The Degree of Alignment Between Circumbinary Disks and their Host Binaries

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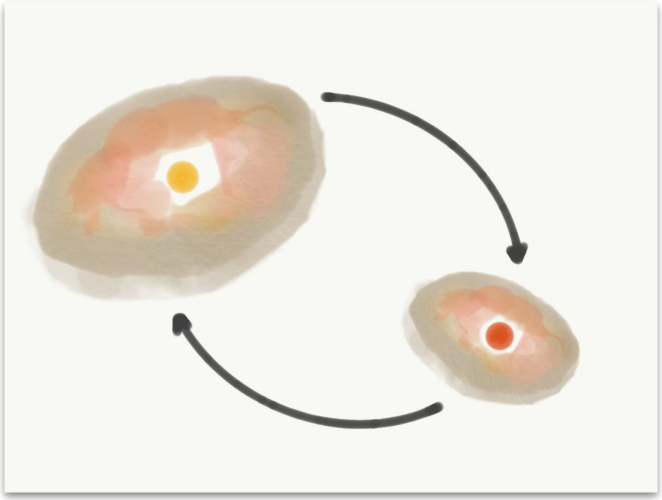
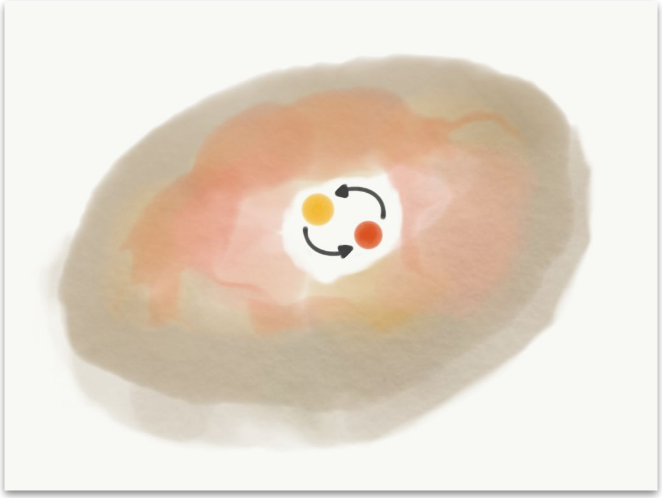
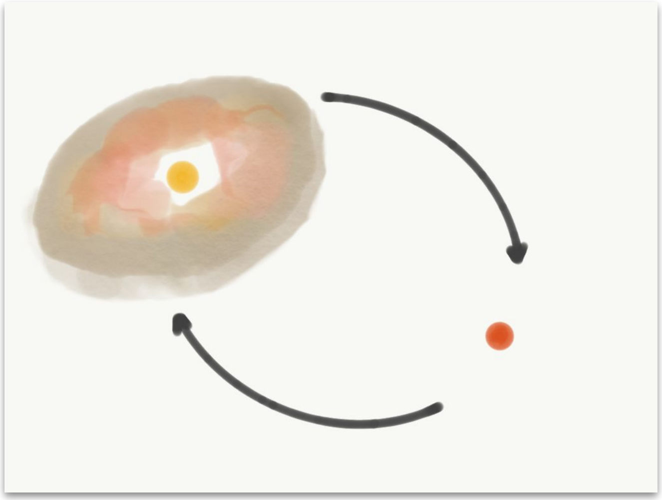
with **Eugene Chiang**, Sean Andrews, Eric Jensen, Guillermo Torres, David Wilner, Keivan Stassun, Bruce Macintosh

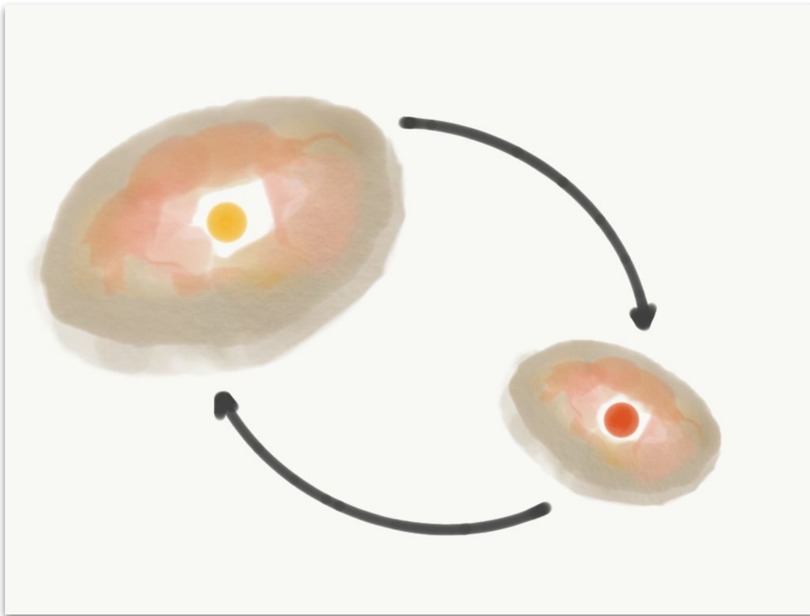
Configurations

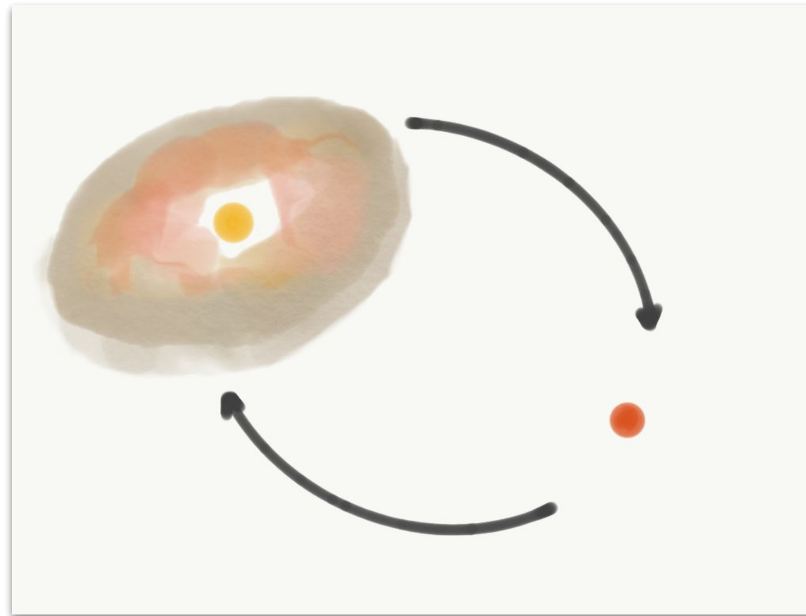






Circum*stellar* disks <u>*in*</u> binaries





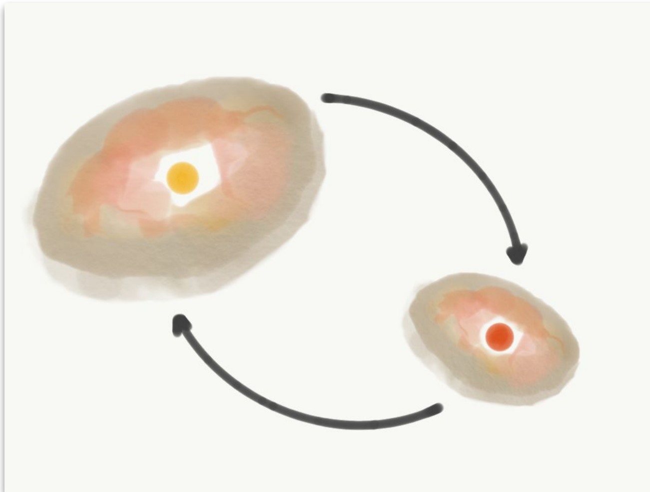
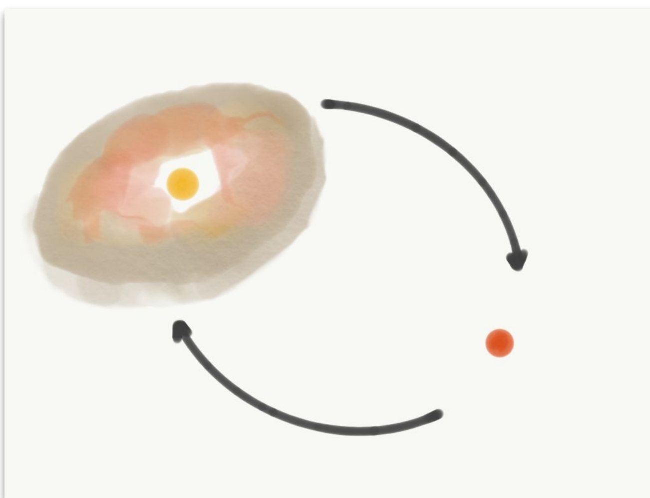
- Truncation of outer disk edges at ~0.2 - 0.3 semi-major axis
- Reduced planet occurrence; pumped eccentricities

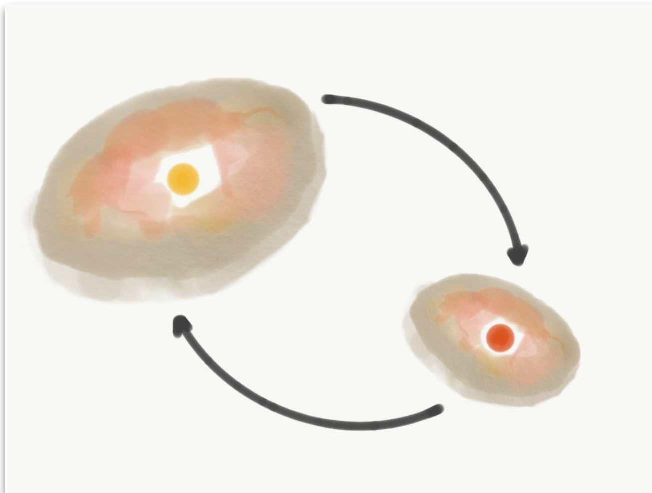
Artymowicz and Lubow 96; Harris+12;
Wang+14; Hirsch+17

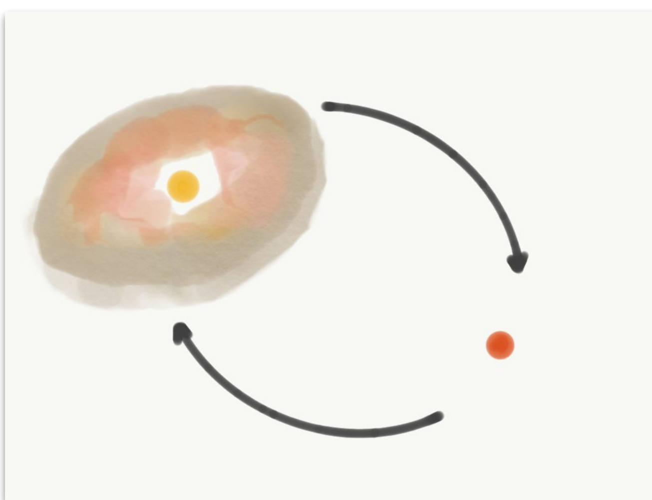
Circumbinary disks

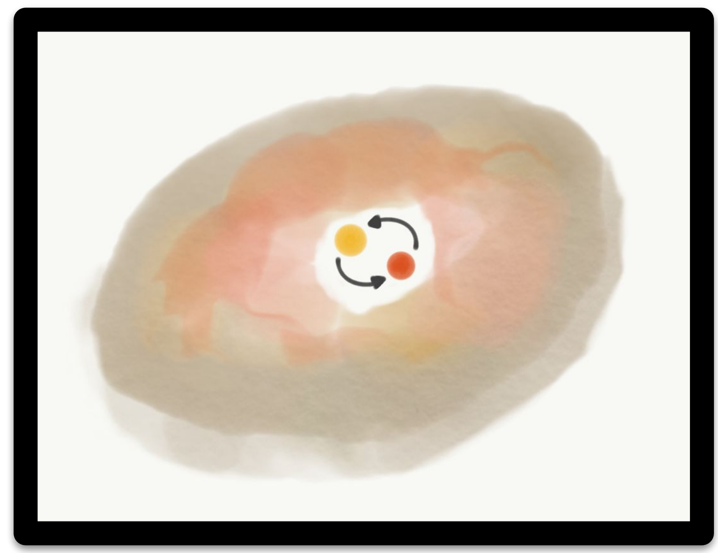
- A disk or planet orbiting *both* stars (“P”-type)
- Truncation of inner disk edge at 2 - 3 times the semimajor axis
- Probe an interesting regime of disk evolution: 2x mass but only 2x flux (not 8 - 30x)

Artymowicz and Lubow 96

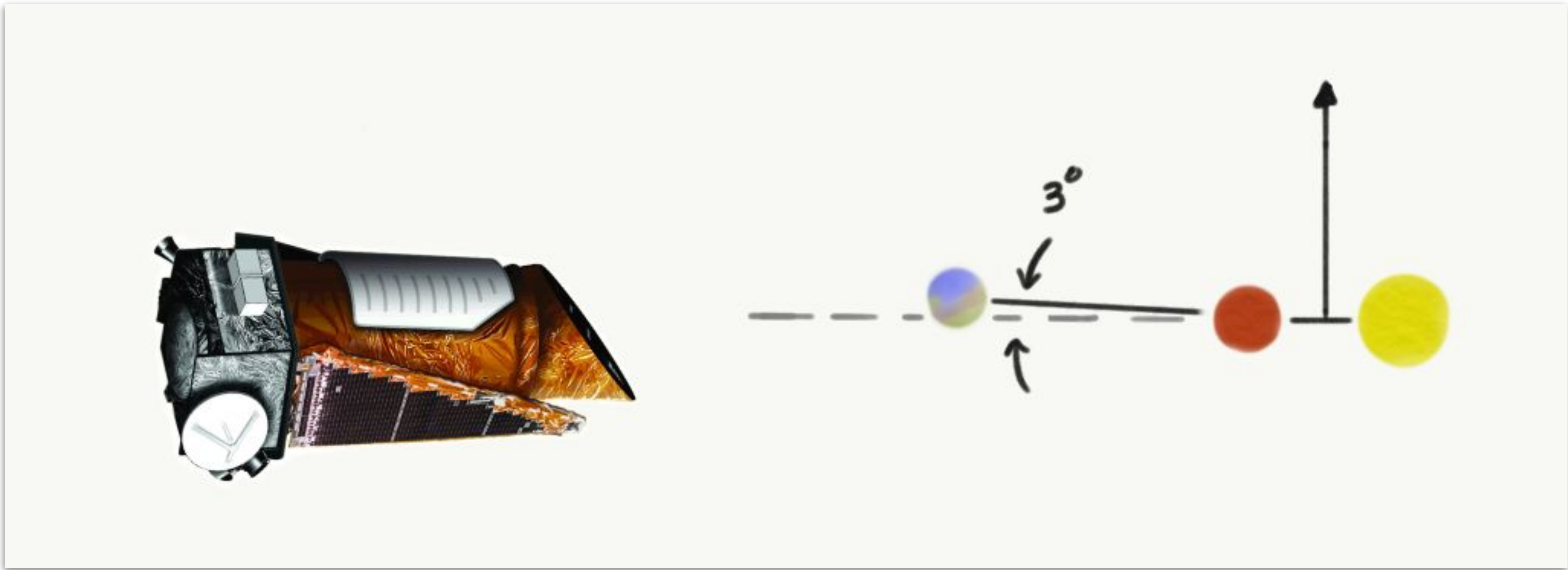





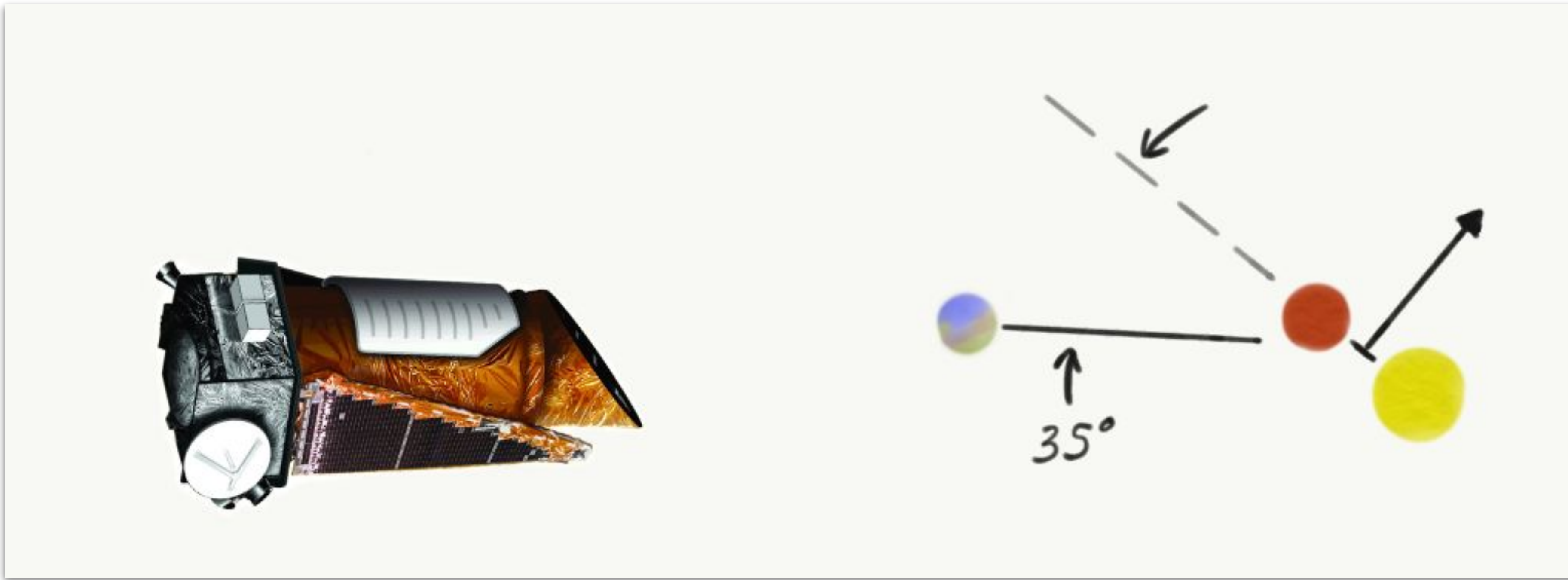


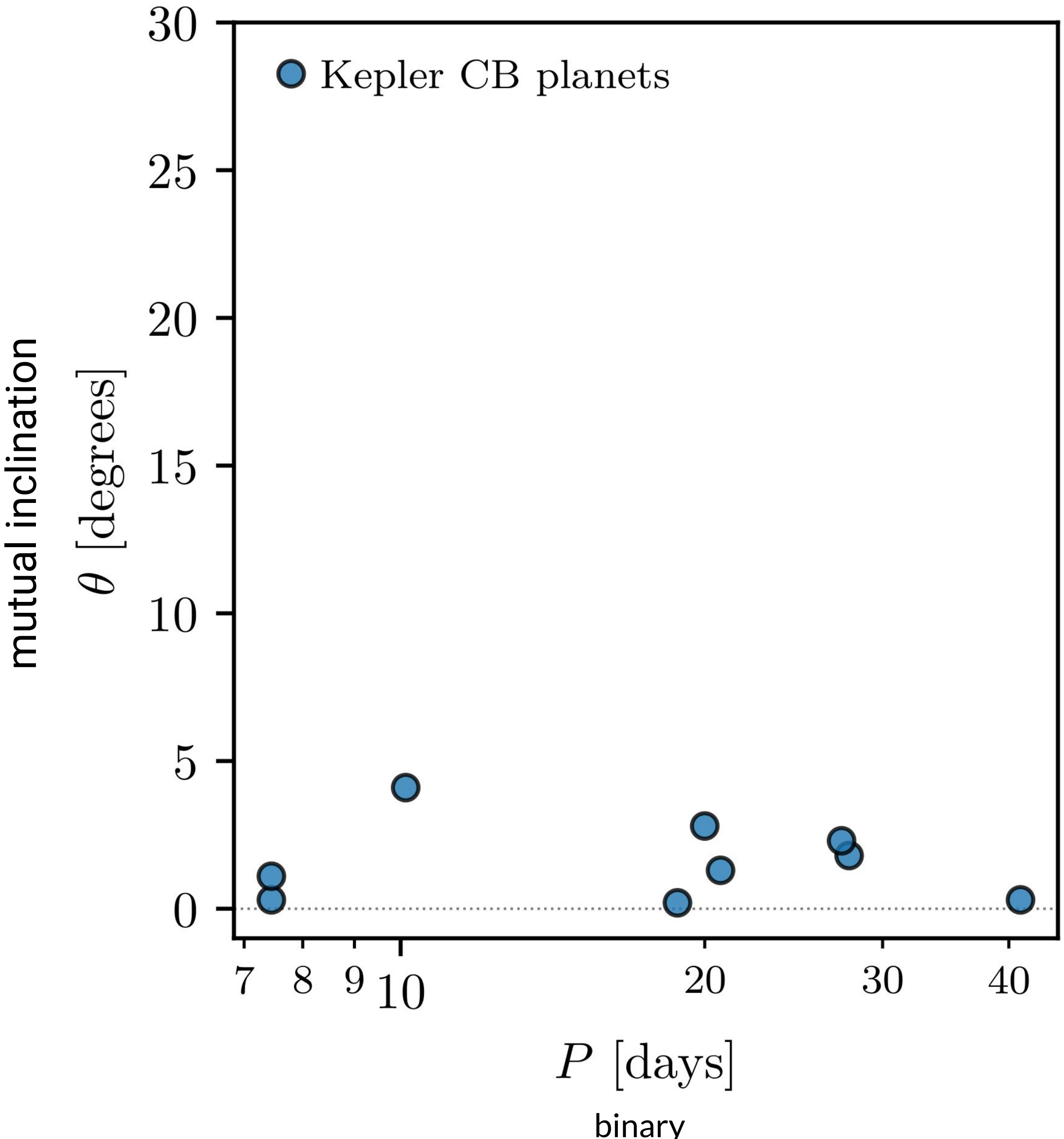
Also see posters by Kuruwita, Robert, Hirsh, & Yang.

Kepler's circumbinary wheelhouse: low mutual inclination systems



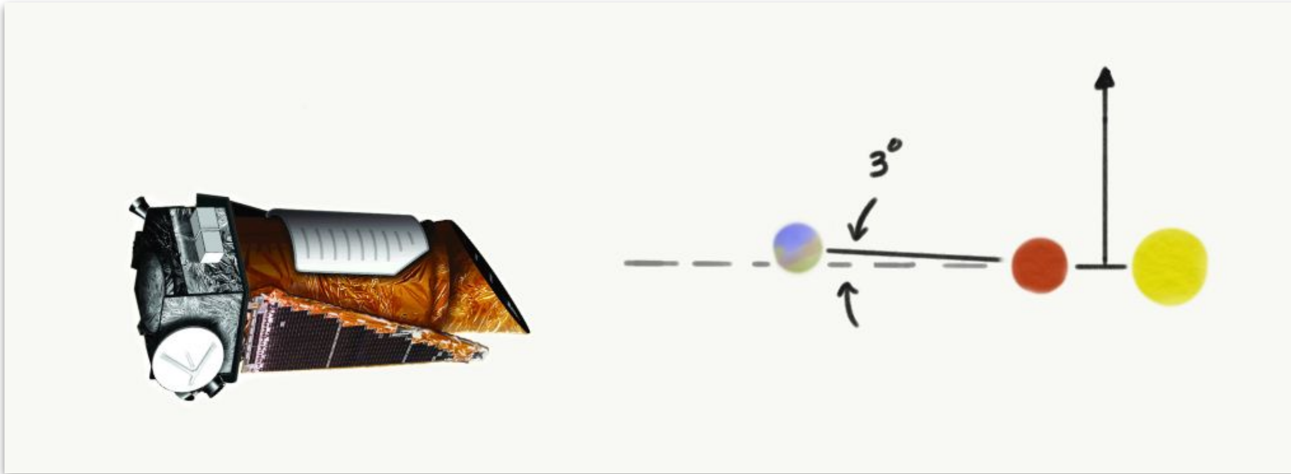
Transits irregularly: unlikely to be confirmed

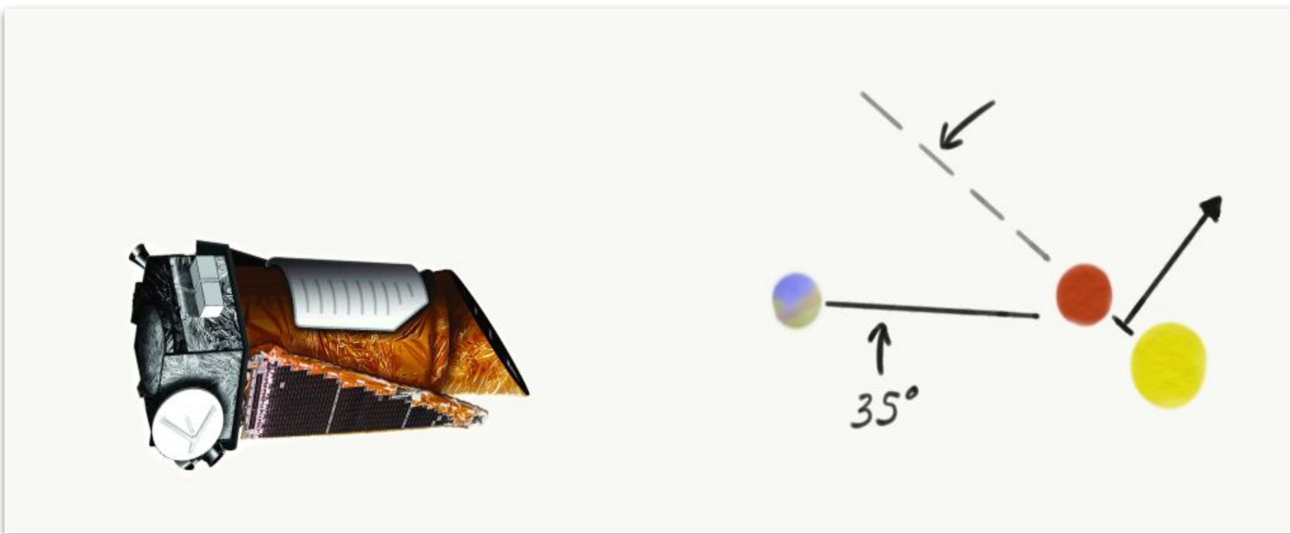


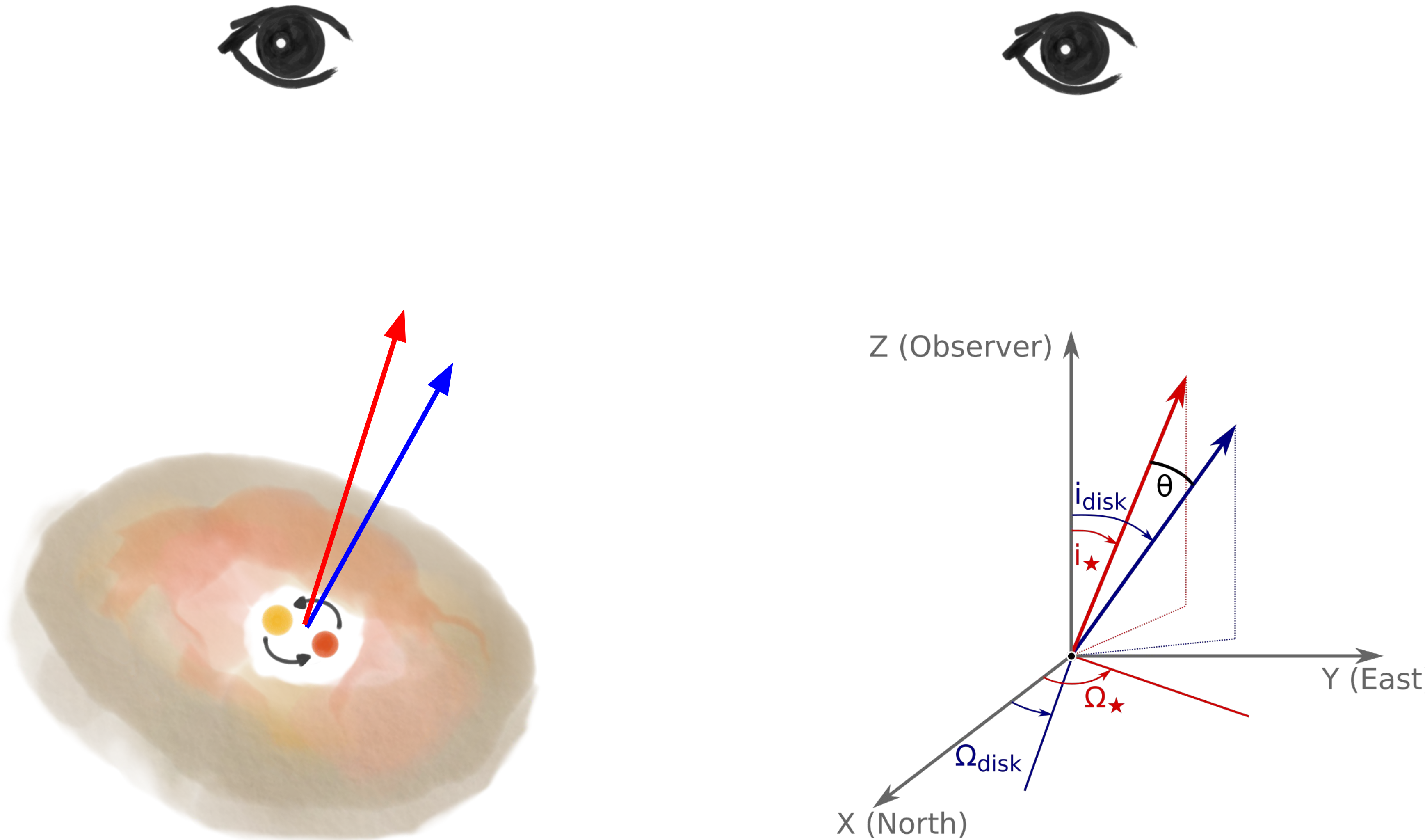


*see OGLE-2007-BLG-349L(AB)c, HD 106906

Winn & Fabrycky 15, Li+16, Couetdic+10, Muñoz and Lai 15; Bennett+16


3°


35°



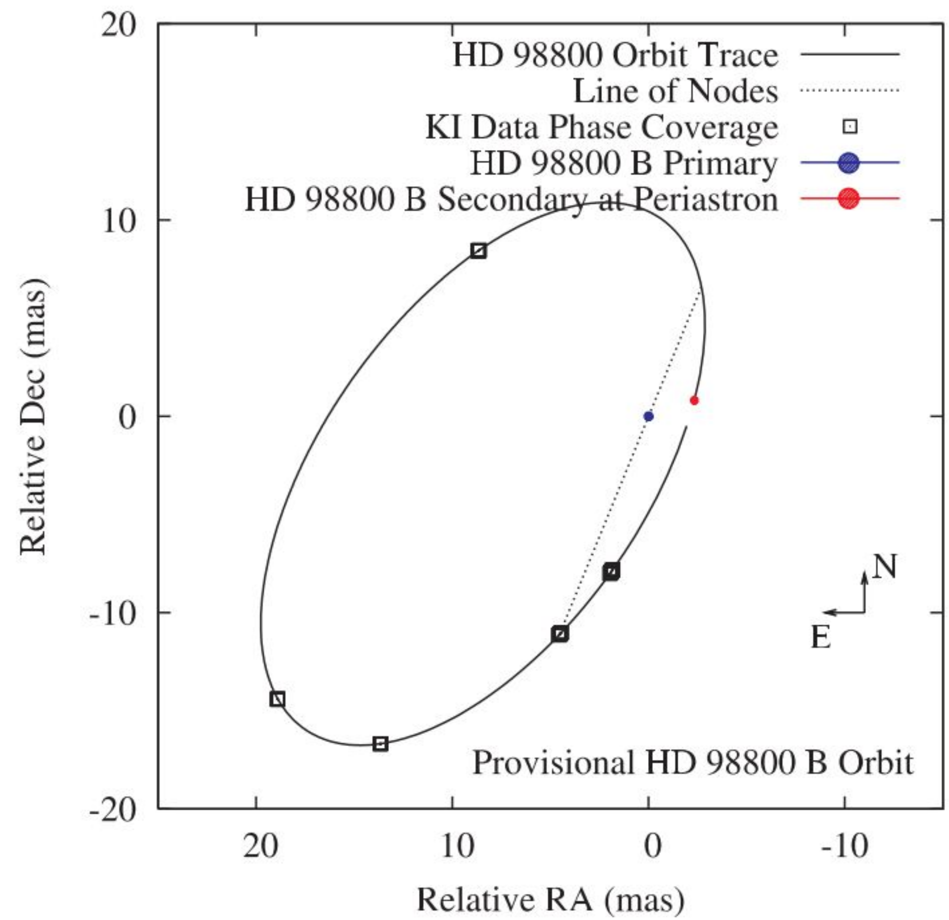
$$\cos\theta = \cos i_{\rm disk}\cos i_\star + \sin i_{\rm disk}\sin i_\star \cos(\Omega_{\rm disk} - \Omega_\star)$$

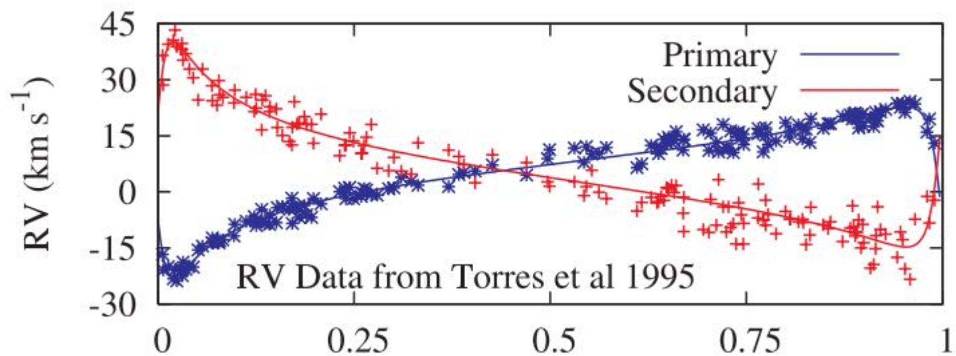
Astrometric observations of longer period binaries yield the ascending node (Ω), and the inclination (*i*) so θ can be calculated directly.

Many famous misaligned examples:

GW Ori, HD 142527, R CrA, SR 24N, GG Tau, IRS 43, HD 98800B, ...

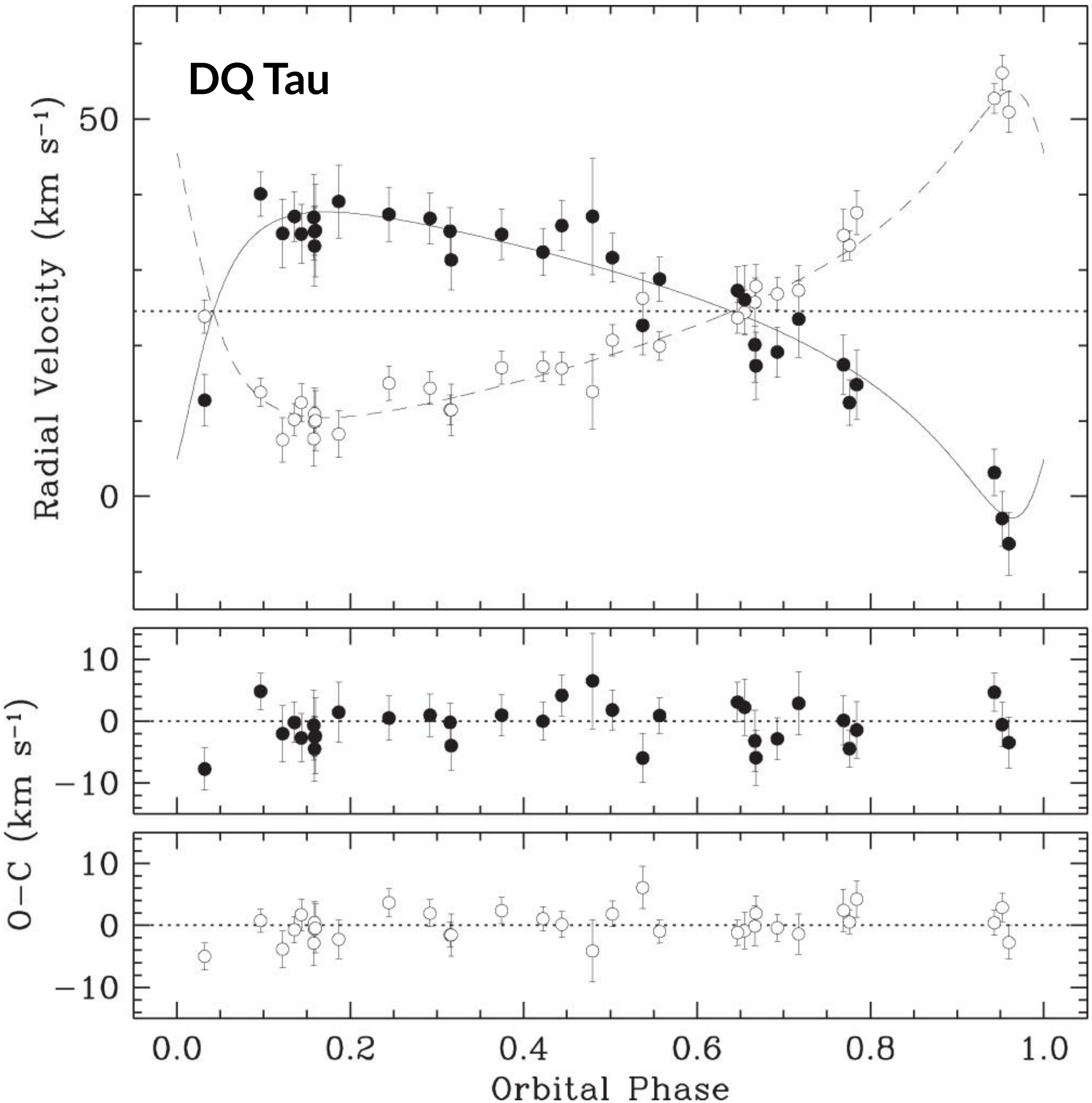
What about tighter binaries?





Boden+05, Andrews+14, Di Folco+14, Dutrey+16, Czekala+17, Prato+17, Kraus+09, Mesa+19, Biller+12, Lacour+16, Boehler+17, Price+18, Kennedy19+, Claudi+19

Spectroscopic binaries with disks



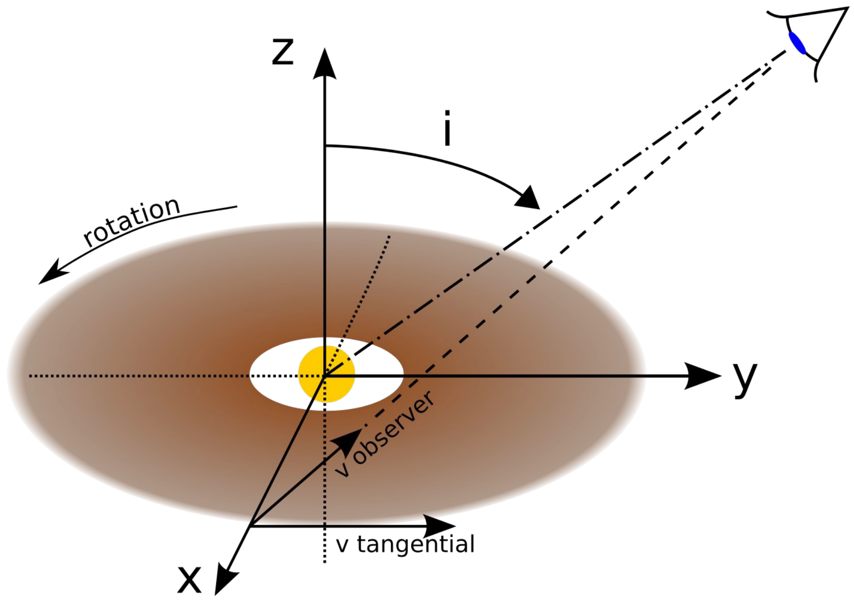
Double-lined RV solution yields

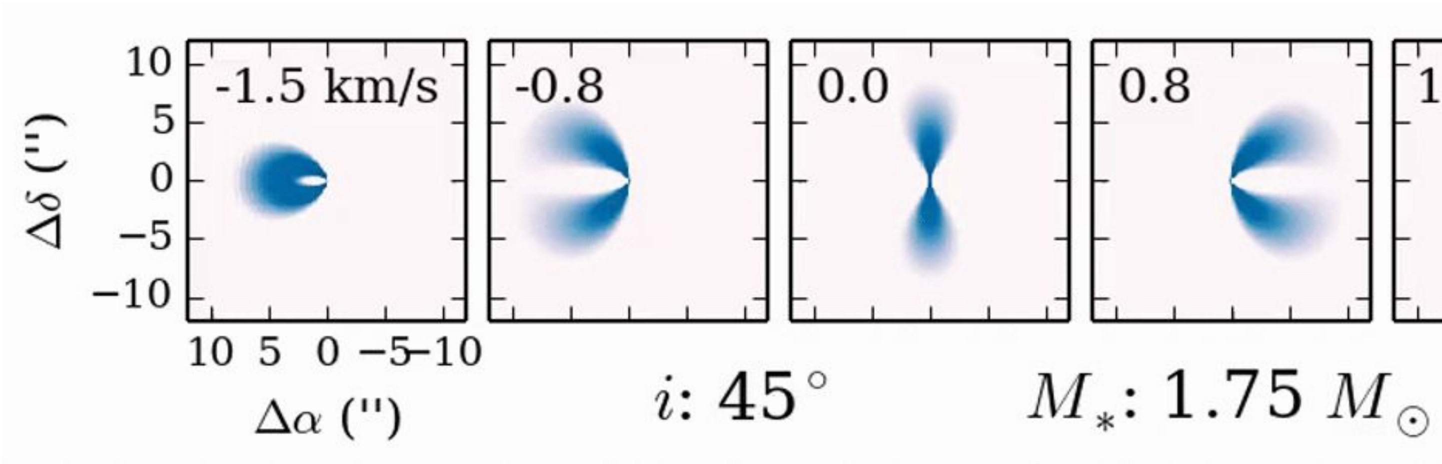
$$M_{\text{tot}} \sin^3 i_*$$

Czekala et al. 16,
Czekala et al. 17a

Protoplanetary disk forward model

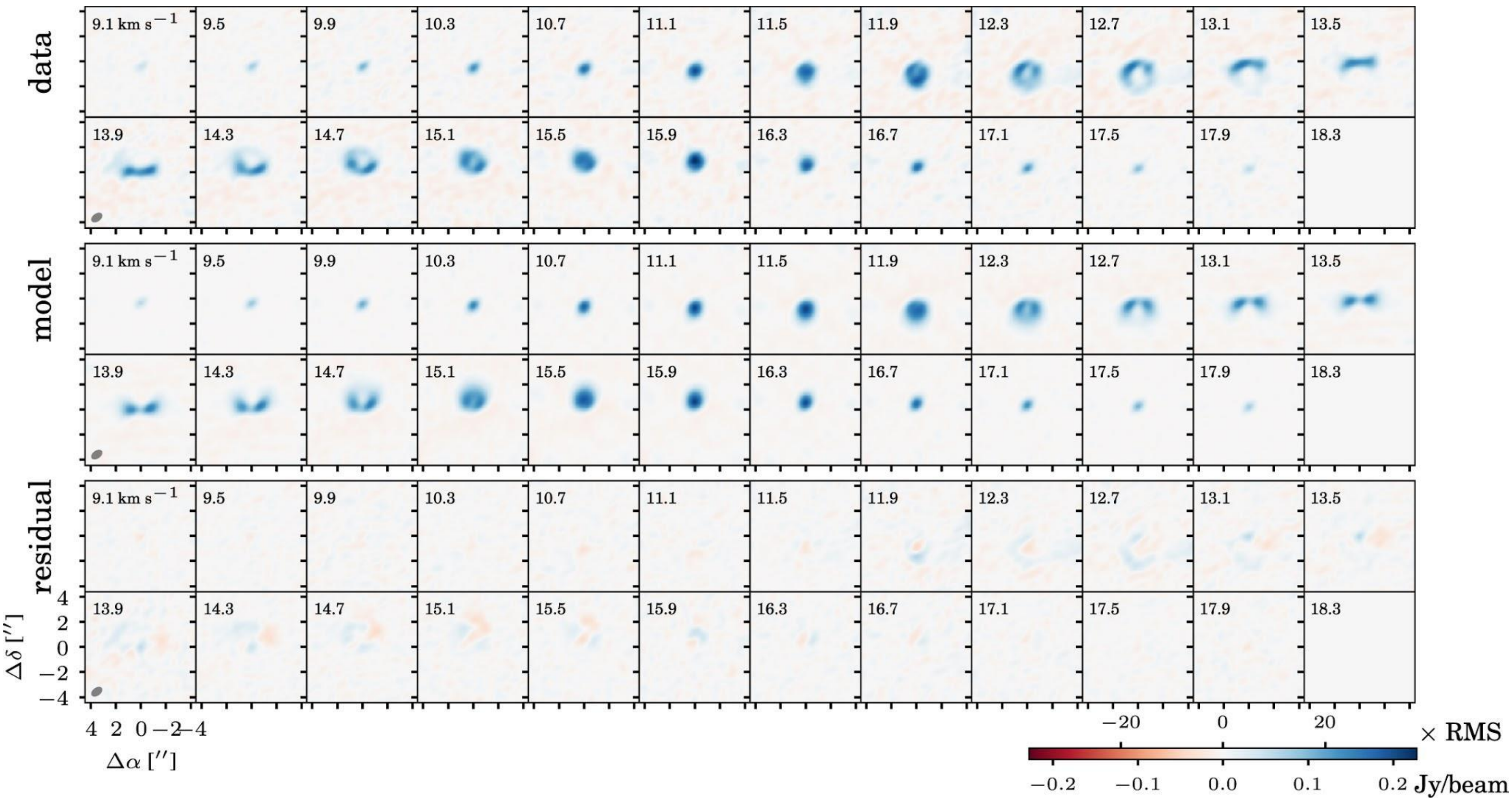
- Parameterize the disk in 3D: density, temperature, and velocity of gas
- Use radiative transfer (`radmc3d`) to synthesize channel maps
- Fourier transform and compare to visibilities

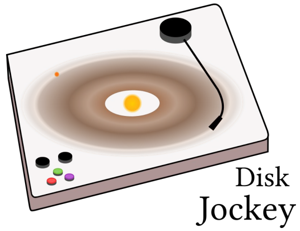




Czekala+15a

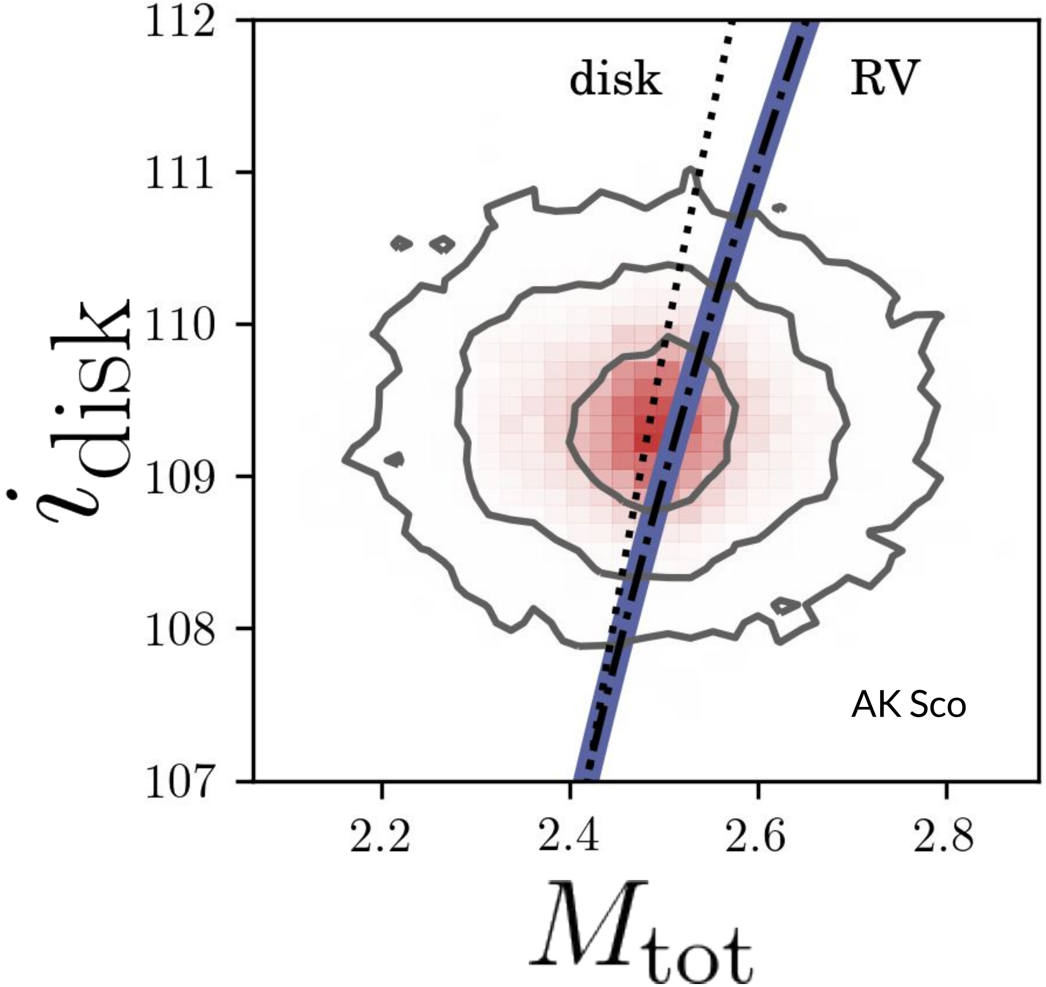
Gas forward-modeling





Open source package for dynamical masses
https://github.com/iancze/DiskJockey/

Czekala+17b



Double-lined RV solution yields

$$M_{\rm tot}\sin^3 i_*$$

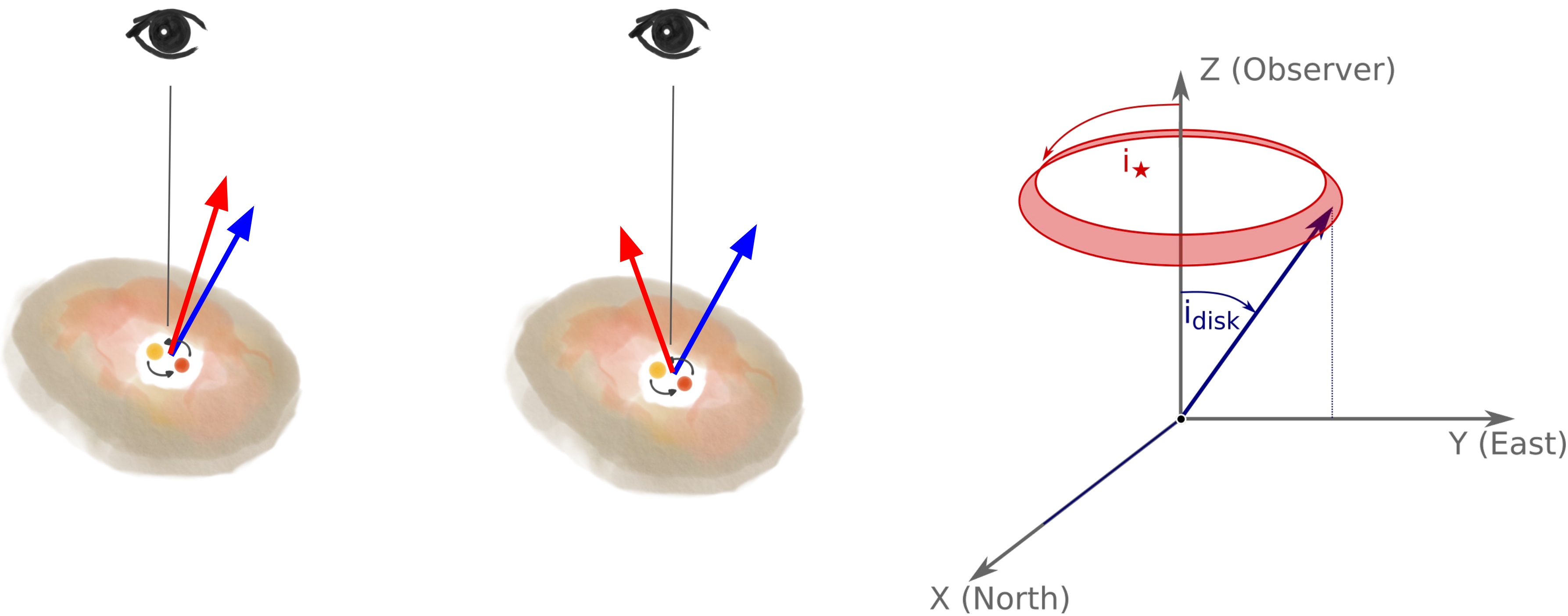
Disk rotation curve: $M_{\rm tot}$

Divide to get: i_*

Compare to: $i_{\rm disk}$

There are four known SB2s with CB disks, and they all have

$$i_* \approx i_{\mathrm{disk}}$$



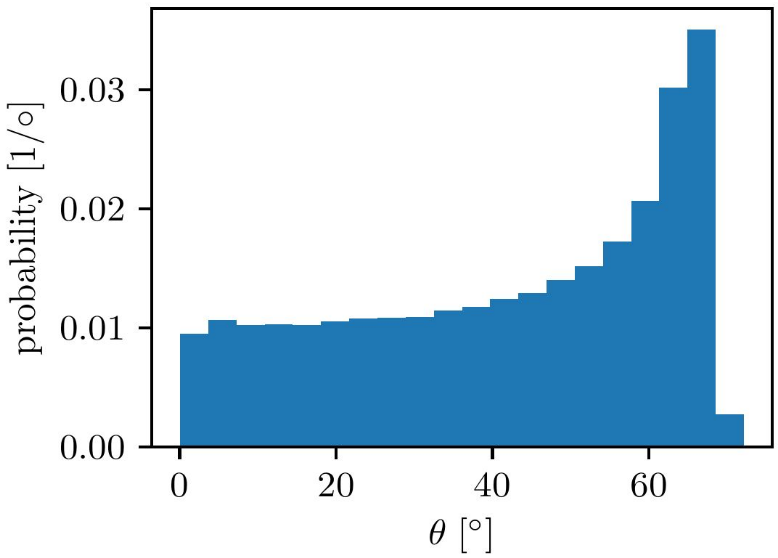
Prato+02; Rosenfeld+12; **Czekala**+15a; **Czekala**+16; **Czekala**+

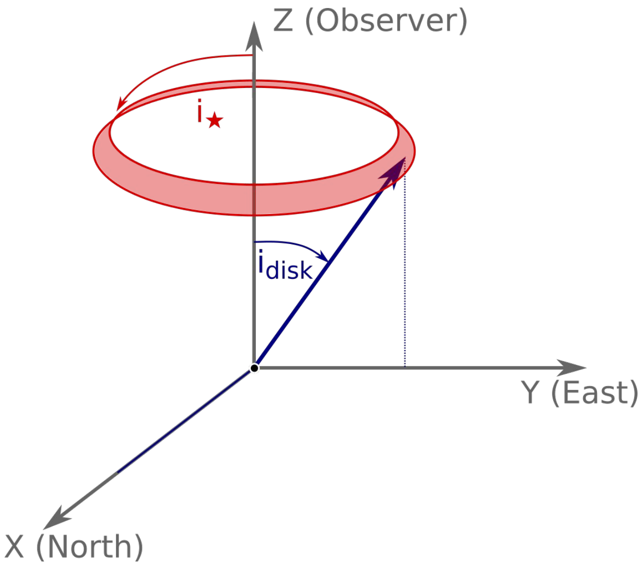
Each SB2 system considered individually

V4046 Sgr

$$i_* = 33.4^\circ \pm 1.0^\circ$$
$$i_{\rm disk} = 33.5^\circ \pm 1.4^\circ$$

$$p(\theta|\, i_*, i_{\rm disk}, \Omega_{\rm disk})$$

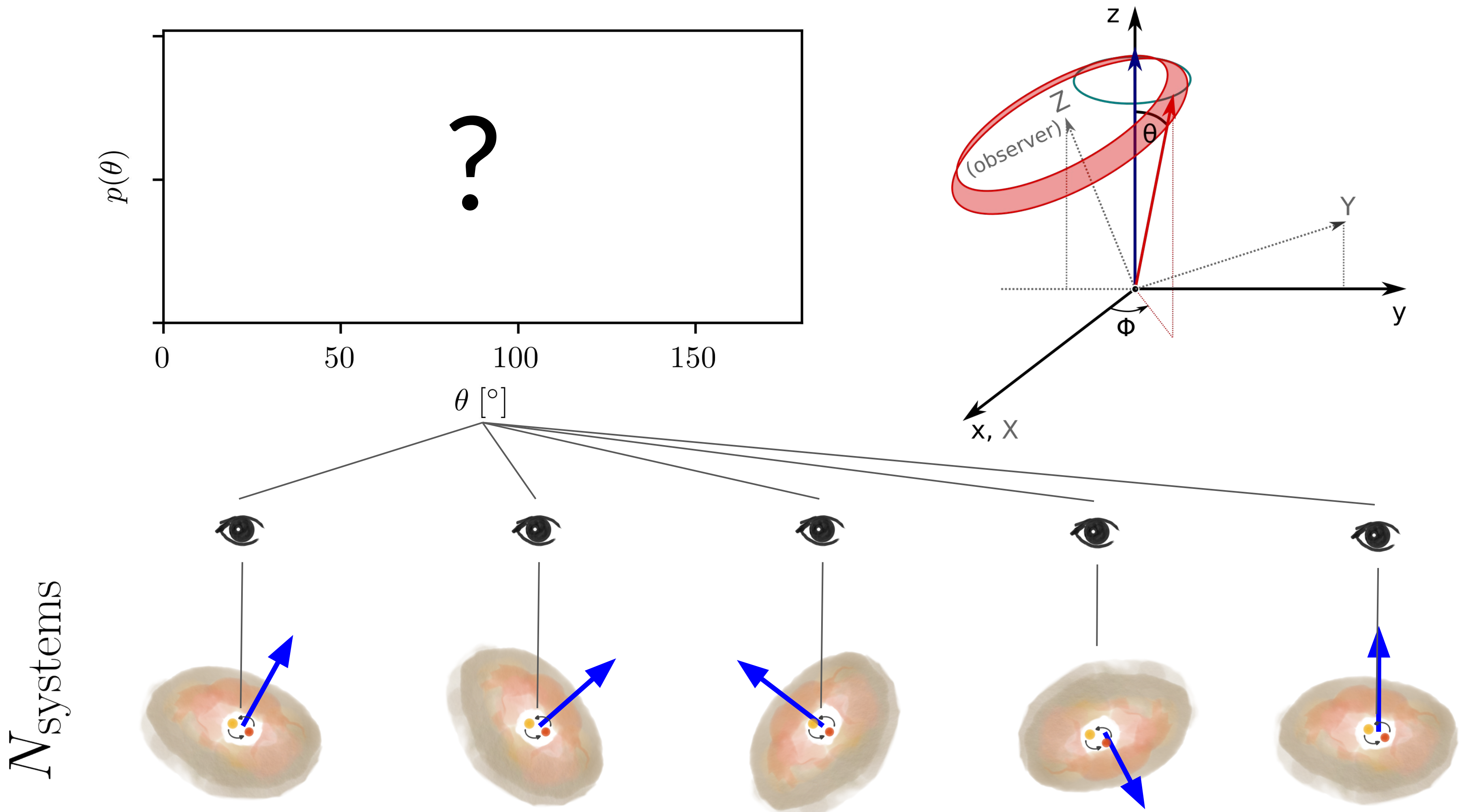




Huh? But we see $i_* \approx i_{\rm disk}$ for 4 systems. What does this say about the population?

Hierarchical Bayesian modeling

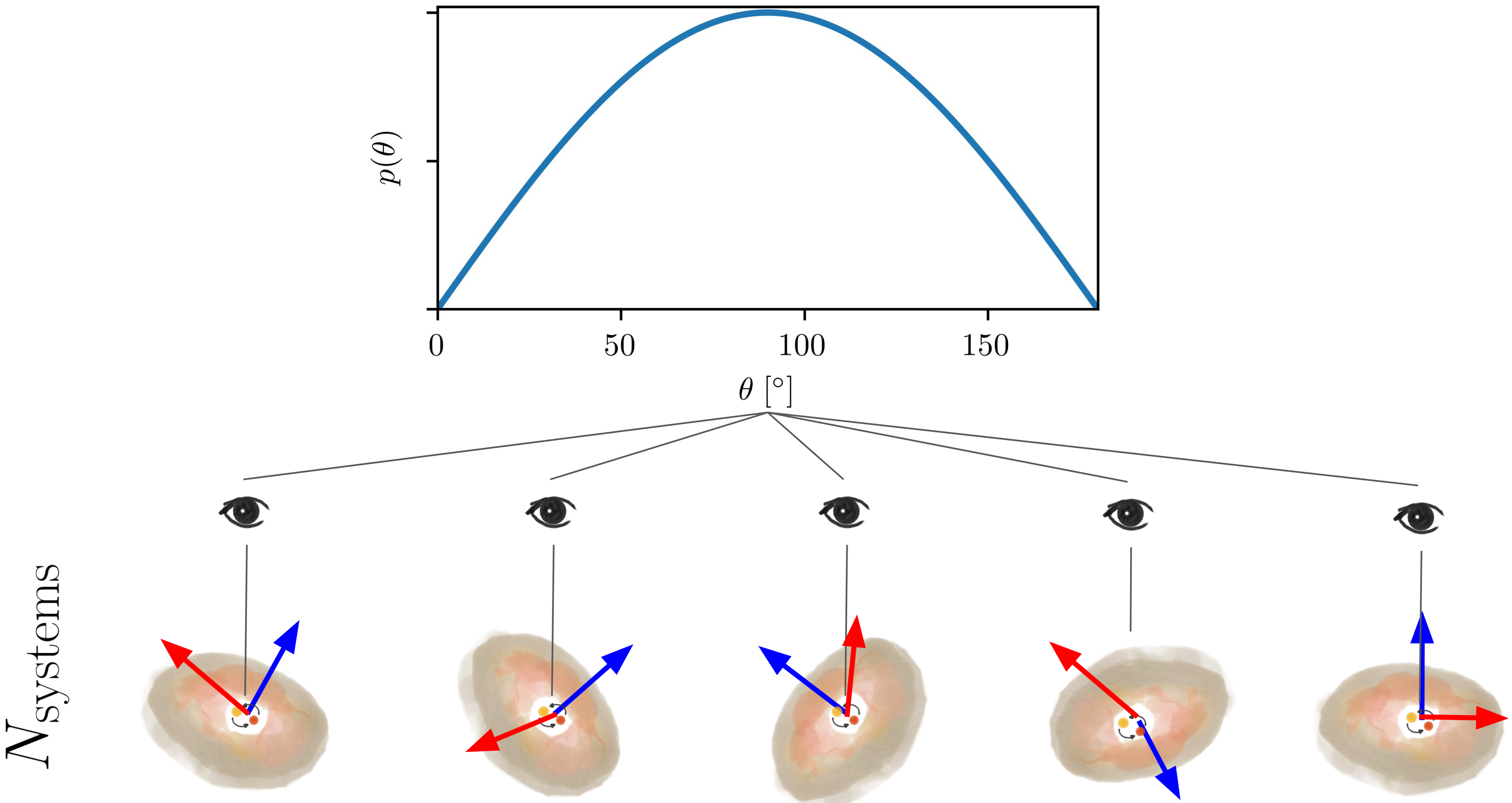
Infer the mutual inclination distribution by fitting all of the systems simultaneously



Disk orientation
Binary orientation

Hierarchical Bayesian modeling

Infer the mutual inclination distribution by fitting all of the systems simultaneously

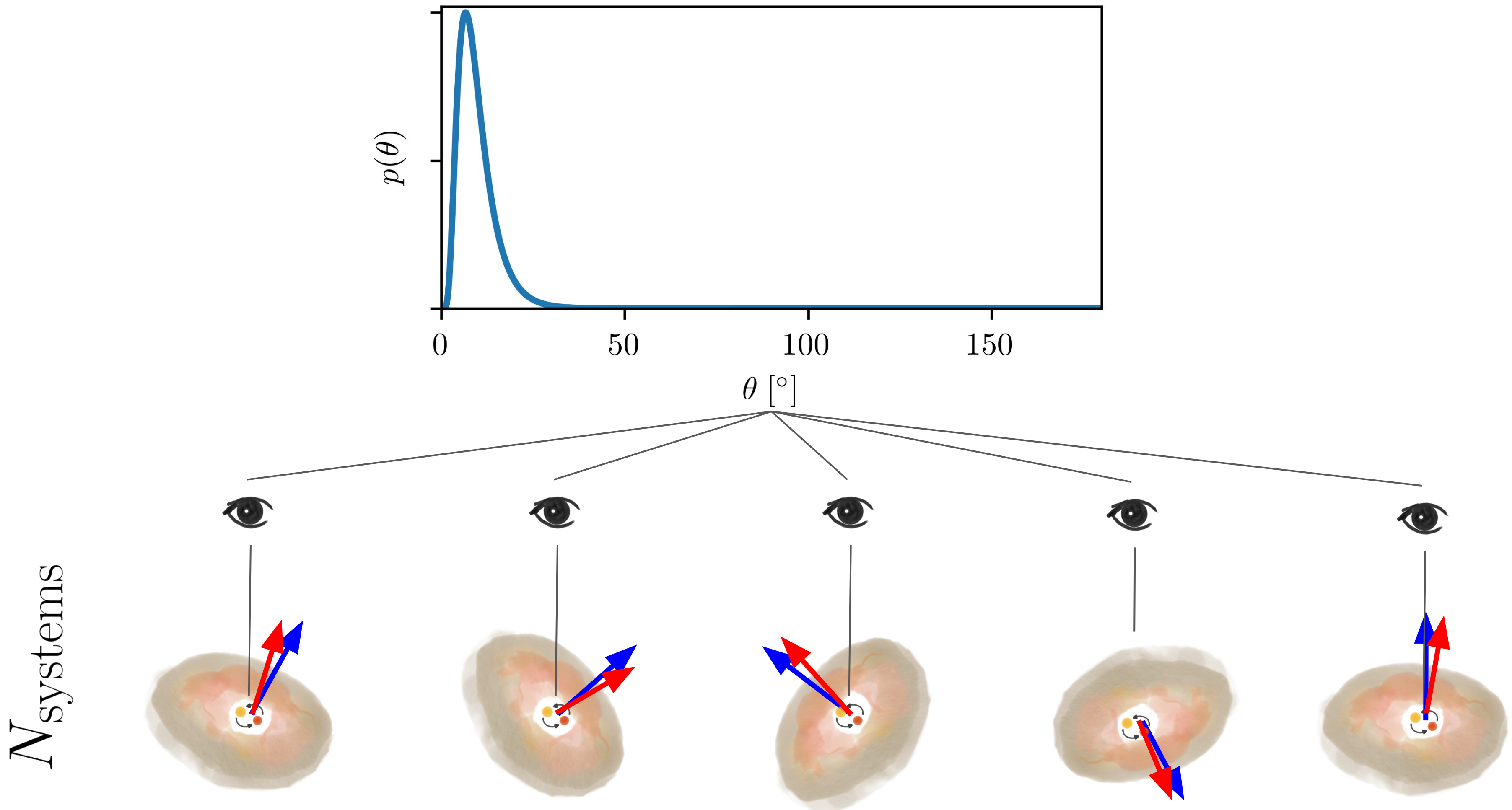


Disk orientation

Binary orientation

Hierarchical Bayesian modeling

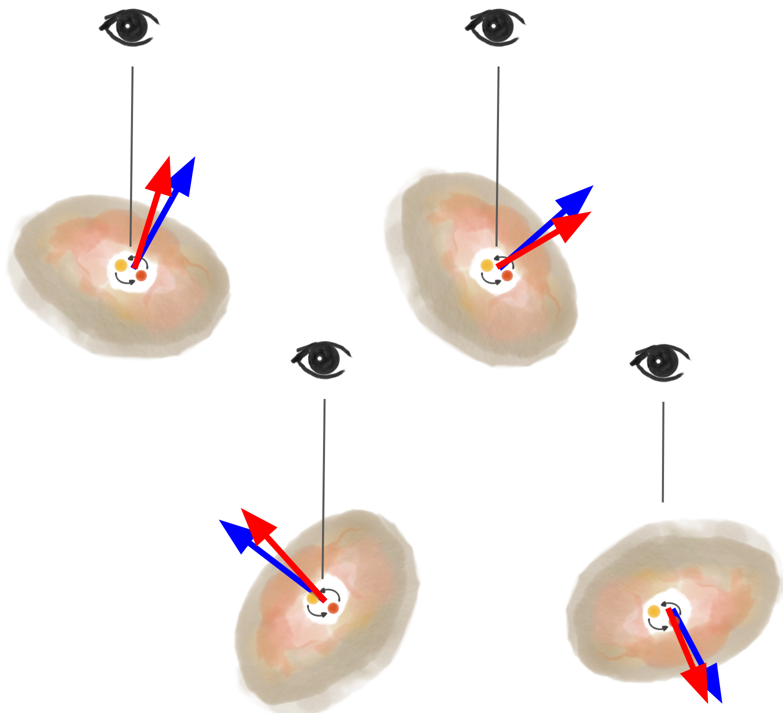
Infer the mutual inclination distribution by fitting all of the systems simultaneously



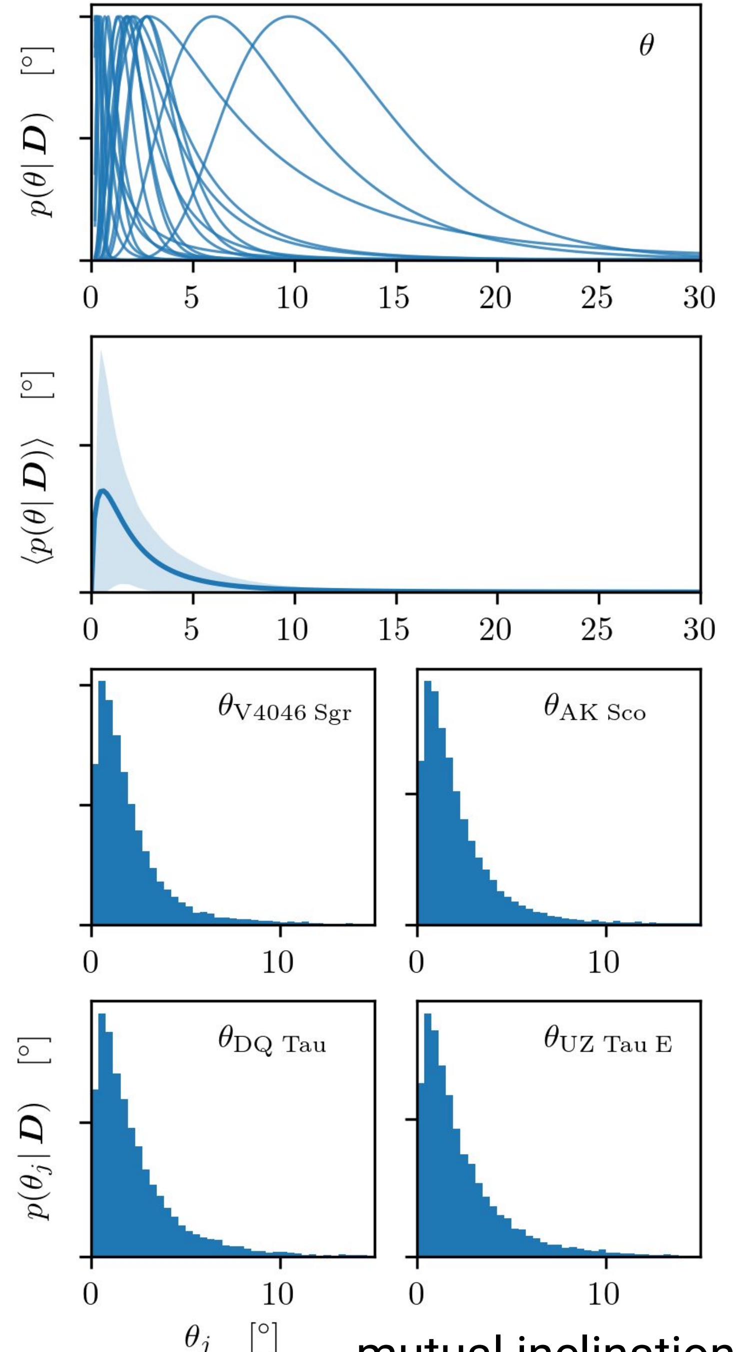
Disk orientation

Binary orientation

Real data

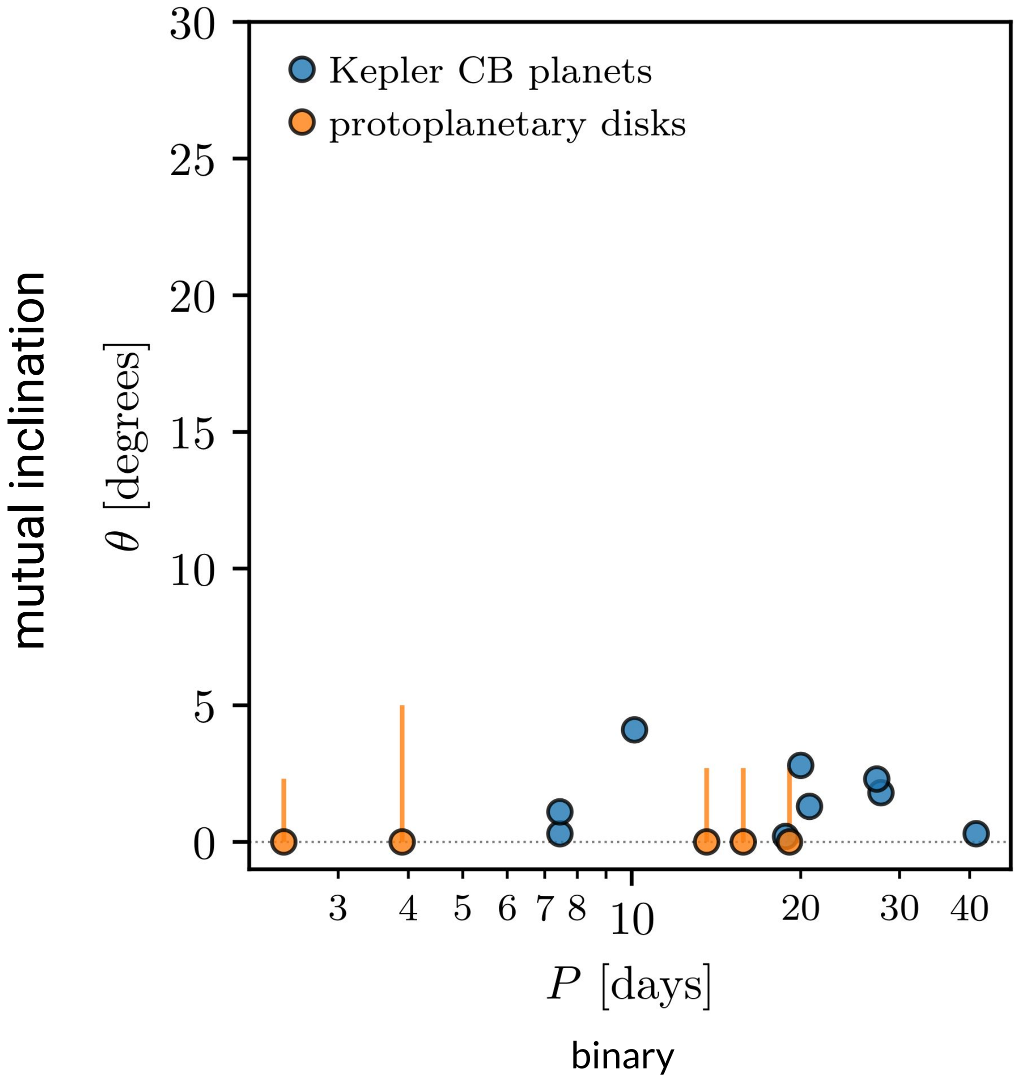


circumbinary disks around spectroscopic binaries (P < 20 days) have low mutual inclinations (68% with θ<3°)



mutual inclination

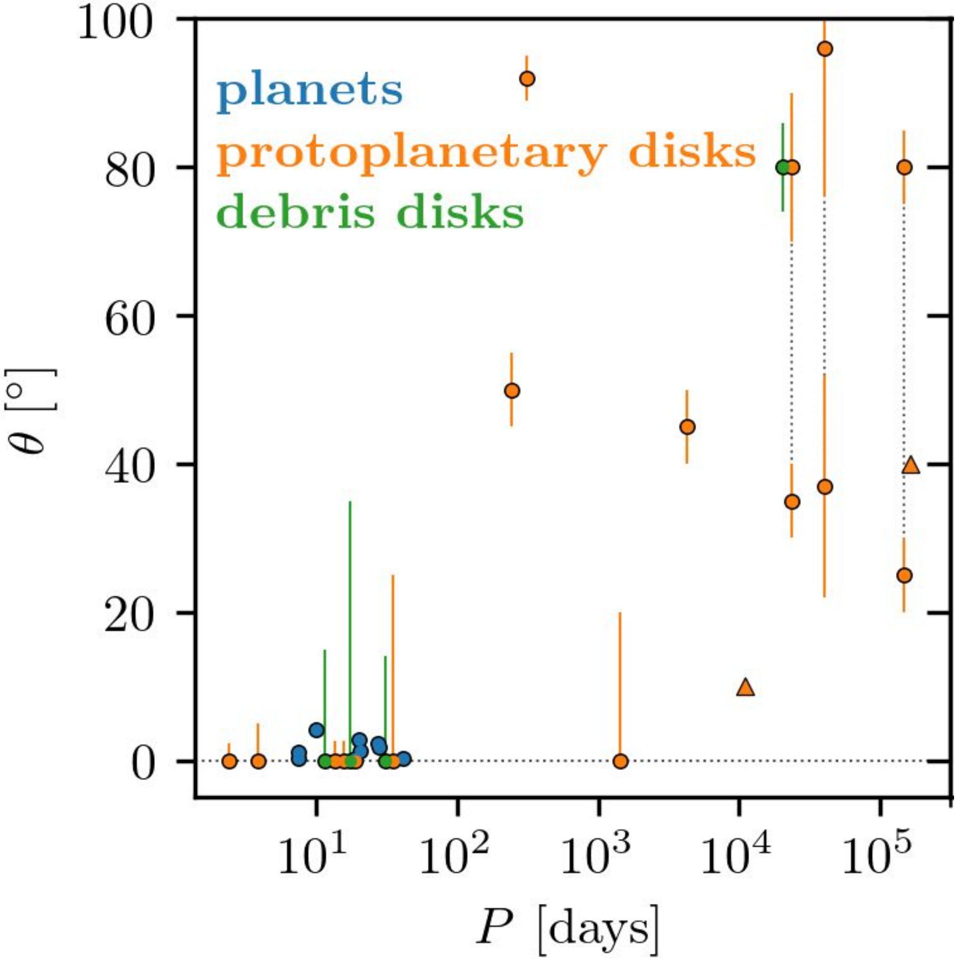
Short period binaries (P < 40 days) and their planets (disks) are *coplanar*



Low mutual inclinations of disks, coupled with the Kepler CB planet sample & detection sensitivity, implies that the CB planet occurrence rate is **~10%** (planet periods up to 300 days, 4 - 10 earth radii) **consistent with that of single stars**

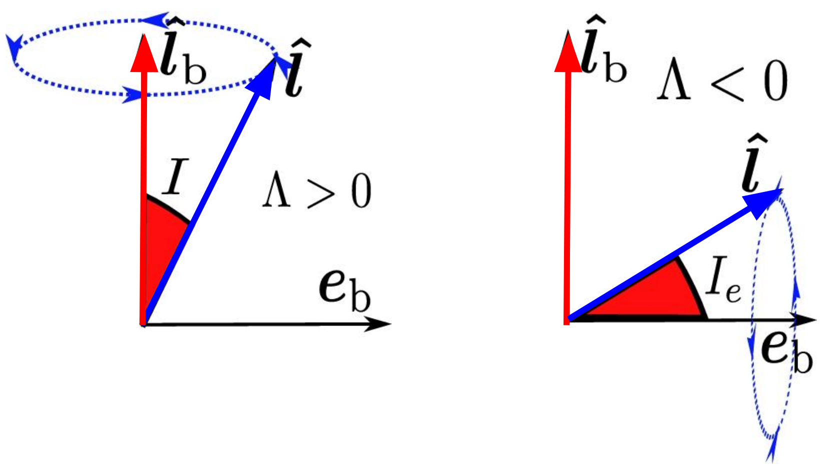
Prato+02; Winn & Fabrycky 15; Rosenfeld+12; Fressin+13; Armstrong+14, Li+16; **Czekala**+15a; **Czekala**+16; Martin+19; **Czekala**+19

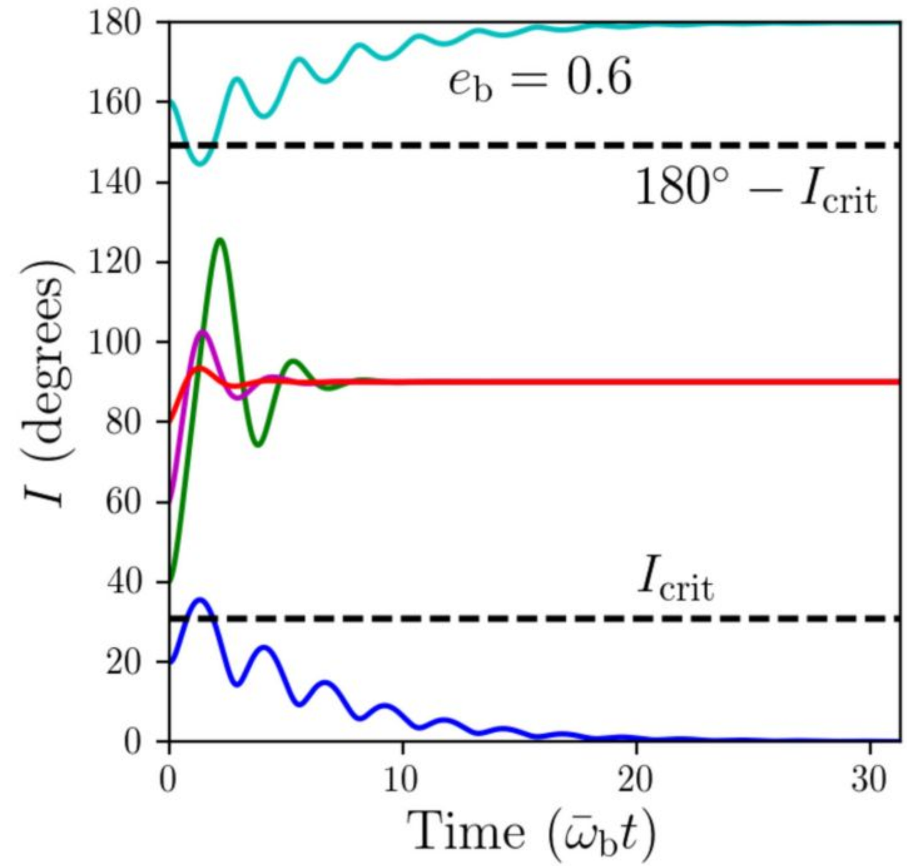
Mutual inclinations



Kennedy+12a,12b,15;
Czekala+17b; Czekala+19

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

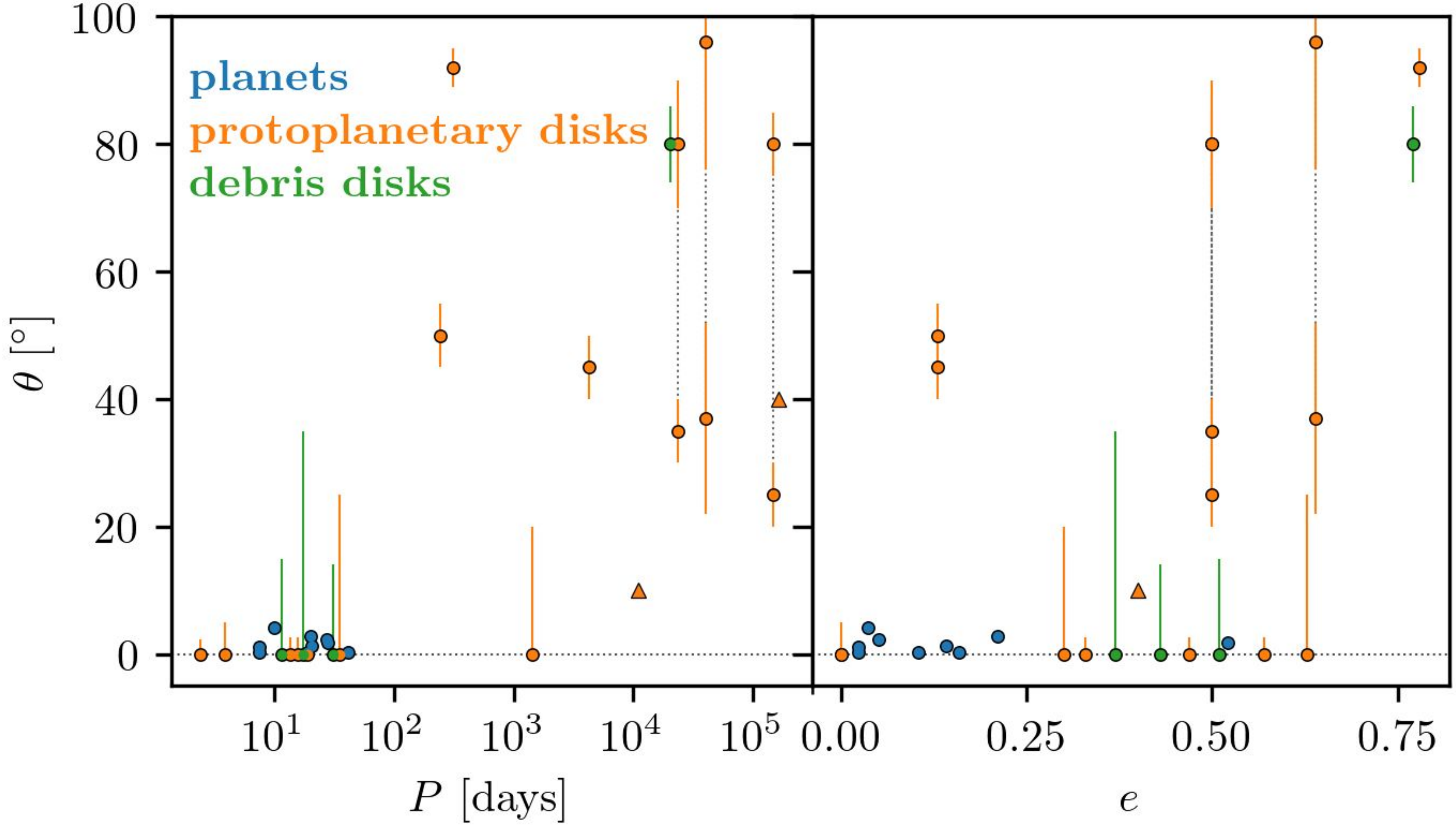




Eccentric binaries can drive large mutual inclinations with disks, especially if initial misalignment is already significant

Foucart & Lai 13, Martin & Lubow 17; Zanazzi & Lai 18, Lubow & Martin 18, Cuello & Guippone19

Formation and alignment mechanisms

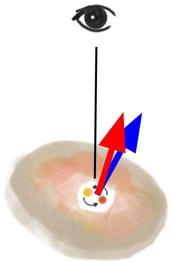


- Difficult to directly form binaries within a < 5 au→ fragmentation at larger distances + migration
- **Short periods** (P = 5 - 40 days) → substantial energy dissipation from orbit/disk interactions, *e* damping
- **Long periods** (P > 40 days) → vestigial random orientation from formation; *e*/*i*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

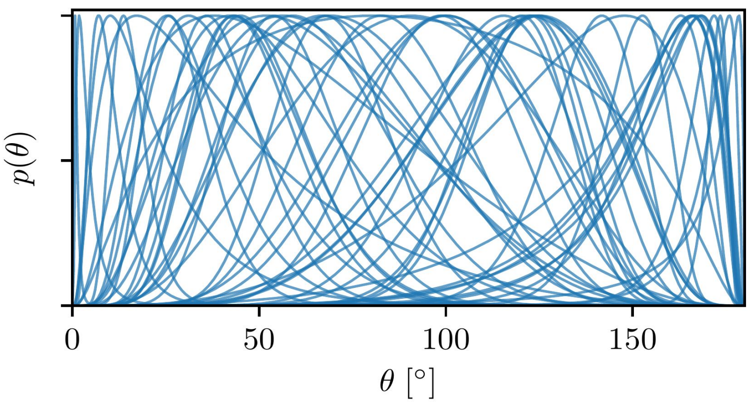
Tokovinin+06; Foucart and Lai 13; Muñoz and Lai 15;
Tokovinin 17; Moe and Kratter+18; Fleming+18, Bate 18

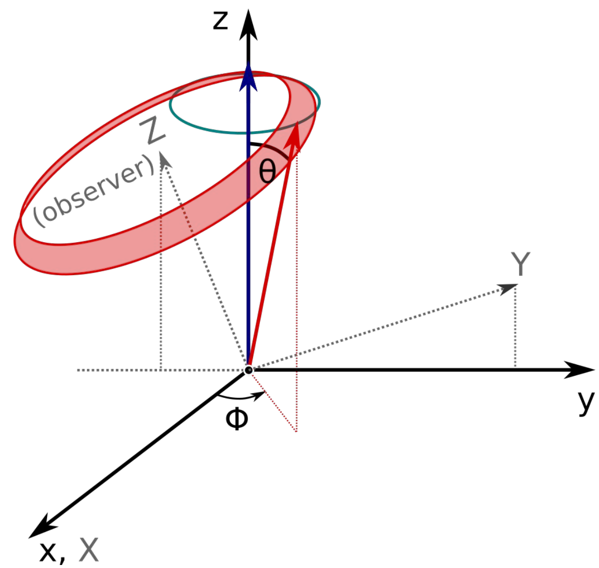
Conclusions

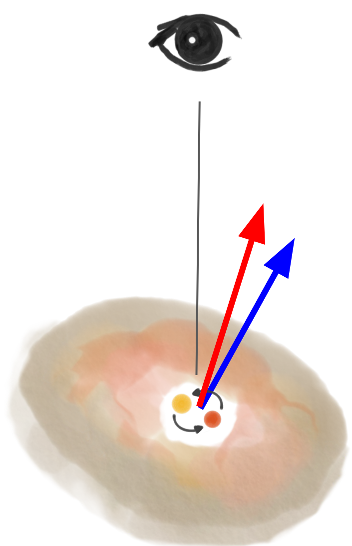
- Circumbinary protoplanetary and debris disks around short-period binaries (P < 40 days) **have low mutual inclinations** (i < 5°)
- Together with the *Kepler* CB planet population, this implies that the circumbinary planet formation rate is **similar to single stars** at these periods
- Binary-disk dissipative interactions shrink and circularize binary orbit, leading to **evolution of a coplanar system**
- CB disks around longer period binaries (P > 40 days) have a **broad range** of mutual inclinations
- **Binary eccentricity** plays a key role in driving large mutual inclinations

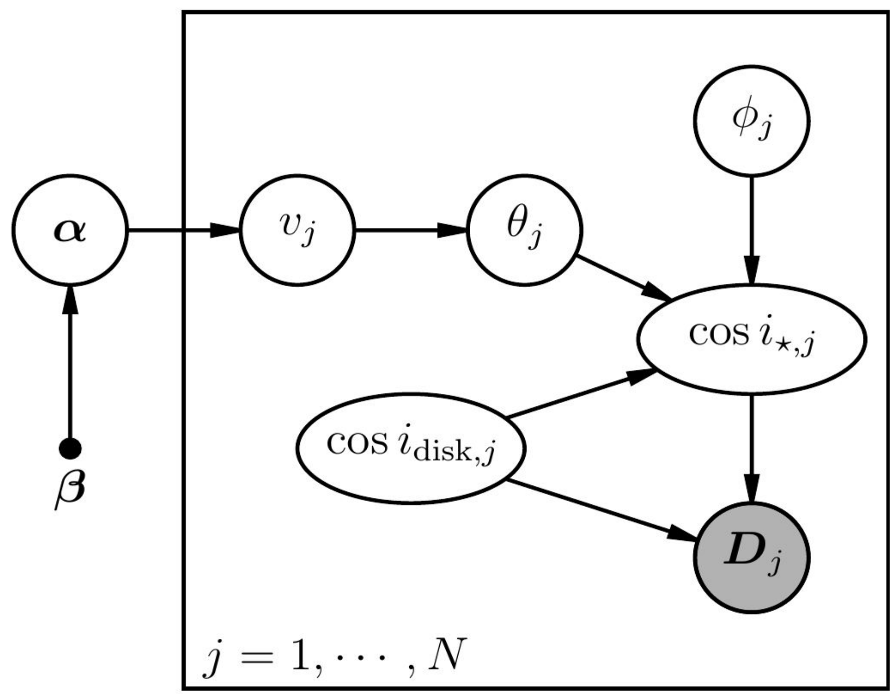


Thank you!

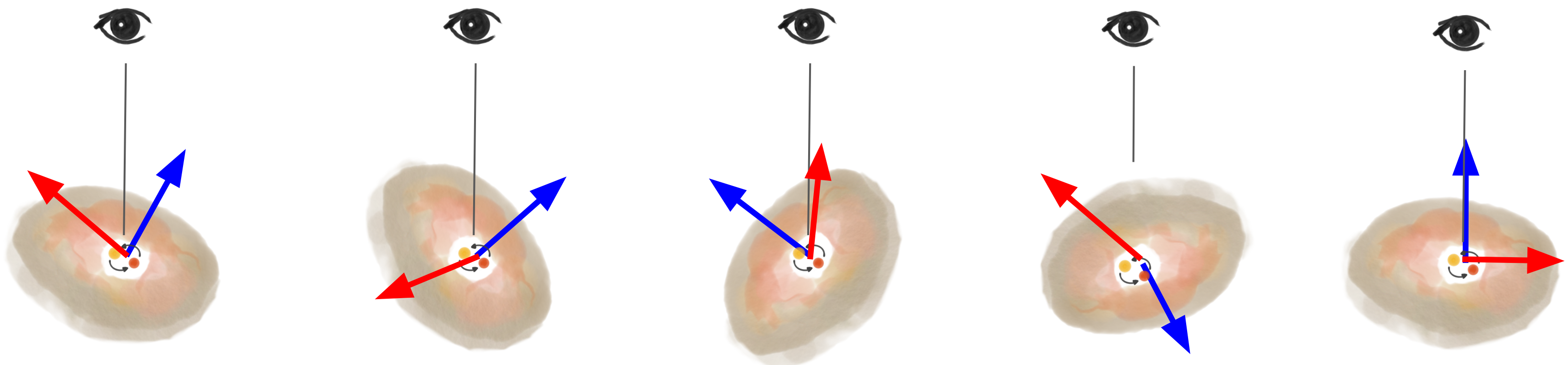

$p(\theta)$
0
50
100
150
θ [°]


z
Z
(observer)
θ
Y
y
Φ
x, X



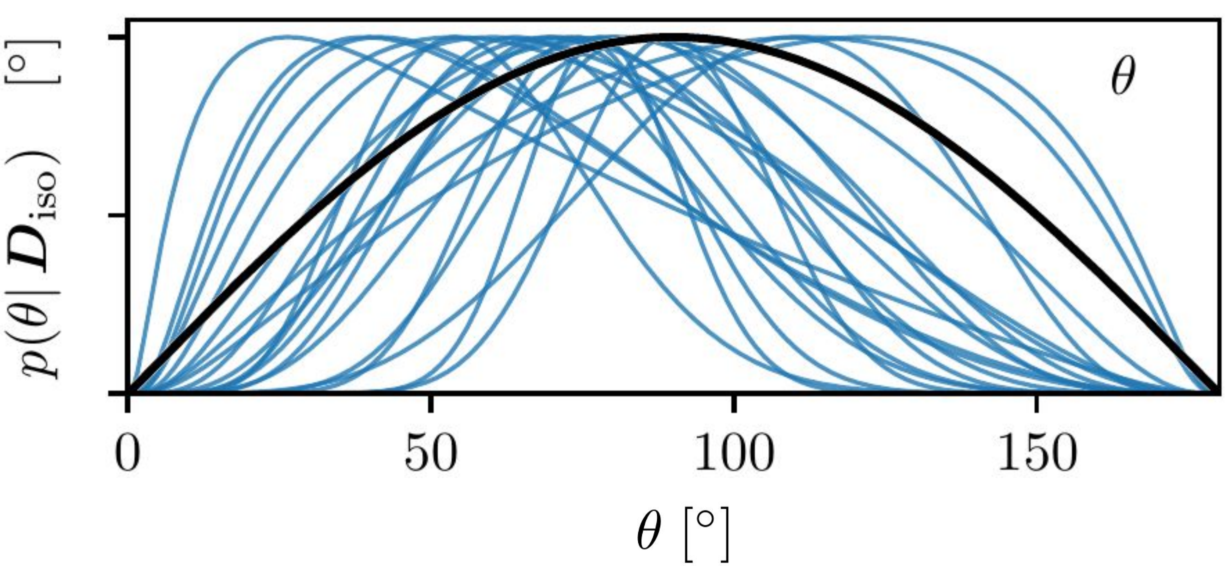

$\boldsymbol{\alpha}$
v_j
θ_j
ϕ_j
$\cos i_{\star,j}$
$\cos i_{\mathrm{disk},j}$
$\boldsymbol{D}_j$
$\boldsymbol{\beta}$
$j = 1, \cdots, N$

Fake data 1:

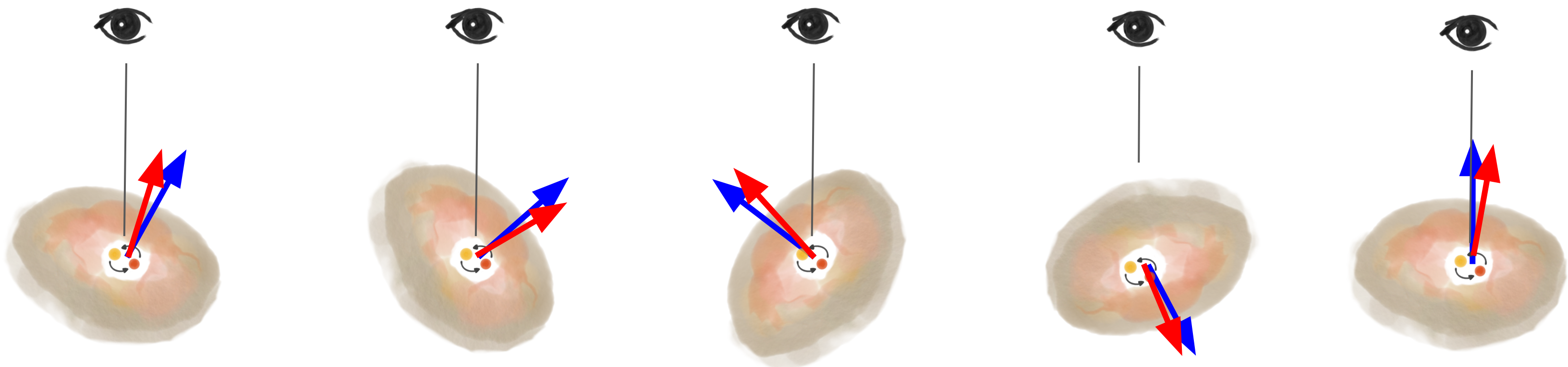


$i_* \neq i_{\rm disk}$

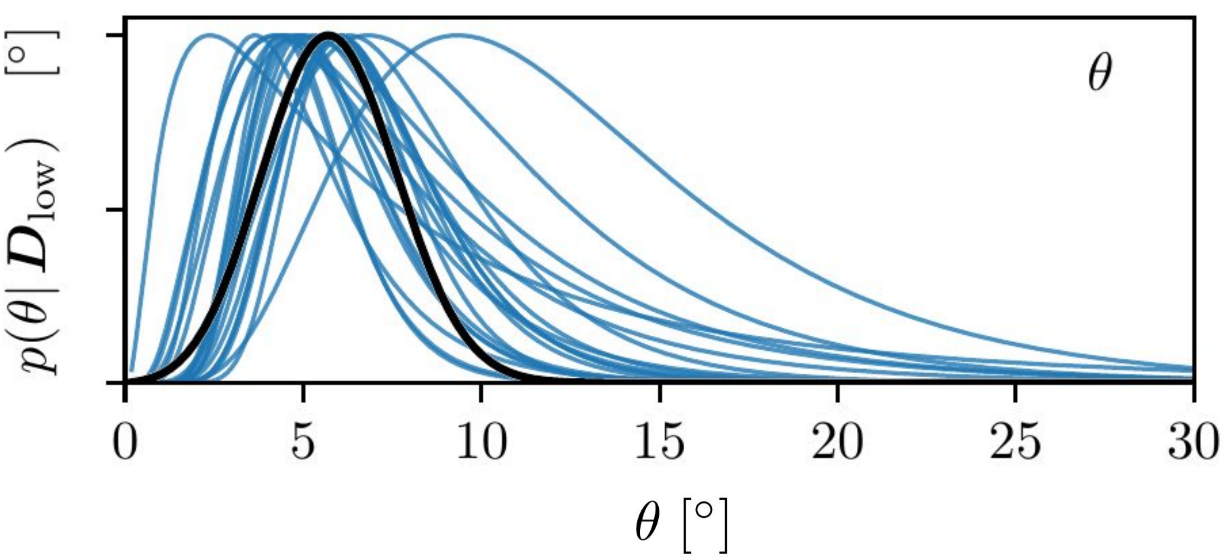
Inferred mutual inclination distribution

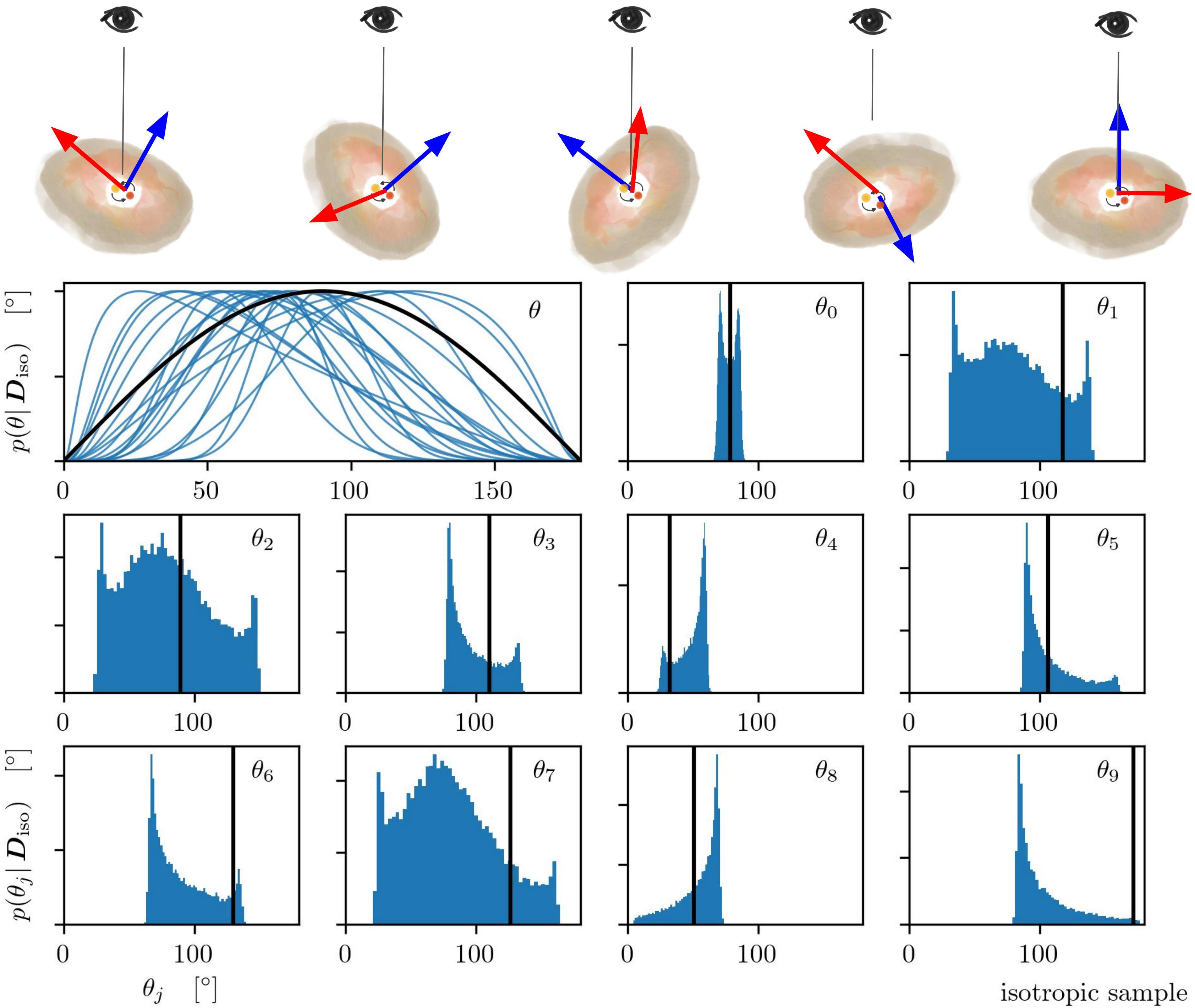


Fake data 2:

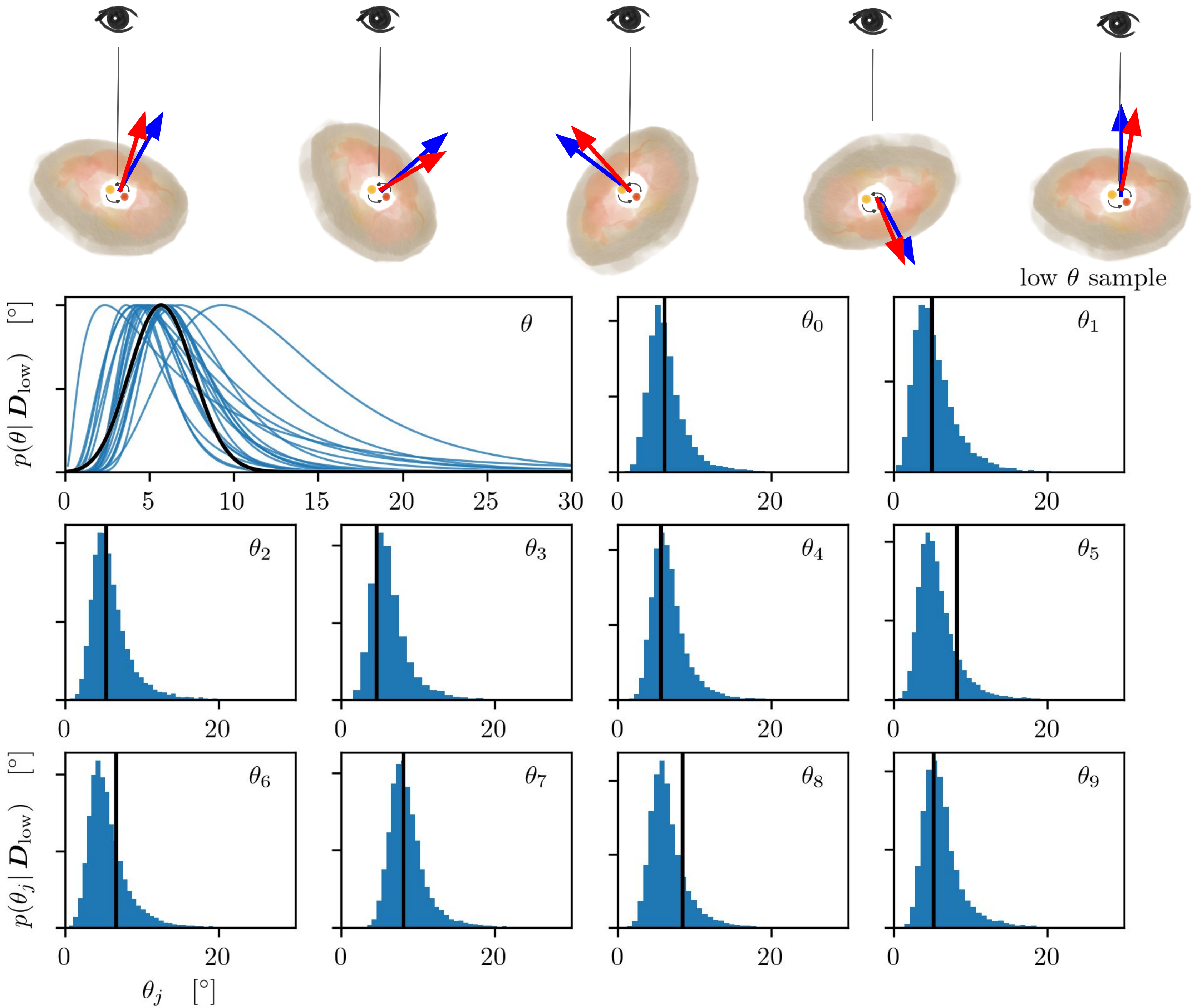


Inferred mutual inclination distribution





θ
θ_0
θ_1
θ_2
θ_3
θ_4
θ_5
θ_6
θ_7
θ_8
θ_9
$p(\theta | \boldsymbol{D}_{\rm iso})$ [°]
$p(\theta_j | \boldsymbol{D}_{\rm iso})$ [°]
θ_j [°]
0
50
100
150
isotropic sample



low θ sample
θ
θ_0
θ_1
θ_2
θ_3
θ_4
θ_5
θ_6
θ_7
θ_8
θ_9
$p(\theta|\,\boldsymbol{D}_{\rm low})\quad[^\circ]$
$p(\theta_j|\,\boldsymbol{D}_{\rm low})\quad[^\circ]$
$\theta_j\quad[^\circ]$
0 5 10 15 20 25 30
0 20