Impact of Self-Gravity on Jet Properties in Collapsar Models

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HARM with the Self-Gravity module

- In the following model of self-gravity, the Teukolsky equation (Teukolsky 1972) is adopted as a perturbation term in the Kerr metric. The global vacuum solution is formulated using the CCK formalism (Chrzanowski 1975; Cohen et al. 1974; Wald 1978), which enables the reconstruction of metric perturbations.

$$\Delta M(t) = \int_0^t \int_0^{2\pi} \int_0^{\pi} \sqrt{-g}\, T^r_t \, d\theta \, d\phi \, dt'$$

$$\delta M(t,r) = \int_{r_g}^{r} \int_0^{2\pi} \int_0^{\pi} \sqrt{-g}\, T^t_t \, d\theta \, d\phi \, dr'$$

$$M(t,r) = M_0 + \Delta M(t) + \delta M(t,r)$$

Evolution of the Black Hole mass with Self-Gravity perturbations.

$$\Delta J(t) = \int_0^t \int_0^{2\pi} \int_0^{\pi} \sqrt{-g}\, T^r_\phi \, d\theta \, d\phi \, dt'$$

$$\delta J(t,r) = \int_{r_g}^{r} \int_0^{2\pi} \int_0^{\pi} \sqrt{-g}\, T^t_\phi \, d\theta \, d\phi \, dr'$$

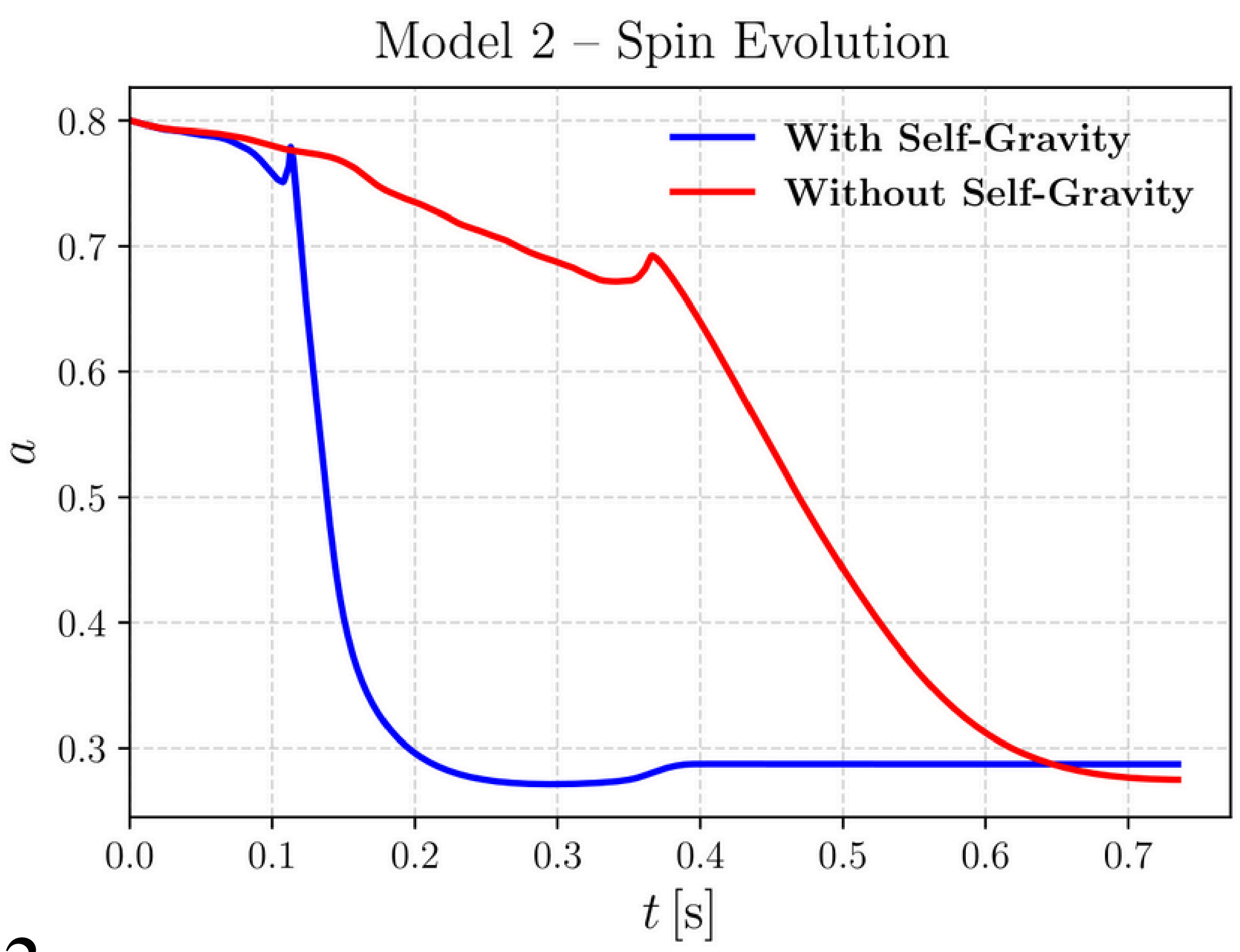
$$J(t,r) = J_0 + \Delta J(t) + \delta J(t,r)$$

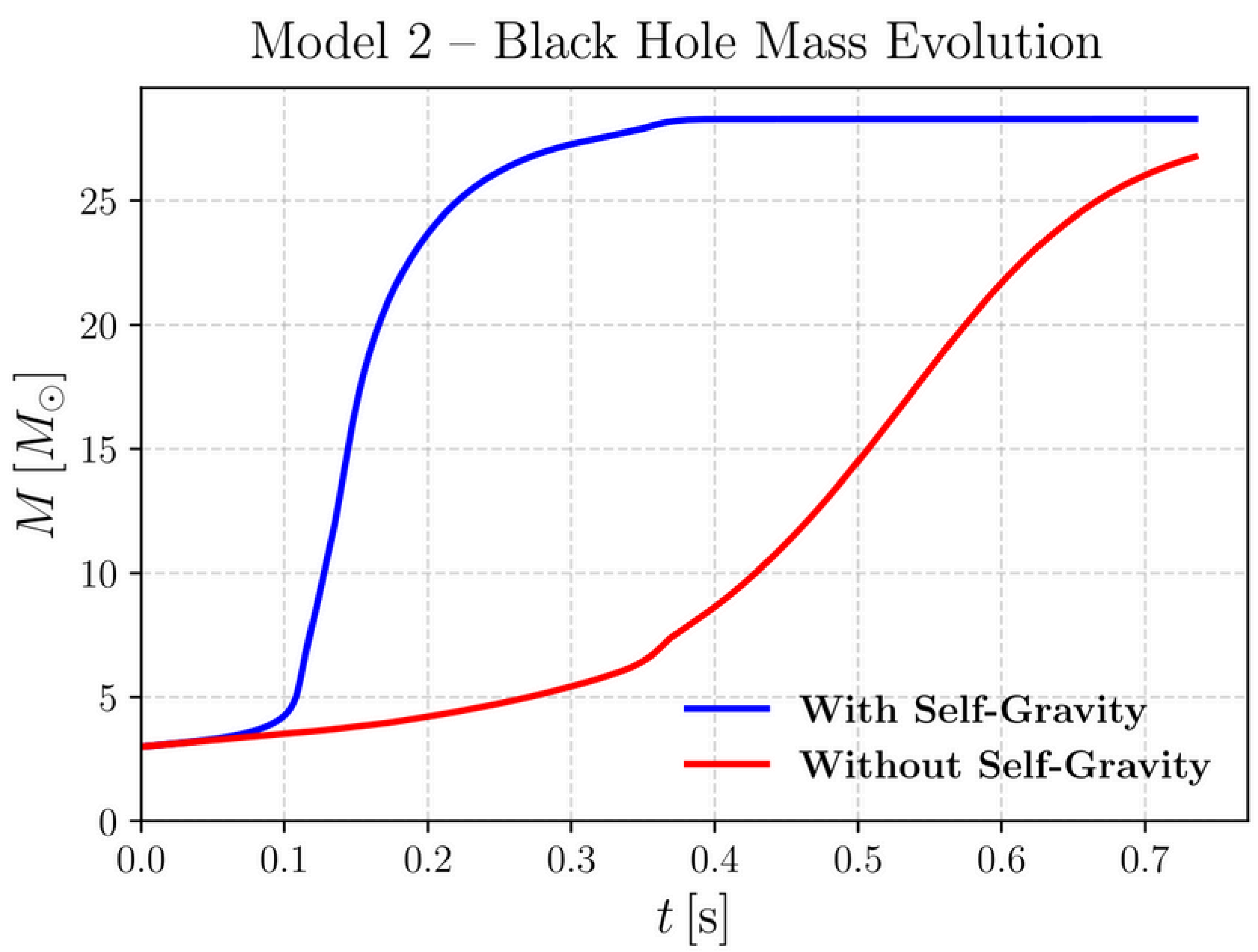
$$a = \frac{J(t,r)}{M(t,r)}$$

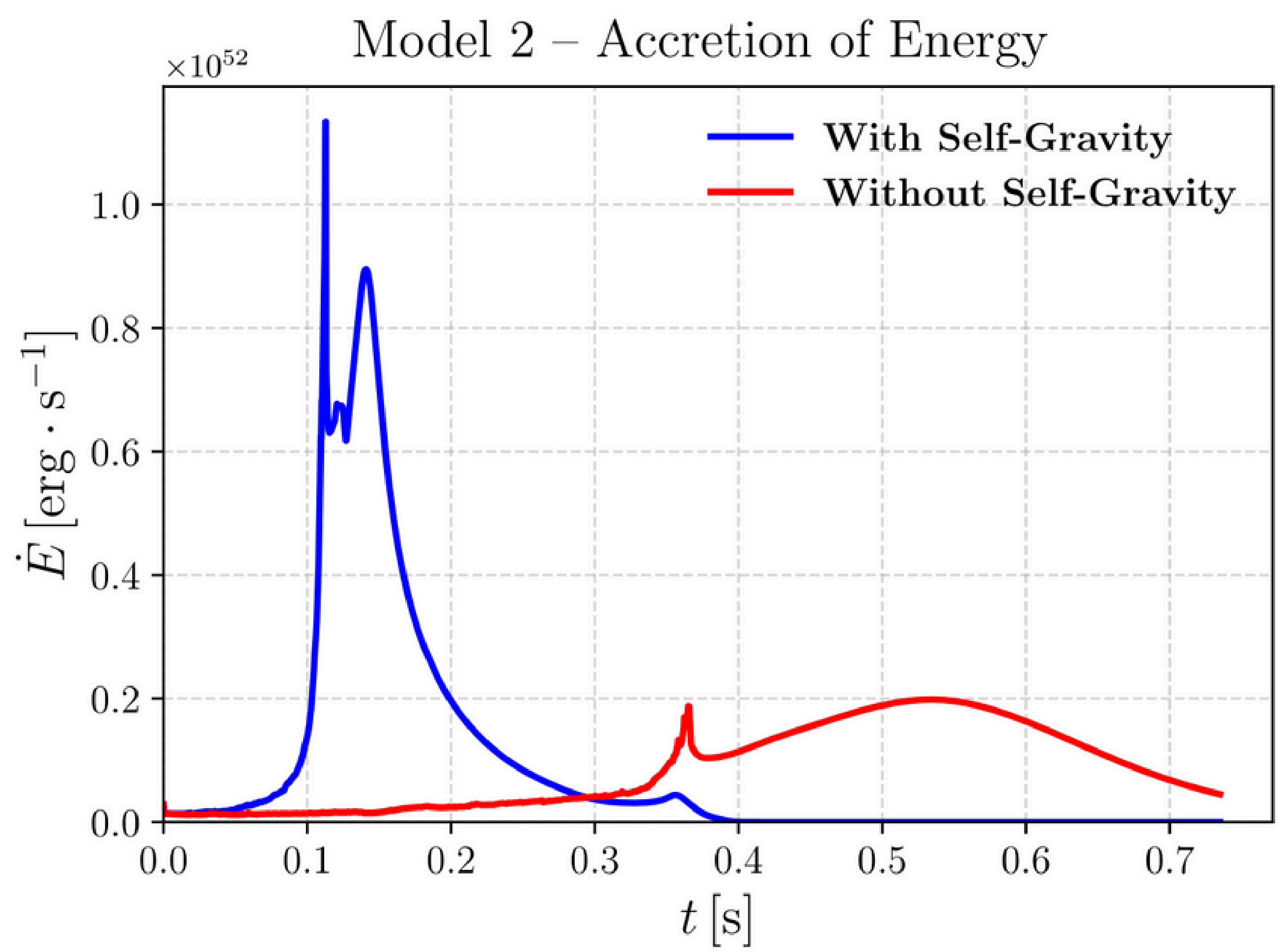
Evolution of the Black Hole spin with Self-Gravity perturbations.

Main effects of self-gravity in collapsars

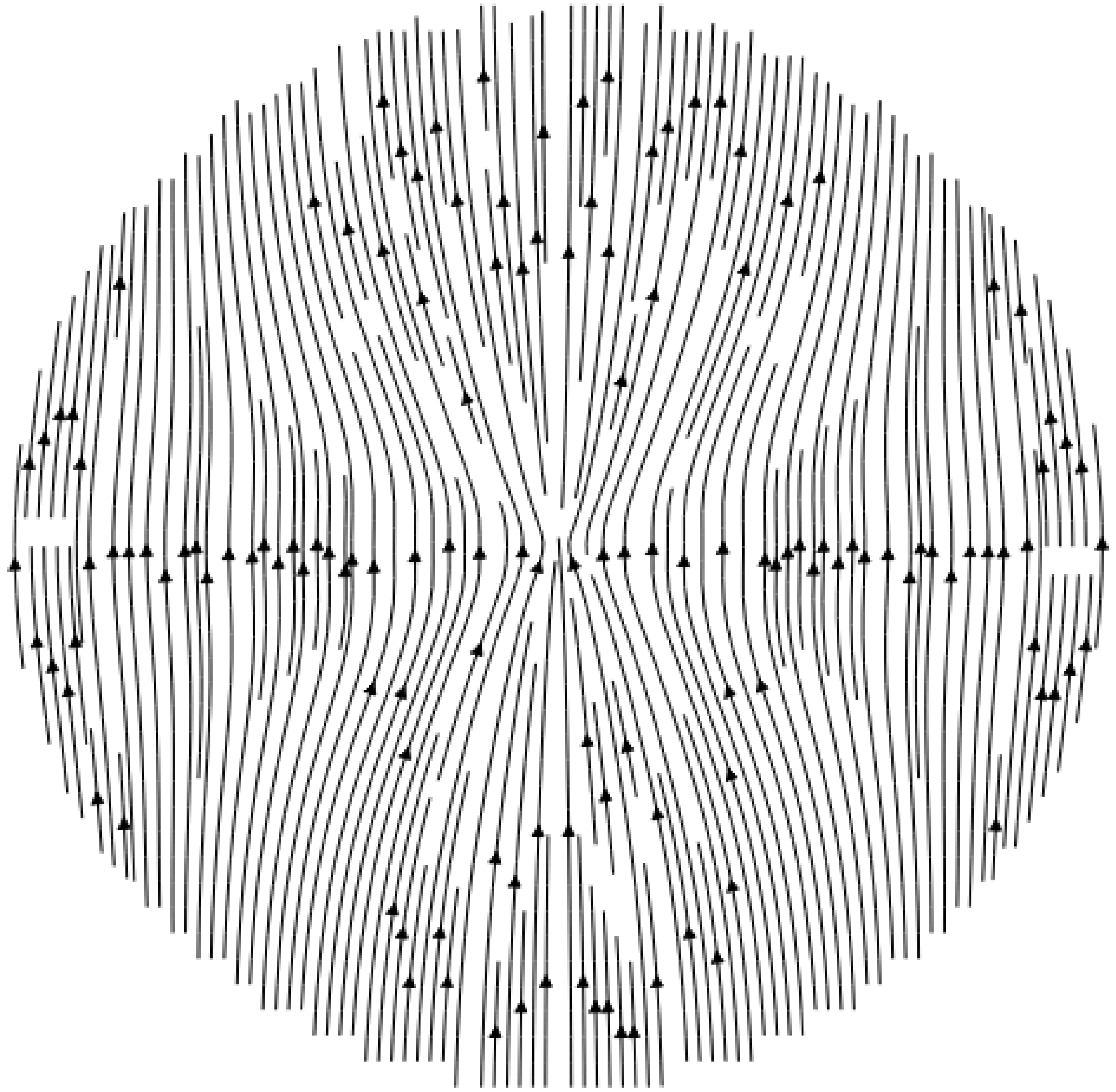
- The black hole's spin and mass evolve **faster** due to the envelope's self-gravity.
- **The accretion-rate variability at early times is much stronger in self-gravitating models.**
- The accretion-rate is significantly **higher** in self-gravitating models.
- Self-gravity effects provide a mechanism for the **transport of angular momentum**, and that final black hole mass and spin are reached much earlier during the collapse (Janiuk et. al 2023).







Initial conditions and jet profiles



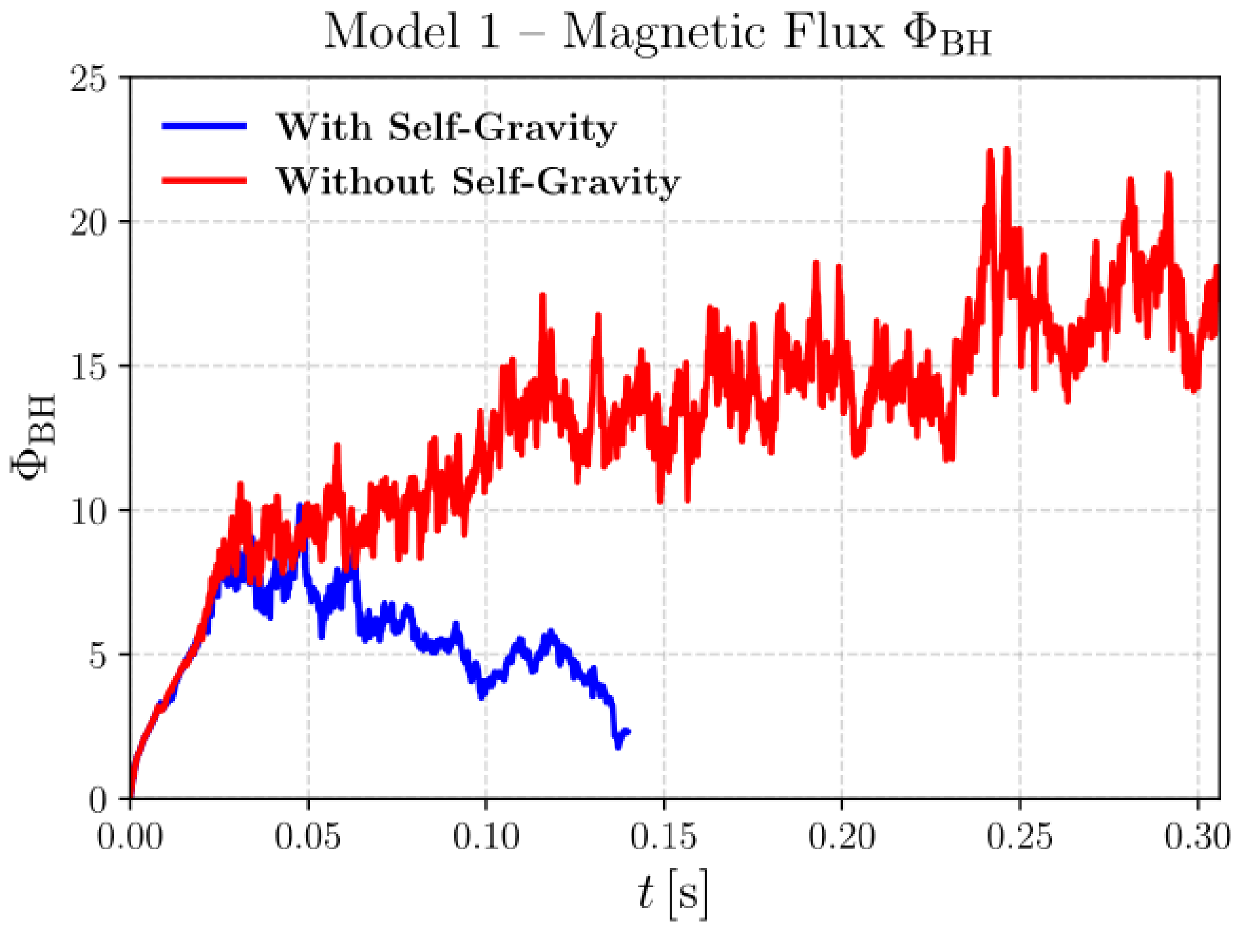
Resolution: $N_r \times N_\theta \times N_\phi = 384 \times 192 \times 128$

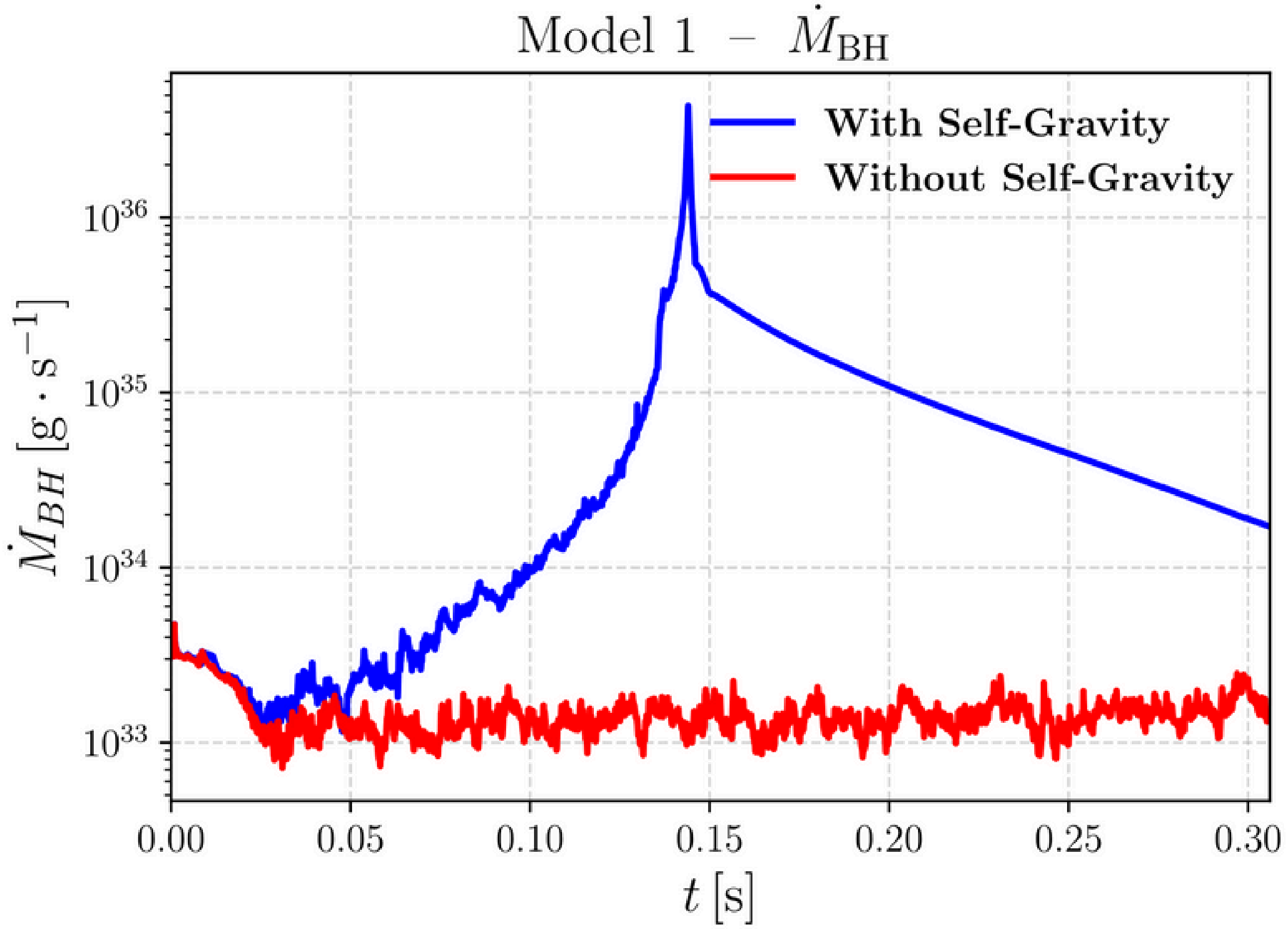
Magnetic field configuration: $A_\mu \propto (0, 0, \frac{1}{2} r \sin\theta)$ and $\beta = 1$

Initial mass of the black hole: $M_{BH} = 3\, M_\odot$

Initial mass of the stellar envelope: $M_{star} = 25 M_\odot$

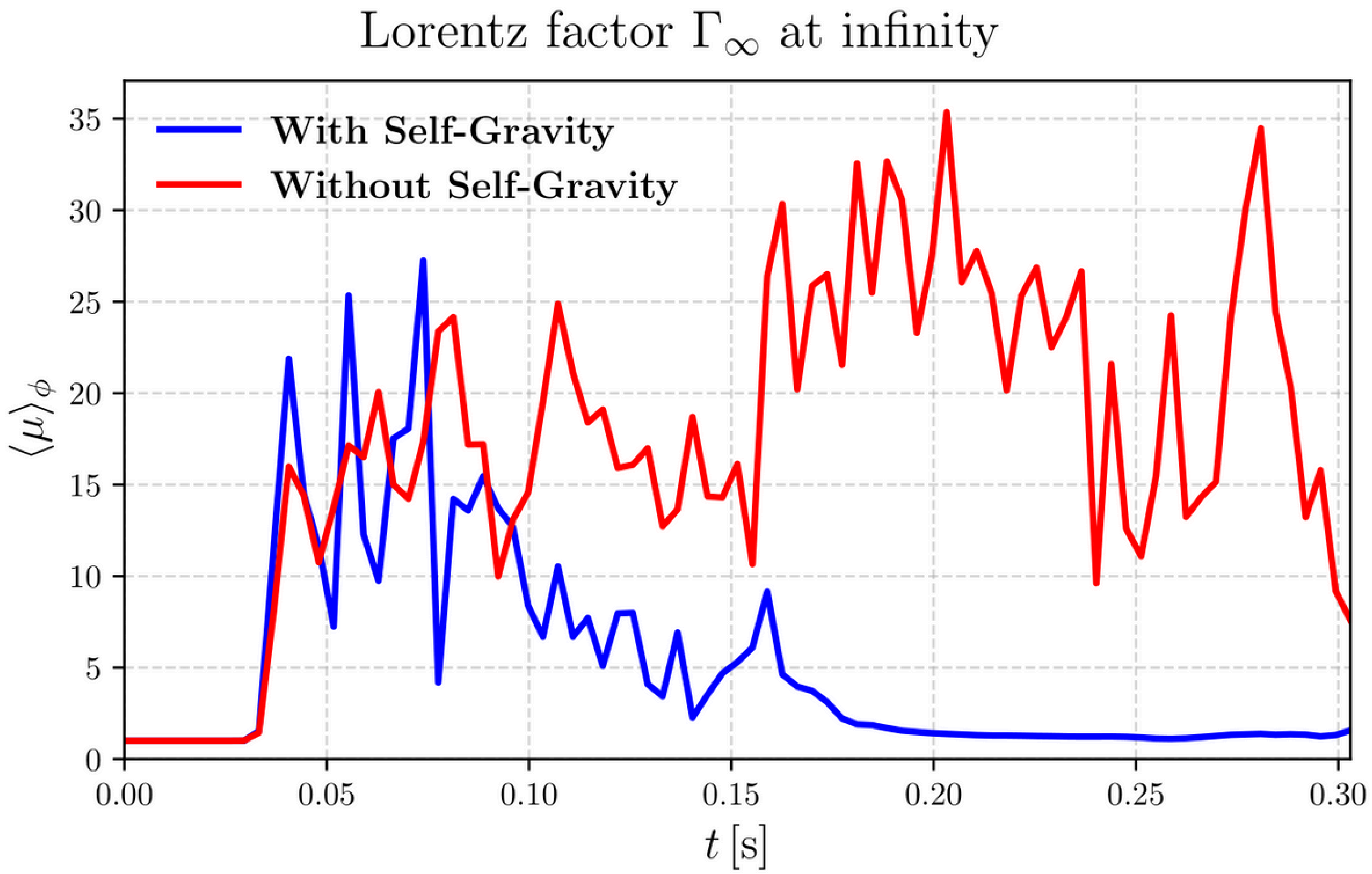
Perturbations in the internal energy: 5%   **Spin:** a = 0.8





$$\Phi_{BH} = \frac{1}{2\sqrt{\dot{M}}} \iint_H |B^r| \sqrt{-g}\, d\theta\, d\phi$$

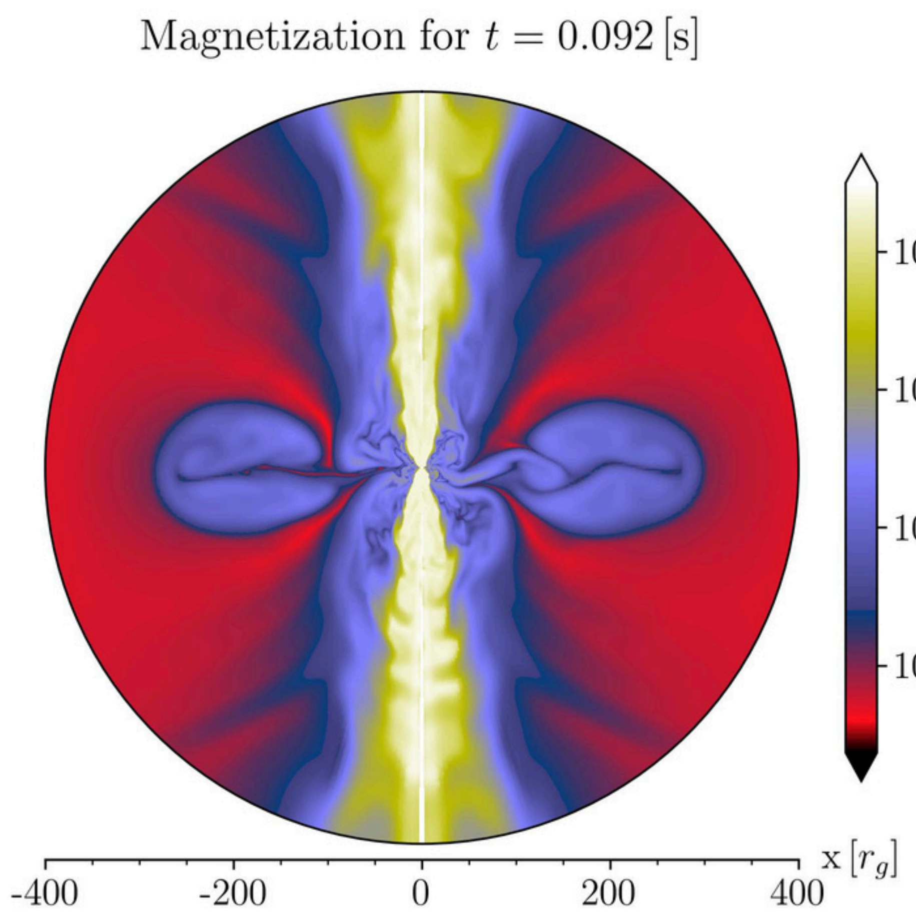
Impact of self-gravity on jet properties



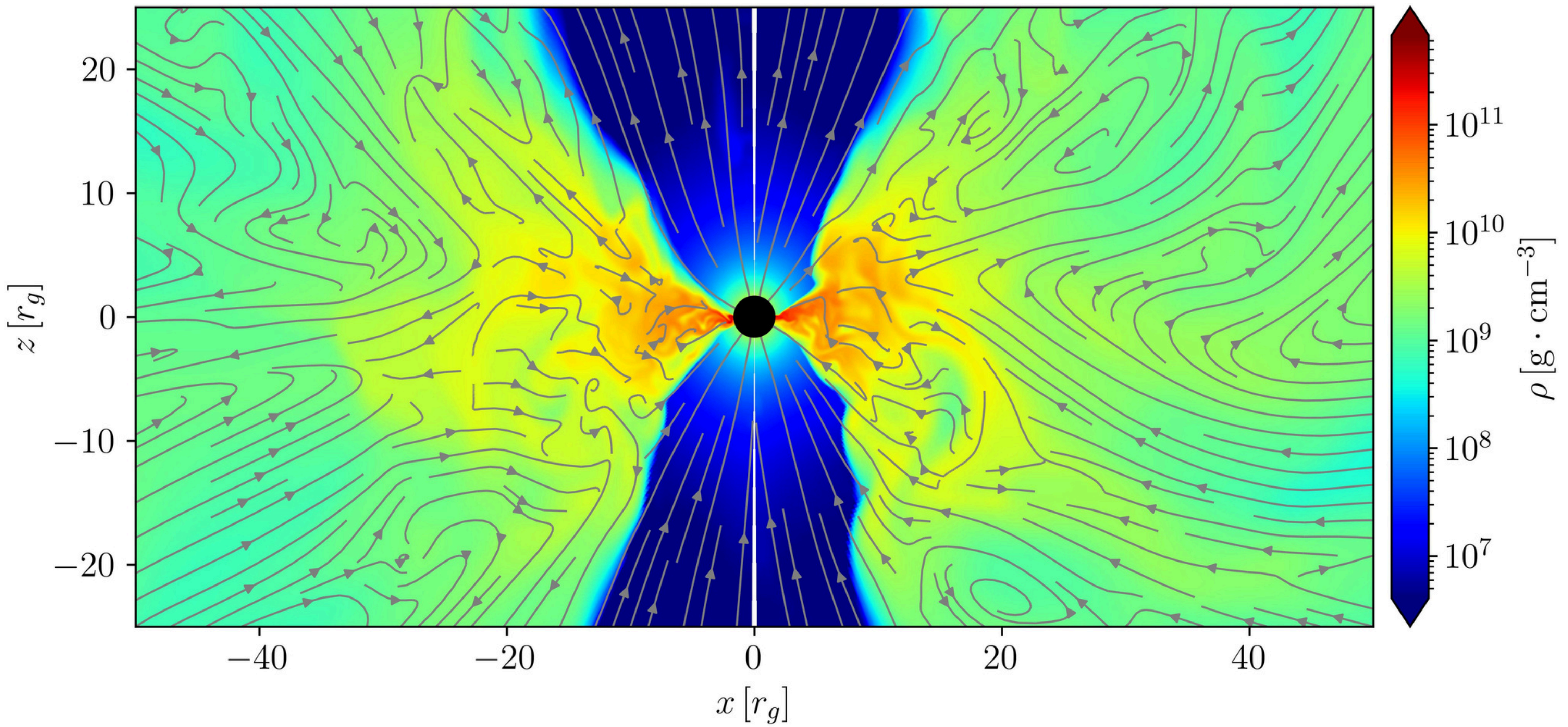
$\langle \sigma \rangle_\phi > 1$ for r $= 150\ r_g$

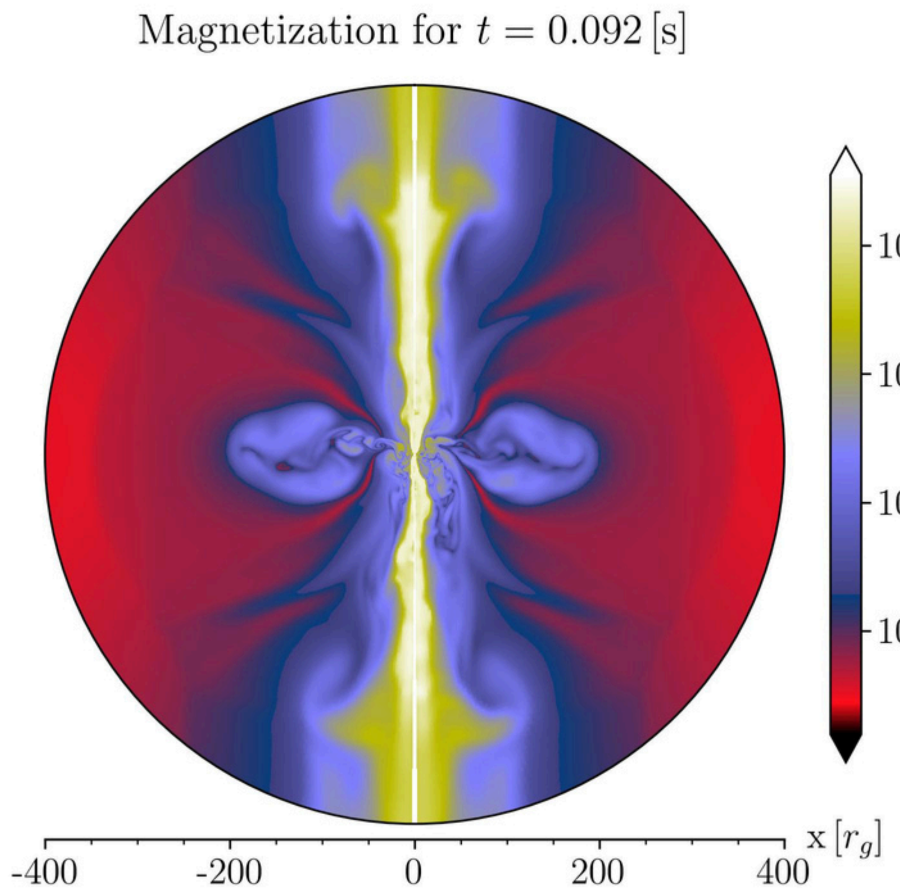
$\langle \mu \rangle_\phi$ for r $= 150\ r_g$ and $\theta = 5^\circ$

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

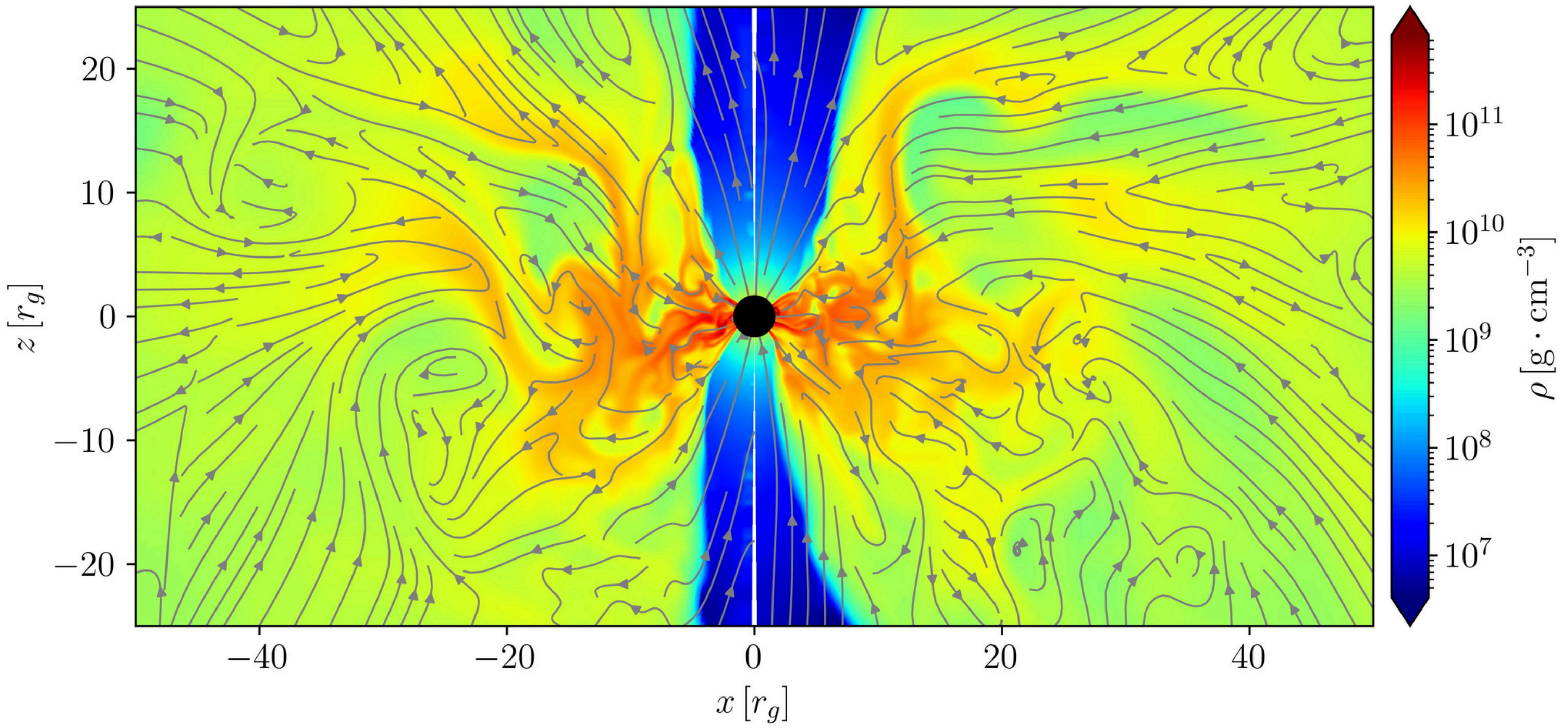


no Self-Gravity





Self-Gravity



Conculsions

- Self-gravity adds inward pressure on the magnetically arrested disk, pushing it toward the black hole and, as a result, stopping the jet emission; without self-gravity, the **jet remains continuously emitted**.
- In the model without self-gravity, the magnetic barrier is strong enough to almost entirely **stop mass accretion** and, as a result, to **stop the growth of the black hole's mass**.
- Both the **opening angles** and the **Lorentz factor** at infinity are greater in the model without self-gravity.