Collapsing self-gravitating massive stars and their EM transients

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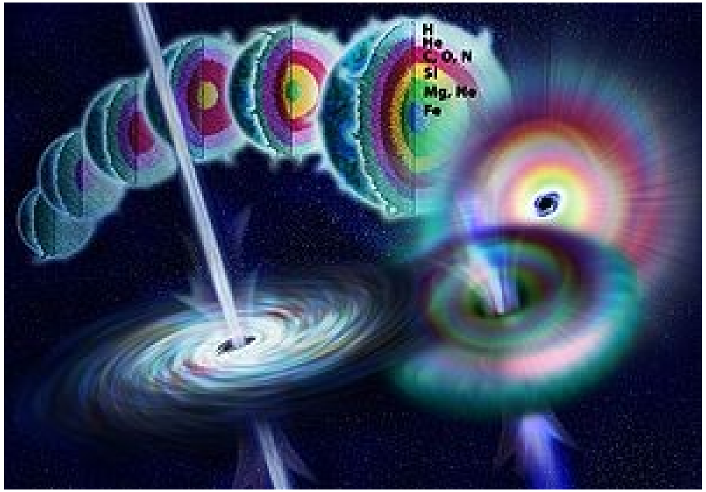
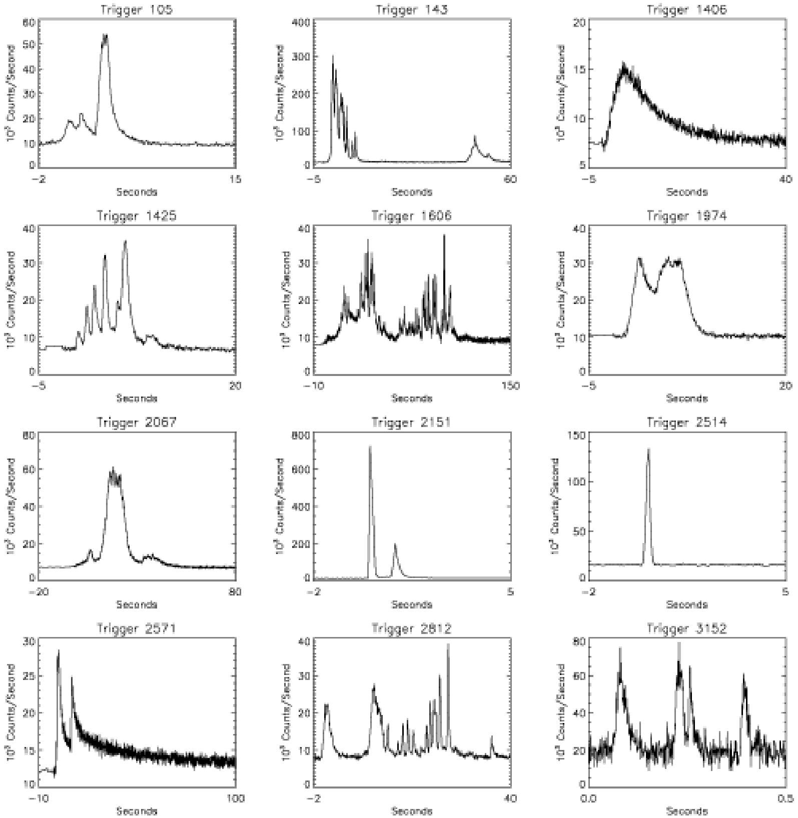
Long gamma ray bursts

- Originate from collapse of massive rotating stars
- Some exhibit strong variability of prompt emission
- We argue that gravitational instability can account for flaring activity.





Our collapse scenario

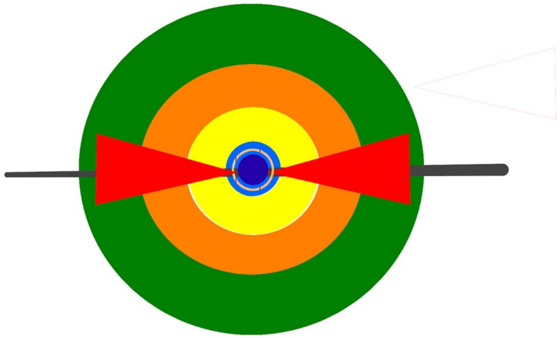
- We use GR MHD scheme, presented in Janiuk et al. (2018, 2023) and Król & Janiuk (2021).
- Space-time Kerr metric is evolving due to changing mass and spin of newly formed black hole in collapsar.
- We also account for perturbative terms due to self gravity of collapsing core.
- The core is squeezed C-O core of WR or pre-SN star, into a volume of ~$[10^9 \text{ cm}]^3$.
- Core rotation leads to formation of mini-disk at equatorial plane.

$$\dot{M}_{BH} = \int d\theta d\phi \, \sqrt{-g} \, T^r{}_t,$$

and

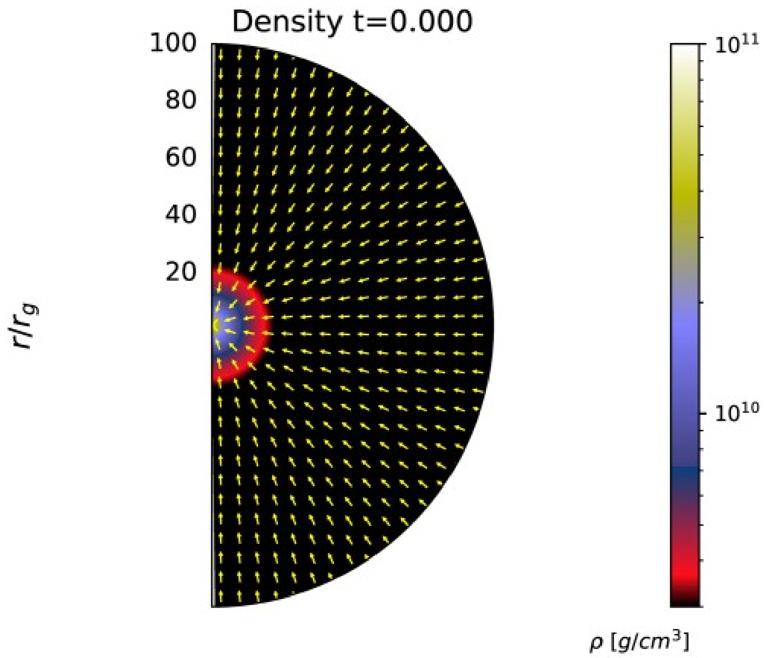
$$\dot{j} = \int d\theta d\phi \, \sqrt{-g} \, T^r{}_\phi,$$

$$\delta M_{BH}(t, r) = 2\pi \int_{r_{hor}}^{r} T^r_t \sqrt{-g} d\theta, \qquad \delta J(t, r) = 2\pi \int_{r_{hor}}^{r} T^r_\phi \sqrt{-g} d\theta.$$



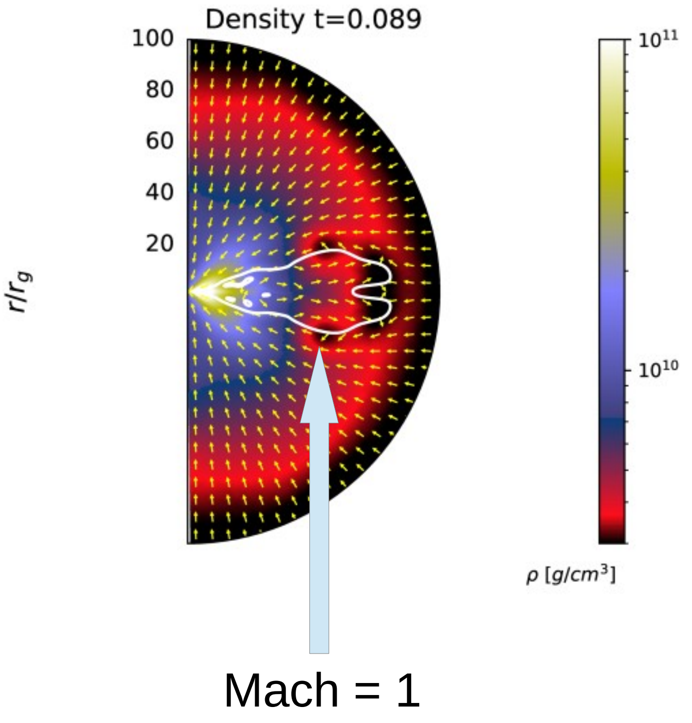
Numerical code and setup

- We work with HARM (high accuracy relativistic magnetohydrodynamics) to solve equations of continuity, energy-momentum conservation, and magnetic induction.
- Polytropic equation of state relates pressure with density.
- Initial condition is posed by transonic solution of slowly-rotating, quasi spherical flow around a Kerr black hole.
- Assumed mass of the core is 25 Solar masses. Rotation of the core and initial spin of black hole are model parameters.



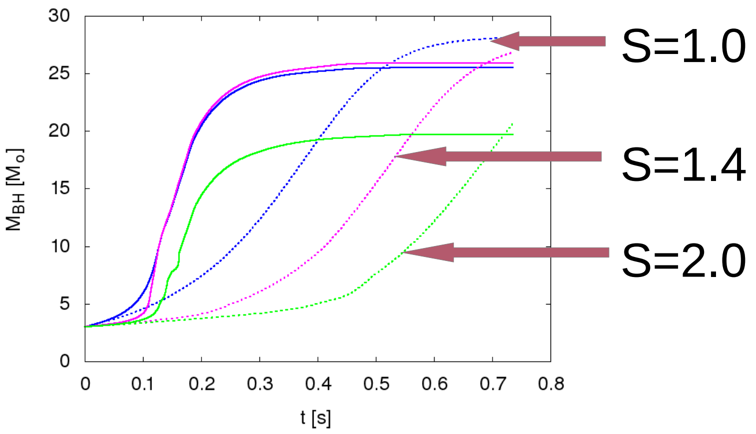
Formation of mini-disk

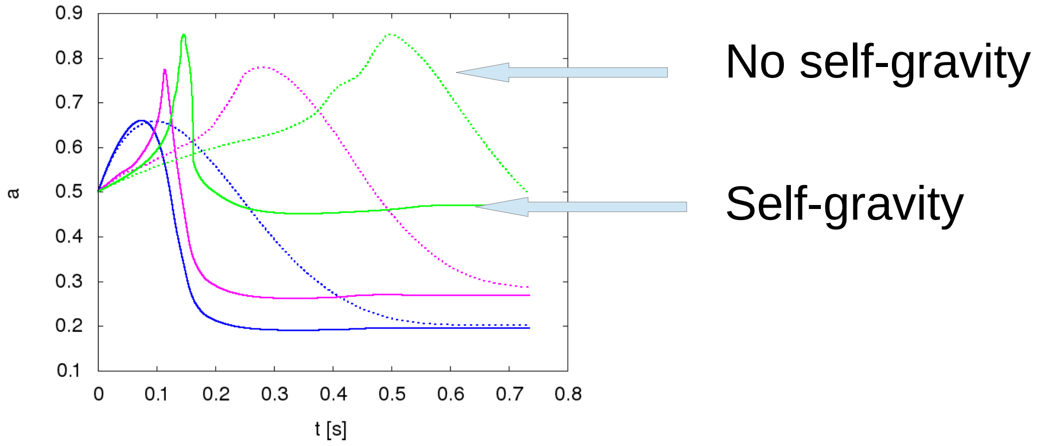
- Toroidal structure forms at equatorial plane, as specific angular momentum is normalized with respect to critical value for circularisation at r_{ISCO}, and scaled with polar angle.
- Below and above the torus, matter falls in supersonically into black hole.



Impact of self-gravity in the core

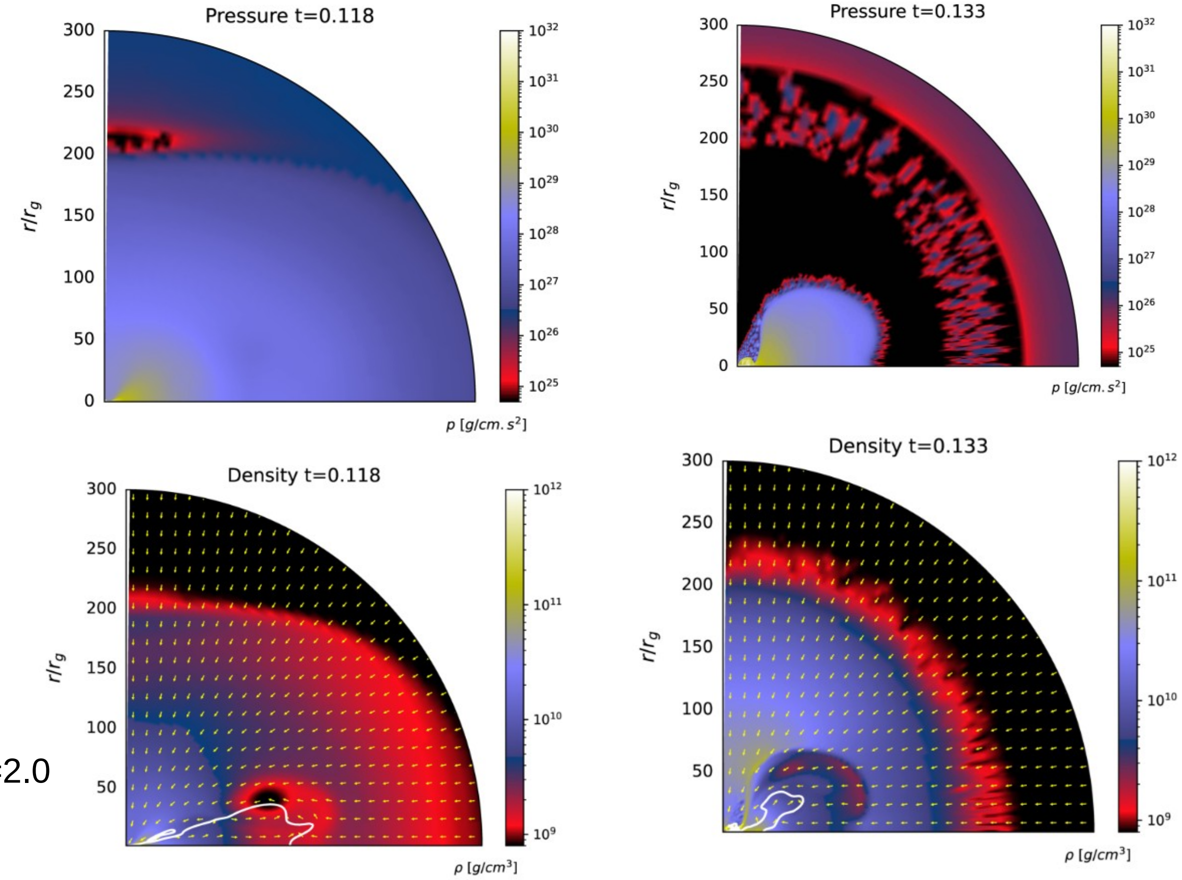
- Mass and spin of black hole changes because of infall of rotating massive shells onto its horizon, during core collapse.
- In addition, self-force in the core adds perturbation to the gravitational potential below given shell’s radius.
- Ultimate evolution pattern is modified.





Instabilities in the collapsing core

- Inhomogeneities and accretion shocks form in all models.
- Smear out as accretion rate fluctuations disapppear
- Equatorial outflows stalled as transonic shocks around 80 r_g



Case with A_0=0.5, S=2.0

Rayleigh-Taylor vs. Self-gravitational Interface instabilities

- We compute the RT and SGI instability growth rates at specific times and locations
- Interface is RT-unstable if heavy fluid lies on top of light fluid. SGI is destabilising across all density interfaces.
- In our collapsar, SGI dominates over RT, and RT growth rates have imaginary values at 20-25 r_g, around the mixing boundary of tenuous and dense spikes.

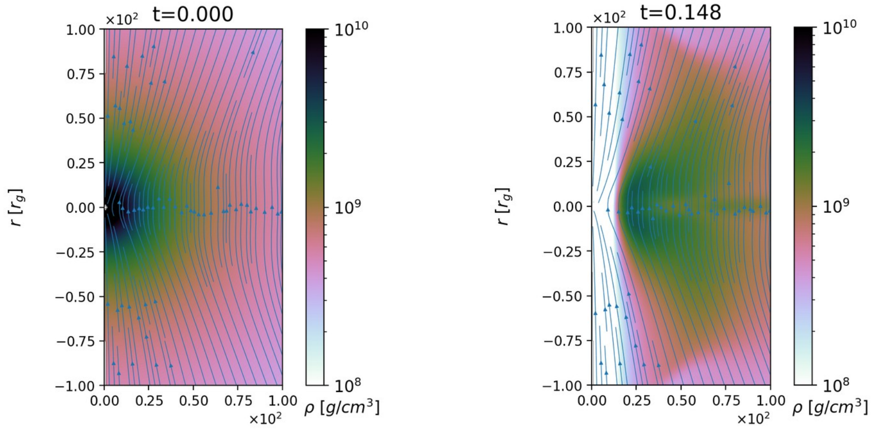
$$\sigma_{SGI} = \sqrt{\frac{2\pi G(\rho_2 - \rho_1)^2}{(\rho_2 + \rho_1)}}.$$

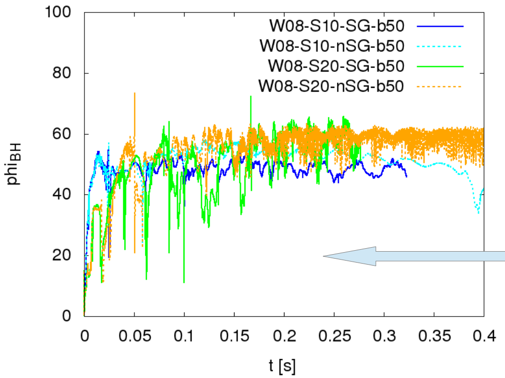
$$\sigma_{RT} = \sqrt{-\frac{p}{\rho}\frac{\partial \ln\rho}{\partial r}\frac{\partial \ln p}{\partial r}}.$$

$r\ (r_g)$	$\sigma^2_{RT}(s^{-2})$	$\sigma^2_{SGI}(s^{-2})$	$\frac{\partial \ln \rho}{\partial r}\frac{\partial \ln p}{\partial r}$
20.0	-4.75×10^{-8}	1.21	> 0
21.0	-7.56×10^{-8}	0.94	> 0
22.0	-13.25×10^{-8}	0.67	> 0
23.0	-24.9×10^{-8}	0.4	> 0
24.0	-50.84×10^{-8}	0.16	> 0
25.0	-90.25×10^{-8}	0.032	> 0

Effects of magnetic field

- We adopt weak poloidal magnetic field. Its geometry is either of a uniform, or dipole field, initially.
- In case of uniform field the rotating Kerr black hole magnetosphere has a repulsive effect (Wald 1974).
- A magnetically arrested state of accretion develops in the core and facilitates bi-polar jet-like outflows.
- They are not able to break out from envelope, and the BH spin drops below a=0.5 at the end of simulations (for a_0=0.8 and S=2.0).
- Density contrast of transonic shocks in SG models is weakened by B field

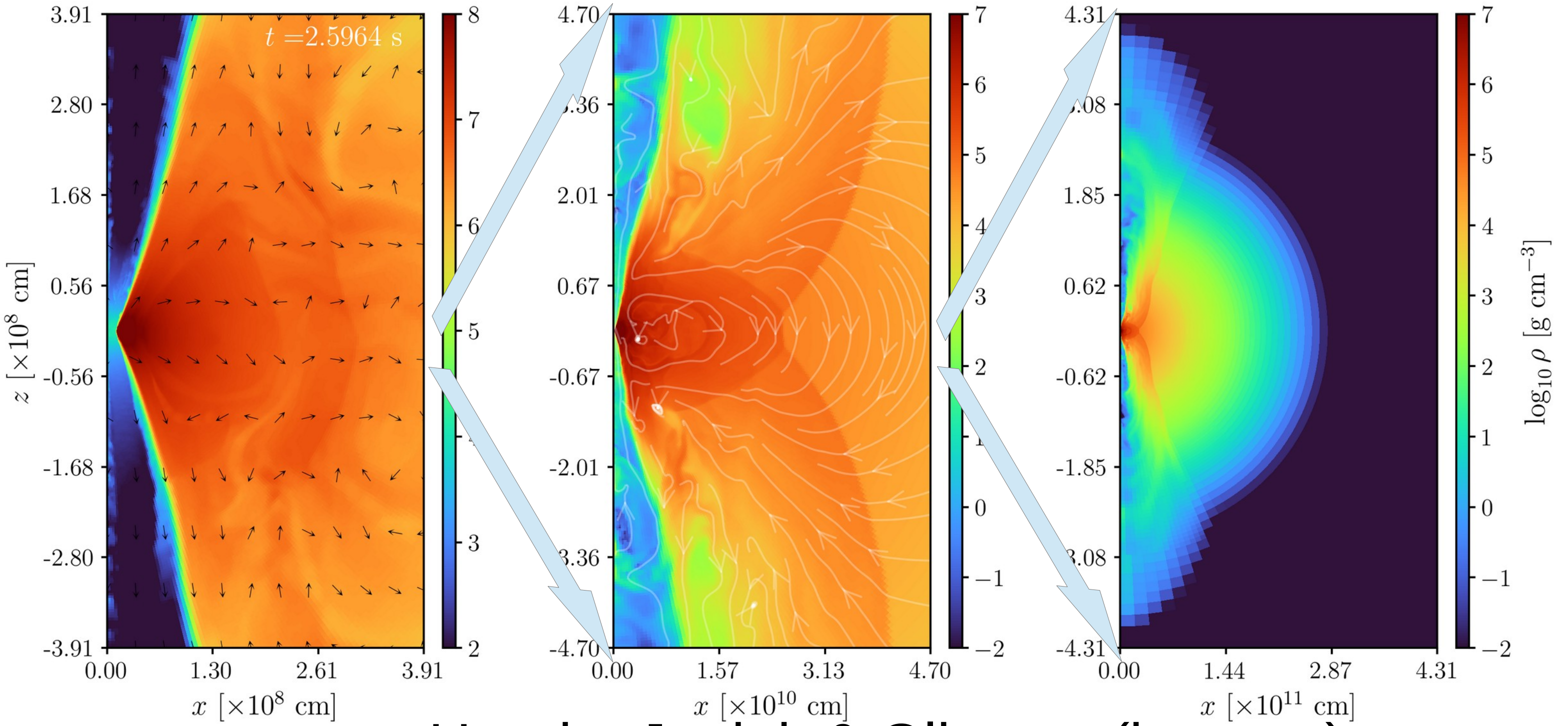




Dimensionless magnetic flux at horizon

(MAD state if >15)

New simulation with jet breakout



Urrutia, Janiuk & Olivares (in prep.)

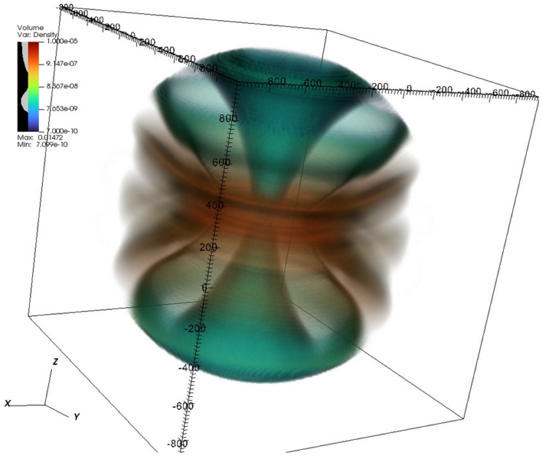
Code BHAC (with adaptive mesh)

Initial condition: evolved star model from MESA

Core magnetized (e.g. Moesta et al. 2015)

3-dimensional simulations

- Work in progress
- Need much more computational resources
- We impose weak magnetic fields and self-gravity
- Search for non-axisymmetric modes in the SGI
- Search for plausible conditions for jet breakout



Published work: Janiuk, Shahamat, Król (2023, A&A, 677, 19)

Stay tuned for follow-up!