

Title: New Perspectives from Gravity's Extremes

Speakers: William East

Series: Colloquium

Date: February 26, 2020 - 2:00 PM

URL: <http://pirsa.org/20020022>

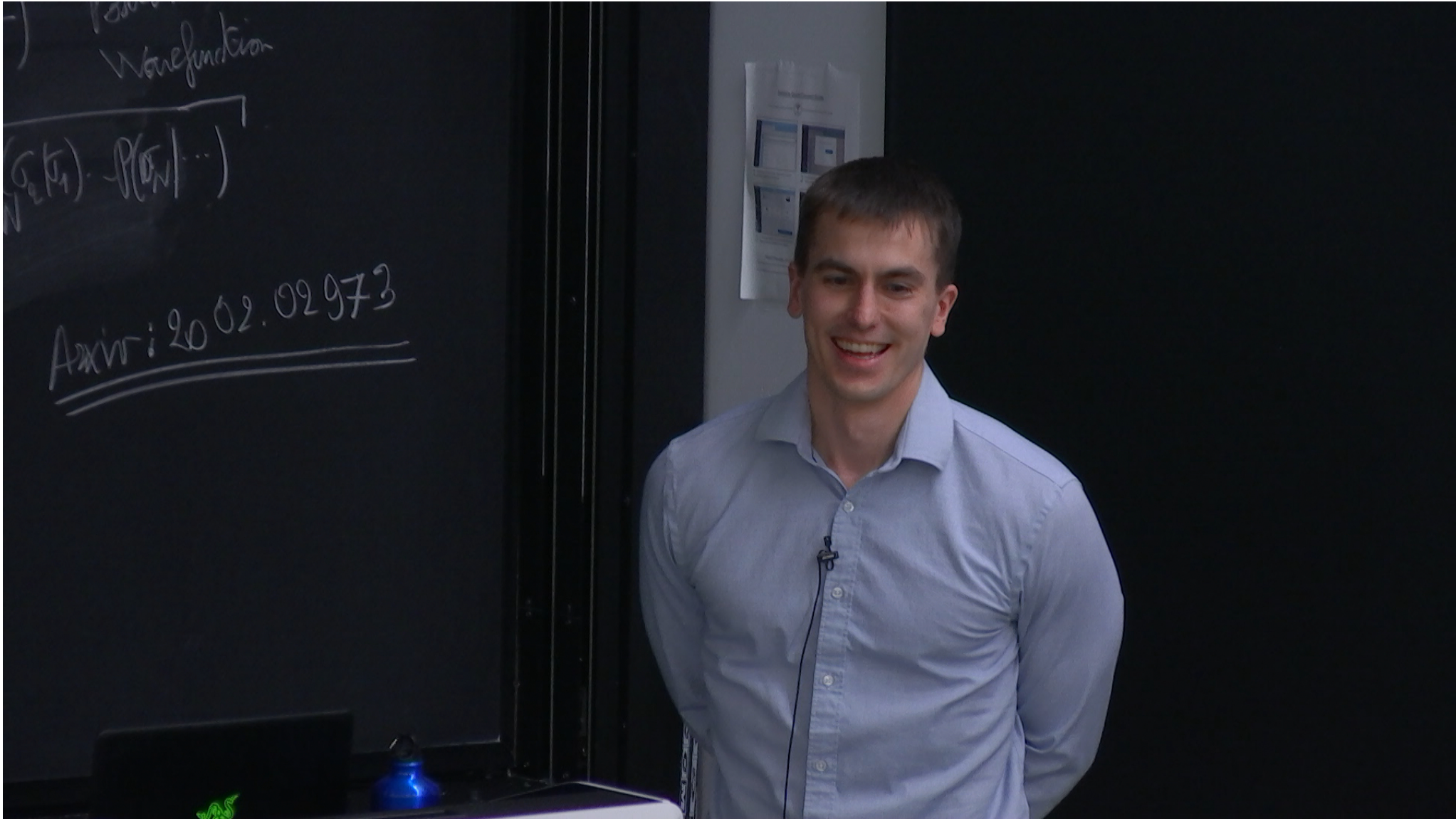
Abstract:

Beginning with the landmark gravitational wave detections by LIGO/Virgo, we have been gaining an unprecedented view of the dynamics of strongly curved spacetime originally predicted by Einstein. Enabling and motivated by these observations, there has been rapid development in the theoretical and computational tools we use to understand and interpret the nature of gravity and matter in this regime. This is essential to fulfilling the promise of gravitational wave astronomy to not only be a new window on the astrophysics of black hole and neutron star mergers, but also to be a unique probe of fundamental physics. I will illustrate this, highlighting the example of how black holes can be used to search for new particles. The same theoretical tools also allow us to push Einstein's theory to the extreme in search of the limits of its predictability, for example testing cosmic censorship, the idea that the breakdown in Einstein's equations associated with unhalted collapse is always hidden behind a black hole horizon. I will describe some recent work resolving a long-standing putative counterexample to this conjecture.

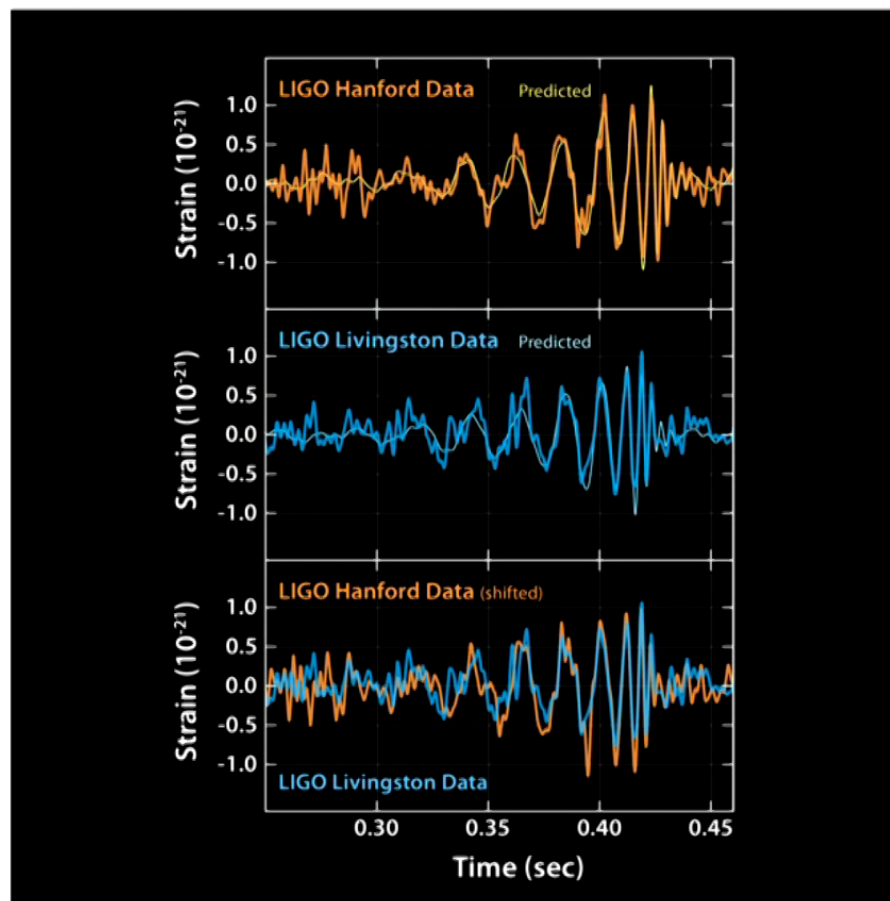


New Perspectives from Gravity's Extremes

William East
Perimeter Institute
February 26, 2020

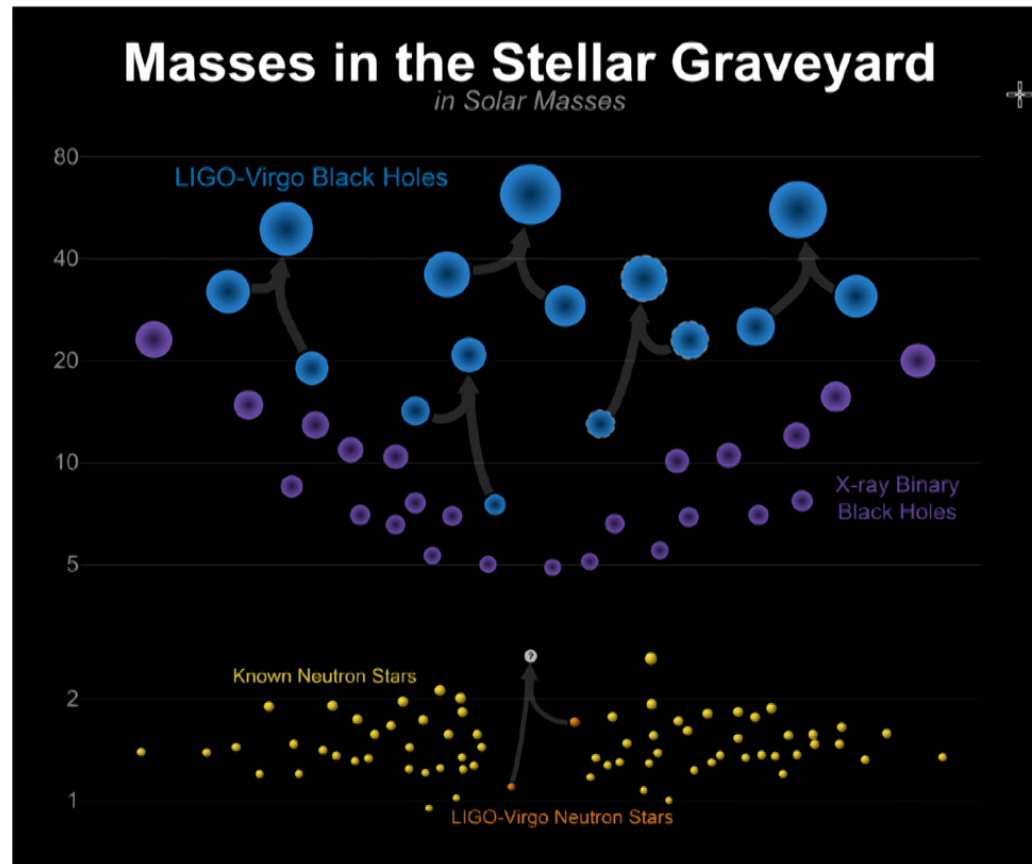


September 14, 2015 Event

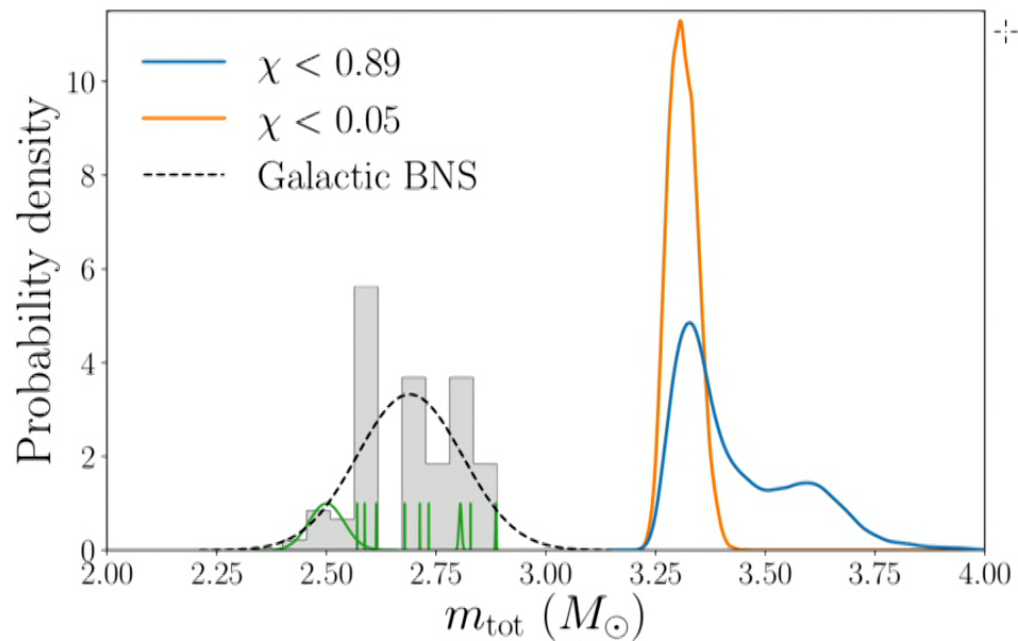


Caltech/MIT/LIGO Lab

Revealing a new population of binary black holes



Latest neutron star merger GW190425



LIGO/VIRGO Collaboration et al. (2020)

Total mass of binary neutron star system is large compared to those in our galaxy.

What will LIGO see?

Primary sources are mergers of compact objects:

- Black hole-black hole mergers (Seen a number)
- Neutron star-neutron star mergers (Seen two... probably)
- Black hole-neutron star mergers (Hints from public alerts)

Other possible sources:

- Stars collapsing and going supernova
- Stochastic gravitational waves, from early universe or otherwise
- ... Surprises!



How do we know what gravitational wave signals to expect/look for?

+

Need to solve Einstein equations for orbiting/merging/oscillating strongly gravitating systems

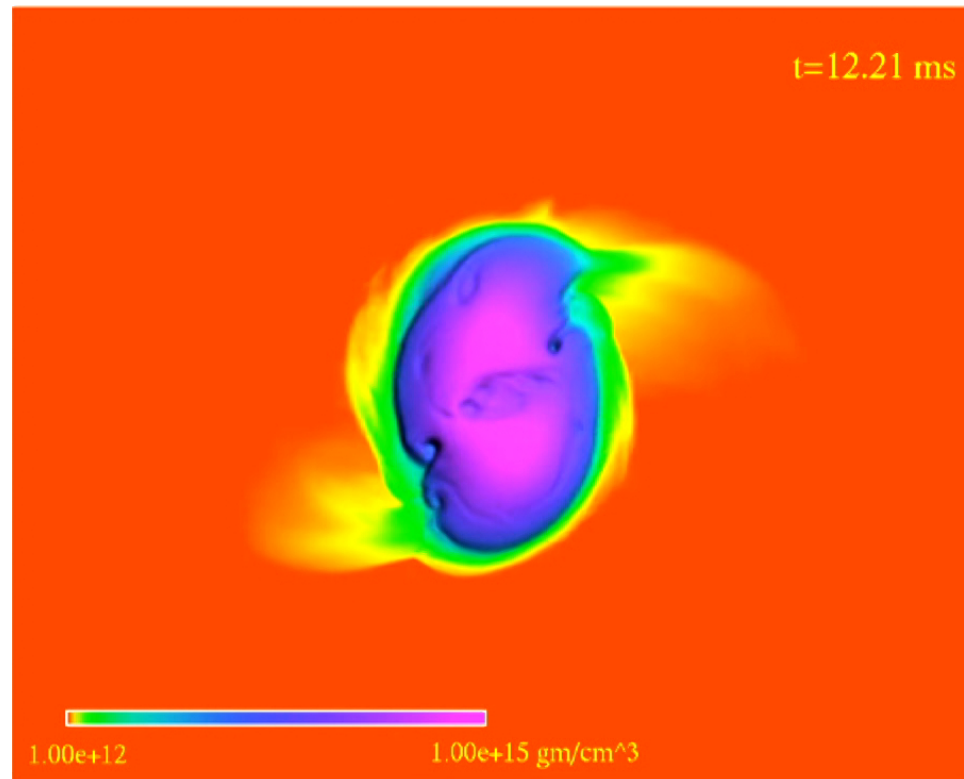
- Solutions for stationary individual black holes/stars are easy
- Various approximations when things aren't moving too fast, etc.
- At merger, these all breakdown. Need to solve full nonlinear equations.

Essential to making and testing predictions for gravitational wave sources.

Going from...

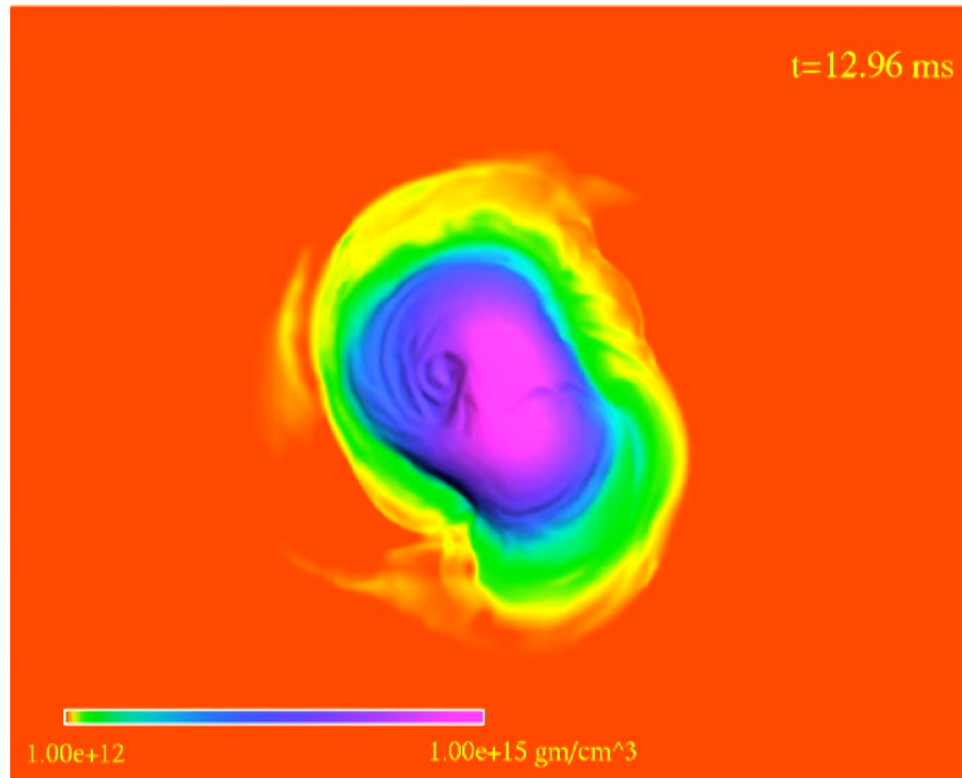


to...



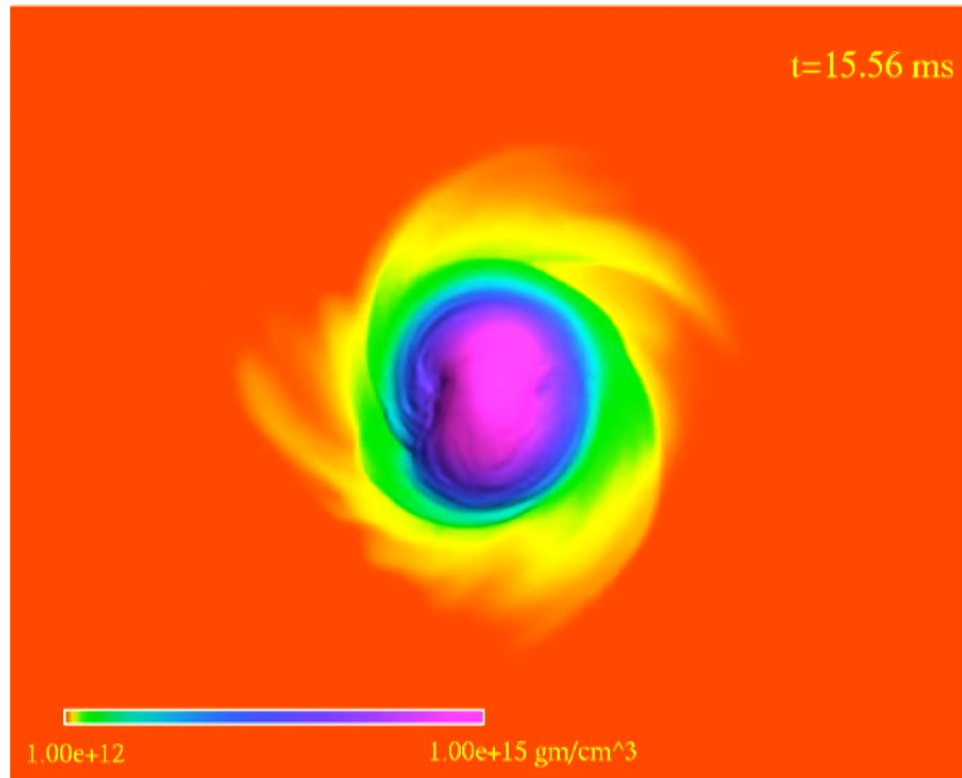
WE+ 2019

to...



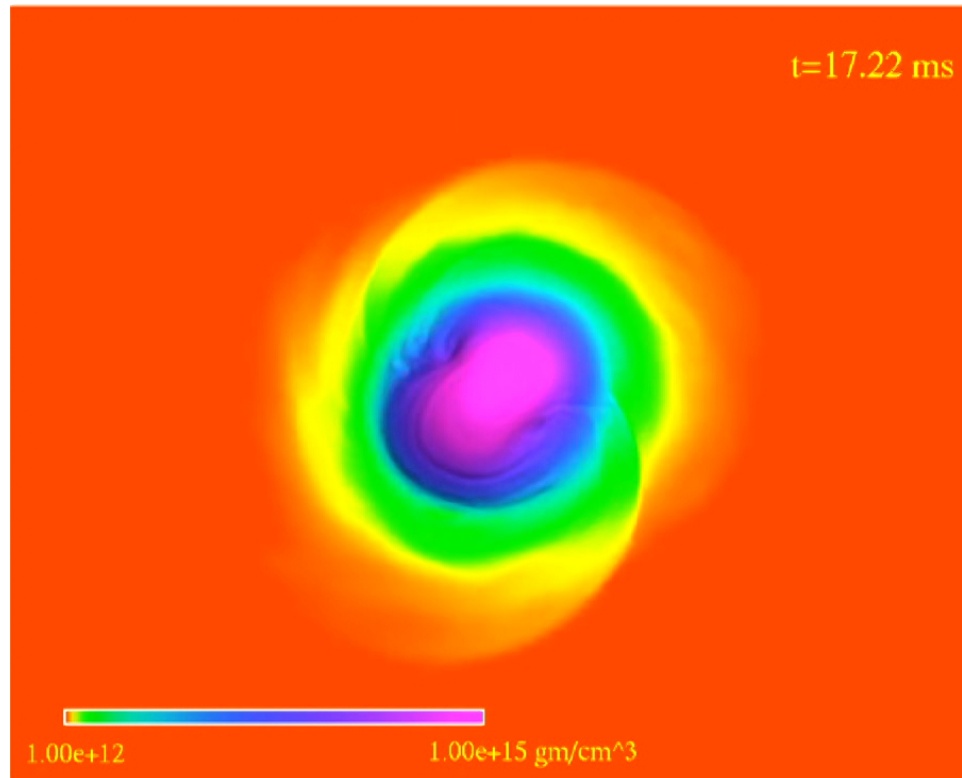
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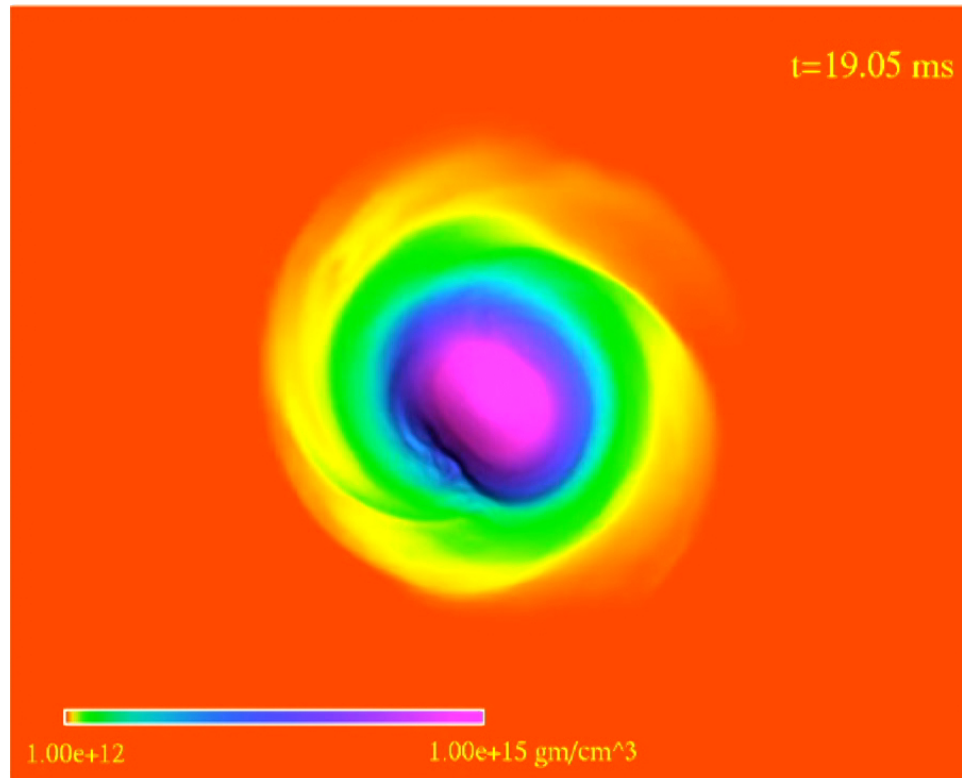
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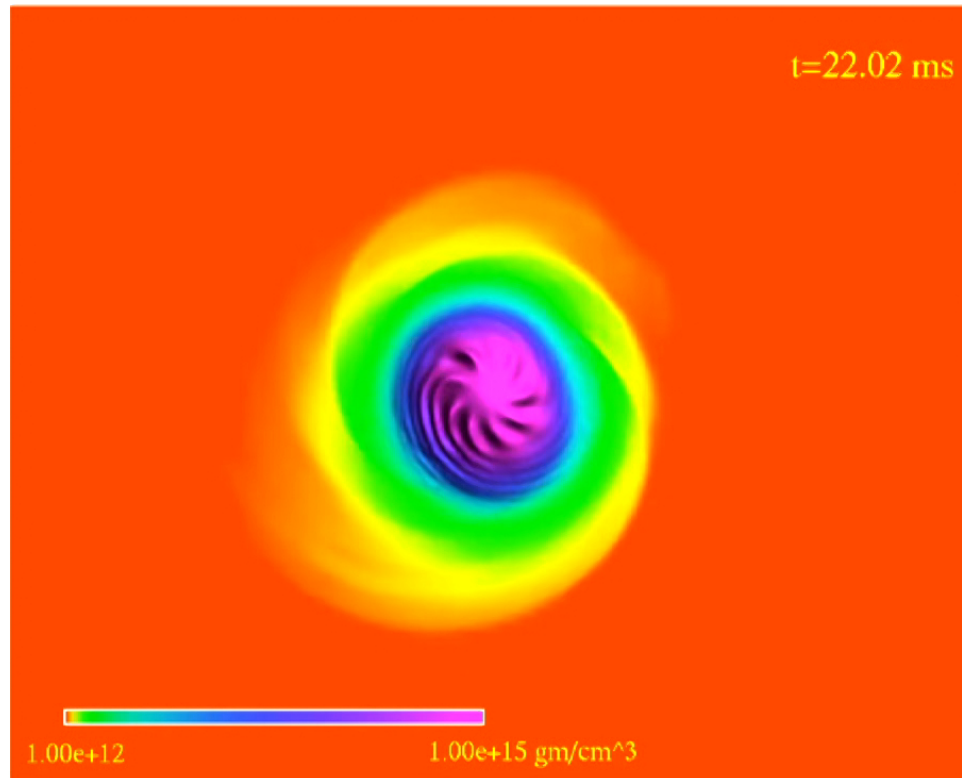
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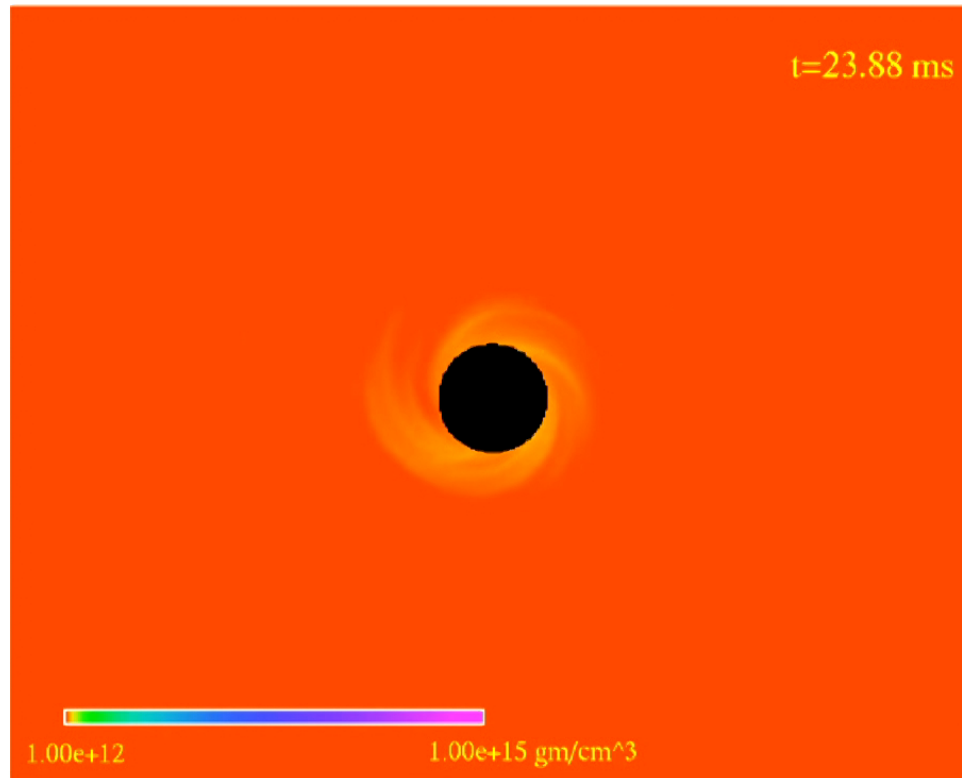
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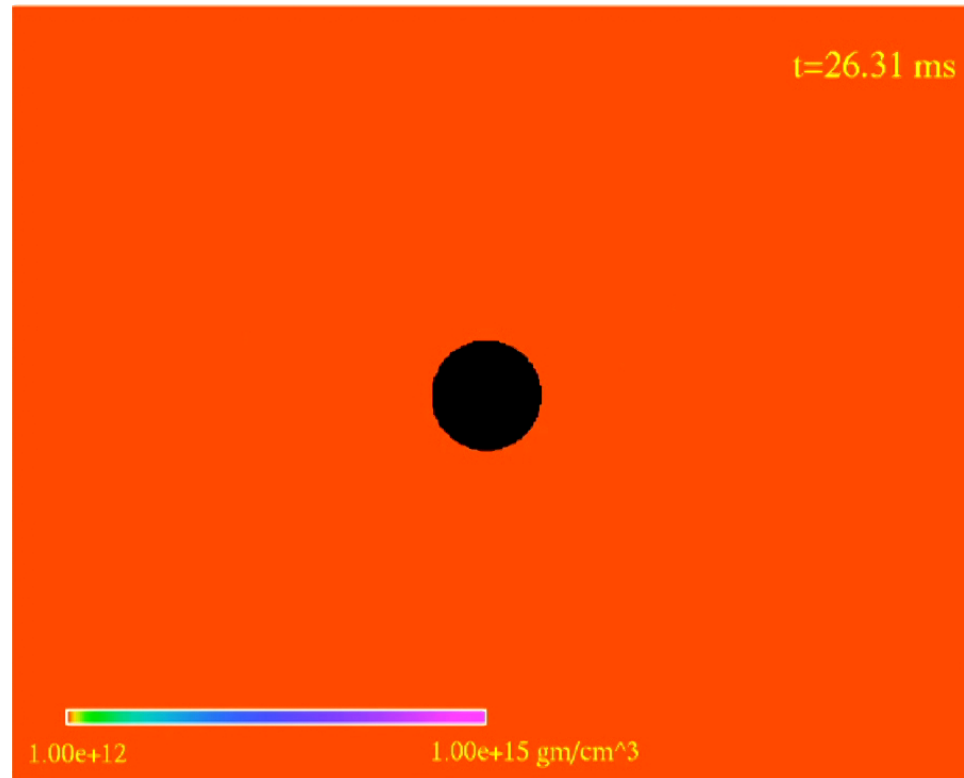
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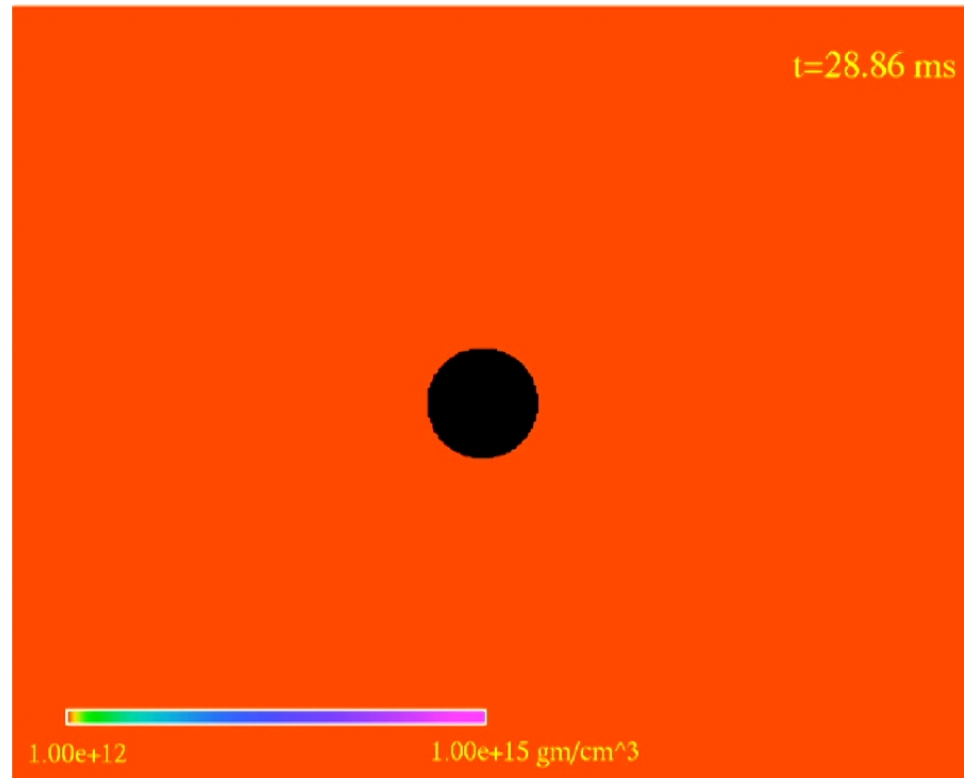
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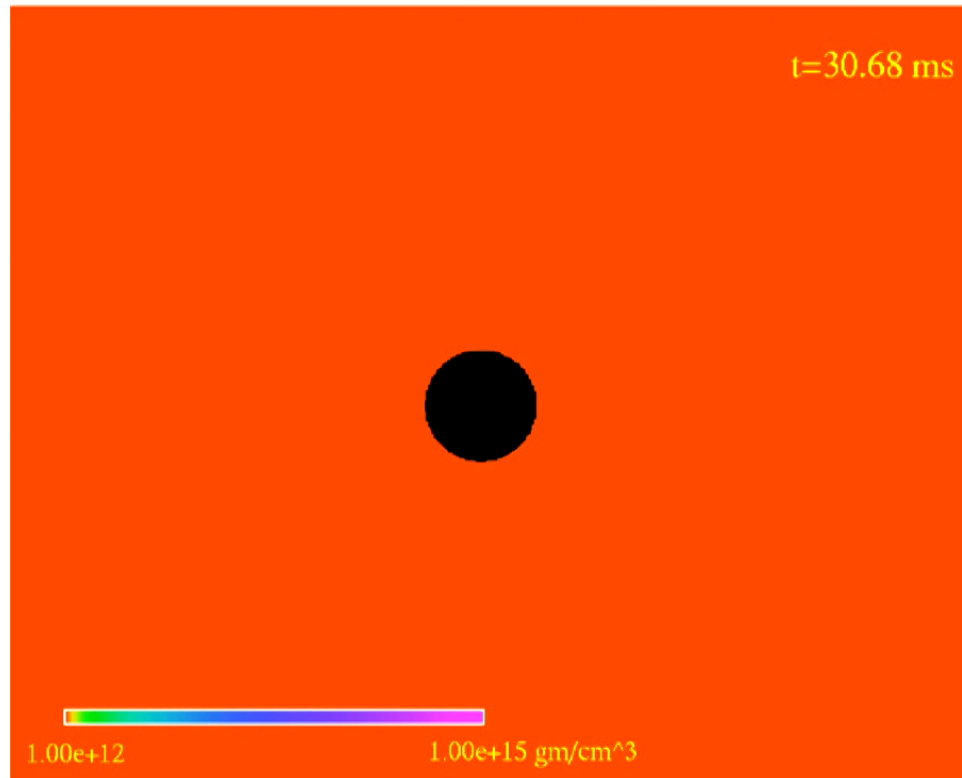
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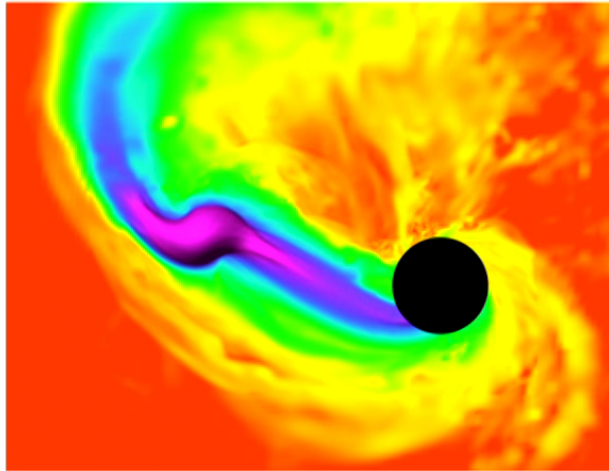
Exploring the Dynamics of Spacetime

- How can we make predictions when gravitational collapse gives rise to singularities? (*Cosmic Censorship*)
- What can gravitational waves teach us about fundamental physics? E.g. new particles, extreme densities, dark matter. (*Black hole superradiance*)

Return to neutron stars at the end. . .

Cosmic censorship

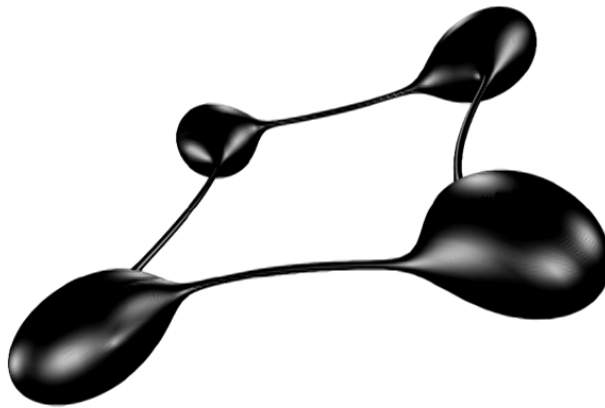
Unhalted gravitational collapse leads to singularities where Einstein's theory breaks down, but can this be ignored?



Weak cosmic censorship conjecture: Excluding regions hidden from far away by black hole horizons, General Relativity generically retains predictability.

Cosmic censorship conjecture

Excluding higher dimensions (Lehner & Pretorius) or fine-tuned configurations (Choptuik critical collapse) has been tested and found to hold in a variety of configurations.



Figueras et al. (2016)

However, back in the 90s...

The New York Times

SUNDAY, MARCH 10, 1991

COMPUTER DEFIES EINSTEIN'S THEORY

Findings of Simulation Stun
Scholars Who Considered
the Results Impossible

By JOHN NOBLE WILFORD

A supercomputer at Cornell University, simulating a tremendous gravitational collapse in the universe, has startled and confounded astrophysicists by producing results that should not be possible according to Einstein's general theory of relativity.

Scientists said the simulation may have exposed a flaw in at least one aspect of Einstein's theory on the behavior of space, time, matter and gravity. Or maybe not. They said further research and testing could still resolve the issue in Einstein's favor. Or maybe not.

In the simulation of Einstein's theory, the computer revealed that if a gigantic cloud of particles, shaped like a football gravitationally, collapses on itself, the regions near the end points will condense into areas of infinite density and gravitational force. Scientists may be able to contemplate them, but nature is not supposed to be able to produce these regions that astrophysicists



Formation of Naked Singularities: The Violation of Cosmic Censorship

Stuart L. Shapiro and Saul A. Teukolsky

*Center for Radiophysics and Space Research and Departments of Astronomy and Physics,
Cornell University, Ithaca, New York 14853*

(Received 7 September 1990)

We use a new numerical code to evolve collisionless gas spheroids in full general relativity. In all cases the spheroids collapse to singularities. When the spheroids are sufficiently compact, the singularities are hidden inside black holes. However, when the spheroids are sufficiently large, there are no apparent horizons. These results lend support to the hoop conjecture and appear to demonstrate that naked singularities can form in asymptotically flat spacetimes.

PACS numbers: 04.20.Jb, 95.30.Sf, 97.60.Lf

Studied collapse of spheroidal cloud of collision particles
(Einstein-Vlasov equations).

Evidence put forth against cosmic censorship:

- Curvature blows up in vacuum region—not a matter caustic
- No apparent horizon found and no turn around of null geodesics in vicinity before calculation ends

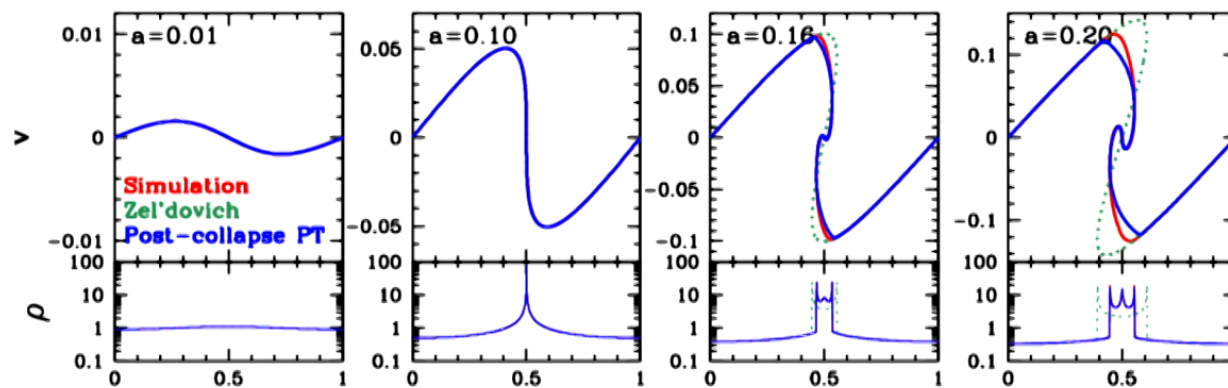
Einstein-Vlasov System

AKA collisionless Boltzmann or cold dark matter

$$\frac{G_{ab}}{8\pi} = T_{ab} = \int f p_a p_b \frac{\sqrt{|g|}}{-p_0} dp^1 dp^2 dp^3$$

Distribution function is invariant along geodesics:

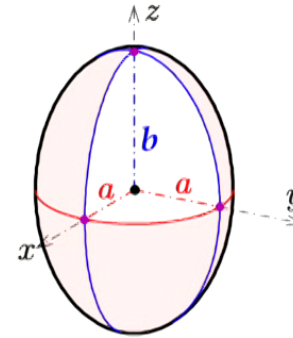
$$\frac{d}{ds} f(x^a(s), p^j(s)) = 0 \text{ with } p^a p_b = -m^2.$$



from Taruya and Colombi (2017)

Cosmic Censorship vs. Hoop Conjecture

Collapse of prolate spheroid with
 $e = \sqrt{1 - a^2/b^2} = 0.9$ and $b/M = 10$



Cosmic Censorship: Singularities arising from gravitational collapse should be hidden behind horizons.

Hoop Conjecture: A black hole forms if and only if a mass M fits within a hoop of circumference $C \lesssim 4\pi M$



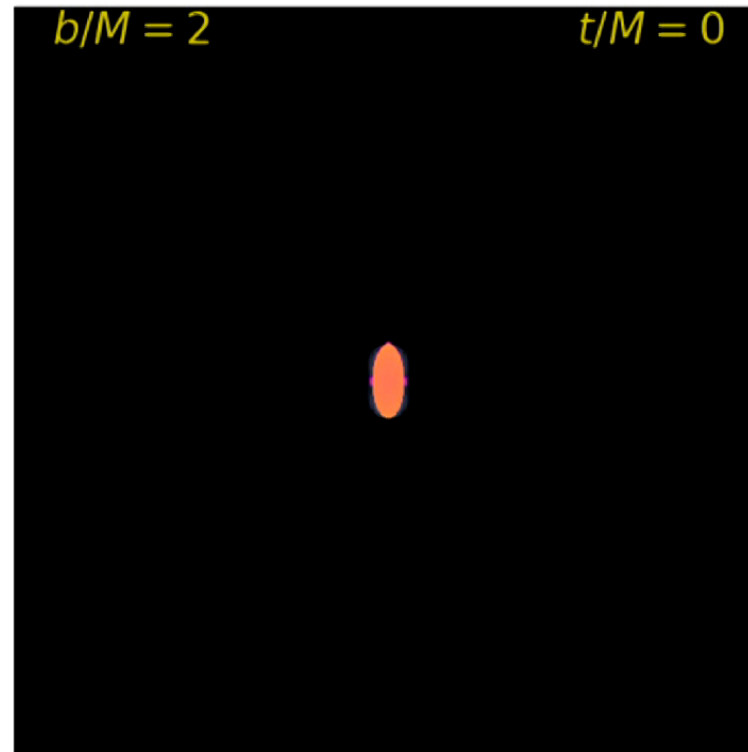
This work

Number of works following up on Shapiro and Teukolsky (> 300 citations) including using higher resolution, extending to 3D, etc., but definitive answer to whether CC is violated still elusive.

This work *WE (2019)*:

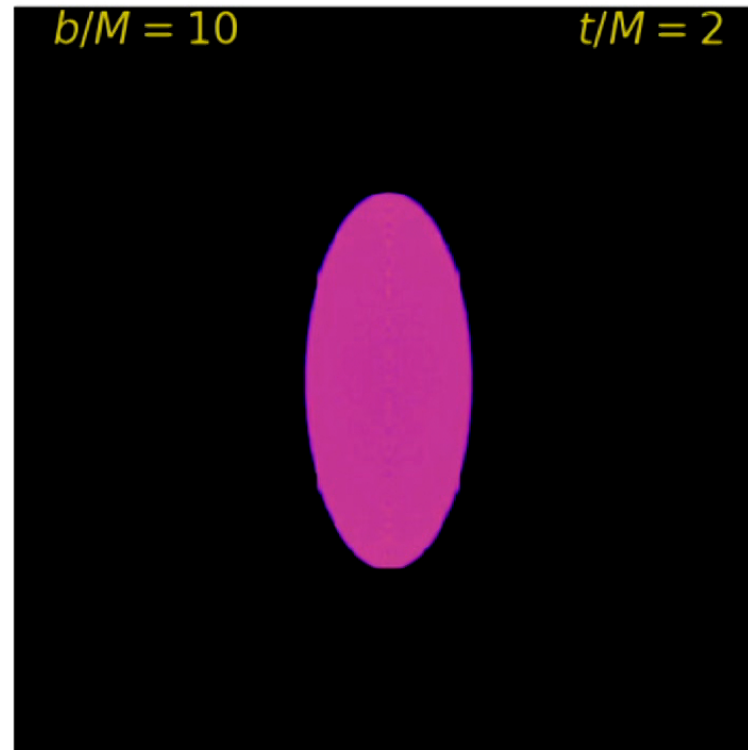
- Revisit such configurations using modern numerical GR techniques (different gauge, adaptive mesh refinement, etc.).
- **Main result:** Final state in all cases studied is a black hole with gravitational radiation.

Results



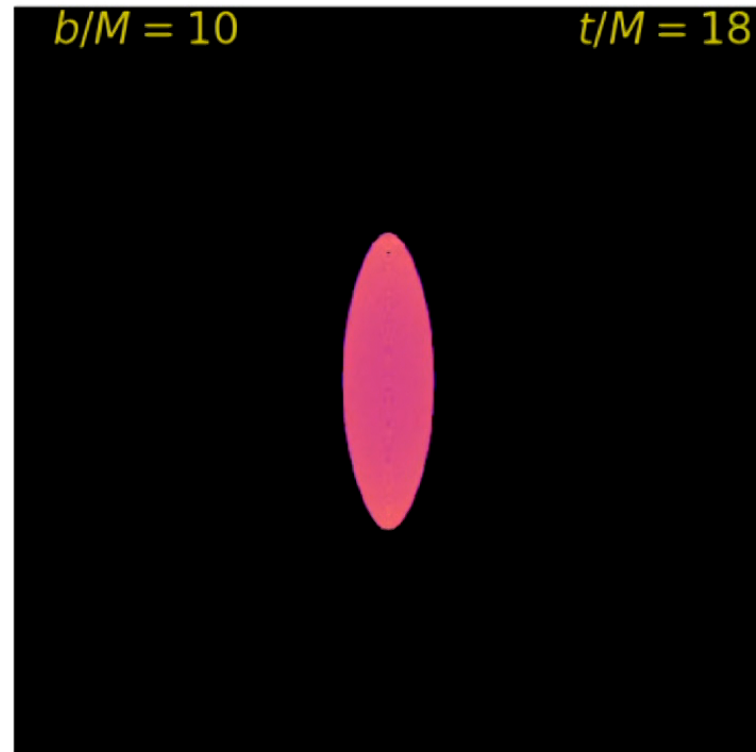
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

Results



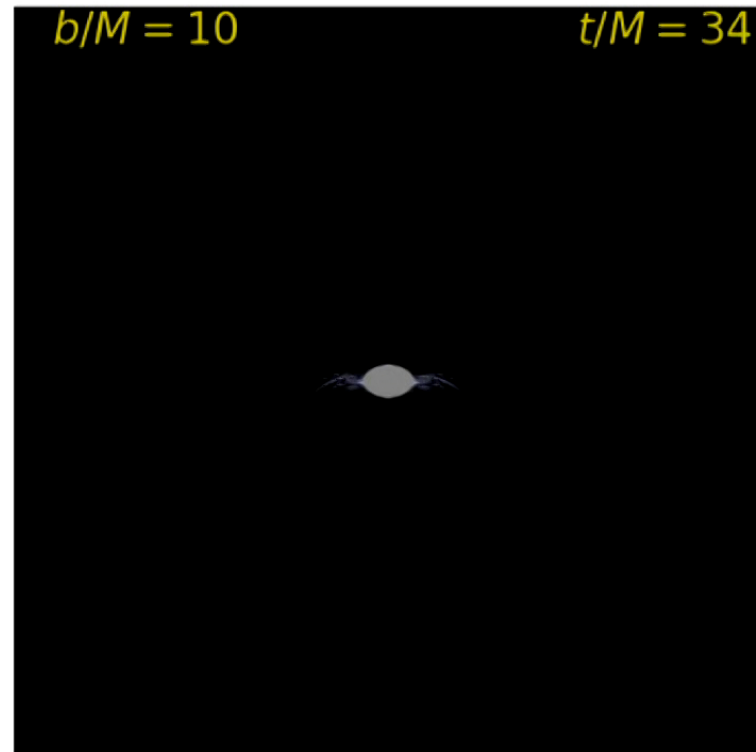
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

Results



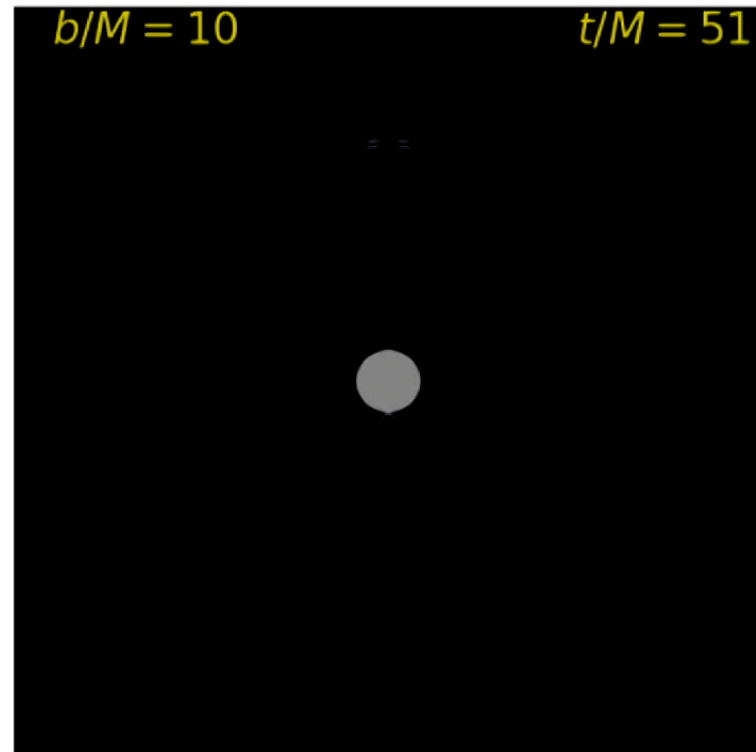
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

Results



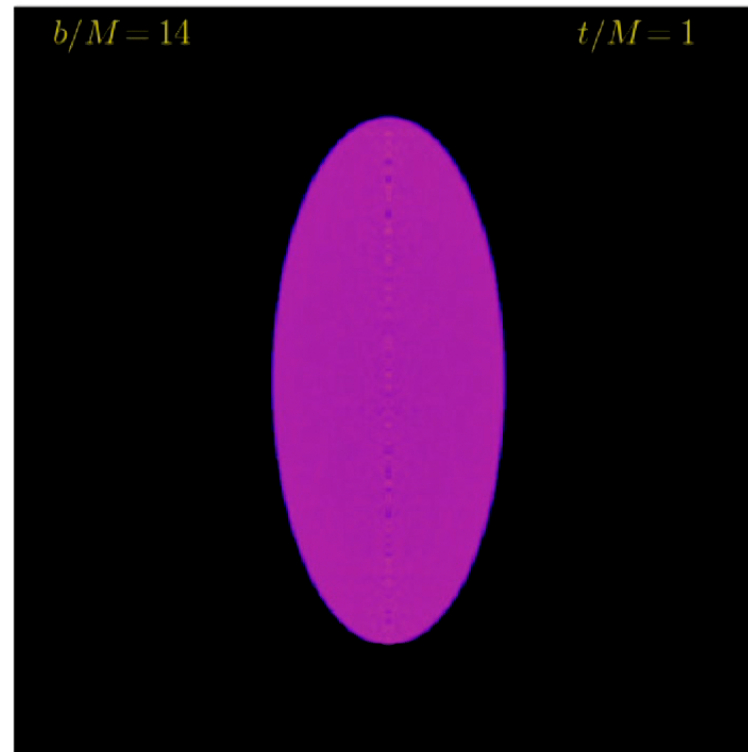
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

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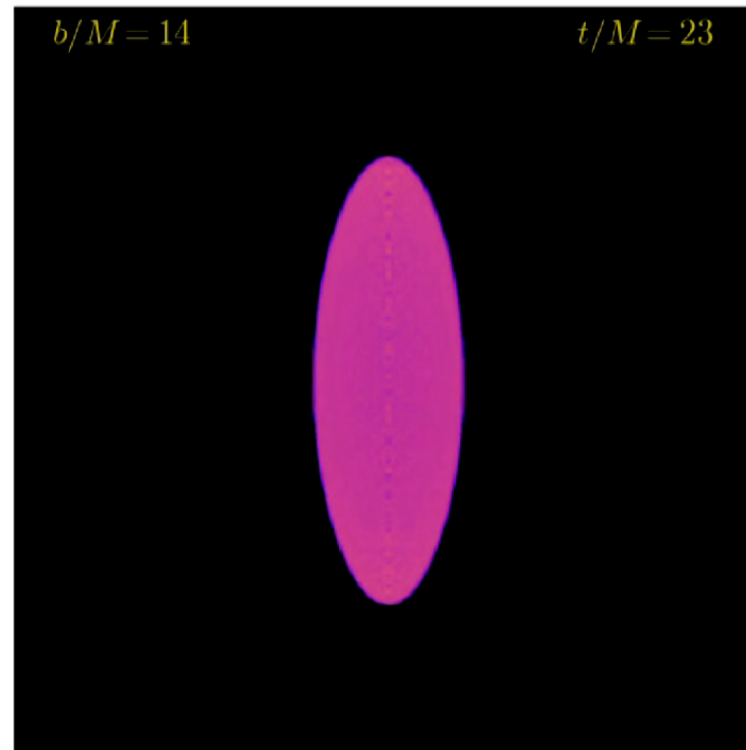
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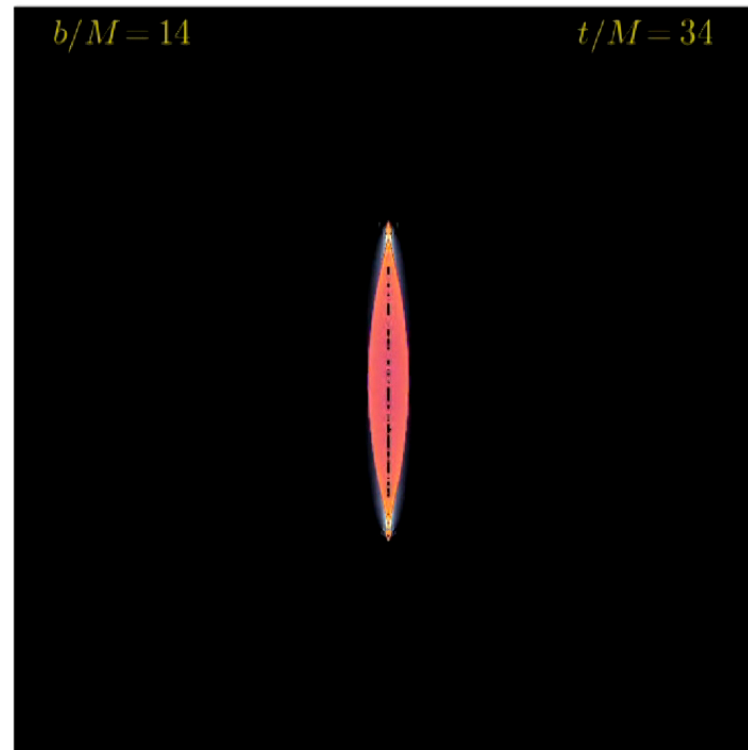
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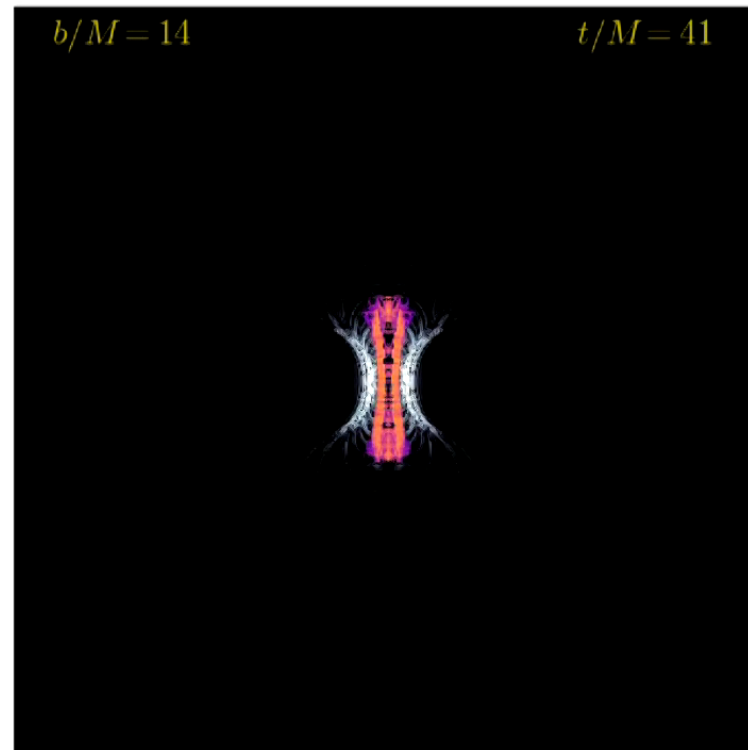
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Results



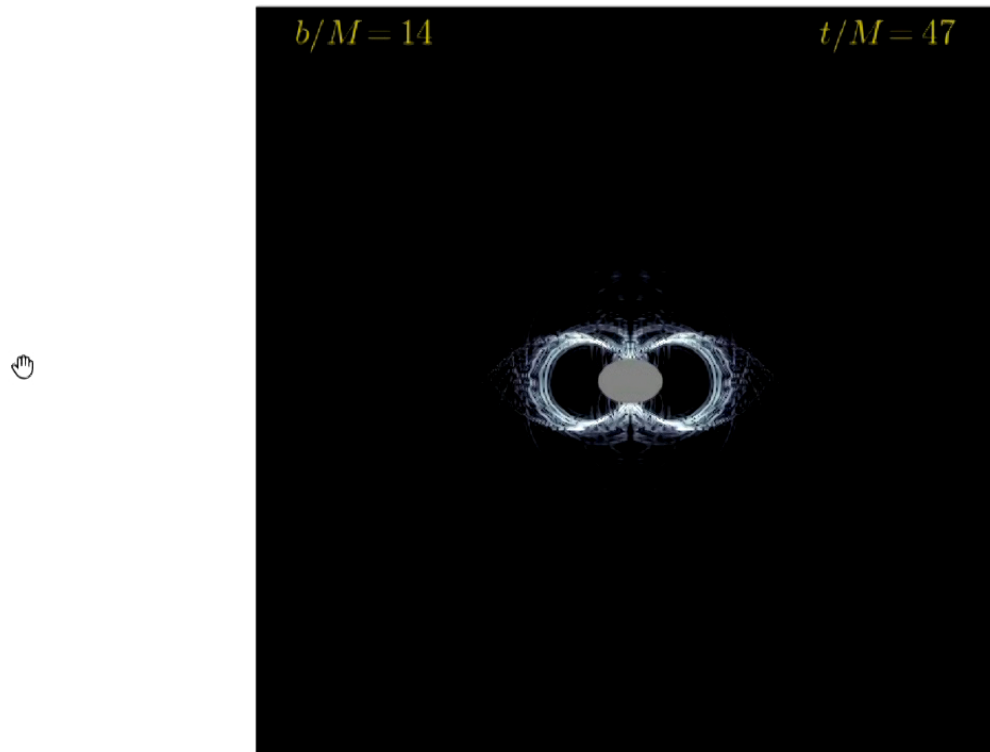
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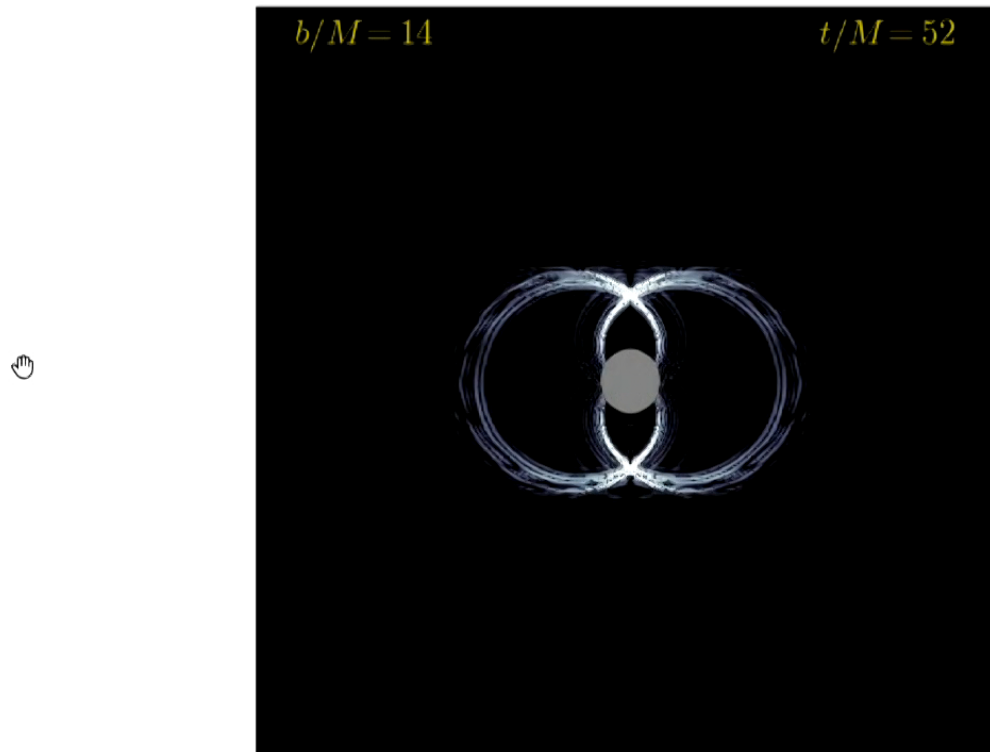
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Results



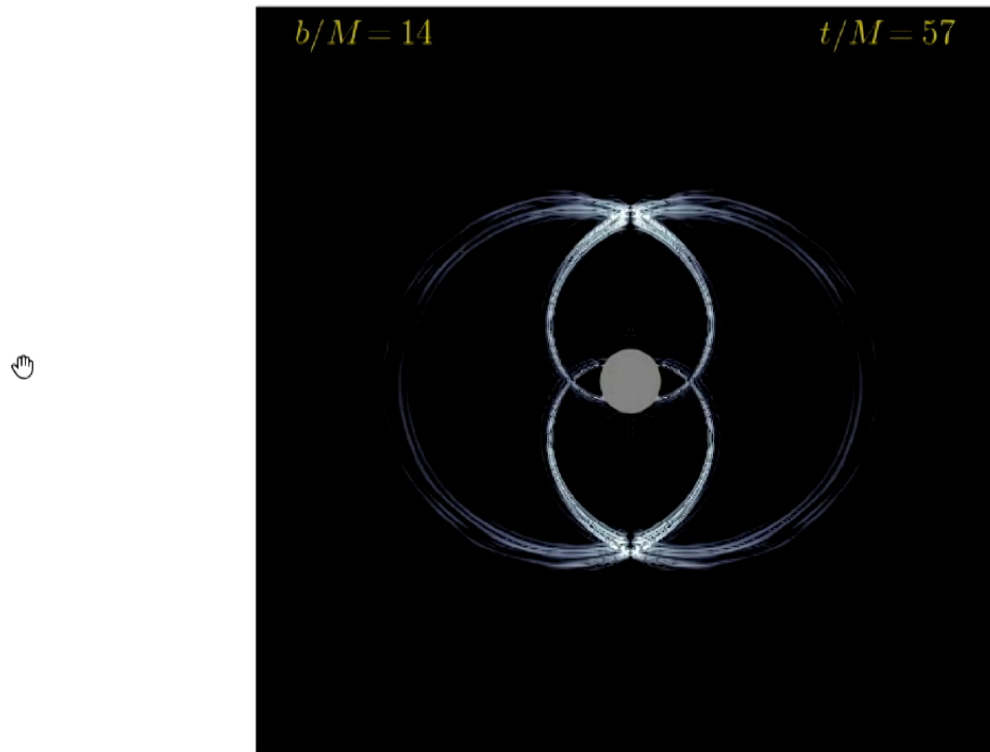
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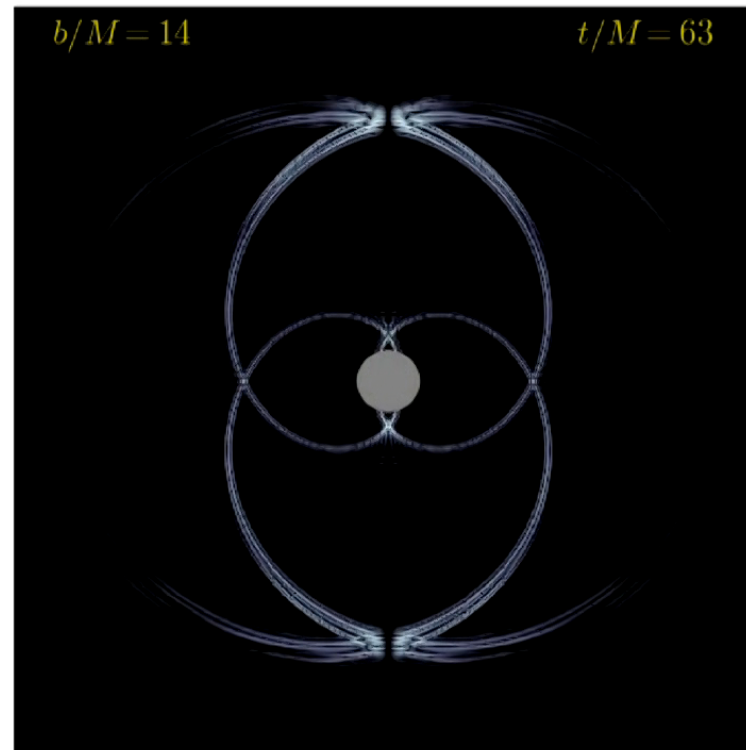
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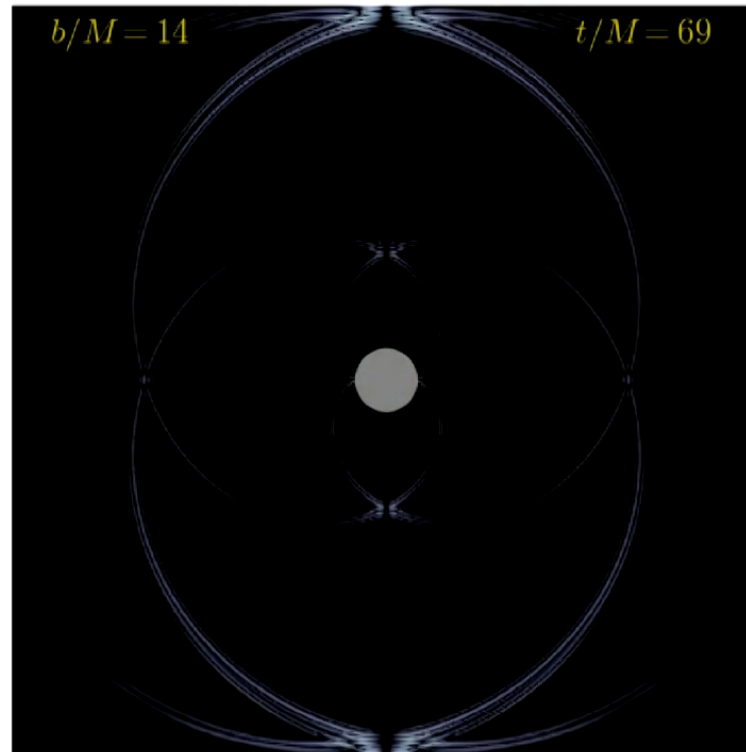
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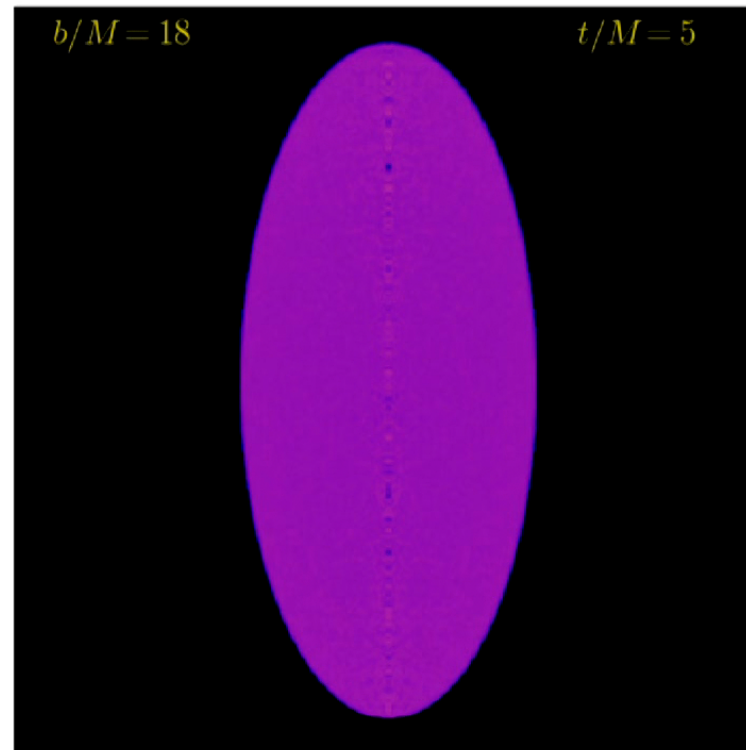
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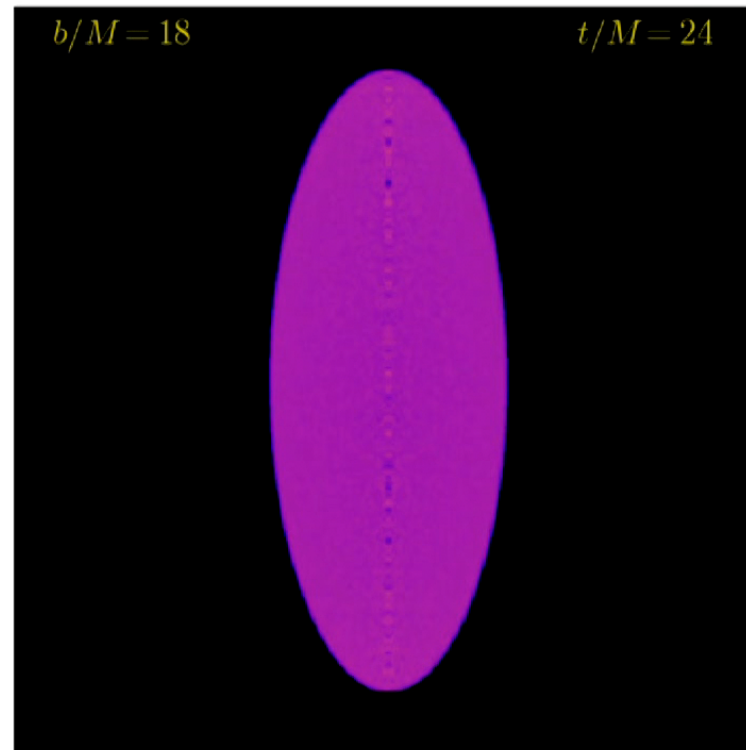
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

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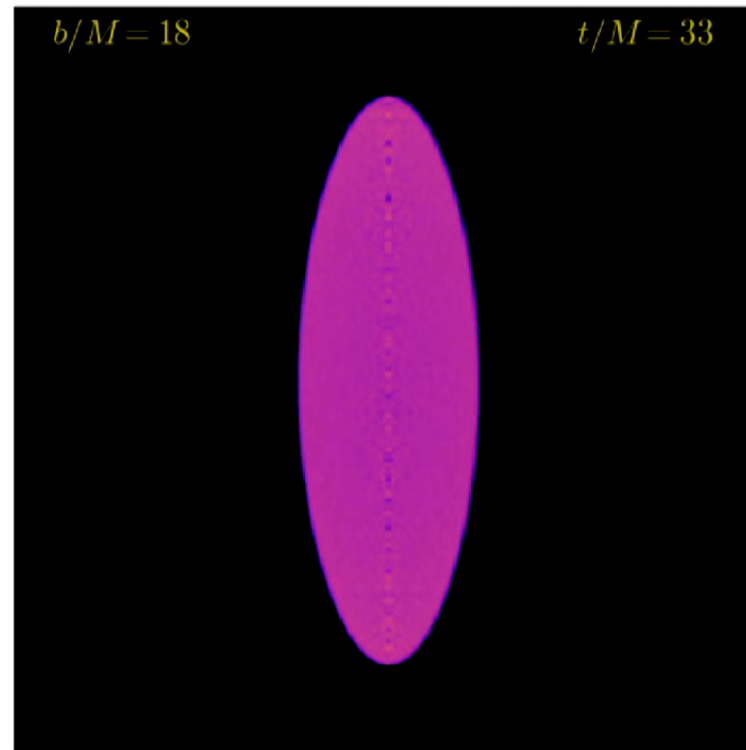
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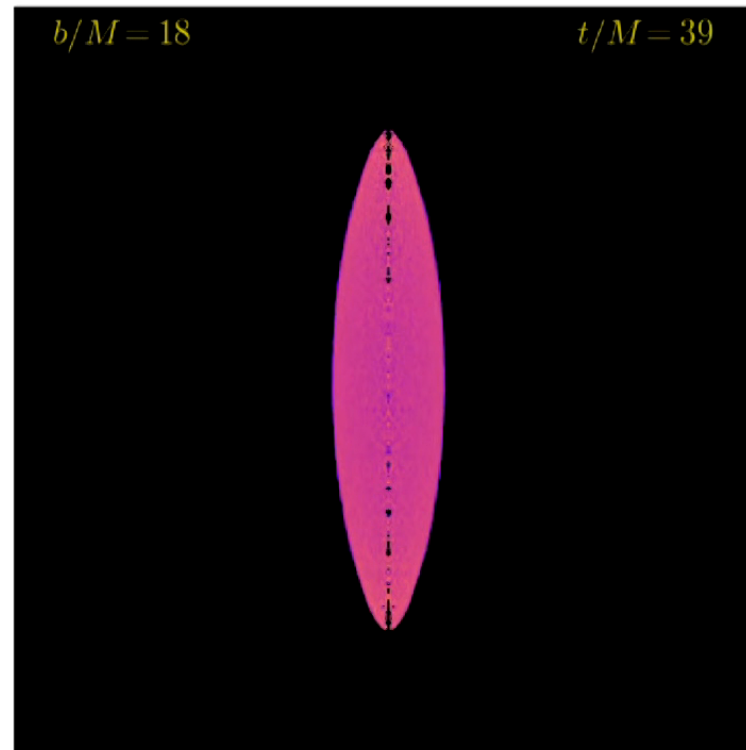
Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

Results



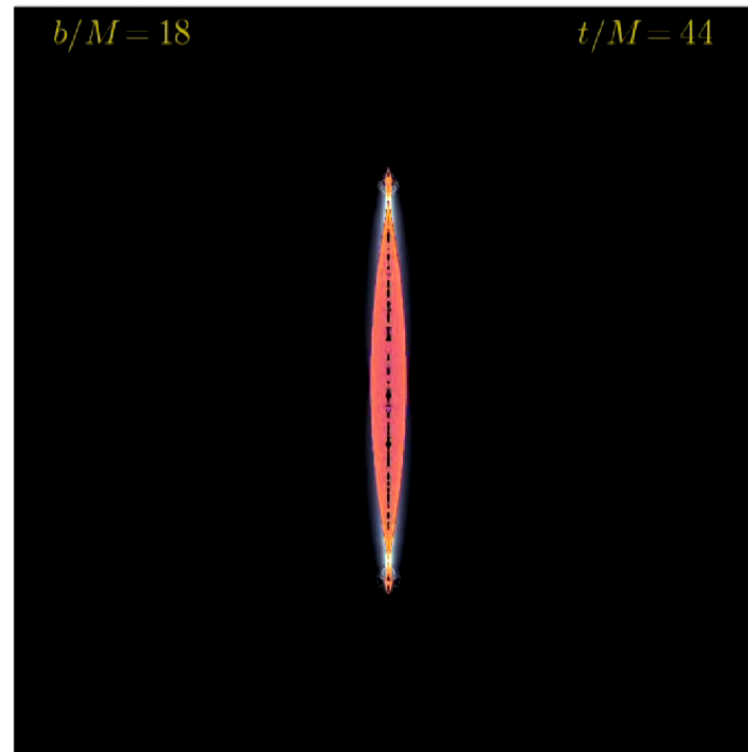
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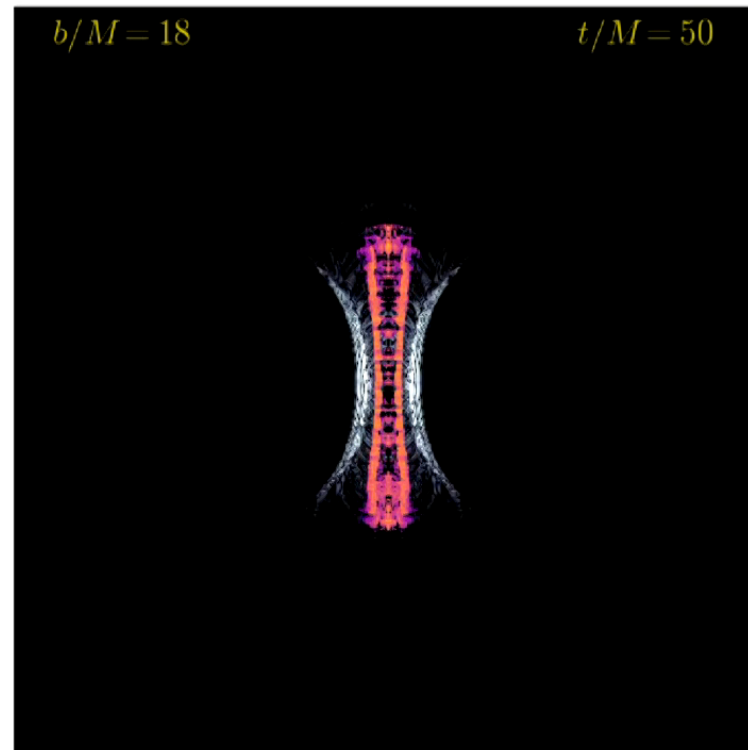
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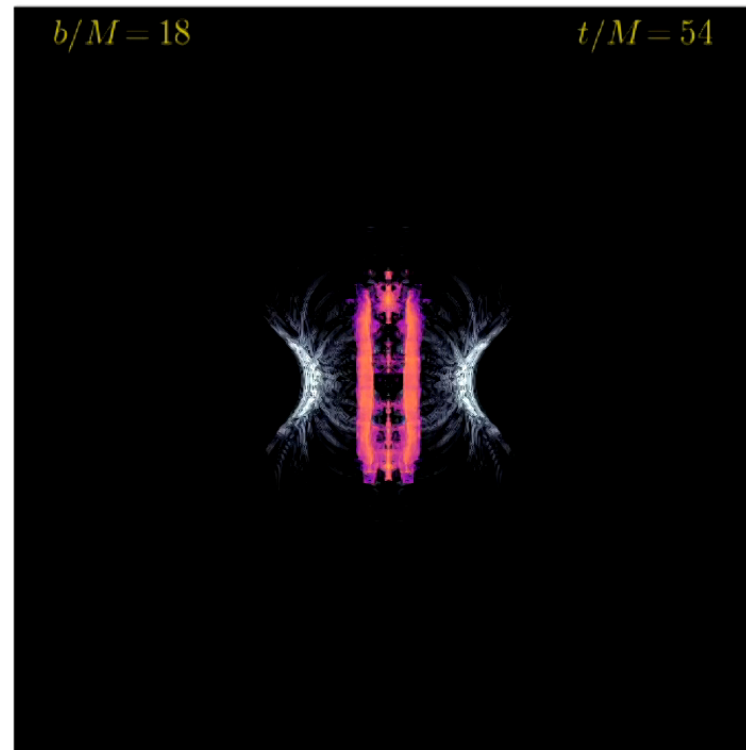
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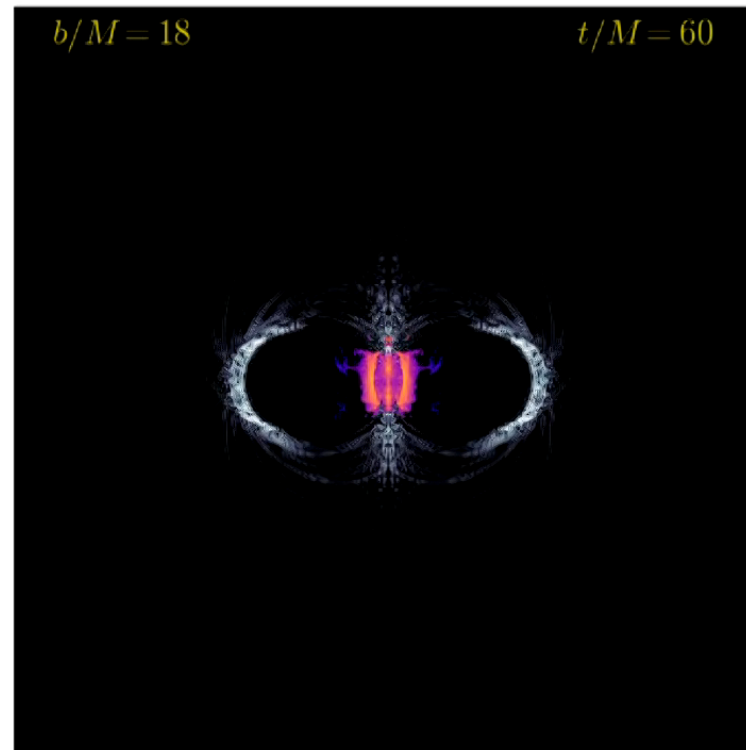
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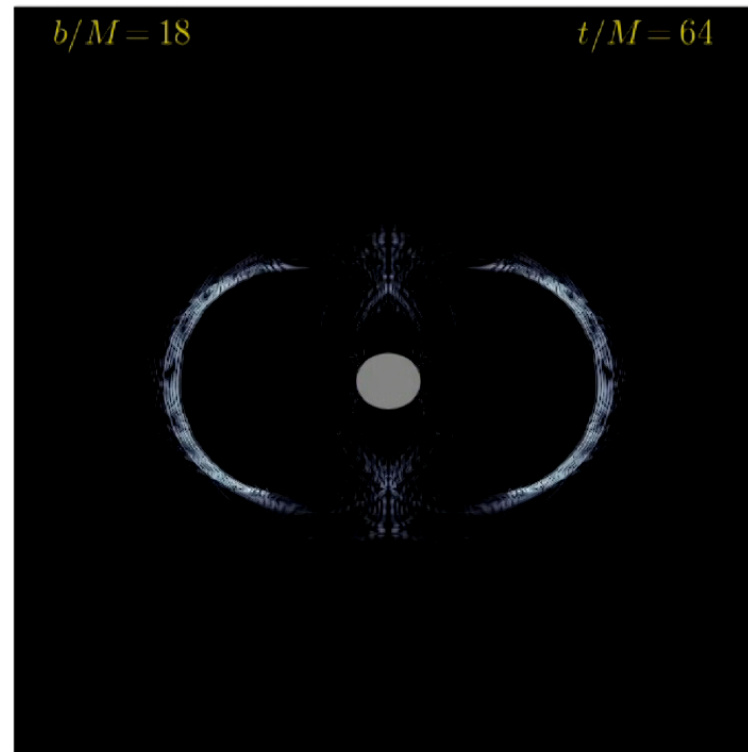
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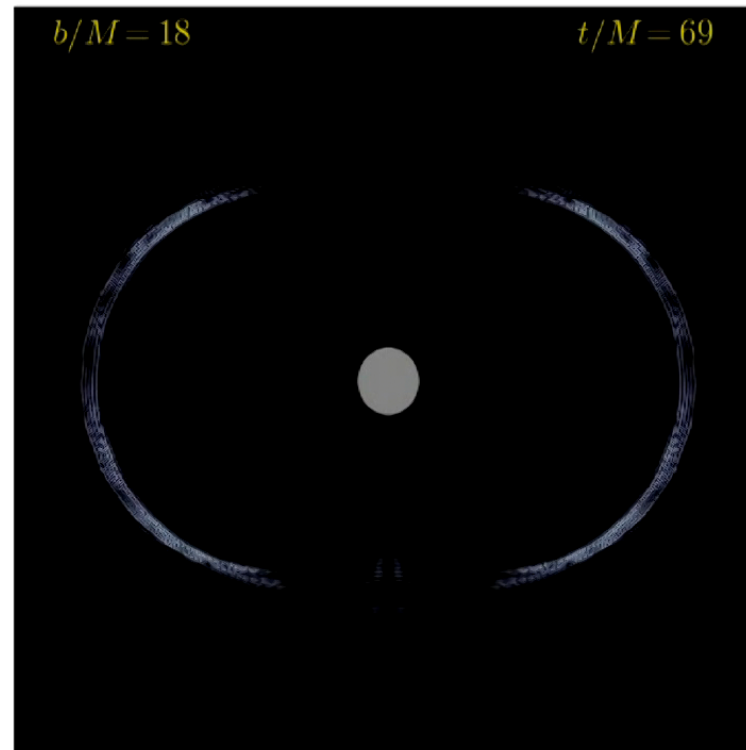
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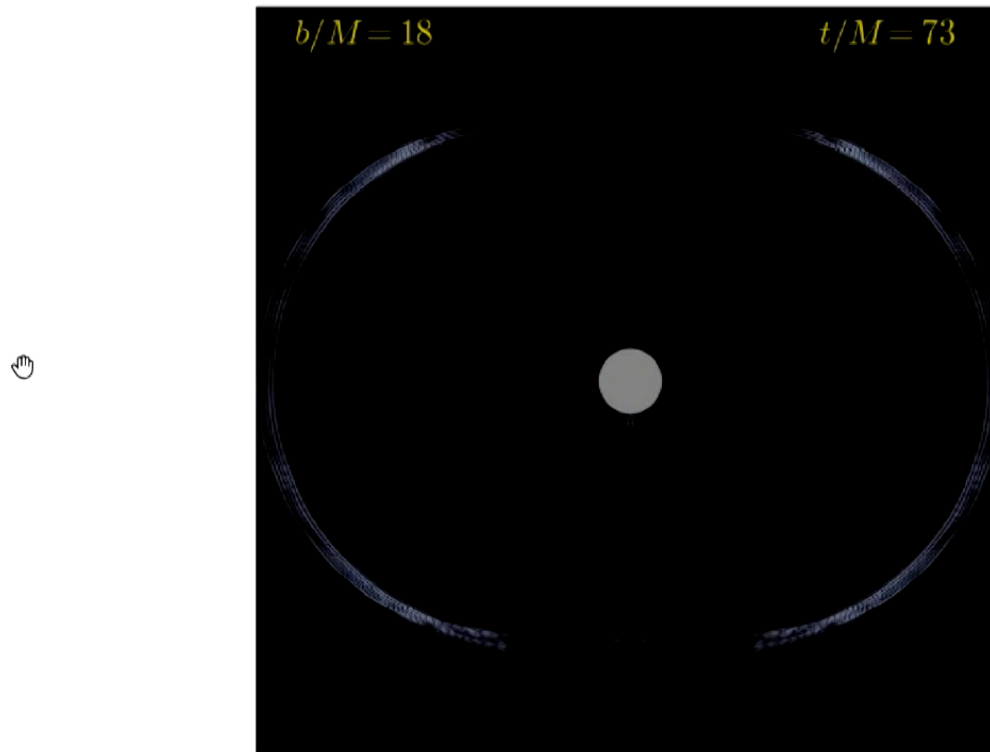
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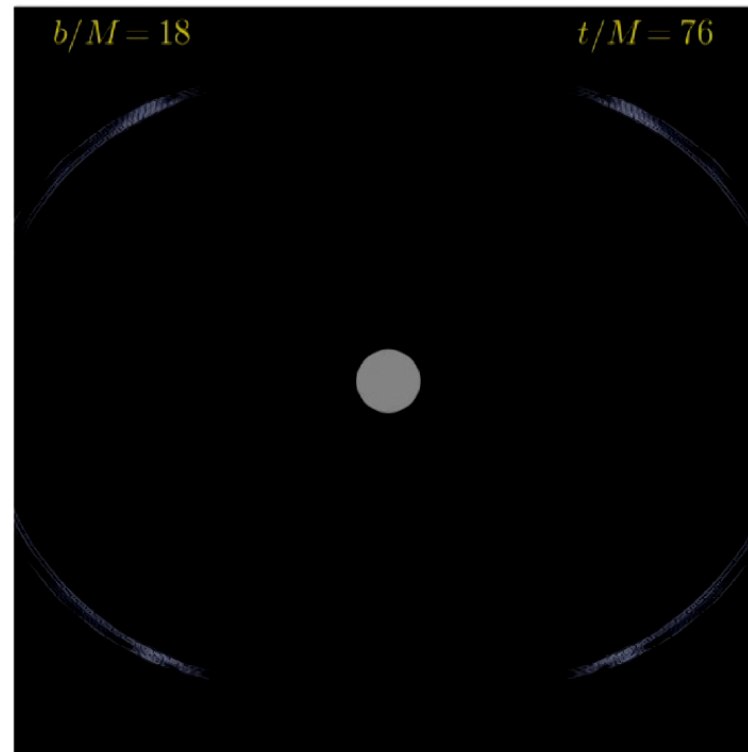
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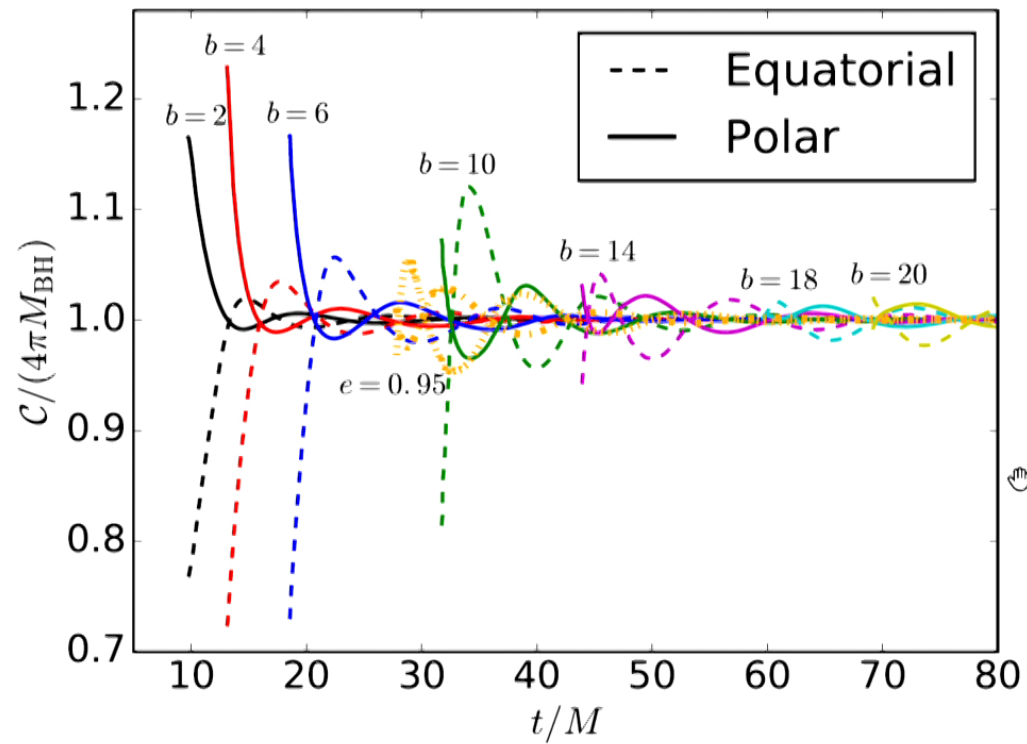
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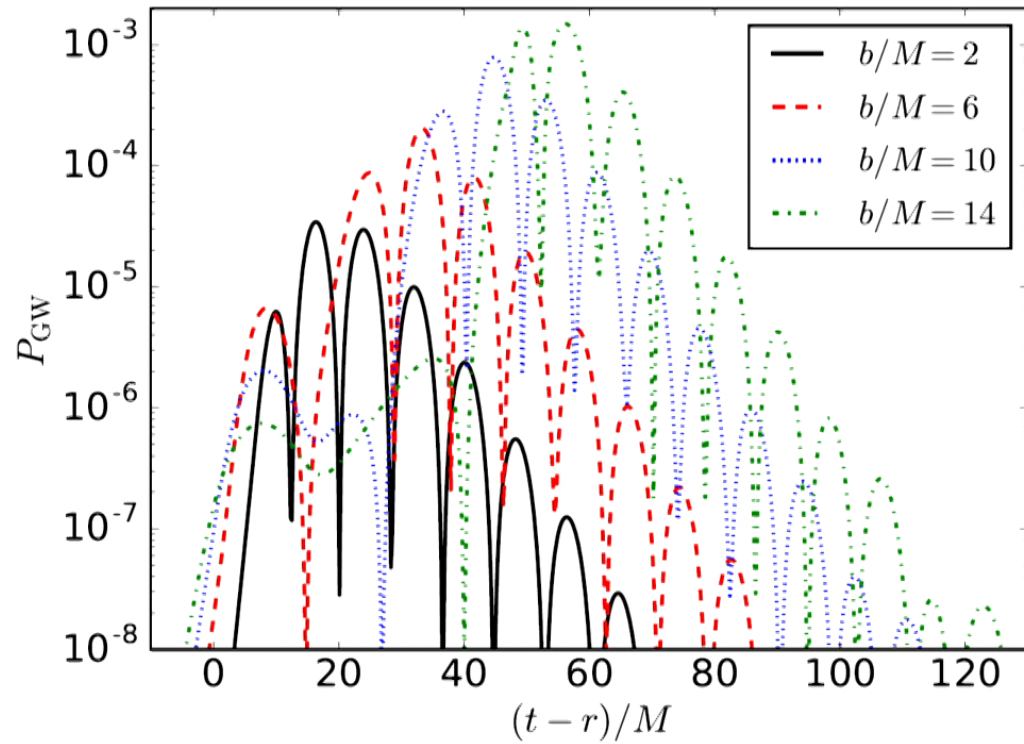


Density (with gravitational waves in gray scale) for increasing values of semi-major axis b

Black Hole Horizon Circumferences

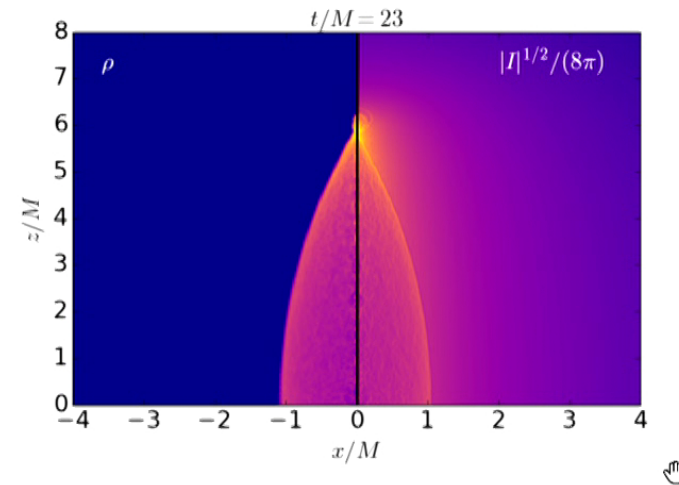
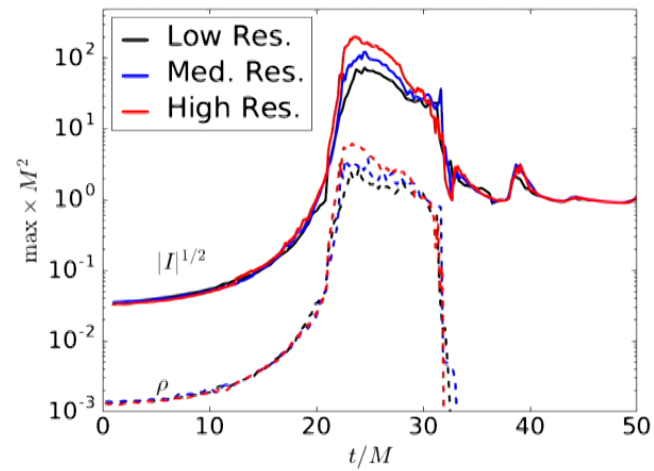


Gravitational waves



Gravitational wave energy up to $\approx 1.5\%$ total spacetime mass.

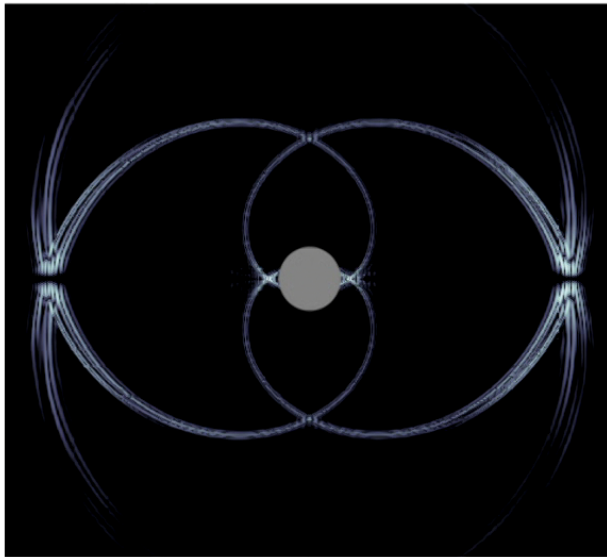
Matter caustic



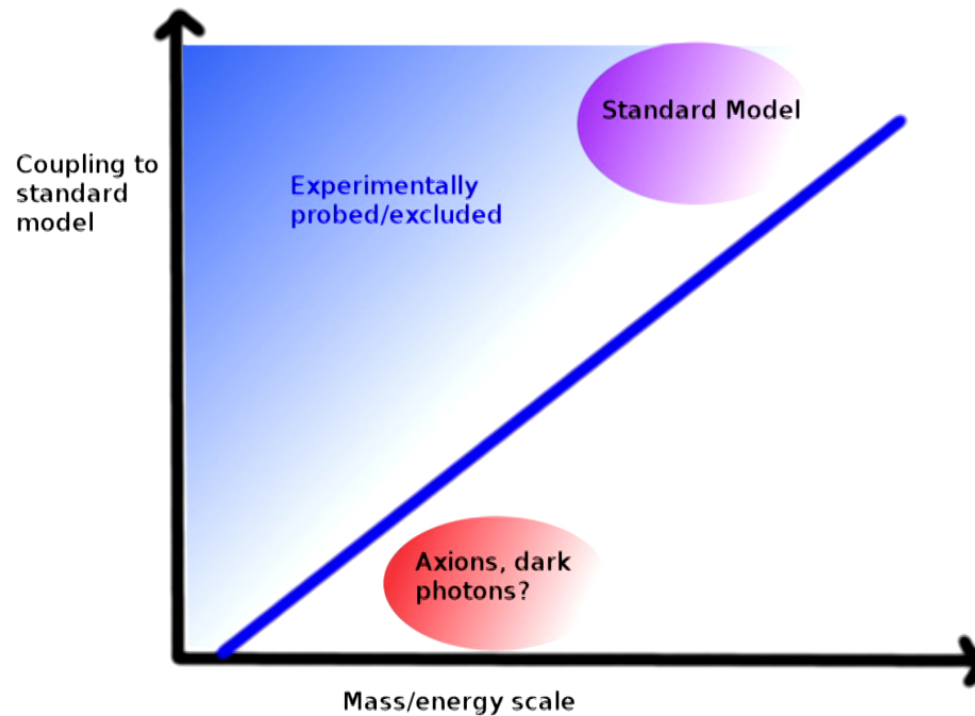
Matter density ρ and Kretschmann scalar $I = R^{abcd} R_{abcd}$ for $b/M = 10$ and $e = 0.9$.

Resolution

- No longer “startled and confounded”: final state of spheroidal collapse is a black hole.
- Neither cosmic censorship nor the hoop conjecture appear to be violated.
- Violent collapse is imprinted in strong gravitational radiation.



Gravitational wave probe of new particles



Search new part of parameter space: ultralight particles weakly coupled to standard model

Black holes superradiance

- For a black hole with an impinging wave (electromagnetic, gravitational, etc.) with frequency ω

$$\delta \text{Area} \propto \delta M_{\text{BH}} (1 - m\Omega_{\text{BH}}/\omega)$$

- Black hole thermodynamics:

$$\delta \text{Area} \propto \delta \text{Entropy} \geq 0$$

Hence $\delta M_{\text{BH}} < 0$ when $\omega < m\Omega_{\text{BH}}$.

- Rotational energy of black holes can be liberated: up to 29% of black hole's mass for maximally spinning!
($E_{\text{rot}} = M - M_{\text{ir}}$)



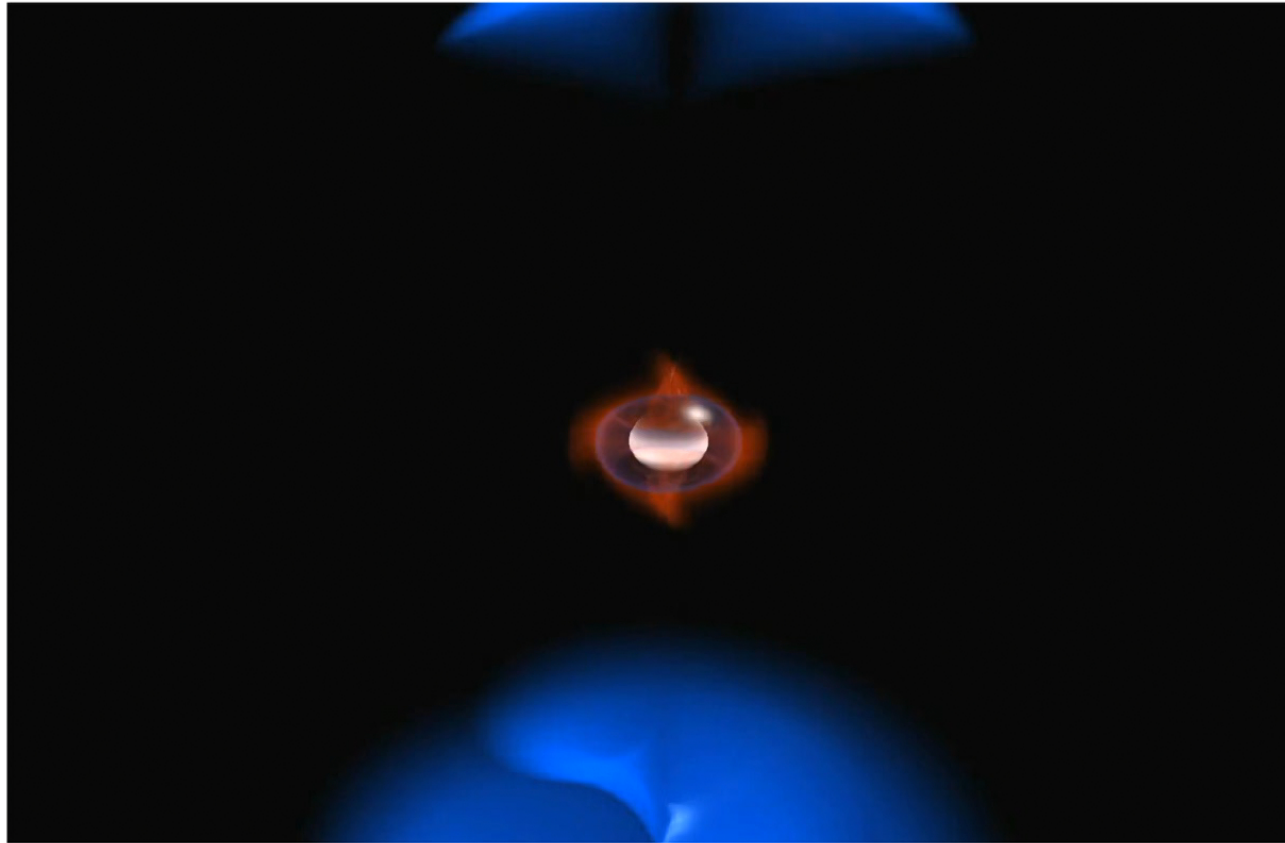
Black holes superradiance



Incoming wave is blue, outgoing wave is red; 120% efficient

WE+ (2013); Visualization: Ralf Kahler

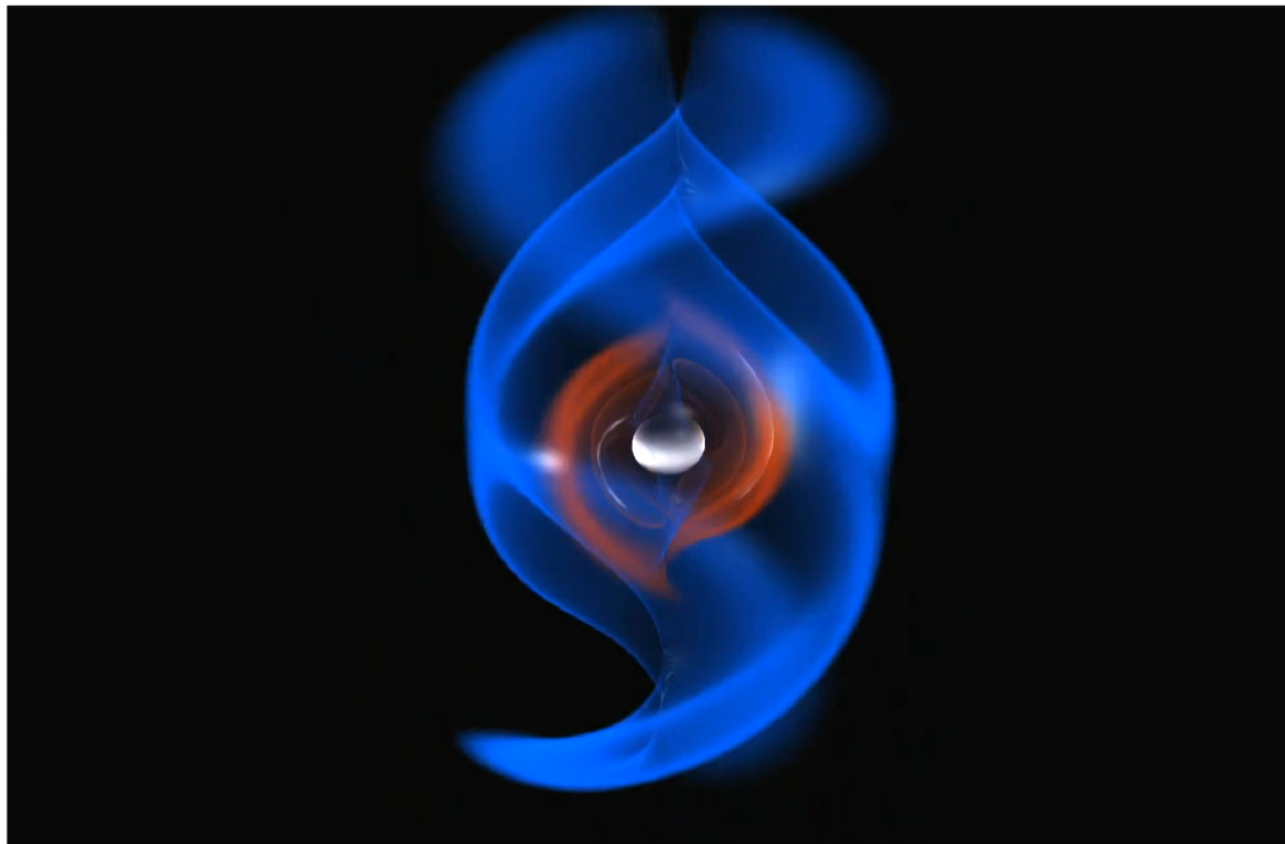
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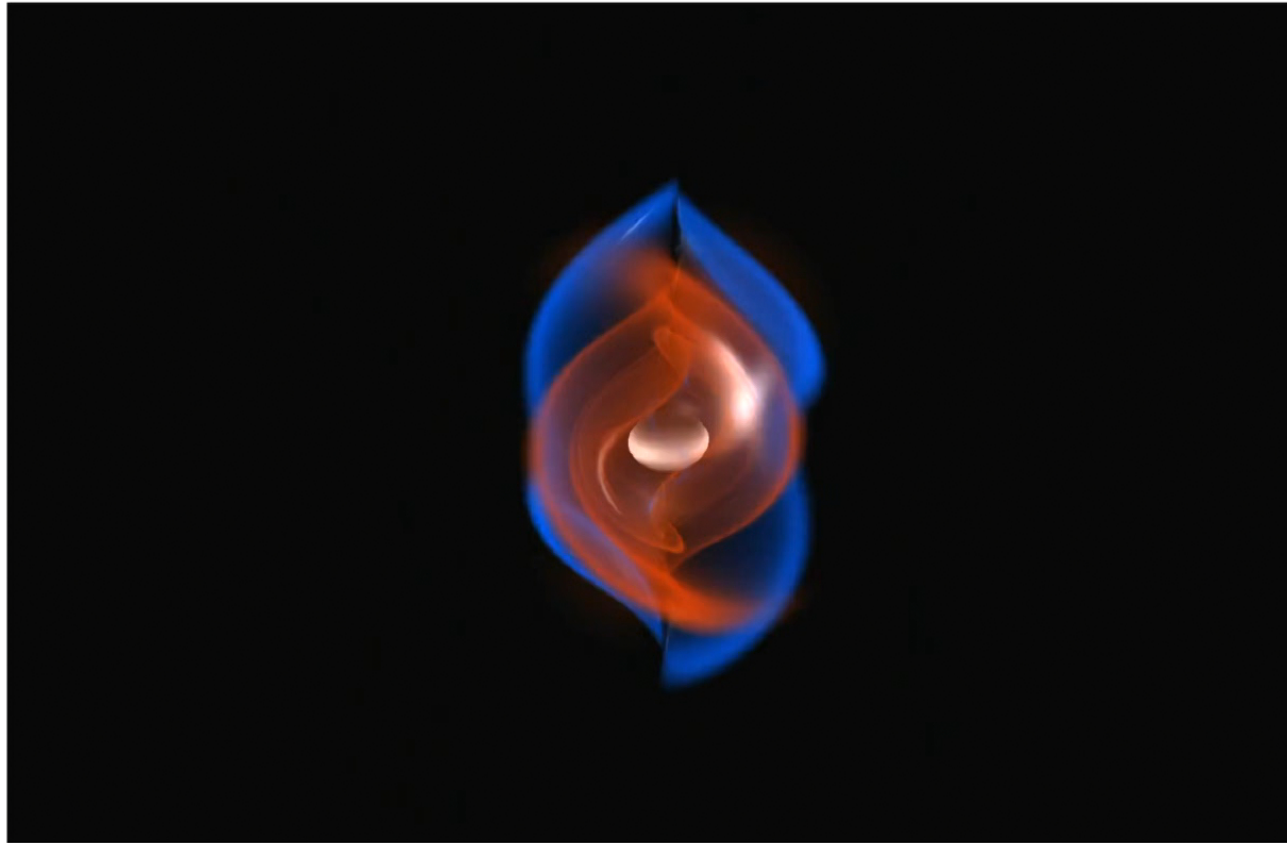
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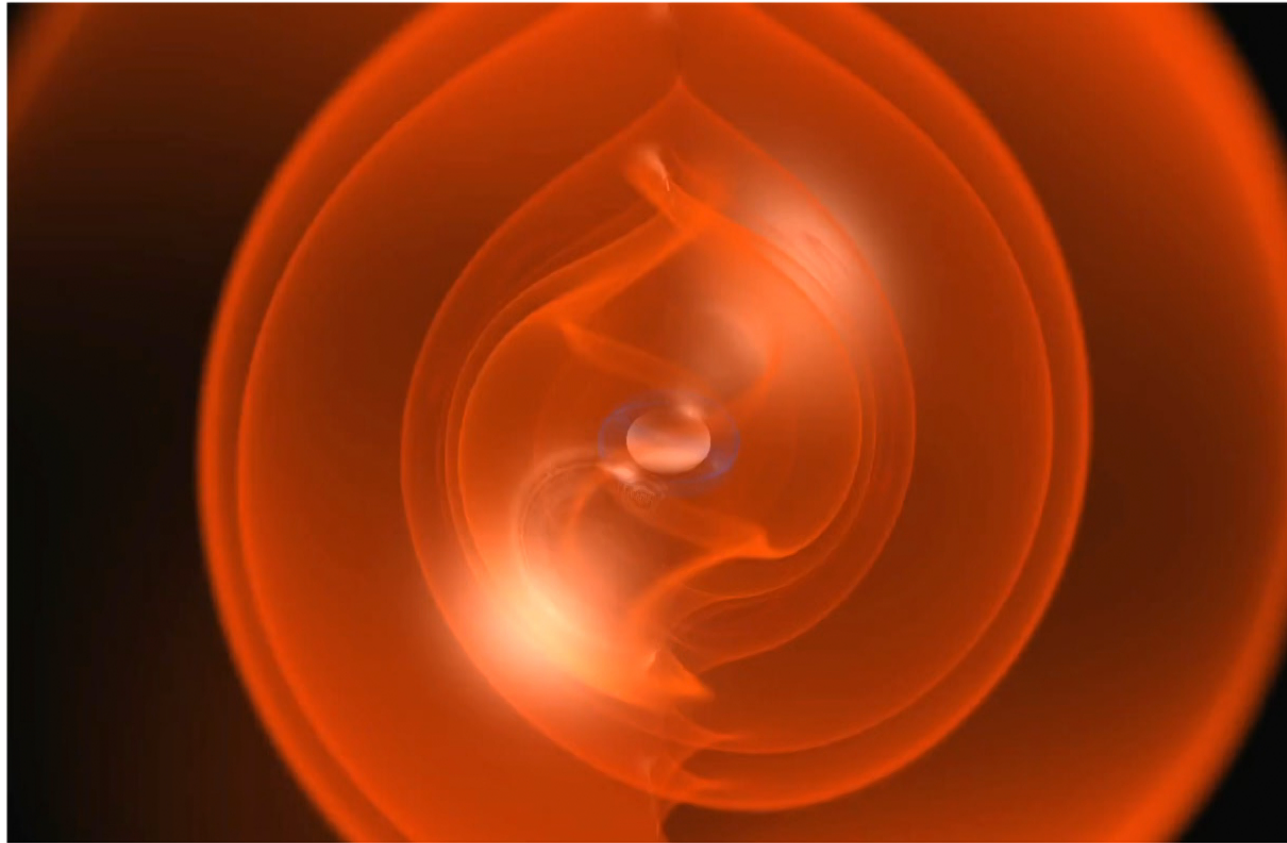
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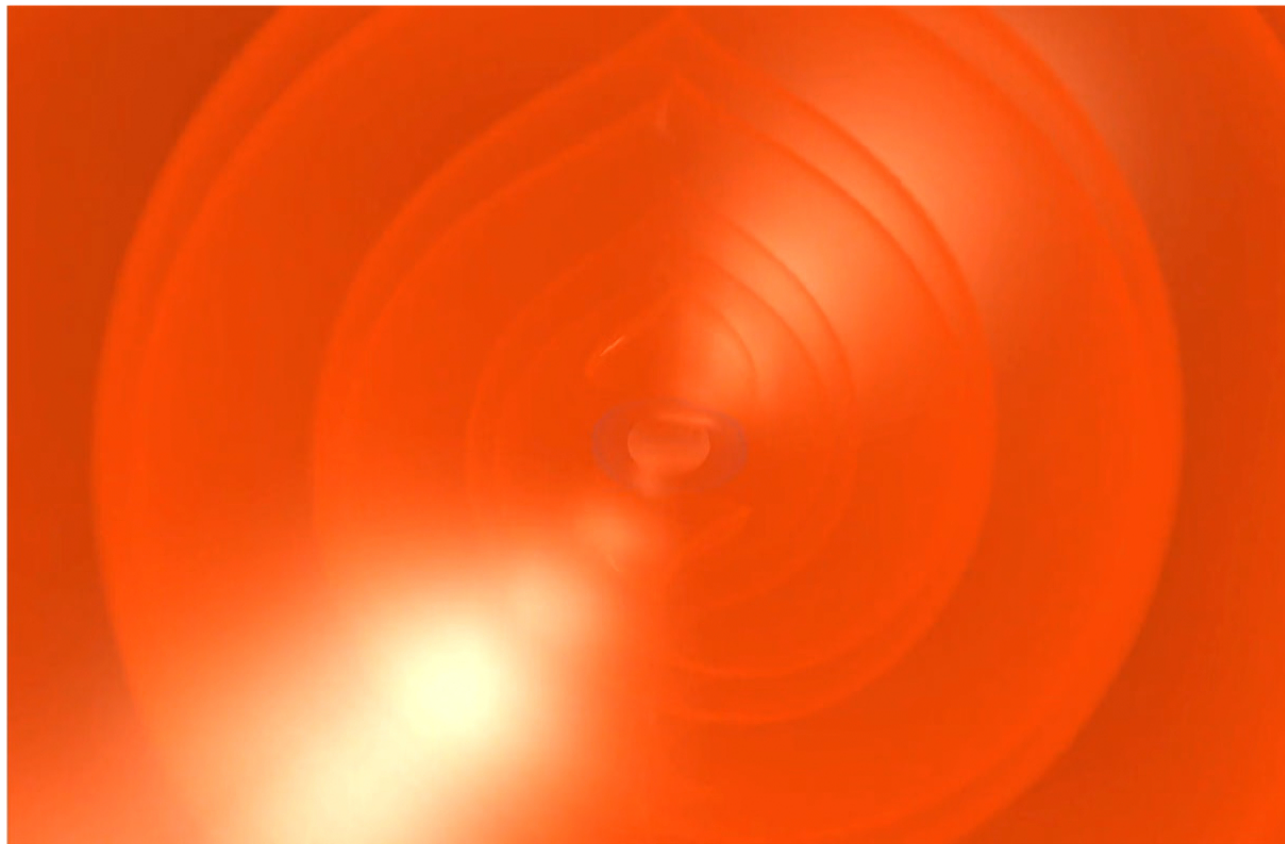
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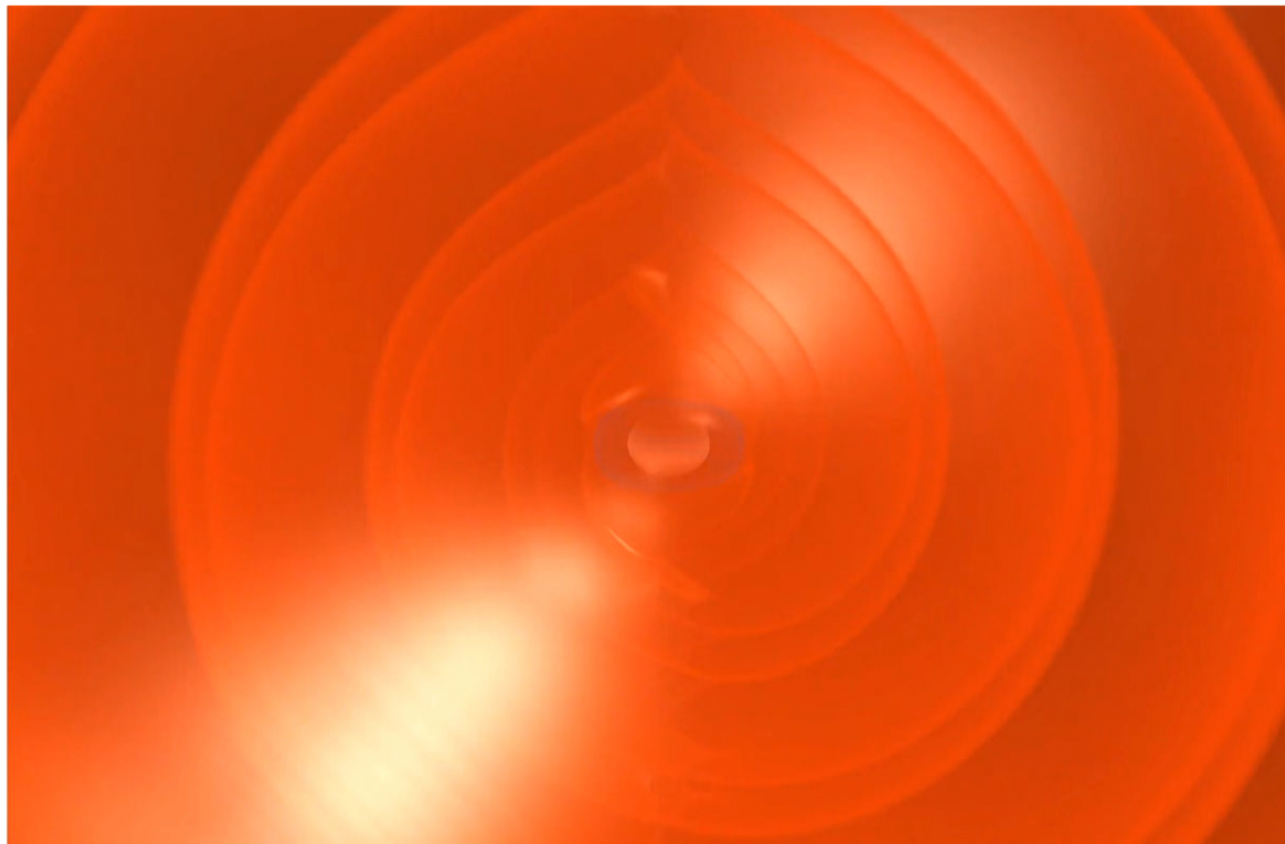
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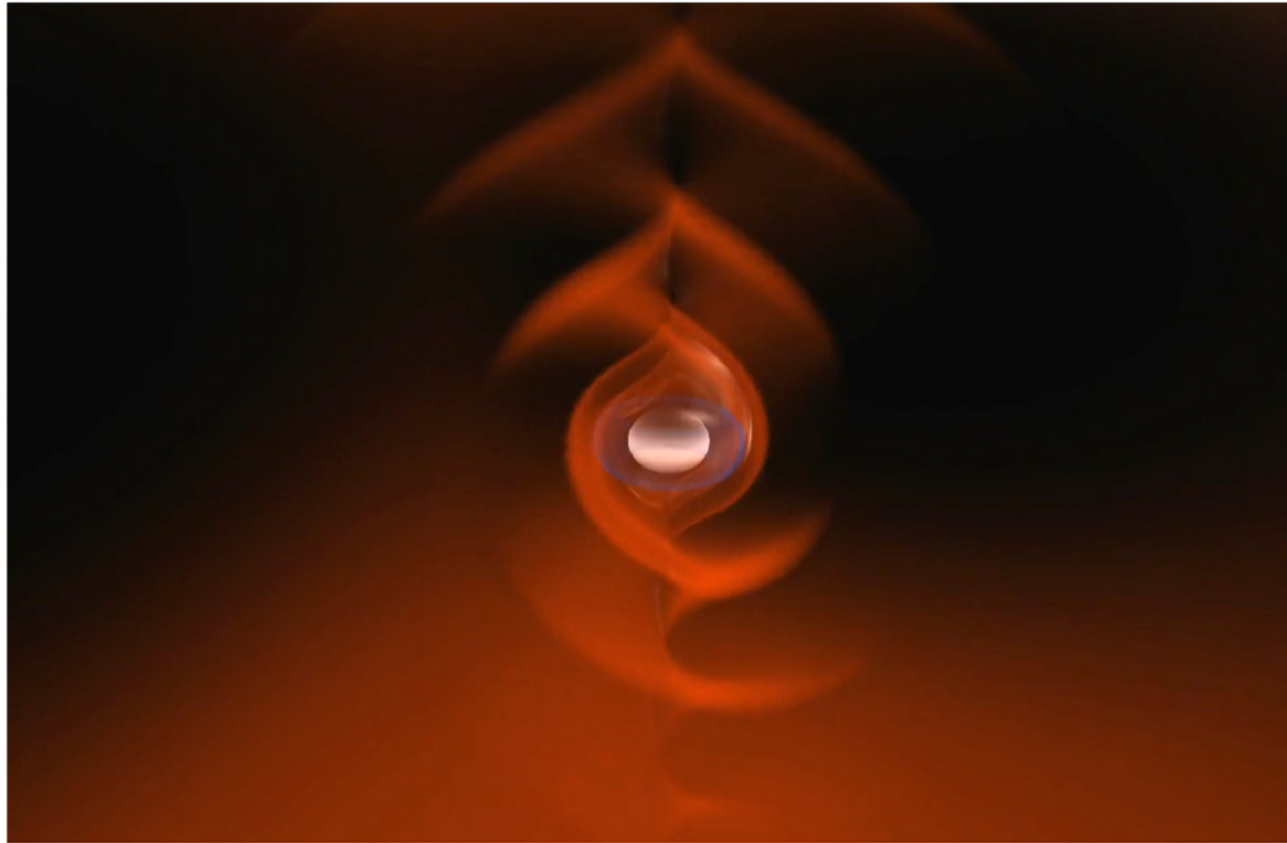
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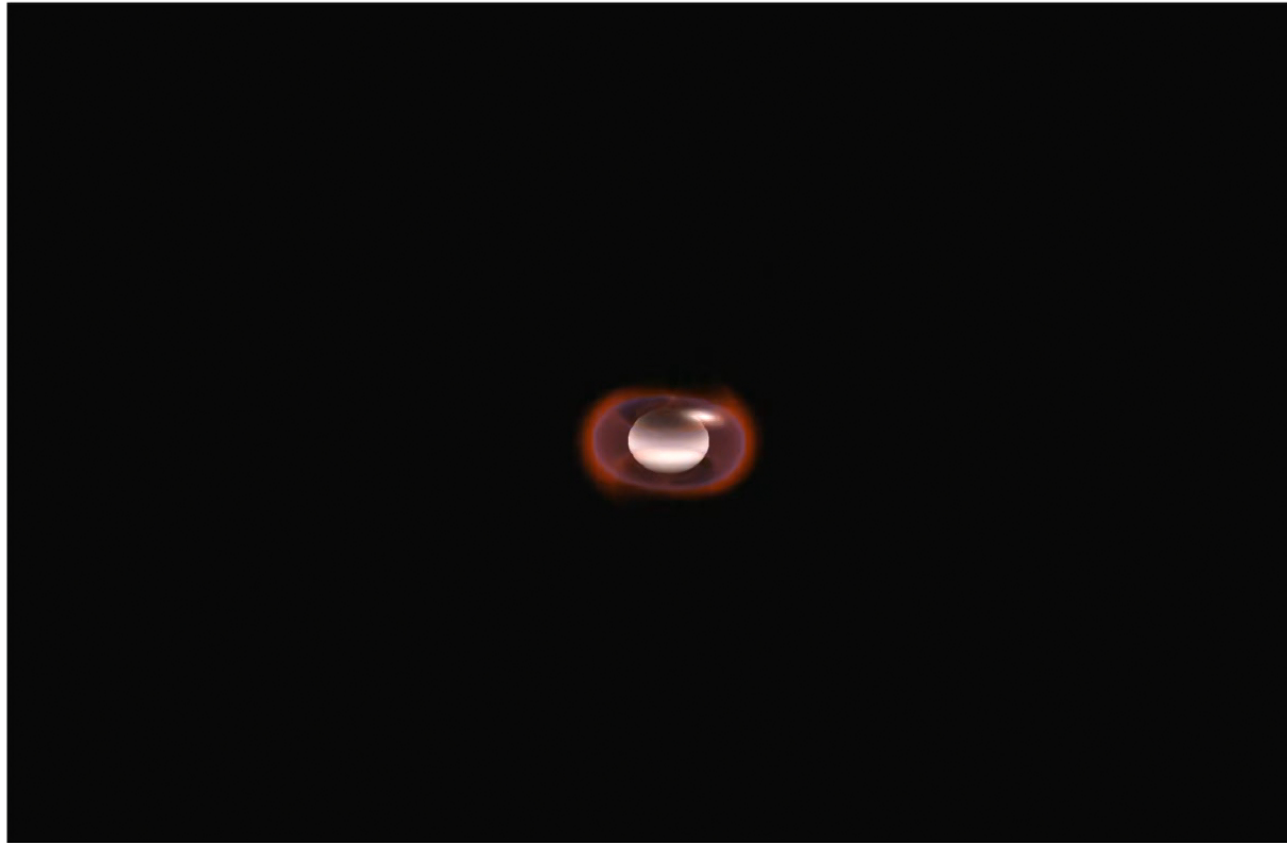
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Black holes superradiance



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Black hole bomb

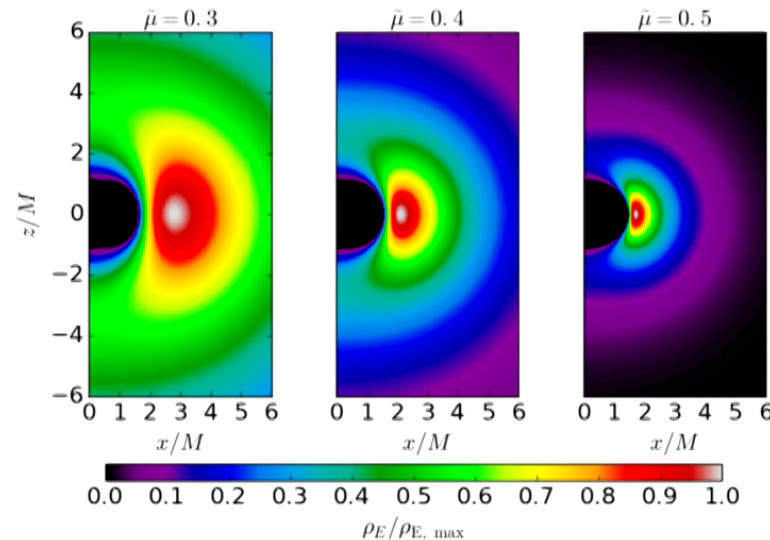
Massless particles (photons, gravitons, etc.) only interact once.
But surround a black hole with a mirror...



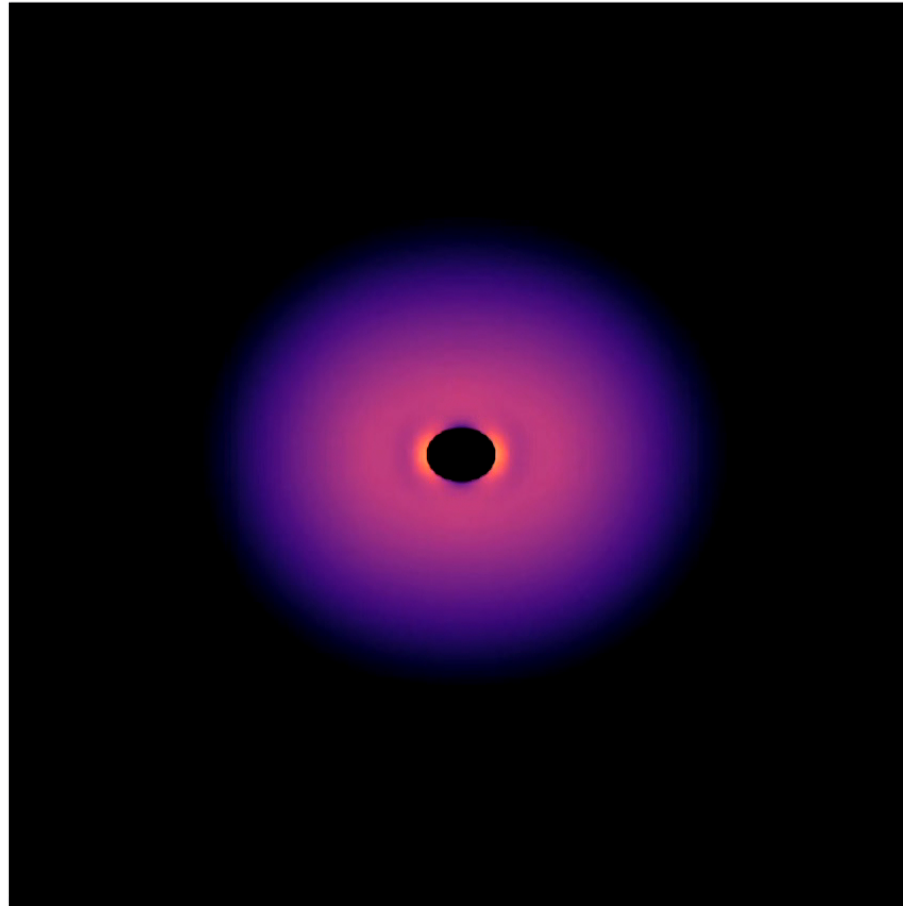
... create a black hole bomb. (Press & Teukolosky 1972)

Superradiant instability: realizing the black hole bomb

- **Massive** bosons can form bound states, when frequency $\omega < m\Omega_H$ grow exponentially in time.
- Search for new ultralight bosonic particles (axions, dark massive “photons,” etc.) with Compton wavelength comparable to black hole radius (Arvanitaki et al.)

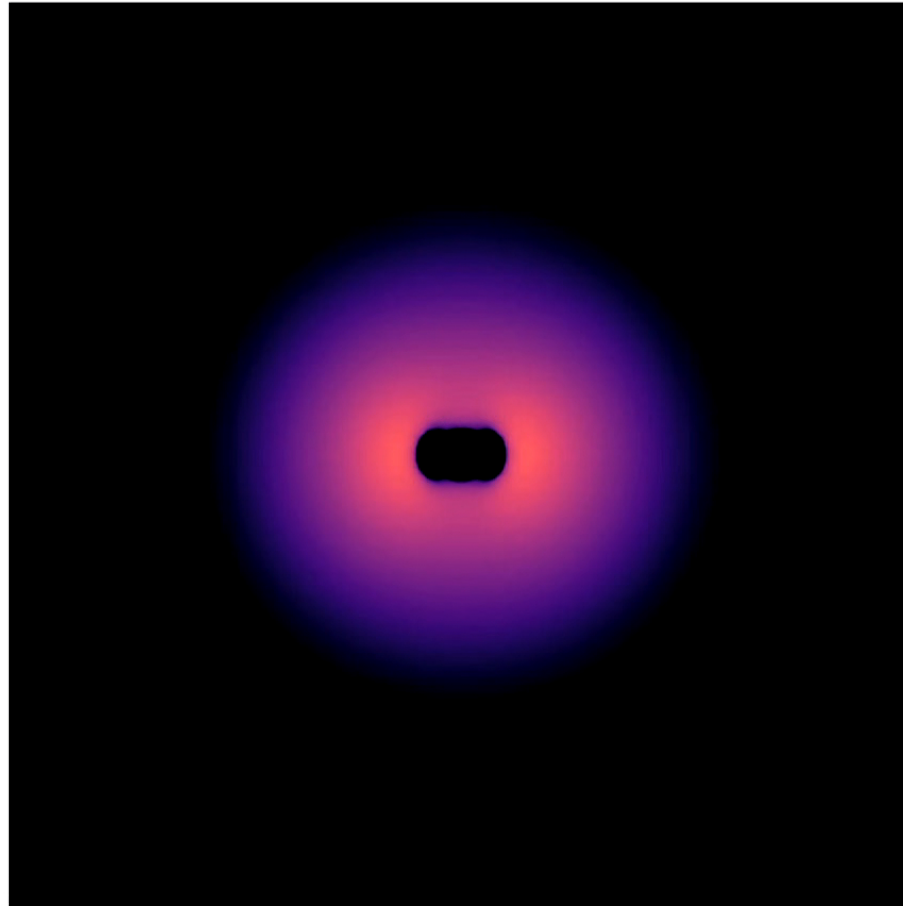


Massive vector field energy density



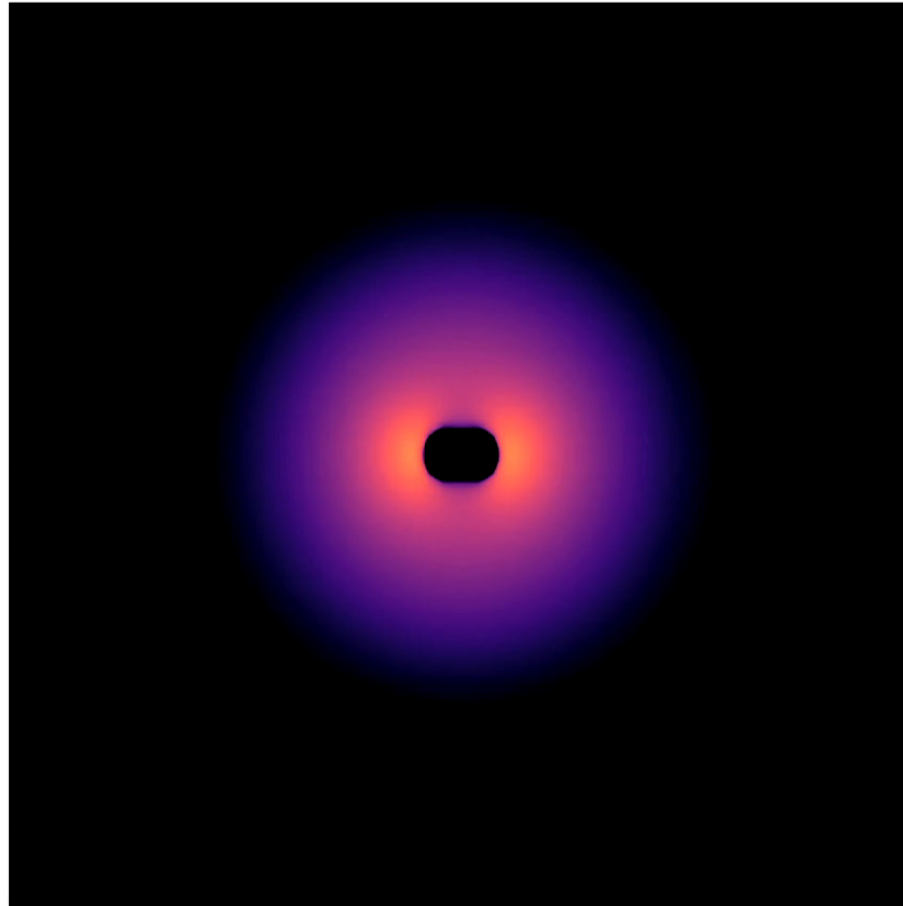
WE (2018)

Massive vector field energy density



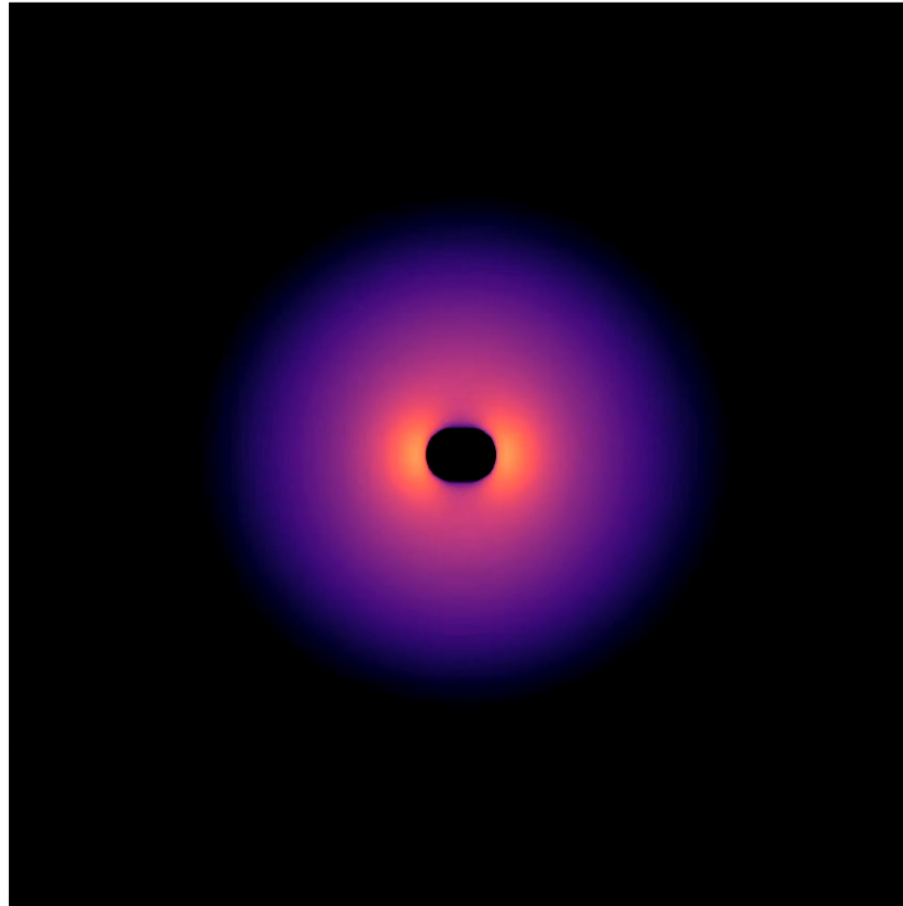
WE (2018)

Massive vector field energy density



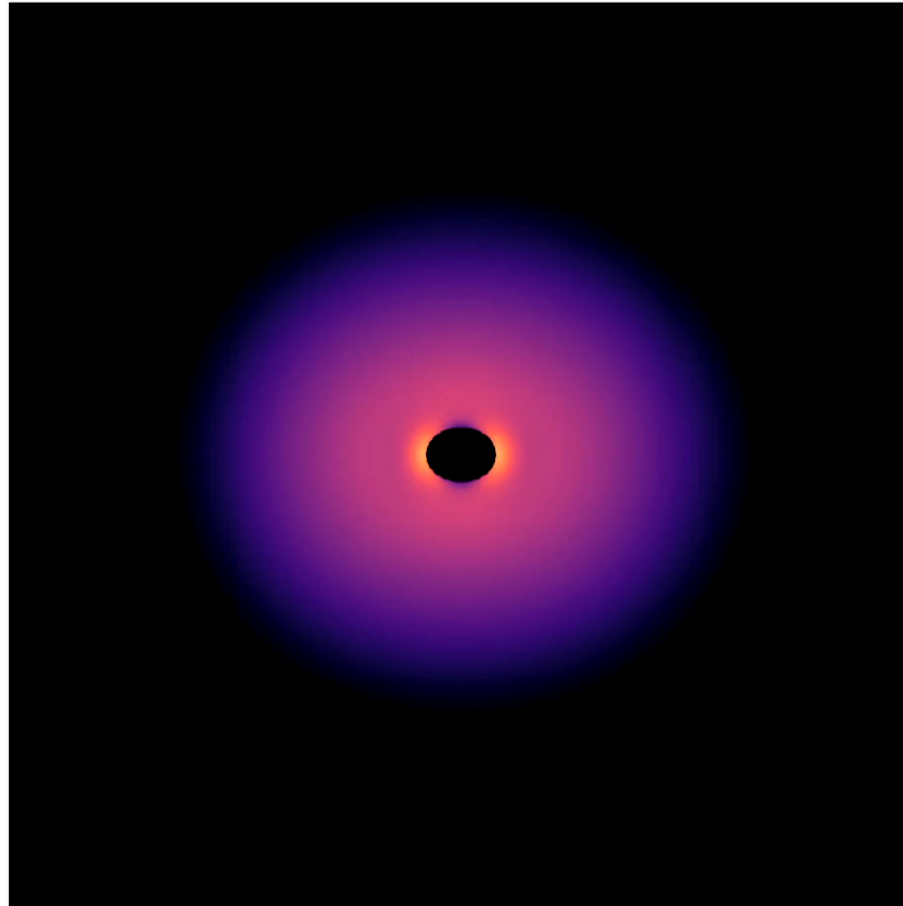
WE (2018)

Massive vector field energy density



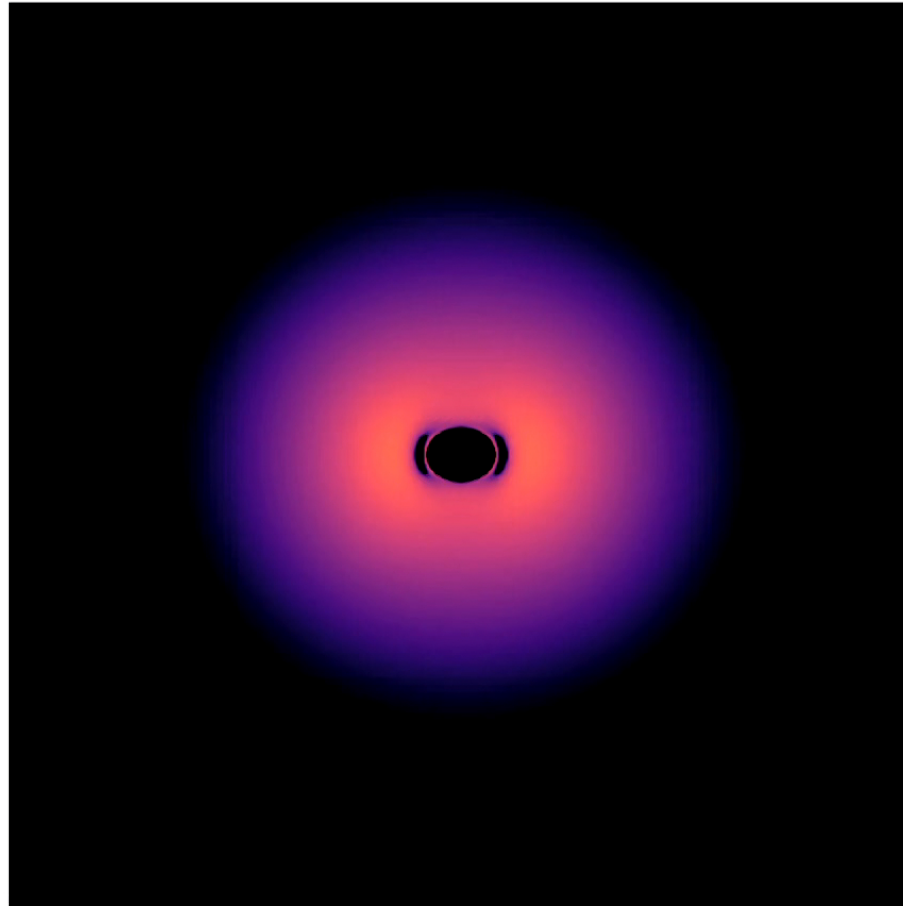
WE (2018)

Massive vector field energy density



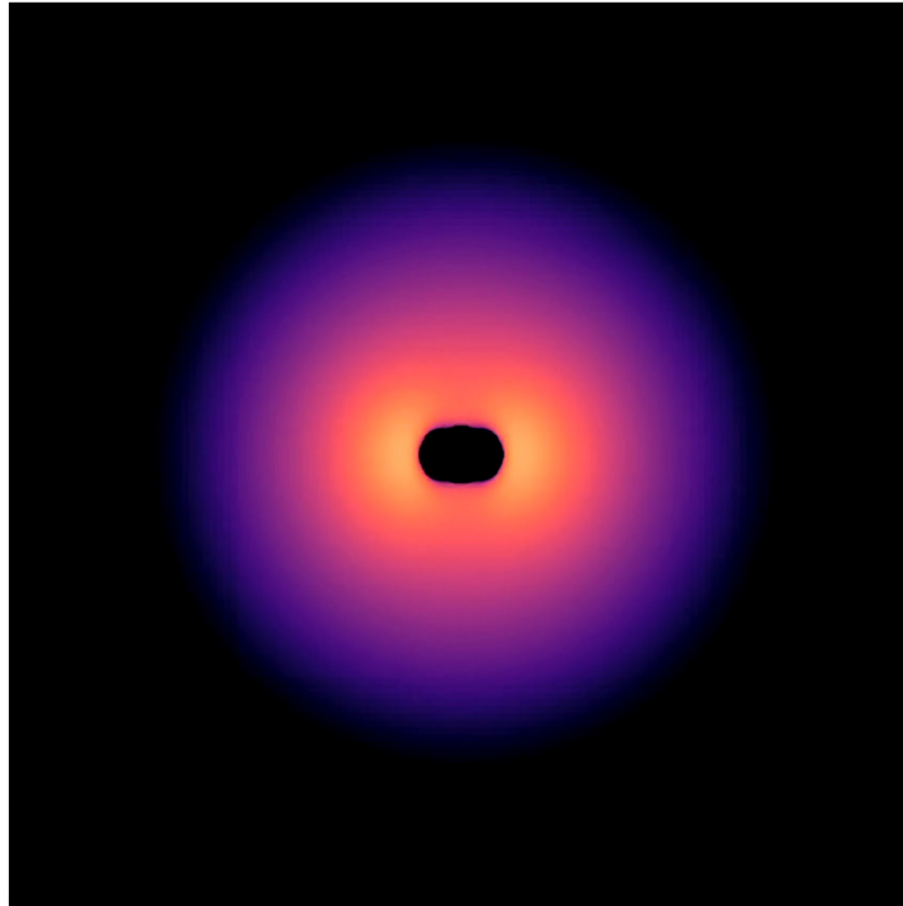
WE (2018)

Massive vector field energy density



WE (2018)

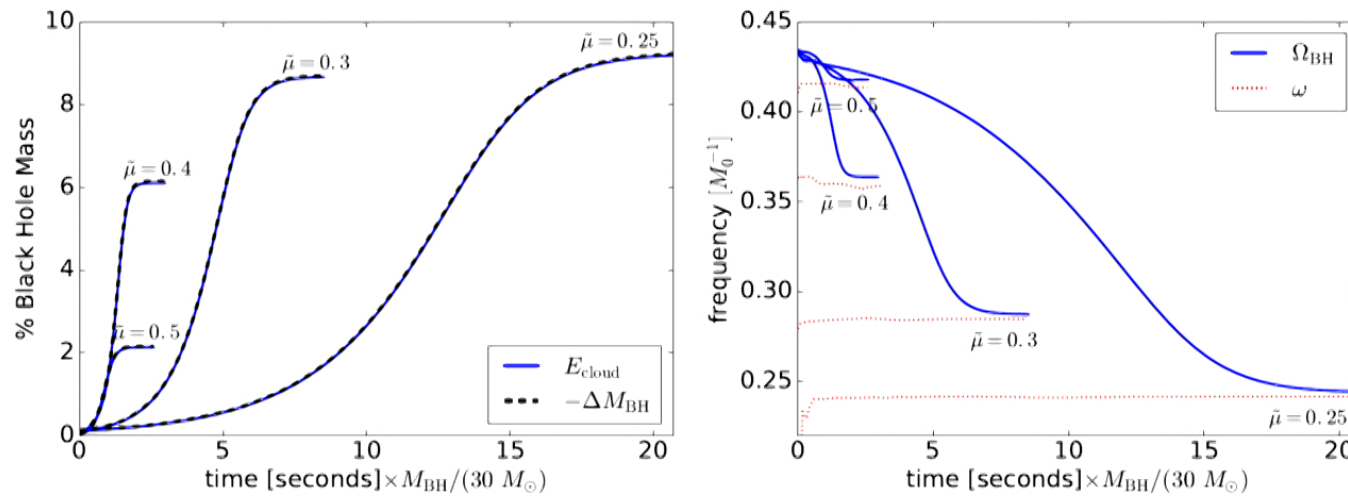
Massive vector field energy density



WE (2018)

Superradiant instability: spinning down a black hole

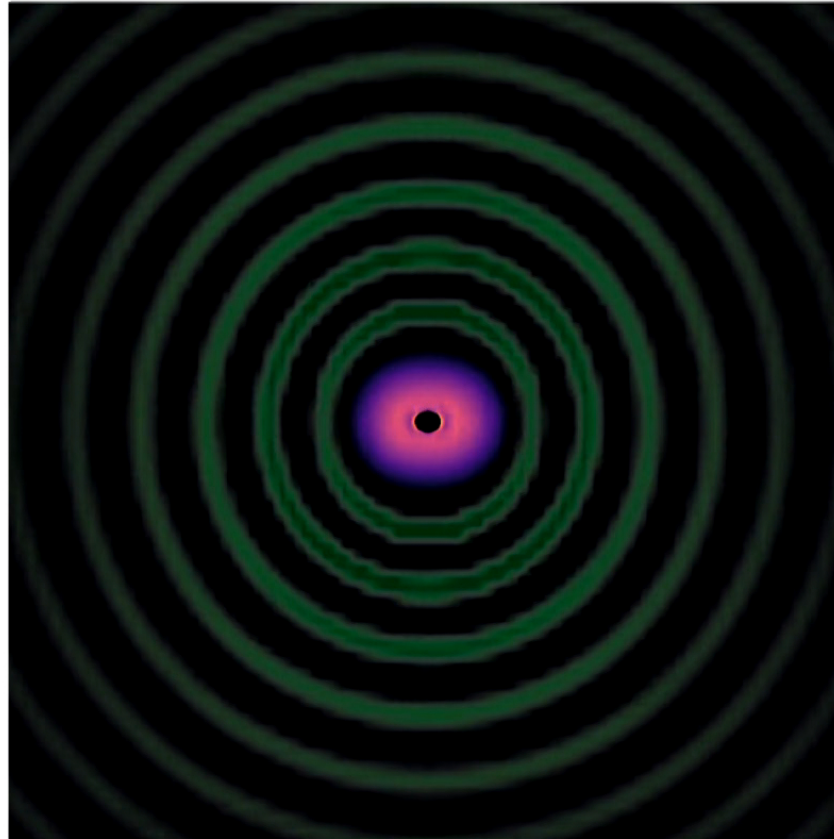
Black hole with initial spin $a = 0.99$.



WE & Pretorius (2017)

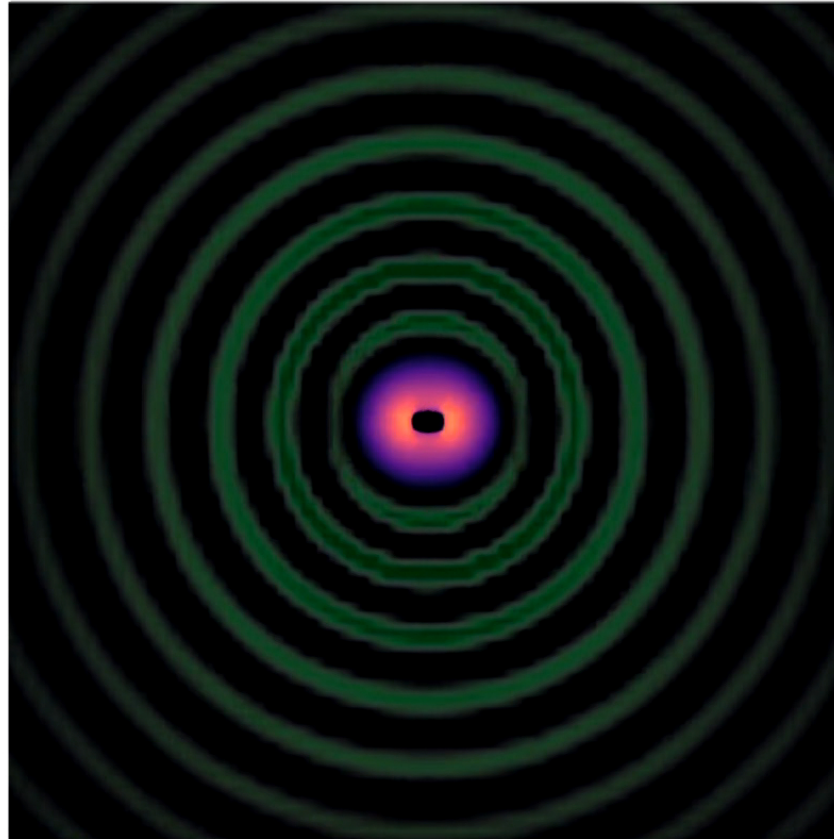
Vector boson mass: $\approx 10^{-12} \text{ eV } (\tilde{\mu}/0.25)(30M_{\odot}/M_{\text{BH}})$

Boson clouds emit gravitational waves



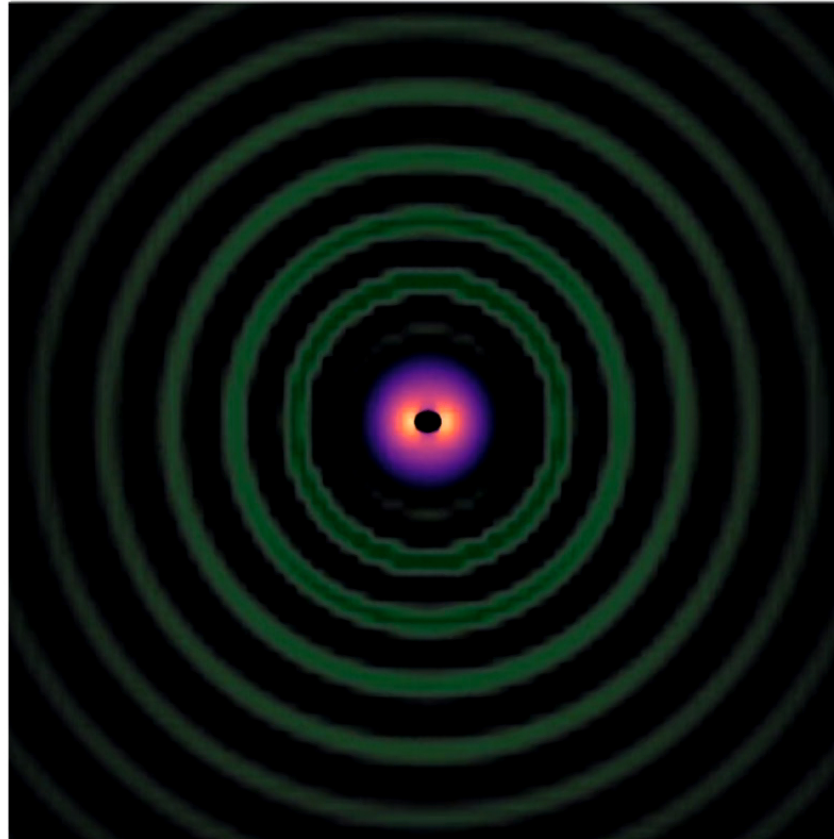
WE (2018)

Boson clouds emit gravitational waves



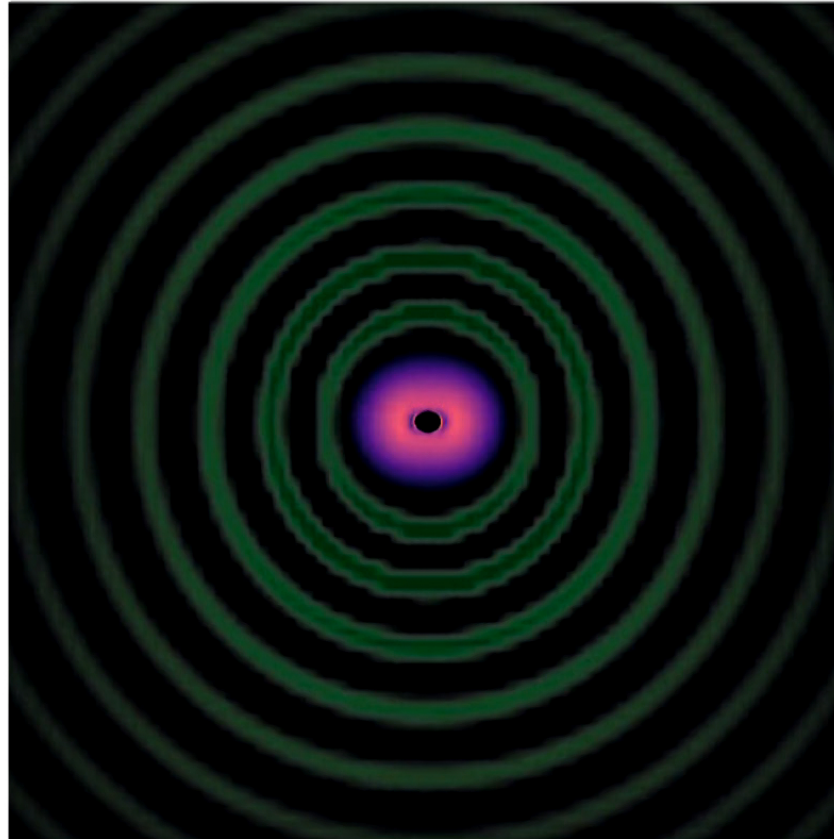
WE (2018)

Boson clouds emit gravitational waves



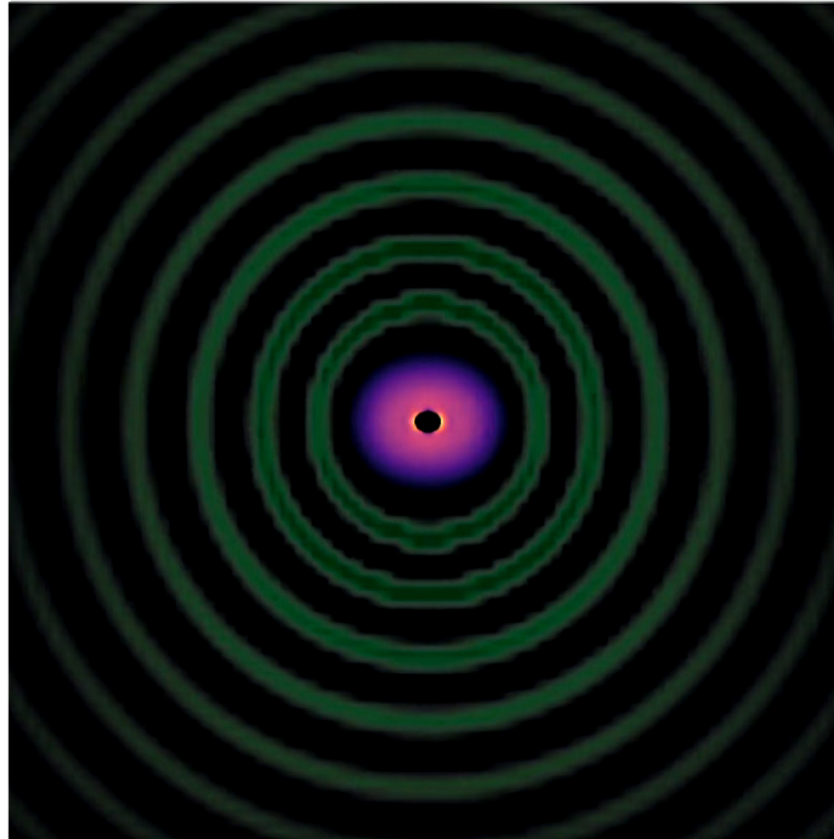
WE (2018)

Boson clouds emit gravitational waves



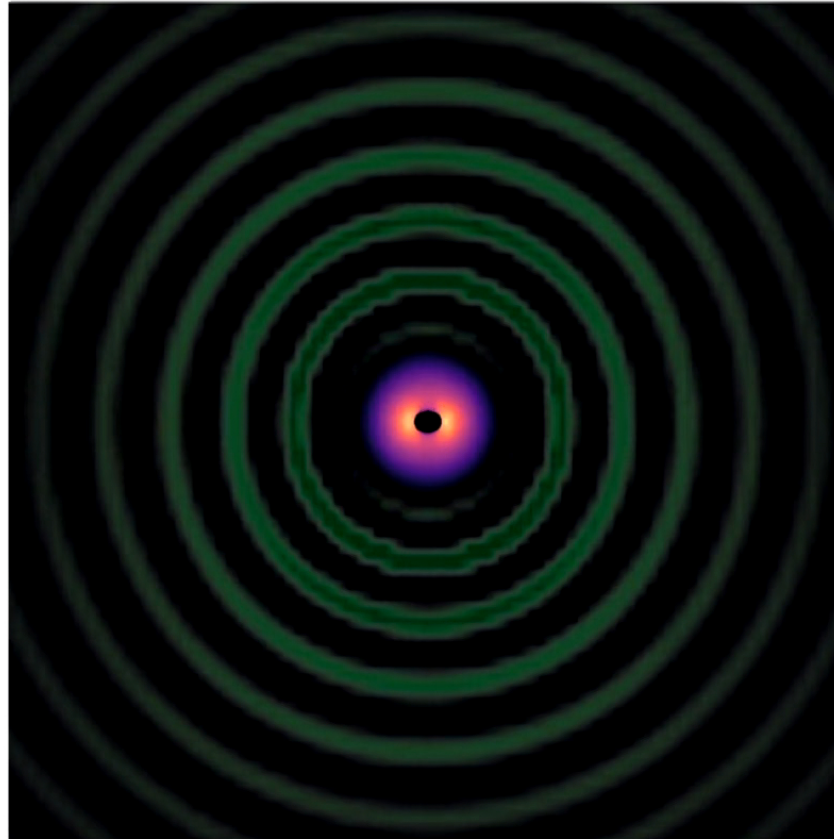
WE (2018)

Boson clouds emit gravitational waves



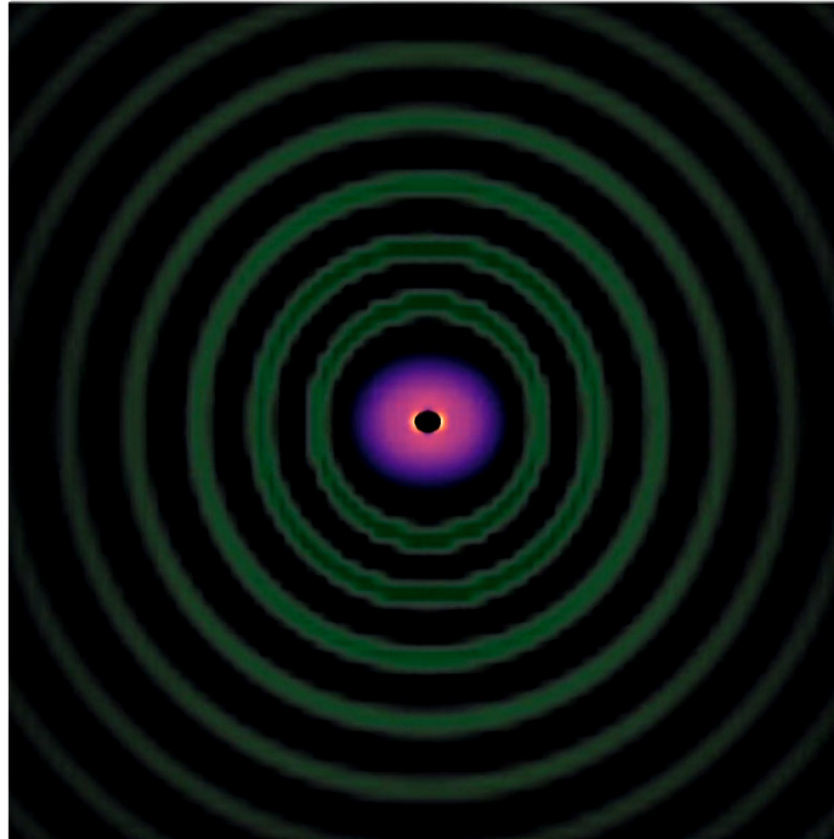
WE (2018)

Boson clouds emit gravitational waves



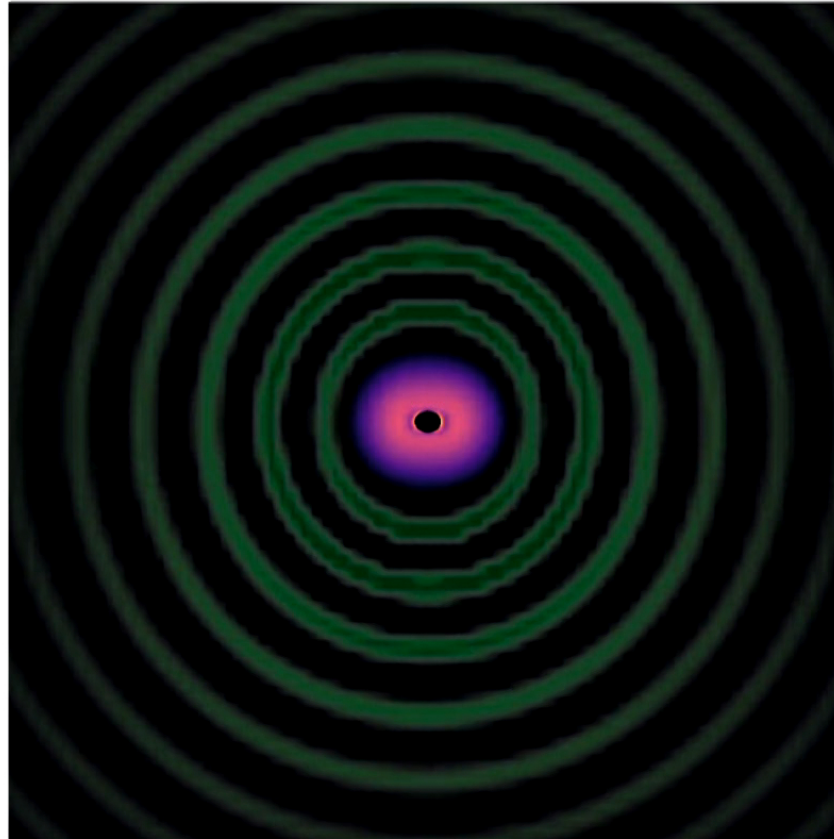
WE (2018)

Boson clouds emit gravitational waves



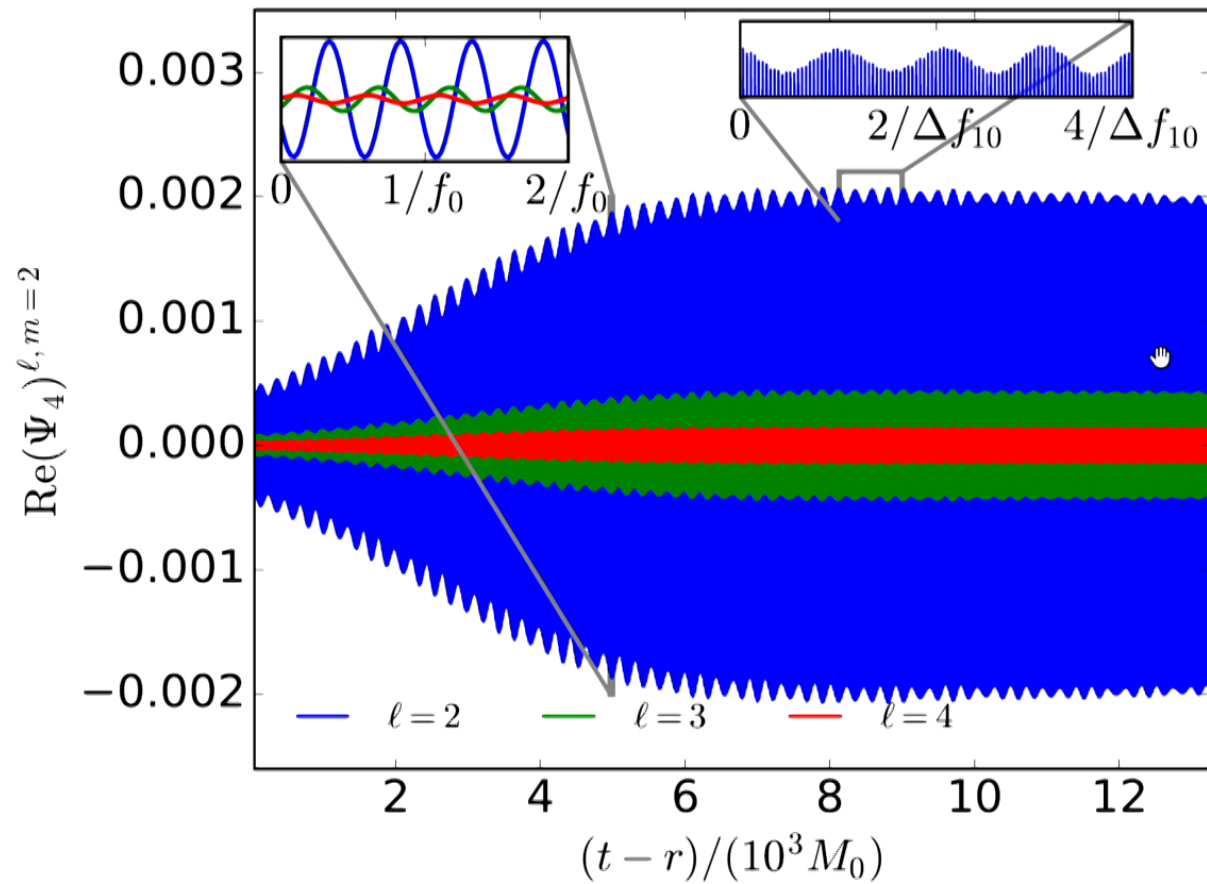
WE (2018)

Boson clouds emit gravitational waves

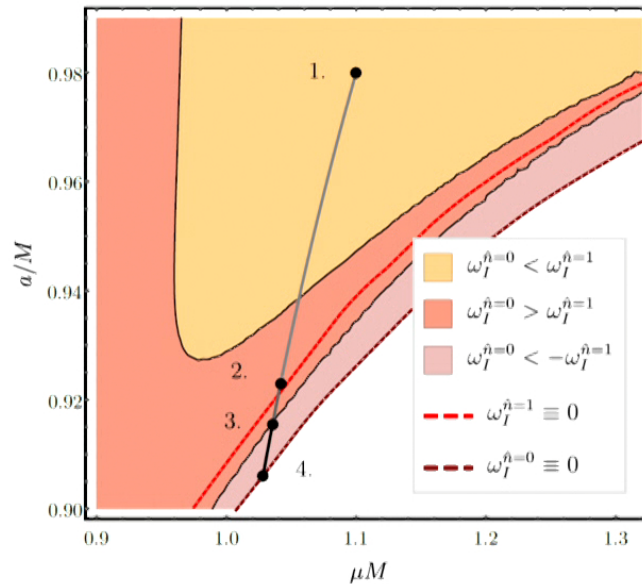


WE (2018)

Gravitational wave signal

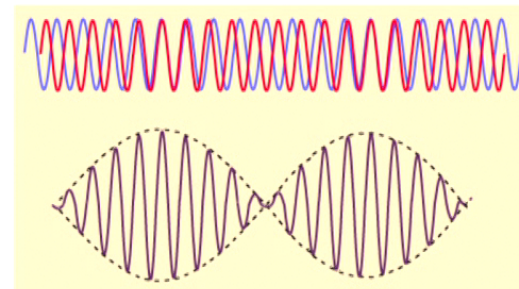


Listening to the beat



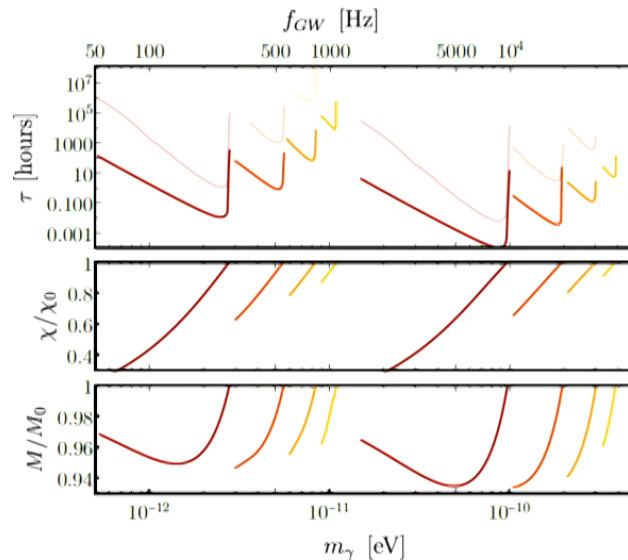
Siemens & WE (2020)

- Fundamental and overtone modes simultaneously populated
- Slightly different frequency leads to beat (lower frequency) gravitational wave signal



Hyperphysics

Boson clouds emit gravitational waves



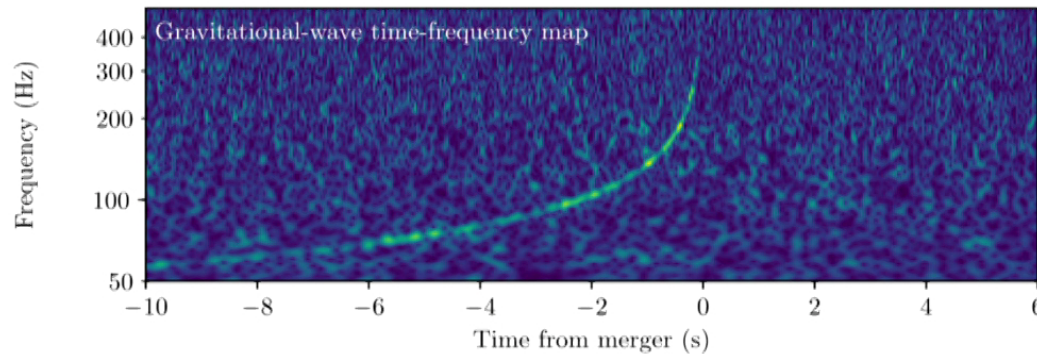
Siemonsen & WE (2020)

- Look for either stochastic or resolved sources with LIGO (Baryakthar et al. 2017; Brito et al. 2017)
- Can “follow-up” black hole merger events
- Signals motivate new searches: stay tuned...

Binary neutron star merger or black hole-neutron star merger

- How do we know an event is a binary neutron star merger and not one involving a black hole?
- Can we rule out an exotic population of low mass ($1 - 3 M_{\odot}$) black holes?

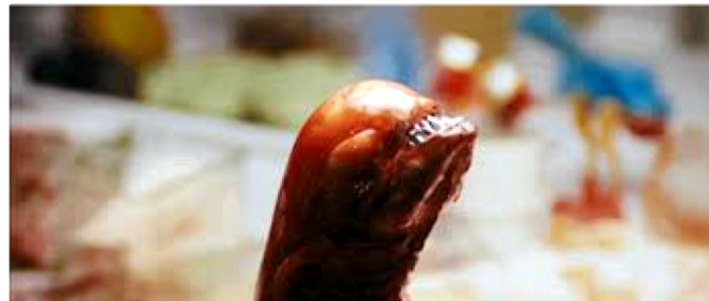
?



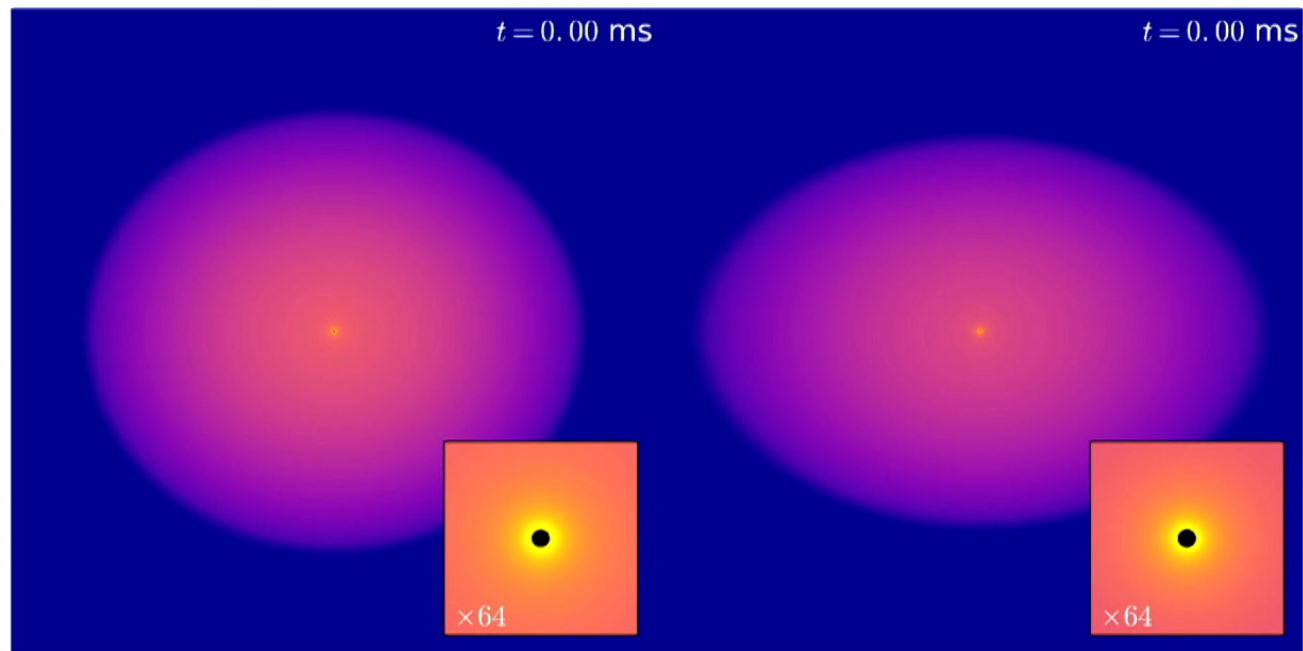
LIGO/VIRGO Collaboration et al. (2017)

Endoparasitic black holes inside neutron stars

- Tiny ($\lesssim 10^{-8}$ solar mass) black hole inside spinning neutron star
- Could arise due to asymmetric dark matter particle or primordial black hole capture
- Invoked to solve astrophysical puzzles: fast radio bursts, r-process material, missing pulsars
- Observational signatures depend crucially on dynamics of angular momentum distribution

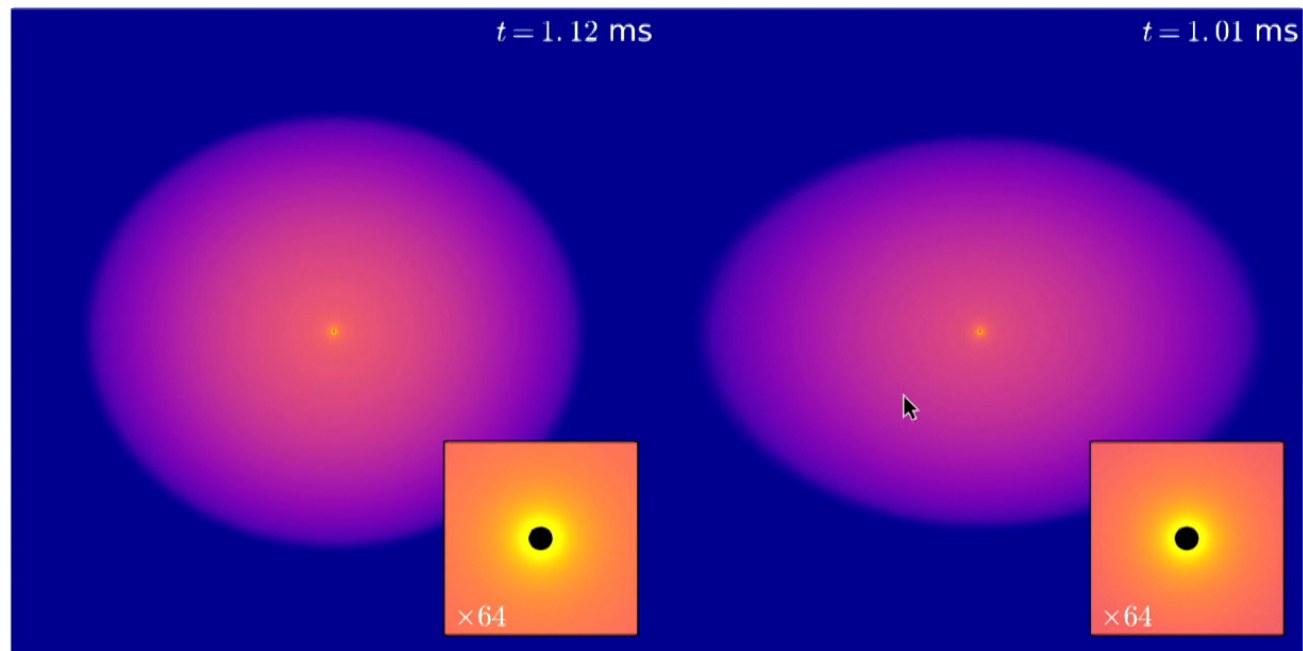


Endoparasitic black holes inside neutron stars



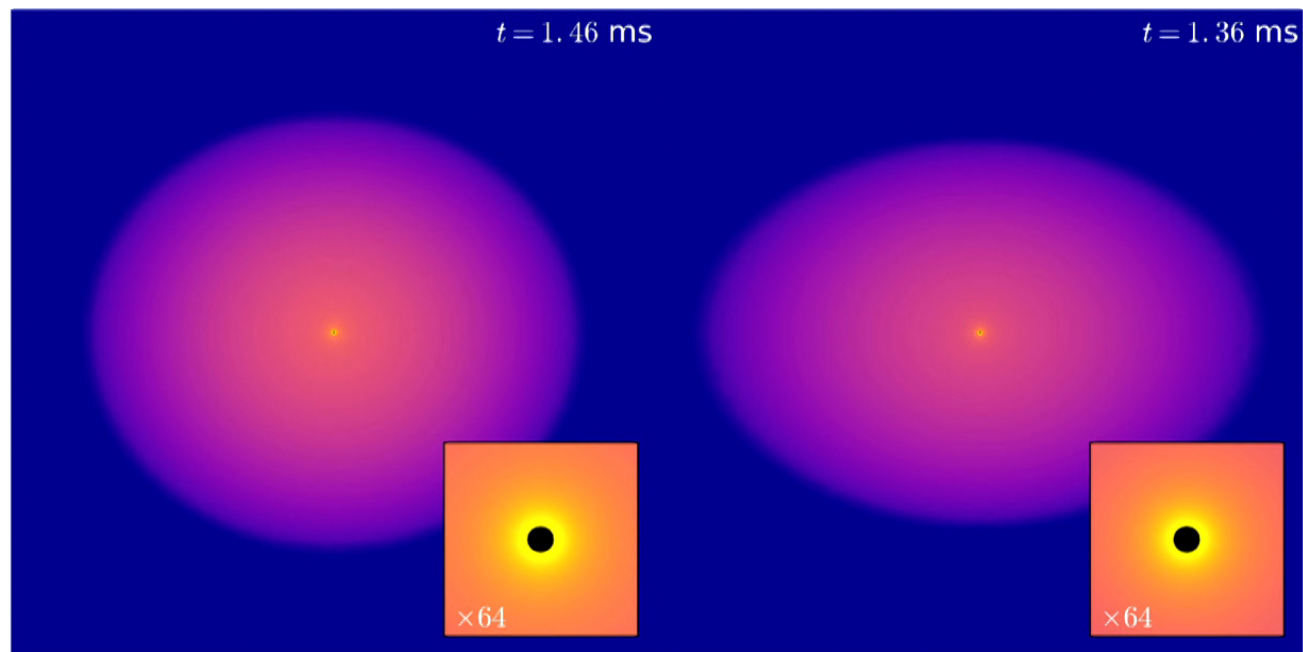
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



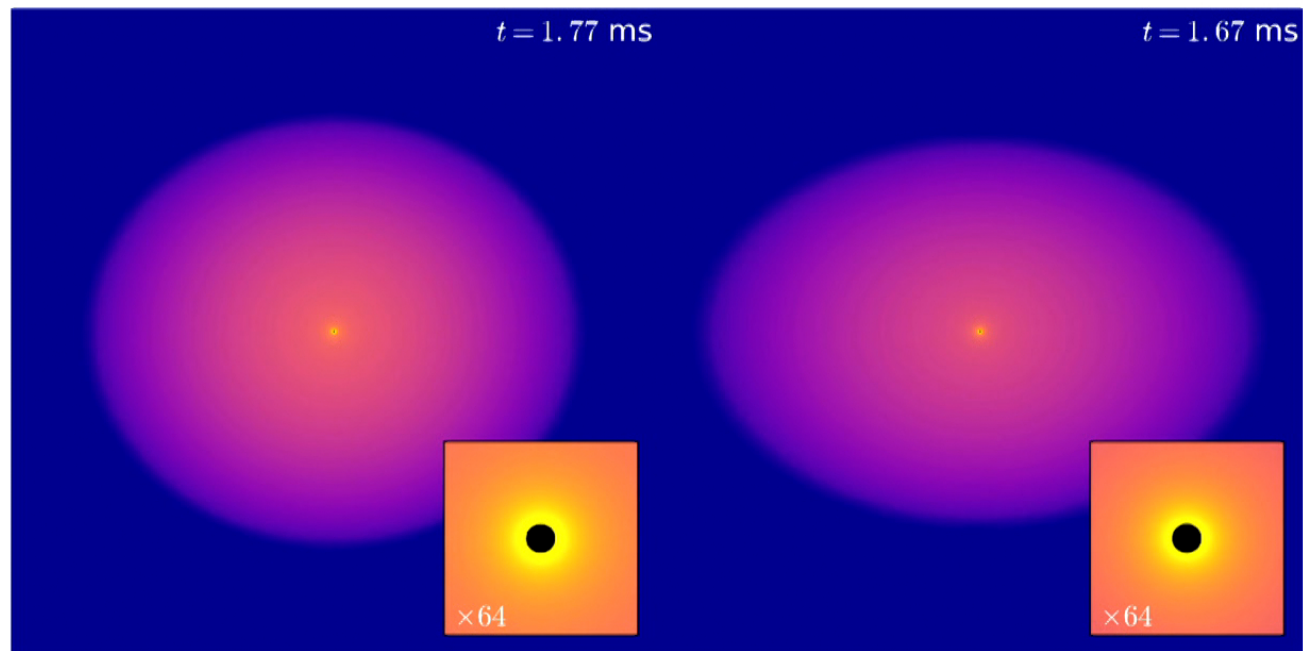
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



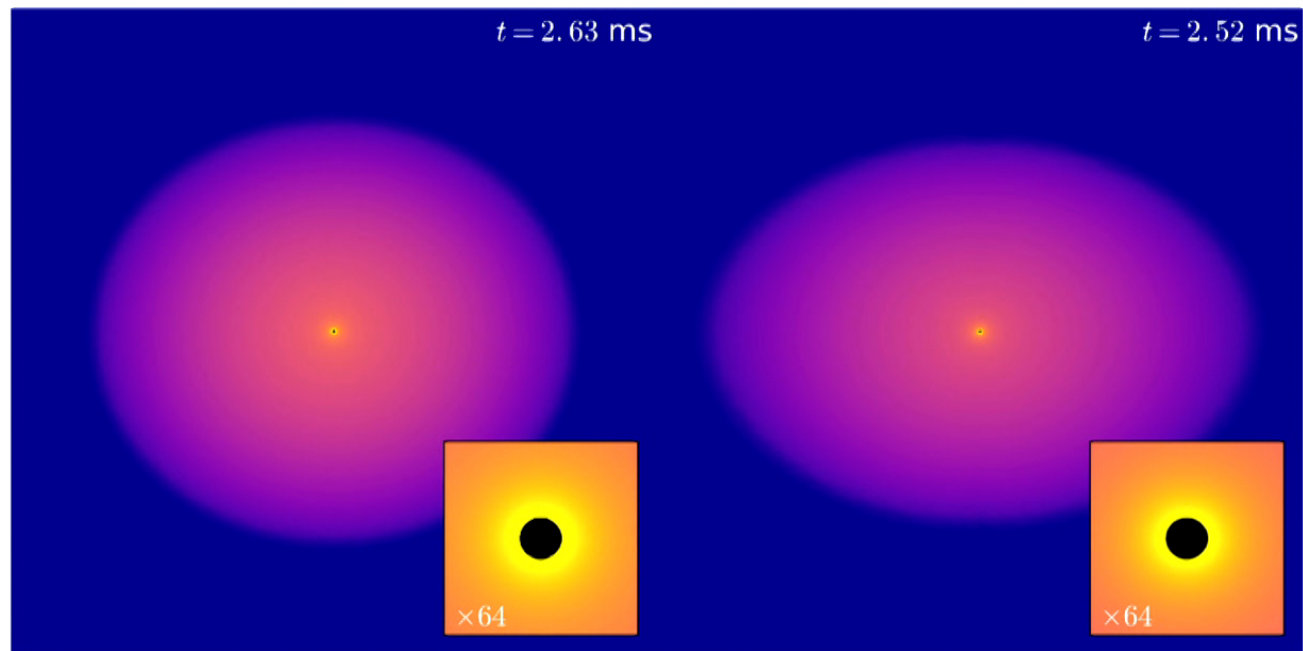
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



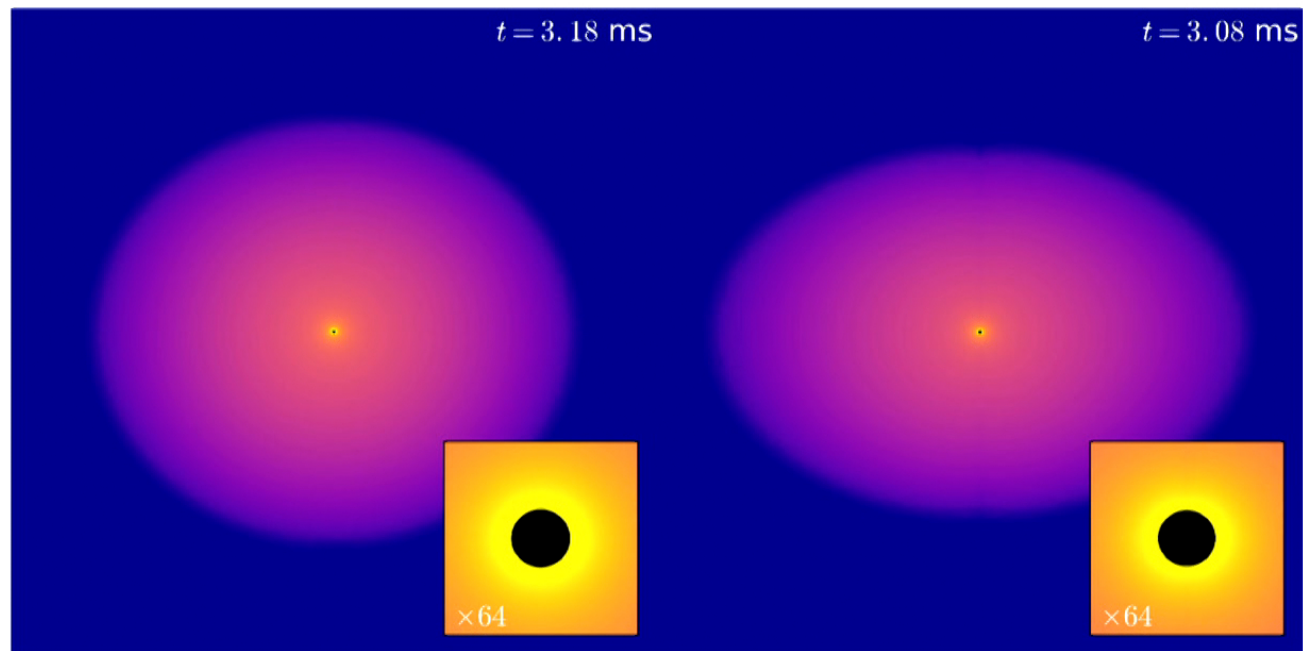
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



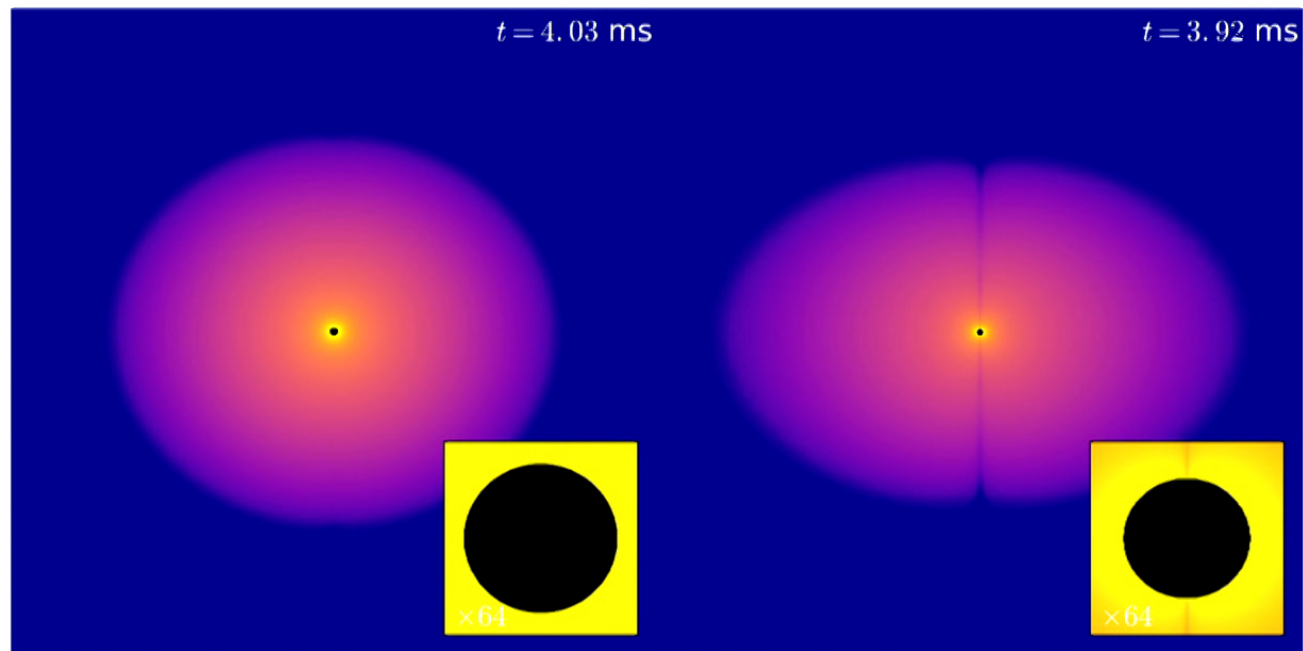
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



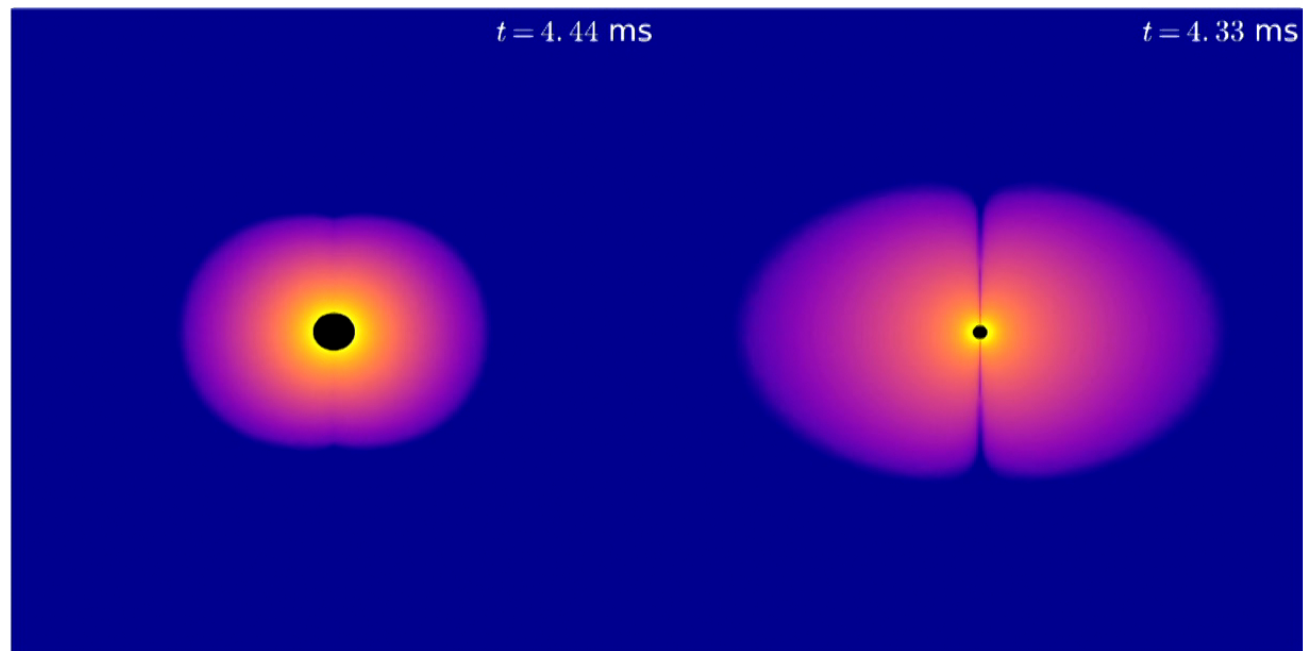
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



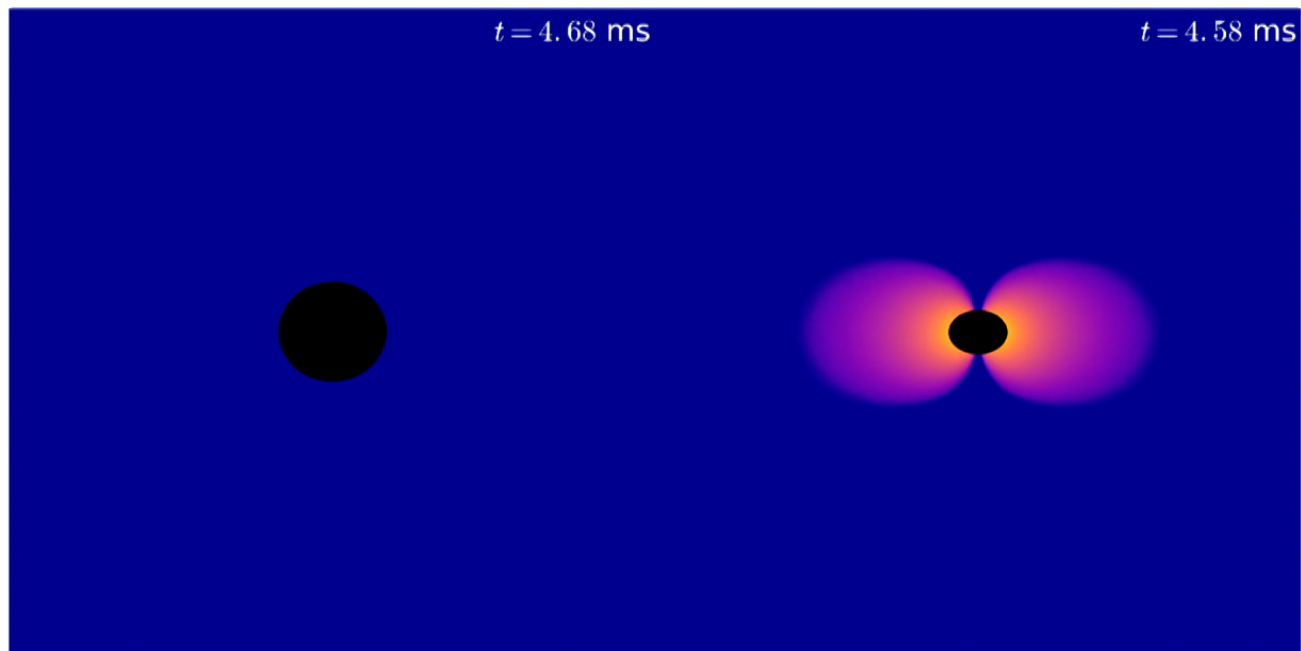
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



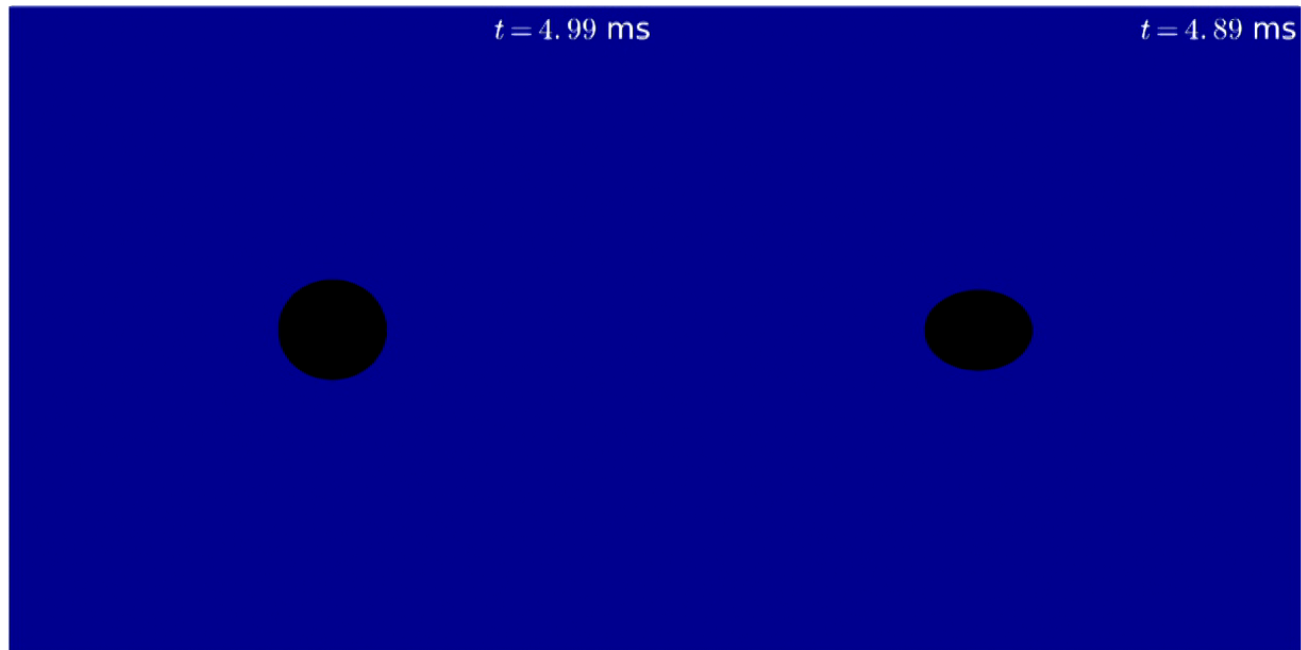
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



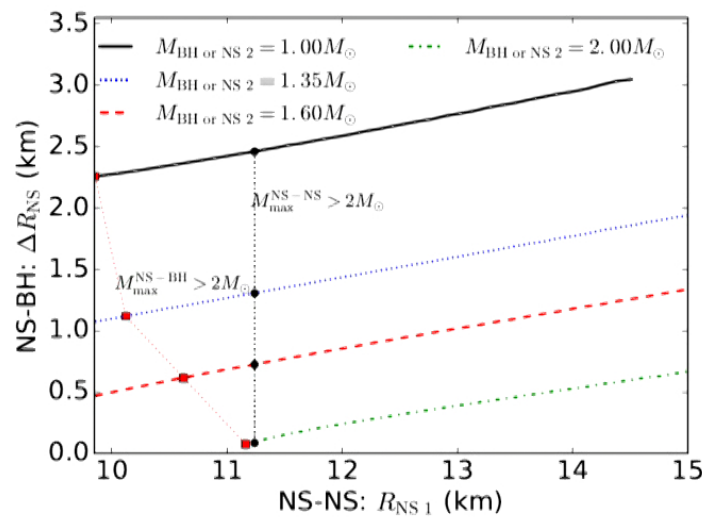
WE & Lehner (2019)

Endoparasitic black holes inside neutron stars



WE & Lehner (2019)

Distinguishing low mass black holes in neutron star mergers



Yang, WE & Lehner (2017)

- Leading order tidal effects are degenerate with uncertainty in equation of state
- Electromagnetic transients may be different, but still parameter degeneracy [see Hinderer et al. (2018), Foucart et al. (2019)]

Conclusion

The age of multimessenger gravitational wave astronomy has begun, allowing us to explore the extremes of spacetime!

Things to look out for:

- Many more black hole and neutron star mergers, and thus more exceptional cases.
- New probes of fundamental physics.
- The unknown unknowns.

Rich dynamics can teach us about the fundamentals of strongly curved spacetime.