Modelling broad emission lines in active galactic nuclei

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Modelling is strongly motivated by observations!

Karl Seyfert

Alla I. Shapovalova

Stationary picture of Seyfert is already well incorporated in models. Time-dependent picture of Shapovalova – not quite yet.

General approach to modelling BLR

1

Assumption of general geometrical setup → **Photoionization modelling of line ratios** → **Comparison with the data**

2

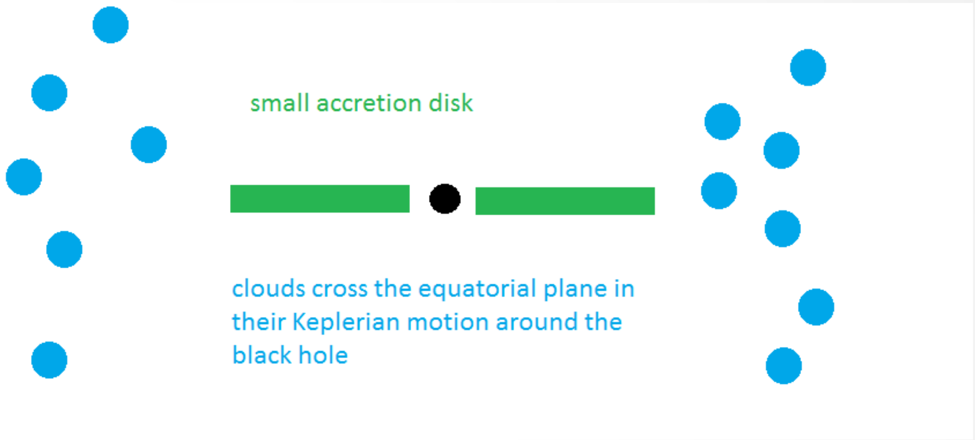
Hints from the data → **Determination of geometrical setup from physical principles** → **Comparison with the data**

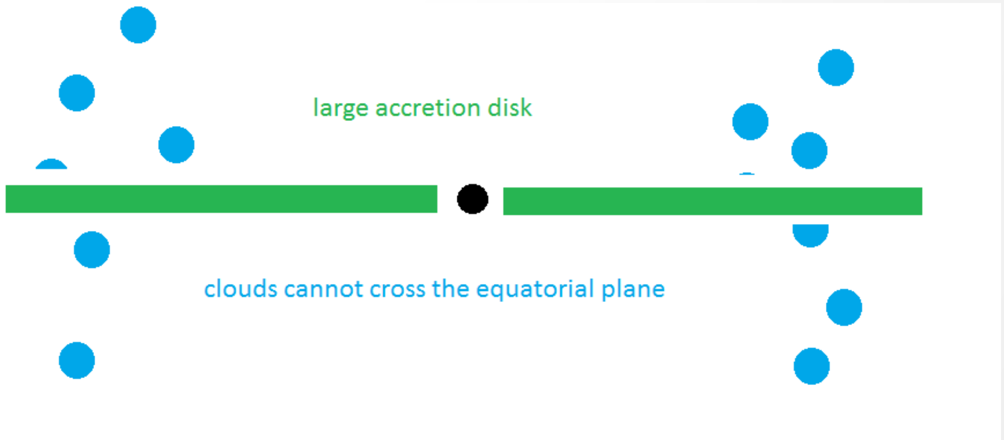
Or a mixture...

Important achievements of 1

APPROACH:

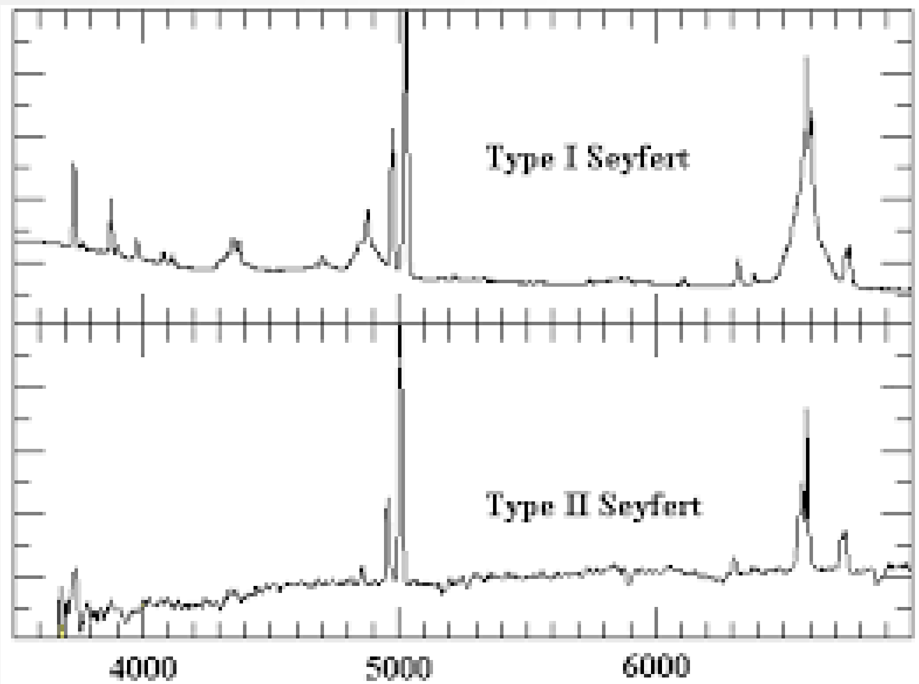
1. assumption of no overlap with underlying accretion disk
2. material is available everywhere
3. clouds in constant density approximation
4. cloud density decreases with radius as a powe law
5. optionally LOC model (range of clouds with different densities at a given radius; Baldwin et al.)
6. photoionization computations done with a complex code (e.g. CLOUDY)





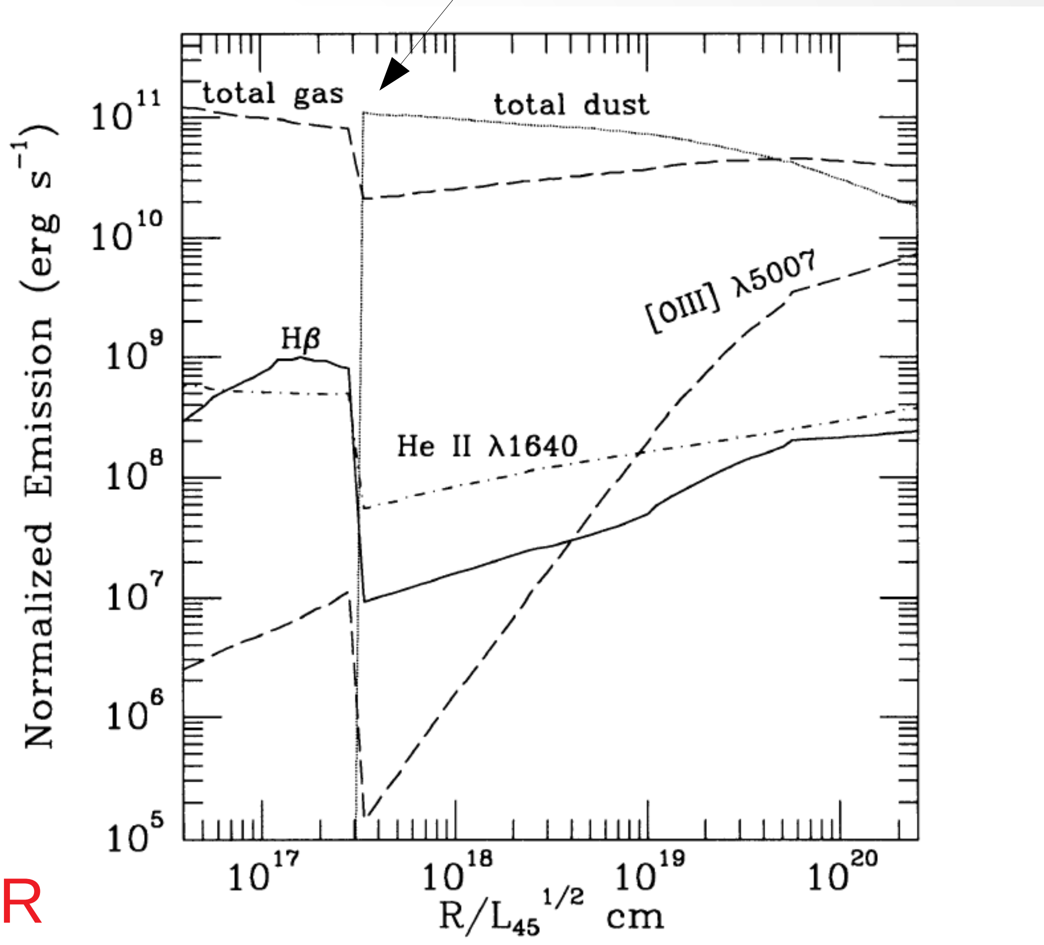
Important achievements of 1

Explanation of the existence of the outer radius of the BLR and a gap between the NLR and BLR



Clear separation between the BLR and NLR is due to dust. Sets the outer radius of BLR.

Dust

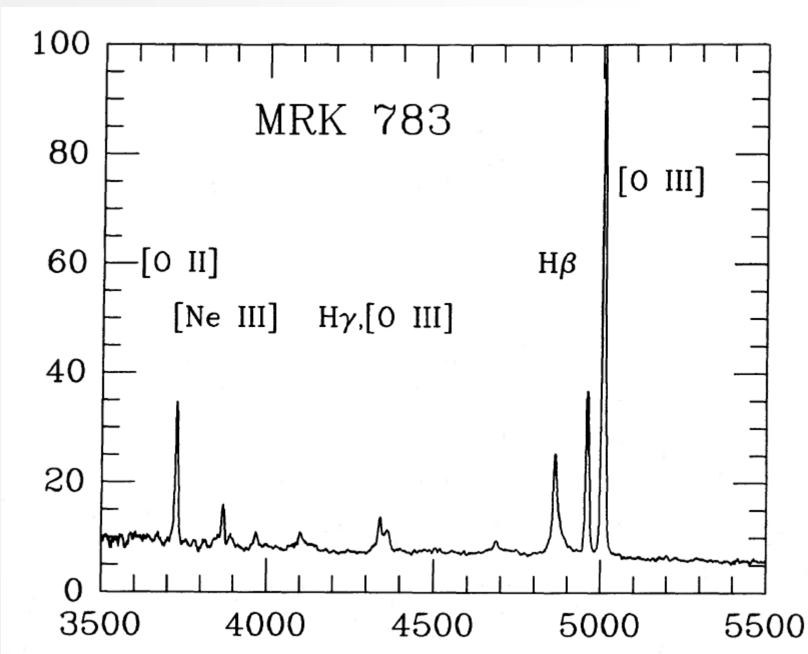


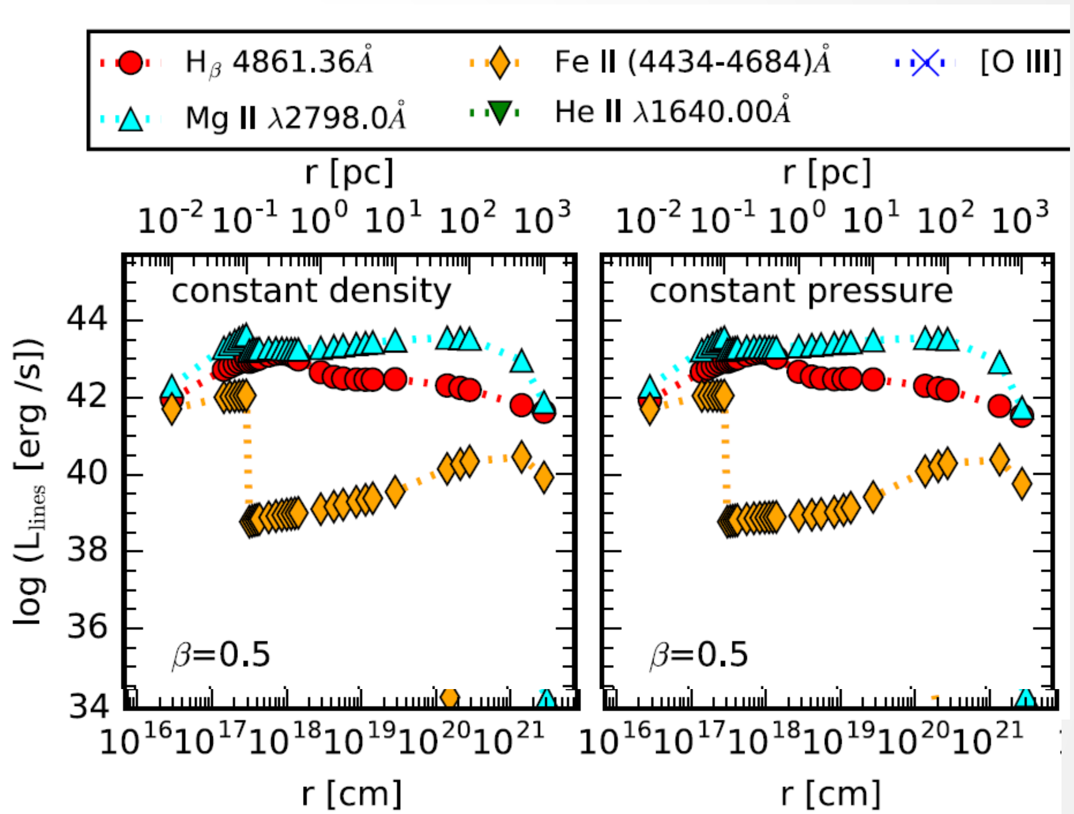
Netzer & Laor (1993)

Important achievements of 1

The case of NLS1 – why they do not show such a gap?

Adhikari et al. (2018)





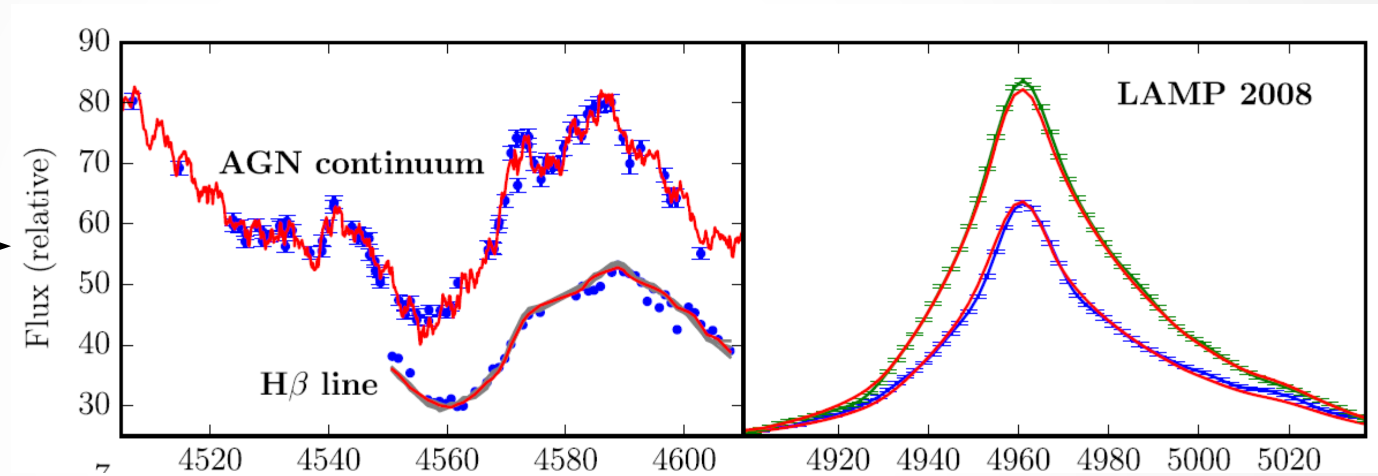
Example from original Osterbrook & Pogge

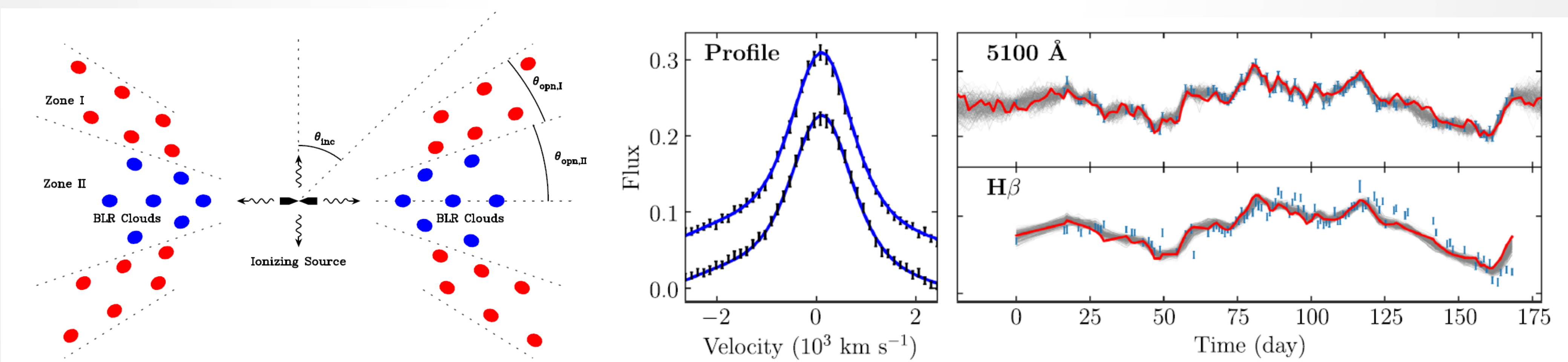
Clear separation between the BLR and NLR vanishes (apart from Fe II!) if we use higher cloud densities.

Important achievements of 1

Multi-parametric models are very successful in modelling the results of reverberation campains.

Exemplary source from Pancoast et al. (2018), complez geometry without reprocessing. Good fit to lightcurve and line shape.





Two-zone model for high accretion rate source Mrk 142 (Li et al. 2018)

So why do we need approach 2?

Parametric approach will never tell us why this material is there.

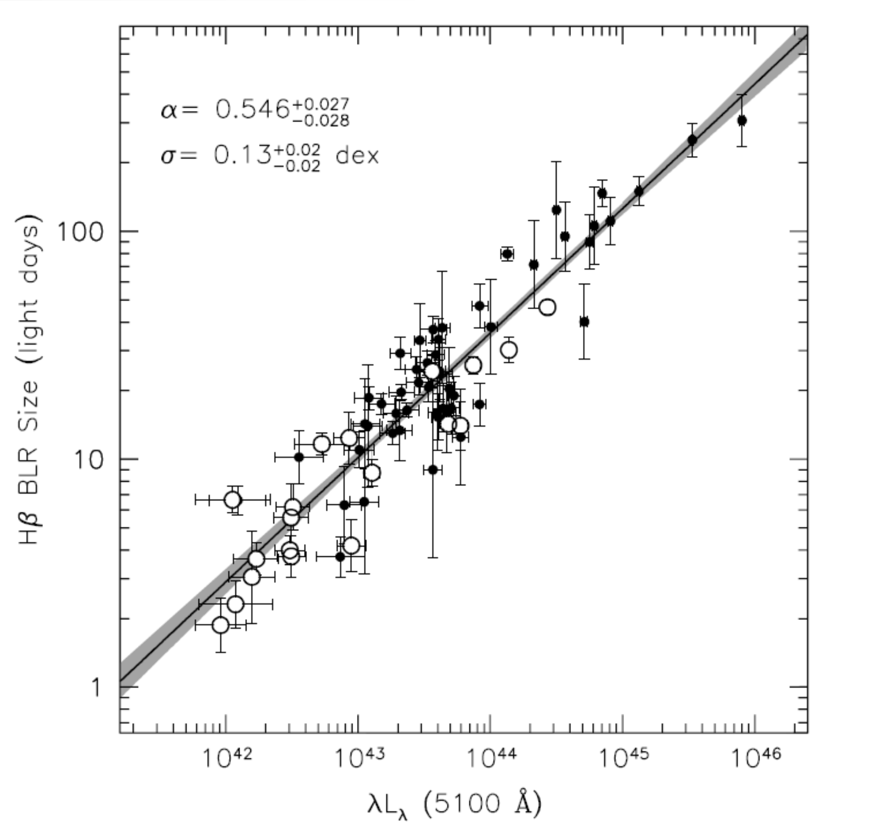
And we know that this material is:
(i) roughly in Keplerian motion
(ii) with some signatures of outflow, stronger in case of high ionization lines
(iii) some(times) signatures of inflow
(iv) the distribution is flattened, but the covering factor is high (0.1 – 0.3) so part of the material is far from the equatorial plane

The origin of the material in BLR

- **Inflow from the outer parts, with subsequent circularization** (e.g. Wang et al. 2017)
- **Accretion disk destruction due to self-gravity** (e.g. Collin & Zahn 1999, Wang et al. 2011,2012)
- **Accretion disk wind or failed wind.**

Accretion disk winds

Inspiration for the **FRADO** model – Failed Radiatively Accelerated Dusty Outflow came from the tight relation Radius – Luminosity reported in early reverberation papers.



Bentz et al. 2013

Why the tight scaling is with the monochromatic flux instead of bolometric or ionizing flux?

Monochromatic flux:

$(M\ Mdot)^{2/3}$

Bolometric flux:

Mdot

FRADO

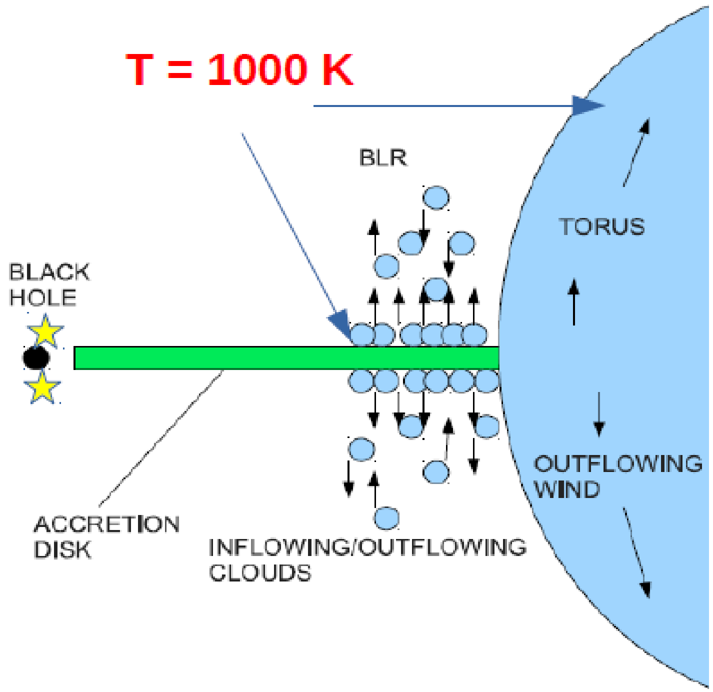


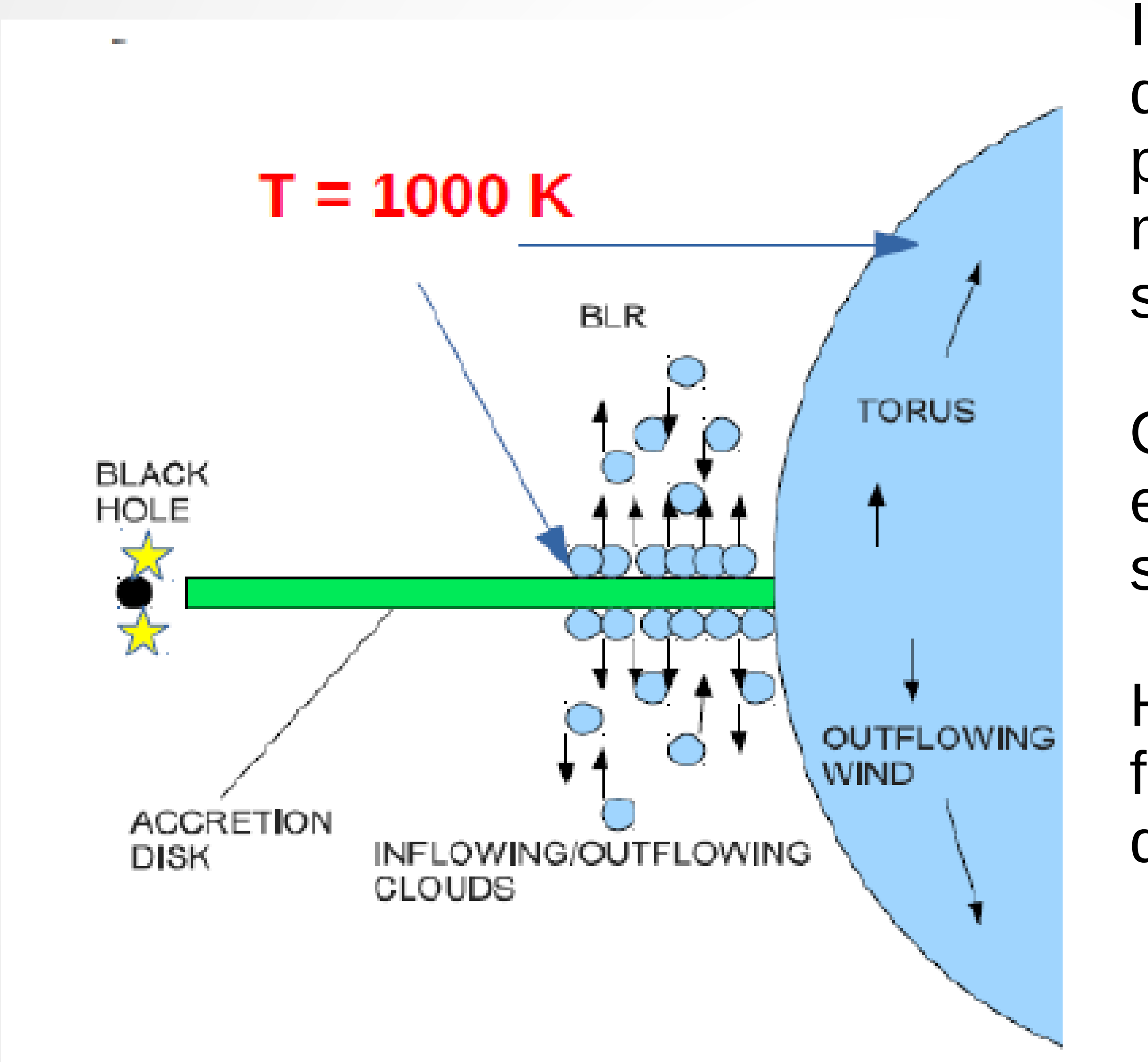
Fig. 1. The BLR region covers the range of the disk with an effective temperature lower than 1000 K: the dusty wind rises and then breaks down when exposed to the radiation from the central source. The dusty torus is the disk range where the irradiation does not destroy the dust

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

Dust determines also the inner BLR radius for LIL



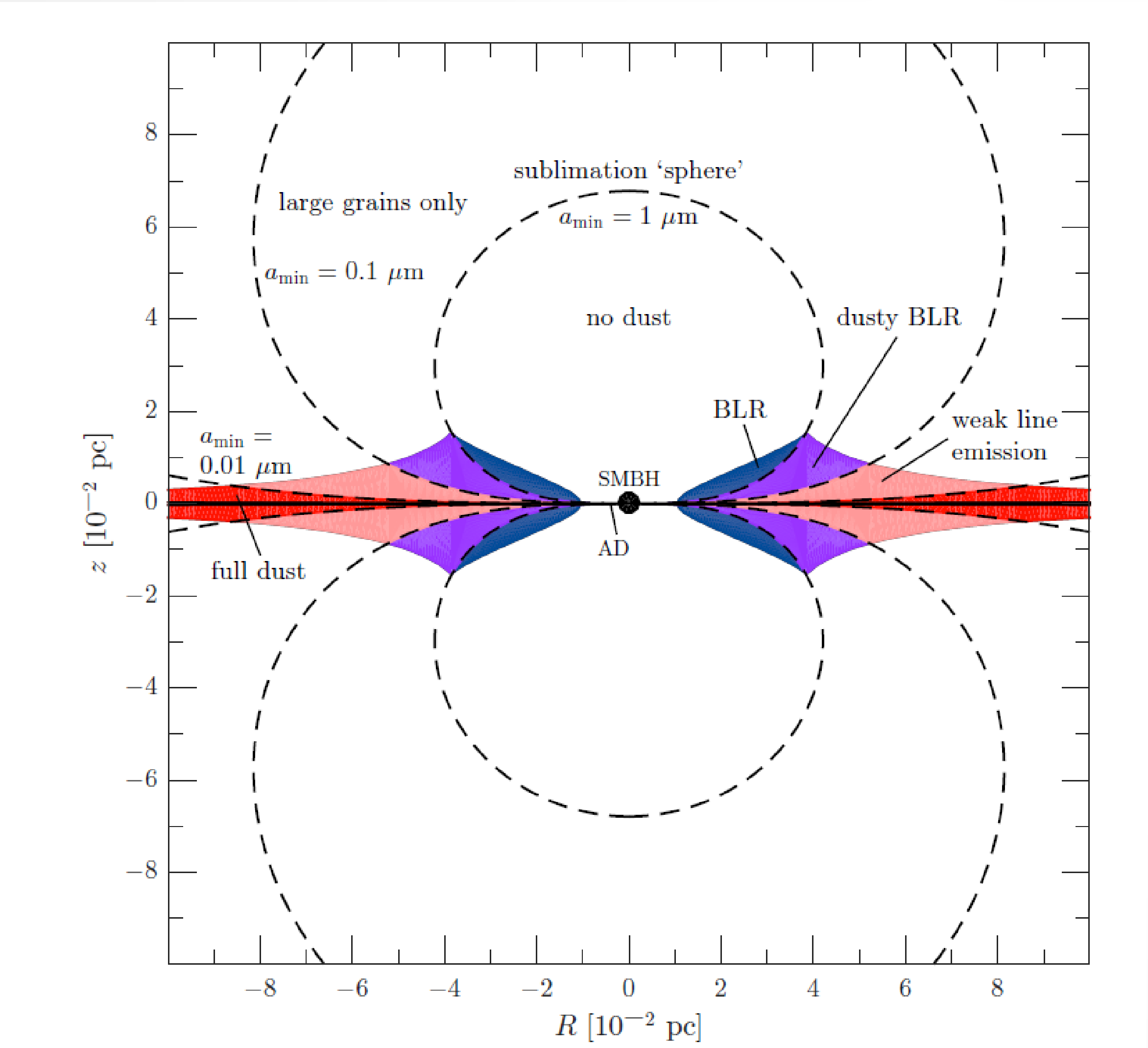
Inner radius: dust in the disk atmosphere, efficient pushing up the disk material, limited by sublimation

Outer radius: dust everywhere, no sublimation

High ionization lines can form closer in, in a line-driven wind.

(Czerny & Hryniewicz 2011, Czerny et al. 2015, Czerny et al. 2017)

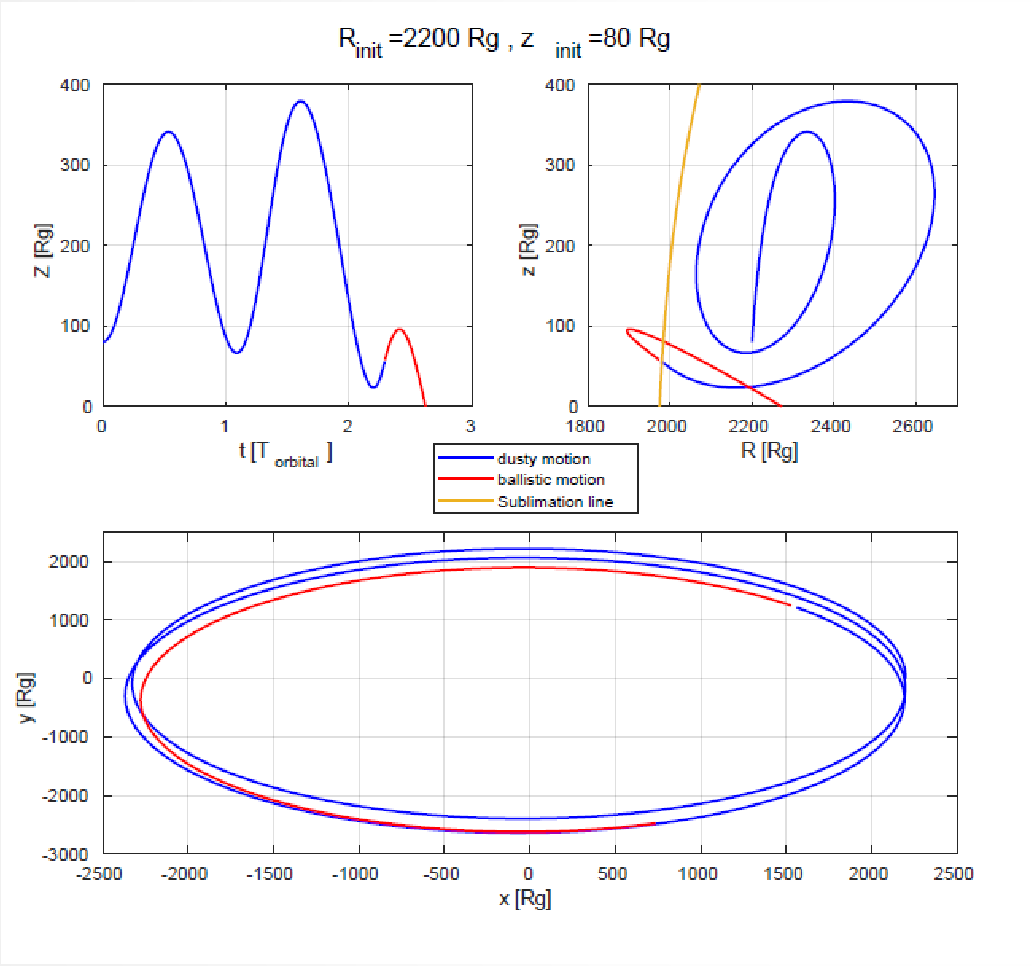
Dynamics of BLR in FRADO



Static model of Baskin & Laor (2018).

They assume that the presence of the dust in the disk atmosphere puffs it up but does not launch the dusty wind. Only Keplerian motion.

Dynamics of BLR in FRADO



Dynamical model. We assume that the presence of the dust in the disk atmosphere launches the dusty wind. Keplerian motion combined with vertical motion.

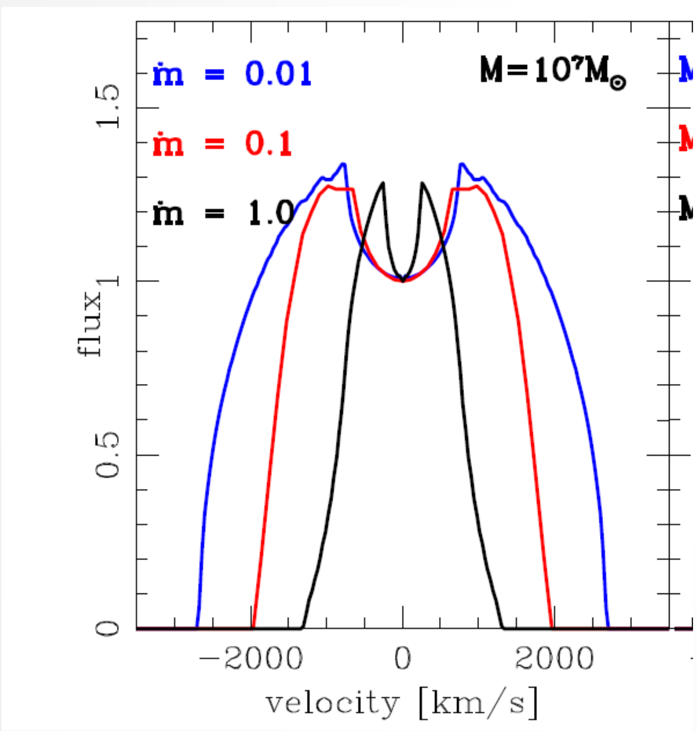
Naddaf et al., in preparation

We now test 3-D motion of individual cloud. We also assume that the cloud is not exposed to all radiation due to shielding or finite optical depth. We hope to have better line wings.

Dynamics of BLR in FRADO

Argument for launching winds:

- Observations of dusty stars (e.g. AGN stars)
- kappa_{Ross} < kappa_{Planck}

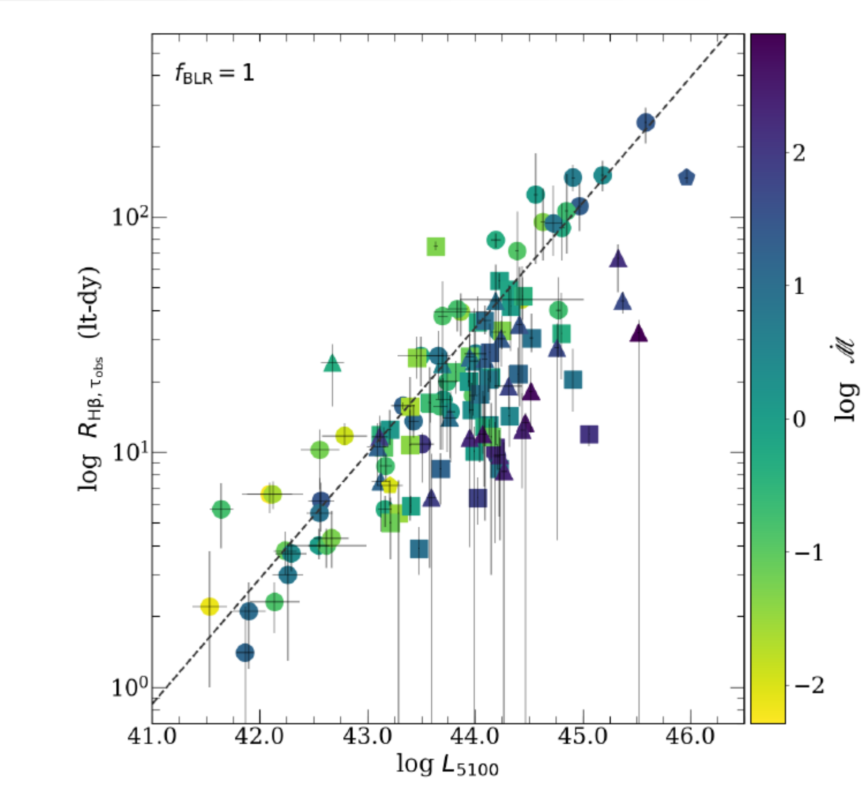


Czerny et al. 2017

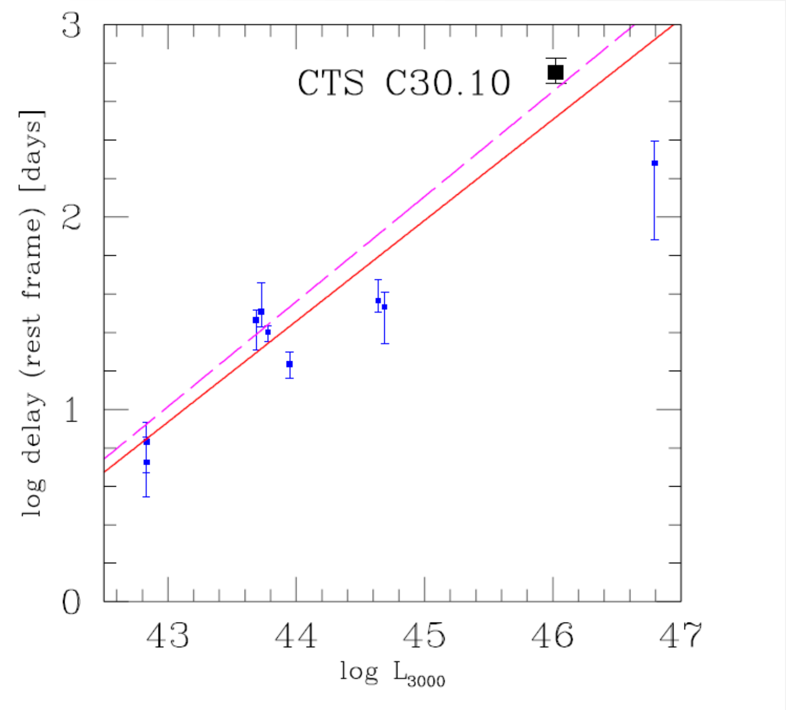
Dynamical model. We assume that the presence of the dust in the disk atmosphere launches the dusty wind. Keplerian motion combined with vertical motion.

Here vertical velocity helped to get somewhat better profiles than just from the Keplerian motion. But still not what we see,

Problems in FRADO



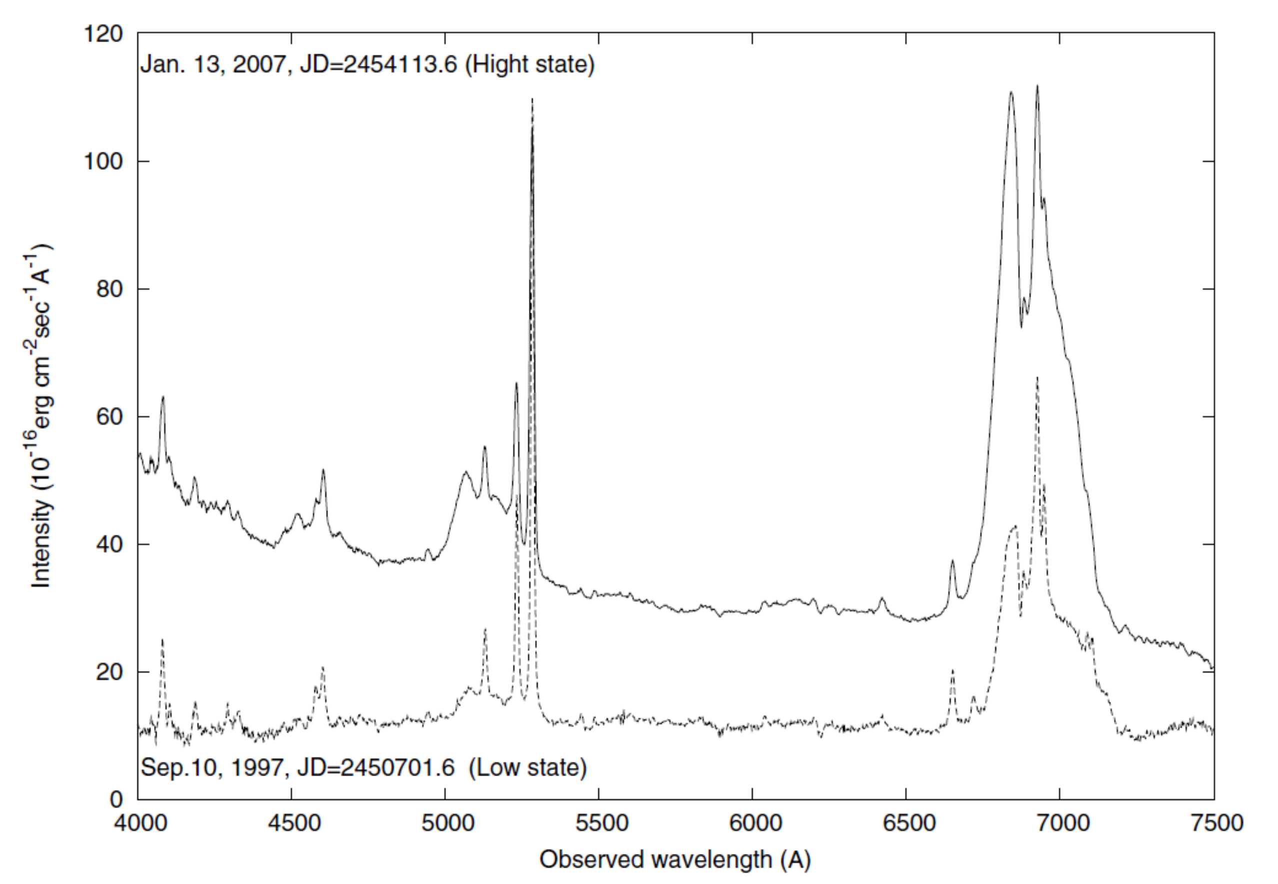
Martinez Aldama., submitted



Czerny et al., submitted

New delay measurement show evident dependence on the accretion rate ...

Time-dependent profiles

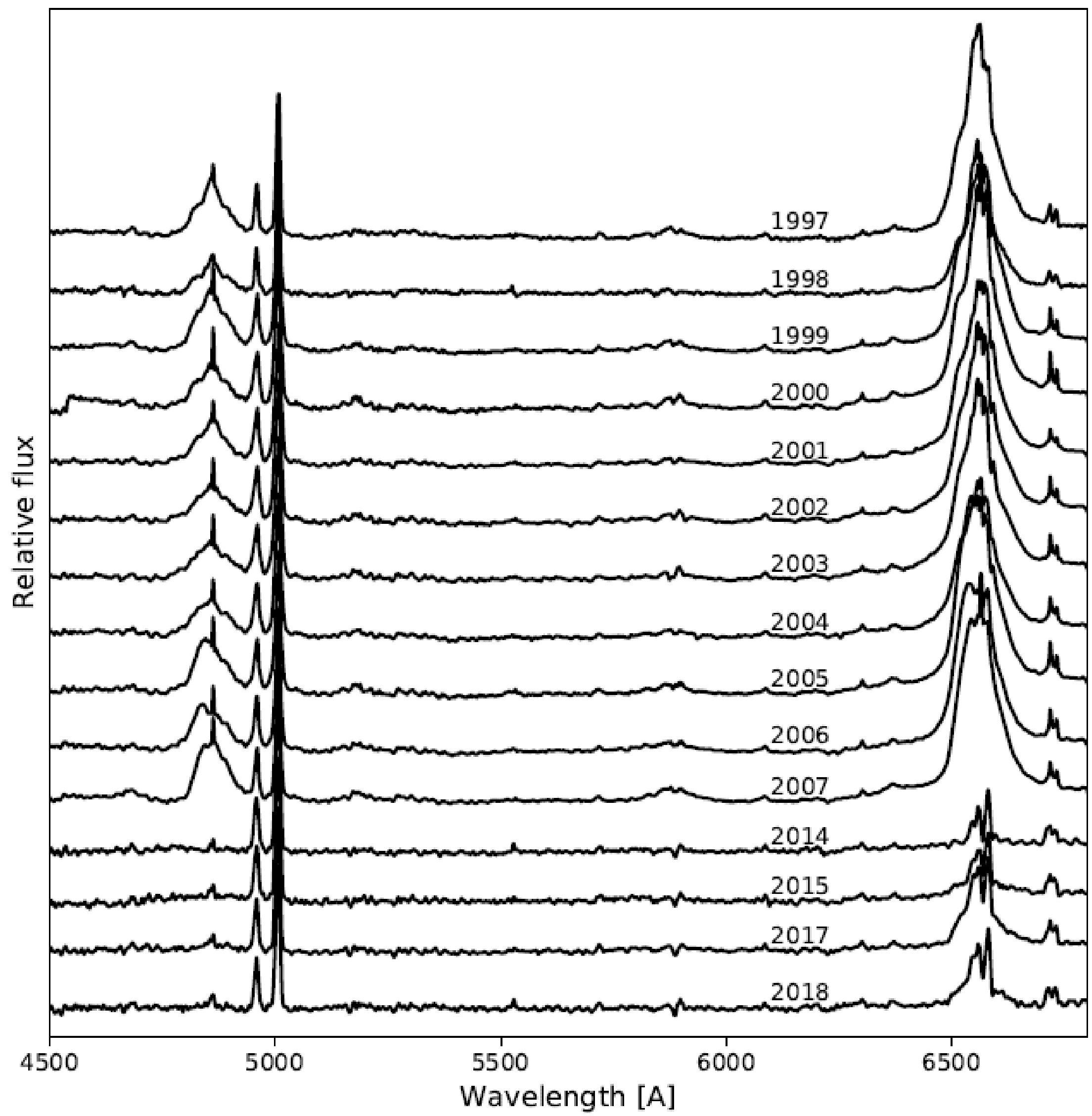


Such sources seem to support the view that part of the emission comes from an accretion disks (double-peak profile).

But modeling requires hot spots, spiral waves or relativistic eccentric disk.

Shapovalova et al. 2010
source C 390.3

Time-dependent profiles



Almost complete disappearance of emission lines.

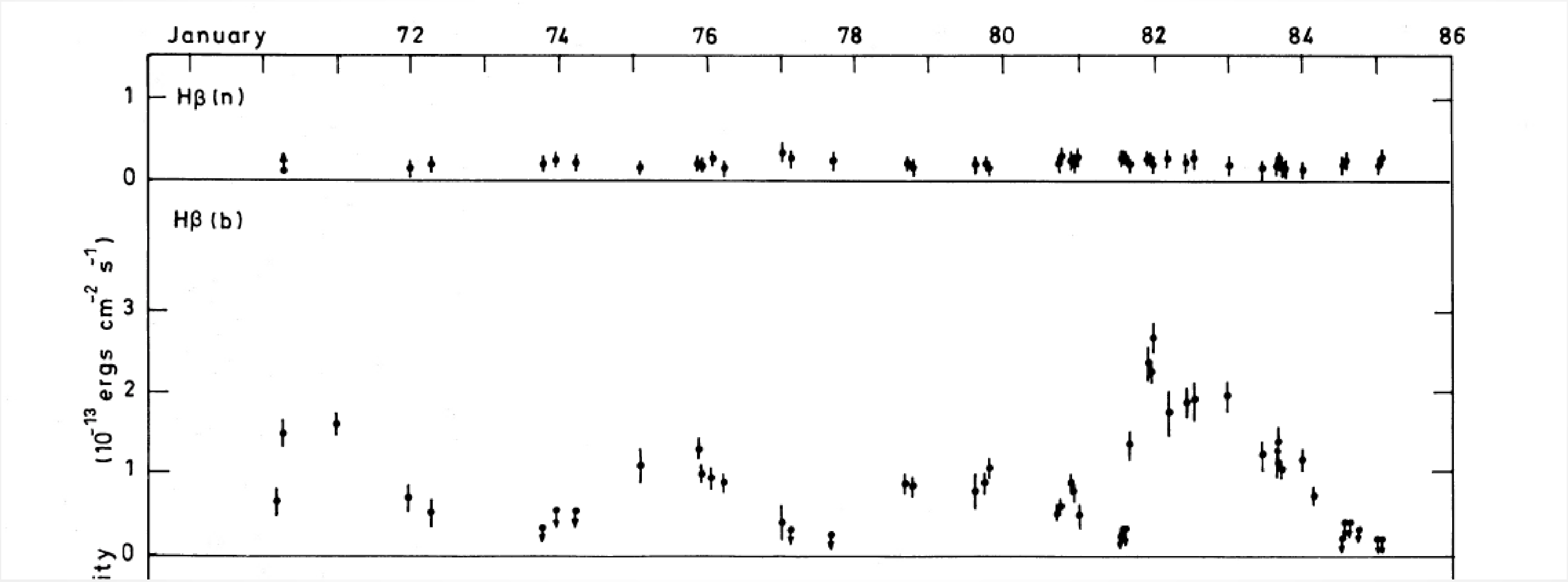
In this case the interpretation through absorption is favored since the line width did not change.

?

Shapovalova et al. 2019, CL source NGC 3516.

Time-dependent profiles

Older example of CL AGN. Several outbursts. Also lack of change in the profile apart from normalization but interpreted as an echo from clouds in unperturbed motion. Time delays suggesting outbursts in UV/X-rays.



Alloin et al. et al. 1985, Alloin et al. 1986, source NGC 1566 .

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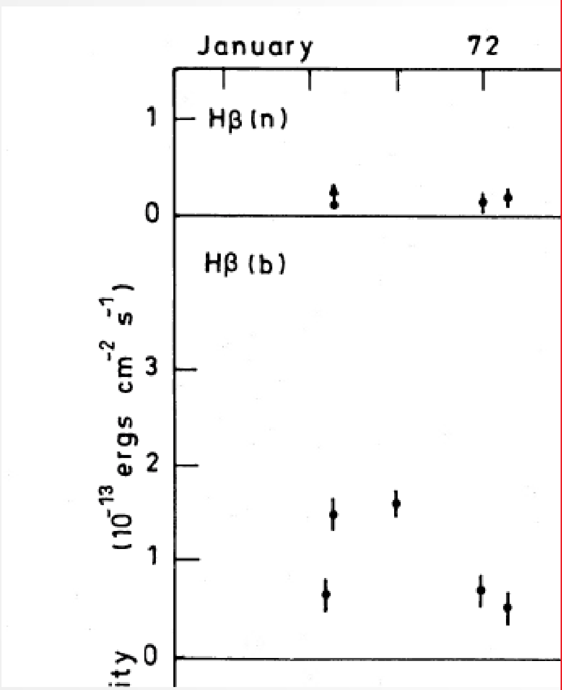


Swift catches the changing-look AGN NGC 1566 in an X-ray outburst again

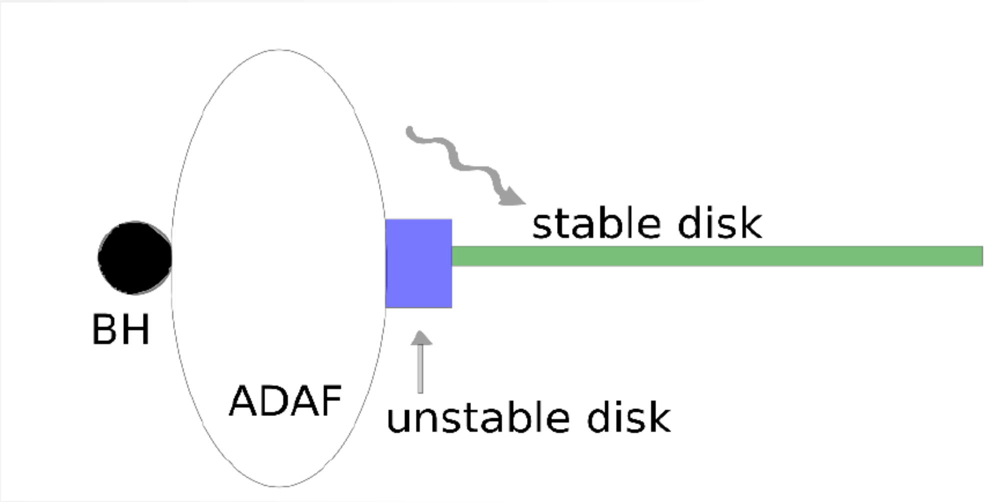
ATel #12826; Dirk Grupe, Rebecca Mikula….

on 31 May 2019; 20:00 UT

Previous outburst: June 2018

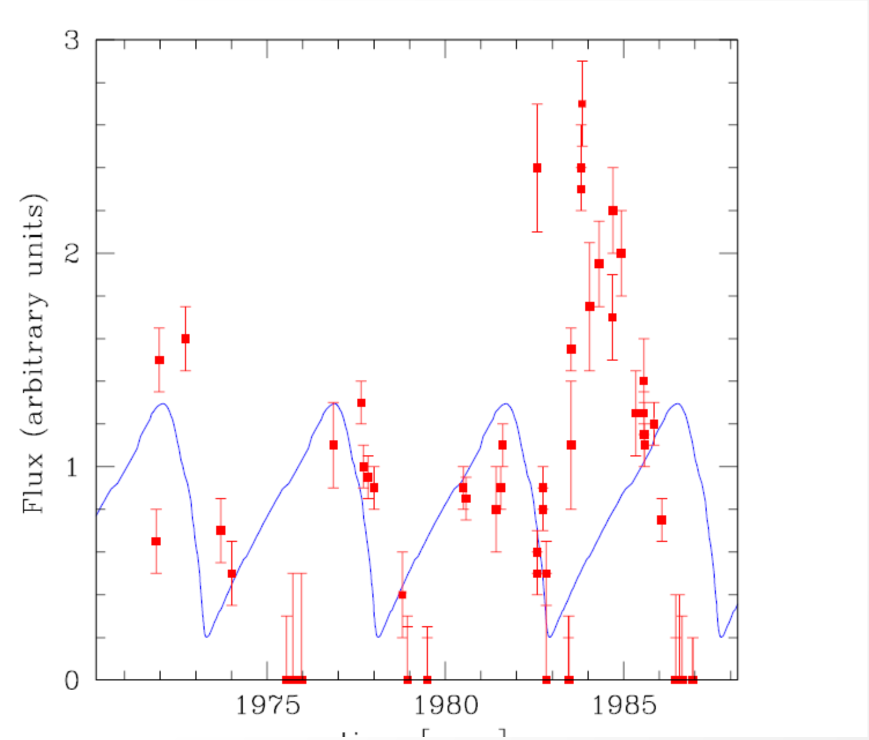
985,
source
NGC 1566 .

… so we try model this as intrinsic change in accretion flow



Śniegowska et al. (in progress)

This mechanism may work for low Eddington ratio sources, where the inner radiation-pressure dominated part of the disk is very narrow, which shortens viscous timescale.

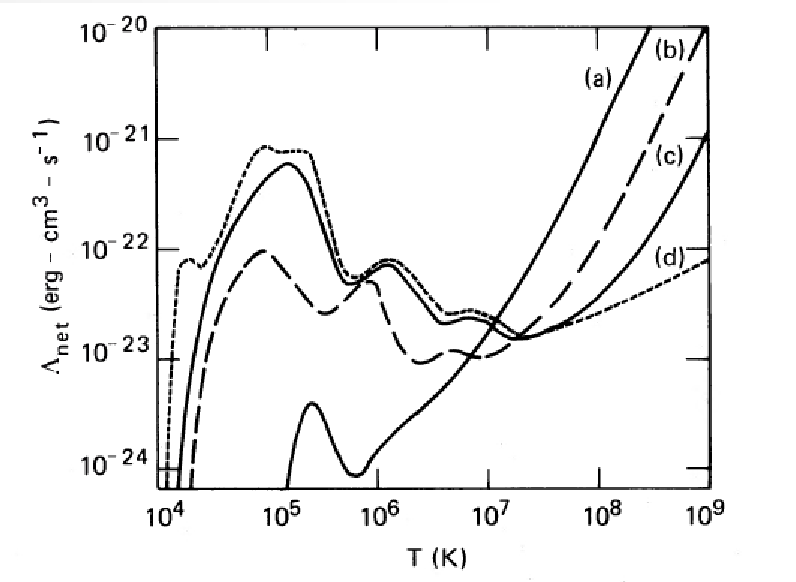


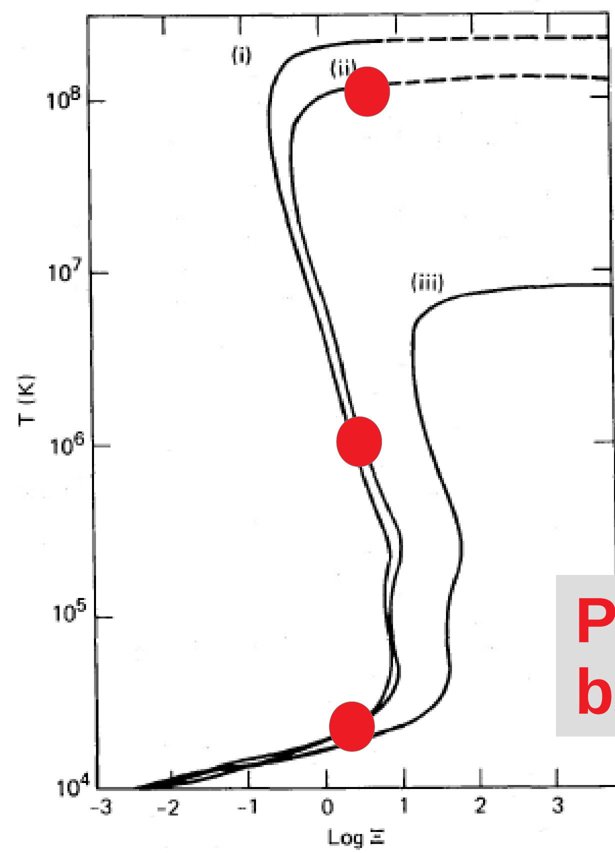
Data points from Alloin et al. (1986)

Last problem: BLR clumpiness

We talk about clumps but disk outflow (if it is an outflow) starts as a continuous wind…

This is not a problem: we thermal instability operating in irradiated medium which gives that:
Krolik, McKee & Turter 1981





$$\Xi = \frac{F_{\rm ion}}{nkTc}$$

Pressure balance

Note a difference from other ionization parameters: small xi and U.

Radiative pressure confinement

From Baskin & Laor (2018):

(i) BLR forms where dust submlimates as in Czerny & Hryniewicz (2011)

$$T_{\rm sub} \simeq 2000 \ \ {\rm K} \quad \rightarrow \quad F = 3.63 \times 10^9 \ {\rm erg \ s^{-1} cm^{-2}}$$

$$F(R_{\rm sub})/c = 0.12 \ T^4_{2000} \ \ {\rm erg \ cm^{-3}}$$

(ii) This is now combined with radiation pressure confinement

$$2nkT = F/c$$

(iii) And since plasma in gaseus phase has

$$T \sim 10^4 \ \ {\rm K},$$

$$n = F/2kTc \sim {\rm few} \times 10^{10} \ {\rm cm^{-3}}$$

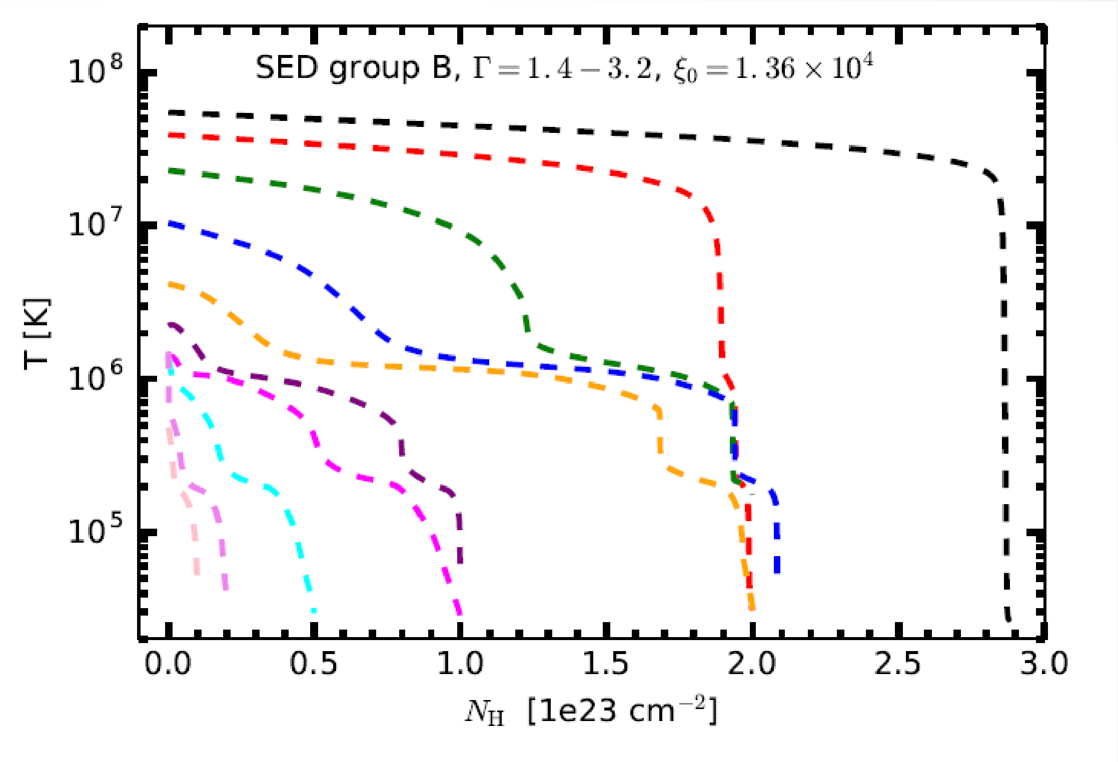
Universal BLR cloud Density !

How large are clouds?

If the radiative transfer computations are done under constant pressure in plane-parralel approximation, cloud have

$N_H \sim 10^{23}$ cm^{-2}

And a few percent of that is concentrated in the dense co core. Core is not well resolved, codes do not like dense fully thermalized medium.

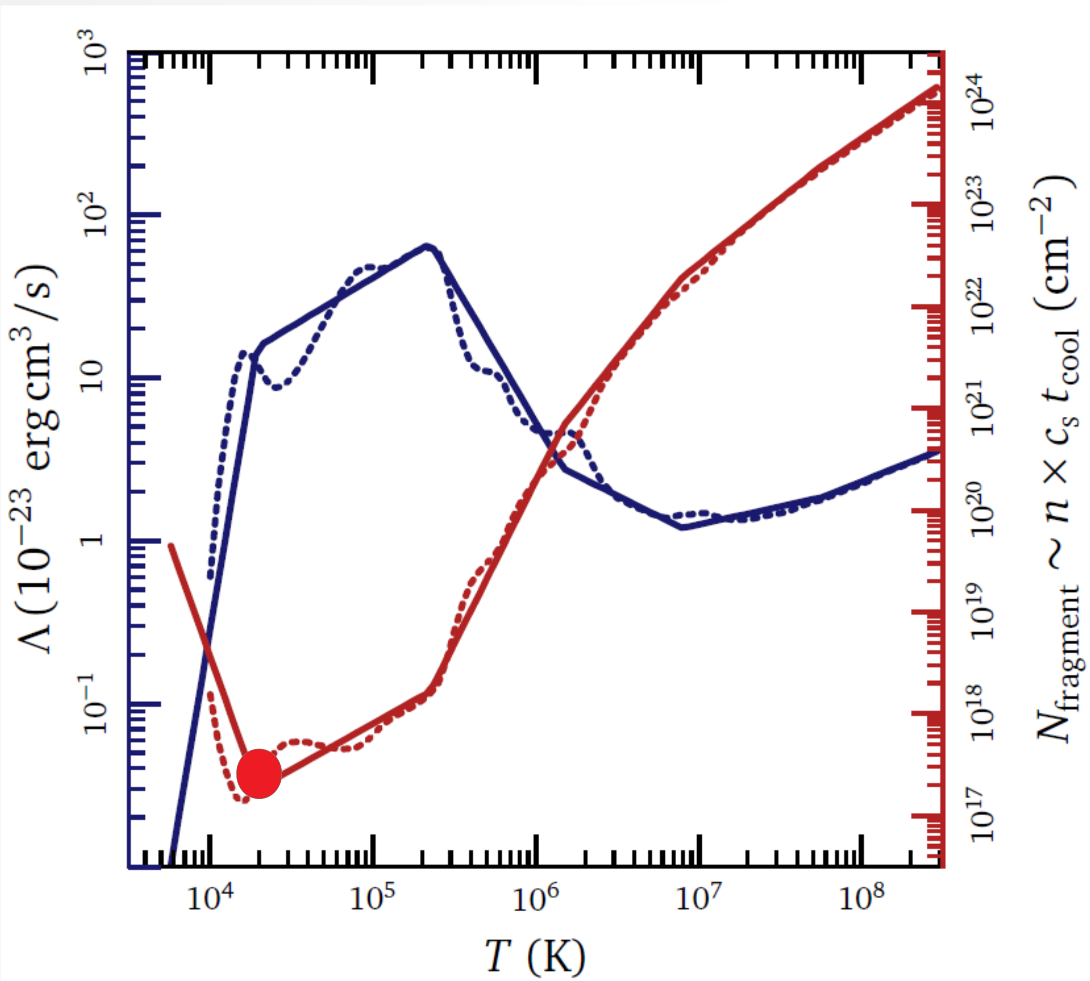


Adhikari et al. (2019)

How it should look in 3-D?

Large clouds or a mist?

McCourt et al. (2018)



Clouds in pressure equilibrium should not be larger than sound speed times the cooling time.

And they break till

$$\ell_{\rm cloudlet} \sim \min\left(c_s t_{\rm cool}\right)$$

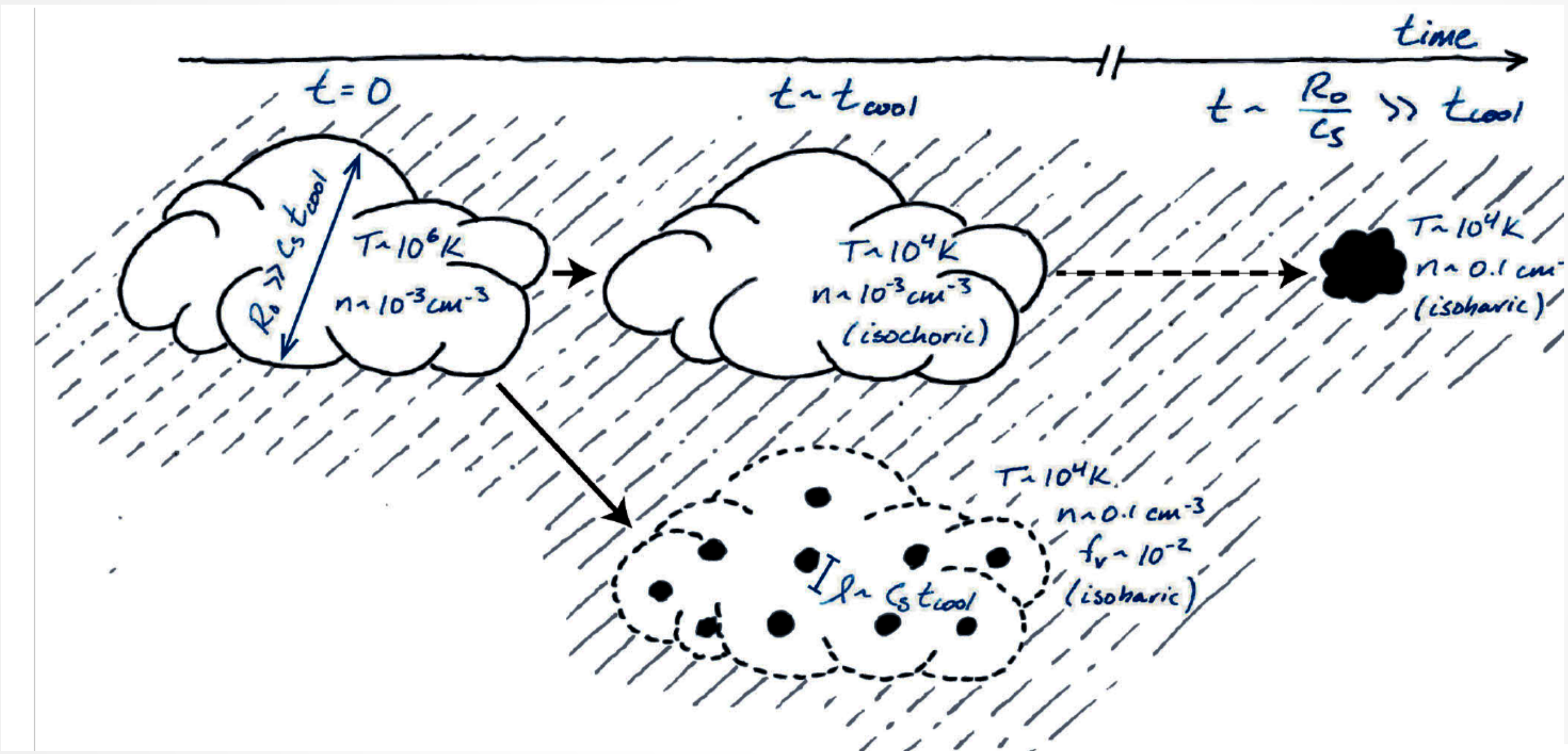
$$\sim (0.1\,{\rm pc}) \left(\frac{n}{\rm cm^{-3}}\right)^{-1},$$

So independently from the surrounding (!)

$$N_{\rm cloudlet} = n\,\ell_{\rm cloudlet} \sim 10^{17}\,{\rm cm}^{-2}$$

Large clouds or a mist?

McCourt et al. (2018)



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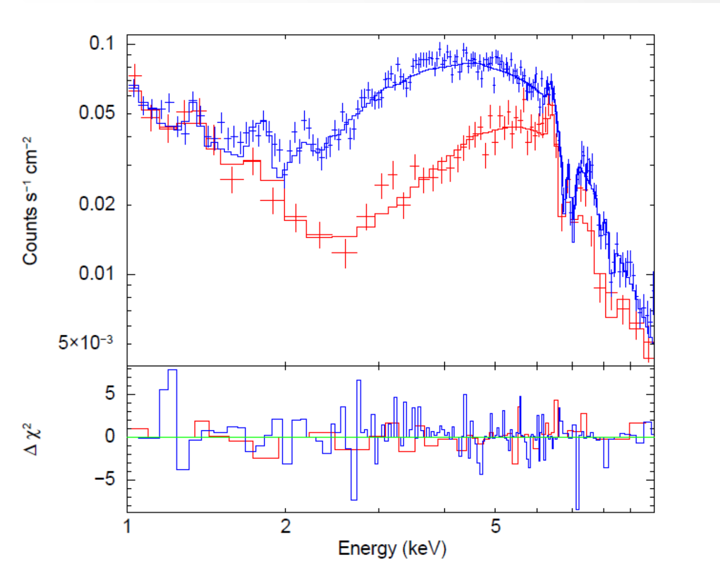
What we see in the data?

Observationally, we are most sensitive to clumpiness in absorption.

In emission, we mostly have upper limits for the number of clouds.

In X-rays: occasional eclipses of the compact X-ray source by BLR clouds



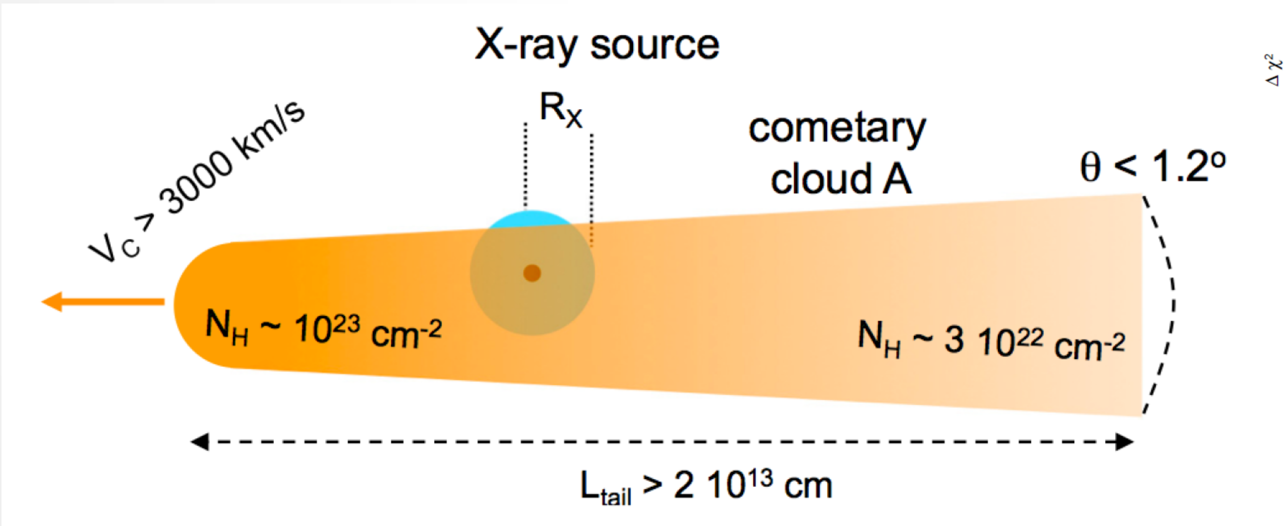


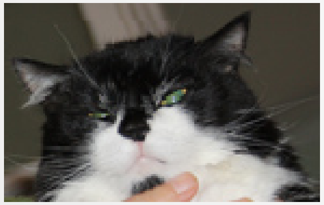
Figure 2: *Structure of the absorbing cloud as obtained from a Suzaku observation of NGC 1365. The estimates are based on the hypothesis of Keplerian motion, and on a black hole mass of 2×10^6 $M_\odot$ [45]. The cloud size is not in the correct scale: the tail is much longer when compared with the source size, which is of the order of a few 10^{11} cm.*

Occultation event in NGC 1365 in Suzaku data

From rev. by Bianchi (2012)

Summary:

- We are getting the basic parameters of the BLR correctly from the theory
- Tests from observations like GRAVITY on 3C 273 passed successfully (*flattened configuration roughly Keplerian motion*)
- Time-dependent line profiles still need more data and more modelling; you will see more on that in the next talks
- Clumpiness still needs more data and more modelling



Thank you