Simulations of accretion onto black holes, neutron stars, and naked singularities

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Results of some state of the art, radiative GRMHD simulations onto black hole mimickers, such as naked singularities and neutron stars, are presented to provide a benchmark for comparison with Kerr black hole predictions.

It is now possible to simulate accretion onto black holes and their mimickers in radiative Magneto-Hydrodynamic Codes in General Relativity (GR). We report our simulations onto black holes (BH), neutron stars (NS), and naked singularities (NkS).

1. Neutron Stars as ULXs

Ultraluminous X-ray sources (ULXs, very bright extragalactic “off-nuclear” objects) were proposed to be accreting intermediate-mass black holes (Colbert & Mushotzky 1999). But some show coherent periodicities, so are definitely neutron stars.

We model accretion onto run-of-the-mill NS with the radiative GRMHD code KORAL. Mildly super-Eddington accretion leads to beamed X-ray emission at apparent luminosities of ~100 Eddington, more than 10^40 erg/s.

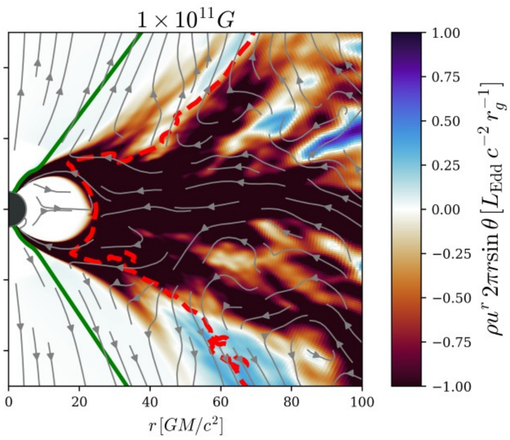


Figure 1: *The momentum density in super-Eddington accretion onto a neutron star in a simulation with KORAL. The red dashed line represents the zero Bernoulli surface, and the green solid line is the photosphere. The arrows depict the radiative flux direction.*

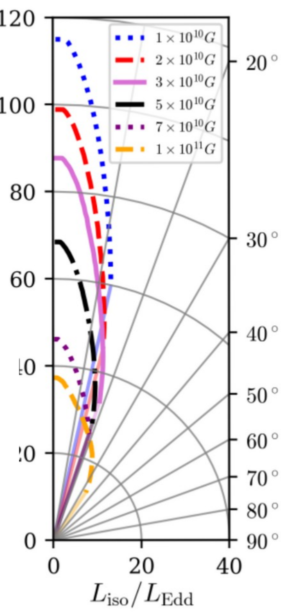


Figure 2: *Isotropic luminosity in Eddington units in polar coordinates. The straight grey solid lines correspond to particular viewing angles (Kayanikhoo et al., arXiv:2508.02563).*

2. GR hydro simulations of Naked Singularities in Reissner-Nordström Space-Time

$$g = -f(r)dt^2 + \frac{1}{f(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta d\phi^2)$$

$$-g_{tt} = f(r) = 1 - 2M/r + Q^2/r^2,$$

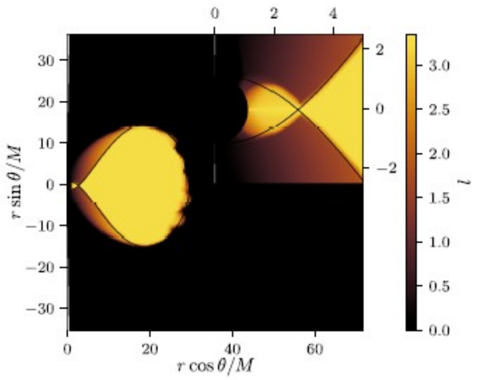
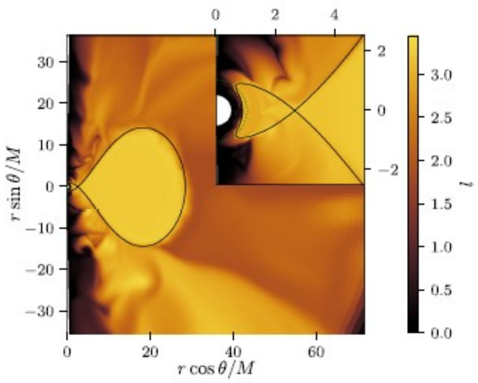


Figure 3: *Accretion onto a BH and a NkS (Kluźniak & Krajewski 2024). The quantity shown is the specific angular momentum of the fluid. The BH absorbs all infalling matter (above). The NkS ejects the infalling fluid (bottom).*



Simulations:

The BH and NkS simulations in the Reissner-Nordström metric (Fig. 3) were performed in the KORAL+ code.

Initial setup: a torus of fluid in hydrostatic equilibrium as a reservoir of matter (visible in meridional cross-section in the figures) filling an equipotential surface (black lines), accretion proceeds through its cusp.

Discussion & Results:

The magnetic field inherent to Neutron Stars channels accretion flow, allowing radiation to escape along the axis, with super-Eddington apparent luminosities.

In Naked Singularities the repulsive core of gravity prevents accretion and leads to strong outflows.

A Black Hole shows neither of these effects, i absorbs all matter through its horizon.

3. Thin-disk accretion onto a NkS

In Čemeljić et al. 2025 were presented results of simulations for a thin disc around a RN NkS, using the newly devised pseudo-Newtonian potential:

$$V(r) = -\frac{M}{r} + \frac{Q^2}{2r^2}$$

reproducing the location of the zero-gravity radius, but also the exact functional form of the Keplerian orbital frequency.

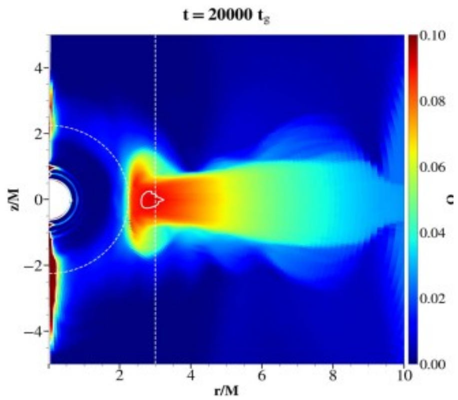
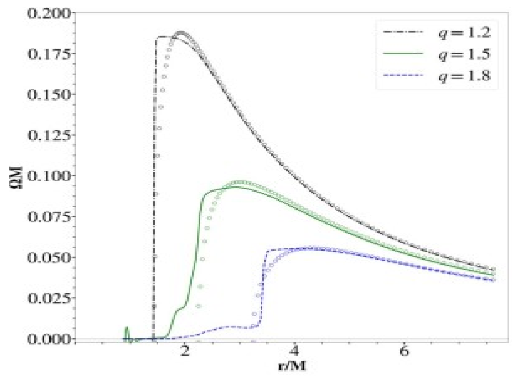


Figure 4: *Orbital velocity in thin-disk accretion onto a NkS. No fluid penetrates the repulsive core at r~2M.*
Above: structure in the meridional plane (PLUTO simulation).
Below: radial dependence of angular velocity for three values of charge to mass ratio, q=Q/M (Čemeljić et al. 2025).



Conclusions.

Accretion and ejection proceeds differently in neutron stars, black holes, and naked singularities. In NS radiation is collimated along the axis; a BH absorbs all incoming matter; a NkS deflects infalling matter. Potentially, observations of outflows and X-rays may discriminate between these three classes of objects.

References:

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Colbert, E.J.M., Mushotzky, R.F., 1999, ApJ 519, 89

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Acknowledgements:

Work in Warsaw is funded by NCN Polish grant no. 2019/35/O/ST9/03965. KORAL+ was developed in house at CAMK (Copernicus Astronomical Center) by T. Krajewski, basing on A. Sądowski’s KORAL. We thank to Debora Lancova and Angelos Karakonstantinakis for help with the KORAL code. We also thank A. Mignone and his team of contributors for the possibility to use the PLUTO code.