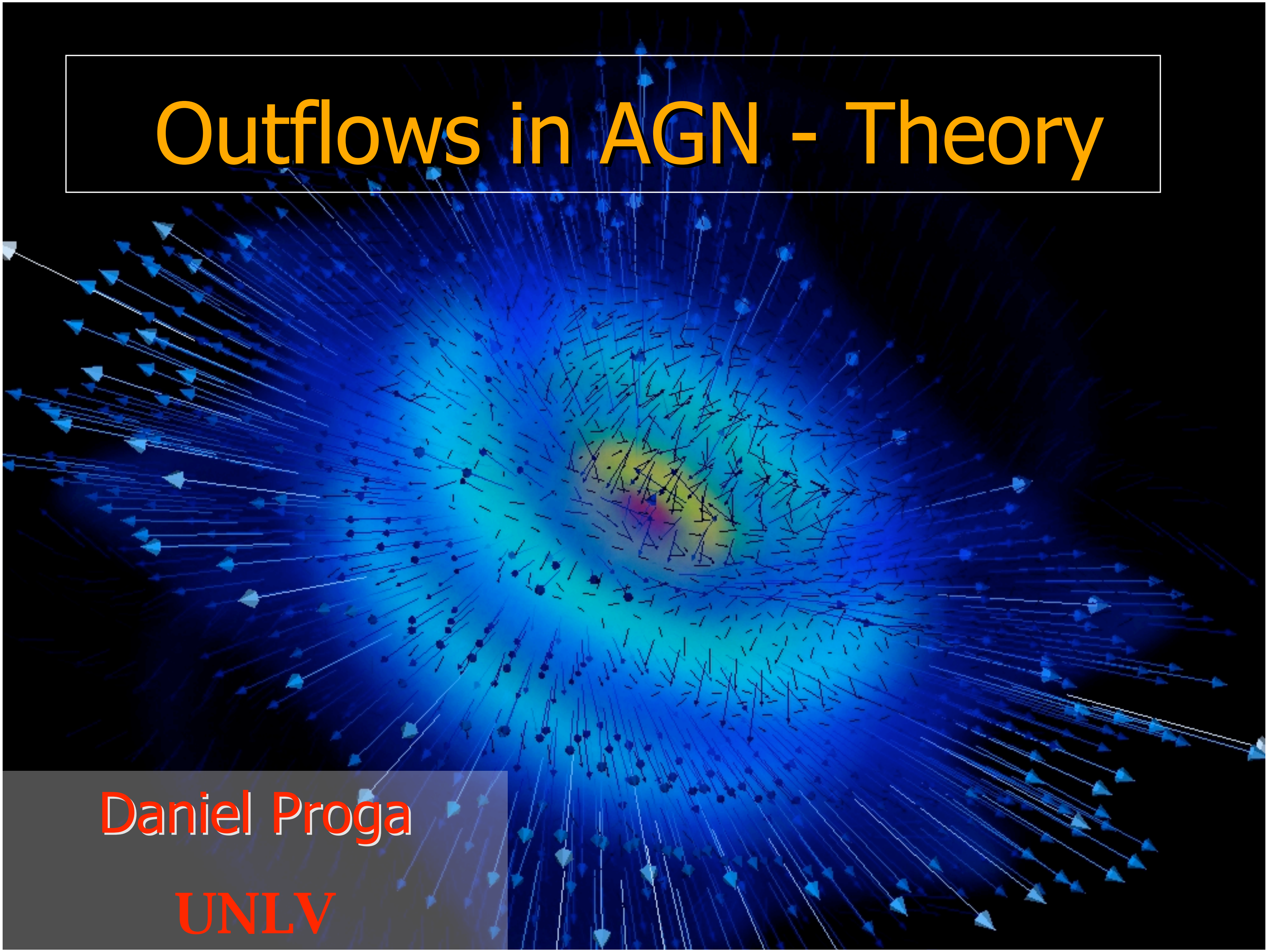
Outflows in AGN - Theory



Daniel Proga

UNLV

Collaborators

- J. Stone (Princeton University)
- J. Drew (Imperial College)
- T. Kallman (GSFC/NASA)
- M. Begelman (JILA)

Motivation

We poorly understand a few key aspects of supermassive black hole astrophysics, e.g.,

- Mass supply to a black hole accretion disk;
- Broad Line Regions and Narrow Line Regions in AGN;
- AGN feedback.

OUTLINE

- Introduction
- Multidimensional, time-dependent simulations:

- outflows from inflows: HD and MHD cases (with and without rotation)

- disk winds: HD and MHD cases

- Conclusions

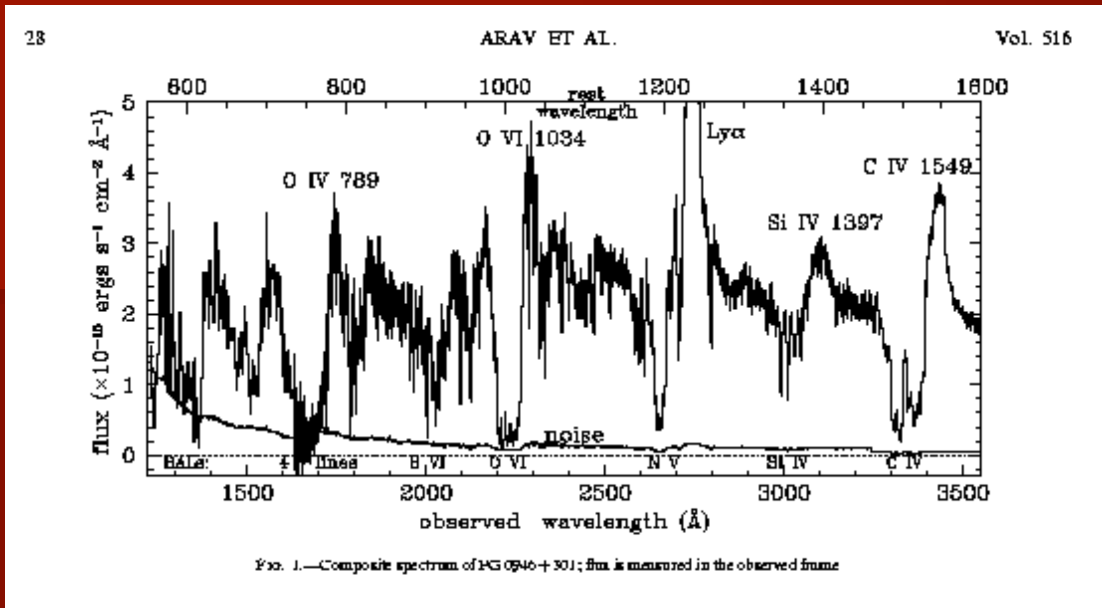
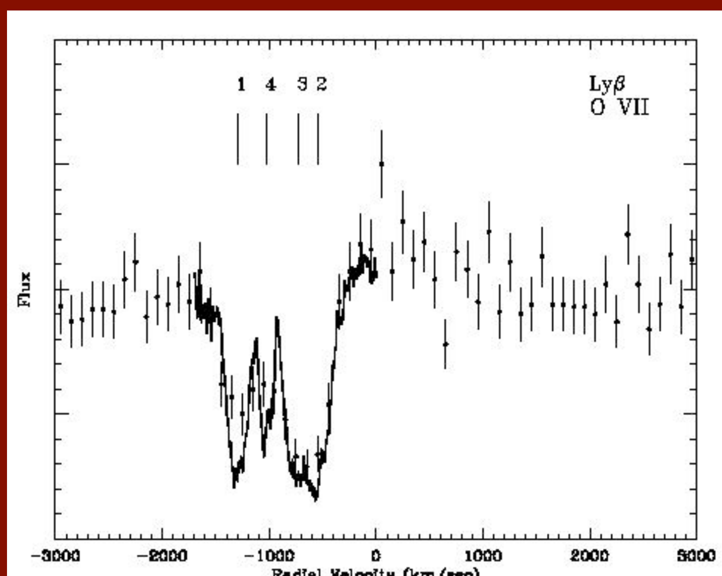


FIG. 1.—Composite spectrum of PG 0946+301; flux is measured in the observed frame

Arav et a. (1999) -- HST and ground-based obs. of PG 0946+301



Gabel et al. (2003) and Kaspi et al. (2002)

What can drive an outflow?

- Thermal expansion
- Radiation pressure
- Magnetic fields

But in most cases, rotation plays a key (directly or indirectly)

Reference: e.g., “Introduction to stellar winds” by H. Lamers and J. Cassinellii

The equations of hydrodynamics

$$\frac{D\rho}{Dt} + \rho \nabla \cdot v = 0$$

$$\rho \frac{Dv}{Dt} = -\nabla P + \rho g + \rho\, f^{rad}$$

$$\rho \frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P \nabla \cdot v + \rho L$$

$$P = (\gamma - 1) e$$

The equations are solved using the ZEUS-2D code (Stone & Norman 1992) extended by Proga, Stone, & Kallman (2000;see also Proga, Stone & Drew 1998, 1999; Proga & Kallman 2002) .

$$f^{rad,e} = \frac{\sigma_e}{c} \frac{L}{4\pi r^2} = \frac{\sigma_e}{c} F$$

the radiation force due to electron scattering

$$f^{rad,e} = g \quad \Rightarrow \quad L_{Edd} = \frac{4\pi c G M}{\sigma_e}$$

the Eddington luminosity

$$\Gamma = L / L_{Edd}$$

the Eddington factor

The accretion disk

$$L_D = \frac{M\dot{M}_a G}{2r_a}$$

$$L_{Edd,D} = \frac{4\pi c G M_a}{\sigma_e}$$

$$\Gamma_D = \frac{L}{L_{Edd}} = \frac{\dot{M}_a \sigma_e}{8\pi c r_a}$$

$$f^{rad,\ l} = \sum_{lines} \frac{\kappa_L F_c \Delta\nu_D}{c} \min(1,\ 1/\tau_L)$$

the radiation force due to lines

$$f^{rad,\ total} = f^{rad,\ e} + f^{rad,\ l} = f^{rad,\ e}\left(1 + M\right)$$

the total radiation force

A key difference between line driving and other driving mechanisms is that in other mechanisms acceleration is independent of density.

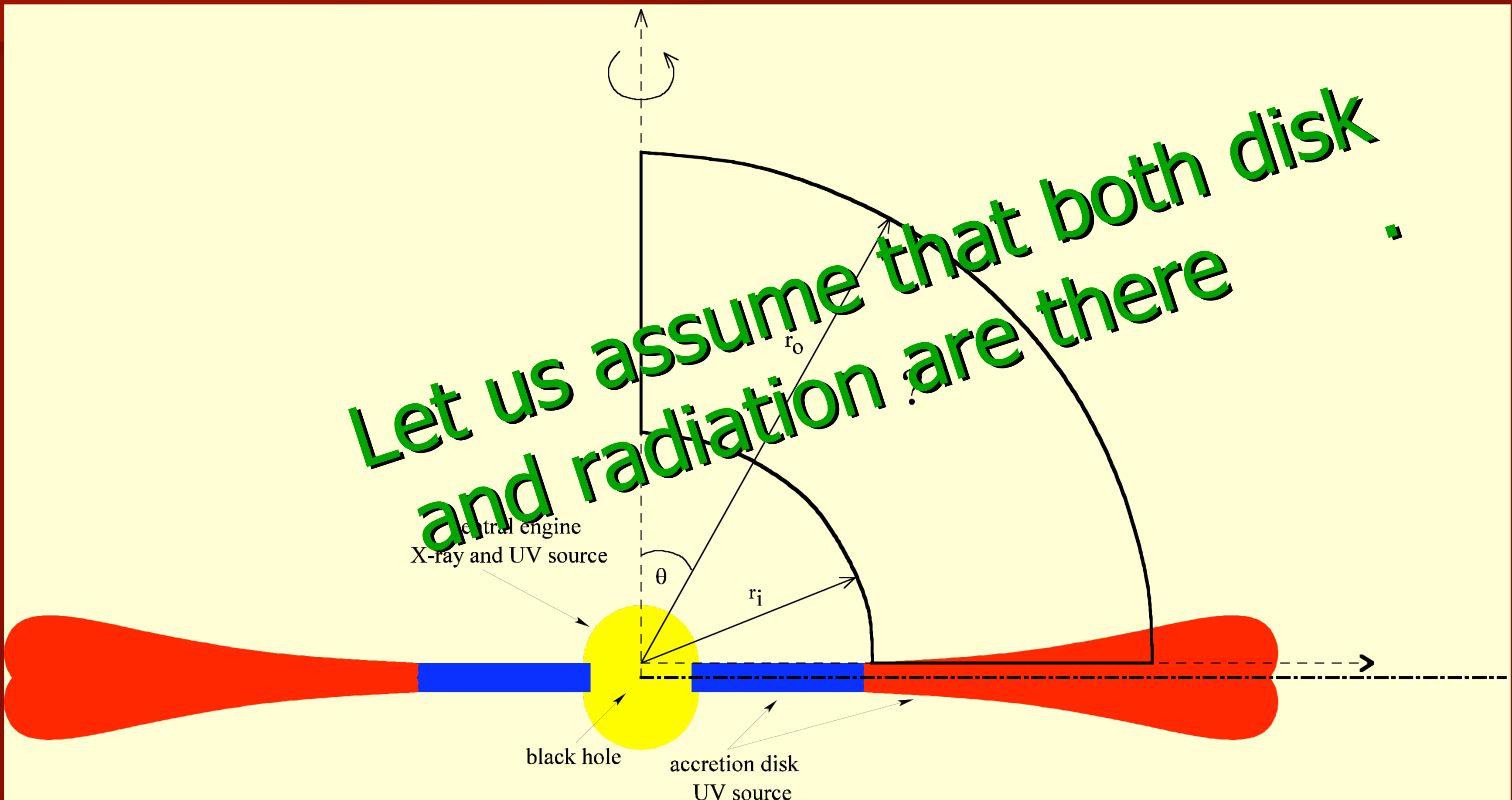
Calculations

- Key elements:
  - axisymmetry
  - radiation from a flat disk and spherical corona
  - adiabatic EOS
  - radiative heating/cooling (thermal driving)
  - radiation pressure
  - HD limit
  - spherical initial and outer boundary conditions

Calculations

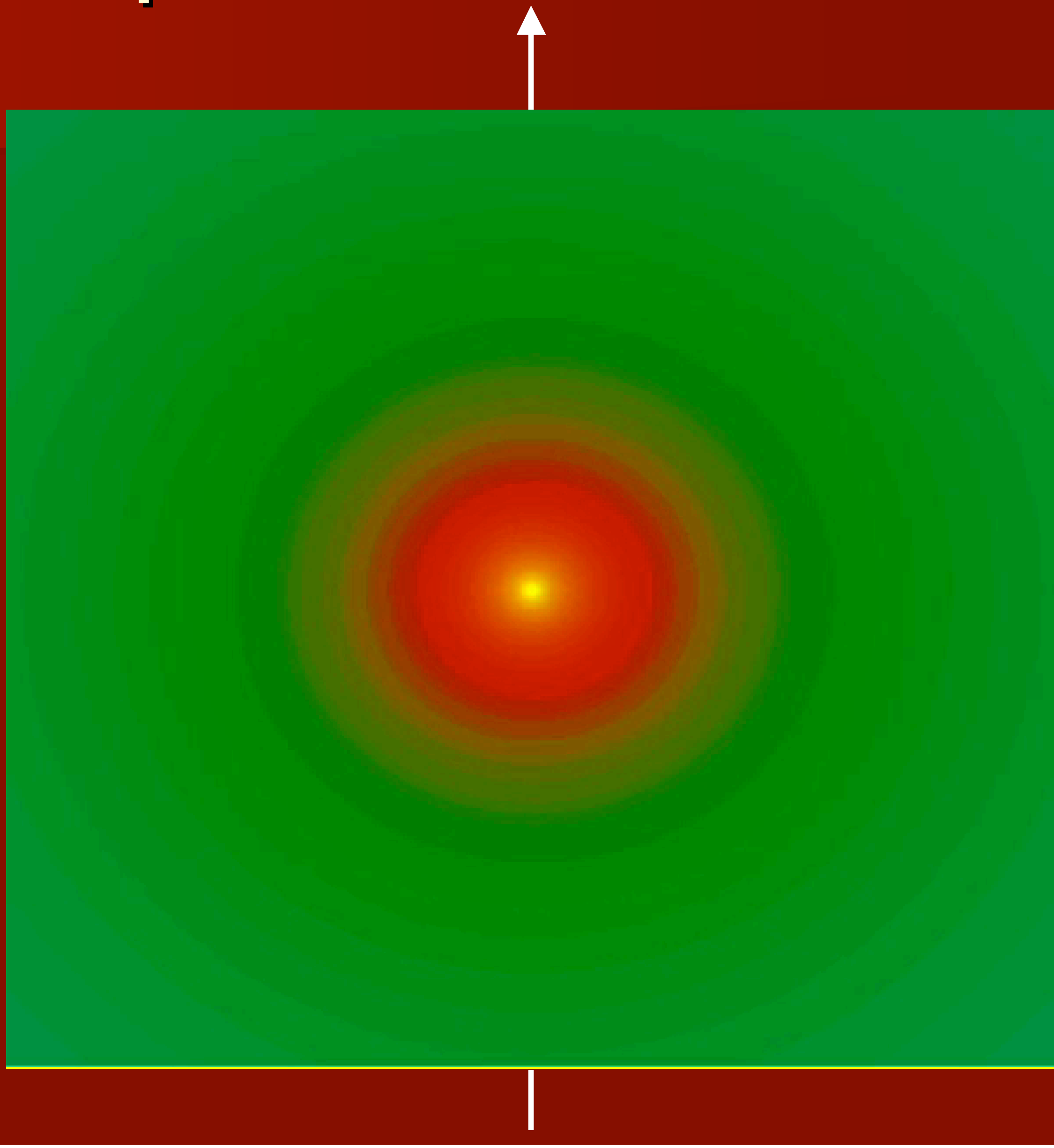
- Model specifications:
  - the black hole mass
  - the radiation field:
    - total luminosity (accretion rate),
    - SED ($f_{UV,} f_x$, T_x)
    - geometry (disk vs corona)

Numerical simulations.

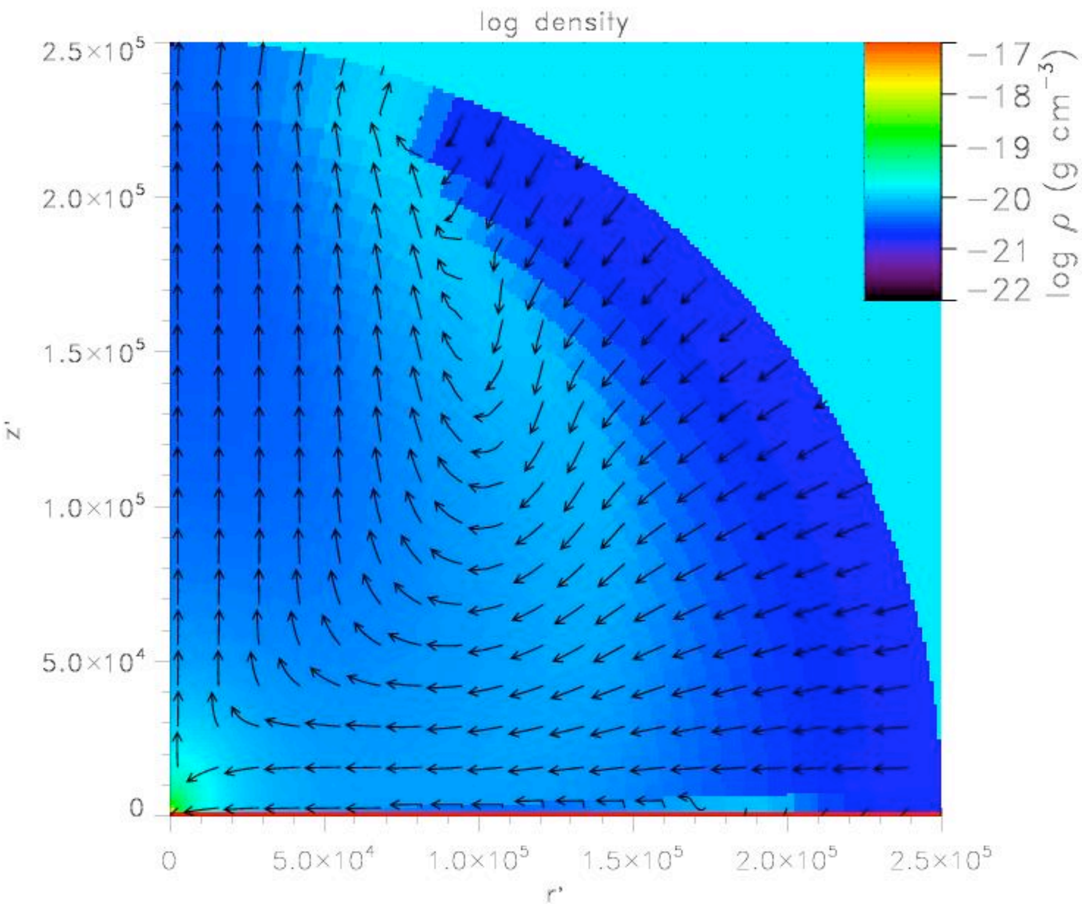


Let us assume that both disk and radiation are there .

Spherical Accretion



Outflows from Inflows



Proga (2006)

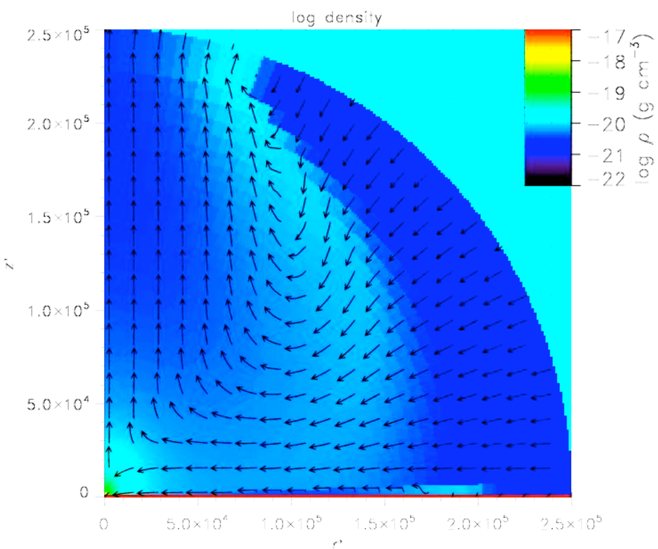
$$M_{BH} = 10^8 M_{SUN}$$

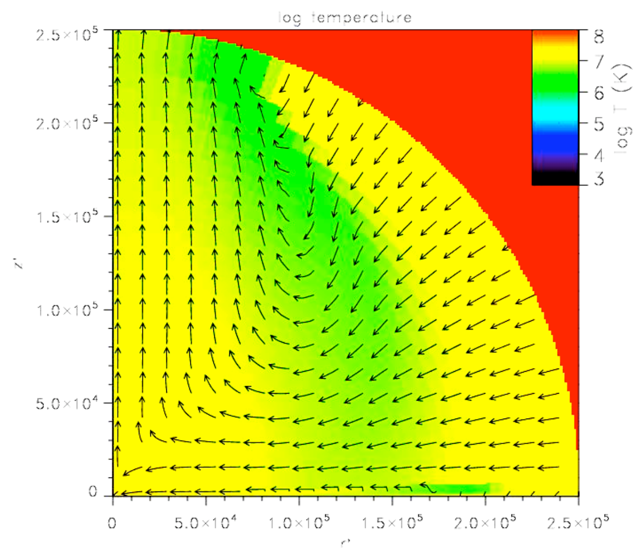
$$\dot{M}_D = 10^{26} g/s = 1.6 M_{SUN}/yr$$

$$T_X = 8 \times 10^7 K$$

$$\rho(r_o) = 10^{-21} g/cm^3$$

$$f_{UV} = f_X = 0.5$$





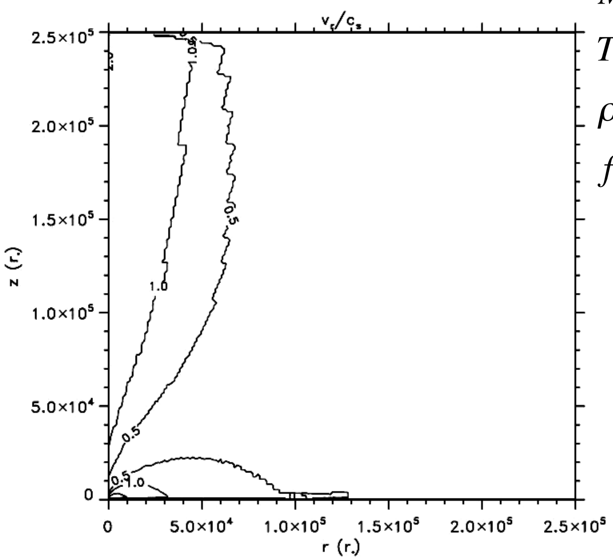
$M_{BH}=10^{8}M_{SUN}$

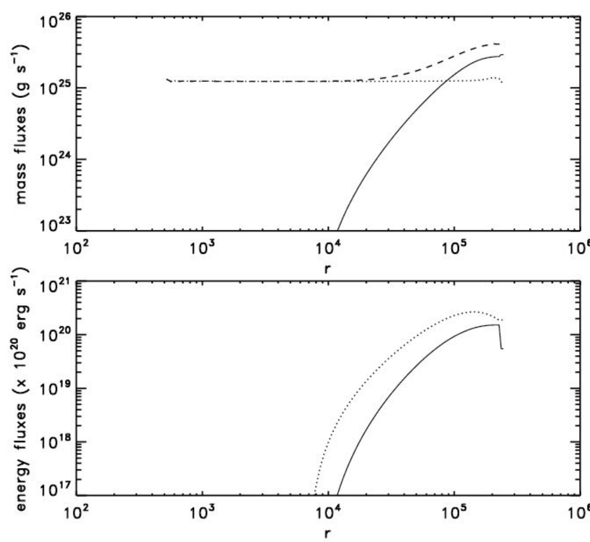
$\dot{M}_{D}=10^{26}g/s=1.6M_{SUN}/yr$

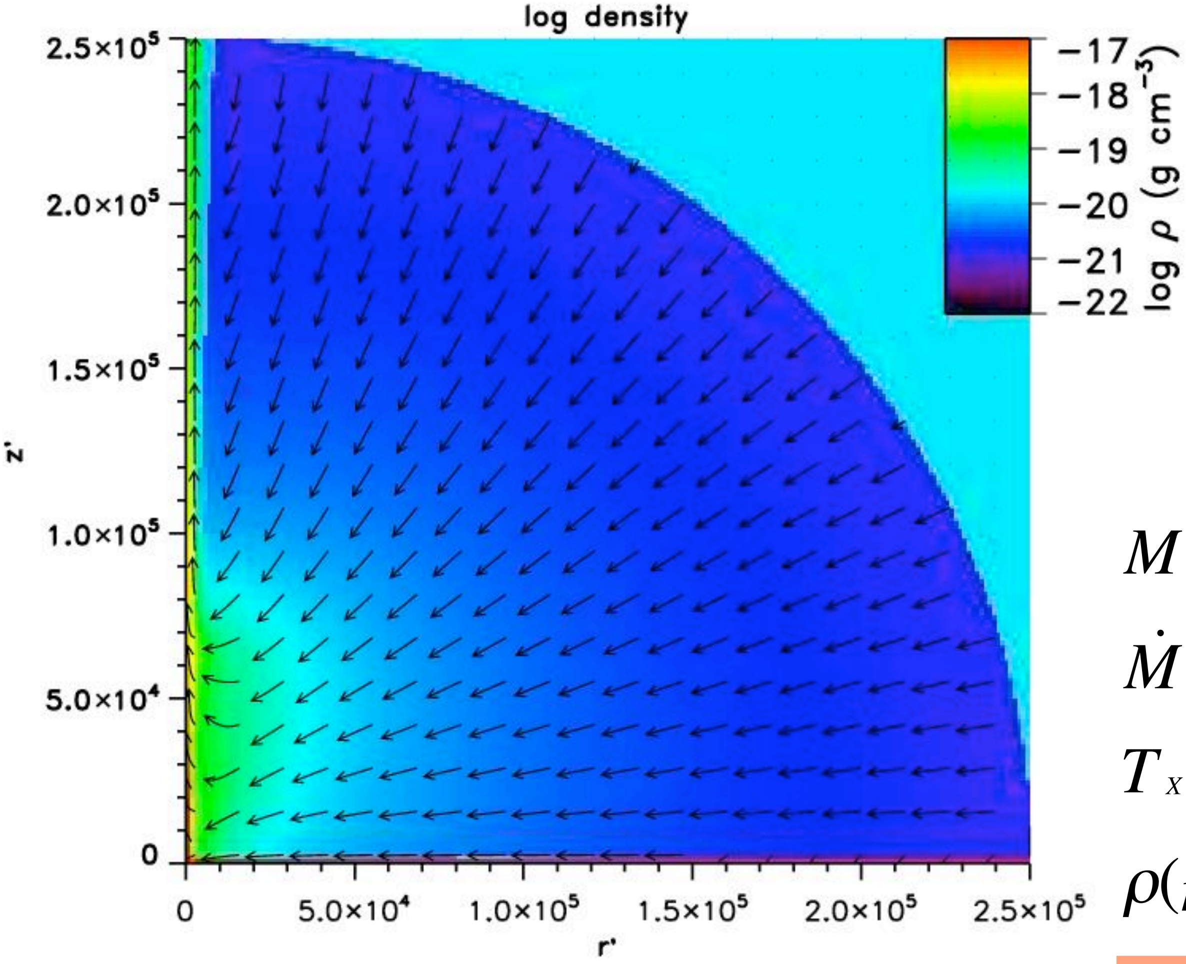
$T_{X}=8\times10^{7}K$

$\rho(r_{o})=10^{-21}g/cm^{3}$

$f_{UV}=f_{X}=0.5$







$$M_{BH} = 10^{8} M_{SUN}$$

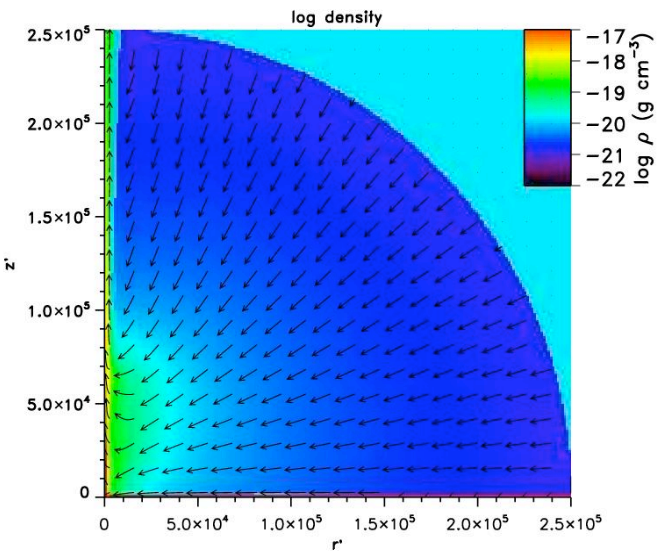
$$\dot{M}_{D} = 10^{26} g/s = 1.6 M_{SUN}/yr$$

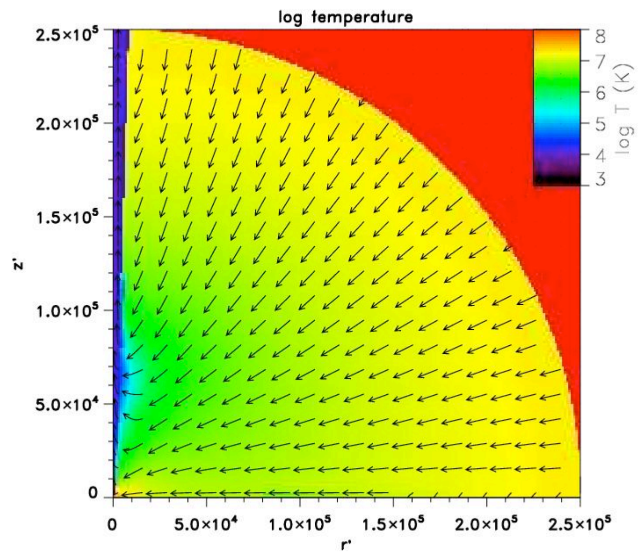
$$T_{X} = 8 \times 10^{7} K$$

$$\rho(r_o) = 10^{-21} g/cm^{3}$$

$$f_{UV} = 0.95 \quad f_{X} = 0.05$$

Proga (2006)





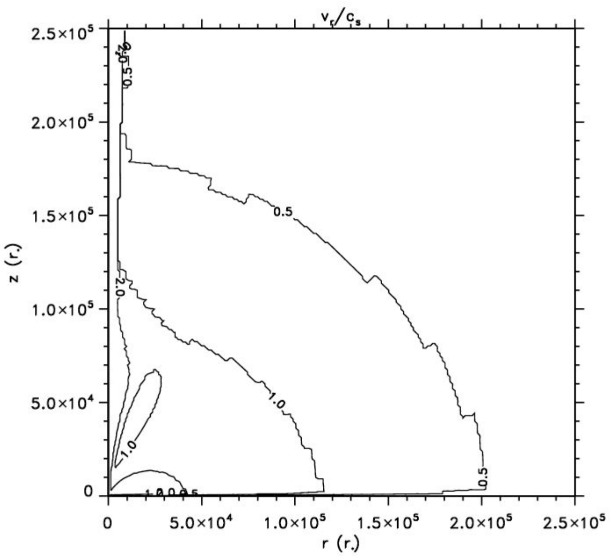
$M_{BH} = 10^8 M_{SUN}$

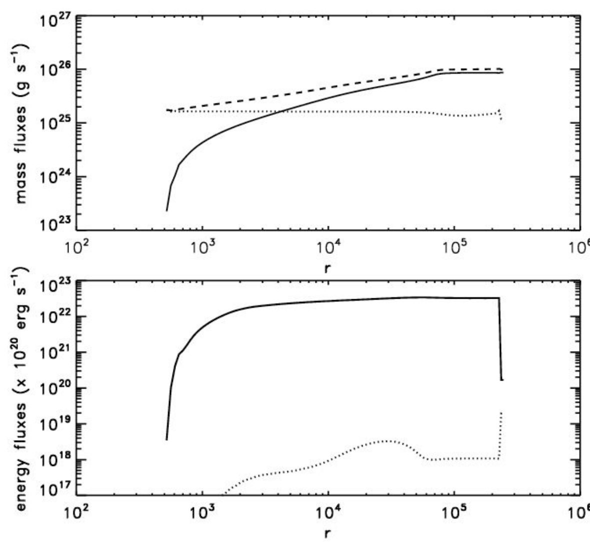
$\dot{M}_D = 10^{26} g/s = 1.6 M_{SUN}/yr$

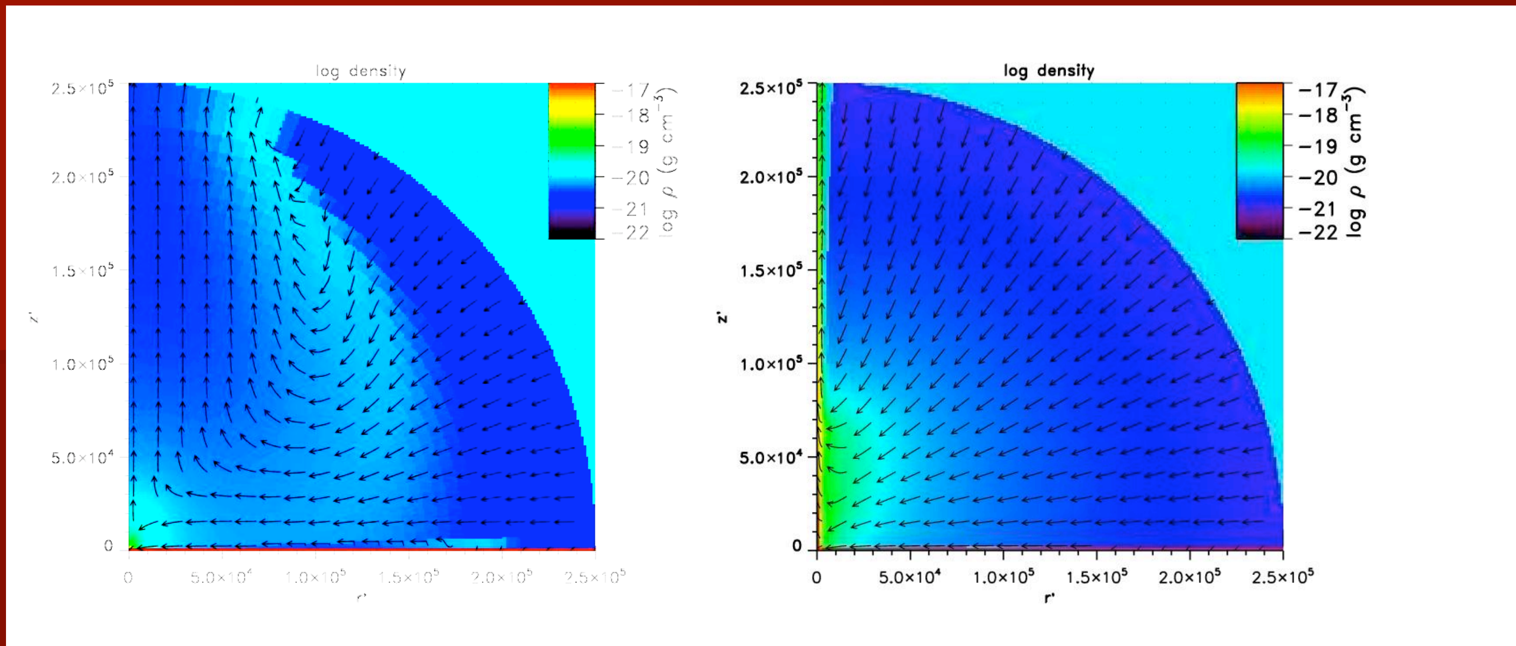
$T_X = 8 \times 10^7 K$

$\rho(r_o) = 10^{-21} g/cm^3$

$f_{UV} = 0.95 \quad f_X = 0.05$







	$f_{UV=}0.5$ $f_x=0.5$	$f_{uv}=0.95$ $f_x=0.05$
Accretion rate	$1x10^{25}$	$1x10^{25}$
Inflow rate	$4x10^{25}$	$1x10^{26}$
Outflow rate	$3x10^{25}$	$9x10^{25}$
Kinetic power	$2x10^{40}$	$4x10^{42}$
Thermal power	$3x10^{40}$	$1x10^{38}$

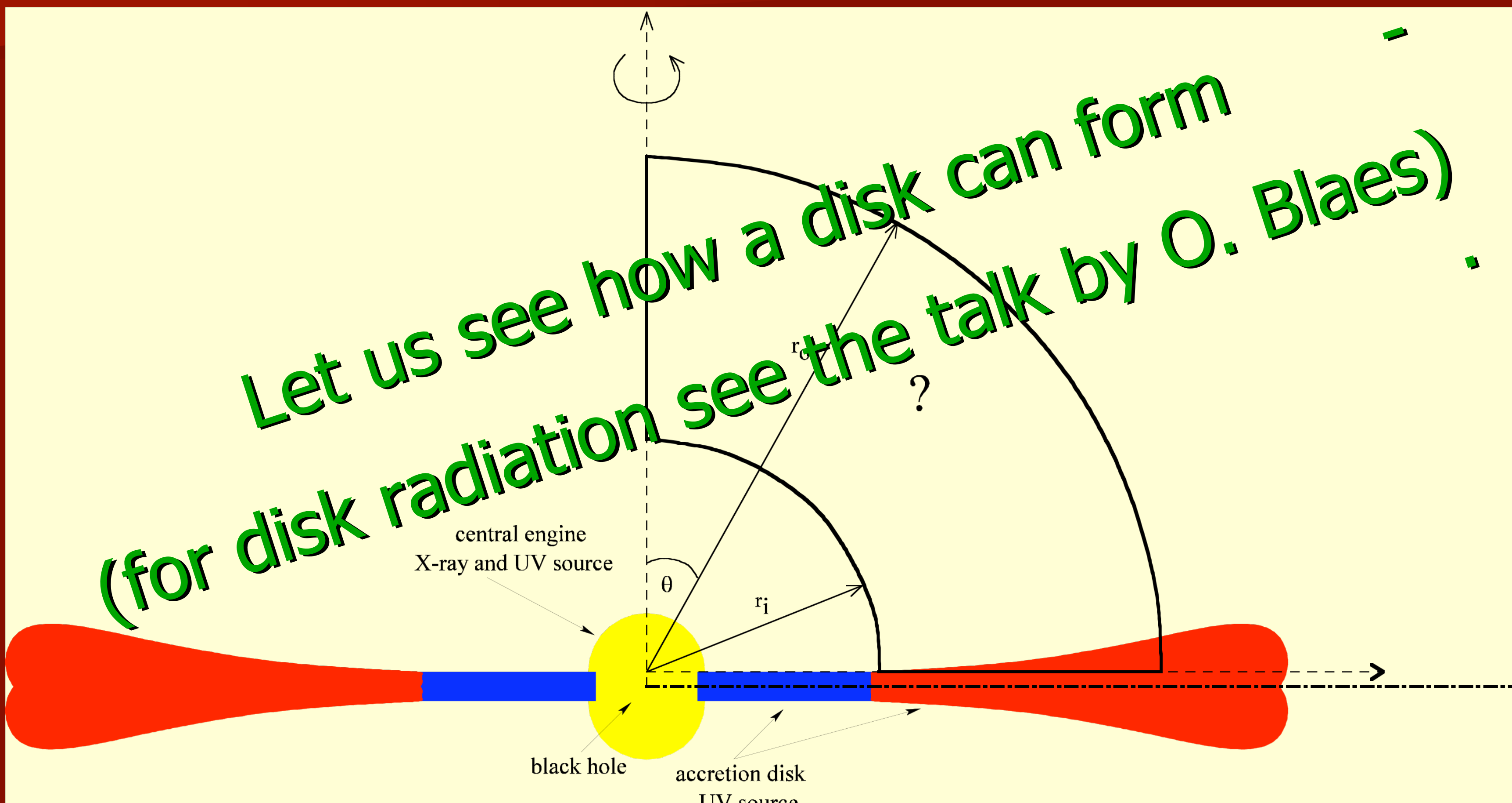
$1x10^{26}$

$6x10^{45}$

Conclusions from Part I

- A significant fraction of the inflowing matter is expelled by radiation pressure and heating.
- The flow settles into a steady inflow/outflow solution.
- The solution is quite robust but its characteristics are very sensitive to the geometry and SED of the central object radiation.

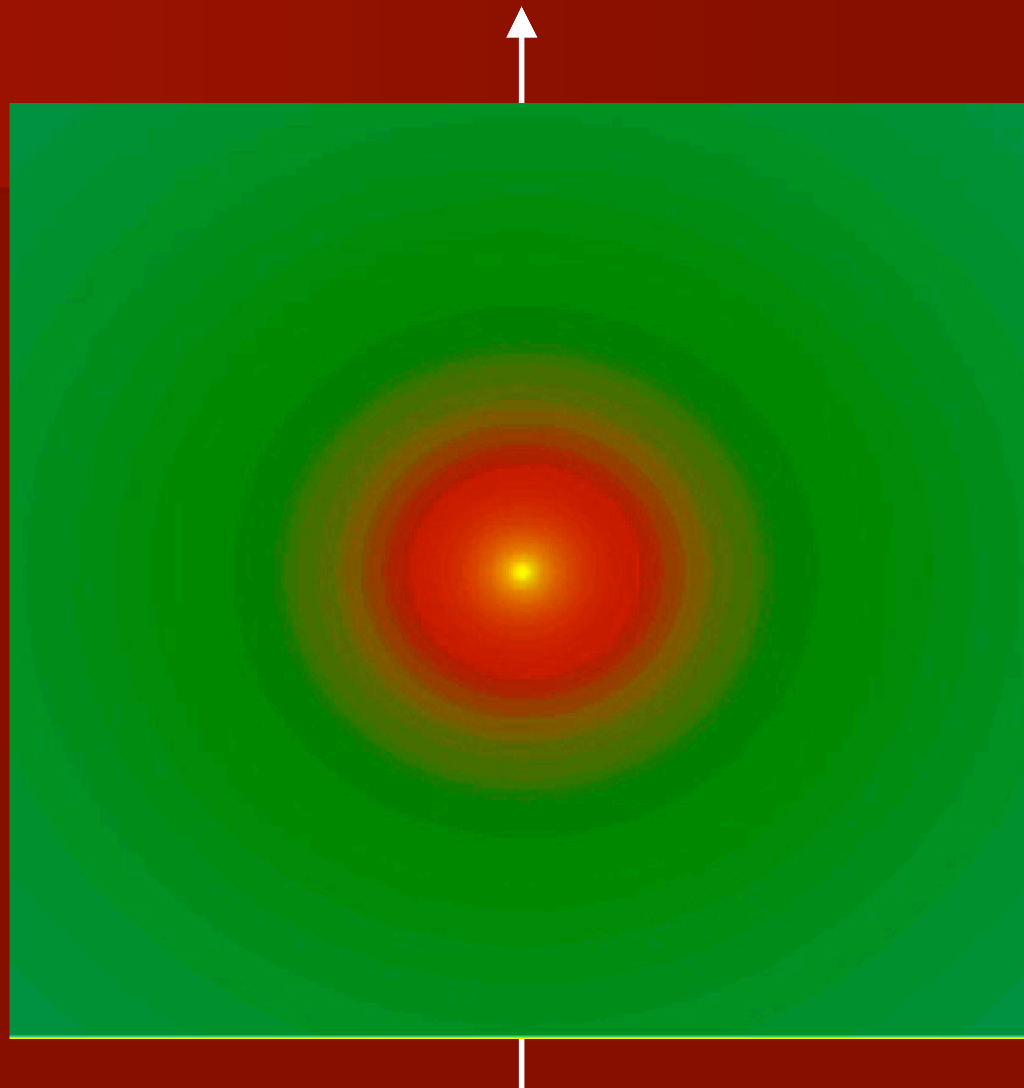
Disk formation and production of radiation



Let us see how a disk can form

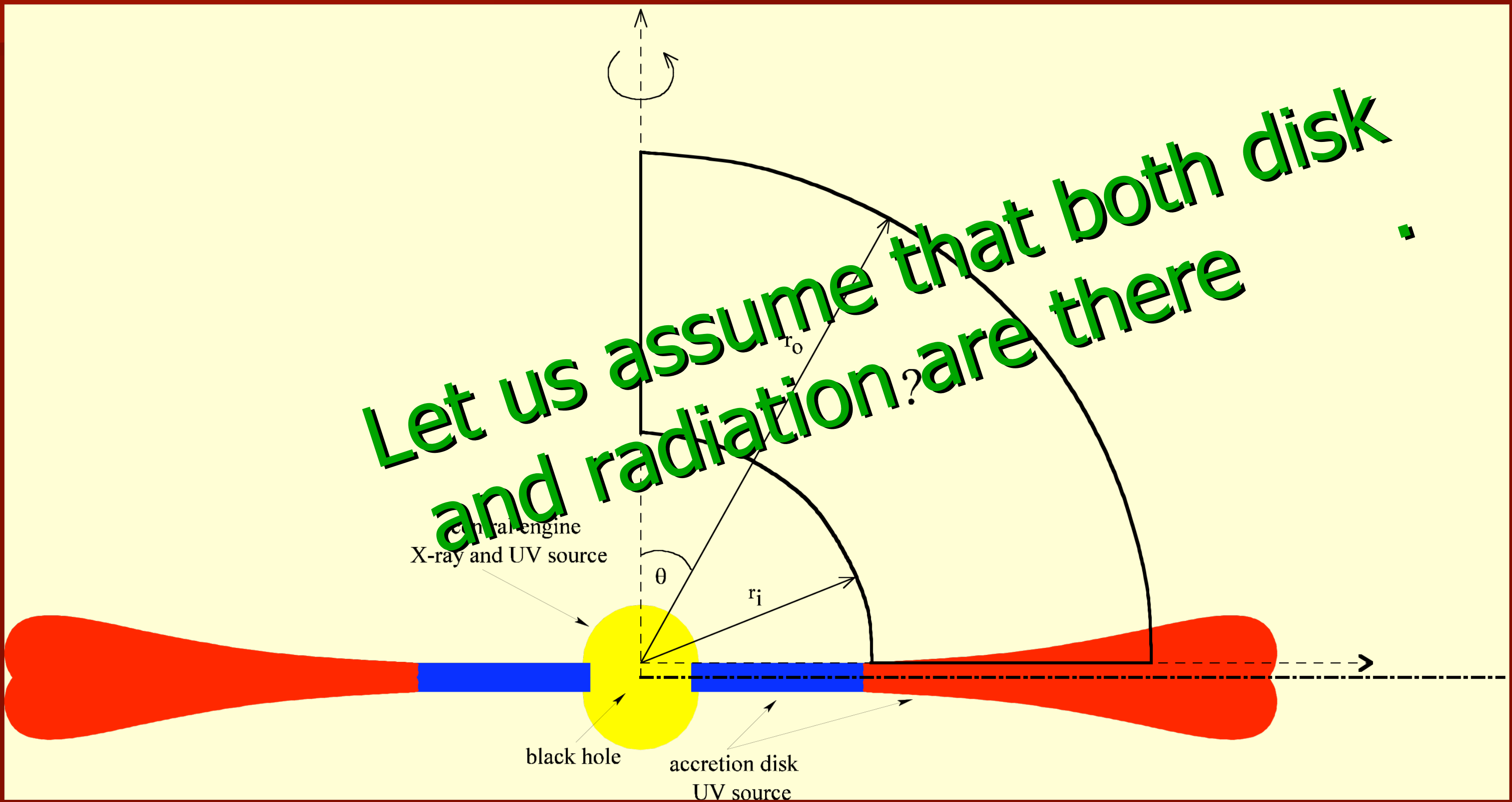
(for disk radiation see the talk by O. Blaes)

A collapse of a rotating envelope (HD inviscid case)



Proga & Begelman (2003a)

Disk formation and production of radiation



Let us assume that both disk and radiation are there .

Calculations

- Geometry:
  - axial symmetry – 2D spatial domain but 3D velocity (i.e., so-call 2.5D)
  - disk: flat, Keplerian and optically thick; radiation field as in the Shakura-Sunyaev model;
  - central object: isothermal sphere; gas - an ideal (gas with isothermal or adiabatic EOS)
- forces: gravity, rotation, gas and radiation pressure effects

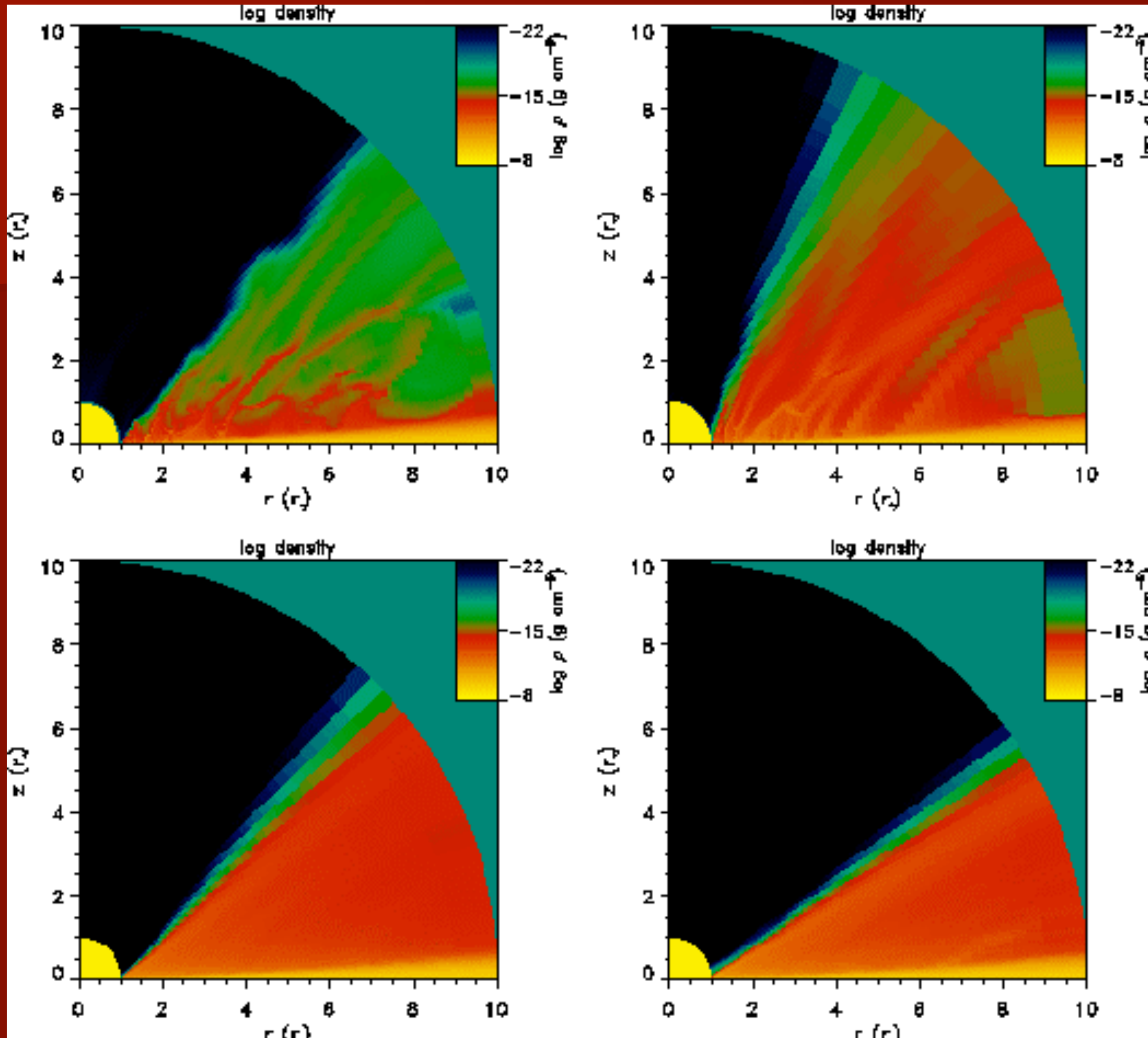
Model Parameters

- the mass, radius, and luminosity of the accretor;
- the mass accretion rate; and
- the SED of the radiation

A case without X-rays

$L_D = 1$
$L_{WD} = 0$

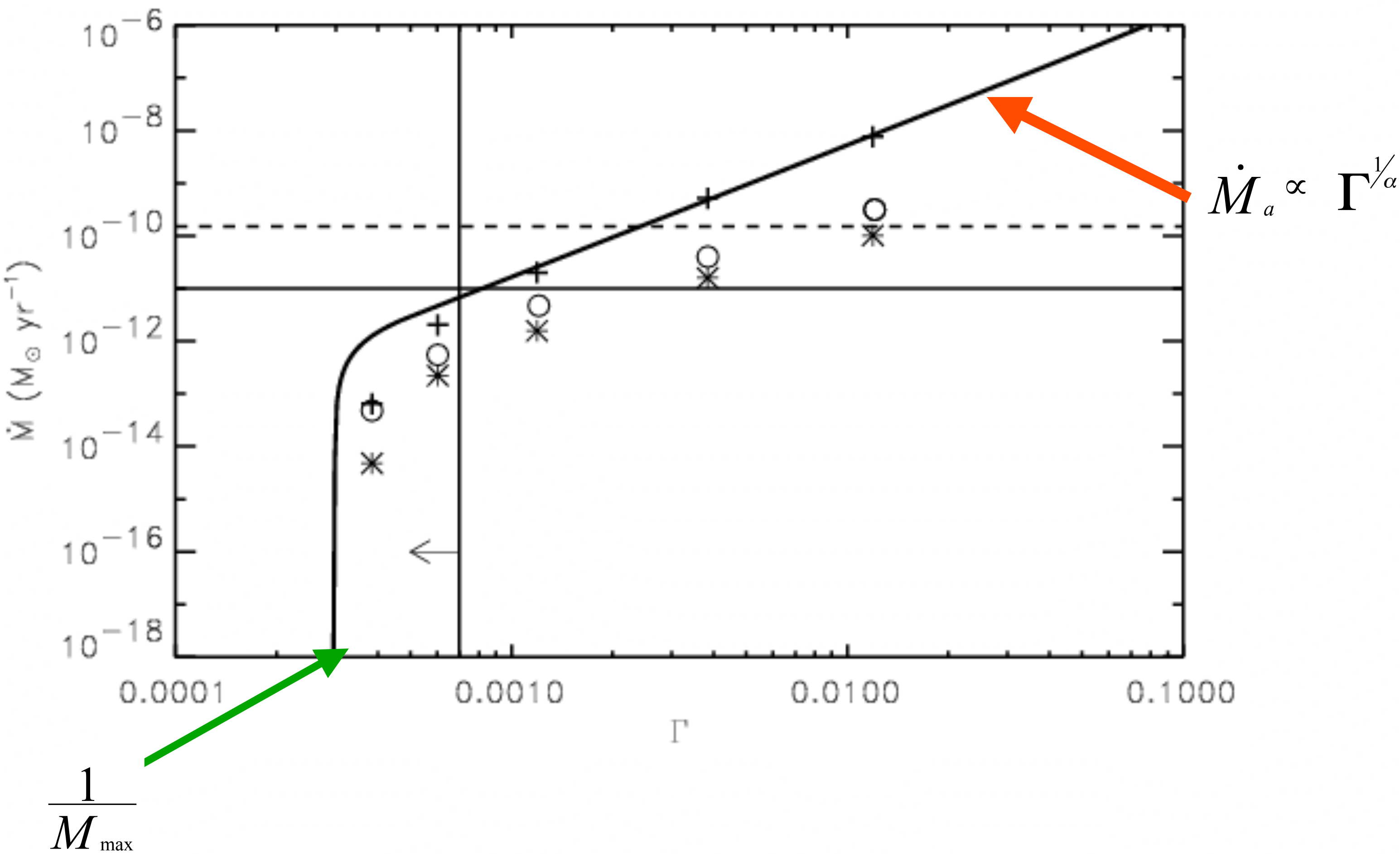
$L_D = 3$
$L_{WD} = 0$



$L_D = 3$
$L_{WD} = 3$

$L_D = 3$
$L_{WD} = 9$

Proga, Stone & Drew (1998)

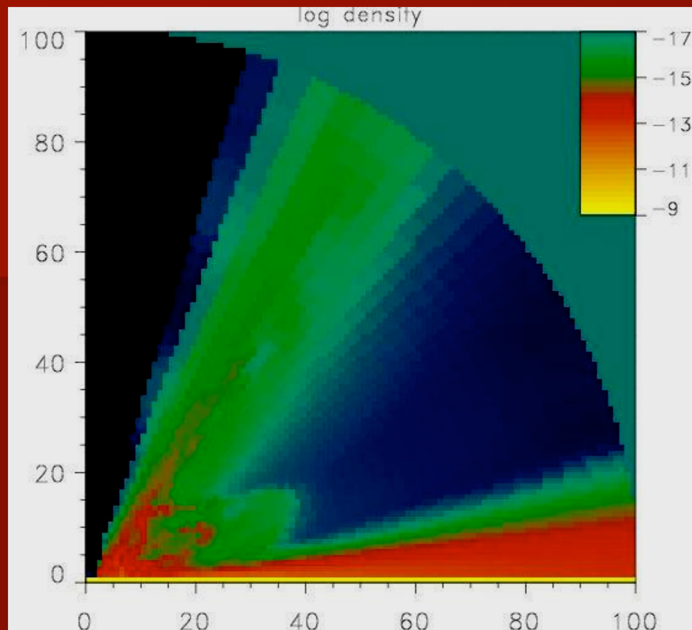


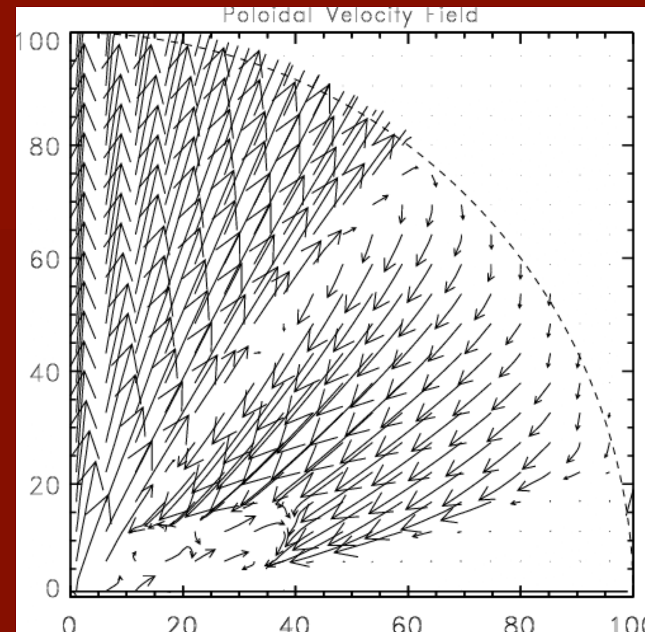
Drew & Proga (1999)

$$M_{max} = 4400, \quad k = 0.2, \quad \alpha = 0.6$$

L(disk)=3

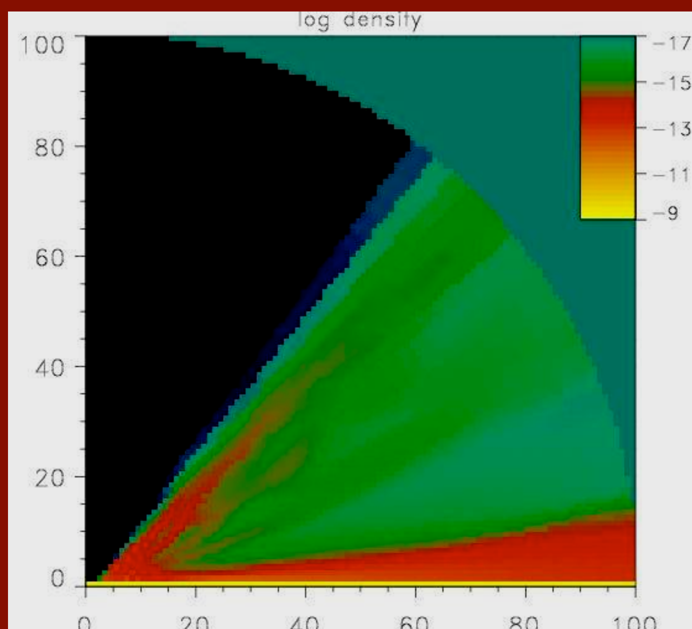
L(star)=0

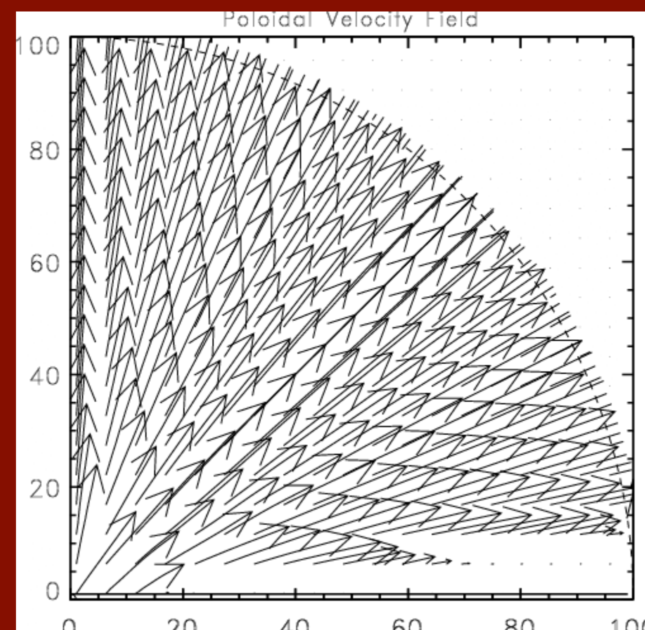




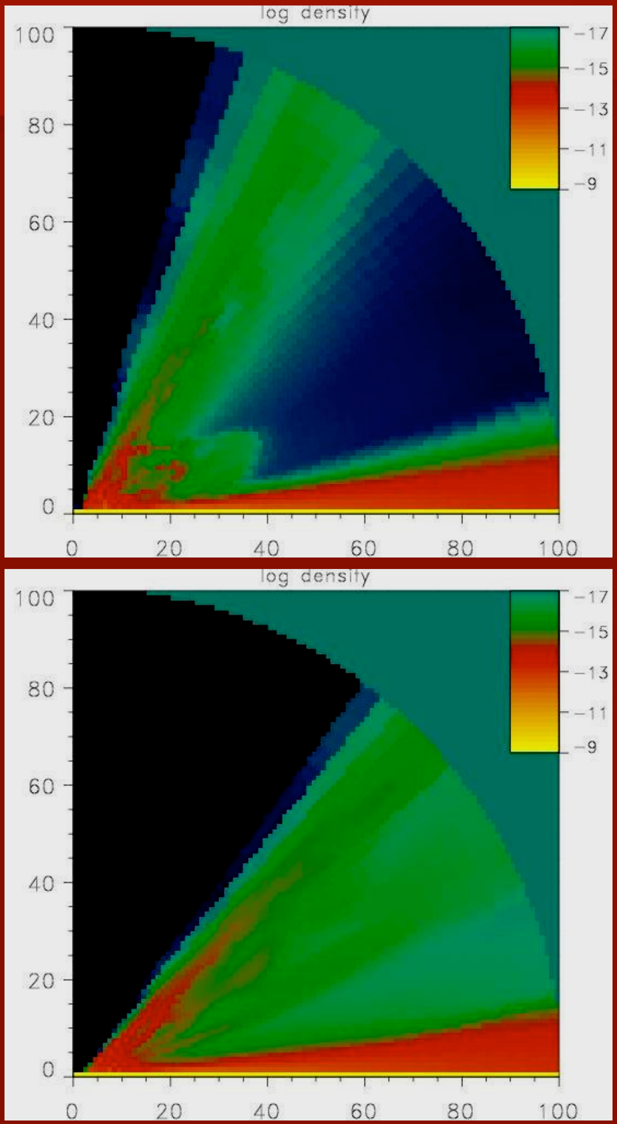
L(disk)=3

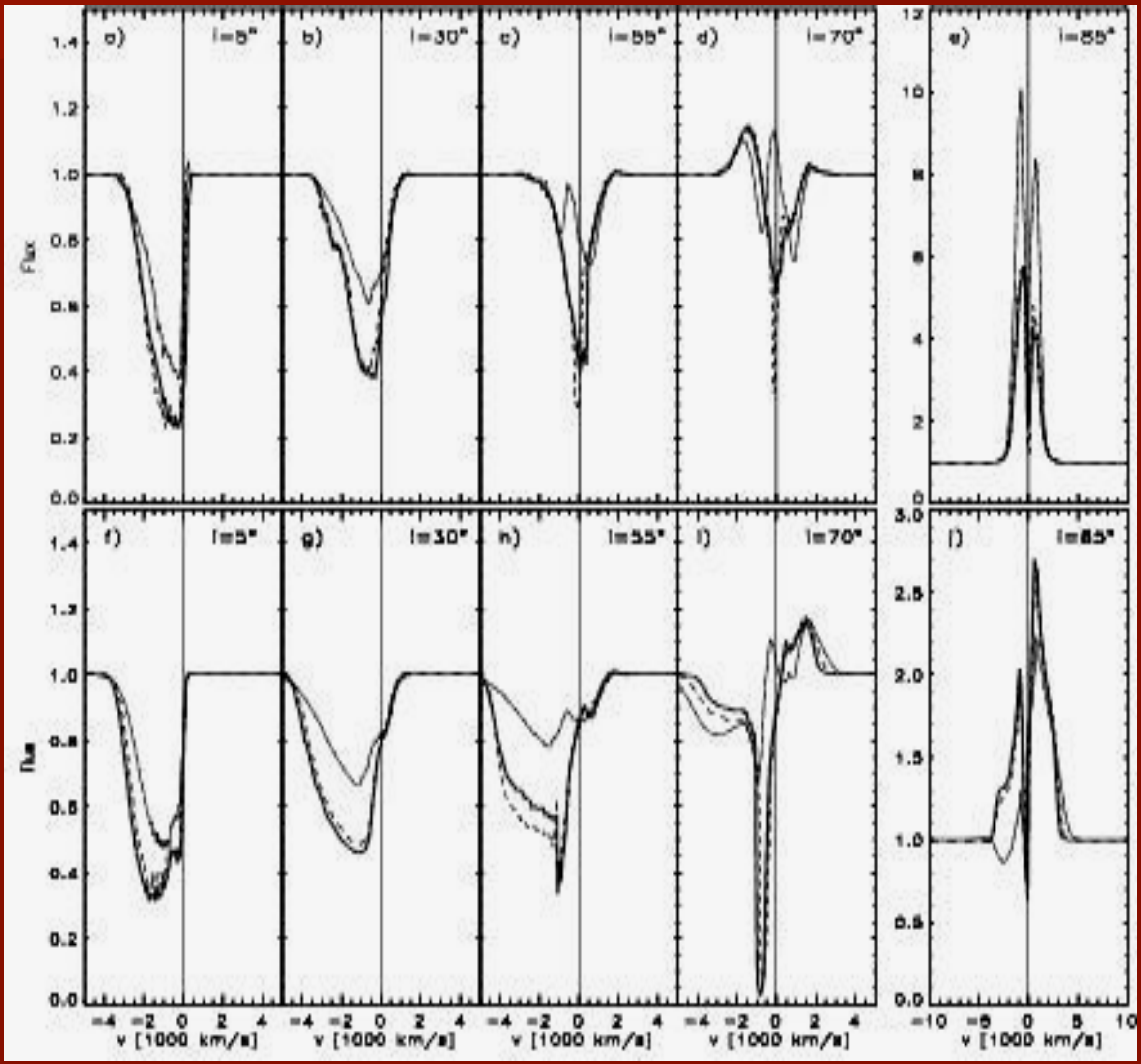
L(star)=3





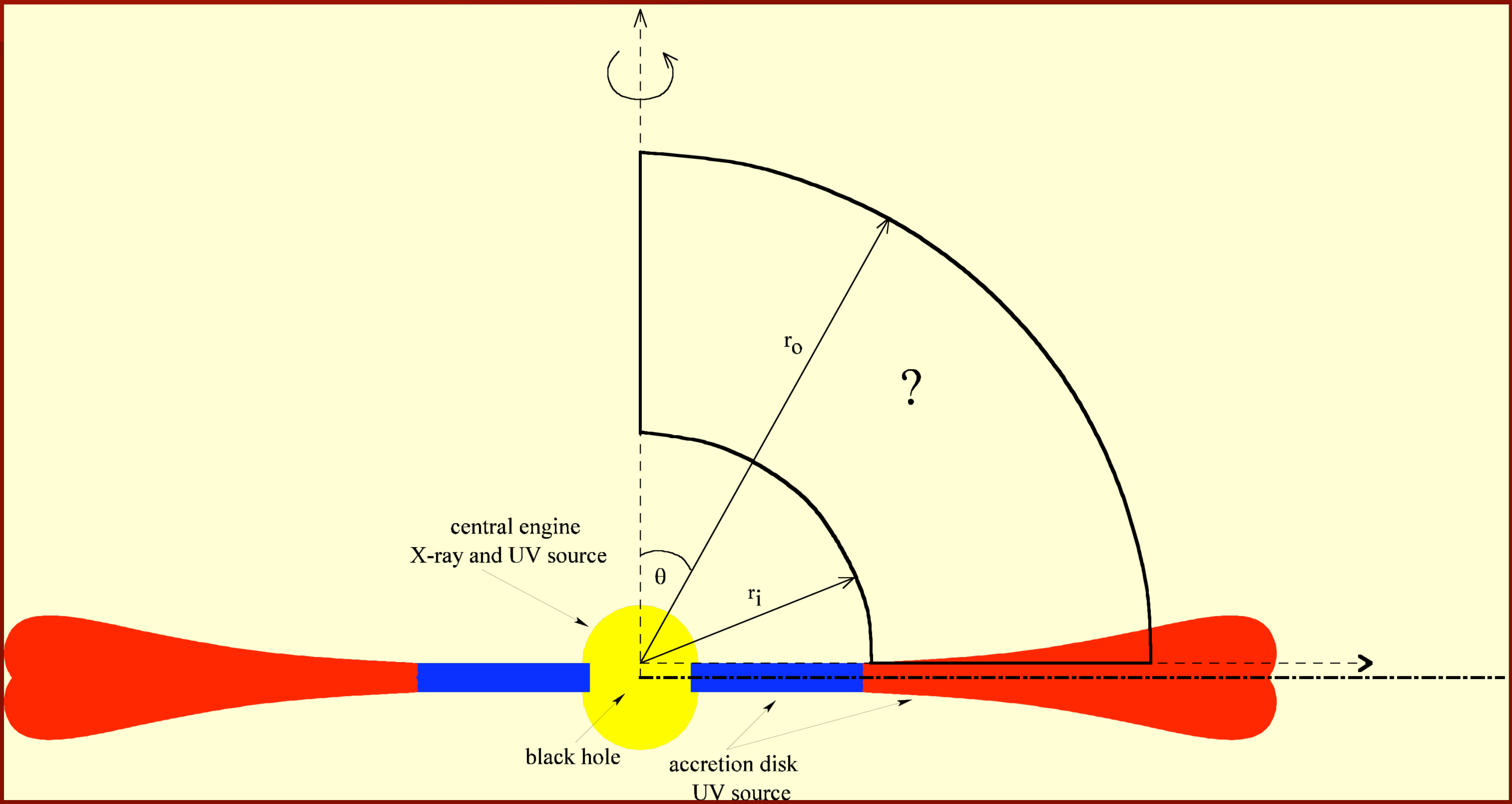
HD simulations and their line profiles

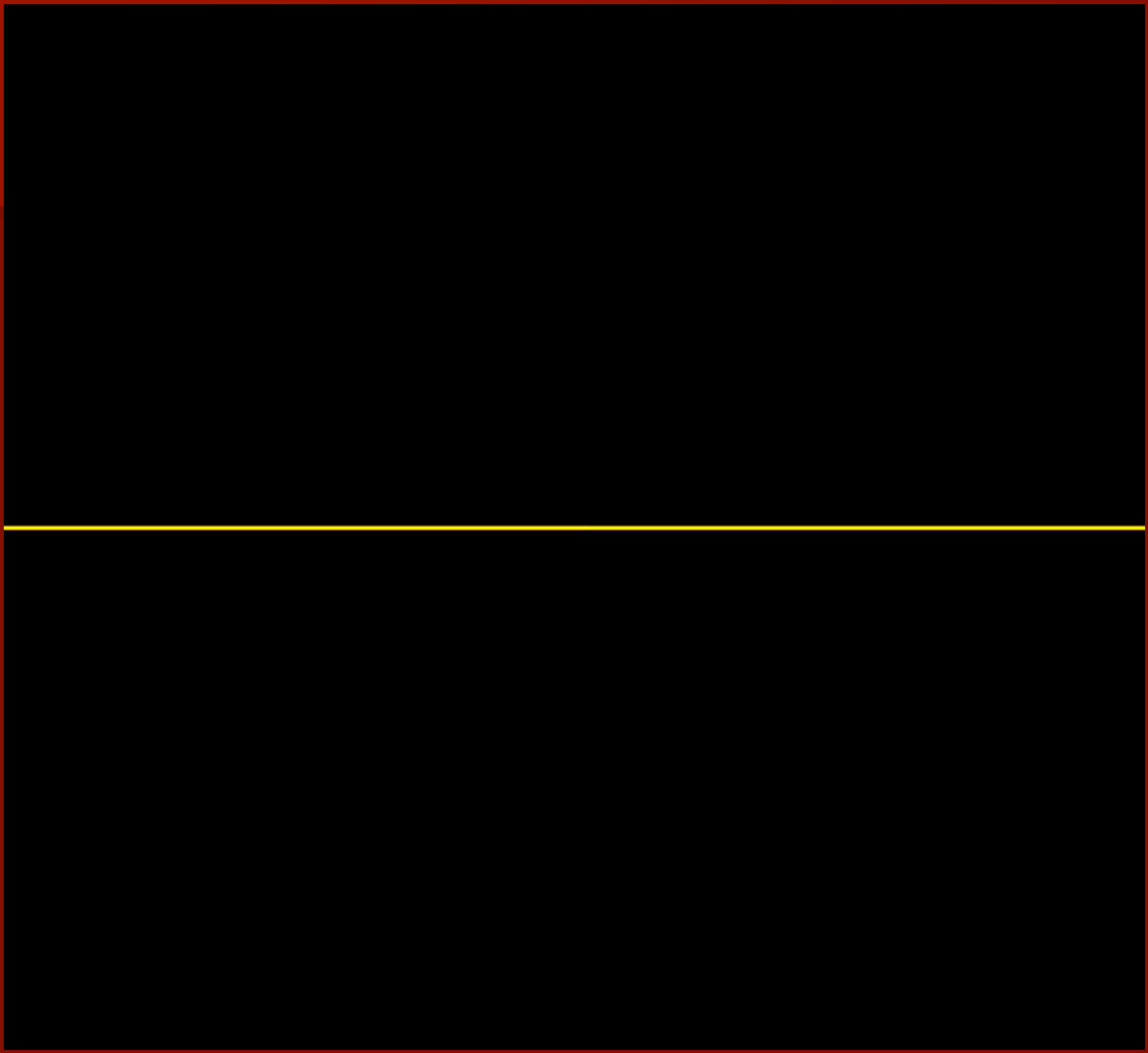




A case with X-rays (and UV)

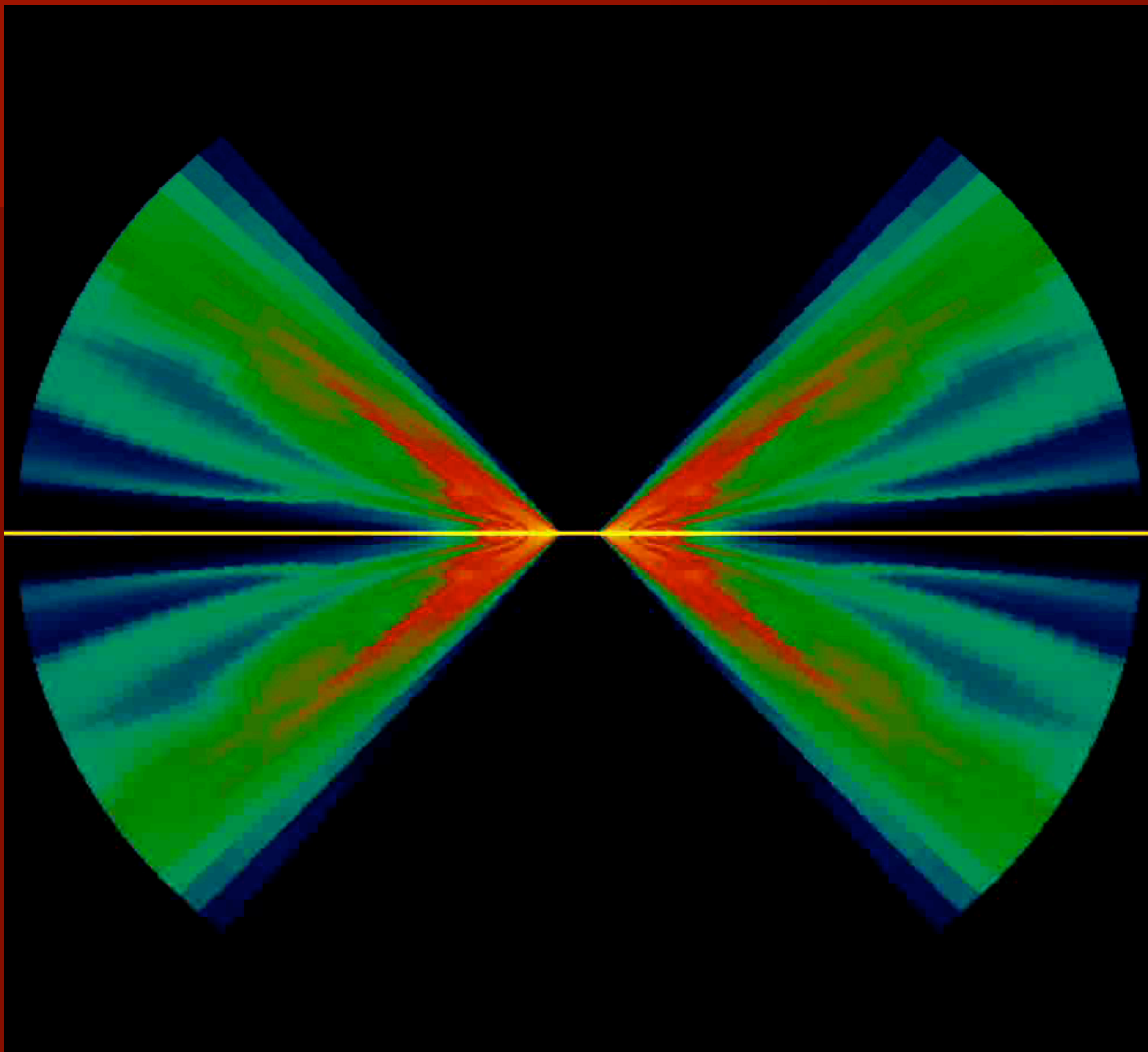
Numerical HD simulations.





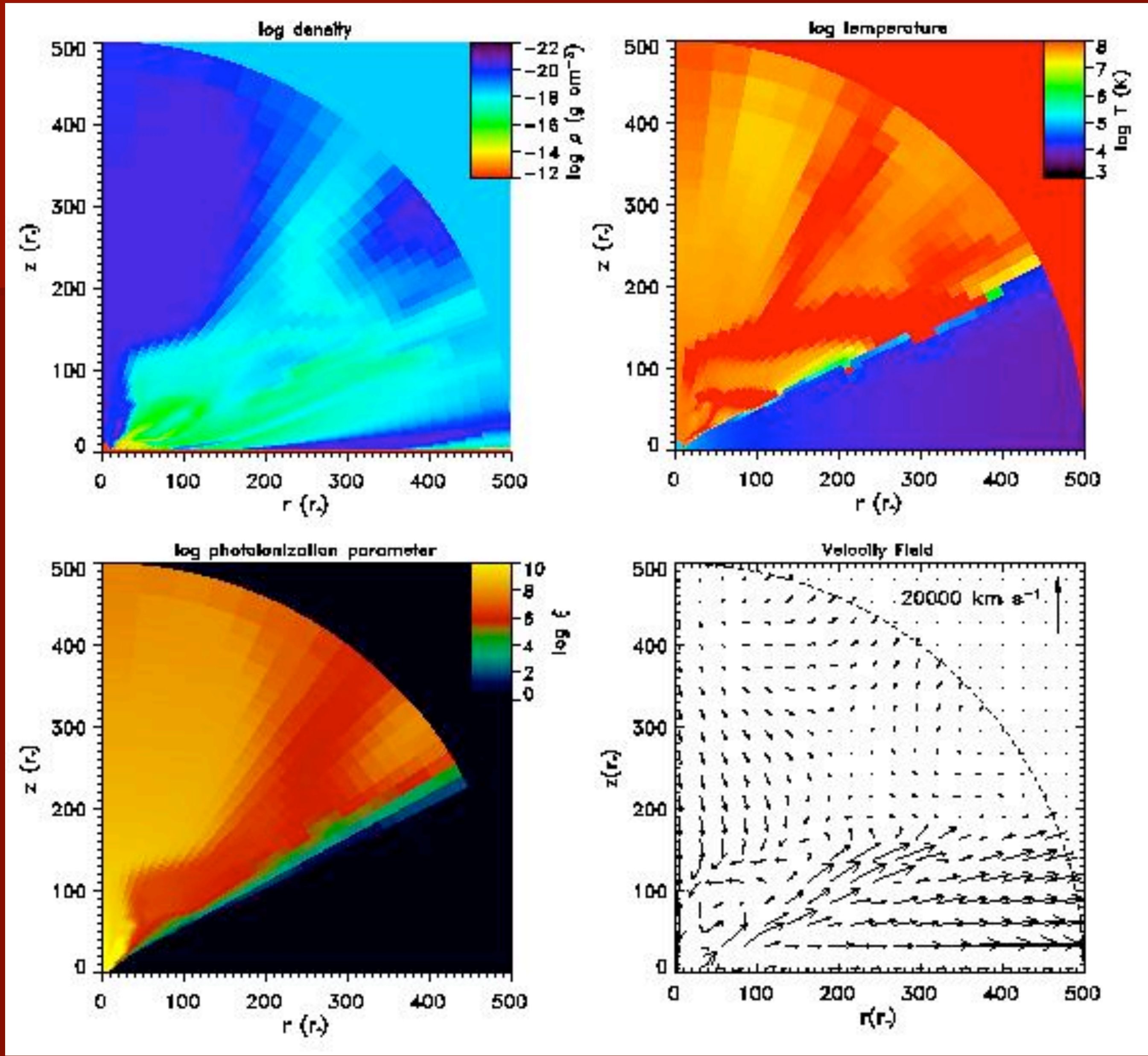
$M_{BH} = 10^{8} Msun$

$\Gamma = 0.6$

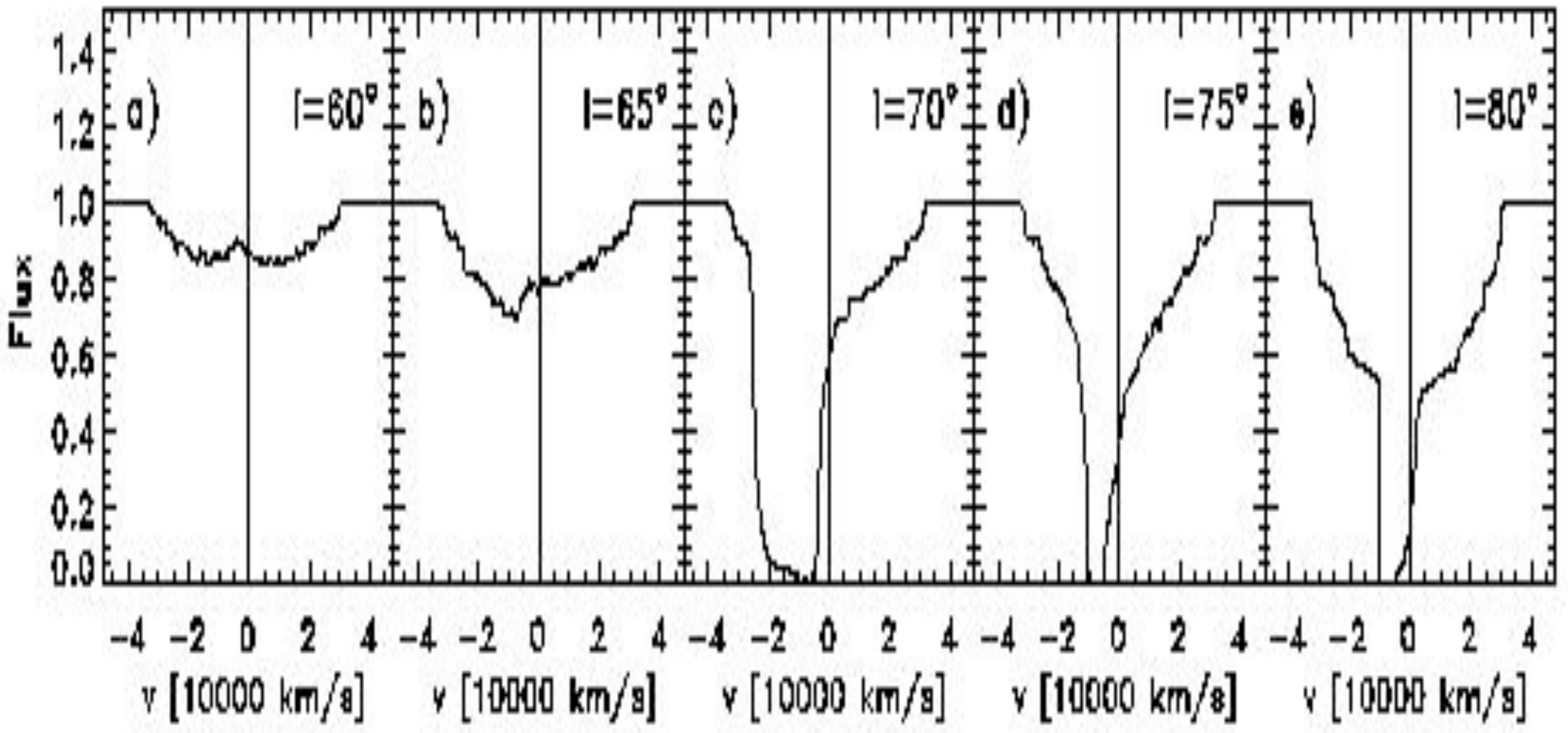


$M_{BH} = 10^8 Msun$

$\Gamma = 0.6$



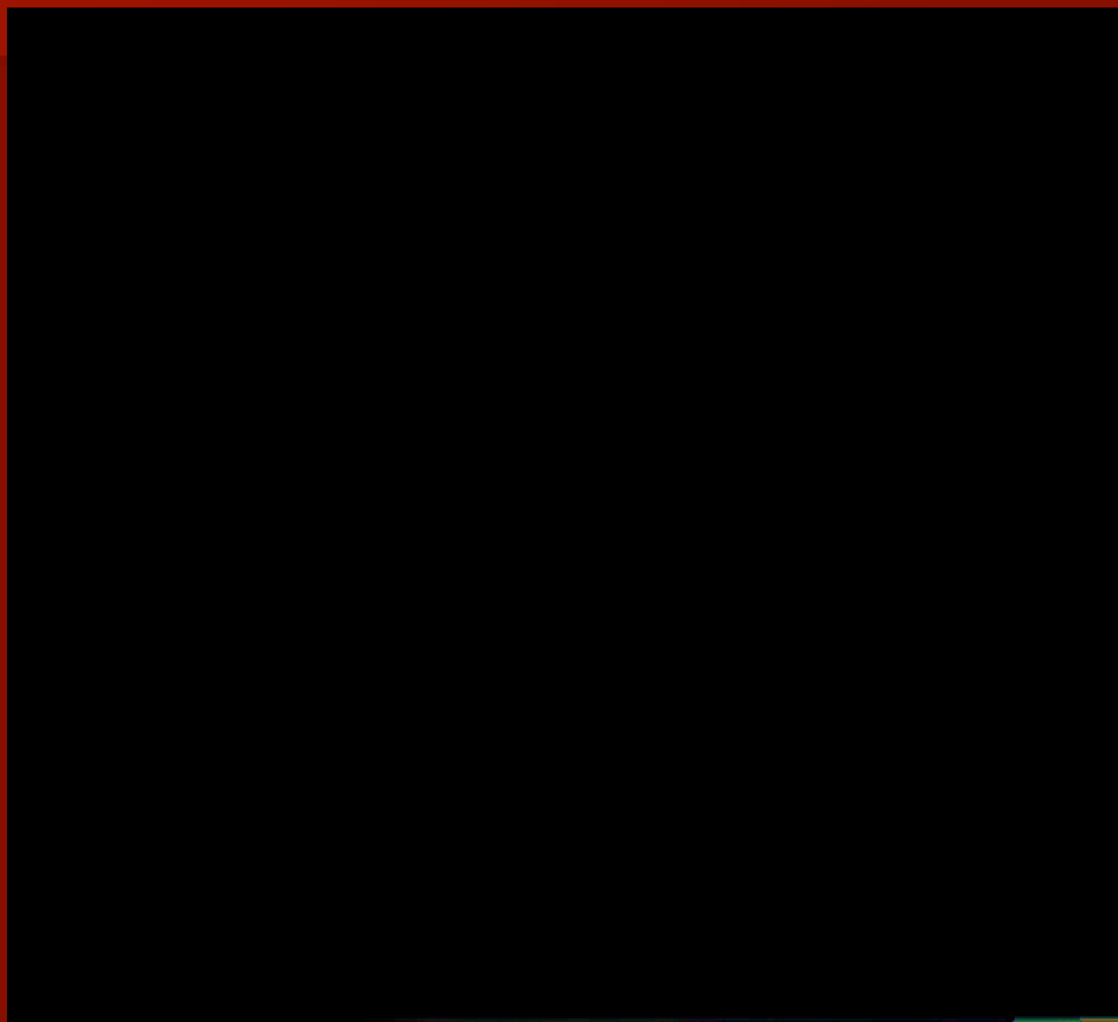
Proga & Kallman (2004)



Proga & Kallman (2004)

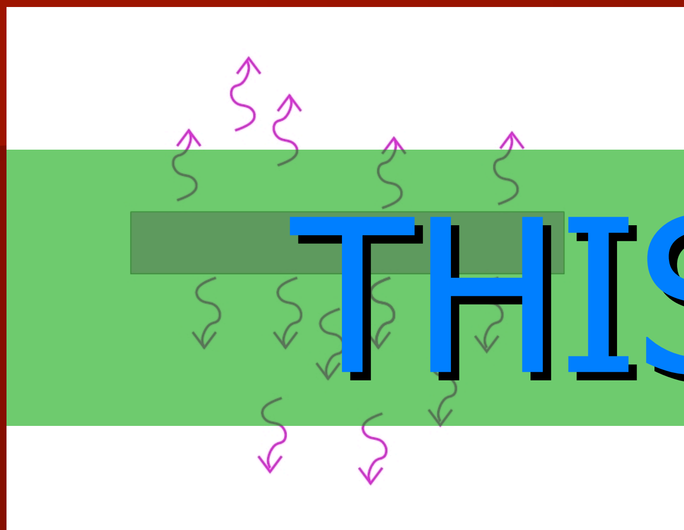
$M_{BH} = 10^{6} Msun$

$\Gamma = 0.9$



Quenching Disk Corona

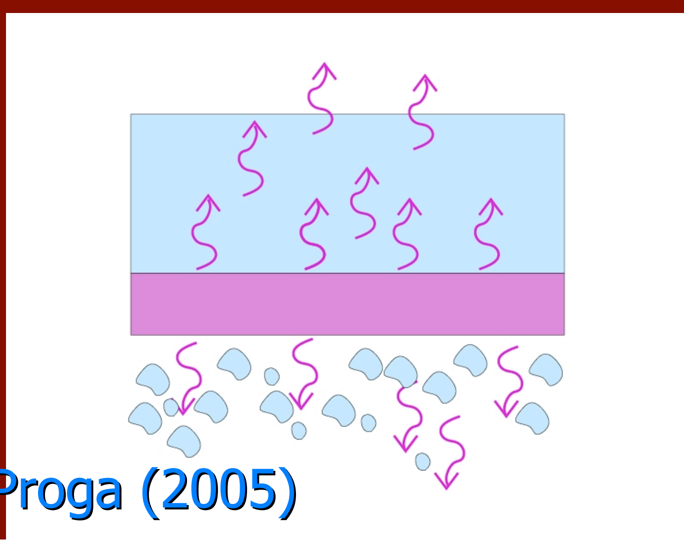
Disk



Disk and inflow/outflow

THIS TALK

Disk and corona



Disk and ????

Proga (2005)

Conclusions from Part II

- Line driving is robust.
- Only bright disks can produce fast outflows, i.e., L(disk)*M(max)> L(Edd).
- Disk winds can be weak and chaotic or strong and time independent.
- Radial component of the radiation force (due to the central object) organizes the disk wind.

Conclusions from Part II

- The ratio between the mass loss rate to mass accretion rate increases rapidly with the mass accretion rate.
- LD disk wind models can reproduce observed UV absorption.
- UV driven disk flows can quench a disk corona

- Old issues: emission lines,

  role of magnetic fields ...

MHD Models

- Why do we need to consider magnetic fields?
- There are a few reasons, for example,

1) weak magnetic fields are most likely responsible for the angular momentum transport in the disk (MRI).
2) strong large scale magnetic fields can drive disk winds (magneto-centrifugal driving or the gradient of the toroidal magnetic field)
3) LD alone does not seem to explain everything

Equations of MHD

$$\frac{D\rho}{Dt} + \rho \nabla \cdot v = 0$$

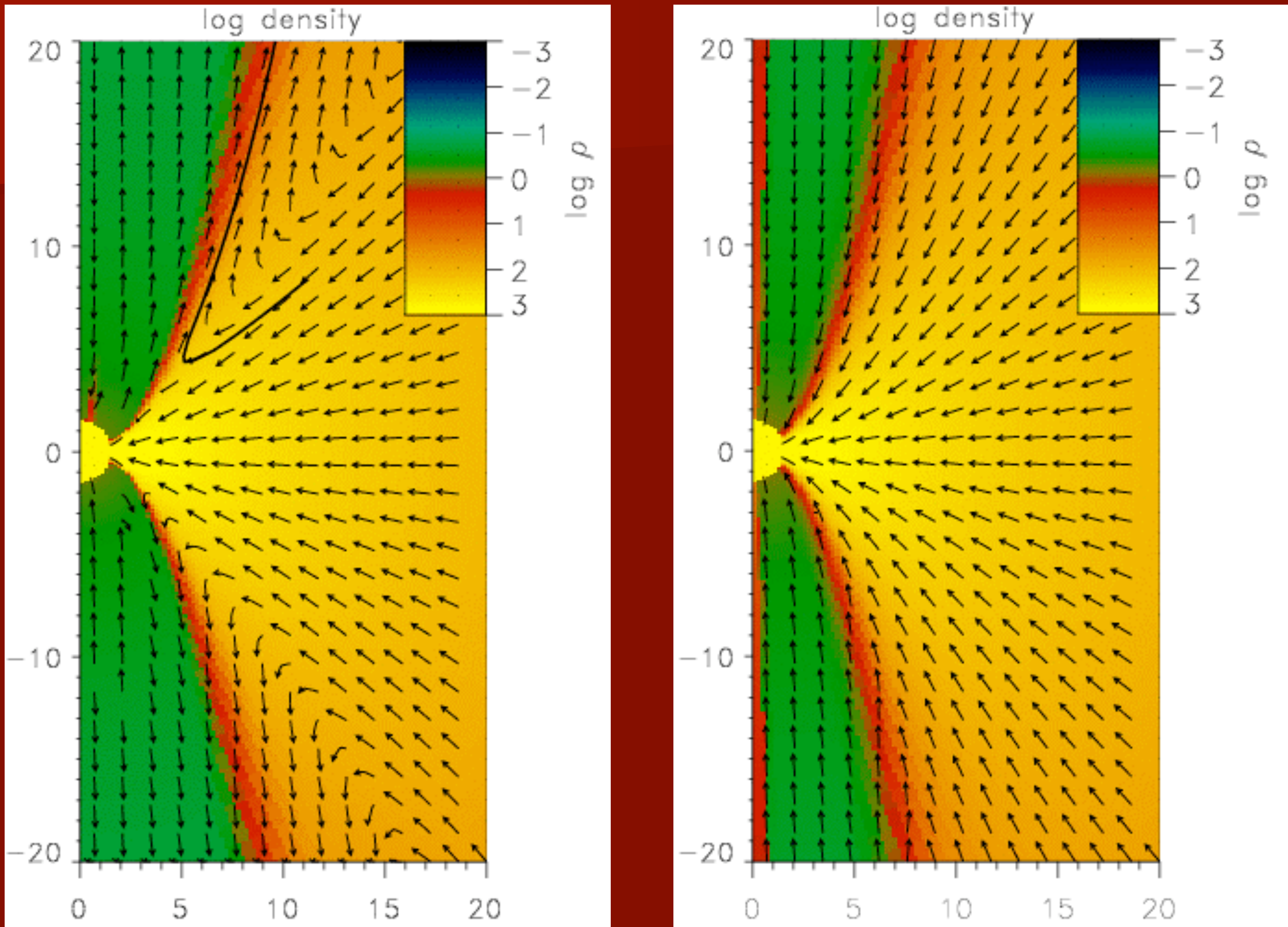
$$\rho \frac{Dv}{Dt} = -\nabla P + \rho \nabla \Phi + \frac{1}{4\pi} (\nabla \times B) \times B$$

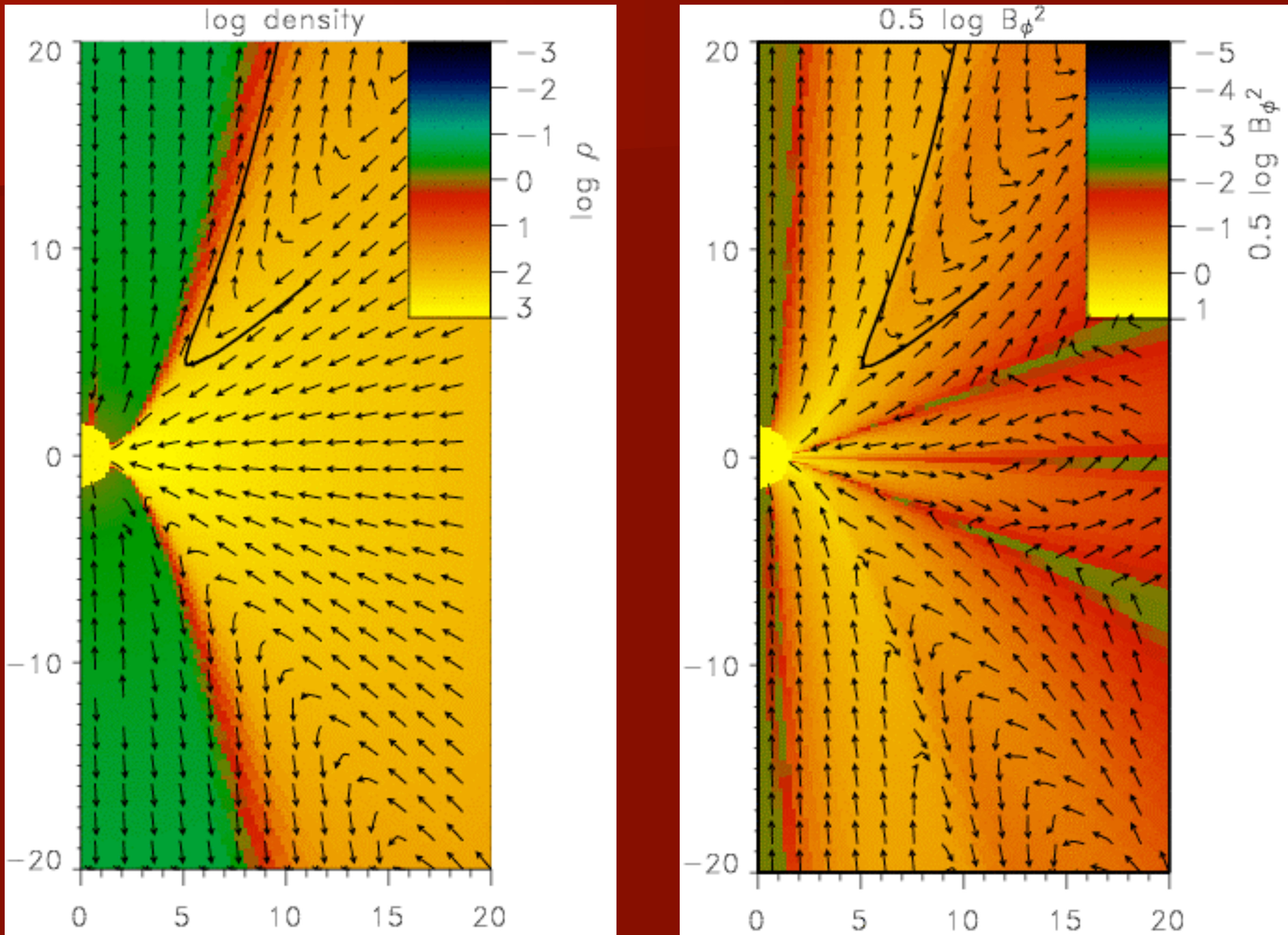
$$\rho \frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P \nabla \cdot v + \eta_r J^2 - L$$

$$\frac{\partial B}{\partial t} = \nabla \times \left(v \times B - \eta_r J \right)$$

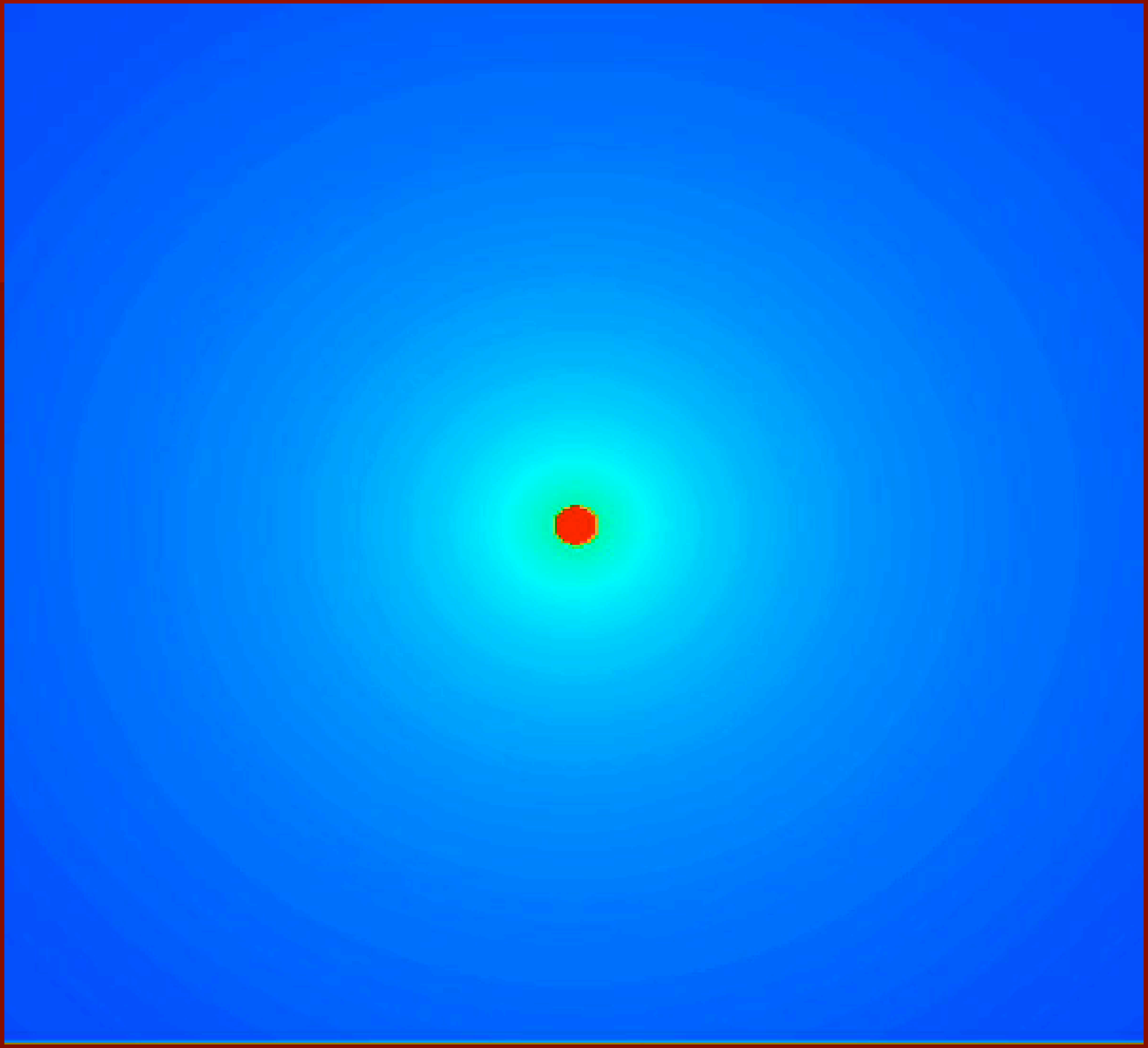
The equations are solved using the ZEUS-2D code (Stone & Norman 1992)

Effects of rotation and magetic fields



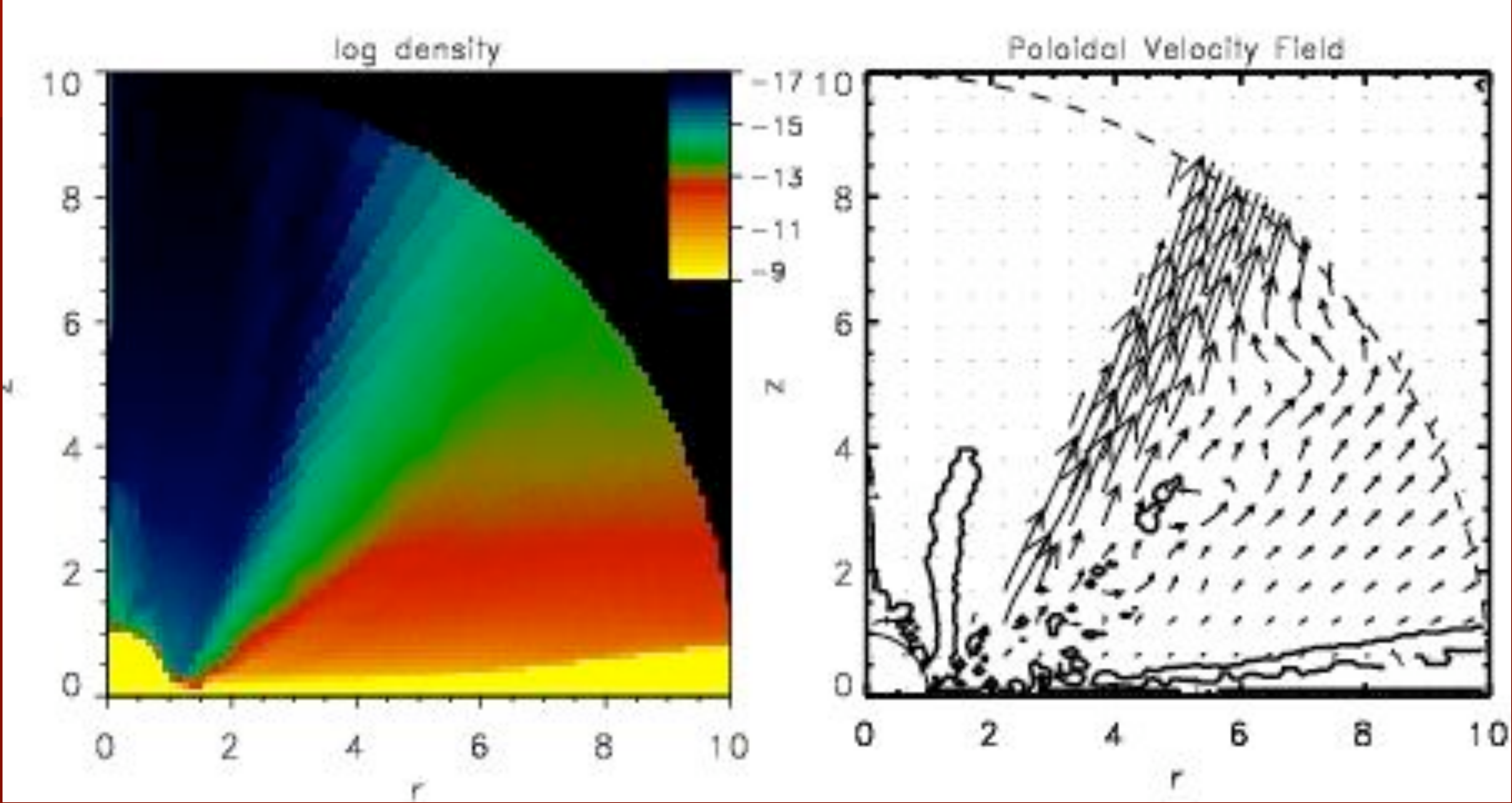


Proga (2005)



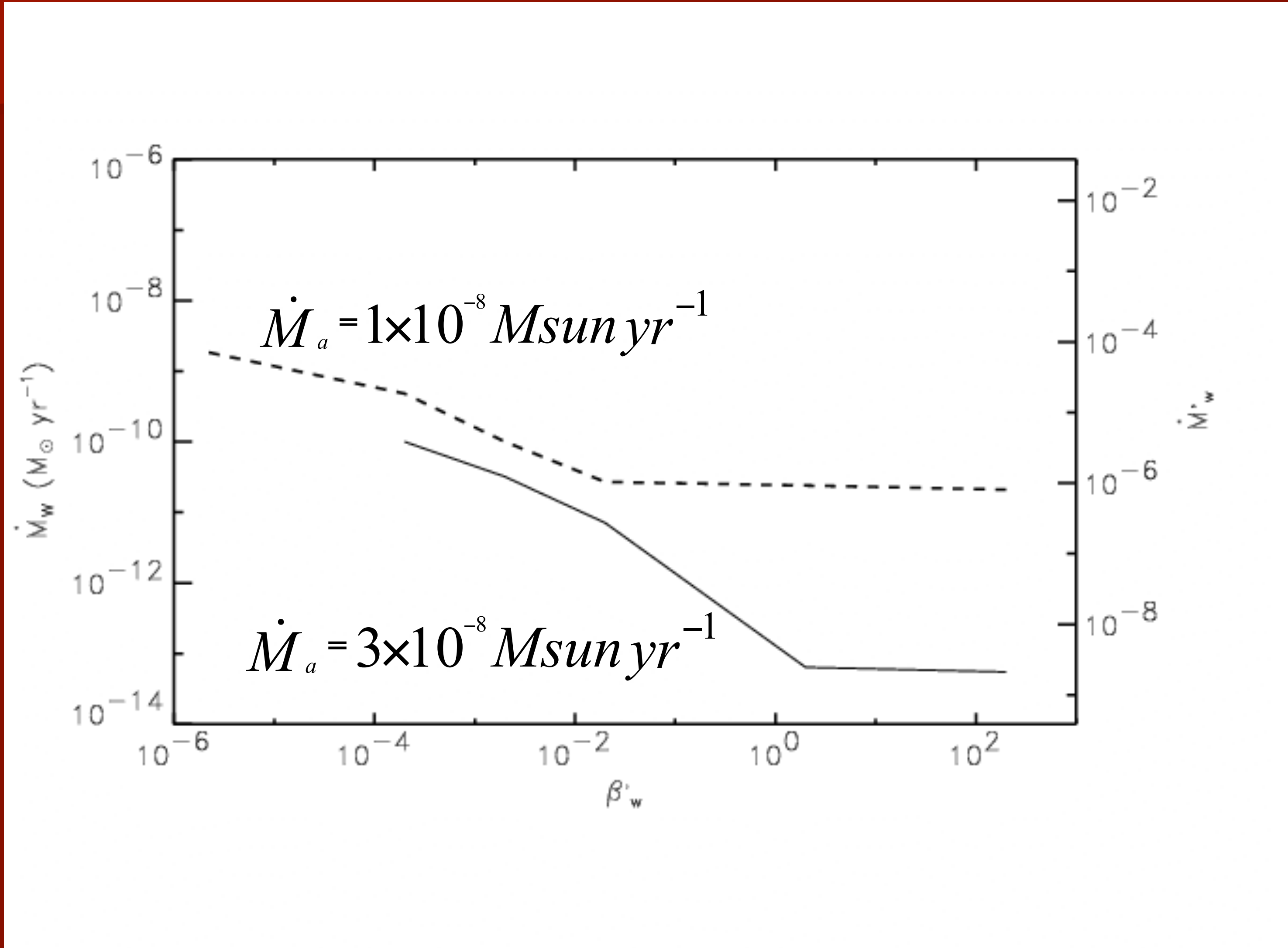
PB’03 and PMAB’03

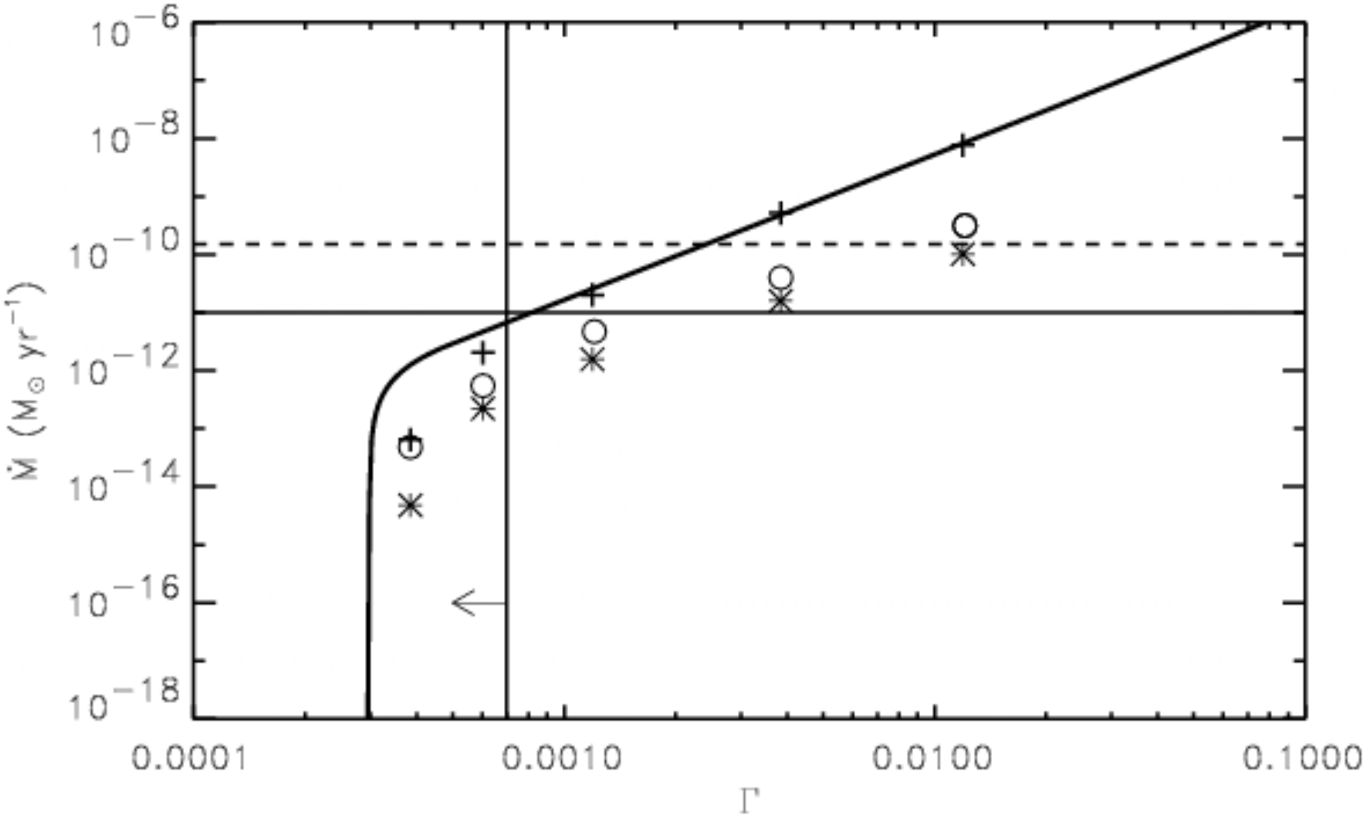
MHD-LD Disk Winds



Proga (2003a)

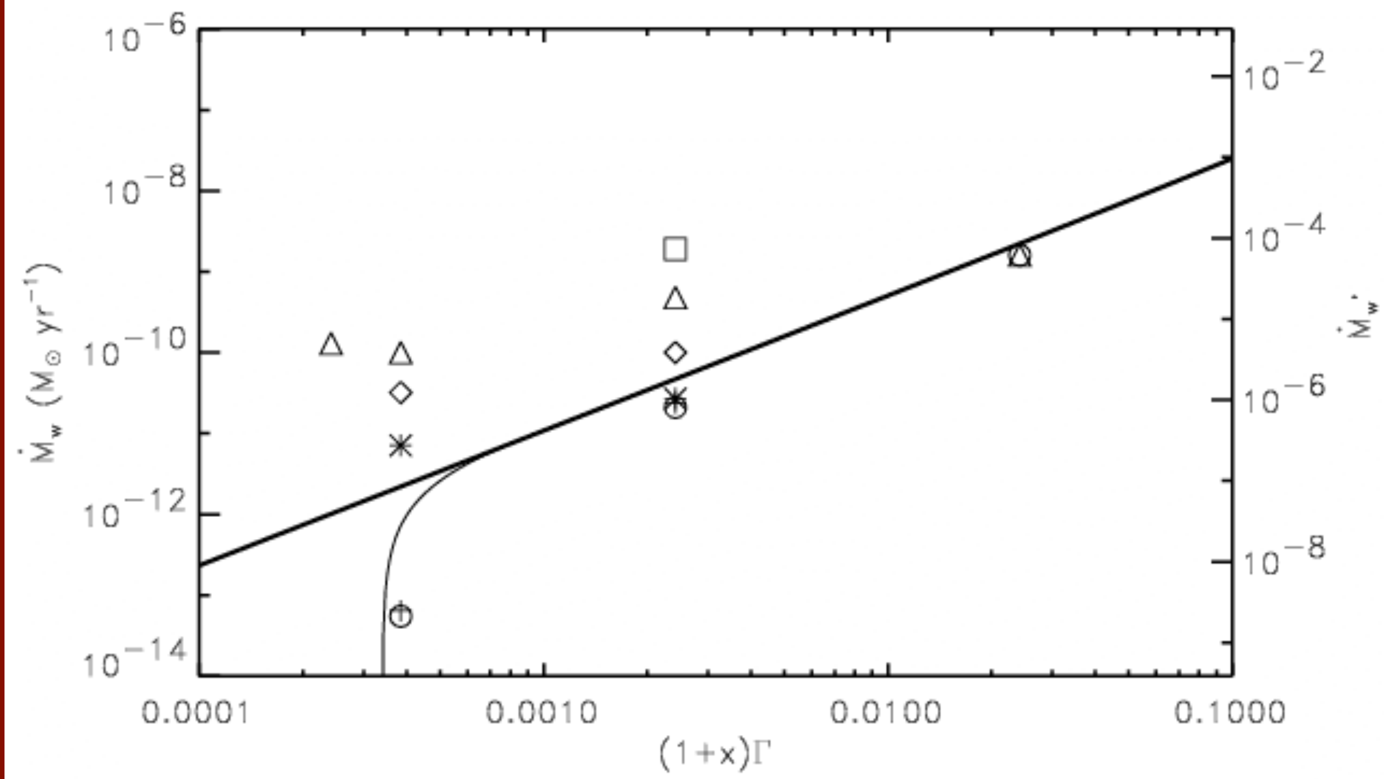
The mass loss rate in MHD-LD winds.





Drew & Proga (1999)

The mass loss rate in MHD-LD winds.



Conclusions from Part III (MHD-LD simulations)

- LD and MHD driving launch different outflows, i.e., MHD winds are denser and slower than LD winds (but both preserve the specific angular momentum)
- MHD driving dominates launching at large radii whereas LD dominates at small radii (MHD driving may also dominate at very small radii).
- The mass loss rate of a hybrid wind can be higher that of a pure LD wind.