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Direct Imaging below the diffraction limit with JWST via Kernel Phase Interferometry

Thomas Vandal – Journées SF2A – 2023/06/21

In collaboration with L. Albert, F. Martinache, D. Mary, R. Doyon, P. Calissendorff, M. De Furio, M. Meyer

Imaging Exoplanets with JWST

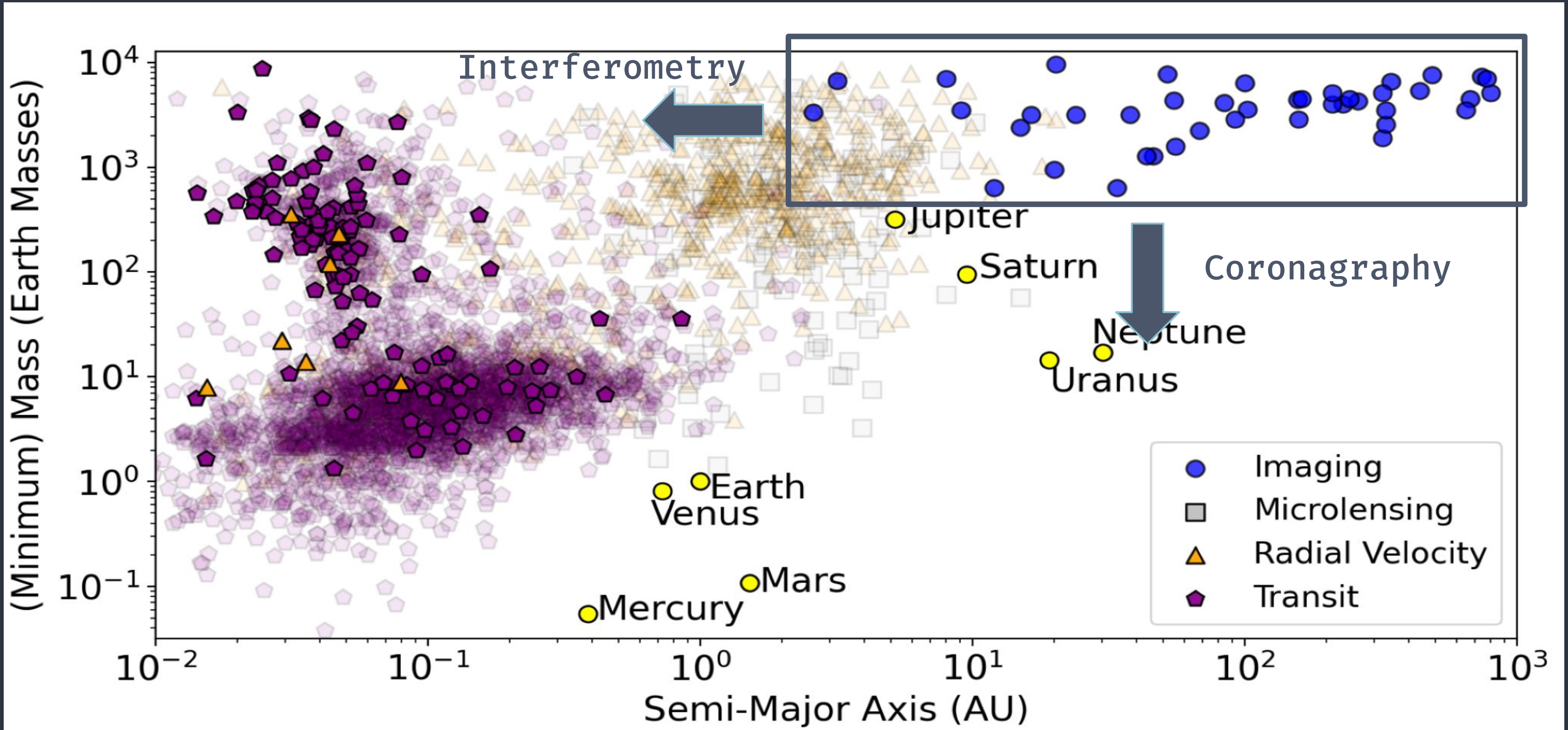


Figure: Currie+ 2022

JWST/NIRISS Aperture Masking Interferometry (AMI)

- 🙂 High contrast ~ 10^4
- 🙂 Short separations < 100 mas

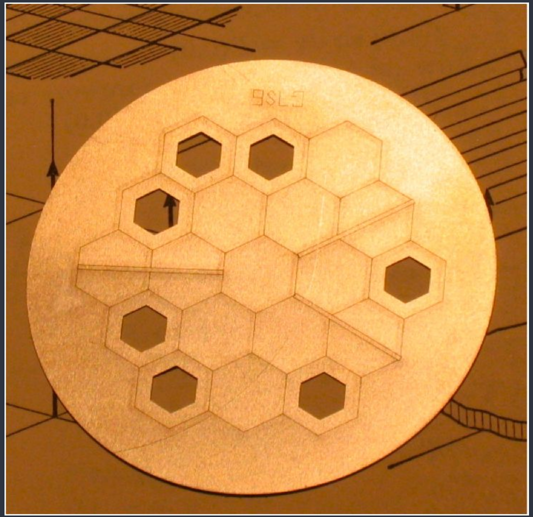


Figure: A. Sivaramakrishnan

JWST/NIRISS Aperture Masking Interferometry (AMI)

- 🙂 High contrast ~ 10^4
- 🙂 Short separations 100 mas
- 🙁 15 % Throughput

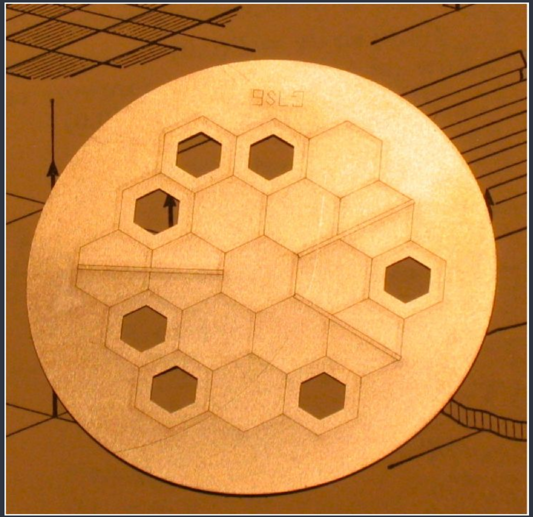


Figure: A. Sivaramakrishnan

Can we do this without the mask?

- 🙂 High contrast
- 🙂 Short separations
- 🙂 CLEAR Pupil

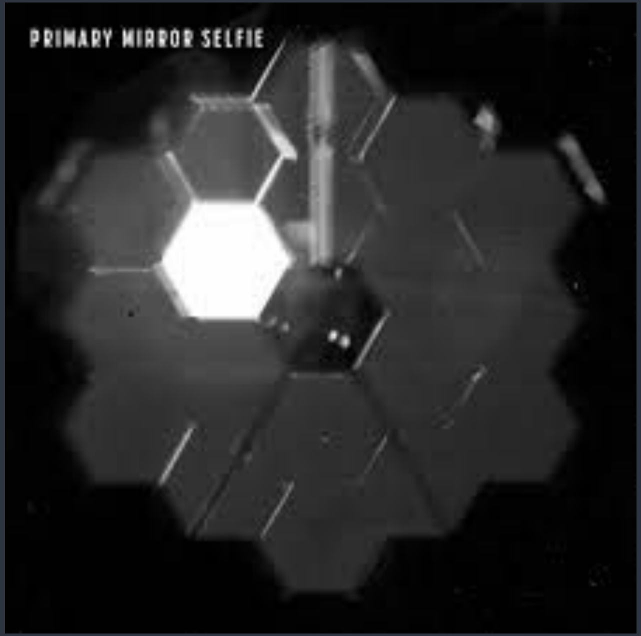
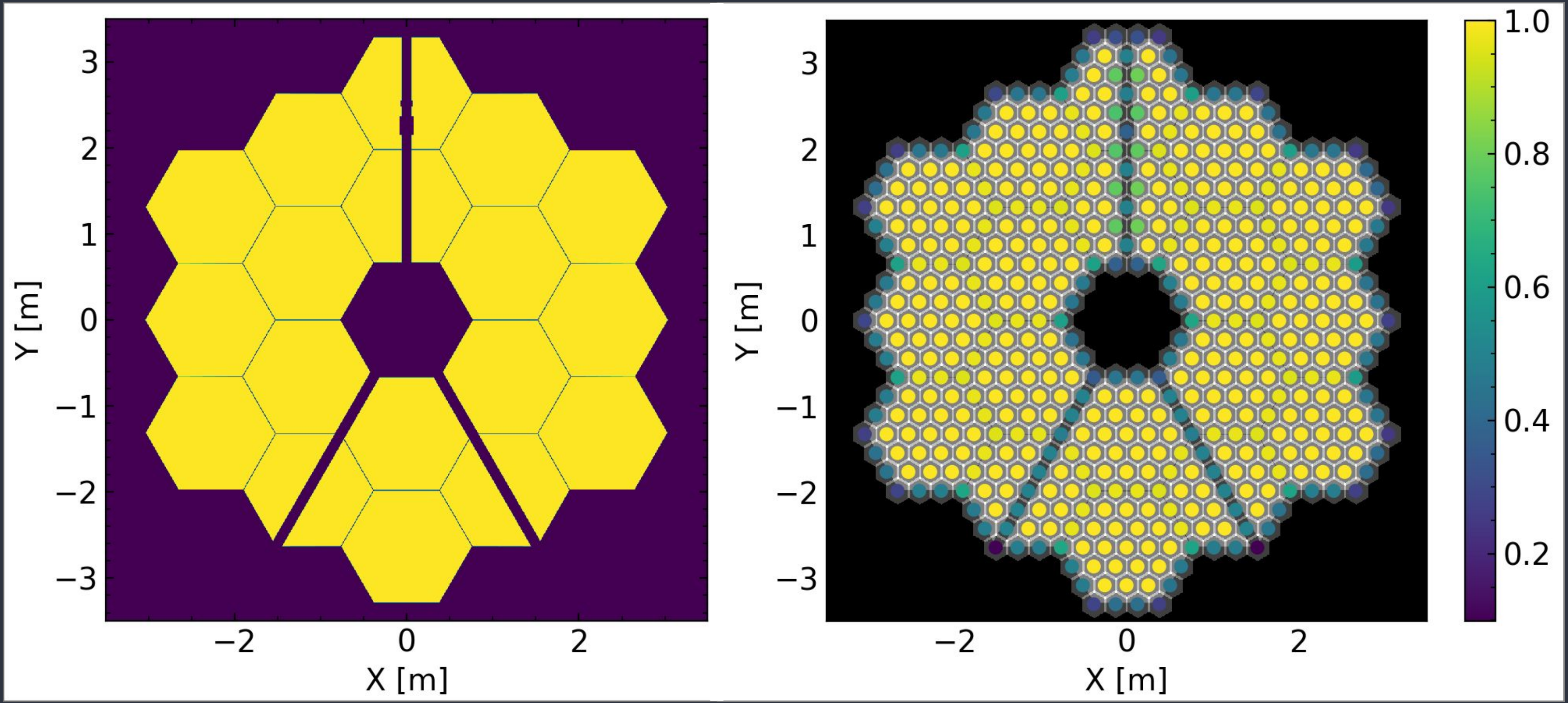
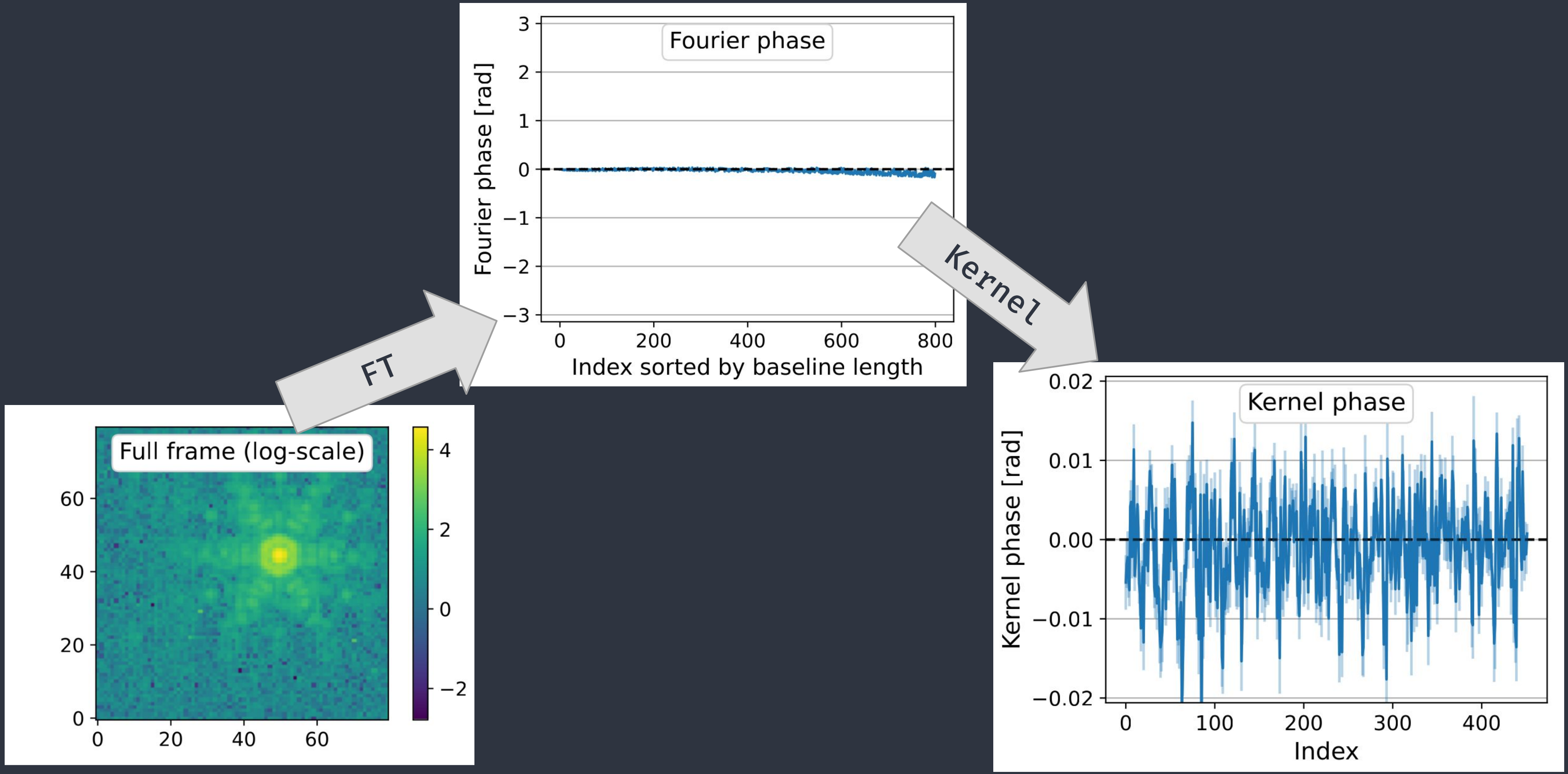


Figure: NASA

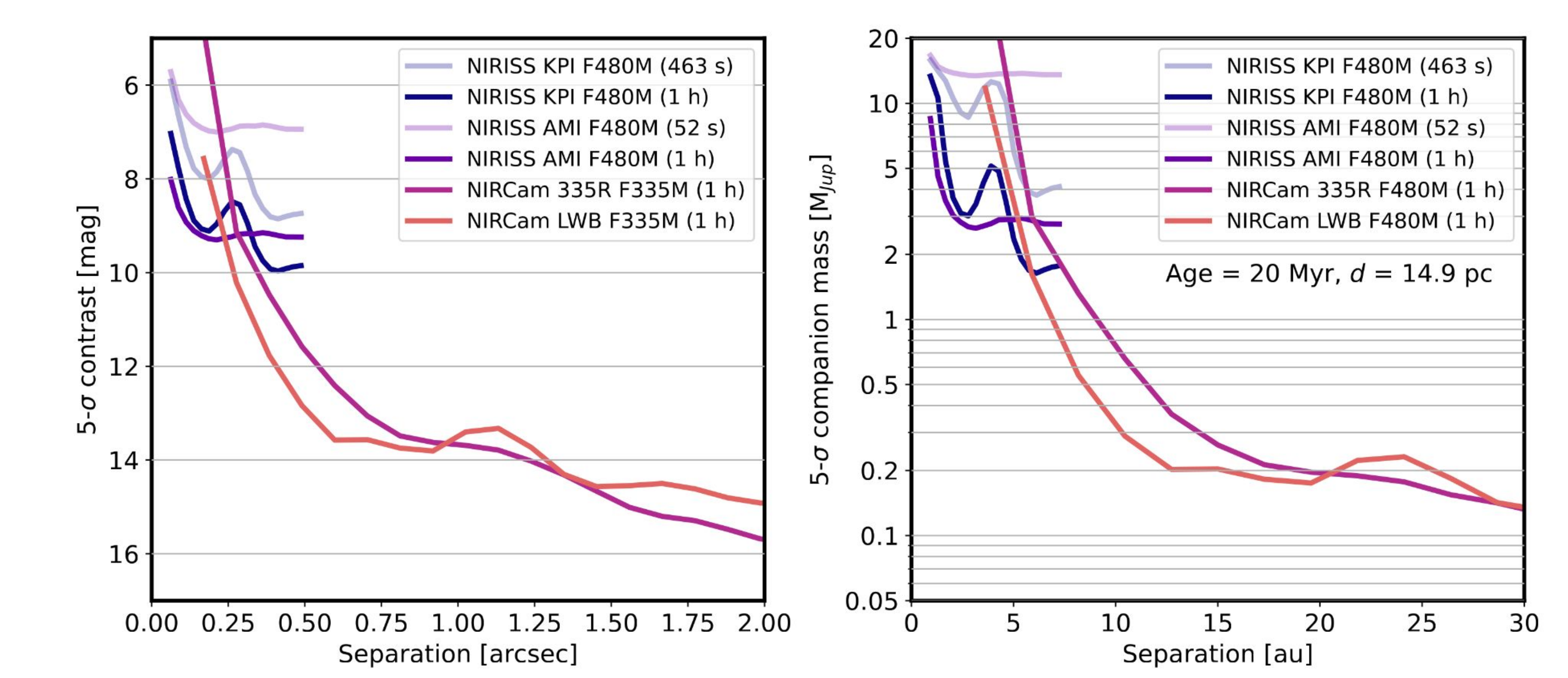
KPI: Modelling the Pupil as an "Interferometer"



JWST KPI Extraction in Practice

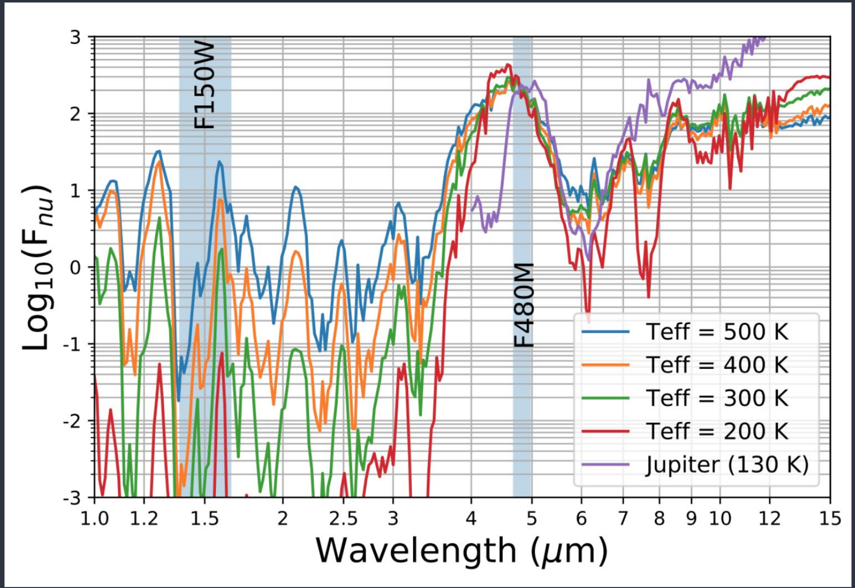


JWST Imaging Modes: Comparison from Commissioning



KPI with JWST: multiplicity survey of Y dwarfs

- 22 Y Dwarfs observed in total
- Probe short separations (< 100 mas)
- Search cold companions
- Compare KPI and ePSF on JWST
- Constrain multiplicity
- Expected yield: ~3 companions
- 16 targets observed so far



WISE-0336: The first Y+Y binary

Detected via ePSF modelling (Per Calissendorff et al., 2023)

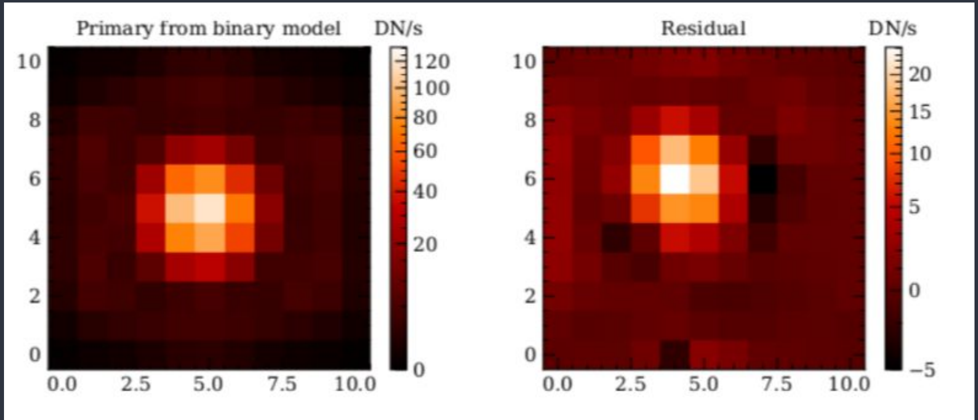
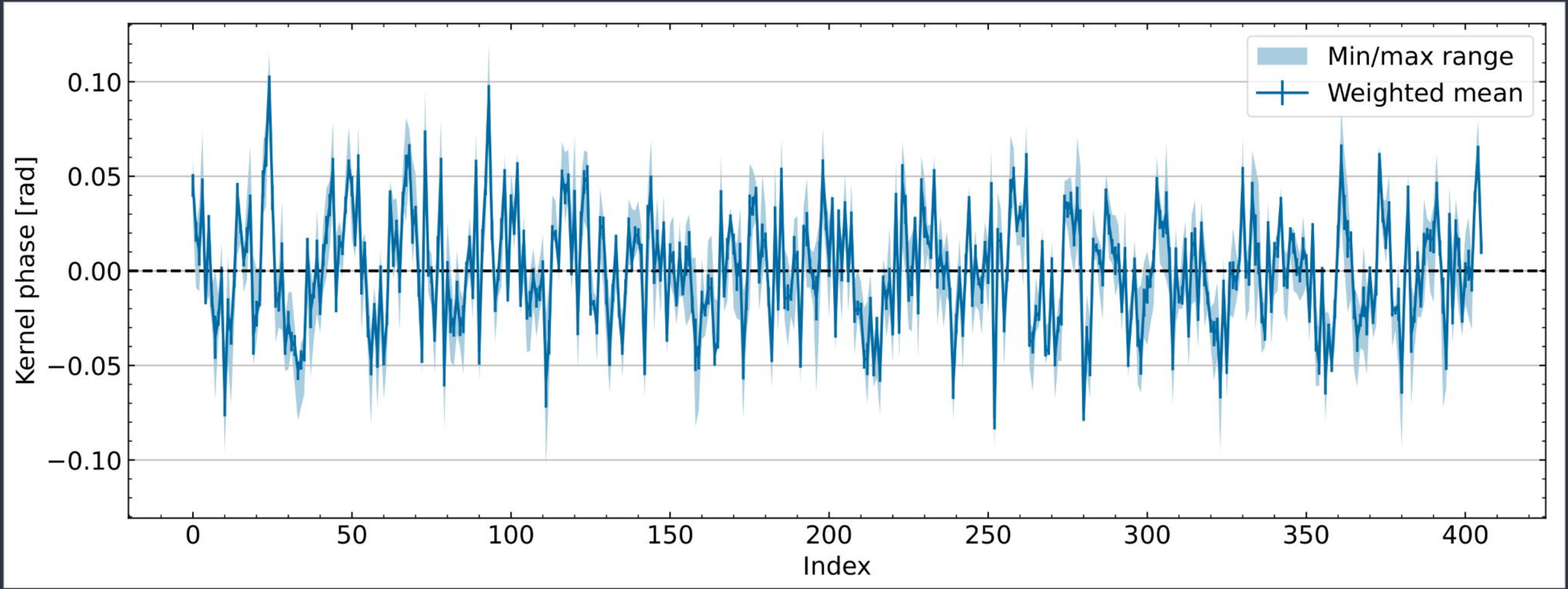


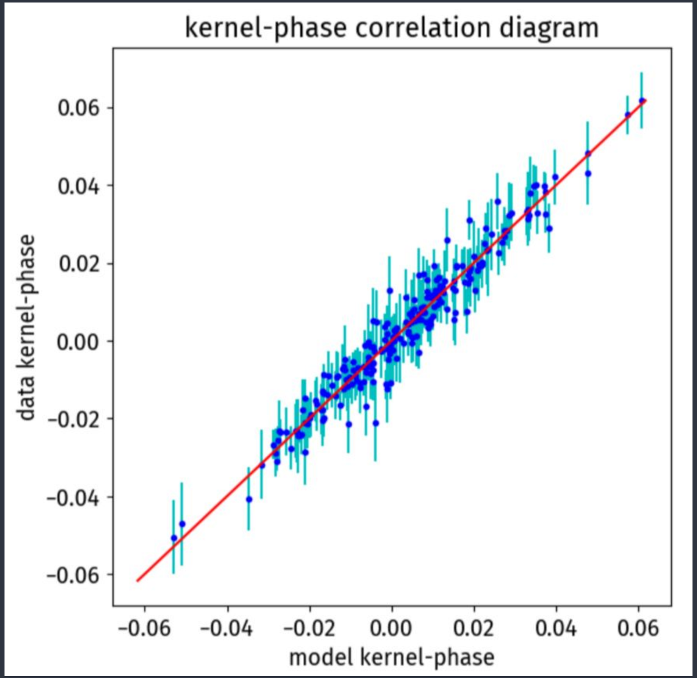
Table 1
Properties of the W0336 Binary System

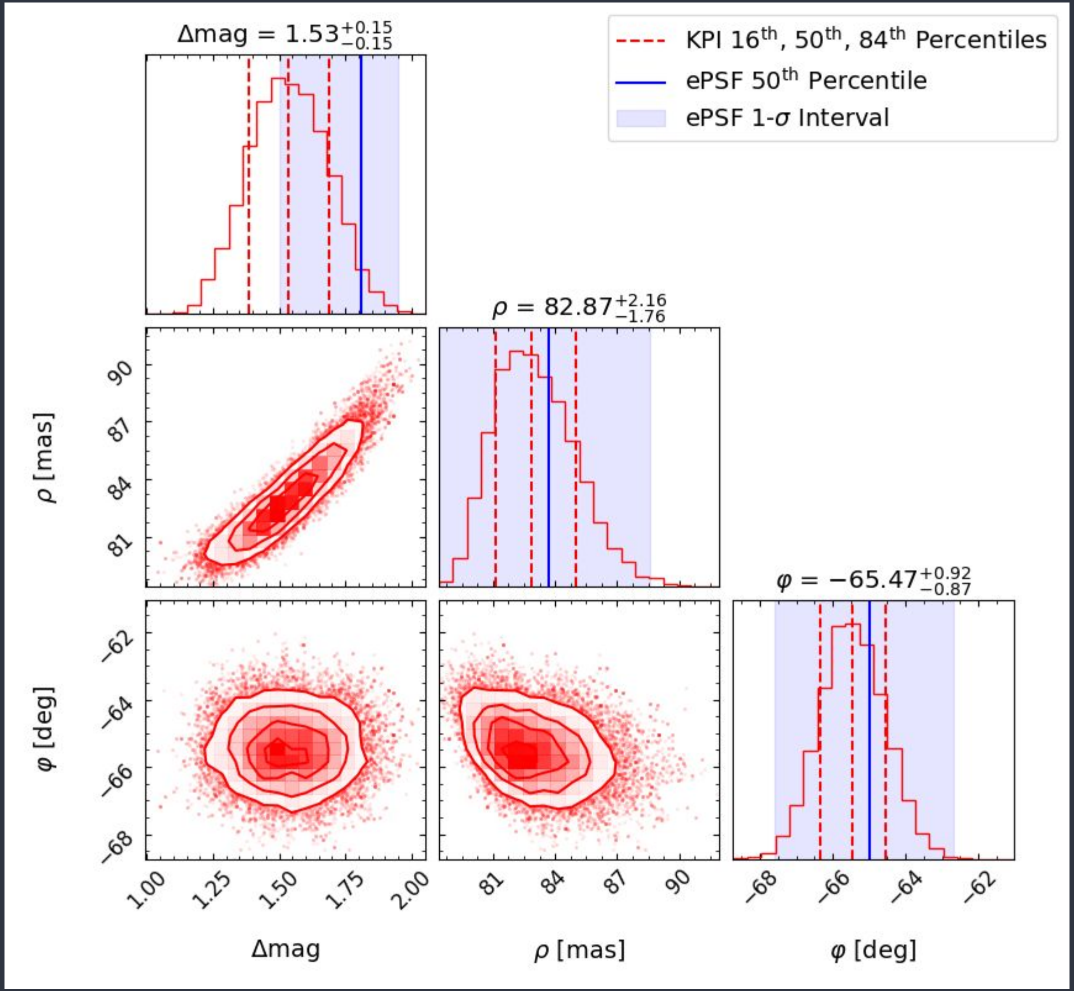
Band	F150W	F480M
Separation [mas]	$89.8^{+3.8}_{-4.1}$	$83.7^{+4.9}_{-8.2}$
Position angle [deg]	299.1 ± 3.4	$295.4^{+2.3}_{-2.6}$
Contrast [mag]	$2.82^{+0.19}_{-0.11}$	$1.81^{+0.14}_{-0.31}$
W0336AB	21.97 ± 0.01	14.52 ± 0.01
W0336A	22.05 ± 0.01	$14.71^{+0.02}_{-0.05}$
W0336B	$24.87^{+0.18}_{-0.10}$	$16.51^{+0.12}_{-0.26}$
Component	Primary	Secondary
$T_{\rm eff}$ [K]	415 ± 20	325^{+15}_{-10}
M [$M_{\rm Jup}$] (1 Gyr)	8.5 ± 1	5 ± 1
M [$M_{\rm Jup}$] (5 Gyr)	18 ± 2	11.5 ± 1
Physical separation [au]	$0.97^{+0.05}_{-0.09}$	
Orbital period [yr]	7 ± 2	
Mass fraction $q = M_{\rm B}/M_{\rm A}$	0.61 ± 0.05	

WISE-0336 with NIRCam KPI

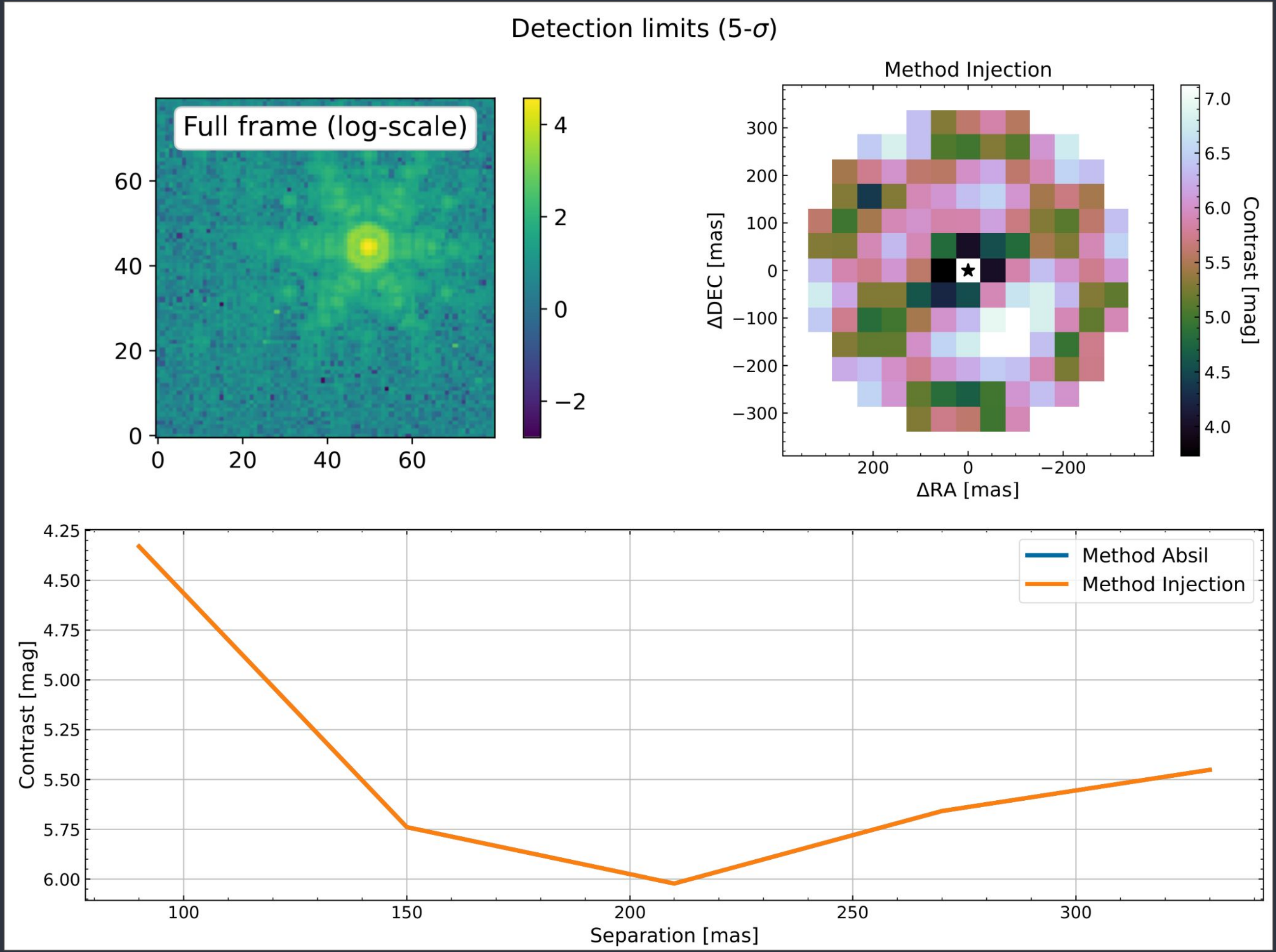


WISE 0336 NIRCam KPI (WIP)





Example 5-σ Detection Limits (WIP)



What's next?

- Explore calibration/reference star strategies
  - 20 science targets with NIRCam
  - 2 science targets + 1 reference with NIRISS
- Detection limits for all 22 targets
- Compare performance with ePSF modelling
- Multiplicity analysis

In Summary

- Interferometric imaging with JWST opens short separation around bright and faint targets
- First Y+Y binary WISE 0336 detected with ePSF and KPI
- JWST-KPI pipeline publicly available
- Current contrast limits:
    - 4.5 mag at 100 mas
    - 6.0 mag at 200 mas
- Soon (hopefully!):
    - Companion constraints for all targets
    - In depth, robust comparison with ePSF modelling
    - Multiplicity analysis

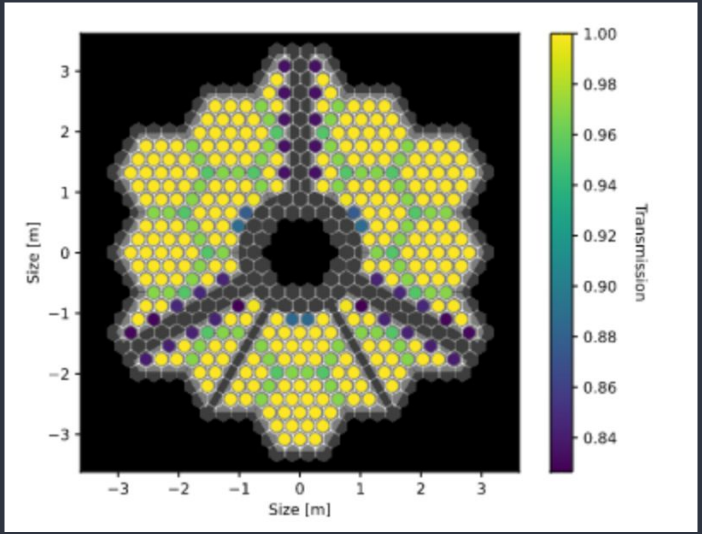
EXTRA MATERIAL

Kernel Phase Formalism

KPI: Treat telescope as interferometer

$$e^{i\varphi_k} \approx 1 + i\varphi_k$$

$$\phi = \mathbf{A}\varphi$$



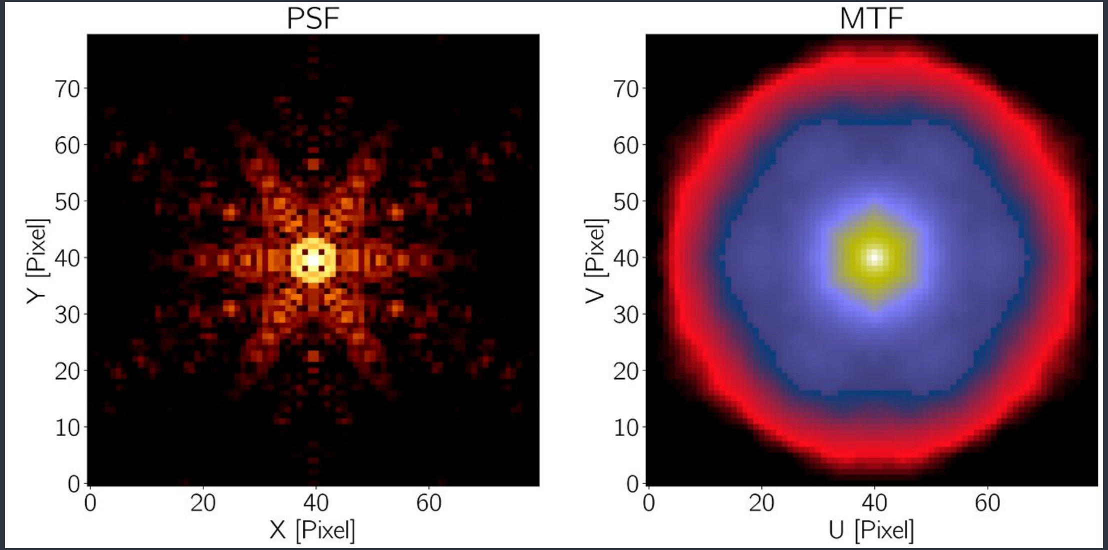


Figure: Kammerer+ 2022

KPI: Treat telescope as interferometer

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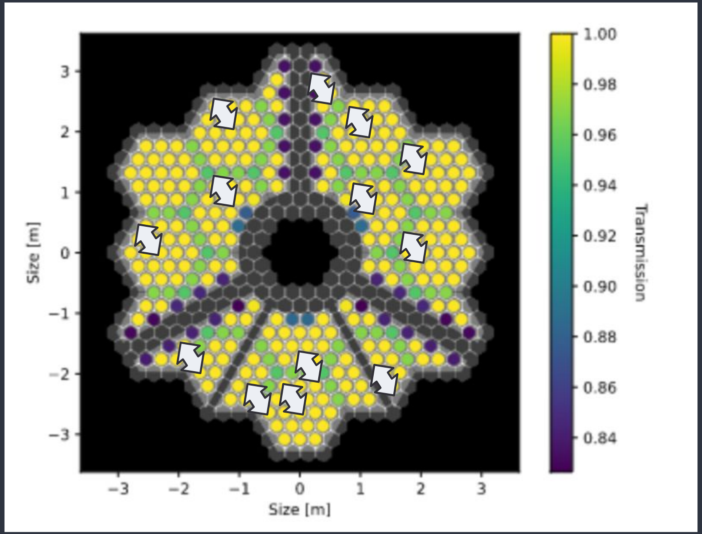

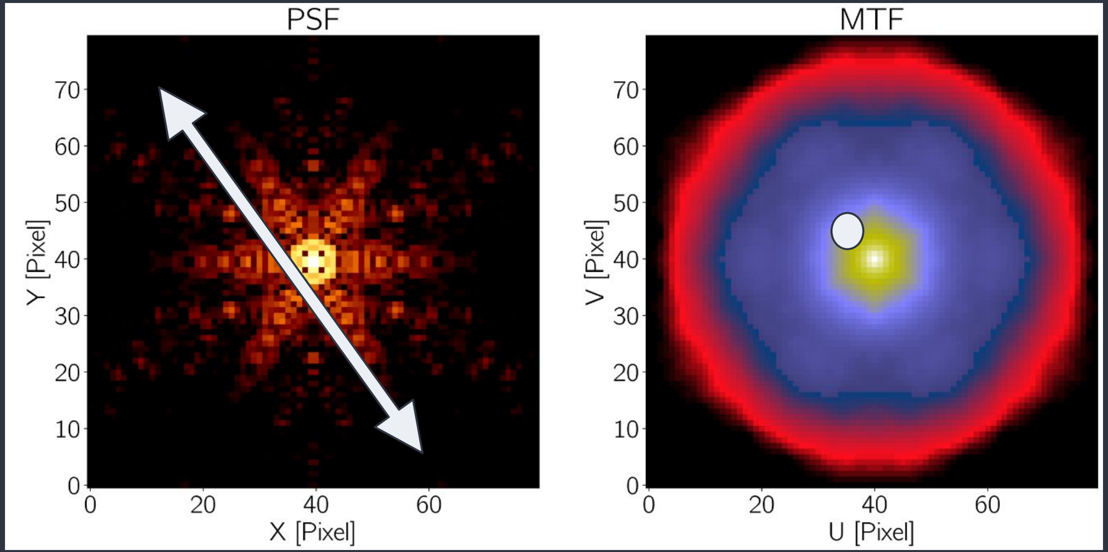

Figure: Kammerer+ 2022

KPI: Treat telescope as interferometer

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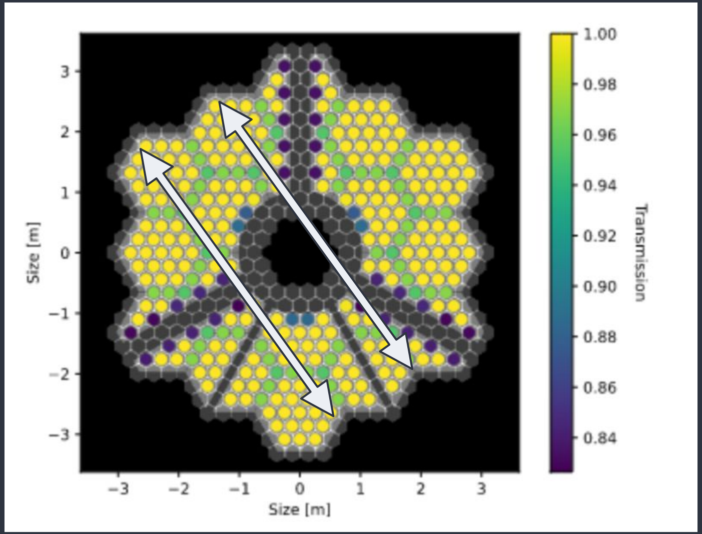
$$\phi = \mathbf{A}\varphi$$



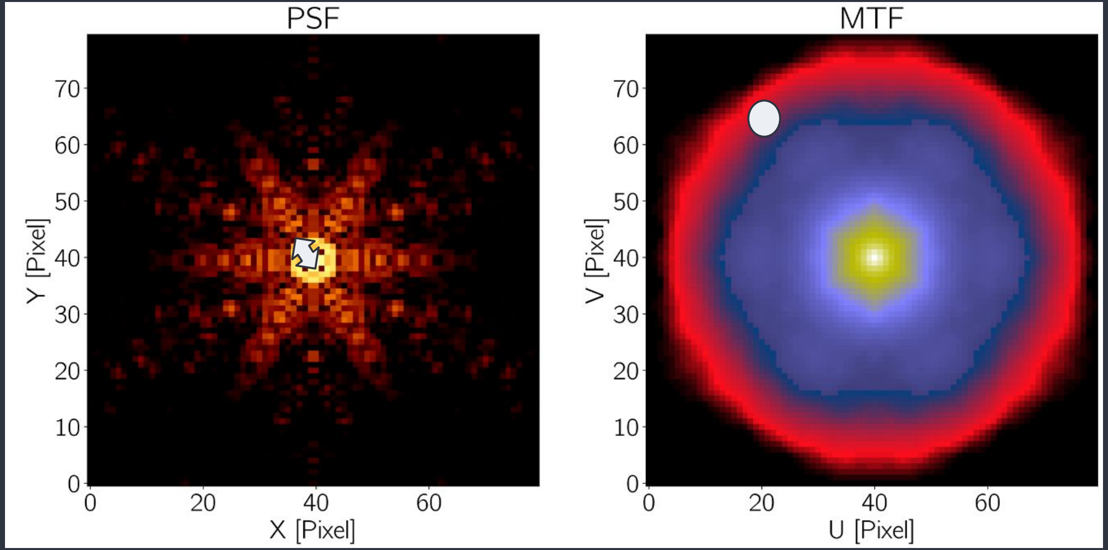
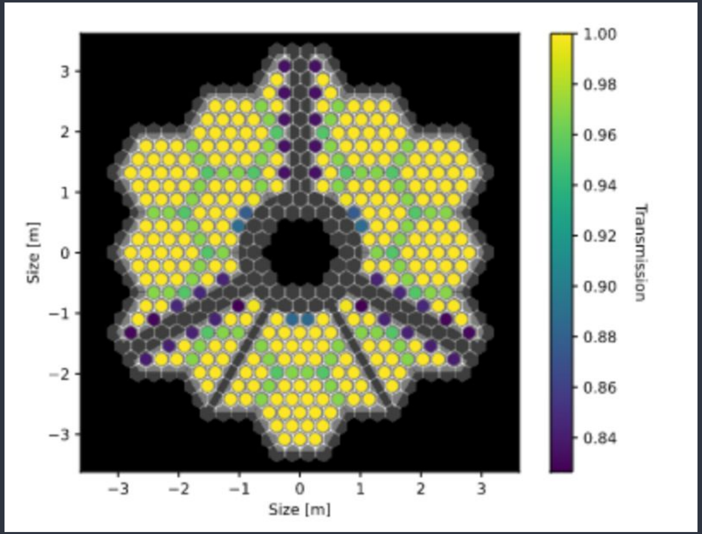


Figure: Kammerer+ 2022

KPI: Treat your telescope as an interferometer

Object Errors

$$e^{i\varphi_k} \approx 1 + i\varphi_k \qquad \phi = \phi_O + \mathbf{A}\varphi$$



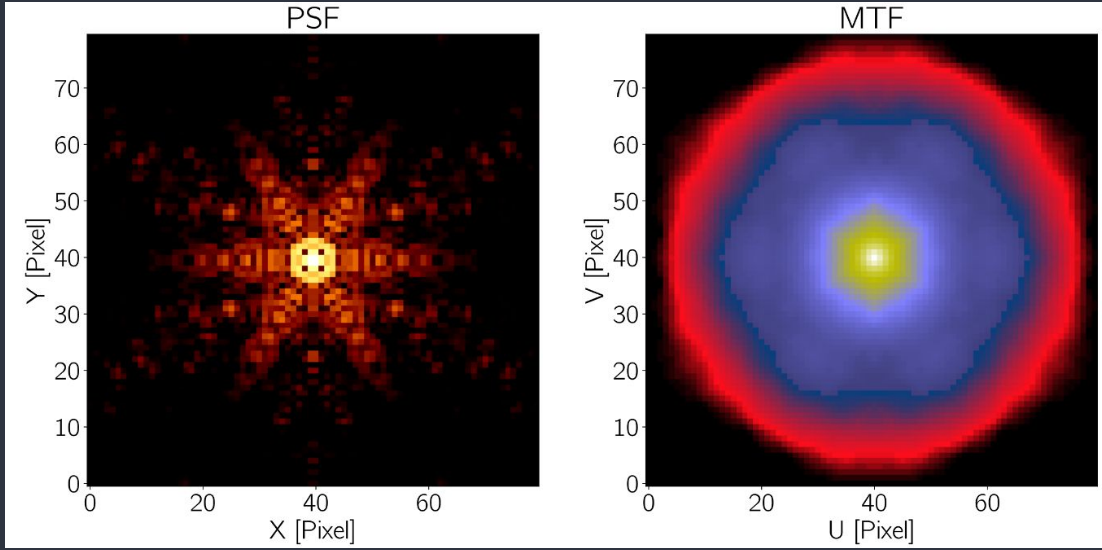


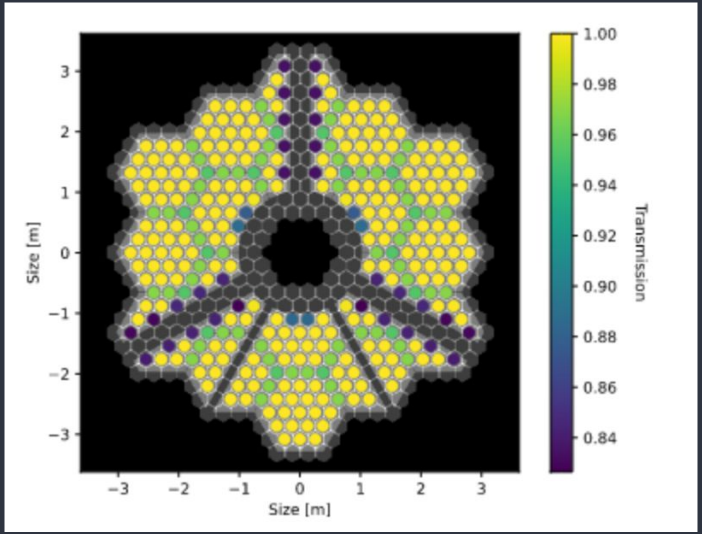
Figure: Kammerer+ 2022

KPI: Treat telescope as interferometer

$$\phi = \phi_O + \mathbf{A}\varphi$$

$$e^{i\varphi_k} \approx 1 + i\varphi_k$$

$$\mathbf{K}\phi = \mathbf{K}\phi_O + \mathbf{K}\mathbf{A}\varphi \rightarrow 0$$



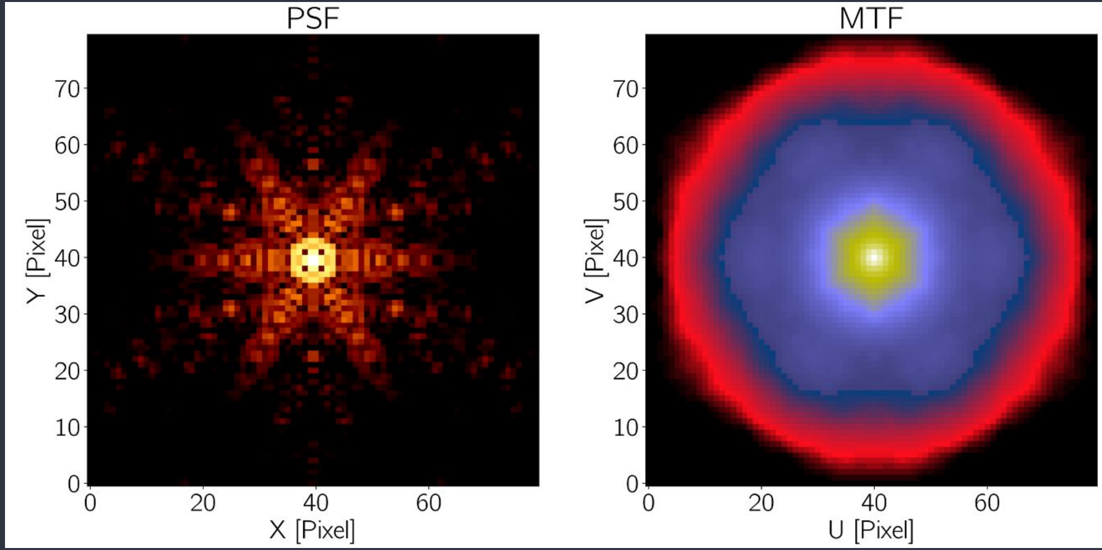
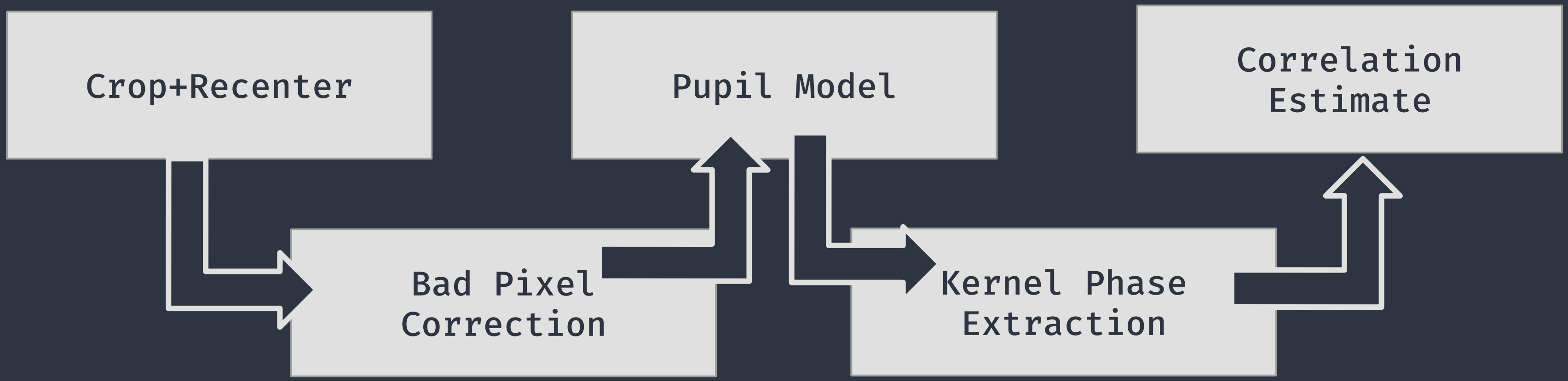


Figure: Kammerer+ 2022

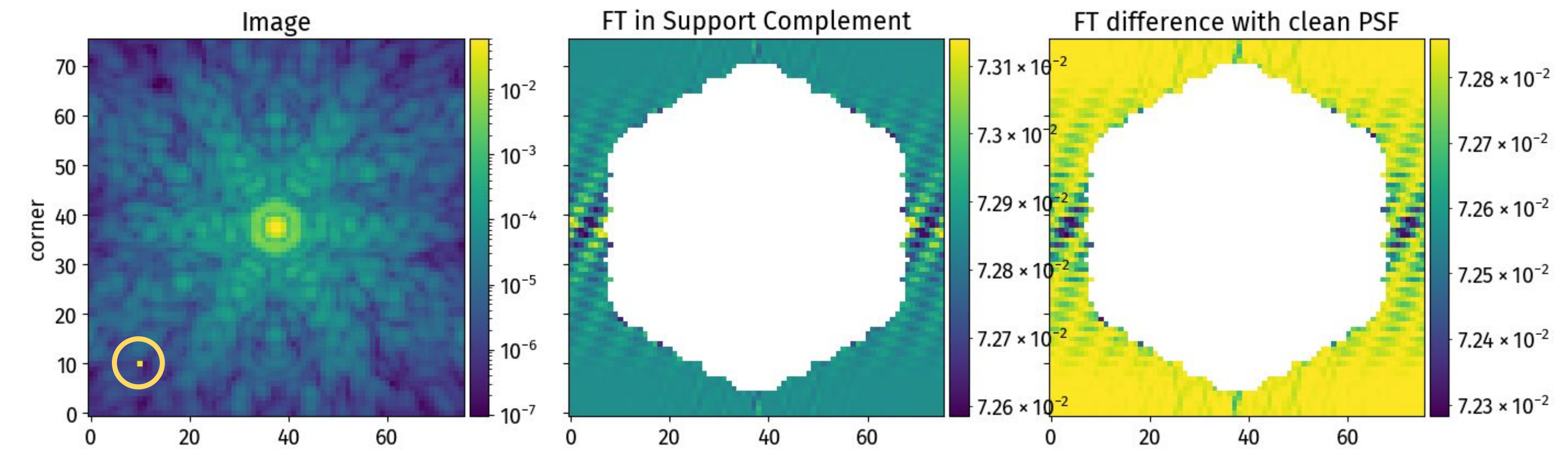
NIRISS Commissioning: JWST KPI Pipeline (“Stage 3”)



Work led by Jens Kammerer

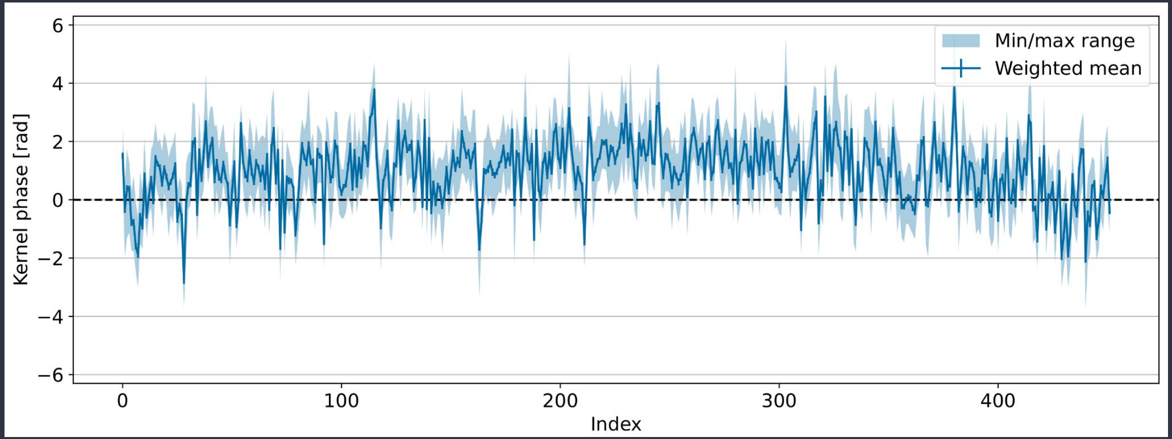
NIRISS Bad pixels

Fourier-plane bad pixel correction

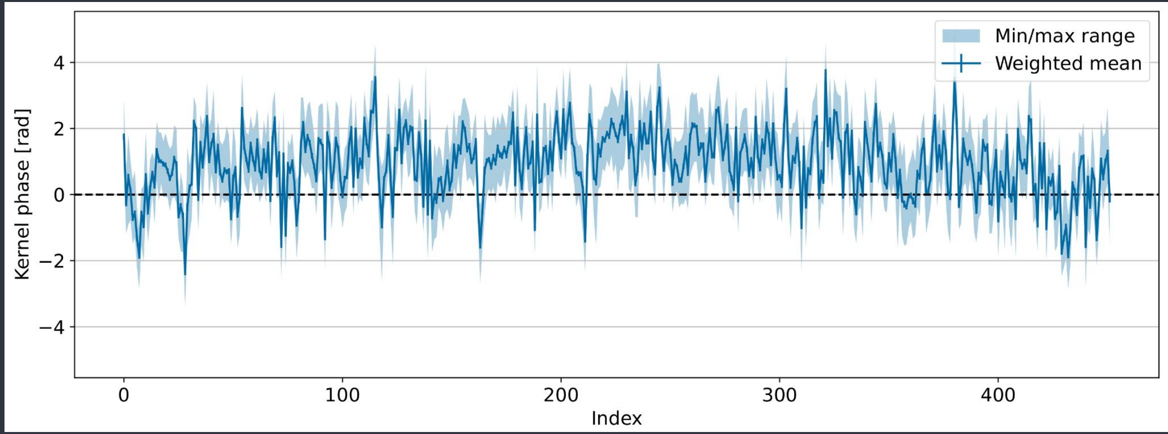


WISE-1828 and WISE-0855: Kernel Phases

WISE-1828



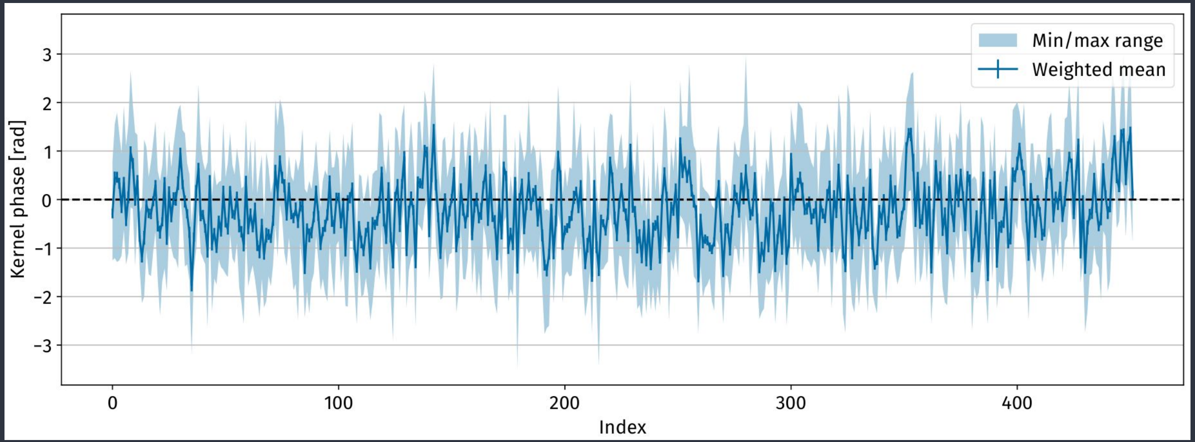
WISE-0855



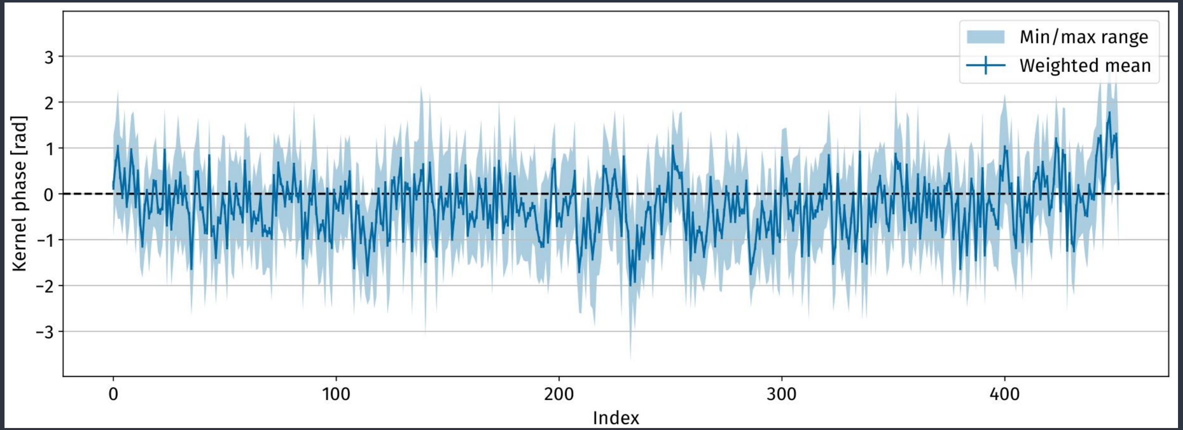
*Non-normalized KP

WISE-1828 and WISE-0855: Kernel Phases
+
Fourier correction

WISE-1828



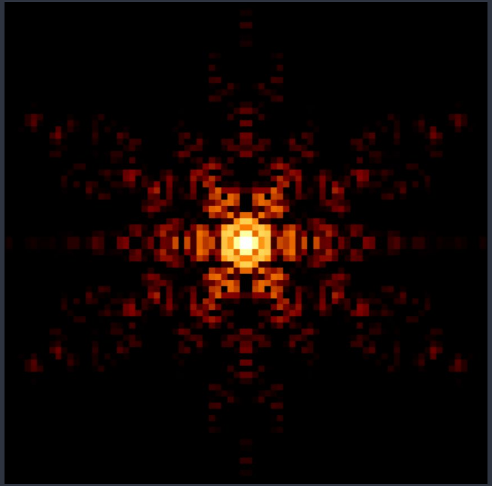
WISE-0855



*Non-normalized KP

NIRISS AMI

JWST/NIRISS Aperture Masking Interferometry (AMI)



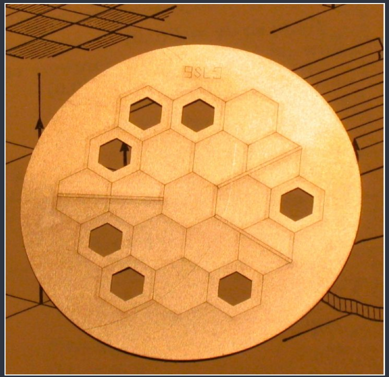
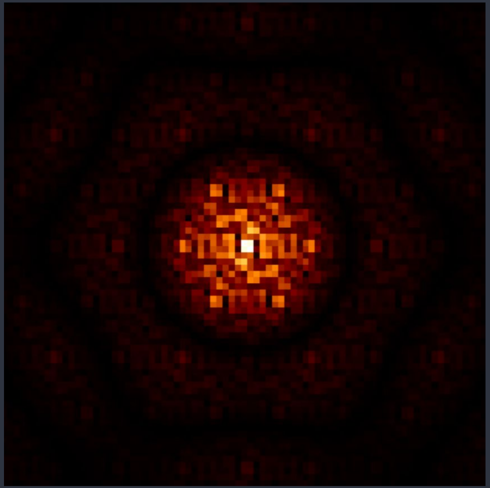


Figure: A. Sivaramakrishnan



NIRISS AMI Guaranteed Time Observations (GTO)

HR 8799

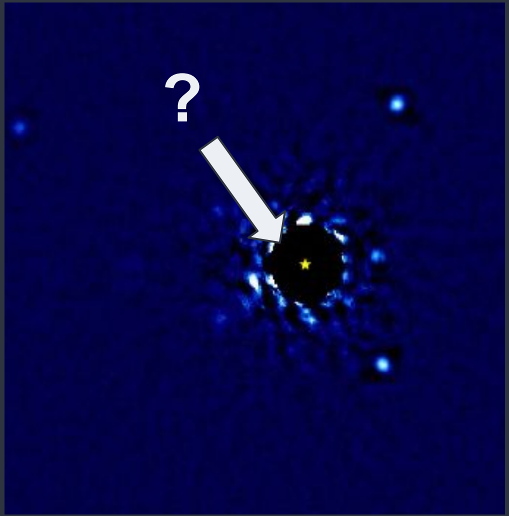


Figure: J. Wang/C. Marois

HD 95086

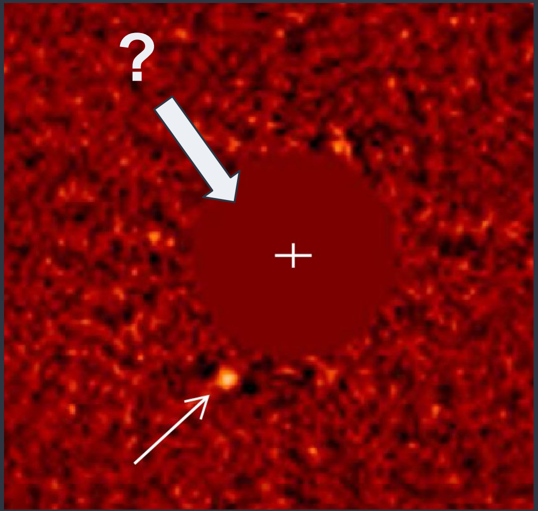


Figure: J. Rameau

HD 115600

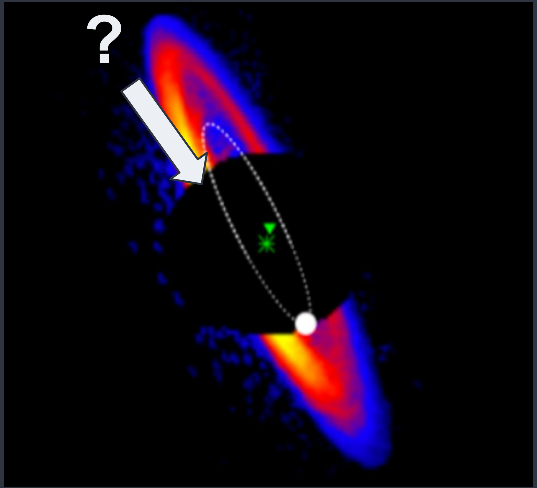
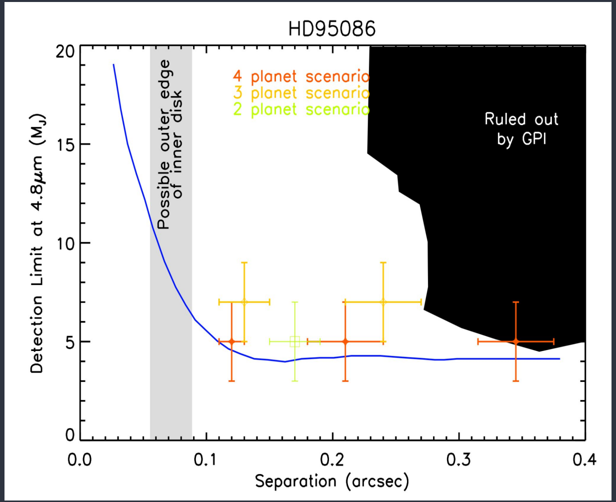
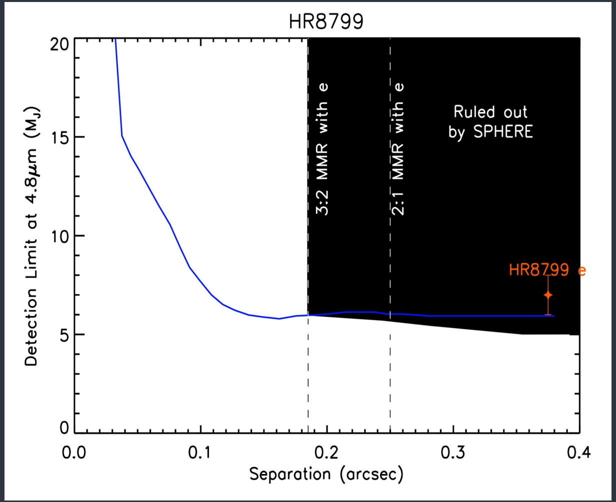
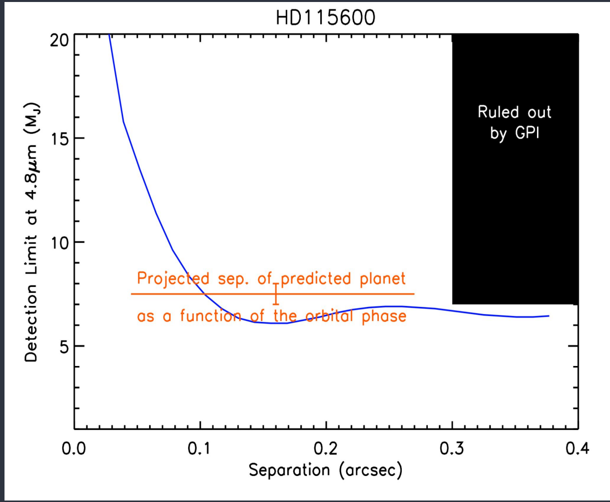


Figure: T. Currie

AMI with JWST/NIRISS







Closure Phase

Atmospheric turbulence: Impact on phase

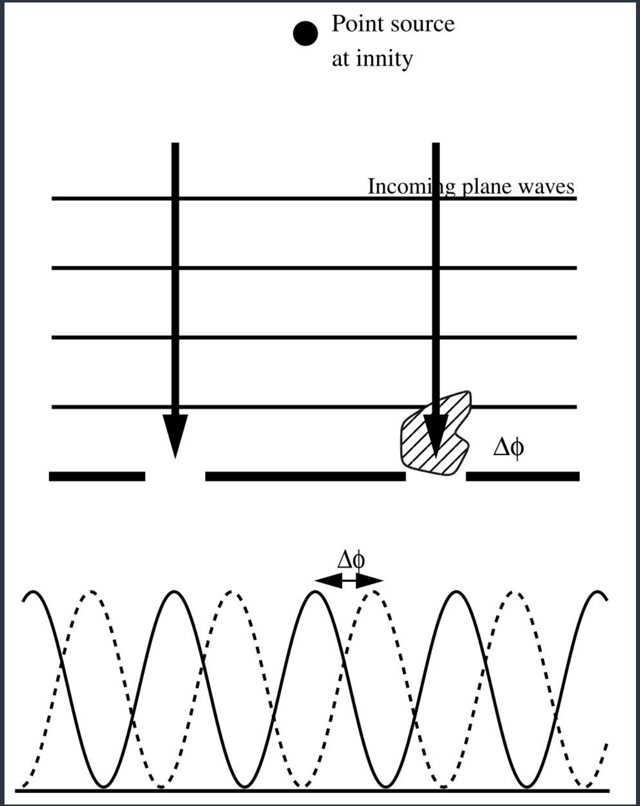
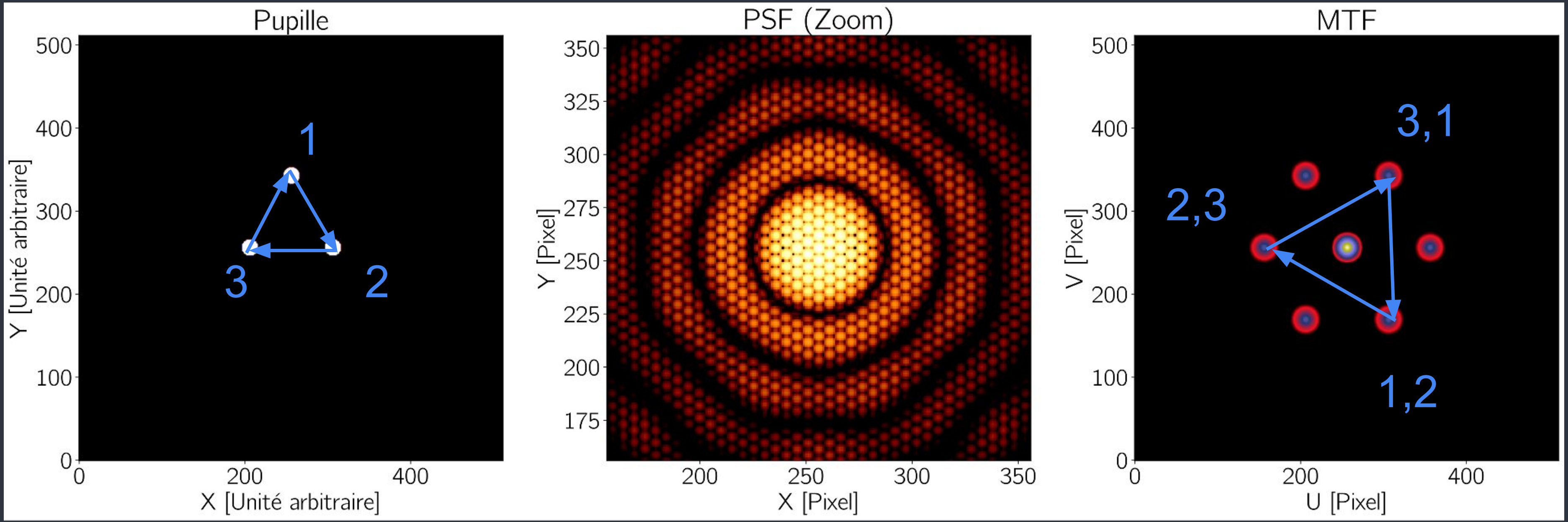


Figure: Monnier 2007

Solution: Closure Phase

$$\phi_{1,2} = \phi^{O}_{1,2} + \cancelto{0}{\varphi_2} - \cancelto{0}{\varphi_1}$$
$$\phi_{2,3} = \phi^{O}_{2,3} + \cancelto{0}{\varphi_3} - \cancelto{0}{\varphi_2}$$
$$\phi_{3,1} = \phi^{O}_{3,1} + \cancelto{0}{\varphi_1} - \cancelto{0}{\varphi_3}$$

$$\mathbf{\Phi}_{1,2,3} = \phi_{1,2} + \phi_{2,3} + \phi_{3,1} = \phi^{O}_{1,2} + \phi^{O}_{2,3} + \phi^{O}_{3,1}$$



AMI with JWST/NIRISS