X-ray / UV / Optical Variability of AGN and Continuum Reverberation

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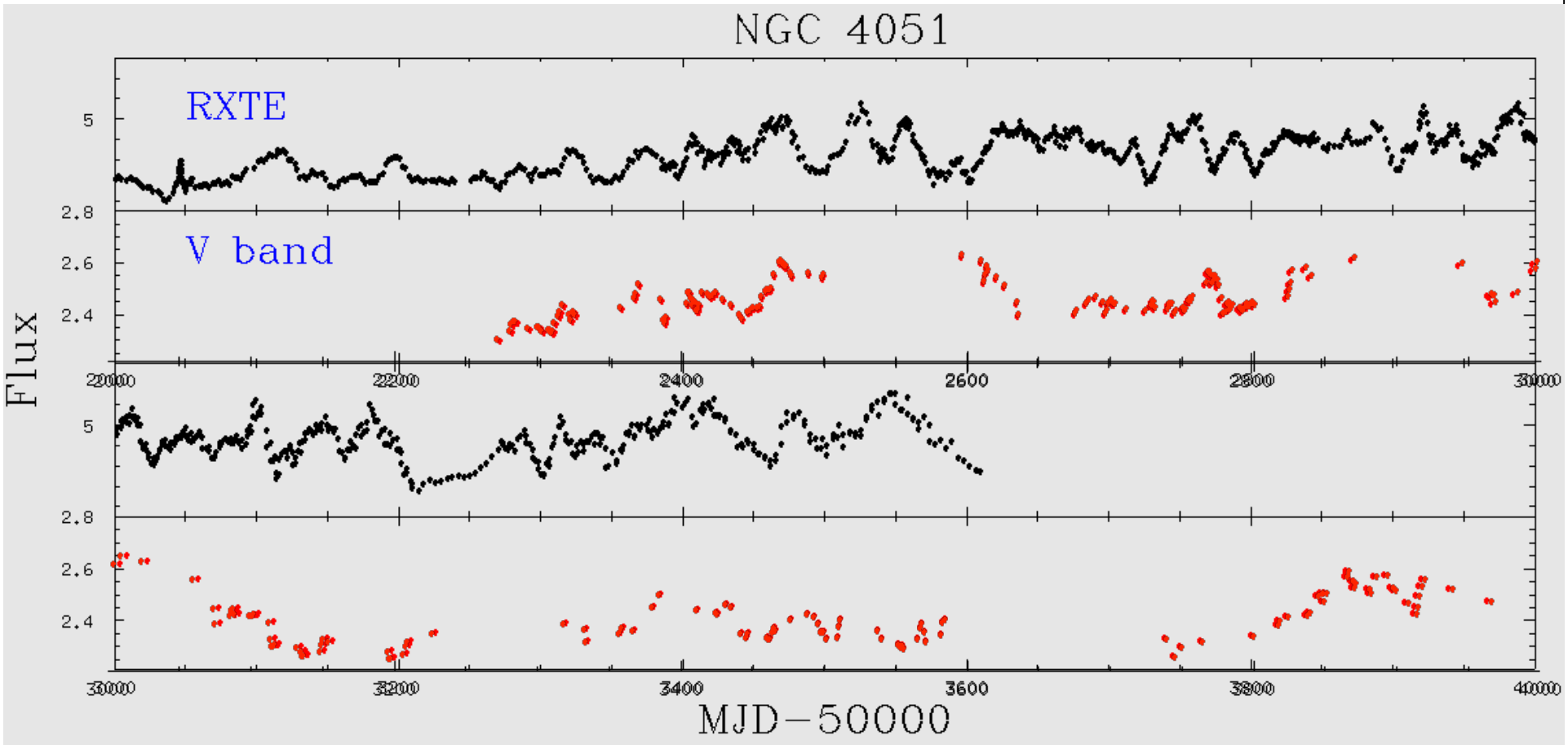
What drives UV / optical variability in AGN?

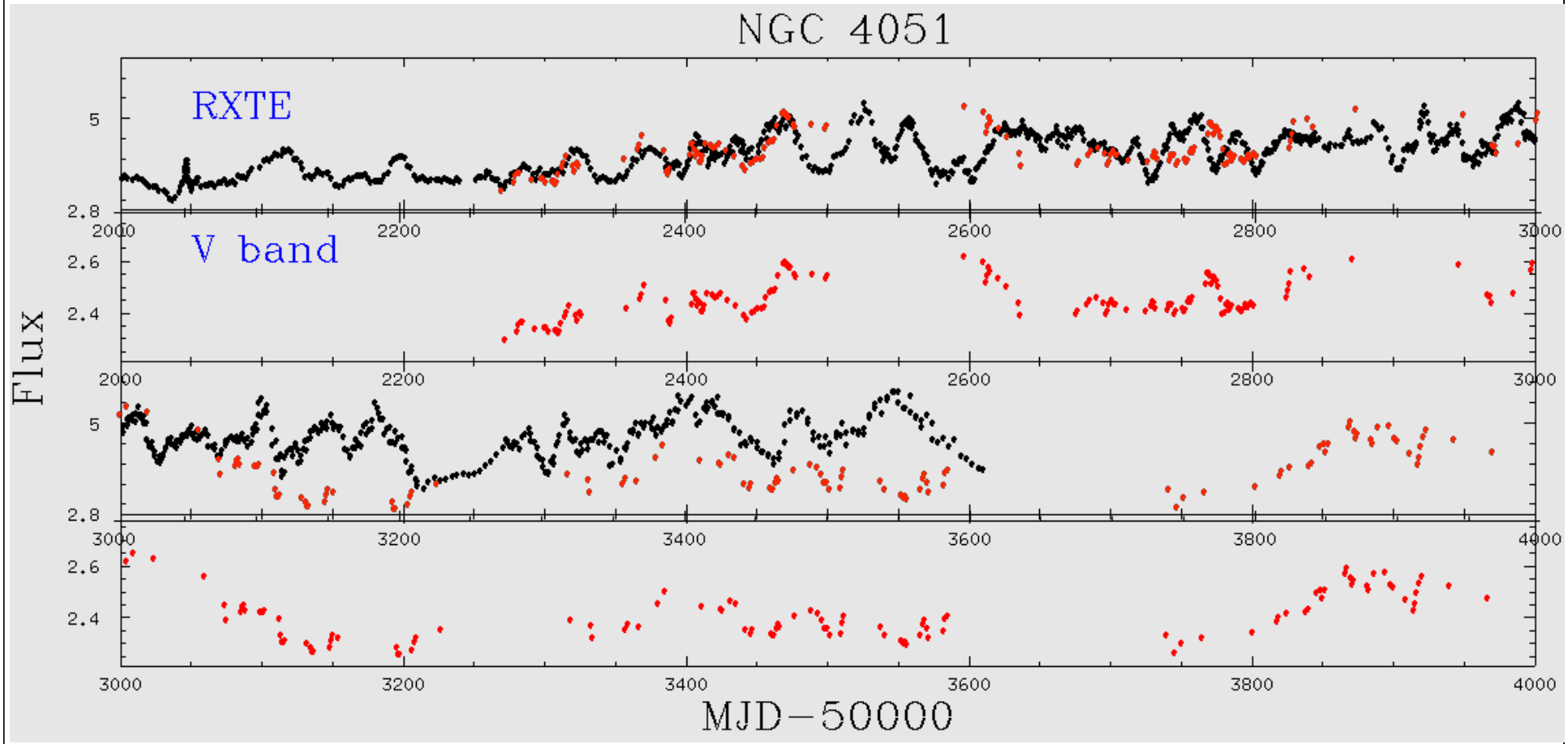
What can we learn about AGN inner structure by studying X-ray / UV / optical variability?

The X-ray / Optical Relationship

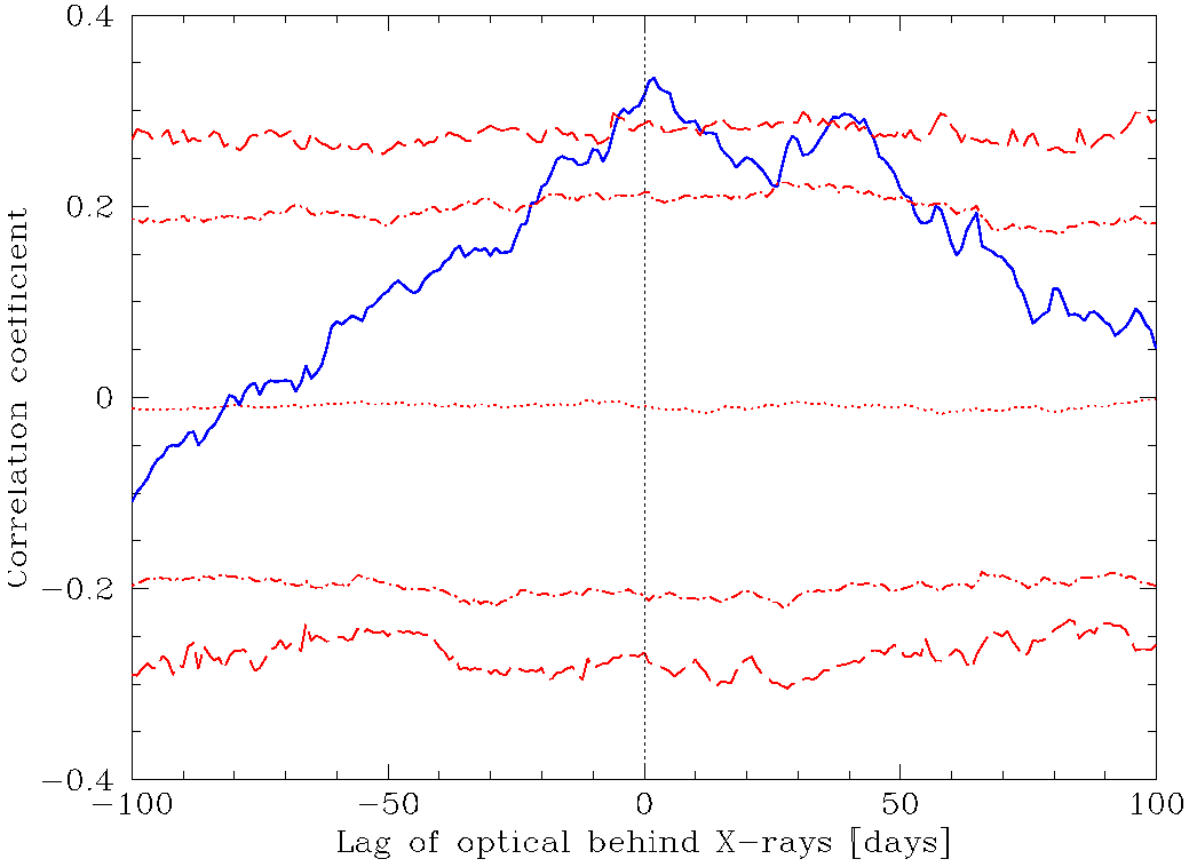


Many RXTE + ground based optical programmes; eg Breedt et al 2010

NGC 4051


NGC 4051
RXTE
V band
Flux
MJD−50000
2000
2200
2400
2600
2800
3000
3200
3400
3600
3800
4000
2.8
2.4
2.6
5

NGC4051



Breedt et al 2010

99% confidence

95% confidence

Optical lags by 1.5 +/- 0.5 d, consistent with some reverberation contribution, but there is something else going on.

Need better data. Many similar results from RXTE

Hard to explain with reprocessing: UV rise without X-ray counterpart

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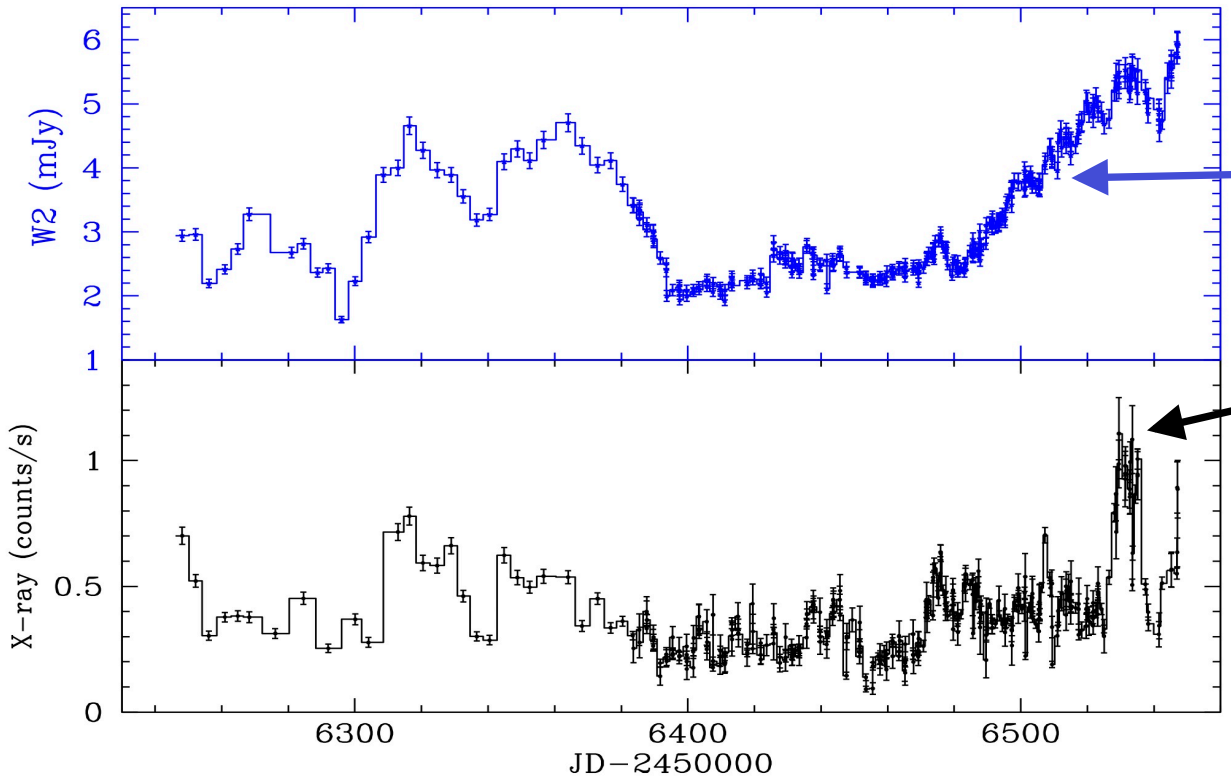


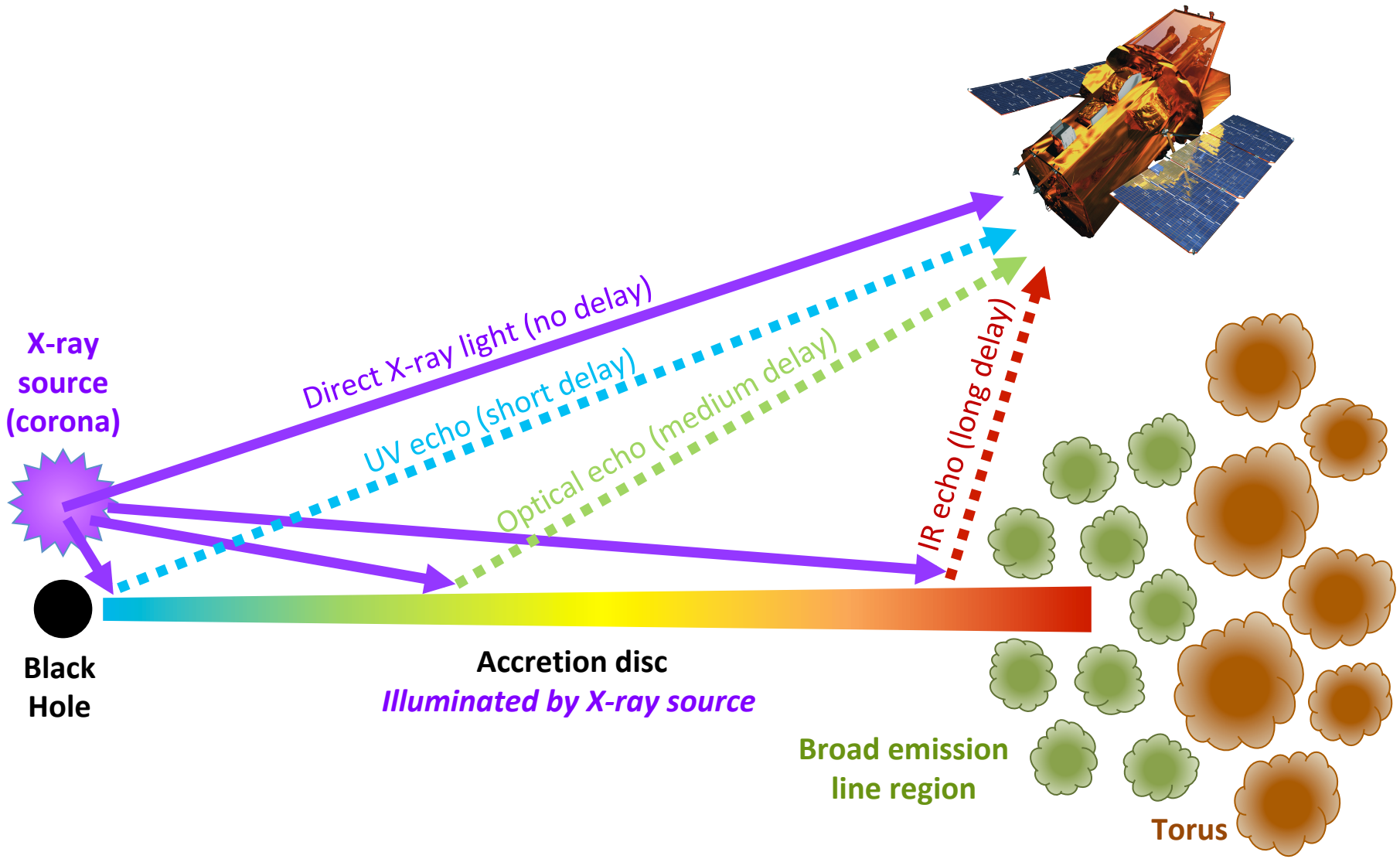
(NGC5548, McHardy+ 2014)

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.

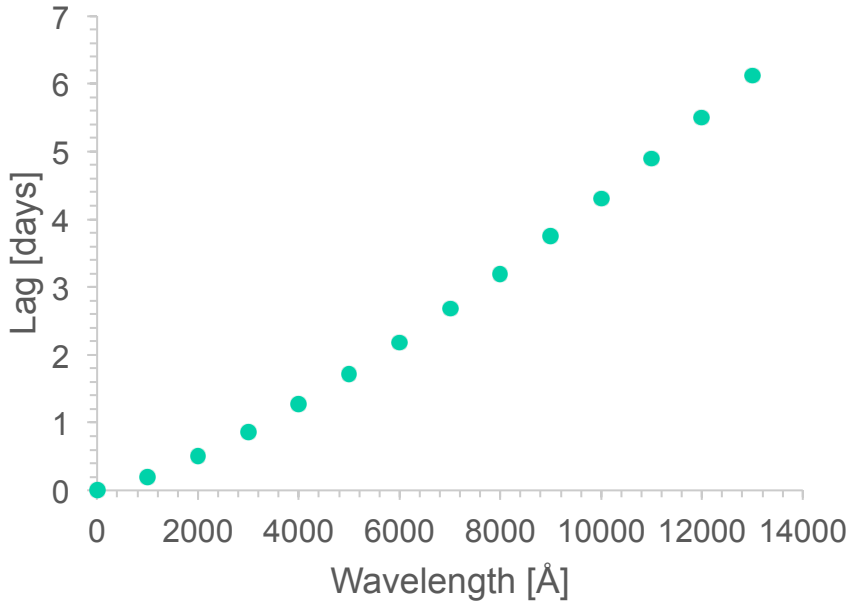
Reverberation:
What do we expect to see?

See Blandford and McKee, 1982.



Lags depend on the geometry, including size and location of X-ray source
Might even expect some reverberation from BLR

Expected Disc Reverberation Lags

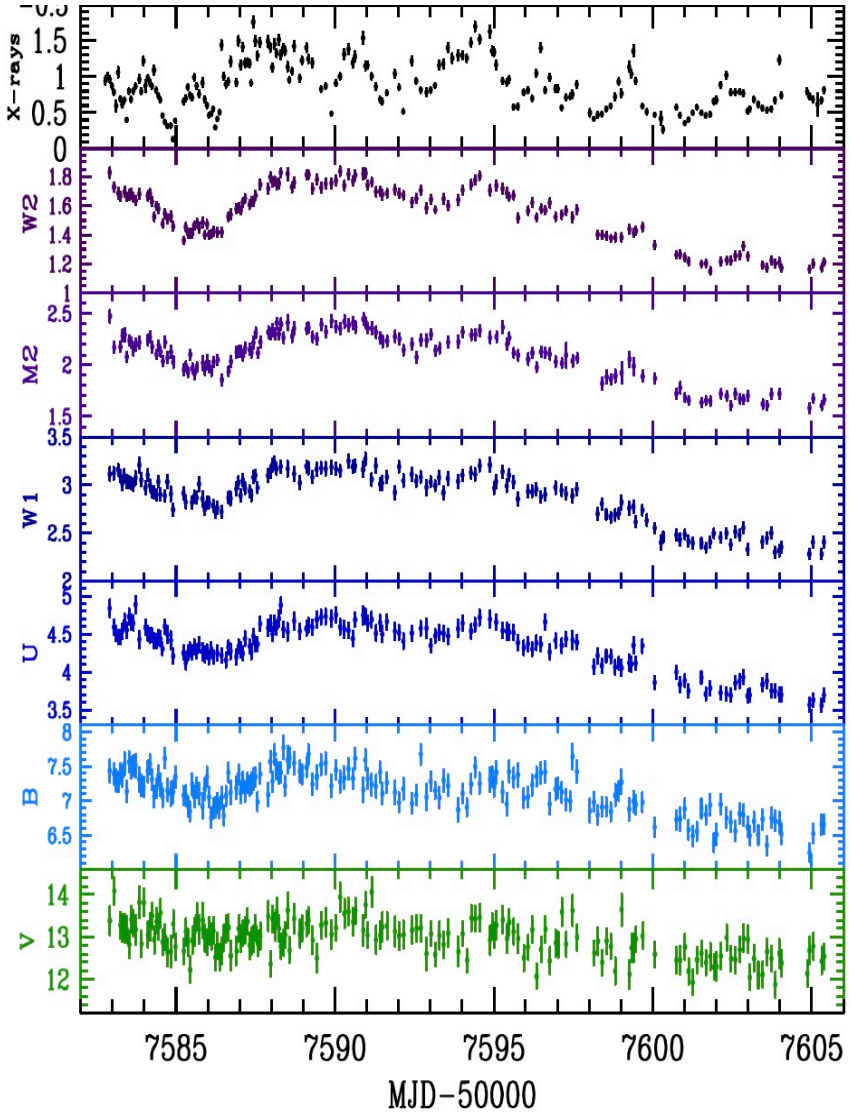


If disc has temperature profile as defined by Shakura+Sunyaev, 1973, then..

$$Lag \propto Wavelength^{4/3}$$

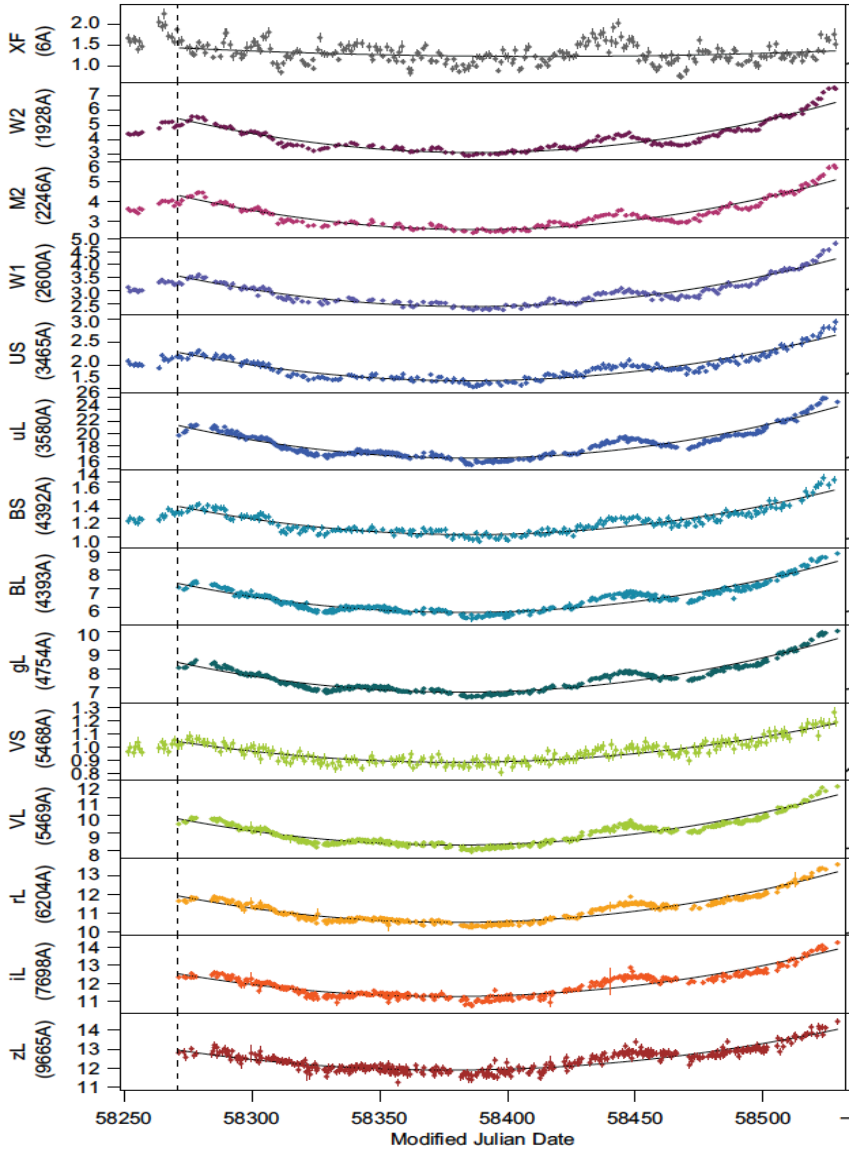
Swift-based Lightcurves

NGC4593



McHardy etal 2018

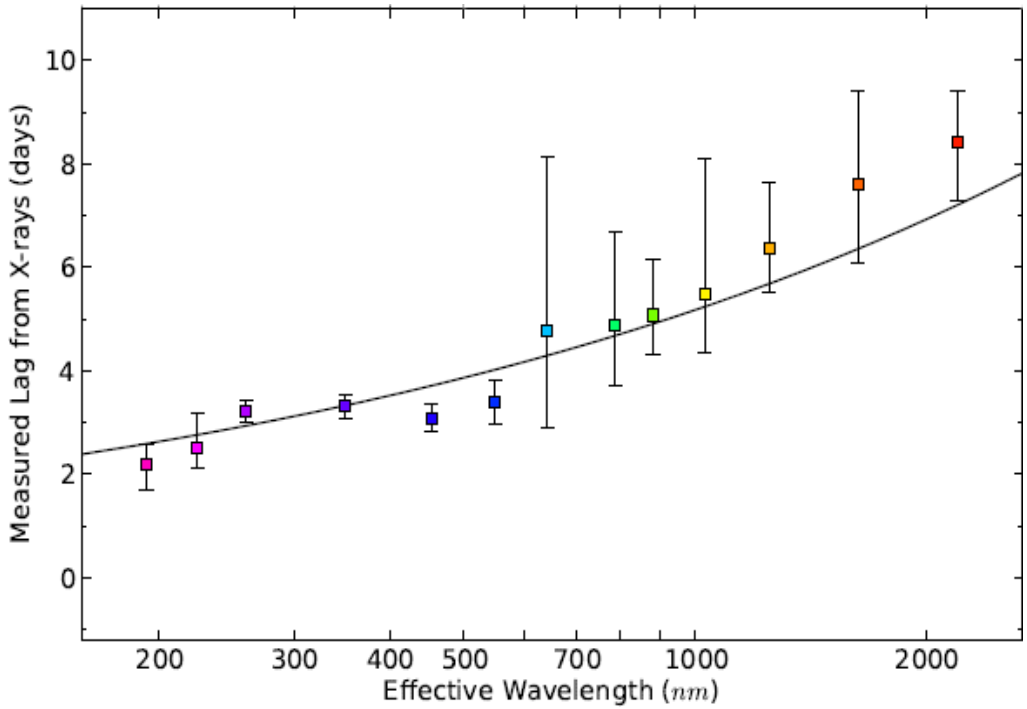
Fairall 9



Hernandez-Santisteban, Edelson etal 2020

Lags – and problems

1. The Excess X-ray Lag

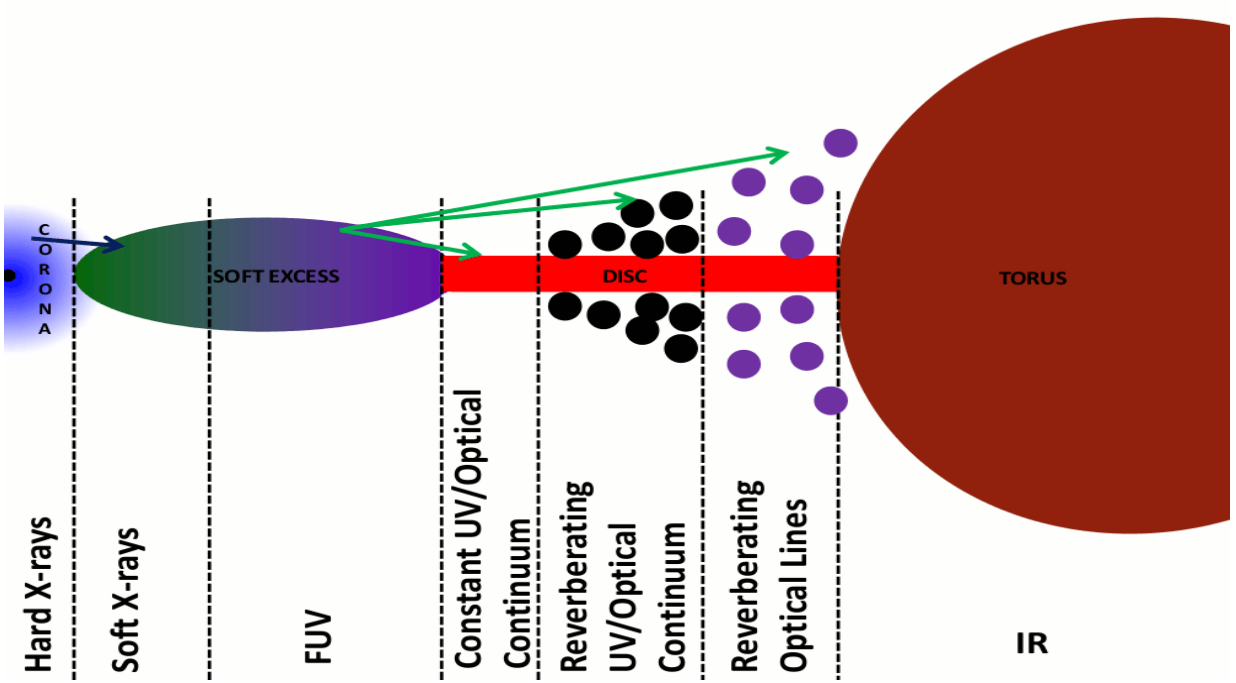


NGC2617 – Shappee et al 2014

Reasonable fit to disc reprocessing in the uv/optical bands

but fit does not go through X-ray zero point – EXCESS X-RAY LAG

Possible geometry for off-set X-ray lags

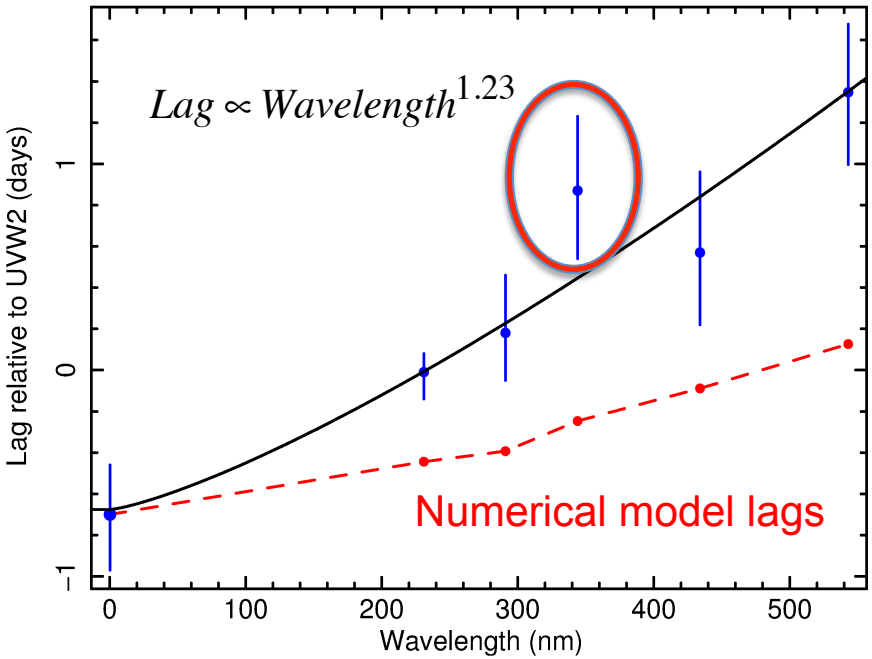


Gardner +Done 2016

Very inner disc absorbs, scatters and delays X-rays, re-radiating as far-UV

Problem 2: Implied disc sizes used to be too big

NGC5548



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

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

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

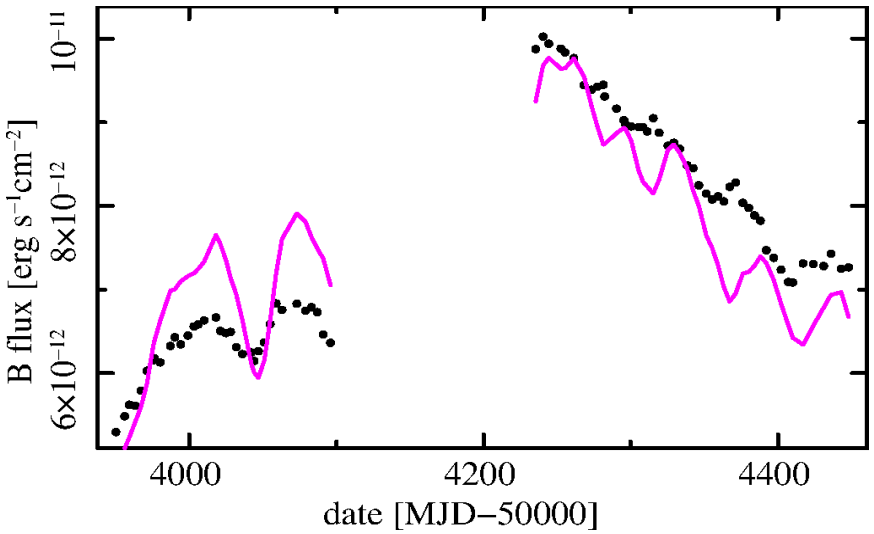
But better modelling,
eg Kammoun et al 2021,
reduces this problem.

Also note excess lag in u-band

See Daniel Kynoch talk

Problem 3: Observed optical lightcurves are too smooth.

MR2251-178
Arevalo et al 2008



Model B-band is produced by convolving the X-ray lightcurve with the response function of the accretion disc.

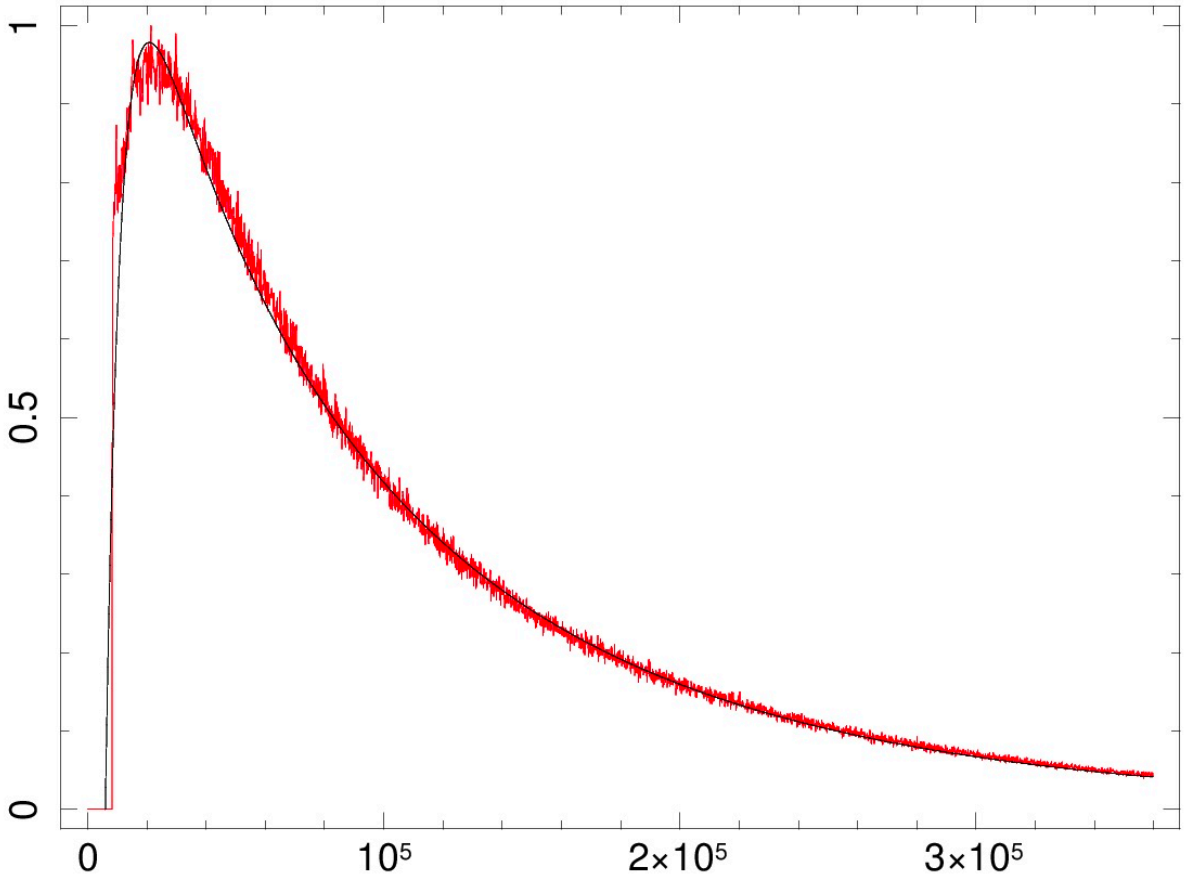
It should be rapidly variable, like X-rays

However observed B-band lc (black dots) is smoother than model lc (purple)

Need illuminating source scale height ~100 Rg to smooth out the model lightcurve
– 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)

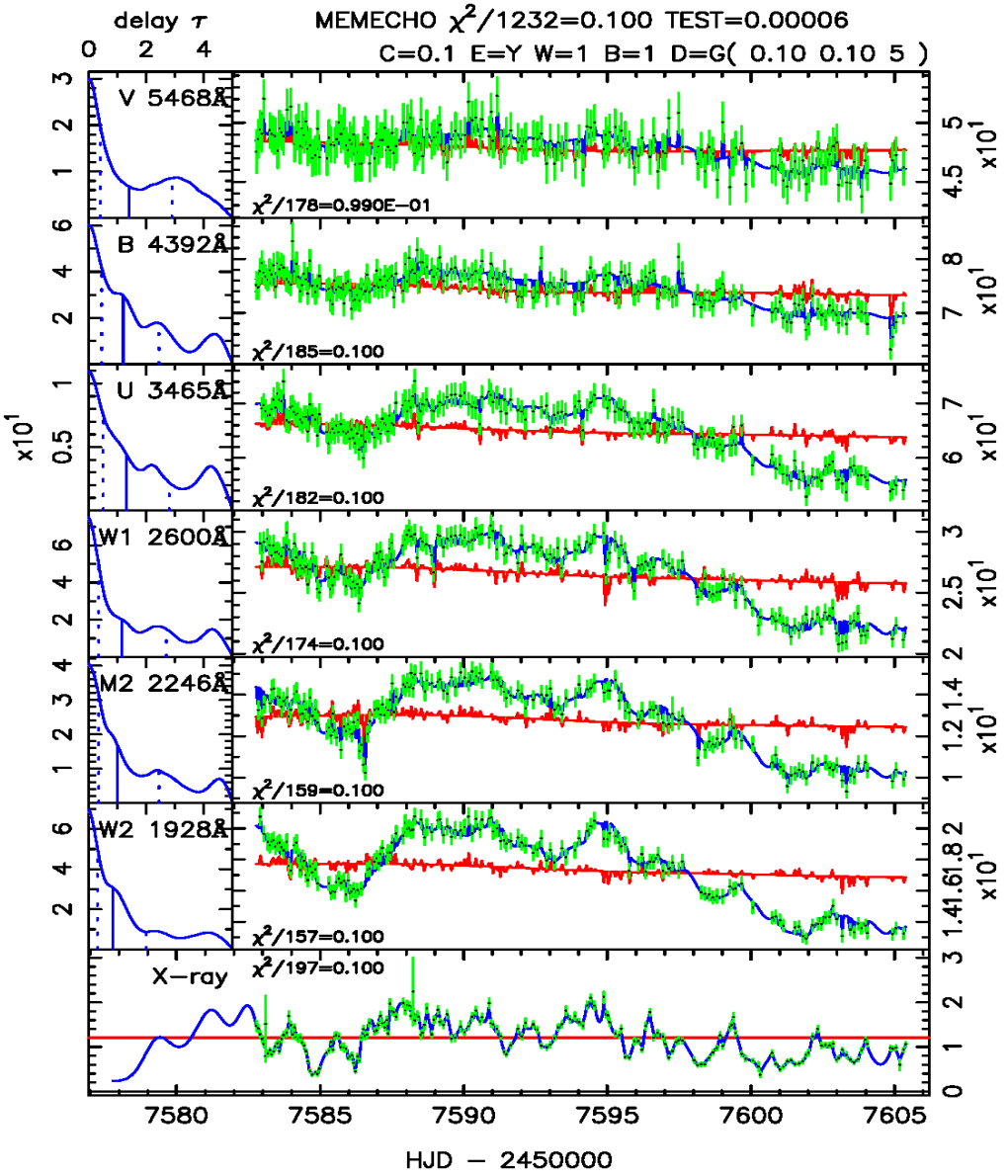
UV Impulse Response Function



Expected UV/optical response from an accretion disc to delta-function X-ray impulse illumination

Convolve the X-ray lightcurve with response function to get UV/optical lightcurves.

Or...Response functions with long tails



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

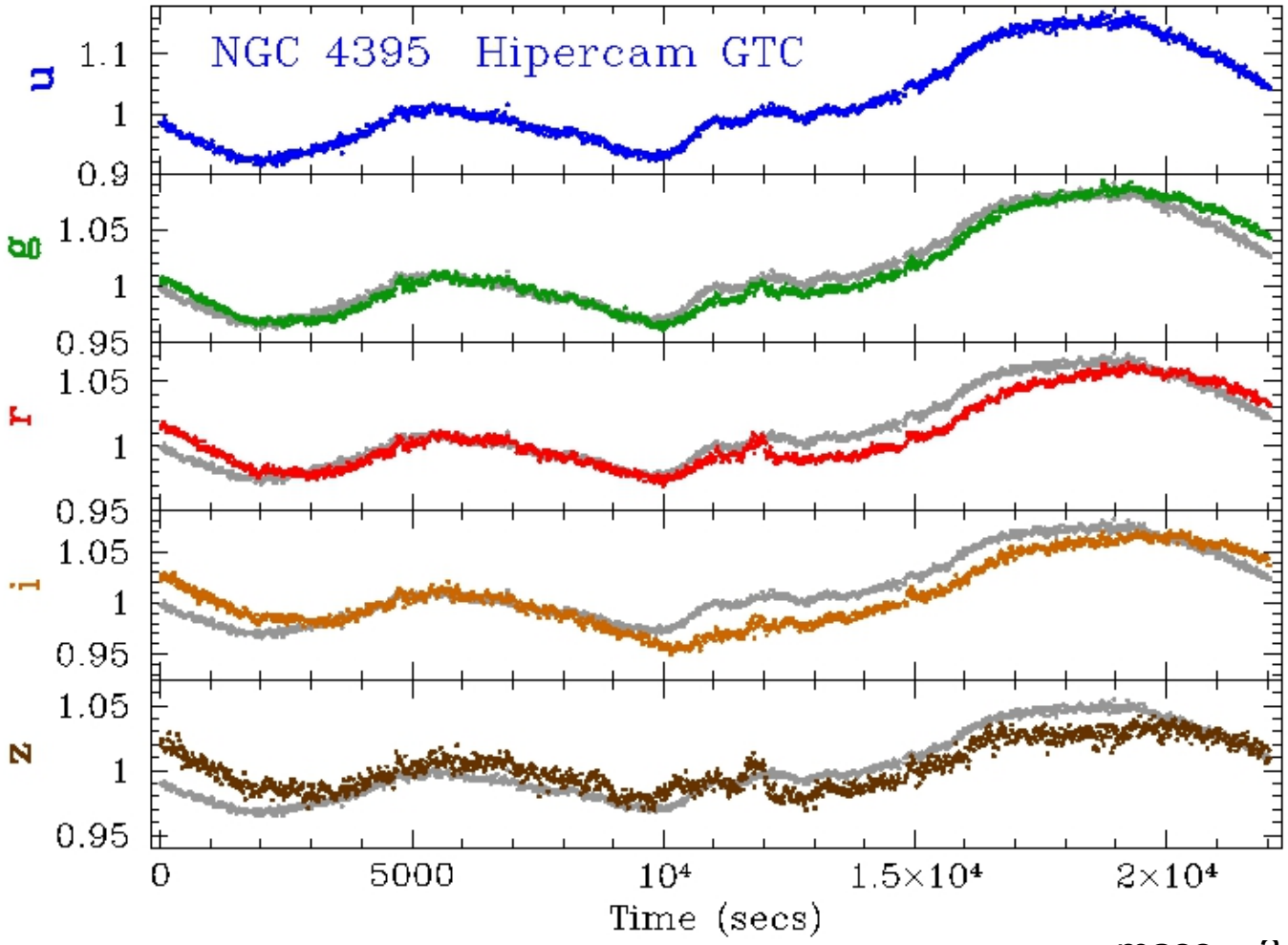
The response functions consist of a peak at short timescales (accretion disc) and an extended tail (surrounding BLR gas).

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

Problem 4.
The Lags don’t always fit $\lambda^{4/3}$
- Importance of disc outer radius

NGC 4395,
Very low mass and accretion rate

Highly precise lags between ugriz bands measured with Hipercam on GTC



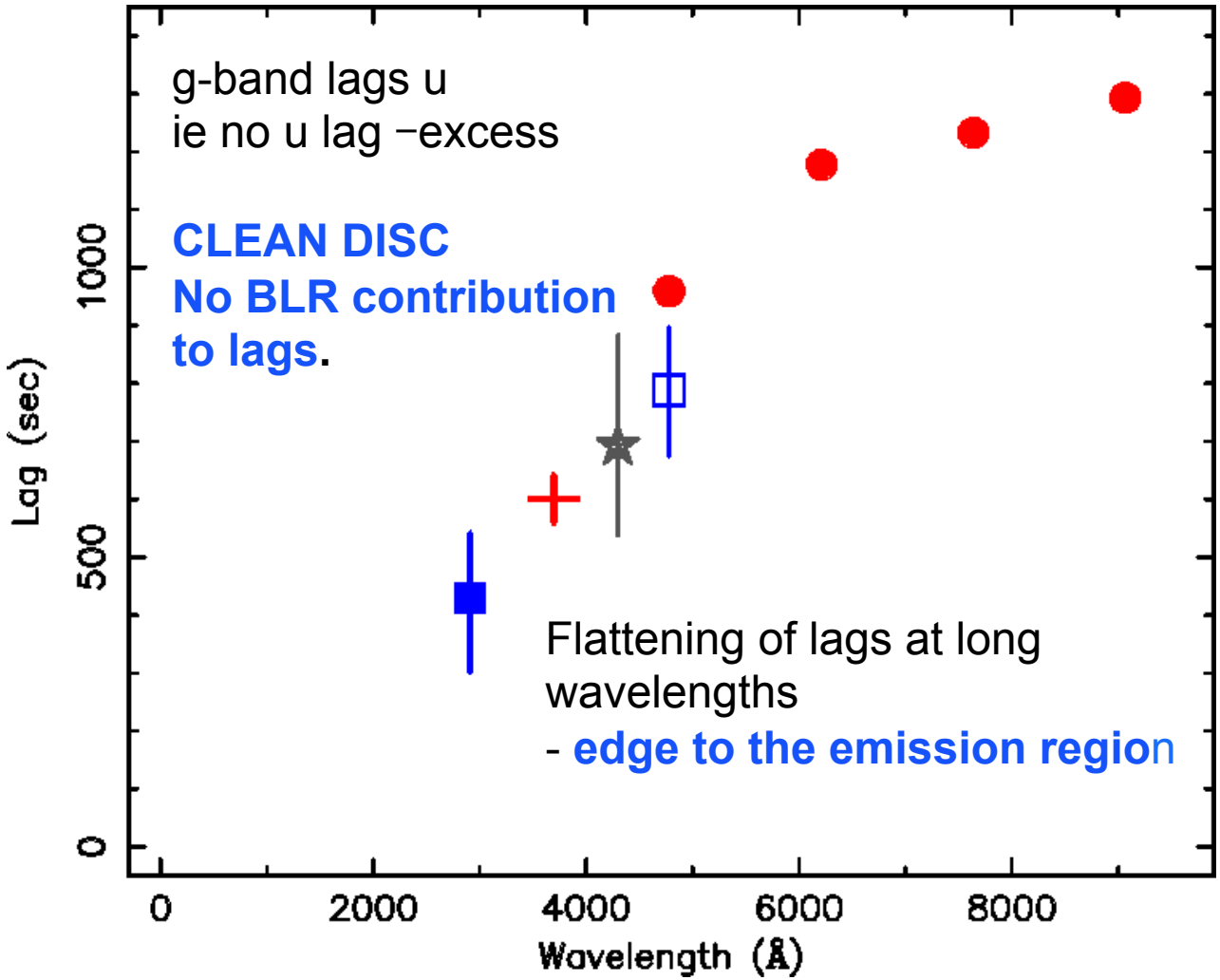
u-band is grey underneath other bands

Ignore bumps in middle - tracking problems

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

(McH+23)

NGC4395 – lags without models



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

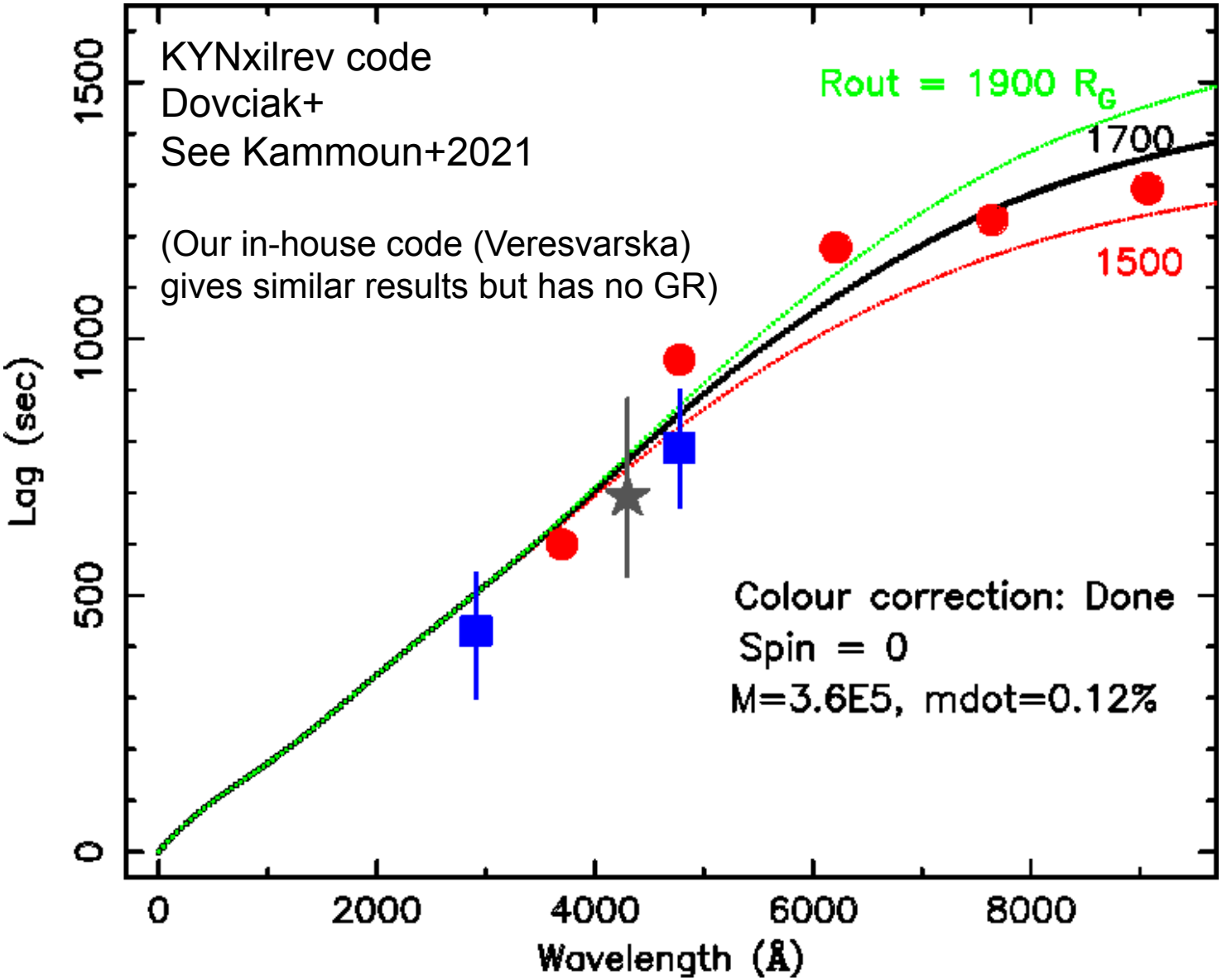
Blue filled square – XMM OM UVW1 relative to X-rays.

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

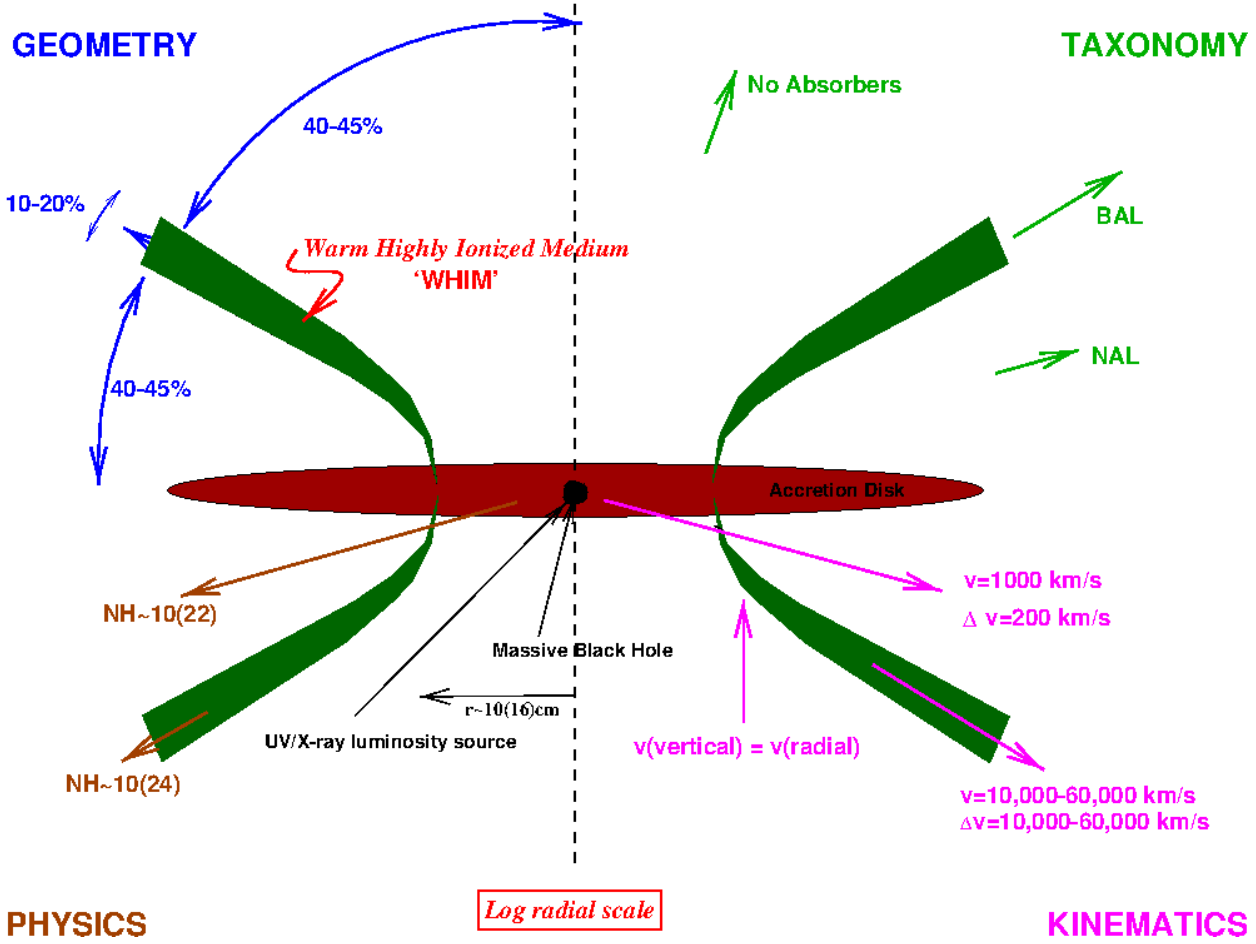
Truncated disc models − vary Rout

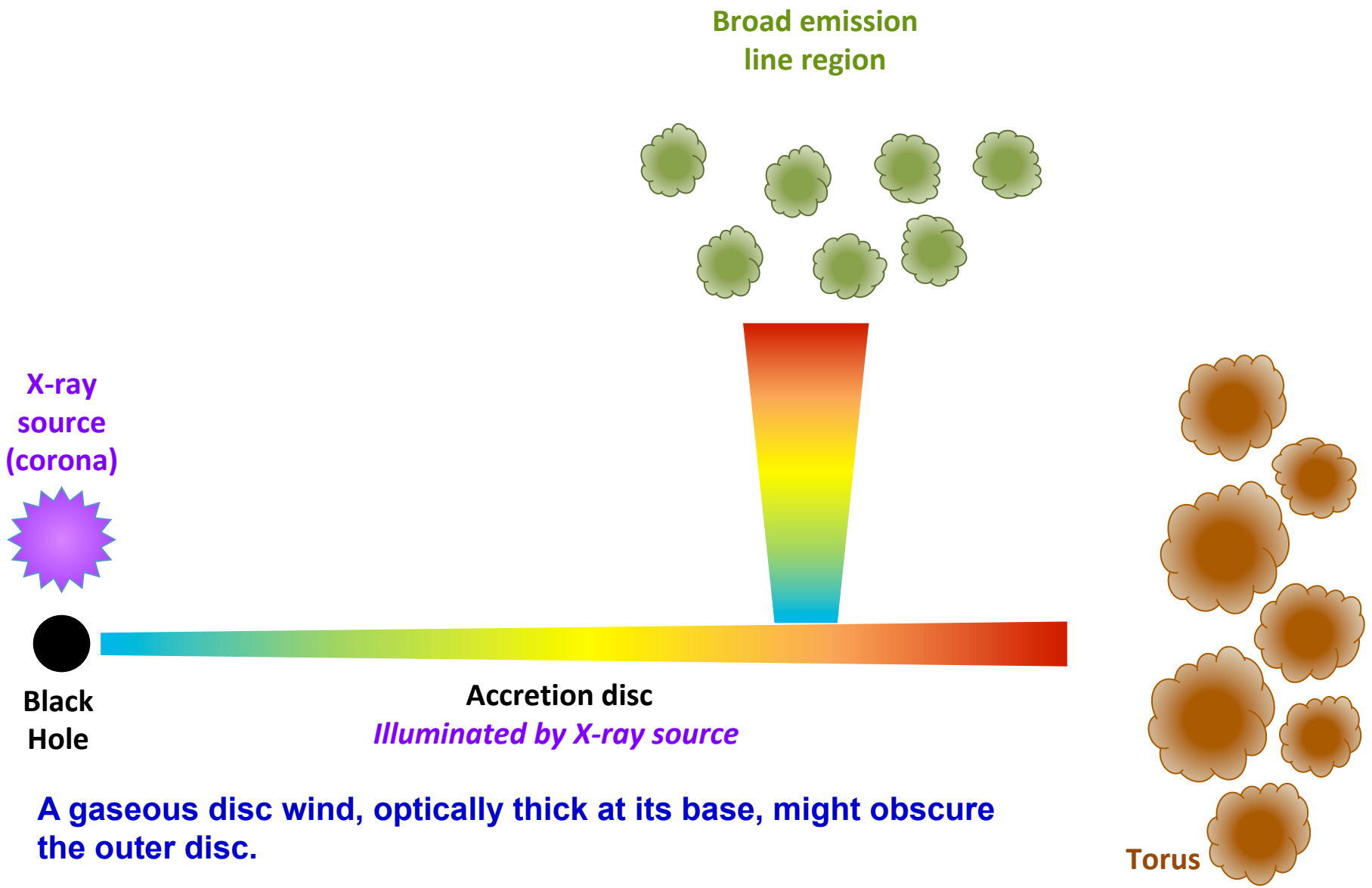


Possible explanation for disc edge
Elvis Wind Scenario

Southampton

Elvis 2000





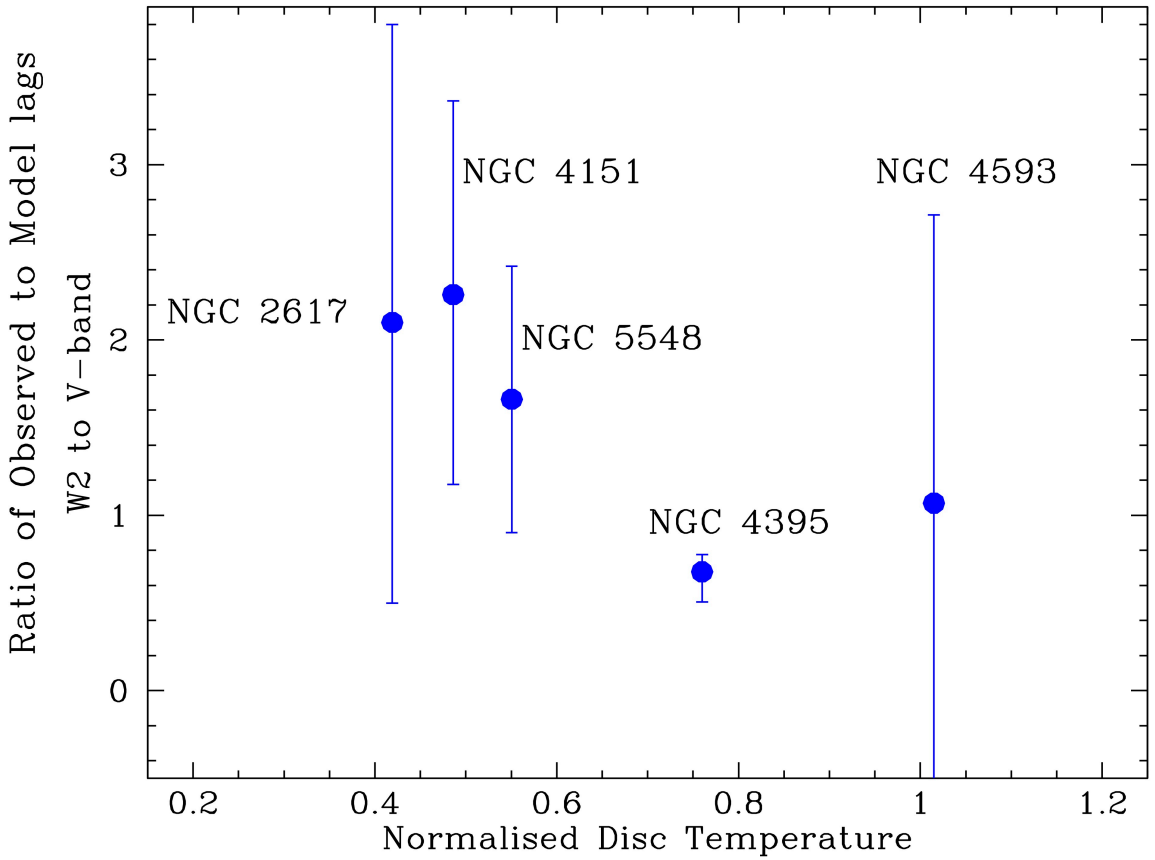
A gaseous disc wind, optically thick at its base, might obscure the outer disc.

Might become the BLR at greater heights

(In NGC4395 it probably isn't a dusty wind as temp is too high)

Comparison between AGN

Observed UV to V-band lags compared to model predictions

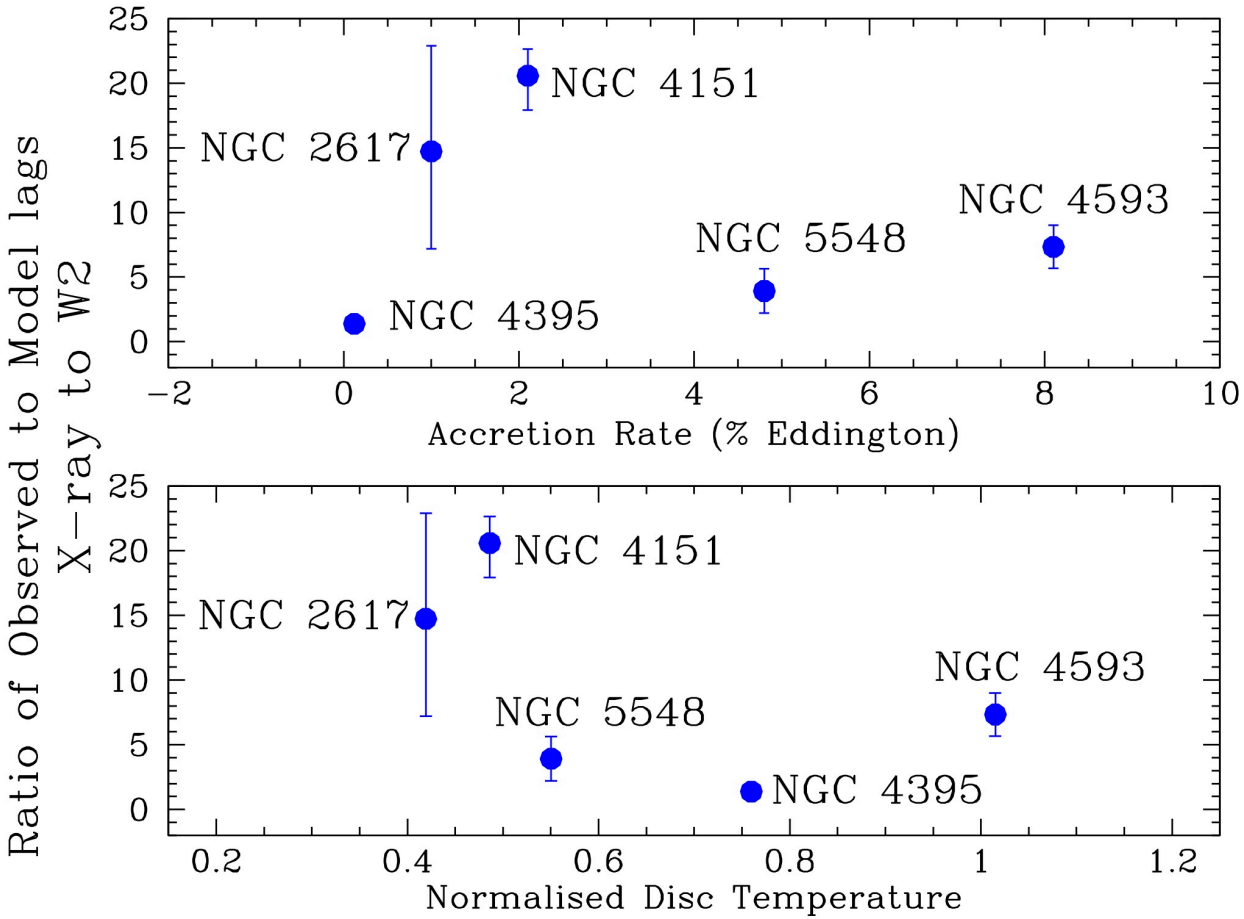


From McHardy+ 2018

All similar and close to SS disc theory

We broadly understand discs.

Observed X-ray to UV lags compared to disc predictions



From McHardy+ 2018

All different and miles away from SS disc theory

We don't understand the X-ray source. Obscuration?

Conclusions

Reprocessing of X-rays by disc can explain many aspects of UV/optical variability − but not all.

Need a second source of UV/optical variability, maybe intrinsic disc variations caused by accretion rate fluctuations.

Also need a second, larger, reprocessor (more from Daniel Kynoch).

Many aspects of disc physics still need attention, eg obscuring winds, inflated inner edges, ionisation/colour effects.

Also need to know the size and shape of the X-ray source and understand the importance of obscuration (Andy Fabian)