X-RAY/UV/OPTICAL CONTINUUM REVERBERATION MAPPING OF AGN WITH SWIFT

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WAYNE STATE UNIVERSITY

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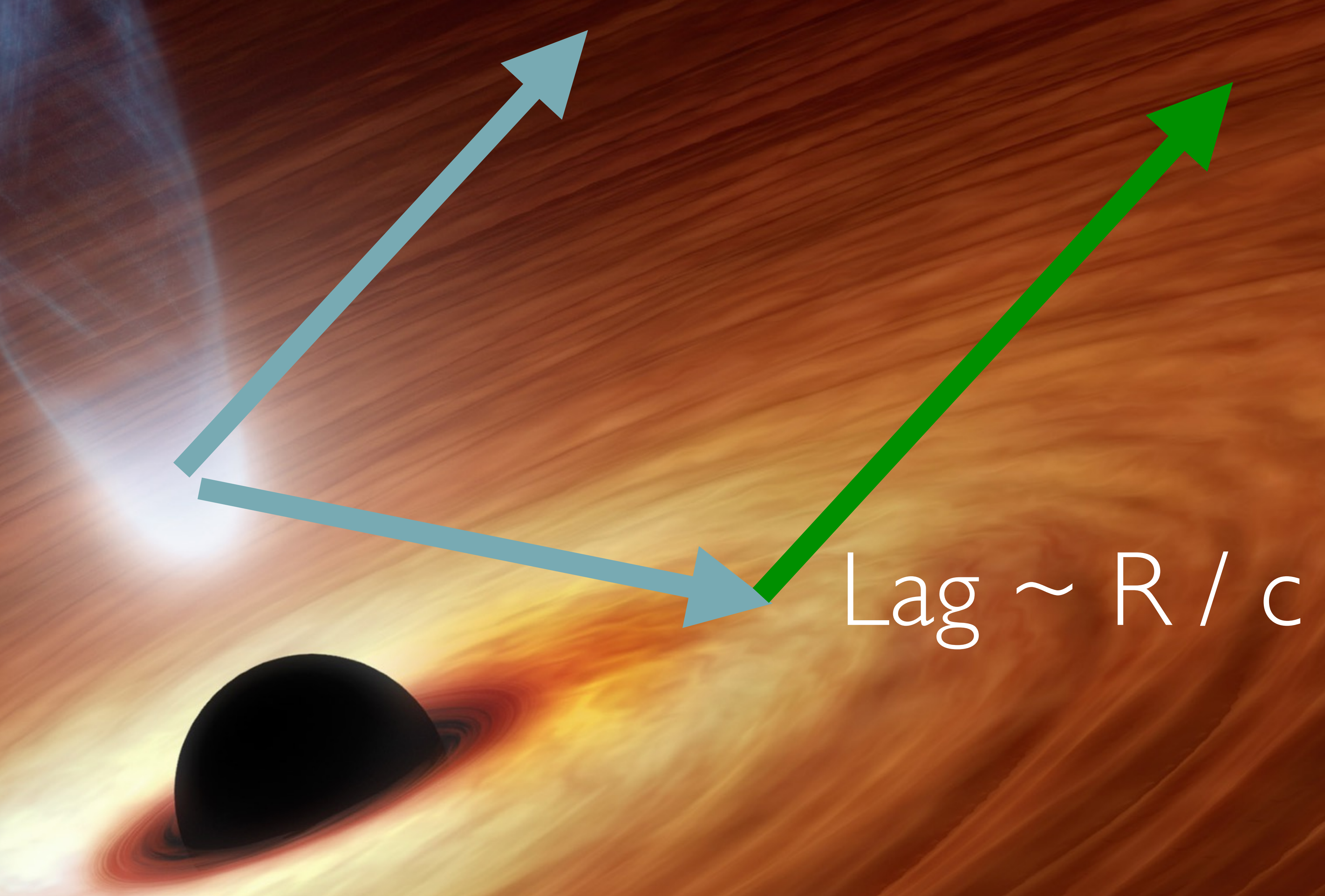

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REVERBERATION FROM X-RAYS TO IR

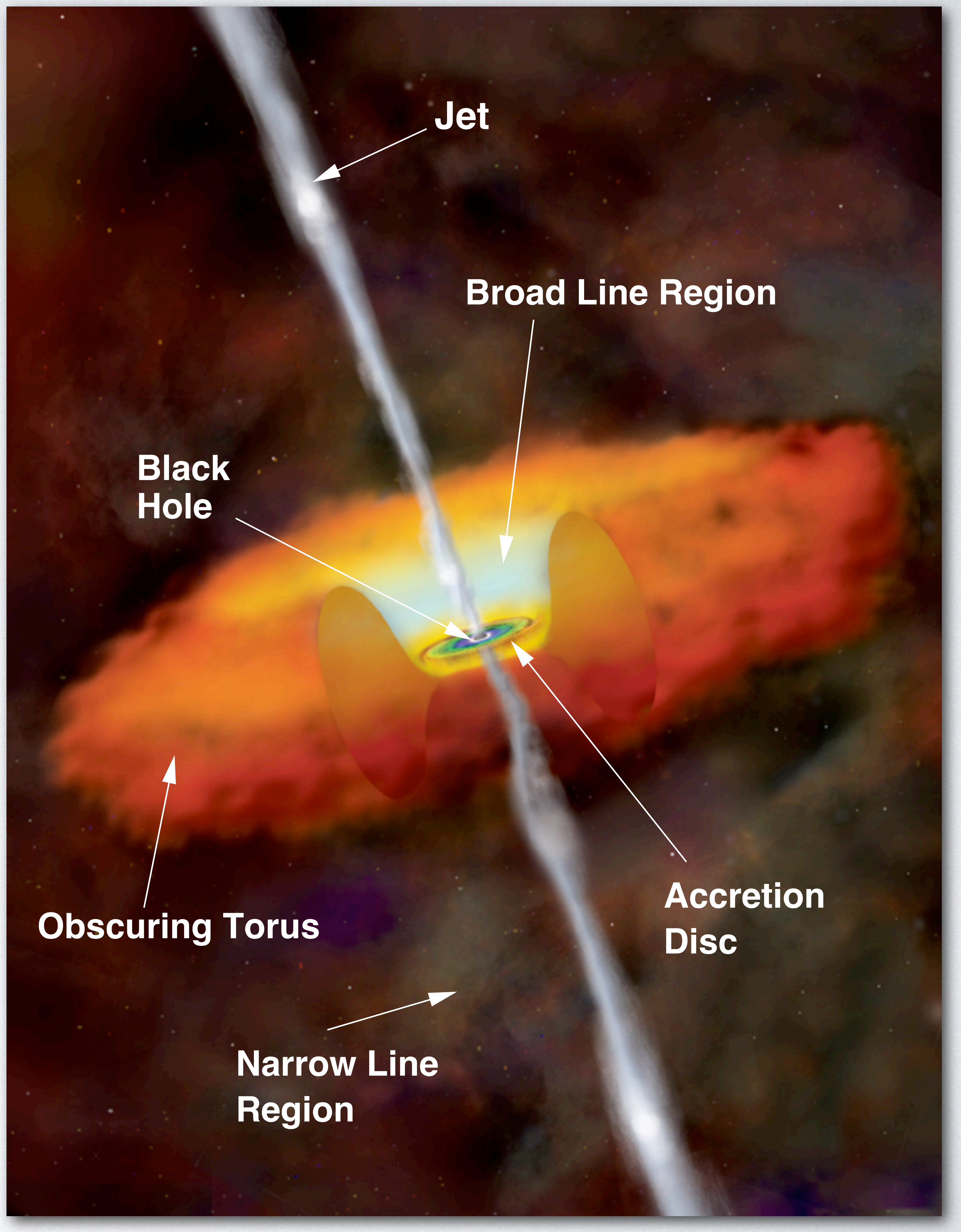
- **X-ray reverberation:** probes innermost region of corona/accretion disk (a few tens of R_g; **hundreds of light-seconds.** Note: 1 $R_g = GM/c^2 = 50$ light-seconds for $10^7\ M_\odot$)

- **UV/optical continuum reverberation:** accretion disk; **light-days** (hundreds to thousands of R_g)

- **Broad emission line reverberation:** broad line region (BLR); **light-weeks** (tens of thousands of R_g)

- **Dust reverberation:** 'torus'; **light-months to light-years**

Cackett, Bentz & Kara (2021) reviews each



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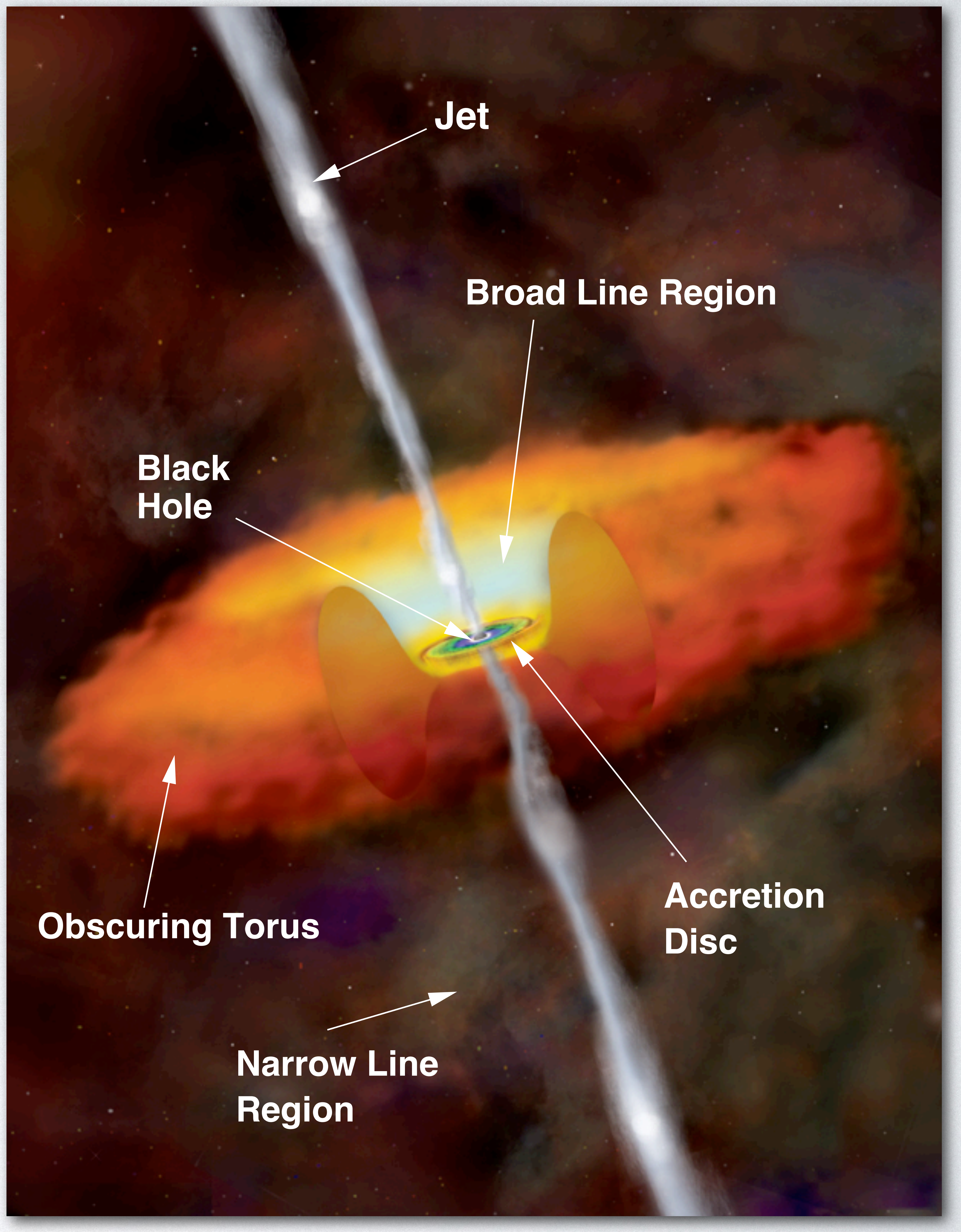

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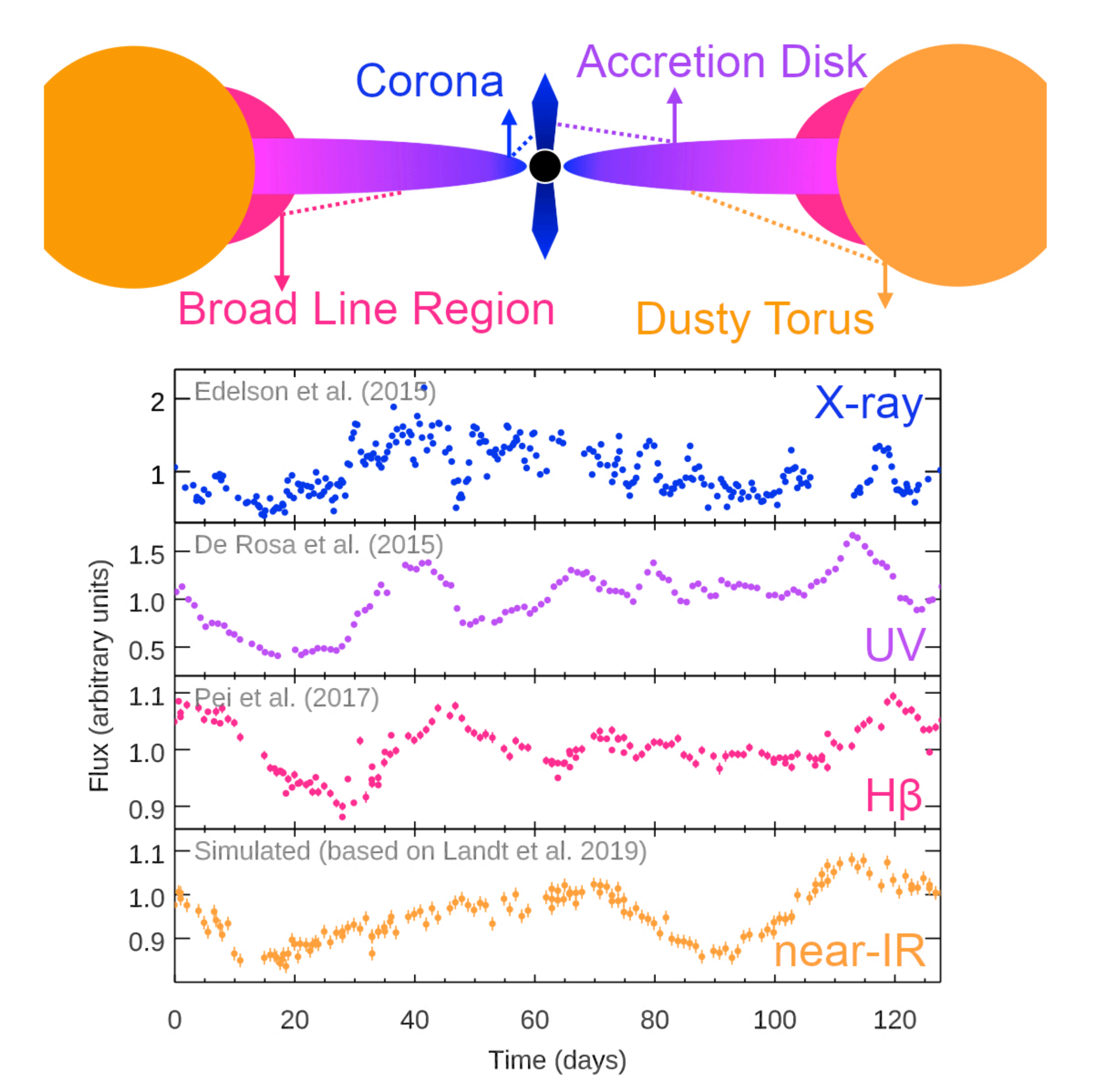
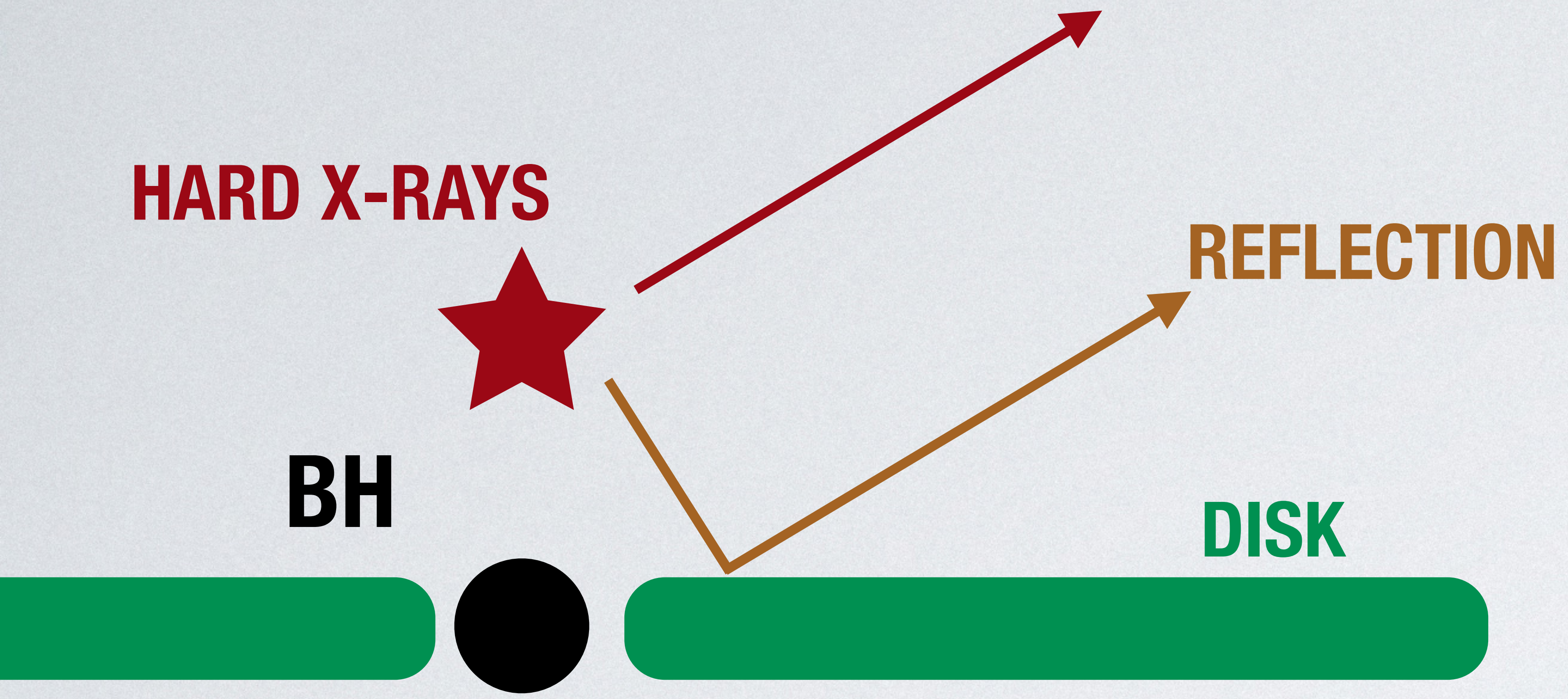
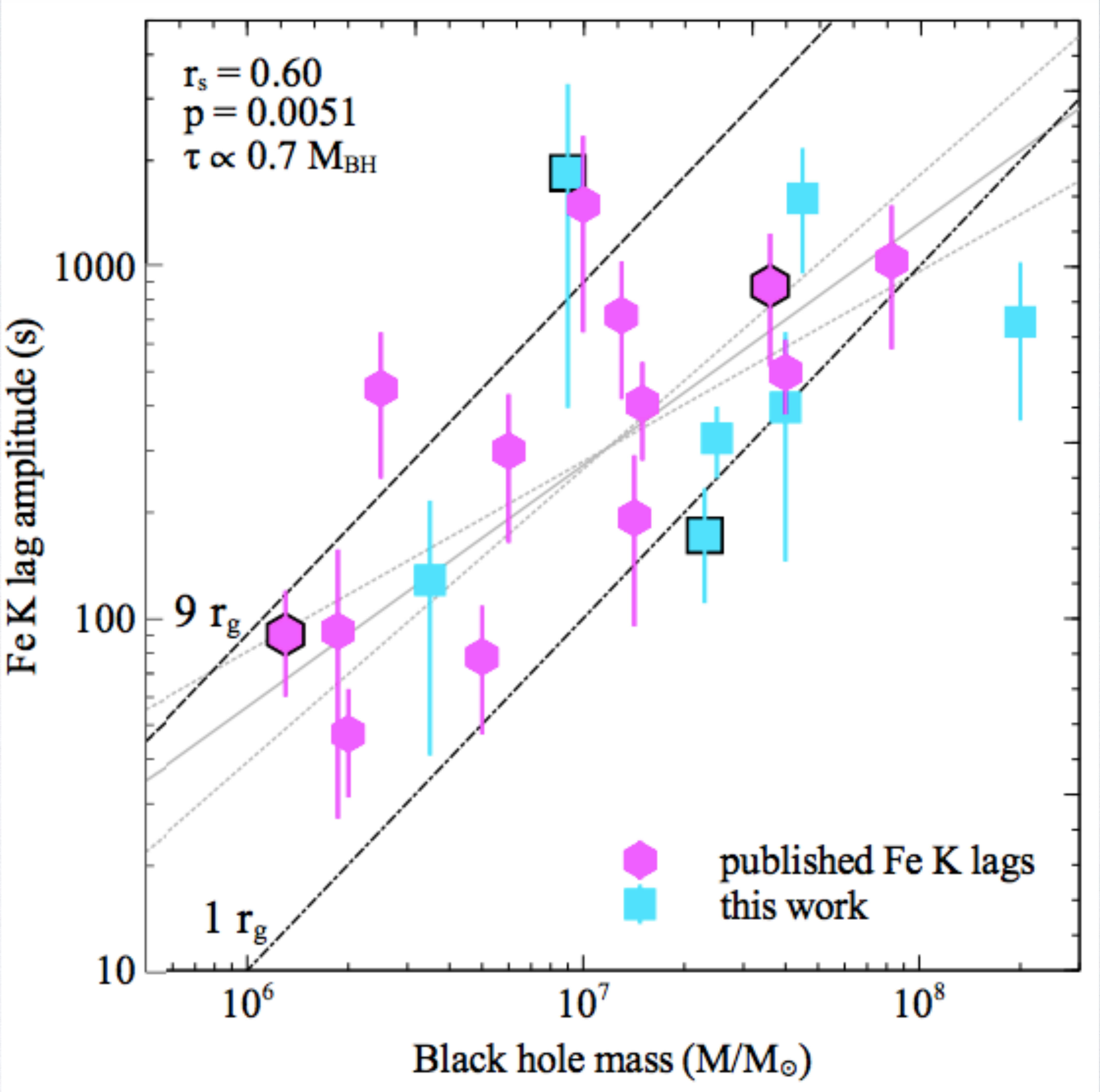


X-RAY CORONA IS COMPACT



- X-ray reverberation shows that corona is a few R_g from the black hole (e.g. Wilkins et al. 2013, Cackett et al. 2014, Kara et al. 2016)

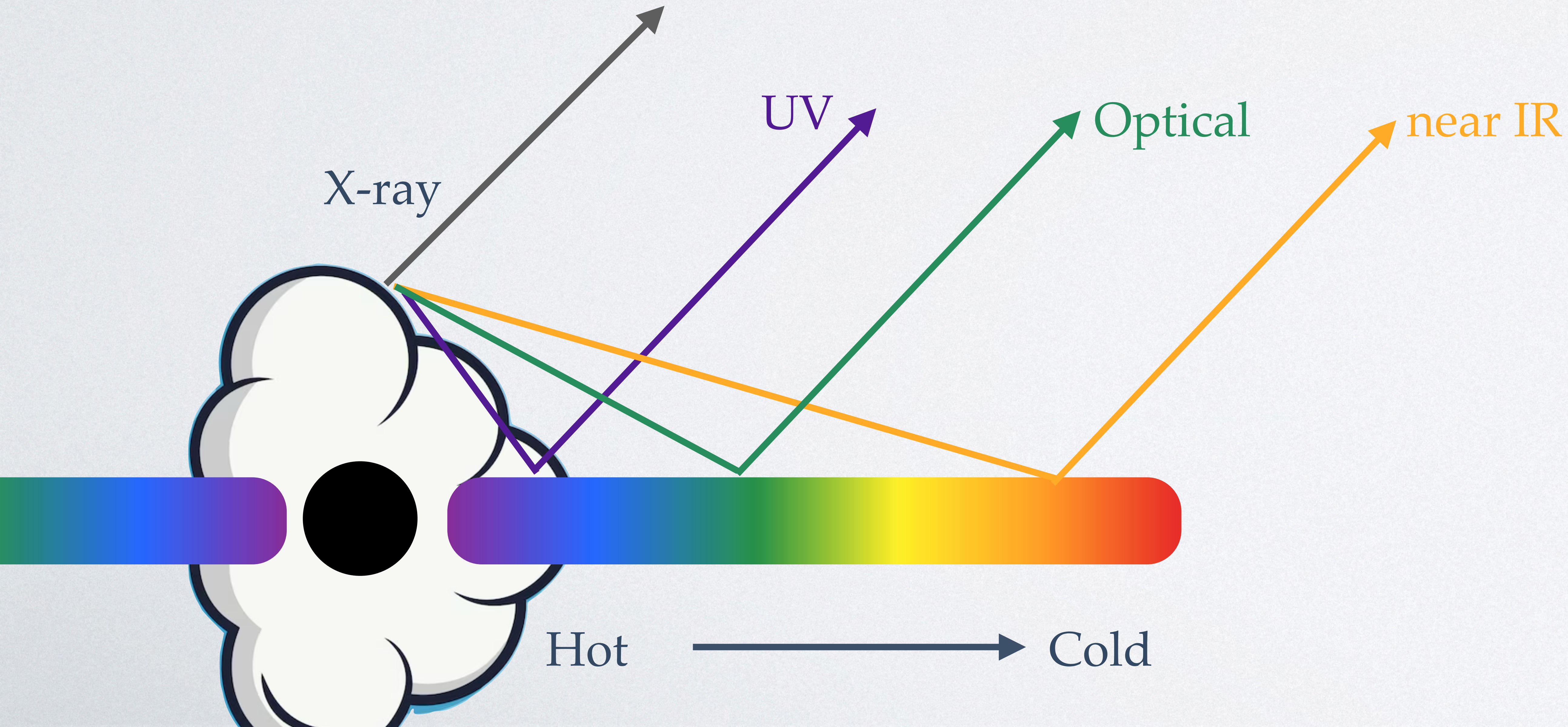
- Gravitational microlensing also shows the X-ray emitting region is <10 R_g (e.g. Dai et al. 2010; Morgan et al. 2010)

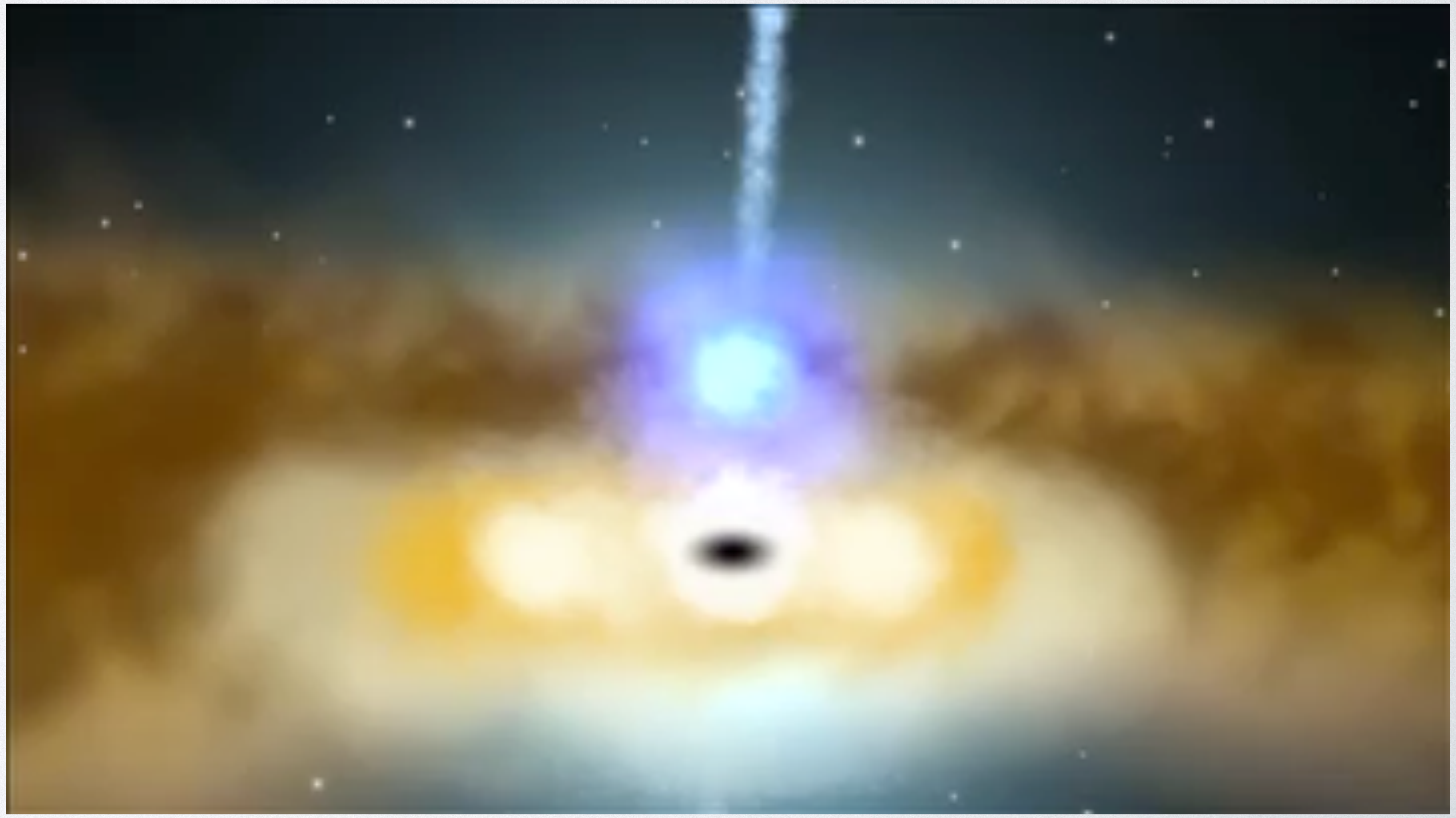


Kara et al. (2016)

THERMAL REPROCESSING - DISK REVERBERATION

- Can connect X-rays to UV/optical disk further out by measuring interband delays
- Disk emits like a multicolor blackbody
- Hot, inner disk sees variable irradiating (X-ray?) source before cooler, outer disk
- Expect correlated continuum bands, with lags that depend on the temperature profile of the disk





TEMPERATURE PROFILE

Temperature profile of an irradiated Shakura & Sunyaev (1973) disk:

$$T(R) = \left(\underbrace{\frac{3GM\dot{M}}{8\pi\sigma R^3}}_{\text{Viscous}} + \underbrace{\frac{(1-A)L_X H}{4\pi\sigma R^3}}_{\text{Irradiation}} \right)^{1/4}$$

$$T = X\frac{hc}{k\lambda}$$

where $X \sim 3$ for blackbody radiation assuming a flux-weighted emission radius

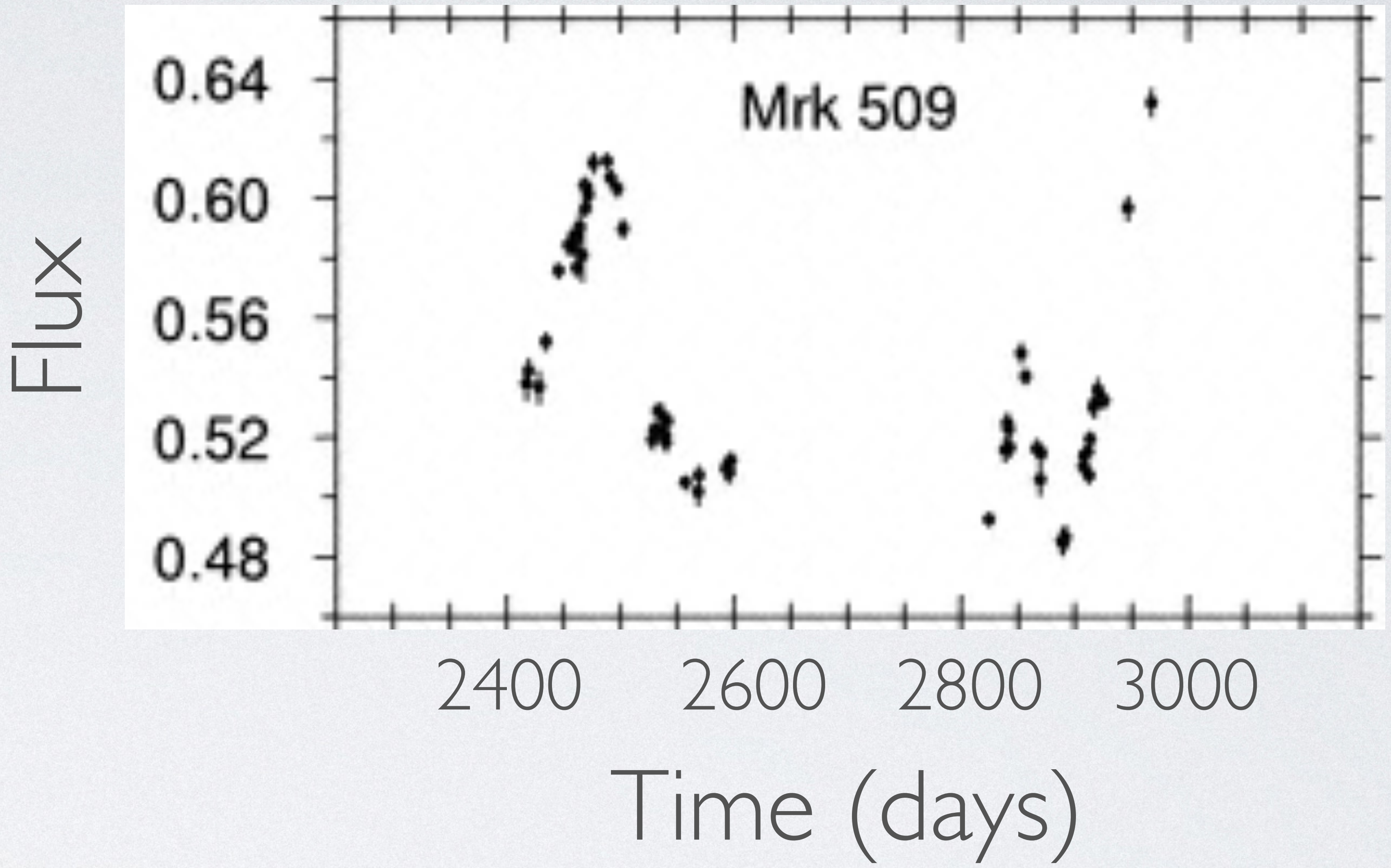
$$R \propto (M\dot{M})^{1/3} T^{-4/3} \longrightarrow \tau \propto (M\dot{M})^{1/3} \lambda^{4/3}$$

for a classical geometrically thin, optical thick disk
see, e.g. Collier et al. (1999); Cackett et al. (2007); Fausnaugh et al. (2016)

Measuring $\tau(\lambda)$ gives you $T(R)$

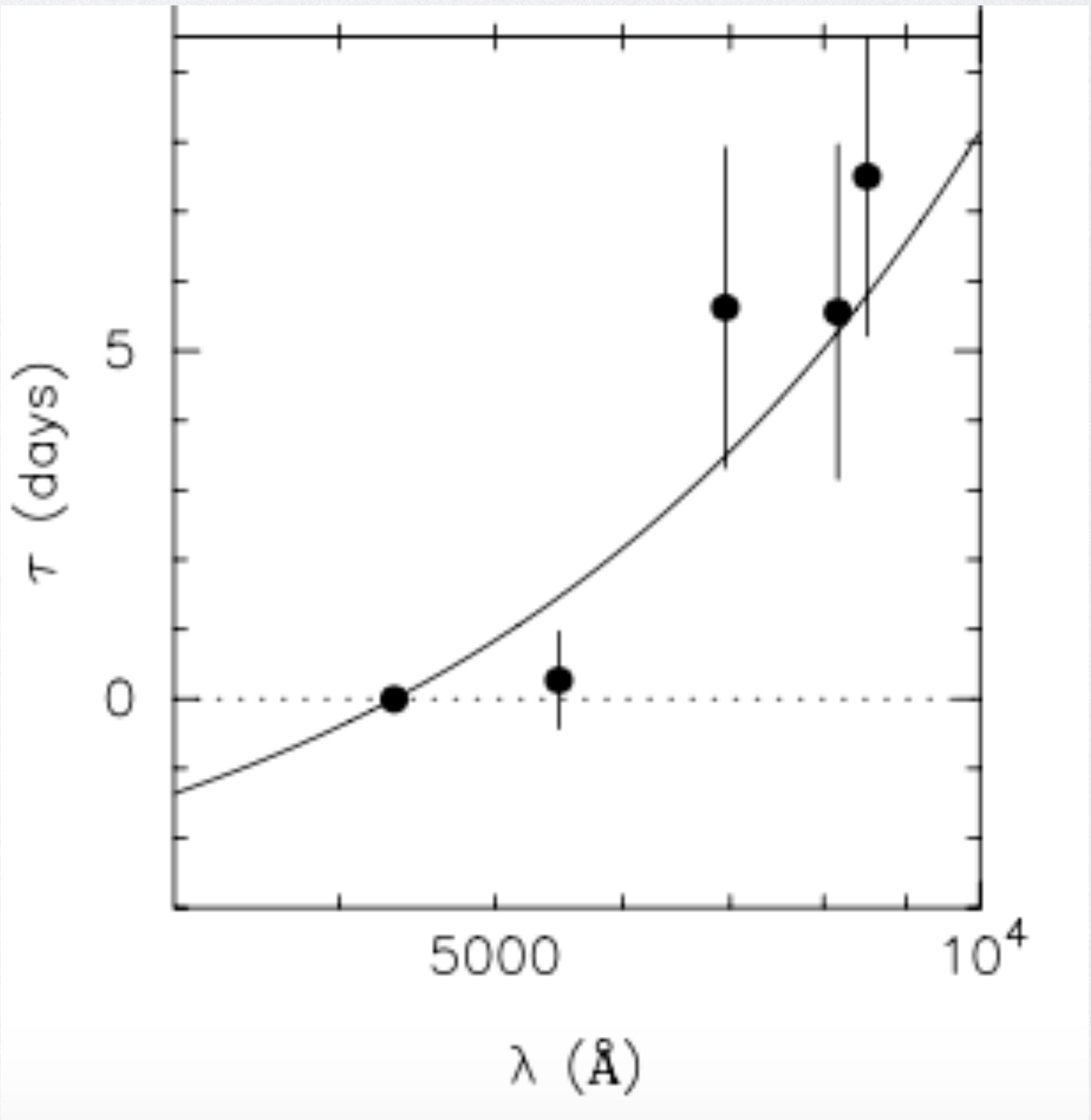
CONTINUUM REVERBERATION LAGS - PRE 2014

- A number of studies pre-2014 looked for continuum lags
- None were statistically significant at $>3\sigma$
- But, lags roughly followed $\lambda^{4/3}$
- See, e.g., 14 AGN from Sergeev et al. (2005) analyzed in Cackett et al. (2007)



B light curve (Sergeev et al 2005)

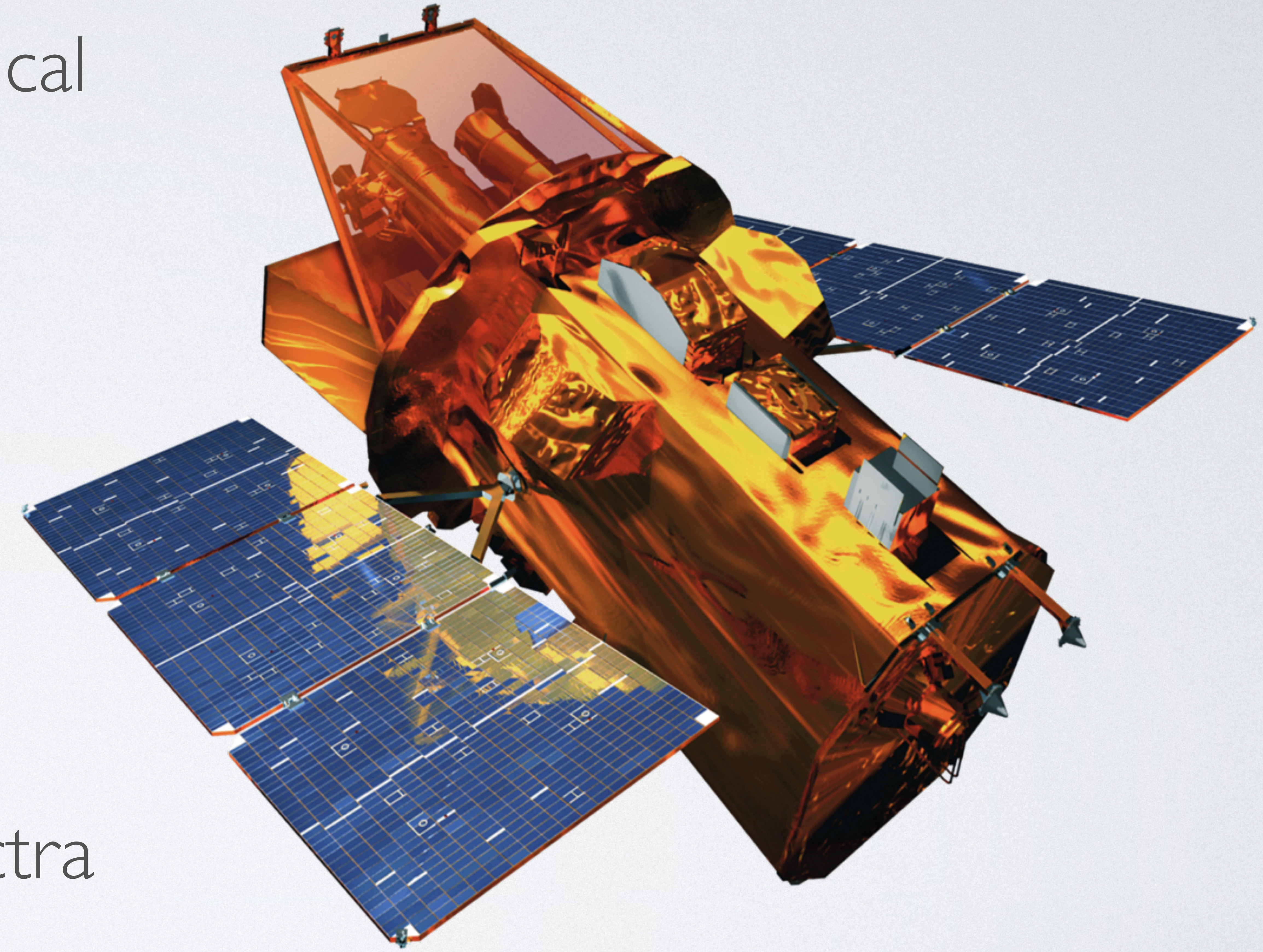
59 points over 2 years



Cackett et al (2007)

A NEW ERA OF ACCRETION DISK REVERBERATION MAPPING

- *Swift* can perform regular, high cadence monitoring of AGN in X-ray + 6 UV/optical filters
- Cadence better than one per day and hundreds of epochs
- Using ground-based robotic telescopes
- NICER high cadence, sensitive X-ray spectra
- Hubble Space Telescope - UV spectroscopy



ENTER ACCRETION DISK RM WITH SWIFT

Key is **high-cadence** (at least daily) sampling for **hundreds of epochs**, and coordinated observations with many telescopes

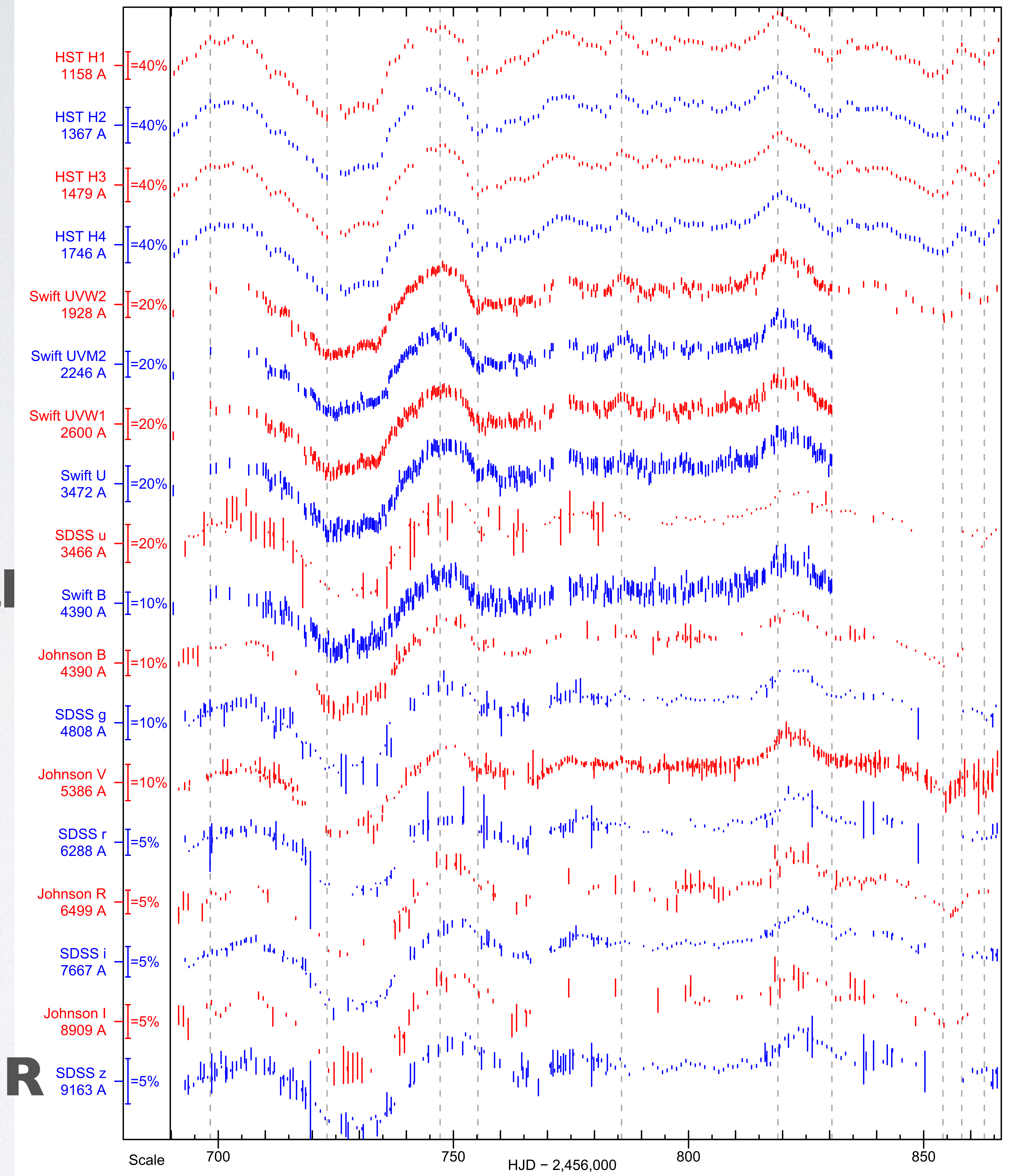
NGC 5548, AGN STORM: Edelson et al. (2015), Fausnaugh et al. (2016)

Many other campaigns, e.g., Shappee et al. (2014), Edelson et al. (2017, 2019), Cackett et al. (2018, 2020, 2023), McHardy et al. (2014, 2018), Hernandez Santisteban et al. (2020), Vincentelli et al (2021), Kara et al.. (2021), Gonzalez et al (2024)……

UV

Optical

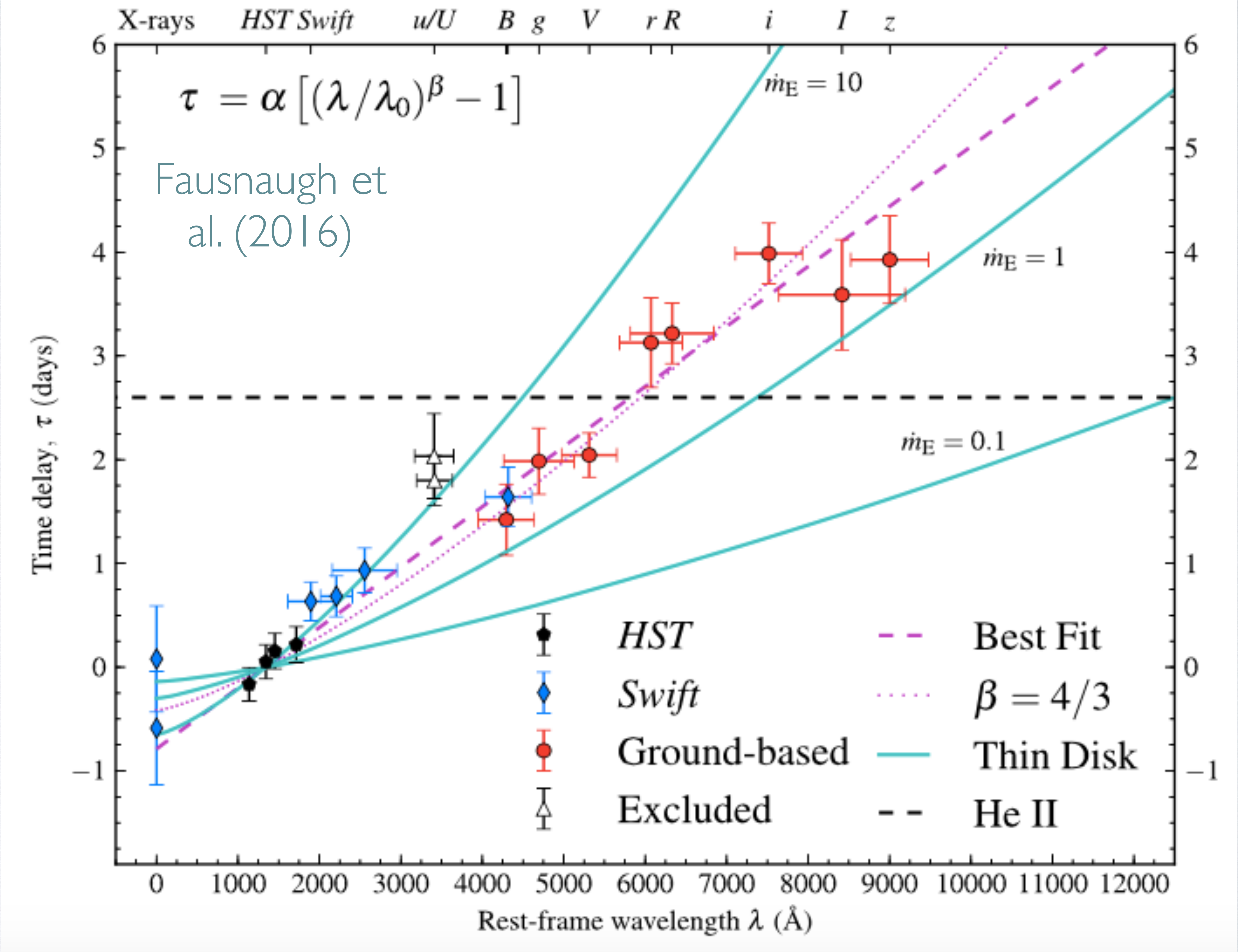
near-IR



Fausnaugh et al. (2016)

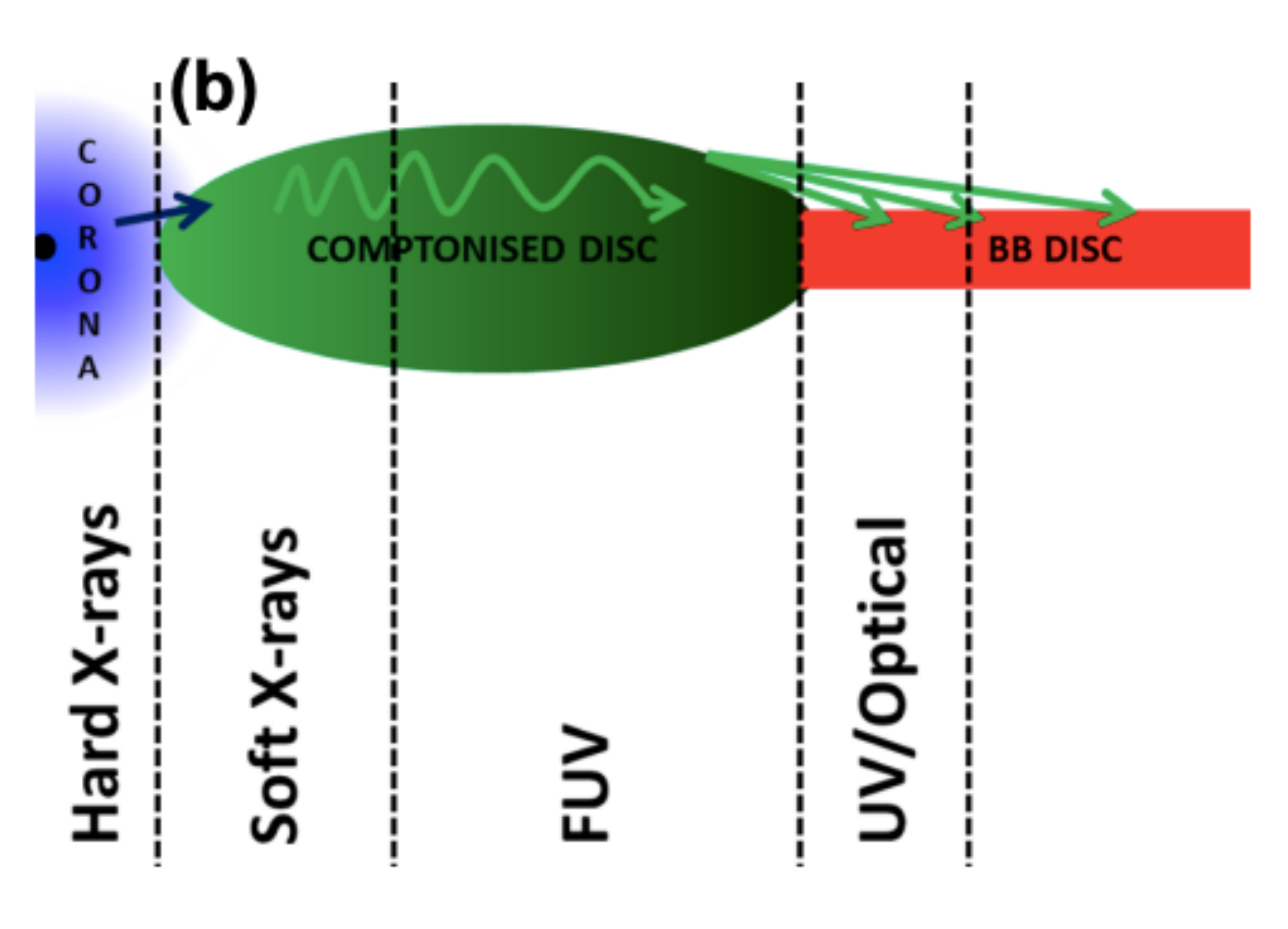
ACCRETION DISK TEMPERATURE PROFILE AND SIZE

- Lags broadly consistent with $\tau \propto \lambda^{4/3}$
- But, under reasonable assumptions about the mass accretion rate, the **disk appears too big** by a factor of 2 - 3
- Excess lag in u



WHY ARE THE LAGS TOO LONG?

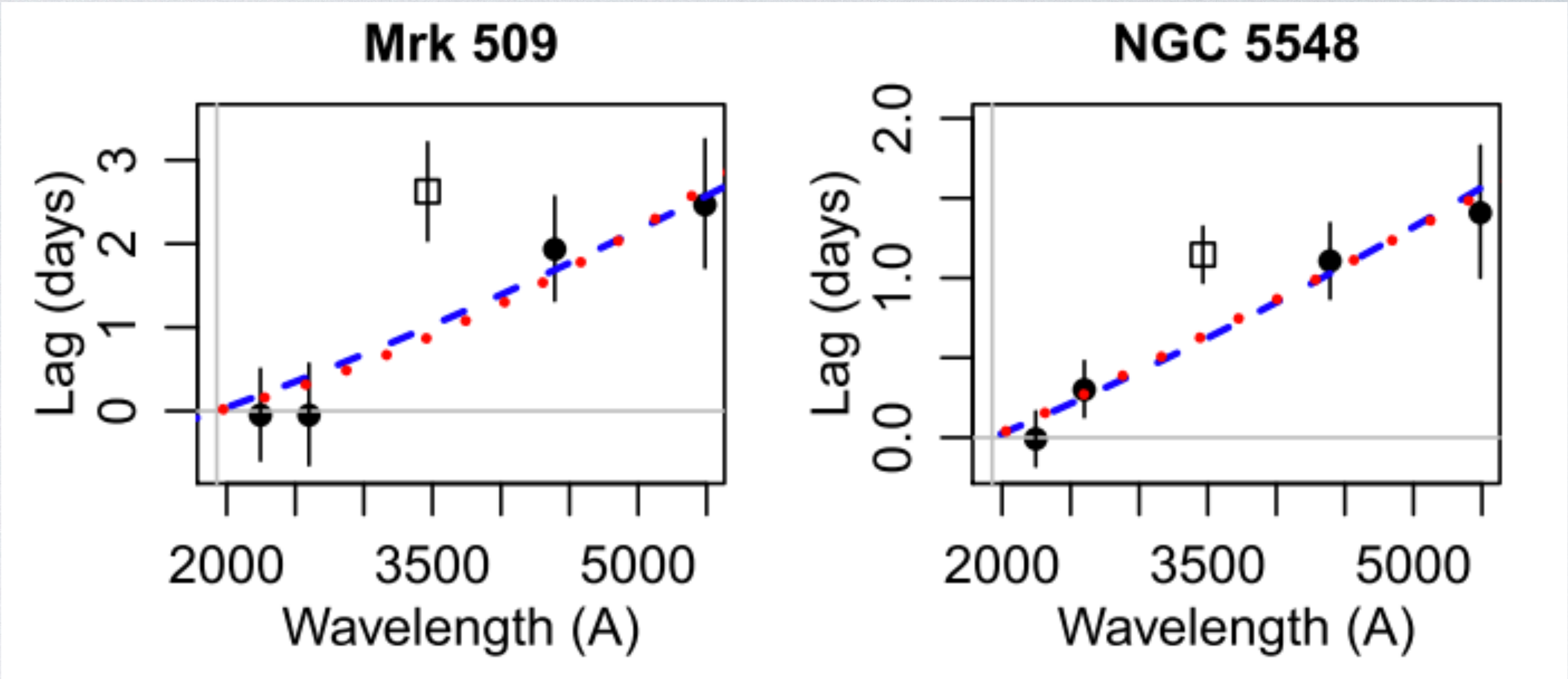
- Contribution of broad lines to photometric bands will enhance lags (e.g. Chelouche et al. 2013), but, not a large effect (e.g., Fausnaugh et al. 2016)
- BLR contribution to continuum lags (Korista & Goad 2001,2019; Lawther et al. 2018, Chelouche et al. 2019)
- Different geometry, e.g., Gardner & Done (2017)
- Lags are not reverberation (e.g. Sun et al. 2020)
- Simple analytic scaling incomplete - need complete GR treatment (Kammoun et al. 2021a,b, 2023, 2024)



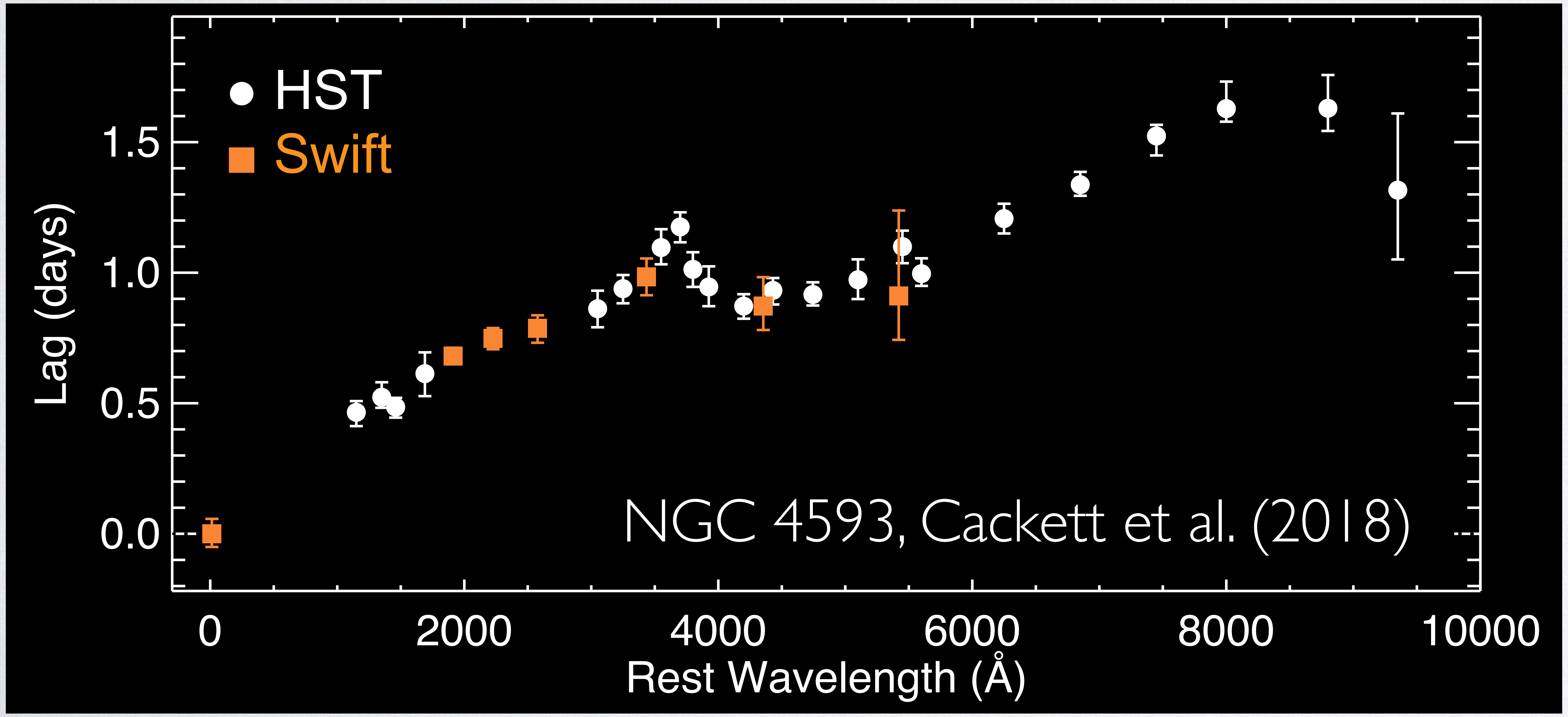
Gardner & Done (2017)

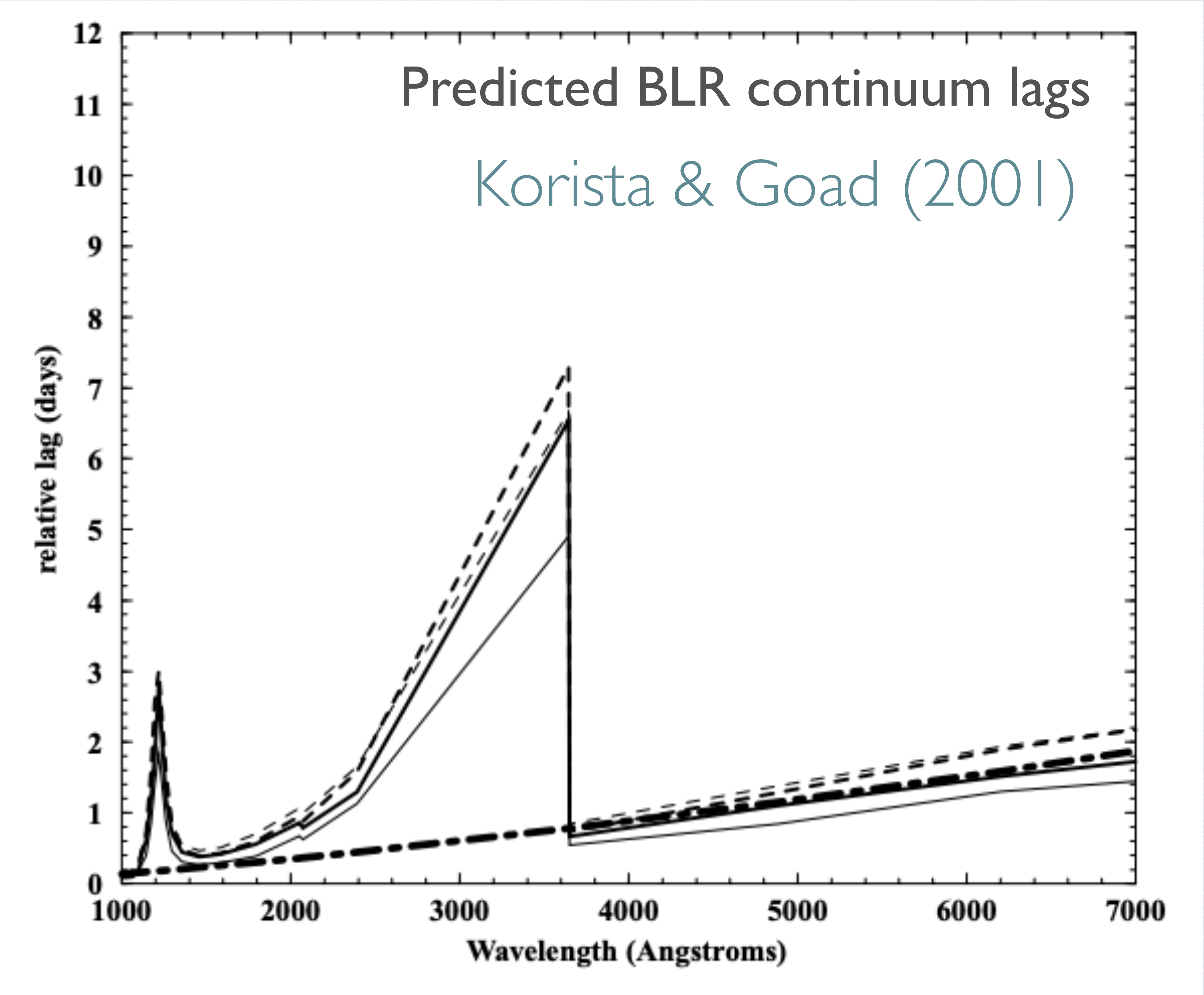
CONTINUUM EMISSION FROM THE BLR

- Enhanced u-band lag may indicate contribution from diffuse gas in the broad line region
- Korista & Goad (2001, 2019), Lawther et al. (2018), Netzer (2022): expect continuum emission (dominated by hydrogen free-bound emission) from the BLR
- Strongest feature at the Balmer jump (3646Å - in the u band)



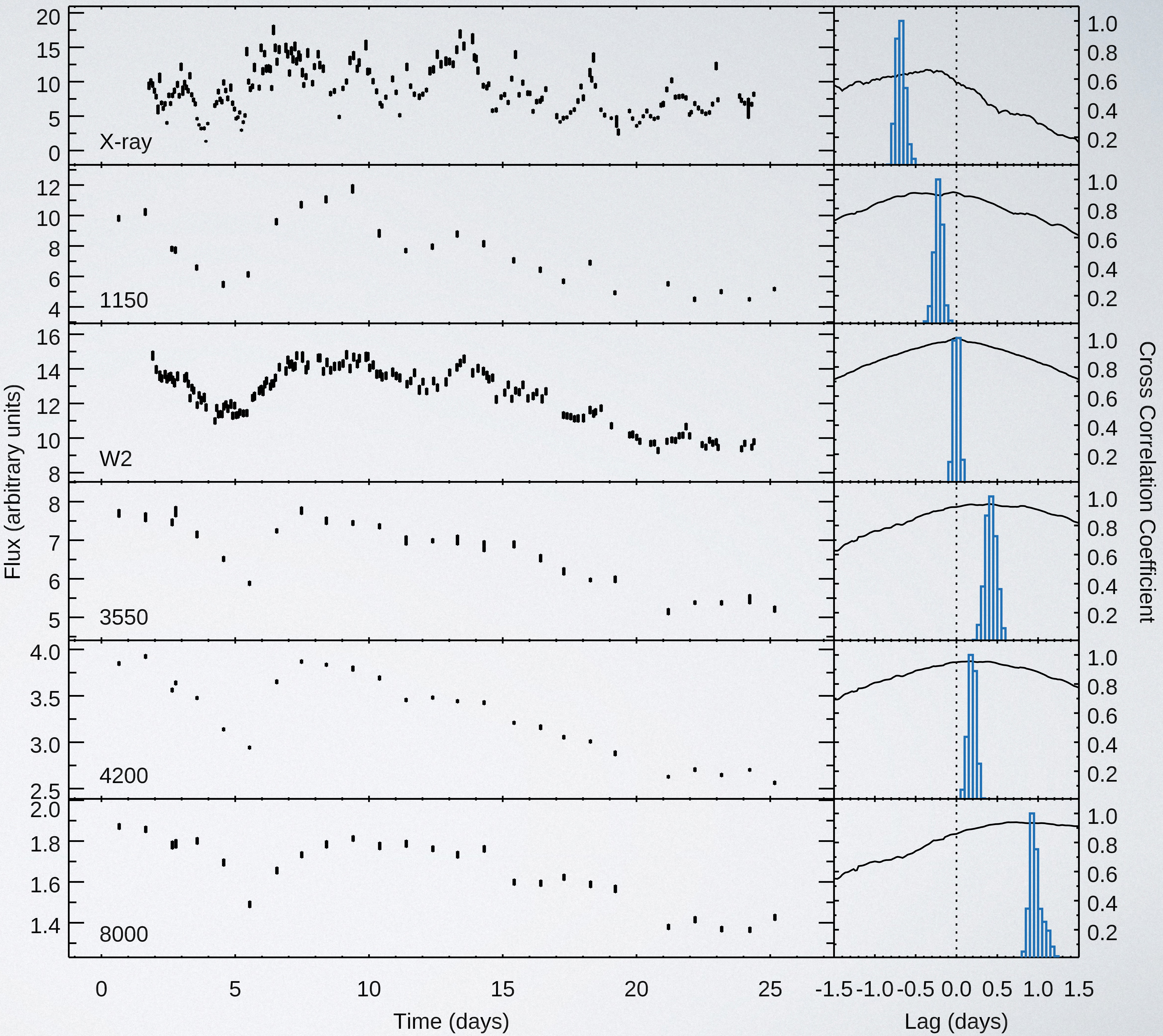
Edelson et al. (2019)





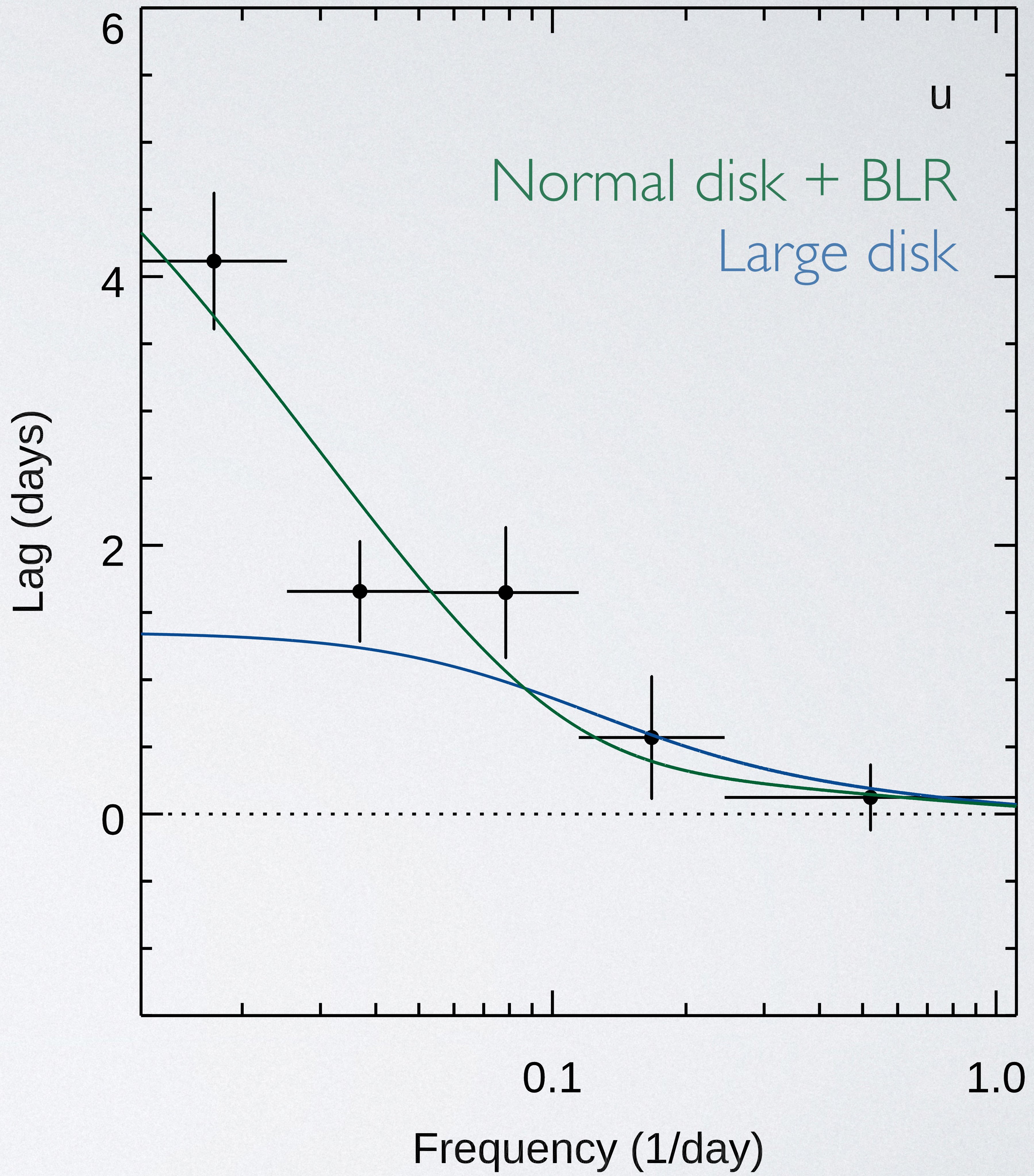
SWIFT ENABLED THIS RESULT

- 26 HST observations over 27 days (Cackett et al. 2018)
- But, 150 Swift observations! (McHardy et al (2018)
- Average of about 6 per day
- Swift provided the 'anchor' for lag measurements



FREQUENCY-RESOLVED LAGS

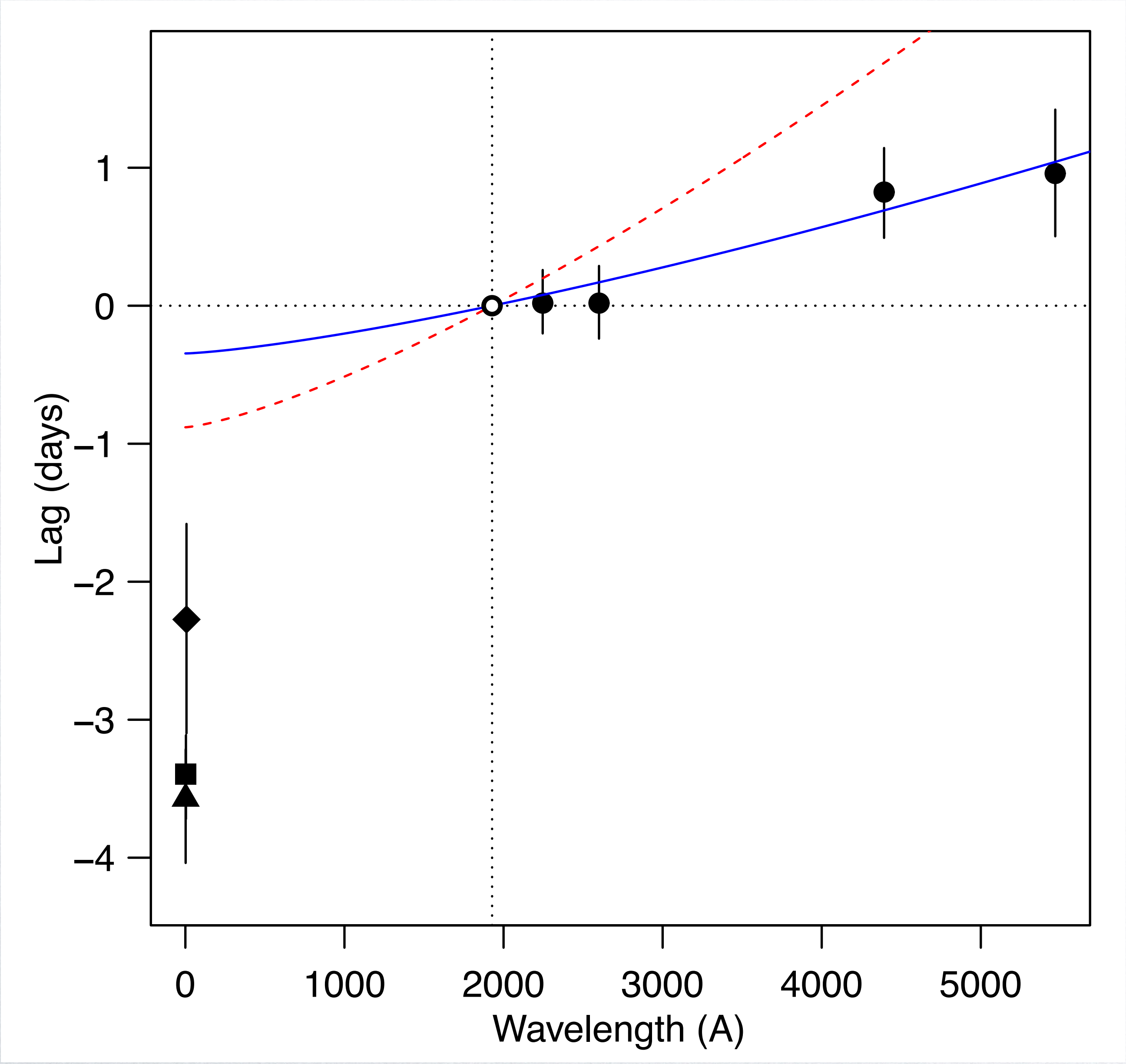
- Calculating the lag at different Fourier frequencies allows for separating the signals on different size scales (smaller size scales will respond at faster, i.e. at higher frequencies)
- But data is unevenly sampled, so need to apply techniques to deal with the gaps (Zoghbi, Reynolds & Cackett 2013)
- We applied this to UV/optical reverberation for the first time (Cackett, Zoghbi & Ulrich, 2022). Similar results for Mrk 335 by Lewin et al (2023).
- Lags are best fit by a normal-sized disk, but with additional significant emission from a distant BLR-like reprocessor



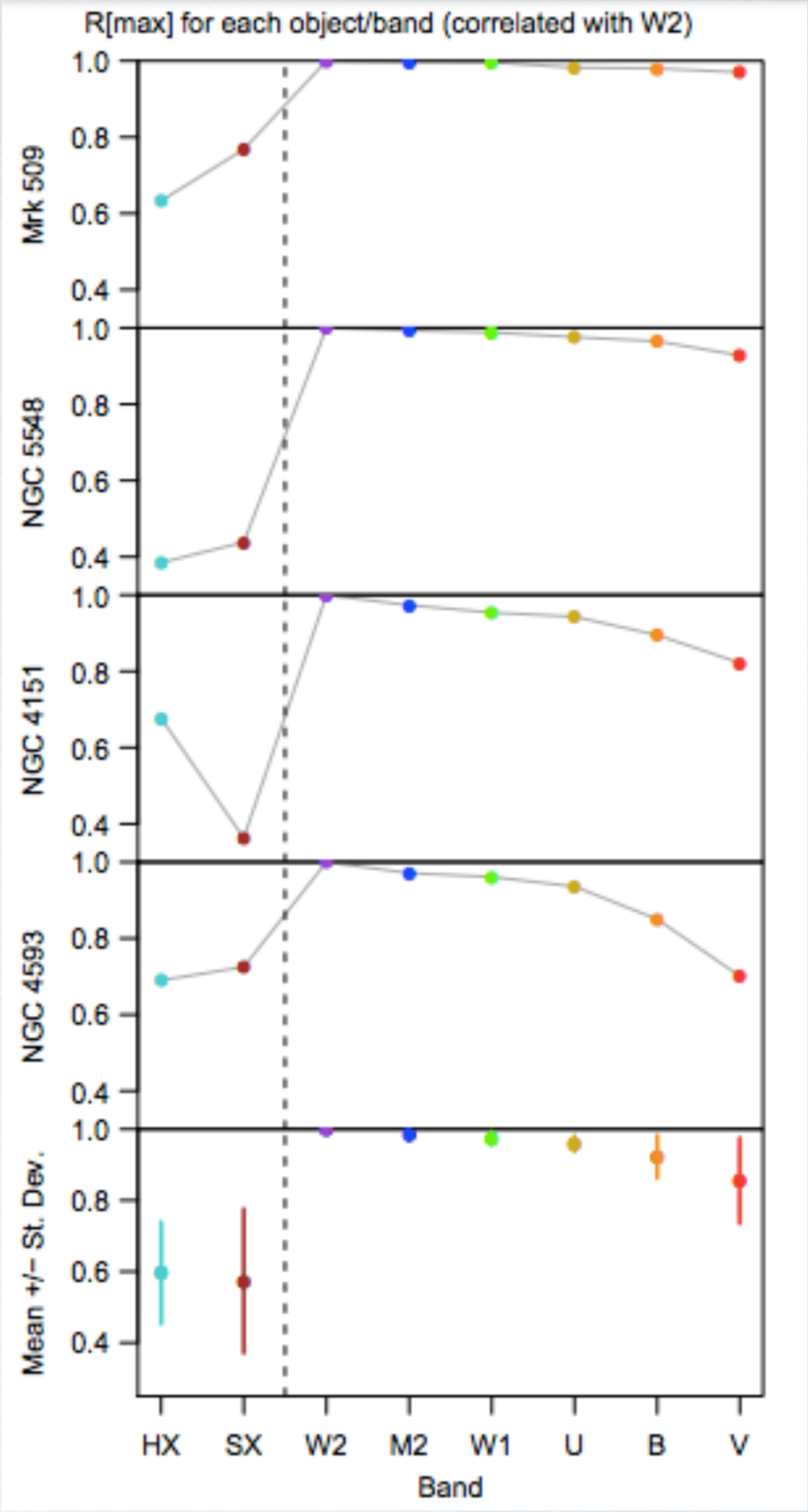
Cackett, Zoghbi & Ulrich, 2022

HOW DO THE X-RAYS FIT IN?

- Consistently poorer correlation between X-ray and UV and UV and optical (Edelson et al. 2019)
- X-ray lags not always consistent (e.g. Edelson et al. 2017)
- Some objects have no correlation at all (e.g. **Mrk 817**: Morales et al. 2019, Kara et al. 2021, **IRAS 13224-3809**: Buisson et al. 2018, **Mrk 335**: Komossa et al. 2020)
- Poorer correlation could be explained by a dynamic corona (Panagiotou et al. 2022)



NGC 4151; Edelson et al (2017)
X-rays don't fit!



Max. correlation with UVW2

Edelson et al. 2019

AGN STORM 2: MRK 817

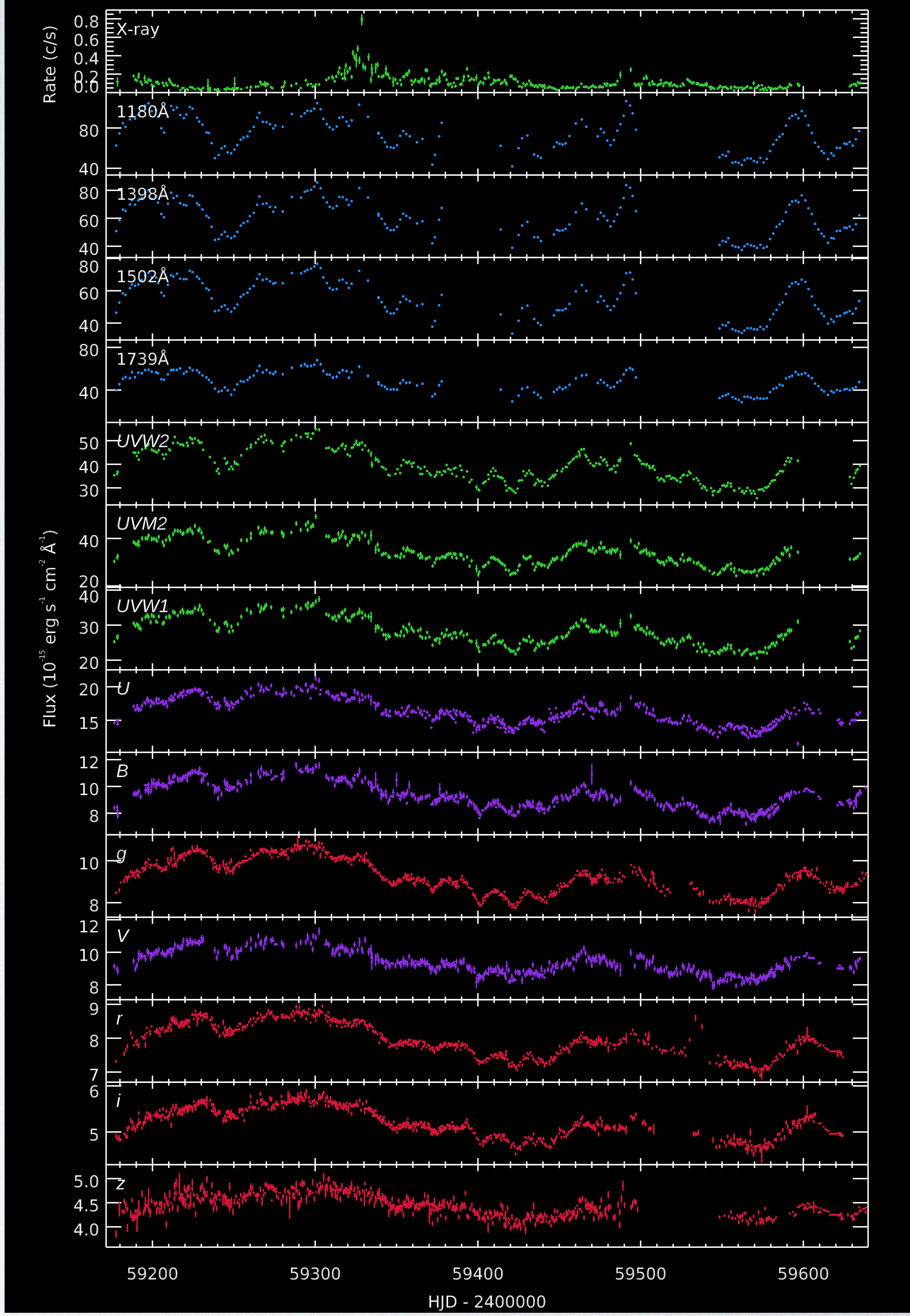
- Only the second ~200 orbit Hubble Space Telescope monitoring campaign on an AGN in its 30-year life! See Kara et al (2021) for overview.
- **HST** (every other day): UV spectra spanning ~**460 days** (Homayouni et al. 2023, 2024)
- **Swift** (every day): X-ray + 6 UVOT filters (Cackett, Gelbord et al. 2023)
- **XMM**: series of longer observations (Kara et al. 2021, Zaidouni et al. 2024)
- **Ground-based** (many telescopes): UBgVriz, average of 2x per night in g (Montano et al in prep)
- 10 papers so far + more in the works….

X-ray

UV

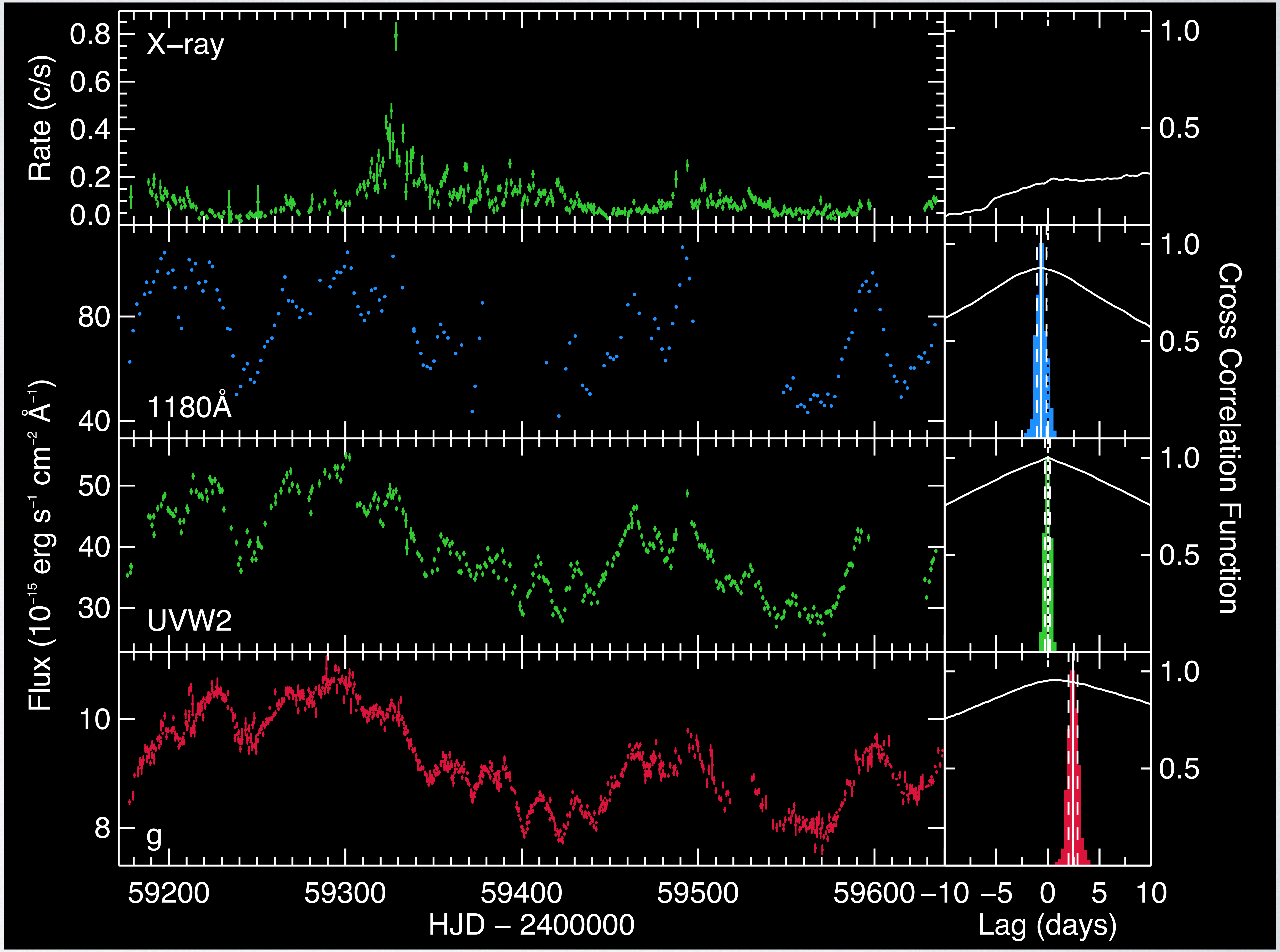
Optical

near-IR



AGN STORM 2: MRK 817

- **X-rays do NOT look like UV/optical**
- First seen in Mrk 817 by Morales et al (2019)
- STORM2 results: Kara et al (2021), Cackett et al. (2023), Partington et al. (2023)

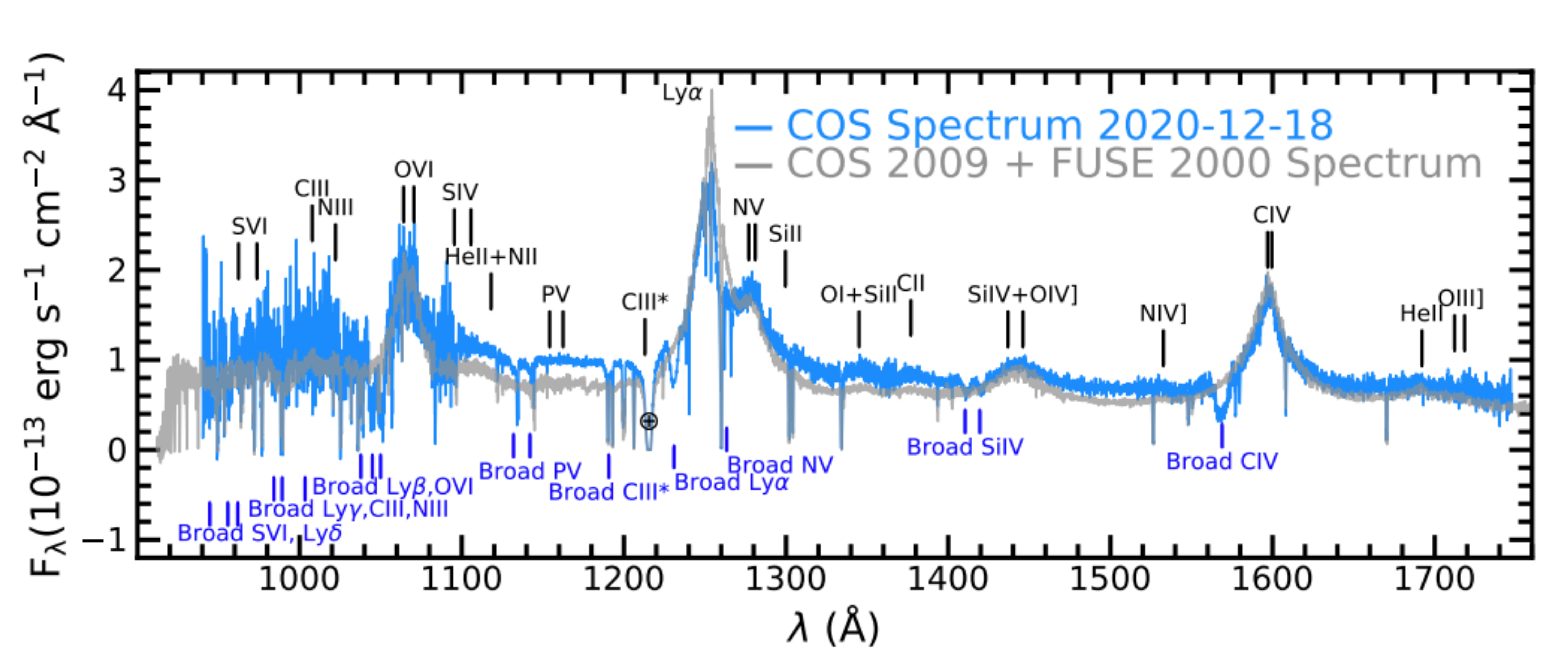


AGN STORM 2: MRK 817 HIGHLY OBSCURED

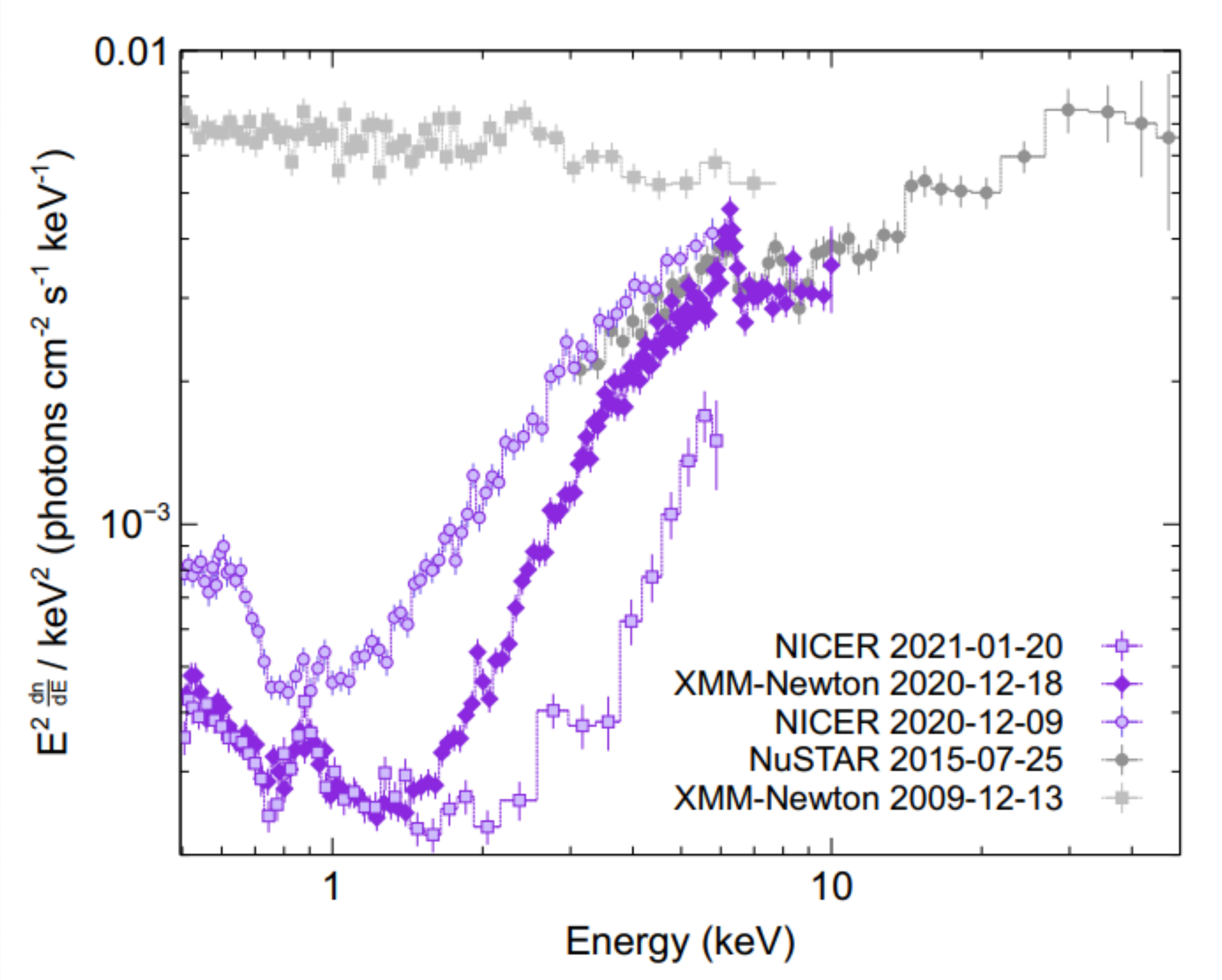
Unexpected, highly variable absorption in UV and X-ray - from a disk wind?

X-rays ~10x fainter than archival!

Kara et al (2021)



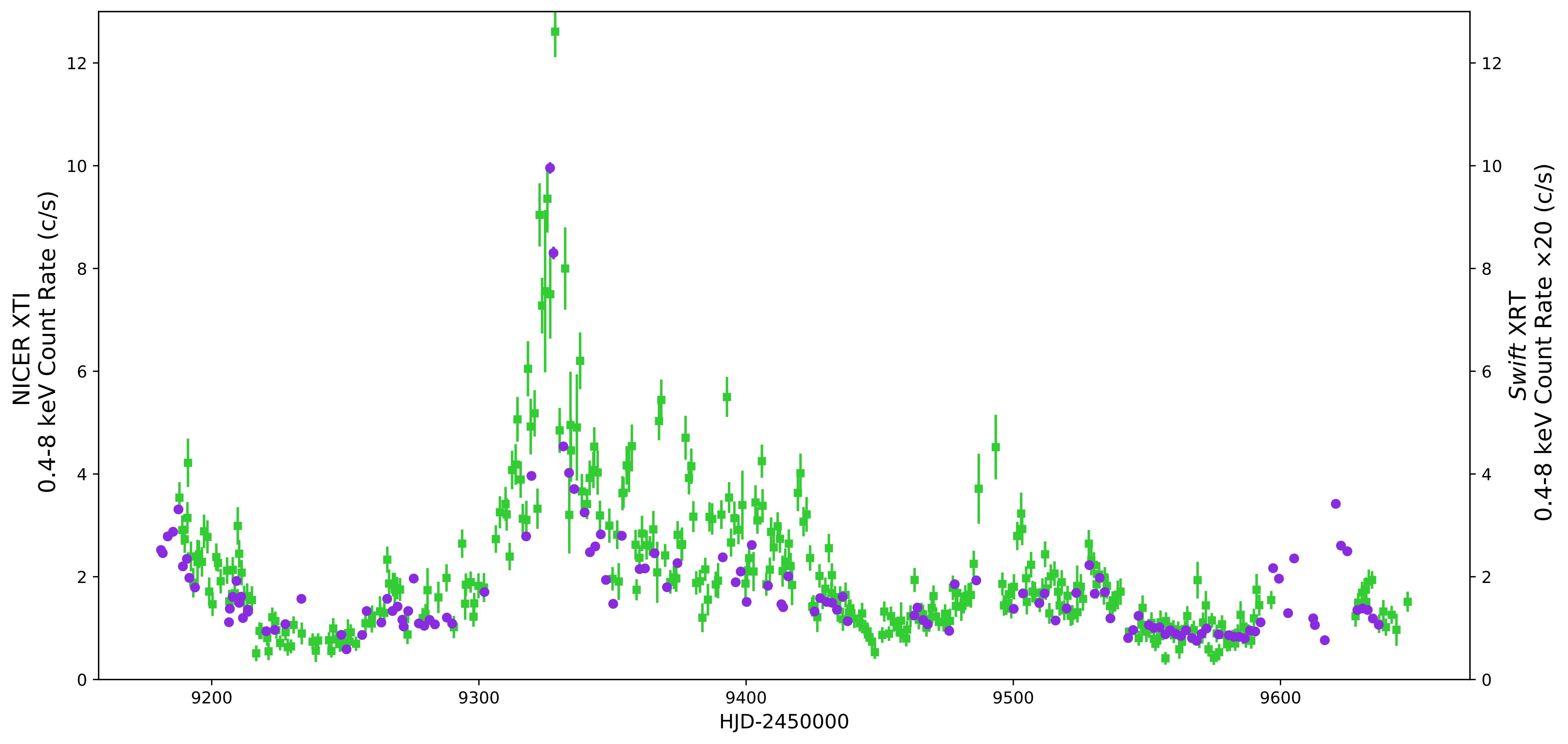
Hubble spectrum compared to archival



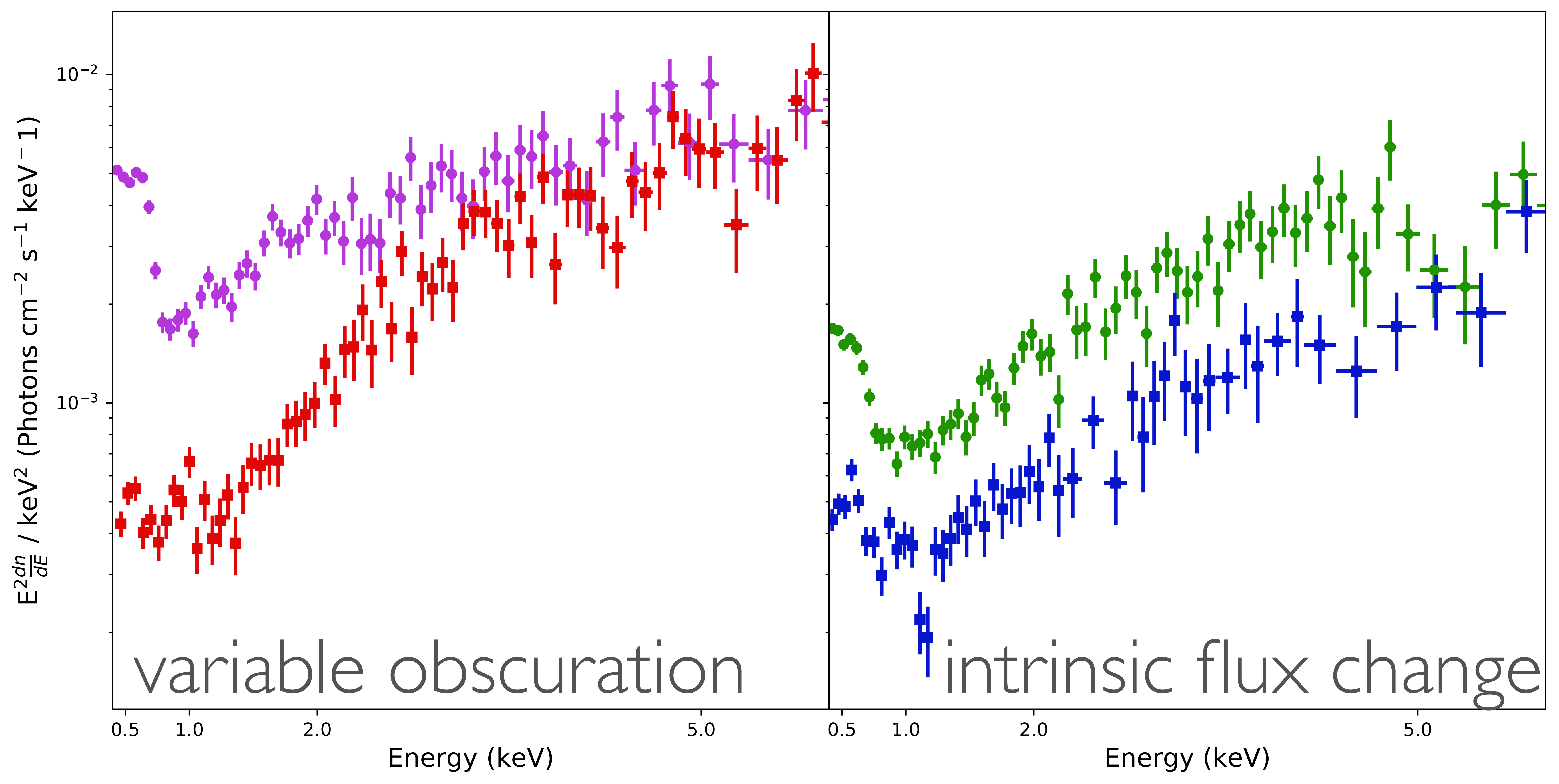
Variable, obscured X-ray spectra with XMM, NICER, NuSTAR (see also Miller et al. 2021)

X-RAY VARIABILITY WITH NICER

- Mrk 817 with **Swift** & **NICER** (Partington et al. 2023)

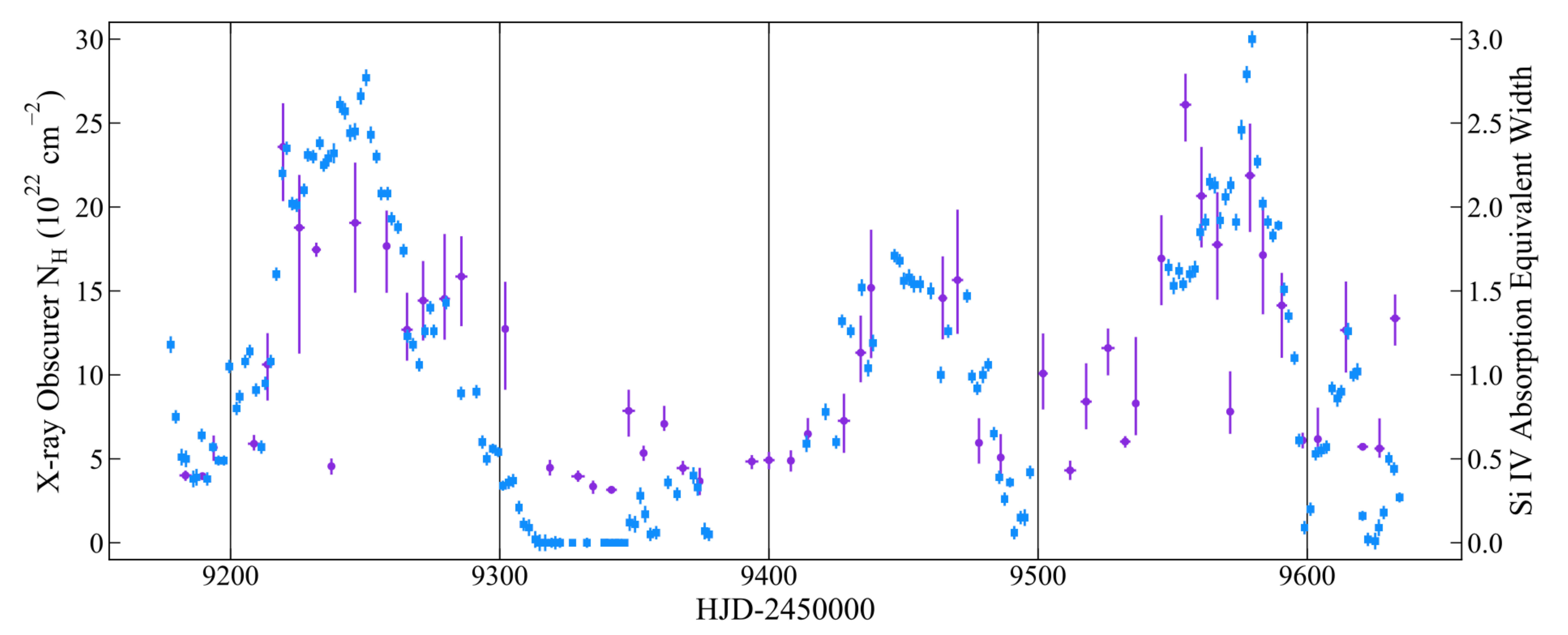


- With NICER we can distinguish between variable obscuration (left) and intrinsic flux changes (right)



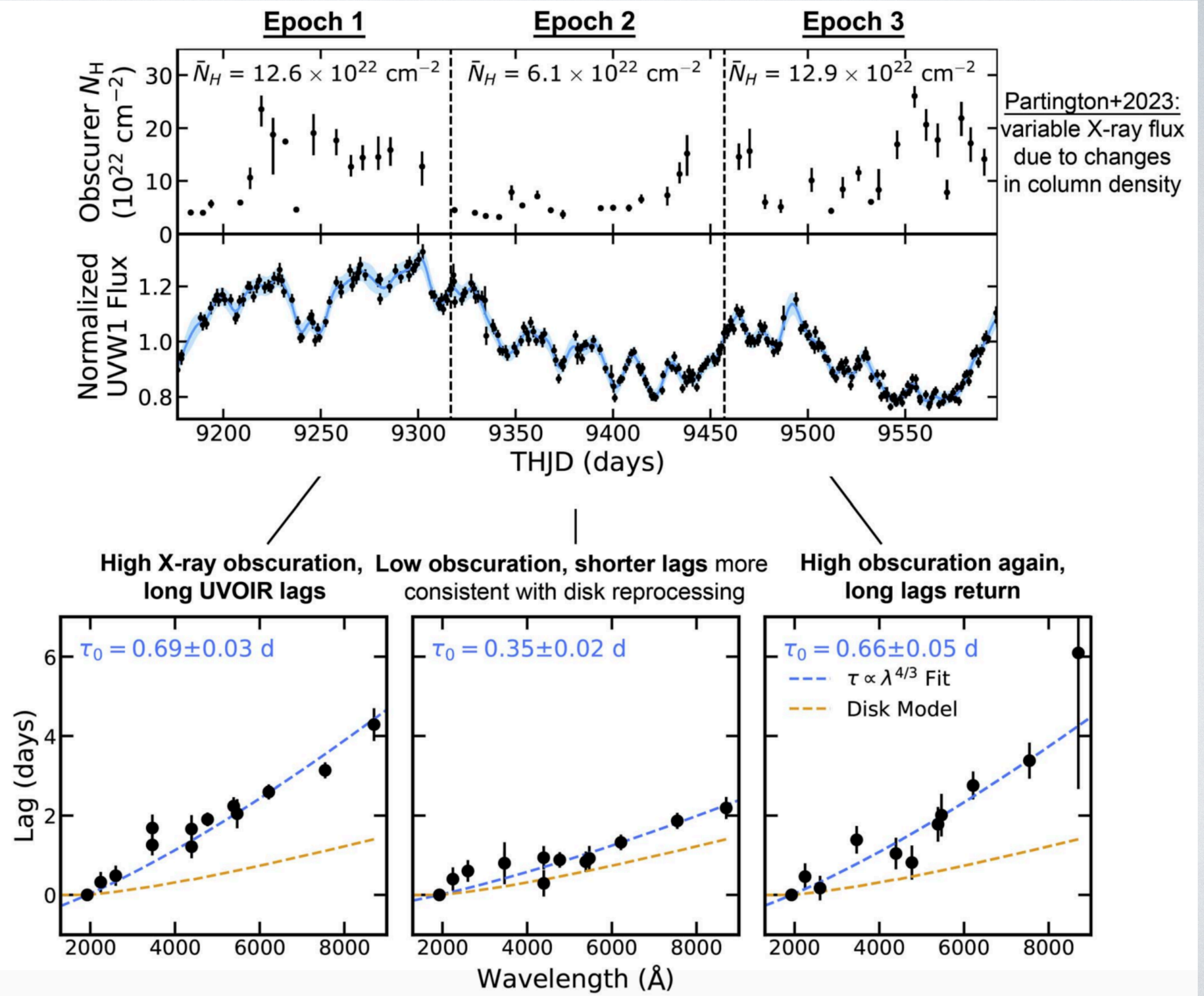
X-RAY AND UV ABSORPTION CORRELATED

- Highly variable **N_H from NICER**, correlated with **EW of broad Si IV absorption trough** in UV spectra
  - ➡ *Same gas (clumpy disk wind?) obscuring X-rays and UV*
  - ➡ *Dust-free, ionized obscurer located at the inner BLR*



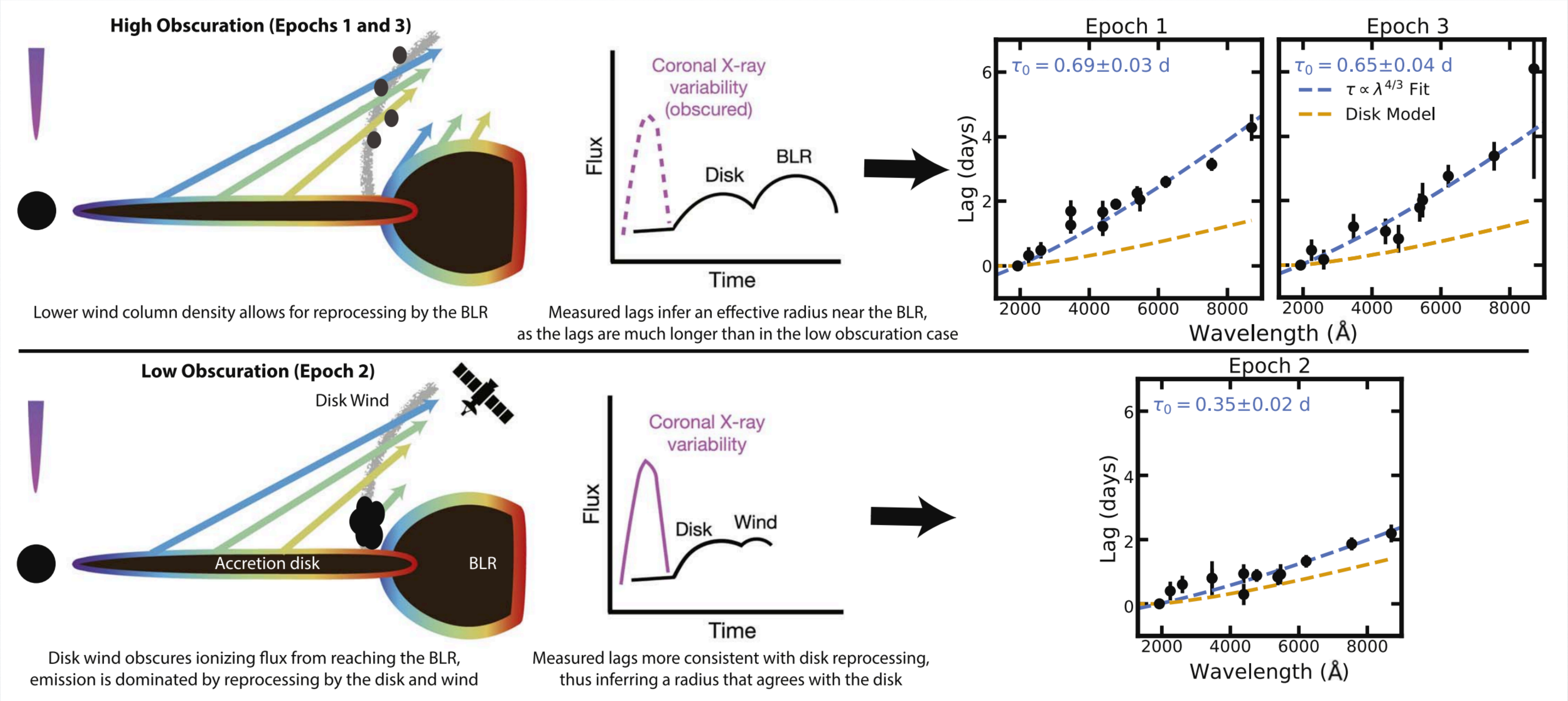
UV/OPTICAL REVERBERATION IN MRK 817

- Despite X-ray variability not correlated with UV/optical, we still see UV/optical reverberation
- Lags change throughout the campaign, suggesting complex geometry (Lewin et al 2024)



UV/OPTICAL REVERBERATION IN MRK 817

- Different stages of wind launching could explain link between obscuration and lag (Lewin et al. 2024)



SUMMARY

- UV/optical continuum reverberation mapping is a way to probe size scales too small to be resolved otherwise

- ***Swift revolutionized these studies***

- Challenges to the simplest irradiated accretion disk picture:

    - Are we seeing non-disk emission from further out? Progress with better models and more data

    - How do the X-rays fit in?

    - How does accretion flow change with mass and mass accretion rate?