Studies of black hole accretion flows with computational astrophysics methods

Astroparticle Physics in Poland

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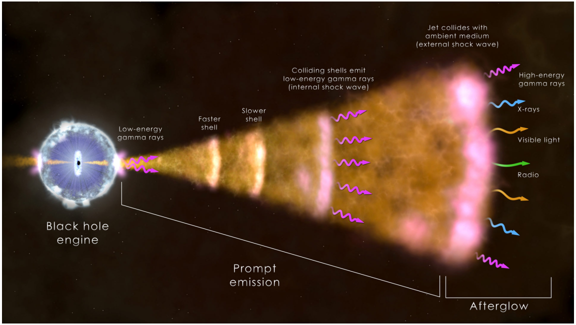
Astrophysics group in Center for Theoretical Physics

- The NCN grant *Astrophysics of processes around compact objects* - prof. Janiuk, 2013–2018
- Grant goals - study the relation between the observable variability of outcoming radiation from systems containing compact object (neutron star or black hole) and the physical processes going on in the accretion flow on these objects
- Study of BHs in different situations - formation of BH in collapsar/merger connected with GRB, properties of accretion disc of stellar mass BH in binaries, properties of corona in stellar mass/supermassive BHs
- Postdocs:
  - dr Petra Suková
  - dr Szymon Charzyński (CFT PAN / FUW)
- PhDs:
  - Mikołaj Grzedzielski
  - Bartłomiej Kamiński (until September 2014)

Astrophysics group in CFT – collaborators

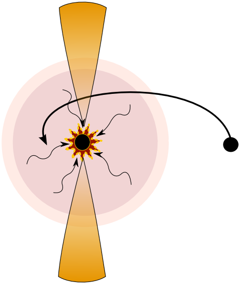
- prof. Bożena Czerny (CFT PAN)
- dr hab Michal Bejger (CAMK PAN)
- prof. Marek Abramowicz, Wenchi Yan (CAMK PAN)
- Maciek Wielgus (IMIF PW)
- dr Magdalena Kunert-Bajraszewska (Centrum Astronomii UMK)
- dr Fiamma Capitanio (INAF), Stefano Bianchi (DMF UR3) – Rome, Italy
- prof. Ranjeev Misra (IUCAA, Pune, India)
- doc. Oldřich Semerák, Vojtěch Witzany (MFF UK Prague, Czech Republic)
- prof. Josef Málek (MFF UK Prague, Czech Republic)
- prof. Kumbakonam Rajagopal (TAMU, College Station, USA)

- GRB - extremely energetic, transient events
- possible mechanism - collapse of massive star (long GRB) or merge of 2 compact objects (short GRB) $\rightarrow$ new BH
- engine of the process - hot and dense accretion disc with hyper-Eddington accretion rate (up to 1 $M_{\odot} s^{-1}$) triggers powerful, ultra-relativistic jets, which produce gamma ray radiation far away from the central region



A. Janiuk and S. Charzyński
Binary black hole merger simulations

- combination of the two scenarios (close binary of massive OB star + BH) can yield the longest GRBs
- simulations of such scenario very complicated, consists of several steps:



  - spinning up the massive star, common envelope phase
  - core collapse and accretion of inner envelope, primary BH mass and spin evolution, possible jet launch
  - binary BH merger in vacuum
  - accretion of the envelope onto the merged product

poster *Simulations of binary black hole mergers*

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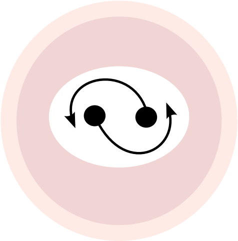

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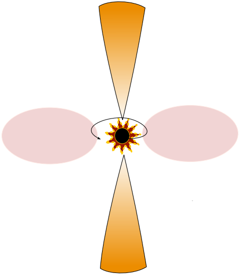

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poster *Simulations of binary black hole mergers*

A. Janiuk – Neutrino cooled GRB central engine

- last phase of long GRB - accretion of heavy torus made from gas remnants onto the newly born rotating black hole
- initial conditions: equilibrium model of a thick torus around spinning black hole "Polish donut" (`Fishbone & Moncrief 1976, Abramowicz et al. 1978`)
- poloidal magnetic field inside the torus, strength parametrized by the β parametr - gas pressure to magnetic pressure ratio
- relativistic, partially degenerate species (free nuclei, e^-, e^+, n, p^+, He)
- gas in beta equilibrium (partially) opaque to absorption and scattering of neutrinos is cooled by neutrino emission, advection, photodissociation of α-particles and radiation
- nuclear equation of state of disc around Kerr black hole with arbitrary spin computed numerically from nuclear reaction balance (`Janiuk et al.(2007), Janiuk & Yuan (2010)`)

High Accuracy Relativistic Magnetohydrodynamics

HARM – `Gammie et al.(2003)` – provides solver for continuity and energy-momentum conservation equations:

$$(\rho u^{\mu})_{;\mu} = 0; \qquad T^{\mu}{}_{\nu;\mu} = 0, \qquad p = K\rho^{\gamma} = (\gamma - 1)u$$

where:

$$T^{\mu\nu} = T^{\mu\nu}_{gas} + T^{\mu\nu}_{EM}$$

$$T^{\mu\nu}_{gas} = (\rho + u + p)u^{\mu}u^{\nu} + pg^{\mu\nu} \qquad T^{\mu\nu}_{EM} = b^2 u^{\mu}u^{\nu} + \frac{1}{2}b^2 g^{\mu\nu} - b^{\mu}b^{\nu}$$

assuming force-free approximation.

Modification – each time step calculation of gas nuclear structure satisfying the balance of nuclear reaction → neutrino production rate → computation of neutrino optical depths of scattering and absorption → neutrino cooling rate → internal energy reduced

Mass and energy flow in the simulations

- computation of the mass accretion rate through the horizon
- evaluation of the radial energy flux, as the power of the Blandford-Znajek process:

$$\dot{E} \equiv 2\pi \int_0^{\pi} d\theta \sqrt{-g} F_E$$

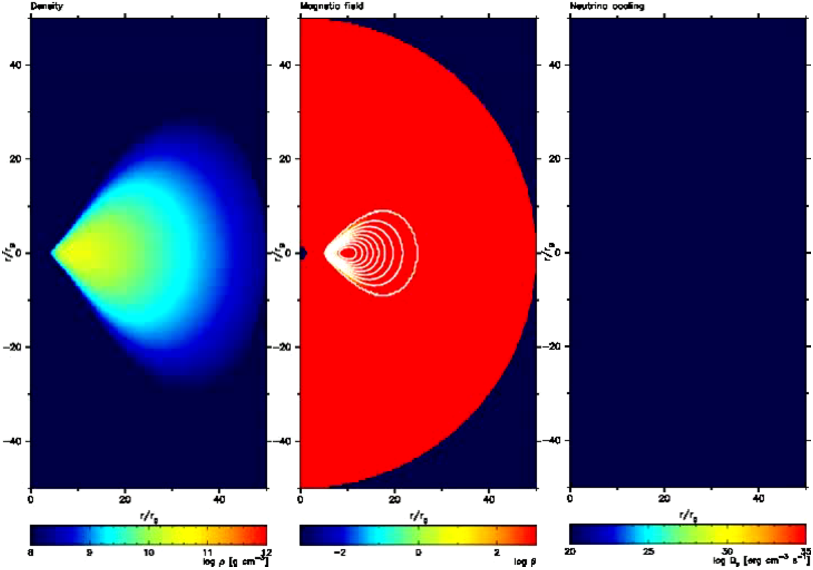
where $F_E \equiv -T^r_t$. This can be subdivided into a matter $F_E^{(MA)}$ and electromagnetic $F_E^{(EM)}$ part, although in the force-free limit the matter part vanishes (McKinney & Gammie 2004).

- neutrino cooling rate is given by the two-stream approximation

$$Q^-_\nu = \frac{\frac{7}{8}\sigma T^4}{\frac{3}{4}} \sum_{i=e,\mu} \frac{1}{\frac{\tau_{\mathrm{a},\nu_\mathrm{i}}+\tau_\mathrm{s}}{2} + \frac{1}{\sqrt{3}} + \frac{1}{3\tau_{\mathrm{a},\nu_\mathrm{i}}}} \times \frac{1}{H} \ [\mathrm{erg\ s^{-1}\ cm^{-3}}]$$

$$L_\nu = \int Q^-_\nu dV \ [\mathrm{erg\ s^{-1}}].$$

Density | Magnetic field | Neutrino cooling



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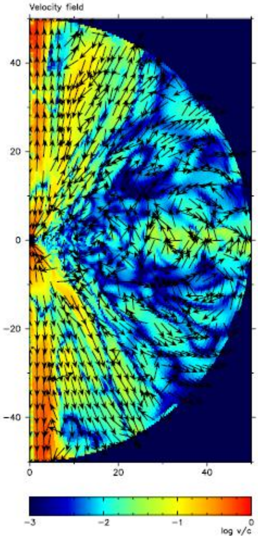
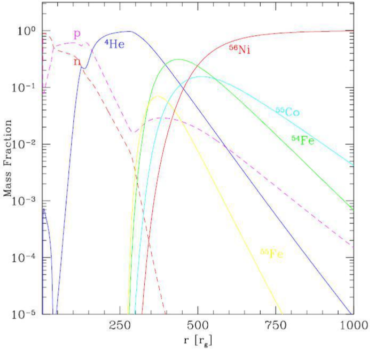
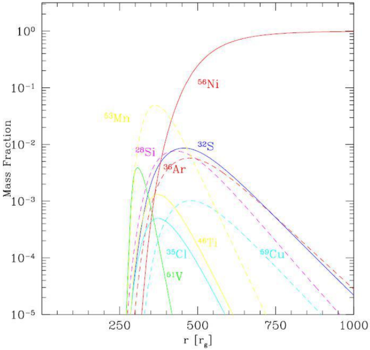


- jet launch in the polar region
- wind takes away more mass than accreted
- neutrinos produced in disc and wind
- energy for jets is available due to annihilation of neutrino-antineutrino pairs (efficiency $\sim$ few percent) and transfer of the BH rotation energy through the Blandford-Znajek process
-

BH spin	$a = 0.8 - 0.98$
Time averaged $\dot{M}$	$\dot{M} = 0.3 - 1.7 M_{\odot}/s$
Neutrino luminosity L_{ν}	$8 \cdot 10^{51} - 4 \cdot 10^{53}$ erg/s
Blandford-Znajek luminosity at L_{BZ}	$6 \cdot 10^{50} - 2 \cdot 10^{52}$ erg/s

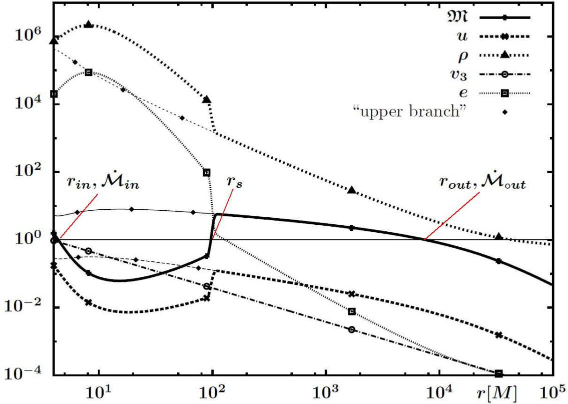
- 1D version of similar computations to high radii
- nucleosynthesis and abundances of heavy elements in the outer part computed – thermonuclear reaction network code (< 1MeV) $\rightarrow$ creation of Ni, Co, Fe, Si, Ar, Cu, V, Mn etc.



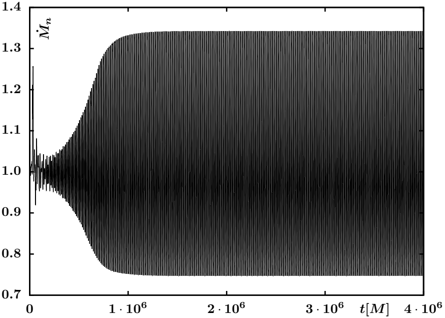


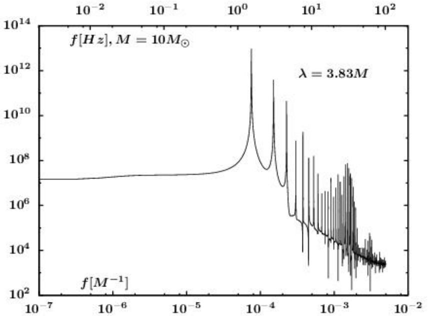
- Study the variability of low luminous X-ray sources or the part of the variability of high luminous sources connected with the hot corona
- Low luminous galactic nuclei including Sgr A* $\rightarrow$ quasi-periodic oscillations (QPOs) and flares observed
- Stellar black hole binaries in the quiescent state bright flares (change of count rate by a factor of 5-8)
- In some stellar black hole candidates QPOs with changing frequency have been observed (e.g. GX 339-4)
- Possible explanation – quasi-spherical accretion flow with shocks forms instead of an evaporated Keplerian accretion disc or around it
- Influence on velocity and density profiles, time dependence of mass accretion rate

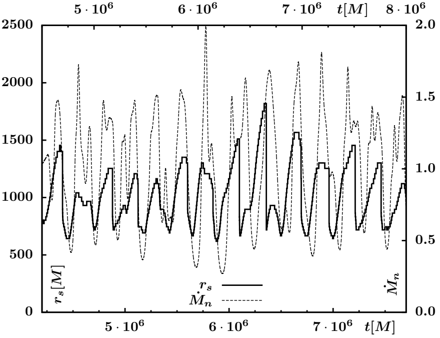
- semi-analytical treatment of shocks in quasispherical flow (1D)
- position of critical points and shock front found for the steady state in dependence on several parameters - specific energy ε, specific angular momentum λ and adiabatic index γ

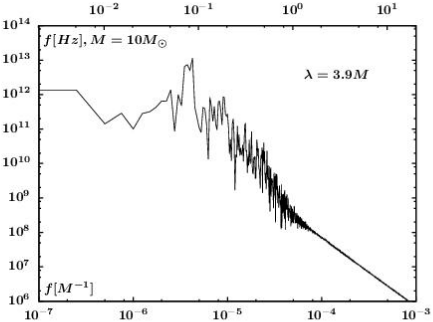


$\gamma = 4/3$,
$\varepsilon = 0.0001$,
$\lambda = 3.78M$,
$r_{\rm in} = 4.39M$,
$r_{\rm out} = 7482.81M$,
$r_s = 110.57M$

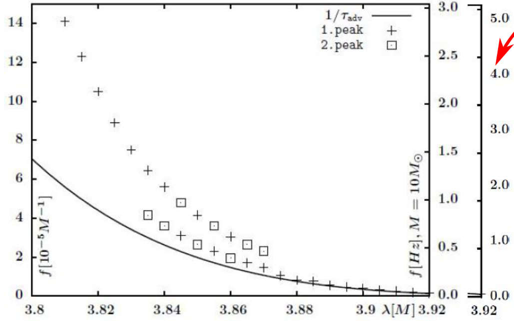

$\dot{M}_n$
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0
$1 \cdot 10^6$
$2 \cdot 10^6$
$3 \cdot 10^6$
$t[M]$
$4 \cdot 10^6$


10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
$f[Hz], M = 10M_\odot$
$\lambda = 3.83M$
10^{14} 10^{12} 10^{10} 10^{8} 10^{6} 10^{4} 10^{2}
$f[M^{-1}]$
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2}


$5 \cdot 10^6$ $6 \cdot 10^6$ $7 \cdot 10^6$ $t[M]$ $8 \cdot 10^6$
2500 2000 1500 1000 500 0
2.0 1.5 1.0 0.5 0.0
$r_s[M]$
$\dot{M}_n$
r_s
$\dot{M}_n$
$5 \cdot 10^6$ $6 \cdot 10^6$ $7 \cdot 10^6$ $t[M]$

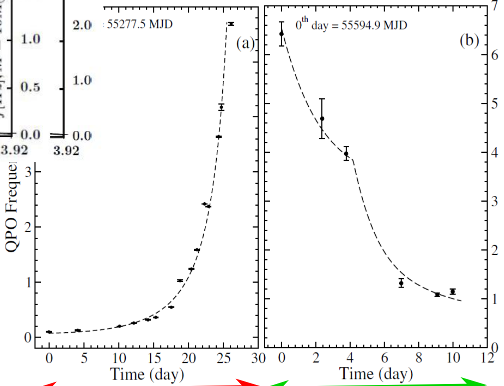

10^{-2} 10^{-1} 10^{0} 10^{1}
$f[Hz], M = 10M_\odot$
$\lambda = 3.9M$
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6}
$f[M^{-1}]$
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3}

Dependence of oscillations on angular momentum



GX 339-4 $M = 5.8 \pm 0.5 M_{\odot}$

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

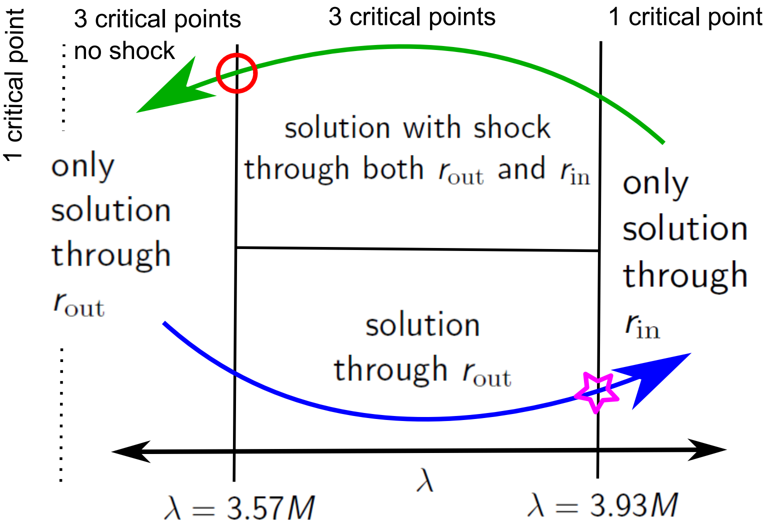


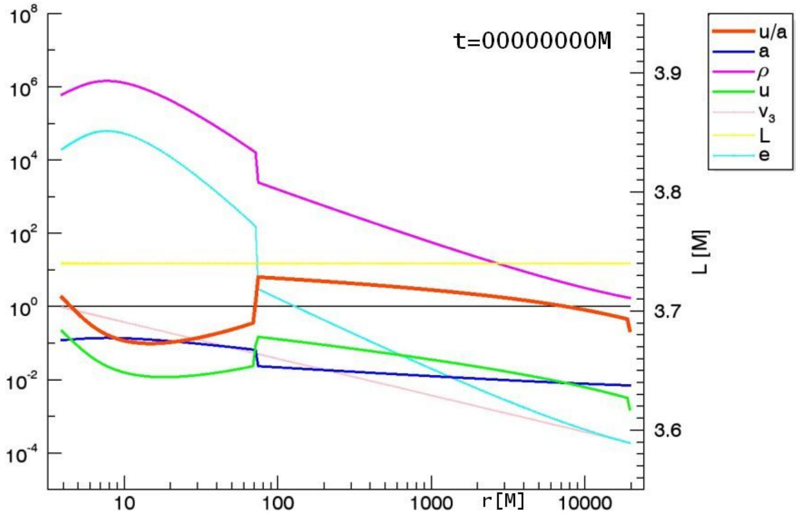
dependence of frequency of oscillations on ang. momentum

0.102Hz → 5.692Hz

6.42Hz → 1.149Hz

Changing λ at the outer boundary and hysteresis loop

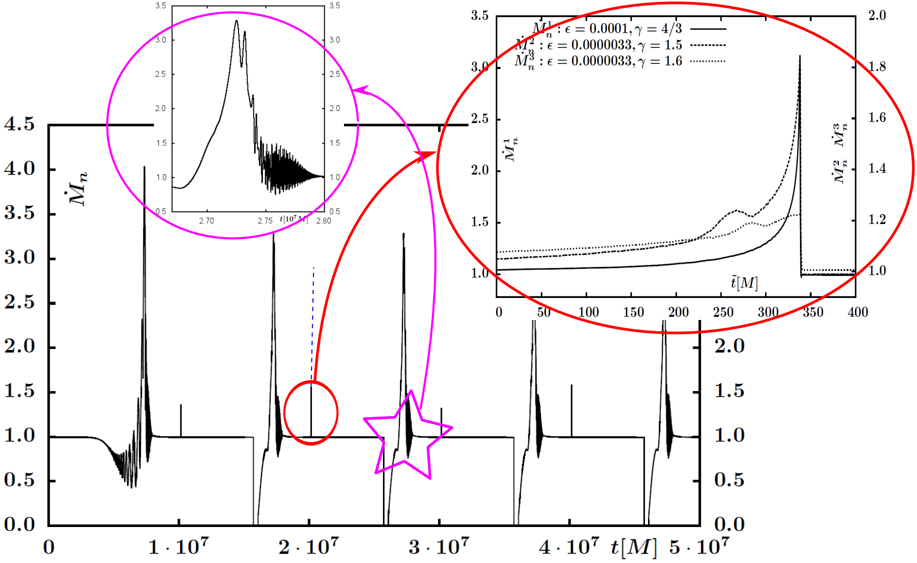




$$\gamma = 4/3,\ \varepsilon = 0.0001,\ \lambda_0 = 3.74M,\ \Delta\lambda = 0.18M,\ T_v = 10^7 M$$

$$v_3(t) = \lambda(t)/r, \qquad \lambda(t) = \lambda_0 + \Delta\lambda \sin\left(\frac{2\pi t}{T_v}\right),$$

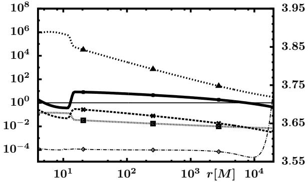
Broader and sharper peaks in $\dot{M}$ during hysteresis loop



Broader and sharper peaks in $\dot{M}$ during hysteresis loop

Two types of events:

- "purple star" – broad peak
  crossing upper boundary of multi-solution region from below
  caused due to the switch to the shock solution with higher density for high λ and its lowering with decreasing λ
  depends on T_v: $\sim (0.1 - 5)\%$
  when T_v is too long - oscillations develop
- "red circle" – sharp peak
  crossing lower boundary of multi-solution region from above
  very short event
  $\sim 50 - 250M$



timescale $\sim$ time of fall from minimal shock position $r_s^{\min}$
$\Rightarrow$ depends on γ, does not depend on T_v

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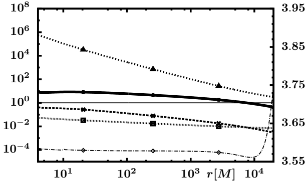

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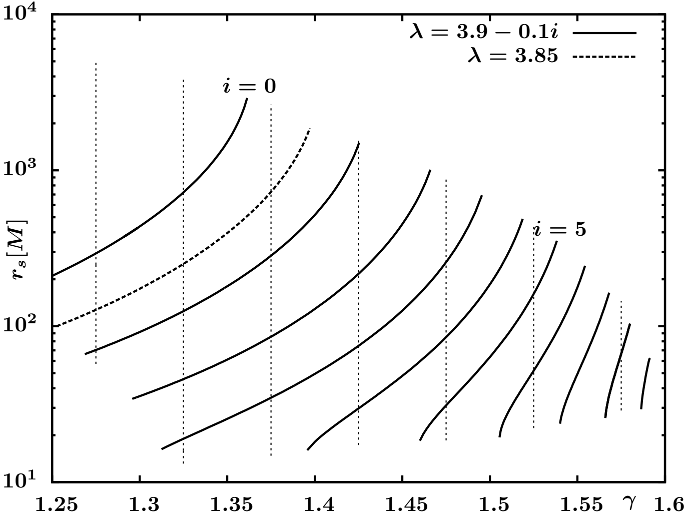
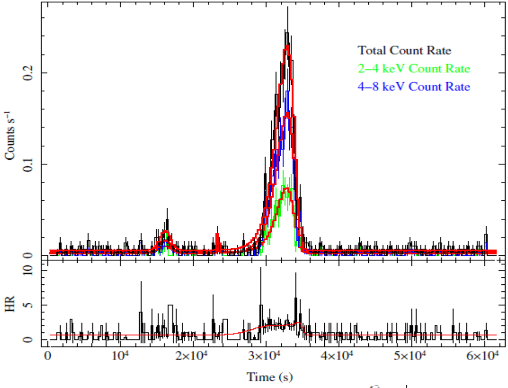
Dependence of shock position on adiabatic index



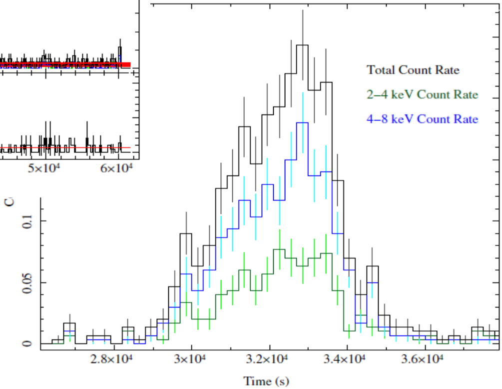
for constant γ and changing λ:
different range of possible shock position ($r_s^{\min}$; $r_s^{\max}$)

Bright flare of Sgr A*



Nowak et al., 2012, ApJ, 759, 95

Sgr A* observation



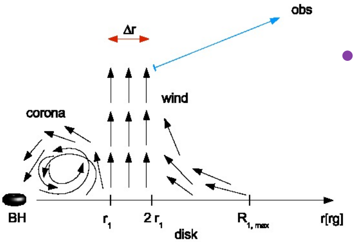
Sgr A* $M \sim 4.3 \cdot 10^6 M_\odot$

$[t] = 1M \approx 21.5s$

$5ks \approx 230M$

Shocks in low angular momentum flows – Conclusions

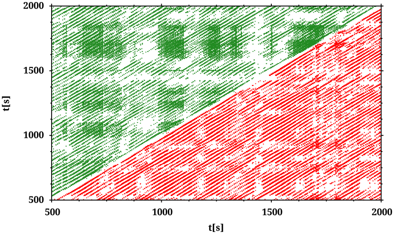
- Semi-analytical treatment of shock existence in quasi-spherical flow with low angular momentum in 1D
- 1D numerical simulations with ZEUS code
- For subset of parameters oscillations of shock position found, frequency depends on λ, for stellar BH frequency in the range (0.01 – 10) Hz (slight dependence on the artificial linear and quadratic viscosity)
- Case with changing λ of the incoming matter studied
- Hysteresis loop proposed by `Das & Czerny (2012)` observed
- Broader and sharper peaks in accretion rate connected with the reshape of the flow observed
- Sharper peaks depend on γ (not on T_v), time scale and shape in agreement with the Sgr A* flare

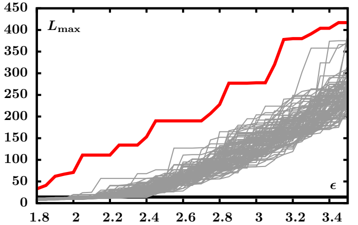


- heartbeat state of IGR J17091 - state of quasi-periodic faint flare-like events $\sim$ tens of seconds, amplitude increases several times, similar to GRS 1915+105 (much brighter)

- part of the generated energy during heating accelerates particles $\rightarrow$ wind $\rightarrow$ heating reduced $\rightarrow$ the amplitude of oscillations decreases, frequency increases
- for some parameters in agreement with observation of IGR J17091 (amplitude and frequency of oscillations, observation of winds parameters)
- Details on poster *Heartbeat oscillations and wind outflow in IGR J17091-3624*

M. Grzedzielski, A. Janiuk and P. Suková
Recurrence analysis of the XRBHB lightcurves





- evolution of accretion disc due to radiation instability cycle is low-dimensional non-linear (chaotic) dynamical system
- traces of non-linear behaviour is imprinted in the lightcurve (RXTE usually 2-10 keV – corresponds to disc)
- time series analysis (= recurrence analysis) and comparison with surrogate data (same distribution and spectrum)
- poster *Searching for deterministic chaos in the accreting BH*

Astrophysics group in CFT

Studies of BH in various cosmic enviroments:

1. BH mergers
2. Collapsars and GRB central engine
3. BH in Galaxy Center
4. Microquasars

using time analysis of X-ray data, semi-analytical approach and numerical hydro-simulations with relativistic MHD

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http://www.cft.edu.pl/astrofizyka

including links to papers, talks, group schedule, lectures and simulation results