Numerical GRMHD Simulations of Self-Gravitating Collapsing Stars

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ABSTRACT

- We present, for the first time, **3D GRMHD** simulations of **collapsars**, including both the **black hole gravity** and the **self-gravity of the stellar envelope** in the framework of general relativity.
- Models with self-gravity (**SG**) and without self-gravity (**NSG**) are compared under **identical initial conditions** to assess the effects of self-gravity on the **jet properties** and the **electromagnetic transient**.
- This work is a **continuation** of the two-dimensional study on self-gravity effects in collapsars (Janiuk et al. 2023).

COLLAPSAR MODEL

- The **collapse** of a rapidly **rotating massive** star leads to **long gamma-ray bursts** (Woosley 1993).
- The inner core collapses into a rapidly rotating **Kerr black hole** (in some cases via a proto-neutron star stage).
- The **progenitor** must have **sufficient angular momentum** to form an equatorial **accretion disk**.
- **Relativistic jets** are launched along the **rotation axis** of the black hole.

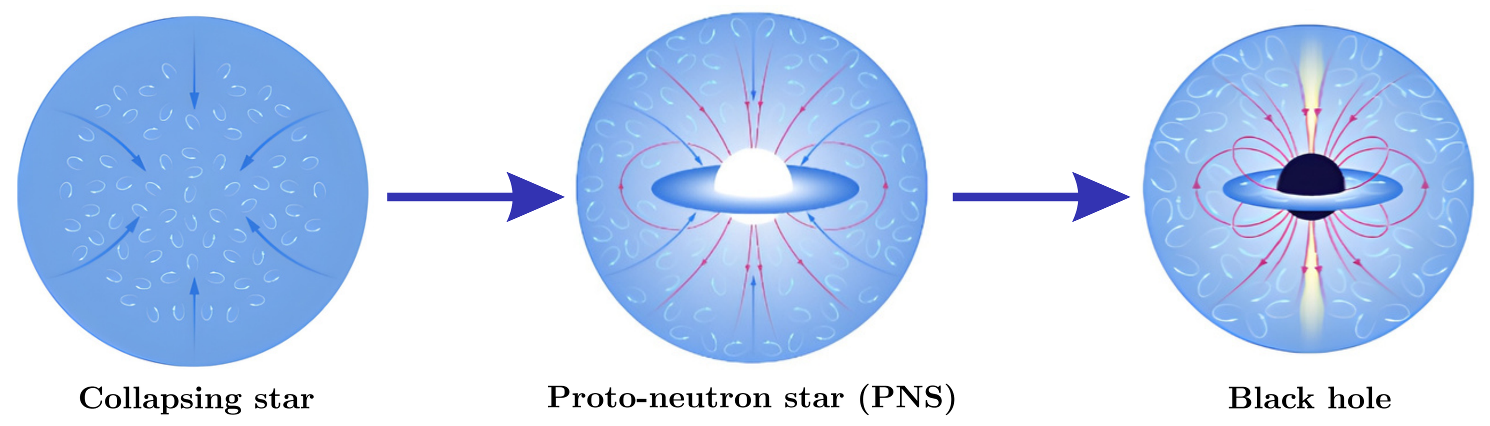

Figure 1: Schematic view of the collapse of a massive star to a black hole with the proto-neutron star stage (Gottlieb et al. 2024).

METHODS AND SELF-GRAVITY IMPLEMENTATION

- We performed numerical simulations using the code **HARM** (Gammie et al. 2003; Noble et al. 2006), which solves the following GRMHD equations (the **continuity** equation, the **conservation of energy and momentum**, and the **induction equation** governing the evolution of the magnetic field):

$$\nabla_\mu(\rho u^\mu) = 0, \quad \nabla_\mu(T^\mu_\nu) = 0, \quad \nabla_\mu(u^\mu b^\nu - u^\nu b^\mu) = 0.$$

- The implementation of **self-gravity** is based on the **time-dependent Kerr metric** approximation:

The usual static Kerr–Schild metric used in GRMHD simulations (**does not depend on time**):

$$g_{\mu\nu}(r, \theta, \phi, M_0, a_0)$$

Our implementation of the self-gravitating dynamical Kerr–Schild metric (**depends on time**):

$$g_{\mu\nu}(r, \theta, \phi, M_0, a_0, \Delta M(t), \delta M(t,r), \Delta a(t), \delta a(t,r))$$

- The motivation for including self-gravity is the large **mass difference** between the **initial black hole** and the **stellar envelope** ($3\,M_\odot$ and $25\,M_\odot$).

$$\begin{cases} \Delta M(t) = \int_0^t \int_0^{2\pi} \int_0^\pi \sqrt{-g}\, T^r_t \, d\theta\, d\phi\, dt' \\ \delta M(t,r) = \int_{r_h}^r \int_0^{2\pi} \int_0^\pi \sqrt{-g}\, T^t_t \, d\theta\, d\phi\, dr' \\ \Delta J(t) = \int_0^t \int_0^{2\pi} \int_0^\pi \sqrt{-g}\, T^r_\phi \, d\theta\, d\phi\, dt' \\ \delta J(t,r) = \int_{r_h}^r \int_0^{2\pi} \int_0^\pi \sqrt{-g}\, T^t_\phi \, d\theta\, d\phi\, dr' \end{cases}$$

Model	β	$M_{\rm BH}$ ($M_\odot$)	M_{star} ($M_\odot$)	a_0	S	Magnetic Field	Perturbation (%)	Jet
Model-1-SG	1	3	25	0.8	2	vertical	5	yes
Model-1-NSG	1	3	25	0.8	2	vertical	5	yes

- Resolution was set to: $(N_r,\ N_\theta,\ N_\phi) = (384, 192, 128)$

JET LAUNCHING AND PROPERTIES

- The main mechanism responsible for launching **Poynting jets** is the **Blandford–Znajek process** (Blandford & Znajek 1977). The majority of the energy is initially stored in the **electromagnetic field,** then dissipated, **converted** into the kinetic energy of particles, and eventually partially emitted as **highly energetic radiation**.
- To measure the energetics of jets, we use the **Lorentz factor estimated at infinity**. This parameter is defined under the assumption that, at infinity, all forms of energy are **converted** into baryonic bulk **kinetic energy**.

$$\mu = \Gamma_\infty = -\frac{T^r_t}{\rho u^r}.$$

- Since, in Poynting jets, almost the entire energy is stored in the electromagnetic field, we calculate the **power of the jet** by taking the **electromagnetic flux** through the enclosed surface above the **event horizon**.

$$P_{jet} = -\int_0^{2\pi} \int_0^\pi \sqrt{-g}\,(b^2 u^r u_t - b^r b_t)\, d\theta\, d\phi.$$

- The model with self-gravity exhibits more **variable** jet emission, with intervals of **halted** emission, which is generally more **consistent** with observed **prompt gamma-ray emissions**.
- The main **Quiescent interval** is directly related to rapid **mass accretion,** which leads to the jet **quenching**.

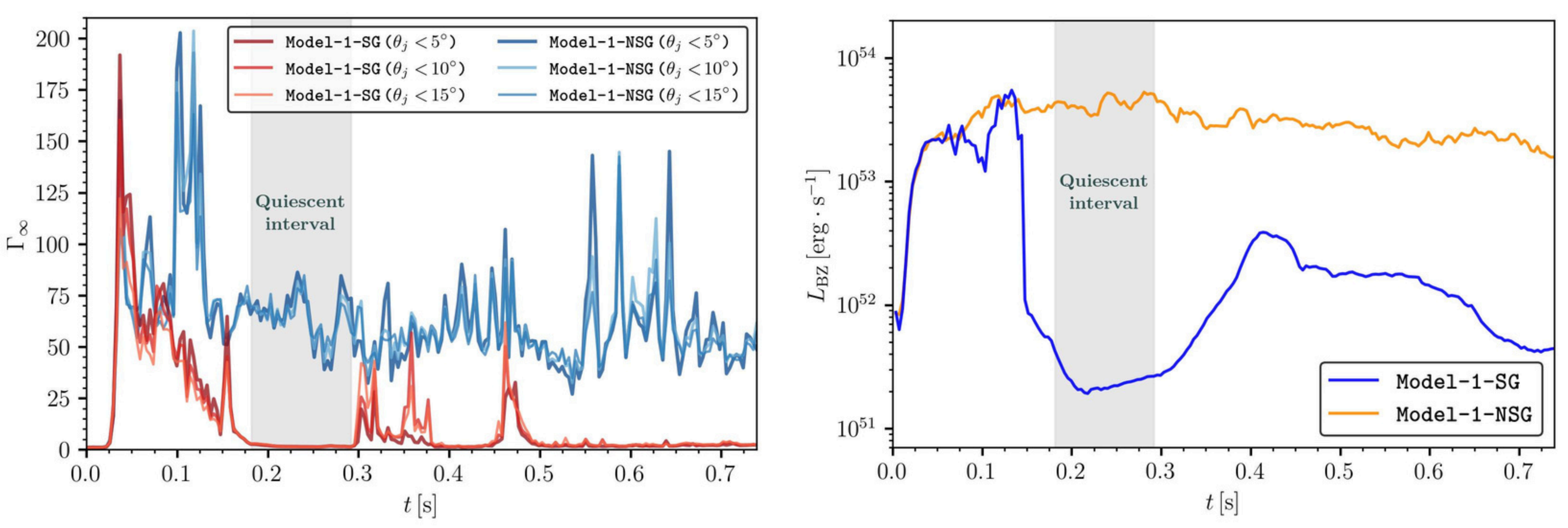

Figure 2: Terminal Lorentz factor, and the jet power evolution.

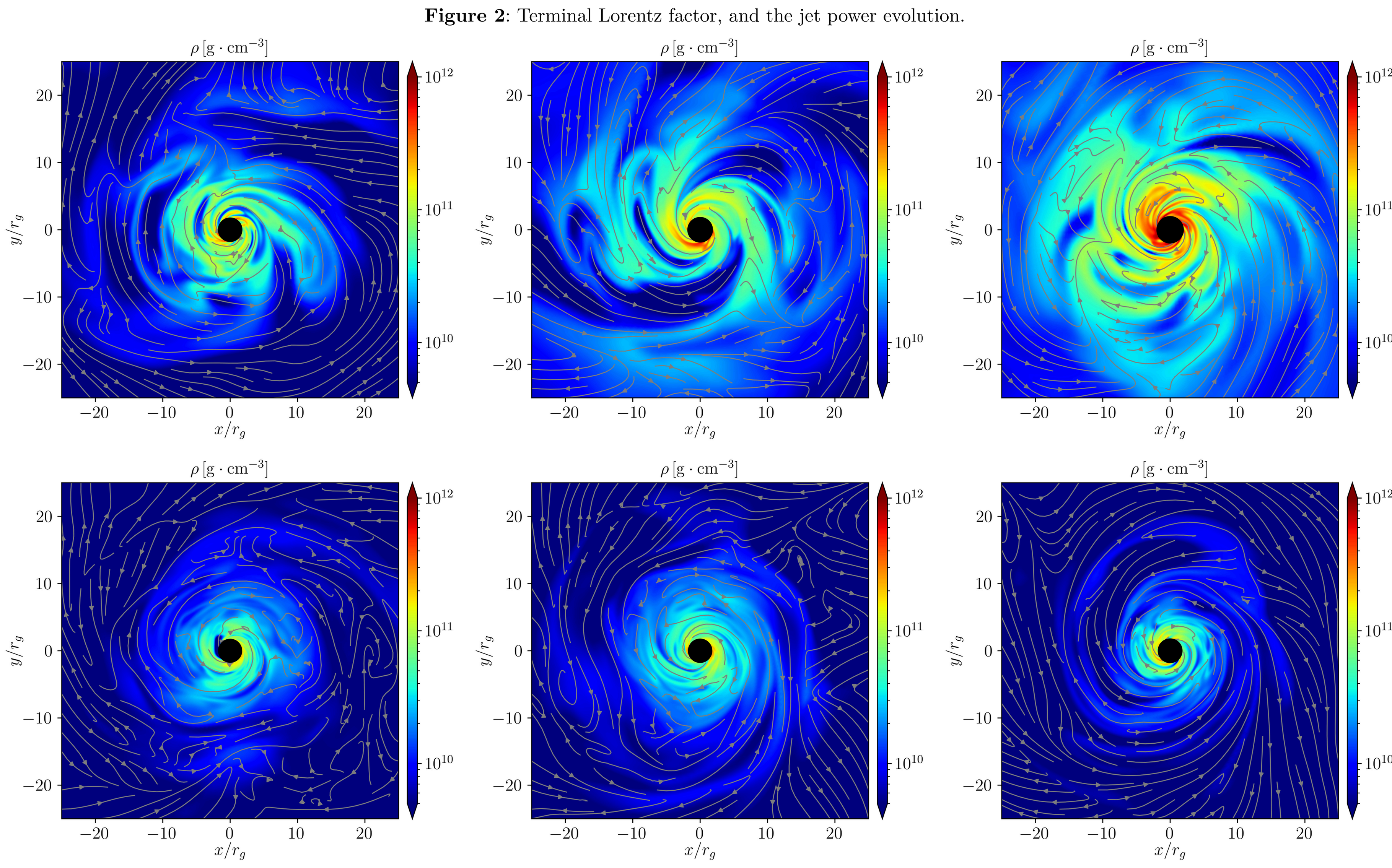

Figure 3: Mass density, overlaid with magnetic field lines for **Model-1-SG (top row)** and **Model-1-NSG (bottom row)**. Columns from left to right correspond to times t = 0.074 s, 0.092 s, and 0.111 s, respectively. In the model with self-gravity, we observe the **mass accumulation** in the **vicinity of the black hole**.

ACCRETION FLOW AND BLACK HOLE EVOLUTION

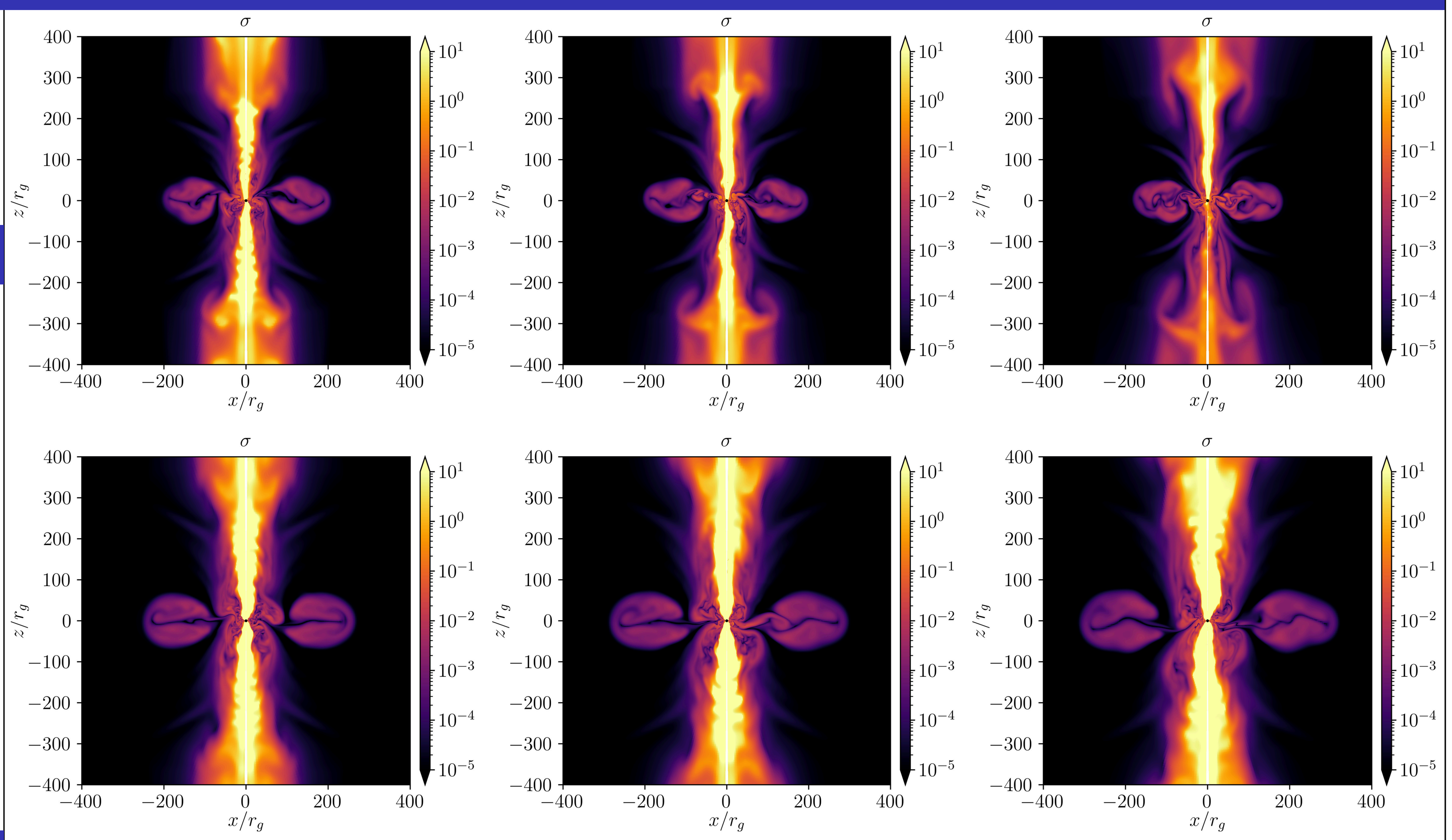

Figure 4: Poloidal maps of magnetization σ for **Model-1-SG** (top row) and **Model-1-NSG** (bottom row). Columns from left to right correspond to times t = 0.074 s, 0.092 s, and 0.111 s, respectively. The gradual **jet quenching** in the self-gravity model is responsible for the **Quiescent interval**.

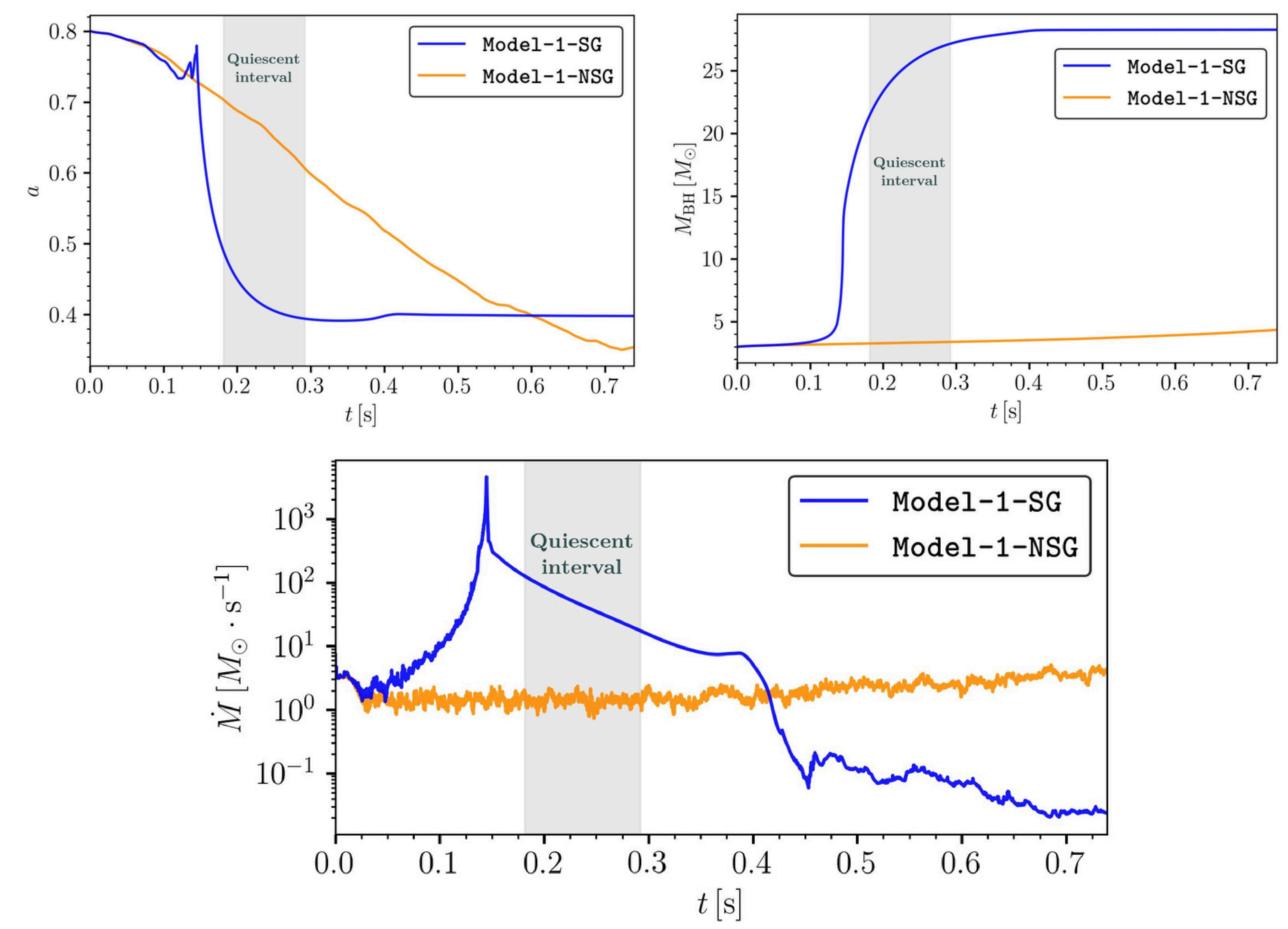

Figure 5: Evolution of the black hole spin, mass, accretion energy rate.

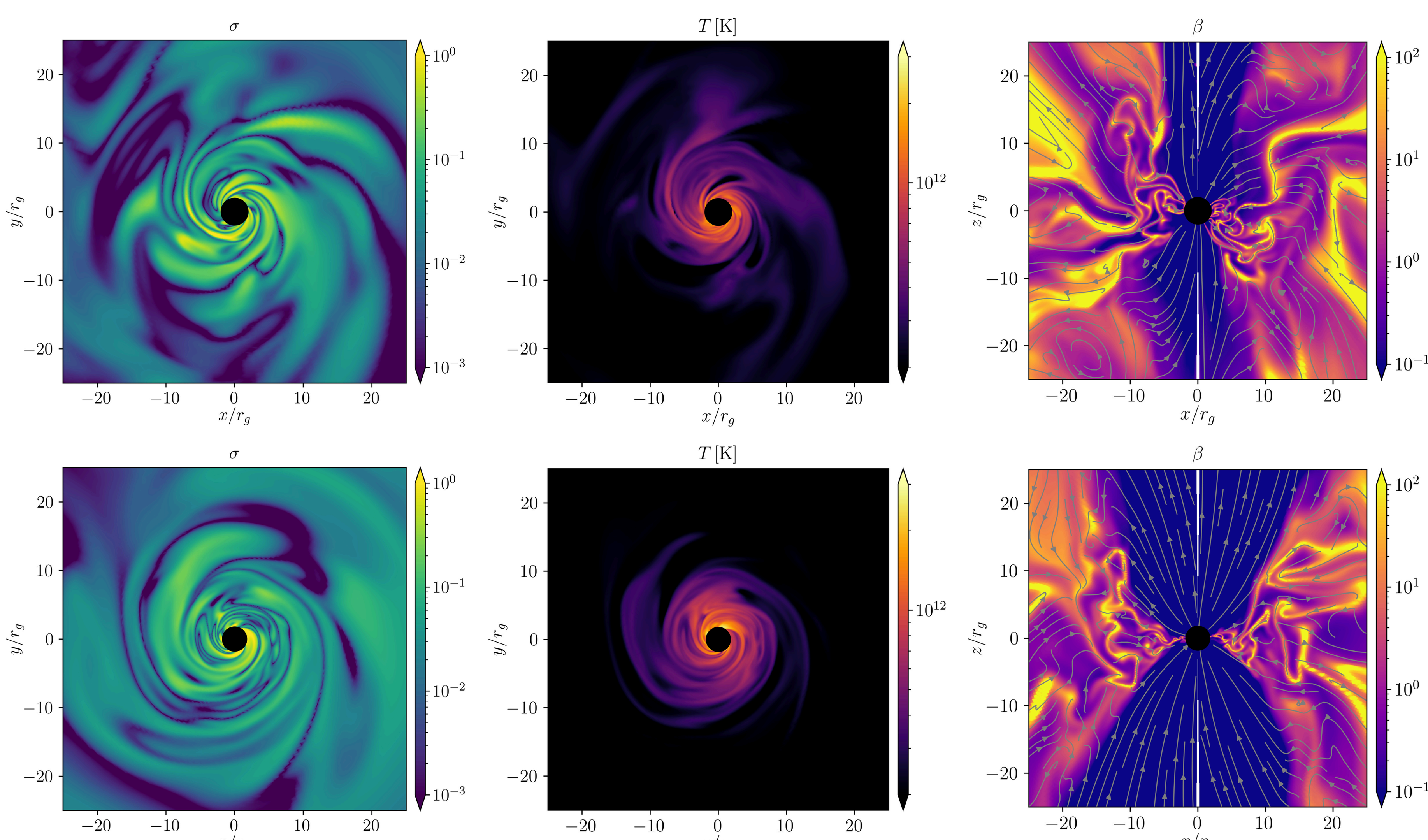

Figure 6: Maps of magnetization, temperature, and plasma beta for **Model-1-SG** (top row) and **Model-1-NSG** (bottom row). The columns correspond to t = 0.111 s. In the self-gravity model, due to the **mass accumulation**, the system becomes more **chaotic** and the mass begins to **penetrate** the **jet funnel**.

CONCLUSIONS

- **Model-1-SG** shows that the mass accumulation leads to the gradual **suppression of jet** emission, resulting in the **Quiescence interval**. Then, **emission reappears**, when when most of the **stellar envelope** mass is accreted.
- Self-gravity leads to a **faster evolution** of the **black hole spin and mass**. Additionally, we observe that the model without self-gravity **extracts more rotational energy** from the black hole.
- There is **no** substantial **difference** in the **jet launching start time** between the two models.
- The **opening angle** of the jet in **Model-1-SG** is **smaller** than in **Model-1-NSG**, which is related to additional **inward pressure** to the **jet funnel** in the model with self-gravity.

The main conclusion:

Some quiescent intervals in the prompt emission of long GRBs could be attributed to a mass accumulation in the vicinity of the black hole, which temporarily suppresses jet activity.

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