Recent progress in accretion disk theory,

or rather a critical overview where we are...

Bożena Czerny

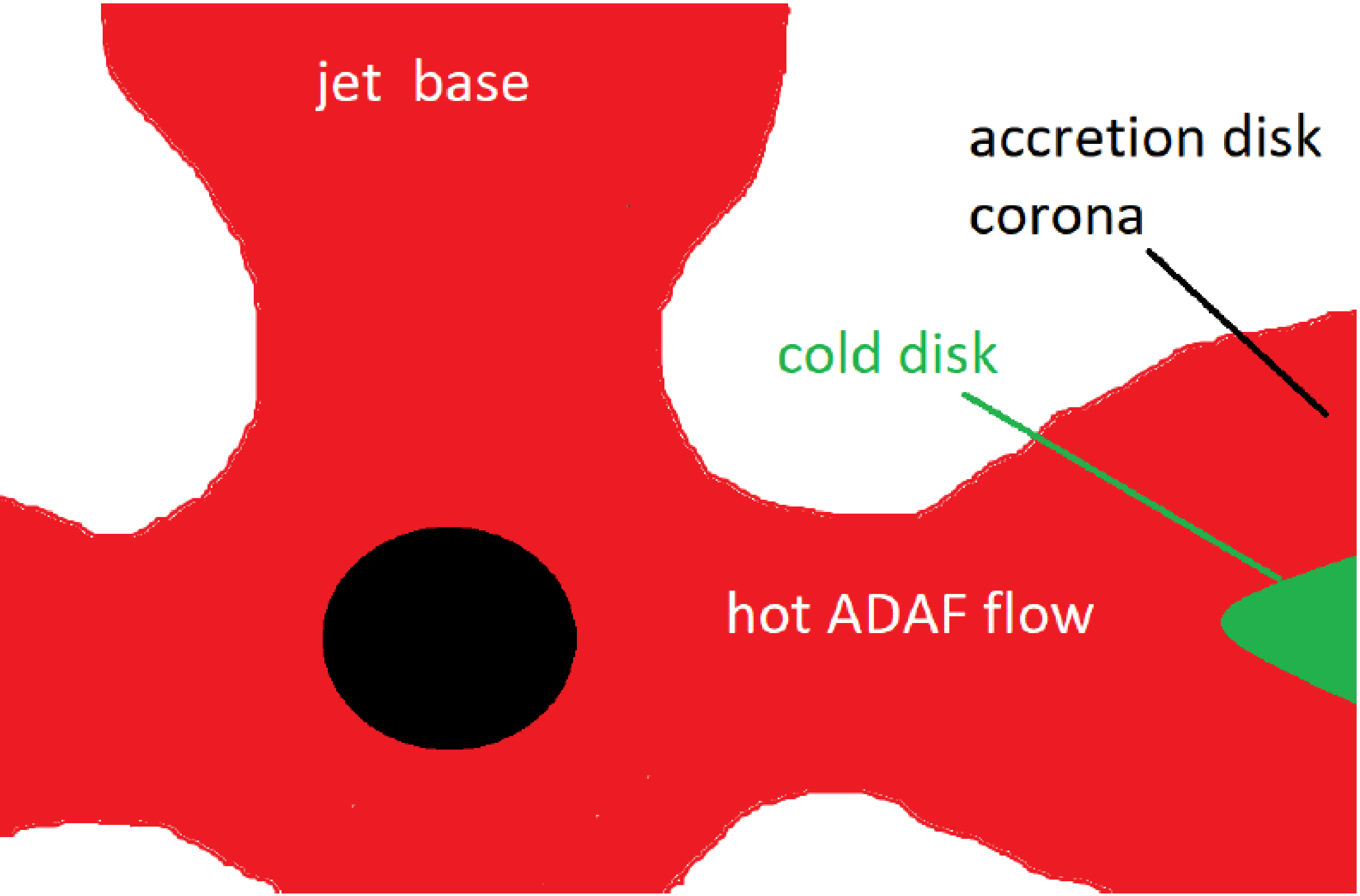
Center for Theoretical Physics

After I choose the color for my presentation I have learnt that violet means (in various cultures):

- **Wisdom**
- **Magic**
- **Mystery**
- **Mourning**

So we should approach to the issue of accretion disk theory with equally mixed feelings...

Basic elements of an AGN

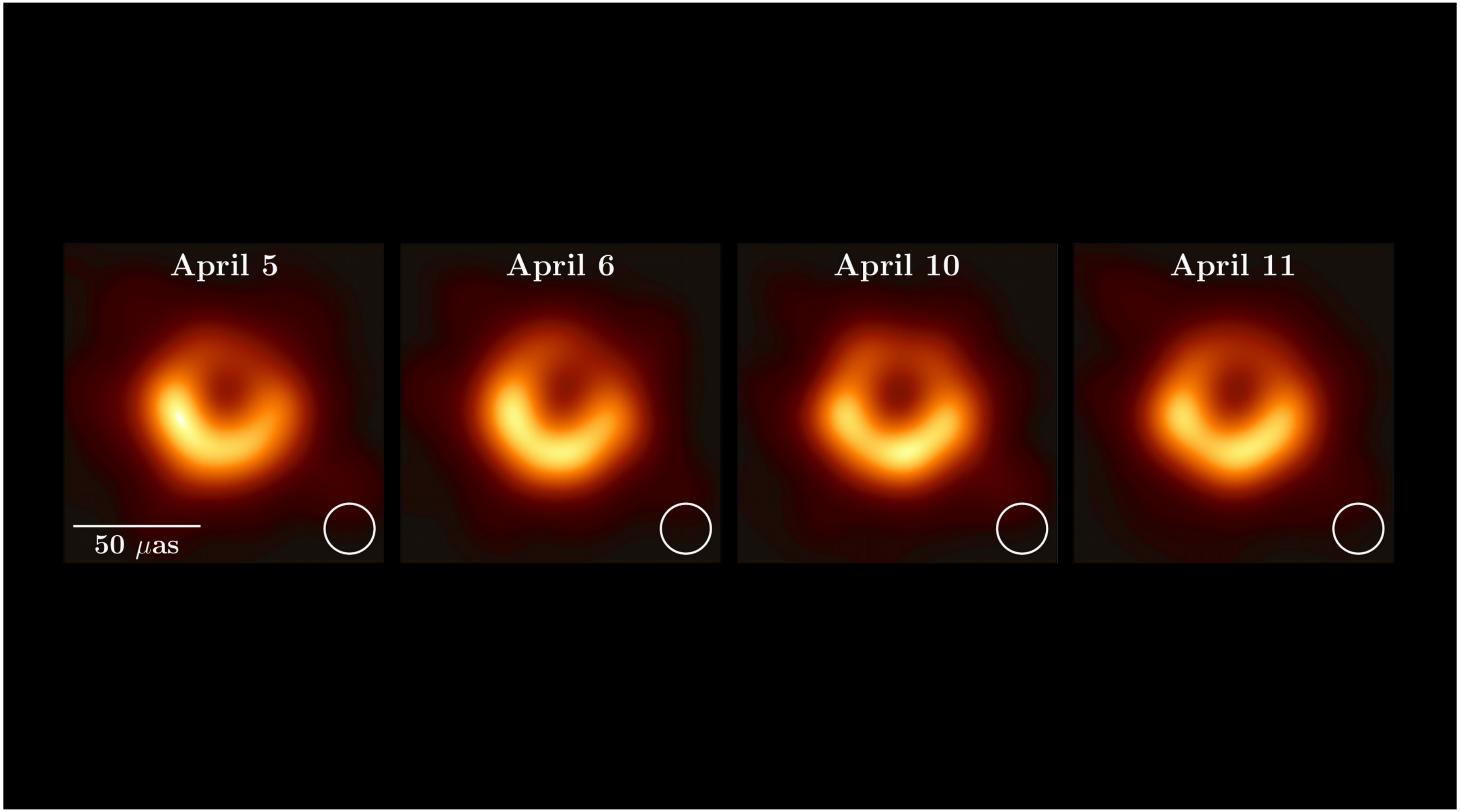


In AGN a classical geometrically thin optically thick Keplerian disk is only one of the elements of the accretion flow.

It is the dominant element of the quasar spectra but it is still strongly coupled to the remaining components.

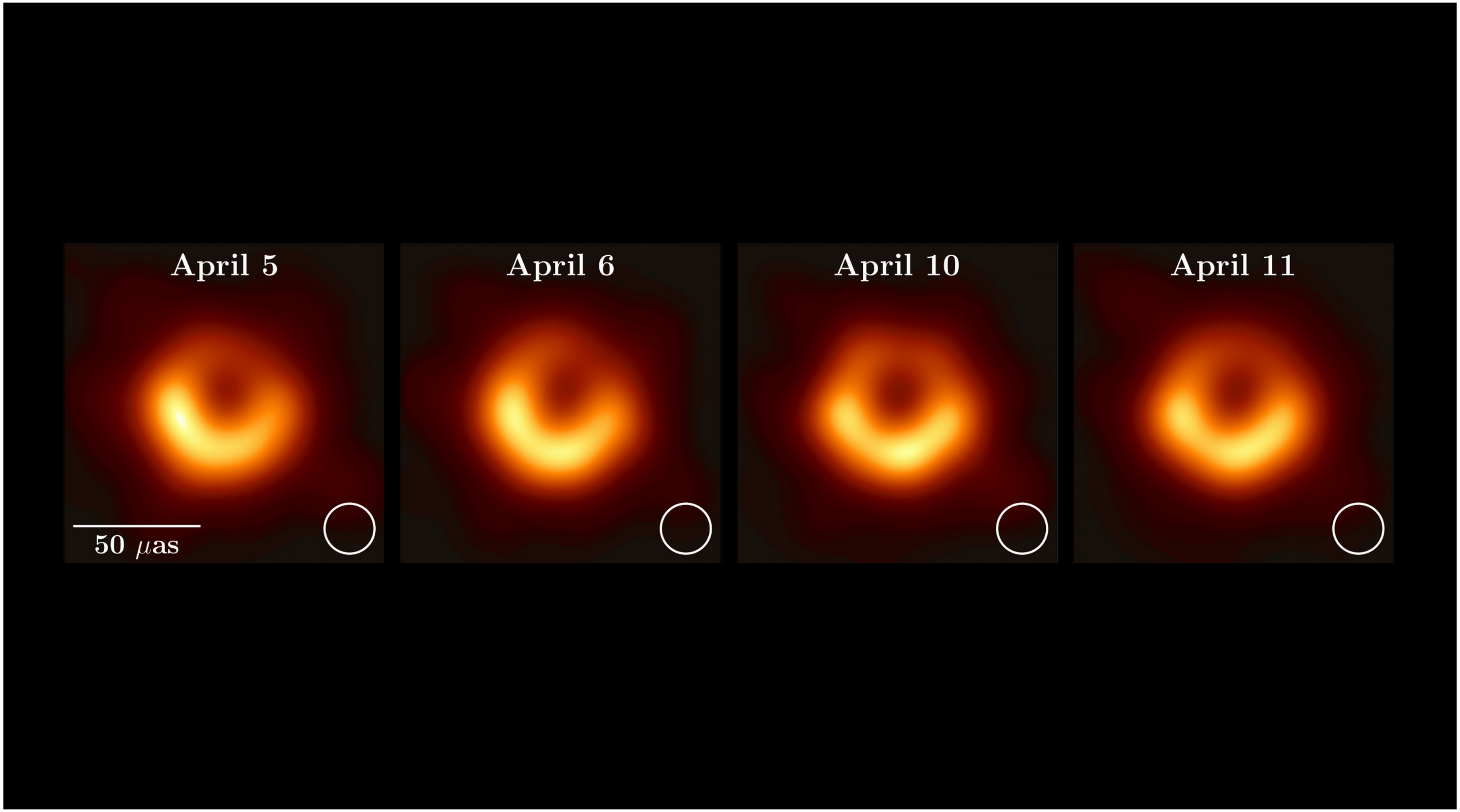
We additionally have winds.

Does the spatial resolution helps ?



M78: Hot optically thin accretion disk (Event Horizon Telescope Collaboration et al. 2019)

Does the spatial resolution helps ?



M78: Jet (Davelaar et al. 2019; same model but with non-thermal electrons...)

Standard accretion disk

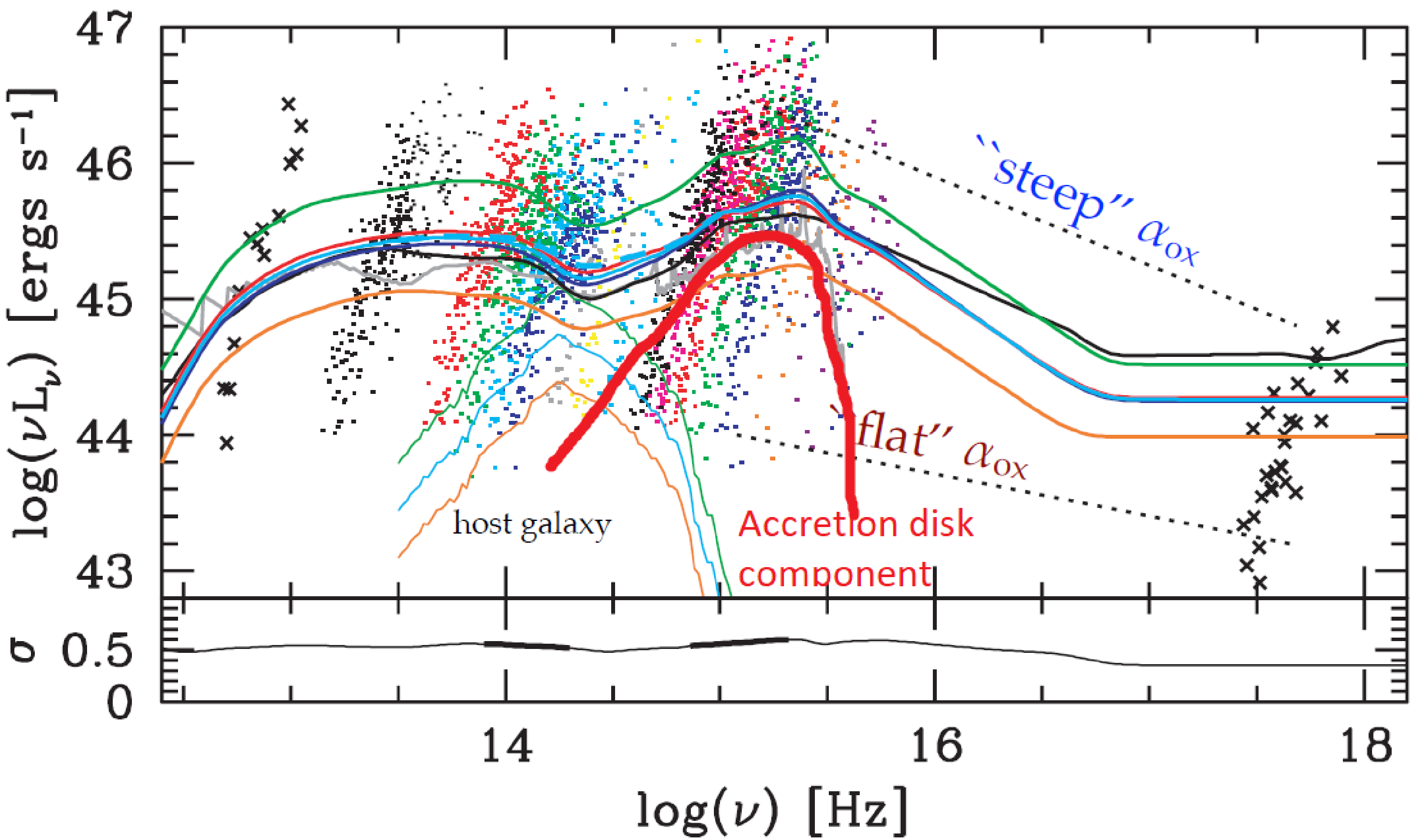


figure from Richards et al 2006, ApJS, 166, 470

Standard accretion disk

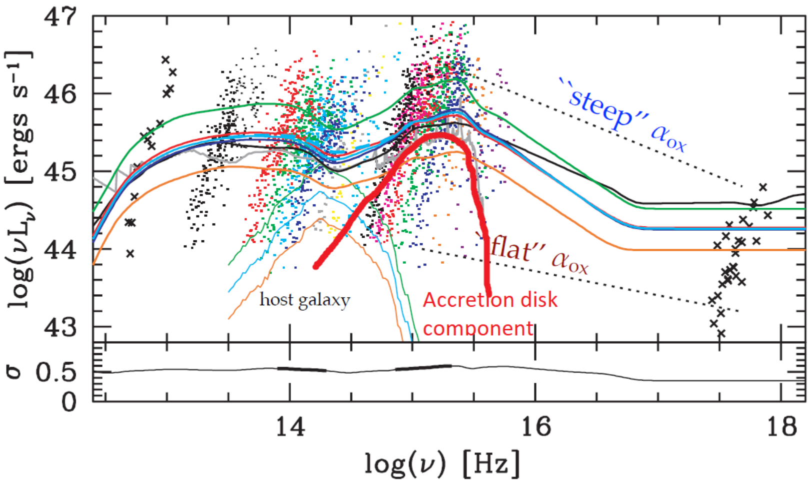


figure from Richards et al 2006, ApJS, 166, 470

Standard accretion disk theory was formulated by Shakura (1972) and Shakura & Sunyaev (1973), GR (Kerr metric) version Novikov & Throne (1973).

If the disk is

- Stationary
- Optically thick
- Geometrically thin (Keplerian)

then we do not need any knowledge about the disk structure. All comes from conservation laws.

Local radiation flux is given by:

$$F(r) = \frac{3GM\dot{M}}{r^3} f(r)$$

And if we assume that the disk locally radiates as a black body, we can calculate the SED. It can be approximated as

$$\nu F_\nu = A(\dot{M}M)^{2/3} \nu^{4/3} exp(-h\nu/kT^*)$$

$$T^* \propto (\frac{\dot{M}}{M^2})^{1/4}$$

Basic timescales in the standard accretion disk

$$t_{dyn} = \Omega_K^{-1} = \left|\sqrt{\frac{GM}{r^3}}\right|^{-1}$$

Dynamical timescale gives us the orbital period aroung a black hole, but also the free fall timescale, the local epicyclic frequency (e.g. rotation of the foot of the magnetic field loop), and the sound-crossing timescale in the vertical direction.

For a 10^8 solar mass black hole we have

Radius	Light Travel time	Dynamical Timescale
10 Rg	8.3 min	4.4 h
100 Rg	1.4 h	5.8 days
1 000 Rg	0.58 days	0.5 year
20 000 Rg	10 days	44 years (BLR region)

These timescales scale linearly with mass.

If the vertical velocity in the BLR region is a fraction of an orbital velocity, and the height of the BLR is also a fraction of the radius, then this is also a timescale for the reconstruction of the BLR, if the material has to come from the disk.

And this is the end of a firm theory. Now we go to modelling.

Outline of the rest of the talk:

Modelling of the disk vertical structure:

- Alpha-disks
- Semi-analytical models with magnetic field transport
- Shearing-box MHD simulations

Modelling of the disk radial structure:

- Disk-ADAF transition
- subsonic/supersonic ADAF flow

Modelling the inflow:

- Disk infall
- Accreting corona infall

Modelling the outflow:

- Jets
- Winds

Global models:

- Semi-analytical time-dependent models
- MHD models

Disk vertical structure – alpha disks

Alpha parameter is a shortcut for the turbulent dynamical motion in the disk or turbulent magnetic field:

For kinematic viscosity: $\nu = \rho v_t L = \alpha \rho v_s H,$ and it shows immediately the meaning of 'anomalous viscosity' frequently used in the past.

If we use alpha-viscosity locally we have the local dissipation of the energy: alpha P_{tot} (or in general alpha $P_{tot}^{\mu} P_{gas}^{1-\mu}$) we can calculate the local vertical structure of the disk including

- radiative and convective transfer
- realistic opacities
- self-gravity and/or marginal self-gravity (important for outer disk part, high mass black hole)

(e.g. Rozanska et al. 1999, Czerny et al. 2016).

Important further development: models of slim accretion disk (optically thick, geometrically moderate) with radial advection of the energy (Muchotrzeb & Paczynski 1982, Abramowicz et al. 1988).

Alpha disks

We can also calculate the time evolution of the model, and for μ in the range of 0.5 – 1 the model is unstable, global time evolution can be calculated, and the model performes limit-cycle oscillations (lower branch – gas dominated, upper branch – advection-dominated). Details depend on alpha and μ.

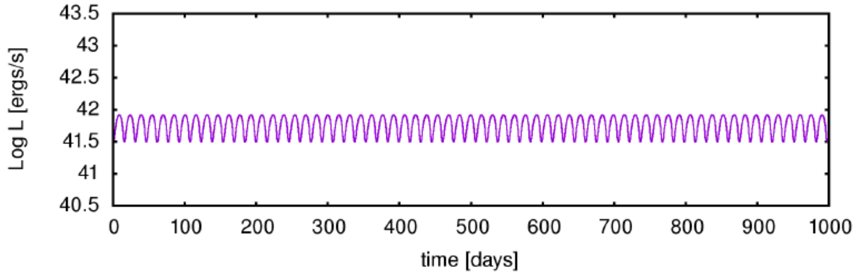


Fig. 4. Typical flickering light curve for intermediate mass black hole and smaller μ ($M = 3 \times 10^4$, $\mu = 0.5$ $\dot{m} = 0.25$).

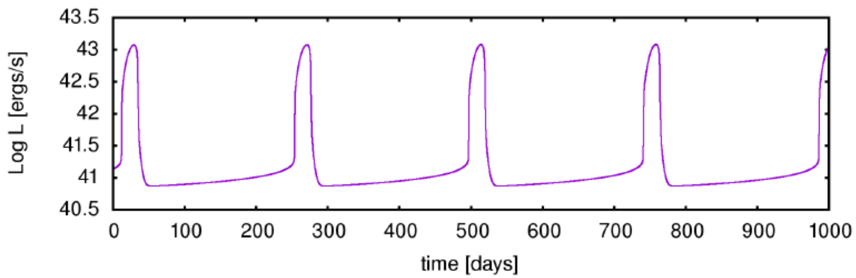


Fig. 5. Typical outburst light curve for intermediate mass black hole and larger μ ($M = 3 \times 10^4$, $\mu = 0.6$ $\dot{m} = 0.25$).

Grzedzielski et al. 2017

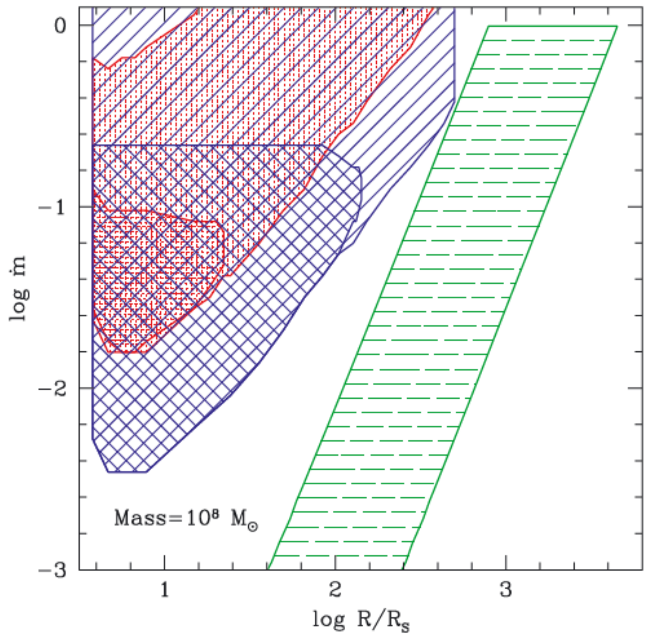


Figure 1. The extension of the radiation pressure (solid and dotted lines) and hydrogen ionization (green, dashed lines) unstable zones, depending on mean accretion rates (Eddington units). The results are for two heating prescriptions: $\alpha P_{\rm tot}$ (blue, solid lines) and $\alpha\sqrt{P_{\rm gas}P_{\rm tot}}$ (red, dotted lines). The crossed regions mark the results for a non-zero fraction of jet power, described by equation (1) with $A = 25$. The black hole mass is $M = 1 \times 10^8\,M_\odot$ (bottom) and $M = 10\,M_\odot$ (top). The viscosity is $\alpha = 0.01$.

Janiuk & Czerny 2011

Alpha-disk timescales

Thermal timescale: $$t_{th} = \alpha^{-1} t_{dyn}$$ it does not depend on the optical depth or the cooling mechanism (works also for hot flow). Fairly reliable.

Viscous timescale: $$t_{visc} = t_{th} \left(\frac{r}{h_d}\right)^2.$$ strongly depends on the details of the disk structure through the disk thickness. For hot flow with the local virial temperature, $r = h_d$.

If quasar variability timescales in the optical band happens locally in thermal timescales, then from this timescales (directly, or structure function etc.)

alpha ~ 0.02

e.g. Siemiginowska & Czerny (1988), Starling et al. (1994), Kozlowski (2016).

For a 10^8 solar mass black hole we have

Radius	Light Travel time	Thermal Timescale
10 Rg	8.3 min	9.1 days
100 Rg	1.4 h	0.8 year
1 000 Rg	0.58 days	25 years
20 000 Rg	10 days	2 200 years (BLR region)

Alpha-disk timescales

Thermal timescale: $t_{th} = \alpha^{-1} t_{dyn}$ it does not depend on the optical depth or the cooling mechanism (works also for hot flow). Fairly reliable.

Viscous timescale: $t_{visc} = t_{th} (\frac{r}{h_d})^2.$ strongly depends on the details of the disk structure through the disk thickness. For hot flow with the local virial temperature, r = h_d.

If quasar variability timescales in the optical band happens locally in thermal timescales, then from this timescales (directly, or structure function etc.)

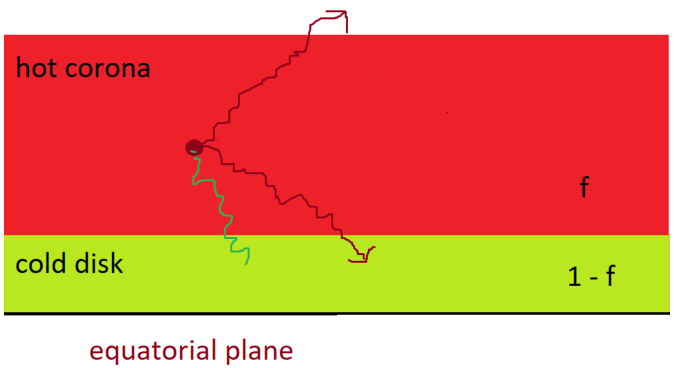
alpha ~ 0.02

e.g. Siemiginowska & Czerny (1988), Starling et al. (1994), Kozlowski (2016).

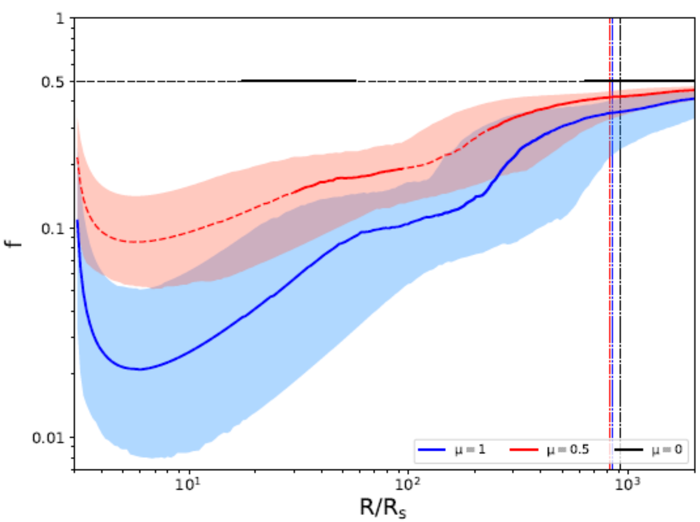
For a 10^8 solar mass black hole, **1.0 Eddington ratio !)**, we have

Radius	Light Travel time	Viscous Timescale
10 Rg	8.3 min	20 days
100 Rg	1.4 h	11.6 year
1 000 Rg	0.58 days	1 000 years
20 000 Rg	10 days	3.e7 years (BLR region)

Semi-analytic models with magnetic field transport



Haardt & Maraschi (1991)



Arcodia et al. (2019)

Models with assumed parameter f:

- Optically thin hot corona (e.g. Svensson & Zdziarski 1994); large f stabilized the disk
- Optically thick warm corona (e.g. Rozanska et al. 2015)

Models with calculated parameter f as a function of radius:

- Mass exchange between the disk and corona calculated from the electron condution for pre-existing corona (e.g. Liu et al. 1999, Rozanska & Czerny 2000)
- From the alpha prescription for a given μ, Arcodia et al. (2019)

$$f = \frac{Q_{cor}}{Q_+} \qquad Q_{cor} = v_D P_{mag} \qquad P_{mag} = \alpha_0 P_{gas}^{\mu} P_{tot}^{1-\mu}$$

$$f = \sqrt{\frac{2\alpha_0}{k_1^2}} \left(1 + \frac{P_{rad}}{P_{gas}}\right)^{-\mu/2}$$

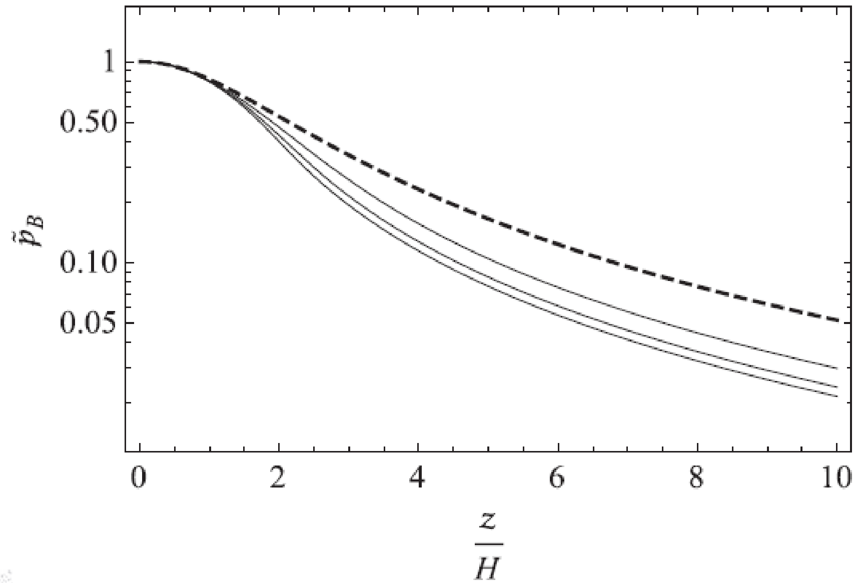
Model roughly explains L_{UV}-L_X scaling in AGN

(Lusso & Risaliti)

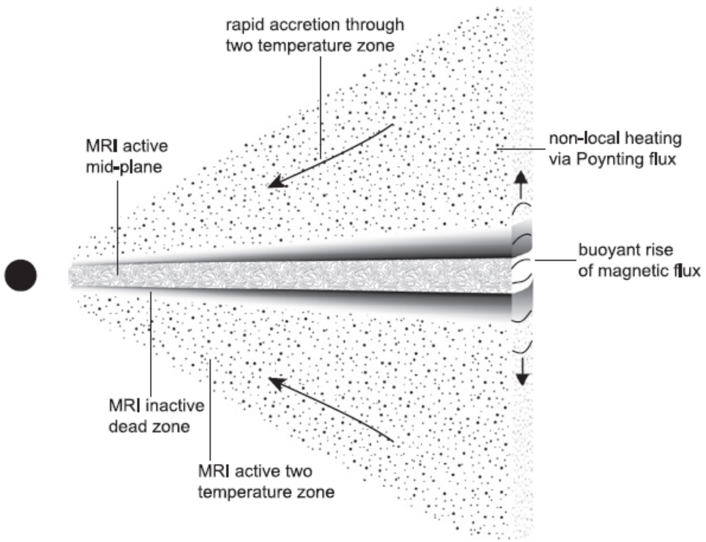
Semi-analytical models with magnetic field transport

Begelman et al. (2015)

„ Using simple model for the creation of this field, its buoyant rise, and its coupling to the gas, we show how disks could be driven into this magnetically dominated state and deduce the resulting vertical pressure and density profiles. Applying an established criterion for MRI to operate in the presence of a toroidal field, we show that magnetically supported disks can have two distinct MRI-active regions, separated by a "dead zone" where local MRI is suppressed, but where magnetic energy continues to flow upward from the dynamo region below."



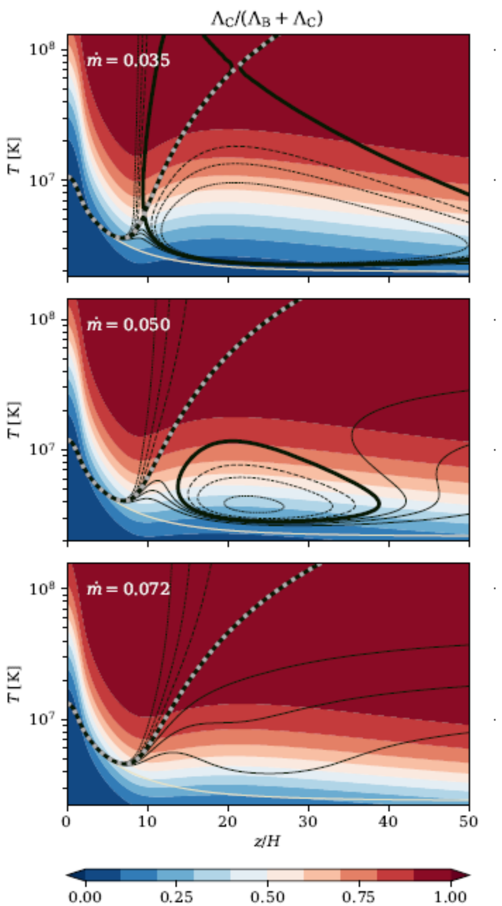
equation of state $\tilde{p} = \tilde{\rho}^{\gamma}$,

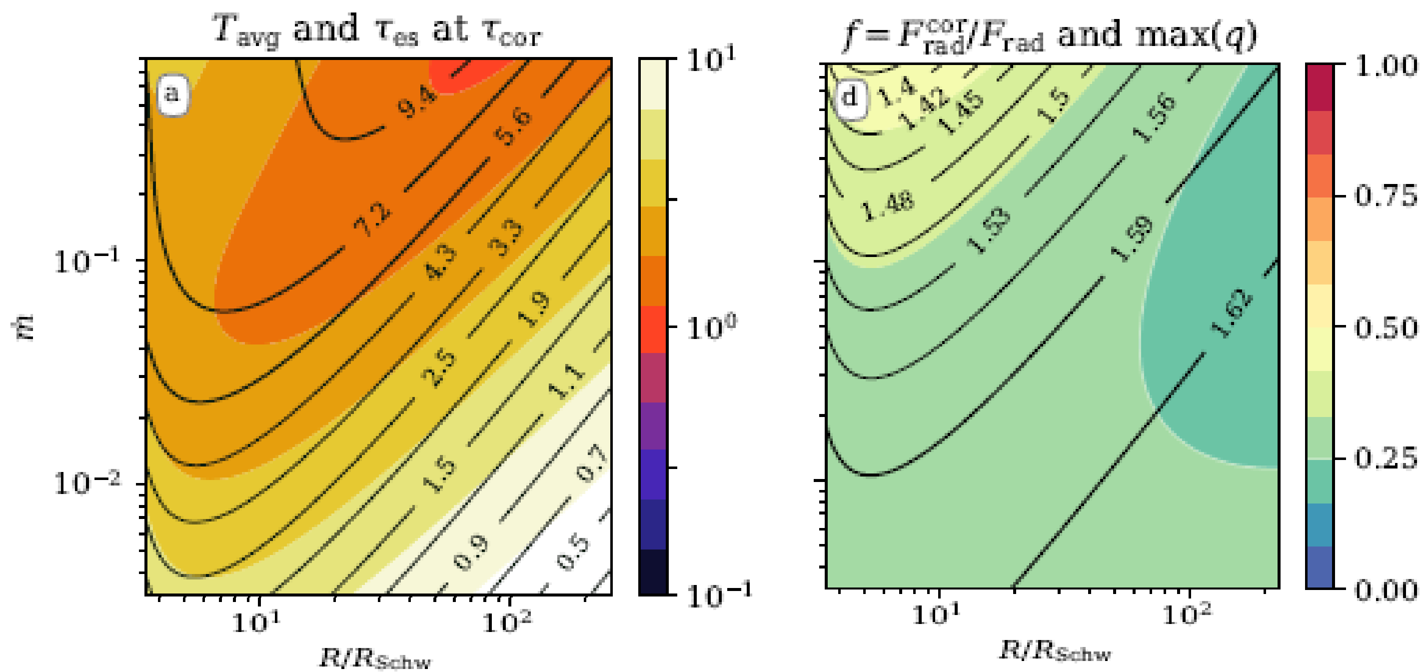


The need for toroidal field, parametric equation of state etc. but it is an interesting step forward.

Semi-analytical models with magnetic field transport

Begelman et al. (2015) model was pursued in more realistic set-up (heating/coling balance etc) by Gronkiewicz et al. (2019). They faced thermal instabilities in the accretion range between 0.035 and 0.072.





Left: contours mark optical depth, colors mark temperature in keV.
Right: colors give the fraction of energy dissipated in the corona.
Model was calculated only for Galactic sources, M = 10 Msun.

Shearing-box MHD simulations

We know (Balbus & Hawley 1991) that magnetorotational instability (MRI) is responsible for the anomalous disk viscosity. In principle, this should give us unique prescription of the disk structure.

Problems:

- combining time-dependent MHD with the rest of the physics
- Initial conditions (large scale magnetic field)

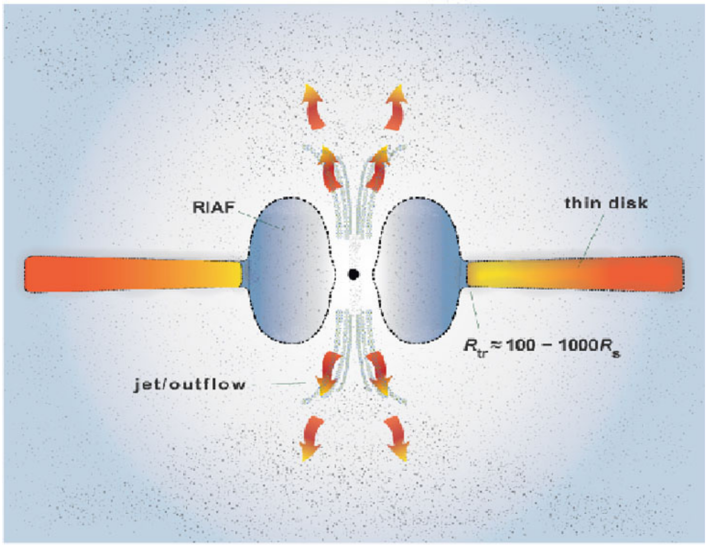
Corona strength:

- Miller & Stone (2000): 25 % of energy in the hot corona
- Turner (2004); surface layers now are optically thick, weak corona ? No temperature profile shown
- Jiang Y.F et al. (2014) – 3.4% in the corona (for standard Sigma)
- Jiang Y.F at al. (2019) – 50% in the corona (for much lower Sigma)

Stability under radiation pressure:

- Turner (2004): disk thermally stable
- Hirose et al. (2009) – disk thermally stable
- Jiang Y.F. et al. (2013) – disk thermally unstable
- Jiang Y.F. et al. (2016) – disk thermally stable
  … but this was not for a global model, just a narrow ring.

Modelling of the disk radial structure:cold disk/ADAF transition



It is generally accepted that for lowe Eddington ratios (below 0.01) there is an inner hot flow (Ichimaru 1977, Narayan & Yi 1984). There is also older solution by Shapiro, Lightmann & Eardley 1976 (SLE)

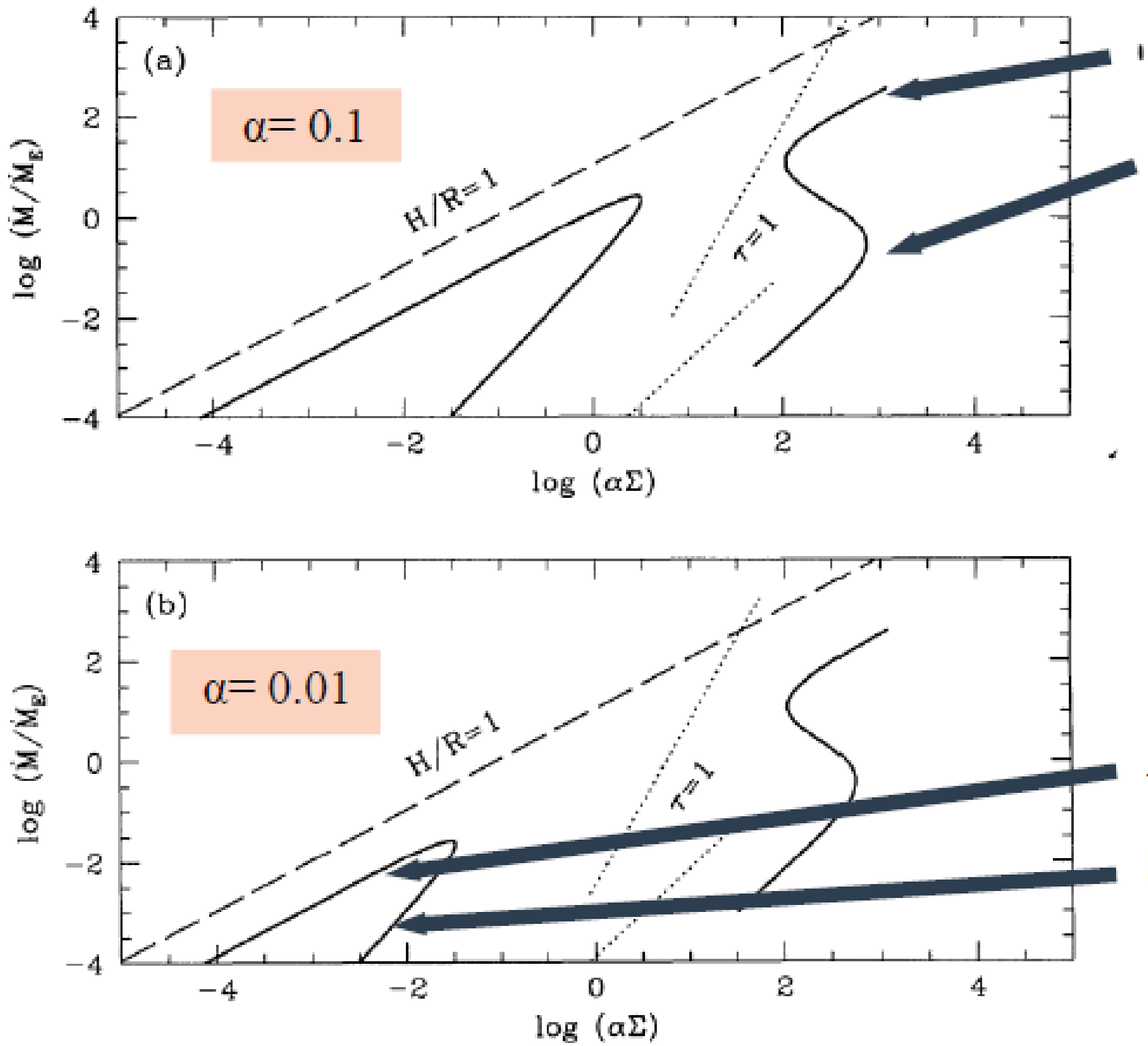
Properties:

ADAF	SLE
Optically thin	optically thin
Two-temperature	two-temperature
Cooling by advection	Compton cooling
Stable	unstable

Original ADAF - δ small

Estimates give large values of about 0.5 (Bisnovatyi-Kogan & Lovelace 1997; Yuan & Narayan 2014; Marcel et al. 2018),

Cold disk/ADAF transition



Slim disk

Standard disk

IMPORTANT POINTS

- ADAF is never very 'bright'
- It gets brigher with rising α

ADAF

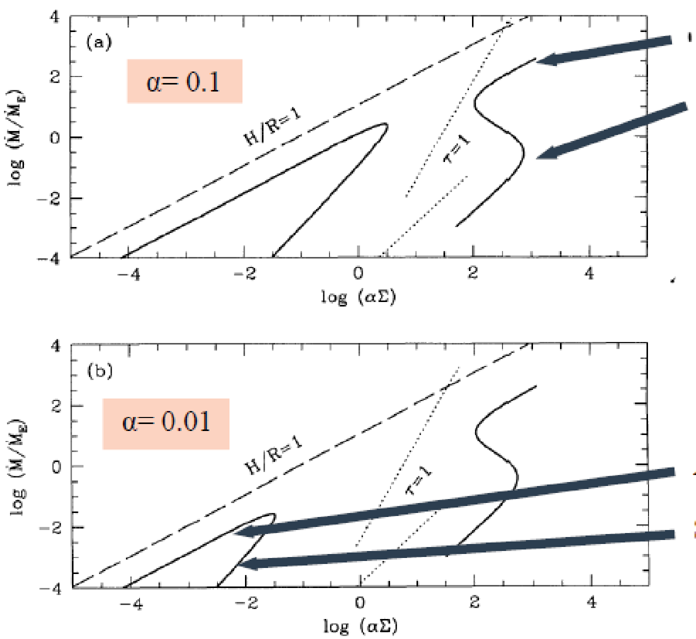
SLE

Note that here Mdot does not contain efficiency !

Abramowicz et al 1995

FIG. 3.—(*a*) Thermal equilibria for optically thick (the right solid S-shaped

Cold disk/ADAF transition



Slim disk

Standard disk

IMPORTANT POINTS

- ADAF is never very 'bright'
- It gets brigher with rising α

ADAF

SLE

Note that here Mdot does not contain efficiency !

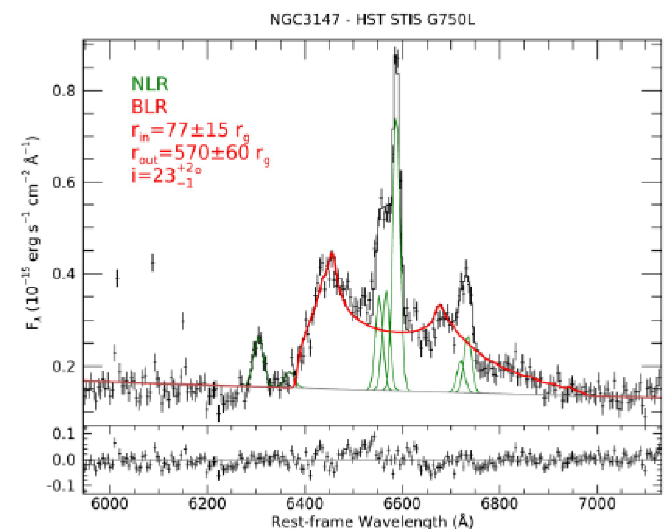
Abramowicz et al 1995

FIG. 3.—(a) Thermal equilibria for optically thick (the right solid S-shaped

Hot branch and cold branch in general do not meet.

Hot branch has upper limit for its existence so sometimes '*strong ADAF principle*' is assumed, i.e. ADAF forms whenever it can form.

However, Bianchi et al. (2019):



Standard SS disk is still optically thick.

L/Ledd = 1.e-4

$R_{ADAF} < 77$ Rg

Strong ADAF principle:

$$R_{ADAF} = 2\ (\alpha_{0.1})^4 (L/Ledd)^{-2}\ R_{Schw}$$

i.e. RADAF should be 3.2e5

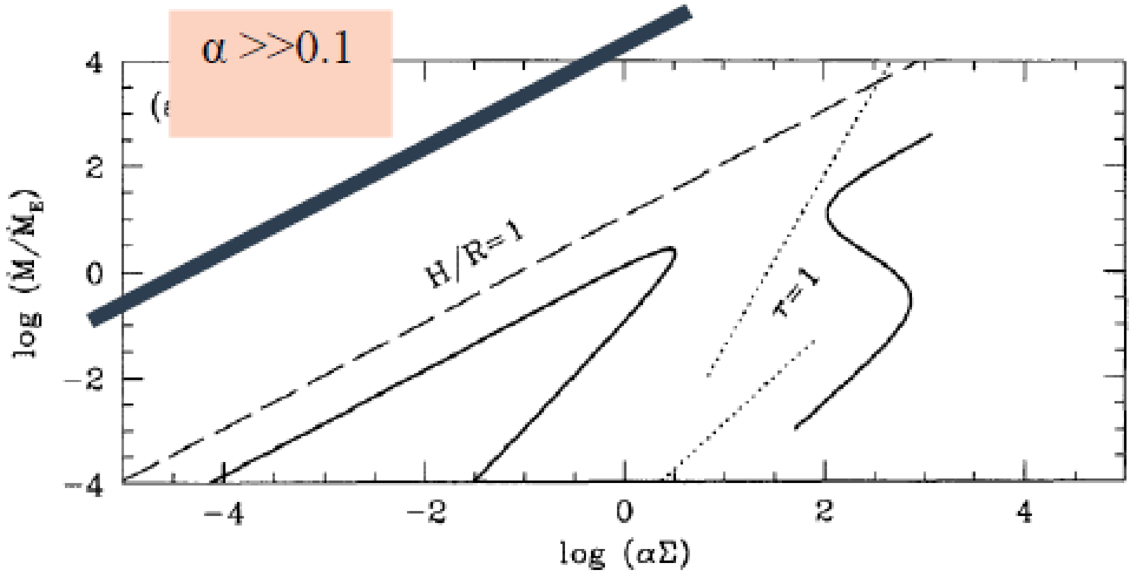
ADAF/RIAF hot flow and its L/L_{Edd} limitations

For data fitting, particularly for Galactic sources, it is convenient to have hot flow also at high accretion rates. How can we do that?

What that effectively means?

$V_r = v_s (r/h) \alpha = v_s \alpha$

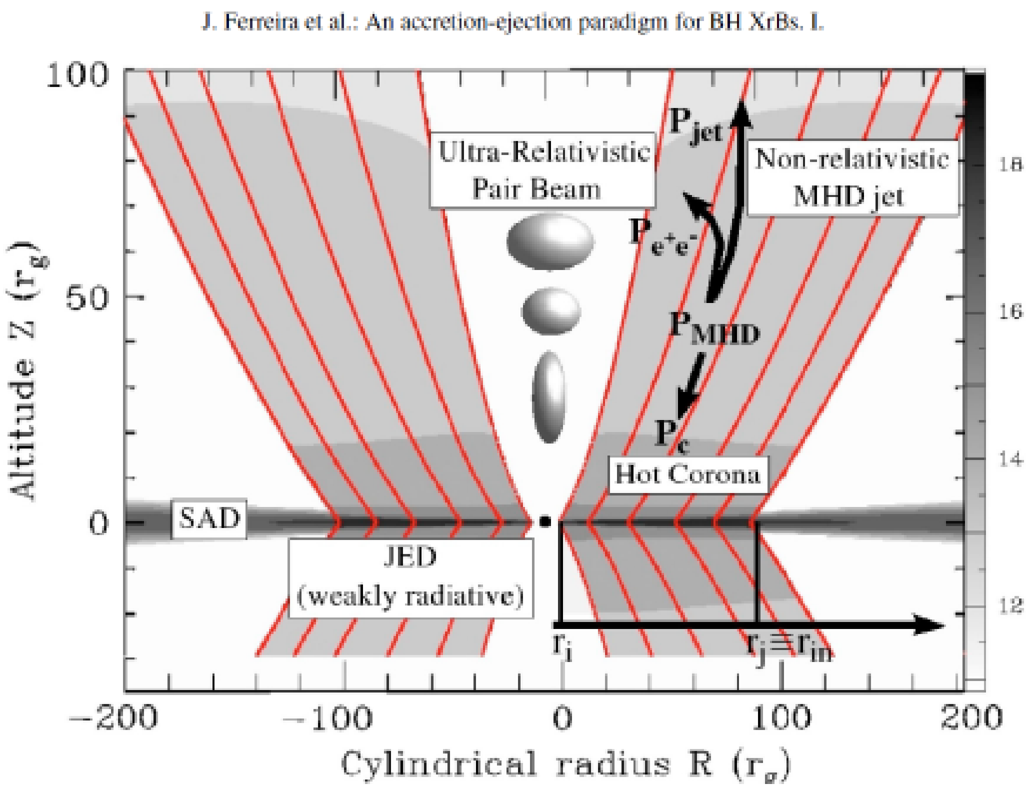
Flow is highly supersonic.



A series of such models were developed by Ferreira et al. (2006), Marcel et al. (2018,2019).

The physics is based on the magnetically driven wind, with magnetic field carrying the angular momentum (but not much mass). The radial velocity is then supersonic as the loss of angular momentum is arbitrary fast, set by the strength of the assumed large scale magnetic field.

Jet/ADAF supersonic solution



Key point: supersonic motion combined with the extraction of the angular momentum.

Personally I have problems with understanding this point. In supersonic motion perturbations propagate inward not outward, so how can we have effective angular momentum outward?

Authors: fast magnetosonic waves.

?

SAD – Standard Accretion Disk
JED - Jet-emitting disk

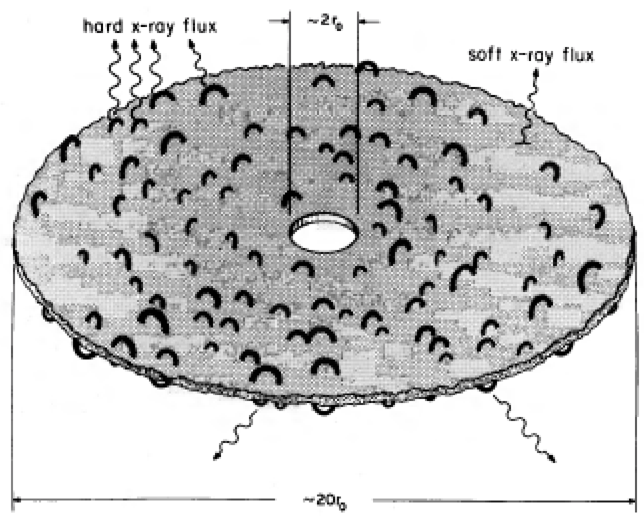
In this model SED/JED transition is a free parameter of the model.

Modelling the inflow

In the region when a standard disk exist the accretion proceeds:

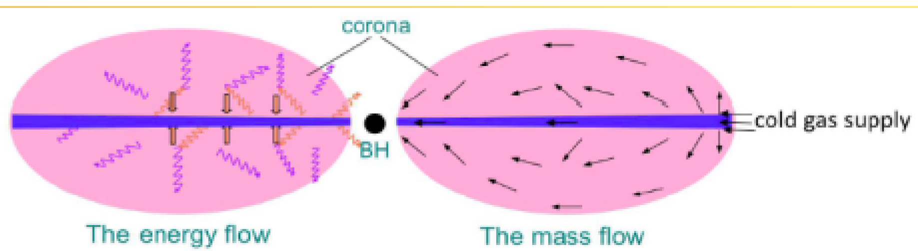
- Only though a disk
- Partially through a hot coronal flow

- Transportation of the energy from the accretion disk to the corona by magnetic field
  (Galeev, Rosner and Vaiana 1979, many later papers)



- Coronal accretion flow

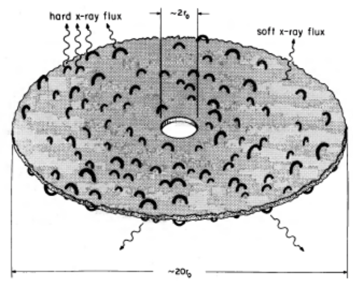
Życki et al. 1995, Chakrabarti & Titarchuk (1995), many later papers



Liu et al.

Modelling the inflow

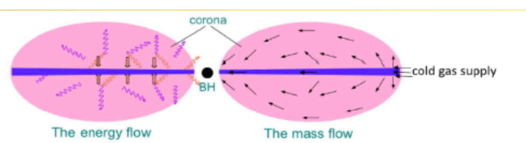
- Transportation of the energy from the accretion disk to the corona by magnetic field (Galeev, Rosner and Vaiana 1979, many later papers)



- Coronal accretion flow

Życki et al. 1995, Chakrabarti & Titarchuk (1995), many later papers

Liu et al.



As I discussed before, disk inflow is very slow, coronal flow takes place roughly in the thermal timescale.

For a 10^8 solar mass black hole we have

Radius	Light Travel time	Thermal Timescale
10 Rg	8.3 min	9.1 days
100 Rg	1.4 h	0.8 year
1 000 Rg	0.58 days	25 years
20 000 Rg	10 days	2 200 years (BLR region)

For a 10^8 solar mass black hole, **1.0 Eddington ratio !)**, we have

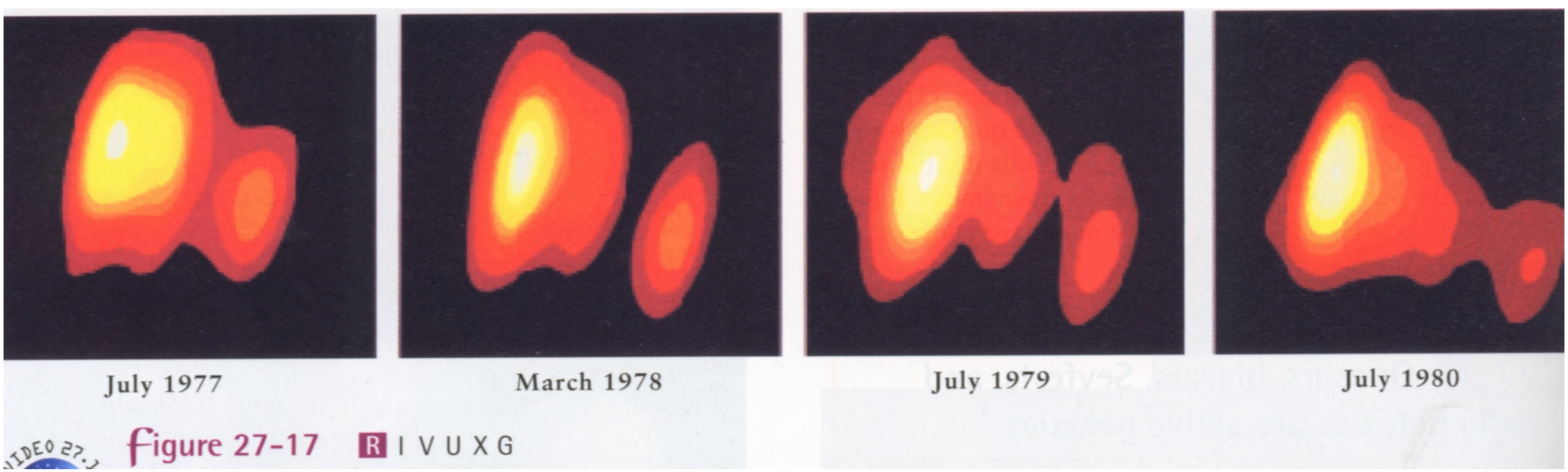
Radius	Light Travel time	Viscous Timescale
10 Rg	8.3 min	20 days
100 Rg	1.4 h	11.6 year
1 000 Rg	0.58 days	1 000 years
20 000 Rg	10 days	3.e7 years (BLR region)

Modelling the outflow: jets

Everybody agrees that jet formation requires geometricall thick disk in direct vicinity of a black hole, to provide the guiding large scale magnetic field. It is rather inner ADAF flow, but might be a hot corona on the top of accretion disk, I suppose.

Sometimes it is considered that we have two types of jets:

- Stationary jet (at lower Eddington ratios)
- Blobby jet (at higher Eddington ratios)

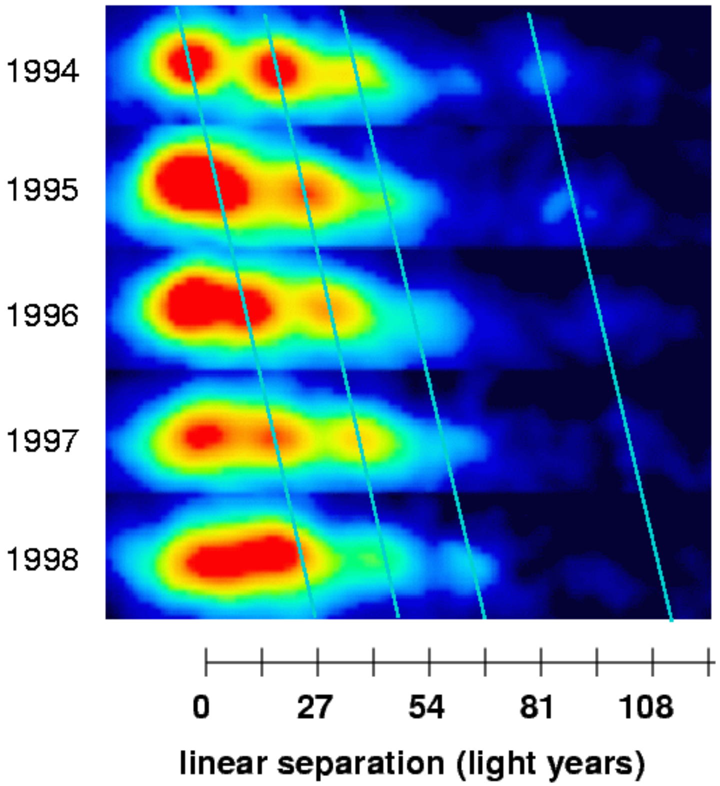


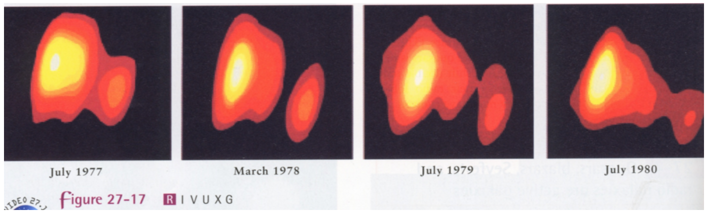
Blobby ejections in 3C 273

Modelling the outflow: jets

Sometimes it is considered that we have two types of jets:

- Stationary jet (at lower Eddington ratios)
- Blobby jet (at higher Eddington ratios)



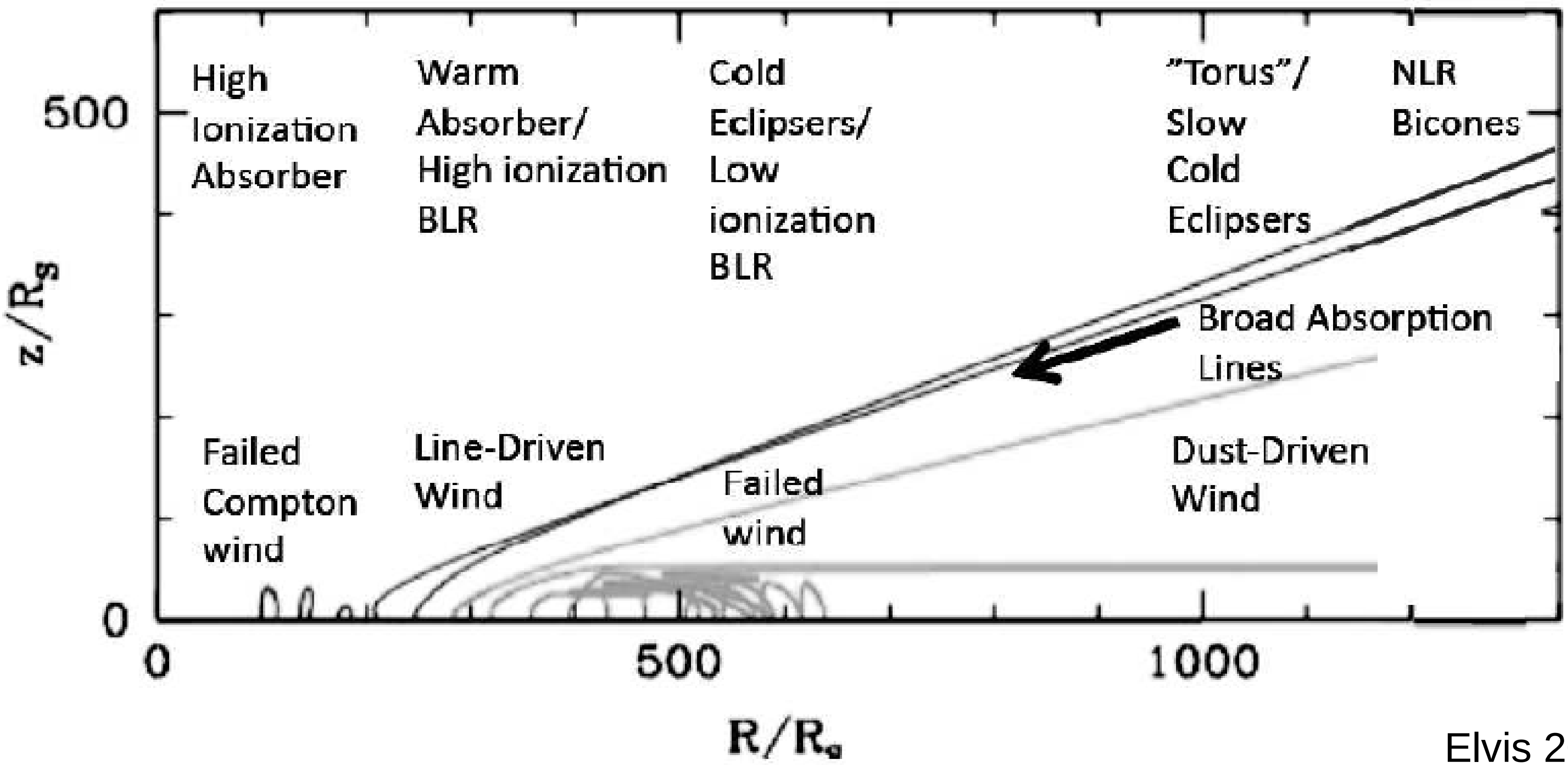


3C 273

Blobby ejections in M87; overall might be similar…

But difference in black hole mass.

Modelling the outflow: winds



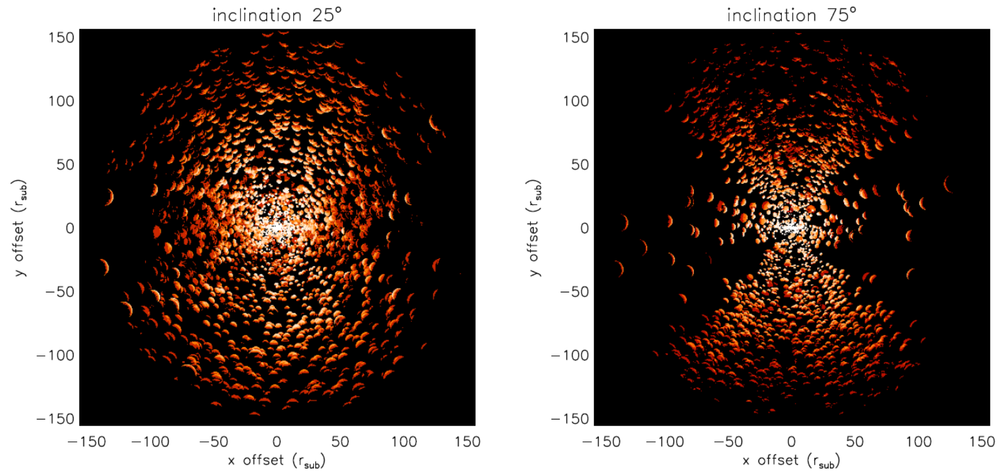
Elvis 2012

This would be a topic for another 35 minutes…..

Modelling the outflow: winds

Winds can certainly modify the state of the disk. Massive wind are generally expected in the outer parts, and they can carry mass of the same order as the accretion rate itself. Estimates from absorption features.

Dusty winds give the effect of the dusty/molecular torus ?



Disk (inflow) + wind (outflow)model of the IR emission of AGN, Hoenig & Kishimoto (2017)

Departure from a stationary disk in optical/UV/IR starlight-corrected SED ?

In the innermost part highly ionized winds can also carry energy, mass and angular momentum.

Where UFO's are launched?

Global models: semi-analytic

Stationary models:

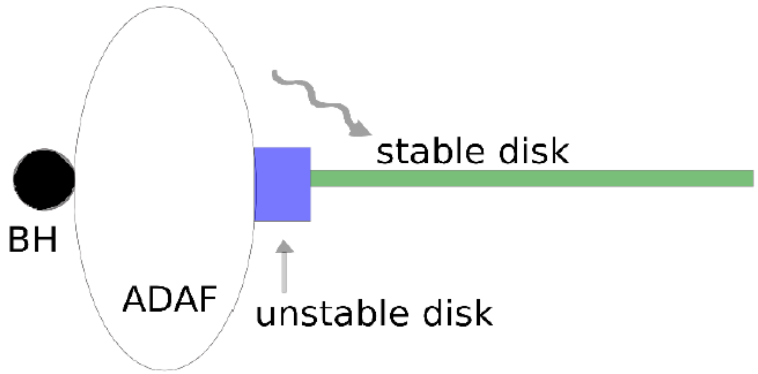
For broad-band SED fitting
- the models of Chris Done et al. (optX)
- SAD/JED models of Marcel et al. (not applied to AGN so far)

Semi-analytic models allow to obtain broad band spectra which can be directly compared to the data

---

Time-dependent models:

If radiation pressure instability operates in a disk, there are models (e.g. GLADYS by Janiuk et al.) which can do that. Outburst timescales are long.



However, if we allow for an inner ADAF, for lower Eddington ratio the unstable disk ring is narrow which shortens the timescales.

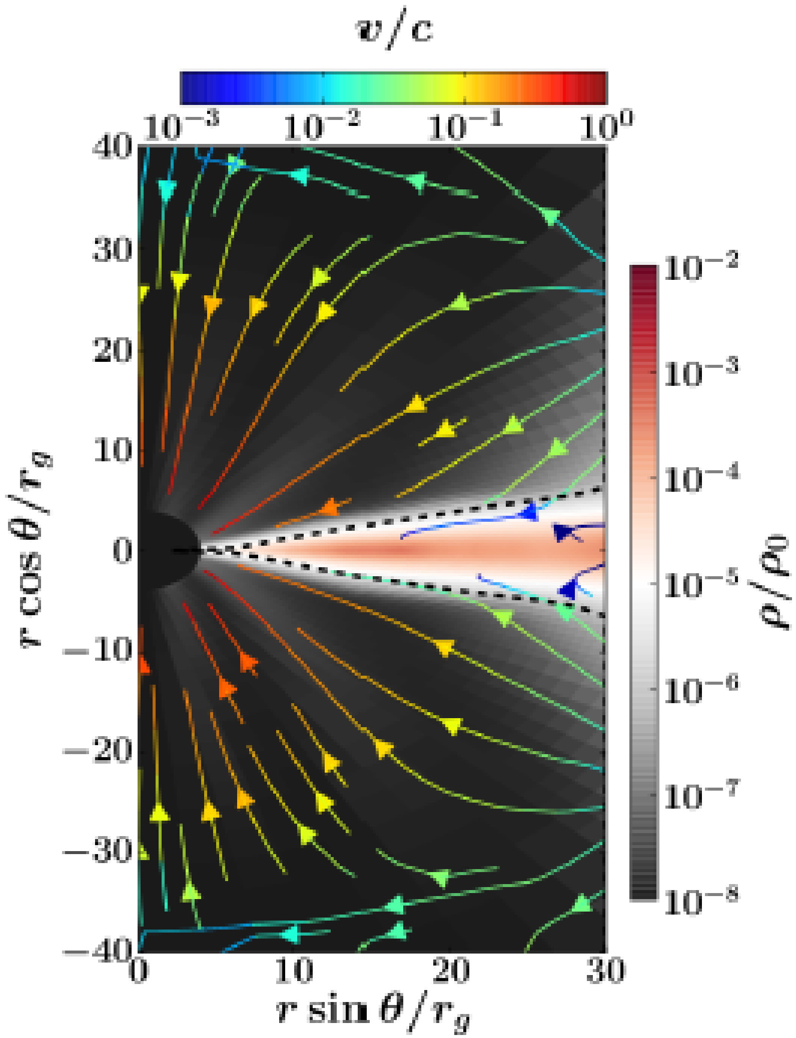
Śniegowska et al. (2019)

$$\tau_{visc} = \tau_{visc,SS}\frac{\Delta R}{R}$$

Global models: MHD

In principle, they should produce everything: disk, jet, wind, corona.

In practise, there was a tremendous progress in these simulations, but they are stilll not quite ready to be compared with the data. Computations are extremely time-consuming and the radiation spectra are not provided. But they give us information about theoretically expected viscosity parameter and the disk structure.



MHD global models of sub-Eddington disks (Jiang et al. 2019)

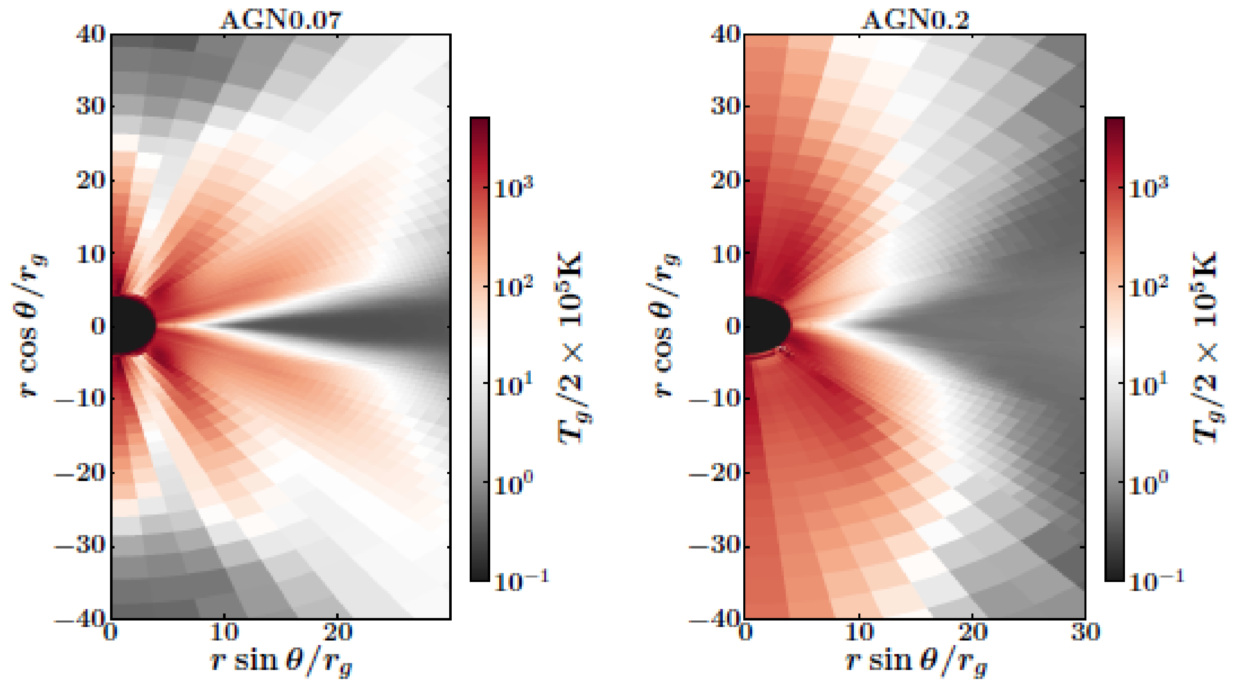
Global models: MHD

In principle, they should produce everything: disk, jet, wind, corona.

In practise, there was a tremendous progress in these simulations, but they are stilll not quite ready to be compared with the data. Computations are extremely time-consuming and the radiation spectra are not provided. But they give us information about theoretically expected viscosity parameter and the disk structure.

MHD global models of sub-Eddington disks (Jiang et al. 2019)

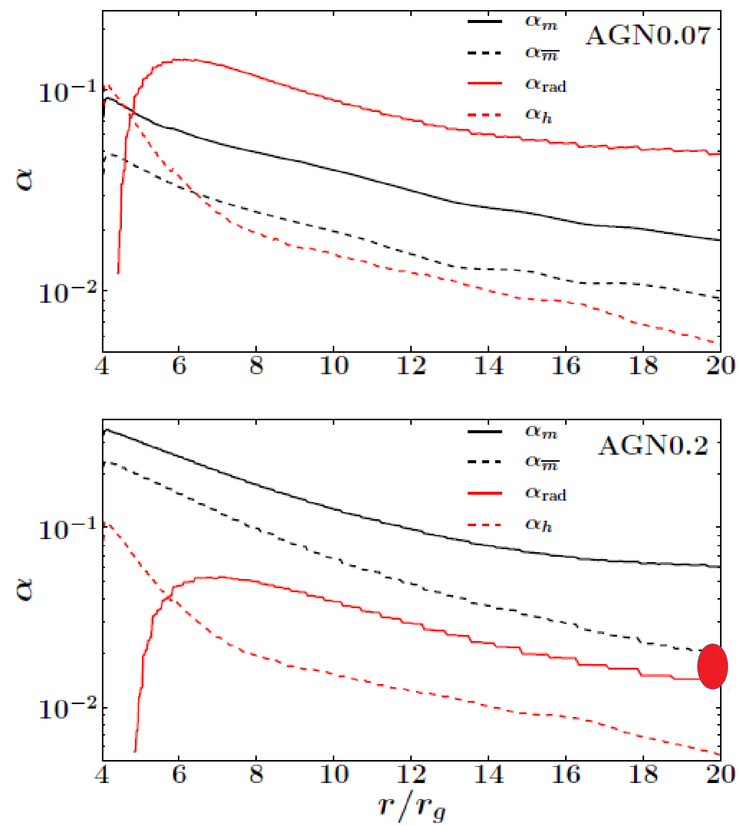
We have hot corona and cold disk, no inner ADAF (Eddington ratio 0.07 and 0.20). No model for still lower accretion rate.



Global models: MHD

In principle, they should produce everything: disk, jet, wind, corona.

In practise, there was a tremendous progress in these simulations, but they are stilll not quite ready to be compared with the data. Computations are extremely time-consuming and the radiation spectra are not provided. But they give us information about theoretically expected viscosity parameter and the disk structure.



0.02
from quasar variability

Figure 7. Radial profiles of the time and shell averaged ratios between Reynolds (α_h, dashed red lines), Maxwell (α_m, solid black lines), radiation ($\alpha_{\rm rad}$, solid red lines) stresses and total pressure for the run AGN0.07 (top) and AGN0.2 (bottom). The dotted black lines ($\alpha_{\overline{m}}$) are for stresses due to the azimuthally averaged mean $\langle B_r \rangle$ and mean $\langle B_\phi \rangle$.

MHD global models of sub-Eddington disks (Jiang et al. 2019)

Summary

- The issue is rather complex, with time-dependent magnetic field being the source of the problems
- A combination of approaches is useful (semi-analytic models, MHD)
- Disks in AGN are not really stationary (long timescales at larger radii)
- There are a lot of processes close to the black hole which can happen in short (thermal) timescale:
  - corona formation
  - corona ejection
  - disk thermal pulsations ….
- Observations can help to decide what to choose, but an effort in modelling is necessary

Thank you !