Perturbation of the accretion flow onto supermassive black hole by a passing star

Petra Suková

Astronomical Institute of the CAS
Prague, Czech Republic

Cooperation with
Vladimír Karas, Vojtěch Witzany, Michal Zajaček

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Motivation

- Supermassive black holes – surrounded by dust and gas (the constituents of the accretion flow), different stellar-size objects (stars, neutron stars or stellar-mass black holes) and (possibly) strong magnetic field
- Both the classical accretion discs or the radiative inefficient accretion flows (RIAF) can be perturbed by the stellar-size objects
- Interaction between different constituents has observable consequences $\Rightarrow$ multiwavelength variability of galactic nuclei
- Can stars push out gas into jets (enrich jet by baryons) or form compact corona above the nuclei (lamp-post corona model)?
- GRMHD simulation of the flow $\rightarrow$ implementation into HARM

GRMHD 2D/3D simulations with HARM

- Open source software package for GRMHD computations `HARMPI` (Gammie et al, 2003; Tchekhovskoy et al., 2016)
- ideal MHD – no resistivity, magnetic field frozen into gas
- solver for continuity $((\rho u^{\mu})_{;\mu} = 0)$ and energy-conservation equation $(T^{\mu}{}_{\nu;\mu} = 0;\ T^{\mu\nu}_{gaz} = (\rho + \rho\varepsilon + p)u^{\mu}u^{\nu} + pg^{\mu\nu})$
- conservative scheme:

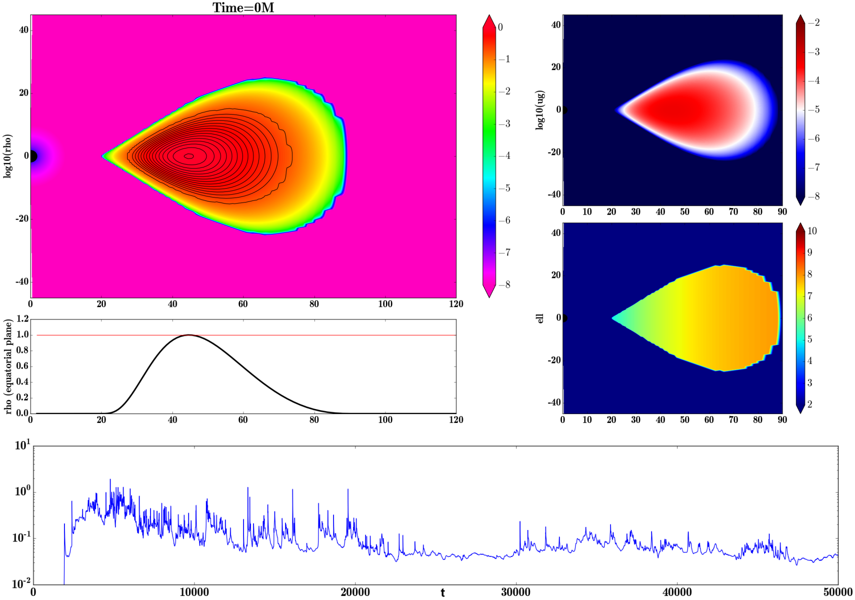
$$\partial_t \mathbf{U}(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P}) \tag{1}$$

  U – conserved vars, **P** – primitive vars, $\mathbf{F}^i$ – fluxes, **S** – sources
- numerical inversion of non-linear relation **U**(**P**)
- fixed background (Kerr metric) – faster computation
- spherical coordinates – suitable for our geometry
- logarithmic grid in r – no need of grid refinement

Initital conditions – evolved thick torus (RIAF)

- Classical solutions – Fishbone & Moncrief, 1976; Abramowicz et al., 1978 – thick torus without magnetic field
- Komissarov, 2006, Montero et al., 2007
  – magnetized solution with purely azimuthal magnetic field
  – different EOS, constant angular momentum
- Witzany & Jefremov, 2018
  – extension to 2-parametric family of tori, non-constant profile of angular momentum (both growing and decreasing),
  closed form of the solution
  different shapes of the torus (height versus radial extent)
- Our initial torus is large (20M – 90M) – reservoar of matter
- Instead of azimuthal magnetic field, the torus is interlaced with weak magnetic field – field lines inside the torus follow equipotentials of density $\Rightarrow$ MRI in short time

Initial conditions – evolved thick torus (RIAF)

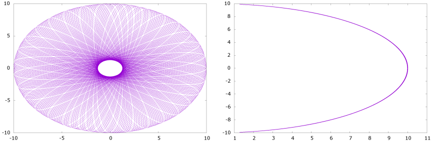


Perturbation by a star

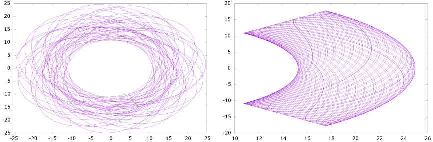
- Motion of a star in the accreting medium is complicated – approximations needed
- Dynamical effect of the star on the gas
  - Consecutive perturbation by moving star – velocity of gas in cells corresponding to the volume of the star is prescribed to equal star's velocity
- We do not evolve the stellar structure nor the feedback from the accretion flow on the star trajectory – star motion solved by geodesic equation on given Kerr background
- Evolved state of the torus ($t = 25000M$) as initial condition (ideally in a relaxed stationary accretion state)
- 2D runs: ϕ coordinate of the star is "forgotten"
- Changes in accretion rate + outflows

- 7x 2D runs: different star trajectory
  begins at $t = 25000$M of the "basic" run
  $t_f = 50000M$ or $100000M$
  star radius usually $r_{\rm star} = 1M$ (for Sgr A* $1M \sim 9r_\odot$)
  resolution 252 x 192
  - Run 1: Star moves close to $\sim$ 10M, into "funnel" along axis
  - Run 2: Star moves between $\sim$ 12M – 25M, not in funnel
  - Run 3: Star moves between $\sim$ 25M – 50M, embedded in disc, close to equatorial plane
  - Run 4: Star moves close to $\sim$ 50M, into funnel close to axis
  - Run 5: Star moves close to $\sim$ 50M, not into funnel
  - Run 6: Star same as Run 5, radius of star $R = 10$M
  - Run 7: Star same as Run 1, radius of star $R = 0.1$M
- 1x 3D run – Run 8: Star same as Run 1, $t_f = 30000M$, resolution 252 x 192 x 96

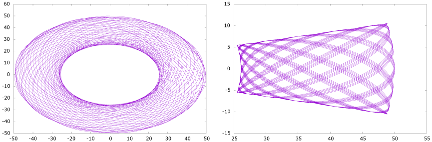
Run 1, 7



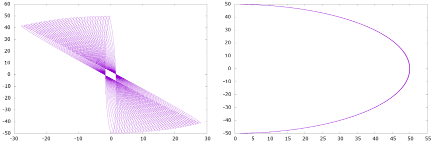
Run 2



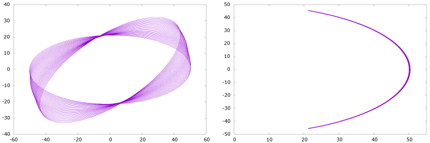
Run 3



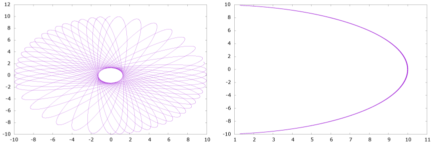
Run 4



Run 5, 6

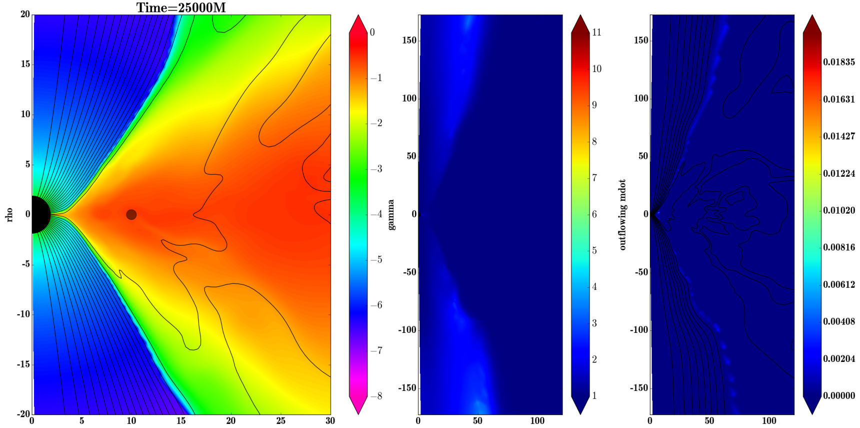


Run 8



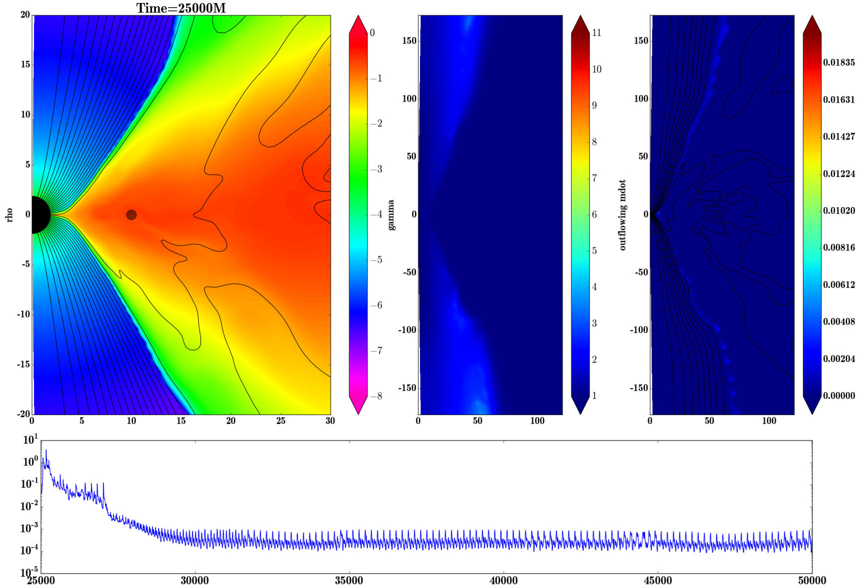
x-y plane r-z plane x-y plane r-z plane

Run 1 – gas evolution

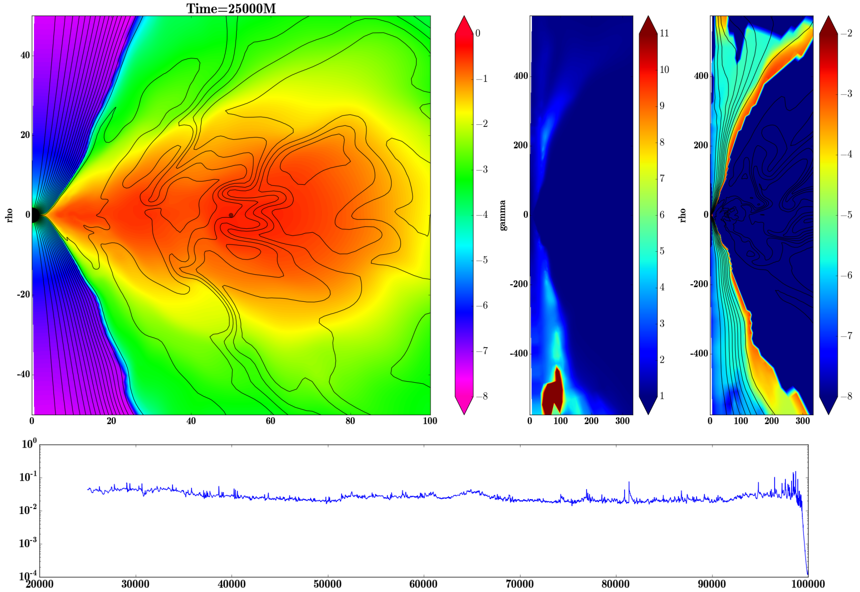


$$\dot{\mathcal{M}}_{\rm out}(r) = \rho(r)\frac{u^r(r)}{u^t(r)}\sqrt{-g}\,\mathrm{d}\theta\mathrm{d}\phi \quad \text{for}\ \gamma > 1.155$$

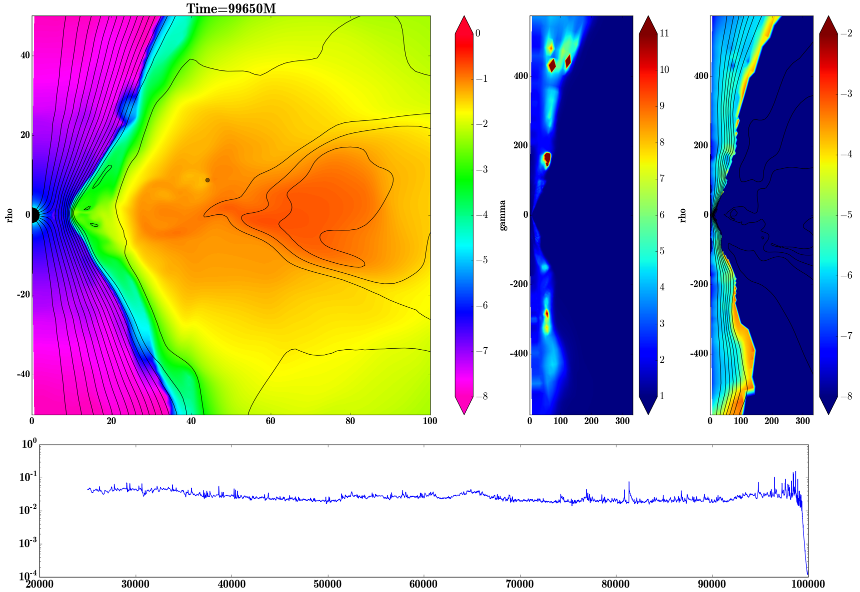
Run 1 – gas evolution

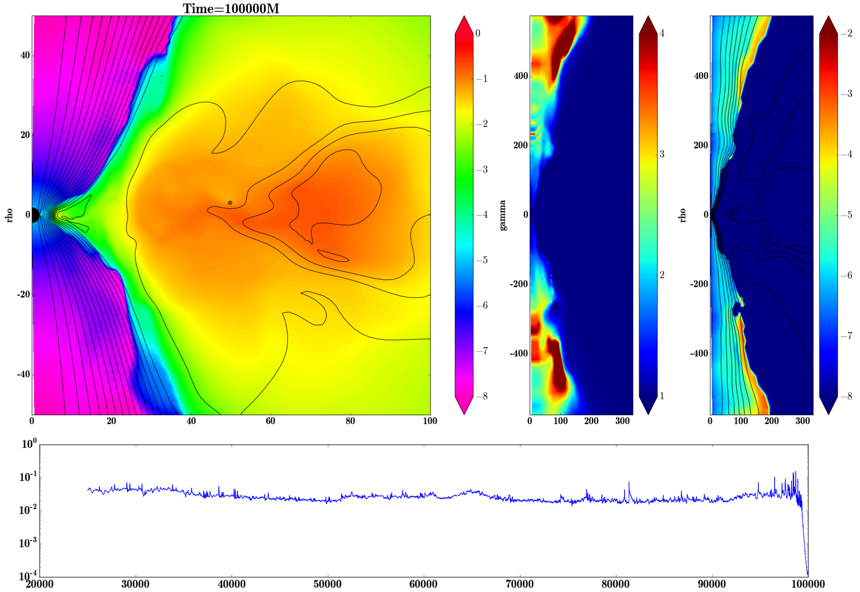


Run 3 – gas evolution

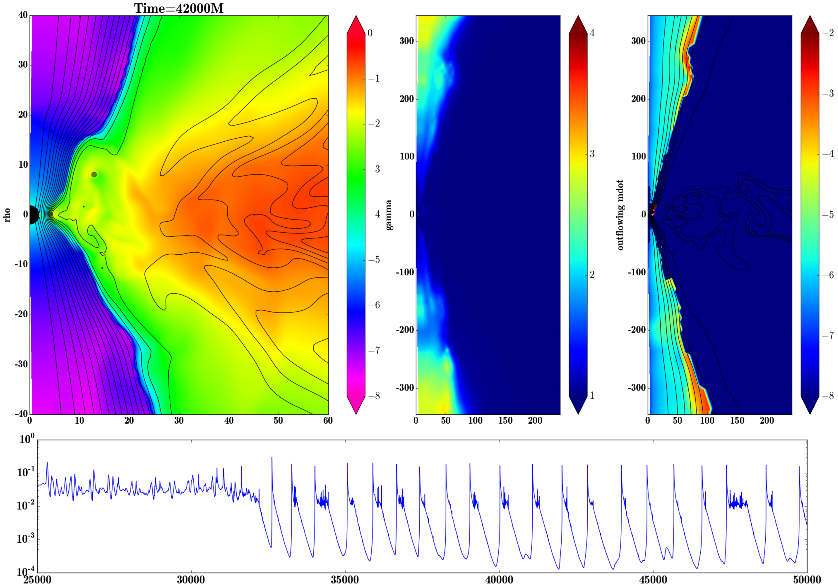


Run 3 – gas evolution

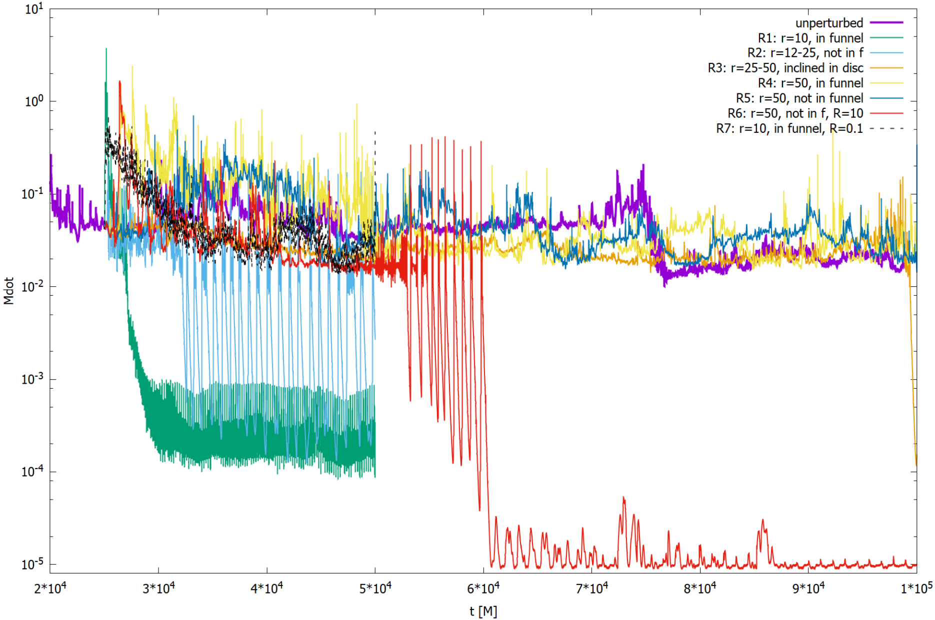



Time=100000M
rho
gamma
rho

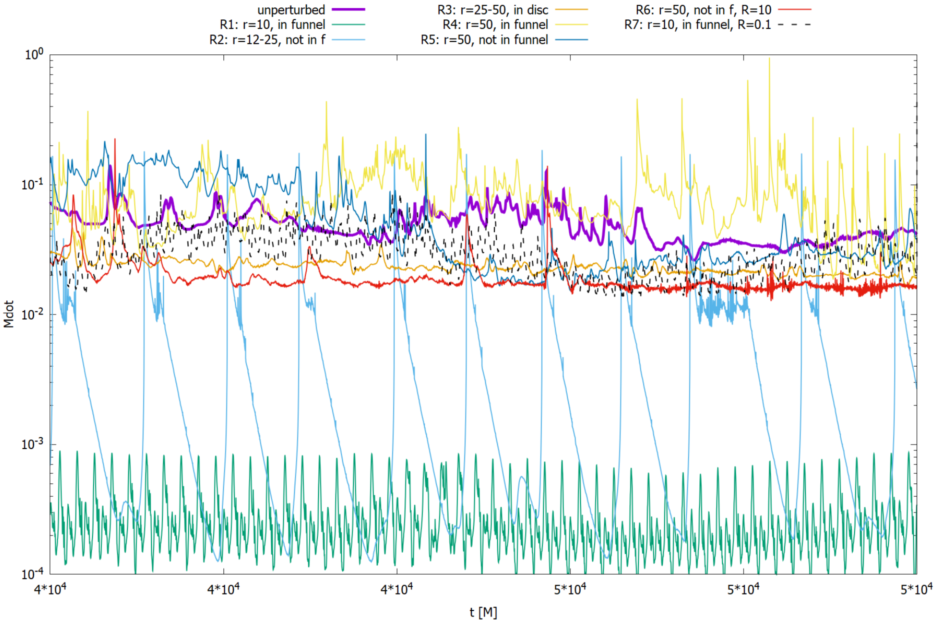
Run 2 – gas evolution



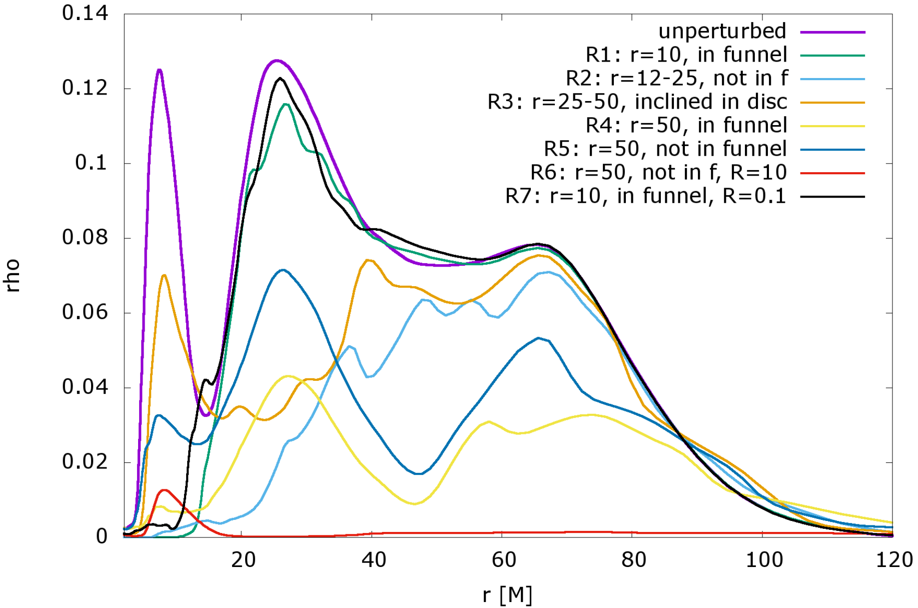
mdot of unperturbed run + 7 perturbed runs



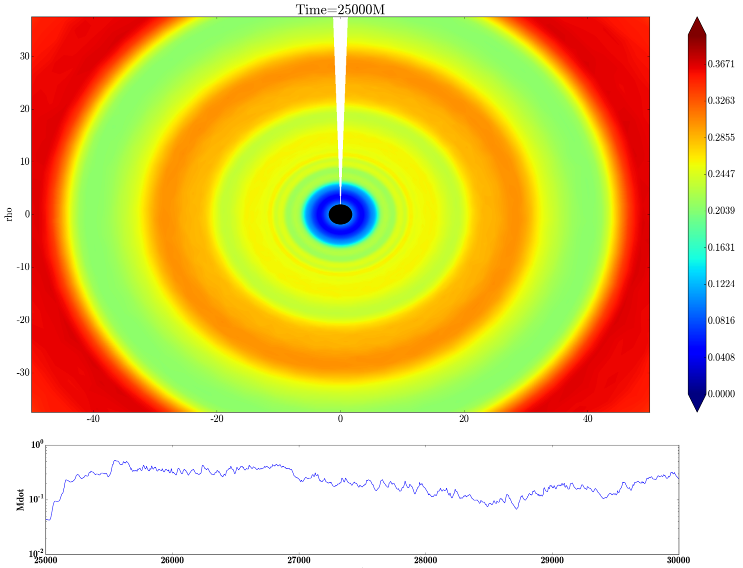
mdot of unperturbed run + 7 perturbed runs



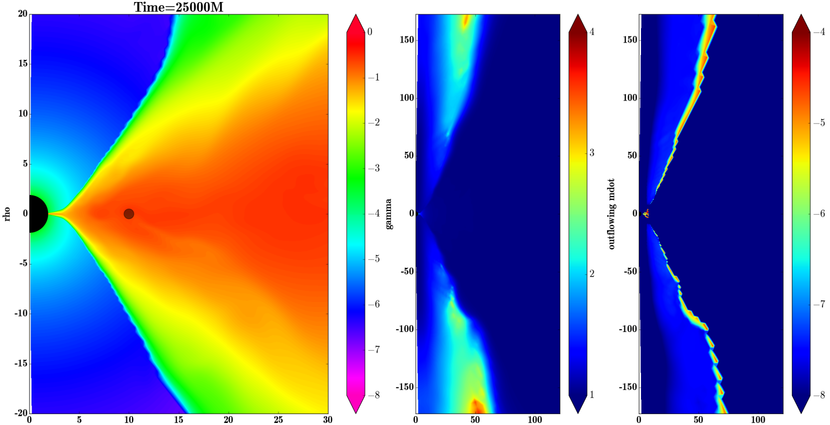
θ-averaged profile of ρ at $t = 50000$M



3D run


Time=25000M
rho
30
20
10
0
-10
-20
-30
-40
-20
0
20
40
0.3671
0.3263
0.2855
0.2447
0.2039
0.1631
0.1224
0.0816
0.0408
0.0000
Mdot
10^0
10^{-1}
10^{-2}
25000
26000
27000
28000
29000
30000

3D result averaged in ϕ-direction only for visualisation

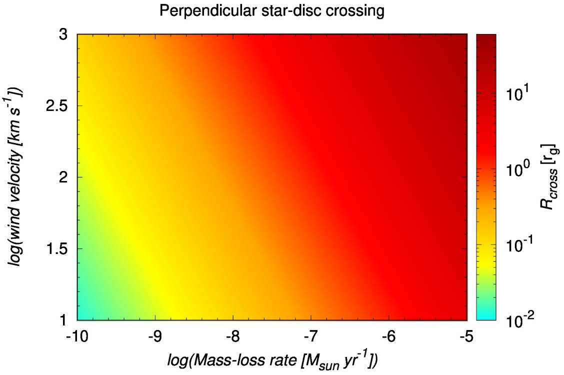


3D run much shorter than 2D runs - stationary state not achieved
similar properties – outflowing blobs along edge of funnel
quantitative differences – smaller amount of outflowing mass

Dimensions discussion

- Computation in geometrical units - scaled by black hole mass
- Interplay between BH mass, star's physical size and mass and the resolution of the grid
- Tidal radius r_t - distance from BH where the star rips
  - Sgr A*: $M_{\rm BH} = 4.2 \cdot 10^6 M_\odot \to 1M = 6.3 \cdot 10^6 km$
  - Sun: $1 r_\odot = 7 \cdot 10^5 km = 1/9M \to r_t = 18M$
  - massive star $M \sim 100 M_\odot, r \sim 9 r_\odot = 1M \to r_t = 35M$
  - white dwarf
    $M \sim 0.5 M_\odot, r \sim 0.015 r_\odot = 0.002M \to r_t = 0.33M$
- Grid resolution near $r \sim 10M \to \sim 0.2M$
  Most of our runs – star radius $R = 1$M
  test with $R = 0.1$M – worked well, so far the lower limit

- Star with strong wind (S2: $M = 13.6 M_\odot, r = 5.53 r_\odot = 0.6 M$)
- Stagnation radius $R_{\rm stag}$ = equilibrium between wind kinetic pressure and gas ram pressure
- `Wilkin (1996)`: Cross-section of bow shock $r = 1.73 R_{\rm stag}$ (perpendicular crossing) – up to 10M at radii $r \sim 50$M



To conclude

- Preliminary observations
  - Outgoing density waves in the accretion flow
  - Outgoing relativistic blobs in the funnel (γ up to several units)
    – the gaseous blobs go along the boundary between the funnel and the torus
  - Effects on the accretion rate :
    – decreased up to 2.5 orders of magnitude (4 orders in extreme case)
    – or even increased for some time period
    – quasiperiodic peaks and drops
    – stronger effect in 2D runs as anticipated
  - Influence on the total mass of the torus and the matter distribution
  - 3D simulation shows similar features with quantitatively lower effects

Thank you for your attention.