DYNAMICS OF ALIGNED AND MISALIGNED CIRCUMBINARY DISKS

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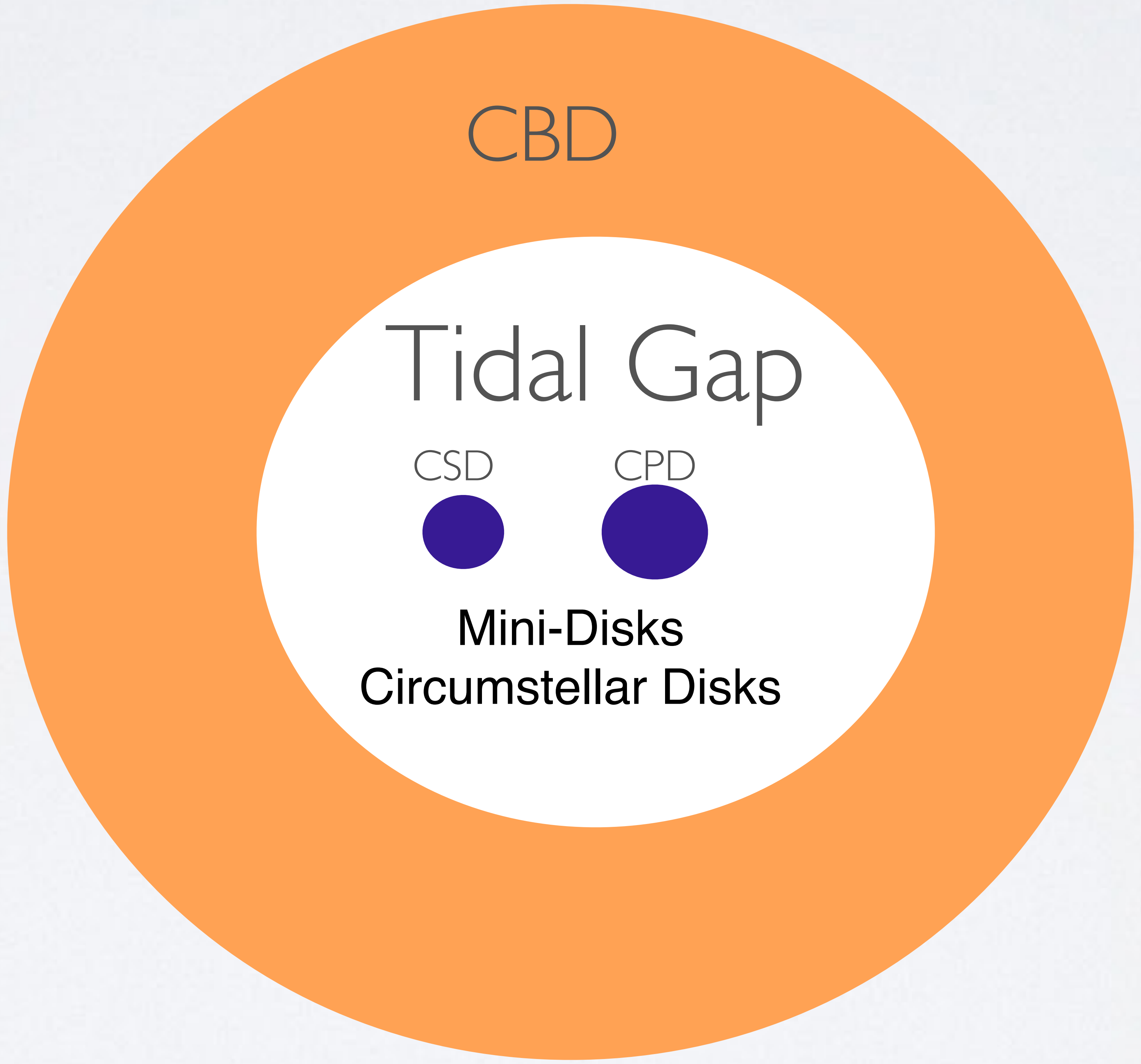
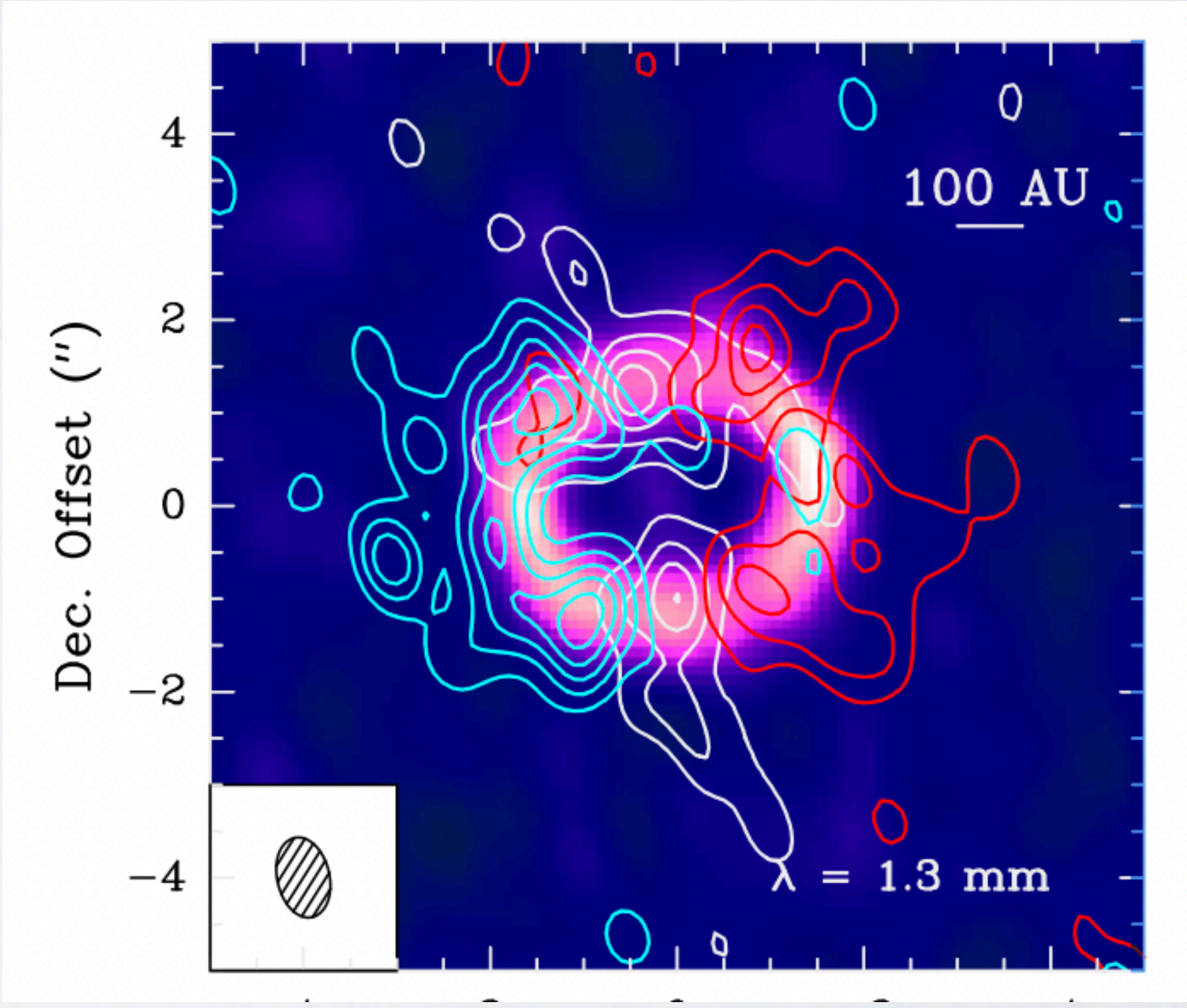
BINARY DISKS

Interested in SMBH binaries and young stellar binaries

- 3 Disks
  - circumsecondary (CSD)
  - circumprimary (CPD)
  - circumbinary (CBD)



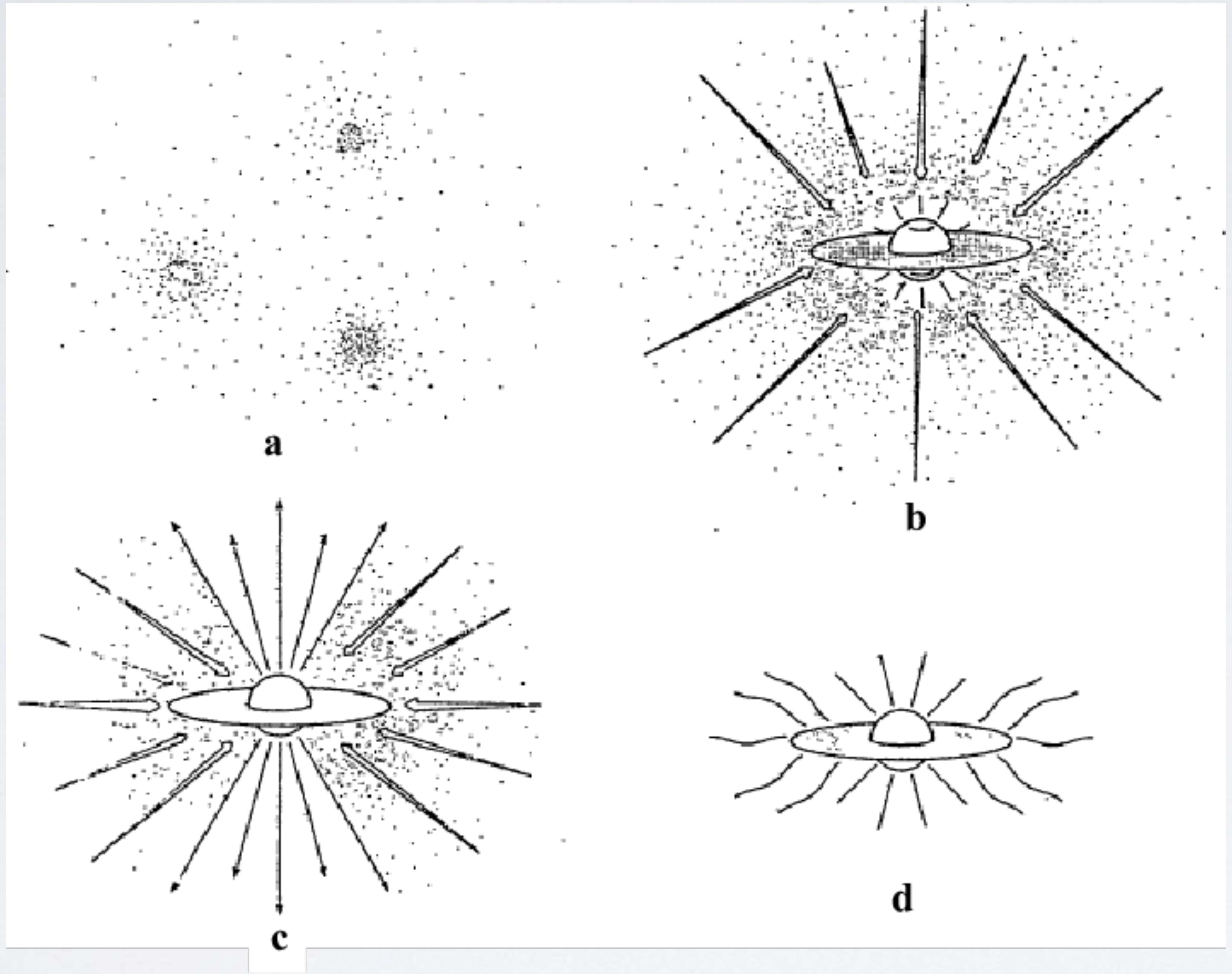
GG Tau



Guilloteau et al. (1999)

Dutrey et al. 2016

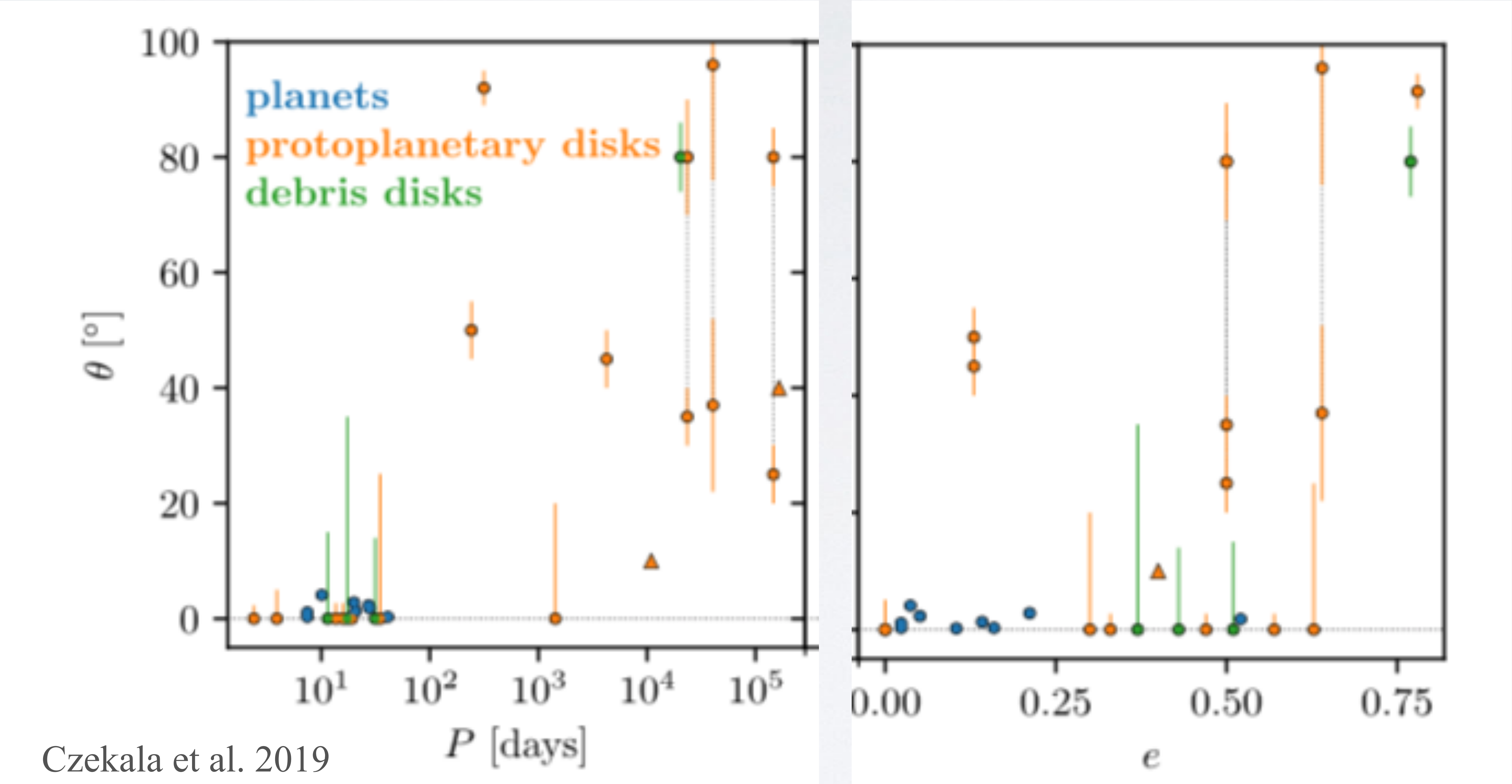
SINGLE STAR FORMATION



Shu, Adams, Lizano 1987

Single rotation direction

BINARY/PLANET/CB DISK ALIGNMENT OBSERVATIONS

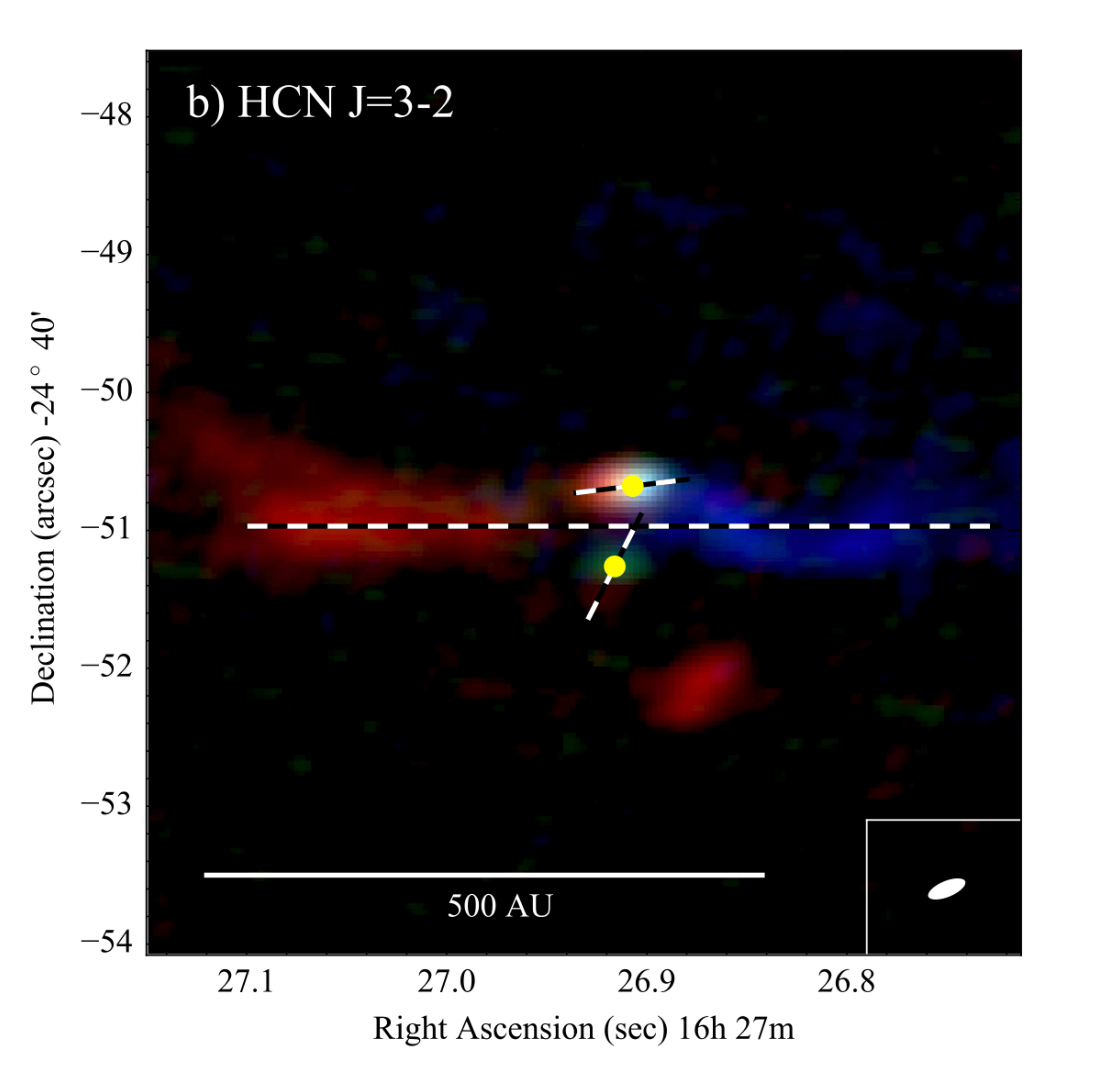


Czekala et al. 2019

- CB disk alignments for P < 30d ;
  Correlated with binary eccentricity

3 MISALIGNED DISKS

IRS 43



Brinch et al. 2016

Also SMBH case

OUTLINE

- Simulations/Model Limitations

- Coplanar case

- What is different for misaligned dynamics?
  - Gap Opening
  - Kozai-Lidov Disks (CSD; CBD in triple)
  - Polar CBDs

SIMULATION LIMITATIONS

- Want models for CBDs around SMBH and young star binaries

- Simulations often assume:
  - alpha model, $0.001 < \alpha < 0.1$, sometimes MRI
  - $0.03 < H/r < 0.1$

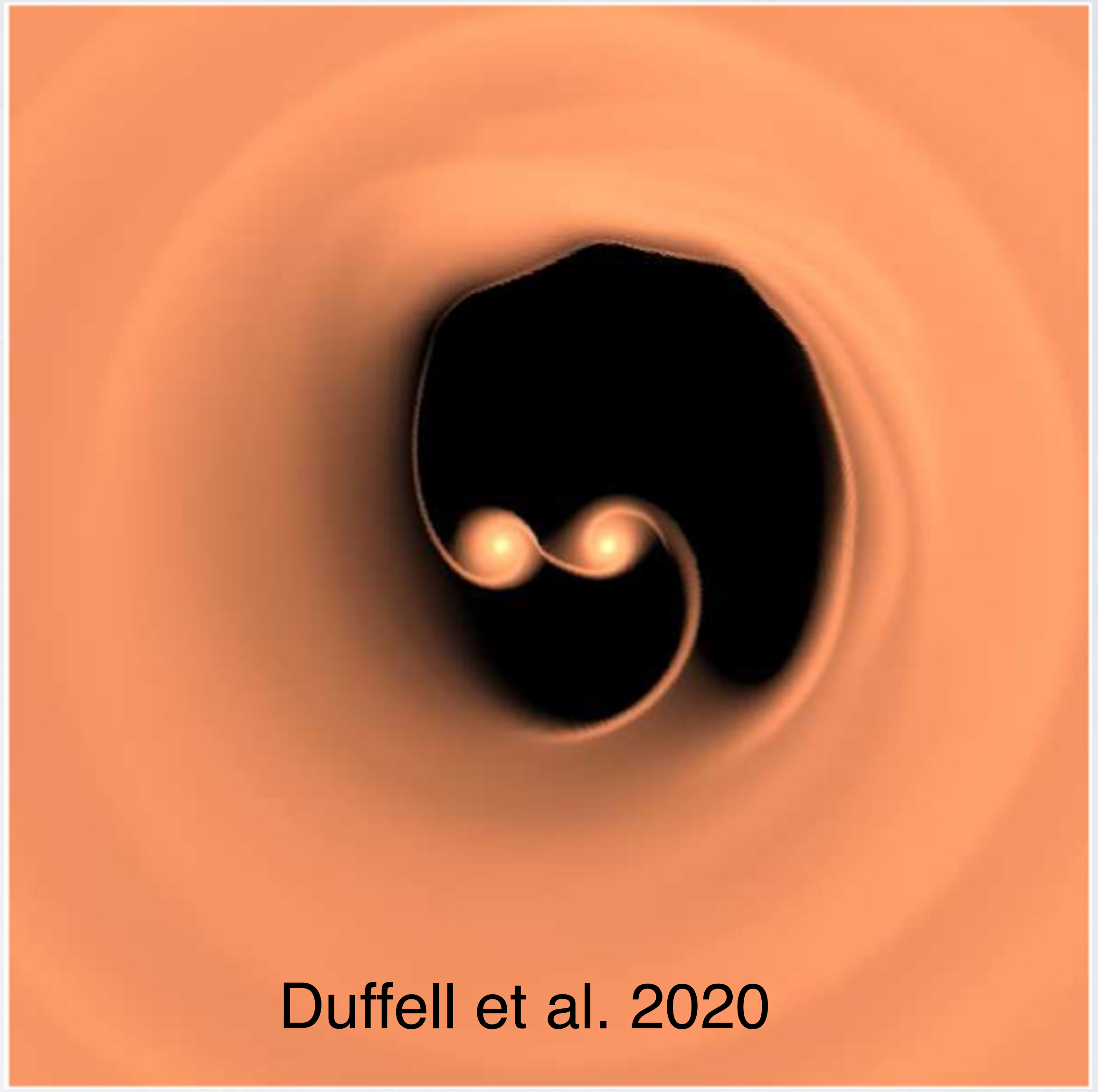
- SMBH and young star binaries fall outside these expected actual parameter ranges:
  -SMBH: $0.001 < H/r < 0.01$, $\alpha > 0.01$ for fully ioinzed MRI, also radiation effects
  -Young binaries: $0.02 < H/r < 0.1$, α highly uncertain: may be very small $\alpha < 0.0001$, could be dead zones, complex nonideal MHD, winds

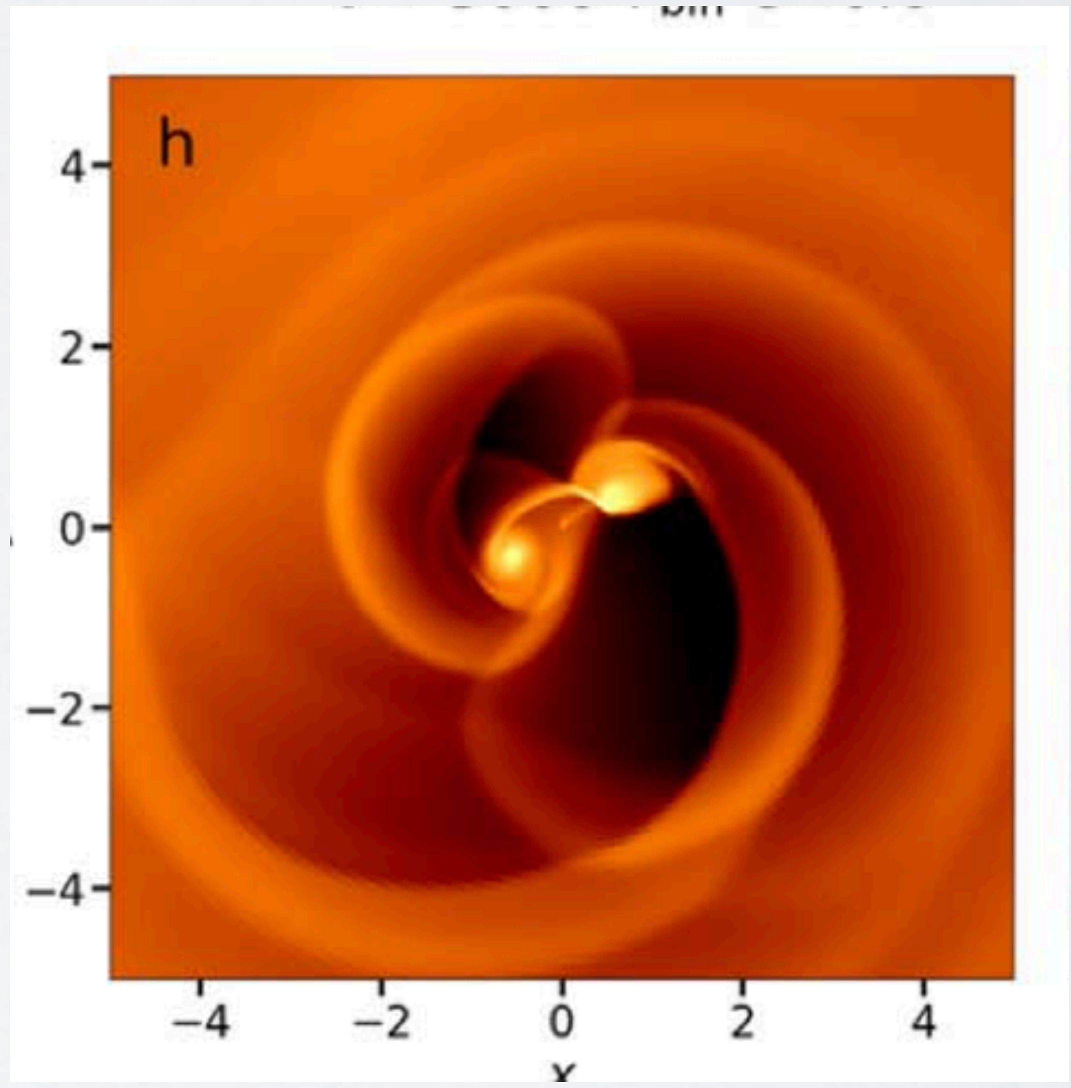
- Analytic models can help extend these ranges.

- Models typically assume coplanarity

COPLANAR PROGRADE FLOW

- Gap opening by tidal field of binary (Artymowicz & Lubow 1994; Miranda & Lai 2015, Lubow et al. 2015)
- Gas streams in the gap (Artymowicz & Lubow 1996, Gunther & Kley 2002, MacFadyen & Milosavljevic´ 2008, Shi et al. 2012, D'Orazio et al. 2013, Farris et al. 2014, 2015, Munoz et al. 2016, 2019, 2020 Duffell et al. 2020, Moesta et al. 2019, Heath & Nixon 2020, D'Orazio & Duffell 2021, Tiede et al. 2021, Dittman & Ryan 2022)
- Gas streams typically cause pulsed accretion onto mini-disks through gap
- CBD can become eccentric, even if binary orbit is circular
- Important coplanar prograde issues remain on how binary orbit evolves, gas stream properties, etc.


Duffell et al. 2020



Moesta, Taam, & Duffell 2019

GAP OPENING IN RETROGRADE DISKS

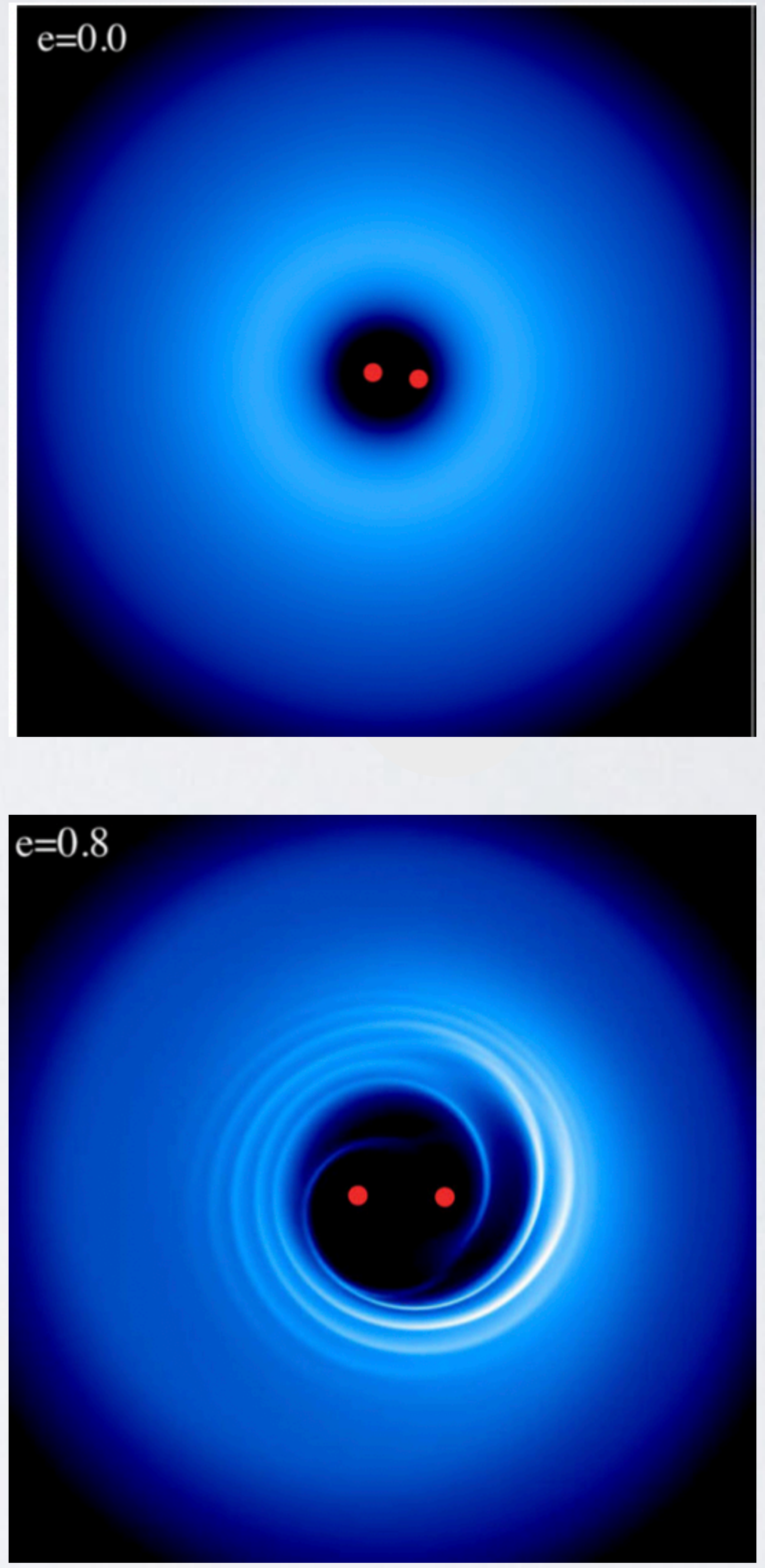
- Gaps get smaller in tilted disks because tidal resonances are weaker: binary farther away from disk and disk moves faster relative to binary (Miranda and Lai 2015; Lubow et al. 2015)

- No tidal (Lindblad) resonances for retrograde disks with $e_b = 0$, get small gap (Nixon et al. 2011)

- Binary orbit efficiently loses angular momentum and can become eccentric (Nixon et al. 2011, Schnittman & Krolik 2015)

- For $e_b = 0, i \sim \pi$, get $T_{2,2} \propto (i - \pi)^8$ for near retrograde disk (Lubow et al. 2015)

- Weak resonances for eccentric orbit binary with retrograde disk $T_{-1,2} \propto e_b^6$; retrograde bars at high e_b (Nixon & Lubow 2015)



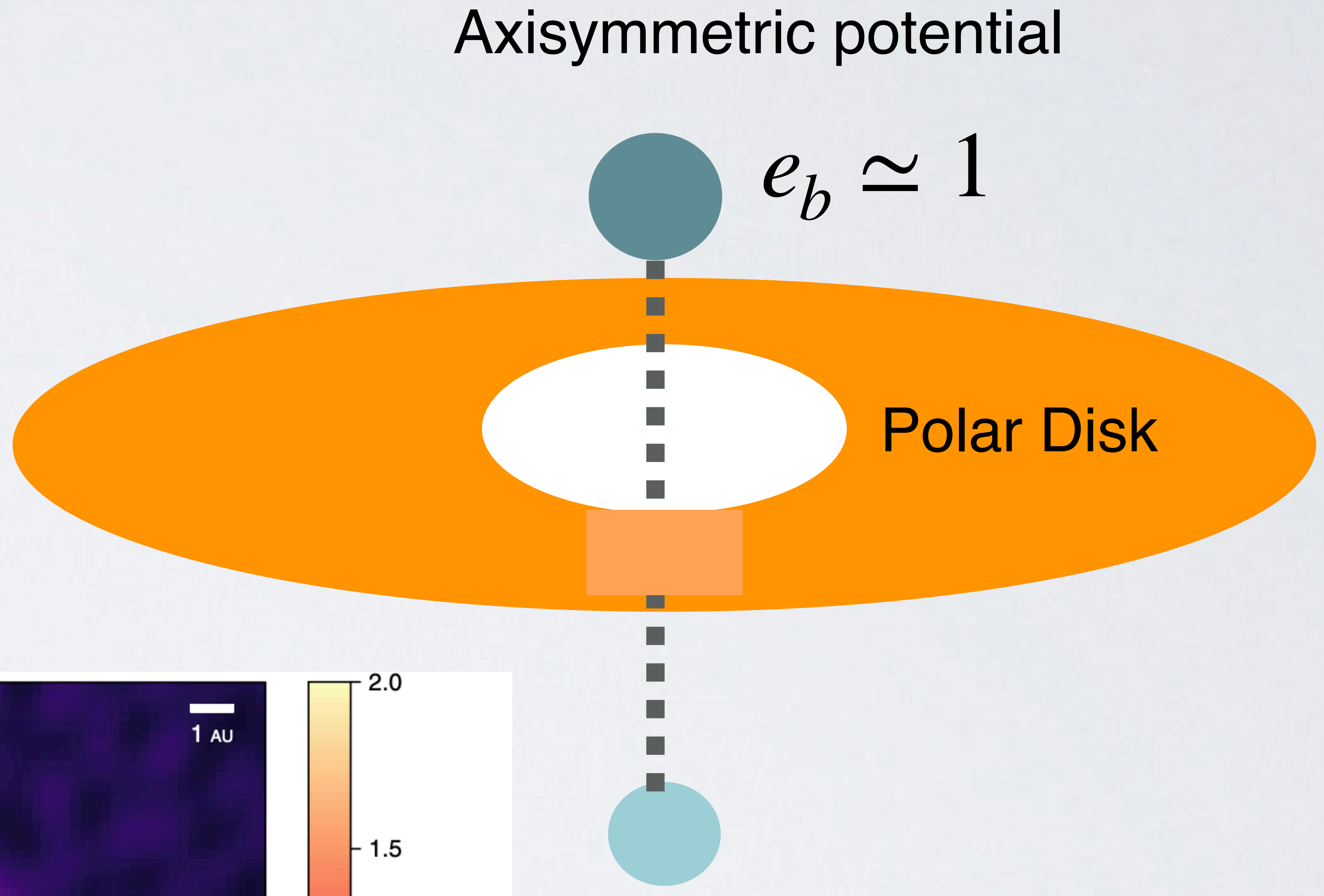
Nixon & Lubow 2015

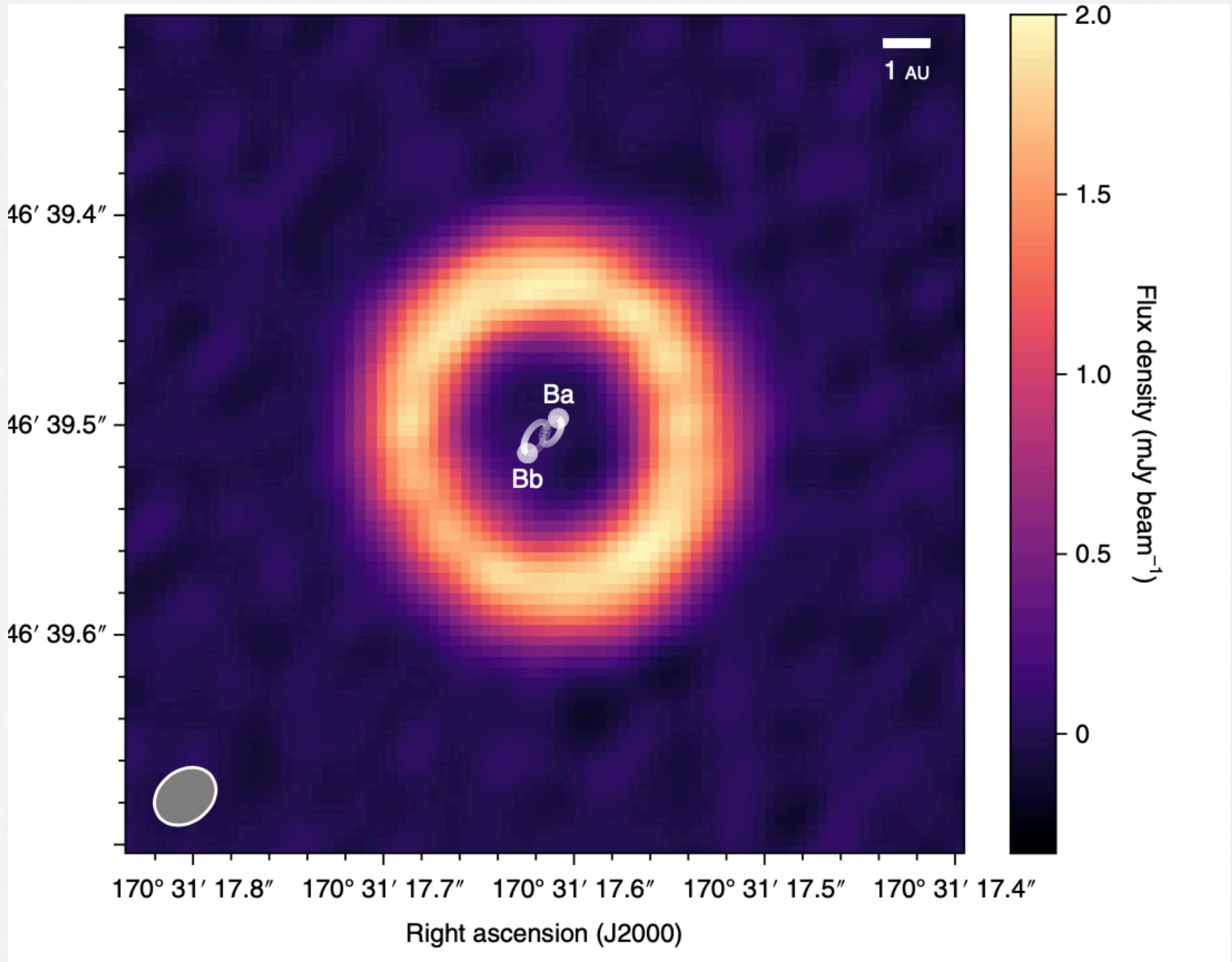
POLAR DISK TORQUE AT $e_b \simeq 1$

- At high e_b coplanar disk sees highly nonaxisymmetric potential, strong torque.

- At high e_b polar disk $i = 90°$ sees nearly axisymmetric potential, small torque

- Applies to observations of polar disk HD98800 $e_b = 0.785$ (Kennedy et al. 2019)

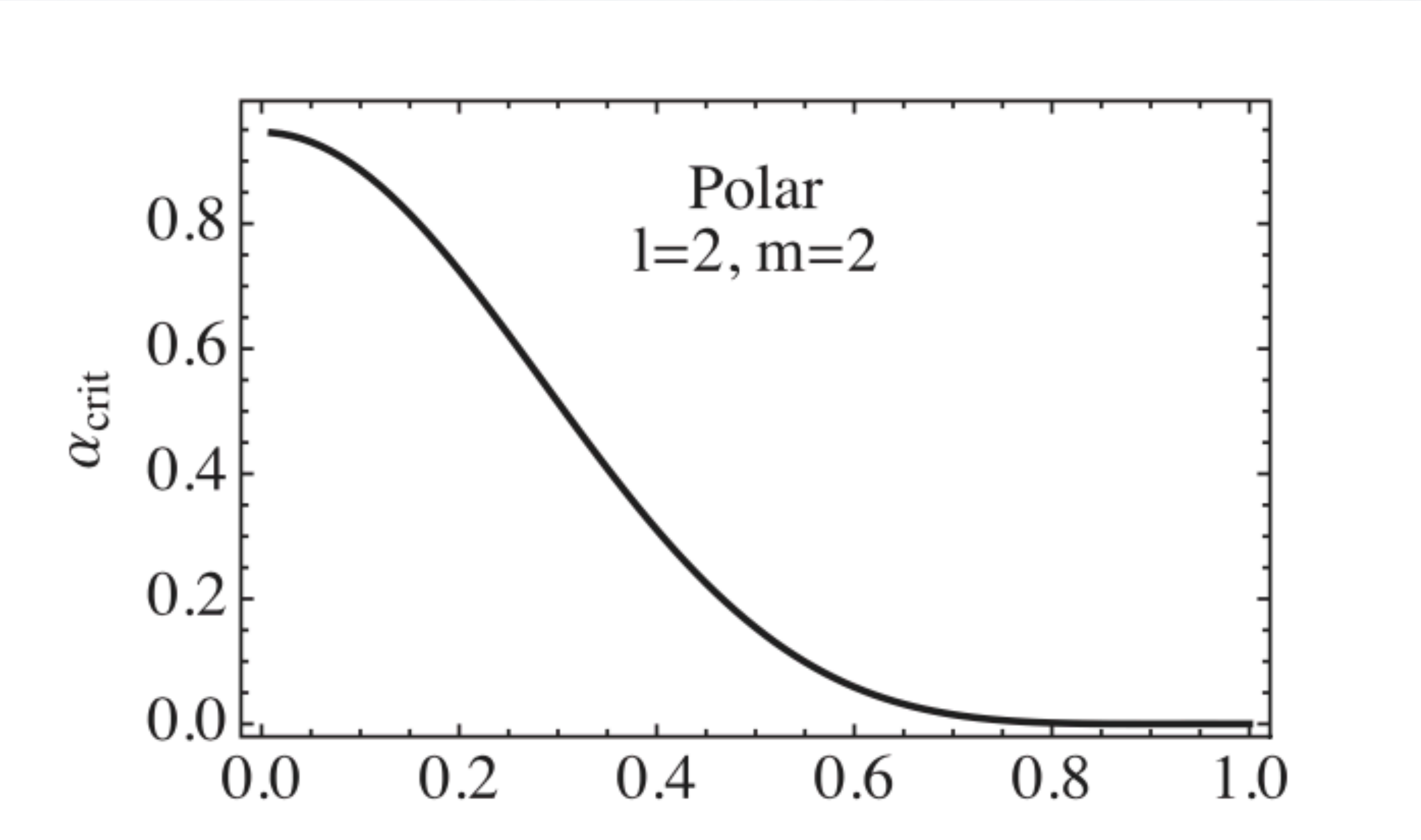




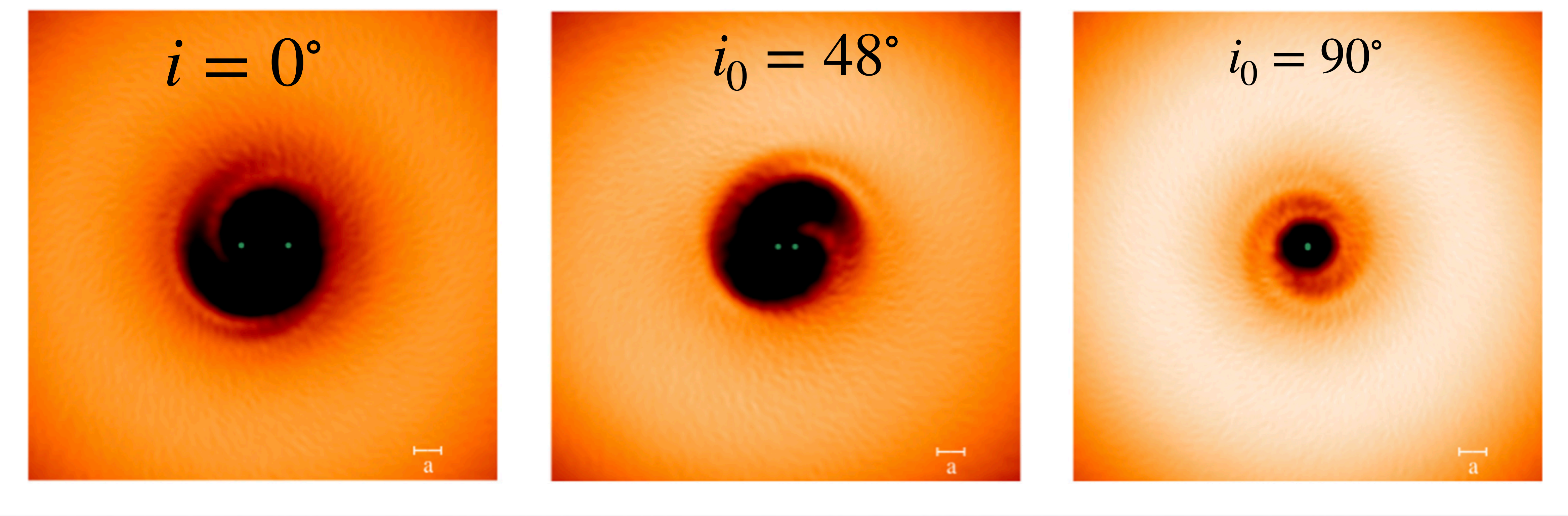
Kennedy et al. 2019

GAP OPENING IN POLAR DISKS

- Polar disk Lindblad torque, for $e_b \sim 1$, $T \propto (1 - e_b)^k, k > 1$ (done w/o using series expansion in e_b Lubow & Martin 2018)
- Gaps smaller for polar disks at high e_b
- Consistent with observations of polar disk HD98800 $e_b \simeq 0.8$
- Type of flow in polar gap? No hint yet of gas streams (Smallwood et al. in preparation).



Lubow & Martin 2018



Franchini, Lubow, & Martin 2018

NODAL PRECESSION

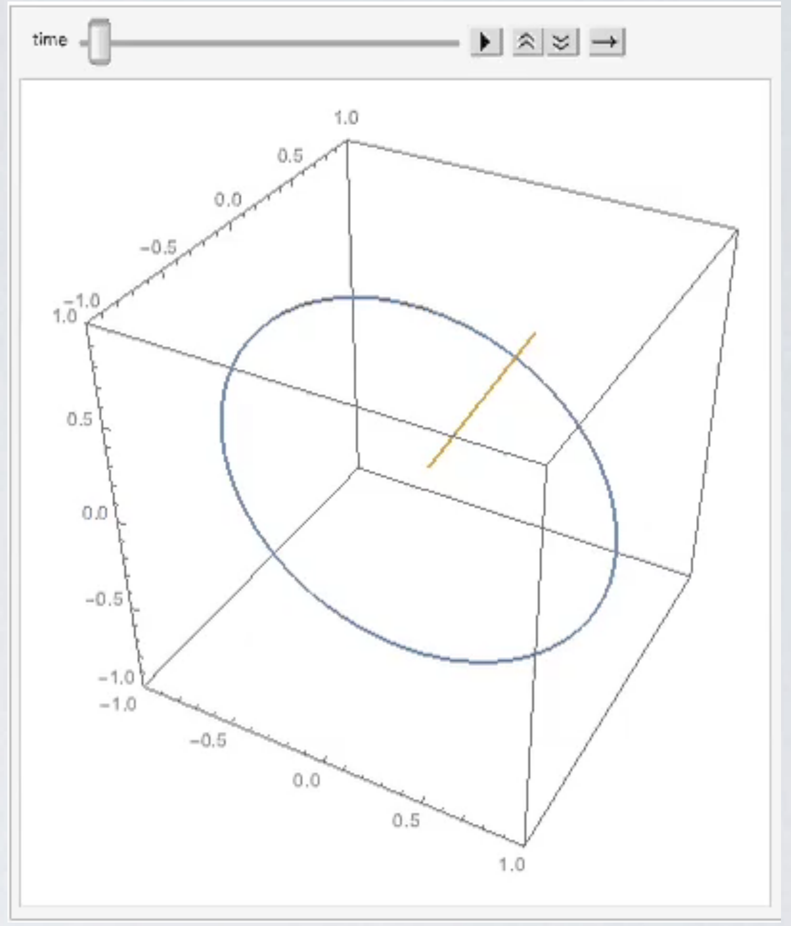
- Tilted disks in binary systems undergo nodal precession, gyroscopic motion

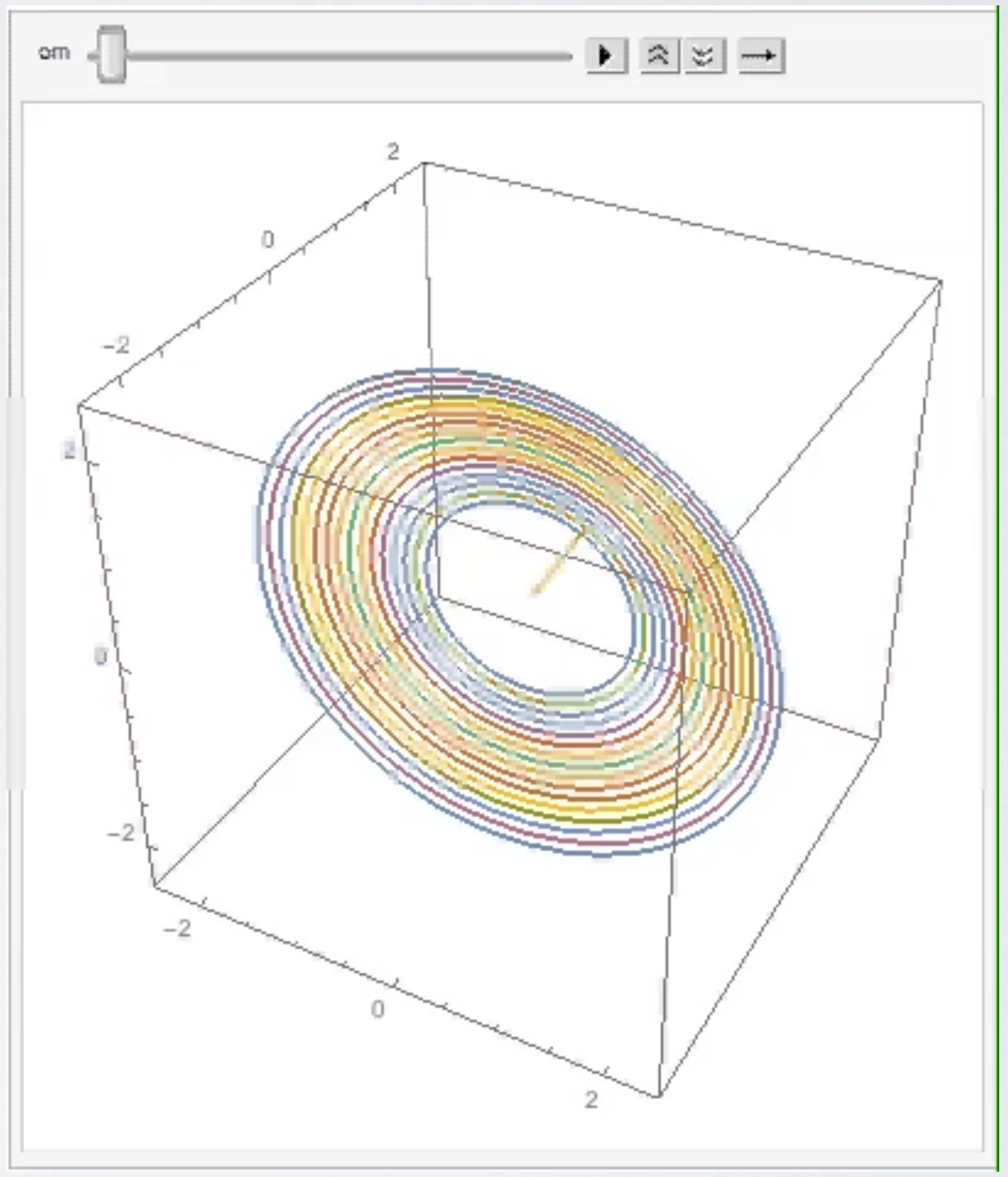
- Disk behaves like a solid body (little warping) if differential precession timescale is longer than radial sound crossing timescale (Papaloizou & Terquem 1995; Larwood & Papaloizou 1997)

- Otherwise get strong warps and possibly breaking

- Evolution to coplanarity for circular orbit binaries, typically (Papaloizou & Terquem1995, Lubow & Ogilvie 2000, Lodato & Facchini 2013, Foucart & Lai 2014, Martin, Zhu, & Armitage 2020)

- Is there something qualitatively new/different for misaligned disks?



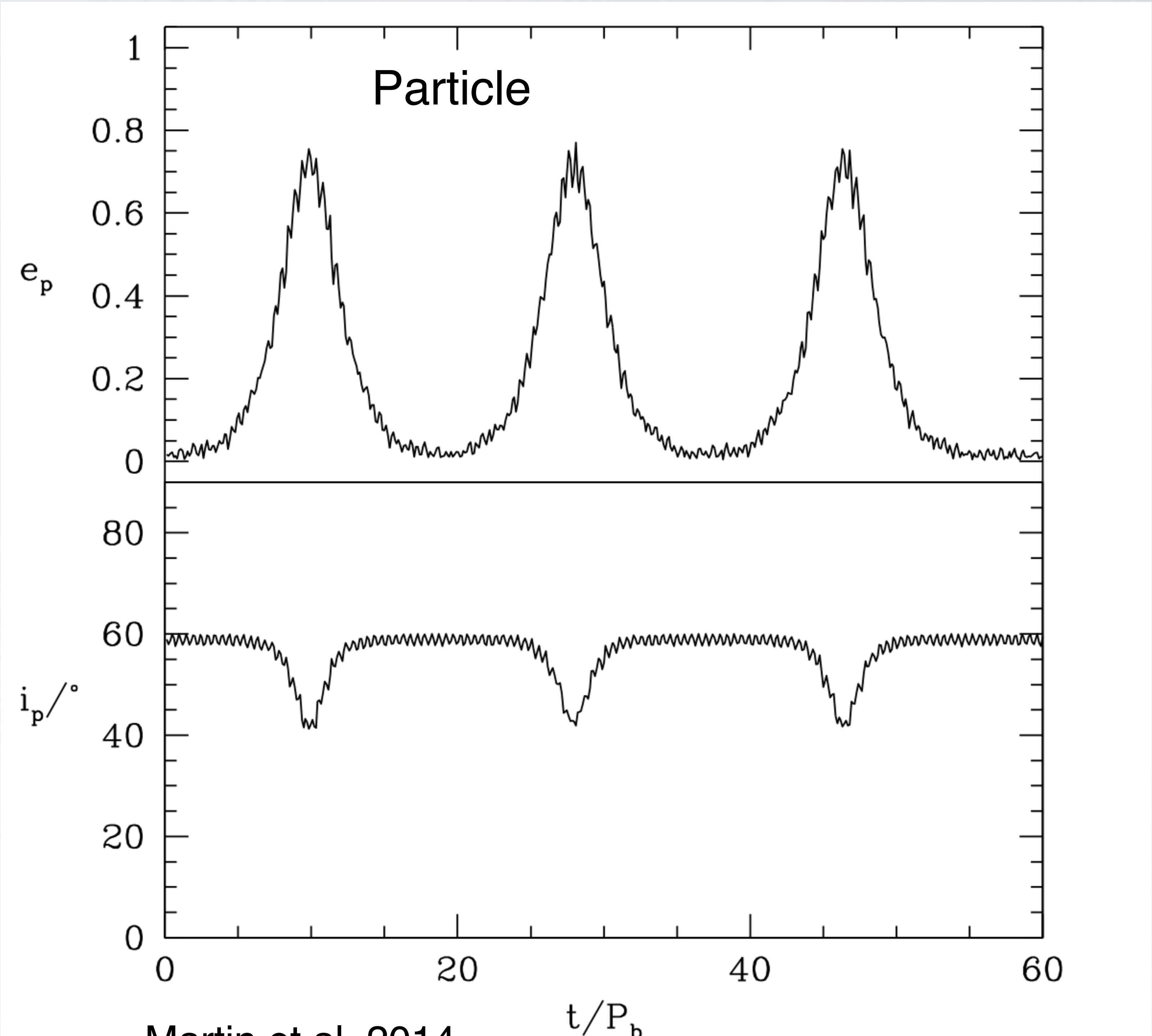


Differential precession of particles

KOZAI-LIDOV (KL) DISKS

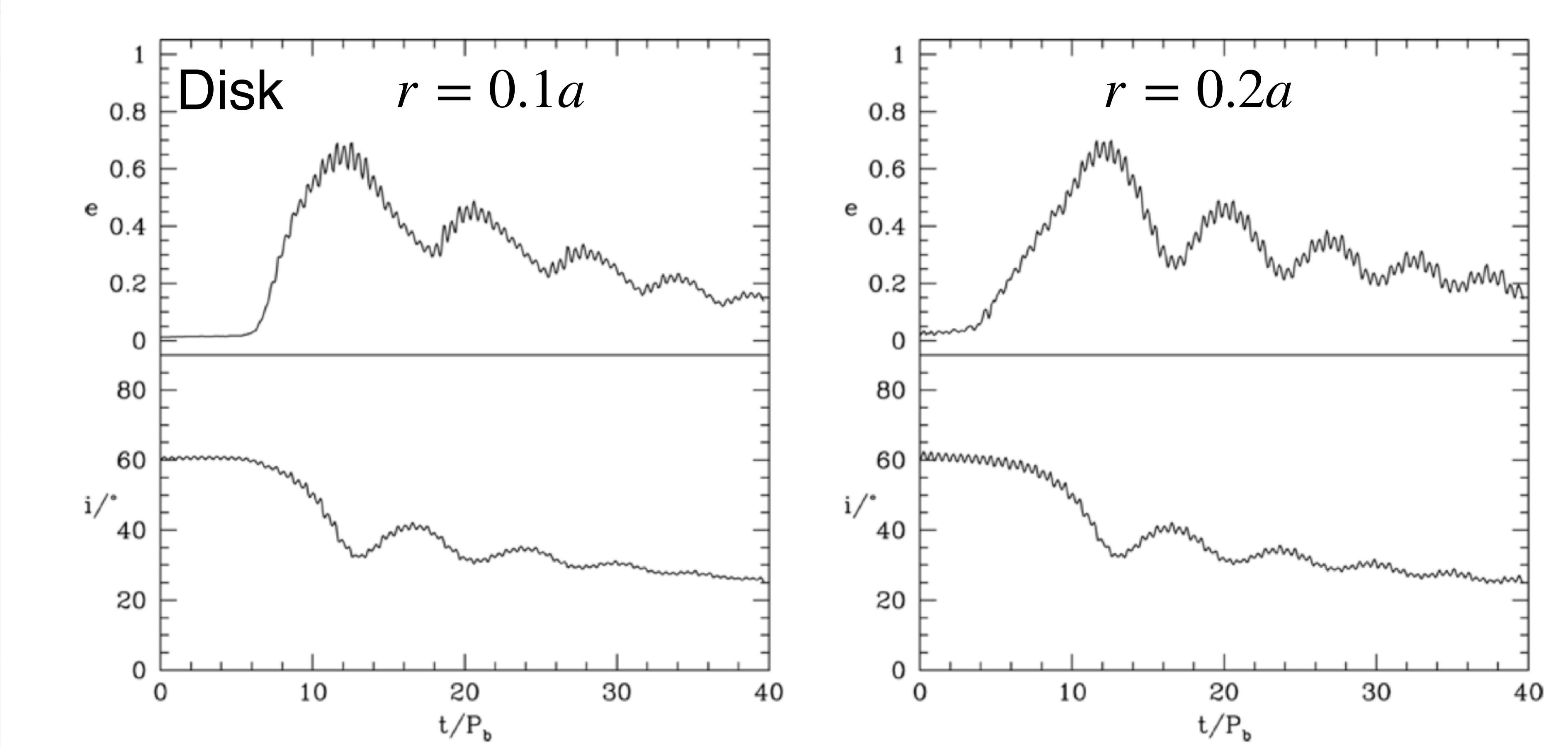
- External companion interacts with disk

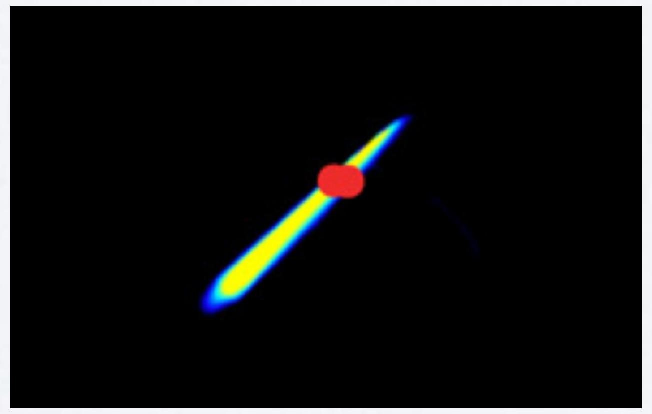
- Initially circular particle orbit around central object
  - Tilt oscillations for $i_0 > 39°$
  - For $i_0 = 60°$ gain eccentricity to $e_{max} = 0.76$ at lowest inclination $i_{min} = 39°$



Martin et al. 2014

- KL CSDs (Martin et al. 2014, Zanazzi & Lai 2017, Lubow & Ogilvie 2017)
  - Need some pressure, but not too much
    - enough pressure to prevent disk breaking
    - not too much: need $\omega_{gr} > \omega_{pr}$ (apsidal precession rates)
  - KL disks experience eccentricity, dissipation, and shocks
  - Tilt damps to lower value

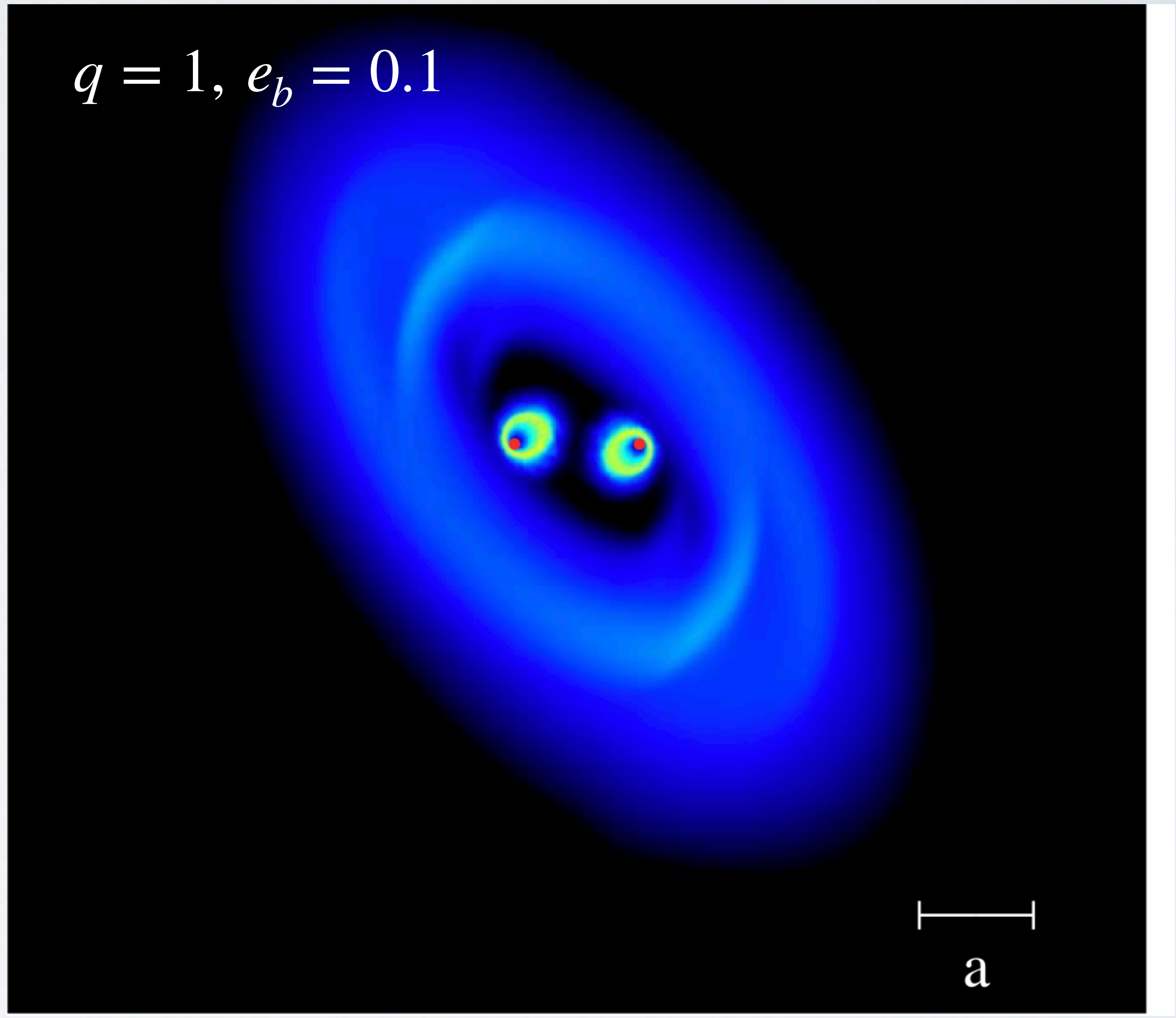




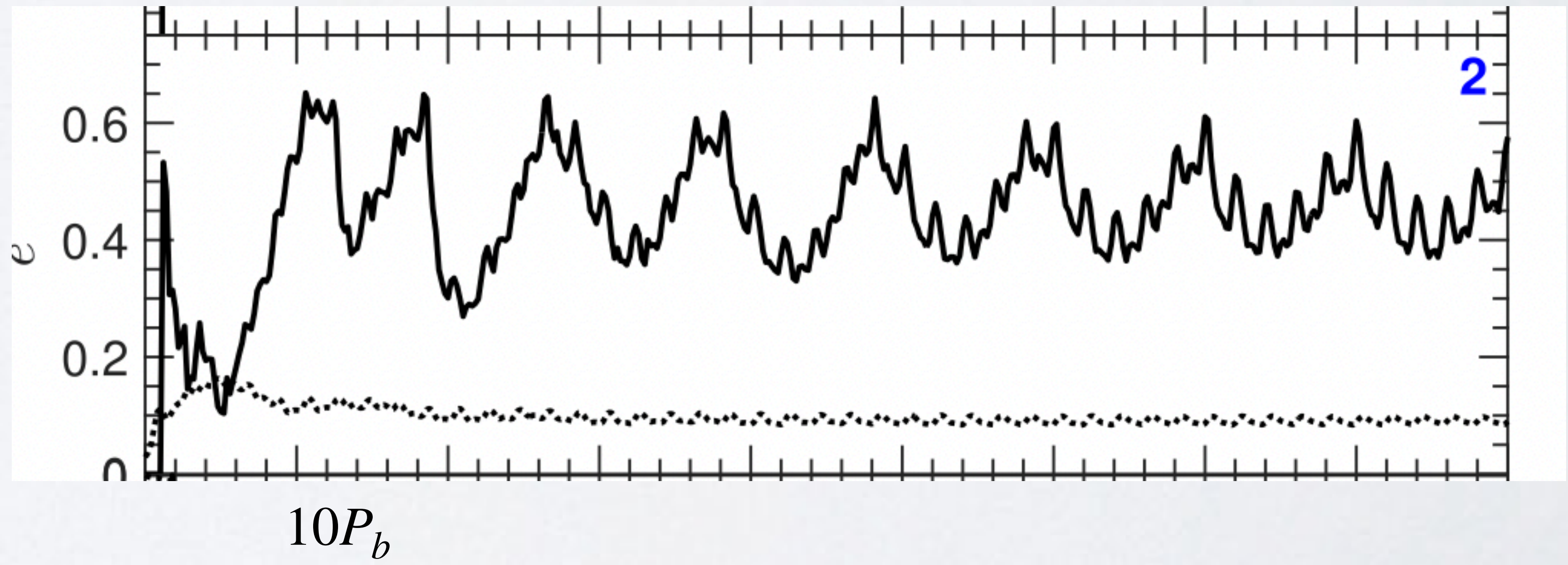
- KL CBDs also possible in triple systems (Martin et al. 2022)

SUSTAINED KOZAI-LIDOV (KL) OSCILLATIONS

- Inclined CBD continuously feeds gas to CSDs via inclined gas streams
- Resulting CSDs are also inclined
- CSDs undergo sustained KL oscillations and time varying accretion
- Dust rings in KL disks (Martin & Lubow 2022)

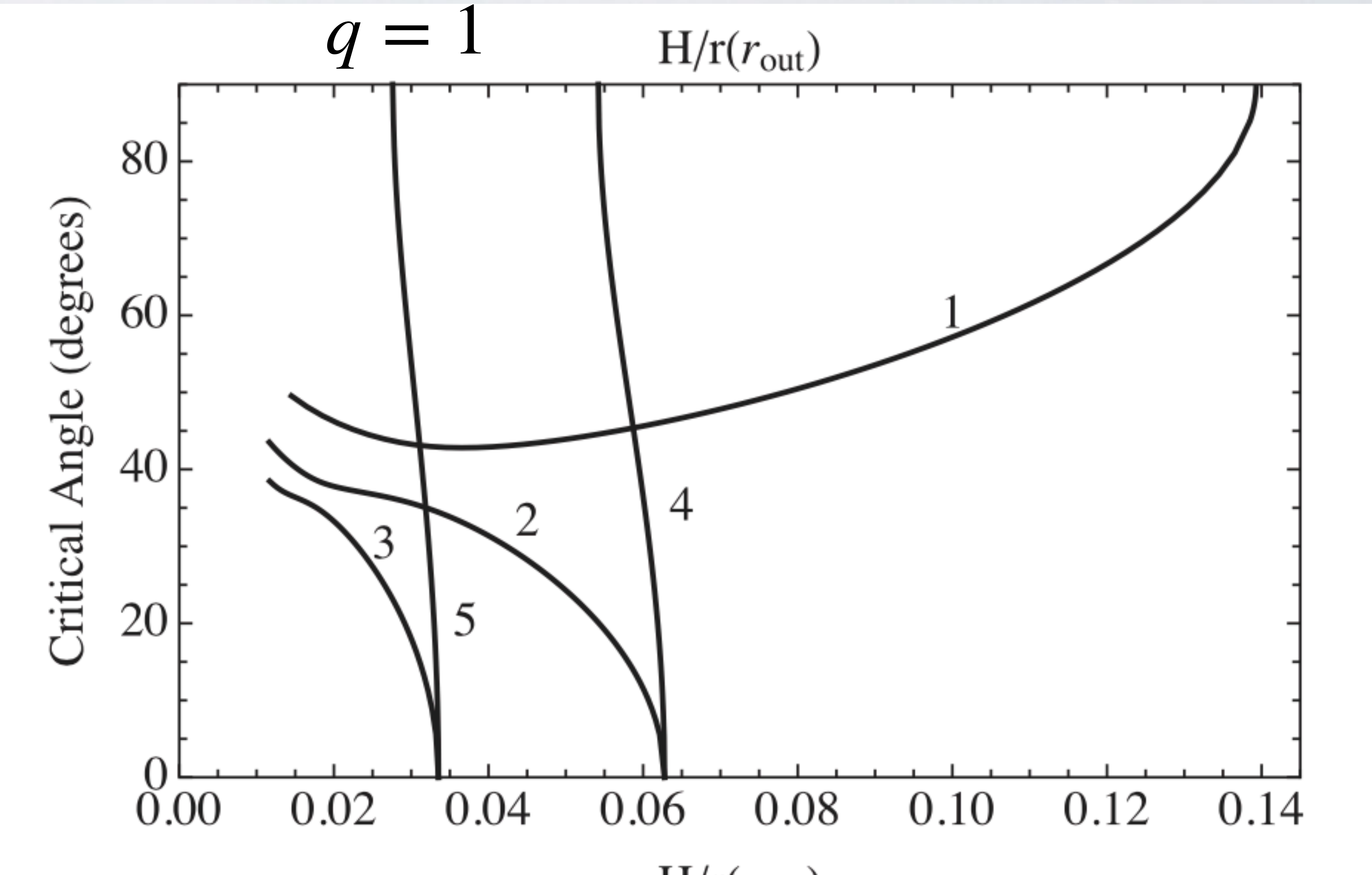


Smallwood, Martin, & Lubow 2021



KOZAI-LIDOV DISKS

- Linear theory when e is small (Zanazzi & Lai 2017, Lubow & Ogilvie 2017)
- Upper limit of H/r ~ 0.15 for typical KL disks
- Multiple unstable modes are present. Fastest growing mode most important.
- Minimum inclination angle for instability can be quite low, well below particle angle of 39 degrees. Resonance where apsidal and nodal precession rates match.
- But growth rate is generally low below 39 degrees., below mode 1.



Lubow & Ogilvie 2017

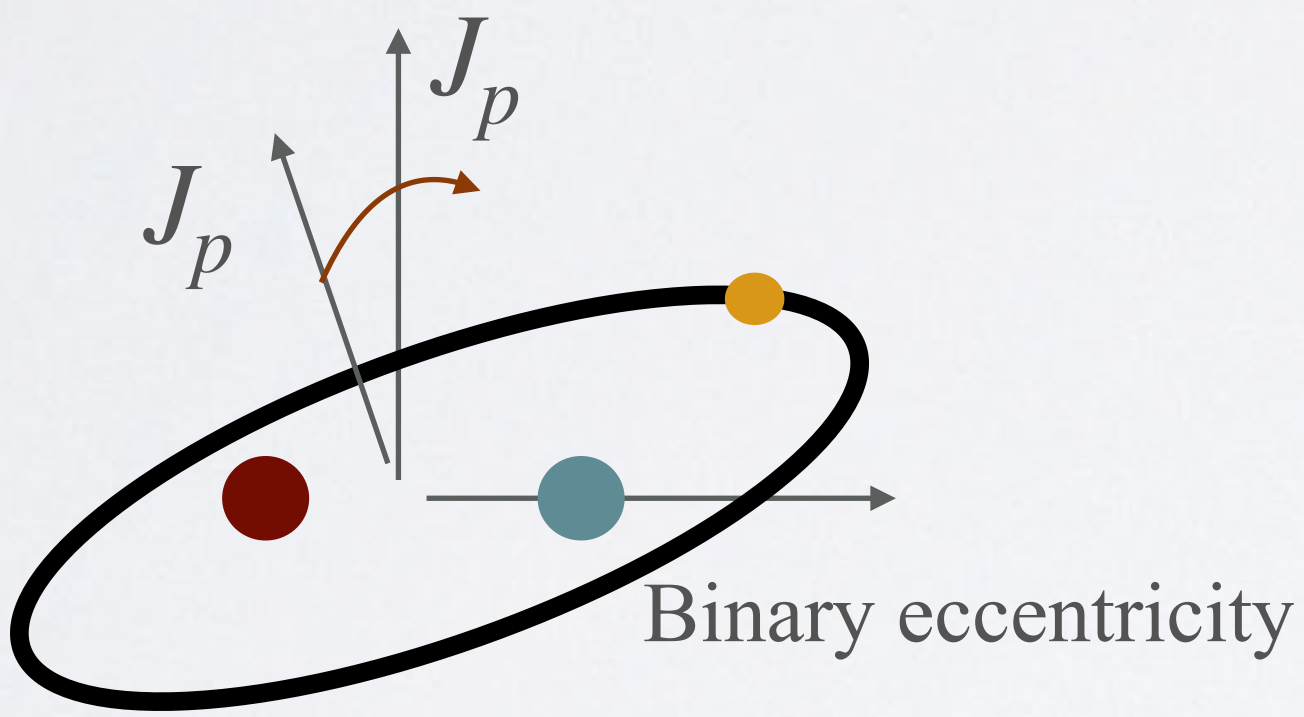
PARTICLE ORBITS AROUND ECCENTRIC BINARIES

Farrago & Laskar (2010)

Eccentric orbit binary: secular triaxial potential

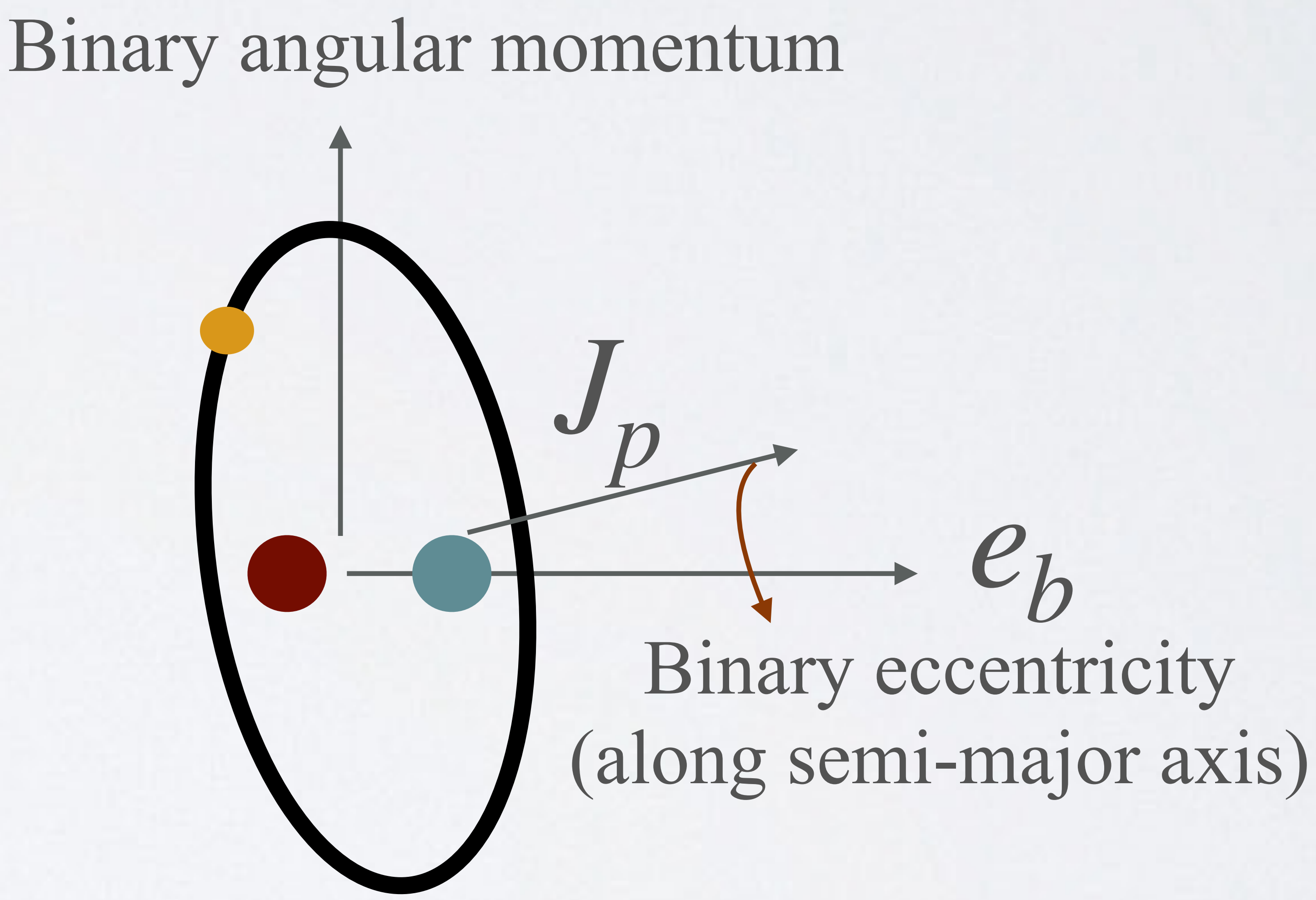
Nearly coplanar

$i \simeq 0^\circ$



Nearly polar: e_b nearly along J_p

$i \simeq 90^\circ, \Omega \simeq 90^\circ$

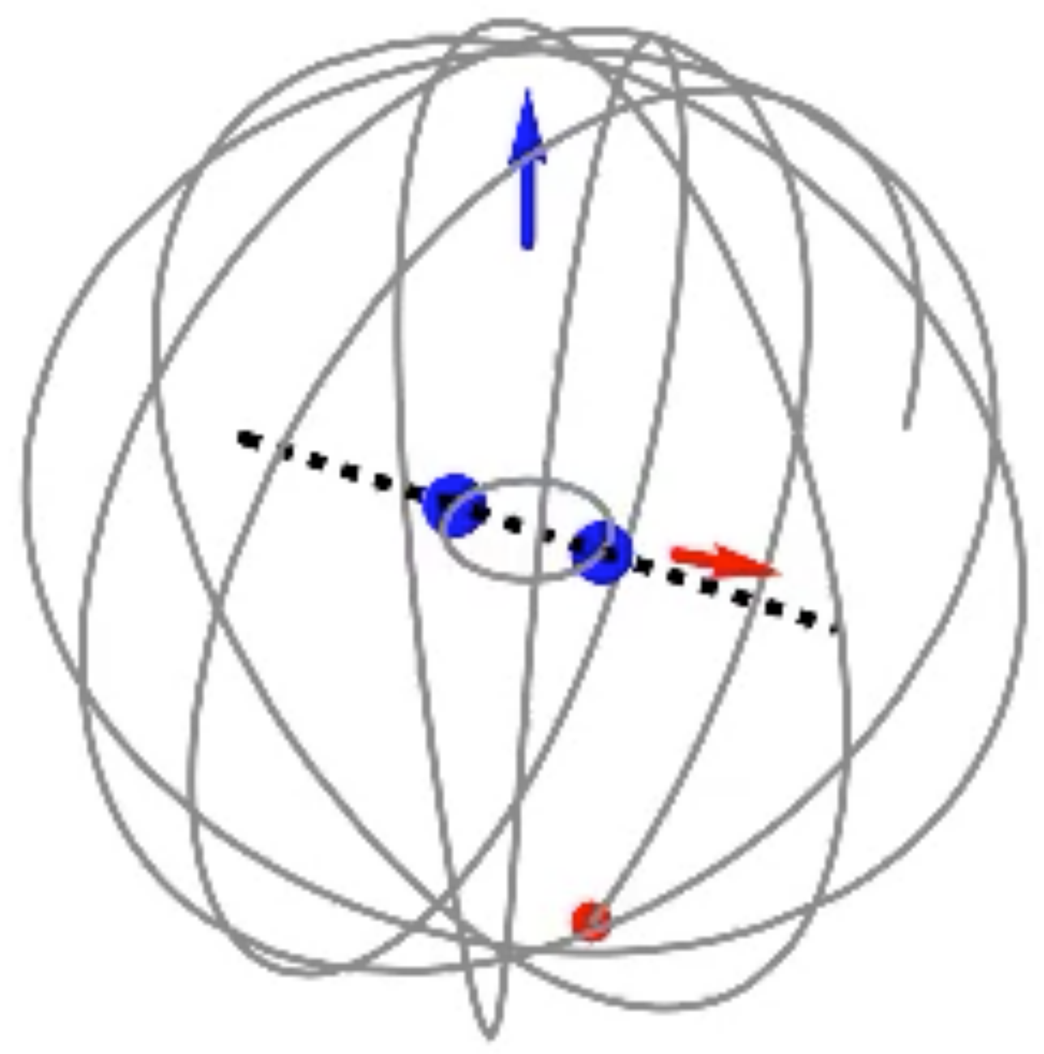


tilt oscillations

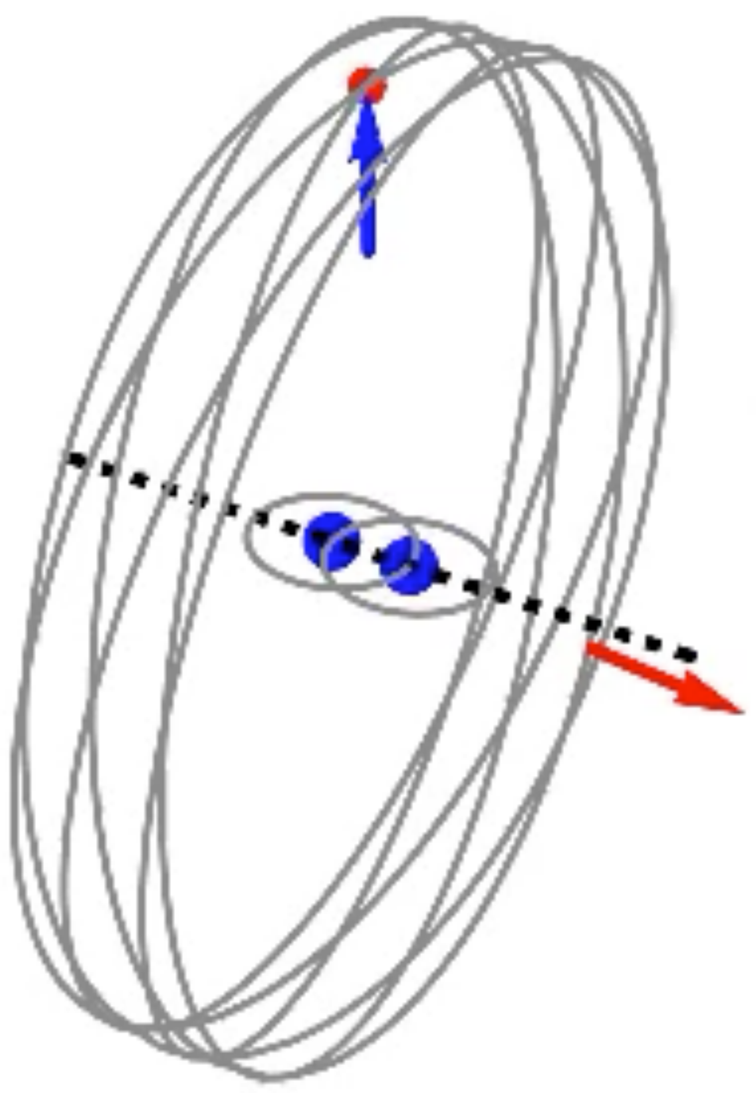
HIGH INCLINATION PARTICLE ORBITS

Circular Binary

Eccentric Binary



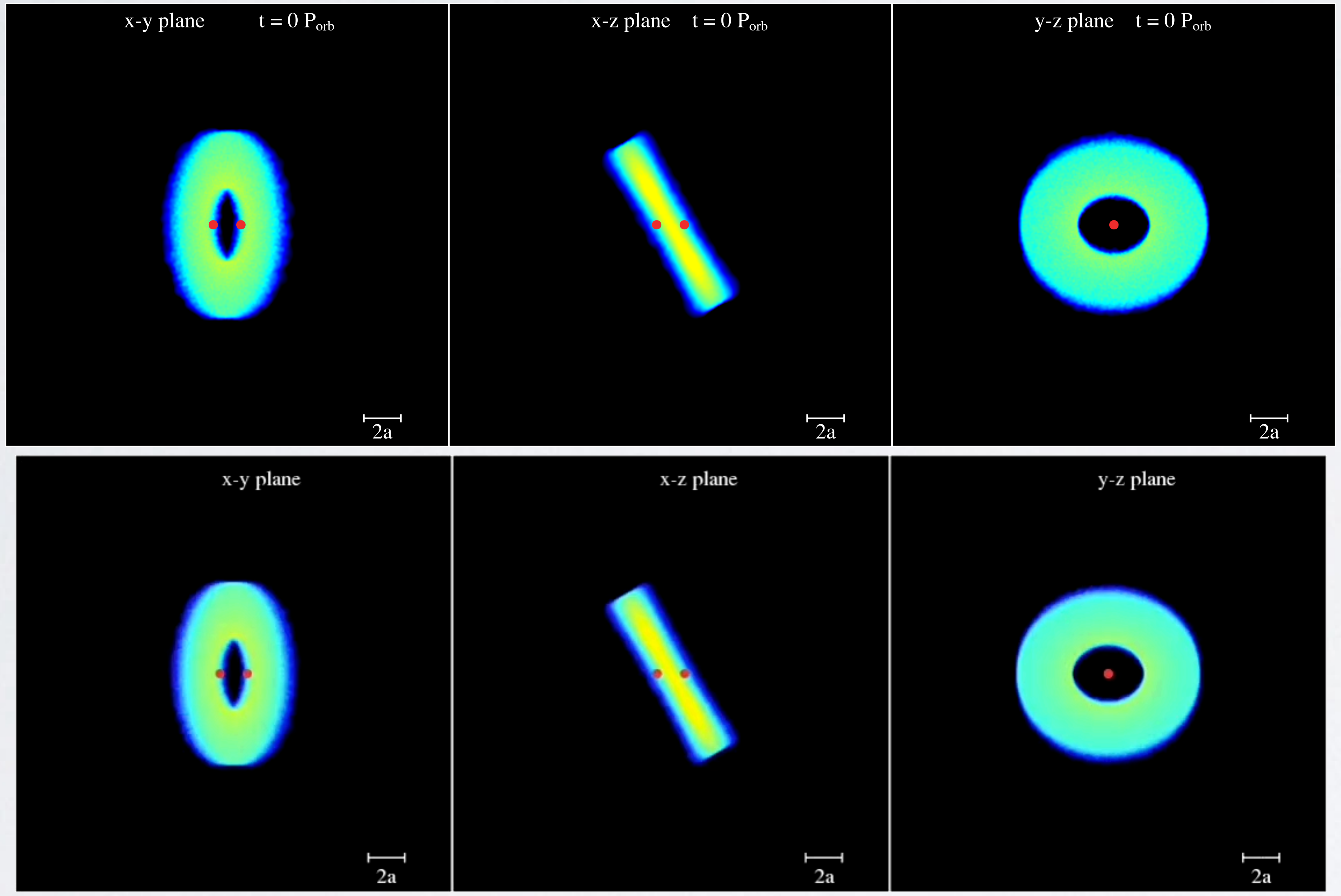
Disks become coplanar

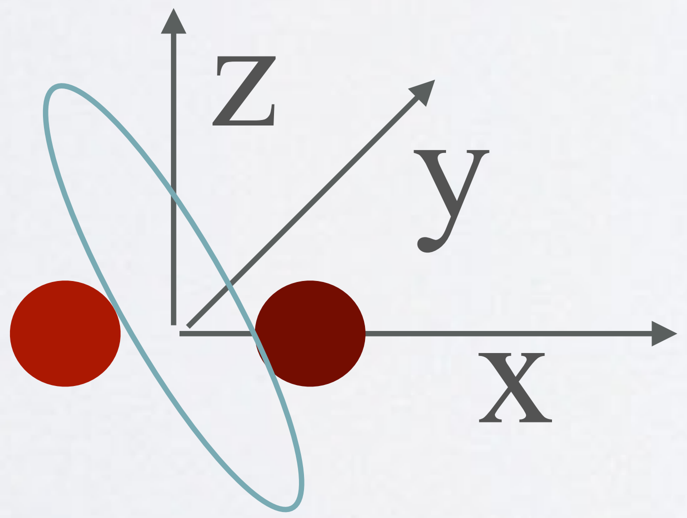


Disks can become polar

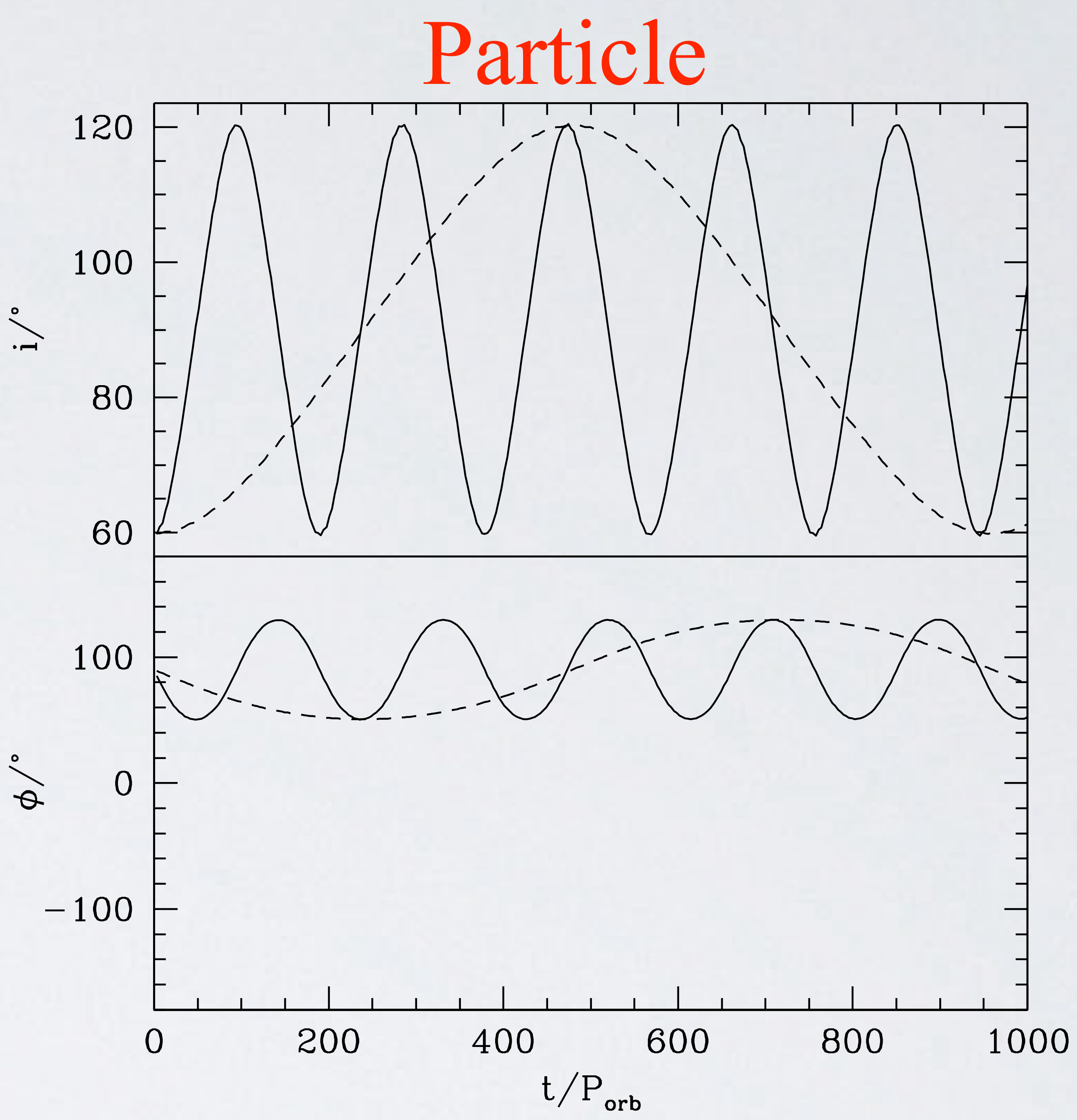
POLAR DISKS

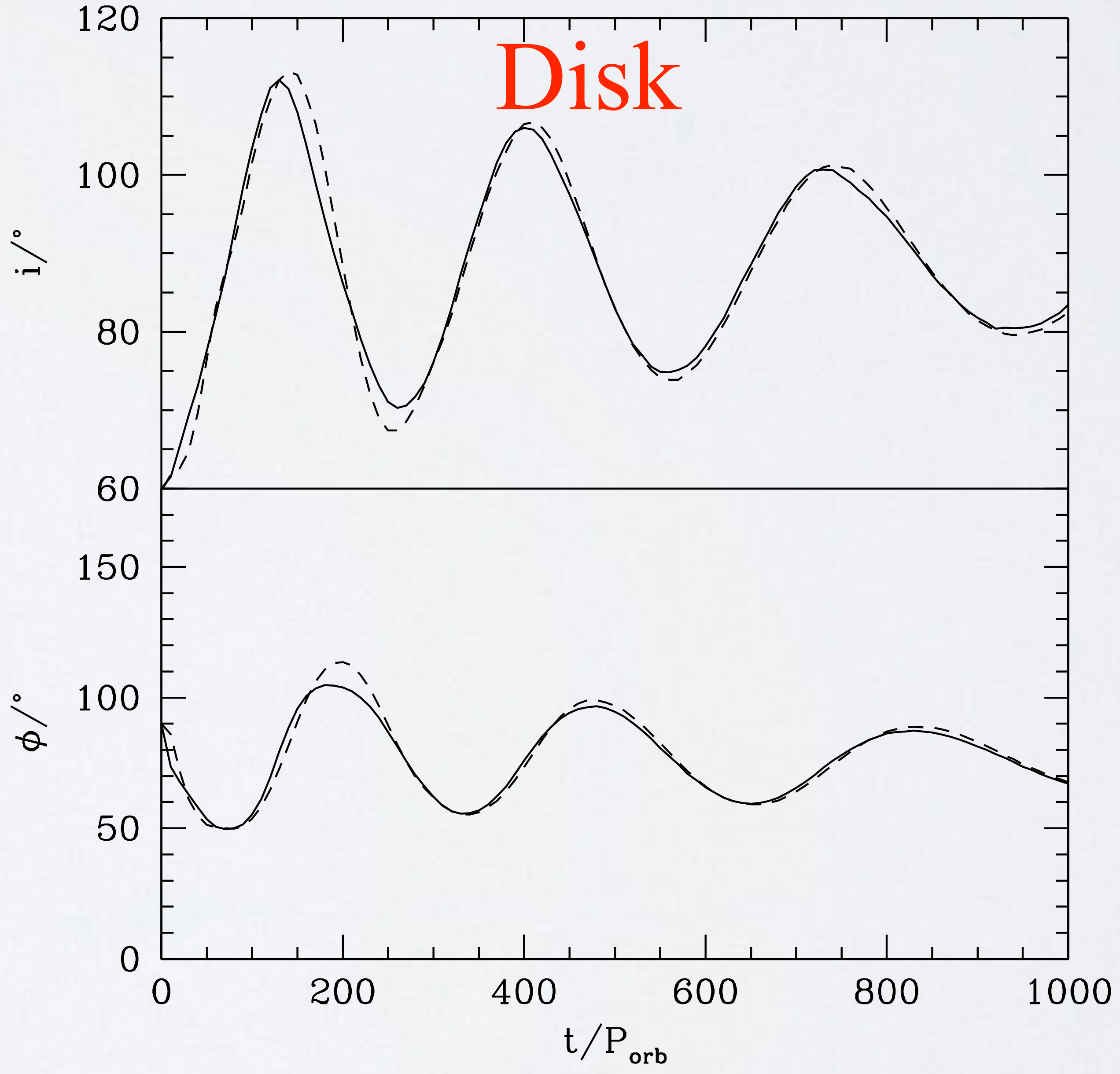
Misaligned CBDs can evolve to polar via dissipation (Aly et al. 2015, Martin & Lubow 2017)





binary in x-y plane





TILT EVOLUTION PROCESS

- Viscous damping changes tilt
- Pressure induced bending waves

Linear equations:

tilt flux torque

$$\Sigma r^2 \Omega \frac{\partial \mathbf{l}}{\partial t} = \frac{1}{r} \frac{\partial \mathbf{G}}{\partial r} + \mathbf{T}$$

$$\frac{\partial \mathbf{G}}{\partial t} - \omega_{\mathrm{a}} \mathbf{e}_z \times \mathbf{G} + \alpha \Omega \mathbf{G} = \frac{\Sigma H^2 r^3 \Omega^3}{4} \frac{\partial \mathbf{l}}{\partial r}$$

Lubow & Ogilvie (2000)

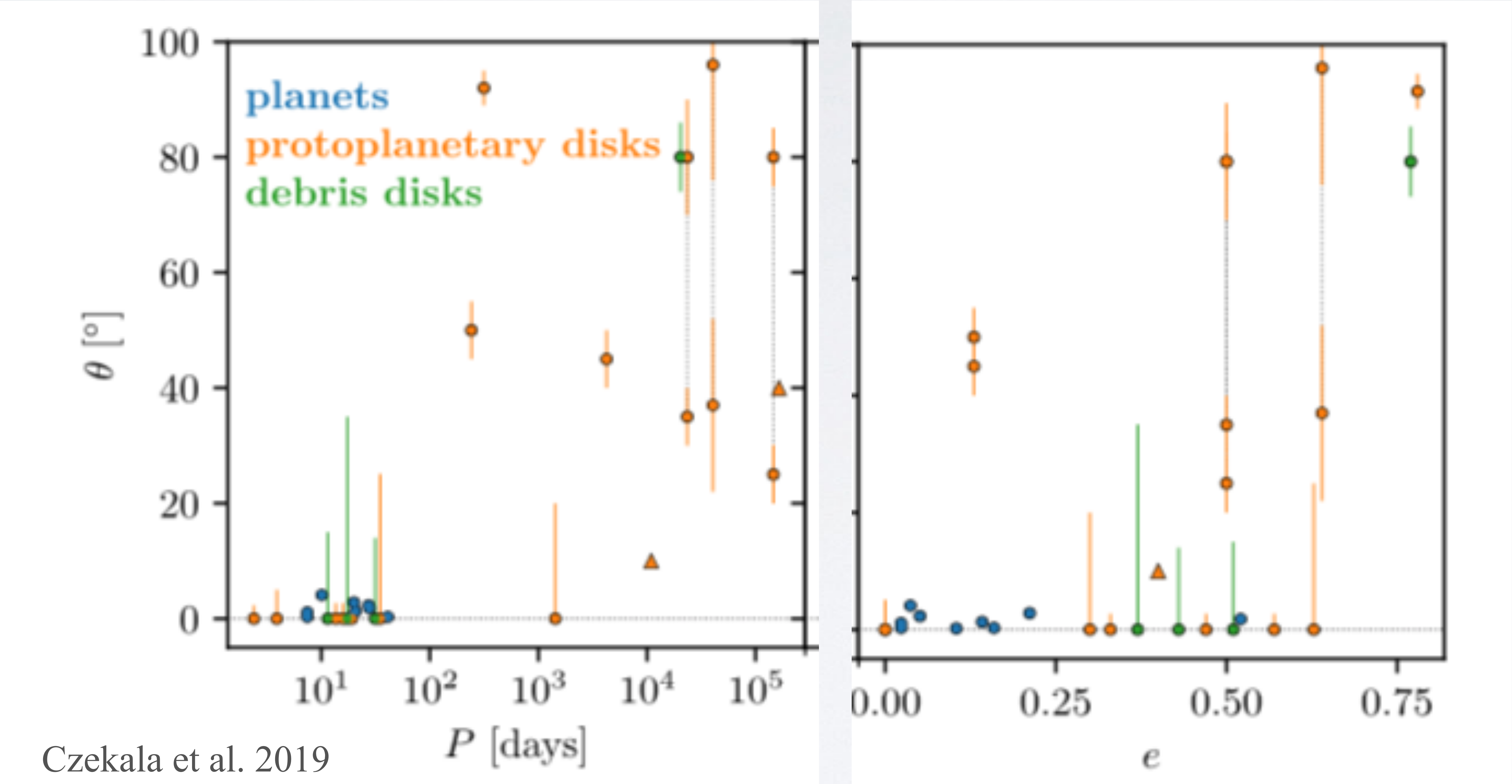
Apply to nearly polar disk: Zanazzi & Lai 2018, Lubow & Martin 2018

Shows evolution to polar orientation at rate close to simulations

Evolution to polar more likely at high e_b:

For $e_b = 0.5$, need $i_0 > 40°$; for $e_b = 0.8$, only need $i_0 > 20°$

BINARY/PLANET/CB DISK ALIGNMENT OBSERVATIONS



Czekala et al. 2019

- CB disk alignments for P < 30d ;
  Correlated with binary eccentricity

DISKS AROUND SPHEROIDAL POTENTIALS

Dobrovolskis, Borderies, & Steiman-Cameron (1989)

Both evolve to horizontal alignment

Coplanar alignment is at an energy minimum for tilts at constant radius.
Polar alignment is at an energy *maximum* for tilts at constant radius: energy is conserved by radial infall (accretion)

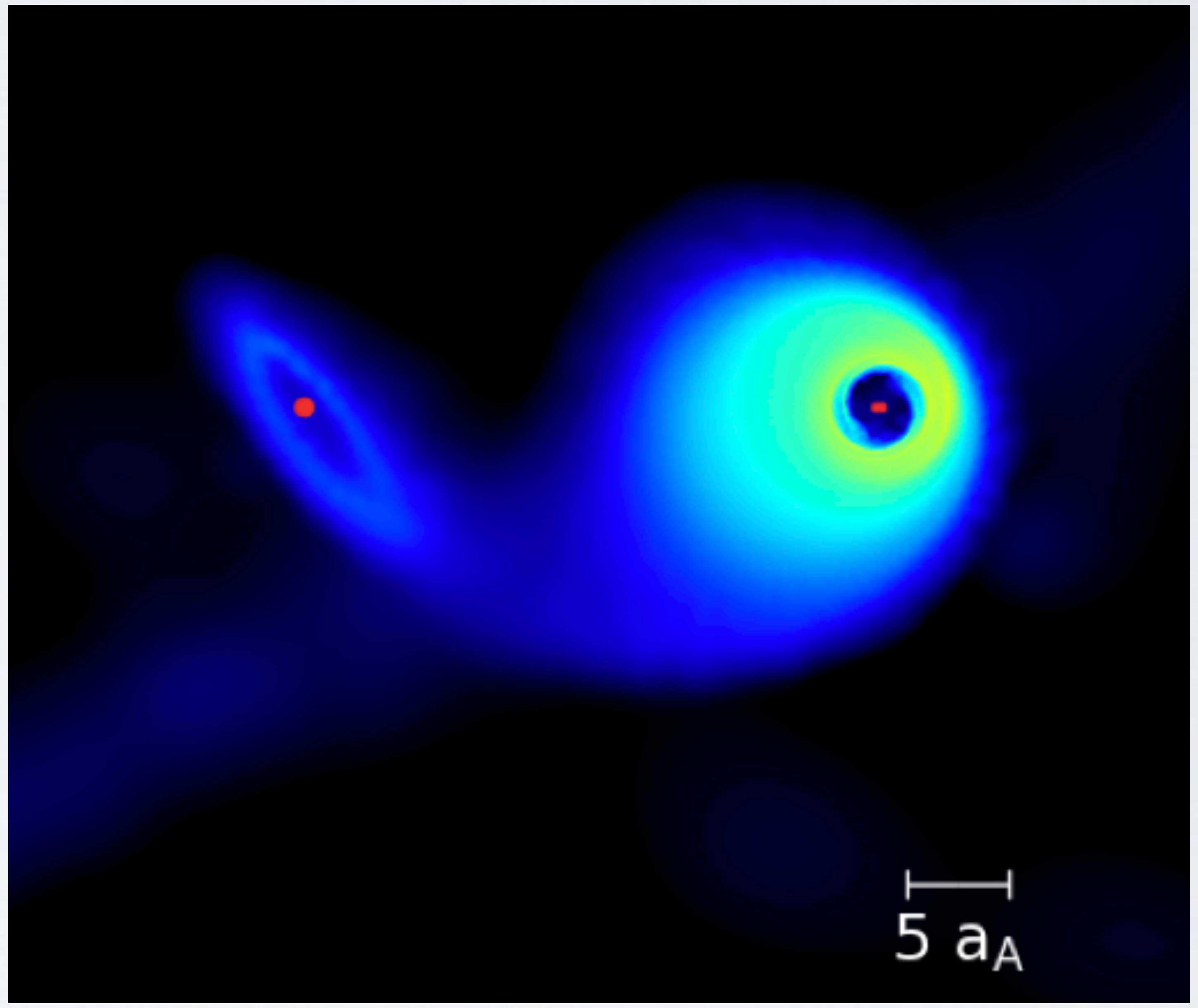
TRIPLE SYSTEMS

- Misaligned CBDs in triple systems: both evolution to polar and/or KL oscillations

- Outcome depends on dominant torque: inner binary (polar) vrs outer star (KL)

- Can result in eccentric polar disks

- CBD in triple HD98800 dominated by central binary and evolves to polar



Martin et al. 2022

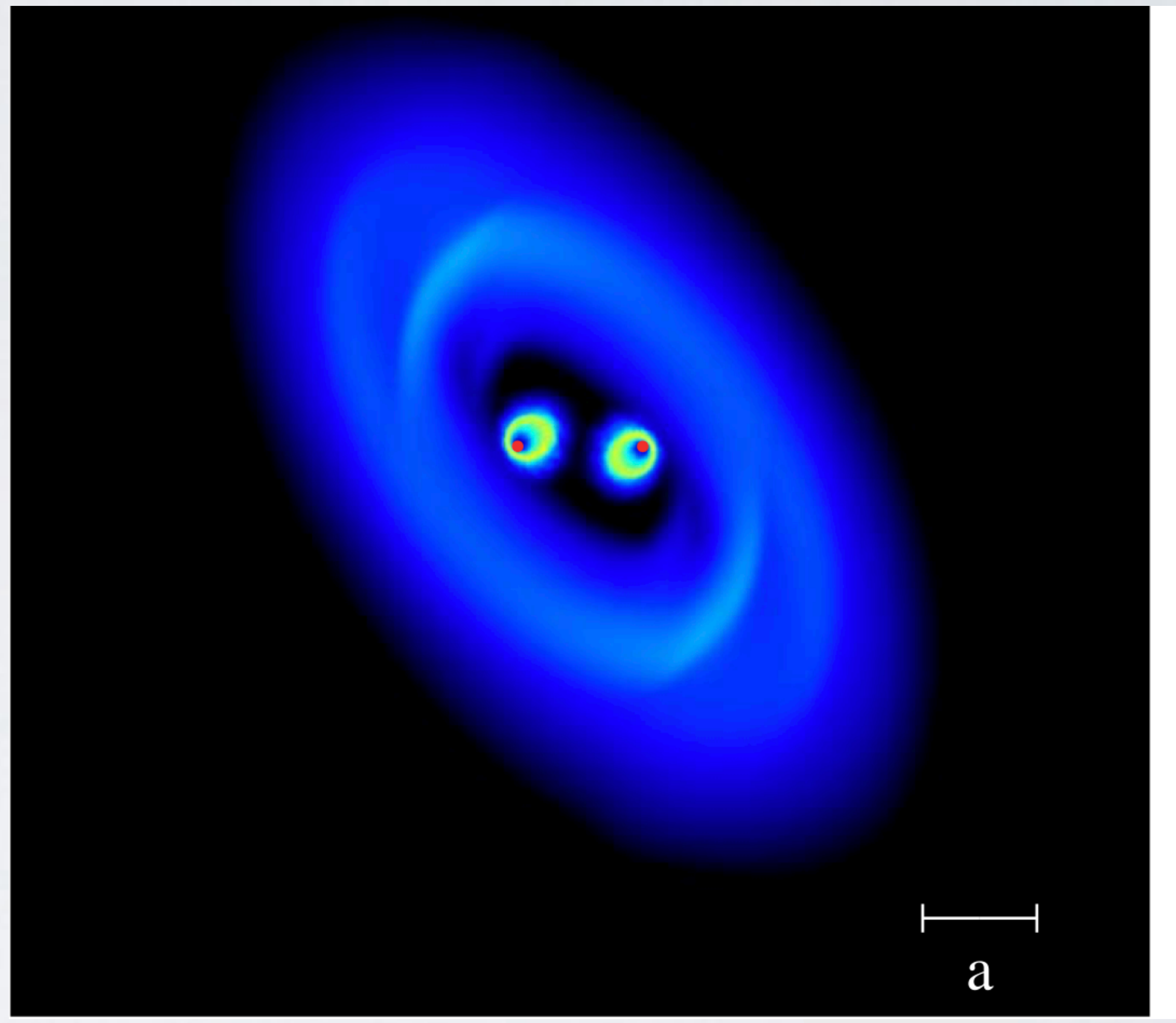
CONCLUSIONS

- Inclined/retrograde disks in binaries differ from coplanar prograde case
  - close retrograde encounters with binary, efficient binary angular momentum loss
  - KL oscillations: highly eccentric disks
  - Polar CBD alignment: favored at higher e_b

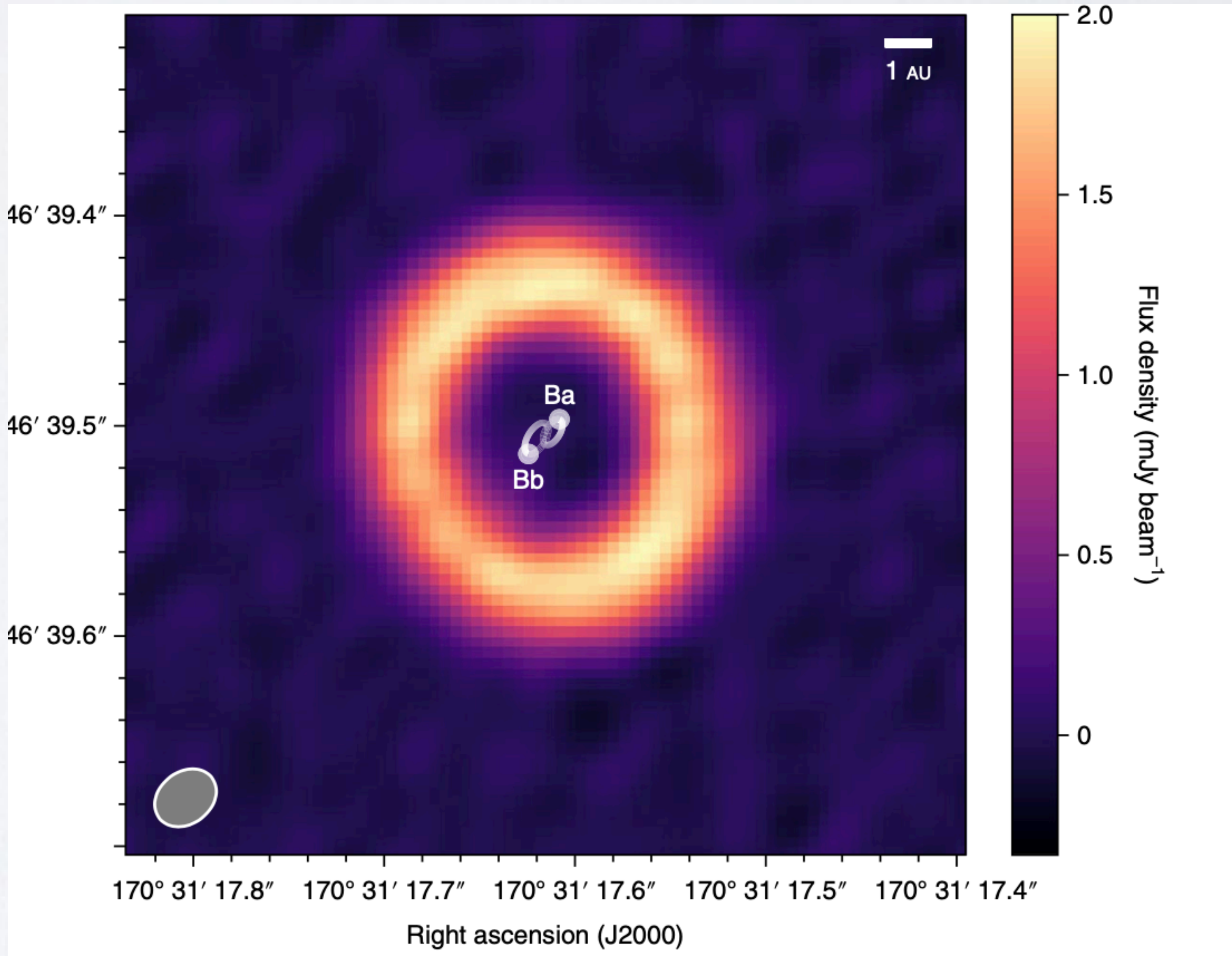
- No observational evidence yet of KL disks

- Polar orientations of gas disk HD98800 and debris disk 99 Her can be explained by evolution from an initially modestly misaligned CBD

- Expect correlation between e_b and i. Implications for misaligned CB planets



Smallwood et al. 2021



Kennedy et al. 2019