Spherical and choked accretion onto rotating black holes

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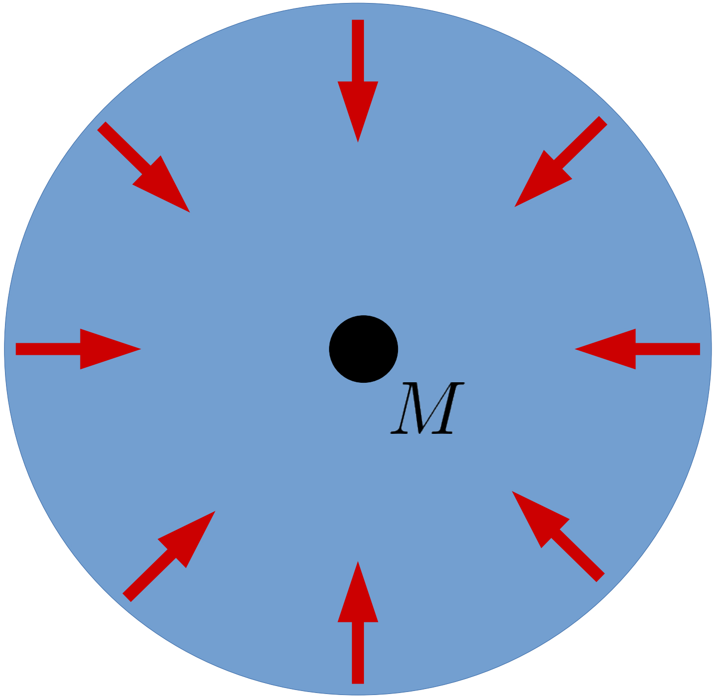
Outline

- Part I: Spherical accretion onto rotating black holes
  - Review and comparison of Bondi (1952) and Michel (1972) solutions
  - Summary of more than 300 simulations exploring the effect of the black hole spin on the mass accretion rate, the flow morphology, and the sonic surface
- Part II: Choked accretion
  - Brief summary of the mechanism
  - Choked accretion and rotating black holes

Bondi solution



Spherical symmetry, Steady state,
Gas at rest in infinity

Asymptotic state of the fluid: $\rho_\infty,\ P_\infty,\ T_\infty$

$$\mathcal{C}_\infty^2 = \gamma \frac{P_\infty}{\rho_\infty} \qquad \Theta_\infty = \frac{k_\mathrm{B}\, T_\infty}{\bar{m}\, c^2} = \frac{P_\infty}{\rho_\infty\, c^2}$$

Bondi radius

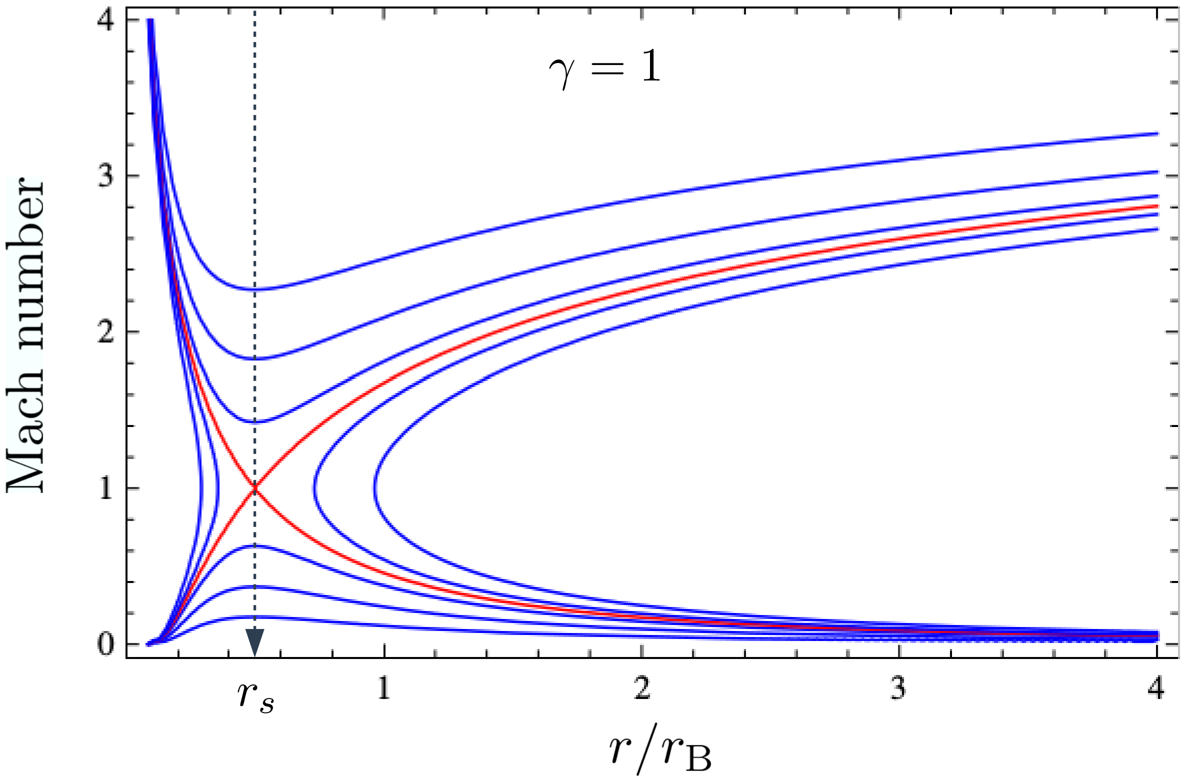
$$r_\mathrm{B} = \frac{GM}{\mathcal{C}_\infty^2}$$

$r \gg r_\mathrm{B}$ gas cloud essentially unperturbed by *M*

$r < r_\mathrm{B}$ gas dynamics dictated by *M*

Bondi (1952)

Bondi solution



- Unique transonic solution (compatible with BC)
- Maximizes the mass accretion rate:

$$\dot{M}_B = 4\pi\, \lambda_B \frac{(GM)^2}{\mathcal{C}_\infty^3} \rho_\infty$$

$$\lambda_B = \frac{1}{4}\left(\frac{2}{5-3\gamma}\right)^{\frac{5-3\gamma}{2(\gamma-1)}}$$

$\lambda_B(5/3) = 0.25,$
$\lambda_B(4/3) \simeq 0.71,$
$\lambda_B(1) \simeq 1.12$

$$1 \leq \gamma \leq 5/3$$

- Scale free with respect to $M,\ \mathcal{C}_\infty,\ \rho_\infty$
- Adiabatic index is the only relevant parameter

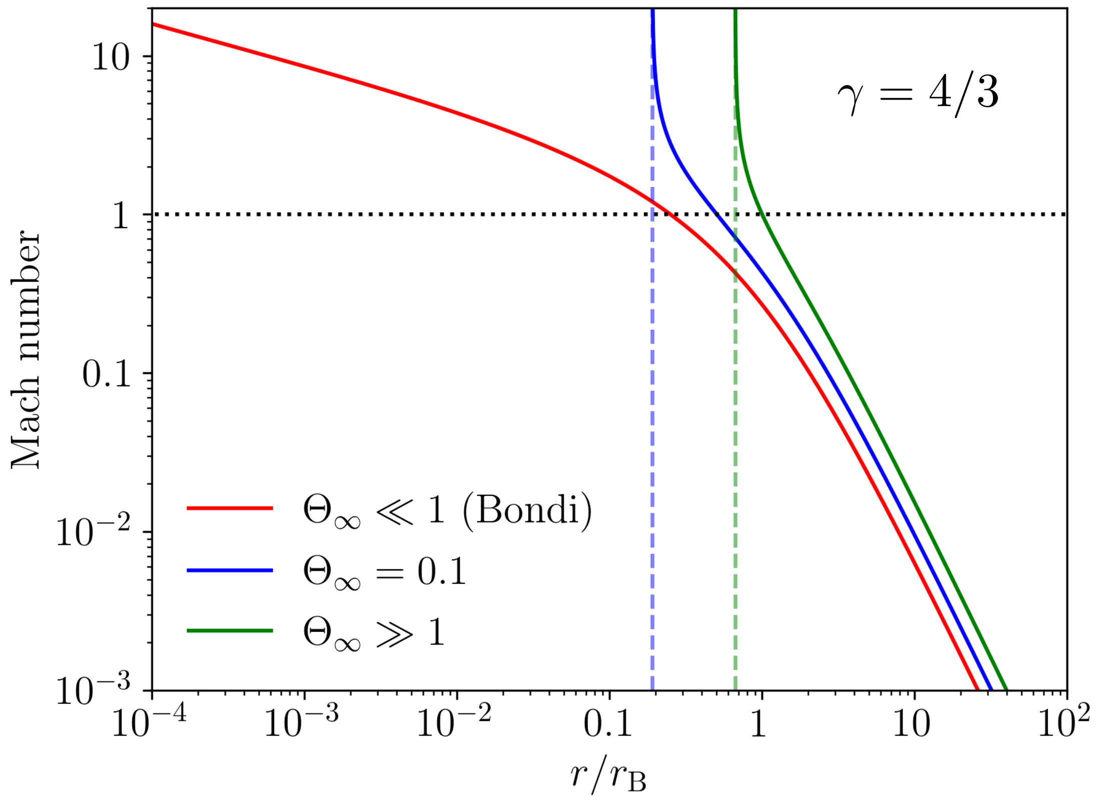
Bondi (1952)

Michel solution

Relativistic generalization of Bondi's problem for a non-rotating black hole (Schwarzschild spacetime)

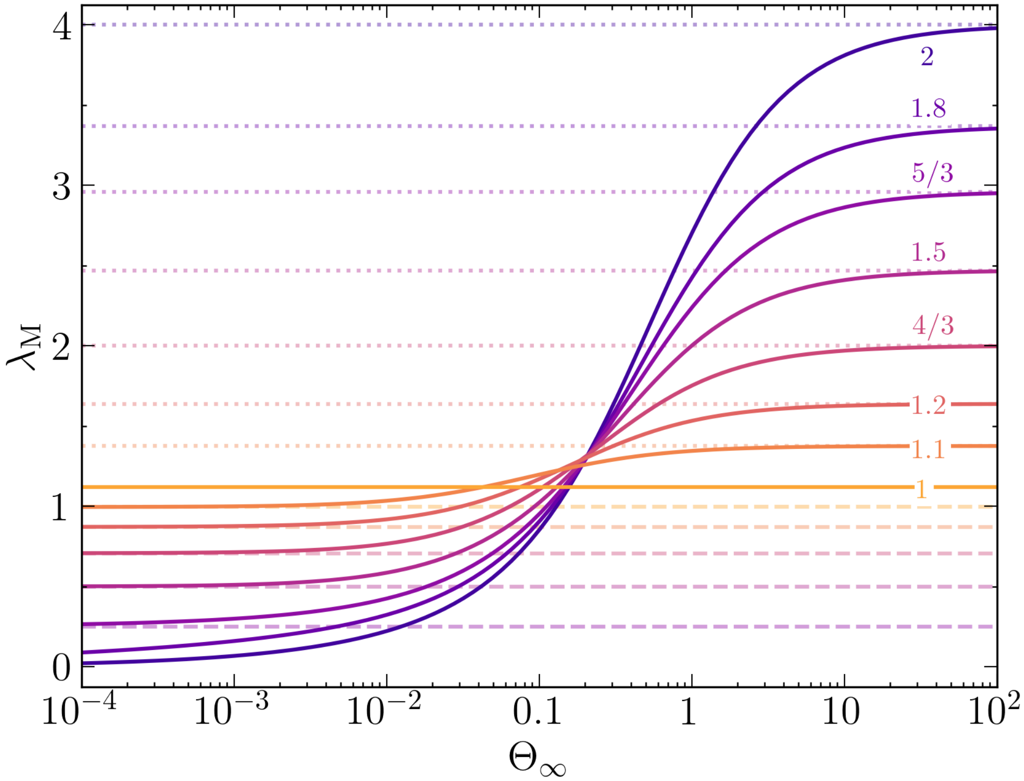
Two characteristic speeds imply that there are now two free parameters:

$$\gamma,\ \Theta_\infty$$



Michel (1972)

Michel solution



$$\dot{M}_{\mathrm{M}} = 4\pi\, \lambda_{\mathrm{M}} \frac{(GM)^2}{\mathcal{C}_\infty^3} \rho_\infty$$

$$\lambda_{\mathrm{M}} = \frac{1}{4} \left(\frac{h_s}{h_\infty} \right)^{\frac{3\gamma-2}{\gamma-1}} \left(\frac{\mathcal{C}_s}{\mathcal{C}_\infty} \right)^{\frac{5-3\gamma}{\gamma-1}}$$

Michel (1972)

Comparison between Bondi and Michel

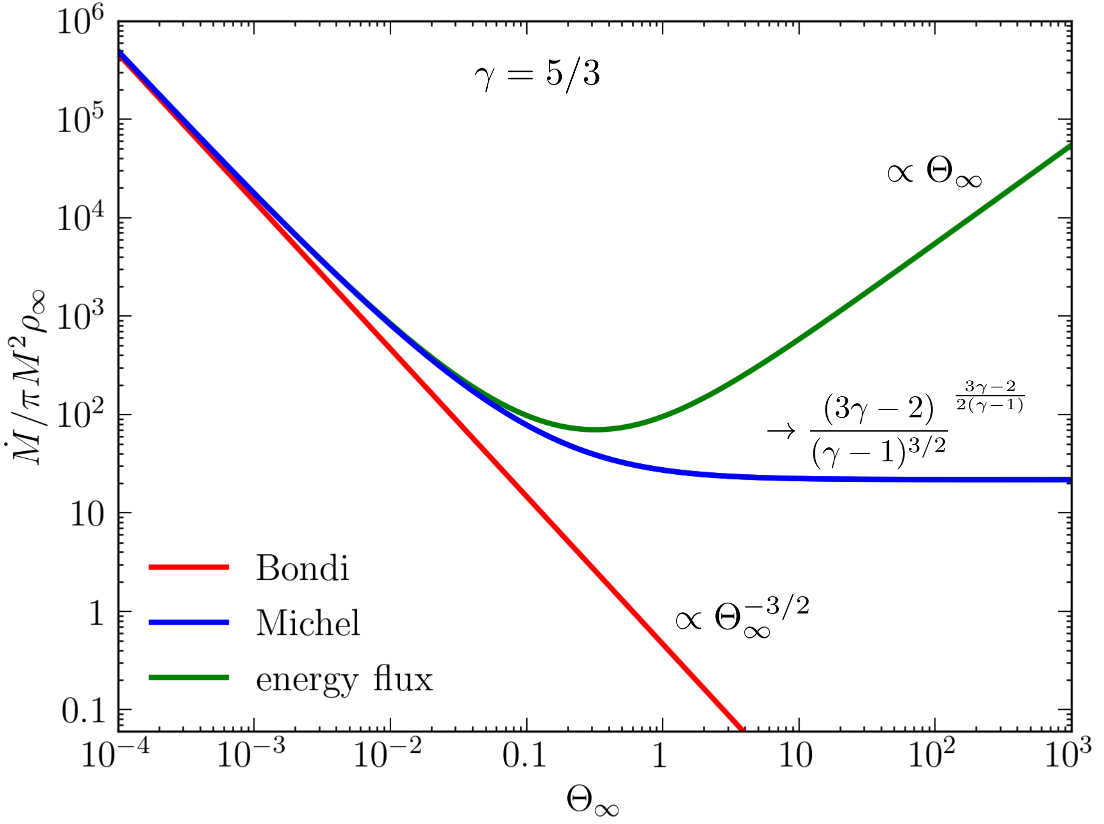
$$\dot{M}_{\rm B} = 4\pi\, \lambda_{\rm B} \frac{(GM)^2}{\mathcal{C}_\infty^3} \rho_\infty$$

$$\dot{M}_{\rm M} = 4\pi\, \lambda_{\rm M} \frac{(GM)^2}{\mathcal{C}_\infty^3} \rho_\infty$$

$$\dot{\mathcal{E}}_{\rm M} = 4\pi\, \lambda_{\rm M} \frac{(GM)^2}{\mathcal{C}_\infty^3} \rho_\infty\, h_\infty$$

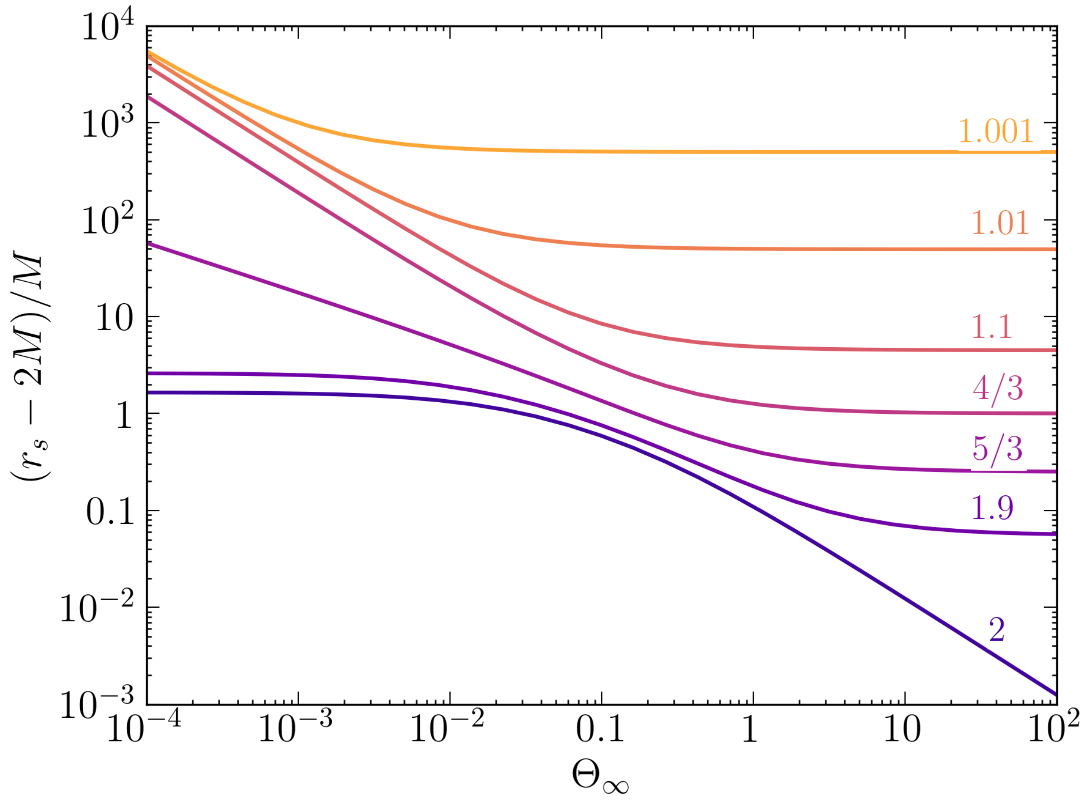
Newtonian regime $\quad \mathcal{C}^2 = \dfrac{\partial P}{\partial \rho} \implies \mathcal{C}_\infty \to \Theta_\infty^{1/2}$

Relativistic regime $\quad \mathcal{C}^2 = \dfrac{\partial P}{\partial e} \implies \mathcal{C}_\infty \to (1-\gamma)^{1/2}$



Aguayo-Ortiz et al (2021)

Michel solution: sonic radius



In the isothermal case $(\gamma = 1)$

$$\Theta \equiv \Theta_\infty$$

$$r_s \gg M, \qquad \dot{M}_{\rm M} \to \dot{M}_{\rm B}$$

When $\gamma > 5/3$ a relativistic description is needed even for non-relativistic temperatures

For a stiff fluid $(\gamma = 2)$

$$r_s \to 2M$$

Aguayo-Ortiz et al (2021)

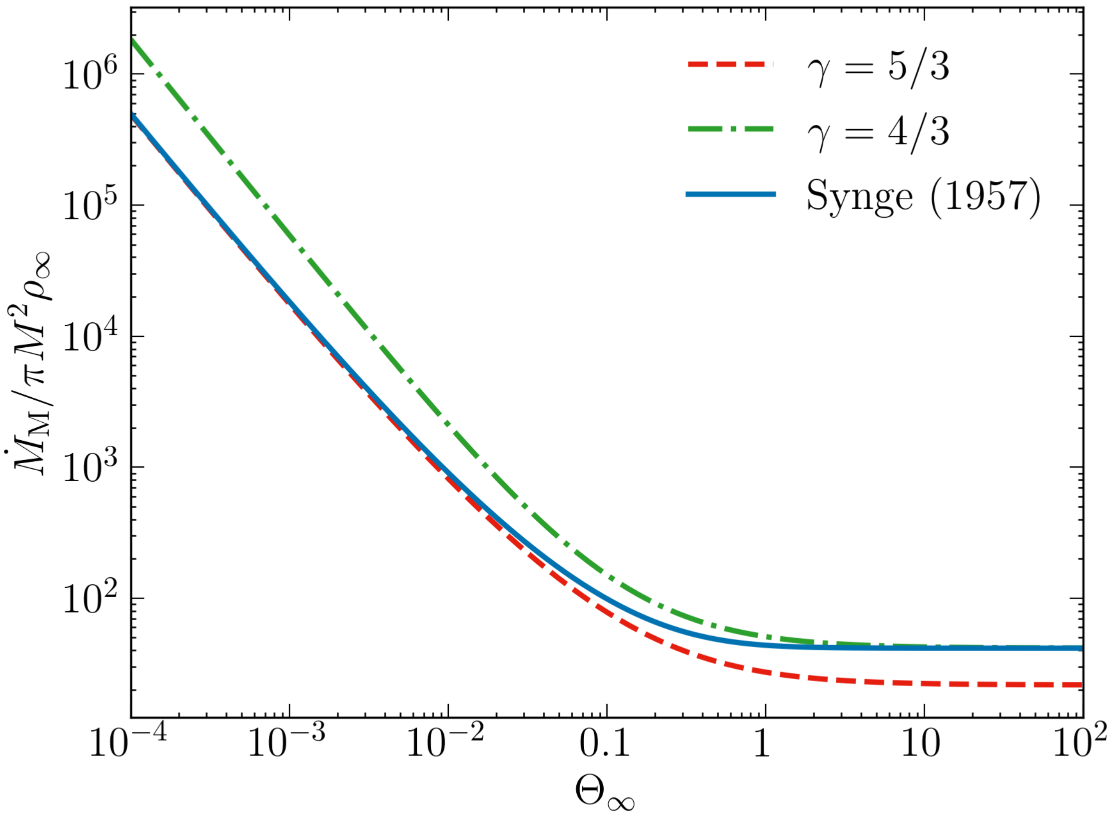
Relativistic equation of state

Considering a monoatomic ideal gas, the polytropic condition is strictly valid only for

$$\Theta_\infty \ll 1 \qquad \Longrightarrow \qquad \gamma = 5/3$$

$$\Theta_\infty \gg 1 \qquad \Longrightarrow \qquad \gamma = 4/3$$

In order to study the whole temperature domain, it is necessary to adopt a realistic EoS as derived from relativistic kinetic theory (Jüttner 1911, Synge 1957)



Aguayo-Ortiz et al (2021)

Kerr spacetime

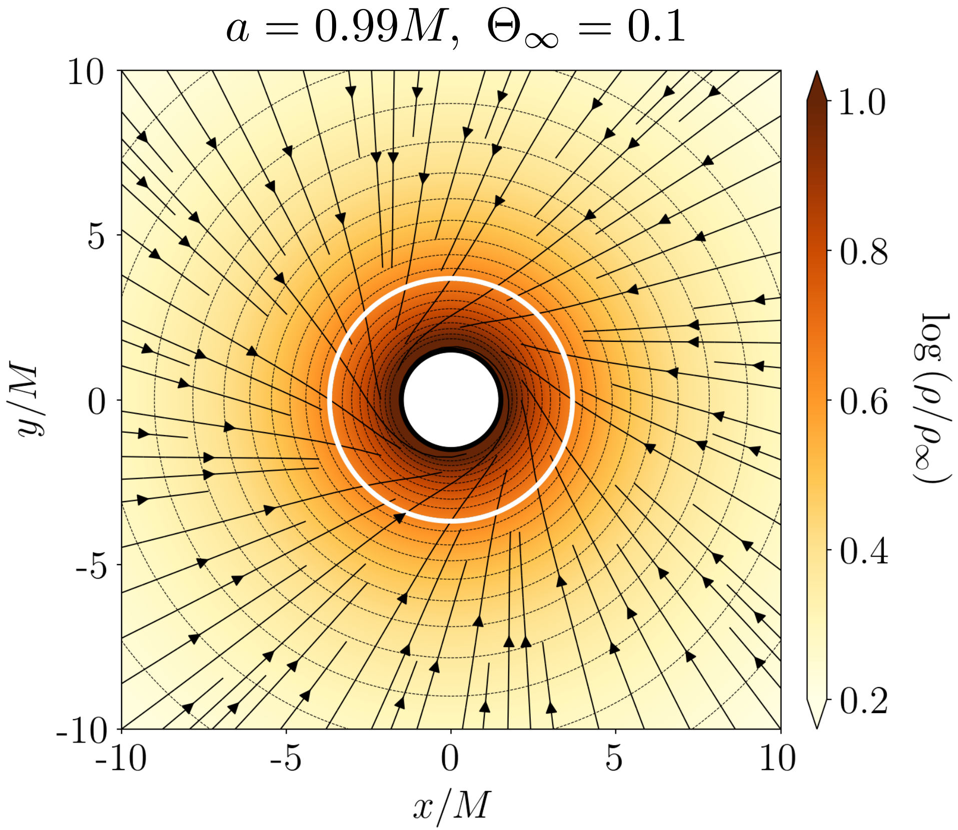
Spherical symmetry is lost

Only one known analytic solution:
ultra-relativistic stiff fluid
(Petrich, Shapiro & Teukolski 1988)

We studied this problem by means of hydrodynamic numerical simulations performed with the *aztekas* code

311 simulations exploring

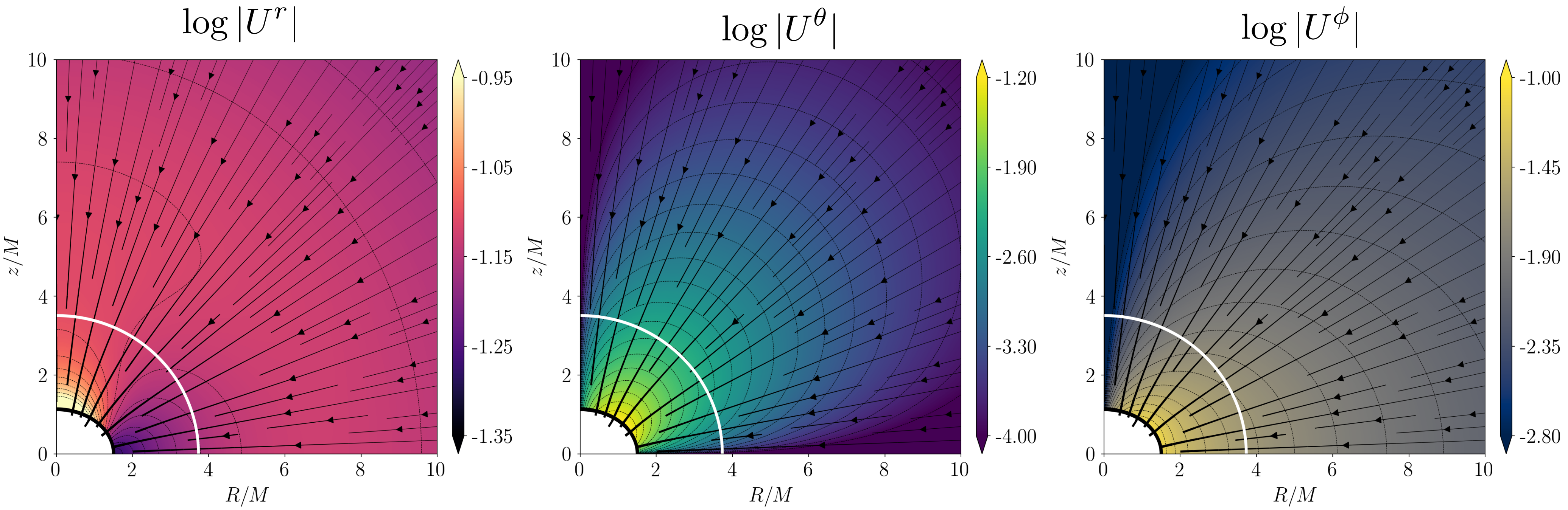
$$a, \quad \gamma, \quad \Theta_\infty$$



Aguayo-Ortiz et al (2021)

Kerr spacetime

$$a = 0.99M,\ \Theta_\infty = 0.1$$

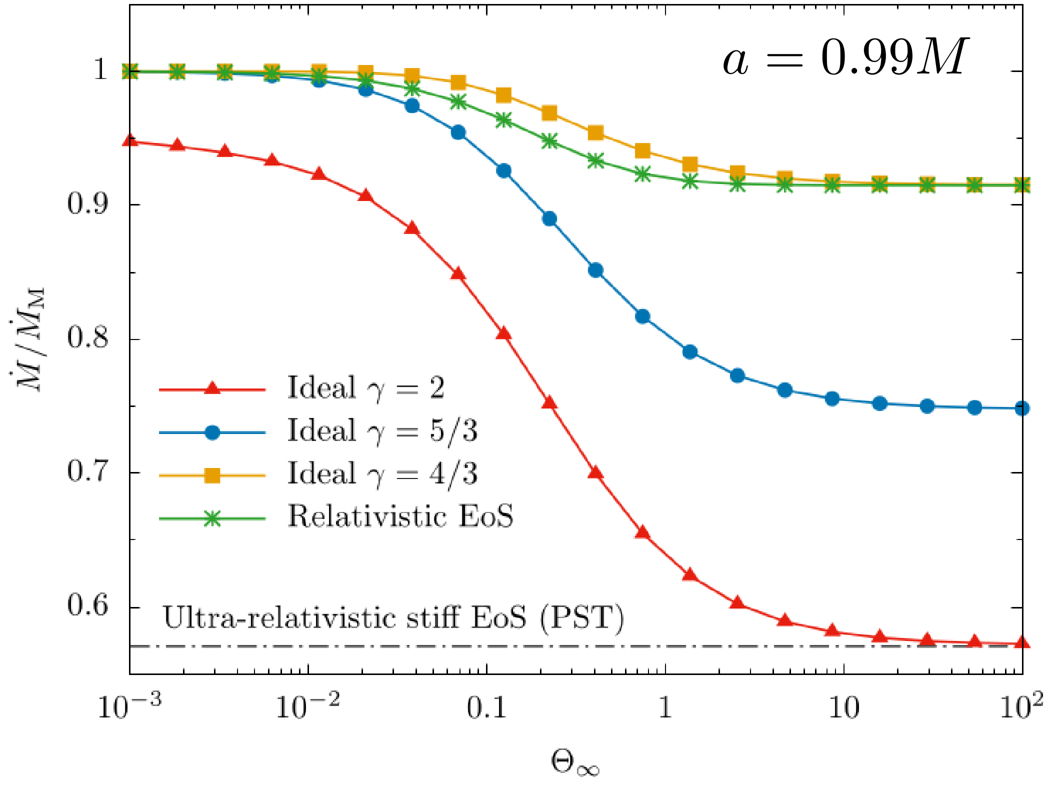


Aguayo-Ortiz et al (2021)

aztekas code

- Finite volume method (exact conservation built-in)
- Godunov’s method (Riemman solver) for high-resolution shock capture
- Relativitistic hydrodynamics in a fixed background metric
- Open source (GNU General Public License) https://github.com/aztekas-code/aztekas-main
- Developed by A. Aguayo-Ortiz & S. Mendoza at IA-UNAM

Temperature dependence



Spin effects become signifincant for $\Theta_\infty > 0.1$ and as the EoS stiffens

Effects due to the spin parameter are negligible for

$$\Theta_\infty \ll 1, \qquad \gamma \leq 5/3$$

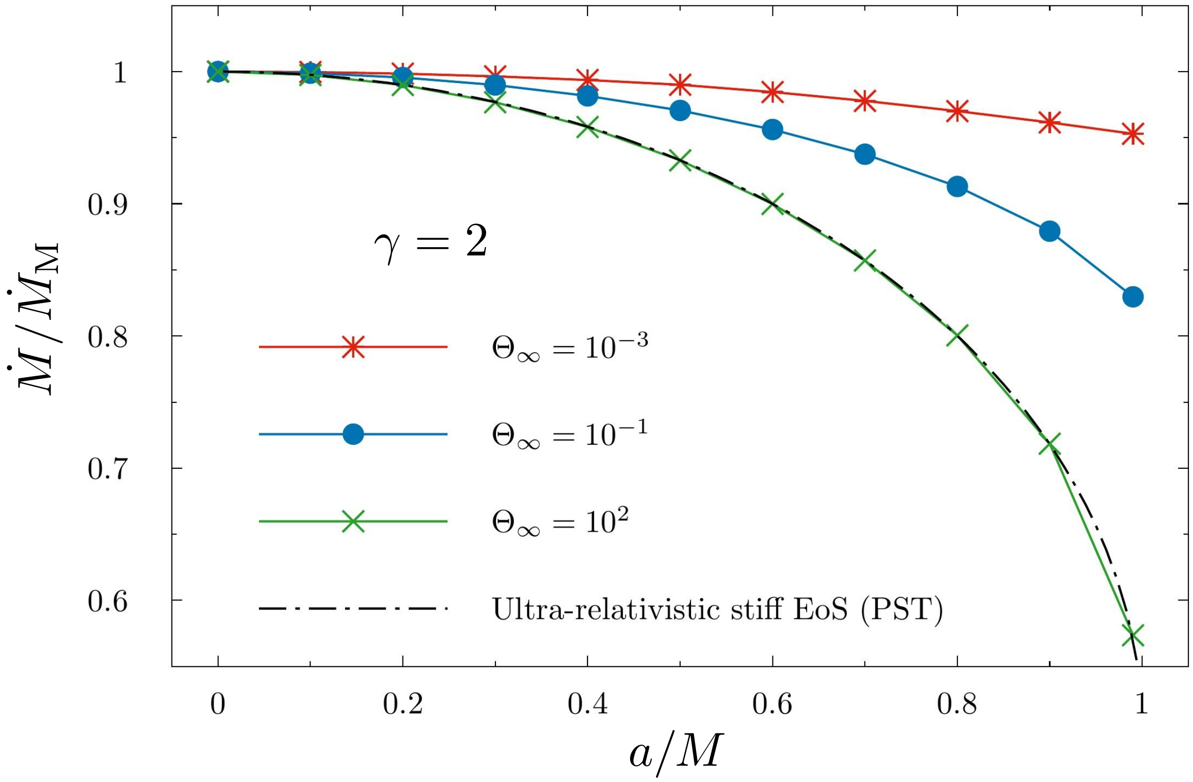
Aguayo-Ortiz et al (2021)

Spin dependence

Excellent agreement with PST analytic solution

The mass accretion rate drops by as much as 50% for a stiff EoS

This reduction is of at most 10% for a more realistic EoS



Aguayo-Ortiz et al (2021)

Astrophysical applications

- These results should be useful for studying spherical accretion onto rotating and non-rotating black holes in extreme environments ($\Theta_\infty \sim 1$) or that are well approximated by a stiff EoS ($\gamma > 5/3$)

- Accretion onto primordial black holes during the radiation era in the early universe evolution. Especially between the quark and lepton epochs when 10^{10} K $< T <$ 10^{15} K (Jedamzik 1997; Lora-Clavijo et al. 2013)

- Mini black holes accreting from the interior of a neutron star ($\gamma \sim 2$) (Capela et al. 2013; Génolini et al. 2020, Roberts et al 2021)

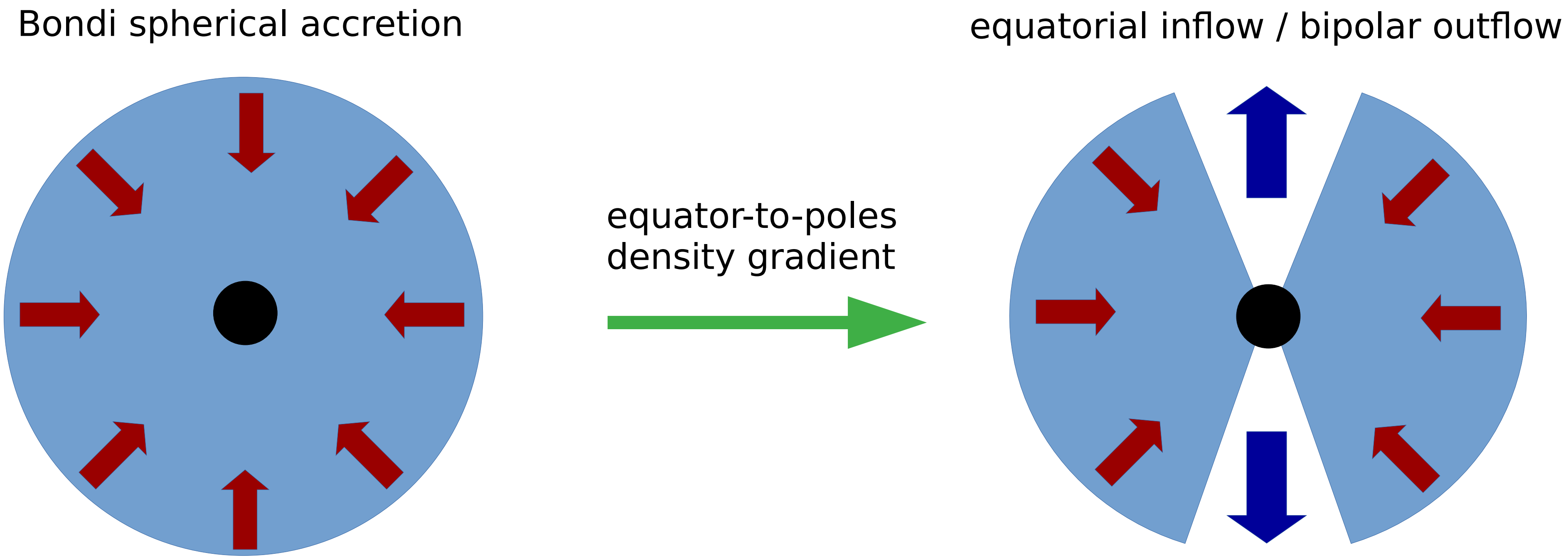
Conclusions (part I)

- Bonid and Michel's solutions start to deviate significantly when $\Theta_\infty > 0.1$
- In the ultra-relativistic limit $\dot{M}_M$ approaches a constant value while $\dot{M}_B$ continualy deacreases
- The extension of Michel's solution for a relativistic EoS smoothly transitions from a $\gamma = 5/3$ to a $\gamma = 4/3$ polytrope as Θ_∞ increases
- When $a > 0$ the flow is no longer spherically symmetric. The effects due to the BH spin are more evident at large temperatures and as the EoS stiffens
- For $\Theta_\infty < 0.1$ and $\gamma < 5/3$ spin effects are negligible. At large temperatures these effects are of at most 50% for $\gamma = 2$ (10% for $\gamma = 4/3$)

Choked accretion:

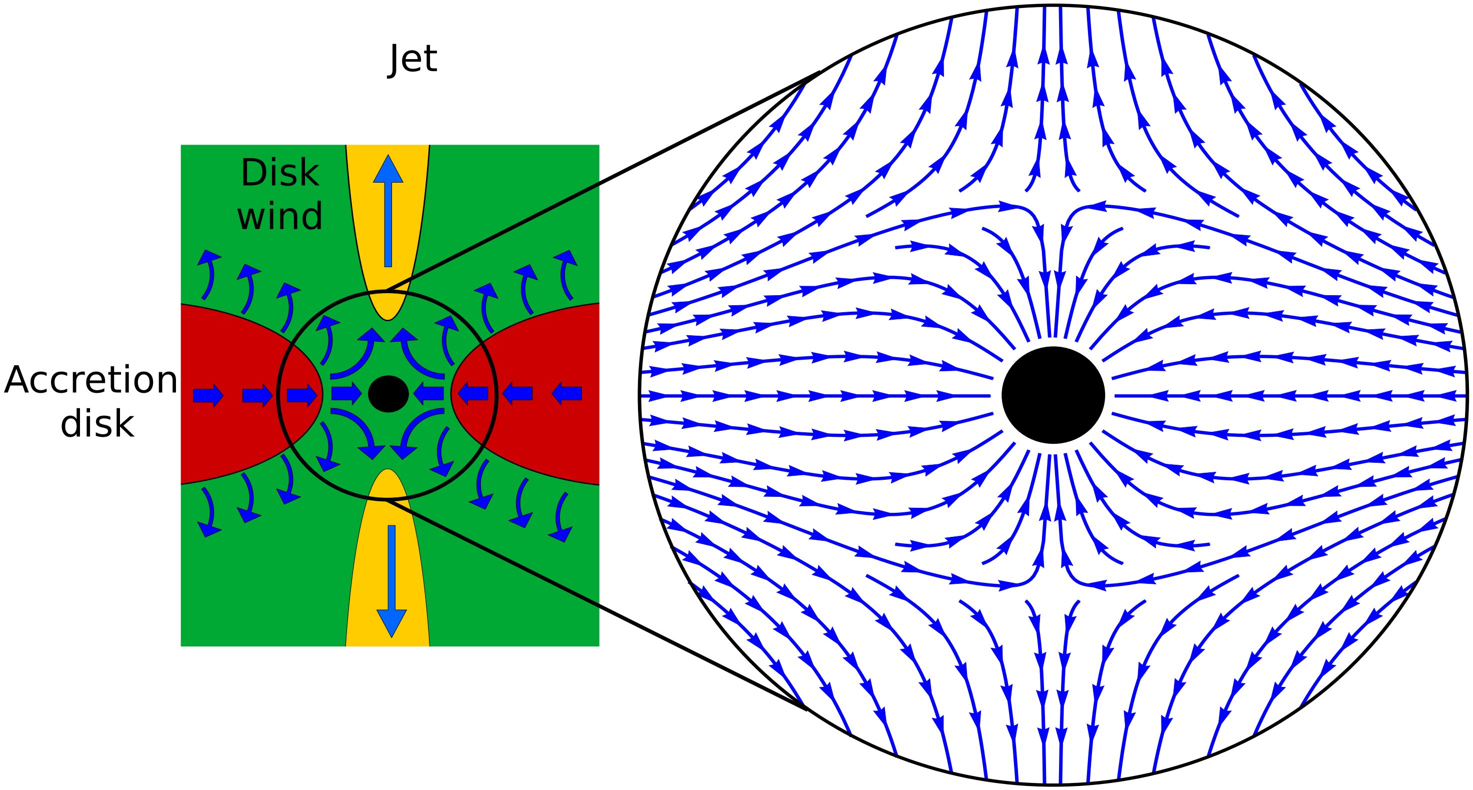
from Bondi accretion to bipolar outflows

Basic idea



Hernandez et al (2014) showed analytically that the Bondi flow is unstable against small-amplitude, large-scale density perturbations

Toy model for accreting black hole systems



Choked accretion in a nutshell

- Perturbation away from Bondi accretion solution by imposing a small-amplitude, large-scale density gradient from equator to poles

- Purely hydrodynamical mechanism that transforms an originally radial accretion flow on to an equatorial inflow / bipolar outflow structure

- Finding: **Flux-limited accretion regime**. The incoming material chokes at a gravitational bottleneck and the excess flux is redirected by the density gradient as a bipolar outflow

Choked accretion

- Analytic model (ultra-stiff EoS) and 2D GRHD numerical simulations (polytrope)

- Newtonian regime:

  Aguayo-Ortiz, Tejeda & Hernandez 2019
  2019MNRAS.490.5078A

- Schwarzschild BH:

  Tejeda, Aguayo-Ortiz & Hernandez 2020
  2020ApJ...893...81T

- Kerr BH:

  Aguayo-Ortiz, Sarbach & Tejeda 2021
  2021PhRvD.103b3003A

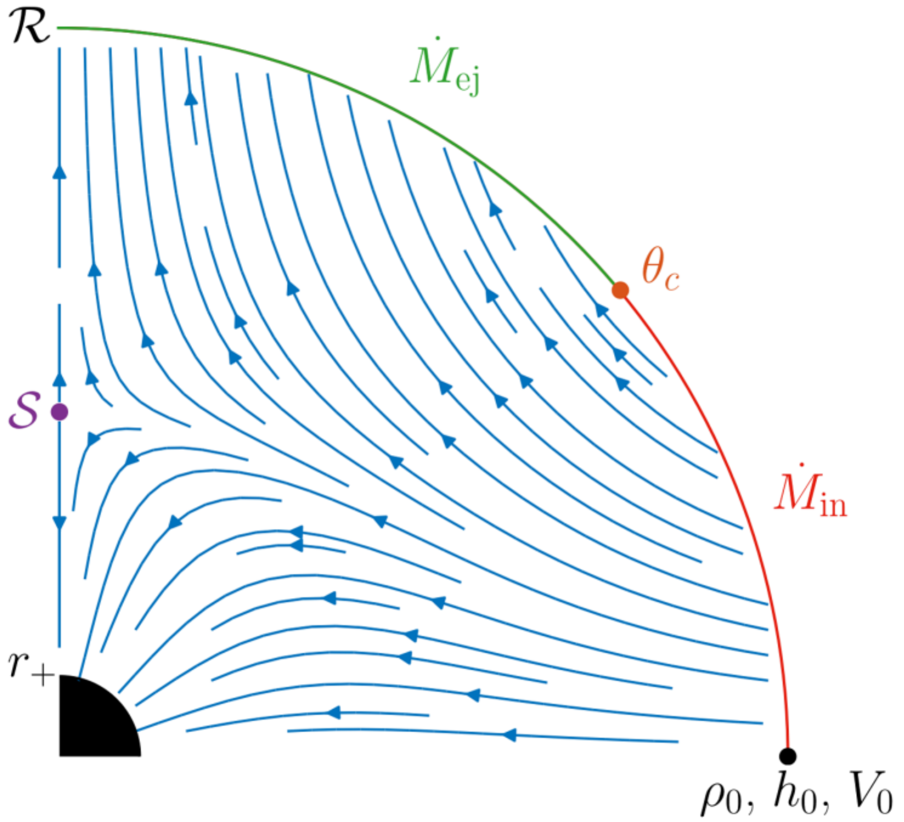
Analytic model

- Steady-state
- Axisymmetry
- Irrotational (Potential flow)
- Ultra-relativistic stiff fluid
  (Petrich, Shapiro & Teukolsky 1988)

$$P = K\,\rho^2$$

$$h\,U_\mu = \partial_\mu \Phi$$

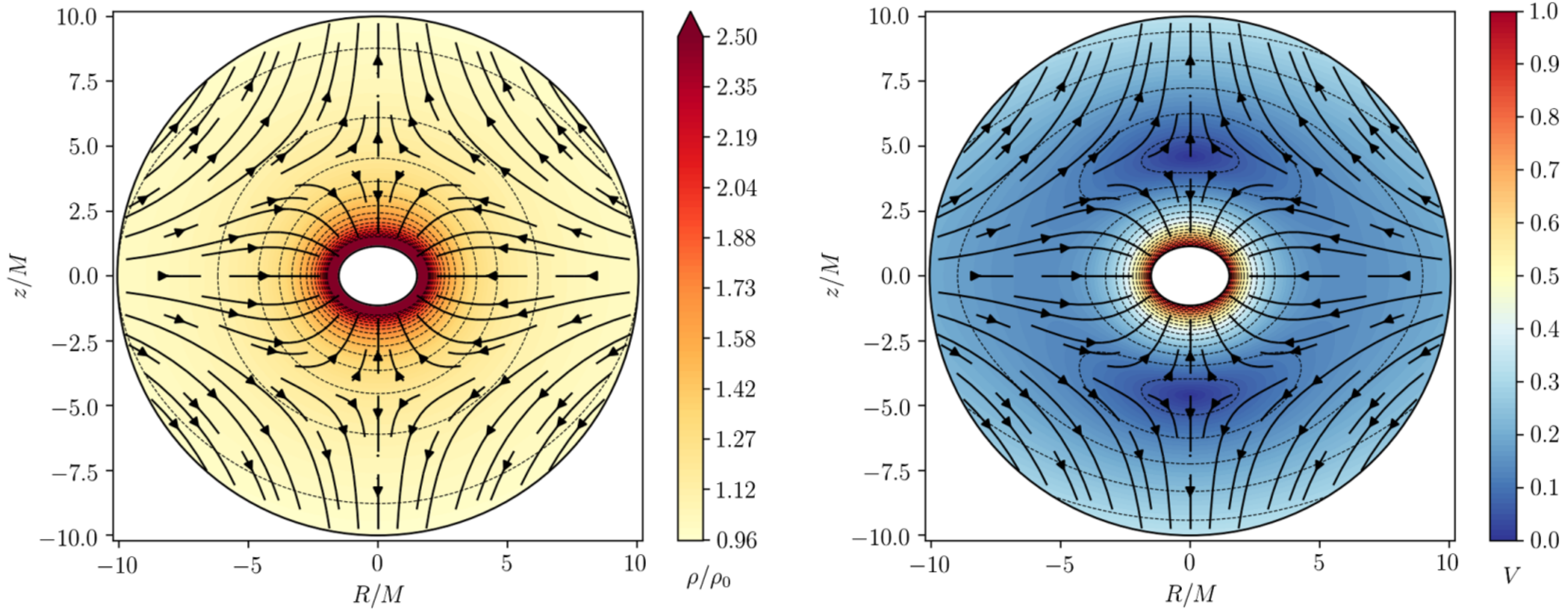
$$\nabla_\mu(\partial^\mu \Phi) = 0$$



Aguayo-Ortiz, Sarbach & Tejeda (2021)

Analytic model

$$\text{Kerr BH, } a = 0.99M, \ \mathcal{R} = 10M, \ V_0 = 0.2$$



Aguayo-Ortiz, Sarbach & Tejeda (2021)

Numerical GRHD simulations with *aztekas*

- Axisymmetric (2D)
- Perfect fluid

$$P = K\,\rho^{\gamma}$$

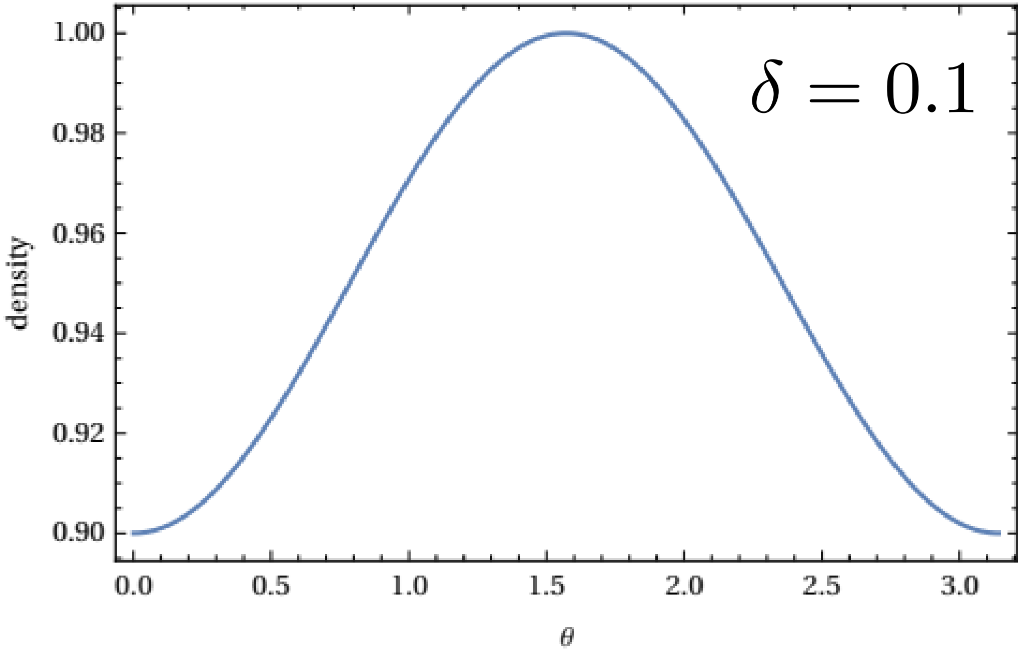
- Boundary condition

$$\rho(\mathcal{R},\theta) = \rho_0\left(1 - \delta\cos^2\theta\right)$$

$$\delta = 1 - \frac{\rho(0)}{\rho(\pi/2)}$$

- Velocity free to evolve

Density profile at the injection sphere $\mathcal{R}$



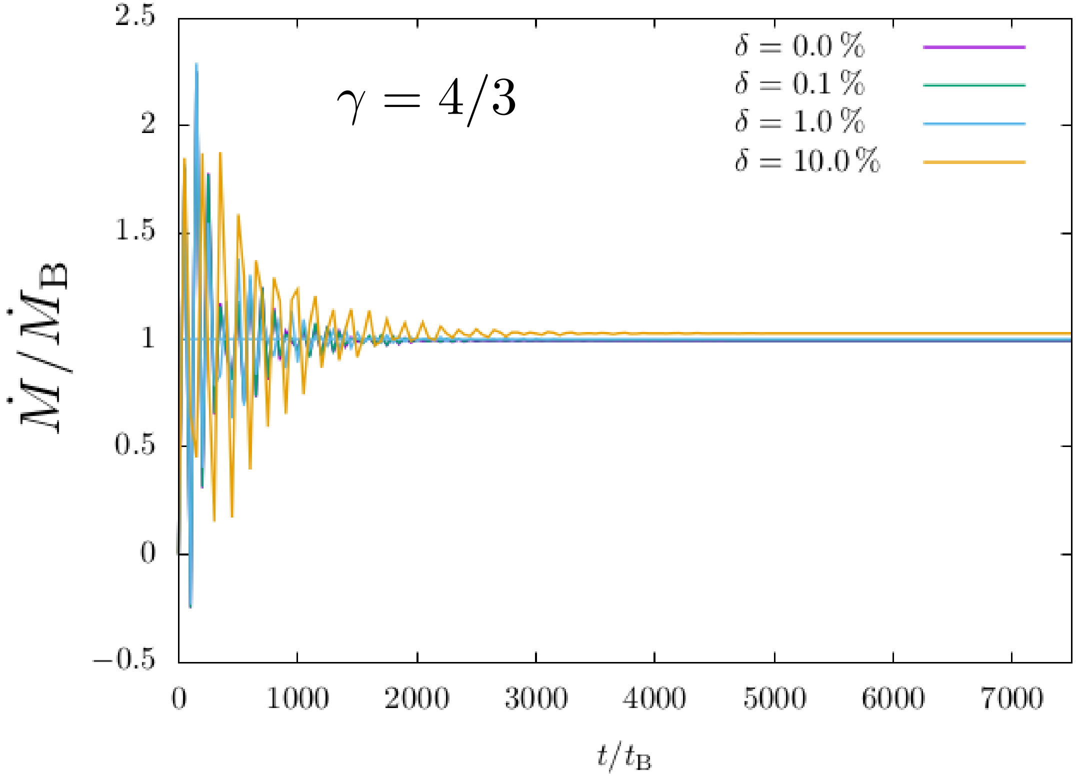
Aguayo-Ortiz, Tejeda & Hernandez (2019)

Numerical simulations

- Simulations run until steady state is reached

$$(\dot{M} \simeq \text{const.})$$

- Parameter space
  - BH spin parameter a
  - Density contrast δ
  - Adiabatic index γ
  - Fluid state $\rho_0,\ P_0,\ T_0$

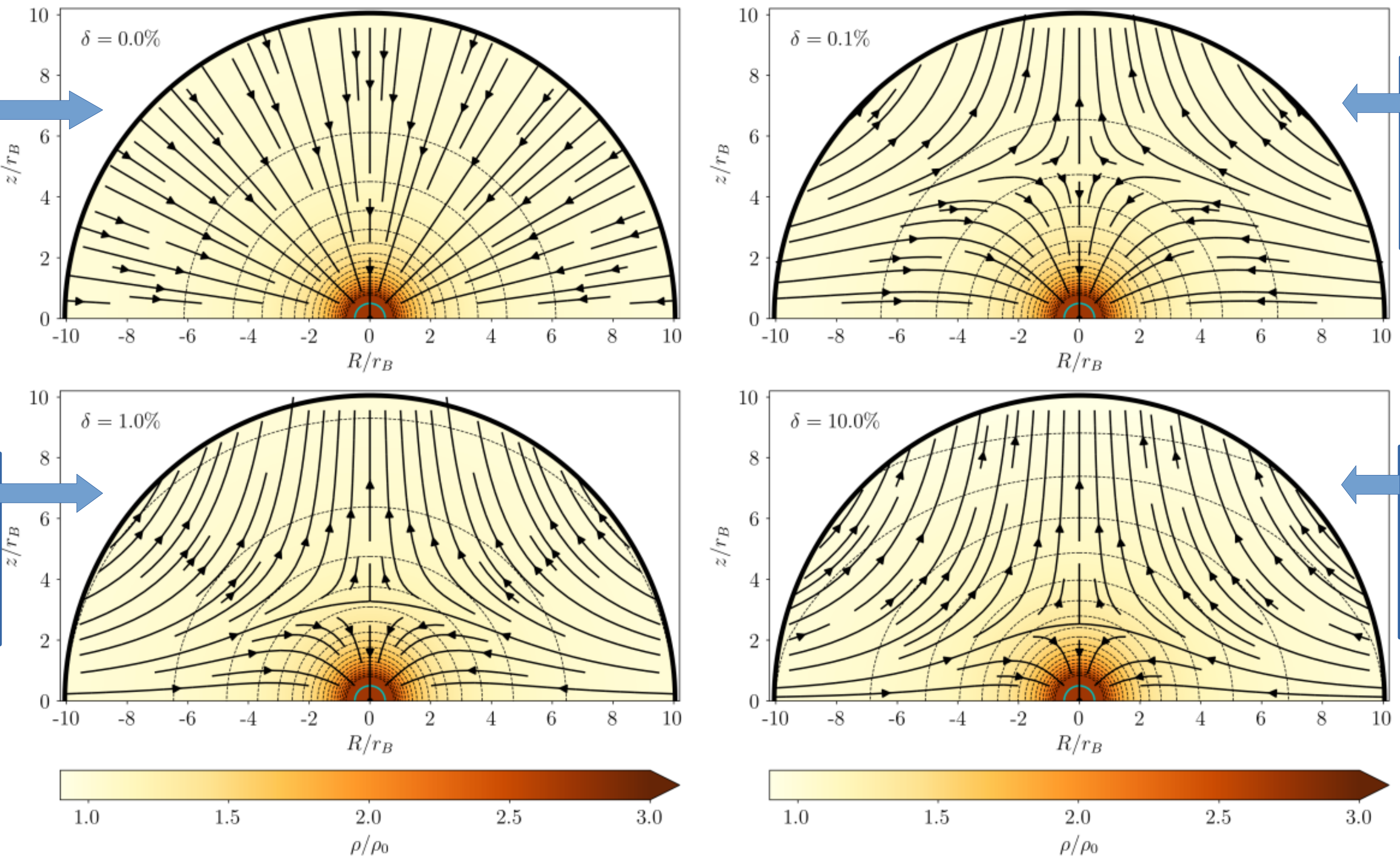


Aguayo-Ortiz, Tejeda & Hernandez (2019)

Dependence on $\boldsymbol{\delta}$ (Newtonian regime, γ =4/3)

$\delta = 0.0\%$
$\dot{M} = 1.0\dot{M}_{\rm B}$
$\text{out/in} = 0$

$\delta = 0.1\%$
$\dot{M} = 0.99\dot{M}_{\rm B}$
$\text{out/in} = 0.48$

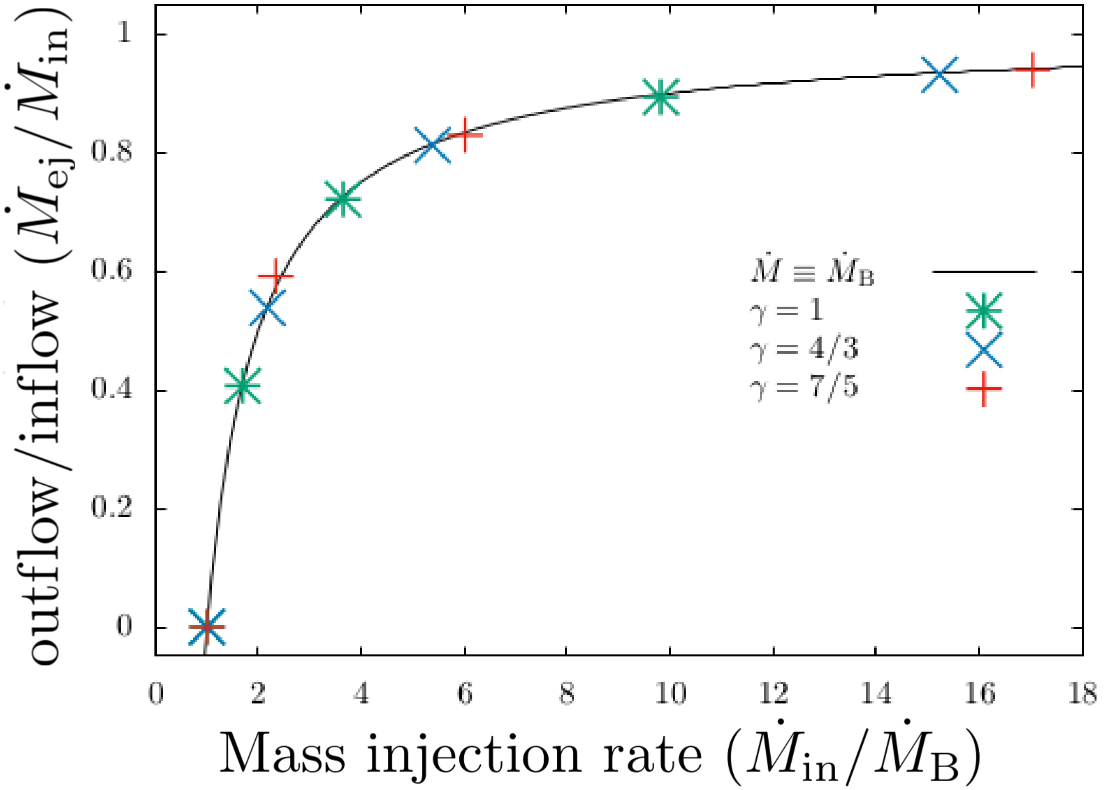


$\delta = 1.0\%$
$\dot{M} = 1.02\dot{M}_{\rm B}$
$\text{out/in} = 0.75$

$\delta = 10\%$
$\dot{M} = 1.05\dot{M}_{\rm B}$
$\text{out/in} = 0.89$

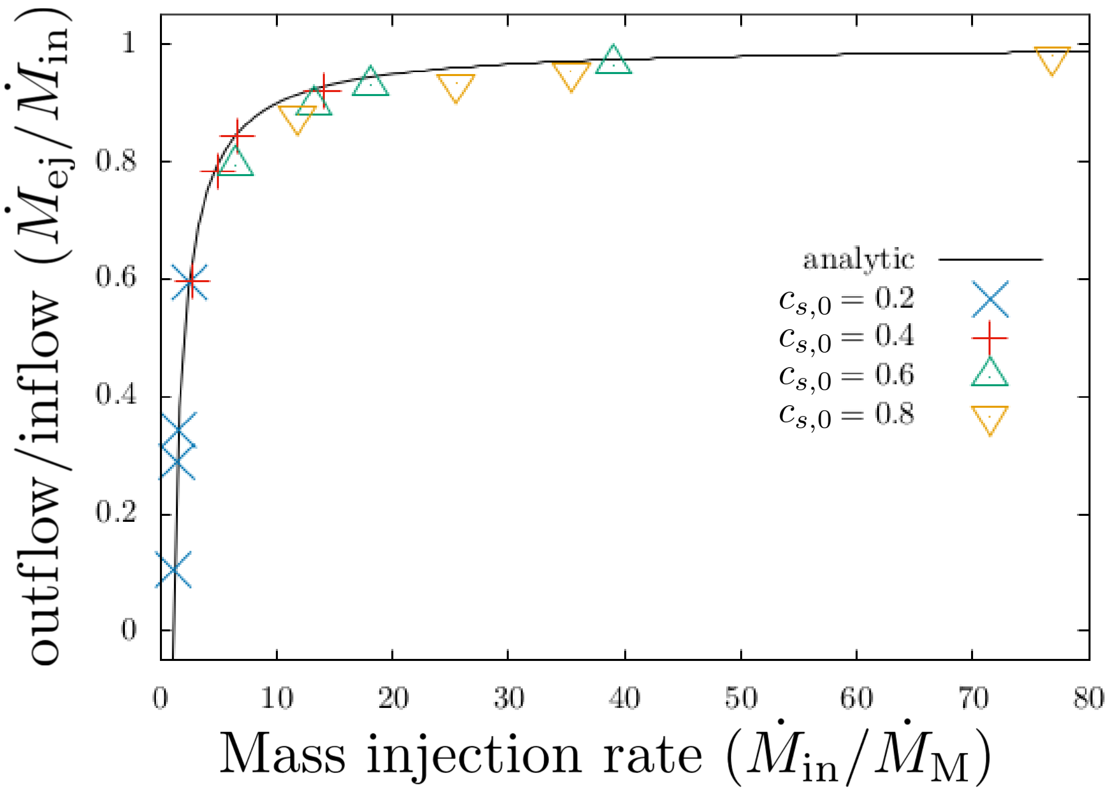
Aguayo-Ortiz, Tejeda & Hernandez (2019)

Choked accretion - Newtonian regime



Aguayo-Ortiz, Tejeda & Hernandez (2019)

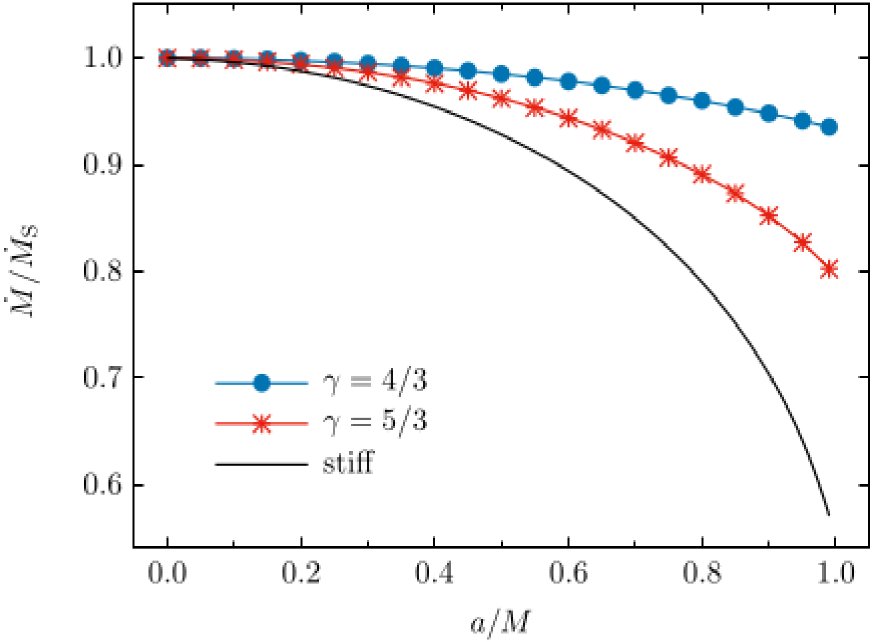
Choked accretion - Relativistic regime

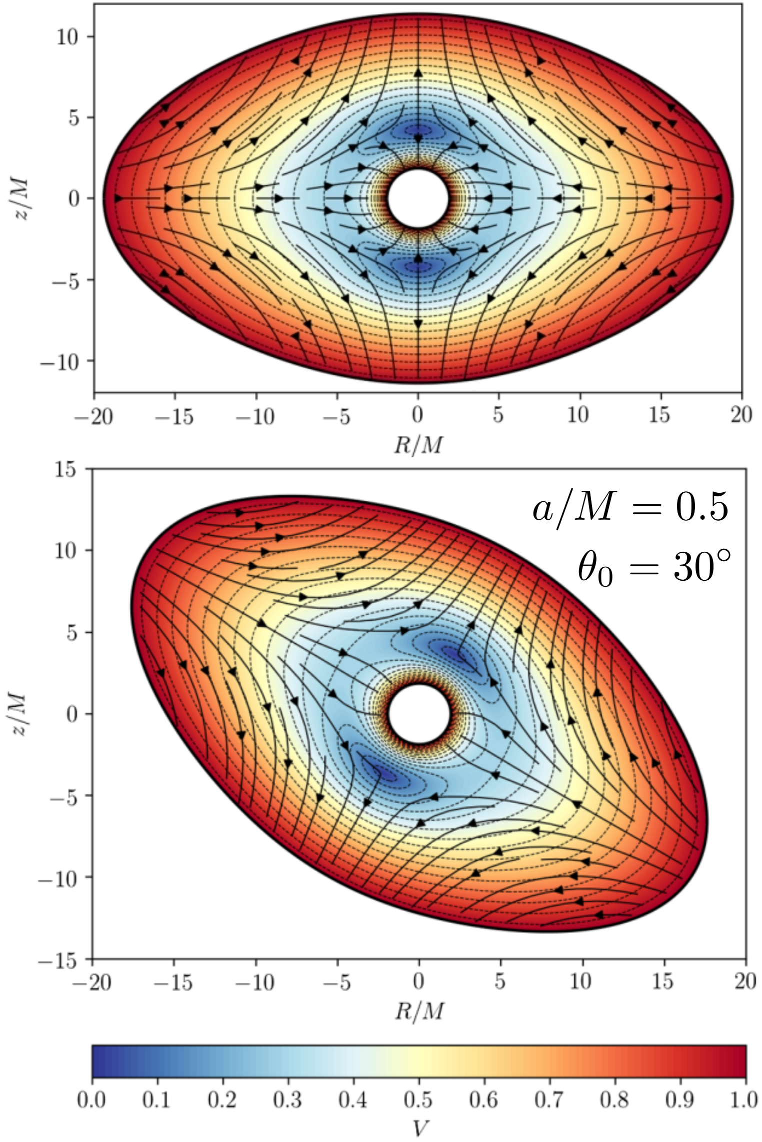


Tejeda, Aguayo-Ortiz & Hernandez (2020)

Kerr spacetime

Aguayo-Ortiz, Sarbach & Tejeda (2021)





Astrophysical applicability

Very high temperatures needed for hydrodynamics alone to work

$$\Theta_0 = \frac{P_0}{\rho_0} \simeq 1 \quad \Longrightarrow \quad \begin{array}{ll} T_0 \simeq 10^{12}\,\mathrm{K} & \text{ionized hydrogen} \\ T_0 \simeq 10^{9}\,\mathrm{K} & \text{electron-positron plasma} \end{array}$$

Possible connection with hot accretion flows (Yuan & Narayan 2014) and other radiative inefficient accretion flows

Additional physical ingredients (magnetic reconnection, radiation, rotation) could increase the effective temperature as well as the density contrast, thus potentially increasing the applicability of choked accretion

Also see recent works by Waters et al (2020) and Zeraatgari et al (2020)

Conclusions (part II)

- Novel hydrodynamical mechanism that transforms an originally radial accretion flow on to an inflow/outflow configuration

- Bridge between spherical accretion and outflow-generating systems

- Main findings:
    - Flux-limited accretion regime. The incoming material chokes at a gravitational bottleneck and the excess flux is redirected by the density gradient as a bipolar outflow
    - Appealing simple connection between inflow and outflow