Gravitational Waves from Black Holes Surrounded by Massive Accretion Disks

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Abstract

What we are studying: Gravitational Waves (GWs)

- GWs were predicted by Einstein's theory of general relativity theory in 1915 and were first detected after 100 years in 2015 using a special telescope called LIGO (laser interferometer gravitational-wave observatory).
- While LIGO and detectors like it can only detect the strongest and highest frequency GWs in the universe, more sensitive detectors in the works will be able to detect GWs with smaller amplitudes and lower frequencies.
- We work to model astrophysical sources that produce GWs so that future detectors know what to look for.

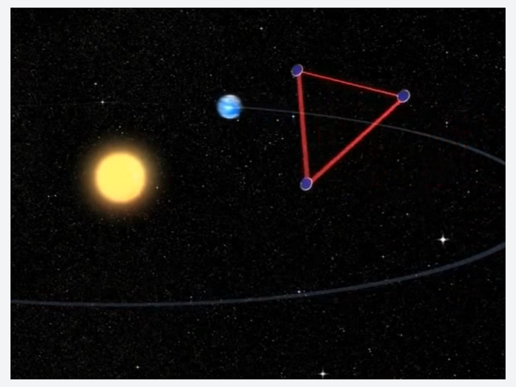
How we study GWs: Numerical Relativity

- 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.
- We use general relativistic magnetohydrodynamics (GRMHD)—which combines Einstein's equations with Maxwell's equations and fluid dynamics–to simulate systems such as black holes, neutron stars, and accretion disks.

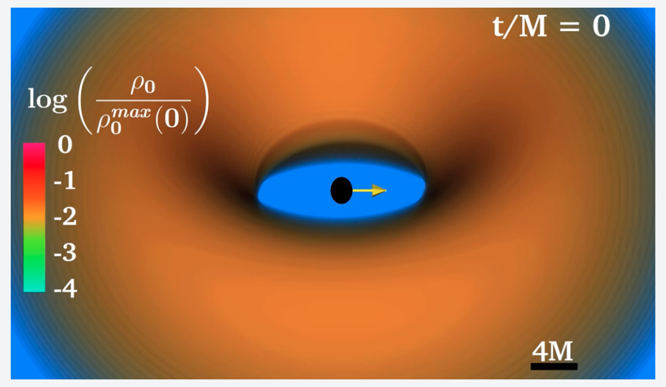
Different types of GW sources

- (BOX A): In general relativity, GWs arise when a system has a mass quadrupole moment that changes in time. A few analytical examples are shown here.
- (BOX B): The strongest GWs, and the only GWs we've detected, come from collisions between the densest objects in the universe: black holes and neutron stars. GWs from two binary black hole simulations are shown.
- (BOX C): Because of the Papaloizou-Pringle instability, black holes surrounded by a self-gravitating gaseous torus emit GWs detectable by next-generation detectors such as Cosmic Explorer and LISA. These types of GWs haven't been detected yet, but black-hole tori are a promising candidate for future GW sources.

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



(b) Laser Interferometer Space Antenna (*Credit: AEI/Milde Marketing*)



(c) Rapidly spinning black hole surrounded by gaseous donut (initial configuration of the BOX C model)

BOX B: Gravitational Waves from Binary Black Hole Systems

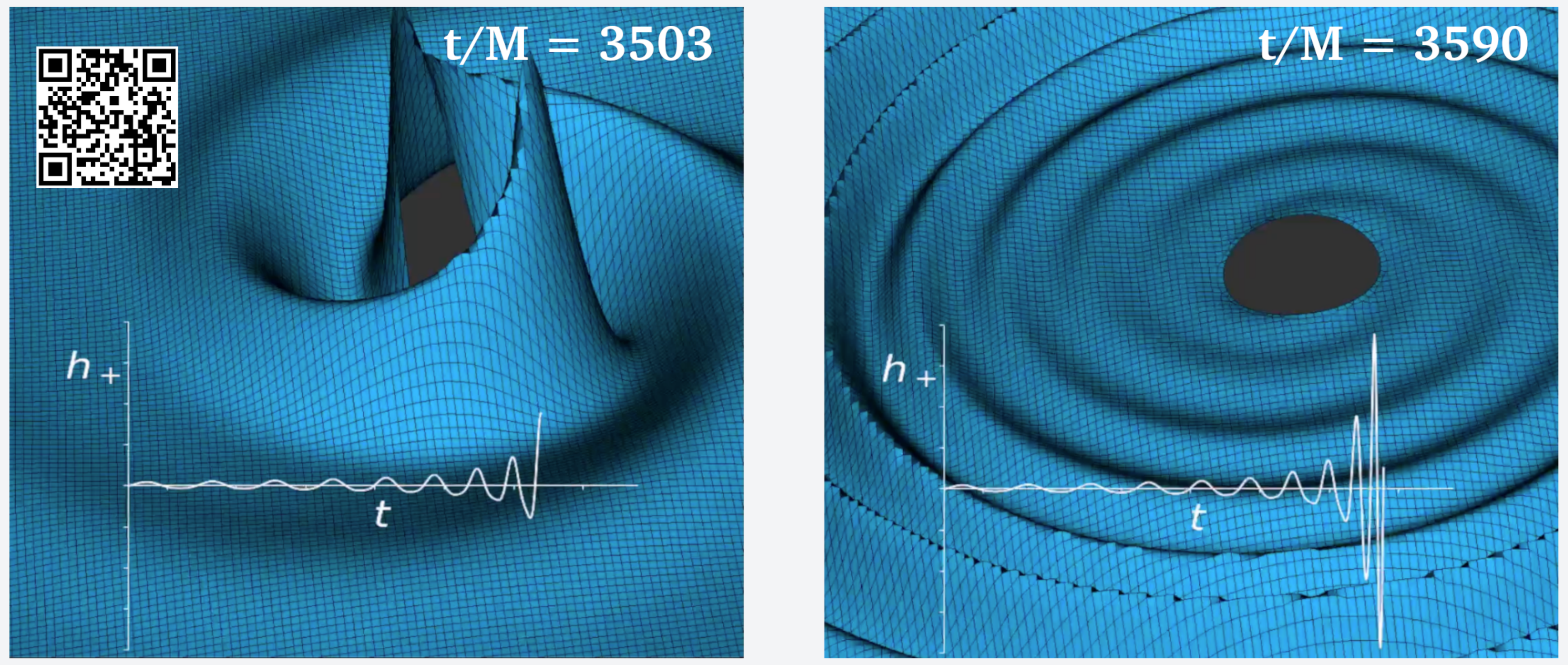


Figure: Gravitational Waves from a Binary Black Hole System with Equal Mass Black Holes

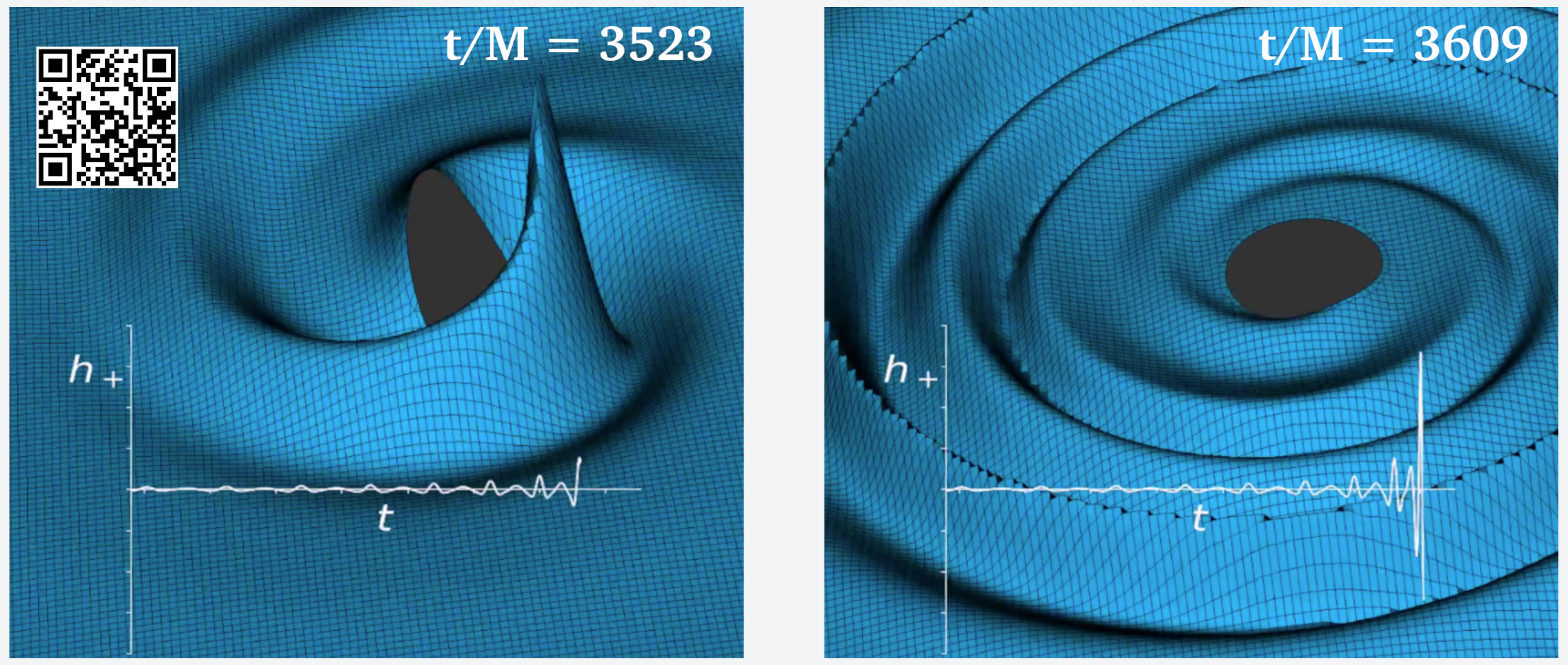
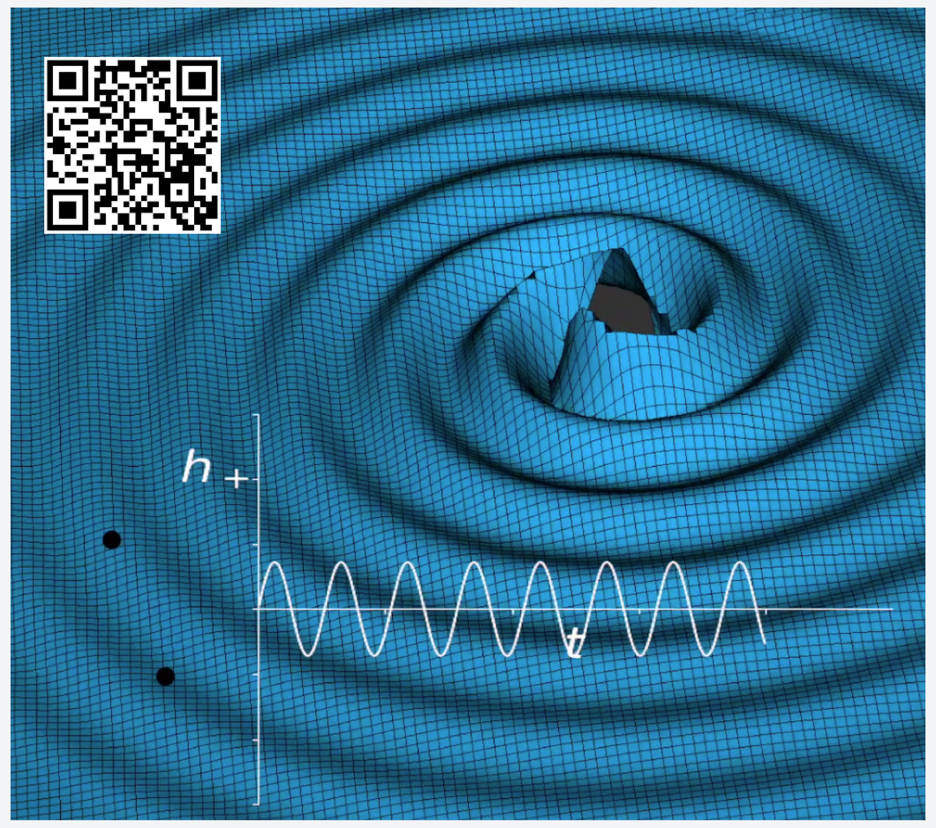
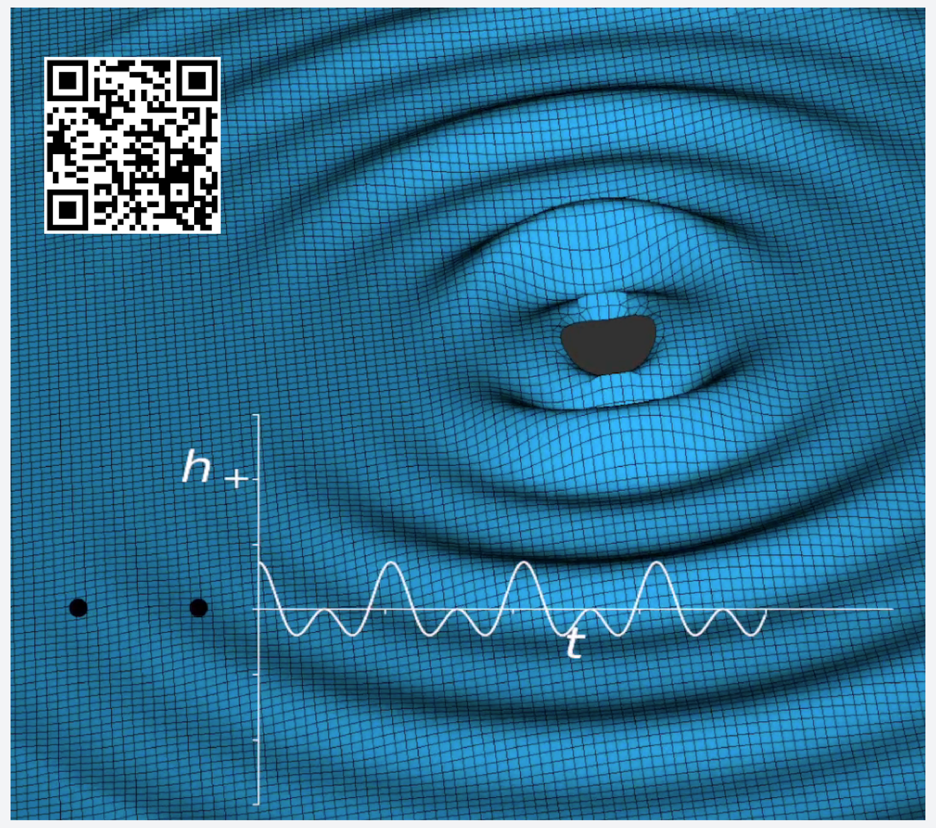


Figure: Gravitational Waves from a Binary Black Hole System with a 4:1 Black Hole Mass Ratio

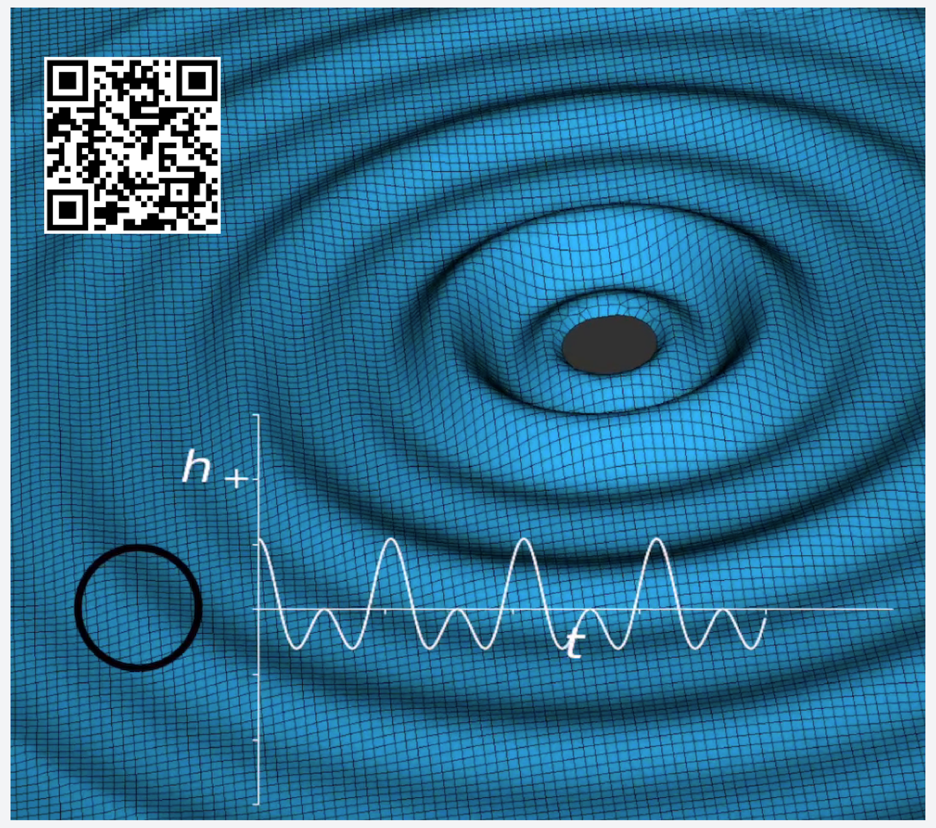
BOX A: Gravitational Waves from Analytical Sources Derived Explicitly from General Relativity



(a) Two Point Masses Rotating at a Constant Radius

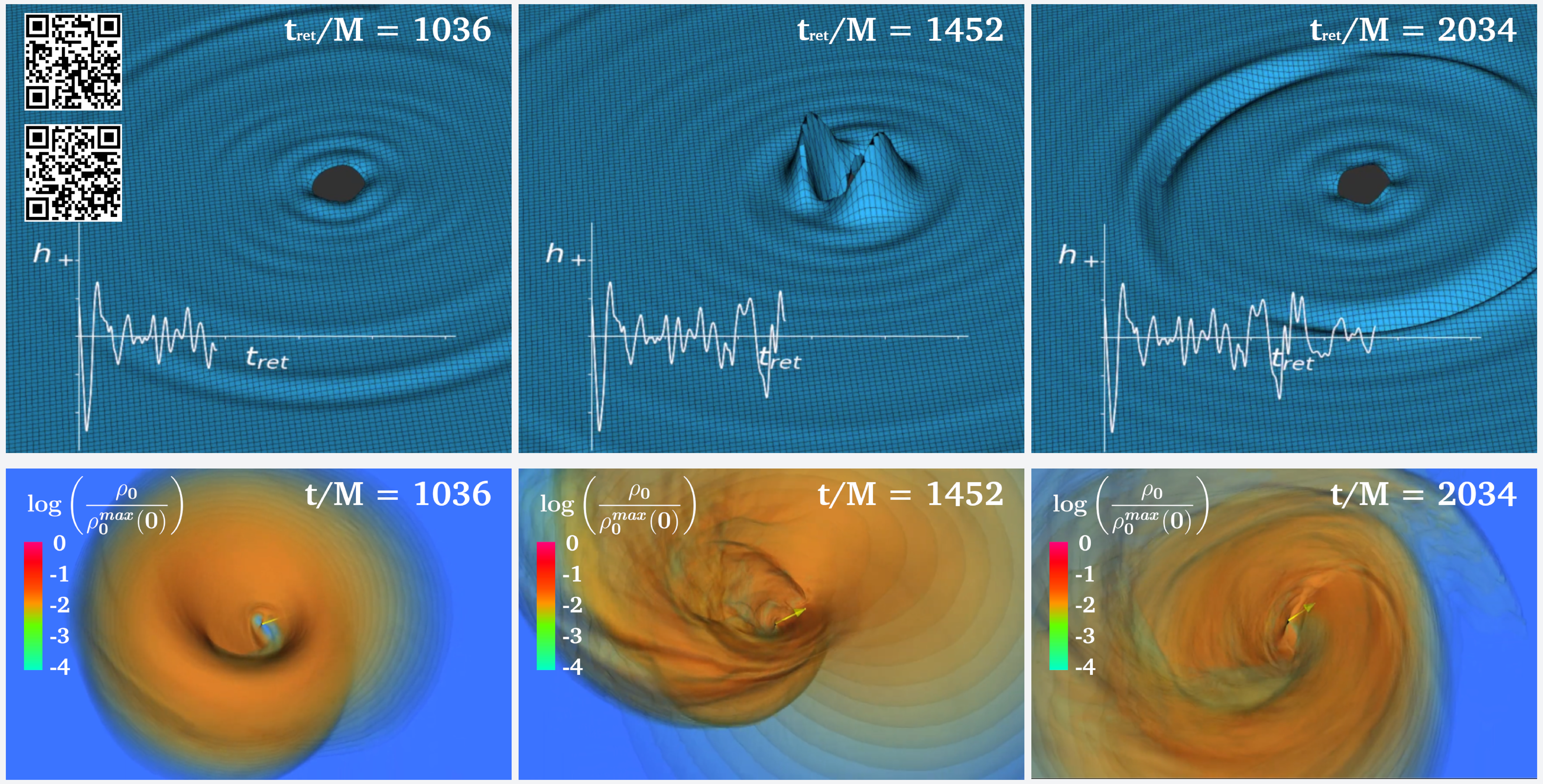


(b) Two Point Masses Pulsating Back and Forth on an Axis



(c) An Infinitesimal Ring With a Pulsating Radius

BOX C: Gravitational Waves from a Rapidly Spinning Black Hole Surrounded by a Self-Gravitating Torus



Conclusions

Analysis

- The GW visualizations of the analytical sources (BOX A) are compared to those extracted from numerical simulations (BOX B and C) to check whether we should believe the output of our simulations.
- For the black-hole disk, which is still only a theoretical source of GWs, we compare the GW visualizations with the matter visualizations to see if 'events' that occur in the matter evolution are mirrored in the GW data.

Results

- Based on comparison to the analytical sources, we hypothesize that the GWs from the black-hole torus system are dominated by a pulsating quadrupole moment rather than the traditional rotation associated with binary systems.
- We find that the violent behavior of the torus caused by the Papaloizou-Pringle instability is echoed by a large GW (middle column of BOX C). This gives us assurance that the simulation can be trusted and that these types of GWs may be out there in the universe waiting to be discovered.

References

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[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] M. Ruiz, A. Tsokaros, and S. L. Shapiro. "General Relativistic Magnetohydrodynamic Simulations of Accretion Disks Around Tilted Binary Black Holes of Unequal Mass," arXiv:2302.09083, 2023.

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