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The disk/corona/BLR connection in AGN: theory

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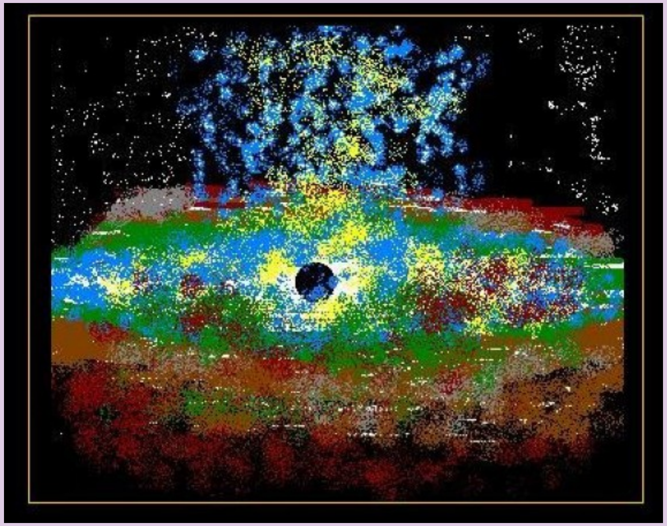
FERO 18 May 2018 Heraklion

Theory ….

„Theory” should be a physically motivated complete picture of the phenomenon, with considerable predictive power.

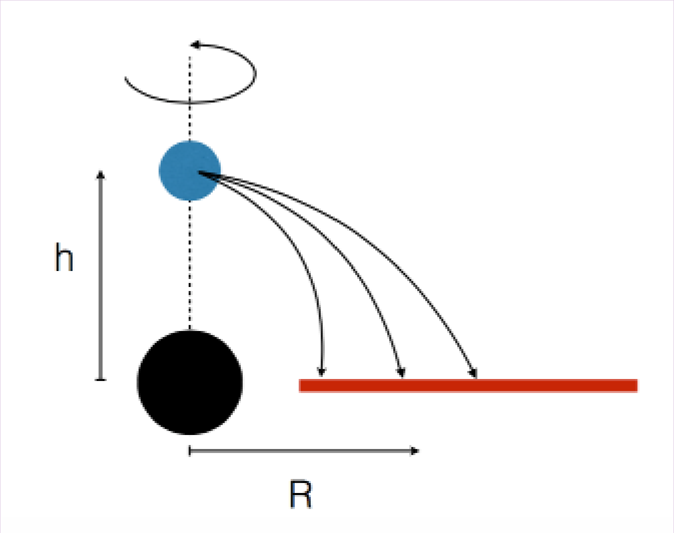
We have „accretion disk theory” for Keplerian geometrically thin disks etc. but most of the remining phenomena are described by models, with some hints for physics, at best.

I will not concentrate that much on models, but more on physical hints and reasonable possibilities. Part of issues are specific for AGN (outer region), part is both for AGN and GBH.



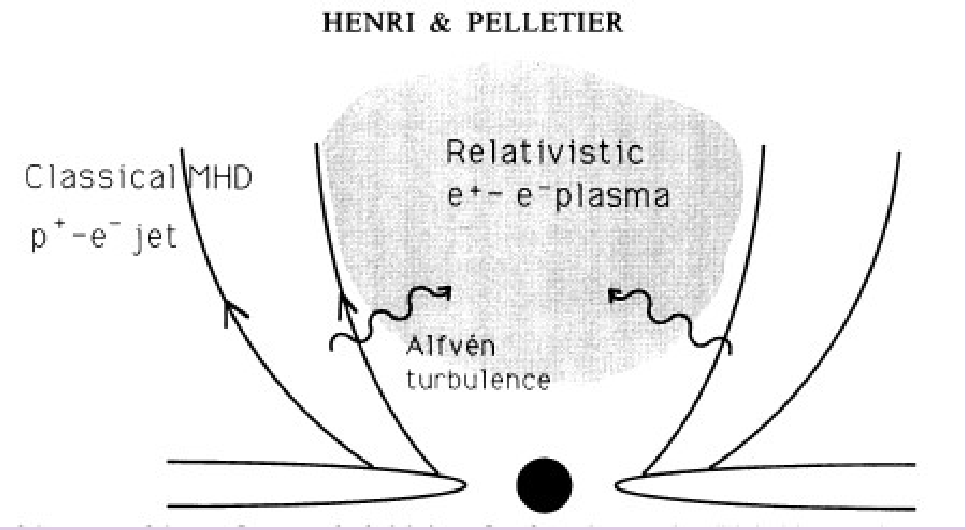
To introduce some organization into this messy topic, I will move outwards, starting from the direct vicinity of a black hole.

Lamp-post or compact corona /jet base



- Produces relatively hard X-ray power low emission
- Is likely present is low Eddington ratio sources (e.g. Sgr A*) and high Eddington ratio sources (e.g. 3C 273)

- Size of about 1 – 10 RS (from variability, reflection, quasar microlensing in X-rays)
- Blobby ejections in high Eddington ratio sources?



Lamp-post or compact corona /jet base

It seems to be close to the pair-creation limit, as postulated long ago by Bisnovatyi-Kogan et al. 1971; Svenson 1982-84; Zdziarski 1985); now seen in the data:

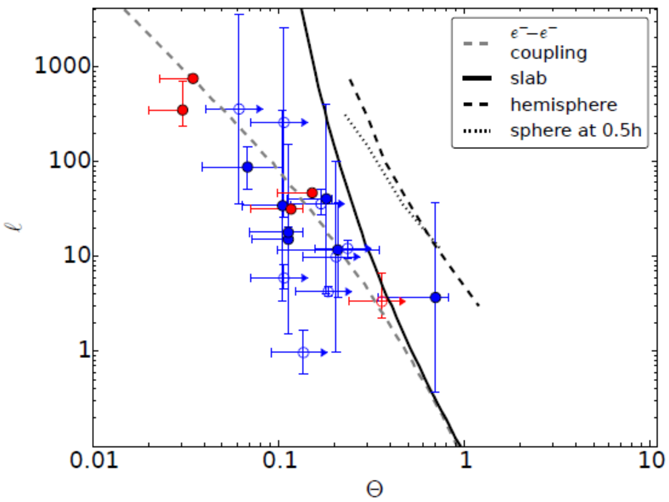


Figure 2. $\Theta - \ell$ distribution for *NuSTAR* observed AGN (blue points) and BHB (red points). The e–e coupling line from GHF is included. Pair lines from Stern et al (1995) are shown. The slab line has been extrapolated slightly to higher ℓ.

Fabian et al. 2015

It has to form due to the presence of the strong large scale magnetic field which requires geometrically thick inner disk. The important process – magnetic field reconnection (e.g. Beloborodov 2017).

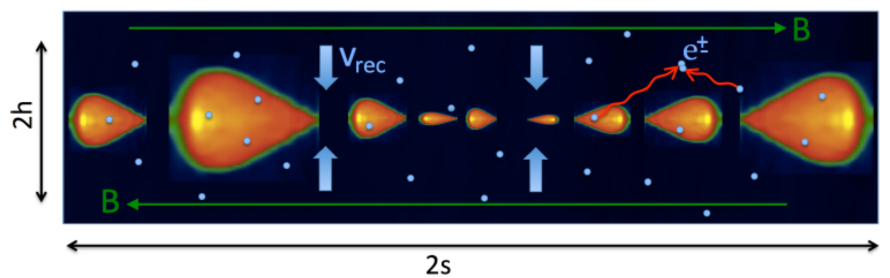


FIG. 1.— Schematic picture of the reconnection layer. Opposite magnetic fluxes converge toward the midplane of the layer with velocity $v_{rec} \sim 0.1c$. The reconnected magnetic field forms closed islands (plasmoids), which move horizontally with various relativistic speeds.

Or blob ejections related to MAD (Magnetically Arrested Disks)?

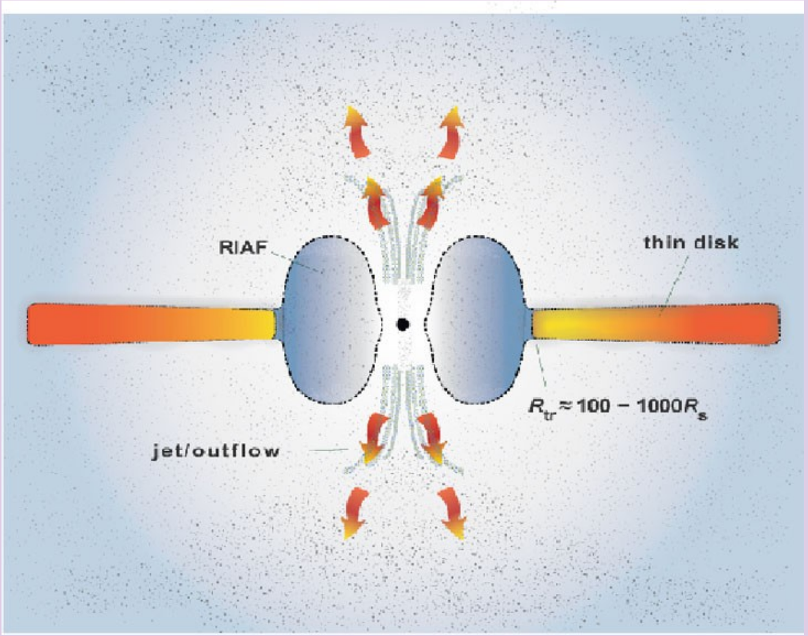
This takes us to inner disk issue.

Inner hot flow

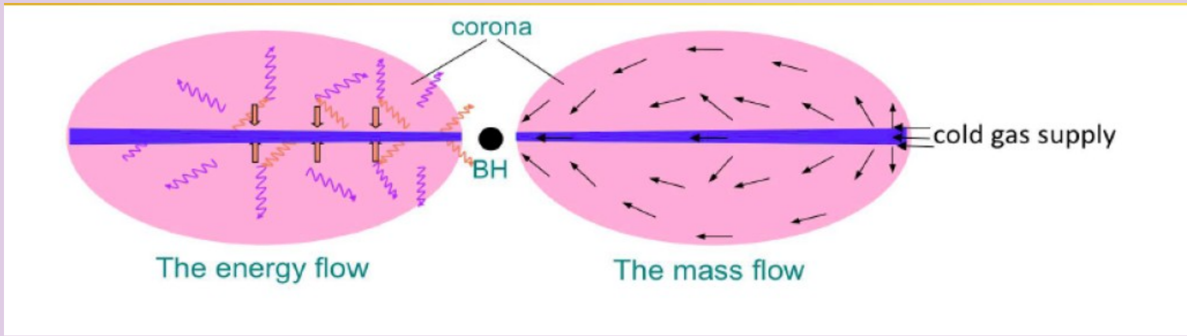
Relativistic jet speed canot be achieved in a funnel of a slim disk (geometrically thick but also optically thick disk).

This leave us two options:

Inner ADAF (Ichimaru 1977, Narayan & Yi 1984)



Accreting corona on the top of the disk (Życki et al. 1995, Chakrabarti & Titarchuk (1995)



Inner hot flow

Formation of the hot flow is still an issue. Ions must be at virial temperature to support large scale magnetic field.

- In very inactive galaxies like Sgr A* there is only hot flow

- In other sources we need a transition from outer cold flow to inner ADAF or inner most flow

- Physics included in some studies (e.g. Rozanska et al. 2000, Liu et al. many papers) include electron conduction but not ion conduction

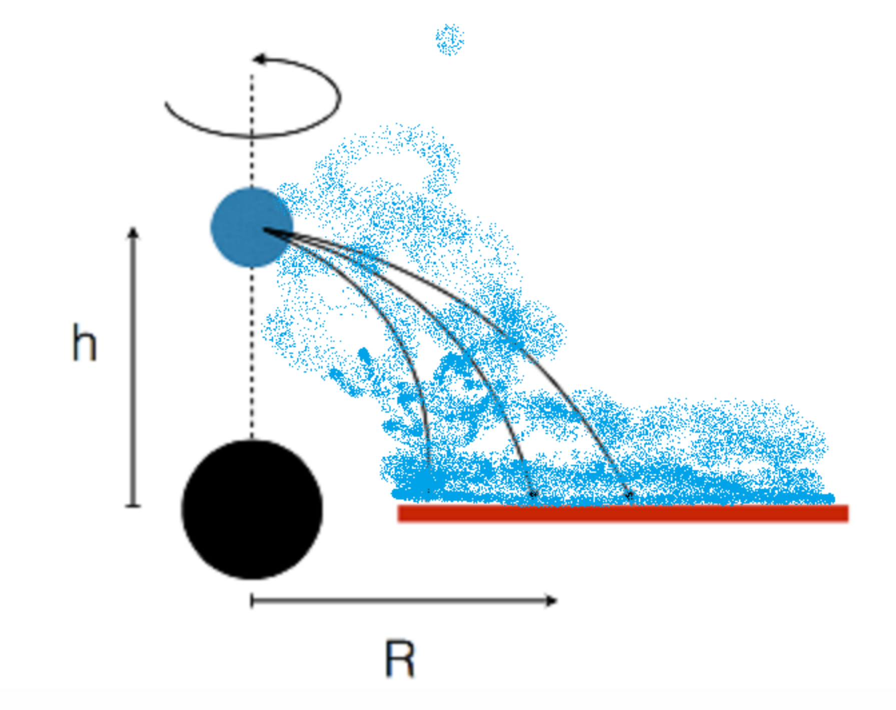
- The origin of the large scale magnetic field is not clear (must be external ? Or cosmic battery?), and this field is only included in MHD simulations of ADAF-type, coronal flow cannot be calculated.

- coronal flow (warm corona) seemd to be required for higher L/LEdd

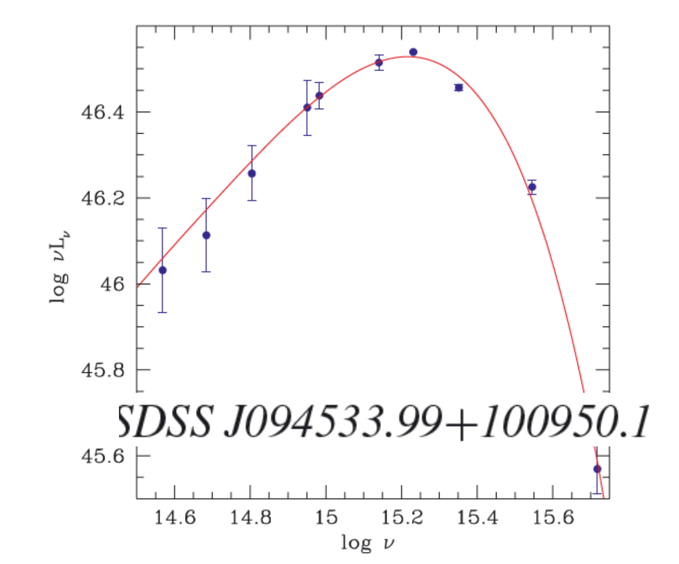
Inner most flow - consequences

Inner coronal flow and X-ray reflection: is it a problem?

Perhaps the flow there is optically thin enough?



Hot flow leads to outflow (ADIOS etc.), both thermally driven and magnetically driven. Efficiency of such outflow is impossible to predict theoretically but we can have observational constraints.



Quasar SDSS J0945 does not show any need for an inner hot flow (Czerny et al. 2011)

Inner most flow - consequences

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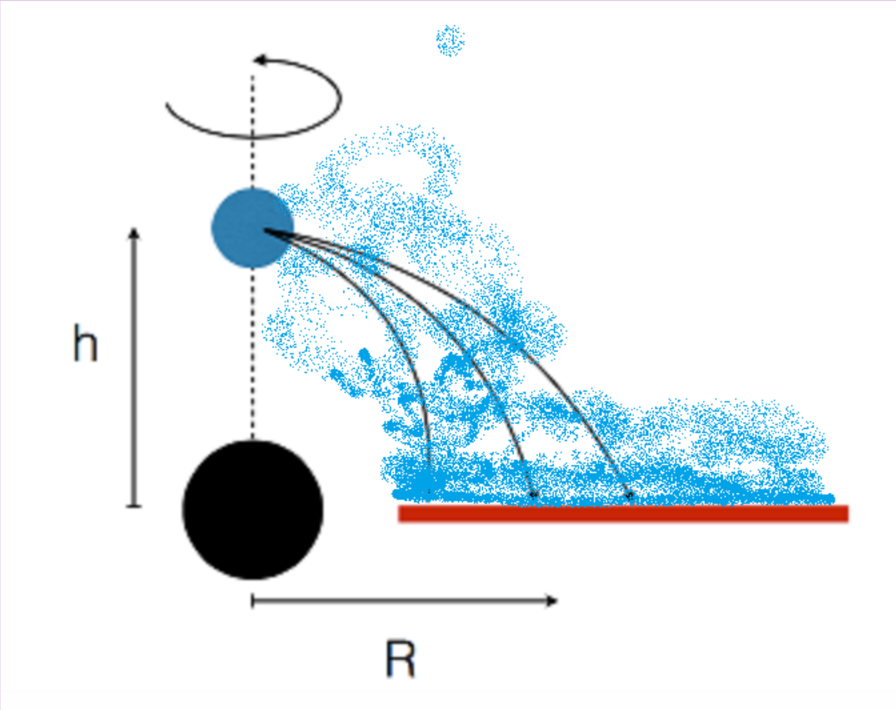

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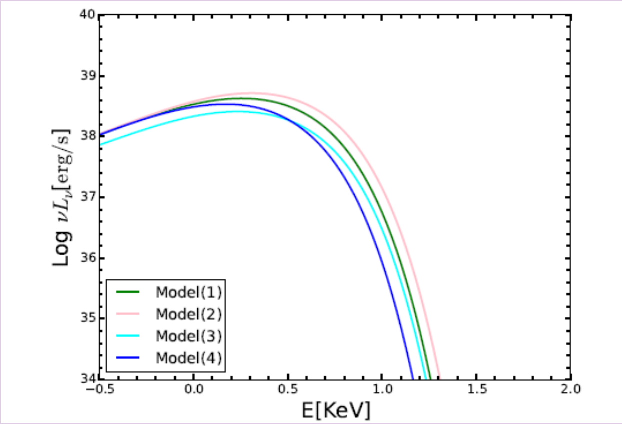

We made some experiments for galacitc sources (You et al. 2016).

A bit further up ? Warm corona.

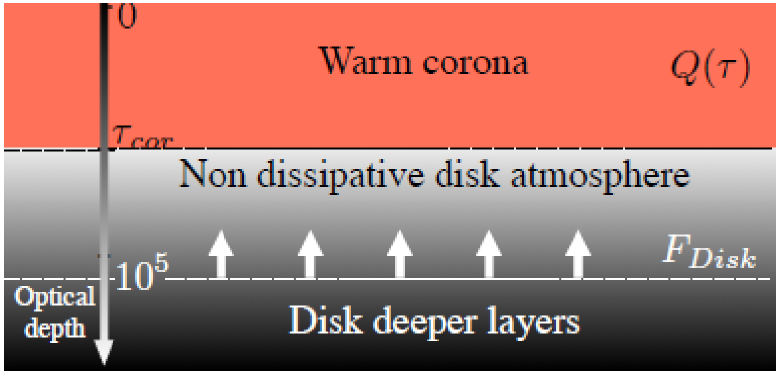

Fig. 1. Sketch of the dissipative slab corona atop the non-dissipative atmosphere of the accretion disk.

The driver is small scale magnetic field, the strength of the warm corona cannot be predicted (always an arbitrary parameter invloved; e.g. Rozanska et al. 2015; Begelman & Silk 2017).

Such a warm corona with the temperature of about 1 keV and optical depth about 10 is required by observations in soft steep X-ray states (e.g. NLS1), and to explain soft X-ray excess. Initially proposed as hot corona by Haardt & Maraschi (1991).

It can stabilize the disk, otherwise subject of radiation pressure instability, and reproduced soft X-ray emission (e.g. Czerny et al. 2003).

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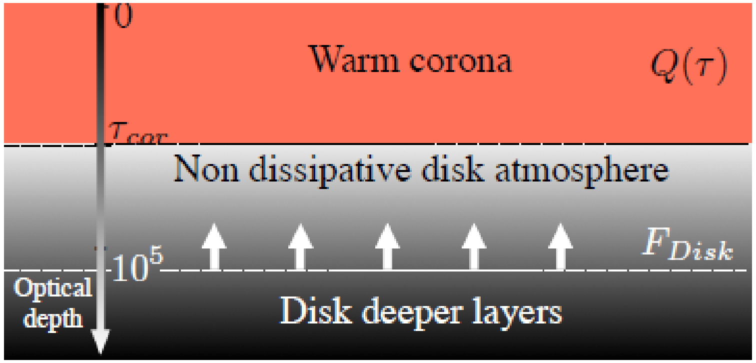


Fig. 1. Sketch of the dissipative slab corona atop the non-dissipative atmosphere of the accretion disk.

$$W \propto B^2 v_A H^{\zeta}, \tag{18}$$

with ζ being an arbitrary coefficient.

In this case our previous stability criterion (see Eq. (14)) takes a more general form

$$\beta > \frac{2 - 2\,w - 2\zeta\,w}{5 - 5\,w - 1.5\zeta\,w}. \tag{19}$$

This means that the radiation pressure dominated disk (with $\beta \approx 0$) is stable if

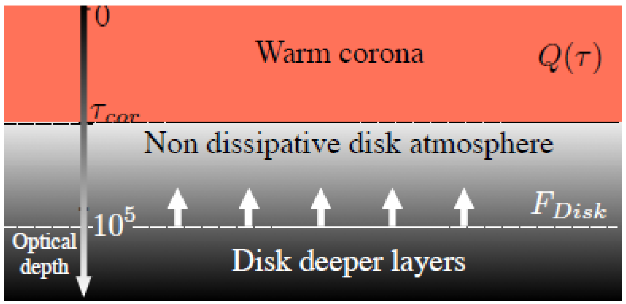
$$w = \frac{1}{1 + \zeta}. \tag{20}$$

The predicted Compton amplification factor of the warm skin is therefore

$$A = \frac{1 + \zeta}{\zeta} \tag{21}$$

It can stabilize the disk, otherwise subject of radiation pressure instability, and reproduced soft X-ray emission (e.g. Czerny et al. 2003).

Warm corona.



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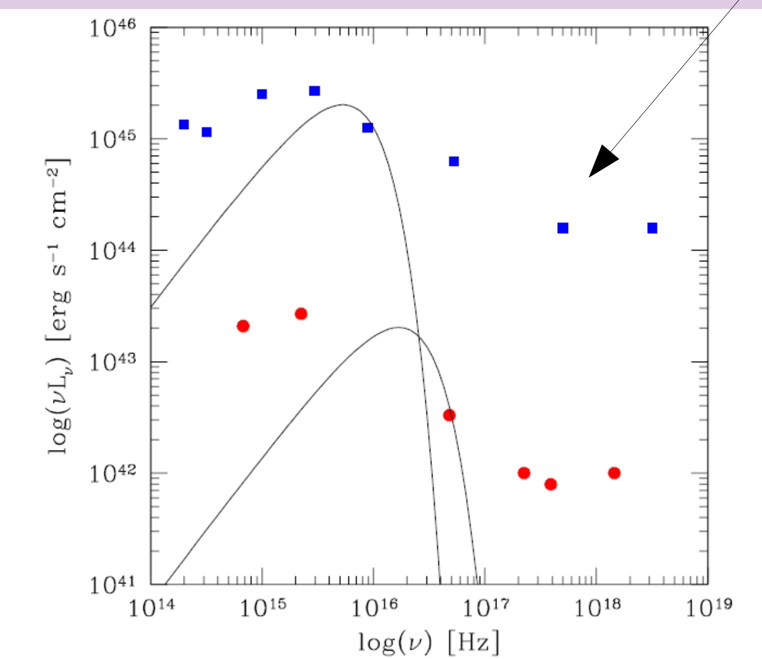
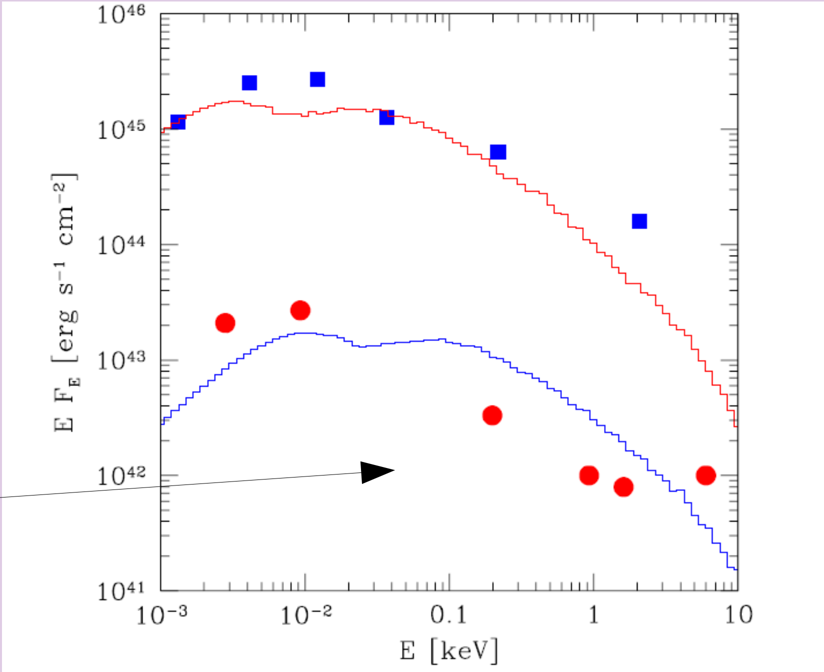


Model of the composite quasar spectrum and of Mkn 359 with SS disk and with warm corona in Czerny et al. (2003)



It can stabilize the disk, otherwise subject of radiation pressure instability, and reproduced soft X-ray emission (e.g. Czerny et al. 2003).

Still further up

Two phenomena must appear:

- Inverse Compton heated corona

- Line driven winds

Both are well understood separately, but the conditions for both to happen are contradictory.

Most likely IC corona works in GBH, line driven wind mostly in AGN. Line driven winds in CV.

Inverse Compton heated corona & wind

Proposed by Begelman et al. (1983)

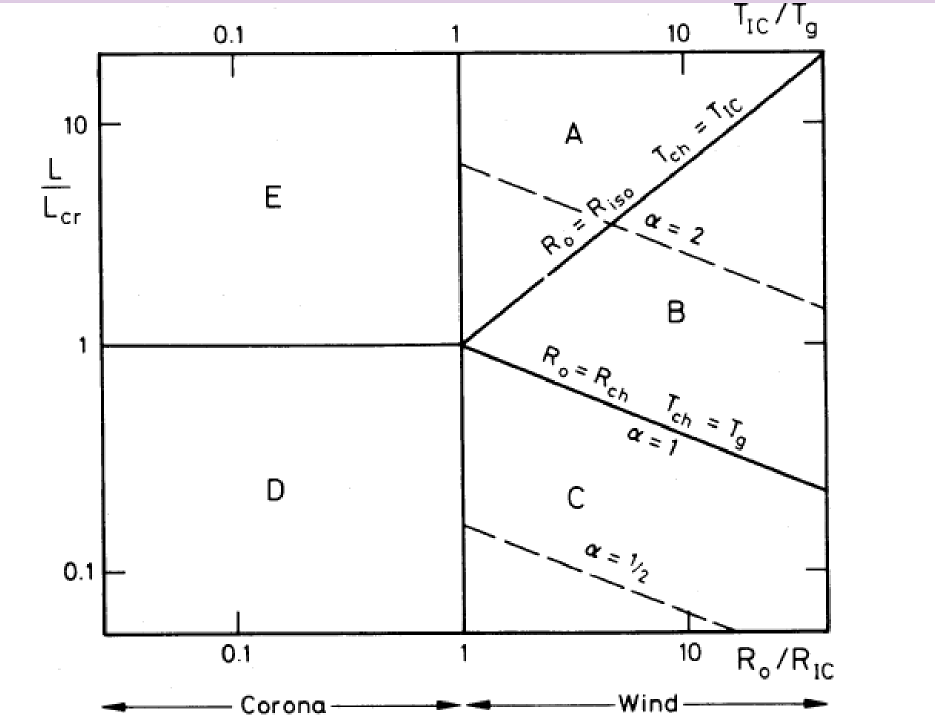


FIG. 1.—Parameter space for Compton-heated winds from accretion disks. The radius R_0 at which a streamline originates on the

The temperature of this corona is about 10^6 – 10^7 K, depends only on the shape of the incident radiation. But unlike warm skin, this corona is optically very thin. Physics of the process is very simple.

When T_{IC} is larger than the local virial temperature, a wind must form. Corresponding transition at R ~ 10^5 -10^6 R_S.

Line driven winds

Well known in stars. Radiation pressure due to the line absorption (force multiplier about 100) exceeds gravitational attraction. Basic physics well known, details difficult. For AGN idea developed by Murray et al. (1995) and Murray & Chiang (1997).

Line driven winds are clearly seen in AGN (UFO, WA, BAL, part of BLR). Thus launching those winds must be possible.

On the other hand, strong irradiation by the nucleus (IC corona/wind) kills the wind. Most computations go around it by decupling the dynamics and th eradiative transfer.

Shielding as a way out is under discussion since many years.

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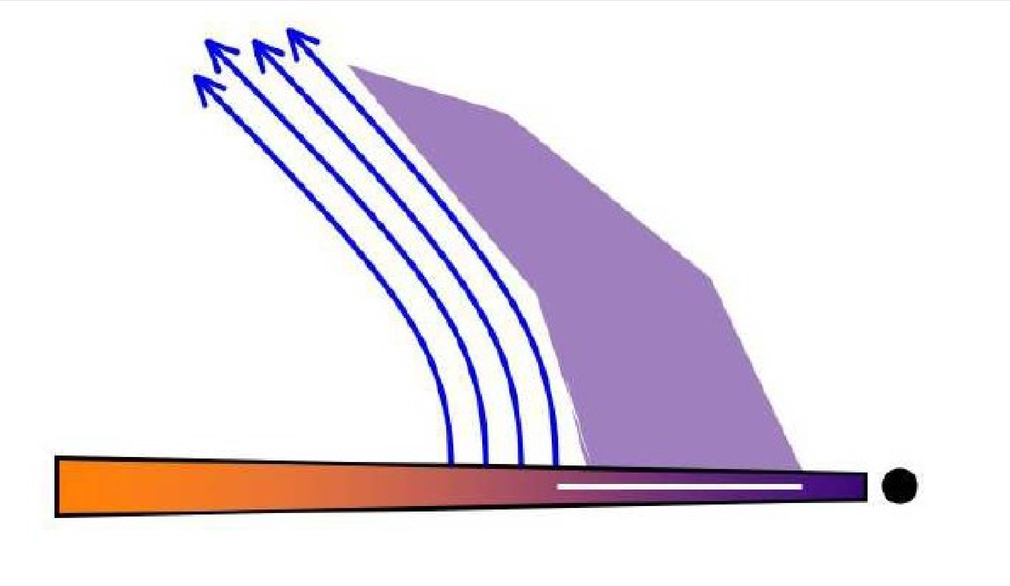
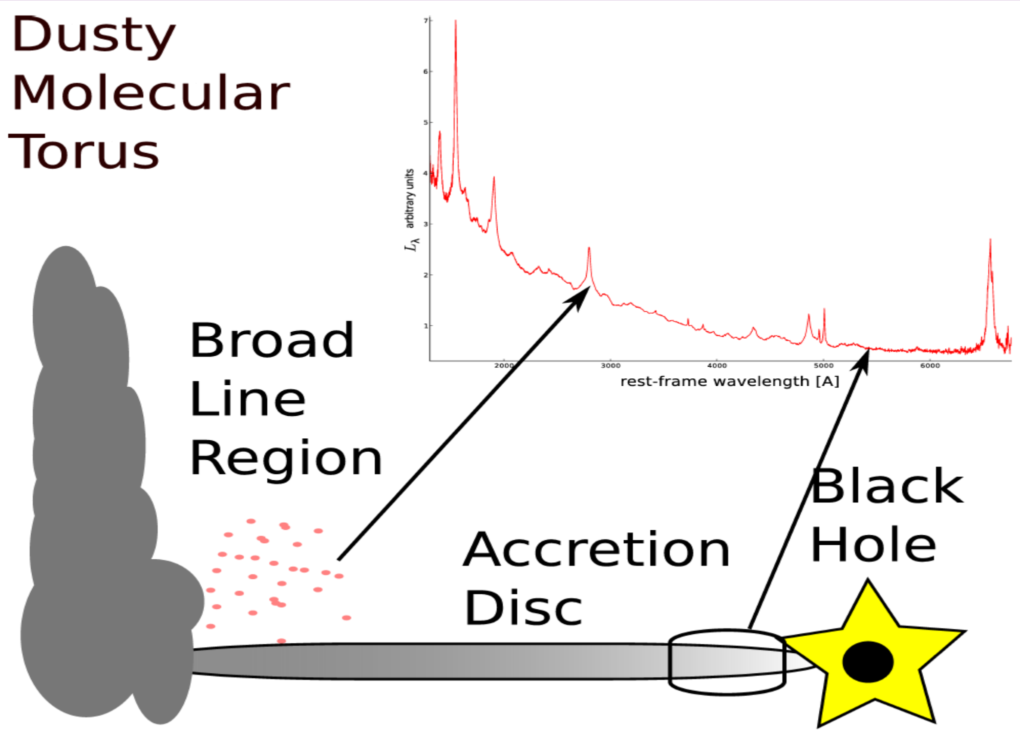


A picture from Gallagher & Everett (2007)

But if you shield it too well you cannot launch it. This is not yet done self-consistently.

Geometrically, we are now in the BLR



Nice broad emission lines in the optical an UV band are the most basic signatures of quasars.

Type 1 AGN do have them, Type 2 do not, and those are divided into sources with hidden BLR and true type 2 AGN (no hidden BLR). Observationally a difficult task, but very low luminosity AGN indeed do not show BLR. I will return to this point later on.

Sgr A* certainly does not have it.

Properties of the BLR are mapped by the reverberation technique. The firm result from these studies is the luminosity-radius relation (fit to a sample with fixed slope)

$$\log R_{BLR} = 1.47 + 0.5 \log L_{44,5100} \quad \text{[days]}$$

(Czerny et al. 2016)

BLR structure

1. BLR is complex, and consists of Low Ionization Lines and High Ionization Line regions (Collin-Souffrin et al. 1988). HIL (He II, CIV) form closer in, show outflow signatures (strong assymetry) and are most likely from the line driven wind, as discussed before. LIL (Hbeta, Mg II, Fe II) form further out, they are frequently symmetric, come from higher density medium, closer to the disk.

2. Even BLR measured by Hbeta is extended,

3. Reverberation mapping shows mostly Keplerian motion, but also signatures of inflow or outflow in different sources.

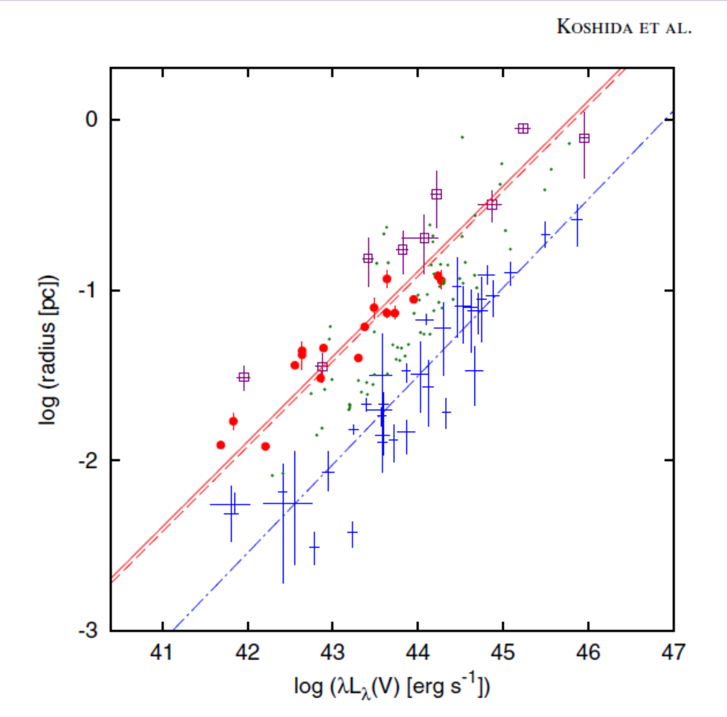


Figure 13. Radii of the innermost dust torus and the broad emission-line region (BLR) plotted against the *V*-band luminosity. Filled circles (colored red in

Koshida et al. (2014)

FRADO model of the LIL BLR

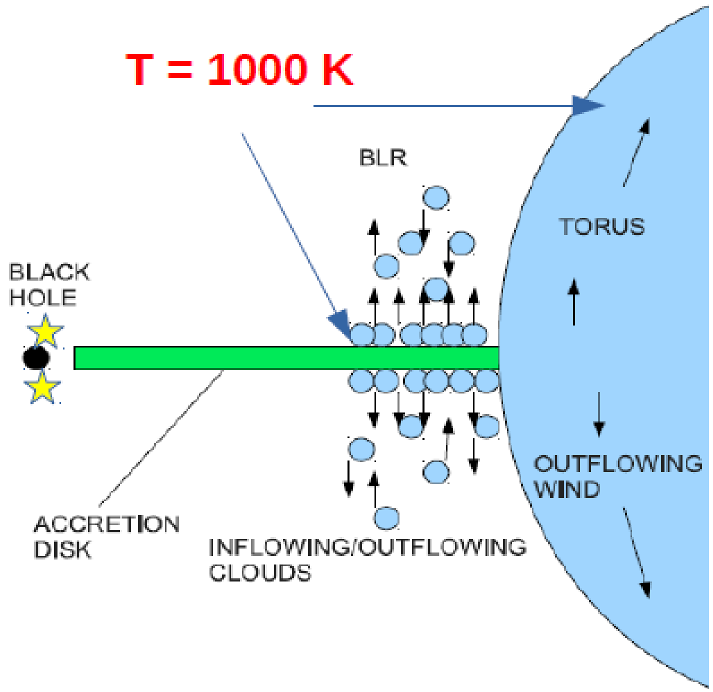


Fig. 1. The BLR region covers the range of the disk with an effective temperature lower than 1000 K: the dusty wind rises and then breaks down when exposed to the radiation from the central source. The dusty torus is the disk range where the irradiation does not destroy the dust

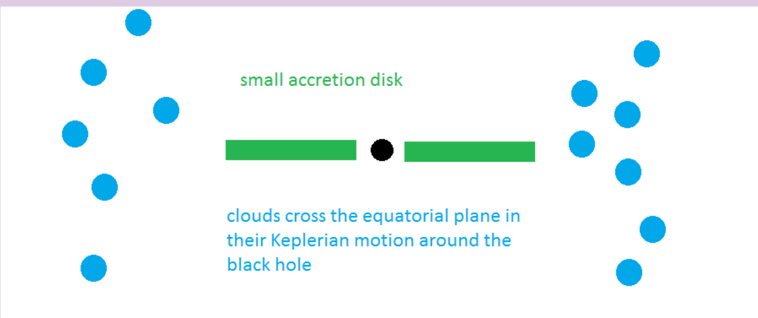
Theory outlined in Czerny & Hryniewicz (2011):

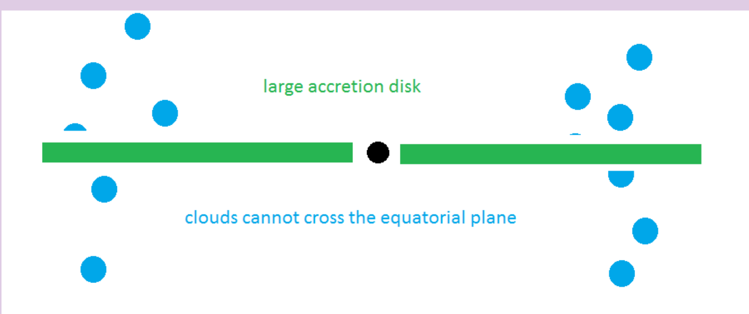
- Large outflow forms in the region where the disk temperature is below 1000 K and allows for dust formation
- Ouflow is caused by radiation pressure acting on dust grains
- Far from the disk the dusty clouds are irradiated and dust evaporates
- Dustless material looses support against gravity and falls back
- Failed wind forms

FRADO – Failed Radiatively Accelerated Dusty Outflow

The issue of the disk outer and inner radius

Our FRADO model requires the existence of the cold disk in the BLR. Observationally, the situation is not completely clear.





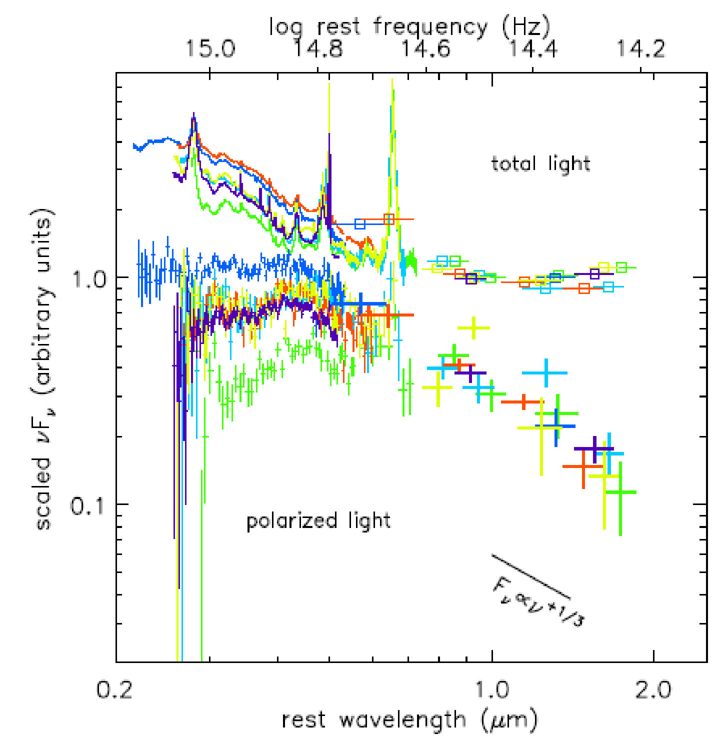


Figure 1: **Overlay of the polarized- and total-light spectra observed in six different quasars.** We plot scaled νF_ν data: Q0144-

In polarized light the disk extends down to T about 1800 K (Kishimoto et al. 2008)

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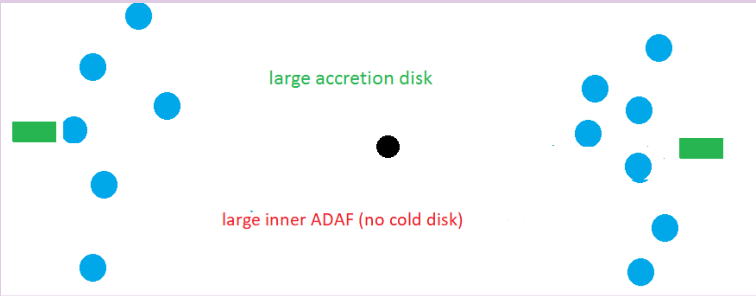
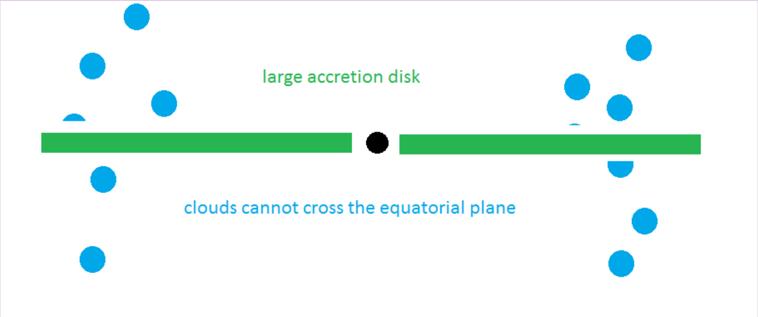
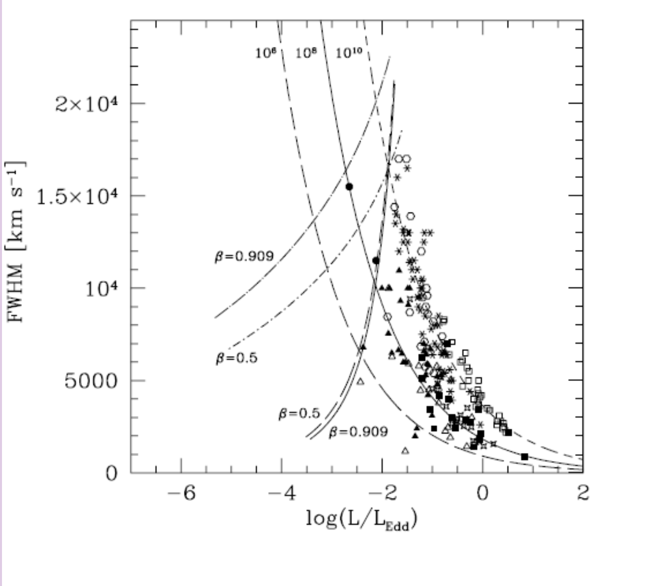




If inner ADAF is very extended, then BLR should also disappear

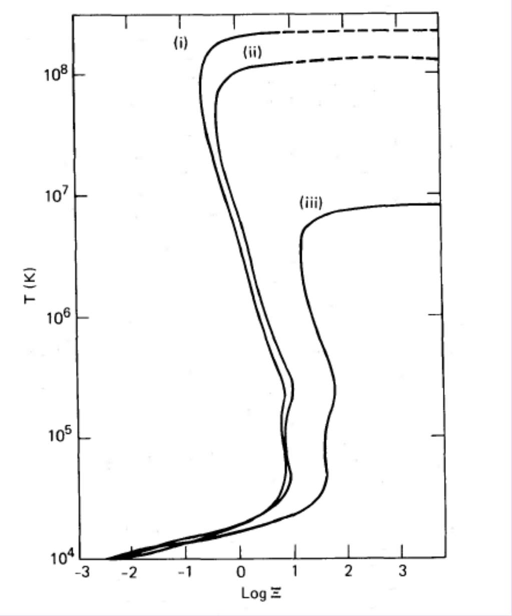


Constraints from the disk evaporation (Czerny+2004)

BLR clouds

Continuous wind vs. clumpy wind (clouds) is another long-standing observational issue. Emission line profiles are smooth, so the number of clouds has to be large, or cloud shapes have to be complex. X-ray absorption events suggest a cometary cloud shape.

On the theoretical side: irradiated medium is subject to thermal instability (Krolik, McKee & Tarter 1981). Clouds should form spontaneously if the incident spectrum is hard enough.



Krolik et al. 1981)

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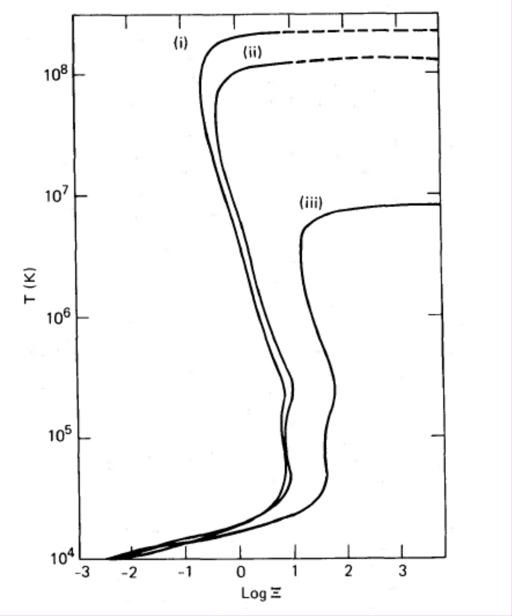


Krolik et al. (1981)

Thermal instability vs. pressure confinement

Another way of looking at the cloud parameters is the radiation pressure confinement (Stern et al. 2014; Baskin & Laor 2018)

Compression of the gas by the incident radiation pressure (RPC) gives $P_{gas} = P_{rad}$, i.e.

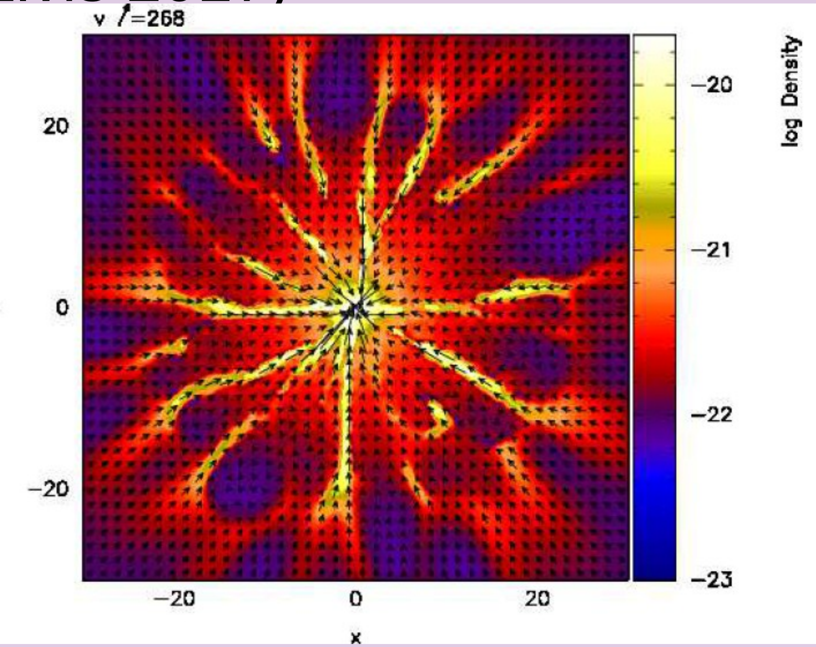
$$2nkT = F/c \tag{4}$$

i.e. instead of thermal balance a dynamical condition is superimposed. This, however, requires the pre-existence of a boundary, and does not contain the dependence on the spectral shape.

The mixed inflow-outflow

Two-phase medium leads to more complex dynamics, and in particular a combination of inflow and outflow, depending on the medium conditions.

Denser colder clouds may inflow more easily while surrounding hot plasma may have temperature higher than virial and flow out. Examples: Sgr A* region (Różańska et al. 2014; Barai et al. 2014; Elvis 2017)



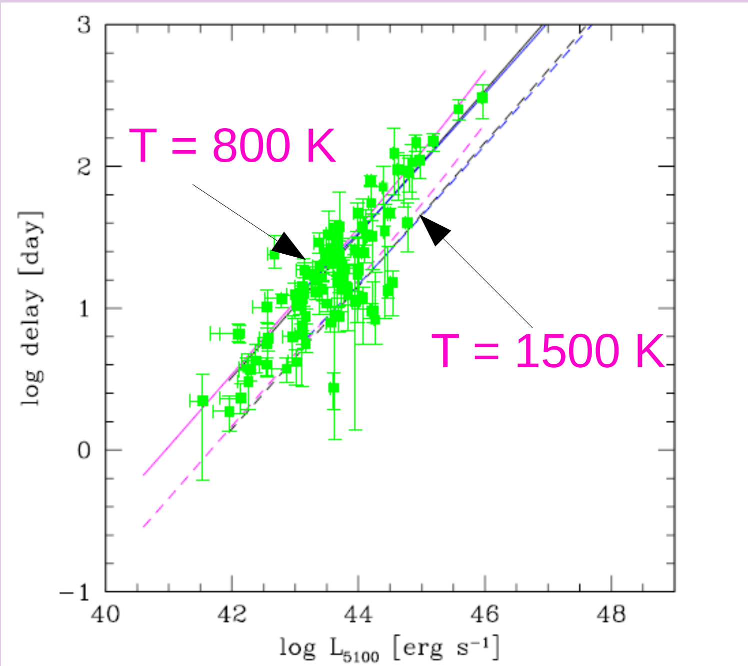
However, colder clouds may be subject of increased radiation pressure from the nucleus, and then they will rather flow out than in. Net effect was not calculated.

Numerical results of a two-phase medium flow from Barai et al. 2014.

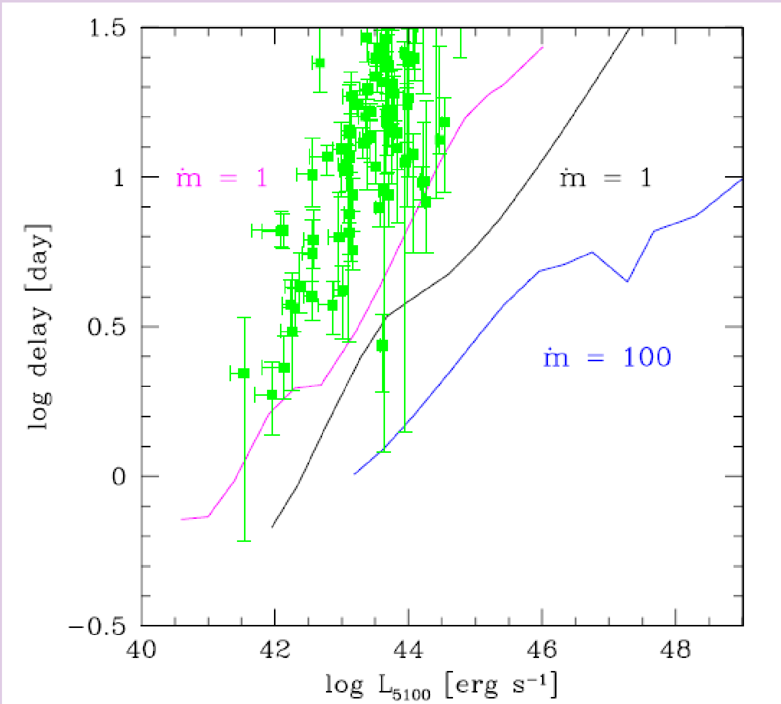
Disk outer radius due to self-gravity

This is certainly important only in AGN since the ratio of the disk mass to the black hole mass scales roughly with the black hole mass. Phenomenon is simple, easy to calculate for a known accretion disk model (e.g. alpha disk of Shakura-Sunyaev).

Self-gravity should disrupt the disk and causes star formation in situ. Hower, the standard Toomre criterion is apparently too strong (Czerny et al. 2016). Argument for strongly magnetized disk?



FRADO model predicts well the radius



Self-gravity criterion implies too small radius

Where the outer radius should be ?

1. Circularization radius of the infalling material

2. Non-stationary disk expansion if wind does not carry away all the angular momentum

3. Unlike in GBH, the tidal forces from the Nuclear Stellar Cluster probably cannot take away the angular momentum; outer excretion disk?

This is connected with the issue of fuelling AGN, not really solved consistently.

AGN surrounding

At the distances at least as close as BLR there are following elements:

- Nuclear Stellar Cluster (NSC)
- Interstellar medium

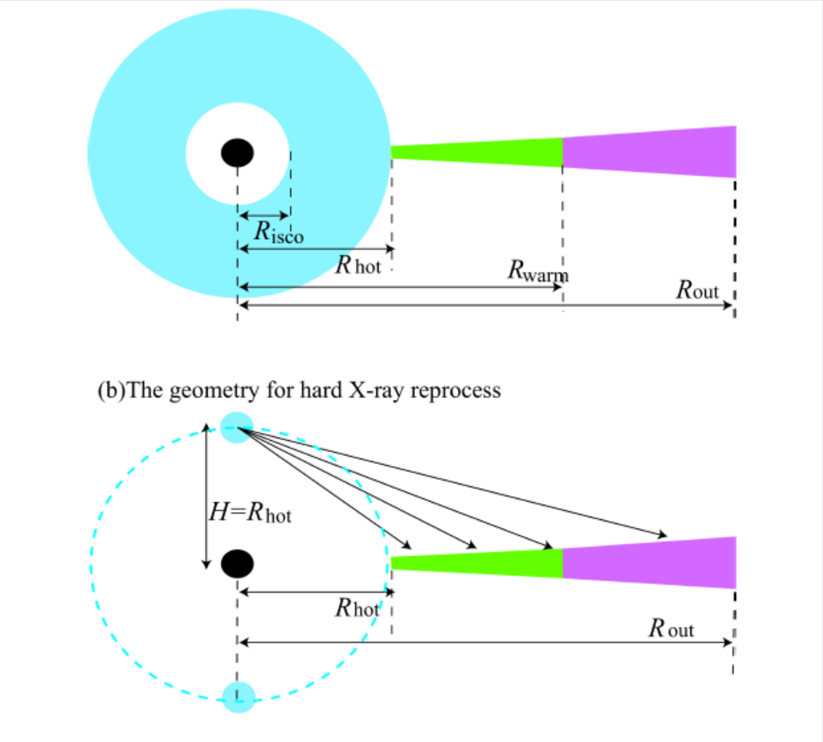
NSCs interact with an active nucleus through events of stellar disruptions (TDE), but also possibly passages through the accretion disk.
Interstellar medium may provide inflow or may be blown away, usually not incorporated in the AGN models. Outflow domination in the ionization cone (spatially resolved images of the NLR).
VLBI interferometry implies also dust in the ionization cone for a few nearby sources.

In the future this should be a part of the (time-dependent) global model.

Instead of a summary – two global models

Model 1 – Kubota & Done

This model is meant to use for the broad band data fitting. Has the following elements:



- hot corona
- warm corona
- outer cold disk

The model is basically parametric, but Kubota & Done argue that the energy in the hot corona is constant, independent from L/Ledd. It might be due to limited optical depth of the corona, I suppose.

Model 2 – Lusso & Risaliti (2017)

This model was designed to explain the observed tight correlation between the X-ray flux at 2 keV, UV flux at 2500 A, and the line width:

$$(\log L_X - 25) = (0.610 \pm 0.019)(\log L_{UV} - 25) + (0.538 \pm 0.072)[\log \upsilon_{fwhm} - (3 + \log 2)] + (-1.978 \pm 0.100),$$

It contains:
- hot corona
- inner standard disk

but does not have any arbitrary parameters. The corona is present in the **outer** part of the disk, where half of the energy from the disk goes to corona, and the transition radius is set by transition from radiation pressure dominated to radiation pressure dominated part of the disk.

Thank you