Variability of accreting black holes induced by shocks in low angular momentum flows

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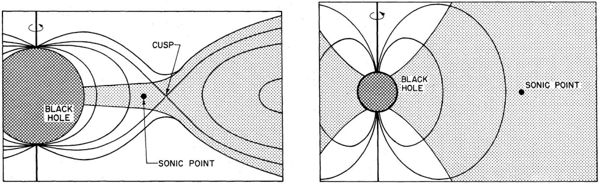
Low angular momentum flows and shocks

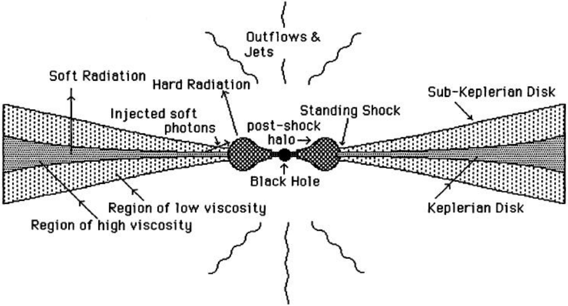
- Abramowicz & Zurek (1981) - rotational bistability of transonic accretion, discontinuous sonic point location (sonic point - inward speed of gas equals local sound speed $\mathfrak{M} = u/a = 1$)
  Two regimes of accretion of polytropic gas
  - disklike accretion - high value of angular momentum λ
    sonic point located close to compact object ($r_s < 3r_g$)
  - quasispherical accretion – low λ
    sonic point located far away from the compact object



Abramowicz & Chakrabarti (1990), Das (2002, 2003), Das & Czerny (2012)

Low angular momentum flows and shocks

- Chakrabarti & Titarchuk (1995) discussed two component accretion flow with Keplerian disc and low angular momentum layer (quasi-spherical or surrounding the disc)



- The existence of multiple critical points leads to the possibility standing shock existence and hysteresis efect ⇒ slow change of parameters can evoke asymmetric oscillatory behaviour

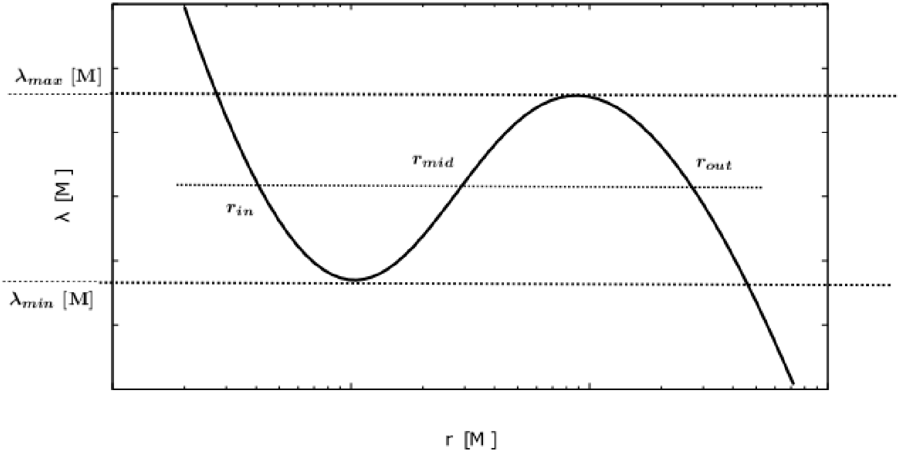
Shock existence in 1D – Quasi-spherical flow

- Continuity equation + energy conservation for the steady state + polytropic EOS ($p = K\rho^\gamma$)
  $\rightarrow$ radial gradient of the flow velocity

$$\frac{\mathrm{d}u}{\mathrm{d}r} = \frac{\frac{\lambda^2}{r^3} - \frac{\mathrm{d}\Phi(r)}{\mathrm{d}r} + \frac{2c_s^2}{r}}{u - \frac{c_s^2}{u}} = \frac{\frac{\lambda^2}{r^3} - \frac{1}{2(r-1)^2} + \frac{2c_s^2}{r}}{u - \frac{c_s^2}{u}}, \qquad (1)$$

  $\Phi(r) = -\frac{1}{2(r-1)}$ – Paczynski-Wiita gravitational potential (pseudo-newtonian description of gravity)
- Describing smooth inward accretion of gas:
  if denominator $= 0 \Rightarrow$ numerator $= 0$ – critical points
  (in our case: critical points = sonic points)

Position of critical points

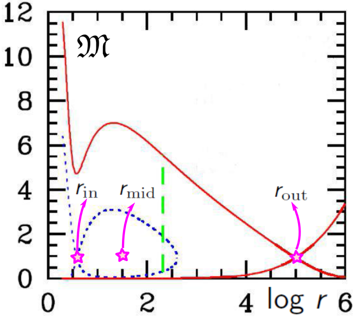


logarithmic scale of r

- Some parameters – 3 critical points (2 possible sonic points)
- Two different branches of solution going through the inner and outer critical point with the same $\dot{M}$, but different $\dot{\mathcal{M}}$

$$\dot{\mathcal{M}}_{ci} = \dot{M} K_{ci}^n \gamma^n = u_{ci} r_{ci}^2 a_{ci}^{2n} \tag{2}$$

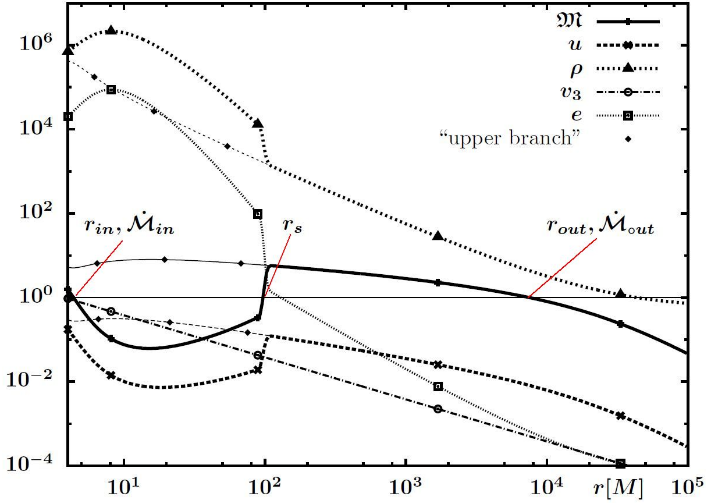
- $\dot{\mathcal{M}}_{ci}$ and K_{ci} given by $r_{c\,i}$, $u_{c\,i}$ and $a_{c\,i}$, $n = \frac{1}{\gamma+1}$



Das & Czerny (2012)

- Accretion flow with shock – outer branch with lower entropy accretion rate jumps to inner branch with higher entropy accretion rate $\dot{\mathcal{M}}_{\rm in} > \dot{\mathcal{M}}_{\rm out}$
- Rankine-Hugoniot conditions satisfied at some radius $r_s \Rightarrow$ shock possible (but not inevitable!)

1D pseudo-Newtonian computation in ZEUS



$\gamma = 4/3$, $E = 10^{-4}$, $\lambda = 3.78M$, $r_{\rm in} = 4.39M$, $r_{\rm out} = 7483M$, $r_s = 111M$

Suková & Janiuk (2015) MNRAS, 447, 1565

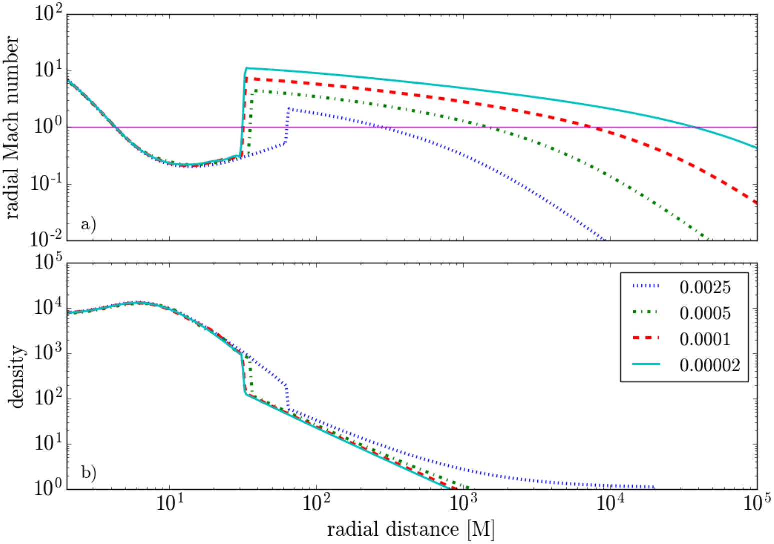
GRHD 1D/2D/3D simulations

- Open source software package for GRMHD computations `HARMPI` (Gammie et al, 2003; Tchekhovskoy et al., 2011)
  - grid based ideal MHD
  - 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:

$$\partial_t \mathbf{U}(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P}) \qquad (3)$$

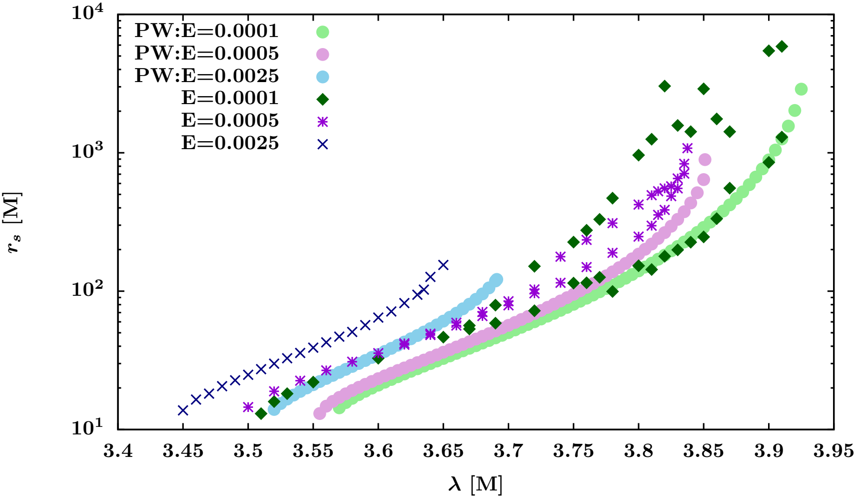
    $\mathbf{U}$ – conserved vars, $\mathbf{P}$ – primitive vars, $\mathbf{F}^i$ – fluxes, $\mathbf{S}$ – sources
  - numerical inversion of non-linear relation $\mathbf{U}(\mathbf{P})$
  - fixed background (Kerr metric) – faster computation
  - spherical coordinates – suitable for our geometry
  - logarithmic grid in r – no need of grid refinement
- Comparison with the semi-analytic results and 1D pseudo-Newtonian simulations $\Rightarrow$ first the simplest case: HD with $a = 0$, ideal gas $p = (\gamma - 1)\rho\varepsilon$

GRHD 1D simulations - stationary shock solutions



Suková, Charzyński & Janiuk (2017) MNRAS, stx2254

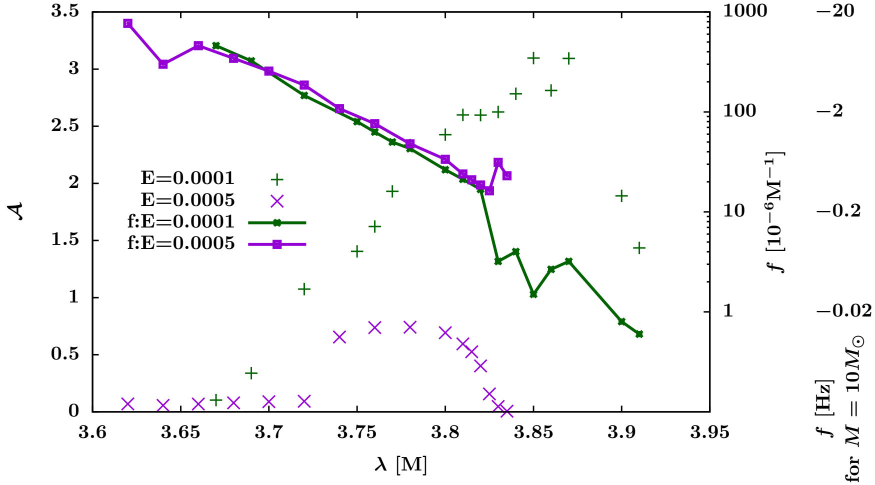
GRHD 1D versus PW comparison - shock position



Oscillations of the shock front – non-stationary solution

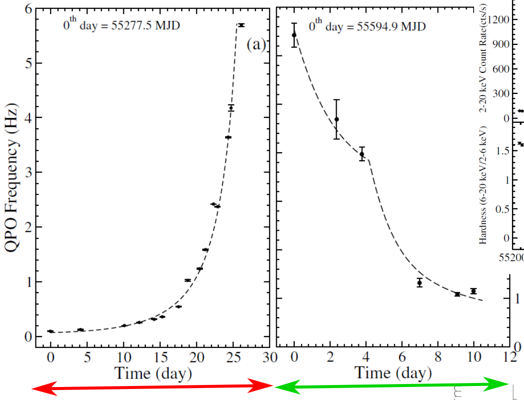
$\Rightarrow$ variable accretion rate on the black hole

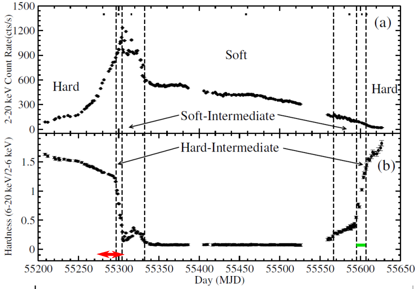
GRHD 1D simulations - oscillations of mass accretion rate

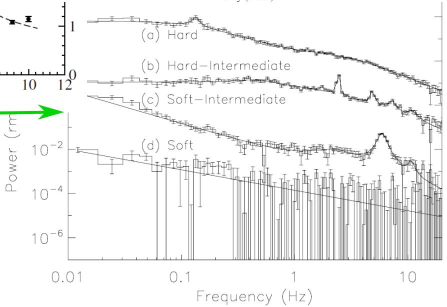


$$\mathcal{A} = (\max(\dot{M}) - \min(\dot{M}))/\bar{\dot{M}}$$

Changing QPO frequency during outburst of GX 339-4





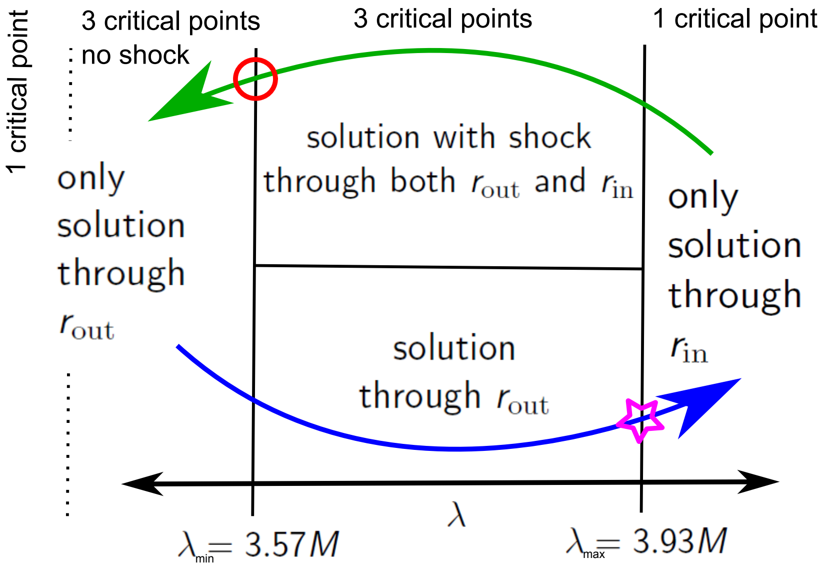


0.102Hz→5.692Hz

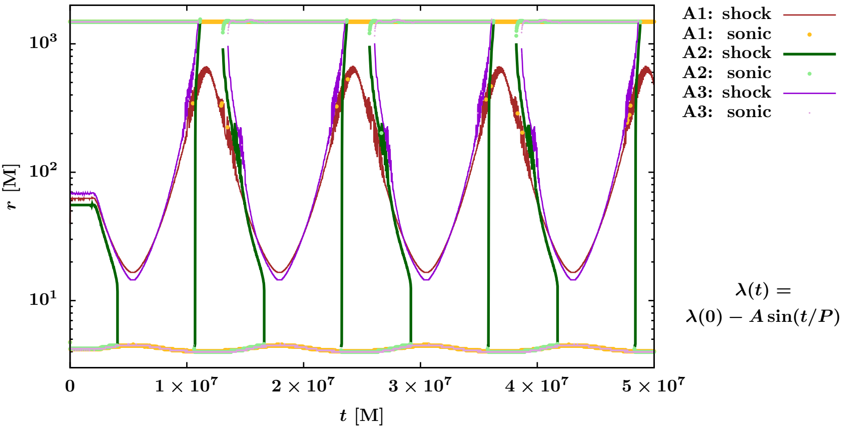
6.42Hz→1.149Hz

Nandi et al., 2012, A&A, 542, A56

Changing λ at the outer boundary and hysteresis loop

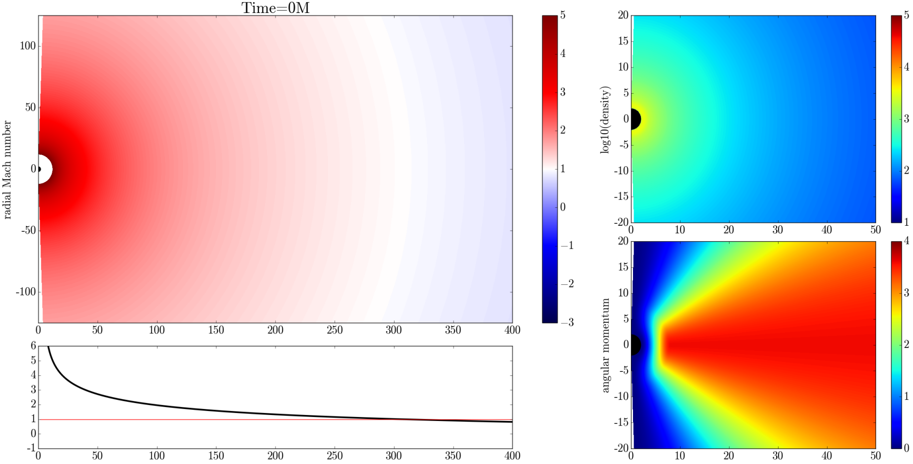


Hysteresis loop in 1D GRHD simulations



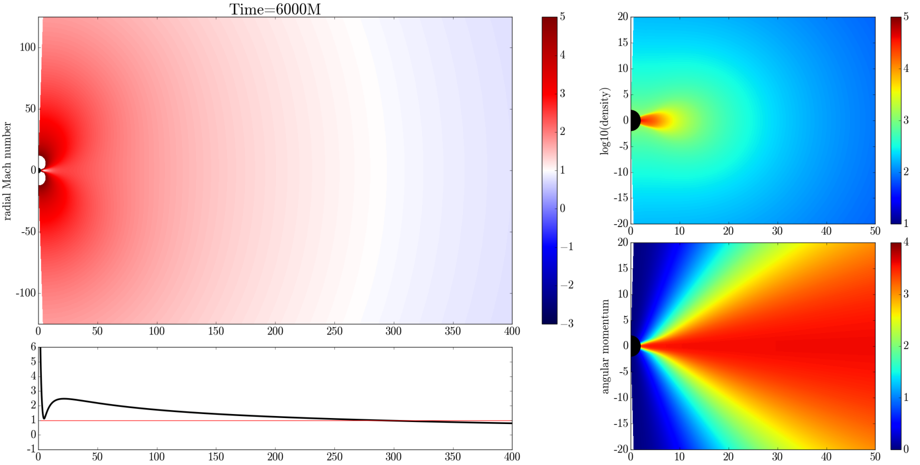
A1 – does not cross any boundary; A2 – crosses lower and upper boundary; A3 – crosses upper boundary

Bondi configuration + slow rotation



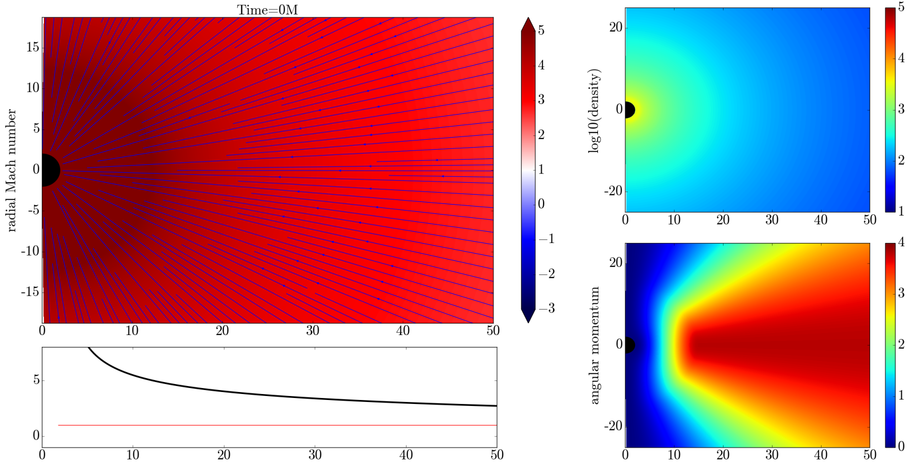
$\gamma = 4/3$, $E = 0.0025$, $\lambda = 3.6M$, $r_{\mathrm{in}} = 4.9M$, $r_{\mathrm{out}} = 284.3M$, $r_s = 34.9M$

Bondi configuration + slow rotation

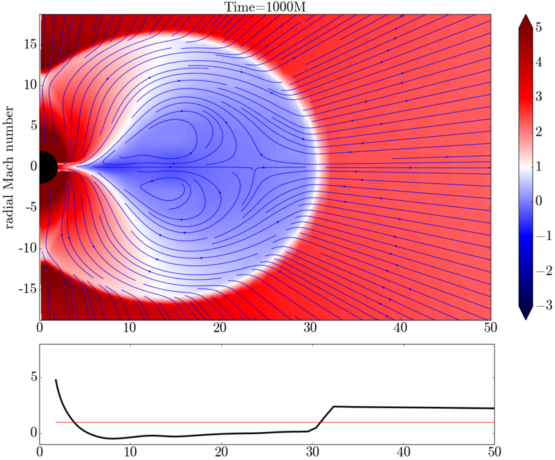


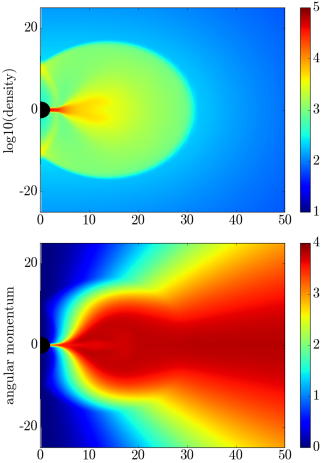
$$\gamma = 4/3,\ E = 0.0025,\ \lambda = 3.6M,\ r_{\rm in} = 4.9M, r_{\rm out} = 284.3M,\ r_s = 34.9M$$

Bondi configuration + higher λ, t=0M



$\gamma = 4/3,\ E = 0.0025,\ \lambda = 3.8M$





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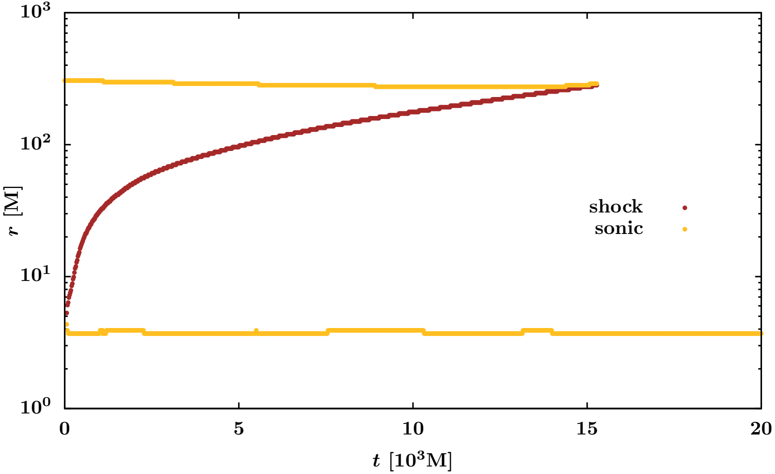

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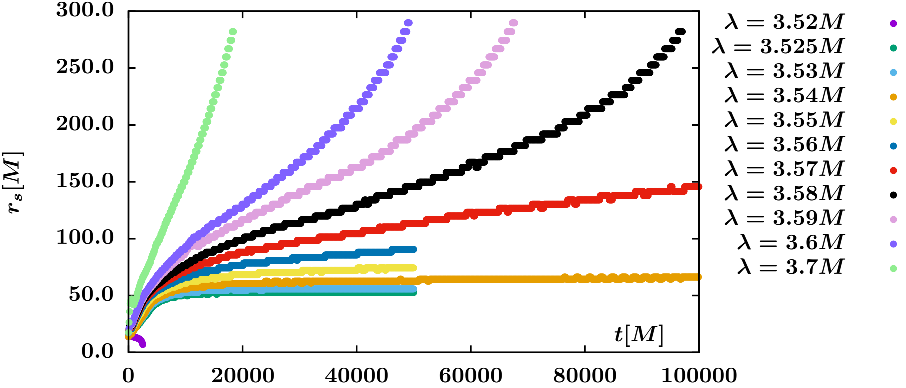
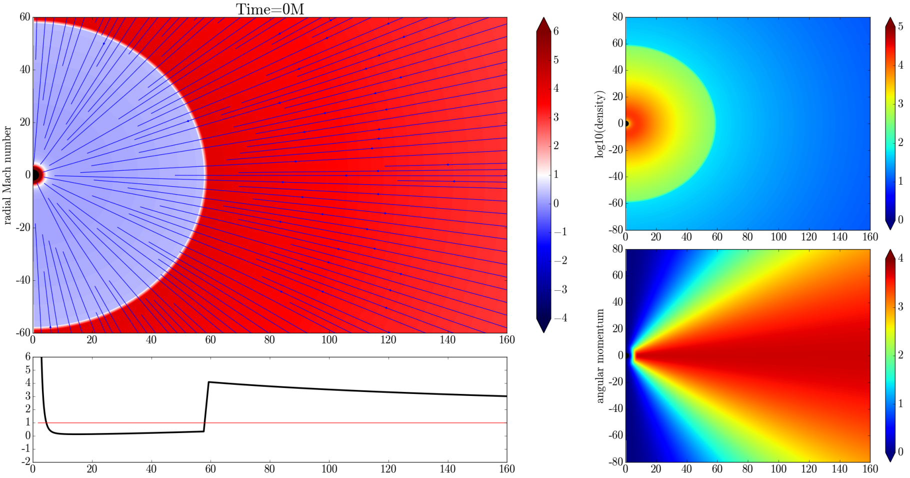


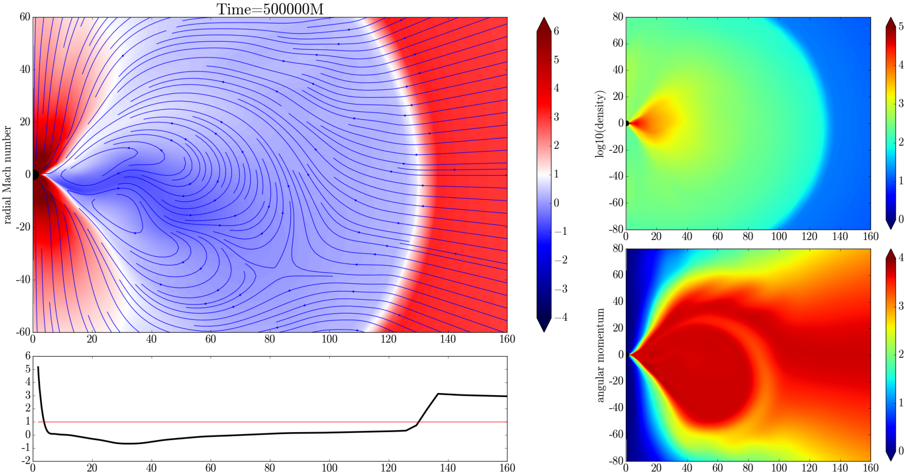
$\gamma = 4/3$, $E = 0.0025$, `Suková & Janiuk (2016), Proceedings of the International Astronomical Union, S324, 23`

Shock solution with spherical density distribution - lower E



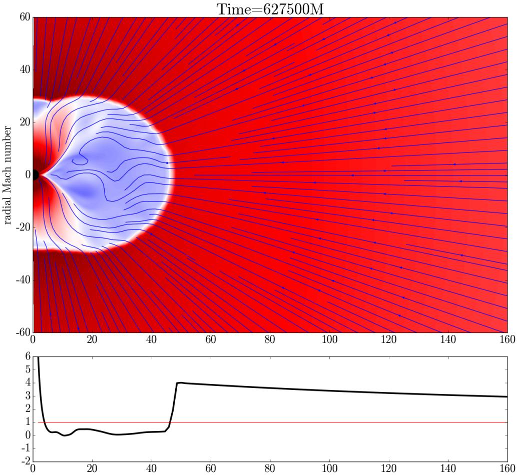
$\gamma = 4/3,\ E = 0.0005,\ \lambda = 3.72M$

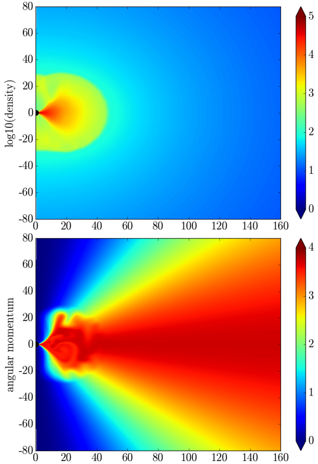
Shock solution with spherical density distribution - lower E



$$\gamma = 4/3,\ E = 0.0005,\ \lambda = 3.72M$$

Shock solution with spherical density distribution - lower E





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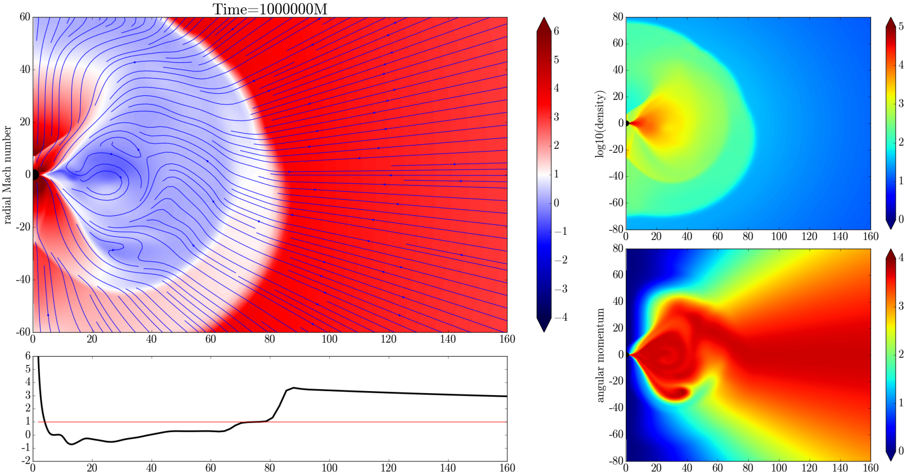
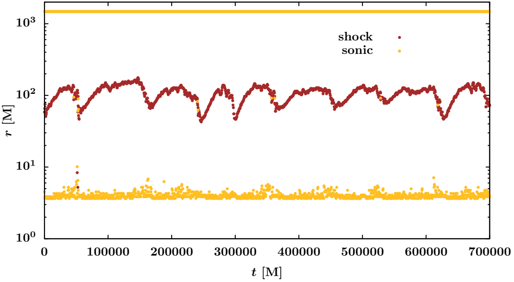
Shock solution with spherical density distribution - lower E



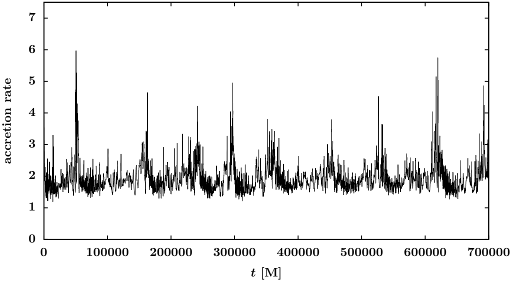
$$\gamma = 4/3,\ E = 0.0005,\ \lambda = 3.72M$$

Time dependent shock position and accretion rate



$\gamma = 4/3$
$E = 0.0005$
$\lambda = 3.72M$

$M = 10M_\odot$:
$10^5 M \approx 5$s



Similar results for spinning black hole:
smaller values & narrower range of λ
$a = 0$: $\lambda \in (3.59 - 3.8)$M;
$a = 0.3$: $\lambda \in (3.35 - 3.48)$M;
$a = 0.8$: $\lambda \approx 2.8$M;
$a = 0.95$: $\lambda \approx 2.45$M

Suková, Charzyński & Janiuk (2017) MNRAS, stx2254

Conclusions & Future plans

- Semi-analytical treatment of shock existence in quasi-spherical flow with low angular momentum in 1D + simulations
- Hysteresis loop proposed by `Das & Czerny (2012)` in 1D
- First results in GRHD in 2D/3D with `Einstein toolkit` and `HARMPI` – outer Bondi-like branch of solution confirmed, shock solution – steady standing shock configuration or shock growing, shock front moving outside, slightly different values of parameters, oscillations observed
- Near future goals:
  - Influence of magnetic field on shock geometry – transport of angular momentum
- Further goals:
  - Inclusion of the Keplerian component into the simulations
  - Add more physical properties (better EOS, radiation, etc.)
  - Comparison with AGNs' flares and microquasars' outbursts (models and observational data)

Important literature

- Observations and modelling
  - Chakrabarti et al., 2008, A&A, 489, L41
  - Mościbrodzka et al., 2006, MNRAS, 370, 219
  - Nandi et al., 2012, A&A, 542, A56
  - Nowak et al., 2012, ApJ, 759, 95
- Hydrodynamical simulation in 2D
  - Proga, Begelman, 2003, ApJ, 582, 69
  - Janiuk, Proga, Kurosawa, 2008, ApJ, 681, 58
- Theoretical studies about the possible shocks existence
  - Abramowicz, Zurek, 1981, ApJ, 246, 314
  - Abramowicz, Chakrabarti, 1990, ApJ, 350, 281
  - Chakrabarti, Titarchuk, 1995, ApJ, 455, 623
  - Das, 2002, ApJ, 577, 880
  - Das, Czerny, 2012, NA, 17, 254
- Our results
  - Suková & Janiuk (2015) MNRAS, 447, 1565
  - Suková & Janiuk (2015) JPCS, 600, 012012
  - Suková at al (2016) Proc. of IAU, S324, 23
  - Suková at al (2017) MNRAS, 472, 4327