Cyclic evolution of misaligned circumstellar disks in Be/X-ray binaries

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Outline

1. Be stars
2. Be/X-ray binaries
3. Dynamic modeling of misaligned Be/X-ray binaries
4. Concluding remarks

1. Be stars

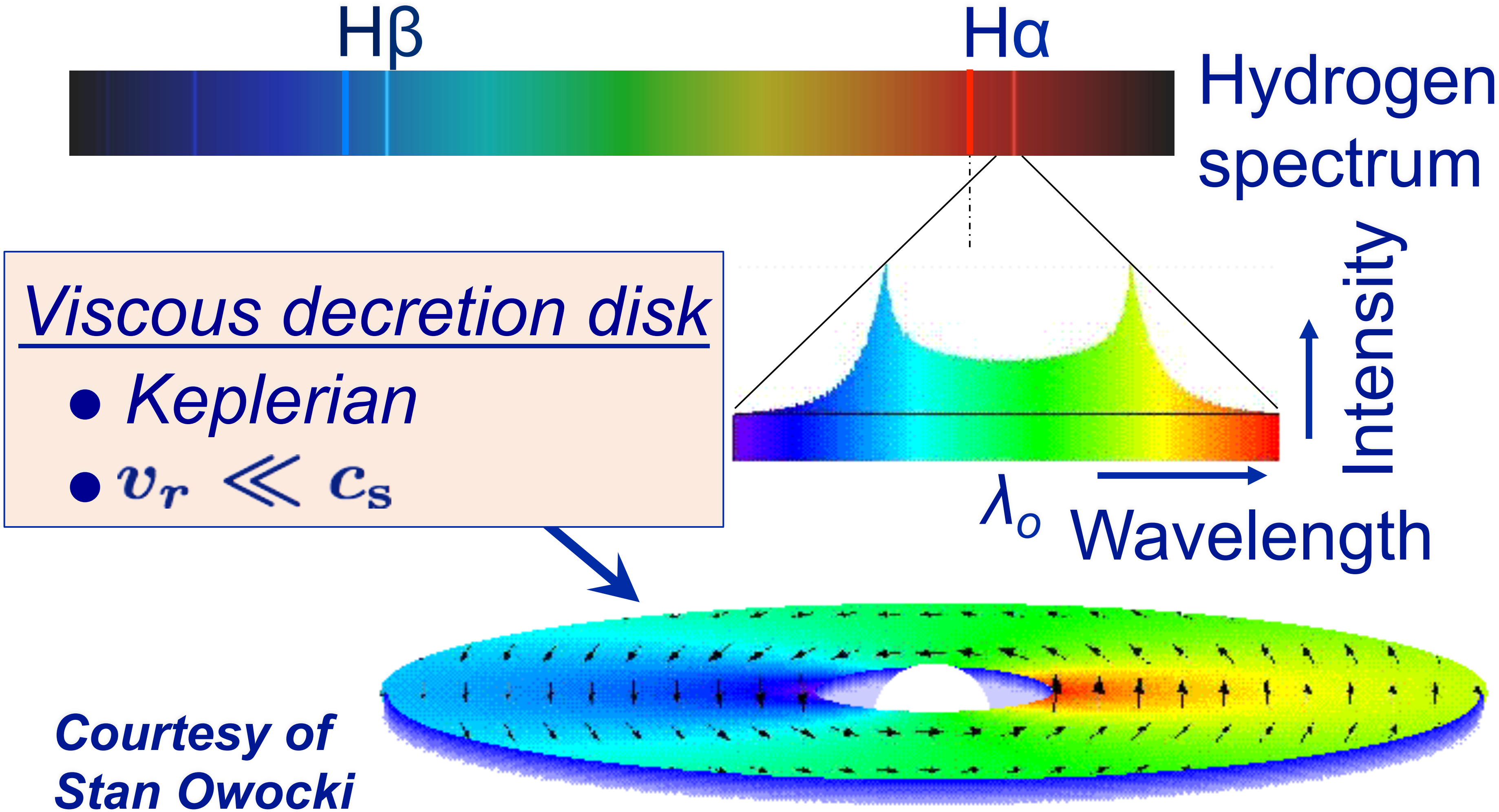
Massive Stars

- Luminous $(L \sim M^{3.5})$
  - ⇨ Strong stellar winds (driven by radiation)

    $\dot{M} \sim 10^{-8}\, M_\odot\ \mathrm{yr}^{-1}$ for B0V

    cf., solar mass-loss rate driven by gas pressure: $\dot{M} \sim 10^{-14}\, M_\odot\ \mathrm{yr}^{-1}$
- Rapid rotation
  - ⇨ If close to critical rotation
    - ⇨ Equatorial mass ejection from star
    - ⇨ Formation of a circumstellar disk
    - ⇨ **Be stars**

Be star: schematic diagram



Viscous decretion disk

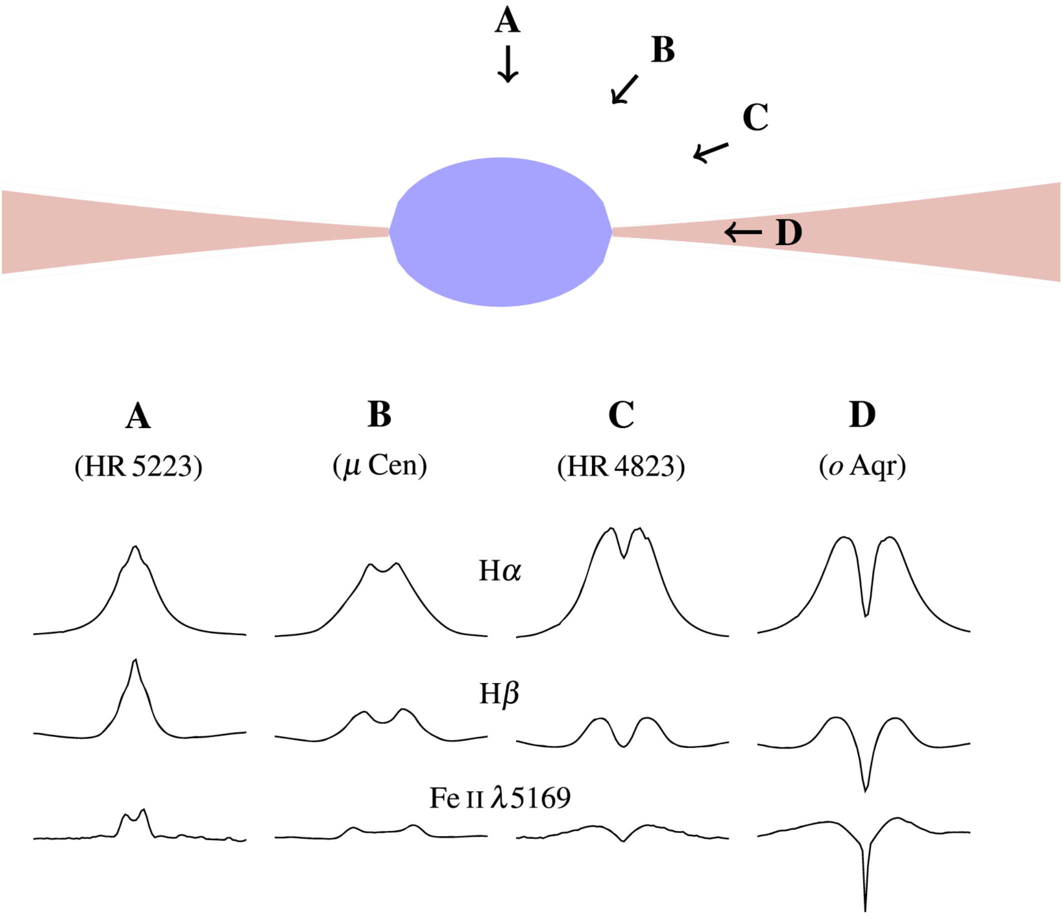
- *Keplerian*
- $v_r \ll c_s$

Courtesy of Stan Owocki

Emission line profiles

Line profiles depend on:

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



(Rivinius+ 2013)

2. Be/X-ray binaries

X-ray binaries

Low Mass X-ray Binaries

- a low mass star
  + a NS or BH

Roche lobe overflow

High Mass X-ray Binaries

Wind accretion

- Supergiant X-ray binaries (~50%)
  a blue supergiant + a NS or BH

Accretion from Be disk

- Be/X-ray binaries (~50%)
  a Be star + a NS or BH

Be/X-ray binaries

- System: a Be star + (mostly) a neutron star (there is one Be+BH binary)
- Orbit: wide (10 d < P_{orb} < 300 d) and eccentric (e < 0.9)
- X-ray activity: quiescent in most of the time; shows only transient activity as outbursts

X-ray outbursts

Two types of X-ray outbursts:

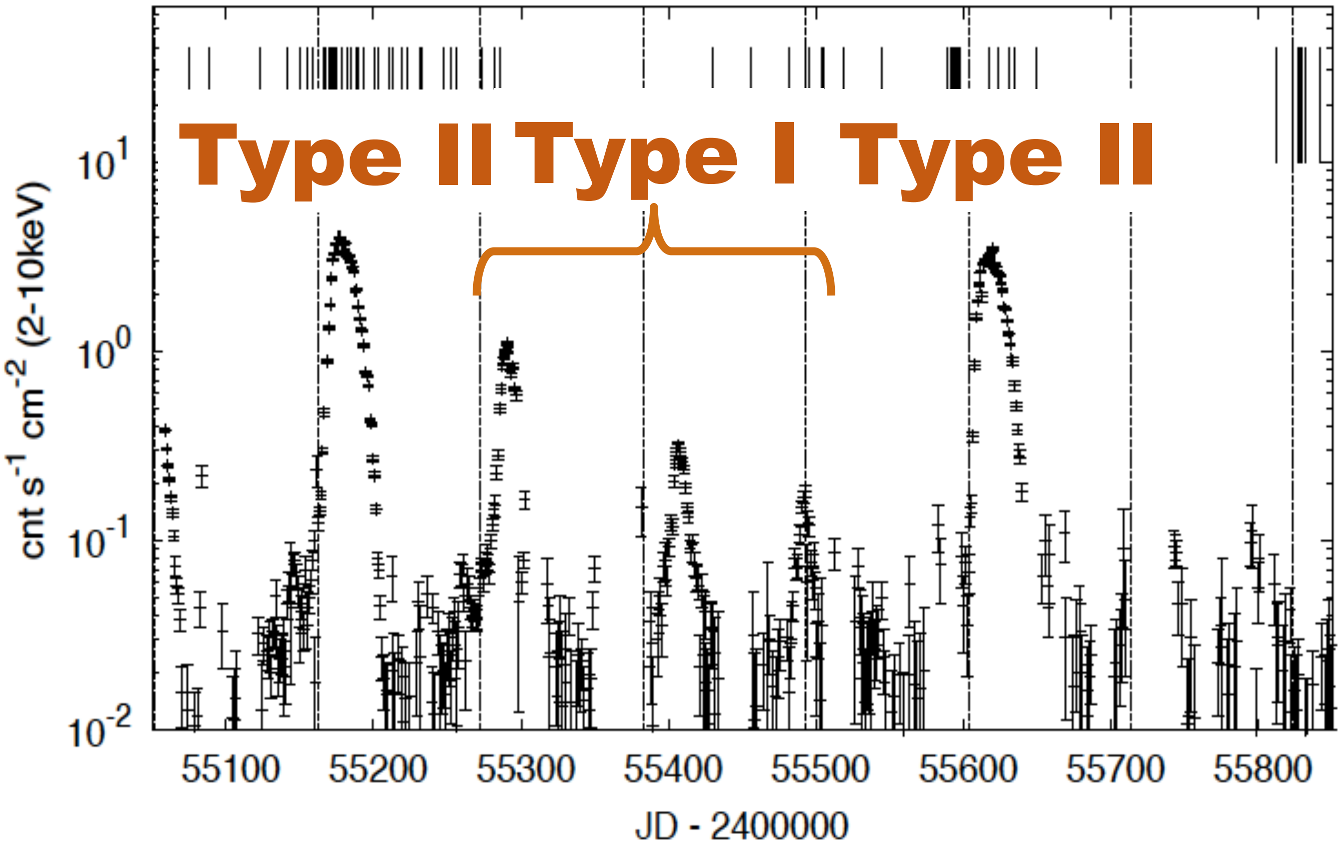
- Type I (normal) outbursts
  - $L_{\rm X} \sim 10^{36-37}\,{\rm erg\,s^{-1}}$
  - Periodic at $P_{\rm orb}$
  - Often associated with Type II
- Type II (giant) outbursts
  - $L_{\rm X} \gtrsim 10^{37}\,{\rm erg\,s^{-1}}$
  - Occasional; maybe quasi-periodic
  - Be disk strongly deformed before/during Type II

(Stella+ 1986; Negueruela+ 1998)

biggest mystery in Be/X-ray binaries

Two types of X-ray outbursts

A 0535+262 (P_{orb}=110d, e=0.47)



(Moritani+ 2013)

Giant X-ray outbursts: proposed mechanisms

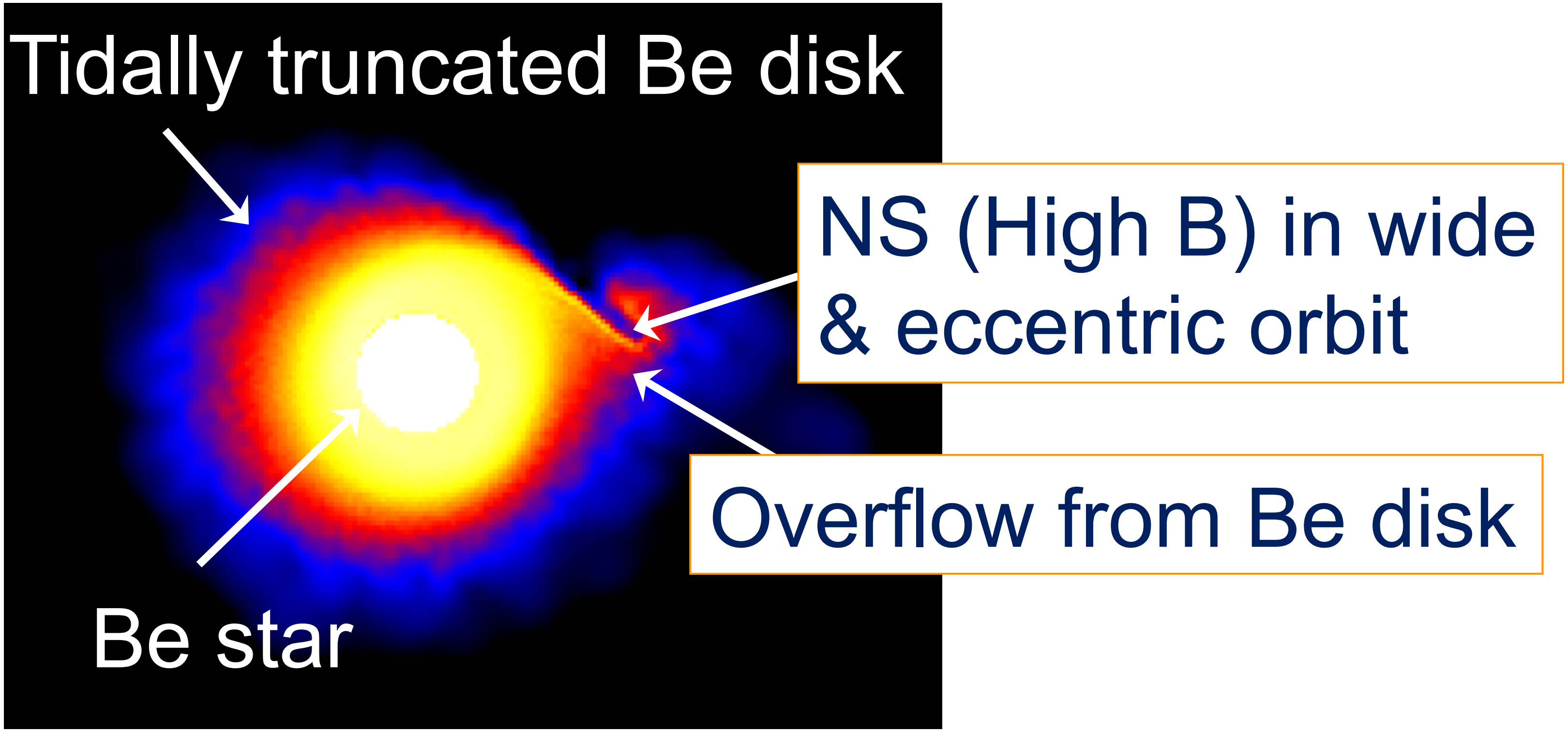
- **Tidal precession** of a warped, misaligned Be disk (Moritani+ 2013)
- **Kozai-Lidov oscillation** of a highly misaligned [$i \gtrsim 45^\circ$ (Fu+ 2015)] Be disk, where disk inclination is periodically exchanged for disk eccentricity (Martin+ 2014)

⇨ KL oscillation is quickly damped in a viscous disk (Martin+ 2014; Fu+ 2015).

⇨ How can giant outbursts repeats if the KL oscillation is the sole mechanism?

Be X-ray binaries: Mass supply mechanism

Overflow from Be disk near periastron
⇨ X-ray outburst



Tidally truncated Be disk

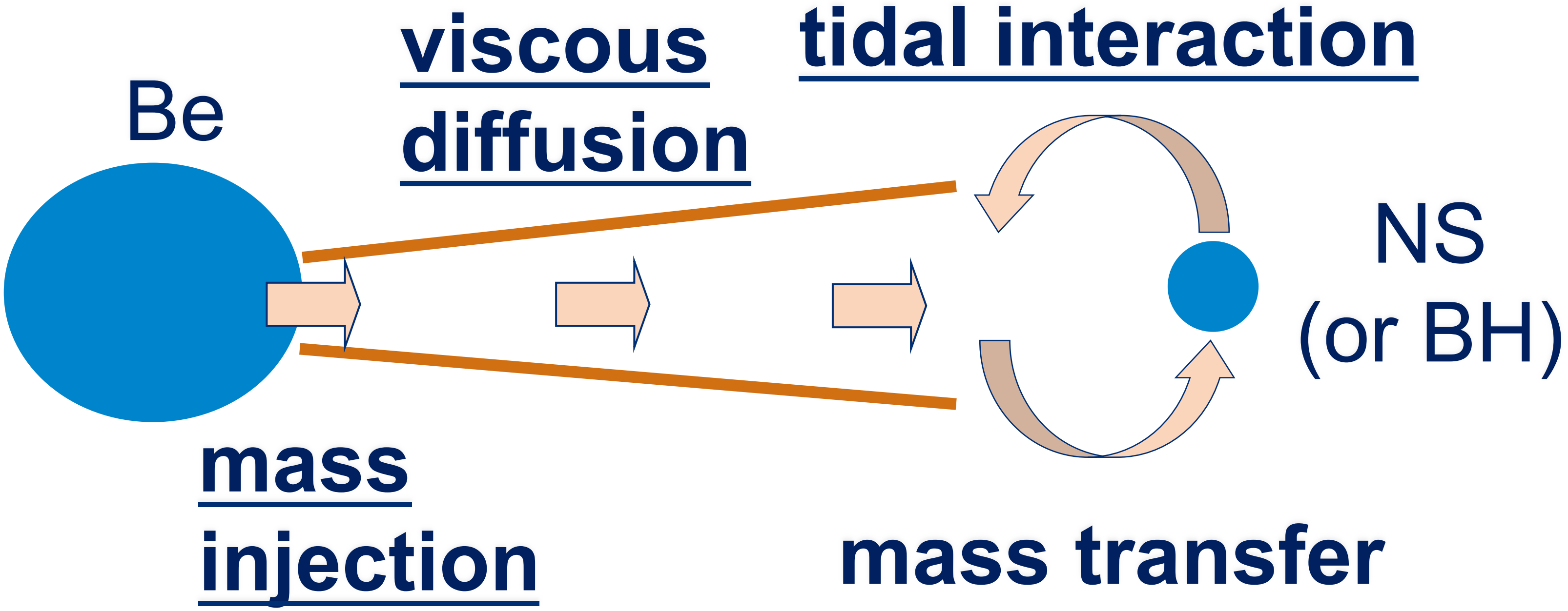
NS (High B) in wide & eccentric orbit

Overflow from Be disk

Be star

Complicated interactions in Be/X-ray binaries

- Disk gas supplied by central star
- Disk forms by the effect of viscosity
- X-ray activity controlled by tidal interaction



Various aspects of tidal interaction

Due to tidal interaction with a compact object, a Be disks ia subject to:

- Tidal/resonant truncation
- Tidal warping and precession if a disk is misaligned with binary orbital plane
- Kozai-Lidov oscillations if a disk is highly misaligned
- Tearing of disk

as is an accretion disk.

3. Dynamic modeling of misaligned Be/X-ray binaries

Numerical setup

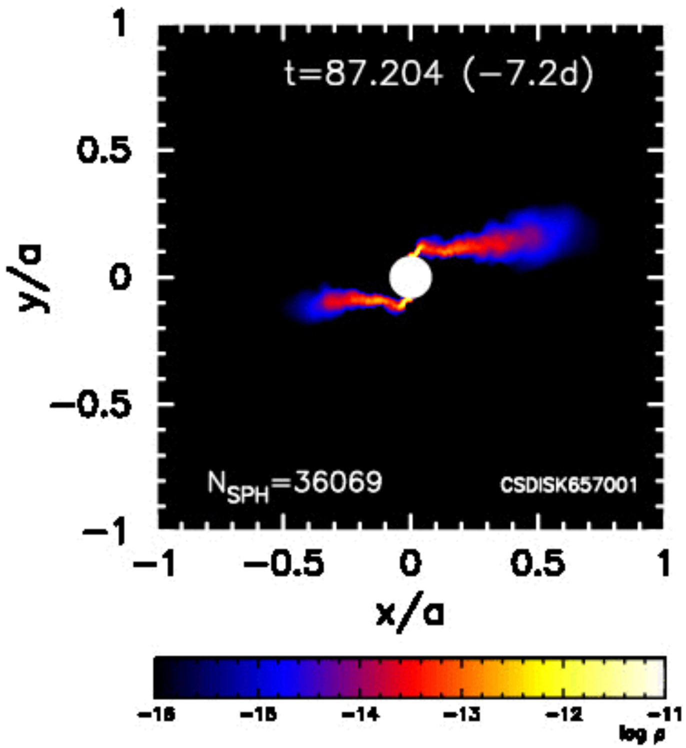
- 3D Smoothed Particle Hydrodynamics
- Artificial viscosity roughly corresponding to the shear viscosity parameter $\alpha = 0.1$.
- Be star's spin axis highly misaligned with the binary orbit plane
- Mass injection from stellar equatorial region
- Two targets: (1) 4U 0115+634 (P_{orb}=24.3d, e=0.34; quasi-periodical giant outbursts) and (2) A 0535+262 (P_{orb}=110d, e=0.47; occurrence of giant outbursts unpredictable)

(1) 4U 0115+634

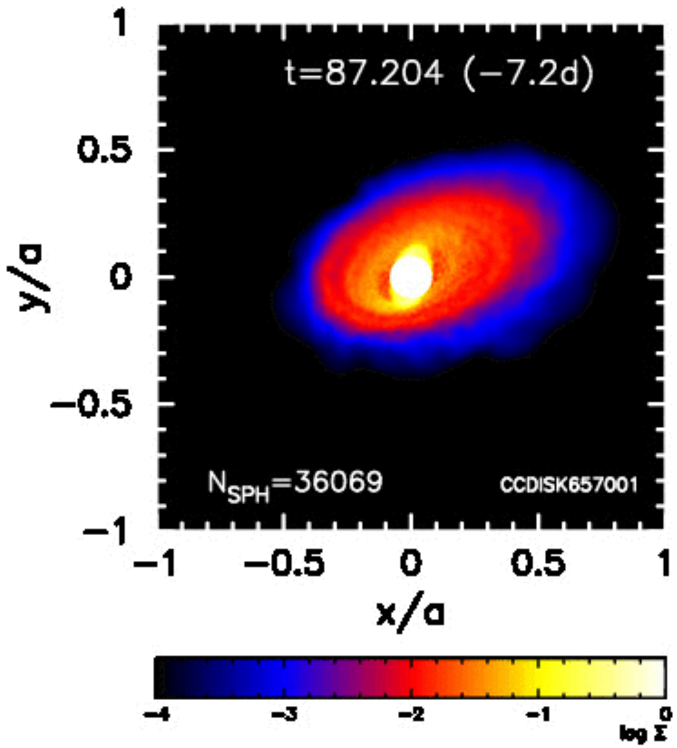
Tearing of Be disk in 4U0115+634

(Okazaki+ 2017, in prep.)

Be disk is torn at the base when tidal torque becomes stronger than mass-addition torque



Density in orbital plane

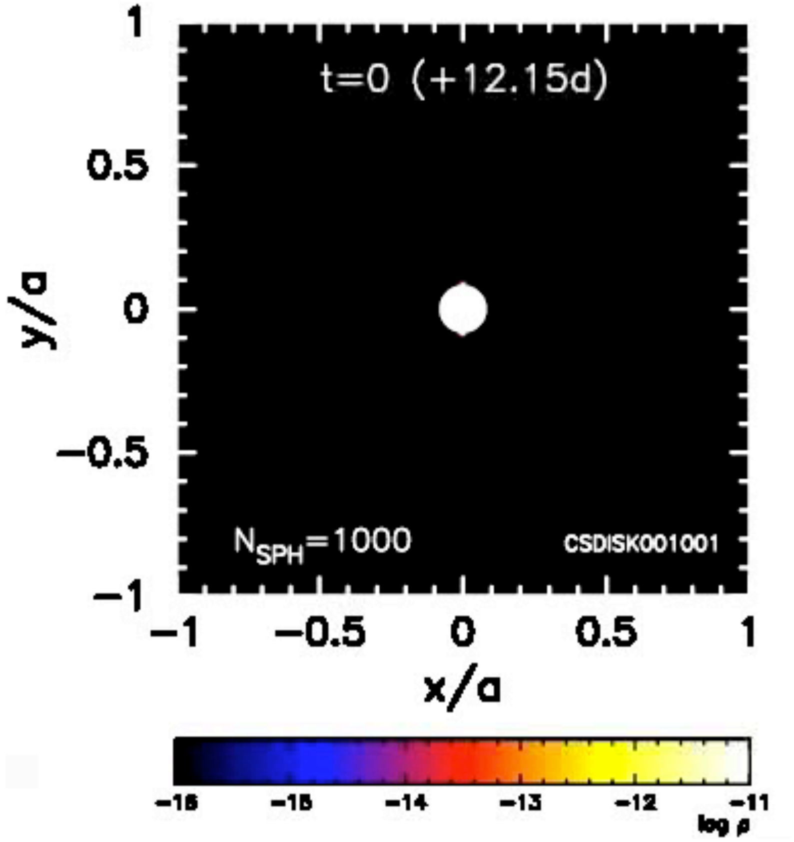


Column density along z-axis

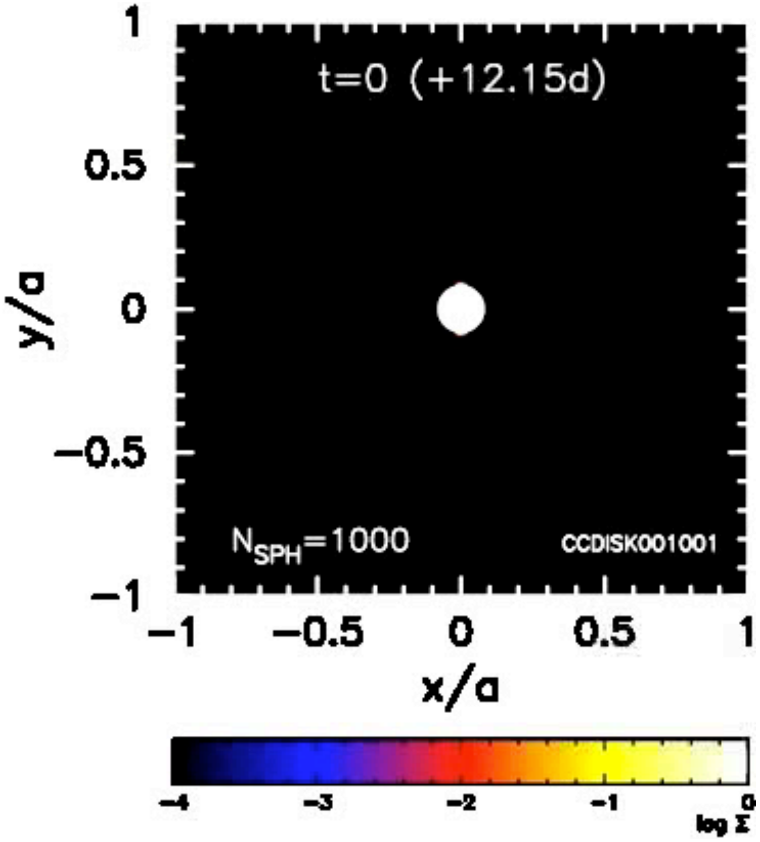
$P_{orb}=24.3$ d, $e=0.34$, $i_{disk}=60$ deg. about y-axis (=semi-minor axis)

Tearing of a misaligned Be disk triggers cyclic disk evolution

P_{orb}=24.3 d, e=0.34, i_{disk}=60 deg. about y-axis



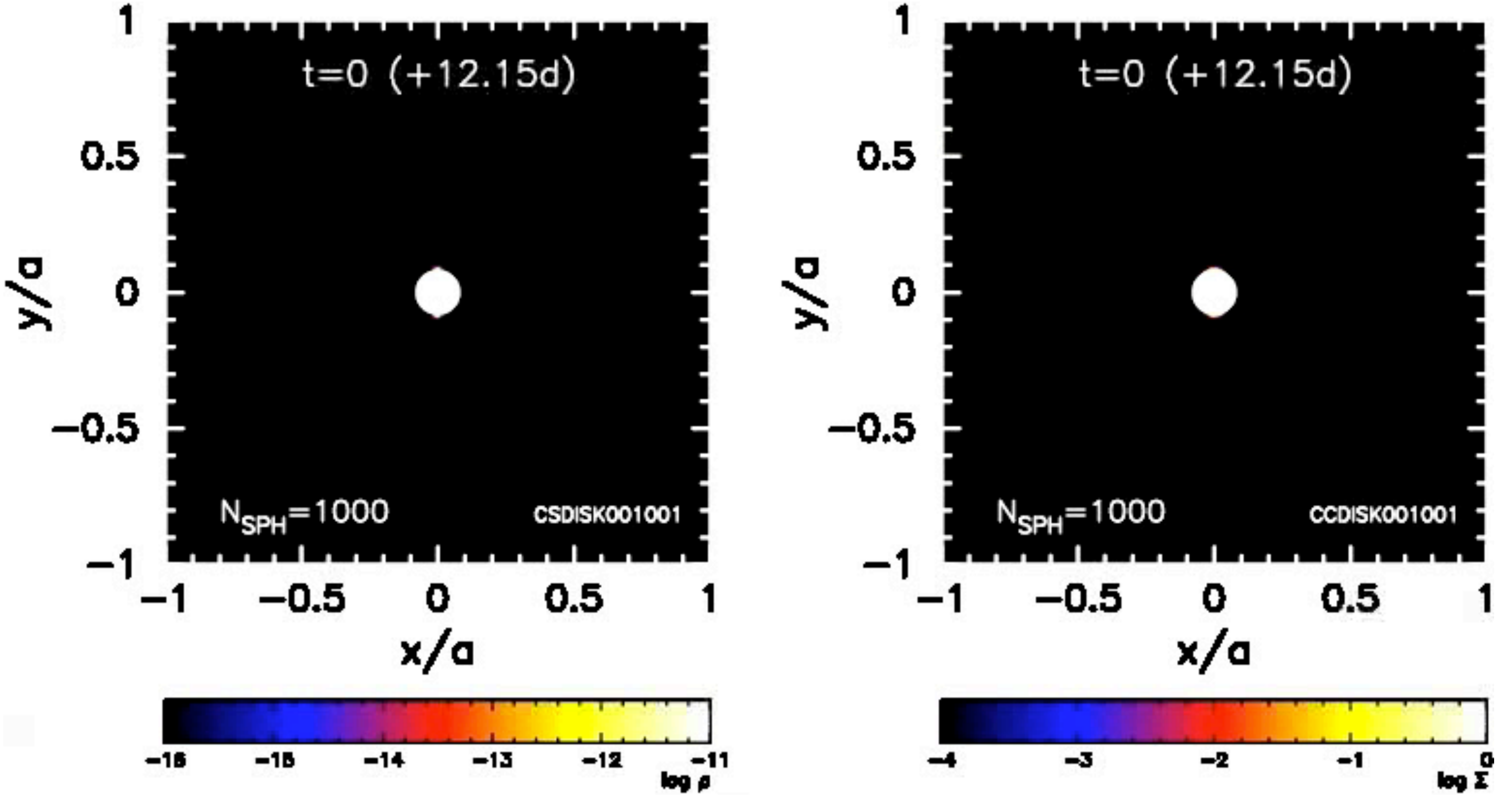
Density in orbital plane



Column density along z-axis

Tearing of a misaligned Be disk triggers cyclic disk evolution

P_{orb}=24.3 d, e=0.34, i_{disk}=45 deg. about y-axis



Density in orbital plane

Column density along z-axis

A new type of Be-disk evolution cycle in Be/X-ray binaries

Initially circular disk becomes eccentric by the Kozai-Lidov mechanism.

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

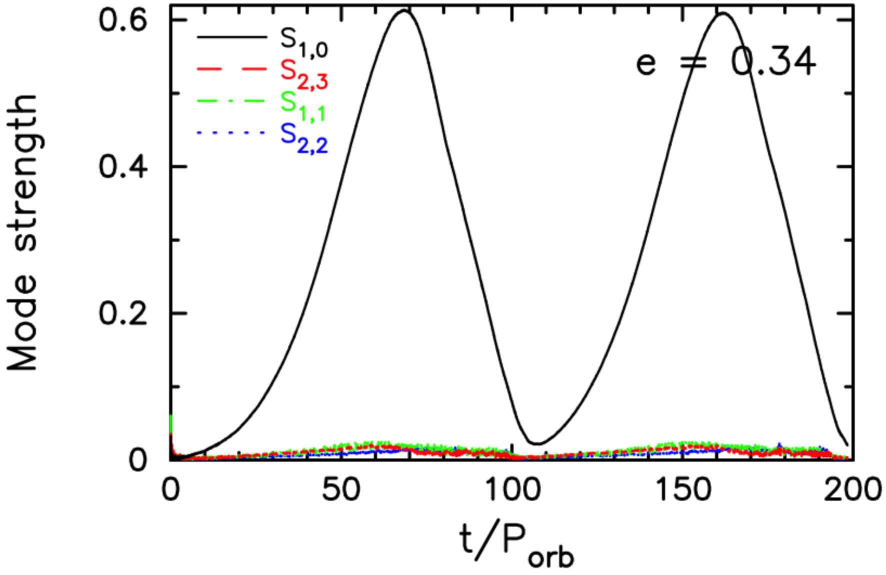
⇨ Gap opens between the disk base and mass ejection region.

⇨ New disk forms in the stellar equatorial plane.

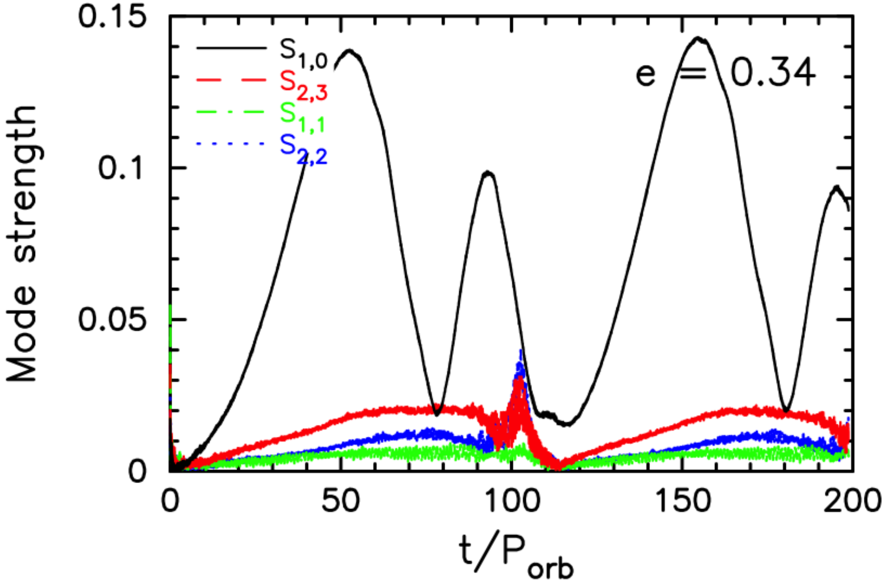
Formation of a new disk resets KL oscillation

$P_{cycle} \sim 100P_{orb}$

i=60 deg.



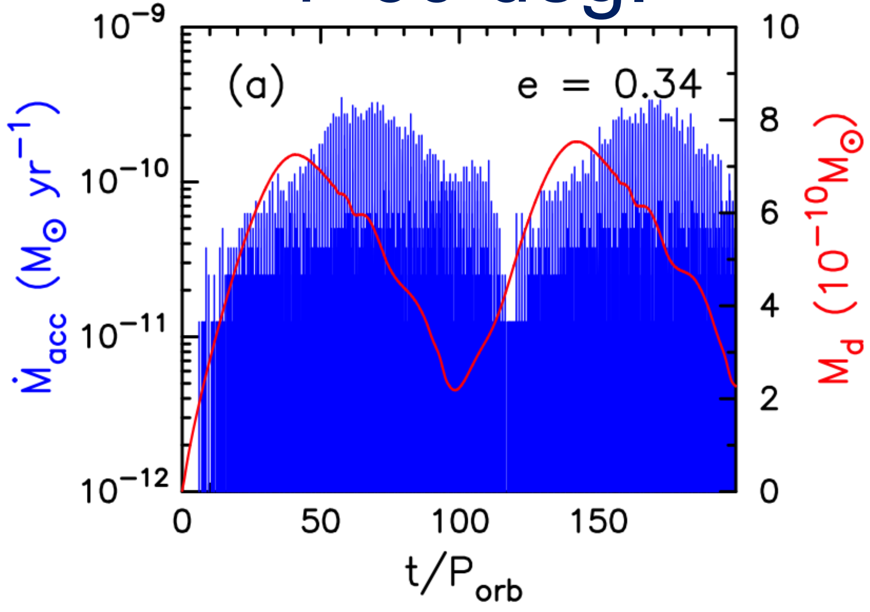
i=45 deg.



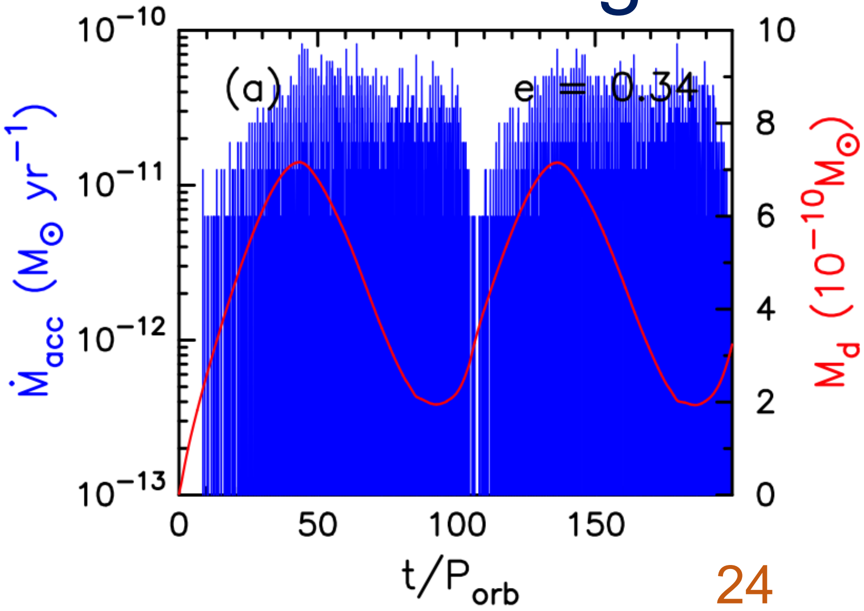
Origin of giant X-ray outbursts is still an open question?

- Cycle length (~7 yr) is comparable to observed ~3 yr interval in 4U 0115+634.
- Accretion rate shows large modulation, but it occurs gradually.

i=60 deg.



i=45 deg.



In each ~5 yr cycle of 4U0115+634, X-ray outbursts come in pairs

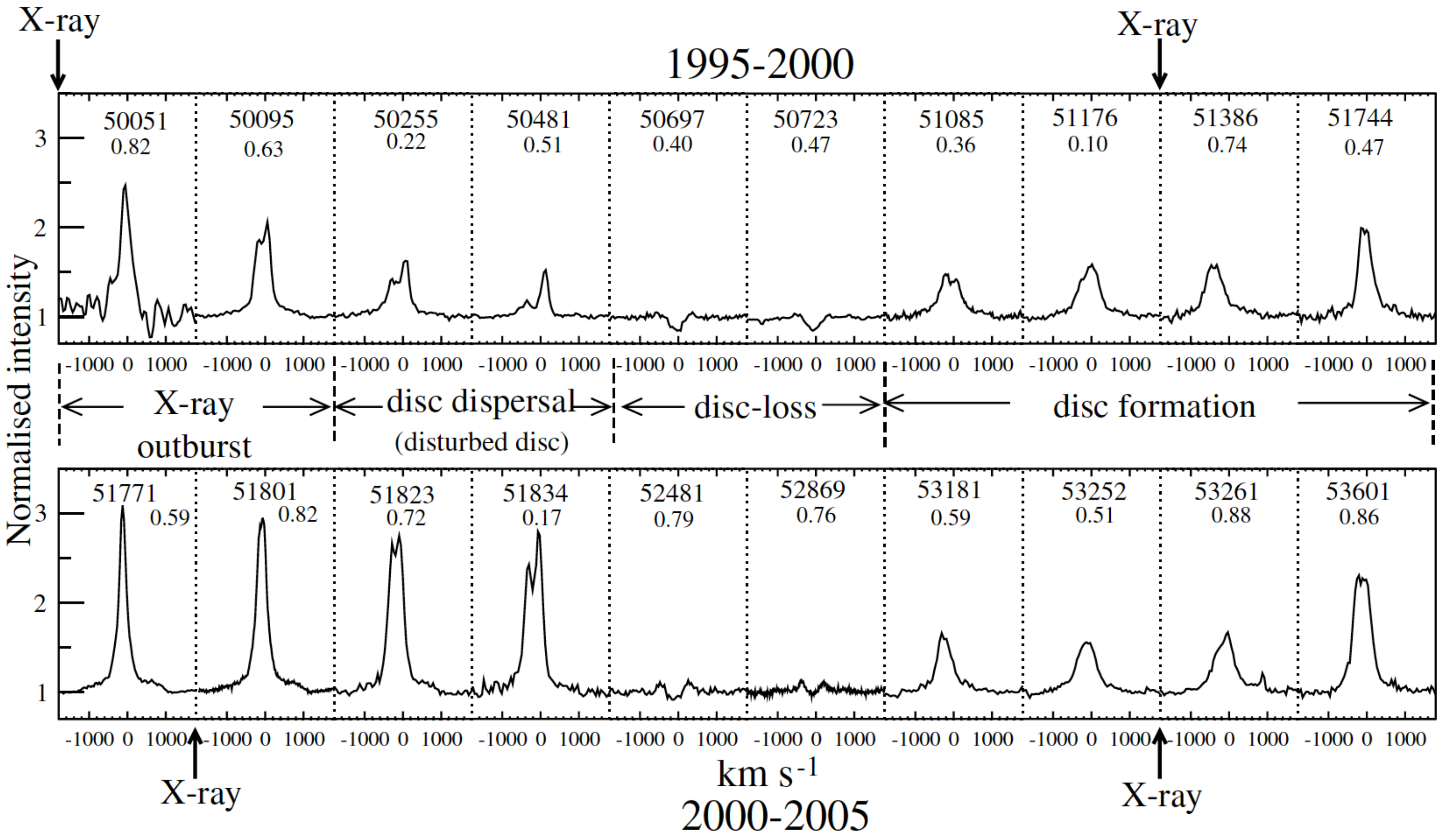


Fig. 2. Evolution of the Hα line profile over the ~5 year quasi-cycle. The spectra were normalised to the neighbouring continuum and the wavelength converted to velocity units. Indicated are the MJD and orbital phase according to the orbital solution of Tamura et al. (1992). The *Y*-axis scale was left the same in all panels to facilitate comparison.

(Reig+ 2007)

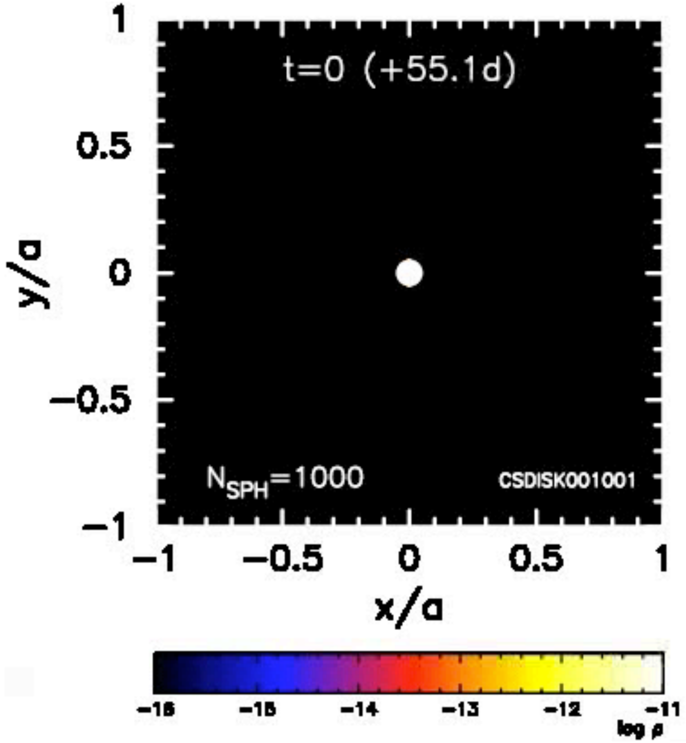
Summary of 4U 0115+634 simulations

- A new, self-regulated, disk evolution cycle is found in this moderately eccentric system:
  1. Disk eccentricity grows
  2. Tidal precession starts, providing NS to capture significantly larger amount of mass from disk for X-ray outbursts
  3. New disk forms and replaces old disk
- In this cycle, the Koza-Lidov mechanism plays a crucial role to trigger tidal precession and make room for new disk formation.

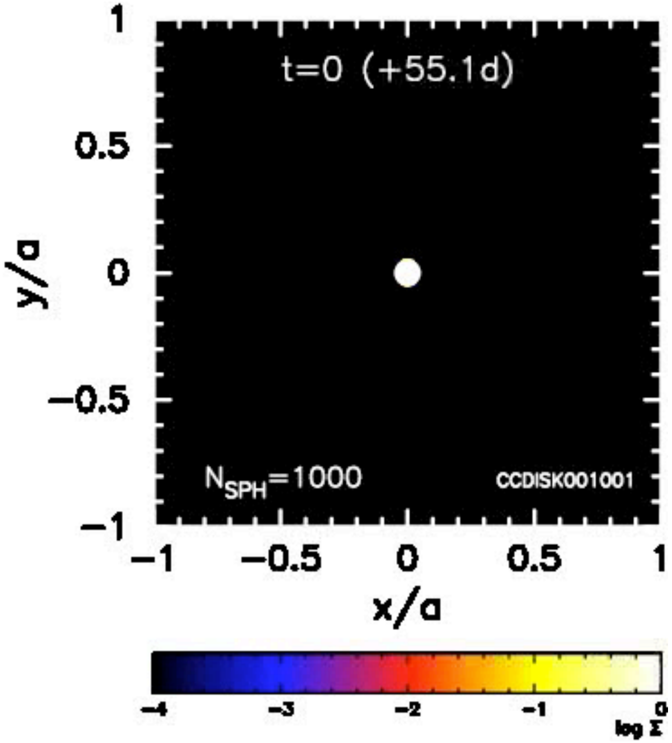
(2) A 0535+262

No disk tearing occurs in A0535+262 if constant mass ejection from star

Tidal torque is too weak compared to mass-addition torque



Density in orbital plane

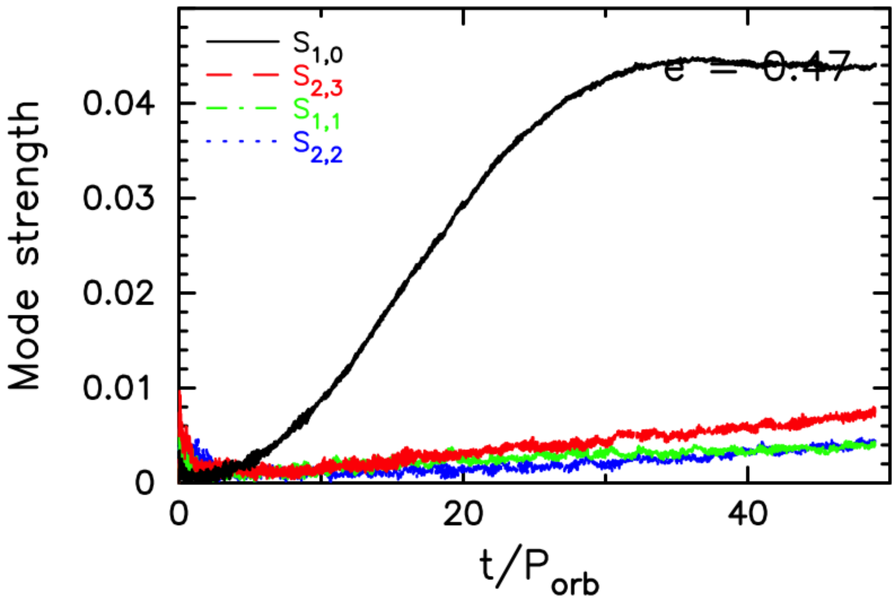


Column density along z-axis

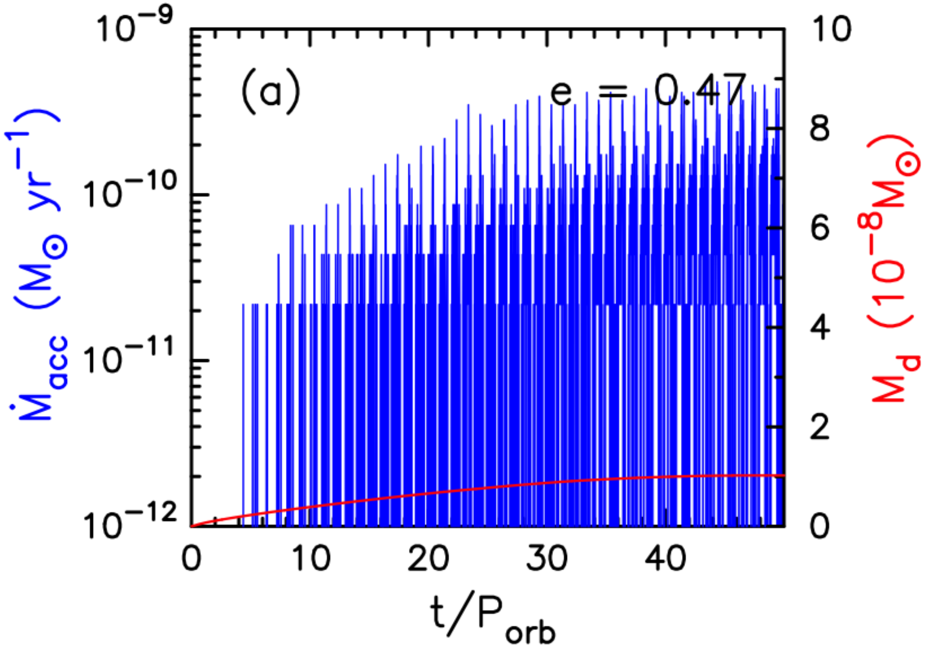
P_{orb}=110 d, e=0.47, i_{disk}=45 deg. about y-axis (=semi-minor axis)

Small disk eccentricity, small mass capture rate by NS

Disk eccetricity

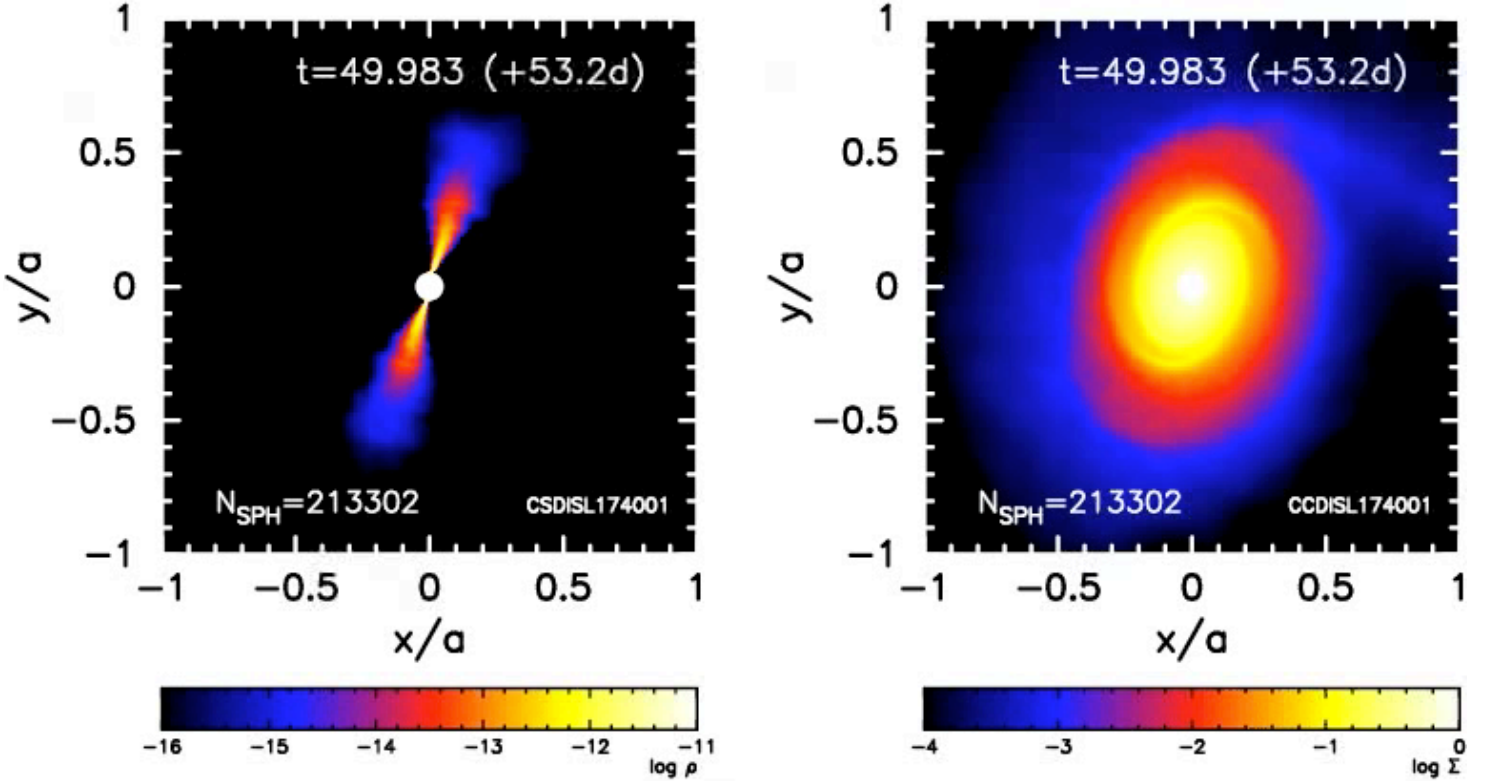


Mass capture rate



Disk tearing occurs in A0535+262 if mass ejection from star drops

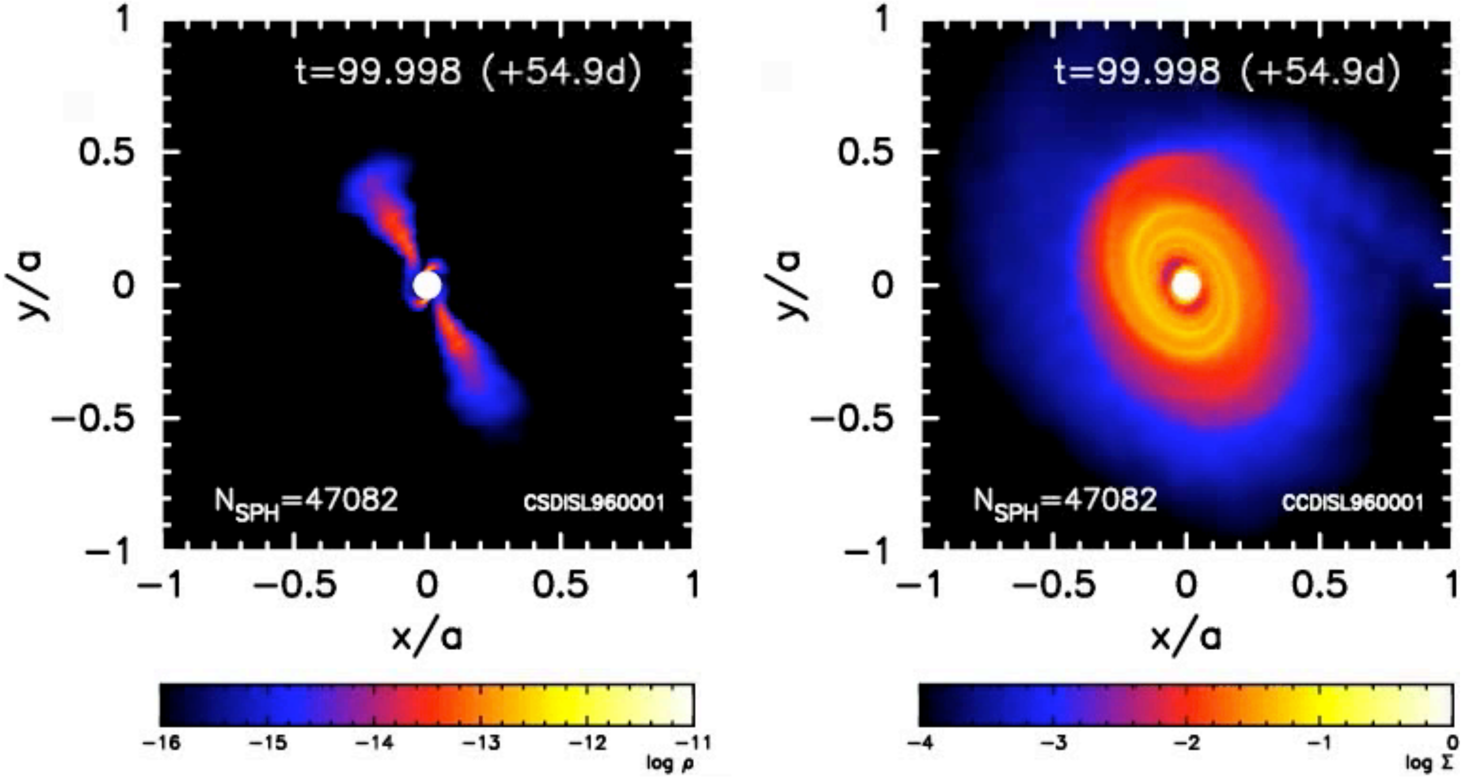
M_{dot} decreased by a factor of 2 for $t=50\text{-}100P_{orb}$



Sudden decrease in mass-ejection rate makes tidal torque relatively stronger

New disk forms in A0535+262 once mass ejection from star recovers

M_{dot} recovered $t=100P_{orb}$

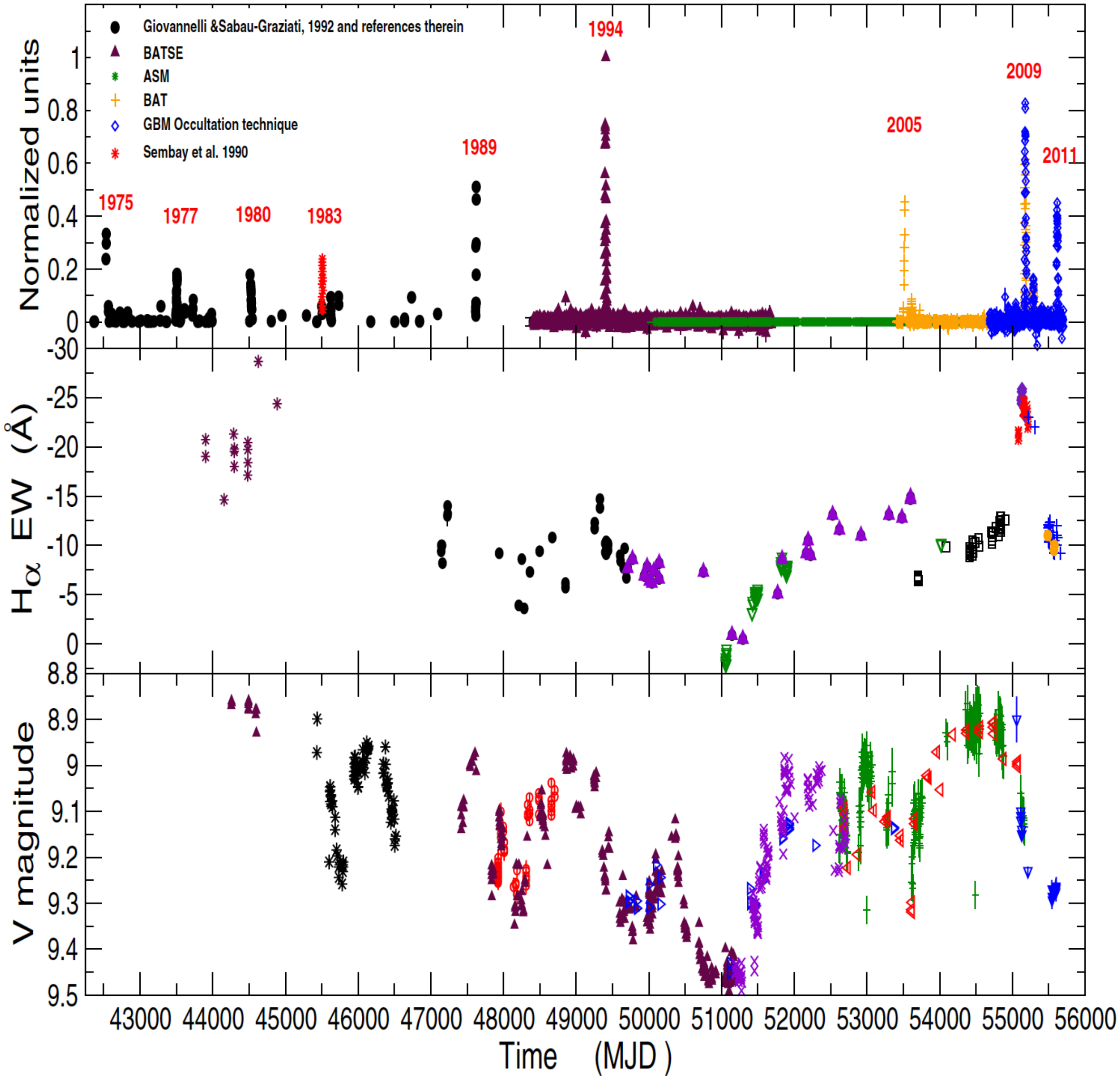


In this case, disk evolution cycle is controlled by stellar mass-ejection cycle

Summary of A 0535+262 simulations

- No cyclic disk evolution occurs in A0535+262 if mass-ejection rate from star is constant.
- But, if mass ejection from star significantly decreases for some time and later recovers, it causes similar cyclic evolution and enhanced mass-capture rate by NS
- Such a cycle is not self-regulated. But, it explains the observational fact that emission from disk inner region starts decreasing long before a giant X-ray outburst occurs.

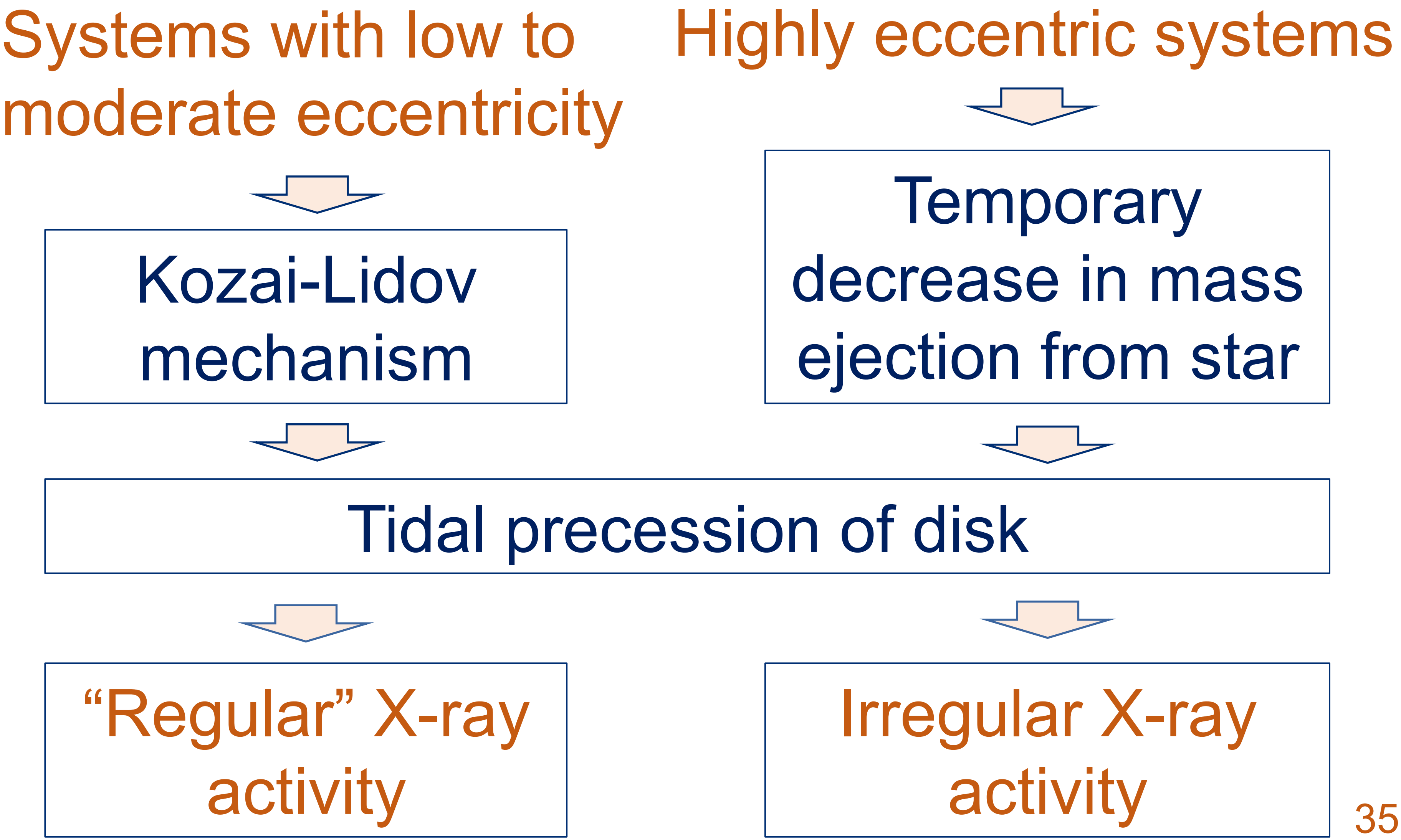
X-ray outbursts vs. optical emission strength in A 0535+262



(Camero-Arranz+ 2012)

4. Concluding remarks

Two different paths to giant X-ray outbursts in Be/X-ray binaries?



Systems with low to moderate eccentricity

Kozai-Lidov mechanism

Highly eccentric systems

Temporary decrease in mass ejection from star

Tidal precession of disk

“Regular” X-ray activity

Irregular X-ray activity