TeVPA 2021 Extragalactic session

Fast X-ray variability[1] of radio galaxy M87

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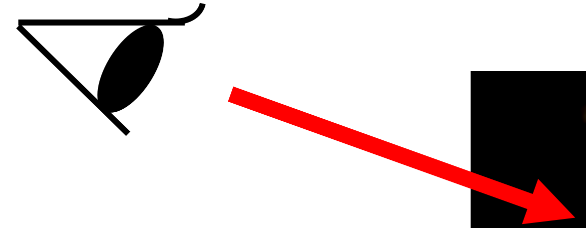
[1] R. Imazawa, Y. Fukazawa, H. Takahashi,
"The Study of X-Ray Flux Variability of M87", ApJ, 2021, July

Introduction

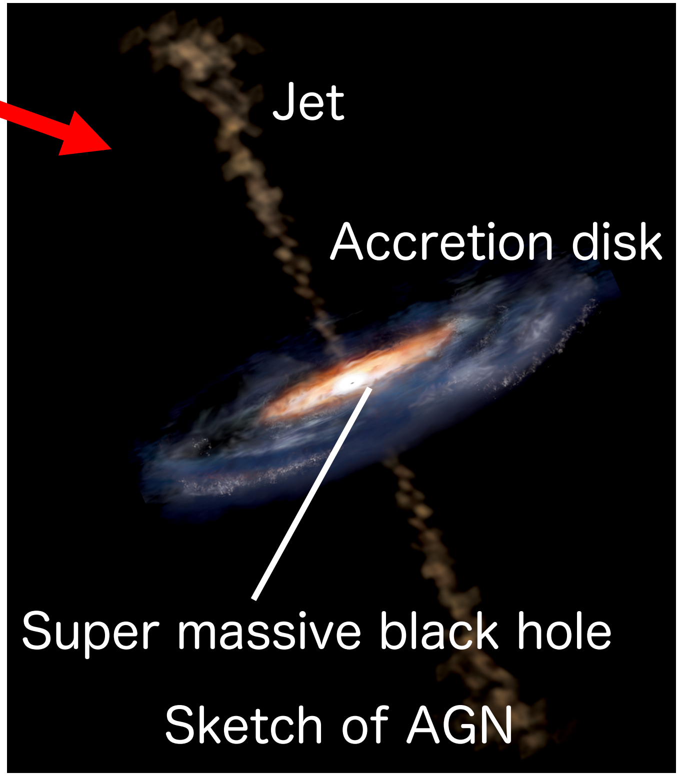


○ Particle acceleration in AGN

TeV gamma-ray emission
➡ Suggesting particle acceleration above TeV

Where is the particle acceleration occur ?

➡ One of the open questions of AGN, related to the production of very high energy cosmic rays.

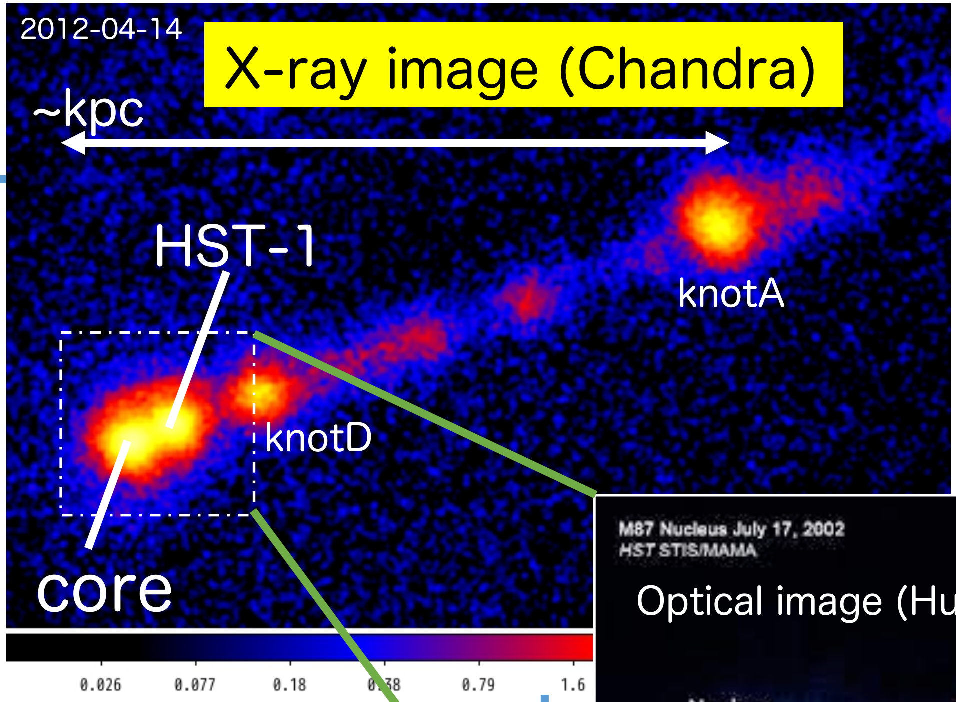


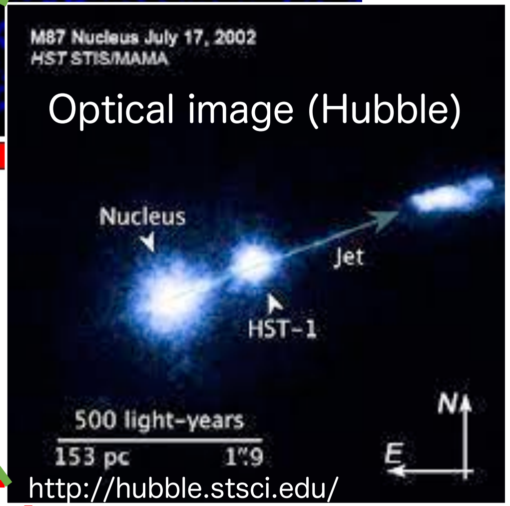
Credit: Aurore Simonnet, Sonoma State University

Radio galaxy

➡ One type of AGN, whose jet is seen in large inclination.
It is possible to see radiation from the BH vicinity.
Suitable objects for studying the site of particle acceleration.

Introduction





○Radio galaxy M87

Reported TeV emission in several times.
(Aharonian et al. 2006, Acciari et al. 2008, Albert et al. 2008)
HST-1 X-ray flare — core X-ray flare

Distance ~16 Mpc (z ~0.0043)

Several jet components are visible in radio to X-rays.

➡ **Particle acceleration above TeV suggested, good object for this study.**

Motivation: To investigate the site of particle acceleration from the M87 jet using fast X-ray flux variability.

↳ X-ray ➡ Synchrotron radiation from the jet.
X-ray fast variability indicates the presence of high energy electron.

Observation/Analysis

Data from Chandra, NuSTAR, and Suzaku which has long exposure (>10ks) observations.

➡ Total: 22 obs. Chandra (ACIS:13, HRC:2), NuSTAR (6), Suzaku (1)

Satellites	Detectors	Features
Chandra	ACIS	Good angular・energy resolution
	HRC	Good angular・time resolution Cannot perform spectral analysis
NuSTAR	FPMA, FPMB	Hard X-ray is detectable
Suzaku	XIS0, XIS1, XIS3	Good energy resolution

(ACIS and HRC: They can resolve each component)

➡ Performed light curve and spectral analysis for each observation

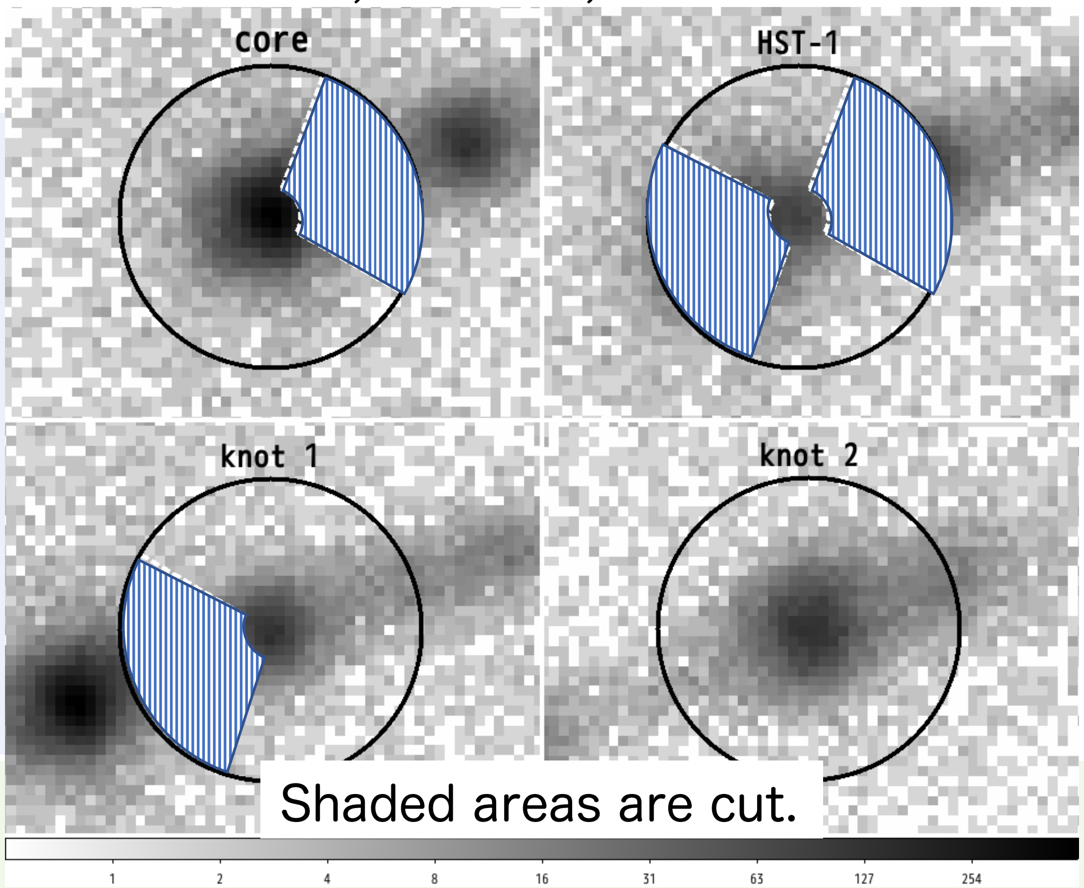
Observation/Analysis

■ Lightcurve analysis

Source region: Circle
Background: annulus or box

- Chandra (2 arcsec, 2.0-10.0 keV)
- NuSTAR (0.5 arcmin, 3.0-80.0 keV)
- Suzaku (3.0 arcmin, 3.0-10.0 keV)

Chandra; 2 arcsec, 2.0-10.0 keV



Shaded areas are cut.

■ Spectral analysis with Xspec[1]

Galactic absorption *(2-temperature galaxy cluster plasma + AGN component):
wabs* (vapec + vapec + pegpwrlw)

(Soft X-ray)

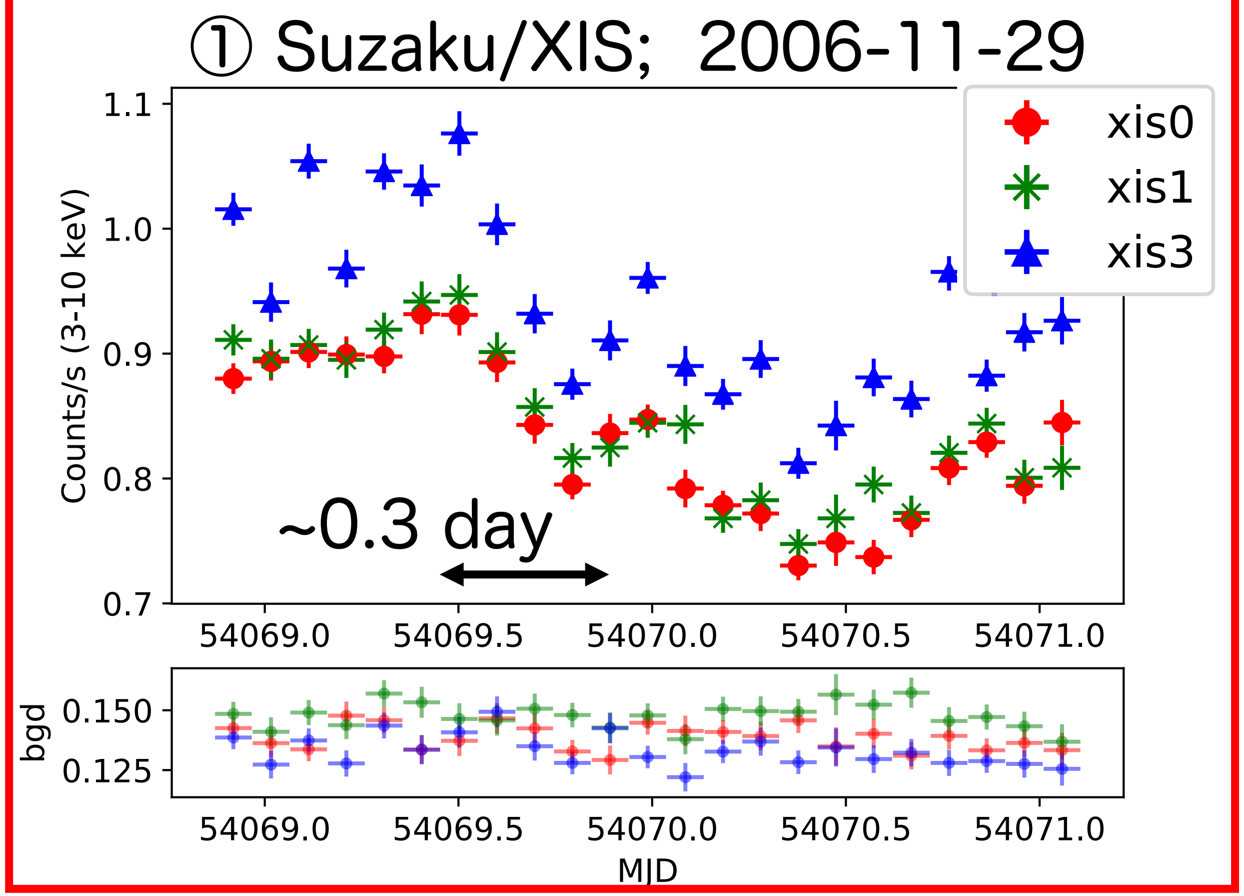
free parameters:
Photon Index, normalization (flux)

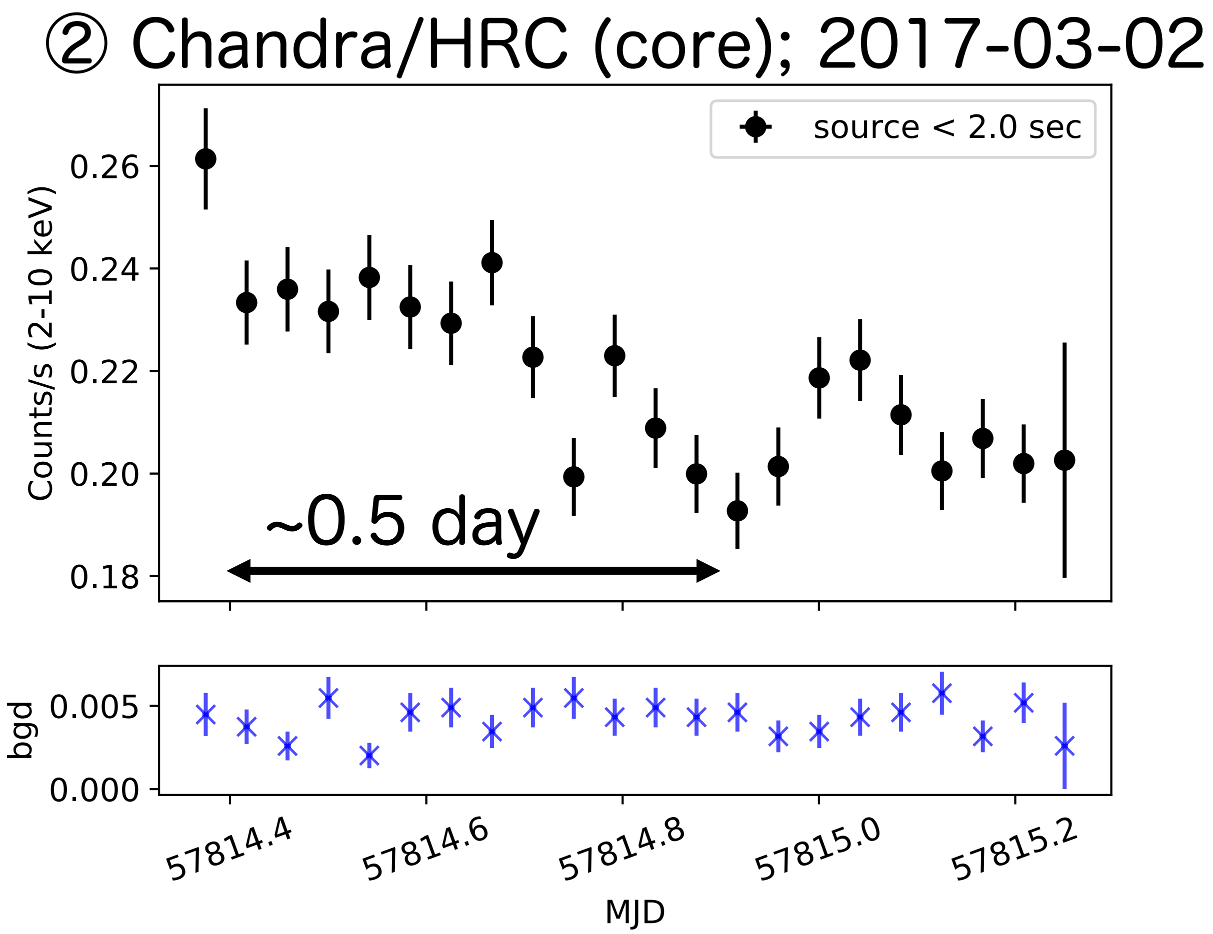
Parameters estimated by Chandra, Suzaku

1. NASA/HEASARC

Result: Lightcurve

Of the 22 observations, one Suzaku observation and one Chandra observation showed variability within a day.

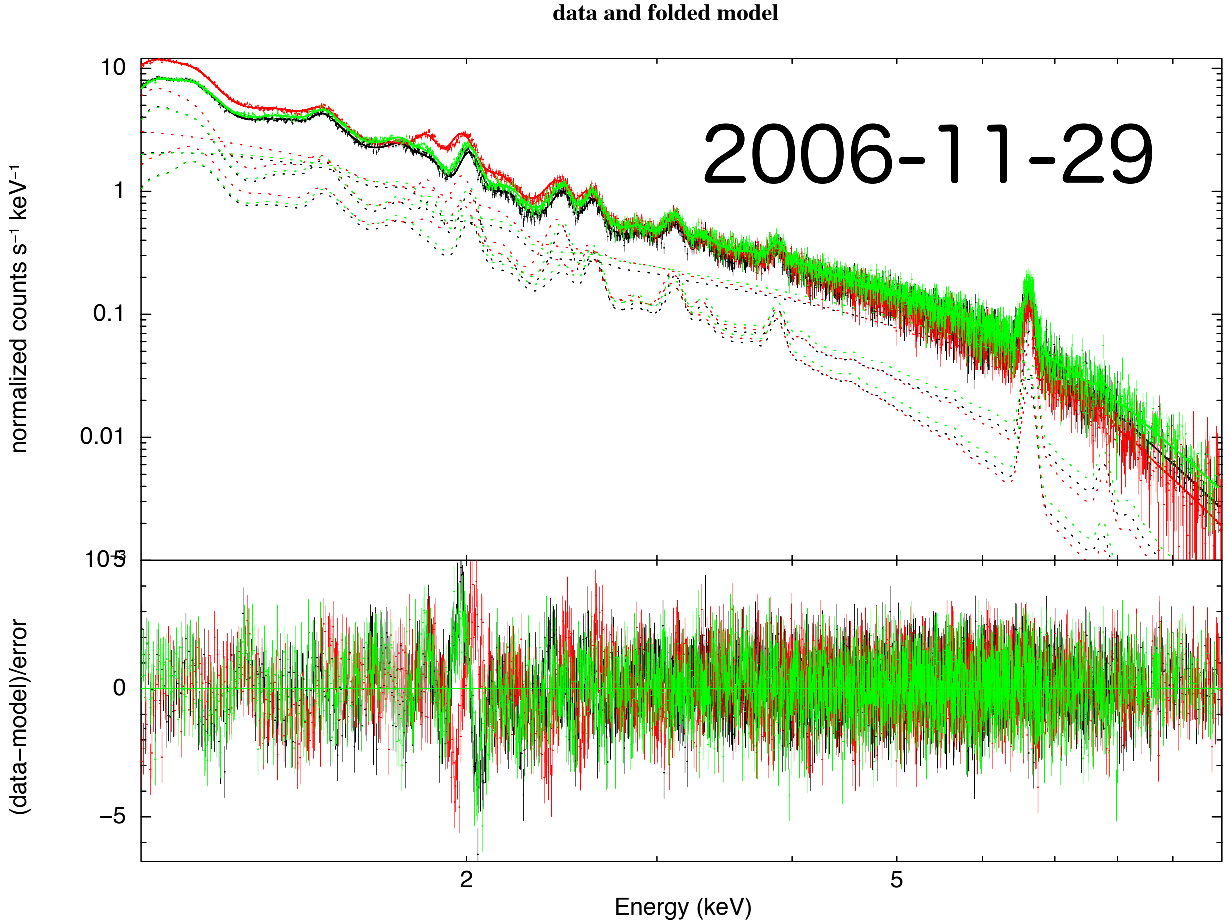


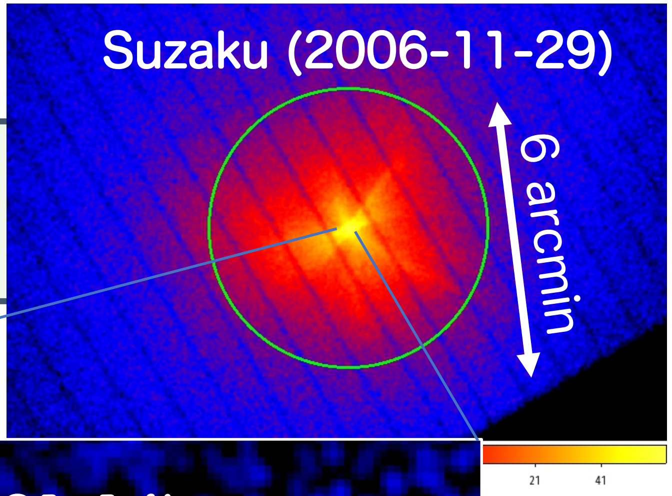


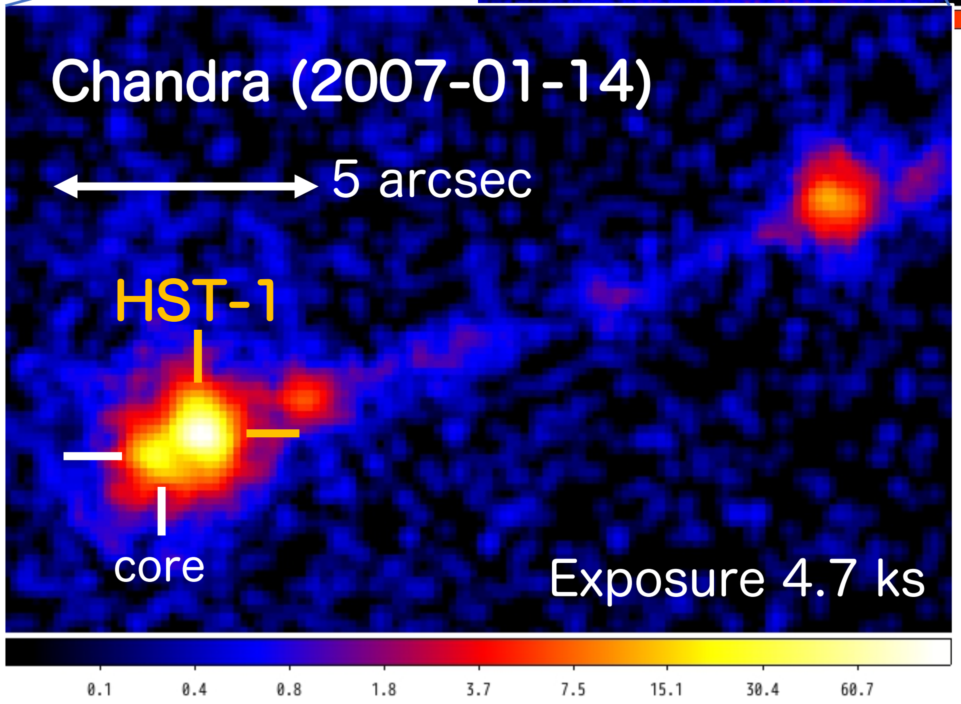
At first, I'll discuss about the variability of ①

Result: Spectrum (Suzaku 2006)

The spectrum of Nov. 2020 ➡ $\Gamma = 2.38^{+0.07}_{-0.04}$, soft







Chandra observation 2006 to 2007
➡ HST-1 very bright (pile-up)

Discussion: Magnetic field strength (Suzaku 2006)

Focusing on the fast variation of Suzaku (2006)
Soft spectrum ➡ Assume that the decay is due to synchrotron cooling.

Decay timescale

$$\tau_s = 3.2 \times 10^4 \times \boldsymbol{B}^{-3/2} \times E_{ph}^{-1/2} \times \delta^{-1/2}\ \text{(s)}$$ [2]

Magnetic field

τ_s: 0.3 day

E_{ph}: Photon energy in the observer system = 6.5 keV

$$B \approx 1.94\ \delta^{\frac{1}{3}}\ \text{mG}$$

δ: Dopplar factor ~ 5[3]

Consistent with multi-wavelength Synchrotron Self Compton model fit results.[4]

[2] Tashiro et al. 1995, PASJ, 34647, 131
[3] C. C. Wang et al., 2009, MNRAS 395, 301
[4] The EHT MWL Science Working Group *et al* 2021 *ApJL* 911 L11

Discussion: Electron energy in the emission region (Suzaku 2006)

Electron energy calculation from the magnetic field and the energy of the emitted synchrotron photons

Electron energy

$$\gamma \cdot \gamma m_e c^2 = (B_{cr}/B) E_{ph}$$

(B_{cr}: critical magnetic field) [5]

B: 1.94 $\delta^{1/3}$ mG

Critical magnetic field: 4.4 × 10^{13} G

[5] Kifune, T. *Physics of high energy cosmic rays*, Tokyo: Baifu-kan, 2004

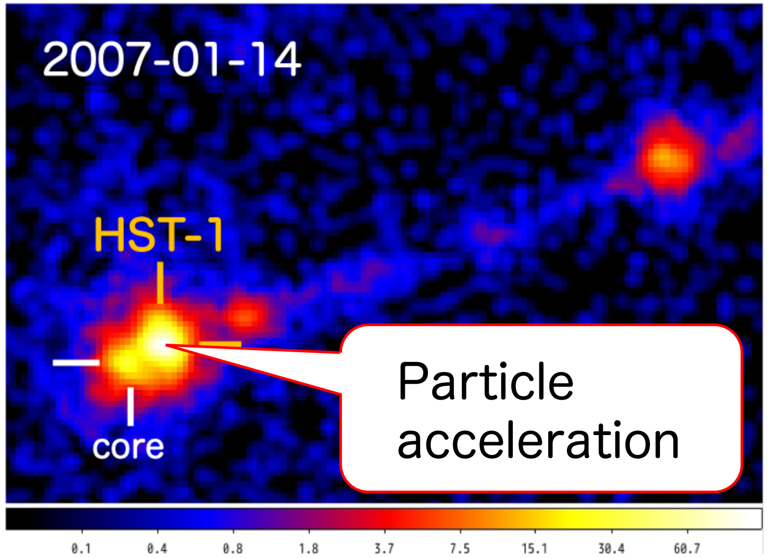
Electron energy

$$\gamma m_e c^2 \approx 8.7\, \delta^{-1/6}\ \text{TeV} \quad \gtrsim \text{TeV}$$

$\delta \sim 5$

2006 was HST-1 dominant period

➡ Suggests acceleration of particles above TeV at HST-1



Result/Discussion: Chandra 2017 (core region)

Hard spectrum $\boldsymbol{\Gamma} = \mathbf{1.96^{+0.05}_{-0.04}}$ in the core, Δt ~ 0.5 day

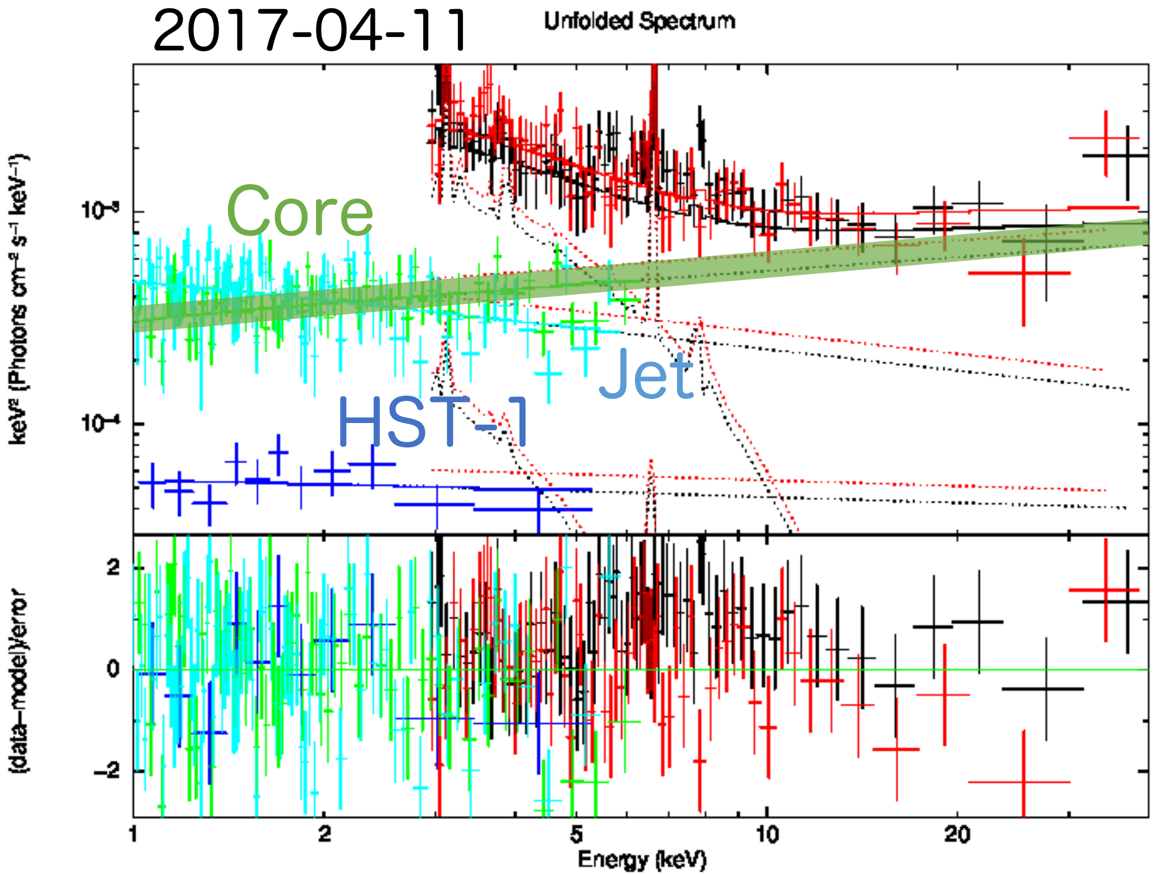
Invserse Compton (jet) or ADAF

Decay timescale ~0.5 day
➡ Size of emission region
~Schwarzchild radius
Too small for ADAF.

Fast variability is by inverse Compton in the core (jet upstream)？

Possibly different from the cause of variation in 2006.

2017-04-11



Conclusion

■ What we did

Study of the flux variability and spectrum from X-ray satellite data

■ Results

- Suzaku in 2006 (HST-1 flare) ➡ Δt_{decay}~0.3 day, Soft spectrum
- Chandra in 2017 (Chandra; core) ➡ Δt_{decay}~0.5 day, Hard spectrum

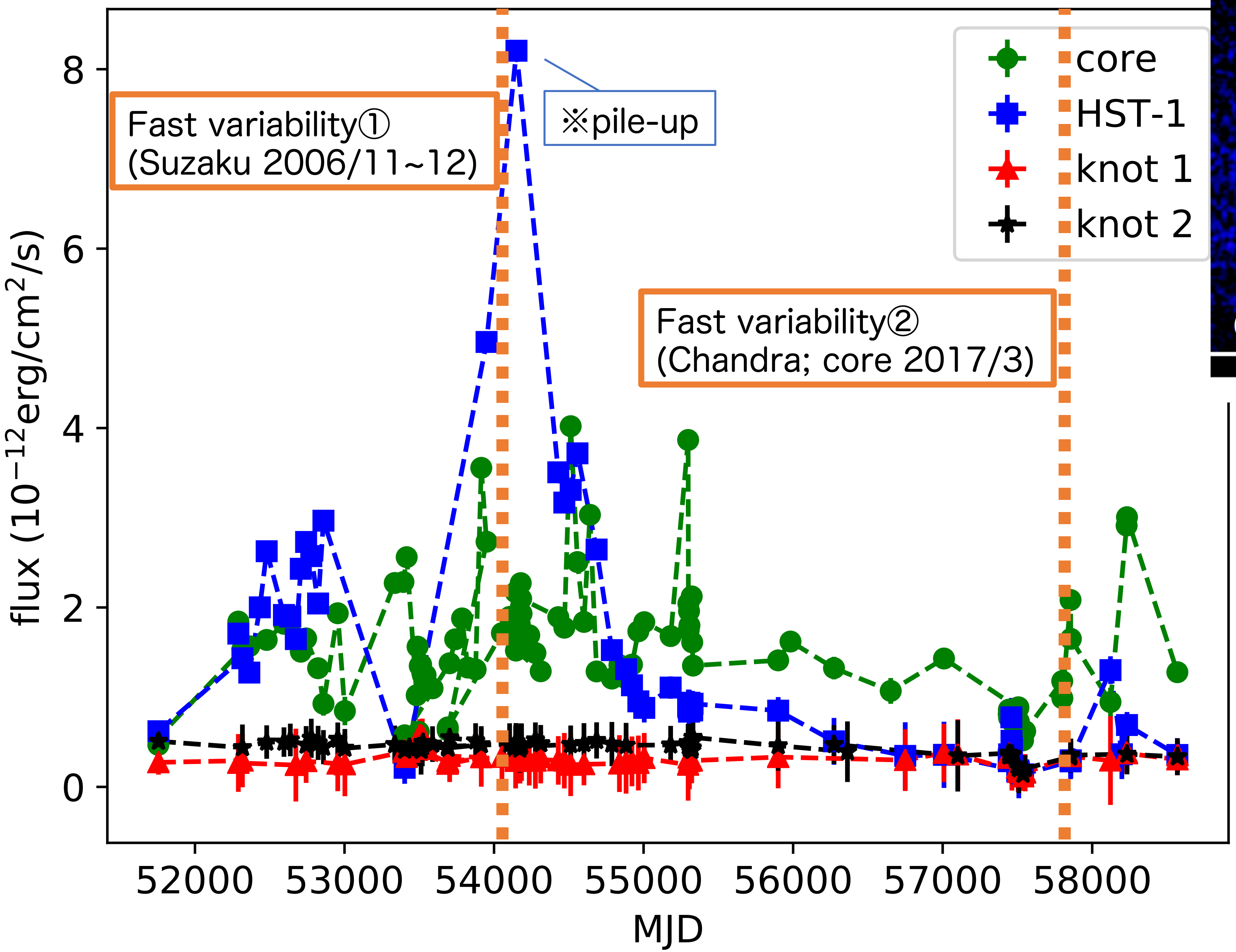
■ Discussion

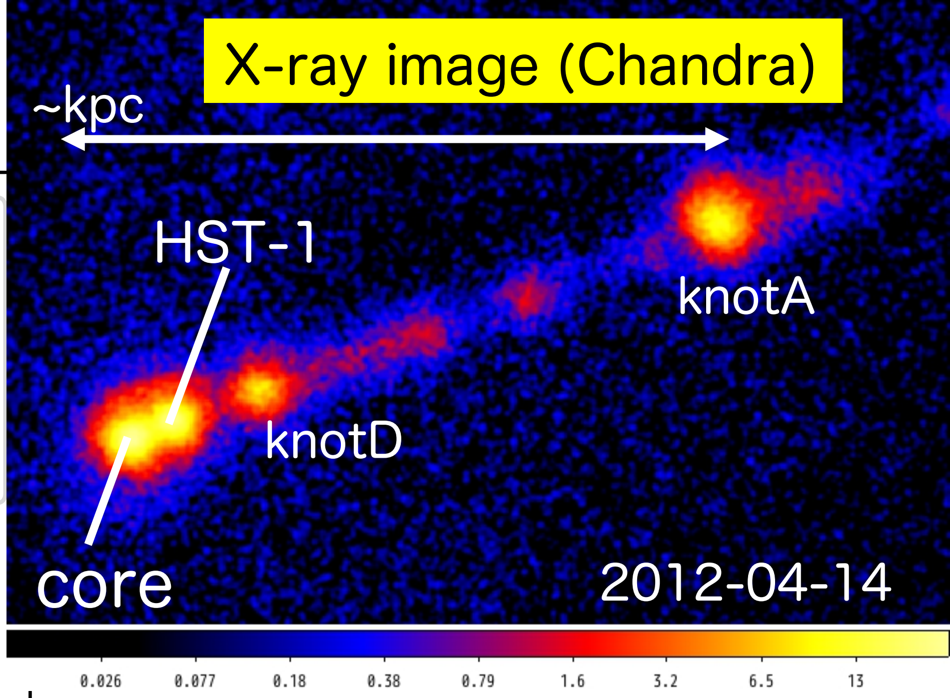
2006: Assume that the decay is due to synchrotron cooling,
Magnetic field: $B = 1.94\,\delta^{1/3}$ mG
Electron energy: $\gamma m_e c^2 \approx 8.7\,\delta^{-1/6}$ TeV $\gtrsim$ TeV
➡ Suggests that particle acceleration above TeV occurred in HST-1.

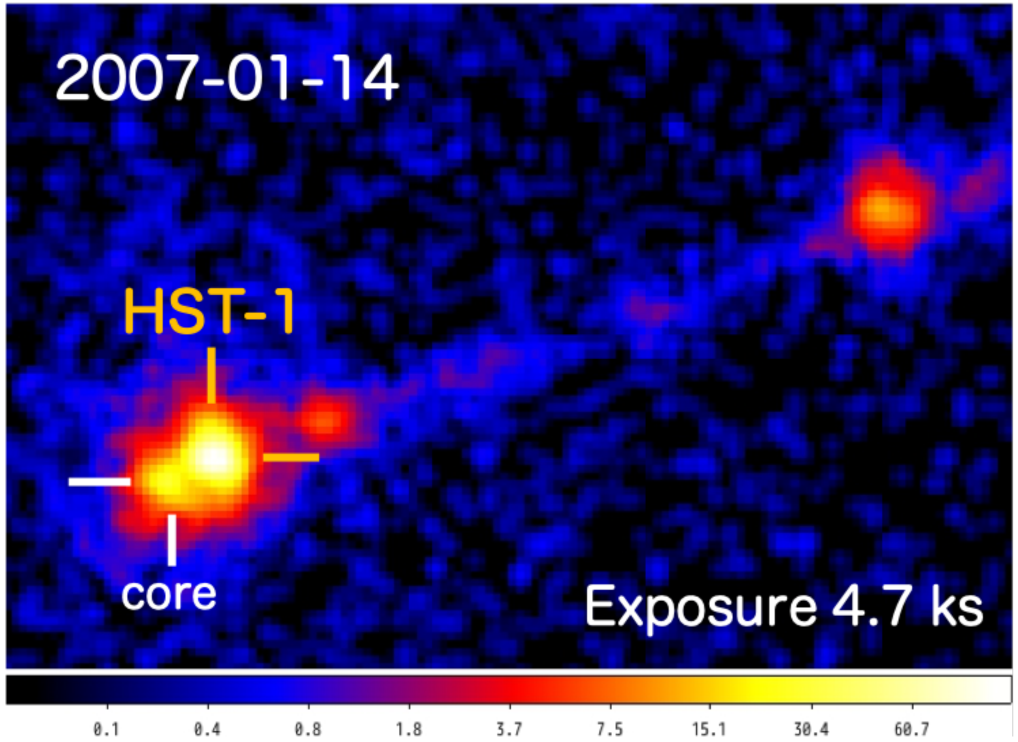
2017: From the spectrum and flux variability,
fast variability may from inverse Compton scattering upstream of the jet.

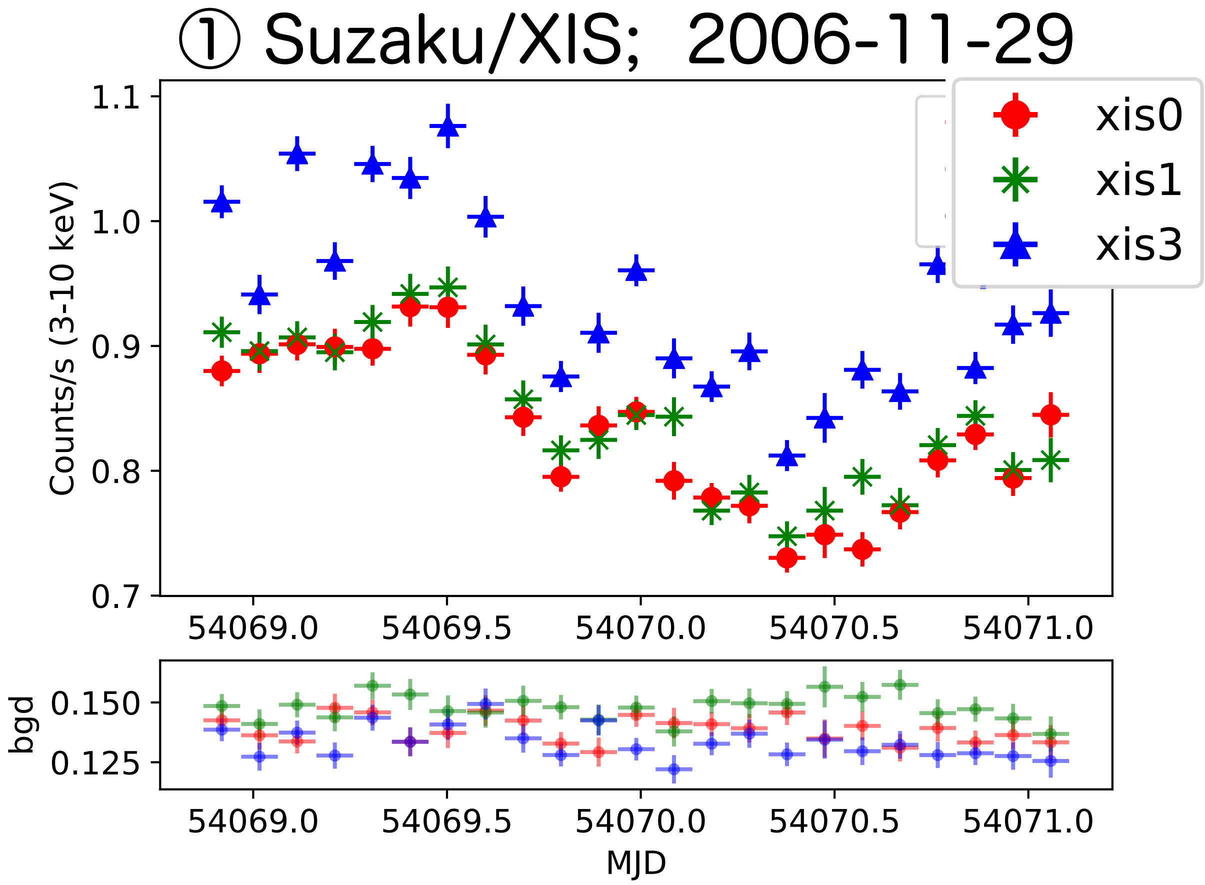
Backup Slides

Light curve in eash component (Chandra)









Flux ratio of HST-1/core = 4.5

Assuming that HST-1 is stable,
Explain the variability with only core variability,
it needs variability ~260% amplitude ➡ unreasonable

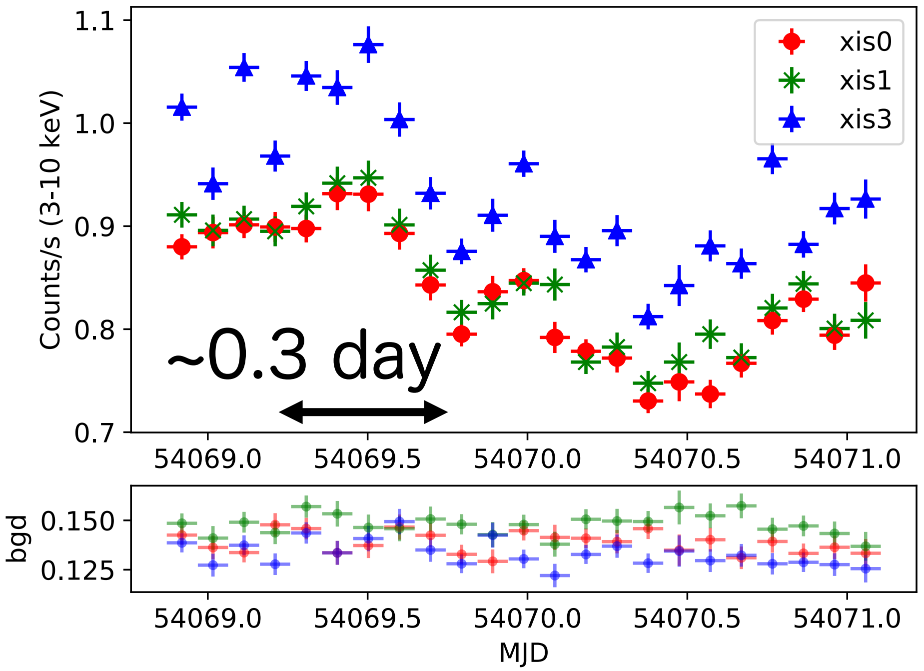
Result: Lightcurve

Fast variability = “2 σ RMS > 0”, and checked by eyes

$$\mathrm{RMS} = \sqrt{\frac{\sum_i[(d_i-\bar{d})^2-e_i^2]}{N\bar{d}^2}}$$

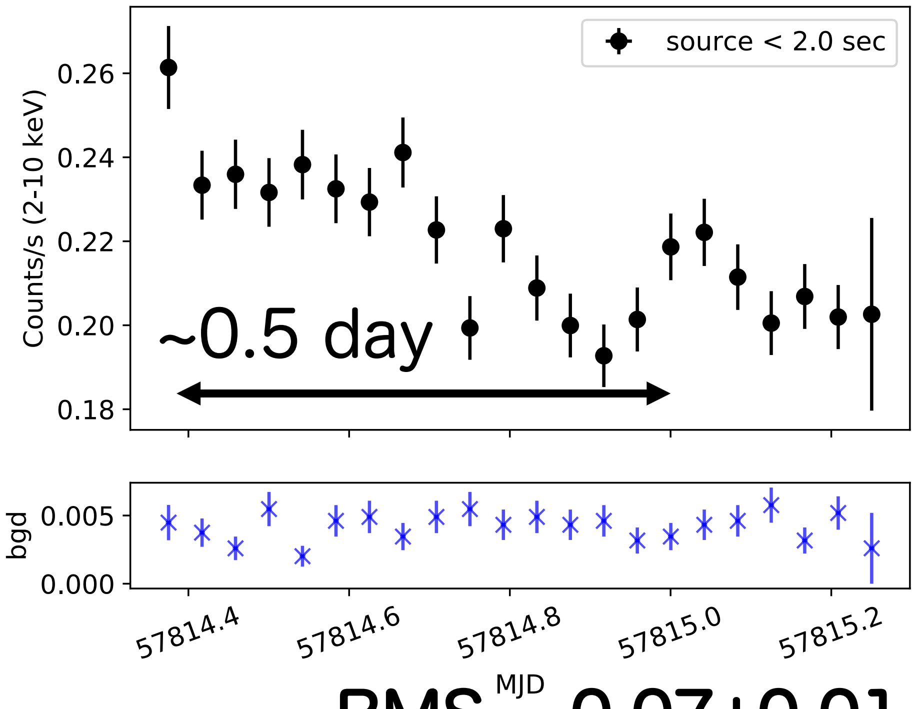
(d_i: *i-th countrate*, N: bin number, $\bar{d}$: mean countrate, e_i: statistical error)

Suzaku/XIS0,1,3 2006-11-29

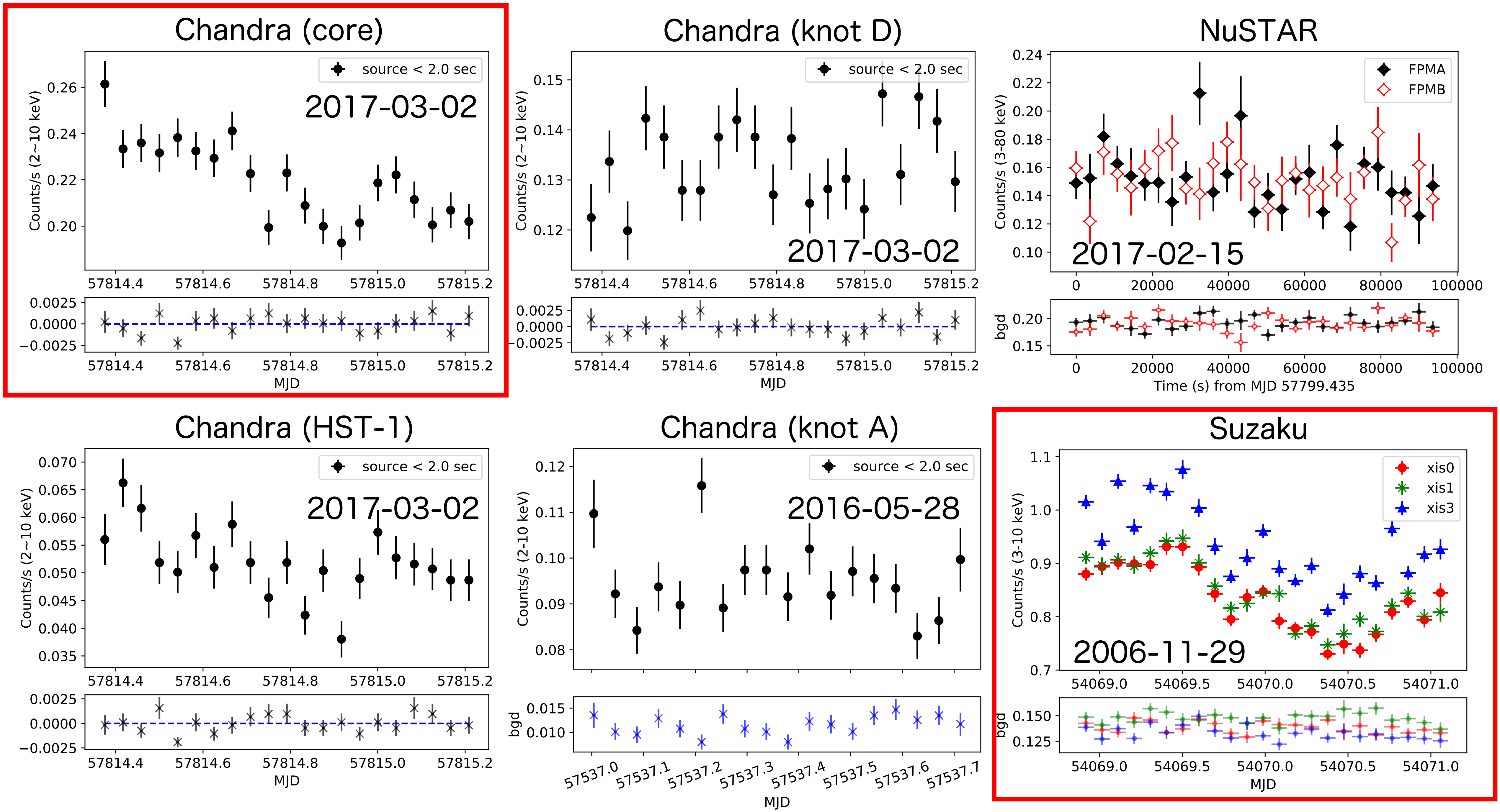


RMS = 0.071±0.007

Chandra/HRC (core) 2017-03-02



RMS = 0.07±0.01



Chandra (core)
source < 2.0 sec
2017-03-02
Counts/s (2~10 keV)
MJD
Chandra (knot D)
source < 2.0 sec
2017-03-02
Counts/s (2~10 keV)
MJD
NuSTAR
FPMA
FPMB
2017-02-15
Counts/s (3-80 keV)
bgd
Time (s) from MJD 57799.435
Chandra (HST-1)
source < 2.0 sec
2017-03-02
Counts/s (2~10 keV)
MJD
Chandra (knot A)
source < 2.0 sec
2016-05-28
Counts/s (2-10 keV)
bgd
MJD
Suzaku
xis0
xis1
xis3
2006-11-29
Counts/s (3-10 keV)
bgd
MJD