Accretion processes onto black holes - theoretical problems, constraints from the optical data

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Basic brics of AGN

Needed elements:

- Supermassive black holes
  As soon as the nature of quasars as extragalactic sources was recognized (Schmidt 1963), supermassive black holes were considered to be responsible for the activity (Salpeter 1964, Zeldovich 1964)
- Accretion flow onto a supermassive black hole
  This provides the source of radiation which we see. This could be a hot ionized material (e.g. M87, Sgr A*) or cold (10^5 K) black body emitting material in Seyfert galaxies or quasars. The material is provided by the host galaxy.

Unwanted complications:

- Jets
  We see the clearly in radio images, but also at other wavelenghts
- Uncollimated winds
  We see those as well, most directly in absorption lines
- Dusty/molecular torus

Basic brics of stellar black holes

Needed elements:

- A black hole of ~ 10 solar mass
  Clearly predicted by the evolution of massive stars
- Accretion flow onto a black hole
  Efficient accretion can be either from a close companion star, or from the host star during the collapse of a supernova. First X-ray sources detected on the sky were of this class

Unwanted complications:

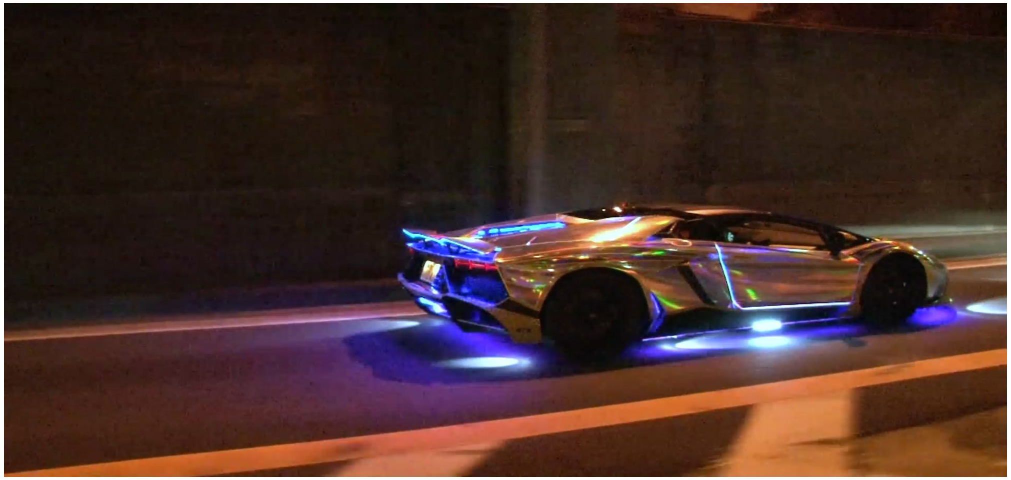
- Jets
  We see them clearly in radio images
- Uncollimated winds
  We see those as well, most directly in absorption lines
- Outer disk rim and exclipses

There is a lot of similarity between the stellar and supermassive black holes, after scaling they can provide a lot of complementary information!

Broad band spectra

AGN are like cars: viewing angle is essential. Some objects (due to orientation) are less convenient for general studies.

https://www.brindley.co.uk/news/when-to-use-different-types-of-car-lights-while-driving/

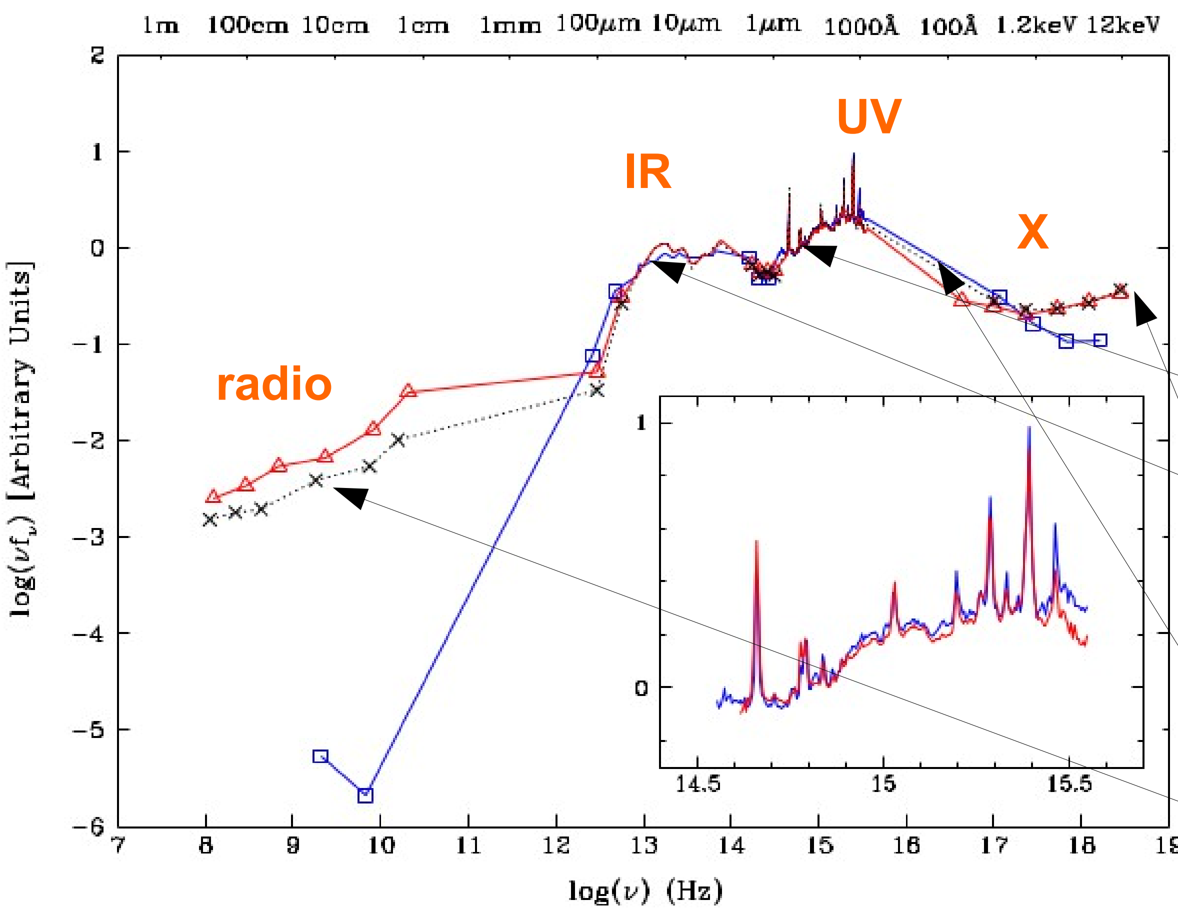


https://www.caranddriver.com/car-accessories/a38025968/led-lighting-for-cars/

So for the moment I will skip blazars...
In galactic sources jets are usually fainter apart from the gamma-ray bursts. So I will skip those as well.

Broad band spectra of AGN

Mean spectrum for radio-loud (red) and radio-qiet objects (blue) from the sample of bright AGN (quasars)

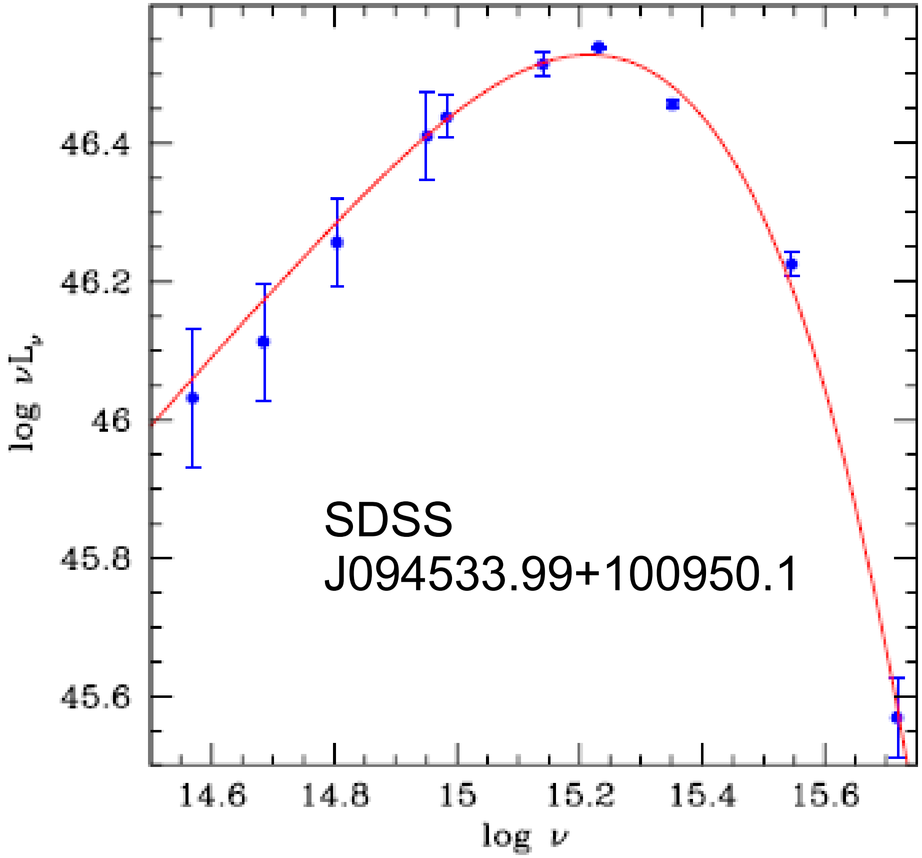


Quasars are black holes accreting at high rate and luminosity basically above 1 % of Eddington.

Elements:

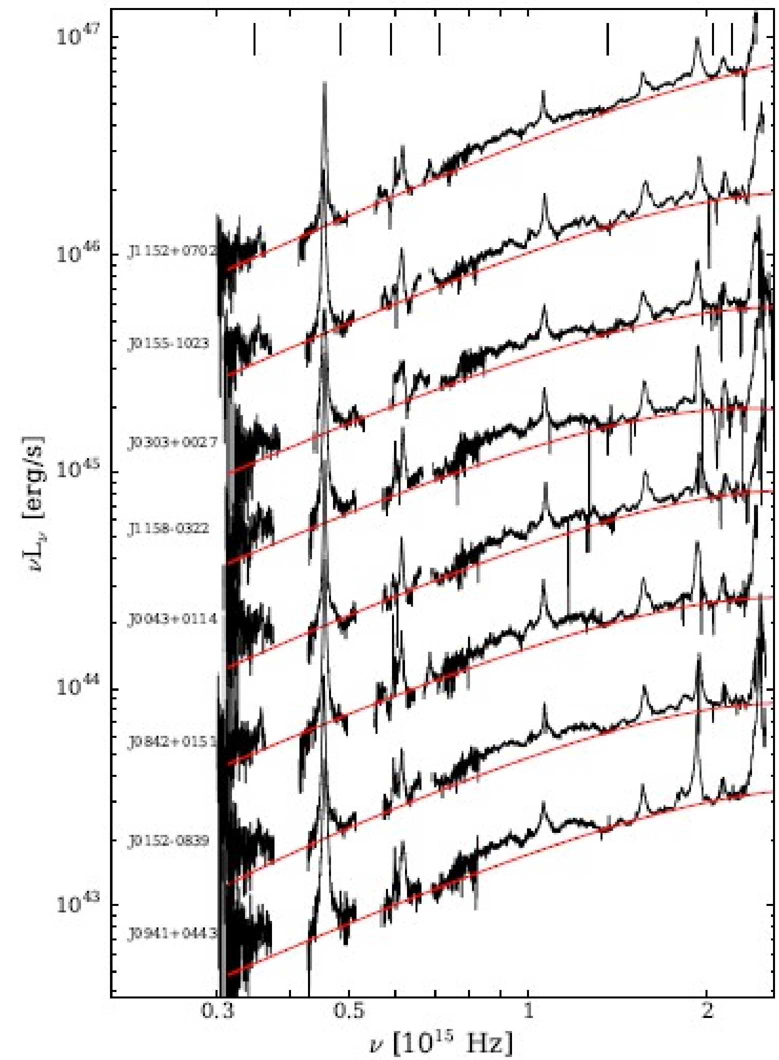
- Cold disk
- Dusty torus
- Compact X-ray corona
- Soft X-ray excess
- Jet

Optical/UV spectra in bright quasars



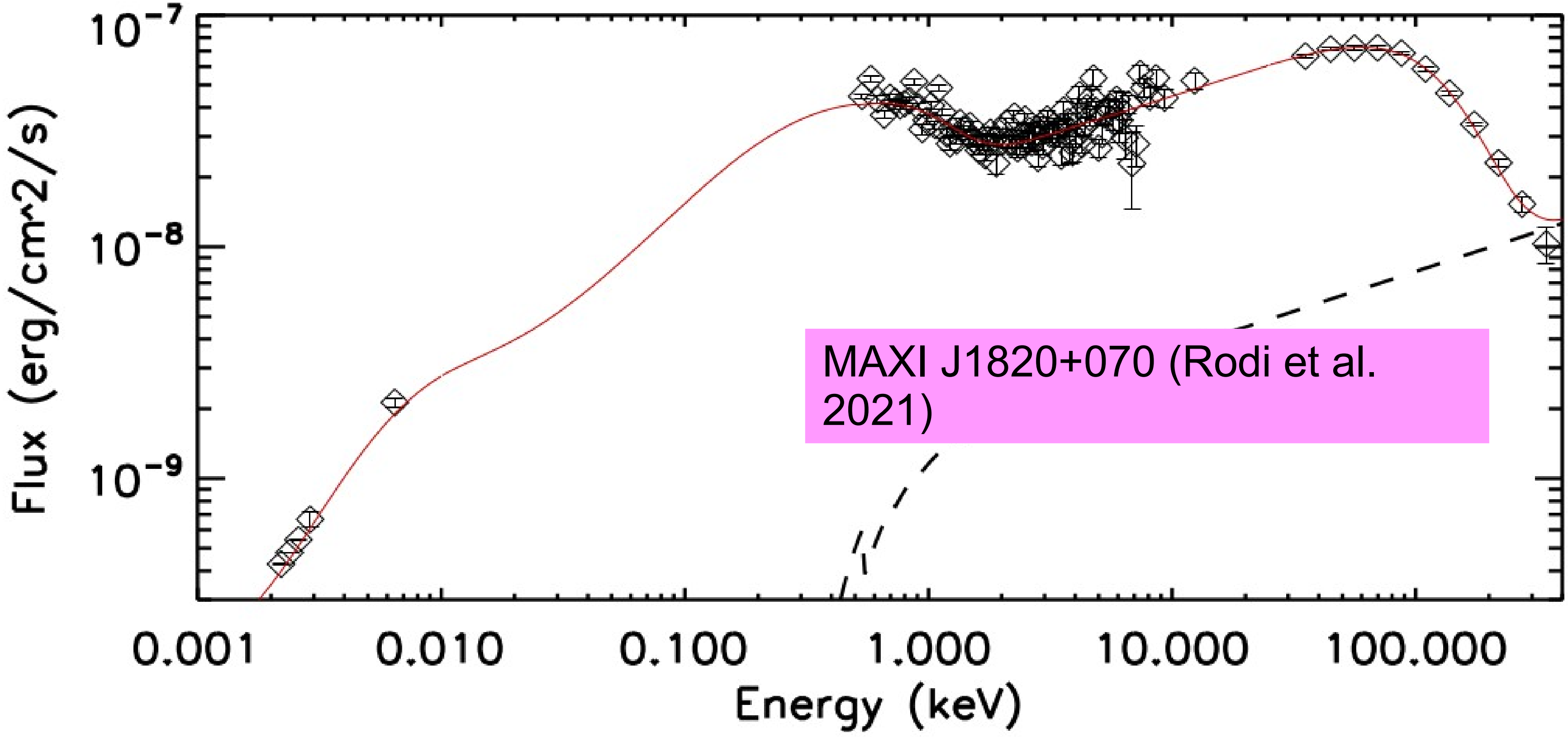
Czerny et al. 2011

They are will fitted by the standard disk down to ISCO.



Our spin was 0.3, Capellupo et al. (2015, plot on the right) have spins from high retrograde to high prograde.

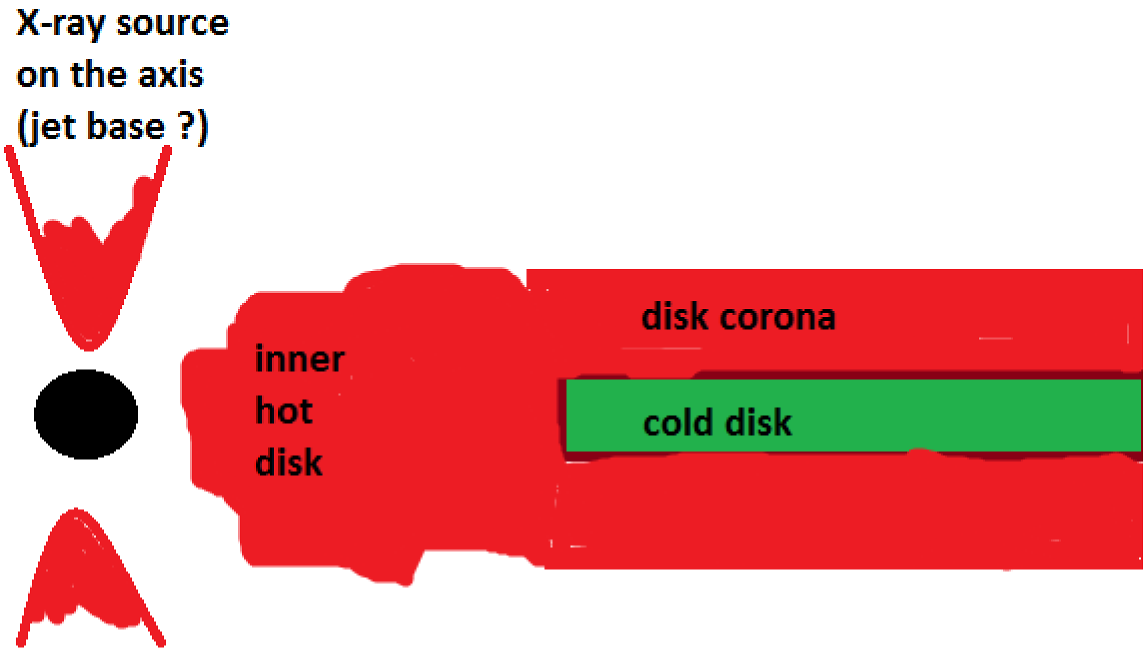
Broad-band spectra of GBH



There is a systematic difference by a factor of 100 between the temperature of the cold disk in GBH and AGN. Hot plasma and jet have roughly the same properties, apart from the local density, but the optical depth is the same.

General picture of inner flow

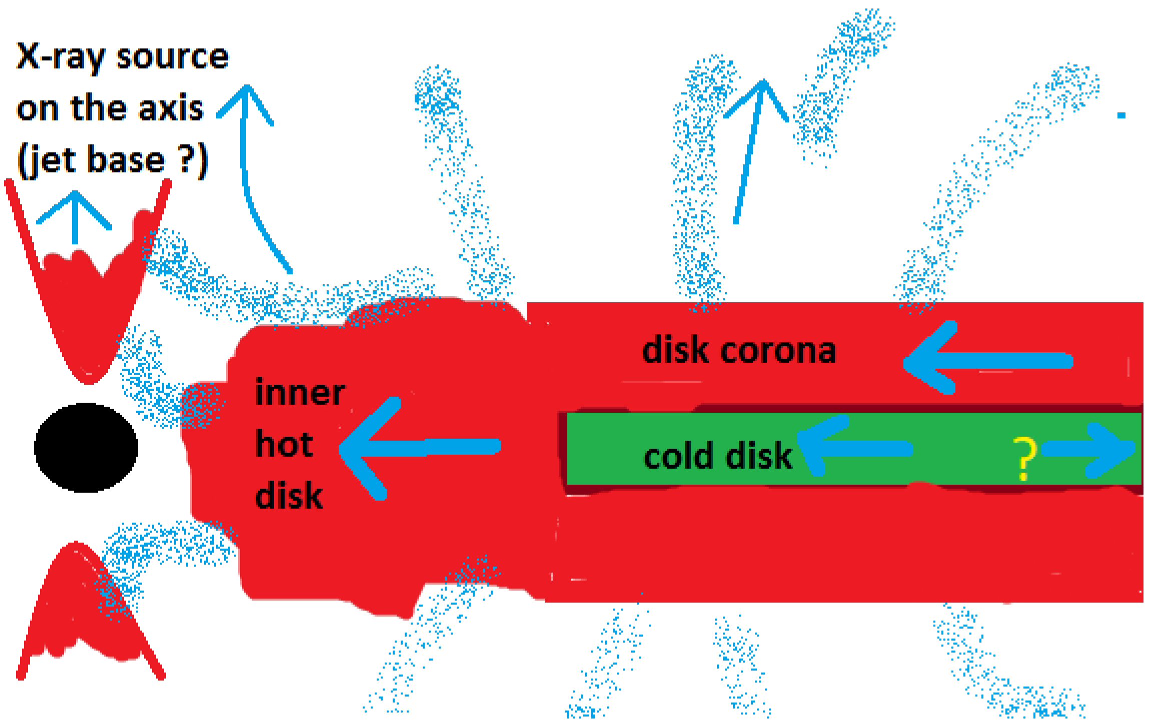
The picture is universal, varying proportions you can get any AGN or a GBH.



There is no proper theory of this picture but an impressive amount of data information accumulates which should allow to address all these details. They come from variability. I will discuss that later.

General picture of inner flow

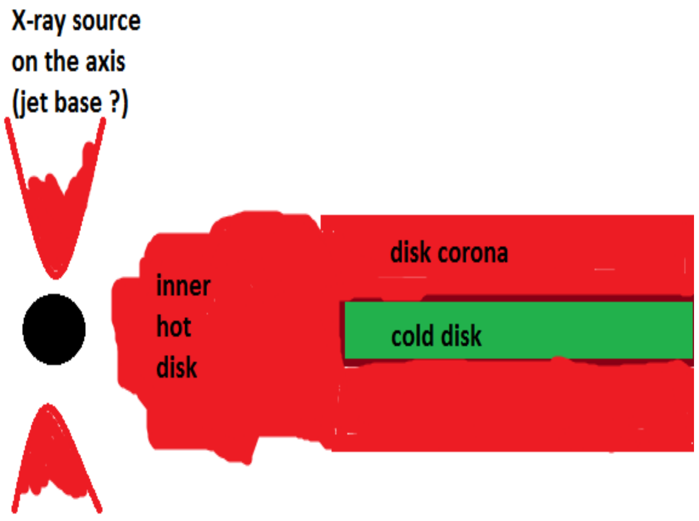
We can add the information about the flow directions and thus mark the additional presence of the diluted medium.



Marked velocities are not in proportion to actual velocities!

General picture of inner flow

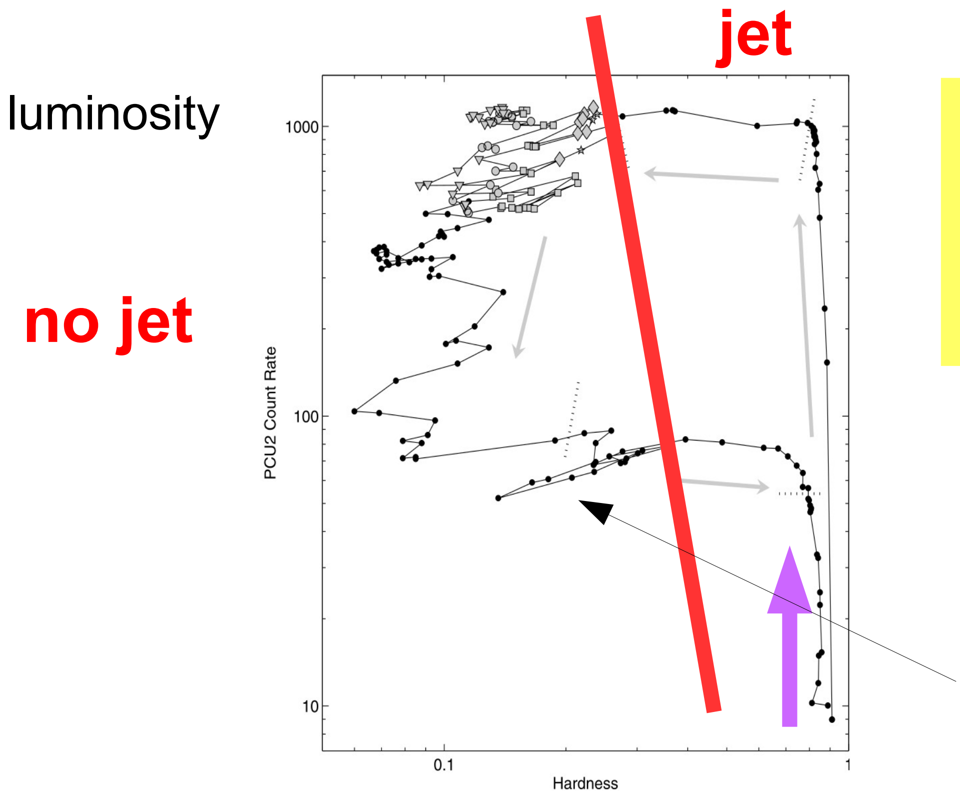
The picture is universal, varying proportions you can get any AGN or a GBH



- Radio-loud objects: jet is not heavily matter-loaded, accelerates well to highly relativistic speeds (confined by the outer wind ?); inner hot flow likely needed
- Radio-quiet sources: jet has problems in propagation, most of energy dissipated close to a black hole (lampost model), and weak (nonrelativistic ?) jet goes up to several pc
- High accretion rate sources: cold disk extends down to ISCO (Innermost Stable Circular Orbit), inner corona likely forms an optically thick coolish warm corona layer (10^6 K in AGN) responsible for the soft X-ray excess, jet (hard X-ray emission) weak
- Lower accretion rate sources: cold disk recedes (or even does not form, e.g. Sgr A*), hot flow (ADAF) and jet dominate.

Very important jet property

The key difference between AGN and GBH is the size, and consequently the timescale of the evolution. A strong jet is not a permanent property of the source, it may require spinning black hole but it also requires not just a special total luminosity but enough of hot plasma close to a black hole.



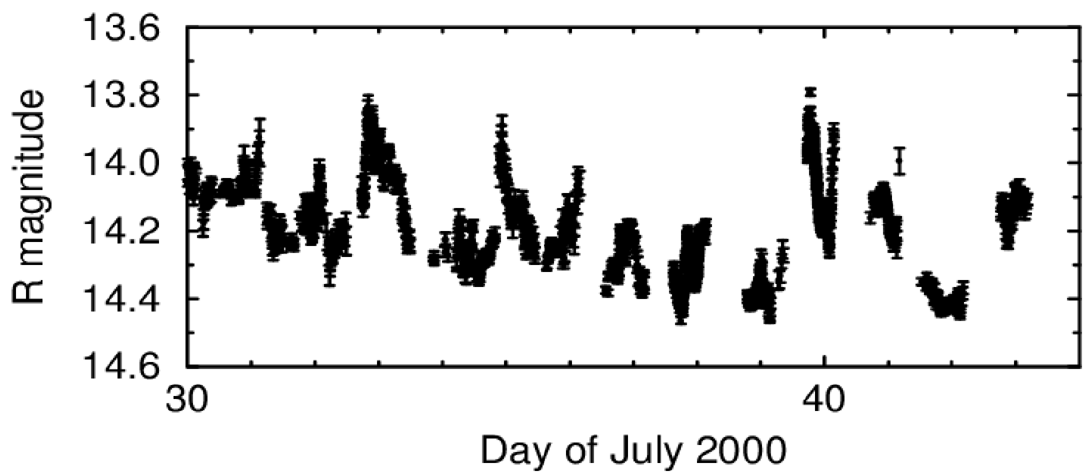
This is evolution of a single source (GX 339–4, Belloni et al. 2005). Jet is present only for a fraction of outburst, where there is plenty of hot plasma close to a black hole. It turns off when the cold disk forms.

In AGN similar evolution (if happens there) would take milions of years!

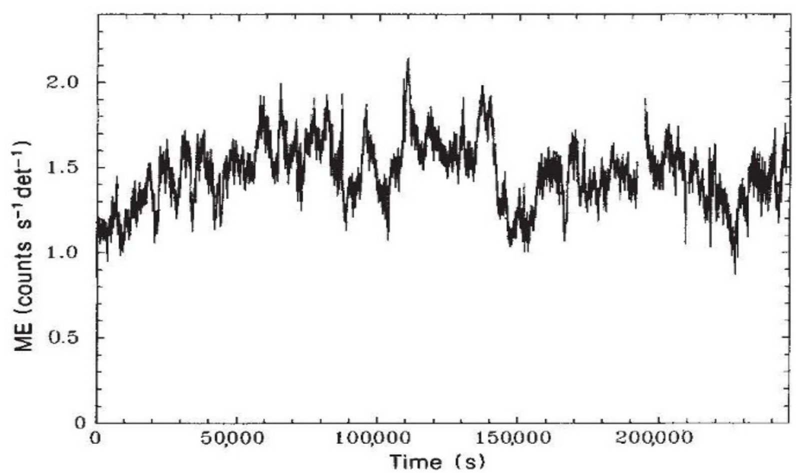
Here analogy of Changing-Look AGN ?

AGN variability

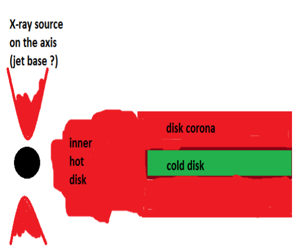
This is a well known observational fact – optical variability is behind the name of the BL Lac object (standard name for a variable star), and X-ray variability of AGN was discovered with the EXOSAT.



Boettcher et al. 2003), BL Lac



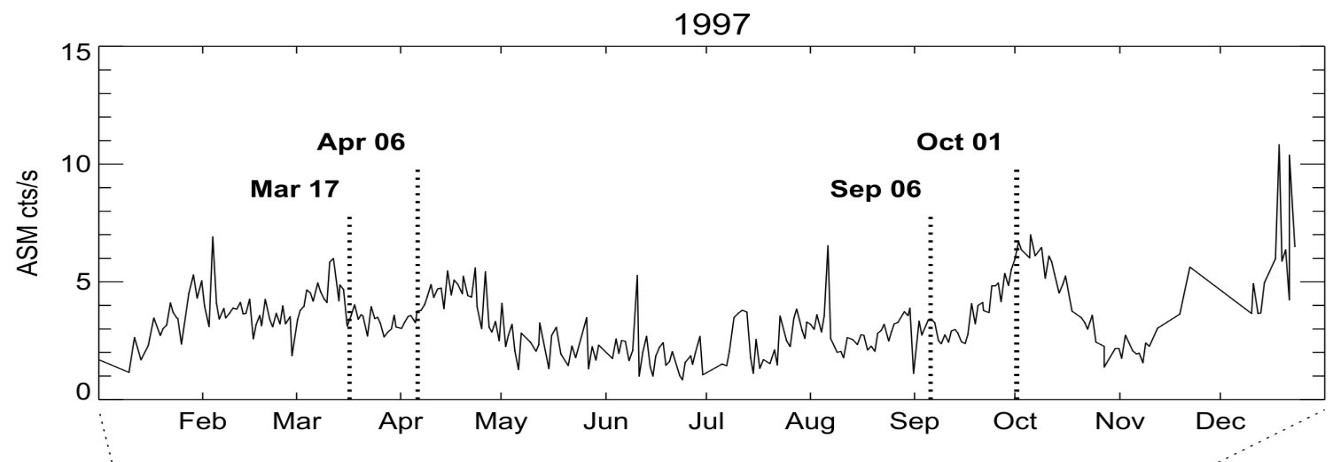
McHardy & Czerny (1987), NGC 5506



Those are standard (persistent) levels of variability. On top of that we have QPO, QPE, TDE, and CL AGN. I will touch that shortly later.

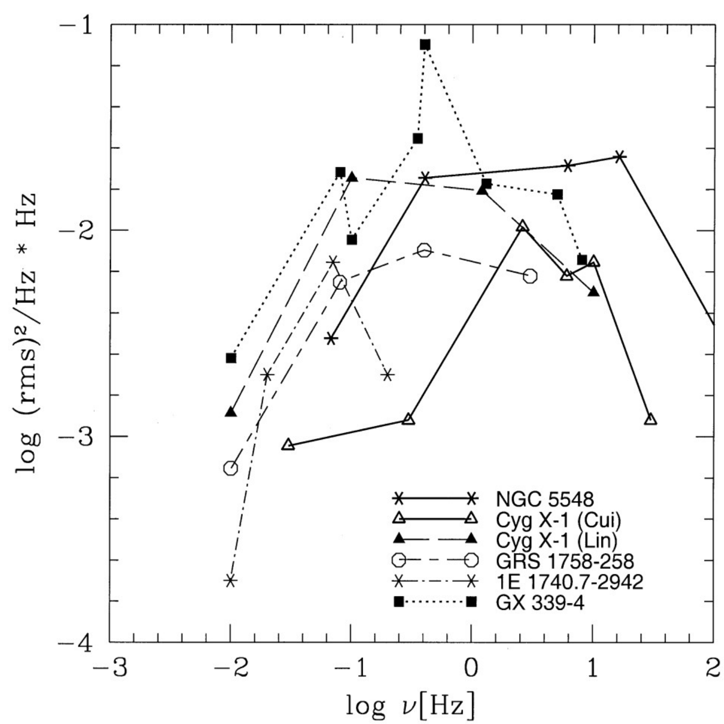
GBH variability

In X-rays it looks the same, but the timescales are shorter which is best seen in the power spectrum plot,



Corongiu et al. (2003), X339-4

Those are standard (persistent) levels of variability. On top of that we have QPO, QPE, TDE, and CL AGN. I will touch that shortly later.



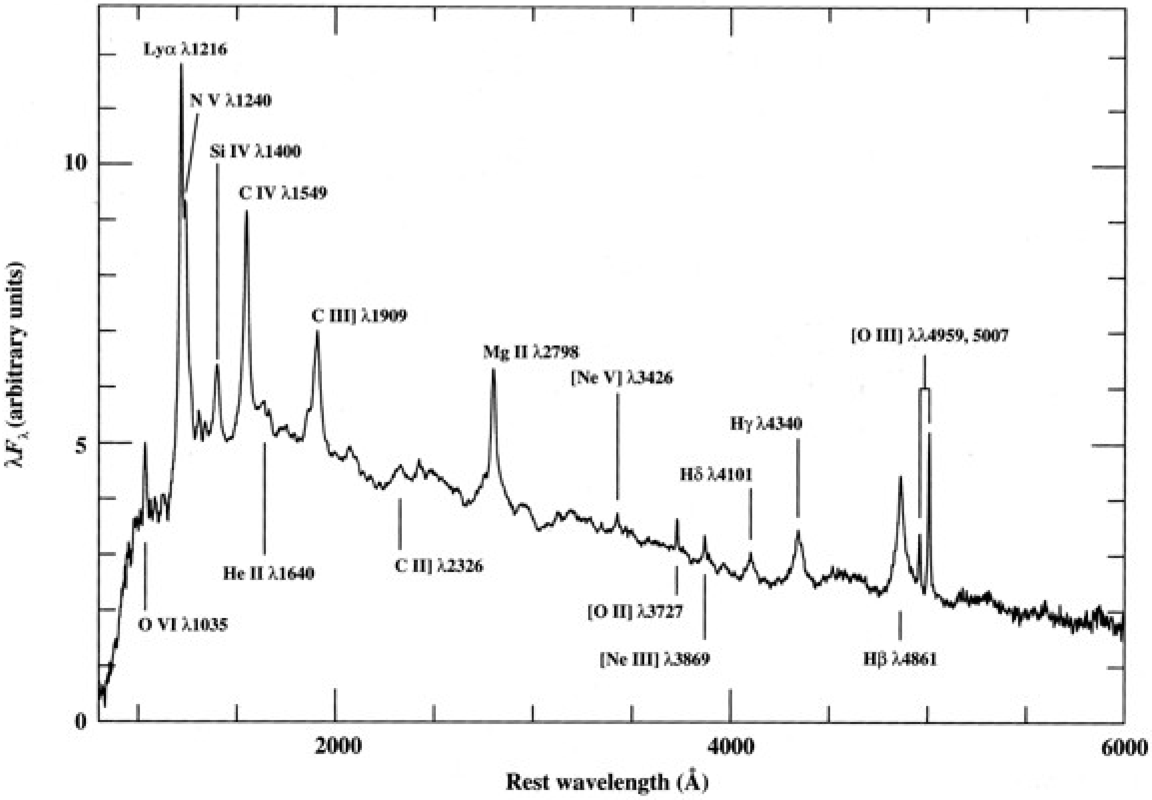
NGC 5448 was horizontally shited in log scale by 6.83 to account for a mass difference (Czerny et al. 2001).

AGN vs. GBH

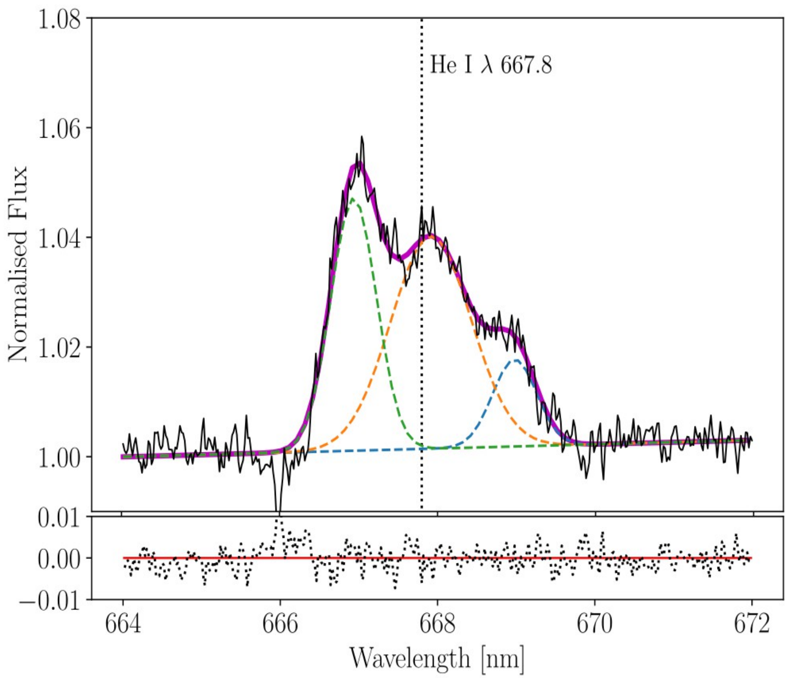
Partial summary:

- Overall, the accretion properties of AGN and GBH are identical apart of the scaling of the cold disk temperature and variability timescales, and the central engine has the same contaminants:
  - BLR in AGN, winds in GBH

BLR in AGN and GBH



Quasar composite spectrum (Francis et al. 1991)



He I line in MAXI J1820+070 from VLT/X-shooter (Rodi et al. 2021)

AGN vs. GBH

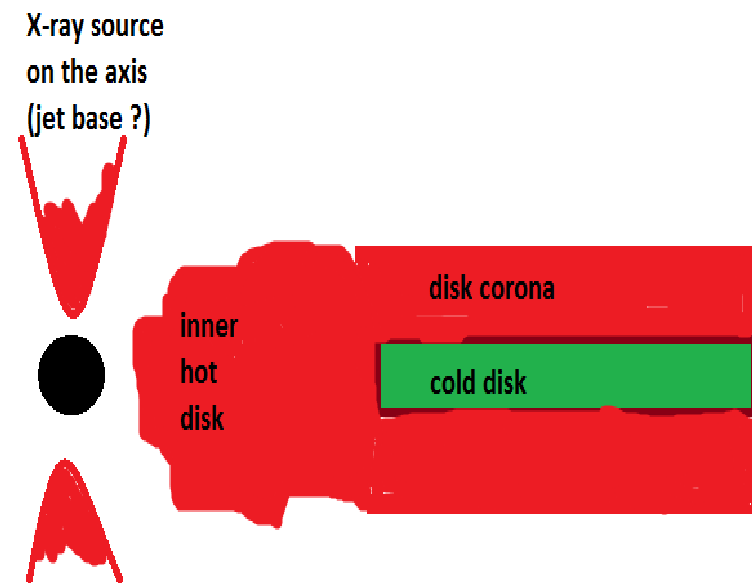
Partial summary:

- Overall, the accretion properties of AGN and GBH are identical apart of the scaling of the cold disk temperature and variability timescales, and the central engine has the same contaminants:
  - BLR in AGN, winds in GBH
  - host galaxy in AGN, donor star in GBH (in optical/IR)
  - dusty torus in AGN, donor and outer disk rim in GBH

- AGN better resolve the relatively short timescales: light crossing time in AGN – 1000 s (measurable), in GBH – 0.1 msec (not measurable despite countrate higher countrate in X-rays)
- GBH better show the global evolution which in AGN can be studies only statistically, like in stars

Open questions about the central engine of AGN and GBH

We have a satisfactory phenomenological description of this picture but we have no real physically-based model of the elements and the **transitions** which accompany the change of the luminosity.



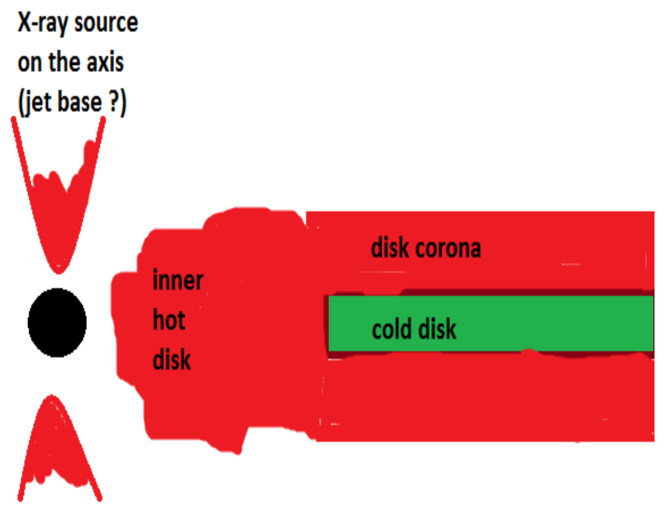
To progress, we need an insight into the dynamics of the flow.

That can came rather from the observed variability, particularly from the extreme variability events.

Disk-jet-wind-corona time coupling

All the basic elements participate in this variability, so tracing various variability aspects is quite complicated and requires dense coordinated monitoring. The coupling is due to:

- Inflow
- Outflow
- Irradiation

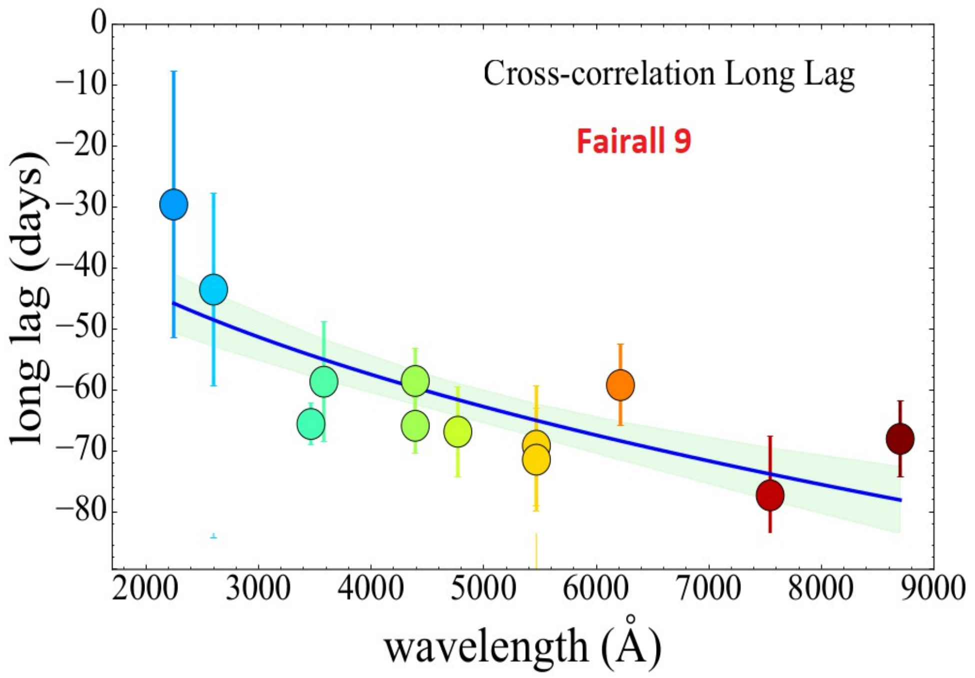


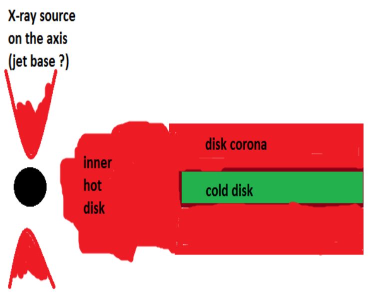
Inflow is obvious, but difficult to follow!

Inflow

Inflow is obvious, but difficult to follow!
A tool: long negative lags in the optical/UV band.

Changes in the outer disk, e.g. due to local magnetorotational instability should propagate inwards, and this now the canonical explanation of multiscale standard variability in AGN and Galactic black holes. But there are prospects.



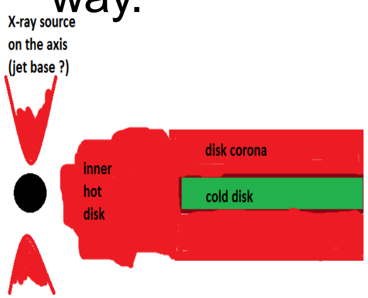


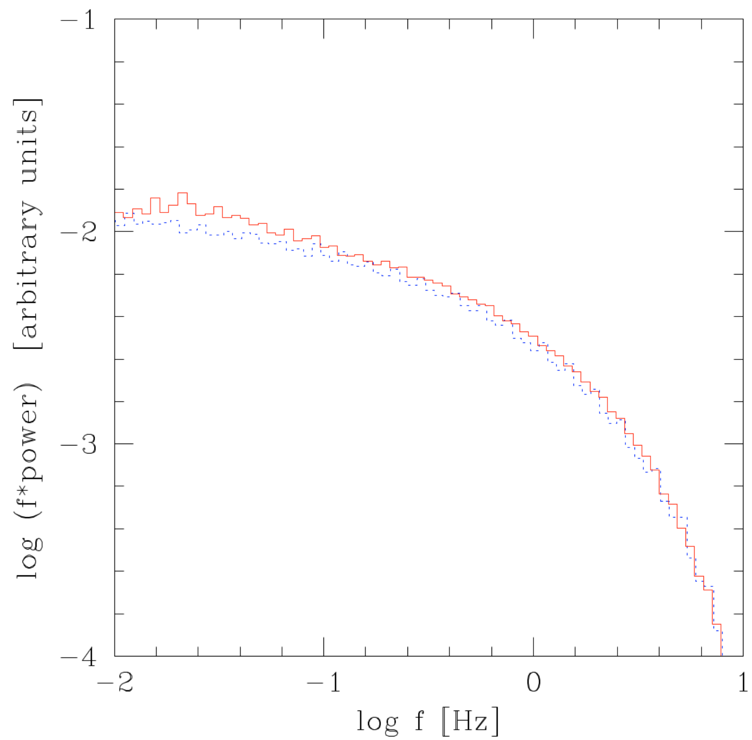
Negative lags (signal appears first at the longest wavelengths) are seen now for example in Fairall 9 (Yao et al. 2022). Timescales will be easily accessible with LSST (Secunda et al. 2023).

Inflow

Inflow is obvious, but difficult to follow!
A tool: long negative lags in the optical/UV band.

The observed negative delay of order of 30 days implies rather high height to disk thickness ratio, and actually perturbations are smeared when propagating in the cold disk. They most likely propagate through the accreting corona, thus perturbing the disk on its way.





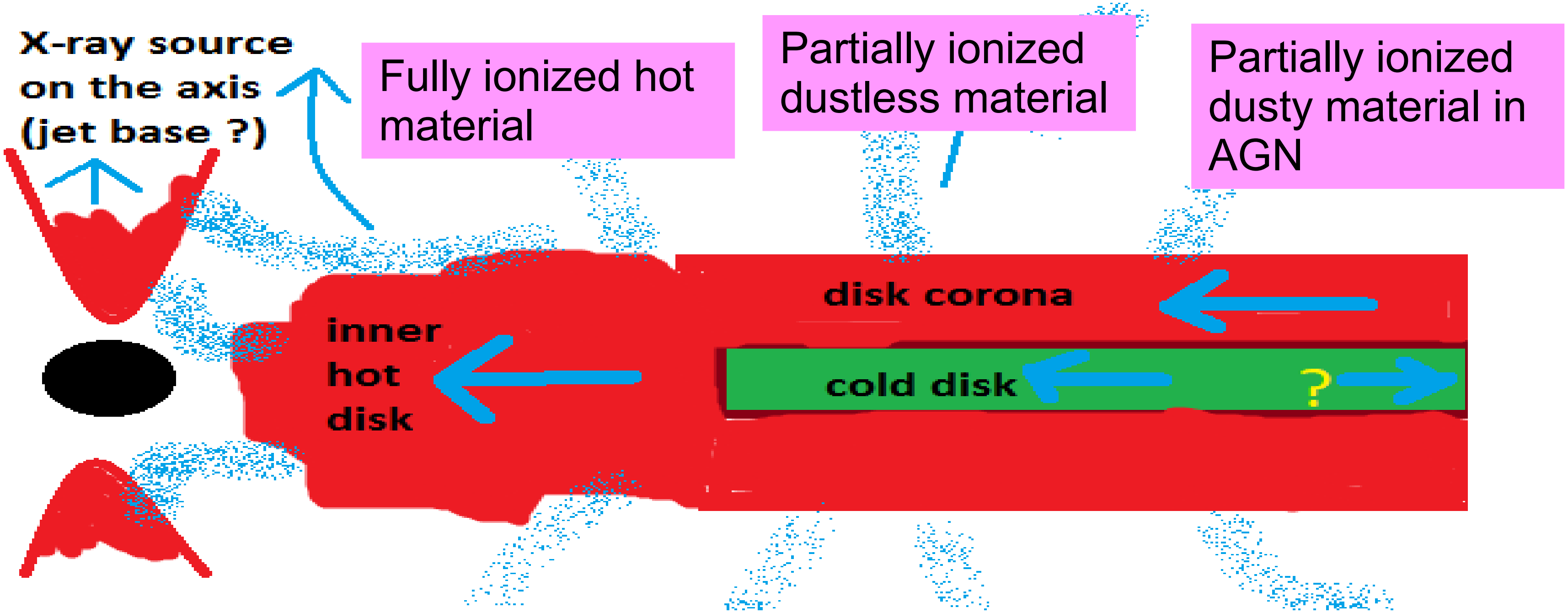
Janiuk & Czerny (2007)

We could get the proper shape of the power spectrum only when we assumed the MRI turbulent cells scaling with the disk radius (like in corona), and not the cold disk height.

Disk-jet-wind corona coupling: outflow

Outflow is also a source of problems. Outflow (apart from jets) is predominantly seen as absorption features, along the line of sight, so it is not easy to localize it, but we have information about the velocity and the ionization level. Outflows can be also traced in indirect methods.

Outflows reprocess part of the cetral flux not only through absorption but also through re-emission/scattering.



Irradiation coupling

All the basic elements participate in this variability, so tracing various variability aspects is quite complicated and requires dense coordinated monitoring. The coupling is due to:

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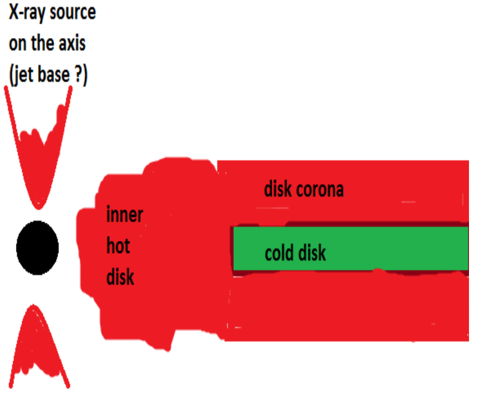
- Irradiation

Results of irradiation are well studied, as implicitly mentioned before. Longer wavelenghts in the optical/UV spectrum lag behind UV. Several dense monitoring reveal the pattern similarily and delays.



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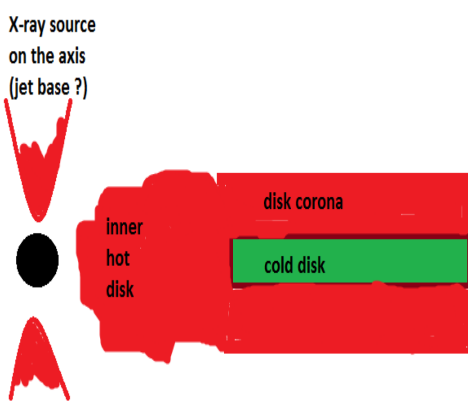
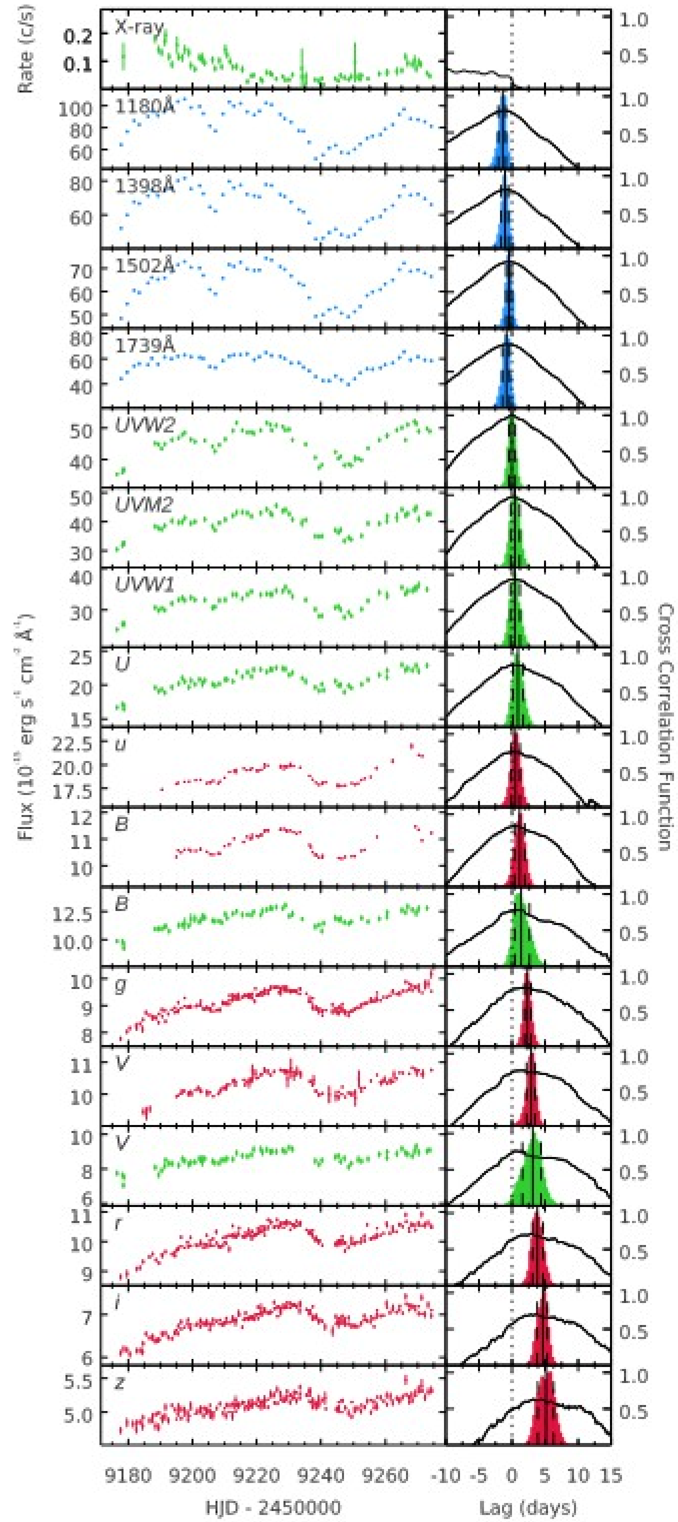
Results of STORM project for Mrk 817 (Kara et al. 2021)

Irradiation (even stronger than in AGN) is also seen in GBH but not so well resolved in the wavelength bands.

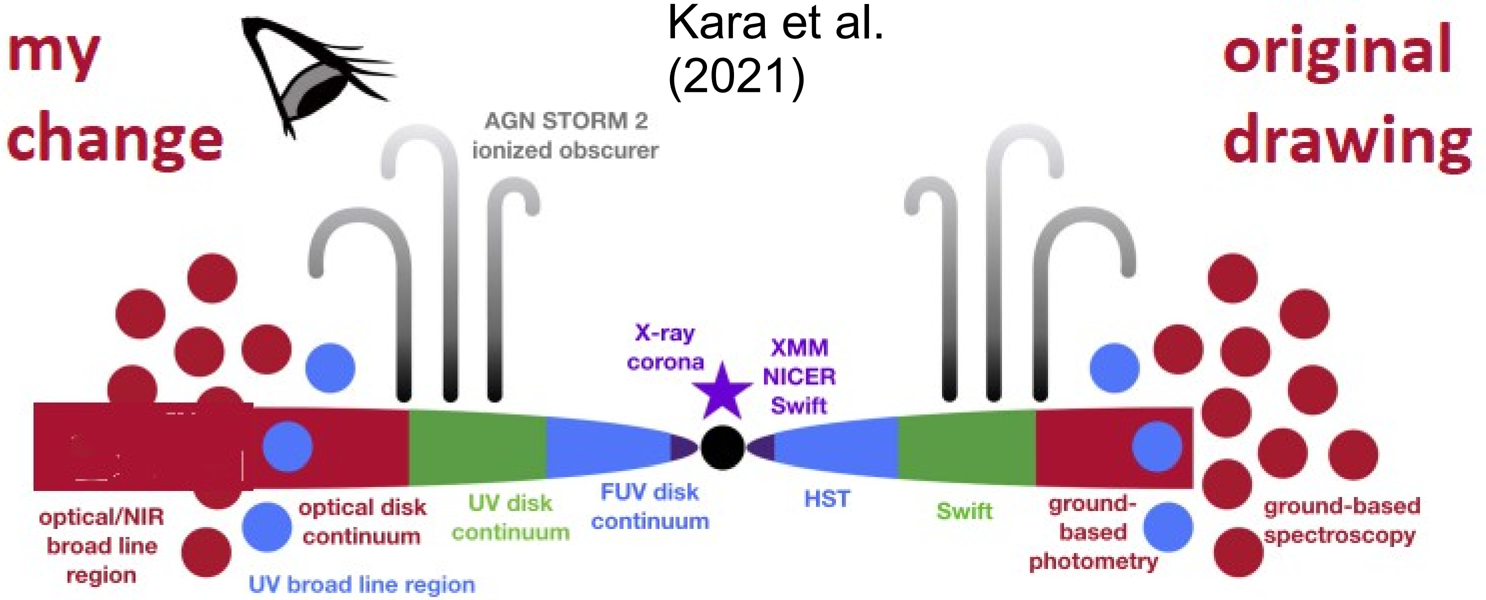


Time delays are consistent with the basic theory of the standard accretion disk if the additional contamination by the BLR is accounted for.



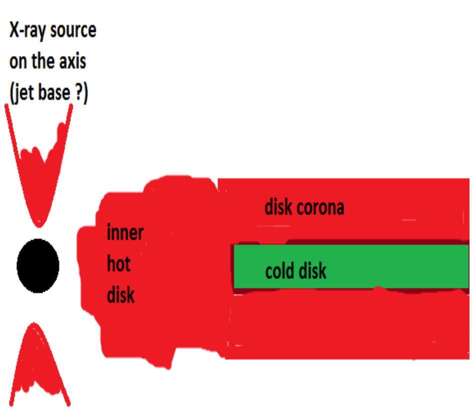
Irradiation

Kara et al. (2021)



Problem: hard X-rays are not actually the driver of the AGN variability (poor correlation with UV, energy budget problem).

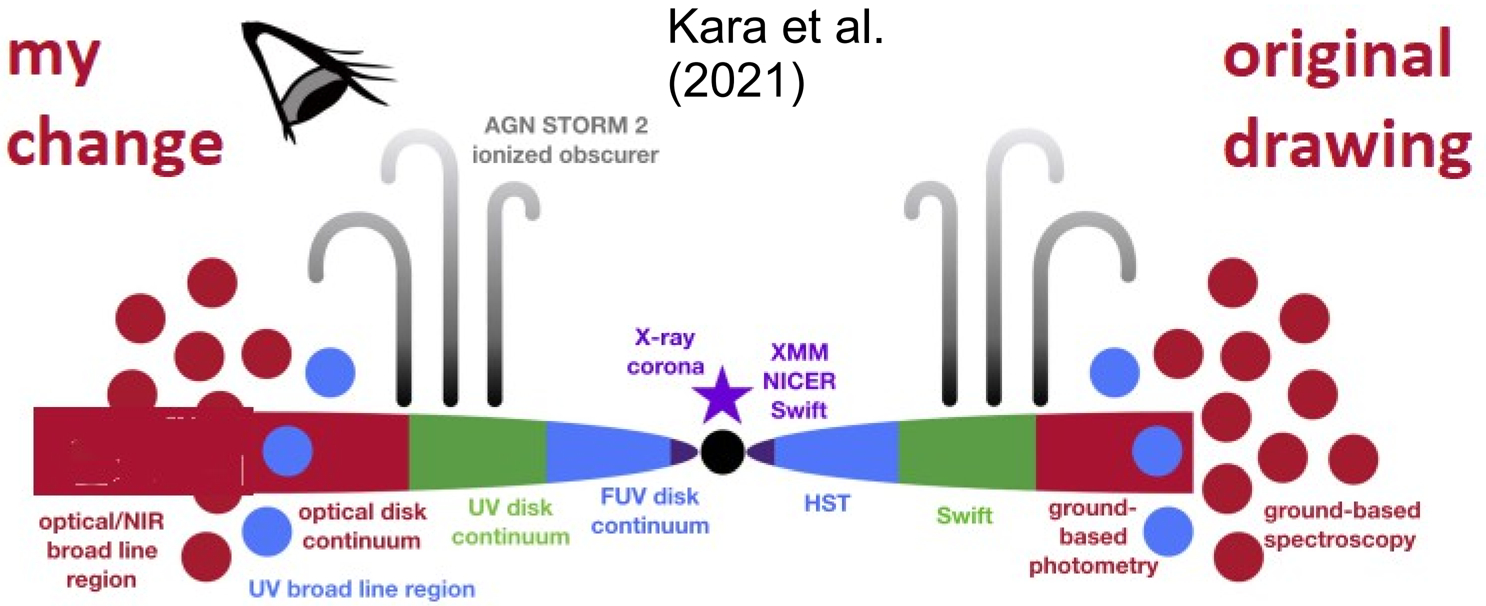
Driver: EUVE



Results of irradiation:

- Relativistically broadened Kalpha line in X-rays
- Short timescale delays (soft bands lagging behind hard bands in X-rays
- Optical/UV time delays rising with the wavelenghts
- Wavelenght-resolved reverberation mapping of BLR

Irradiation



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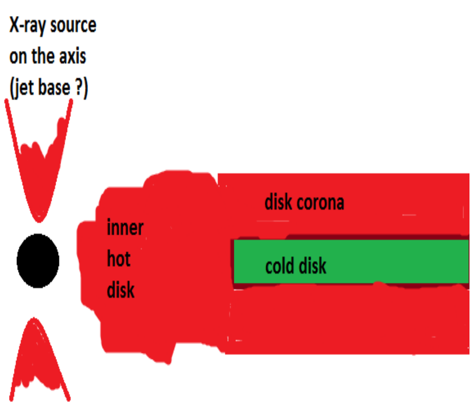

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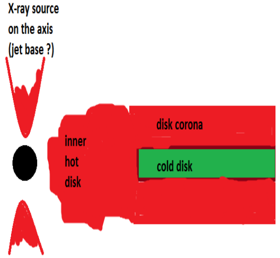
Dramatic events

Apart from the ususal persistent variability, we have other types of events :

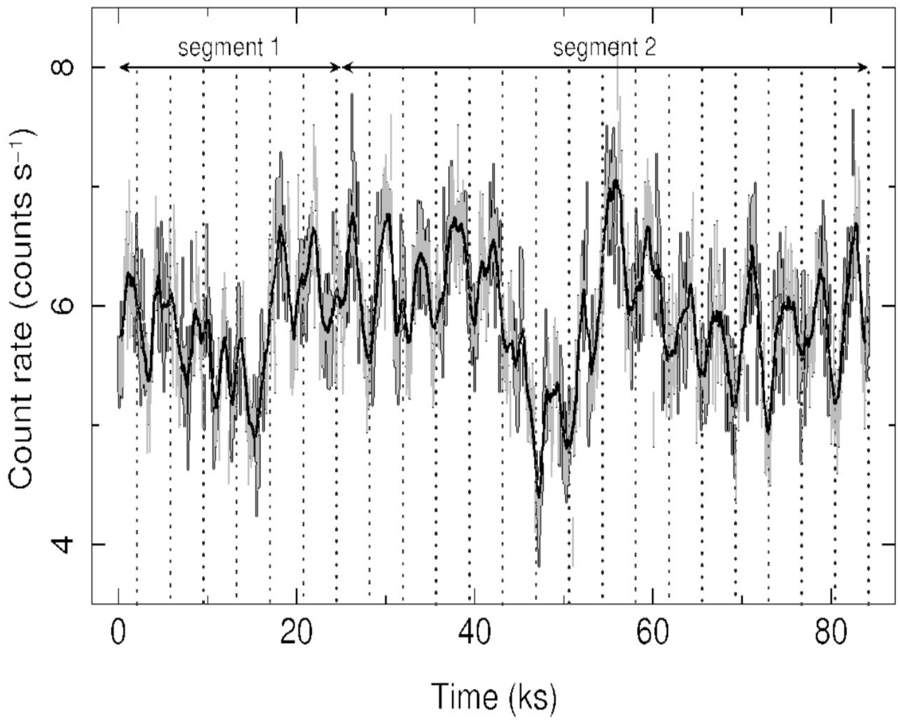
- Quasi-Periodic Oscillations (QPO) – rare, firmly seen in one AGN source but frequent in GBH
- Changing-Look AGN (at least over 100 sources, and number is rising fast)
- Tidal Disruption Events (in quiet galaxies and in AGN)
- Quasi-Periodic Eruptions (5 objects)
- Hearbeat states in GBH
- Temporary formation of MAD states



The first two are intrinsic to an object, the other two most likely related to interaction of stars with the disk, the final two again intrinsic.

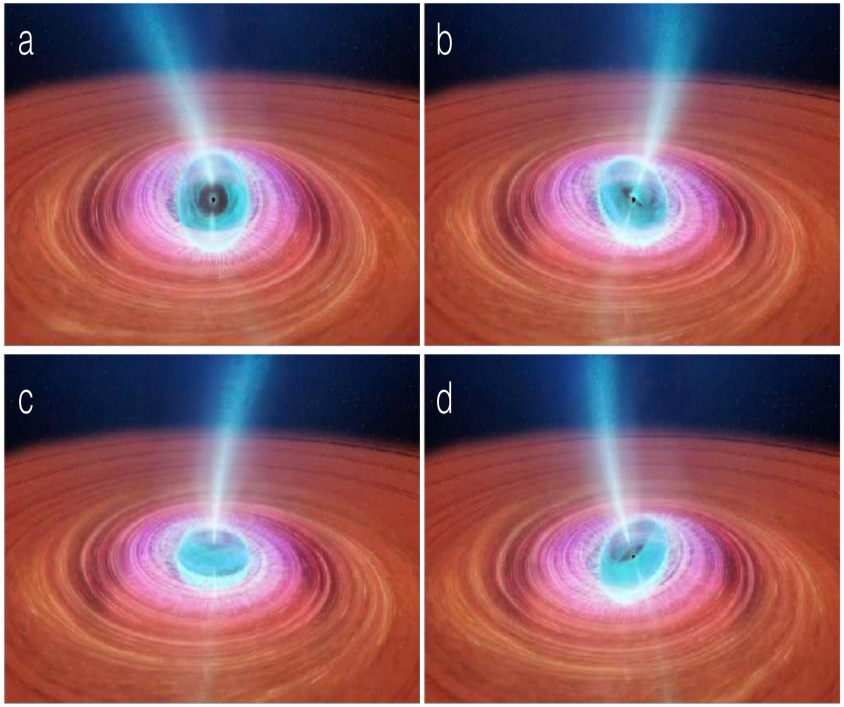
Quasi-Periodic Oscillations (QPO)

Well seen in RE J1034+396 in a number of observations.



X-ray lightcurve of RE J1034+396 (Gierliński et al. 2008) where QPO (~ 1 hour) were seen for the first time.

The leading model: precession of the inner hot flow



From the review of Ingram & Motta (2019)

Different QPO are frequently seen in Galactic Black Holes.

Changing-Look AGN

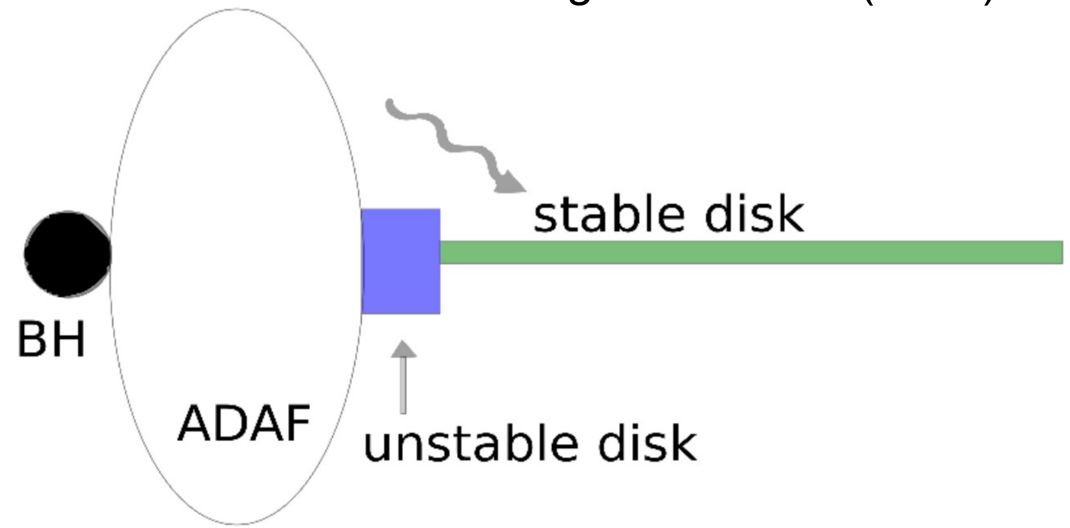
It was first introduced to name the sources which go in X-rays from Compton-thick to Compton-thin (or reverse, or both; Matt et al. 2003), later adopted also to sources which change the properties of the BLR (disappearance/appearance of broad lines).

Obscuration contributes to the phenomenon, but the essential change is the rise/drop in the source central flux, affecting the ionization level of winds along the line of sight, and line emission. This rise/drop must happen very close to the black hole.

Possible scenarios:

- Radiation pressure instability
- Some other phenomenon most likely at the transition radius between the cold disk and the inner flow
- Temporary formation/disappearance of the warm corona
- MAD -magnetically arrested disk (hot flow) which may affect all the flow

Śniegowska et al. (2020)



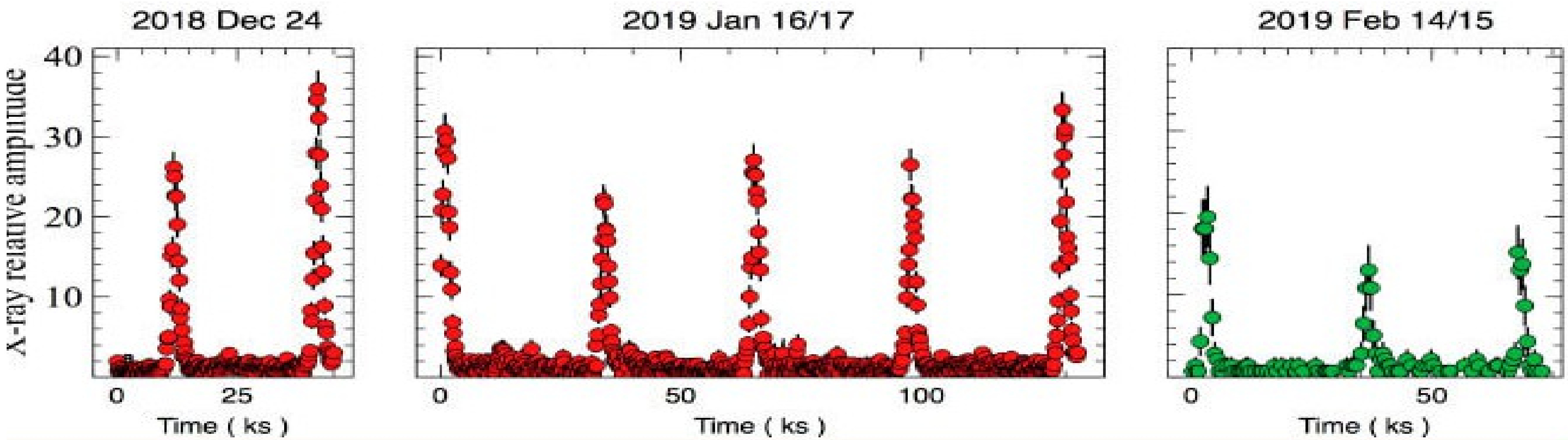
TDE and QPE

Tidal Disruption Events (TDE) do not have direct counterpart in GBH, although they can show some similarility to the behaviour of the X-ray novae. However, mass reservuar in TDE is much more compact and relatively smaller, the event lasts hundreds of days to a few years.

Quasi-Periodic Eruptions last hours in $10^5 M_s$ black holes.

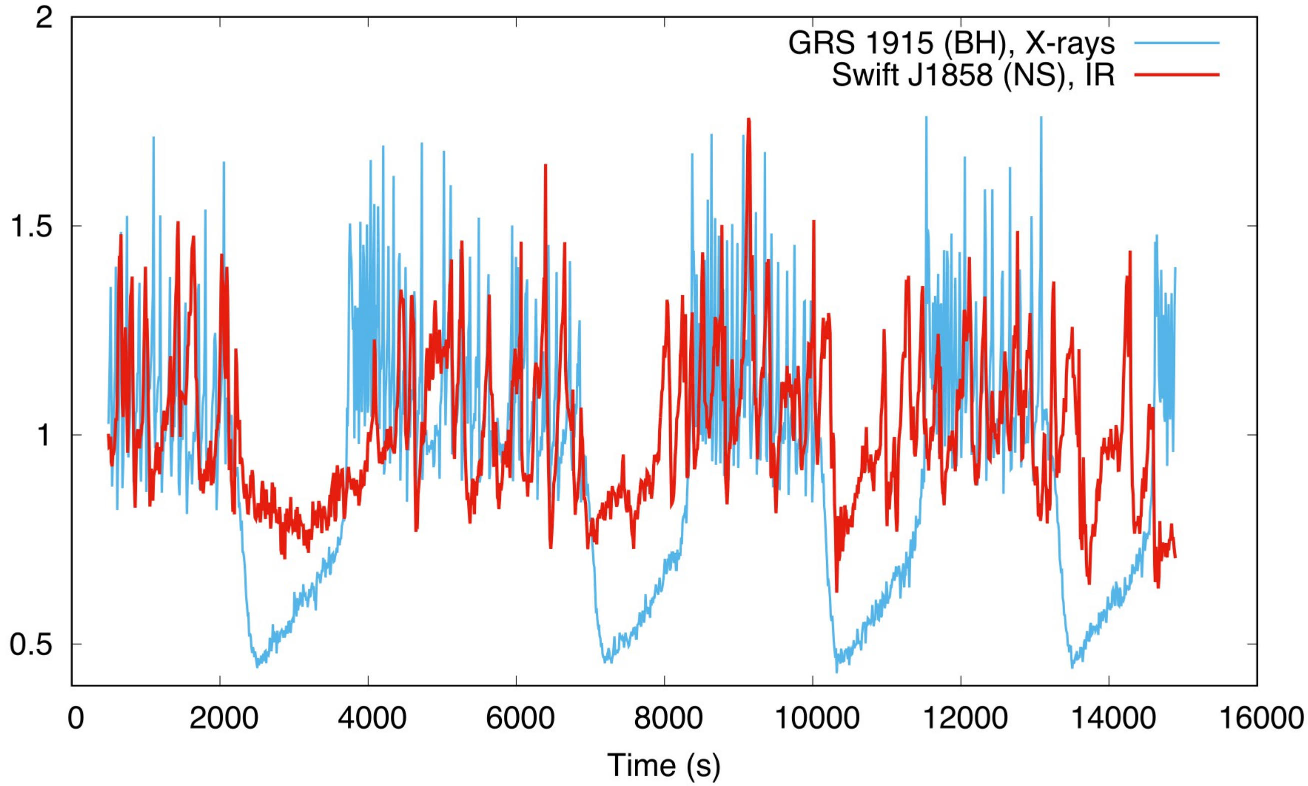
Miniutti et al. (2019); see also Minutti et al. 2023!

Could we see something like that in a GBH? The duration (after scaling by a factor 10 000 would be 3 seconds!



Heartbeat states

Discovered in GRS 1915+105 twenty years ago. With Agnieszka Janiuk we modeled these outbursts as the effect of the radiation pressure instability. The issue is still not set, but the effect is now seen in a few more sources including neutron stars (Vincentelli et al. 2023).



Vincentelli et al. (2013)

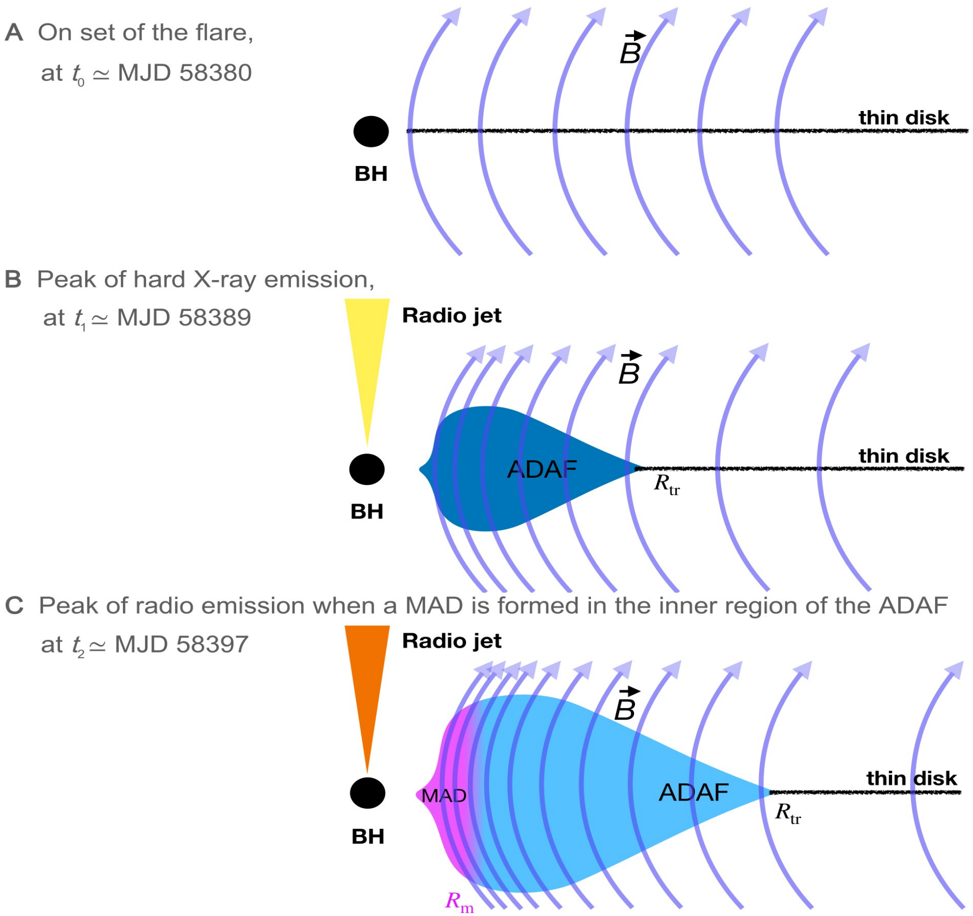
It is not clear if CL AGN share the same phenomenon.

But numerous young radio sources are well explained by this model (e.g. Czerny et al. 2009, Śniegowska et al. (2023)

MAD (magnetically arrested disk) states

Proposed to form 20 years ago to form in a hot flow (Narayan, Igumenshchev, & Abramowicz 2003; see also Bisnovatyi-Kogan and Ruzmaikin 1974 for a theoretical idea), studied in several contexts, particularly as a mechanism of jet formation and star-disk interaction.

In our recent paper on MAXI J1820+070 (You et al. 2023) we showed that the radio and optical fluxes are delayed by about 8 and 17 days respectively, compared to the X-ray flux. We interpret this as evidence for the formation of a MAD during the peak of the radio flare, and we perform simple time-dependent computations to support this claim.



The key problems - summary

- We are making a considerable progress in the description of the outer parts of the accretion disk, in modelling winds, BLR and relative phenomena, although still a lot of work to do. Treatment of 'clumpiness' is one of the difficult issues.

- The inner disk is more of the problem: (violent ?) transition of cold disk/hot flow, formation of the warm corona, inner hot flow including MAD state and finally the actual formation and acceleration of the jet at its innermost part

- GR R MHD is helping but probably we still miss some microphysics there

- Observational studies of variability is the most promissing way