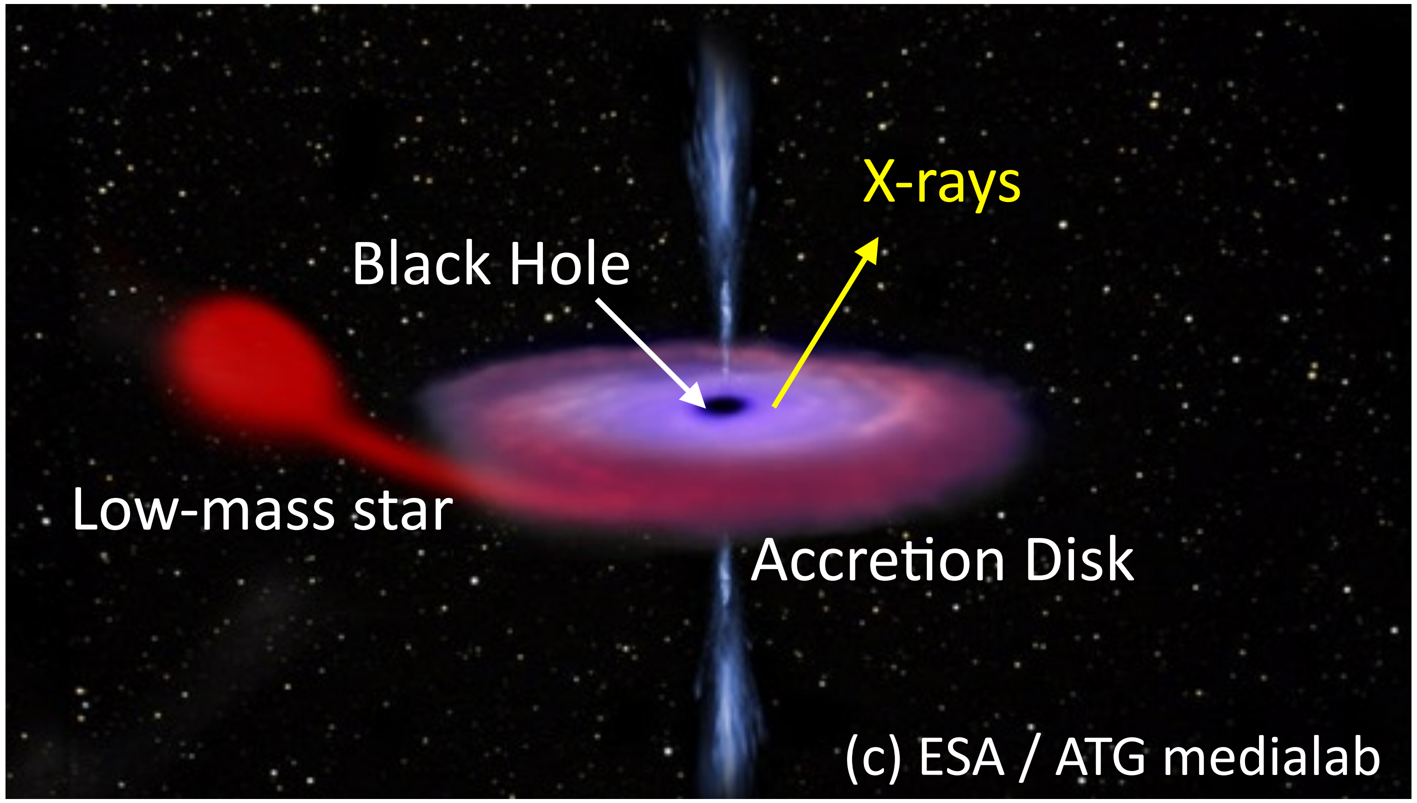
MAXI 2016 Conference (2016.12.5–7)

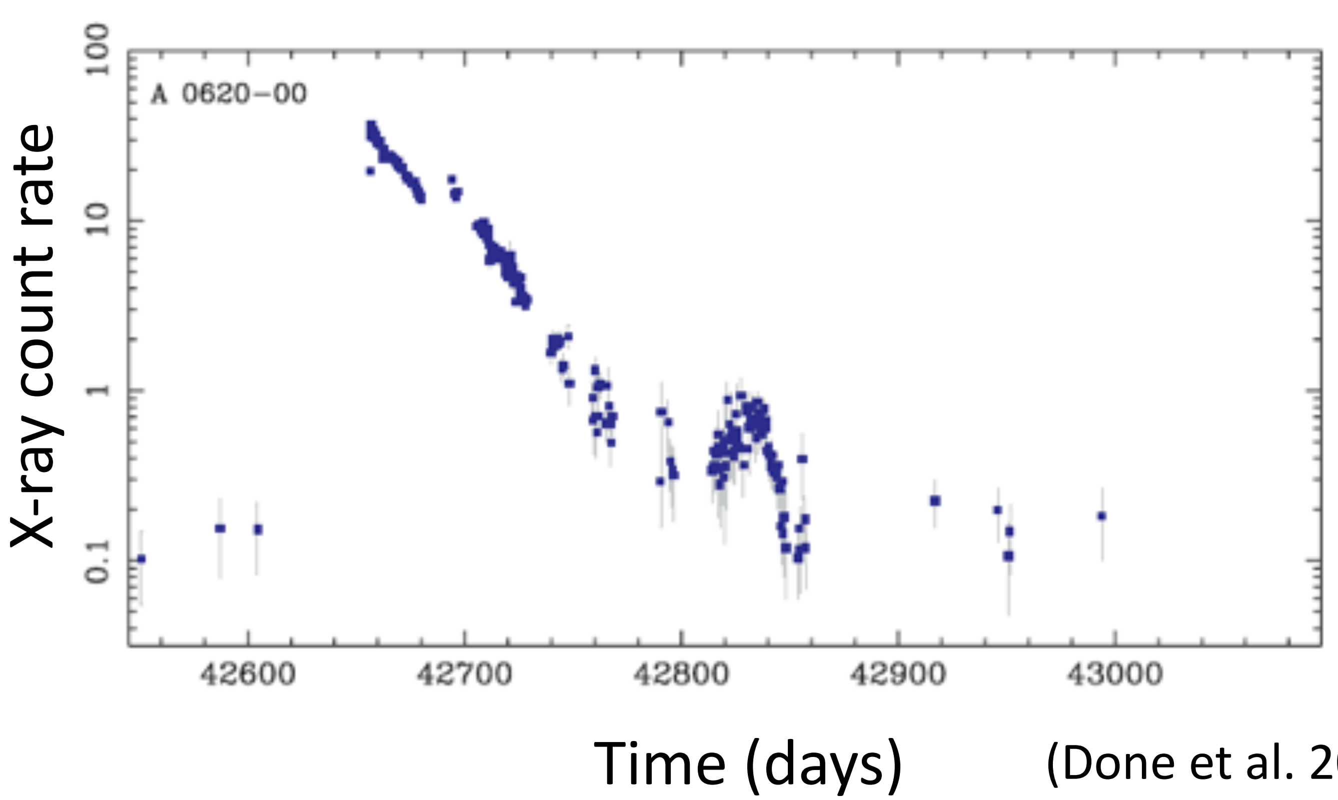
Violent Optical Variations and Correlation with X-ray Variability in the 2015 Outbursts in V404 Cygni

Presenter: Mariko Kimura (Kyoto University, Japan)

Co-workers: Keisuke Isogai, Taichi Kato, Yoshihiro Ueda, Daisaku Nogami, Teruaki Enoto, Takafuki Hori (Kyoto University), Megumi Shidatsu (RIKEN), Satoshi Nakahira (JAXA), and VSNET team

Low Mass X-ray Binaries (LMXBs)





(Done et al. 2007)

- Subclass of close binary systems
  (the primary) a black hole/a neutron star
  (the secondary) a low-mass star
- have an accretion disk
- Classified into persistent and transient sources
- Transient LMXBs show episodic outbursts
  (duration) a few hundreds days
  (interval) years — tens of years

Mechanism of Outbursts

- Outbursts are caused by thermal instability in accretion disks.
- Thermal instability is triggered by partial ionization of Hydrogen in an accretion disk at the temperature of 10^3—10^4 [K].
- Repeat accretion to the primary and accumulation in the disk alternately.

gas accumulates in the disk (quiescence)

↓

gas accretes to the primary (outburst)

↓

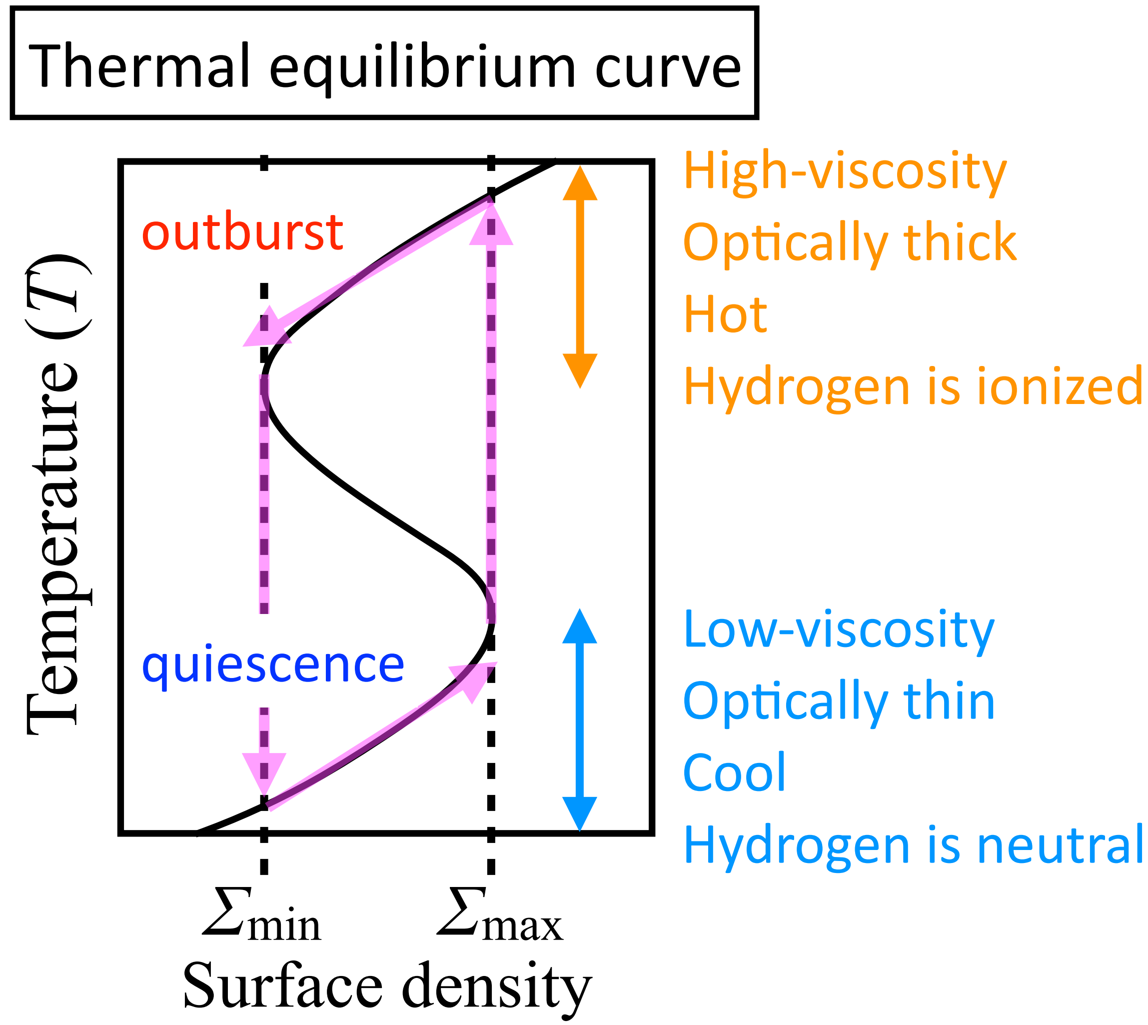
gas accumulates in the disk (quiescence)

↓

gas accretes to the primary (outburst)

↓

endless…

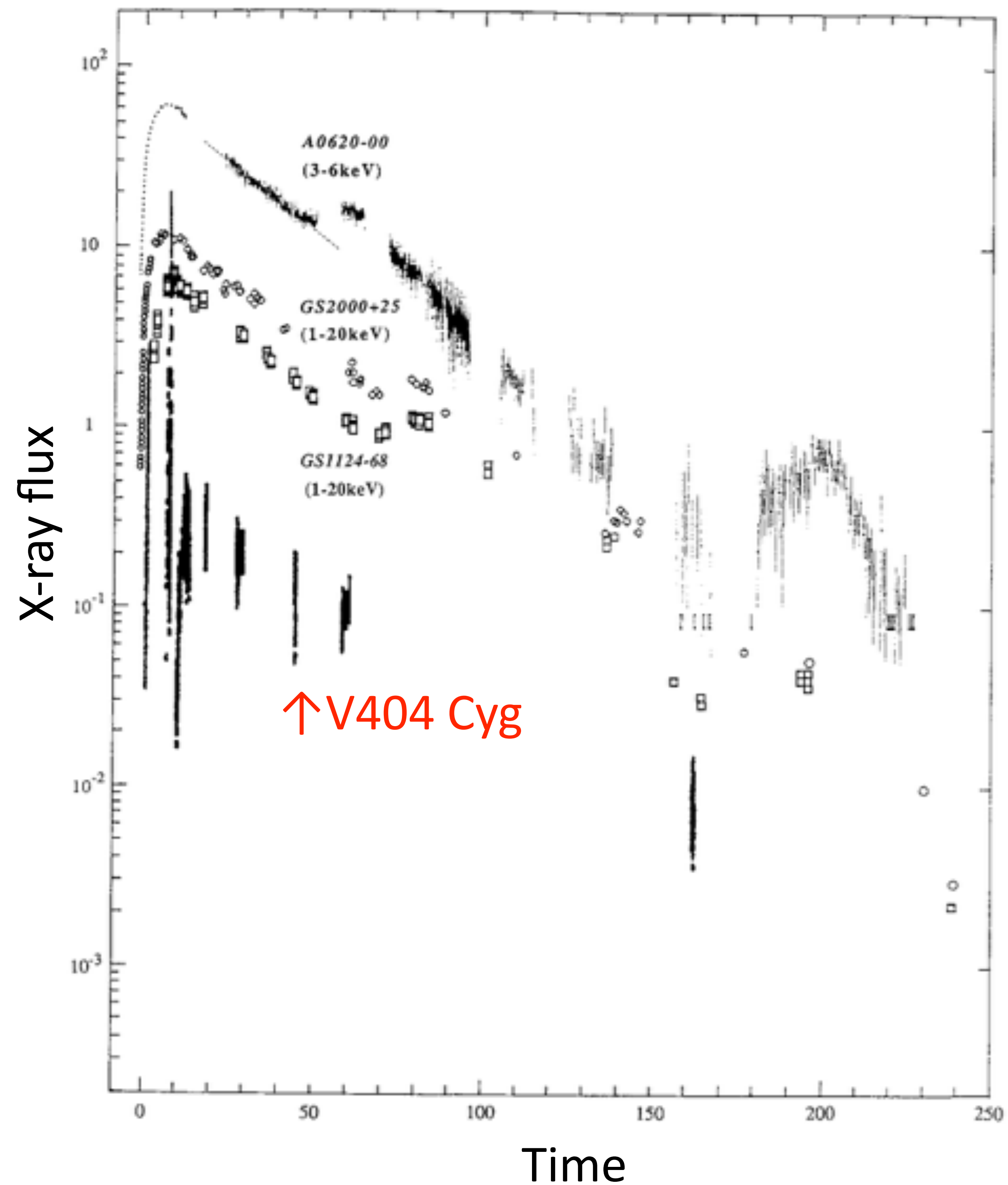


What is V404 Cyg ?

- One of transient LMXBs. The primary is a $9M_\odot$ black hole.
- Located at a distance of 2.4 kpc (very close to the Earth !)
- Discovered as a nova in 1938, and identified as a transient X-ray binary by *GINGA* satellite in 1989.
- Showed violent X-ray variations in the 1989 outburst. so rare !

This system underwent outbursts *twice* in 2015 after 26 years dormancy !

1. 2015.6.15 Swift/BAT triggered V404 Cyg.
2. 2015.12.23 as above



(Tanaka & Shibazaki, 1996)

International Optical Observations

- We performed CCD photometry at 27 places with 36 telescopes.
- Observers: The VSNET (Variable Star Network) team *(Japan and other countries)*, TAOS (The Taiwanese-American Occultation Survey) team *(Taiwan)*, Space Research Institute *(Russia)*
- Terms: 2015.6.15—7.5 & 2015.12.23—2016.1.4
- Filters: Ic, Rc, V and B bands, No filter
- Exposure times: 2—60 [s]
- Size of telescopes: 20[cm]—2[m]
- We also used the public AAVSO data.

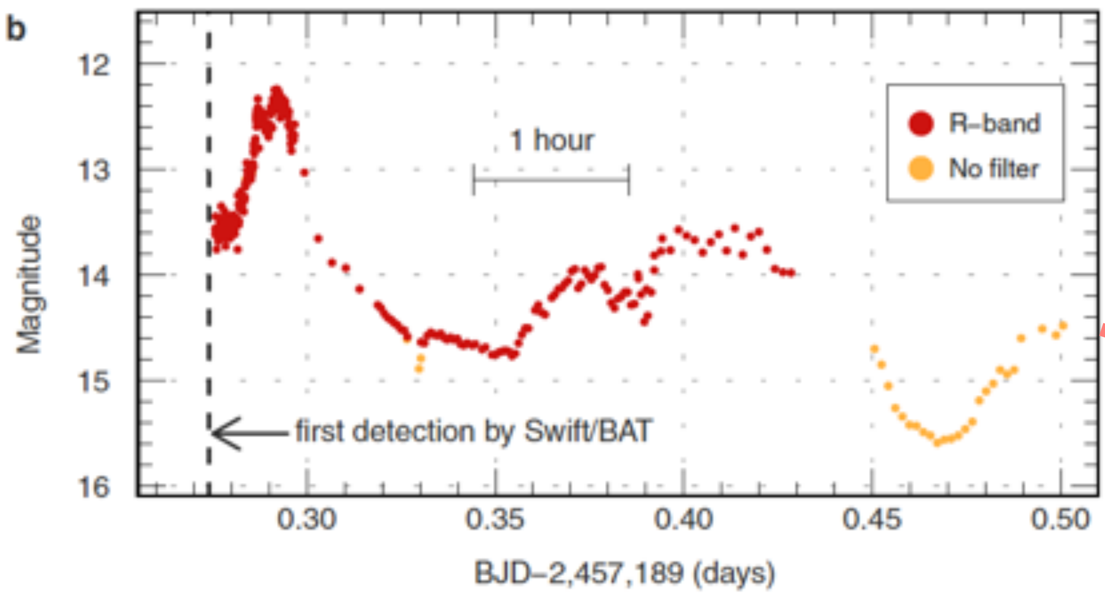
VSNET
Intensive An International Mailing List on Variable Stars

Comparison with X-ray observations

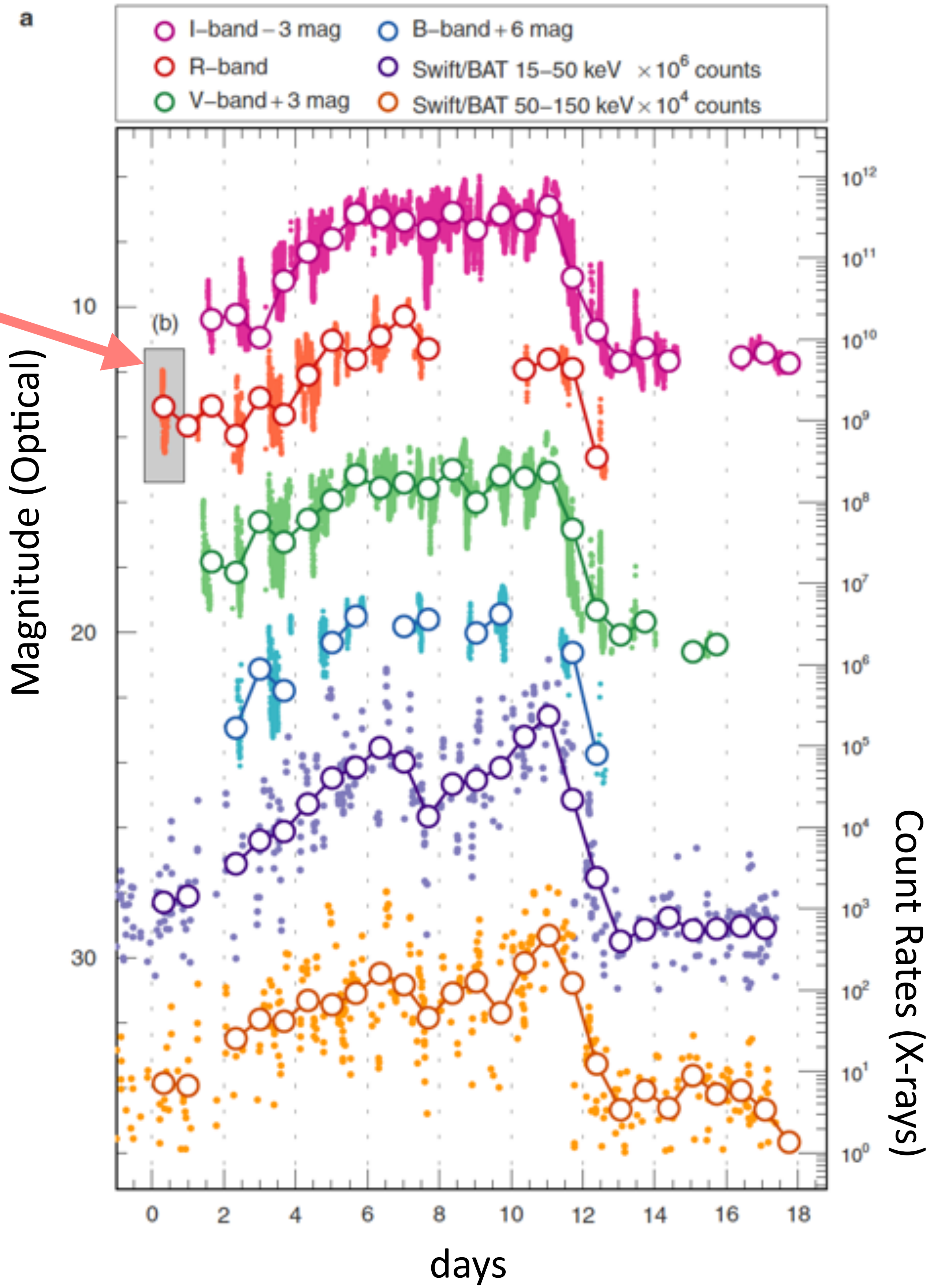
- We used the Swift/BAT, XRT and INTEGRAL IBIS/ISGRI data.

★ : observational place

The 2015 June—July Outburst: Light Curves

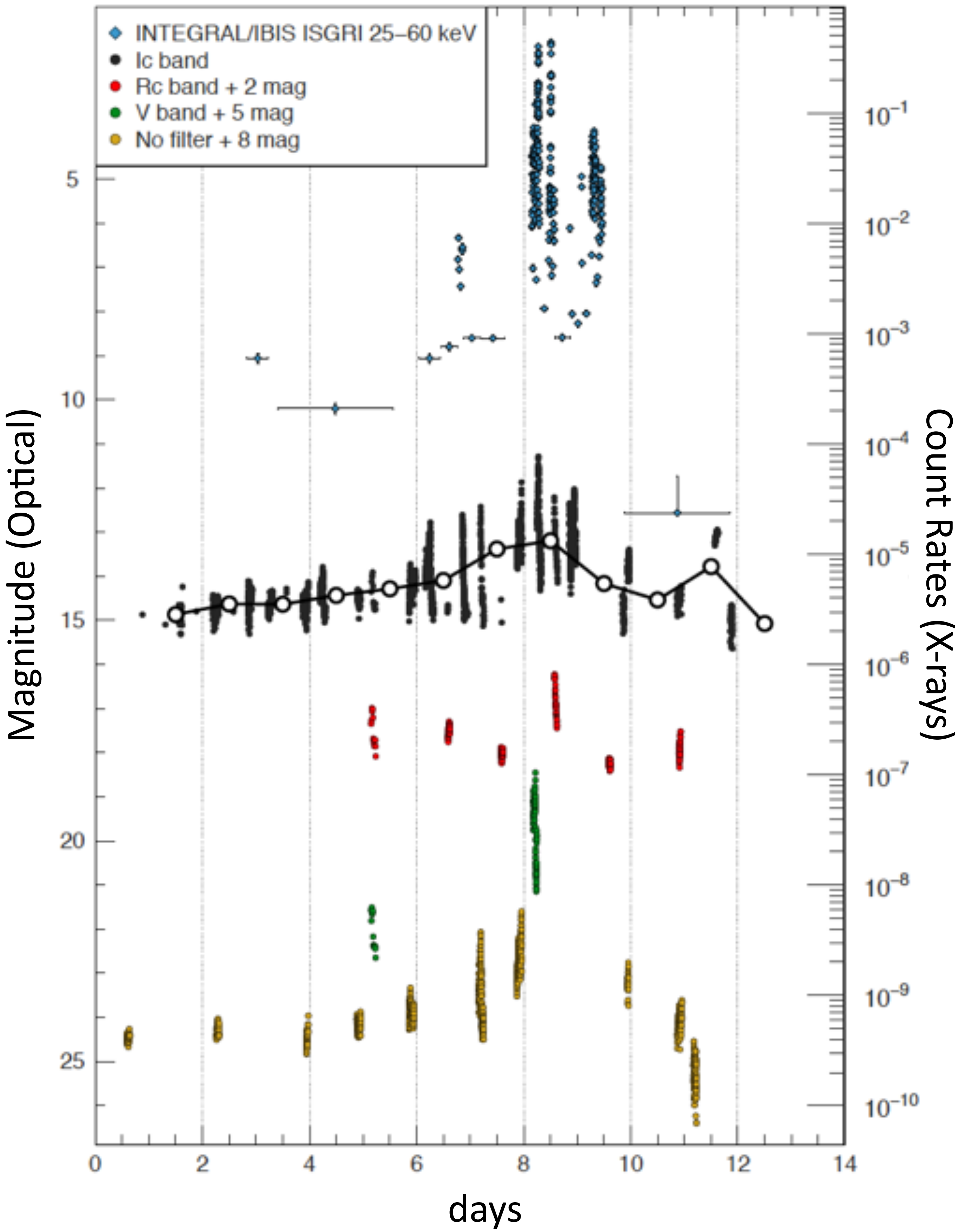


↑less than 3 minutes after the first detection !



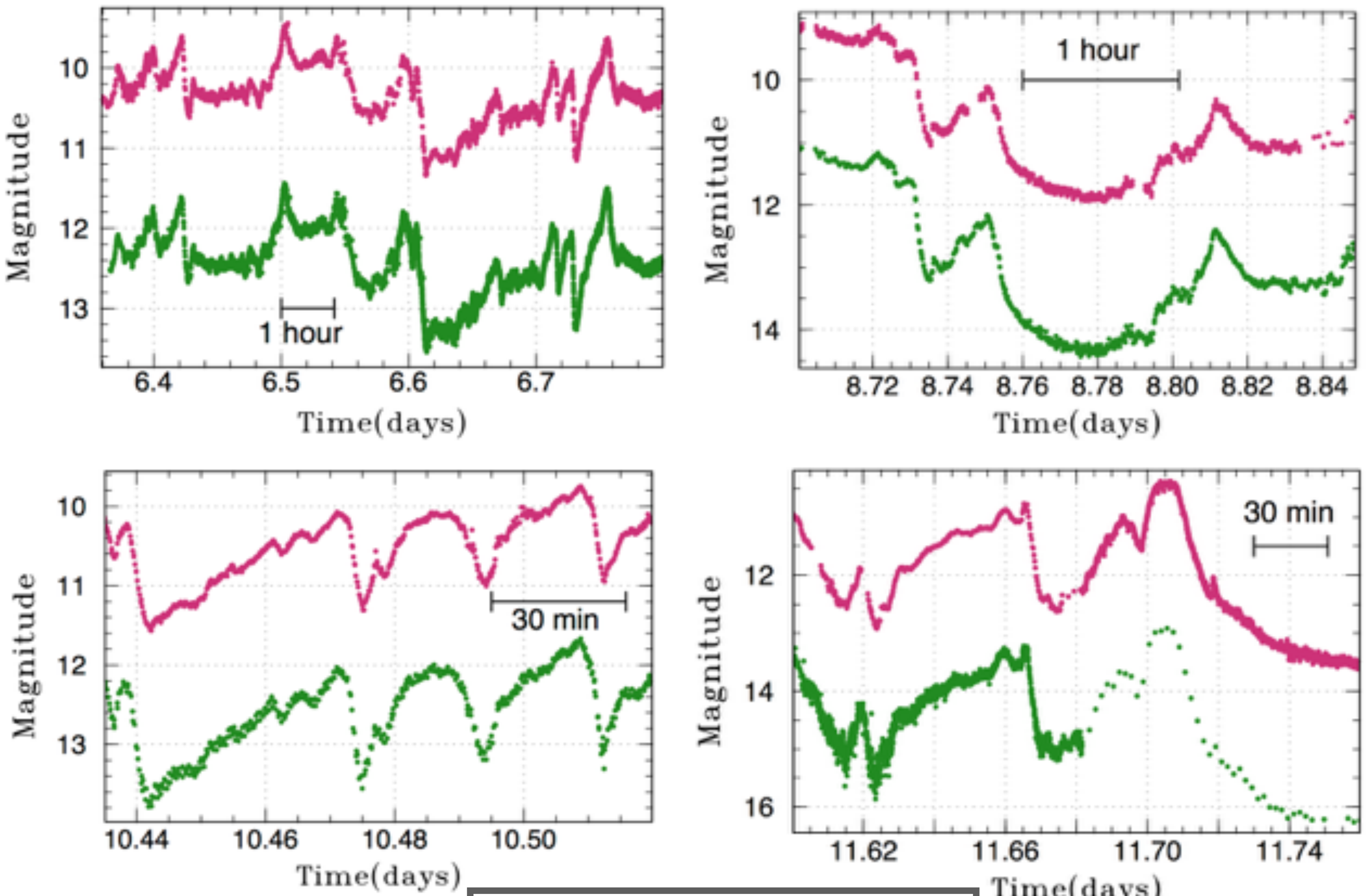
- Violent optical variations were observed during the outburst !
- Optical light curve was similar to X-ray one
- Outburst duration: ~18 days
- Outburst amplitude: ~6 mag
- Outburst trend: slow rise & rapid decay

The 2015 December Outburst: Light Curves

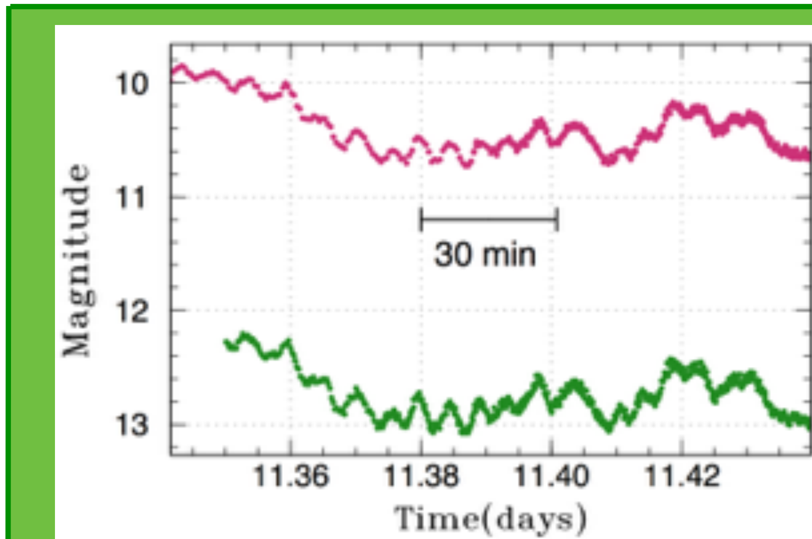


- Violent optical variations were observed through the outburst !
- Optical and X-ray variations seem to correlate in some terms.
- Outburst duration: ~14 days
- Outburst amplitude: ~3.5 mag
- Outburst trend: slow rise & rapid decay

The 2015 June—July Outburst: Light Curves



- I band
- V band



Dip-type oscillations

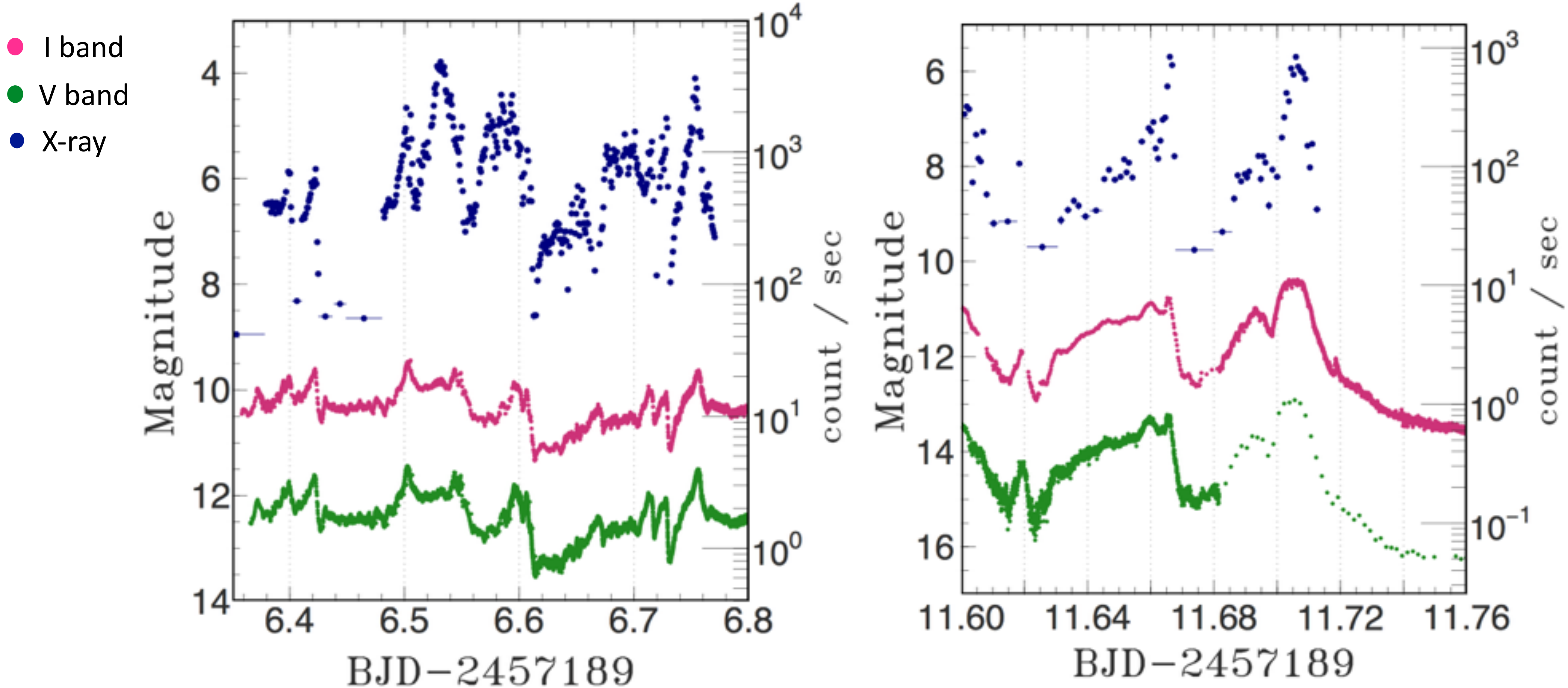
- repetitions of a gradual rise followed by a sudden dip, sometimes with accompanying spikes
- timescales: 30 min — 2.5 hours, amplitudes: ~2 mag

Heartbeat-type oscillations

- repetitive small spikes
- timescales: about 5 min, amplitudes: ~0.1 mag

- Optical variations with repetitive patterns were observed !

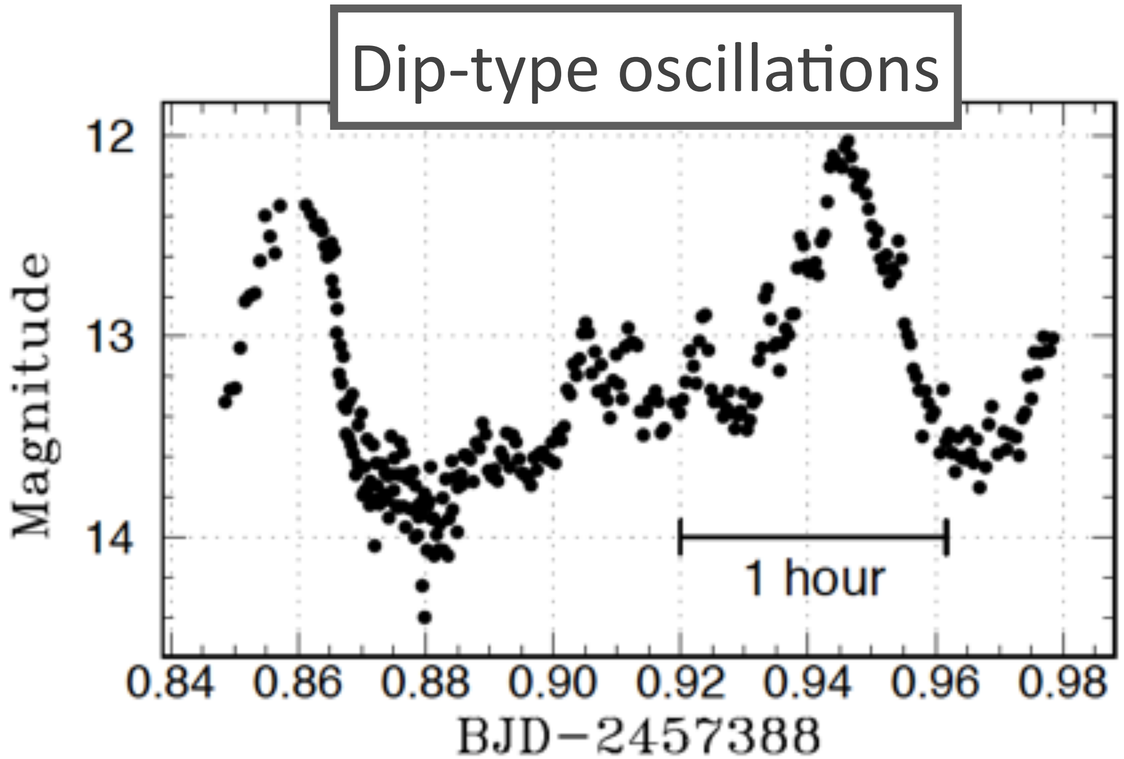
The 2015 June—July Outburst: Comparison with X-rays



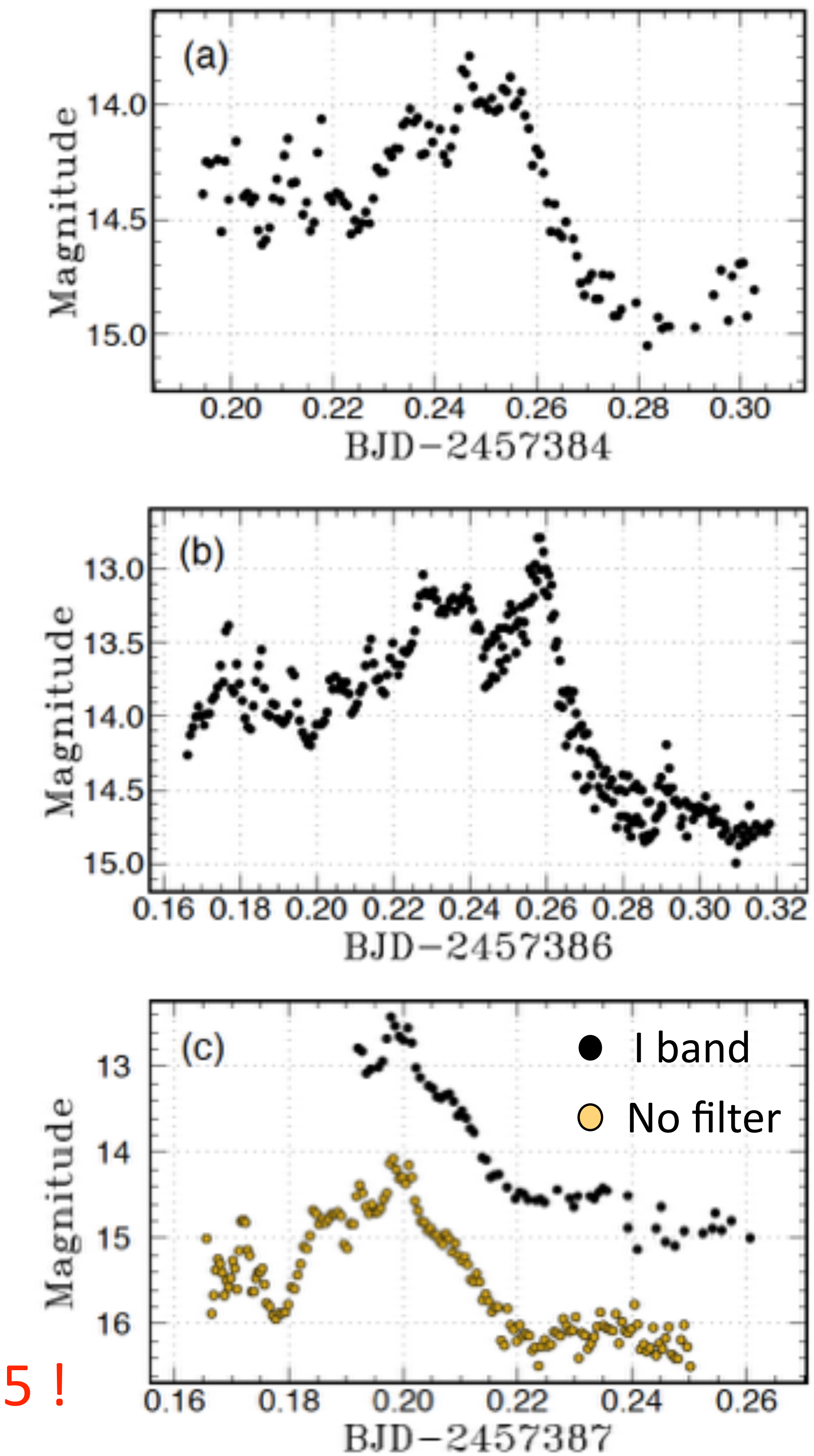
- The correlation between optical and X-ray variations was good.
- Time delay to the X-ray variations: ~1 min

Optical repetitive variations represented the activity in the inner disk as X-ray ones did.

The 2015 December Outburst: Light Curves



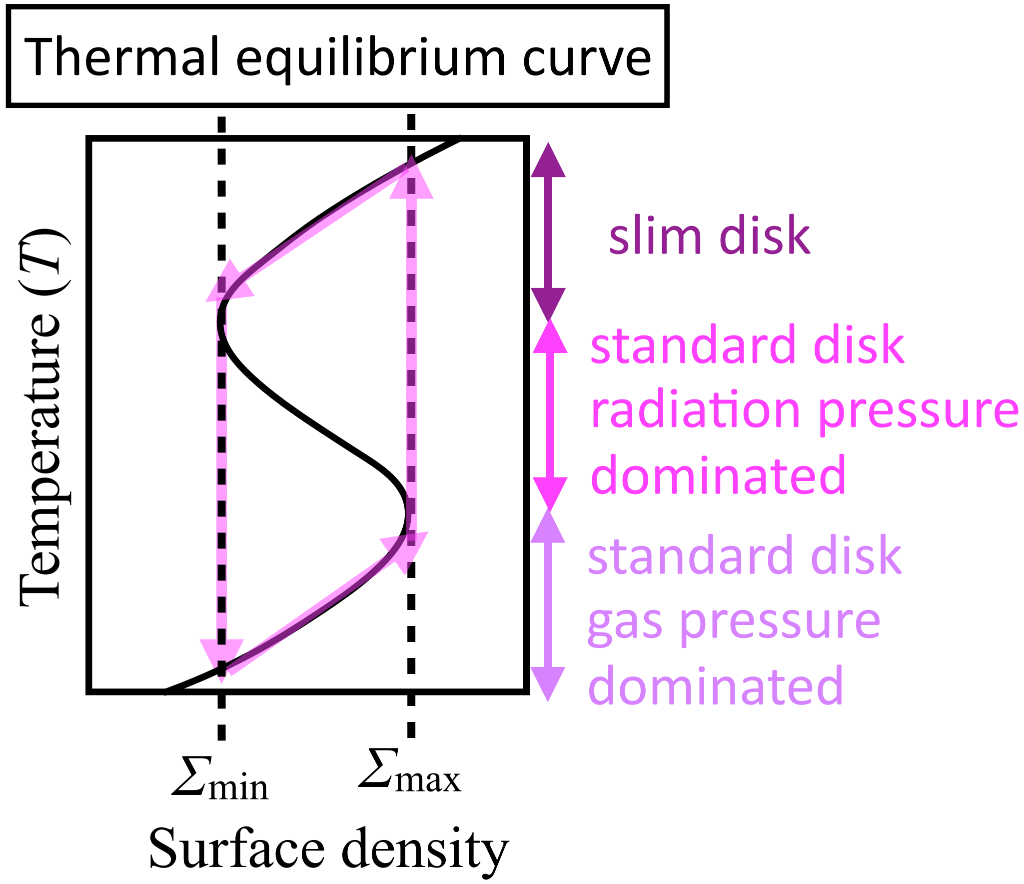
- Dip-type oscillations were observed in one term.
- In other terms, part of dip-type oscillations were observed ?
- timescales : 1—3.5 hours
- amplitudes: ~2 mag

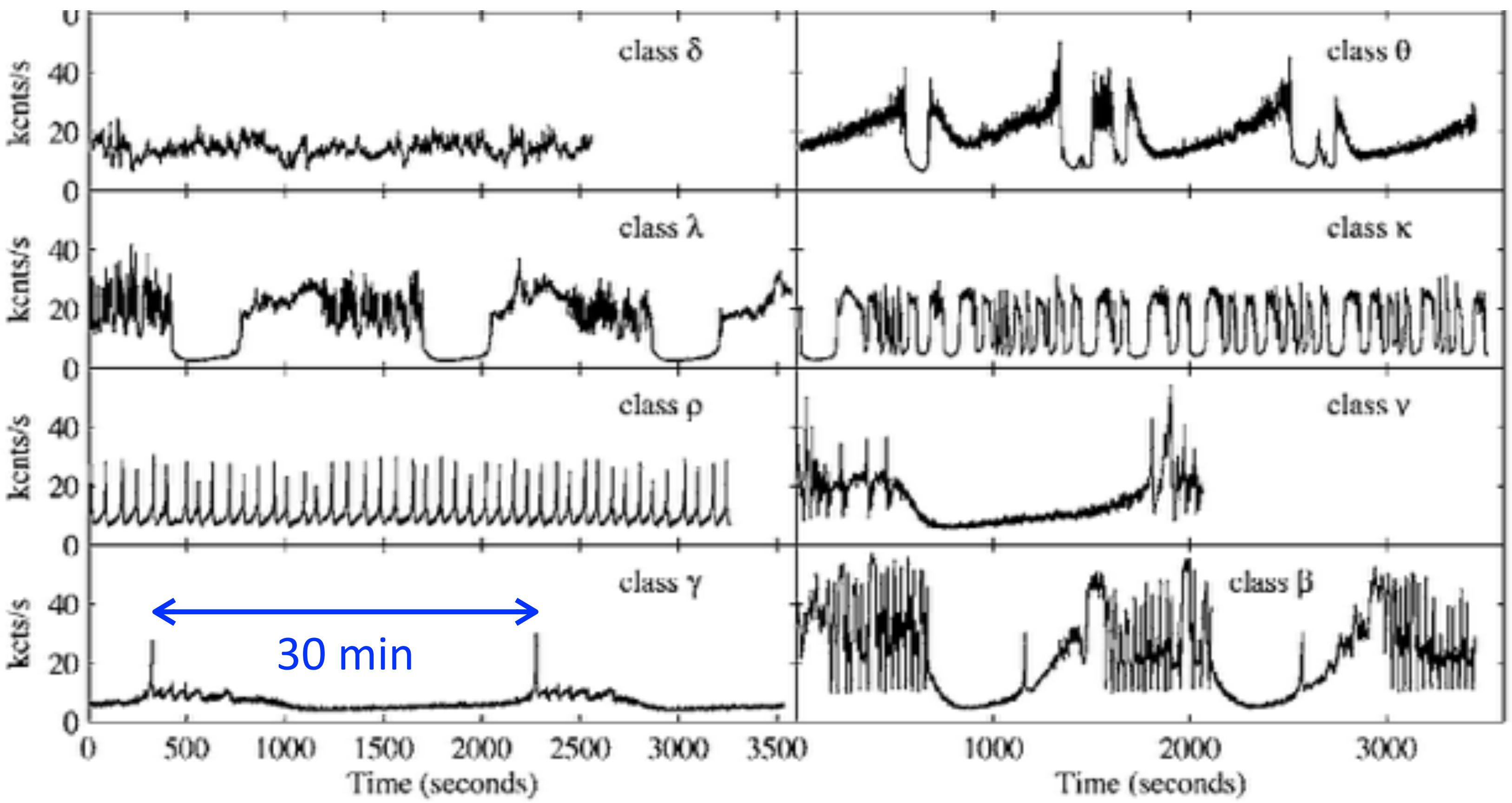


Similar to X-ray variations observed in GRS 1915+105 !

GRS 1915+105

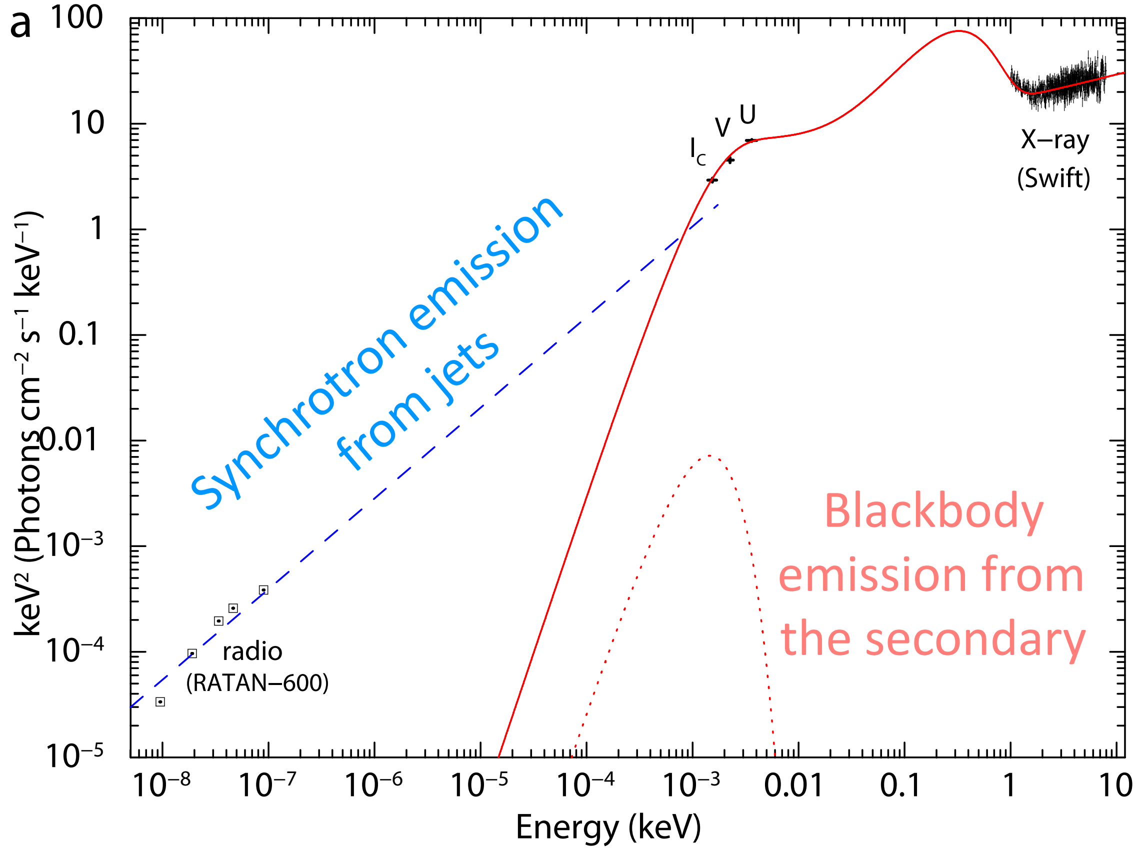
- GRS 1915+105 is one of black-hole X-ray binaries.
- Show repetitive X-ray variations at high luminosity (near the Eddington luminosity) with timescales of 1—30 min.
- Repetitive variations are considered to be caused by radiation pressure instability triggered at the temperature of ~10^7[K] in the inner accretion disk.

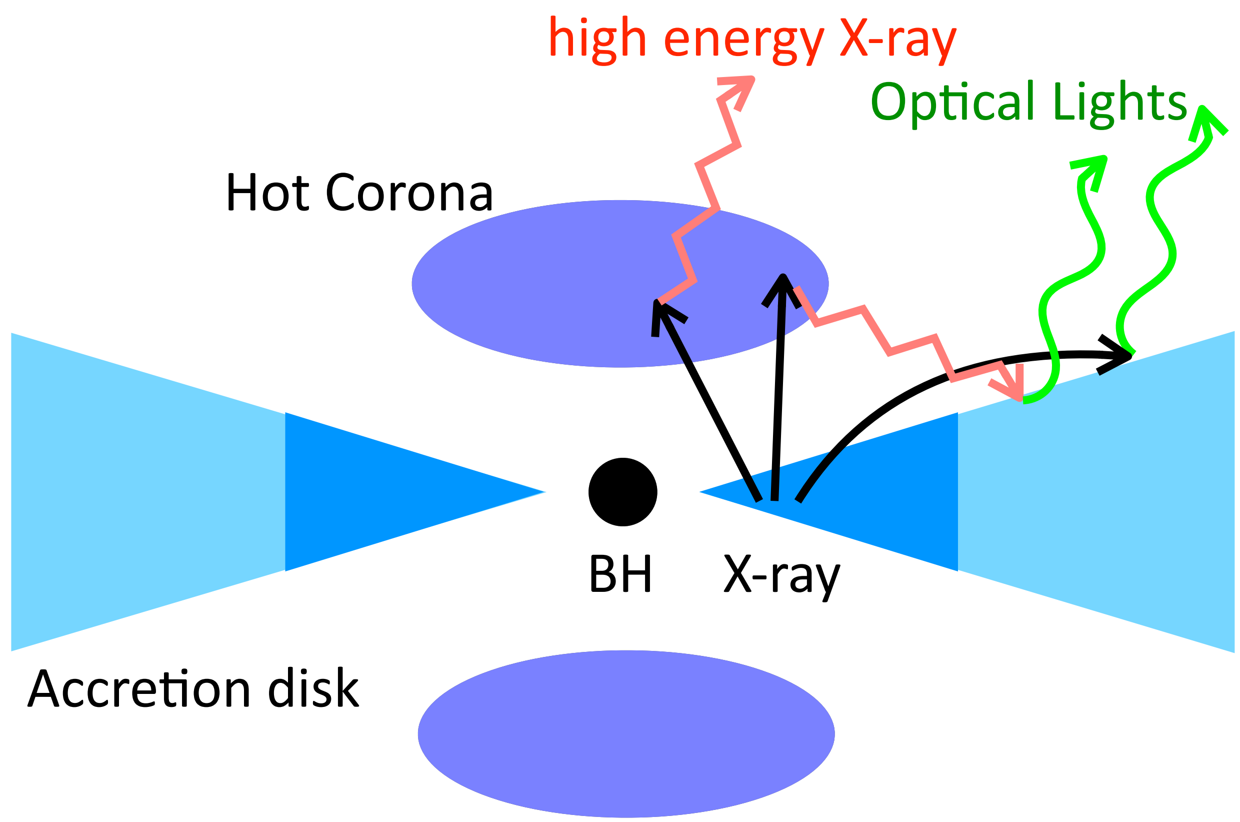




(Fender & Belloni 2004)

The 2015 June—July Outburst: Origin of Optical Variations





- The high optical flux could not be reproduced only with synchrotron emission from compact jets.
- Outer disk radius: 2.0×10^{12} [cm] & Time delay to the X-ray variations: ~1 min

⇨ The high optical flux were mainly produced by reprocessing of X-ray irradiation in the disk.

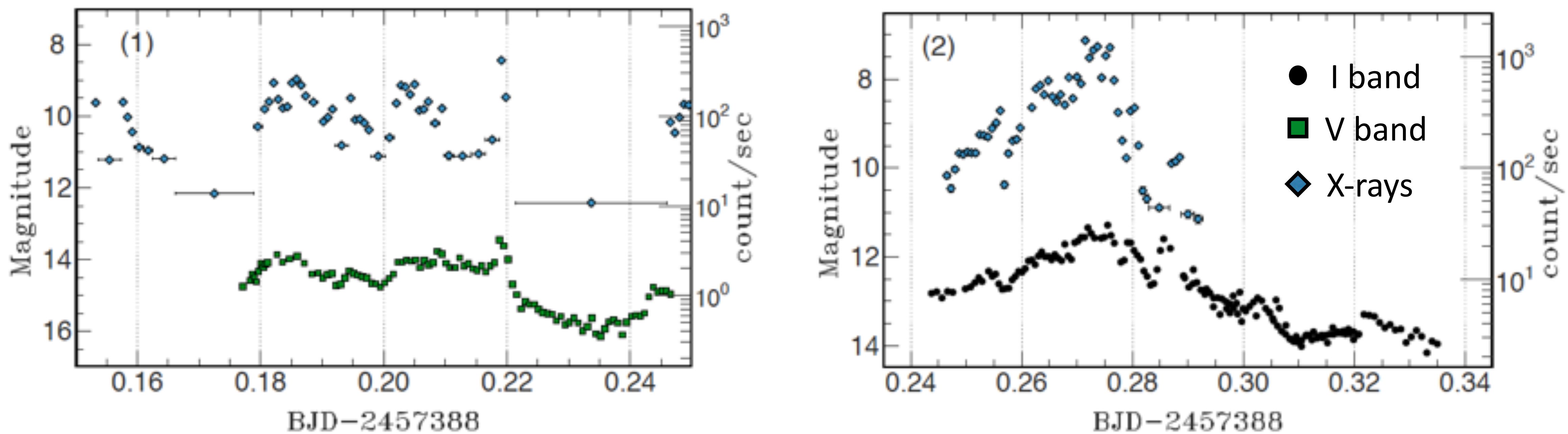
+ Repetitive variations were detected even at low luminosity (~$0.01 L_{Edd}$)

⟷ radiation pressure instability (at high luminosity)

Unknown instability ?

The 2015 December Outburst: Comparison with X-rays

- We found two intervals in which the random optical and X-ray light curves seems to correlate.



- We want to estimate the time lags between the optical and X-ray variability, but there are some problems…

1. Irregularly observed time-series data
2. Seasonal gaps (due to bad weather)
3. X-ray & optical flux are not on an identical baseline

so difficult… (> <)

→ We can use the bayesian strategy proposed Tak+2016 !

R package "timedelay" for their method is already provided by Dr. Tak

Bayesian Estimation of Time Delay (Tak et al. 2016)

- Non-grid based approach: O—U process is adopted to model latent light curves

✳ O—U process describes stochastic variability of accretion-type light variations (e.g., quasars)

- We can search time lags for the whole space

likelihood function

posterior distribution $P(\theta|X) = \frac{P(X|\theta)P(\theta)}{P(X)}$ prior distribution

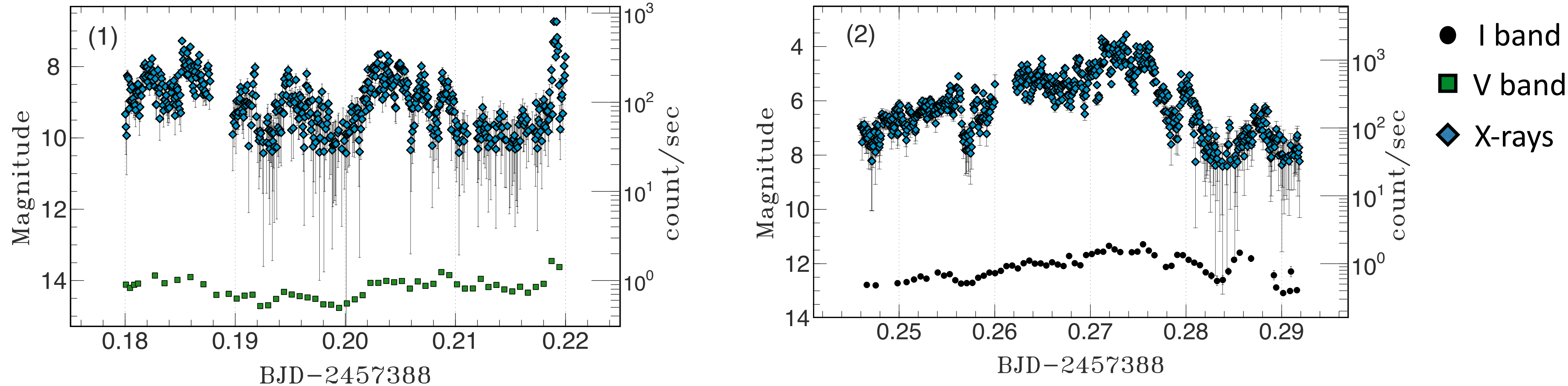
time delay, latent LC, μ, σ, τ

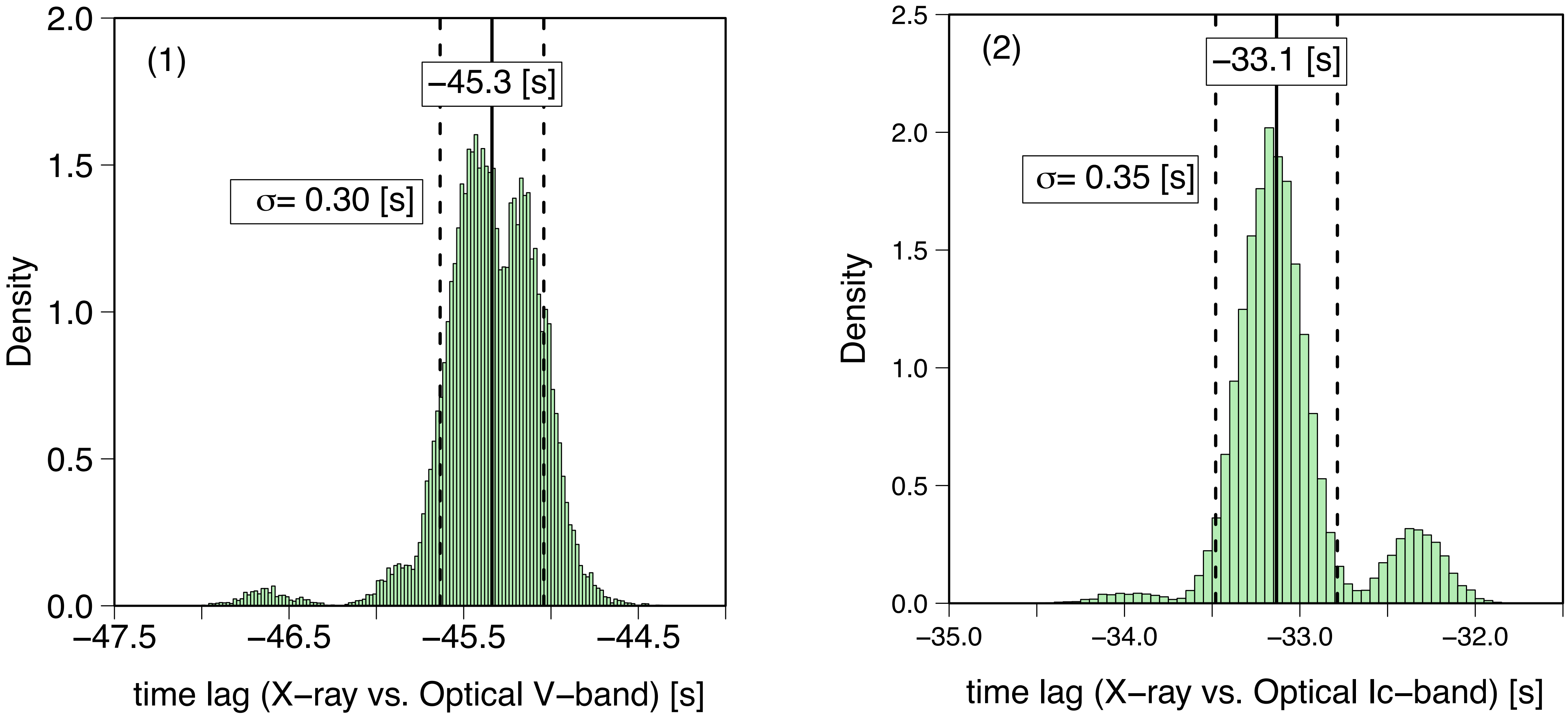
obs. LC

This method is useful for observational data in Astronomy.

1. Irregular observation time
2. Seasonal gap
3. Measurement error

Application to Variations in V404 Cyg



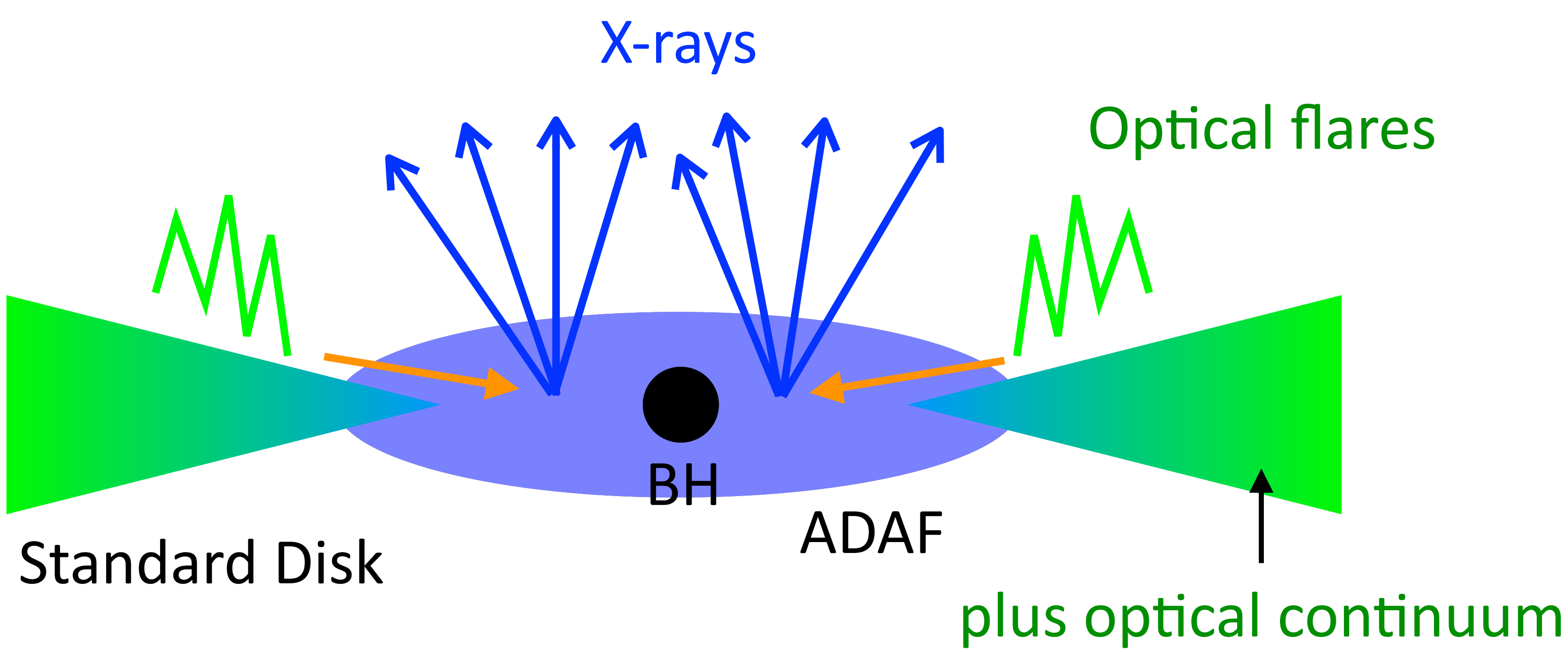


We detected the ~30—45 [s] X-ray delay to optical lights !

Origin of the X-ray Delay to Optical Lights

- The X-ray variations delayed ~30—45 [s] to optical variations.
- In ADAF, matter falls to BH in free-fall time scales (Narayan, Yi 1995).

  → The estimated transition radius is ~3–5 × 10^8 [cm]



➡ The detected time delay is explained well by ADAF plus thin disk.

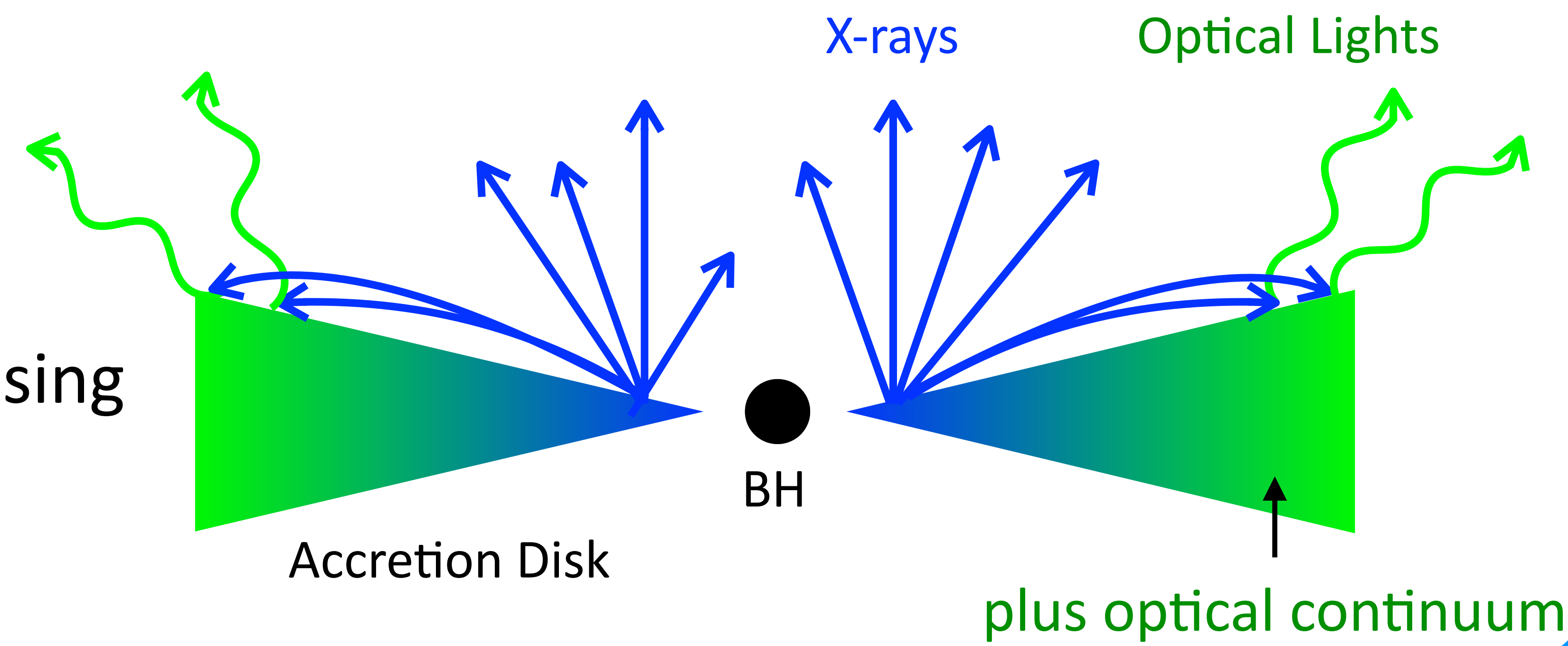
- According to Motta+15, this system showed the low/hard spectral state in the December outburst. → ADAF is preferable

Summary & Future Work

★ V404 Cyg showed violent optical variations at low luminosity both in the two outbursts in 2015.

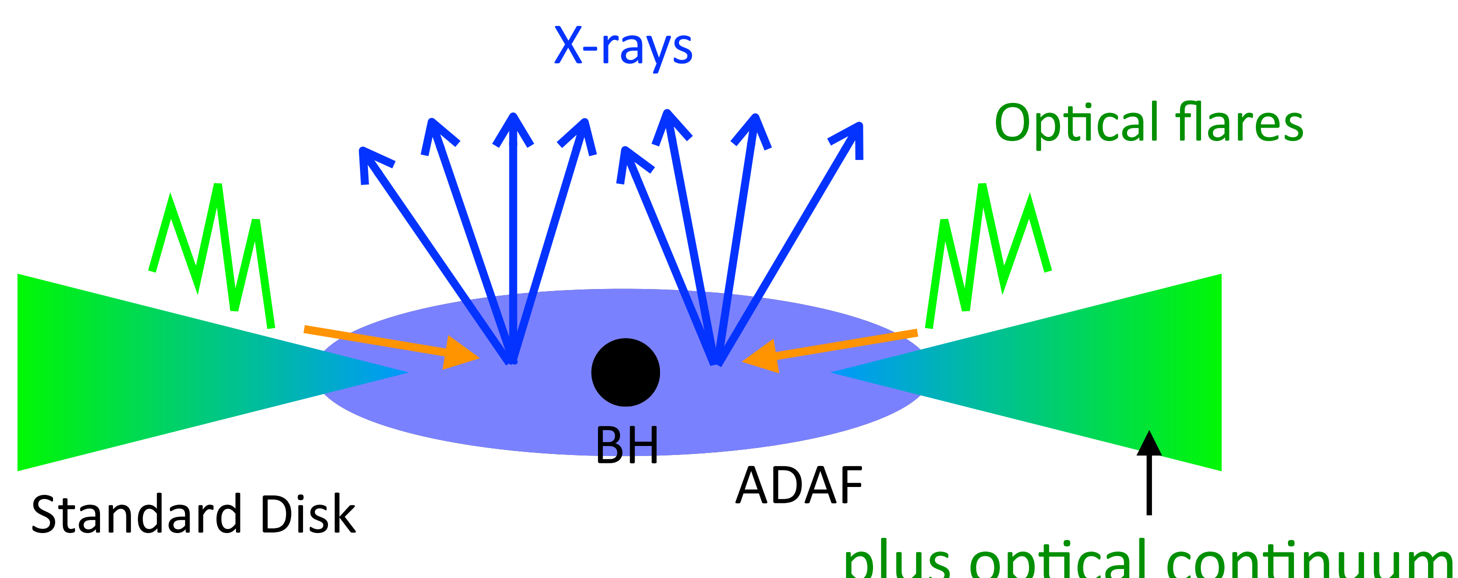
Dip-type oscillations

- caused by X-ray reprocessing
- produce optical delay



Random variations

- produce short X-ray delay
- The delay is interpreted by propagation of accretion flow through ADAF



Summary & Future Work

- ★ V404 Cyg showed violent optical variations at low luminosity both in the two outbursts in 2015.
- ★ An unknown instability may be related with dip-type oscillations.
  - → It is necessary to solve the mechanism causing large-amplitude optical variations in black-hole X-ray binaries.
- ★ In the bayesian method of time lag estimation by Tak+16 is useful to the observational data in Astronomy.
  - → This method may provide a new frontier in multi-wavelengths analysis. For example, improving to deal with spread time delay (e.g., normal distribution), we could know the structure of the disk (reverberation mapping).