Circumbinary Accretion Disks

From Supermassive Binary BHs to Circumbinary Planets

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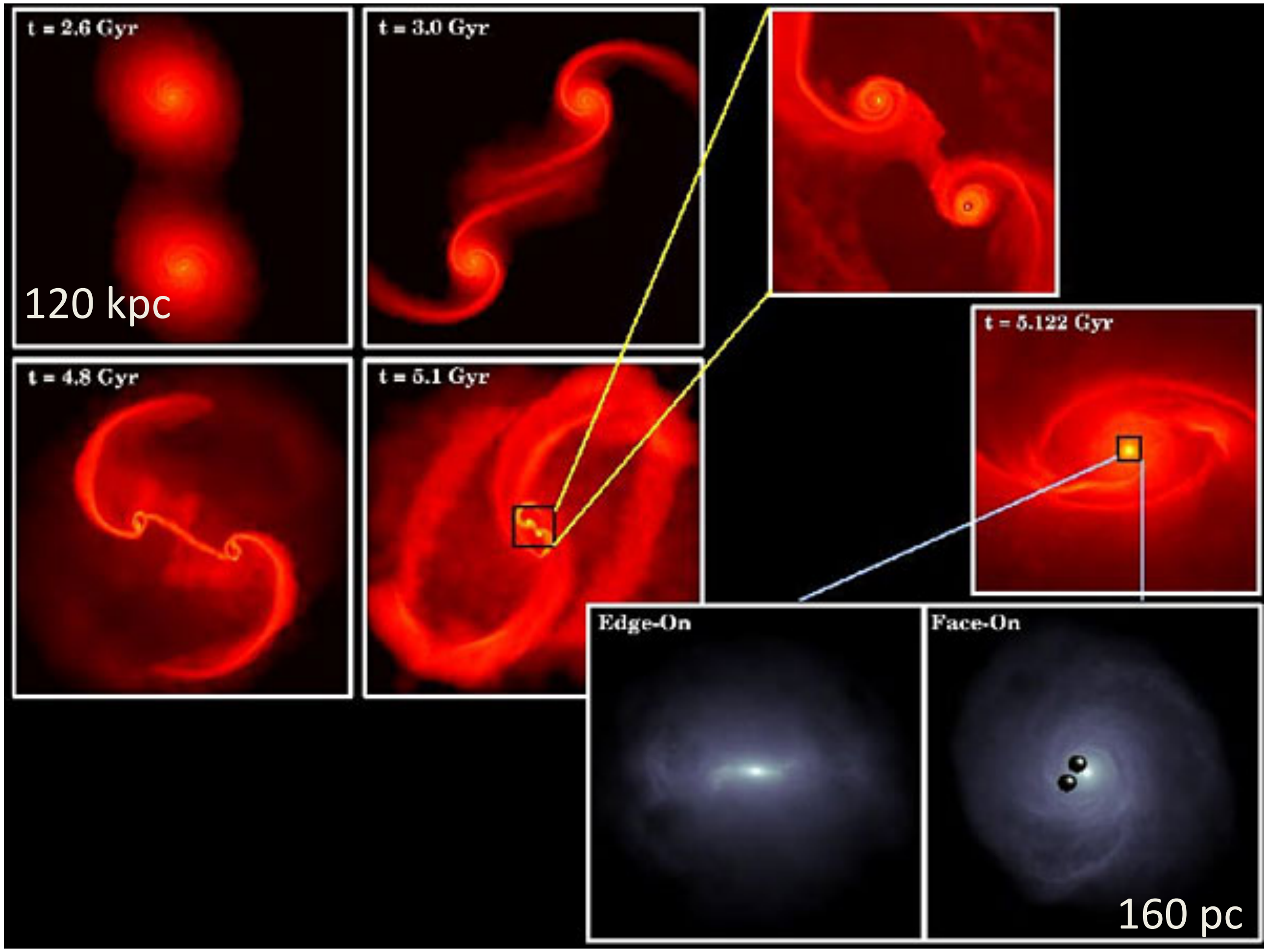
KIAA Astrophysics Colloquium, April 4, 2018

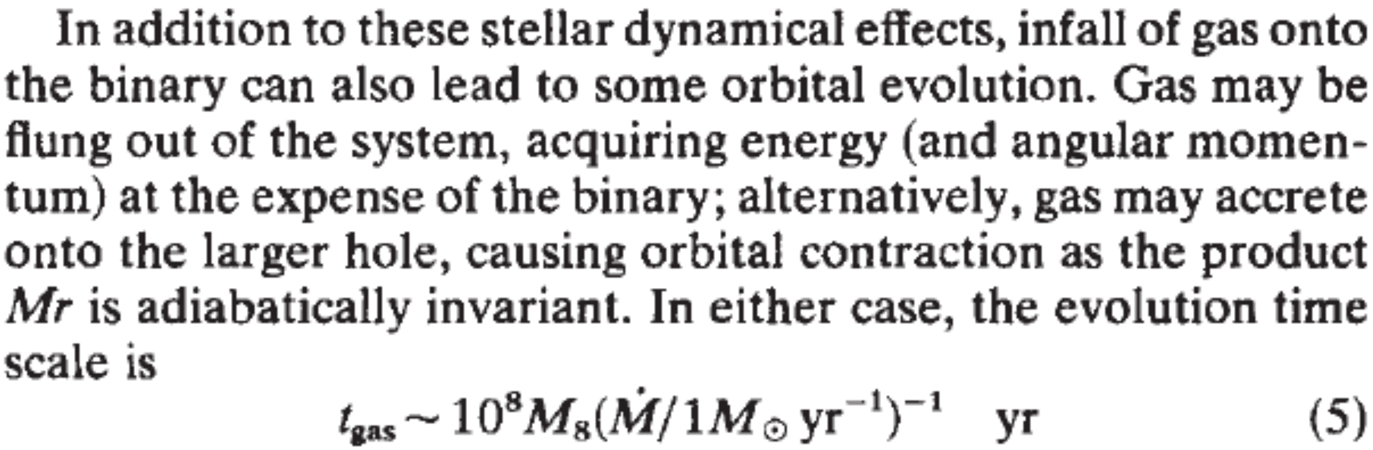
Galaxy merger ➔ SMBH binary in gas disk/torus



Mayer et al 2007

First discussion of the effect of gas accretion on binary BHs:

Begelman, Blandford & Rees 1980 Nature

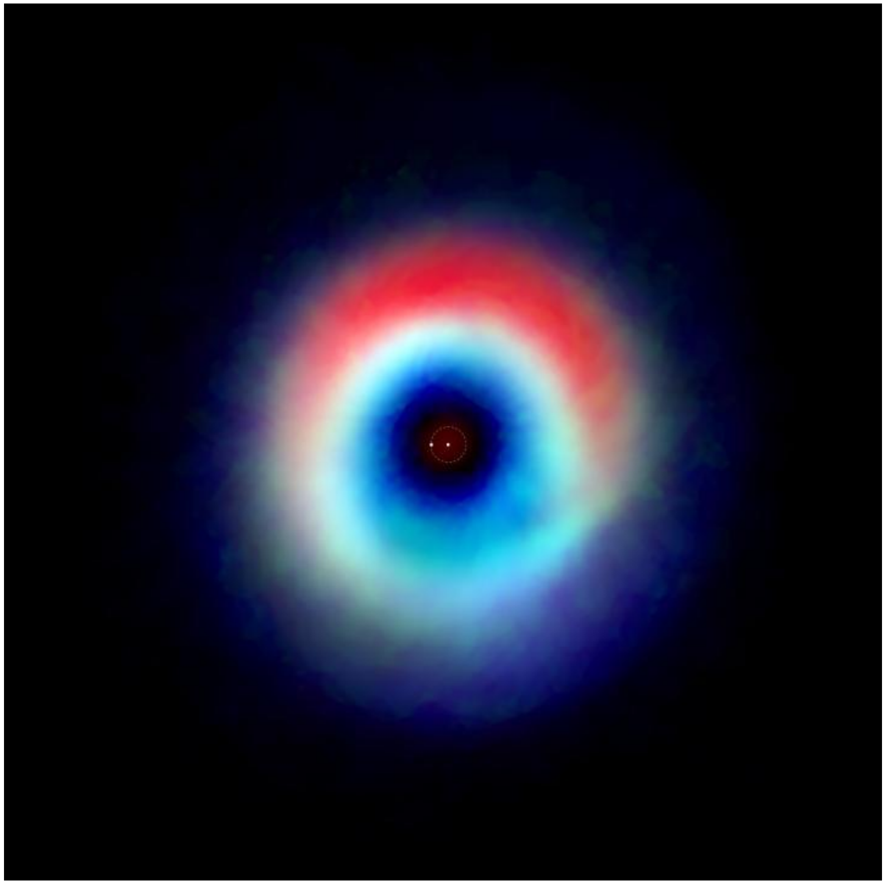


In addition to these stellar dynamical effects, infall of gas onto the binary can also lead to some orbital evolution. Gas may be flung out of the system, acquiring energy (and angular momentum) at the expense of the binary; alternatively, gas may accrete onto the larger hole, causing orbital contraction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

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

Disks around proto-stellar Binaries

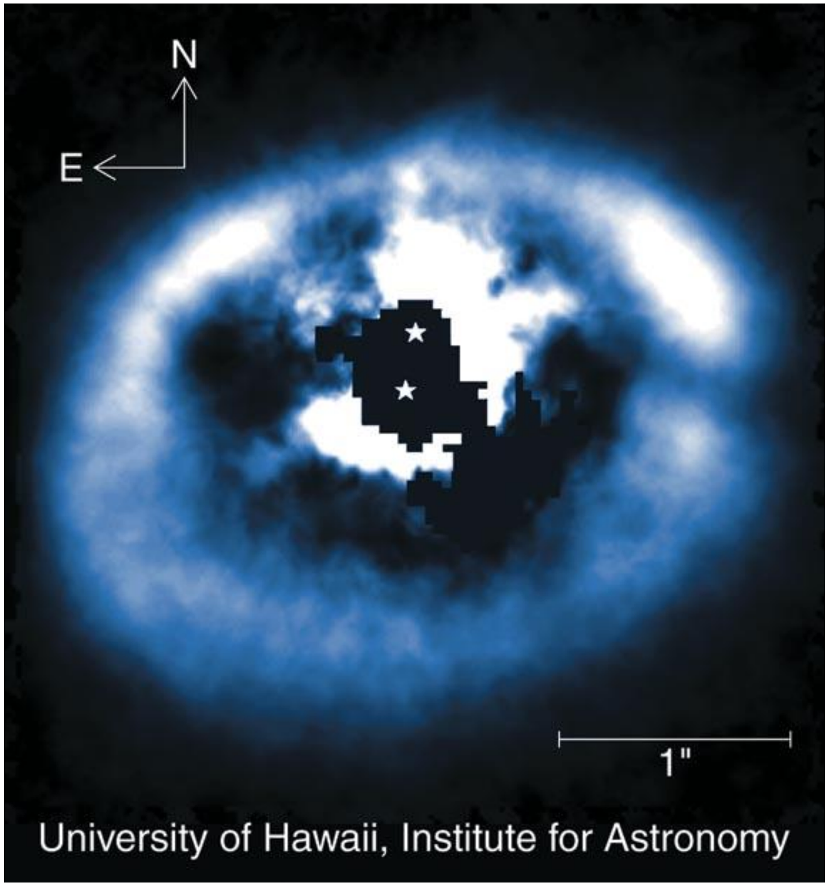
HD 142527



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

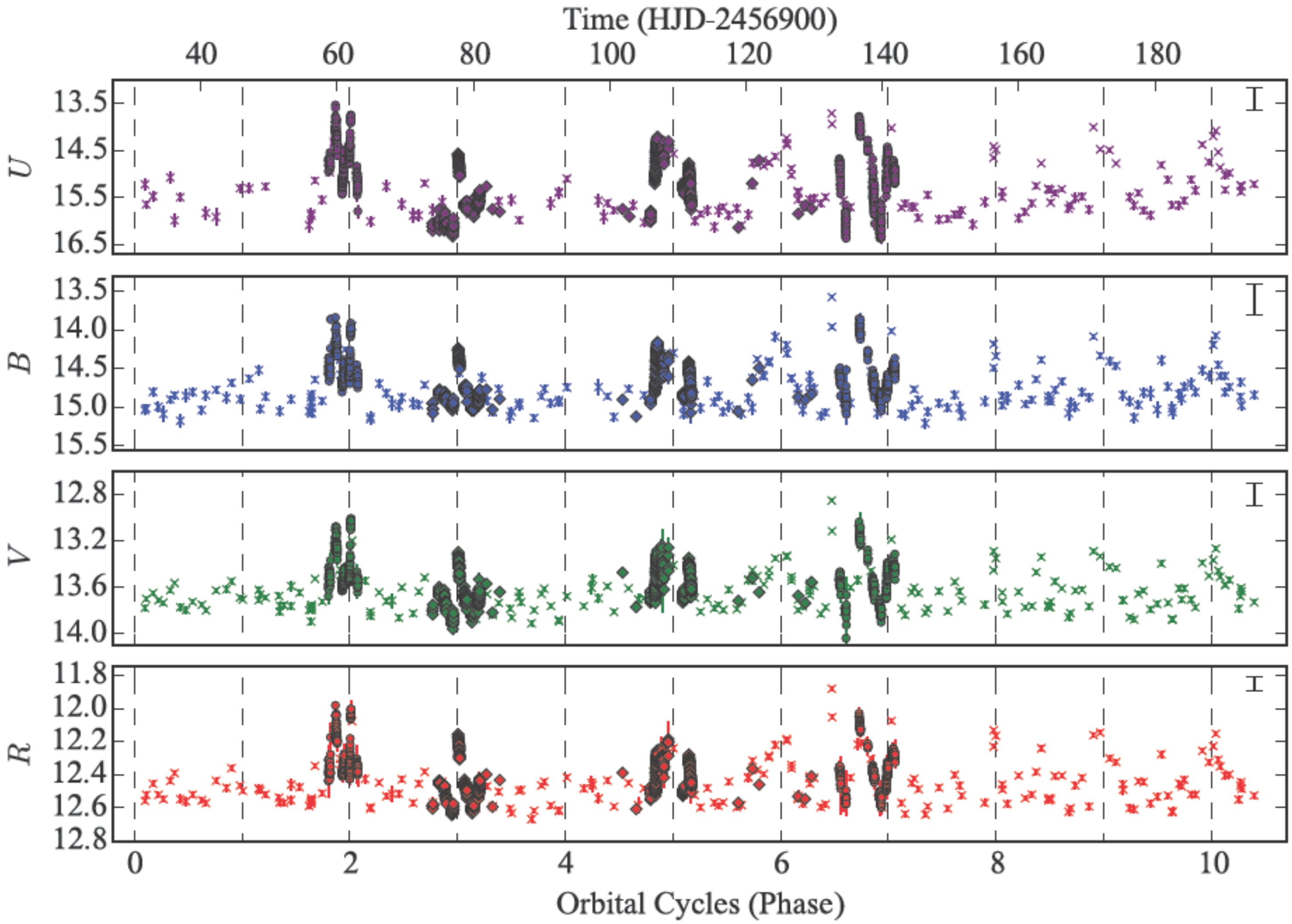
A. Isella/ALMA

GG Tau



Binary: ~60 AU

Pulsed Accretion Observed in T Tauri Binaries



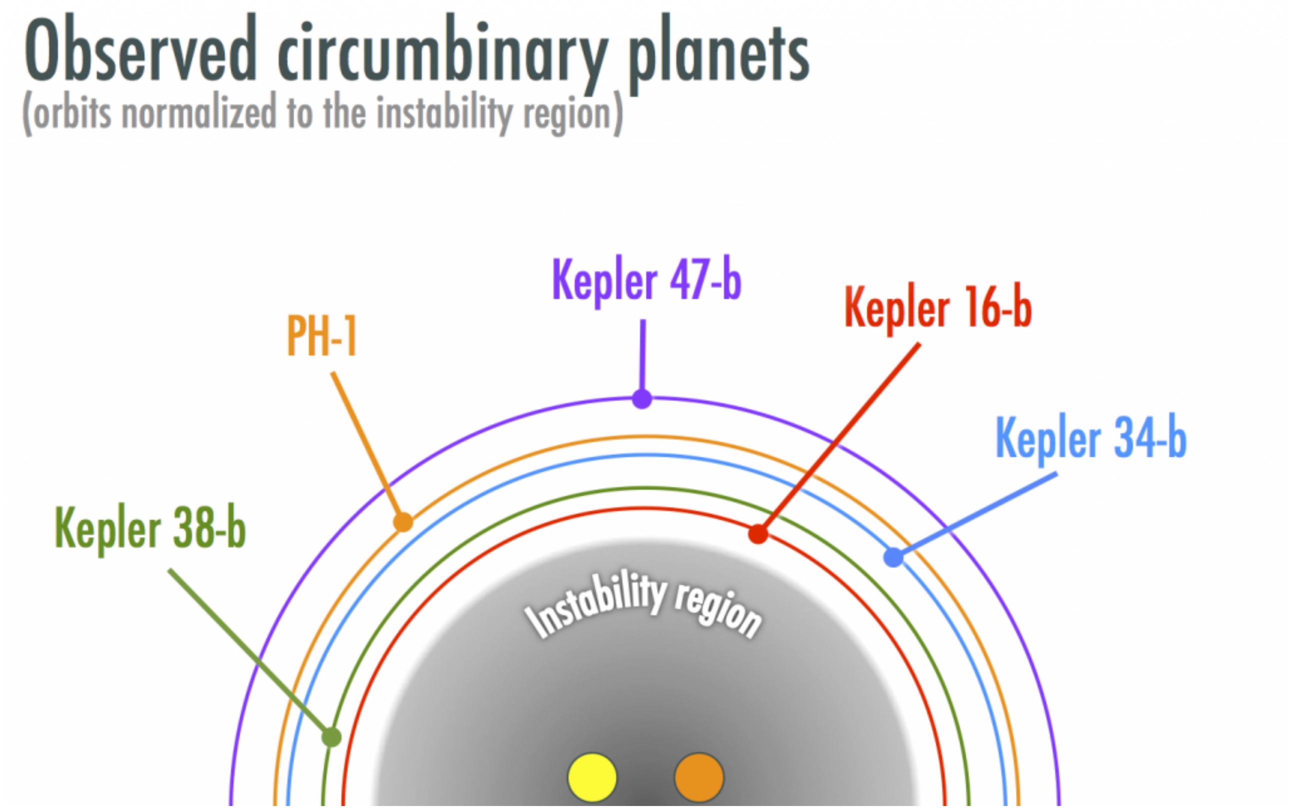
DQ Tau:

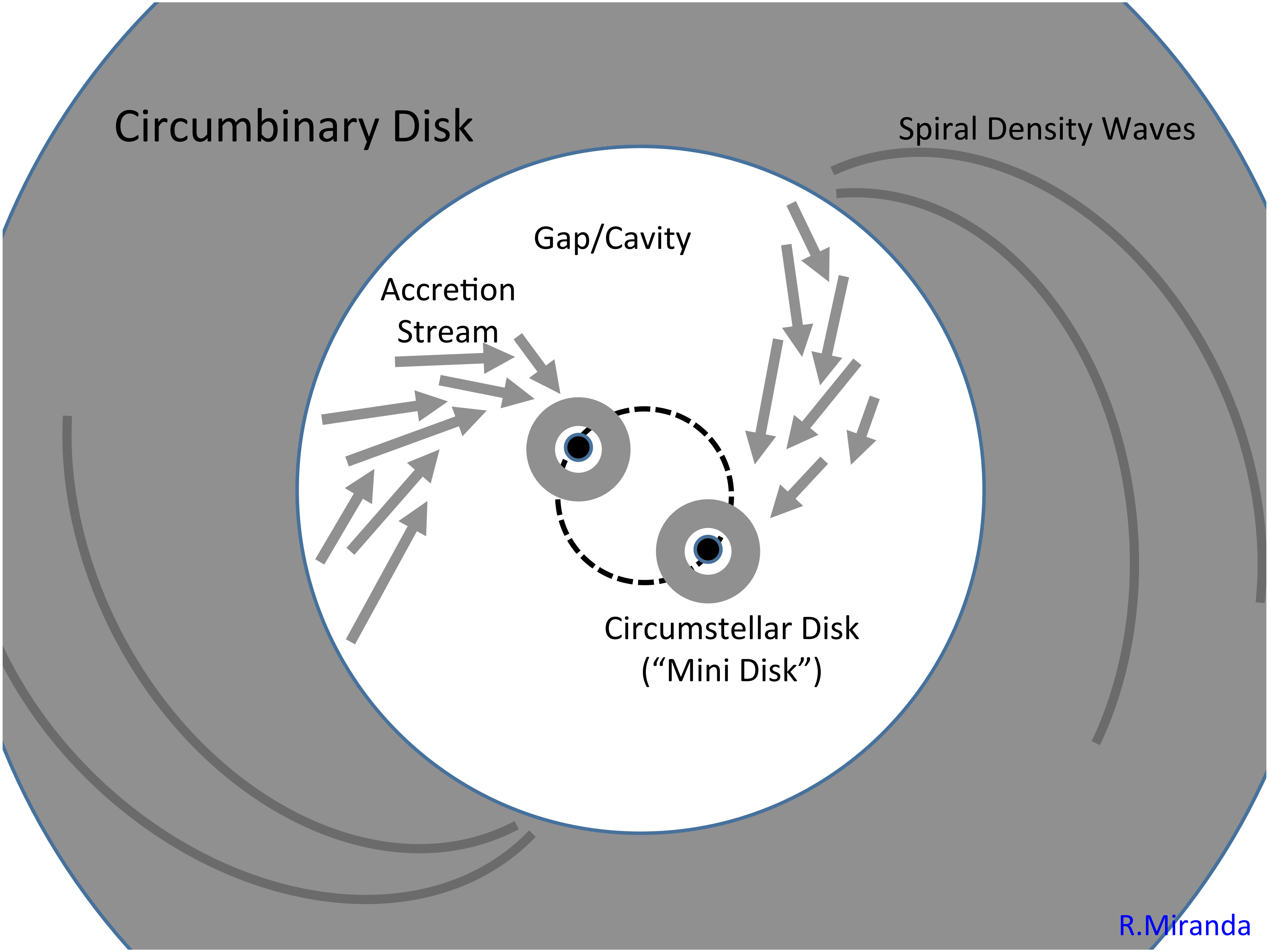
P=15.8 days
a=0.13AU
e=0.57
M1~M2~0.6Sun

Tofflemire et al. 2016

Planets Around Binaries

~12 systems found by transit method



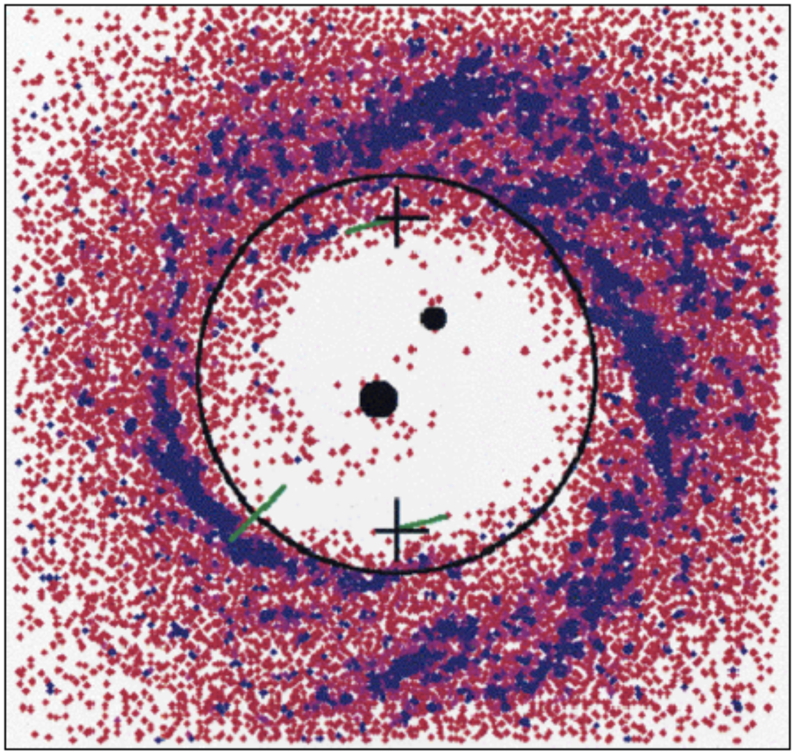

Circumbinary Disk
Spiral Density Waves
Gap/Cavity
Accretion Stream
Circumstellar Disk (“Mini Disk”)
R.Miranda

Simulations of Circumbinary Accretion

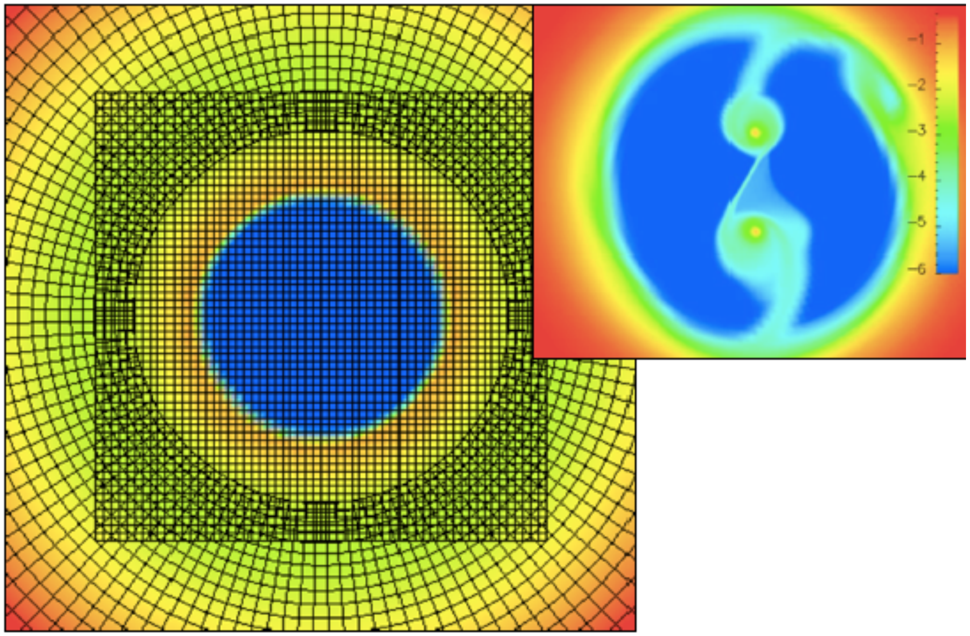
Artymowicz & Lubow 1996; Günther & Kley 2002; MacFadyen & Milosavljević 2008; Cuadra et al.09; Hanawa et al. 2010; de Val-Borro et al. 2011; Roedig et al. 2012; Shi et al. 2012; D'Orazio et al. 2013; Pelupessy & Portegies-Zwart 2013; Farris et al. 2014; Shi & Krolik 2015; Lines et al. 2015; O'Ozario et al. 2016; Ragusa et al. 2016….

Simulations of Circumbinary Accretion

Artymowicz & Lubow (1996) – SPH



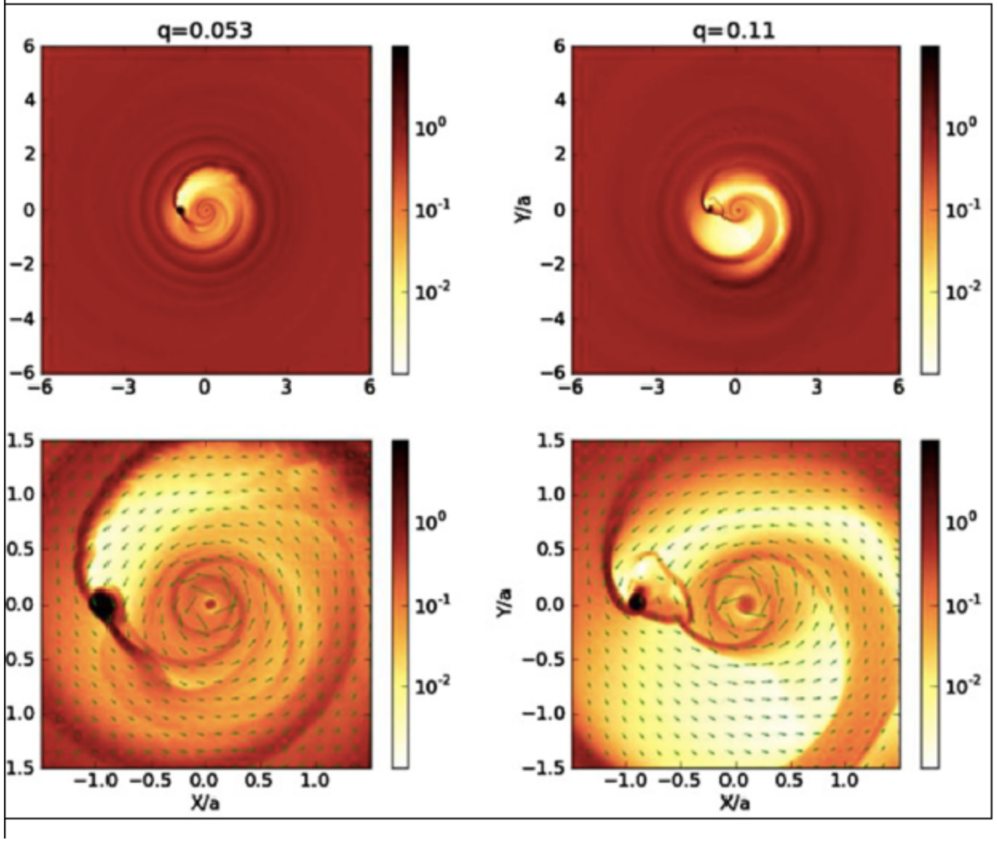
Günther & Kley (2002) – Hybrid grid

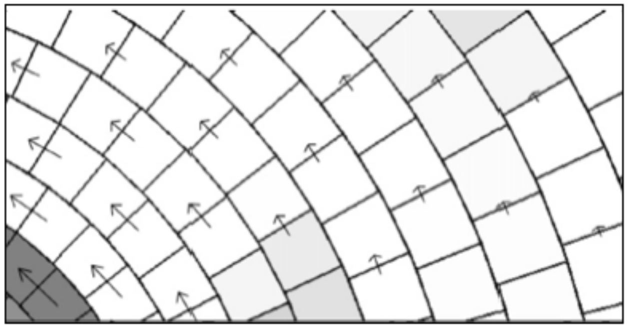


also:
de Val-borro et al. (2011) – cartesian grid
Hanawa et al. (2010) – Nested cartesian

Simulations of Circumbinary Accretion

Farris et al. (2014) – moving rings grid





Duffell & MacFadyen (2012) –
DISCO code

What we do:

Munoz & DL 2016, ApJ
Miranda, Munoz & DL 2017, MNRAS
Munoz, Miranda & DL, in prep

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

Ryan Miranda
(Cornell PhD'17->IAS)

Goals:

-- Accretion onto circular/eccentric binaries: circumbinary->circumstellar disks
-- Short-term & long-term accretion variabilities
-- Disk structure and dynamics (eccentricity, precession)
-- Angular momentum transfer between binary and disk
-- Key feature: Disk reaches quasi-steady state

$$\left\langle \dot{M}(r,t) \right\rangle \simeq \text{const}$$

Numerical Tools

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

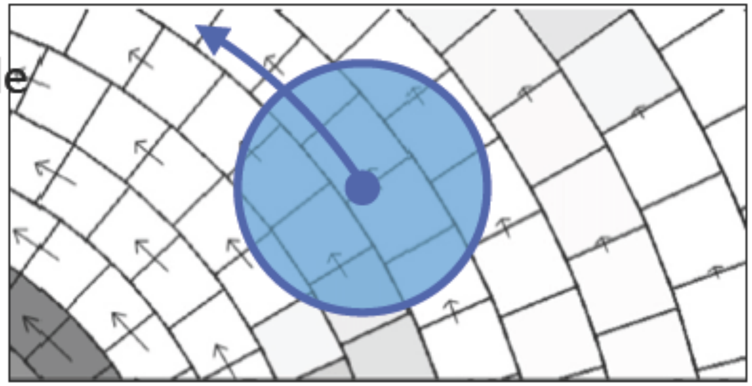
-- Numerical codes:

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 $0.02a_b$

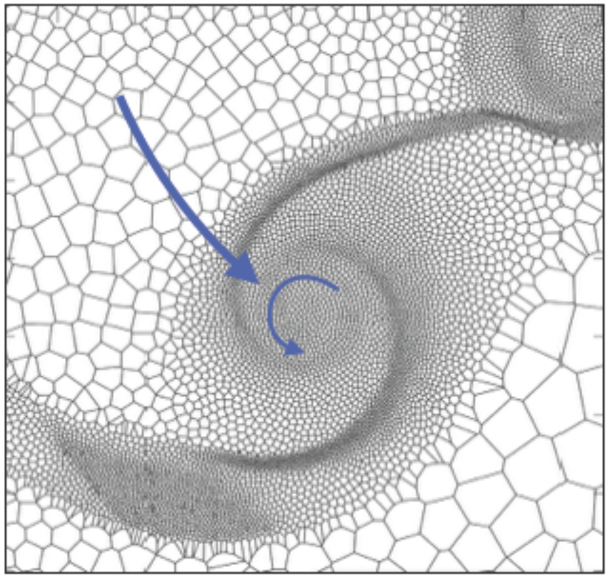
AREPO (Springel, 2010)

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

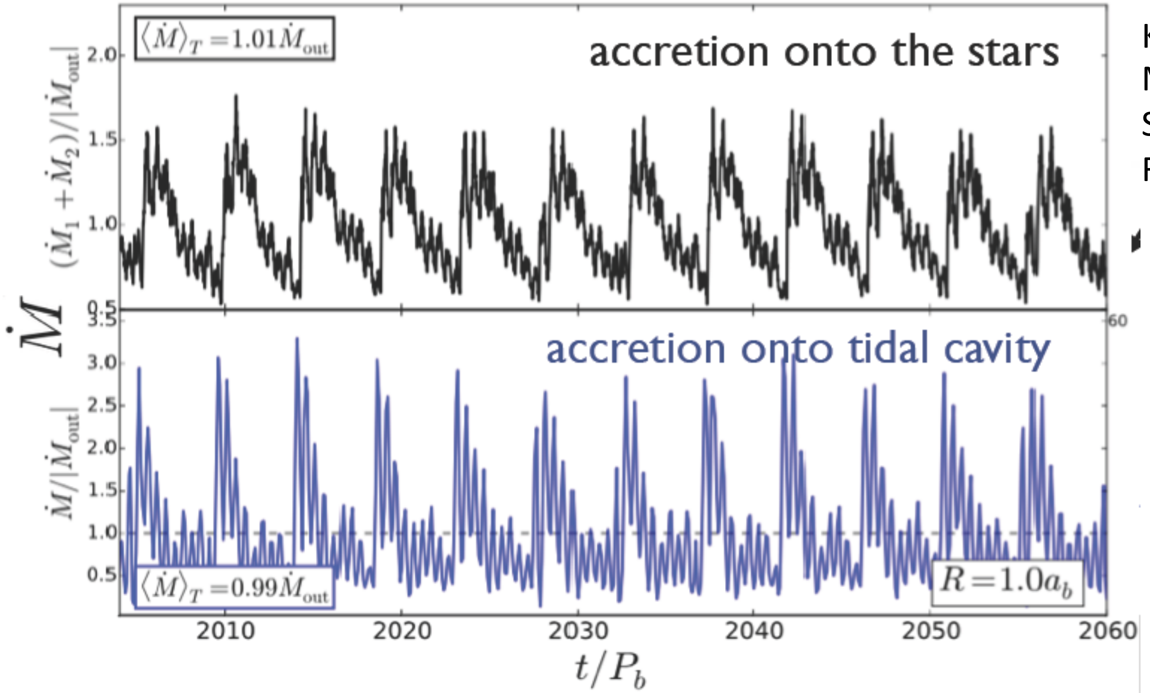
Binary mass ratio $q \sim 1$ ($\gtrsim 0.2$)

Disk $H/r \sim 0.1$, $\alpha = 0.05 - 0.1$

Short-term (~P_b) Accretion Variabilities

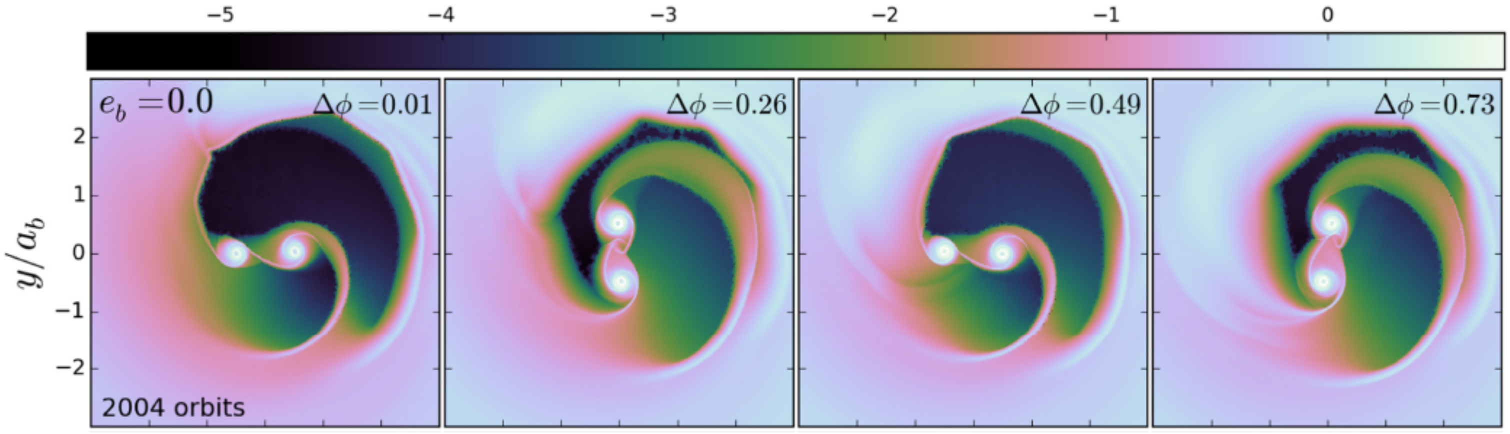
For $e_b \lesssim 0.05$: $\dot{M}(=\dot{M}_1+\dot{M}_2)$ varies at $\sim 5P_b$ (Kepler period at r_{in} ~ $3a_b$)

e_b=0



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

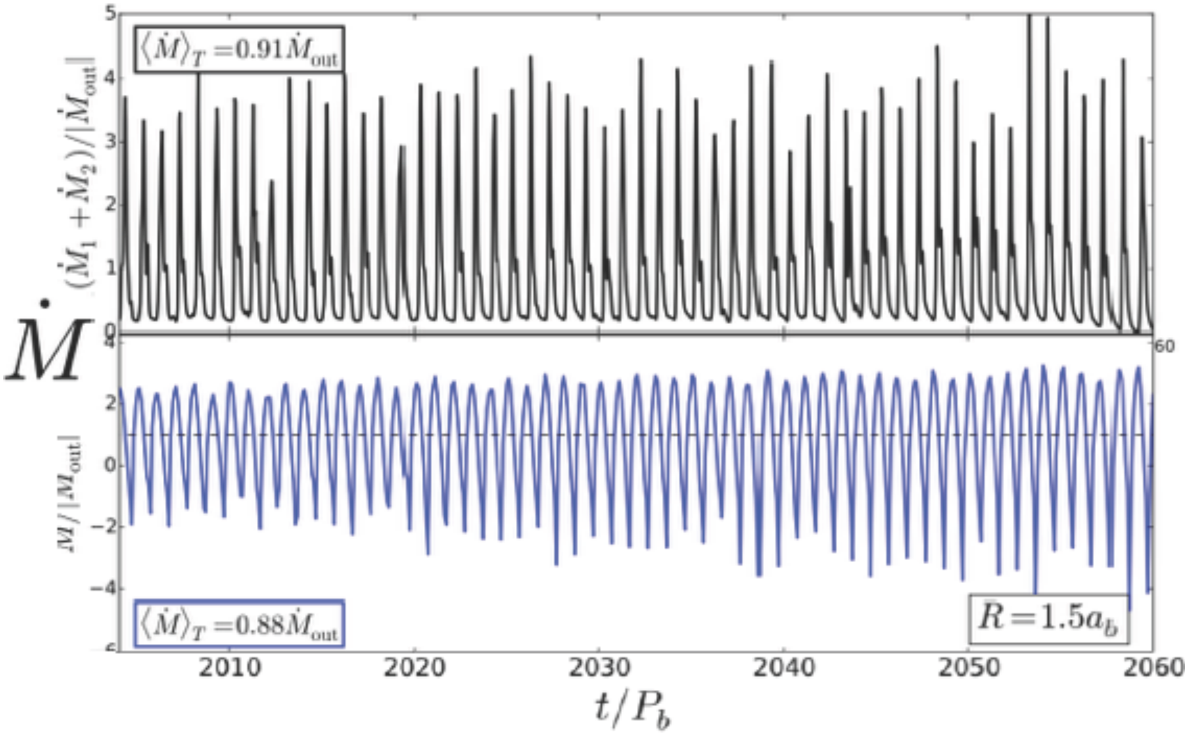
Munoz & DL 16



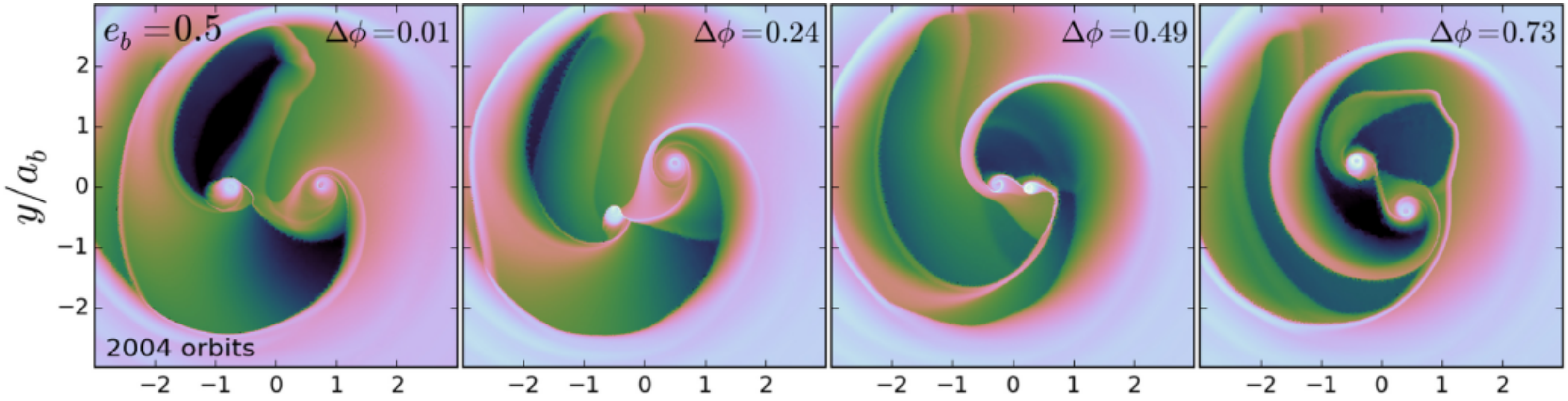
Short-term (~P_b) Accretion Variabilities

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

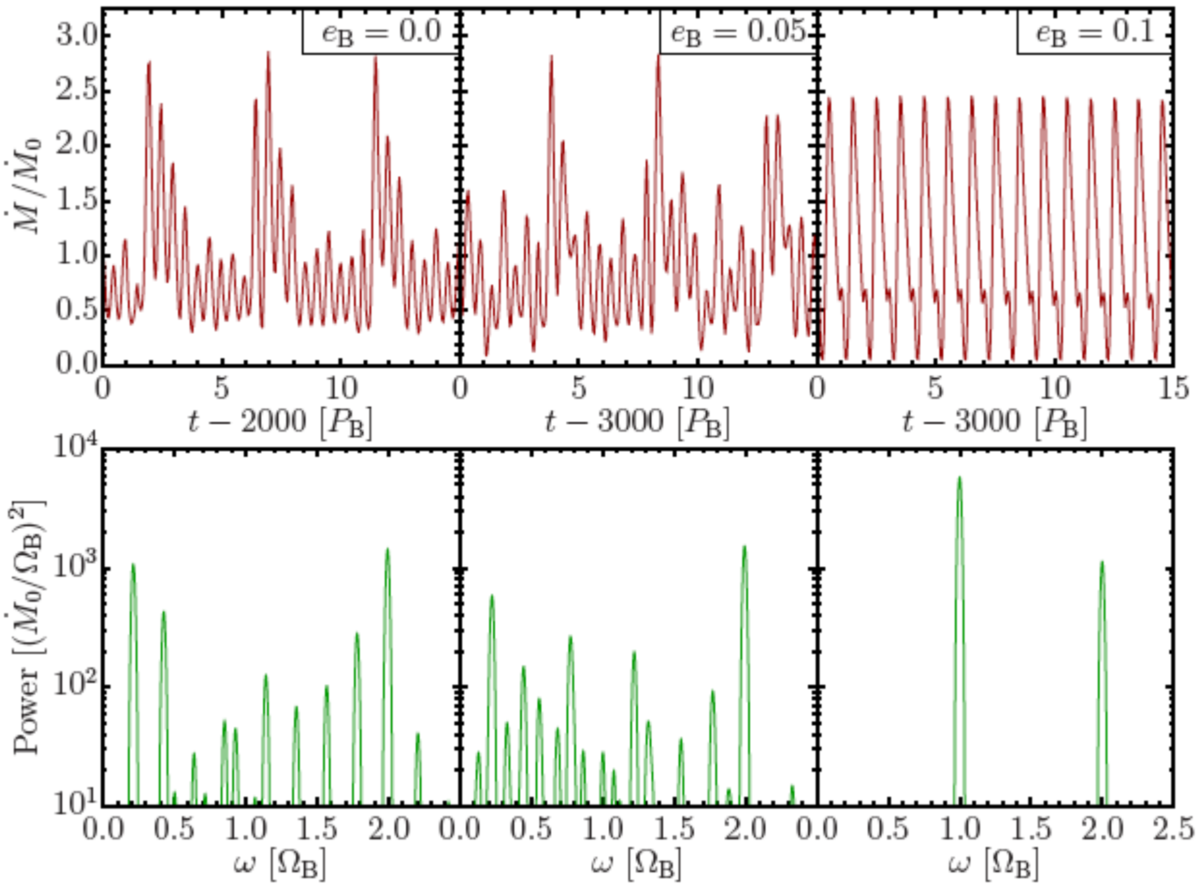


Short-term (~P_b) Accretion Variabilities

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 $\simeq P_b$

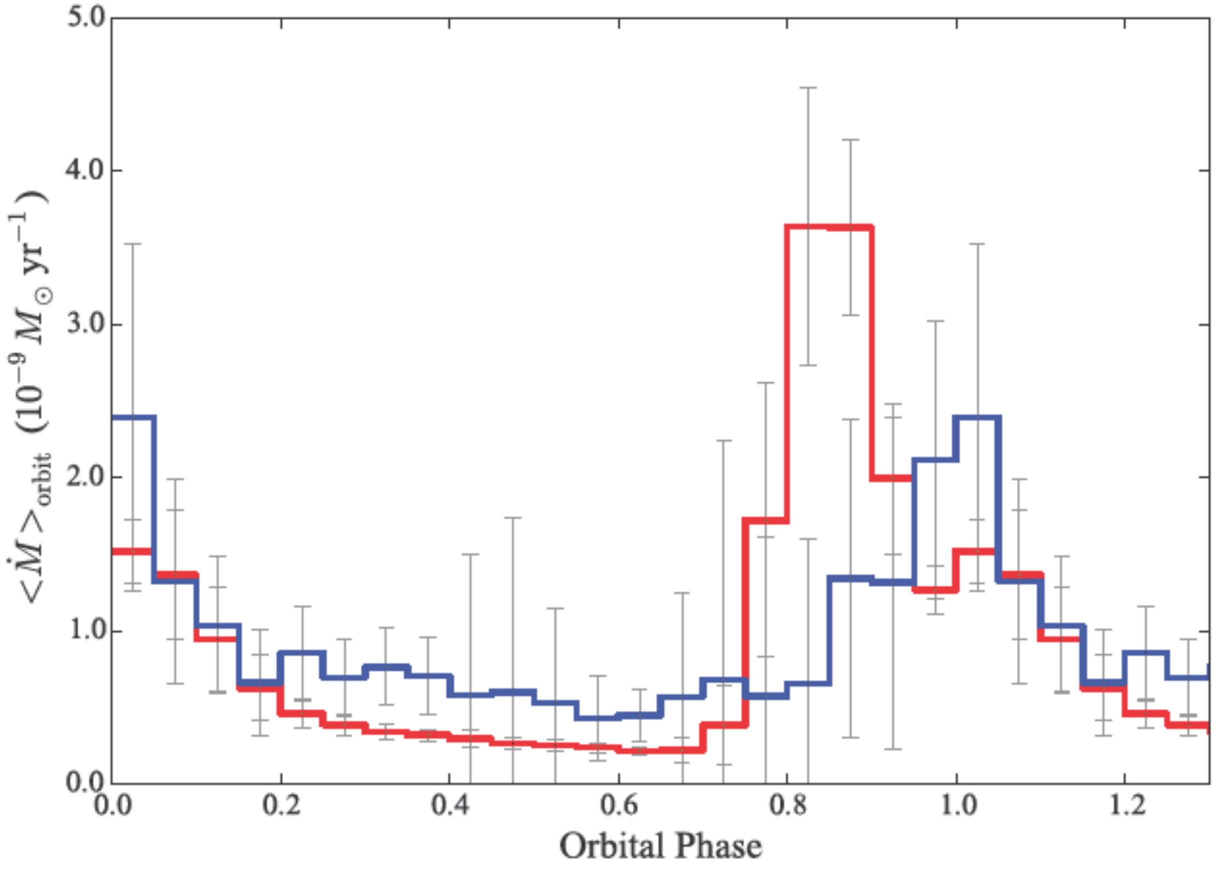
Power spectrum



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



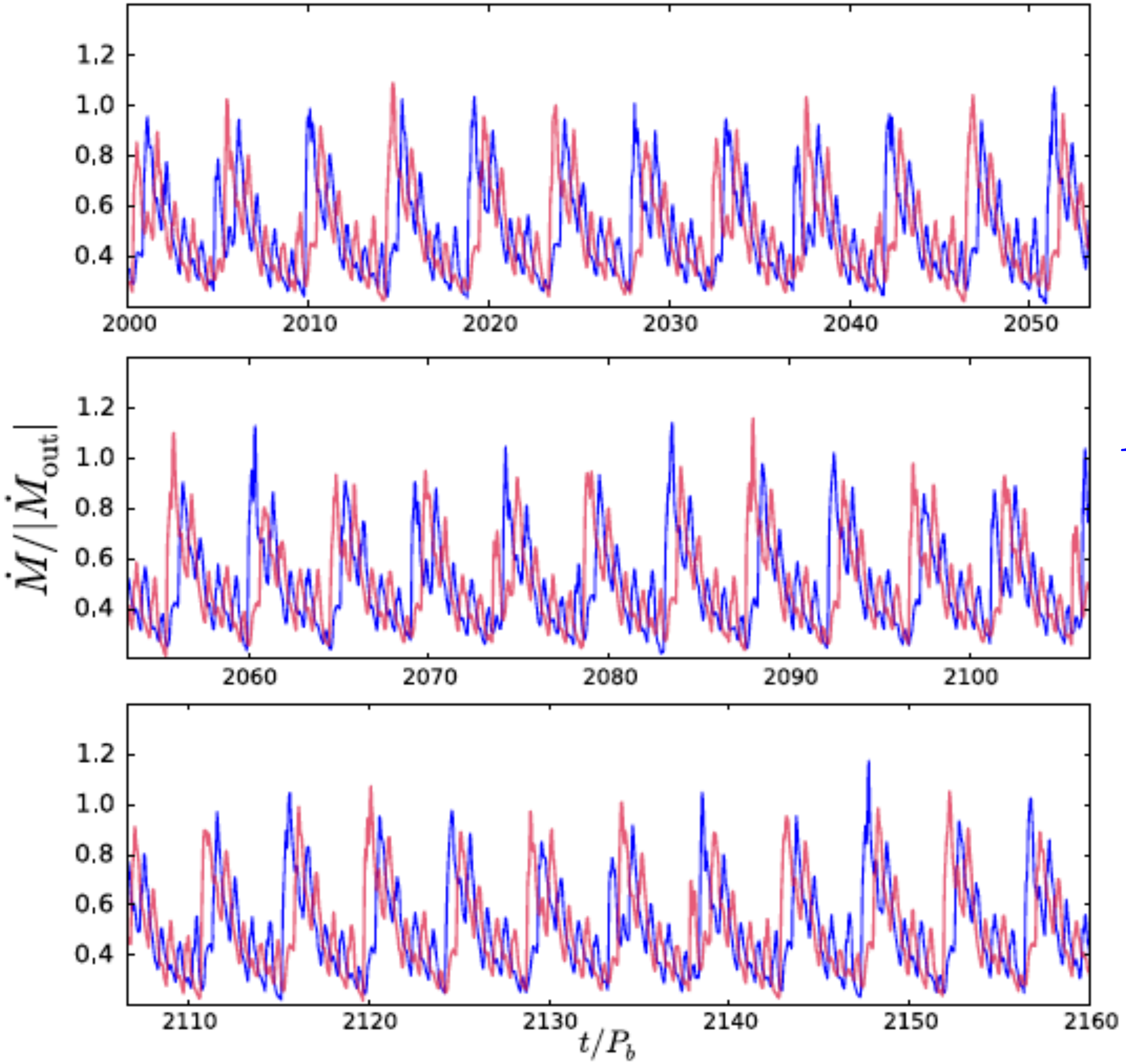
red: simulation (D. Munoz)

blue: observations

➔ Can resolve the effective size of stars

Ben Tofflemire, Mathieu et al (in prep)

Long-Term Evolution:

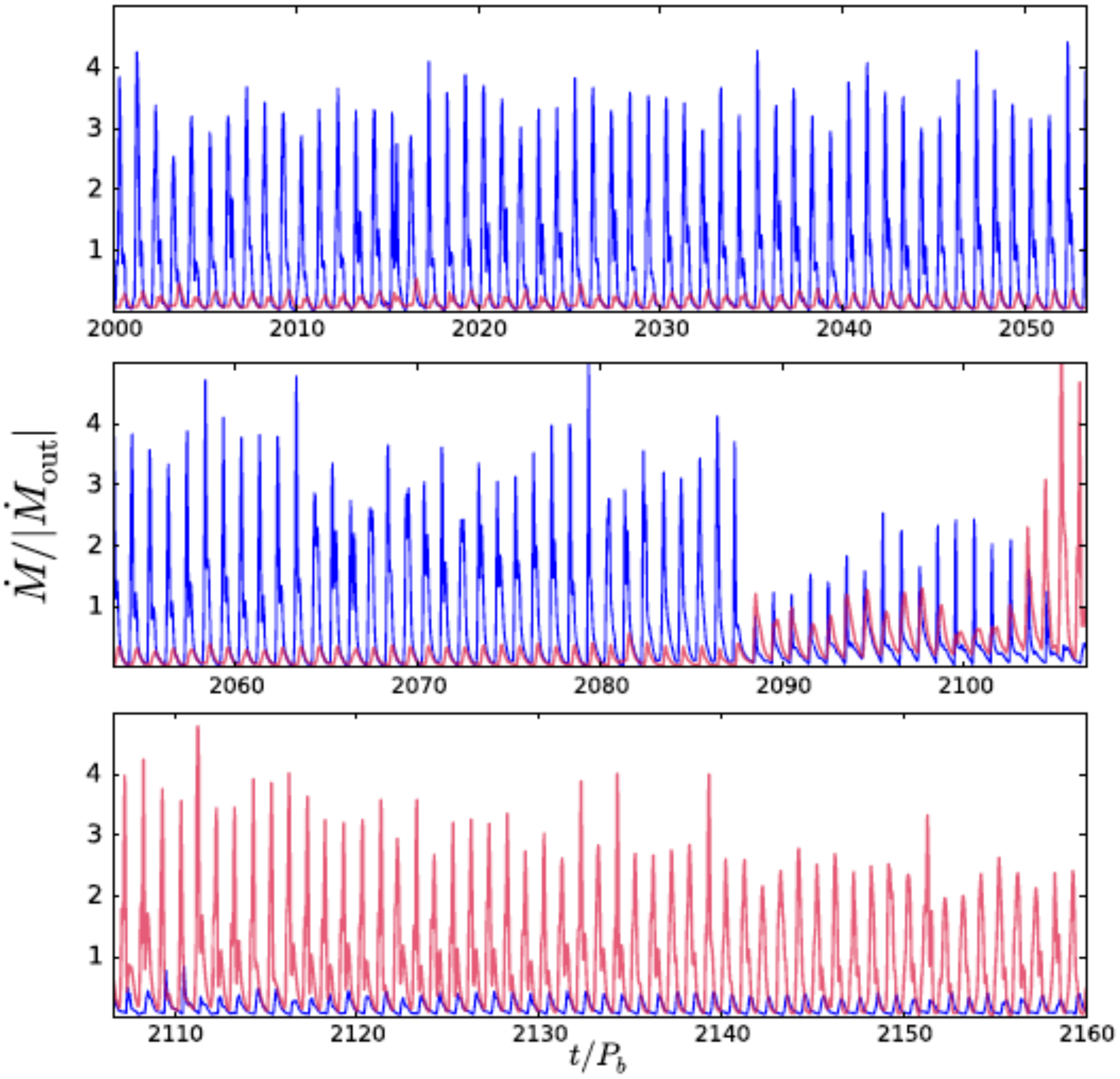


e_b=0

q_b=1

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

Long-Term Evolution: Symmetry Breaking



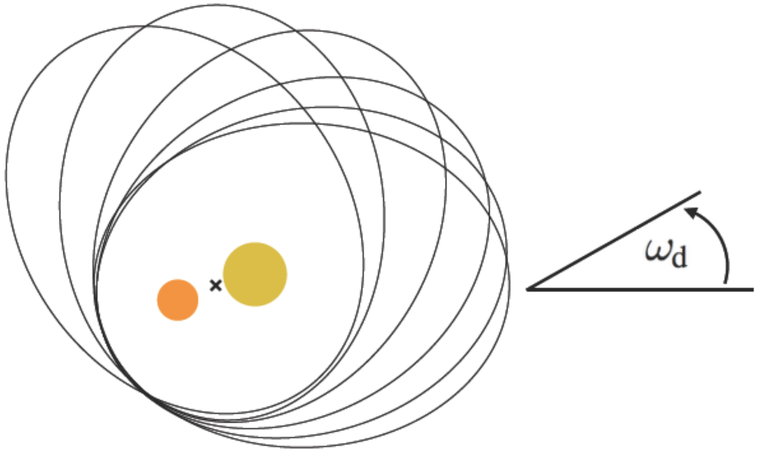
e_b=0.5
q_b=1

Switch between
$\dot{M}_1 \gtrsim 20\dot{M}_2$
and
$\dot{M}_2 \gtrsim 20\dot{M}_1$
every ~200 P_b

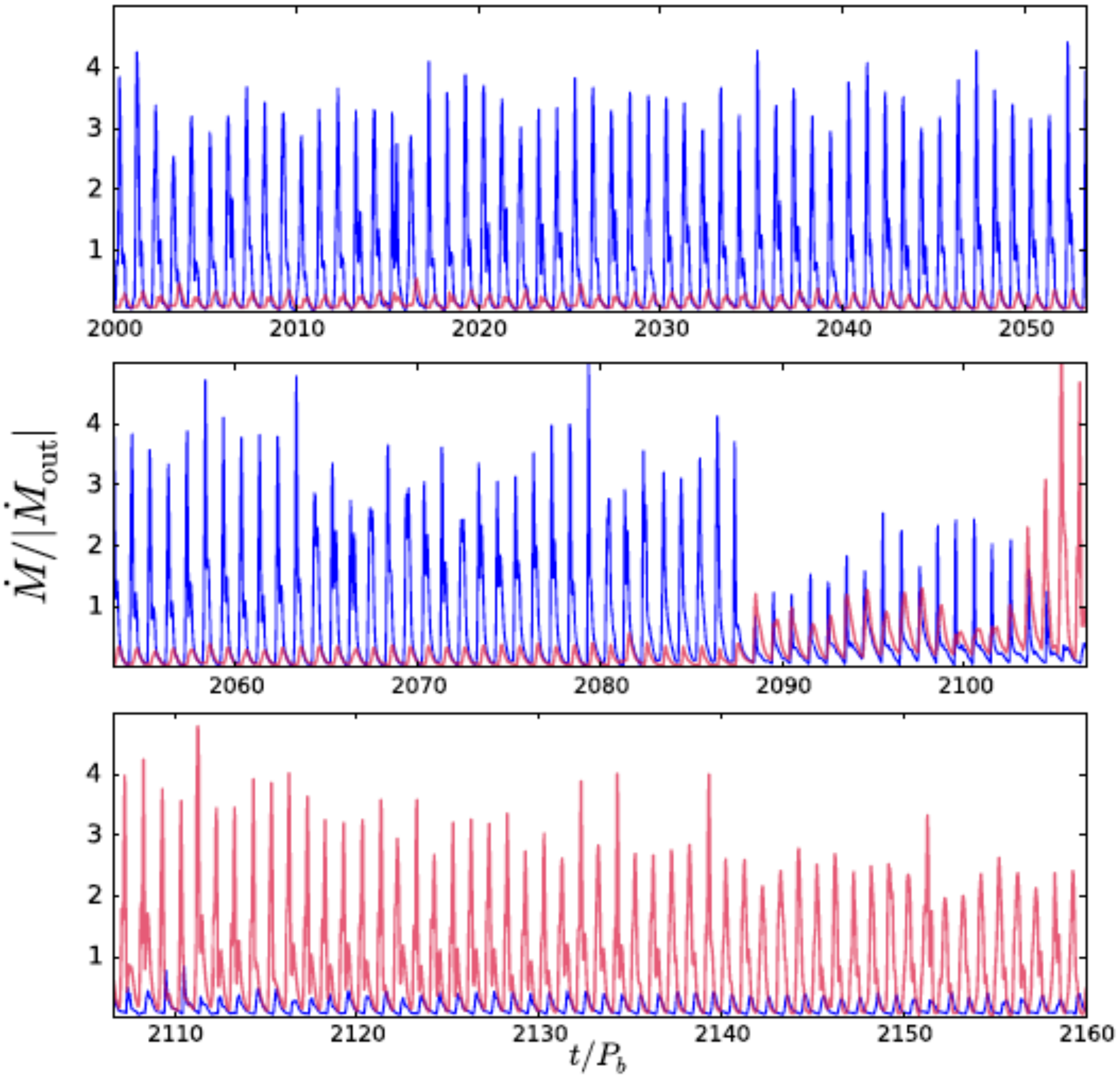
Apsidal precession of eccentric disk around the binary

$$\dot{\omega}_{\rm d} \simeq \frac{3\Omega_{\rm b}}{4}\frac{q_{\rm b}}{(1+q_{\rm b})^2}\left(1+\frac{3}{2}e_{\rm b}^2\right)\left(\frac{a_{\rm b}}{R}\right)^{7/2}$$
$$\sim 0.006\,\Omega_{\rm b}\left(\frac{3a_{\rm b}}{R}\right)^{7/2},$$

Precession period 200-300 P_b



Long-Term Evolution: Symmetry Breaking



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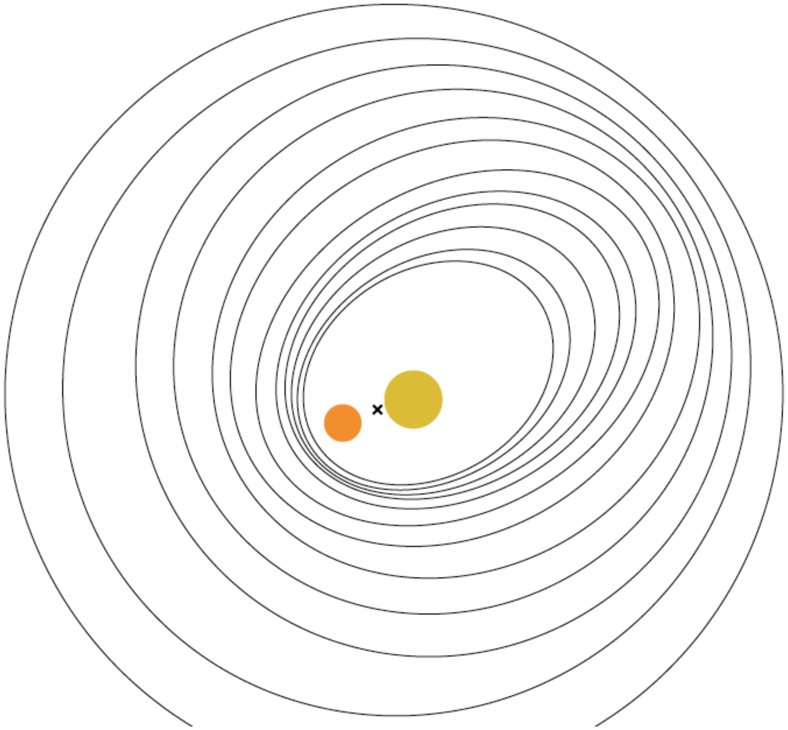
Long-Term Evolution: Disk Eccentricity

Inner disk ($<10a_b$) is coherently eccentric



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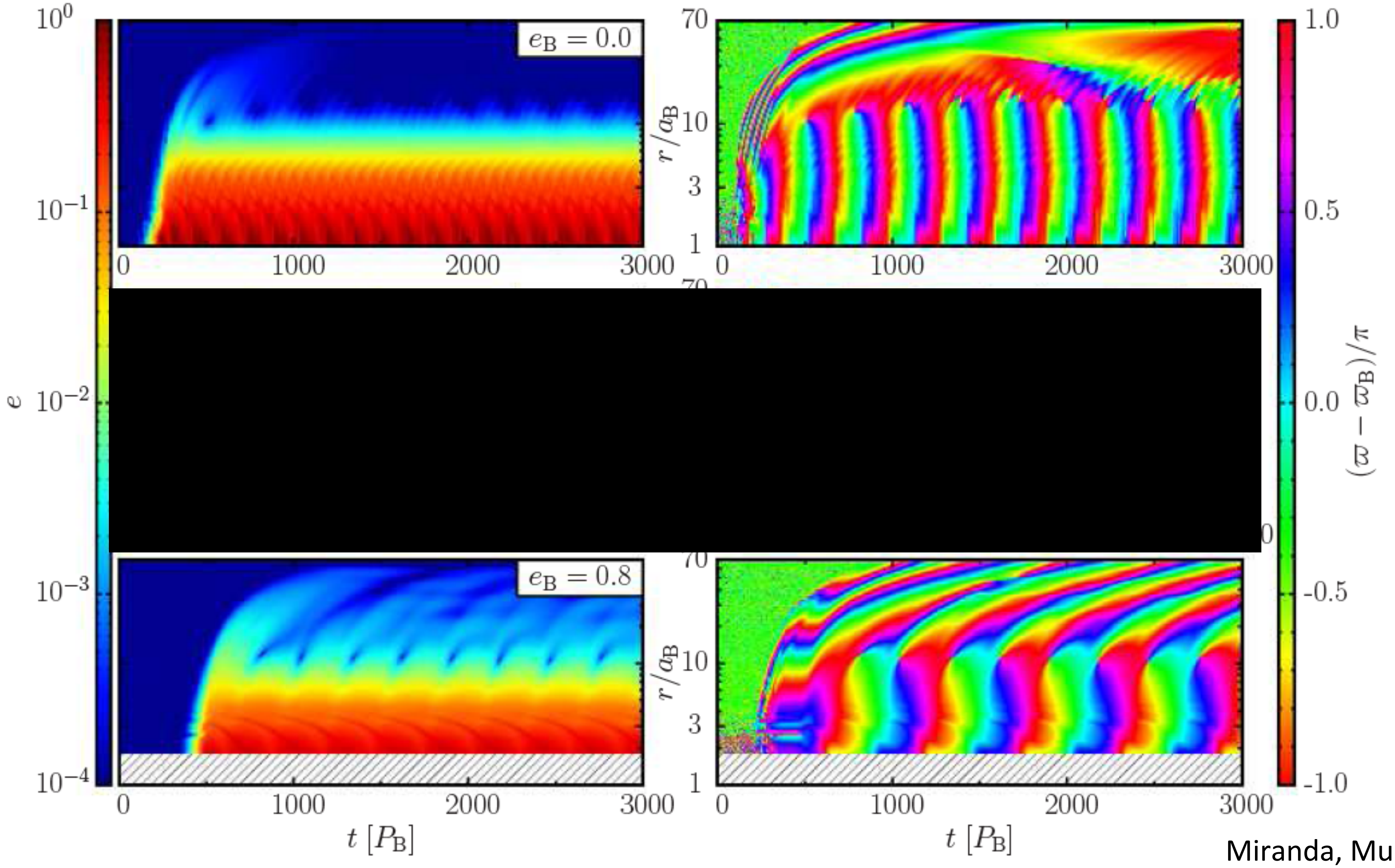
Long-Term Evolution: Disk Eccentricty

Inner disk (<10 a_b) is coherently eccentric

For $e_b \lesssim 0.2$ and $\gtrsim 0.4$: coherent apsidal precession



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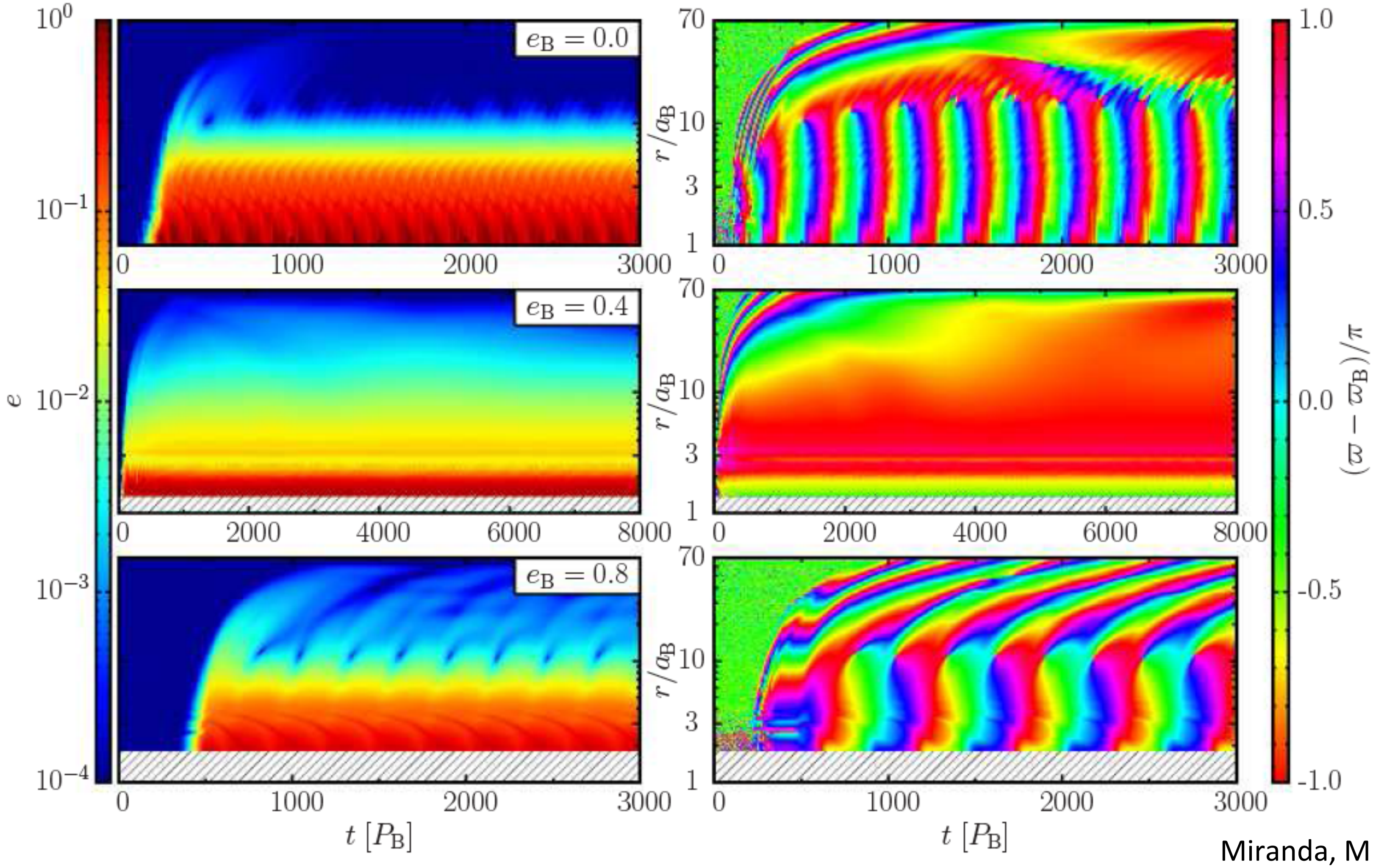
Long-Term Evolution: Disk Eccentricty

Inner disk (<10 a_b) is coherently eccentric

For $e_b \lesssim 0.2$ and $\gtrsim 0.4$: coherent apsidal precession

For $0.2 \lesssim e_b \lesssim 0.4$: apsidally locked to binary



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Theory of Eccentric Disks: Driving and Dynamics

Tidal potential from inner binary on disk:

$$\Phi(r,\phi,t) = \sum_{m,N} \Phi_{mN} \cos(m\phi - N\Omega_b t) = \sum_{m,N} \Phi_{mN} \cos\left[m(\phi - \omega_p t)\right]$$

$$m = 2, 3, \cdots\,, \quad N = 1, 2, \cdots \qquad (\text{for } q_b = 1)$$

$$\text{Pattern frquency}: \ \omega_p = \frac{N\Omega_b}{m}$$

cf. Lubow 91

Goodchild & Ogilvie 2006

Miranda, Munoz & DL 2017

Eccentricty excitation by rotating potential

"Eccentric Lindblad Resonance"

(parametric resonance)

Epicyclic motion of test mass in disk

$$\frac{d^2\Delta r}{dt^2} + \kappa^2 \Delta r = 0 \qquad (\kappa \simeq \Omega)$$

In the presence of the potential $\Phi_{mN}\cos[m(\phi - \omega_p t)]$:

$$\frac{d^2\Delta r}{dt^2} + \kappa^2 \left[1 + \epsilon \cos m(\omega_p - \Omega)t\right] \Delta r = 0 \qquad (\epsilon \propto \Phi_{mN})$$

Parametric resonance occurs when

$$m(\omega_p - \Omega) = 2\kappa \simeq 2\Omega \quad \Longrightarrow \quad \Omega = \frac{m\,\omega_p}{m+2} = \frac{N\Omega_b}{m+2}$$

Theory of Eccentric Disks: Driving and Dynamics (continued)

Parametric resonance occurs when

$$m(\omega_p - \Omega) = 2\kappa \simeq 2\Omega \quad \Longrightarrow \quad \Omega = \frac{m\,\omega_p}{m+2} = \frac{N\Omega_b}{m+2}$$

The most important tidal components are

$$m = 2,\ N = 1: \quad \text{Resonance at } \Omega = \frac{\Omega_b}{4}, \quad \Phi_{21} \propto e_b$$

$$m = 2,\ N = 2: \quad \text{Resonance at } \Omega = \frac{\Omega_b}{2}, \quad \Phi_{21} \propto \left(1 - \frac{5}{2}e_b^2\right) \text{ and} \to 0 \text{ for large } e_b$$

Combine eccentricity driving by at resonances with pressure and viscosity

$$\begin{aligned} 2r\Omega\frac{\partial E}{\partial t} &= -\frac{\mathrm{i}E}{r}\frac{\partial}{\partial r}\left(r^2\frac{\partial \Phi_2}{\partial r}\right) + \frac{\mathrm{i}E}{\Sigma}\frac{\partial P}{\partial r} \\ &+ \frac{\mathrm{i}}{r^2\Sigma}\frac{\partial}{\partial r}\left[(1-\mathrm{i}\alpha_\mathrm{b})Pr^3\frac{\partial E}{\partial r}\right] \\ &+ \sum_i 2a_\mathrm{B}\gamma_i r\Omega E\delta(r - r_{\mathrm{res},i}), \end{aligned} \qquad E = e\exp(\mathrm{i}\varpi)$$

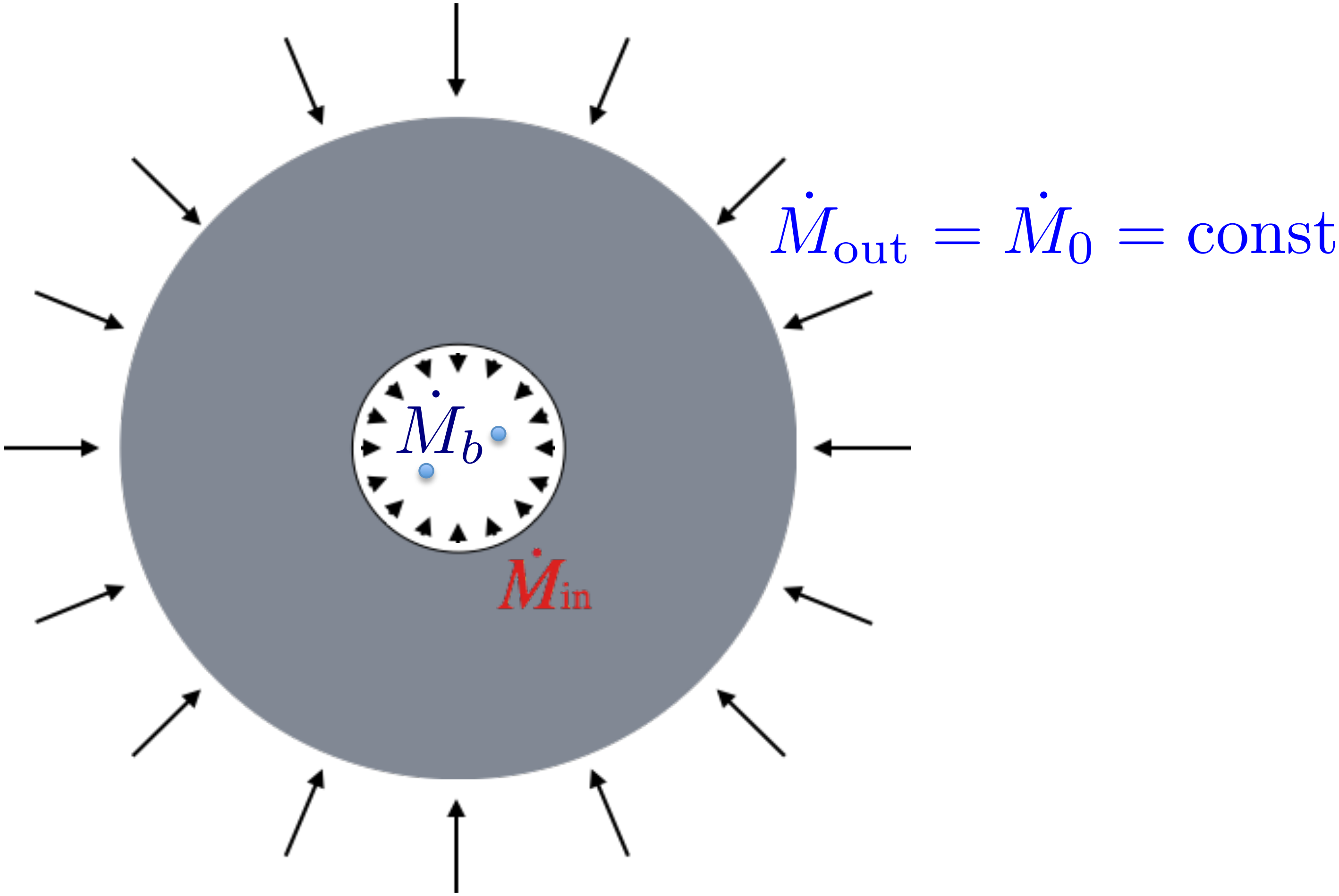
$\Longrightarrow$

$$\text{For } e_b \lesssim 0.2: \quad e \text{ driven by } \Omega = \frac{\Omega_b}{2} \text{ resonance; disk precesses}$$

$$\text{For } e_b \gtrsim 0.4: \quad e \text{ driven by } \Omega = \frac{\Omega_b}{4} \text{ resonance; disk precesses}$$

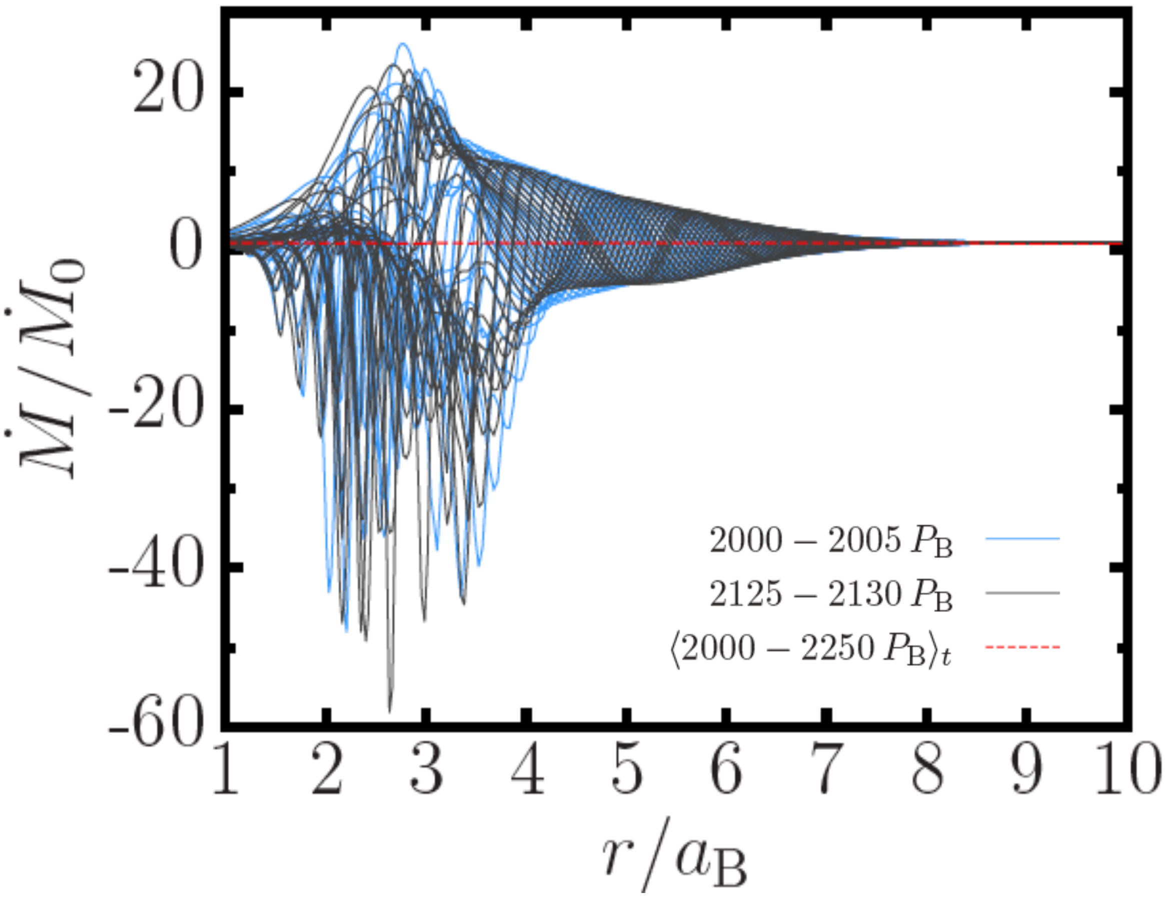
$$\text{For } 0.2 \lesssim e_b \lesssim 0.4: \quad e \text{ driving suppressed by viscosity} \Longrightarrow e\exp(i\omega) \text{ freezes}$$

Angular Momentum Transfer to Binary


$\dot{M}_{\rm out} = \dot{M}_0 = {\rm const}$
$\dot{M}_b$
$\dot{M}_{\rm in}$

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

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



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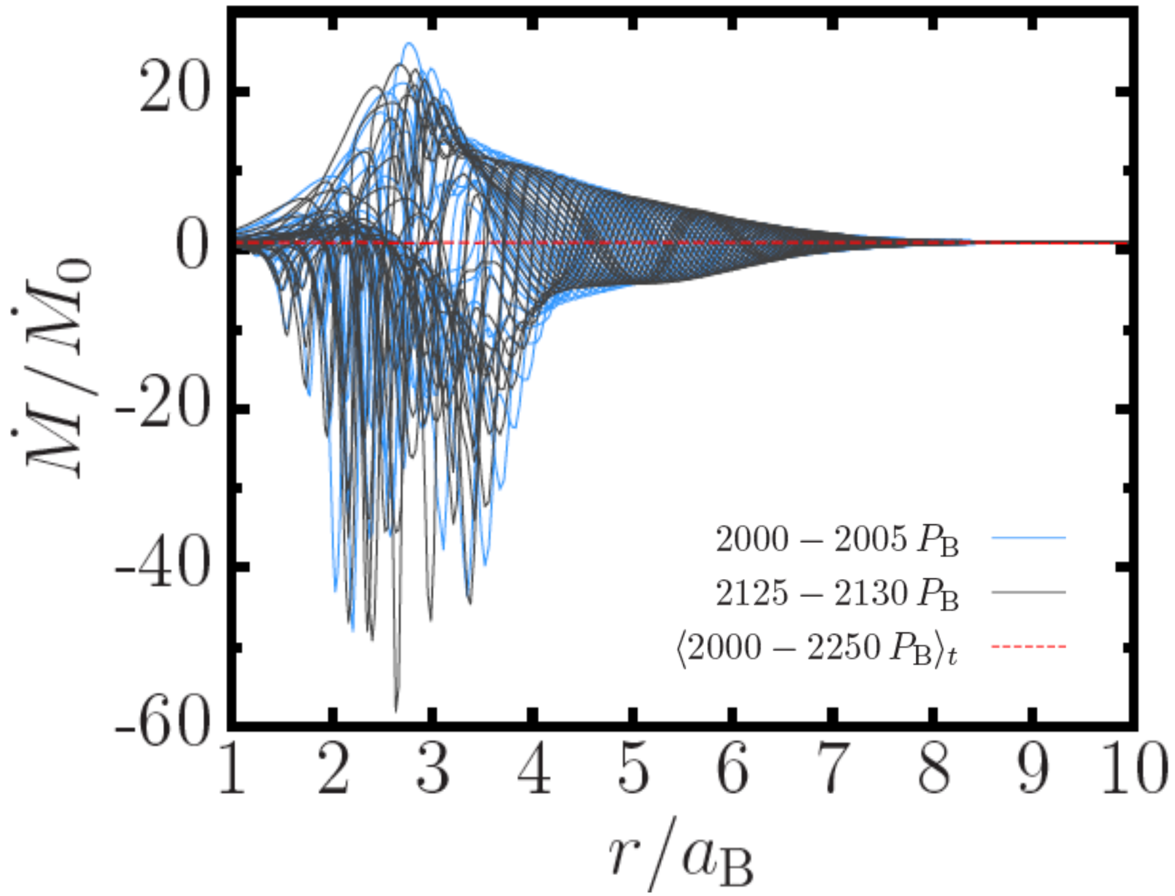
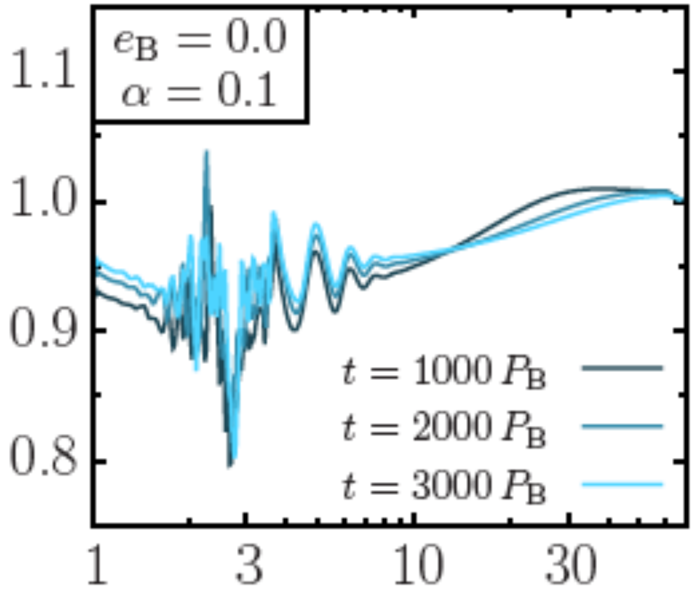


$\langle\dot{M}\rangle/\dot{M}_0$ (averaged over 250 P_b)



Angular Momentum Transfer Rate

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

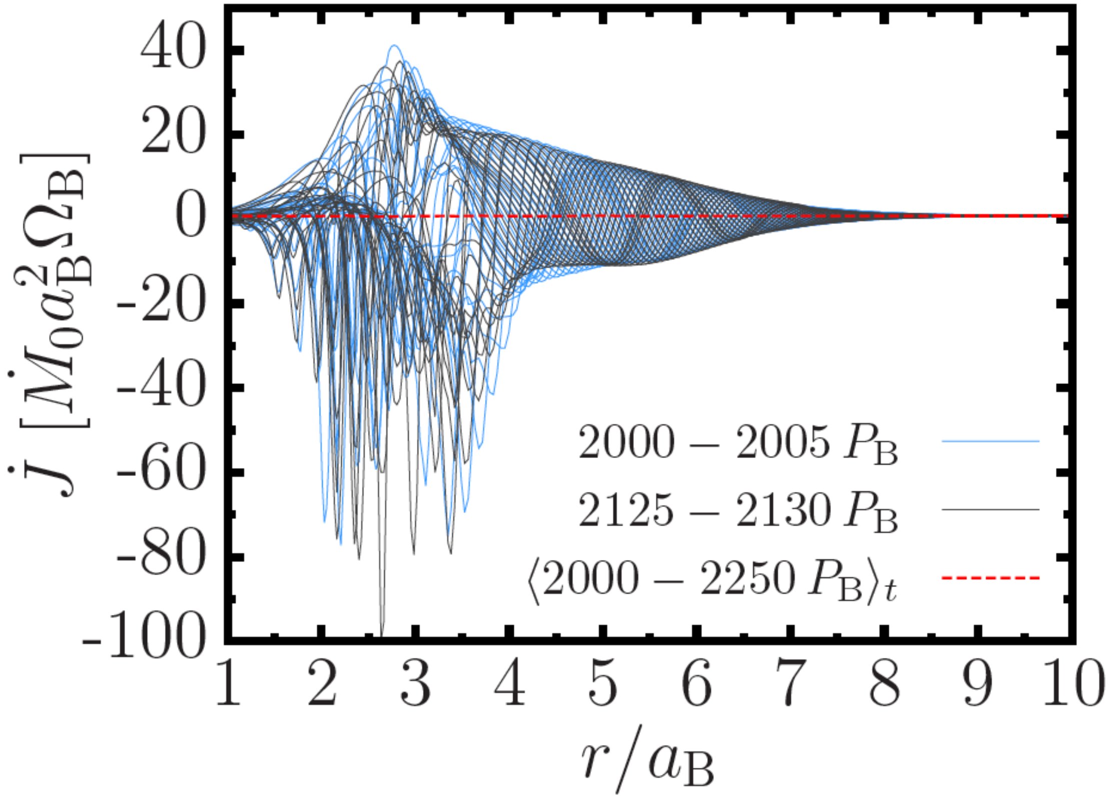
$$\dot{J}_{\rm adv} = -\oint r^2 \Sigma u_r u_\phi {\rm d}\phi$$

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

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

Angular Momentum Transfer Rate

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



Angular Momentum Transfer Rate

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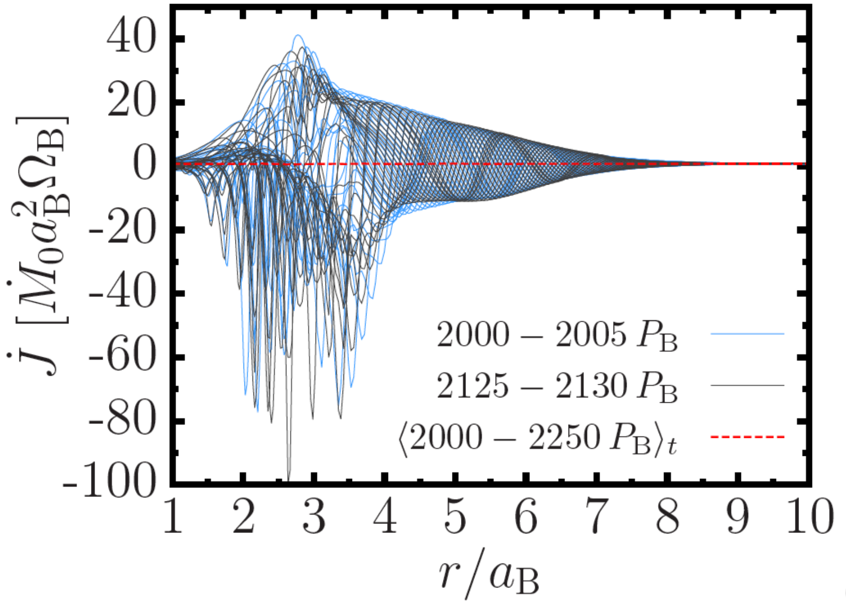
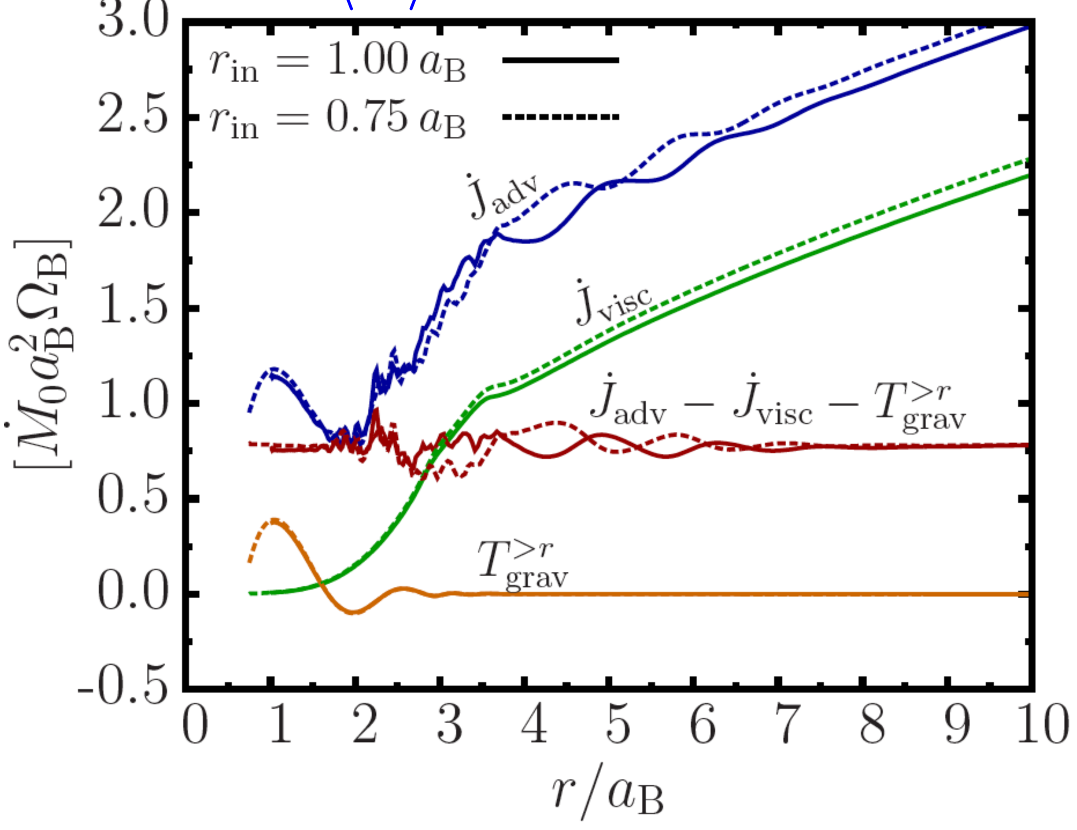


$\langle \dot{J} \rangle$ (averaged over 250 P_b)



Angular Momentum Transfer Rate

Recap: Although the accretion flow is highly dynamical, the system reaches quasi-steady state (when averaged over ~200-300 P_b, the precession period):

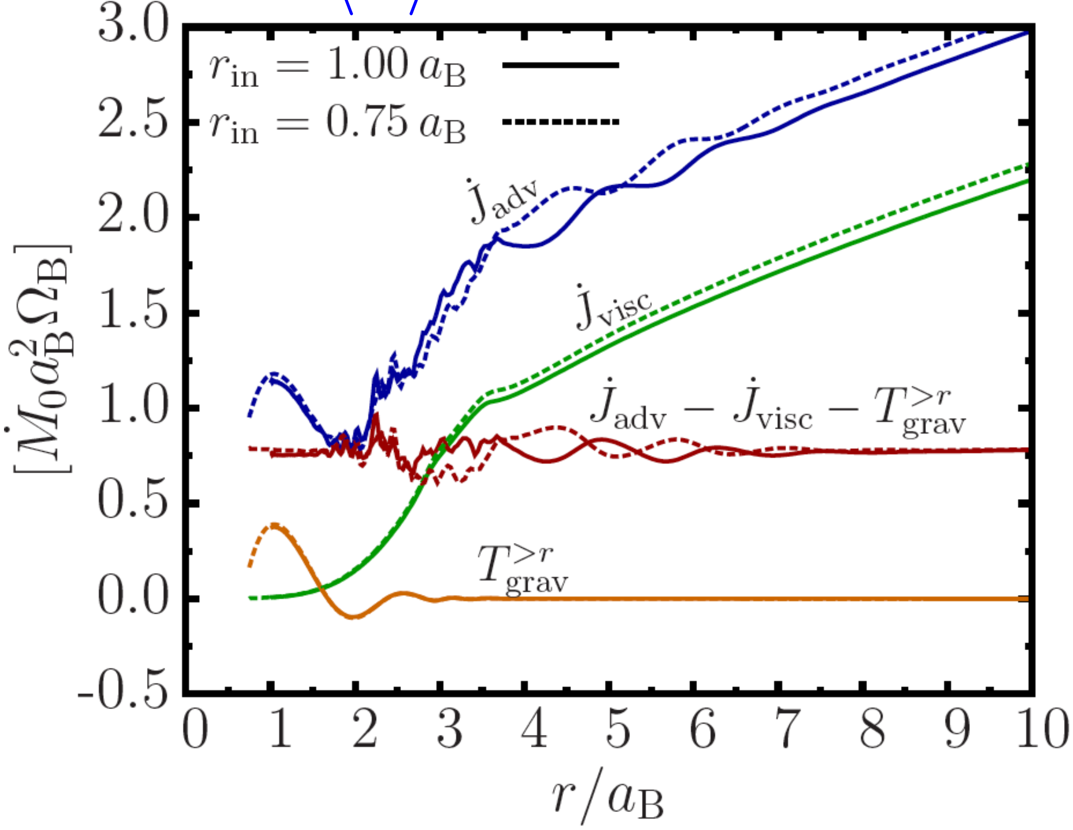
$$\langle \dot{M} \rangle \simeq \dot{M}_{\rm out} = \dot{M}_0 ({\rm const})$$

$$\langle \dot{J} \rangle \simeq {\rm const}$$

Net angular momentum per unit mass transferred to the binary:

$$l_0 \equiv \frac{\langle \dot{J} \rangle}{\langle \dot{M} \rangle}$$

$\langle \dot{J} \rangle$ (averaged over 250 P_b)



Angular Momentum Transfer Rate

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$$\langle \dot{M} \rangle \simeq \dot{M}_{\rm out} = \dot{M}_0 (\rm const)$$

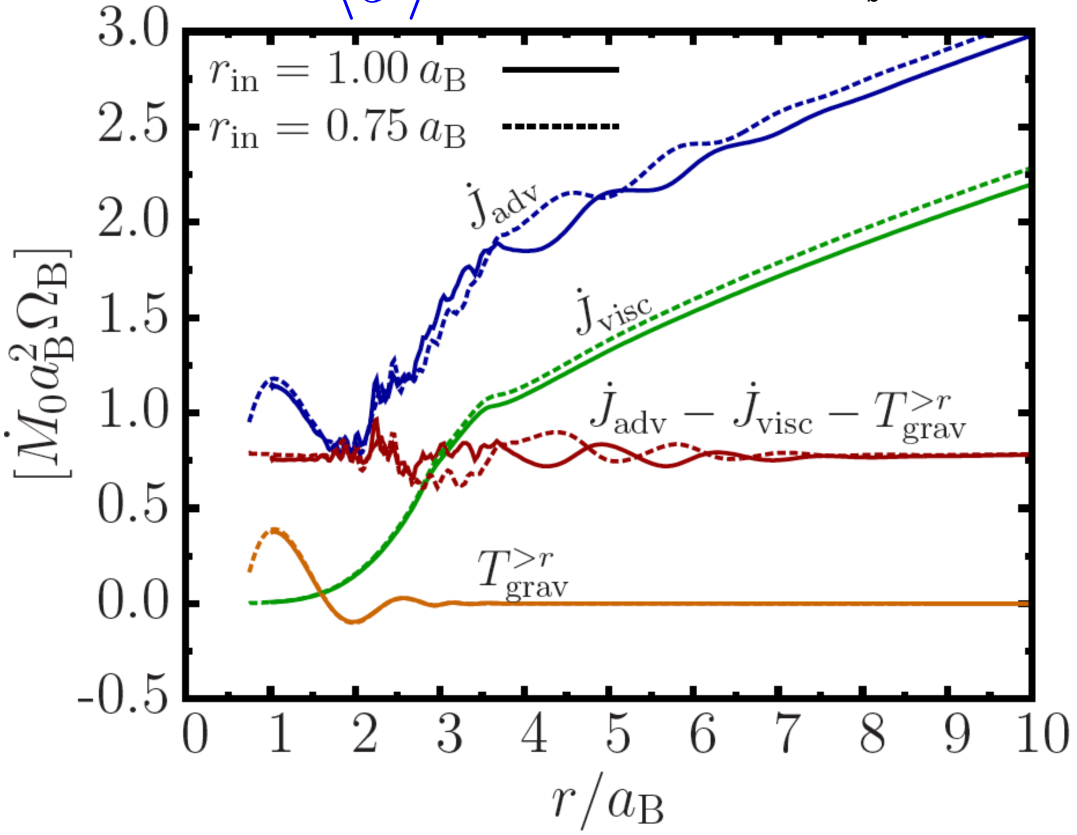
$$\langle \dot{J} \rangle \simeq \rm const$$

Net angular momentum per unit mass transferred to the binary:

$$l_0 \equiv \frac{\langle \dot{J} \rangle}{\langle \dot{M} \rangle}$$

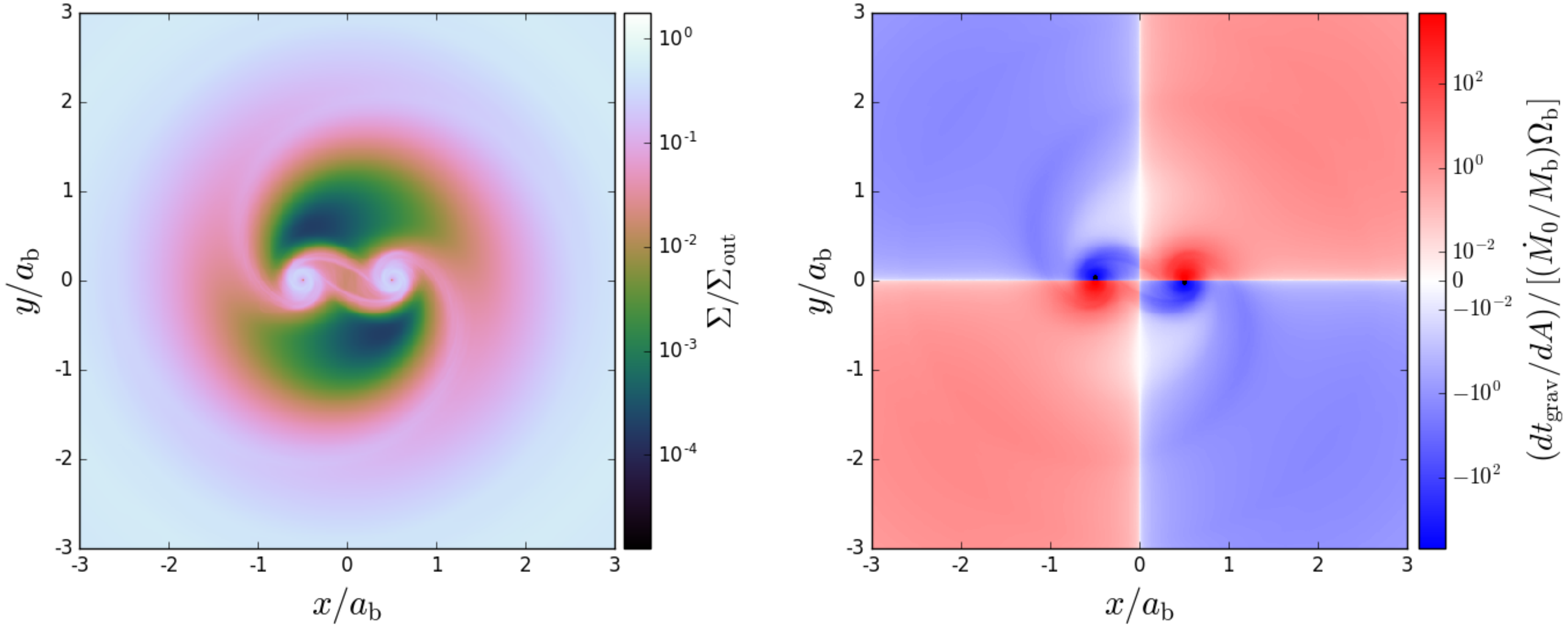
$$l_0 \simeq 0.75\, a_B^2 \Omega_B$$

$\langle \dot{J} \rangle$ (averaged over 250 P_b)



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)

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

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

$$\dot{J}_B = \dot{M}_B l_0 \qquad l_0 \simeq 0.7\, l_B \qquad \text{where } l_B = a_B^2 \Omega_B$$

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

Binaries can expand due to circumbinary accretion !

Notions/Claims of binary decays due to cicumbinary disk

-- Numerical simulations:

Transient vs quasi-steady state?

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

Notions/Claims of binary decays due to cicumbinary disk

-- Numerical simulations:

Transient vs quasi-steady state?

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

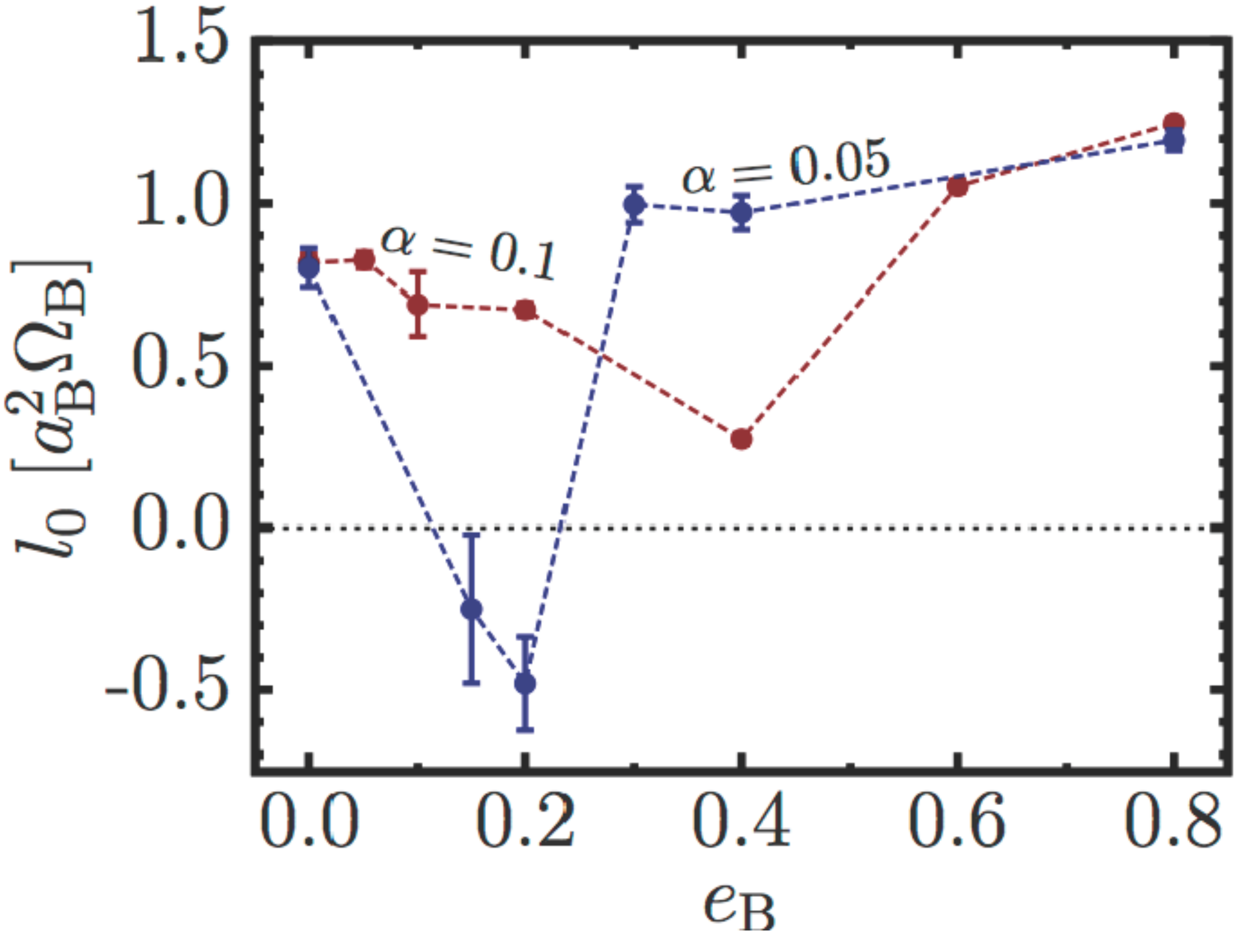
-- Is binary decay possible? (e.g. Supermassive BH Binaries, final pc)

Yes…

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

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

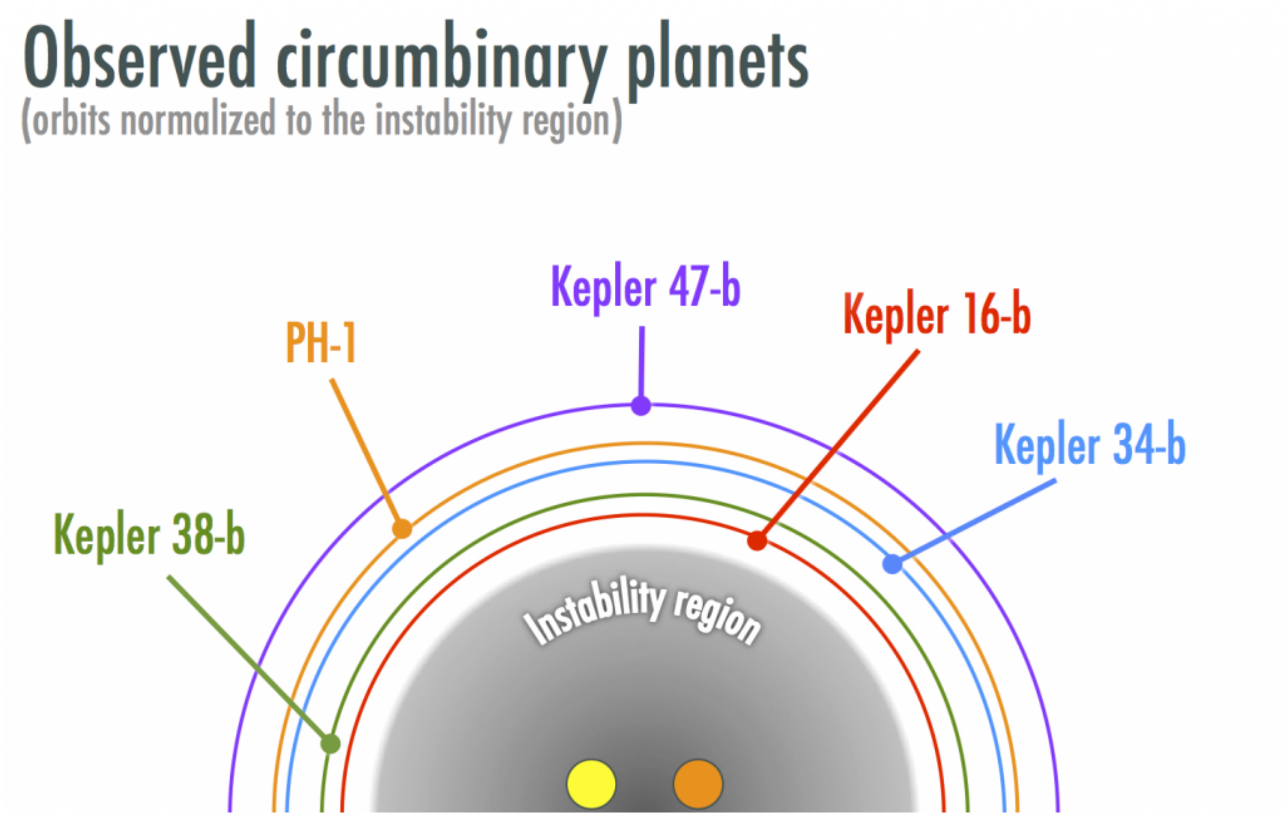
Preliminary: Eccentric Binaries: $\langle \dot{J} \rangle = \langle \dot{M} \rangle \, l_0$



-- $l_0 > 0$ in most cases (i.e. binary receives angular momentum)
-- "dip" in l_0 at intermediate e_b (corresponding to inner eccentric disk apsidally aligned with binary)

Implications for Planet Formation Around Binaries

Many observed circumbinary planets are close to instability limit
(consistent with uniform distribution in log a; Li, Holman & Tao 16)



Implications for Planet Formation Around Binaries

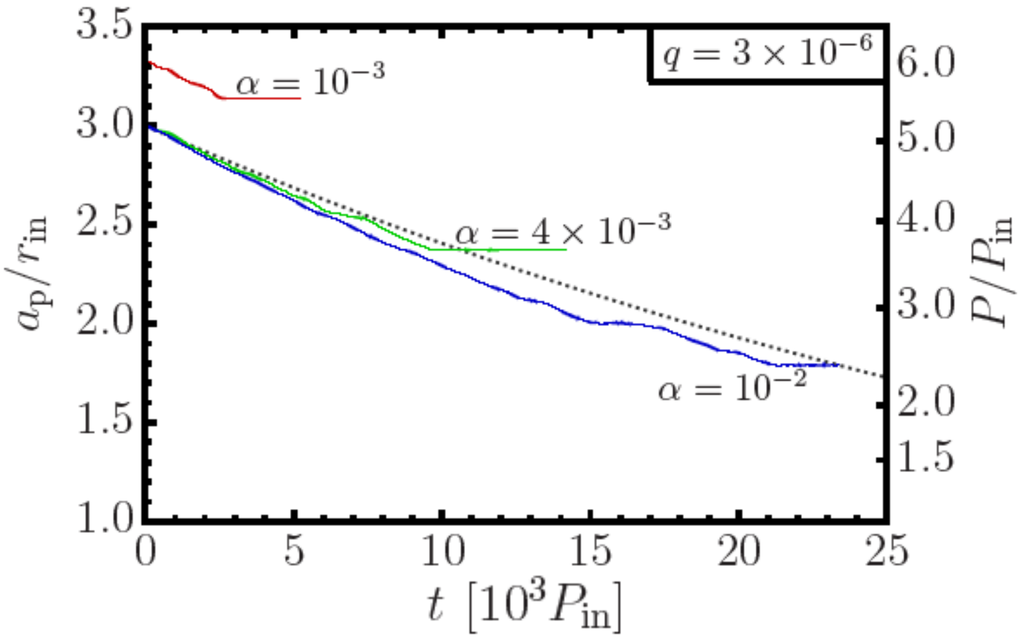
-- Planetesimal growth is likely suppressed

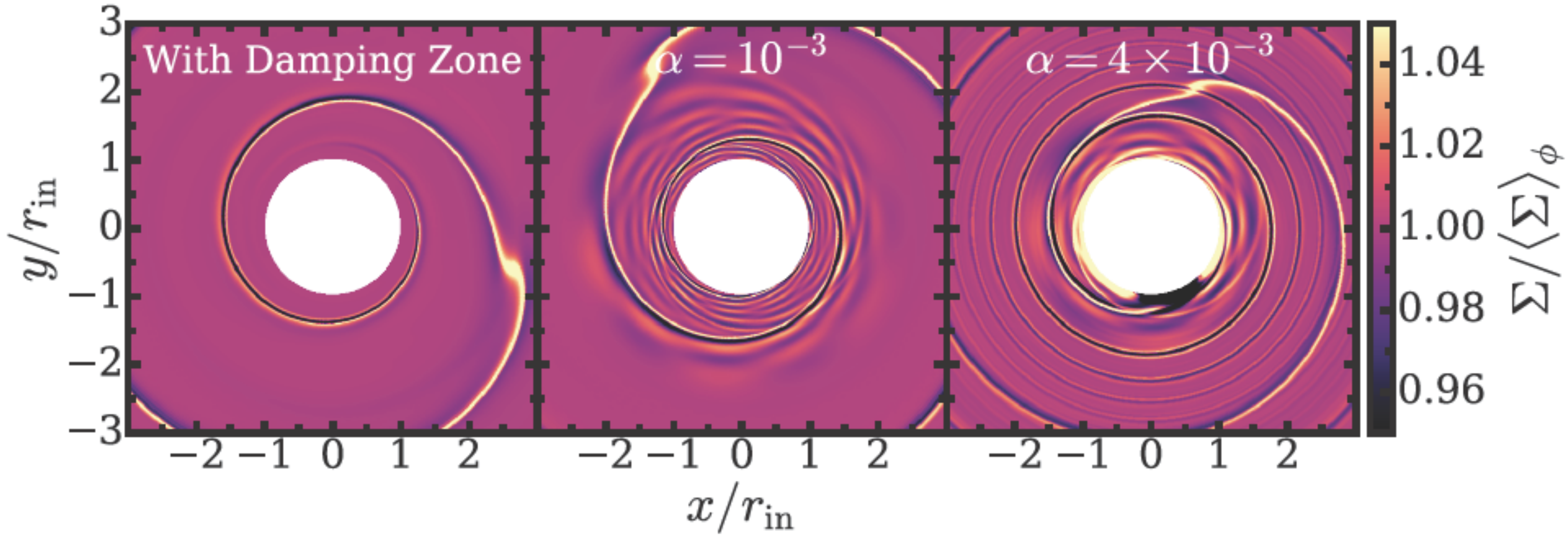
At r ~3-4 a_b, disk e ~ 0.05-0.2 ➔
relative velocity of planetesimals ~ eV_k ~ 5 km/s (at 0.2AU) >> v_{esc} ~10 m/s (10 km body)

-- 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

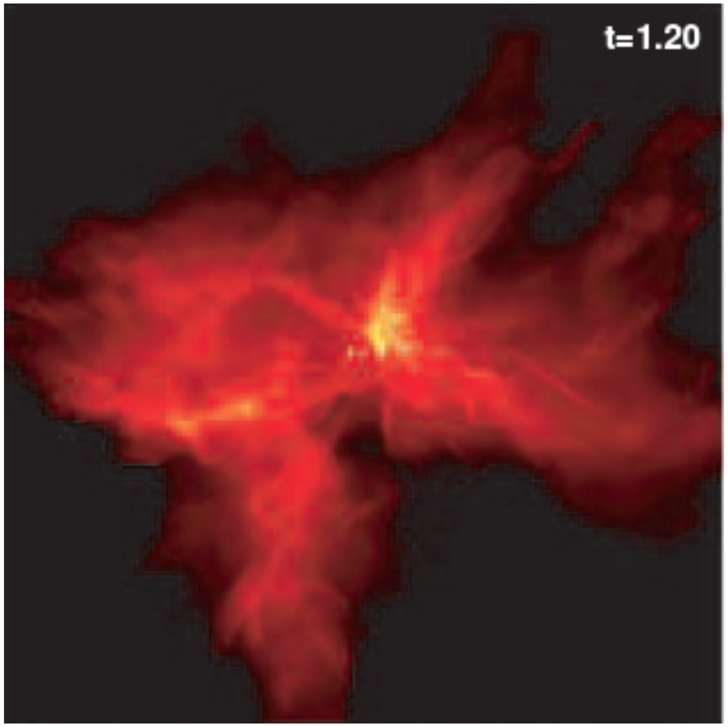
What about misaligned disks ?

Misaligned Disks are "Naturally" Expected

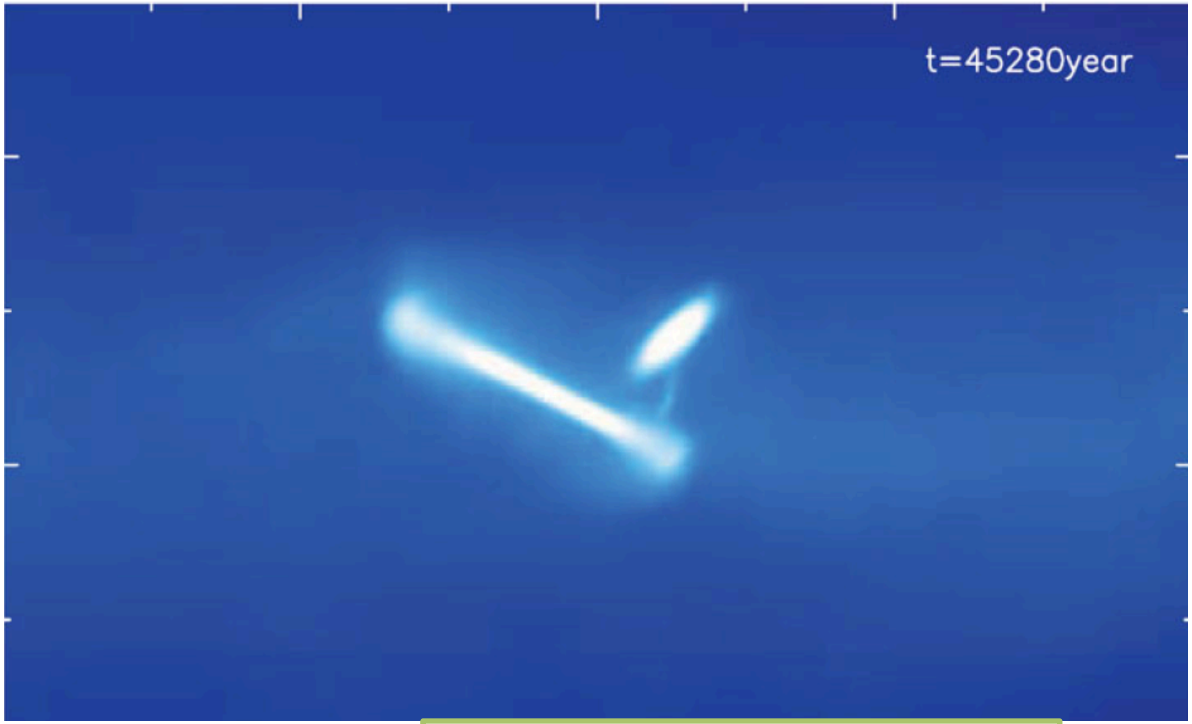
Star Formation in Turbulent Molecular Clouds

-- Supersonic turbulence --> clumps --> stars

-- Clumps can accrete gas with different rotation axes at different times



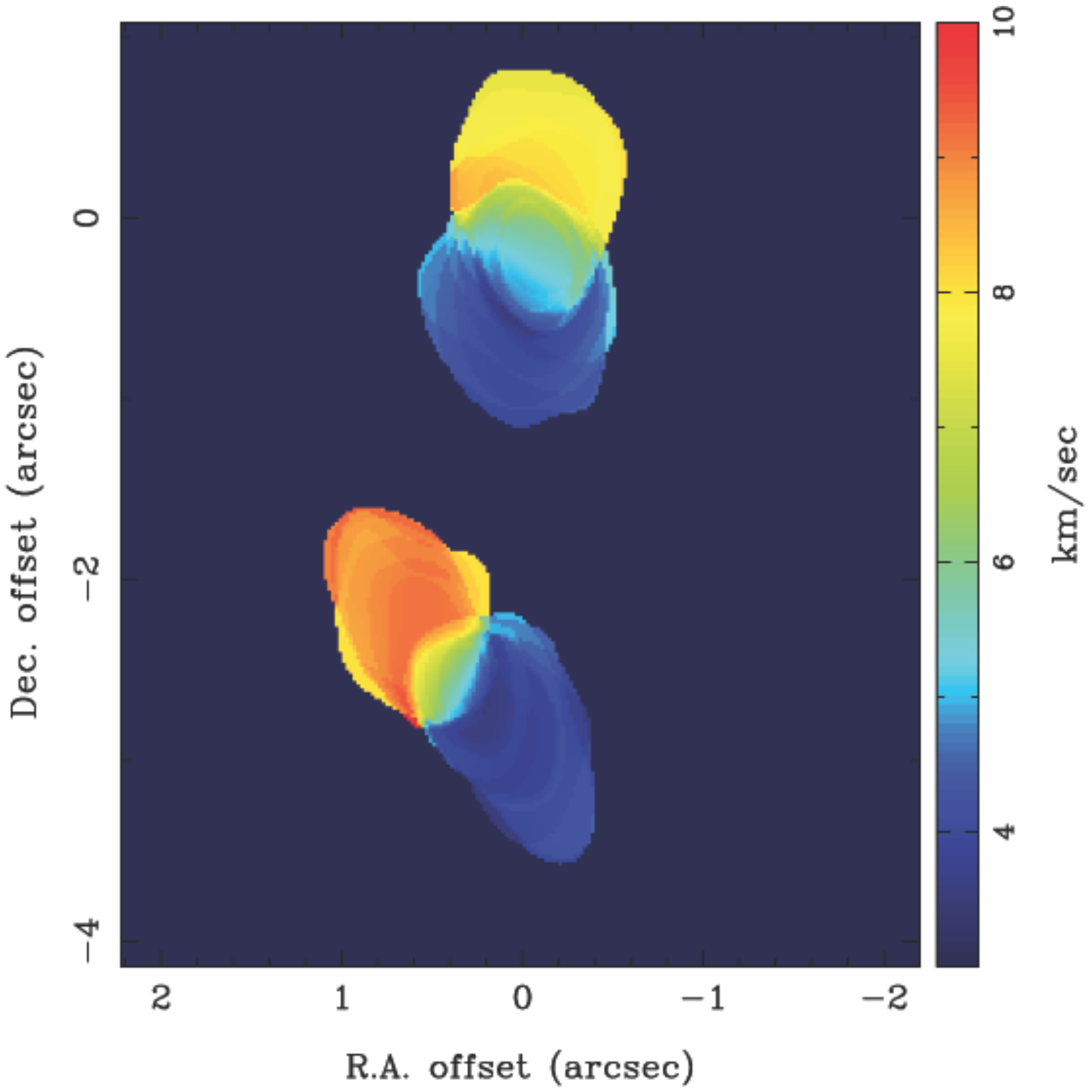
Bate et al. 2003



Tsukamoto & Machida 2013

Observations

Circumstellar disks within wider binaries are generally misaligned



HK Tau:

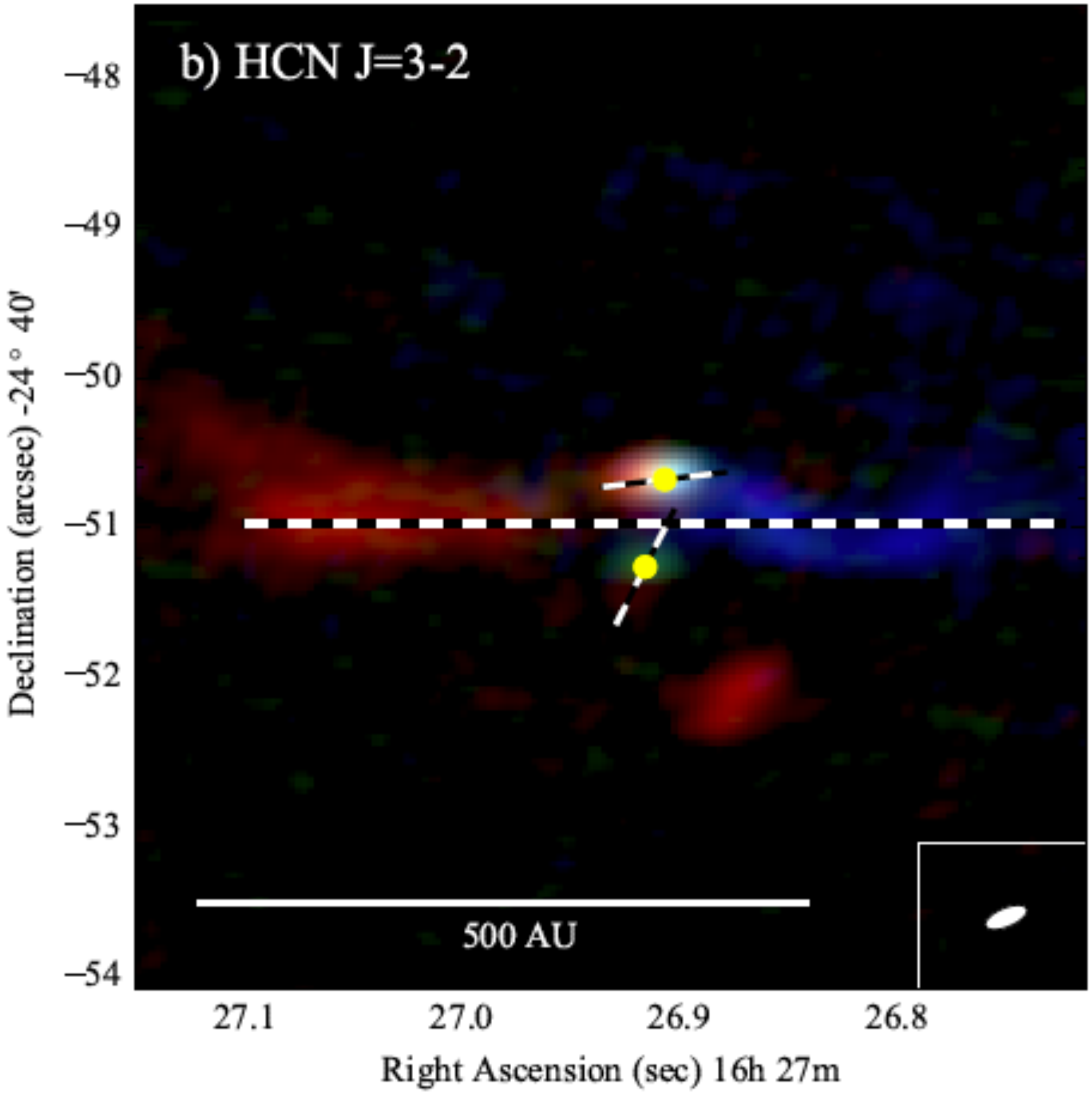
ALMA CO 3-2 emission

(a_b ~ 400 AU)

Jensen & Akeson 14

Observations

Misaligned circumbinary disks



IRS 43

ALMA

a_b ~ 74 au, three disks

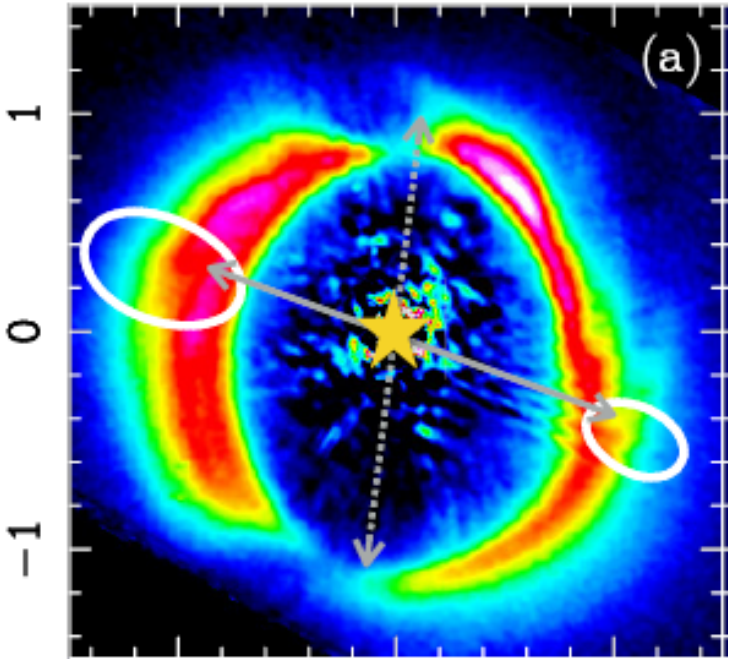
Brinch et al. 2016

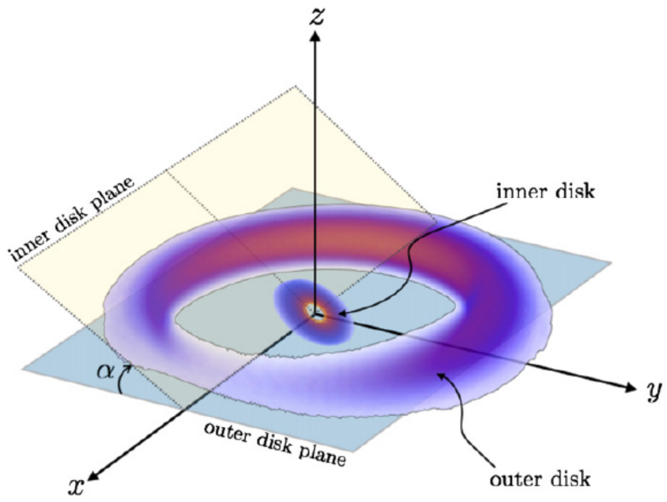
Other Misaligned circumbinary debris disks:

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

99 Herculis (Kennedy+12)

HD 142527: a well-known gapped disk system



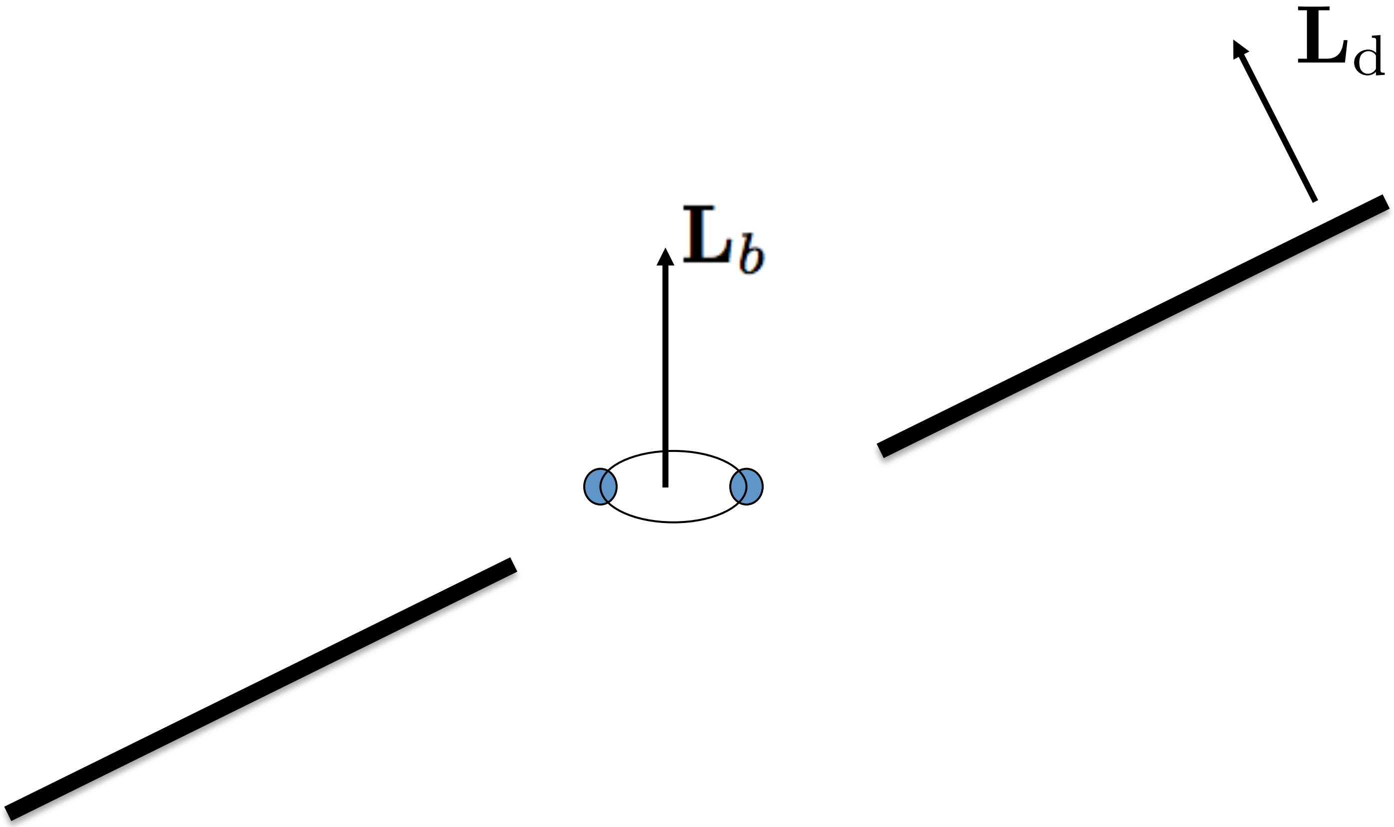


Inner (circumstellar) and outer (circumbinary) disks misaligned by 70 degrees (Marino et al. 15)

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

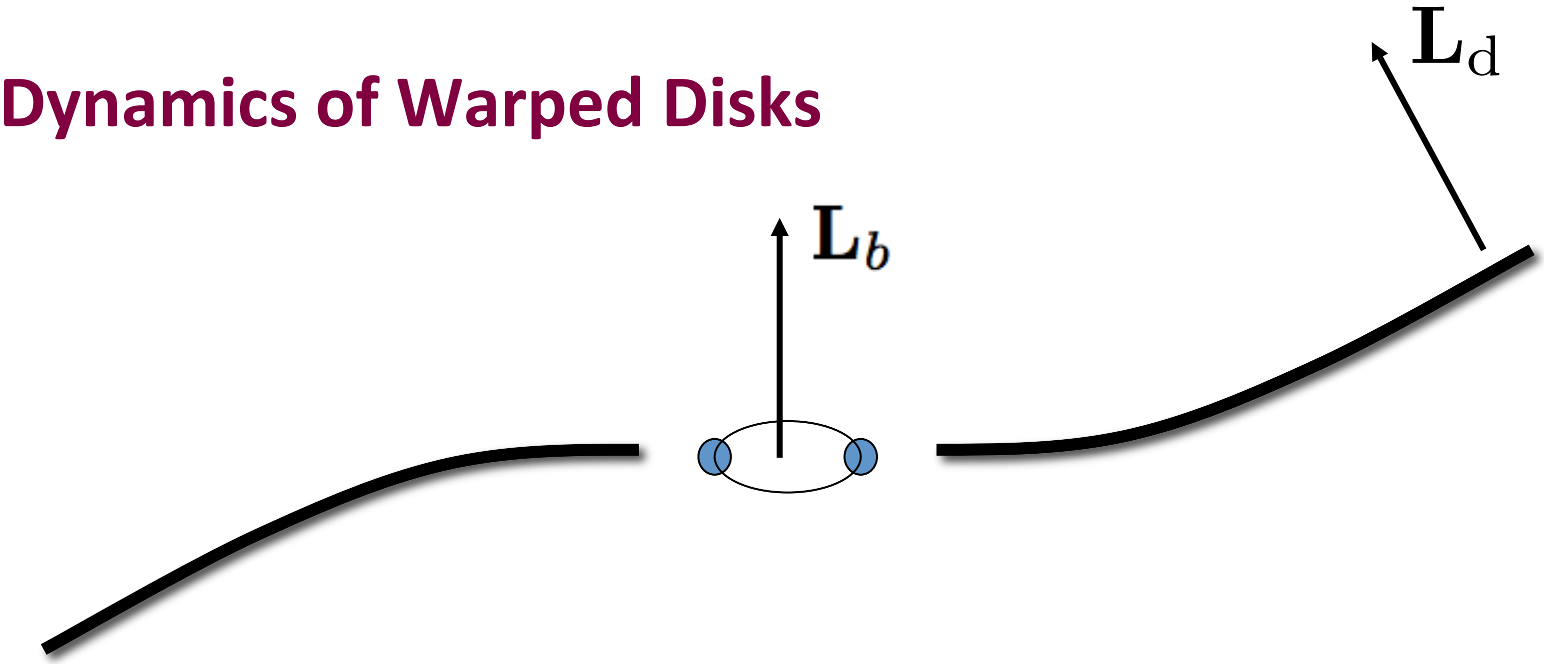
see Owen & DL 2017

Consider (circular) Binary + Inclined (initially) Disk



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

Dynamics of Warped Disks

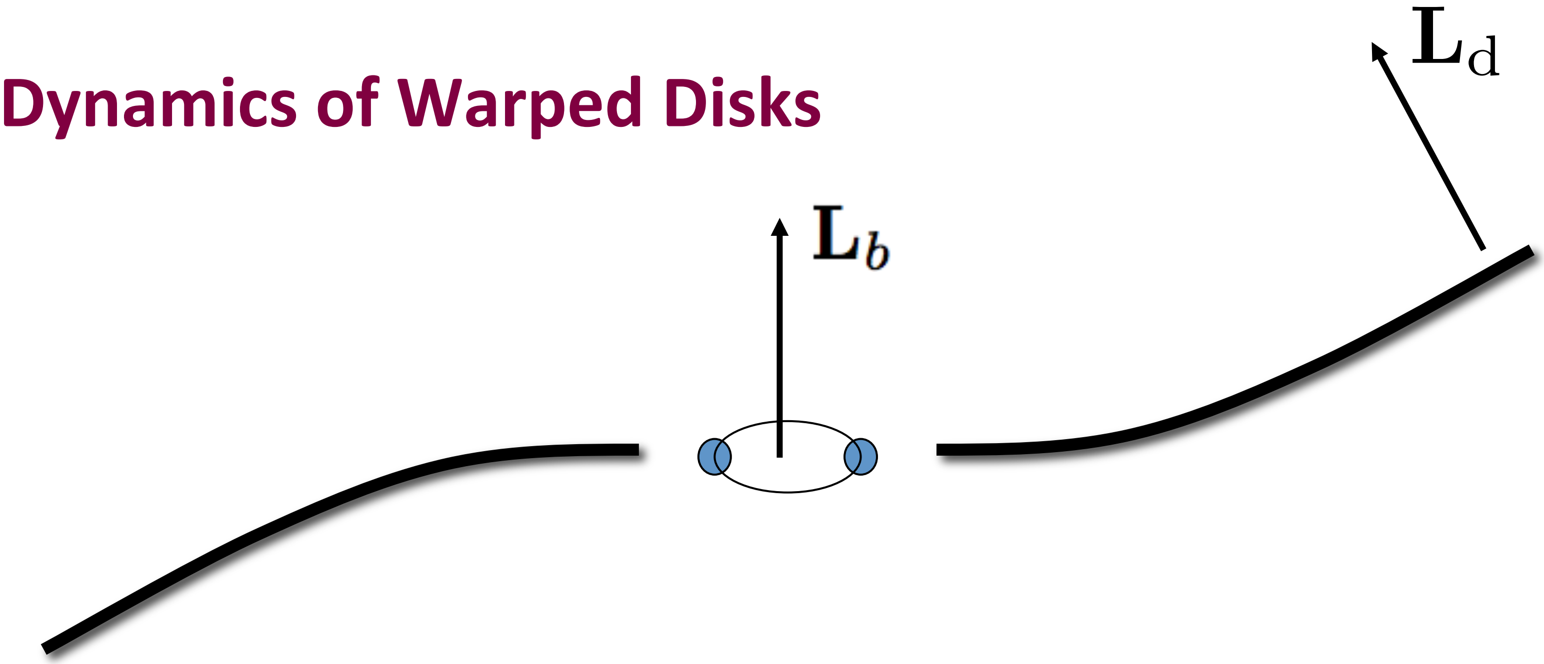


Torque from binary on disk => disk (ring) nodal precession

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

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

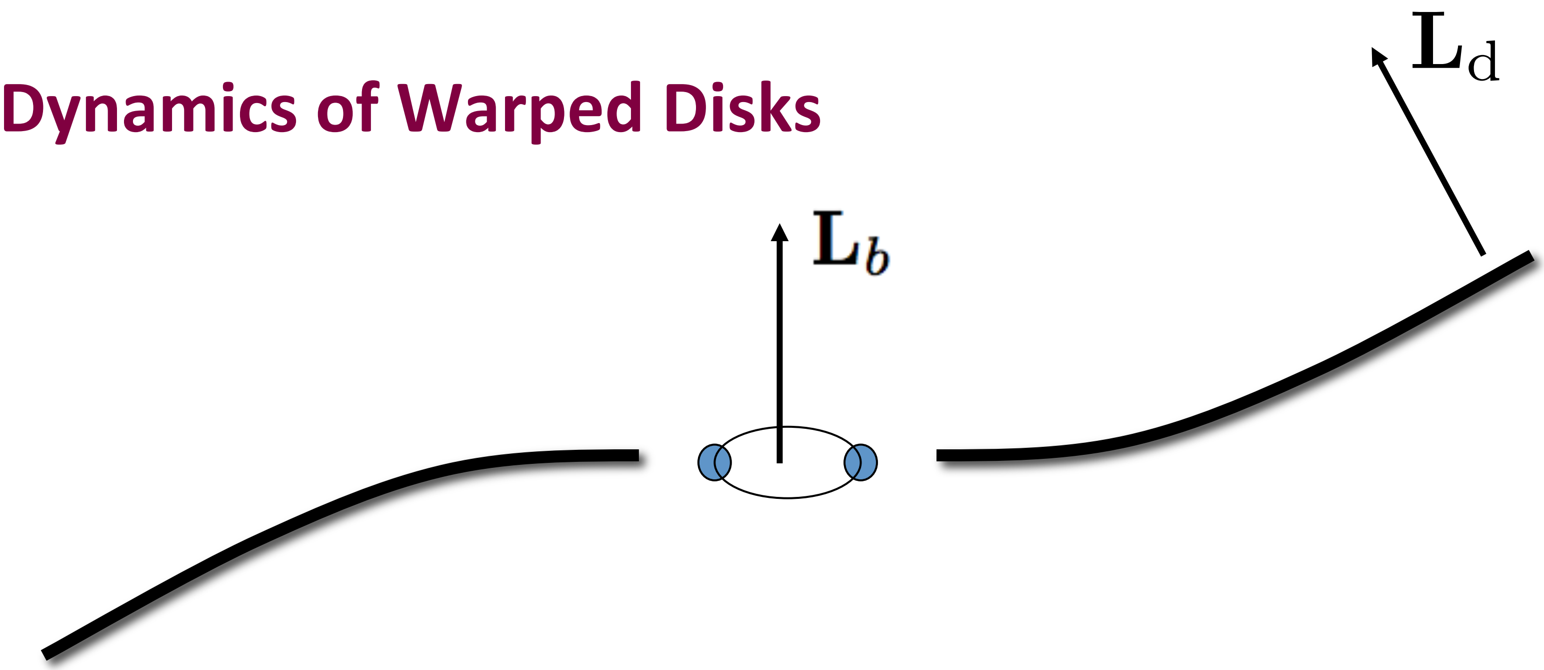
Dynamics of Warped Disks



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 $\mathbf{L}_b$ and $\mathbf{L}_d$

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

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

Typical alignment time ~ precession period

Foucart & DL 2014
Zanazzi & DL 2018

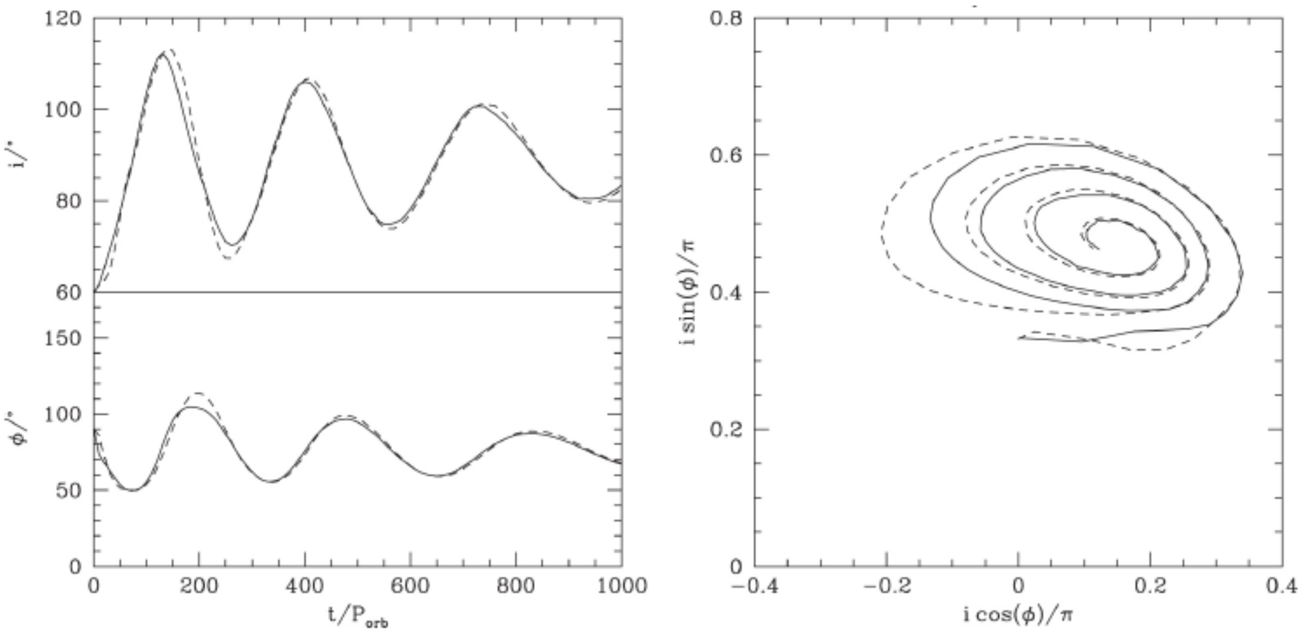
Surprise: Disk around eccentric binary may evolve toward polar alignment

Surprise: Disk around eccentric binary may evolve toward polar alignment

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

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

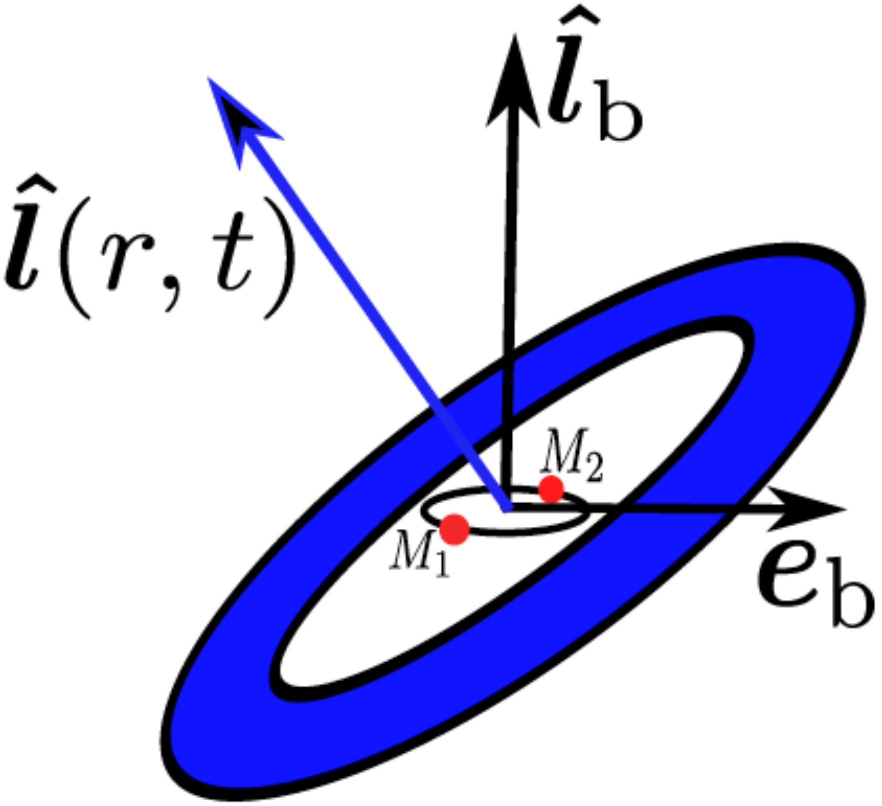
Binary eccentricity $e_b = 0.5$.



Theoretical Analysis:

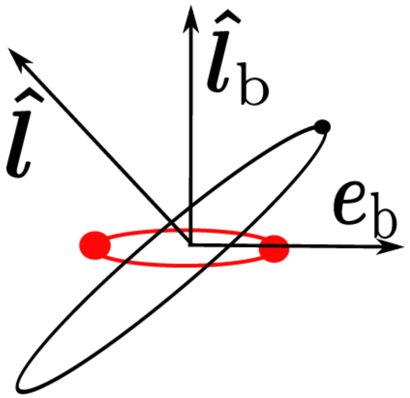
Inclination Evolution of Disks Around Eccentric Binaries

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; Naoz + 2017)

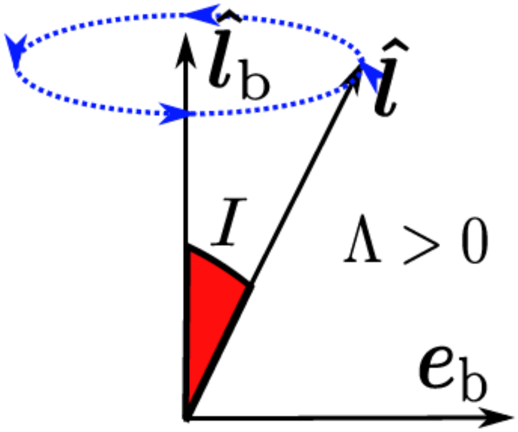


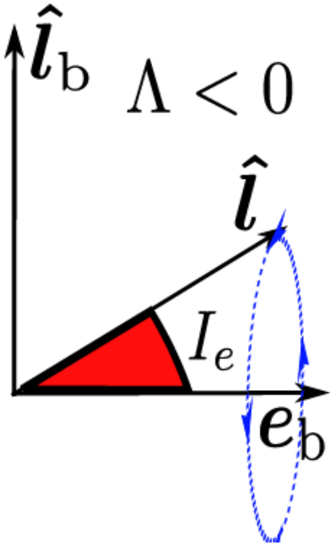
Test particle has two "masters" (by symmetry)

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

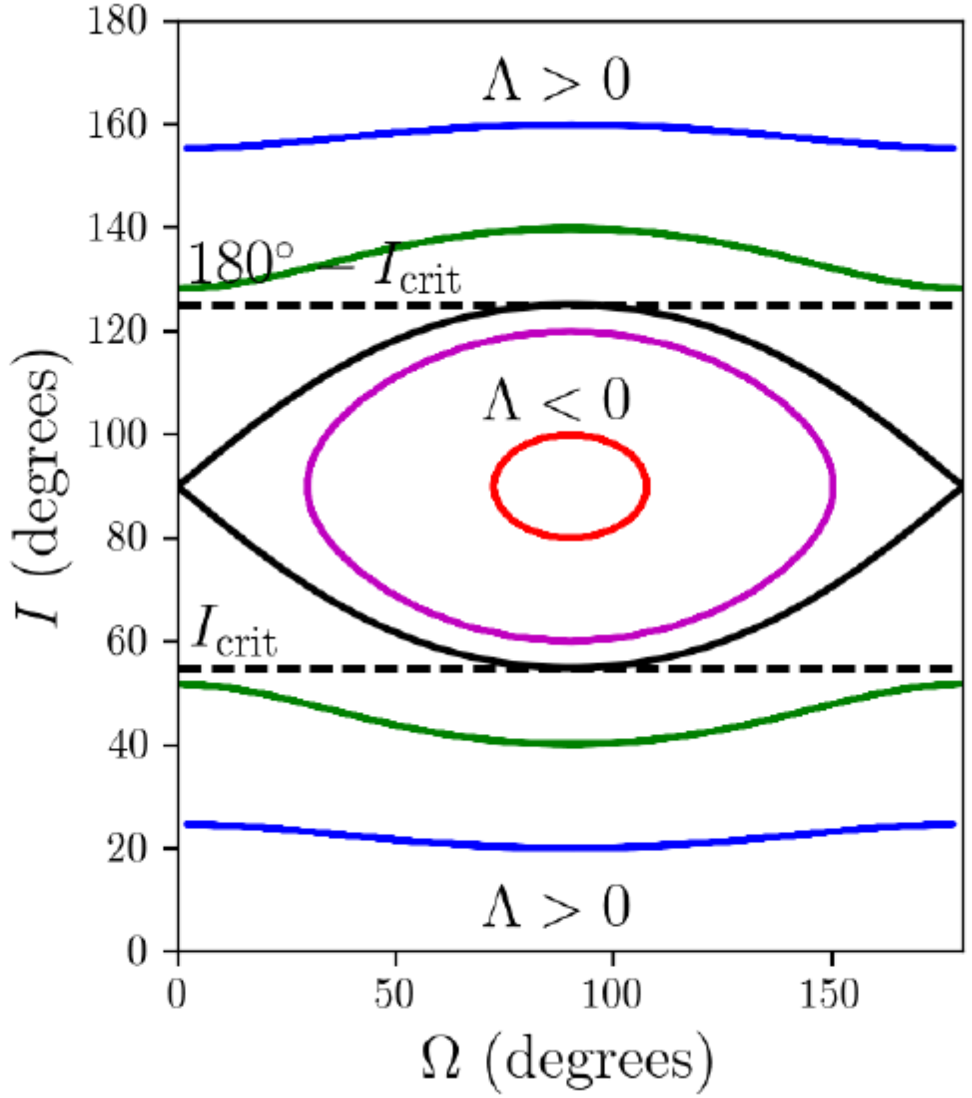
If $\hat{l}$ initially close to $\hat{e}_b$: $\hat{l}$ precesses around $\hat{e}_b$

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





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



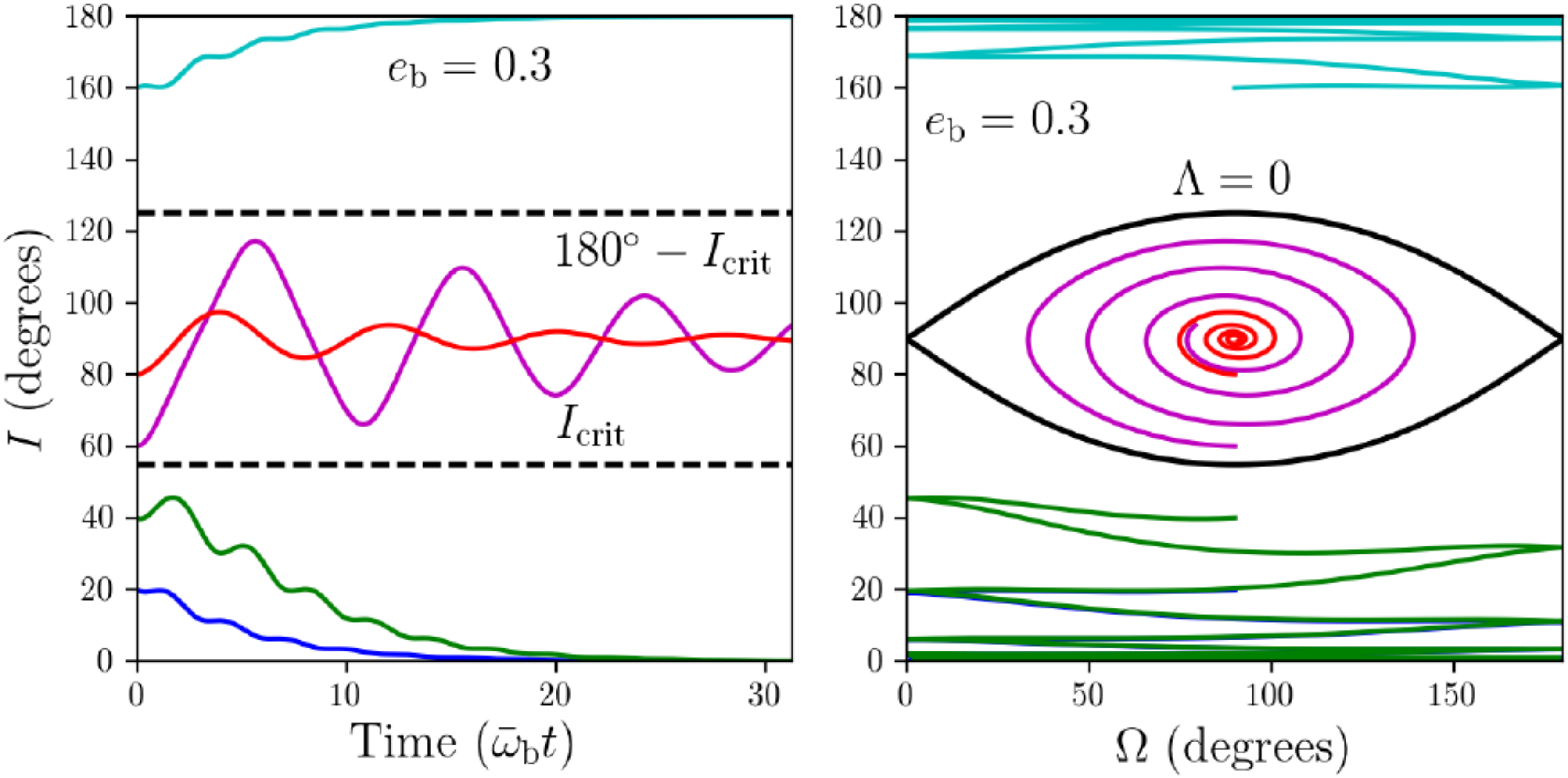
For $\hat{l}$ to precess around $\hat{e}_b$, require $\sin I > \sin I_{\rm crib}$

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

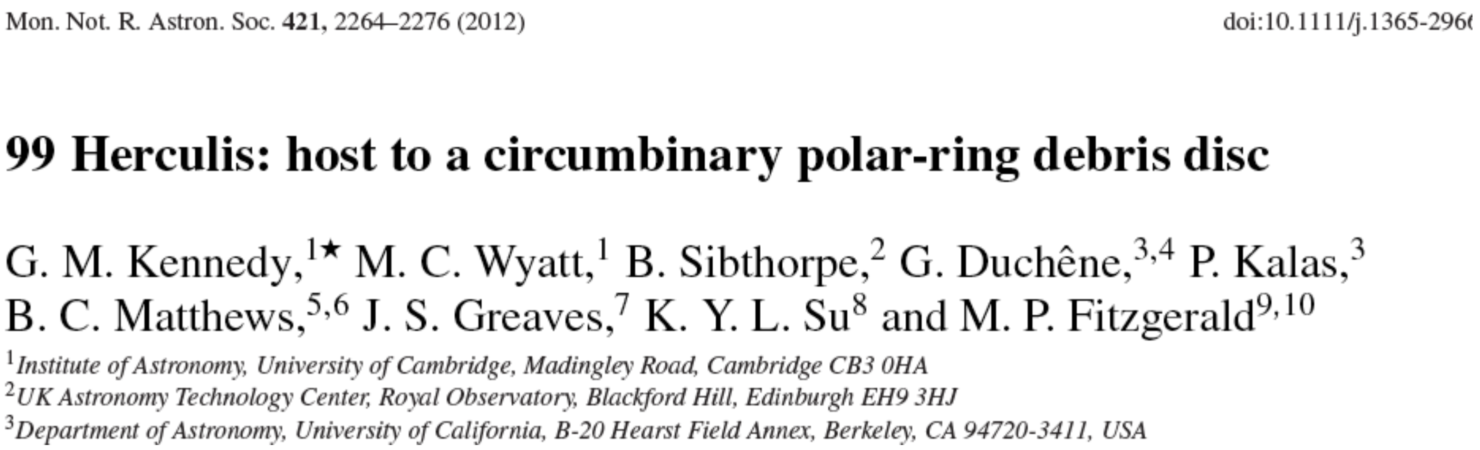
Zanazzi & DL 2018

Warped viscous disk around eccentric binary

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



Zanazzi & DL 2018



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

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B. C. Matthews,[5,6] J. S. Greaves,[7] K. Y. L. Su[8] and M. P. Fitzgerald[9,10]
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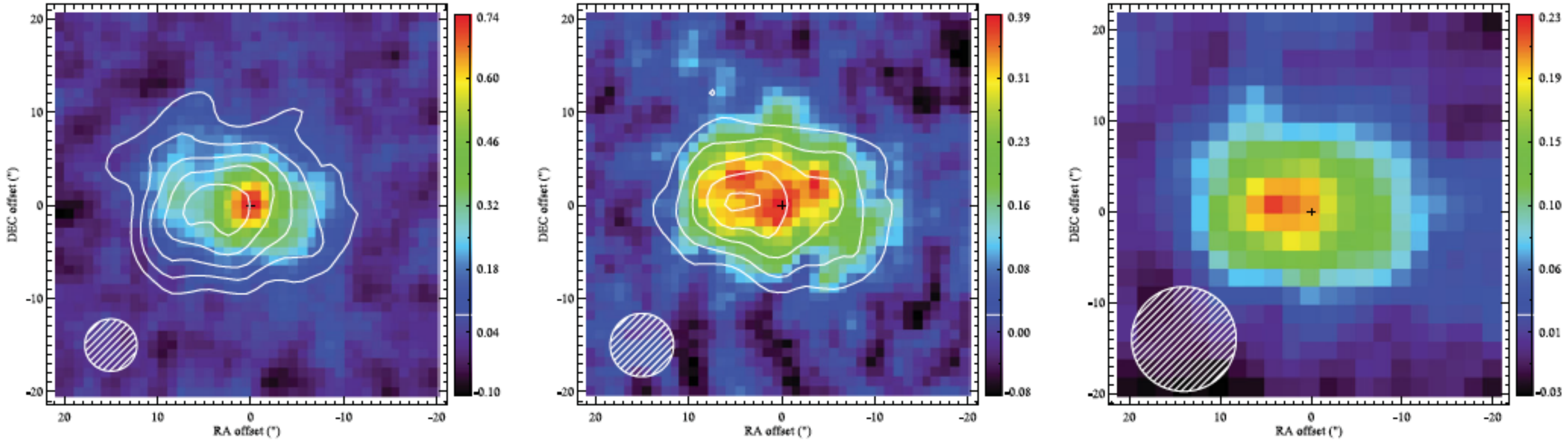


e_b=0.77, P_b=56 yrs

Are there misaligned circumbinary planets?

Kepler mission:

~12 transiting circumbinary planets

3 non-transiting planets (candidates) around eclipsing binaries
(detected using eclipse timing variation) (Bill Welsh, 2017)

SUMMARY

◆ 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

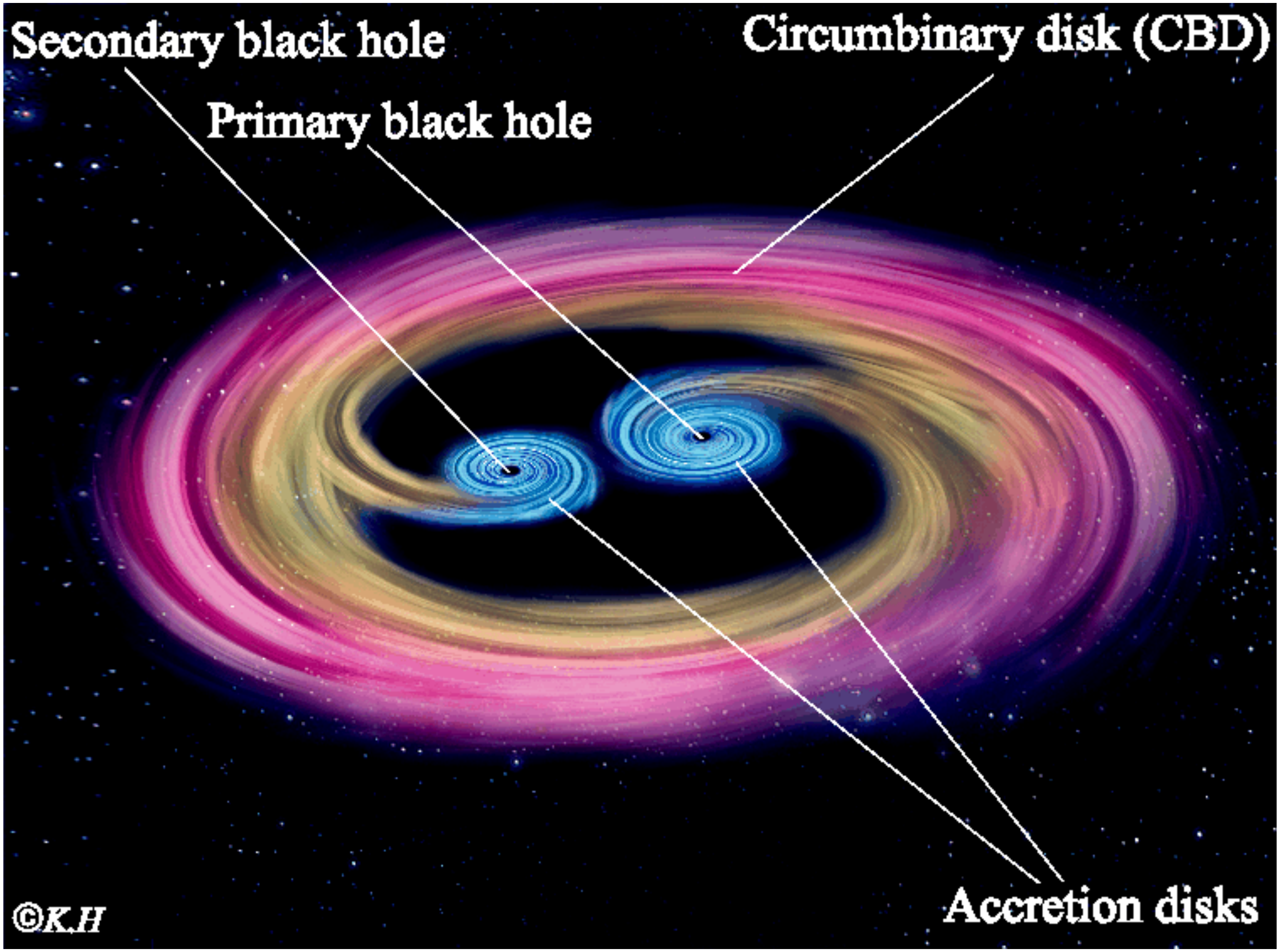
◆ Key Recent Results:

-- Quasi-steady state can be achieved
-- short-term variabilities: ~ 5 P_b (for e_b~0) vs P_b (high e_b)
-- Symmetry breaking in accretion ($q=1$, $e_b>0$)
-- Inner disk is eccentric: precess coherently vs apsidal locking
-- Binary can gain angular momentum and can expand

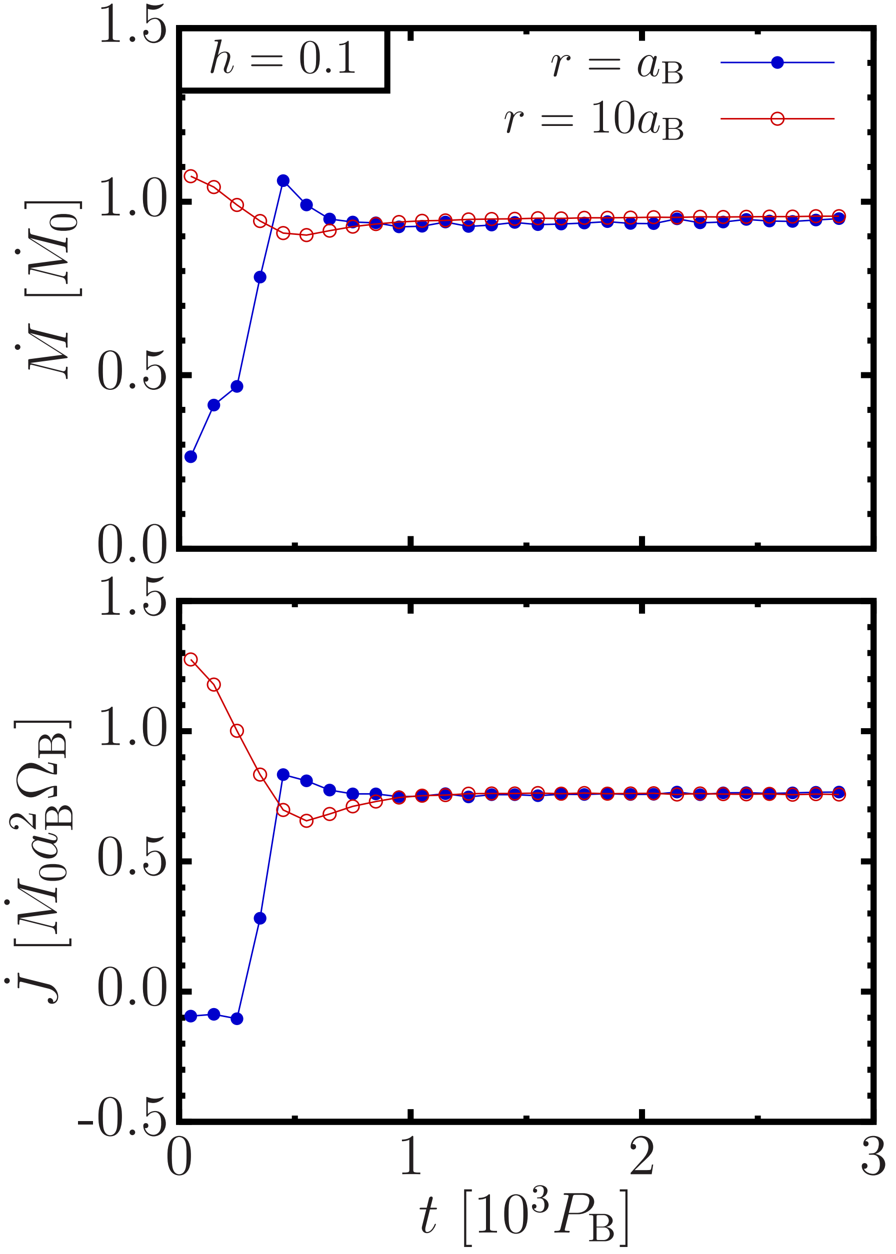
◆ Misaligned disks

-- Observed around young stars
-- Quasi-rigid precession with small warp
-- Dissipation leads to either alignment of polar alignment with binary

Thanks.


Secondary black hole
Circumbinary disk (CBD)
Primary black hole
Accretion disks
©K.H

Approaching Quasi-Steady State:



Each point is obtained by averaging ~250 P_b

Spreading Circumbinary Disk (Torus)

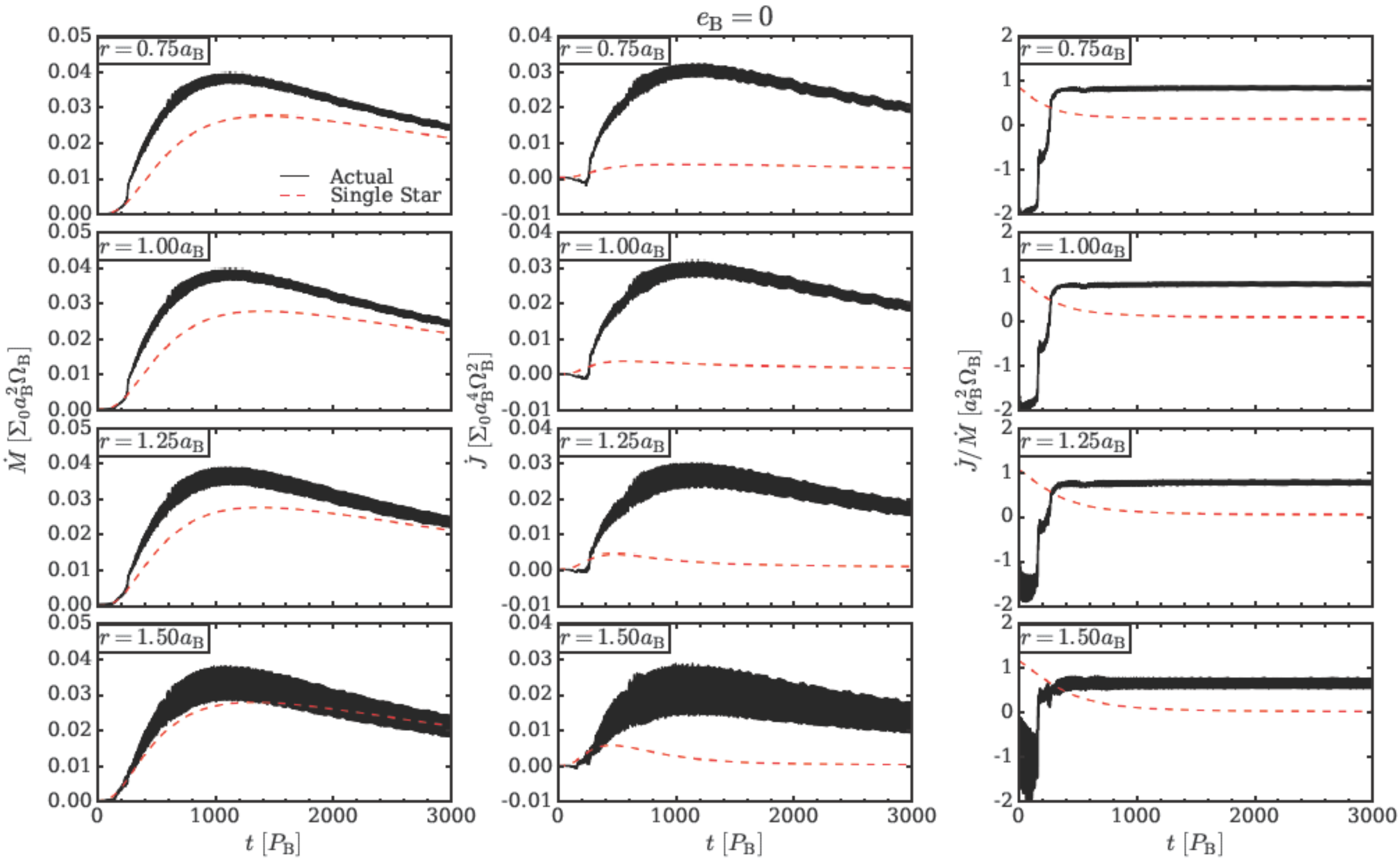


Figure 1. Mass accretion rate (left), angular momentum transfer rate (middle), and their ratio (right), smoothed over 10 orbits, at different radii for a spreading circumbinary disk. The initial bump of material starts at $20a_B$, and the disk has $H/r = 0.1$ and $\alpha = 0.1$. The binary is equal-mass and has $e_B = 0$. The dashed red lines show the analytic behavior for a disk around a single star of equivalent mass. In this run, the inner boundayr has been placed at a very small separation from the binary.

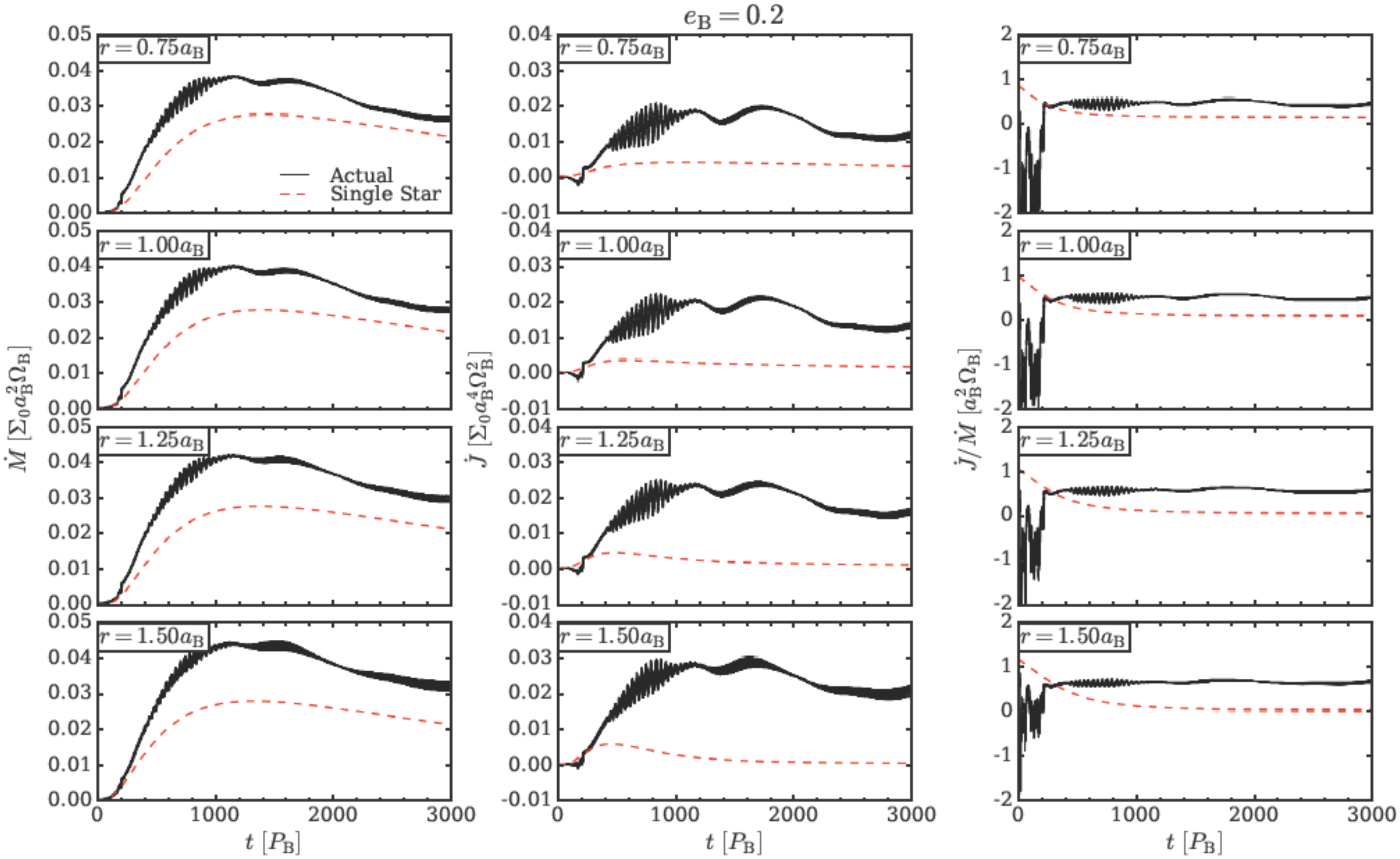


Figure 2. Same as the previous figure, but for $e_B = 0.2$.

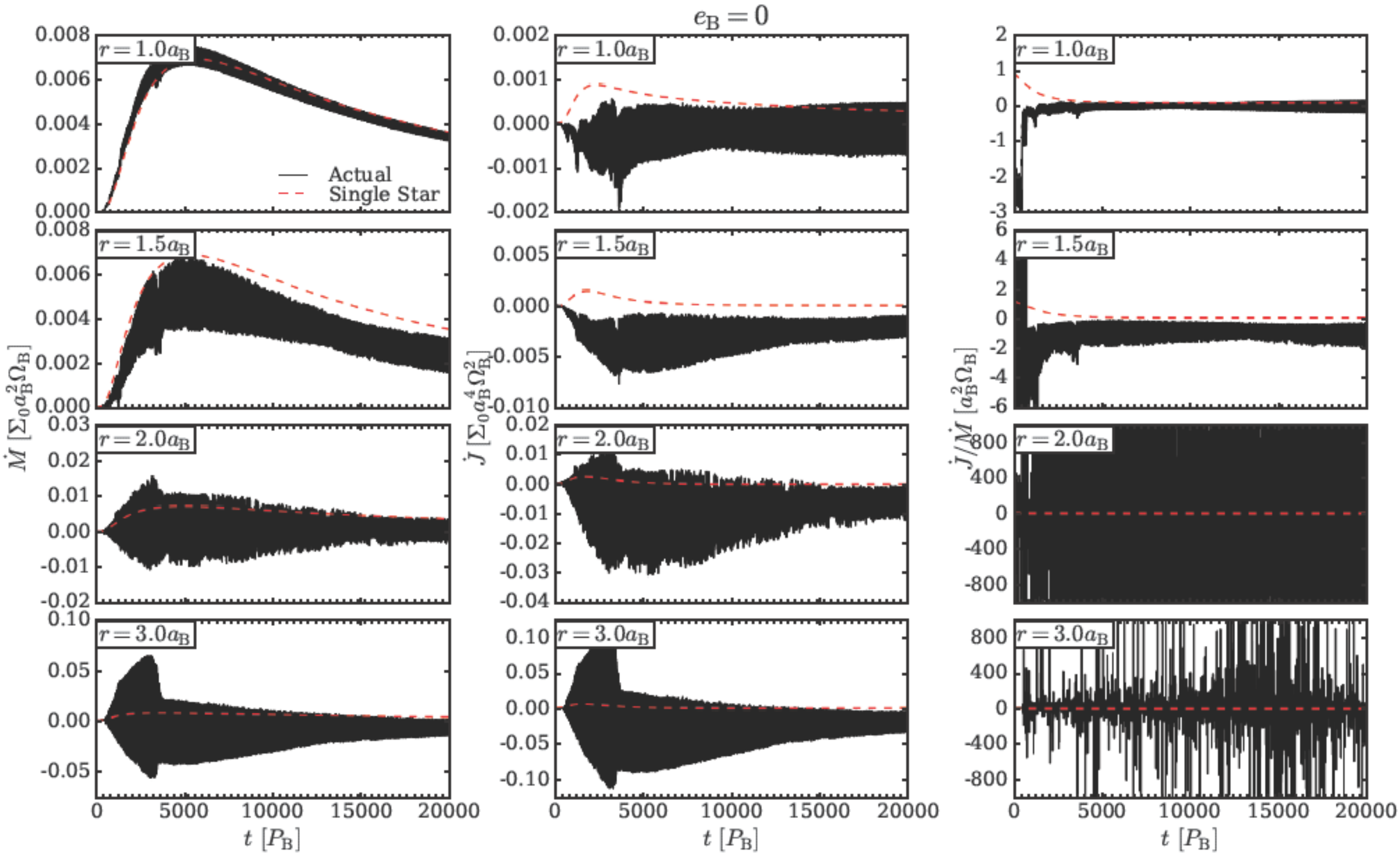
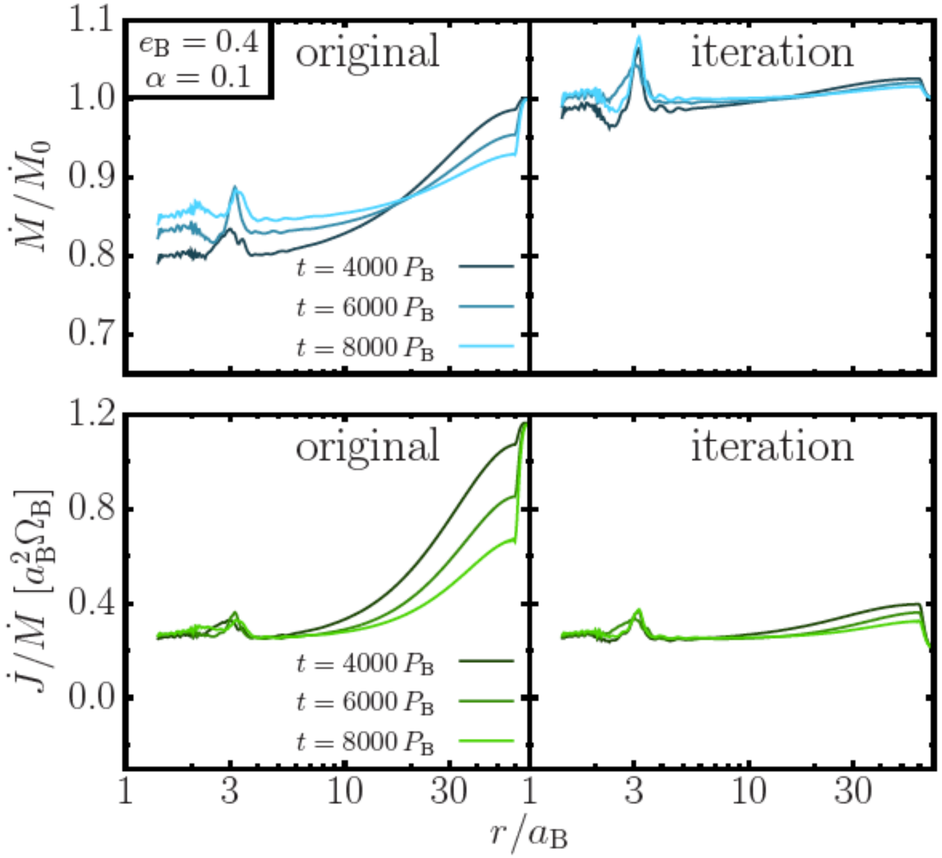
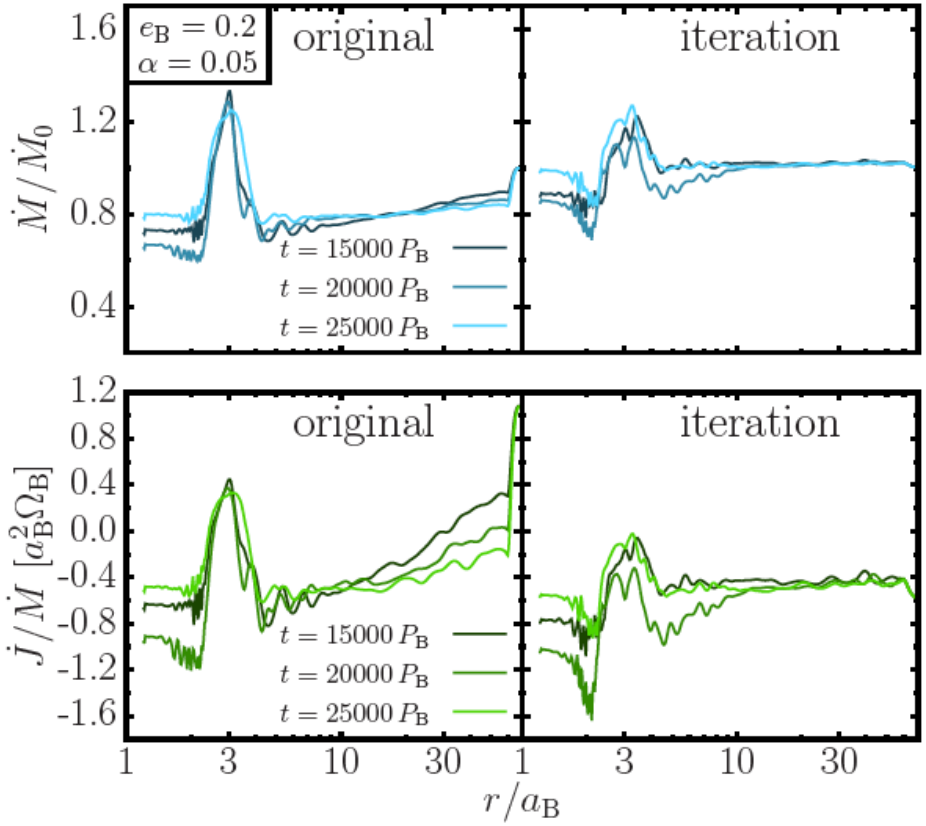


Figure 3. Same as Figure 1, but with $H/r = 0.05$.

Convergence in the "dip" cases





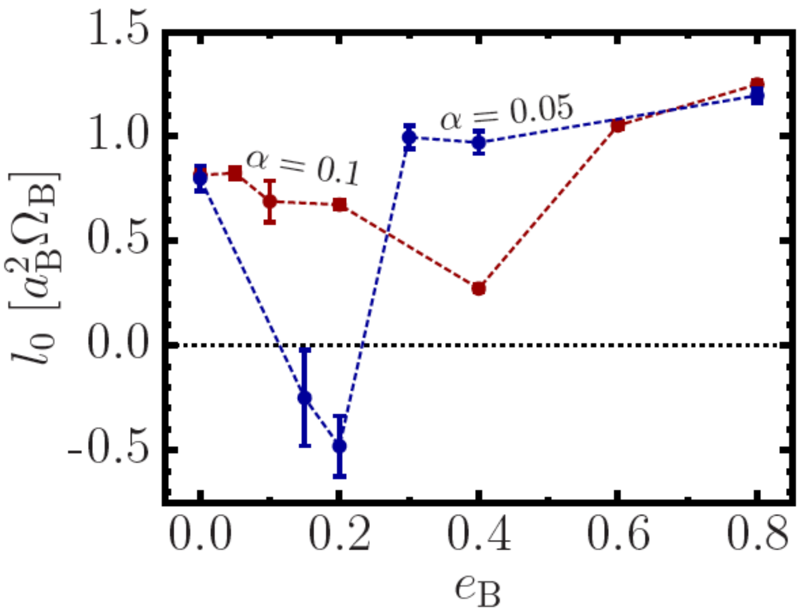
Implication of $l_0 > 0$

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

$$\dot{J}_B = \dot{M}_B l_0$$

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

where $l_B = a_B^2 \Omega_B$



Binaries can expand due to circumbinary accretion !

Note: For $q \neq 1$ and $e_B > 0$ binaries:

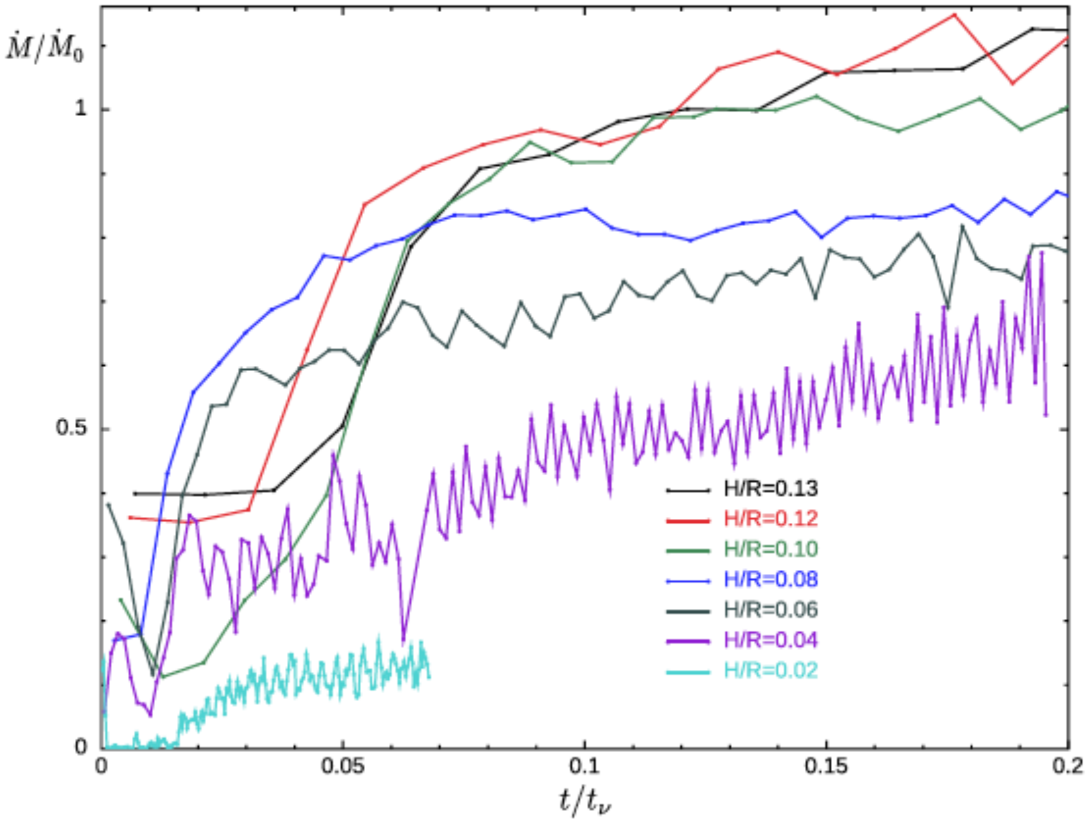
$$\frac{\dot{J}_\mathrm{B}}{J_\mathrm{B}} = \frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{2}\frac{\dot{M}_\mathrm{B}}{M_\mathrm{B}} + \frac{1}{2}\frac{\dot{a}_\mathrm{B}}{a_\mathrm{B}} - \left(\frac{e_\mathrm{B}}{1-e_\mathrm{B}^2}\right)\dot{e}_\mathrm{B}$$

?

Caveats/Issues??

Accretion onto binary is suppressed for H/r <~ 0.1

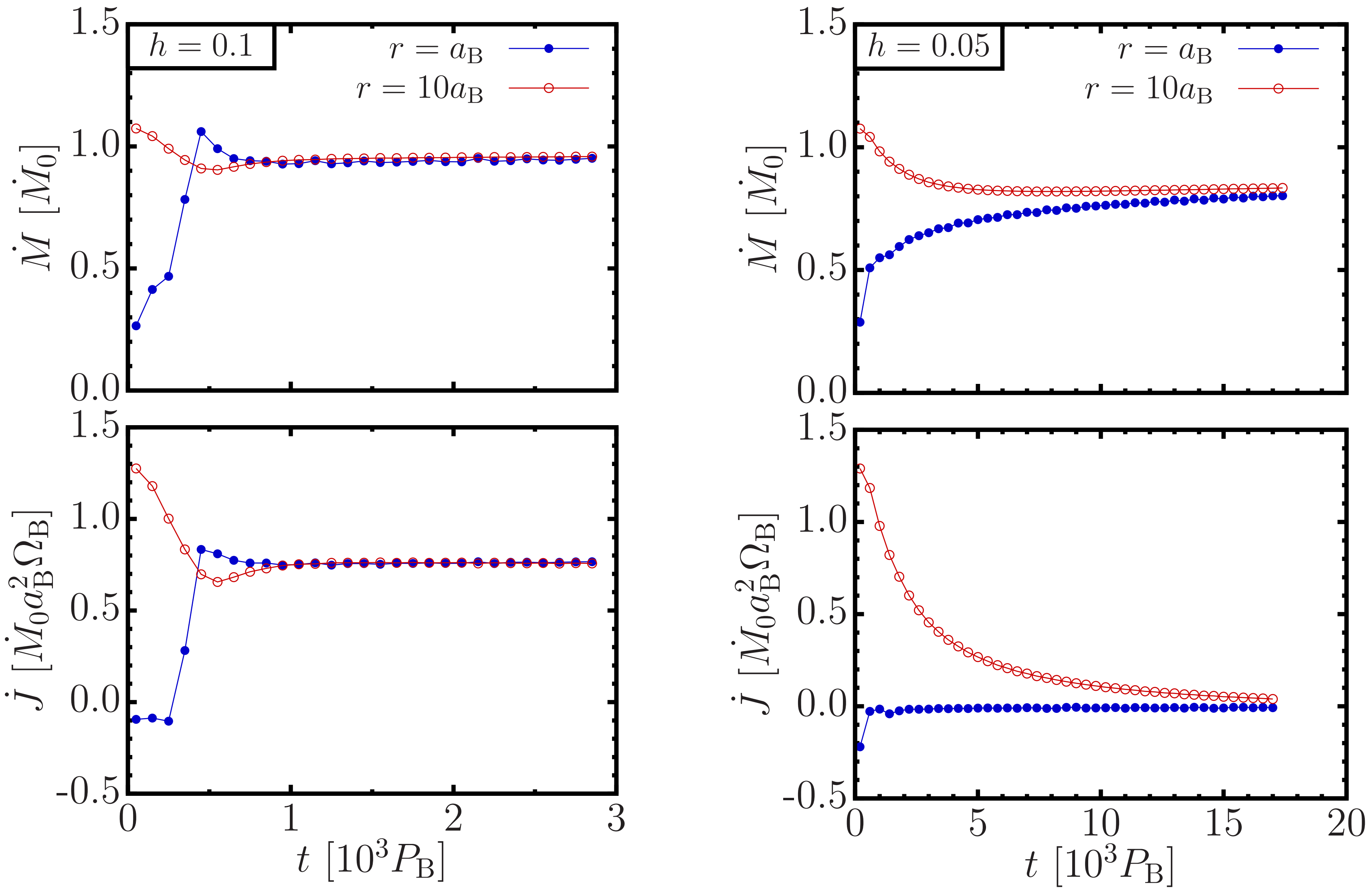
Ragusa, Lodato & Price 16



SPH simulations of spreading layer initially at 2.3-5 a_b

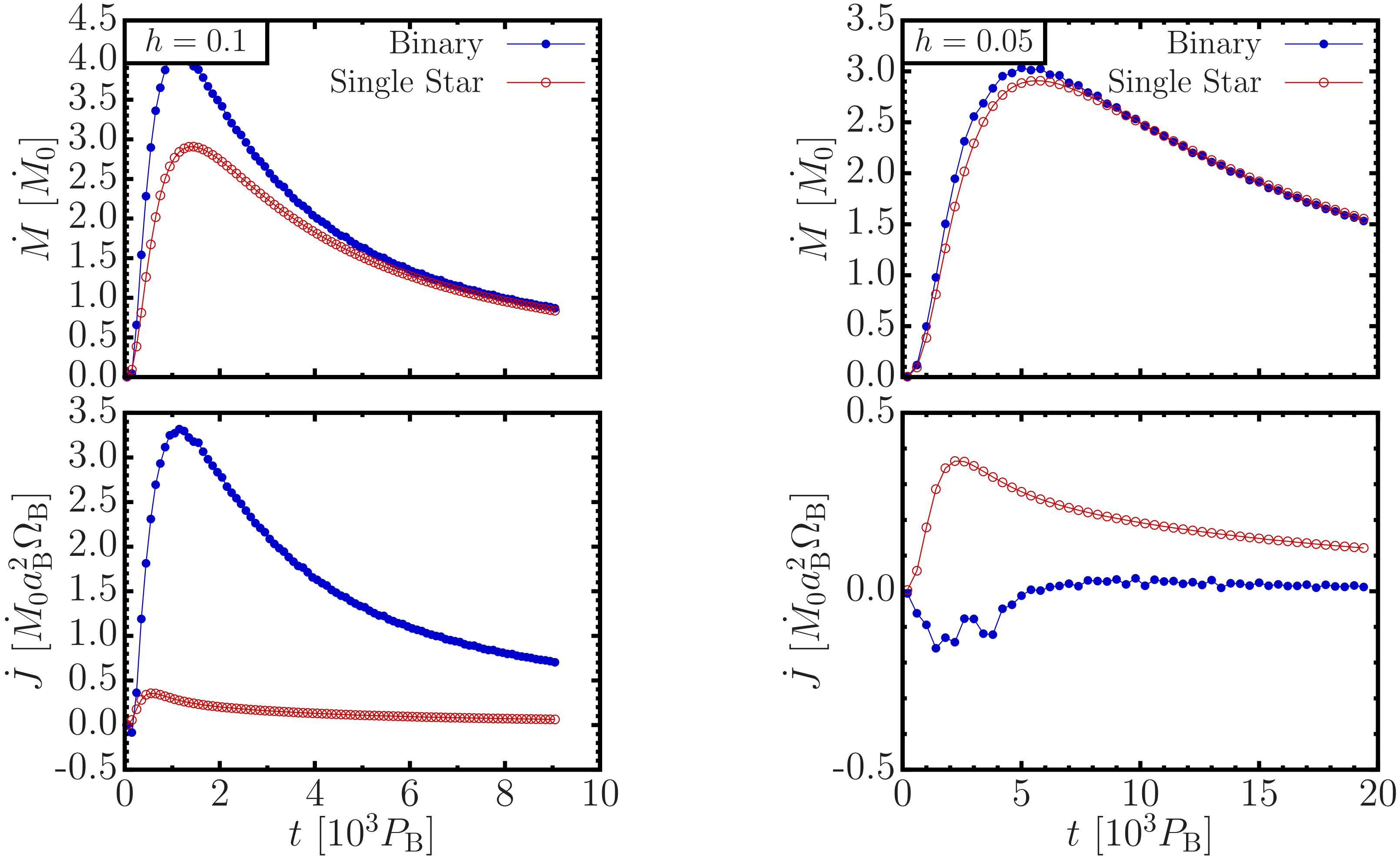
Caveats/Issues??

Disk with constant mass supply (Preliminary run by R. Miranda)

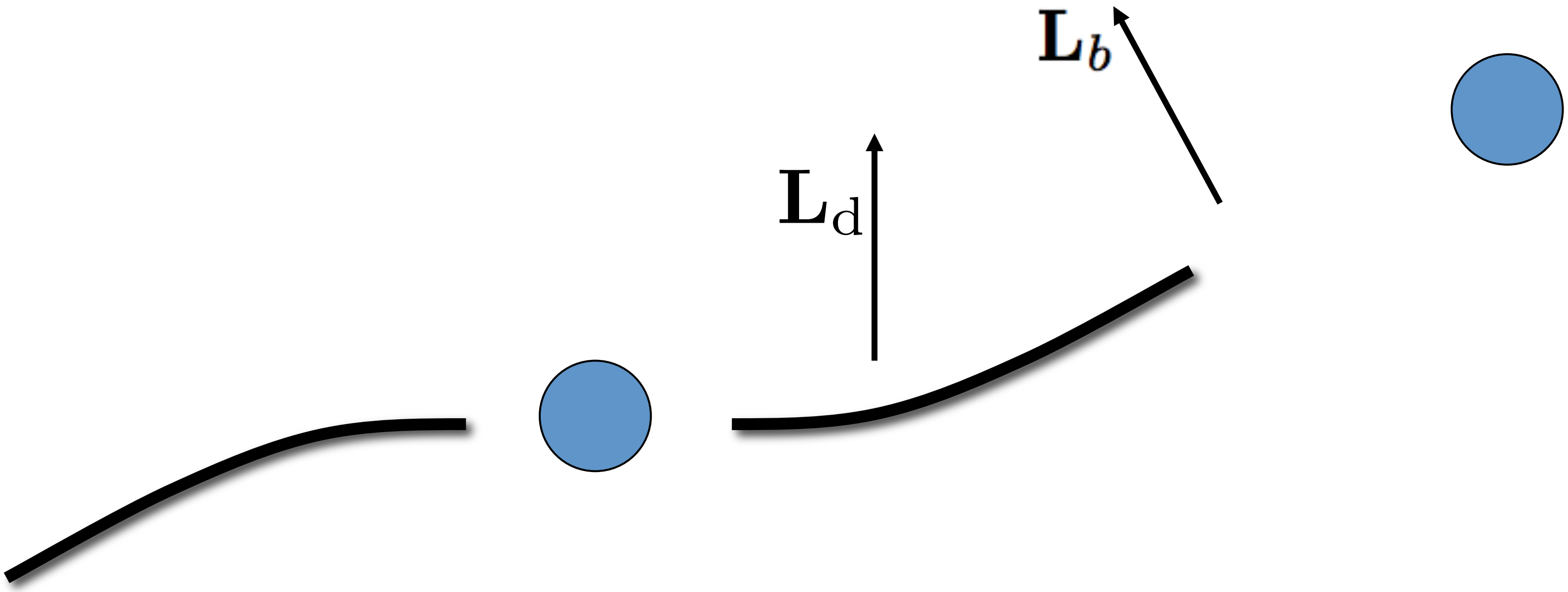


Caveats/Issues??

Spreading layer (Preliminary run by R. Miranda)



Circumstellar Disk within Binary

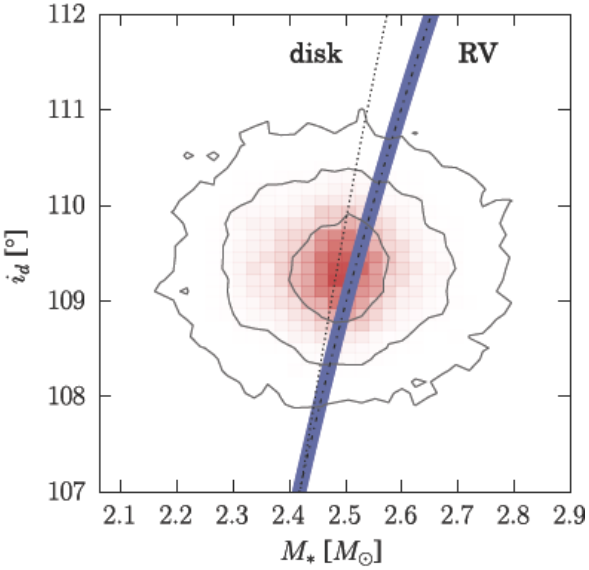


Disk is warped at outer region
➔ Smaller warp

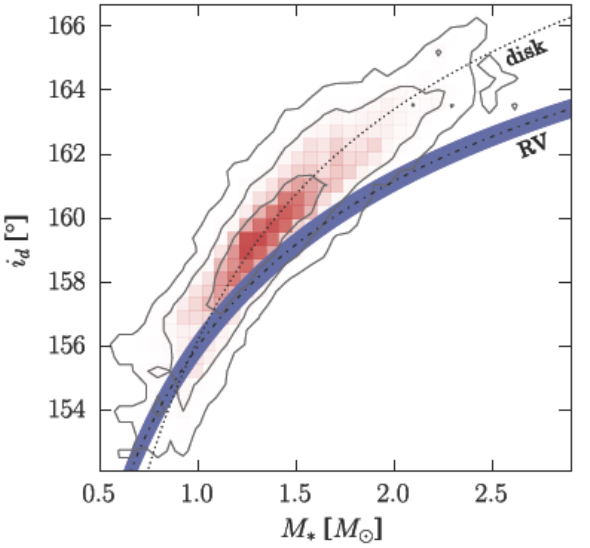
Typical alignment time >> precession period
➔ Misalignment can persist

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)