Observations of circumbinary discs and their alignment across a range of stellar populations

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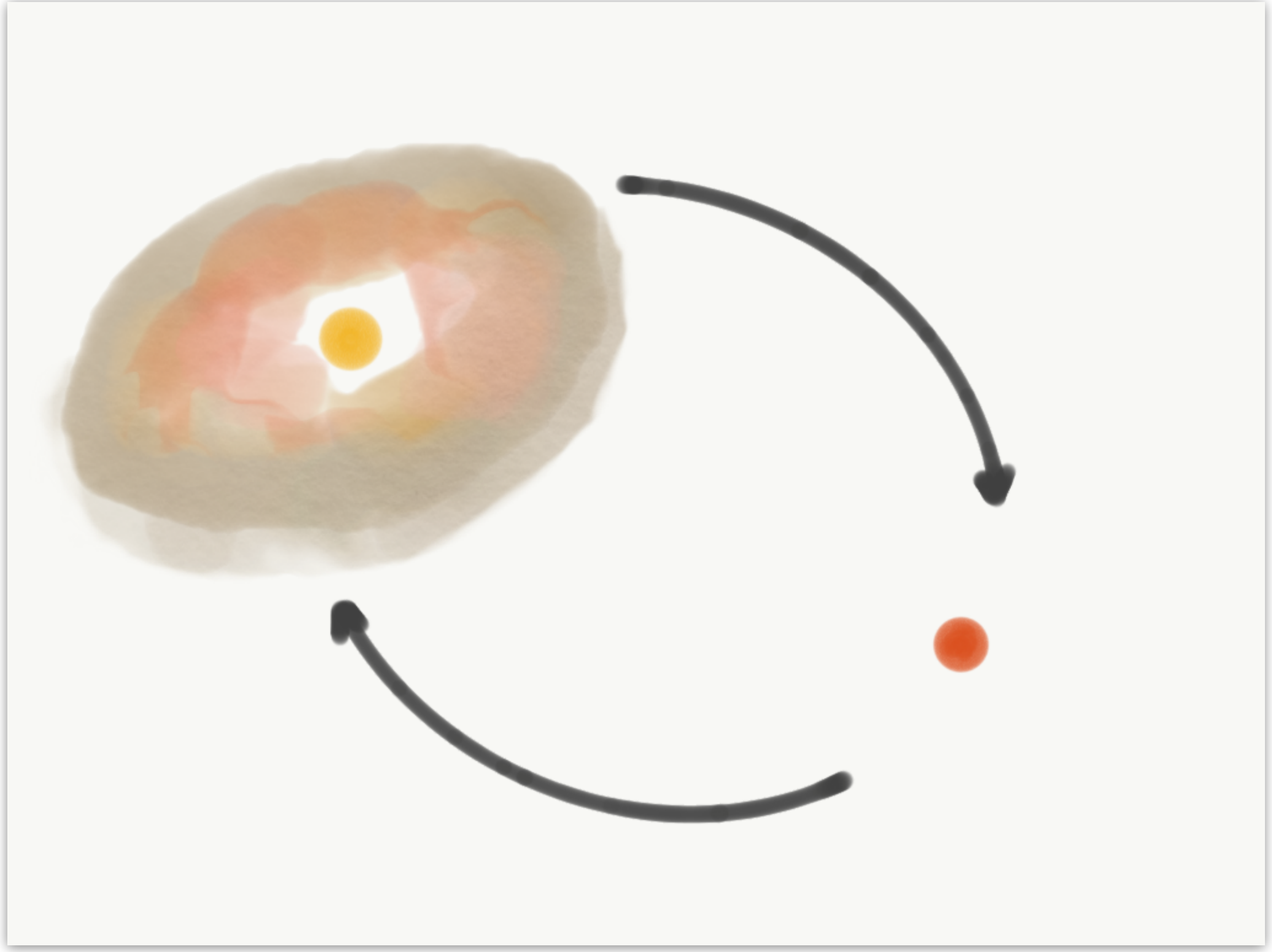
Outline

- **Intro**: stellar binary and circumbinary disk geometry
- **Techniques**: observations and what they tell us
- **Results**: alignment trends with stellar properties
- **Discussion**: implications for formation and evolution

Binary Disk Configurations



circumstellar disk with binary companion

binary star with **circumbinary** disk

Alignment of stellar and disk planes

θ is the angle between the angular momentum vector of the stellar binary and the angular momentum vector of the circumbinary disk

Frequently called the ***mutual inclination***

Colloquially, the “alignment” between the binary and the disk

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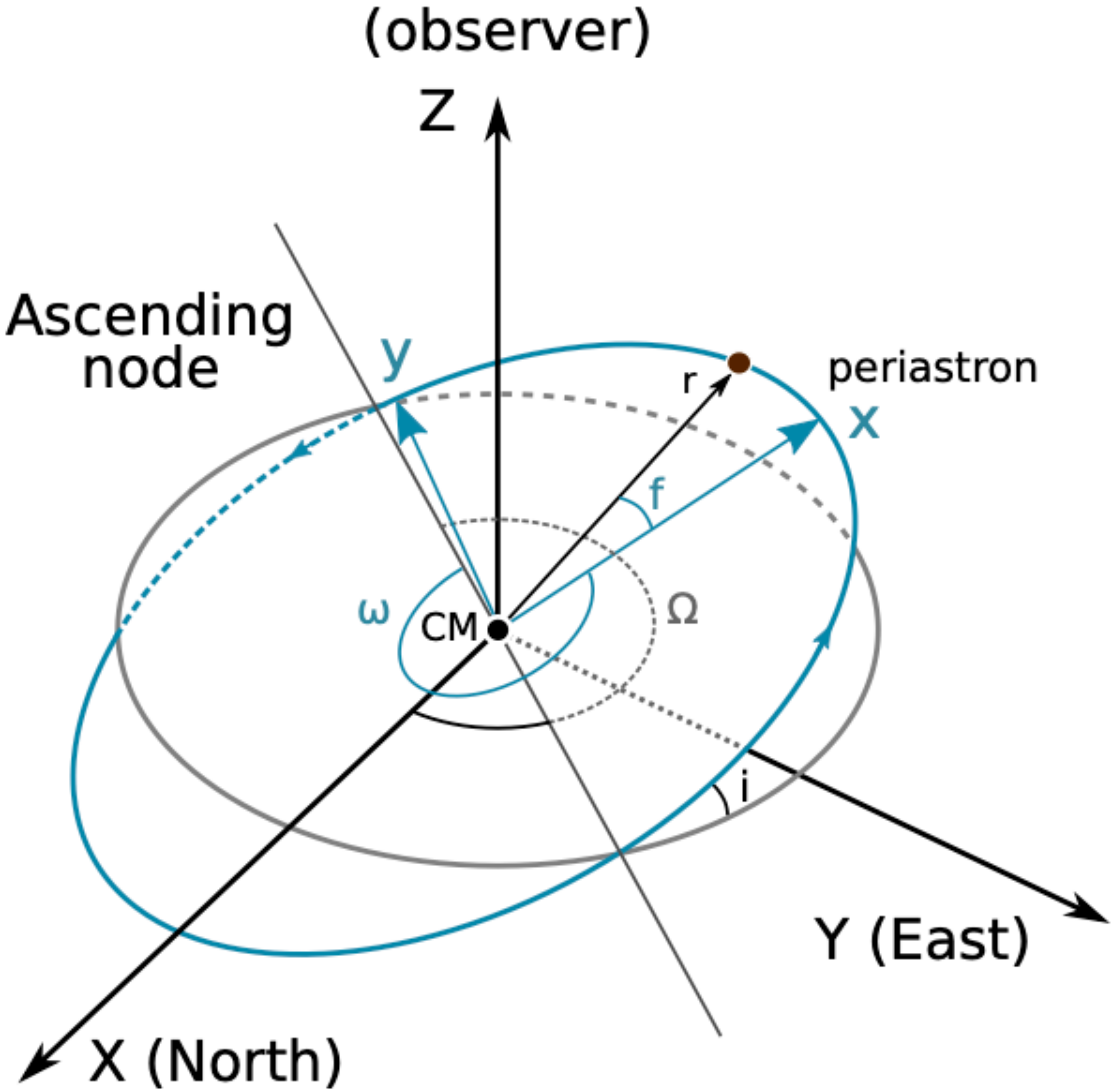
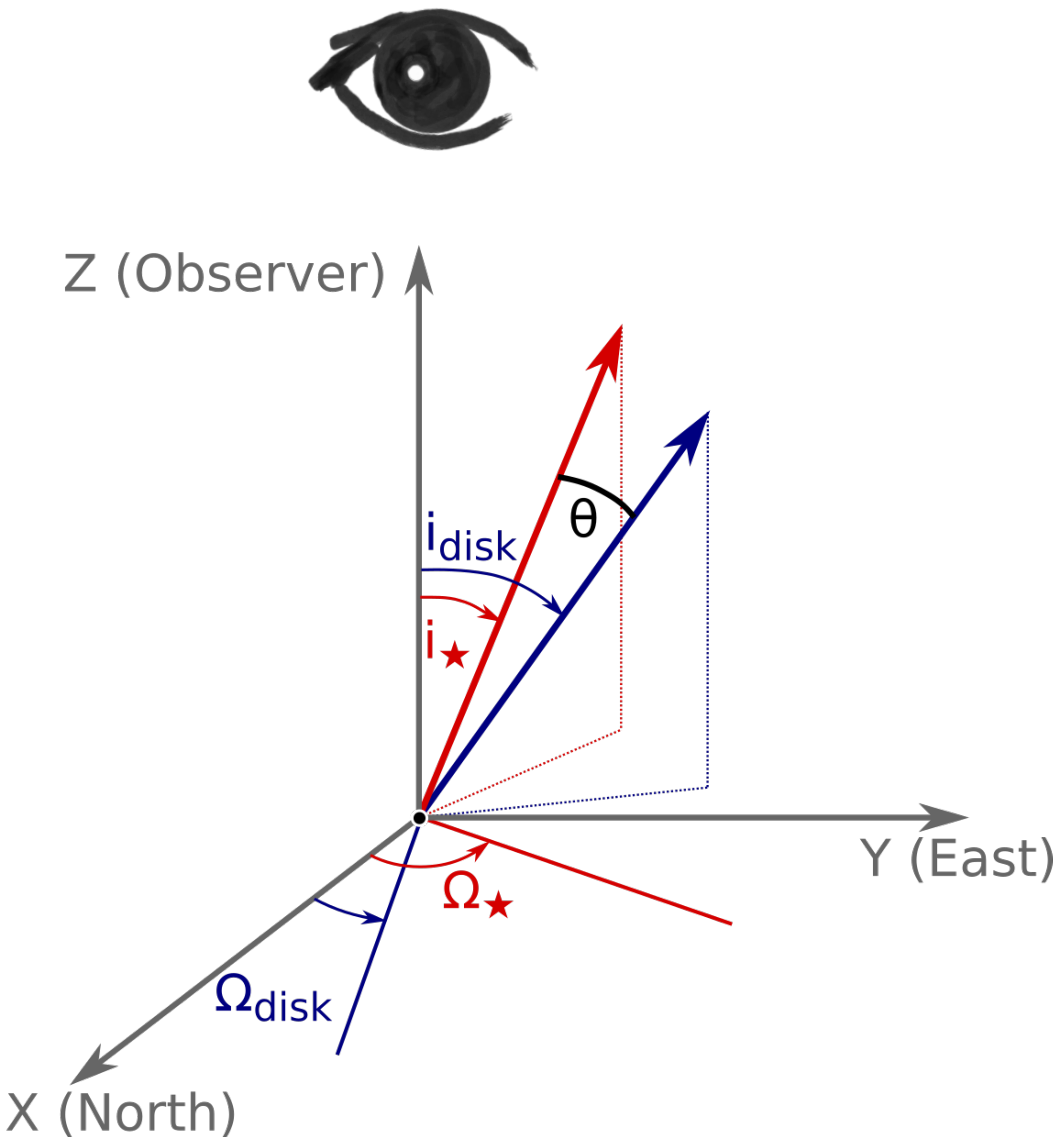
Orbital elements



Mutual inclination



$$\cos\theta = \cos i_{\rm disk} \cos i_\star + \sin i_{\rm disk} \sin i_\star \cos(\Omega_{\rm disk} - \Omega_\star)$$

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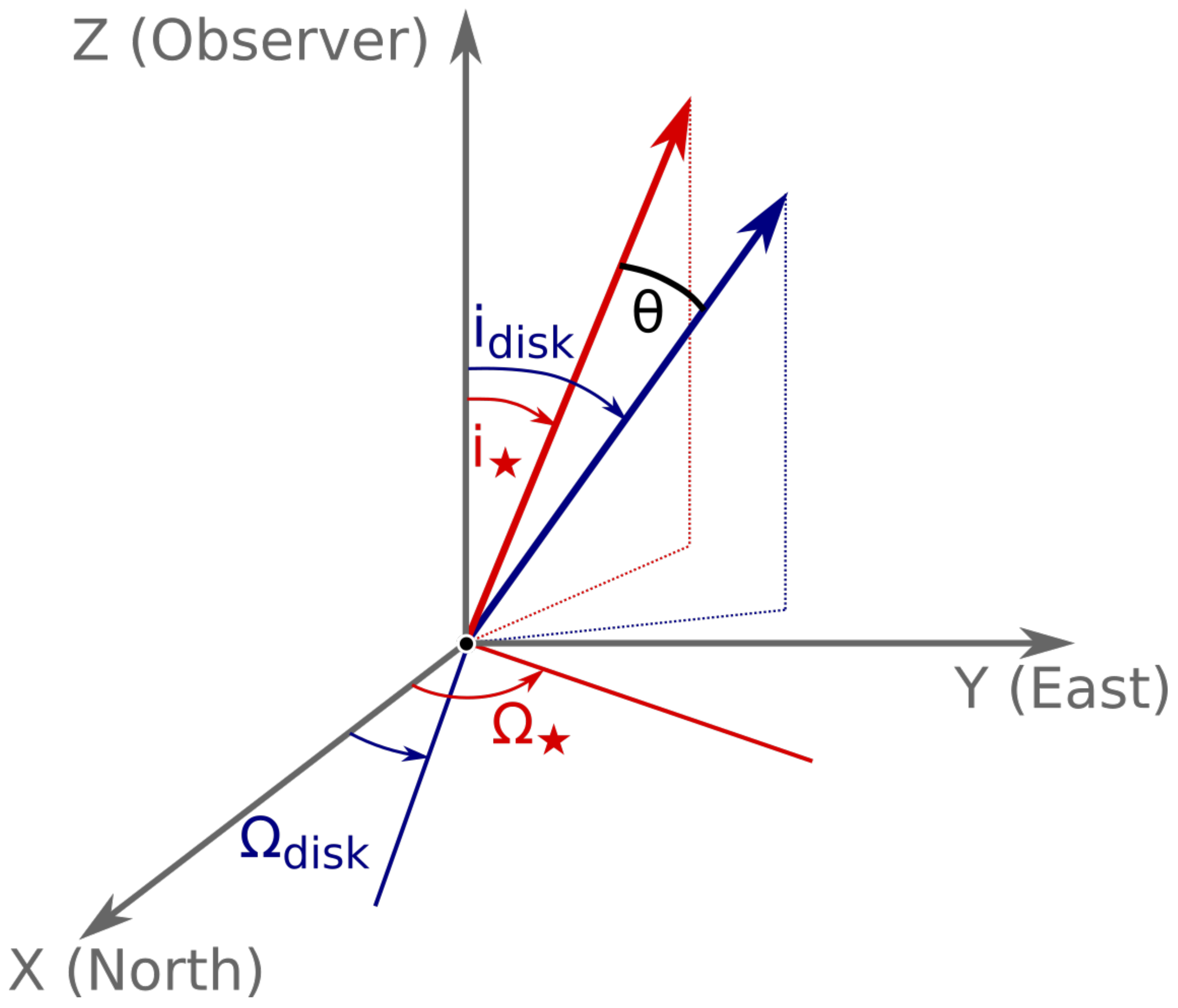
Observational requirements

To calculate mutual inclination θ, you need

- $i_\star$: inclination of stellar binary relative to sky
- $\Omega_\star$: position angle of ascending node of binary
- $i_{\rm disk}$: inclination of disk relative to sky
- $\Omega_{\rm disk}$: position angle of ascending node of disk

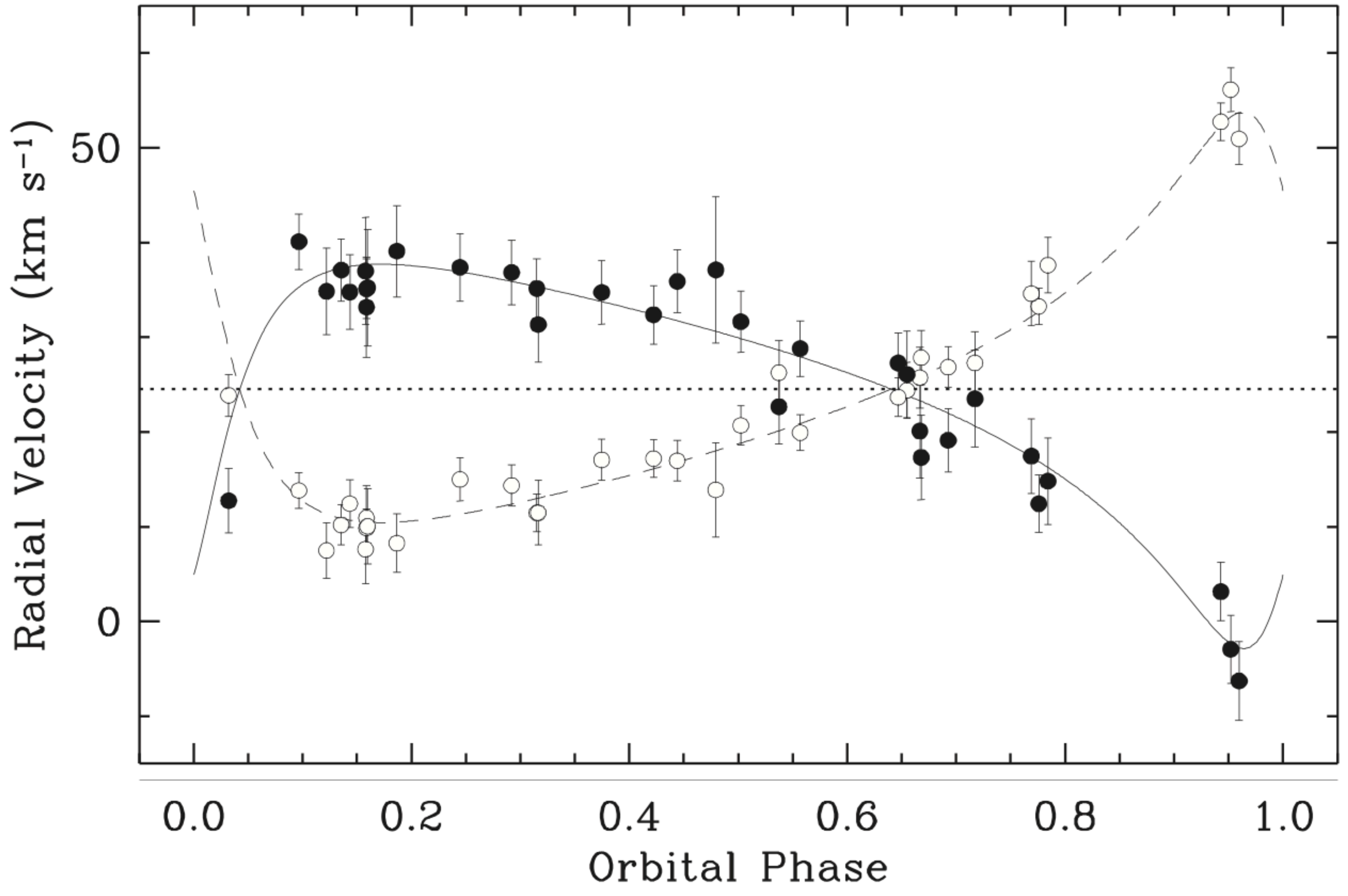


$$\cos\theta = \cos i_{\rm disk}\cos i_\star + \sin i_{\rm disk}\sin i_\star\cos(\Omega_{\rm disk} - \Omega_\star)$$

Stellar orbital properties: $i_\star$, $\Omega_\star$

High Resolution Spectroscopy Only

- Constrains $(M_1 + M_2)\sin^3 i_\star$ via semi-amplitudes
- Good for binaries with $P < 1$ yr
- No knowledge of $\Omega_\star$ (no spatial resolution)
- Combined with disk dynamical constraint, yields $i_\star$ with $\pm 90°$ degeneracy

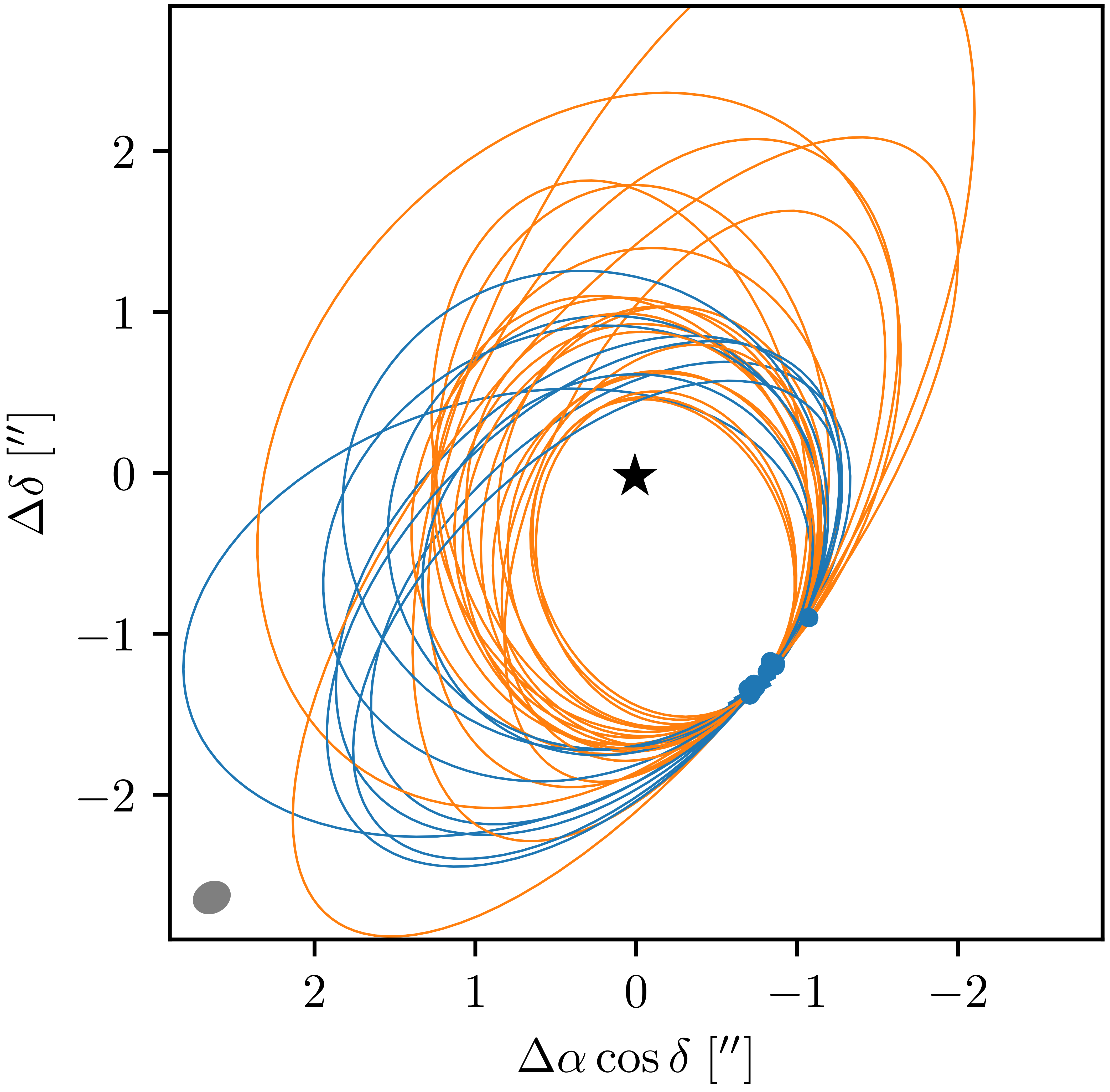


Czekala et al. 2016

Stellar orbital properties: $i_\star$, $\Omega_\star$

Visual / Adaptive Optics / NRM

- Good for binaries with $a > 10$ au
- Usually need 5+ yrs of observations to cover significant orbit
- Measures $i_\star$ with no degeneracy
- Measures $\Omega_\star$ with $\pm 180^\circ$ degeneracy
- Note: different subfields use different $\Omega_\star$ conventions



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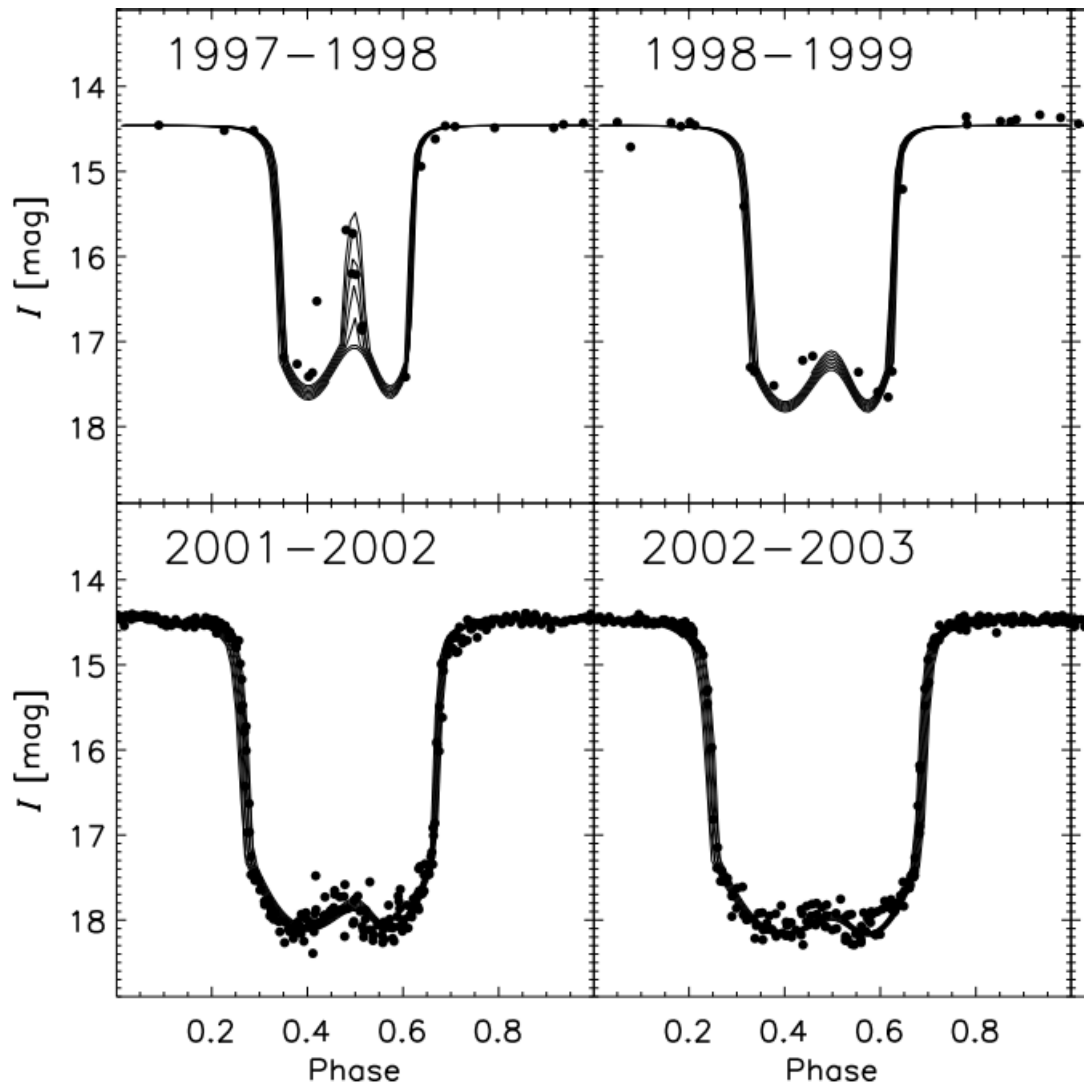
Other techniques for stellar orbits

- Photometric time series for eclipsing binaries: gold standard *but*
  - geometrically rare
  - light curve variable w/ disk
- Joint RV + astrometry is amazing, *but* requires
  - short P for radial velocity
  - long P for astrometry
  - few systems in the sweet spot w/ CB disks

KH 15D



Winn et al. 2006

Disk geometry: sub-mm interferometry

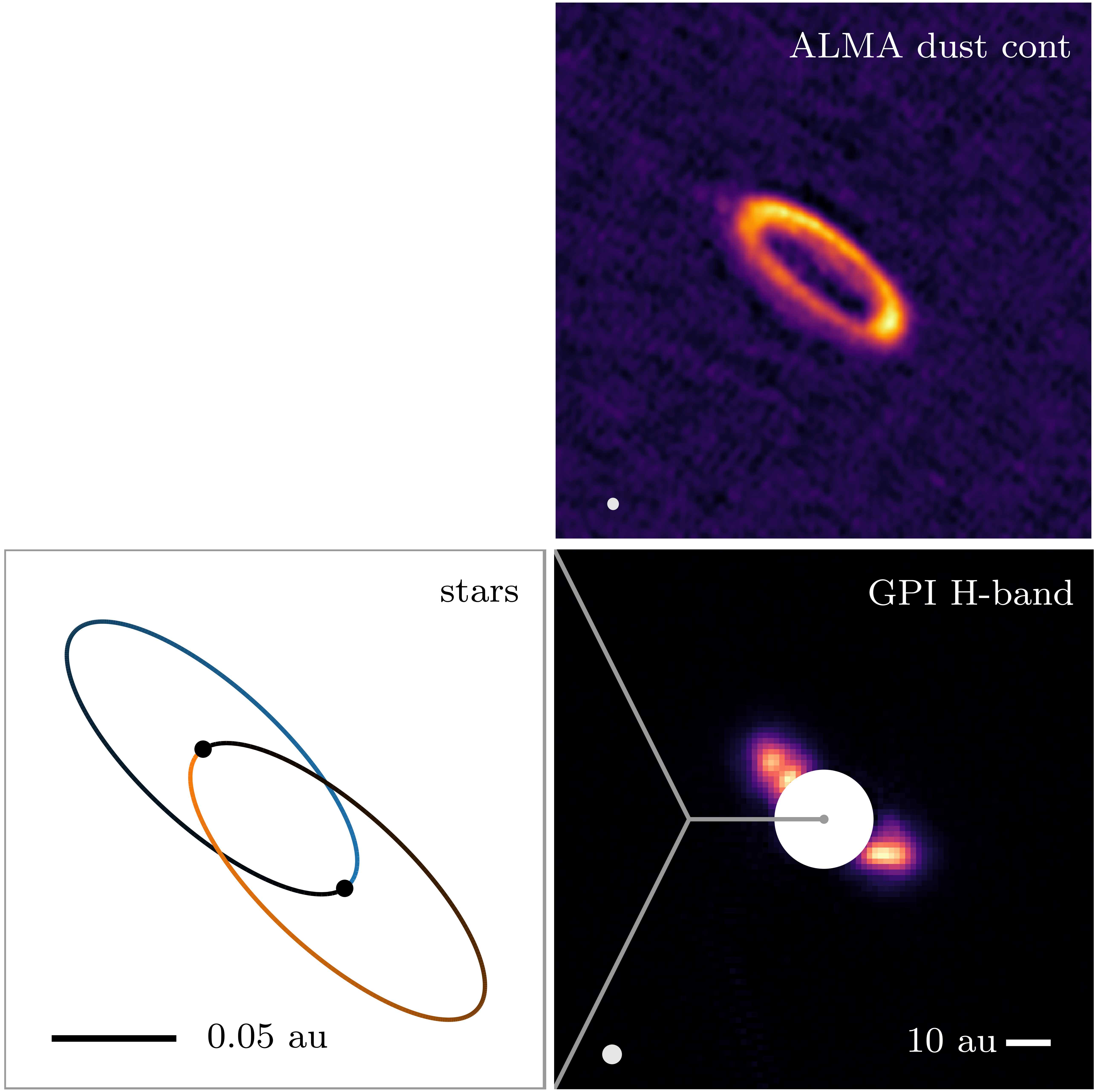
A. Marinkovic/X-Cam/ALMA (ESO/NAOJ/NRAO)

Disk geometry: $i_{\mathrm{disk}}, \Omega_{\mathrm{disk}}$

Spatially resolved, sub-mm observations of **dust continuum**

- $i_{\mathrm{disk}} \pm 90^{\circ}$
- $\Omega_{\mathrm{disk}} \pm 180^{\circ}$
- 4 possible $\{i_{\mathrm{disk}}, \Omega_{\mathrm{disk}}\}$ pairs
- Note: multiple definitions of inclination and position angle abound, unrelated to stellar orbital conventions

IR observations of scattered light partially break degeneracy with forward scattering: brighter side is the near side



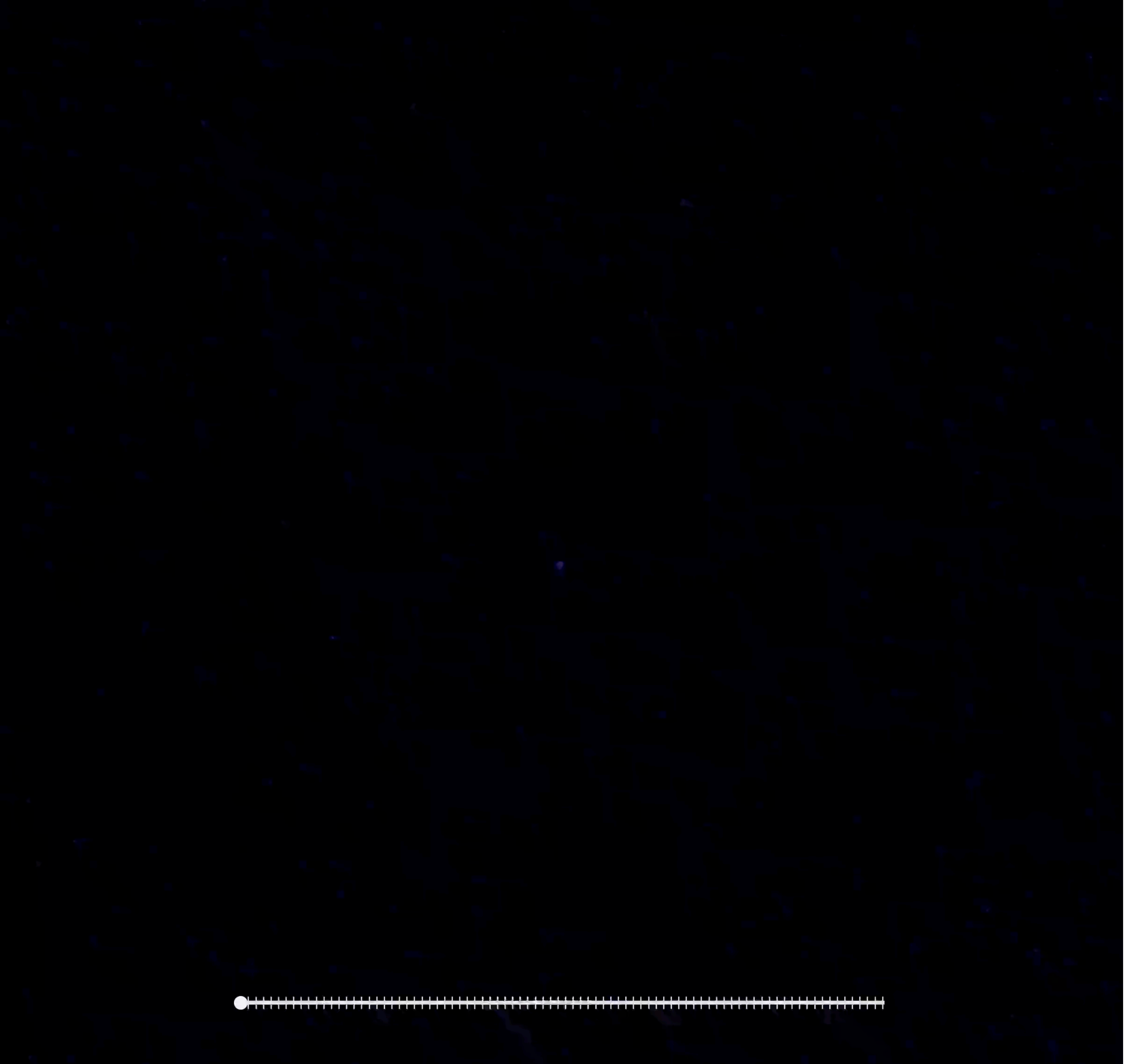
Czekala et al., in prep; Esposito et al. 2020

Disk geometry: i_{disk}, Ω_{disk}

Example of partial degeneracy:

- amazing scattered light observations reveal flared disk surface
- But don't know which way disk rotates
- 2 possible $\{i_{\mathrm{disk}}, \Omega_{\mathrm{disk}}\}$ pairs

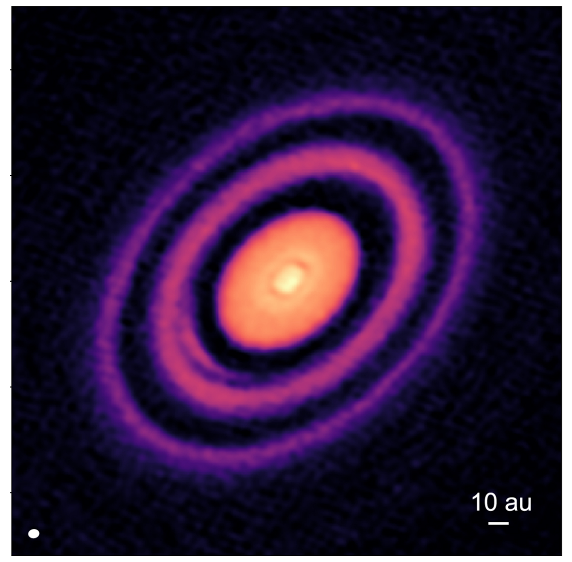
ESO/H. Avenhaus et al./DARTT-S collaboration



Molecular line spectroscopy shows which way disk rotates

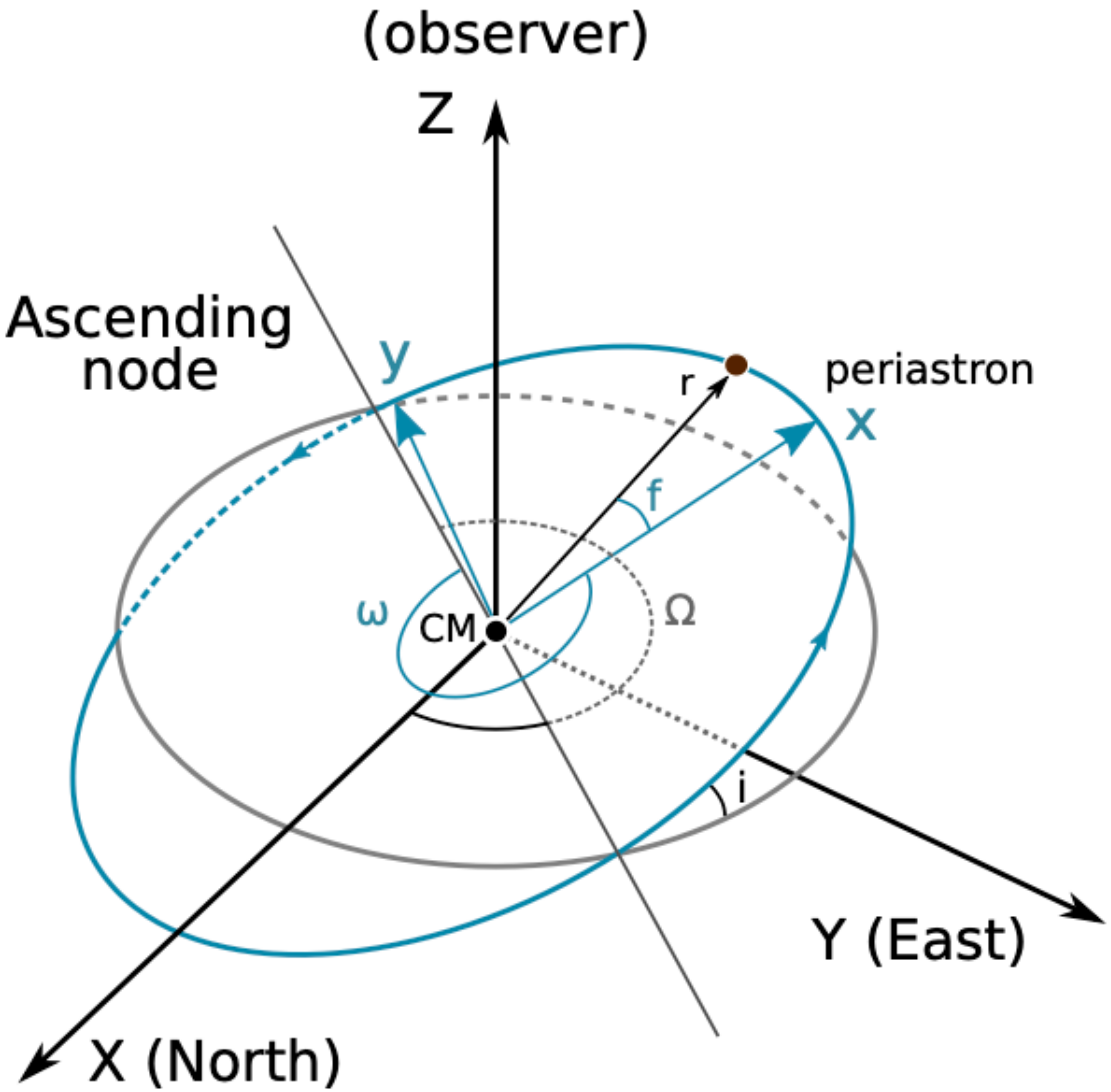
Doppler-shifted CO emission reveals kinematic information on orbits of material in disk

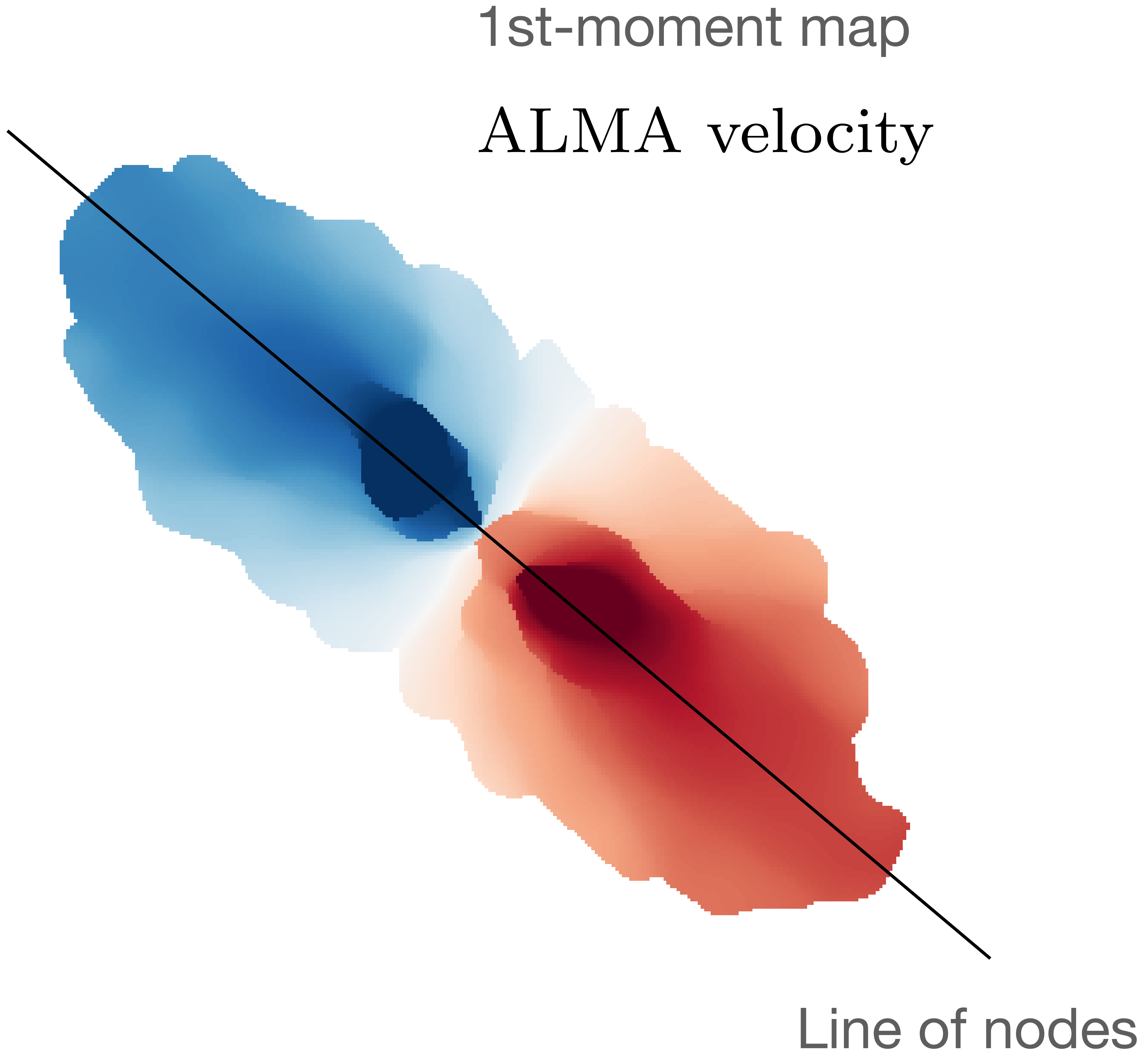
reveals $\Omega_\star$ unambiguously



continuum for reference

DSHARP Survey; Isella+18





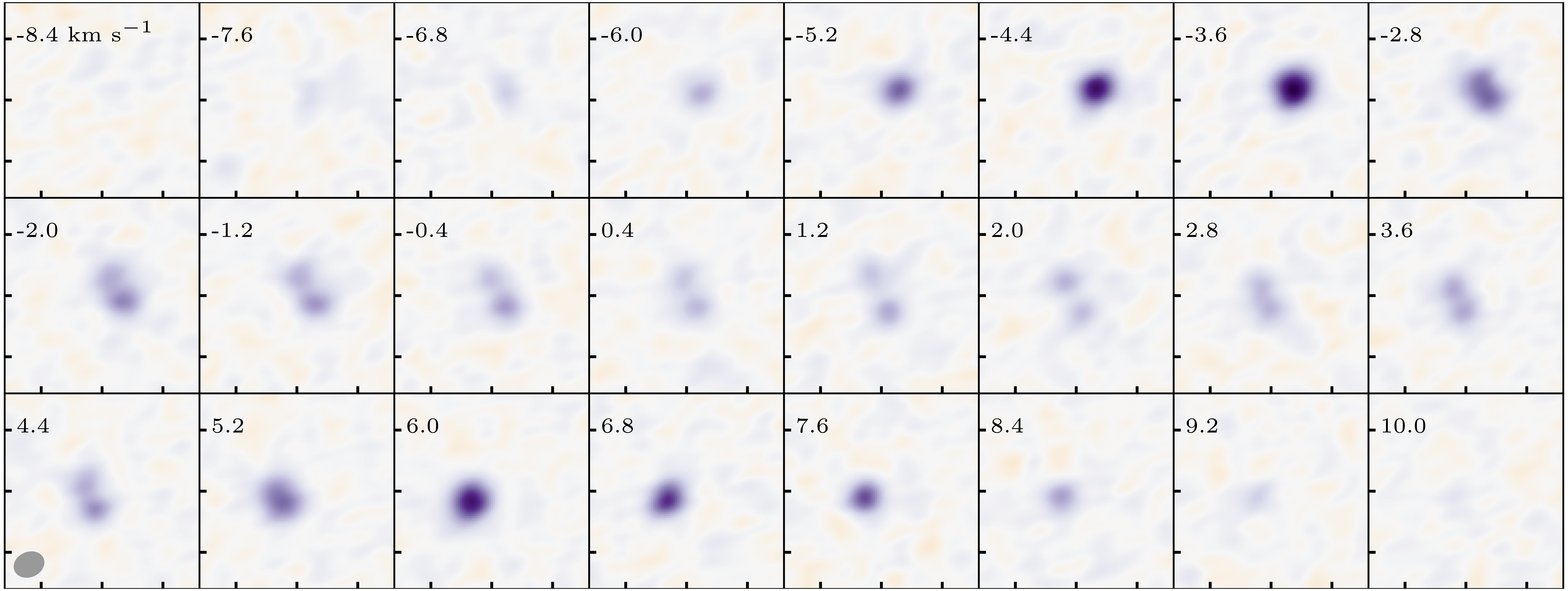
1 known $\{i_{\rm disk}, \Omega_{\rm disk}\}$ pair

Techniques

Czekala et al. in prep

Dynamical Mass Modeling $M_1 + M_2$

ALMA 12CO J=2-1 Data: TWA 3A Circumbinary Disk



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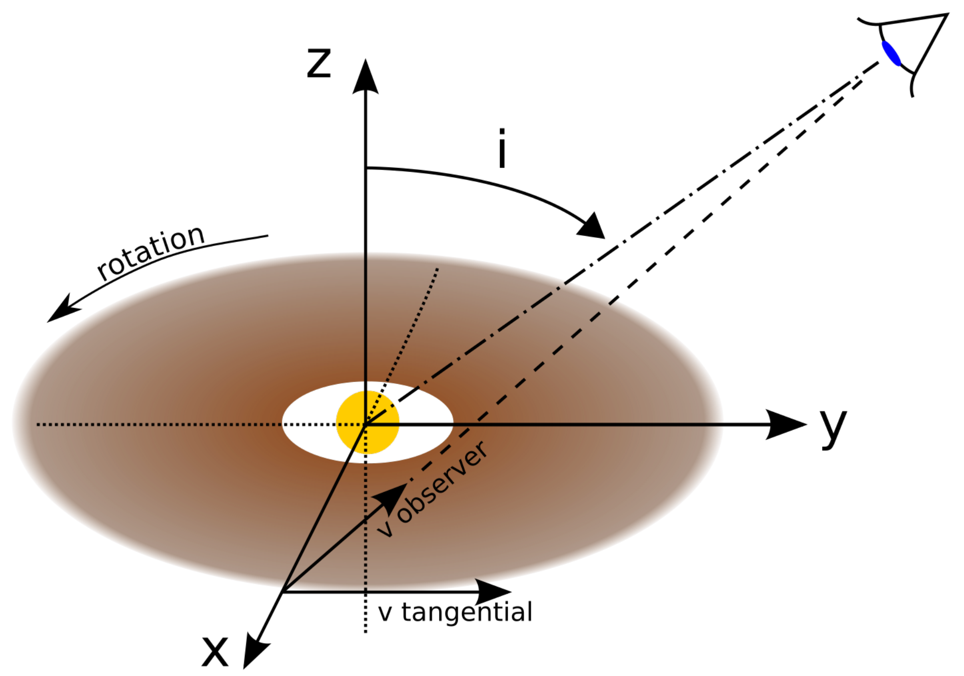
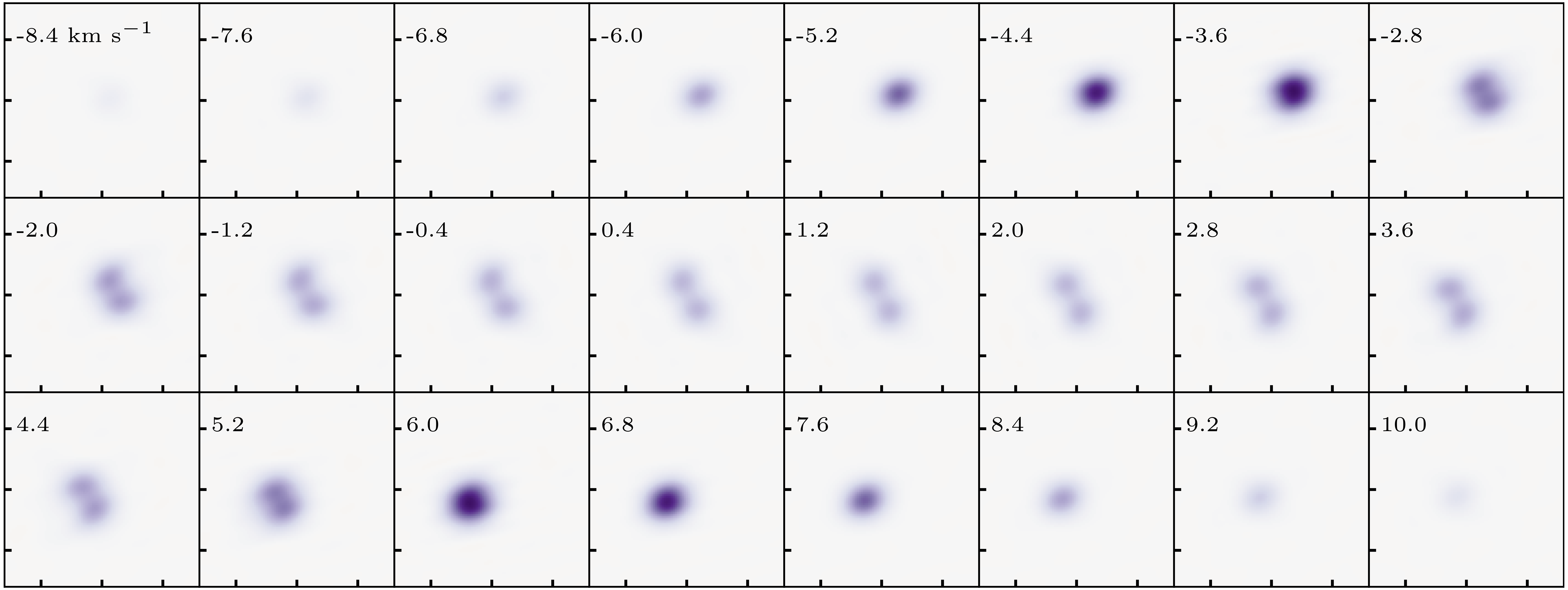
TWA 3A Circumbinary Disk

ALMA 12CO J=2-1 Model





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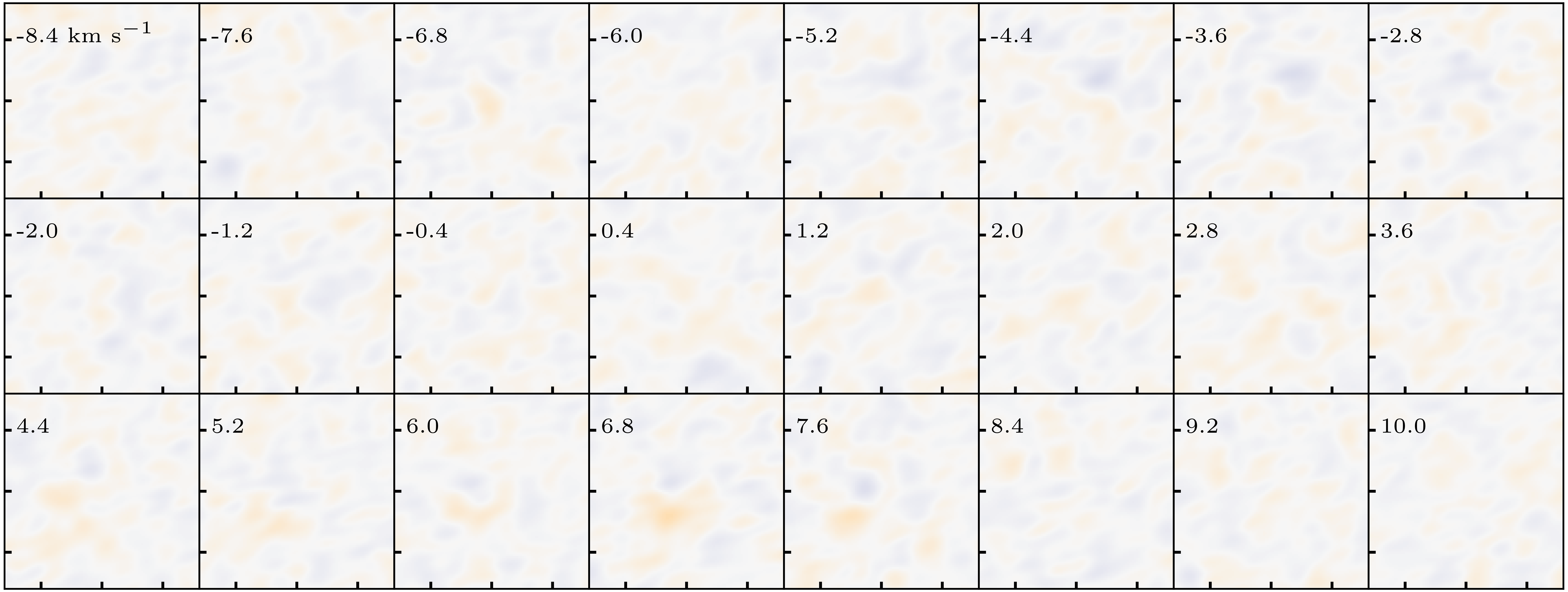
TWA 3A Circumbinary Disk

ALMA 12CO J=2-1 Residuals



Combine dynamical mass modeling $(M_1 + M_2)$ with spectroscopic binary constraints $(M_1 + M_2)\sin^3 i_\star$ to derive $i_\star$

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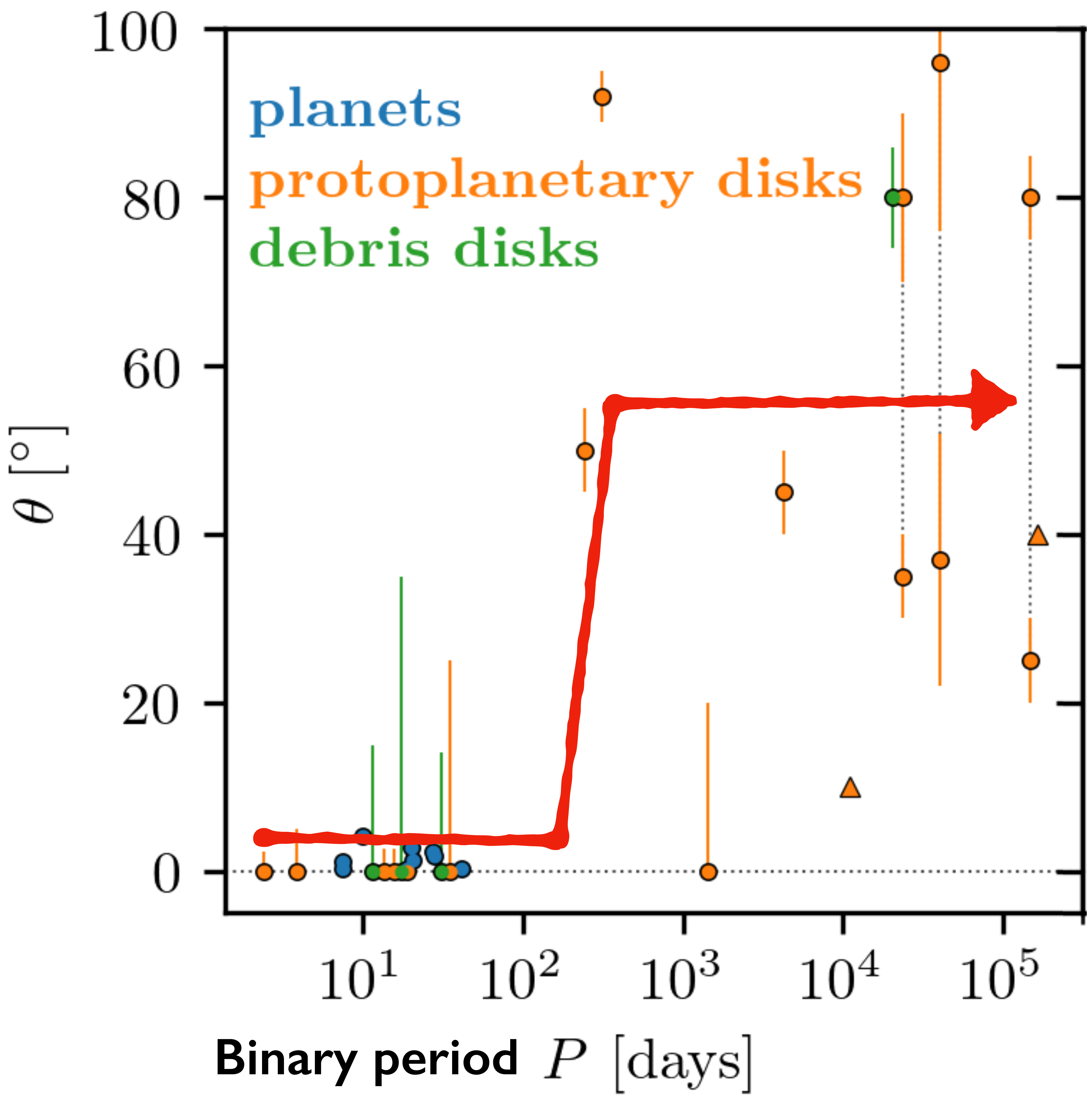
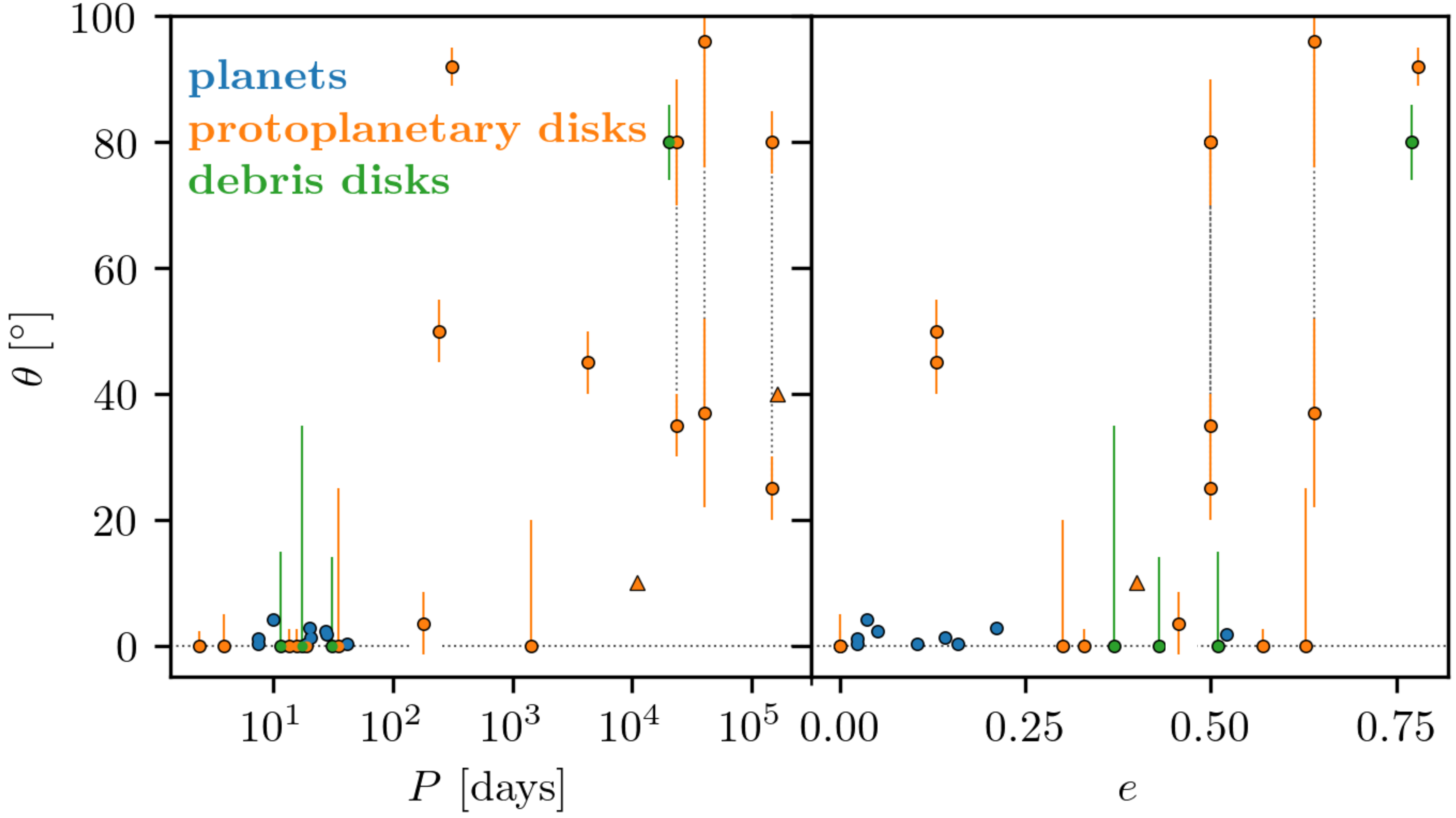
Mutual inclinations of circumbinary protoplanetary disks



Czekala+19

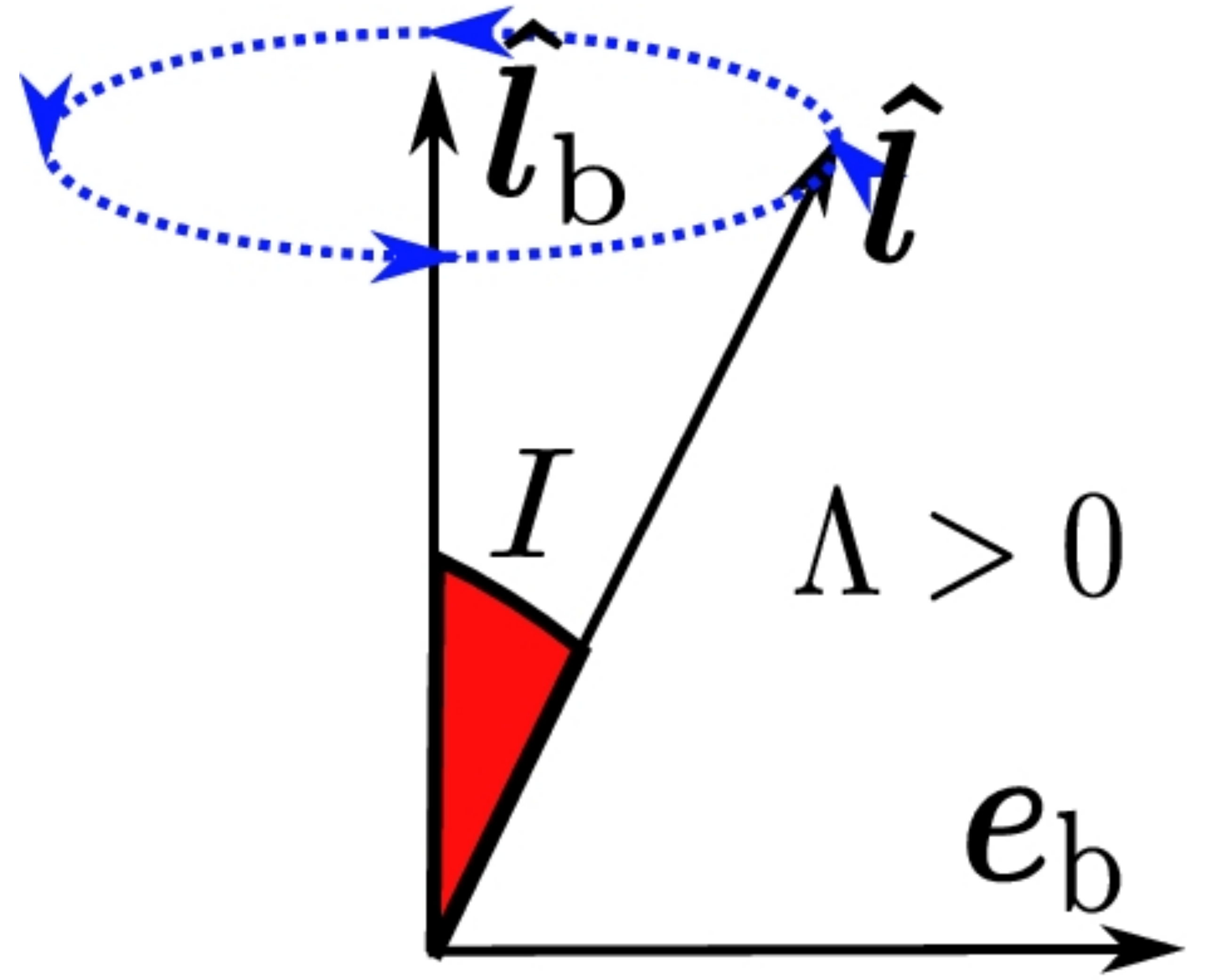
The mutual inclination landscape

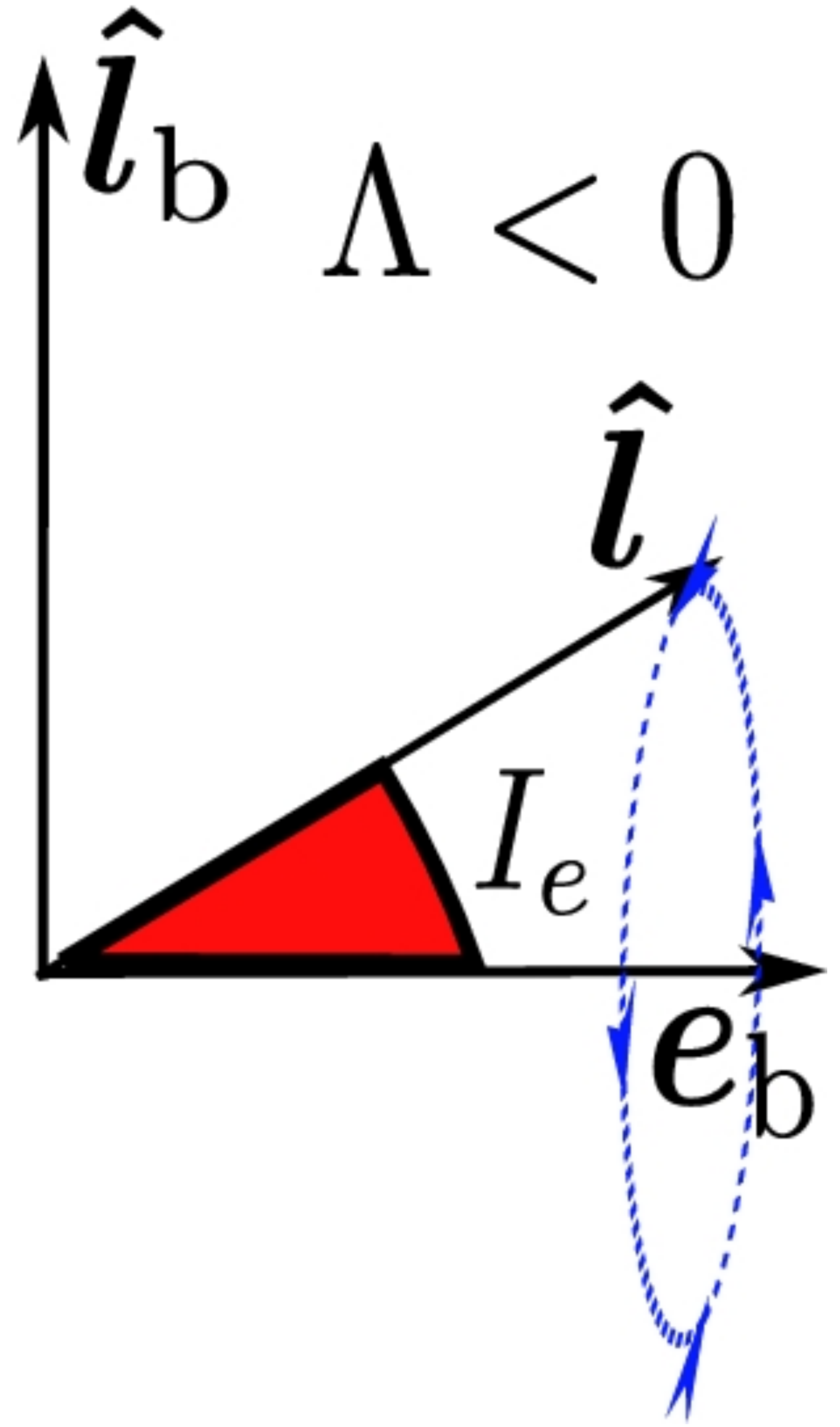


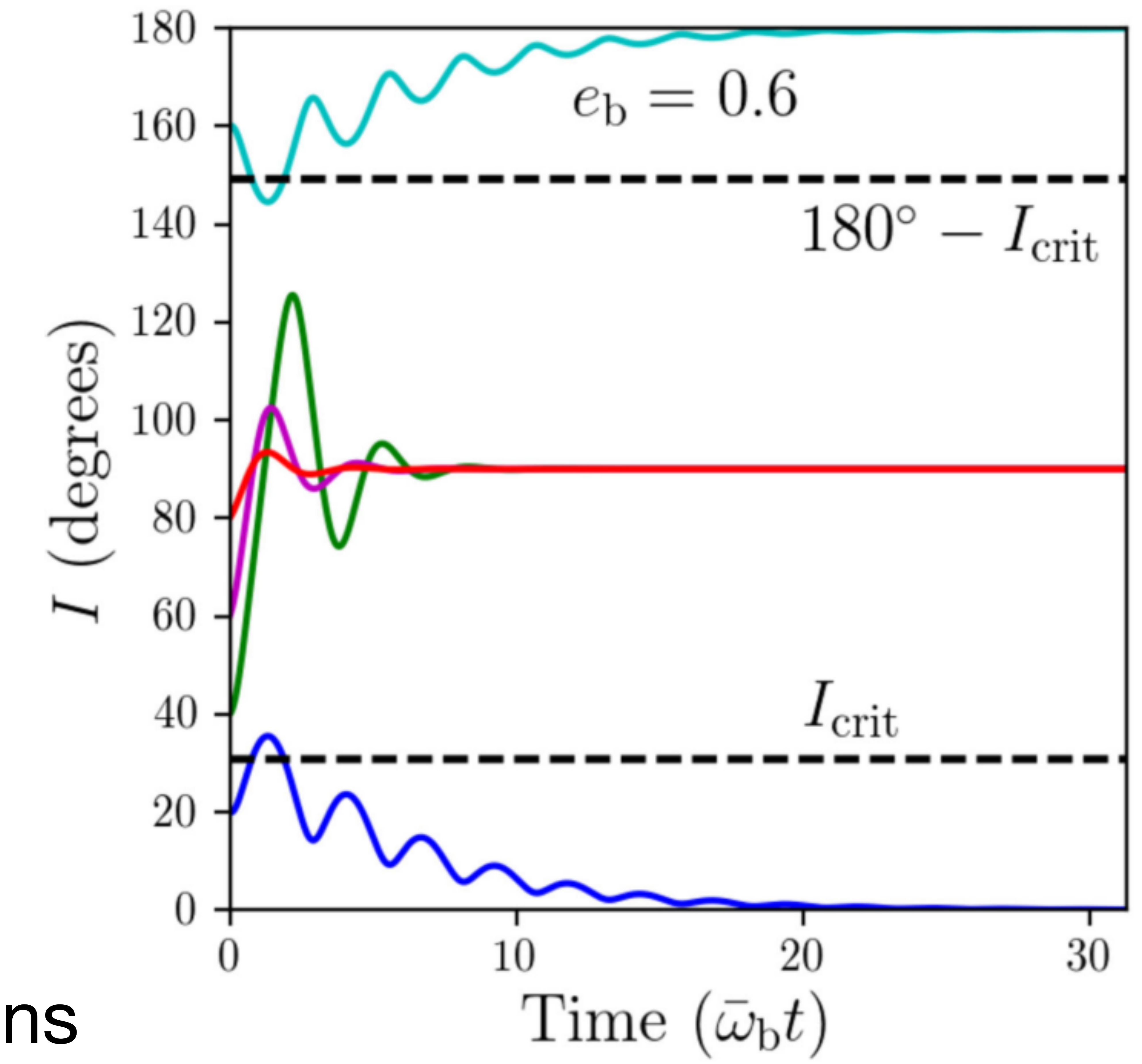
- Circumbinary disks & planets remain (as a rule) coplanar out to ~40 days
- Dispersions widen after this—by how much and how quickly?
- WW Cha $P = 207$ days, $e = 0.45$, $\theta < 8^\circ$
- HD 98800 B $P = 315$ days, $\theta = 87^\circ$

***Czekala**+21a; GRAVITY collaboration+21*
See also Zurlo et al. 2023

Theory predicts a CB disk around an eccentric binary will evolve to *either* a coplanar or polar orientation







Eccentric binaries can drive large mutual inclinations with disks, especially if initial misalignment is already significant

Foucart & Lai 13, Martin & Lubow 17; Zanazzi & Lai 18, Lubow & Martin 18, Cuello & Guippone 19

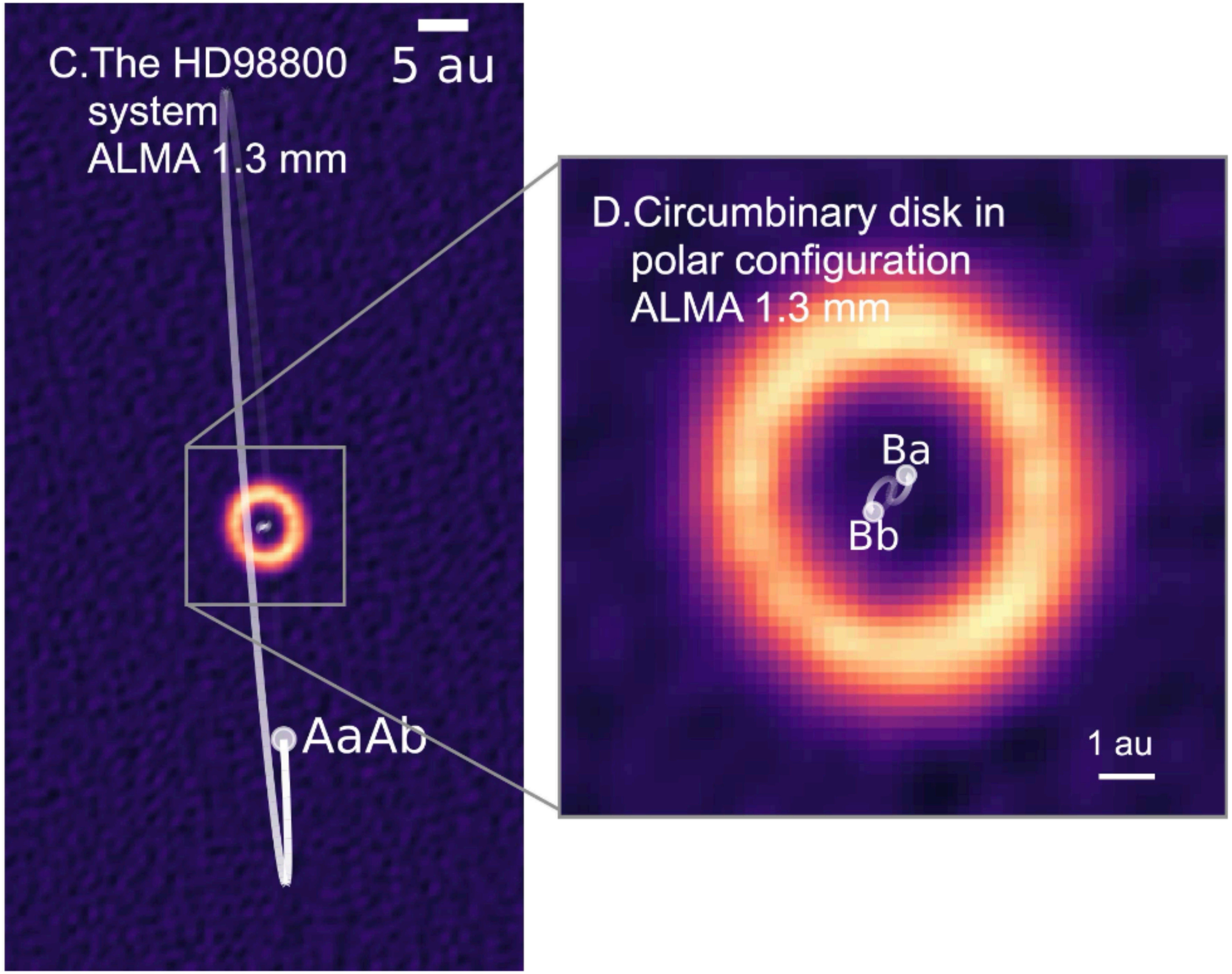
HD 98800B

$e = 0.78$

$P = 315$ days

$a = 1.05$ au

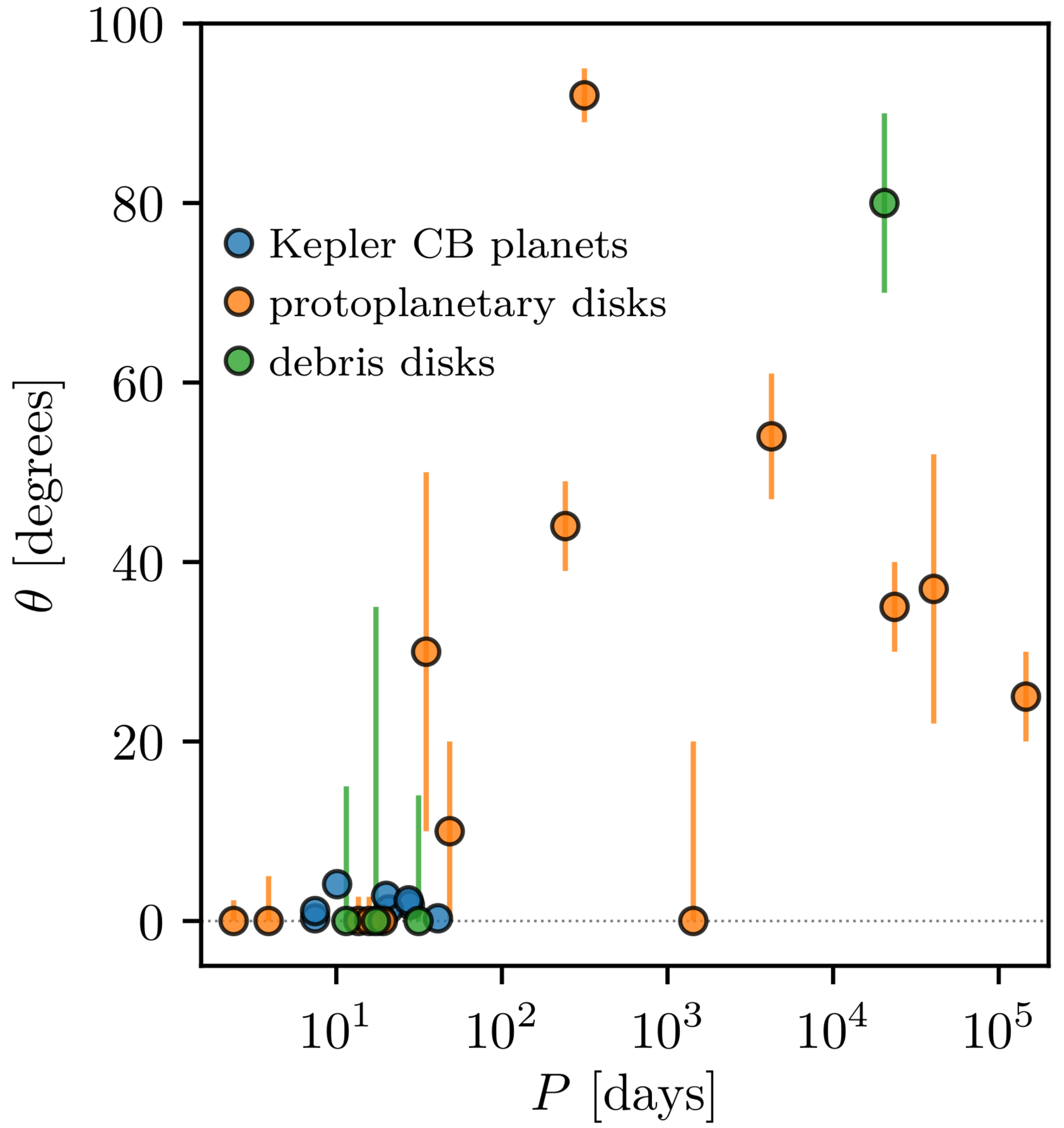
$\theta \approx 90°$

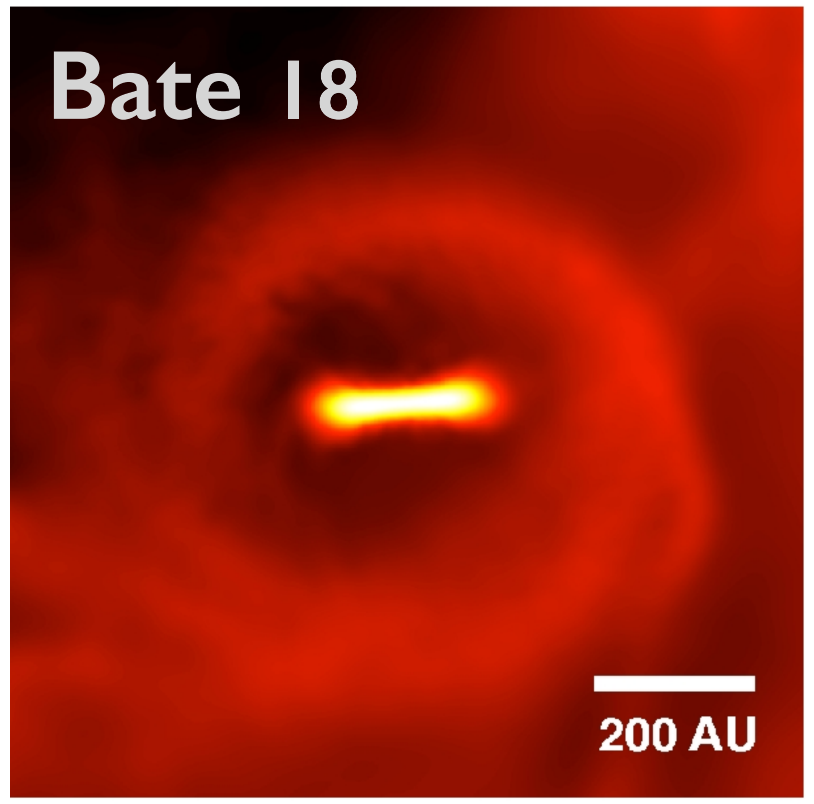


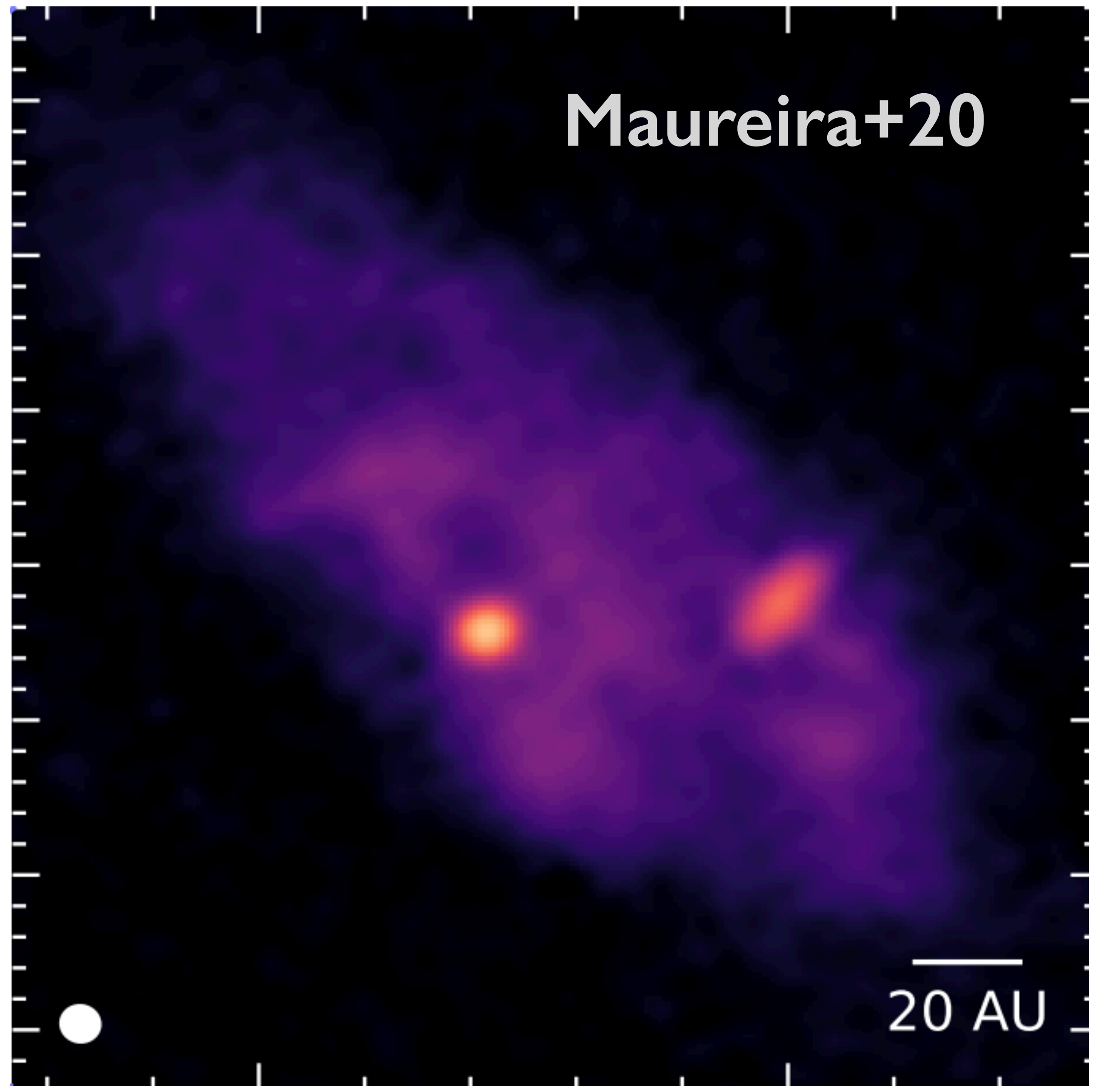
Kennedy+19

Washington Post /
Cleeves

Formation and alignment

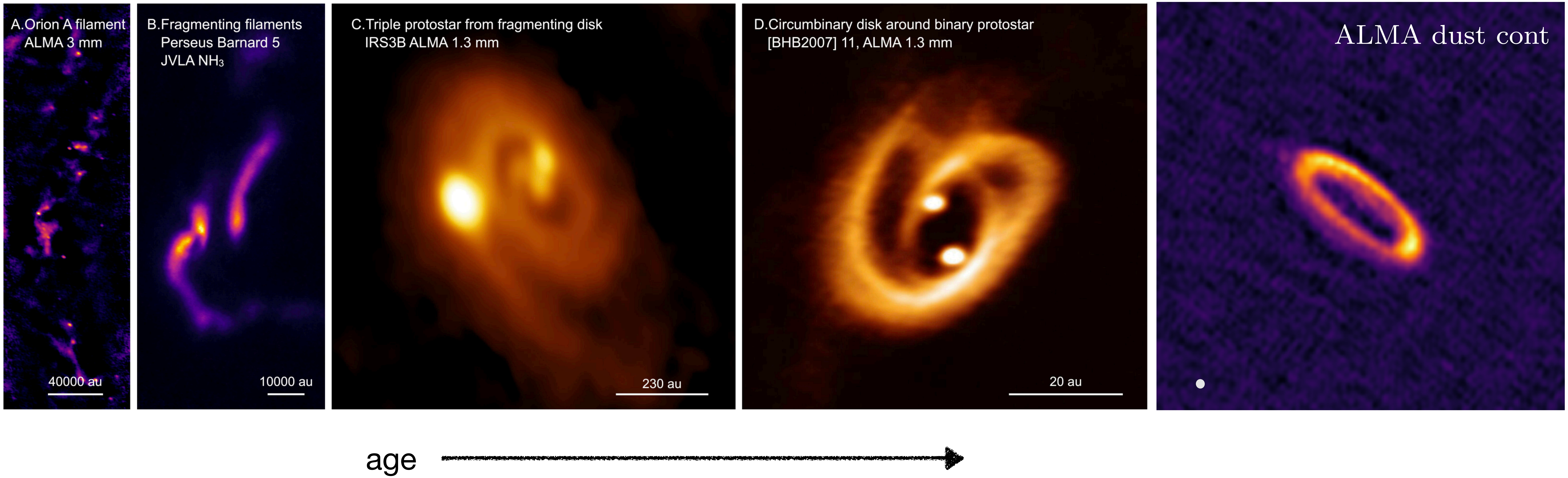






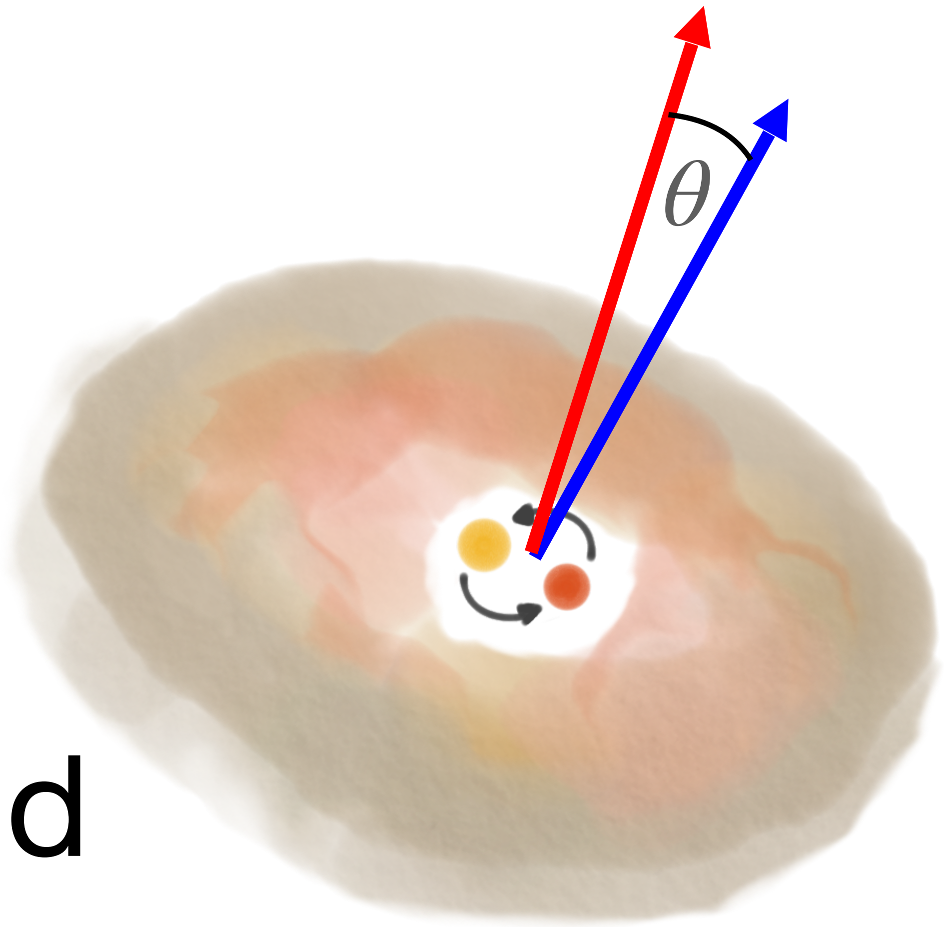
- Difficult to directly form binaries within $a < 5$ au→ fragmentation at larger distances + migration
- Short periods (P = 5 - 40 days) → substantial energy dissipation from orbit/disk interactions, e damping
- Long periods (P > 40 days) → vestigial random orientation from formation; e/i pumping more effective

Tokovinin+06; Foucart and Lai 13; Muñoz and Lai 15; Tokovinin 17; Moe and Kratter+18; Fleming+18, Bate 18; Maureira+20



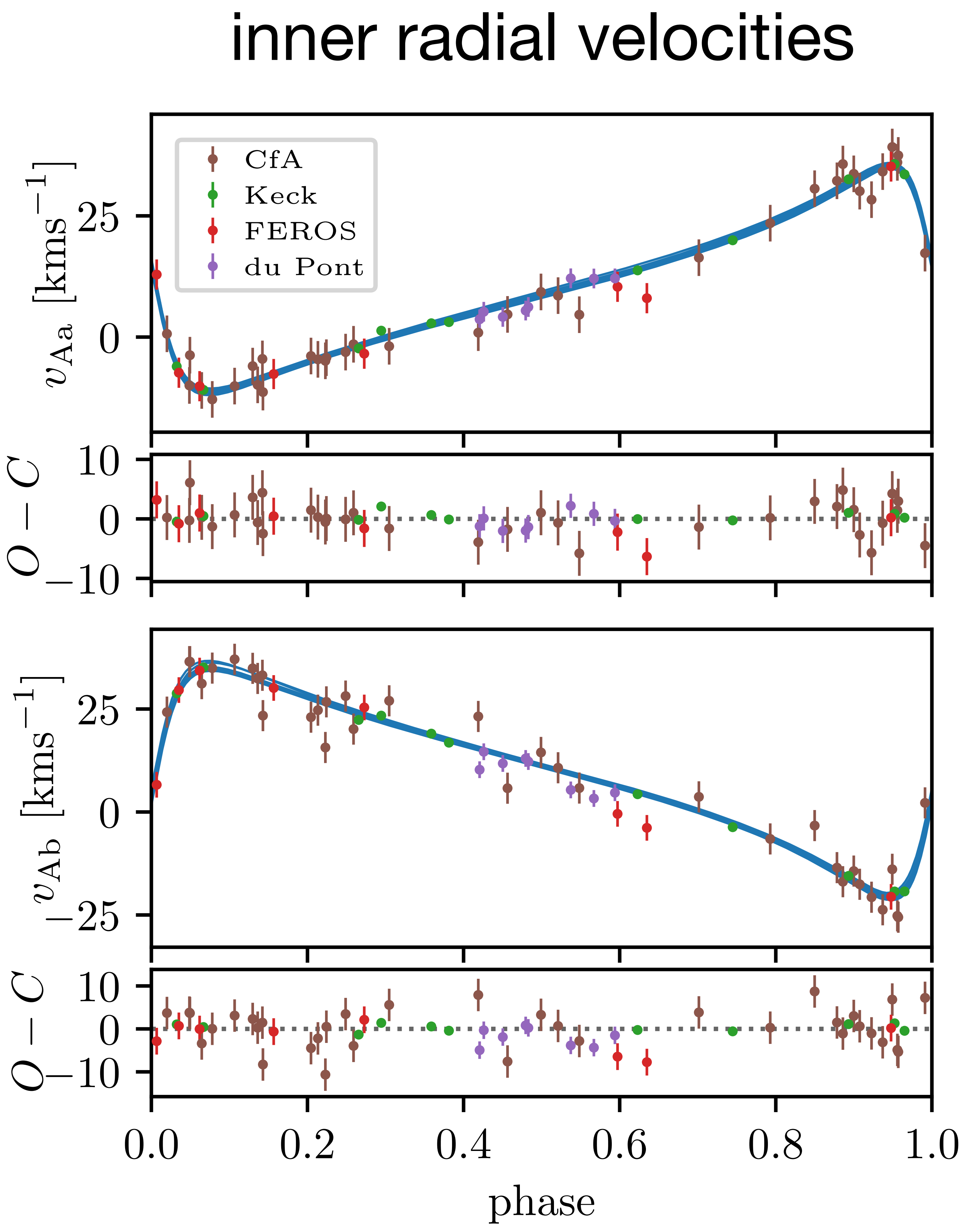
Kainulainen+17, Pineda+15, Tobin+16, Alves+19, in Zurlo et al. 2023,
Czekala et al. in prep

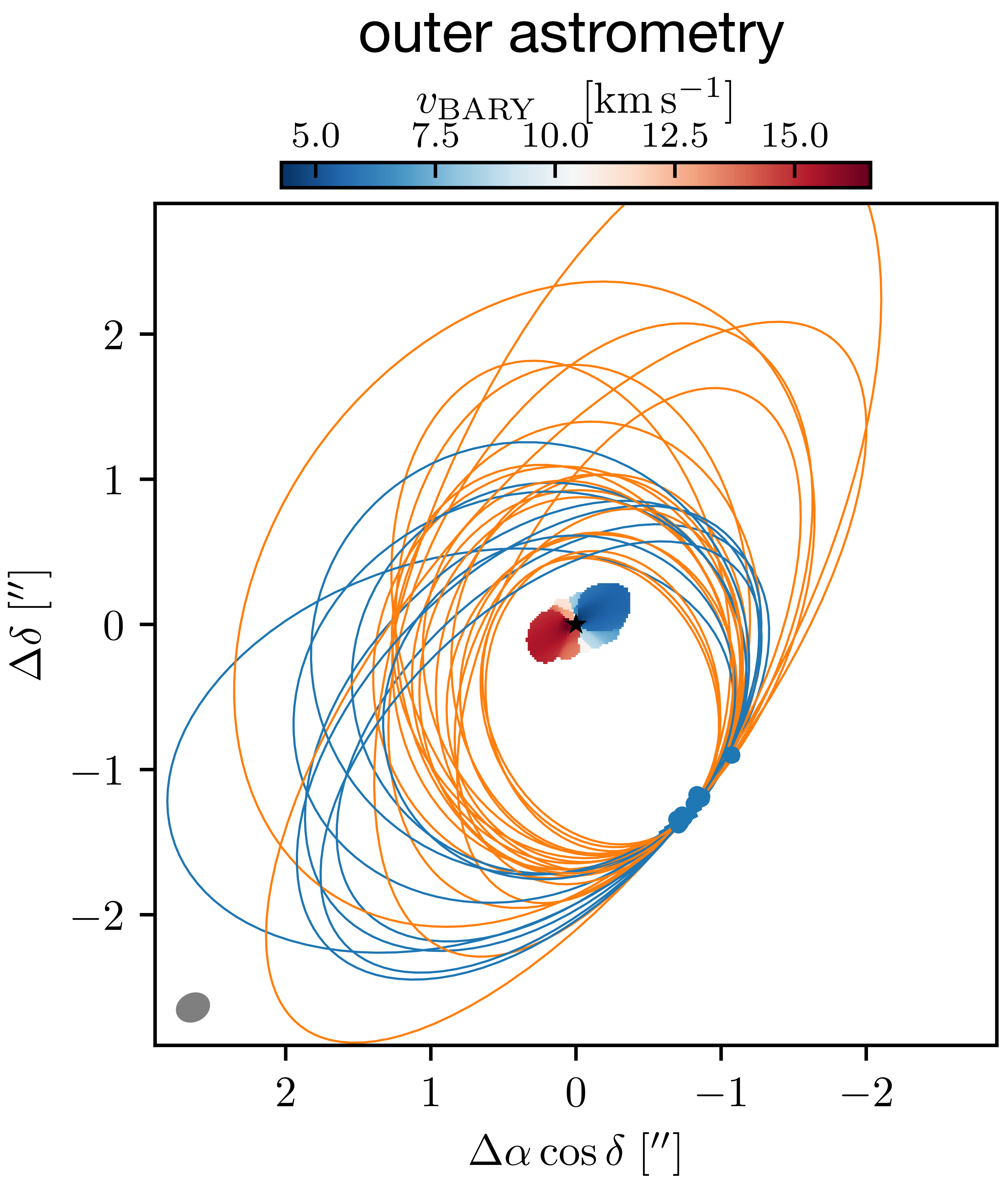
Summary



- **Mutual inclination** is the angle between the stellar binary and circumbinary disk orbital planes
- **Measurement** usually requires a combination of high spectral resolution and high spatial resolution observations over a significant time period
- **Short period (**$P <$ months**):** star and disk planes aligned
- **Long period (**$P >$ months**):** some systems aligned, others wildly misaligned
- **Highly misaligned** systems require stellar orbits with **high eccentricity**

TWA 3 Architecture Hierarchical triple

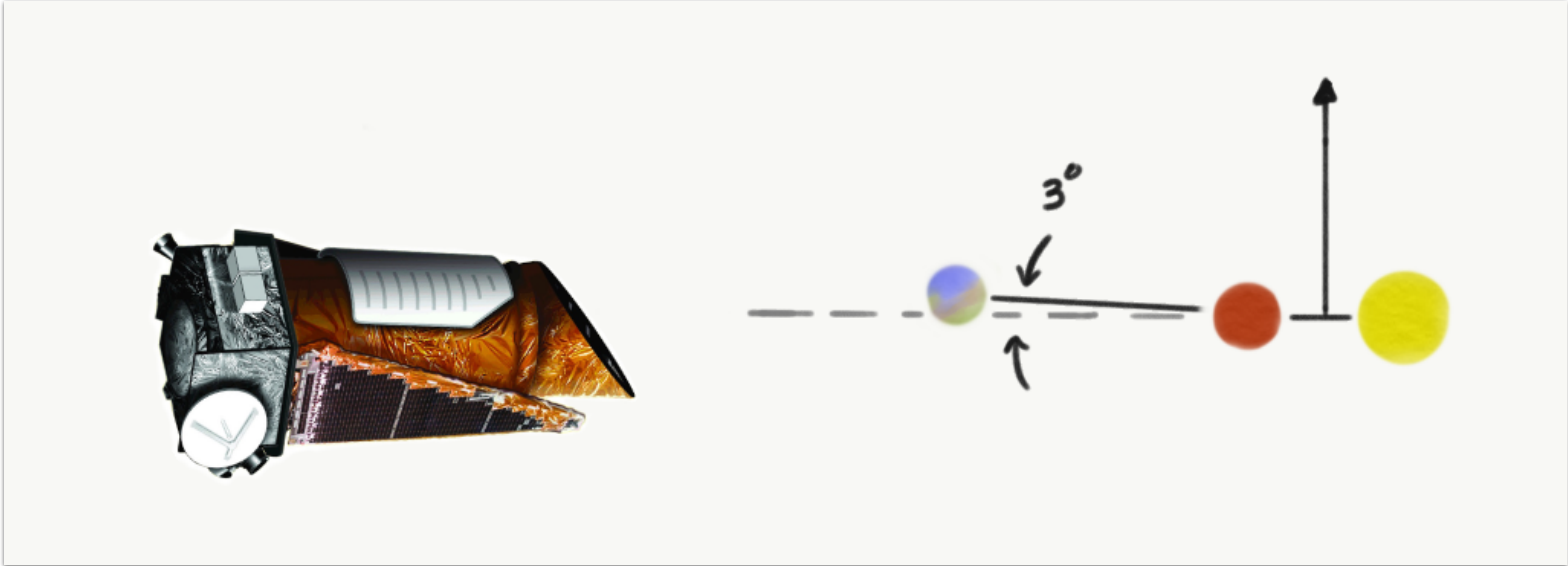




Czekala*+21a; *Kellogg+17; Foreman-Mackey, **IC**,+20

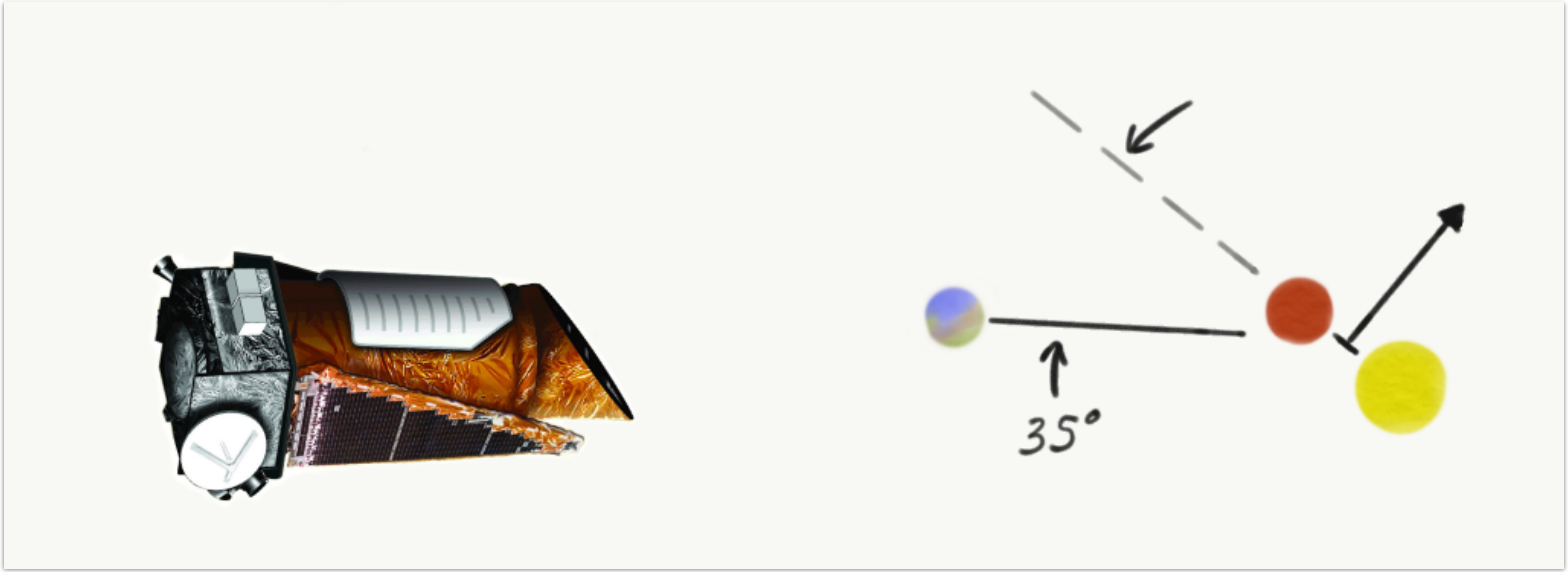
Mutual inclination: exoplanet connection

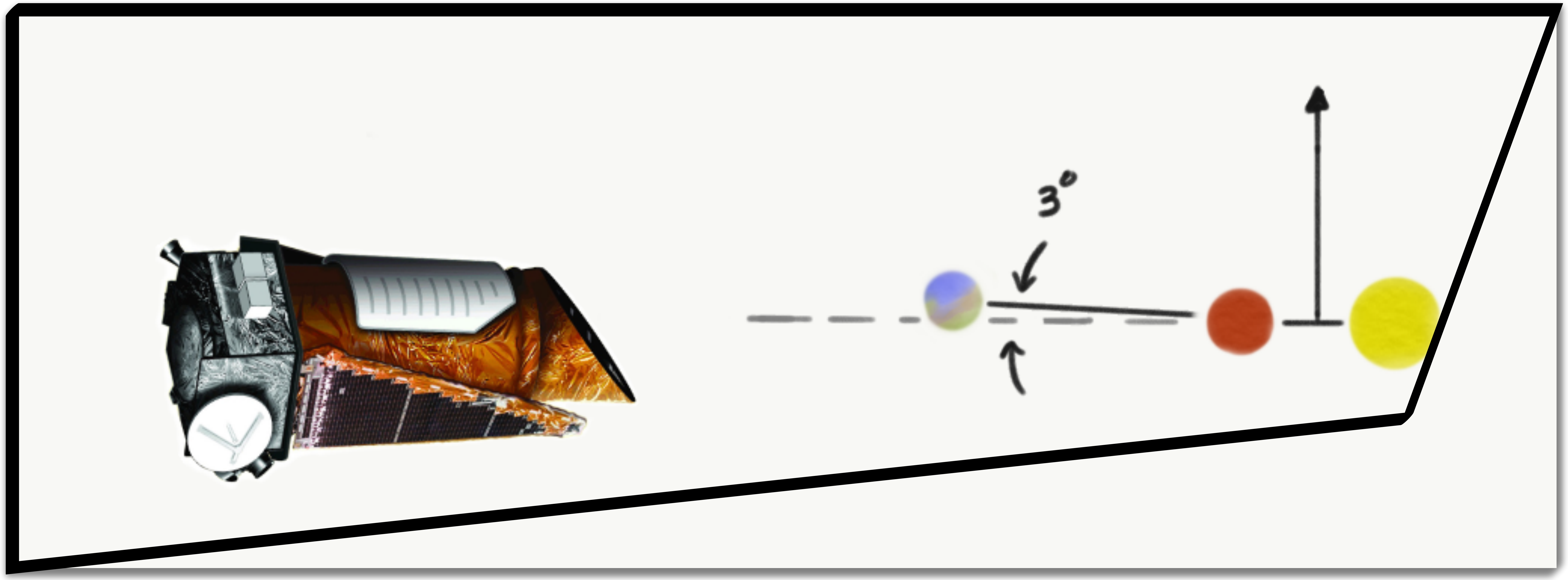
Circumbinary systems



the angle between the binary orbital plane and the disk/planet orbital plane

Transits irregularly: unlikely to be confirmed




3°


?
35°