Cooling-Induced Structures in Collapsar Accretion Disks

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The collapse of massive rotating stellar cores and the associated accretion is thought to power long GRBs. The physical conditions make neutrino emission the main cooling agent in the flow. We have carried out an initial set of calculations of the collapse of rotating polytropic cores in three dimensions, making use of a pseudo-relativistic potential and a simplified cooling prescription. We focus on the effects of self gravity and cooling on the overall morphology and evolution of the flow for a given rotation rate in the context of the collapsar model. For the typical cooling times expected in such a scenario we observe the appearance of strong instabilities on a time scale t_{cool} following disk formation. Such instabilities and their gravitational interaction with the black hole (BH) produce significant variability in the obtained accretion rates, which would translate into luminosity variations when a more realistic neutrino cooling and luminosity scheme is implemented in future work.

Introduction

To date it is generally accepted that GRBs are the result of cataclysmic events involving NSs or BHs. More over, long GRBs are generally associated with actively star forming galaxies and sometimes with a SN (type Ib or Ic) taking place at the same time and place. A review by Woosley & Bloom (2006) shows the existing evidence at the time for the link of long GRB at low redshift with type Ic SNe. One of the most accepted candidates for producing such long GRBs is the *collapsar model* (Woosley 1993) to in which the formation of a GRB follows from the collapse of a pre-supernova (PreSN) star. In such a scenario, a BH is formed from the star's Fe core while the outer rotating layers collapse and form an accretion disk around the BH. With the high temperatures and densities the material reaches at the disk, neutrino emission becomes the main cooling mechanism. These neutrinos may contribute, along with magnetically powered outflows, to power the GRB. Despite previous works on 2D (Proga et al. 2003), and 3D (Taylor et al. 2011) have been made, we do not yet have a complete understanding of the importance of structure formation in the accretion flow and or heating/cooling mechanisms. Here we focus on the study of the effects of self gravity and cooling on 3D simulations of the collapse of a rotating polytropic envelope onto a BH in the context of the collapsar model.

The Simulation

In the context of the collapsar model, we studied the collapse and accretion of $2.5M_\odot$ rotating polytropic envelopes ($\gamma = 5/3$) onto a $2M_\odot$ BH fixed at the center of the distribution. All numerical simulations were made using a modified version of GADGET-2 (Springel 2005).

Envelope & BH Properties

The $2.5M_\odot$ spherical polytropic envelope properties are shown on Table 1. Such a polytropic envelope was given a solid body rotation below breakup, which also guaranteed a circularization radius $r_c = 7.49\ r_{acc}$, close to the accretion radius r_{acc} (shown on Table 1). We will consider a Paczynski-Wiita (PW) pseudo-potential (Paczynski & Wiita 1980) to account for the most important general relativistic effects determining the motion of matter near a non-rotating BH, and our accretion radius will be given by the innermost stable circular orbit ($r_{isco} = 3r_g = 6GM_{BH}/c^2$) of a Schwarzchild BH.

Property	M_{tot}	M_{env}	R_s	r_{int}	$t_{dyn} = \sqrt{\frac{R^3}{GM_{tot}}}$	$r_{acc} = 3r_g$	$r_c = 7.49\ r_{acc}$
	$4.5\ M_\odot$	$2.5\ M_\odot$	1715.7 km	844.69 km	0.0919 s	17.729 km	132.79 km

Table 1 Total & envelope masses M_{tot} and M_{env}, outer & inner radii R_s and r_{int}, dynamical time scale t_{dyn}, and accretion & circularization radii r_{acc} and r_c.

Neutrino Cooling Estimation

A neutrino cooling time scale $t_\nu = u/q_\nu$ for the densities and temperatures expected near the BH can be obtained by considering:

- Approximated EOS $u(T, \rho)$ (relativistic non-degenerate e^-, e^+ pairs, radiation and ionized H).
- Neutrino cooling $q_\nu(T, \rho)$ (pair annihilation and e^-, e^+ capture) (Narayan et al. 2001).

$$u = \frac{3}{2}\frac{kT\rho}{\mu m_p} + \frac{11}{4}aT^4, \qquad q_\nu \simeq 5 \times 10^{33} T_{11}^9 + 9.0 \times 10^{23} \rho T_{11}^6 \text{ erg cm}^{-3}\text{ s}^{-1} \tag{1}$$

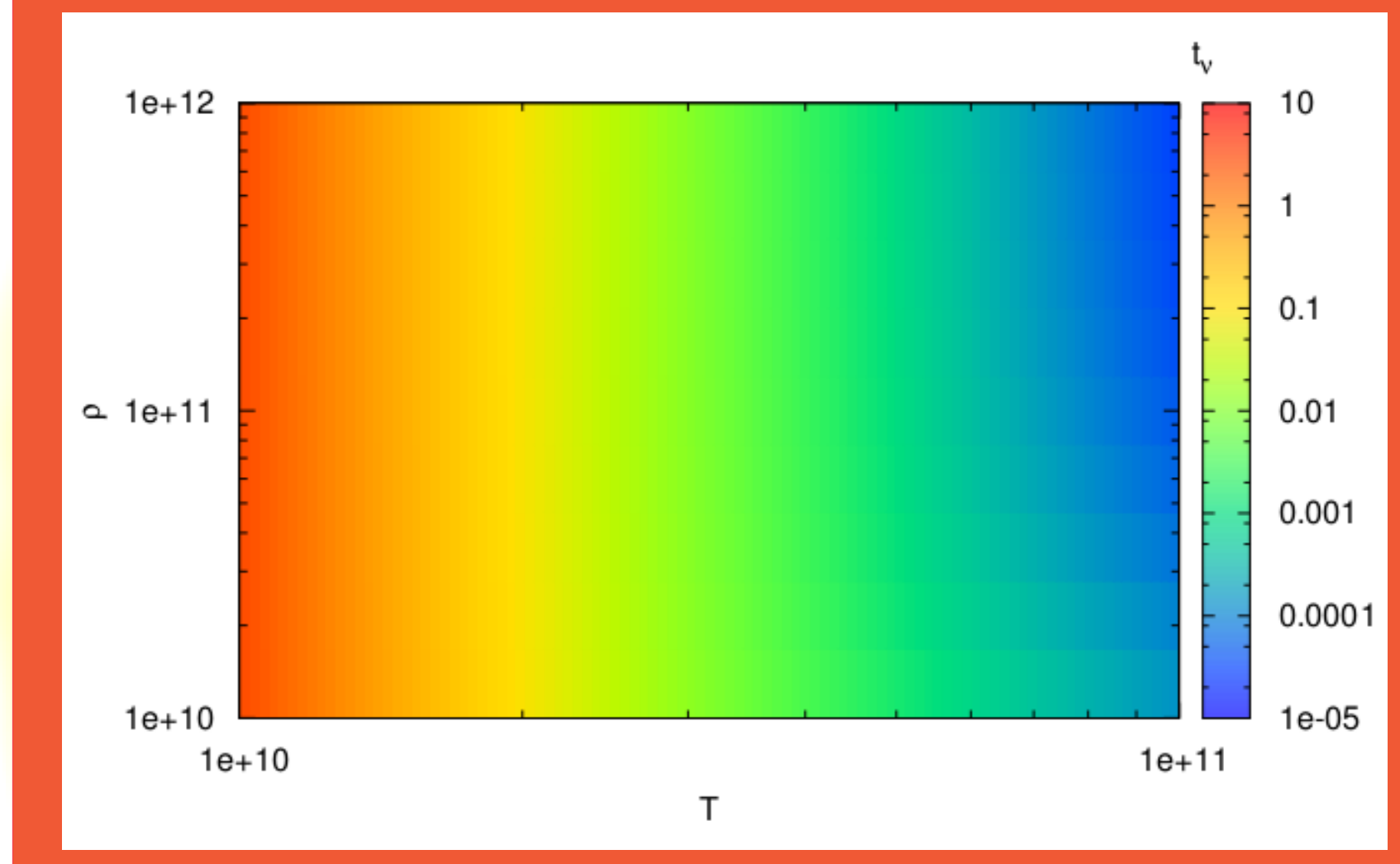


Figure 1 Neutrino cooling time scale t_ν estimated for an ideal gas ($\mu = 1/2$) with a non-degenerated relativistic electron-positron pairs and radiation pressure contribution, for densities 10^{10} g cm$^{-3} \lesssim \rho \lesssim 10^{12}$ g cm^{-3} and temperatures 10^{10} K $\lesssim T \lesssim 10^{11}$ K.

Cooling Prescription

We adopted a simplified cooling prescription based on a fixed cooling time t_{cool} dependent on the dynamical time scale of the accretion disk $t_{disk} \sim 0.1$ s formed around the BH. The efficiency parameter β determines how many times the gas orbits the BH before it gets significantly cooled.

$$t_{cool} = \beta t_{disk}\ , \qquad \frac{du}{dt} = -u/t_{cool}. \tag{2}$$

- Explore dependence of accretion flux & structure formation on cooling efficiency.
- Using $t_{cool} = t_\nu$ for neutrino cooling time scales showed on Figure 1.
- Envelope properties and cooling efficiencies explored on tables 1 & 2 respectively.

Model	Cooling efficiency β	t_{cool}
$\beta 2.6$	2.6487	0.24639 s
$\beta 1.3$	1.3243	0.12319 s
$\beta 0.67$	0.66215	0.061595 s
$\beta 0.13$	0.13243	0.012319 s

Table 2 Cooling times t_{cool} and efficiency parameters β used on our simulations. All times range on the neutrino cooling time t_ν previously estimated.

Structure Formation Events

We analized the evolution of two parameters that would give us quantitative information on the structures formed at the accretion disk:

- Non-axisymmetric instabilities at the disk ⇒ Fourier transform of the azimuthal distribution of mass $\Phi_M = \int[\int \rho(\phi, r, z)dz]r\ dr$ (Zurek & Benz 1986) defining the amplitude of the mode m (number of arms) by:

$$C_m = \frac{1}{2\pi}\int_0^{2\pi} e^{im\phi}\Phi_M d\phi. \tag{3}$$

- Unstable regions at the disk ⇒ Toomre parameter maps, determined by the surface density Σ, the local sound speed c_s and the local epicyclic frequency κ.

$$Q_T = \frac{\kappa c_s}{\pi G \Sigma} \tag{4}$$

Model $\beta 1.34$

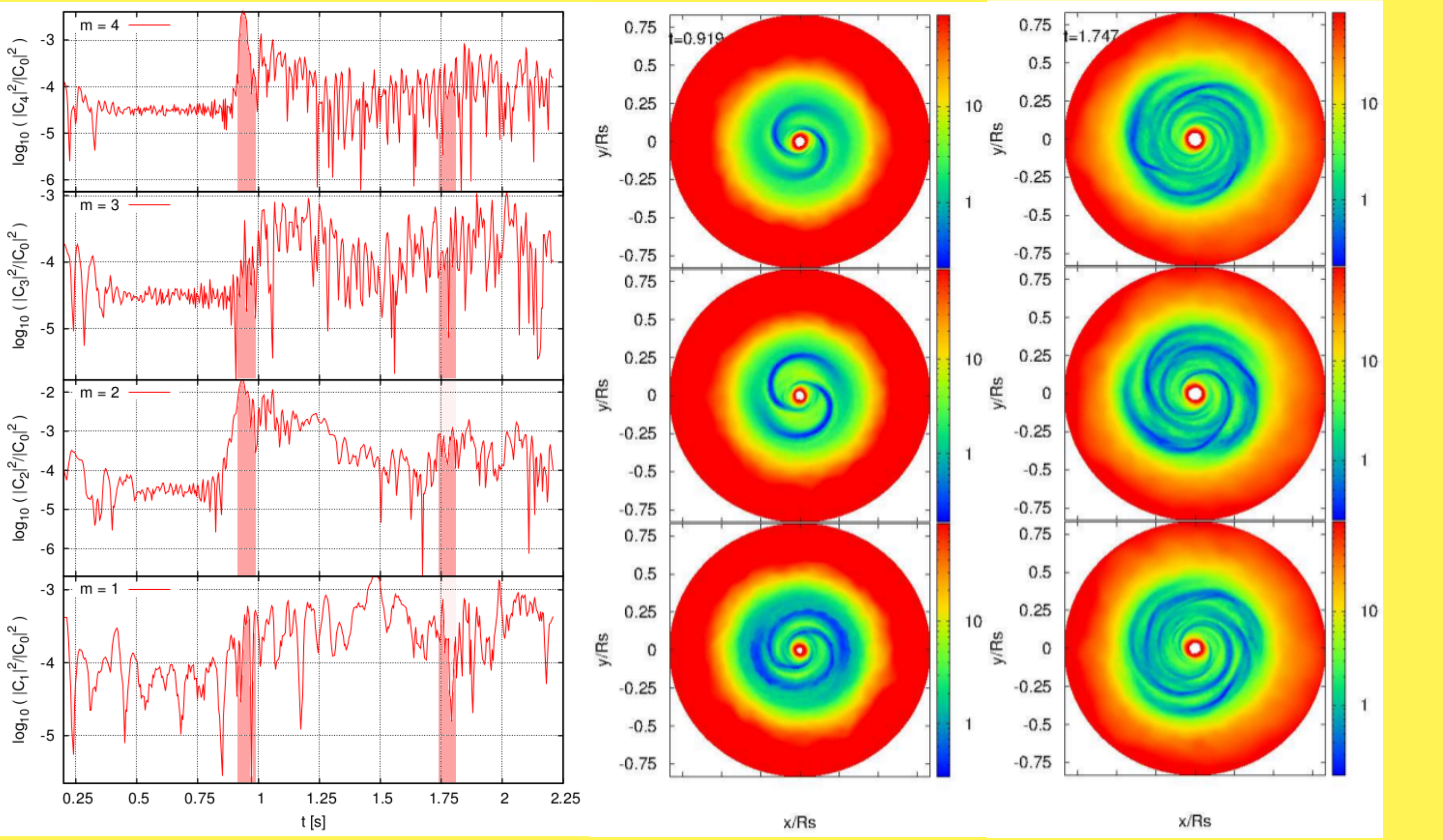


Figure 2 Relative power $|c_m|^2 = |C_m|^2/|C_0|^2$ ($m = 1, 2, 3, 4$) of model $\beta 1.3$ (left panel), and Toomre parameter Q maps for the disk at times $t \simeq 0.91$ s (middle panel) and $t \simeq 1.75$ s (right panel). Red shaded regions on left panel correspond to the Q maps time span.

Model $\beta 0.67$

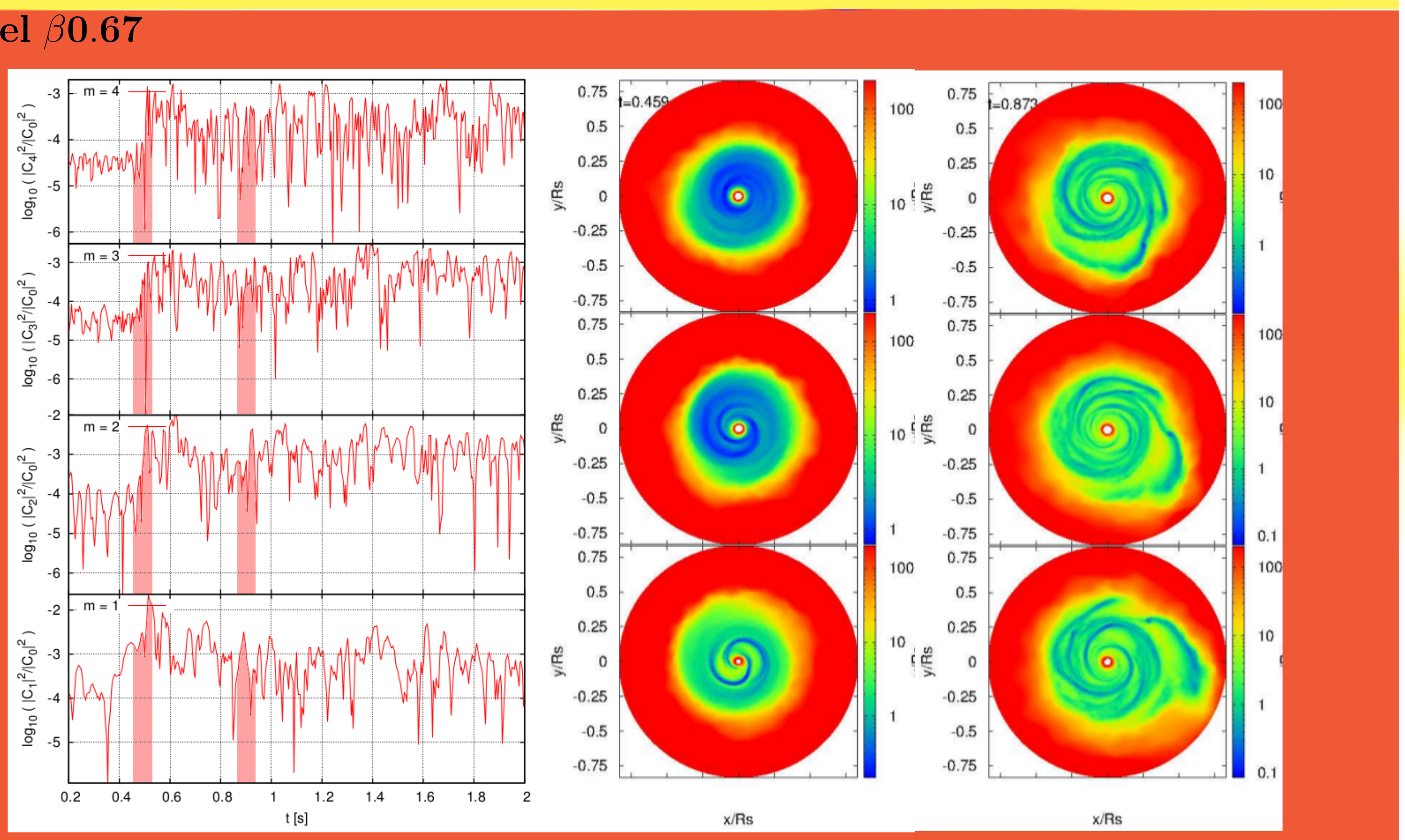
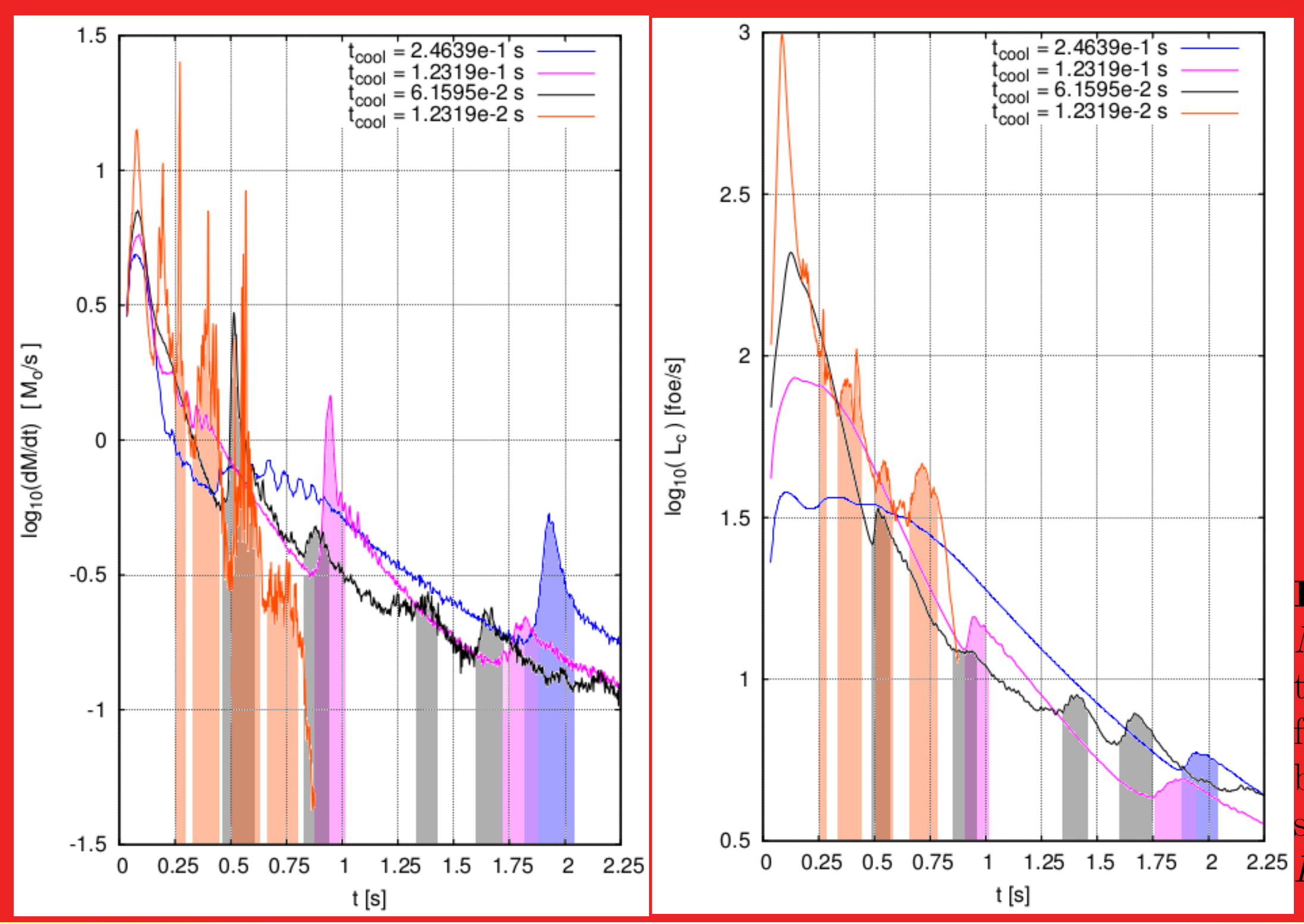


Figure 3 Relative power $|c_m|^2 = |C_m|^2/|C_0|^2$ ($m = 1, 2, 3, 4$) of model $\beta 0.67$ (left panel), and Toomre parameter Q maps for the disk at times $t \simeq 0.45$ s (middle panel) and $t \simeq 0.87$ s (right panel). Red shaded regions on left panel correspond to the Q maps time span.

Variations in $\dot{M}$ and $L_c = du/dt$



- Increasing cooling efficiency increases the number and intensity of variations on both $\dot{M}$ and L_c.
- Intense increases in $\dot{M}$ and L_c appear to coincide in time.
- An increase in L_c implies that the disk's gas is heating (possibly from structure formation).
- The most important variations on $\dot{M}$ (showed also on L_c) can be associated with an important structure formation event.

Figure 4 Logarithm of the BH accretion mass rate $\dot{M}$ in solar masses per second (top) and Logarithm of the energy loss rate L_c in foe/s (10^{51} erg/s) (bottom), for models $\beta 2.6$, $\beta 1.3$, $\beta 0.67$ and $\beta 0.13$ (blue, pink, black and orange lines respectively). Shaded regions show intense increases (or variations) on both $\dot{M}$ and L_c.

Summary

- When an important structure formation event (formation of spiral structures) takes place, an intense variation on both L_c and $\dot{M}$ is induced. This is possibly related to the fact that overdense regions become hotter and thus more intense emitters, and that the spiral structures they are associated with transport angular momentum more efficiently, raising the accretion rate.
- Increasing sufficiently the cooling efficiency induces formation of gas clumps which in case of close encounters with the BH can induce intense and short lasting increases in $\dot{M}$ and L_c.
- We expect that when more realistic initial conditions and more detailed neutrino cooling are implemented on future work, intense and copious structure may form, altering the neutrino emission itself, as well as the assumed BH-disk symmetric gravitational interaction.

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