Imaging Planet Formation on Solar System Scales

Christina Vides[1], Steph Sallum[1], Josh Eisner[2], Andy Skemer[3], and Ruth Murray-Clay[3]

1. University Of California, Irvine 2. University of Arizona 3. University of California, Santa Cruz

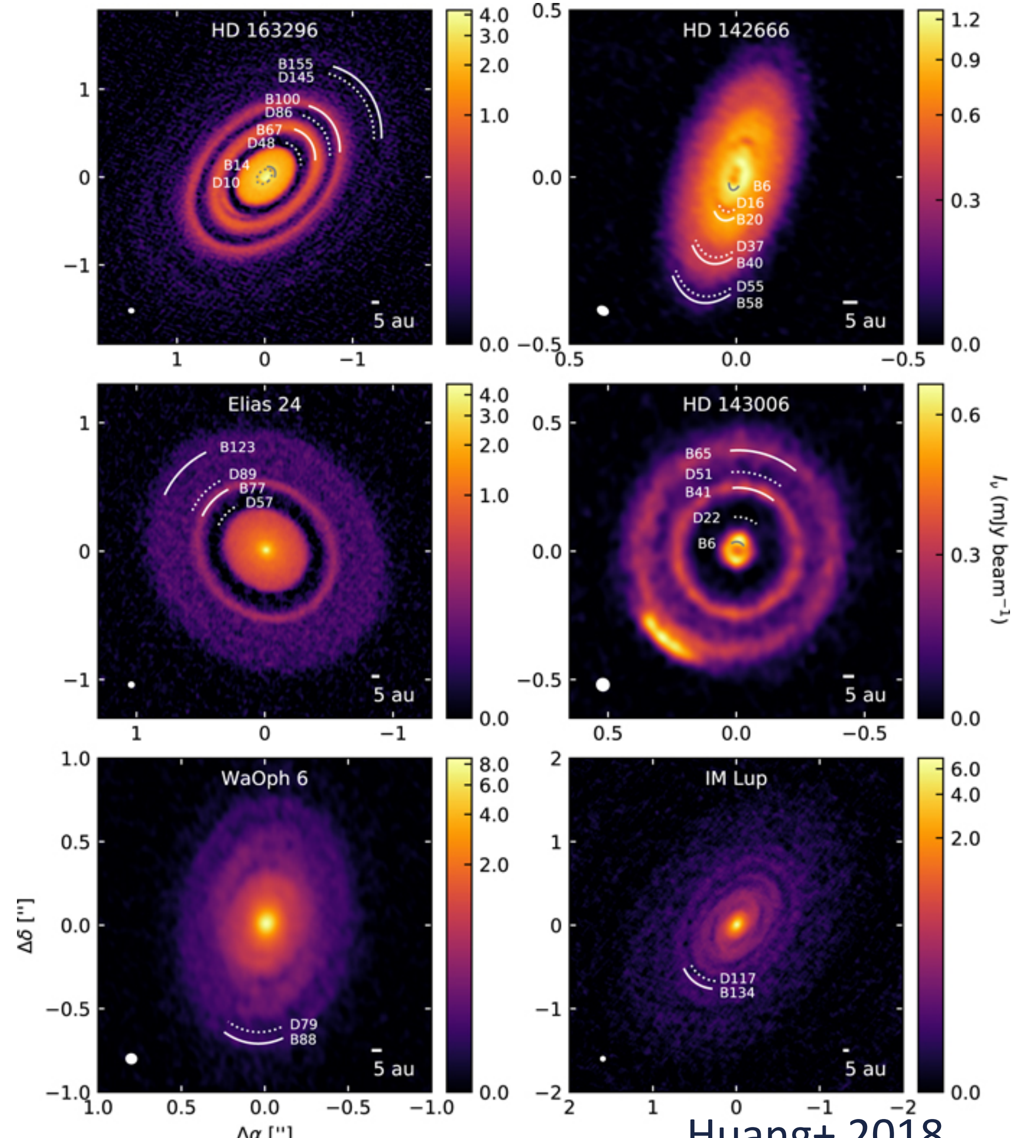
ExSoCal 2023

Why Should We Observe Planet Formation?

Observations of Protoplanetary Disks: The Birthplace of Planets

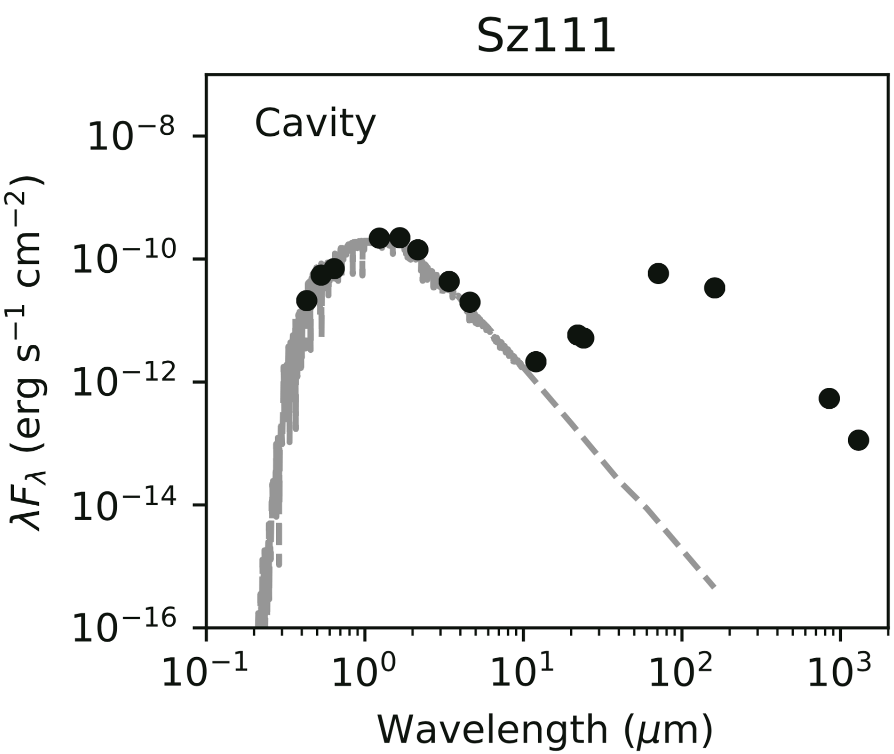
DSHARP Survey

- Mapped the 1.25 mm continuum of protoplanetary disks
- Spatial Resolution of ~5 au
- Found rings, gaps, and spiral arms/ warping driven by planet formation

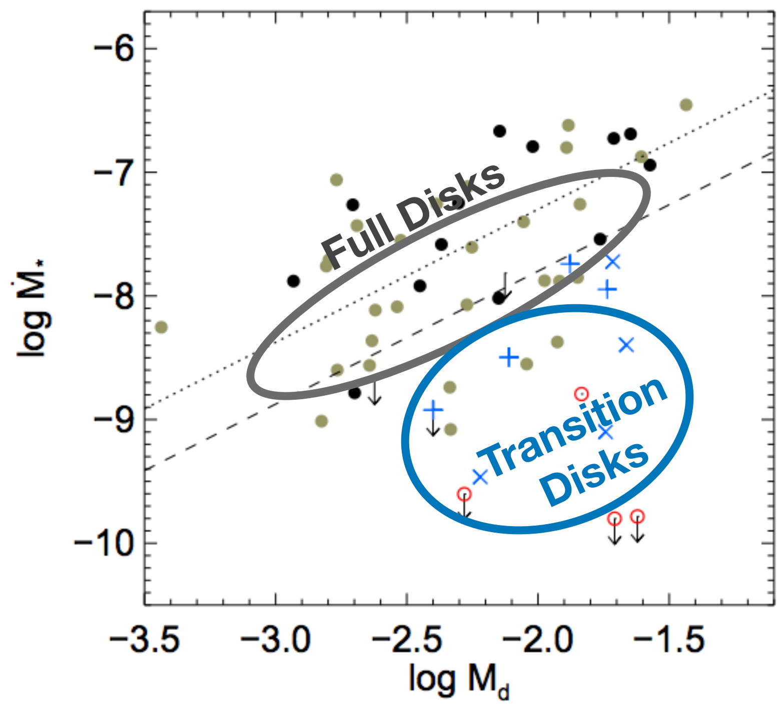


Huang+ 2018

Transition Disks: Further Evidence of Ongoing Planet Formation



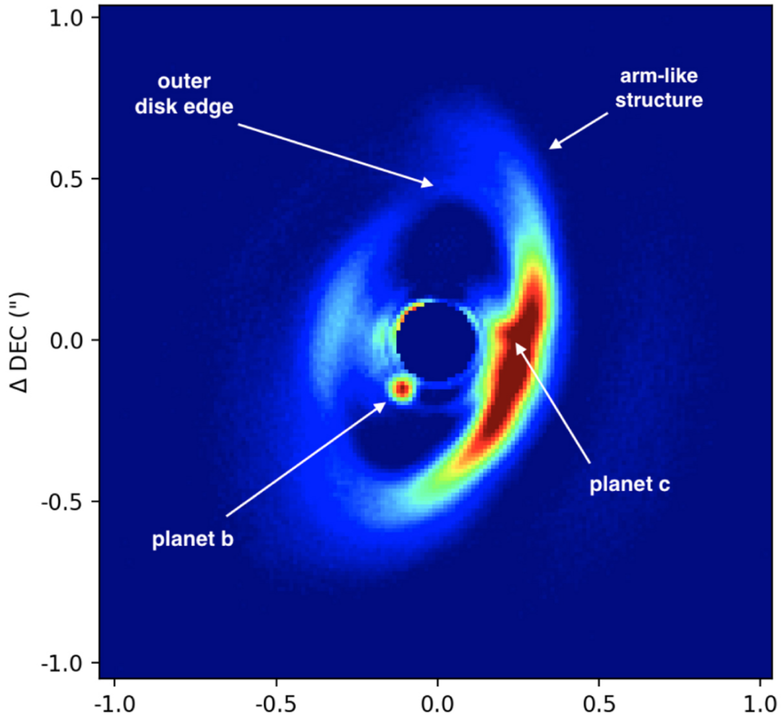
van der Marel+2023



Najita+2015

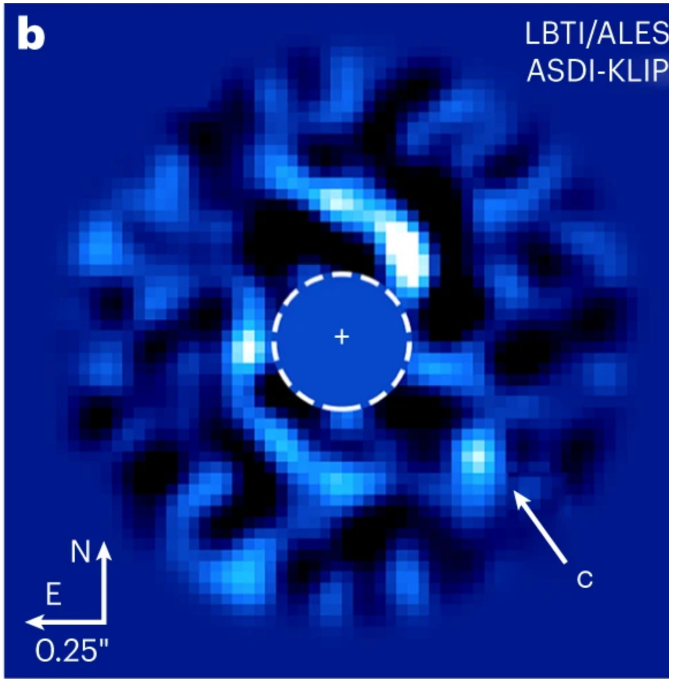
Observations of Protoplanets within Transition Disks

PDS 70



Juliard + 2022

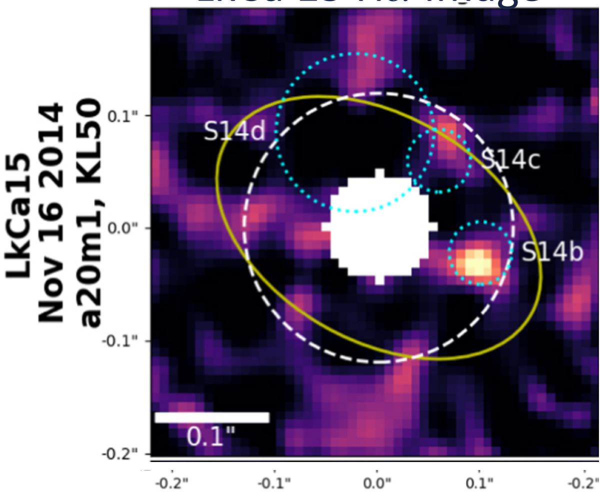
MWC 758



Wagner + 2023

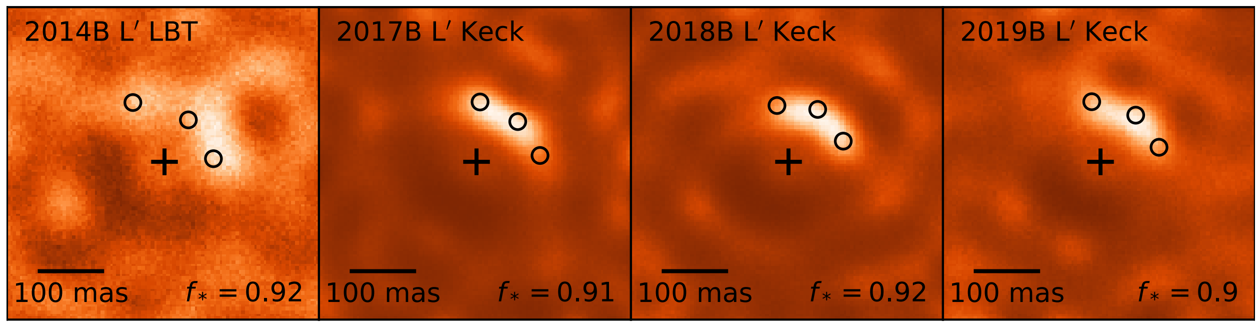
Hα Differential Imagery Companion Candidates

LkCa 15 Hα Image

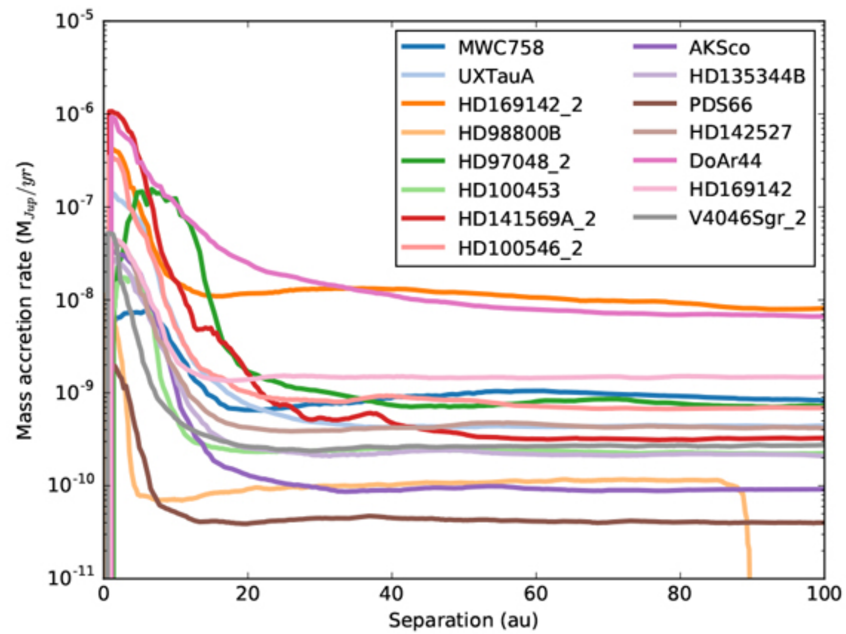


Follette+2023

LkCa 15 L-band Multi-Epoch Imaging



Sallum+2023

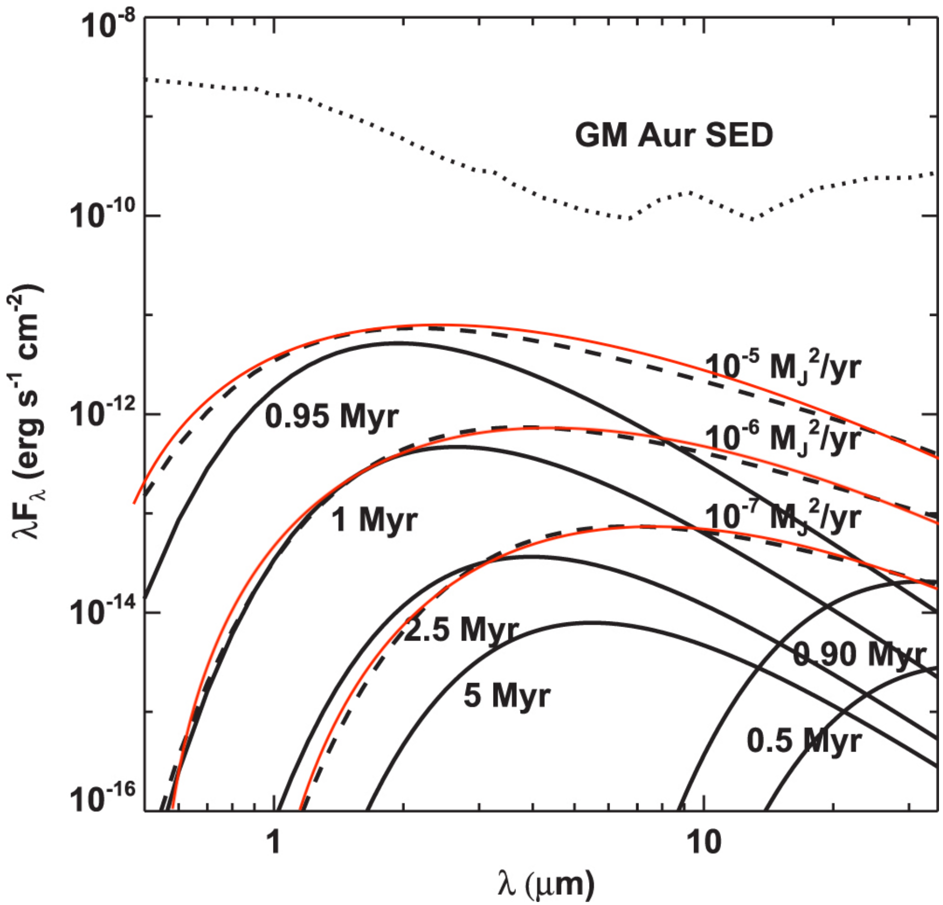


Zurlo+2019

- LkCa 15 b was detected in 2015, but was not recovered in 2016.
- Long time baseline monitoring shows that the position angle evolution needs to be explained by a dynamic disk.
- Hα surveys can access close-in separations, but can be limited by extinction.

The Spectral Energy Distributions of Protoplanets

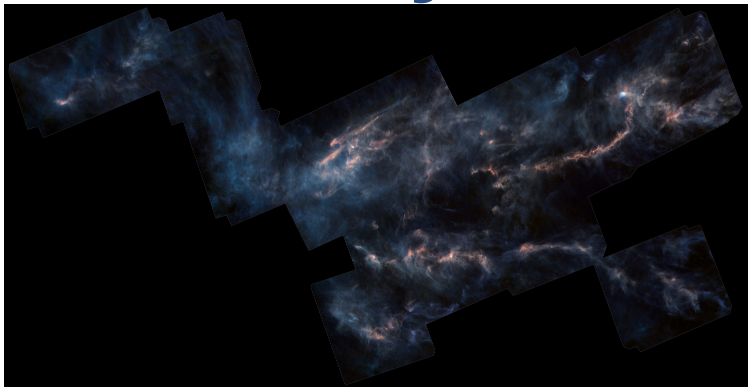
$$L_{acc,p} = \frac{GM\dot{M}}{R}$$



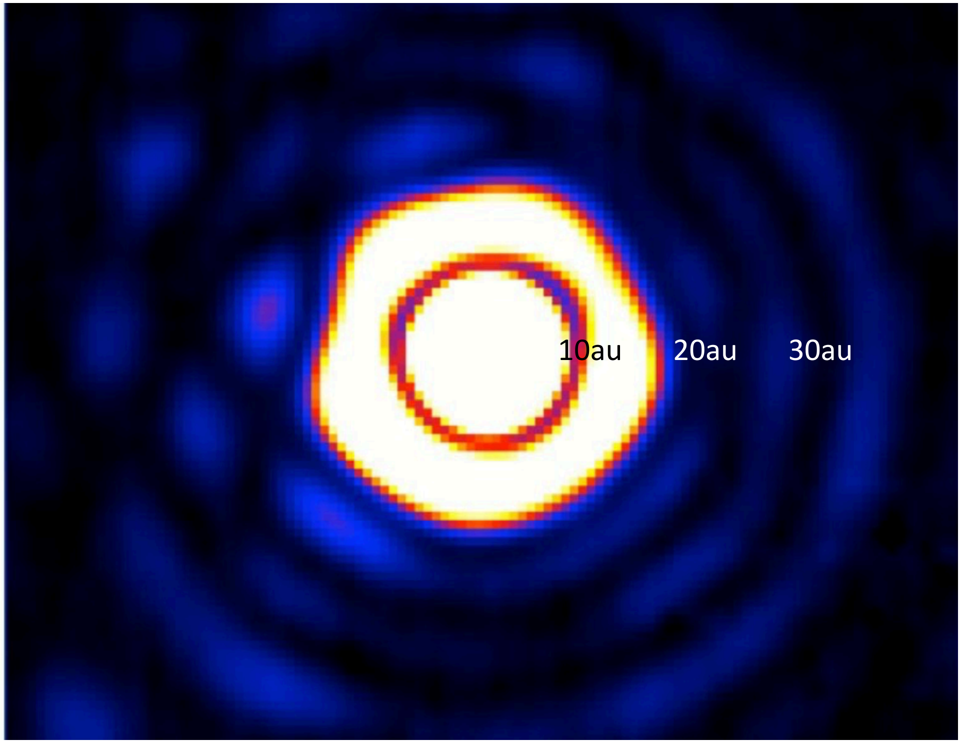
Eisner, 2015

Rapidly accreting protoplanets are most luminous between ~2 μm-5μm

Limitations of Observing Planet Formation on Solar System Scales



Distance to nearest star forming regions $\gtrsim$ 100 pc

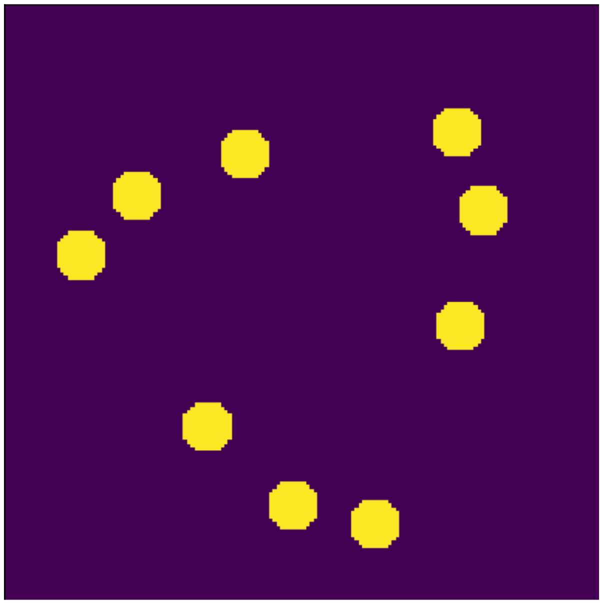


D = 10 m

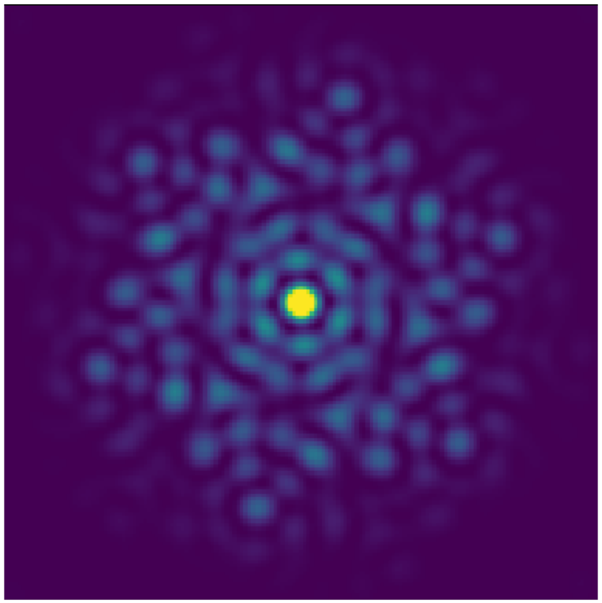
Insufficient angular resolution with conventional imaging techniques

Non-Redundant Masking (NRM): A Tool for Observing Planet Formation on Solar System Scales

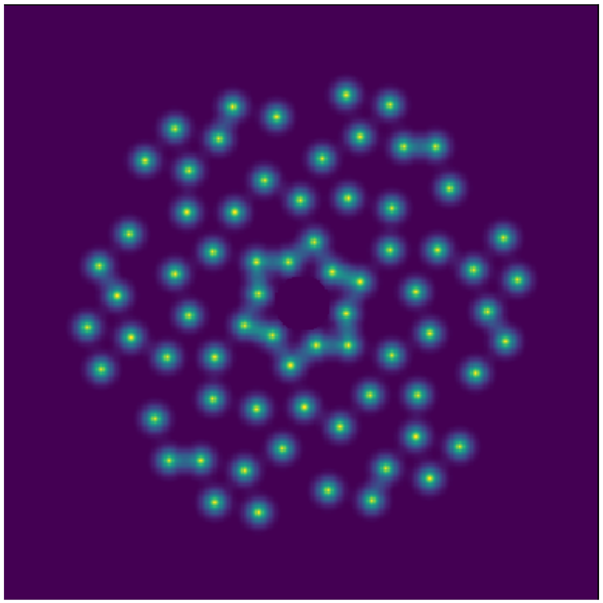
Mask



Interferogram



FT (Interferogram)

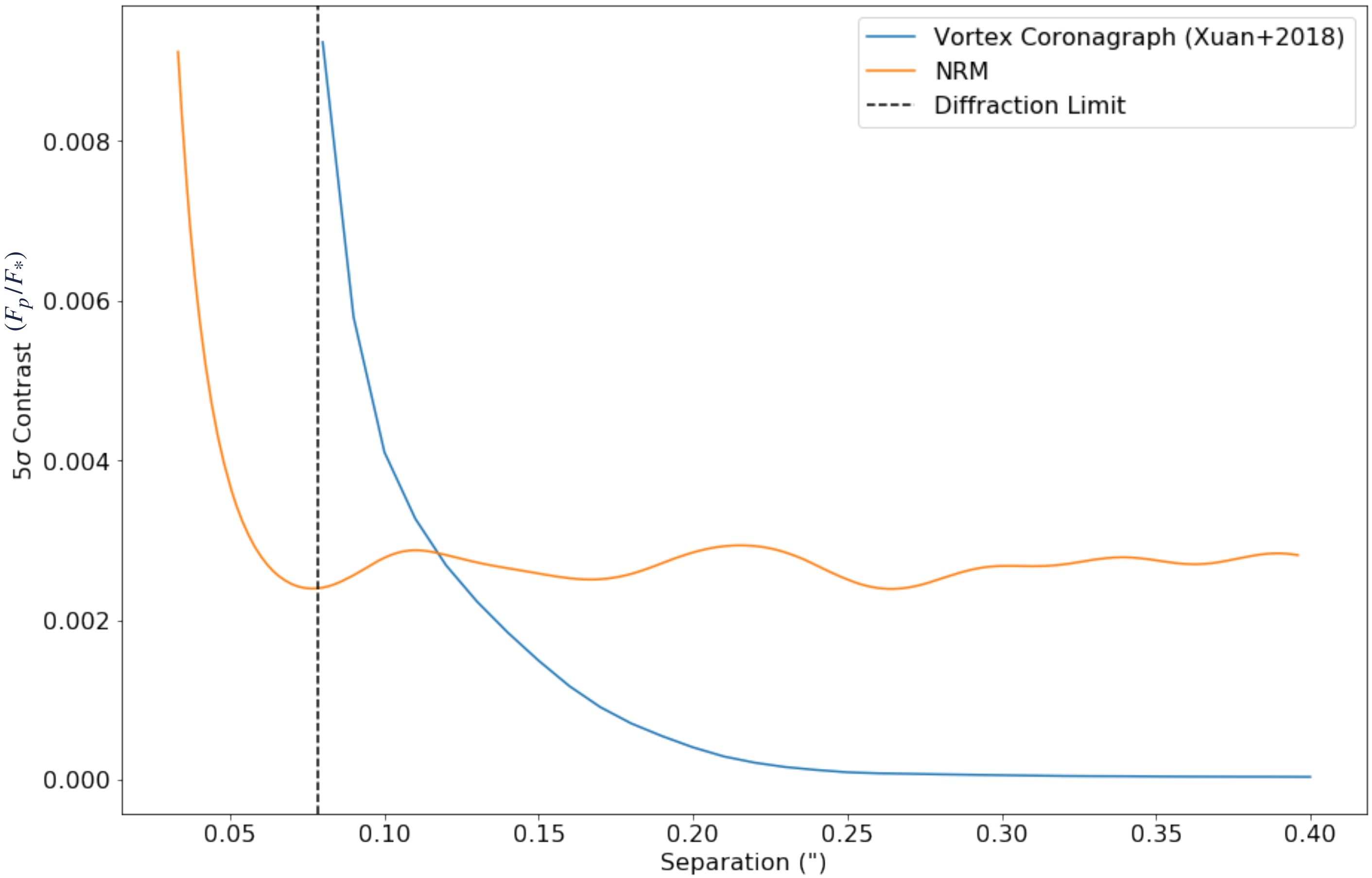


Observables:

- Squared visibilities (V^2s)
- Closure phases (CPs)

NRM provides moderate contrast at angular separations down to and within the diffraction limit.

Comparison of NRM to Traditional Imaging Methods

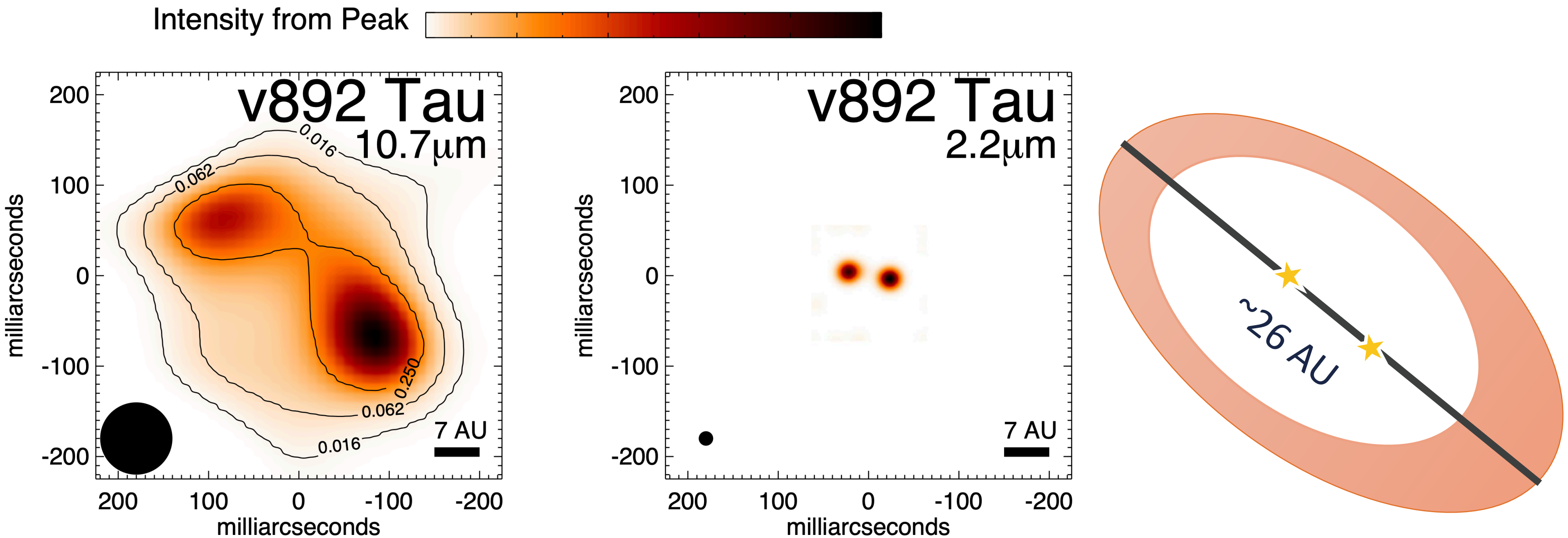


Direct Imaging Survey of Transition Disks with Keck2/NIRC2 and NRM

Survey Goals

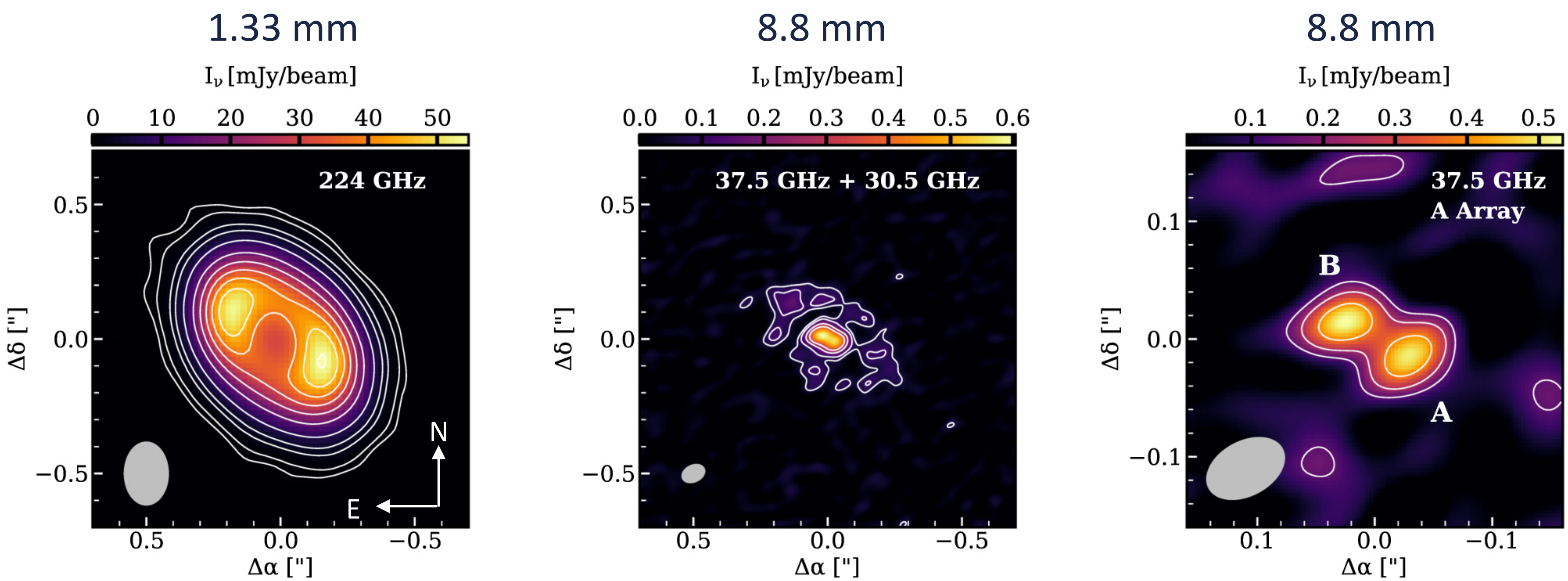
- Detect and characterize rapidly accreting giant protoplanets at solar-system scales in a significant sample of transition disks
- Characterize disk structure and dynamical interactions
- Place statistical constraints on the underlying protoplanet population and timescales under which they form

The V892 Tau Circumbinary Disk



Monnier +2008

A More Detailed View of the V892 Tau System



Long + 2021

Semi-major axis = 7.1 ± 0.1 au

Orbital Period = 7.7 ± 0.2 yr

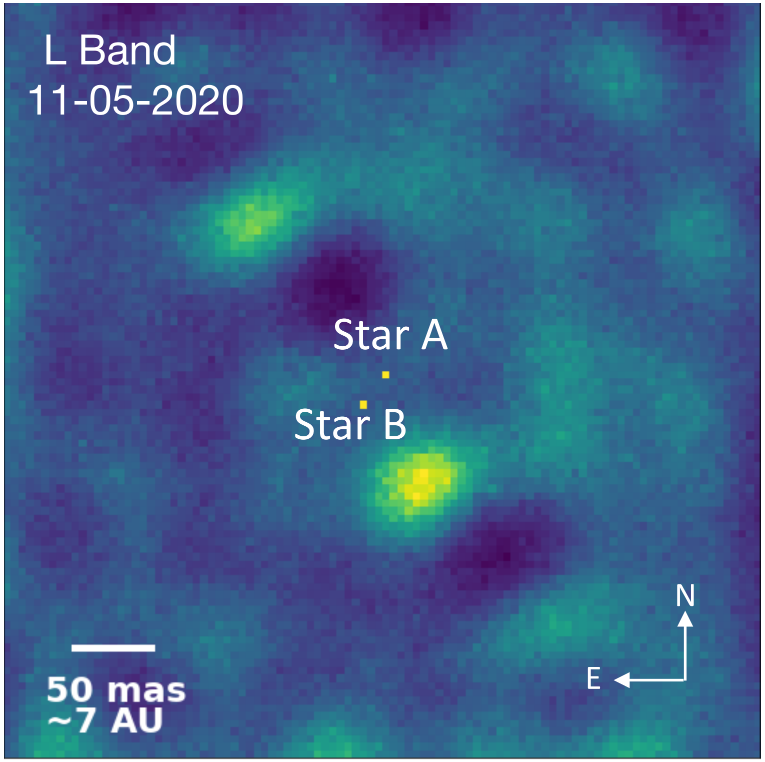
Eccentricity = 0.27 ± 0.1

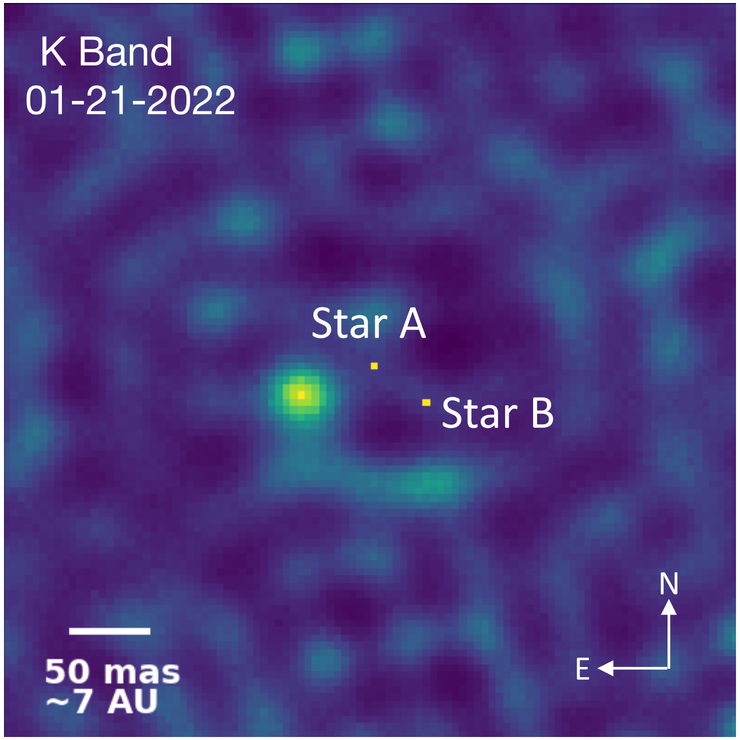
Binary Inclination = 59.3 ± 27°

Dynamical Mass = 6.0 ± 0.2$M_\odot$

Disk inclination =∼ 55°

Results: V892 Tau Reconstructed Images

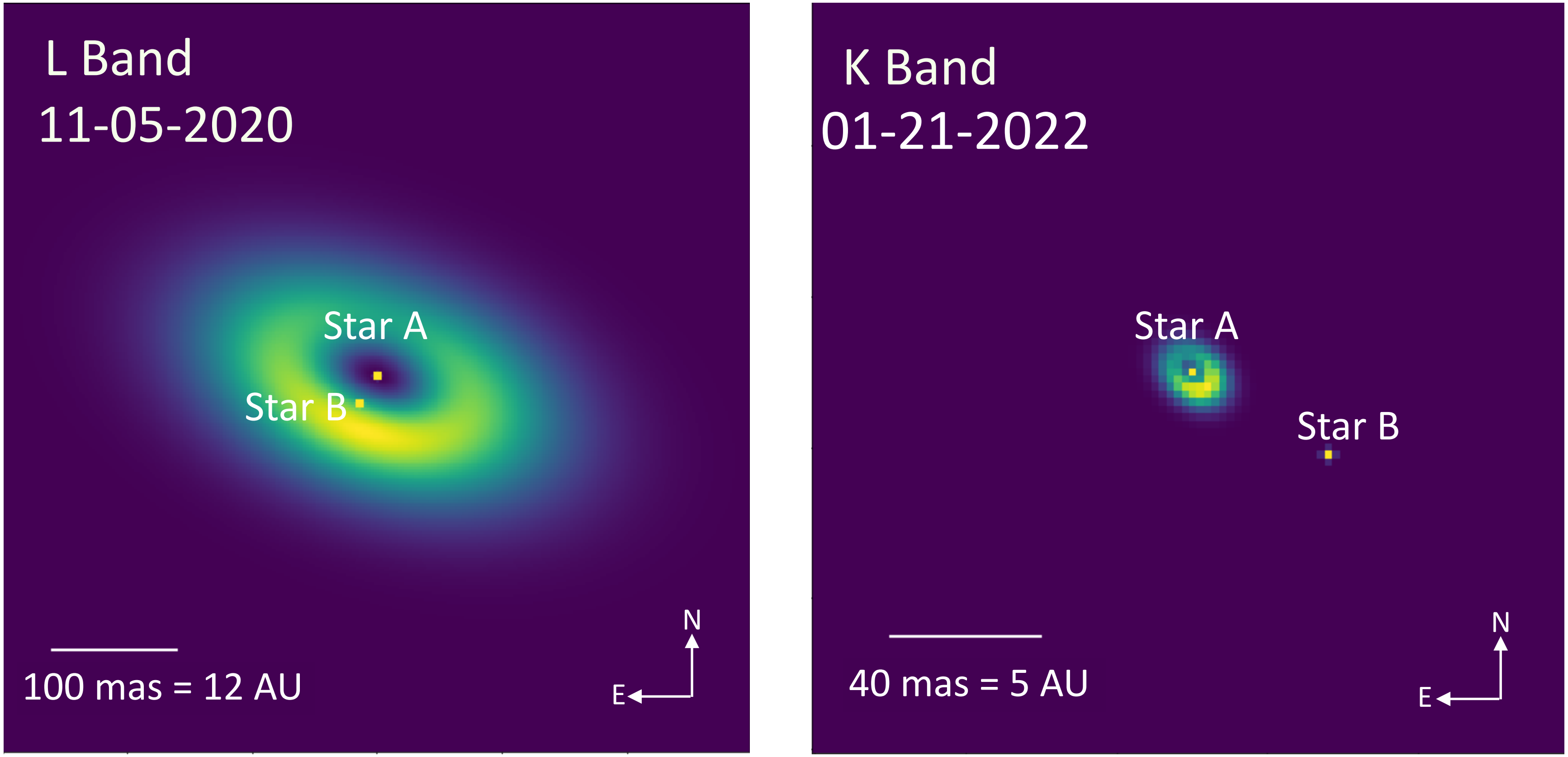




Vides+2023

Results: V892 Tau Geometric Model Fitting

A circumbinary disk and stellar companion are preferred at L band and a circumprimary disk and companion are preferred at K band.

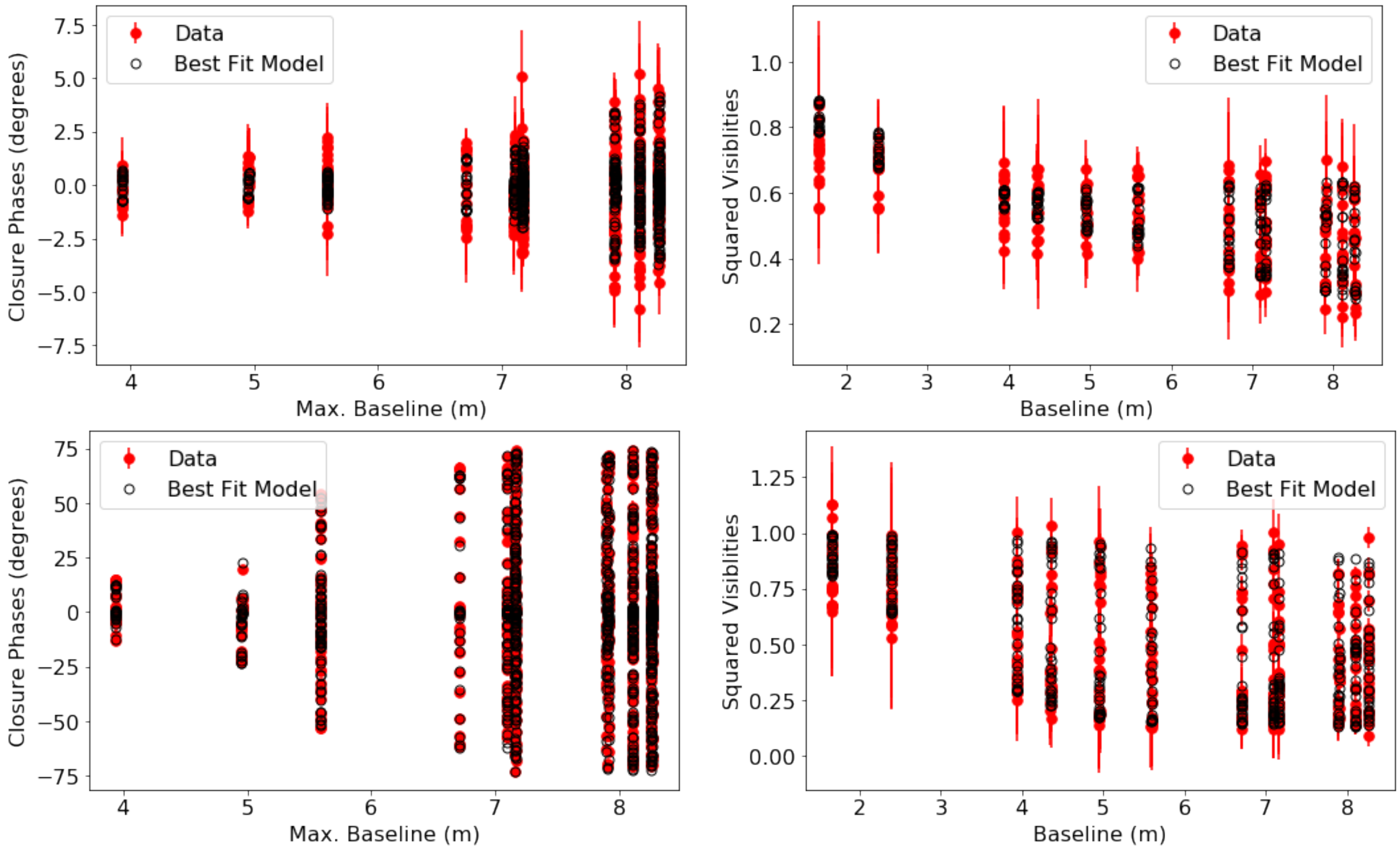


Vides+2023

Results: V892 Tau Disk+Companion Model Observables

L Band

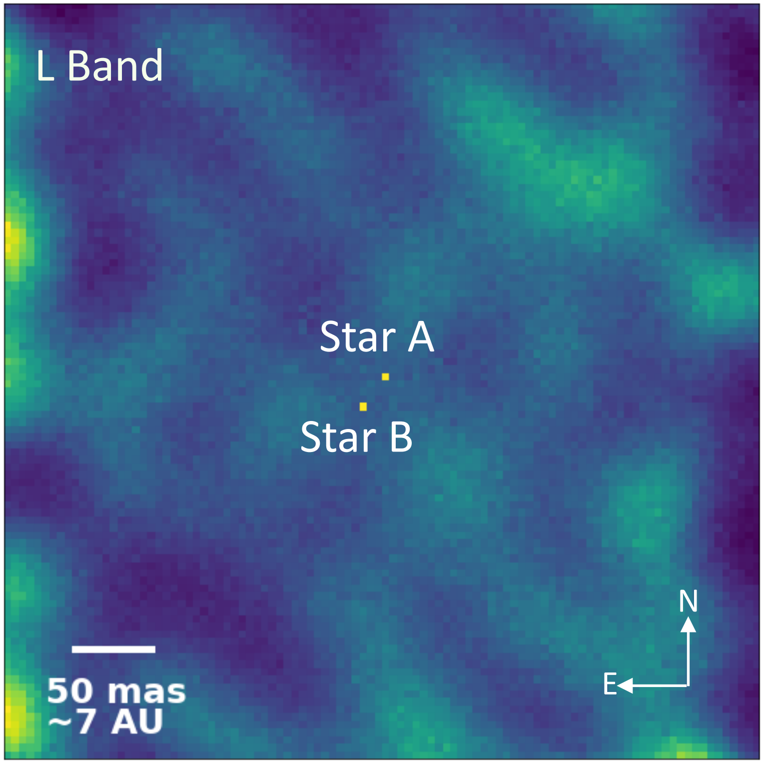
K Band

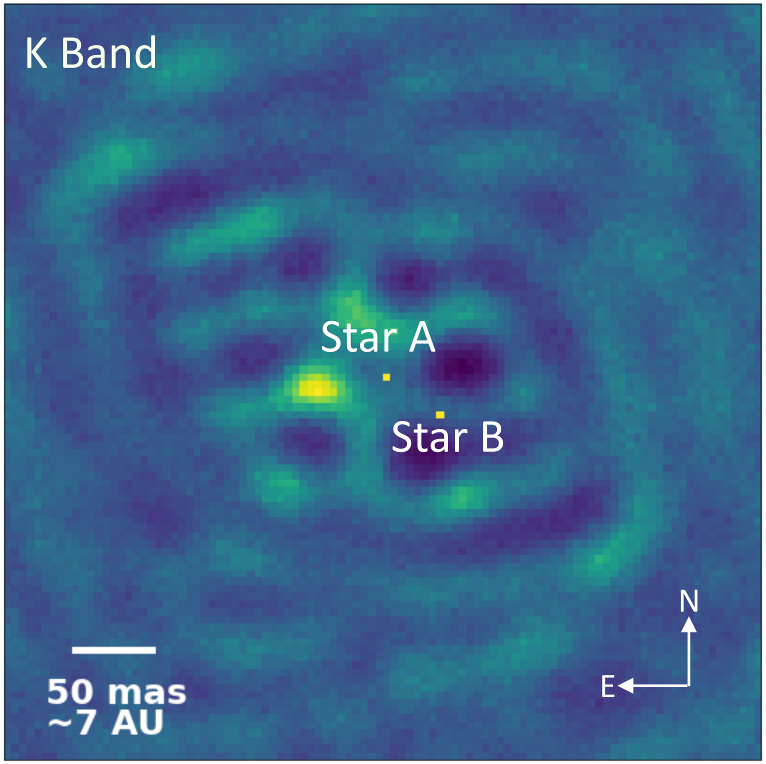


Vides+2023

Results: V892 Tau Best-Fit Model Reconstruction

Images reconstructed from the best-fit disk + companion CPs and V^2s

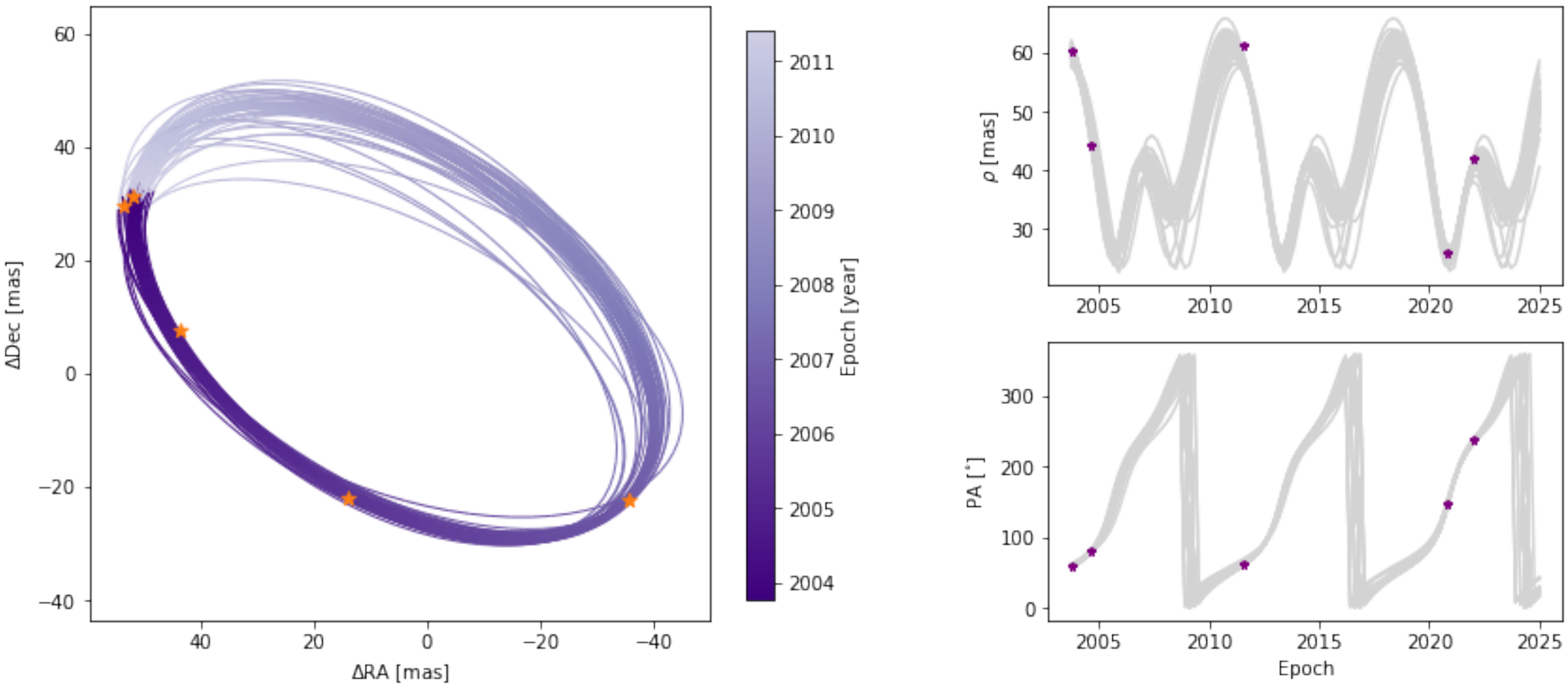




The best-fit model reproduces the data at K band but struggles at L band

Results: V892 Tau Orbit Fitting

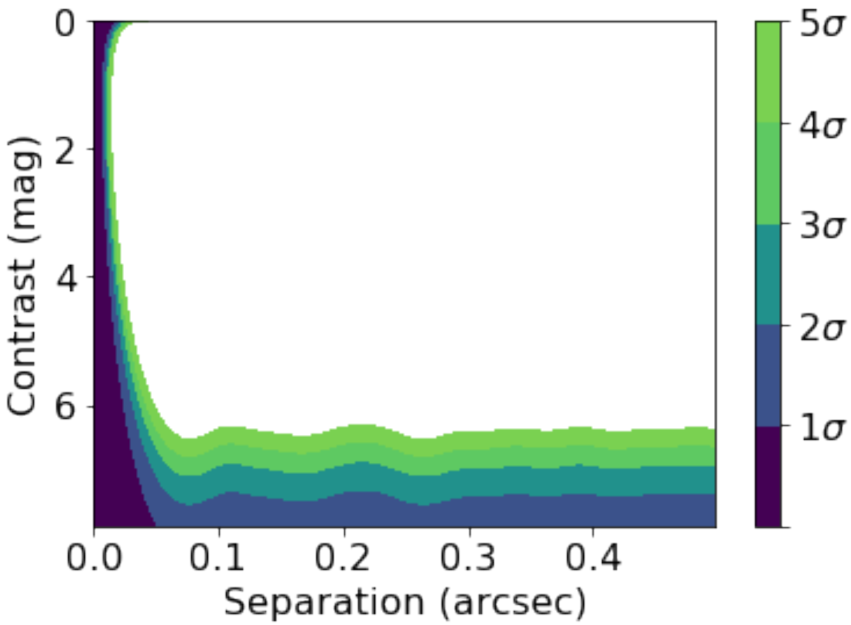
- 50 random orbits sampled from the posterior distribution



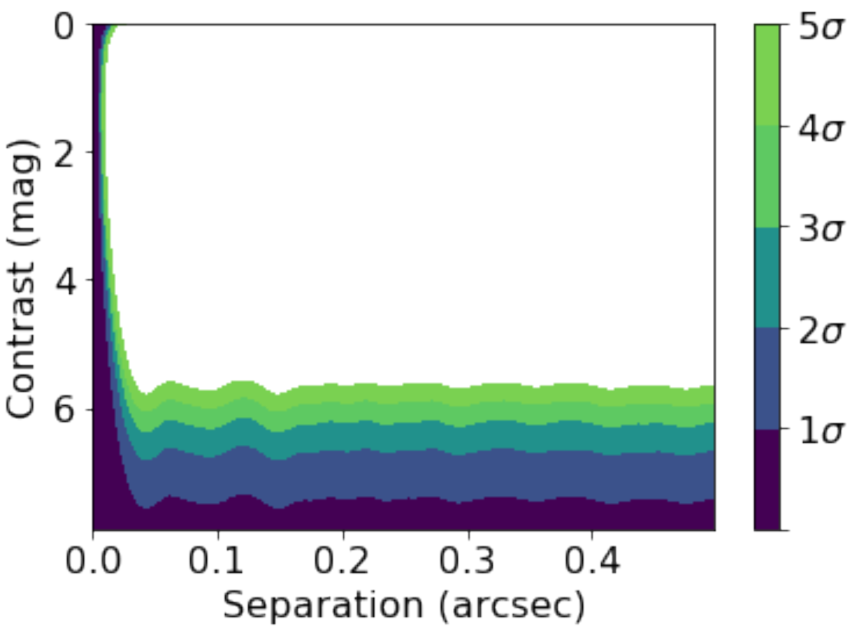
We update the orbit of the binary with Orbitize! (Blunt et al. 2019). From our astrometry, we fit an orbit to the data and constrain the parameters.

Results: V892 Tau Companion Contrast Limits

L band V892 Tau Contrast Curve



K band V892 Tau Contrast Curve



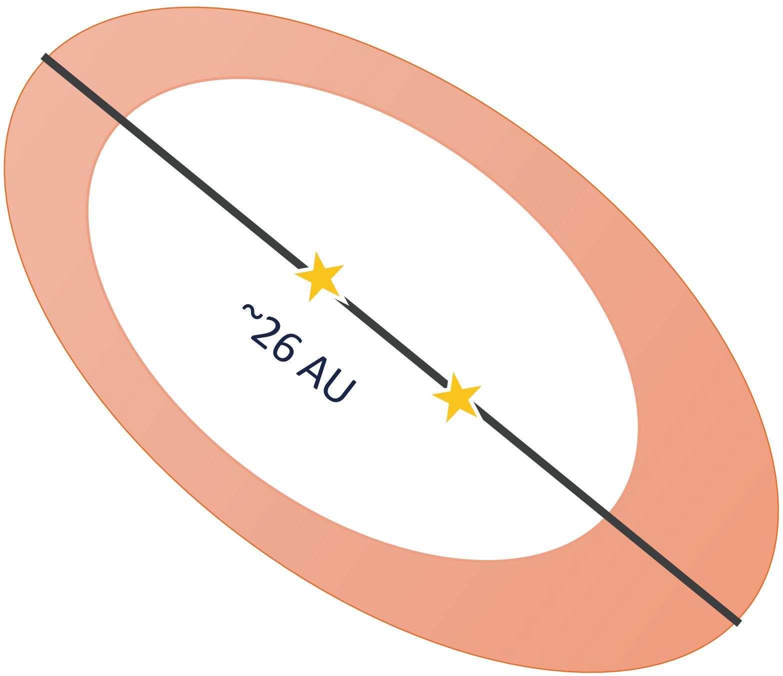
- Sensitive to 20 M_J companion at L band and 50 M_J at K band
- Sensitive to rapid giant planet accretion (~4 x 10^{-5} M_J^2/year) at L band

Summary and Comparison to Previous Results

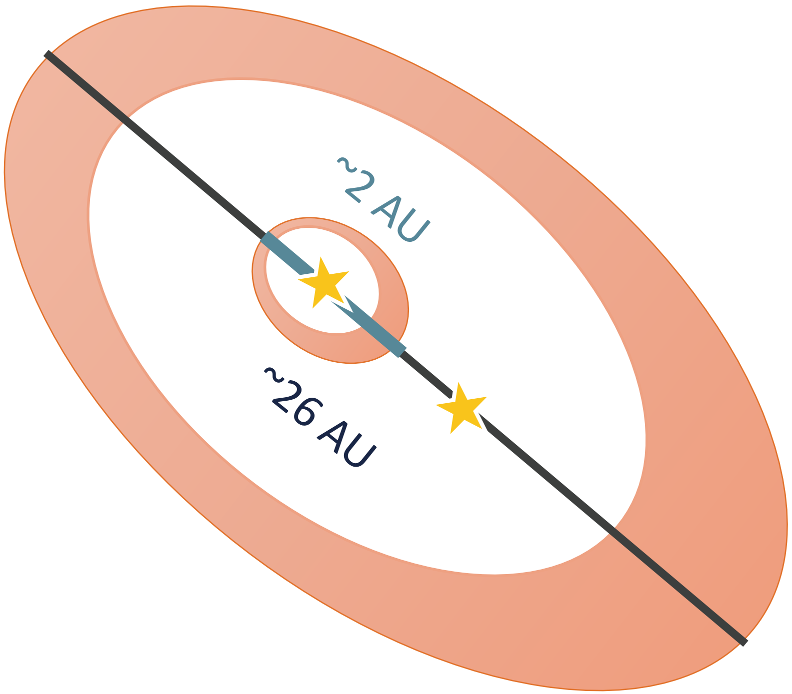
New discovery! We detect a circumprimary disk and update the geometry of the V892 Tau system.

Orbital parameter	Long et al. 2021	This work
Semi-major Axis (au)	7.1 ± 0.1	$6.8 \pm^{0.06}_{0.03}$
Period (yrs)	7.7 ± 0.2	$7.2 \pm^{0.04}_{0.06}$
Eccentricity	0.27 ± 0.1	0.25 ± 0.04
Inclination (degrees)	59.3 ± 2.7	57.9 ± 2.8
Dynamical Mass ($M_\odot$)	6.0 ± 0.2	$6.1 \pm^{0.2}_{0.1}$

Our understanding of the V892 Tau system geometry:



Before this paper

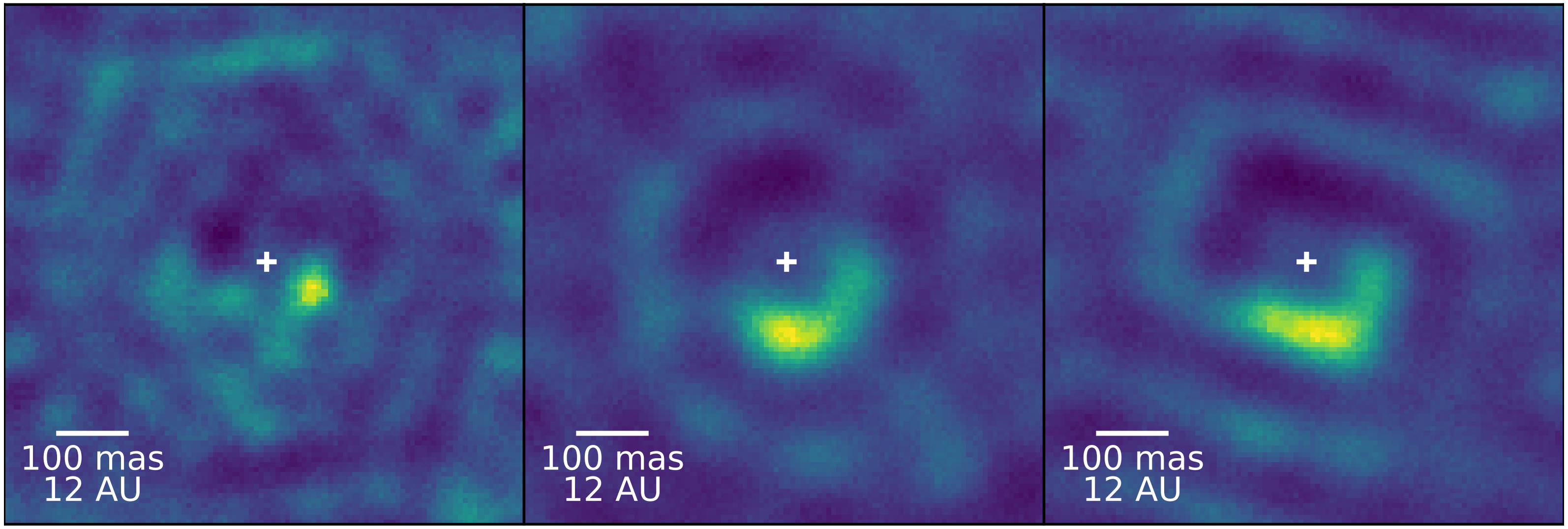


After this paper

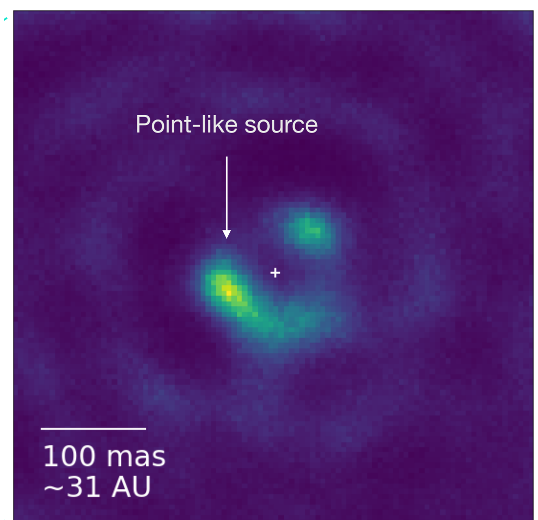
Future Work: Companion Candidate Detections

Companion Candidate 1

2019 | 2021 April | 2021 June



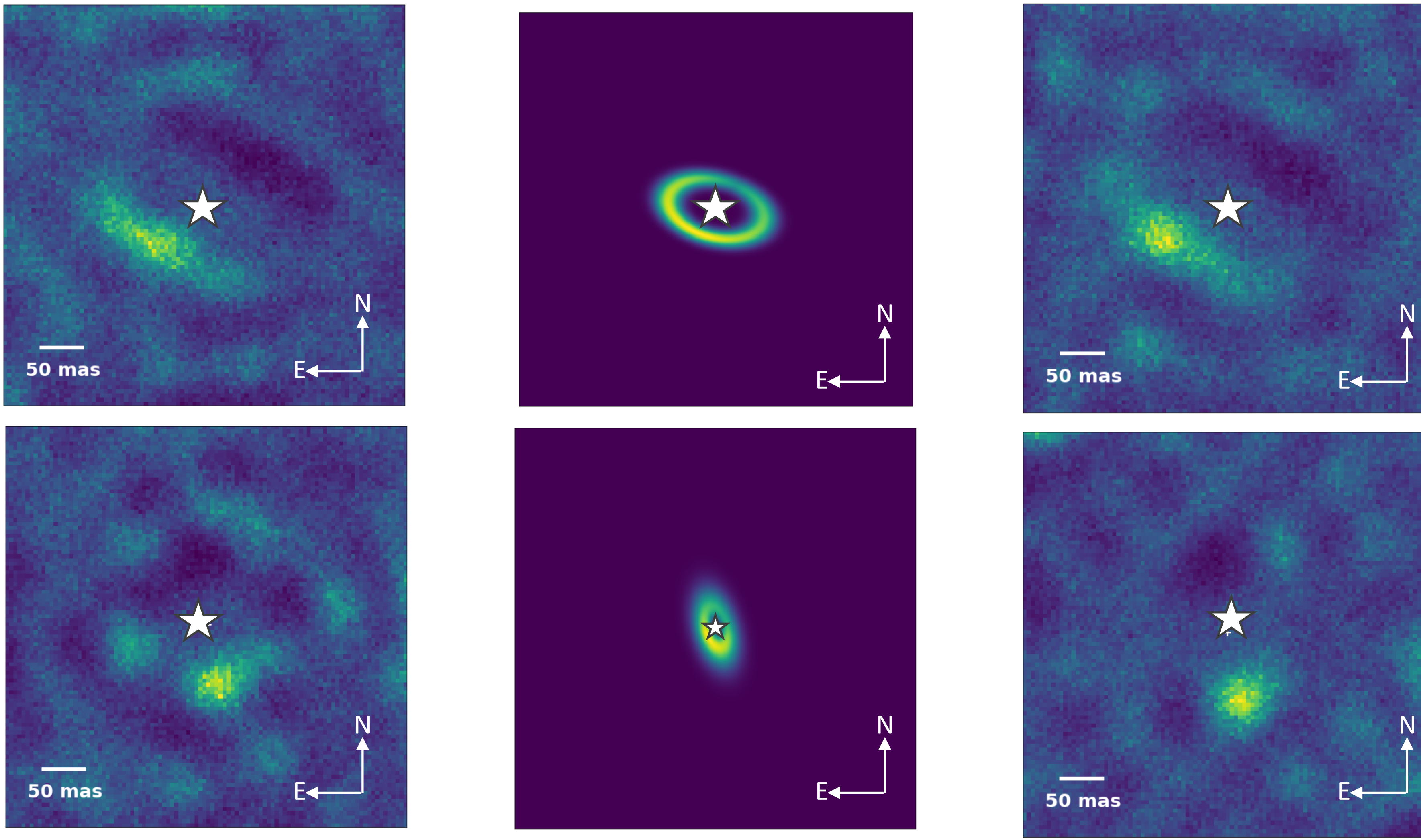
Companion Candidate 2



Vides et al. in prep

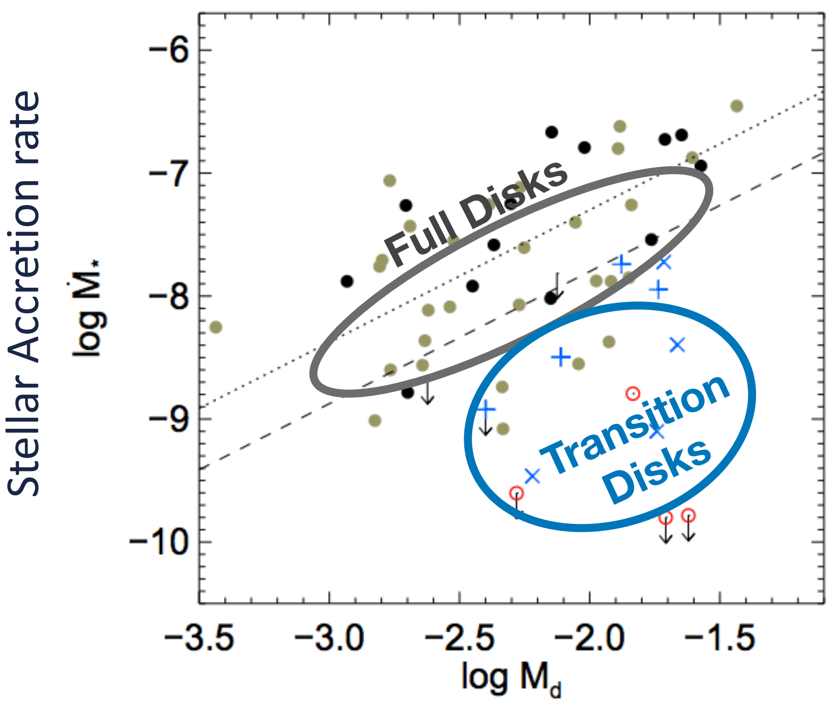
Future Work: Imaging the Inner Regions of Transition Disks

Data Reconstruction | Geometric Model | Model Reconstruction

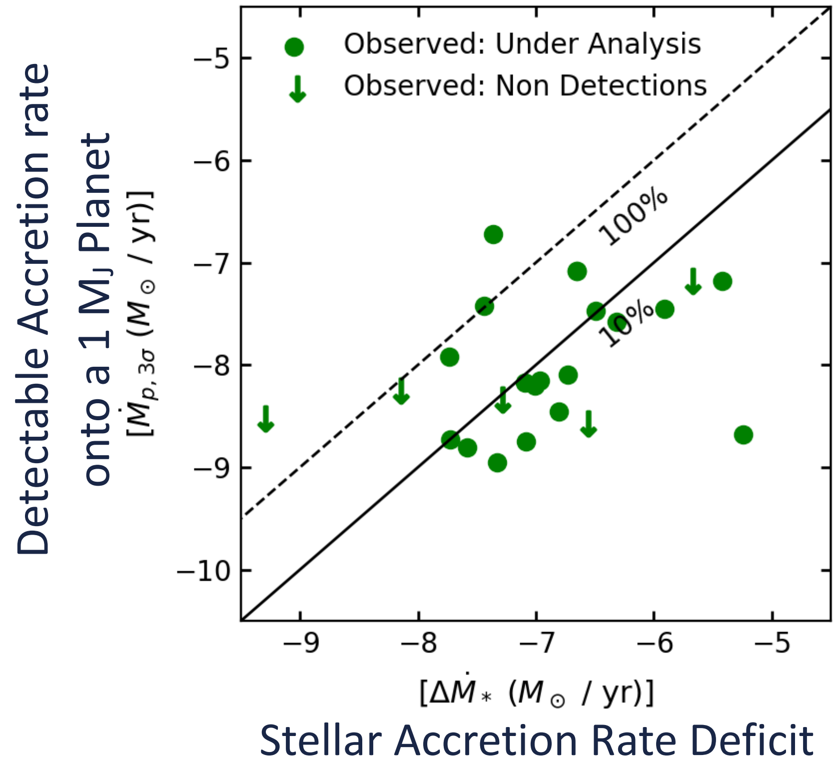


Vides et al. in prep

Overall Survey: Planet Mass x Accretion Rate Sensitivity



Najita+2015



Vides et al. in prep

Key Take Aways

V892 Tau:

- First detection of a circumprimary disk with FWHM= ~2 AU.
- We place contrast limits on undetected companions and characterize the AO performance of NRM + the Keck PyWFS.
- Multi-epoch, multi-wavelength data allows us to differentiate between disk emission and emission from an orbiting companion.

Science impacts of this survey overall:

- Detect and characterize rapidly protoplanets at solar-system scales
- Characterize disk structure and dynamical interactions
- Place statistical constraints on the underlying protoplanet population

High-angular-resolution Imaging of the V892 Tau Binary System: A New Circumprimary Disk Detection and Updated Orbital Constraints

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Acknowledgments

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