Circumbinary Accretion Disks & Stellar Binaries (& CBPs)

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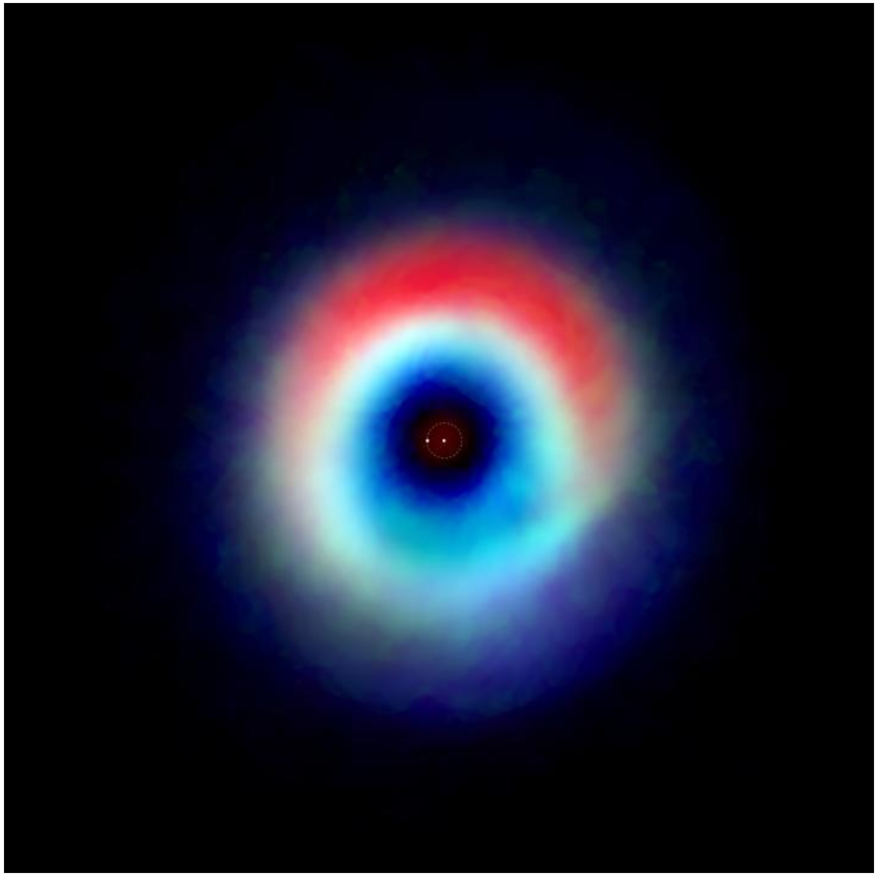
Circumbinary planets Across the HR Diagram, Florence, Jan.14, 2025

Disks around proto-stellar binaries

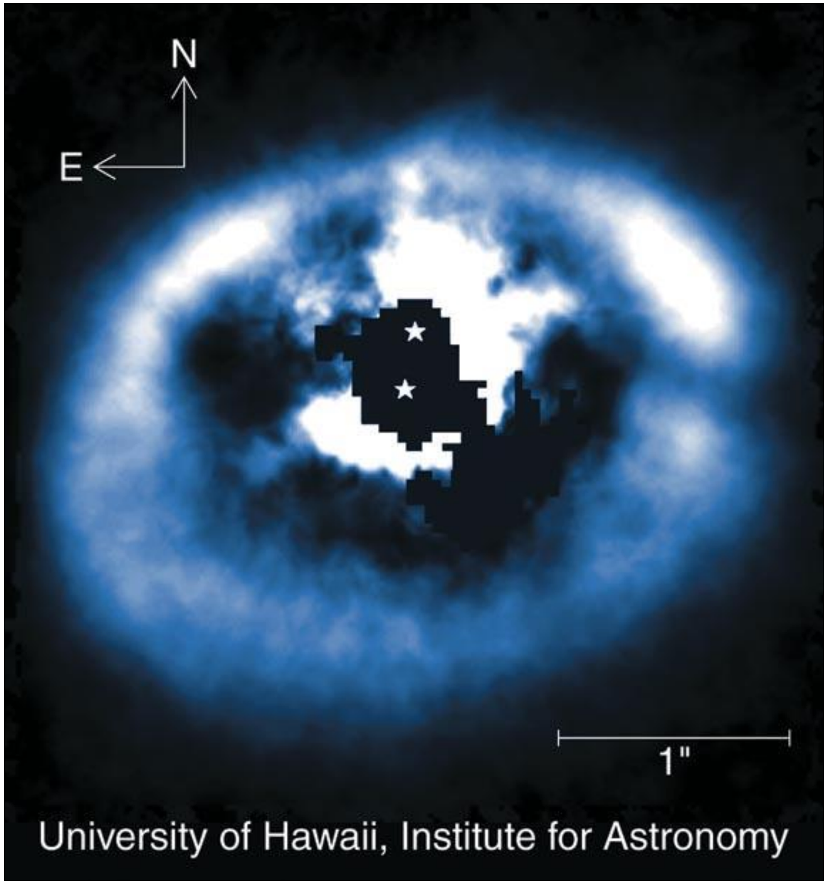
HD 142527



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

A. Isella/ALMA

GG Tau



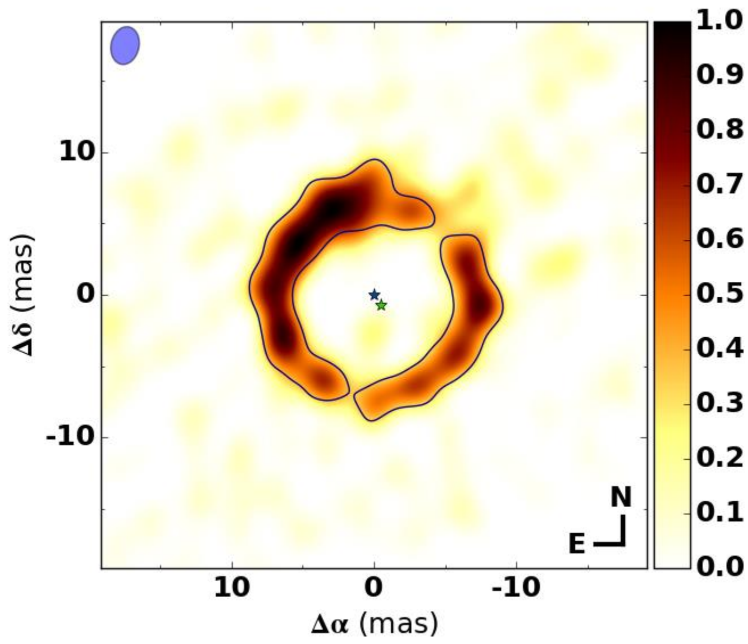
Binary: ~60 AU

Disks around MS binaries

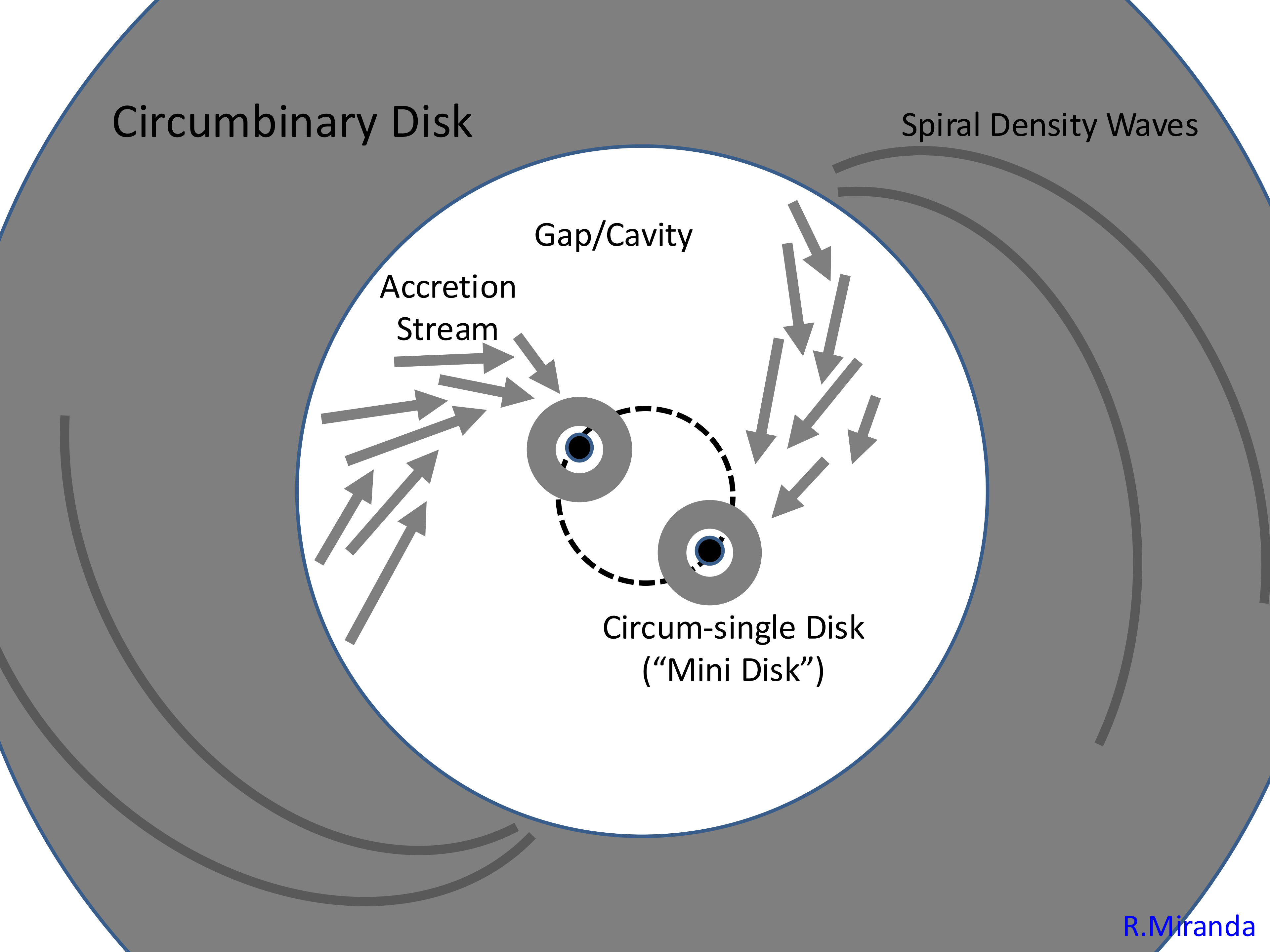
suggested… e.g. triple systems (evolved tertiary supplies mass)

Disks around post-AGB binaries

SEDs, imaging



Hillen et al.2016

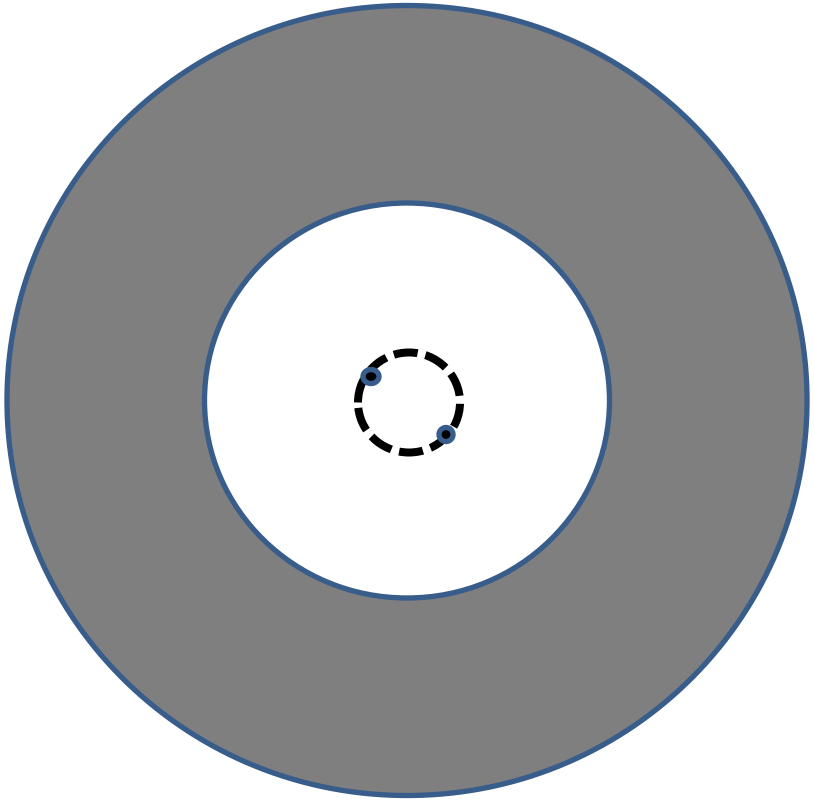

Circumbinary Disk
Spiral Density Waves
Gap/Cavity
Accretion
Stream
Circum-single Disk
("Mini Disk")
R.Miranda

Outline:
Physics/dynamics of binary-CBD Interactions

- Disk cavity/truncation
- Accretion variability
- Disk structure/asymmetry
- Long-term evolution of the binary
- Misalignment
- CB planets

Some/most material found in: Lai & Munoz 2023 ARAA

Disk around Binary: Gap/Cavity opening



Binary produces a gravitational potential on disk:

$$\Phi(\mathbf{r}, t) = \sum_{mn} \Phi_{mn}(r) \cos(m\phi - n\Omega_{\rm b} t)$$

Transfer angular momentum to the disk through "Lindblad resonance":

$$n\Omega_{\rm b} - m\Omega(r) = \kappa \simeq \Omega(r)$$

➔ Disk is "pushed" outward

Viscosity ➔ disk diffuses inward

Cavity radius $\approx (2-3)a_b$

Simulations of Circumbinary Accretion

Artymowicz & Lubow 1996; Günther & Kley 02; MacFadyen & Milosavljević 08; Cuadra et al.09; Hanawa et al. 10; de Val-Borro et al. 11; Roedig et al. 12; Noble et al.12; Shi et al. 12; D'Orazio et al. 13; Pelupessy & Portegies-Zwart 13; Farris et al. 14; Shi & Krolik 15; Lines et al. 15; O'Ozario et al. 16; Ragusa et al. 16, Munoz & Lai 2016; Miranda, Munoz & Lai 2017; Tang et al. 17; Bowen et al.17,19; Munoz, Miranda, Lai 2019; Moody, Shi & Stone 19; Munoz, Lai et al.2020; Duffell et al.20; Tiede et al. 20; Heath & Nixon 20; D'Orazio & Duffell 21; Zrake et al.21; Penzlin et al.22; Siwek et al.22, Wang et al.2023; Siwek et al. 2024; Duffell et al. 2024....

Many simulations excised the inner "cavity"

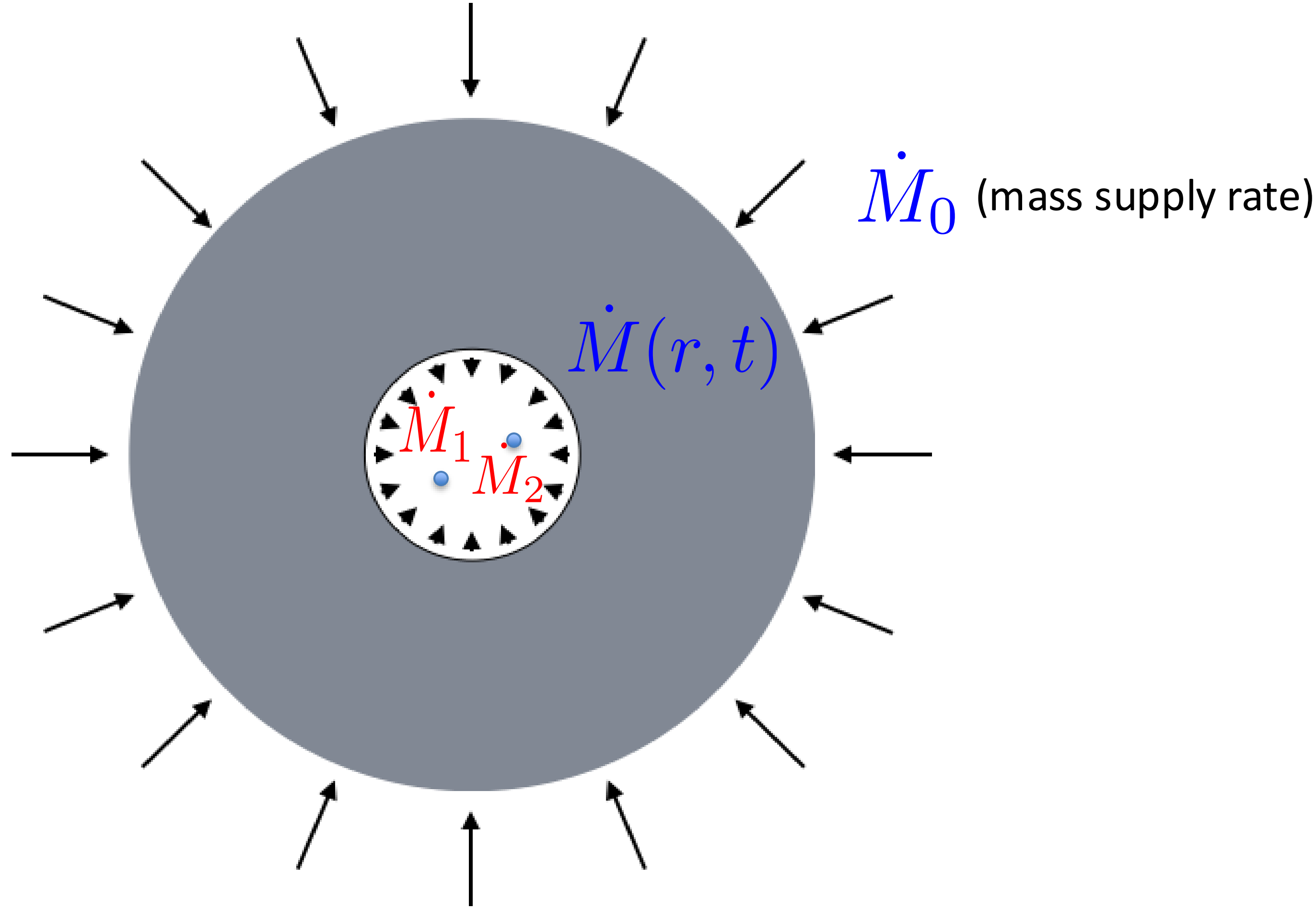
Some cover the whole domain: Circumbinary disk → stream → circumsingle disks:

- SPH
- Finite-volume moving mesh codes:
  - DISCO: Farris, Duffell, MacFadyen, Haiman 2014...
  - 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; Wang, Bai & Lai 2023)

Summary of Key Simulation Results

- Short-term variabilities
- Long-term variabilities
- Disk eccentricity
- Binary evolution

“Idealized” Simulations:


$\dot{M}_0$ (mass supply rate)
$\dot{M}(r,t)$
$\dot{M}_1$
$\dot{M}_2$

Summary of Key Simulation Results

- Short-term variabilities
- Long-term variabilities
- Disk eccentricity
- Binary evolution

"Idealized" Simulations:

-- Solve viscous hydrodynamic equations in 2D
-- alpha viscosity, (locally) isothermal sound speed (or EOS with simple cooling)

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

Our own works: with Diego Munoz (Harvard PhD'13->Cornell -> … -> NAU)
Ryan Miranda (Cornell Ph.D.'17->IAS -> Data science)
Haiyang Wang (Fudan U.-> Caltech)
Xuening Bai (Tsinghua U)

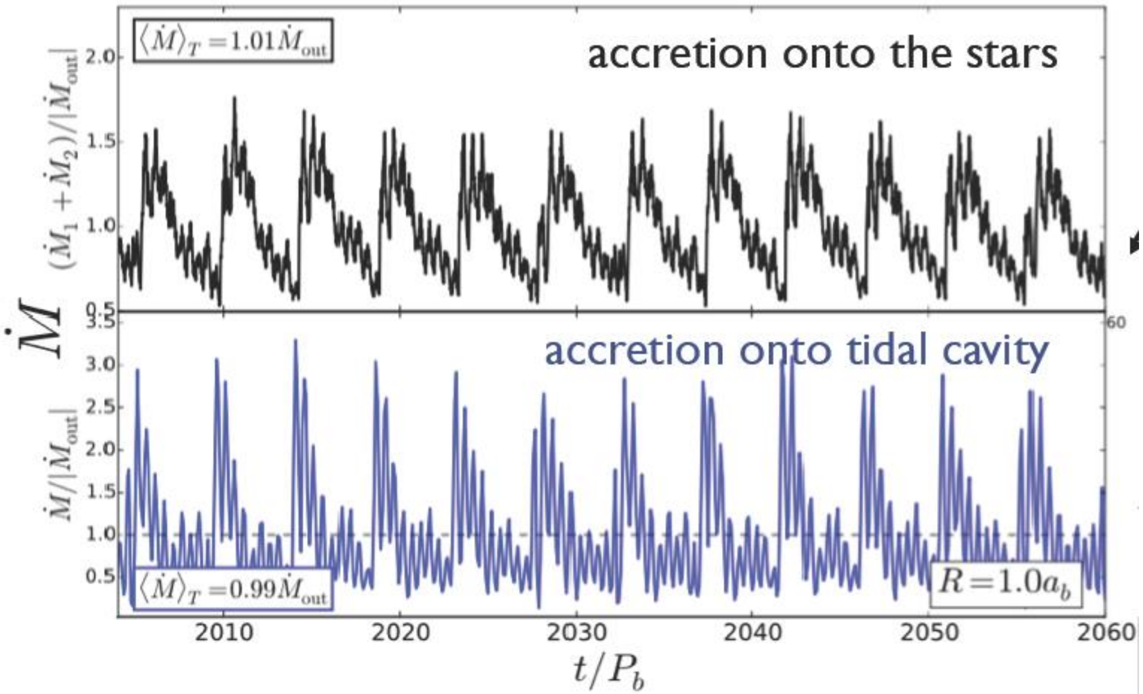
Munoz & DL 2016, ApJ; Miranda, Munoz & DL 2017, MNRAS
Munoz, Miranda & DL 2019; Munoz, DL et al 2020; Wang, Bai, DL et al.2023a,b

REFs: Lai & Munoz 2023 ARAA + other recent papers…

Short-term (~P_b) Accretion Variabilities

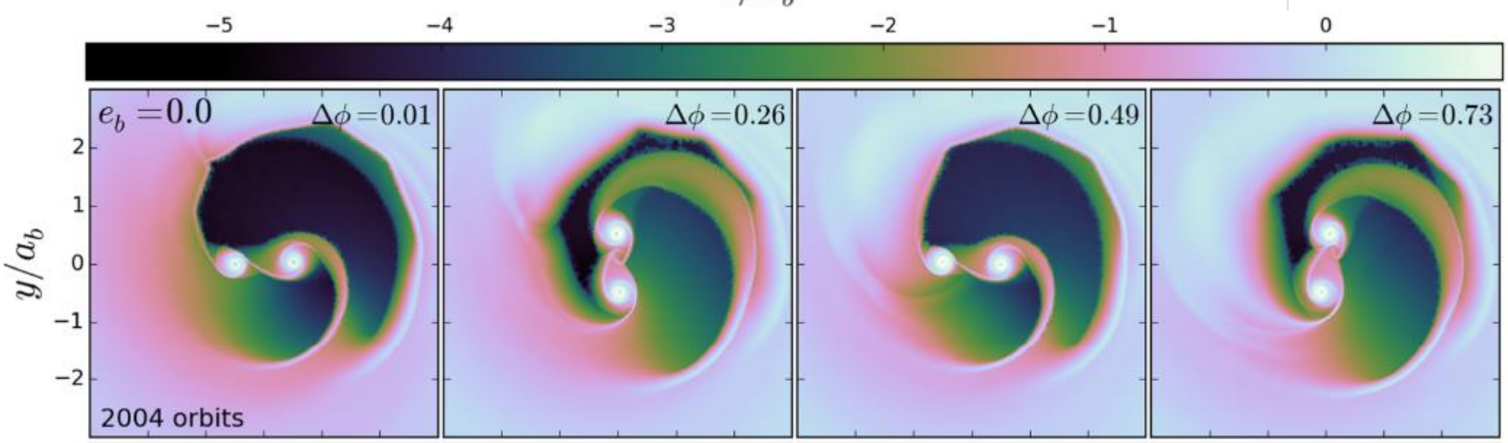
For $e_b \lesssim 0.05$: $\dot{M}(= \dot{M}_1 + \dot{M}_2)$ varies at $\sim 5P_b$ (Kepler period at r_{in} ~ $3a_b$)

e_b=0



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

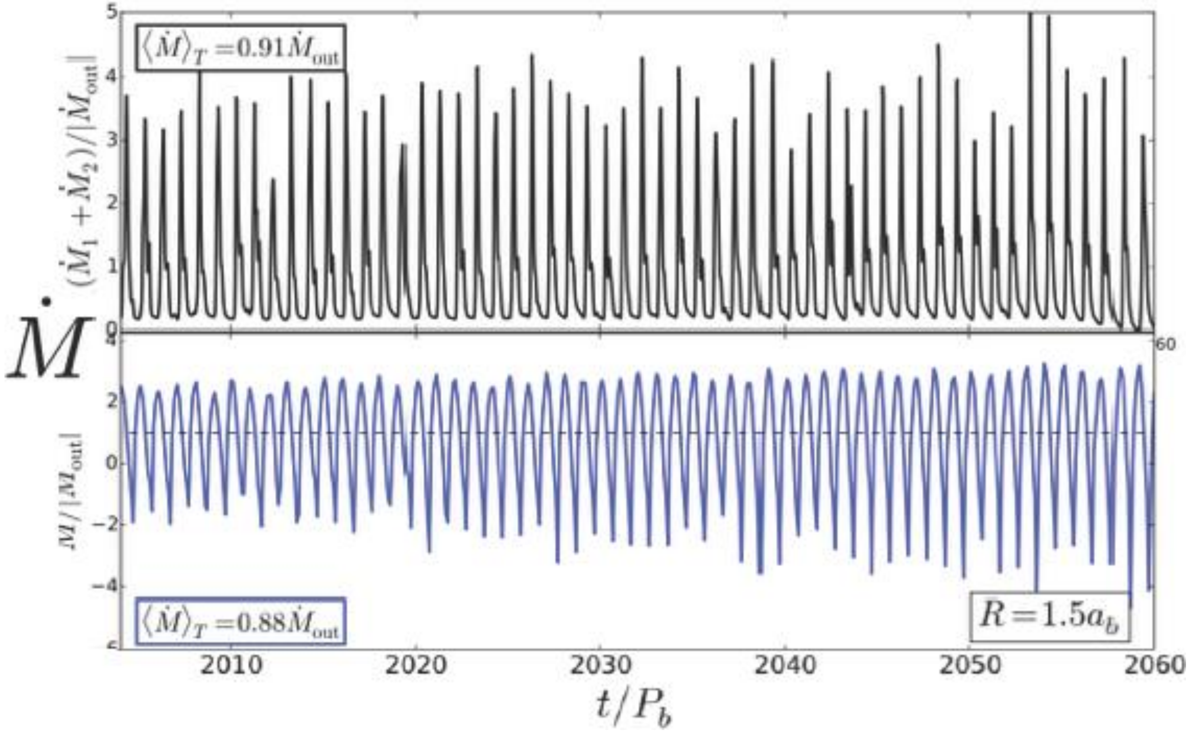
Munoz & DL 16



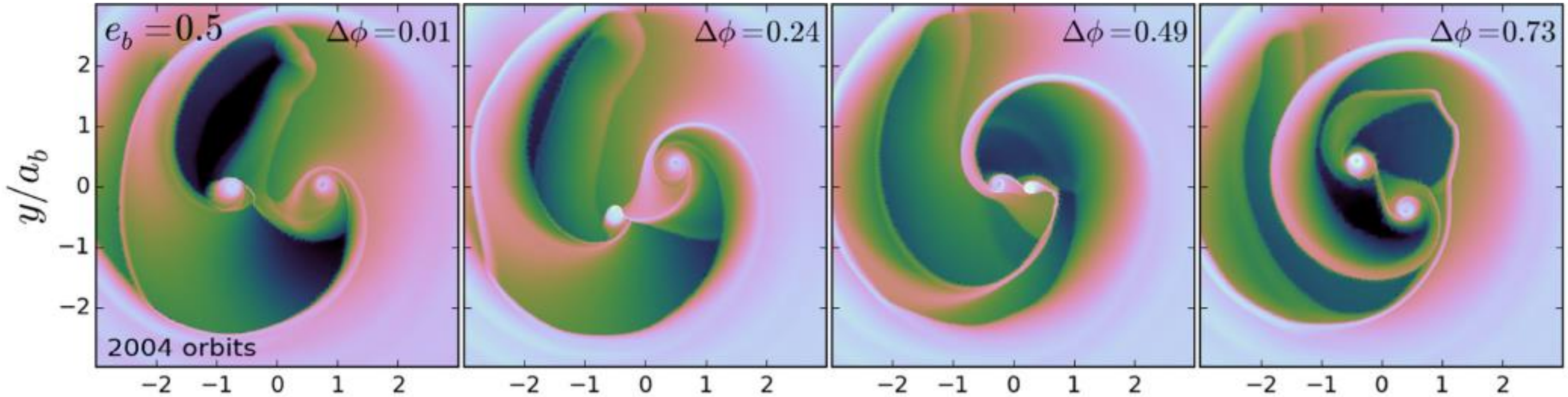
Short-term (~P_b) Accretion Variabilities

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

e_b=0.5



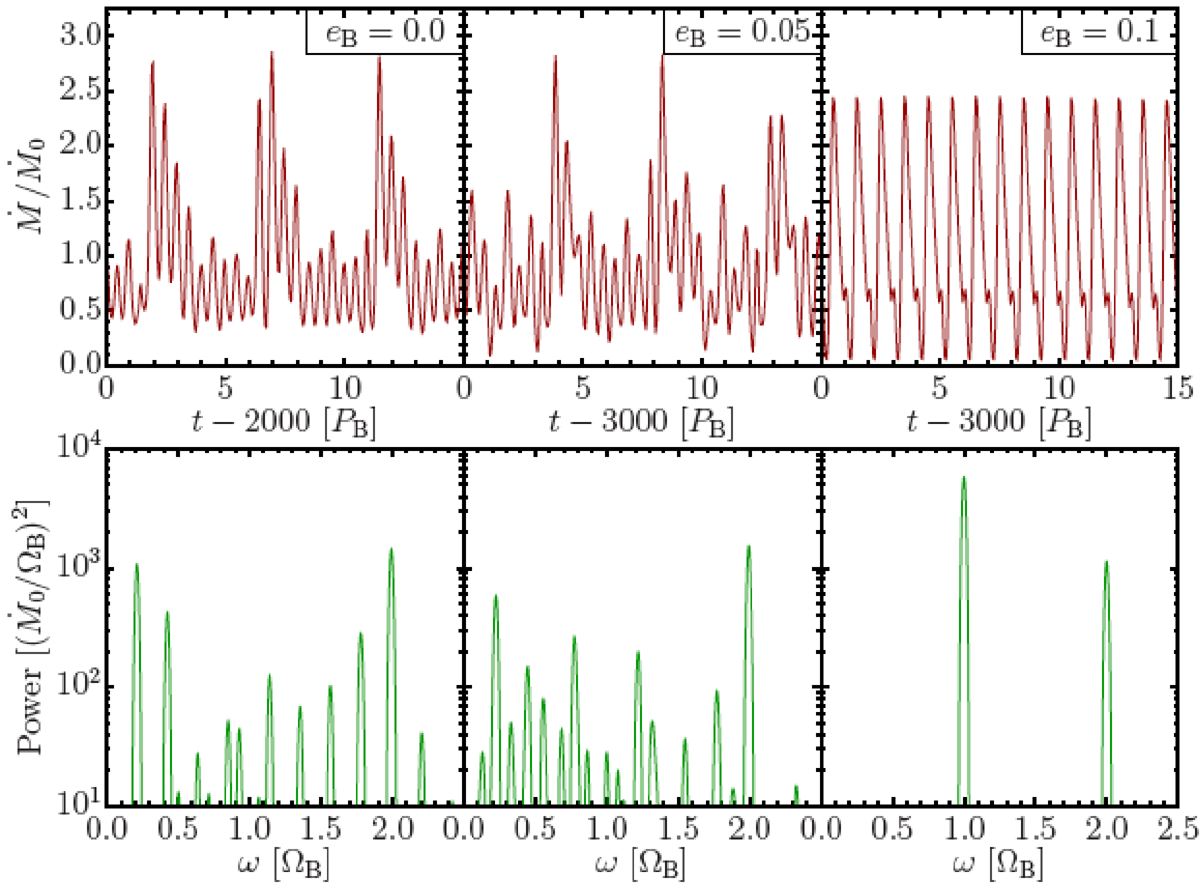
Munoz & DL 16



Short-term (~P_b) Accretion Variabilities

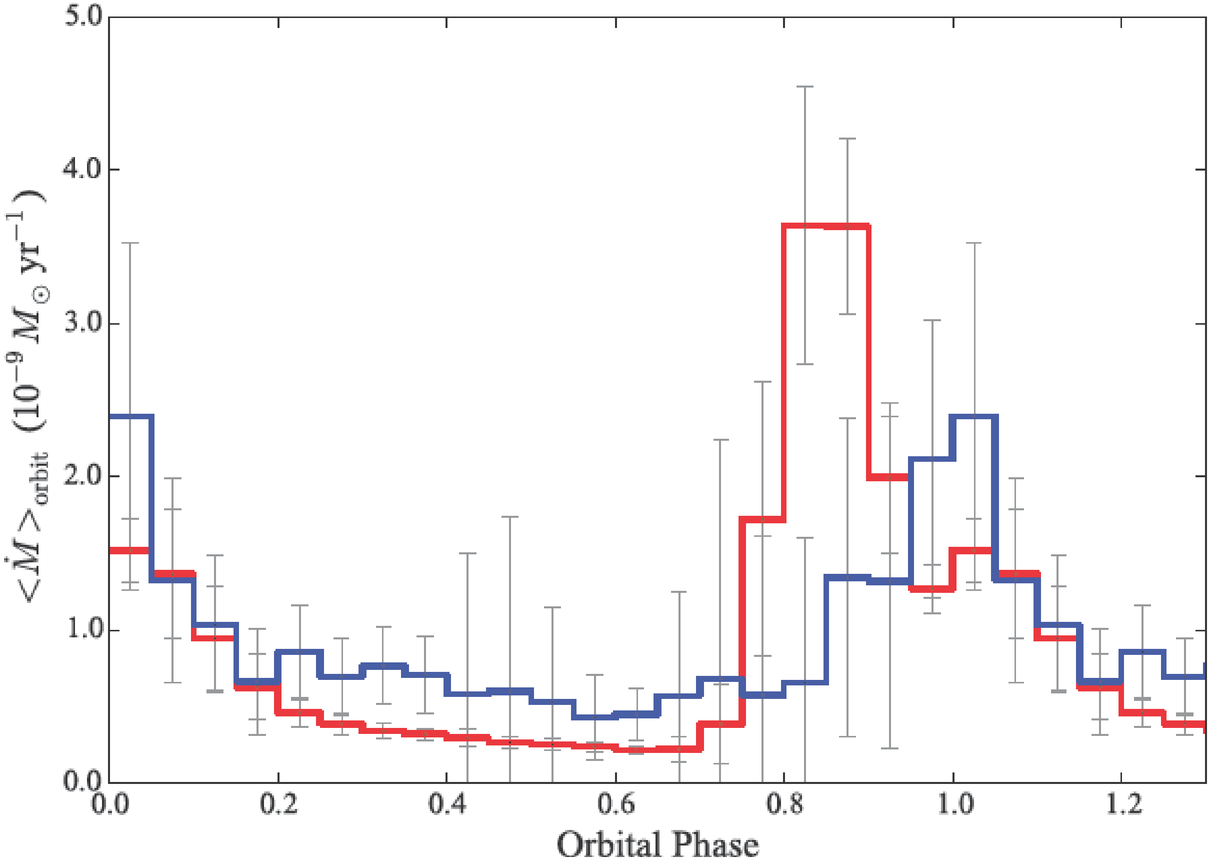
For $e_b \lesssim 0.05$: $\dot{M}(= \dot{M}_1 + \dot{M}_2)$ varies at $\sim 5P_b$
For $e_b \gtrsim 0.05$: $\dot{M} = \dot{M}_1 + \dot{M}_2$ varies at $\simeq P_b$

Power spectrum



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

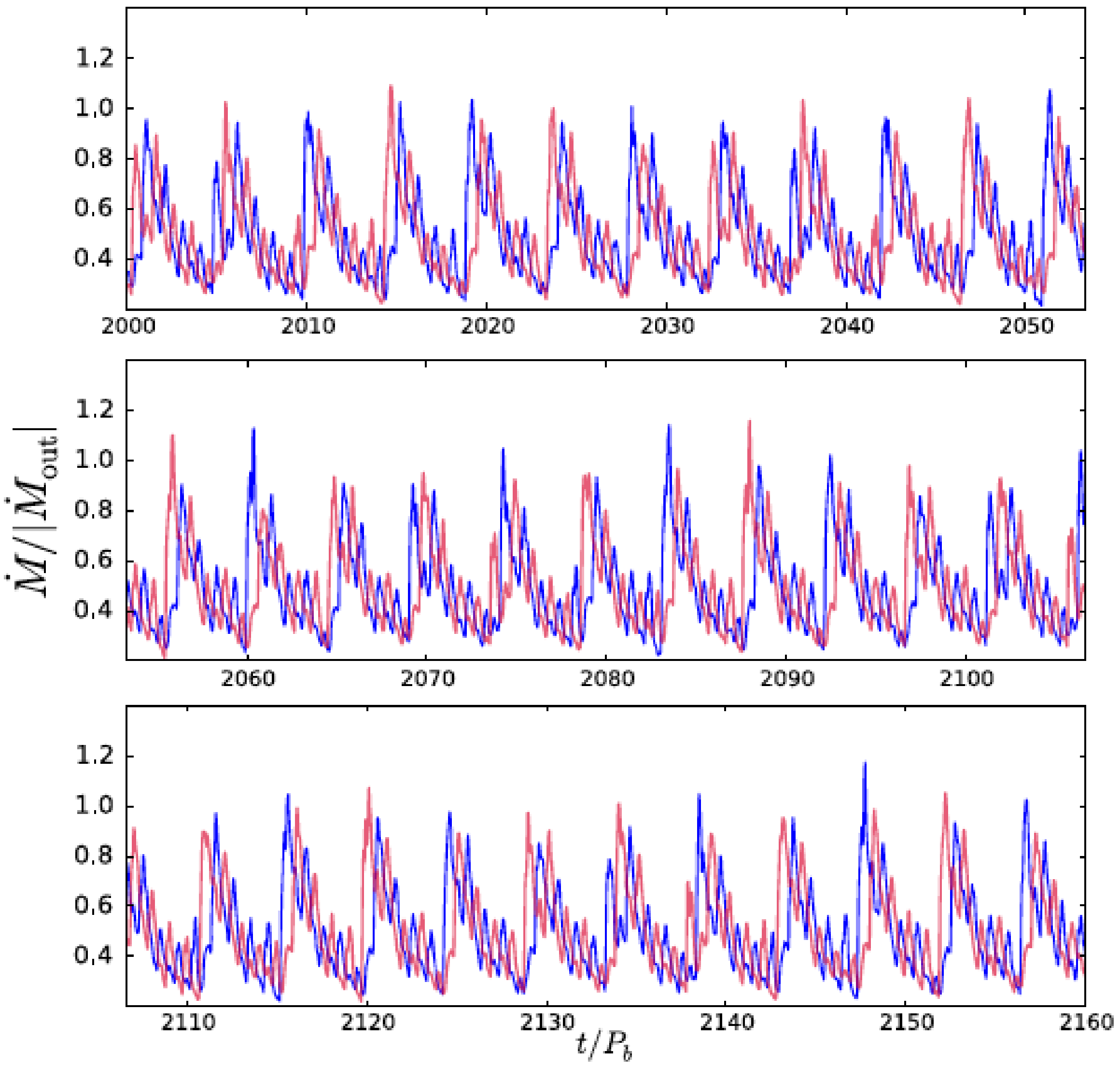


red: simulation (D. Munoz)
blue: observations

➔ Can resolve the effective size of stars

Tofflemire, Mathieu et al. 2017

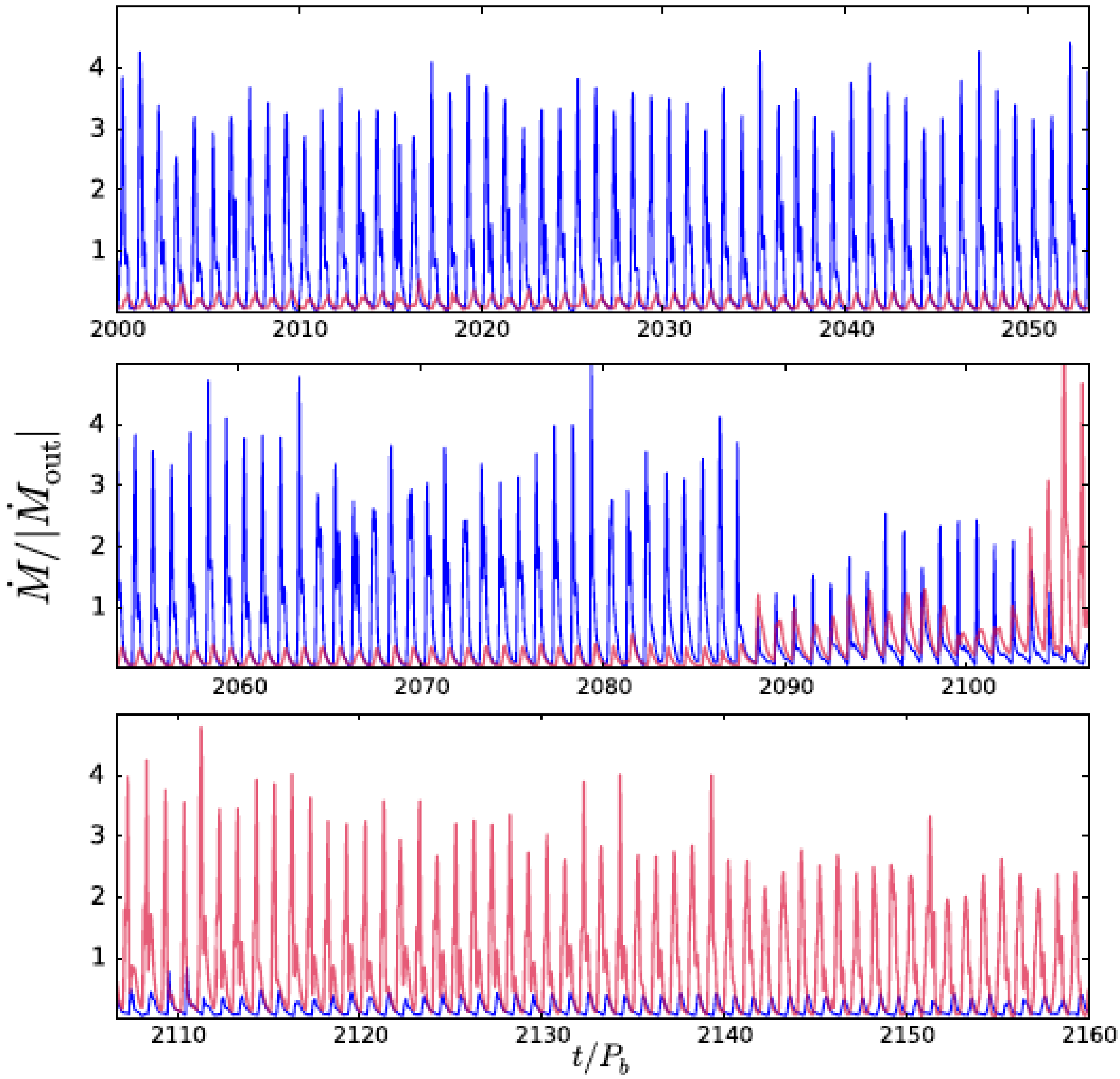
Long-Term Variability:



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

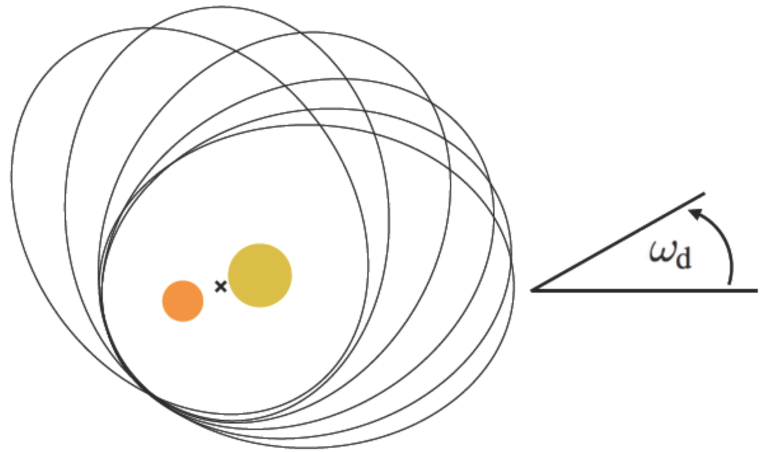
$\dot{M}_2 \gtrsim 20\dot{M}_1$

every ~200 P_b

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

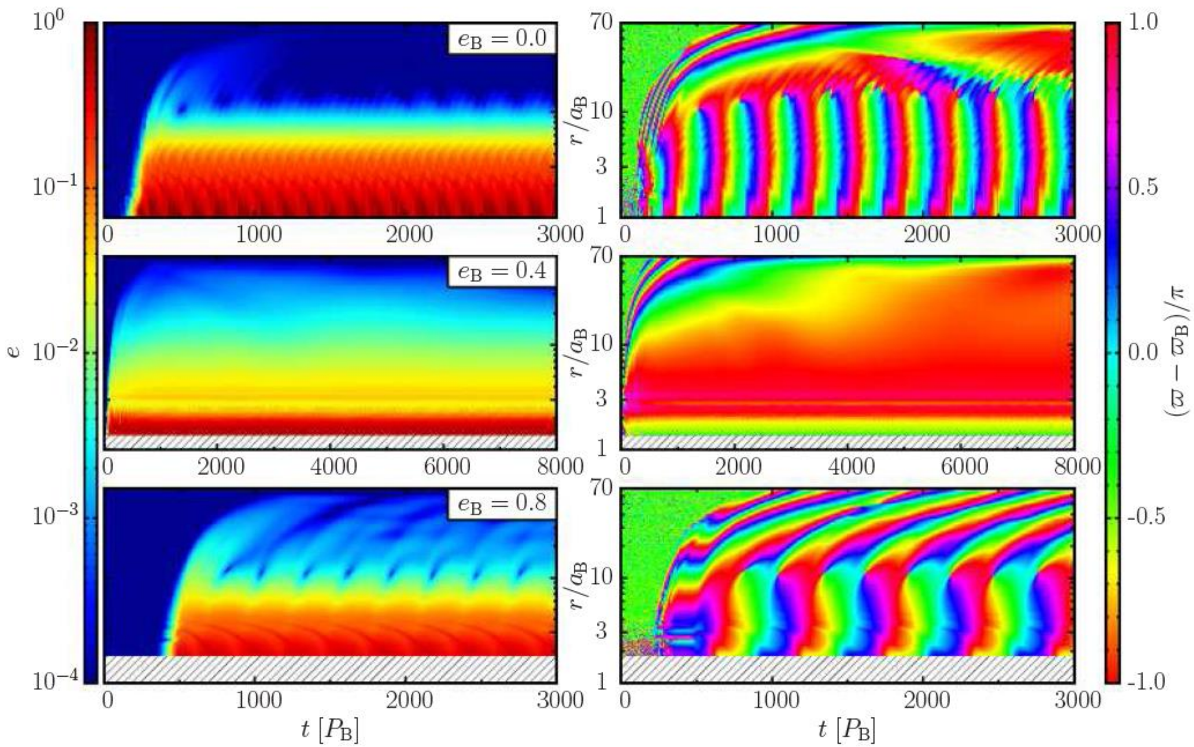


Long-Term Evolution: Disk Eccentricty

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



Explained by
“**Eccentric Lindblad Resonance**”
with viscous damping ?
(Lubow 91; Goodschild & Ogilvie 2006)

Theory of eccentric disks around binary: see Miranda, Munoz & Lai 2017
Munoz & Lithwick (2020)
Wang HY, Lai, Bai (2023)

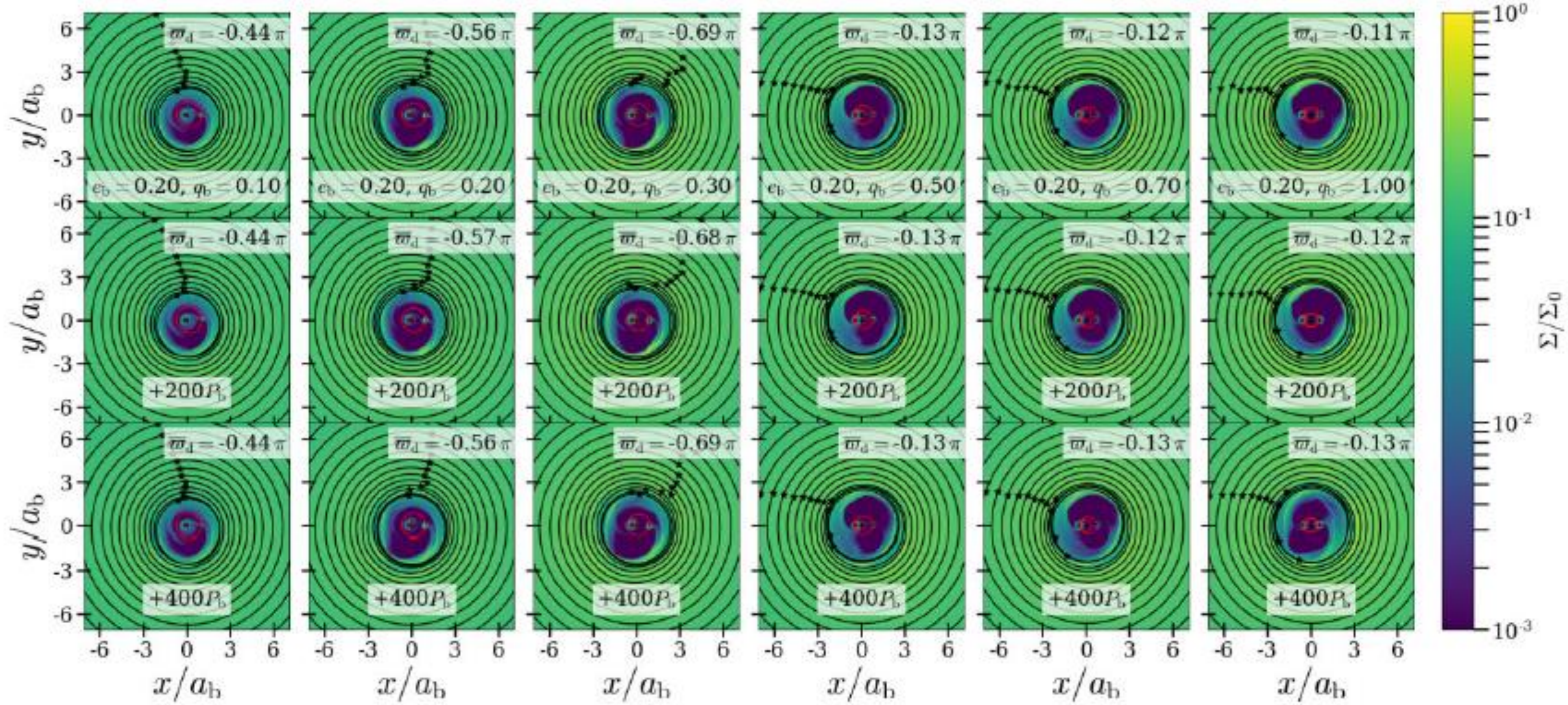
Inner disk (< 10 a_b) is coherently eccentric (e ~ 0.1-0.2 at r ~ 4a_b),

can either precess or be apsidally locked with binary (but not always aligned),

depending on binary mass ratio (q_b) and eccentricity (e_b)

Mass ratio q_b: 0.1 0.2 0.3 0.5 0.7 1

e_b=0.2



Siwek et al. 2023

Implications for Planet Formation Around Binaries

-- Planetesimal growth may be suppressed

At $r \sim 4\, a_b$, disk $e_b \sim 0.1\text{-}0.2$ ➔

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)

Angular Momentum Transfer to Binary and Long-term Orbital Evolution

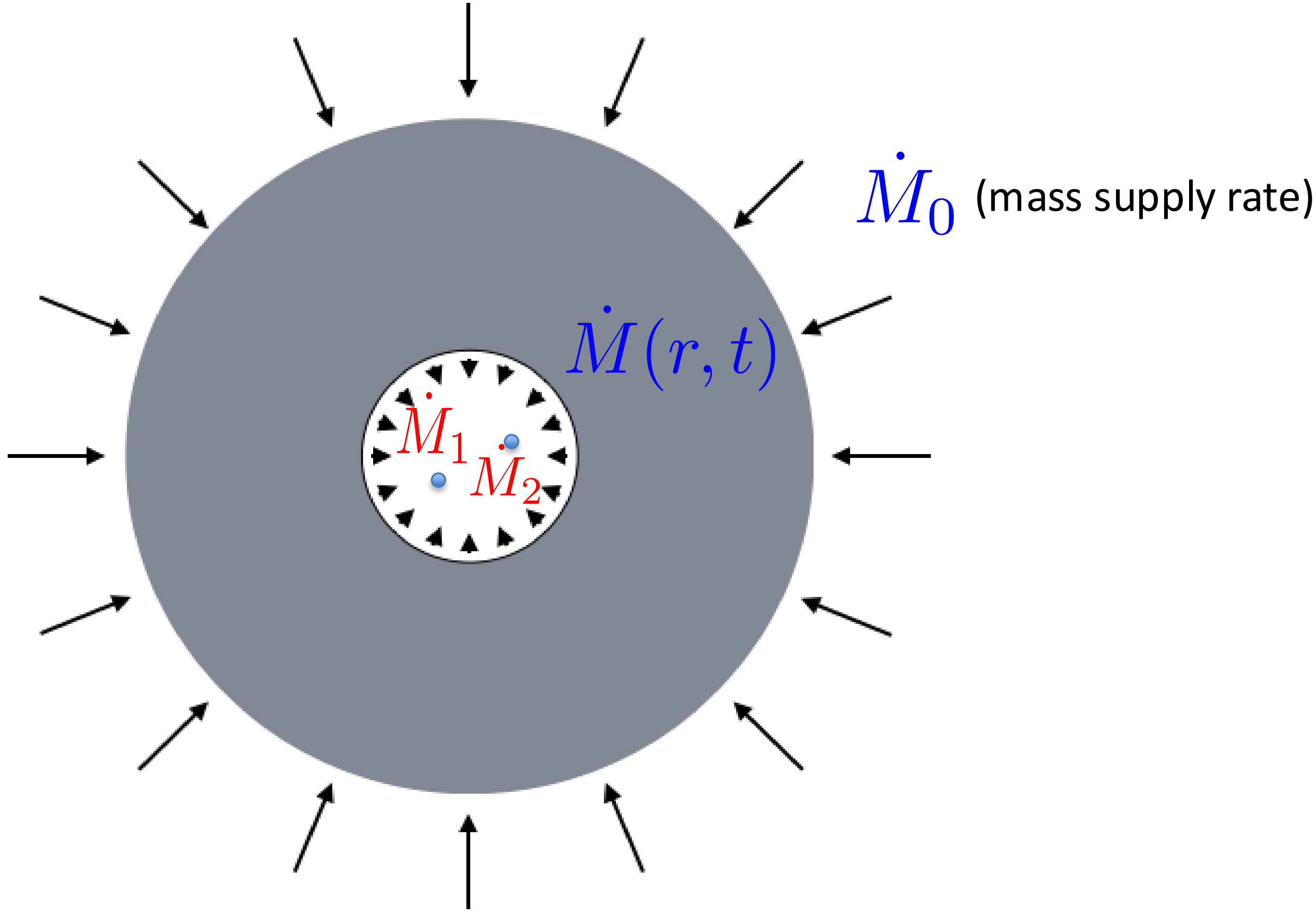
Many claims of orbital decays (1980s-2017):

Suppressed accretion onto binary (?), binary loses AM through outer Lindblad torque …

We now understand that:

In the presence of accretion, the binary may expand or contract

(depending on gas viscosity, thermodynamics, etc)



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

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

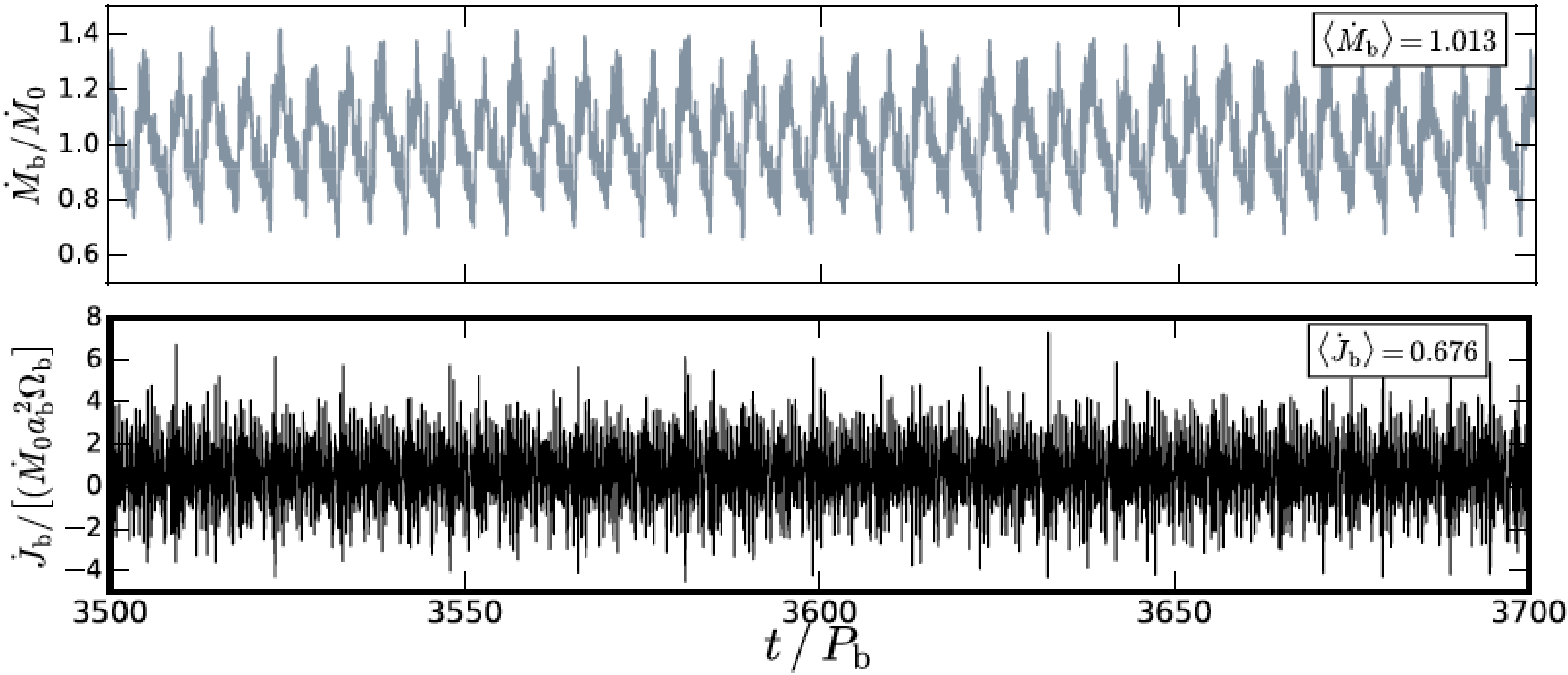
Two ways of computing the torque on the binary:

1. Direct computation:

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

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

Direct computation of torque on the binary



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

e_b=0 $(\alpha = 0.05 - 0.1, H/r = 0.05 - 0.1)$

Angular momentum transfer to the binary per unit accreted mass

2. Angular Momentum Current (Transfer Rate) in CBD

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

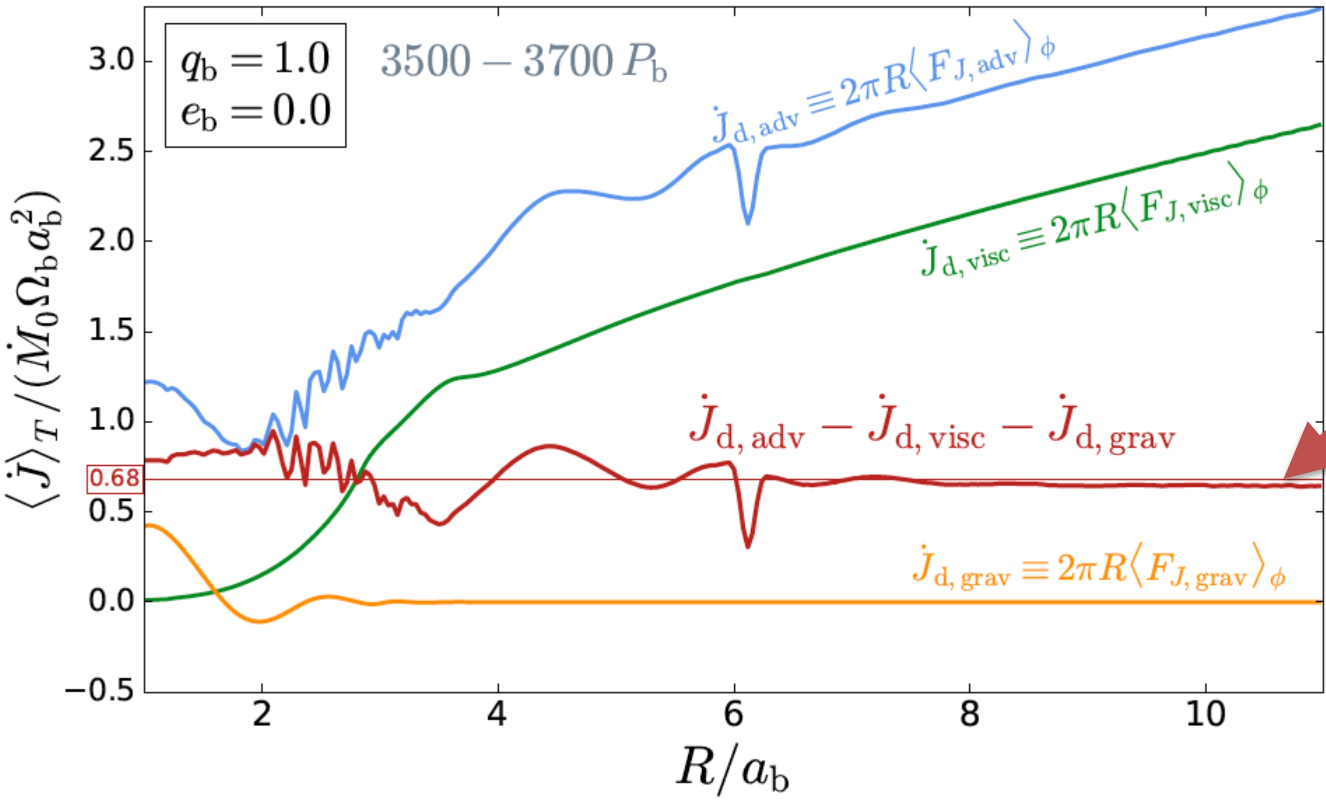
$$\dot{J}_{\rm adv} = -\oint r^2 \Sigma u_r u_\phi {\rm d}\phi$$

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

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

2. Angular Momentum Current (Transfer Rate) in CBD

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



Net AM flux across the disk

$$\dot{J}_b \simeq 0.68 \dot{M} a_b^2 \Omega_b$$

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:

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

(for alpha=0.05-0.1, H/r=0.05-0.1)

Munoz, Miranda & DL 2019

Confirmed by Moody, Shi & Stone 2019 (ATHENA++)
Duffell et al. (2020,2024), ….

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

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

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

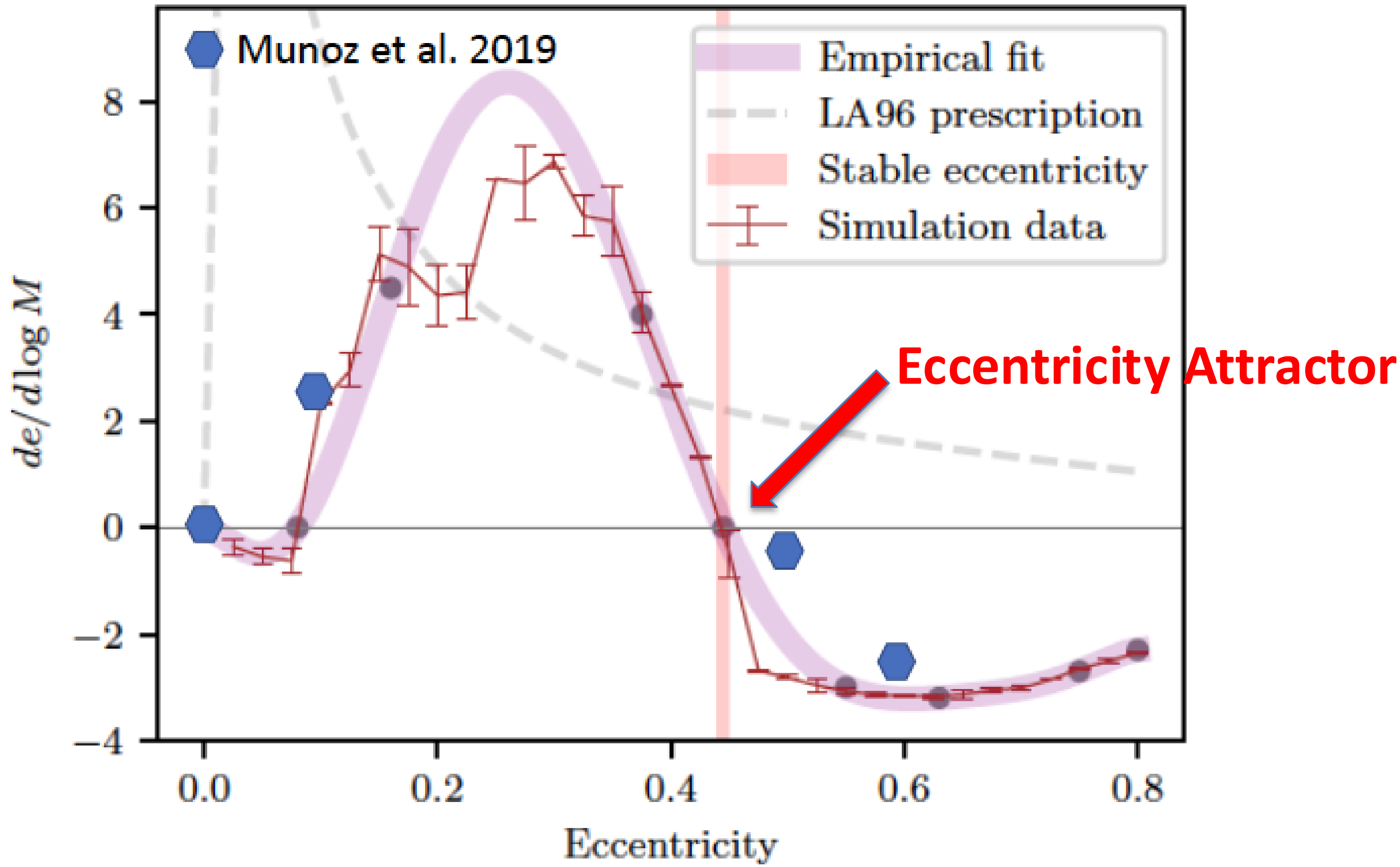
$$\rightarrow \quad \frac{\dot{a}_\mathrm{B}}{a_\mathrm{B}} = 8\left(\frac{l_0}{l_\mathrm{B}} - \frac{3}{8}\right)\frac{\dot{M}_\mathrm{B}}{M_\mathrm{B}}$$

Binaries can expand due to circumbinary accretion !

For e_B=0:

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

Eccentric Binaries



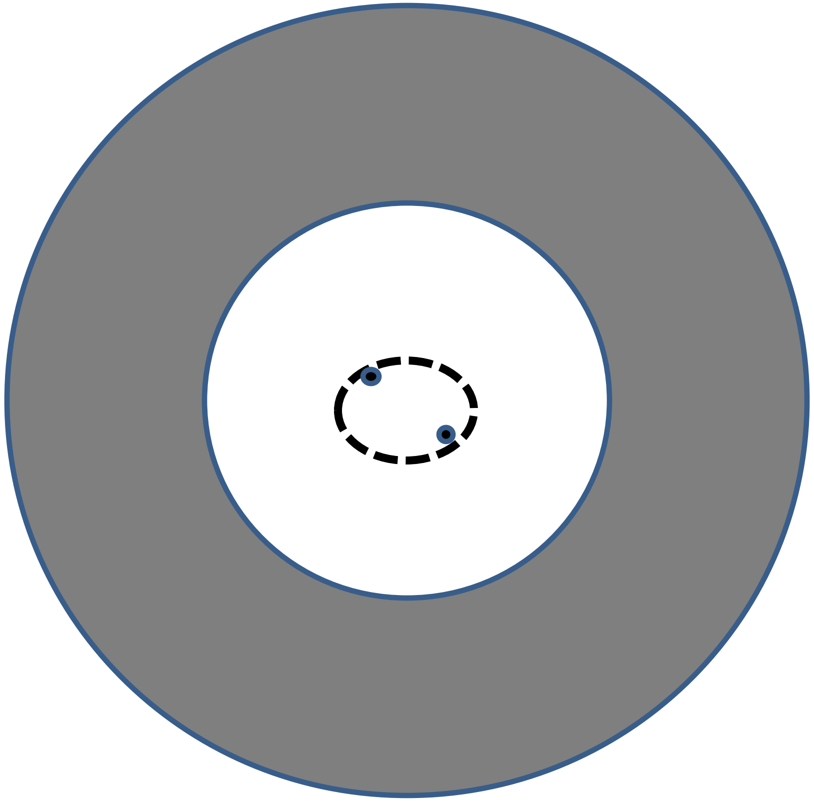
Zrake et al. 2021
See also D'Orazio & Duffell 2021
Siwek et al. 2023,2024

Why eccentricity attractor?

No "precise" theory…
But it arises from accretion torque and gravitational torque

One-sided gravitational torque (i.e. outer Lindblad resonance) can drive eccentricity…

Recall: Disk around Binary



Binary produces a gravitational potential on disk:

$$\Phi(\mathbf{r}, t) = \sum_{mn} \Phi_{mn}(r) \cos(m\phi - n\Omega_{\rm b} t)$$

Transfer angular momentum to the disk through "Lindblad resonance":

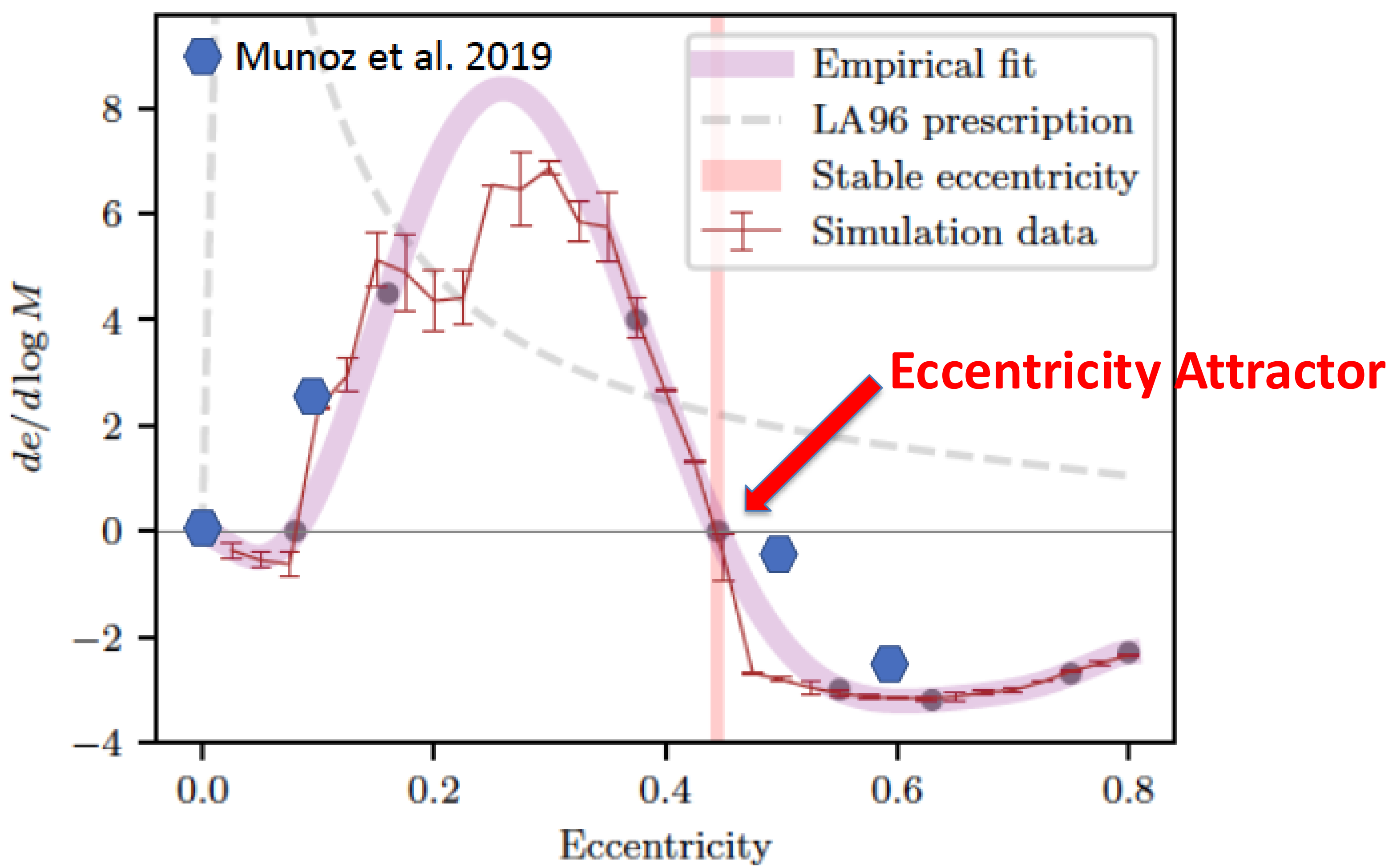
$$n\Omega_{\rm b} - m\Omega(r) = \kappa \simeq \Omega(r)$$

Binary loses orbital AM and energy to CBD…

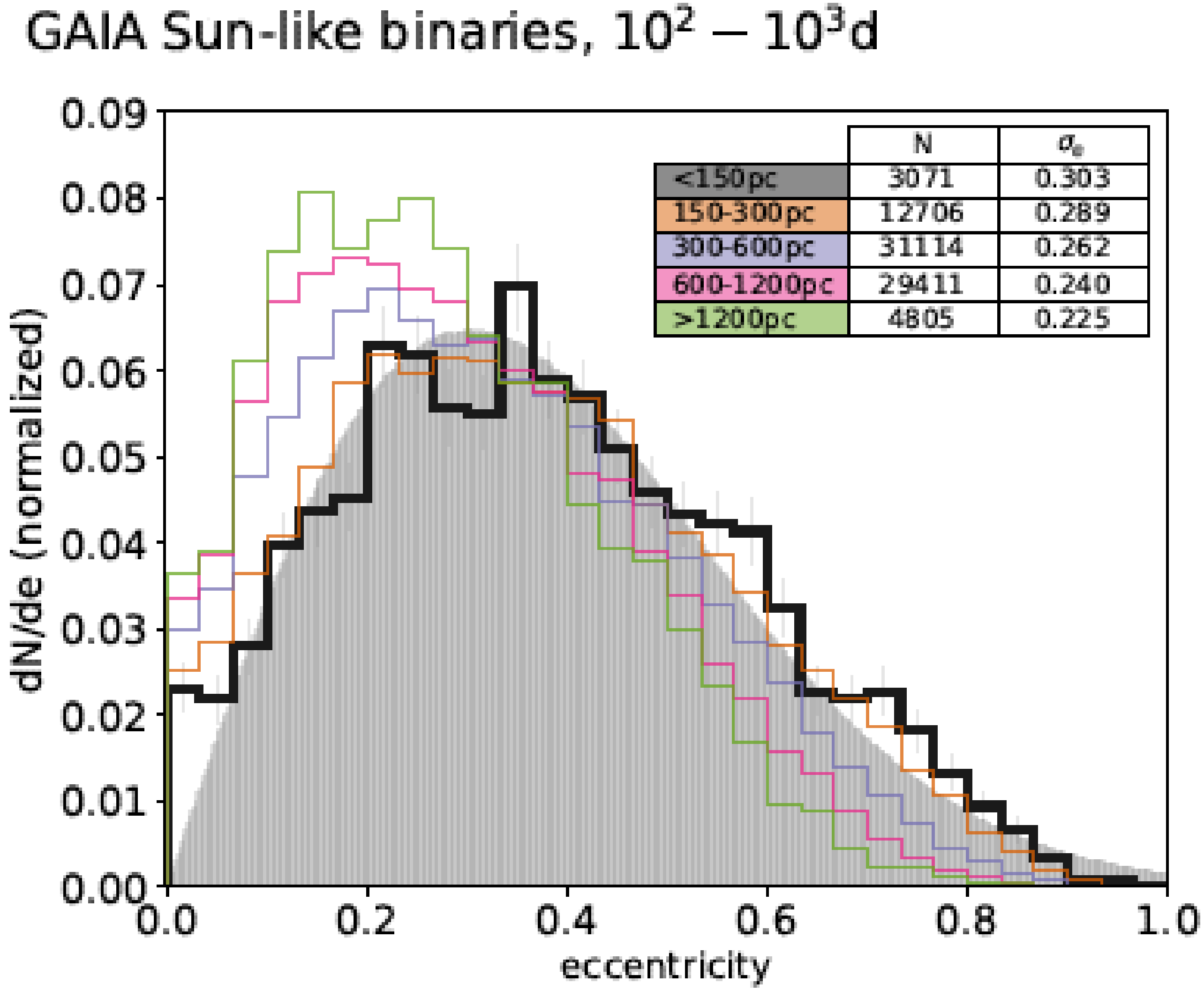
➔ $\frac{de_b}{dt}$

For m=2, n=1 component: $\frac{de_b}{dt} > 0$

Eccentric Binaries

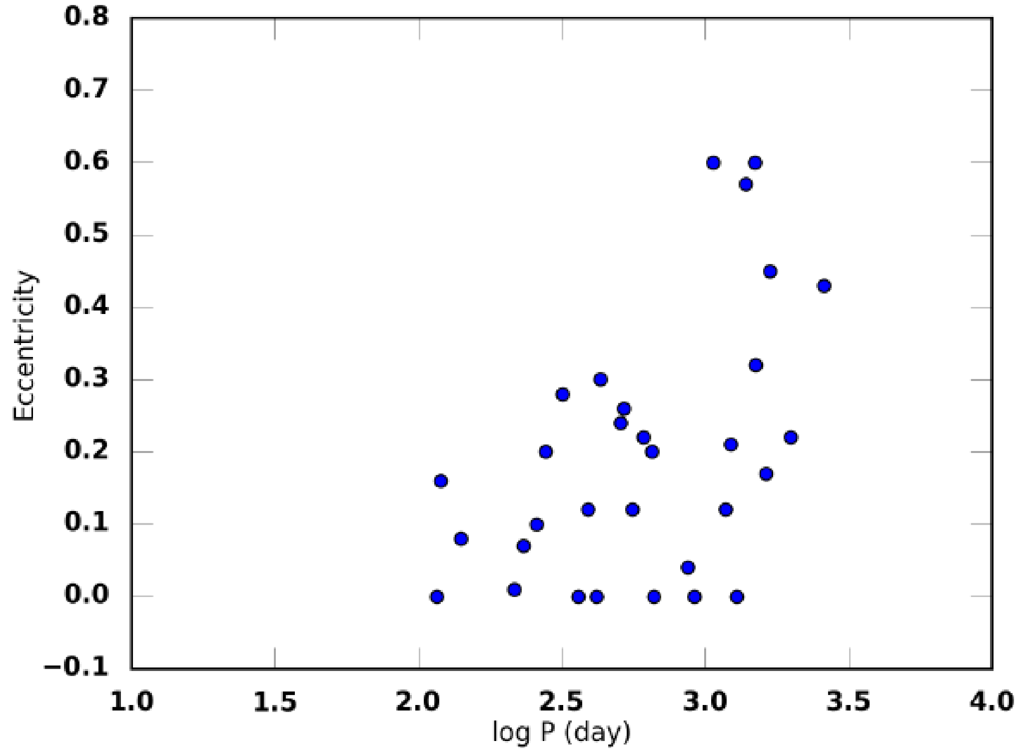


Zrake et al. 2021
See also D'Orazio & Duffell 2021
Siwek et al. 2023,2024



Wu et al. arXiv:2411.09905

Post-AGB binaries:



Van Winckel 2018

Unequal-mass binaries

$q = M_2/M_1 < 1$

$e_b = 0$

Munoz, Lai, Kratter, Miranda 2020

See also Duffell+2020,2024;
Siwek et al 2024

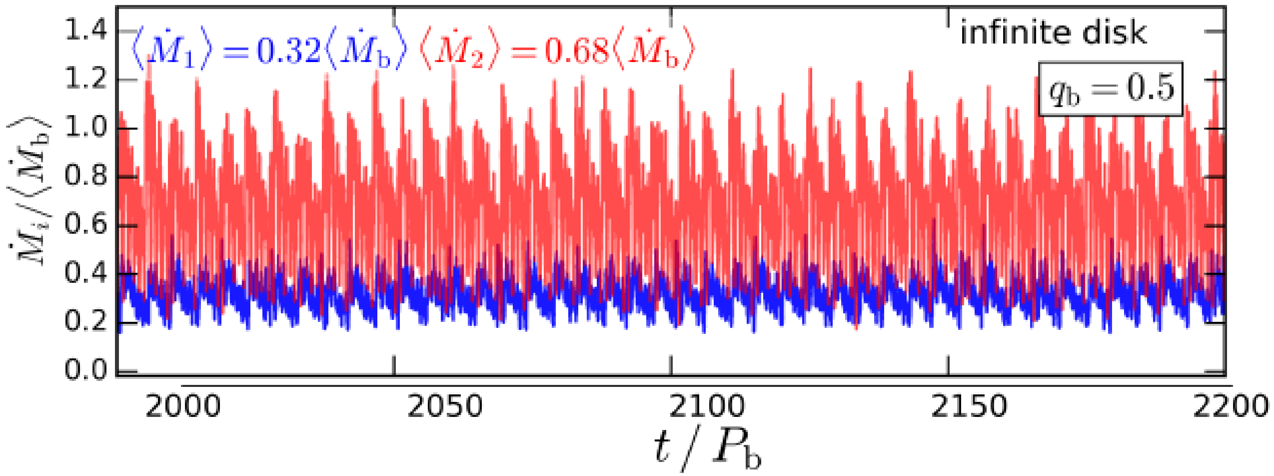
Unequal-mass binaries

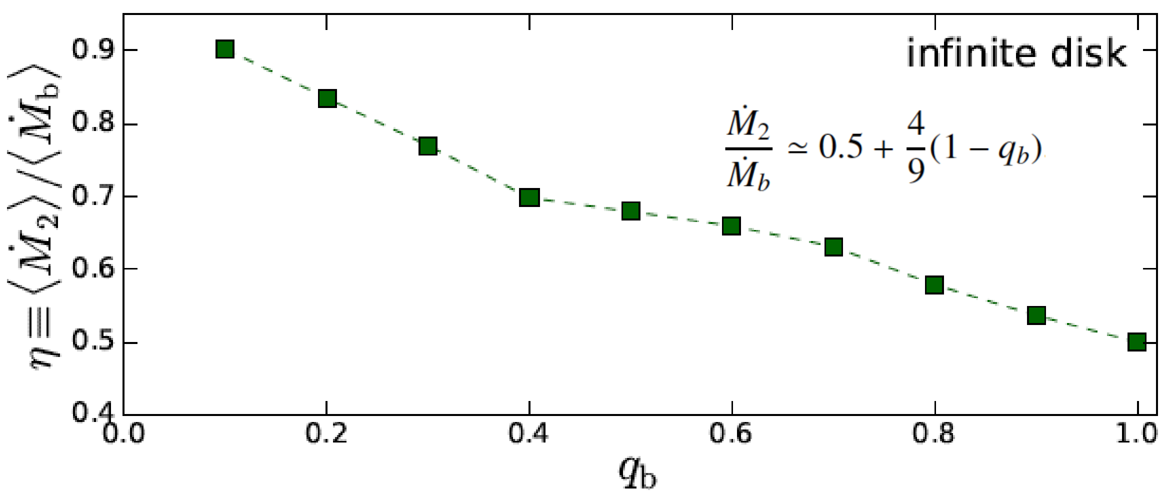
$q = M_2/M_1 < 1$

$e_b = 0$ Munoz, Lai et al 2020

-- Low-mass component accretes more

See also Bate+2000; Farris+2014





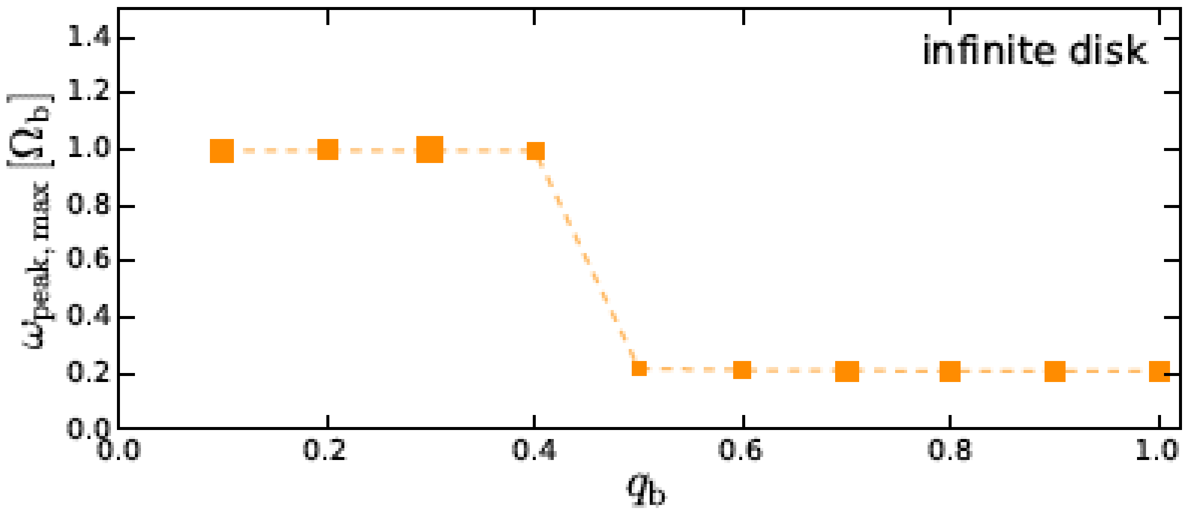
Unequal-mass binaries

$q = M_2/M_1 < 1$

$e_b = 0$

Munoz, DL +2020

-- Dominant variability frequency



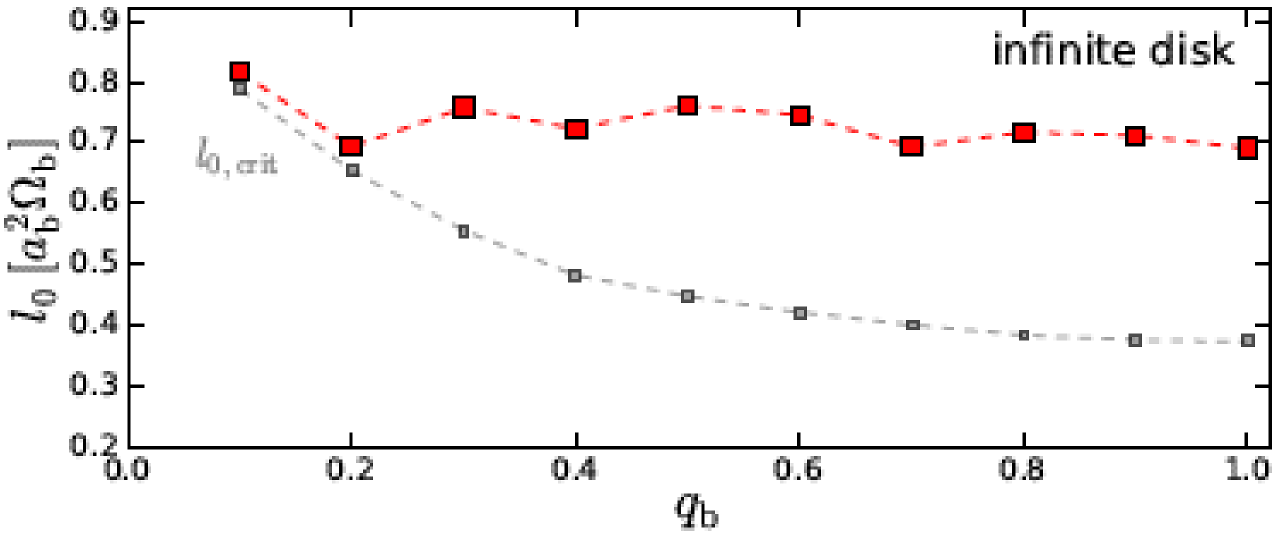
Unequal-mass binaries

$q = M_2/M_1 < 1$

$e_b = 0$

Munoz, DL +2020

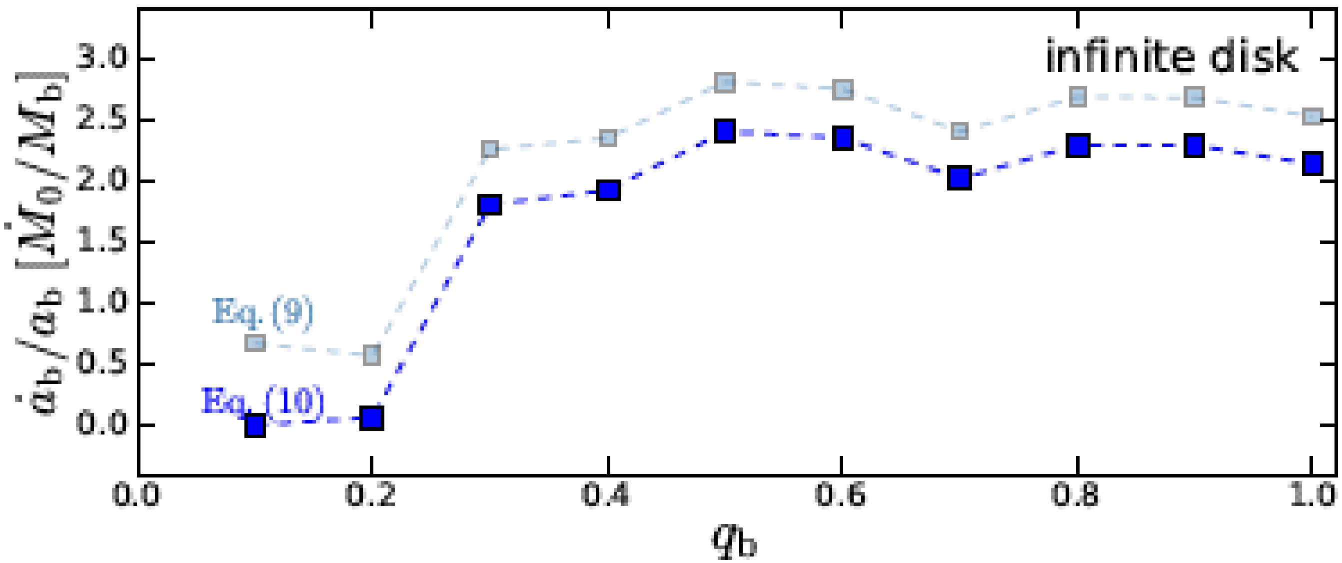
-- Angular momentum transfer



Unequal-mass binaries

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

-- Orbit evolution



Munoz, DL +2020

See also Duffell et al. 2020: $\dot{a}_b < 0 \text{ for } q_b \lesssim 0.05$

Unequal-mass, eccentric binaries:

Siwek et al. 2023

Recap:

In quasi-steady state, comparable-mass binary can
Expand or contract while accreting from CBD

Eccentricity attractor: ~0.4

Is binary decay possible ?

Is binary decay possible ?

Yes…

e.g. Thin (low-viscosity) disks

“steady-state”? finite torus = mass-fed disk? Pressure?

Tiede et al. 2022,2024

e.g. Large (locally) massive disk:

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

e.g. Gas could get ejected in outflow (?)…

Caveats of 2D viscous hydro simulations:

Equation of state/cooling (Haiyang Wang et al 2023)

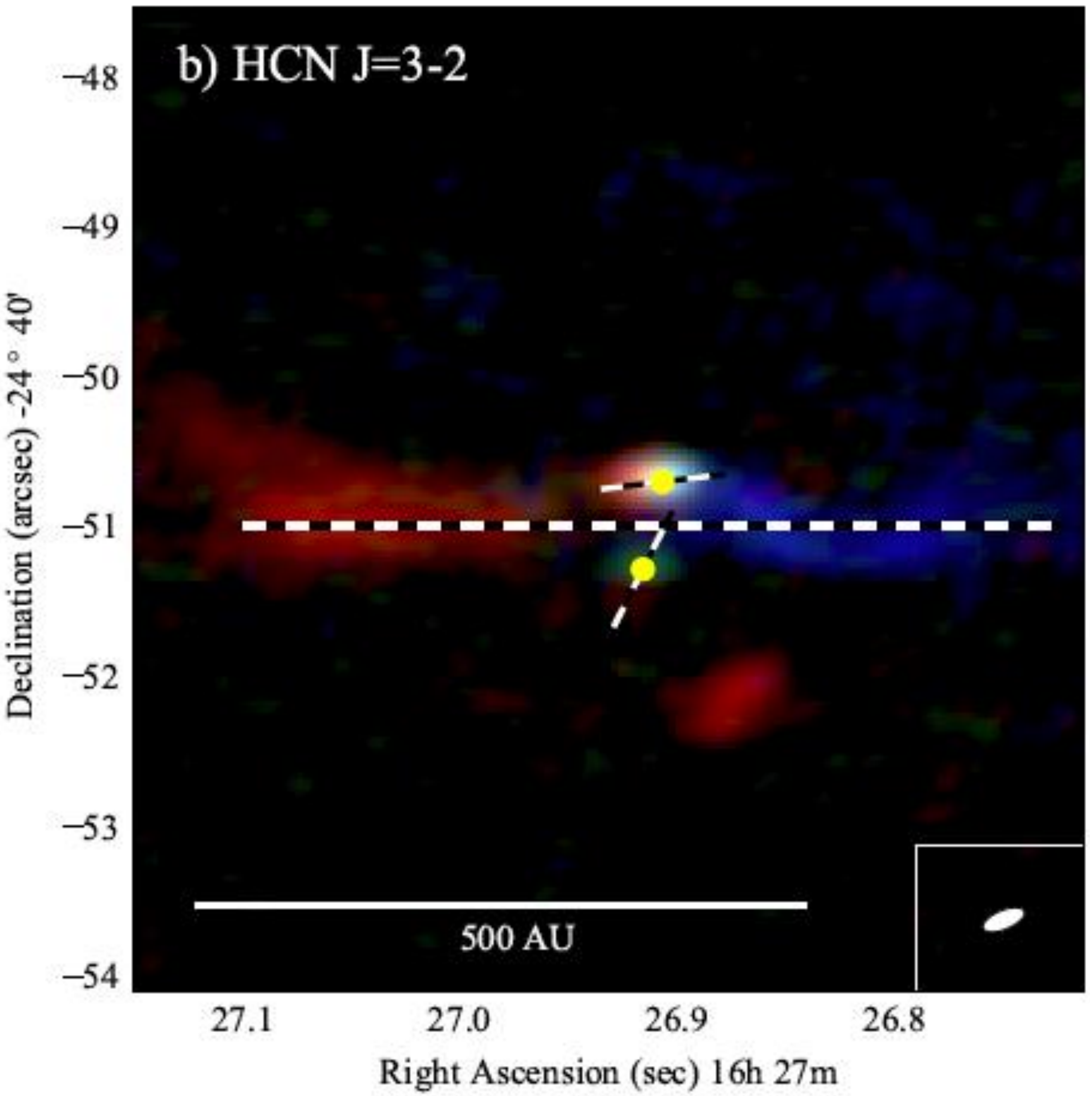
B fields, turbulence…..

So far: Co-planar disks

What about misaligned disks ?

Observations:

An example of Misaligned circumbinary disk



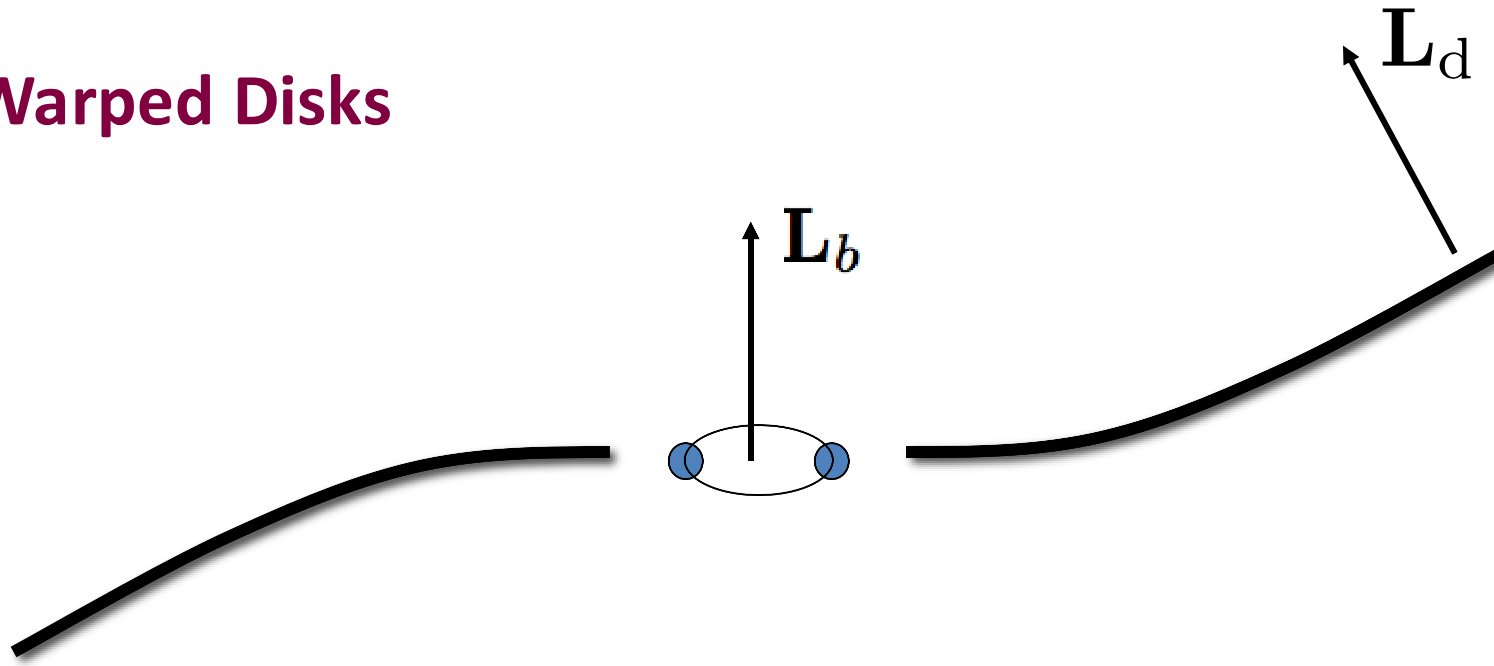
IRS 43

ALMA

a_b ~ 74 au, three disks

Brinch et al. 2016

Warped Disks

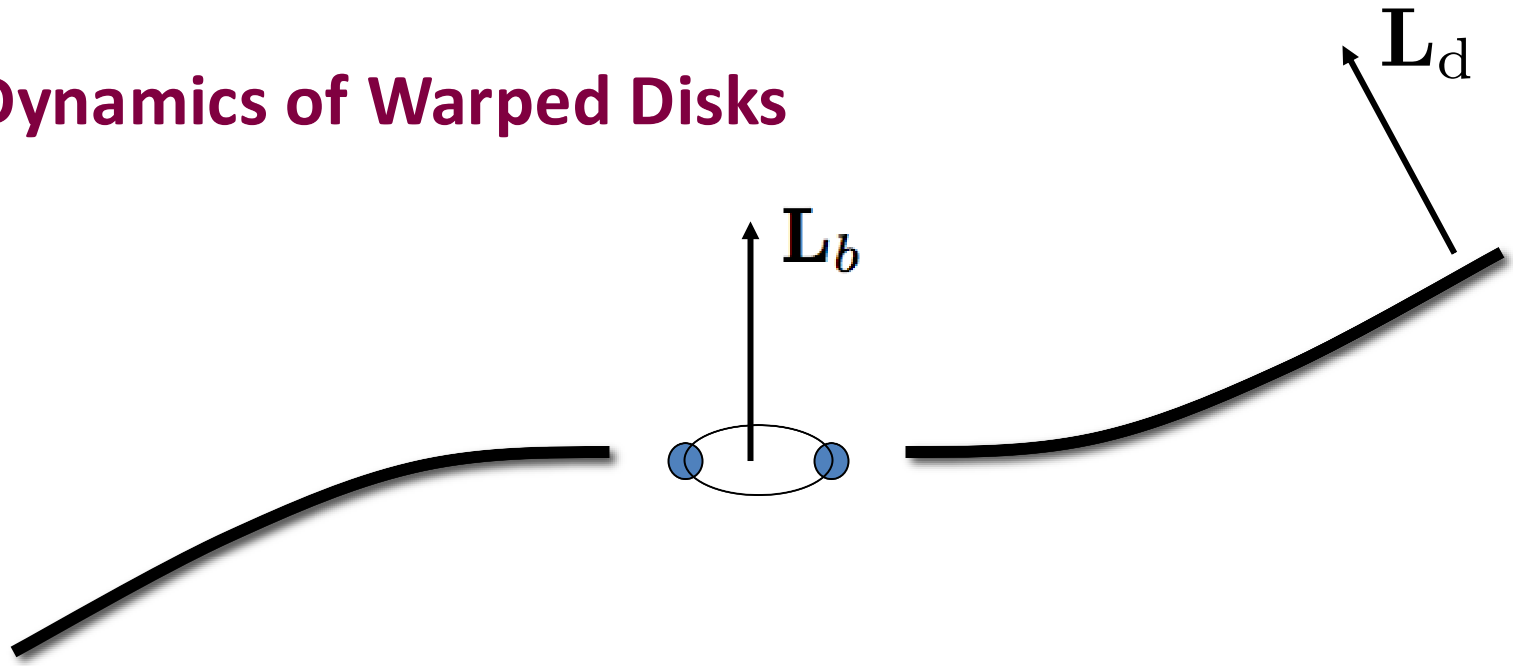


Torque from binary on disk => disk (ring) nodal precession

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

Differential precession + internal fluid stress ==> warped/twisted disk
(small warp)

Dynamics of Warped Disks



Warp + Viscosity ➔ Dissipation ➔ Align $\mathbf{L}_b$ and $\mathbf{L}_d$

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

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

Typical alignment time can be short
(~ precession period)

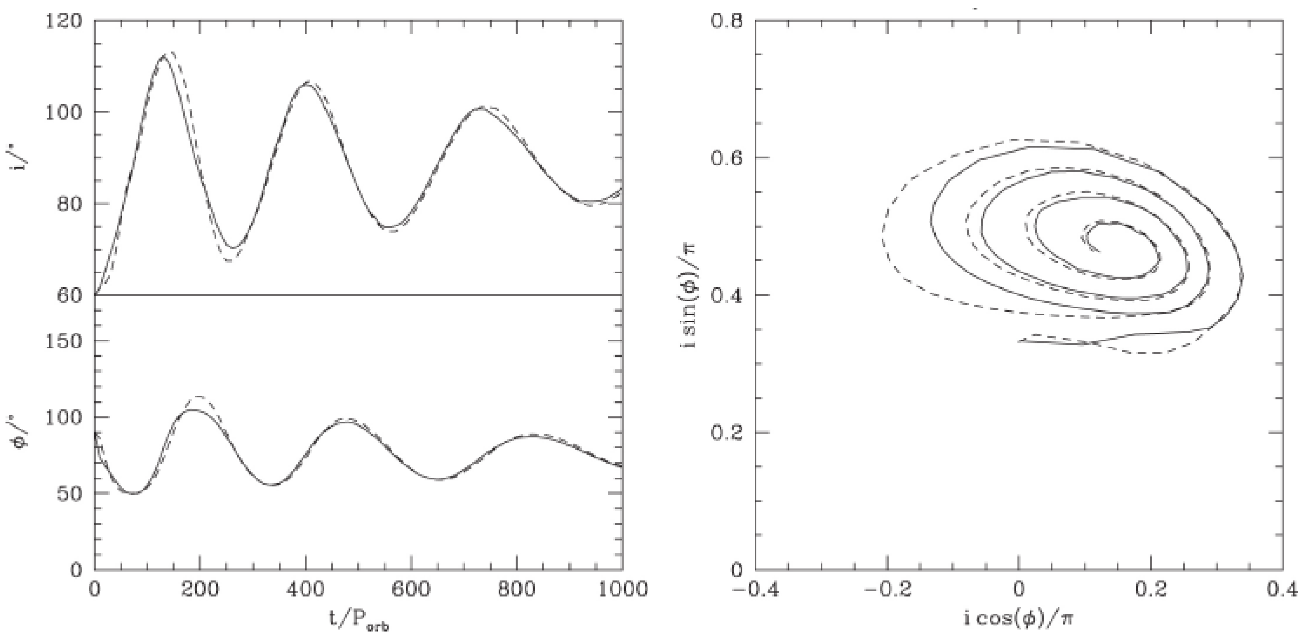
Foucart & DL 2014
Zanazzi & DL 2018

Surprise: Disk around eccentric binary may evolve toward polar alignment

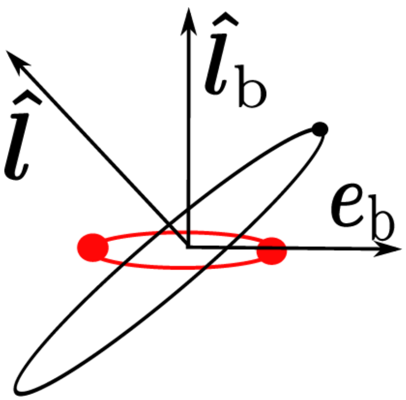
Martin & Lubow (2017): viscous hydro simulation using SPH

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

Binary eccentricity $e_b = 0.5$.

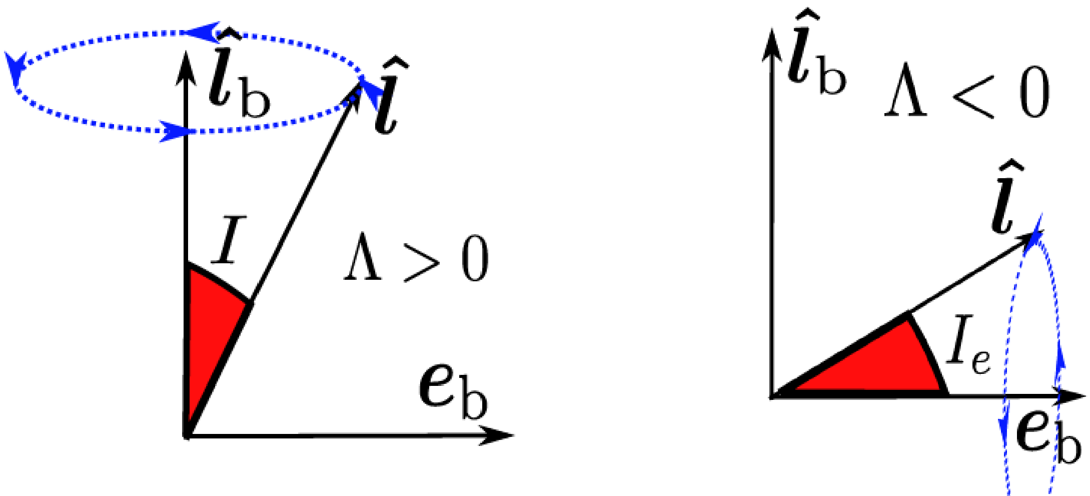


Theoretical Understanding of Polar Alignment of Disks Around Eccentric Binaries



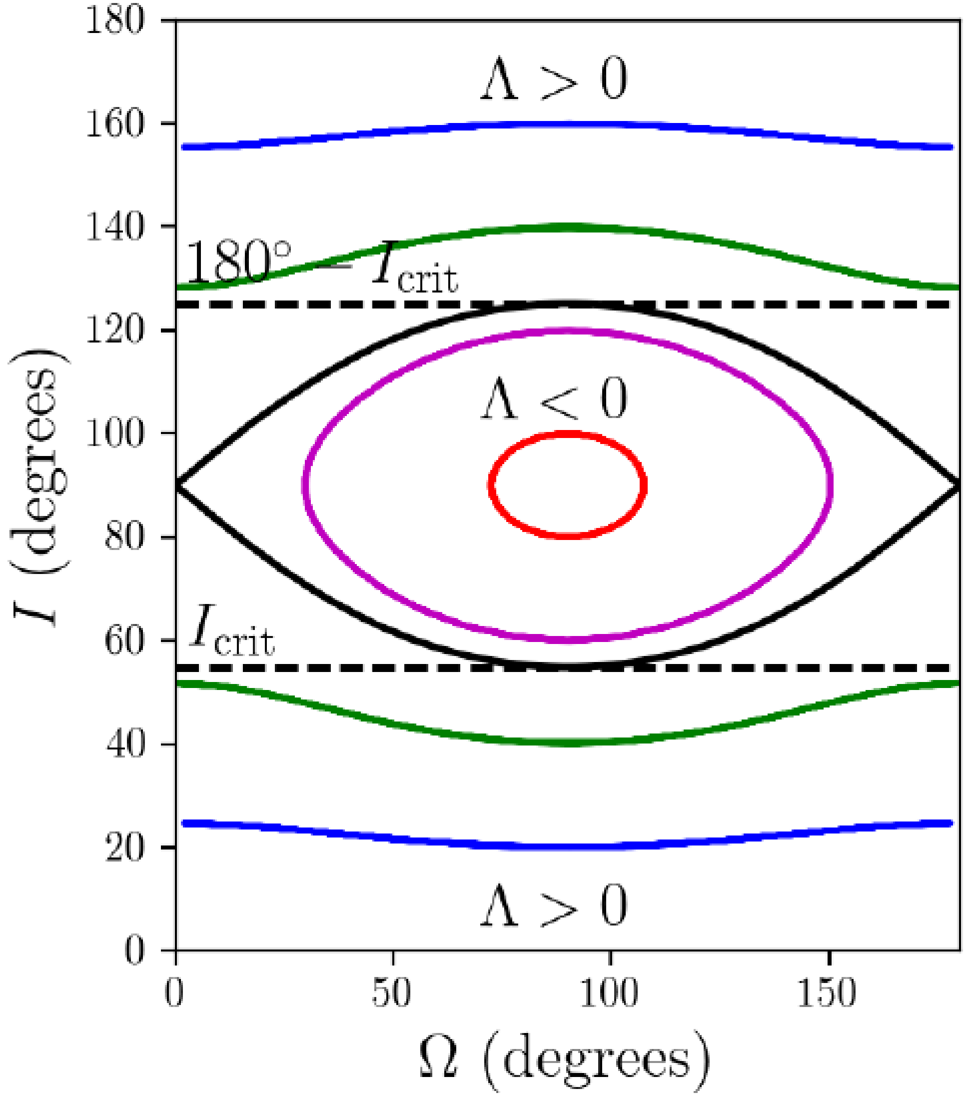
Test particle around eccentric binary has two "masters"

$$\Lambda = (1 - e_b^2)(\hat{\boldsymbol{l}}\cdot\hat{\boldsymbol{l}}_b)^2 - 5(\hat{\boldsymbol{l}}\cdot\boldsymbol{e}_b)^2$$



Zanazzi & Lai 2018

$$\Lambda = (1 - e_b^2)(\hat{\boldsymbol{l}}\cdot\hat{\boldsymbol{l}}_b)^2 - 5(\hat{\boldsymbol{l}}\cdot\boldsymbol{e}_b)^2$$



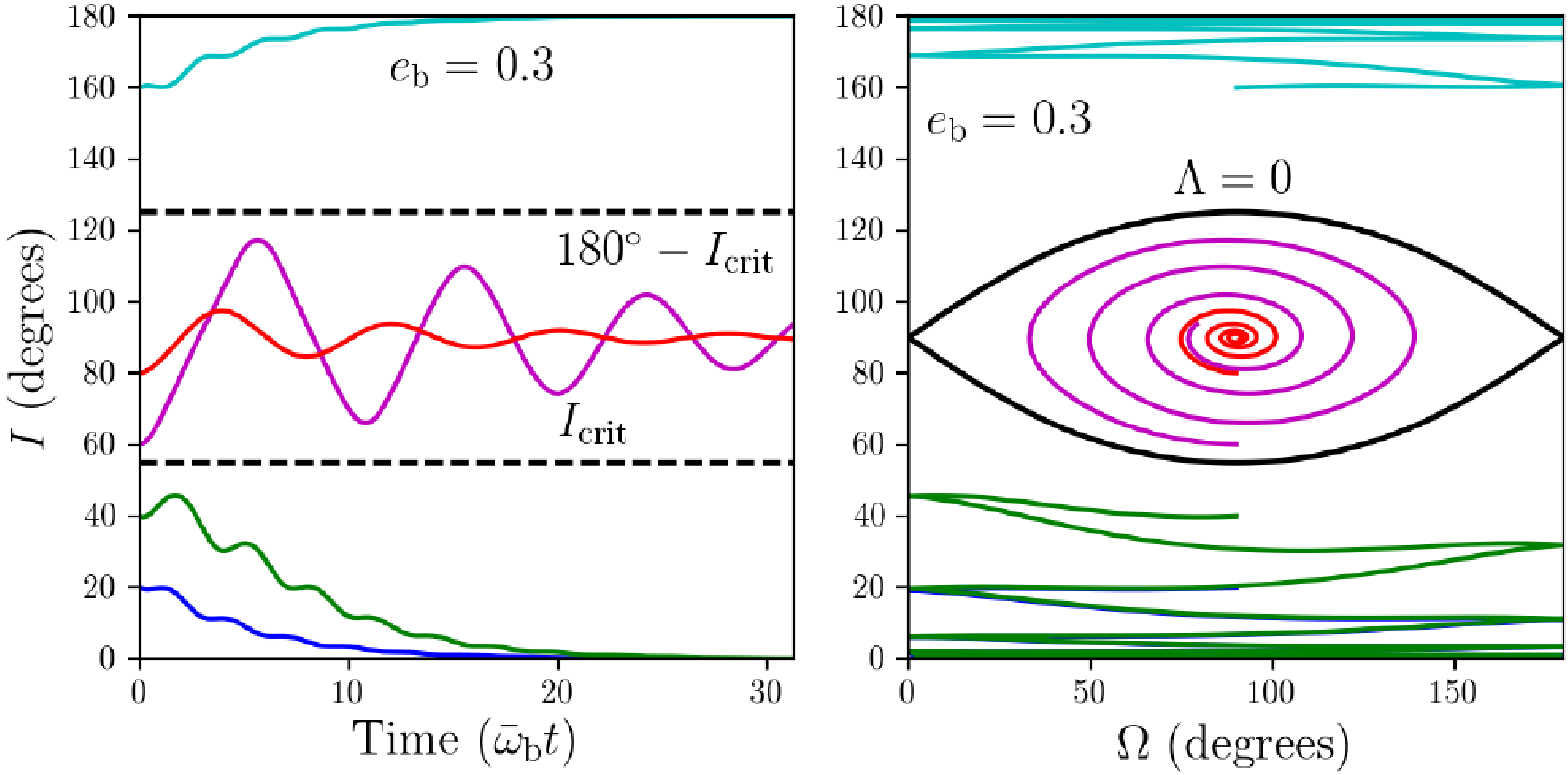
For $\hat{l}$ to precess around $\hat{e}_b$, require $\sin I > \sin I_{crib}$

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

Zanazzi & DL 2018

Warped viscous disk around eccentric binary

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

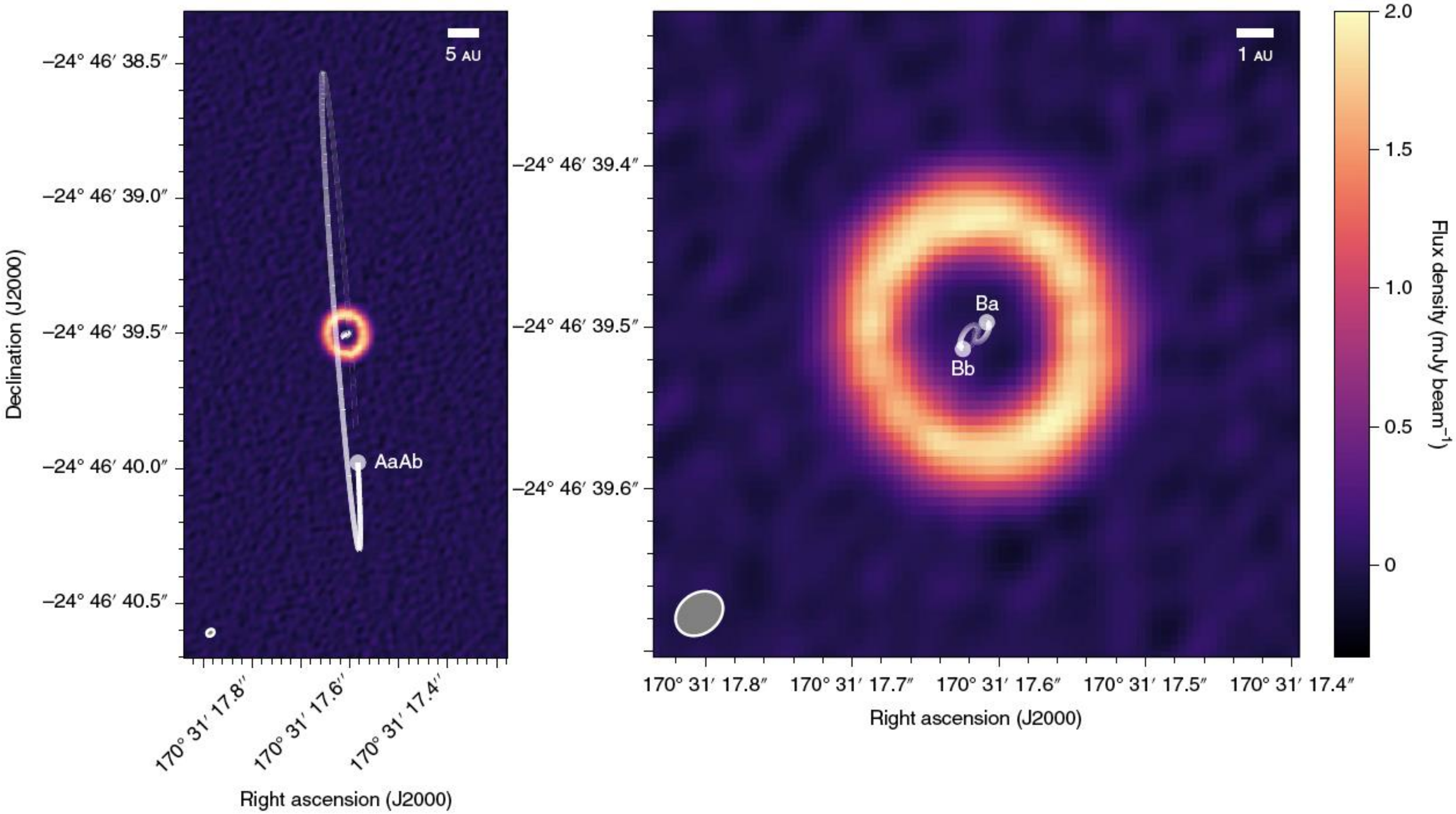


Zanazzi & DL 2018

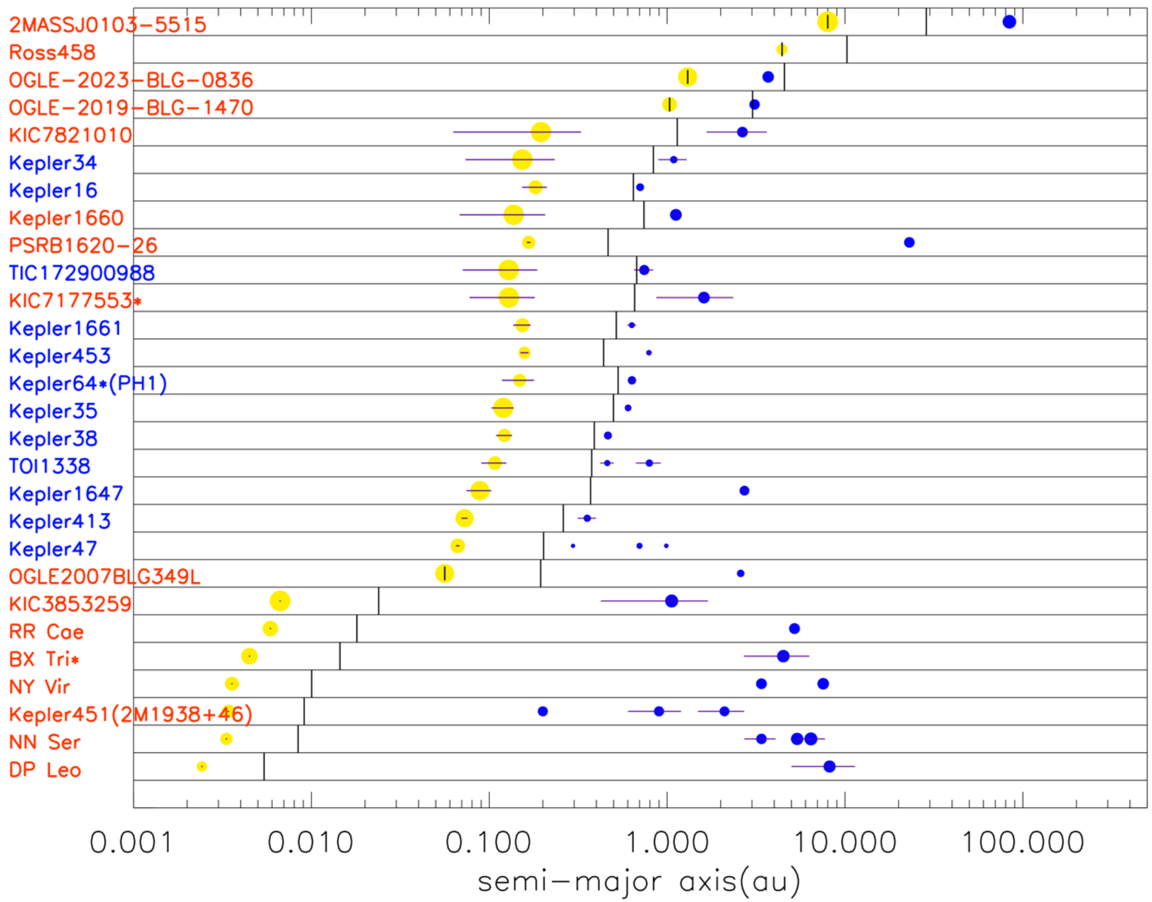
LETTERS
https://doi.org/10.1038/s41550-018-0667-x
nature astronomy
Corrected: Publisher Correction

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]



Lack of CBPs around short-period (<10 day) binaries



From exoplanet.eu

Lack of CBPs around short-period (< 7 day) binaries

Previous works (Munoz & Lai 2015; Martin, Mazeh & Fabrycky 2015):

> A short-period binary is formed by Lidov-Kozai driven high-e tidal migration (due to a tertiary); a CBP may become misaligned with the binary and therefore avoid detection

But it is not clear that short-period binaries are formed by high-e migration…

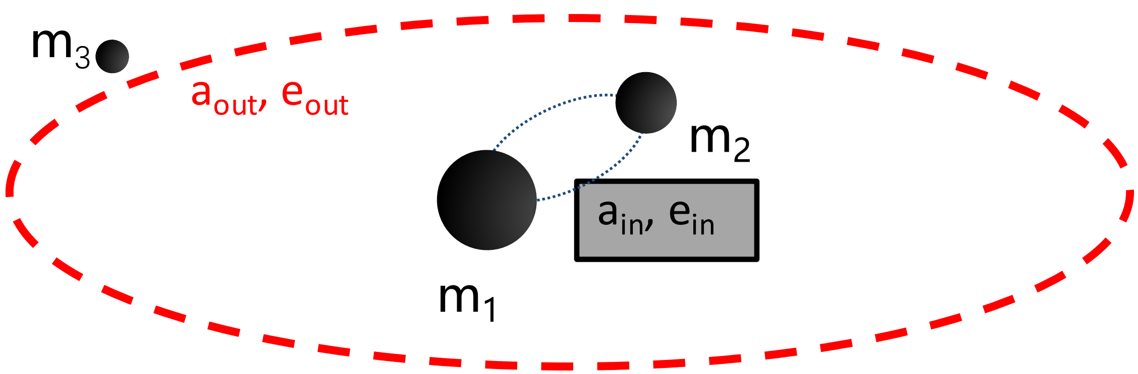
Lack of CBPs around short-period (< 7 day) binaries

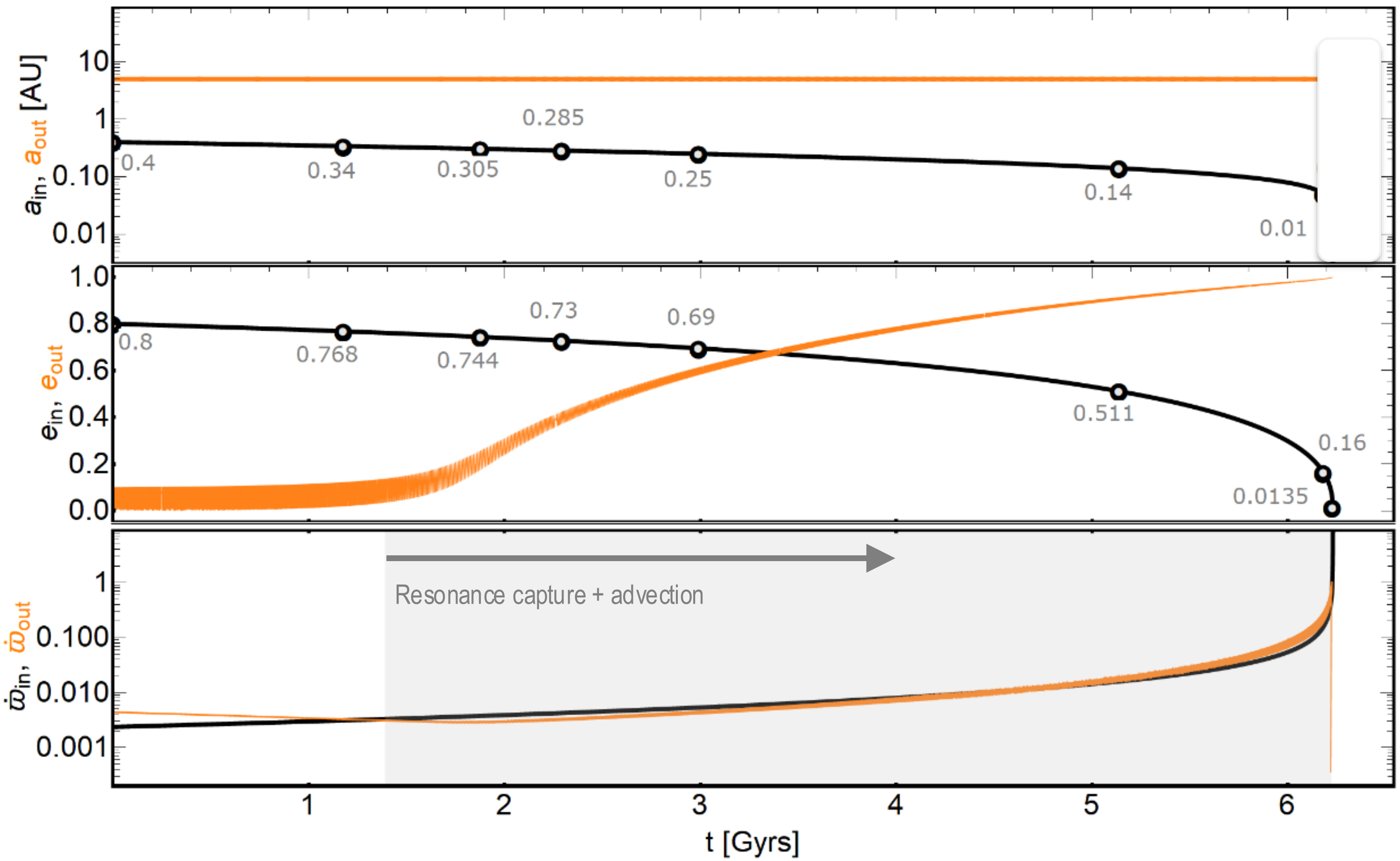
New idea (Bin Liu & Lai 2025, in prep):

An eccentric binary ($e_i \sim 0.5$) with $P_i < 10$ days can undergo modest tidal orbital decay while circularizing:

$$a_i \implies a_F = a_i(1 - e_i^2)$$

A surrounding planet may be excited to high eccentricity, triggering dynamical instability and destroying the CBP in the system.





Apsidal precession resonance:

Inner binary precession due to stellar ride

Outer binary (planet) precession driven by inner binary

Summary

◆ Circumbinary accretion:

-- 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, finite e_b)

-- Inner disk is coherently eccentric, can either precess or be apsidally locked with binary

-- Binary can expand or contract

-- Eccentricity attractor e_b~0.4: observational signature found (?)

◆ Misaligned disks

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

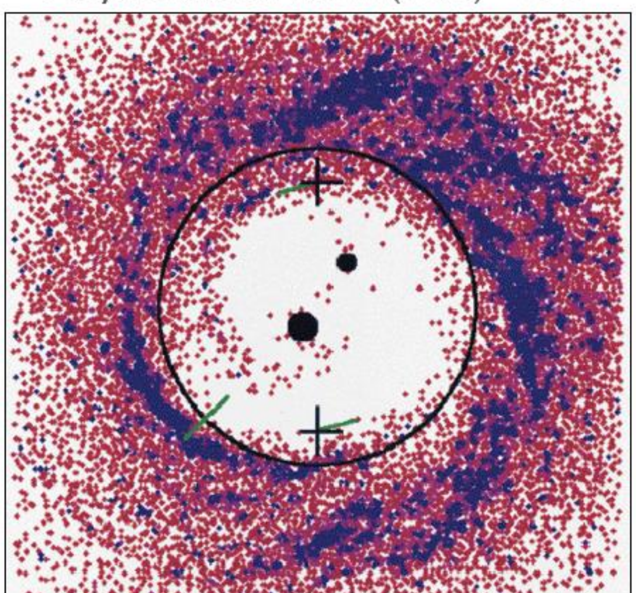
◆ Missing CBPs around short-period binaries

Simulations of Circumbinary Accretion

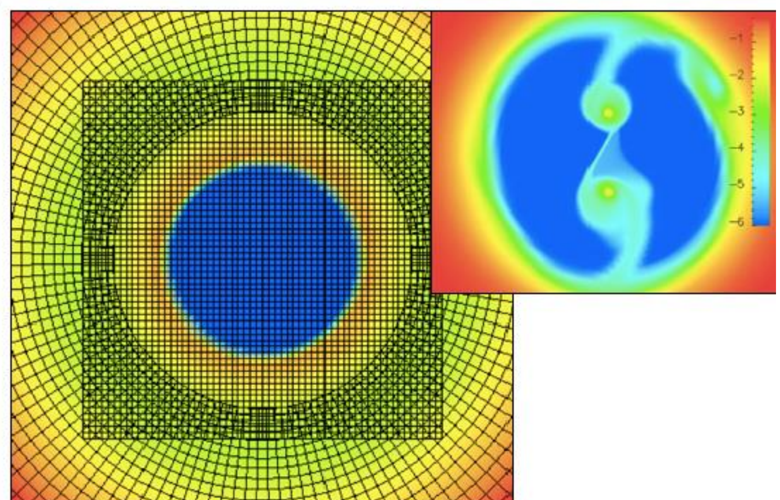
Artymowicz & Lubow 1996; Günther & Kley 02; MacFadyen & Milosavljević 08; Cuadra et al.09; Hanawa et al. 10; de Val-Borro et al. 11; Roedig et al. 12; Noble et al.12; Shi et al. 12; D'Orazio et al. 13; Pelupessy & Portegies-Zwart 13; Farris et al. 14; Shi & Krolik 15; Lines et al. 15; O'Ozario et al. 16; Ragusa et al. 16, Munoz & Lai 2016; Miranda, Munoz & Lai 2017; Tang et al. 17; Bowen et al.17,19; Munoz, Miranda, Lai 2019; Moody, Shi & Stone 19; Munoz, Lai et al.2020; Duffell et al.20; Tiede et al. 20; Heath & Nixon 20; D'Orazio & Duffell 21; Zrake et al.21; Penzlin et al.22; Siwek et al.22; Wang et al. 2023; Siwek et al. 2024; Duffell et al. 2024....

Some pioneering works:

Artymowicz & Lubow (1996) – SPH



Günther & Kley (2002) – Hybrid grid



DELETE: Eccentric Binaries

To obtain $\dot{a}_b$ and $\dot{e}_b$, we need $\dot{J}_b$ and $\dot{E}_b$

$$\mathcal{E}_b \equiv \frac{1}{2}\dot{\mathbf{r}}_b^2 - \frac{GM_b}{r_b} \qquad \text{where } \mathbf{r}_b = \mathbf{r}_1 - \mathbf{r}_2,\ M_b = M_1 + M_2$$

$$\frac{d\mathcal{E}_b}{dt} = -\frac{G\dot{M}_b}{r_b} + \dot{\mathbf{r}}_b \cdot (\mathbf{f}_1 - \mathbf{f}_2)$$

$$\mathbf{f}_1 = (\text{force/mass on } M_1) = \mathbf{f}_{1,\text{gravity}} + \mathbf{f}_{2,\text{accretion}}$$

Munoz et al. 2019

e_b	$\dot{J}_b\ [\dot{M}_b a_b^2 \Omega_b]$	$\dot{a}_b/a_b\ [\dot{M}_b/M_b]$	$\dot{e}_b\ [\dot{M}_b/M_b]$
0	0.68	2.2	0.0
0.1	0.43	0.75	2.4
0.5	0.78	0.95	-0.20
0.6	0.81	0.47	-2.34