3D Visualizations of Rapidly Spinning, Tilted Black Holes with Self-Gravitating Accretion Disks

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Abstract

What we are studying: Black Hole Disks (BHDs)

- BHDs can arise from the collapse of massive stars and from the merger of a binary black hole-neutron star system [4].
- Massive BHDs with supermassive black holes can be found at the center of galaxies [1].

How we study BHDs: Numerical Relativity

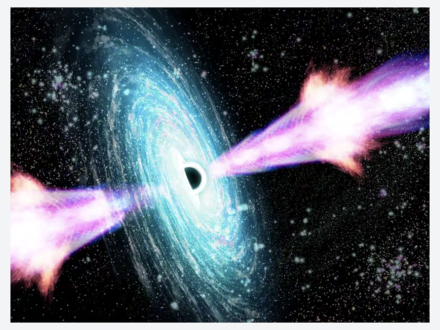
- Einstein's equations are decomposed into 3+1 dimensions using Baumgarte-Shapiro-Shibata-Nakamura formalism. Space and time are separated allowing the time evolution of an initial spatial slice.
- General relativistic magnetohydrodynamics (GRMHD) combine Einstein's equations with Maxwell's equations and fluid dynamics to allow study of systems such as accretion disks and neutron stars.

How BHDs can be observed: Multi-Messenger Astronomy

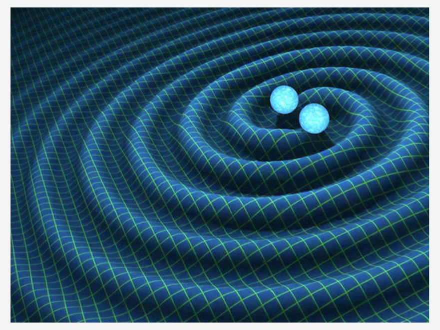
- Fluid donuts with angular momentum in a central potential are subject to the Papaloizou-Pringle instability (PPI). In BHDs, PPI leads to the emission of gravitational radiation detectable by next-generation detectors like Cosmic Explorer and LISA [2].
- Accretion of magnetized matter can lead to magnetic winding around the black hole poles, which can launch ionized matter at relativistic speeds: a necessary requirement for detectable gamma-ray bursts.

Our Models

- All the models have self-gravitating disks with angular momentum in the 'up' direction.
- The black holes are highly spinning with dimensionless spins $\chi > 0.85$.
- The spins of the black holes are tilted 45° with respect to the angular momentum of the disks.



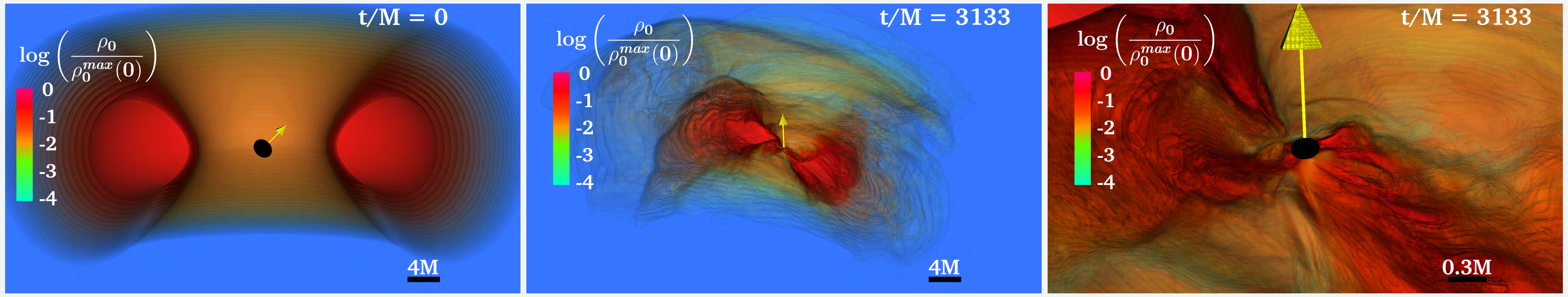
(a) Artist's rendition of a gamma-ray burst (*Credit: Nuria Jordana-Mitjans*)



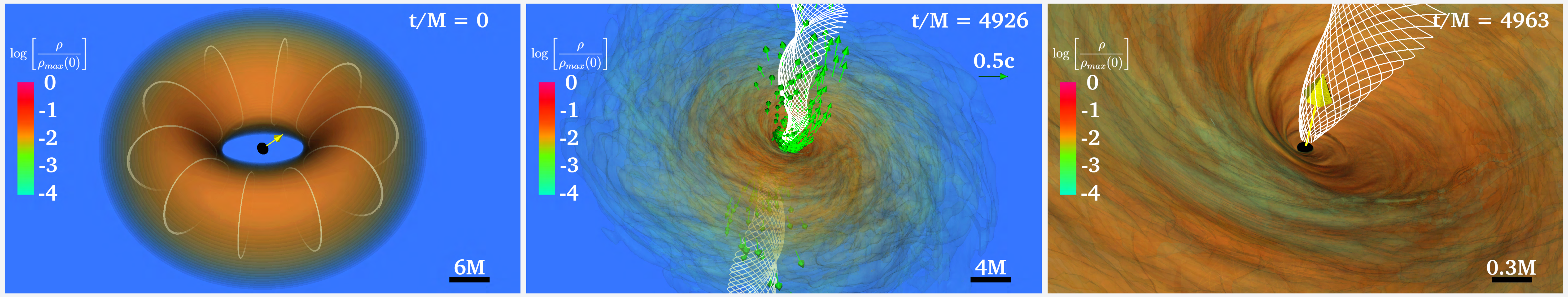
(b) Artist's rendition of gravitational waves (*Credit: Robert Hurt*)

(c) LIGO Livingston (*Credit: Caltech/MIT/LIGO Lab*)

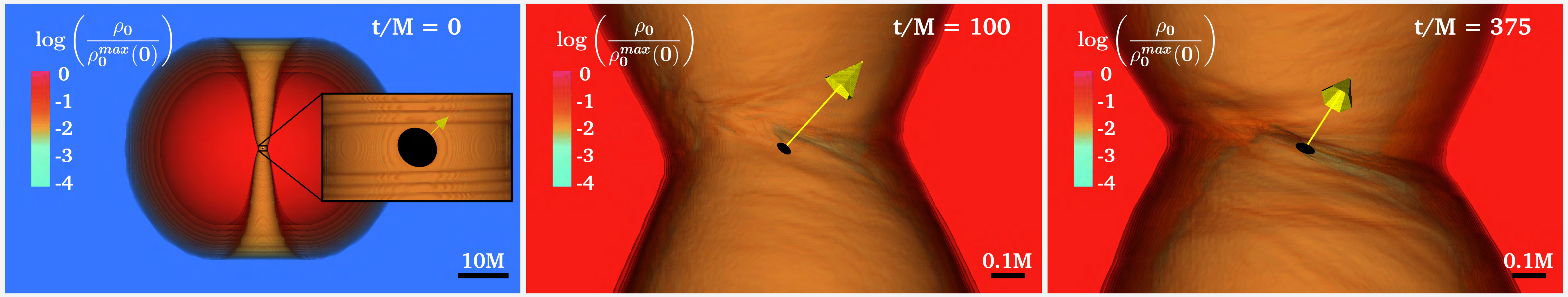
MODEL A1: Purely Hydrodynamic Disk · 6:1 Black Hole to Disk Mass Ratio · Black Hole Spin $\chi \approx 0.95$



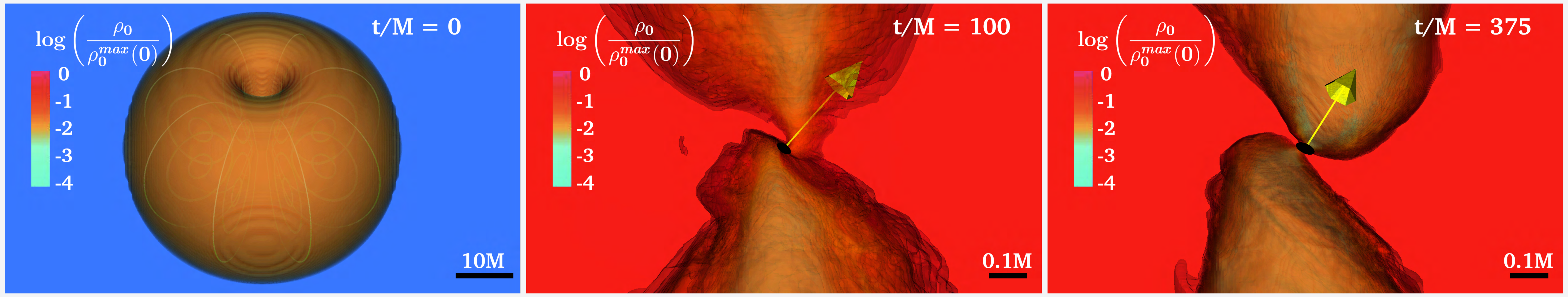
MODEL A2: Magnetized Disk · 6:1 Black Hole to Disk Mass Ratio · Black Hole Spin $\chi \approx 0.95$



MODEL A3: Purely Hydrodynamic Disk · 1:9 Black Hole to Disk Mass Ratio · Black Hole Spin $\chi \approx 0.85$



MODEL A4: Magnetized Disk · 1:9 Black Hole to Disk Mass Ratio · Black Hole Spin $\chi \approx 0.85$



Results

In all models, the disk's gravitomagnetic field causes black hole precession around the disk's rotation axis. At the same time, the Lense-Thirring effect twists and warps the disk [1].

Model A1

- The Papaloizou-Pringle instability leads to the disk developing higher density 'clumps'. These clumps orbit the black hole and emit gravitational radiation that will be detectable by next-generation observatories such as Cosmic Explorer, DECIGO, and LISA [1][3].

Model A2

- At the end of the evolution, we observe collimated magnetic field lines and an outflow of matter, signifying a relativistic jet, which is a necessary requirement for detectable gamma-ray bursts. However, the magnetorotational instability suppresses the Papaloizou-Pringle instability, leading to weaker gravitational radiation [3].

Model A3

- The larger mass of the disk leads to a higher black hole precession frequency than A1. Currently, there isn't significant accretion due to the absence of magnetorotational instability (MRI).

Model A4

- The presence of magnetic fields leads to magnetorotational instability (MRI), which gives the disk an effective 'viscosity'. MRI quickly amplifies small magnetic fields and speeds up accretion [3].

References

[1] A. Tsokaros, M. Ruiz, S. L. Shapiro, and V. Paschalidis, "Self-gravitating disks around rapidly spinning, tilted black holes: General-relativistic simulations," *Phys. Rev. D*, vol. 106, no. 10, p. 104010, 2022.

[2] E. Wessel, V. Paschalidis, A. Tsokaros, M. Ruiz, and S. L. Shapiro, "Gravitational waves from disks around spinning black holes: Simulations in full general relativity," *Phys. Rev. D*, vol. 103, no. 4, p. 043013, 2021.

[3] E. Wessel, V. Paschalidis, A. Tsokaros, M. Ruiz, and S. L. Shapiro, "Effect of magnetic fields on the dynamics and gravitational wave emission of PPI-saturated self-gravitating accretion disks: simulations in full GR," arXiv:2304.07282, 2023.

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Movies for Model A1 at

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