The flip-flop instability of the shock cone around the rotating black hole

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Outline

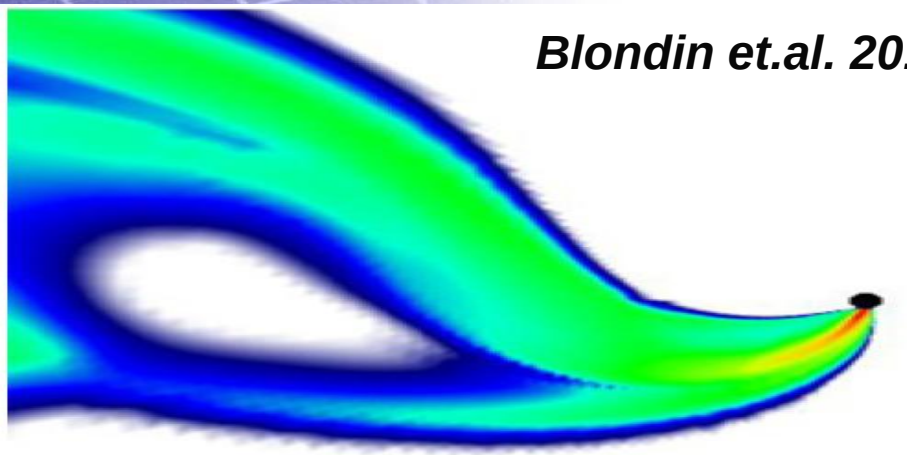
- Intro.
- GRH equations
- Results from numerical simulations
- QPOs
- Final remarks

Flip-flop instability?

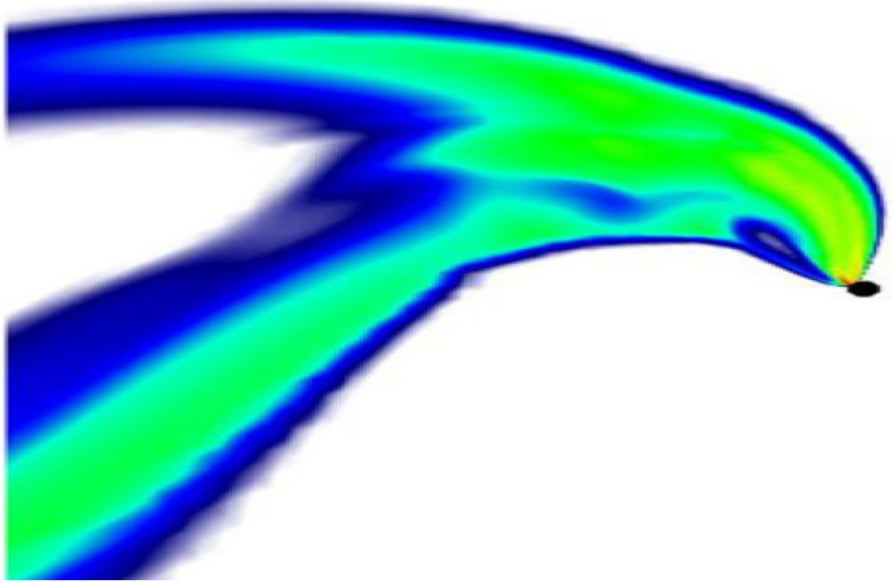
- Can cause the variation of torque
- Explain erratic spin behaviour of the black hole or neutron stars
- Wind fed X-ray binaries (Vela X-1,GX 301-2, 4U 1700-377 …) and may be Sgr A*?
- Galaxies in clusters
- Star formation

What we know about flip-flop-1?

- There are 2D numerical simulations which indicates flip-flop oscillations(Blondin 2010, Foglizzo, 2005)
- They are all in Newtonian hydrodynamics.
- And the shock is mostly attached to the accreator.



Blondin et.al. 2010



What we know about flip-flop-2?

- **Although some observational results (Sgr A*) show the detached (bow) shock.**
- **There is not clear evidence of the flip-flop oscilation in 3D.**
- **It is never found in a relativistic region either in 2D or 3D.**

GRH Equations-1

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

$$\nabla_\mu T^{\mu\nu} = 0, \qquad \nabla_\mu J^\mu = 0.$$

$$T^{\mu\nu} = \rho h u^\mu u^\nu + P g^{\mu\nu} \Rightarrow$$ ***stress energy tensor***

$$J^\mu = \rho u^\mu \Rightarrow$$ ***current density***

$$h = 1 + \varepsilon + \frac{p}{\rho} \Rightarrow$$ ***entalphy***

GRH Equations-2

$$\frac{\partial \vec{U}}{\partial t} + \frac{\partial \vec{F}^{\,i}}{\partial x^i} = \vec{S}$$

$\vec{U} \Longrightarrow$ ***Conserved Variables*** $\qquad \vec{F}(\vec{U}) \Rightarrow$ ***Flux*** $\qquad \vec{S} \Longrightarrow$ ***Sources***

$$\vec{U} = \begin{pmatrix} D \\ S_j \\ \tau \end{pmatrix} = \begin{pmatrix} \sqrt{\gamma} W \rho \\ \sqrt{\gamma}\, \rho h W^2 v_j \\ \sqrt{\gamma}\,(\rho h W^2 - P - W\rho) \end{pmatrix}$$

$$\vec{F}^{\,i} = \begin{pmatrix} \alpha(v^i - \frac{1}{\alpha}\beta^i) D \\ \alpha\{(v^i - \frac{1}{\alpha}\beta^i) S_j + \sqrt{\gamma} P \delta^i_j\} \\ \alpha\{(v^i - \frac{1}{\alpha}\beta^i)\tau + \sqrt{\gamma} v^i P\} \end{pmatrix}$$

Initial Conditions

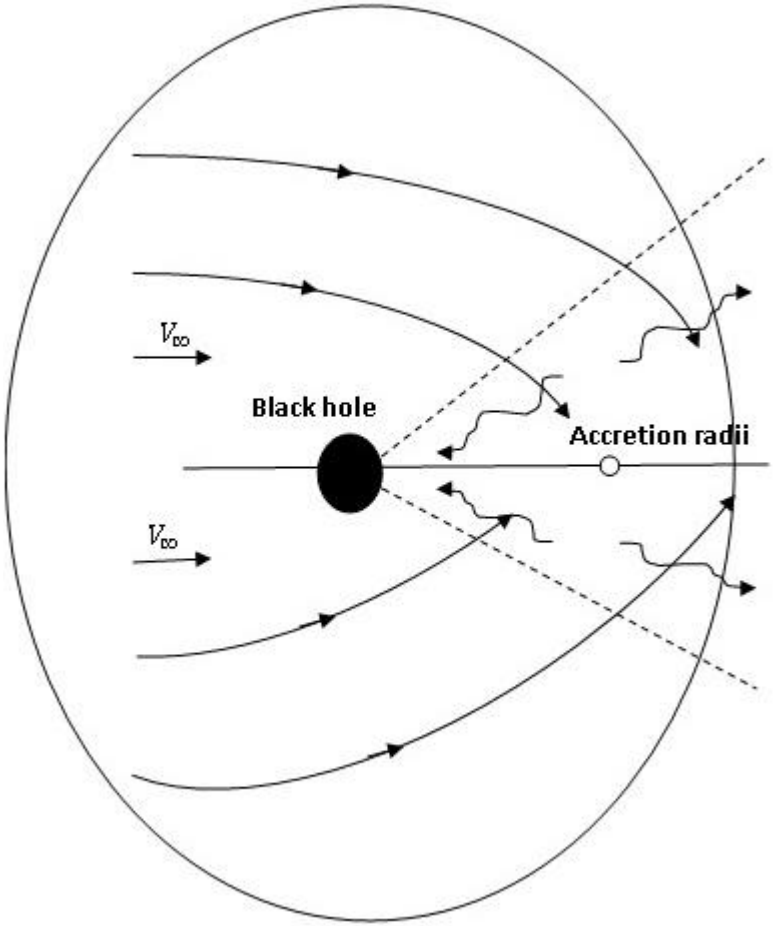
$$(r-\phi), 1.78M \le r \le 44M \text{ ve } 0 \le \phi \le 2\pi$$

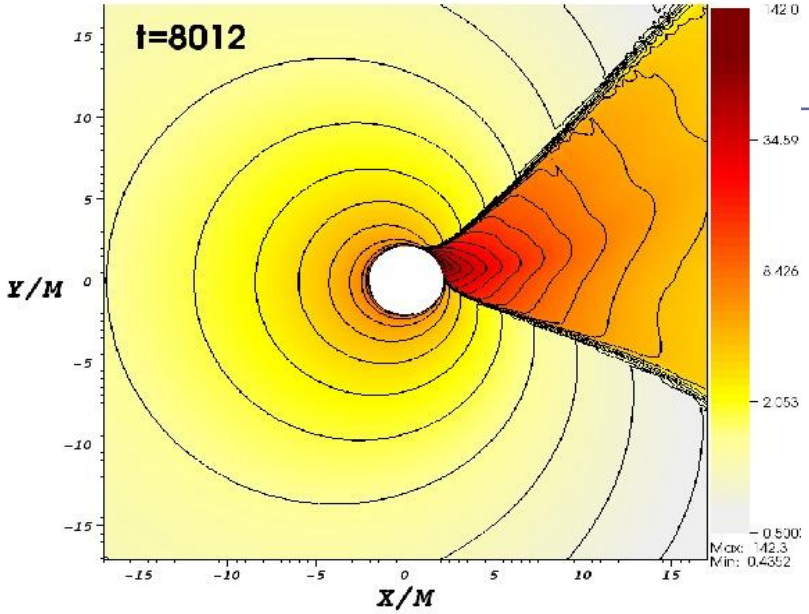
$$G = c = 1$$

$$V^r = (\gamma^{rr})^{1/2} V_\infty \cos(\phi)$$

$$V^\phi = -(\gamma^{\phi\phi})^{1/2} V_\infty \sin(\phi)$$

$$a, \Gamma, M, Cs$$

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X/M
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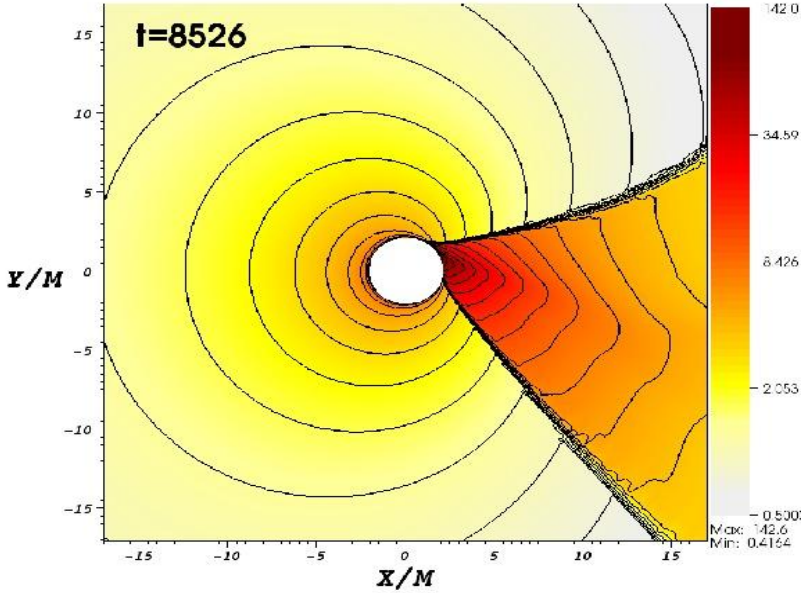
34.59
8.426
2.053
0.500
Max: 142.3
Min: 0.4352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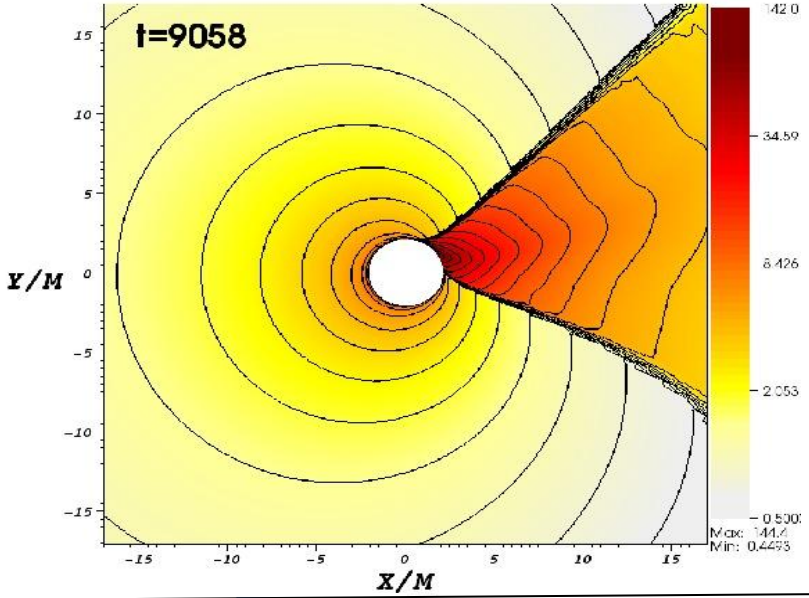
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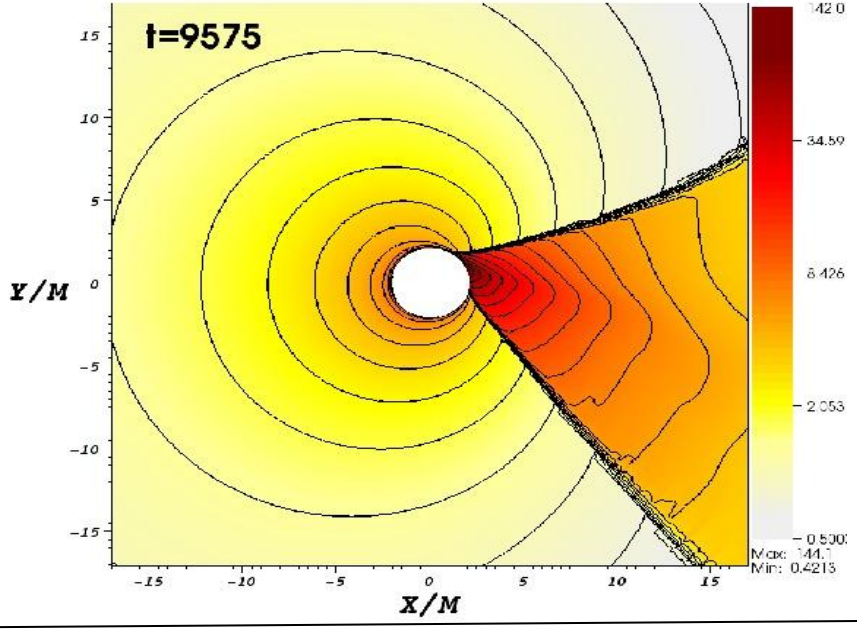
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0.500
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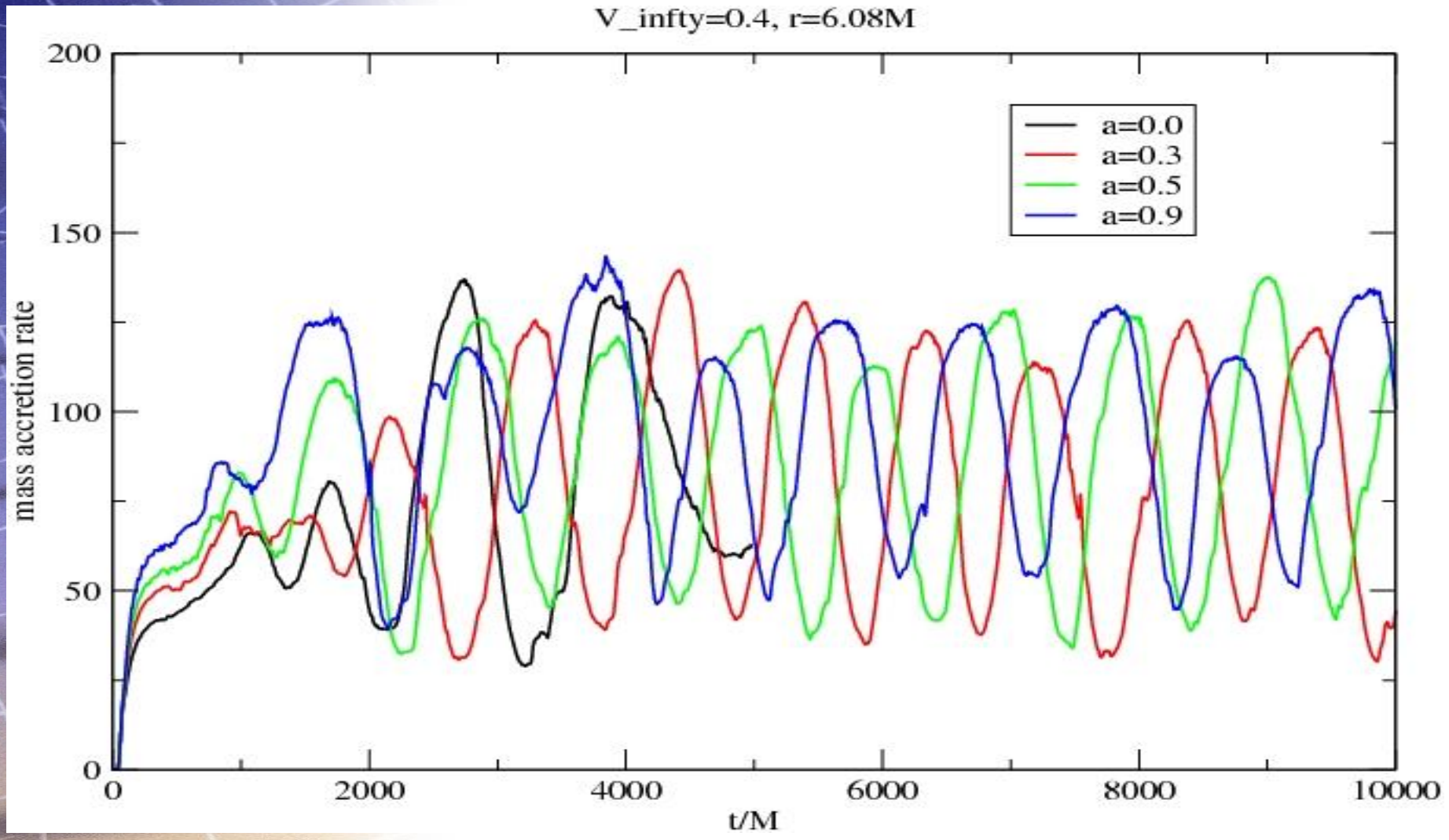
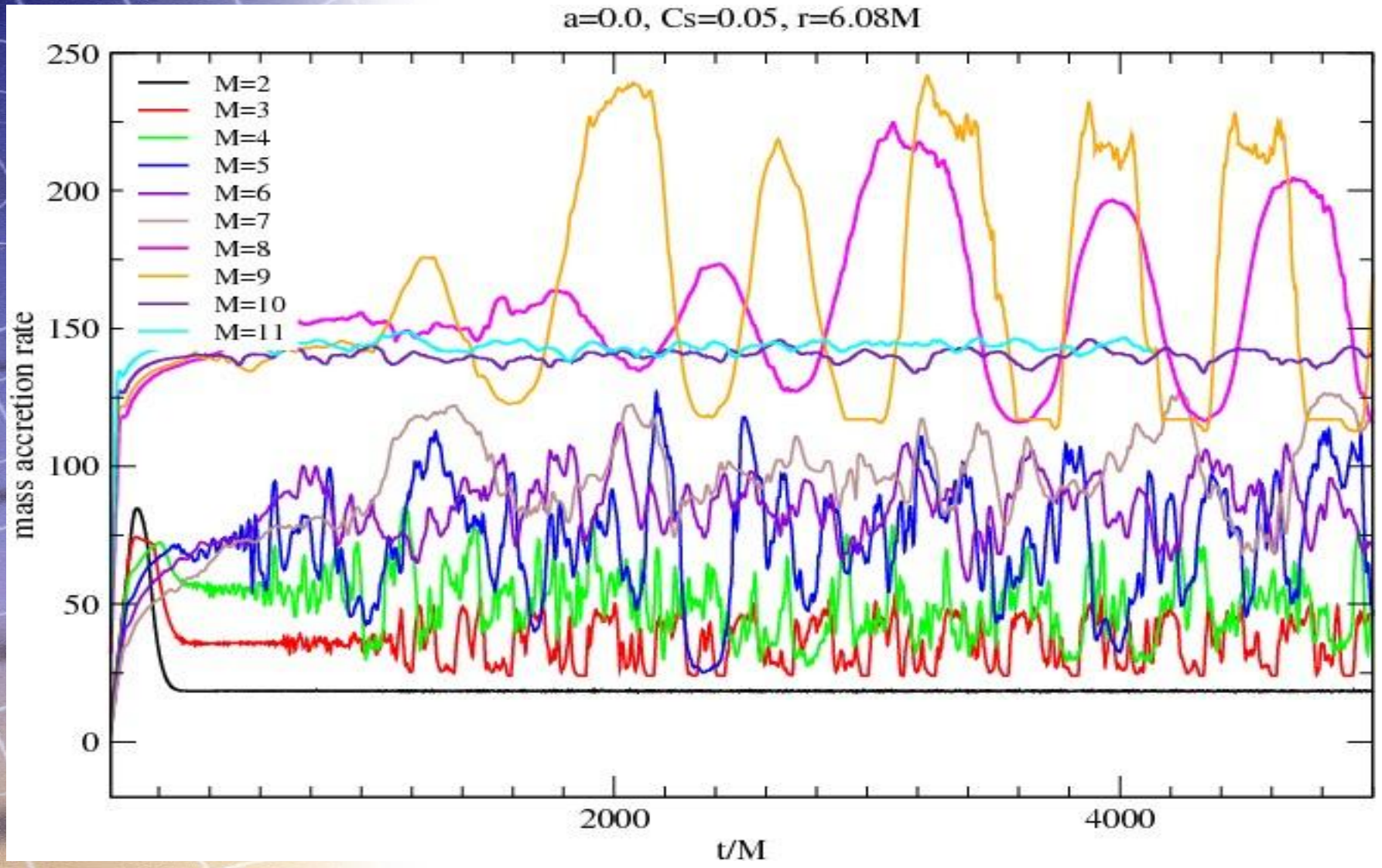
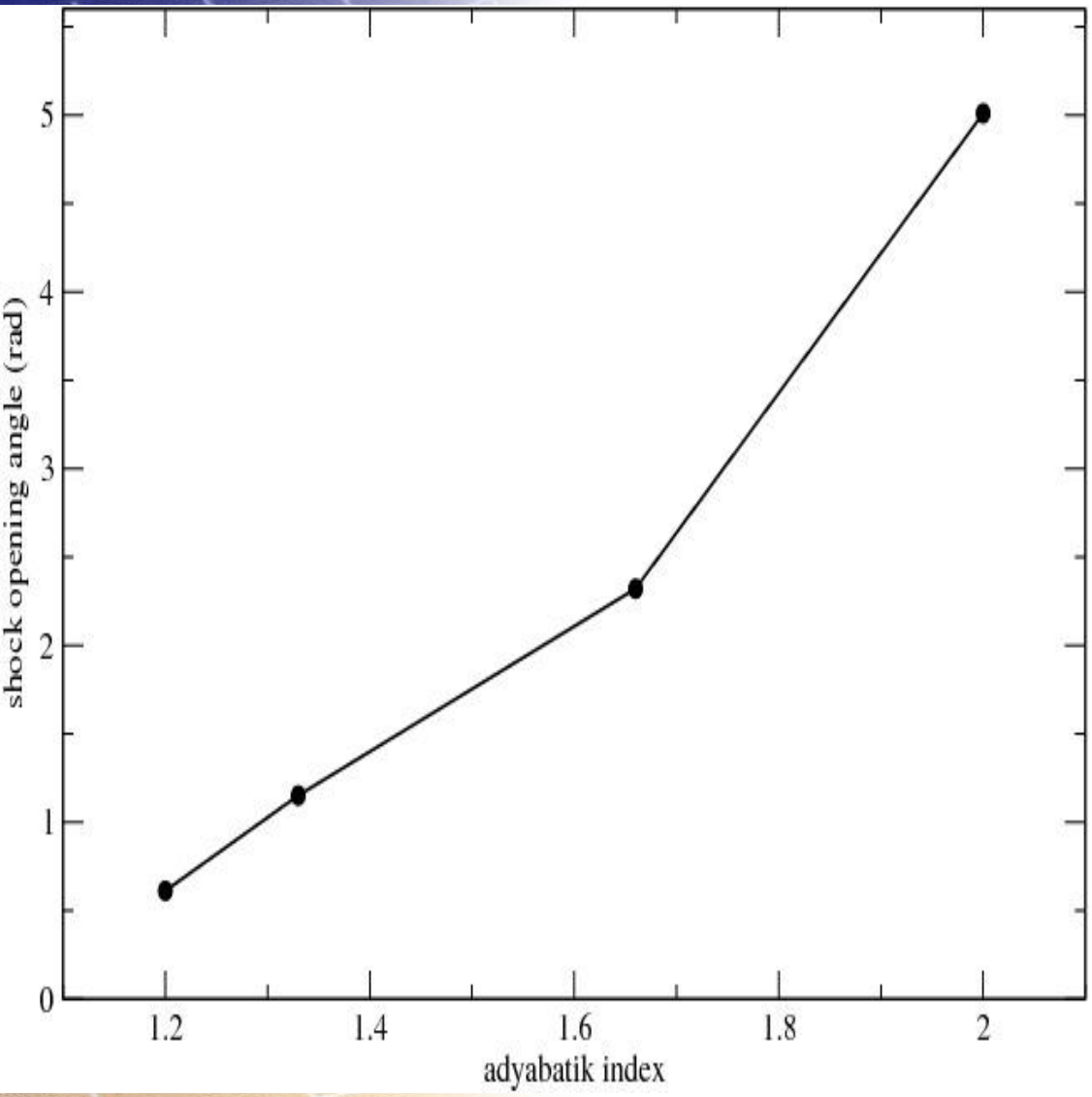
Mass accretion rate-1



Mass accretion rate-2



Shock opening angle

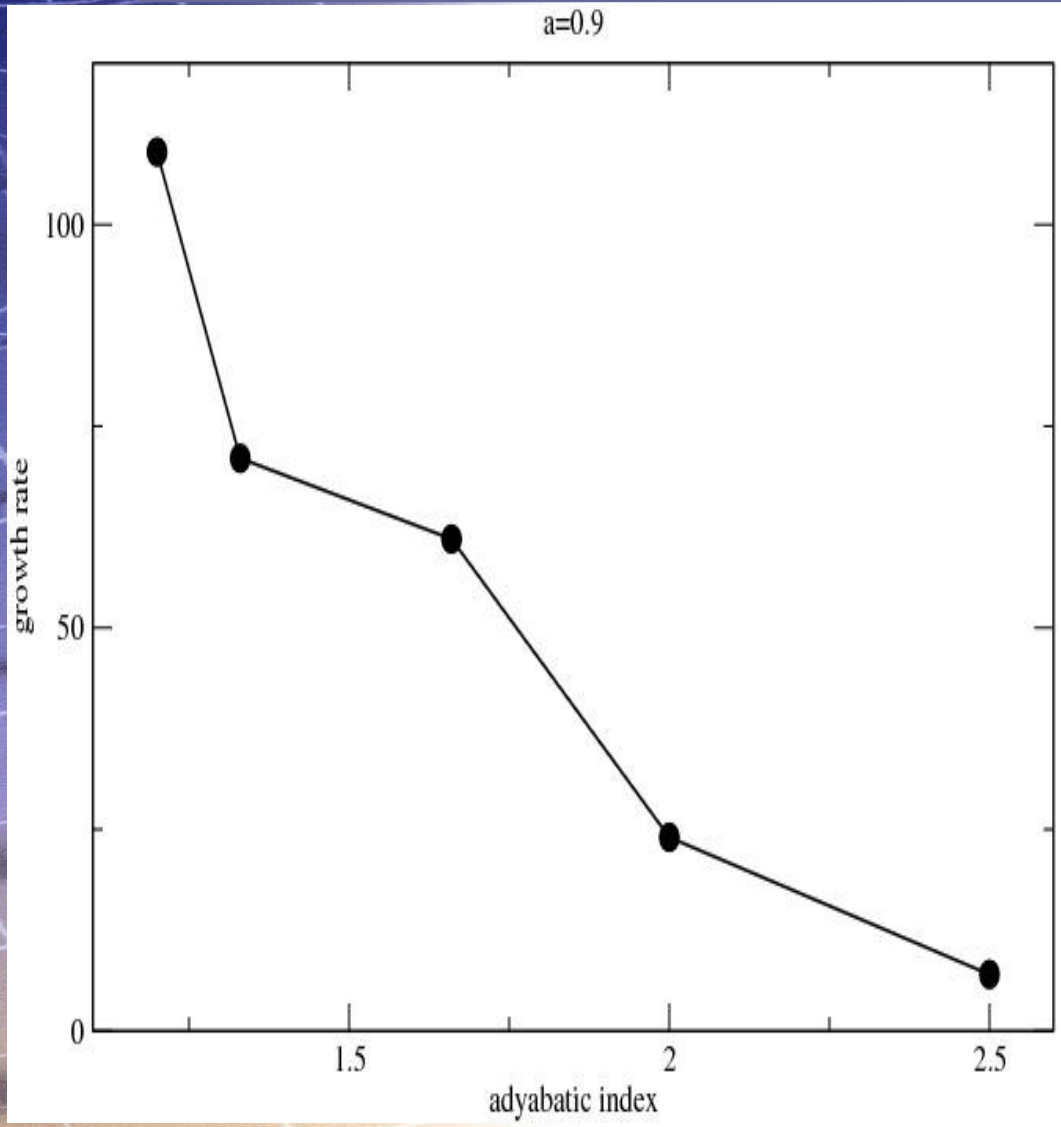


Above the shock is detached from accreator $\Gamma \approx 2$

Foglizzo et. al 2005 suggested that shock should be detached (bow) in planar flows with $\Gamma \approx 3$

The some observational results of Sgr A* show the detached shock

Growth of instability

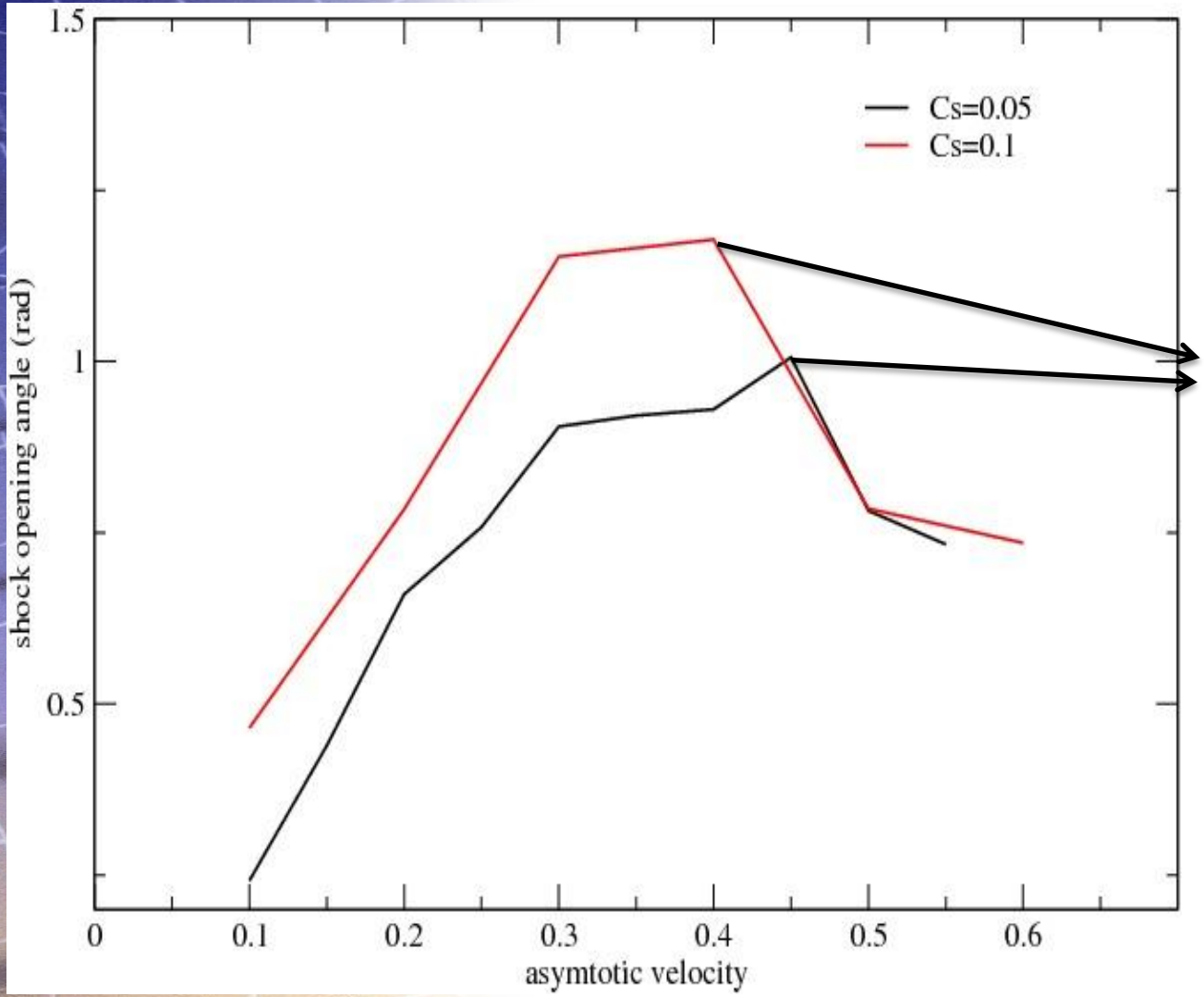


Monotonic decrease in the growth rate

It is consistent with the results found in Newtonian (Blondin 2010)

The disk does not have any flip-flop oscilation $\Gamma \geq 2$

Shock opening angle



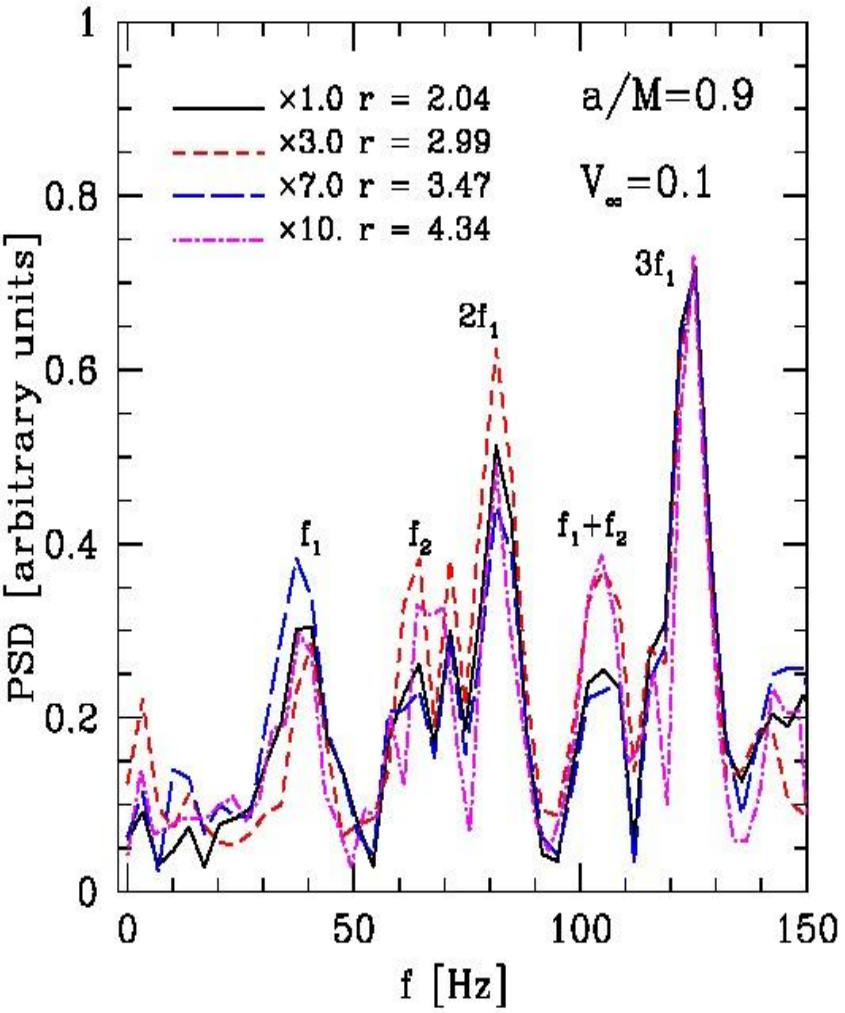
Flip-flop instability

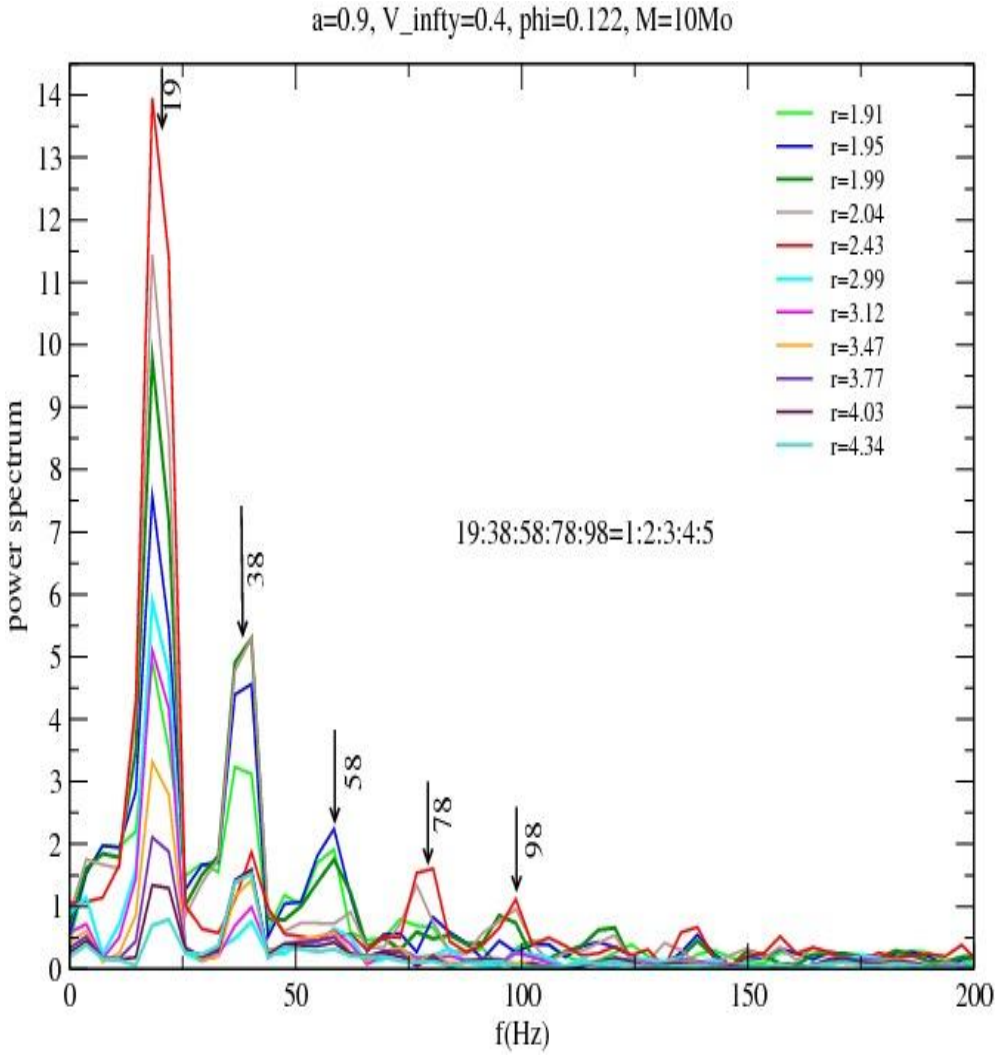
"YES"

Livio et.al. 1991

QPOs

(Donmez at. al., MNRAS 2011)





Final Remarks-1

- *Attached shock is created for* $\Gamma = 1.2, 4/3, 5/3$
- *Deattached shock is seen for* $\Gamma = 2.5$ *and it is consistent with theoretical suggestion made by Foglizzo et al. (2005)*
- *Mass accretion rate and shock openin angle are increasing function of* V_∞. *After a certain value of* V_∞ *they decrease.*
- *Instability of shock cone depends of different parameters such as* V_∞, C_s, R_* / R_a, *and* M

Final Remarks-2

- ***The robust flip-flop instability can be achived by using supersonic flow with moderate Mach number.***
- ***The shock opening angle increases with increasing sound speed***
- ***The flip-flop instability is not results of velocity or density gradient of the flow.***
- ***It is not due to numerical artifacts***
- ***Needs to be confirmed in 3D in relativistic region.***

Movies

$$a = 0,\ \Gamma = 4/3,\ V_\infty = 0.4$$

$$a = 0.9,\ \Gamma = 4/3,\ V_\infty = 0.4$$

$$a = 0.9,\ \Gamma = 2.5,\ V_\infty = 0.4$$