Accretion disk reverberation mapping

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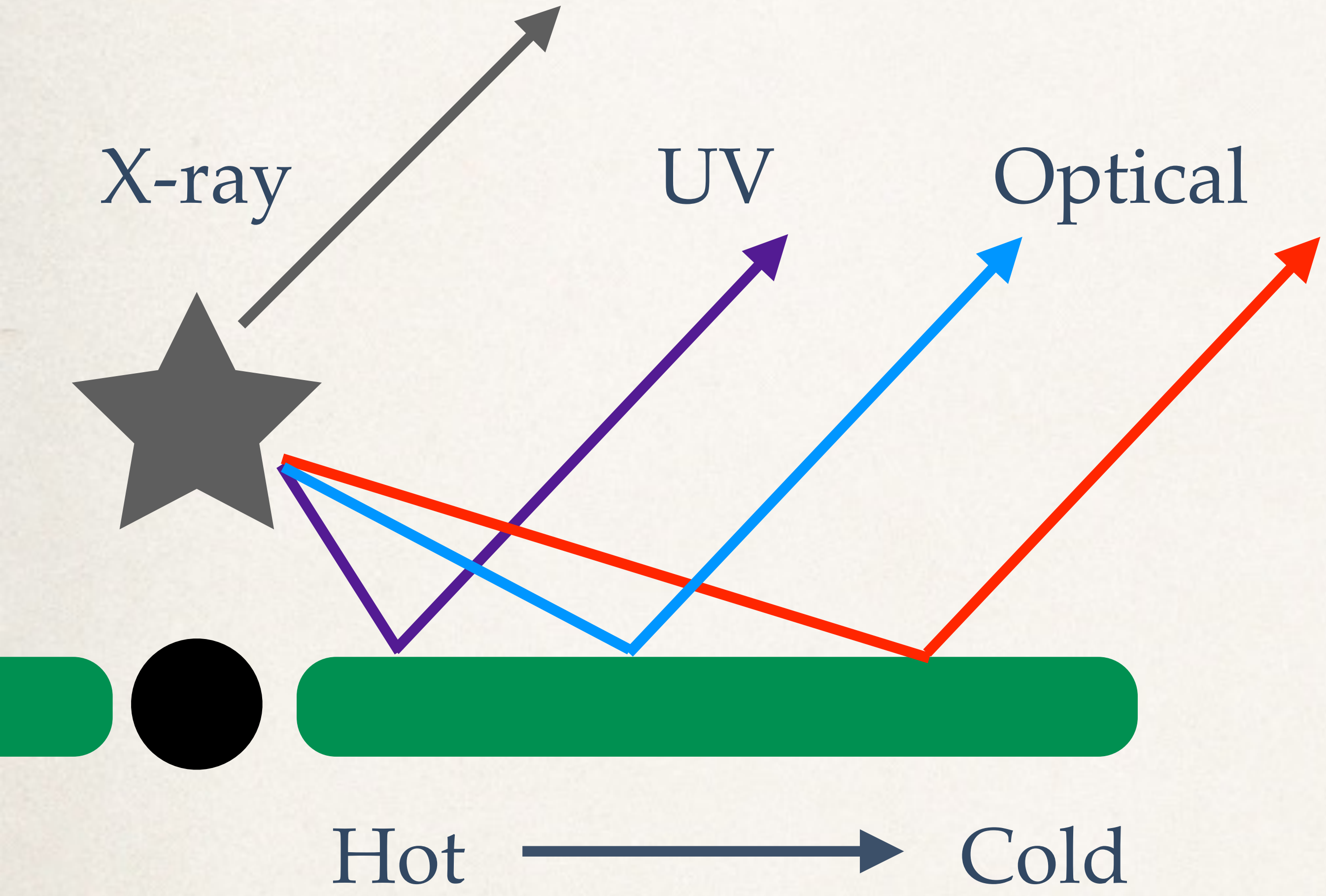
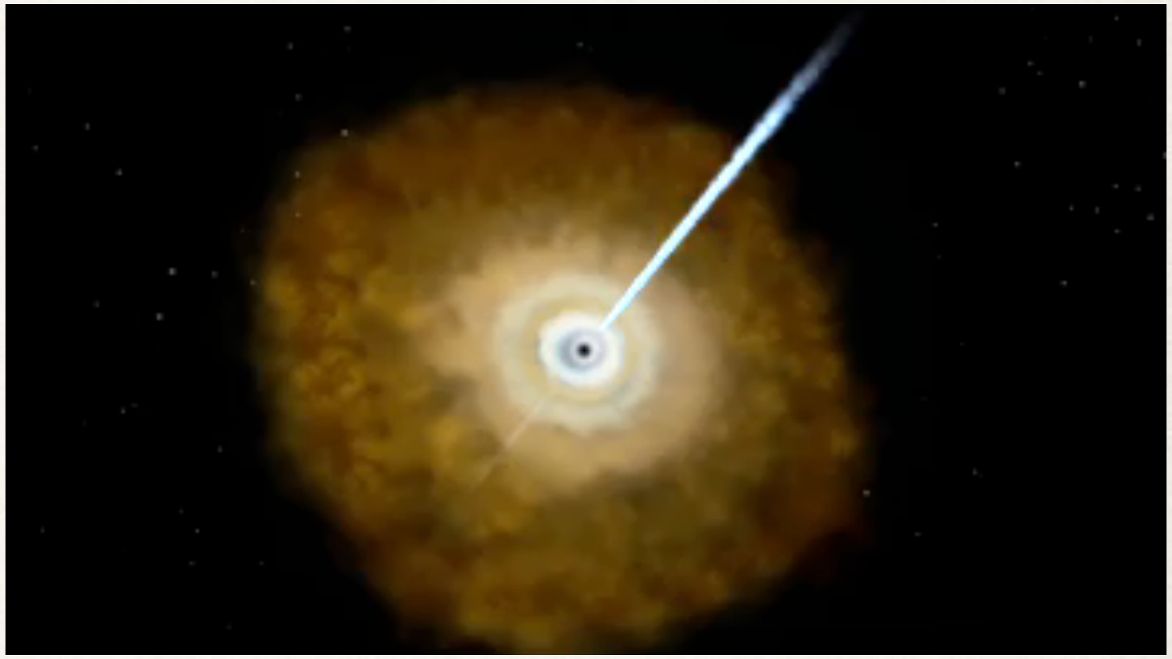
Thermal reprocessing





- Hot, inner disk sees variable irradiating source before cooler, outer disk
- Expect correlated continuum bands, with lags that depend on the temperature profile of the disk

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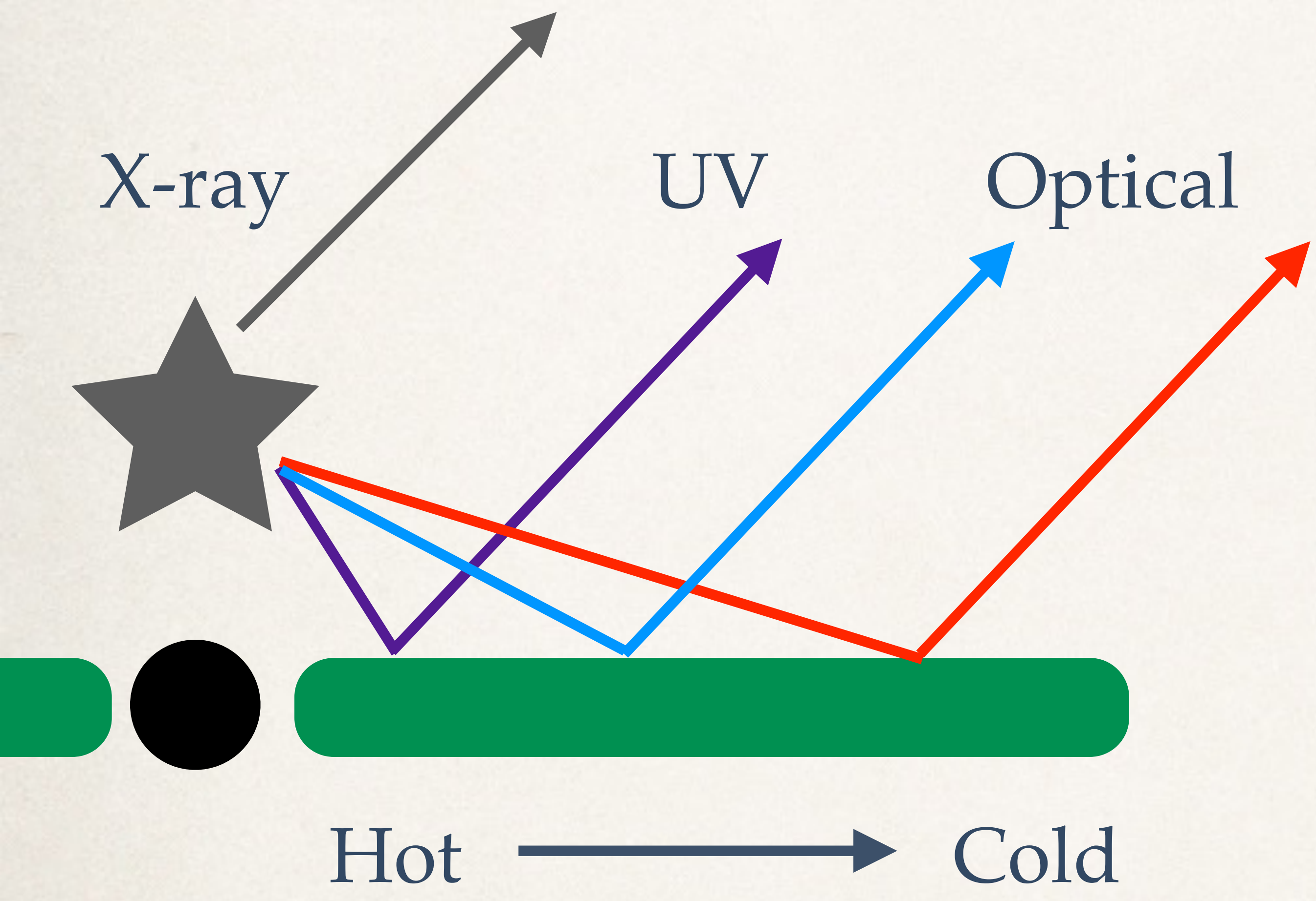

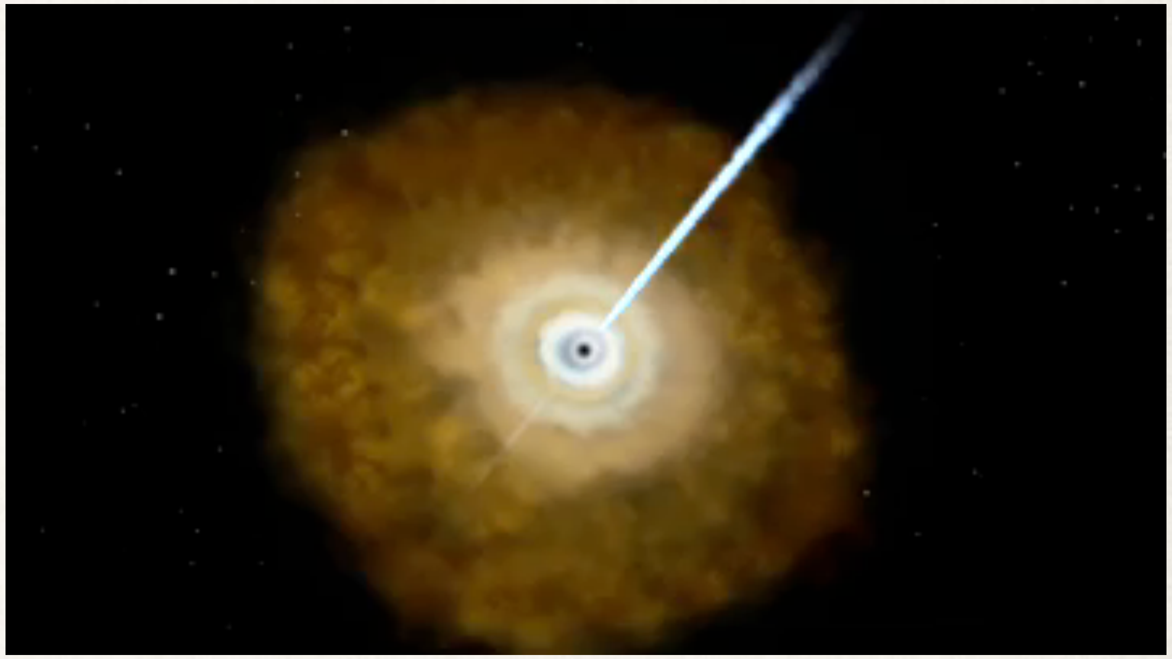

- Hot, inner disk sees variable irradiating source before cooler, outer disk
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Temperature profile

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

Viscous Irradiation

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

where X ~ 3 for blackbody radiation assuming a flux-weighted emission radius

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

for a classical geometrically thin, optically thick disk

see, e.g. Collier et al. (1999), Cackett et al. (2007), Fausnaugh et al. (2016)

Getting a distance?

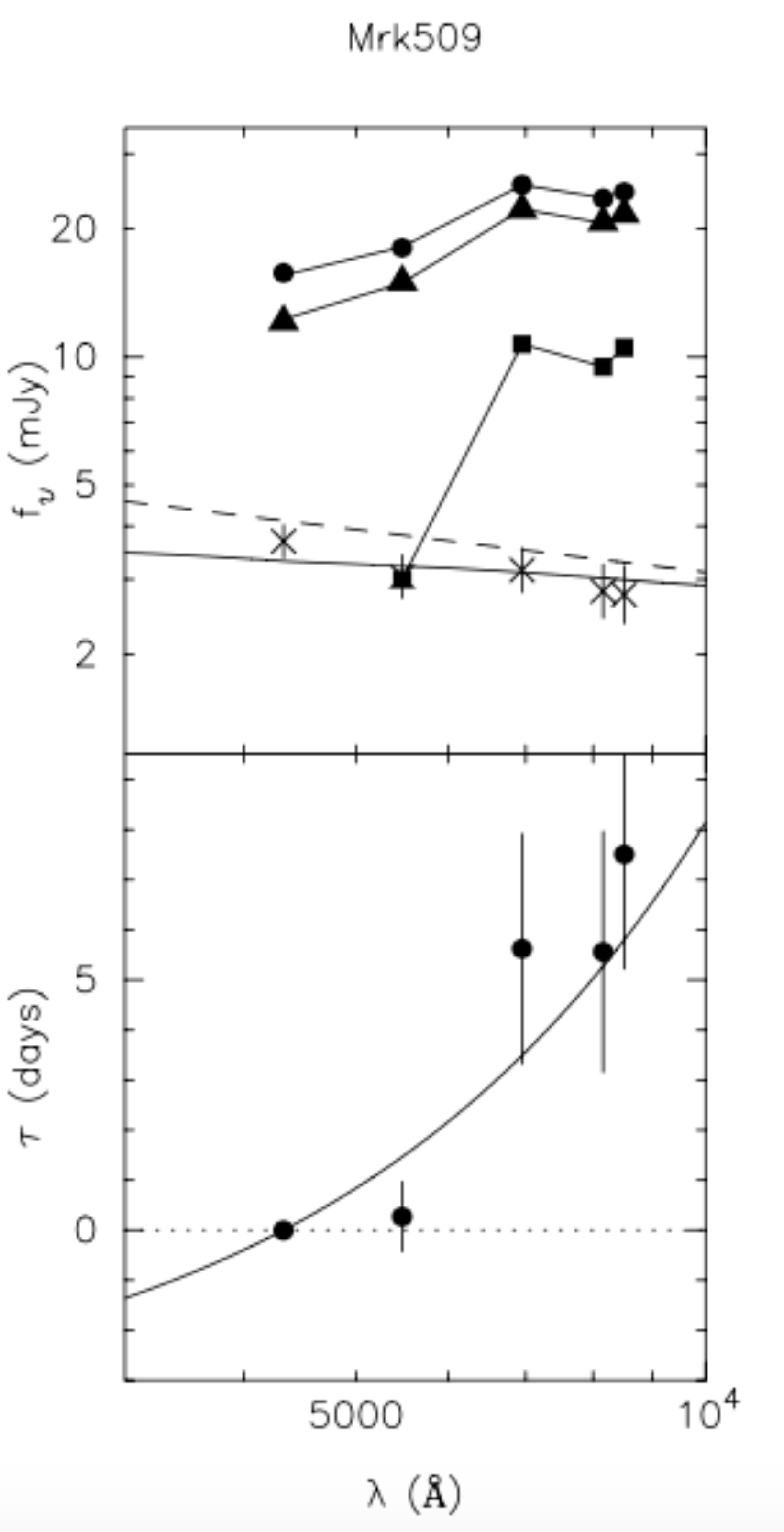
- Since measuring ***τ*(*λ*)** gives you ***T(R)***, can determine what the ***disk luminosity*** should be, and hence get the implied ***distance*** (Collier et al. 1999, Cackett et al. 2007):

$$D \propto \tau \lambda^{-3/2} f_{\nu}^{-1/2}$$

- Potentially very powerful given AGN luminosities
- ***But,*** will work IFF we understand the disk properties (doesn't have to be a standard thin disk, but we need to understand what it is - needs to be calibrate-able)

Putting it into practice

- AGN SEDs don't look like a standard disk
- But, ***variable*** component should
- Fit for host galaxy flux & internal reddening to match fluxes and lags
- In Cackett et al. (2007) we applied this to the 14 AGN in the Sergeev et al. (2005) sample



● Maximum flux

▲ Minimum flux

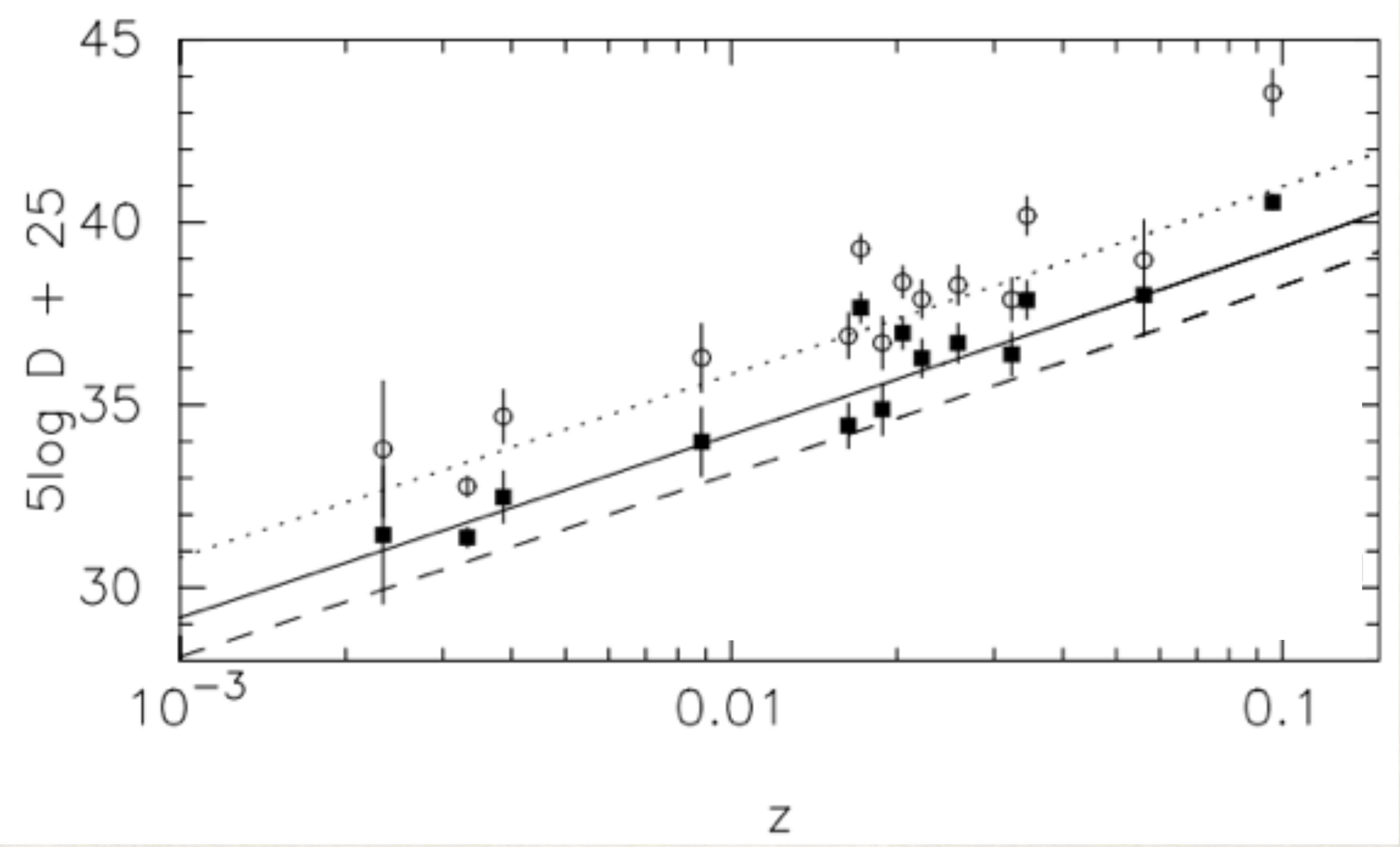
■ Host galaxy fluxes

× Difference (disk) spectrum

$$\tau \propto \lambda^{4/3}$$

But….we must be missing something

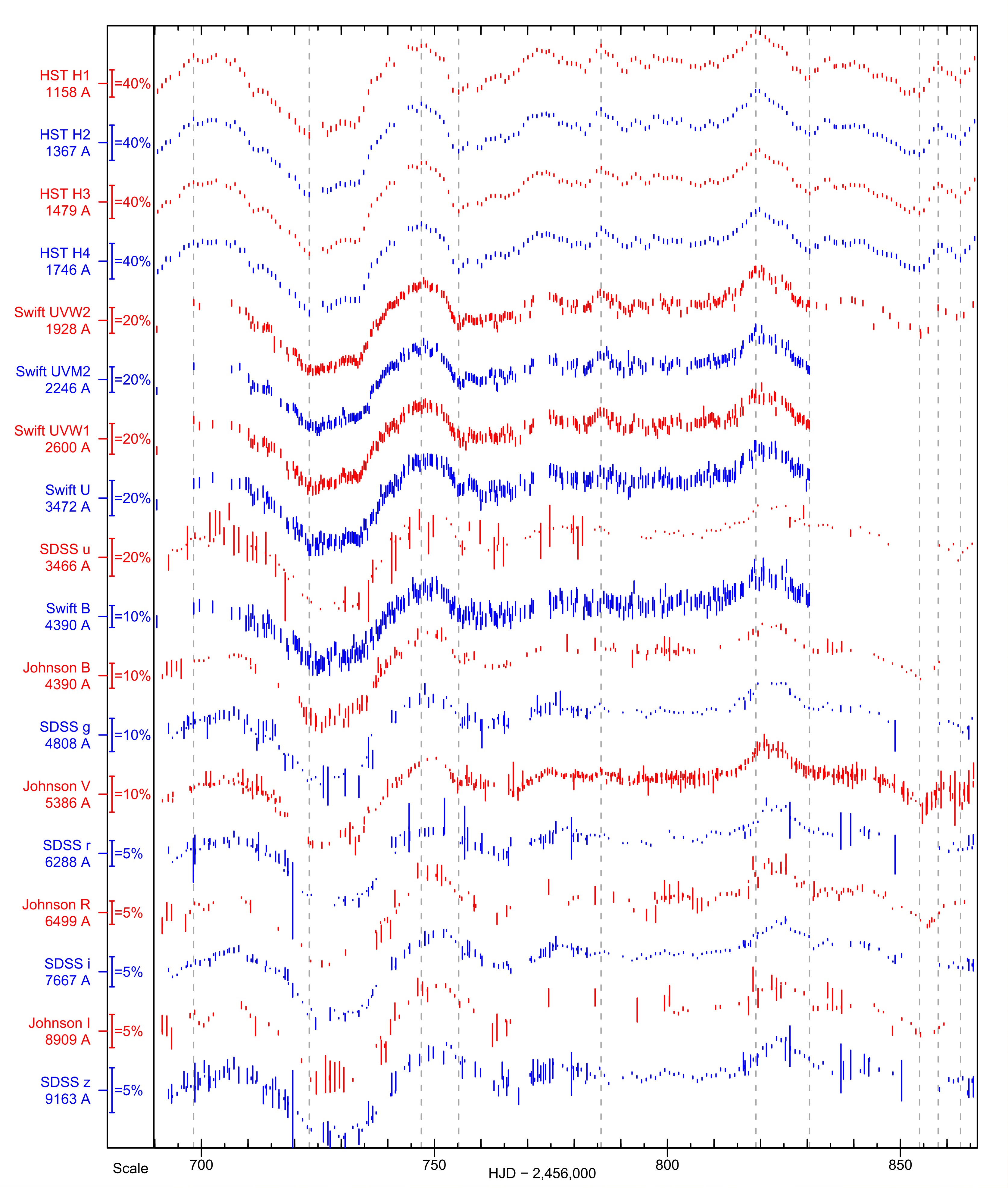
- A fit to all 14 AGN implies $H_0 = 44 \pm 5$ km s^{-1} Mpc^{-1}, a factor of 1.6 too small
- The disks are too faint, or, alternatively, the disks are a factor of 1.6 bigger than expected



Cackett et al. (2007)

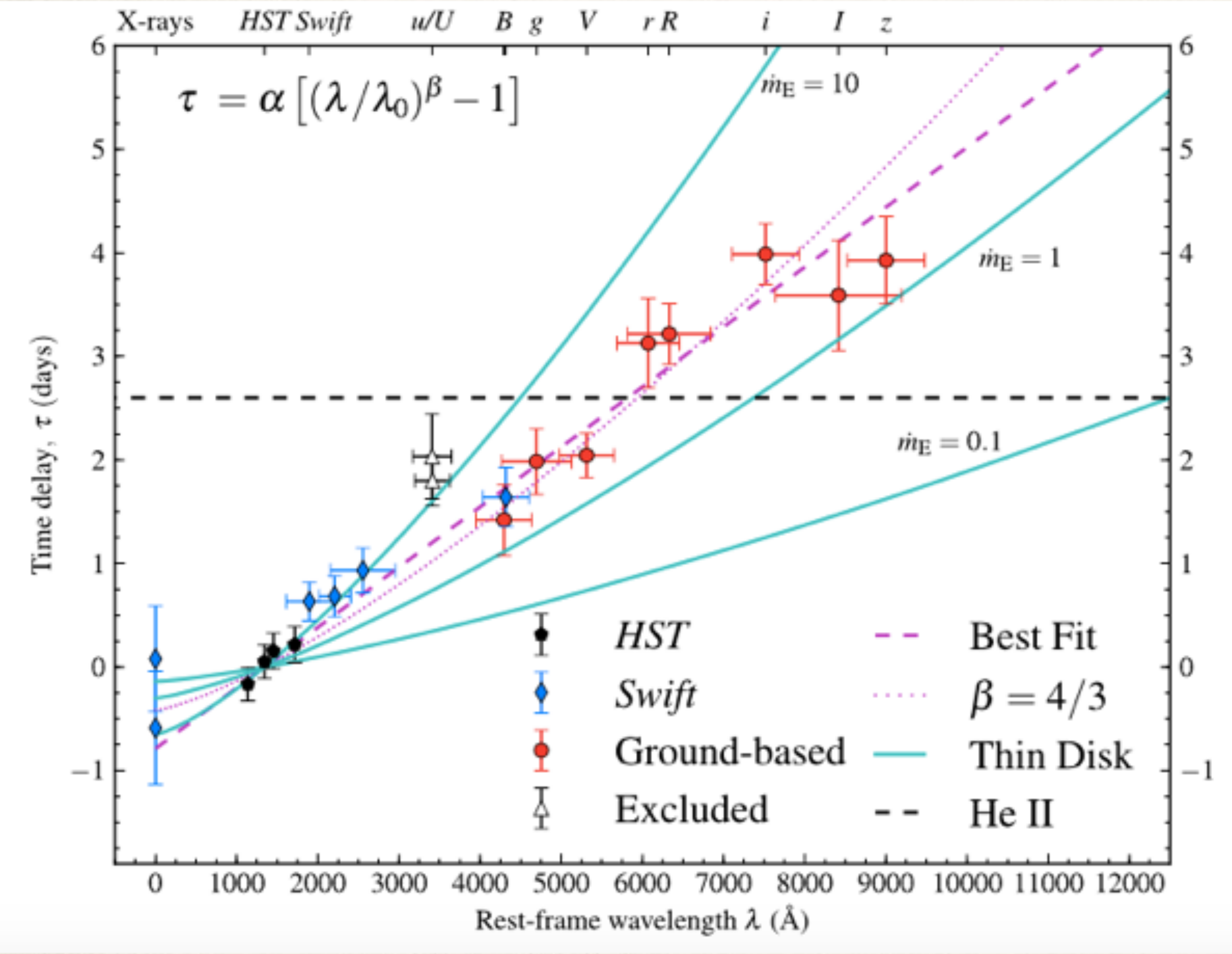
Enter AGN Storm….

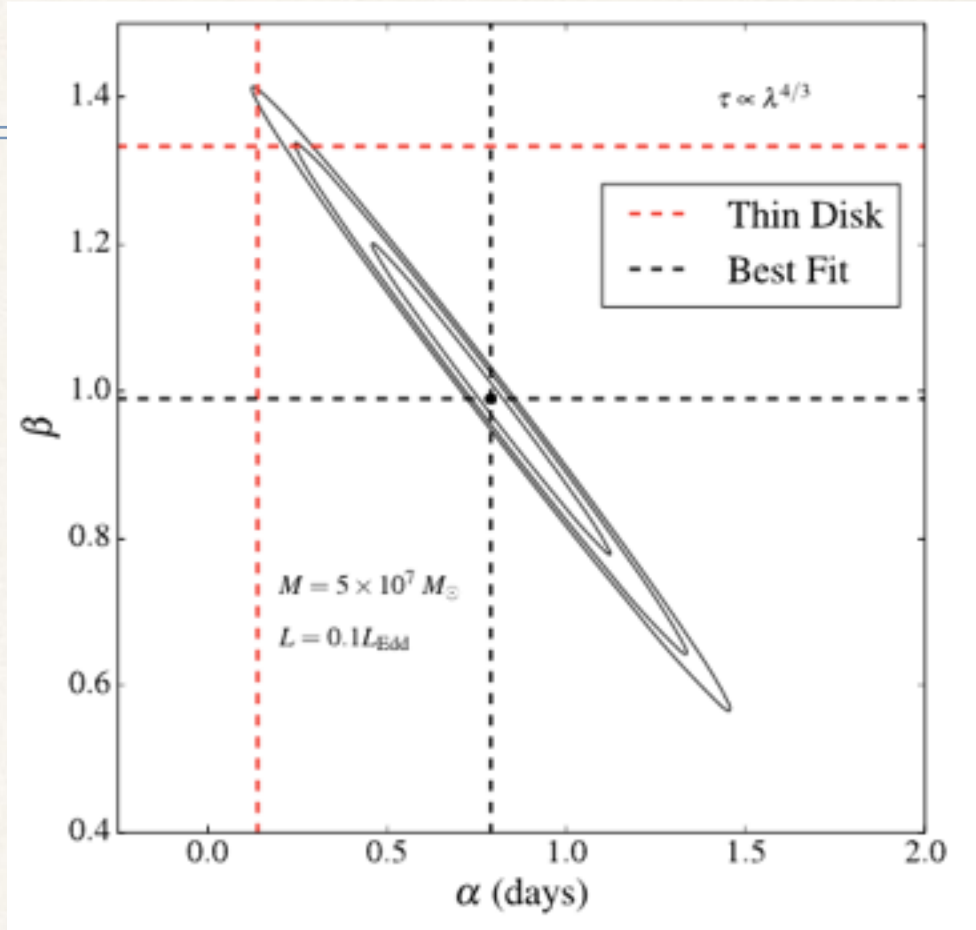
- HST, Swift and ground-based monitoring of NGC 5548 in 2014
- Cadence for Swift <0.5d
- See Edelson et al. (2015), Fausnaugh et al. (2016)



Fausnaugh et al. (2016)

Disk appears to be a factor of 3 too big



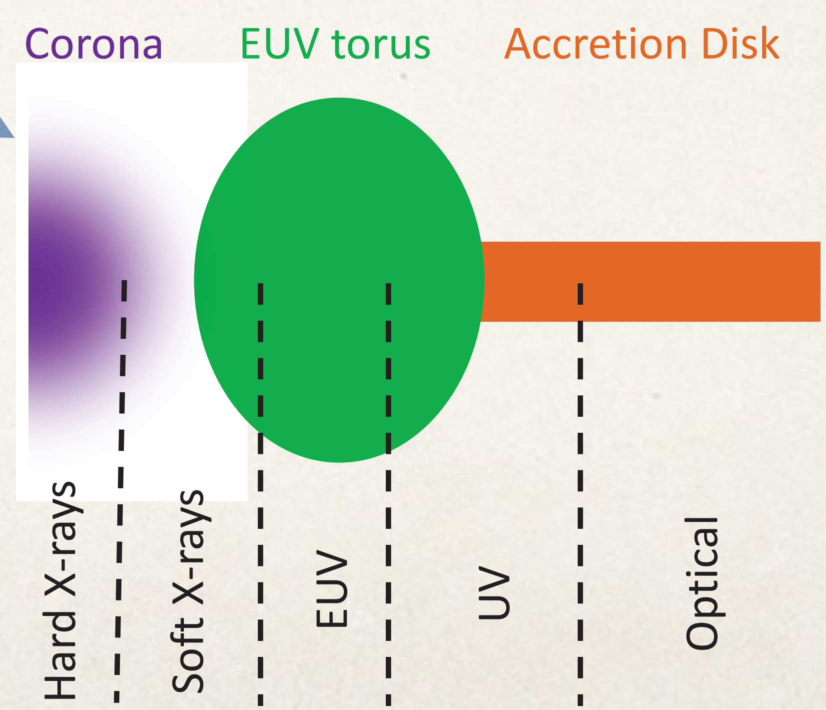


Fausnaugh et al. (2016)

- Moreover, X-rays not well-correlated and not the driving lightcurve (Starkey et al. 2016, Gardner & Done 2016)
- Enhanced u-band lag may indicate contribution to lags from Balmer continuum (Edelson et al. 2015)

Why is the disk too big?

- Contribution of broad lines to photometric bands will enhance lags (e.g. Chelouche et al. 2013), but, not a large effect here (Fausnaugh et al. 2016)
- BLR diffuse continuum lags (Korista & Goad 2001), but Fausnaugh et al. (2016) suggest it is not significant aside from the u-band
- Gardner & Done (2016) suggest there is an "FUV torus" between X-ray emitting region and UV/optical region
- Inhomogeneous disk (Dexter & Agol 2010)
- Tilted inner disk (Starkey et al. 2016)



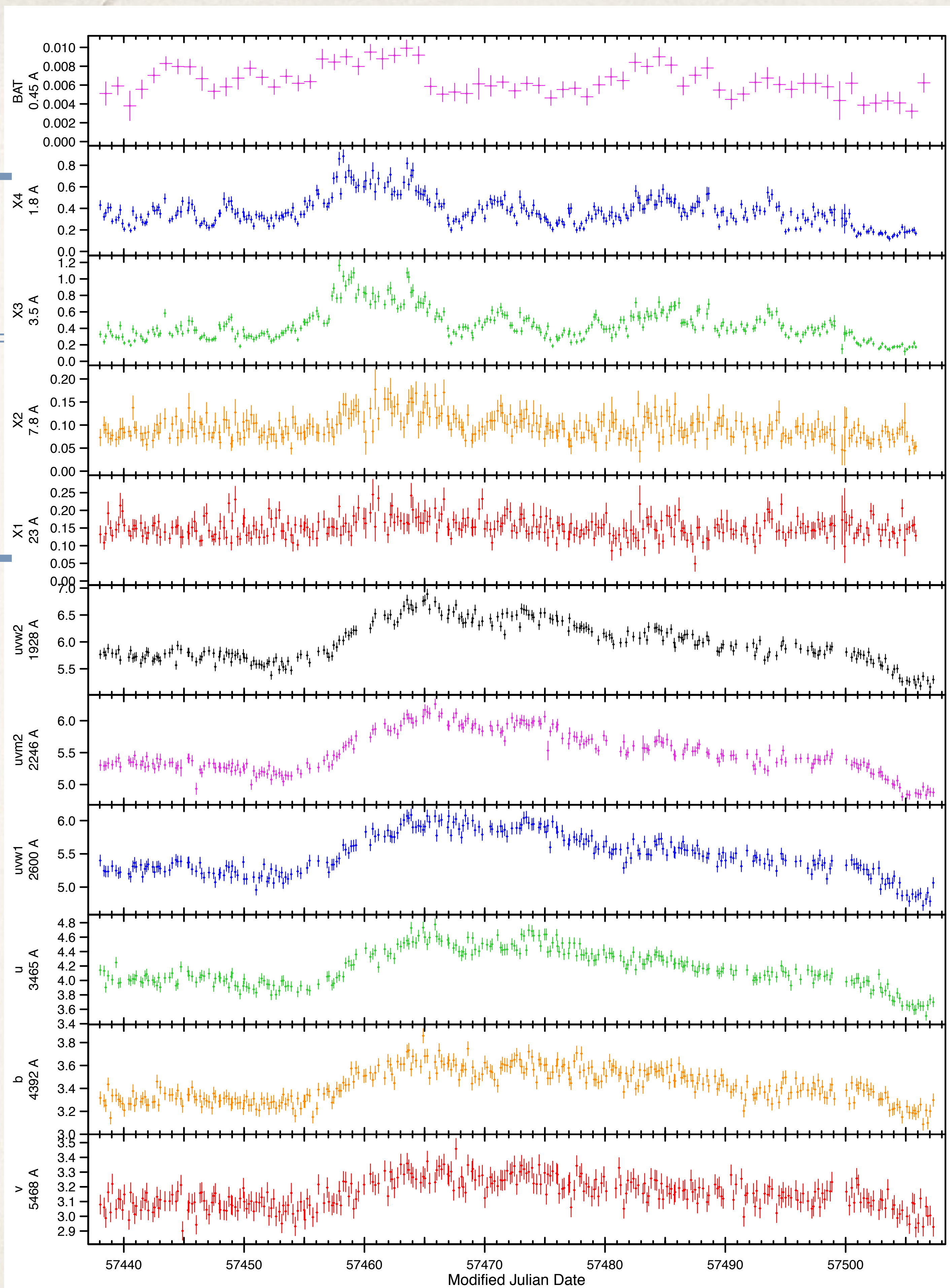
NGC 4151 with Swift

Hard X

4 X-ray bands

UV

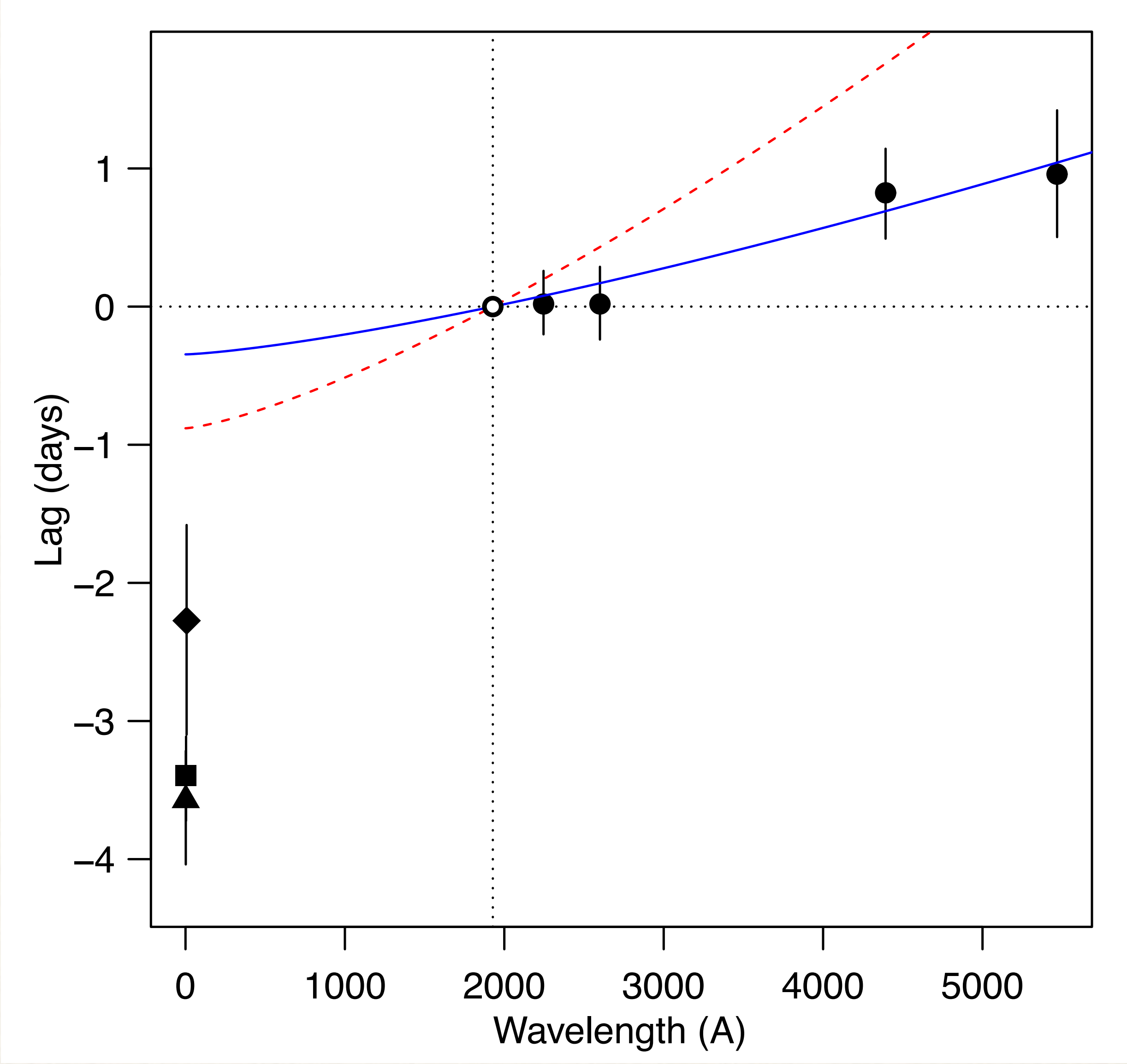
V



- Campaign from early 2016 (PI: Edelson)
- 6 hour sampling (!!) for 69 days (319 obs)
- Edelson et al, submitted

NGC 4151 with Swift

- >3-day lag from X-ray to UV
- <1-day lag from UV to optical
- **Not**, consistent with standard lamp-post geometry to explain X-ray to UV offset
- UV to optical only **is** consistent with standard thin disk (within large uncertainties)

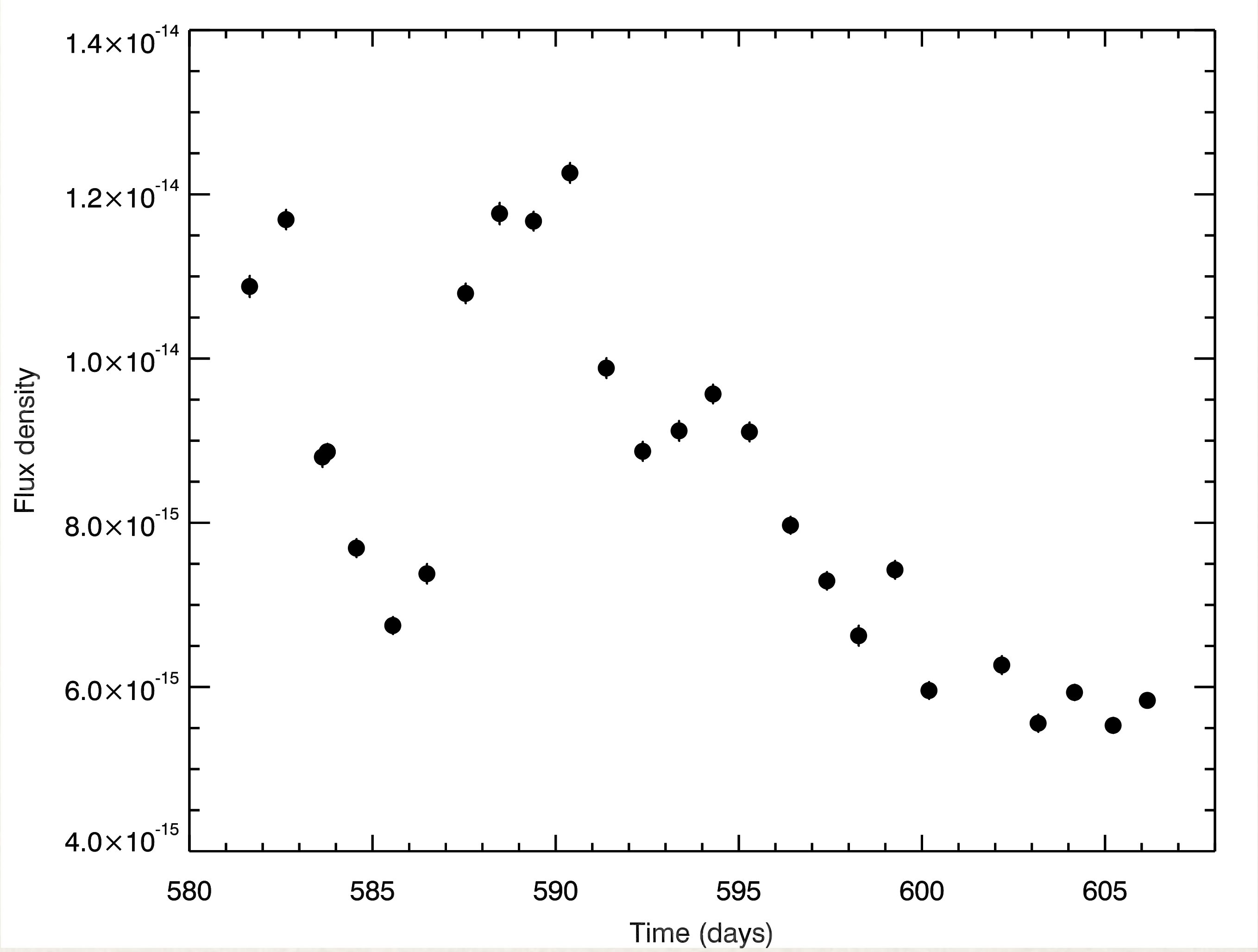


Edelson et al., submitted

NGC 4593 with Swift/HST/Kepler

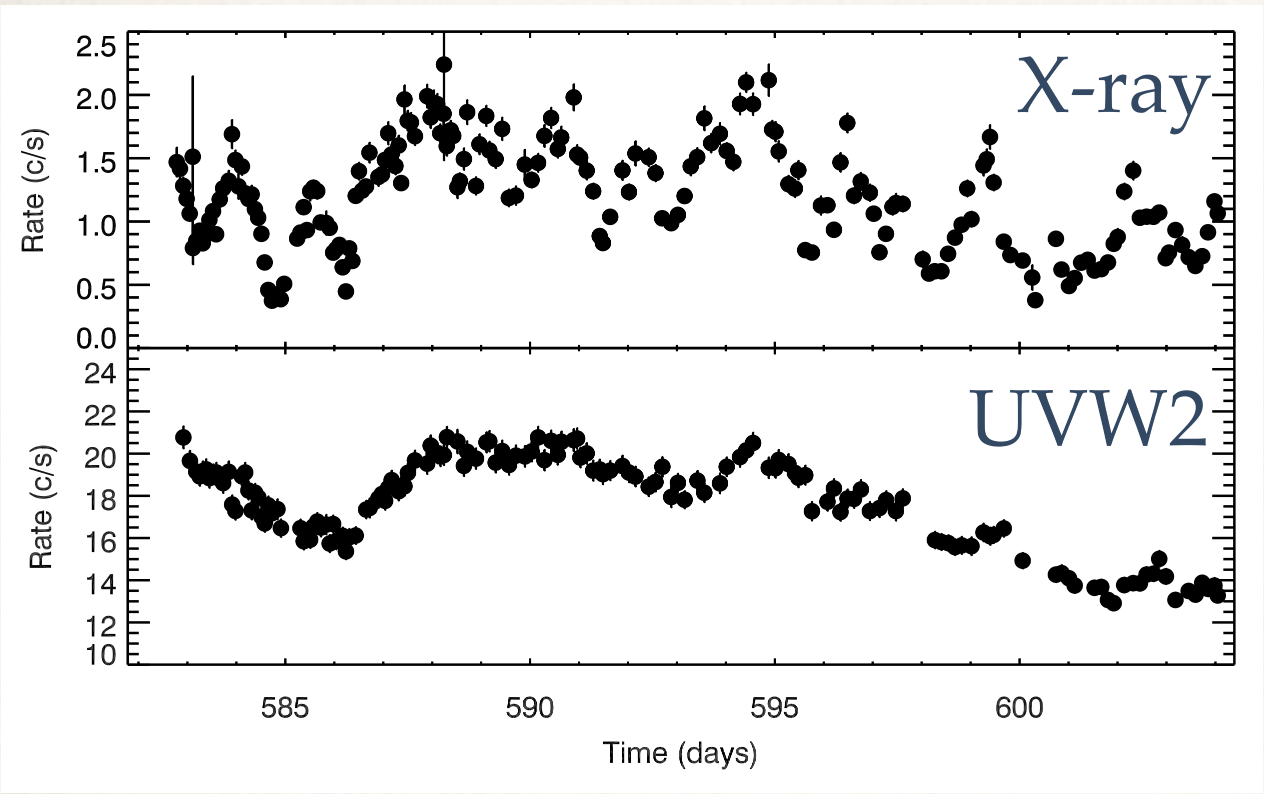
- NGC 4593 in the Kepler field of view from July - October 2016 (PI: Edelson)
- Visibility overlapped with Swift & HST for July 2016 only
- Monitoring with HST once per day for 27 days (PI: Cackett)
- Obtained G140L, G430L and G750L spectra each visit, covering 1100Å to 10000Å
- Monitoring with Swift with ~200 observations over 23 days (PI: McHardy)

1300Å HST lightcurve

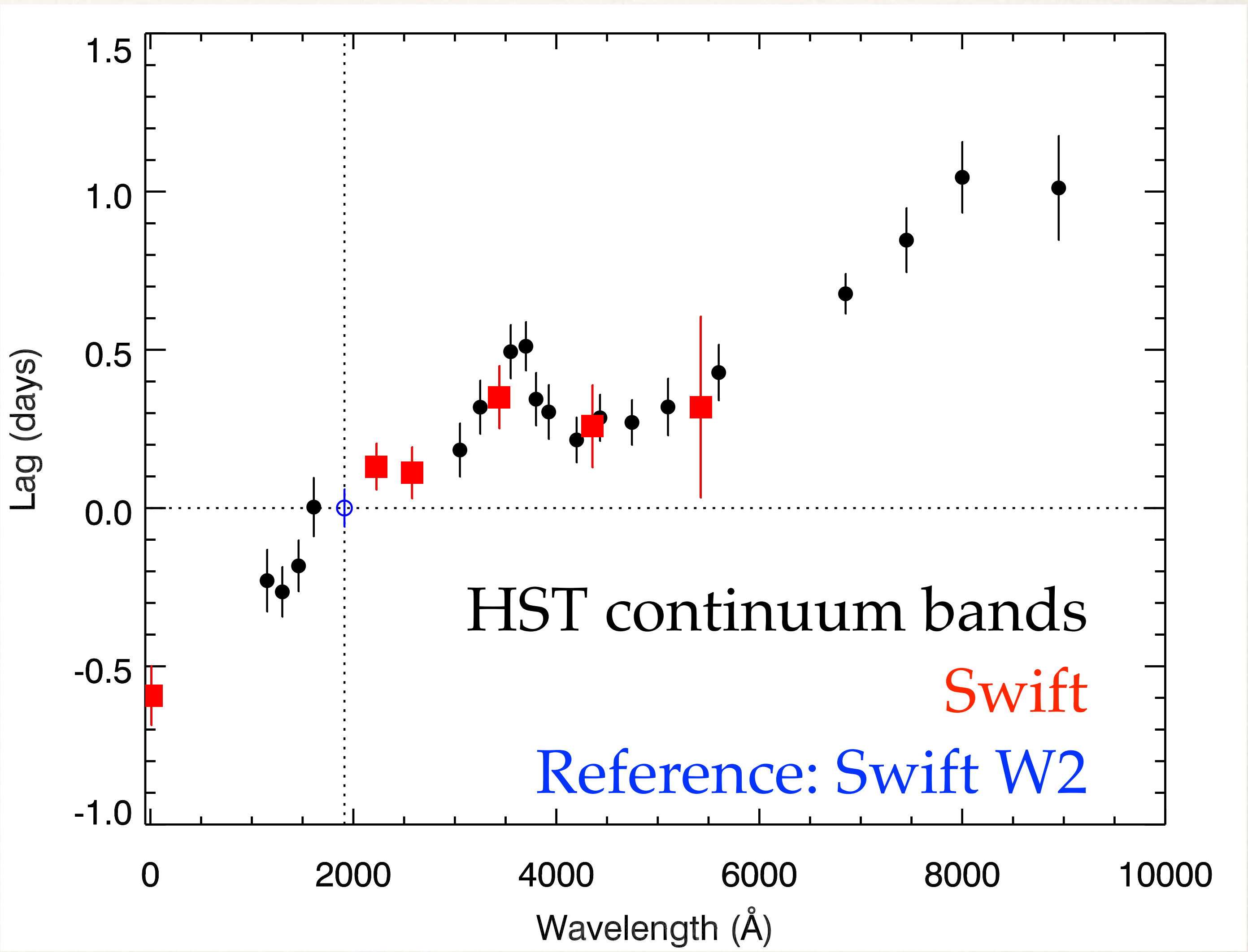


Cackett et al., in prep.

HST 4593 with Swift/HST



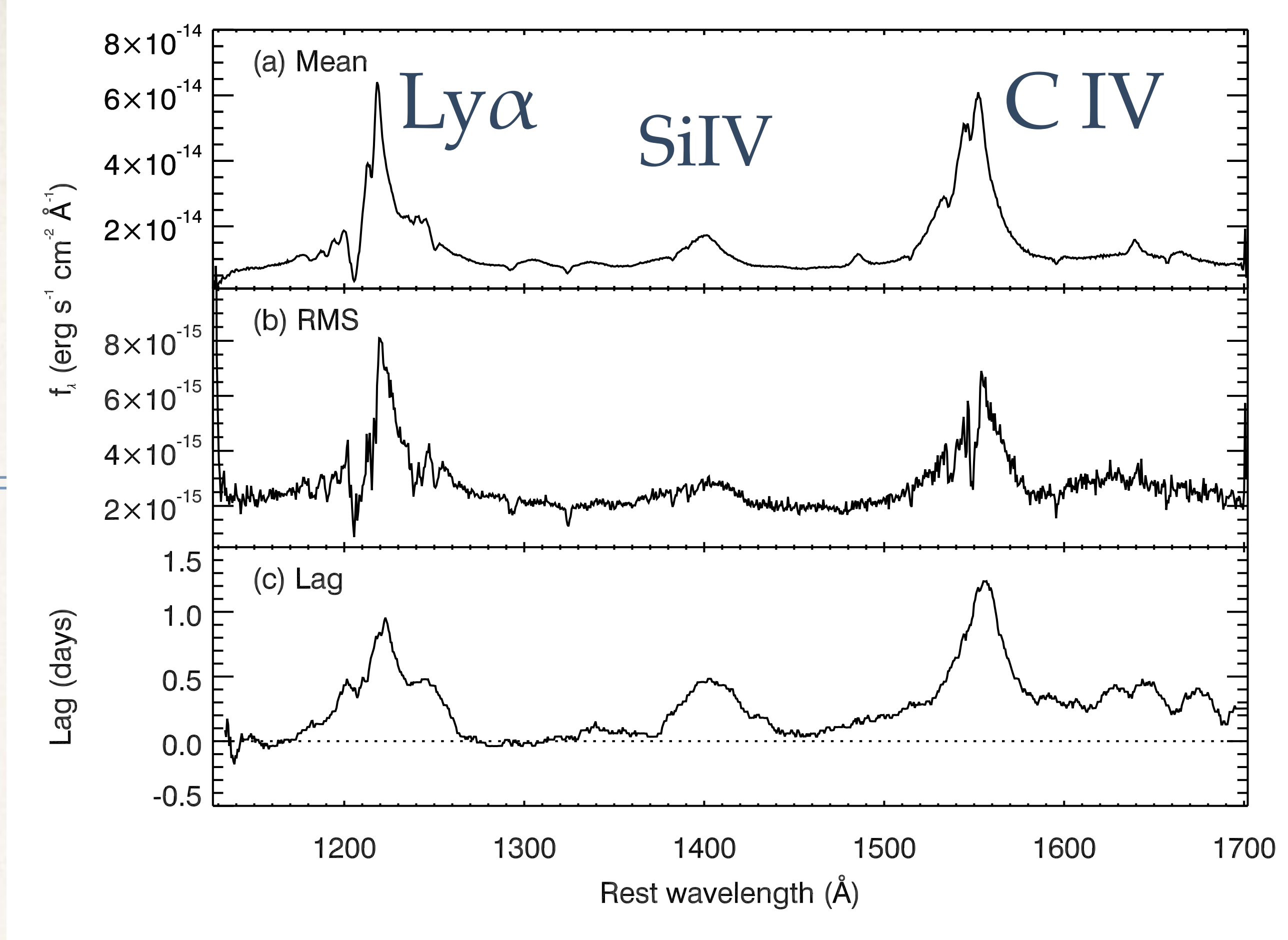
Swift data: McHardy et al., in prep
HST data: Cackett et al., in prep

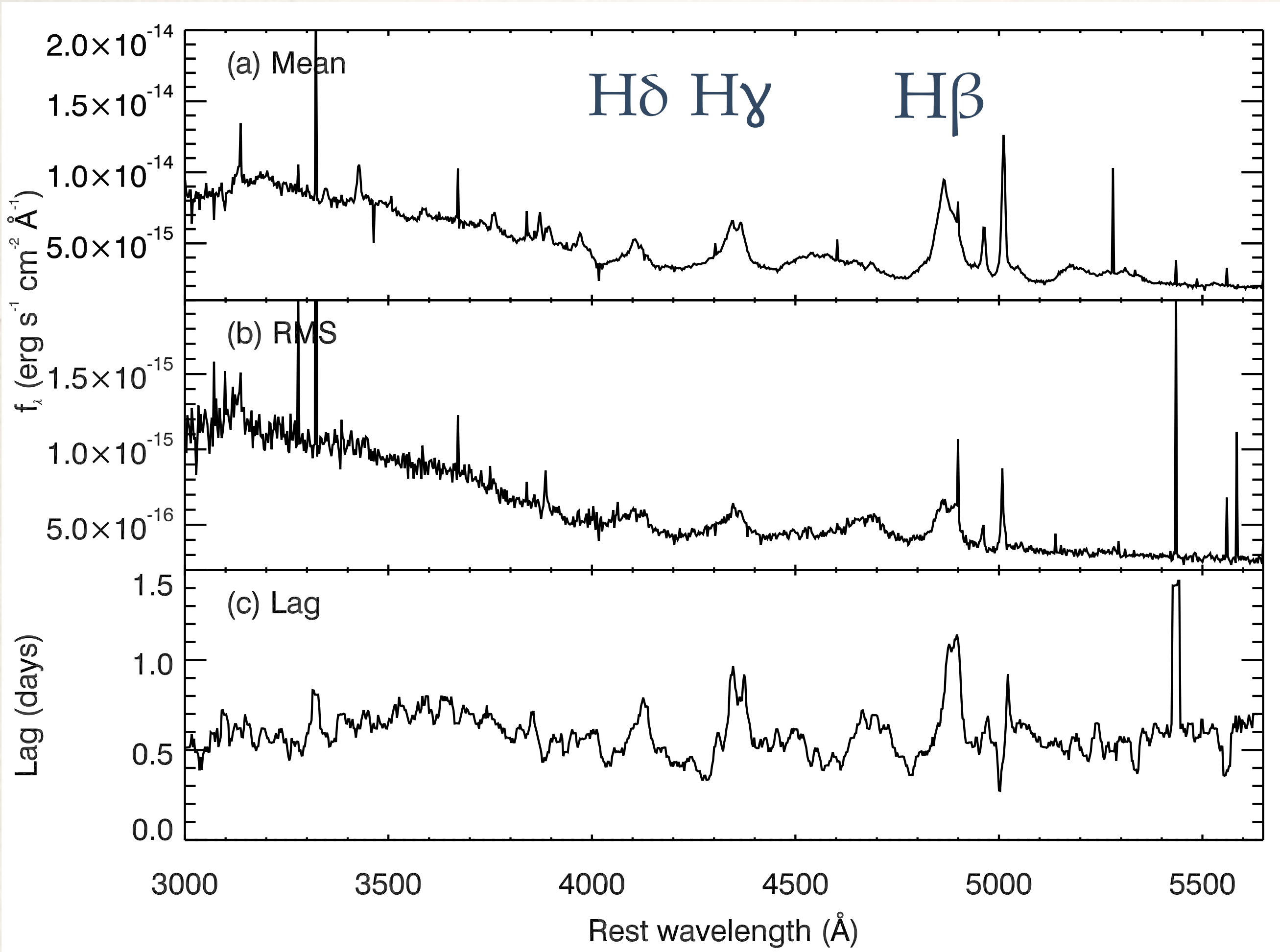


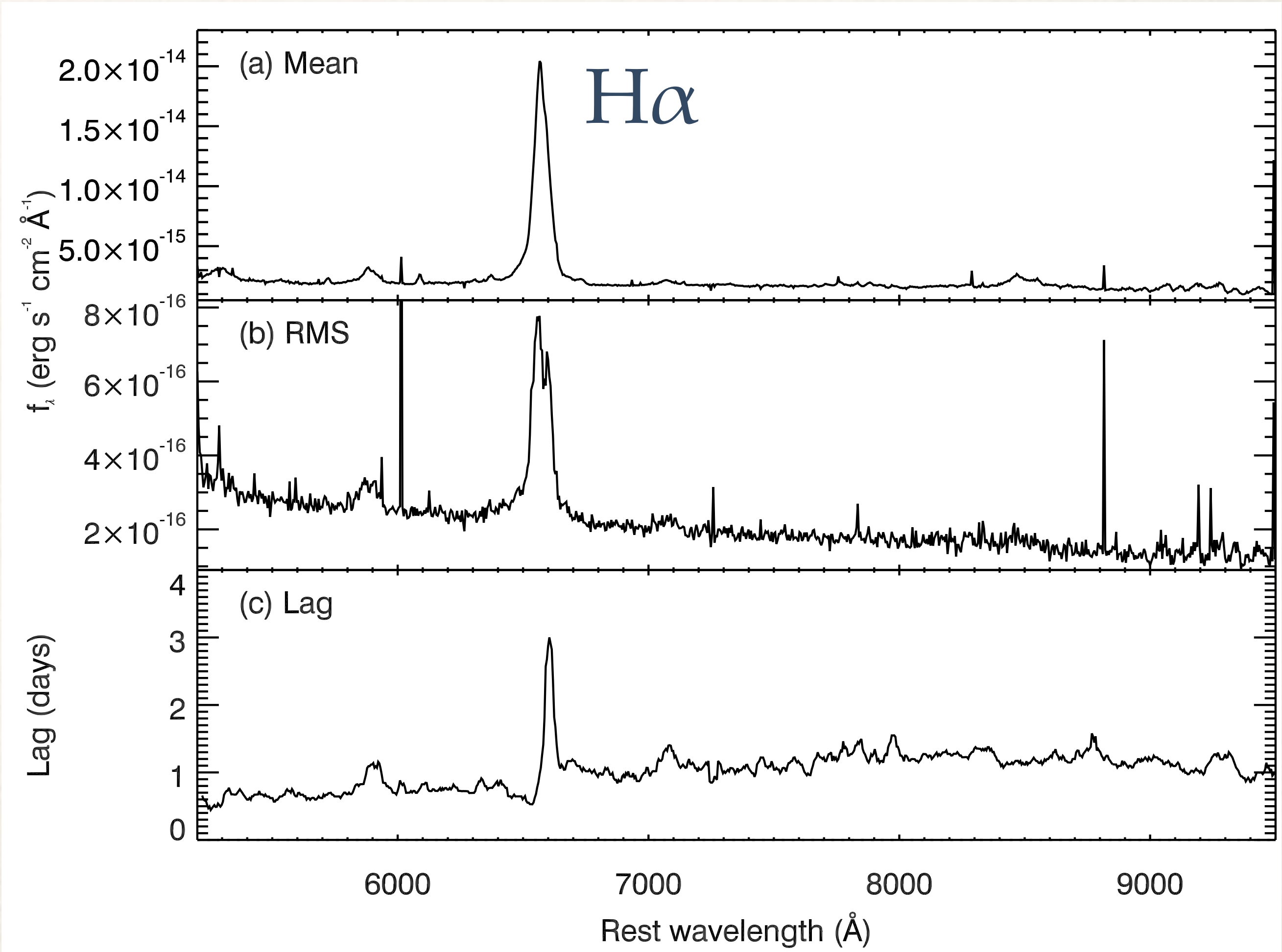
- Strong feature at Balmer jump
- X-rays are consistent with being the driving lightcurve

Mean, RMS and Lag spectra

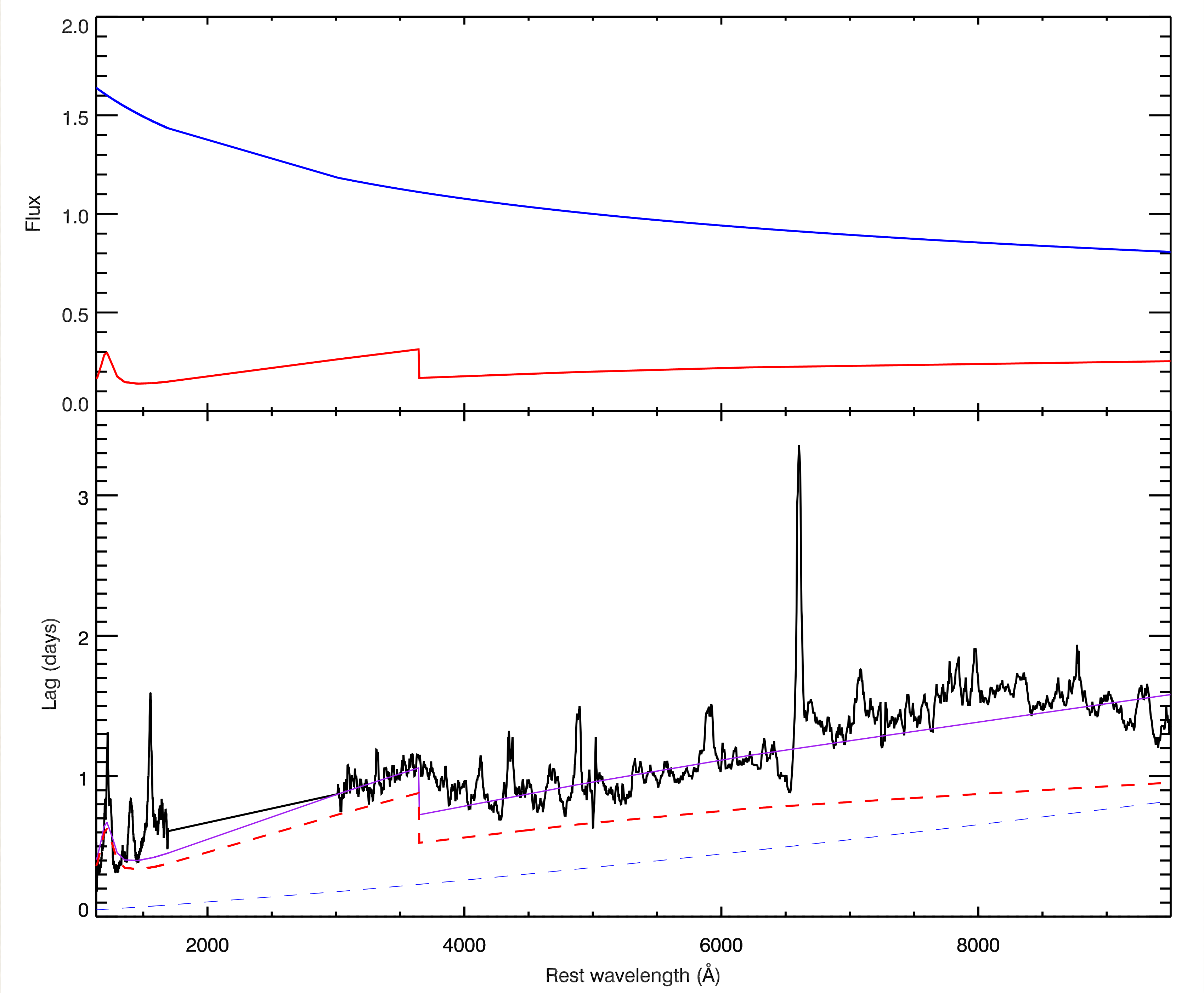
- Calculate lags using ICCF, and sliding box to get a ‘lag spectrum’







Significant Balmer continuum contribution to lags



Disk flux

BLR diffuse continuum flux

Model from Korista & Goad (2001)

Overall lags

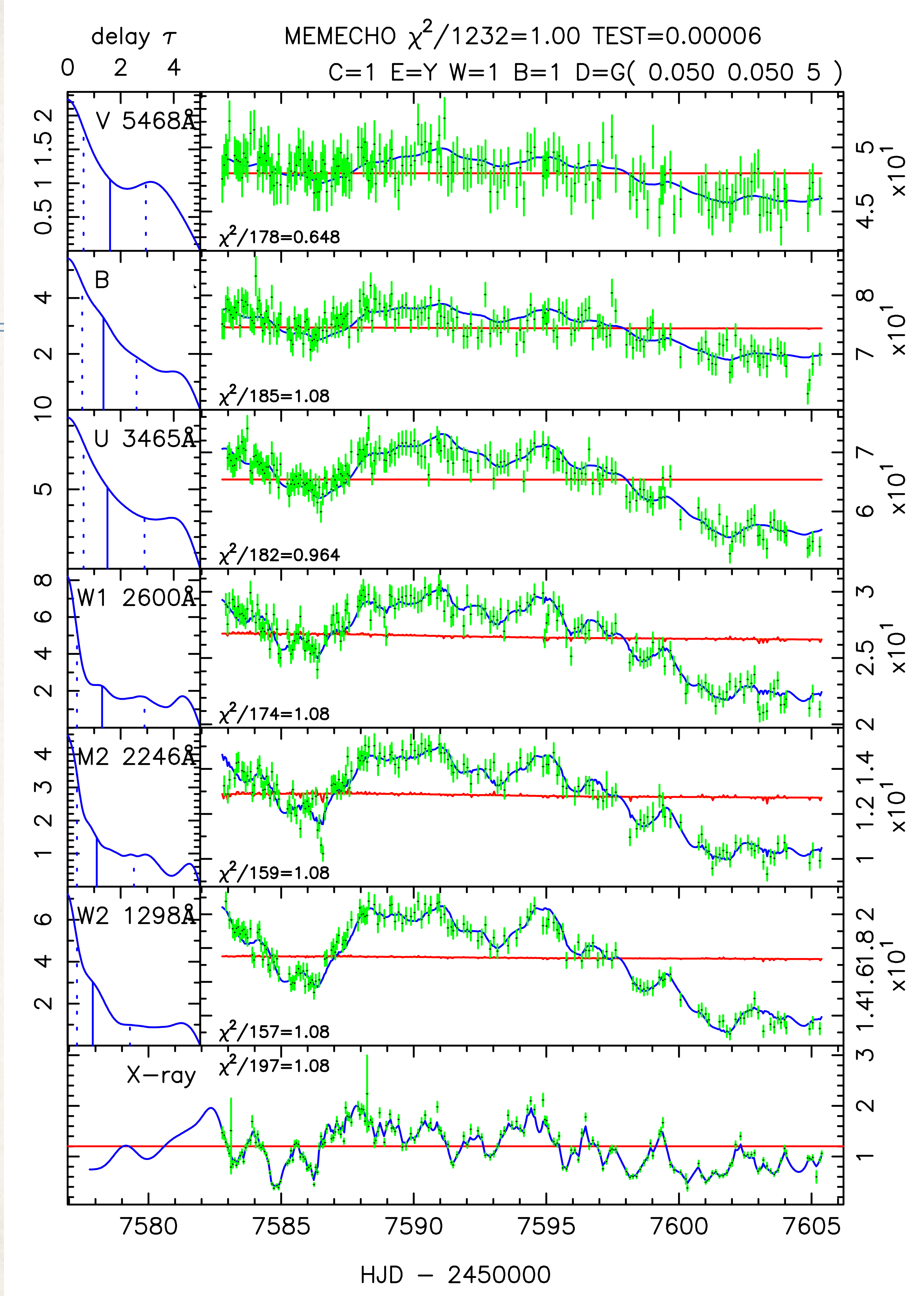
BLR continuum lags

Disk lags

X-rays work as driving lightcurve in NGC 4593

- MEMECHO fits to NGC 4593 from Keith Horne
- Several examples where X-rays **do** look like the driving lightcurve, e.g.:

  NGC 2617 (Shappee et al. 2014)
  NGC 6814 (Troyer et al. 2016)
- NGC 5548 and NGC 4151 may be the exception rather than the rule

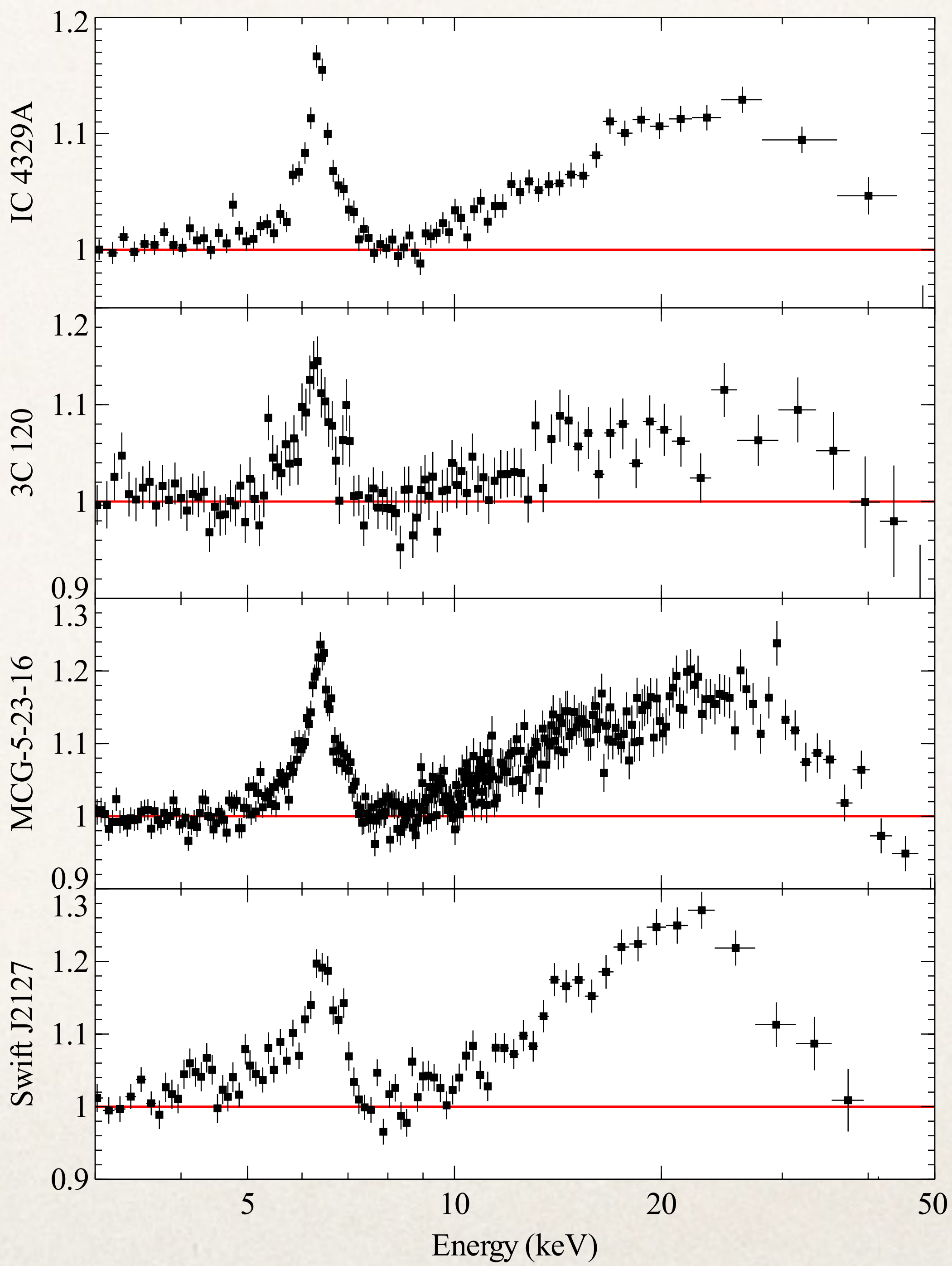


X-ray reverberation mapping

- UV/optical continuum reverberation probes size-scales of light-hours - light-days
  - 1 light-day ~ 1750 R_g for a 10^7 $M_\odot$ BH [Note: 1 R_g = 1 GM/c^2]
- X-ray reverberation probes size-scales of light-minutes
  - 1 light-minute ~ 1 R_g for a 10^7 $M_\odot$ BH
- X-ray reverberation can get within a few gravitational radii of the BH!
- Huge progress in last ~5 years - see review of Uttley, Cackett et al. (2014)

Broad Fe Kα line

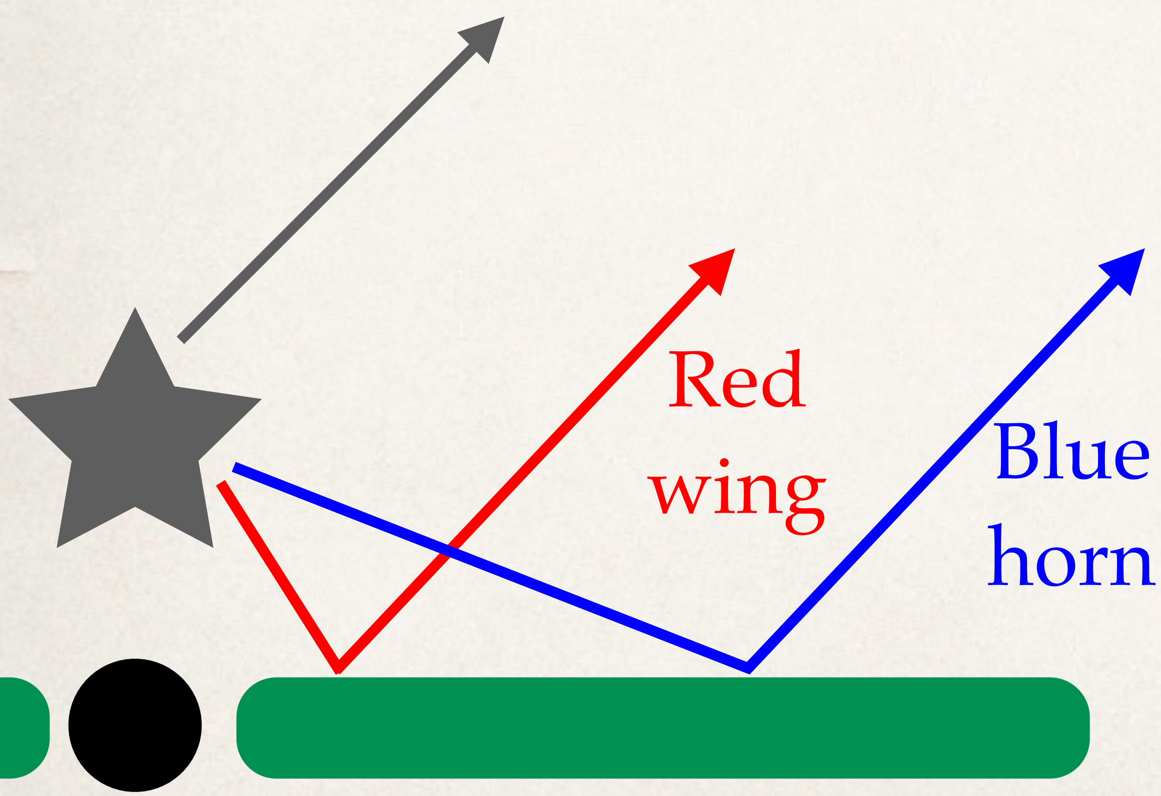
- Broad Fe Kα line prominent in X-ray spectrum of most type I AGN (e.g. Nandra et al. 2007) caused by irradiation of disk by corona ('reflection')
- Relativistically-broadened line and associated reflection continuum seen especially clearly with NuSTAR (e.g. Risaliti et al. 2013)
- If there is reflection - there should be reverberation

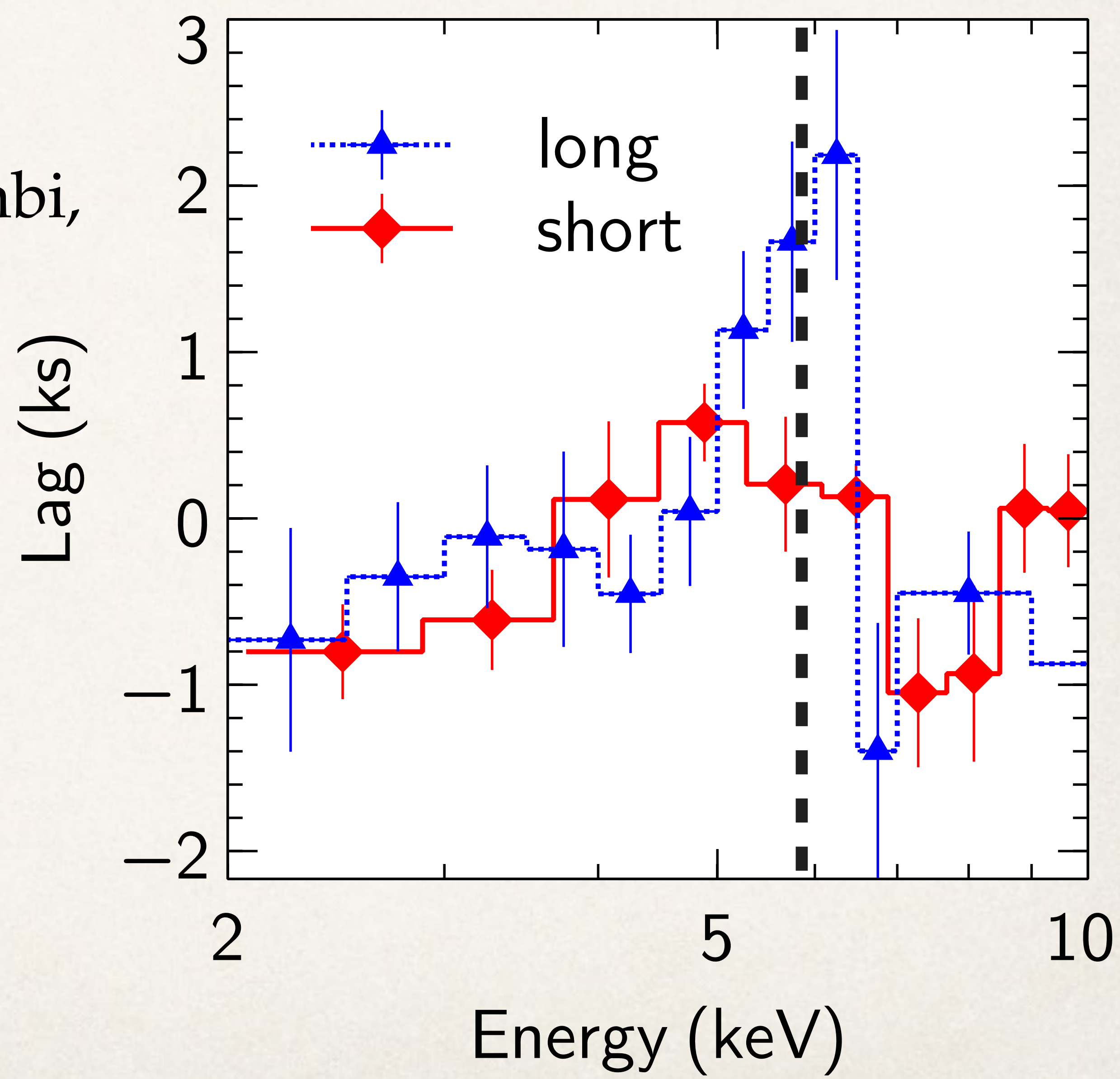


NuSTAR observations of AGN from Fabian et al. (2014)

Fe Kα X-ray reverberation

- Continuum reverberation first seen (Fabian et al. 2009)
- First Fe K lag seen in NGC 4151 (Zoghbi, Fabian, Reynolds & Cackett 2012)



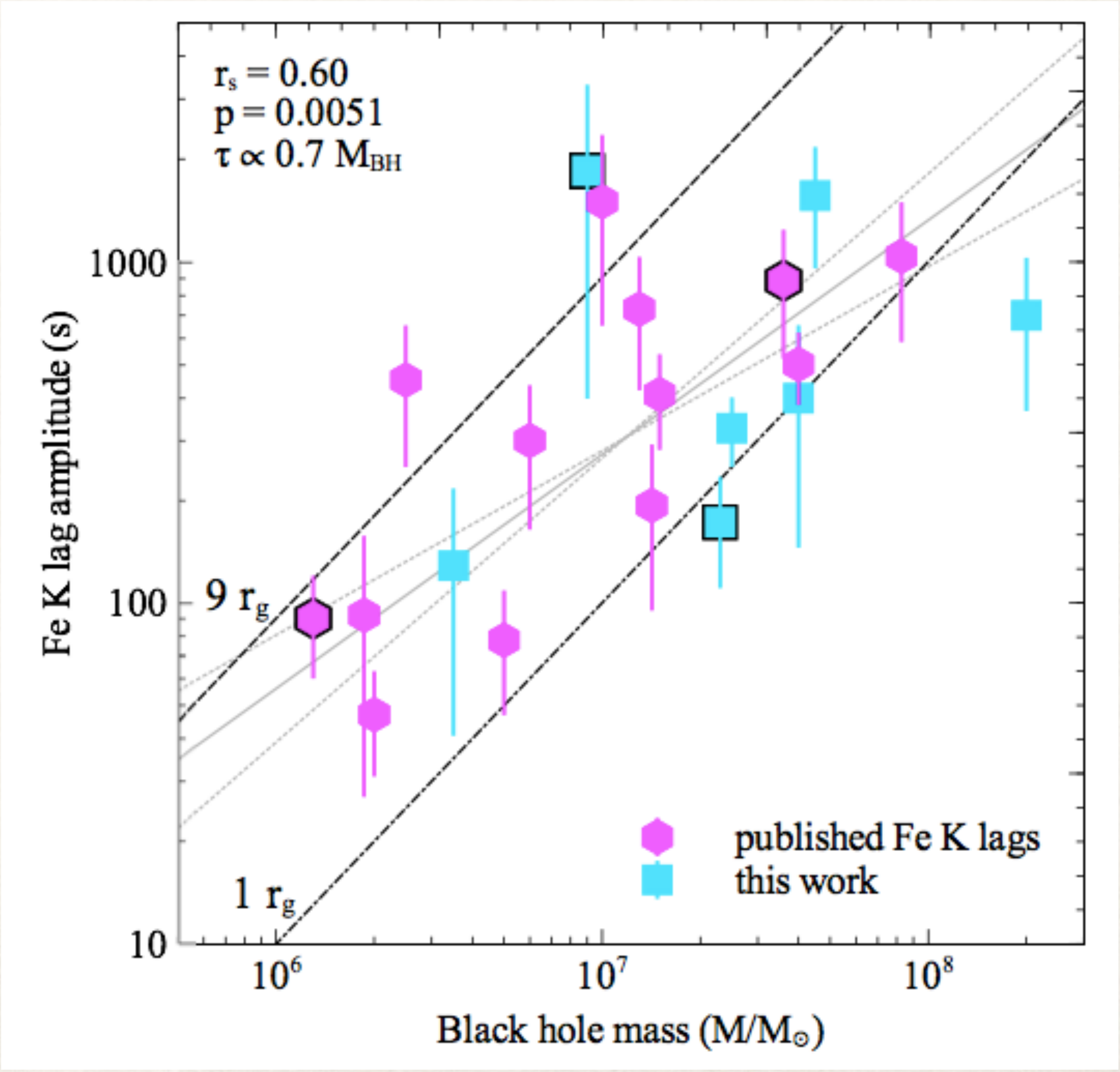


Fe Kα X-ray reverberation

- Significant Fe K lags seen in about 50% of variable type I AGN (20/43) with long enough exposures in the XMM archive (Kara et al. 2016)

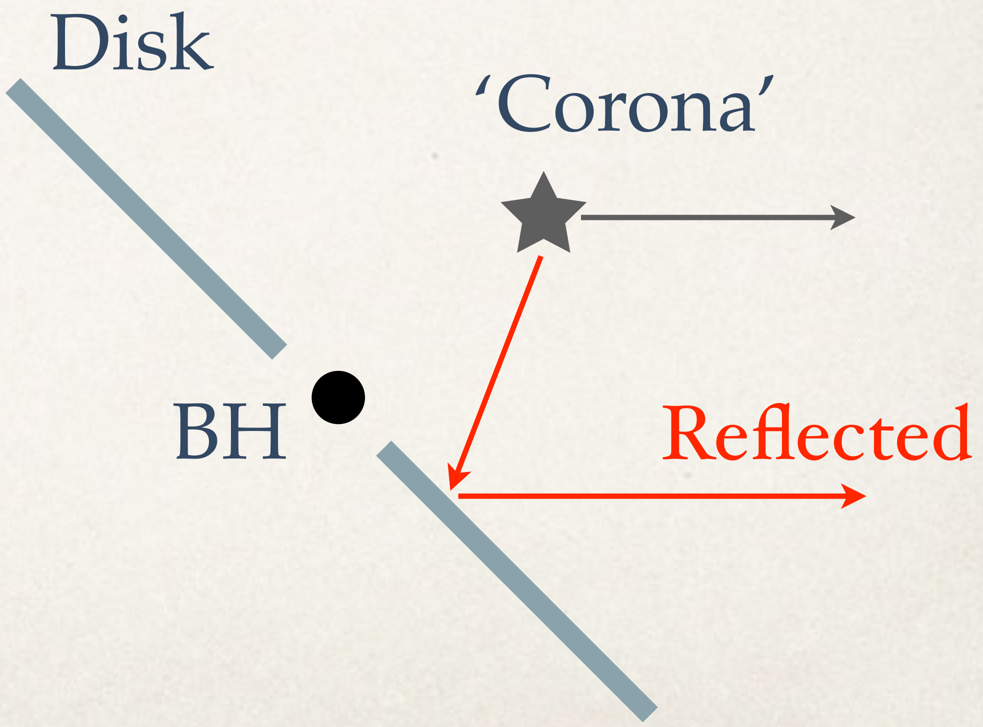
- Lags scale with BH mass

- Lags indicate small corona



Relativistic velocity-delay maps

- Can construct velocity delay maps for relativistic reflection off a disk (e.g. Reynolds et al. 1999, Cackett et al. 2014)
- Assume a simple lamp-post geometry



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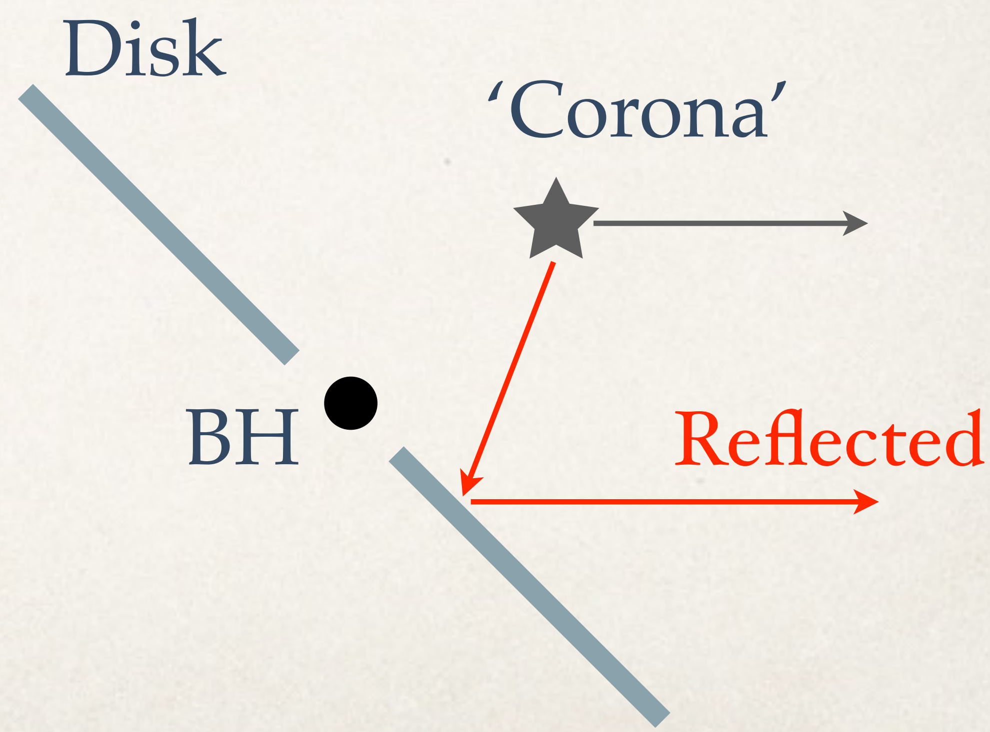
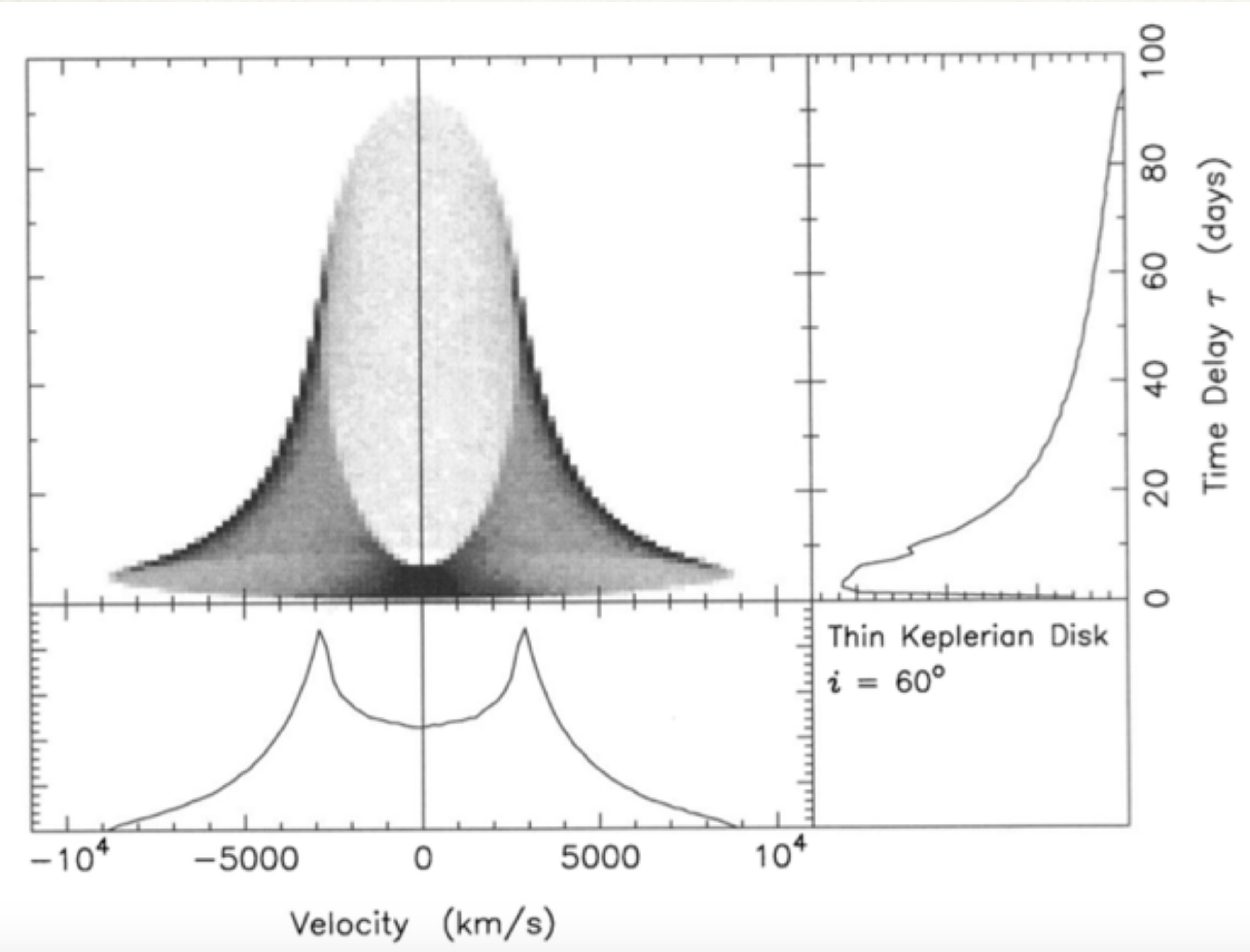


Time-resolved Fe K emission from a disk



Thin Keplerian disk from Welsh & Horne (1991)

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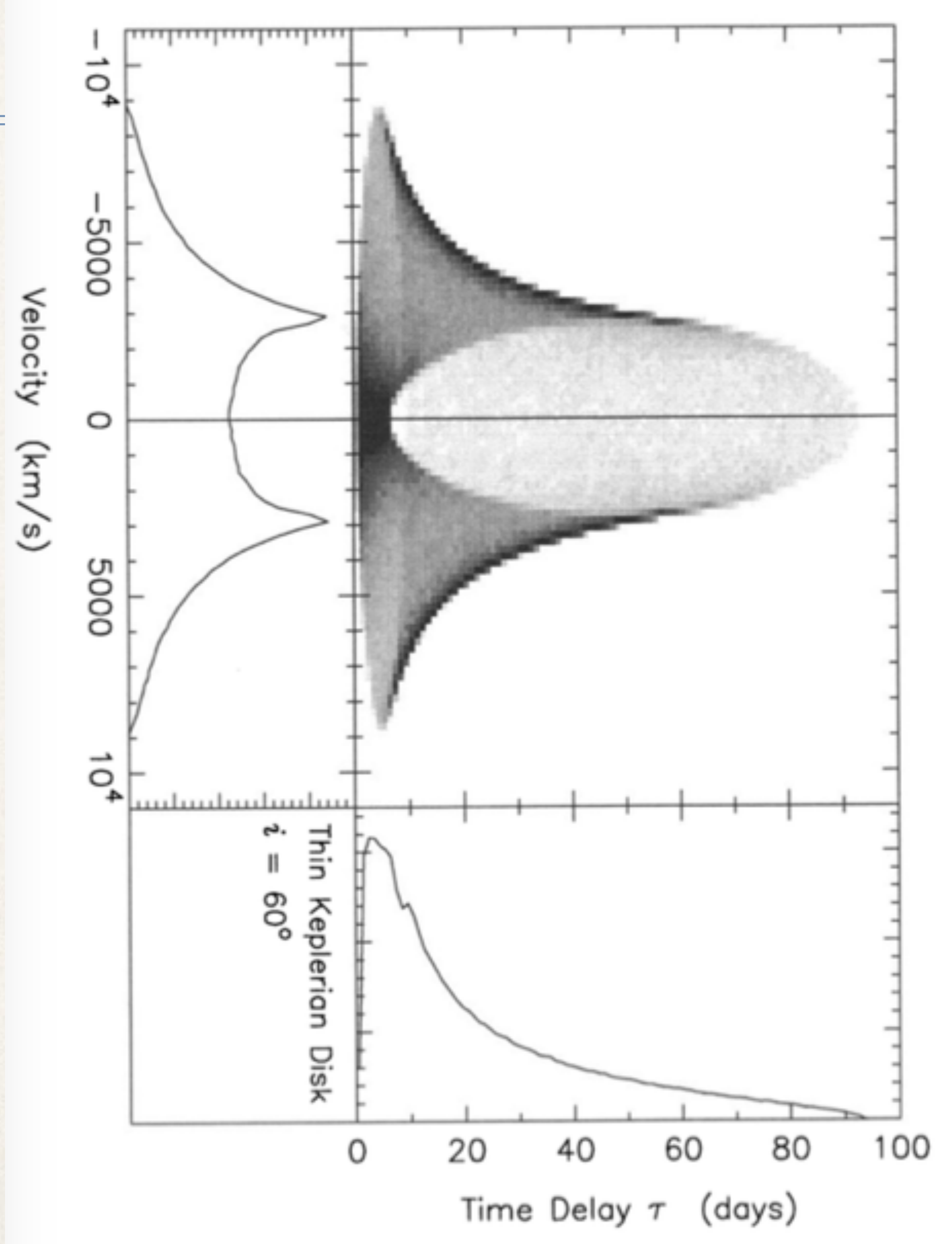

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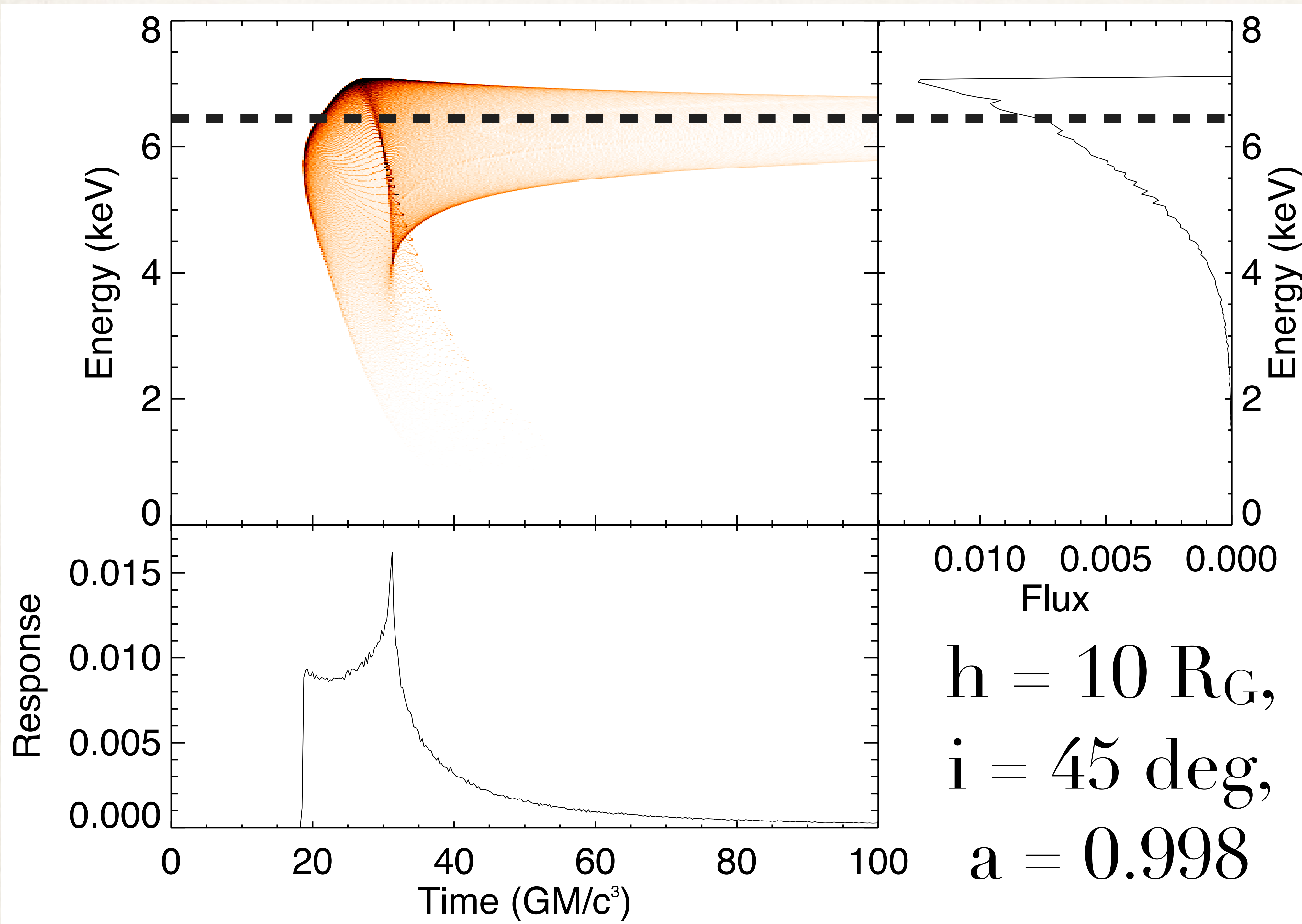
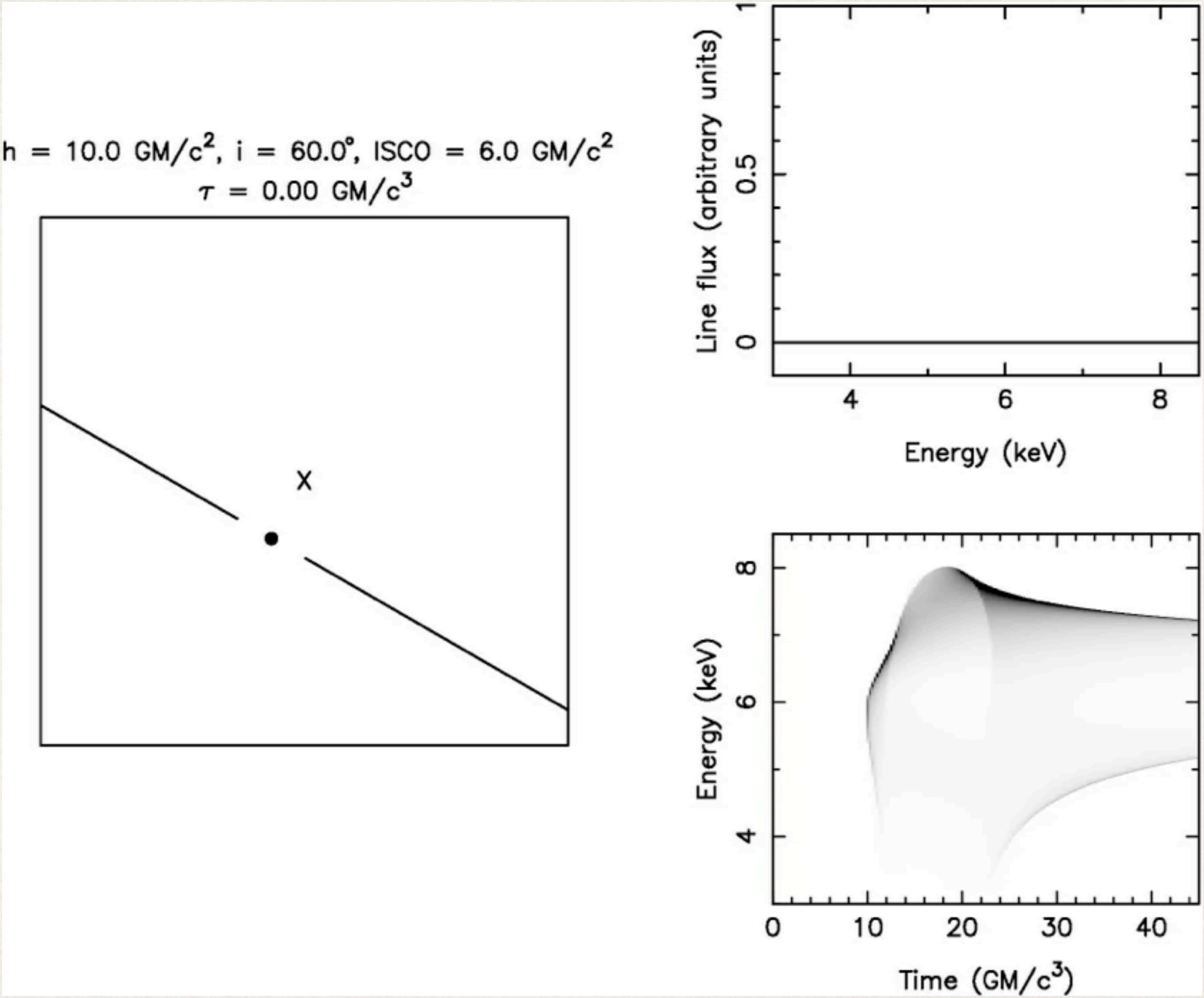
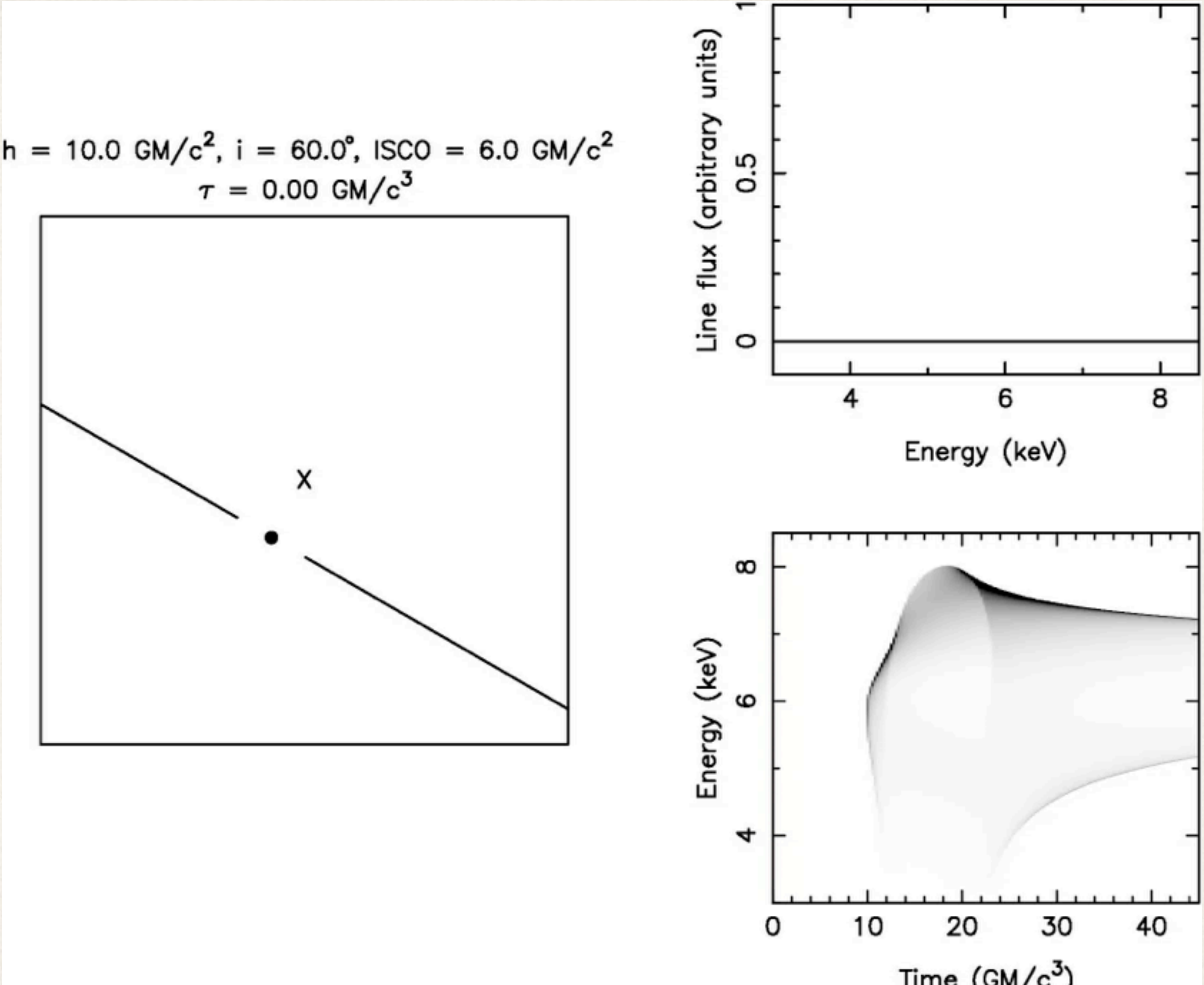


Cackett et al. (2014) after Reynolds et al. (1999)



h = 10.0 GM/c², i = 60.0°, ISCO = 6.0 GM/c²
τ = 0.00 GM/c³
X
Line flux (arbitrary units)
0
0.5
1
4
6
8
Energy (keV)
Energy (keV)
4
6
8
0
10
20
30
40
Time (GM/c³)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Energy (keV)
Energy (keV)
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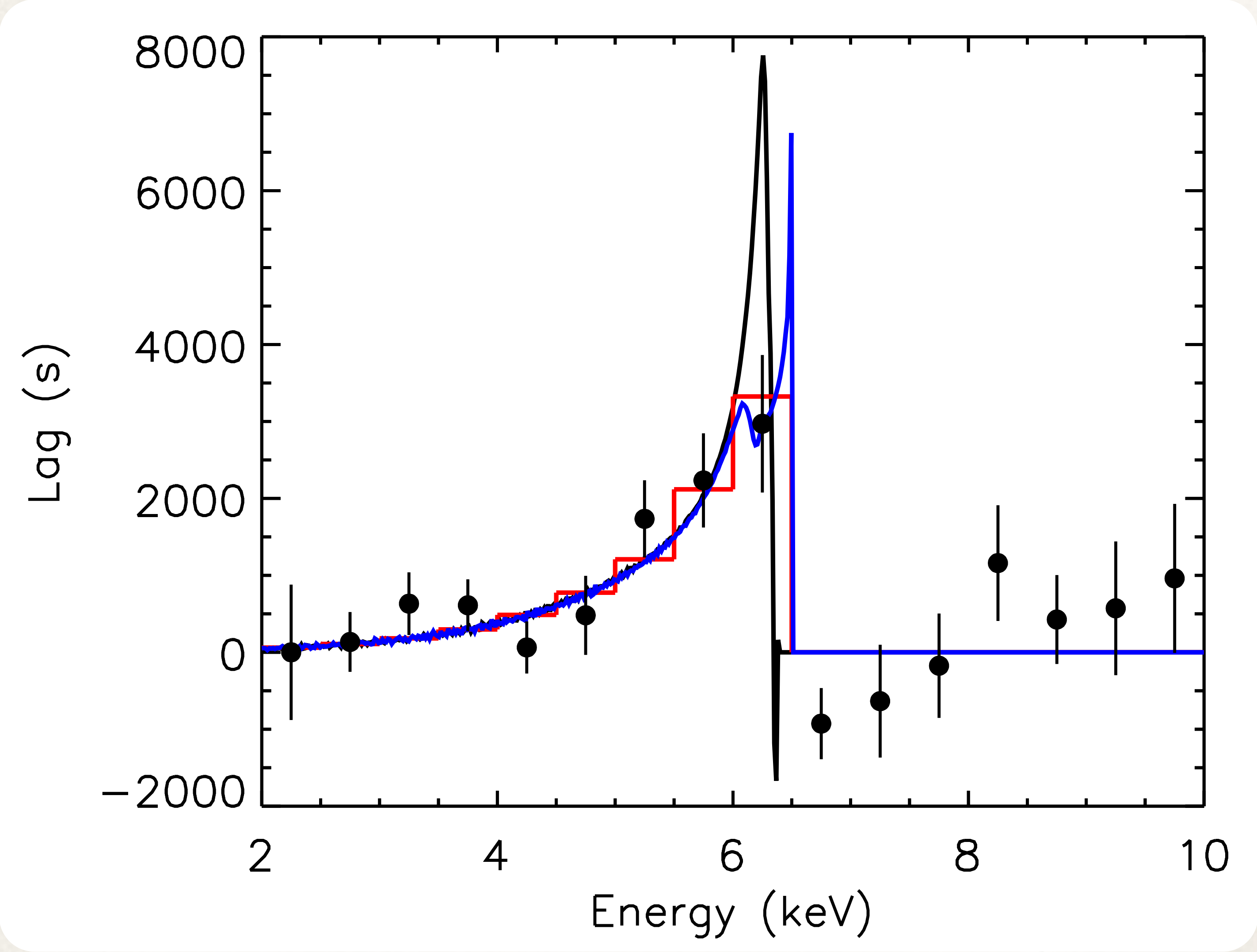
8
0
10
20
30
40
Time (GM/c³)

Fitting NGC 4151 Fe K lag

- We assume optical reverberation mapping mass, $M = 4.6 \times 10^7\ M_\odot$
- Best-fit: X-ray source at height $7 \pm 3\ GM/c^2$ above the black hole
- Low inclination required by zero lag above 6.5 keV



i = 5 deg

i = 20 deg

Cackett et al 2014

Summary

- Accretion disk reverberation mapping using the continuum from X-ray through to near-IR is a powerful way to test accretion disk structure
- IFF we can understand the disks, they have potential to be used as distance indicators, but, currently getting disk sizes a factor of a few out
- NGC 4151: large X-ray to UV lag (3 days), and minimal (<1 day) UV to optical lag
- NGC 4593: clear evidence for significant contribution from BLR diffuse continuum
- X-ray Fe Kα reverberation has potential to understand the size of the corona (appears to be very small)