General properties of continuum variability of radio-quiet AGN in the optical/UV and X-ray bands

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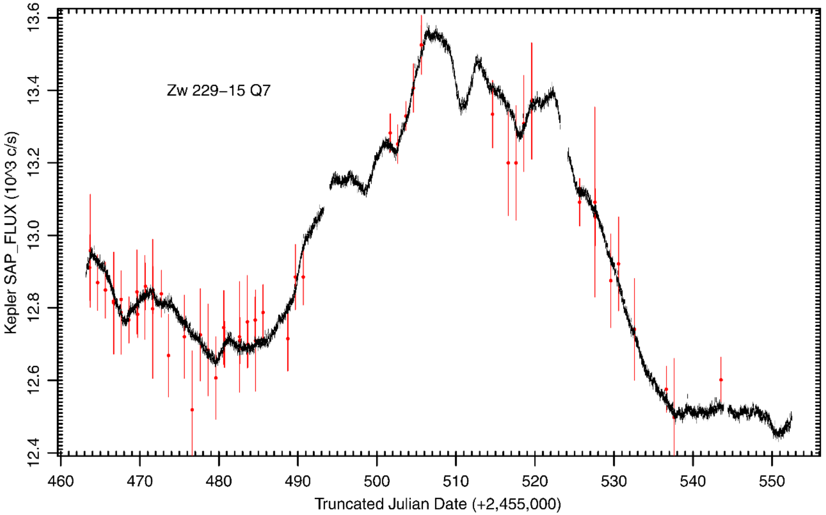
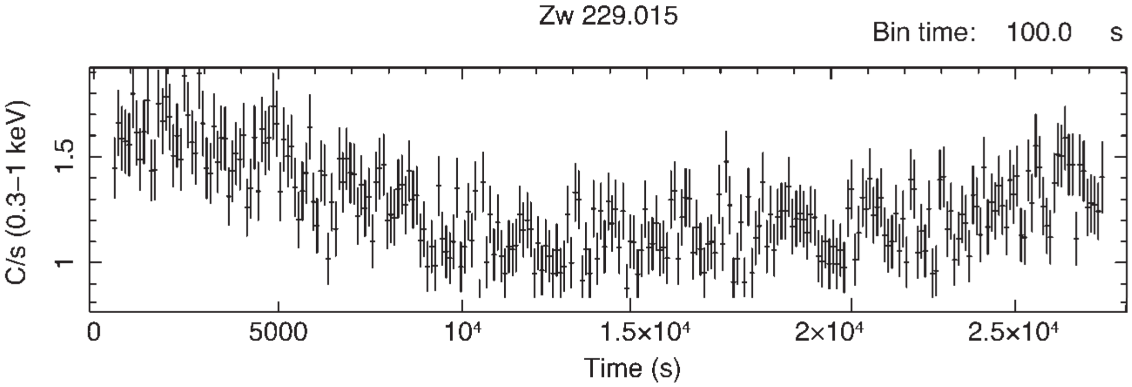
What physical processes shape AGN continuum variability on different timescales?

AGN variability is stochastic

Example of high quality optical data from Kepler satellite (30 min cadence) and X-ray data from XMM (100 s cadence), for the same object, roughly from the same epoch.



Mushotzky et al. (2011)



Adegoke et al. (2017)

Note a difference in the amplitude, particularly for the same duration of the lightcurve.

AGN variability covers an enormous range of timescales

Currently the best data, from Beard et al. (2025), for NGC 4395, covering 7 decades in frequency

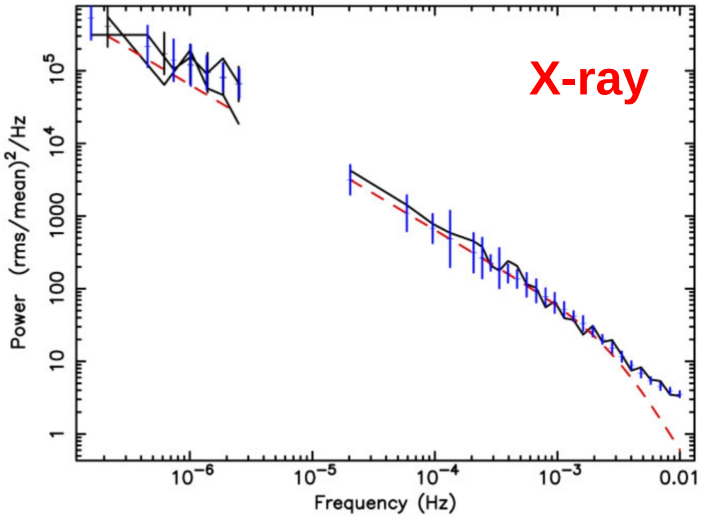


Figure 6. Combined *Swift* and XMM PSD. The data are represented by the continuous solid lines. The dirty model is represented by the errorbars and the underlying PSD is given by the dashed line.

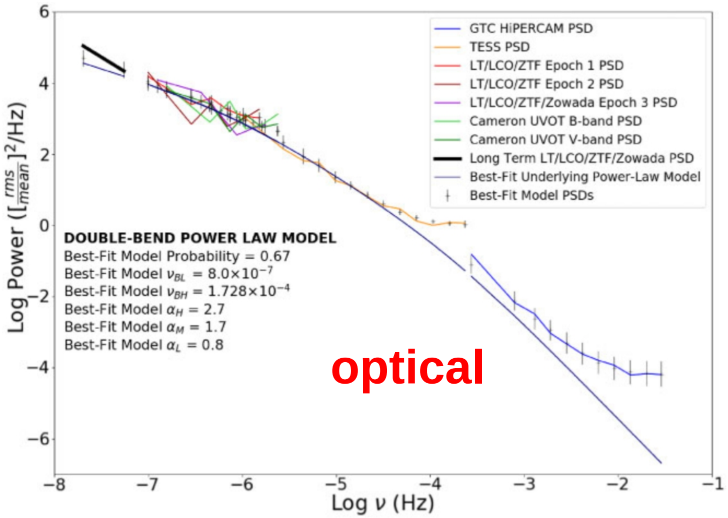
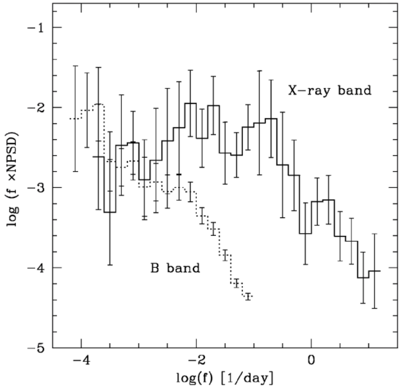


Figure 15. The optical power spectra from our data plotted with their best-fit model PSDs as well as the best-fit underlying power law for a double-bending power law model.

Surely not DRW.

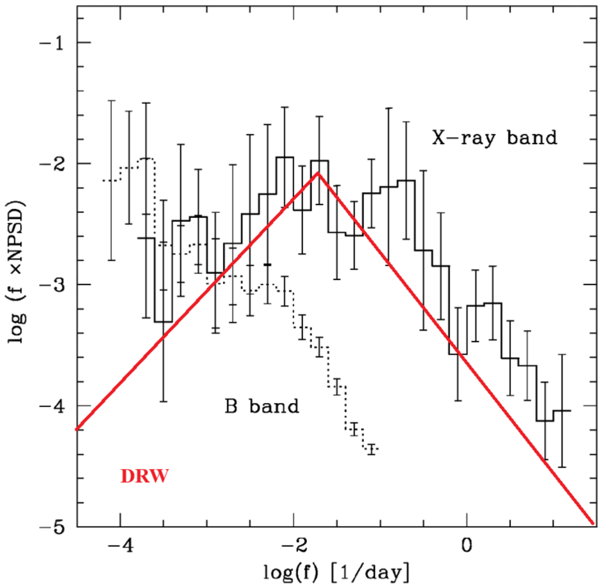
Here power is not muliplied by frequency !

DRW is a convenient phenomenology, but a single characteristic break cannot capture the full multi-timescale structure seen in real AGN



Note that this shape does not look like a Damped Random Walk!

Czerny et al. 2003



DRW has a single break and two slopes: 0 and -2, which on f P(f) is +1 and -1

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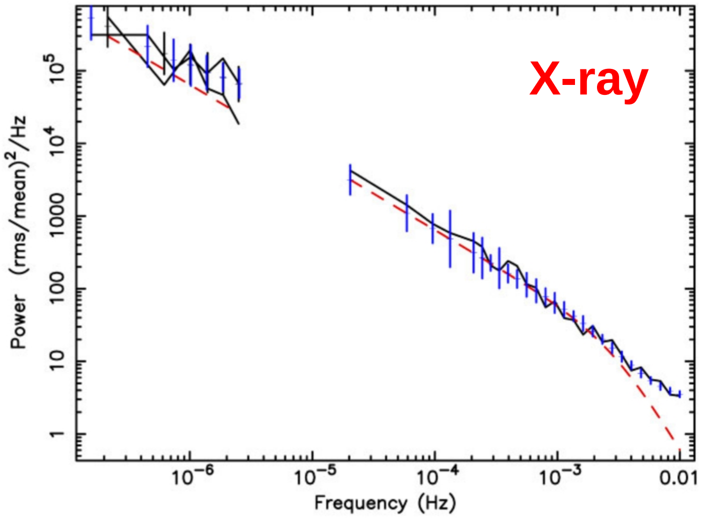

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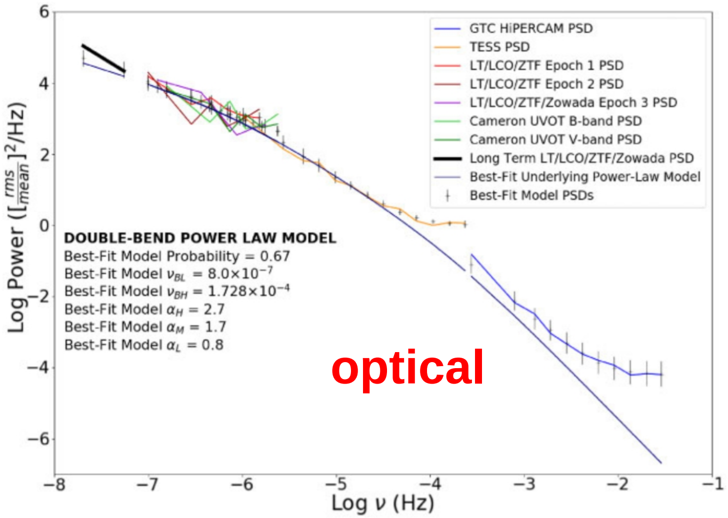

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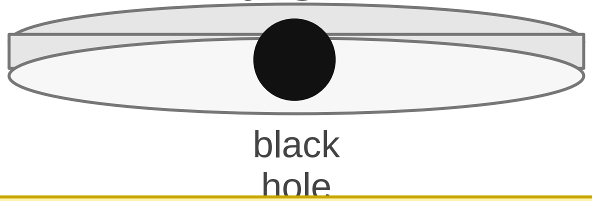
The X-ray variability similar to soft state in X-ray binaries!

But what physical component transports variability across the flow?

Here power is not muliplied by frequency !

From a standard disk to stochastic variability

Shakura–Sunyaev thin disk



MRI turbulence

effective alpha viscosity
+ local stress / dissipation fluctuations

Characteristic local timescales

Dynamical	$t_{dyn} = 1 / \Omega_K$
Thermal	$t_{th} \simeq t_{dyn} / \alpha$
Viscous	$t_{visc} \simeq (R/H)^2 \, t_{th}$

$$t_{dyn} \ll t_{th} \ll t_{visc}$$

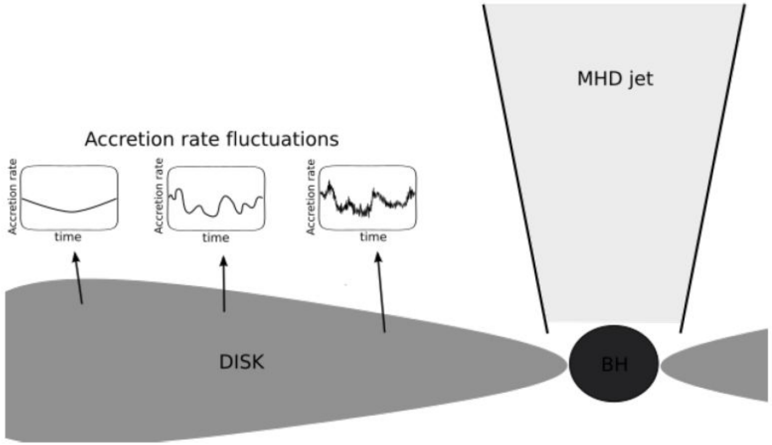
MRI growth: $\sim t_{dyn}$
magnetic / thermal response: up to $\sim t_{th}$

Local fluctuations are generated naturally. The next question is whether they propagate through the accretion flow.

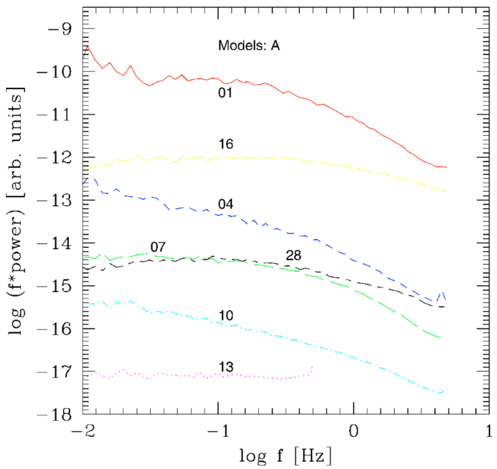
Propagating fluctuations: an attractive framework

Picture of propagating fluctuations (Lyubarskii 1997, Kotov et al. 2001, Arévalo & Uttley 2006) is attractive to explain the power spectrum.

But in realistic propagation the signal can be strongly filtered and distorted, not preserving all accumulated frequencies. And if fluctuations propagate through the accretion flow, the warm corona should naturally participate in this process.



(https://ned.ipac.caltech.edu/level5/Sept18/Rieger/Rieger2.html

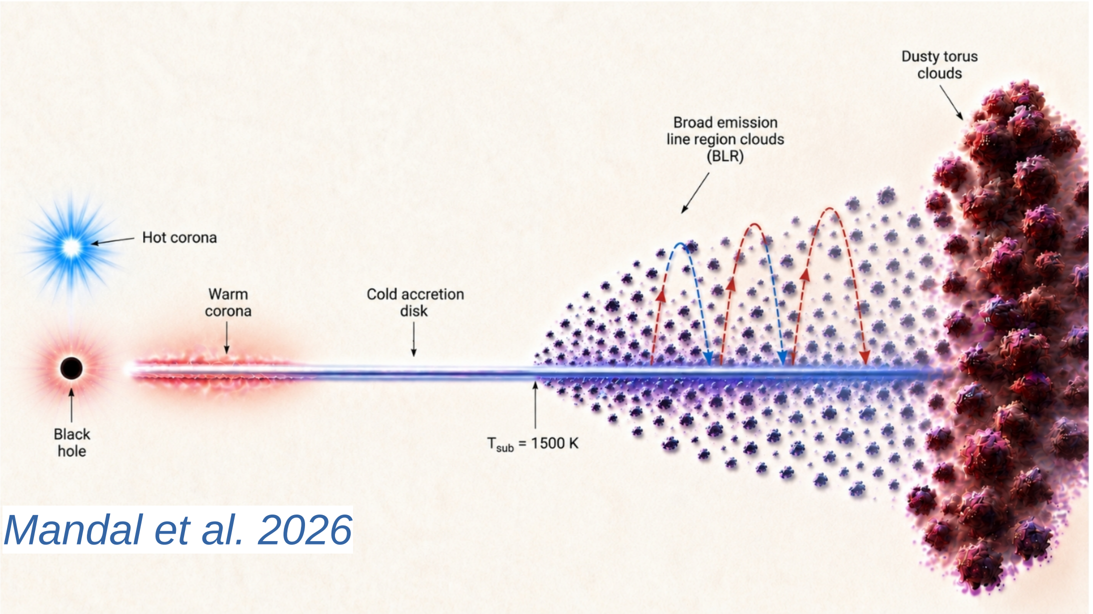


In Janiuk & Czerny 2007) we did some numerical experiments with accreting warm corona which produced more $\sim f^{-1}$ slopes but it was not done systematically enough...

Local fluctuations and their propagation

Local MRI-driven fluctuations may provide the primary stochastic driver. But propagation is complex, even in a single medium. The propagation is not one-sided unless the motion is supersonic. The local fluctuations do not propagate only downstream. But they are also dumpted.

AGN spectra imply a more complex accretion flow



Mandal et al. 2026

Schematic view of an active nucleus: elements

- Hot corona: likely a jet base
- Warm corona – surface layer of the inner disk
- Cold outer disk
- Broad Line Region – likely a form of partially failed dusty wind
- Outer dusty torus
- Inner BLR (line-driven wind) not marked

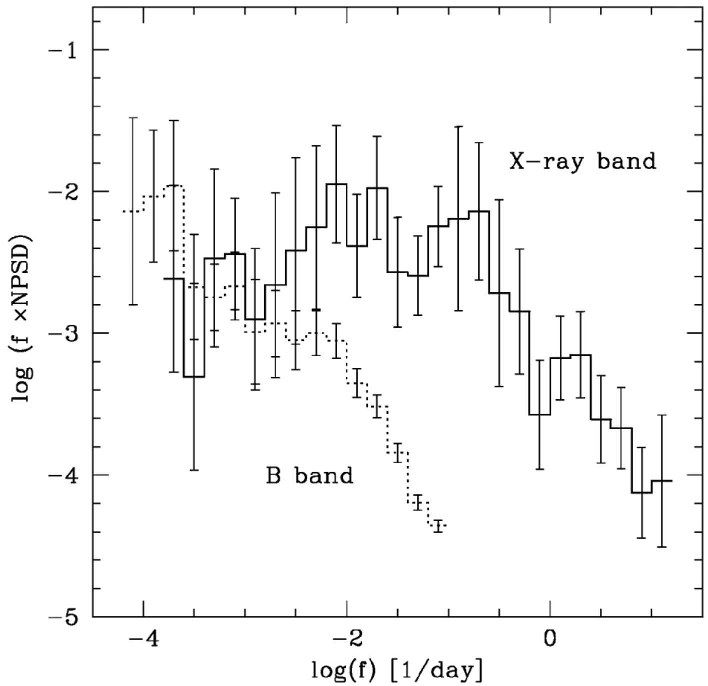
The compact X-ray emitting component provides a natural source of external irradiation.

The disk is also driven non-locally by irradiation

At short timescale optical variability might look like a considerably smeared version of X-rays. At the longest (year) timescales its amplitude gets higher implying intrinsic variability.

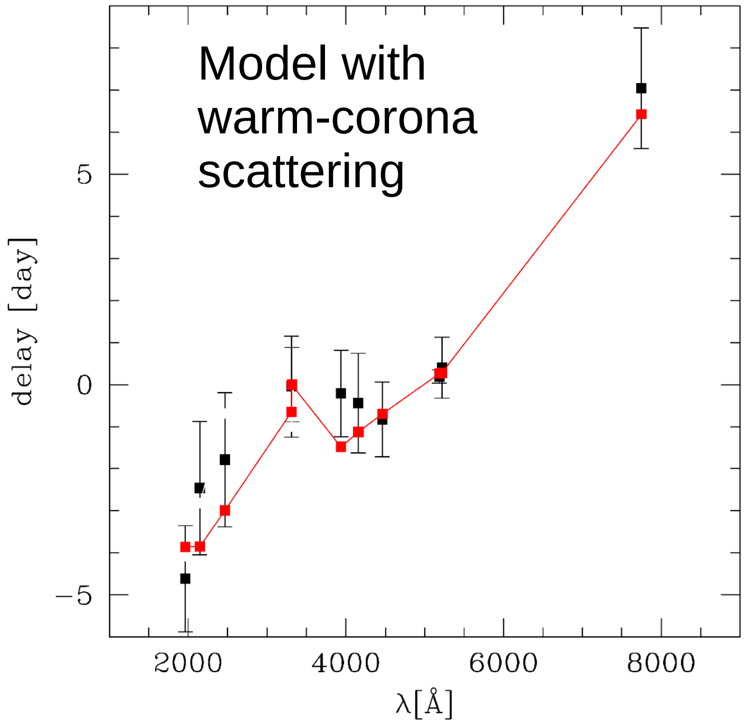
A useful working picture: short timescales are dominated by irradiation, long timescales are intrinsic.

Note that power spectrum is multiplied by frequency!



Czerny et al. 2003

Continuum reverberation: the short-timescale response



Source: Fairall 9

Measured delays (black points): our OCM monitoring + SWIFT (Mandal et al. 2026), measured with respect to λ = 3468.0 Å.

Model:

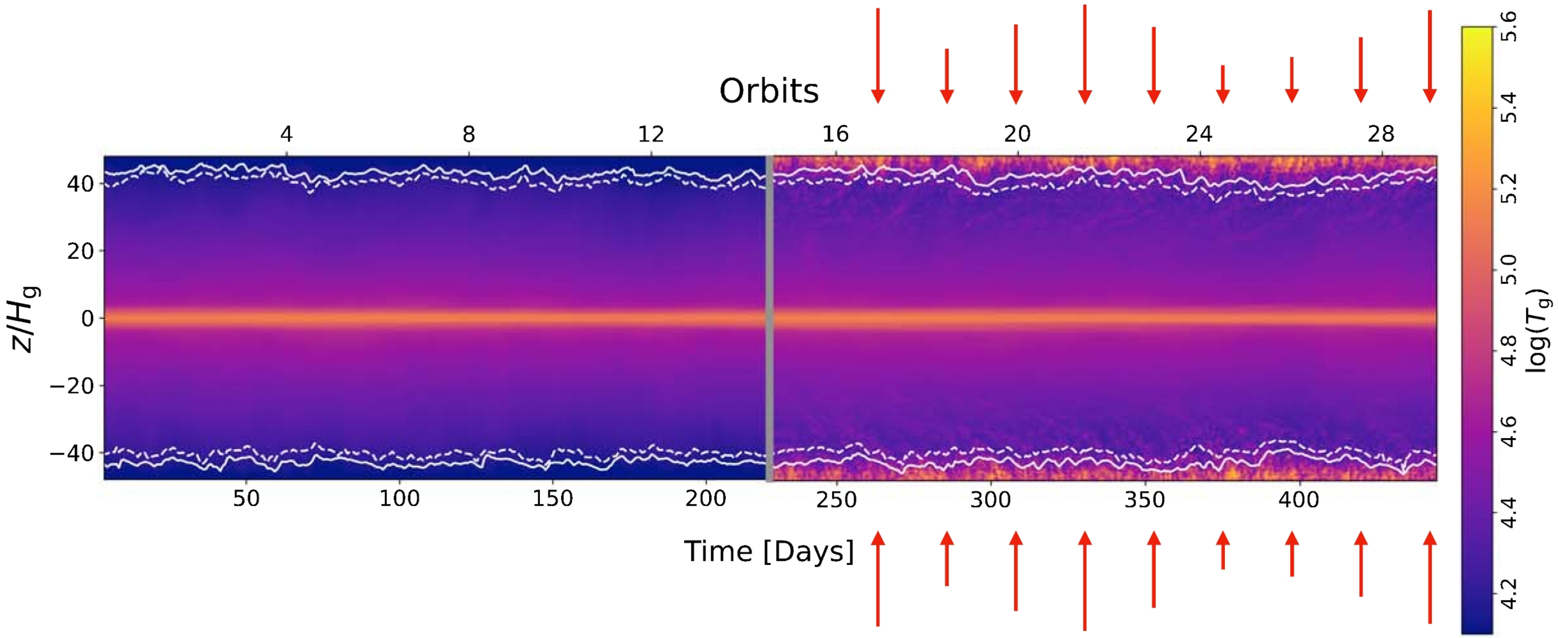
- Hot corona
- Warm corona / scattering layer
- Broad Line Region
- Outer dusty torus

Why are observed disk lags and sizes often claimed to be too large?

Many papers use a semi-analytical formula for standard accretion disk delay and neglect the following effects:

- Irradiation geometry and explicit role of the source height
- Color-temperature correction
- Diffuse continuum from the BLR
- Diffuse continuum from the hot dusty torus (important at long wavelenghts)
- Scattering / reprocessing in an extended warm corona

Local fluctuations — non-local response



Finally, innermost fluctuations through irradiation couple to the local MRI fluctuations at longer timescales.

An example of such simulations from Secunda et al. (2025)

Detrending helps — but it can change the measured lag

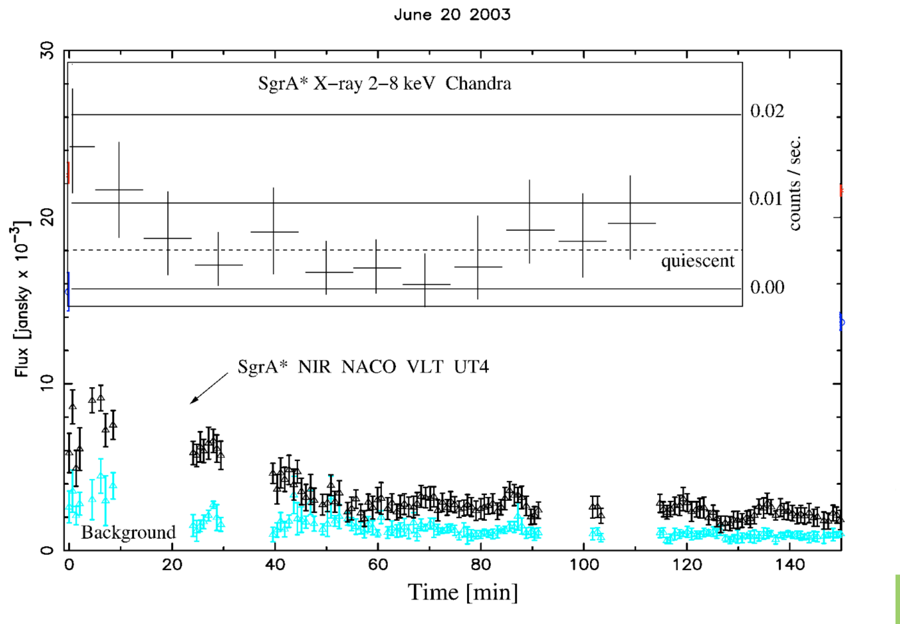
- Detrending can isolate the fast reverberating component.
- It also removes low-frequency power and changes the relative weighting of timescales.
- The inferred lag can therefore depend on the adopted detrending procedure.

Side problem – inner hot flow (ADAF)

So far I concentrated on bright AGN, with the Eddington ratio above a few %. Low luminosity AGN like LINERS. X-ray variability on long timescales (months to years) is very common in Low-Ionization Nuclear Emission Line Region (LINER) galaxies, while short-term variability (hours to days) is rarely or not detected (see e.g. Hernández-García et al. 2014).

The best-studied case is Sgr A*. The source shows fast daily variability in X-ray, IR and mm band, since the source is well resolved spatially, but the variability is more flare-like, reminiscent of blazars, instead of typical roughly uniform stochastic signal.

First detection of simultaneous X-ray and IR burst from Sgr A (Eckart et al. 2004)*



When stochastic variability becomes a state change?

Is this related to other AGN components (ADAF, warm corona) ?

possible connections / open questions

There is not much done in this field. We know about 1 milion of AGN, 1000 Changing Look/Changing State AGN (CL AGN; Chen et al. 2026 from SDSS, LAMOST and DESI) and a dozen of Quasi-Periodic Eruption (QPE). Surely more CL AGN will come.

- Most of these phenomena take place at a few % of the Eddington luminosity where we extect a transition from a cold disk to an inner hot flow close to the black hole
- In QPE most of the variations happen in the soft X-rays, and it looks like a Comptonization turning on/off. Inner ADAF or Warm Corona?
- Timescales are very short, basically corresponding to local thermal timescale
- Timescales in CL AGN are relatively short in comparison with the viscous timescale in a cold disk but interesting in the context of ADAF/Warm Corona
- Amplitude in CL AGN is relatively small in comparison to classical predictions of radiation pressure instability but warm corona can partially stabilize the disk

?

One accretion flow — locally driven, non-locally coupled

- Local stochastic fluctuations / MRI
- Inward propagation through the accretion flow
- Outward radiative coupling and reverberation
- Structural/state changes add a genuinely different level of variability but they are expected knowing the spectral complexity of AGN

AGN continuum variability may have a common local stochastic driver, but the observed signal is shaped by inward propagation, outward radiative coupling and — in extreme states — structural changes.