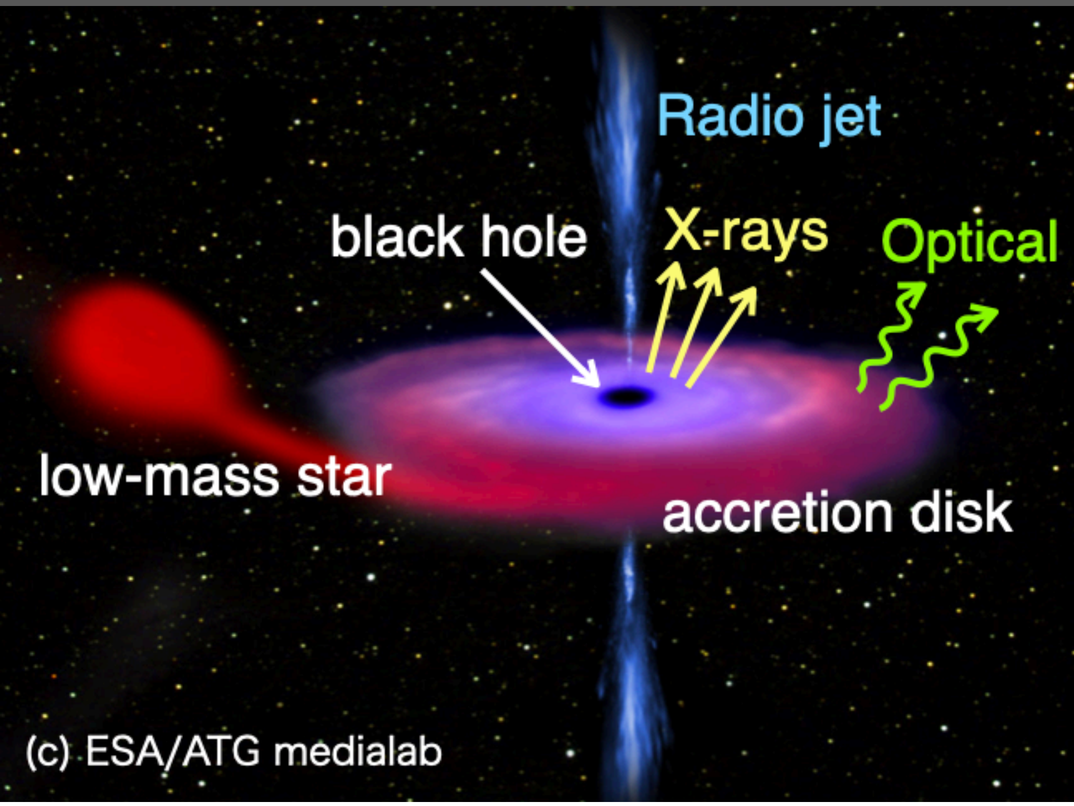
Evolution of X-ray and optical rapid variability during the 2018 outburst of MAXI J1820+070

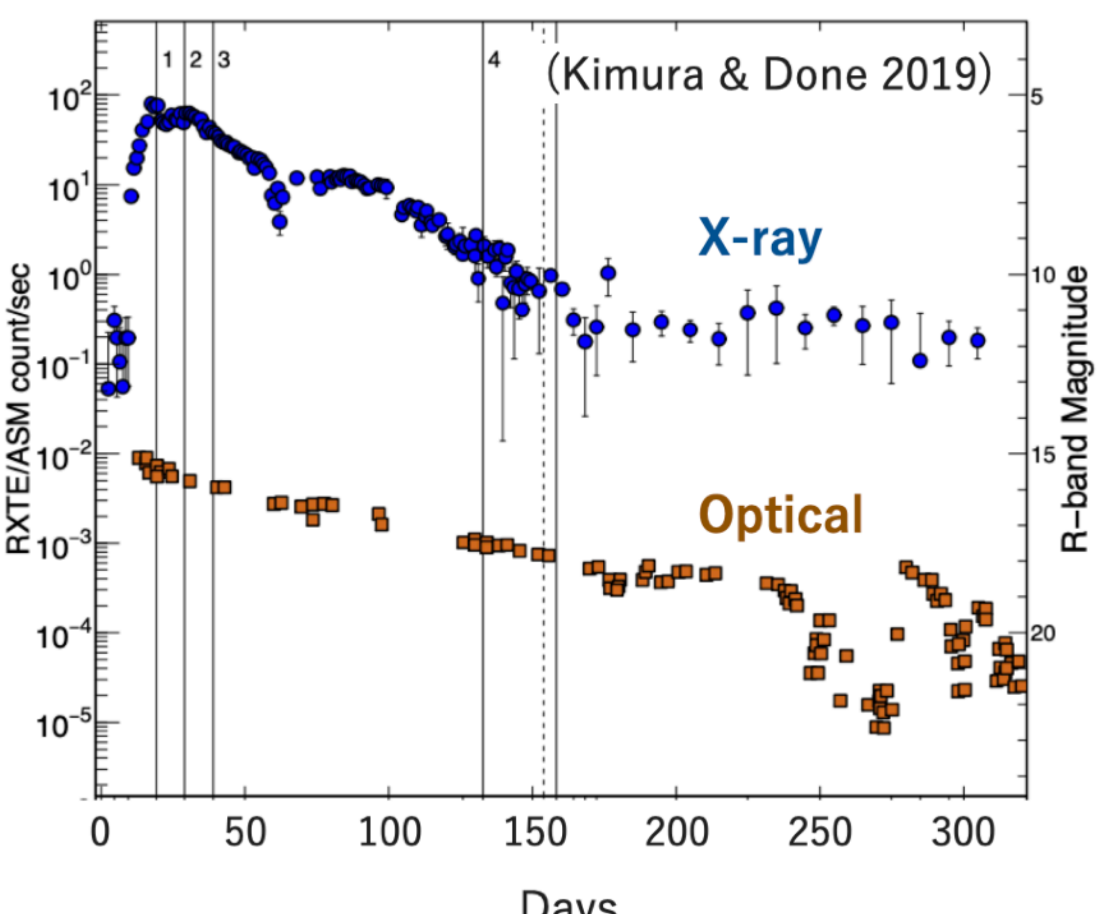
Presenter: Mariko Kimura
(Kanazawa University)

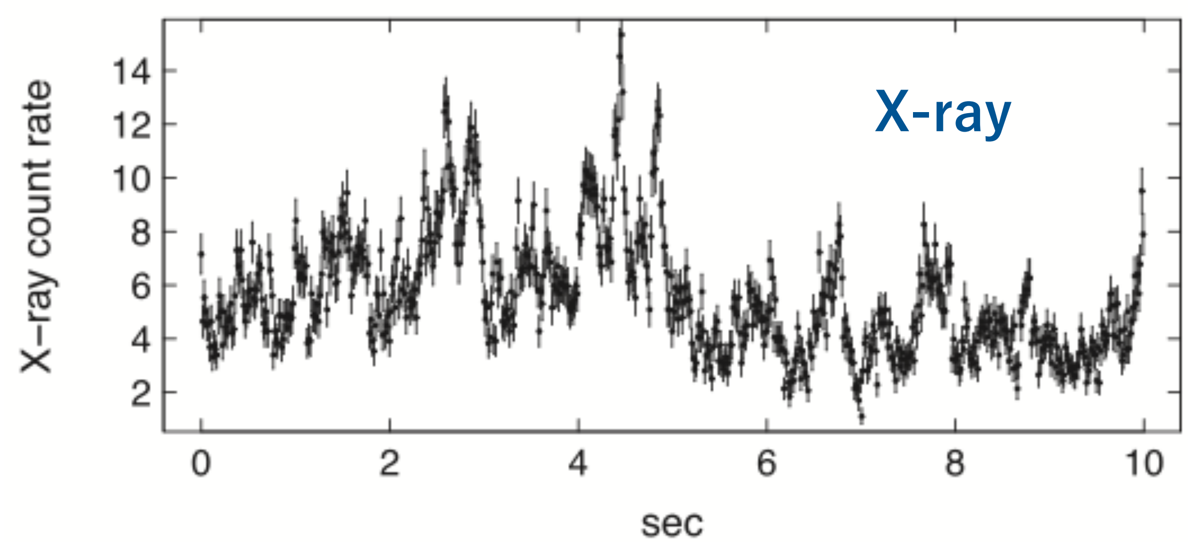
Collaborators:
Hitoshi Negoro (Nihon University), Shinya Yamada (Rikkyo University),
Wataru Iwakiri (Chiba University), Shigeyuki Sako (University of Tokyo),
Ryou Ohsawa (NAOJ)

Black-hole low-mass X-ray binaries



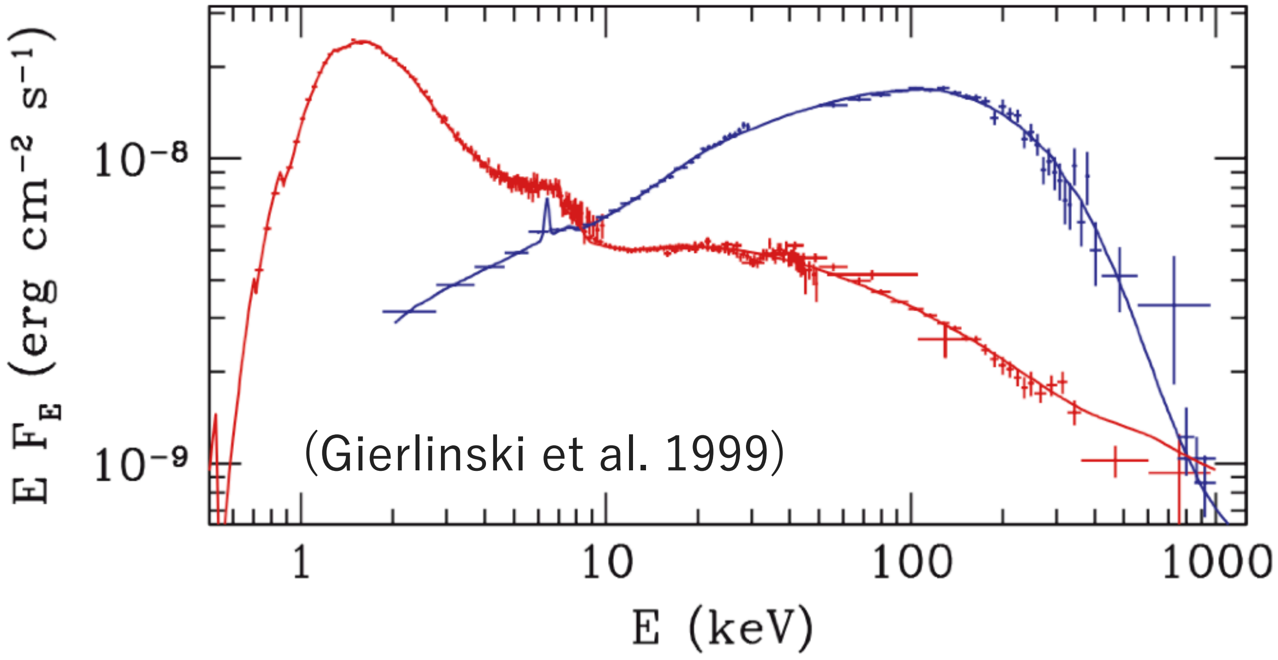
- Close binary system composed of a black hole and a low-mass star
- An accretion disk is formed around the black hole
- Show intermittent outbursts (sudden brightening of the disk) at multi-wavelengths
- Outbursts are triggered by thermal-viscous instability at the disk
- Sub-second flares during outburst

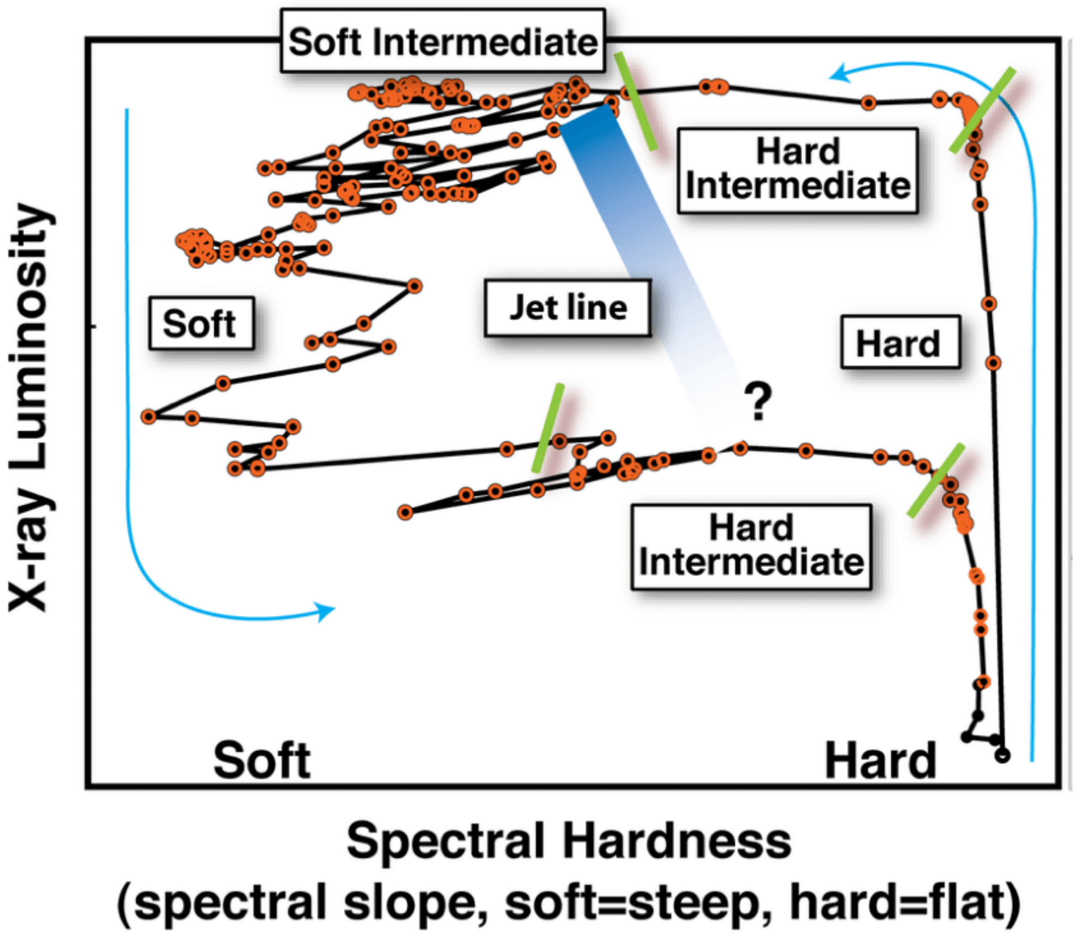




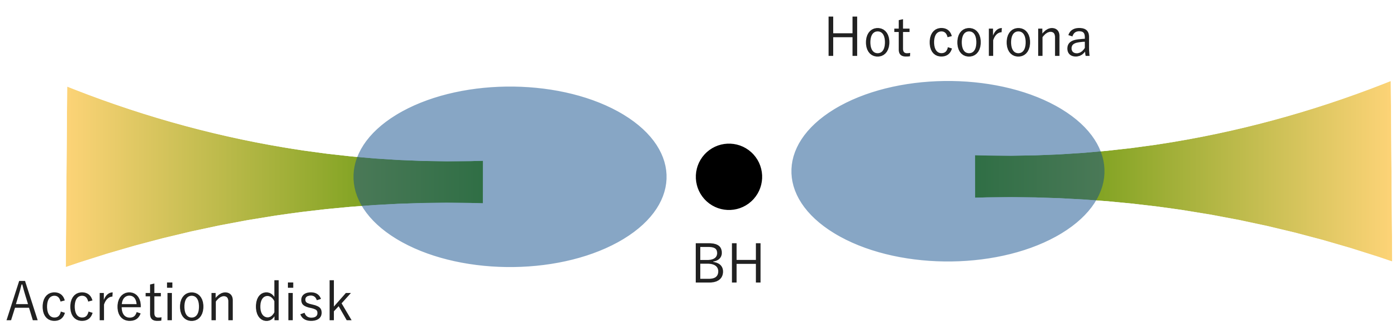
The origin of sub-second flares ?

X-ray spectral transition & variability

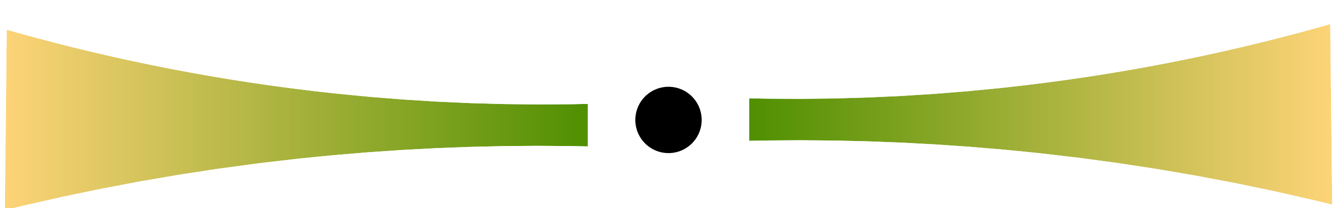




Blue: hard state



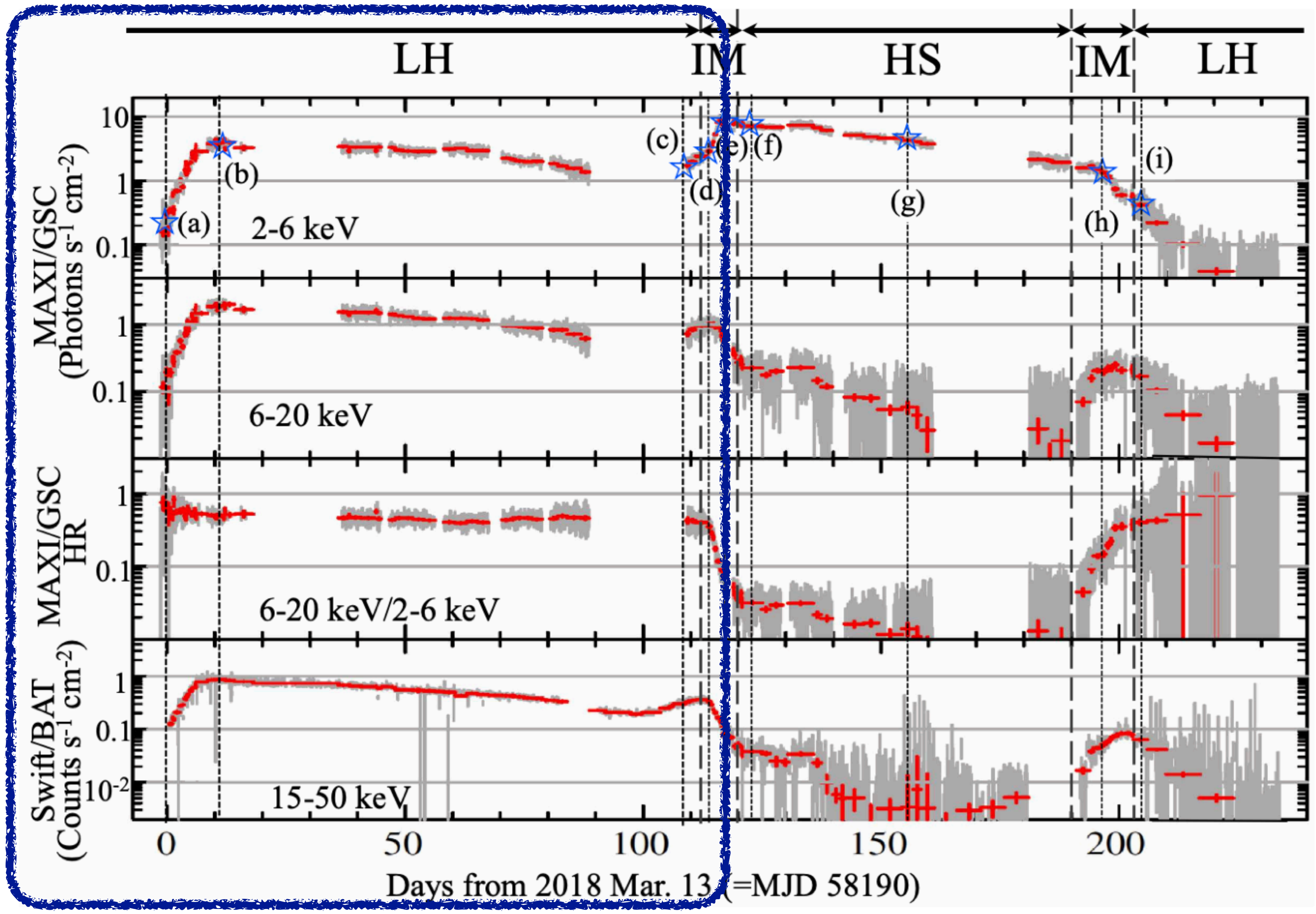
Red: soft state



- **Sub-second variability is observable in the hard state.**
- Typically, the hard-to-soft state transition occurs around the outburst maximum.

MAXI J1820+070 = ASASSN-18ey

hard state



(Shidatsu et al. 2019)

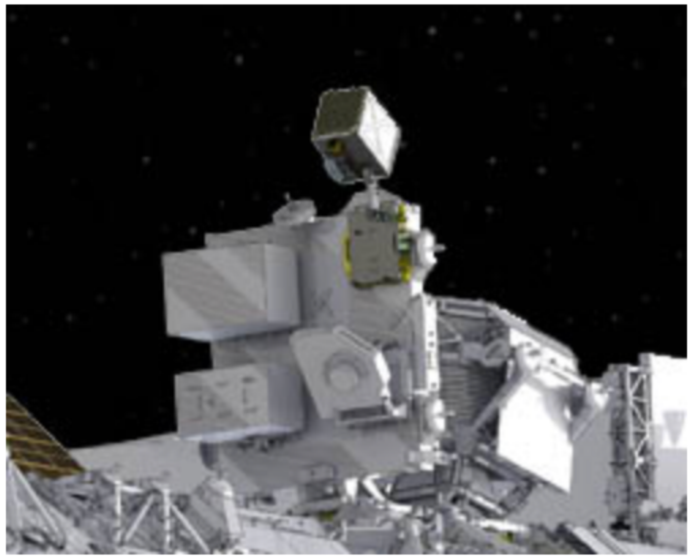
- Entered an outburst in 2018s
- Very bright during outburst in X-ray (10^{-7} ergs/s/cm^2) and optical (12 mag)
- **The hard state lasted for ~100 days !**

↓

Best target for studying sub-second variability.

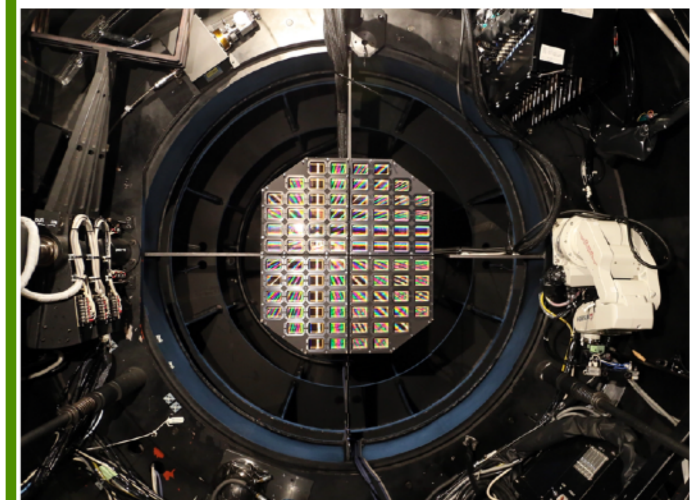
Observations

NICER (X-ray)



- 0.2—12.0 keV
- High time resolution (Absolute timing precision of < 300 ns)
- Mount on ISS
- Long-term monitoring
- Large effective area: ~1900 cm^2 at 1.5 keV

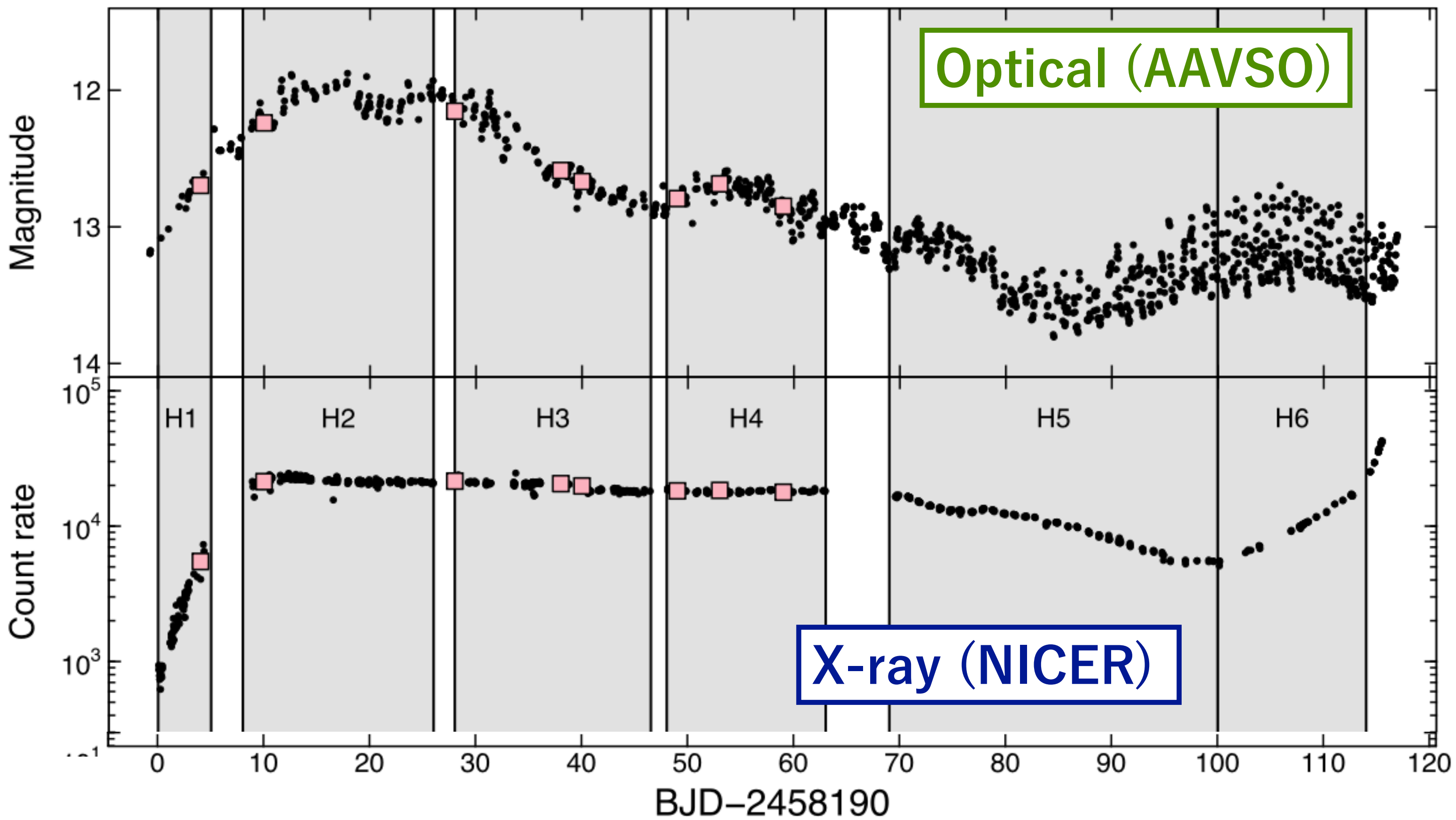
Tomo-e Gozen (Optical)

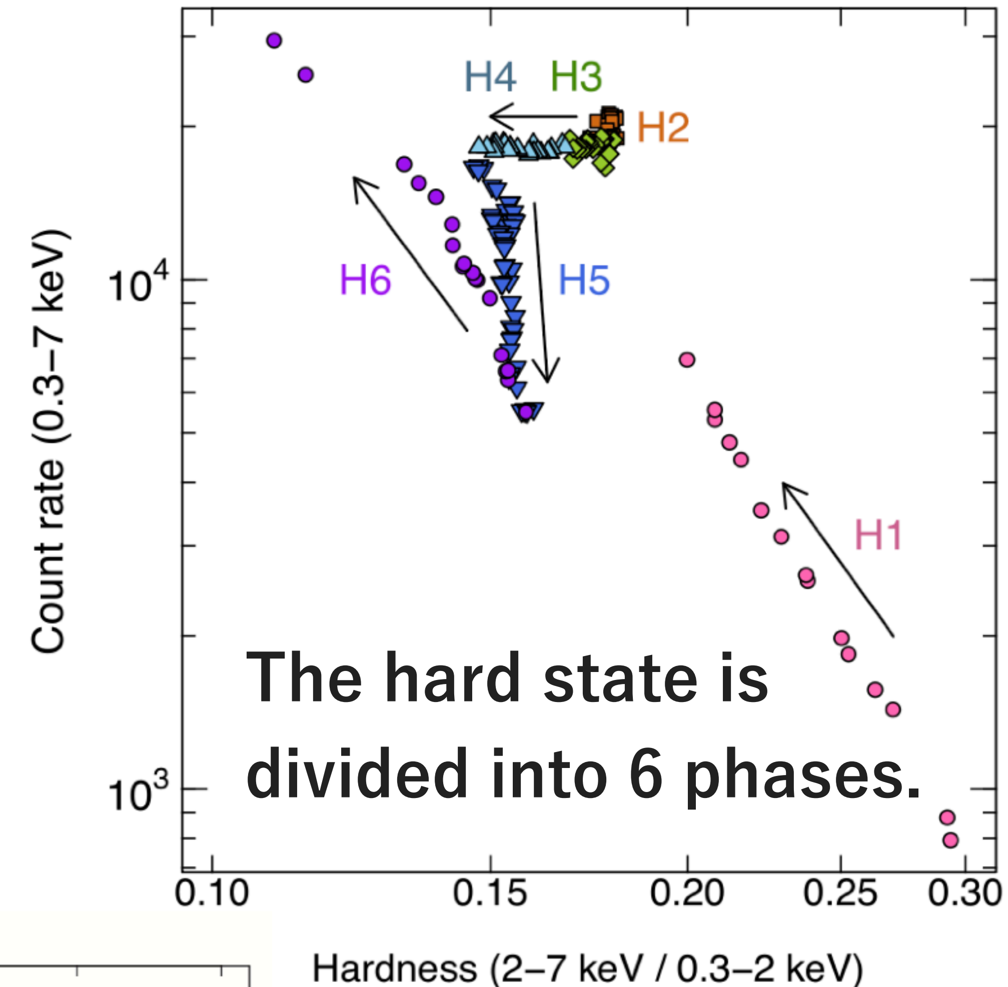


- 400—700 nm
- Absolute time accuracy of 0.2 ms
- Mount on the 1.05-m Kiso Schmidt telescope
- Wide-field video survey (2 fps with a FOV of 20 deg^2 with 84 chips of CMOS)
- **160 fps (max)** in partial-frame

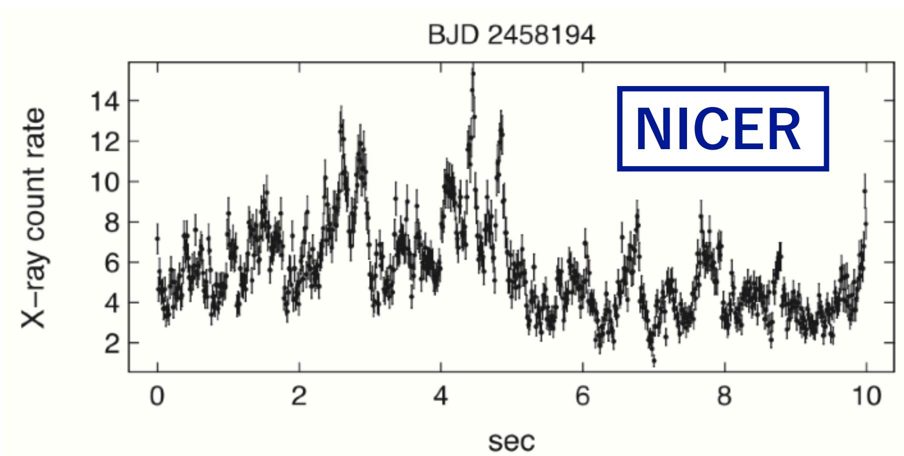
- NICER monitored MAXI J1820+070 during the 2018 outburst.
- We observed MAXI J1820+070 by Tomo-e Gozen with 67 fps on 8 days. (Not completely simultaneously, but on the same date as observed by NICER)

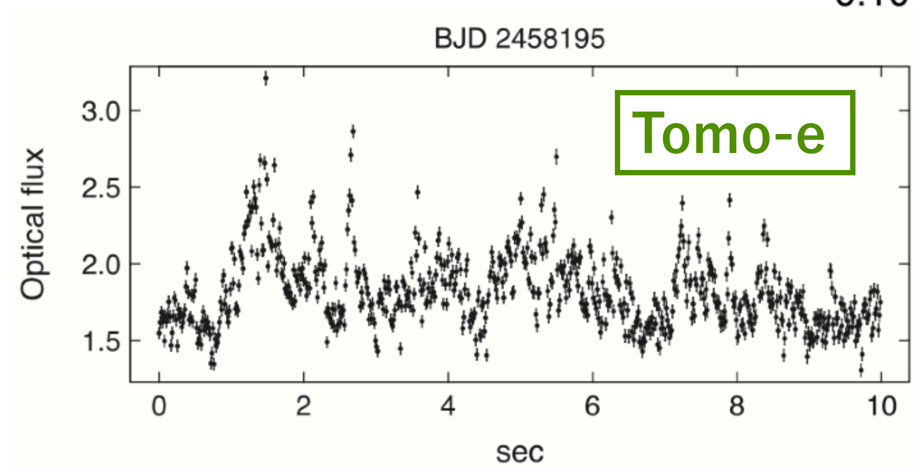
Overall light curves during the hard state





The hard state is divided into 6 phases.





- We detected sub-second variability in X-ray and optical.

Method of shot analyses

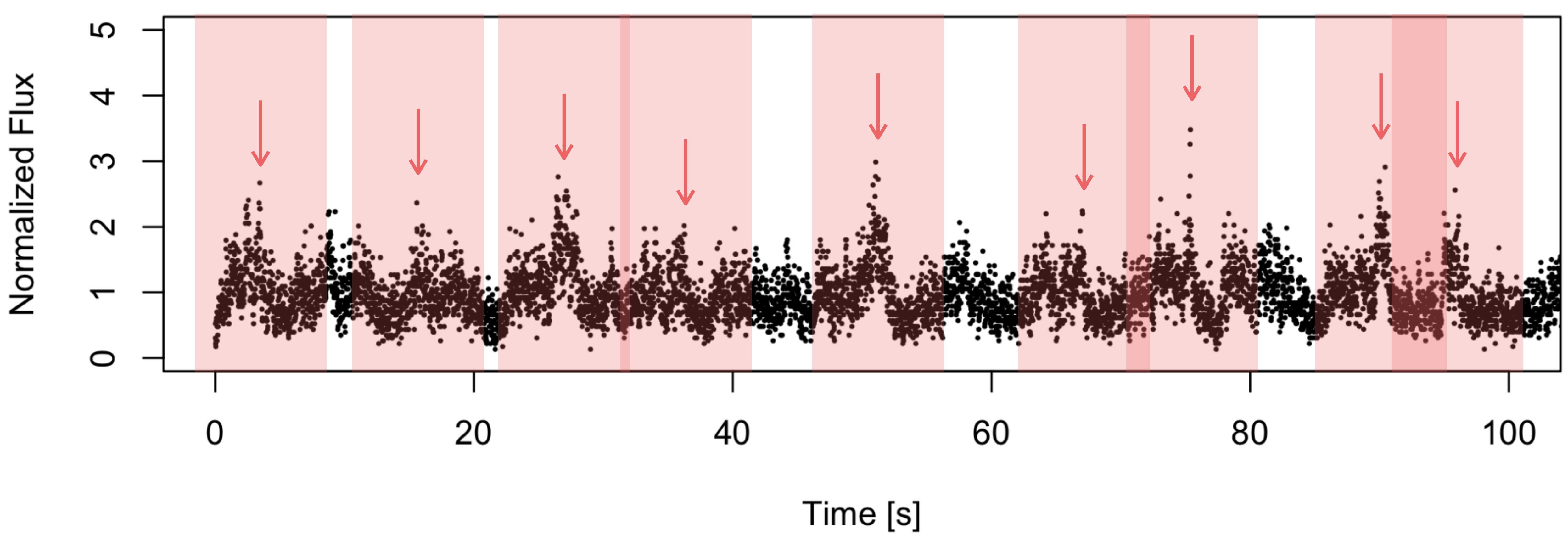
- Create an averaged flare profile (= shot) **per date** by extracting many flares from light curves and superposing them (Negoro et al. 1994).

(1) Determine the time interval of flares (2*t_int)

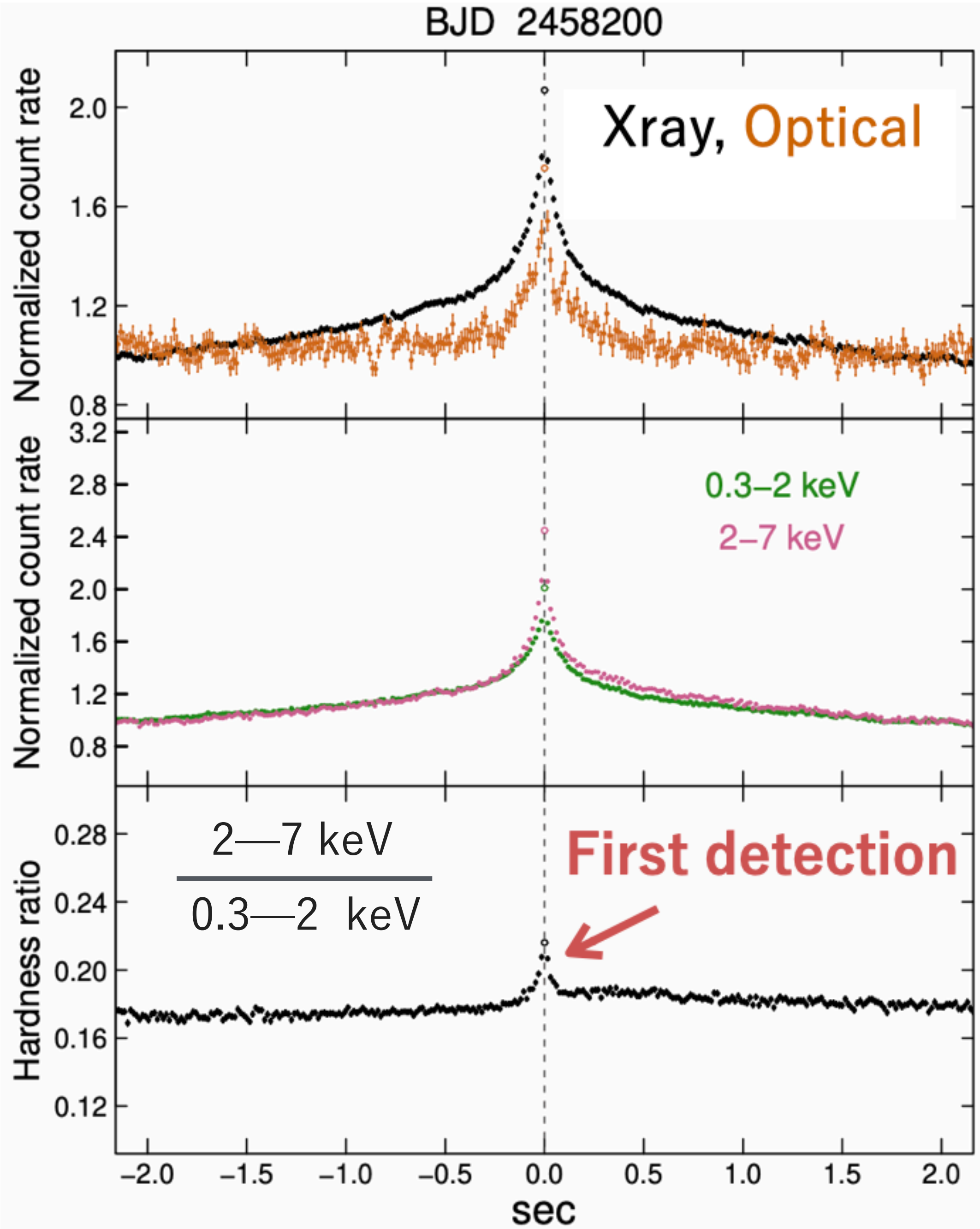
(2) Search the time of maximum flux (t_p) in a window with the length of t_int by shifting the window

(3) Extract the light curve in t_p – t_int < t < t_p + t_int

(4) Superpose flares by centering them with t_p and take averaged flux in each time bin.

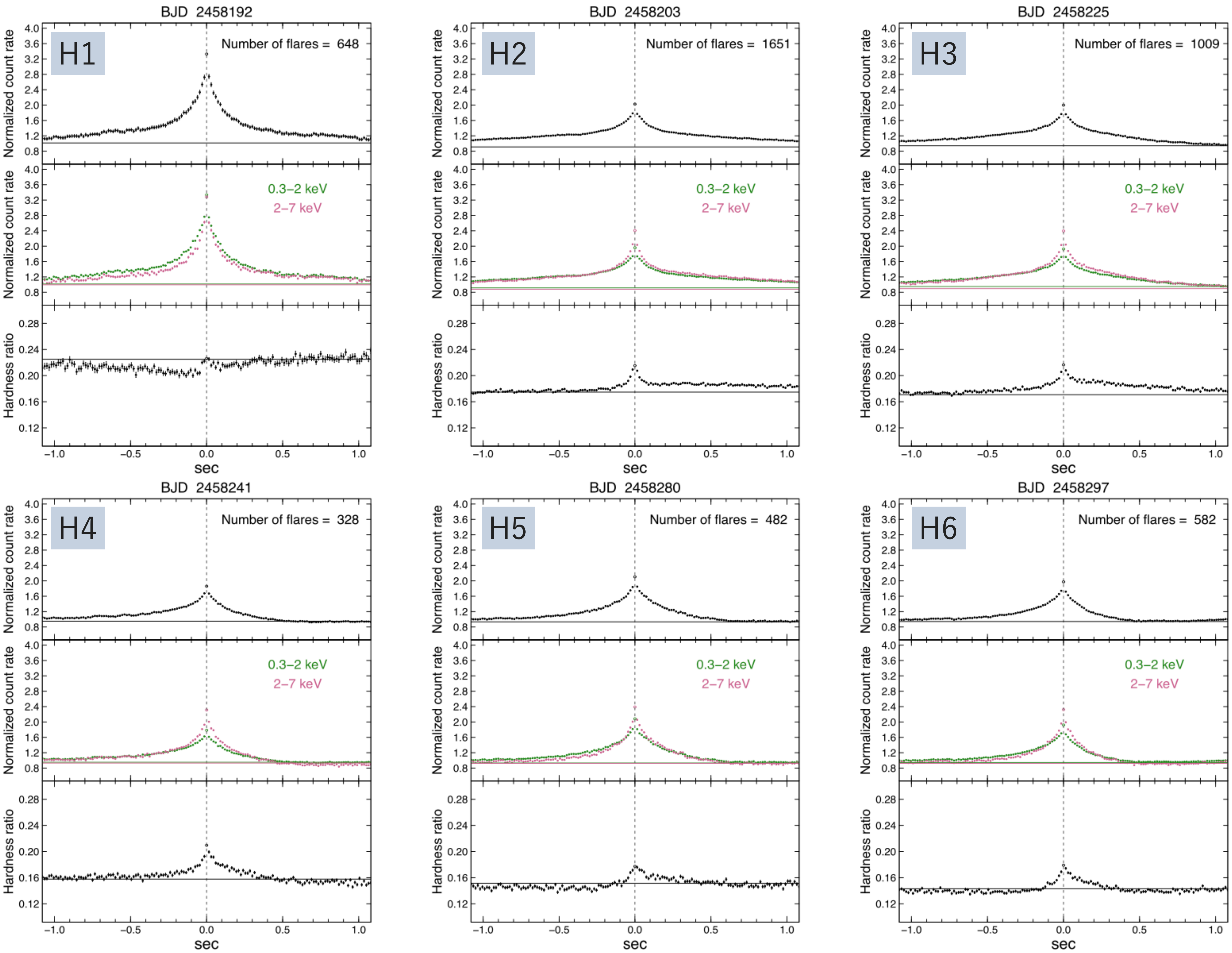


X-ray & optical shot profiles per date

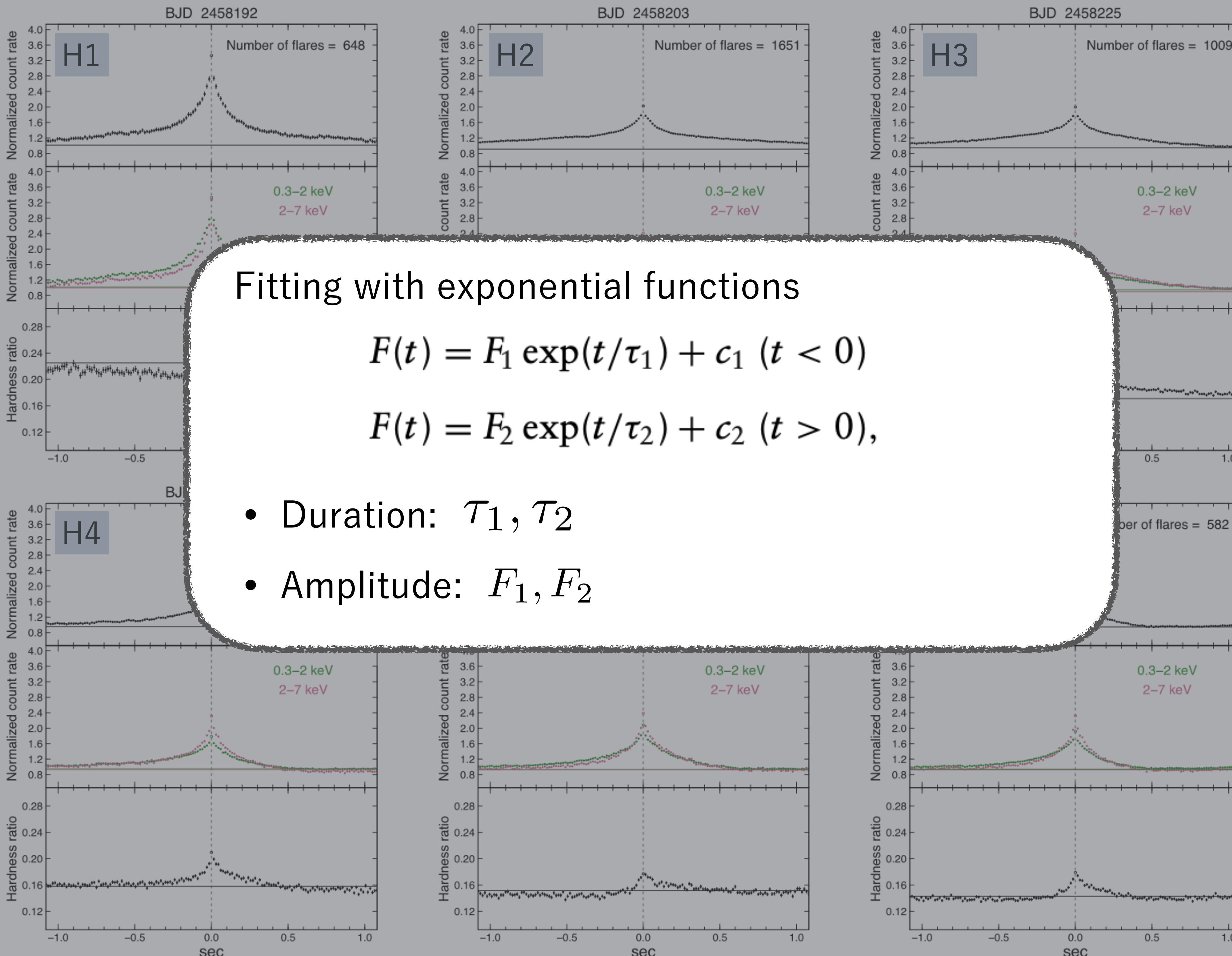


- X-ray flares had a duration of ~0.2 s.
- Optical flares were narrower than X-ray flares.
- The spectrum became harder after the flare.
- **The abrupt increase of the hardness at the center of flares was detected for the first time !**

Time evolution of shot profiles



Time evolution of shot profiles



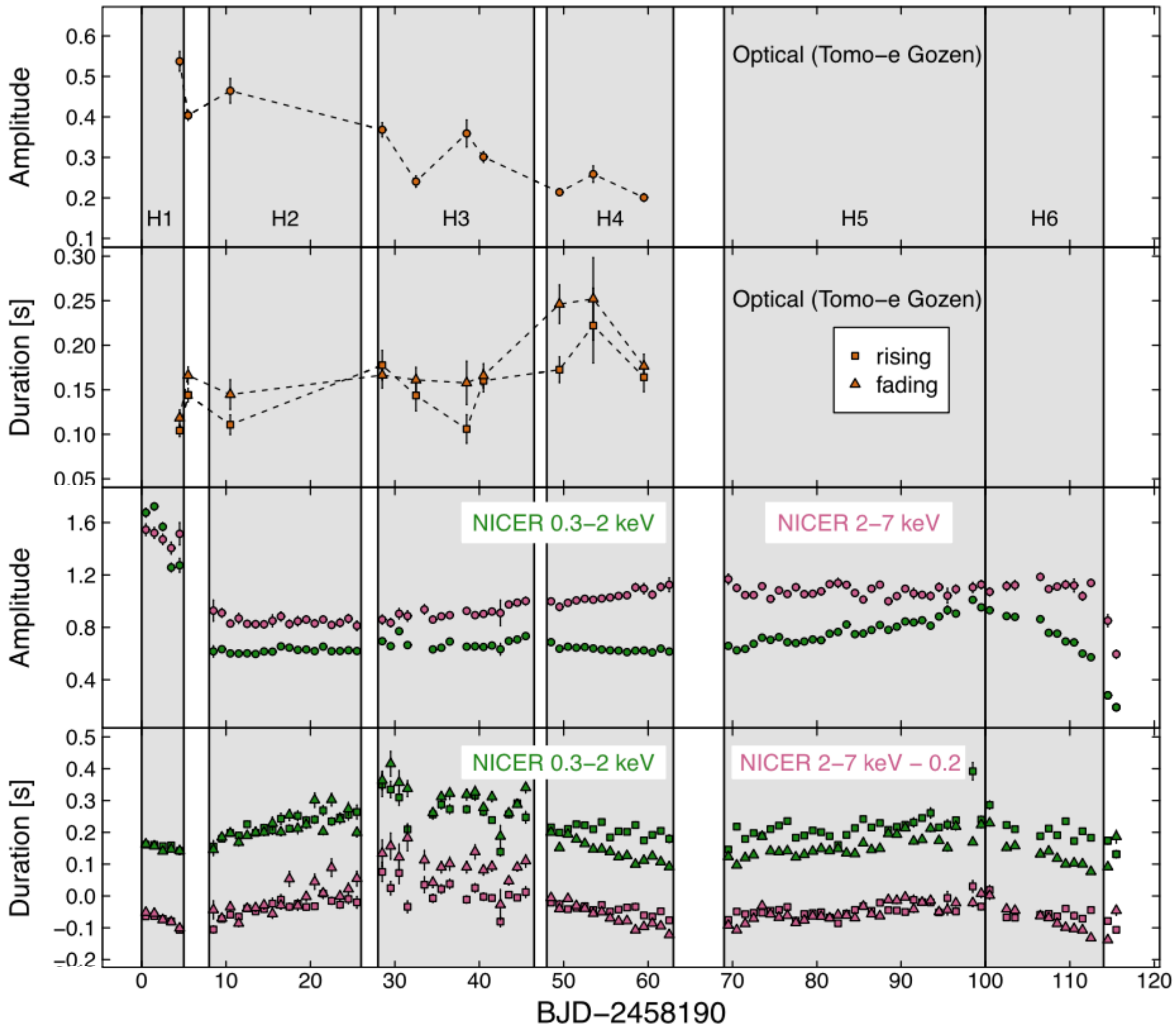
Fitting with exponential functions

$$F(t) = F_1 \exp(t/\tau_1) + c_1 \ (t < 0)$$

$$F(t) = F_2 \exp(t/\tau_2) + c_2 \ (t > 0),$$

- Duration: τ_1, τ_2
- Amplitude: F_1, F_2

Time evolution of shot profiles



- H1: Large amplitude, decreasing duration and amplitude
- H2: Increasing duration
- H3: Asymmetric, increasing amplitude, decreasing duration
- H4: Asymmetric, decreasing duration, soft X-ray amplitude is decreasing & hard X-ray amplitude is increasing
- H5: Asymmetric, soft X-ray amplitude is increasing, increasing duration
- H6: Asymmetric, decreasing amplitude and duration

- The properties of shot profiles changed with the evolution of X-ray spectra.
- Different evolution between X-ray and optical shot profiles.

Origin of X-ray flares

- The amplitude was the largest in H1.
- Flares faded at the hard-to-soft spectral transition.

⟶ **The source is "hot corona" (ADAF-like region).**

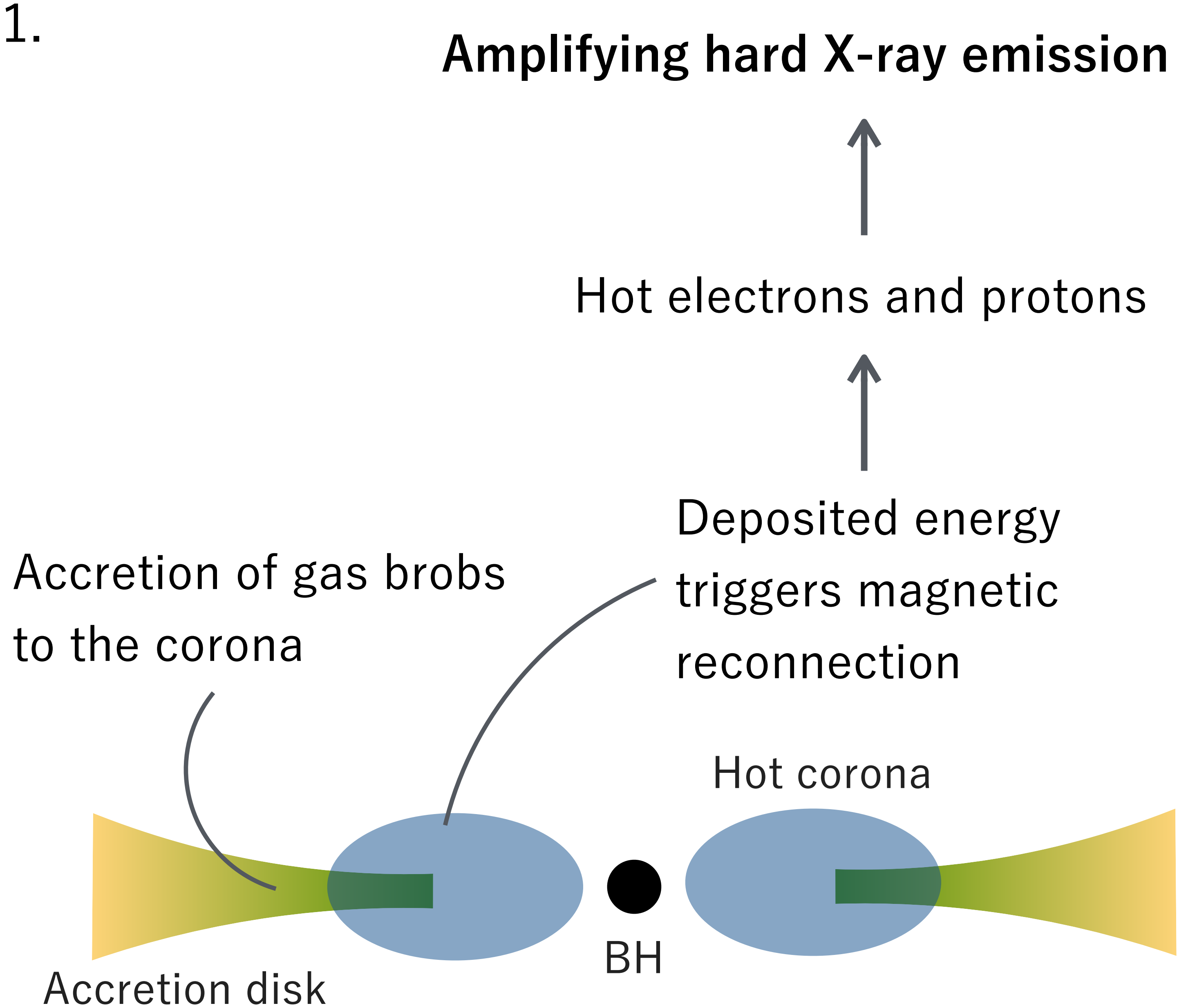
- There are two timescales:

(1) >1 s: Fading tail of flares & spectral hardening after the fading of flares

(2) ~0.2 s: Steep flaring & accompanied abrupt spectral hardening

⟶ **(1) Viscous timescale at the inner disk edge**

(2) Dynamical timescale



Magnetic activity is the key ?

(Machida & Matsumoto 2003; Mineshige et al. 1994)

Origin of optical flares

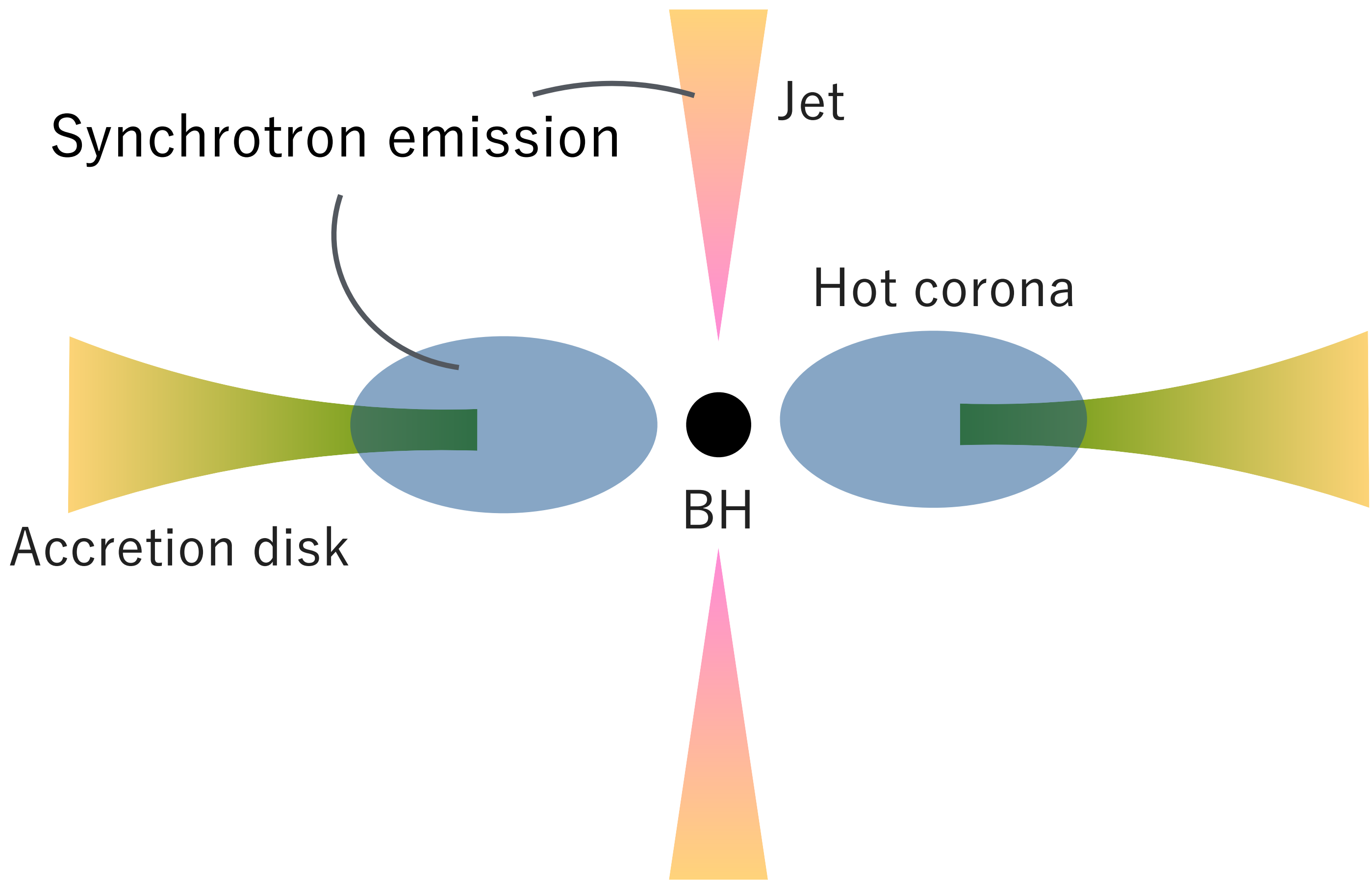
- Optical shots were narrower than X-ray shots.

→ ✗ X-ray reprocessing

○ **Synchrotron emission**

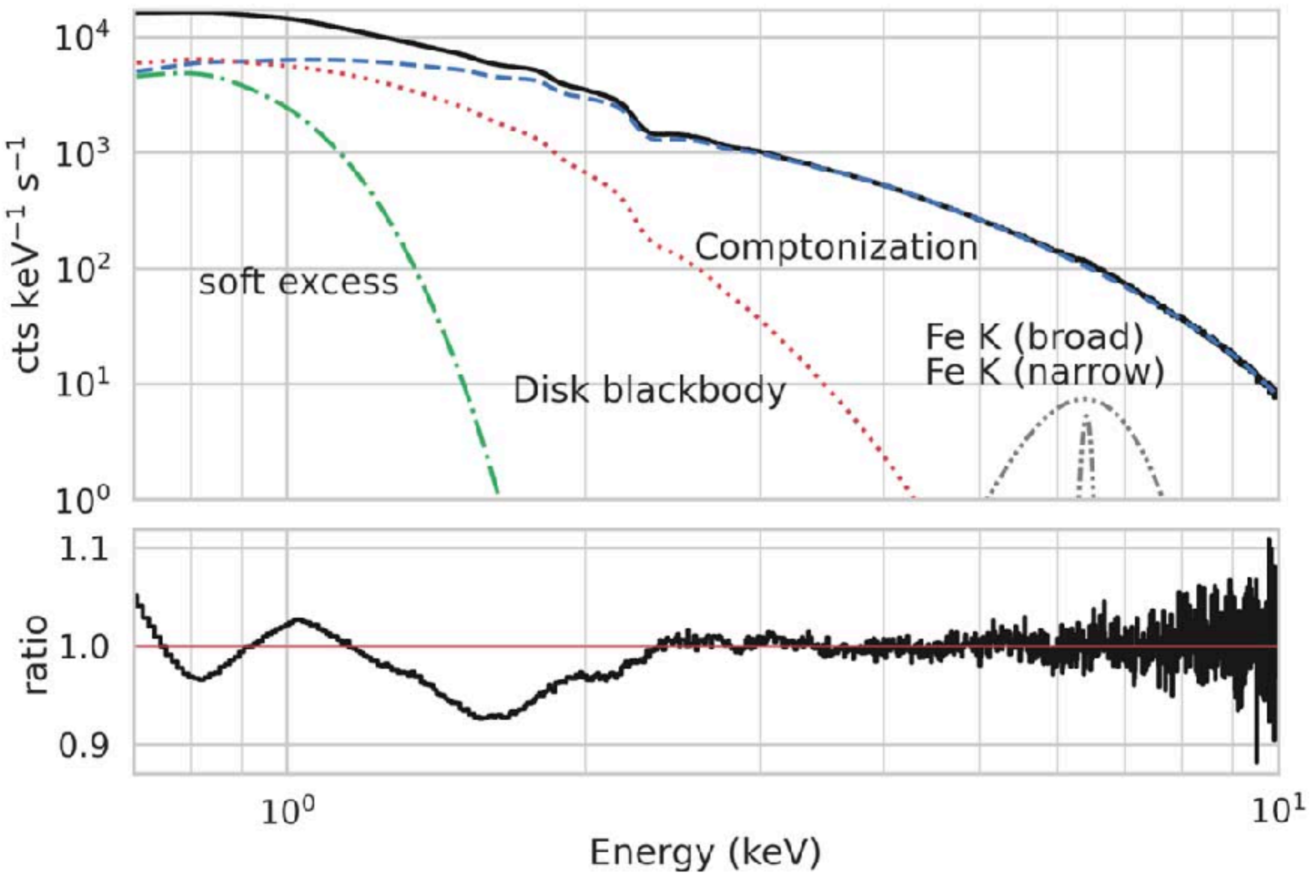
- Different time evolution between X-ray and optical shots.

→ **Not only the emission from the hot corona but also the emission from the jet are related to the variability.**



(Kanbach et al. 2001; Veledina et al. 2011)

What does the time evolution mean ?



(Omama et al. 2023)

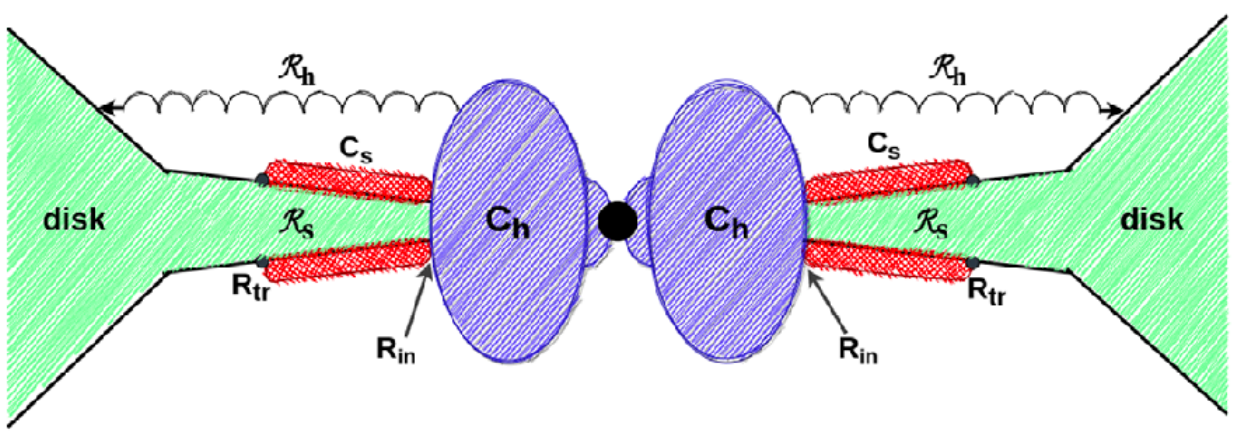
- It is difficult to decompose X-ray spectra during the hard state in MAXI J1820+070.
- **Time-varying properties of X-ray shots suggest the time evolution of the hot Comptonization corona ?**

Evolution in the shot duration

→ Changing size of the hot corona ?

Evolution in the shot amplitude

→ Changing magnetic activity ?



(Zdziarski et al. 2021)

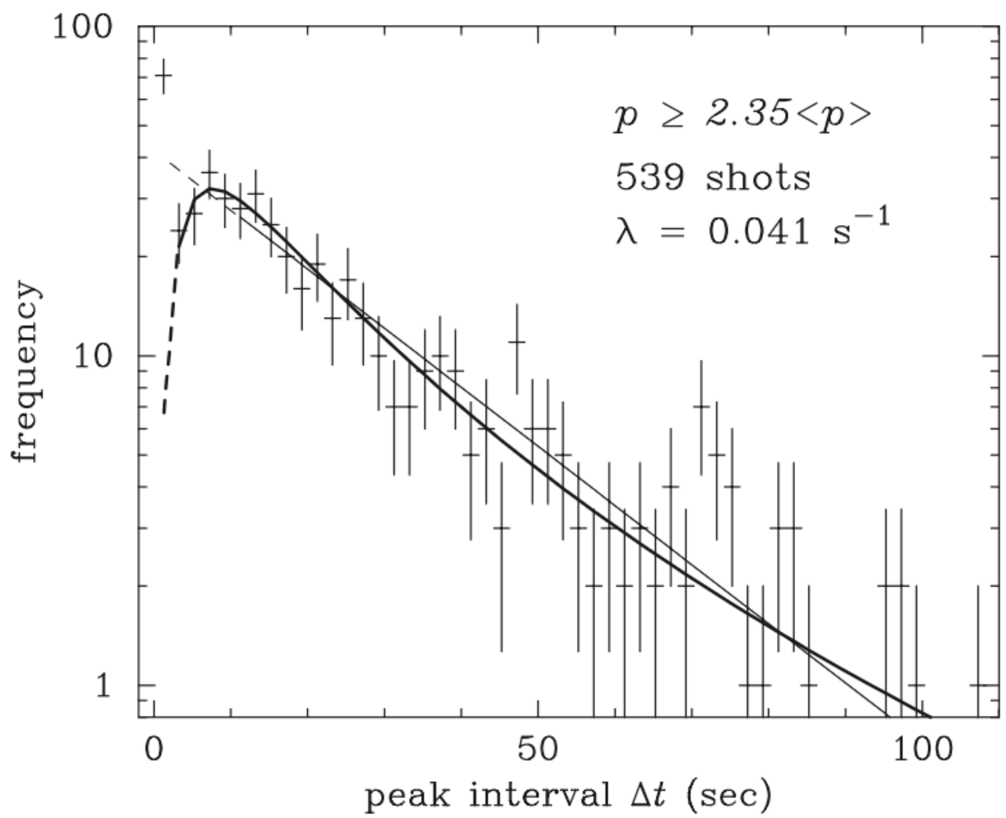
Application for other systems

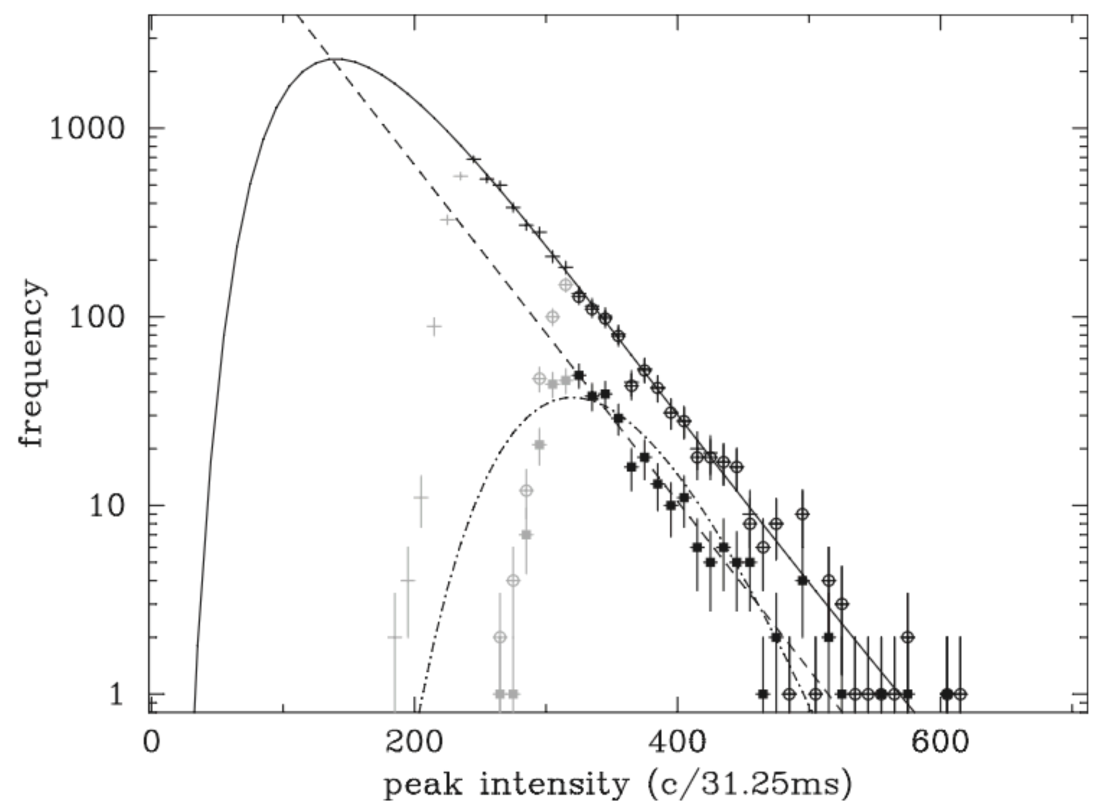
- Shot analyses have been applied to cataclysmic variables (CVs) and active galactic nuclei (AGNs) (e.g., Dobrotka et al. 2019; Sasada et al. 2017)

  ⟶ Understand properties of ADAF

  ⟶ Suggestions about neutrino emission ?

- **Could we apply the shot analysis to the multi-wavelength data of GRBs ?**
- **The variability properties of BHBs in the hard state share common characters with GRBs ?**





(Negoro & Mineshige 2002)

Summary

- We analyzed NICER and Tomo-e Gozen high-time-cadence light curves of MAXI J1820+070 by shot analyses.
  - The hard state is divided into six phases.
  - The duration of X-ray flare was ~0.2 s and an abrupt spectral hardening is accompanied.
  - The optical flare was narrower and smaller than the X-ray flare.
  - The properties of X-ray shots changed with the phase transtion.
- Our results suggest:
  - Accreting gas blobs triggered magnetic reconnection, which enhances hard X-ray emission in the hot corona.
  - Not only hot corona but also jet generated optical flares.
  - Time evolution of flares implies time evolution of hot Comptonization corona.

Origin of asymmetry of X-ray flares

- The density disturbance in the hot corona reproduces a slightly deeper dip at the fading stage (Manmoto et al. 1996) ?
- The temporary depletion of the accreting gas after flaring (Negoro & Mineshige 2002) ?