On the Kozai-Lidov mechanism in Be/gamma-ray binaries

Atsuo T. Okazaki
(Hokkai-Gakuen University, Japan)

In collaboration with
Itumeleng Monageng (U. Cape Town, South Africa),
Yuki Moritani (Kavli IPMU, Japan), and
Vanessa McBride (U. Cape Town, South Africa)

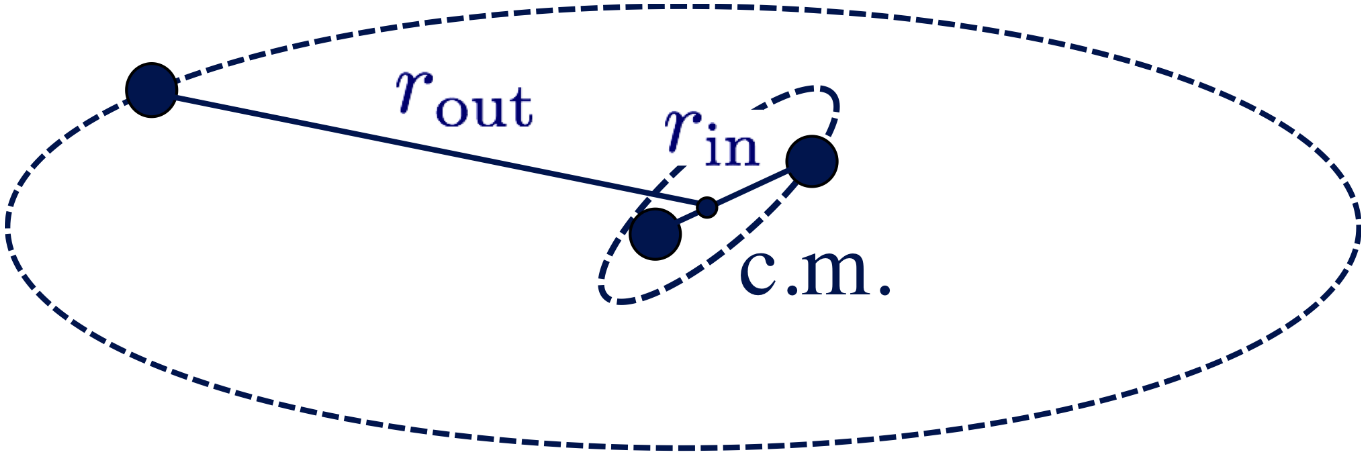
Talk Outline

1. The Koza-Lidov mechanism in particles
2. The Koza-Lidov mechanism in hydro disks
3. Tidal-interaction simulations of LS I +61 303
4. Long-term variation in Be-disk geometry in LS I +61 303
5. Concluding remarks

1. The Kozai-Lidov mechanism in particles

KL mechanism in hierarchical triples

When the orbital plane of the inner binary is inclined to that of the outer binary, the inclination and eccentricity of the inner binary can undergo coupled periodic oscillations (Kozai 1962; Lidov 1962).



$$r_{\rm in} \ll r_{\rm rout}$$

KL mechanism in the quadrupole approximation*

The inclination $i_{\rm p}$ $(\gtrsim 39^\circ)$ and eccentricity $e_{\rm p}$ of the particle motion oscillate in such a way that the angular momentum component along the axis of outer binary orbit is conserved:

$$\sqrt{1-e_{\rm p}^2}\cos i_{\rm p} = {\rm const}$$

(Kozai 1962).

Valid only for a test particle motion in a circular outer binary

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** Quadrupole approximation: The interaction Hamiltonian expanded in a power series of the ratio of semi-major axes is truncated at the order $(a_{in}/a_{out})^2$.*

KL mechanism in the octupole approximation*

For an eccentric outer binary and/or a non-negligible a_{in}/a_{out}, a higher order ("octupole") approximation should be used to model the interaction (e.g., Naoz 2016, ARA&A, 54, 441).

In this approximation, the secular evolution is qualitatively different, e.g., $\sqrt{1-e_{\rm p}^2}\cos i_{\rm p} \neq {\rm const.}$

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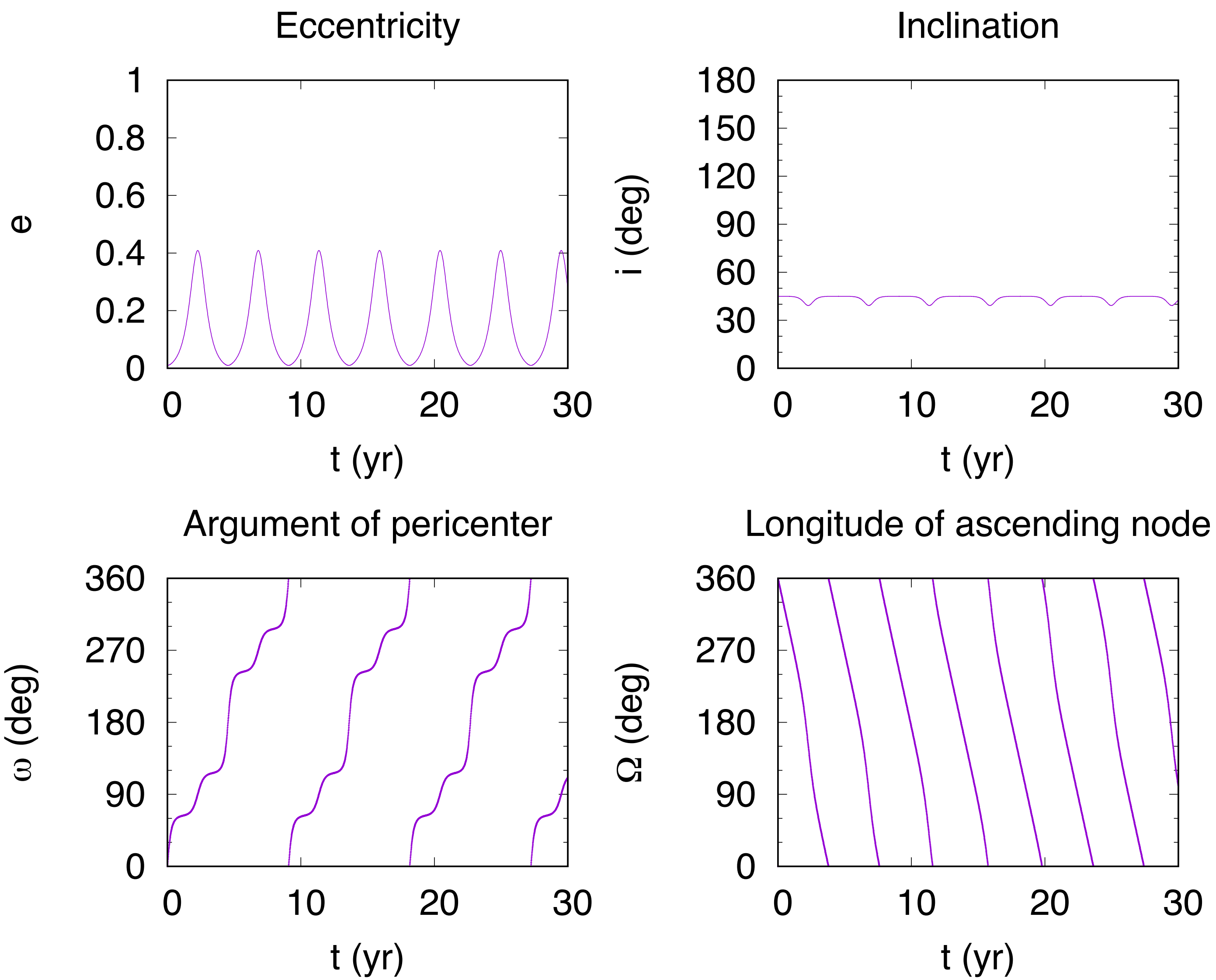
* *Octupole approximation: The interaction Hamiltonian expanded in a power series of the ratio of semi-major axes is truncated at the order $(a_{in}/a_{out})^4$.*

LS I +61 303 in the quadrupole approximation

Initial condition

$$e_{\rm p} = 0.01,$$

$$i_{\rm p} = 45^\circ$$



LS I +61 303 in the octupole approximation

Initial condition

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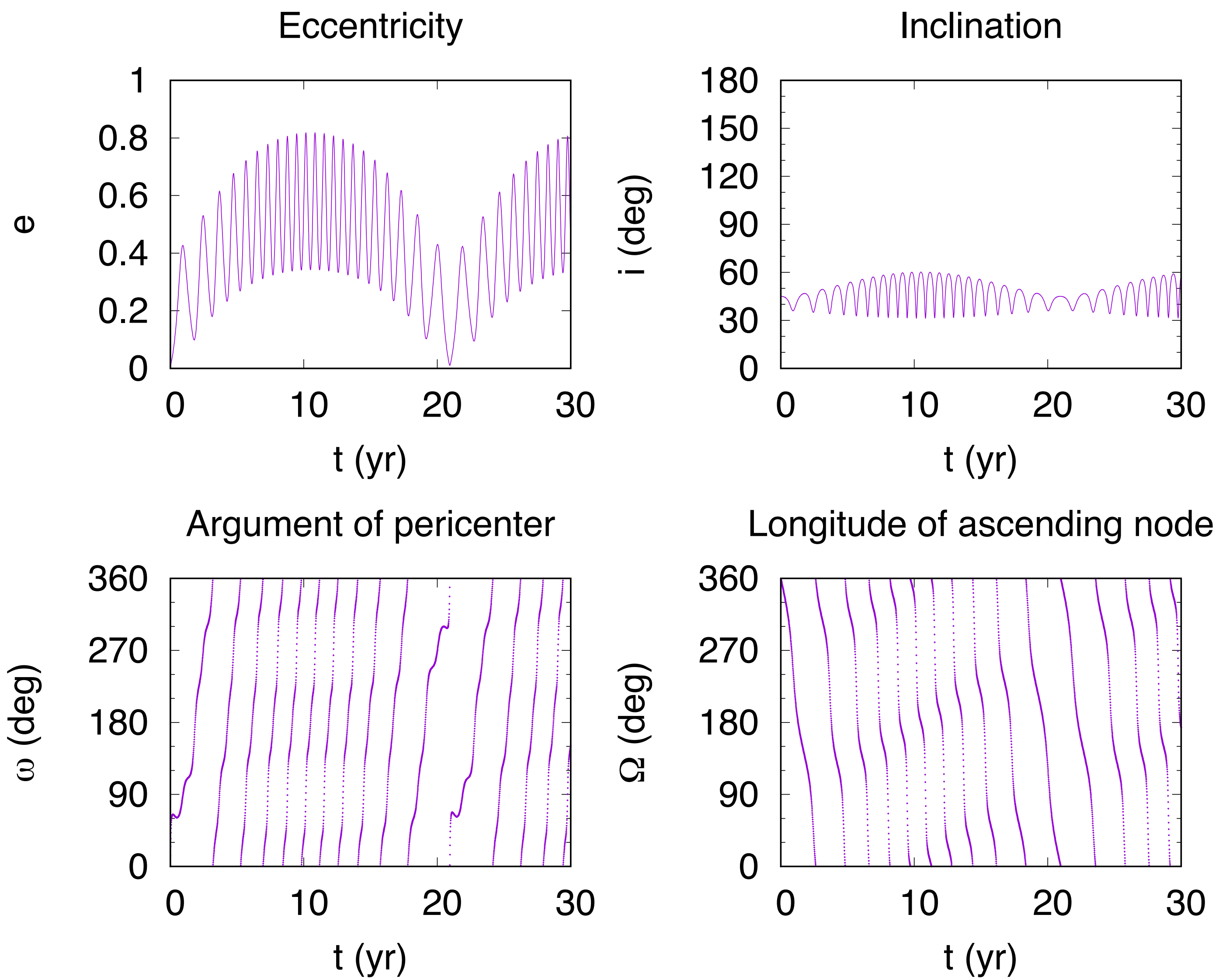


2. The Kozai-Lidov mechanism in hydro disks

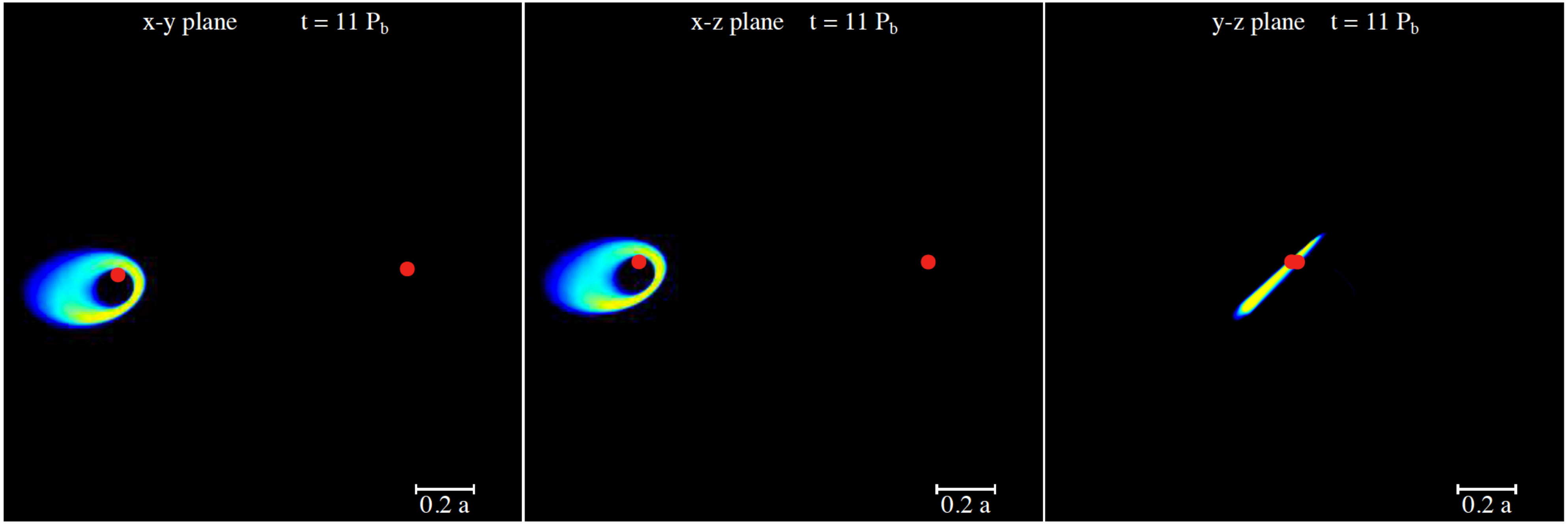
KL mechanism in hydrodynamic disks

- Kozai–Lidov (KL) oscillations also occur in highly misaligned [$i \gtrsim 45^\circ$ (Fu+ 2015)] hydrodynamic disks, where disk inclination is periodically exchanged for disk eccentricity (Martin+ 2014; Fu+ 2015).

- KL oscillations are damped oscillations in viscous disks (Martin+ 2014; Fu+ 2015).

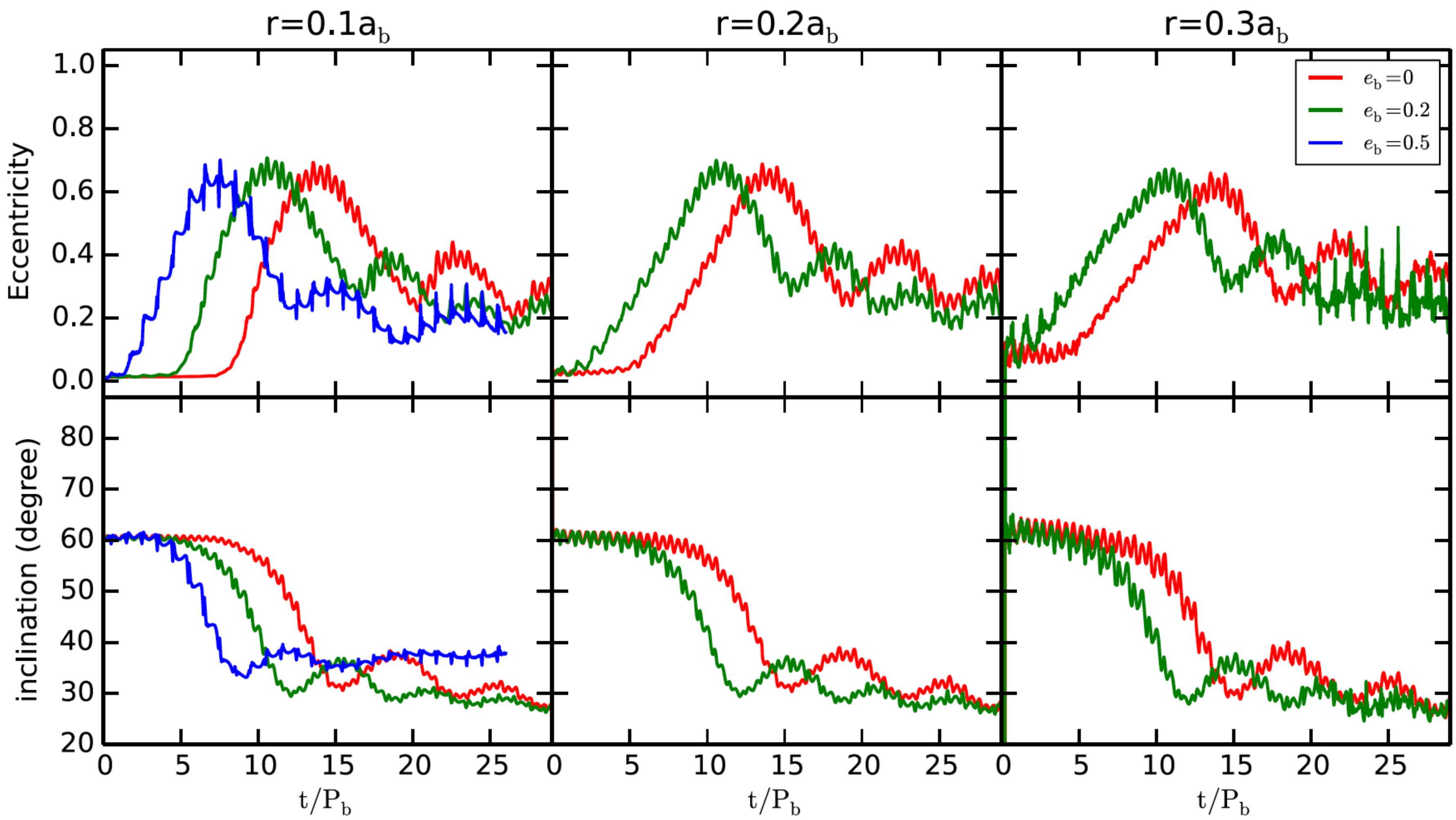
Initially circular disk can become highly eccentric with the exchange for inclination

No mass injection from star in this simulation



(Martin+ 2014)

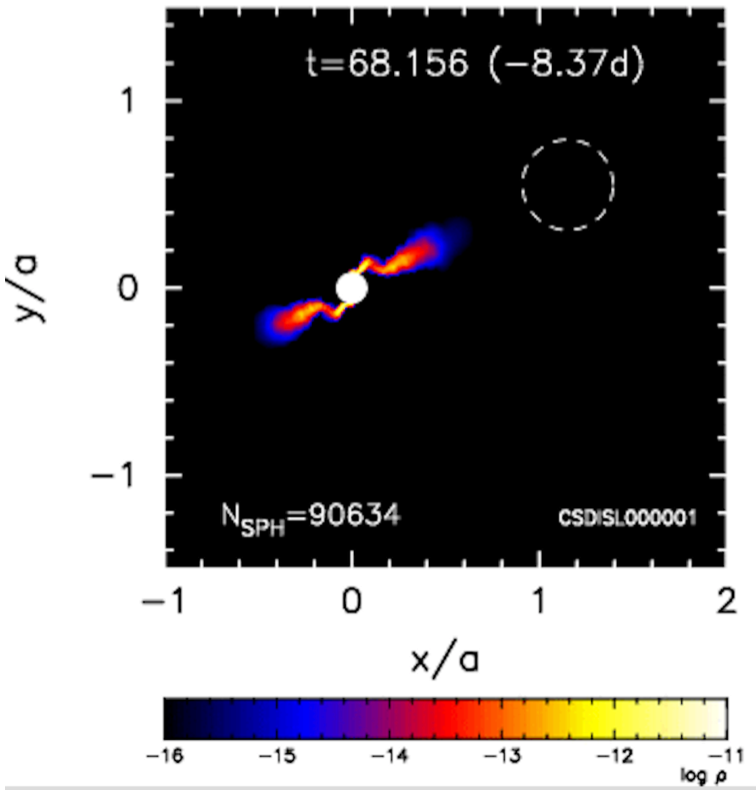
KL oscillation decays relatively quickly due to the effect of viscosity (Martin+ 2014; Fu+ 2015)



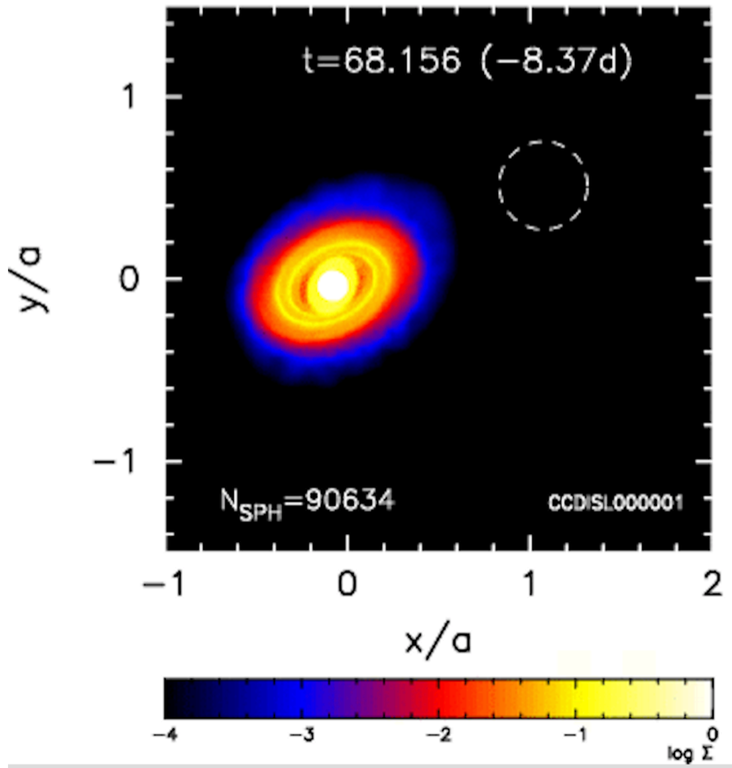
(Fu+ 2015)

Be disk evolution in Be/X-ray binary 4U0115+634

An eccentric Be disk starts precession, being torn near the base. A newly formed disk replaces the old outer disk.

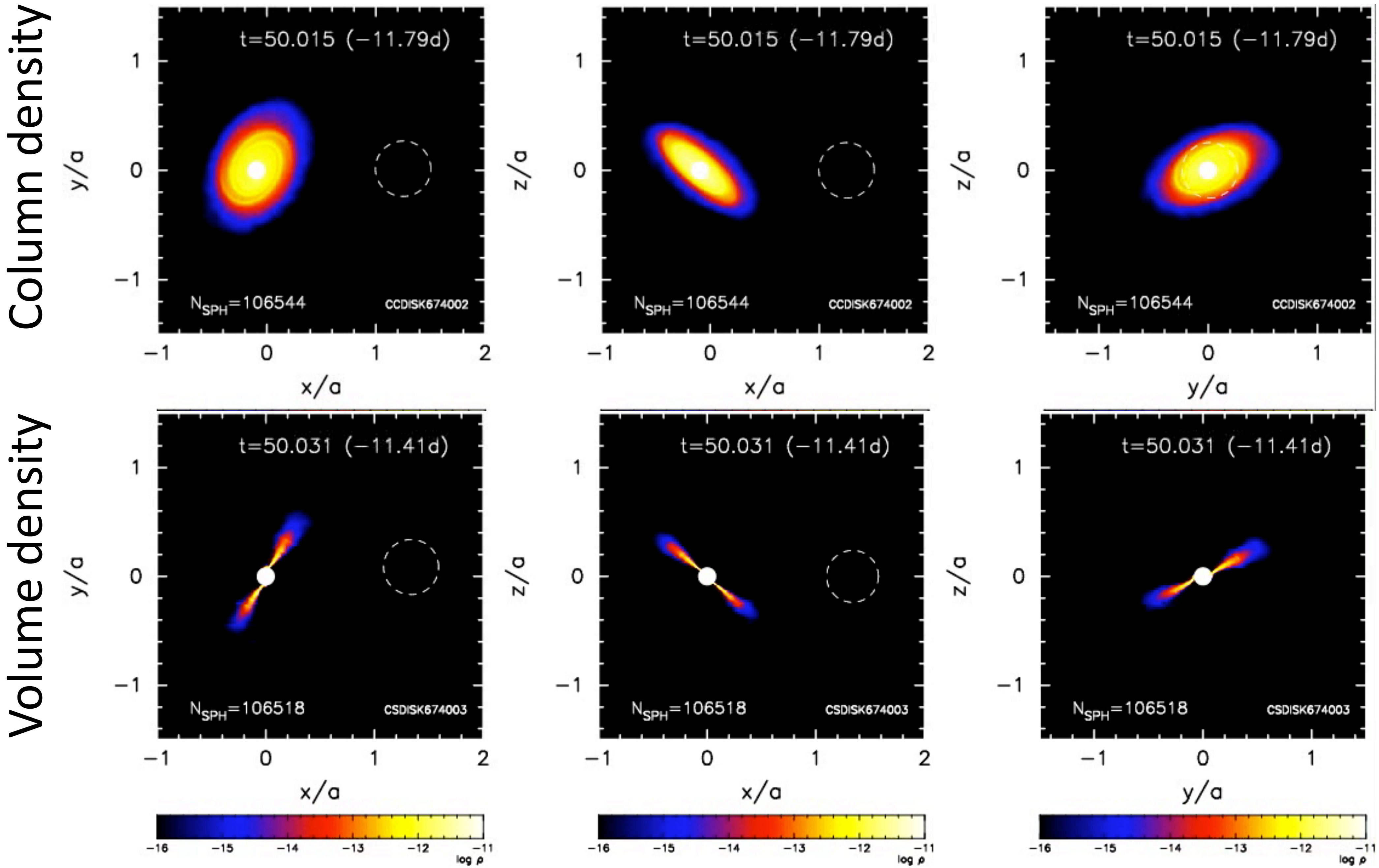


Density on orbital plane



Column density along z-axis

P_{orb}=24.3 d; e=0.34; initial i_{disk}=45 deg. about y-axis (=semi-minor axis)



Column density
Volume density
t=50.015 (−11.79d)
t=50.031 (−11.41d)
N_{SPH}=106544
N_{SPH}=106518
CCDISK674002
CSDISK674003
x/a
y/a
z/a
log ρ

A new type of disk evolution triggered by the eccentric KL mechanism

The initially circular disk becomes eccentric by the Kozai-Lidov mechanism.

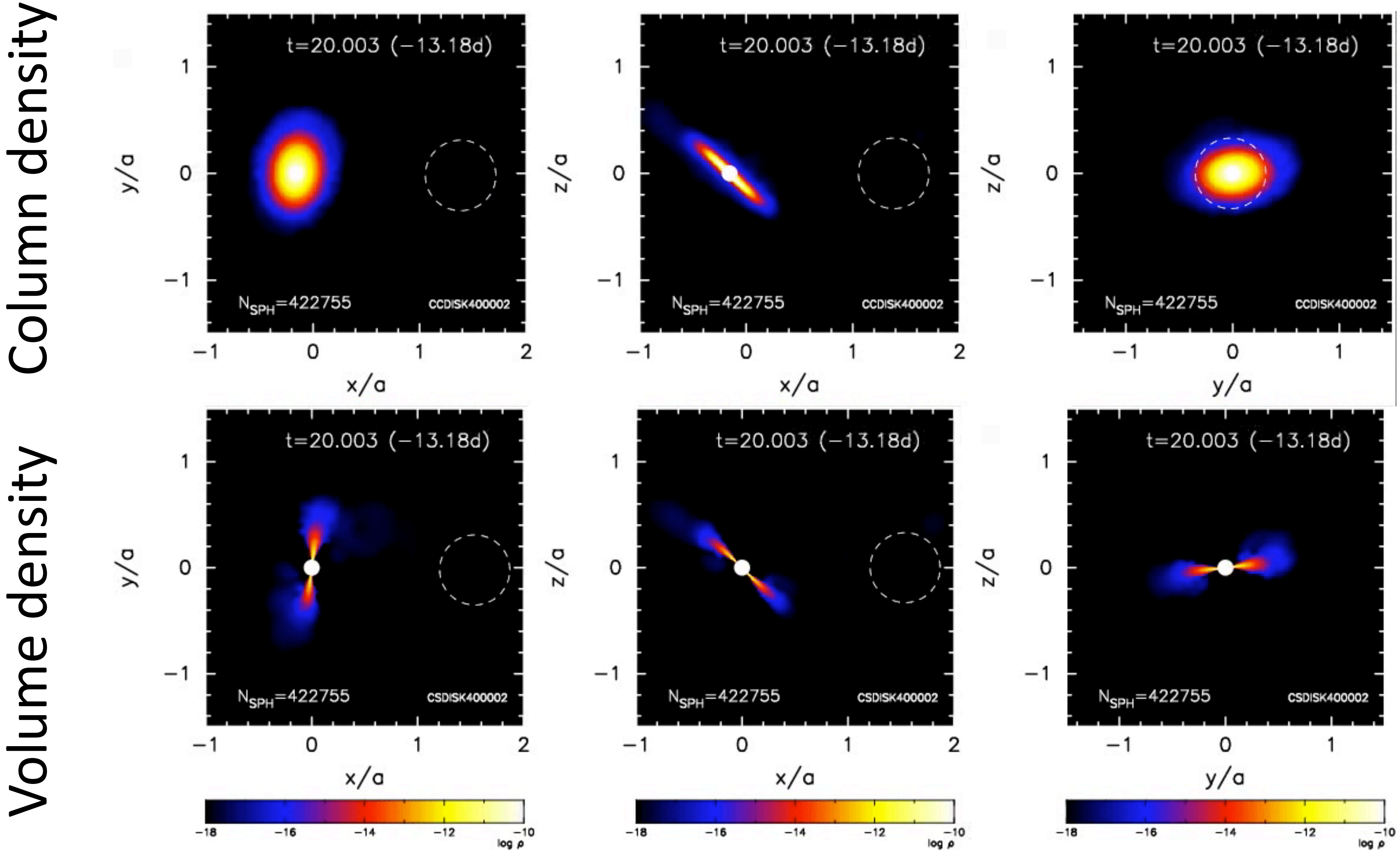
⇨ When the tidal torque becomes stronger than the mass-addition torque, the disk is torn near the base and starts precession.

⇨ A gap opens between the disk base and mass ejection region.

⇨ A new disk forms in the stellar equatorial plane.

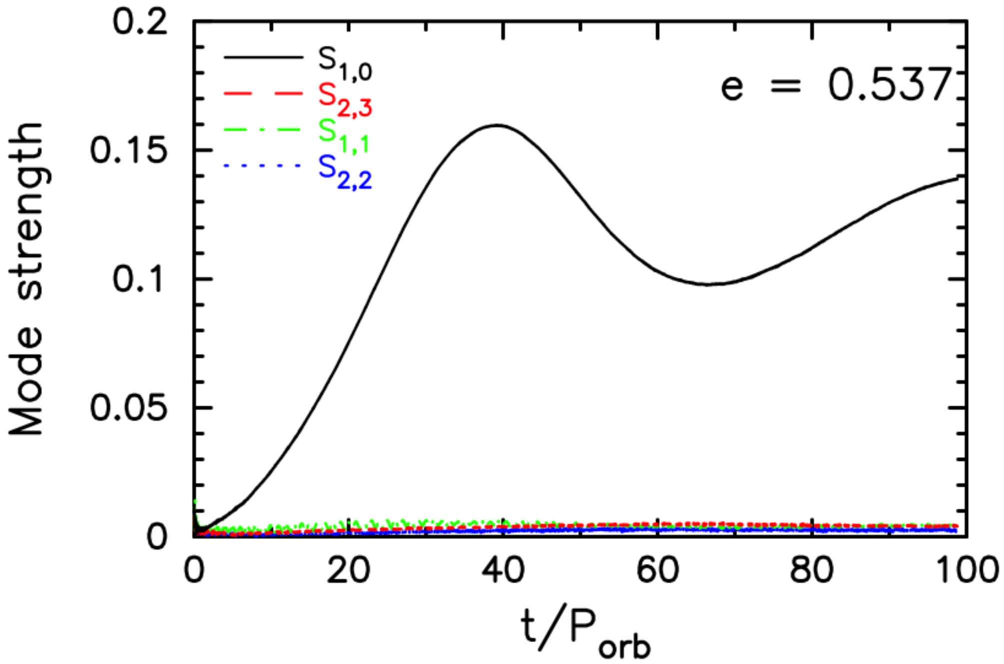
3. Tidal-interaction simulations of LS I +61 303

SPH simulation of a misaligned Be disk (initially 45 deg. about semi-minor axis)

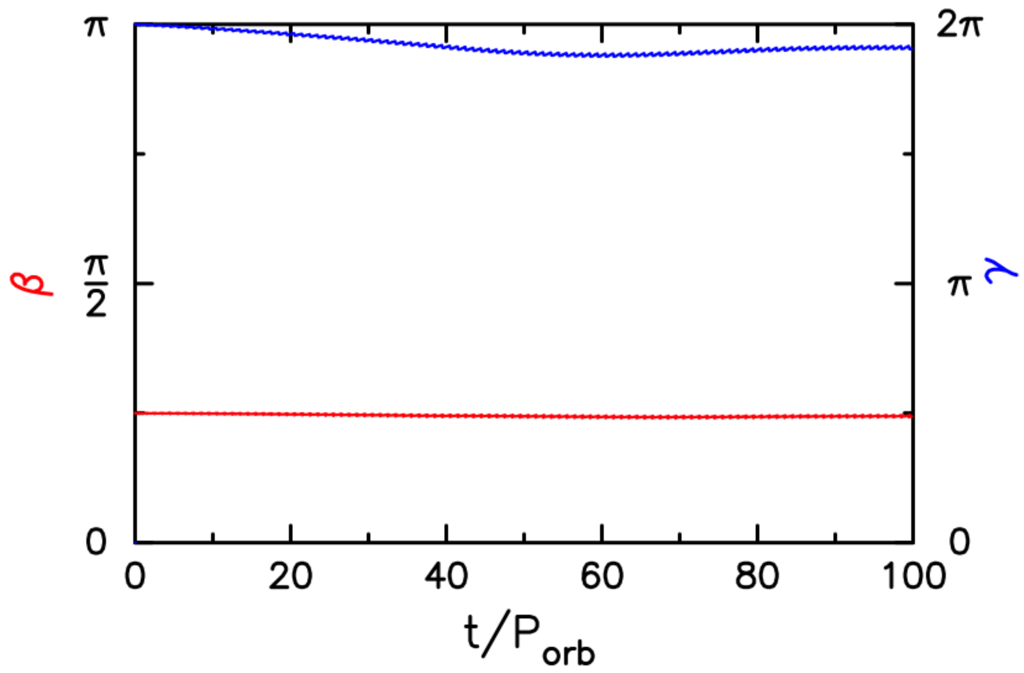


Excitation of disk eccentricity, but no cyclic disk evolution, because no precession occurs

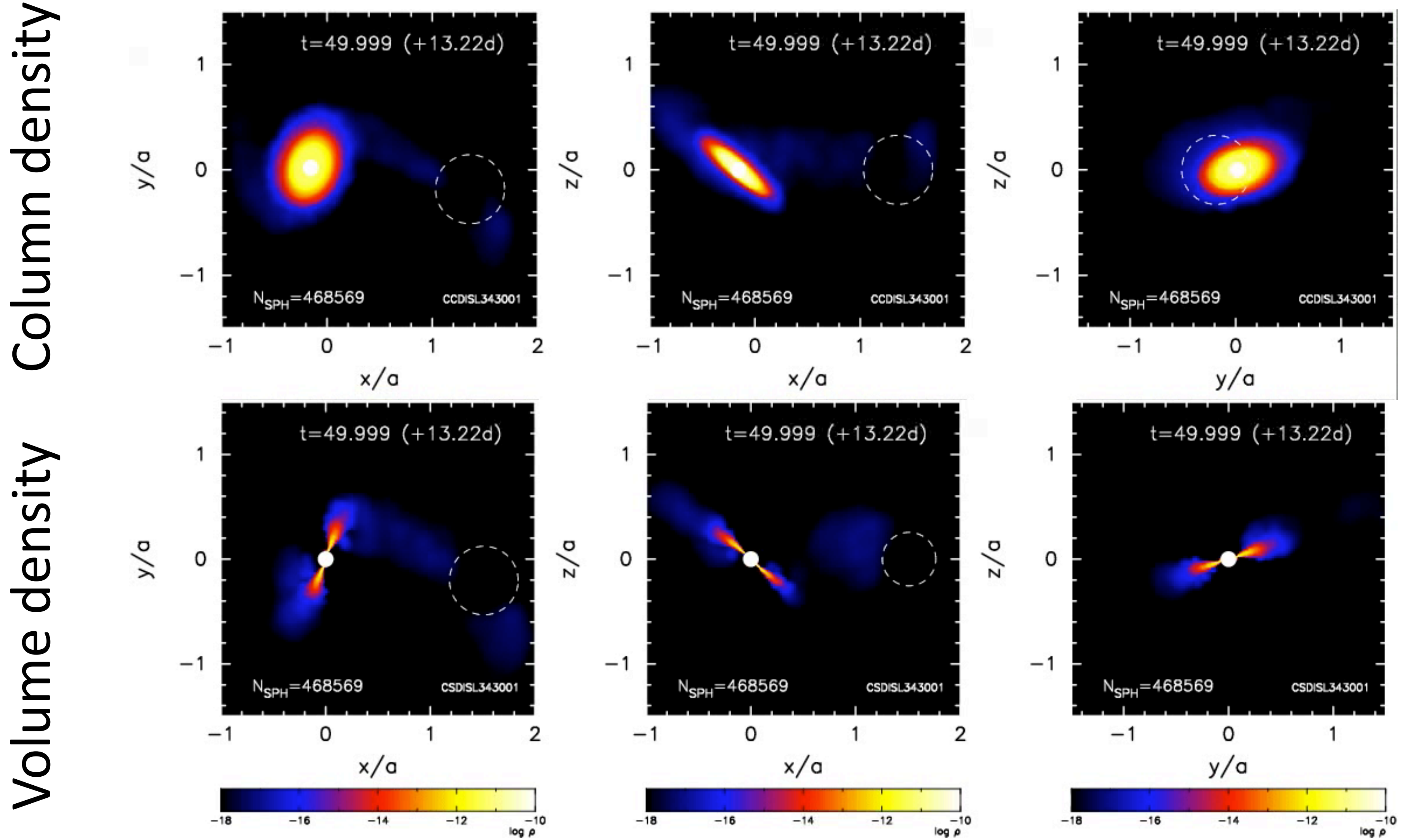
Strength of m=1 mode



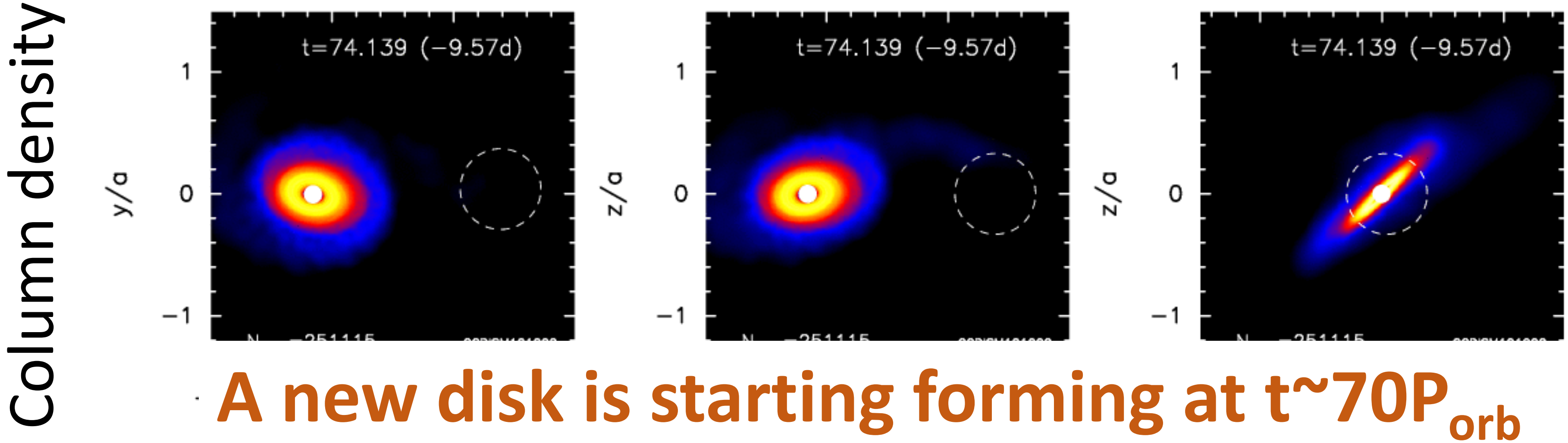
β : tilt angle
γ : azimuth of tilt



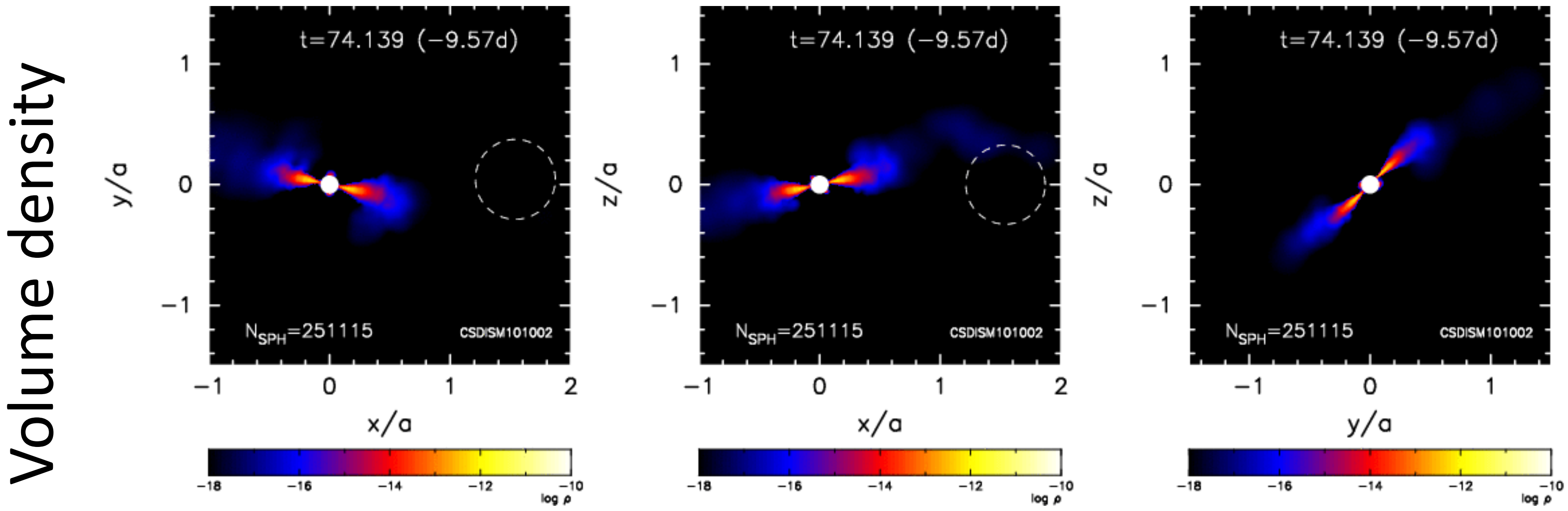
SPH simulation of the same misaligned Be disk, with x1/4 mass-injection rate after $t=50P_{orb}$



SPH simulation of the same misaligned Be disk, with x1/4 mass-injection rate after t=50P_{orb}

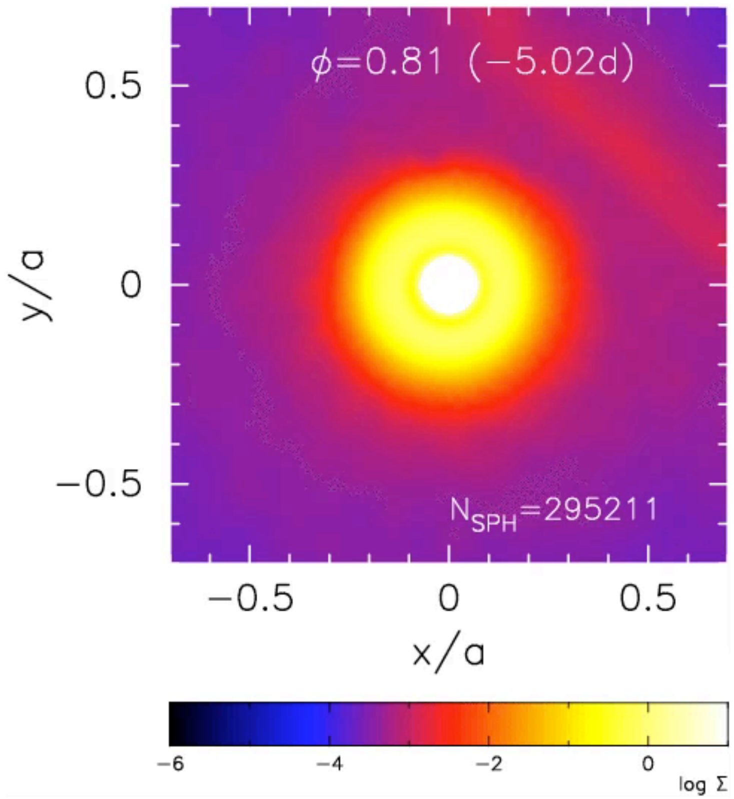


A new disk is starting forming at t~70P_{orb}



Ideally, simulations with PW should be run to study both the PW and tidal effects on Be disk

But, running sims with PW for ~100 P_{orb} is impractical.



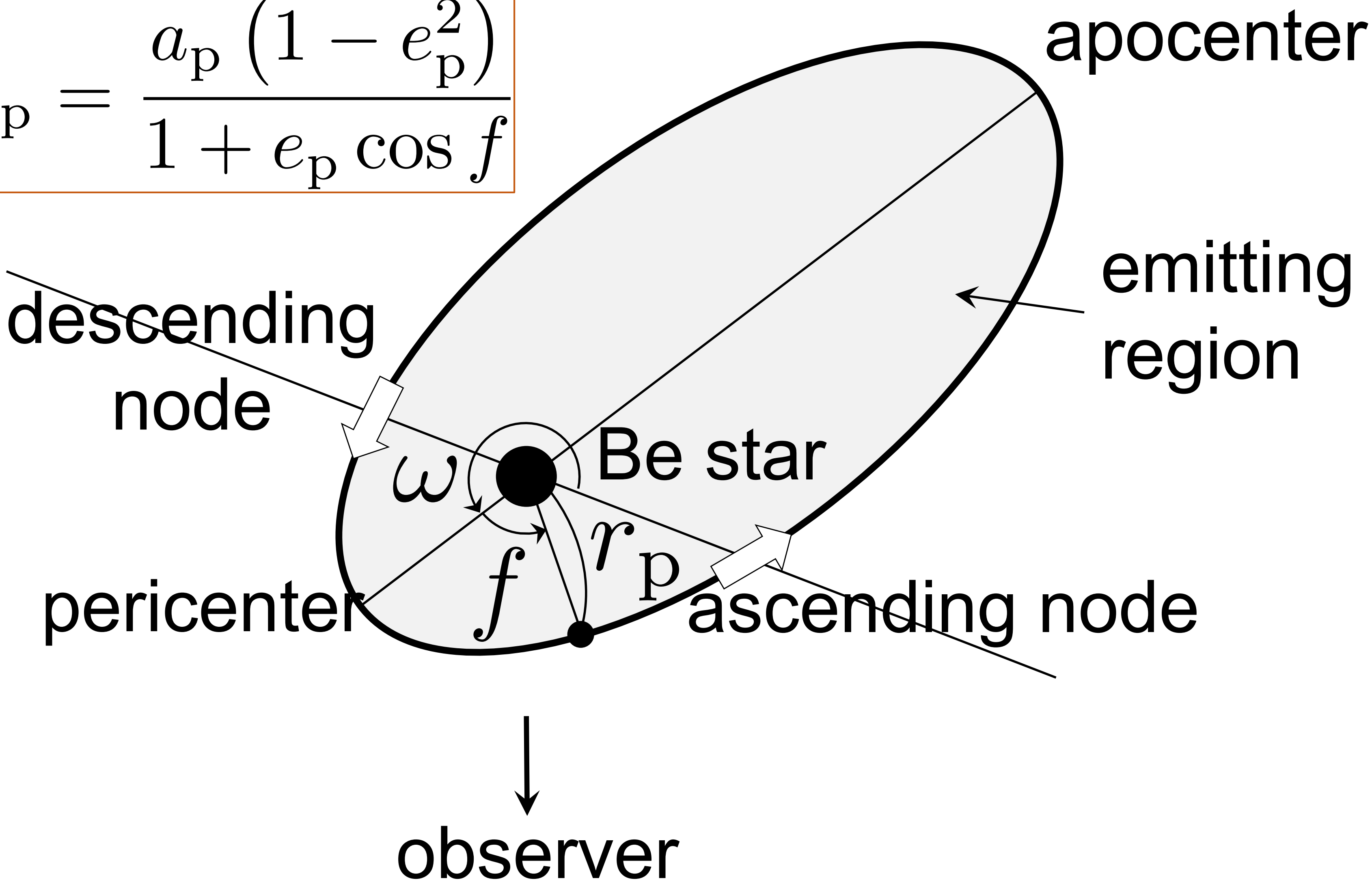
$$\dot{E}_{\rm PSR} = 10^{36}\,{\rm erg\ s^{-1}}, \quad \rho_0 \sim 2\cdot 10^{-11}\,{\rm g\ cm^{-3}}$$

4. Long-term variation in Be-disk geometry in LS I +61 303

(Monageng+, in prep.)

Particle model for the Halpha emitting region

$$r_{\mathrm{p}} = \frac{a_{\mathrm{p}}\left(1 - e_{\mathrm{p}}^{2}\right)}{1 + e_{\mathrm{p}} \cos f}$$



Basic equations

orbit: $r_{\rm p} = \dfrac{a_{\rm p}\left(1-e_{\rm p}^2\right)}{1+e_{\rm p}\cos f}$ ← true anomaly

⇨ radial velocity:

argument of pericenter ↘

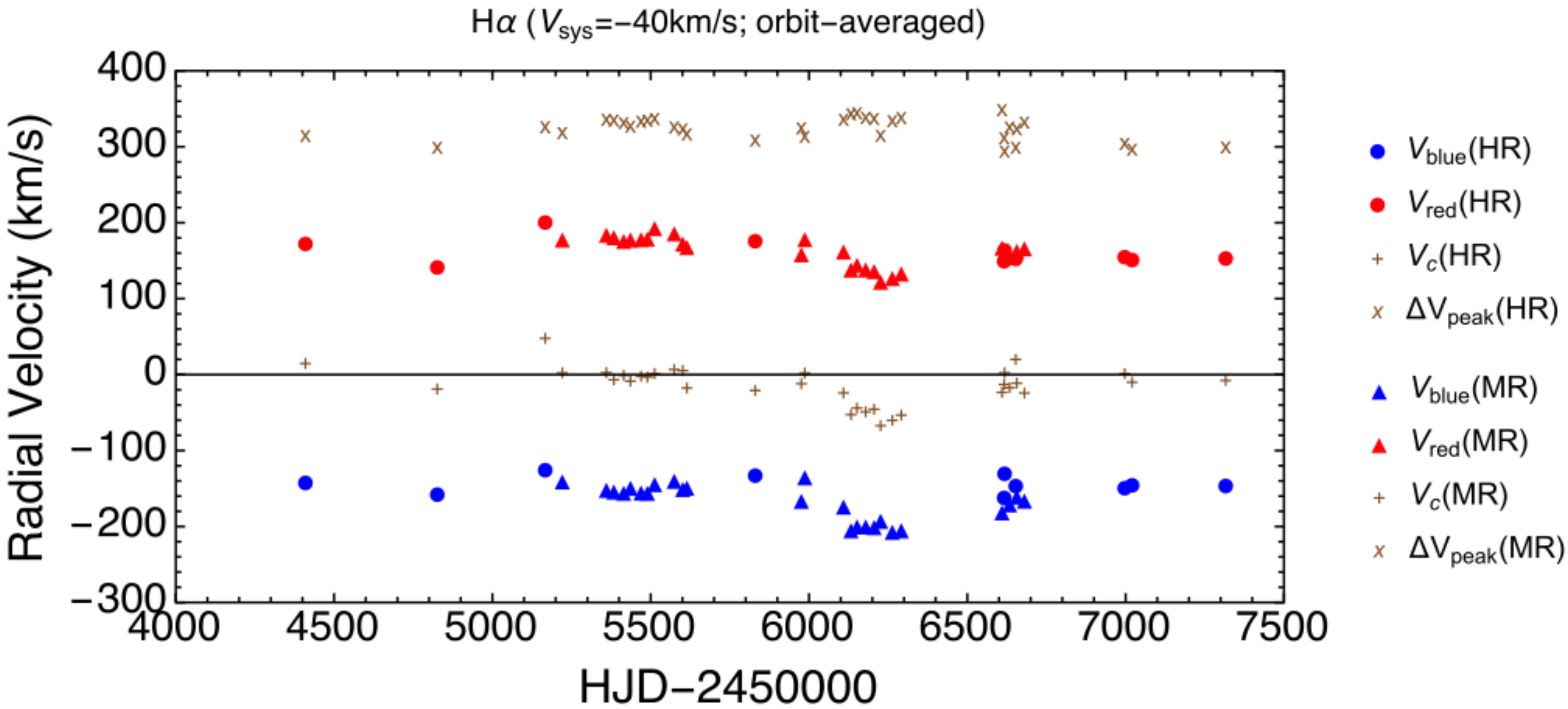
$$v_{\rm rad} = \sqrt{\frac{GM_1}{a_{\rm p}(1-e_{\rm p}^2)}}\sin i\left[\cos(\omega+f)+e_{\rm p}\cos\omega\right]$$

⇨ Blue- and red- peak velocities of a line profile:

$$v_{\rm blue,\ red} = \sqrt{\frac{GM_1}{a_{\rm p}(1-e_{\rm p}^2)}}(\mp 1+e_{\rm p}\cos\omega)\sin i$$

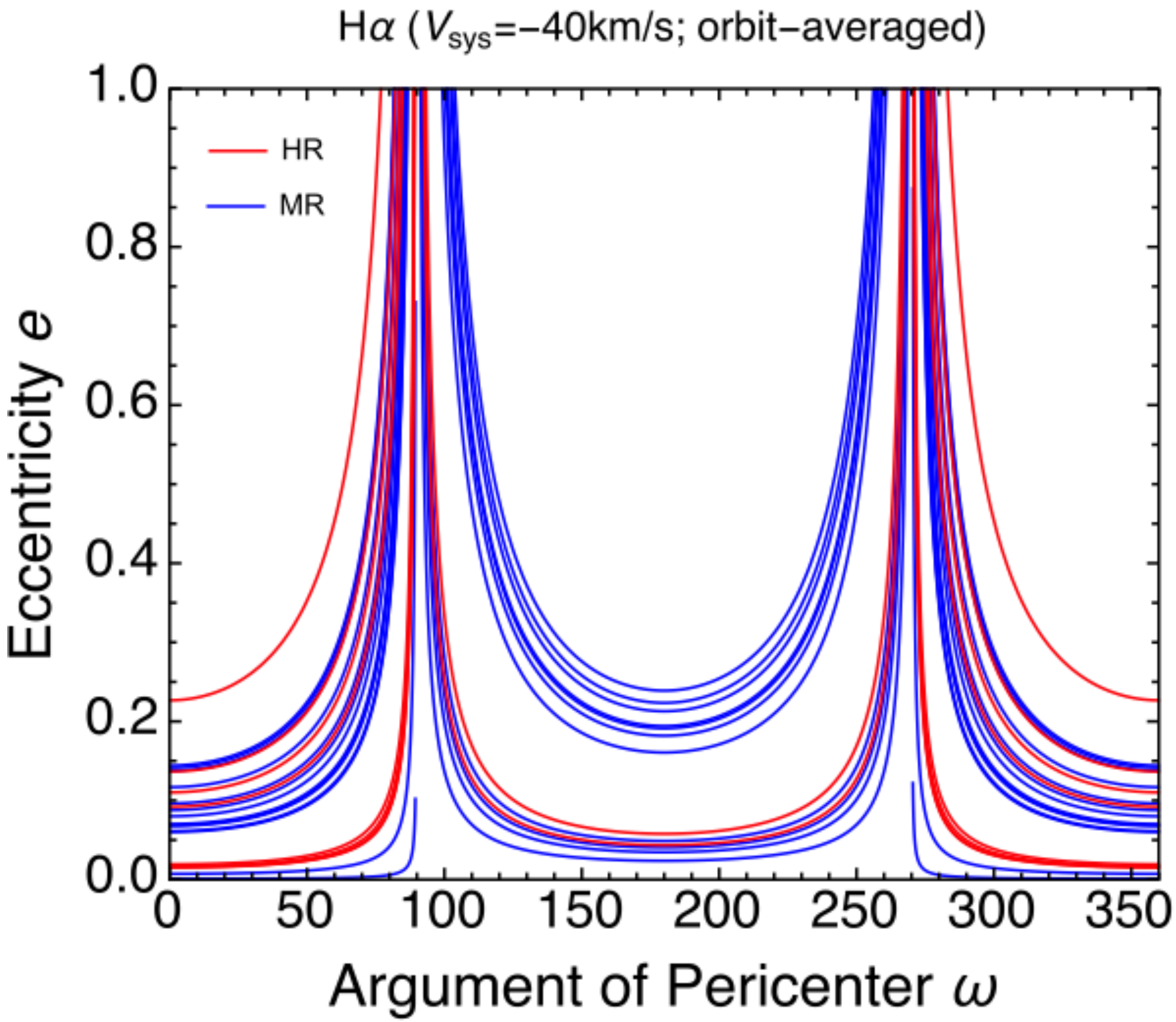
⇨ eccentricity: $e_{\rm p} = \dfrac{v_{\rm red}+v_{\rm blue}}{v_{\rm red}-v_{\rm blue}}\sec\omega$

Variations in orbit-averaged, peak velocities in 2007-2015



Blue: intermediate dispersion; Red: high dispersion

Eccentricity vs. argument of pericenter

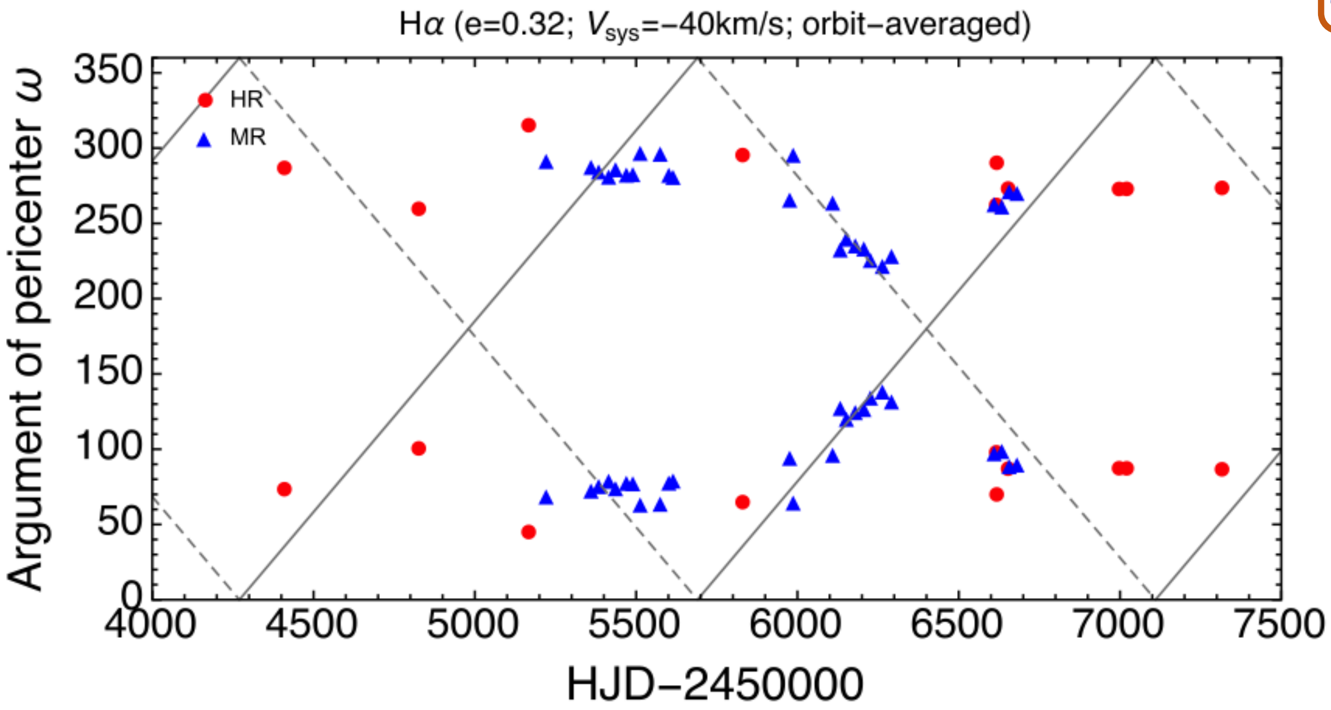


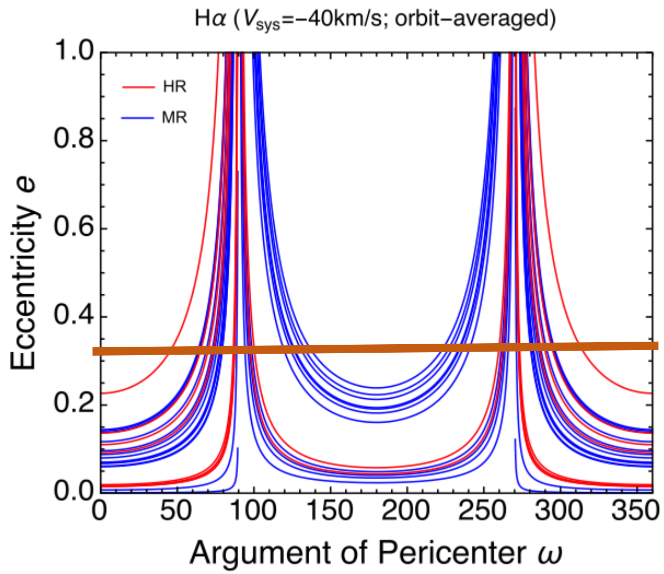
- Be disk was eccentric for most of the monitored period.
- The pericenter direction changed the side repeatedly.

Blue: intermediate dispersion
Red: high dispersion

Fit with *e*=const precessing disk is poor

If *e* is fixed to 0.32, $\omega = \dfrac{HJD - 2454270}{1420}$ ← Period





Disk eccentricity and anrgument of pericenter are likely to vary simultaneously.

KL mechanism?

5. Conclusions

Conclusions

- Excitation of the eccentricity of a misaligned Be disk via the Kozai-Lidov mechanism can trigger the cyclic disk evolution.
- The superorbital modulation of optical emission in LS I +61 303 could be due to this type of cyclic disk evolution.
- 3D SPH simulations of LS I +61 303 with constant mass injection failed to reproduce the cycle. But, when the mass injection rate was reduced, the cycle started.
- Studying the effect of PW is a next step.