Continuum Reverberation Variability of AGN

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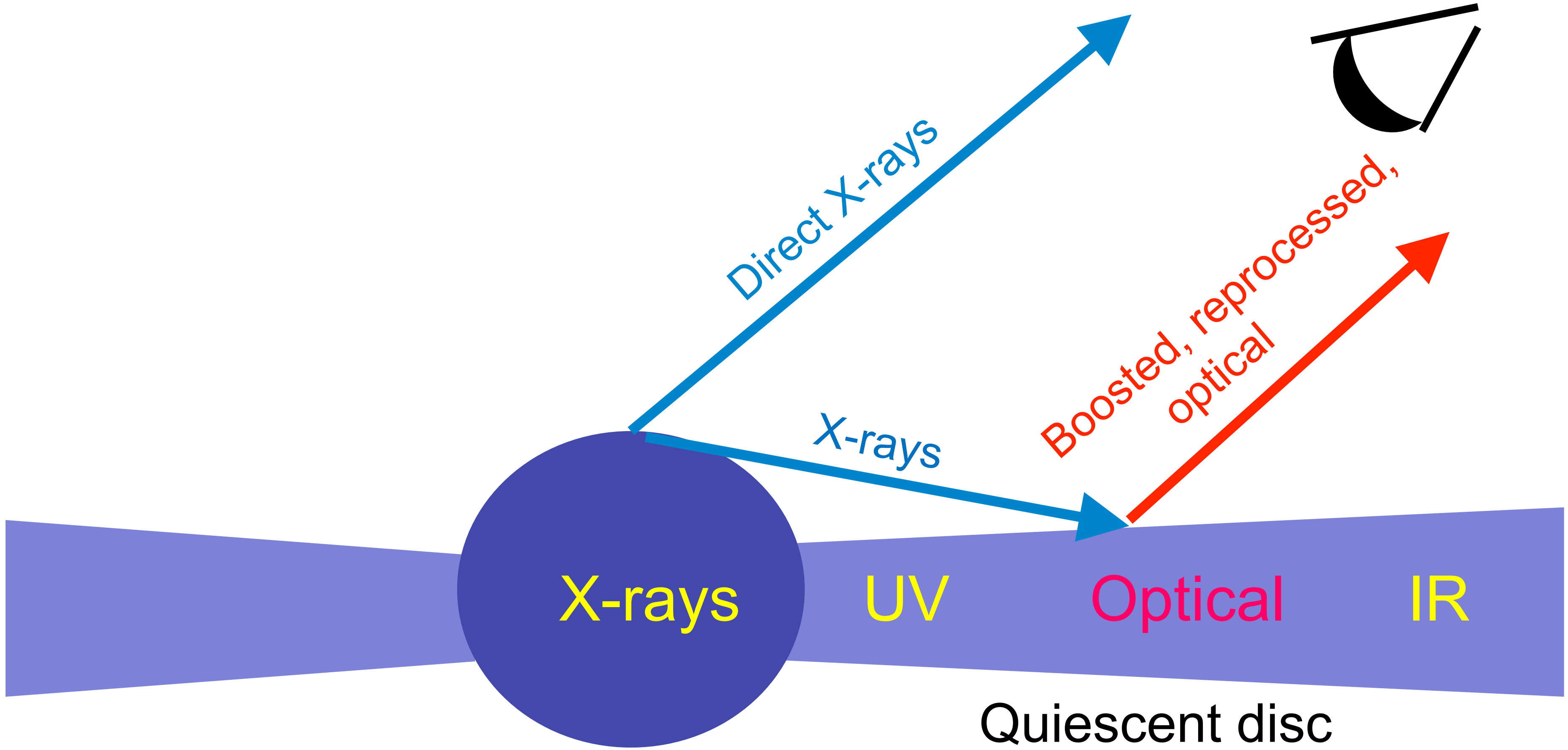
What drives UV / optical variability in AGN?

What can we learn about AGN inner structure by studying X-ray / UV / optical variability?

The Basic Paradigm: Reprocessing of X-rays



Illuminate disc with X-rays
X-rays should lead UV/optical variations
Blue arrives before red

Seed photon variations

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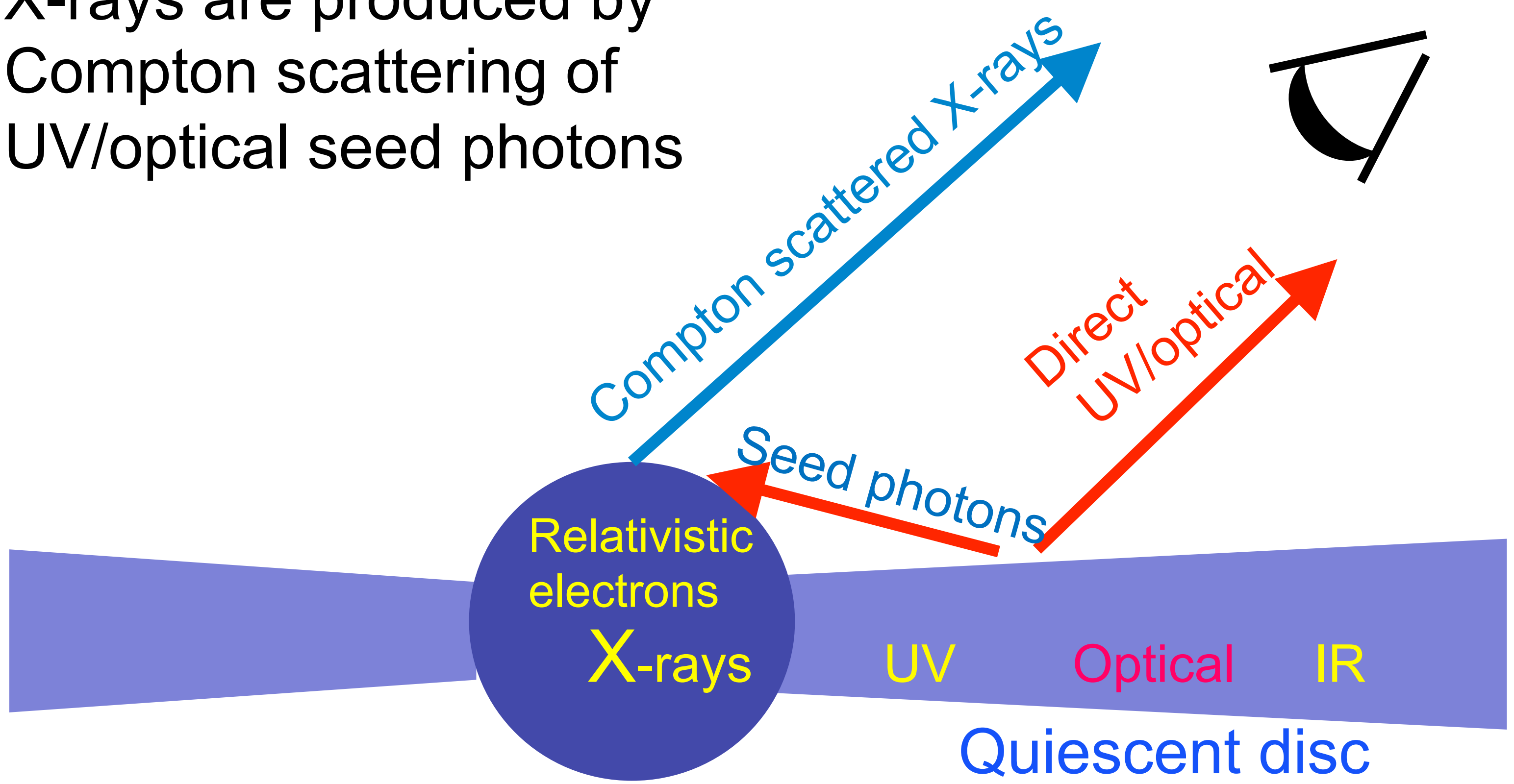
X-rays are produced by Compton scattering of UV/optical seed photons



Vary the UV/optical seed photons from disc.
X-rays should lag behind UV/optical variations

Or UV/optical variations due to variations in ‘quiescent’ disc, eg due to accretion rate variations; very slow, red leads blue

Some questions / topics

1. Can X-ray reprocessing explain all AGN UV and optical variability?

2. Can a disc on its own act as the reprocessor?

3. The timescale-dependence of lags – useful for distinguishing BLR
   - Fourier Cross-Spectra and Power Spectra

4. The imporance of modelling - eg including disc outer radius

5. The effect of absorption

1. Can reprocessing of high energies explain all AGN UV and optical variability?

Reprocessing does a lot

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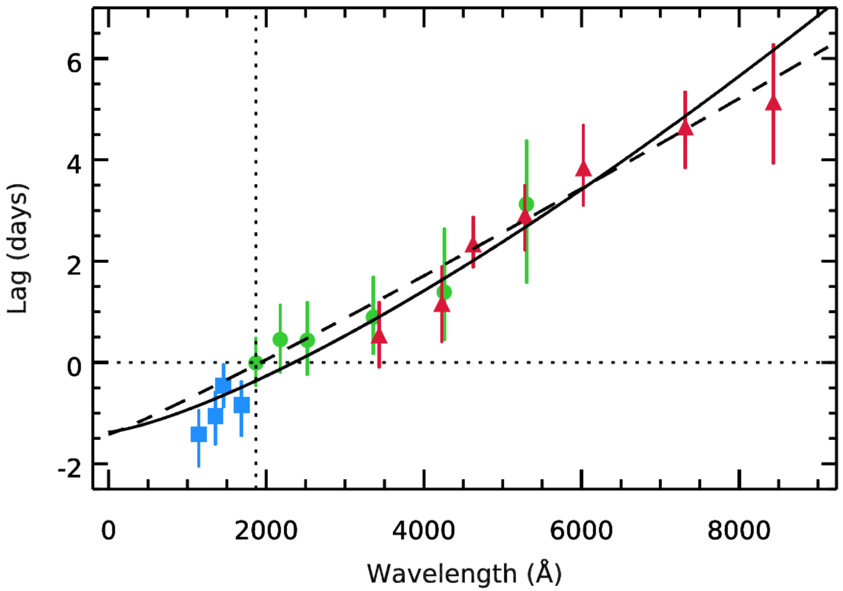
For discs with our ‘standard’ temperature structure (eg Shakura+Sunyaev 73) reprocessing predicts

Lag ~ Wavelength $^{4/3}$ This is commonly seen

(E.g. Shappee+ 2014, Edelson+ 2015, 2017, 2019, McHardy+2014, 2016, 2018, Troyer+ 2016, Cackett+ 2018, 2020,22, Vincentelli+2021,22, Kara+2021 and others – apologies for not mentioning)



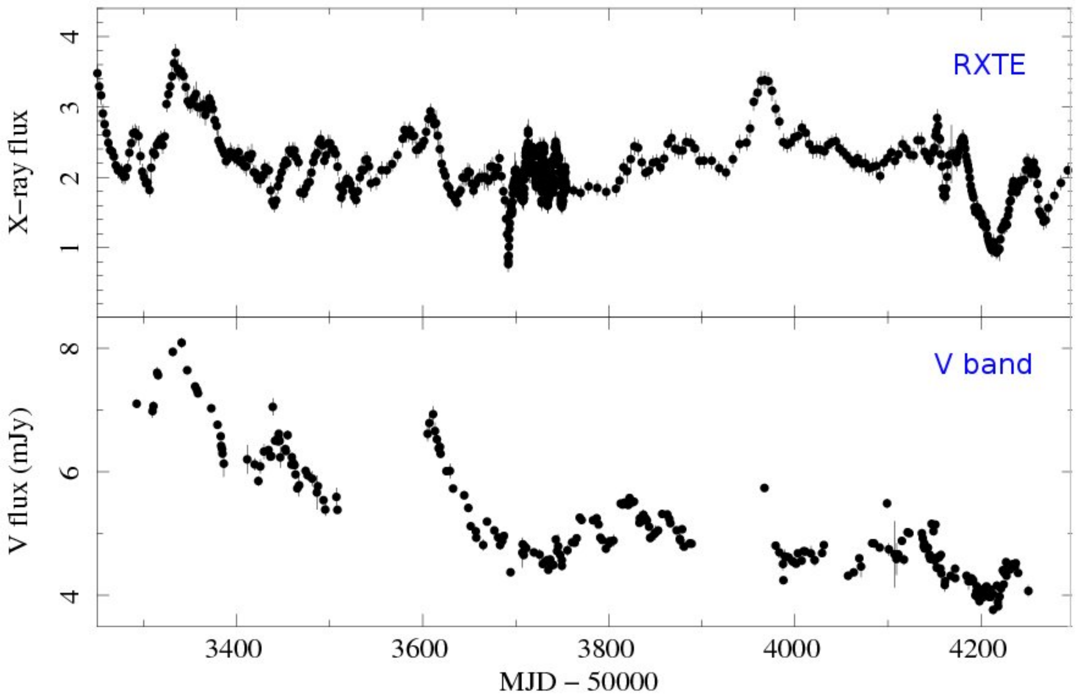
Mrk817,Storm 2, Kara+21

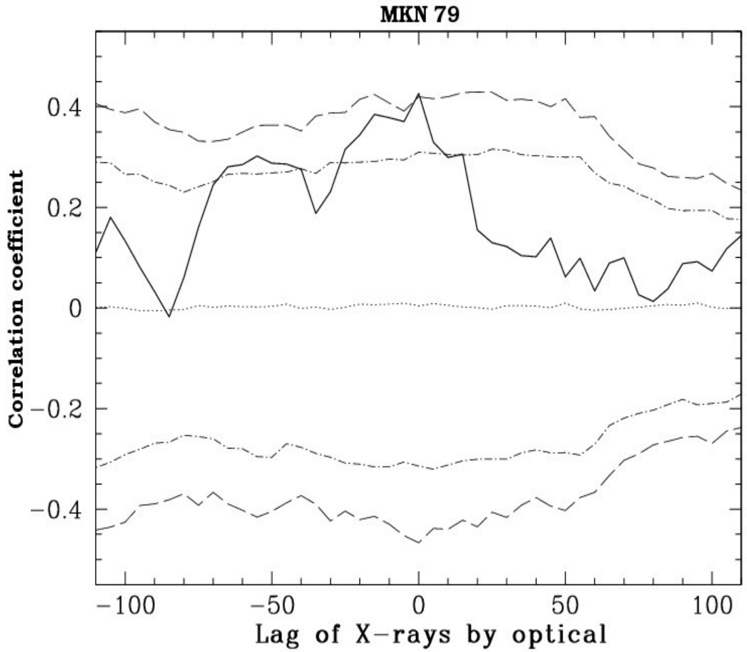
But note the wiggles. More later.

But can reprocessing explain everything?

RXTE / ground-based optical observations

e.g. Mkn 79





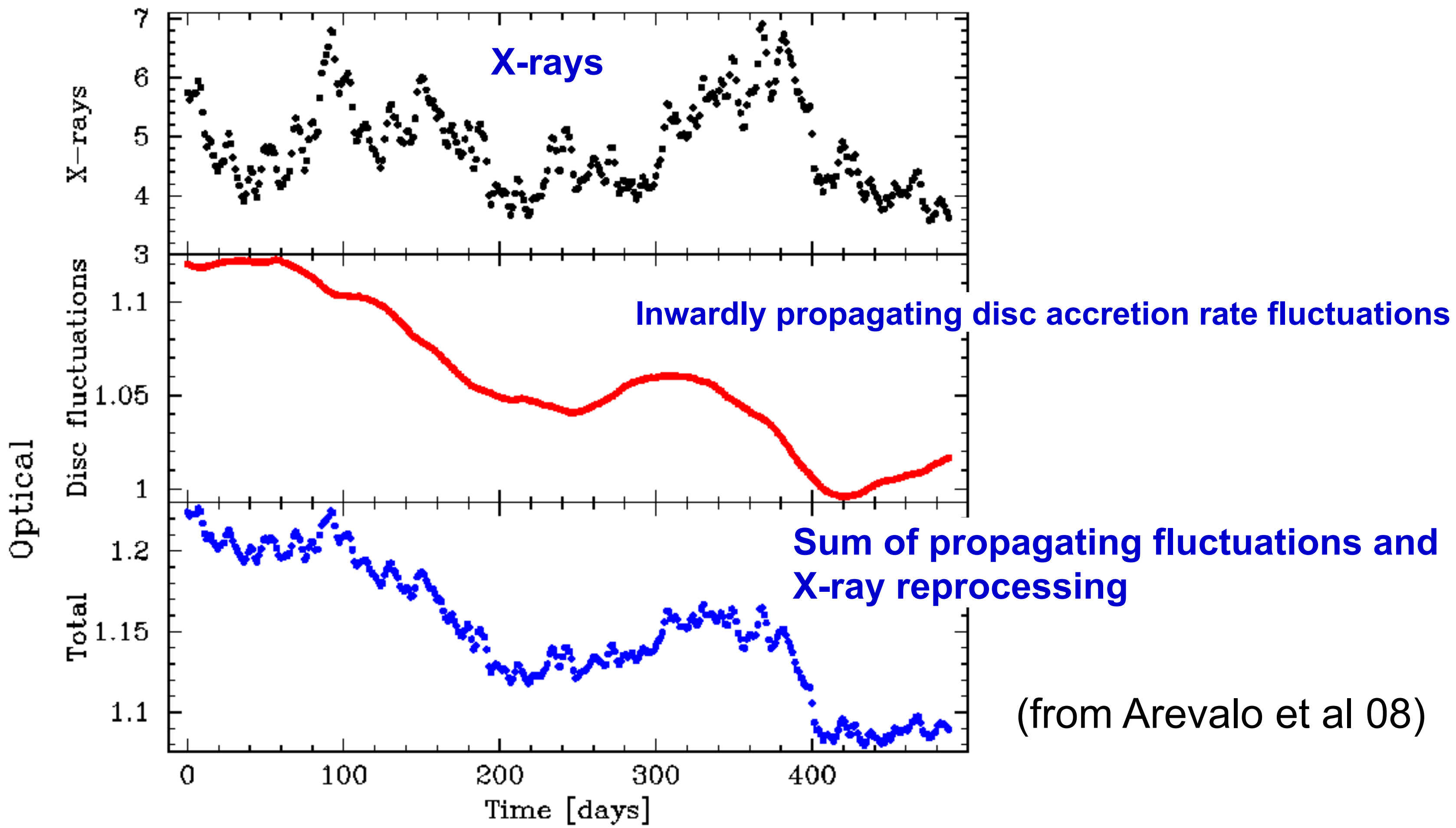
Short term X-ray optical correlation consistent with reprocessing but…

As in all similar RXTE programmes, X-rays lead optical by small amount, ~1d, but with large error (~0.5d)

LONG TERM OPTICAL VARIATIONS NOT SEEN IN X-RAYS – NOT REPROCESSING

(Breedt et al, 2009)

Possible Explanation
Propagating fluctuations plus X-ray reprocessing



(from Arevalo et al 08)

With the availability of long timescale, well sampled, lightcurves, observers are starting to search for long 'red leads blue' lags.
Nothing really convincing so far.

Also hard to explain: UV rise without X-ray counterpart

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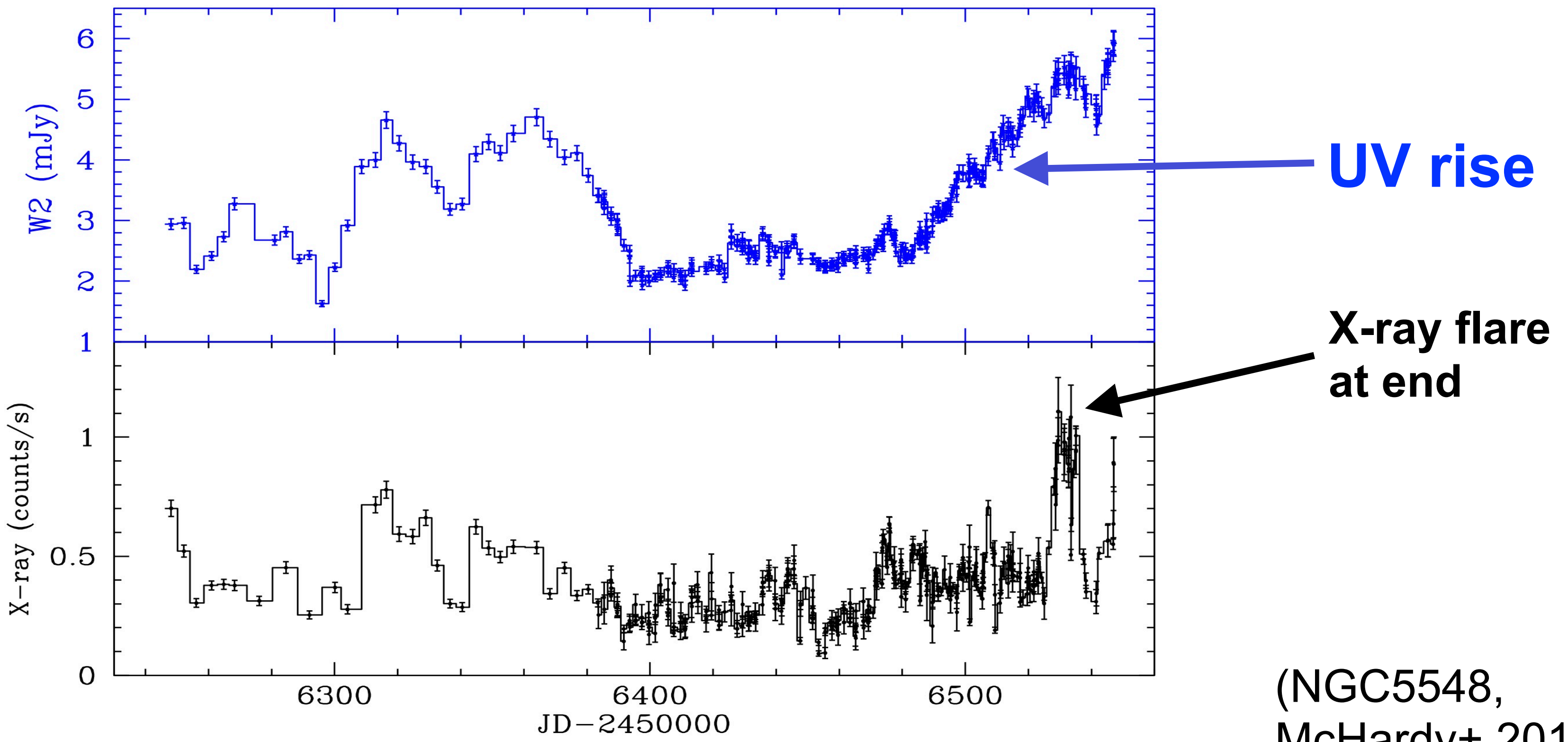

(NGC5548, McHardy+ 2014)

UV possibly affected by increasing accretion rate through disc, eventually dumping energy onto central X-ray emission region.

Observed timescale is short for viscous timescale through disc. Might need to invoke propagation through corona over disc.

Second example: Mrk 335

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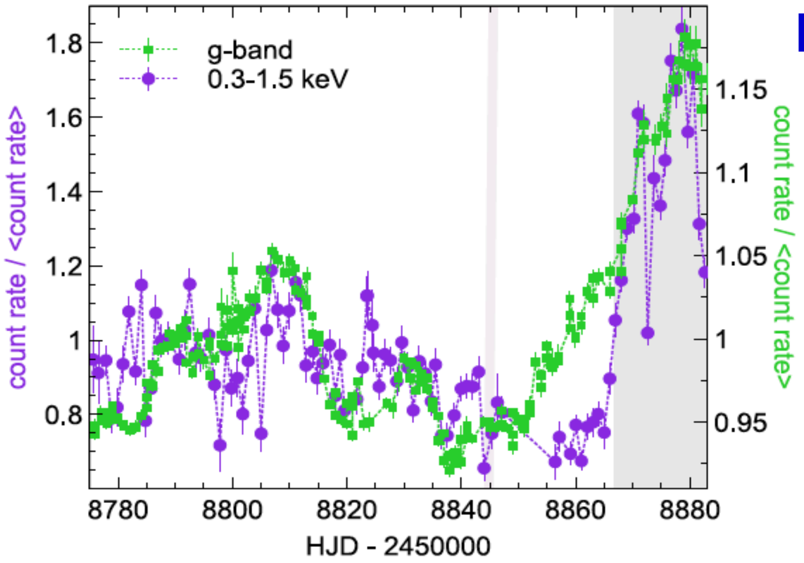
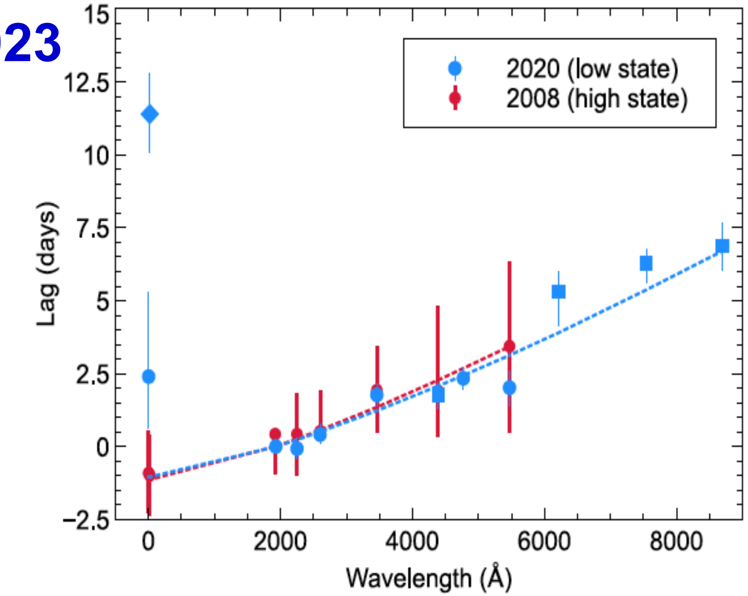
Kara+2023





UV/optical increases at end about 10d before X-rays.
Similar to NGC5548 but faster. However NGC5548 is 3x mass of Mrk335.

Again, timescales are very short for viscous propagation thro disc.

X-ray lag is thus anomalous in un-detrended observations (more later).

2.

There is a reprocessing signature.
Can a disc explain it all?

Well known problems with reprocessing from only a disc

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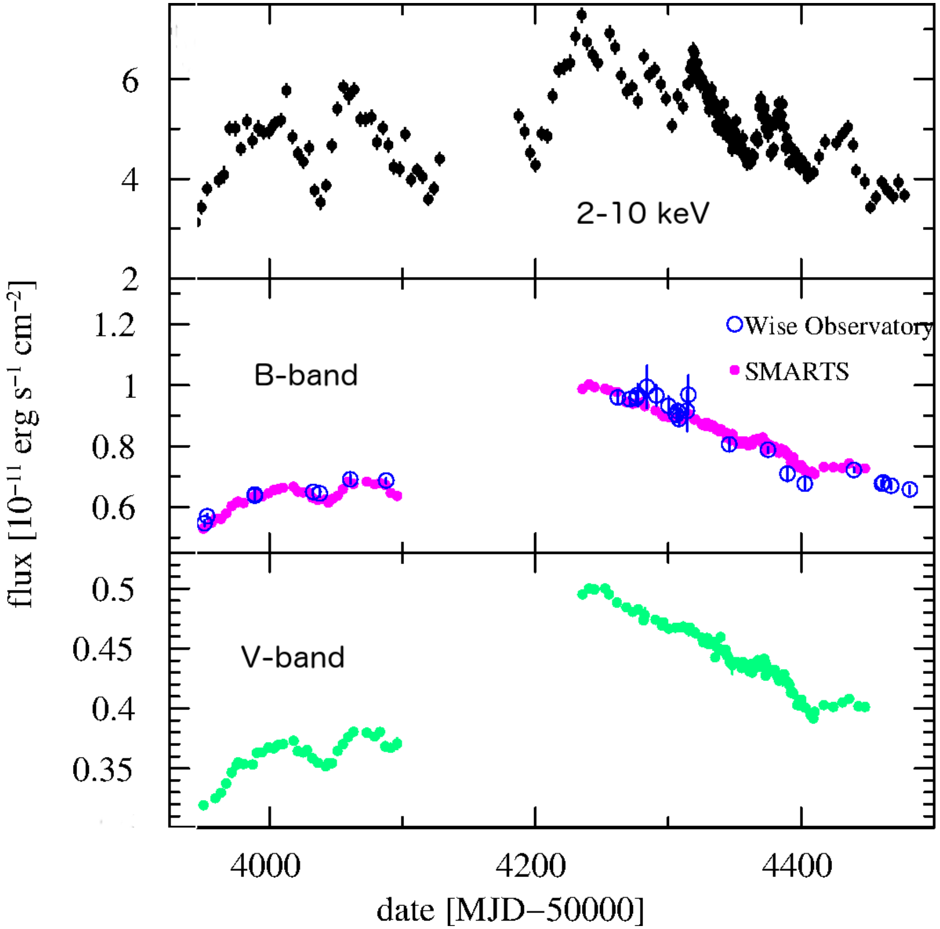
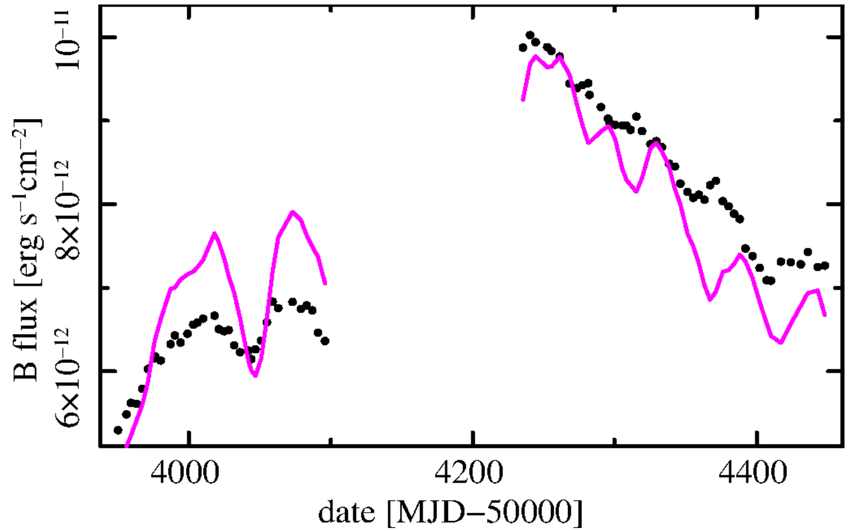
MR2251-178
Arevalo et al 2008



1. Observed B-band lc (black dots) is smoother than model lc (purple)

Kasanas+Nayakshin 2001; Arevalo et al 2008, 2009
Gardner+Done 2017; Kammoun+ 2019



Need illuminating source scale height ~100 Rg for adequate DISC illumination – much larger than measured for X-ray corona
(eg Emmanoulopoulos et al 2014; Cackett et al 2014)

Or need bigger emitter, eg inflated inner disc (Gardner and Done 2017)

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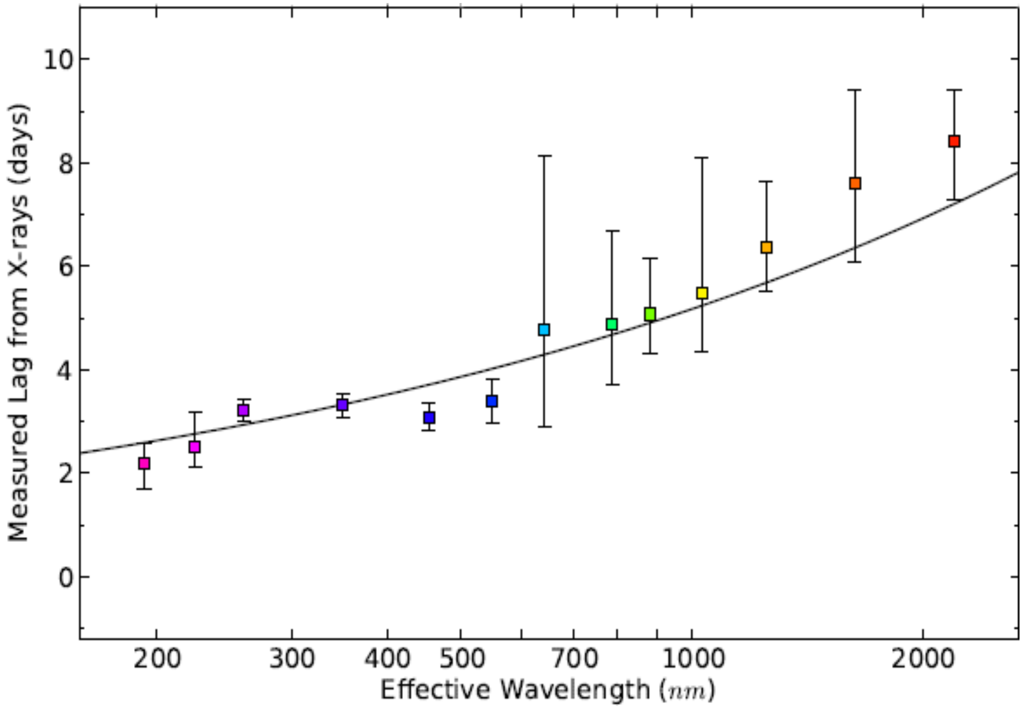
Problem 2: The X-ray excess lag



NGC2617 – Shappee et al 2014

Reasonable fit to disc reprocessing in the uv/optical bands

but fit to UV-optical lags does not go through X-ray zero point.

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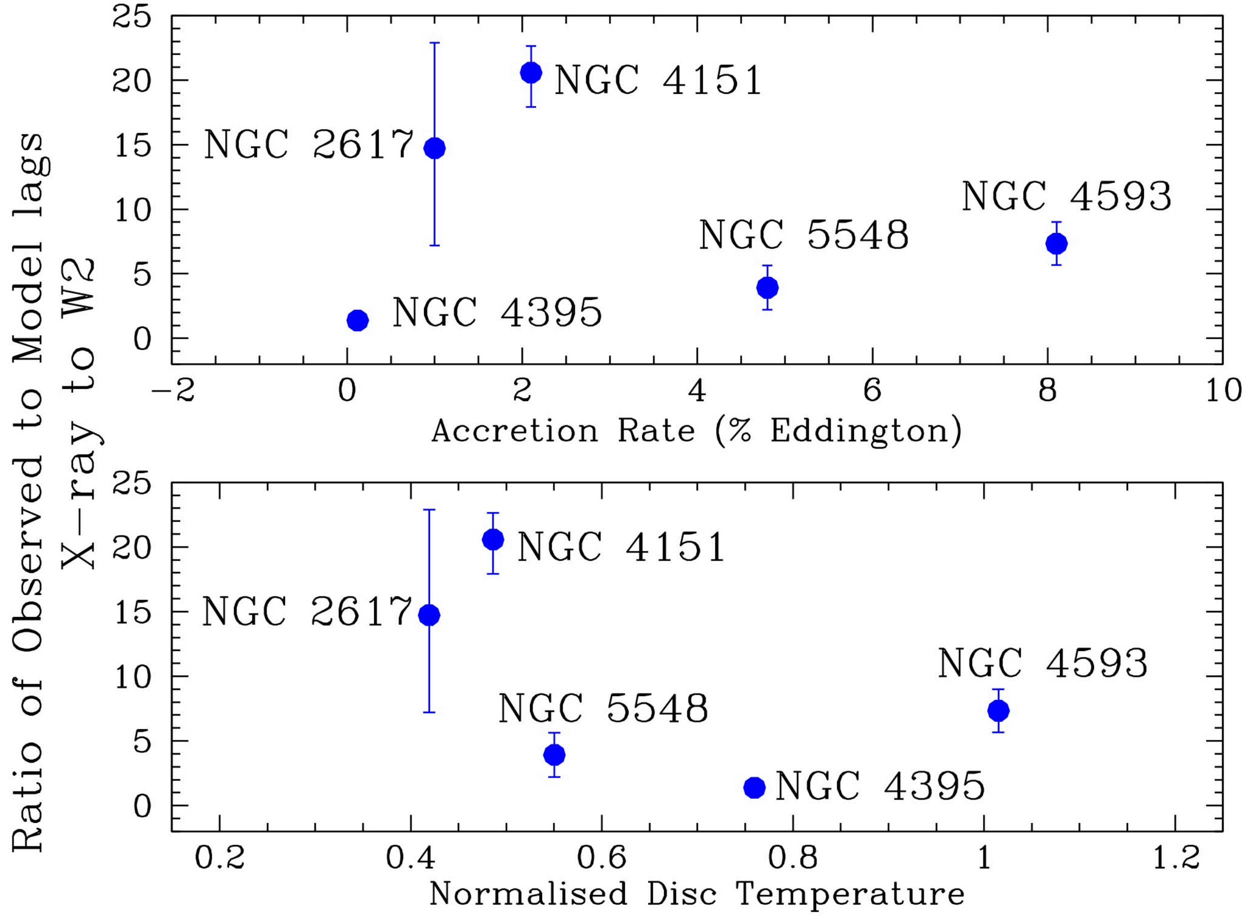
Measured X-ray to UVW2 lags compared to disc model predictions

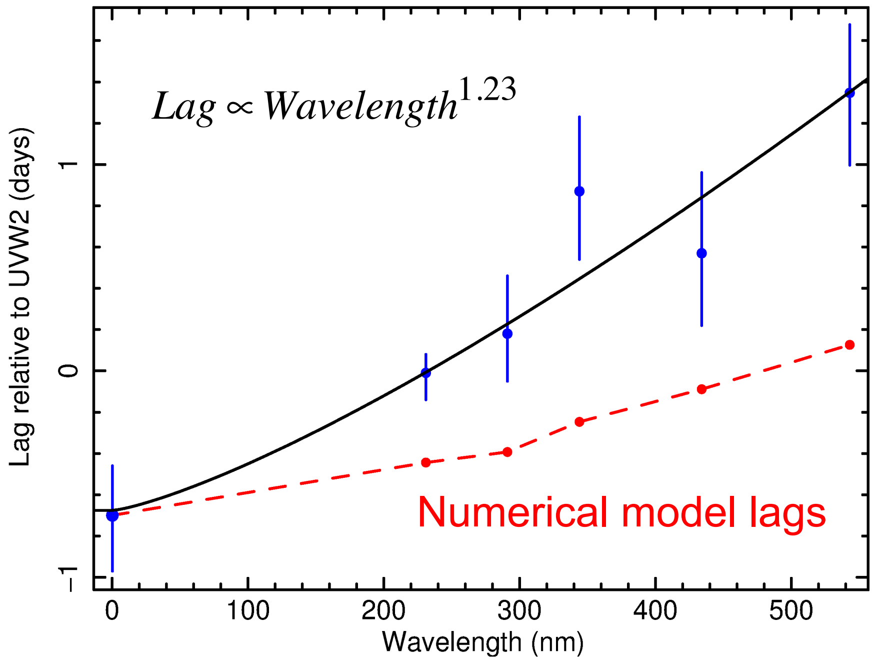


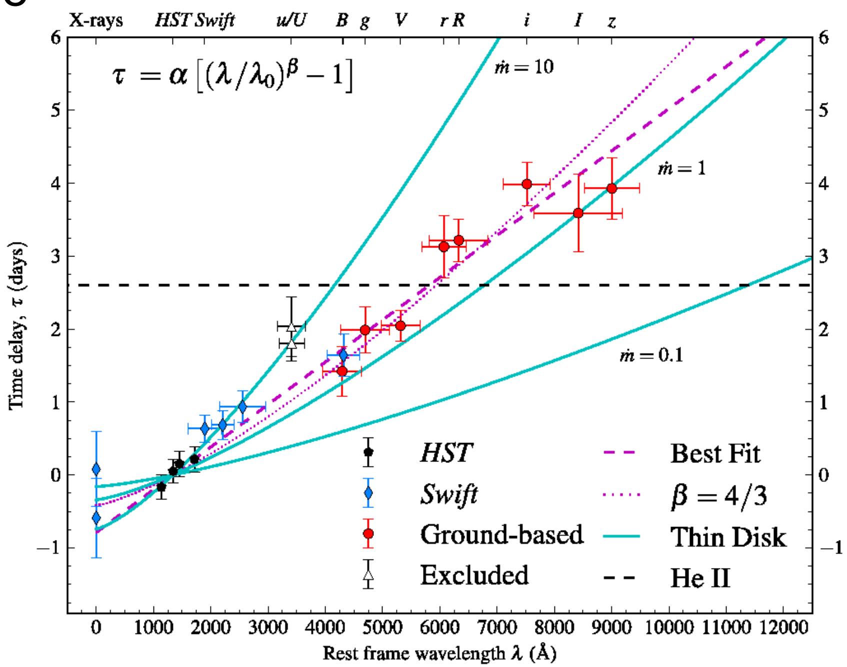
From McHardy+ 2018

All different and miles away from SS disc theory

Problem 3: Implied disc sizes used to be too big

Both NGC5548





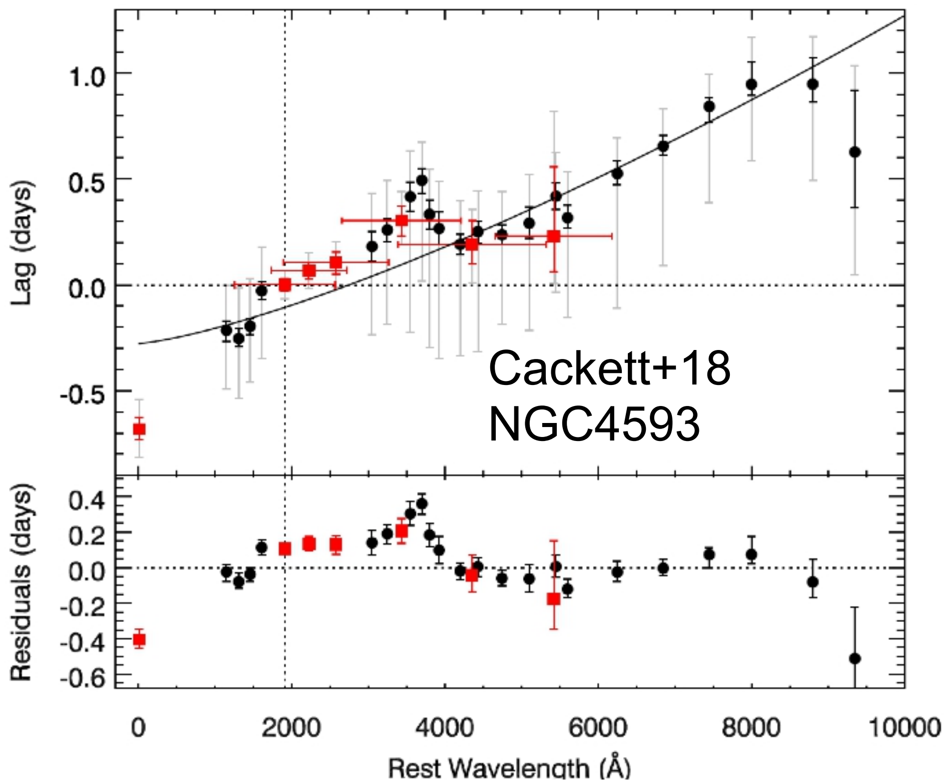
McHardy+2014, **numerical modelling,** based on Shakura Sunyaev disc, Observed lag x2-3 too long

Fausnaugh+16, **analytic formula** gave even bigger differences

See also many other Swift papers, eg Edelson+ 2015, 2017, 2019 and others.

But better modelling, especially Kammoun et al 2021, removes this problem.

Old Problem 4: The U-band excess lag

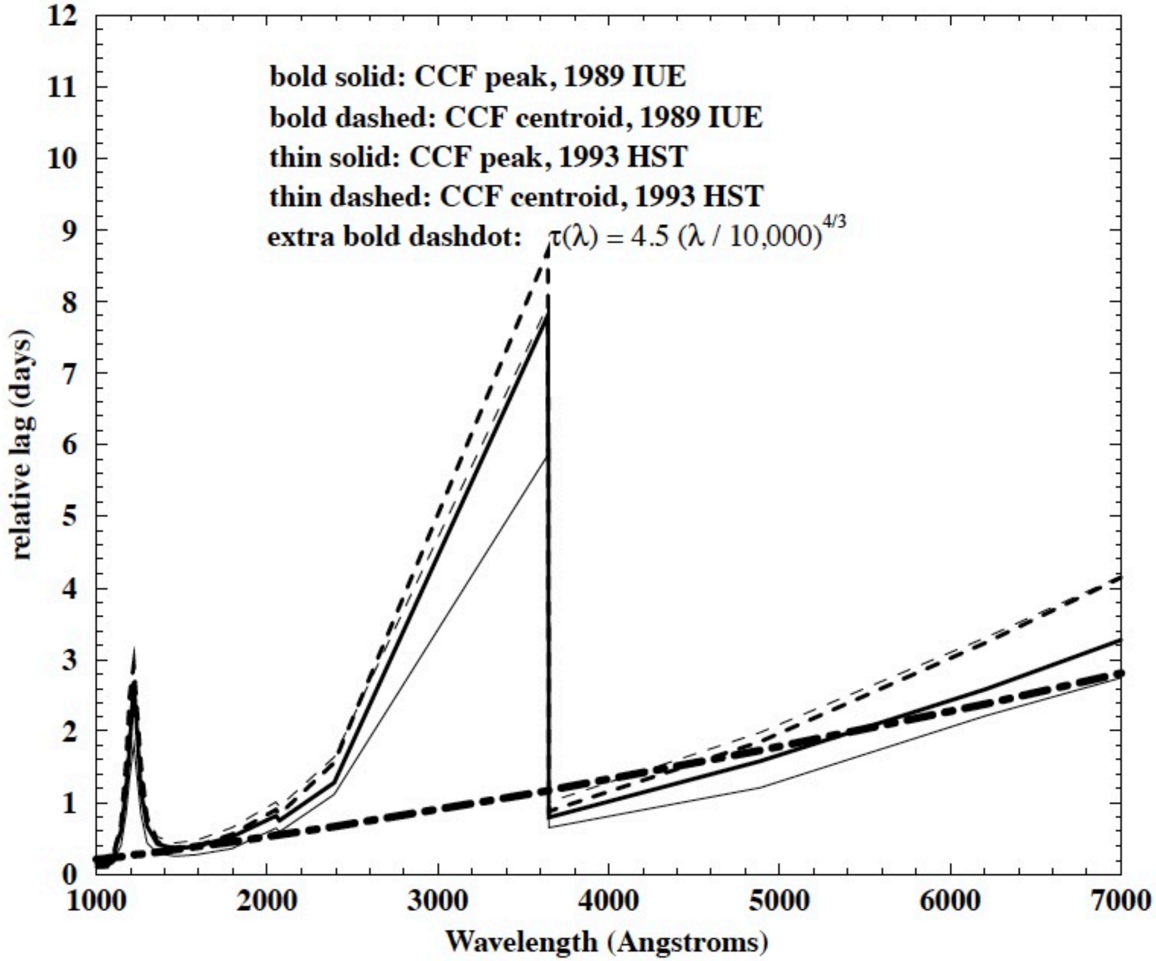


Seen in almost all large Swift programmes

This is no longer a 'problem'. It was rapidly realised to be Balmer continuum from BLR (also Paschen at 7-8000A), predicted by Korista and Goad 2001.

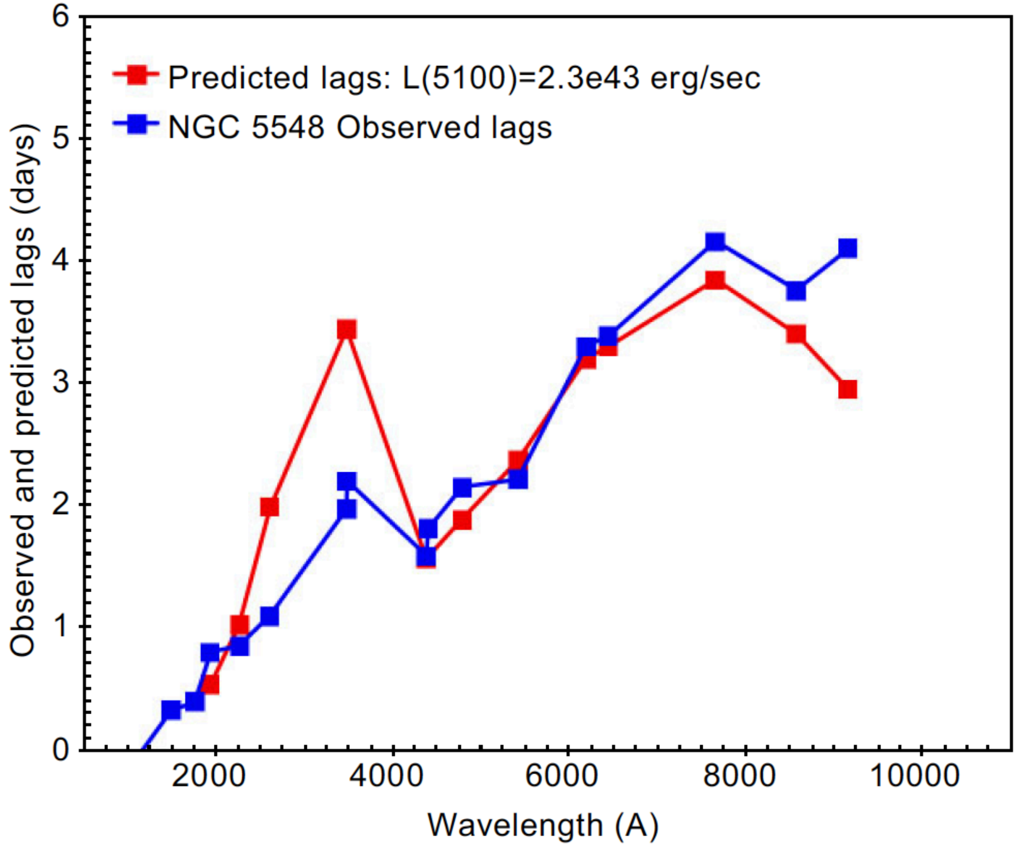
The problem is **how much** of the reprocessed light comes from the BLR (see Netzer 2021, 2022, Cackett+22)

Predicted BLR continuum lags: Korista+Goad 2001



(With reference to the IUE observations of NGC5548)

Netzer BLR model 2022:



Radiation pressure supported clouds, 0.2 covering factor
BLR dominates lags

[Note, if central X-rays are responsible for producing independent lags in disc and BLR,

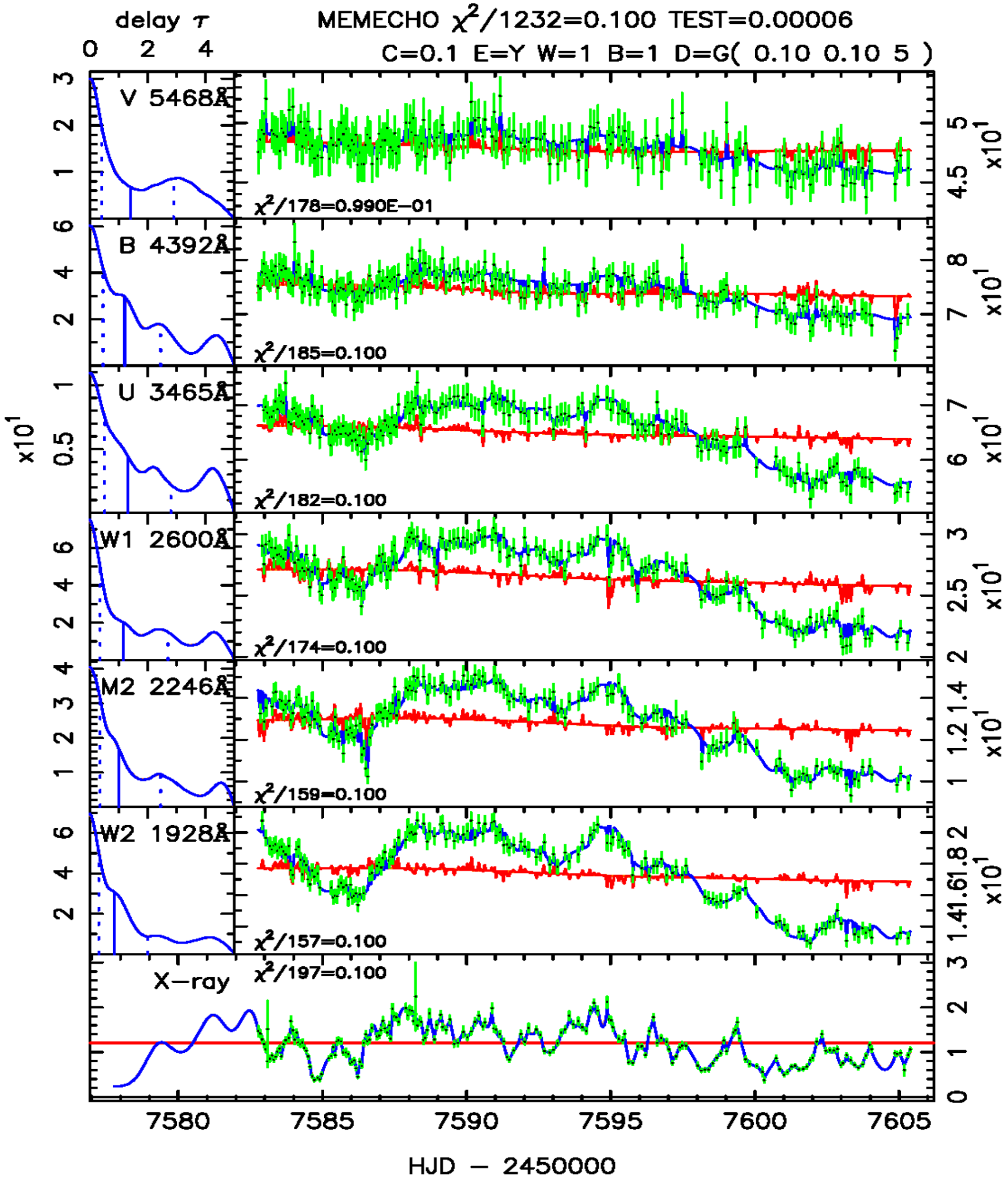
Total observed lag from CCF $\neq$ lag from disc + lag from BLR]

Possible solutions to the excess X-ray lag and the ‘too smooth’ optical lightcurves

- impulse response functions with long tails, eg disc +BLR

- distortion of the real short term lag by underlying trends

Response functions with long tails

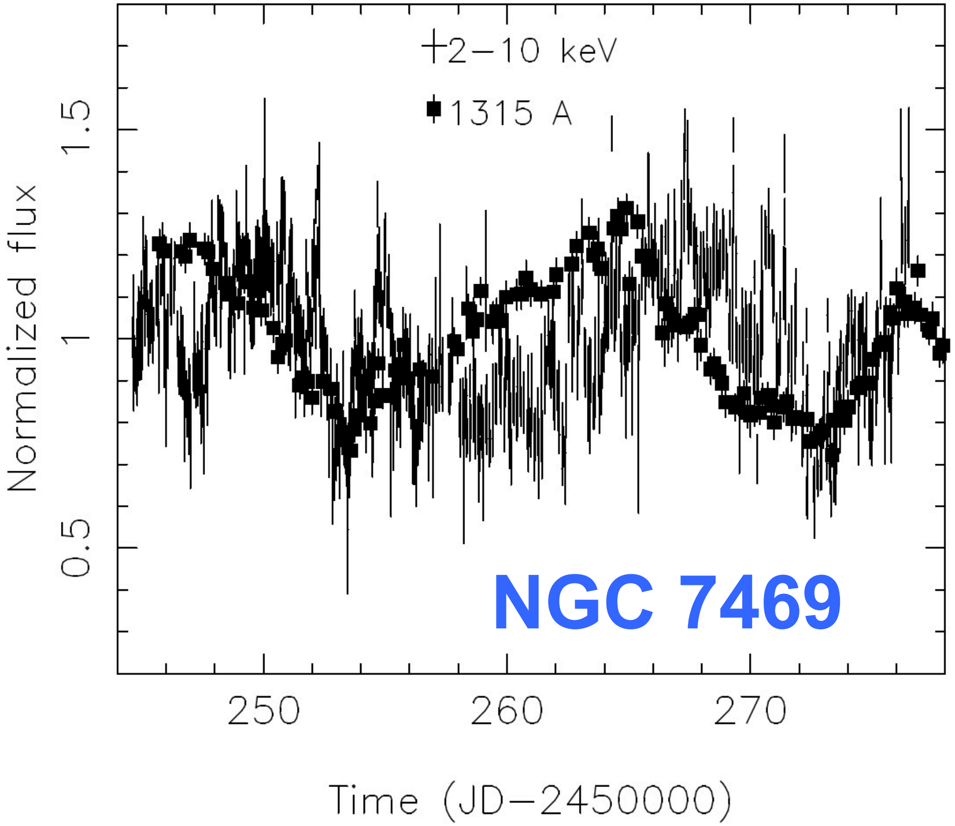


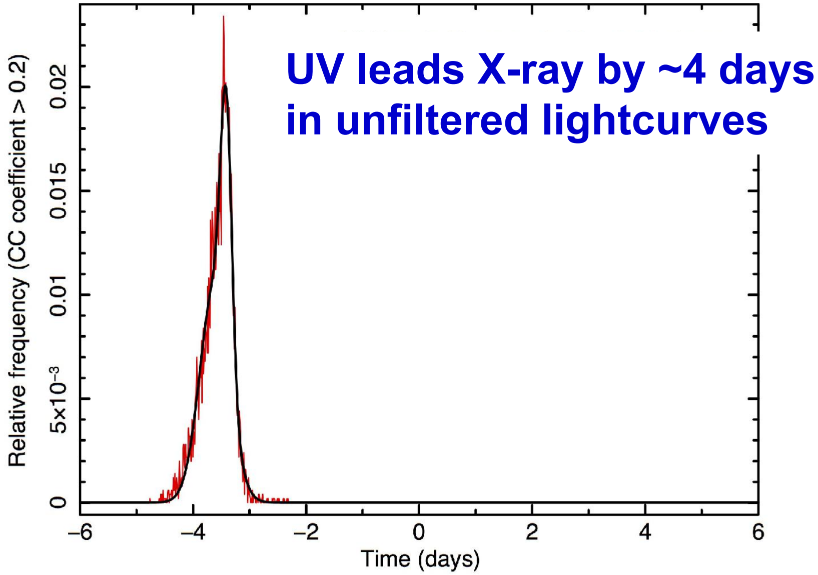
Memecho fit by Keith Horne to NGC 4593 observations (in McH+ 2018)

The response functions consist of a peak at short timescales (accretion disc) and an extended tail (surrounding BLR gas).

Fixes both the ‘excess X-ray lags’ and ‘too smooth’ optical lightcurves

Distortion of lag by underlying trends:





Long timescale trends dominate lags and give UV lead.

Nandra+ 1998, Wanders+ 1997, Kriss+ 2001

See cautionary paper about distortion of correlations by trends by **Welsh 1999**

NGC 7469 – remove variations >5d

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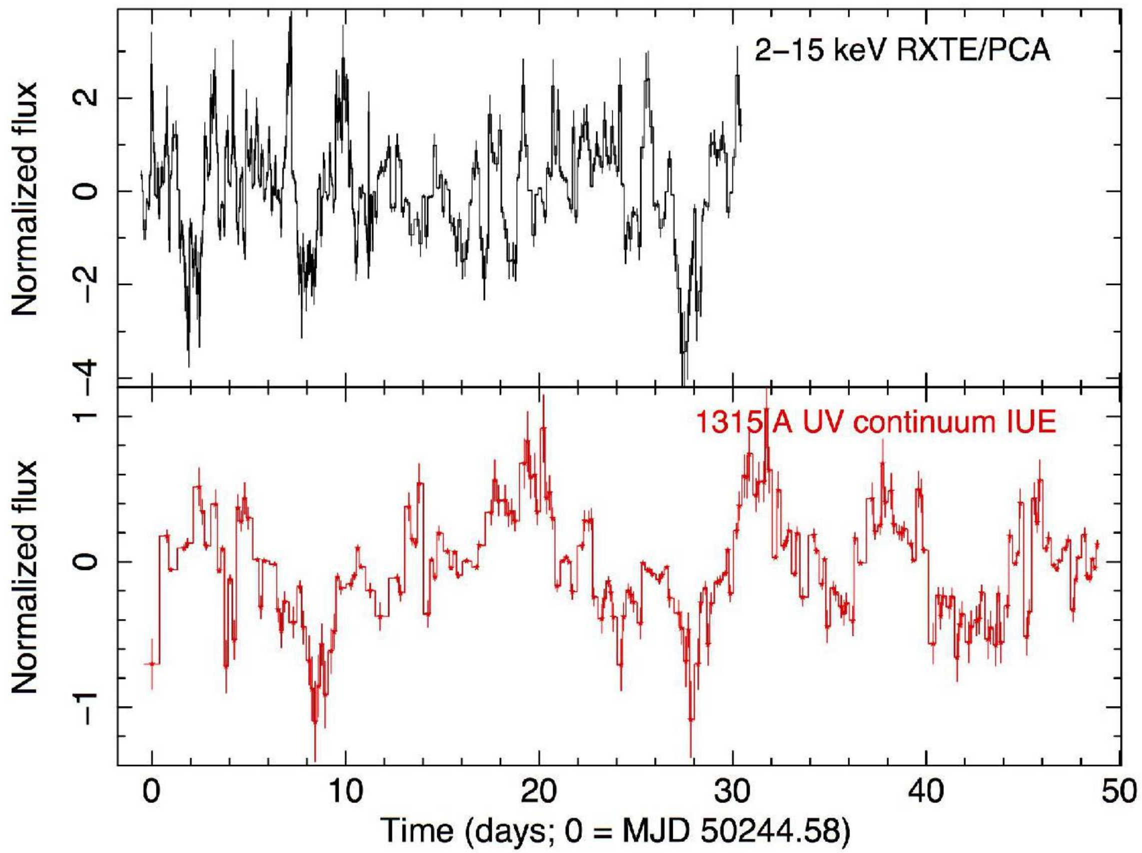
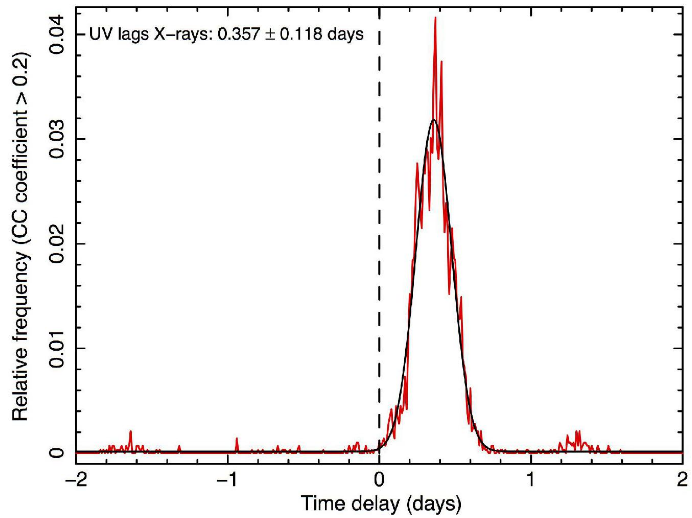


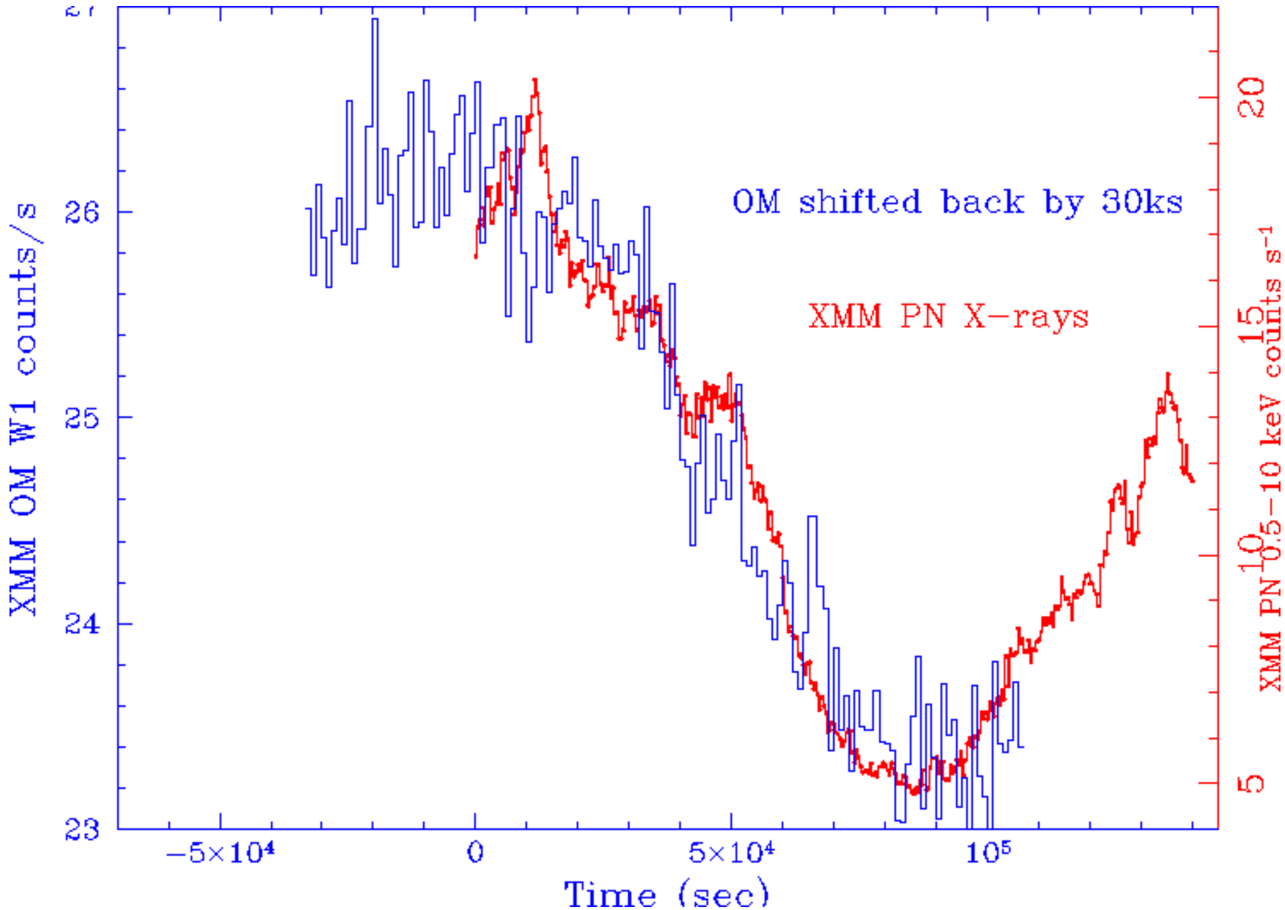


UV lags X-rays

Filter out variations > 5d and then UV slightly lags behind X-rays, like other AGN **(Pahari+ 2020)**

-Timescale-dependence of lags

3. Timescale dependence of lags

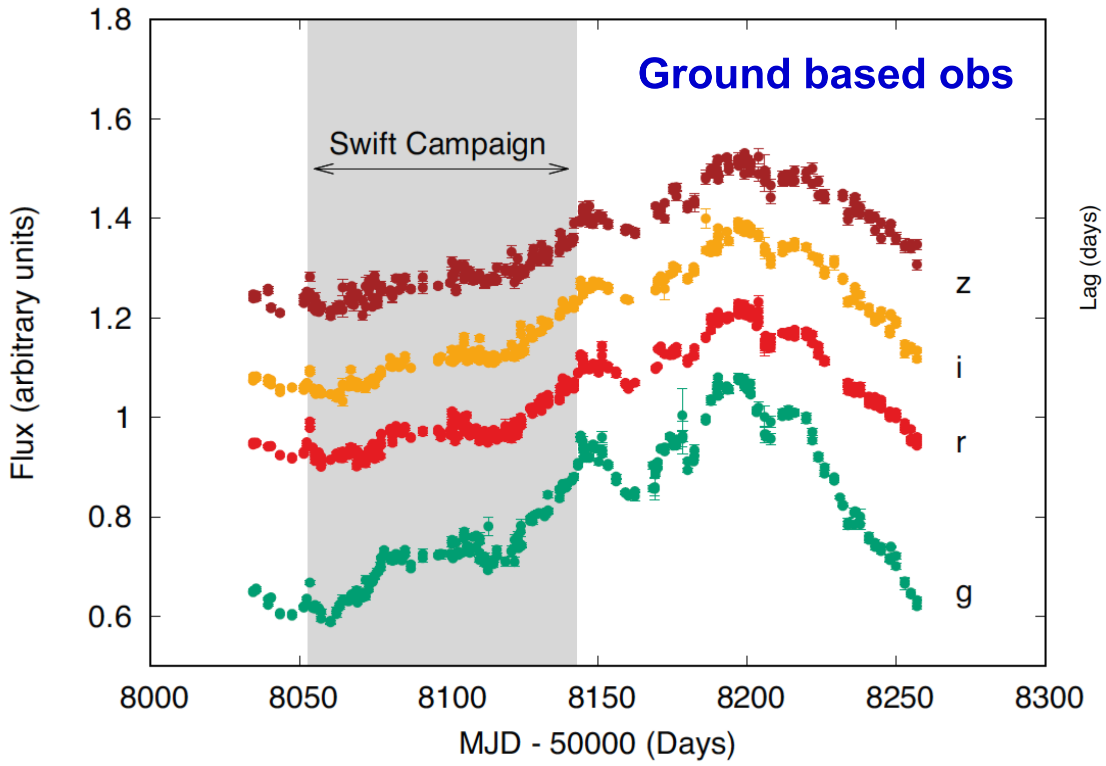


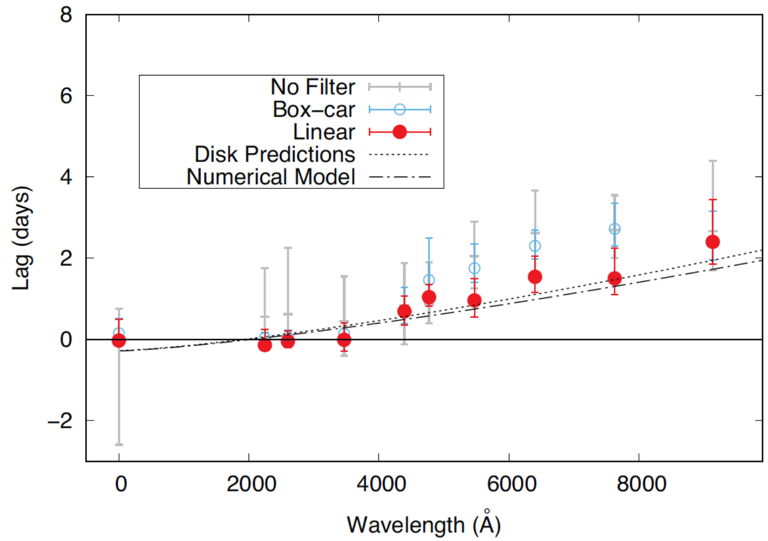
NGC4593
Beard+2023

One orbit of continuous monitoring with XMM gives 30ks lag
Swift regular, but not continuous sampling, gave 60ks (McH+18)

Swift and XMM obs were at same time.

Different Disc and BLR Lag Timescales in Mrk 110: Distinguishing the BLR contribution



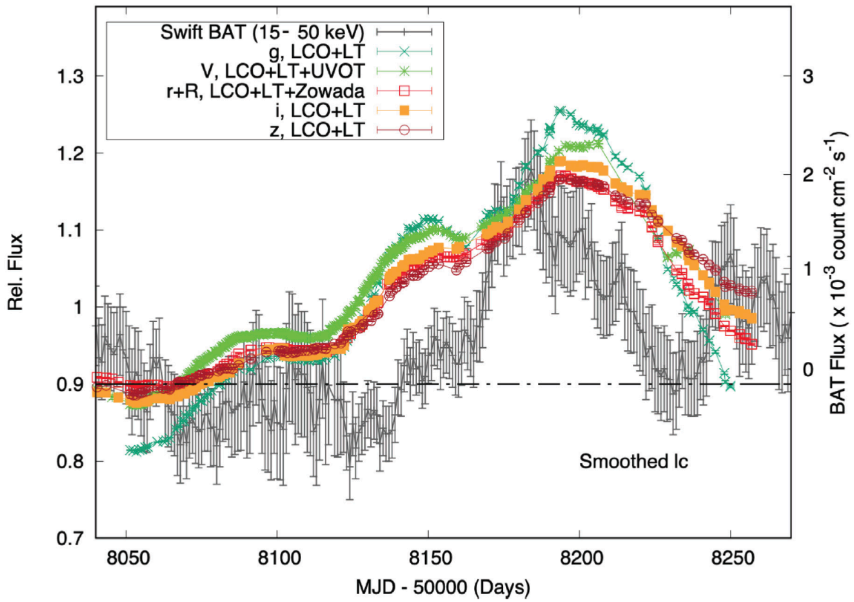


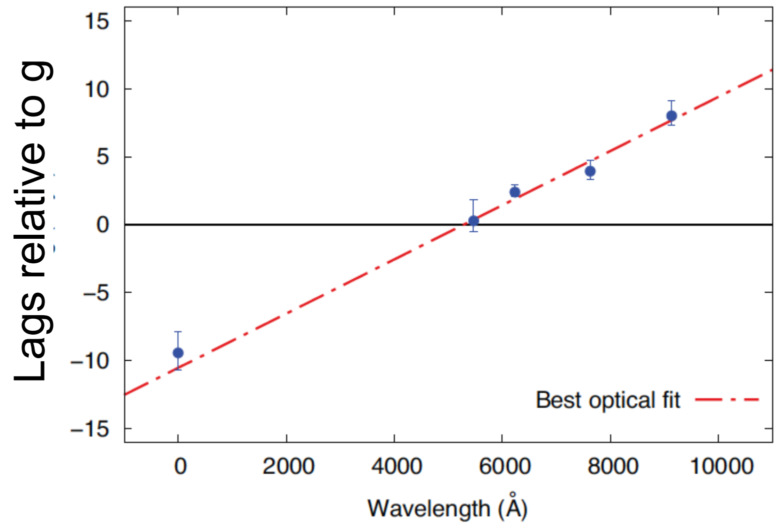
During intense Swift monitoring, short lags (above) are consistent with a disc

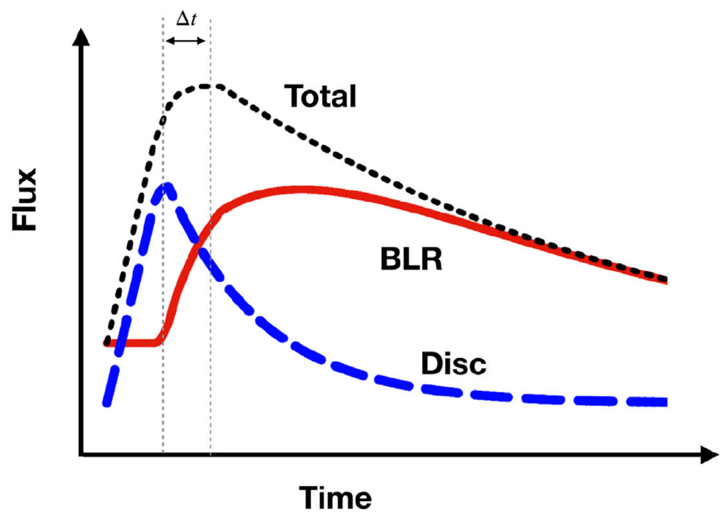
Vincentelli+21, 22

Different Disc and BLR Lag Timescales in Mrk 110:

Long timescales, including BAT hard X-ray







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Frequency-Resolved Lags: The BLR

Commonly used in X-ray astronomy to determine X-ray source geometry and black hole masses (eg Cackett+2014; Emmanoulopoulos+2014).

The argument of the Fourier Transform of the Response function gives the phase, and hence time lag, as a function of frequency that we measure from the Fourier Cross-spectrum between the driving and the reprocessed lightcurves.

So we derive the lag spectrum from observations and compare it with FT of various models of the response function to determine best response function.

Technically difficult for data with gaps (eg Swift and ground-based) Maximum likelihood methods, originally from Miller+2010, used.

Applied by Cackett, Zoghbi and Ulrich (2022) to Swift/HST data on NGC5548.

Frequency-Resolved Lags

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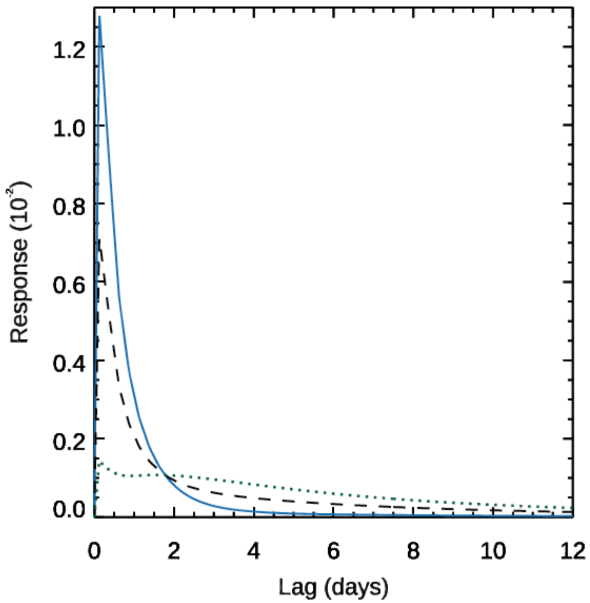
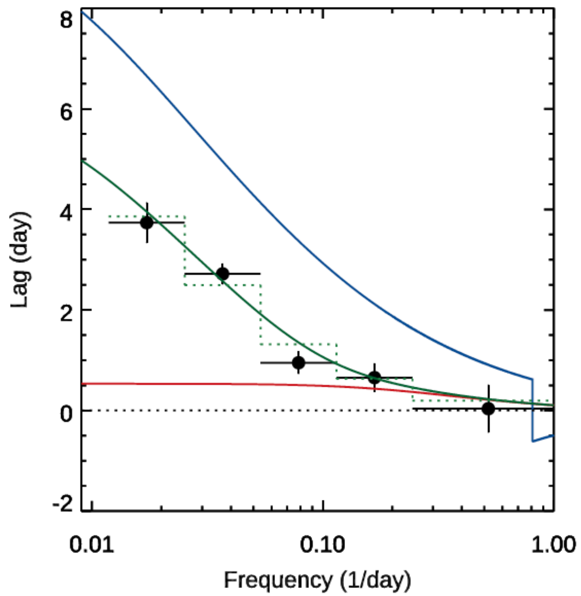
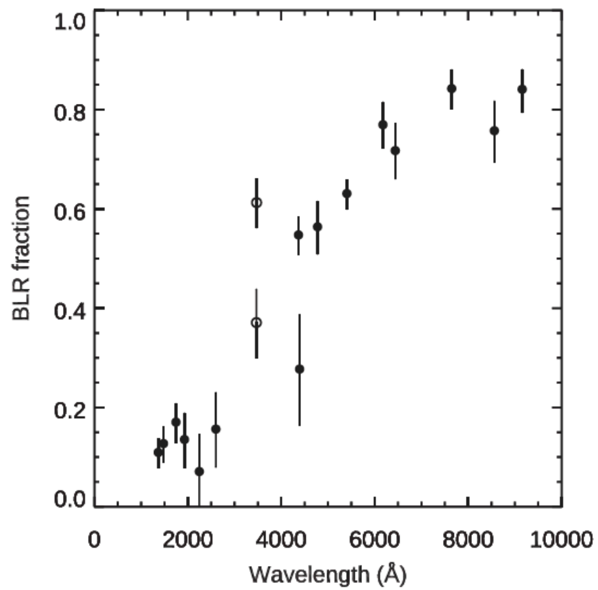
From Cackett+22. HST 1158A used as driving band.







Combined model disc + BLR response functions, with variable BLR fraction, f.

f=0.1 solid blue line
f=0.5 dashed line
f=0.9 dotted green line

Similarities to those from memecho mapping of N4593

1158A to V-band lag spectrum

red line − disc contribution
blue line − BLR
green line - combined

BLR fraction as function of wavelength

Does depend on the model response functions but here we can distinguish the BLR fraction

Another, simpler, Fourier diagnostic

Power Spectra

Power Spectra

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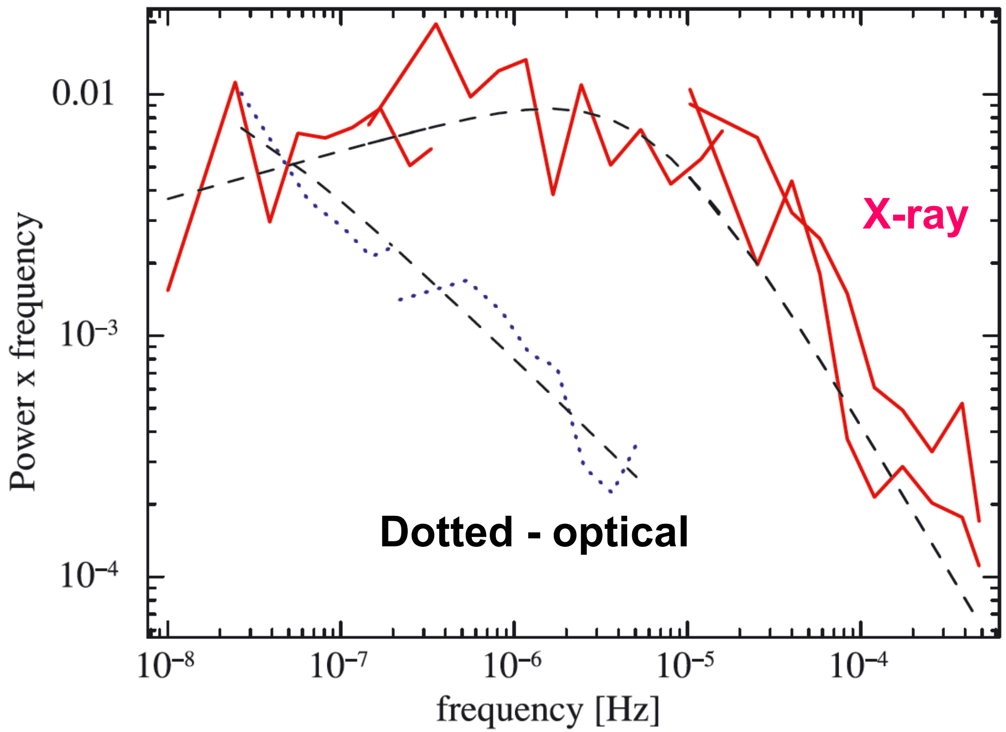
Want to find a reprocessing model which is consistent with both the lags and the optical PSD

- **Produce model response function consistent with lag**
- **Convolve response function with observed X-ray lightcurve to produce simulated optical lightcurve**
- **Calculate PSD of simulated optical lightcurve and compare to observed.**



NGC 3783: Arevalo+ 09

For the observed X-ray/optical lag, no geometry of reprocessor can produce smooth enough long term optical lightcurves.

There has to be a second source of optical variability besides reprocessing.

Power Spectra: NGC5548

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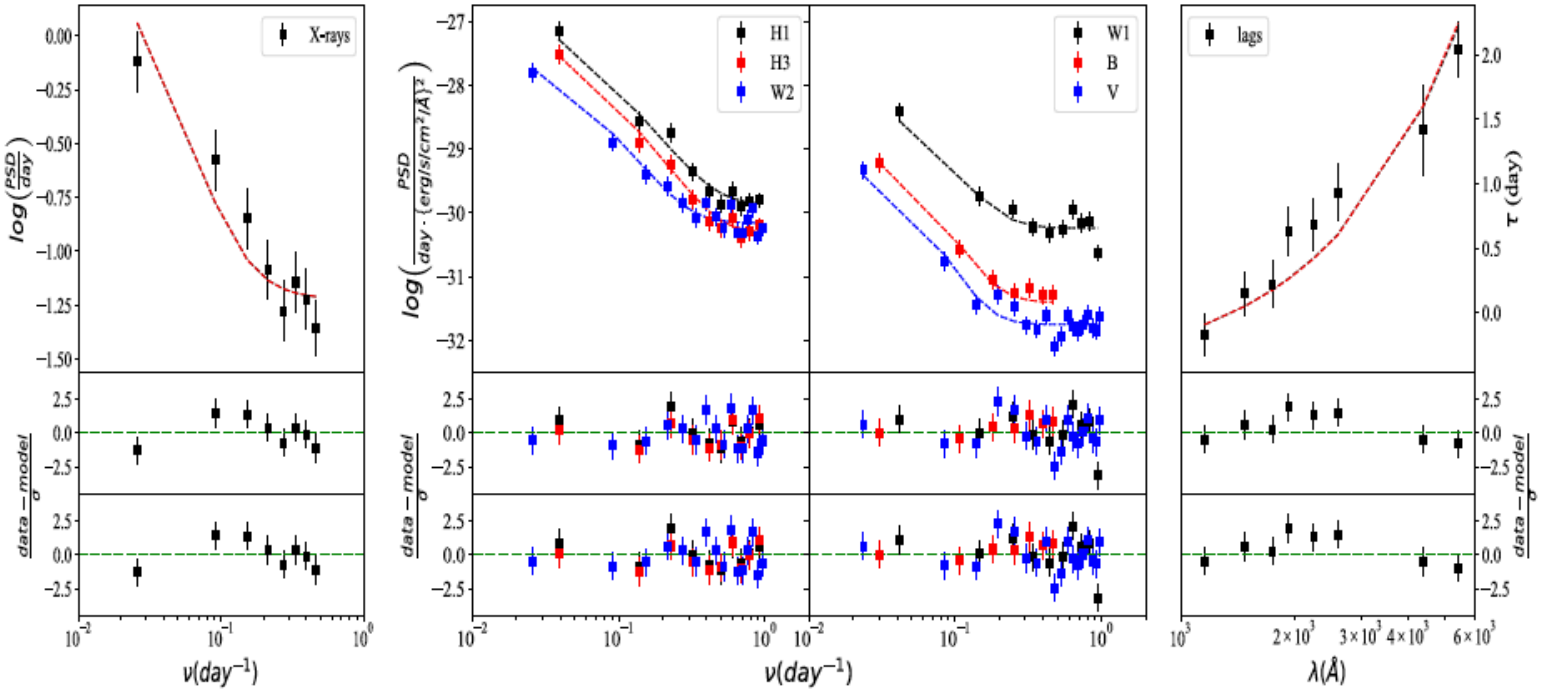
X-ray PSD | **UV and optical PSDS** | **Lags**



Panagiotou+ 22 however find that they can explain both lags and PSDs using KYNXILREV response functions.

But the frequency range of the PSDs is small. Doesn't go to low frequencies.

Need a low mass AGN where it is possible to measure X-ray and optical PSD bend frequencies and low frequency slopes.

Optical Power Spectra: NGC 4395
(3.6x10^5 mass)

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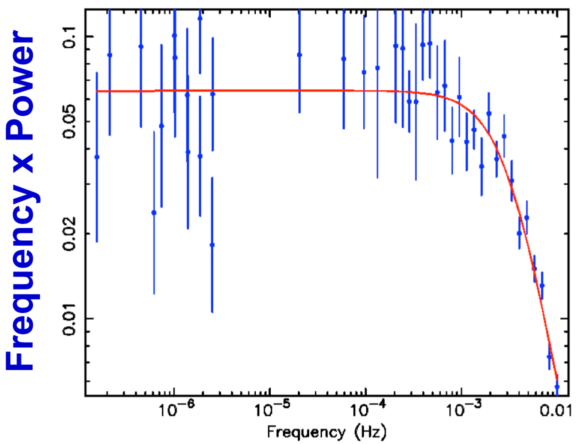
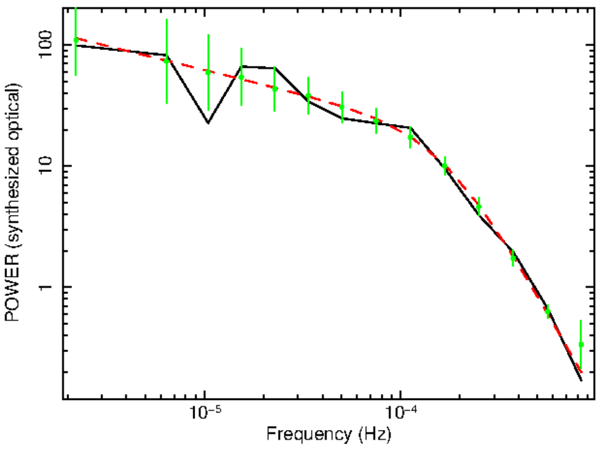
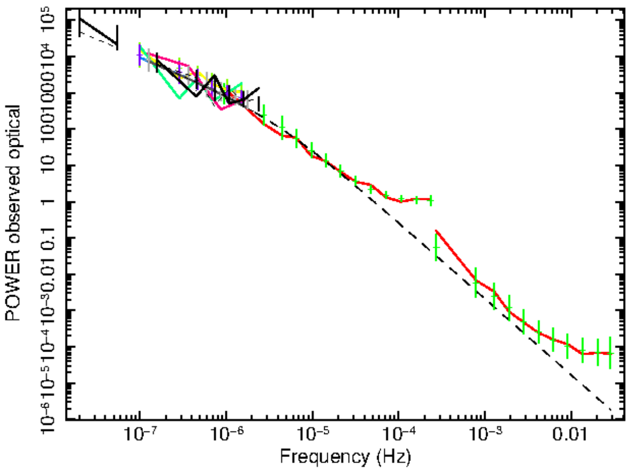
Beard et al, in prep







XMM and Swift **X-ray PSD**

Bend at 10^{-3} Hz

Simulated optical PSD made by convolving XMM X-ray lightcurve with KYNXILVER response based on optical lags

Bend at 10^{-4} Hz

Observed long timescale optical PSD from HiPERCAM, TESS and 3-year ground based monitoring.

It is possible to force a second weak bend at 10^{-4} Hz but main bend is at 10^{-6} Hz.

Additional source of low frequency optical variability needed.

4. The Importance of modelling: Disc outer radius

NGC 4395, Very low mass and accretion rate

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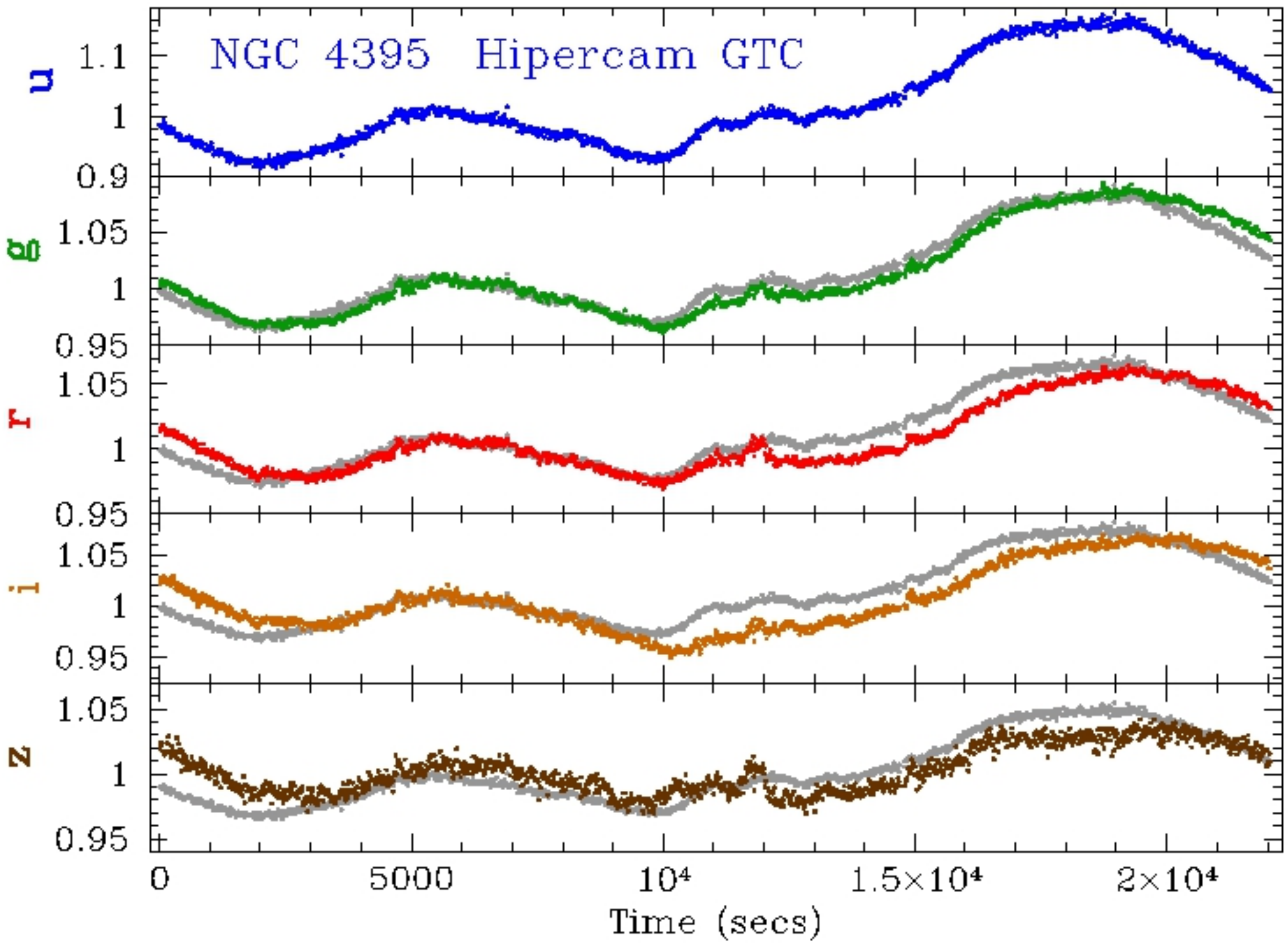
Highly precise lags between ugriz bands measured with Hipercam on GTC



u-band is grey underneath other bands

Ignore bumps in middle - tracking problems

(McH+23)

mass – 3.6 x 10^5 (Peterson+ 2005)
accretion rate – 0.1% Eddington

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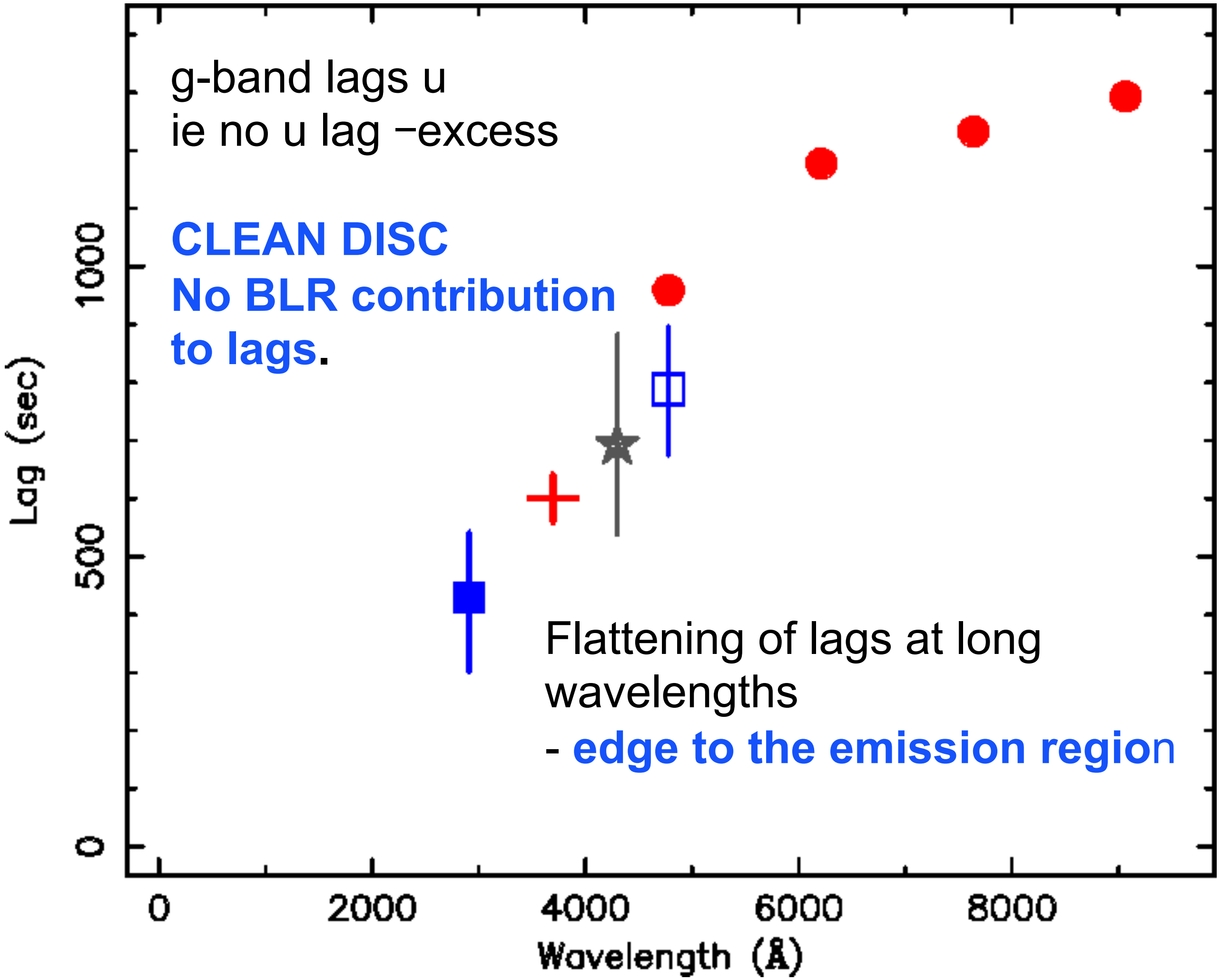
NGC4395 – lags without models



Red circles – hipercam griz relative to u (cross)
Errors all < 15s

Blue filled square – XMM OM UVW1 relative to X-rays.

Blue open square – ground based g-band rel to X-rays (~a bit flakey)

Grey star – B-band rel to g-band (LT)

Hipercam lags are referenced to X-ray frame via XMM OM UVW1 and u-band obs

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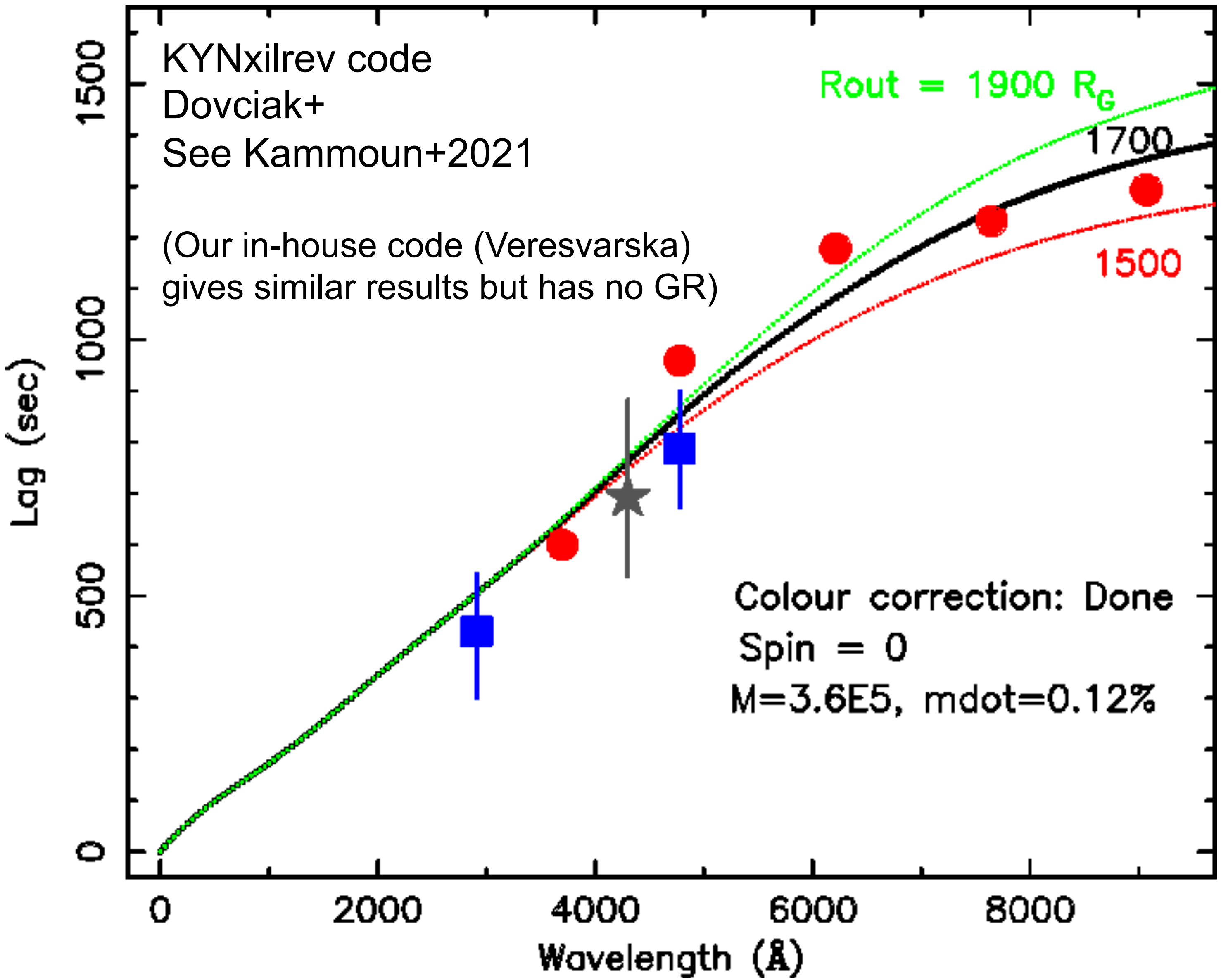
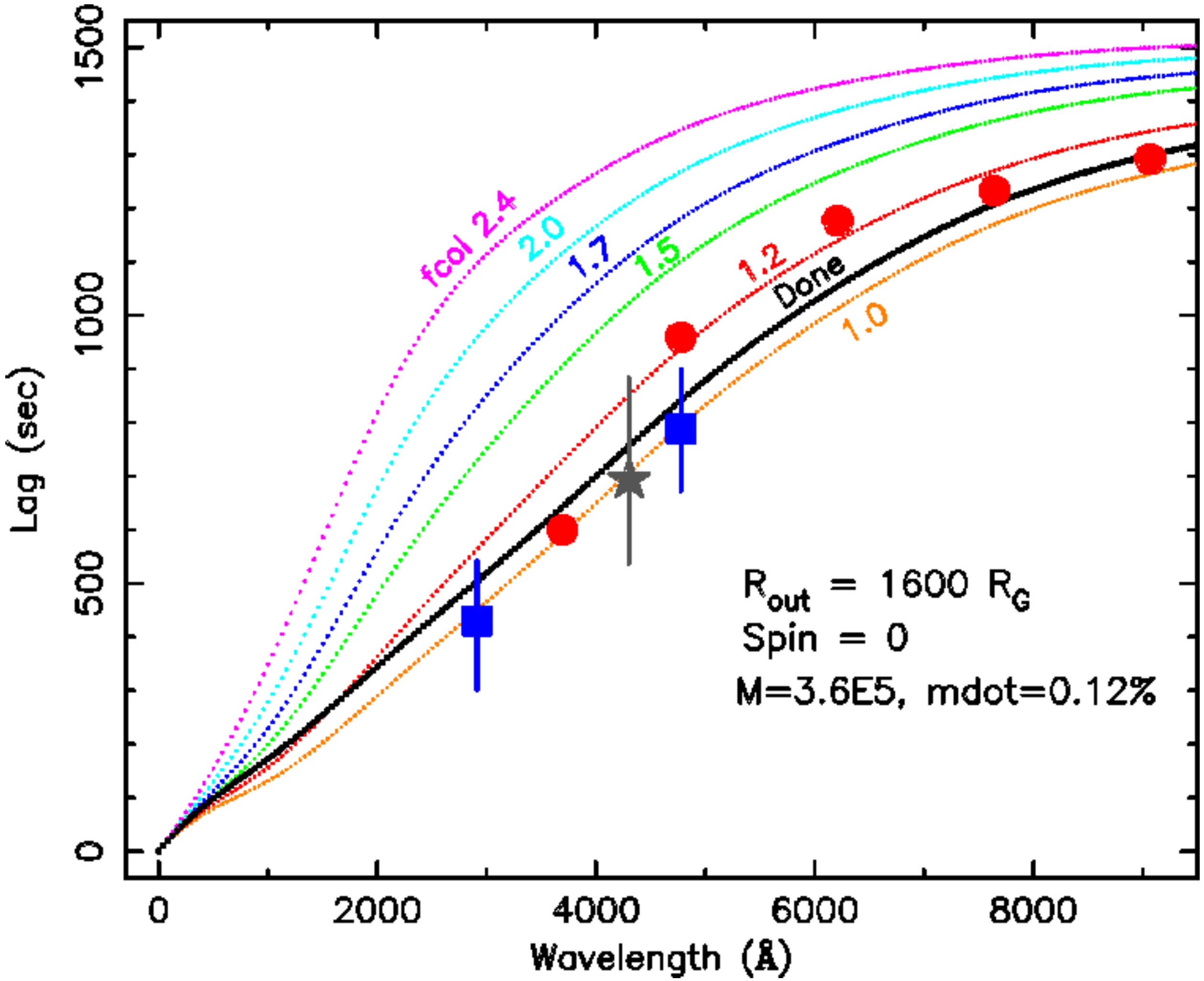
Truncated disc models – vary Rout



Truncated disc models – colour correction factor



Done+2012 fcol, varies from 2.4 at T> 1E5 to 1 at T < 3E4

Colour correction factor can have a **HUGE** effect on model lags.

Need to know disc physics.

Reason for truncation?

Probably a gaseous disc wind, optically thick at the base

Dust sublimation radius is too far out

Gravitational instability probably not important for low mass (Shore+1982)

Largest (z-band) lag is very close to predicted inner BLR radius (Bentz+06) so wind may merge into BLR further from disc.

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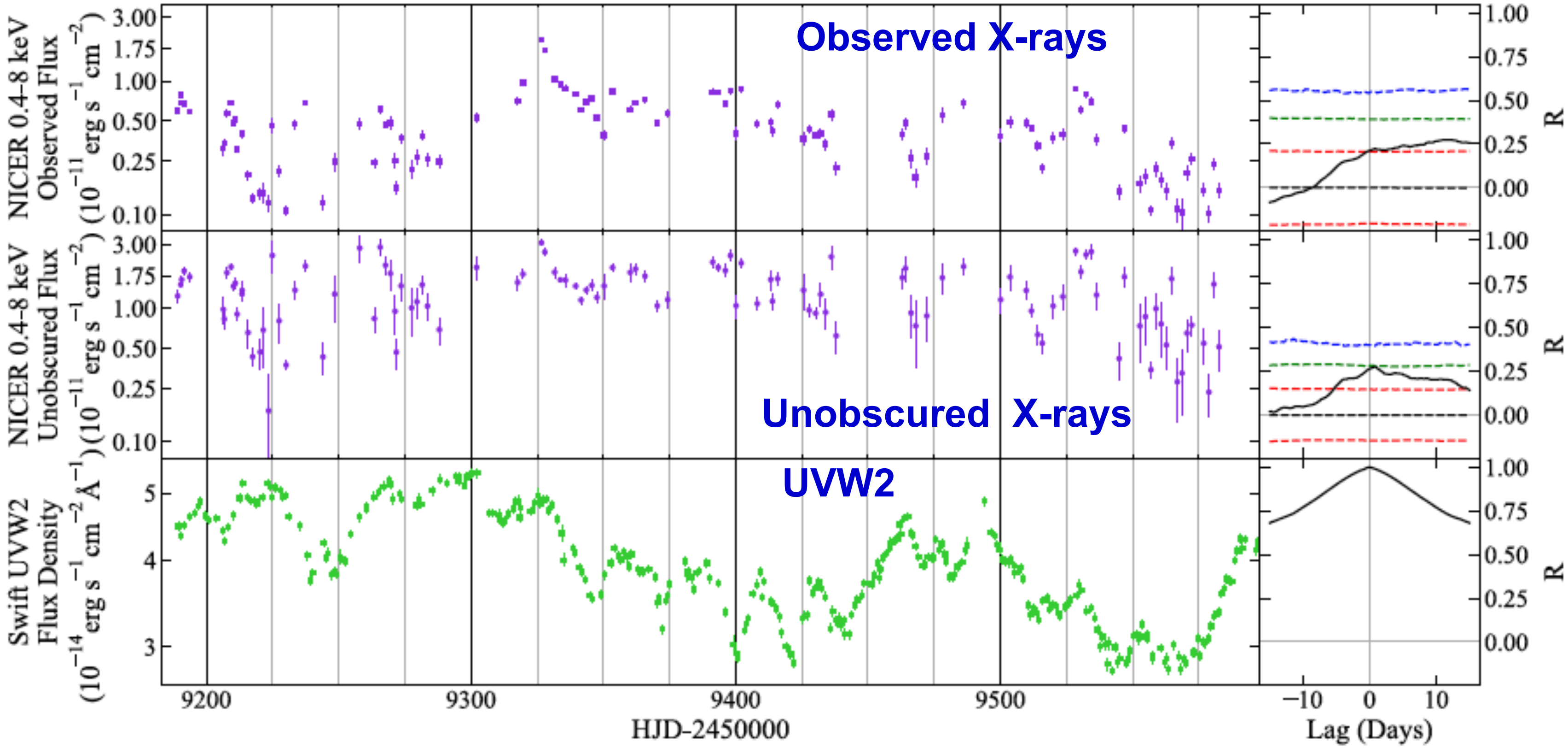
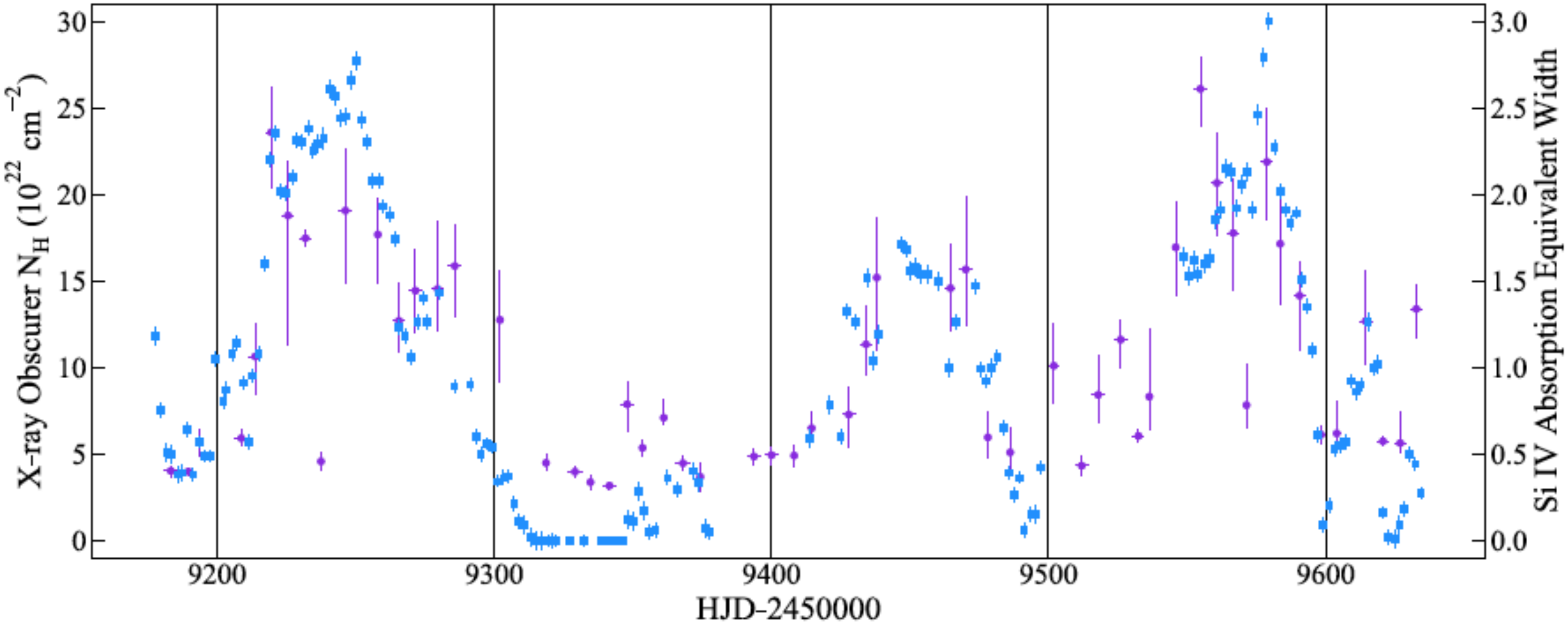
5. Absorption: e.g. Mrk 817



Often there is a good X-ray/UV correlation, even for absorbed X-ray sources, so the X-ray source directly sees the reprocessor (eg Kynoch talk)

But...**Partington+23**: No correlation above 95% significance between X-ray and UV. True even if you de-absorb the X-ray lightcurve.

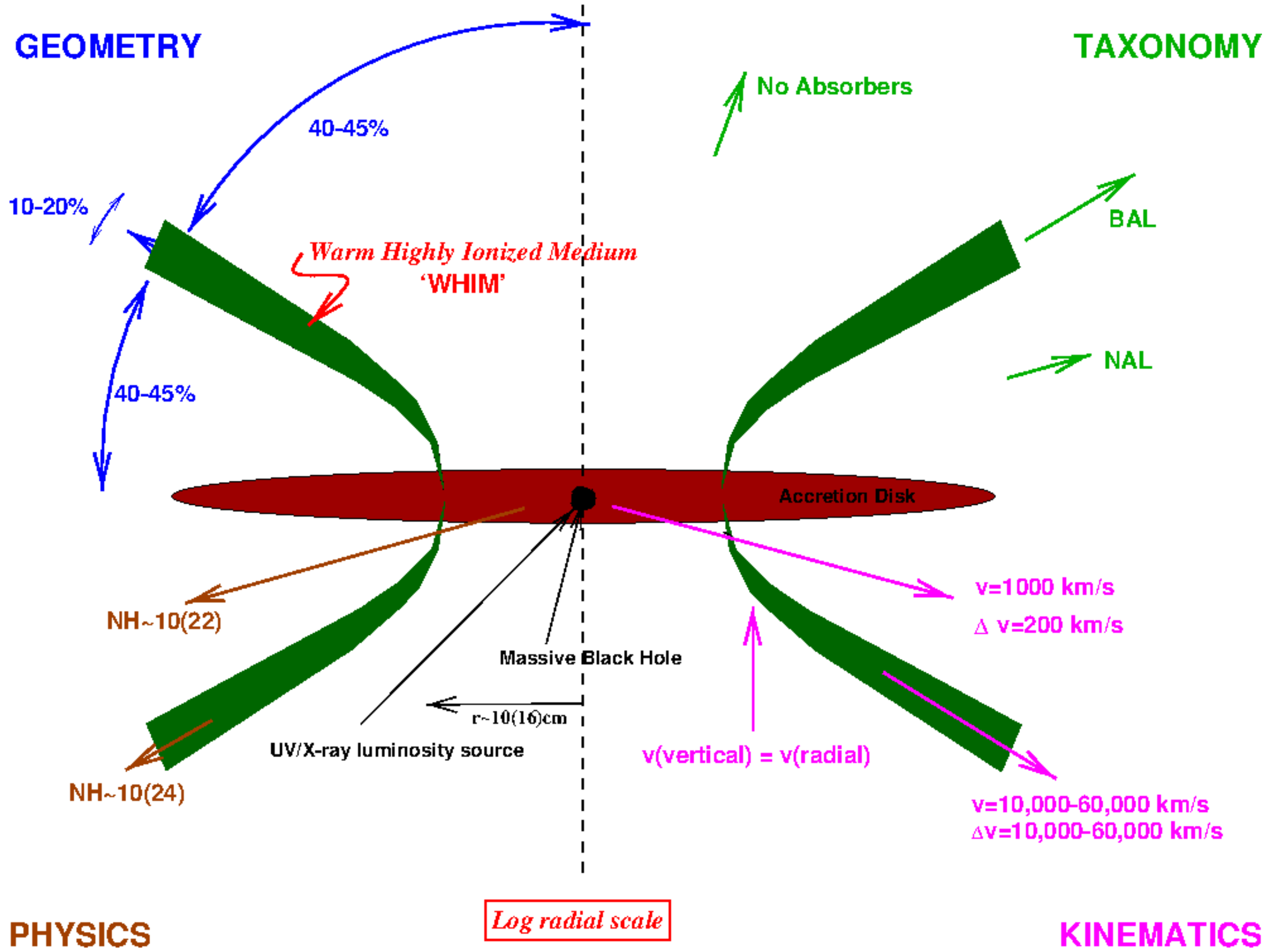
Absorption: Mrk 817



Partington+23: The UV (blue dots) and X-ray (purple) absorption vary similarly.

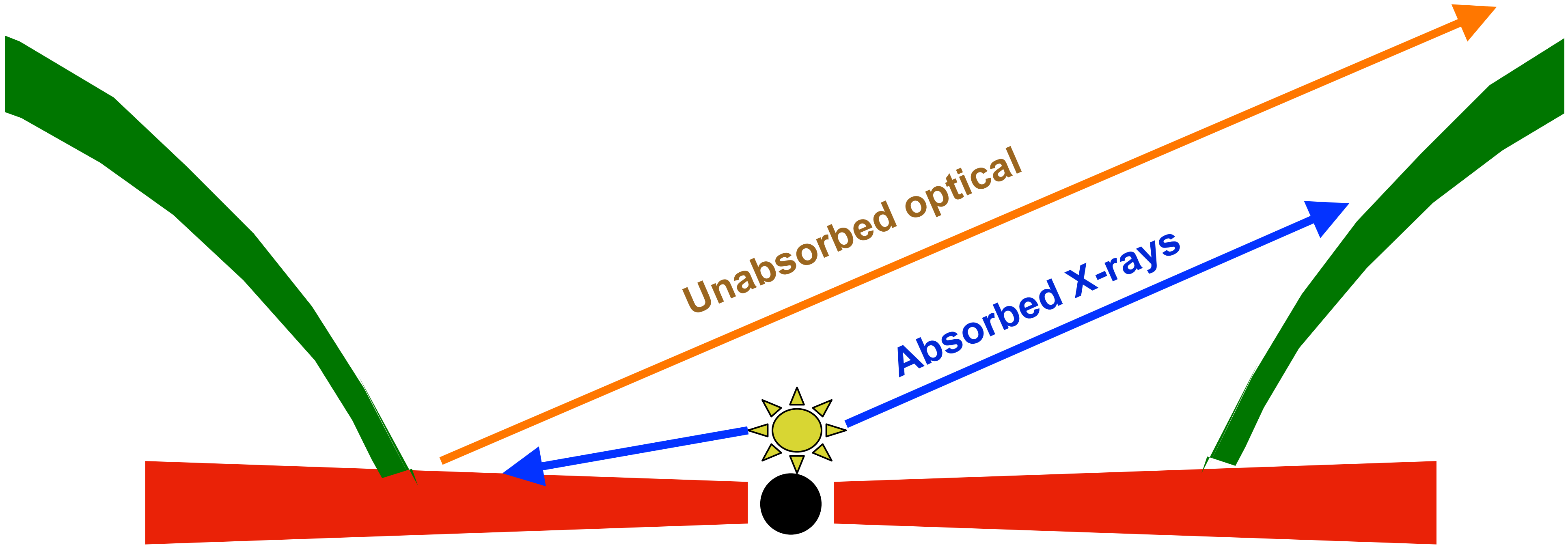
Both X-ray and UV emission regions are seen through the same absorbing gas.

Standard Absorption Paradigm
Elvis Wind Scenario

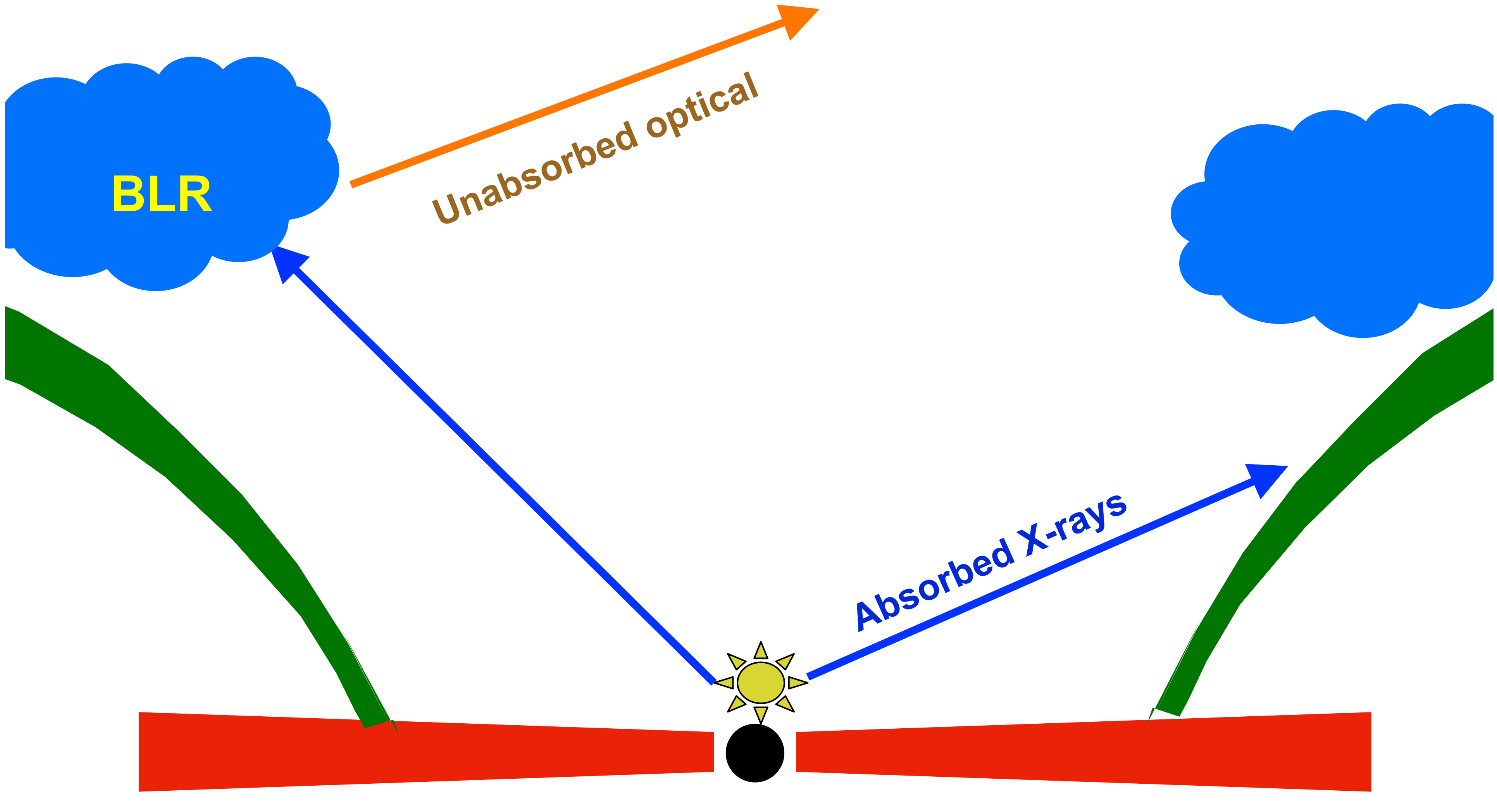


Elvis 2000

Perhaps sometimes the disc wind obscures everything but..



..for a few angles of inclination you might be able to have absorbed X-rays and un-absorbed optical, from far side of disc



Much easier to get absorbed X-rays and unabsorbed optical from BLR

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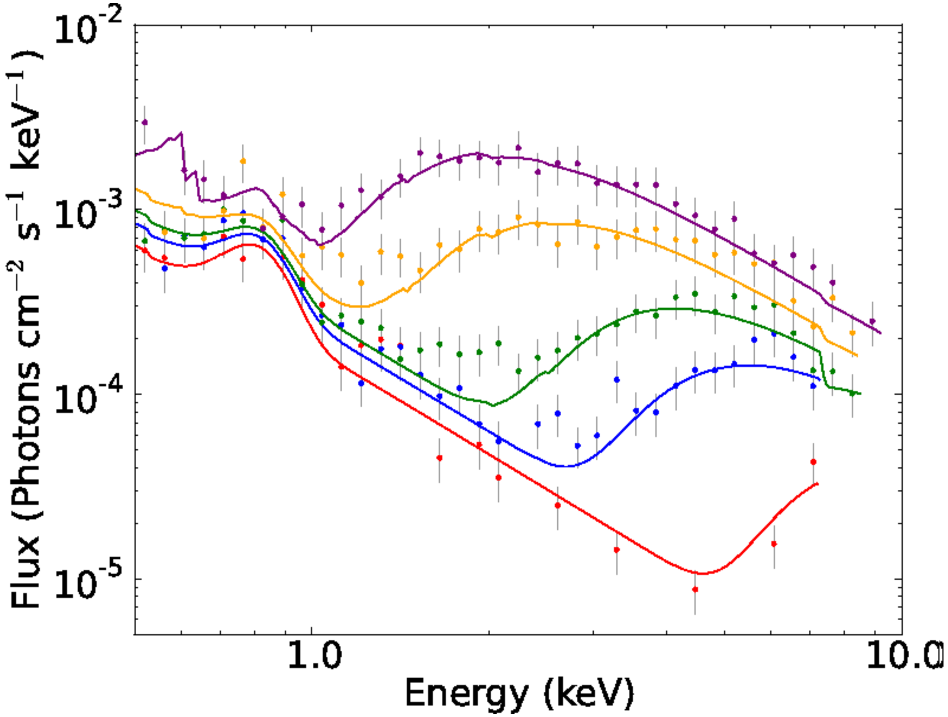
NGC1365 Swift X-ray Spectral Variability

Connolly+ 2014



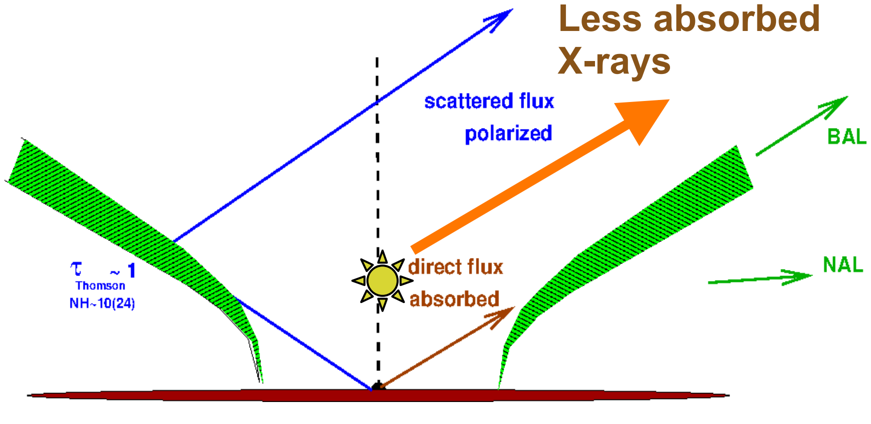


Fig.6 from Elvis 2000

Two components, both increase with total flux

- one weaker, unabsorbed
- one stronger, absorption varies inversely with luminosity

Maybe increasing continuum flux pushes the absorbing wind more out of the way.

or coronal height increases

CONCLUSIONS

Reprocessing of high energies always contributes to short timescale (hours/day) UV/optical variability. On very long timescales (months, years) additional disc processes affect UV/optical variability.

Disc reprocessing dominates short timescale variability but the BLR is important for intermediate scales (few days) variability.

Long timescale trends can distort short timescale lags. After removal the UV almost always lags X-rays and X-ray-to-UV excess lag usually disappears, removing need for Gardner+ Done model scattering in inner disc.

Measured lags are affected by sampling frequency and length of datasets. Where excellent data are available, Fourier Cross-Spectra can distinguish disc and BLR contributions at different wavelengths.

Reliable modelling is essential, eg in measuring disc truncation radius in NGC4395.

Understanding absorption, which may be due to disc winds, is very important for understanding the inner geometry, but the observations are not yet entirely clear.