Black hole accretion with low angular momentum

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Accretion with small angular momentum

The accretion with the rate close to the Bondi rate would lead to a large luminosity:

$$L \sim \eta M_{dot} c^2$$

if η is large (~0.1), unless the mass accretion rate drops well below M_{dot}^{Bondi}

The lower accretion rate is possible e.g. if there is a feedback between the matter supply and X-ray heating or mass outflow from the central region (*Ostriker 1976; Di Matteo 2002*).

Also, the low angular momentum instead of pure spherical accretion may be reducing the mass accretion rate (*Proga & Begelman 2003*).

Low luminosity state in AGN or other accreting compact objects is also possible if the flow is radiatively inefficient (Narayan & Yi 1994).

Hydrodynamical simulations of accretion flows

We are modeling the low angular momentum accertion

in 3D

The rotating gas at “infinity” may be distributed uniformly (axisymmetric case), or more likely have a non-uniform distribution.

Non-axisymmetric effects are important

Initial conditions: spherical accretion

Spherical accretion solution: Bondi 1952

- Non-rotating gas
- polytropic EOS, gamma=5/3
- central gravitational potential
- parameterized by the density and sound speed at infinity

$$M_{dot}^{Bondi} = 4 \pi R_B^2 \rho_\infty c_\infty$$

$$R_B = GM/c^2_\infty$$

Modification of the Bondi problem: the small angular momentum is present at "infinity", and depends on the polar angle as

$$f(\theta) = 1-\cos(\theta)$$

Equations of hydrodynamics

Radiation Force

Continuity equation

$$\frac{d\rho}{dt} + \rho \nabla \vec{v} = 0 \qquad (1)$$

Viscosity

Equation of motion

$$\rho \frac{d\vec{v}}{dt} = -\nabla P + \rho \nabla \Phi + \frac{\kappa + \sigma}{c} \vec{F}_0 + \vec{q_{vis}} \qquad (2)$$

Equation of energy

$$\frac{\partial e}{\partial t} + \nabla (e\vec{v}) = -P \nabla \vec{v} - 4\pi \kappa B + c\kappa E_0 + F_{vis} \qquad (3)$$

$$\frac{\partial E_0}{\partial t} + \nabla (E_0 \vec{v}) = -\nabla \vec{F}_0 + 4\pi \kappa B - c\kappa E_0 - \nabla \vec{v} : \mathrm{P}_0 \qquad (4)$$

Radiative Flux

Absorption/Emission

Radiation pressure tensor

Hydrodynamical simulations using ZEUS-MP code

We solve the hydrodynamics of the flow in the inviscid case. We neglect:

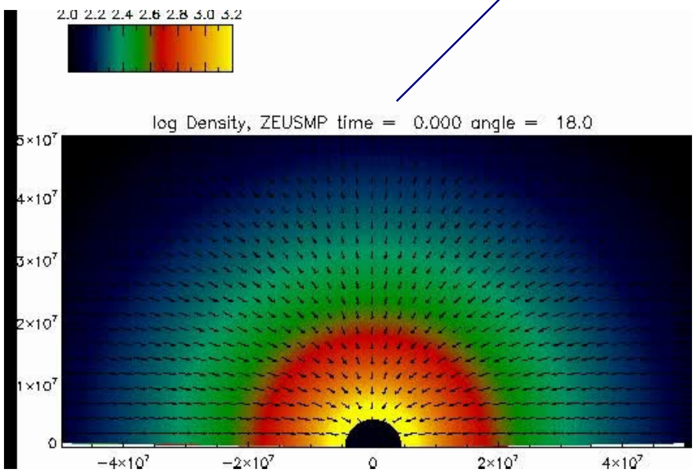
- viscosity
- radiation force
- radiation pressure tensor
- absorption/emission
- ...and magnetic fields

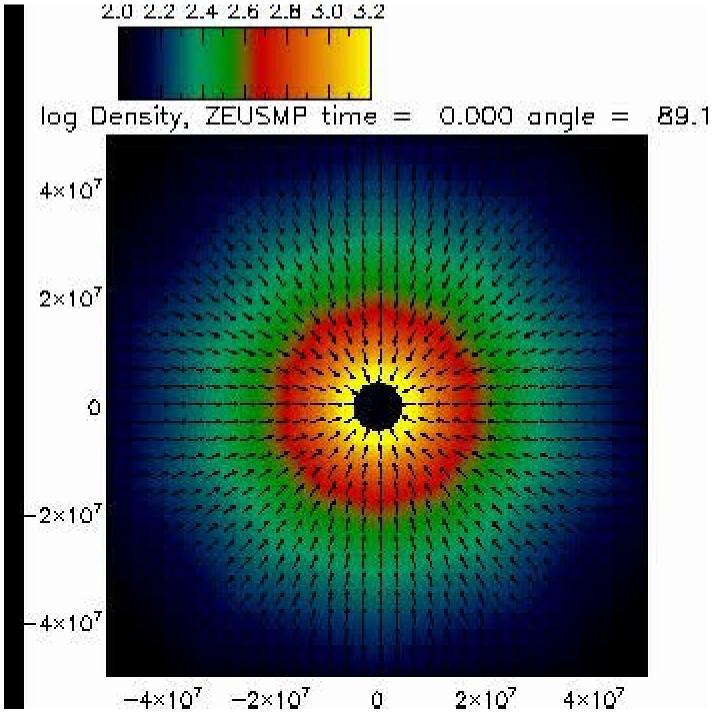
But the flow structure is solved in 3D.

✓ Zeus-MP runs currently on 8 processor computer cluster, with resolution 140x100x60. Larger resolution runs planned on supercomputers (TeraGrid at NCSA)

Formation of the torus in the axisymetric case: 2D and 3D

Density and velocity fields as seen edge-on



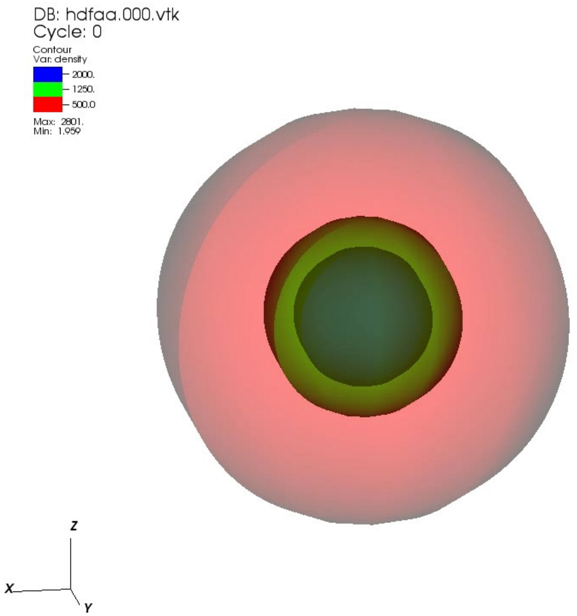


The torus forms after a transient phase of radial infall, when the rotating material reaches the center. The gas is captured by the centrifugal force. An outflow of gas occurs from the equatorial region.

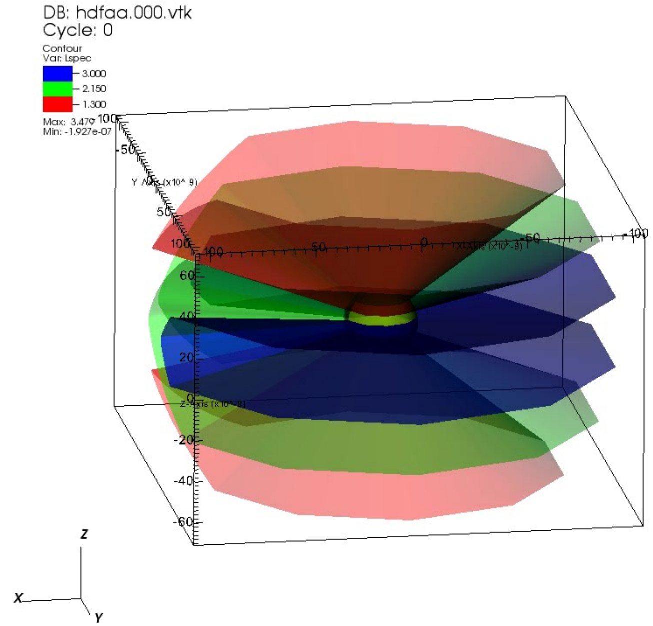
Density and velocity fields at the equatorial plane

Axisymmetric torus

The surfaces of the constant specific angular momentum coincide with the constant entropy surfaces. The surfaces of a constant density are ellipsoids, with the eccentricity $e=[2(2-q)]^{0.5}$ where q is an Omega(r) index.

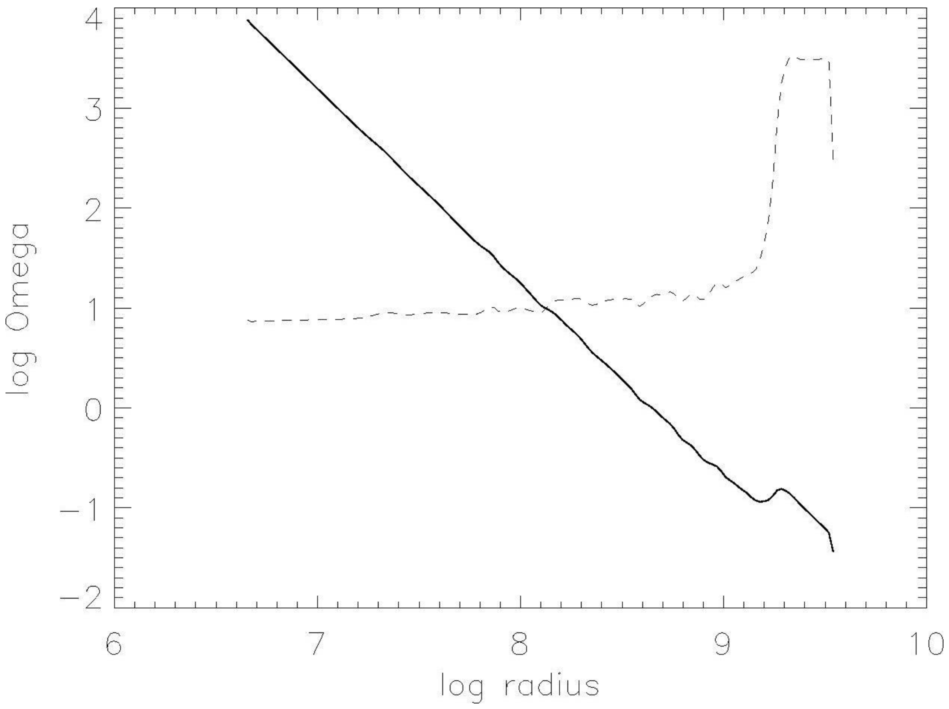


Isodensity contours

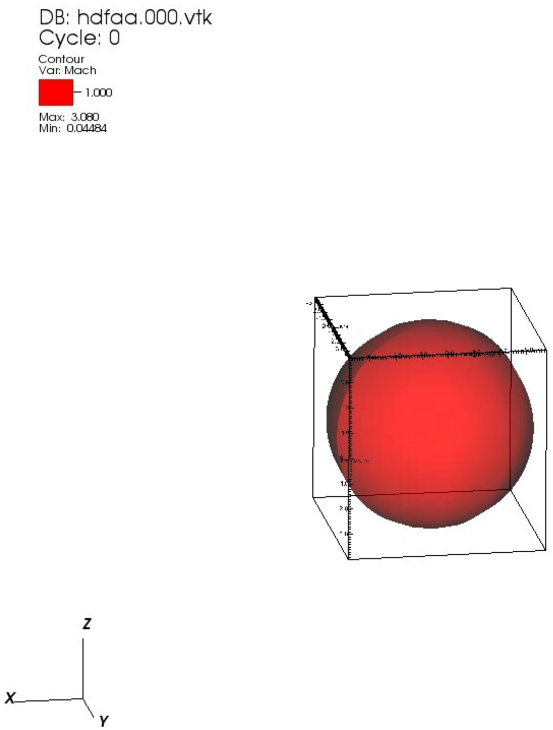


Isocontours of l_{spec}

Omega and sonic surface



Sonic surface is a generalization of the sonic point in 1-d. In case of the zero-vorticity flow the surface shape can be derived analytically: it passes orthogonally through the velocity equipotential surfaces (*Papaloizou & Szuszkiewicz 1994*)

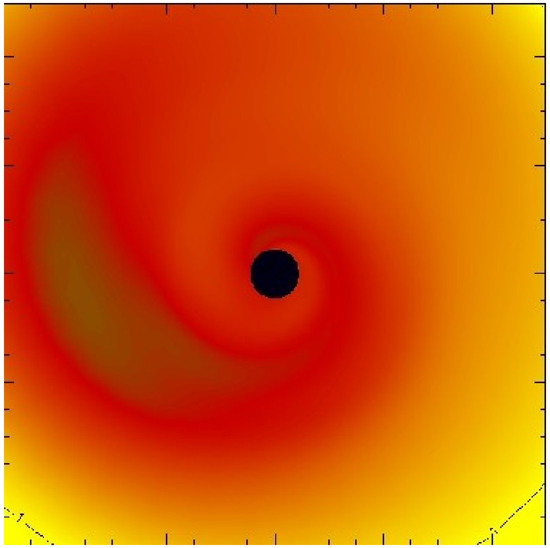


In the equatorial plane the angular velocity drops with radius as Ω~r-1.8 .

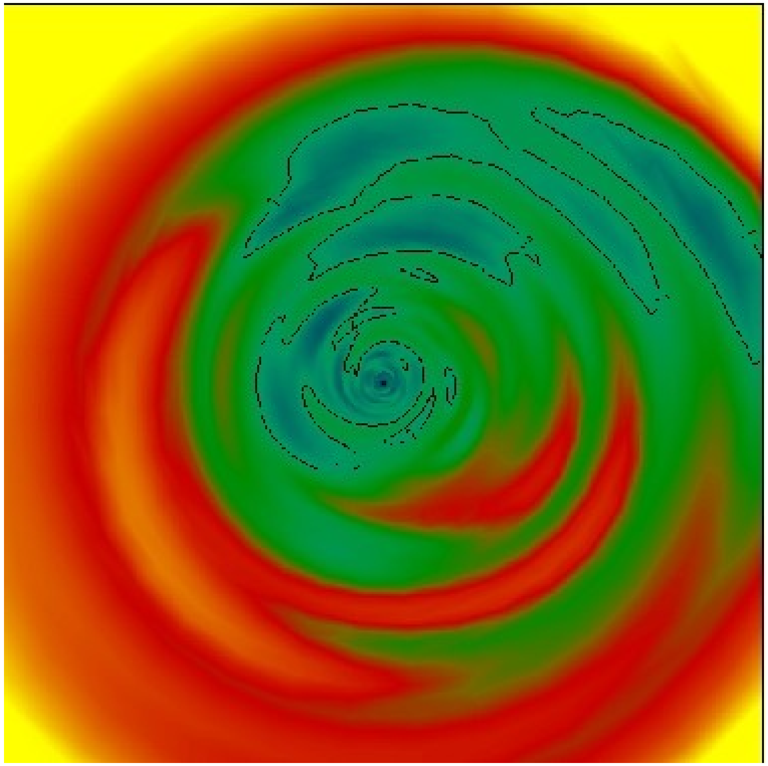
The angular momentum increases outwards and according to the Raileigh's criterion the flow is stable.

Asymmetric initial conditions

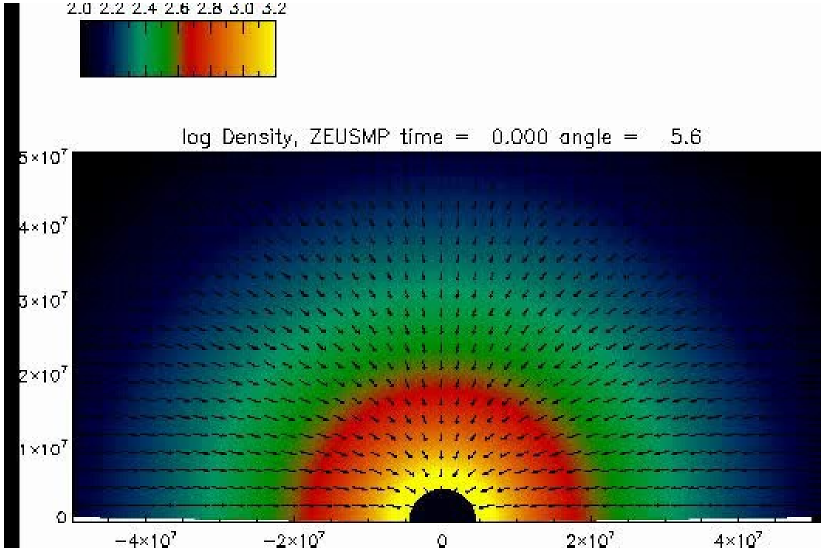
- We could expect that the gas with zero angular momentum would be quickly swallowed by the black hole. After that, the rotationally supported torus will form….

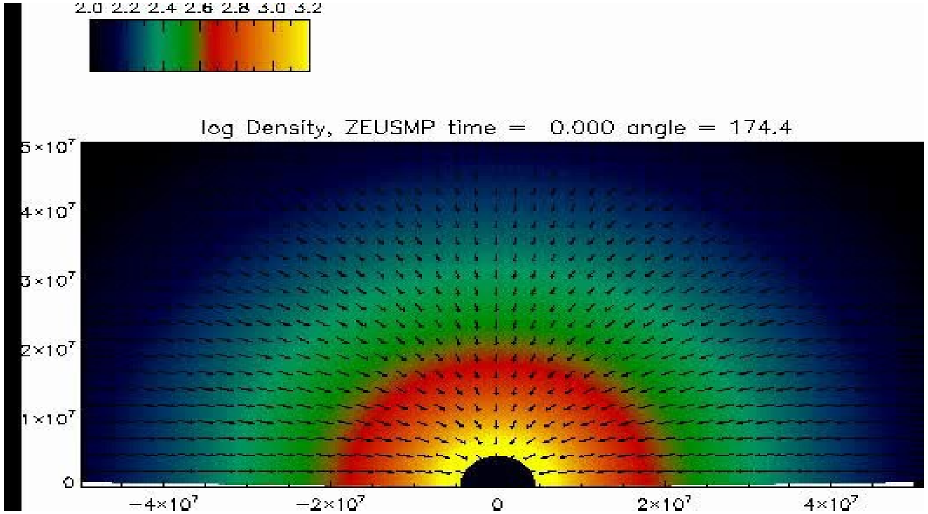


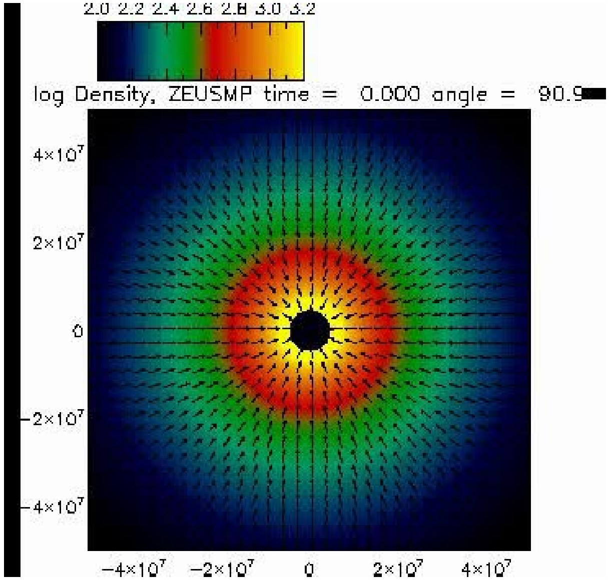
- … but the material with small angular momentum was mixing…



Asymetric model





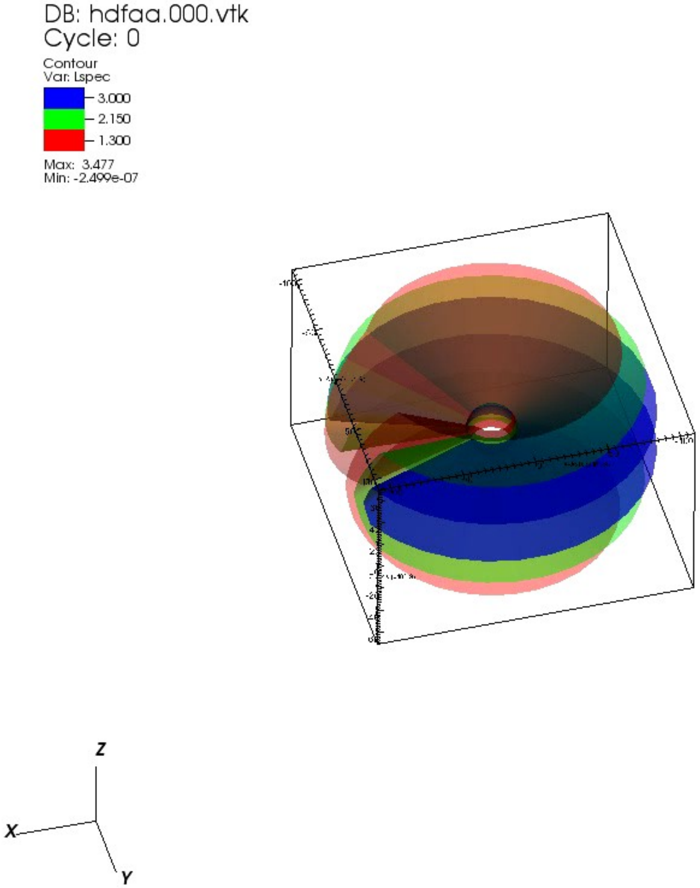


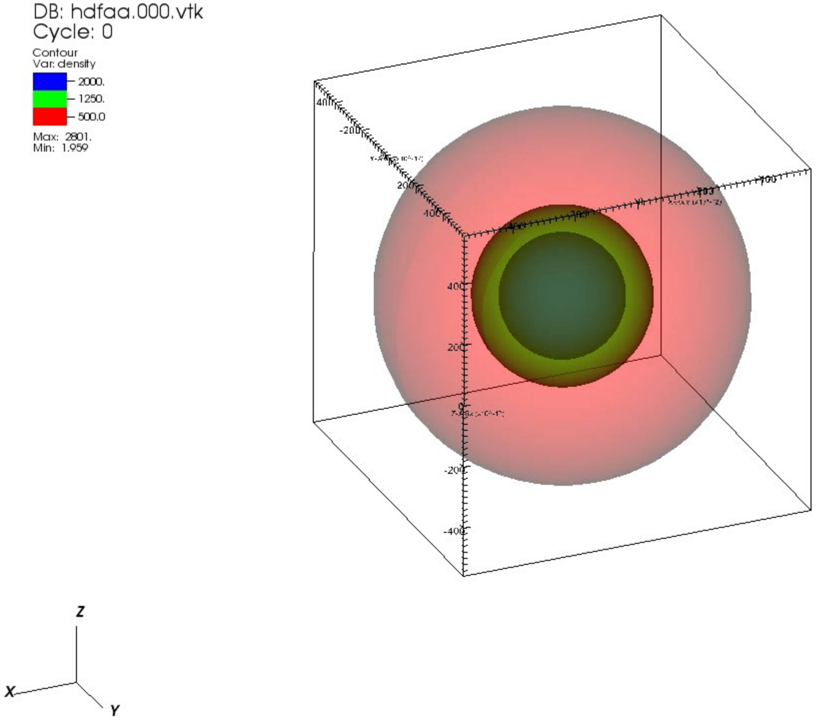
Density and velocity field evolution in the equatorial plane and edge-on views, for small asymetry (the angular momentum was initailly non zero in the range of $\Delta\varphi = 330^\circ$)

Asymmetric torus

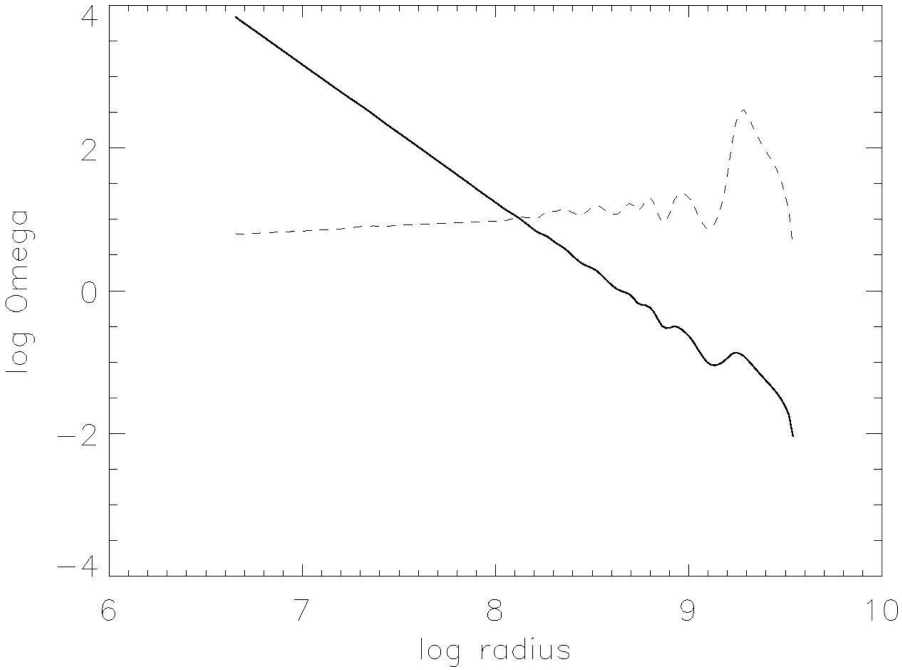
Isontours of lspec

Isodensity contours

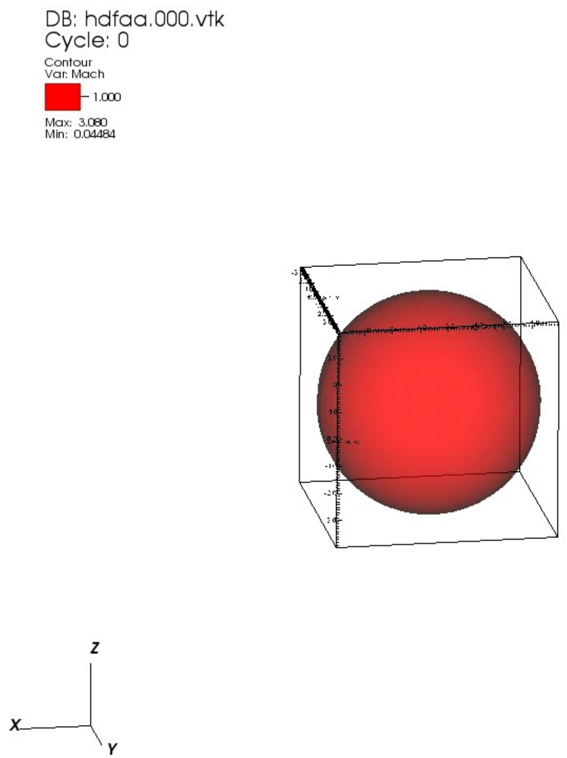




Asymmetric model



Angular velocity and l_{spec}



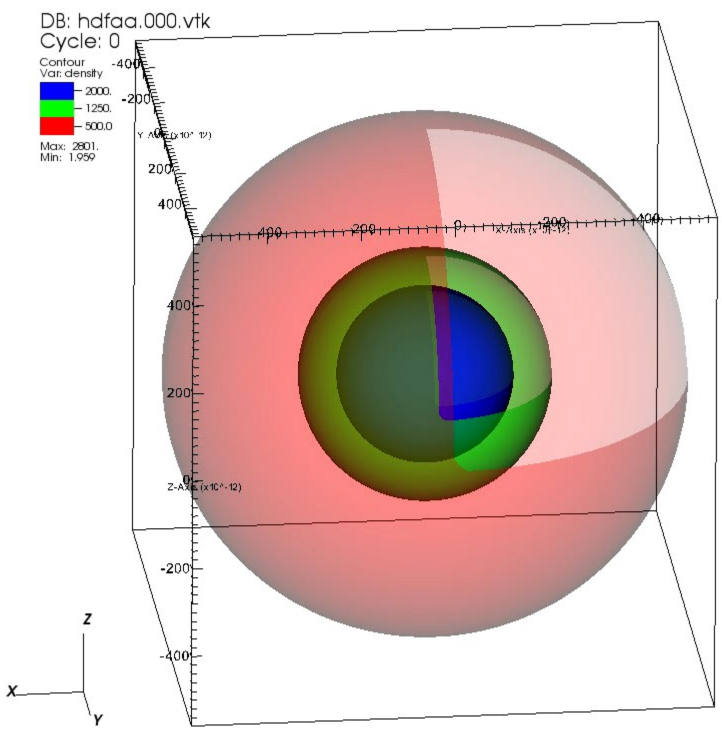
Sonic surface

In our asymmetric disk, the flow becomes compressible in the equatorial plane (velocity divergence is non-zero). This may add a further mode of instability to the classical one.

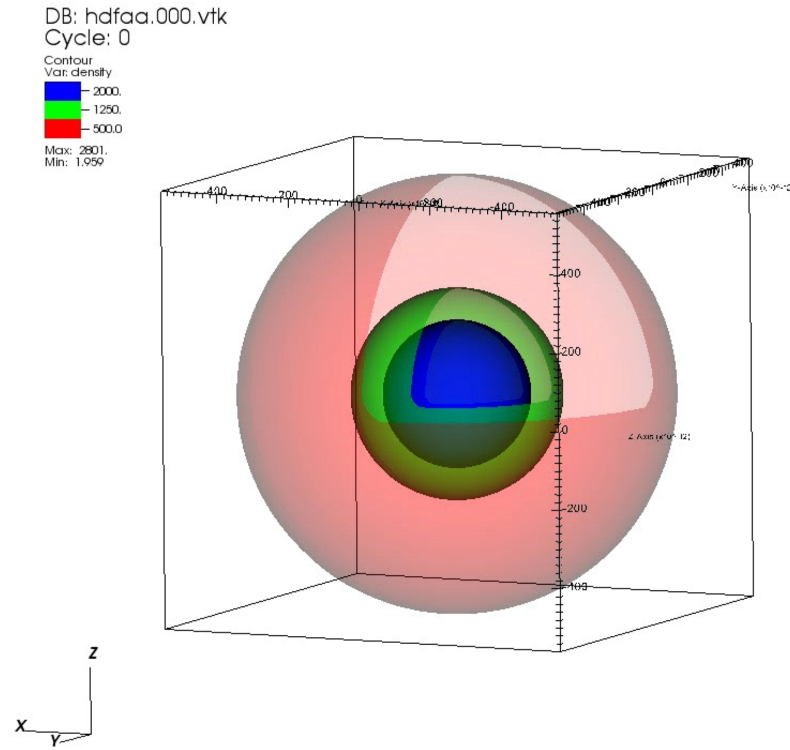
Kelvin-Helmholtz instability (Chandrasekhar 1961) occurs when two superimposed layers of fluid are in a relative motion. When the velocity shear exceeds a critical value, the resulting pressure gradient (from Bernoulli's law) between the peaks and troughs of an interfacial wave overcomes the surface tension and gravity, and the mode grows exponentially.

Papaloizou and Pringle (1985) studied the dynamical stability of the tori with non-constant angular momentum. They found that for low azimuthal number *m* the instability is driven by a Kelvin-Helmholtz mechanism, and modes are stable in disks with $\Omega \sim r^{-q}$, if $q>\sqrt{3}$. For high *m*, the modes regain their sonic character, and there exist sonic modes which are driven by both mechanisms. Their analytical treatment is done in the limit of a Keplerian disk ($q=3/2$)

Large asymmetry: torus does not form



Isodensity contours for $\Delta\varphi = 240^{\circ}$



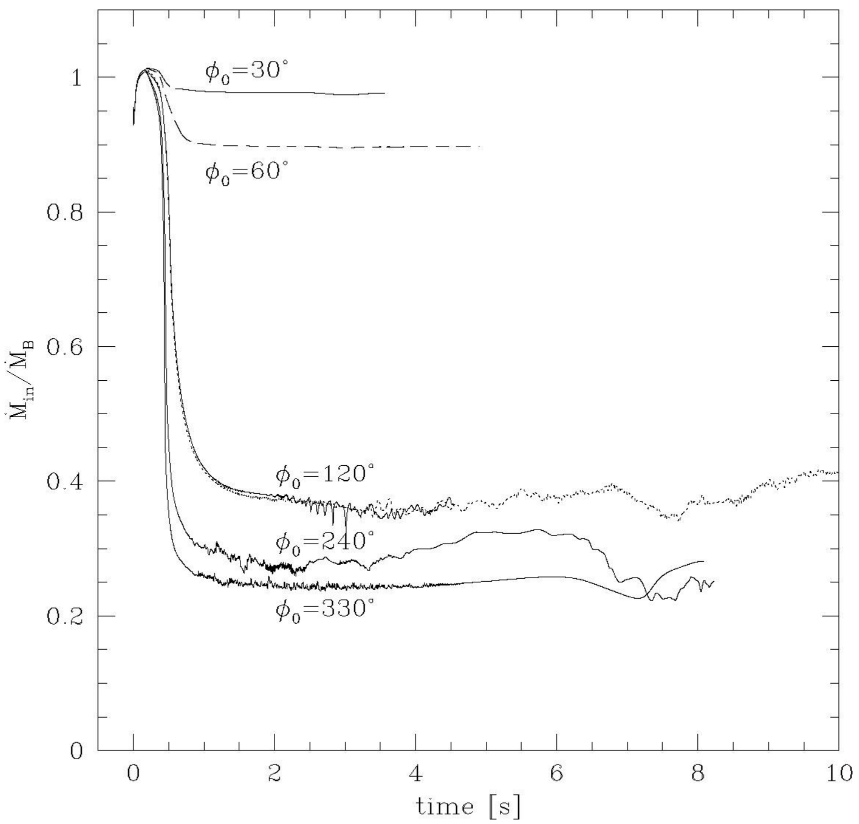
Isodensity contours for $\Delta\varphi = 120^{\circ}$

The rate of mass accretion onto the center

The accretion rate drops to 30-40% of the Bondi rate, *even if the rotationally supported torus does not form*. If only 1/3 of the gas at „infinity" is rotating, it is sufficient for the accretion rate to drop.

Small fluctuations in a dynamical timescale are due to the sound wave instabilities and equatorial outflows.

Longer term variations (about 10^3 t_{dyn}) are due to the non-axisymmetric perturbation



Evolution of the collapsing star: how long is a gamma ray burst?

The thick torus may form during the collapse of a massive, rotating star. This torus is likely to be connected with a jet production and gamma ray burst event.

However, the torus may form, if the rotation will prevent the envelope material from the radial infall onto the newly born black hole. That is, if the specific angular momentum is larger than the critical value:

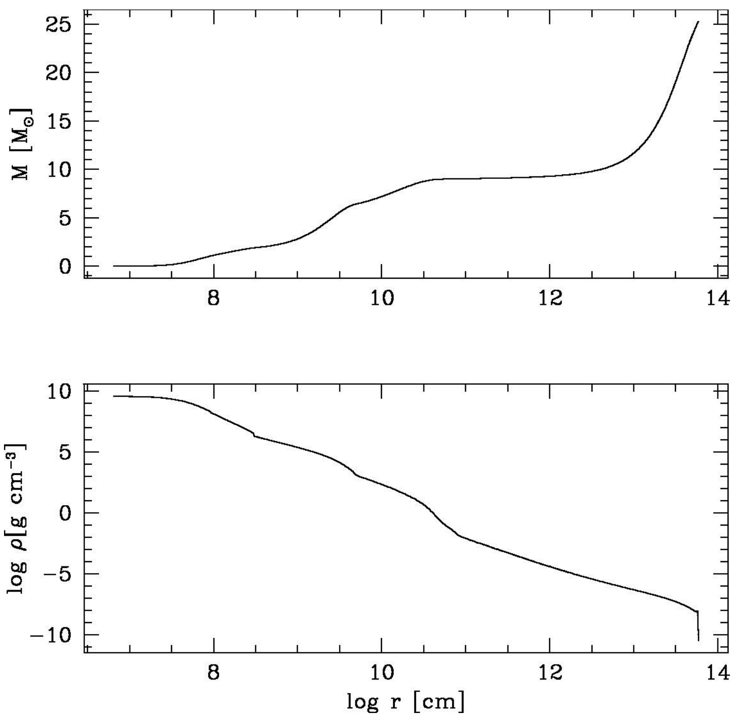
$$l_{crit} = 2 R_S c$$

where R_S is the Schwarzschild radius and depends on the BH mass.

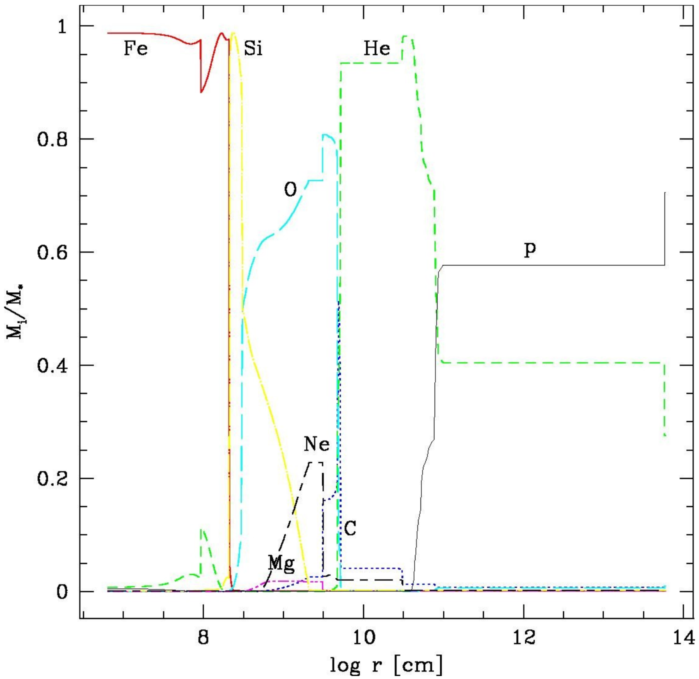
In the collapsar, the BH is growing fast (accretion rate of 0.01-1 Msun/s), so the condition for $l>l_{crit}$ may not be satisfied when BH mass is too large.

How long can be a GRB?

Pre-SN model: iron core + envelope



Density and mass distribution in the pre-supernova star



Chemical composition
(data from Woosley & Weaver 1995)

How the pre-collapse star rotates?

We assume that the distribution of specific angular momentum in the pre-SN star depends on:

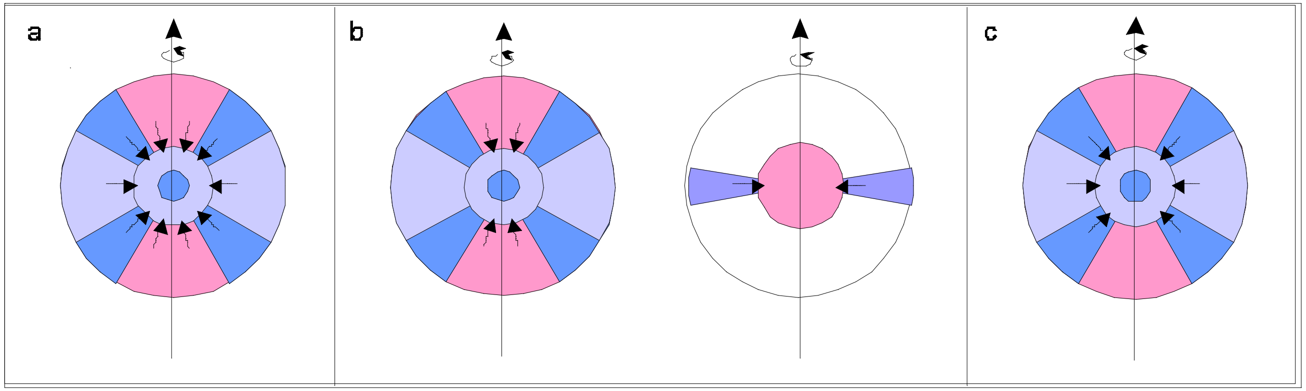
- Polar angle (differential rotation)
- Polar angle and radius

In the latter we take into account the rigid rotation

(with a possible cut-off on l_{spec}) or a constant ratio of centrifugal to gravitational forces

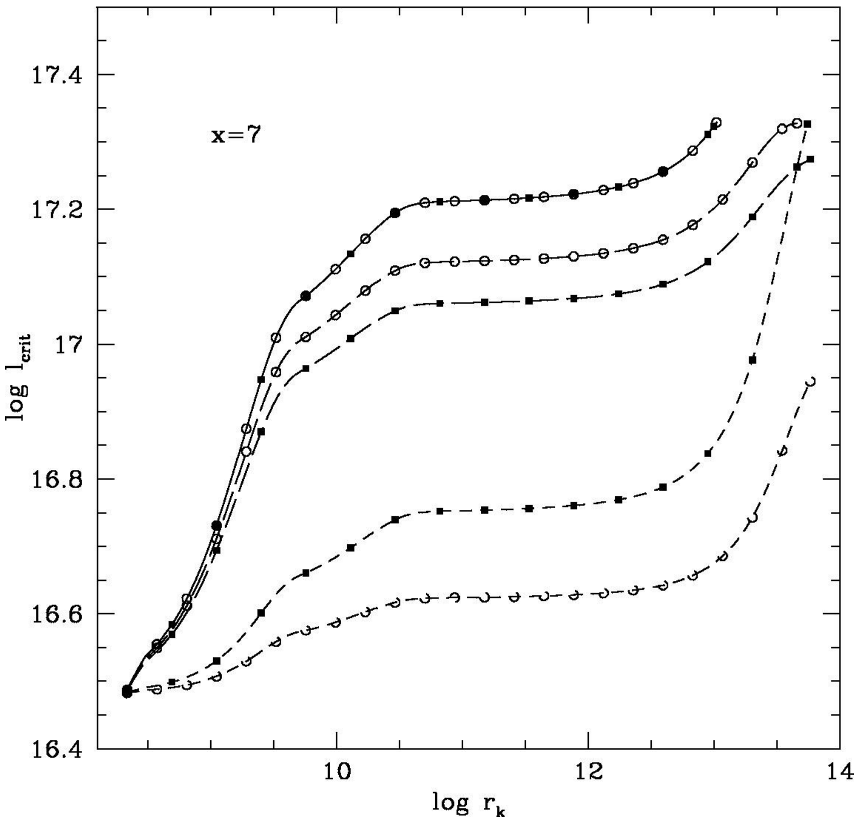
How the black hole grows during the stellar collapse?

We calculate the evolution of the collapsar, starting from the BH mass equal to that of an iron core, and adding the mass to the black hole (non-homologous accretion). How much mass is added, depends on the accretion scenario:



Critical angular momentum increases during the collapse

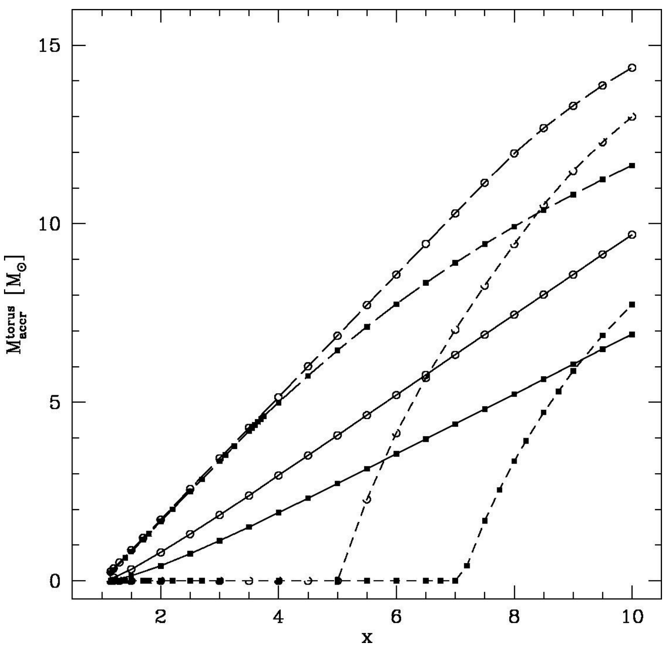
- During the collapse $l_{crit}(M_{BH})$, so the *procedure is iterative*
- The larger l_{crit}, the less material in the envelope is capable of forming the rotationally supported torus
- When there is no torus, the GRB is finished (we assume that the jet is accretion powered)

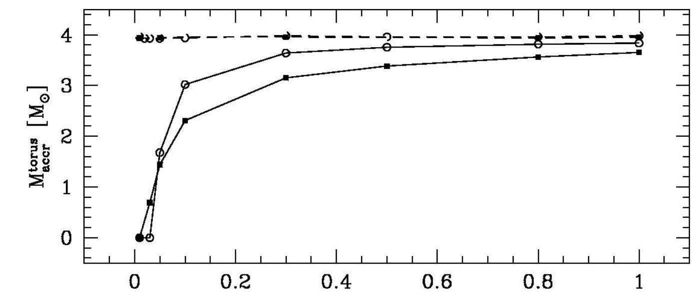


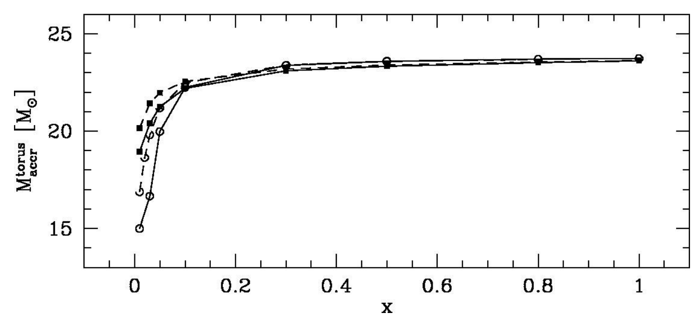
How long is a GRB?

We simplify the problem by assuming *a constant accretion rate*.

The GRB duration is proportional to the mass accreted onto BH through the torus. This is a function of initial normalization of l_{spec} and depends on the model of pre-SN rotation







Rotation depends only on

L_{spec} depends on and radius (with and without cut-off)

Summary

The instabilities found in our 3-D modeling of a rotationally supproted torus around a black hole are likely to be driven by both Kelvin-Helmholtz and sonic mechanisms.

The non-axisymmetric condition for a specific angular momentum distribution results in a torque induced on the torus, its misplacement from the equatorial plane and precession on a period over ~1000 times the dynamical timescale.

The results may fit to the observations of some accreting compact objects, whose jets indicate the signs of precession.

GRB long durations may provide constraints for the rotation law in the pre-SN star.

More realistic rotation laws result in a mass accreted onto the BH through the torus being not more than 4-15 M_{sun}.