連星系・変光星研究会2020 (2021.1.30)

IW And型矮新星の光度変動の研究について、最近の進展

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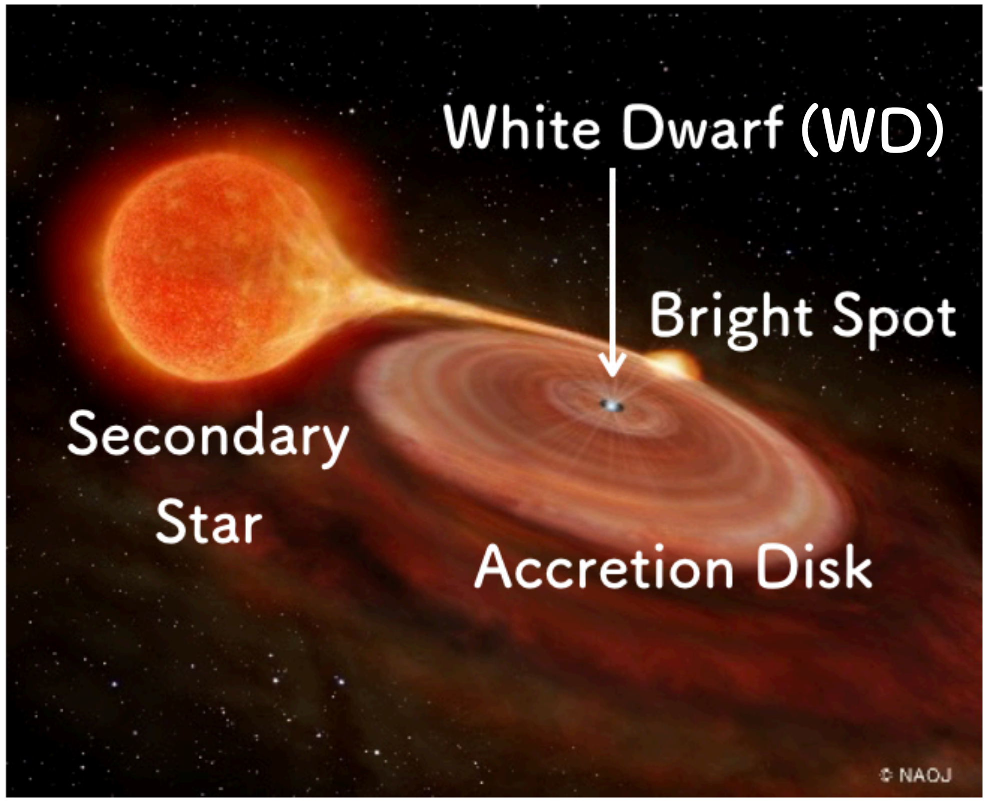
▸ Dwarf-nova outbursts

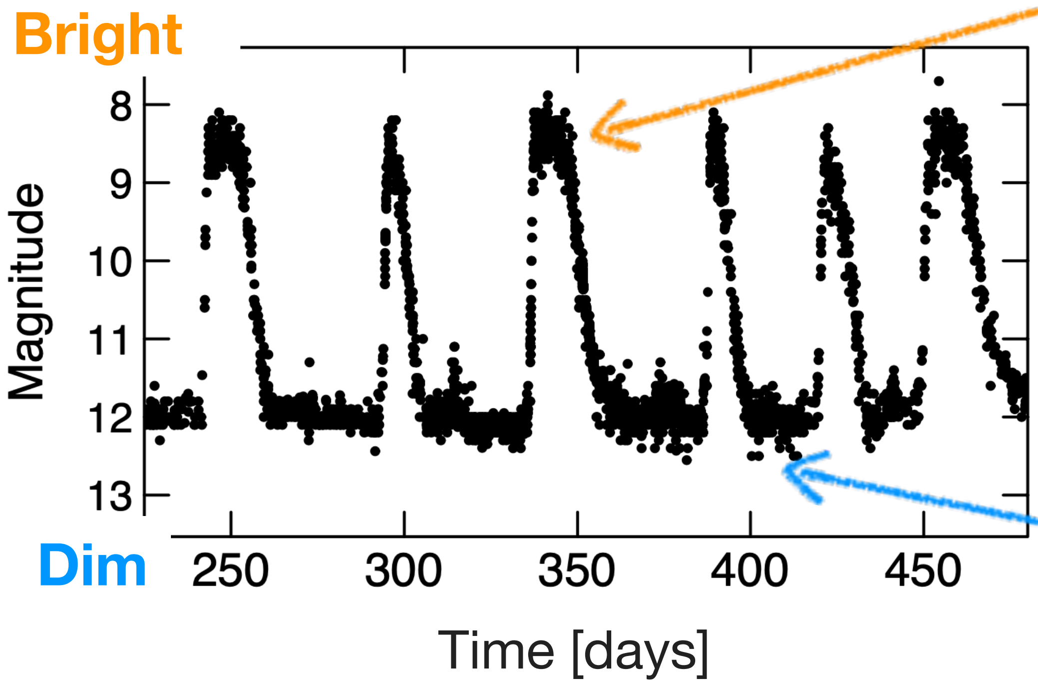
Outbursts = sudden brightening of the disk

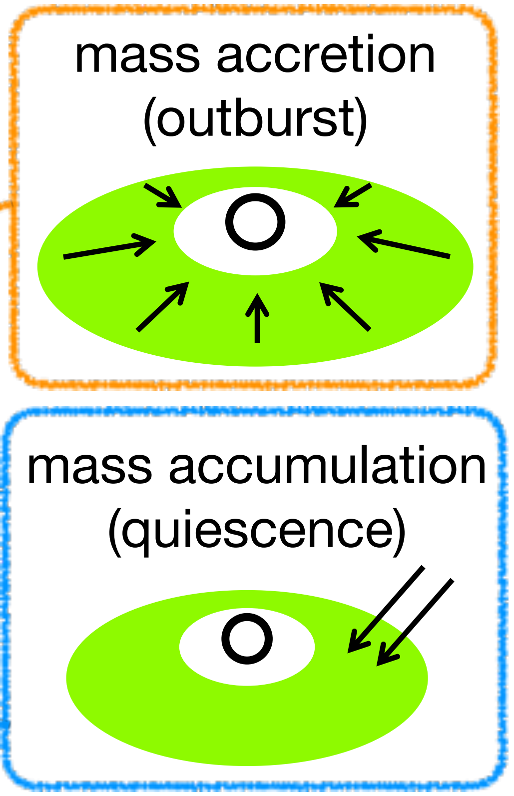
↑

The thermal-viscous instability in the disk

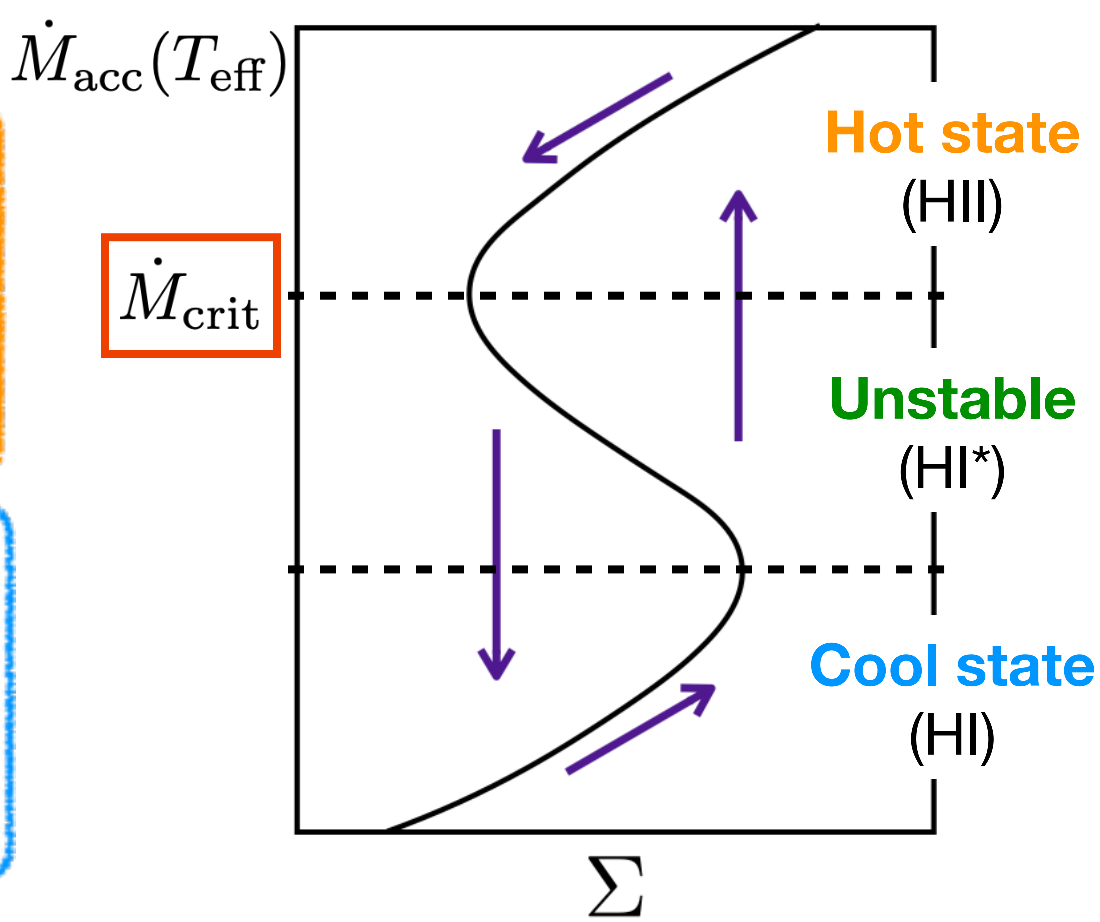
triggered by partial ionization of hydrogen







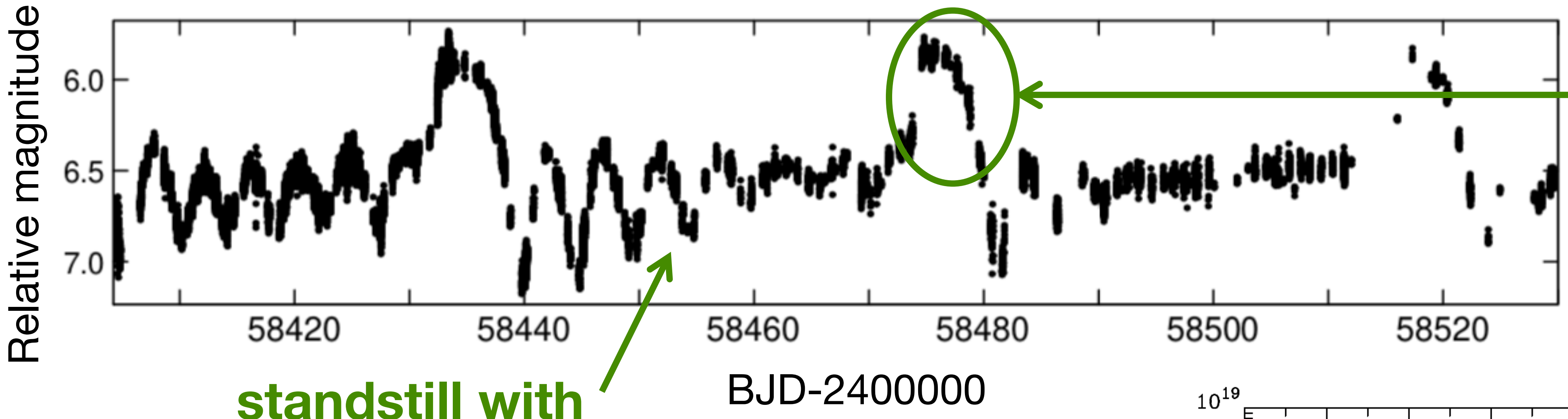
Thermal equilibrium curve



(e.g., Warner 1995; Osaki 1996; Osaki 2005)

▸ IW And-type phenomenon

The 2018 behavior in IM Eri (Kato et al. 2019)



Brightening

Anomalous
Z Cam stars

standstill with
damping oscillations

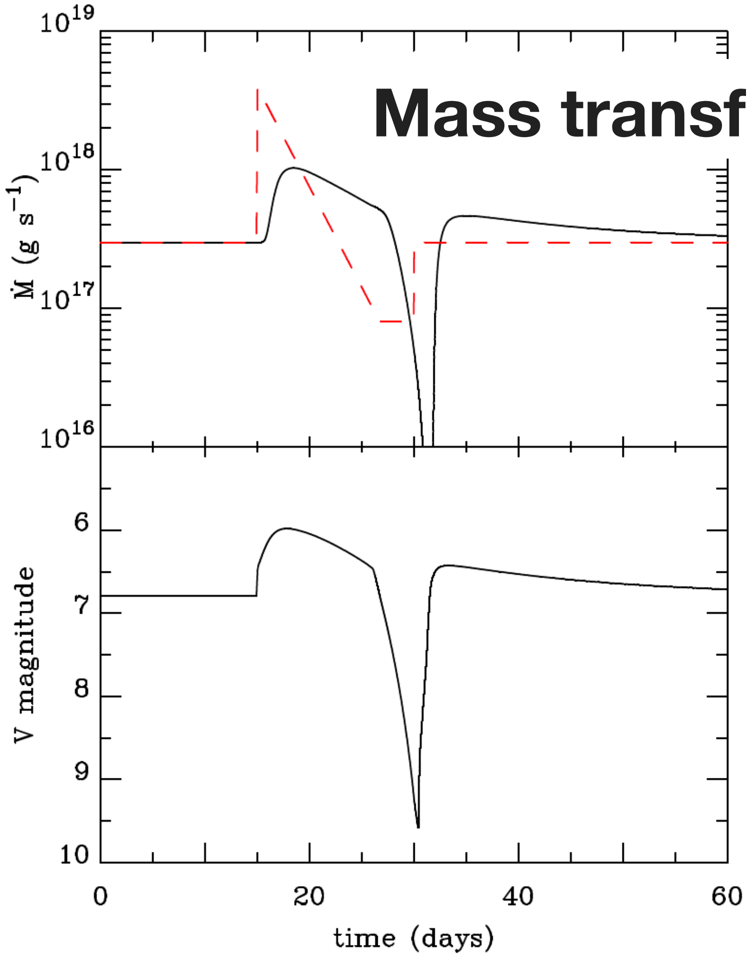
What is the origin of this light variability ?

Discovery of negative superhumps

⟶ **Tilted disks**

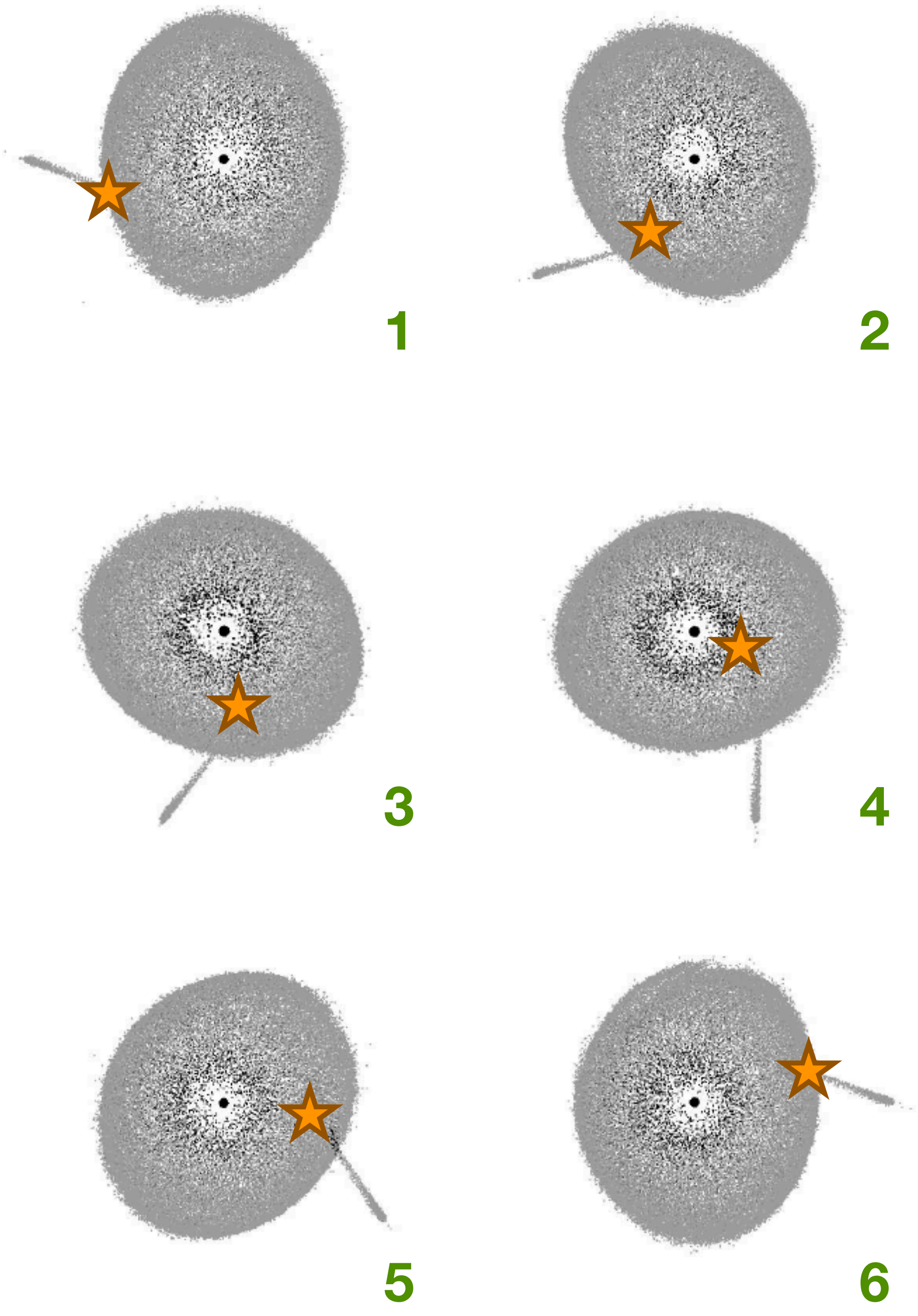
(Gies et al. 2013; Armstrong et al. 2013)

Mass transfer burst ?

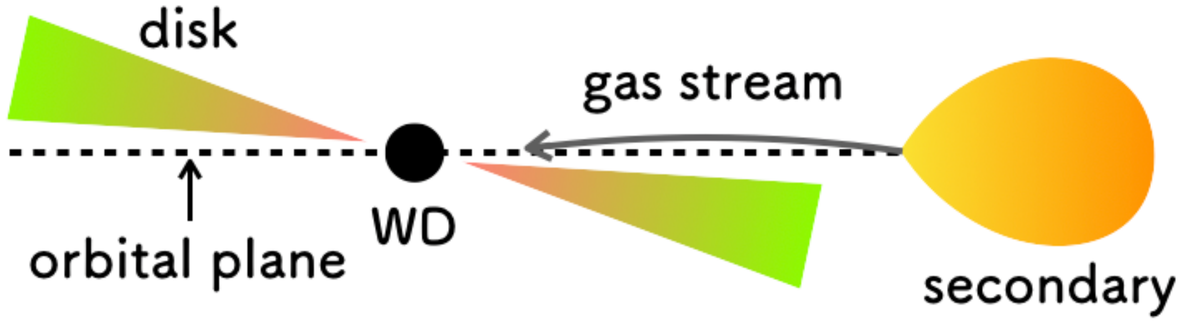


(Hameury & Lasota 2014)

‣ Tilted disks & negative superhumps



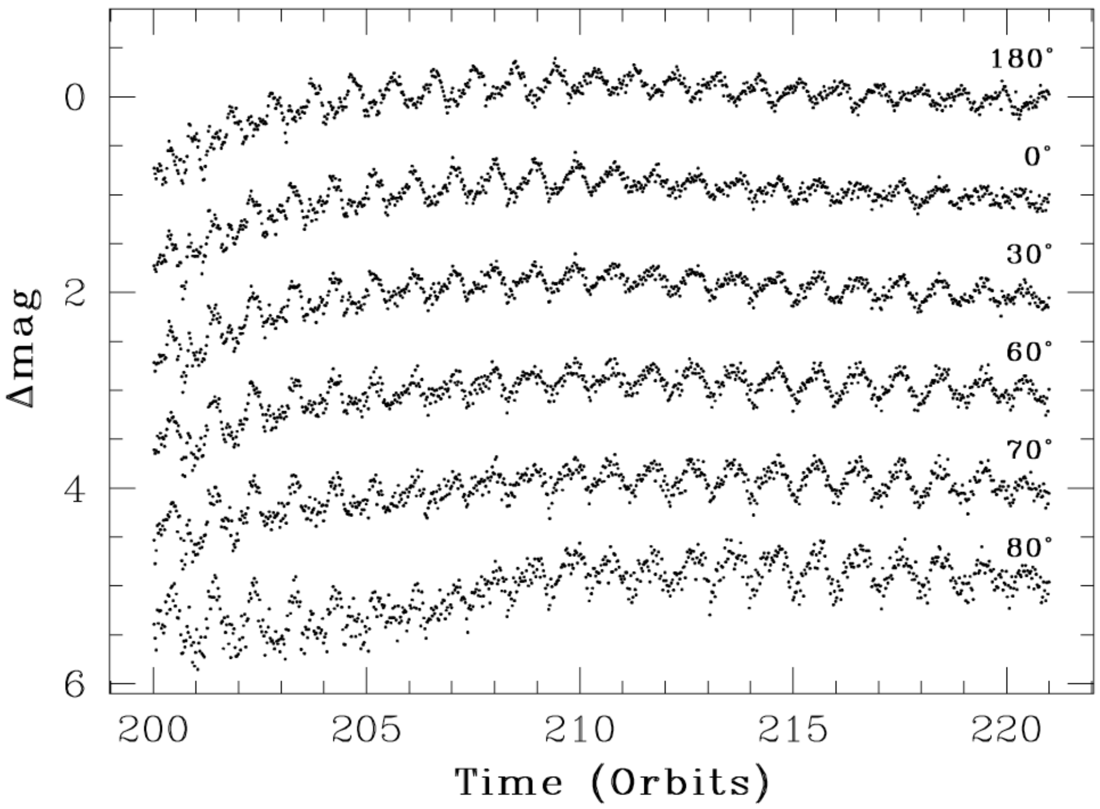
(Wood et al. 2000; Wood & Burke 2007)



The disk enters nodal & retrograde precession

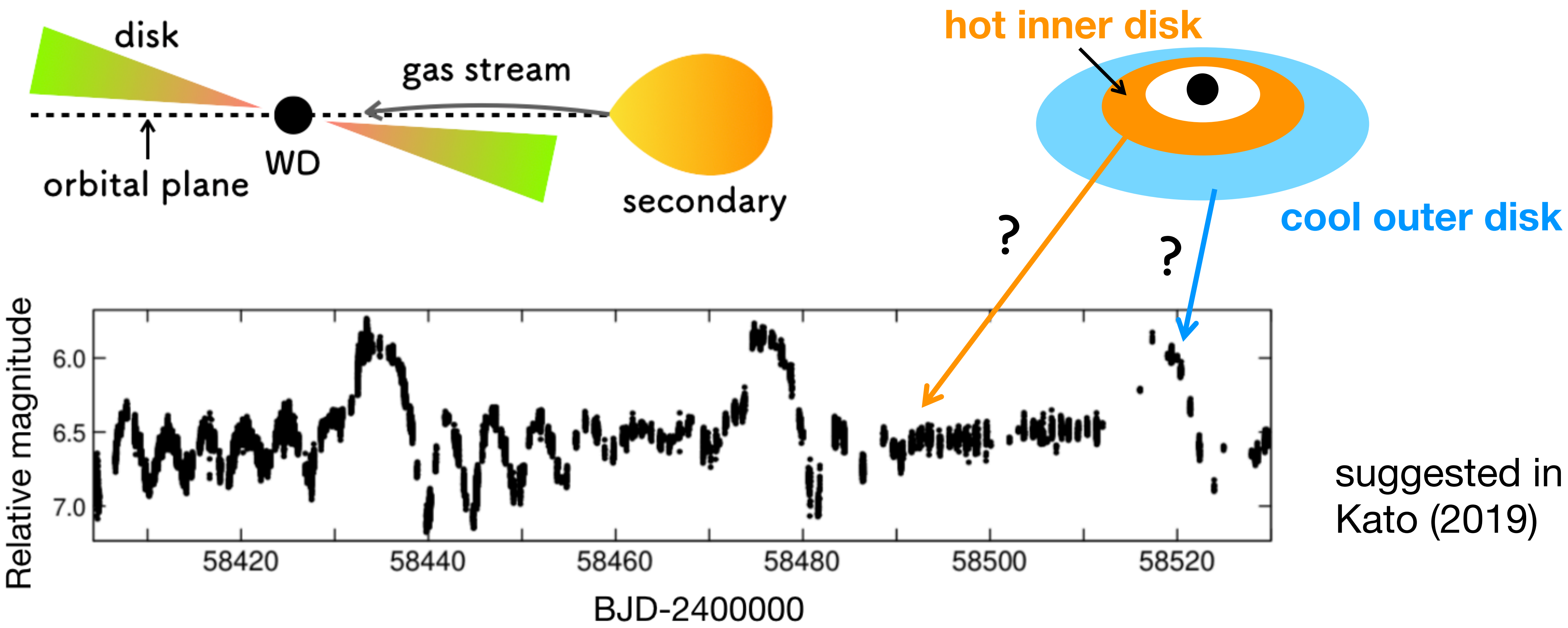
⟶ The bright spot moves with a period slightly shorter than the orbital period

⟶ Negative superhumps



‣ What happens in tilted disks ?

The gas stream from the secondary often flows into the inner disk. → Do tilted disks achieve the hot inner disk & cool outer disk ?



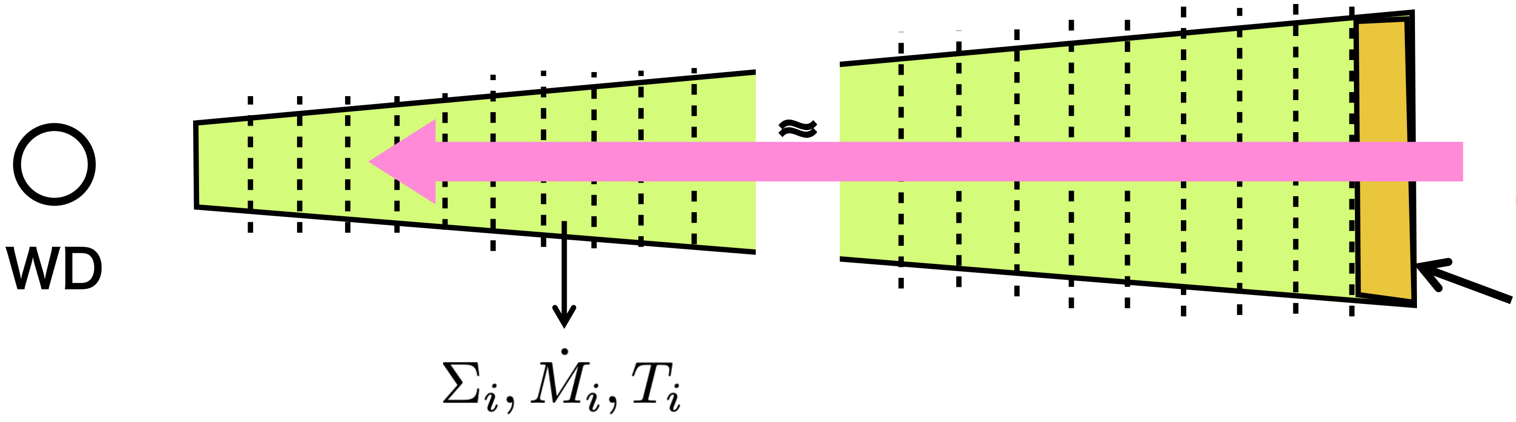
suggested in Kato (2019)

We examined this idea by numerical simulations of the disk instability.

▸ Numerical simulations

One-dimensional time-dependent viscous disk (Ichikawa & Osaki 1992)

Correct treatment of the conservation of angular momentum



mass input from the secondary (tilted disks)

Variable width of the outermost ring

(mass conservation) $\frac{\partial(2\pi r\Sigma)}{\partial t} = \frac{\partial \dot{M}}{\partial r} + \boxed{s}$ mass input rate from secondary

input angular momentum

(angular-momentum conservation) $\frac{\partial(2\pi r\Sigma h)}{\partial t} = \frac{\partial(\dot{M}h)}{\partial r} - \frac{\partial}{\partial r}(2\pi r^2 W) - \boxed{D} + \boxed{h_{\mathrm{LS}}\ s}$

tidal torque by secondary

(energy conservation)

thermal diffusion

$$C_{\mathrm{P}}\left[\frac{\partial}{\partial t}(2\pi r\Sigma T) - \boxed{\frac{\partial}{\partial r}(\dot{M}T)} - 2\pi\Sigma\nu_{\mathrm{th}}\frac{\partial(rF_{\mathrm{r}})}{\partial r} - \boxed{sT}\right] = 2\pi r(Q^+ - Q^-)$$

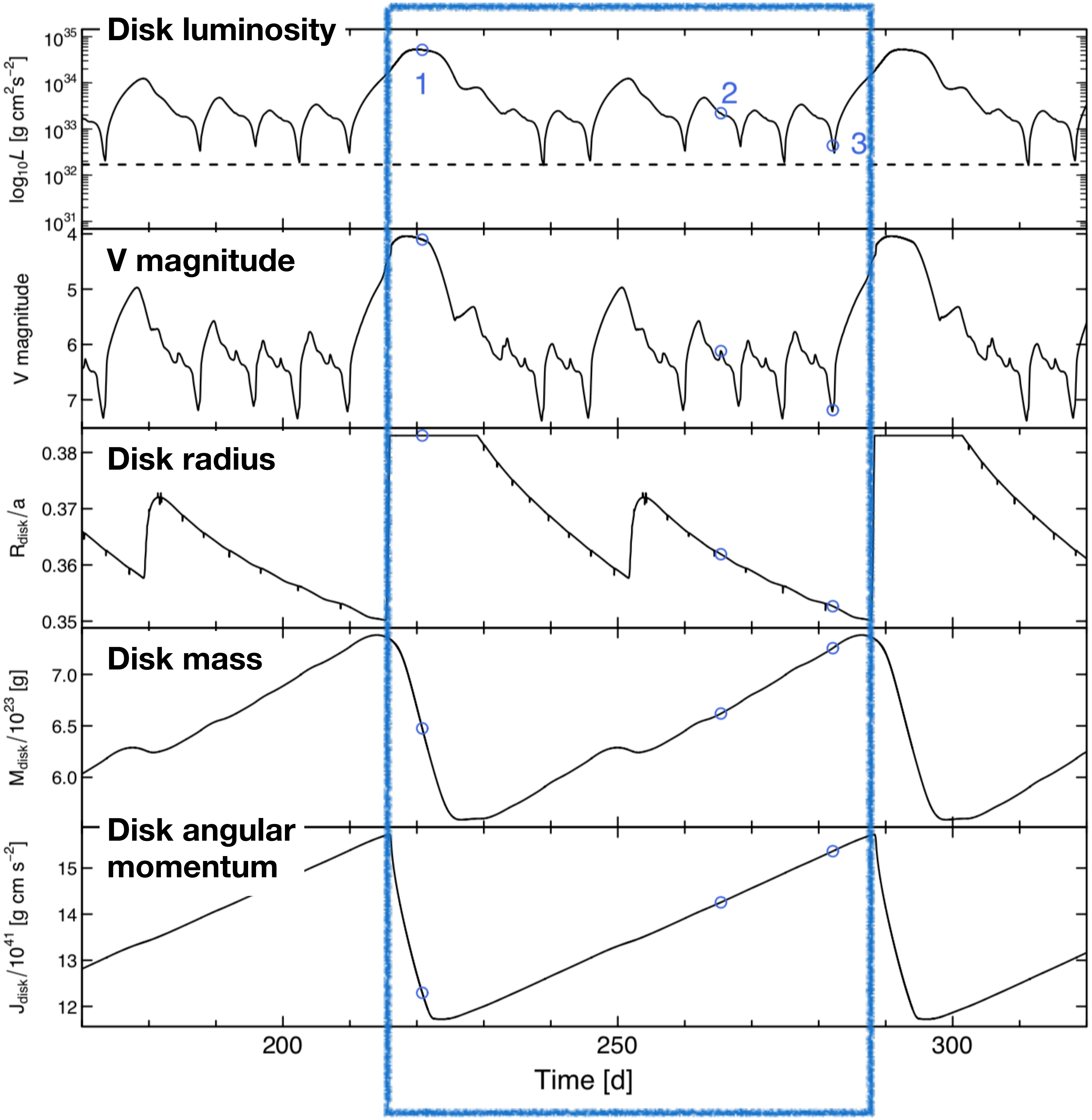
$$F_{\mathrm{r}} = \frac{\partial T}{\partial r}$$

advection heating

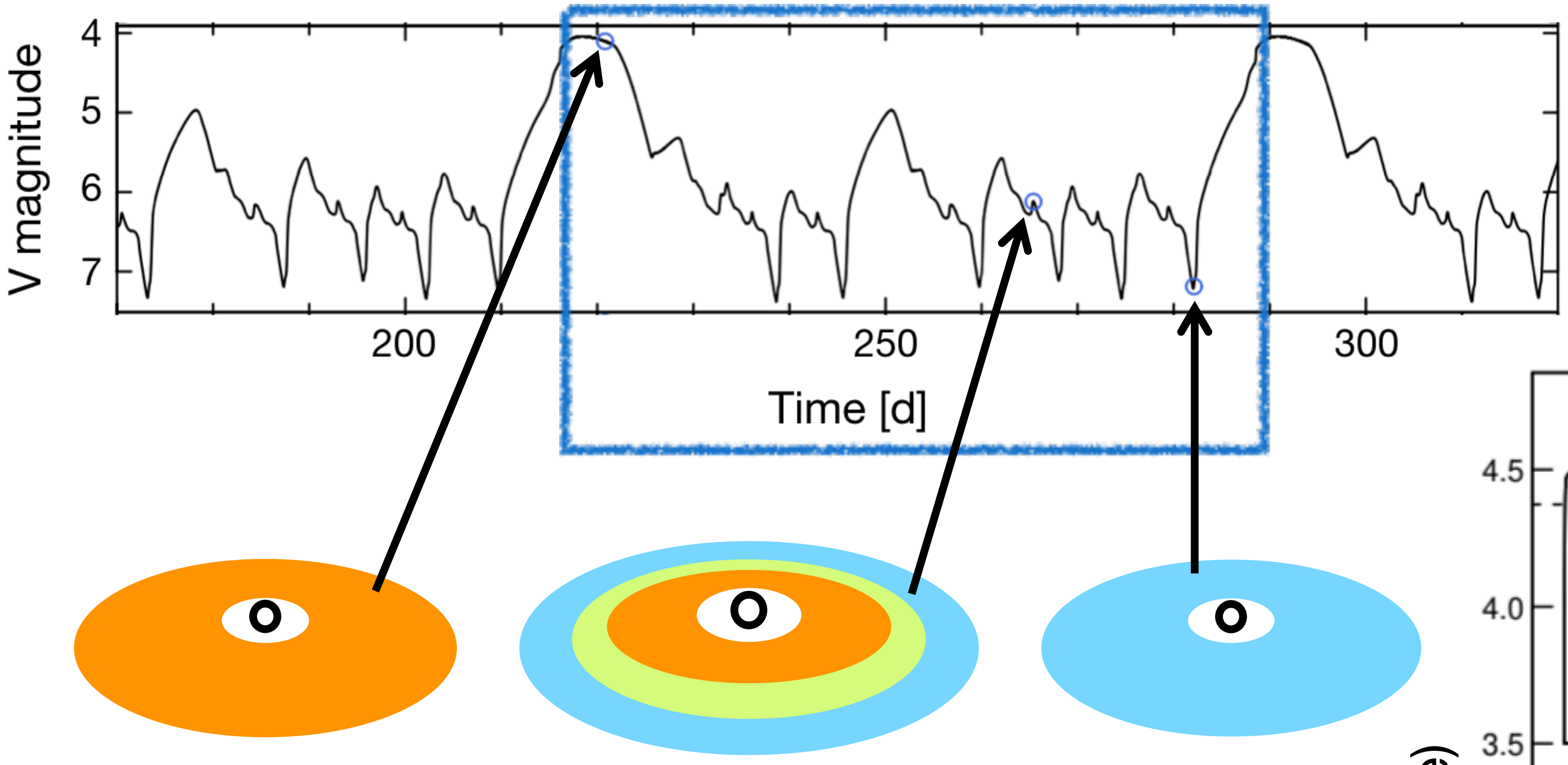
energy of mass input

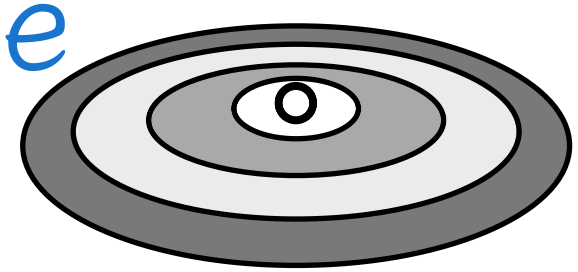
- # Results of moderate tilt case

$\dot{M}_{\rm tr} \sim \dot{M}_{\rm crit}$

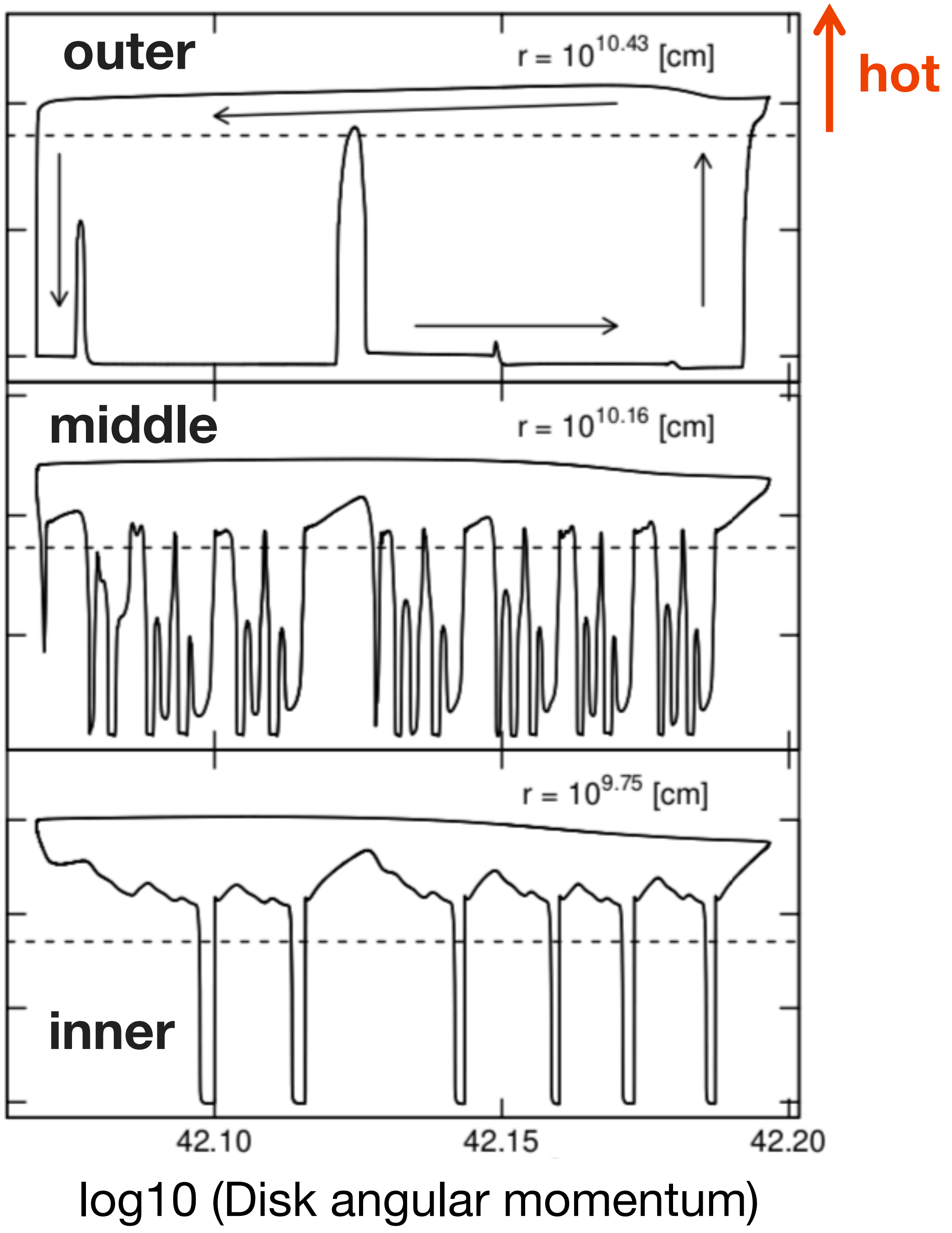


▸ Results of moderate tilt case





How many times each region goes to the hot state.



The entire disk is hot. ⟶ Brightening

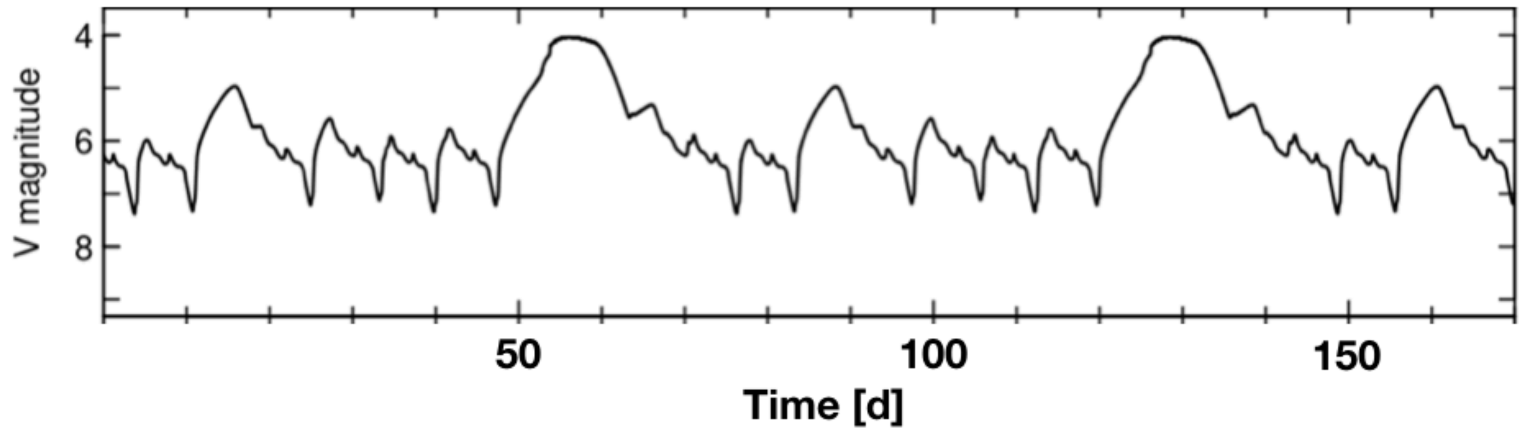
Only the inner disk is hot.

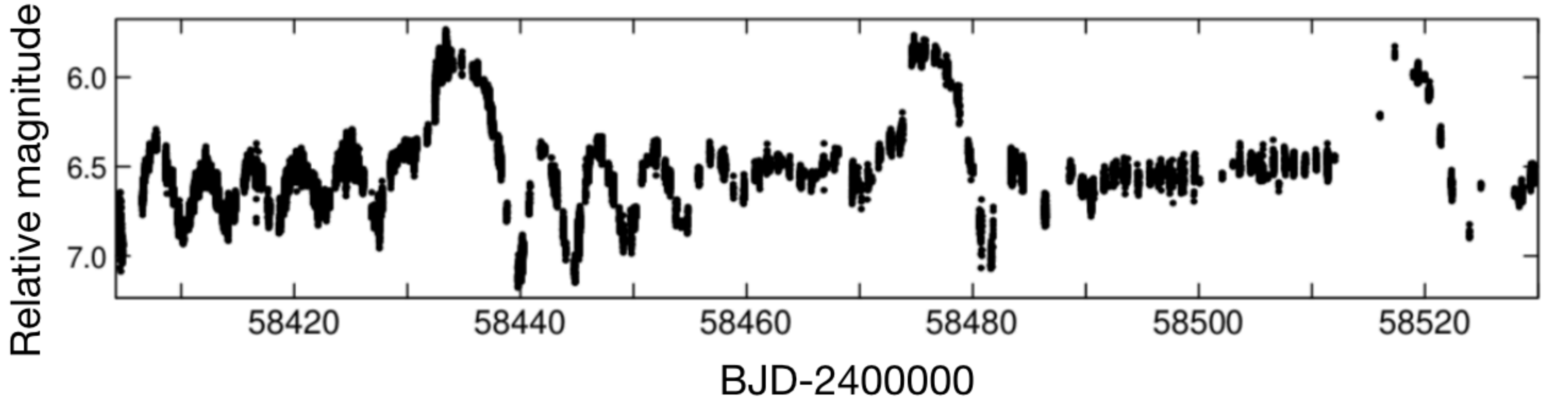
⟶ Mid-brightness interval

The entire disk is cool. ⟶ Dips

(Kimura, Osaki, Kato and Mineshige, 2020, PASJ, 72, 22)

▸ Observations vs. Simulations





Repetition of oscillations and brightening

↓

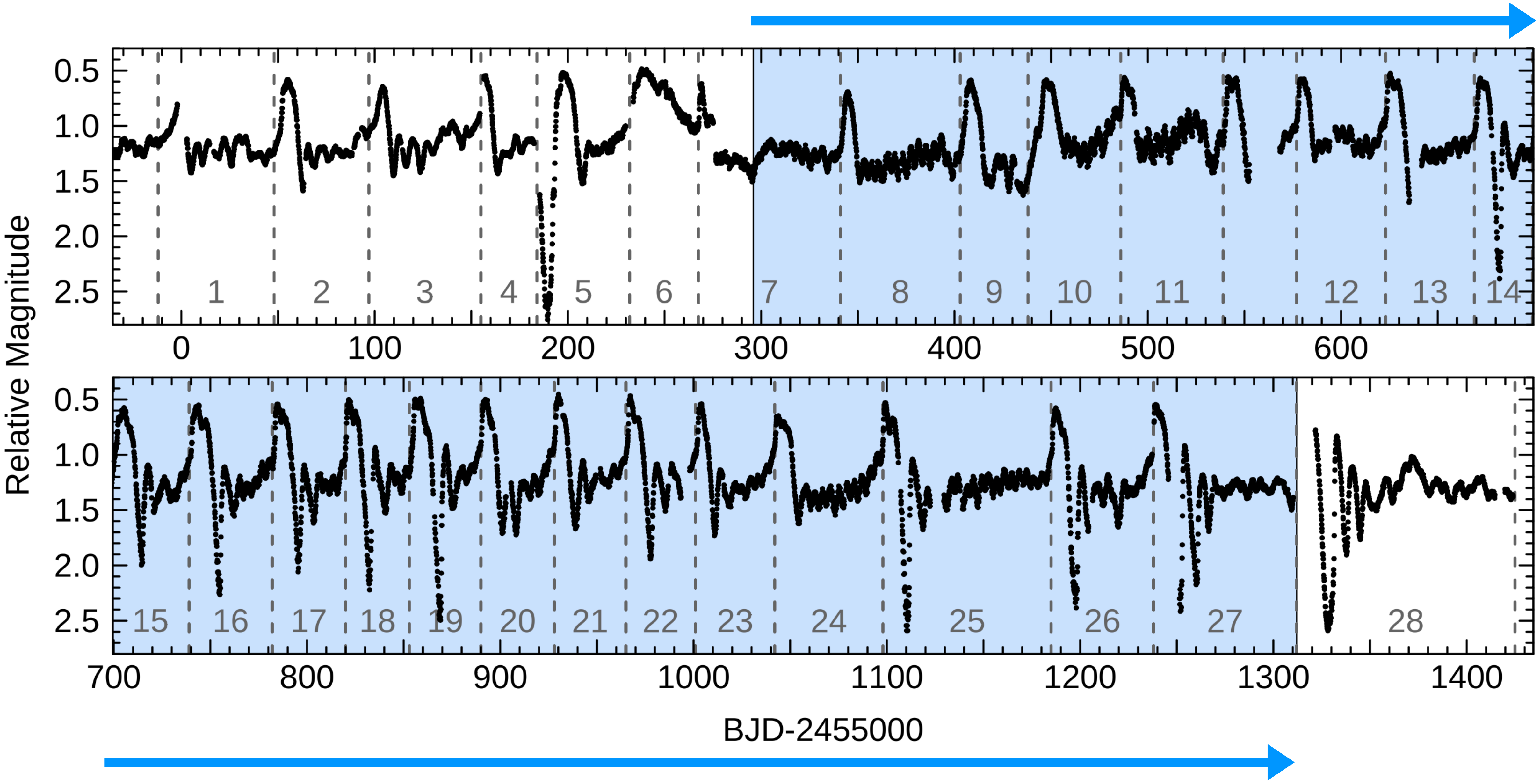
Reminiscent of IW And-type phenomenon

Thermal instability in tilted disks could explain IW And-type phenomenon.

- However, there is a gap between the observations and our results.
  - ✓ Luminosity dips soon after brightening
  - ✓ Small amplitudes
  - ✓ Z Cam-type standstills

‣ Observational study of an IW And star

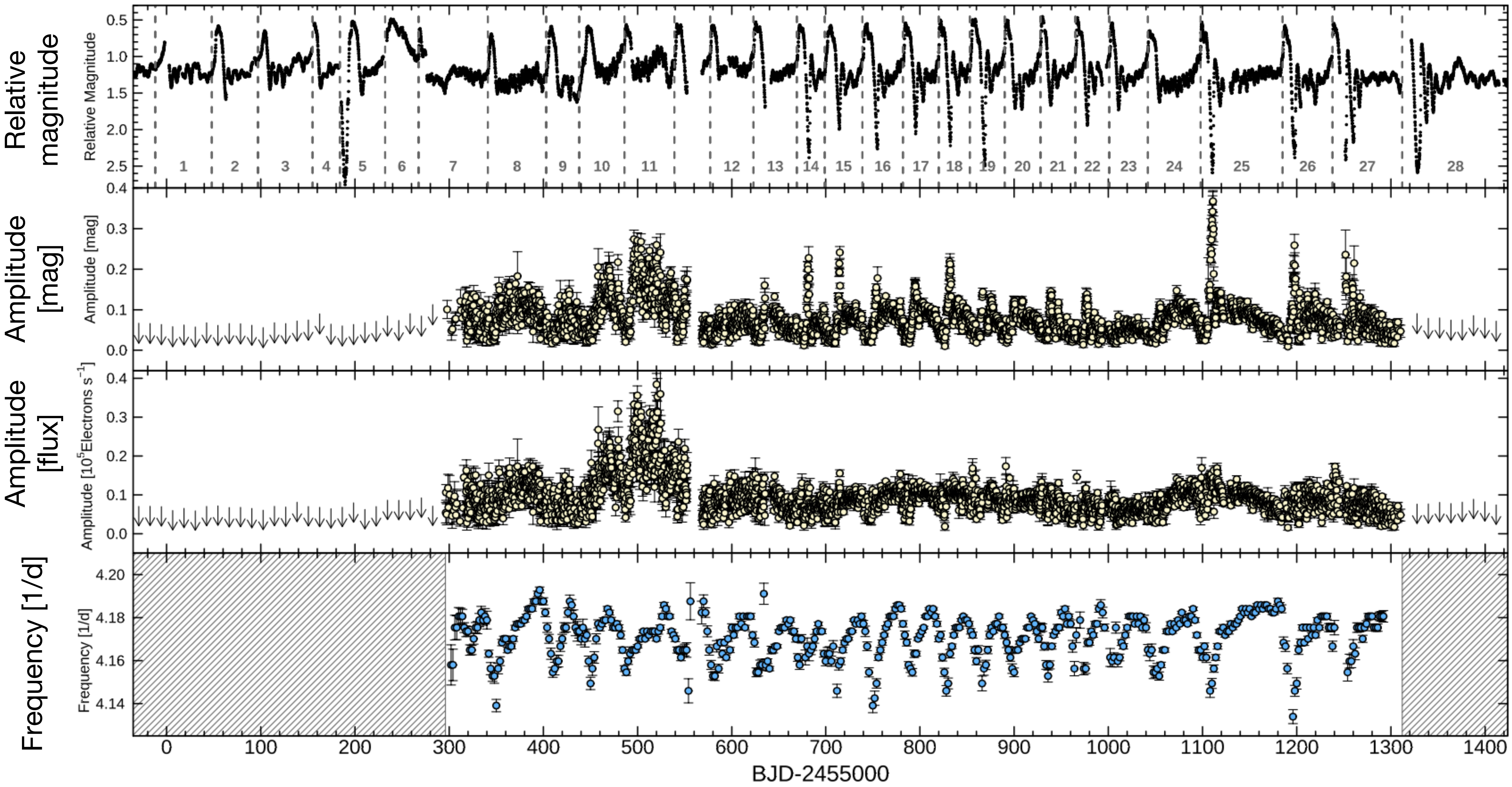
- KIC 9406652 observed by the Kepler satellite for ~1500 days (Gies et al. 2013)



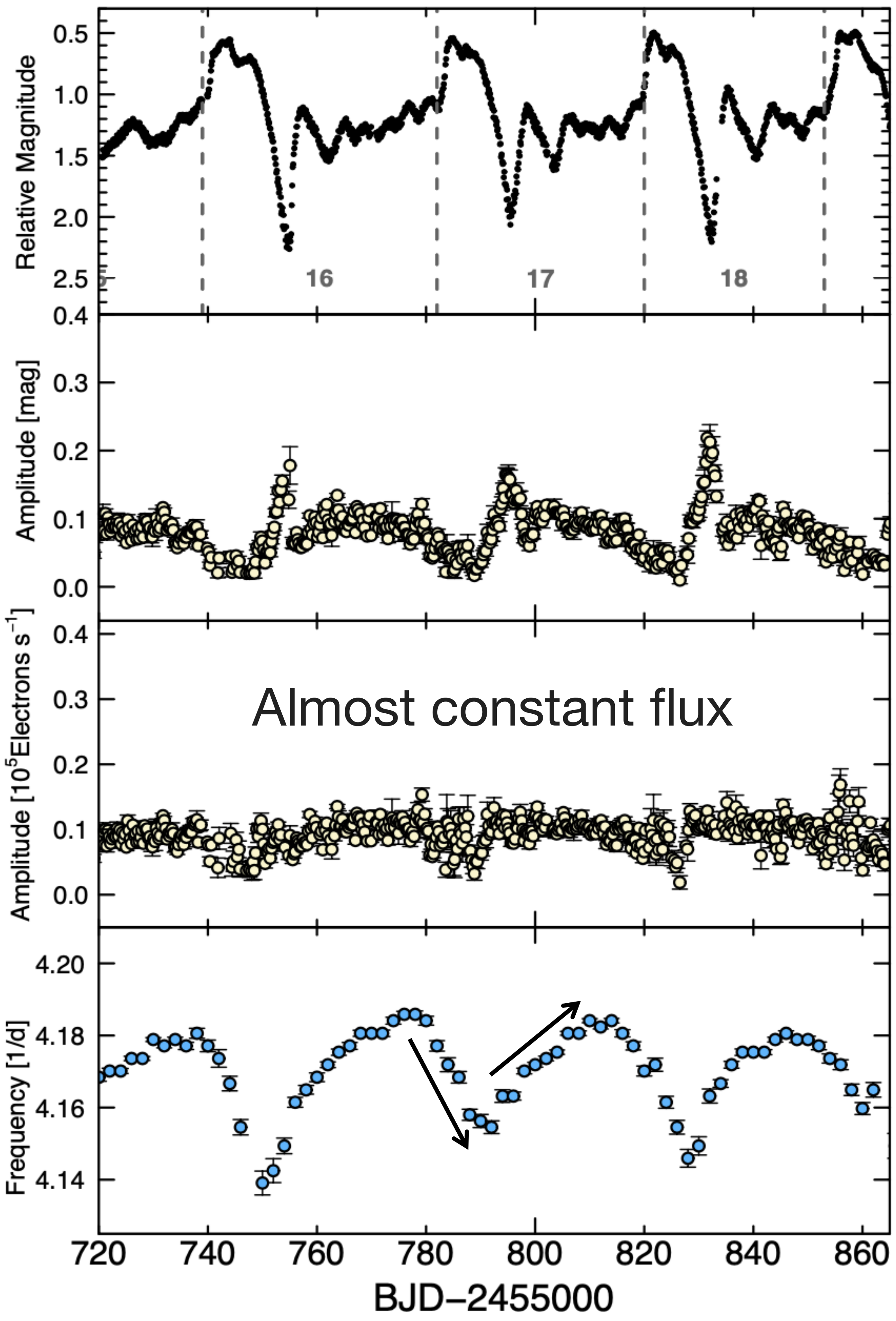
Negative superhumps

Let's investigate the nature of this tilted disk by NSH !

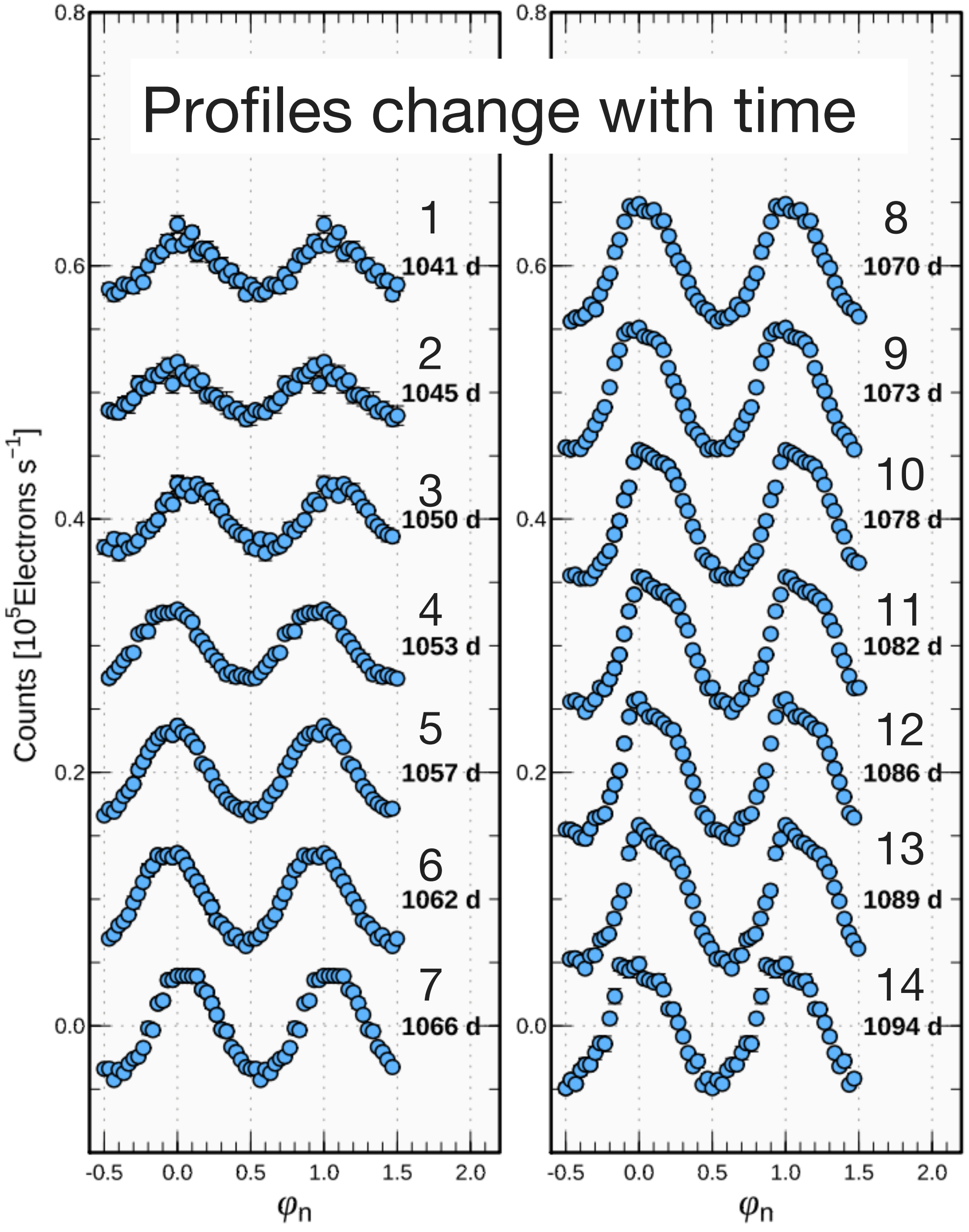
- Time evolution of negative superhumps



‣ Time evolution of negative superhumps



Almost constant flux



Profiles change with time

← Rapid decrease during brightening

&

Slow increase during quasi-standstills

▸ Gas-stream overflow in a slightly-tilted disk ?

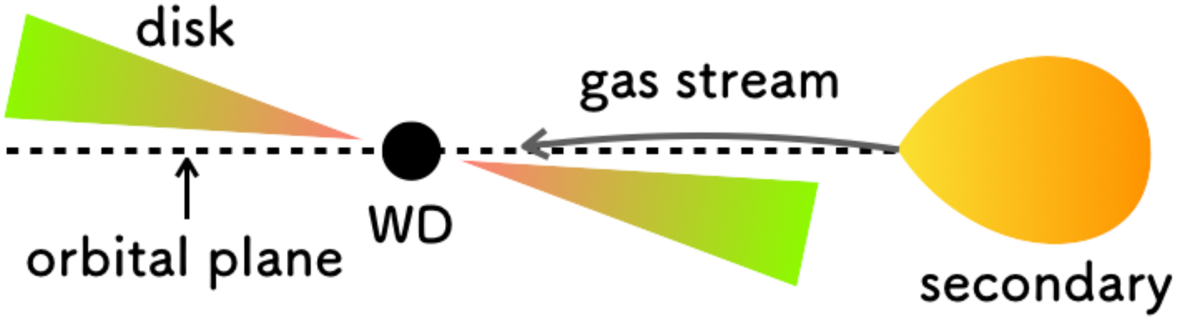
- The flux amplitude is almost constant.

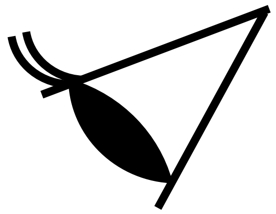
⟶ Rule out the mass-transfer burst model by Hameury & Lasota (2014)

- The light curve profile varies with time. (flat-top, triangular, sinusoidal waveforms)

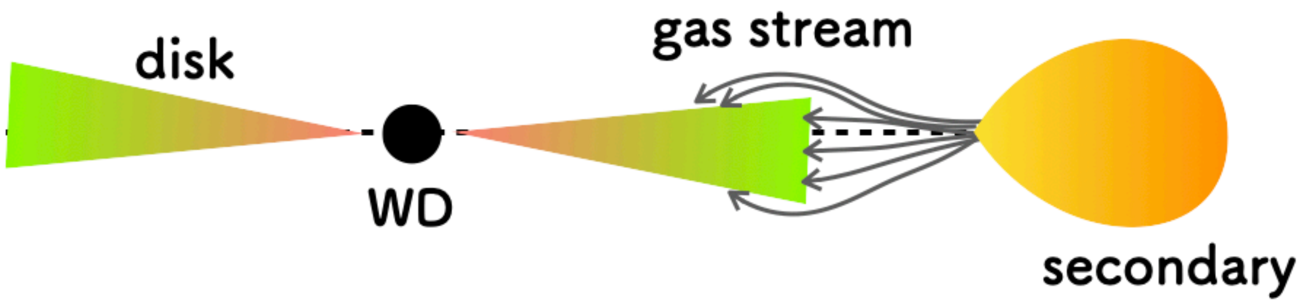
⟶
- **The tilt angle of the disk is small.**
- **The gas stream from the secondary star overflows the disk.**

✗ **Highly-tilted disk**





○ **Slightly-tilted disk**



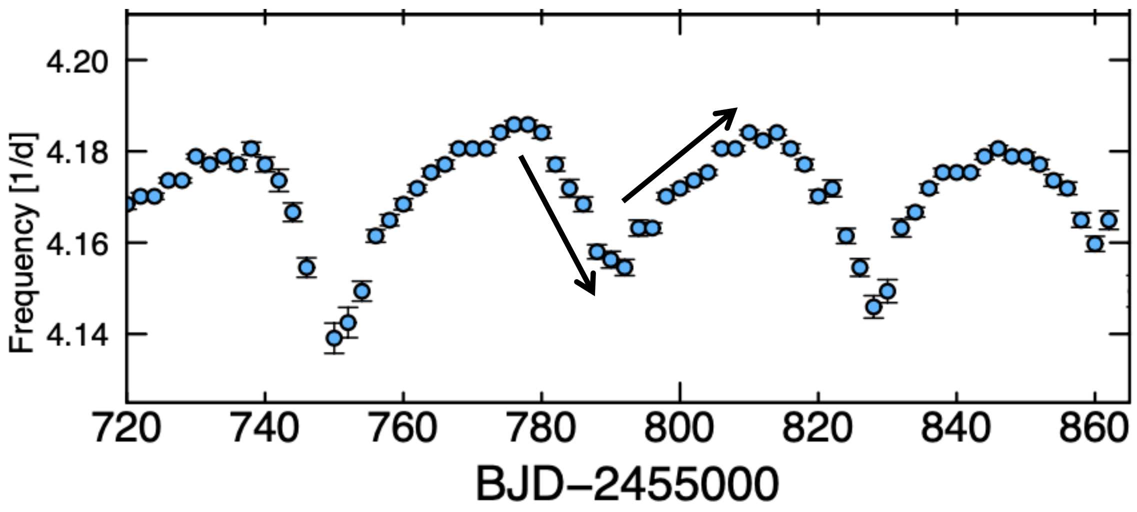
(Armitage & Livio 1998; Kunze et al. 2001)

Kimura et al. (2020) did not consider the gas-stream overflow.

▸ What does the frequency variation mean ?

- The frequency regularly varies per cycle of the IW And-type phenomenon.

1. Rapid decrease during brightening
2. Slow increase during quasi-standstills



$$\nu_{\rm NSH} = \nu_{\rm orb} + \underbrace{\boxed{\frac{3}{8\pi}\frac{\sqrt{GM_2}}{a^3\sqrt{M_1}}}}_{\text{Constant}} \frac{\int \Sigma r^3 dr}{\int \Sigma r^{3/2} dr} \overset{\text{Tilt angle}}{\underset{\sim 1}{\boxed{\cos\theta}}} \longleftarrow$$

Depends on the disk radius & radial mass distribution (Σ(r))

(Larwood 1998)

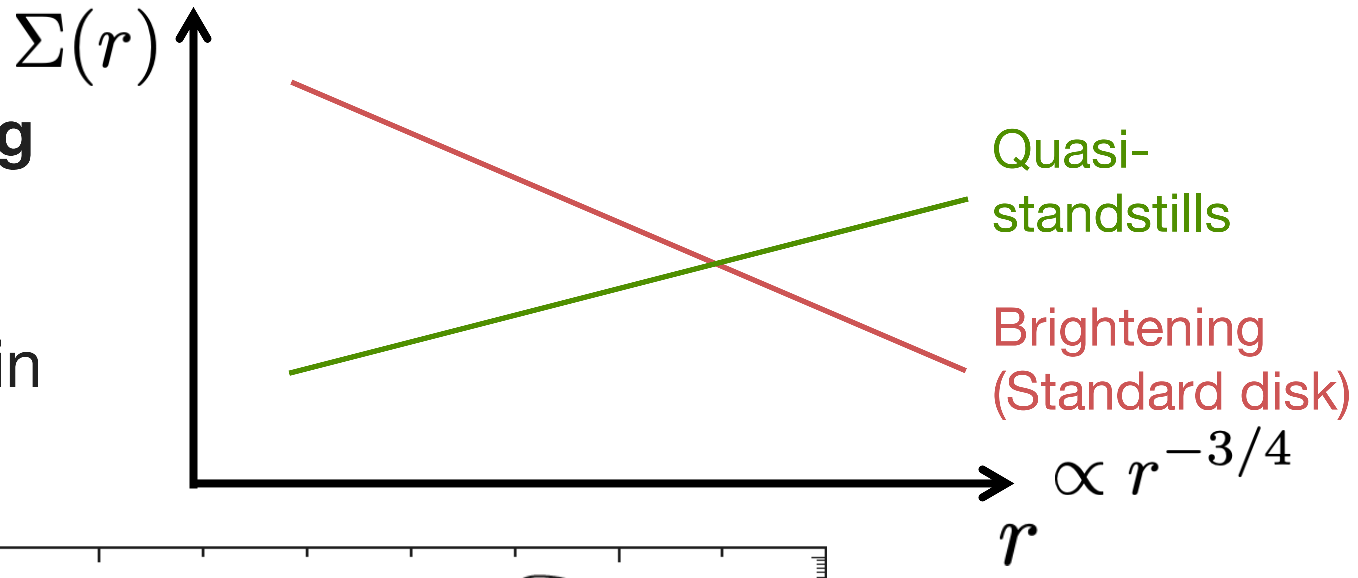
▸ What does the frequency variation mean ?

- The frequency regularly varies per cycle of the IW And-type phenomenon.

$$\nu_{\rm NSH} = \nu_{\rm orb} + \frac{3}{8\pi}\frac{\sqrt{G}M_2}{a^3\sqrt{M_1}}\frac{\int \Sigma r^3 dr}{\int \Sigma r^{3/2} dr}\cos\theta$$

← Depends on the disk radius & radial mass distribution (Σ(r))

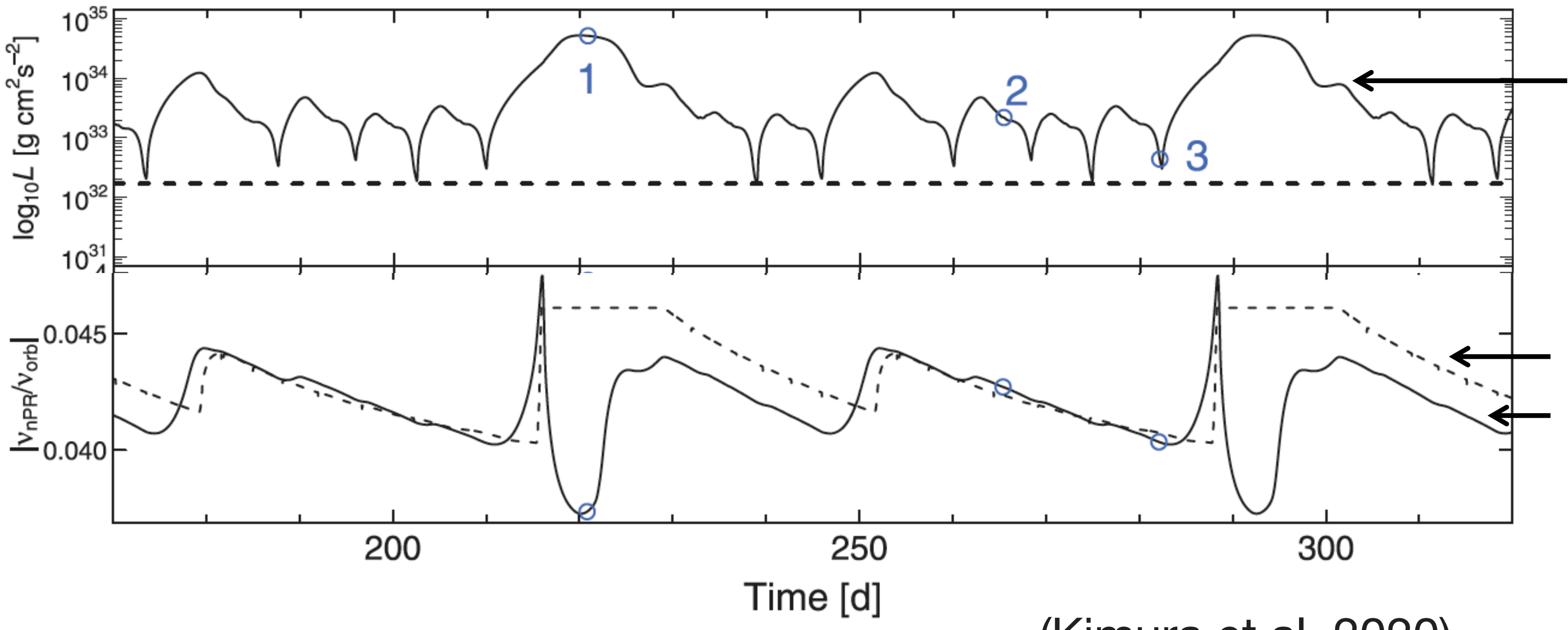
(Larwood 1998)



1. **Rapid decrease during brightening**

→ **Rapid change in Σ(r)**

Consistent with the prediction in Kimura et al. (2020)



← Light curves

← Disk radius

← Frequency

(Kimura et al. 2020)

▸ What does the frequency variation mean ?

- The frequency regularly varies per cycle of the IW And-type phenomenon.

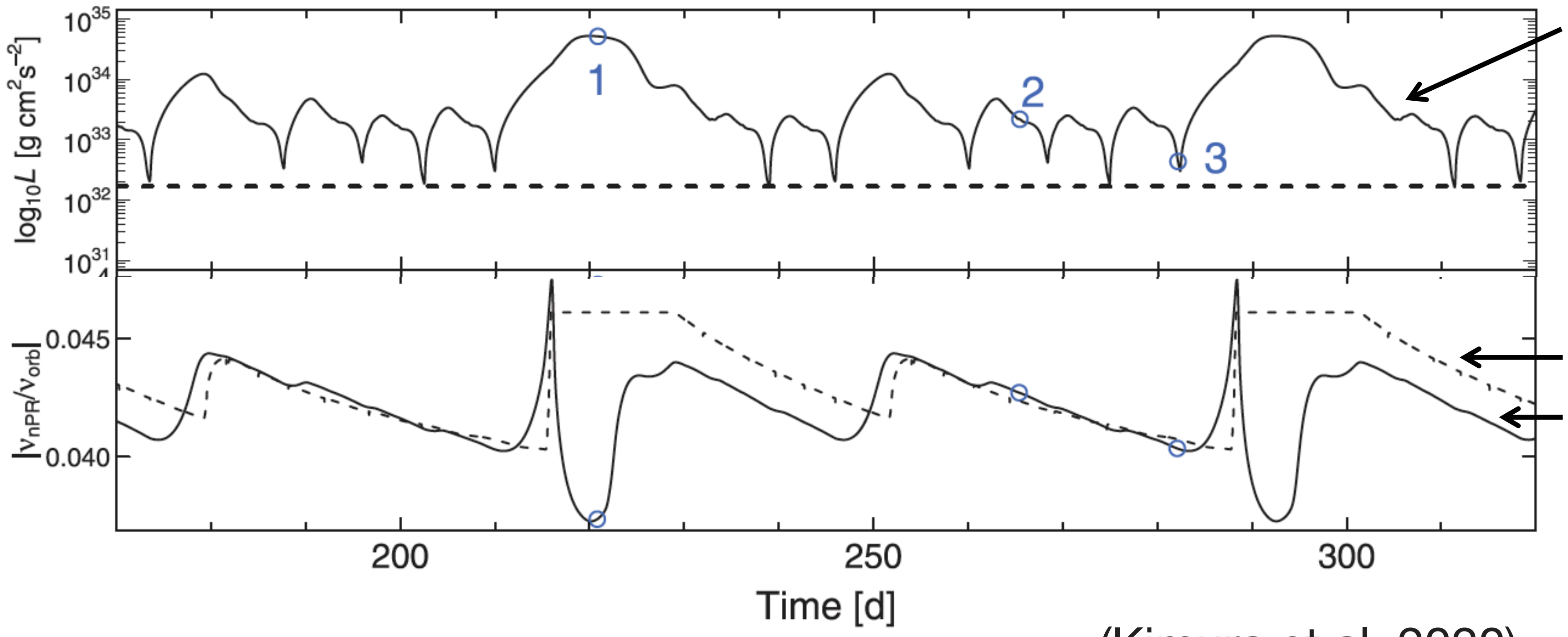
$$\nu_{\mathrm{NSH}} = \nu_{\mathrm{orb}} + \frac{3}{8\pi}\frac{\sqrt{G}M_2}{a^3\sqrt{M_1}}\frac{\int \Sigma r^3 dr}{\int \Sigma r^{3/2} dr}\cos\theta \longleftarrow$$

Depends on the disk radius & radial mass distribution (Σ(r))

(Larwood 1998)

2. Slow increase during quasi-standstills

The model in Kimura et al. (2020) cannot explain this variation ..



Light curves

The disk slowly expands ?

Disk radius

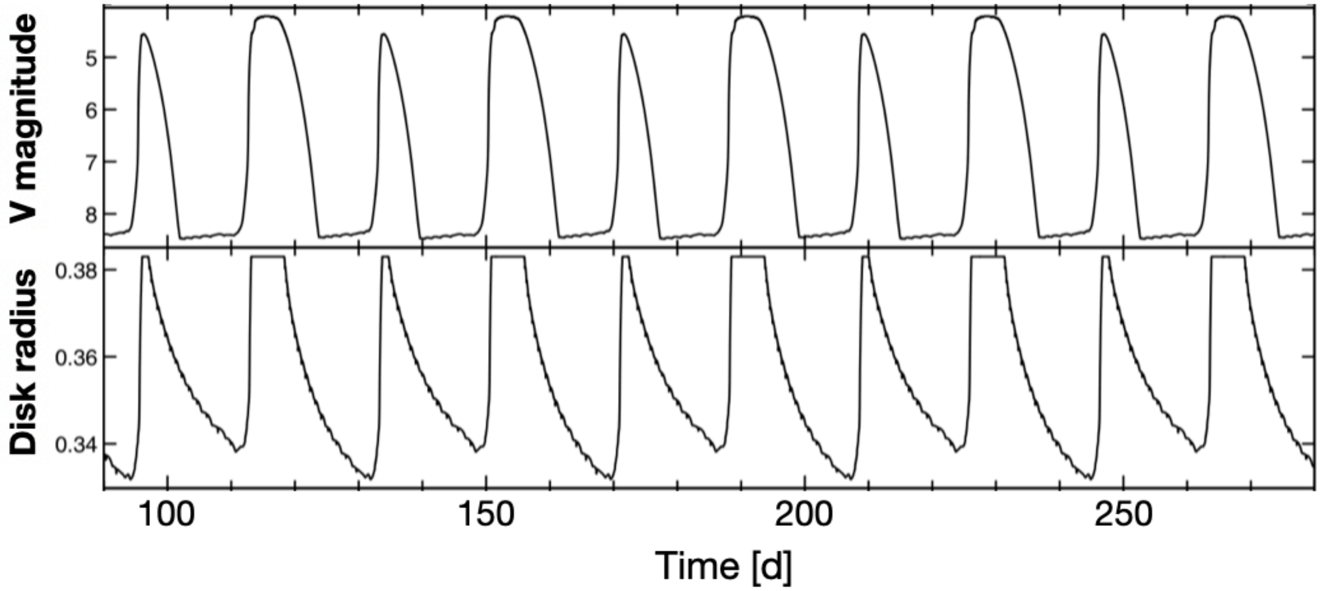
Frequency

(Kimura et al. 2020)

▸ Slow expansion of the disk radius ?

- It is hard to reproduce the gradual expansion of the disk radius by simulations of the thermal instability ..

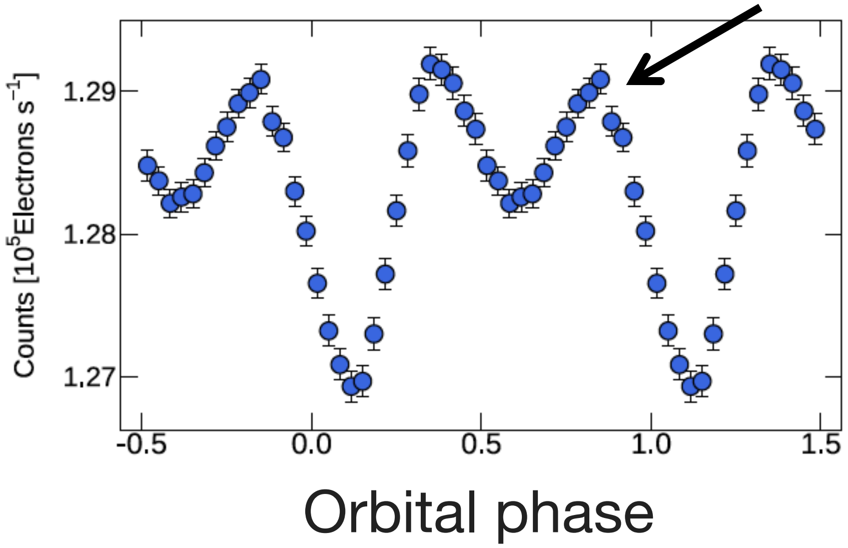
  1. If the outer disk is in the cool state, the disk slowly shrinks.
  2. If the outer disk is in the hot state, the disk radius expands rapidly.



- The outer disk may be not in the hot state in quasi-standstills ?

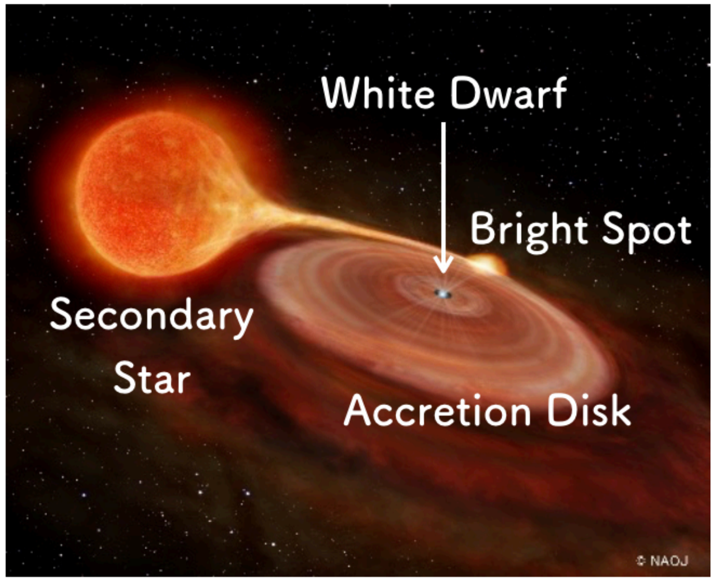
Quasi-standstills

Orbital hump by the bright spot at the disk outer rim



- Irradiation + orbital hump

$$T_{\rm eff} < 10,000 - 15,000 \ {\rm K}$$



(Kimura, Osaki and Kato, 2020, PASJ, 72, 94)

▸ Summary

- We proposed one possible model for IW And-type phenomenon by numerical simulations. **The thermal-viscous instability in the tilted disk**
- We obtained supportive and unsupportive results for that model by optical data analyses of KIC 9406652.

  Slowly expanding disk radius in quasi-standstills cannot be explained.

  Gas-stream overflow should be included.

Future works

- Improve the simulation work by dealing with the gas-stream overflow
- Find more IW And stars by long-term optical monitoring
- Investigate the time evolution of the disk radius and the temperature distribution (Shibata-kun's presentation)