Modeling the circumstellar interaction in the gamma-ray binary LS I +61 303

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Talk Outline

1. Gamma-ray binaries
2. Be stars
3. Gamma-ray binary LS I +61 303 and superorbital activity
4. Long-term variation in Be-disk geometry in LS I +61 303
5. Dynamic modeling of LS I +61 303
6. Concluding remarks

1. VHE gamma-ray binaries

Ground-based VHE gamma-ray astronomy

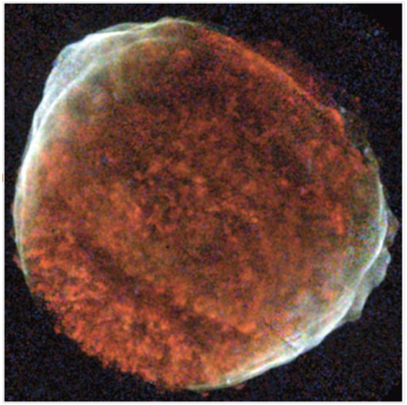
Imaging Atmospheric Cherenkov Telescopes

(H.E.S.S., VERITAS, and MAGIC)

⇨ Discovery of >100 VHE gamma-ray (E > 100 GeV) sources

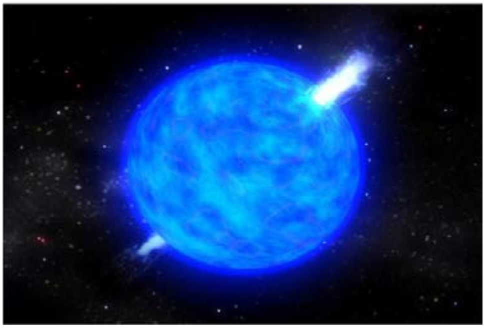
VHE (TeV) gamma-ray sources

- Supernova remnants

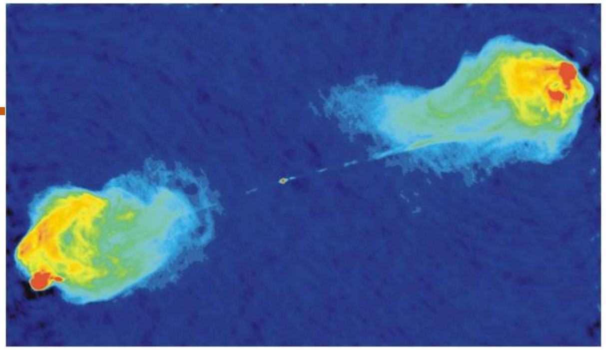


- Pulsar wind nebulae

- Massive binaries
- Gamma-ray bursts



- Active galactic nuclei



(VHE) gamma-ray binaries

- **Binaries with spectral energy distribution (SED) dominated by gamma-ray emission**
- Only 6 systems, all of which consist of an OB star and a compact object
    - **3 systems with a Be (B**-type emission**) star**
    - **3 systems with an O star**
- Nature of compact object established only for one system (PSR B1259-63 with a non-accreting pulsar)
- Two competing scenarios for other systems: **Pulsar wind scenario vs. Microquasar scenario**

High energy emission in PW scenario

Collision shocks between a relativistic pulsar wind and a stellar wind (and/or a Be disk)

⇨ Acceleration of electrons

⇨ {
- synchrotron ⇨ radio, X-rays
- IC ⇨ gamma-rays

High energy emission in MQ (accretion/ejection) scenario

Accretion

⇨ Relativistic jet

⇨

Leptonic model:

IC by relativistic electrons

⇨ gamma-rays

Hadronic model:

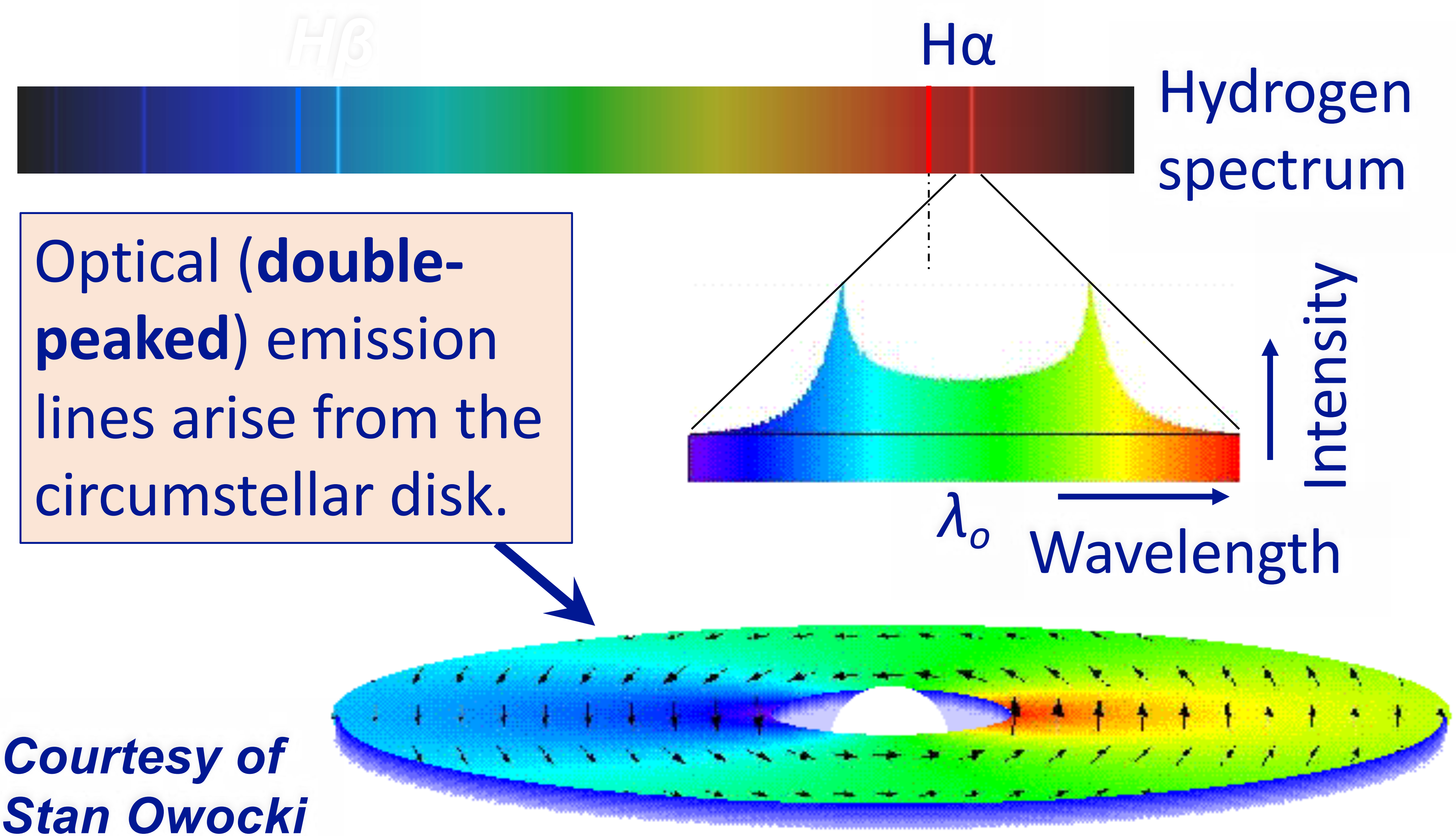
pp interactions ⇨ neutral pions

⇨ gamma-rays

System	Scenario	Optical star	P_{orb} (d)	e
PSR B1259-63	PW	Be	1237	0.87
LS I +61 303	?	Be	26.5	0.54
HESS J0632+057	?	Be	315	0.83
LS 5039	?	O	3.9	0.35
1FGL J1018.6-5856	?	O	16.6	low
CXOUJ053600.0-673507	?	O	10.3	?

2. Be stars

Be star: schematic diagram



Optical (**double-peaked**) emission lines arise from the circumstellar disk.

Courtesy of Stan Owocki

Viscous decretion disk model for Be stars

(Lee, Saio & Osaki 1991)

Observations support an idea that Be disks are formed by the effect of viscosity

Ejection of gas from the stellar equatorial region, at the Keplerian rotation velocity

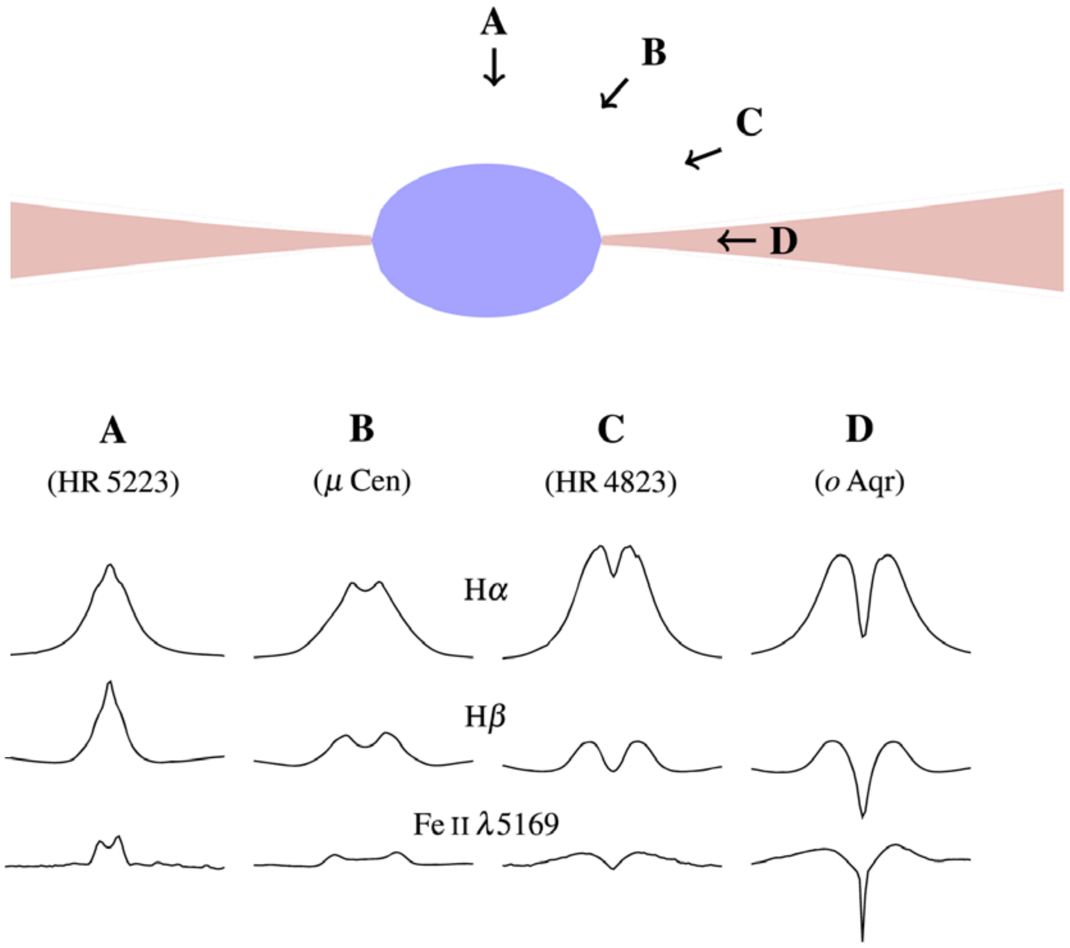
⇨ Outward drift by viscosity

⇨ Formation of a geometrically thin, Keplerian disk, where radial flow is very subsonic

Emission line profiles

Line profiles depend on:

- viewing angle,
- disk size
- disk density
- disk eccentricity
- whether disk is planar or warped

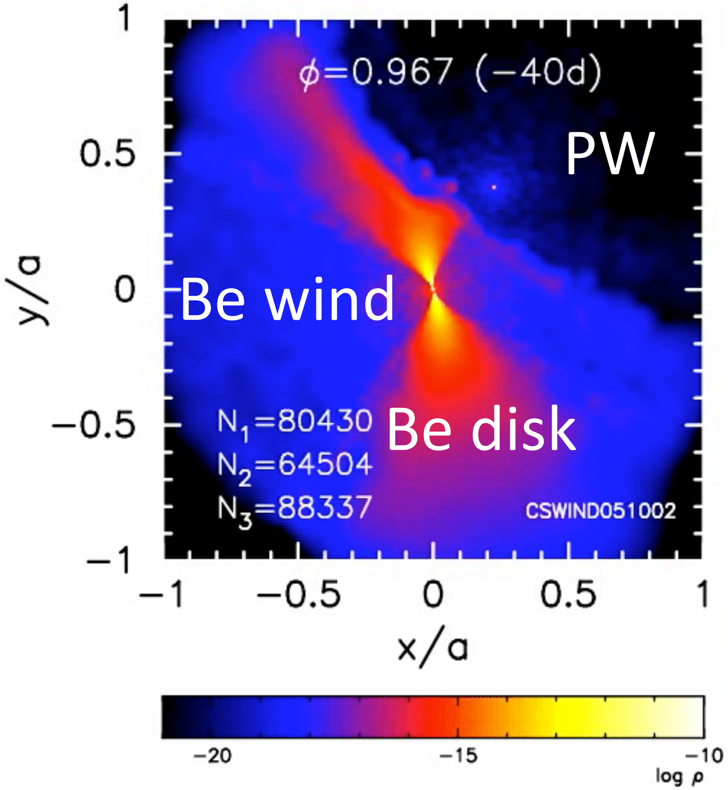


(Rivinius+ 2013)

Gamma-ray binaries with Be stars

- Gas pressure in Be disk >> ram pressure of Be wind

⇨ **High-energy emission arises via the interaction between Be disk and compact object**



Density distribution on orbital plane of PSR B1259-63 (Porb=1237d, e=0.87). Disk misaligned by 45 deg. (Takata+ 2012)

3. Gamma-ray binary LS I +61 303 and superorbital activity

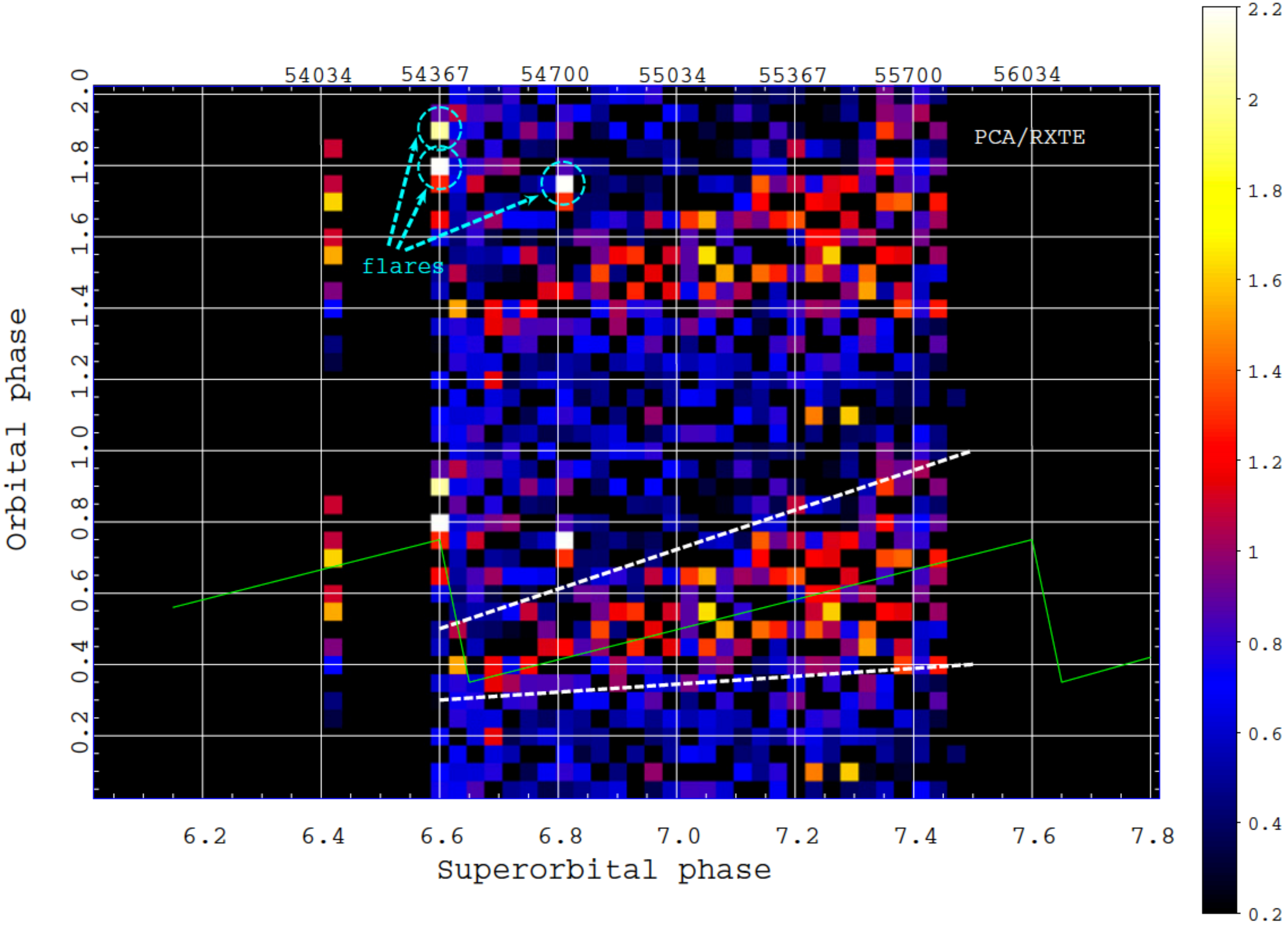
Observed features

- Be star + compact object of unknown nature (P_{orb}=26.5 d, e=0.54)
- TeV emission detected only around apastron previously, while it peaks before periastron recently
- HE (>100MeV) gamma-ray flux peaked after periastron before Mar. 2009, while it is ~const. after Mar. 2009
- radio maps ⇨ jets vs. PW shocks
- Weak X-rays (<10^{34} erg/s) ⇨ Radiatively inefficient accretion flow vs. no accretion

Superorbital modulation in LS I +61 303

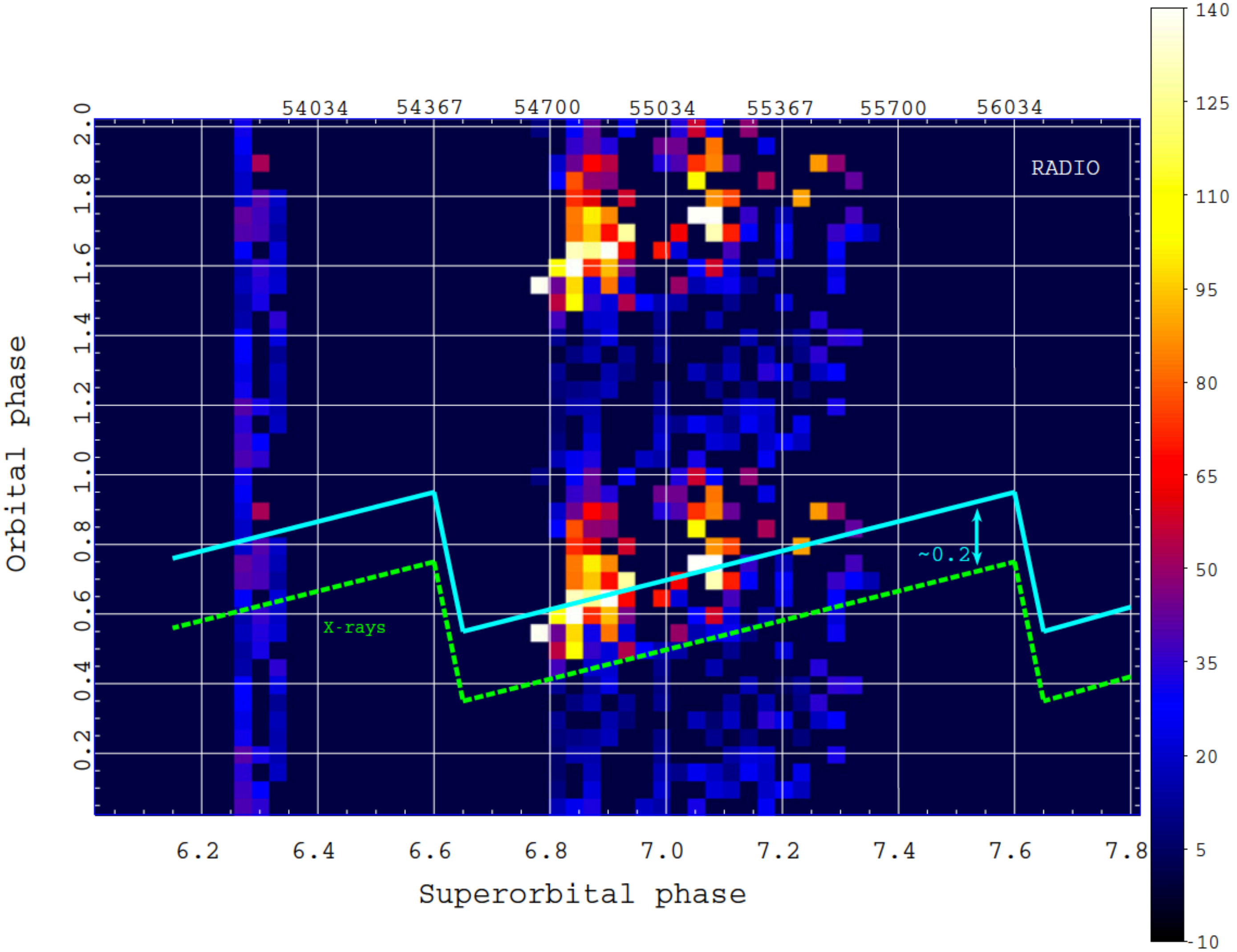
- Radio and X-ray flares modulates on a superorbital **1667 d** (>> P_{orb}) timescale
- Optical brightness and disk emission also modulates on same timescale

Superorbital modulation in X-ray flare phase



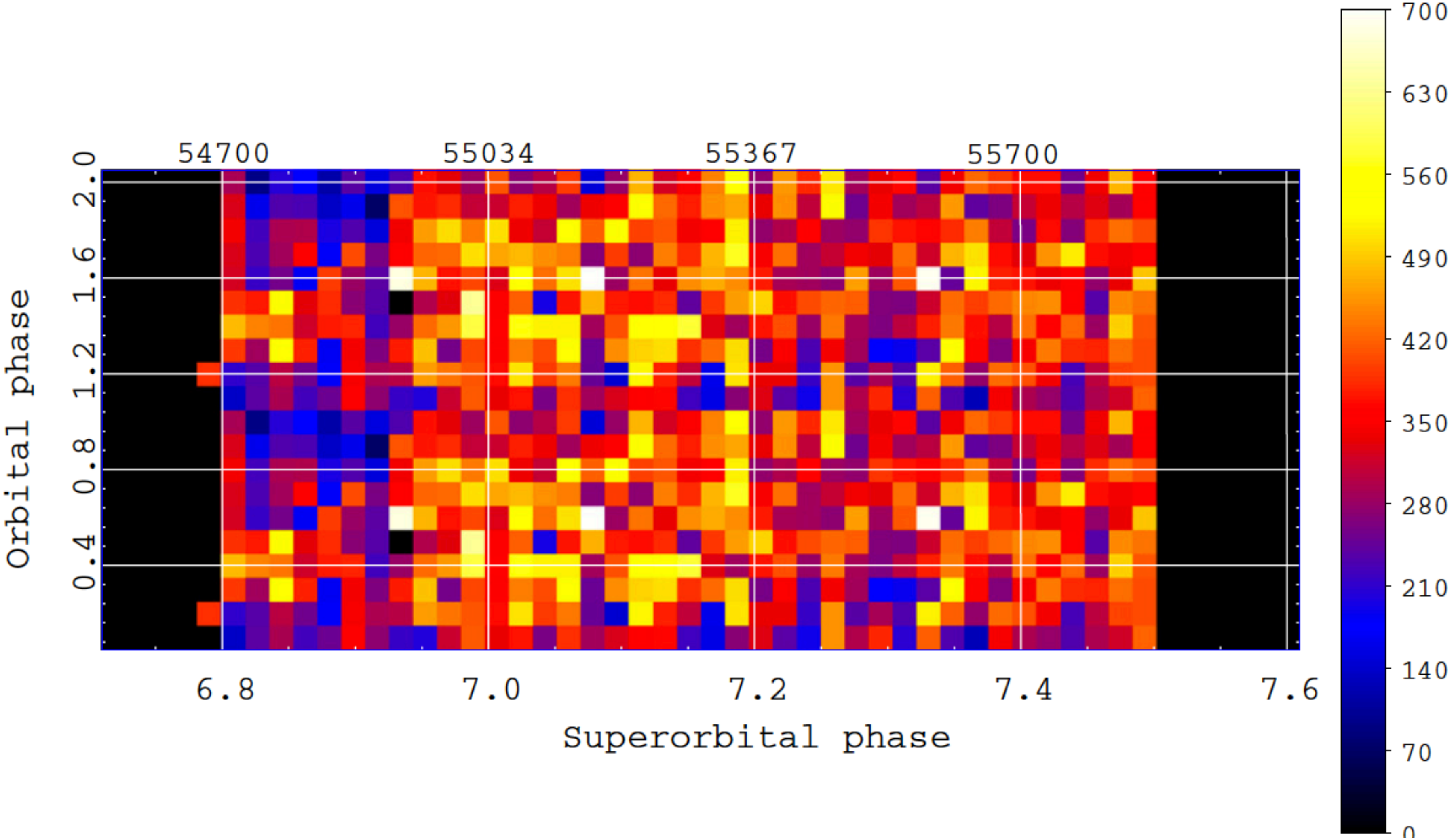
(Chernyakova+ 2012)

Superorbital modulation in radio flare phase



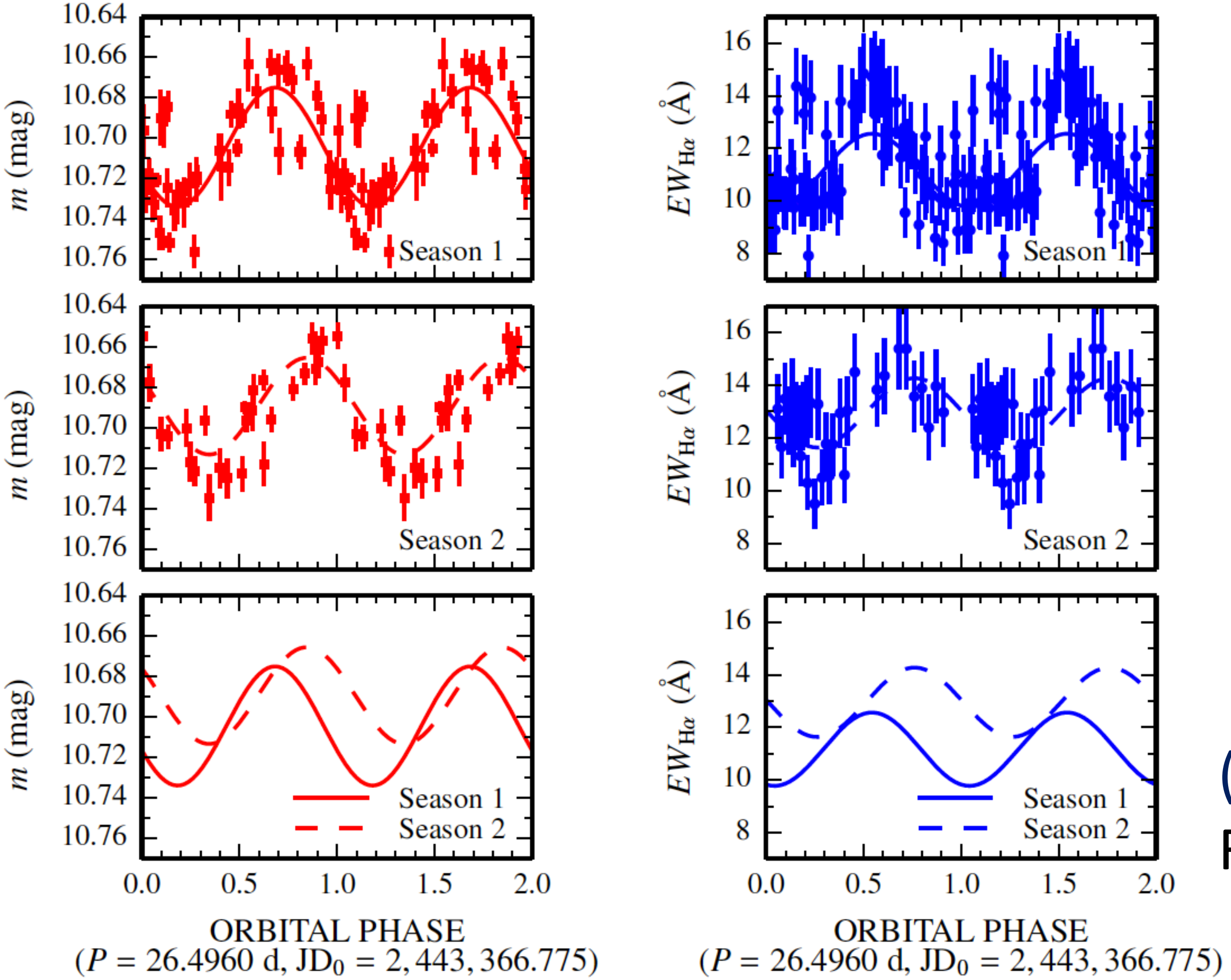
(Chernyakova+ 2012)

Superorbital modulation in gamma-rays?



(Chernyakova+ 2012)

Orbital modulation in optical light curve (left) and EW(Halpha) (right) modulates in superorbital timescale



(Paredes-Fortuny+ 2015)

Superorbital modulation in LS I +61 303

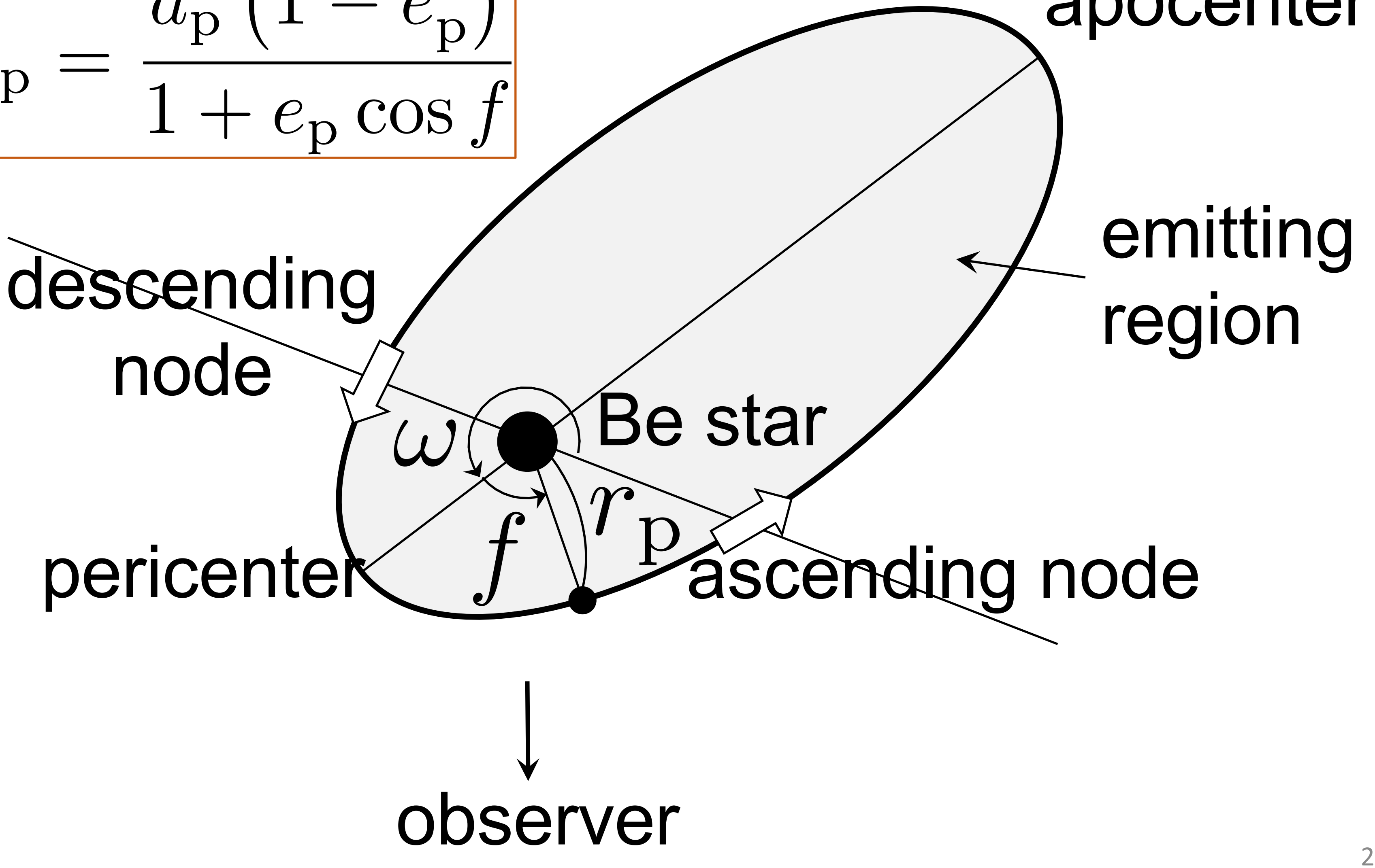
- Radio and X-ray flares modulates on a superorbital **1667 d** (>> P_{orb}) timescale
- Optical brightness and disk emission also modulates on same timescale

What causes the superorbital modulation?
What is/are regularly changing?
Disk size?
Disk eccentricity?
Other disk quantities?

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

Particle model for the Halpha emitting region

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



Basic equations

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

⇨ radial velocity: argument of pericenter

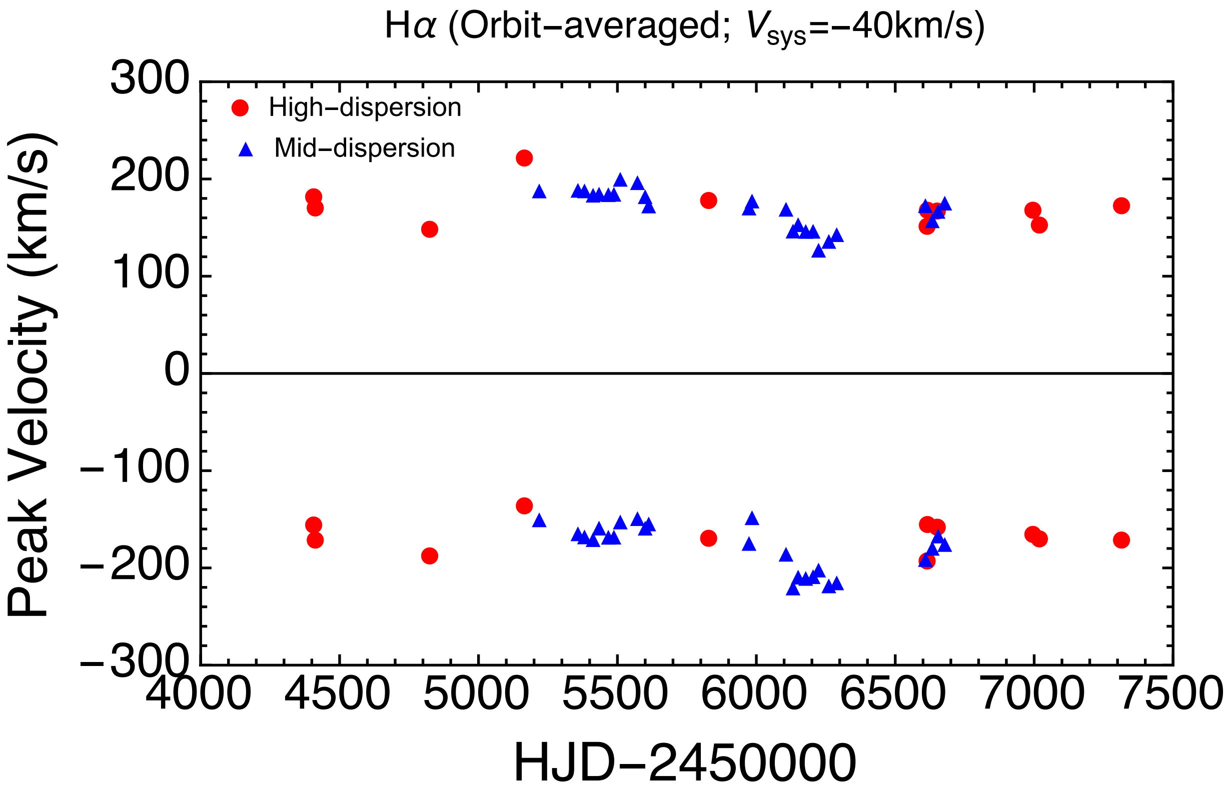
$$v_{\mathrm{rad}} = \sqrt{\frac{GM_1}{a_{\mathrm{p}}(1 - e_{\mathrm{p}}^2)}} \sin i \left[\cos(\omega + f) + e_{\mathrm{p}} \cos \omega\right]$$

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

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

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

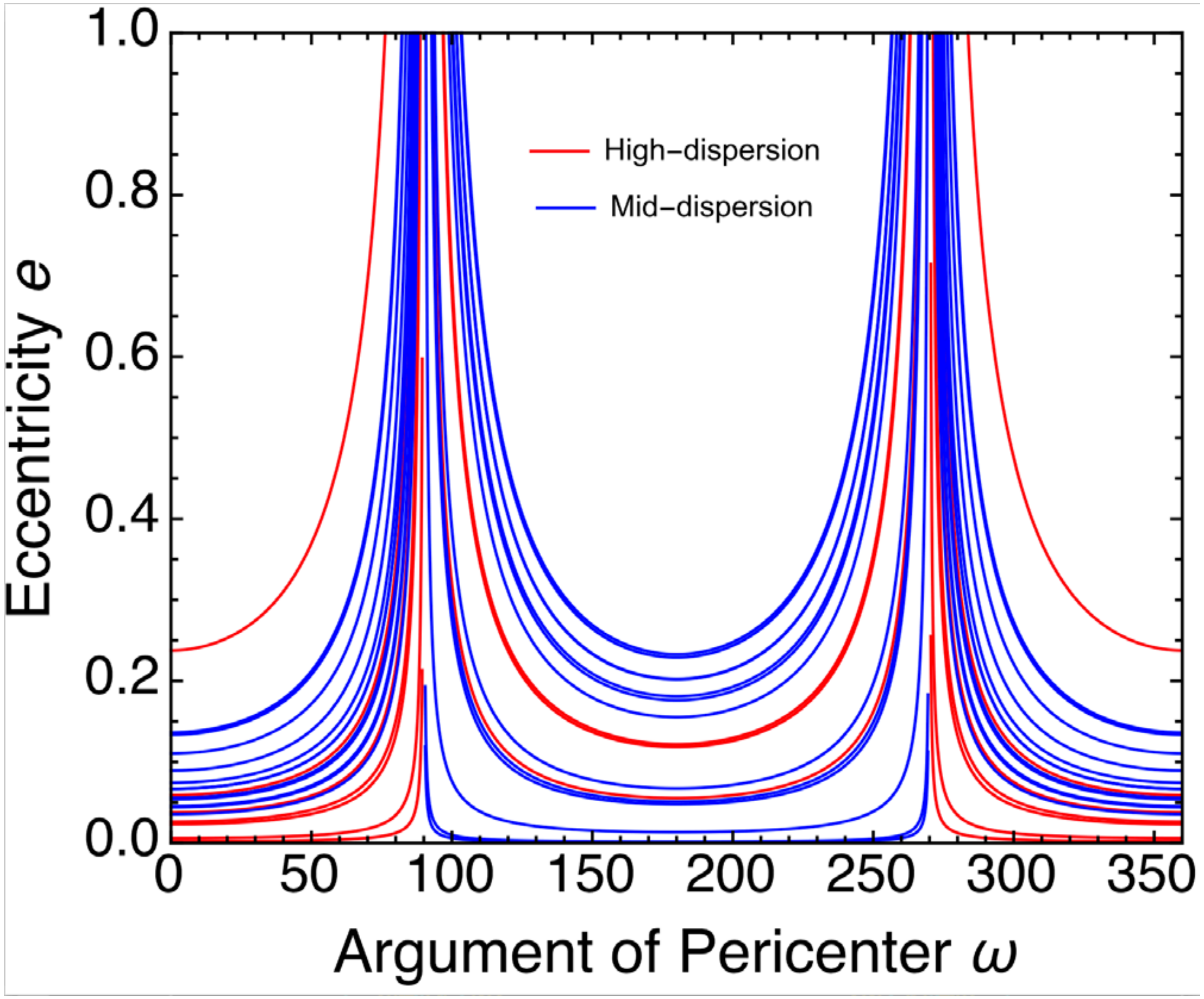
Variations in observed peak velocities in 2007-2015



Blue: mid-dispersion spectra

Red: high-dispersion spectra

Eccentricity vs. argument of pericenter

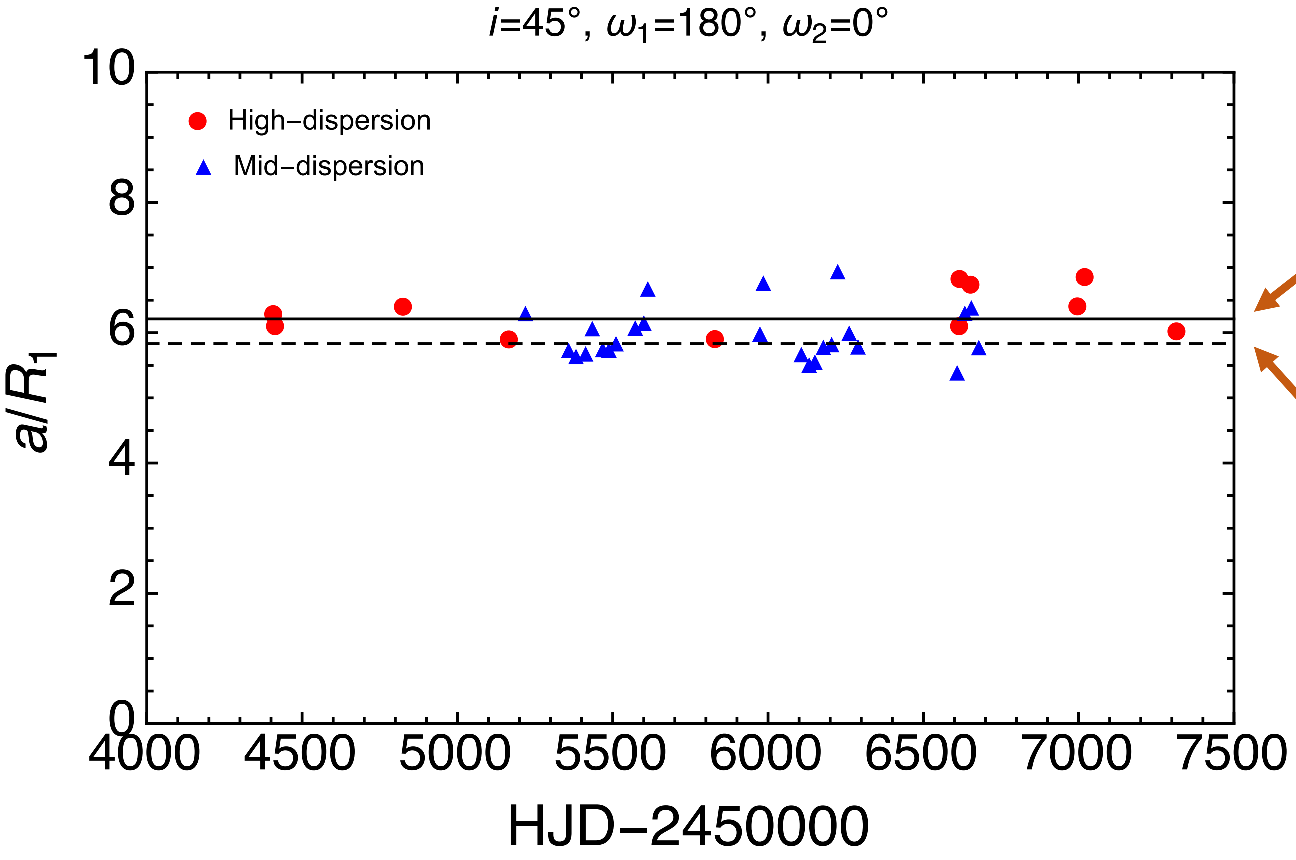


Blue: mid-dispersion spectra

Red: high-dispersion spectra

Disk size ~ constant

$$i = 45^\circ$$



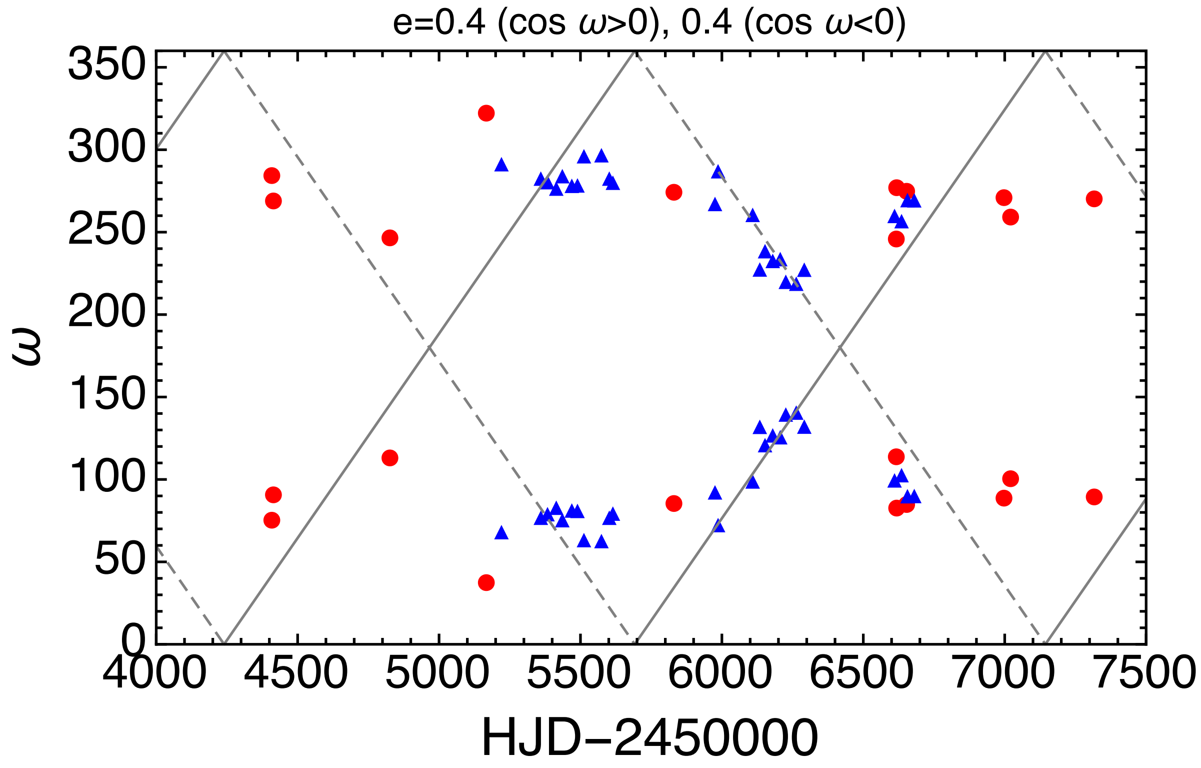
Binary periastron separation

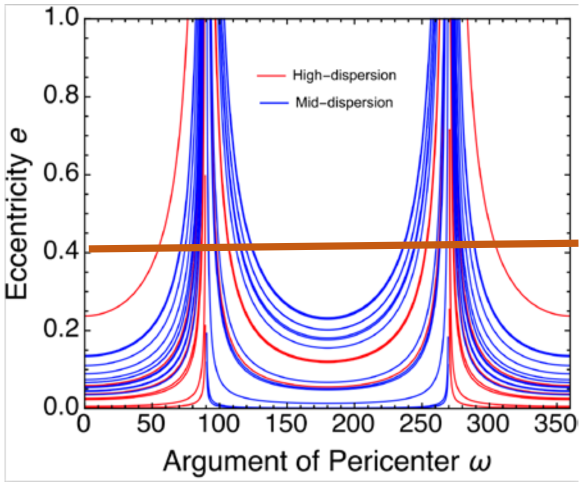
Average Roche-lobe radius of Be star

Fit with *e*=const disk (precessing disk) is poor

If e is fixed to 0.4, $\omega_{\rm fit} = \frac{HJD - 2455676}{\boxed{1459}}$

Period



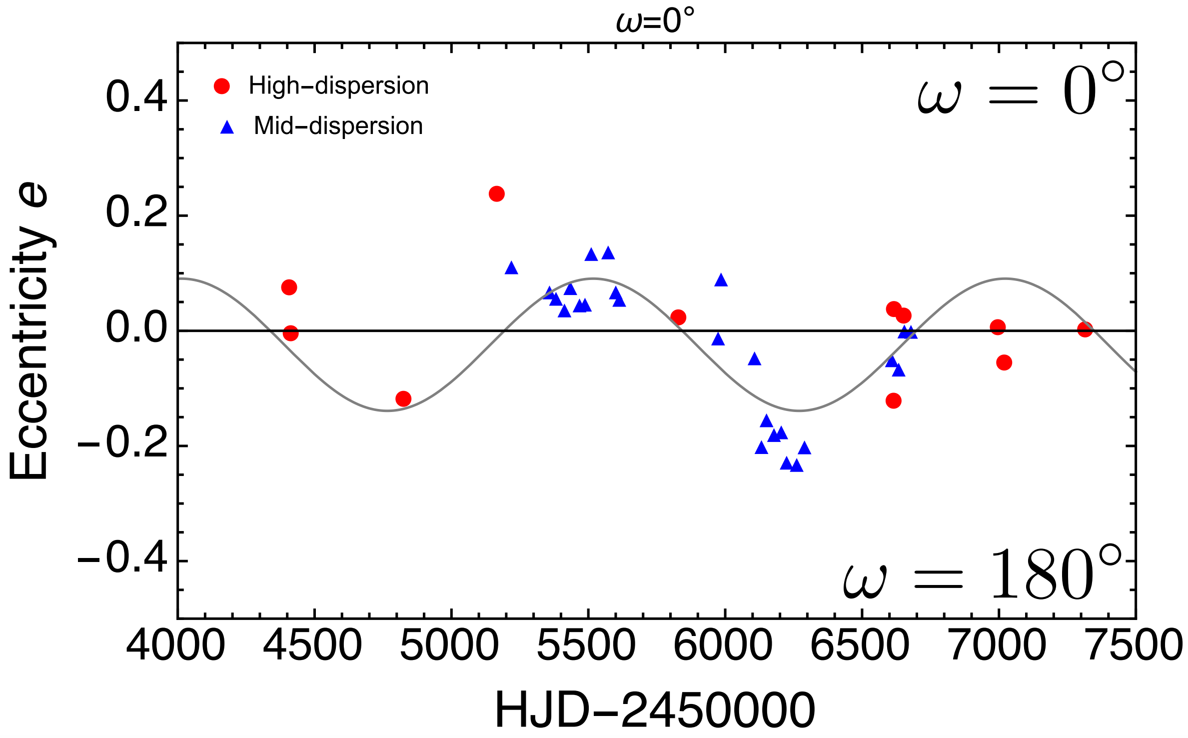


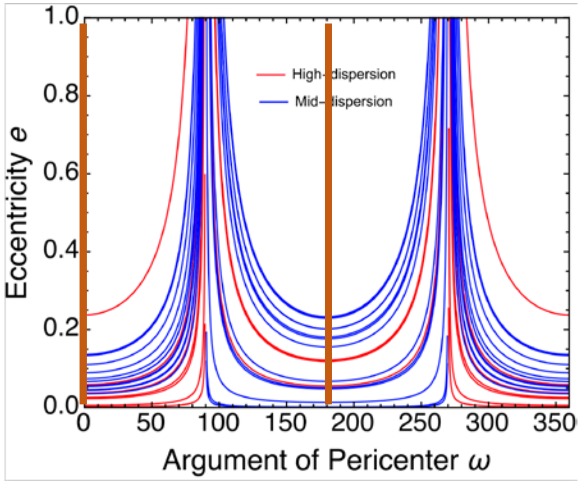
Disk eccentricity varies at ~superorbital period!

If ω is fixed to 0° or 180°,

Period

$$e_{\mathrm{fit}} = 0.115\sin(HJD - 2455142)/\boxed{1505} - 0.0242$$





This suggests that the Be-disk eccentricity and pericenter argument vary simultaneously.

5. Dynamic modeling of LS I +61 303

What is/are responsible for the long-term change in the disk eccentricity and argument of pericenter?

- Variation in the argument of disk pericenter

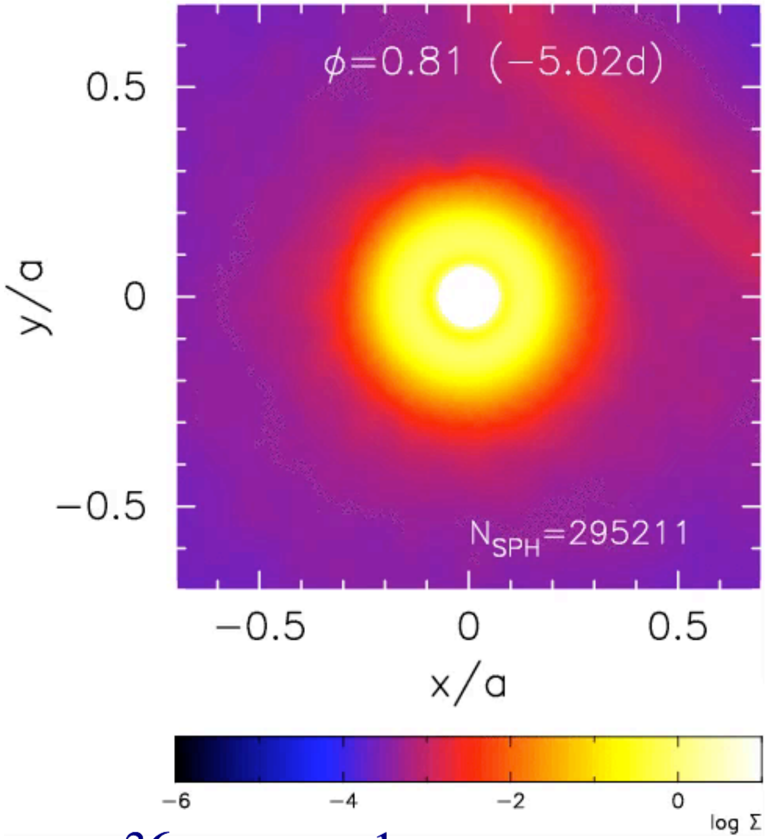
⇨ Tidal precession?

- Variation in the disk eccentricity

⇨ Kozai-Lidov mechanism (exchange between inclination and eccentricity) for a highly misaligned disk?

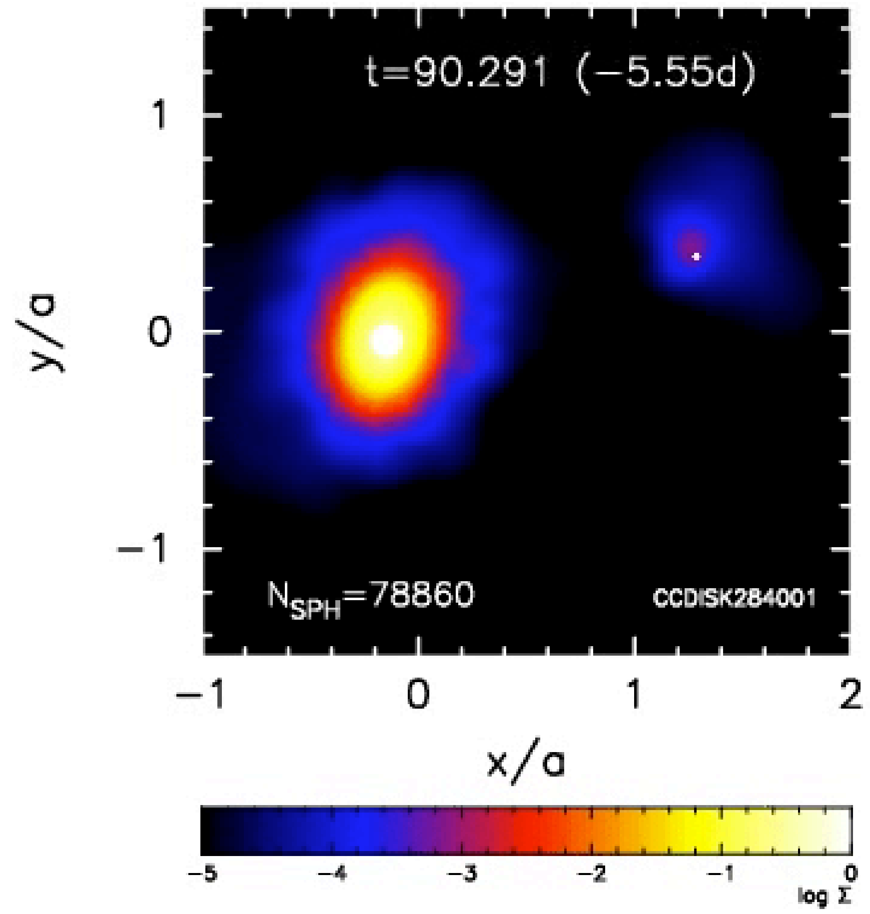
Ideally, simulations with PW should be done to study both the PW and tidal effects on Be disk

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

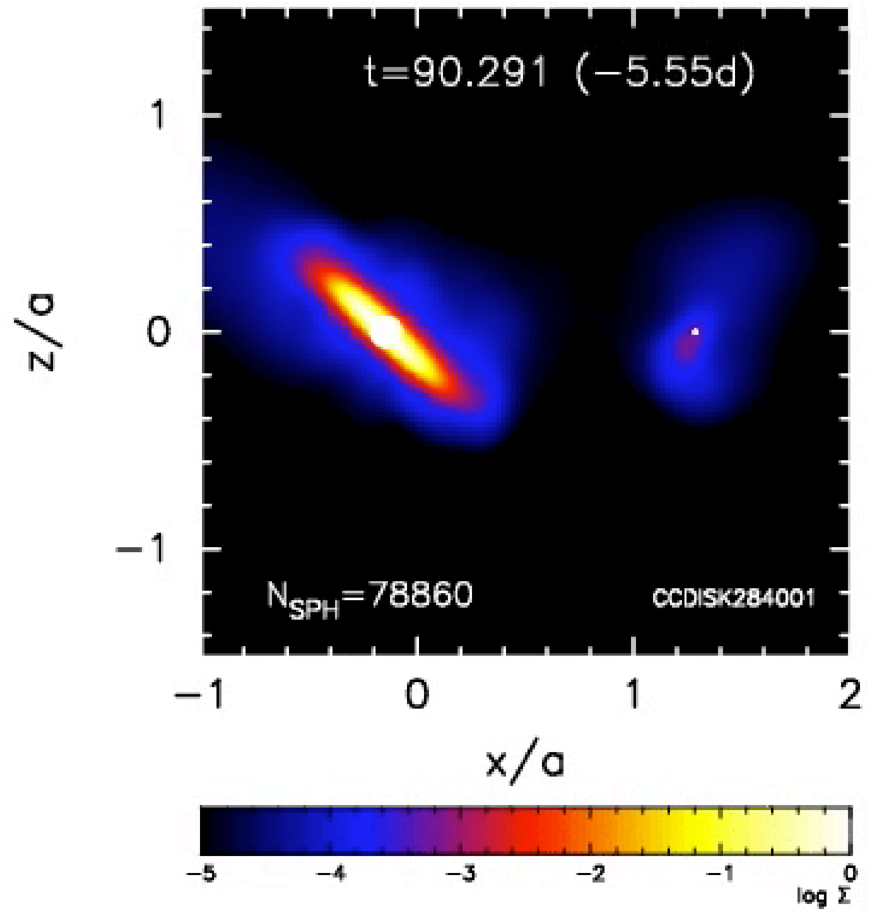


$$\dot{E}_{\rm PSR} = 10^{36}\,{\rm erg\ s^{-1}}, \quad \rho_0 \sim 2\cdot 10^{-11}\,{\rm g\ cm^{-3}}$$

SPH simulation of the tidal interaction between the compact object and the Be disk in LS I +61 303



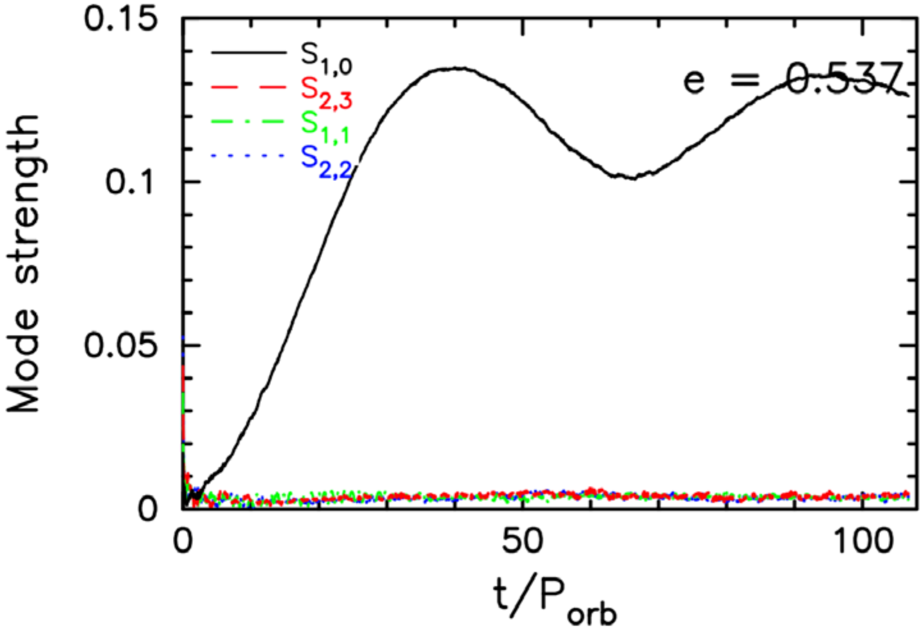
Column density along z-axis



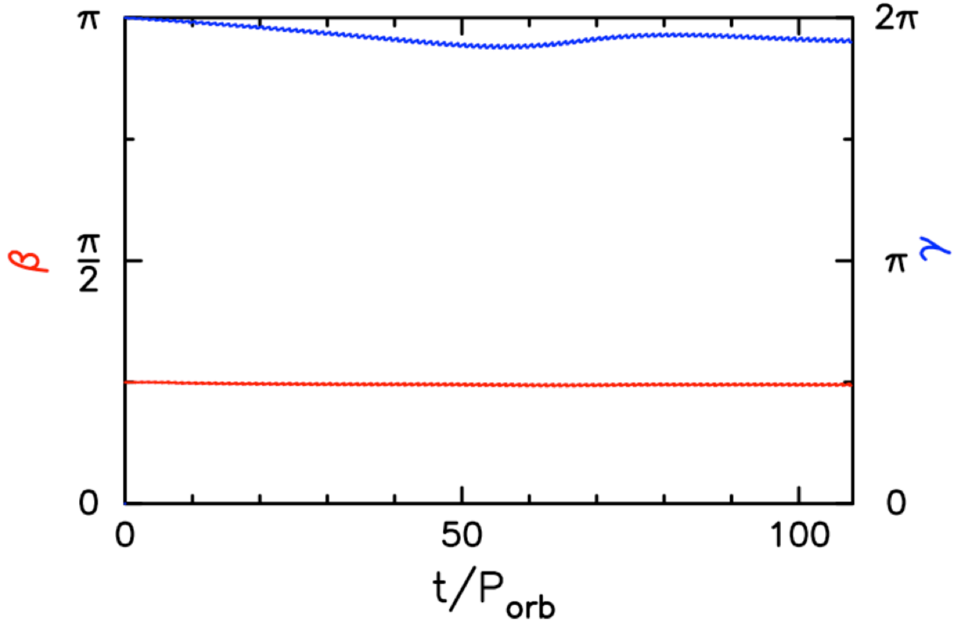
Column density along y-axis

Disk eccentricity varies, but no precession occurs

Strength of m=1 mode



β : tilt angle
γ : azimuth of tilt



6. Concluding remarks

Superorbital modulation in LS I +61 303 is a ~30 years old puzzle, but now

- A simple model to analyze the Be-disk geometry shows that **the superorbital modulation in LS I +61 303 is likely due to the variation in the disk eccentricity coupled with the disk precession**.
- Unfortunately, however, 3D SPH simulations failed to confirm this conclusion.
- This failure may be the lack of resolution of the simulations. Simulations with much more particles are needed.
- Including the effect of PW is also a next step.