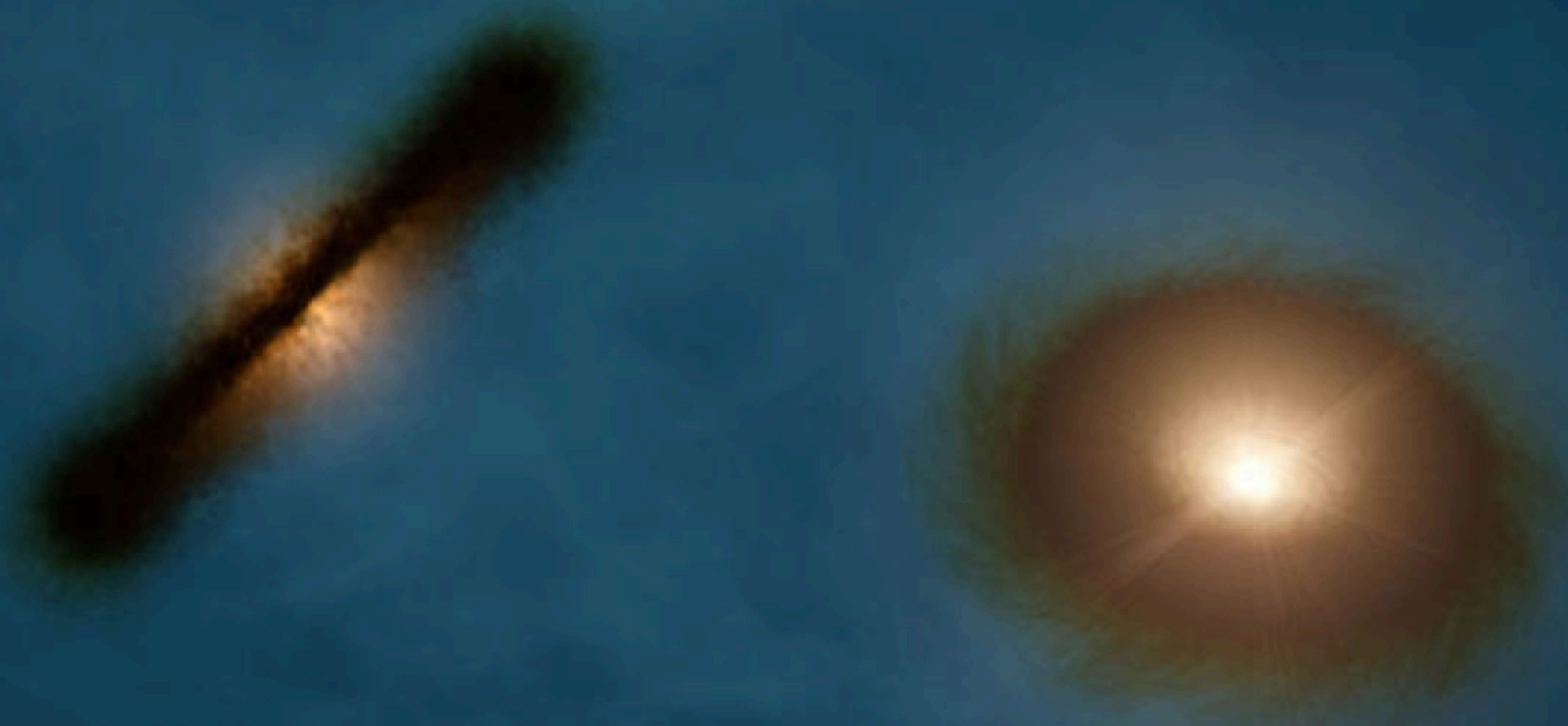
Dynamical processes in planetary systems: disk dynamics



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Most stars are in binaries

- Most stars are in binary systems.

- In the Kepler sample it is estimated that 40-50% of planet host stars are in binaries (Horch et al. 2015).

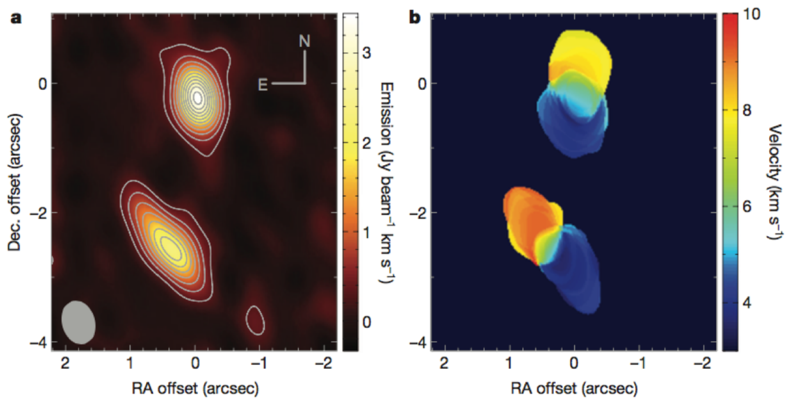
  $\Rightarrow$ **It is important to understand planet formation in binary systems.**

- Planetary systems that form in misaligned systems are subject to secular torques that can affect their orbital evolution.

Disc misalignments are commonly observed for

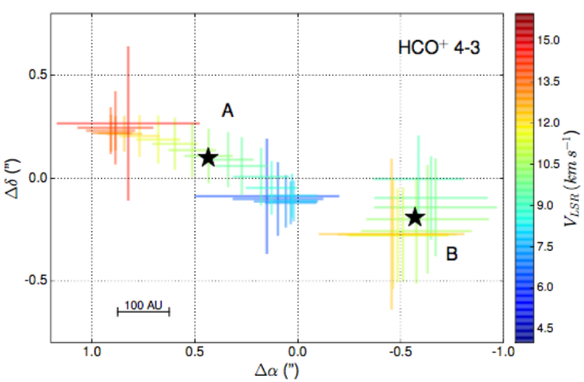
circumstellar discs and circumbinary discs

HK Tauri (a_b = 350AU)



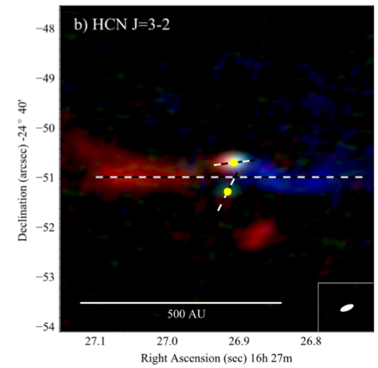
(Jensen & Akeson 2014)

V2434 Ori (a_b=440AU)



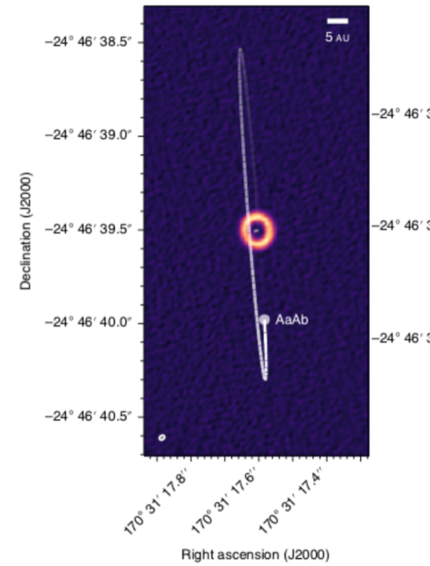
(Williams et al. 2014)

Binary protostar IRS 43



(Brinch et al. 2016)

HD 98800



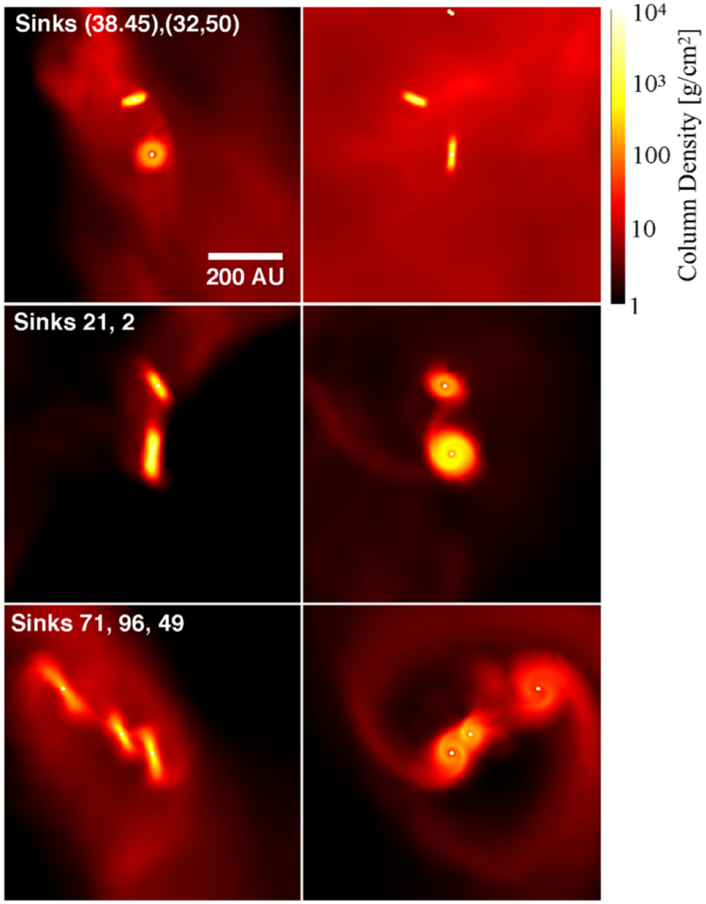
(Kennedy et al. 2019)

CBD's around binaries with orbital period>30 days show a wide range of misalignment angles (Czekala 2019).

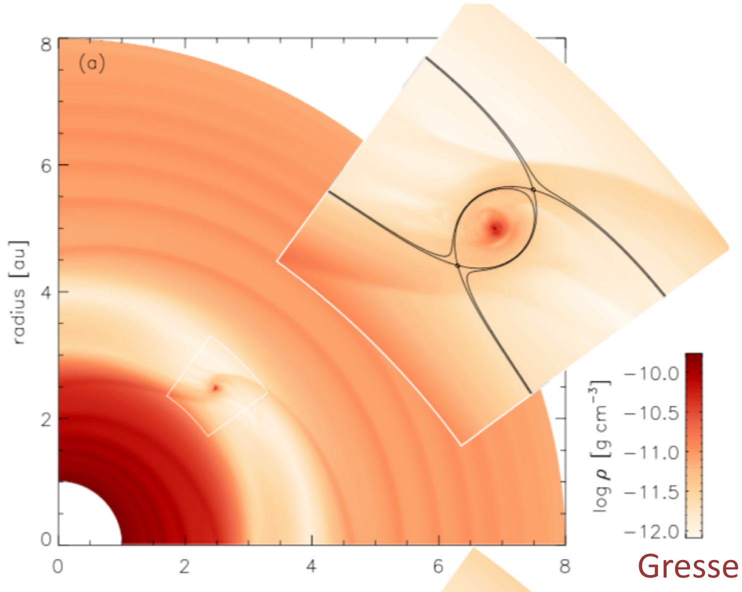
Origin of misalignments

- Stochastic processes during the early phases of star formation are important, such as turbulence (Bate 2018) or dynamical interactions of young protostars (Clarke & Pringle 1993, Cuello et al. 2019). These processes lead to initially misaligned **circumstellar** and **circumbinary discs**.

- **Circumplanetary disc** misalignment to the orbital plane may arise from stochastic accretion of material from a turbulent protoplanetary disc (Gressel et al. 2013) or in binary star systems (e.g. Ballabio et al. 2021).



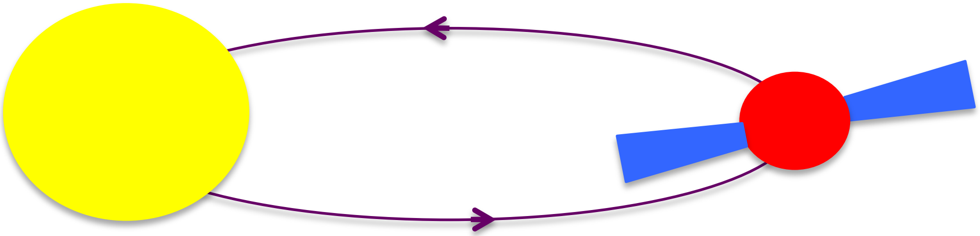
Bate (2018)



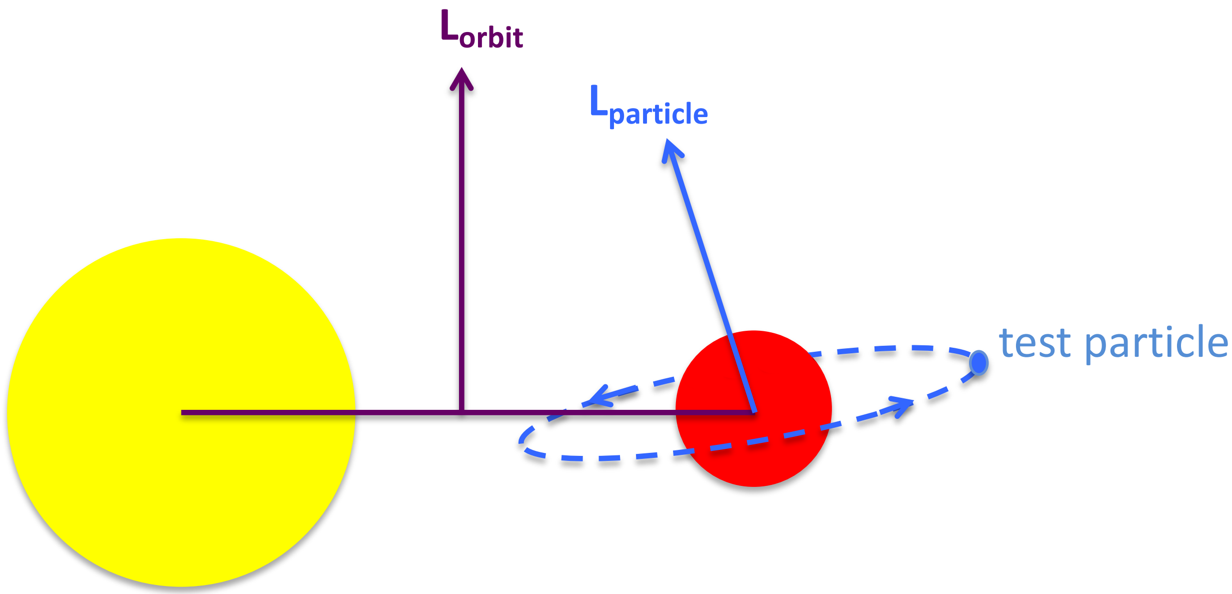
Gressel et al. (2013)

Part I: circumstellar discs

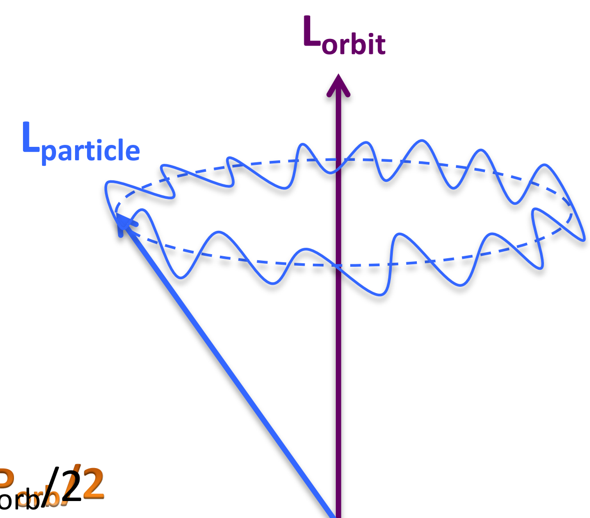
a) low inclination discs



Dynamics of a misaligned test particle



The torque can be written in terms of azimuthal Fourier components $e^{im\phi}$.



The tidal torque has two effects:

1) The m = 0 component causes retrograde nodal precession

2) The m = 2 component causes a “wobble” on a timescale of $P_{orb}/2$

Disc communication

Precession is communicated through the disc by waves that propagate at the sound speed $c_s/2$.

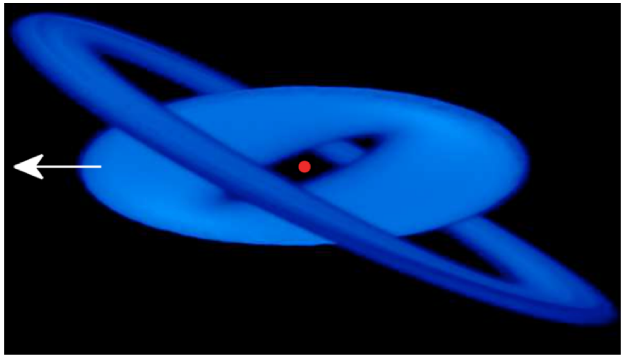
For solid body precession we require,

sound crossing timescale < precession timescale

$$\frac{R}{c_{\rm s}} \lesssim \frac{1}{\Omega_{\rm p}}$$

(Papaloizou & Terquem 1995; Larwood et al. 1996)

If this is not satisfied then the disc warps or even breaks.

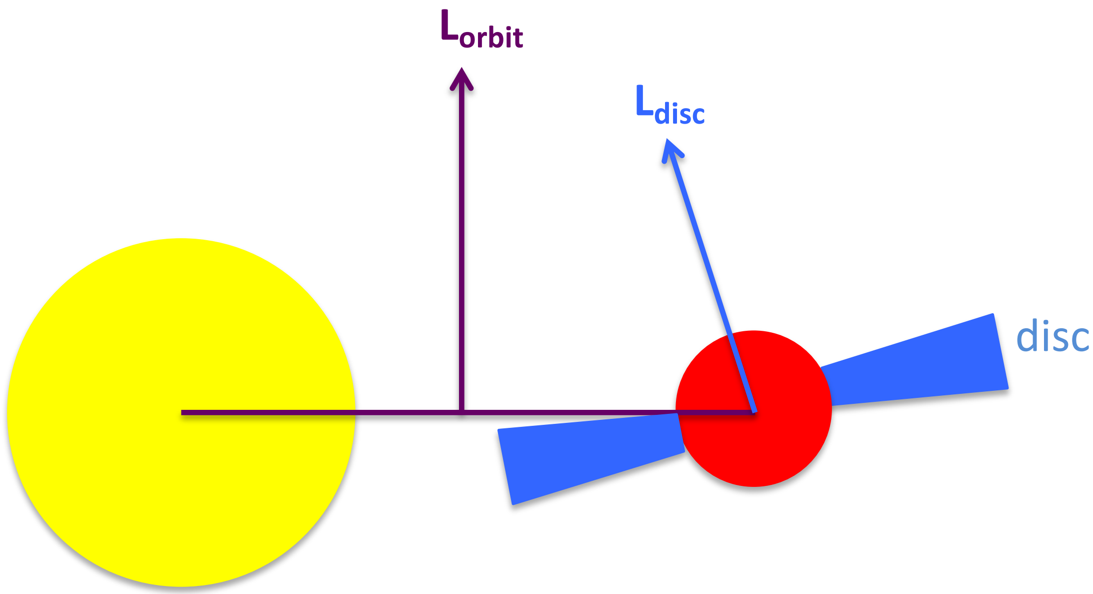


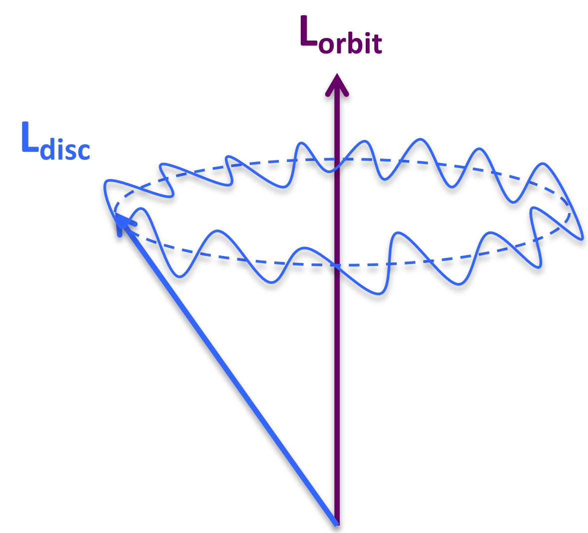
(Nixon et al. 2012, 2013, Facchini et al. 2013, Dogan et al. 2015, Nealon et al. 2015)

- **For typical circumstellar disc and circumplanetary disc parameters, the disc precesses as a solid body.**

- **Circumbinary discs may be sufficiently extended to undergo breaking.**

Dynamics of a misaligned disc



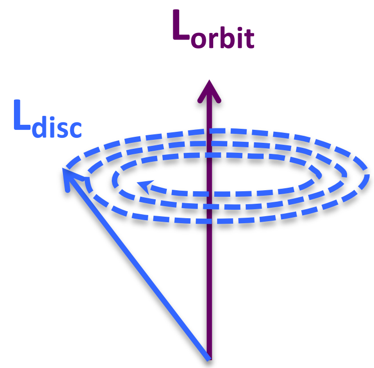


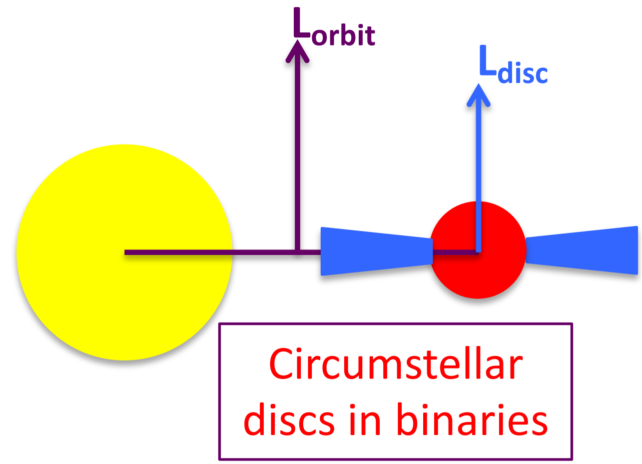
A circumstellar disc holds itself together through wave-like communication and precesses as a solid body

(e.g. Papaloizou & Terquem 1995, Larwood et al. 1996, Terquem 1998).

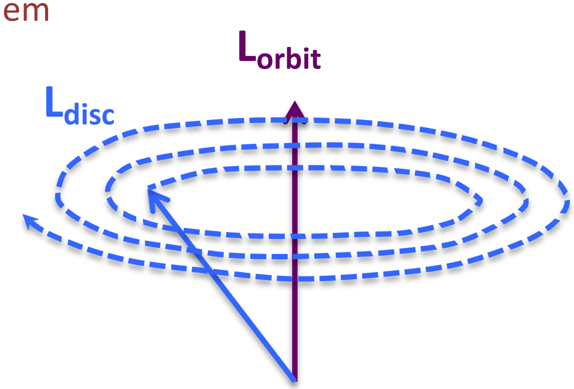
Disc alignment

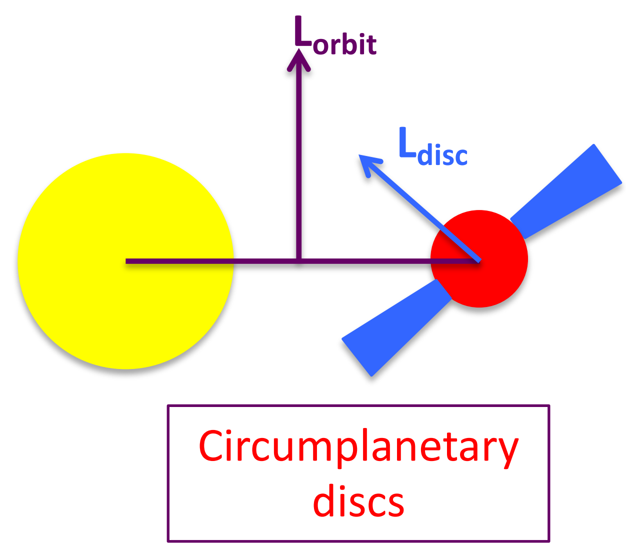
- In the presence of dissipation, the m=0 term leads to **coplanar alignment**.





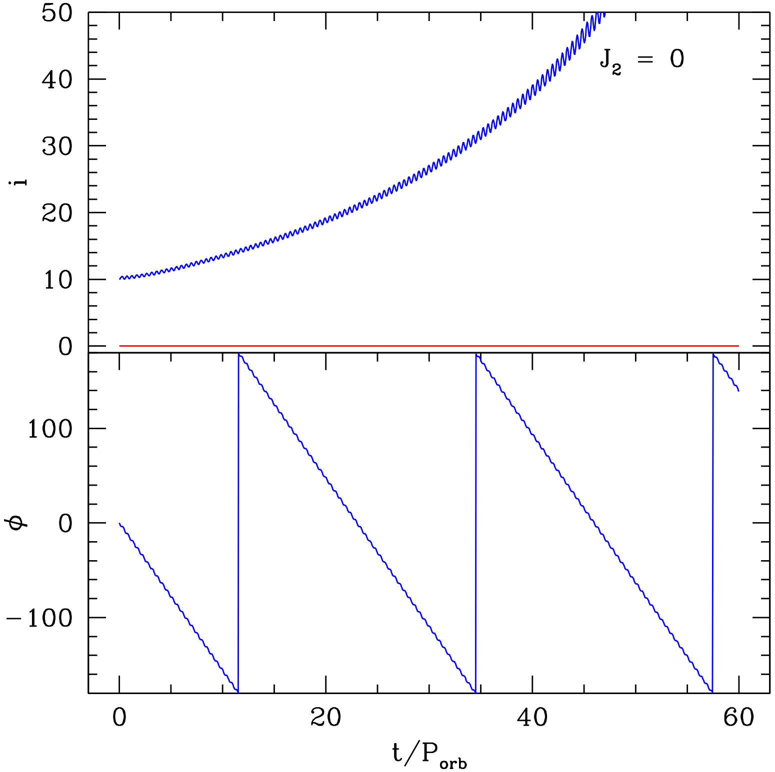
- The m=2 term leads to **tilting** (Lubow 1992, Papaloizou & Terquem 1995, Terquem 1998, Lubow & Ogilvie 2000, Bate et al. 2000).

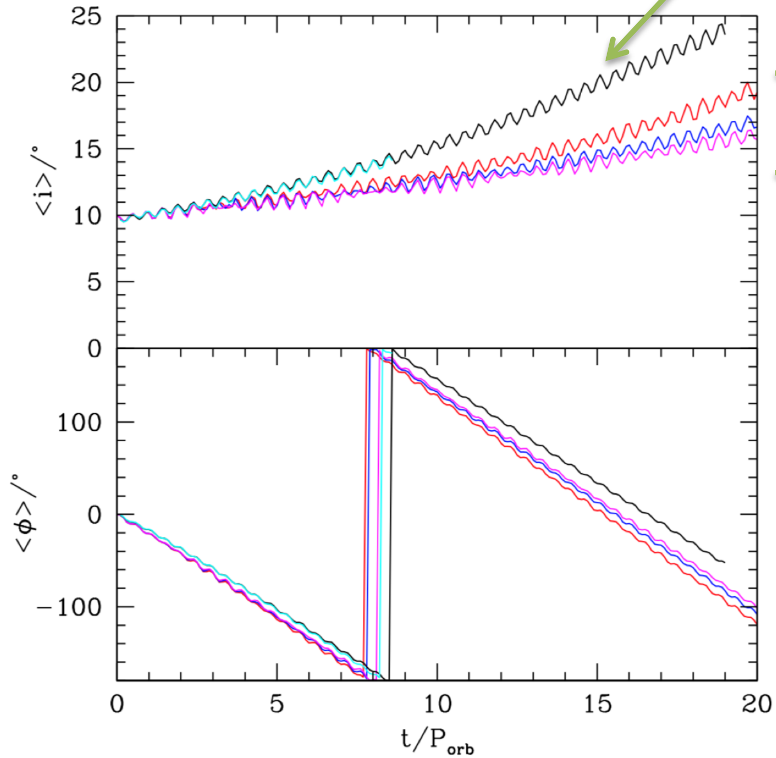




CPD tilt instability

1D model





Grid code (Athena++)

Stone et al. (2020)

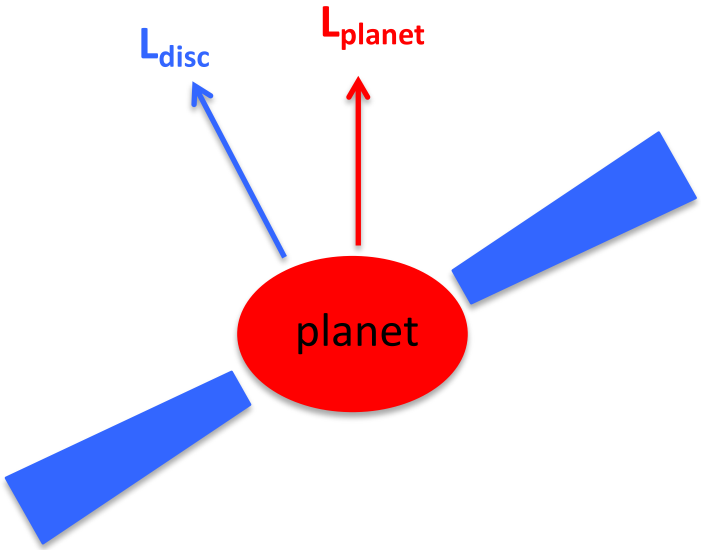
SPH (Phantom)

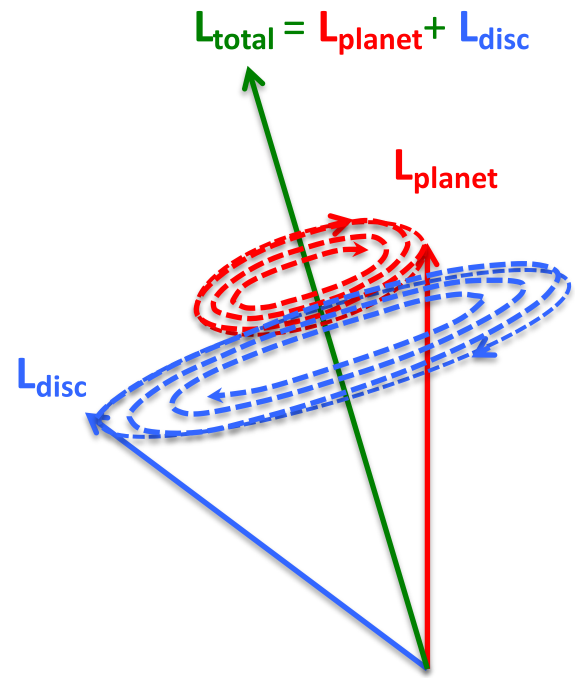
Price (2018)

- We solve the 1D time-dependent linear wave-like warp equations including a torque from the star (Lubow & Ogilvie 2000).
- The small size and large disc aspect ratio of CPD's makes them **unstable to tilting**.

Martin, Zhu & Armitage (2020)

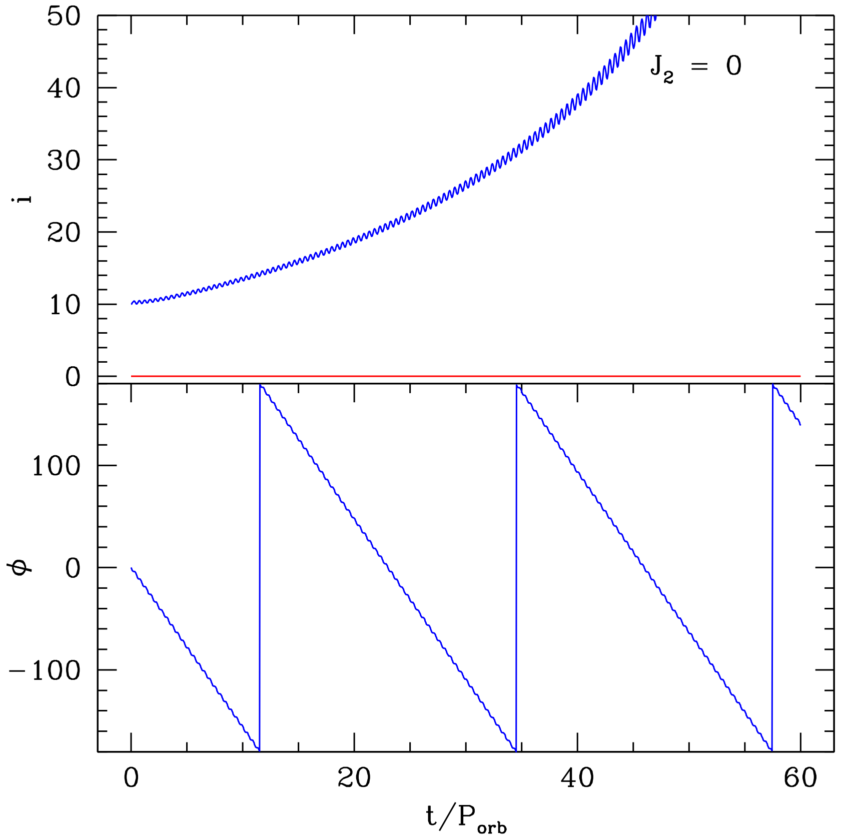
Torque from the spinning planet

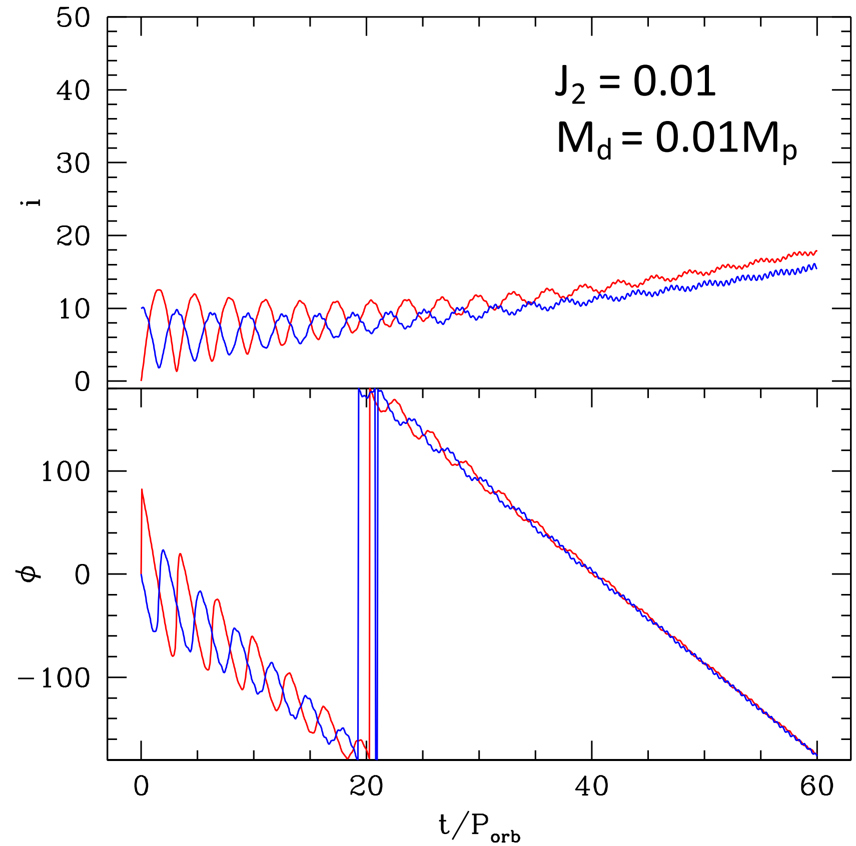




- The spinning oblate planet exerts a torque on a misaligned CPD.
- The misaligned CPD feels an equal and opposite torque.
- In the absence of the star and dissipation, the **CPD and the planet spin precess about their total angular momentum vector**.

1D model with a planet torque



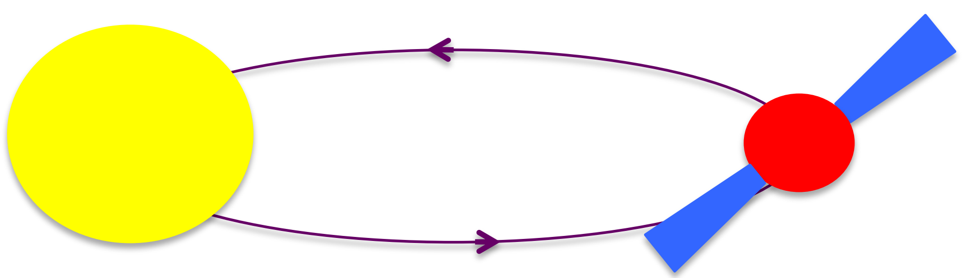


Martin & Armitage (2021)

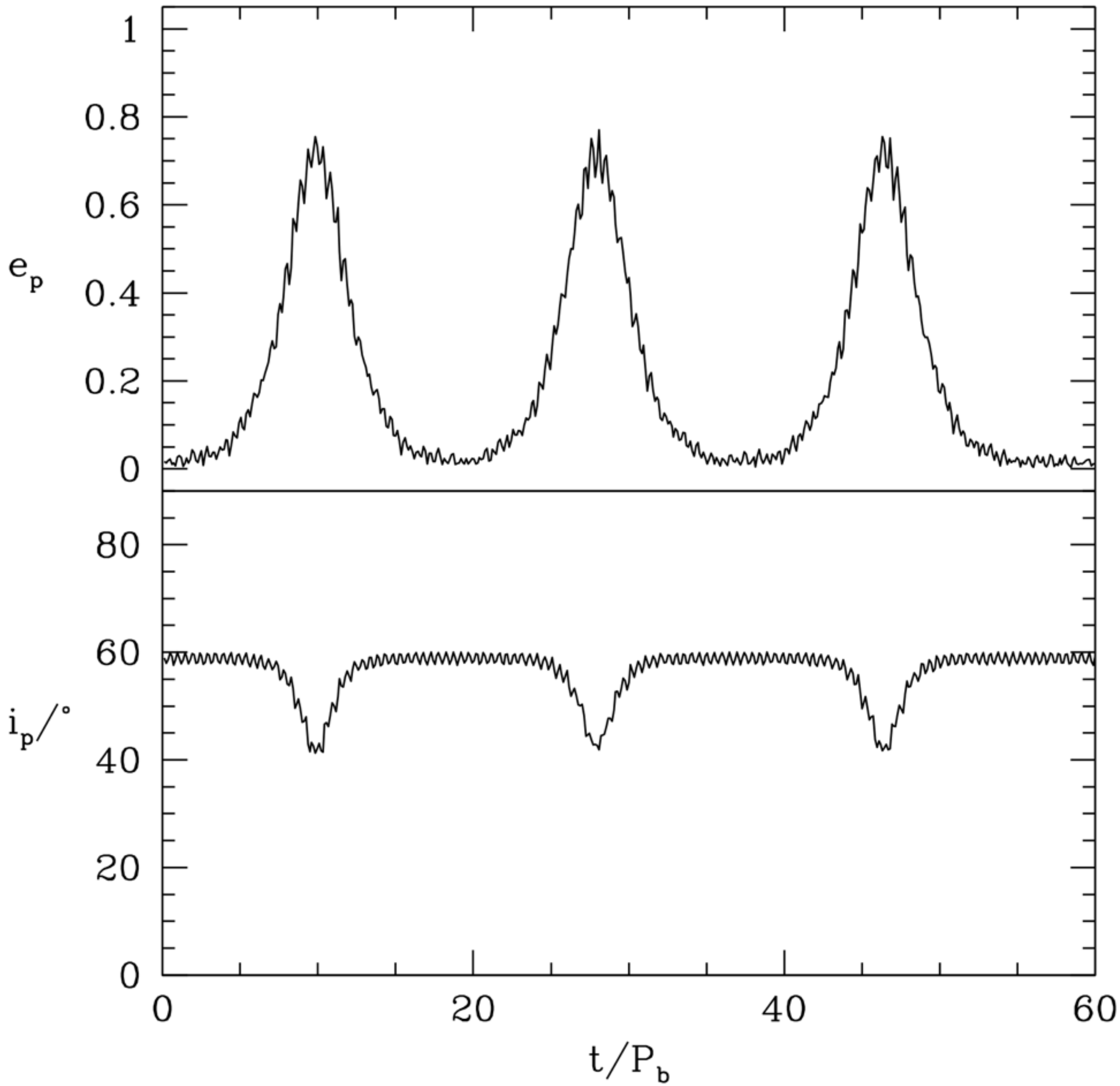
- The disc and planet spin precess about their total angular momentum vector and align to each other.
- The tilt of the planet and the disc spin then increase together.
- Implications for satellite formation in a misaligned CPD (see also Speedie & Zanazzi 2019).

Part I: circumstellar discs

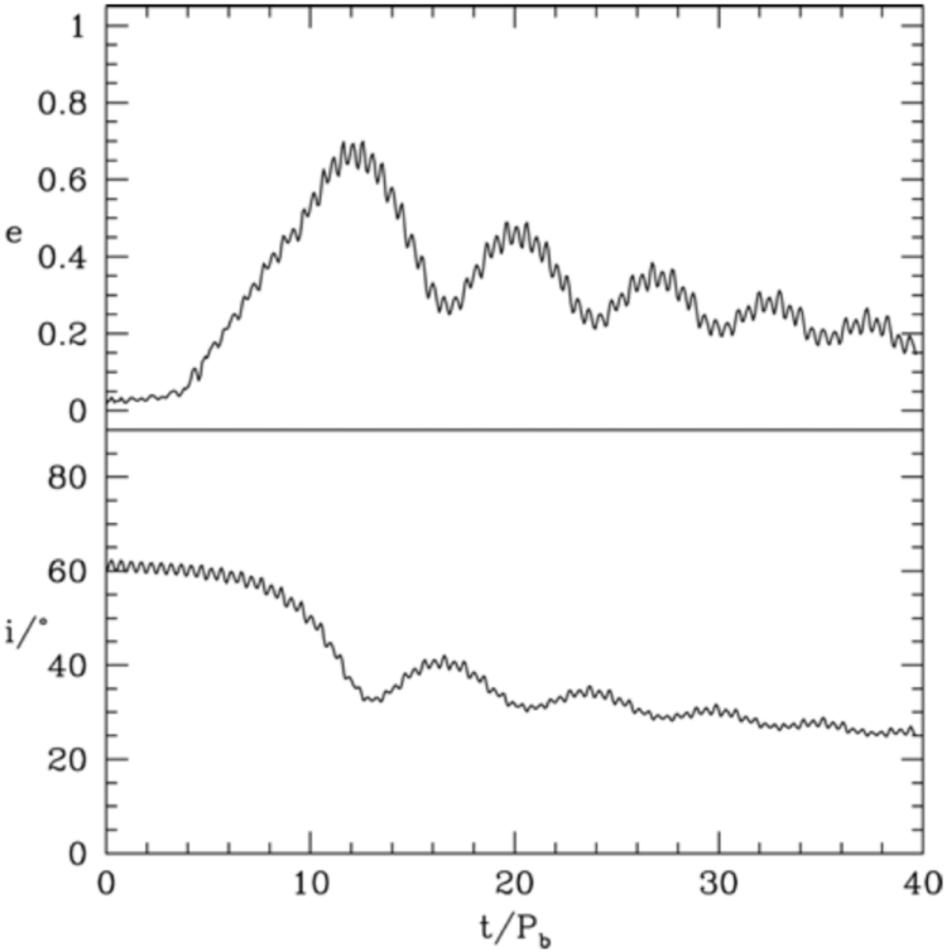
b) high inclination discs

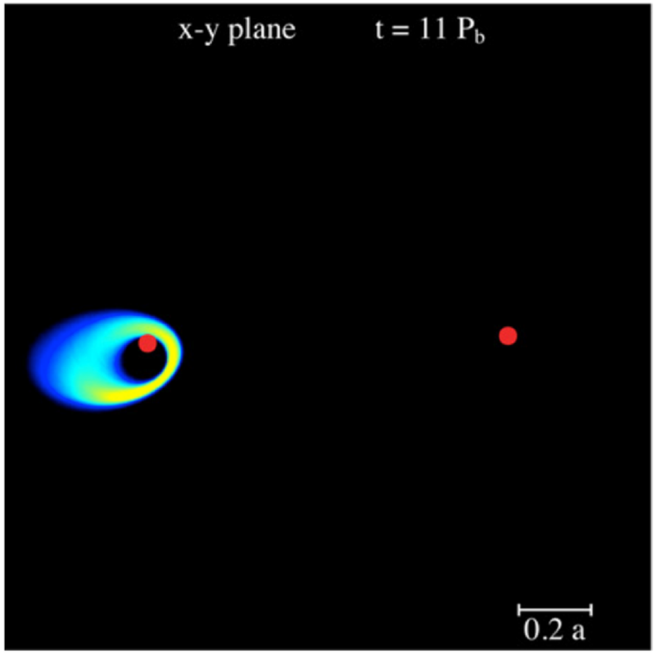


High inclination test particle orbits



A highly misaligned circumstellar disc can undergo KL oscillations

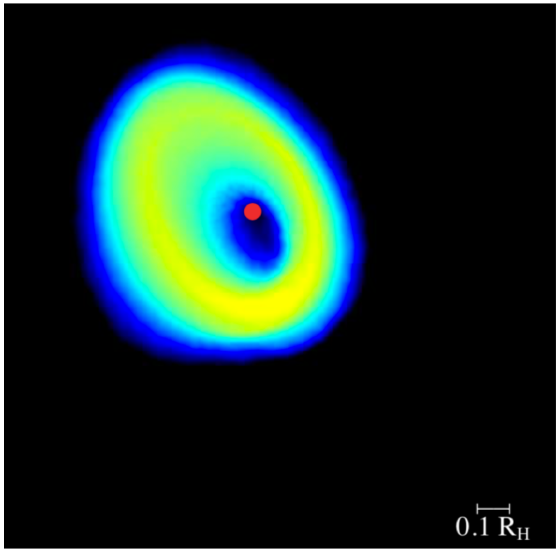




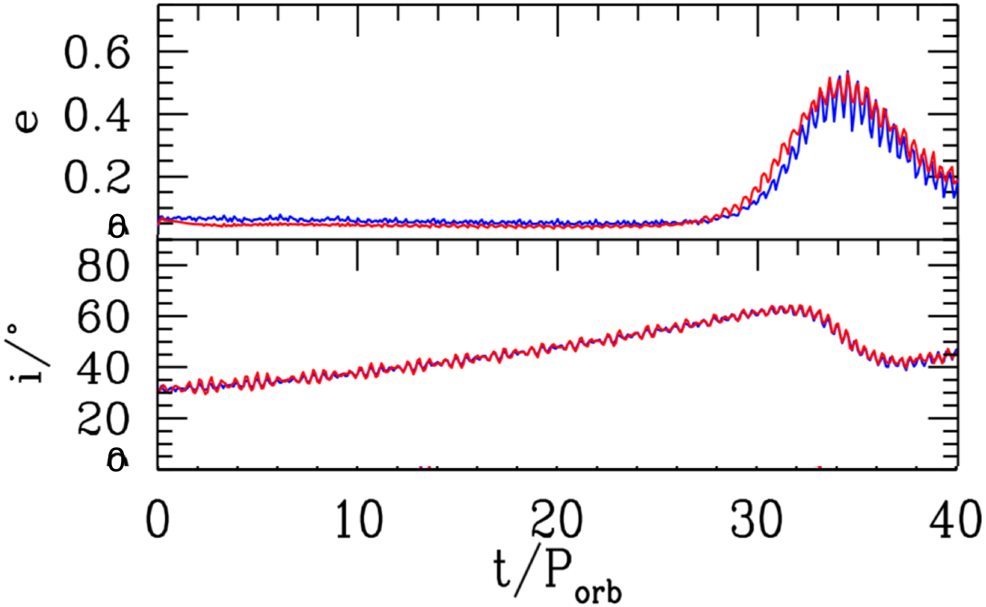
Martin et al. (2014)

- KL oscillations damp due to viscous dissipation.
- KL instability depends upon the disc aspect ratio (Lubow & Ogilvie 2017, Zanazzi & Lai 2017).

High inclination CPD's

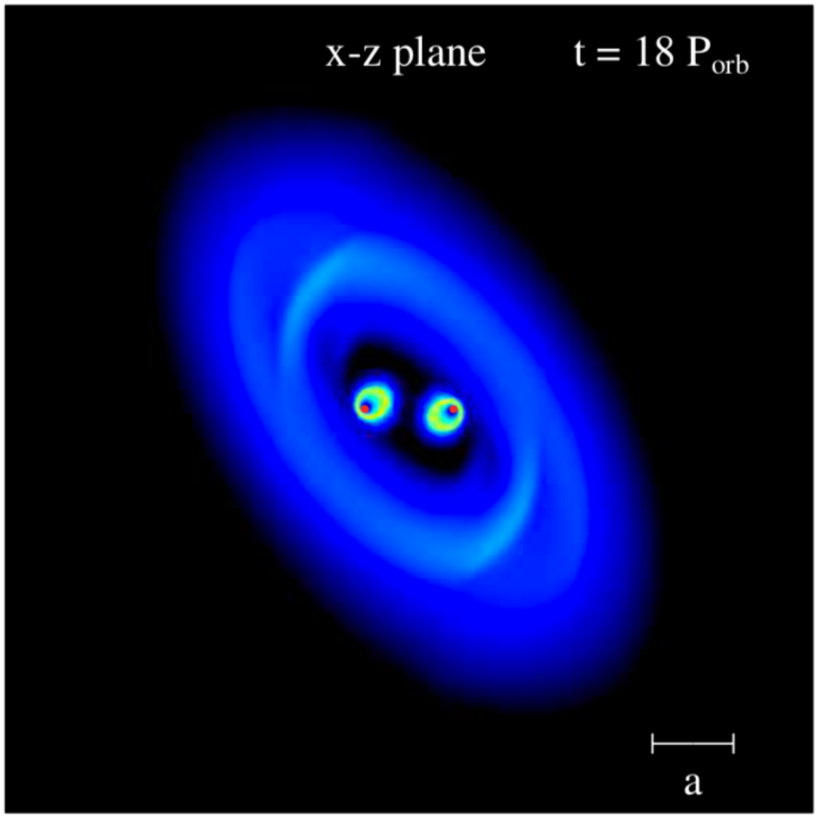


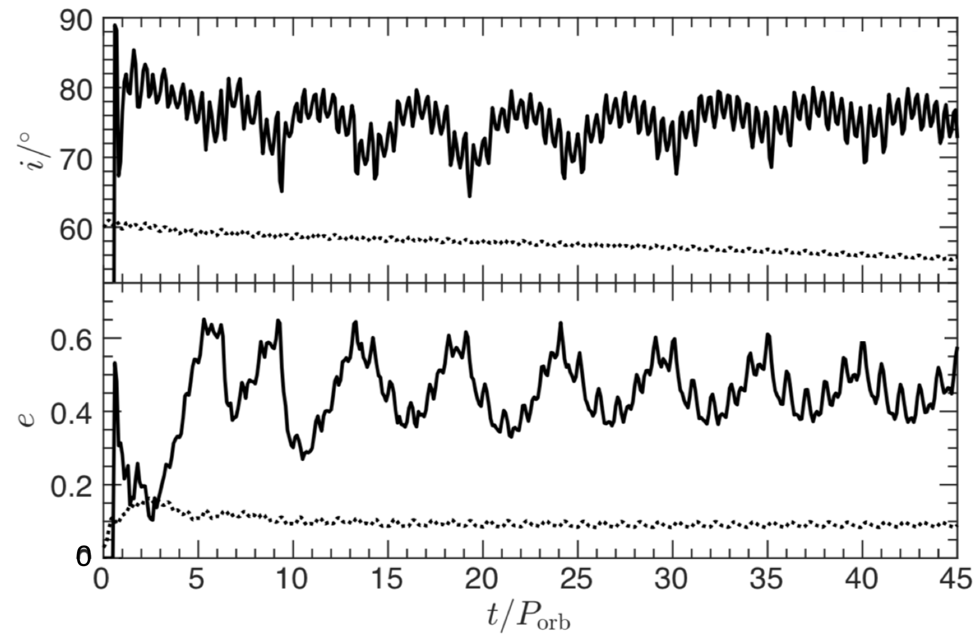
- The CPD tilt instability increases the inclination until it becomes **Kozai-Lidov unstable**.
- The disc undergoes global eccentricity and inclination oscillations.



Martin et al. (2021)

Accretion from a circumbinary disc: sustained KL oscillations



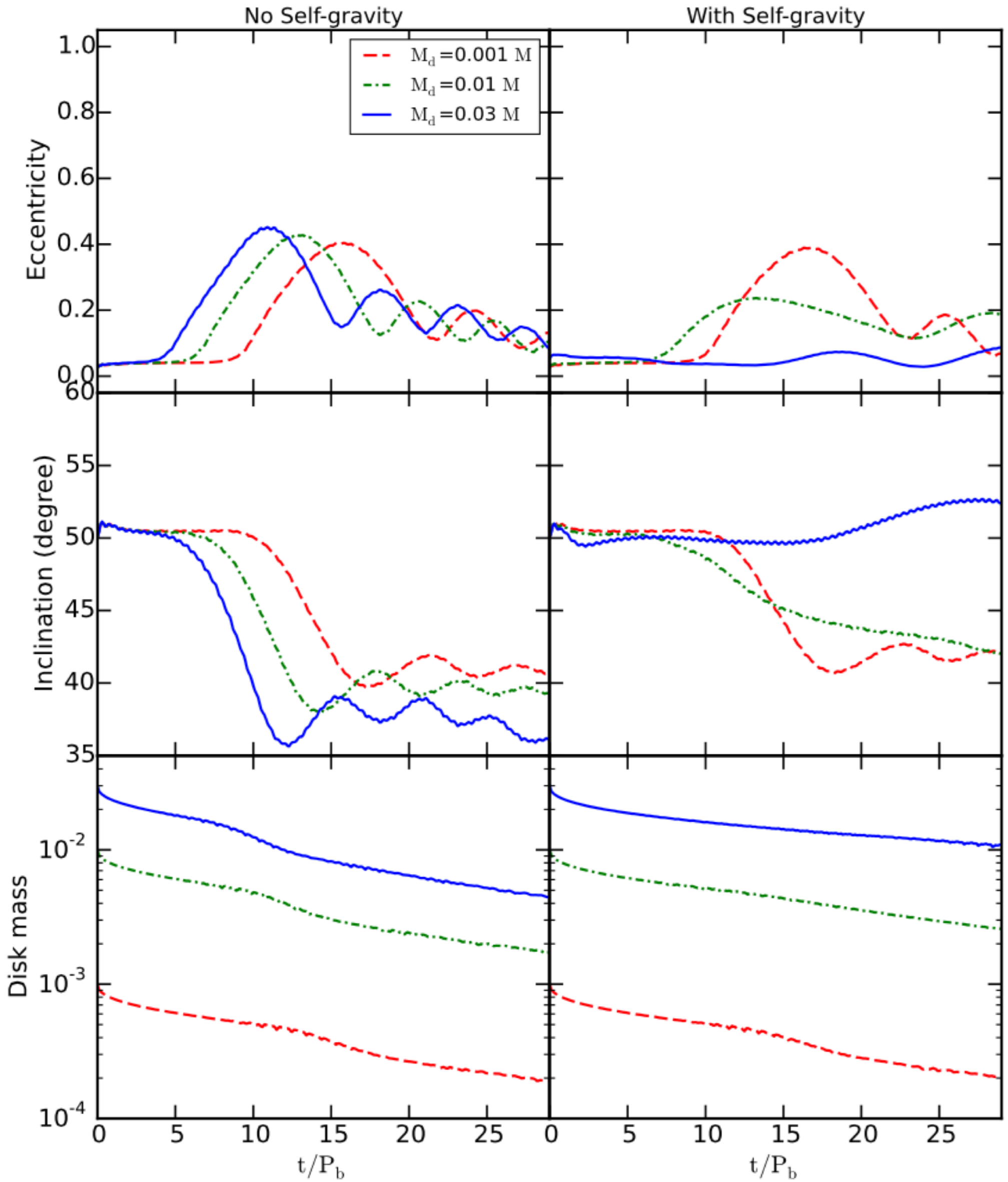


Smallwood et al (2021)

Observational implications for the eccentric/tilted disc.

Eccentric discs may affect the planet formation process (Silsbee & Rafikov 2015).

Disc self-gravity



(Fu, Lubow & Martin 2015b)

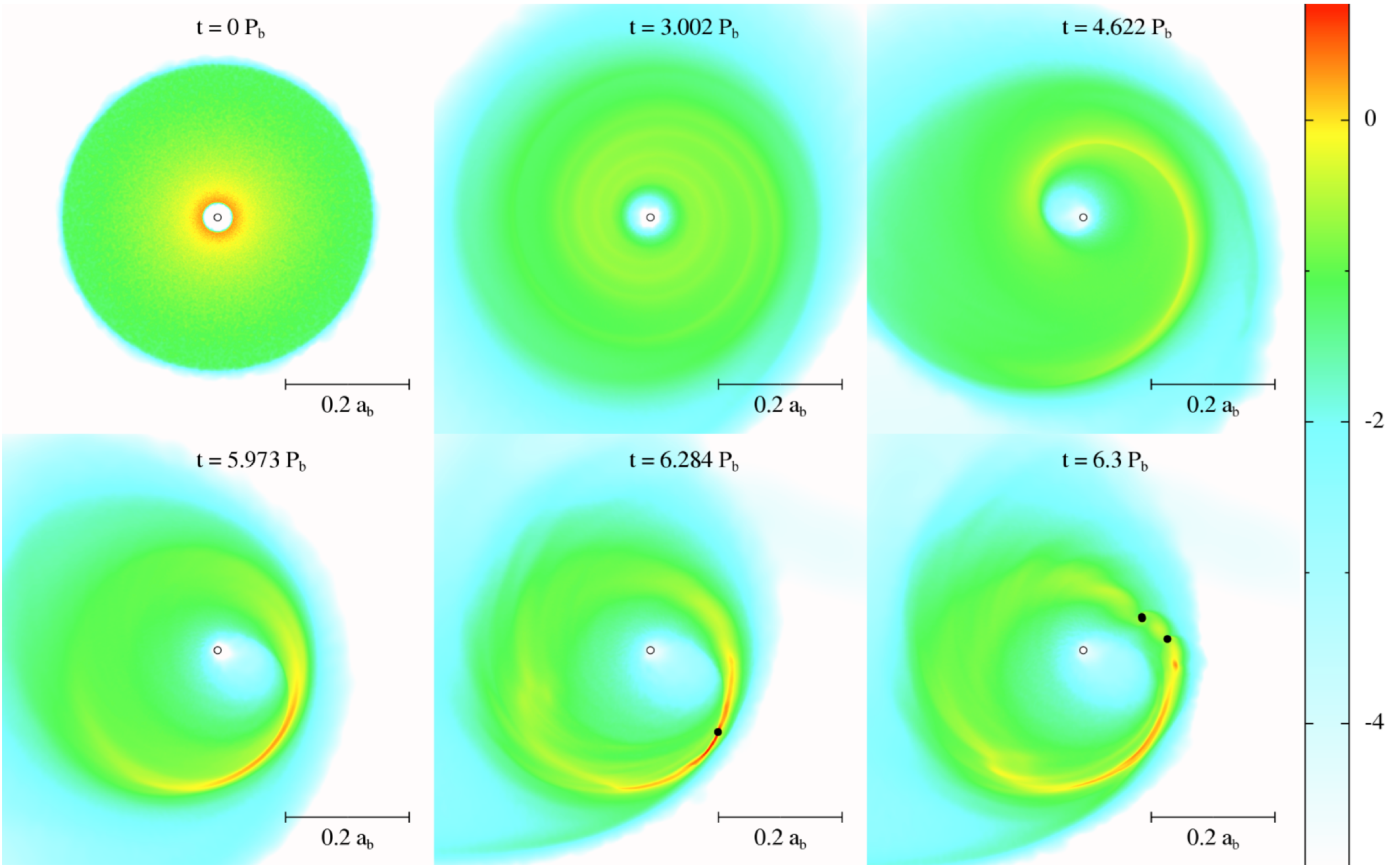
Self-gravity introduces a source of disc apsidal precession.

Self-gravity alone does not allow KL oscillations (Holman et al. 1997, Batygin 2012).

With pressure included, self-gravity can weaken the KL oscillations.

In the early phases of disc evolution while the disc mass is high, KL oscillations may be avoided.

Disc fragmentation
- high disc mass, high inclination

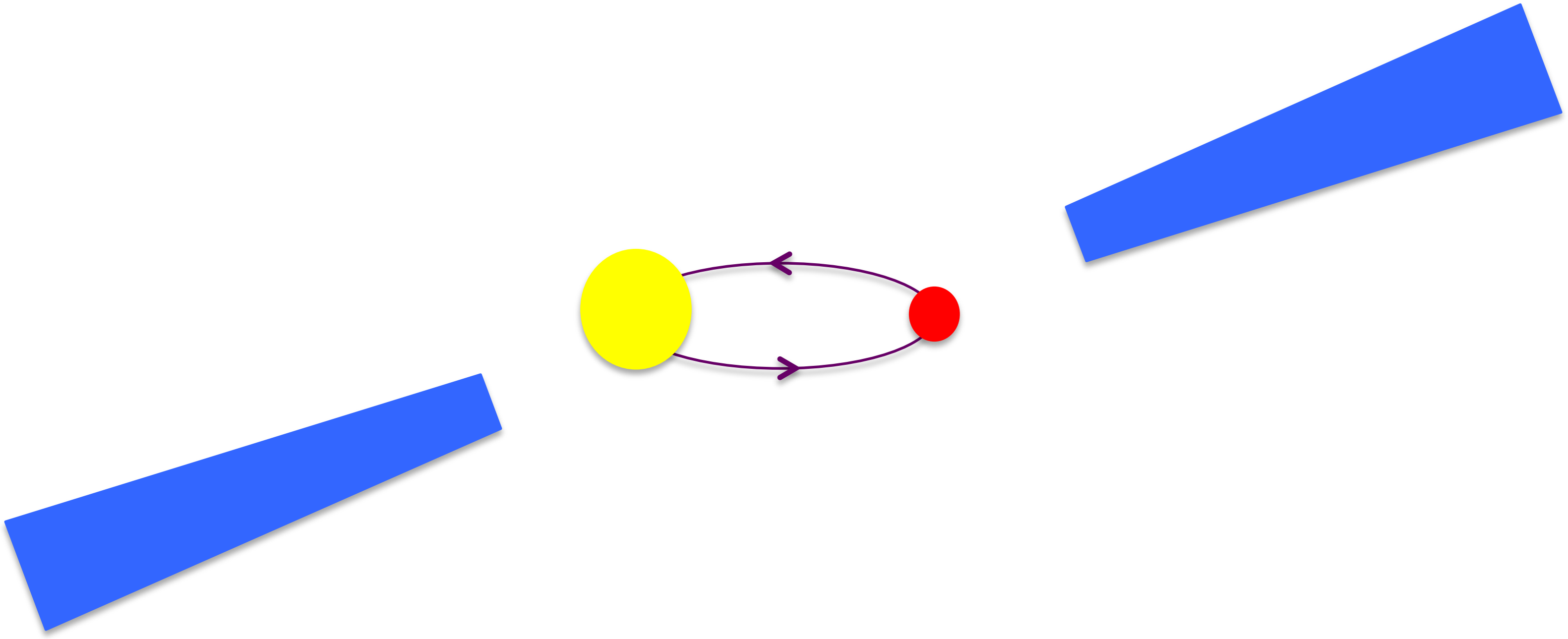


Minimum Q in the disc is 2.2 so in isolation this disc is stable.

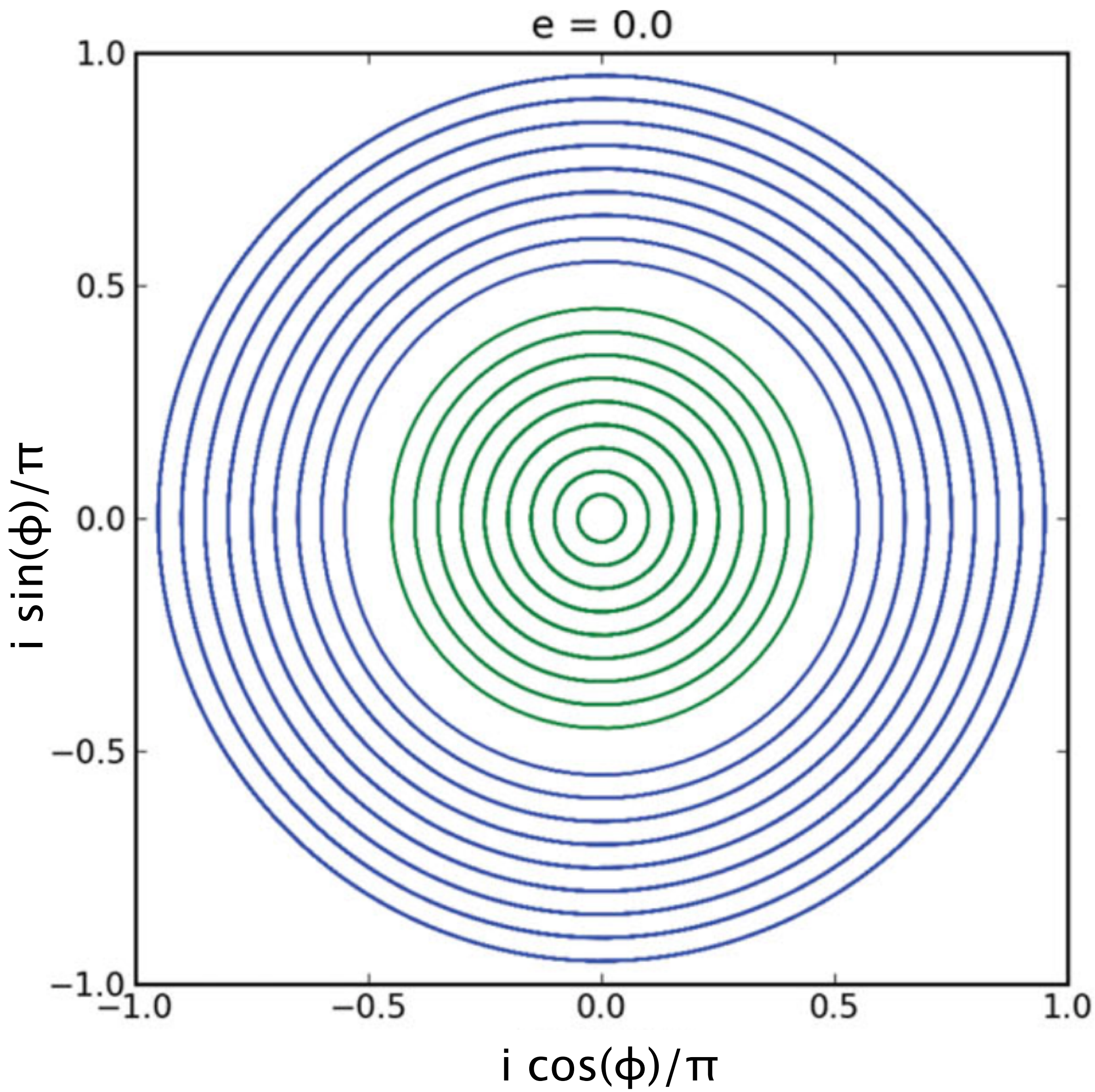
$\Rightarrow$ KL oscillations cause shocks that may aid disc fragmentation.

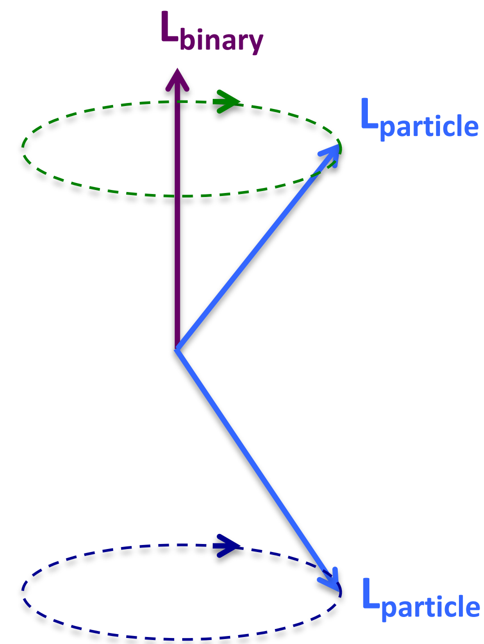
(Fu, Lubow & Martin 2017)

Part II: circumbinary discs



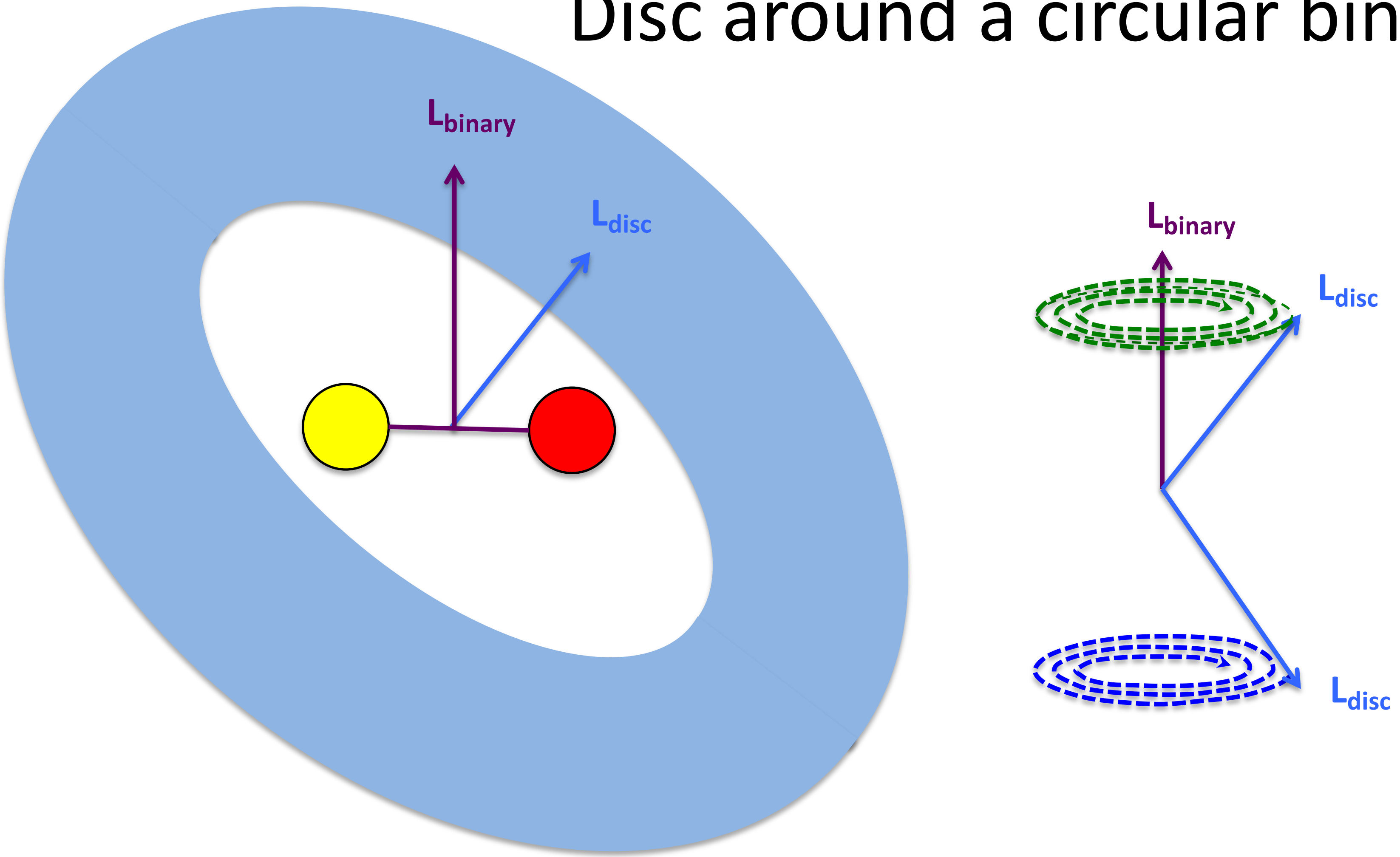
Test particle orbits around a circular binary





Doolin & Blundell (2011)

Disc around a circular binary

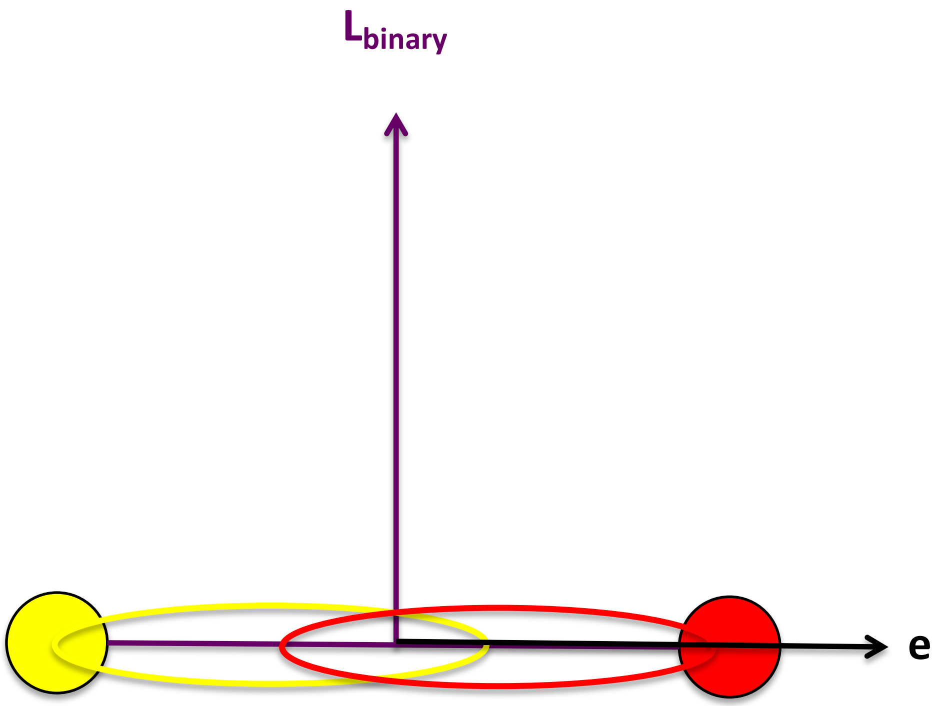


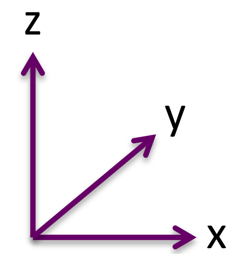
The disc moves towards alignment with the binary orbital plane.

This is due to tidal dissipation associated with turbulent viscosity.

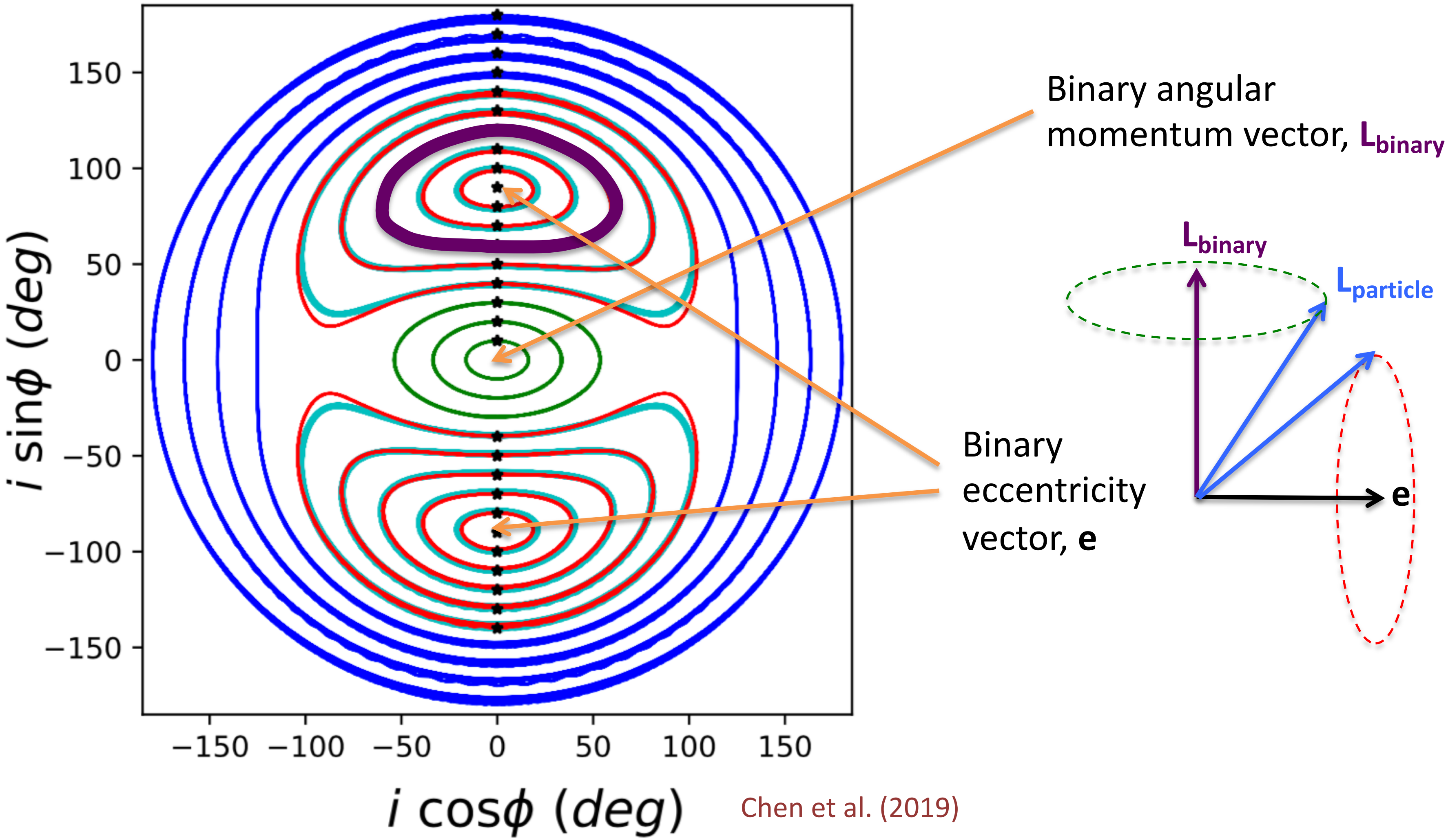
(e.g. Nixon 2012, Facchini et al. 2013, Foucart & Lai 2013, King et al 2013)

Binary eccentricity vector





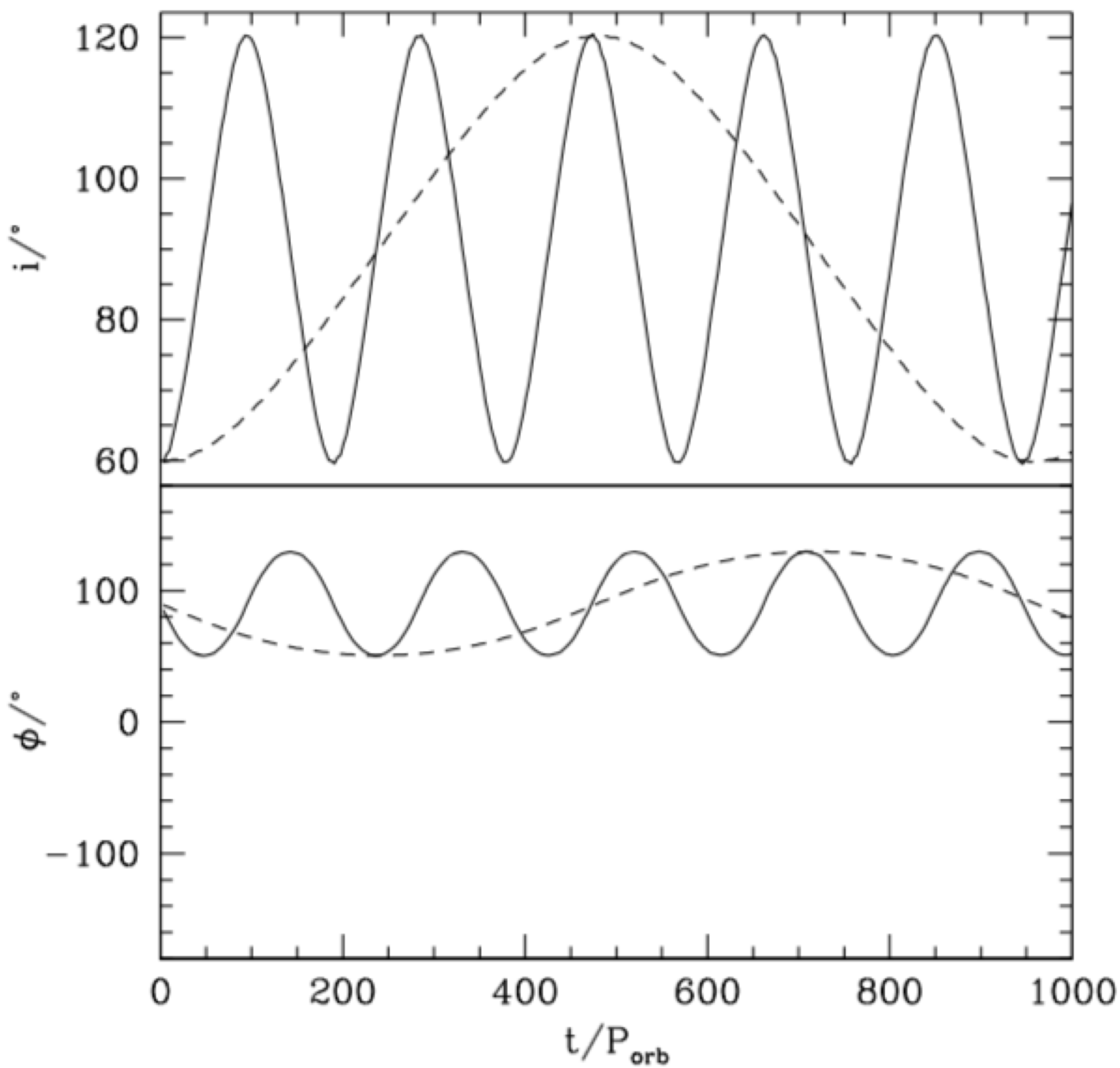
Test particle orbits around an eccentric binary



Chen et al. (2019)

(see also Verrier & Evans 2009, Farago & Laskar 2010, Doolin & Blundell 2011)

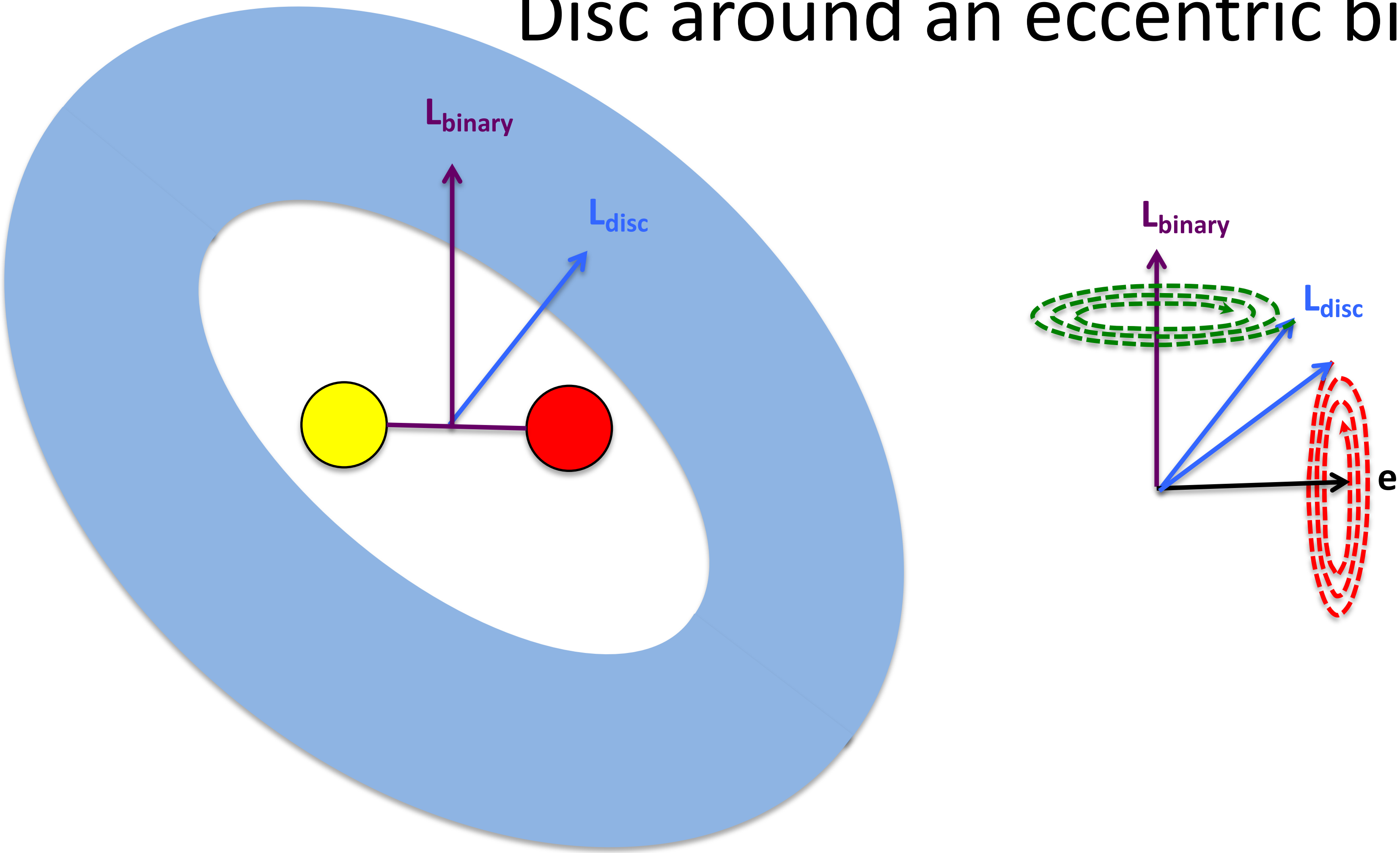
Time evolution



Timescale of oscillations increases away from the binary.

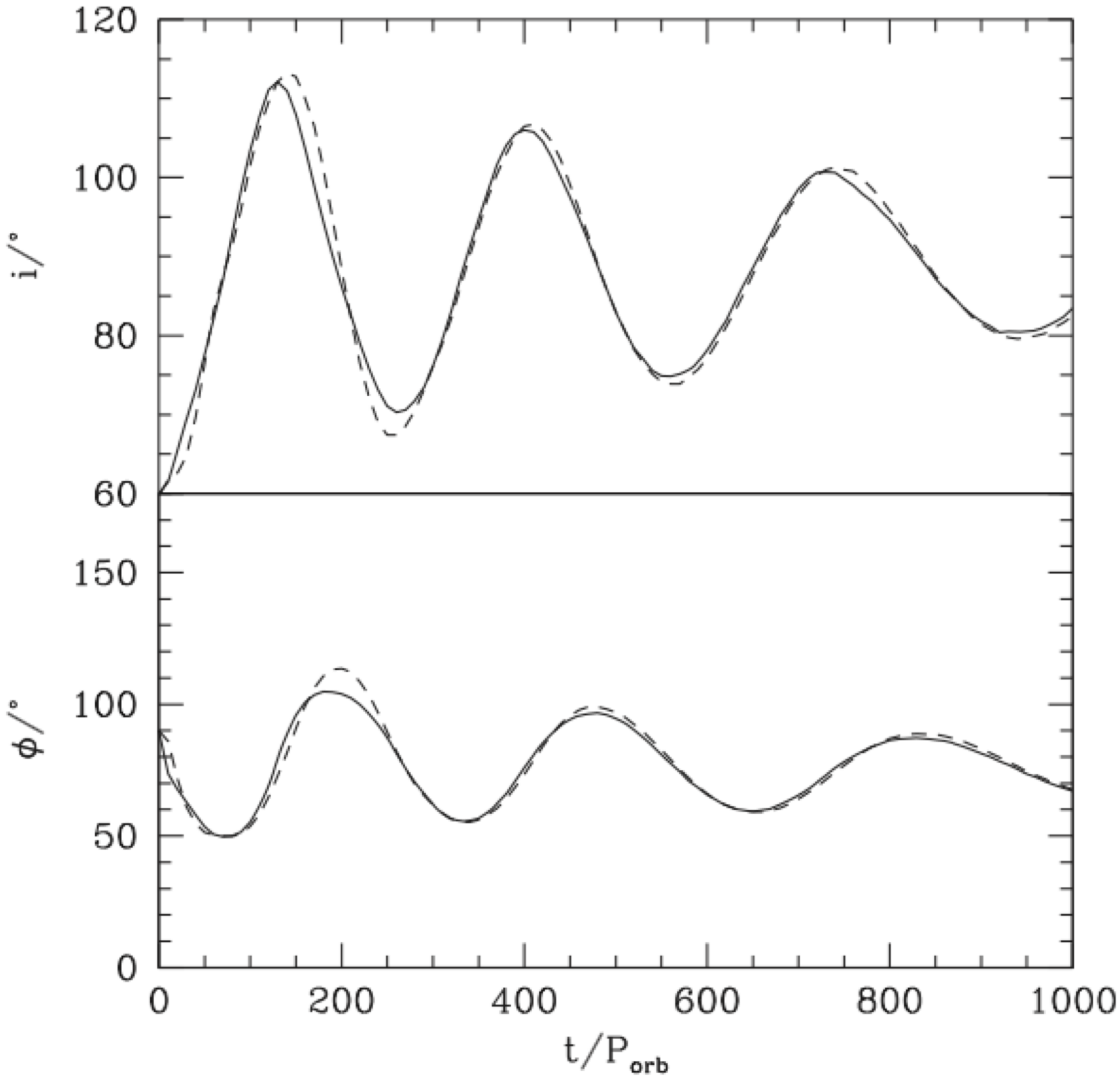
Martin & Lubow (2017)

Disc around an eccentric binary



Depending upon the initial inclination, the disc precesses either about the binary angular momentum vector, or the binary eccentricity vector (Aly et al. 2015, Martin & Lubow 2017).

Global disc evolution

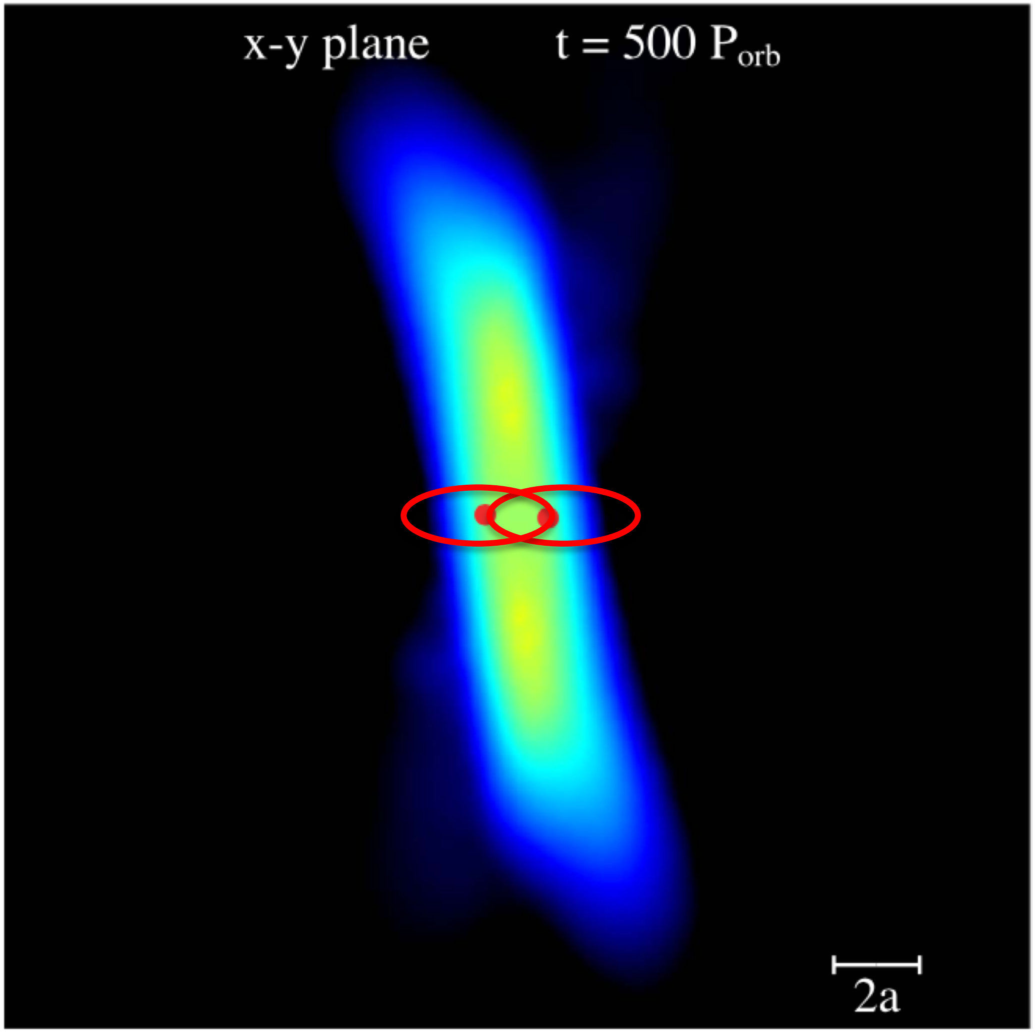


A highly misaligned circumbinary disc can precess about the eccentricity vector (Aly et al. 2015).

A protoplanetary disc can move towards polar alignment in the presence of dissipation.

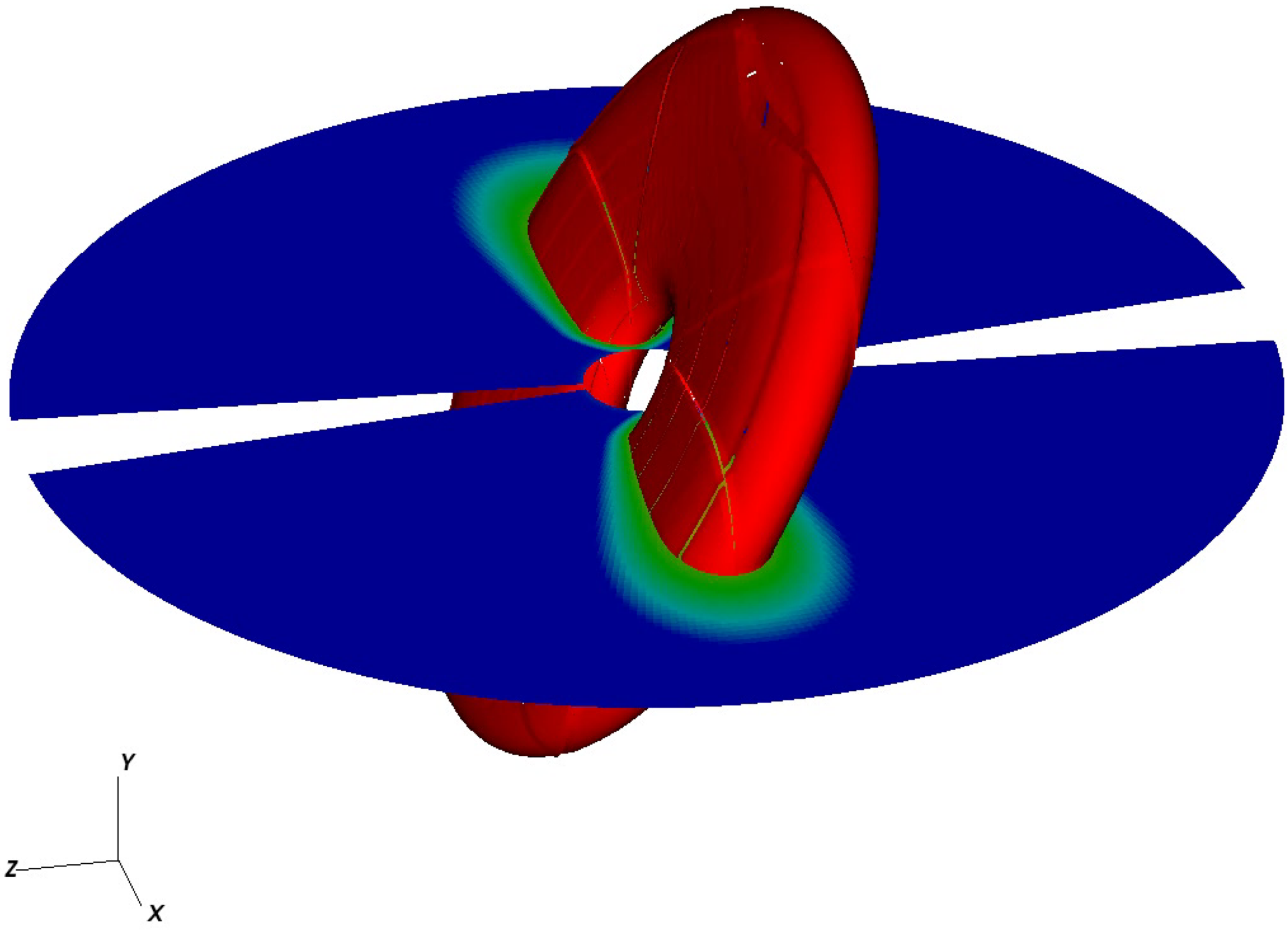
Martin & Lubow (2017)

Polar aligned circumbinary disc



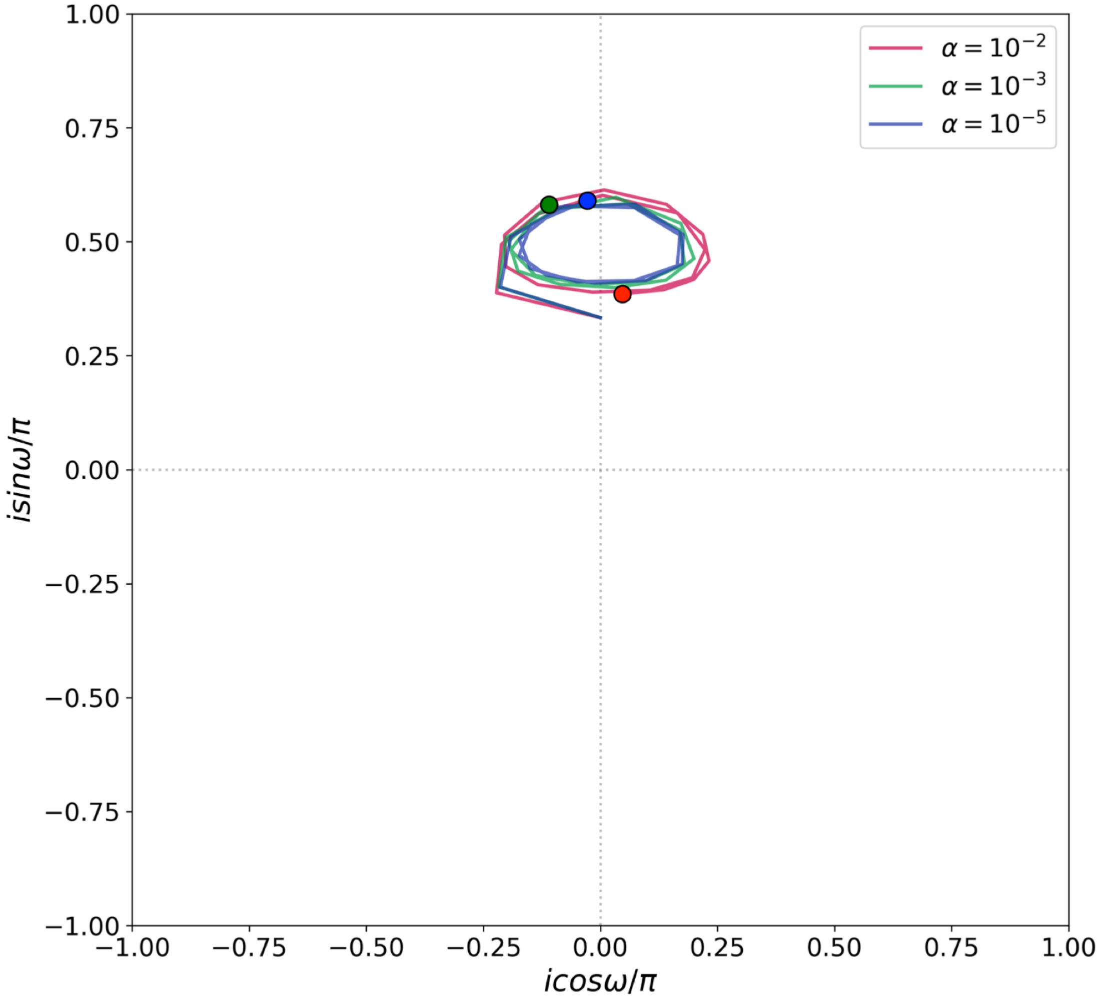
Martin & Lubow (2017)

Polar disc simulation – grid code



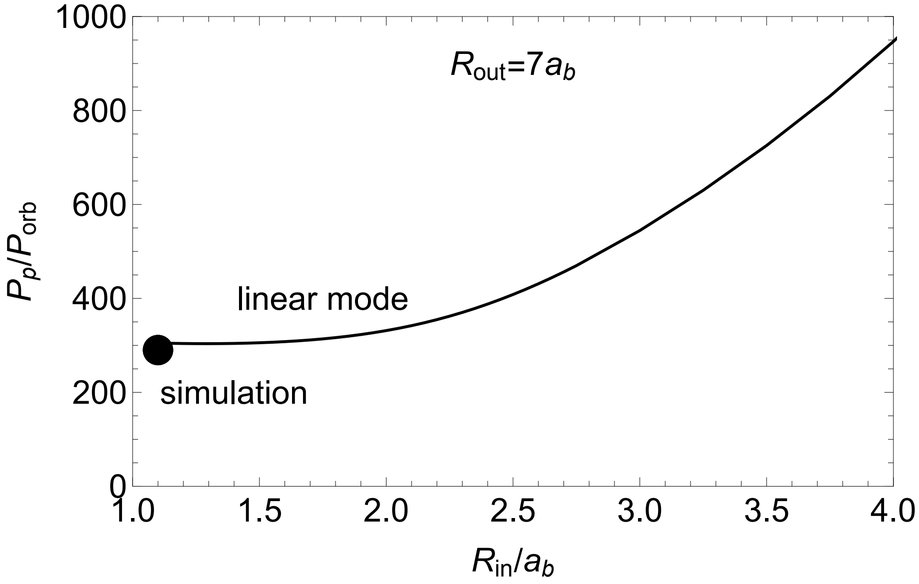
Rabago, Zhu et al. (in prep)

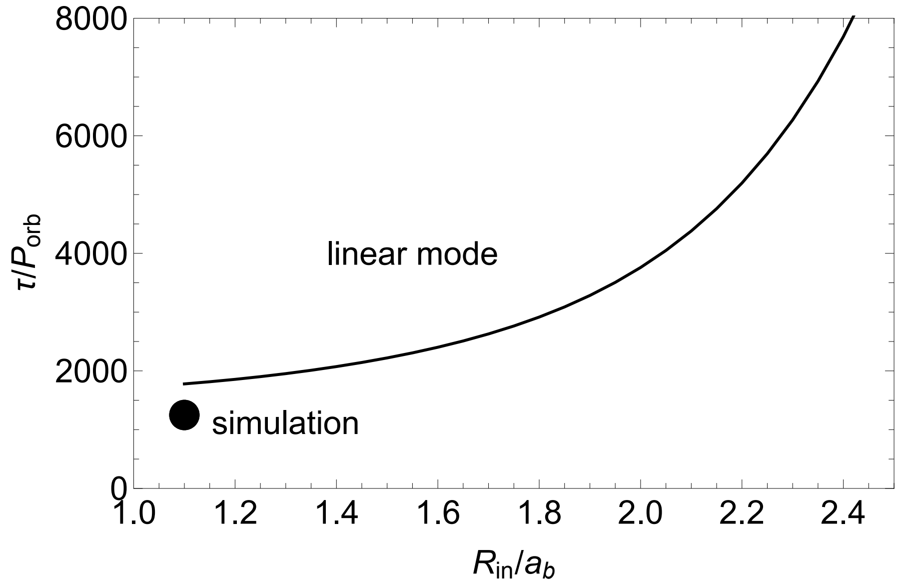
Variation of disc viscosity



Rabago, Zhu et al. (in prep)

Simulations agree with linear theory



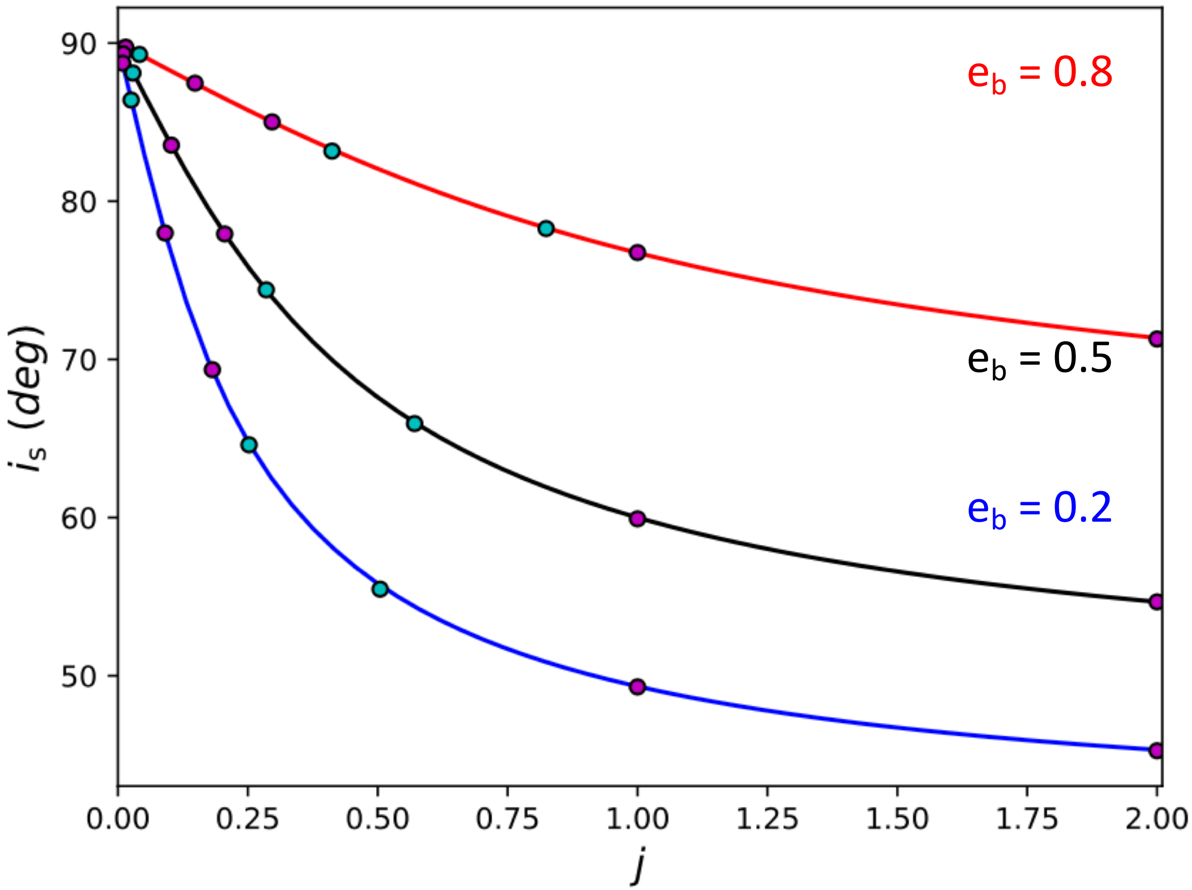


We solve the wave-like warped disc equations (Lubow & Ogilive 2000) assuming the disc is initially close to polar and the warping is small.

Lubow & Martin (2018)

Stationary inclination

The stationary inclination depends upon the binary eccentricity and the angular momentum ratio of the disc to the binary (Zanazzi & Lai 2018, Martin & Lubow 2019).

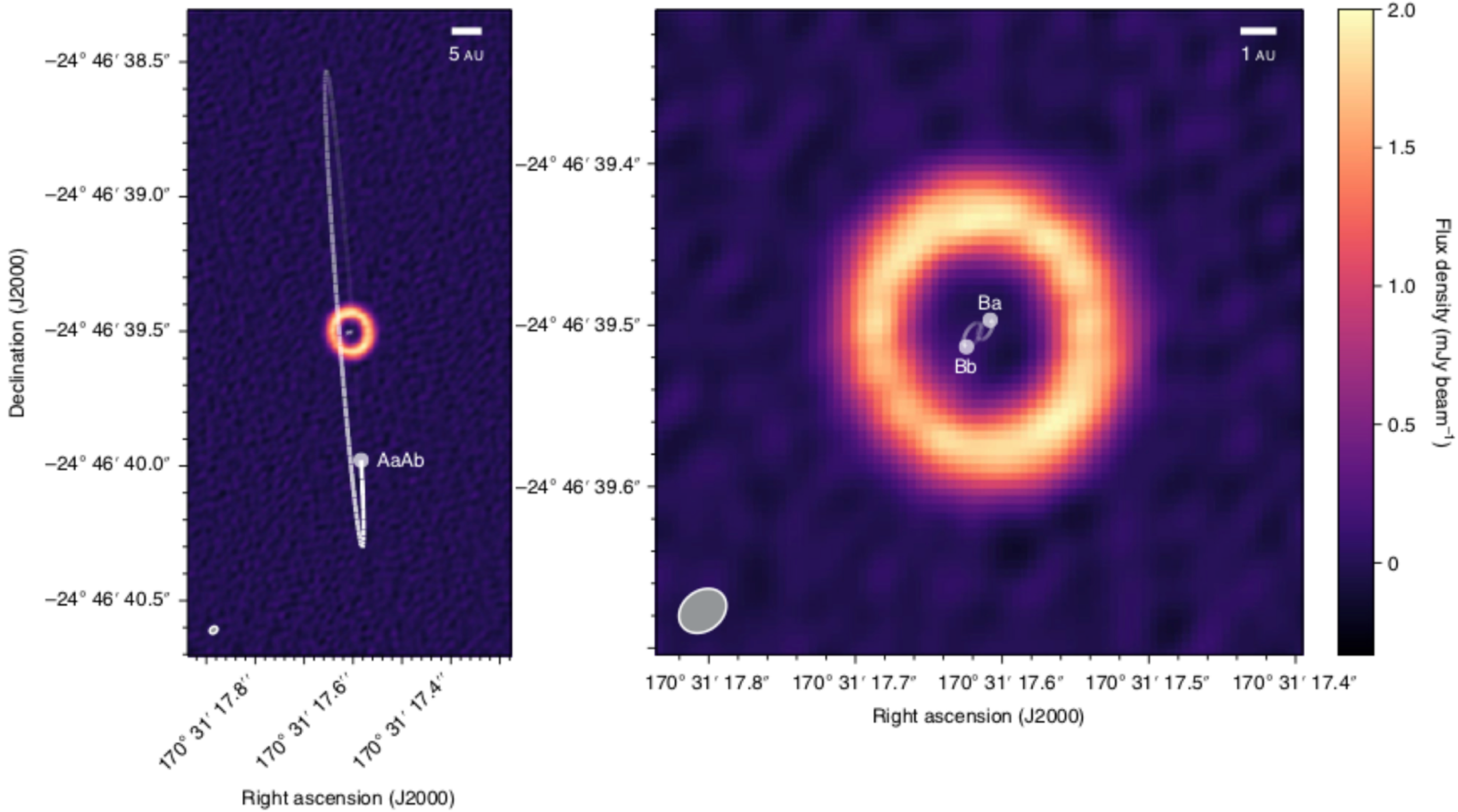


We derived analytically the stationary inclination for a third body based on the equations of Farago & Laskar (2010).

Points correspond to three body simulations.

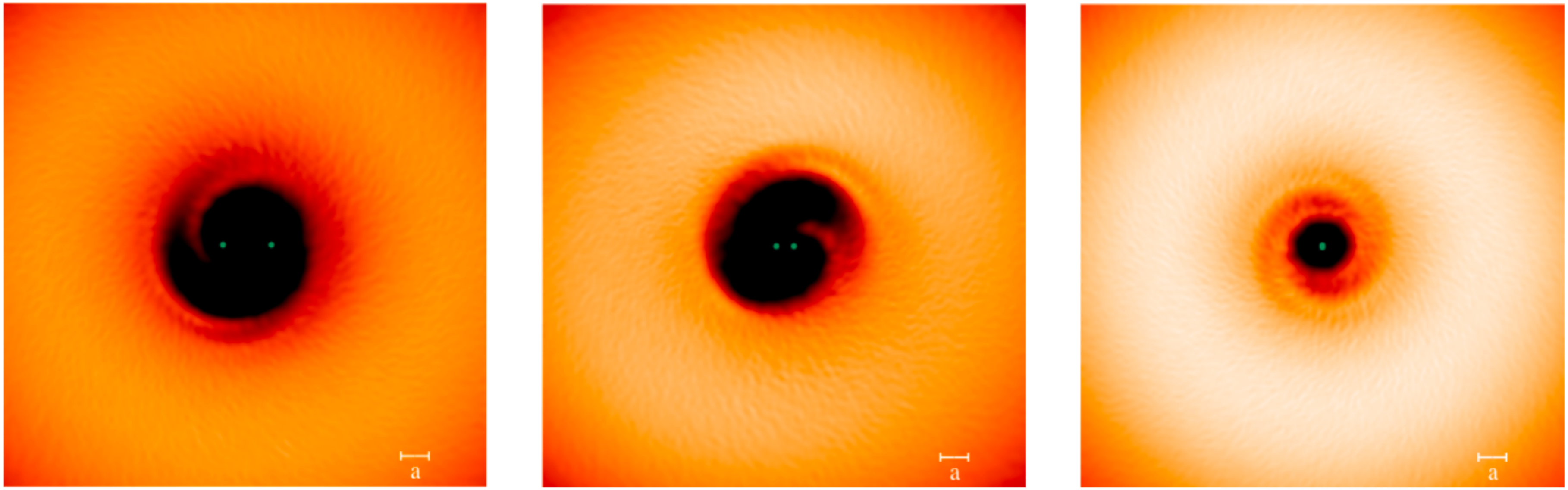
Chen et al. (2019), Martin & Lubow (2019)

HD 98800: first observed polar aligned gas disc



Kennedy et al. (2019)

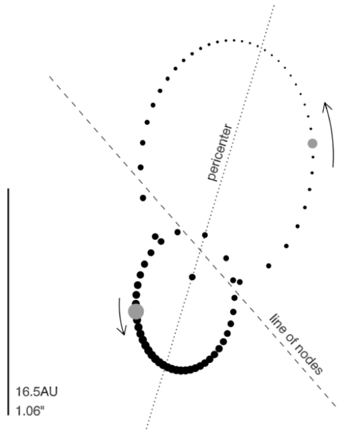
Circumbinary disc radius as an observational diagnostic for misalignment



i=0º   i=48º   i=90º

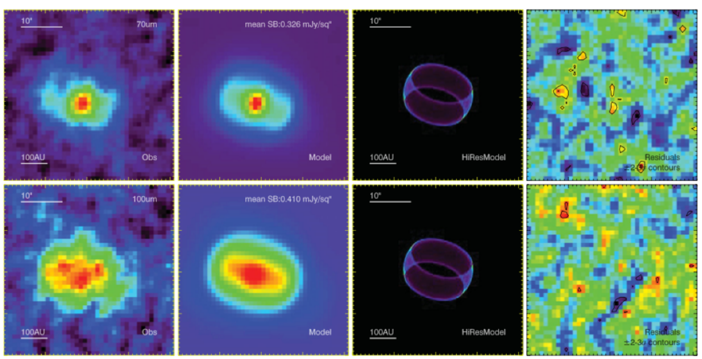
Franchini, Lubow & Martin (2019)

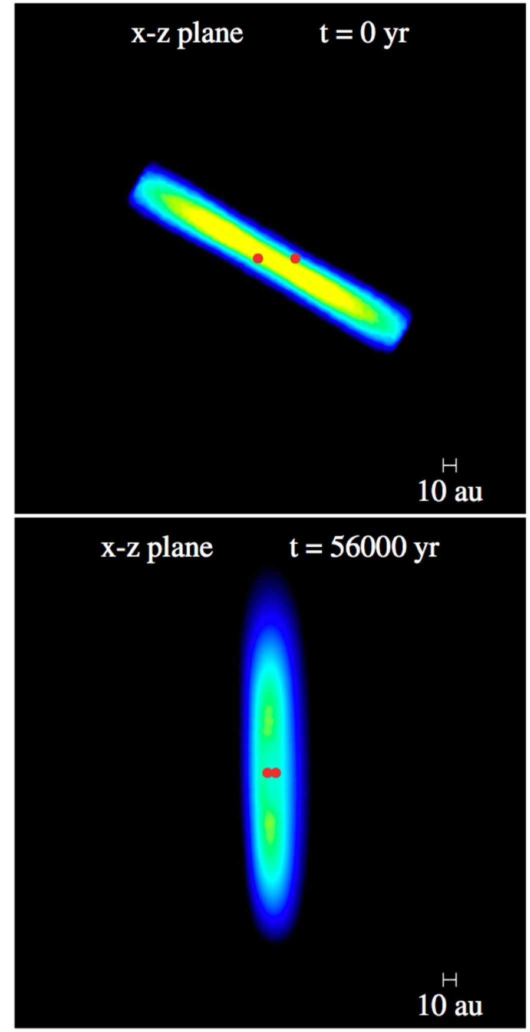
99 Herculis: a circumbinary polar-ring debris disc



- F7V primary orbited by a K4V secondary in an eccentric orbit with e=0.77.
- Best fitting model is a ring of polar orbits that move in a plane perpendicular to the binary pericentre direction.

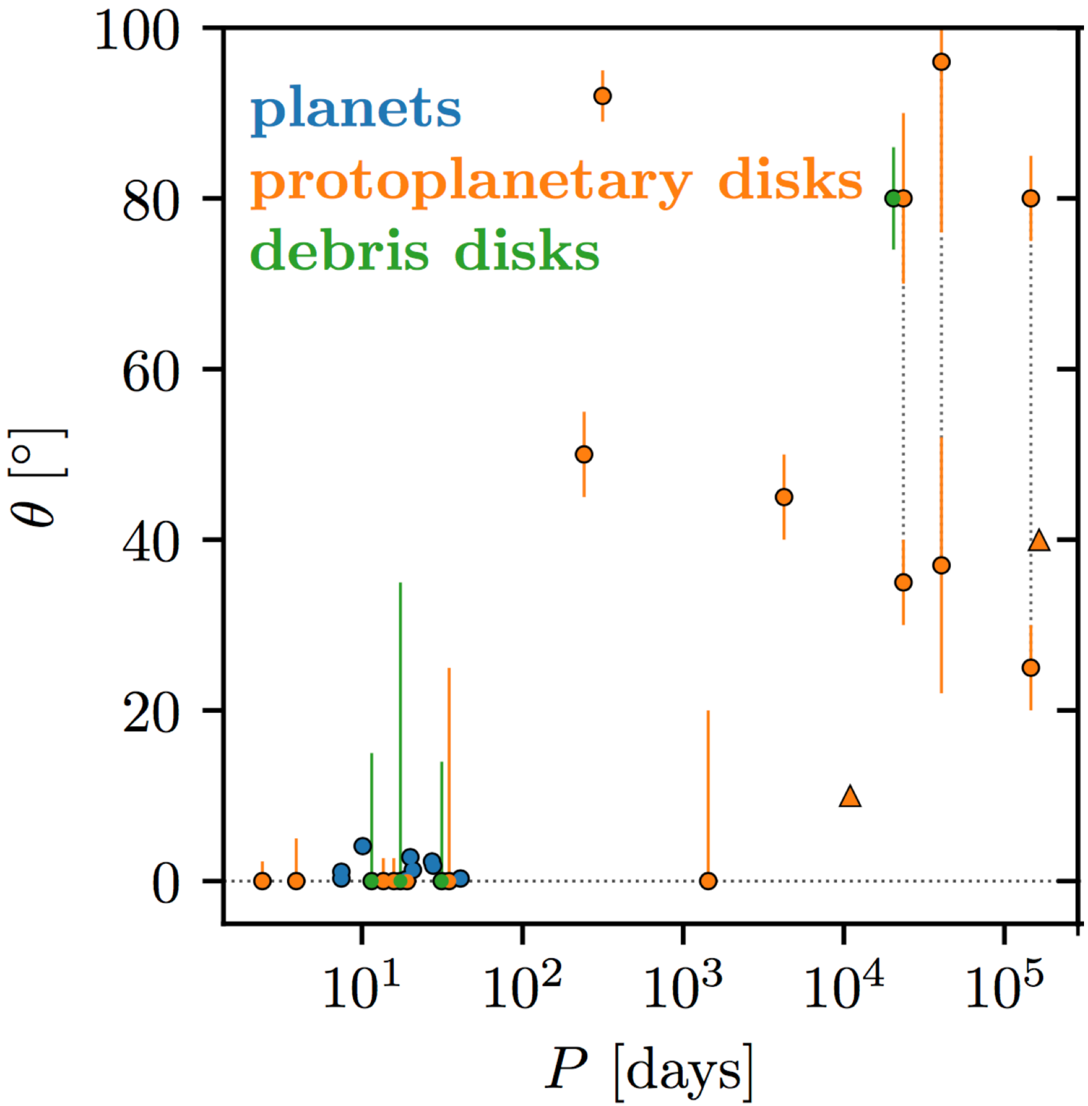
(Kennedy et al. 2012)





A misaligned gas disc with initial inclination >30° moves towards polar alignment on a timescale shorter than the disc lifetime (Smallwood et al. 2020).

Mutual inclinations of Kepler circumbinary planets and observed circumbinary discs

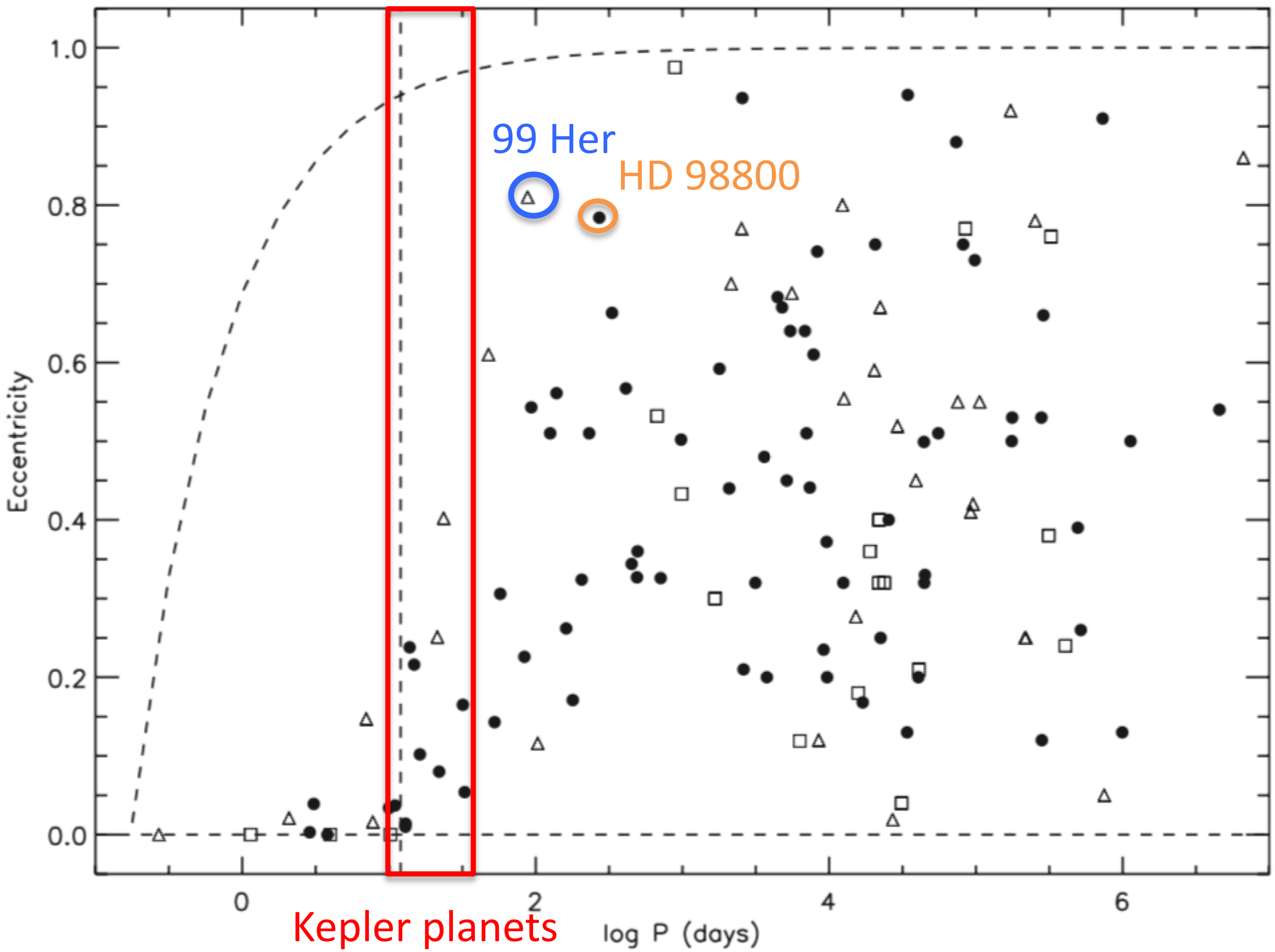


Czekala et al. (2019)

Circumbinary planets

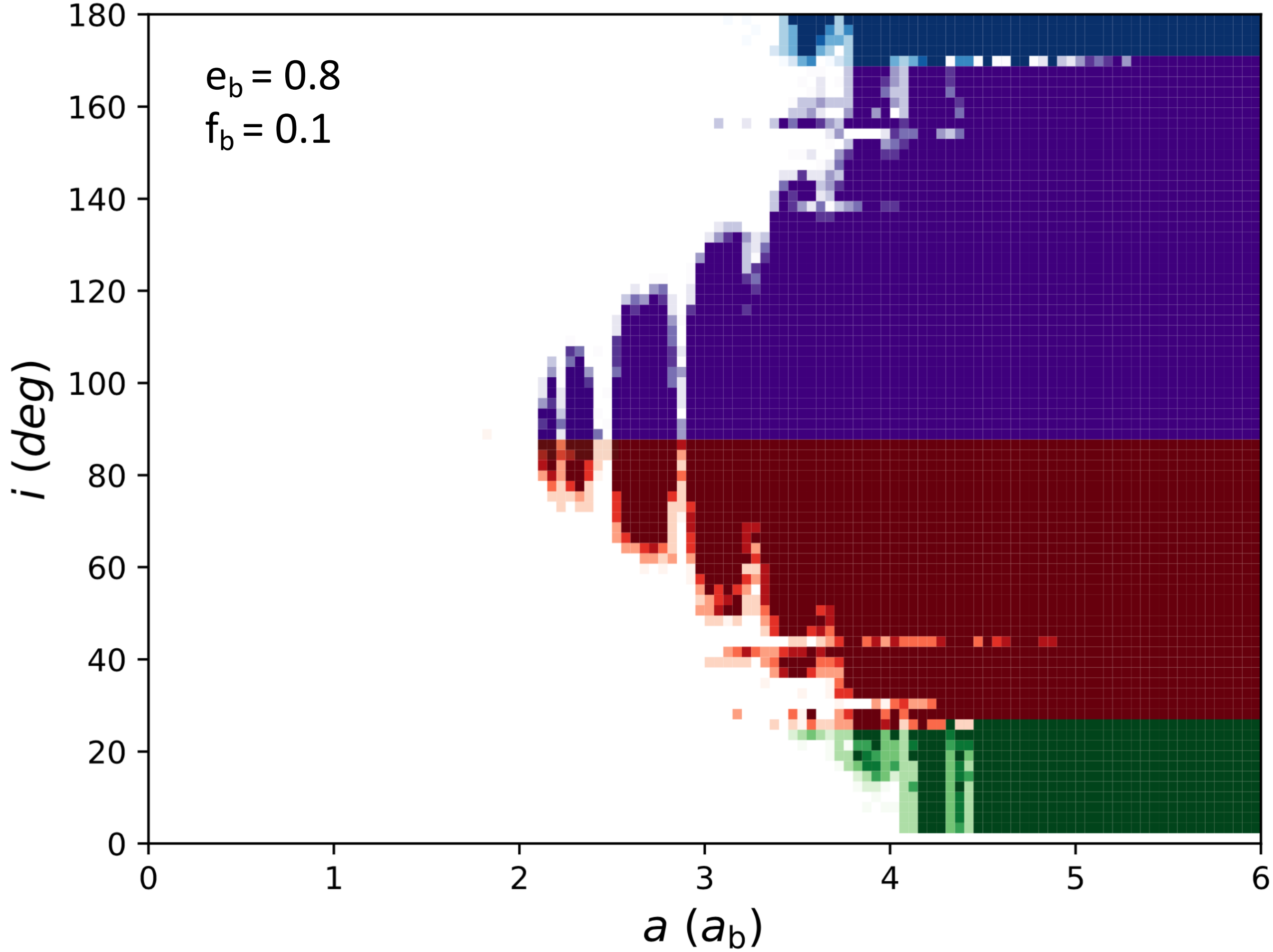
We predict that polar planets exist for longer orbital period binaries than those observed with Kepler.

Polar planets may be found with eclipse timing variations (Zhang & Fabrycky 2019).



Raghavan et al. (2010)

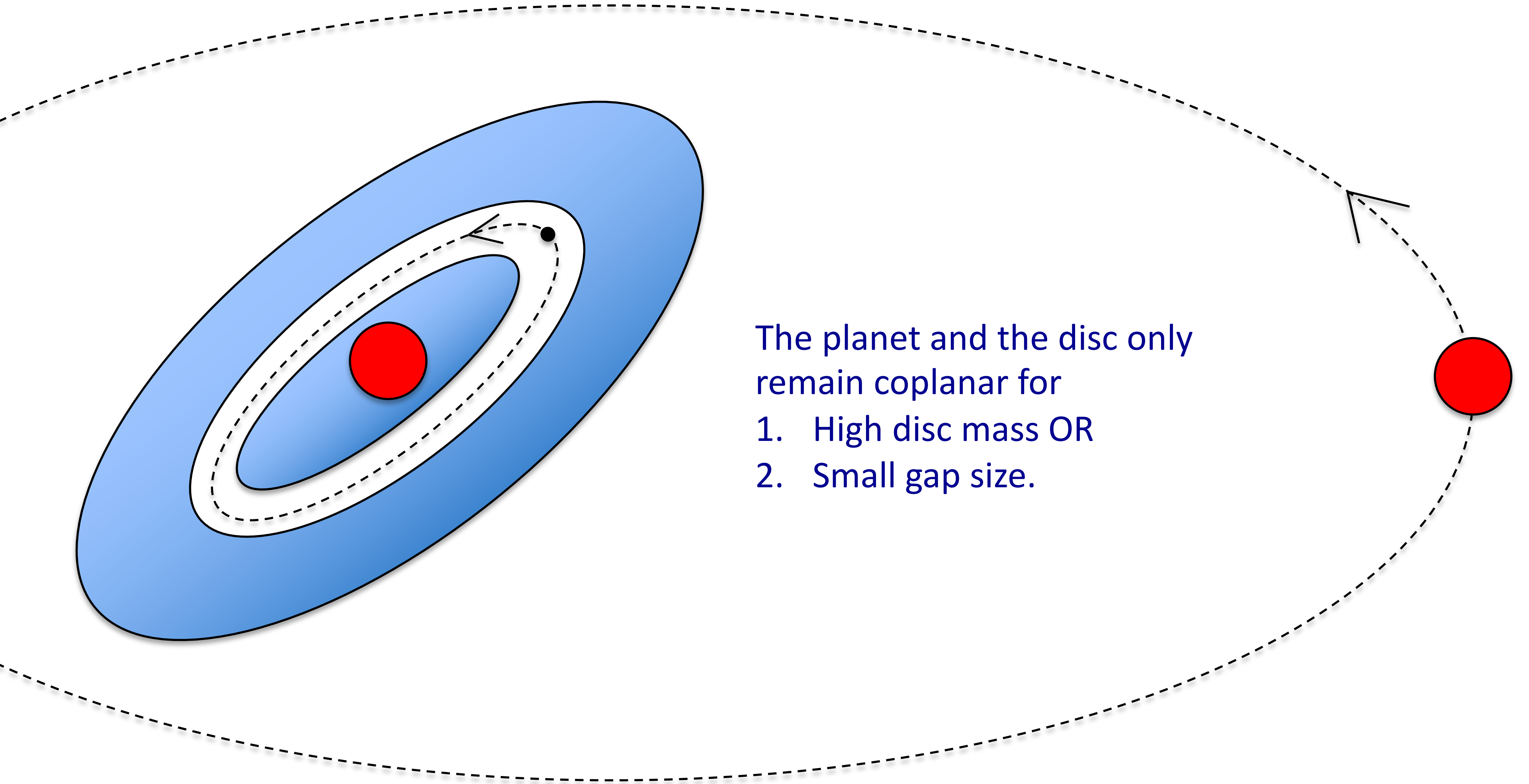
Polar planets are the most stable around eccentric binaries



Polar orbits are stable (Doolin & Blundell 2011, Cuello & Giuppone 2019).

Chen et al. (2020)

Part III: planet-disc interactions in misaligned binaries



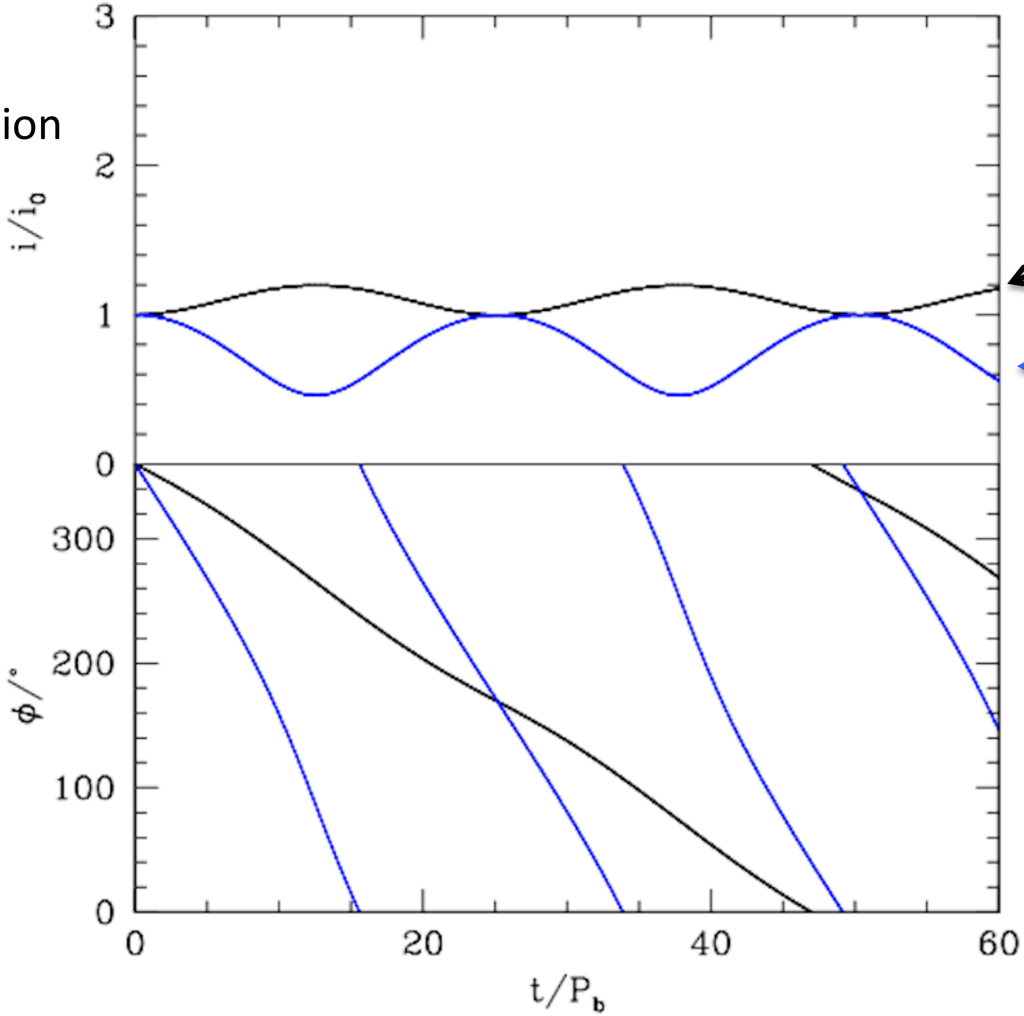
The planet and the disc only remain coplanar for

1. High disc mass OR
2. Small gap size.

Low Inclination - low mass disc

Inclination

Phase Angle



Planet

Outer Disc

Circulating solution
– independent precession

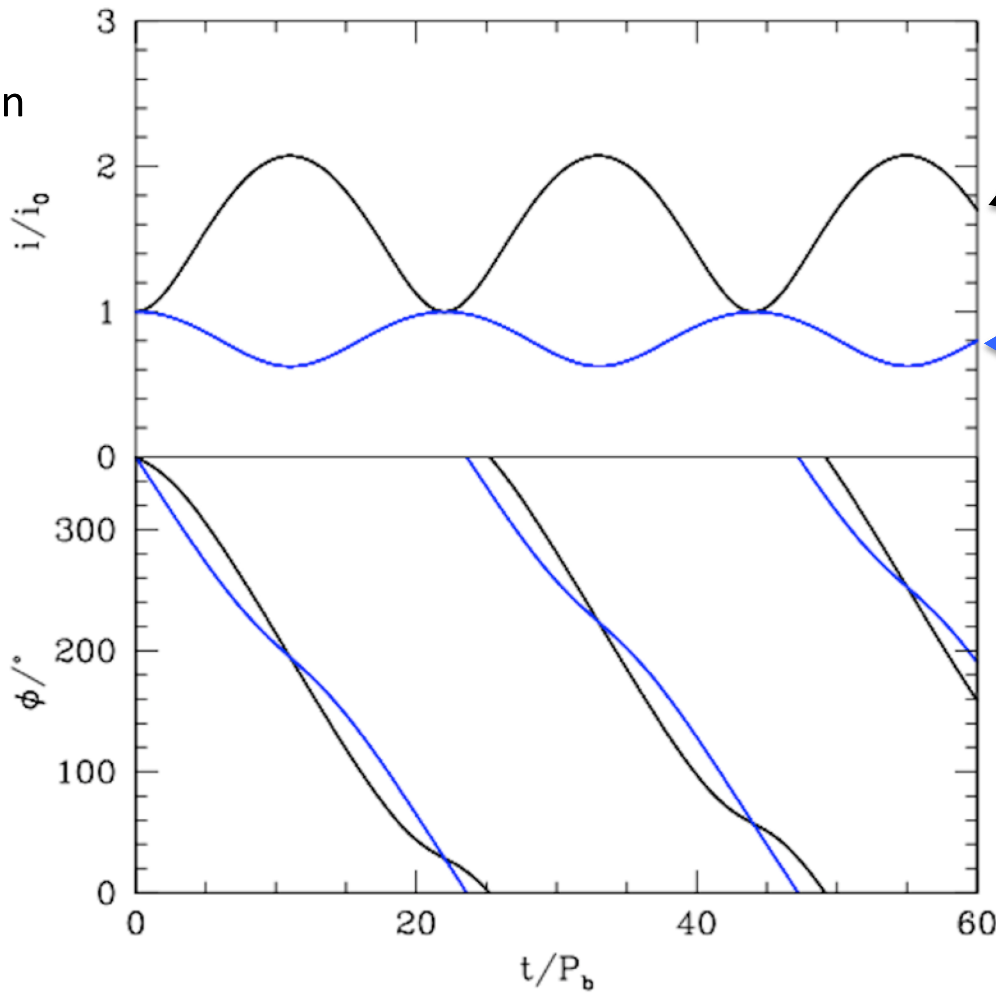
(Lubow & Martin 2016)

Low Inclination- high mass disc

Inclination

Planet

Outer Disc

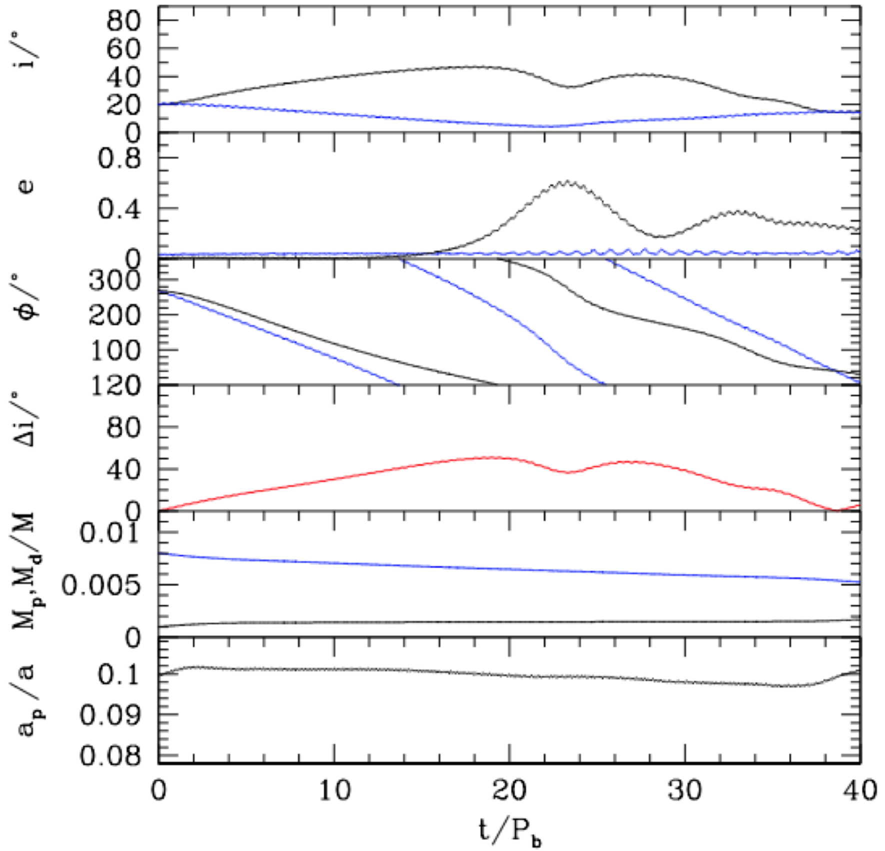


Phase
Angle

Librating solution
– average precession periods
are locked

(Lubow & Martin 2016)

Hydrodynamic simulation
– high disc mass
– initial inclination = 20°



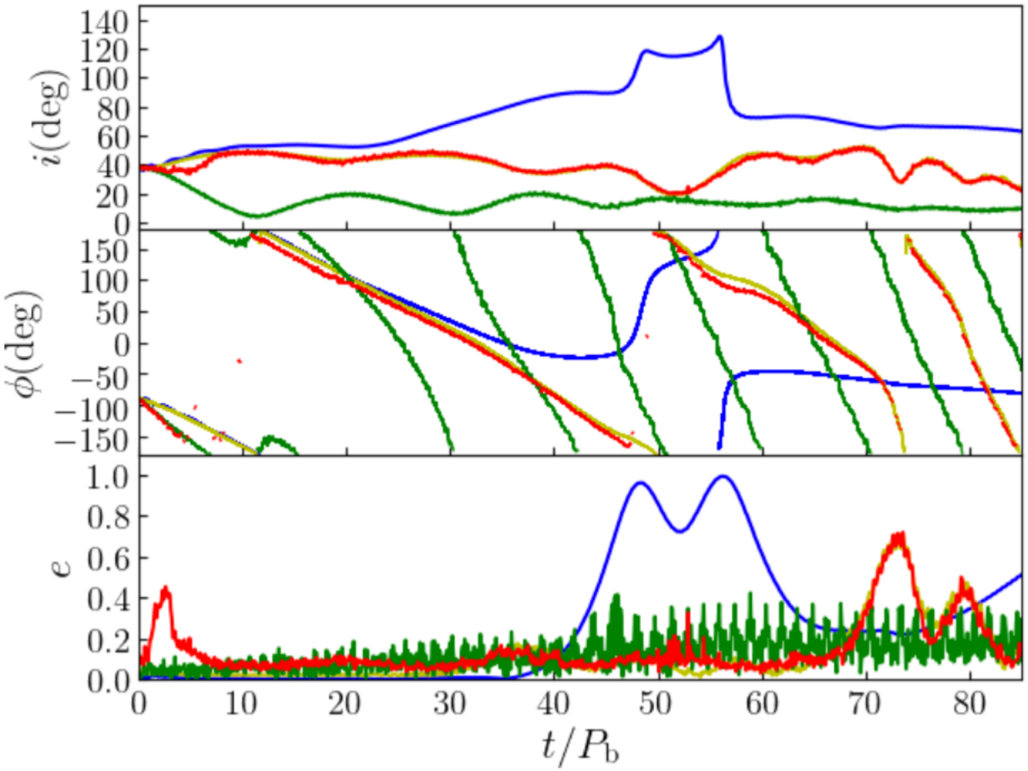
- Secular tilt oscillation drives up the inclination of the planet above the critical KL angle.
- The planet shows KL oscillations.

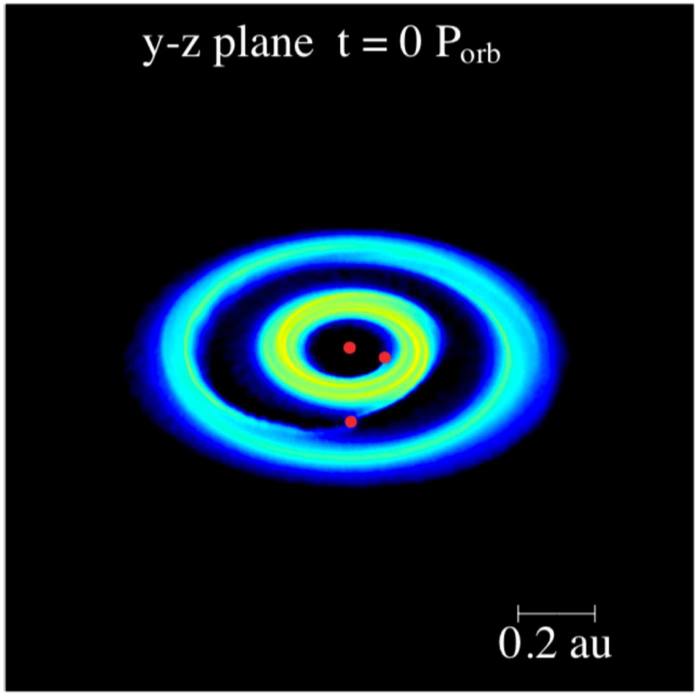
=> Even a mildly misaligned disc can form a KL planet!

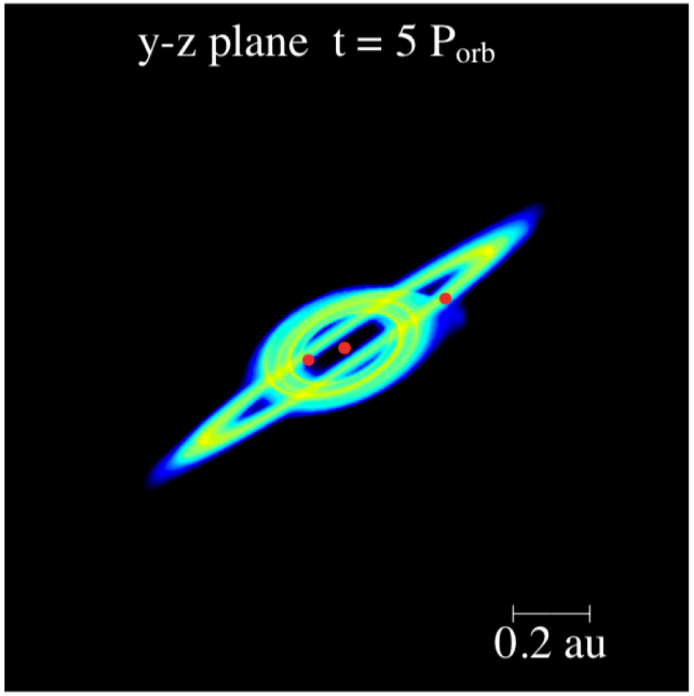
(Martin et al. 2016)

Multi-planet systems

Planet-disc interactions in binaries can lead to retrograde planets

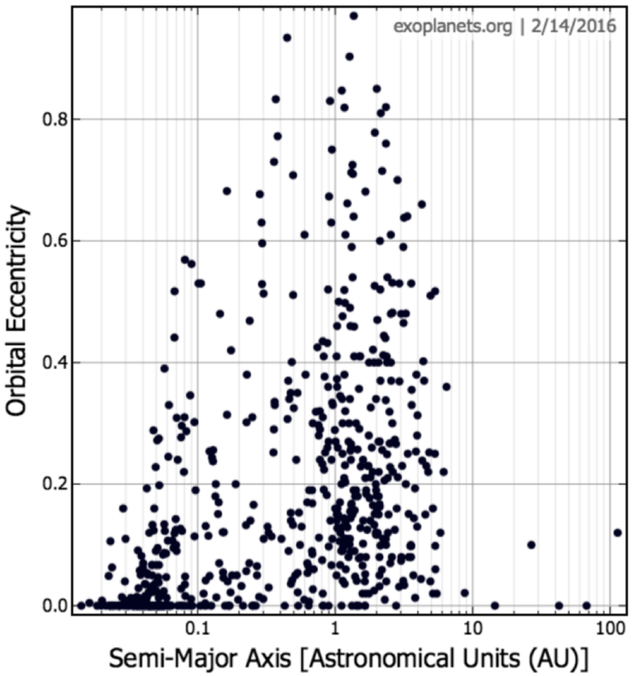




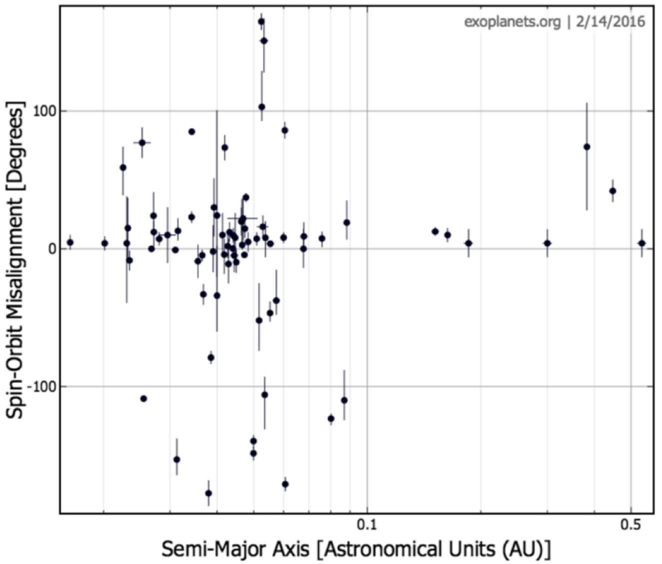


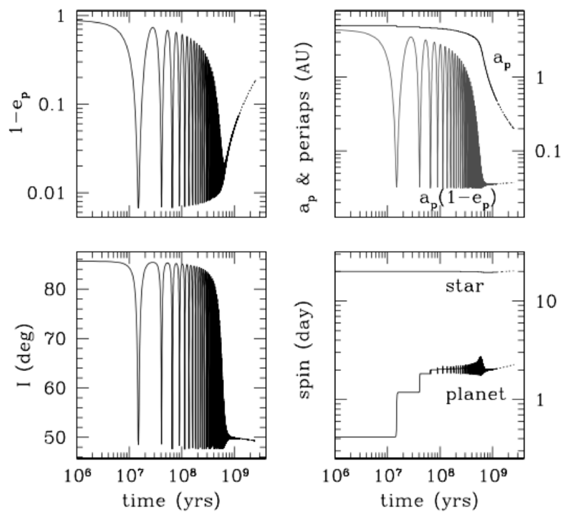
Franchini et al. (2019)

Exoplanet properties



Planet-disc interactions in a binary can form planets with high eccentricities and high inclinations.



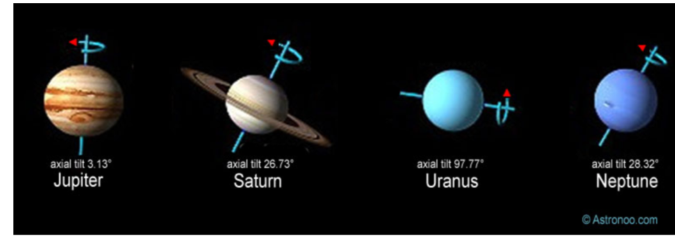


Tidal circularisation of such planets can lead to the formation of hot Jupiters (Wu & Murray 2003).

Conclusions

1. Circumplanetary discs are unstable to tilting.

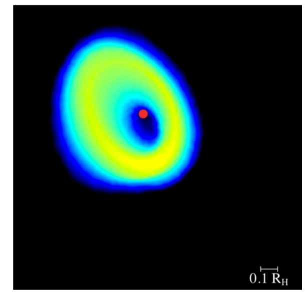
→Planet spin-orbit misalignment

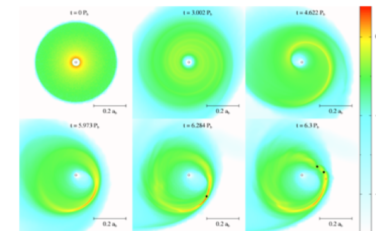


2. A highly misaligned disc around one component a binary can be unstable to Kozai-Lidov oscillations.

→Planet formation in eccentric discs?

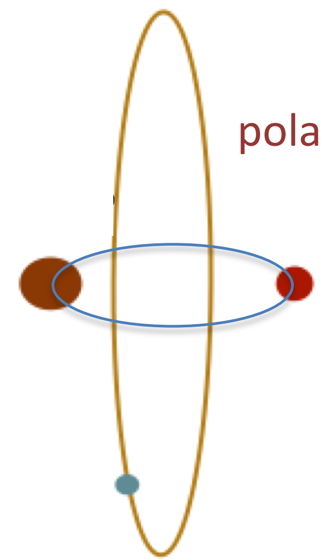
→Planet formation via fragmentation?





3. A misaligned circumbinary disc around an eccentric binary can evolve to a polar configuration.

→Polar planets?



polar planets?

4. Planet-disc interactions in misaligned binaries can lead to the formation of KL planets even with a low initial tilt.

→Eccentric and/or highly misaligned planets