Radiative GRMHD simulations of super-Eddington accretion onto neutron stars

David Abarca[1]
Włodek Kluźniak[1]
Aleksander Sądowski

[1]Nicolaus Copernicus Astronomical Center, Warsaw, Poland

PULX Workshop | Madrid, Spain

Research motivation: Neutron Star Ultraluminous X-ray Sources

- Objects observed outside the central region of galaxies with X-ray luminosity exceeding 10^{39} erg s^{-1} observed alongside pulsations with period $\sim 1s$
- Must be accretion onto neutron stars (NS)!
- 10^{39} erg s^{-1} is about 10 L_{Edd} for 1.4 $M_\odot$ neutron star (NS)
- NSs differ from black holes (BH) by a hard surface and stellar magnetic fields

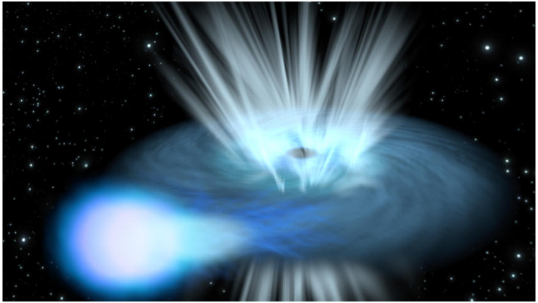


image credit: C. Carreau

General **R**elativistic **R**adiation **M**agneto**H**ydro**D**ynamics

$$\nabla_\mu(\rho u^\mu) = 0 \qquad \text{conservation of mass} \tag{1}$$

$$\nabla_\mu T^{\mu\nu} = G^\nu \qquad \text{conservation of energy-momentum} \tag{2}$$

$$\nabla_\mu R^{\mu\nu} = -G^\nu \qquad \text{conservation of radiation energy-momentum} \tag{3}$$

$$\nabla_\mu F^{*\mu\nu} = 0 \qquad \text{Maxwell (induction for ideal MHD)} \tag{4}$$

Or basically,

$$\frac{\partial}{\partial t}\left[\text{quantity}\right] = -\text{div}\left[\text{flux of quantity}\right] + \text{source of quantity}$$

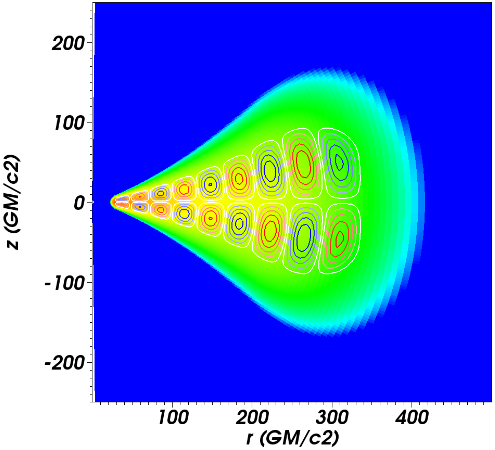
Conserved quantities: mass, momentum, energy are evolved with time

Details of the Koral code (Sądowski et al. 2013, 2015)

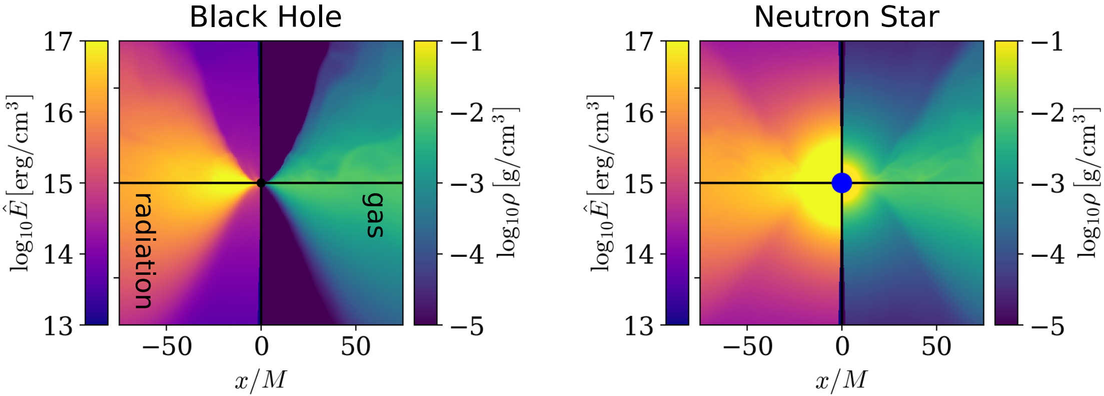
- Radiation is evolved using the M_1 closure scheme
  - There exists a frame, u^{μ}_{R}, where radiation is isotropic, $\widehat{P}_{ij} = \frac{1}{3}\widehat{E}\delta_{ij}$
  - Radiation source computed in this frame and boosted back to lab frame
  - Valid for optically thin and optically thick environments
- M_1 means radiation is treated like a fluid and evolved in parallel with the gas but with opposite signs for the radiative source terms , G^{ν}
- Total energy and momentum are conserved even with radiation, $\nabla_{\mu}(T^{\mu\nu} + R^{\mu\nu}) = 0$
- 2D axisymmetry (2.5D) sustained by mean-field dynamo
- Radiation source terms, G^{ν}, require implicit-explicit time integration
- KORAL uses ideal MHD approximation, electric fields are zero in the fluid frame, and so can be ignored

Simulation Set Up

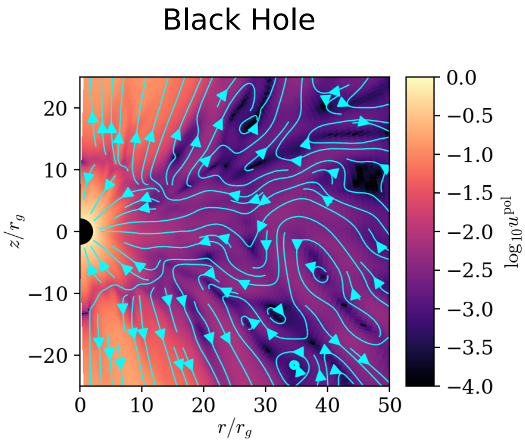
- Initial Condition: Weakly magnetized equilibrium torus in local thermal equilibrium with radiation
- BH inner boundary, outflow underneath event horizon
- NS inner boundary at 5 $\mathrm{r_g}$, reflect radial velocity, set tangential velocity to zero
- Evolve for 80,000 $\mathrm{GM/c^3}$, about 100 orbits at the innermost stable circular orbit,

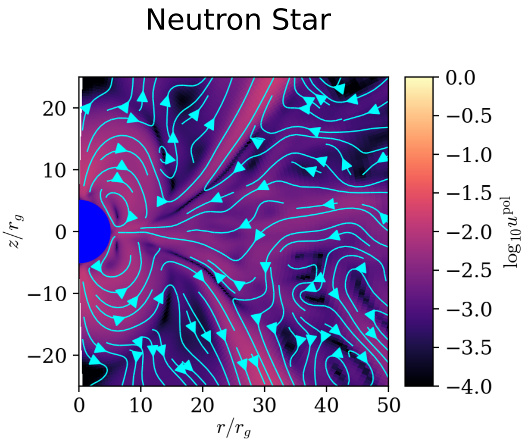


Radiation and gas density in the $r - z$ plane

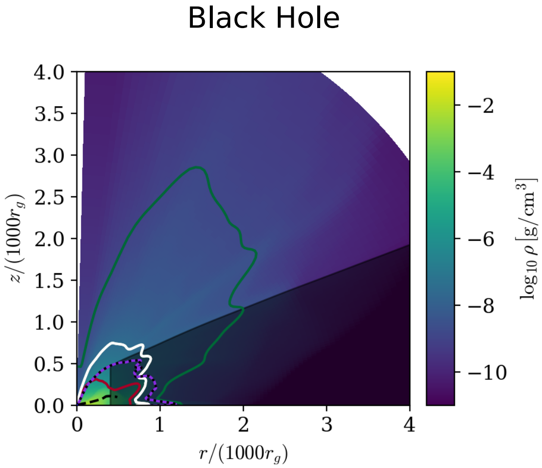


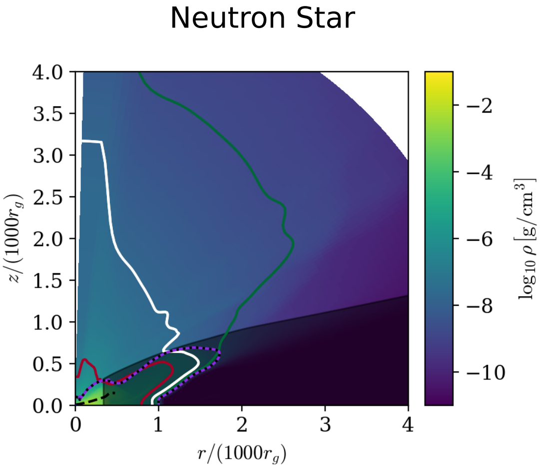
Velocity map – time average $40,000 \sim 80,000 GM/c^3$



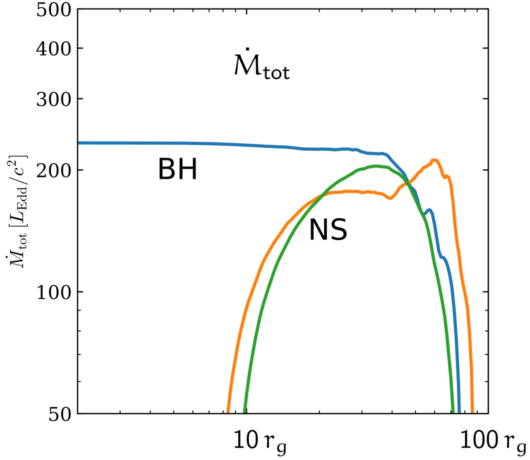


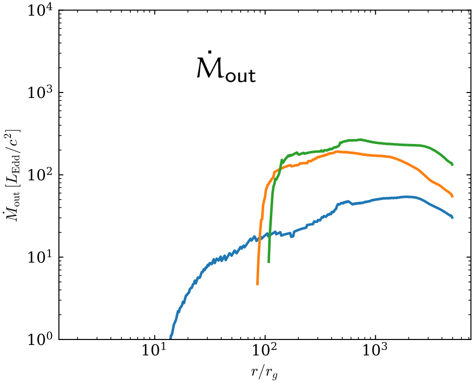
Results: Optical depth and Specific Energy



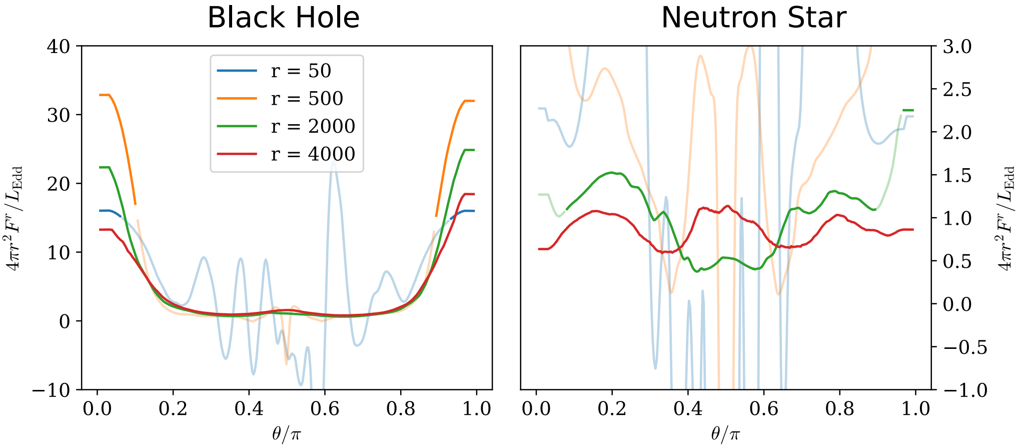


Accretion Rates





Observed luminosity as a function of viewing angle



Conclusions

- Not bright enough for the neutron star to be a ULX!
- Large outflow rate traps radiation
- We need to add stellar magnetic fields

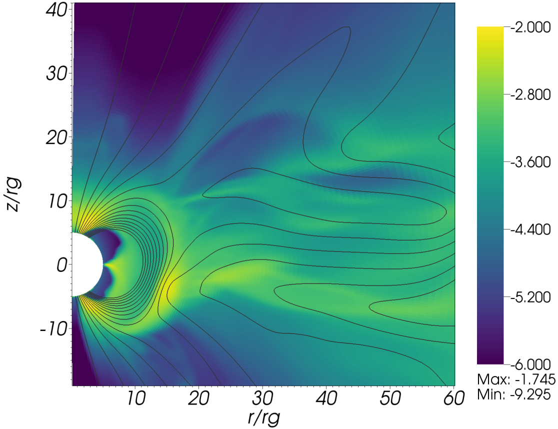
Simulations around magnetized stars

- $T^{\mu}{}_{\nu} = (\rho + u_{\text{int}} + p + b^2) u^{\mu} u_{\nu} + \left(p + \frac{1}{2} b^2\right) \delta^{\mu}_{\nu} - b^{\mu} b_{\nu}.$
- ρ – density, u_{int} – internal energy, $p = (\Gamma - 1) u_{\text{int}}$ – pressure, u^{μ} – four-velocity, b^{μ} – magnetic field four-vector
- Dipole field means $b^2 \propto r^{-6}$
- $(\rho, u_{\text{int}}, p, b^{\mu}, u^{\mu}) \to T^{\mu}{}_{\nu}$ is easy
- $T^{\mu}{}_{\nu} \to (\rho, u_{\text{int}}, p, b^{\mu}, u^{\mu})$ is hard, especially when b^2 is large
- Force-free approximation is used to describe NS magnetosphere (Parfrey & Tchekhovskoy 2017)
- Takahashi & Ohsuga (2017) simulated accretion onto $B = 10^{10}$ G NS without force-free approximation

First results accretion onto magnetized NS (10^{10}G)

$\log_{10}$ gas density in g/cm^3 $\rightarrow$

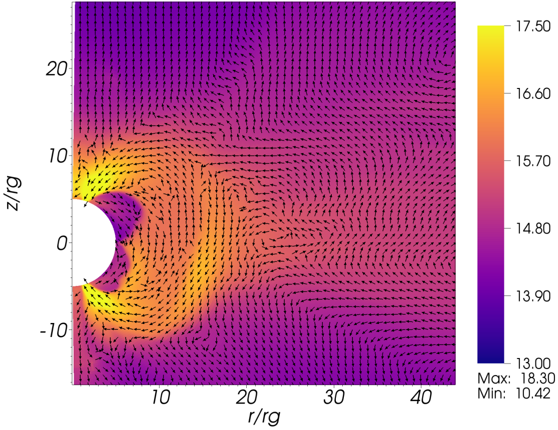
- Quite a few numerical tricks including force-free related adjustments (ignoring plasma momentum)
- Short duration, can not see MRI yet in disk
- Using an absorbing boundary condition



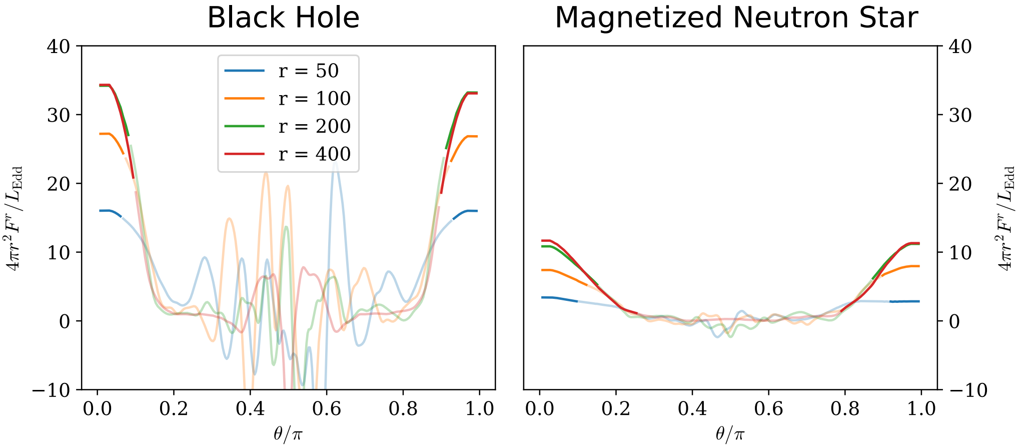
First results accretion onto magnetized NS (10^{10}G)

$\log_{10}$ radiation energy in erg/cm^3 $\rightarrow$

- Radiation in the column is advected into the star with the gas flow
- Radiation diffuses out of the sides of the column and up the axis
- Tilted magnetic axis would lead to pulsations as seen in ULXs



Observed luminosity as a function of viewing angle



Conclusions

- Not bright enough for the neutron star to be a ULX!
- Large outflow rate traps radiation
- We need to add stellar magnetic fields
- 10^{10} G magnetic field enough to reach 10^{39} erg s^{-1}
- Next step is try combine reflection and magnetic fields
- Proper force-free to push to higher magnetic fields, still need to explain 10^{40}, 10^{41} erg s^{-1} observations