Multi-wavelength observations of X-ray binaries & cataclysmic variables

Presenter: Mariko Kimura (Kanazawa University, Japan)

Todays' topics

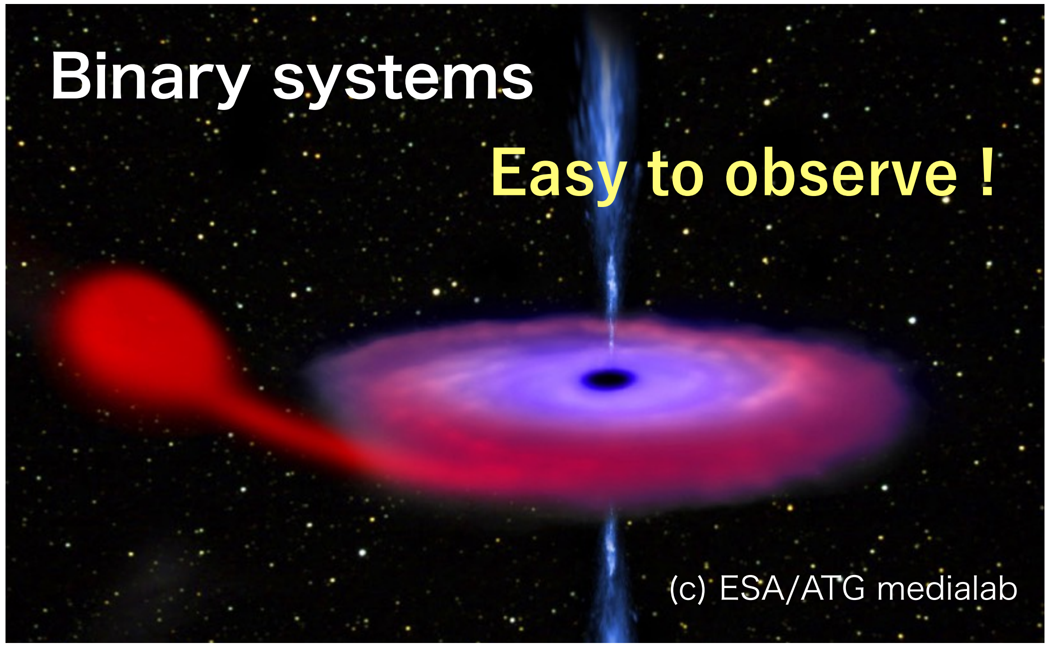
- **Introduction**
  - Transients & accretion disks
  - Outbursts of X-ray binaries and cataclysmic variables
  - Unsolved problems
  - Importance of multi-wavelength observations
- **Our recent works**
  - Repetitive optical & X-ray variability in the black-hole binary V404 Cyg
  - Standstill-like phenomenon in the white-dwarf binary SS Cyg
- **Future observations**
- **Introduction of my career and life**

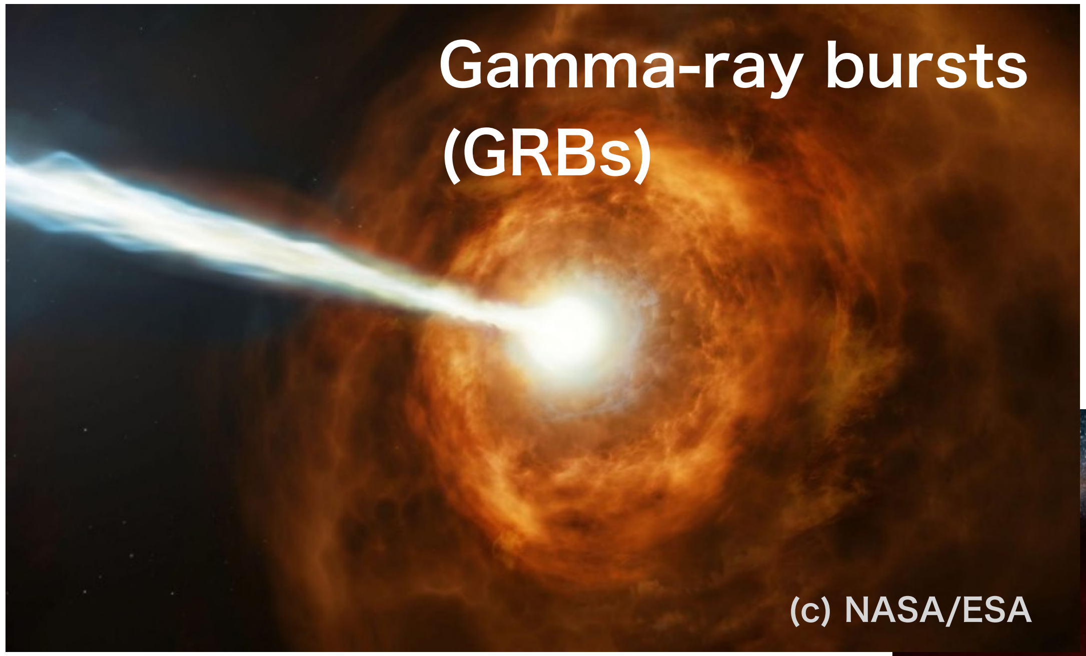
Introduction

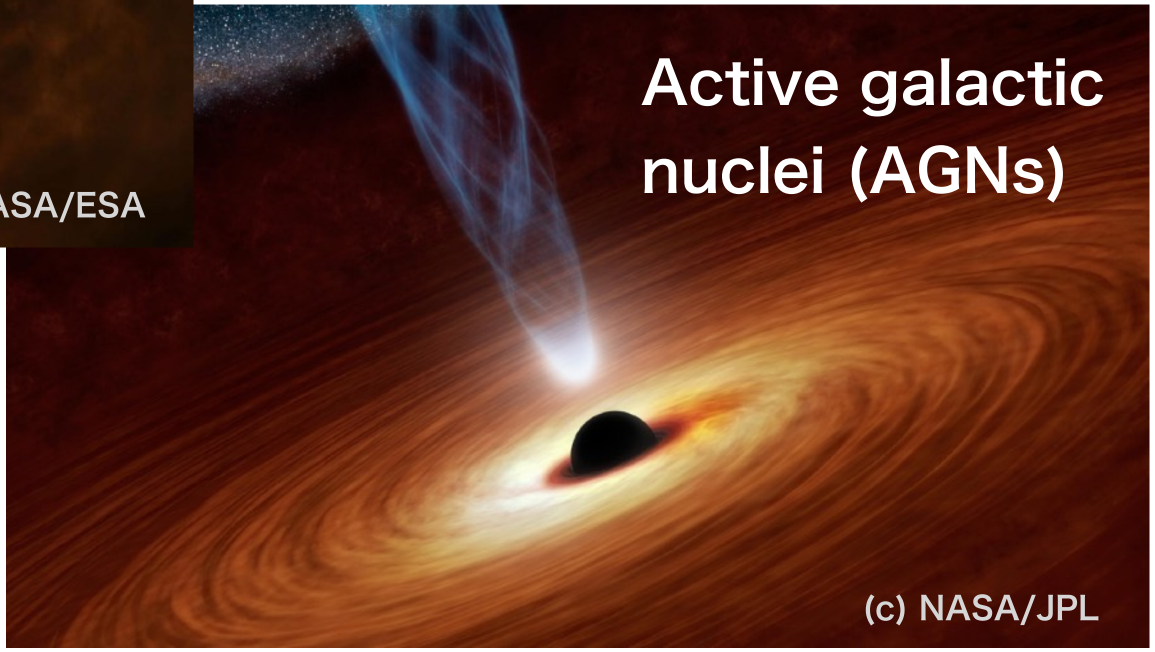
Accretion disks in our universe

Time-domain astronomy

⟶ Study of transient objects



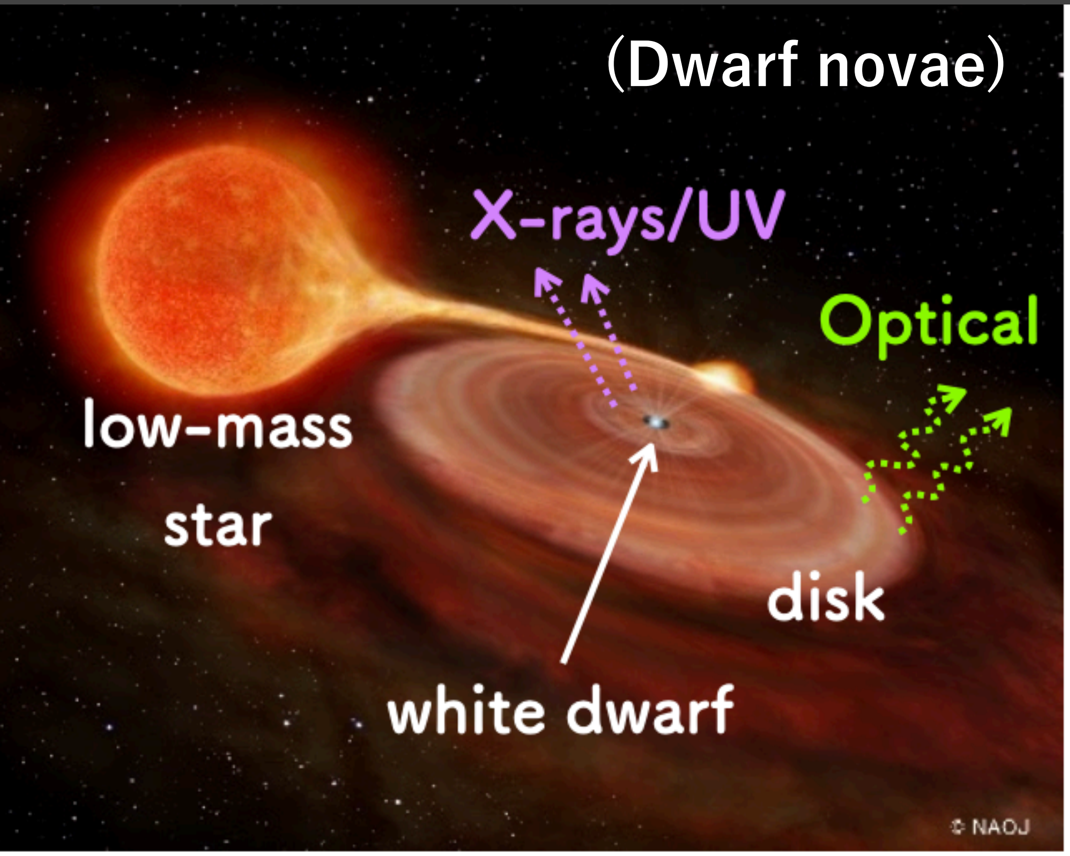


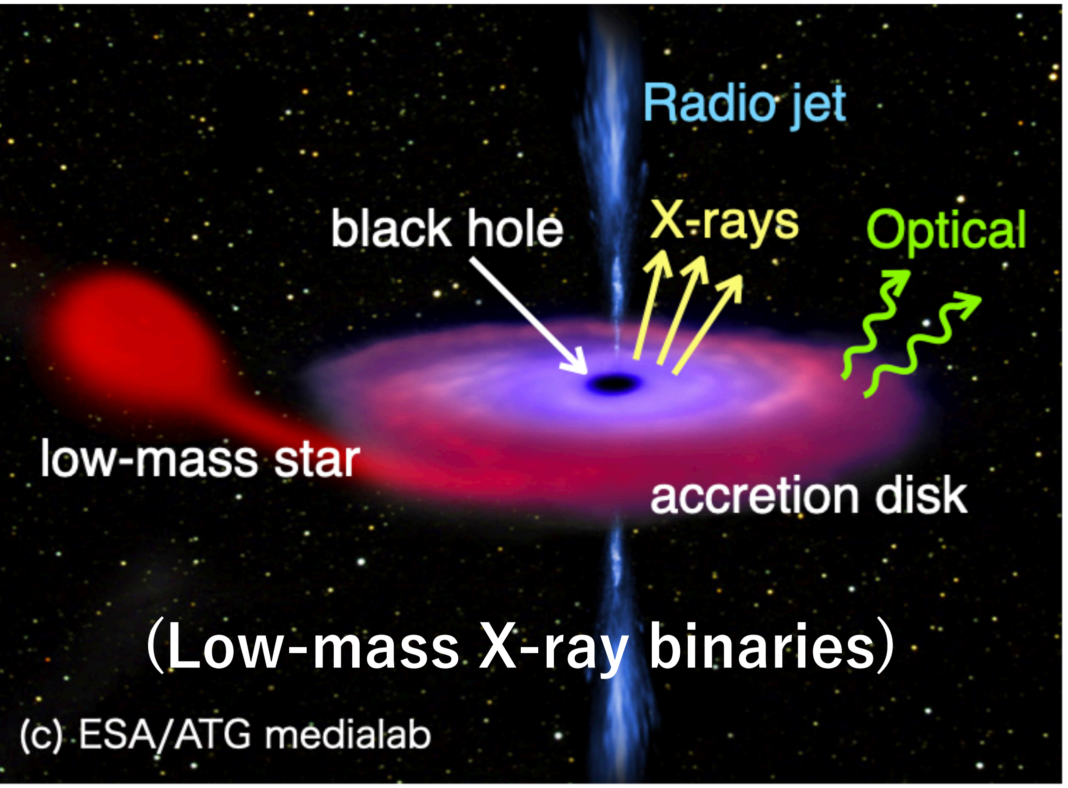


Accretion disks around compact objects (Black holes, white dwarfs, neutron stars)

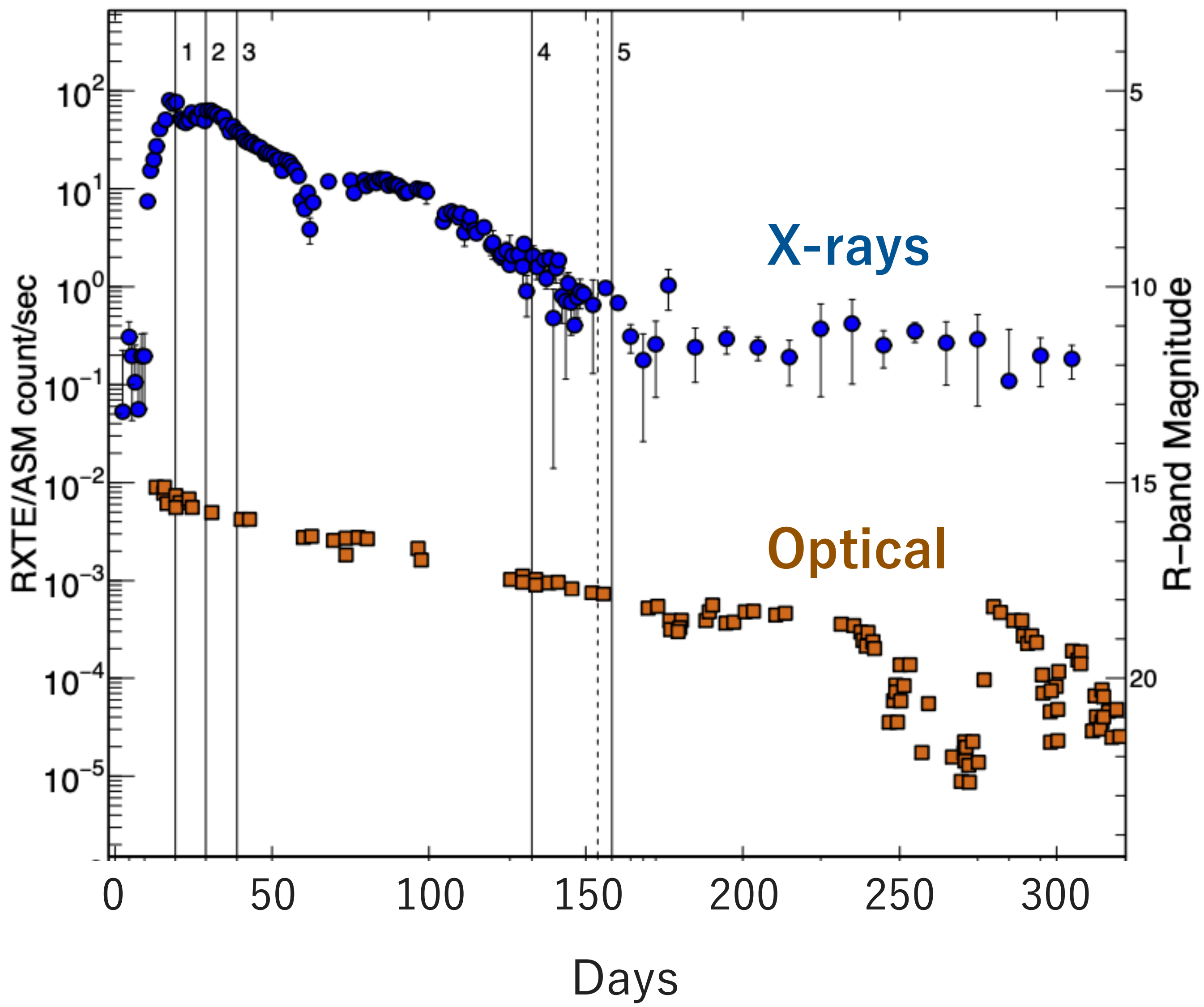
⟶ **Central engine of transient events**

Outbursts in binary systems





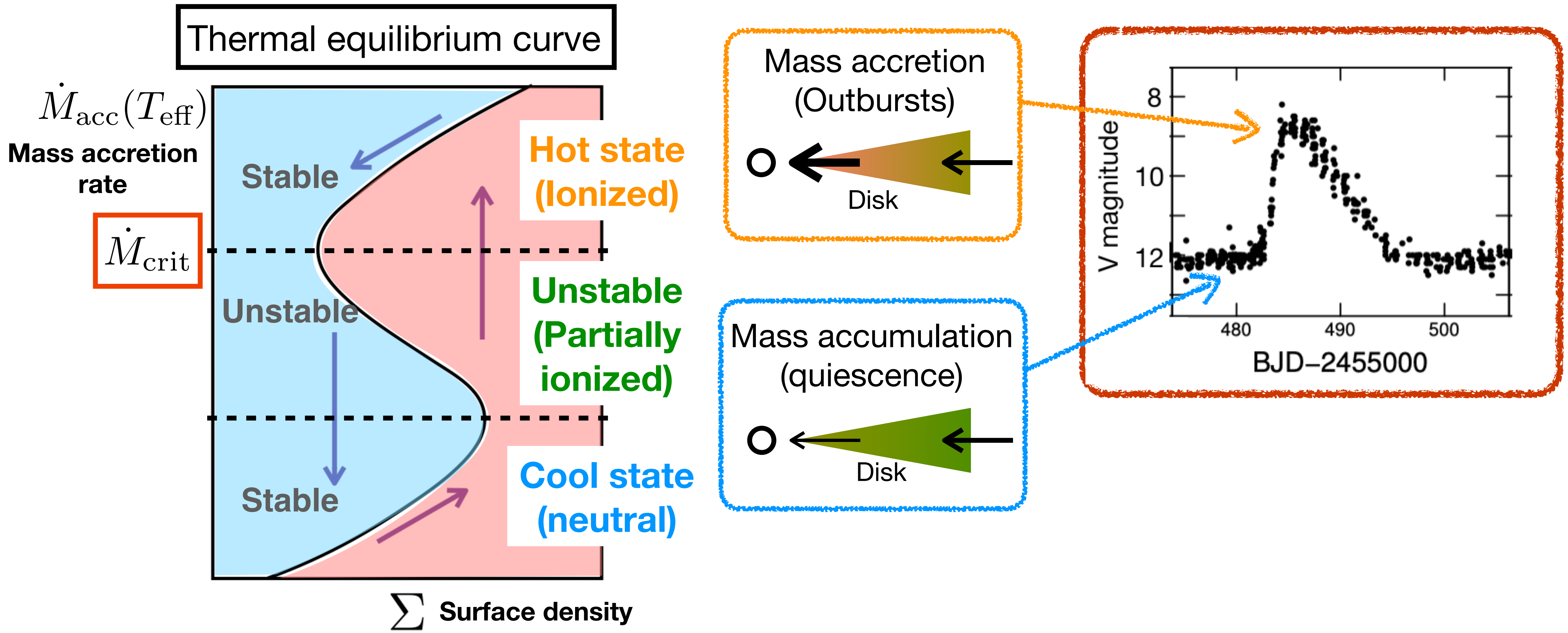
- Easy to be observed (bright, many objects)
- **Outbursts** = sudden brightening of the disk
- **Multi-wavelength emission**



(Kimura & Done 2019)

Mechanism of outbursts

Thermal-viscous instability triggered by partial ionization of hydrogen



Disk instability model

- limit-cycle instability propagates over the entire disk
- **Constant mass transfer rates from the secondary**

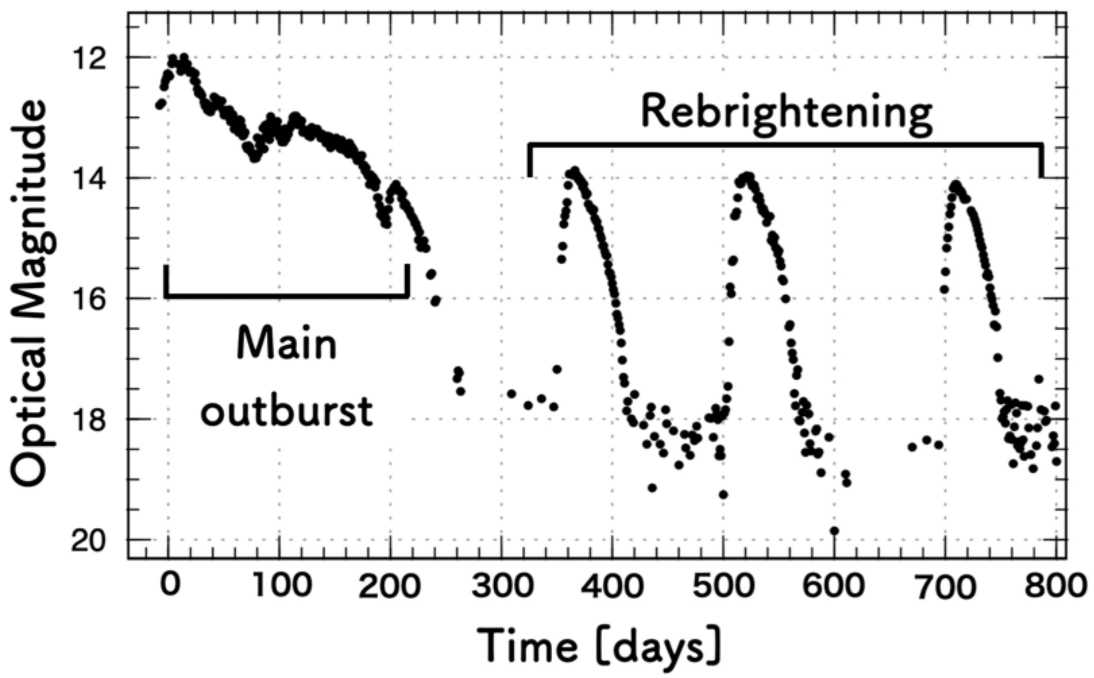
(Hoshi 1979; Meyer & Meyer-Hofmeister 1981; Mineshige & Osaki 1985; Osaki 1996; Meyer & Meyer-Hofmeister 1983)

Unsolved problems

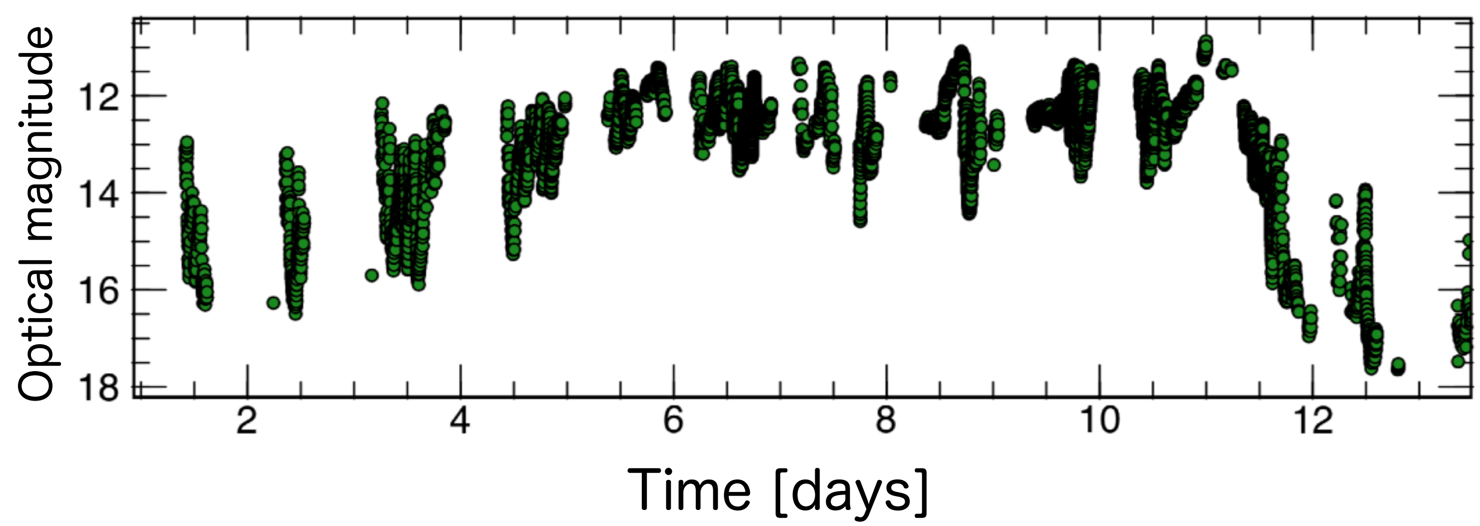
Big data ⟶ Discovery of peculiar outbursts that cannot be explained by the simple model

⟶ **Towards the unified model for rich variety of outbursts**

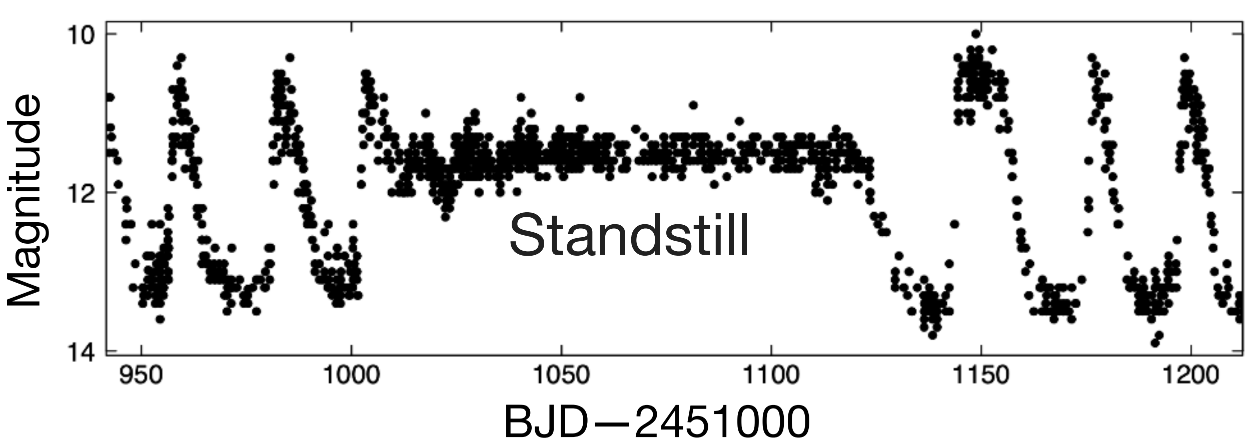
Rebrightening



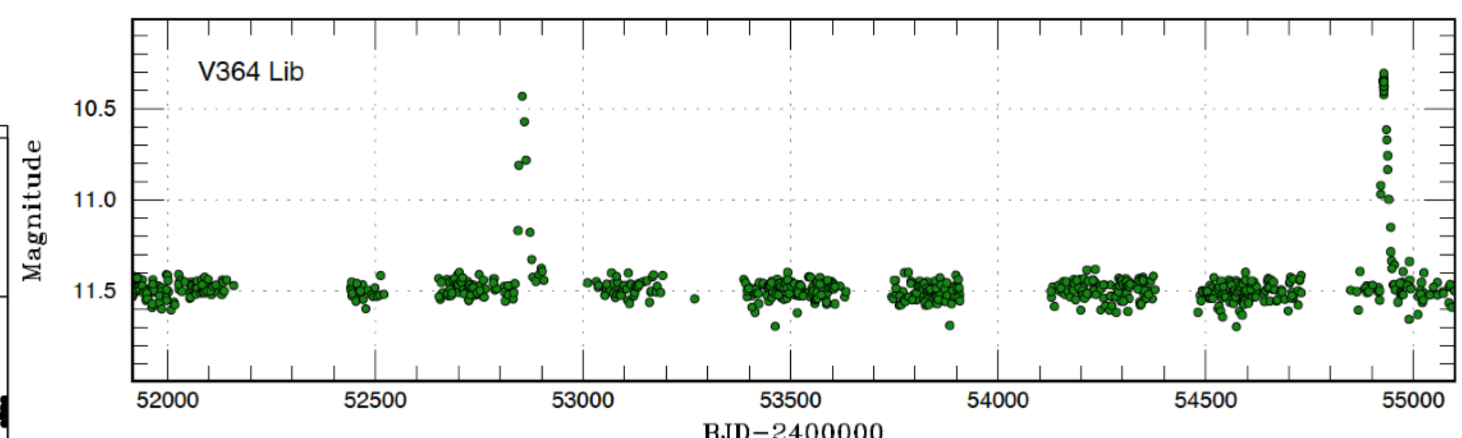
Violent & short-term variability



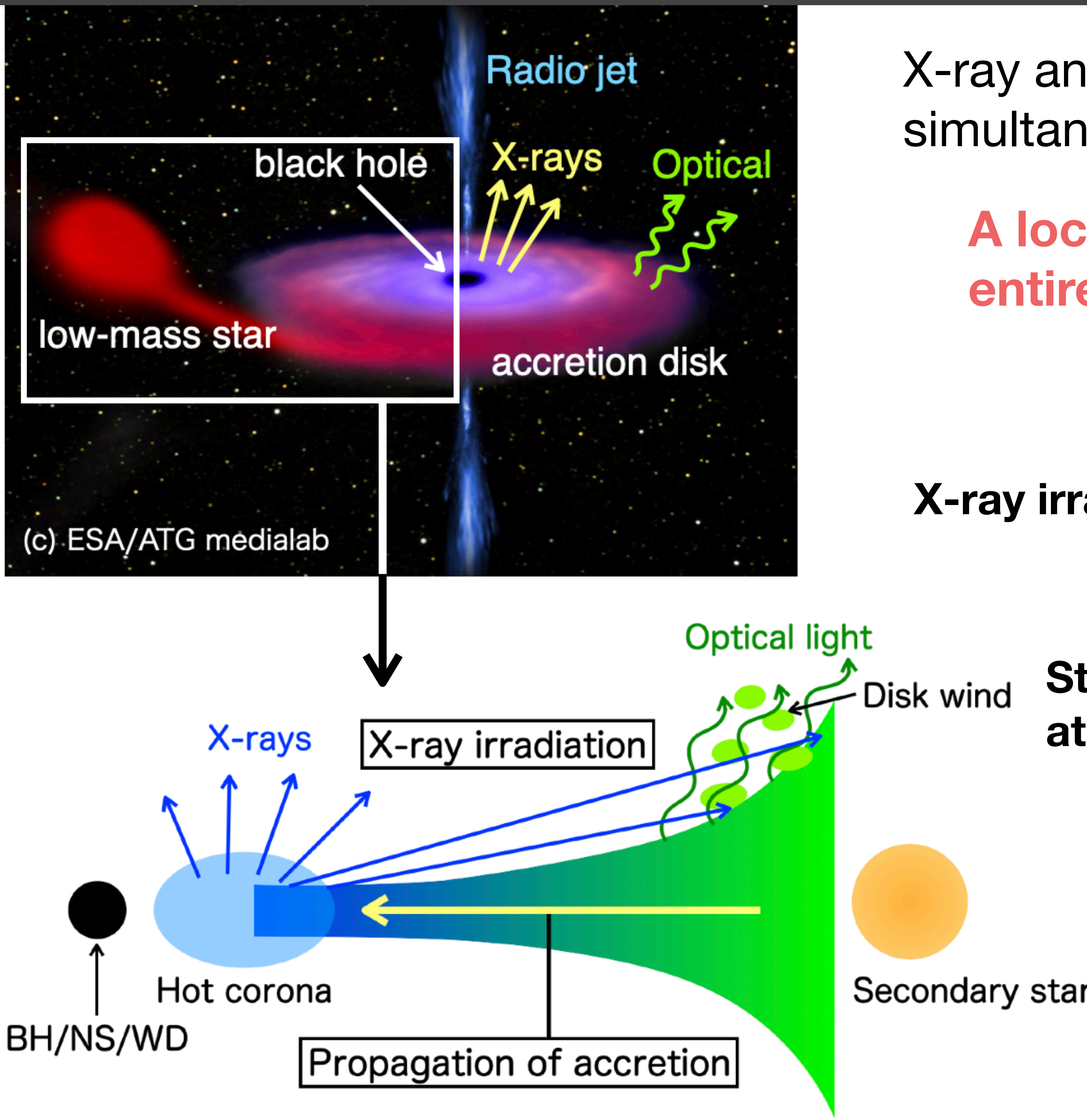
Alternation between standstill and outbursts



Low-amplitude & infrequent outbursts



Importance of multi-wavelength observations



X-ray and optical observations were not simultaneously performed. However, ..

A local phenomenon affects the entire accretion physics.

X-ray irradiation → **Variations of temperature at the outer disk, winds** → **Transfer of mass & angular momentum** → **State transition at the inner disk** → **X-ray irradiation**

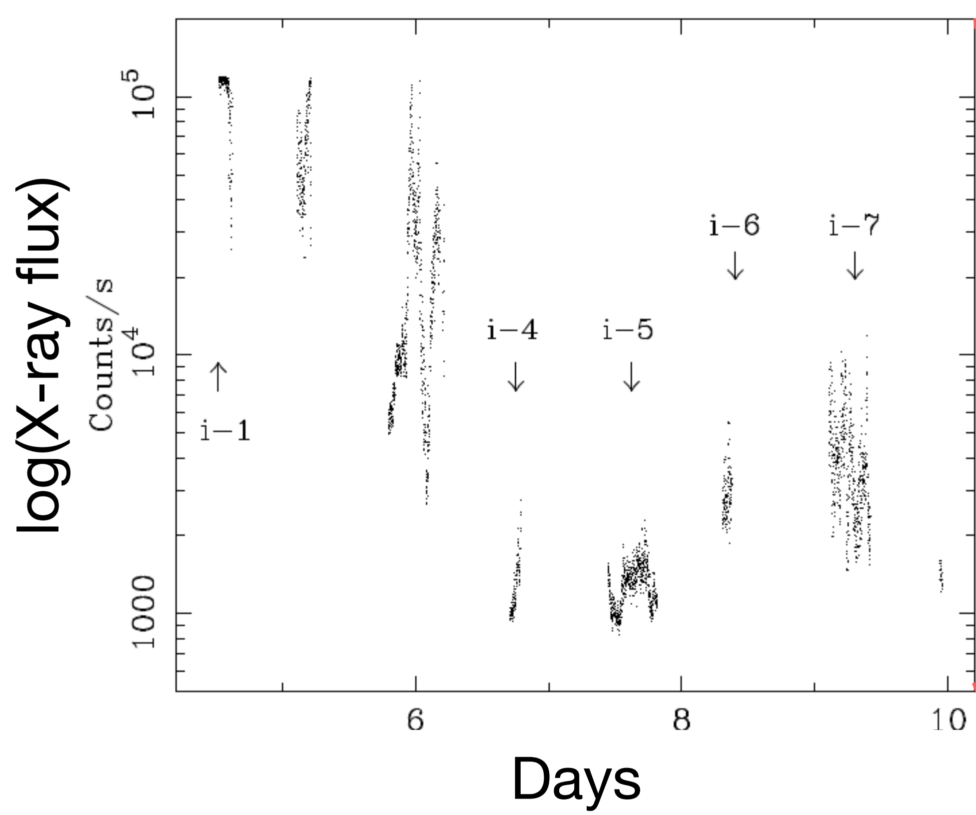
Multi-wavelength observations uncover the entire accretion physics.

Study 1: Repetitive optical & X-ray variability in the black-hole binary V404 Cyg

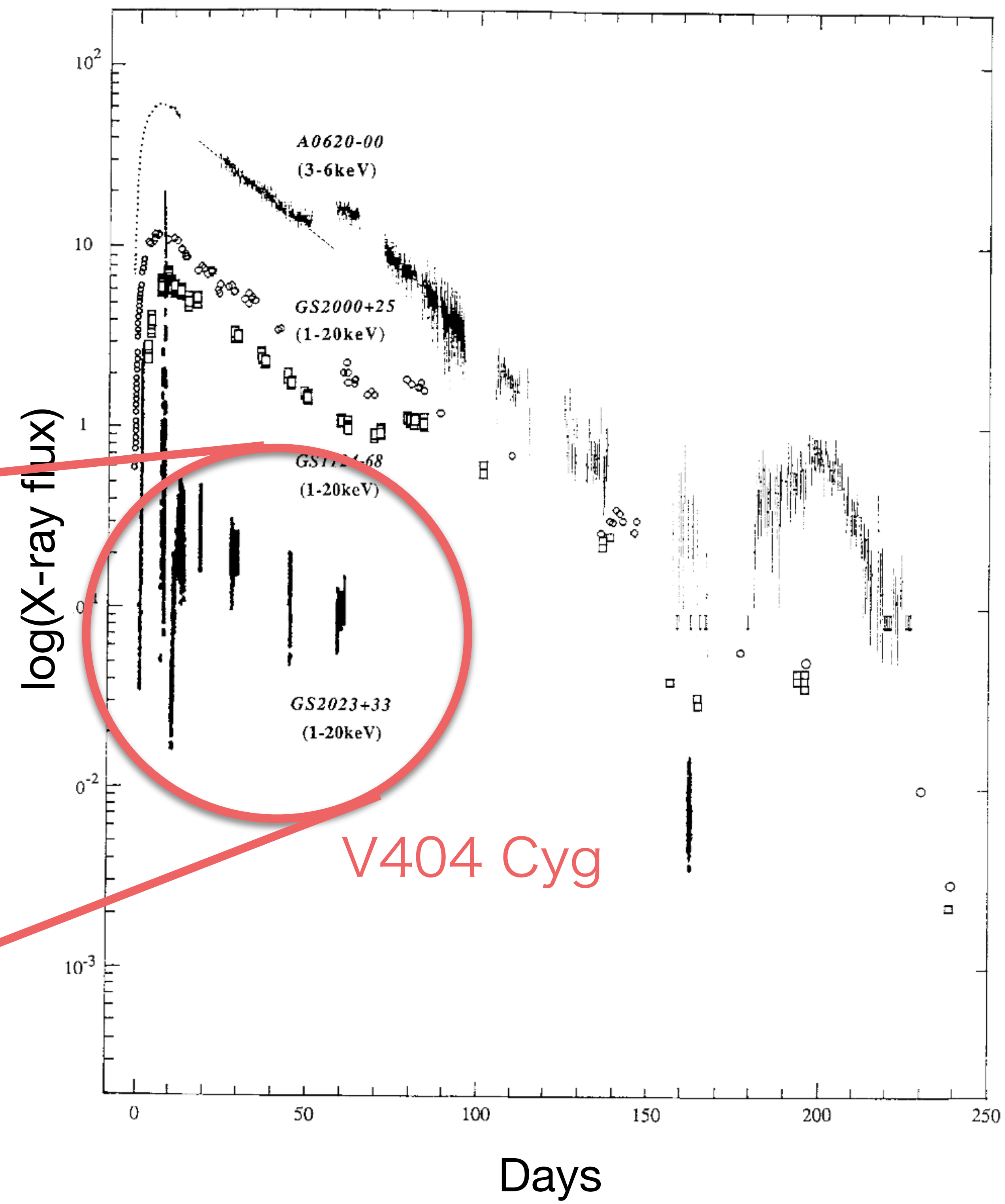
What is V404 Cygni ?

- One of black-hole low-mass X-ray binaries
- ~9 solar mass black hole
- Located near the Earth: 7,800 light years
- Violent X-ray variations in outburst

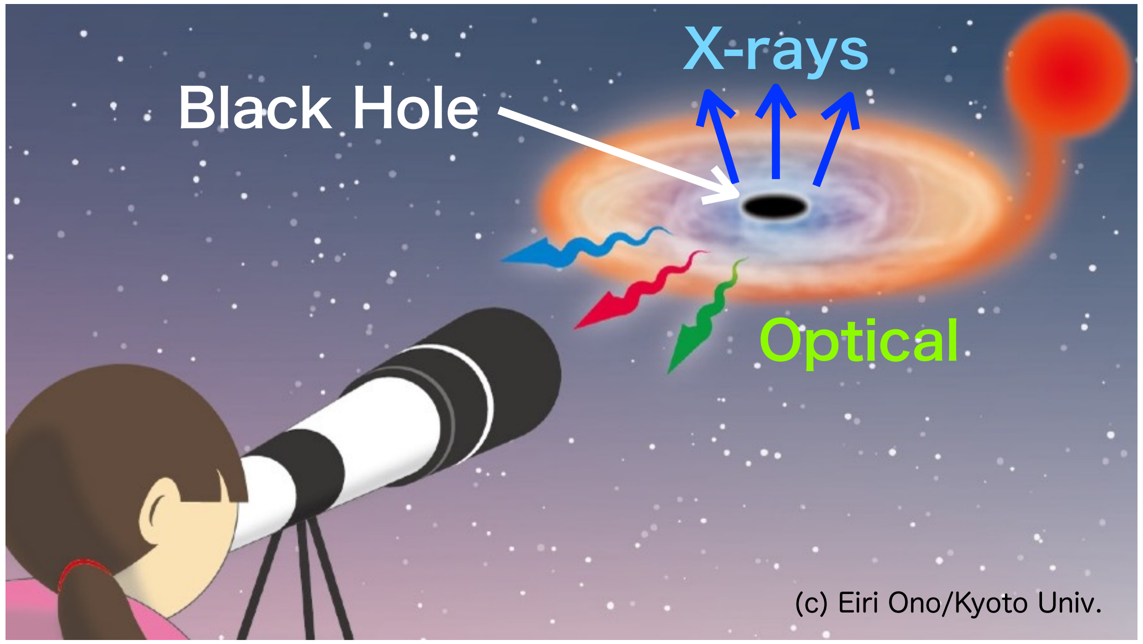
↓ Light Curves in the 1989 outbursts
(Zycki et al., 1999, MNRAS)



(Tanaka & Shibazaki, 1996)

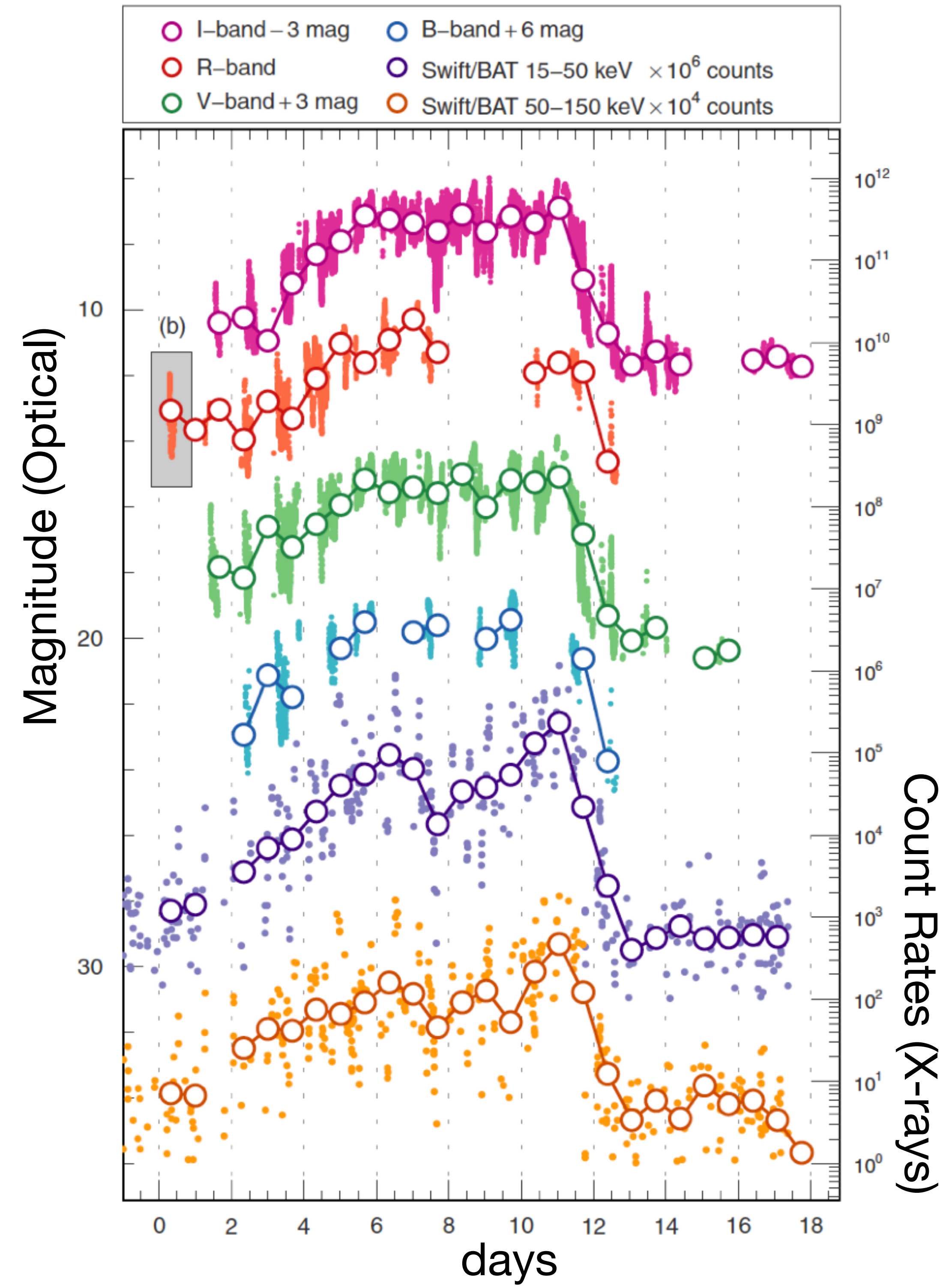


The 2015 summer outburst in V404 Cyg

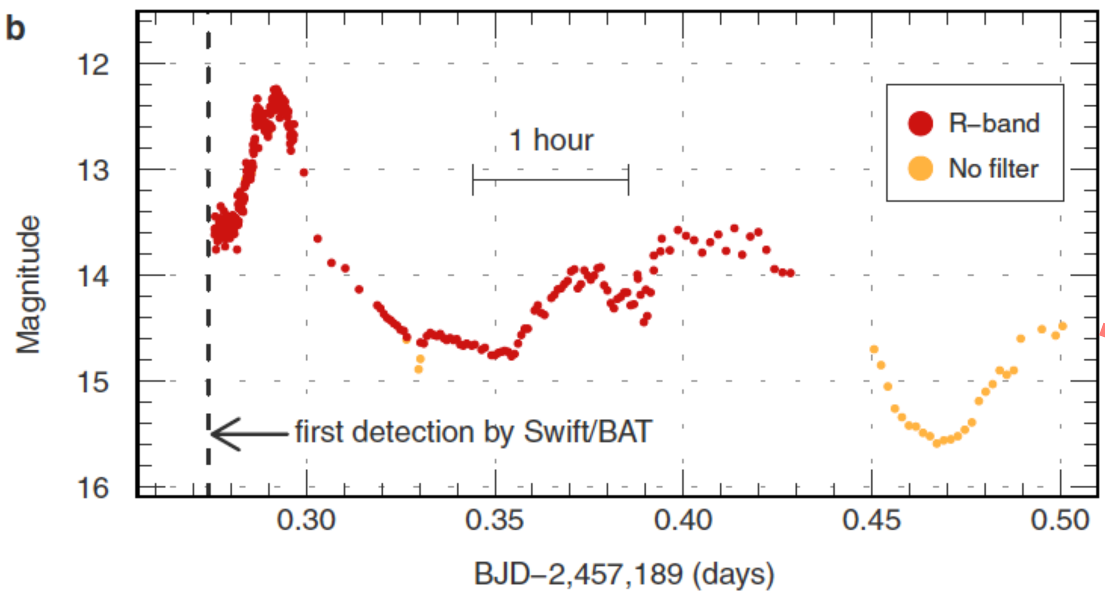


↑ Including many amateur observers

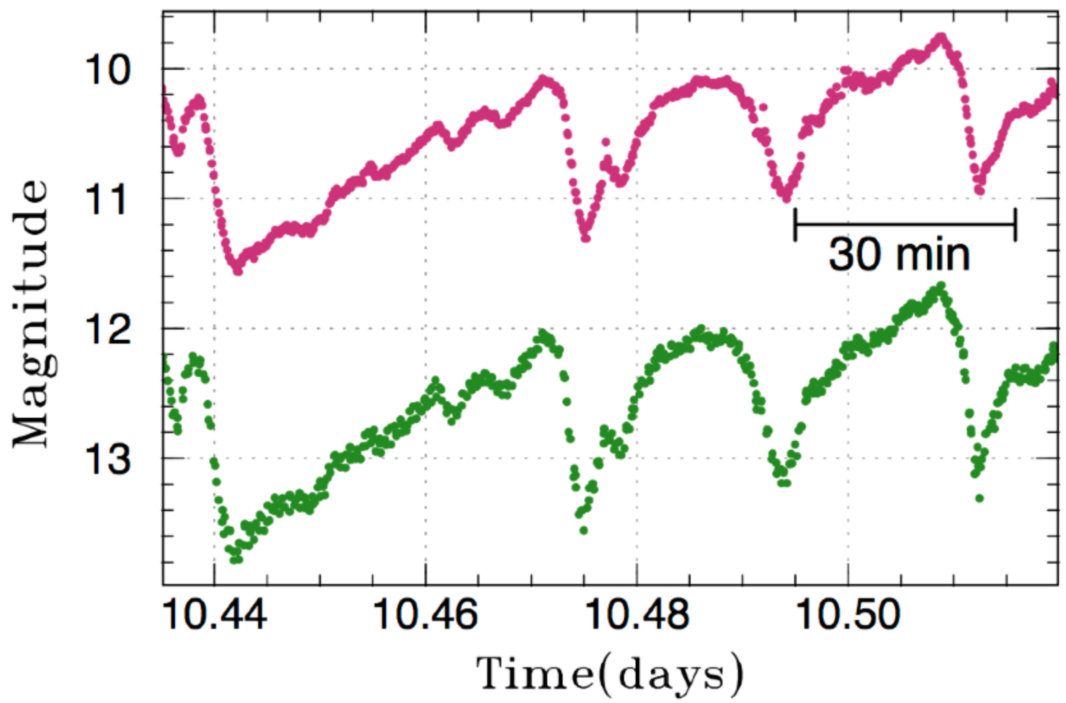
(Kimura et al. 2016)

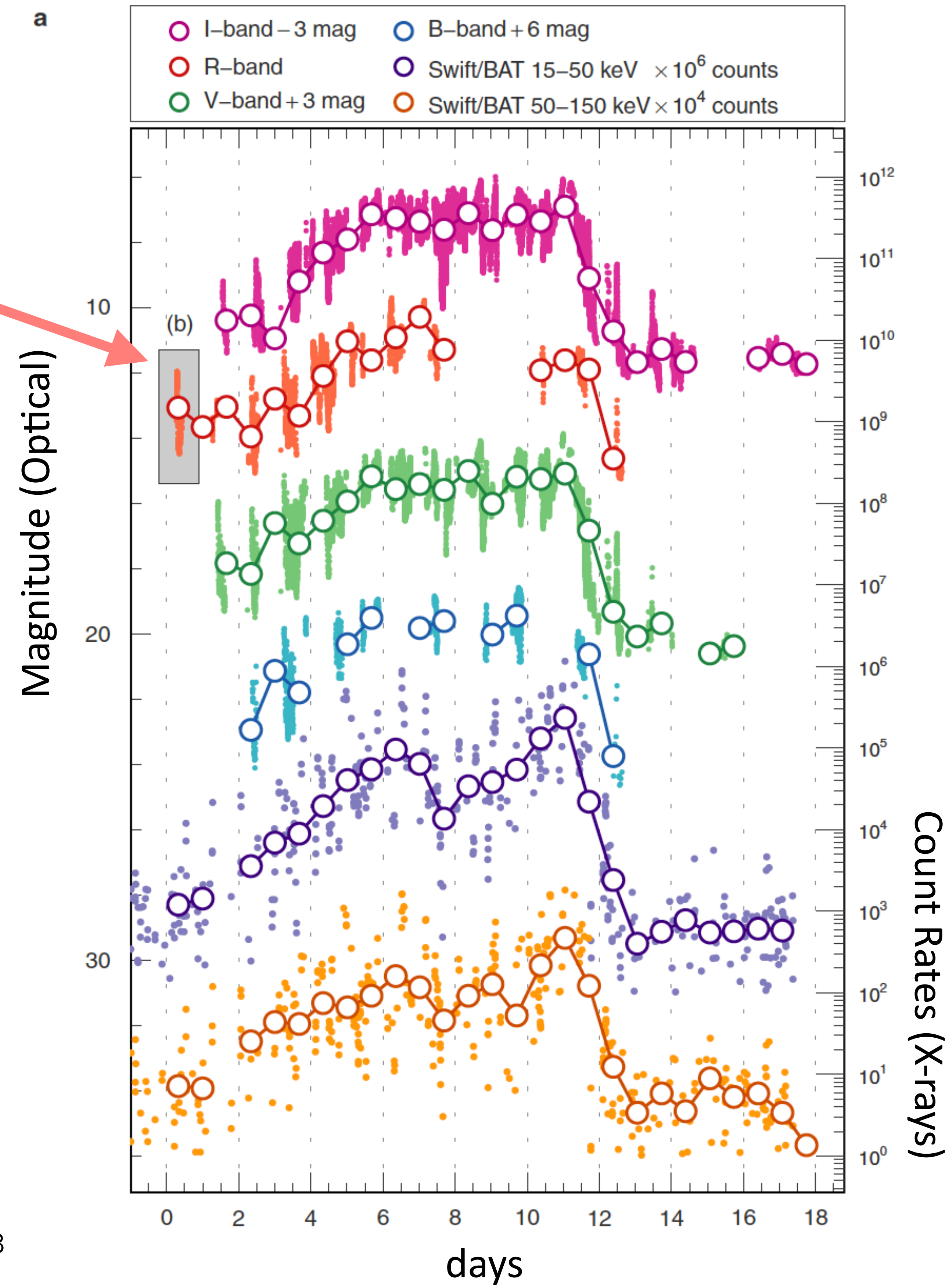


Violent optical variability with repetitive patterns

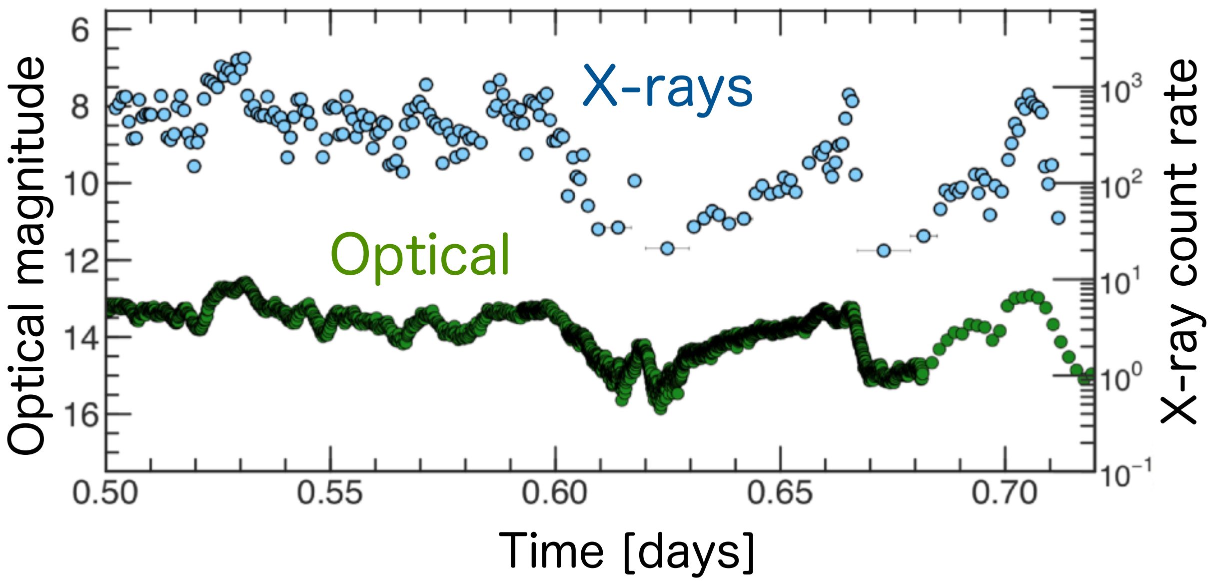


↑ less than 3 minutes after the first detection !

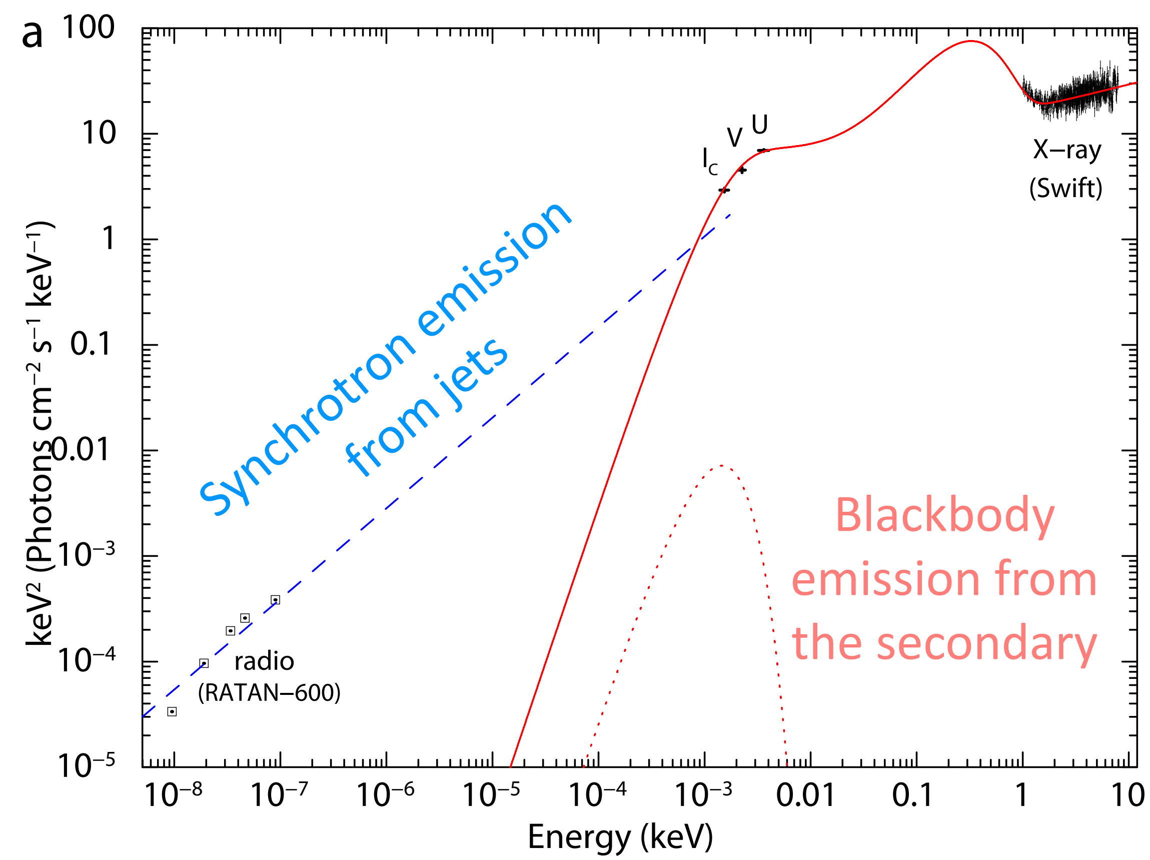




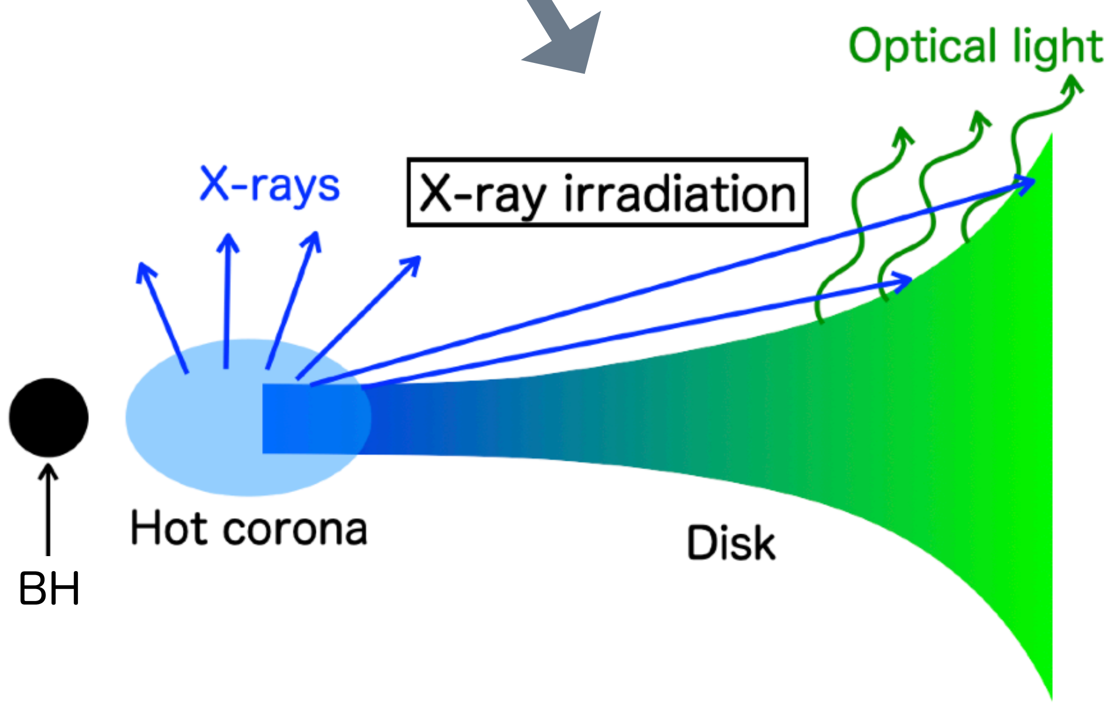
Correlation with X-ray variability



~1 min delay of optical variability against X-ray variability (Gandhi et al. 2016)

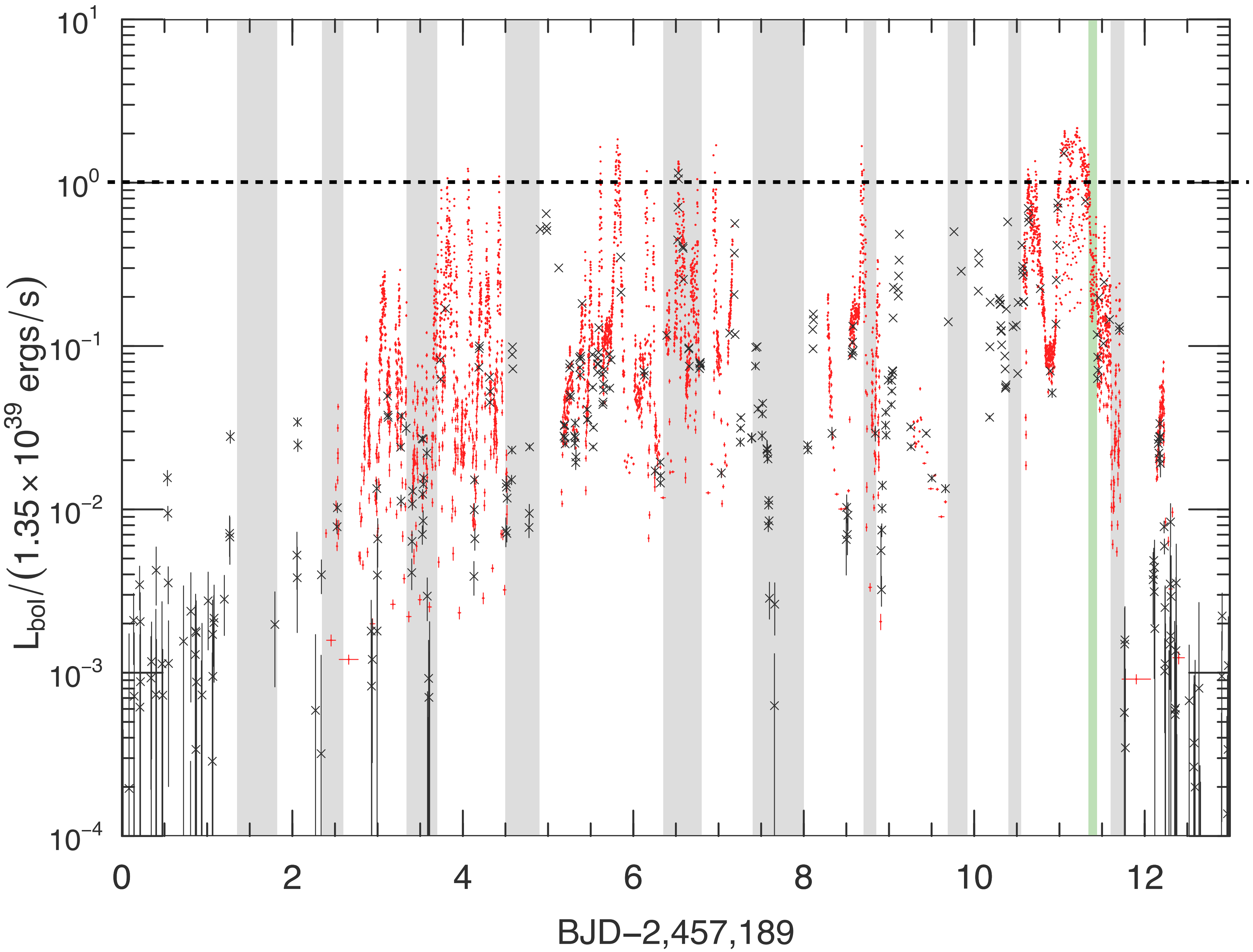


Synchrotron emission is not enough ..



We can see the violent activity in the vicinity of the black hole at optical wavelengths !

Violent variability at low luminosity

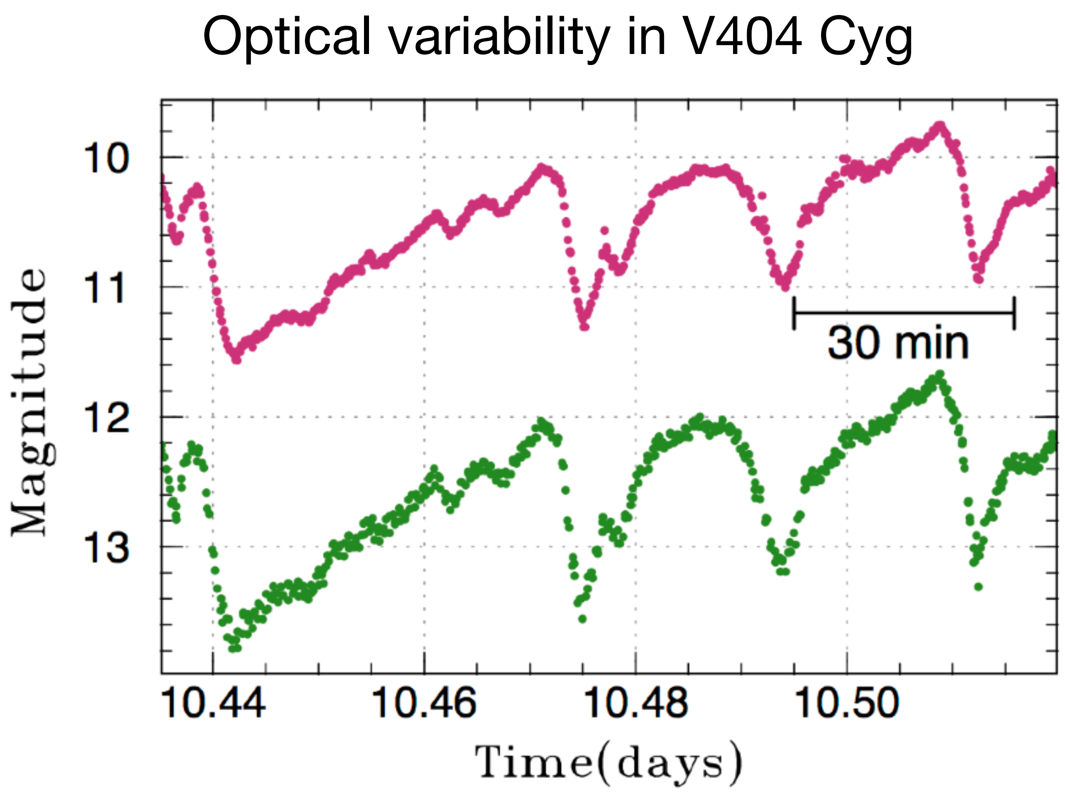


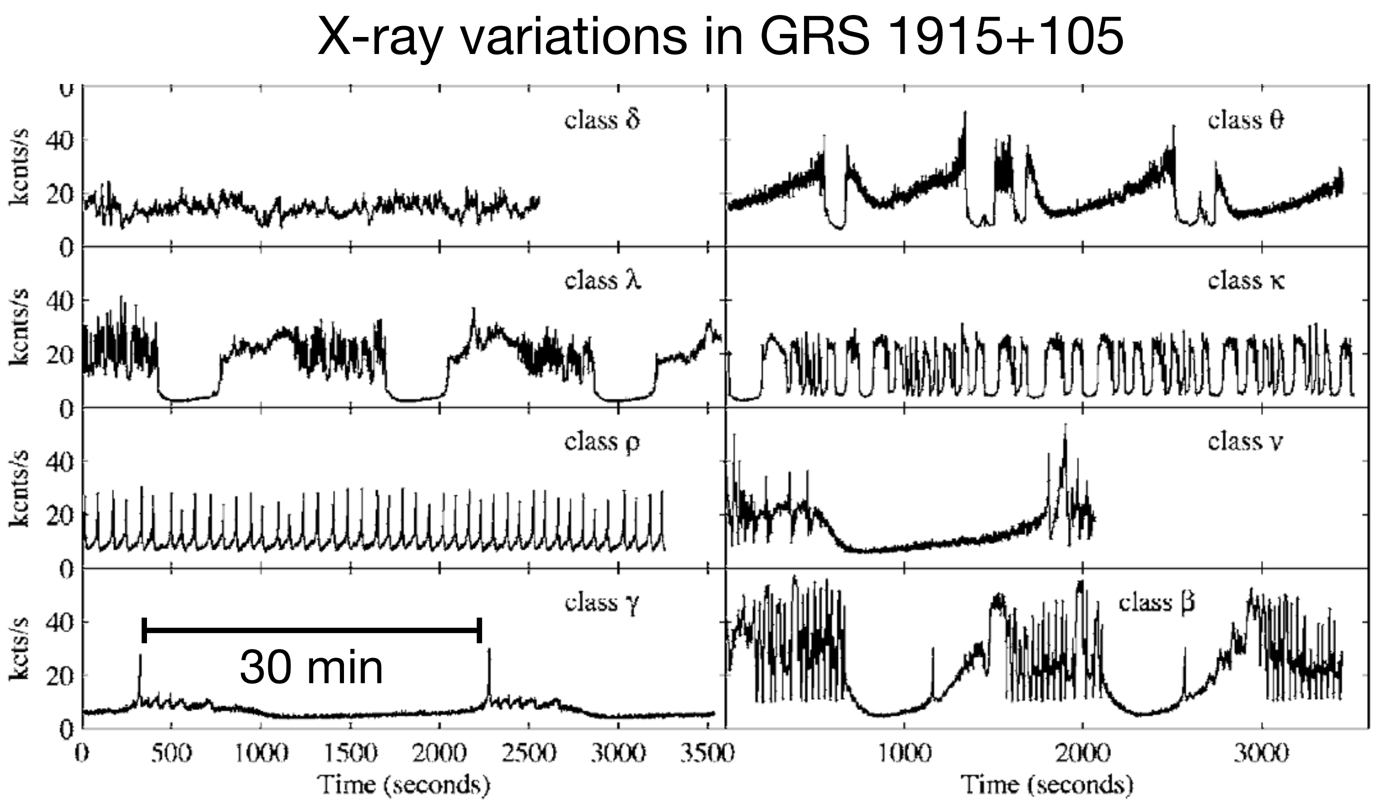
Black: Swift/BAT (15—50 keV)

Red: INTEGRAL/ISGRI (25—60 keV)

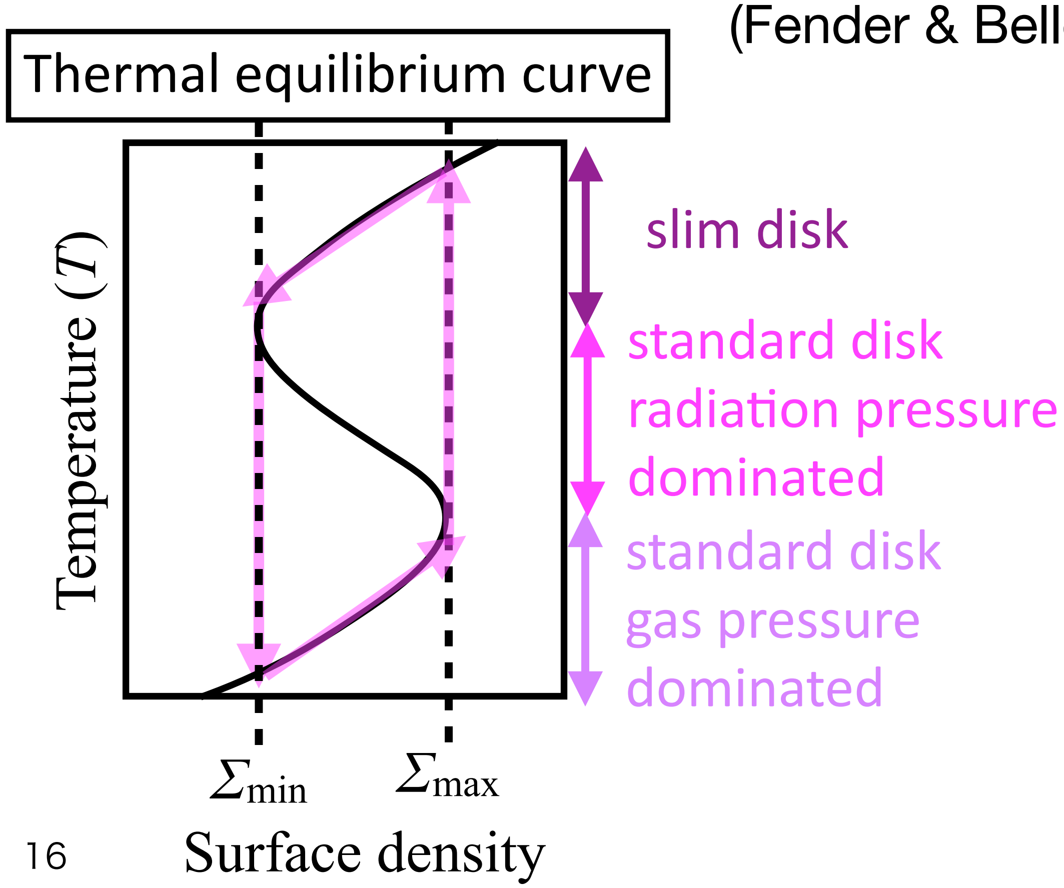
Violent optical variability occurred at 0.001—0.1 L_{Edd}.

Violent variability at low luminosity





(Fender & Belloni 2004)



Radiation-pressure instability does not cause this kind of variability in V404 Cyg..

Short summary

- V404 Cyg entered outbursts in 2015 after 26 yrs dormancy.
- We found **large-amplitude & short-term optical variations with repetitive patterns** for the first time.
- The optical variations were well-correlated with the simultaneous X-ray variations.
- X-ray irradiation was dominant in optical emission.
- Violent variability occurred at low luminosity -> Radiation-pressure instability is unlikely as the mechanism of these variations

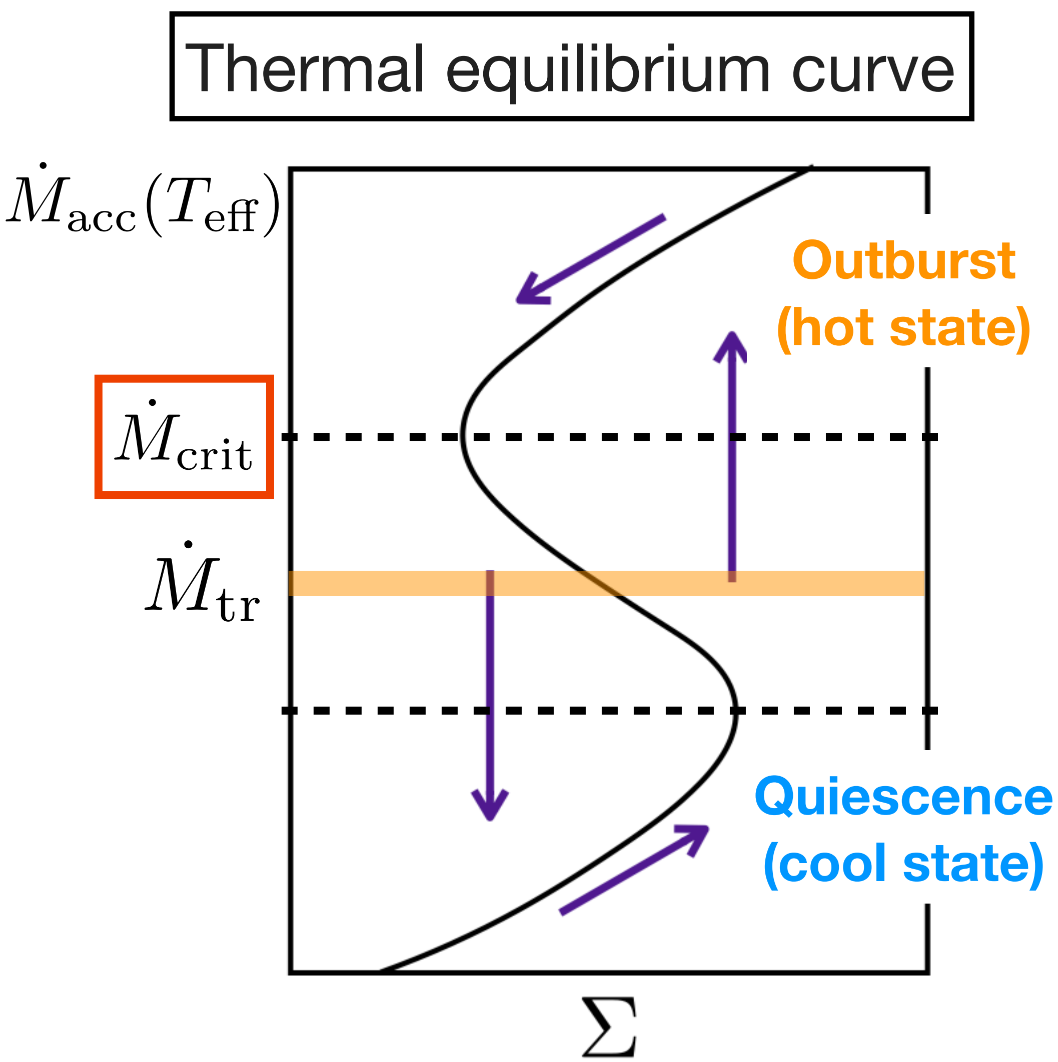
Another kind of instability for long-period systems ?

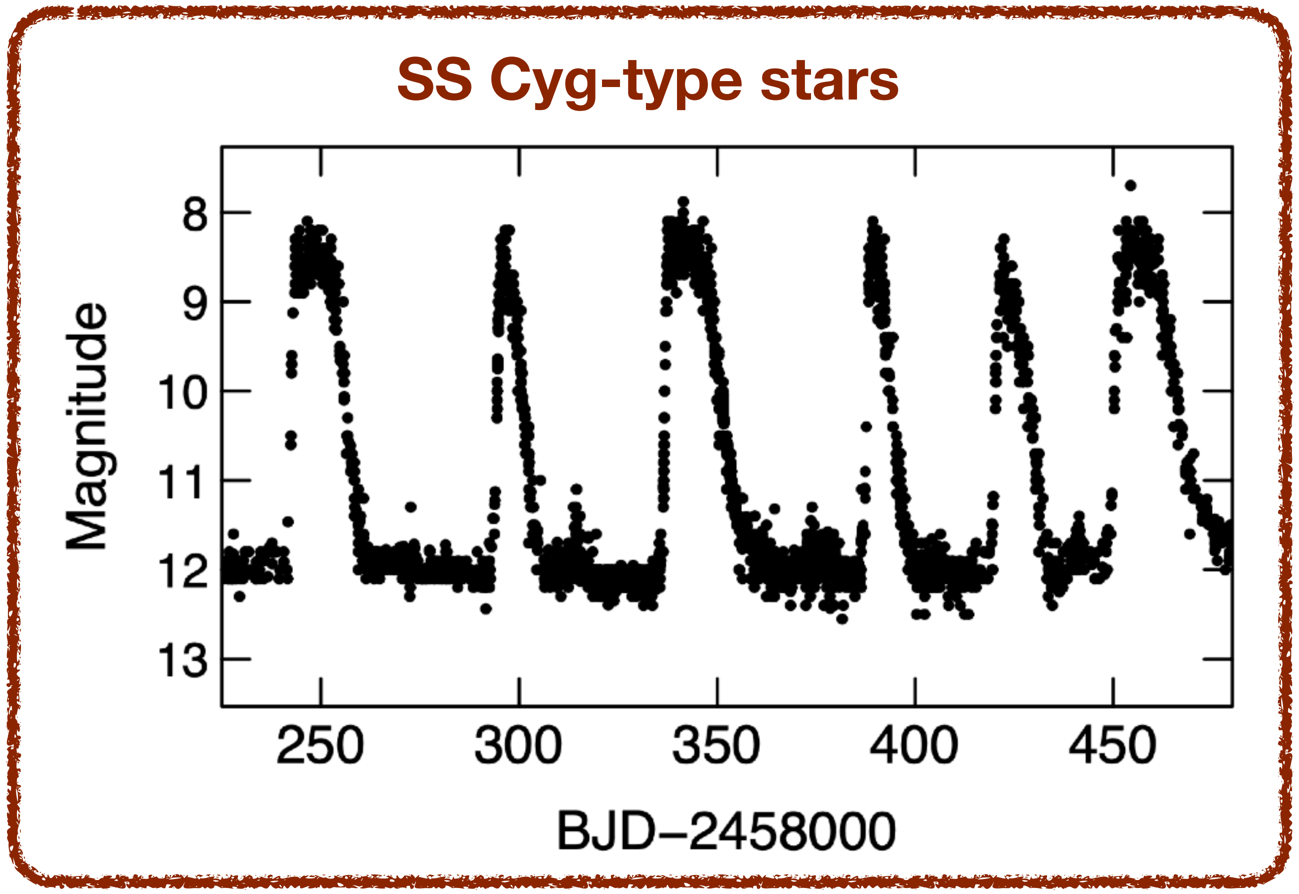
Object name	Orbital period
V404 Cyg	6.5 d
GRS 1915+105	33.9 d
IGR J17091-3624	> 4 d
V4641 Sgr	2.8 d

Kimura et al. (2016, Nature, 54, 529): ``Repetitive patterns in rapid optical variations in the nearby black-hole binary V404 Cygni"

Study 2: Standstill-like phenomenon in the white-dwarf binary SS Cyg

Classification of dwarf novae



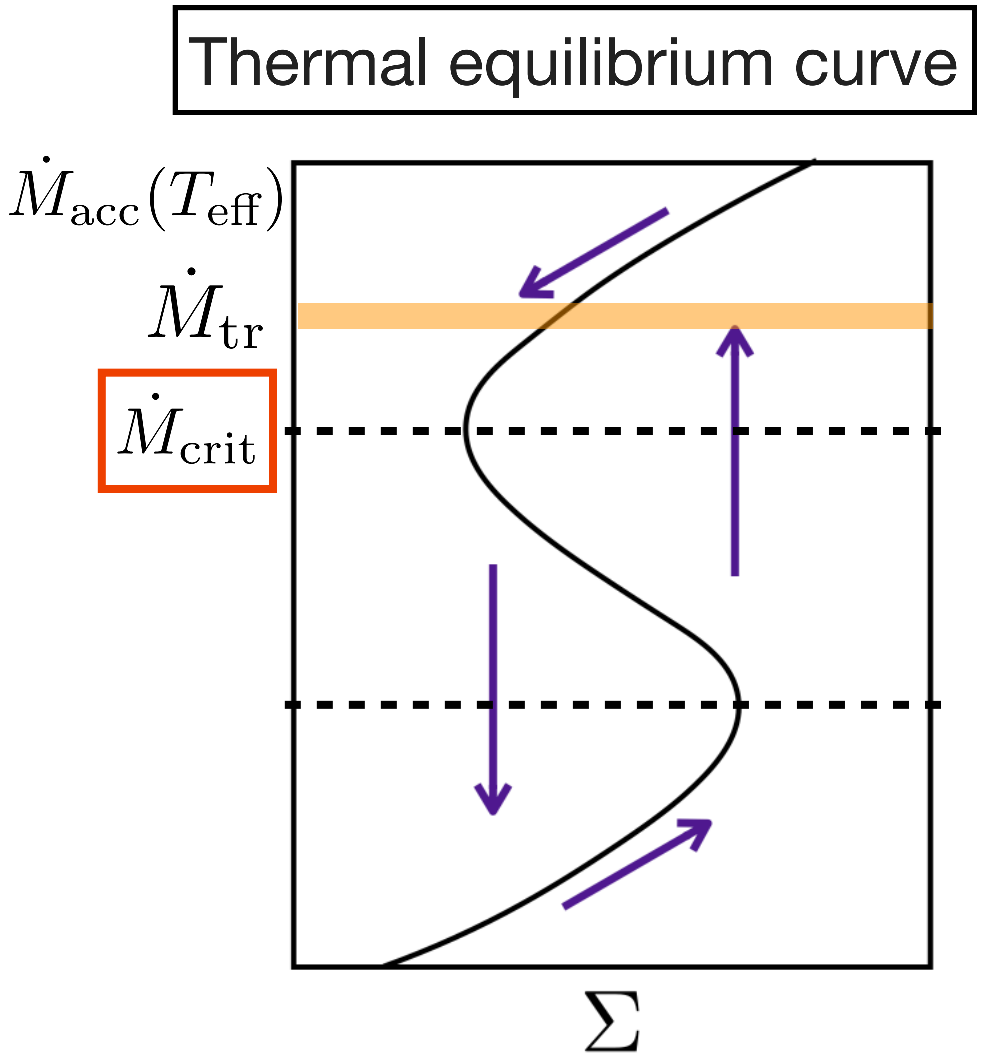


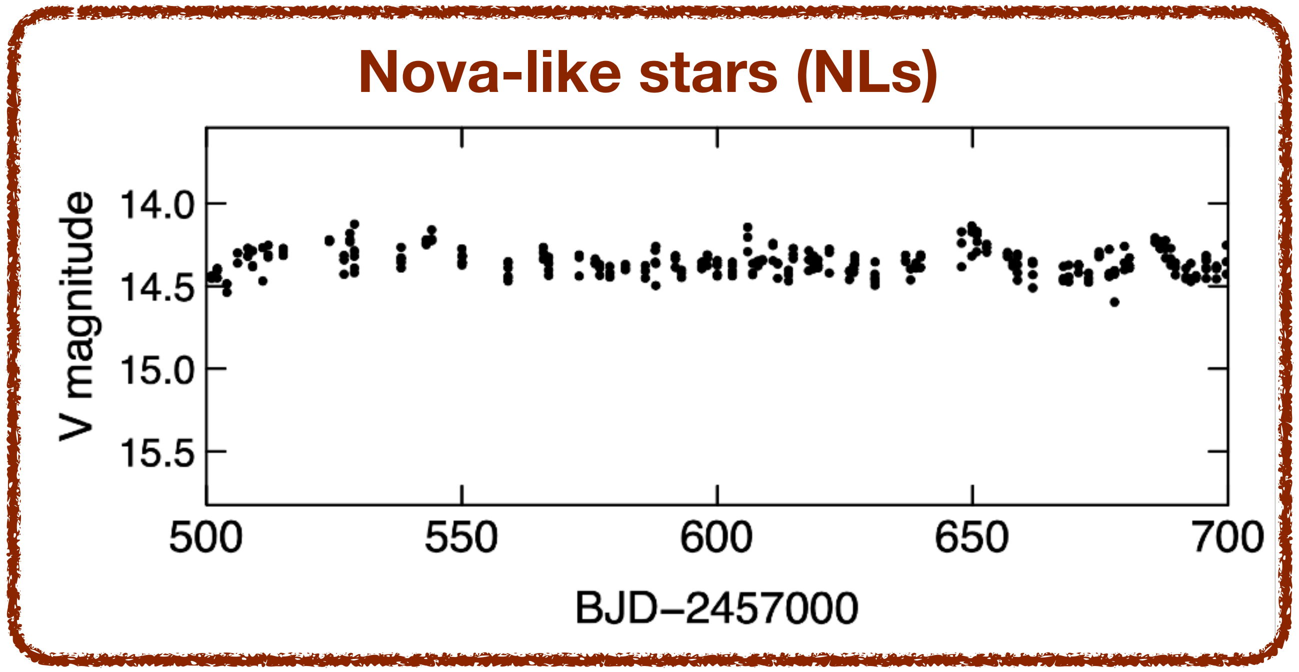
$\dot{M}_{\rm tr} < \dot{M}_{\rm crit}$

- Thermally **unstable** disk
- Repeat outbursts

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

Classification of dwarf novae



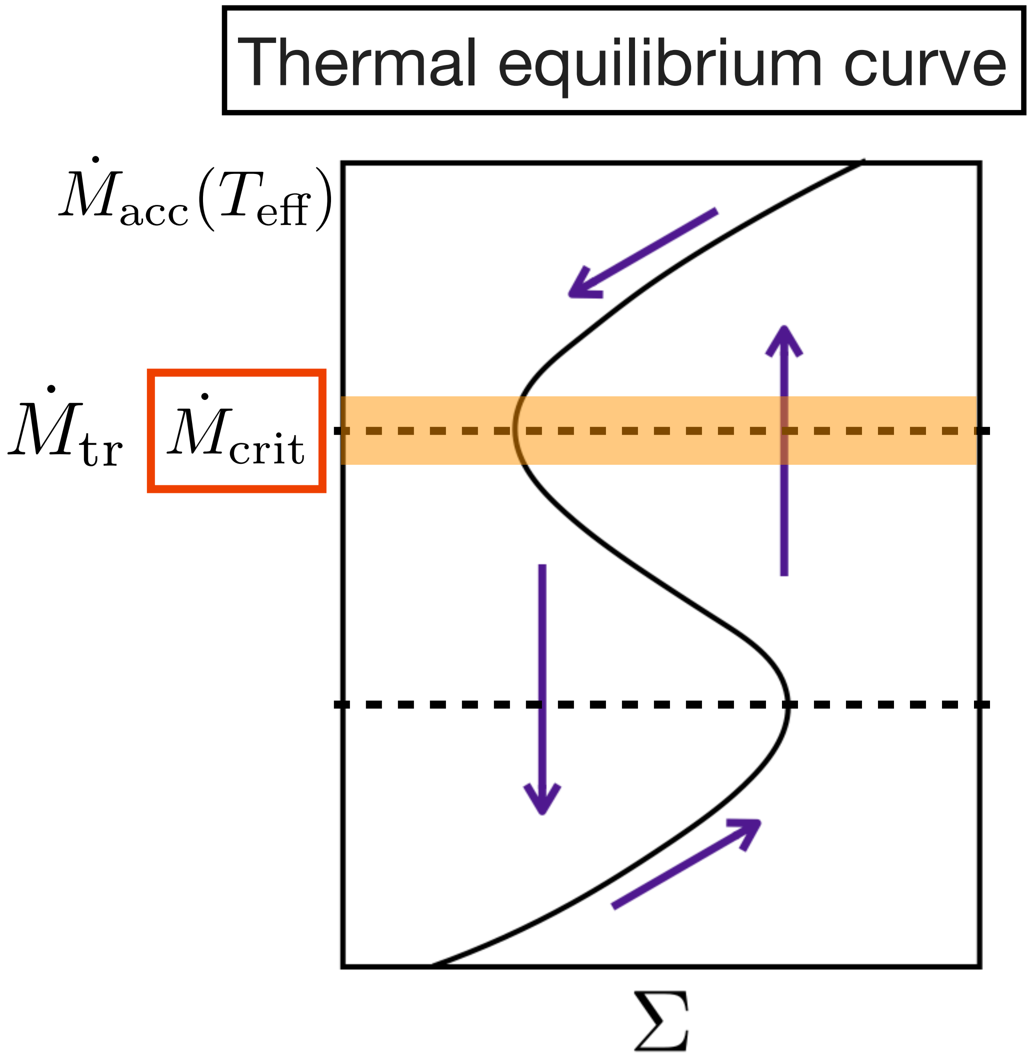


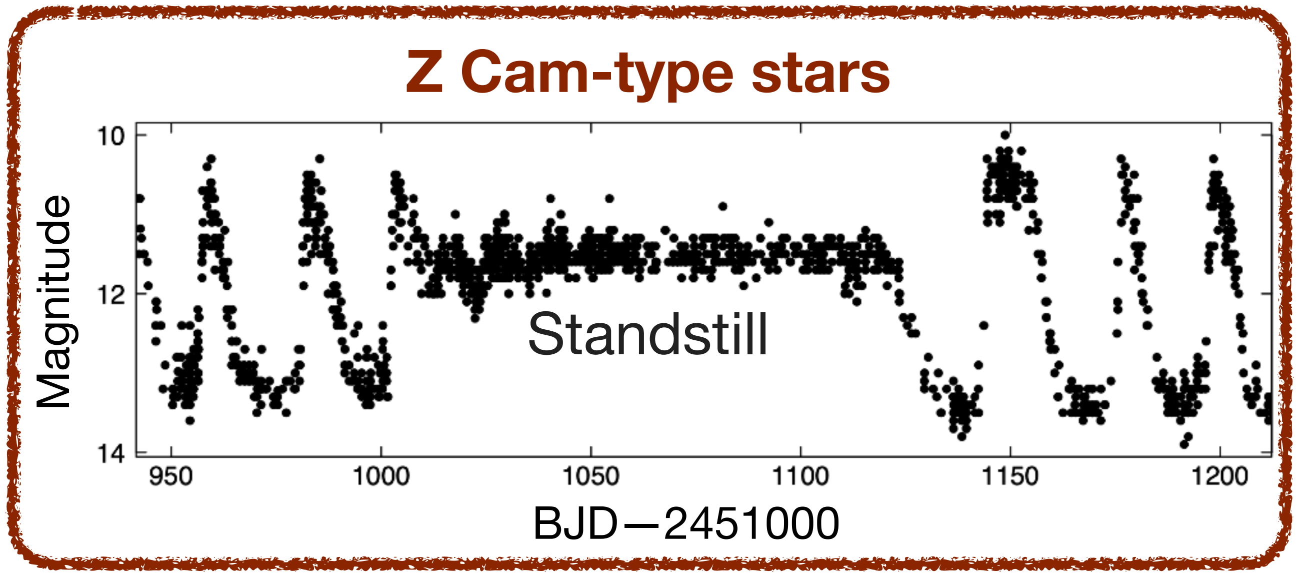
$\dot{M}_{tr} > \dot{M}_{crit}$

- Thermally **stable** disk
- Constant luminosity

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

Classification of dwarf novae





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

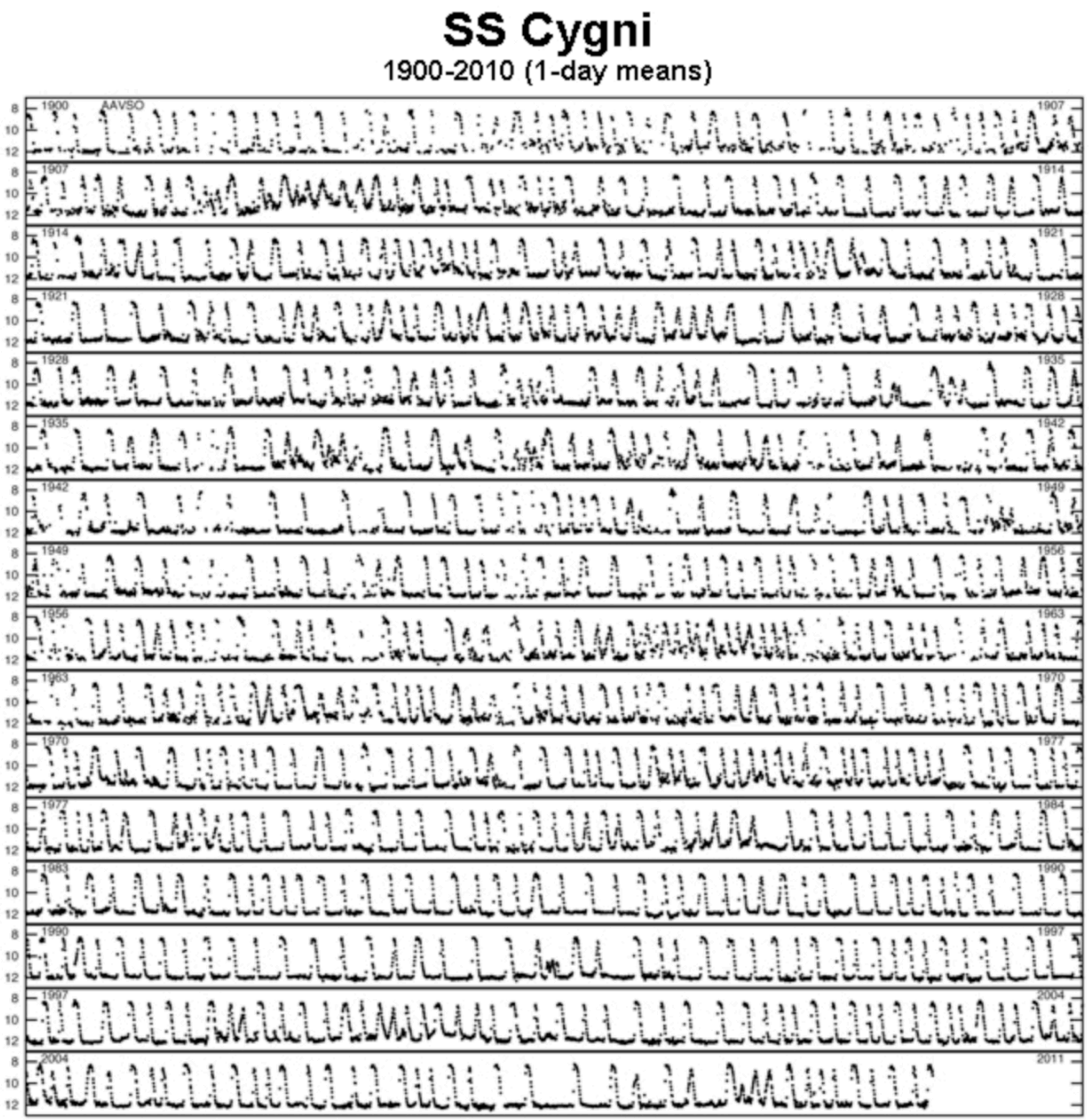
- Intermediate type between NLs and SS Cyg stars
- **Fluctuations of mass transfer rates ?**

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

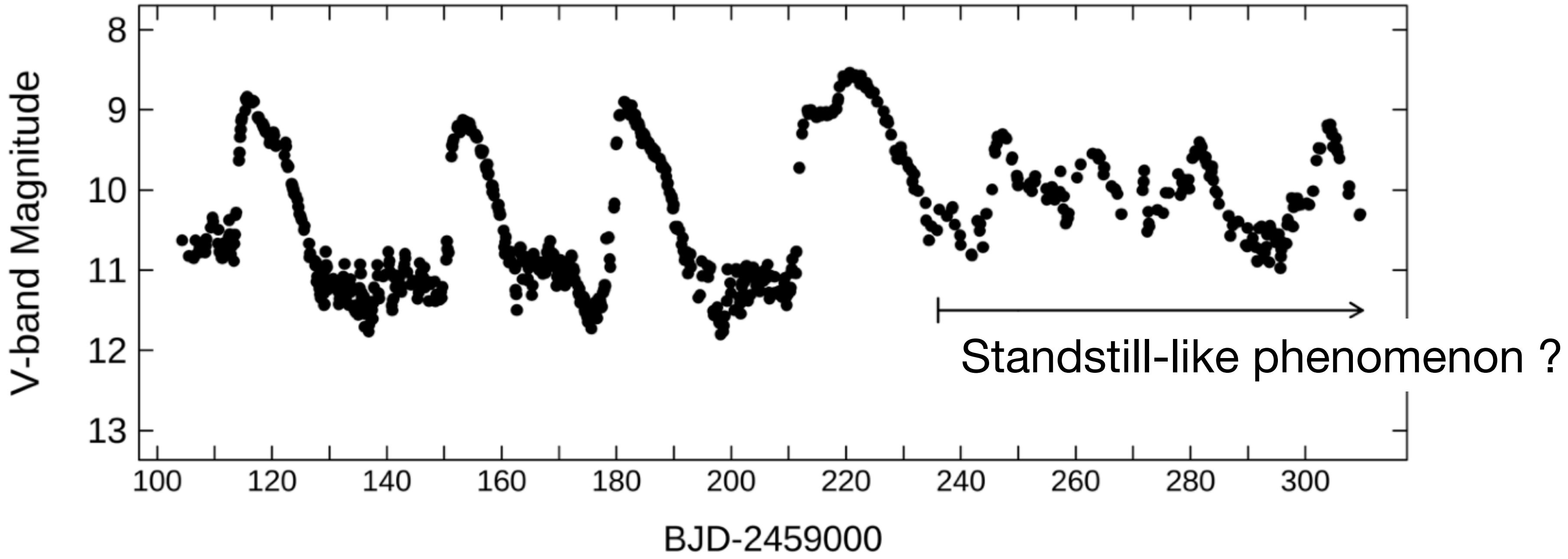


(Historical light curve of AAVSO)

- 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)

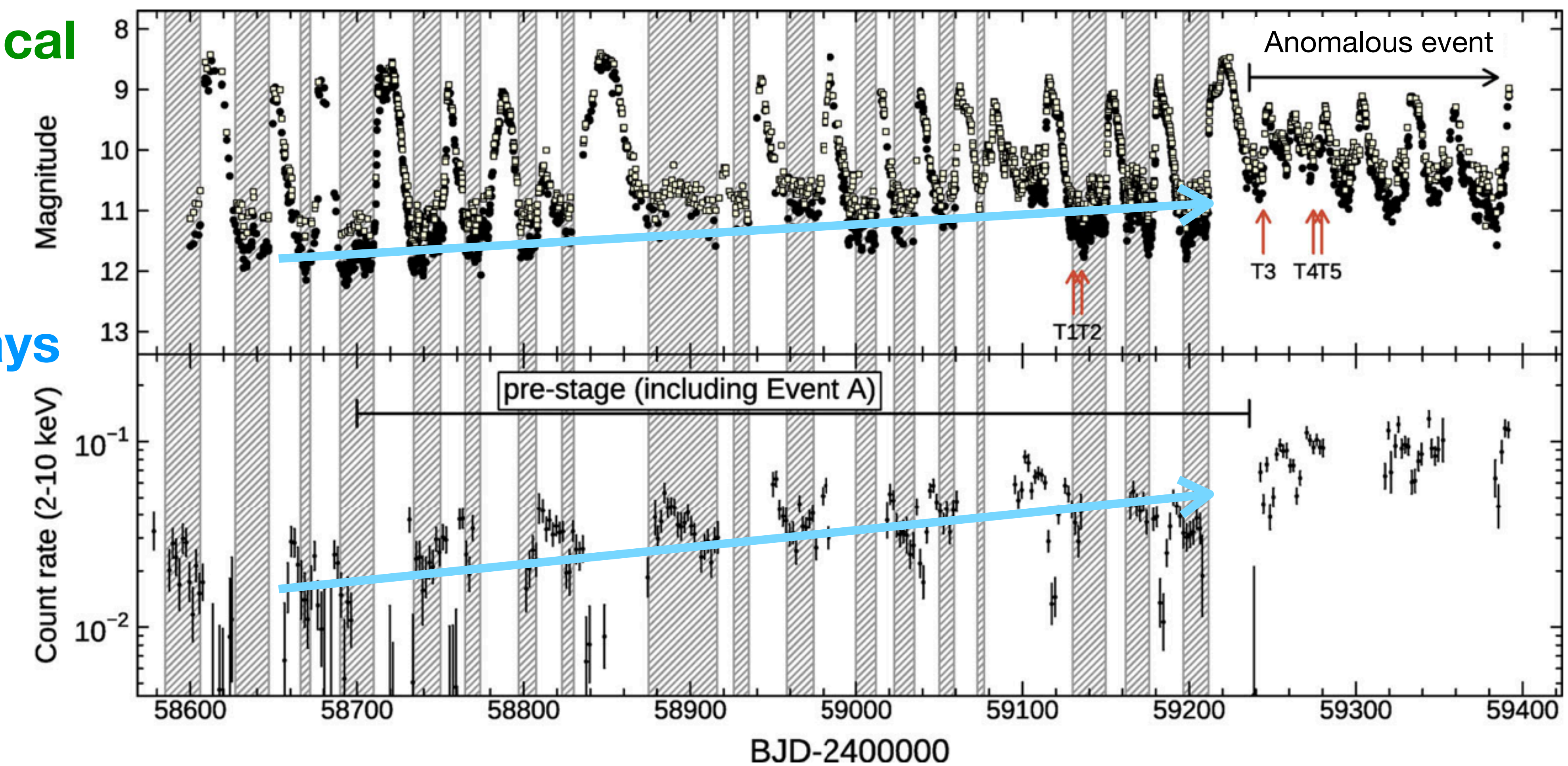
⟶ **What causes standstill in dwarf novae ?**

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

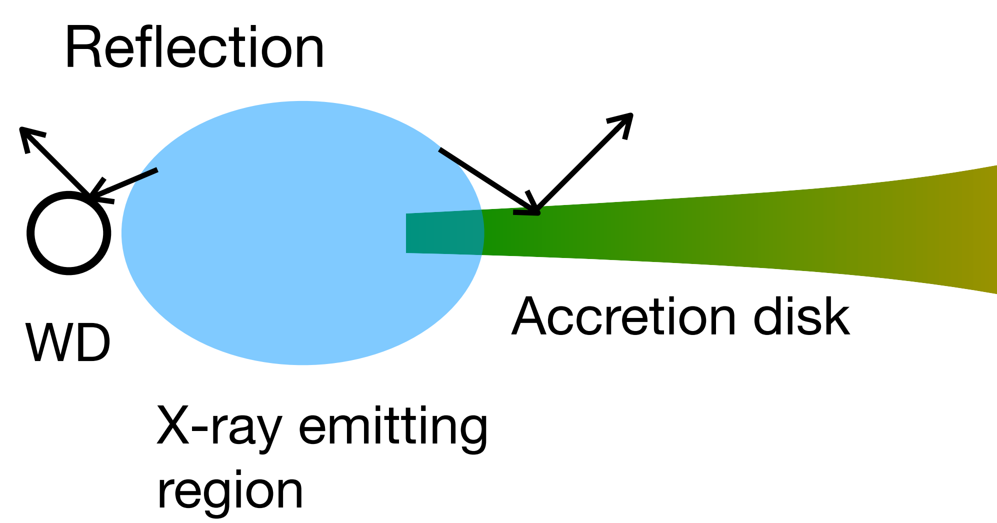
X-rays: NICER, NuSTAR, MAXI, Swift

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

To express Fe fluorescence line

- Tbabs * (reflect * cevmkl + gaussian)

Bremsstrahlung emissivity

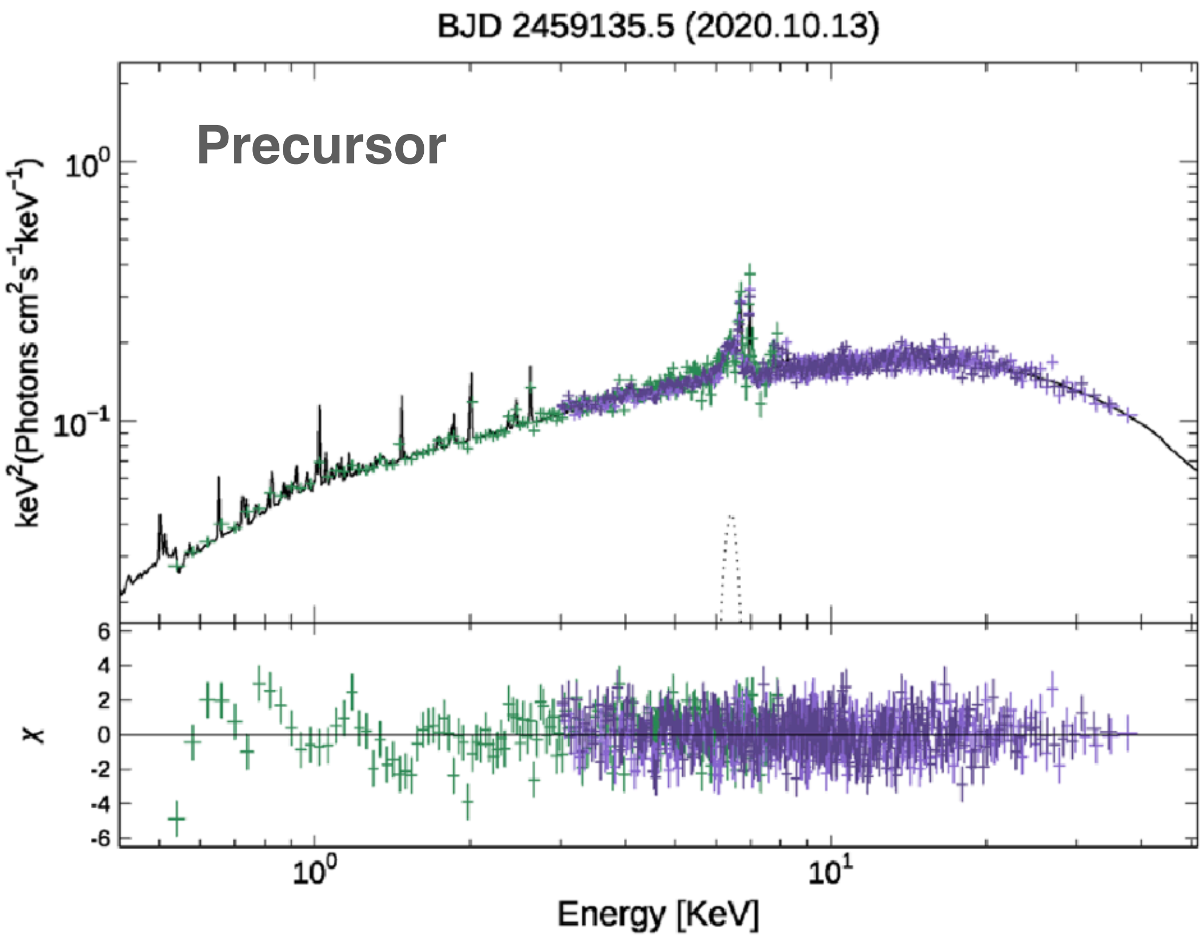
$$L(\nu) \propto \int_{T_{bb}}^{T_{max}} \frac{\epsilon(T, n^2, \nu)}{\epsilon(T, n^2)} dT$$

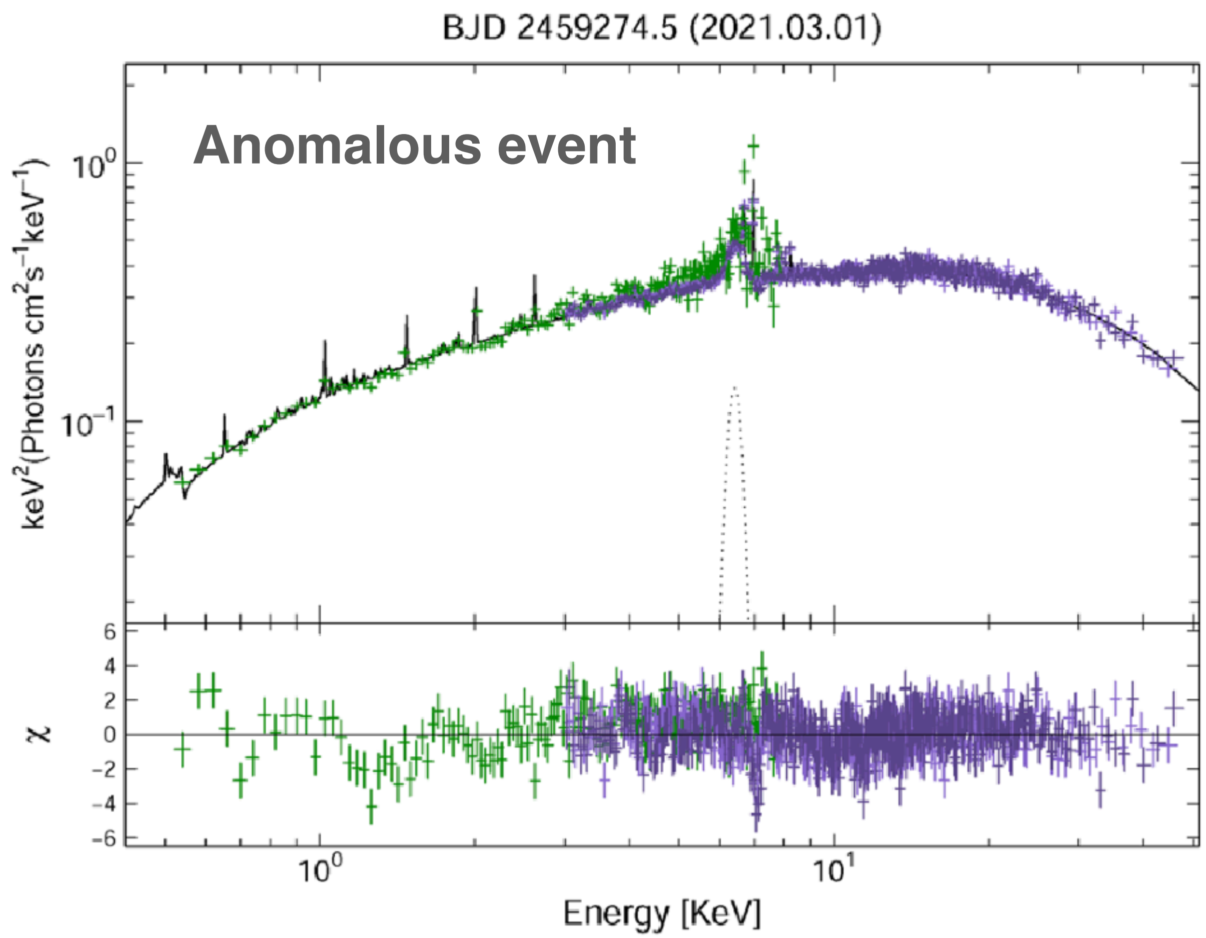
$$d(EM) \propto \left(\frac{T}{T_{\max}}\right)^{\alpha} d(\log T) \propto \left(\frac{T}{T_{\max}}\right)^{\alpha-1} dT,$$

(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



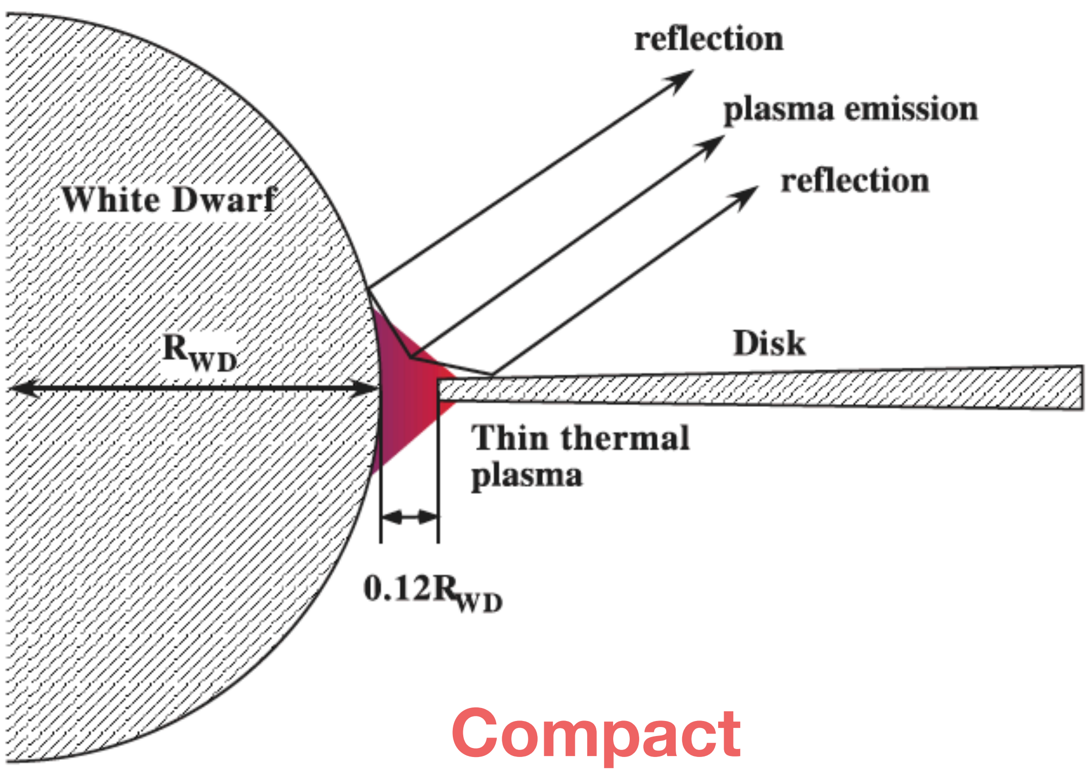


- T_max ~ 25–30 keV
- solid angle ~ 0.2—0.3
- Flux increases by ~2—5 times
- Lx ~ 10^{33} erg / s

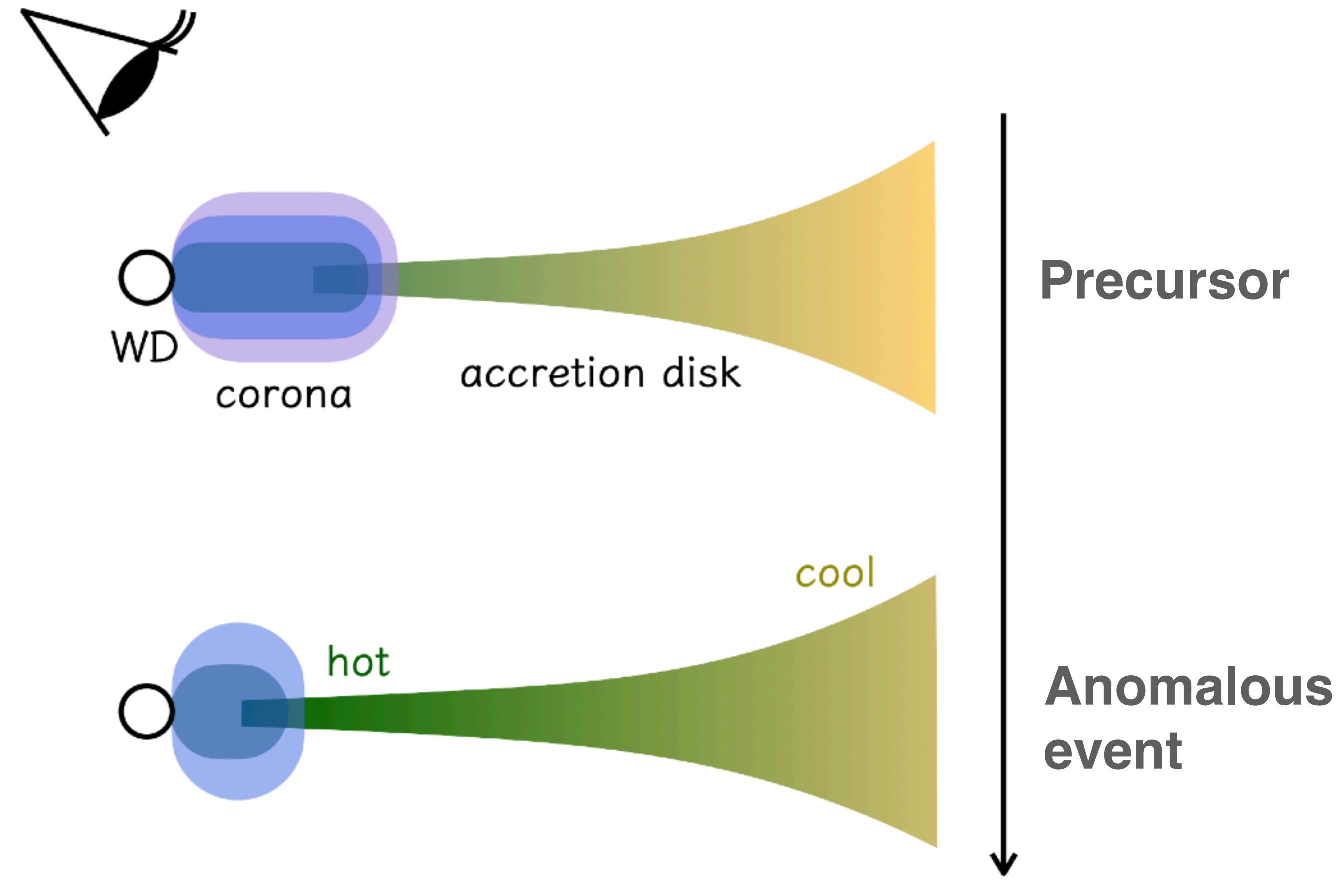
The X-ray irradiation of the disk and the secondary star is inefficient

Geometry of X-ray emitting plasma

Normal quiescence



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

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

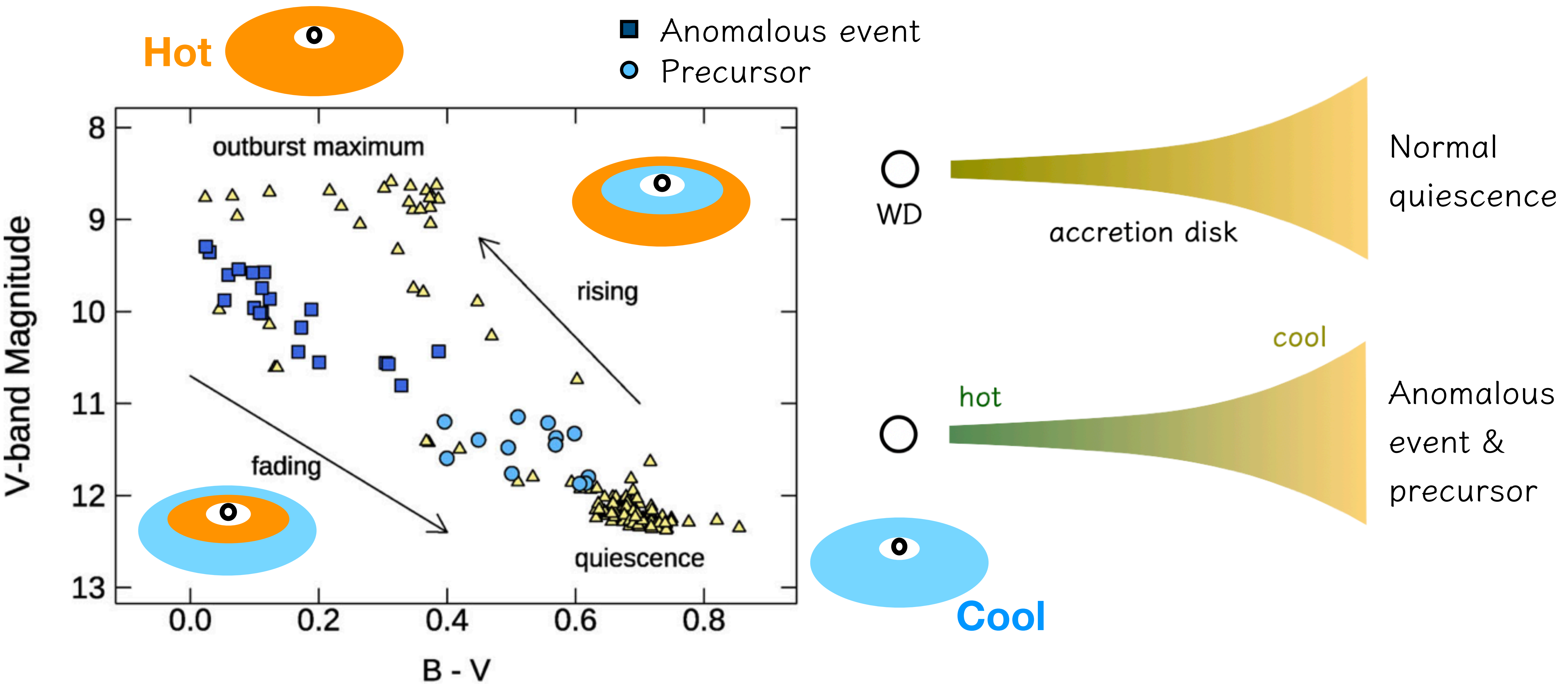
   ↑ No positive evidence

2. Strong X-ray irradiation of the disk and/or the secondary star

   ↑ Weak

3. The accretion rate in the disk increases for some reasons

Bright inner disk during quiescence



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

We can explain the increase of **both** of optical & X-ray flux.

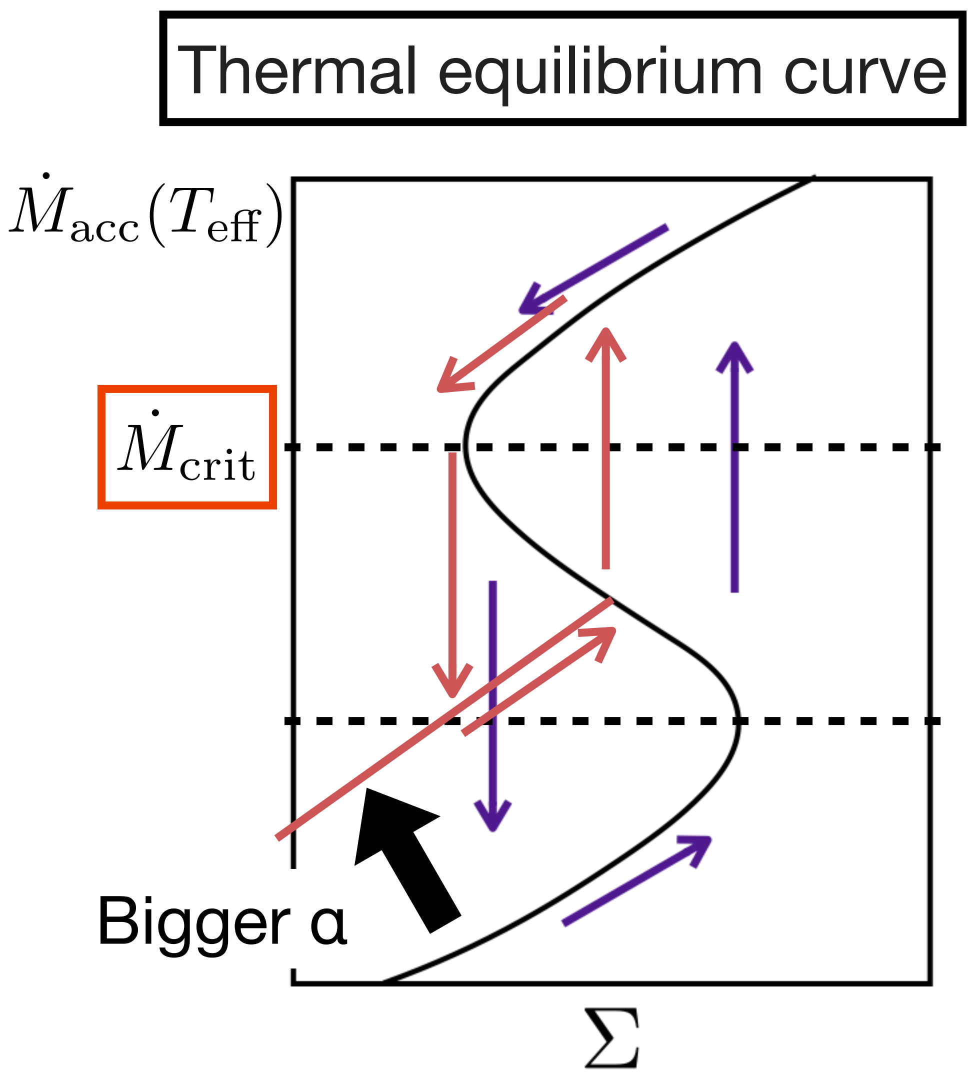
Temporal enhancement of viscosity in the cool state ?

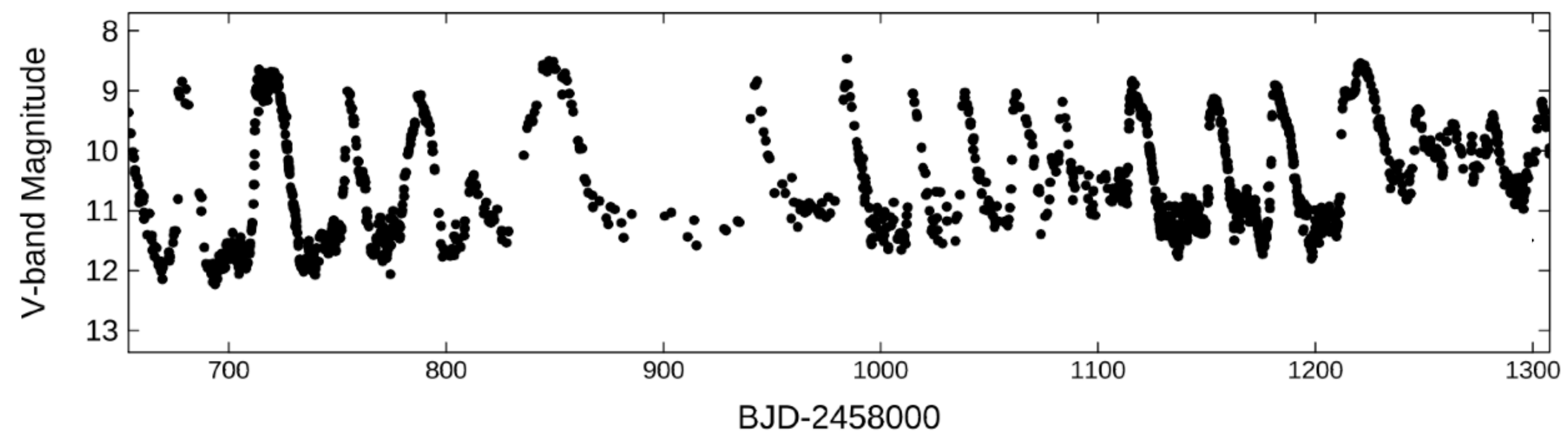
Effect of enhanced viscosity

- Enhancement of viscosity in the cool state

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

Frequent small and inside-out outbursts





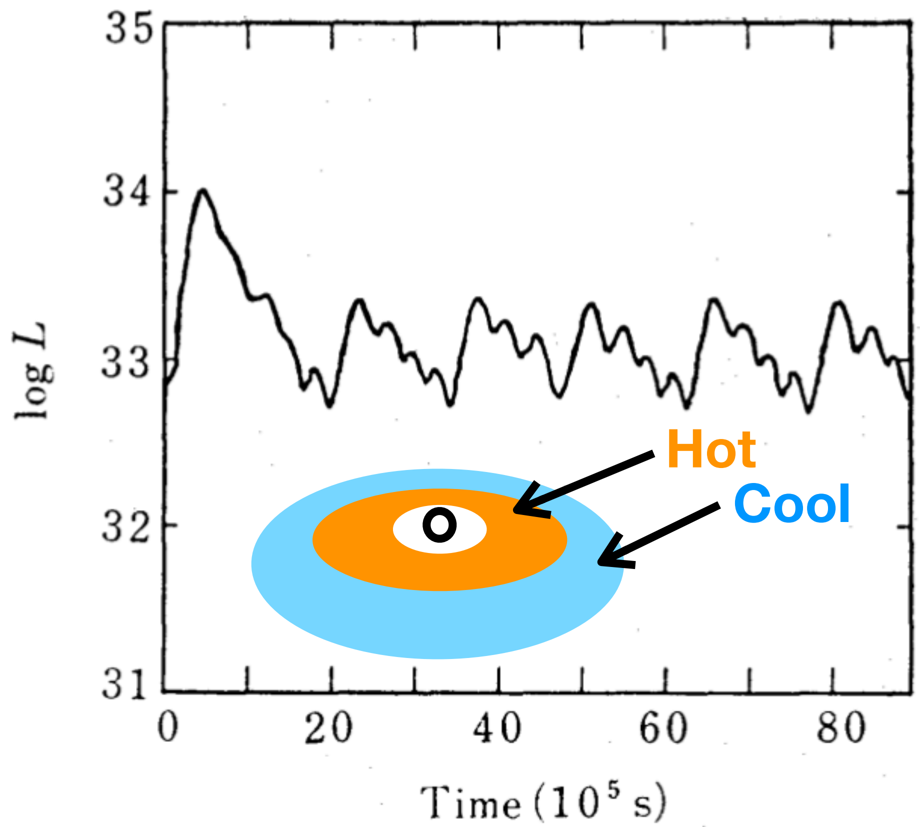
↑ Optical light curve in the precursor

The transition wave does not easily propagate over the disk.

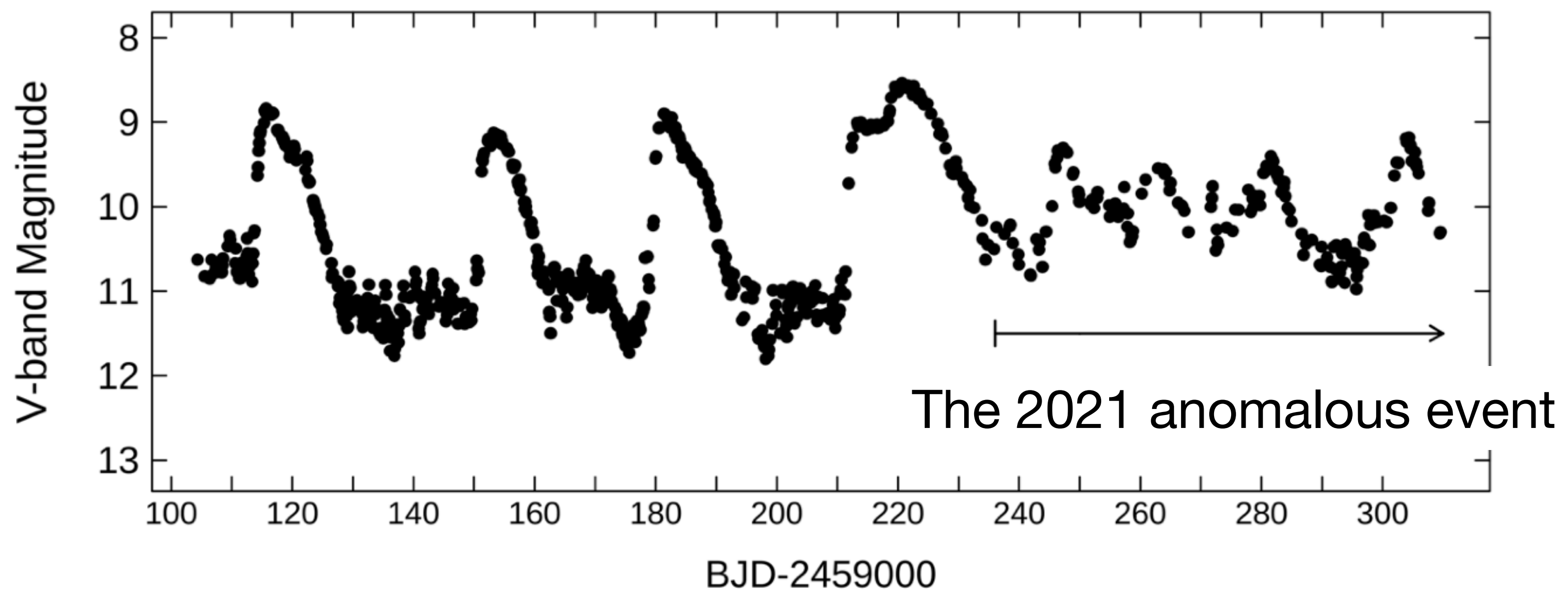
Nature of the 2021 anomalous event

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

⟶ Light curves just oscillate and show no clear outbursts



(Mineshige & Osaki 1985)

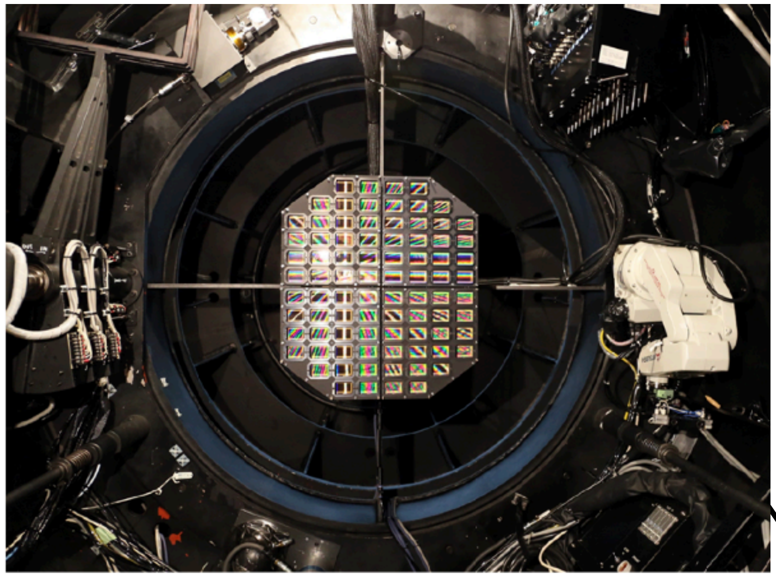


A series of very small outbursts

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〜)

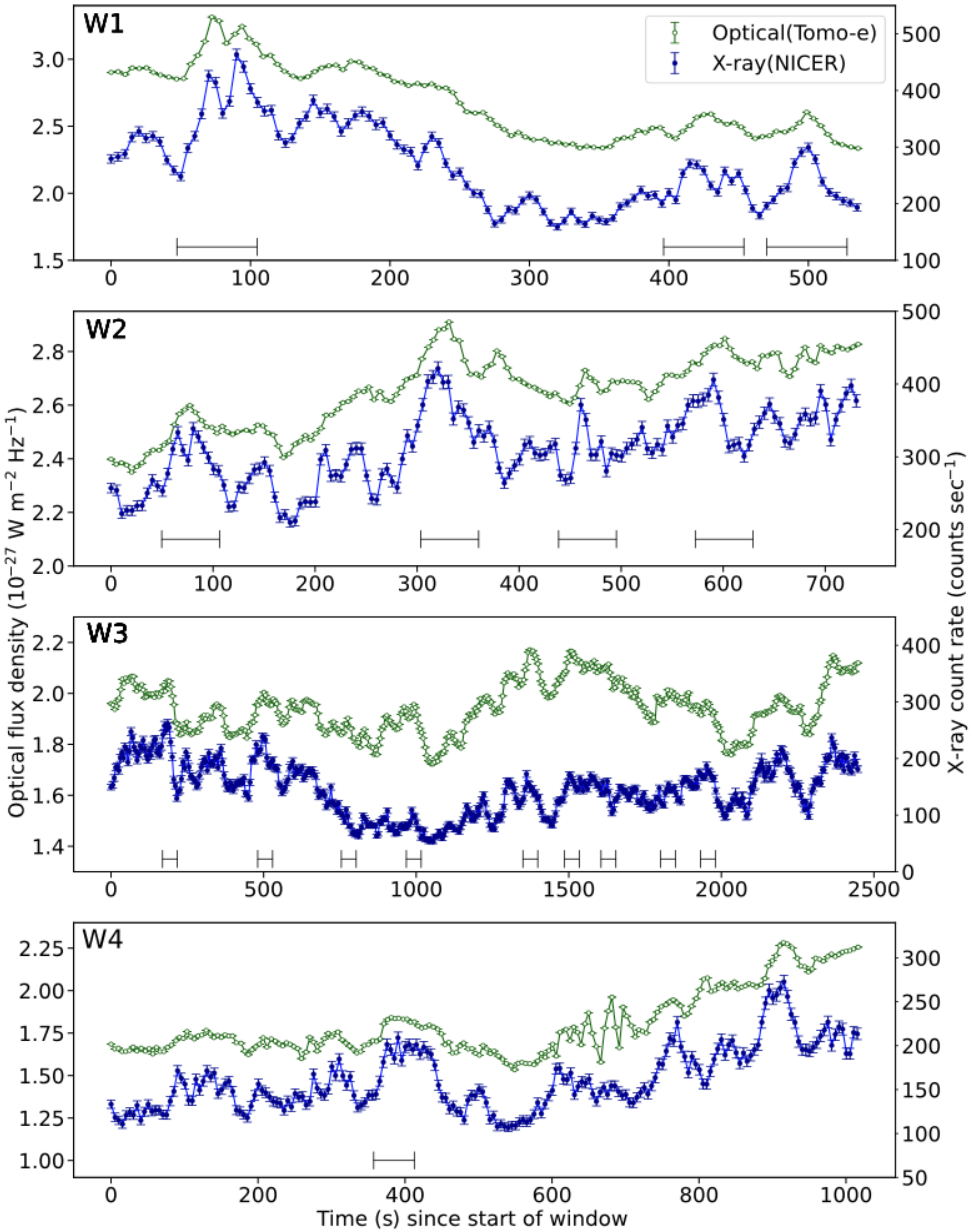
- 0.3—10.0 keV
- High time resolution

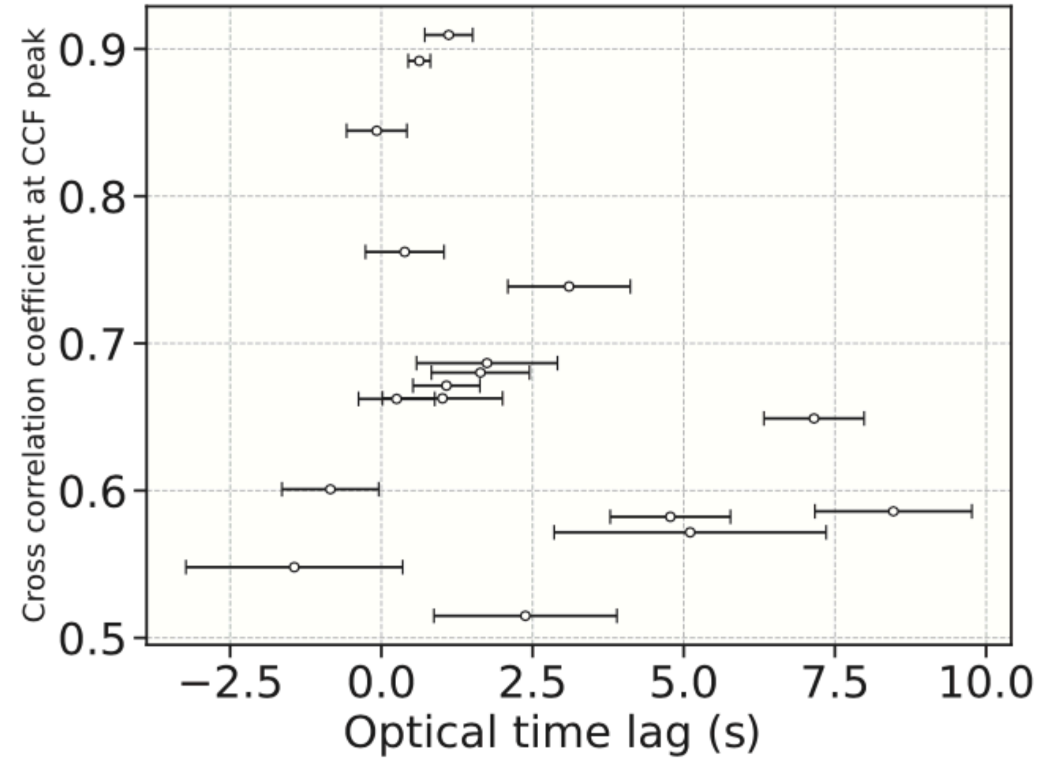
Simultaneous observations with Tomo-e & NICER

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 ?

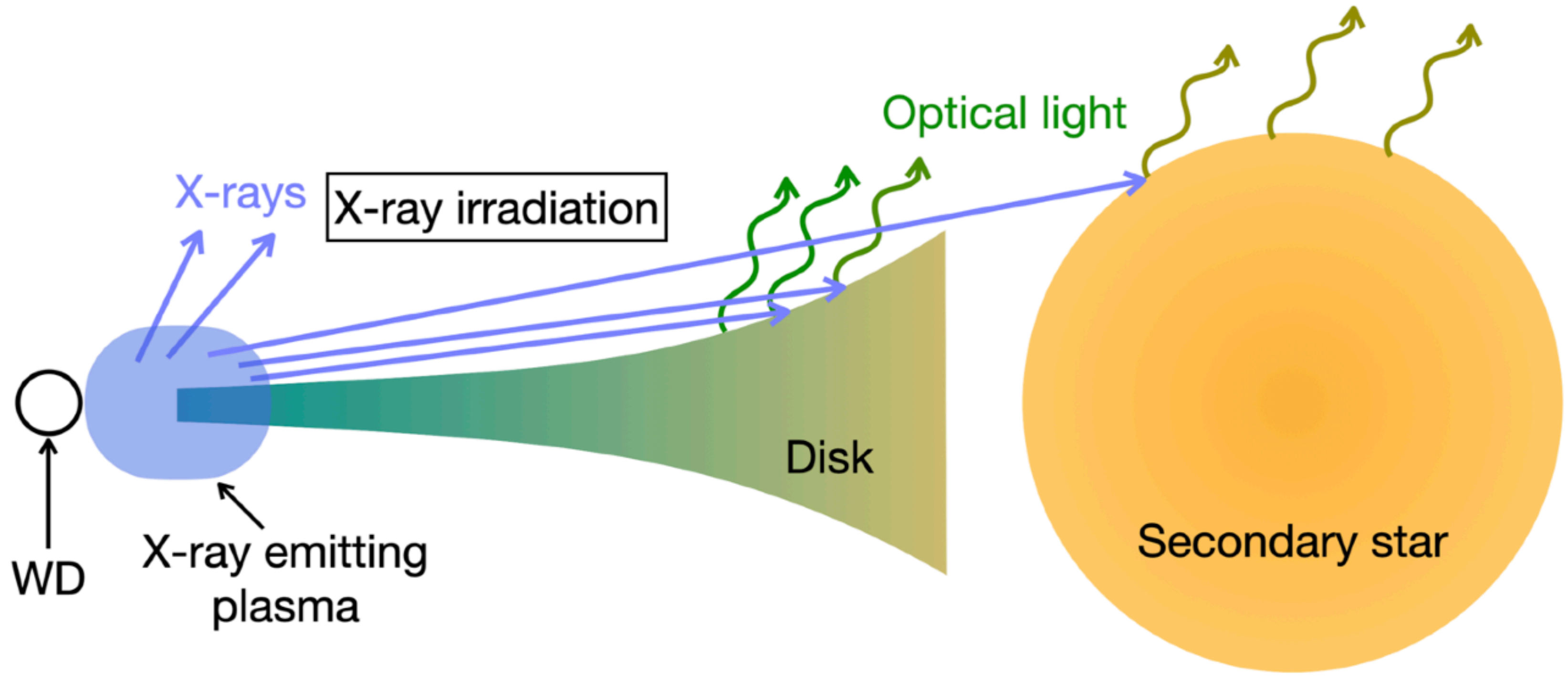
X-ray emitting plasma expanded

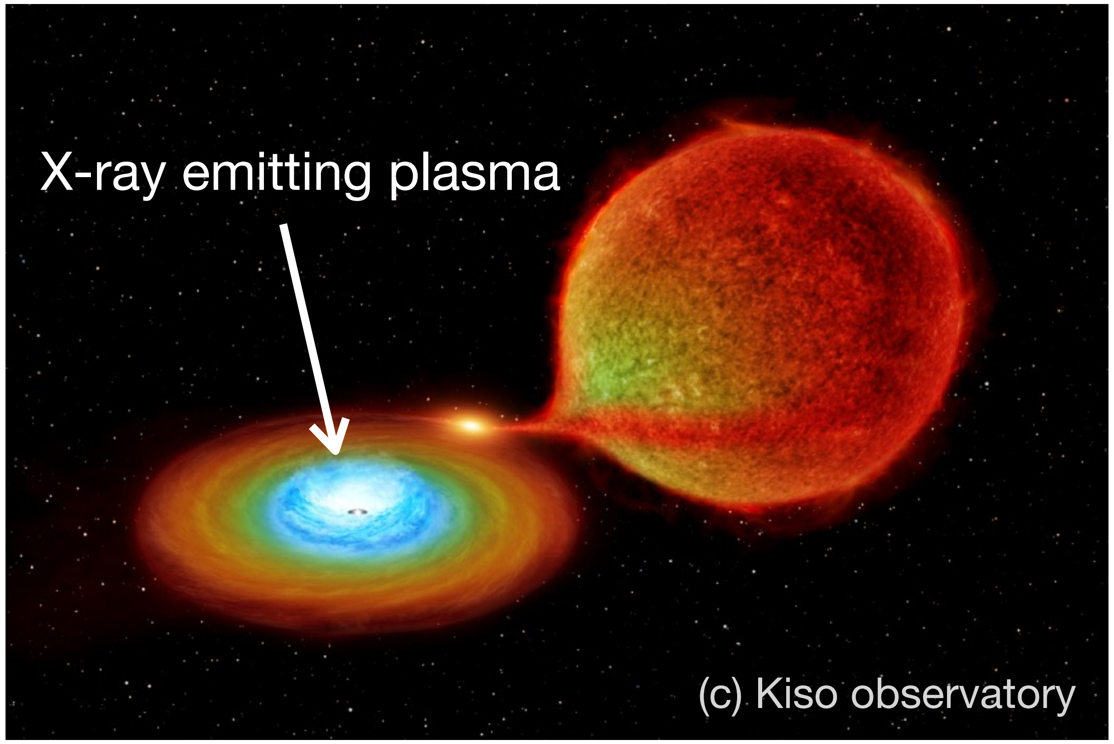
↓

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*"

Short summary

- SS Cyg showed **an anomalous event like standstill in early 2021**.
- We performed X-ray and optical monitoring of this event and its forerunner.
- Our analyses suggest that X-ray irradiation was weak, and that **the viscosity in the disk may be enhanced** during quiescence.

  → applicable for Z Cam-type standstill ?
- The 2021 anomalous event is a group of very small outbursts ?
- The X-ray emitting region was hotter and expanded.

  → X-ray irradiation became stronger.

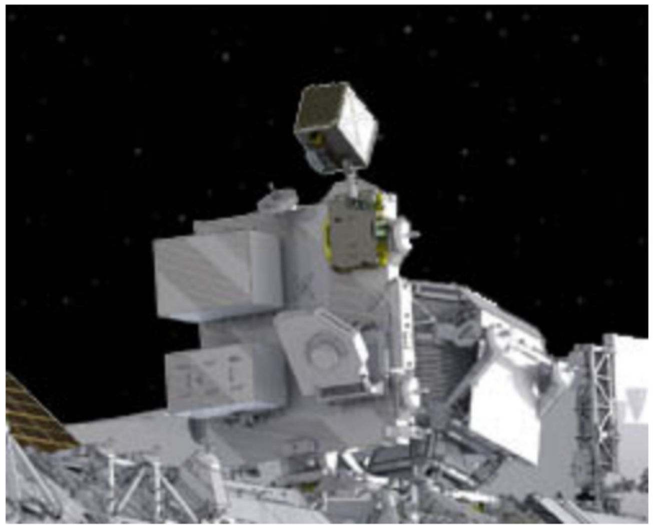
  → Strong correlation between optical & X-ray variations

Future observations

Future observations by upcoming telescopes

X-rays

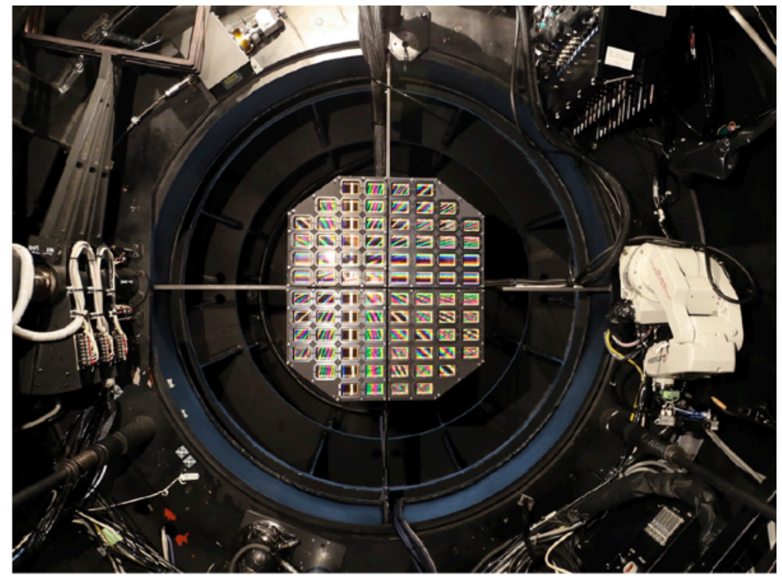
NICER@ISS (2018~)



XRISM (2023~)

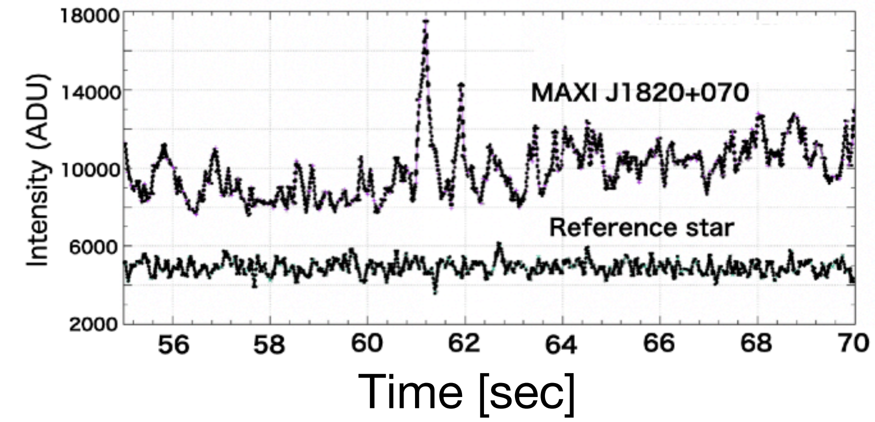
Optical

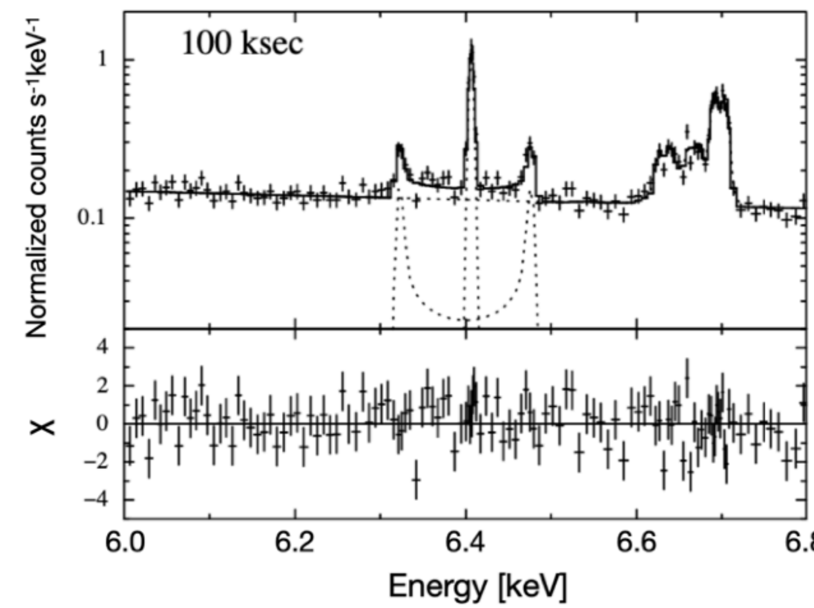
Tomo-e Gozen（2019~）



TriCCS@Seimei（2021~）

Multi-wavelength & high-speed photometry, X-ray detailed spectroscopy





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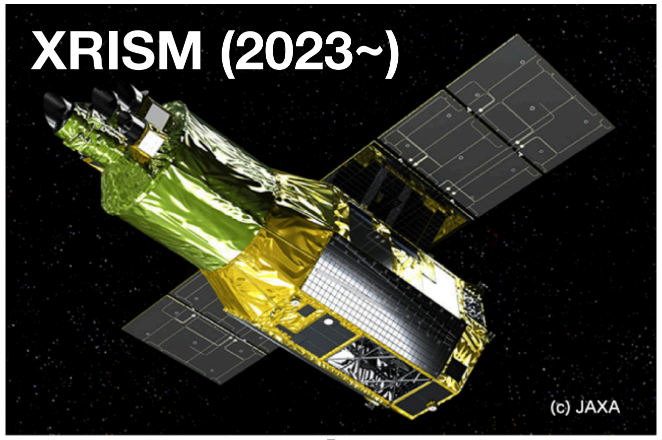
Plasma geometry under the strong gravitational field

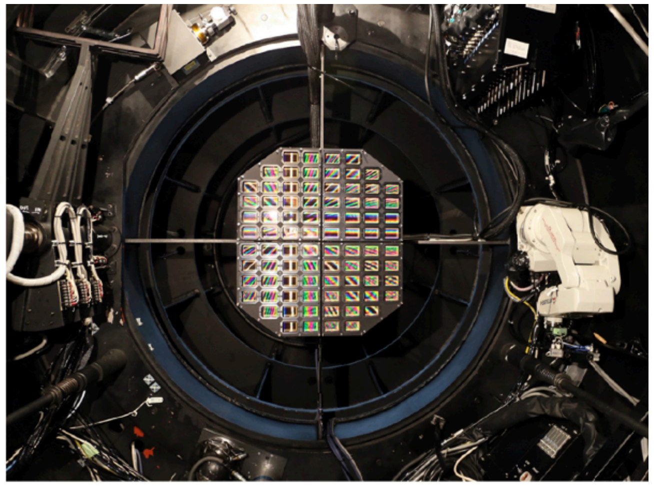
Future observations of SS Cyg

- Coordinated observations by **XRISM, NuSTAR, and Tomo-e Gozen** of SS Cyg **(priority A target during the XRISM PV phase)**



+

Tomo-e Gozen (2019~)



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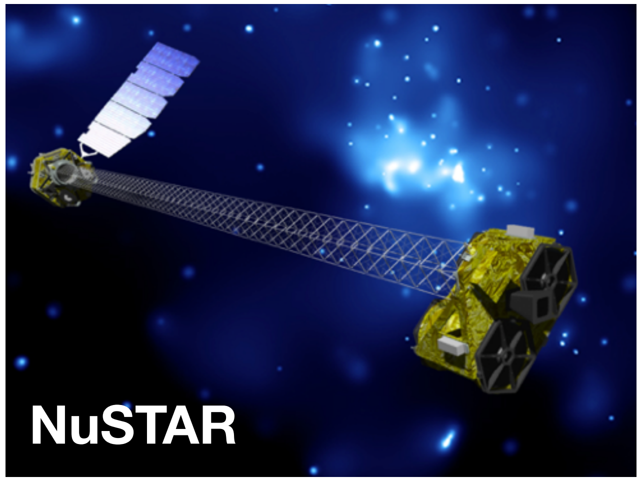
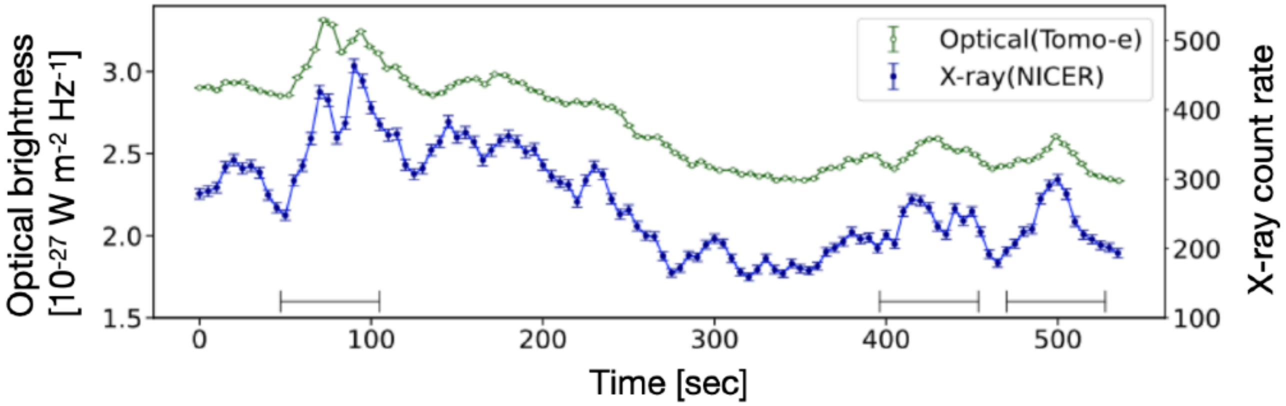
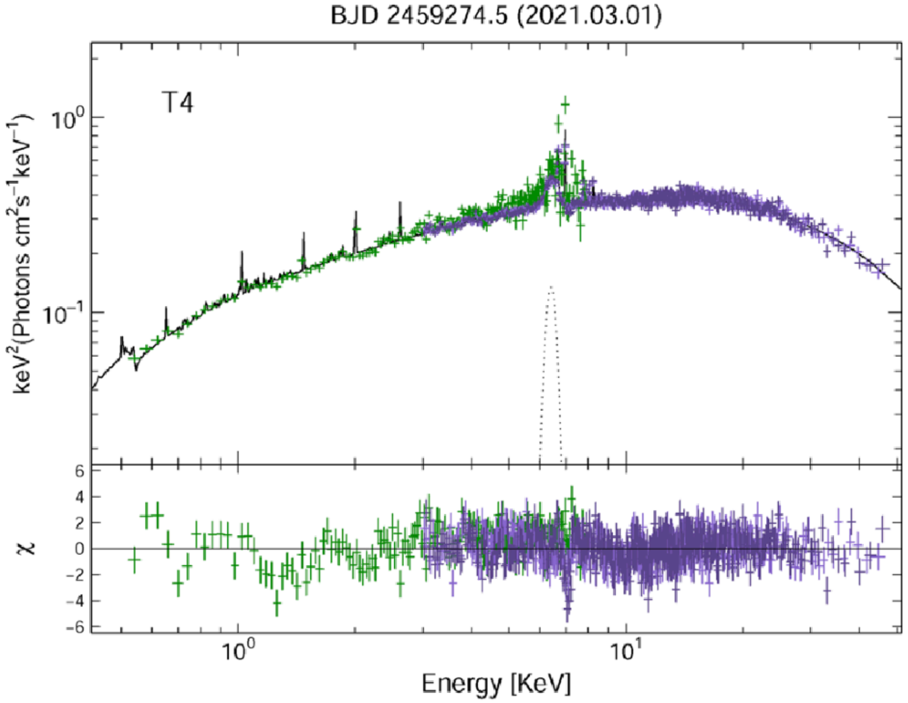
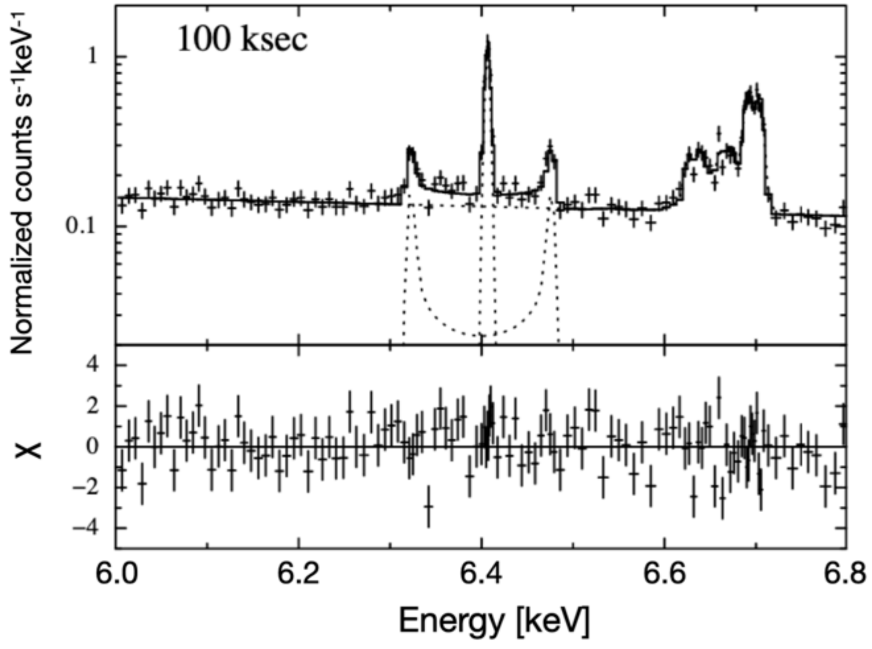








- Return to the normal state ?
- Consistency between X-ray spectra and high-speed multi-wavelength observations
- Density & temperature profiles of X-ray plasma

Future observations (KOYOH・HiZ-GUNDAM)

KOYOH (micro satellite)

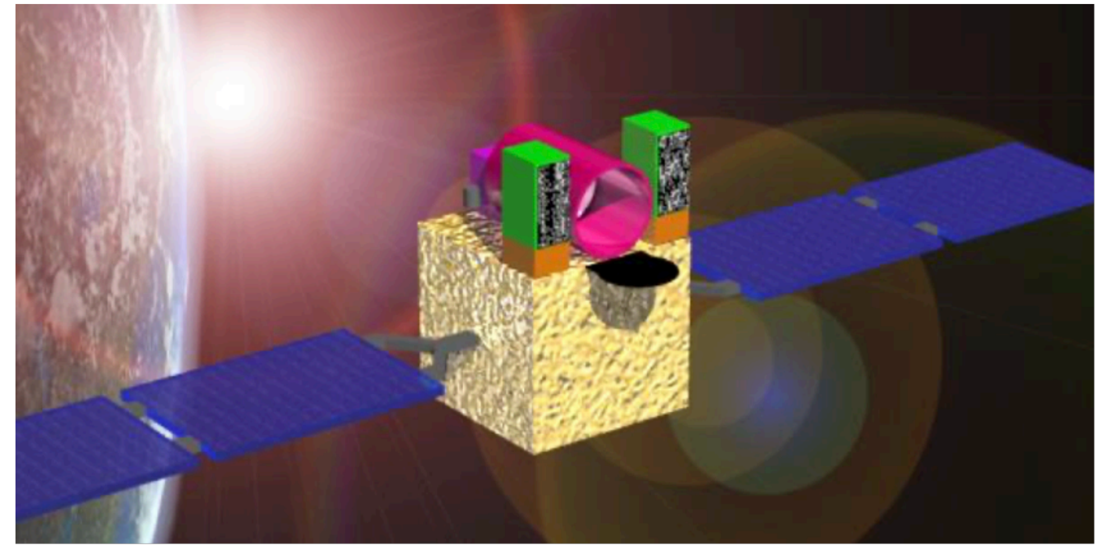
Wide-field X-ray monitor

Gamma-ray detector

↓

Discovery of many kinds of transients (GRBs synchronized with GW, outbursts of CVs and XBs, magnetar flares, ..)

HiZ-GUNDAM



Wide-field X-ray monitor and optical/IR telescopes

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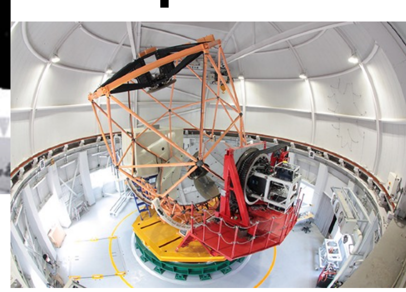
Discovery of high-redshift GRBs and investigate early universe

↓

Multi-wavelength follow-up observations

X-ray

Optical



Radio

Approach to important problems by using small telescopes !

Thank you for your attention.