矮新星の多波長観測が拓くサイエンス：SS Cygの可視光・X線の同時観測を例にとって

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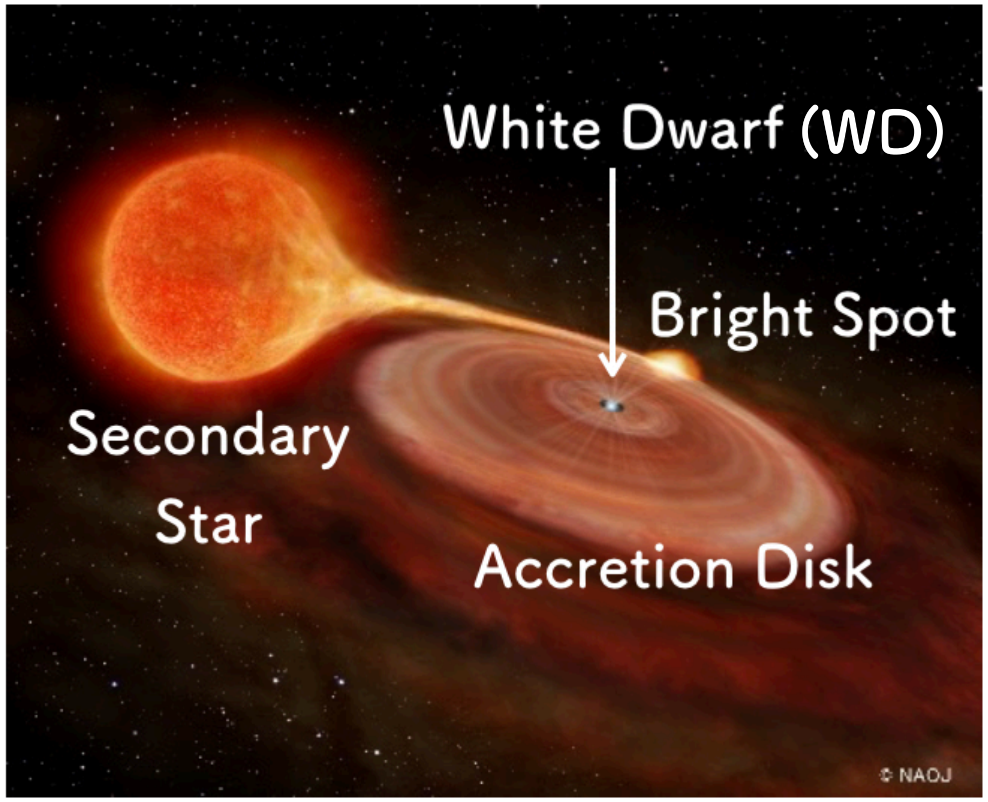
Dwarf novae & their outbursts



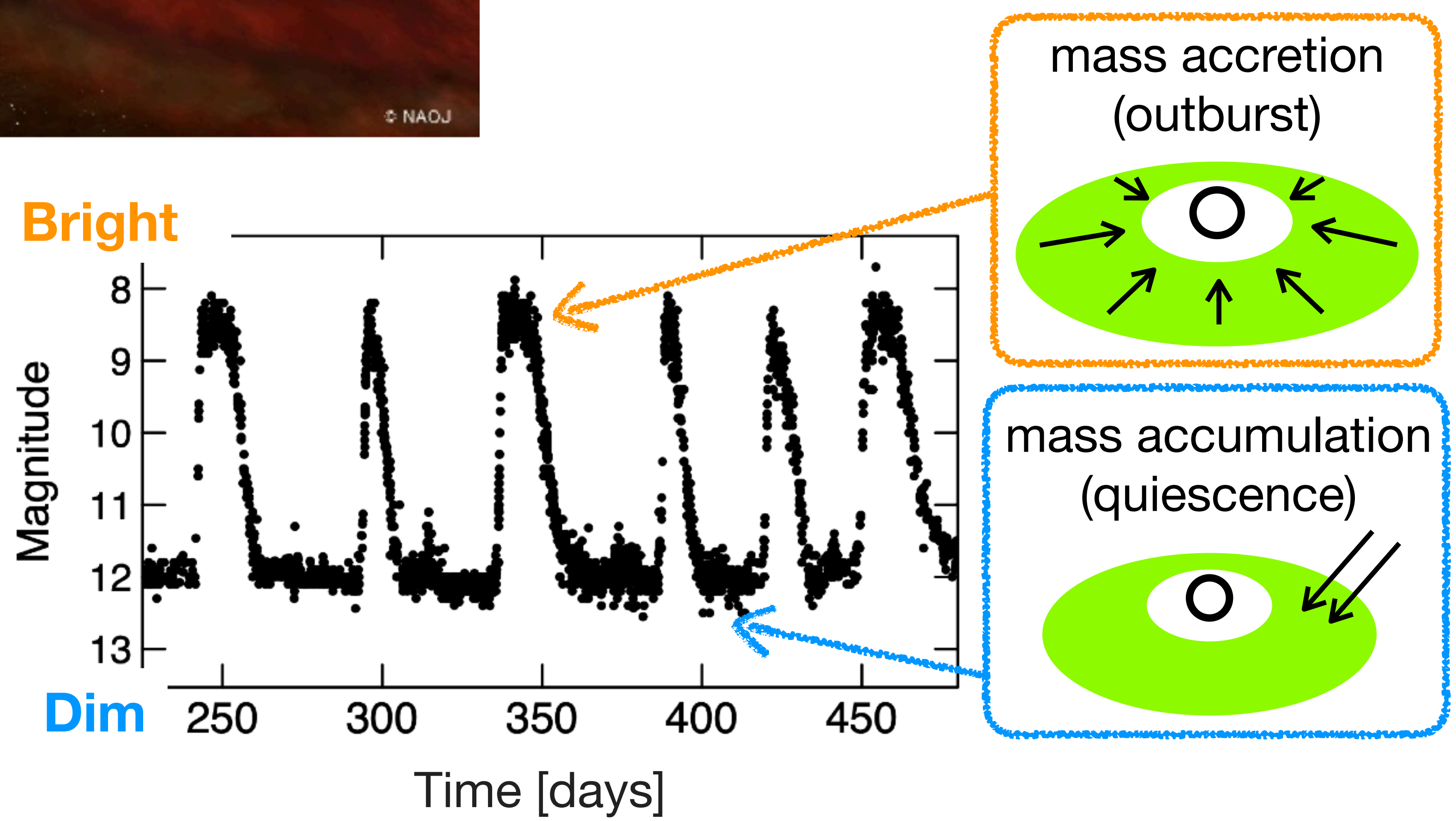
Outbursts = sudden brightening of the disk

↑

Thermal-viscous instability in the disk

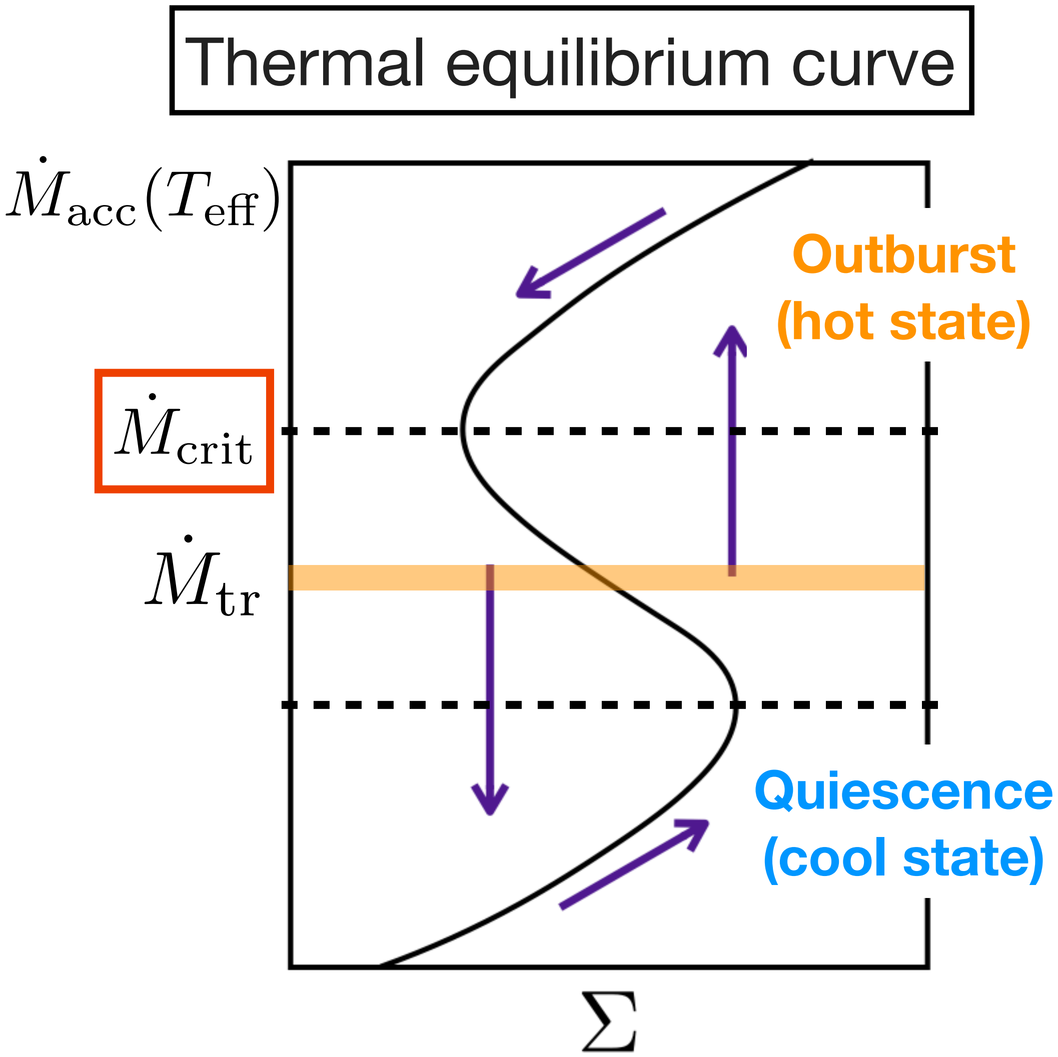
triggered by partial ionization of hydrogen

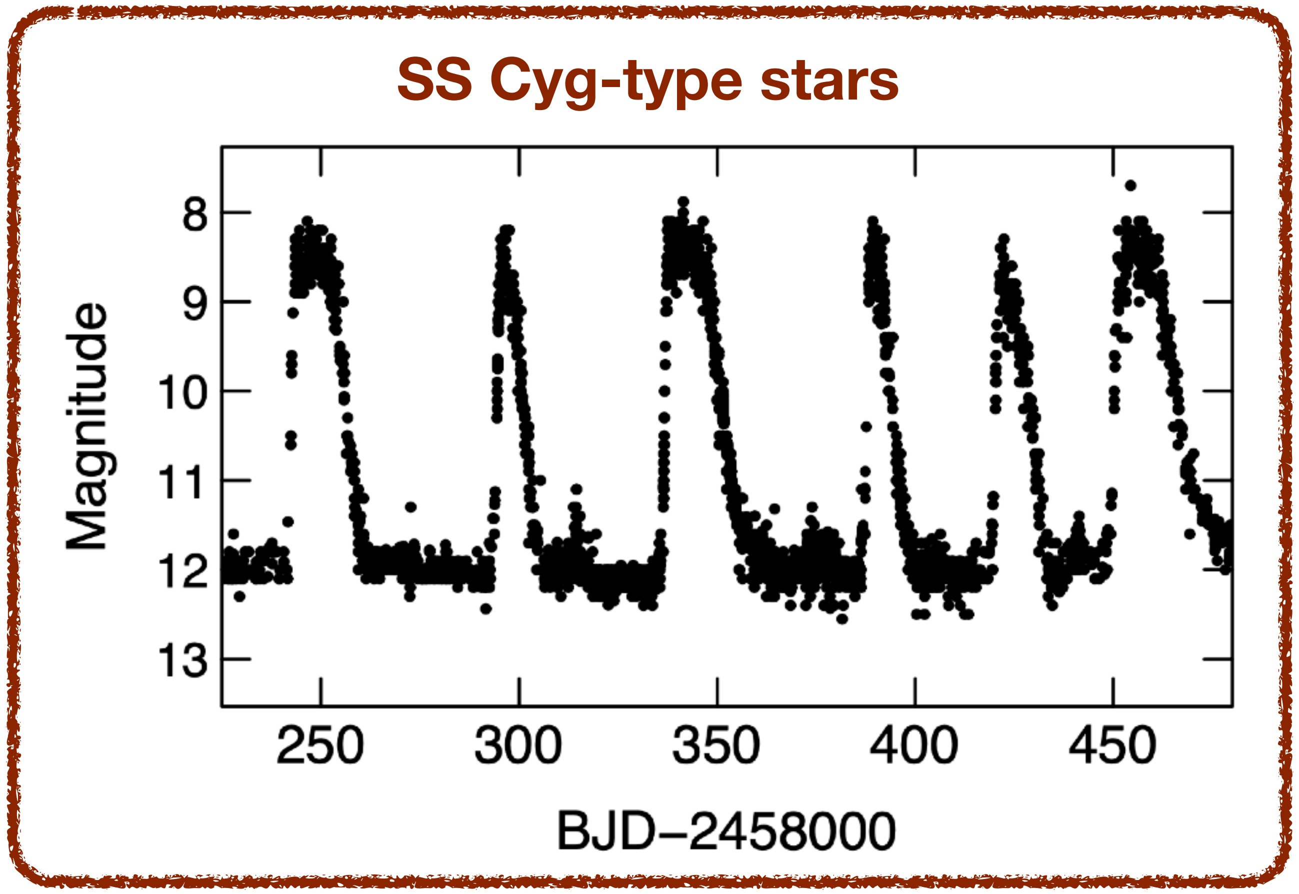
(Disk-instability model)



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

Classification of dwarf novae



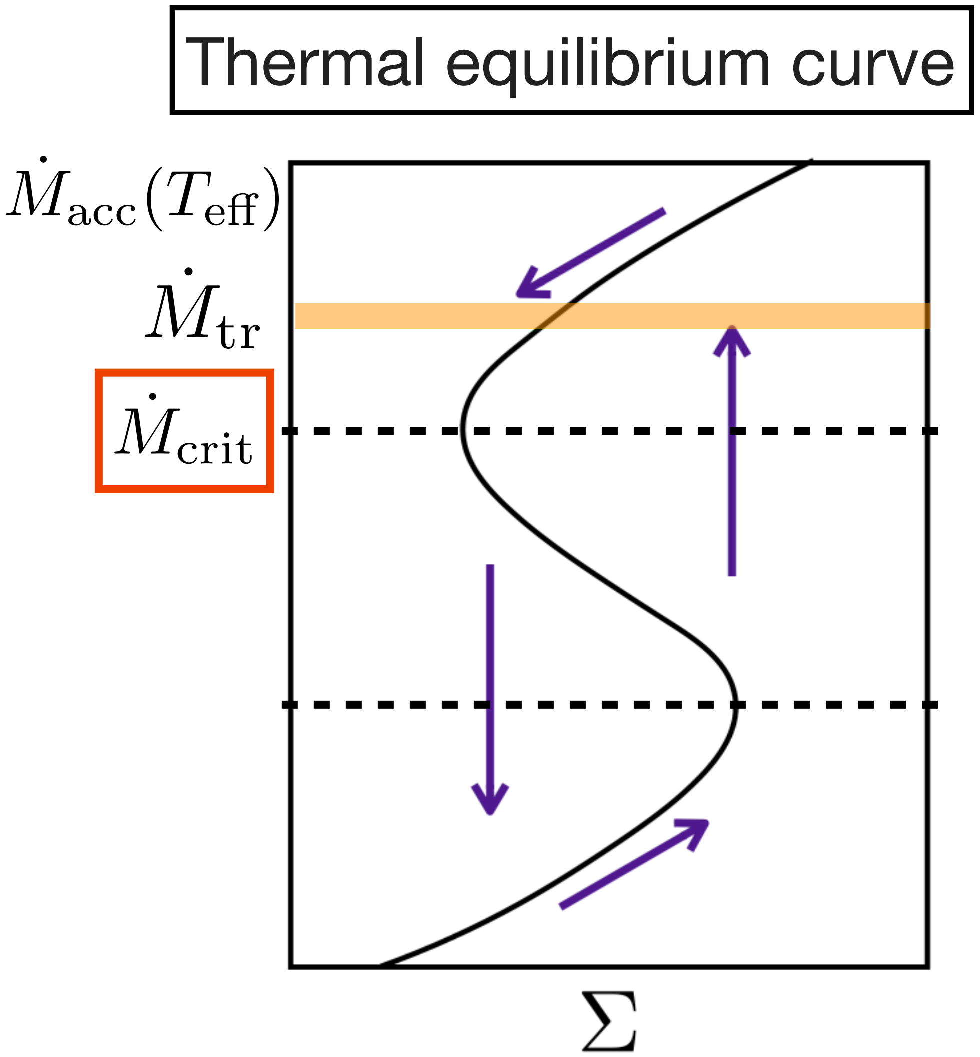


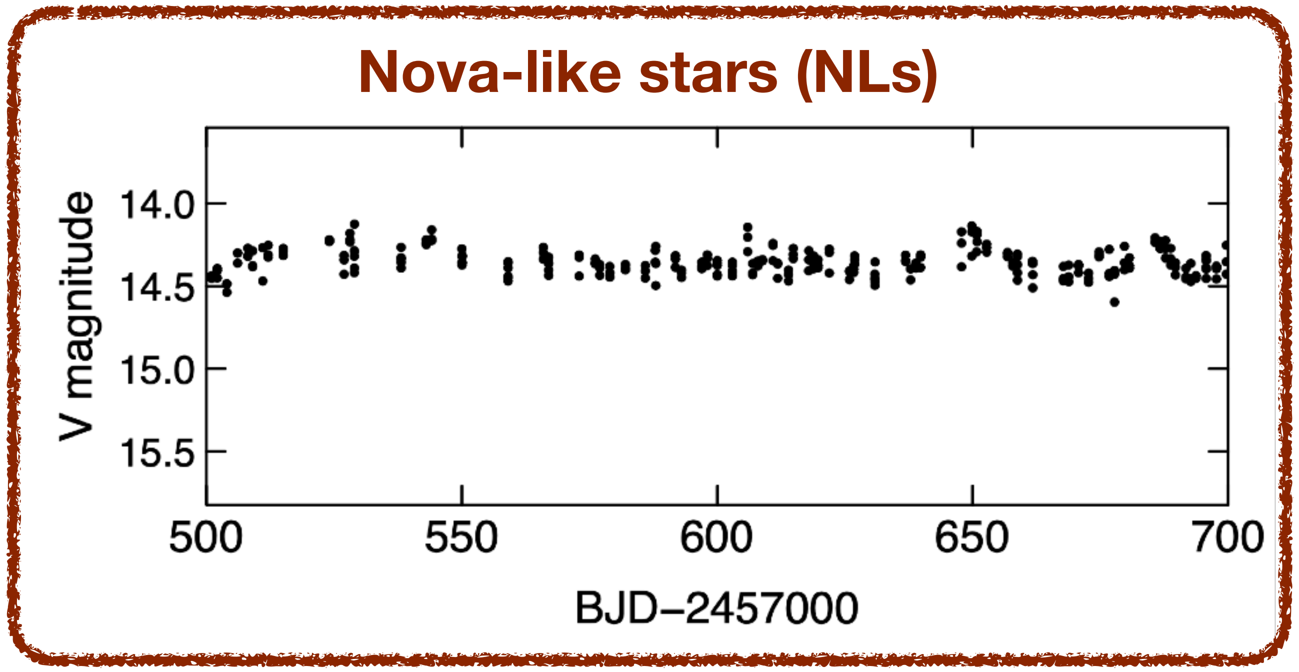
$\dot{M}_{\rm tr} < \dot{M}_{\rm crit}$

- Thermally **unstable** disk
- Repeat outbursts

(Hoshi 1979; Meyer & Meyer-Hofmeister 1981; Mineshige & Osaki 1985; Osaki 1996; Meyer & Meyer-Hofmeister 1983)

Classification of dwarf novae



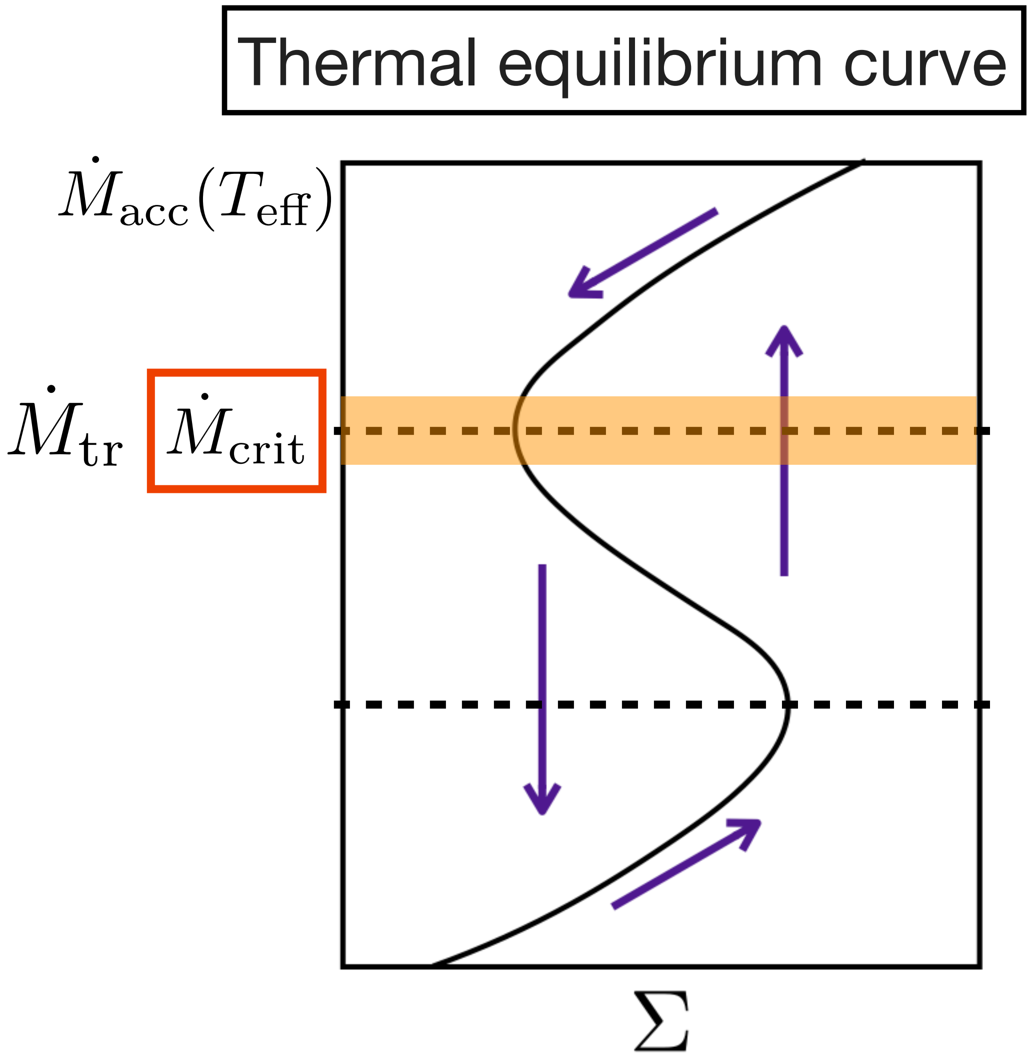


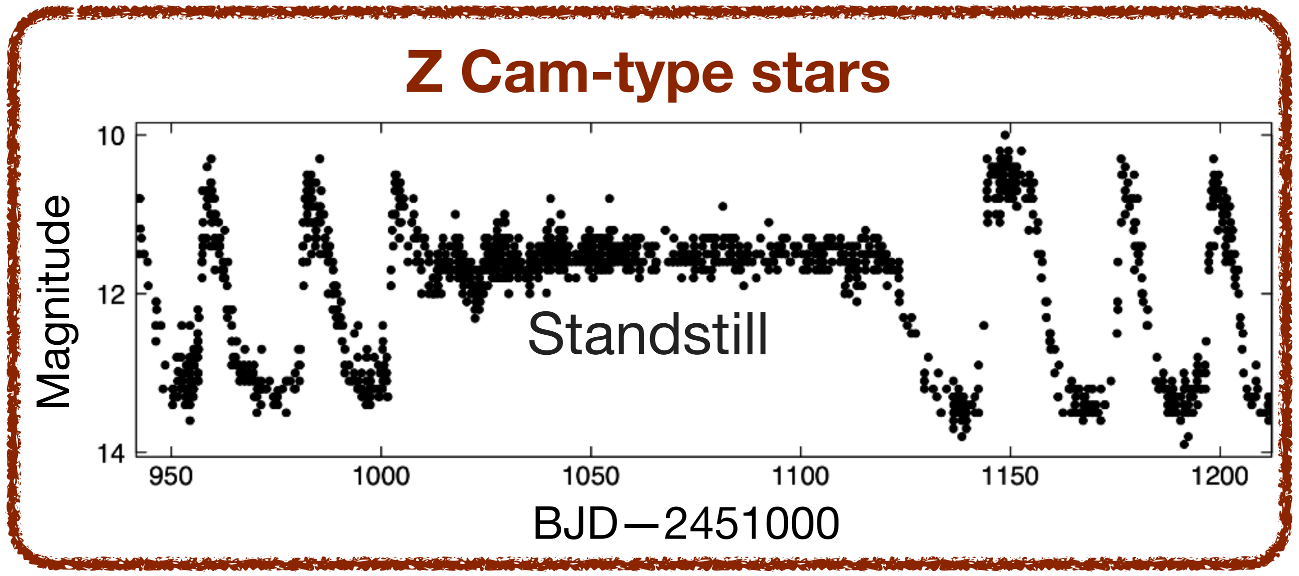
$\dot{M}_{\rm tr} > \dot{M}_{\rm crit}$

- Thermally **stable** disk
- Constant luminosity

(Hoshi 1979; Meyer & Meyer-Hofmeister 1981; Mineshige & Osaki 1985; Osaki 1996; Meyer & Meyer-Hofmeister 1983)

Classification of dwarf novae





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

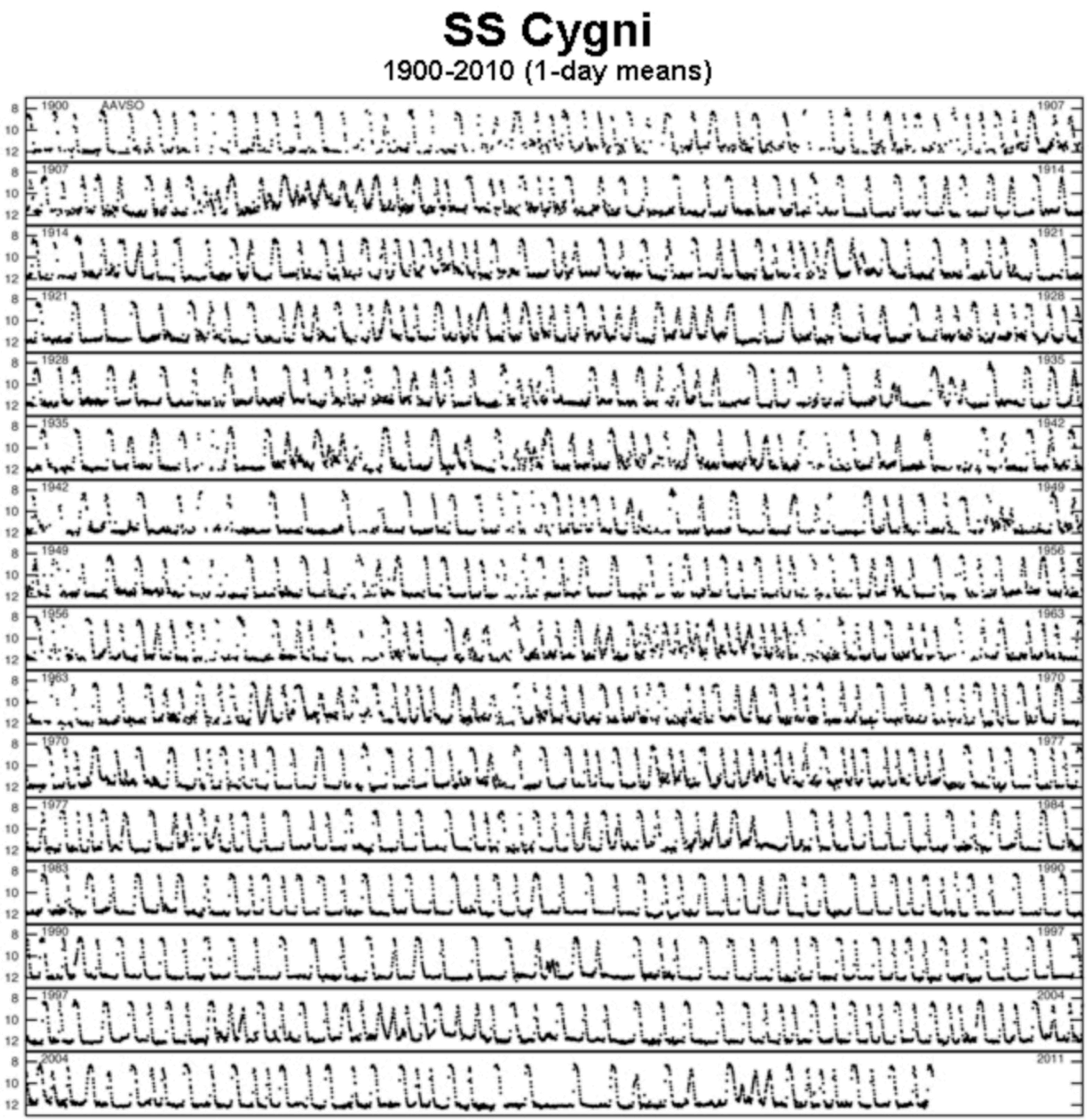
- Intermediate type between NLs and SS Cyg stars
- **Fluctuations of mass transfer rates ?**

The standstill is not explained by the simple disk instability model with constant mass transfer rates.

⟶ **The unified model for outbursts is not completed ..**

(Hoshi 1979; Meyer & Meyer-Hofmeister 1981; Mineshige & Osaki 1985; Osaki 1996; Meyer & Meyer-Hofmeister 1983)

SS Cyg: the brightest dwarf nova

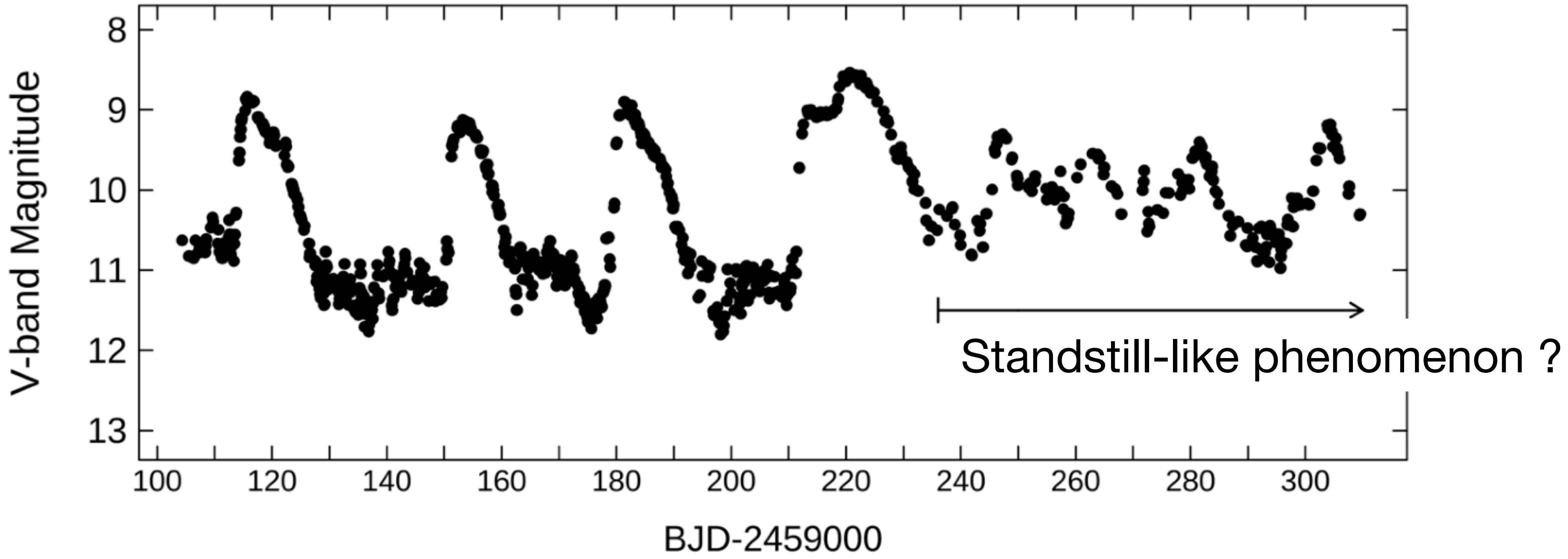


(Historical light curve of AAVSO)

- Monitored at optical wavelengths for >100 years
- Monitored at X-rays for >20 years
- Repeat dwarf-nova outbursts with intervals of ~1 month
- Recognized as the prototype of SS Cyg-type dwarf novae

The 2021 anomalous event & its precursor

- SS Cyg is no longer the prototype dwarf nova ..



- First event in the long history of observations (the 2021 anomalous event)

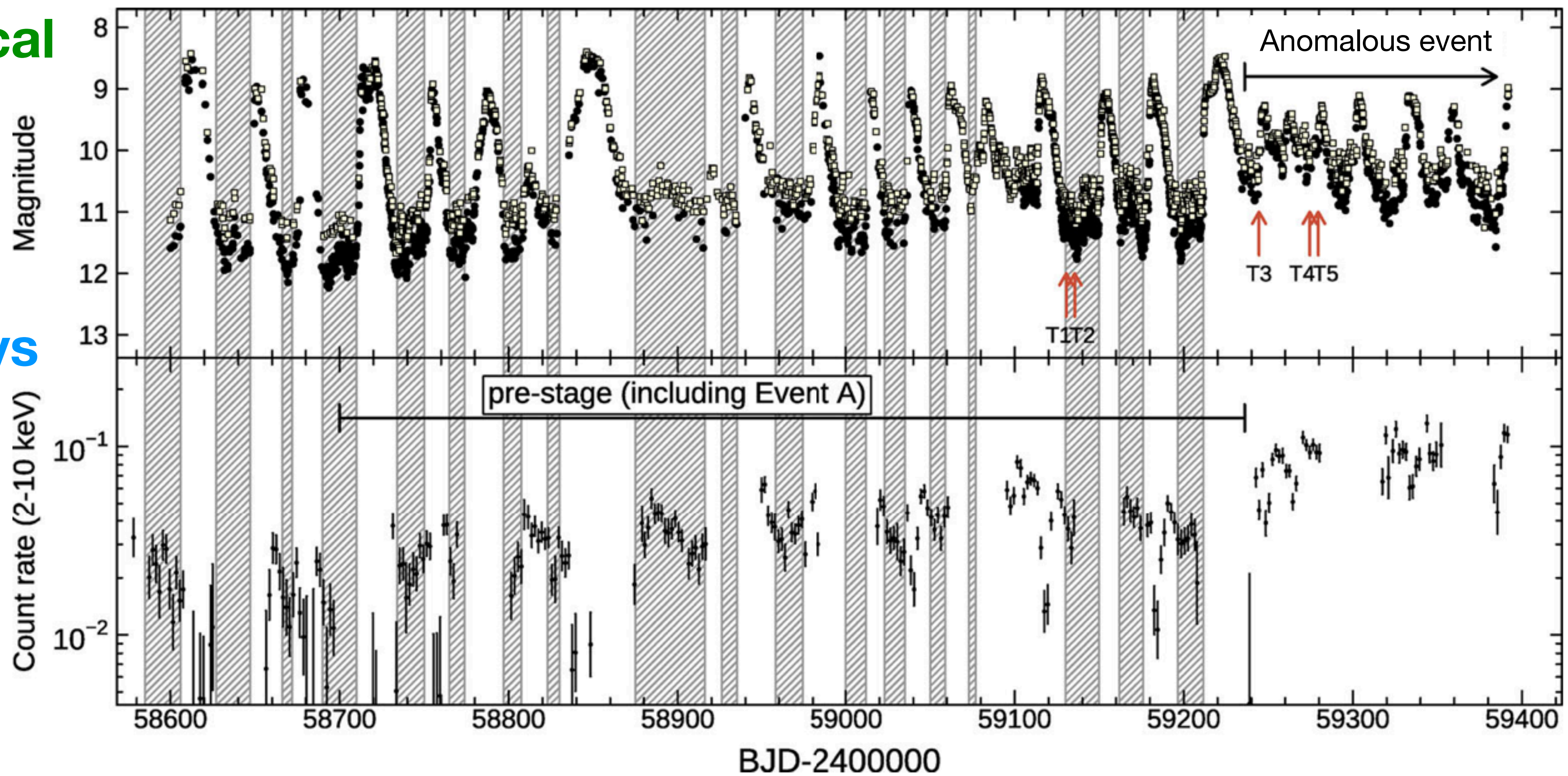
⟶ **What causes standstill in dwarf novae ?**

The 2021 anomalous event & its precursor

Precursor: gradual brightening at optical & X-ray wavelengths

Optical

X-rays



Our campaigns

Optical: Amateur groups (VSNET, AAVSO), Tomo-e Gozen at Kiso Observatory

X-rays: NICER, NuSTAR, MAXI, Swift

Possible scenarios

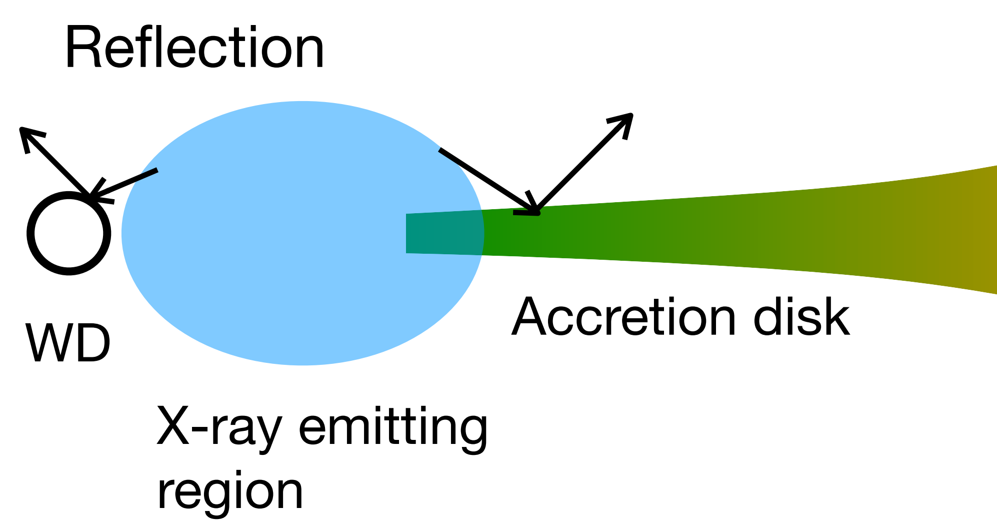
How did the increase in the optical & X-ray flux in quiescence occur ?

1. Increase of mass-transfer rates from the secondary star
   ↑ No positive evidence
2. Strong X-ray irradiation of the disk and/or the secondary star
3. The accretion rate in the disk increases for some reasons

Strong X-ray irradiation ?

Background

- Practically, the X-ray spectra of DNe have been fitted by multi-temperature plasma models.
- We have to consider the reflection by the WD and/or the disk.



Our model

- Tbabs * (reflect * cevmkl + gaussian)

To express Fe fluorescence line

Bremsstrahlung emissivity

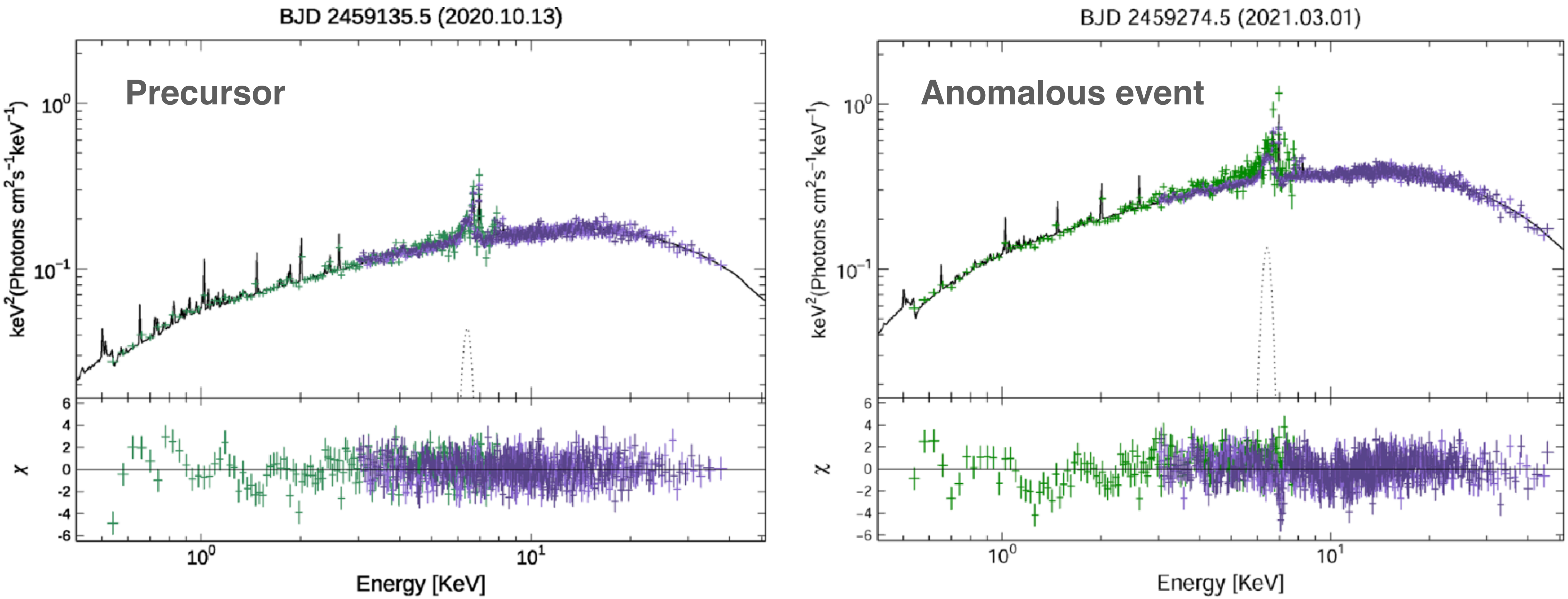
$$L(\nu) \propto \int_{T_{bb}}^{T_{max}} \frac{\epsilon(T, n^2, \nu)}{\epsilon(T, n^2)} dT$$

$$d(EM) \propto \left(\frac{T}{T_{\max}}\right)^{\alpha} d(\log T) \propto \left(\frac{T}{T_{\max}}\right)^{\alpha-1} dT,$$

(Done & Osborne 1997; Ishida et al. 2009; Nakaniwa et al. 2019)

Strong X-ray irradiation ?

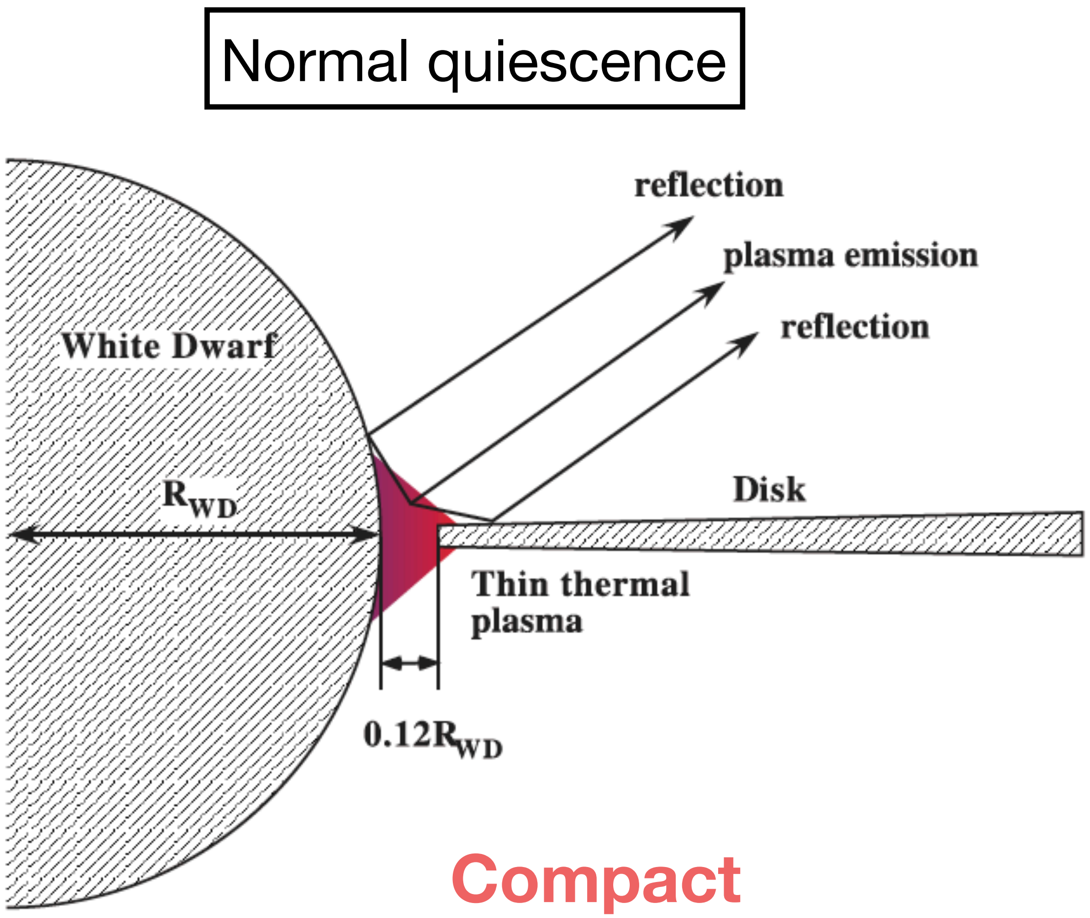
- Green: NICER (0.5–8 keV), Purple: NuSTAR (3.0–50 keV), Black: model



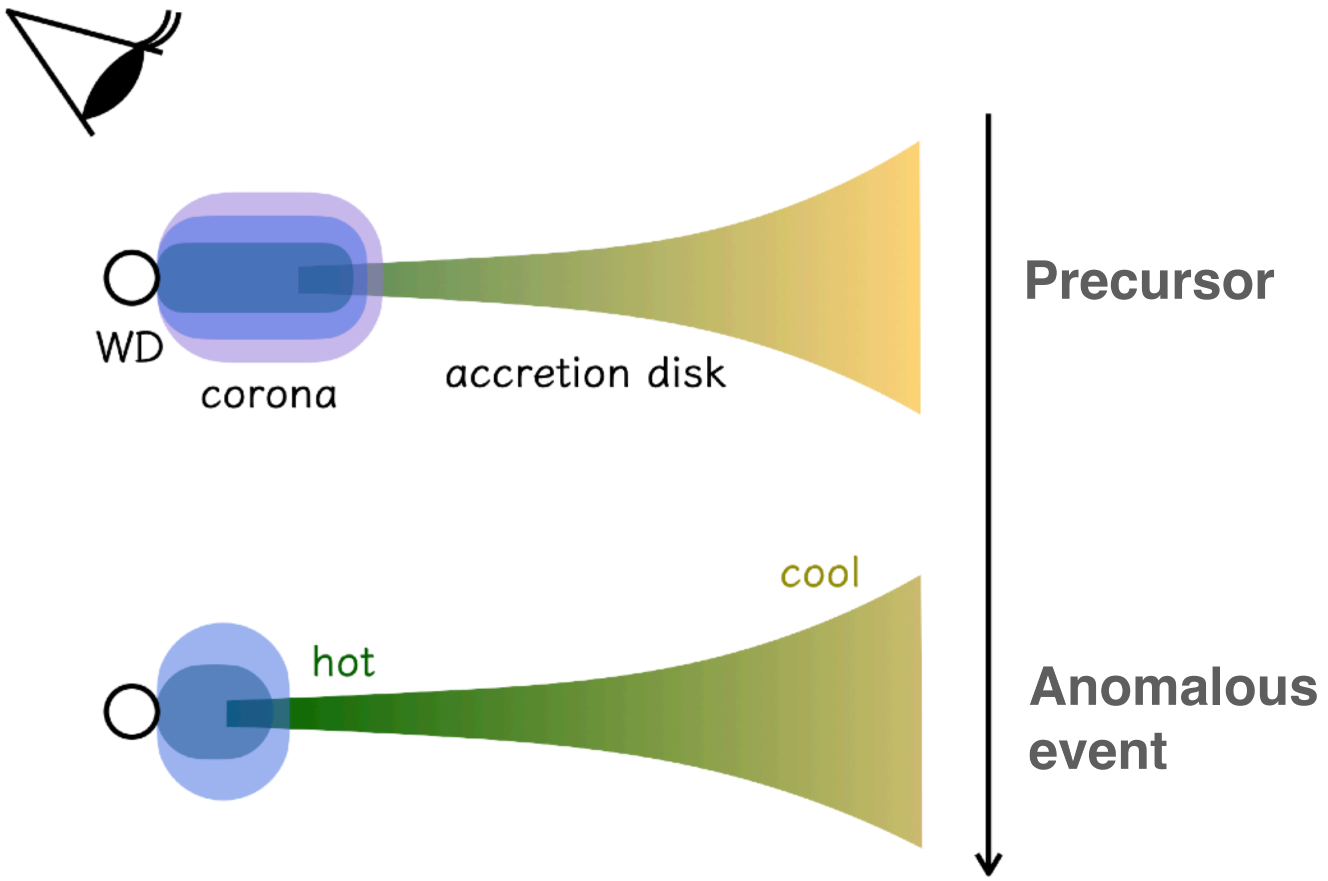
- T_max ~ 25–30 keV
- solid angle ~ 0.2—0.3
- Flux increases by ~2—5 times
- Lx ~ 10^{33} erg / s

The X-ray irradiation of the disk and the secondary star is inefficient

Geometry of X-ray emitting plasma



Compact



Vertically extended

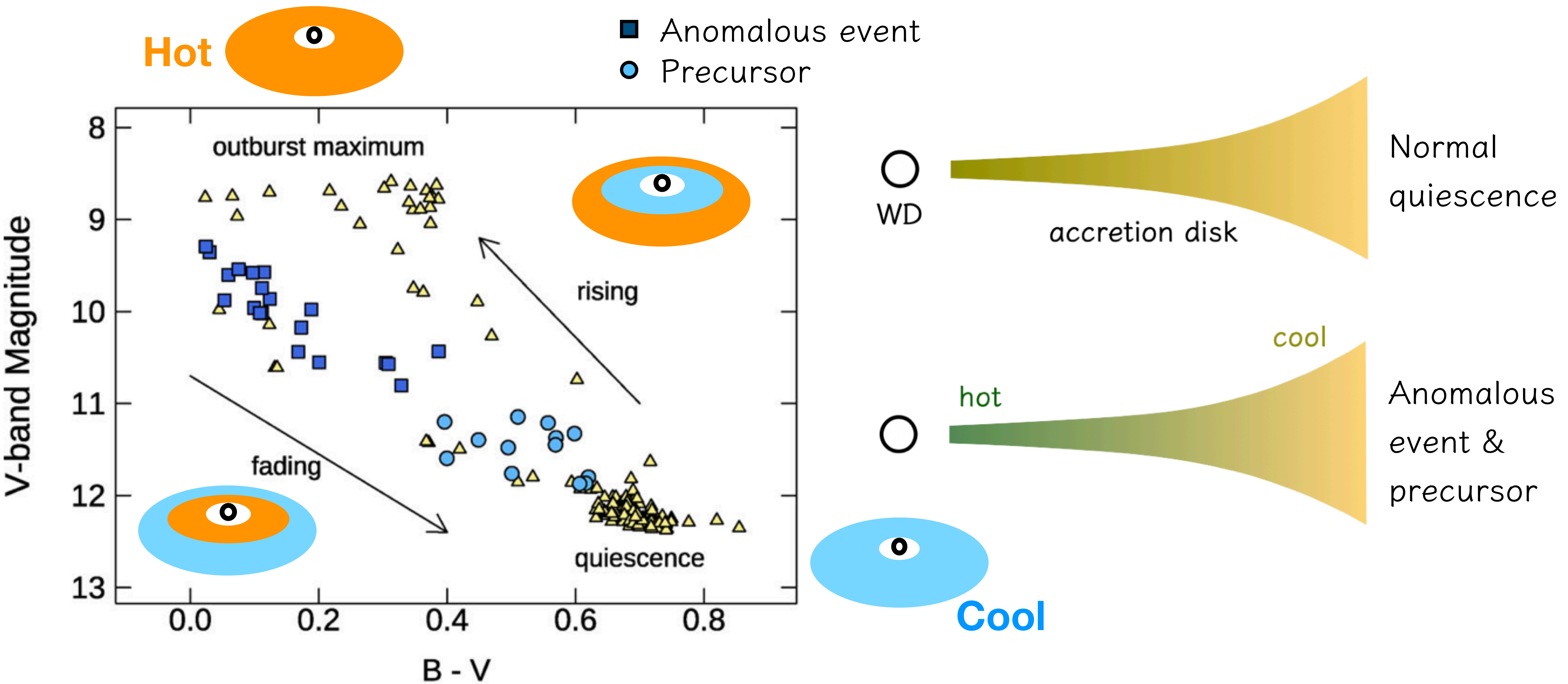
- The solid angle of the reflector was >1
- T_max ~ 20 keV

(Ishida et al. 2009)

Higher temperature → larger pressure → larger scale height

- The solid angle of the reflector was 0.2—0.3
- T_max ~ 25–30 keV

Bright inner disk during quiescence



$$\dot{M}_{\rm in} \propto \alpha_{\rm cool}\Sigma T \longrightarrow L_{\rm X} \sim \frac{GM\dot{M}_{\rm in}}{2r_{\rm in}}$$

We can explain the increase of X-ray flux as well.

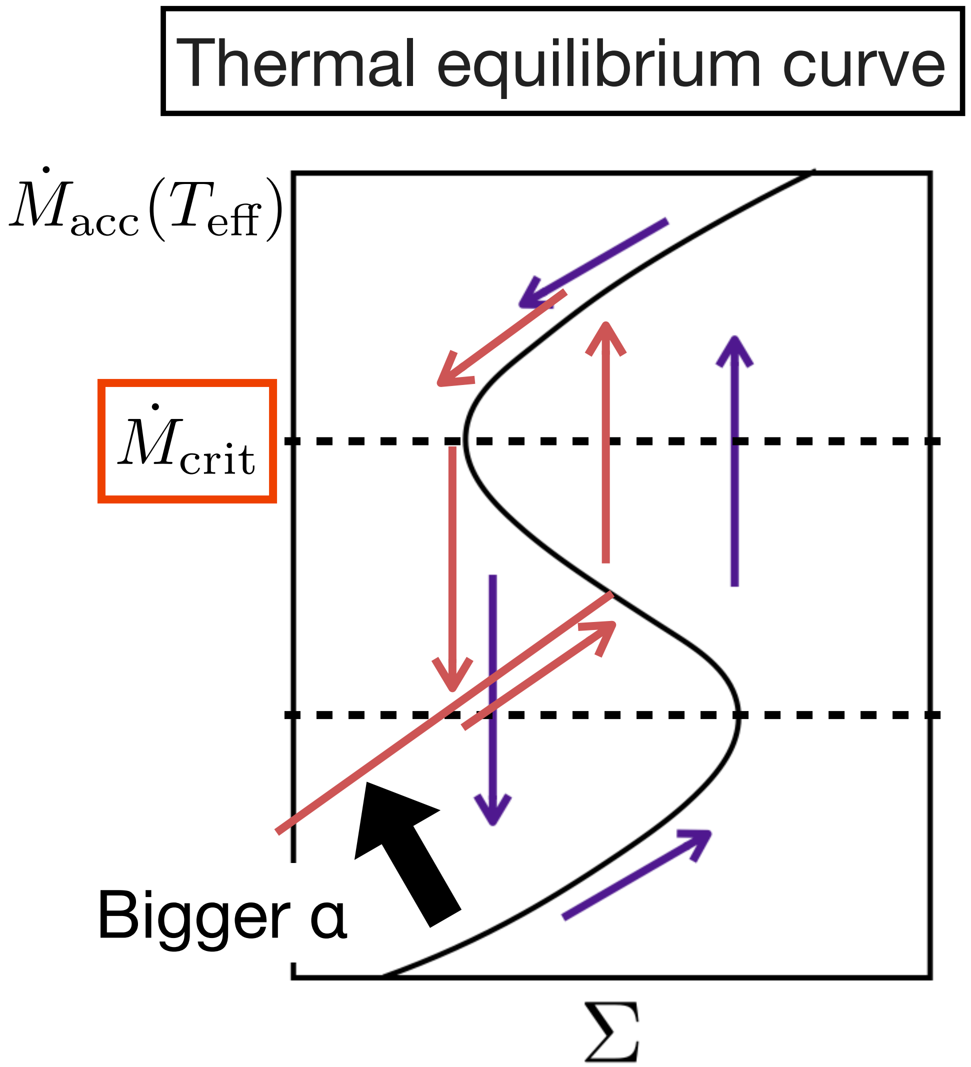
Temporal enhancement of viscosity in the cool state ?

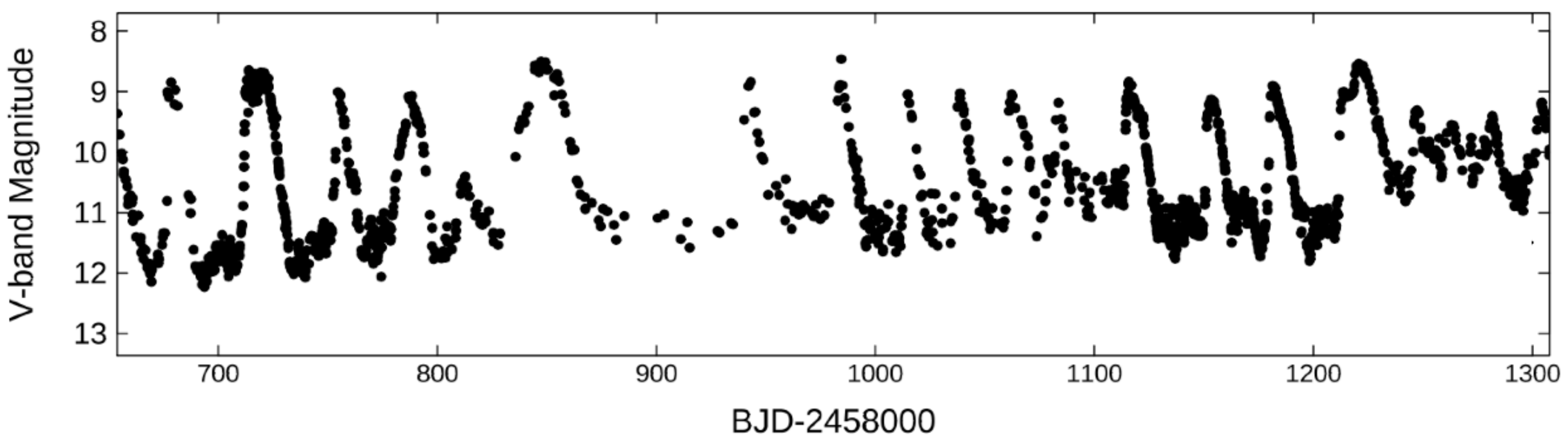
Effect of enhanced viscosity

- Enhancement of viscosity in the cool state

⟶ Smaller limit cycle ⟶ Increase of the flux level in quiescence

Frequent small and inside-out outbursts





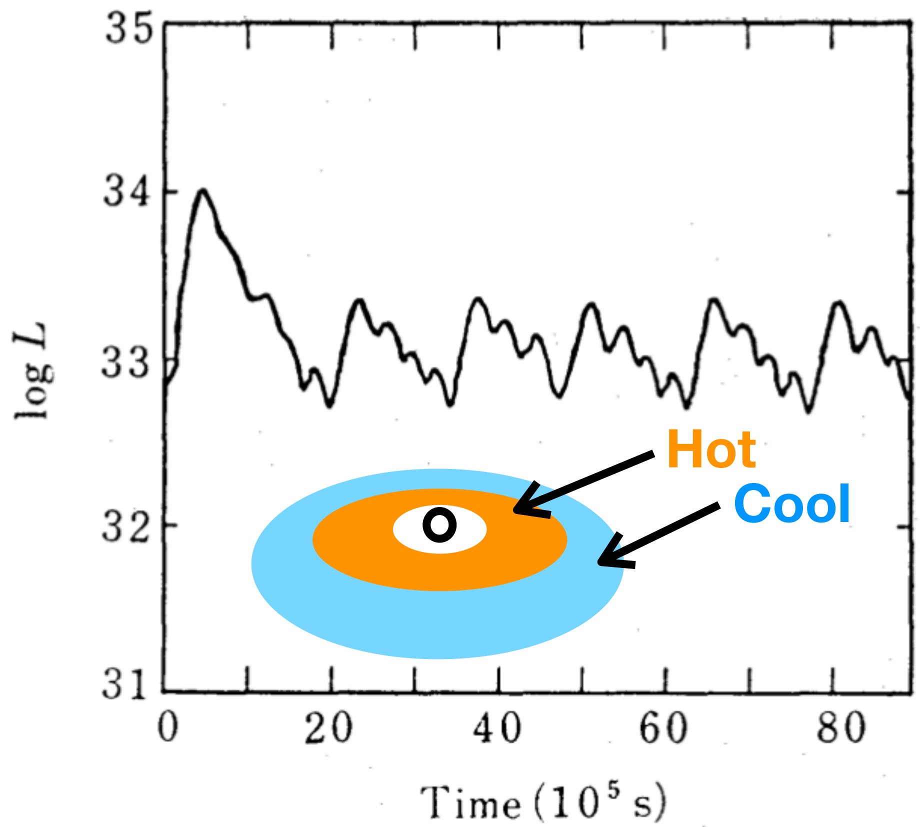
↑ Optical light curve in the precursor

The transition wave does not easily propagate over the disk.

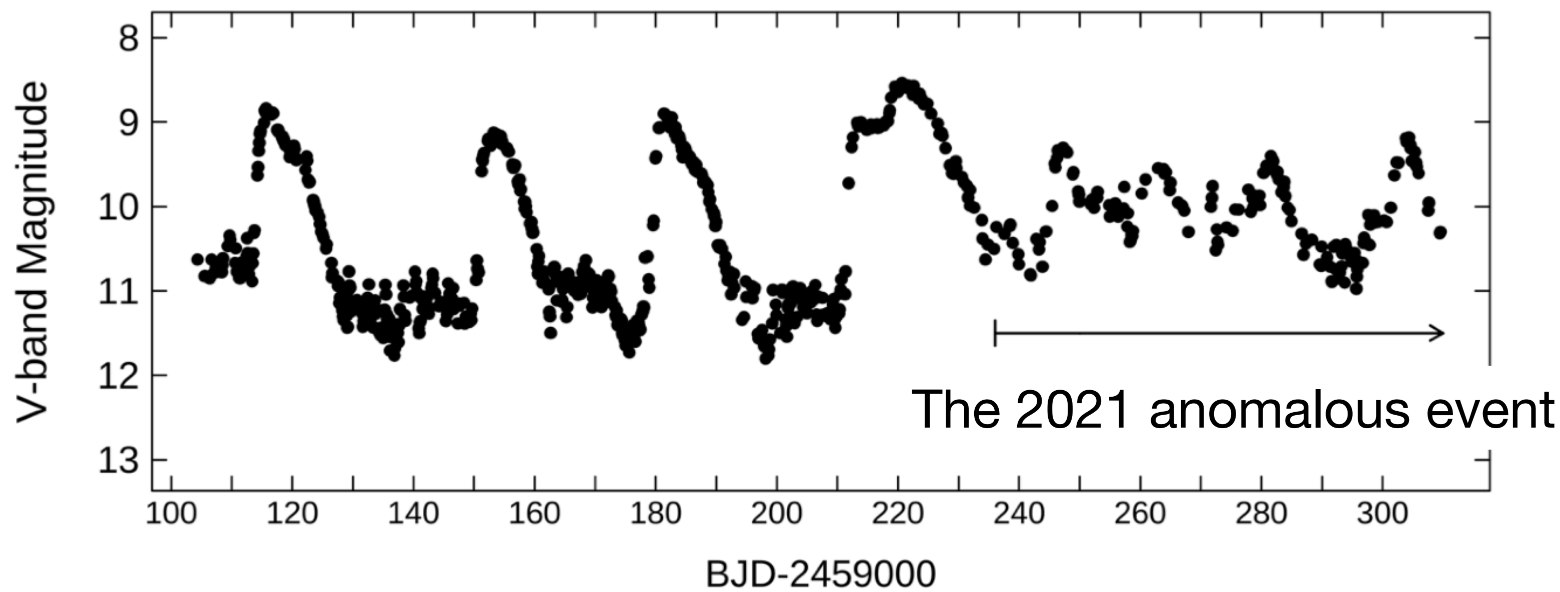
Nature of the 2021 anomalous event

- If the viscosity in the cool state is extremely enhanced ..

⟶ Light curves just oscillate and show no clear outbursts



(Mineshige & Osaki 1985)

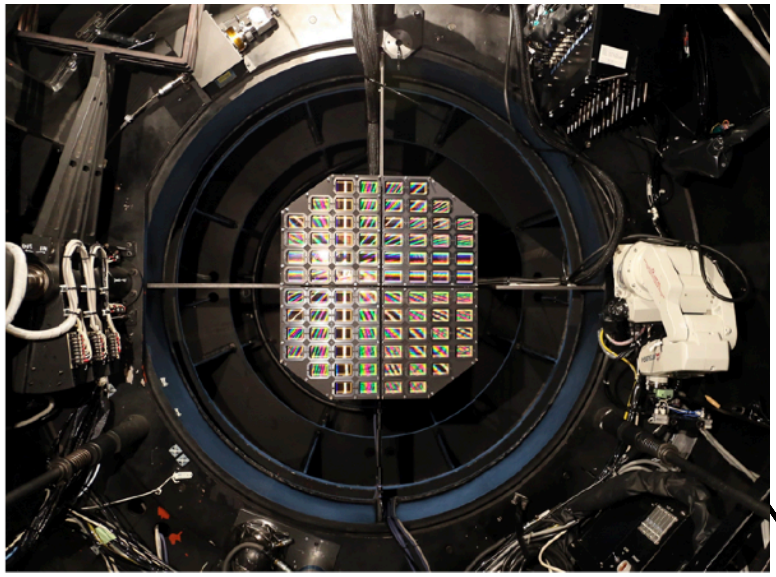


A series of very small outbursts

Kimura et al. (2021, PASJ, 73, 1262): "*On the nature of the anomalous event in 2021 in the dwarf nova SS Cygni and its multi-wavelength transition*"

High-speed observations (optical & X-ray)

Tomo-e Gozen (2019〜)



- 400—700 nm
- Wide-field video survey by CMOS cameras

Suitable for observations of transient events

NICER (2018〜)

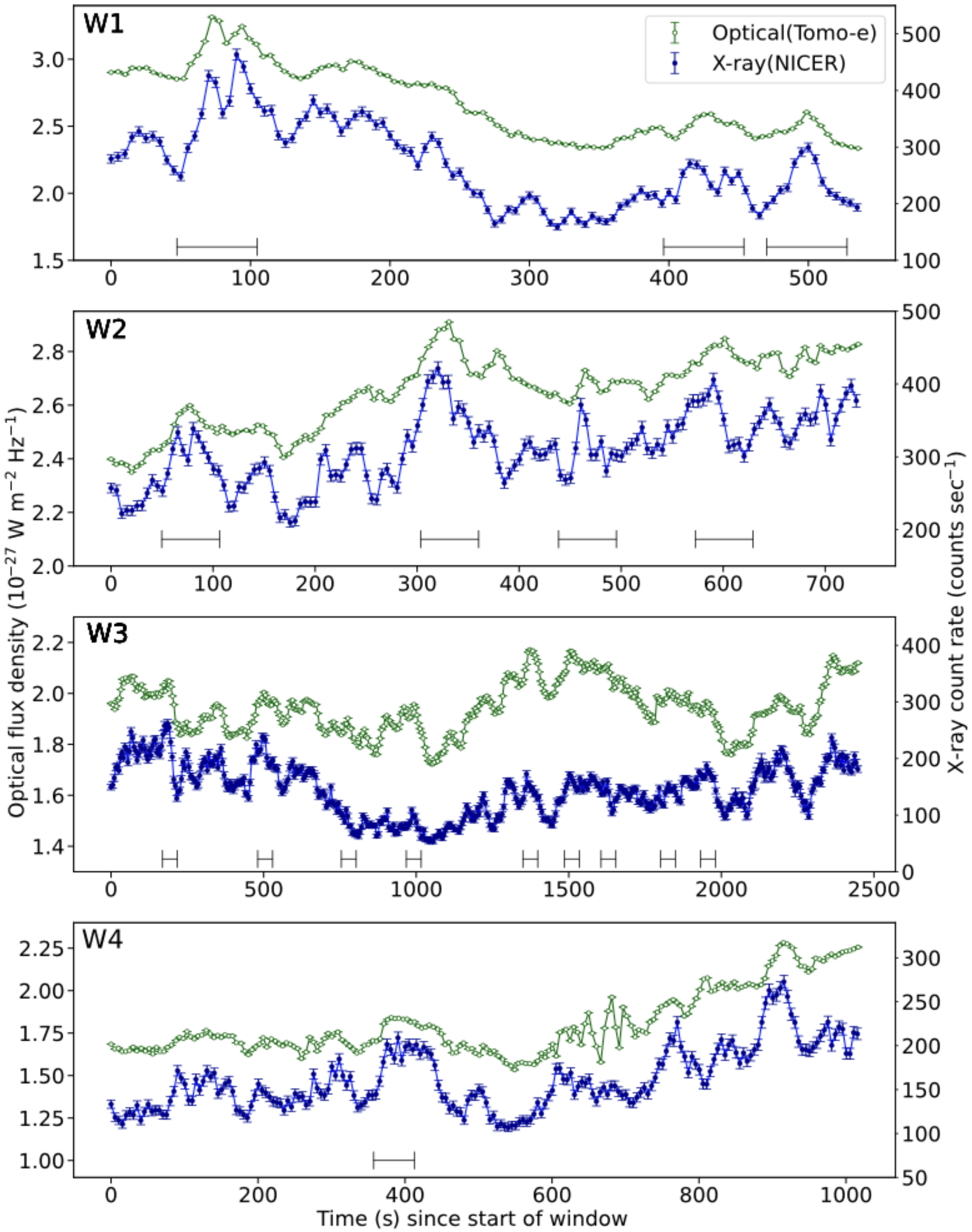
- 0.3—10.0 keV
- High time resolution

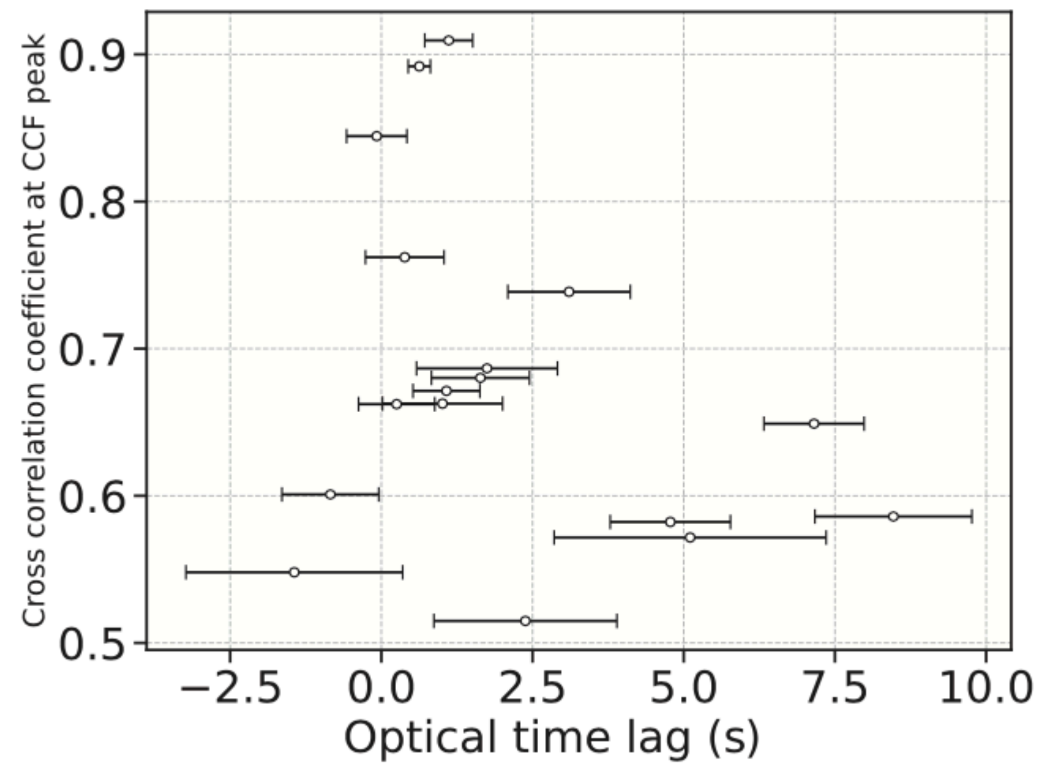
Simultaneous observations with Tomo-e & NICER

日付	装置	開始時間(UTC)	観測時間(s)
2020/9/14	NICER	10:04:00	1000
	Tomo-e	10:12:10	618
2020/9/15	NICER	12:24:20	1000
	Tomo-e	12:29:06	1064
2020/11/14	Tomo-e	11:59:54	3998
	NICER	12:04:48	2554
2020/11/18	NICER	10:32:18	2694
	Tomo-e	10:59:53	1286

↑ Provided by Nishino-kun at Tokyo Univ.

Highly-correlated optical & X-ray variations





Past

- Weak correlation (UV & X-ray)
- X-ray delay (~100—200 sec)

↕

In 2020

- Strong correlation
- Optical delay (~1 sec)

Enhanced X-ray irradiation ?

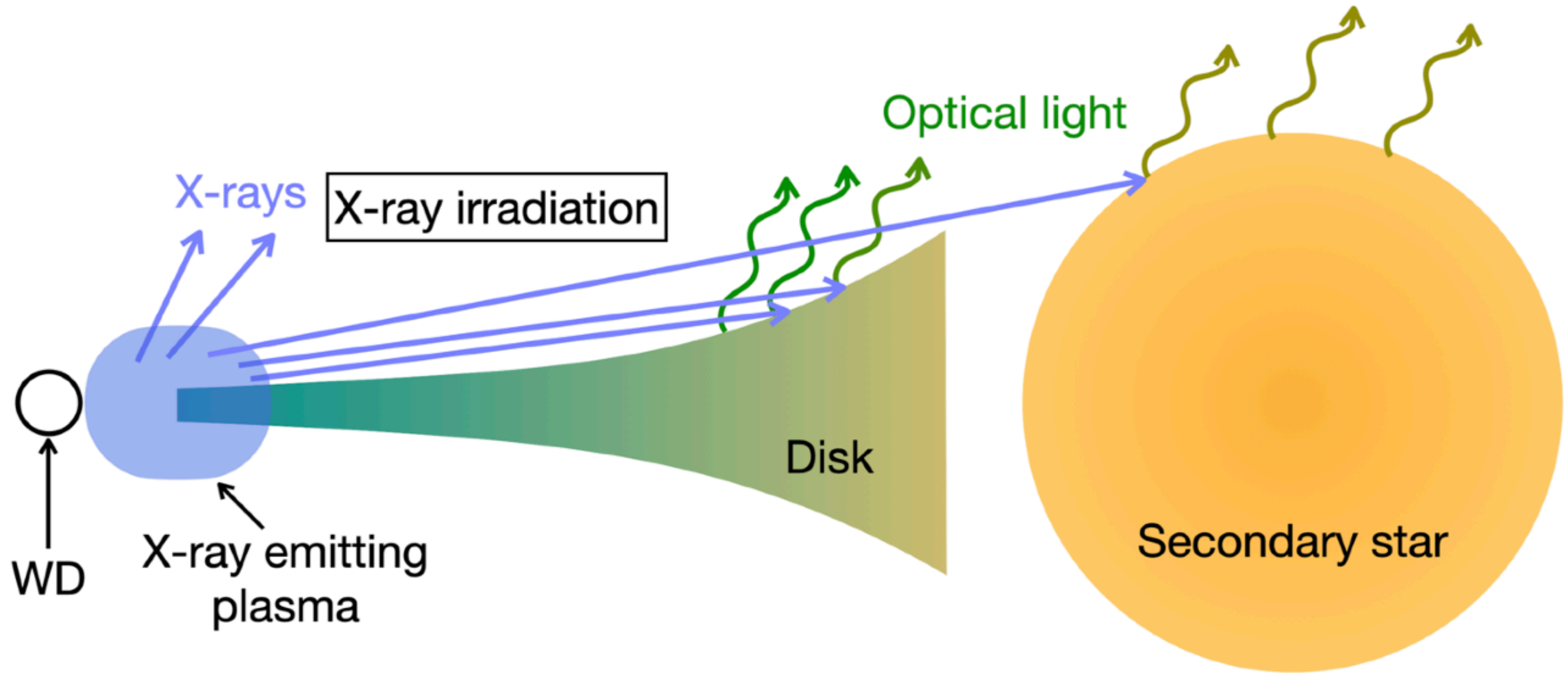
X-ray emitting plasma expanded

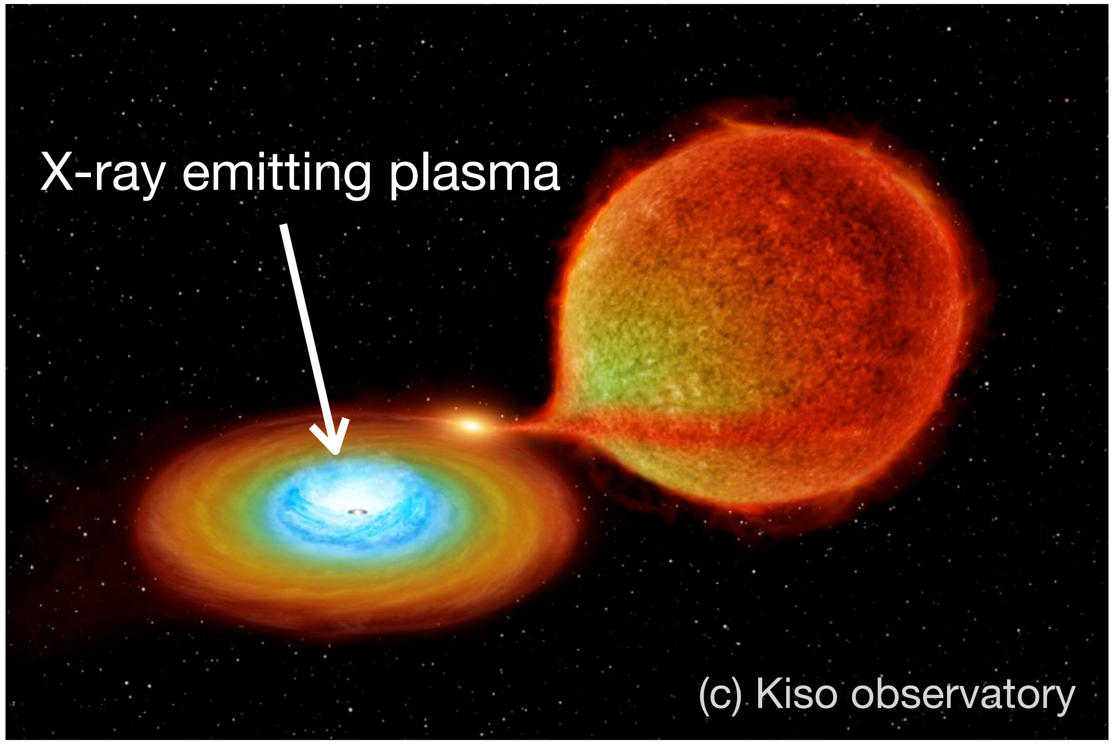
↓

X-ray irradiation was enhanced

↓

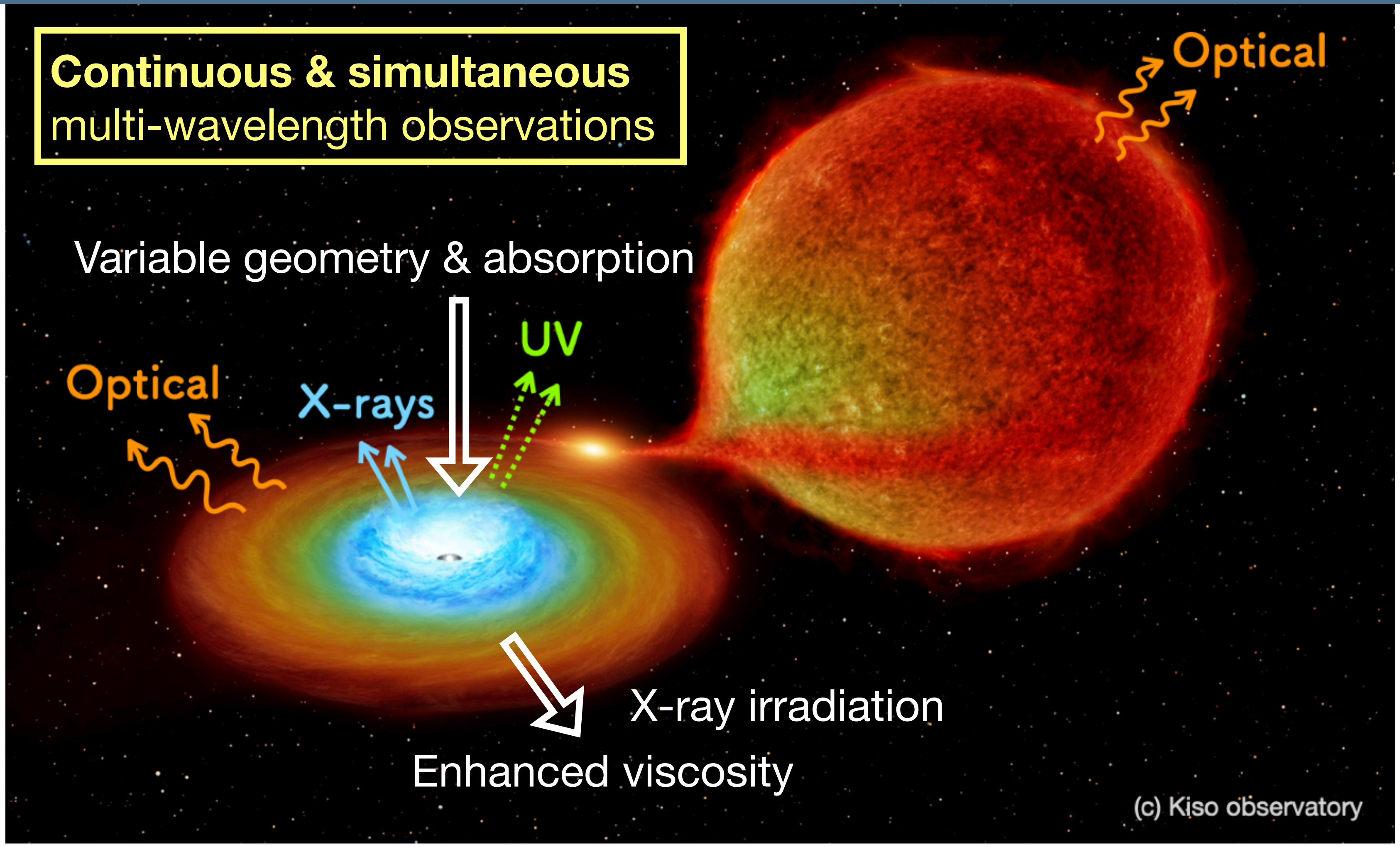
Optical delay against X-rays





Nishino, Kimura, Sako et al. (2022, PASJ, 73, L17): *``Detection of highly correlated optical and X-ray variations in SS Cygni with Tomo-e Gozen and NICER"*

Summary - the effect of multi-wavelength study -



Unsolved problems

- What is responsible for enhancement of viscosity in quiescence ?
- What is the origin of Z Cam-type / IW And-type standstill ?
- What causes stochastic variability in dwarf novae ?

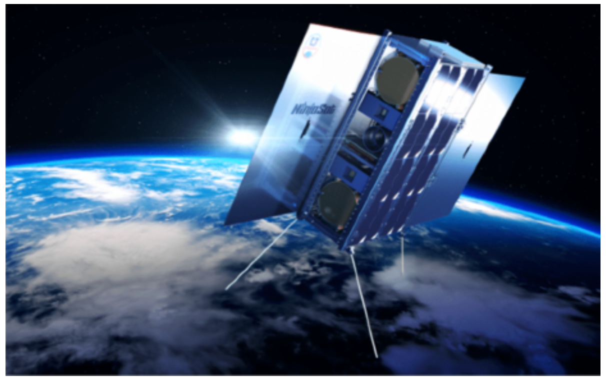
MHD simulations, light-curve simulations ..

Future works

TriCCS (2021~)

XRISM (2023~)

NinjaSAT (2024~)



- High-speed optical multi-band observations and Hα spectroscopy (TriCSS)
- Detailed structure of X-ray emission lines (XRISM)
- Flexible follow-up observations of bright targets (NinjaSAT)

↓

- Exploring the geometry of inner accretion flows
- Estimation of WD mass
- Time variability of accretion rates, structure, disk winds, ..