Circumbinary Accretion

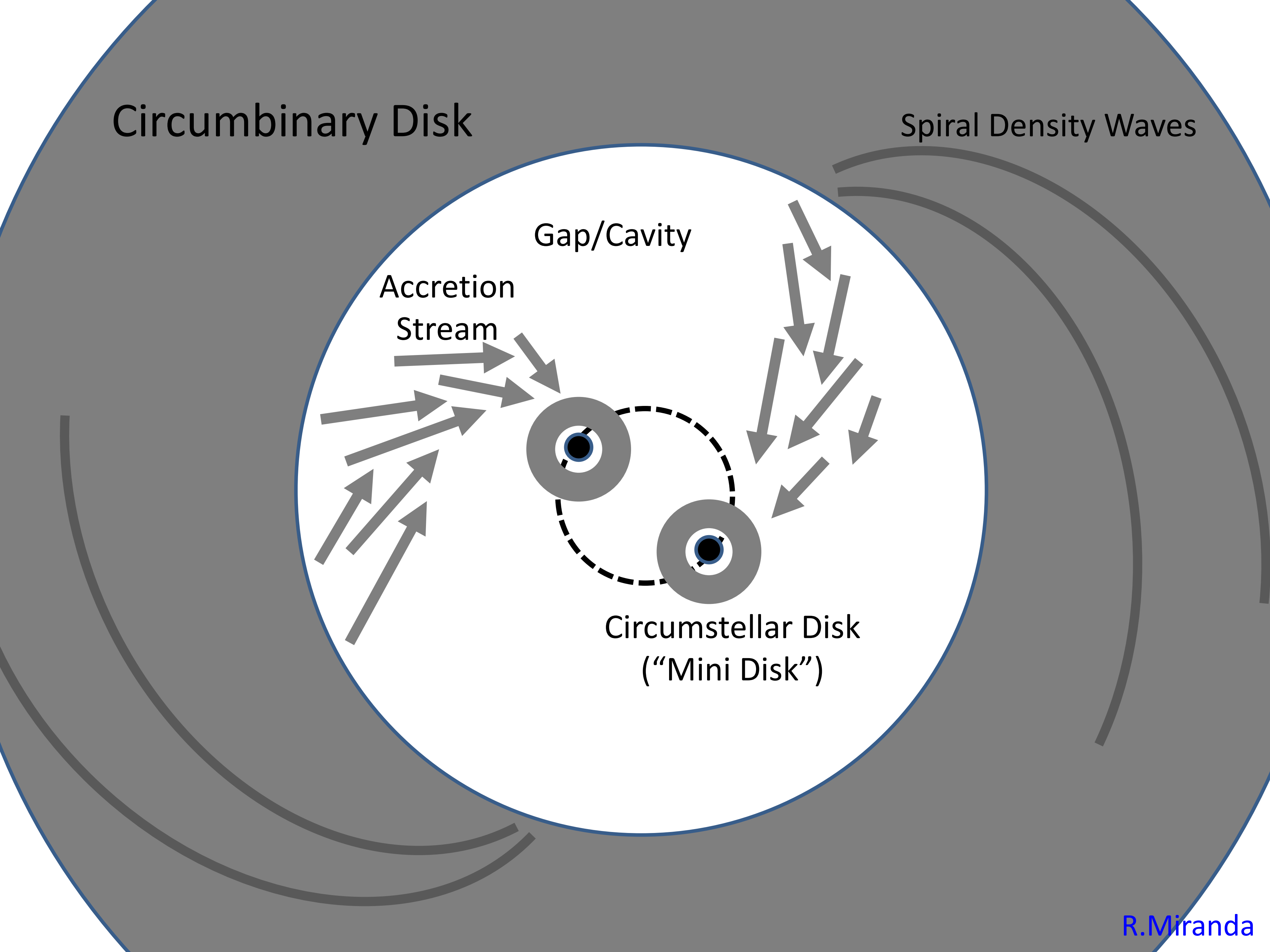
From Supermassive Binary BHs to Circumbinary Planets

Dong Lai
Cornell University

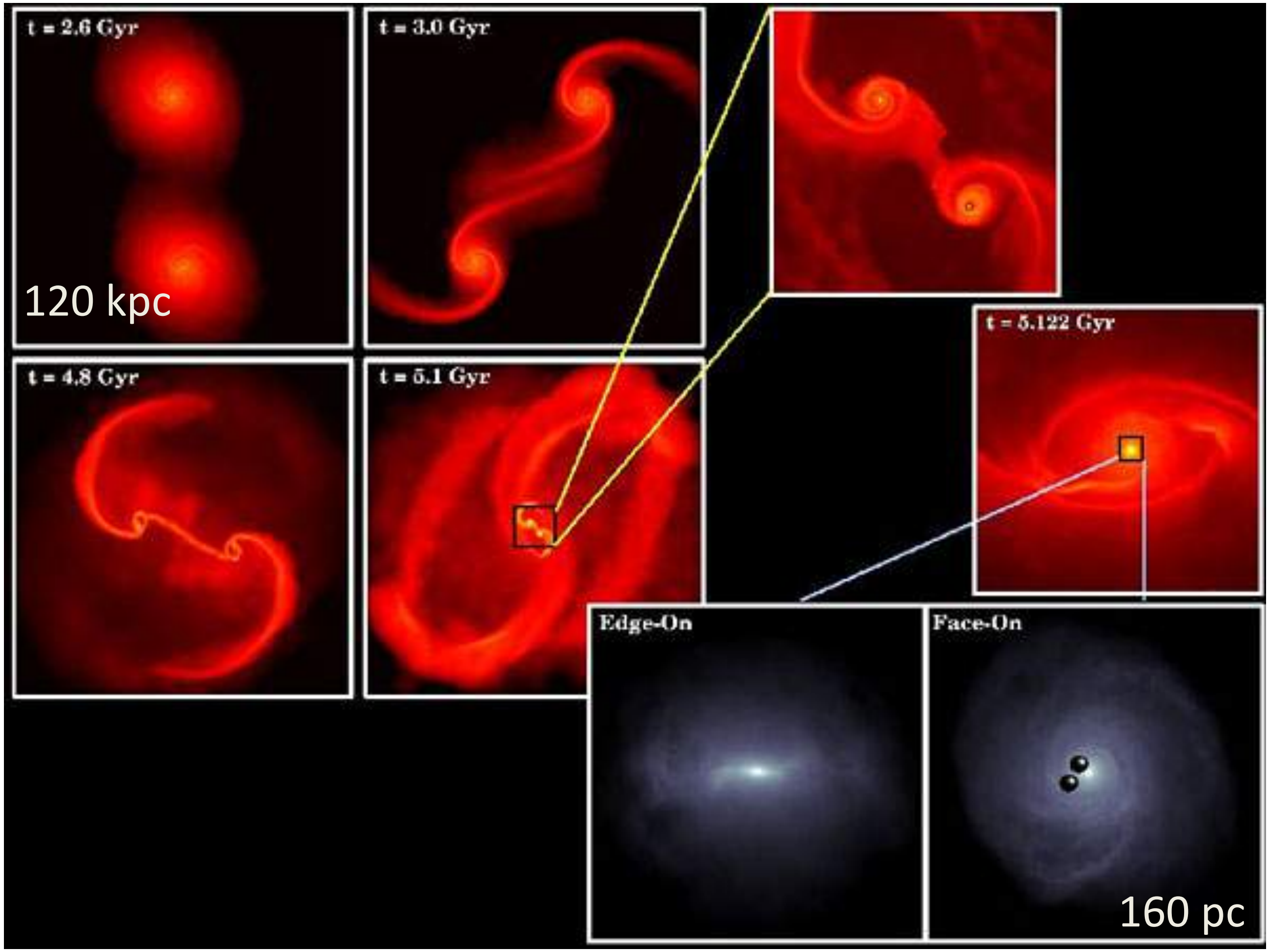
Berkeley/Miller Institute

T.D. Lee Institute

UC Berkeley Astro Colloquium, 3/5/2020


Circumbinary Disk
Spiral Density Waves
Gap/Cavity
Accretion
Stream
Circumstellar Disk
("Mini Disk")
R.Miranda

Galaxy merger → SMBH binary in gas disk/torus



Mayer et al 2007

A key question: Does the binary lose or gain angular momentum?

A key question: Does the binary lose or gain angular momentum?

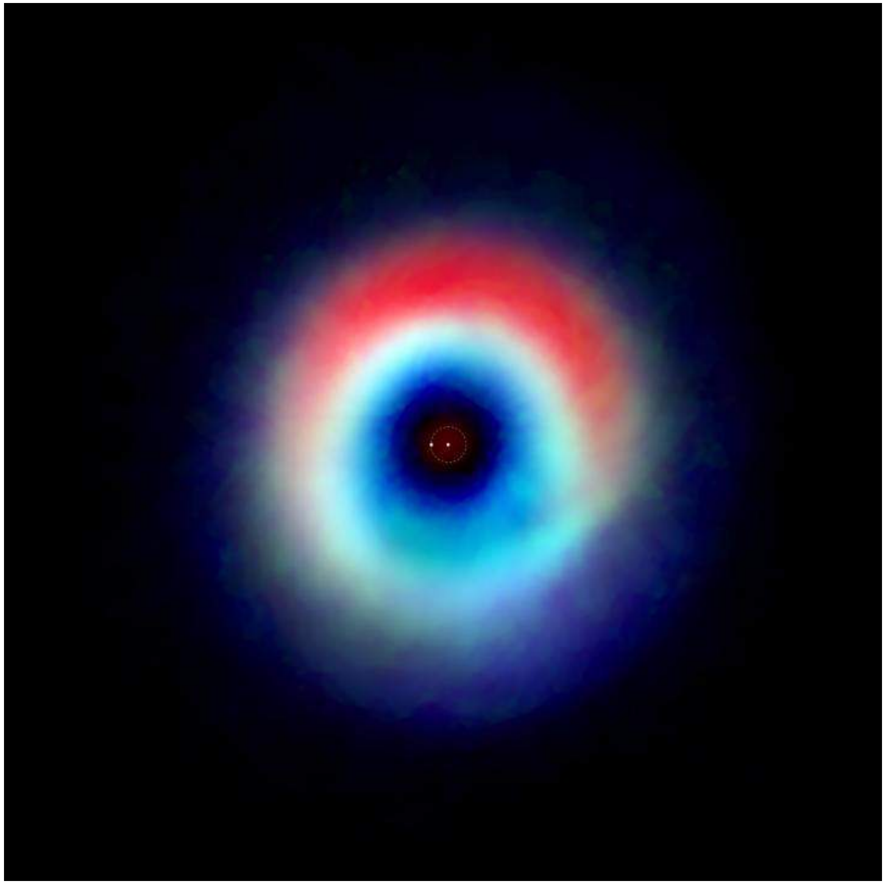
In addition to these stellar dynamical effects, infall of gas onto the binary can also lead to some orbital evolution. Gas may be flung out of the system, acquiring energy (and angular momentum) at the expense of the binary; alternatively, gas may accrete onto the larger hole, causing orbital contraction as the product *Mr* is adiabatically invariant. In either case, the evolution time scale is

$$t_{\rm gas} \sim 10^8 M_8 (\dot{M}/1 M_\odot\, {\rm yr}^{-1})^{-1} \quad {\rm yr} \qquad (5)$$

Begelman, Blandford & Rees 1980 Nature

Disks around proto-stellar Binaries

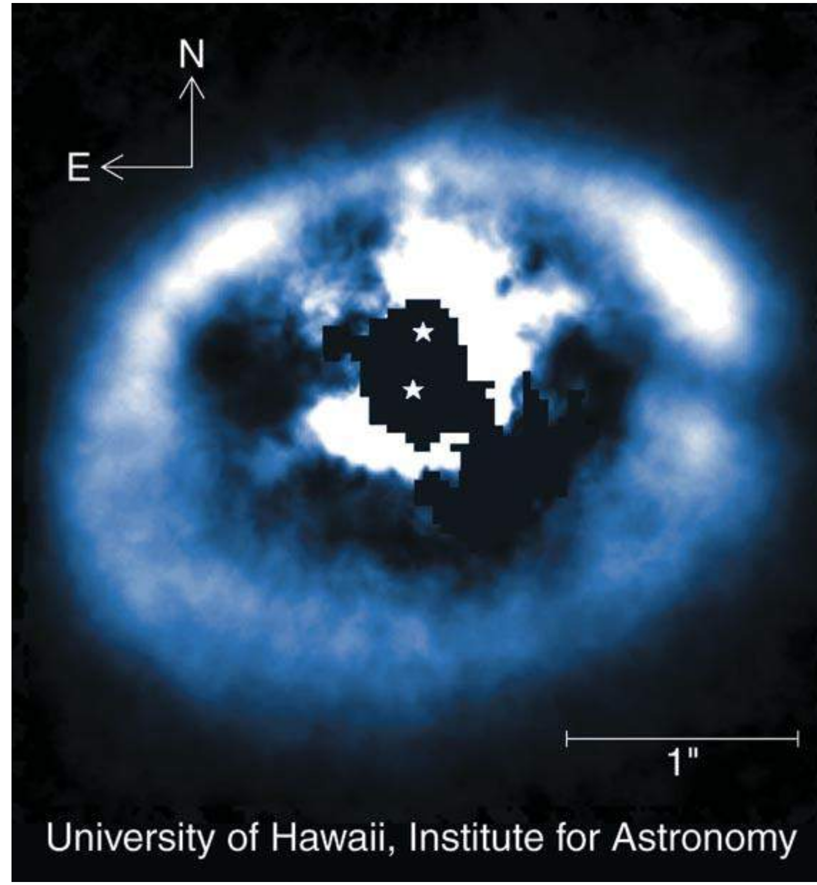
HD 142527



Outer disk : >100 AU
Gap (cavity): 10-100 AU
Inner binary: ~20 AU

A. Isella/ALMA

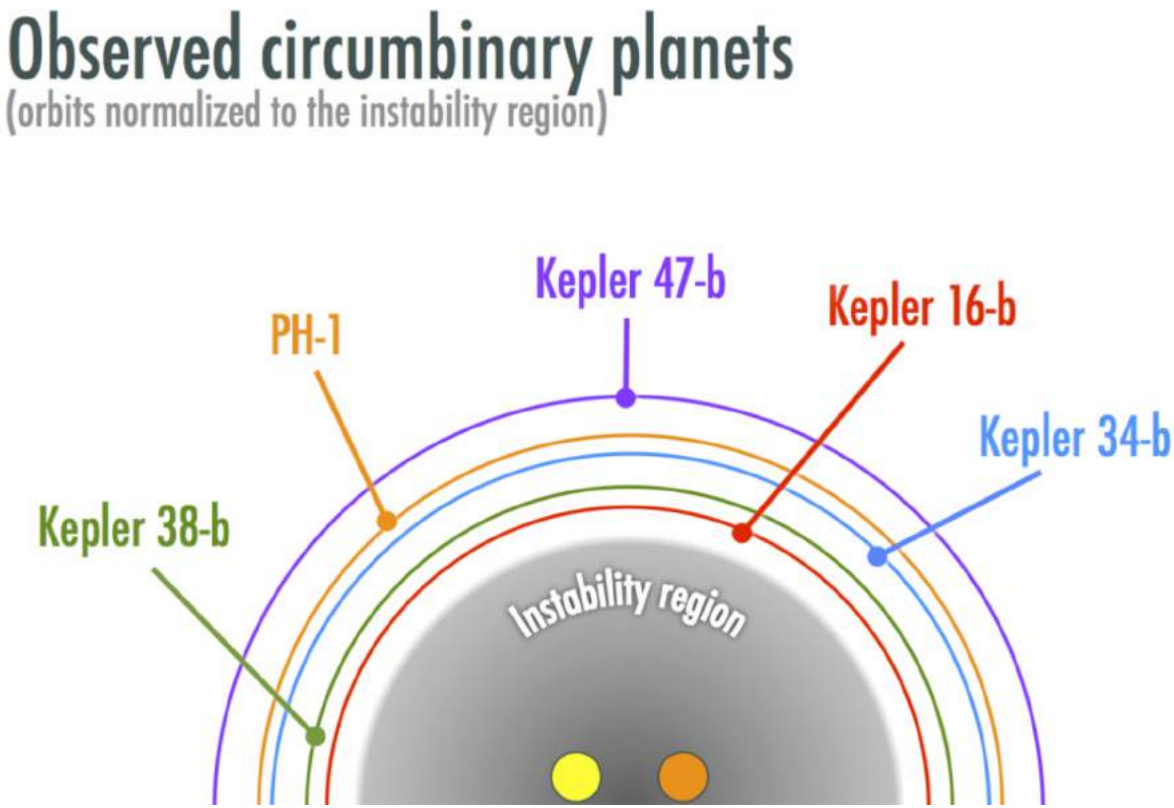
GG Tau



Binary: ~60 AU

Planets Around Binaries

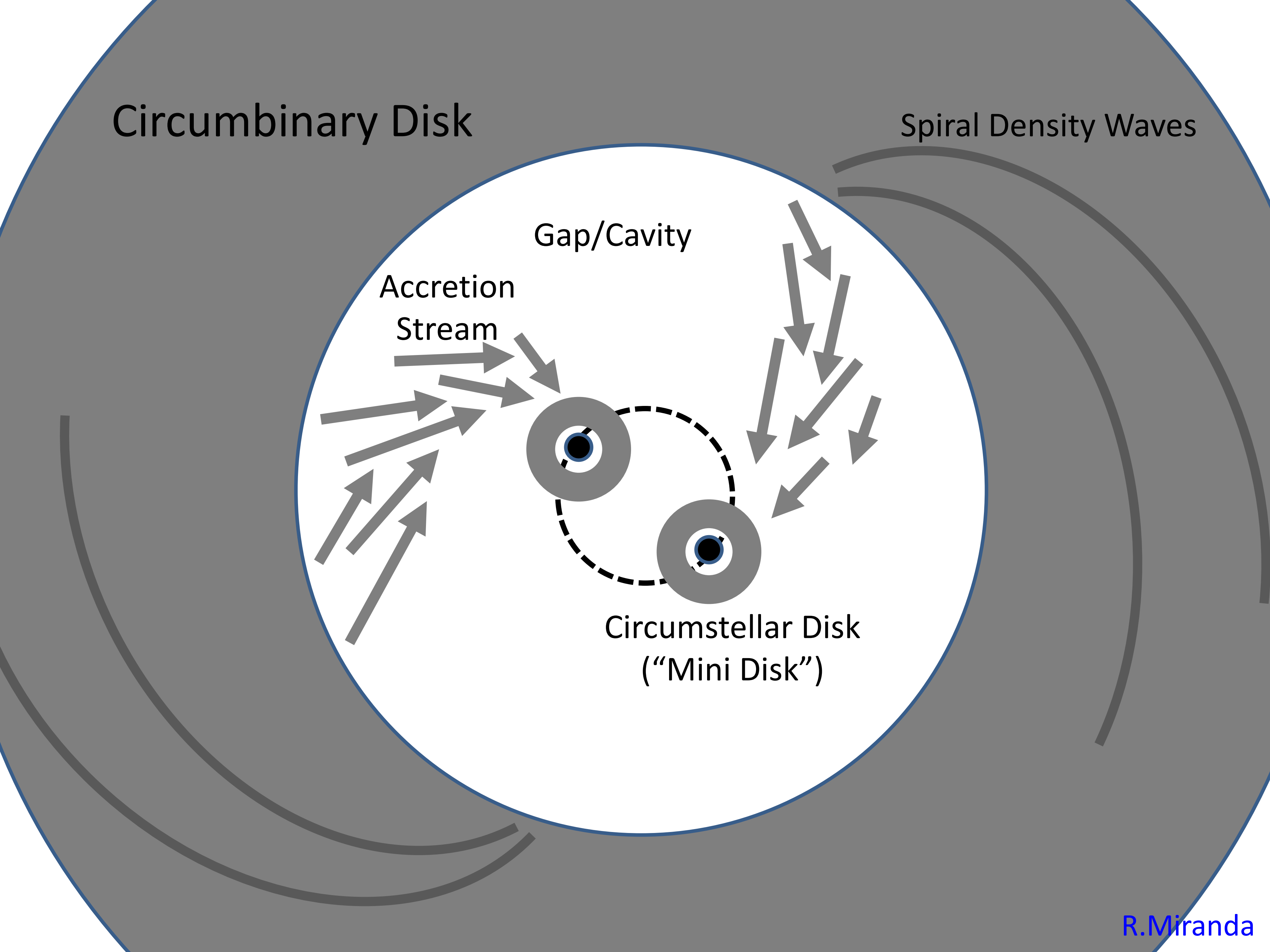
~12 systems found by transit method



Simulations of Circumbinary Accretion

Artymowicz & Lubow 1996; Günther & Kley 2002; MacFadyen & Milosavljević 2008; Cuadra et al.09; Hanawa et al. 2010; de Val-Borro et al. 2011; Roedig et al. 2012; Noble et al.2012; Shi et al. 2012; D'Orazio et al. 2013; Pelupessy & Portegies-Zwart 2013; Farris et al. 2014; Shi & Krolik 2015; Lines et al. 2015; O'Ozario et al. 2016; Ragusa et al. 2016, Munoz & Lai 2016; Miranda, Munoz & Lai 2017; Tang et al. 2017; Bowen et al.2017,19; Munoz, Miranda, Lai 2019; Moody, Shi & Stone 2019; Munoz, Lai et al.2020; Duffell et al.2020;...

A Challenging Problem...


Circumbinary Disk
Spiral Density Waves
Gap/Cavity
Accretion Stream
Circumstellar Disk
("Mini Disk")
R.Miranda

Simulations of Circumbinary Accretion

Artymowicz & Lubow 1996; Günther & Kley 2002; MacFadyen & Milosavljević 2008; Cuadra et al.09; Hanawa et al. 2010; de Val-Borro et al. 2011; Roedig et al. 2012; Noble et al.2012; Shi et al. 2012; D'Orazio et al. 2013; Pelupessy & Portegies-Zwart 2013; Farris et al. 2014; Shi & Krolik 2015; Lines et al. 2015; O'Ozario et al. 2016; Ragusa et al. 2016, Munoz & Lai 2016; Miranda, Munoz & Lai 2017; Tang et al. 2017; Bowen et al.2017,19; Munoz, Miranda, Lai 2019; Moody, Shi & Stone 2019; Munoz, Lai et al.2020; Duffell et al.2020;...

A Challenging Problem…

Many simulations excised the inner "cavity"

Some cover the whole domain: Circumbinary disk → stream → circumsingle disks:

Using finite-volume moving mesh codes:

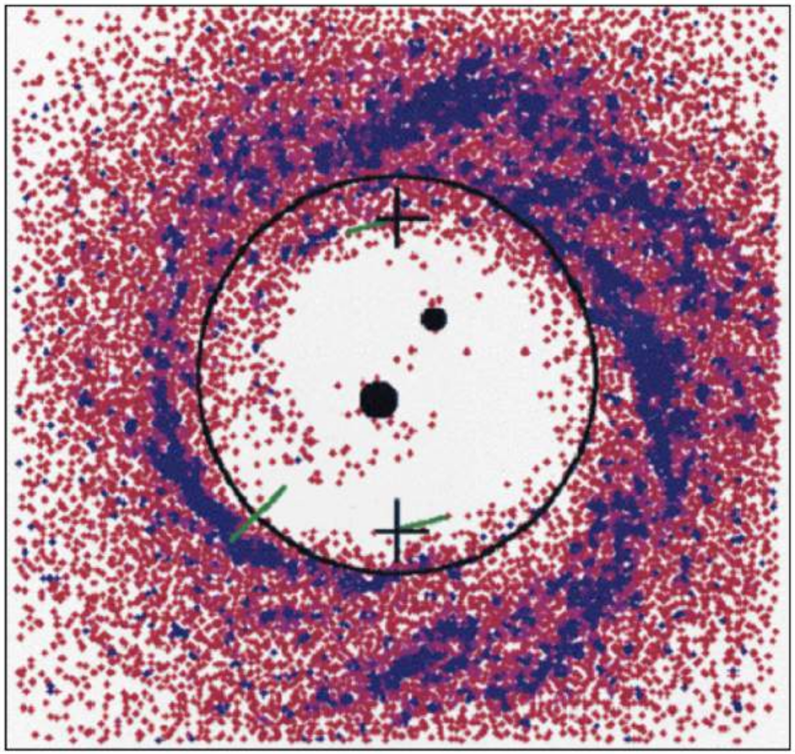
DISCO: Farris, Duffell, MacFadyen, Haiman 2014,15; Tang, MacFadyen, Haiman 2017

AREPO: resolve accretion onto individual body to $0.02a_b$
(Munoz & Lai 2016; Munoz, Miranda & Lai 2019; Munoz, Lai et al 2020)

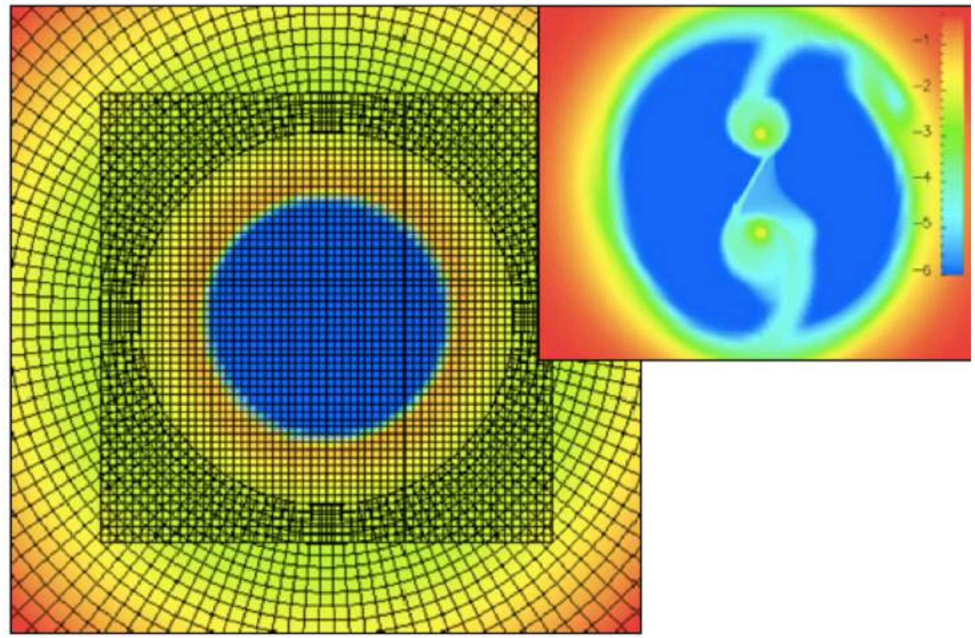
ATHENA++ (Moody, Shi & Stone 2019)

Simulations of Circumbinary Accretion

Artymowicz & Lubow (1996) – SPH



Günther & Kley (2002) – Hybrid grid

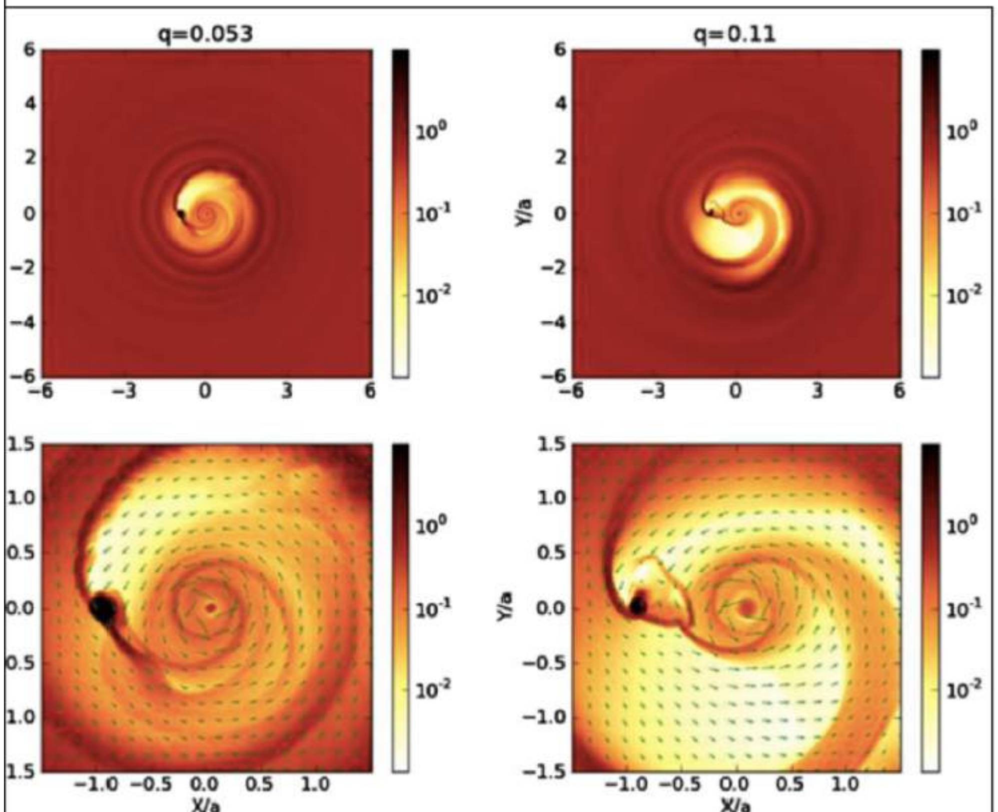


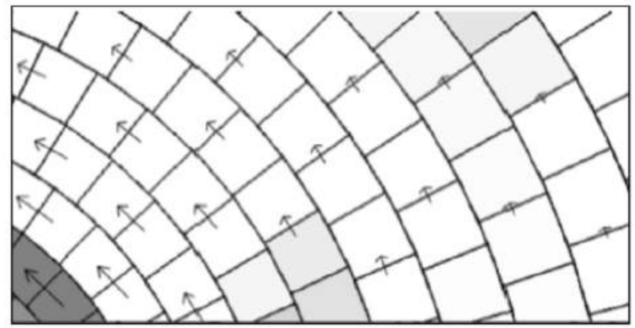
also:
de Val-borro et al. (2011) – cartesian grid
Hanawa et al. (2010) – Nested cartesian

Simulations of Circumbinary Accretion

Finite-volume moving mesh code

Farris et al. (2014) – moving rings grid





Duffell & MacFadyen (2012) – DISCO code

What we do:

Diego Munoz
(Harvard PhD’13->Cornell
-> Northwestern)

Ryan Miranda
(Cornell PhD’17->IAS)

Munoz & DL 2016, ApJ
Miranda, Munoz & DL 2017, MNRAS
Munoz, Miranda & DL 2019
Munoz, DL et al 2020

Goals:

-- Accretion onto circular/eccentric binaries: circumbinary->circumstellar disks

resolve accretion onto individual body to $0.02a_b$

-- Short-term & long-term accretion variabilities

-- Disk structure and dynamics (eccentricity, precession)

-- Angular momentum transfer between binary and disk

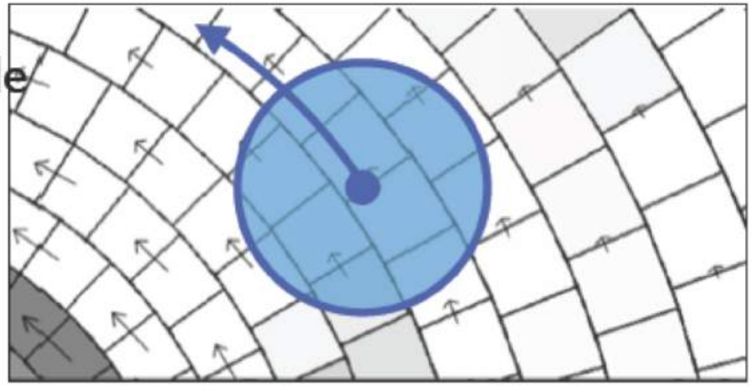
Method:

-- Solve viscous hydrodynamic equations in 2D

-- alpha viscosity, (locally) isothermal sound speed

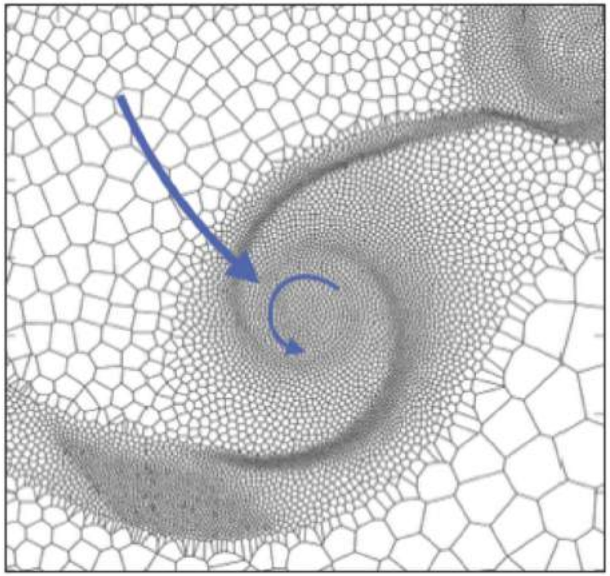
AREPO (Springel, 2010)

Quasi-Lagrangian, moving-mesh code



Main features

- Shock-capturing, finite-volume method
- Unstructured moving grid
- Equations solved in the moving-frame
- Quasi-Lagrangian, adaptive resolution



Applied to disks by
Muñoz et al 2013,2014,2015
(see also Pakmor et al. 2015)

Summary of Key Results

- Short-term variabilities
- Long-term variabilities
- Angular momentum transfer and binary evolution

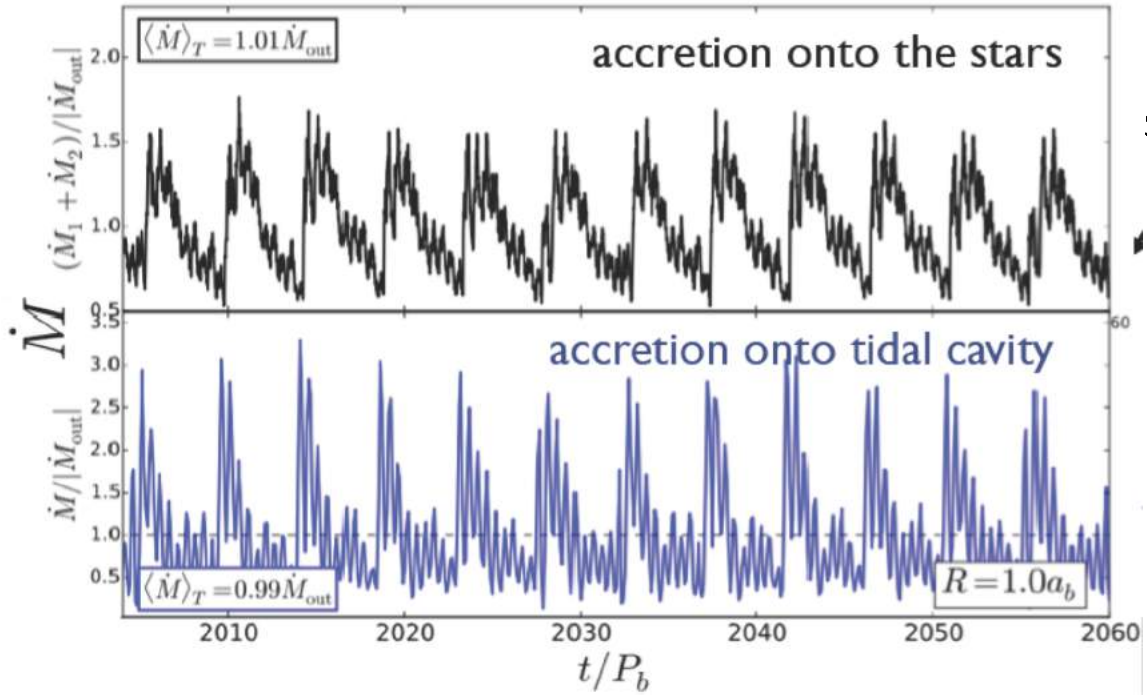
Binary mass ratio $q \sim 1$

Disk $H/r \sim 0.1$, $\alpha = 0.05 - 0.1$ (down to 0.01)

Short-term (~P_b) Accretion Variabilities

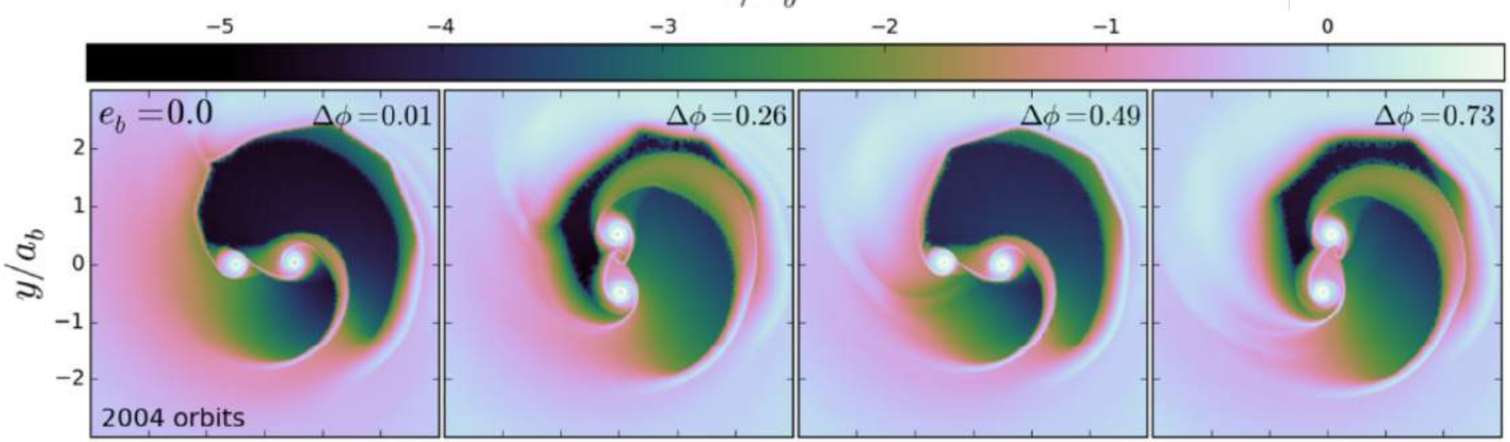
For $e_b \lesssim 0.05$: $\dot{M}(=\dot{M}_1+\dot{M}_2)$ varies at $\sim 5P_b$ (Kepler period at r_{in} ~ $3a_b$)

e_b=0



Known from MacFadyen & Milosavljevic 08, Shi et al.12, D'Orazio et al.13, Farris et al.14

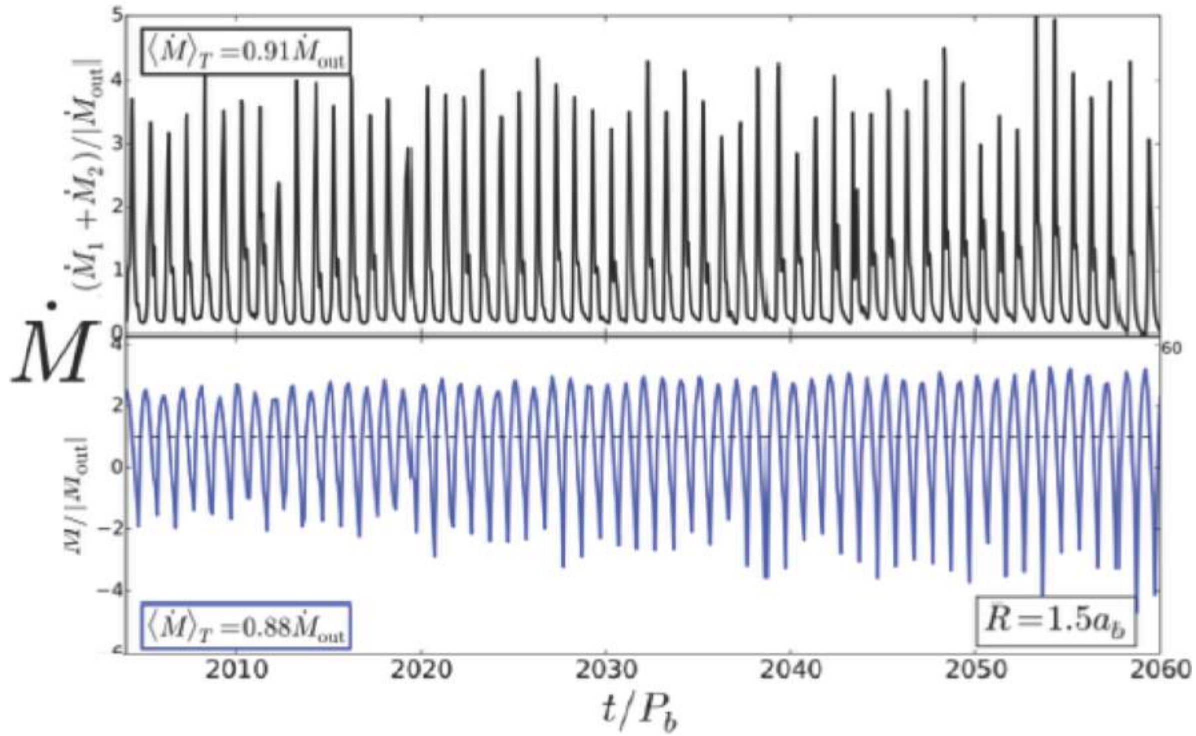
Munoz & DL 16



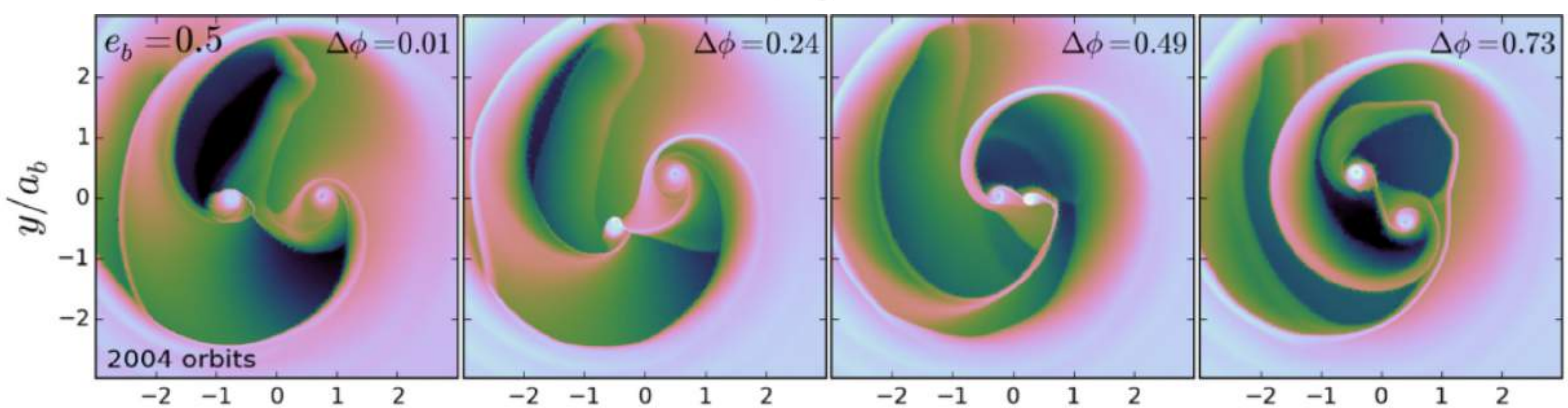
Short-term (~P_b) Accretion Variabilities

For $e_b \gtrsim 0.05$: $\dot{M} = \dot{M}_1 + \dot{M}_2$ varies at $\simeq P_b$

e_b=0.5



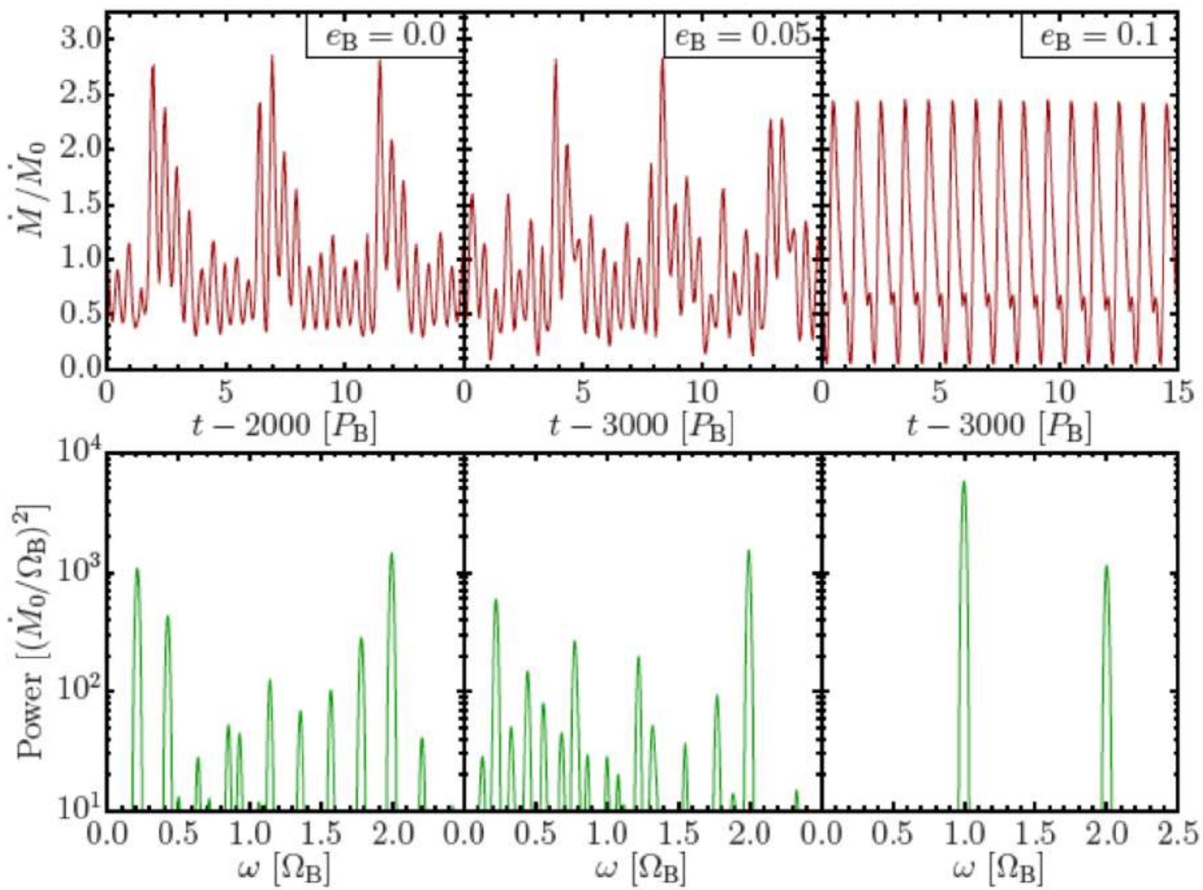
Munoz & DL 16



Short-term (~P_b) Accretion Variabilities

For $e_b \lesssim 0.05$: $\dot{M}(=\dot{M}_1+\dot{M}_2)$ varies at $\sim 5P_b$
For $e_b \gtrsim 0.05$: $\dot{M}=\dot{M}_1+\dot{M}_2$ varies at $\simeq P_b$

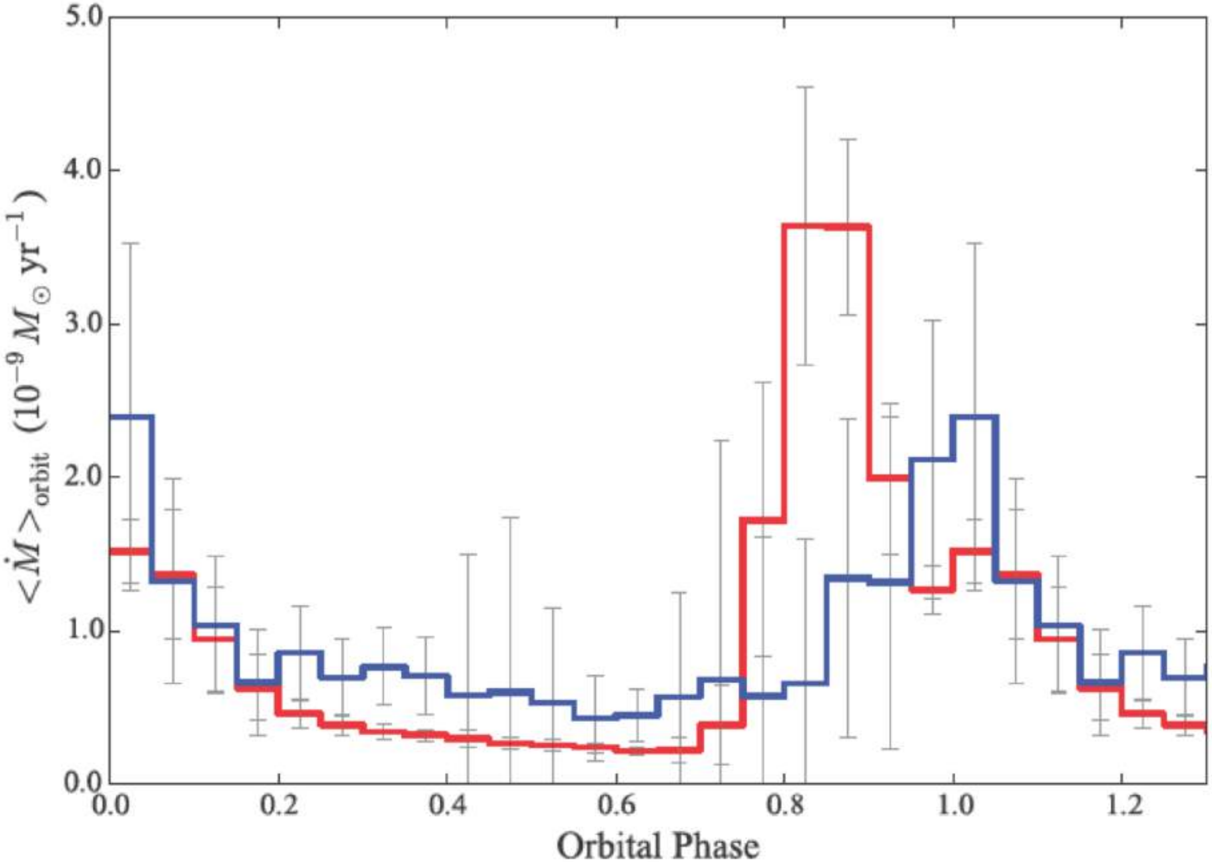
Power spectrum



Miranda, Munoz & DL 17

Compared to Observations: Pulsed Accretion onto DQ Tau (P_b=15.8 d, e_b=0.56)

U-band photometry of DQ Tau for >10 orbital periods

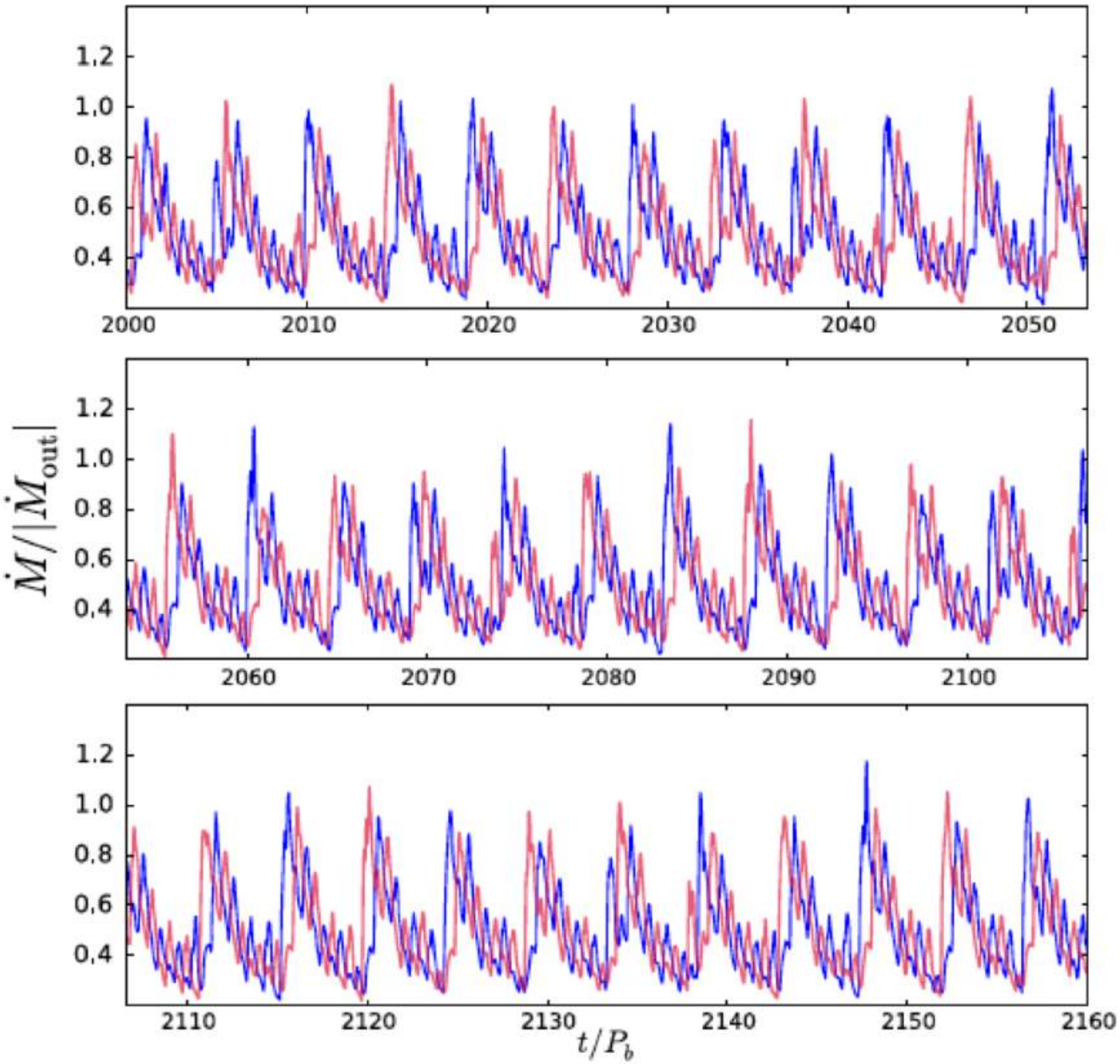


red: simulation (D. Munoz)
blue: observations

➔ Can resolve the effective size of stars

Tofflemire, Mathieu et al. 2017

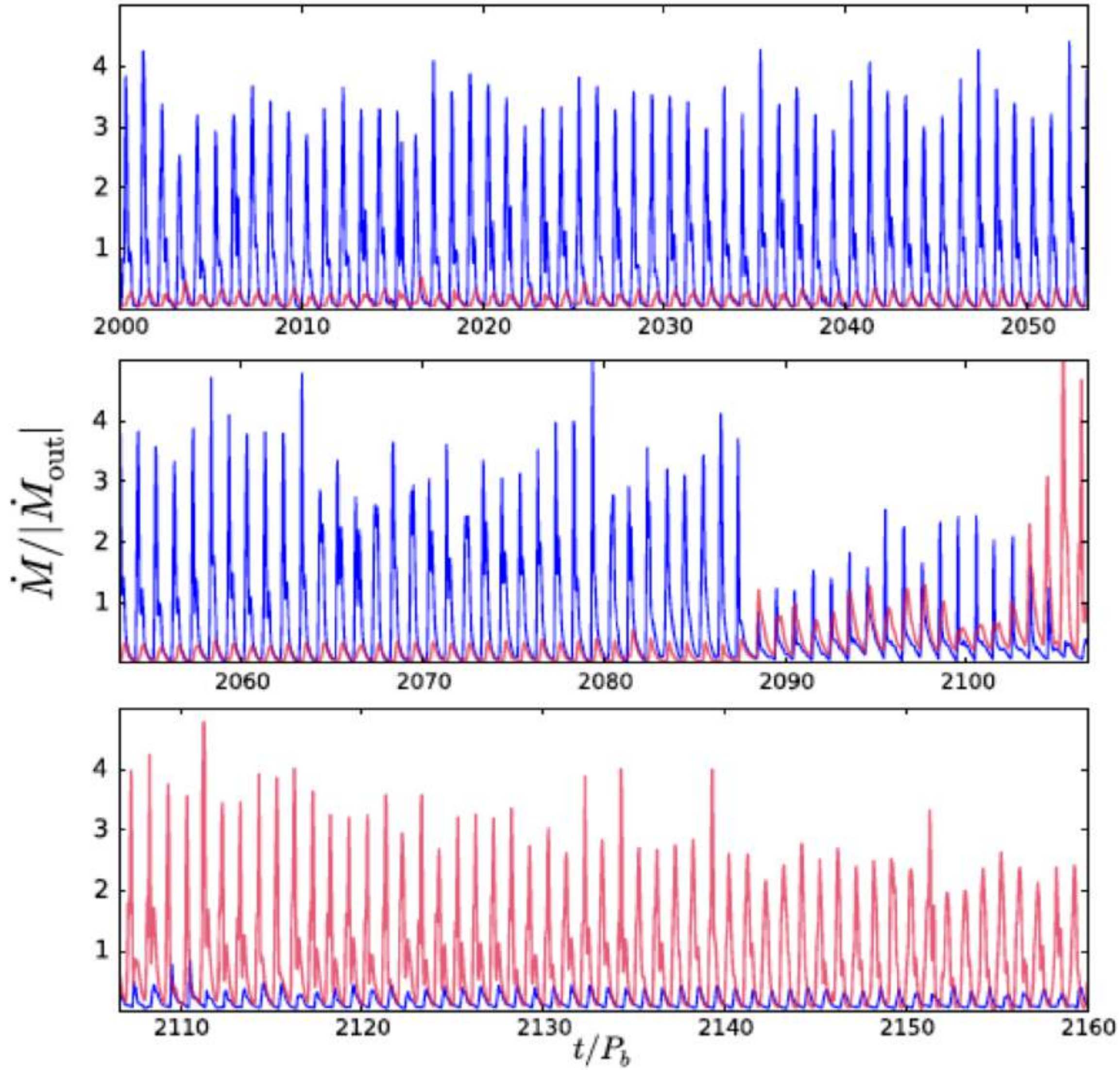
Long-Term Variability:



e_b=0
q_b=1

$$\dot{M}_1 \simeq \dot{M}_2$$

Long-Term Variability: Symmetry Breaking



e_b=0.5
q_b=1

Switch between

$\dot{M}_1 \gtrsim 20\dot{M}_2$

and

$\dot{M}_2 \gtrsim 20\dot{M}_1$

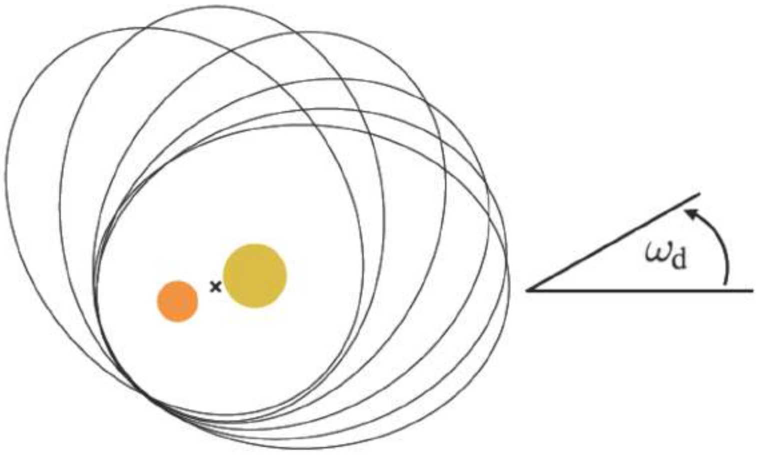
every ~200 P_b

Single AGN with binary BHs ?

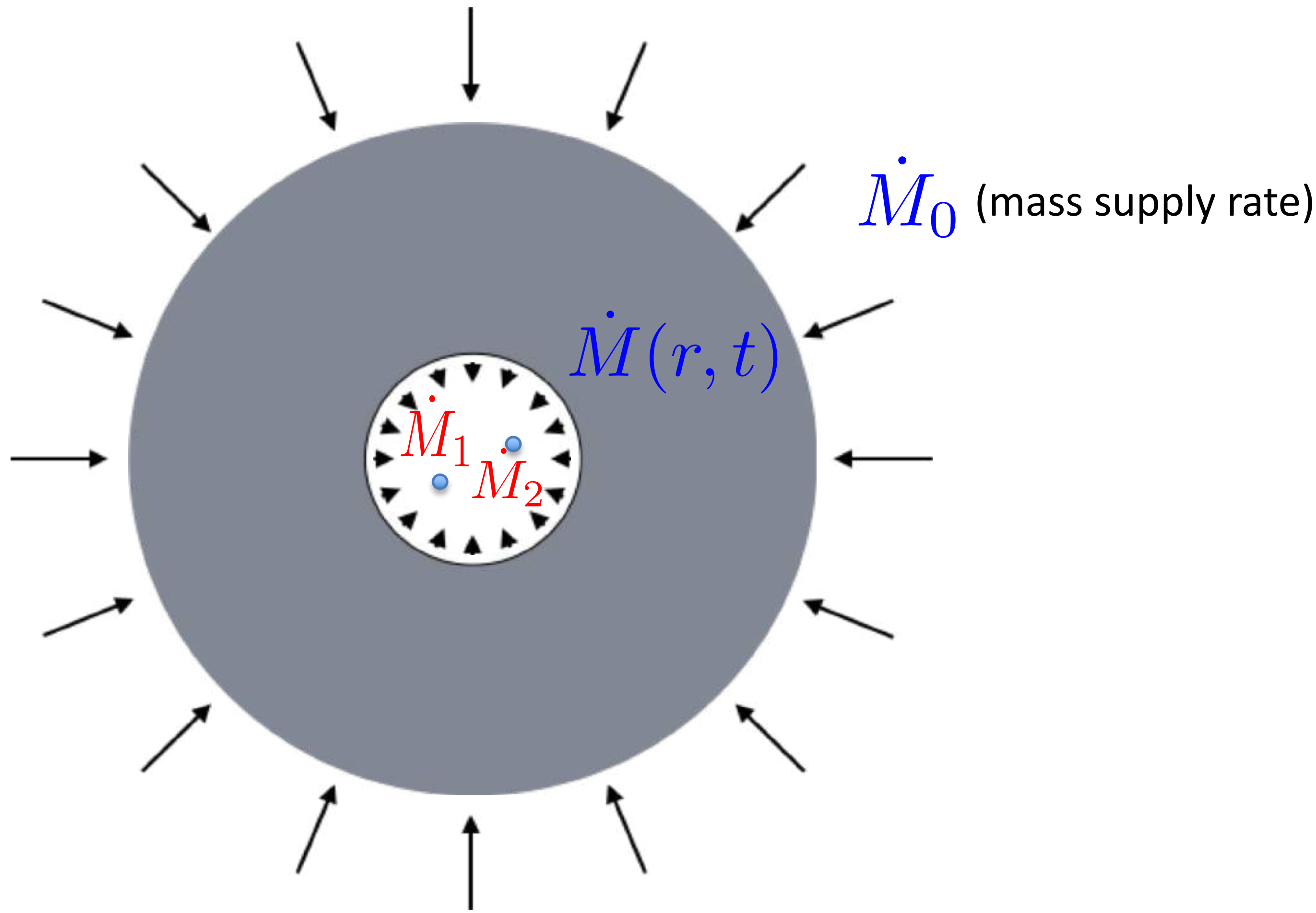
Apsidal precession of eccentric disk around the binary

$$\dot{\omega}_d \simeq \frac{3\Omega_b}{4} \frac{q_b}{(1+q_b)^2}\left(1+\frac{3}{2}e_b^2\right)\left(\frac{a_b}{R}\right)^{7/2}$$
$$\sim 0.006\,\Omega_b\left(\frac{3a_b}{R}\right)^{7/2},$$

Precession period 200-300 P_b



Angular Momentum Transfer to Binary and Long-term Orbital Evolution



$\dot{M}(r,t)$, $\dot{M}_1$, $\dot{M}_2$ are highly variable

Quasi-Steady State: $\langle \dot{M}(r,t) \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_2 \rangle = \dot{M}_0$

Direct computation of torque on the binary

Gravitational torque from all gas
+ Accretion torque (due momentum of accreting gas onto each star)

$$\dot{J}_b = (\dot{L}_b)_{\rm grav} + (\dot{L}_b)_{\rm acc} + (\dot{S}_1)_{\rm acc} + (\dot{S}_2)_{\rm acc}$$

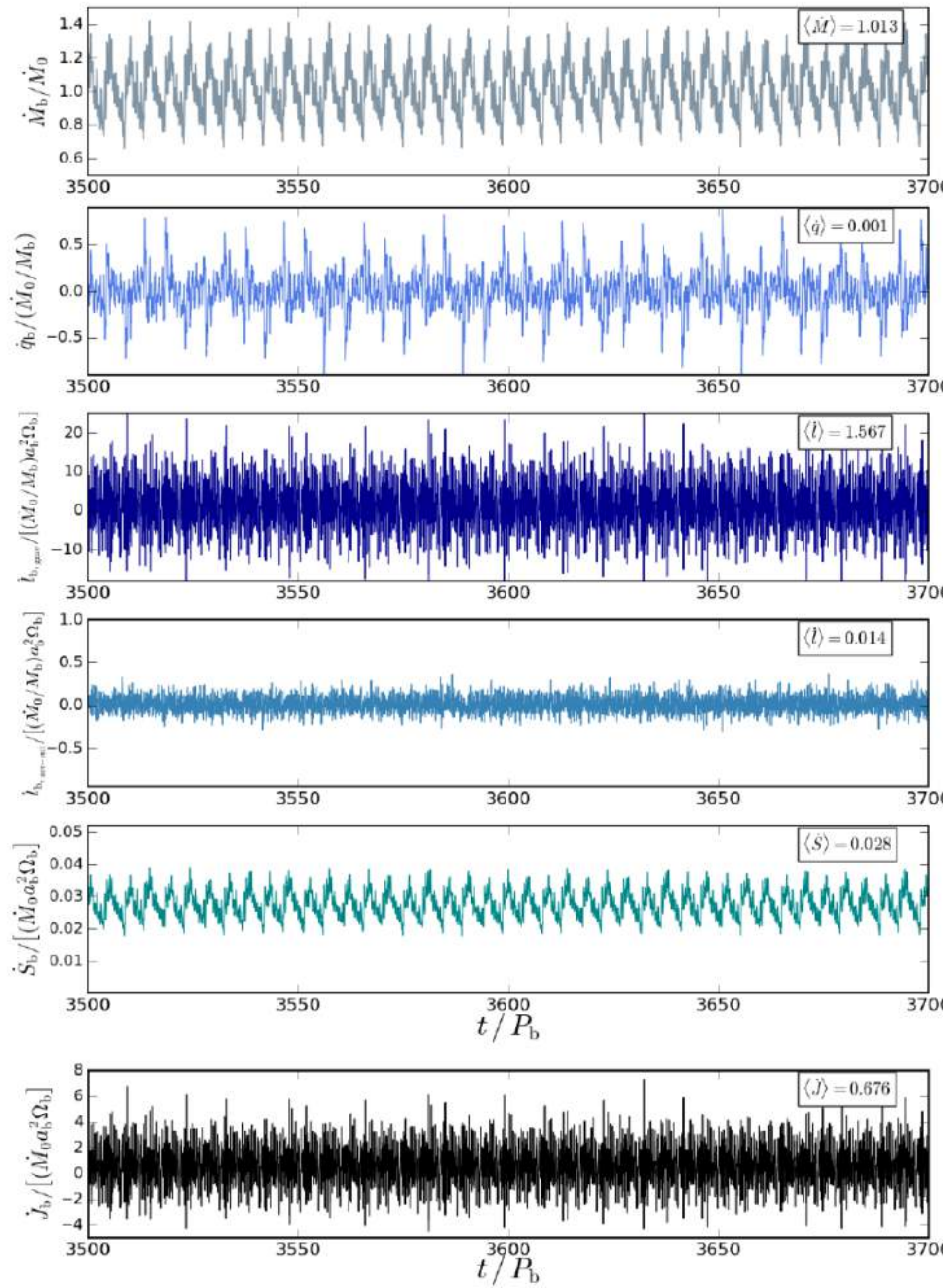


Figure 2. The five different contributions to angular momentum change and its combined effect $\dot{J}_b$. From top to bottom $\dot{M}_b$, $\dot{q}_b$, $\dot{l}_{b,grav}$, $\dot{l}_{b,acc}$ and $\dot{S}_b$ (see Section 2.2.1); and their combined effect $\dot{J}_b$ (bottom panel). In steady state, $\langle \dot{M}_b \rangle \approx \dot{M}_0$ and $\langle \dot{J}_b \rangle \approx 0.676 \dot{M}_0 \Omega_b a_b^2$. Each time series is approximately stationary, and only ~ 30 binary orbits are needed to capture their behavior. The time sampling interval in each panel is $\approx 0.02 P_b$. The accretion eigenvalue in this case is $l_0 \equiv \langle \dot{M}_b \rangle / \langle \dot{J}_b \rangle \approx 0.67 \Omega_b a_b^2$.

Direct computation of torque on the binary

Gravitational torque from all gas
+ Accretion torque (due momentum of accreting gas onto each star)

$$\dot{J}_b = (\dot{L}_b)_{\rm grav} + (\dot{L}_b)_{\rm acc} + (\dot{S}_1)_{\rm acc} + (\dot{S}_2)_{\rm acc}$$

$$l_0 \equiv \frac{\langle \dot{J}_b \rangle}{\langle \dot{M}_b \rangle} = 0.68 a_b^2 \Omega_b$$

e_b=0

Munoz, Miranda & Lai 2019

Angular momentum transfer to the binary per unit accreted mass

Angular Momentum Current (Transfer Rate) in CBD

$$\dot{J}(r,t) = \dot{J}_{\rm adv} - \dot{J}_{\rm visc} - T_{\rm grav}^{>r}$$

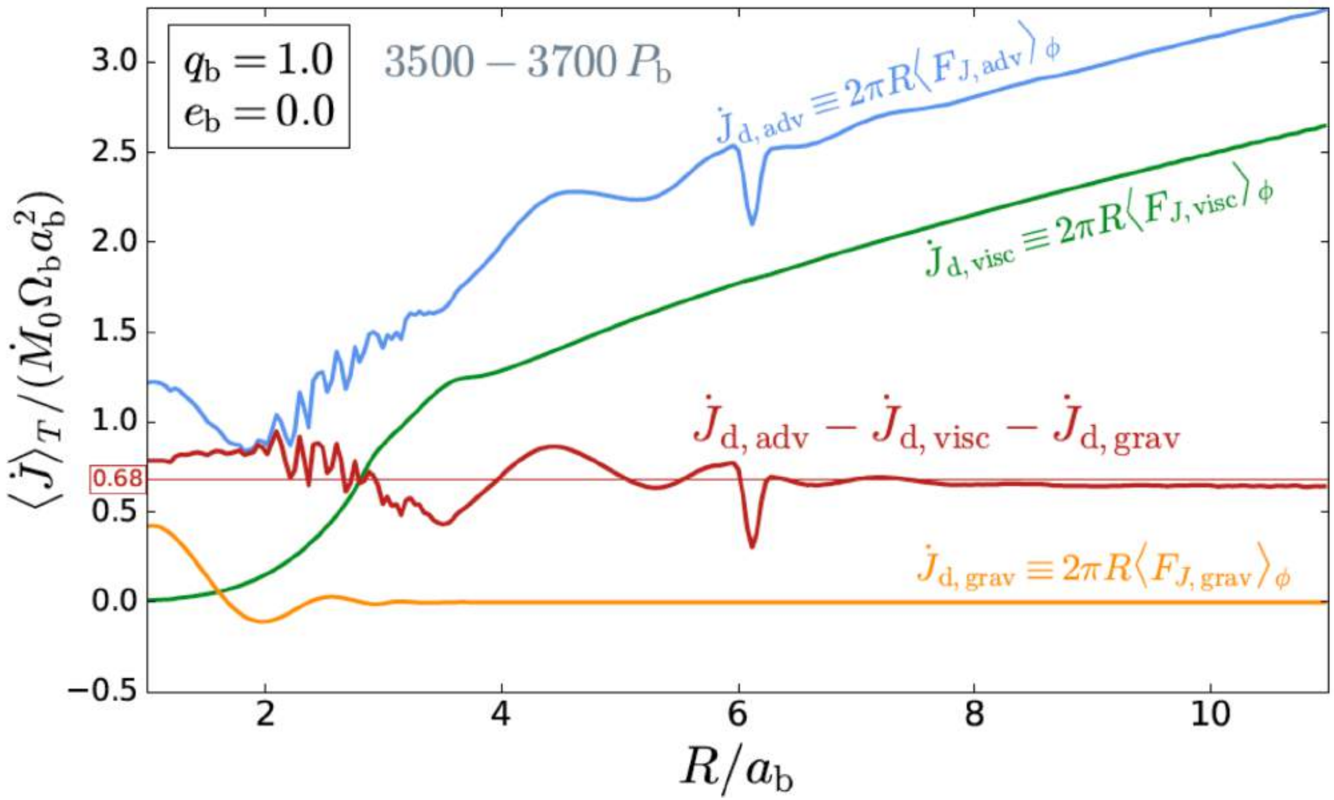
$$\dot{J}_{\rm adv} = -\oint r^2 \Sigma u_r u_\phi {\rm d}\phi$$

$$\dot{J}_{\rm visc} = -\oint r^3 \nu \Sigma \left[\frac{\partial}{\partial r}\left(\frac{u_\phi}{r}\right) + \frac{1}{r^2}\frac{\partial u_{\rm r}}{\partial \phi}\right] {\rm d}\phi$$

$$T_{\rm grav}^{>r} = \int_r^{r_{\rm out}} \frac{{\rm d}T_{\rm grav}}{{\rm d}r}{\rm d}r, \qquad \frac{{\rm d}T_{\rm grav}}{{\rm d}r} = -\oint r\Sigma \frac{\partial \Phi}{\partial \phi}{\rm d}\phi$$

Angular Momentum Current (Transfer Rate) in CBD

$$\dot{J}(r,t) = \dot{J}_{\rm adv} - \dot{J}_{\rm visc} - T^{>r}_{\rm grav}$$



Munoz, Miranda & Lai 19

Recap: Although the accretion flow is highly dynamical, the system reaches quasi-steady state:

$$\langle \dot{M}(r,t) \rangle = \langle \dot{M}_1 \rangle + \langle \dot{M}_2 \rangle = \dot{M}_0$$

$$\langle \dot{J}_b \rangle \simeq \langle \dot{J}_{\rm disk}(r,t) \rangle = {\rm const}$$

Angular momentum transferred to the binary per unit accreted mass:

$$l_0 \equiv \frac{\langle \dot{J}_b \rangle}{\langle \dot{M}_b \rangle} = 0.68 a_b^2 \Omega_b$$

Implication of $\dot{J}_B > 0$:

For $q = 1,\ e_B = 0$ binary:

$$\dot{J}_B = \dot{M}_B l_0 \qquad l_0 \simeq 0.68\, l_B \qquad \text{where } l_B = a_B^2 \Omega_B$$

$$\rightarrow \quad \frac{\dot{a}_\mathrm{B}}{a_\mathrm{B}} = 8\left(\frac{l_0}{l_\mathrm{B}} - \frac{3}{8}\right)\frac{\dot{M}_\mathrm{B}}{M_\mathrm{B}}$$

Binaries can expand due to circumbinary accretion !

For e_B=0:

$$\frac{\dot{a}_B}{a_B} \simeq 2.68 \frac{\dot{M}_B}{M_B}$$

Munoz, Miranda & Lai 2019

Implication of $\dot{J}_B > 0$:

For $q = 1$, $e_B = 0$ binary:

$$\dot{J}_B = \dot{M}_B l_0 \qquad l_0 \simeq 0.68\, l_B \qquad \text{where } l_B = a_B^2 \Omega_B$$

$$\rightarrow \quad \frac{\dot{a}_\mathrm{B}}{a_\mathrm{B}} = 8\left(\frac{l_0}{l_\mathrm{B}} - \frac{3}{8}\right)\frac{\dot{M}_\mathrm{B}}{M_\mathrm{B}}$$

Binaries can expand due to circumbinary accretion !

For e_B=0: $$\frac{\dot{a}_B}{a_B} \simeq 2.68 \frac{\dot{M}_B}{M_B}$$

For e_B=0.6: directly compute $\langle \dot{E}_B \rangle$ and $\langle \dot{J}_B \rangle$ from simulation

$$\frac{\dot{a}_B}{a_B} \simeq 0.38 \frac{\dot{M}_B}{M_B} \qquad \dot{e}_B \simeq -2.34 \frac{\dot{M}_B}{M_B}$$

Munoz, Miranda & Lai 2019

Unequal-mass binaries

$q = M_2/M_1 < 1$

$e_b = 0$

Munoz, DL +2020

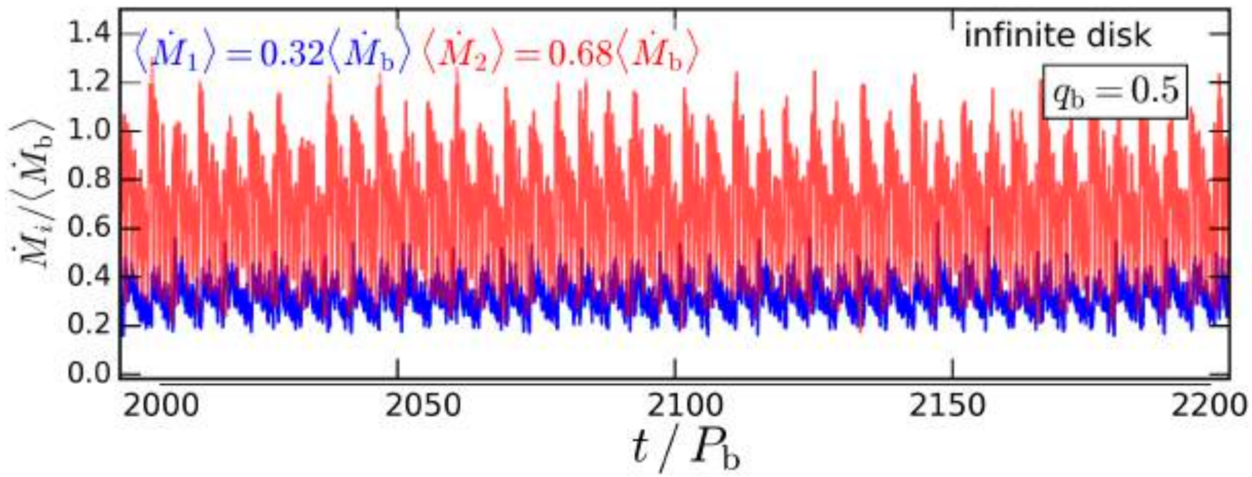
Unequal-mass binaries

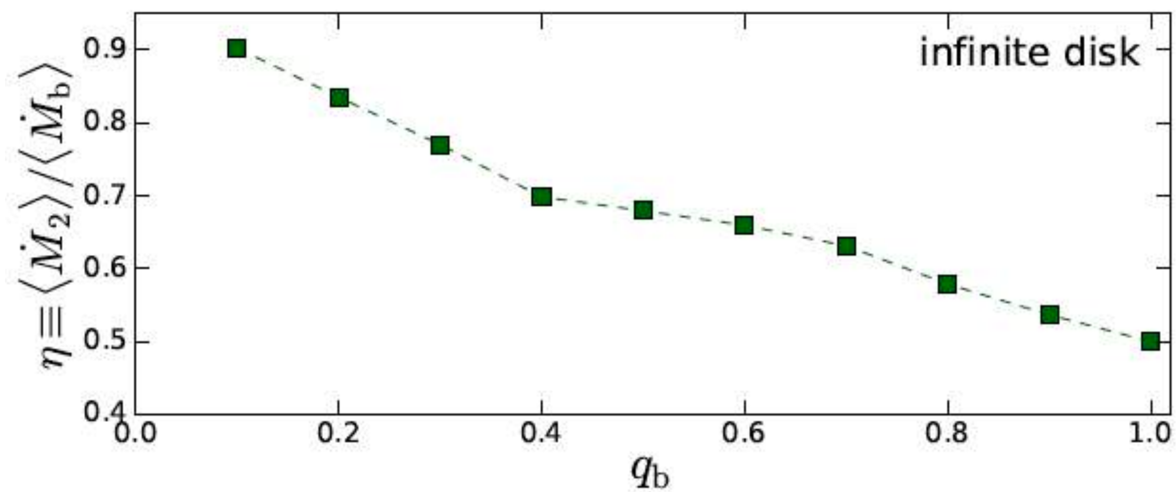
$$q = M_2/M_1 < 1$$
$$e_b = 0$$

Munoz, DL +2020

-- Low-mass component accretes more

See also Bate+2000; Farris+2014





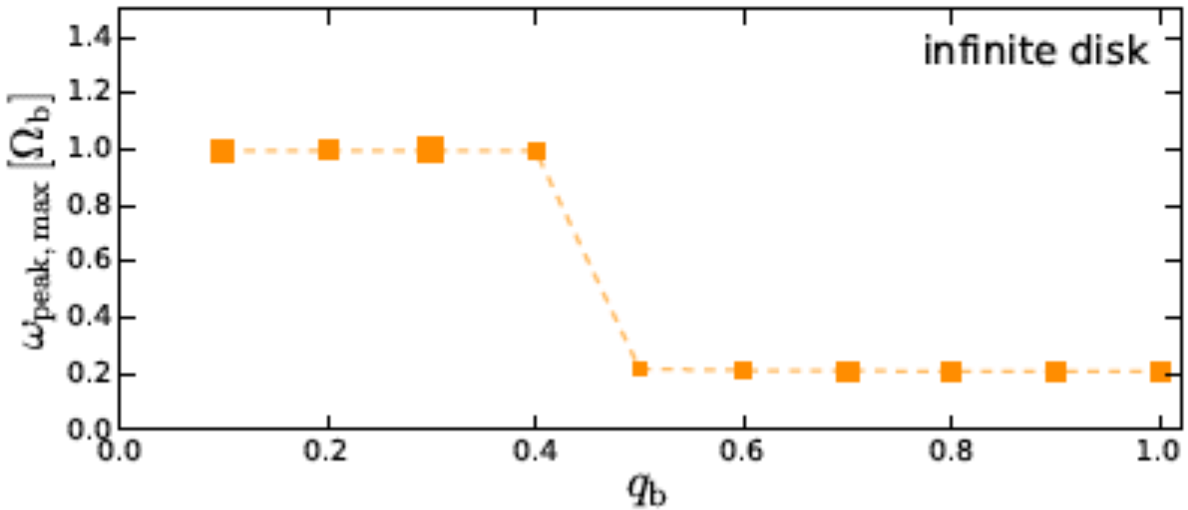
Unequal-mass binaries

$q = M_2/M_1 < 1$

$e_b = 0$

Munoz, DL +2020

-- Dominant variability frequency

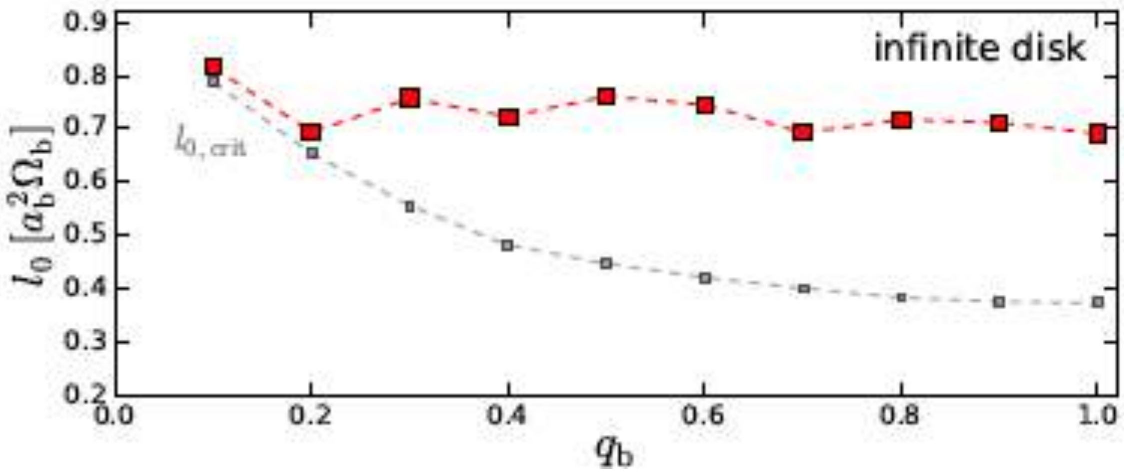


Unequal-mass binaries

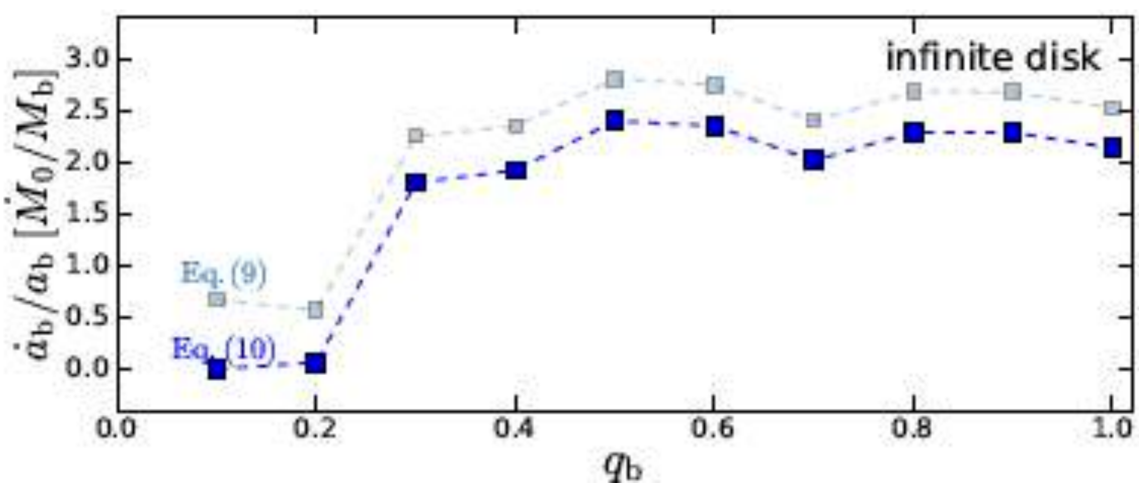
$$q = M_2/M_1 < 1$$
$$e_b = 0$$

Munoz, DL +2020

-- Angular momentum transfer



$$\frac{\dot{L}_{\rm b}}{L_{\rm b}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_{\rm b}}{M_{\rm b}} + \frac{1}{2}\frac{\dot{a}_{\rm b}}{a_{\rm b}}$$



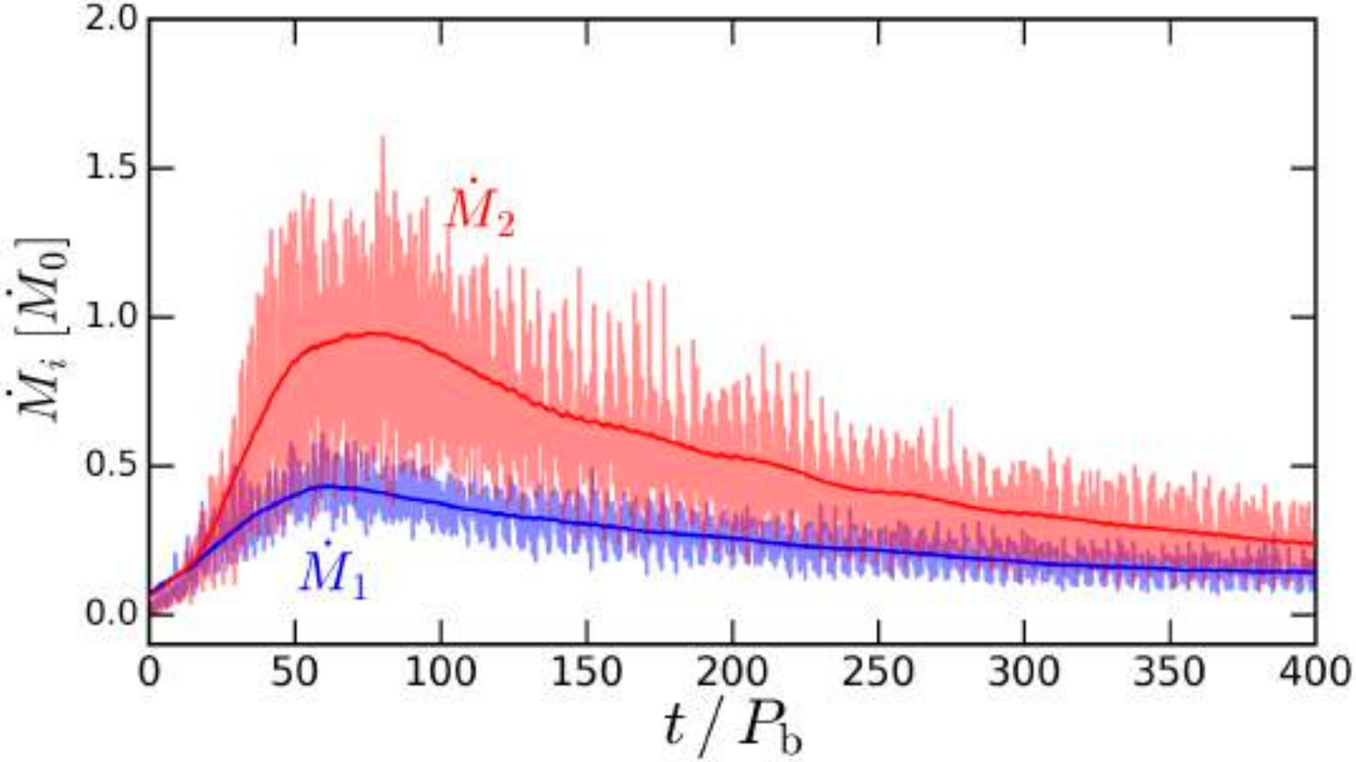
Previous claims of binary decay due to cicumbinary disk ?

-- Numerical simulations:

Mass conservation ? (e.g., the claim of mass pile-up)

Transient vs quasi-steady state?

Binary accretion from a finite disk/torus

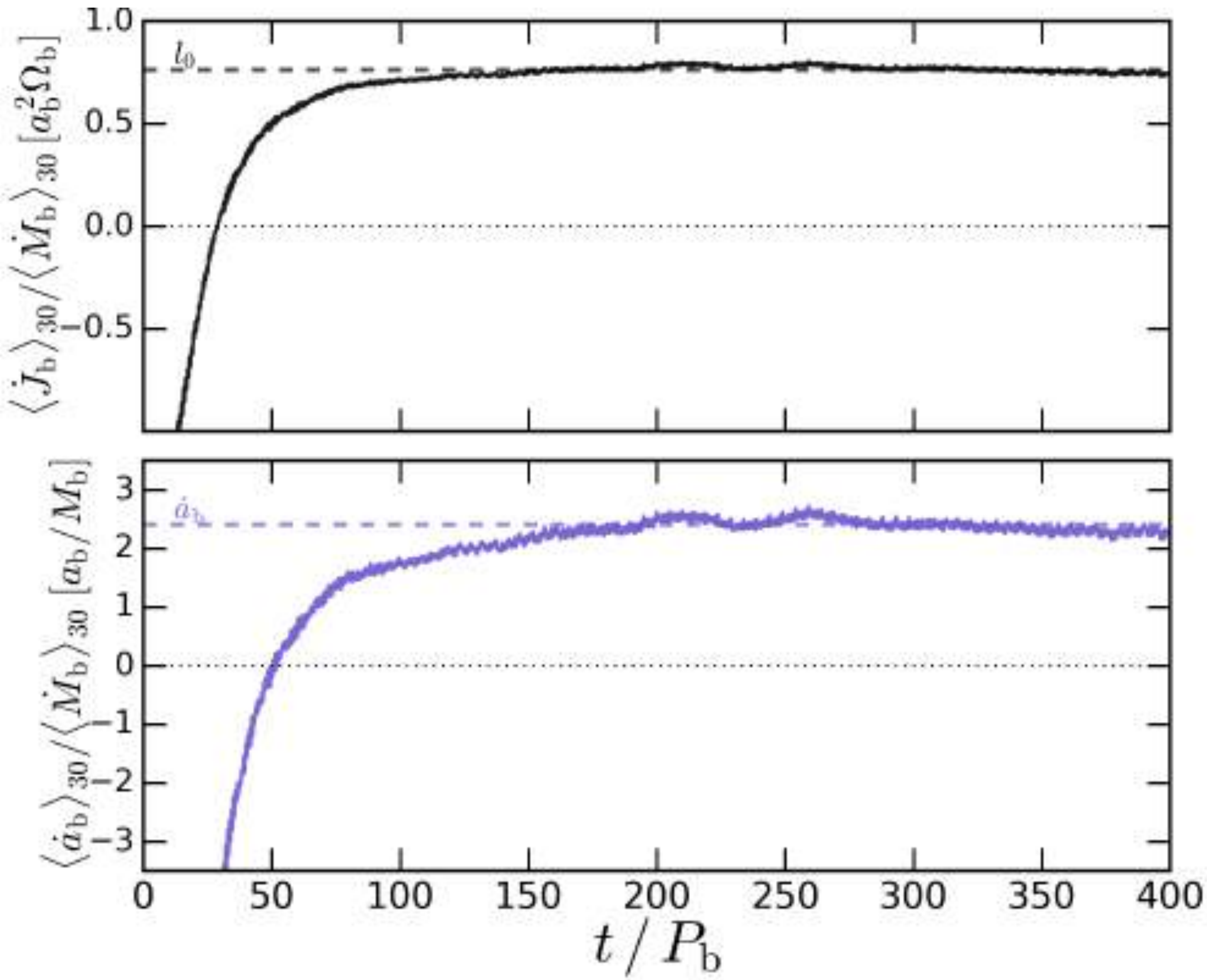


Munoz, DL + 2020

Binary accretion from a finite disk/torus

Angular momentum transfer per unit (accreted) mass

Orbital expansion rate



Munoz, DL + 2020

Is binary decay possible?

e.g. Supermassive BH Binaries, final pc problem
e.g. Formation of close (AU) stellar binaries?

Is binary decay possible?

e.g. Supermassive BH Binaries, final pc problem
e.g. Formation of close (AU) stellar binaries?

Yes…

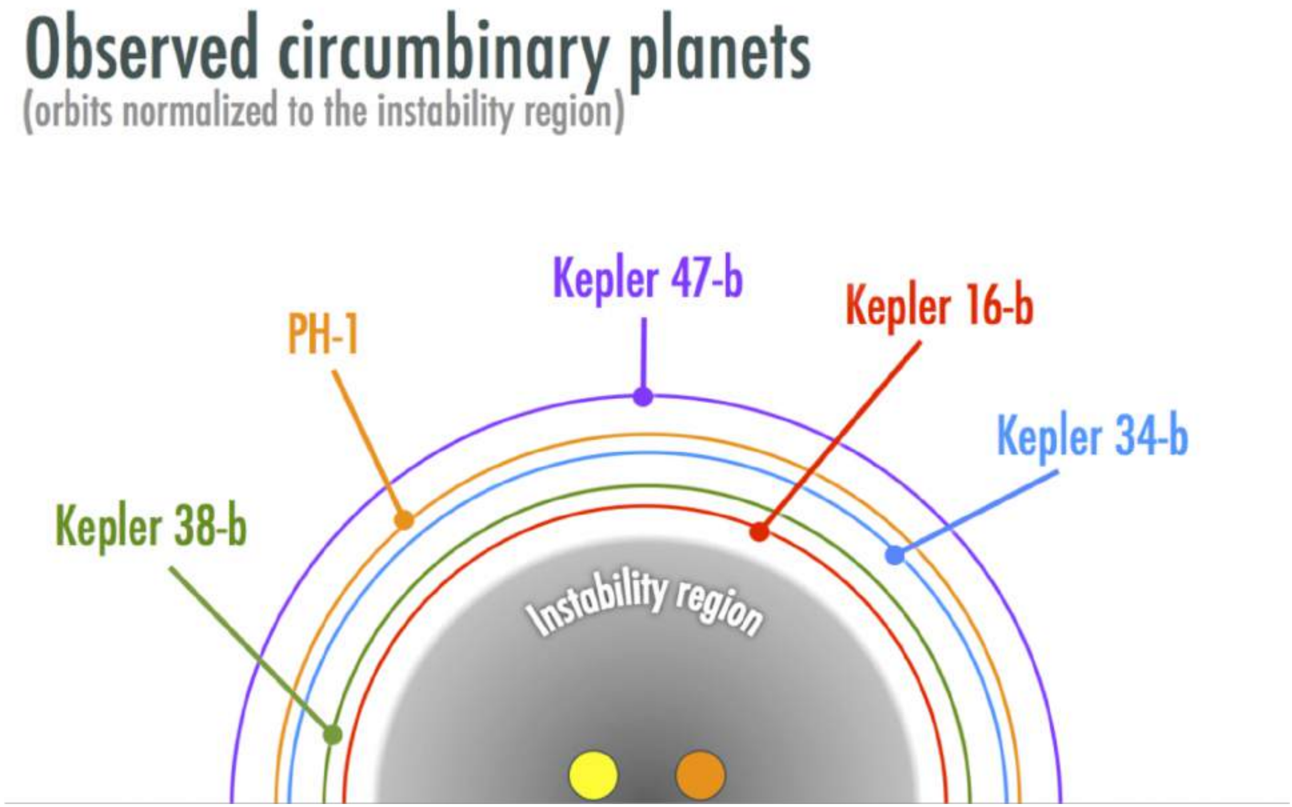
e.g. $M_1/M_2>1$, large (locally) massive disk:

$$\Sigma \pi a_b^2 \gtrsim M_2$$

e.g. Gas gets ejected in outflow…

Implications for Planet Formation Around Binaries

Many observed circumbinary planets are close to instability limit



Implications for Planet Formation Around Binaries

-- Planetesimal growth is likely suppressed

At $r \sim 3\text{-}4\, a_b$, disk $e \sim 0.05\text{-}0.2$ ➔

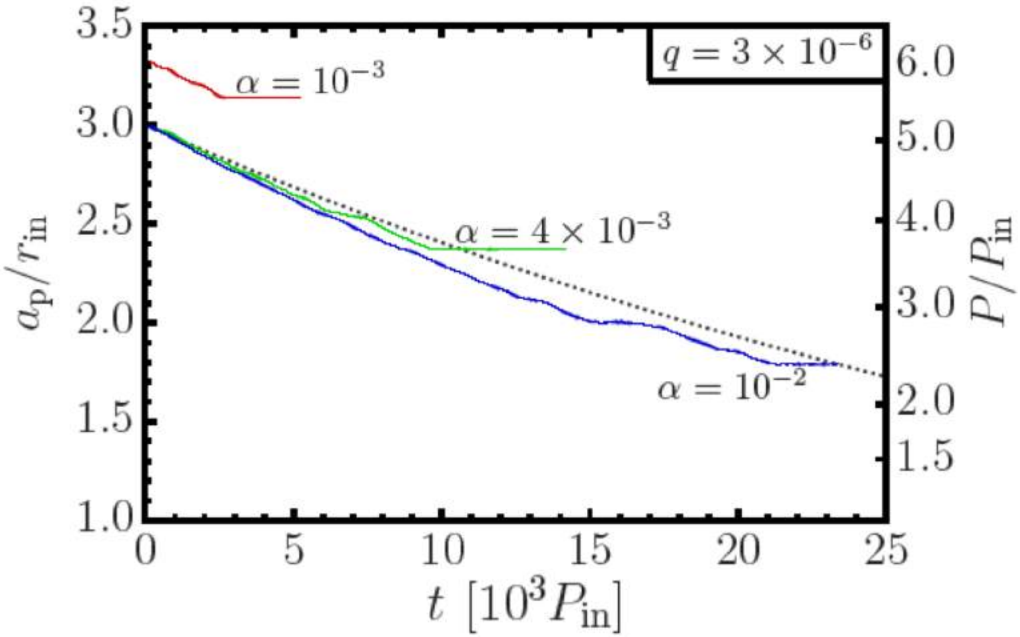
relative velocity of planetesimals $\sim eV_k \sim 5$ km/s (at 0.2AU) >> $v_{esc} \sim 10$ m/s (10 km body)

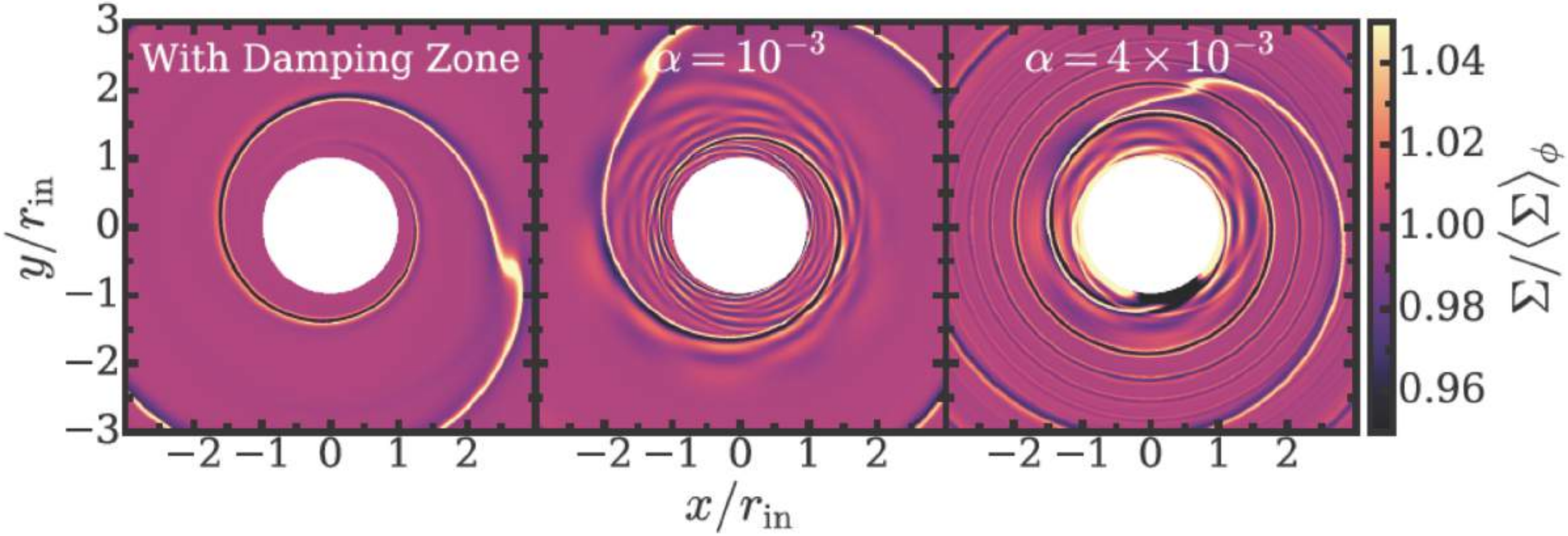
-- Planet migration is strongly affected by disk structure

(e.g. mean-motion resonance with binary, disk truncation)

Planet Migration in Truncated Disks

Miranda & DL 2018





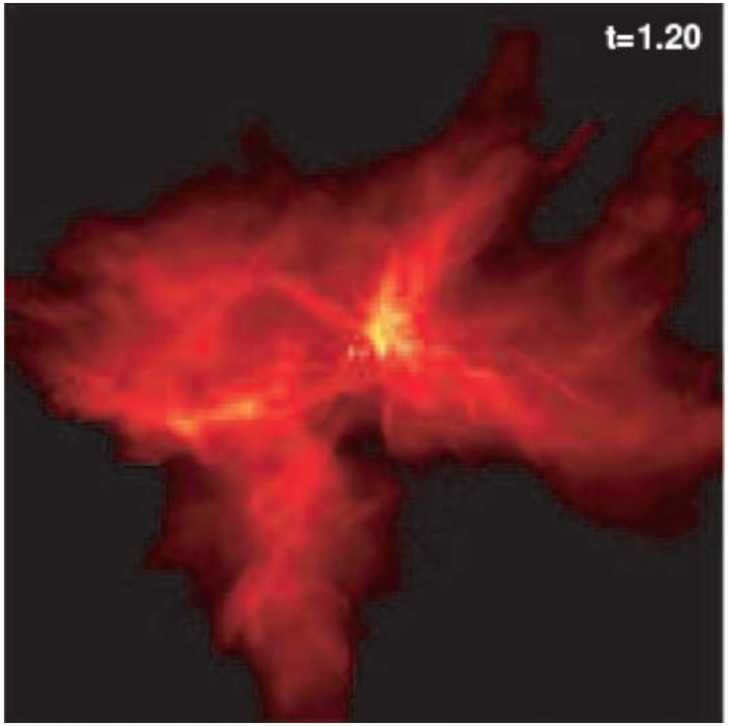
So far: Co-planar disks

What about misaligned disks ?

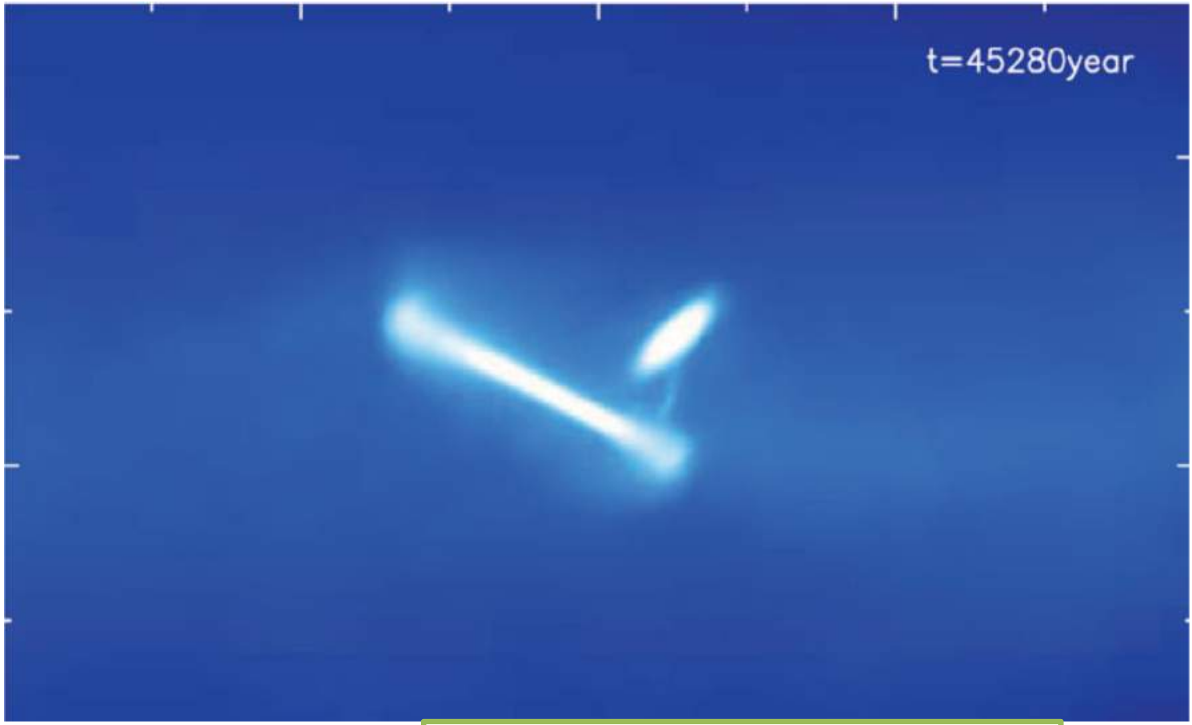
Misaligned Disks are “Naturally” Expected

Star Formation in Turbulent Molecular Clouds

-- Supersonic turbulence --> clumps --> stars
-- Clumps can accrete gas with different rotation axes at different times



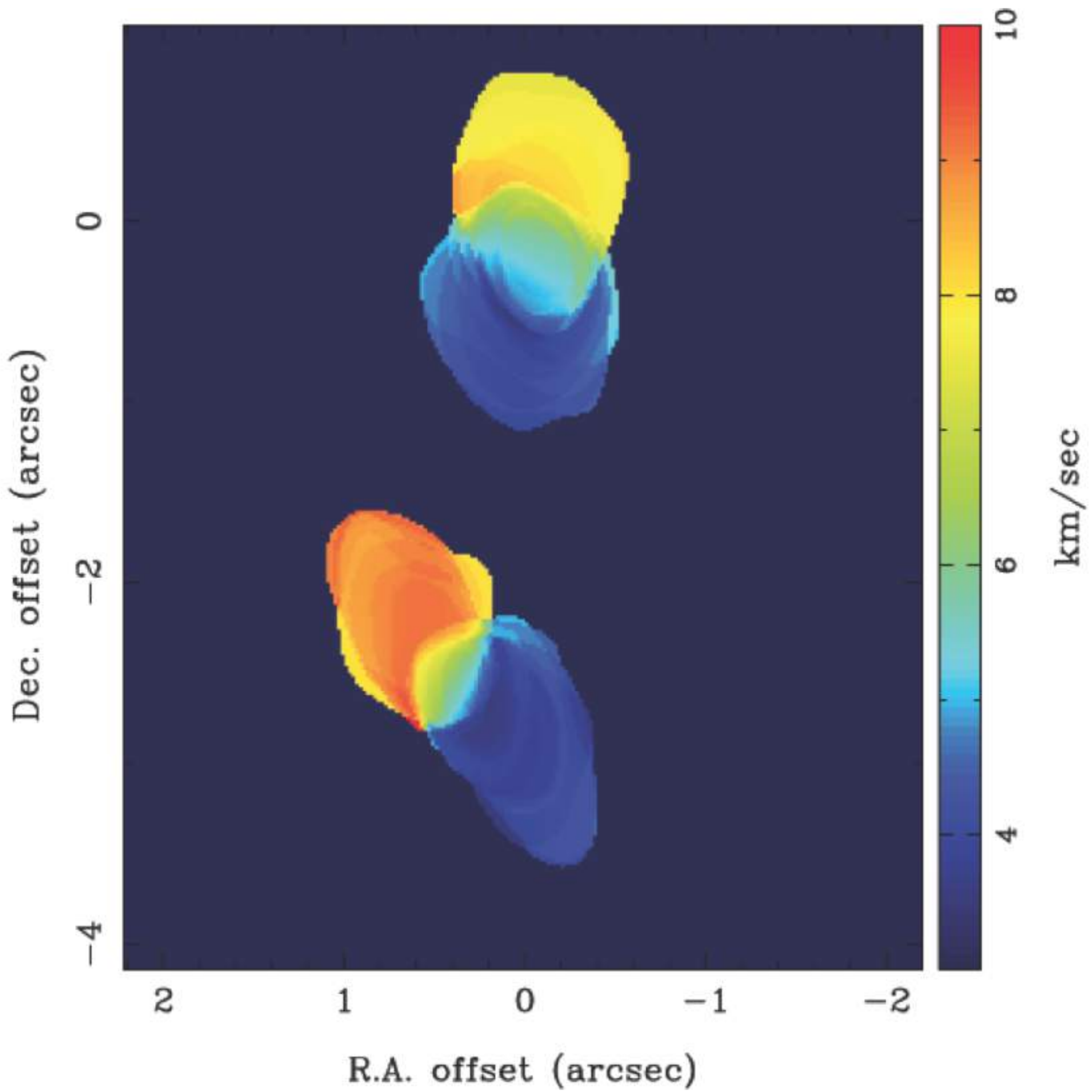
Bate et al. 2003



Tsukamoto & Machida 2013

Observations

Circumstellar disks within wider binaries are generally misaligned



HK Tau:

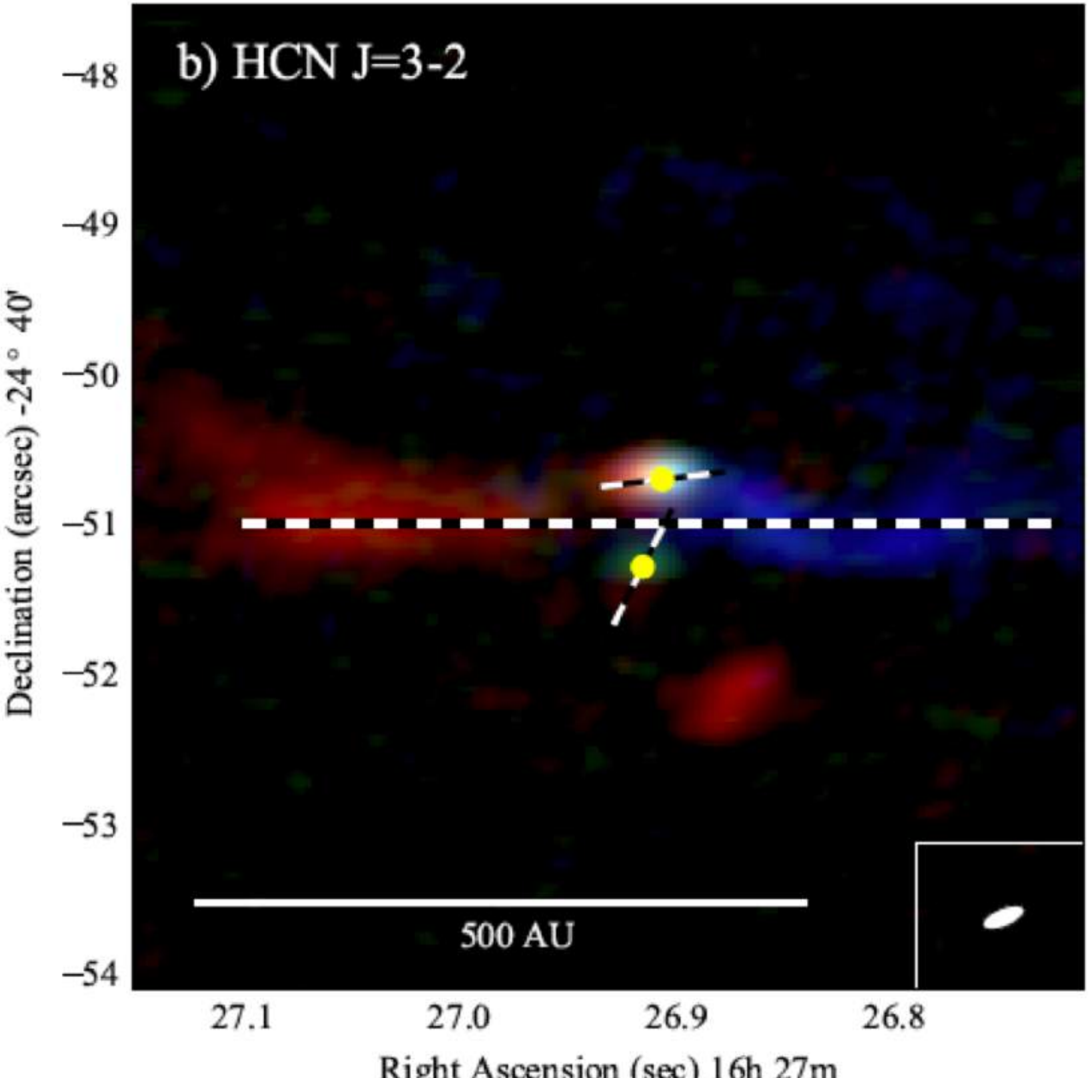
ALMA CO 3-2 emission

(a_b ~ 400 AU)

Jensen & Akeson 14

Observations

Misaligned circumbinary disks



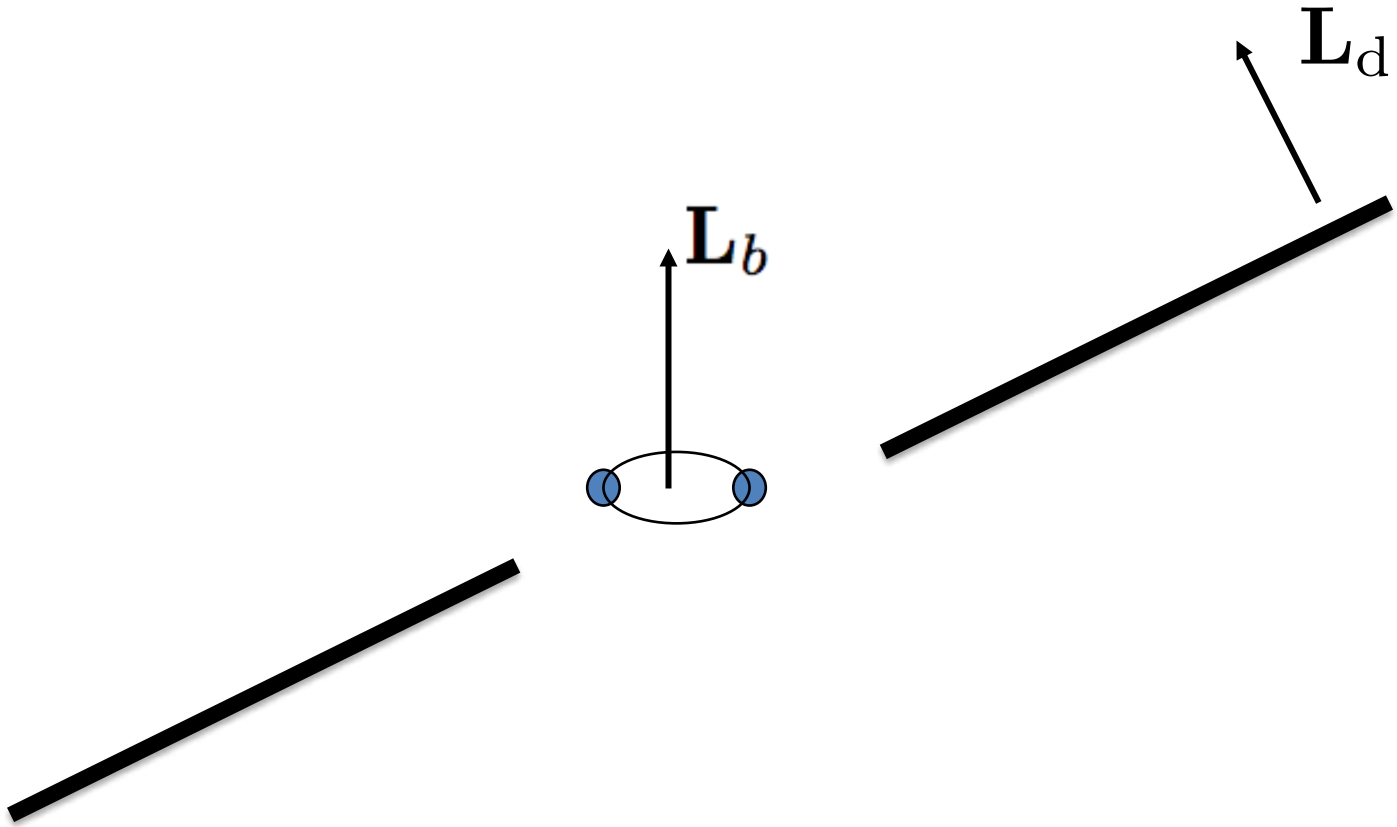
IRS 43

ALMA

a_b ~ 74 au, three disks

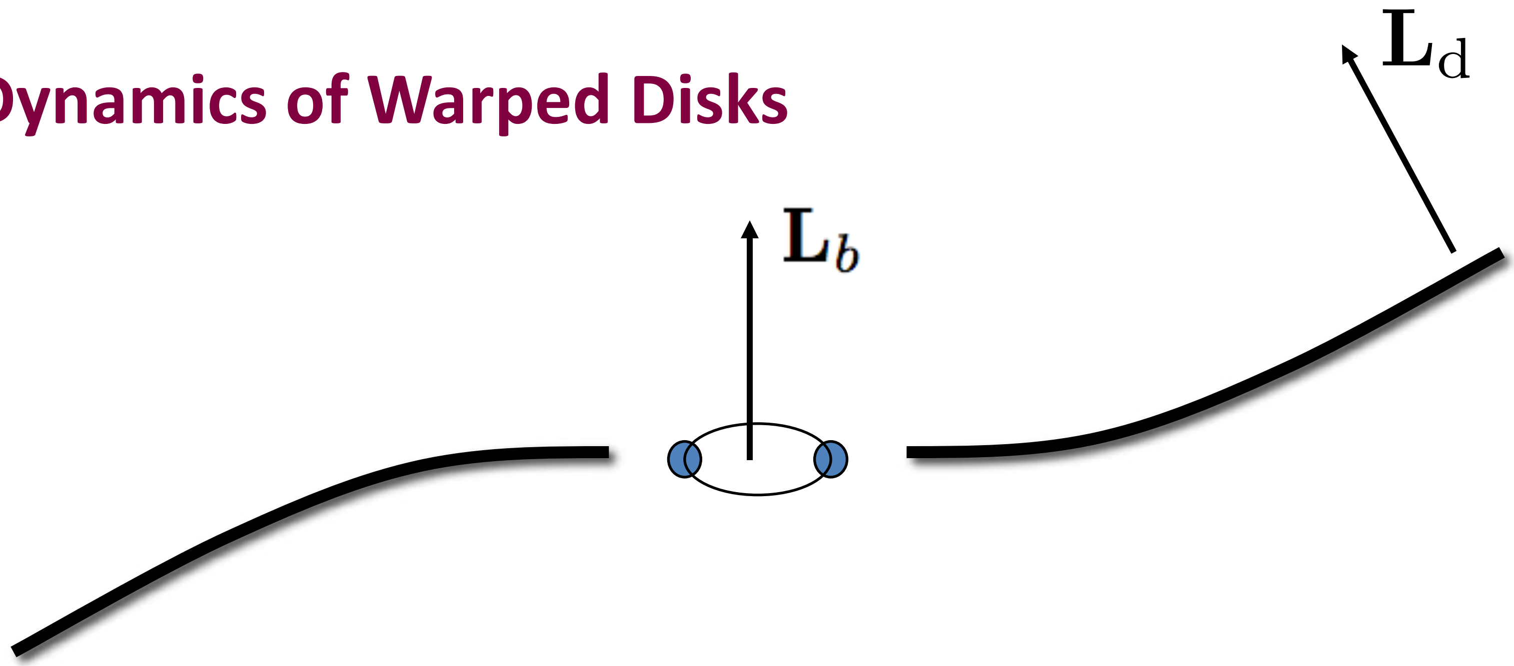
Brinch et al. 2016

Consider (circular) Binary + Inclined (initially) Disk



Questions: What is the shape of the disk?
How does the mutual inclination evolve?

Dynamics of Warped Disks

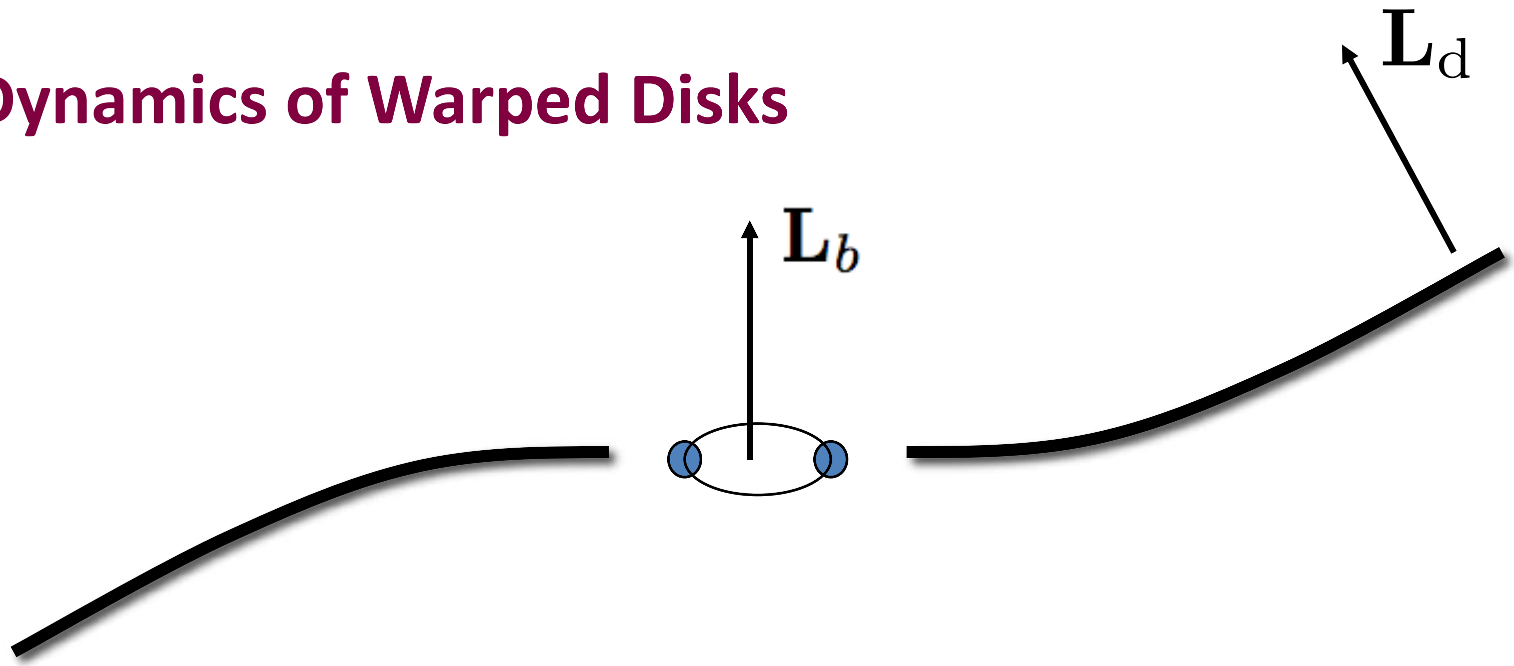


Torque from binary on disk => disk (ring) nodal precession

$$\Omega_p(r) \simeq \frac{3\mu}{4M_t}\left(\frac{a}{r}\right)^2 \Omega(r)$$

Differential precession + internal fluid stress ==> warped/twisted disk

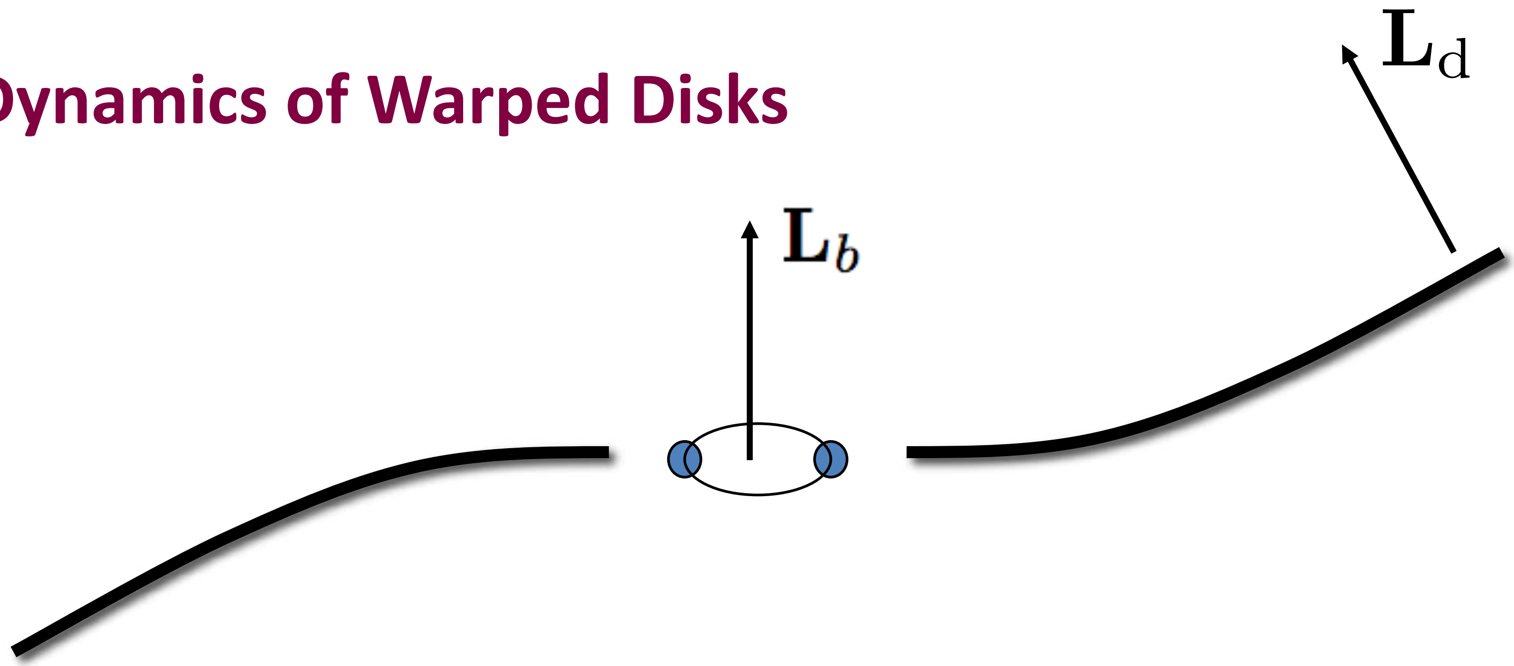
Dynamics of Warped Disks



For protoplanetary disks, warp/twist smoothed by bending waves, which propagate at $c_s/2$ (Lubow & Ogilvie 2000).

Since $r/c_s <<$ precession period ➔ disk is close to flat

Dynamics of Warped Disks



However, small warp exists.

Warp + Viscosity ➔ Dissipation ➔ Align $\mathbf{L}_\mathbf{b}$ and $\mathbf{L}_\mathbf{d}$

$$\frac{\partial \hat{\mathbf{l}}}{\partial \ln r} \sim \frac{\alpha}{c_\mathrm{s}^2}\mathbf{T}_\mathrm{ext} \qquad |\mathbf{T}_\mathrm{ext}| \sim r^2\Omega\,\omega_\mathrm{ext}, \quad \omega_\mathrm{ext} = \Omega_\mathrm{prec}$$

$$\left|\frac{d\hat{\mathbf{l}}}{dt}\right|_\mathrm{visc} \sim \left\langle \left(\frac{\alpha}{c_\mathrm{s}^2}\right)\frac{\mathbf{T}_\mathrm{ext}^2}{r^2\Omega} \right\rangle \sim \left\langle \frac{\alpha}{c_\mathrm{s}^2}(r^2\Omega)\omega_\mathrm{ext}^2 \right\rangle$$

Typical alignment time ~ precession period

Foucart & DL 2014
Zanazzi & DL 2018

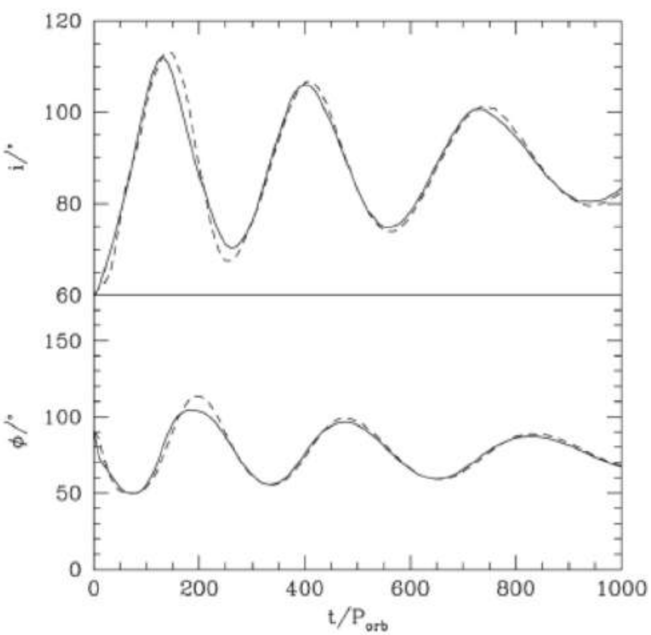
Surprise: **Disk around eccentric binary may evolve toward polar alignment**

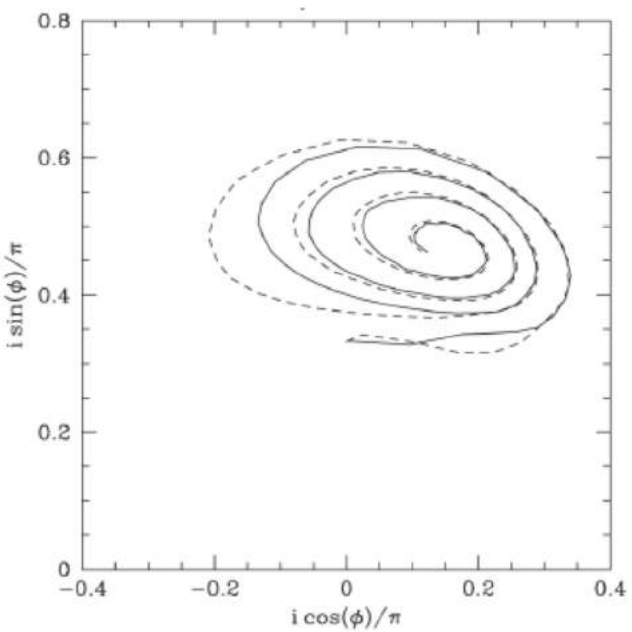
Surprise: Disk around eccentric binary may evolve toward polar alignment

Martin & Lubow (2017): viscous hydro simulation using SPH

Initial disk-binary inclination $I(0) = 60°$

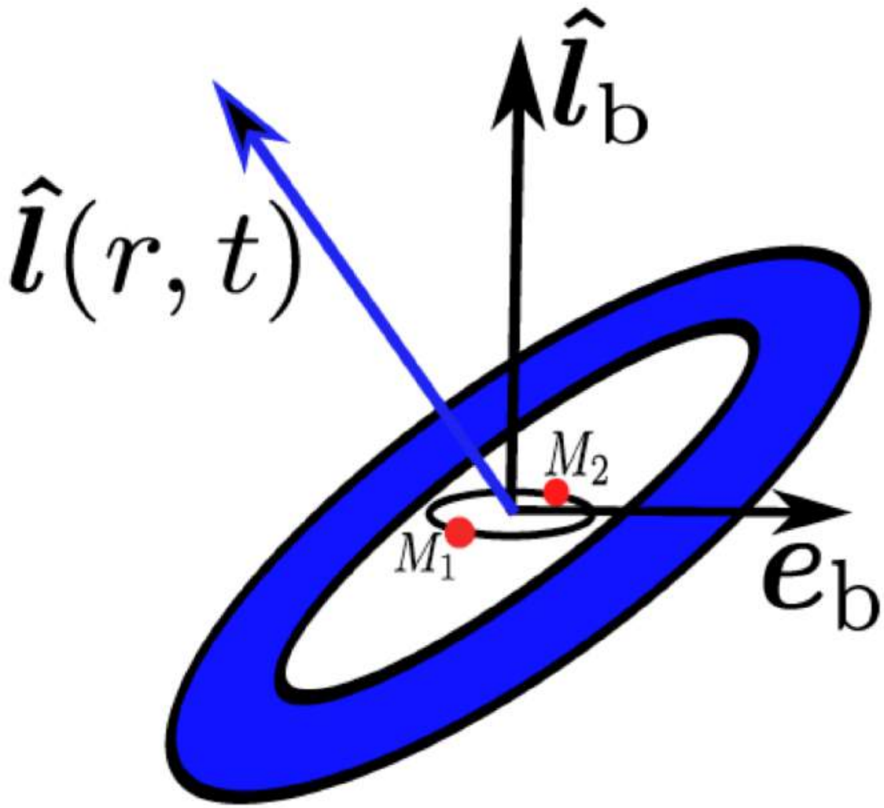
Binary eccentricity $e_b = 0.5$.





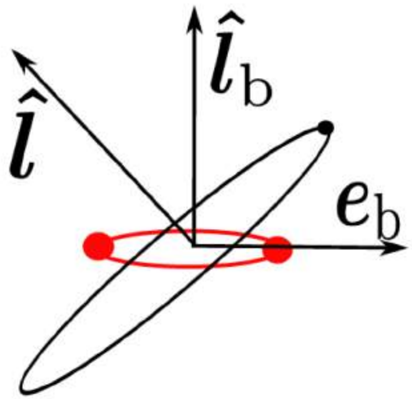
Theoretical Understanding:
Inclination Evolution of Disks Around Eccentric Binaries

With J.J. Zanazzi
(Cornell Ph.D.18→CITA)



Test particle (in circular orbit) around an eccentric binary

(see also Farago & Laskar 2010; Li, Zhou + 2014)

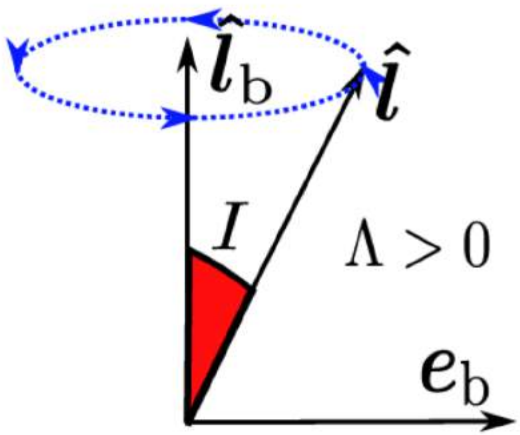


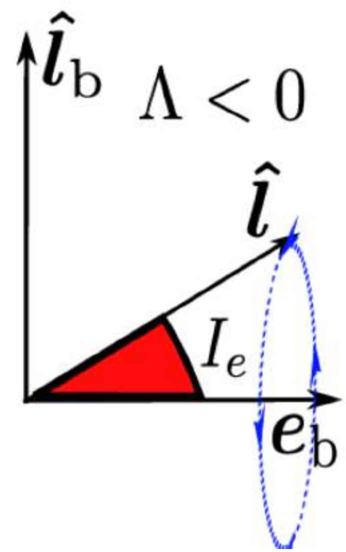
Test particle has two "masters" (by symmetry)

If $\hat{l}$ initially close to $\hat{l}_b$: $\hat{l}$ precesses around $\hat{l}_b$

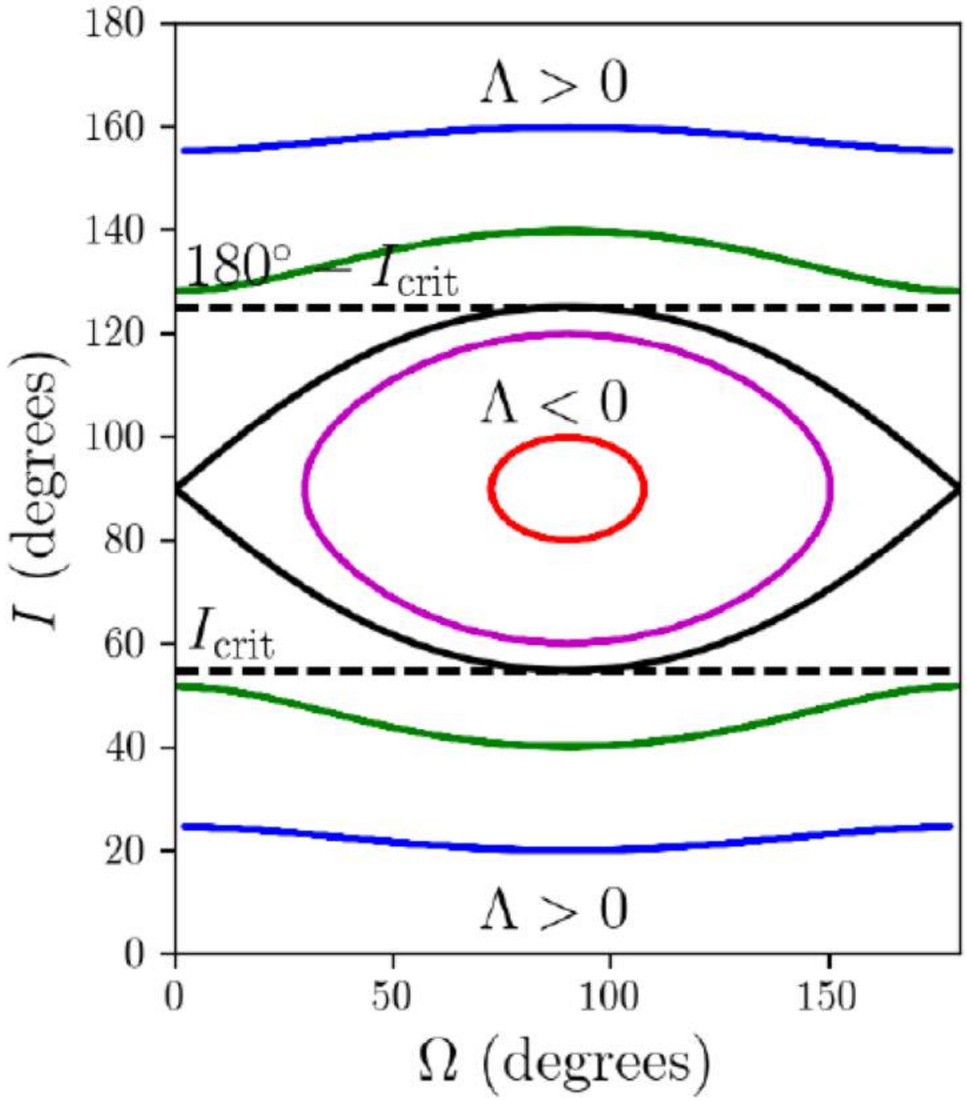
If $\hat{l}$ initially close to $\hat{e}_b$: $\hat{l}$ precesses around $\hat{e}_b$

$$\Lambda = (1 - e_{\rm b}^2)(\hat{\boldsymbol{l}}\cdot\hat{\boldsymbol{l}}_{\rm b})^2 - 5(\hat{\boldsymbol{l}}\cdot\boldsymbol{e}_{\rm b})^2$$





$$\Lambda = (1 - e_{\rm b}^2)(\hat{\boldsymbol{l}}\cdot\hat{\boldsymbol{l}}_{\rm b})^2 - 5(\hat{\boldsymbol{l}}\cdot\boldsymbol{e}_{\rm b})^2$$



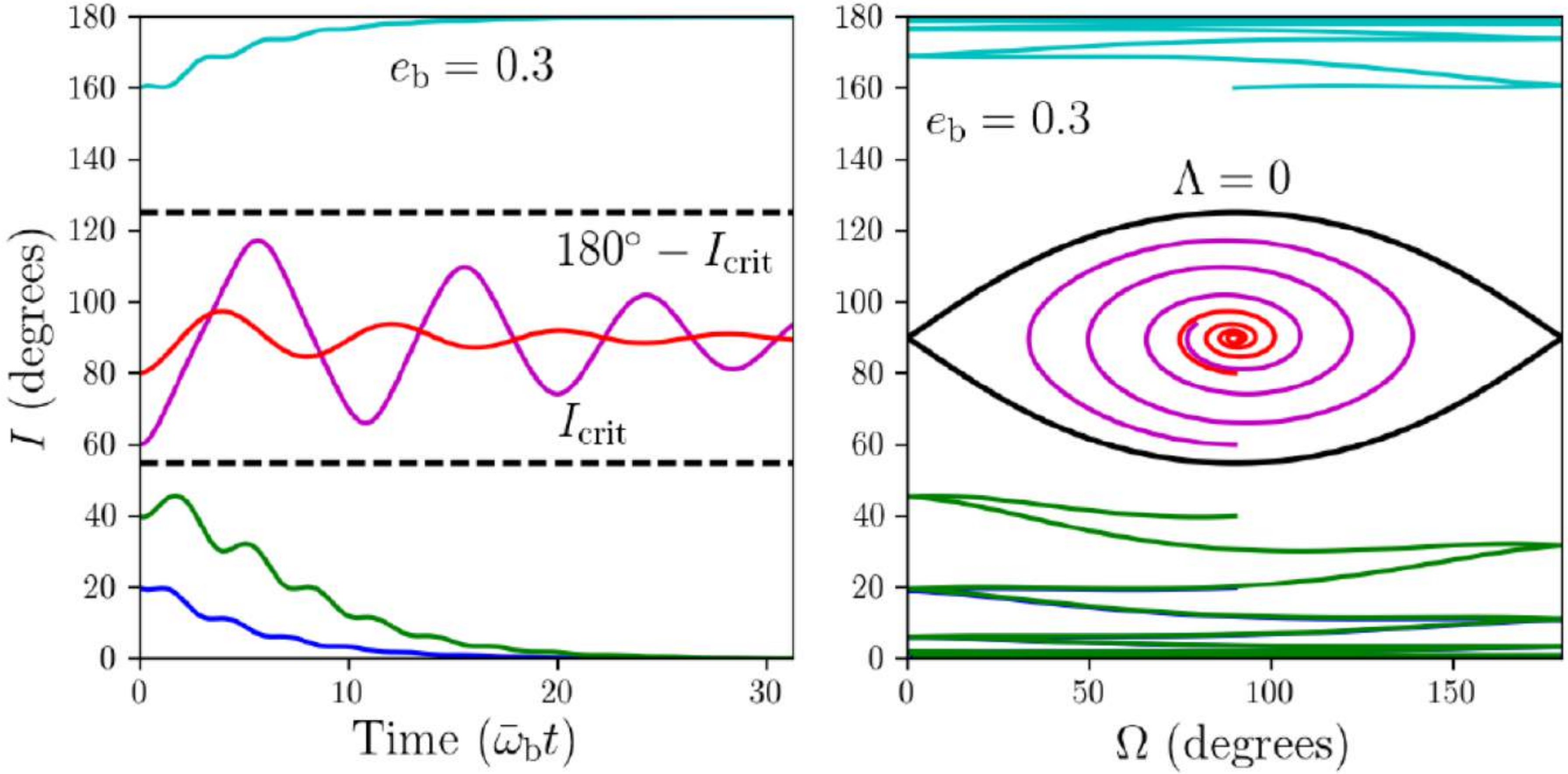
For $\hat{l}$ to precess around $\hat{e}_b$, require $\sin I > \sin I_{\rm crib}$

$$I_{\rm crit} = \cos^{-1}\sqrt{\frac{5e_{\rm b}^2}{1+4e_{\rm b}^2}}$$

Zanazzi & DL 2018

Warped viscous disk around eccentric binary

Evolve towards either align (anti-align) or polar align with the binary



Zanazzi & DL 2018

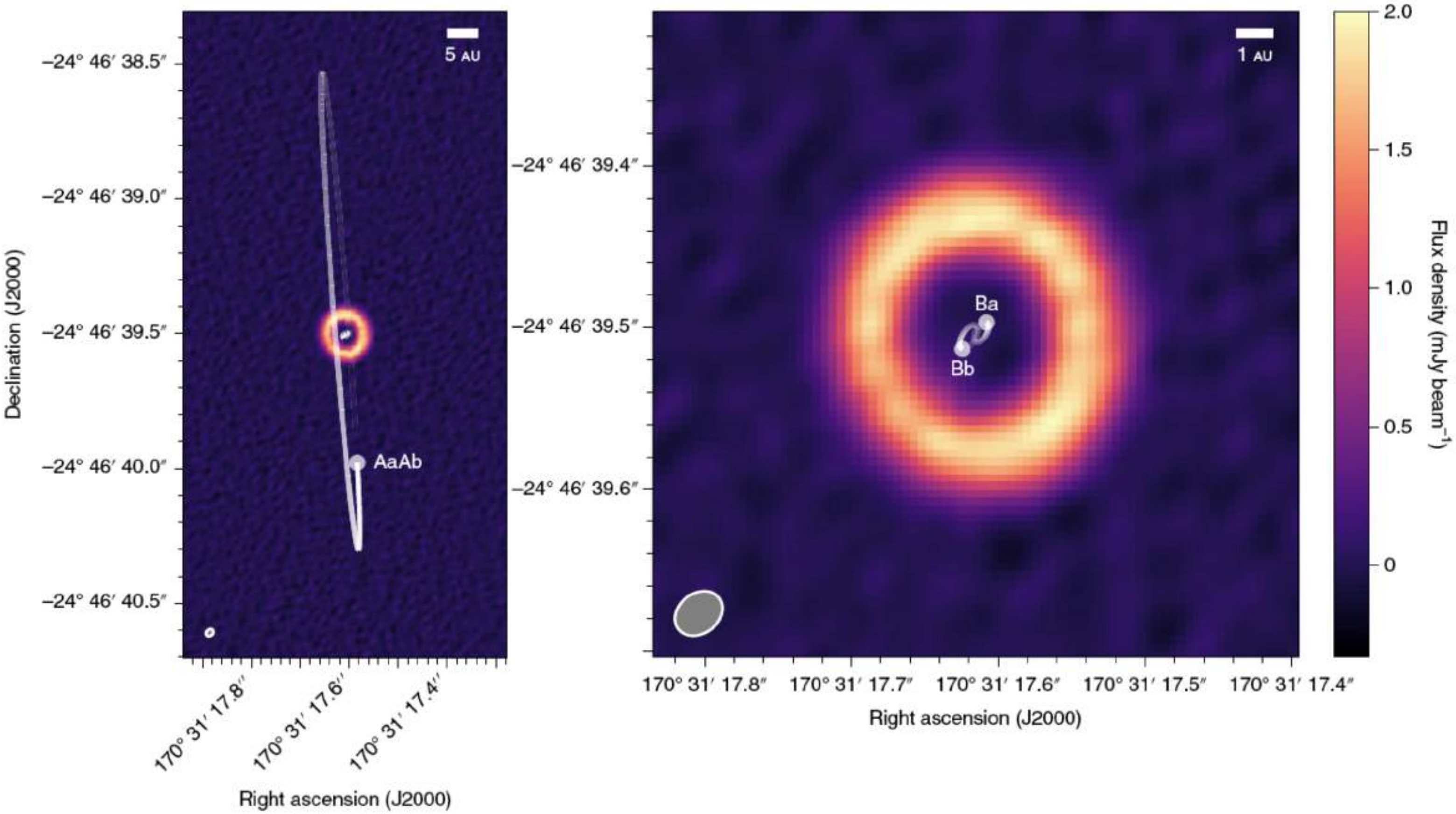
LETTERS
https://doi.org/10.1038/s41550-018-0667-x

nature astronomy

Corrected: Publisher Correction

A circumbinary protoplanetary disk in a polar configuration

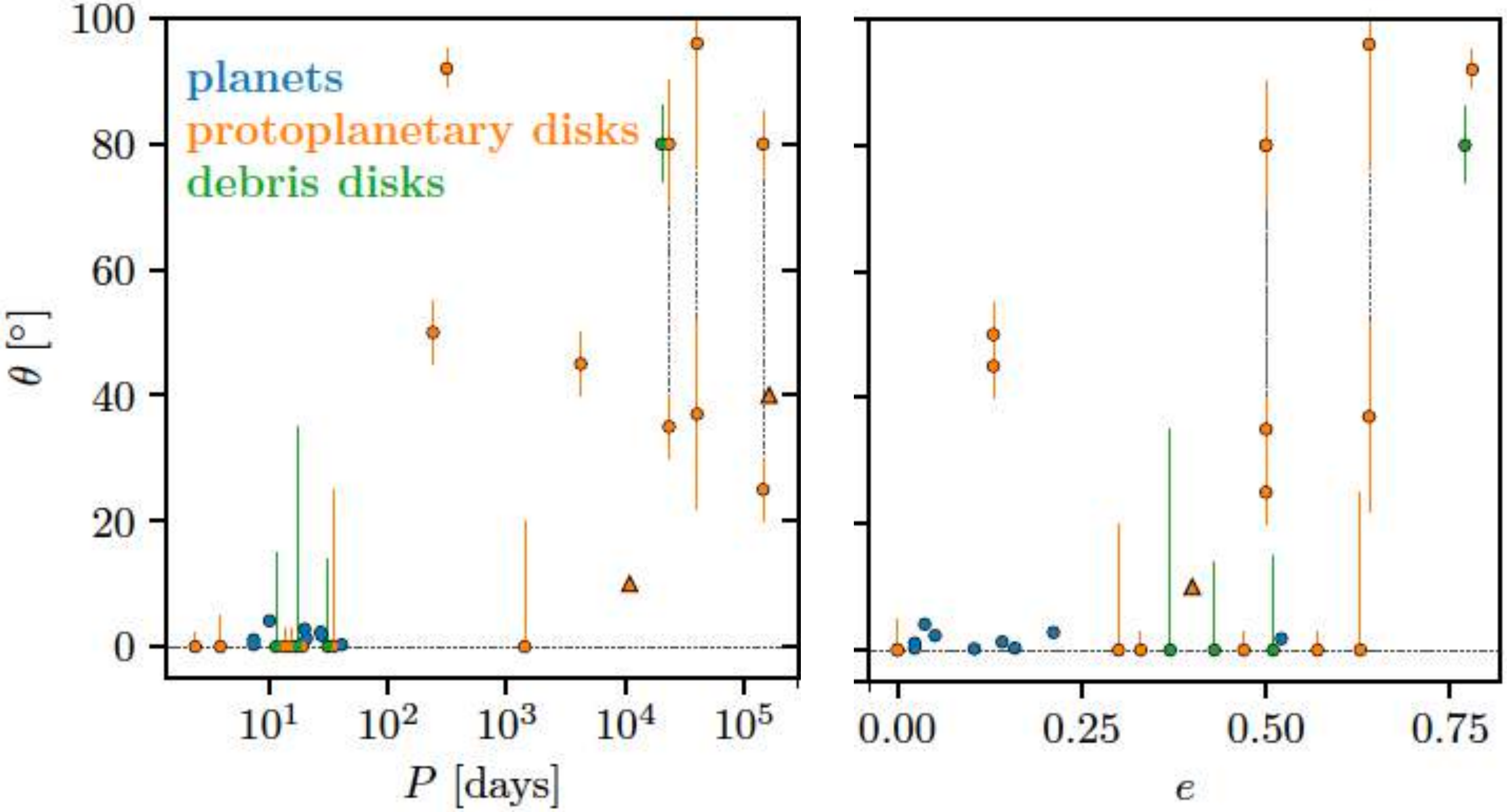
Grant M. Kennedy[1,2*], Luca Matrà[3], Stefano Facchini[4,5], Julien Milli[6], Olja Panić[7], Daniel Price[8,9], David J. Wilner[3], Mark C. Wyatt[10] and Ben M. Yelverton[10]



THE ASTROPHYSICAL JOURNAL, 883:22 (24pp), 2019 September 20 https://doi.org/10.3847/1538-4357/ab287b

The Degree of Alignment between Circumbinary Disks and Their Binary Hosts

Ian Czekala[1,8], Eugene Chiang[1,2], Sean M. Andrews[3], Eric L. N. Jensen[4], Guillermo Torres[3], David J. Wilner[3], Keivan G. Stassun[5,6], and Bruce Macintosh[7]



Are there misaligned circumbinary planets?

~12 transiting circumbinary planets

3 non-transiting planets (candidates) around eclipsing binaries
(detected using eclipse timing variation) (Bill Welsh, 2018)

Take-Home Messages

- **Understanding circumbinary accretion is**

  Important: connect to SMBH binaries, protoplanetary disks and planets

  Challenging: long-term secular effect in the presence of highly dynamical flows

- **Key Recent Results:**

  -- short-term variabilities: ~ 5 P_b (for e_b~0) vs P_b (finite e_b, or $q<0.4$)

  -- Small-mass accretes more; symmetry breaking in accretion ($q=1$, $e_b>0$)

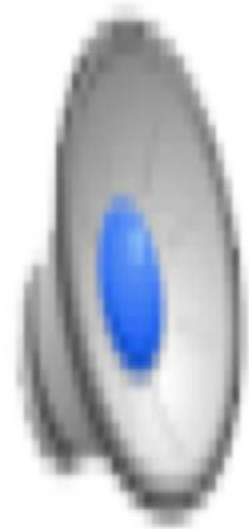
  -- Inner disk is eccentric: precess coherently…

  -- Binary can gain angular momentum and can expand

- **Misaligned disks**

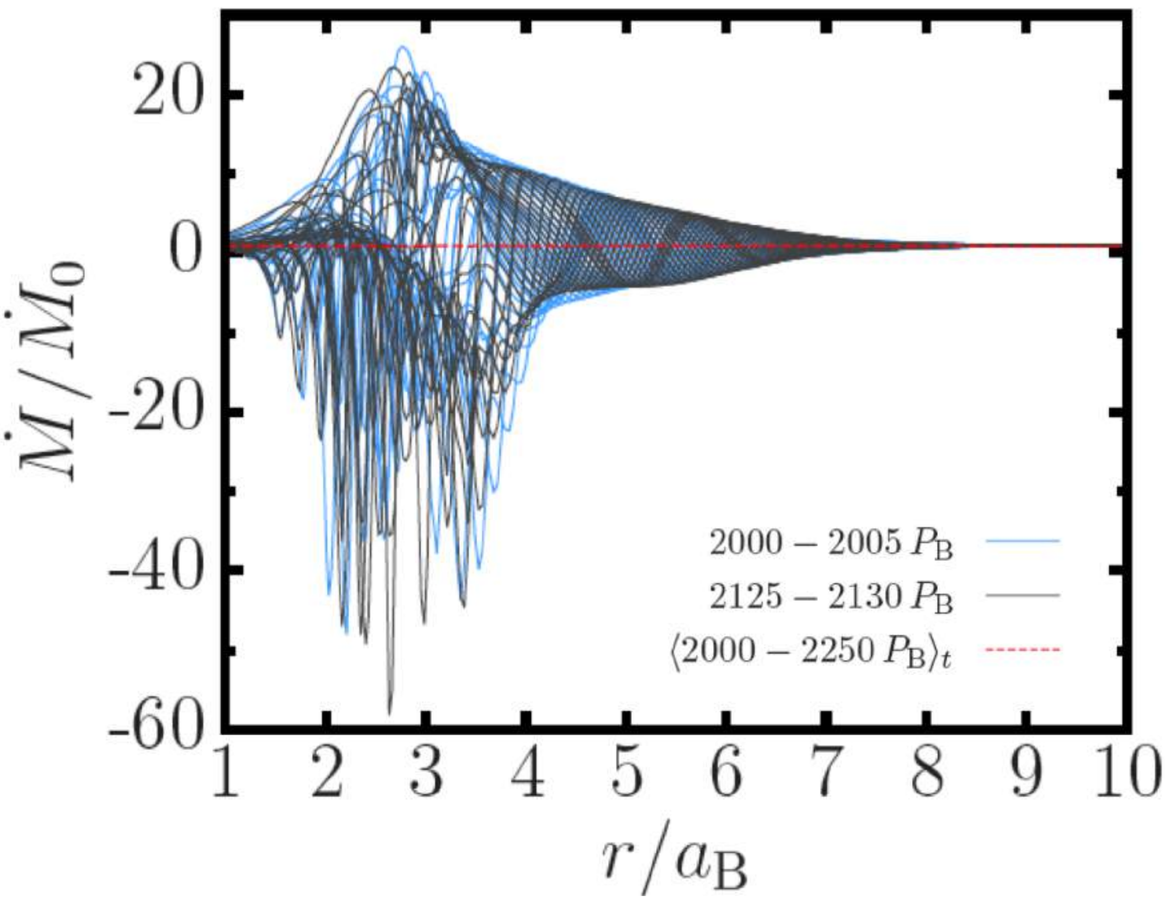
  -- In PPDs, hydro effects efficient ➔ Quasi-rigid precession with small warp

  -- Dissipation leads to either alignment or polar alignment with binary

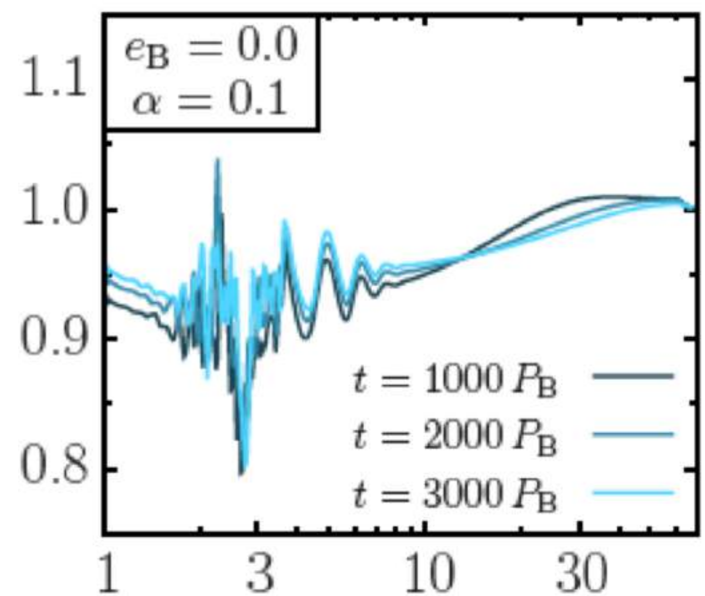


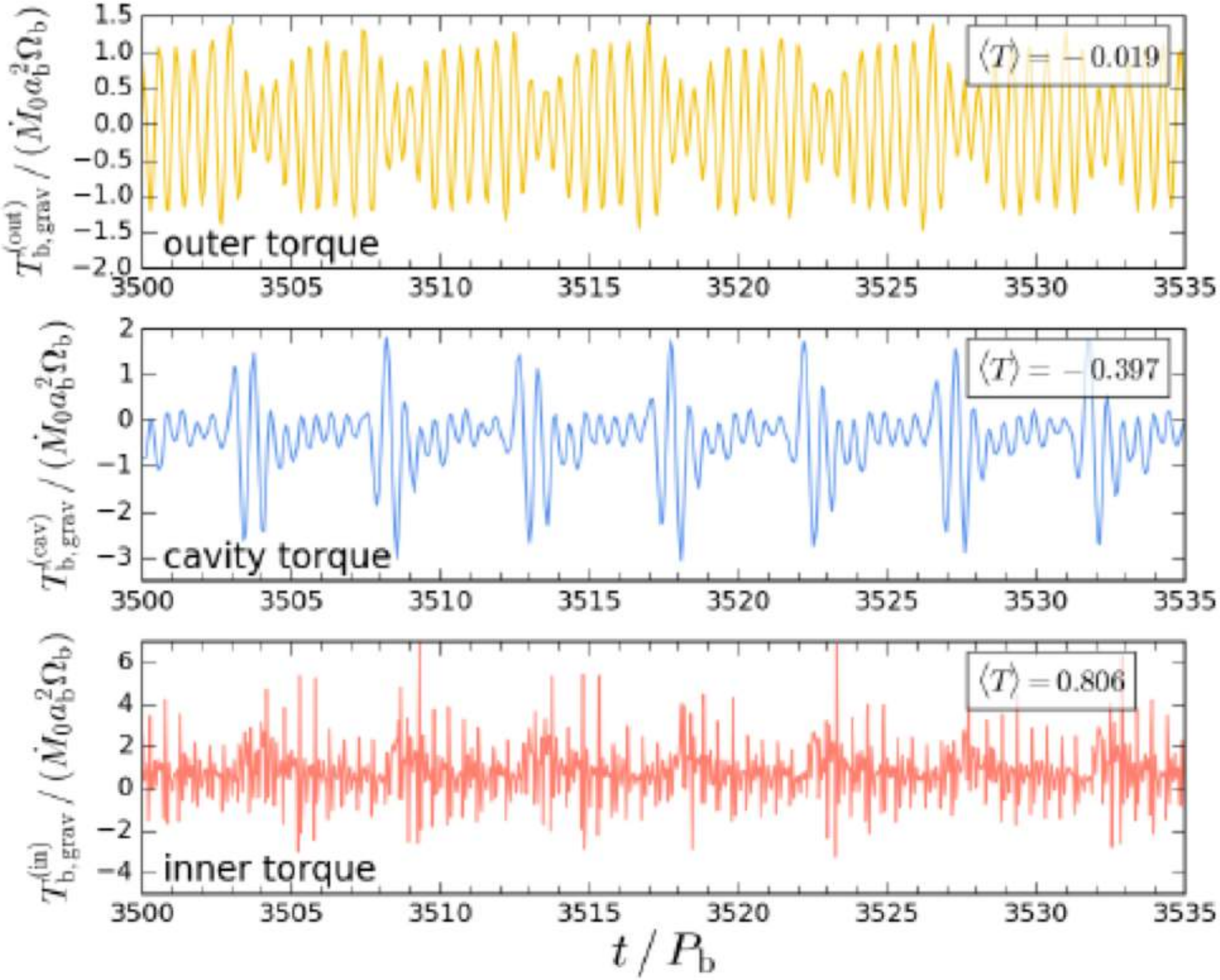
$\dot{M}(r,t)$ is highly variable (in r and t)

$$\dot{M}(r,t) = -\oint r\Sigma u_r \mathrm{d}\phi$$



$\langle\dot{M}\rangle/\dot{M}_0$ (averaged over 250 P_b)





$T^{(\mathrm{out})}_{\mathrm{b,grav}} \,/\, (\dot{M}_0 a_\mathrm{b}^2 \Omega_\mathrm{b})$
$\langle T \rangle = -0.019$
outer torque
$T^{(\mathrm{cav})}_{\mathrm{b,grav}} \,/\, (\dot{M}_0 a_\mathrm{b}^2 \Omega_\mathrm{b})$
$\langle T \rangle = -0.397$
cavity torque
$T^{(\mathrm{in})}_{\mathrm{b,grav}} \,/\, (\dot{M}_0 a_\mathrm{b}^2 \Omega_\mathrm{b})$
$\langle T \rangle = 0.806$
inner torque
$t \,/\, P_\mathrm{b}$

Consider the specific angular momentum $\mathbf{l}_\mathrm{b} = \mathbf{r}_\mathrm{b} \times \dot{\mathbf{r}}_\mathrm{b}$ and specific energy $\mathcal{E}_\mathrm{b} = \frac{1}{2}\dot{\mathbf{r}}_\mathrm{b}^2 - \mathcal{G}M_\mathrm{b}/r_\mathrm{b}$ of the binary. The changes in $\mathbf{l}_\mathrm{b}$ and $\mathcal{E}_\mathrm{b}$ due to an external force $\mathbf{f}_\mathrm{ext}$ (other than the mutual Keplerian force) are

$$\frac{d\mathbf{l}_\mathrm{b}}{dt} = \mathbf{r}_\mathrm{b} \times \mathbf{f}_\mathrm{ext} \tag{32}$$

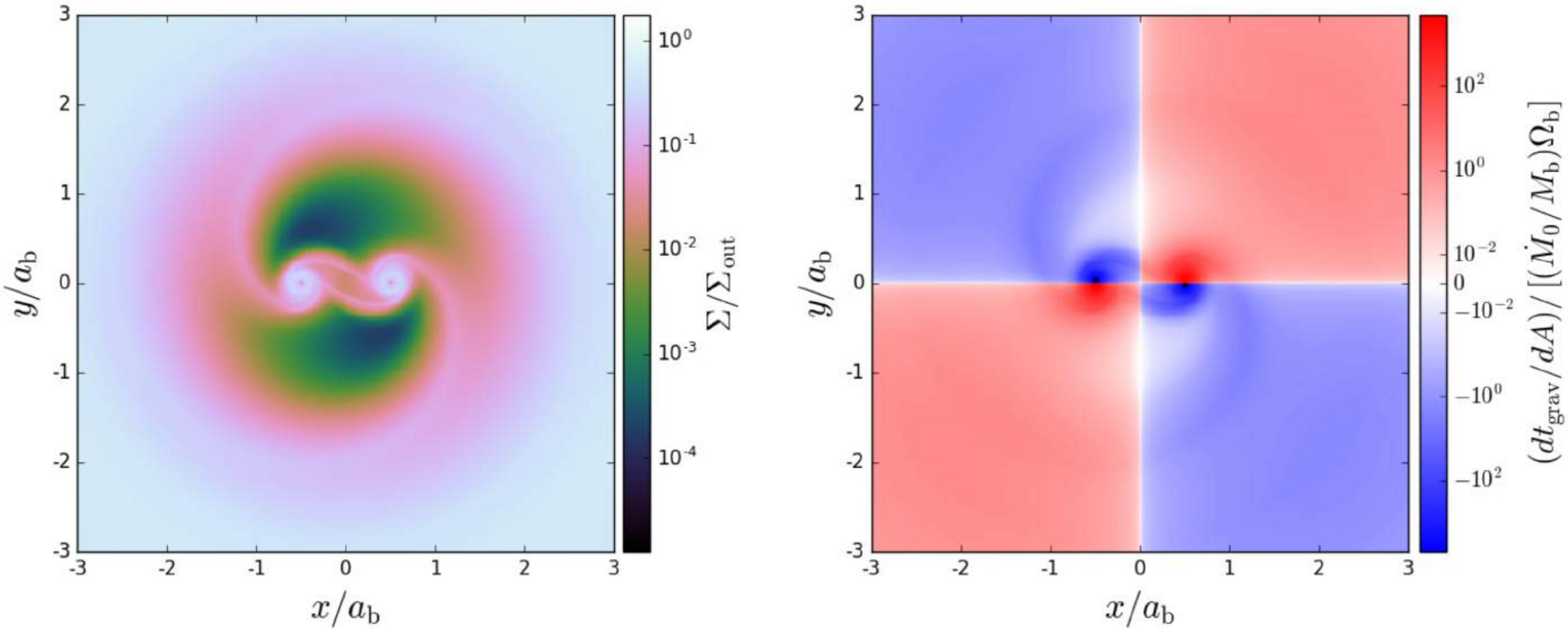
and

$$\begin{aligned} \frac{d\mathcal{E}_\mathrm{b}}{dt} &= -\frac{\mathcal{G}\dot{M}_\mathrm{b}}{r_\mathrm{b}} + \frac{\mathcal{G}\dot{M}_\mathrm{b}}{r_\mathrm{b}^3}\mathbf{r}_\mathrm{b} \cdot \dot{\mathbf{r}}_\mathrm{b} + \dot{\mathbf{r}}_\mathrm{b} \cdot \frac{d\dot{\mathbf{r}}_\mathrm{b}}{dt} \\ &= -\frac{\mathcal{G}\dot{M}_\mathrm{b}}{r_\mathrm{b}} + \dot{\mathbf{r}}_\mathrm{b} \cdot \mathbf{f}_\mathrm{ext} \quad , \end{aligned} \tag{33}$$

where, $d\dot{\mathbf{r}}_\mathrm{b}/dt = -(\mathcal{G}\dot{M}_\mathrm{b}/r_\mathrm{b}^3)\mathbf{r}_\mathrm{b} + \mathbf{f}_\mathrm{ext}$ and $\mathbf{f}_\mathrm{ext}$ is a general (reduced) external force per unit mass affecting both members of the binary: $\mathbf{f}_\mathrm{ext} \equiv \mathbf{f}_\mathrm{ext,1} - \mathbf{f}_\mathrm{ext,2}$. In this case, $\mathbf{f}_{\mathrm{ext},i} = \mathbf{f}_{\mathrm{grav},i} + \mathbf{f}_{\mathrm{acc},i}$ (defined in Section 2.2.1 above). Since $e_\mathrm{b}^2 = 1 + 2l_\mathrm{b}^2\mathcal{E}_\mathrm{b}/(\mathcal{G}M_\mathrm{b})^2$

Direct computation of torque on the binary

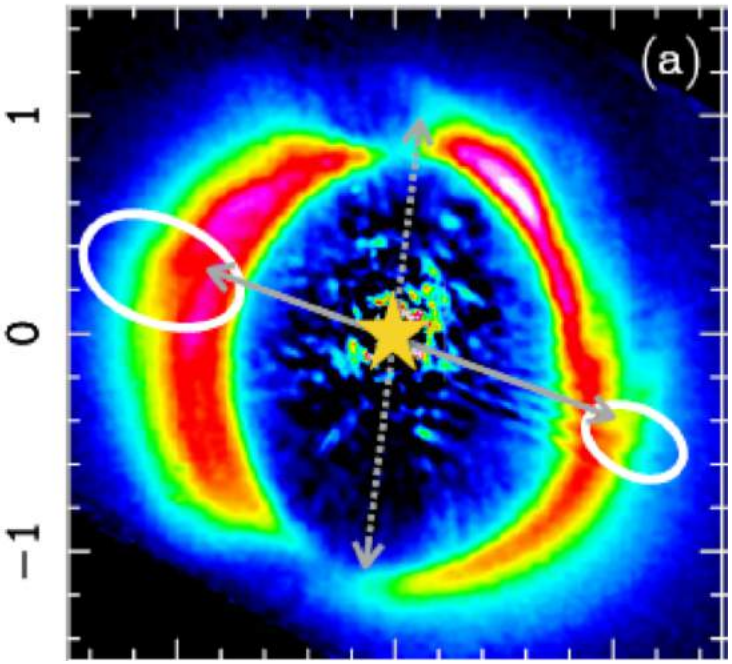
Gravitational torque from all gas
+ Accretion torque (due momentum of accreting gas onto each star)

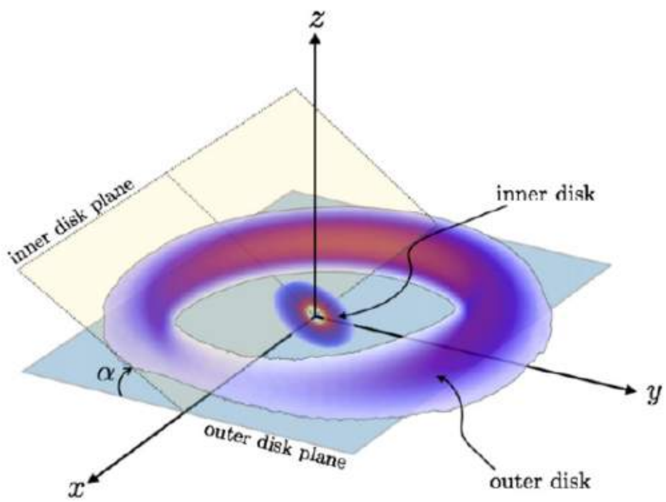


$$\langle T \rangle \simeq 0.7\, \dot{M}_0\, a_B^2 \Omega_B$$
$$\simeq \langle \dot{J} \rangle$$

(for q=1, e_B=1 binary)

HD 142527: a well-known gapped disk system



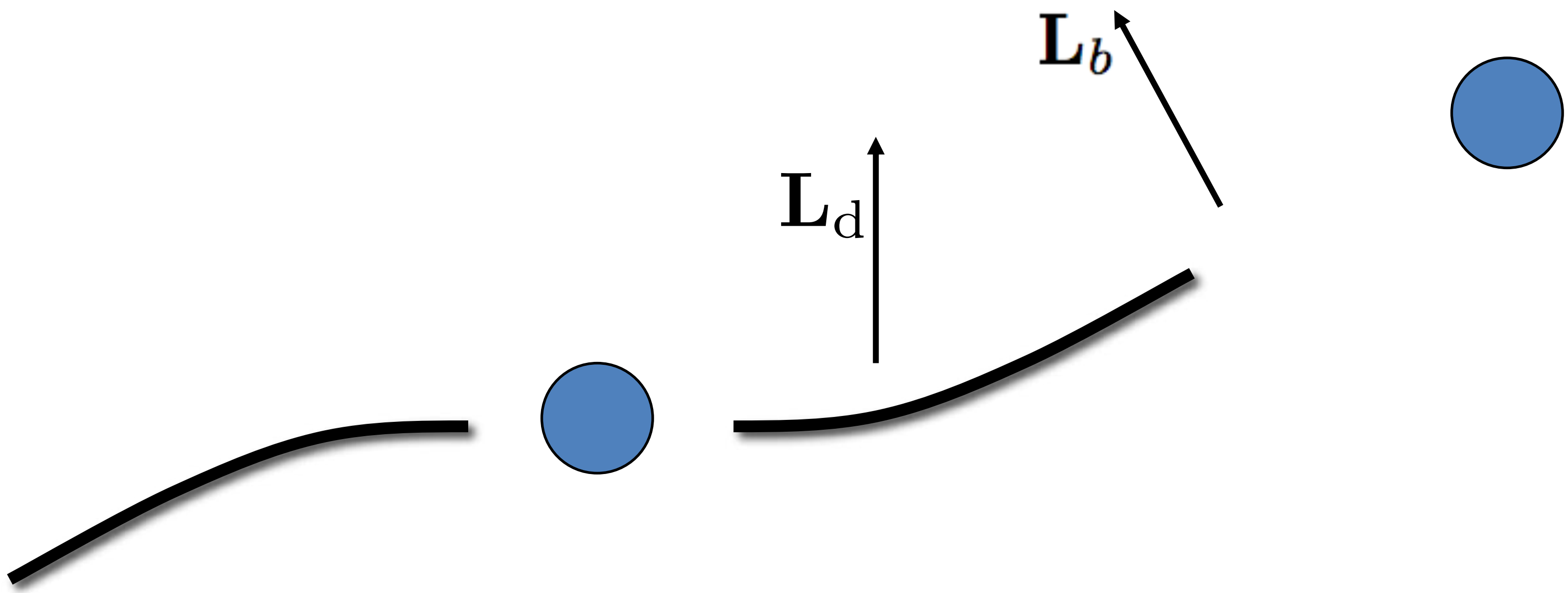


Inner (circumstellar) and outer (circumbinary) disks misaligned by 70 degrees (Marino et al. 15)

Outer disk : >100 AU
Gap (cavity): 10-100 AU
Binary: ~20 AU (2 Sun + M dwarf)

see Owen & DL 2017

Circumstellar Disk within Binary

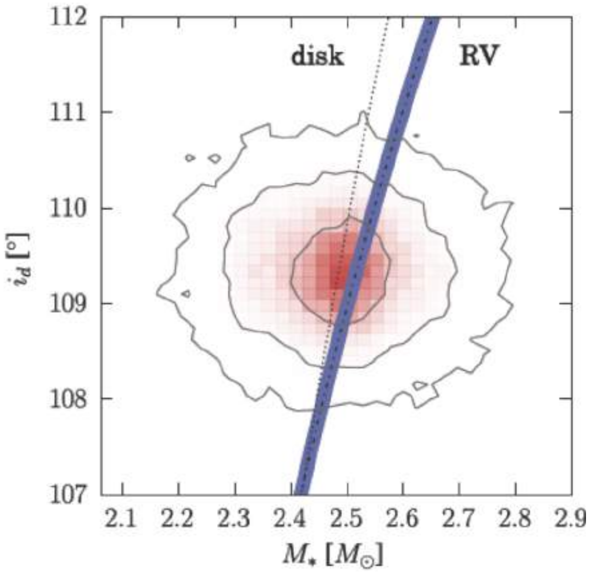


Disk is warped at outer region
➔ Smaller warp

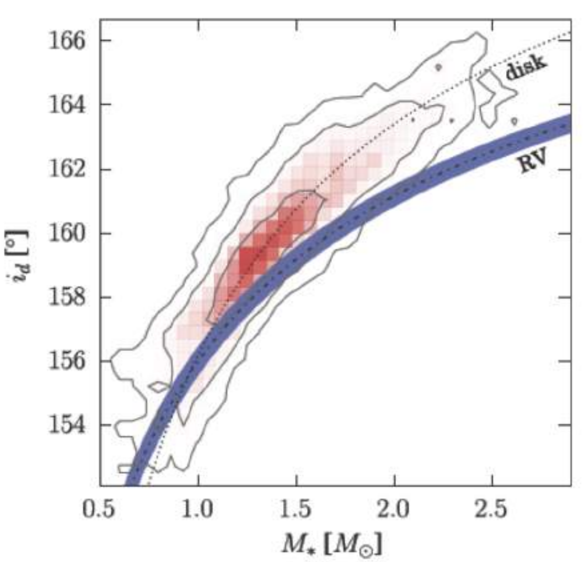
Typical alignment time >> precession period
➔ Misalignment can persist

Observations

Circumbinary disks around binaries ??



AK Sco
Czekala+15



DQ Tau
Czekala+15

Misaligned circumbinary debris disk systems:

KH 15D (Winn+04; Capelo+12)

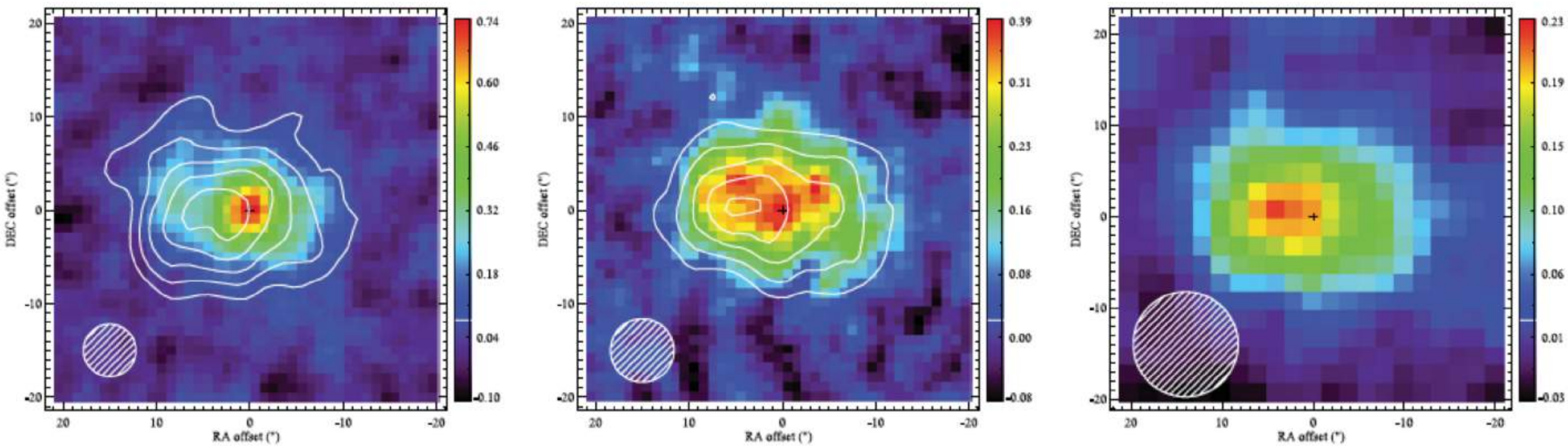
99 Herculis (Kennedy+12)

Mon. Not. R. Astron. Soc. **421,** 2264–2276 (2012) doi:10.1111/j.1365-296

99 Herculis: host to a circumbinary polar-ring debris disc

G. M. Kennedy,[1★] M. C. Wyatt,[1] B. Sibthorpe,[2] G. Duchêne,[3,4] P. Kalas,[3] B. C. Matthews,[5,6] J. S. Greaves,[7] K. Y. L. Su[8] and M. P. Fitzgerald[9,10]

[1] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[2] *UK Astronomy Technology Center, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ*
[3] *Department of Astronomy, University of California, B-20 Hearst Field Annex, Berkeley, CA 94720-3411, USA*



e_b=0.77, P_b=56 yrs

Numerical Tools

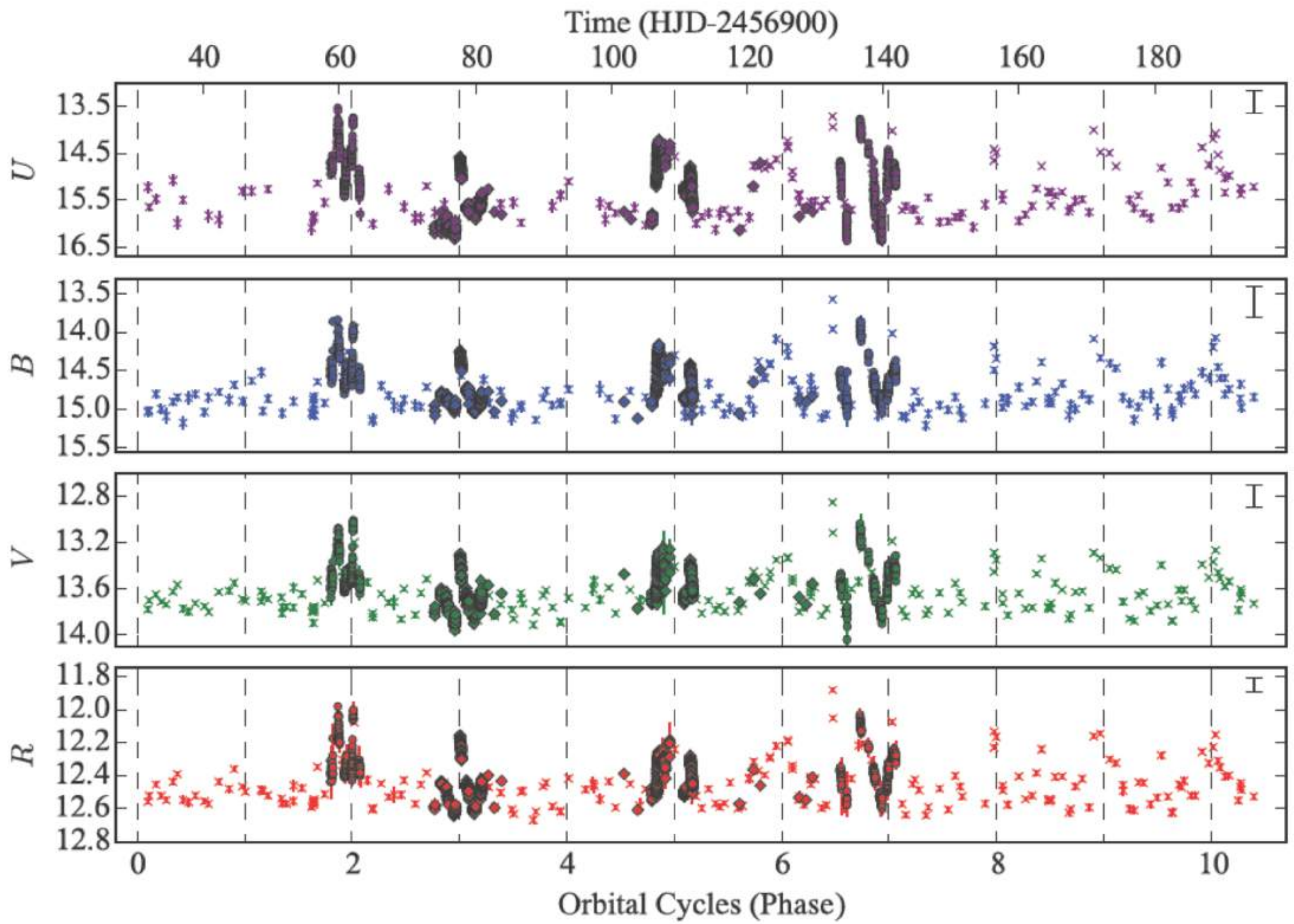
-- Solve viscous hydrodynamic equations in 2D
-- alpha viscosity, (locally) isothermal sound speed

-- Numerical codes:

PLUTO: finite-volume, polar grid (Mignone et al. 07)
domain: $a_b(1+e_b) < r < 70a_b$

AREPO: finite-volume, moving mesh (Springel 2010)
resolve accretion onto individual body to $0.02a_b$

Pulsed Accretion Observed in T Tauri Binaries



DQ Tau:

P=15.8 days
a=0.13AU
e=0.57
M1~M2~0.6Sun

Tofflemire et al. 2016