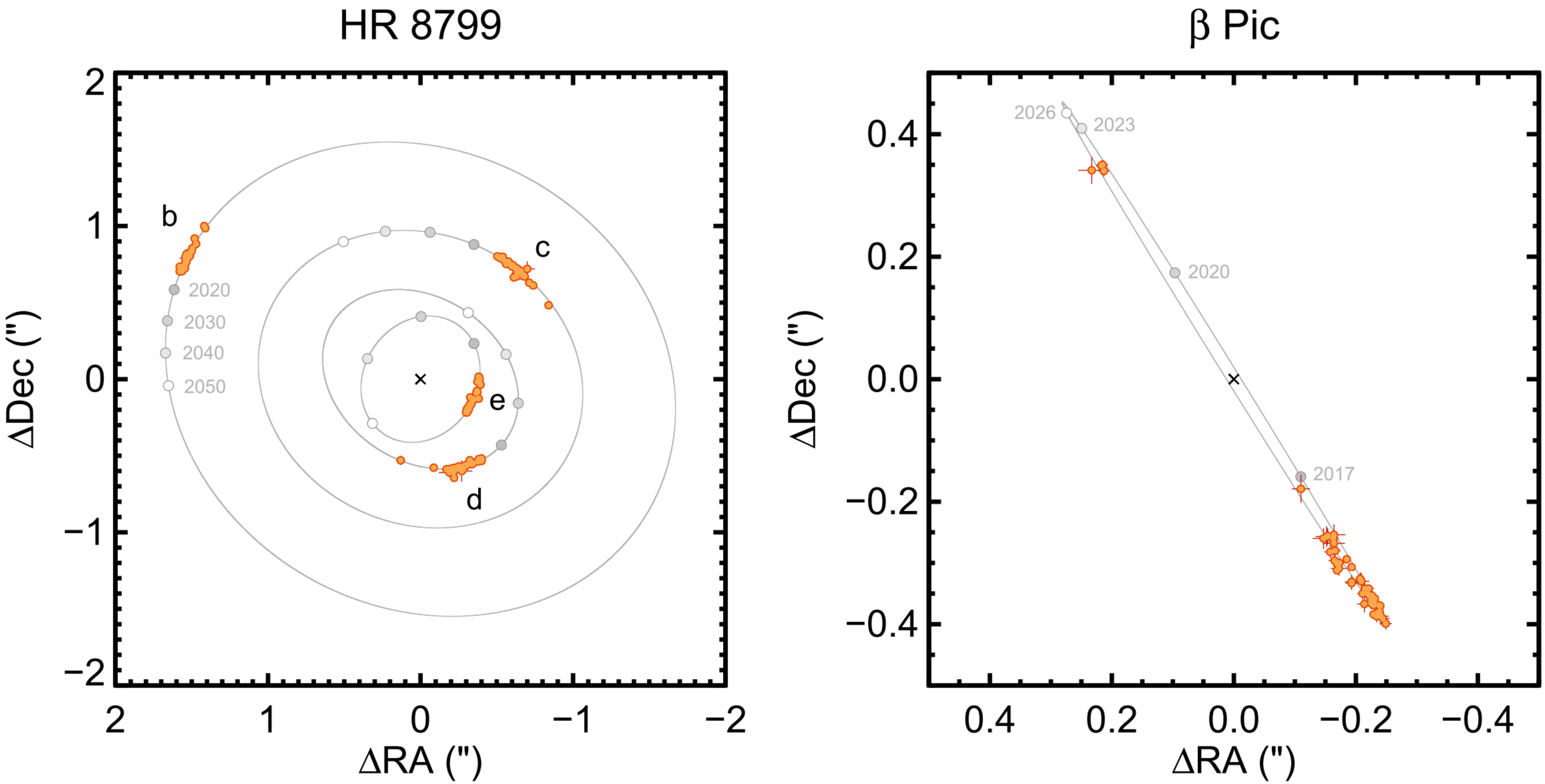
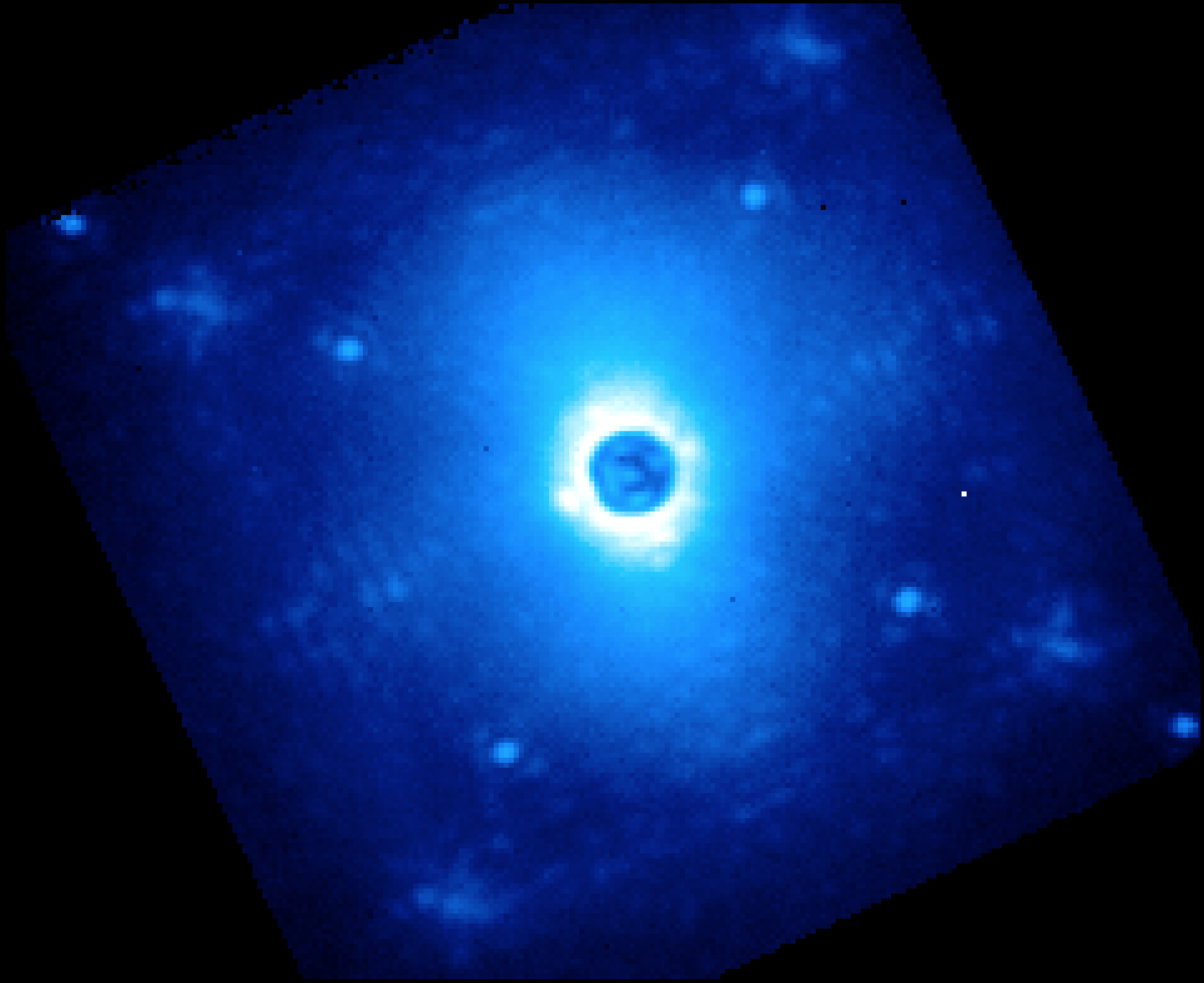
Relative astrometry

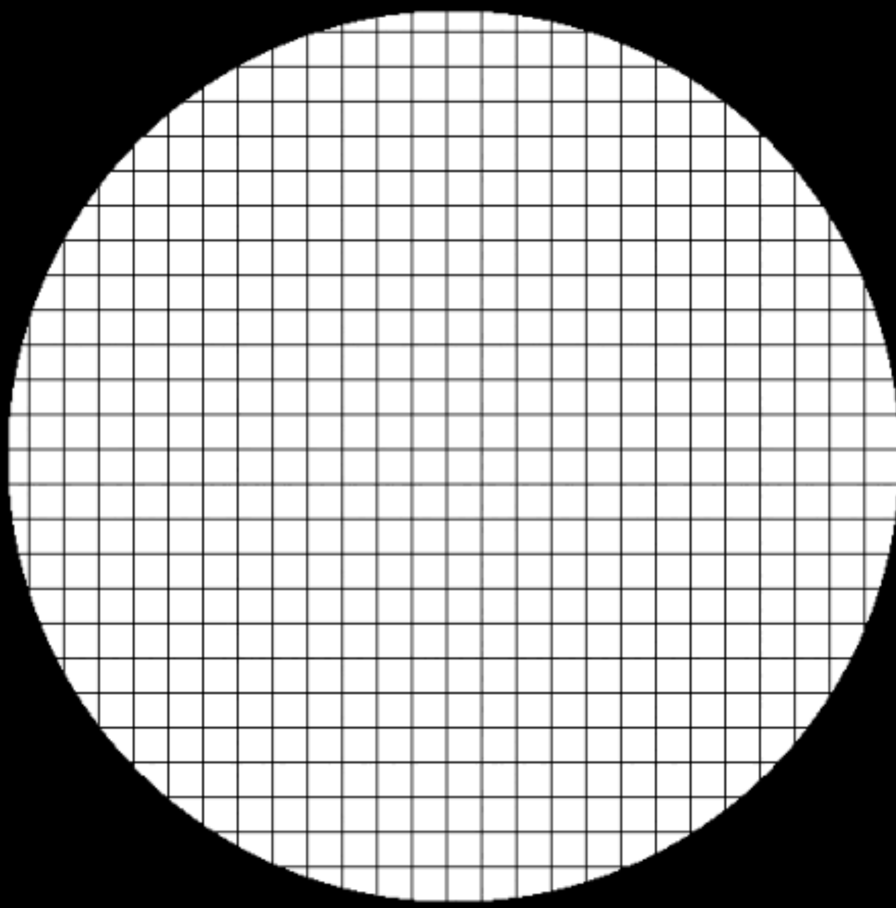


(Bowler et al. 2015)

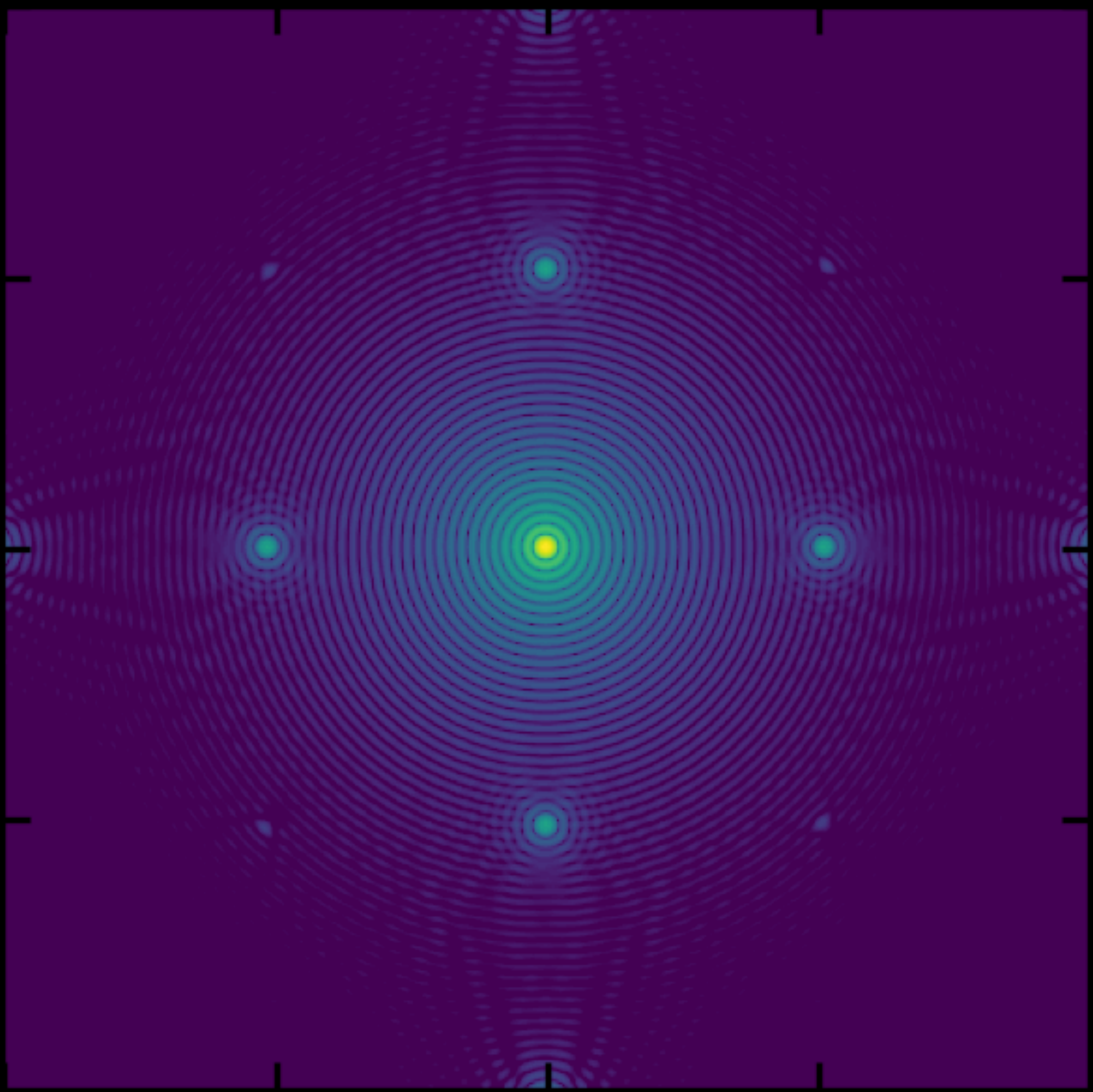

How bright is the star?



Varying thickness



Pupil plane



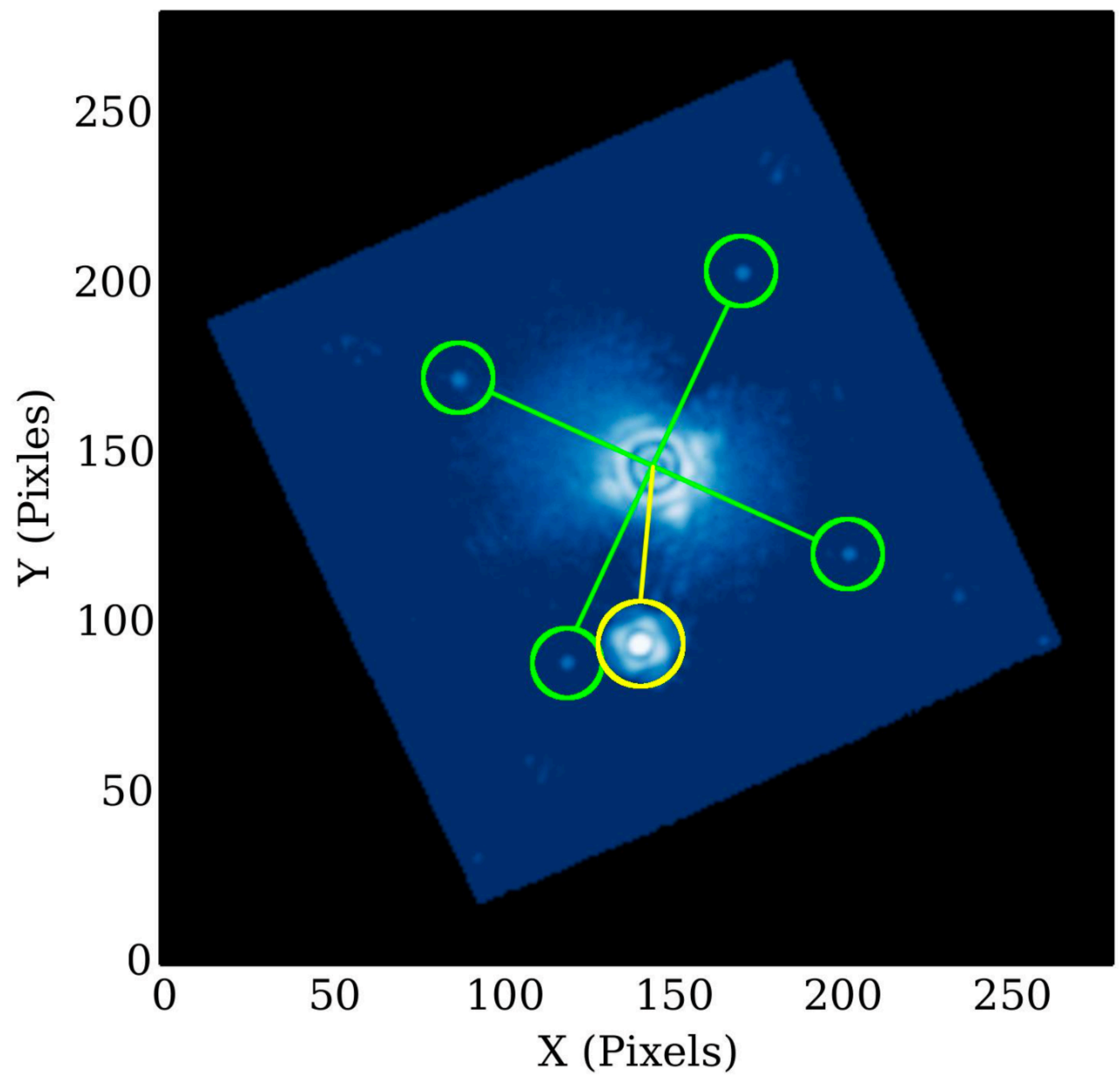
Focal plane

*Monochromatic simulation

Calibrating the calibration spots

Satellite spots are typically 10^3-10^4 fainter than the star and can be difficult to calibrate

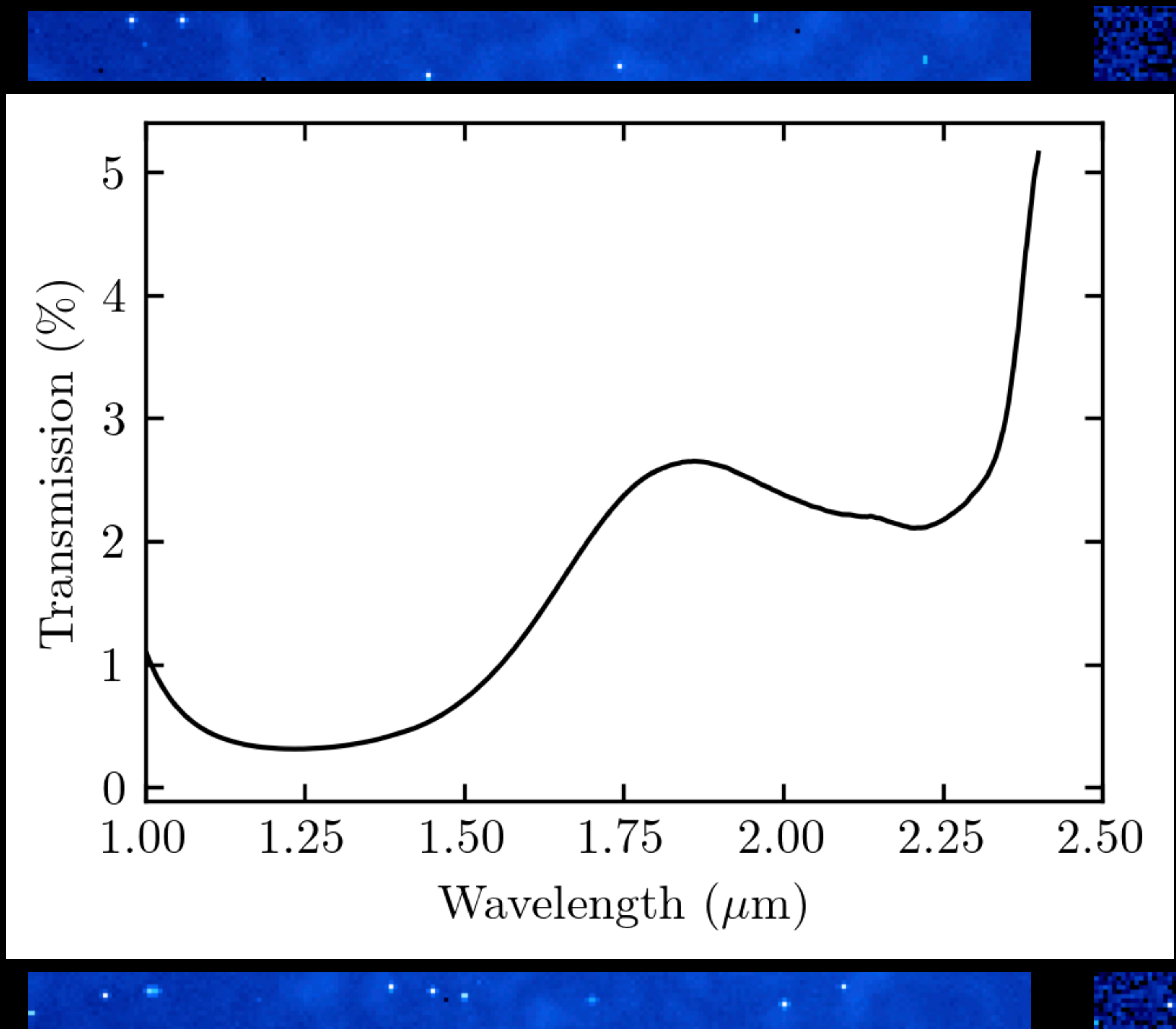
- Internal calibration source using different exposure times.
- High flux ratio companions with well-measured fluxes



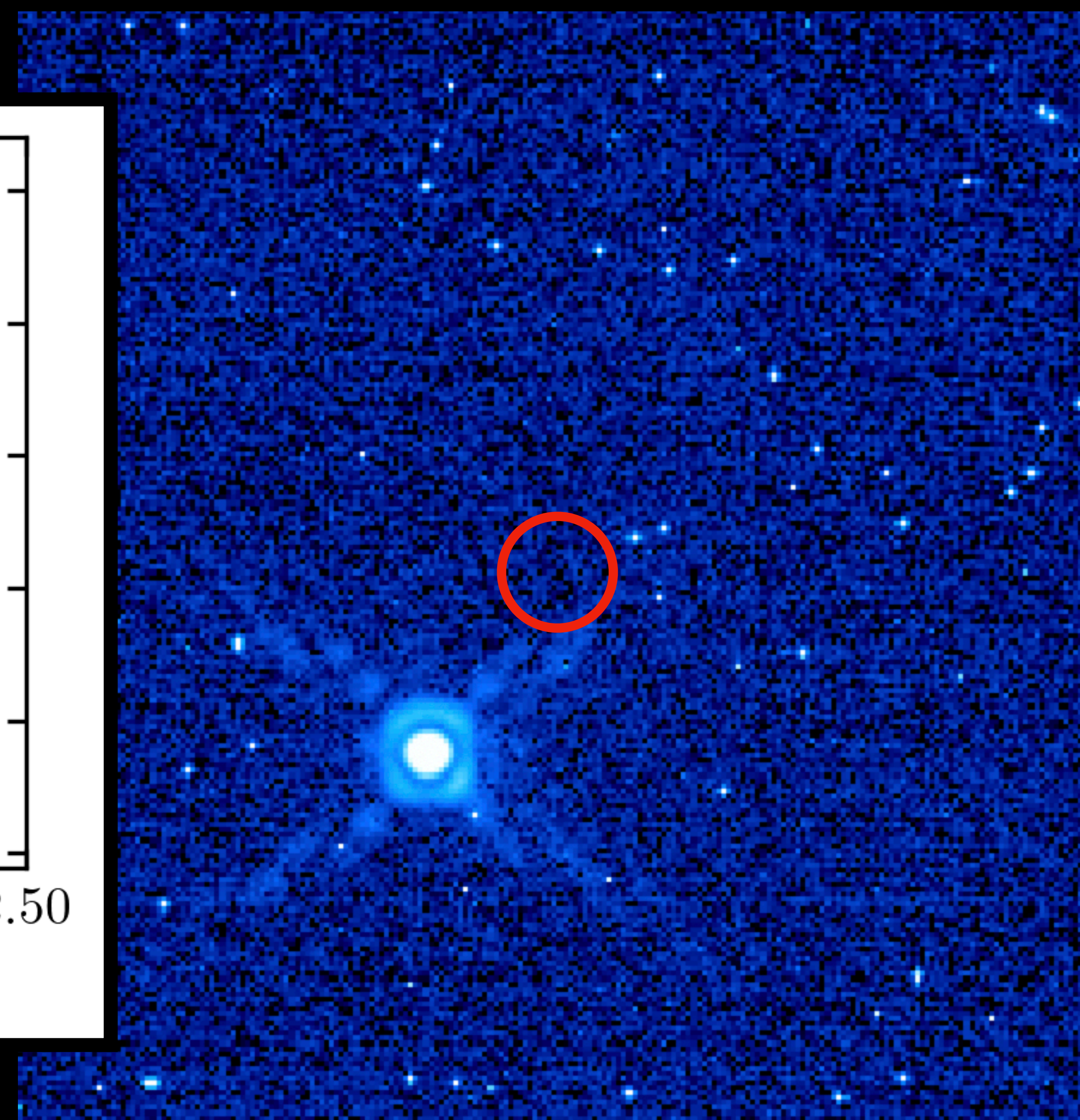
(Wang et al. 2014)

Off-axis PSF measurement

Star occulted (16s)



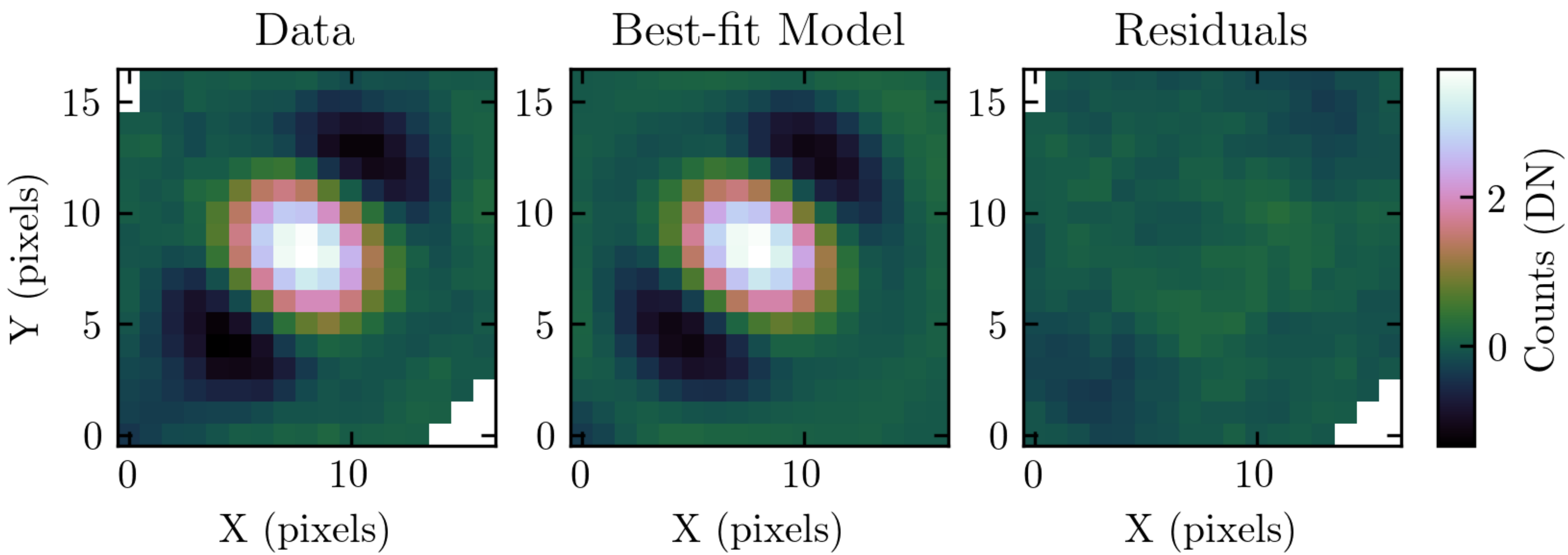
Neutral density filter (0.8s)



… and the planet?

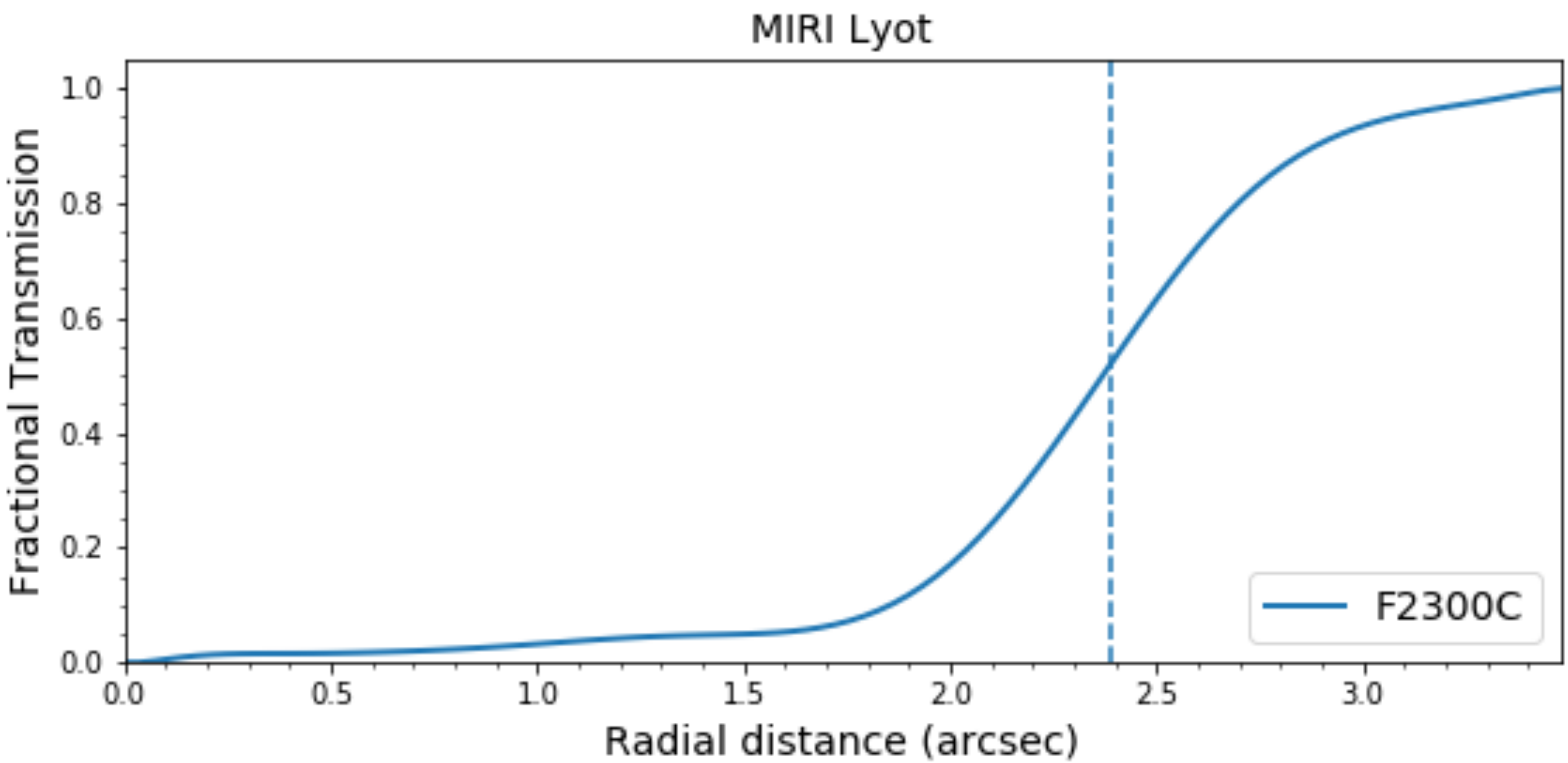
Planet photometry

- As with astrometry, typically done using **forward modeling** or **negative planet injection** techniques.



Throughput (I)

Coronagraphic throughput

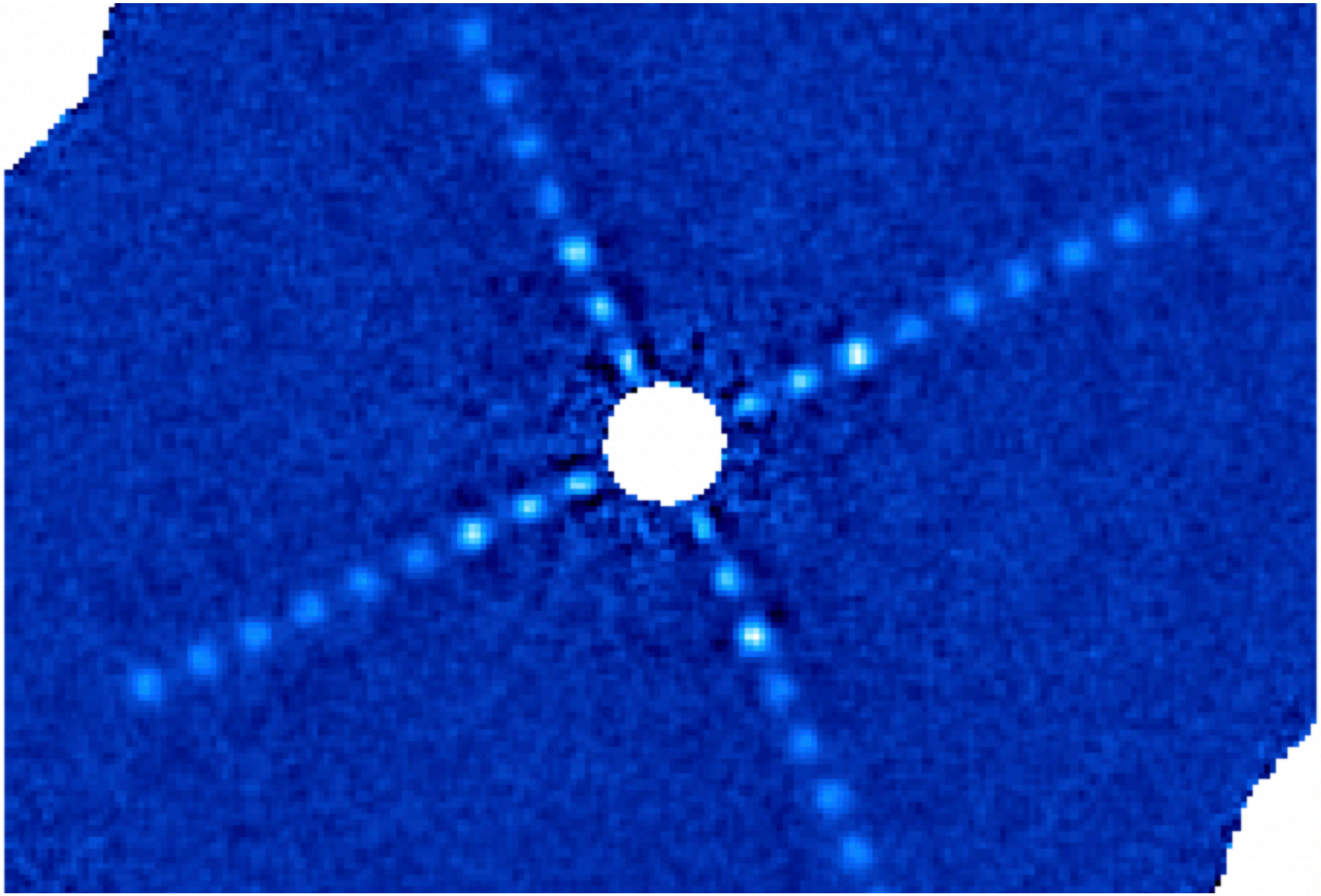


JWST/MIRI Documentation

Throughput (II)

Algorithmic throughput

- Flux losses due to over-subtraction during post-processing.



Flux ratio to absolute flux

Flux of the planet in image

$\div T_{\mathrm{algo.}} \div T_{\mathrm{coro.}}$

$$F_{\lambda,\mathrm{pl}}\left(\lambda\right) = \frac{f_{\mathrm{pl}}\left(\lambda\right)}{f_{\mathrm{star}}\left(\lambda\right)} F_{\lambda,\mathrm{star}}\left(\lambda\right)$$

Absolute flux of the planet

Flux of the star in the same image

Absolute flux of the star

Stellar flux

Basic data :

HD 218396 -- Ellipsoidal Variable

Other object types:	* (HD,AG,...), **MIR** (AKARI,WISEA,...), ** (**,WDS), **El*** (2009yCat), **V*** (V*), **X** (1RXS), **UV** (TD1), **NIR** (2MASS), **IR** (IRAS)
ICRS coord. *(ep=J2000) :*	**23 07 28.7157209544 +21 08 03.310767492 (Optical) [0.0370 0.0396 90] A 2020yCat.1350....0G**
FK4 coord. *(ep=B1950 eq=1950) :*	23 05 00.5212007858 +20 51 51.095996325 [0.0370 0.0396 90]
Gal coord. *(ep=J2000) :*	092.7642280719024 -35.5751122710814 [0.0370 0.0396 90]
Proper motions *mas/yr* :	**108.284 -50.040 [0.056 0.059 90] A 2020yCat.1350....0G**
Radial velocity / Redshift / cz :	**V(km/s) -10.41 [0.23]** / z(spectroscopic) -0.000035 [0.000001] / cz -10.41 [0.23] **(Opt) A 2022yCat.1355....0G**
Parallaxes *(mas)*:	24.4620 [0.0455] A 2020yCat.1350....0G
Spectral type:	**F0+VkA5mA5 C 2003AJ....126.2048G**
Fluxes (6) :	**B 6.21 [0.01] D 2000A&A...355L..27H**
	V 5.953 [0.010] D 2000A&A...355L..27H
	G 5.910741 [0.002960] C 2022yCat.1355....0G
	J 5.383 [0.027] C 2003yCat.2246....0C
	H 5.280 [0.018] C 2003yCat.2246....0C
	K 5.240 [0.018] C 2003yCat.2246....0C

$$M_K = m_K - 5\left(log_{10}\frac{1000}{\varpi} - 1\right)$$

$$f_1 = 10^{\frac{m_1 - m_0}{-2.5}} \times f_0$$

Stellar flux

2MASS flux calibration (Cohen et al. 2003)

TABLE 2
ZERO-MAGNITUDE ATTRIBUTES OF 2MASS BANDS

Filter	Bandwidth (μm)	In-Band (W cm^{-2})	$F_{\lambda(\mathrm{iso})}$ (W cm^{-2} μm^{-1})	λ(iso) (μm)	Bandwidth (Hz)	$F_{\nu(\mathrm{iso})}$ (Jy)	ν(iso) (Hz)
J	0.162	5.082E−14	3.129E−13	1.235	3.189E+13	1594	2.428E+14
Uncert.	0.001	1.608%	5.464E−15	0.006	2.155E+11	27.80	2.746E+12
H	0.251	2.843E−14	1.133E−13	1.662	2.778E+13	1024	1.783E+14
Uncert.	0.002	1.721%	2.212E−15	0.009	2.540E+11	19.95	2.139E+12
K_s	0.262	1.122E−14	4.283E−14	2.159	1.682E+13	666.8	1.390E+14
Uncert.	0.002	1.685%	8.053E−16	0.011	1.409E+11	12.55	1.496E+12

Only useful if you have broadband photometry in JHK…

Stellar flux in other bands

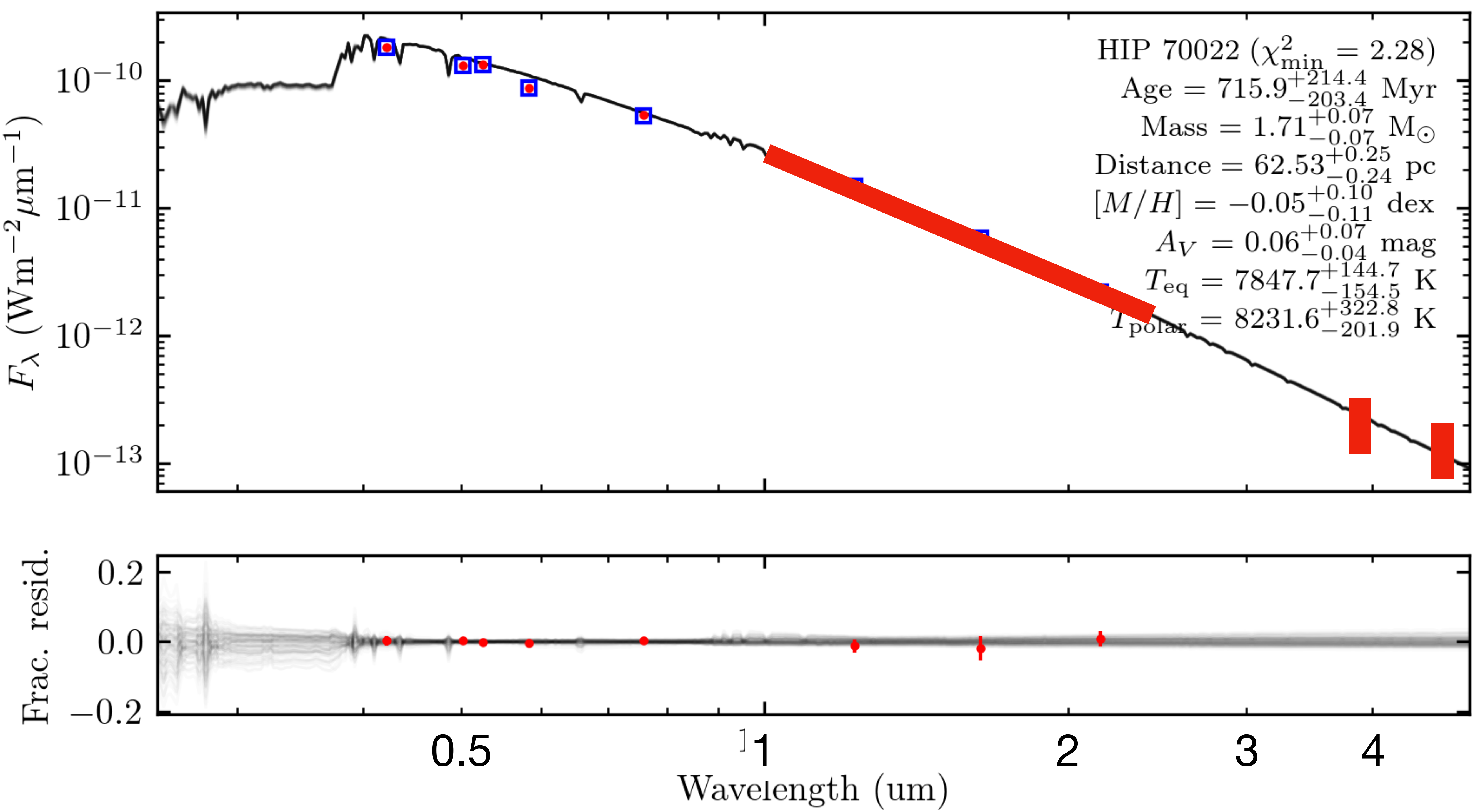
Photometry:

- Color transformations — relies on assumptions

Spectroscopy:

- Blackbody? OK for hot stars in the IR, but not for M-dwarfs
- Stellar models — atmospheric (and evolutionary)
  - e.g. **http://svo2.cab.inta-csic.es/theory/newov2/**

Stellar flux in other bands



Flux ratio to absolute flux

Flux of star from calibration spots/ off-axis image

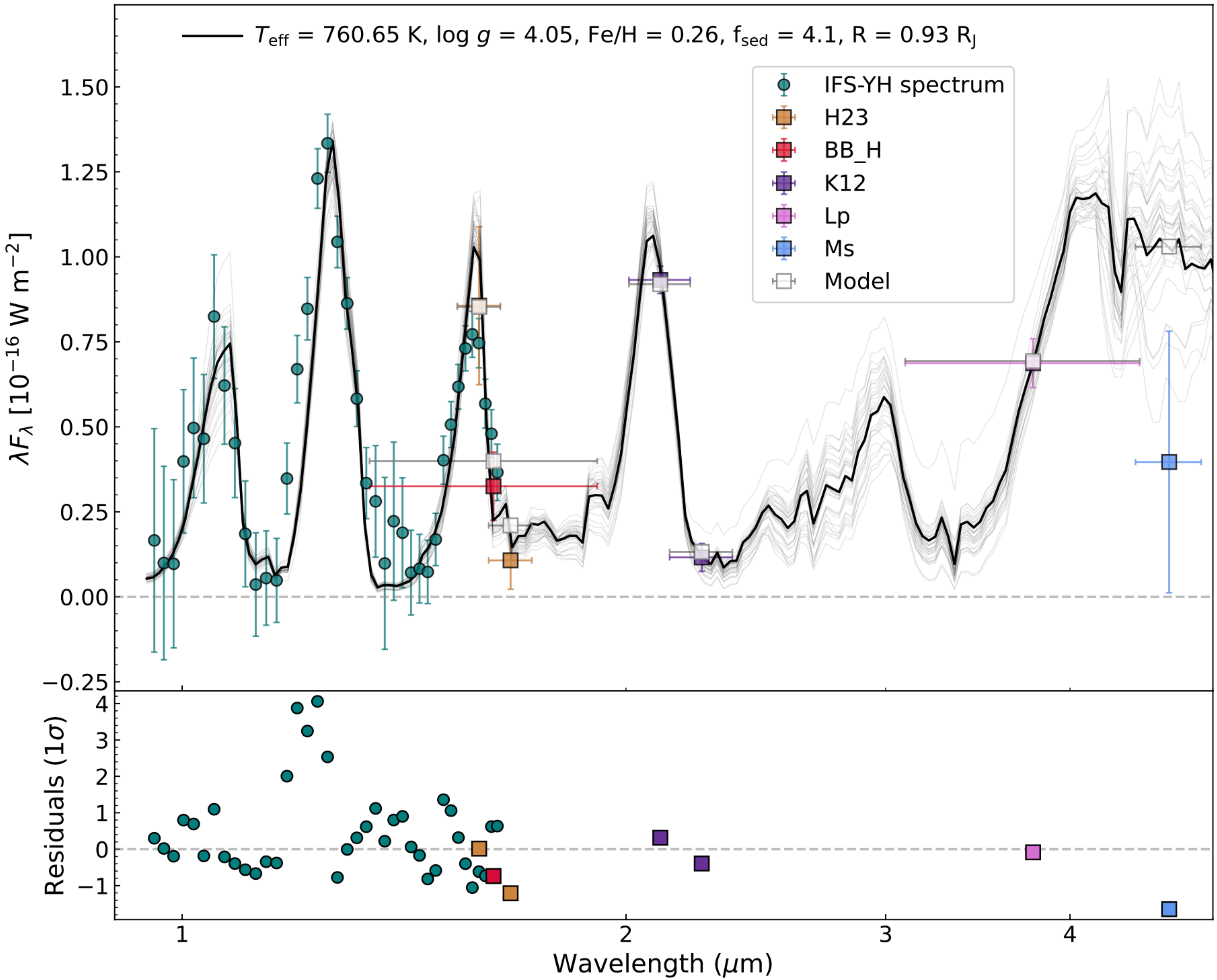
Estimated absolute flux of the star

$$F_{\lambda,\mathrm{pl}}(\lambda) = \frac{f_{\mathrm{pl}}(\lambda)}{T_{\mathrm{algo.}}.T_{\mathrm{coro.}}} \times \frac{1}{f_{\mathrm{spots}}(\lambda)\, X} \times F_{\lambda,\mathrm{star}}(\lambda)$$

Absolute flux of the planet

Throughput-corrected flux of planet

Scaling factor (grid ratio, ND transmission…)



(SED of 51 Eri b; Brown-Sevilla et a. 2022)

In conclusion…

Calibrations are important:

- Observables are meaningless without them (e.g., planet pixel position, count rate in DNs, …)
- Careful calibration needed to compare results between instruments (especially astrometry!).
- Error propagation from start to finish so your published uncertainties are as realistic as possible.

Some topics I missed:

- Polarimetry and interferometry
- Reference star differential imaging - more of a technique than a calibration.

Thanks for your attention!