Title: Uncovering the Dynamics of Spacetime

Date: Oct 25, 2017 02:00 PM

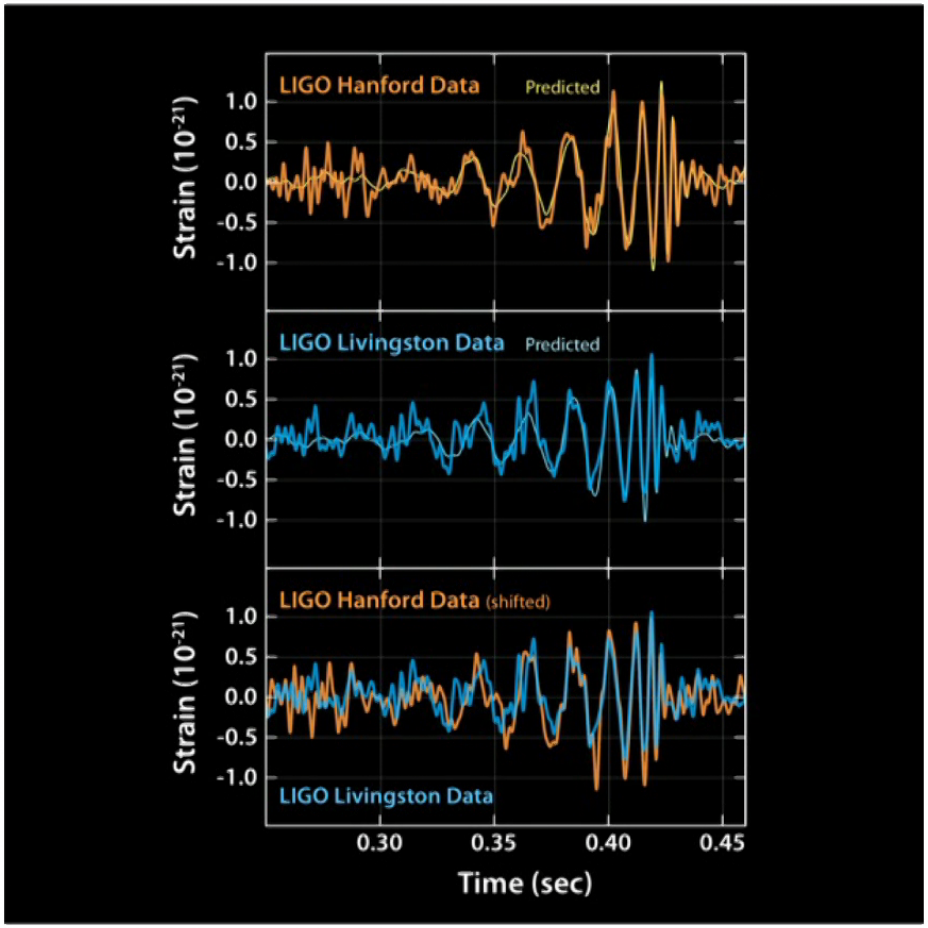
URL: http://pirsa.org/17100058

Abstract: <p>With the groundbreaking gravitational wave detections from LIGO/VIRGO, we have entered the era where we can actually observe the action of strongly curved spacetime originally predicted by Einstein. Going hand in hand with this, there has been a renaissance in the theoretical and computational tools we use to understand and interpret the dynamics of gravity and matter in this regime. I will describe some of the rich behavior exhibited by sources of gravitational waves such as the mergers of black holes and neutron stars. I will also discuss some of the open questions, and what these events could teach us, not only about the extremes of gravity, but about the behavior of matter at nuclear densities, the solution of astrophysical mysteries, and even the existence of new particles.</p>

Uncovering the Dynamics of Spacetime

William East
Perimeter Institute,
October 25, 2017

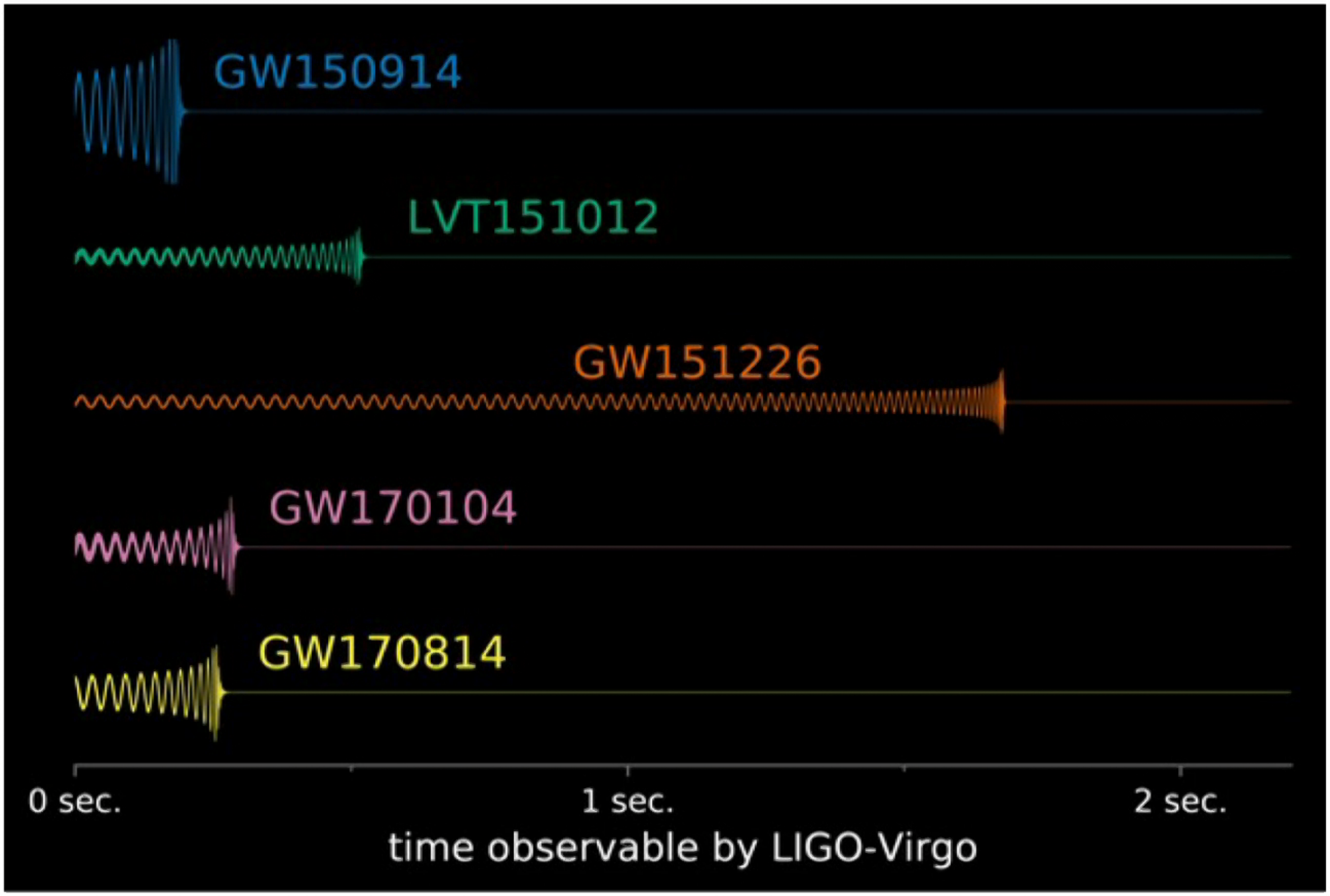
September 14, 2015 Event



- 1.3 billion light years away
- Two black holes, each about 30 $M_{\odot}$, merged
- Completely consistent with Einstein's theory (100 years after it was proposed)

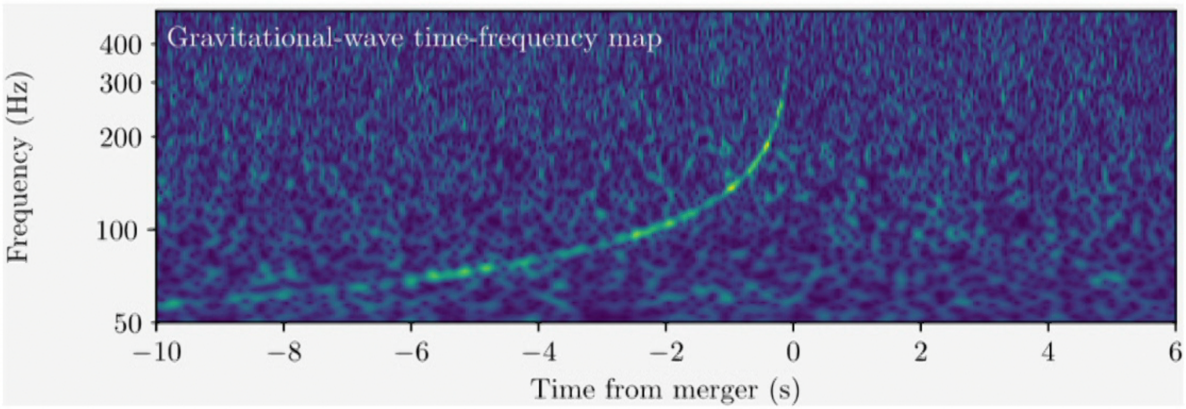
Caltech/MIT/LIGO Lab

More binary black hole mergers



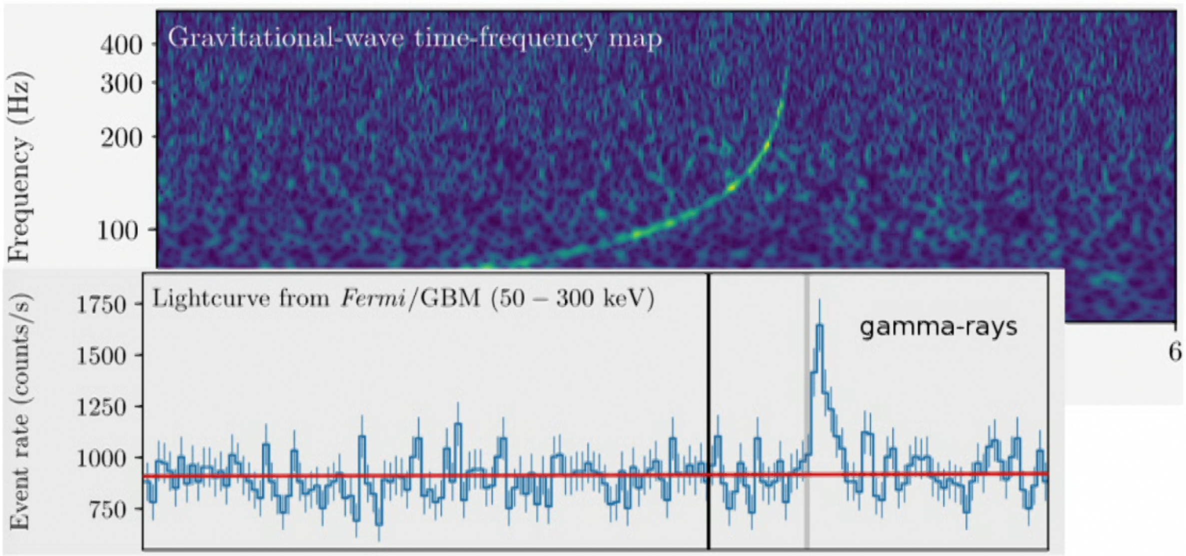
Caltech/MIT/LIGO Lab

A neutron star merger multimessenger signal



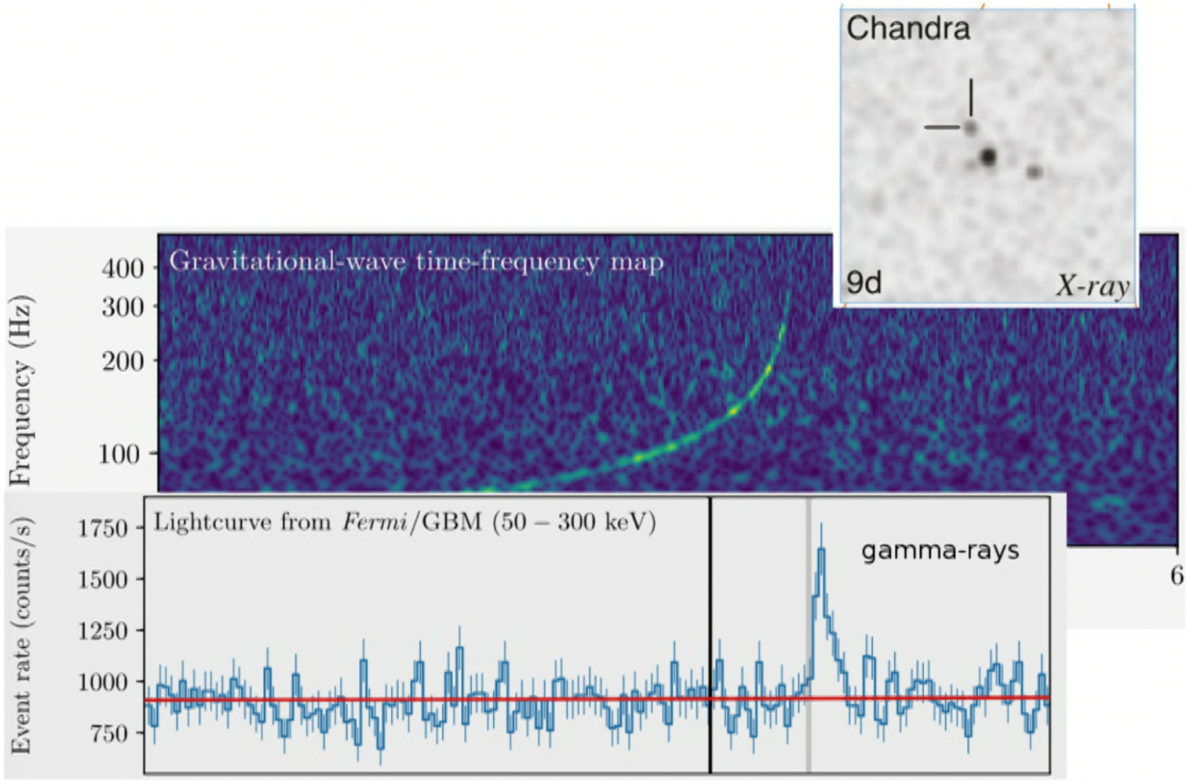
LIGO/VIRGO Collaboration et al. (2017)

A neutron star merger multimessenger signal



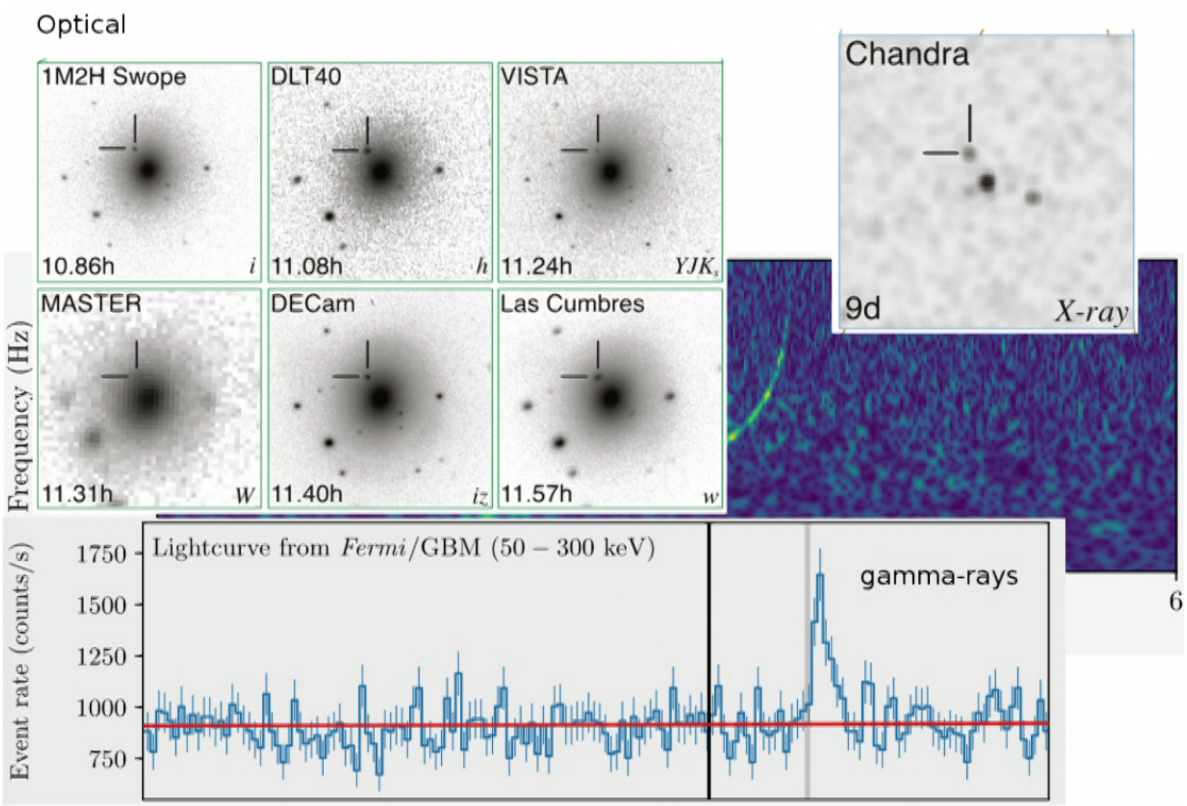
LIGO/VIRGO Collaboration et al. (2017)

A neutron star merger multimessenger signal



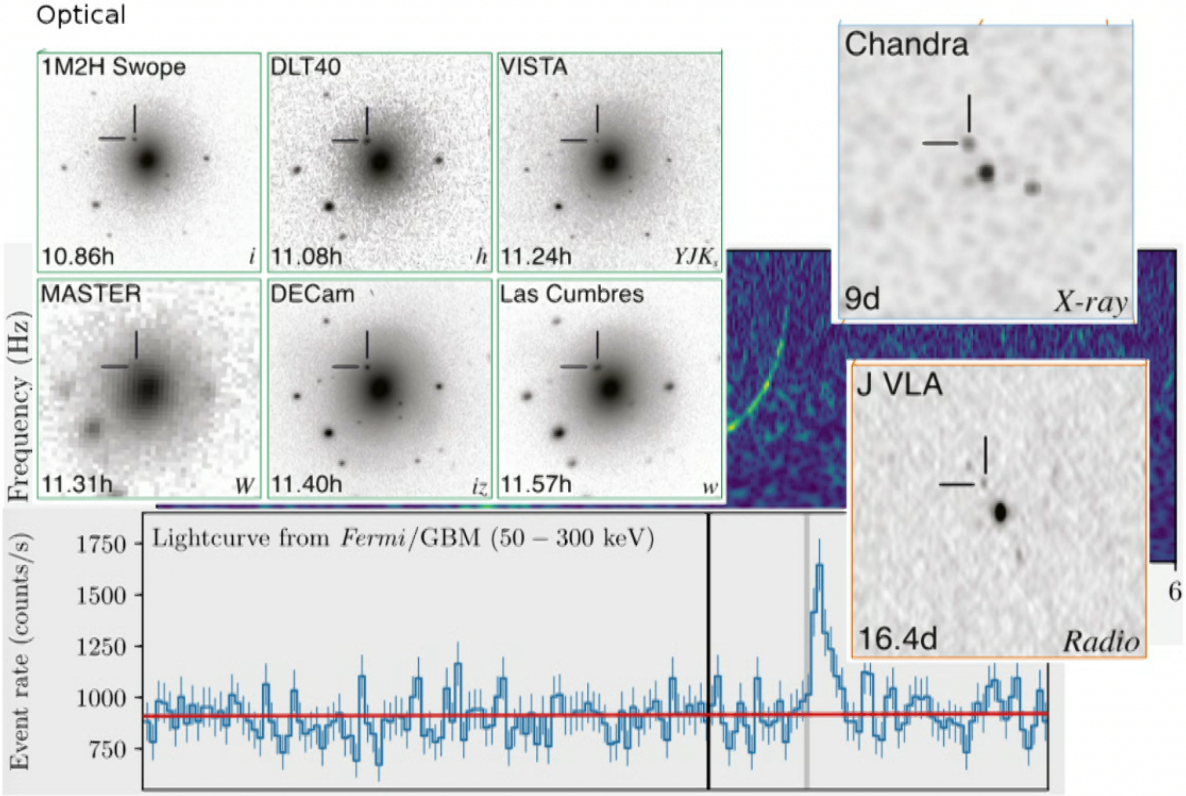
LIGO/VIRGO Collaboration et al. (2017)

A neutron star merger multimessenger signal



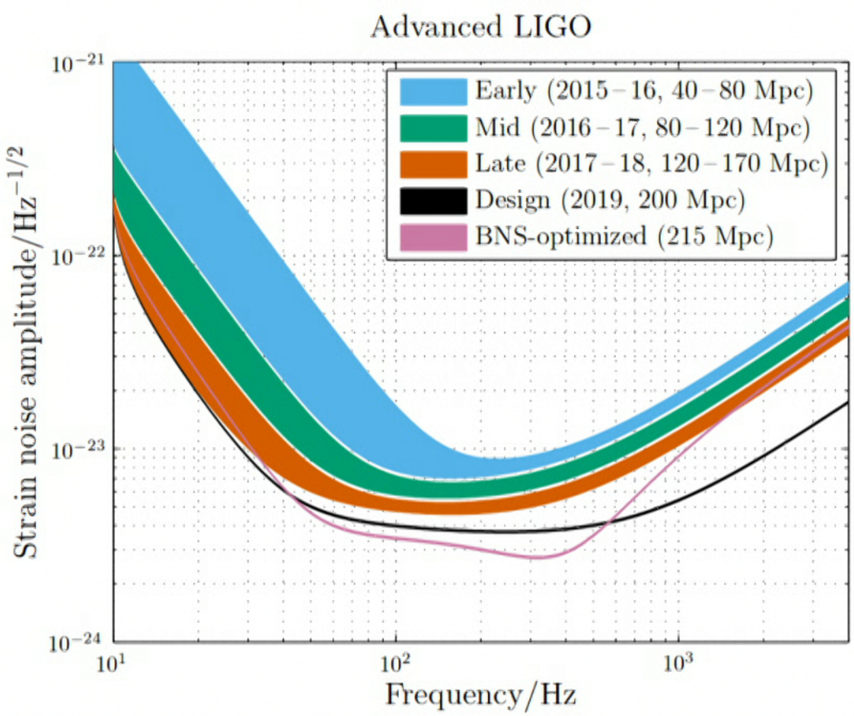
LIGO/VIRGO Collaboration et al. (2017)

A neutron star merger multimessenger signal



LIGO/VIRGO Collaboration et al. (2017)

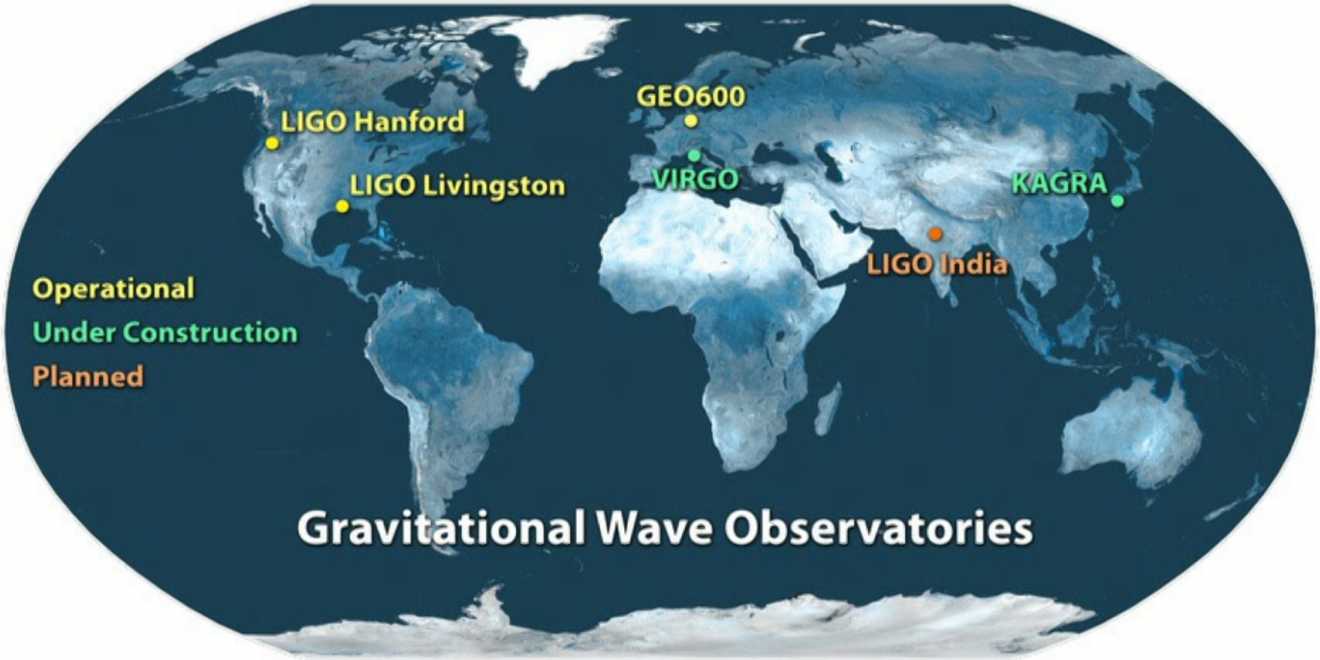
Future is bright



LIGO/VIRGO Collaboration (2016)

Still expect $\sim \times 2$ increase in sensitivity in next couple years

Future is bright



Caltech/MIT/LIGO Lab

Exploring the Dynamics of Spacetime

- How are gravitational waves created?
- How can we maximize what we learn from them?
- What new questions do observations of gravitational waves raise?

Going from. . .

His result, the **Kerr metric**, is given by the following mess:

$$ds^2 = -\left(1 - \frac{2GMr}{\rho^2}\right)dt^2 - \frac{2GMar\sin^2\theta}{\rho^2}(dt\,d\phi + d\phi\,dt)$$
$$+ \frac{\rho^2}{\Delta}dr^2 + \rho^2 d\theta^2 + \frac{\sin^2\theta}{\rho^2}\left[(r^2+a^2)^2 - a^2\Delta\sin^2\theta\right]d\phi^2, \quad (6.70)$$

where

$$\Delta(r) = r^2 - 2GMr + a^2 \quad (6.71)$$

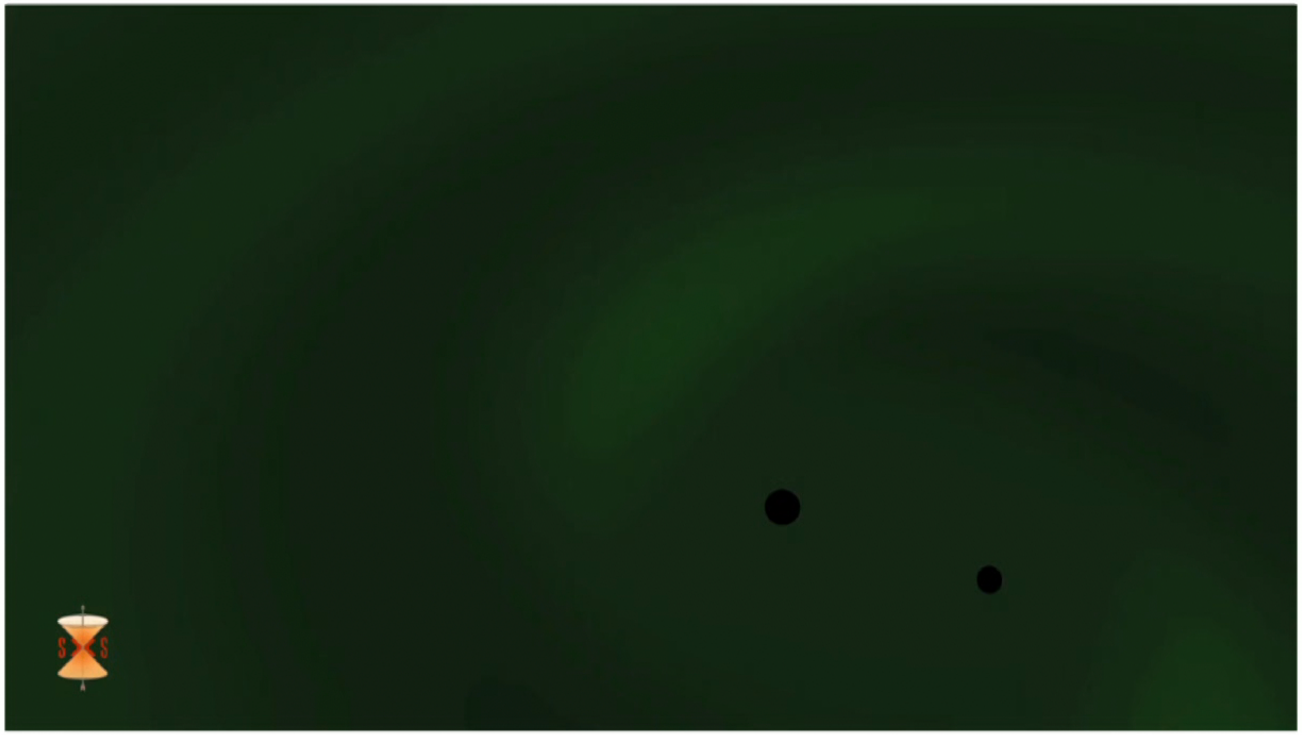
and

$$\rho^2(r,\theta) = r^2 + a^2\cos^2\theta. \quad (6.72)$$

The two constants M and a parameterize the possible solutions. To verify that the

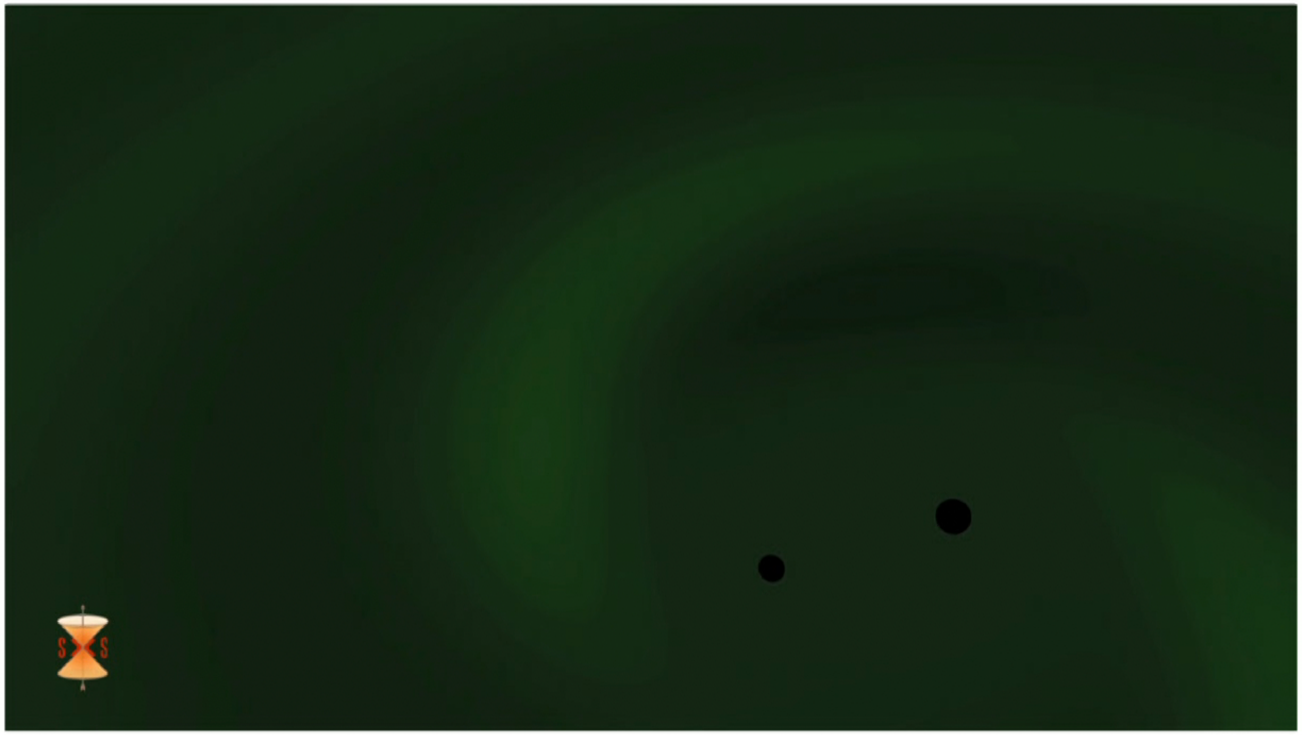
Carroll (2004)

to. . .



SXS Project

to. . .



SXS Project

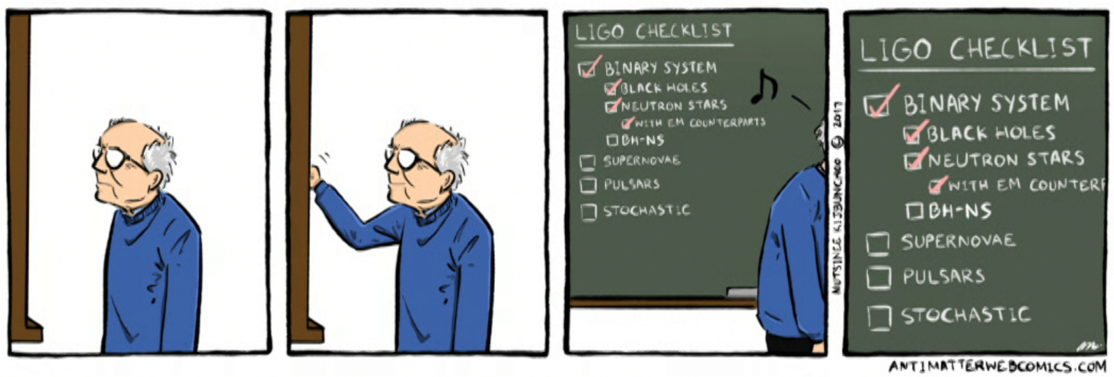
What will LIGO see?

Primary sources are mergers of compact objects:

- Black hole-black hole mergers (Seen at least four so far!)
- Neutron star-neutron mergers (Seen one. . . probably)
- Black hole-neutron star mergers

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?

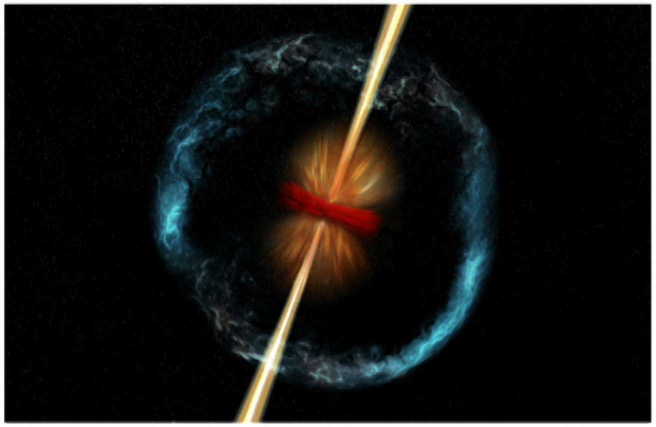
Need to solve Einstein equations for orbiting/merging strongly gravitating systems

- Solutions for 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.

Why the problem is hard

- Einstein field equations are a complex, nonlinear system of partial differential equations
- Have both elliptic (constraint) and hyperbolic (evolution) equations
- Range of length scales: individual compact objects to orbital scale to wave zone
- When coupling to matter, want include lots of physics: hydrodynamics, magnetic fields, radiation transport, etc.

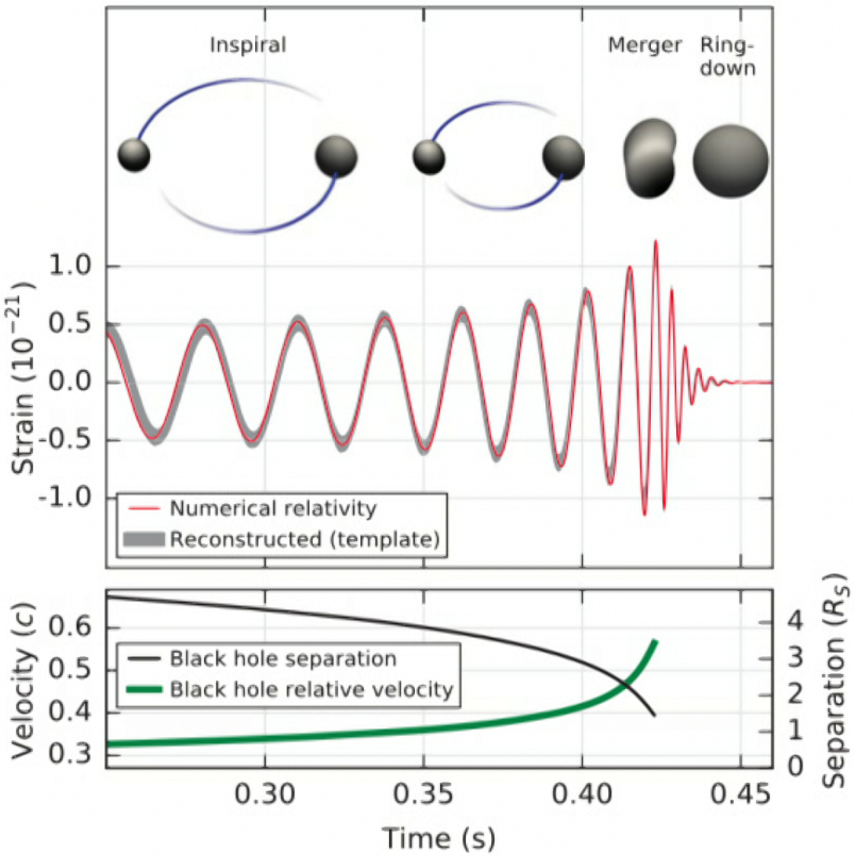


NASA

Three types of compact object mergers

- Black hole-black hole mergers (and using black holes as particle detectors through superradiance)
- Neutron star-neutron mergers
- Black hole-neutron star mergers

Black hole-black hole mergers



September 14th event from LSC/VIRGO 2016

Black holes superradiance

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

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

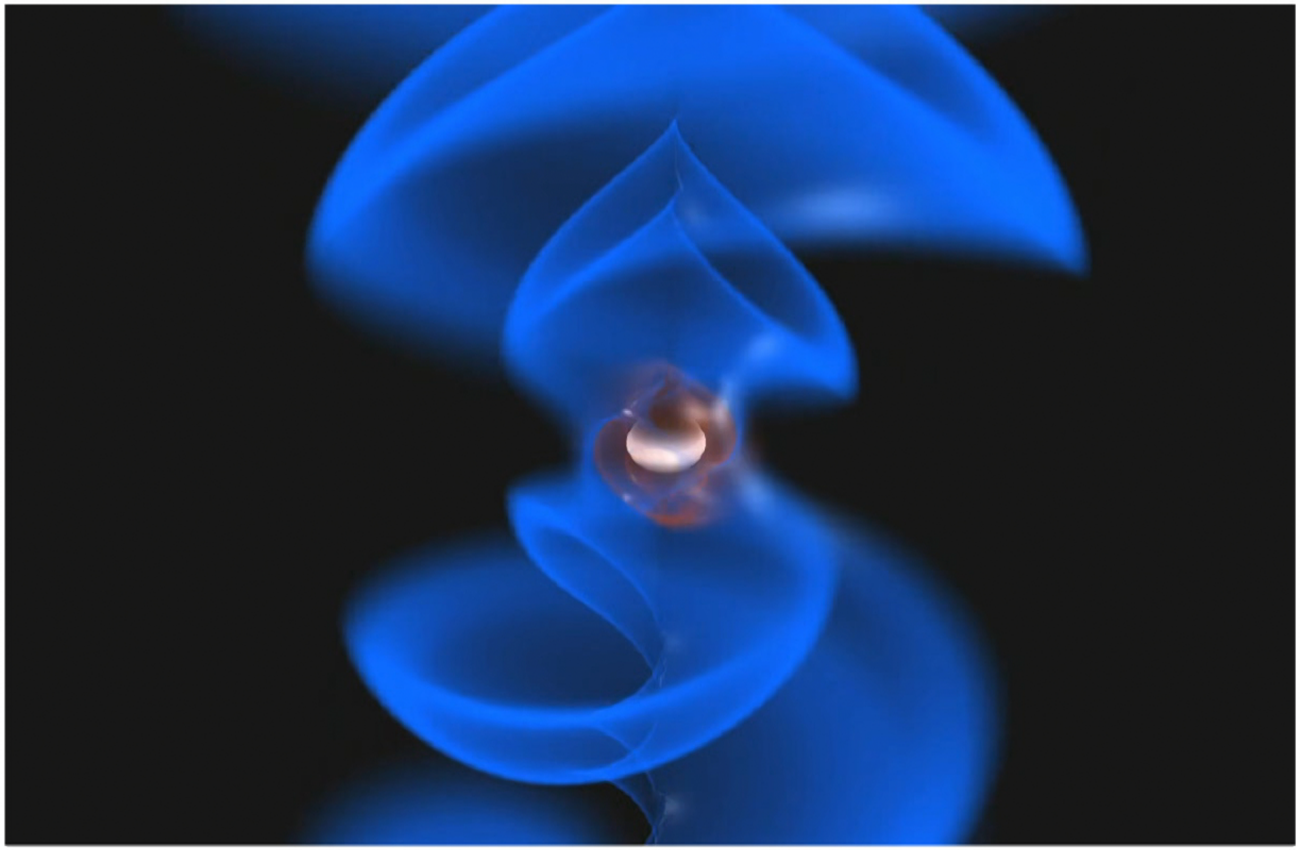
- Black hole thermodynamics:

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

  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! ($E_{\text{rot}} = M - M_{\text{ir}}$)

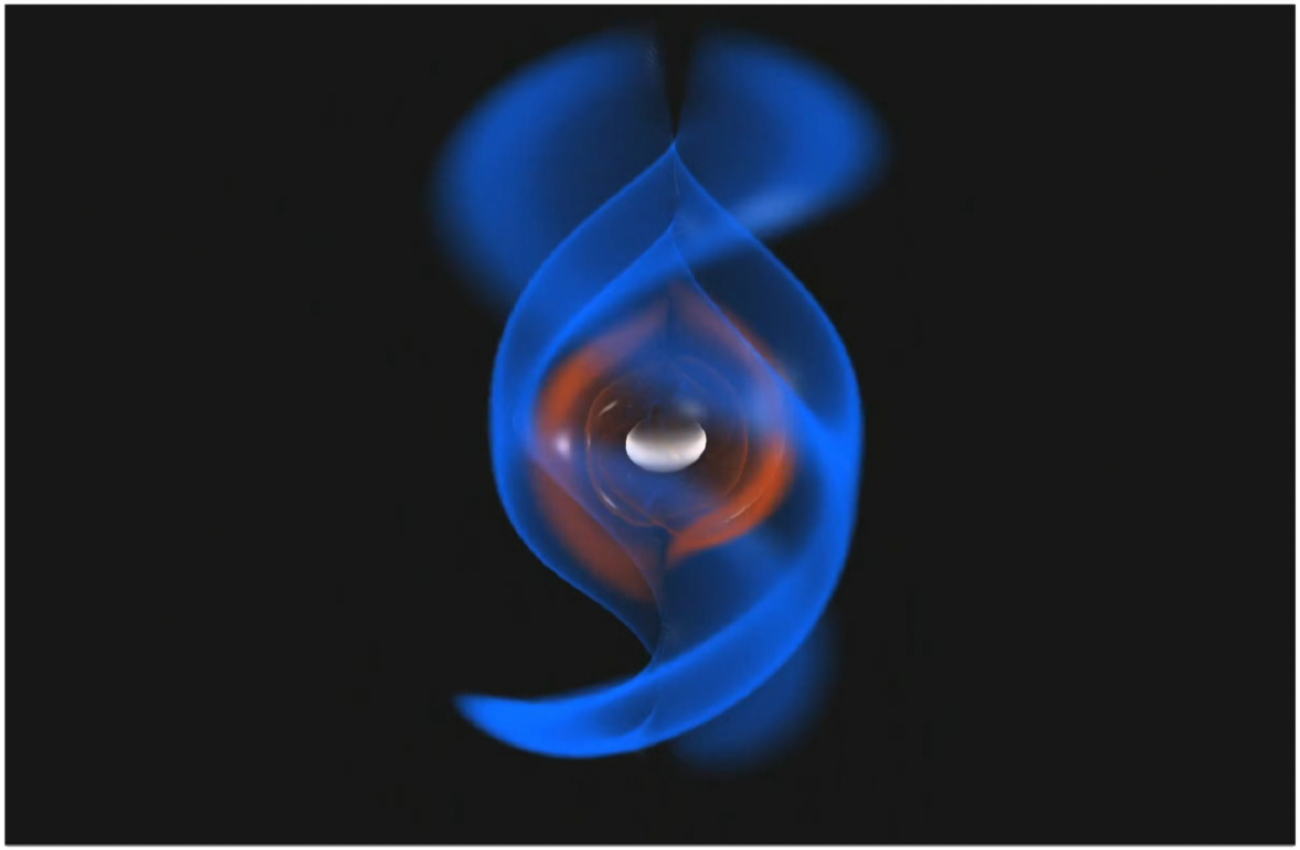
Black holes superradiance



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

East, Ramazanoglu, Pretorius (2013); Visualization: Ralf Kahler

Black holes superradiance



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

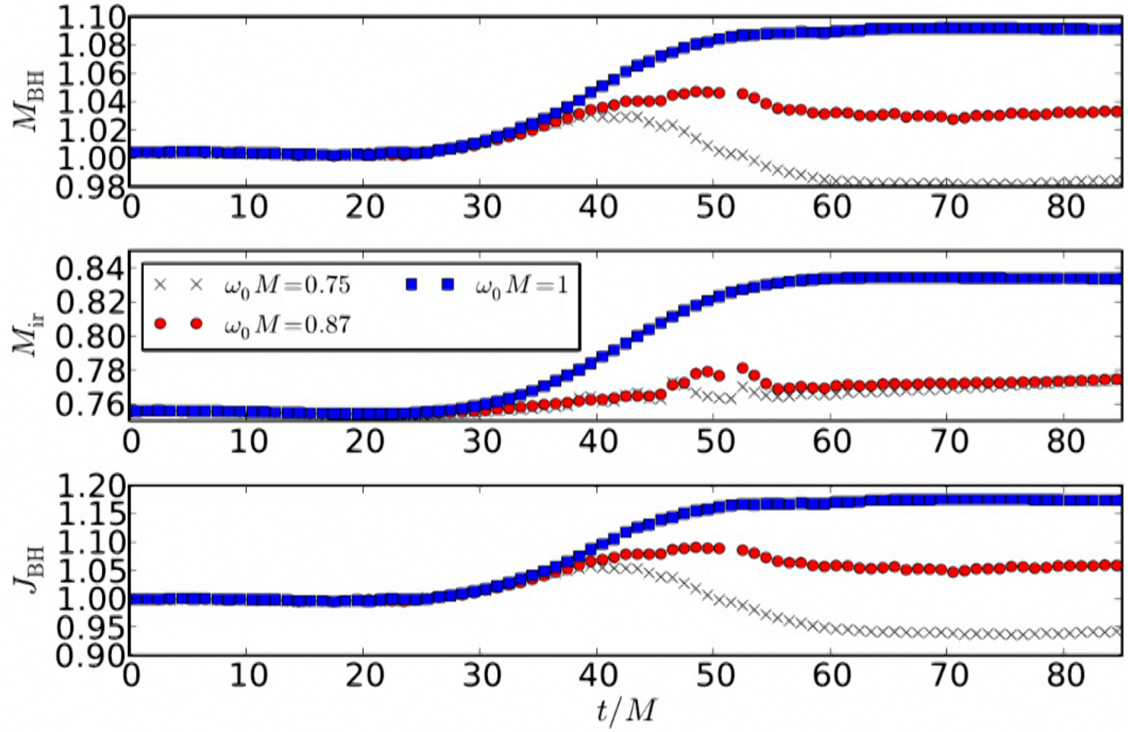
East, Ramazanoglu, Pretorius (2013); Visualization: Ralf Kahler

Black holes superradiance

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

East, Ramazanoglu, Pretorius (2013); Visualization: Ralf Kahler

Liberating energy/angular momentum from a black hole



East, Ramazanoglu & Pretorius (2013)

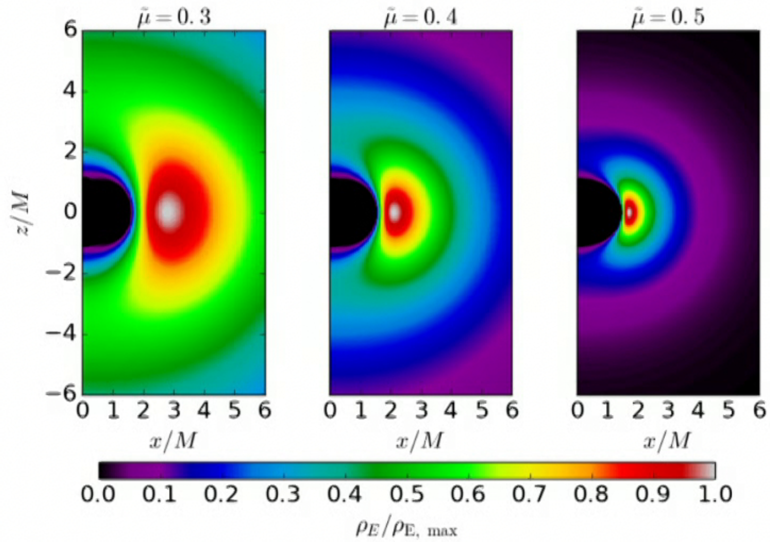
Black hole bomb

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

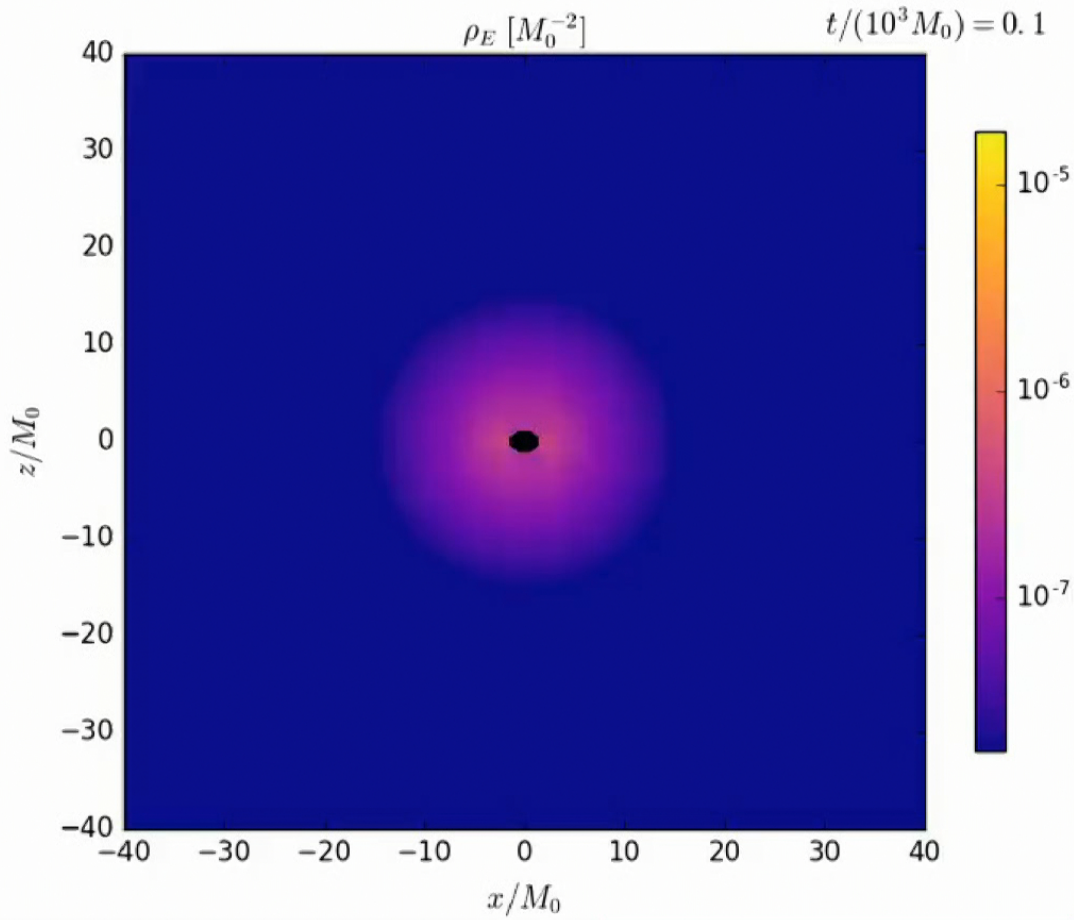
. . . create a black hole bomb. (Press & Teukolosky 1972)

Superradiant instability: realizing the black hole bomb

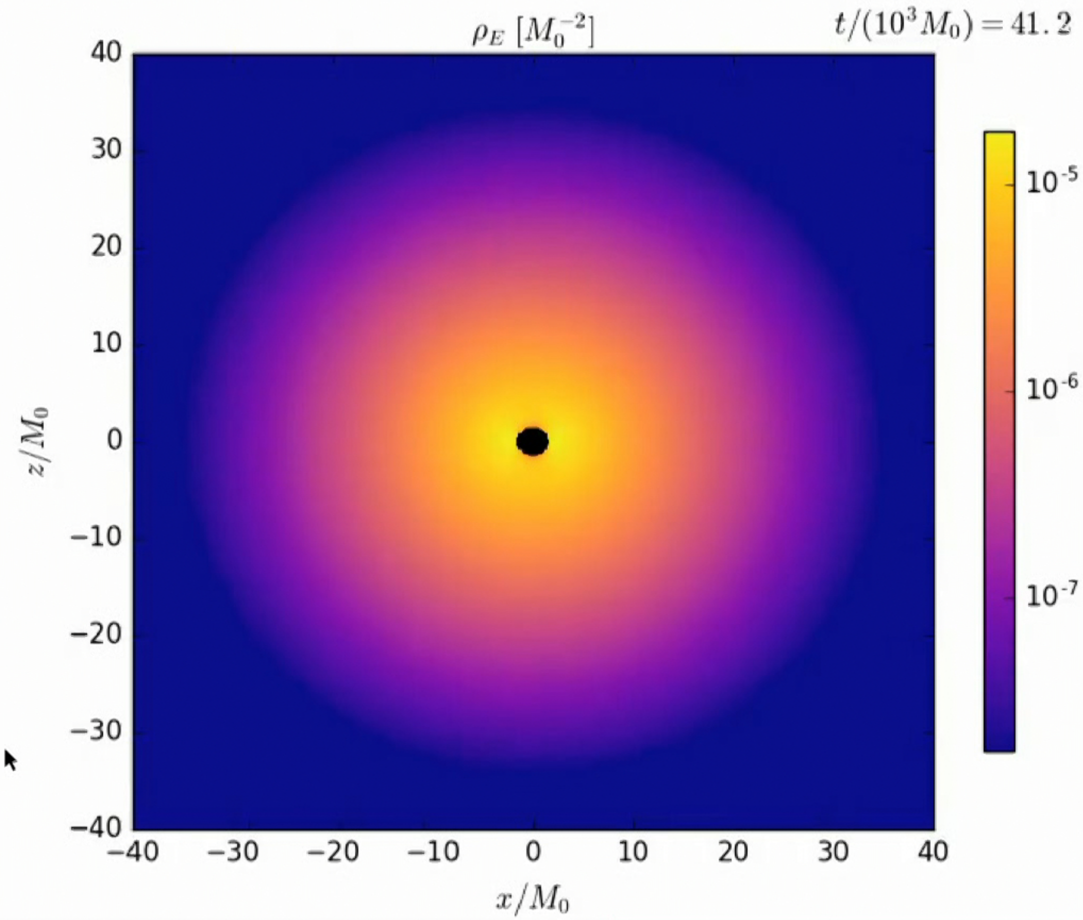
- **Massive** bosons can form bound states, when frequency $\omega < m\Omega_H$ grow exponentially in time.
- Search for new ultralight bosonic particles (axions, dark massive "photons," etc.) with Compton wavelength comparable to black hole radius (Arvanitaki et al.)



Massive vector field energy density

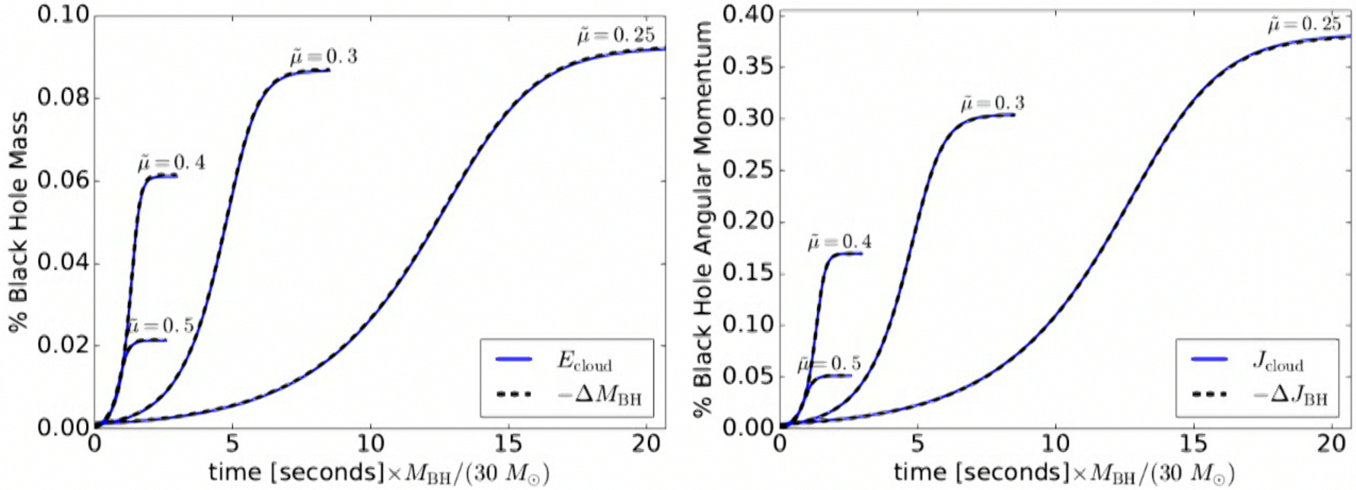


Massive vector field energy density



Superradiant instability: spinning down a black hole

Black hole with initial spin $a = 0.99$.

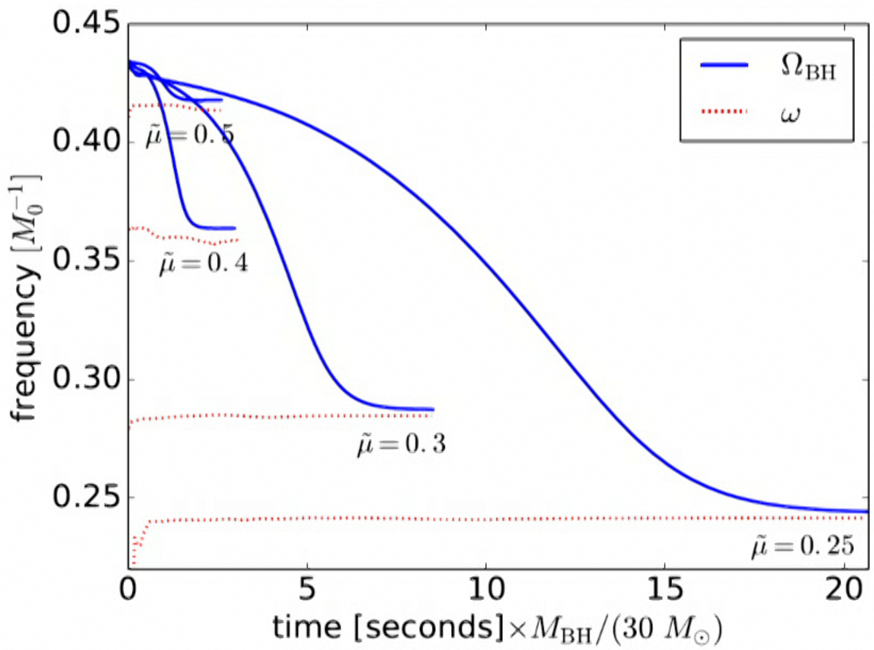


East & Pretorius (2017)

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

Superradiant instability: spinning down a black hole

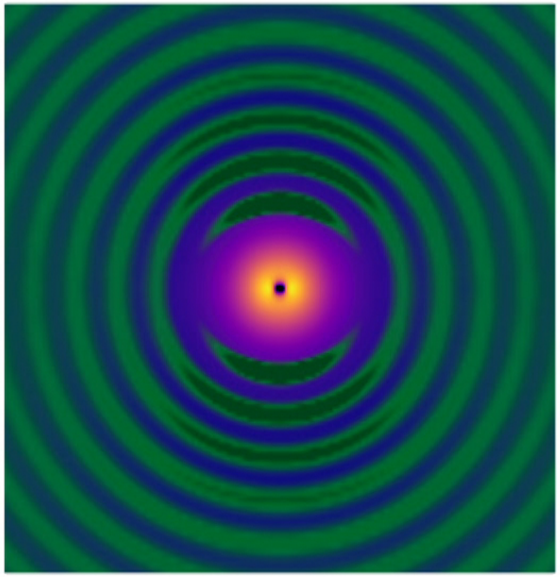
Black hole with initial spin $a = 0.99$.



East & Pretorius (2017)

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

Boson clouds emit gravitational waves



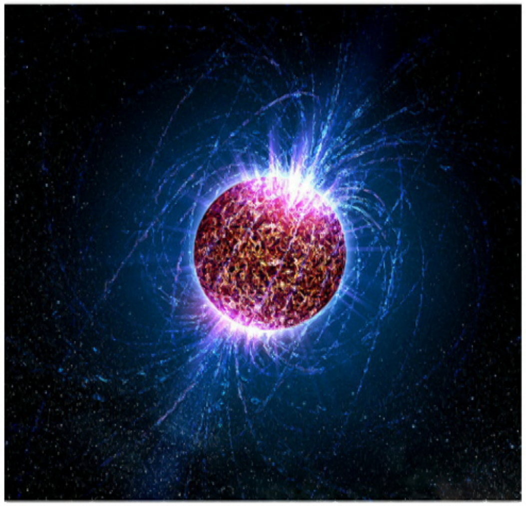
East (2017)

- Monochromatic with $f_{\rm GW} \approx 650$ Hz $\times(\tilde{\mu}/0.3)(30M_\odot/M_{\rm BH})$.
- Look for either stochastic or resolved sources with LIGO (Baryakthar et al. 2017; Brito et al. 2017)
- Indirect probe: Use black hole spin measurements from GWs or accretion disks (Arvanitaki et al. 2015, 2017)

Neutron star mergers

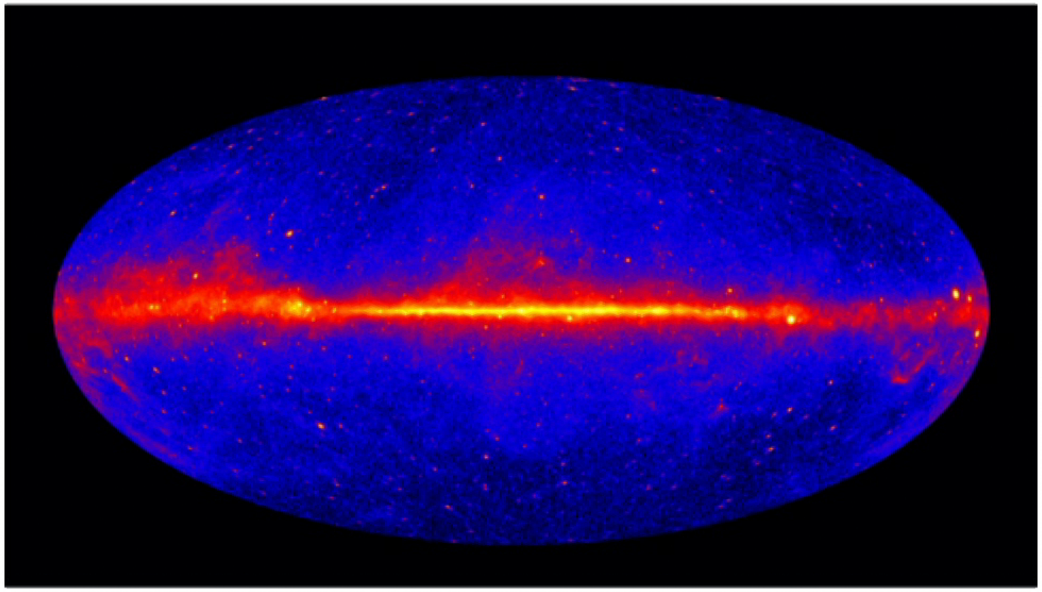
With matter things get even more interesting.

- Neutron stars are suspected to be responsible for a host of electromagnetic signals
- Gravitational waves could be the "sound" to go with the light (radio, optical, X-ray, gamma-ray observations. . .). Concurrent observations with range of telescopes.



Reed

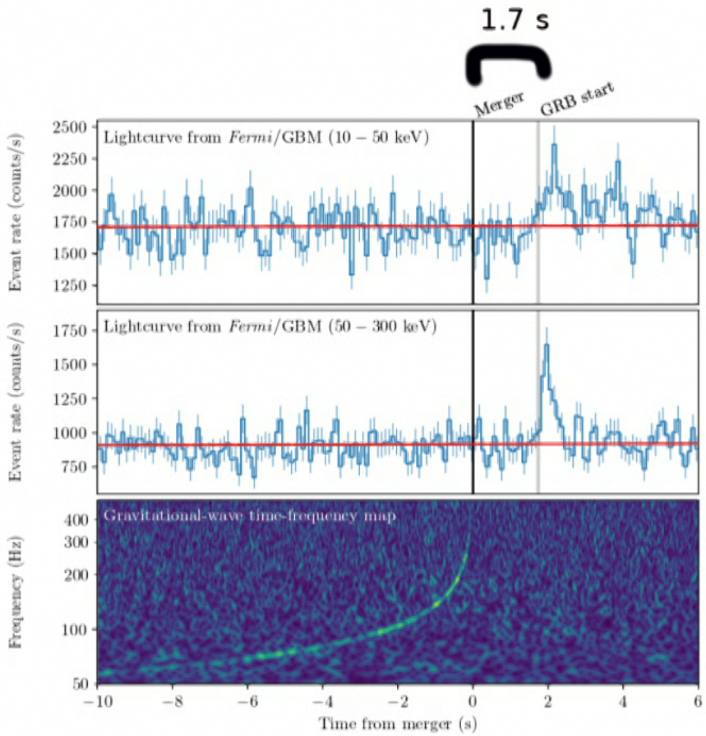
The mystery of short gamma-ray bursts



NASA/DOE/Fermi LAT Collaboration

- Are neutron star mergers the source of gamma-ray bursts seen by telescopes?
- Viability depends on details of merger
- Simultaneous detection of gravitational wave is "smoking gun"

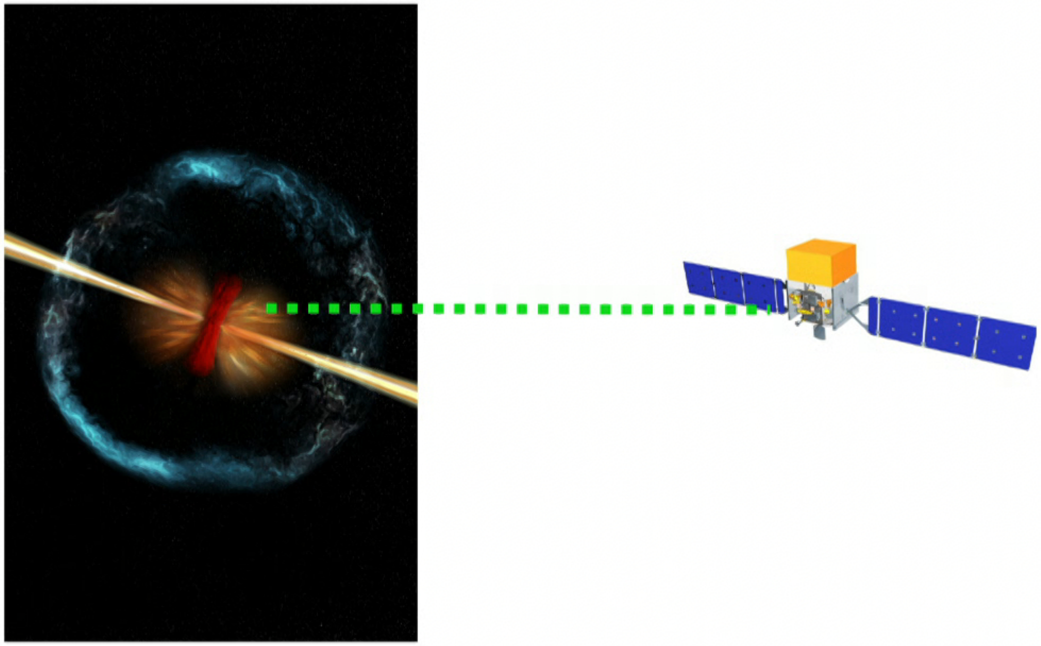
Coincident detection of gamma ray burst and gravitational wave



LIGO/VIRGO Collaboration et al. (2017)

- Are binary neutron star mergers a source or **the** source?
- What causes the 1.7 second delay?
- Why haven't we seen a sGRB this close before?

Coincident detection of gamma ray burst and gravitational wave



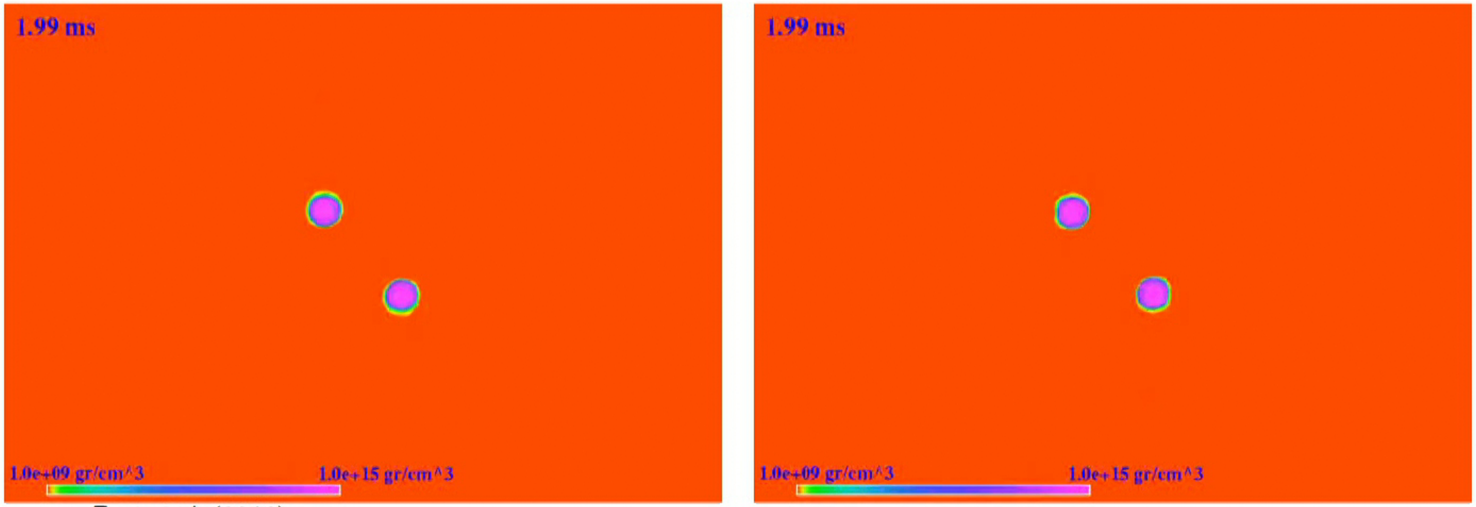
NASA

- Why is the sGRB so weak?
- What is the underlying mechanism of the burst?

Learning Nuclear Physics

- Neutron stars have incredible densities: $\sim 10^{15}$ g/cm^3
- The (unknown) behavior of matter at these densities—the equation of state—impacts the dynamics and outcome of neutron star mergers

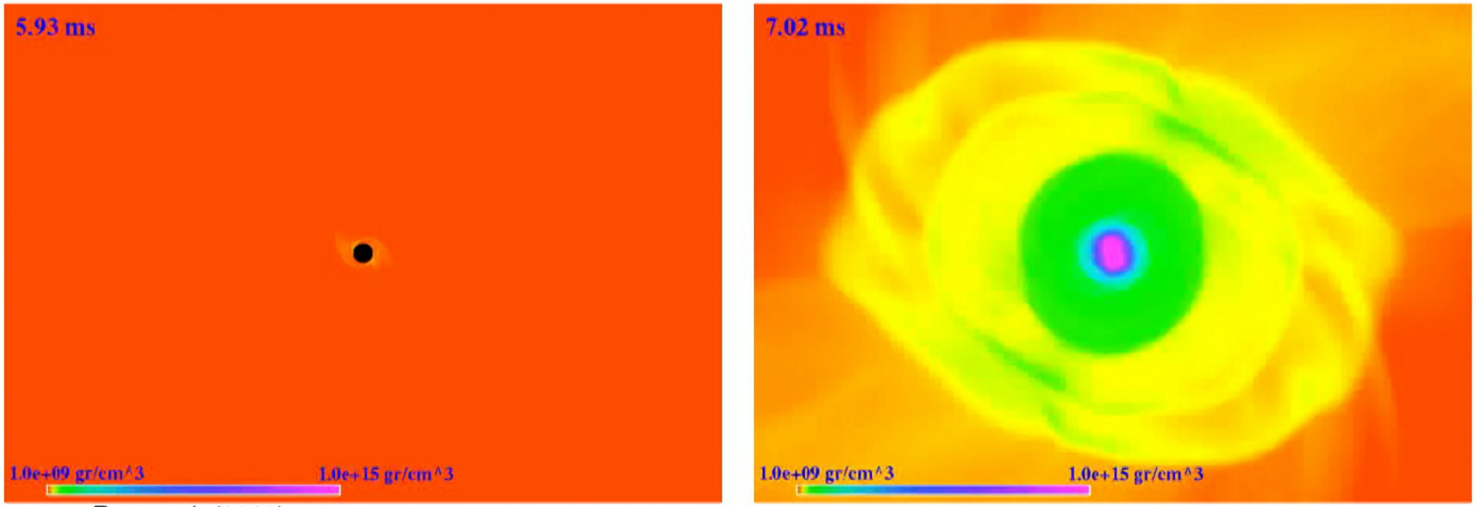
Collapse to black hole versus forming a hypermassive neutron star



East et al. (2016)

Depends on size, spin, unknown nuclear physics, etc.

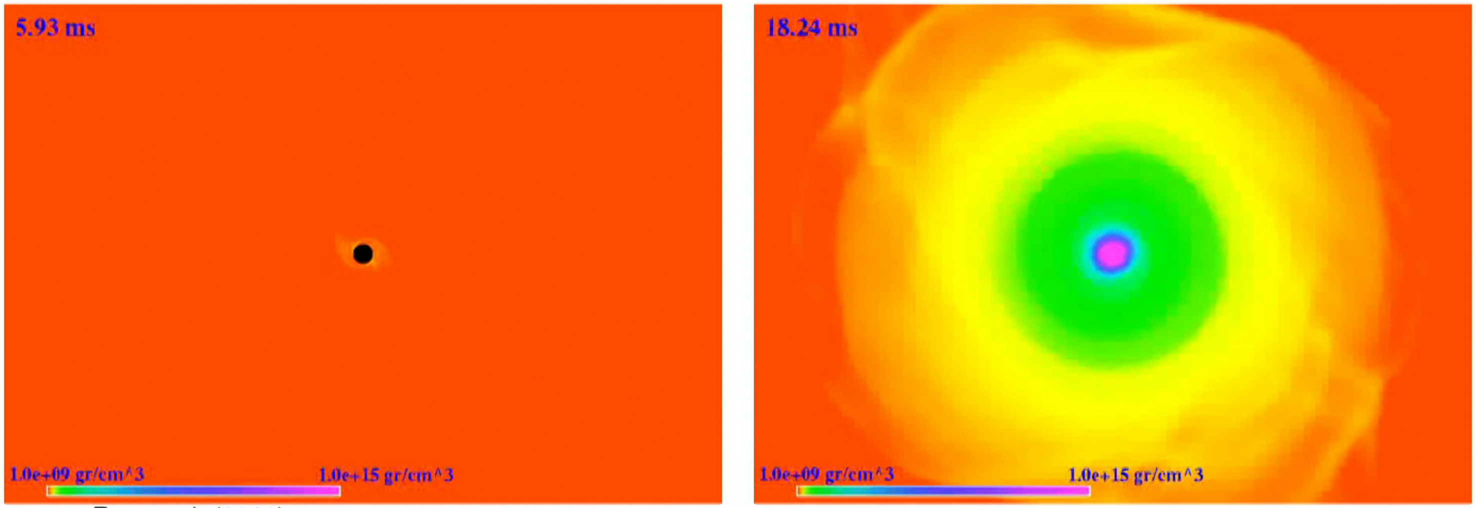
Collapse to black hole versus forming a hypermassive neutron star



East et al. (2016)

Depends on size, spin, unknown nuclear physics, etc.

Collapse to black hole versus forming a hypermassive neutron star

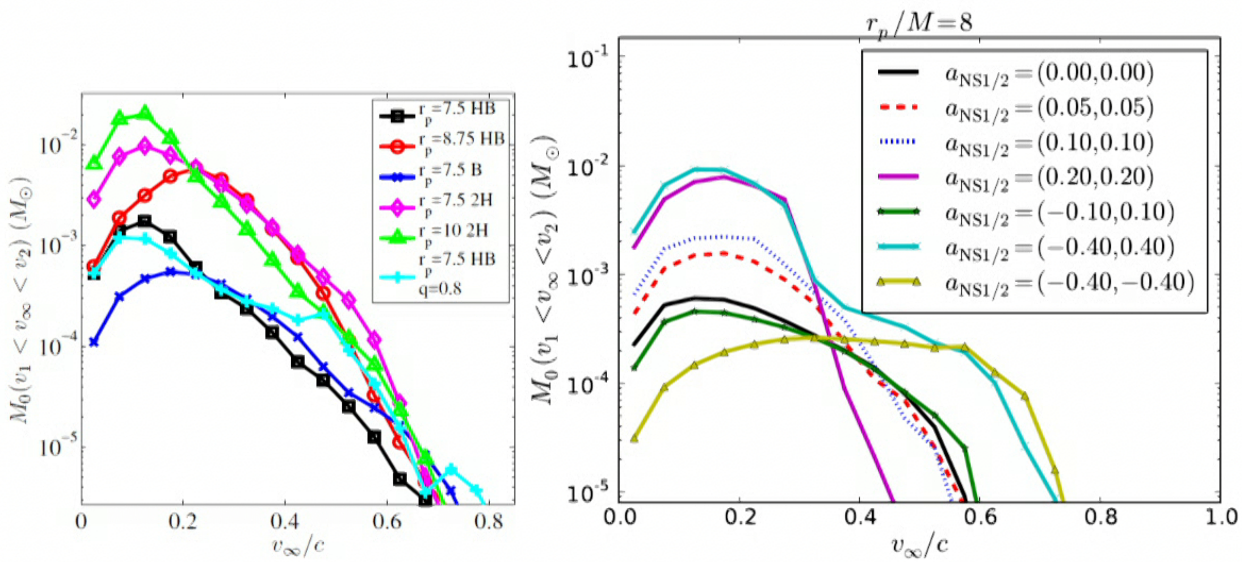


East et al. (2016)

Depends on size, spin, unknown nuclear physics, etc.

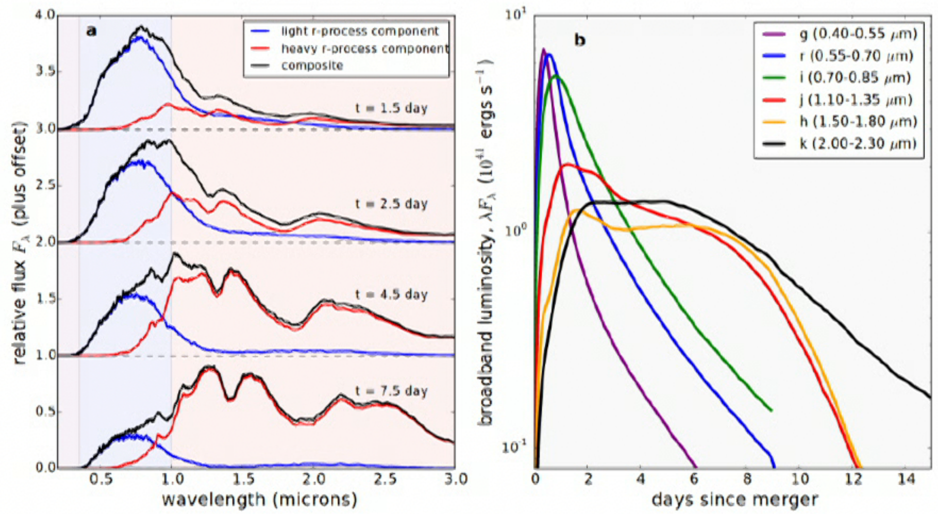
Neutron Star Mergers: Unbound material

Roughly 10^{-2} to 10^{-3} $M_\odot$ but varies with mass-ratio, neutron star radius, spin, ...



East & Pretorius (2012); East et al. (2016)

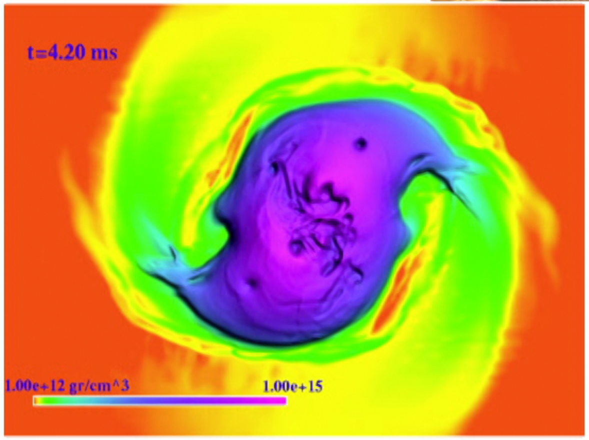
Kilonovae



Kasen et al. (2017)

- Larger than expected ejected mass?
- Dynamically ejected versus material from wind from post-merger accretion disk?

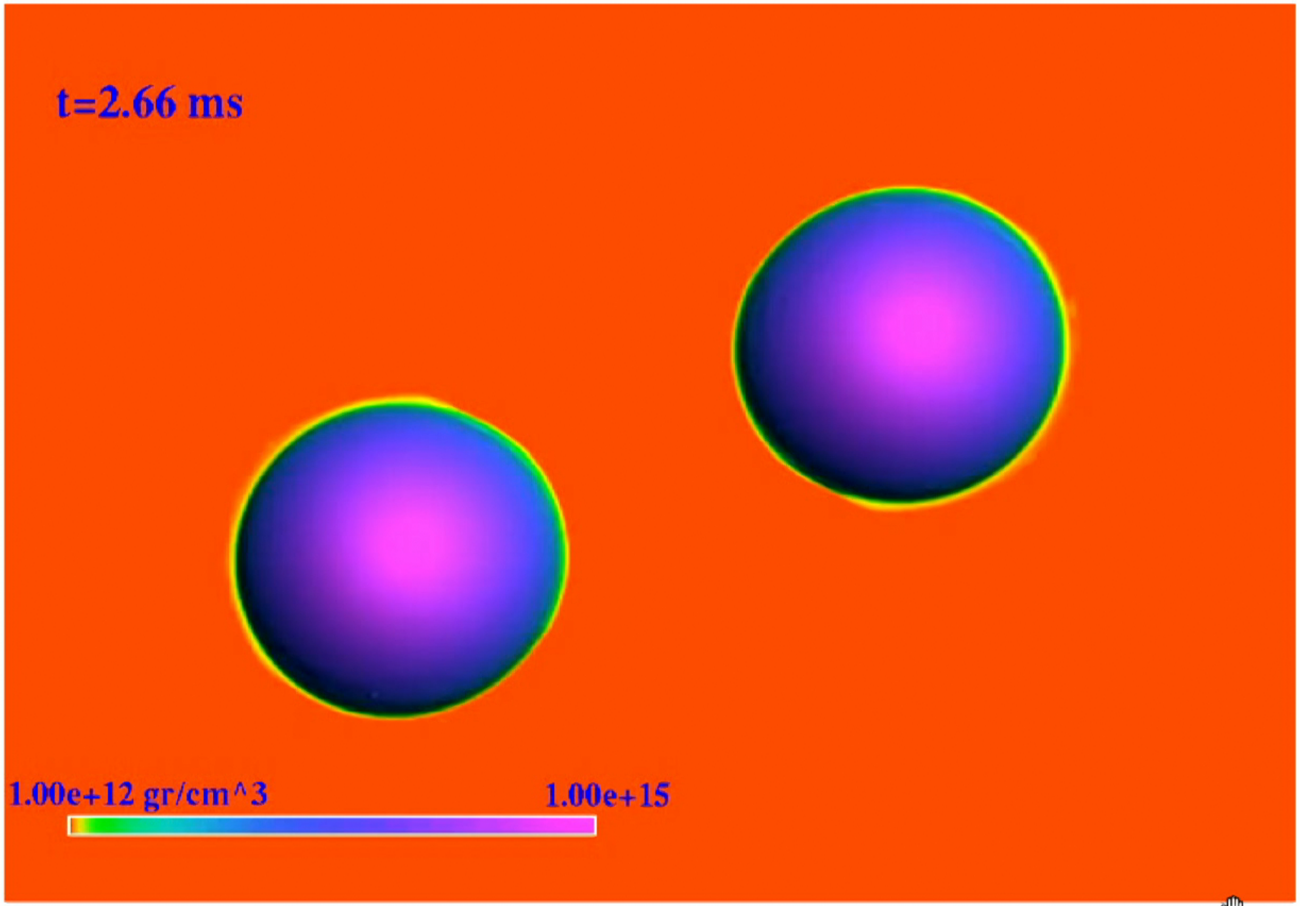
Neutron Star Mergers = Gold?



or

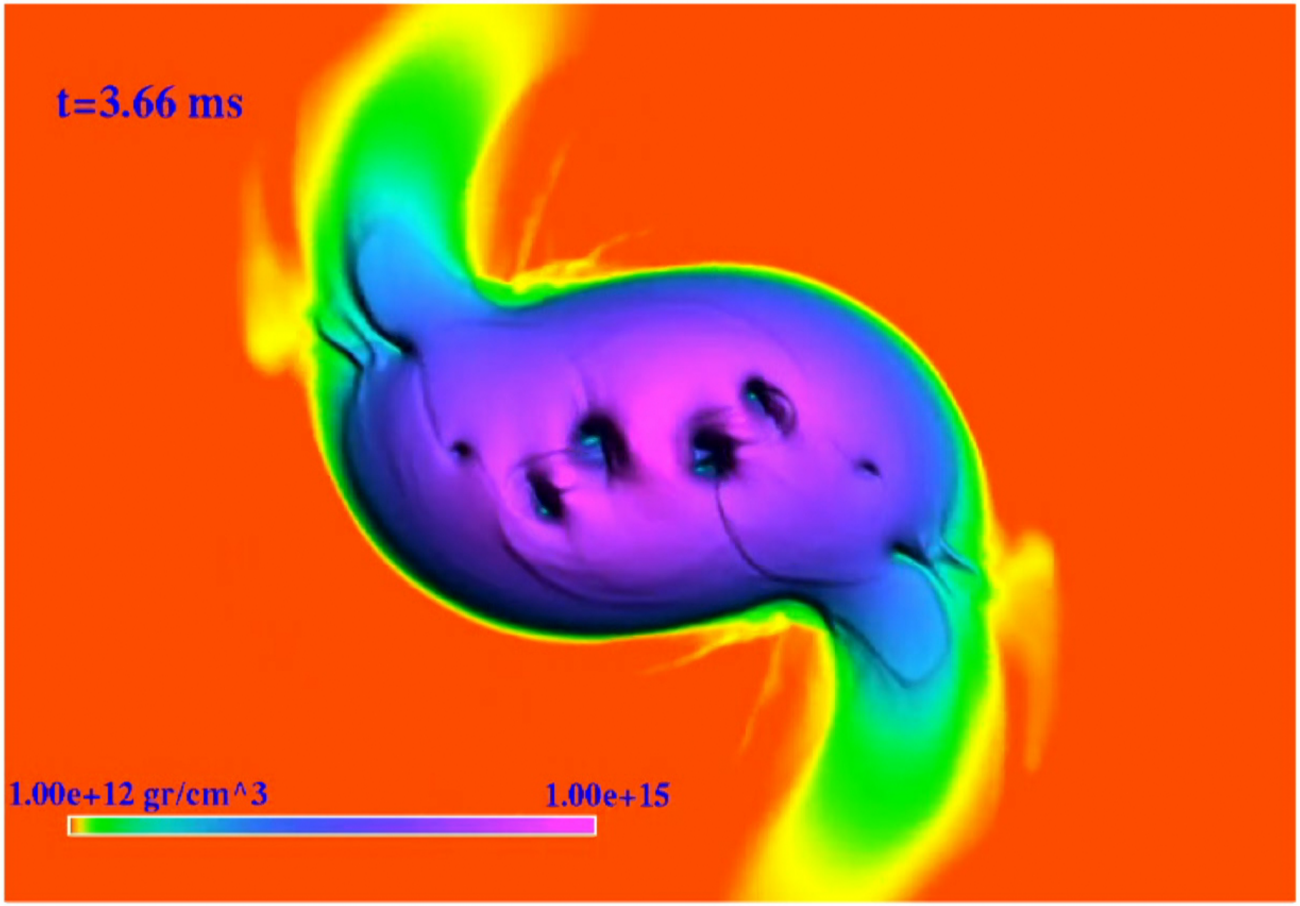
?

Neutron stars merge



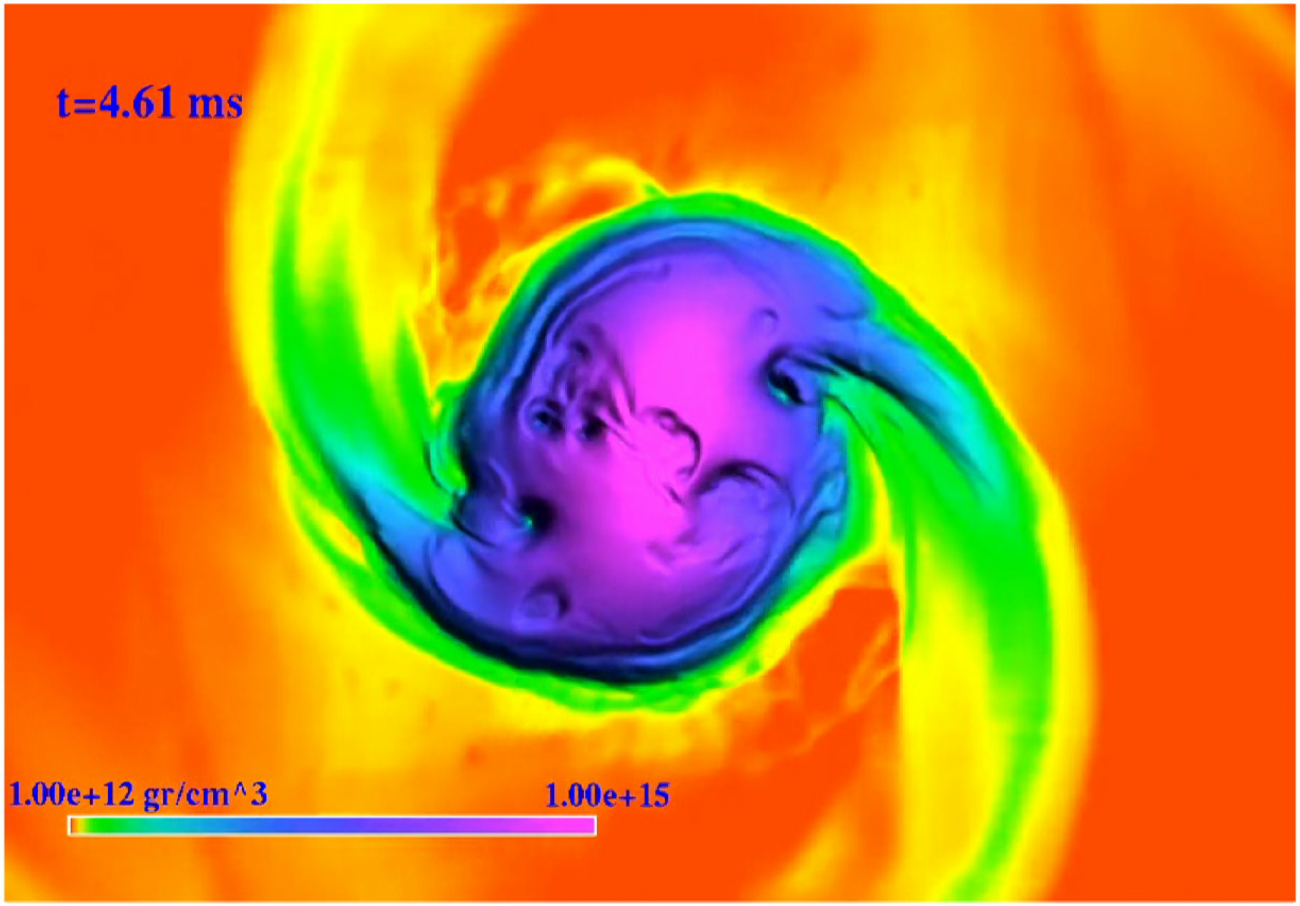
East et al. (2016)

Neutron stars merge



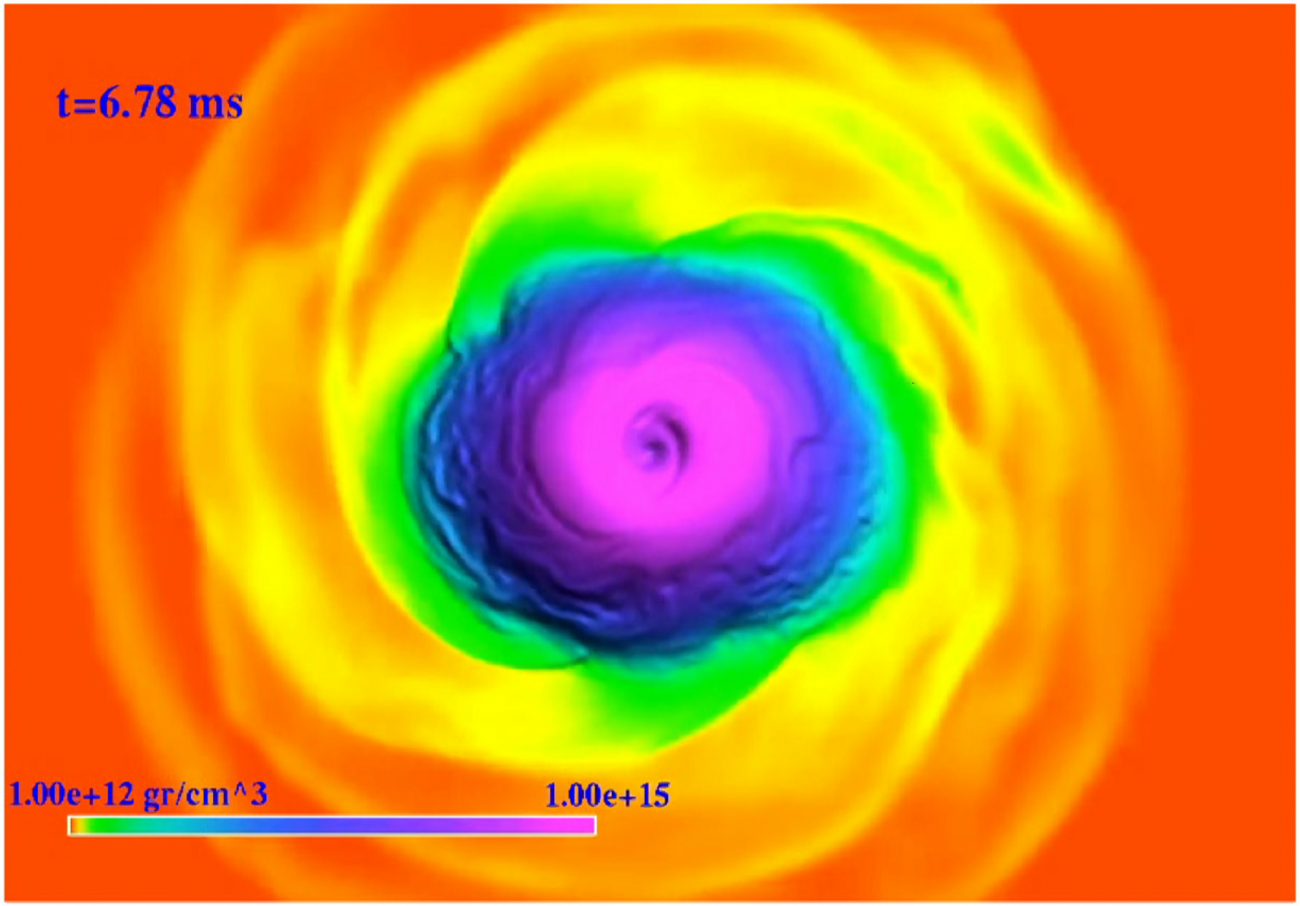
East et al. (2016)

Neutron stars merge



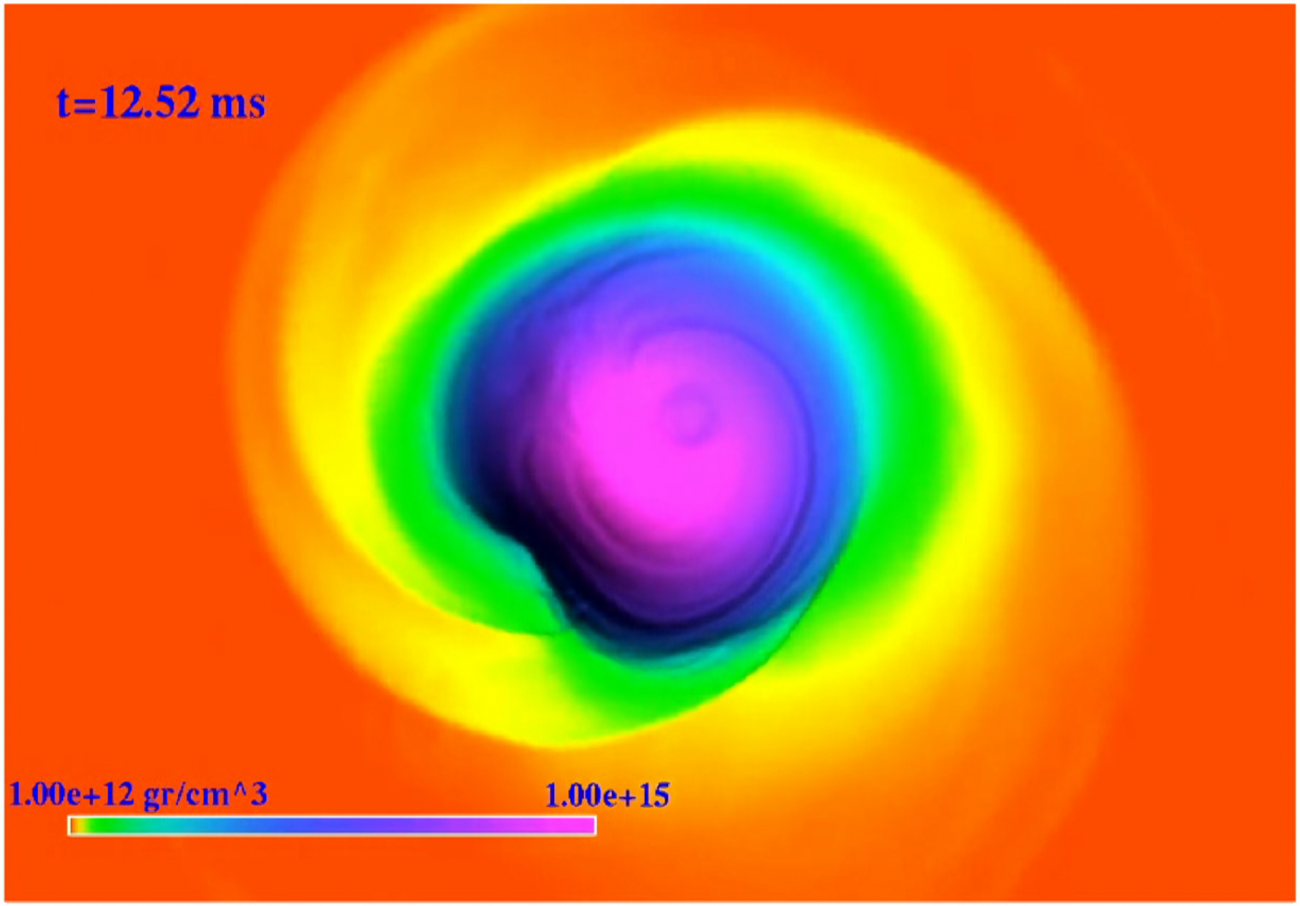
East et al. (2016)

Neutron stars merge



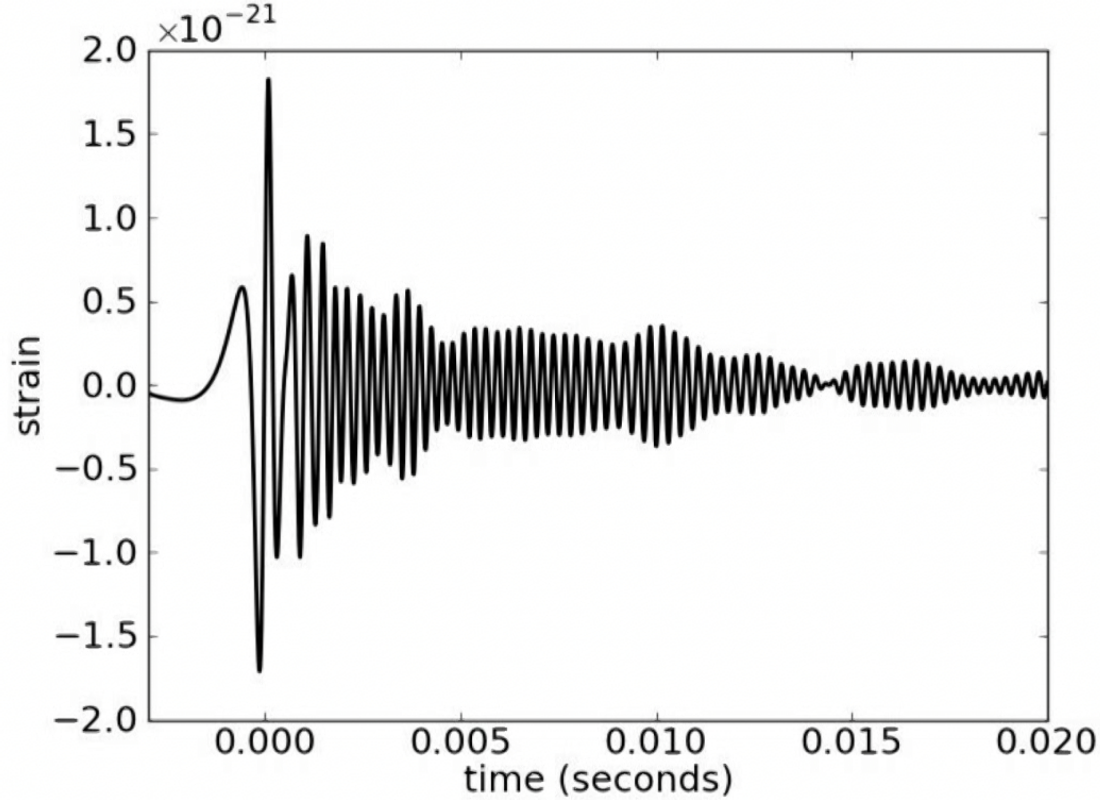
East et al. (2016)

Neutron stars merge

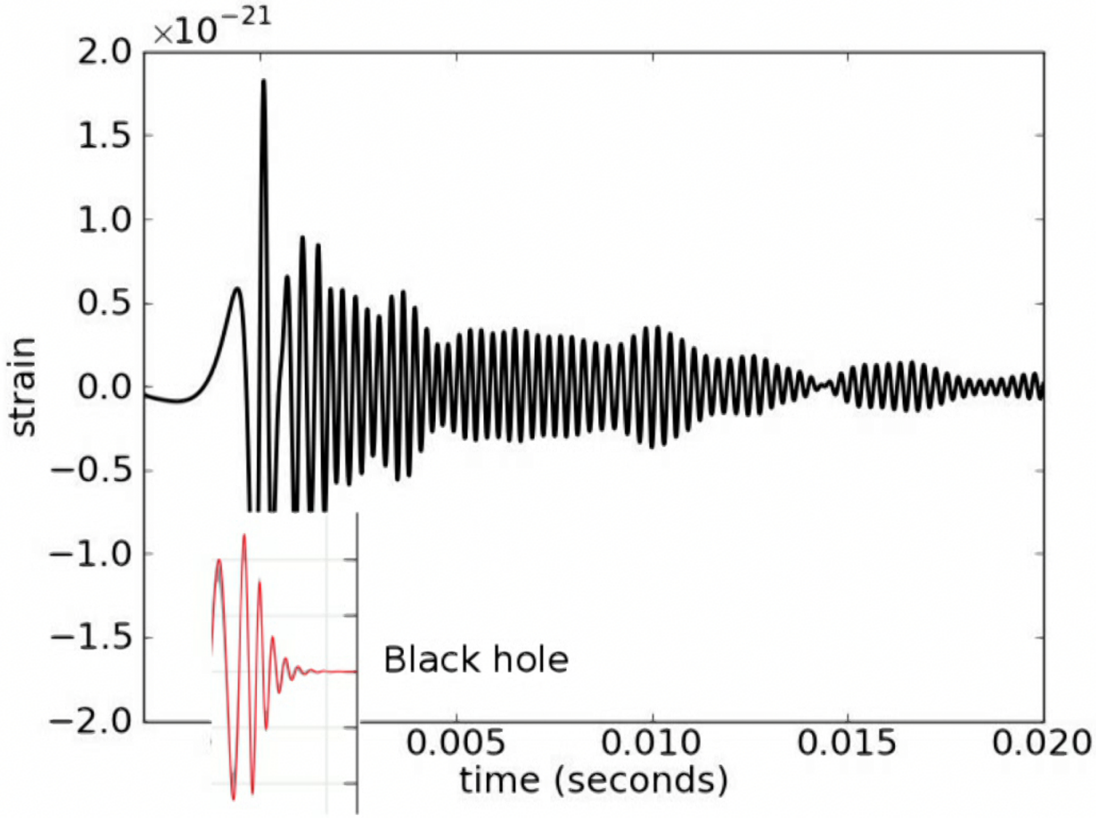


East et al. (2016)

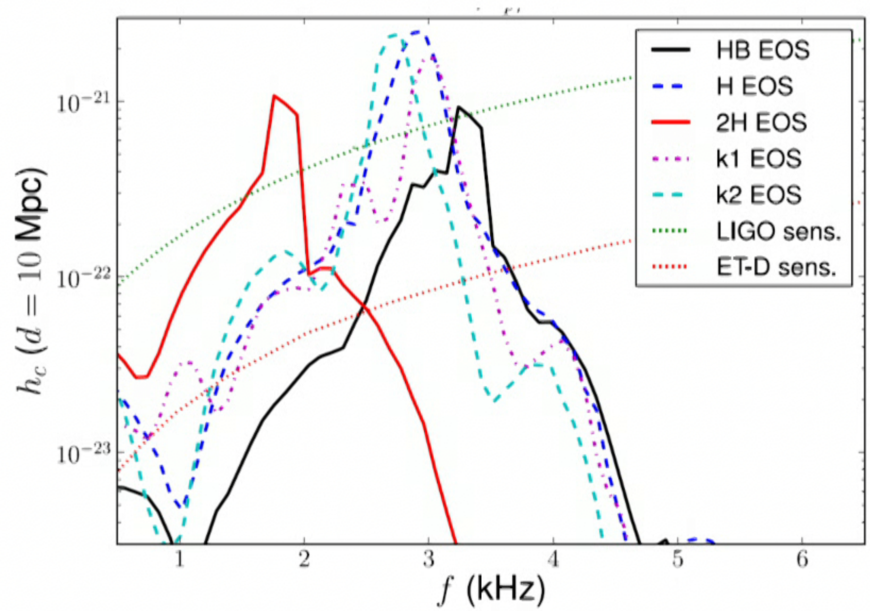
Gravitational waves from hypermassive neutron stars



Gravitational waves from hypermassive neutron stars



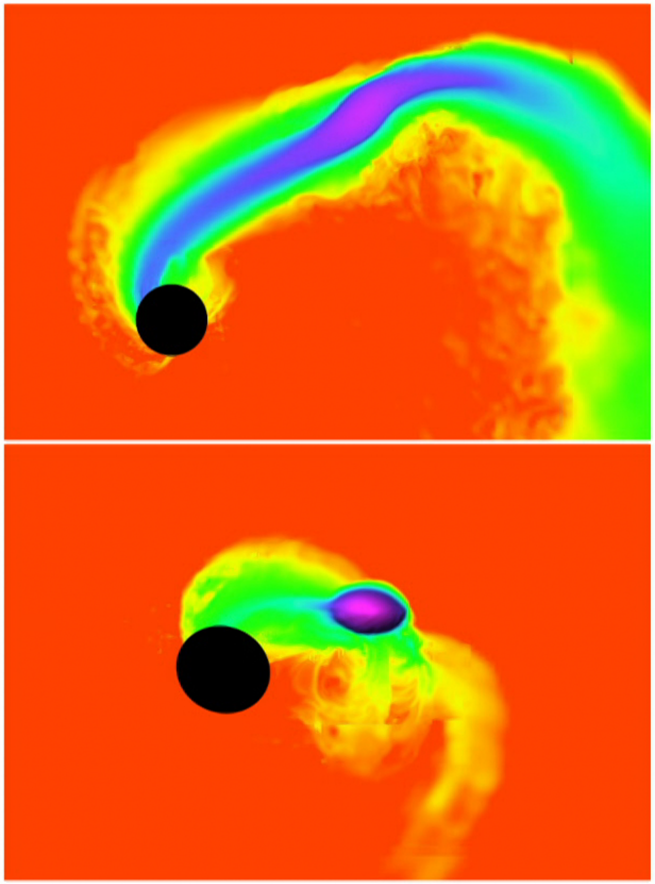
Gravitational waves from hypermassive neutron stars



East, Paschalidis & Pretorius (2016)

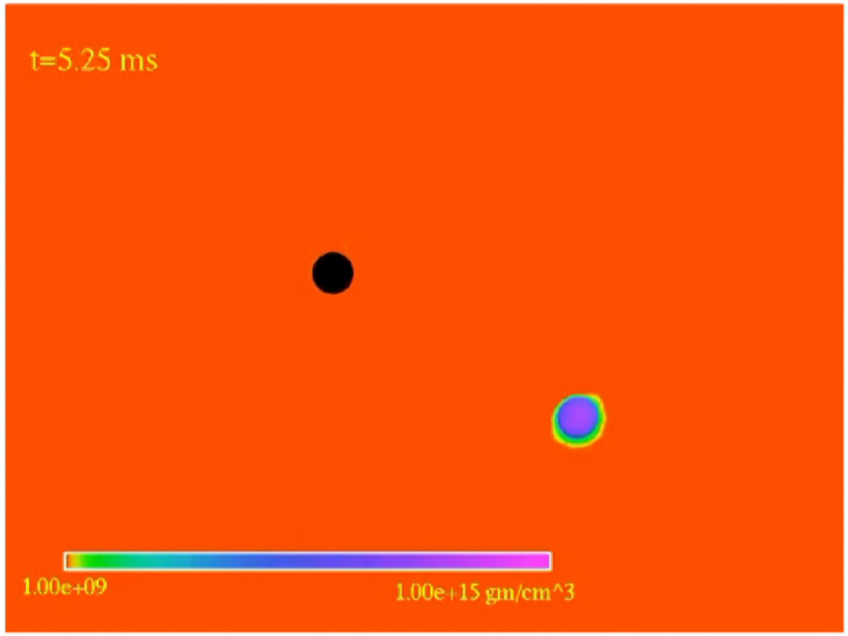
For $t_{\rm HMNS} \approx 10$ ms; Encodes information about equation of state.

Black hole-neutron star mergers



- Can also form black hole accretion disks and eject material
- Depends if star is disrupted outside innermost stable orbit of black hole
- More variation (with mass-ratio, spin, equation of state, etc.)

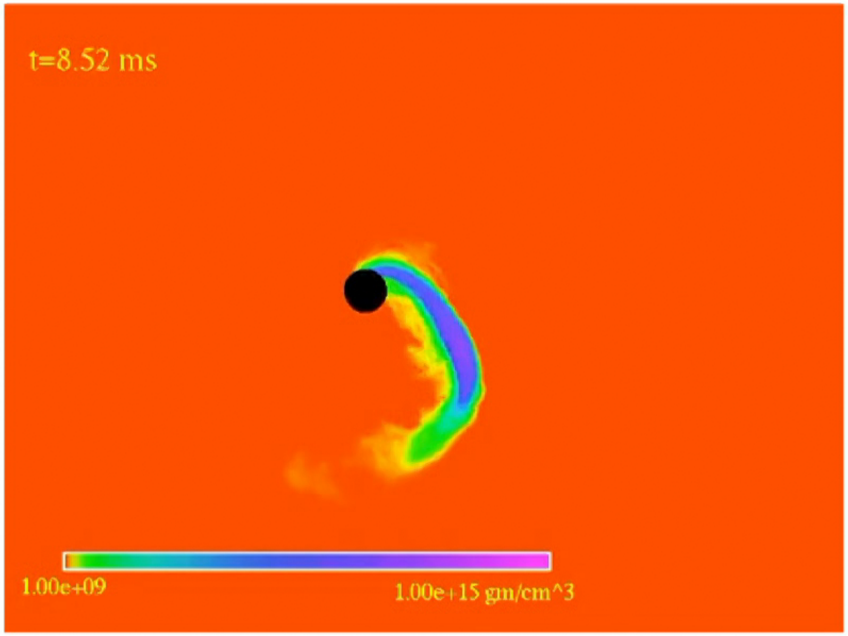
Black hole-neutron star mergers



East, Stephens & Pretorius (2012)

Tidal disruption in action.

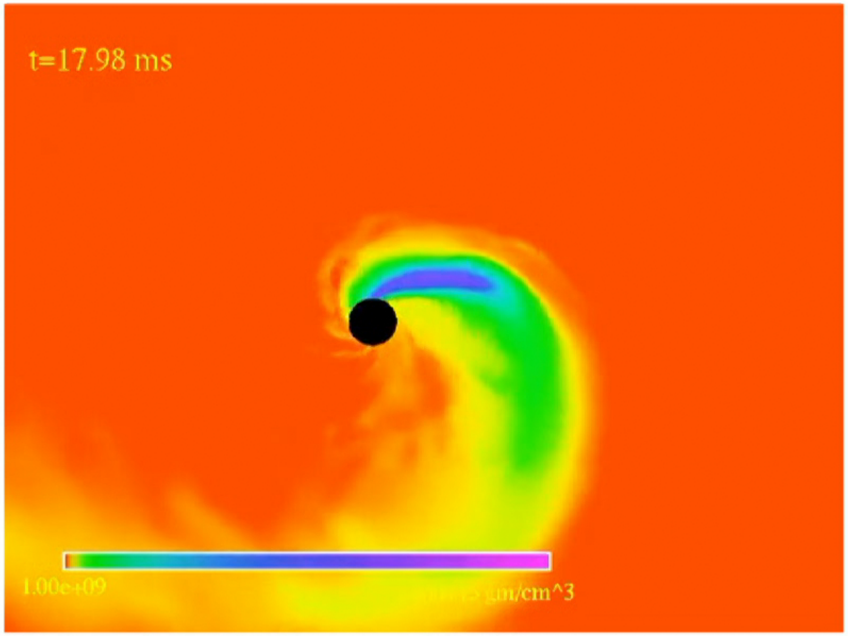
Black hole-neutron star mergers



East, Stephens & Pretorius (2012)

Tidal disruption in action.

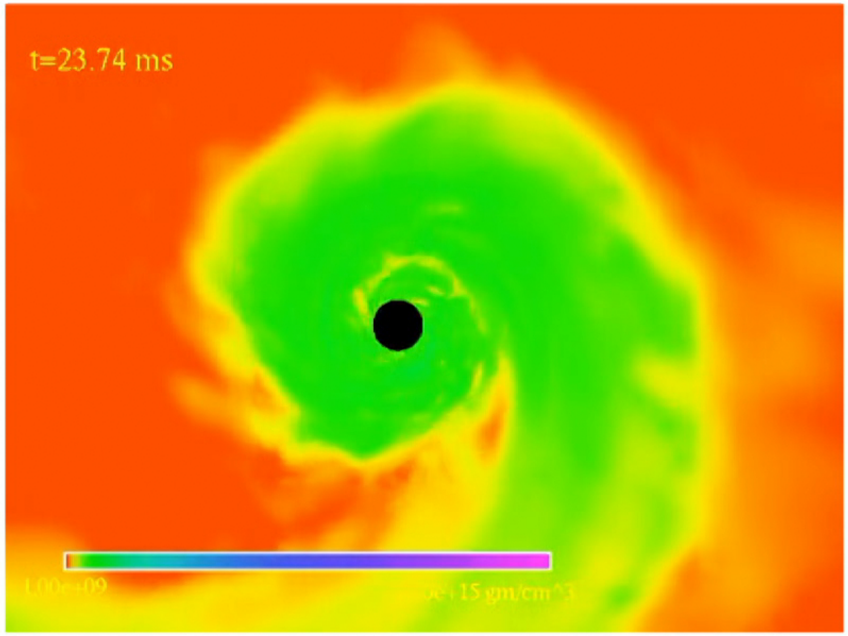
Black hole-neutron star mergers



East, Stephens & Pretorius (2012)

Tidal disruption in action.

Black hole-neutron star mergers



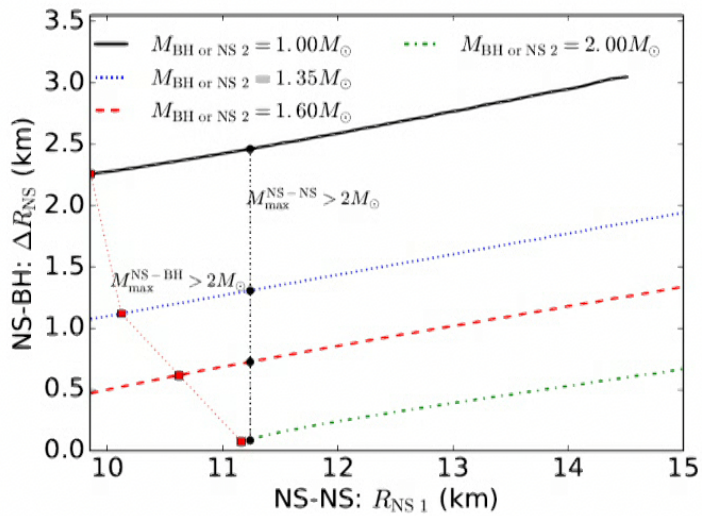
East, Stephens & Pretorius (2012)

Tidal disruption in action.

Binary neutron star merger or black hole-neutron star merger

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

Distinguishing low mass black holes in neutron star mergers

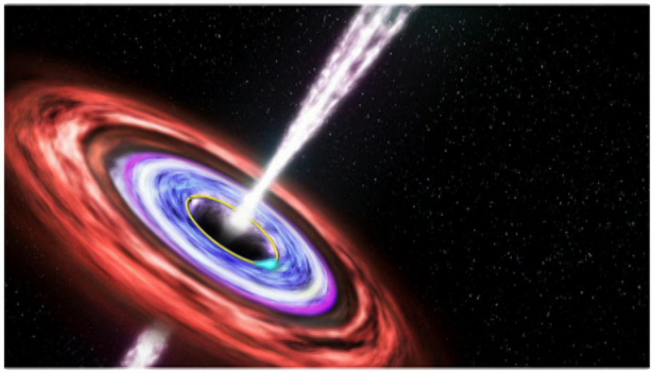


Yang, East & Lehner (2017)

- Leading order tidal effects are degenerate with uncertainty in equation of state
- Electromagnetic transients may be different, but not well enough understood

Challenges in age of multimessenger astronomy

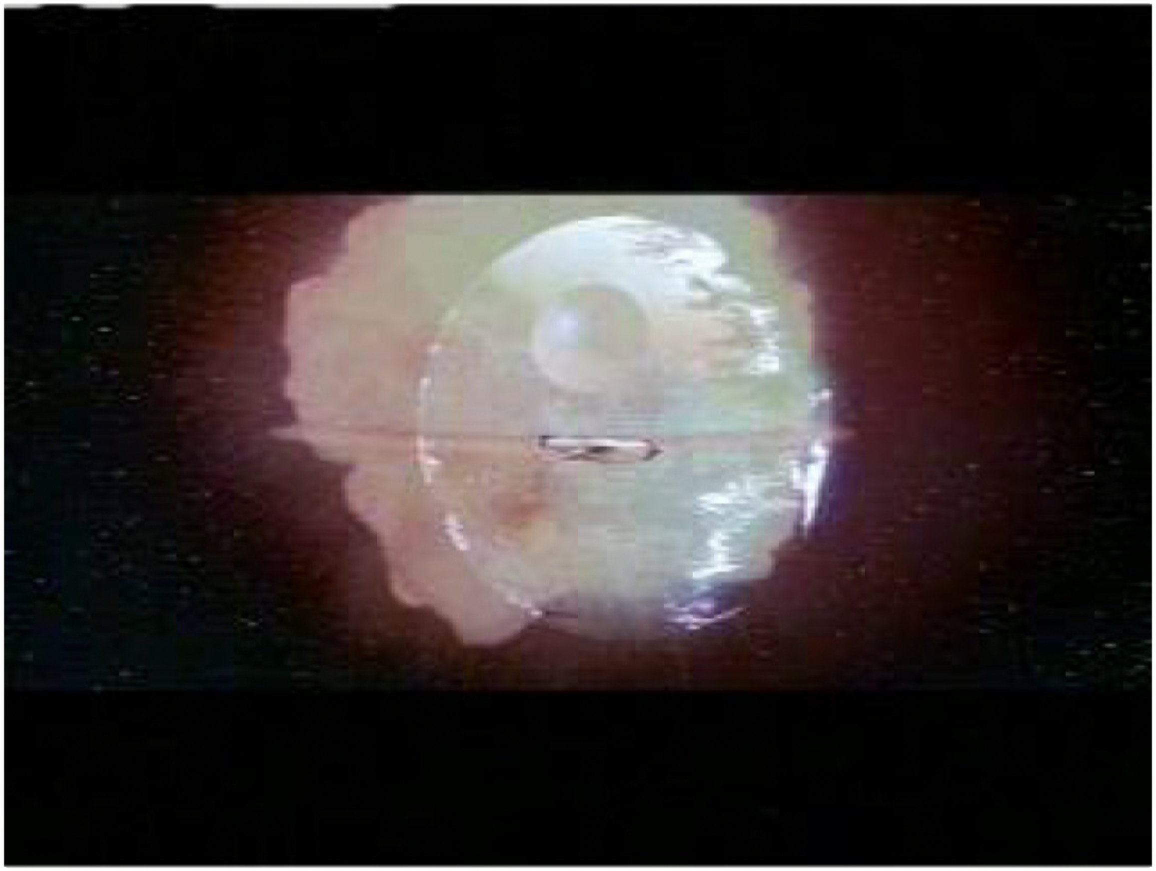
- Tell complete story connecting millisecond time scale of dynamics of merger with seconds to weeks
- Messy astrophysics: magnetic fields, neutrino winds/cooling, etc.
- But with multimessenger astronomy we get to see the opening credits



NASA

With multimessenger astronomy we get to see the opening credits

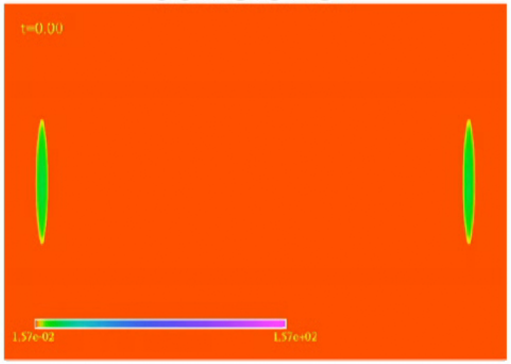
With multimessenger astronomy we get to see the opening credits



Beyond compact object mergers

Beyond compact object mergers

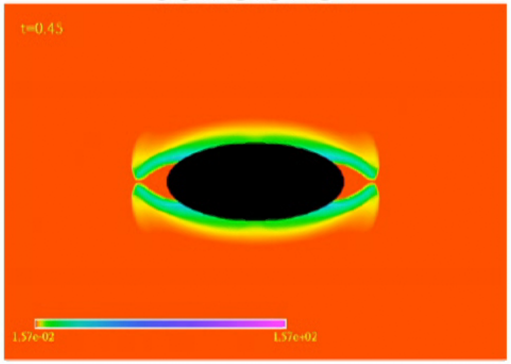
When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

Beyond compact object mergers

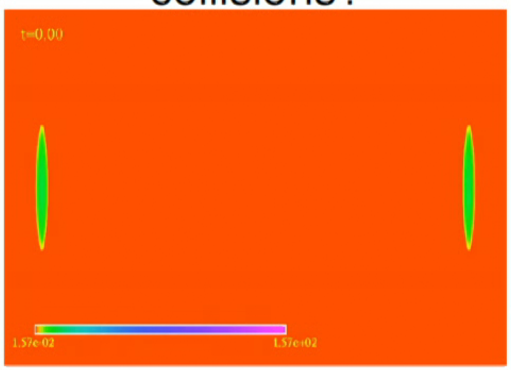
When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

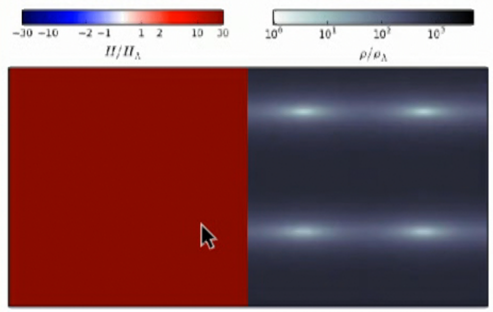
Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

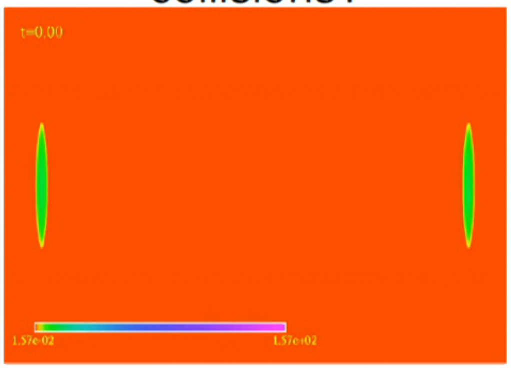
What happens in a very inhomogeneous universe?



East et al. (2016)

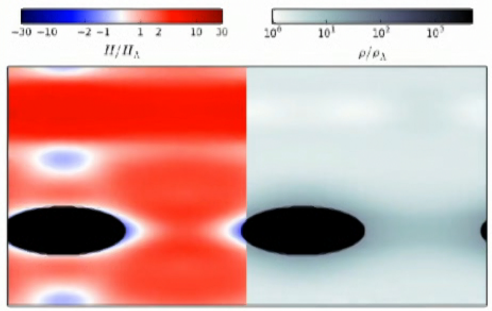
Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

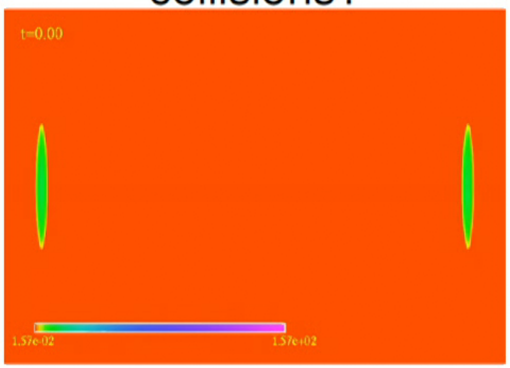
What happens in a very inhomogeneous universe?



East et al. (2016)

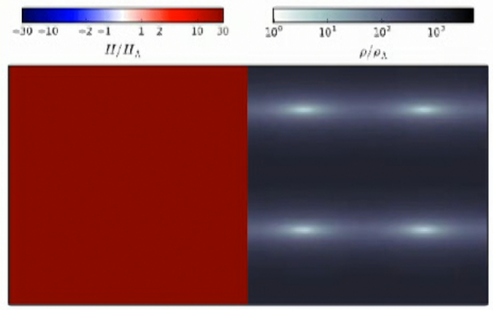
Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?



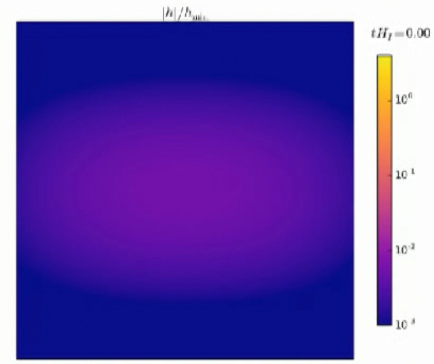
East & Pretorius (2013)

What happens in a very inhomogeneous universe?



East et al. (2016)

Could the Higgs Boson have spelled doom for the early universe?

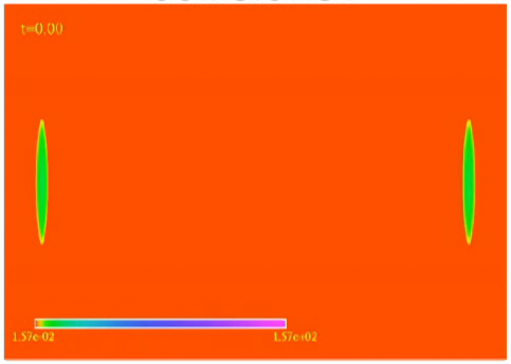


East et al. (2017)

And many other questions. . .

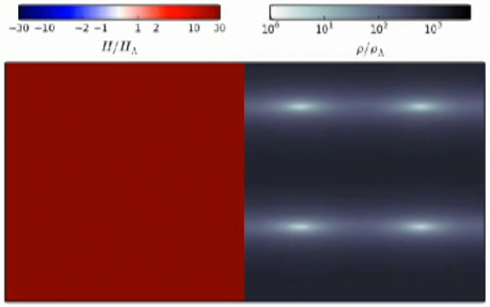
Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?



East & Pretorius (2013)

What happens in a very inhomogeneous universe?



East et al. (2016)

Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?

East & Pretorius (2013)

What happens in a very inhomogeneous universe?

East et al. (2016)

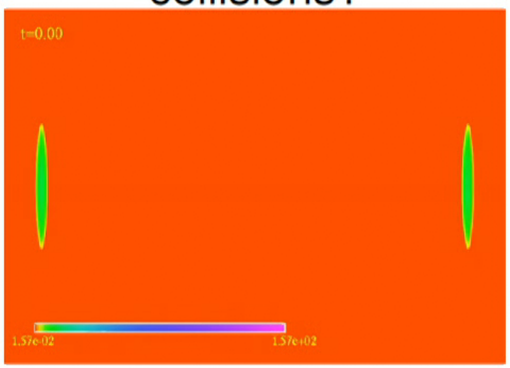
Could the Higgs Boson have spelled doom for the early universe?

East et al. (2017)

And many other questions. . .

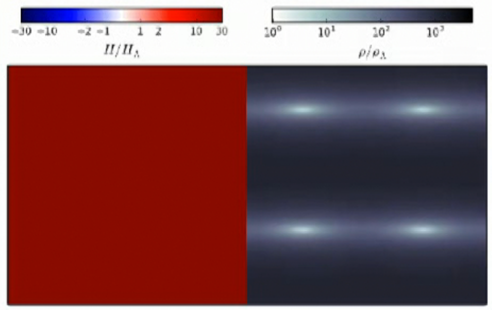
Beyond compact object mergers

When do black holes form from ultrarelativistic collisions?



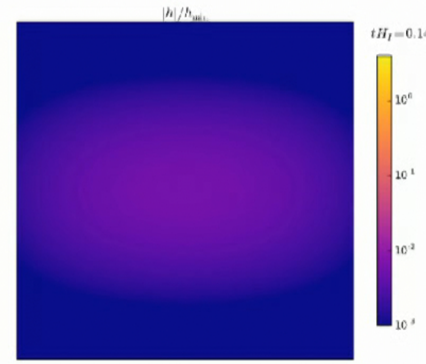
East & Pretorius (2013)

What happens in a very inhomogeneous universe?



East et al. (2016)

Could the Higgs Boson have spelled doom for the early universe?



East et al. (2017)

And many other questions. . .

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.
- More exotic merger scenarios: orbital eccentricity, high black hole or neutron star spin, etc.
- The unknown unknowns.