Title: Hitting the High Notes: The High Frequency Dynamics of Neutron Star Mergers

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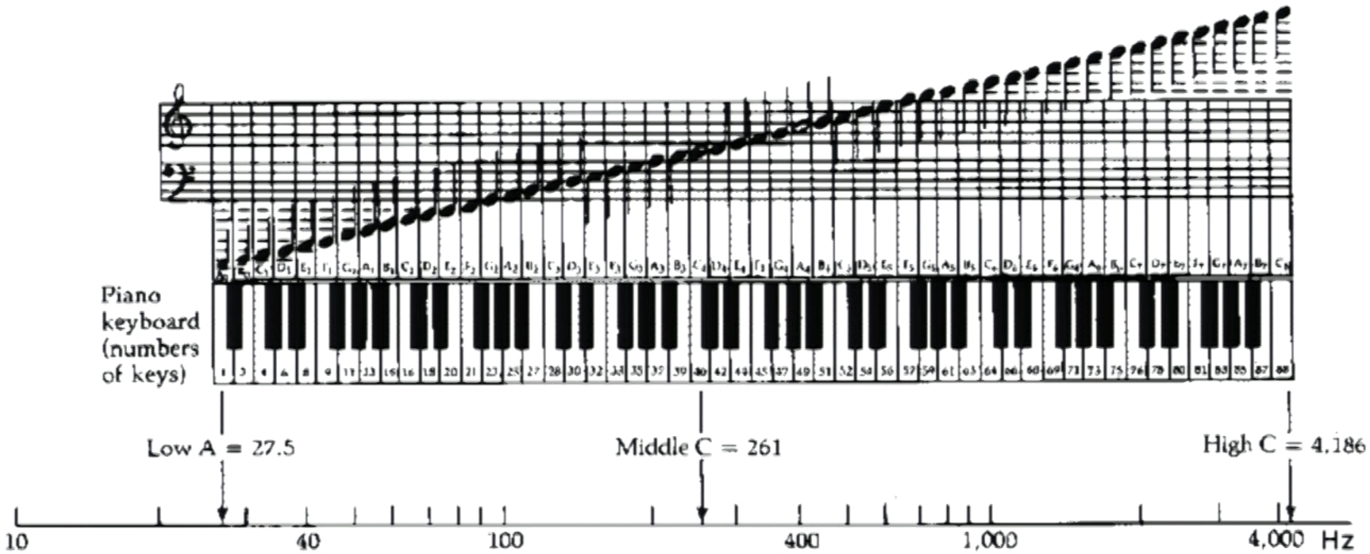
URL: http://pirsa.org/18060045

Abstract:

High frequency dynamics of neutron stars

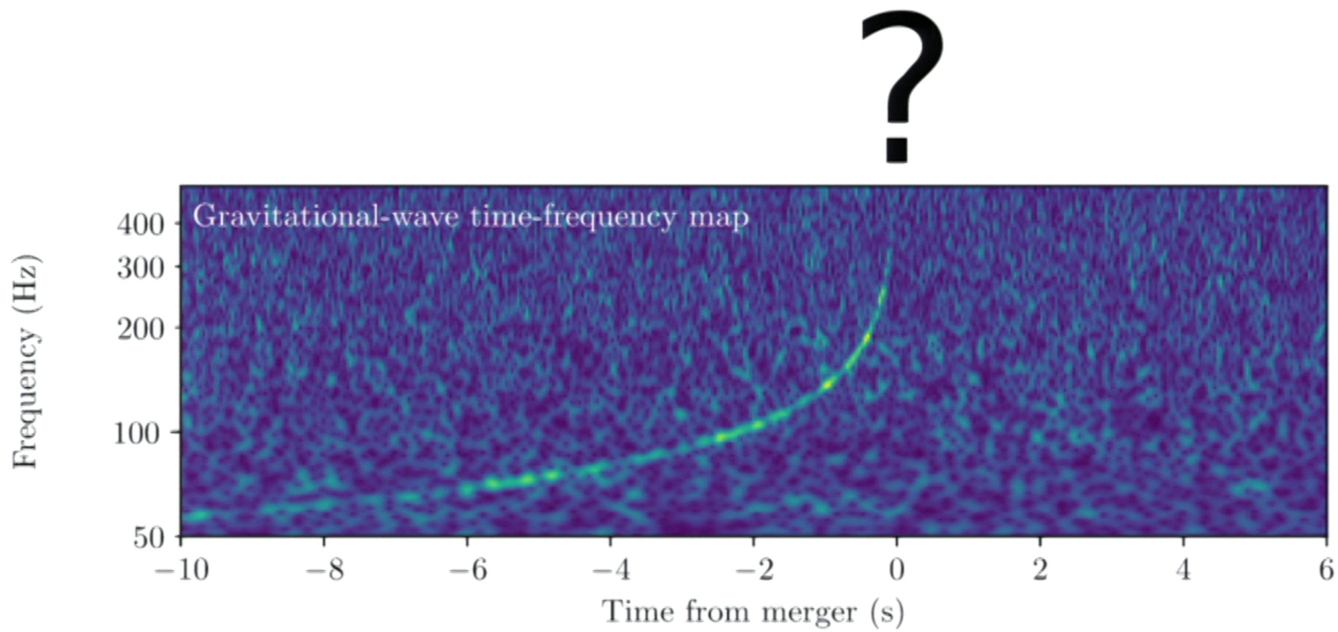
Neutron stars use the whole piano... but we're only hearing the bottom half.



Credit: Port, Introduction to Phonetics

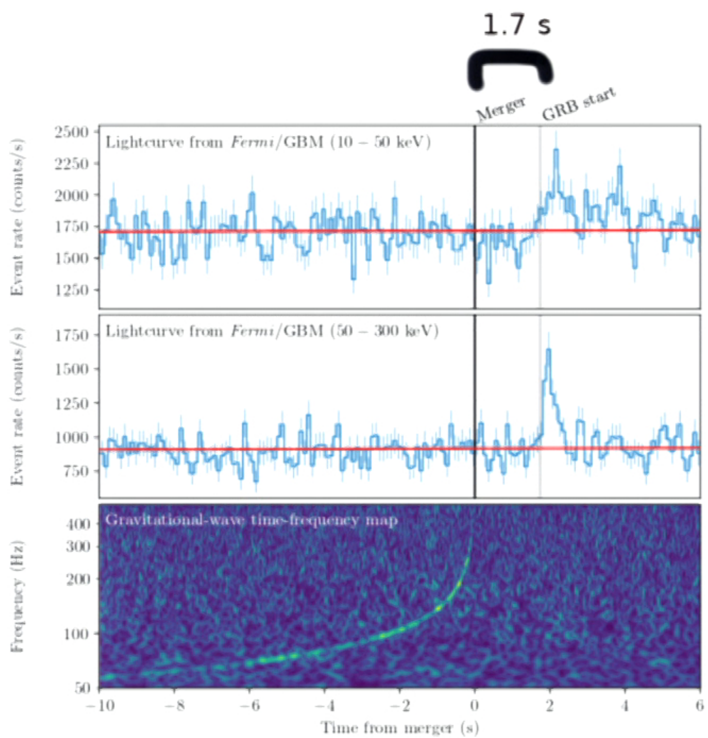
Piano
keyboard
(numbers
of keys)
Low A
10
40

GW170817: neutron star merger



LIGO/VIRGO Collaboration et al. (2017)

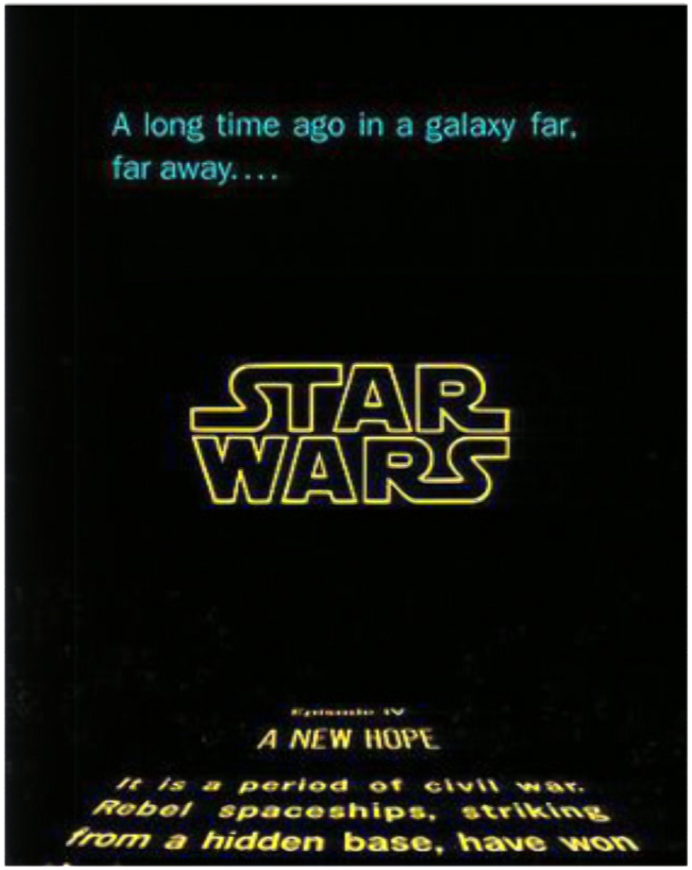
Coincident detection of gamma ray burst and gravitational wave



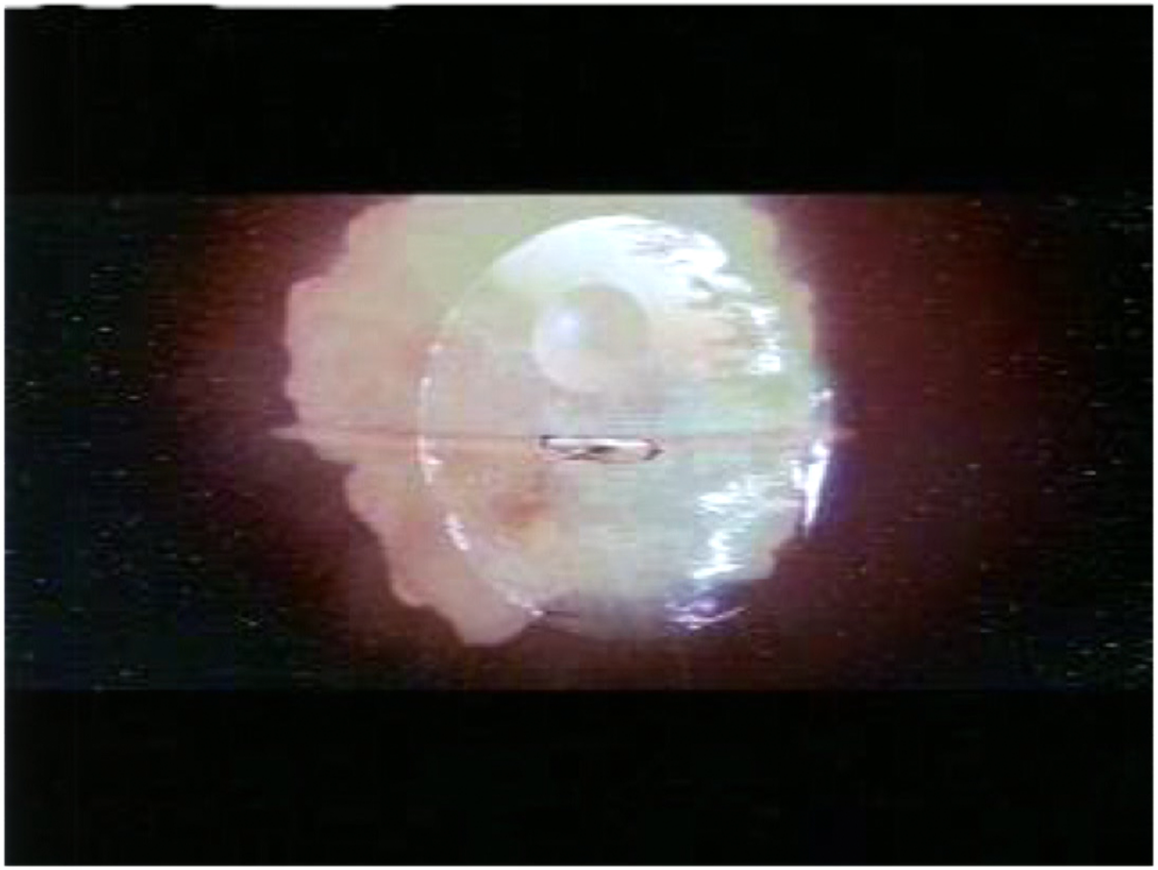
LIGO/VIRGO Collaboration et al. (2017)

- When/is there a final black hole?
- What causes the 1.7 second delay?
- How much material was ejected dynamically, in subsequent wind?

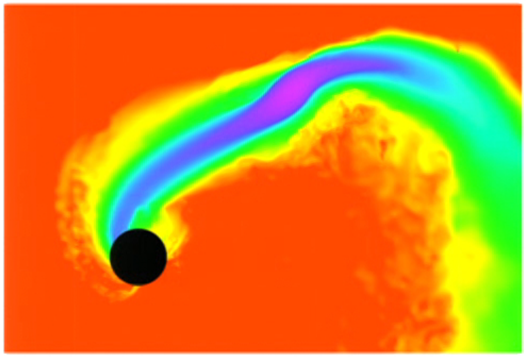
Opening credits with multimessenger astronomy



Opening credits with multimessenger astronomy

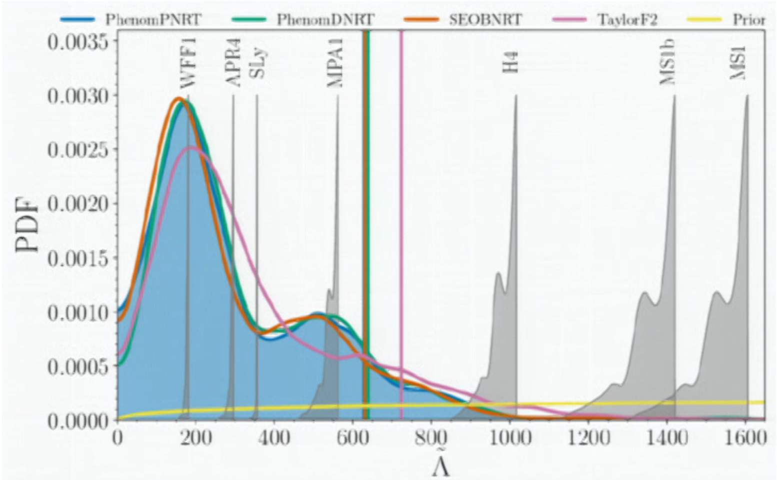


Reasons to go after high frequency neutron star dynamics



- Better understanding of associated electromagnetic transients
- Probe non-vacuum GR in strong field regime
- Sensitive to spin and other subleading parameters
- For black hole-neutron star mergers — probe disruption?
- Encodes information about unknown neutron star equation of state

Matter effects in inspiral



LIGO/VIRGO (2018)

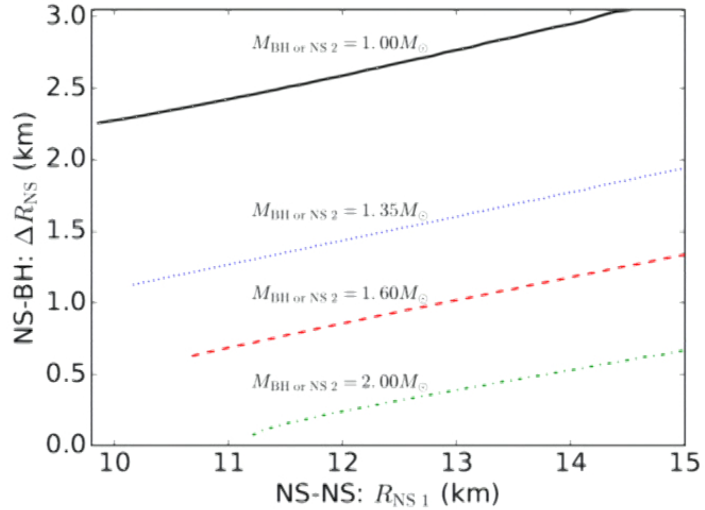
- During inspiral, main matter effect is due to induced quadrapole, 5 PN effect
- Encapsulated in effective tidal deformability parameter $\tilde{\Lambda}$
- Somewhat degenerate with mass-ratio/spin

$$\tilde{\Lambda} = \frac{16}{13}\left[\left(1 + 12\frac{m_2}{m_1}\right)\frac{m_1^5}{M^5}\Lambda_1 + (1 \leftrightarrow 2)\right] \text{ with } \Lambda = \frac{2}{3}k_2(R/m)^5$$

Binary neutron star merger or black hole-neutron star merger

- Devil's advocate: 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?

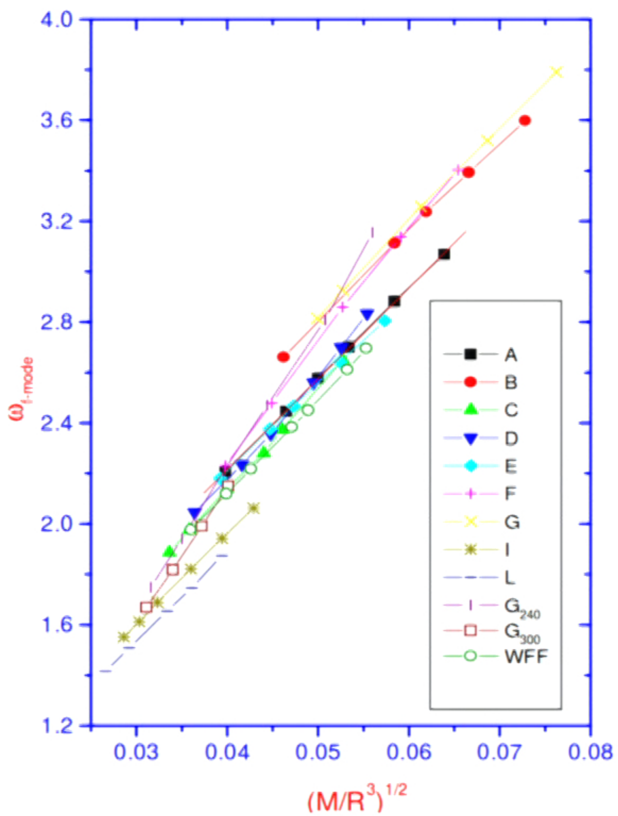
Distinguishing low mass black holes in neutron star mergers



Yang, WE & Lehner (2017)

- Leading order tidal effects are degenerate with uncertainty in equation of state
- Merger dynamics (at high frequencies) will of course be completely different

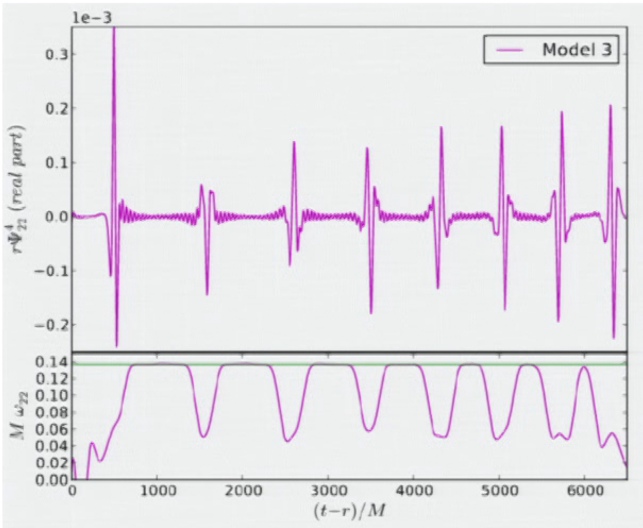
Neutron star f-mode oscillations



Andersson & Kokkotas (1998)

- Fundamental oscillation mode of neutron star, $f \sim 2$ to 3 kHz
- Encodes equation of state information

Neutron star f-mode oscillations



Gold et al. (2012)

- Can be excited during inspiral in eccentric encounters (Turner 1977, WE et al. 2012, Gold et al. 2012)
- Oscillations damp due to GW emission

Primordial vs. dynamically-assembled binaries

Primordial binaries:

- Born in bound system
- Are expected to have negligible eccentricity (i.e. quasi-circular) when detected
- Expected to be primary sources for LIGO/VIRGO

Dynamically assembled binaries:

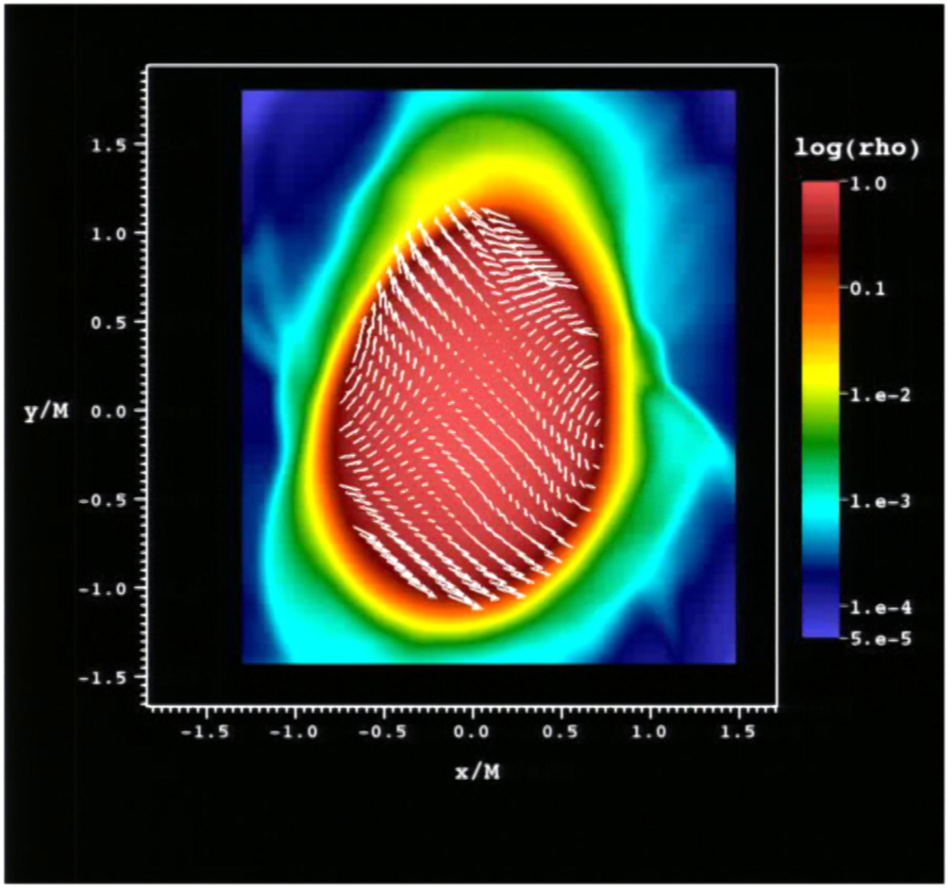
- Arise in dense regions, e.g. globular cores undergoing core collapse.
- Subset will merge with large orbital eccentricities
- Event rates less well understood — could make up some fraction of LIGO observations.

Ongoing work to understand cluster dynamics, three body interactions, etc. (see Lee et al. 2010; Samsing et al. 2013-2017; Antonini et al. 2015; Rodriguez et al. 2015, 2016)

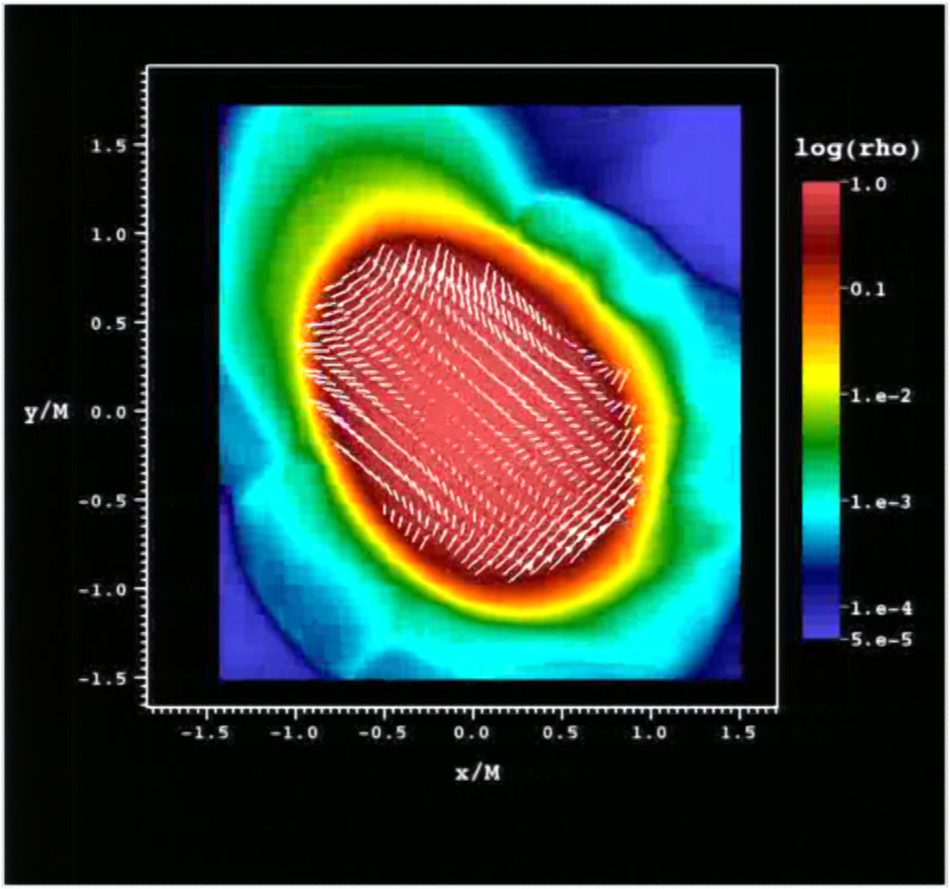
Tidal f-mode excitation in close encounter

WE & Pretorius (2012)

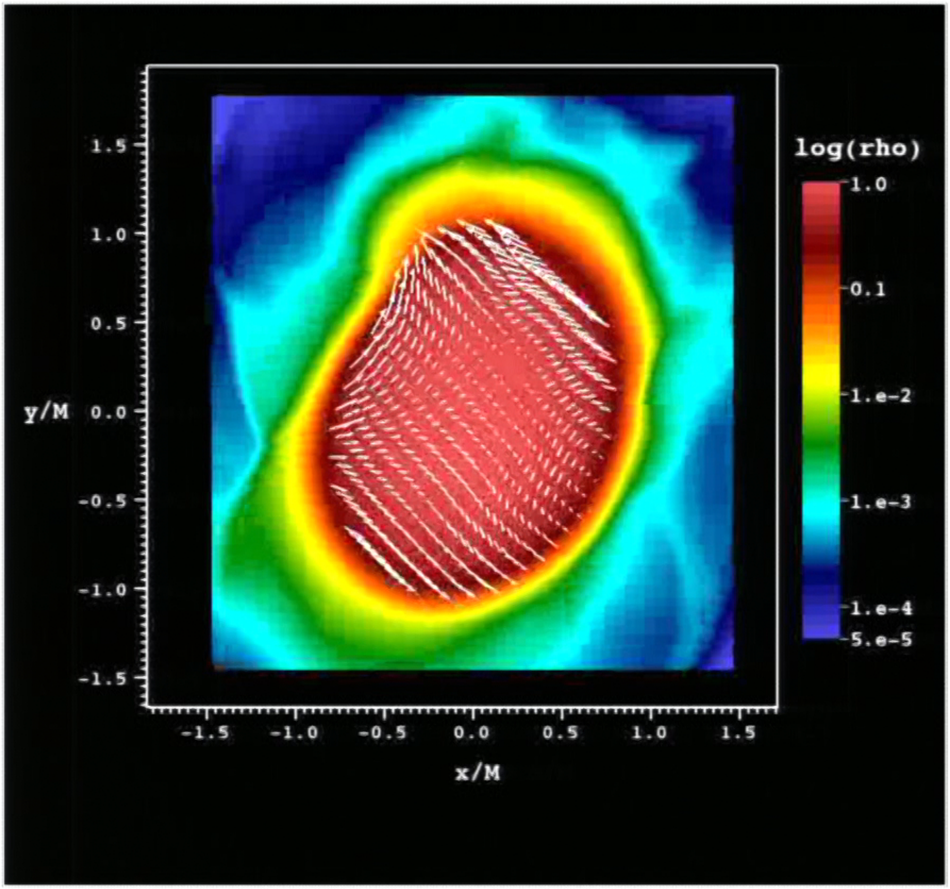
- $M_1 = M_2 = 1.35 M_\odot$
- Initial Newt. orbital param: $r_p = 10M$, $e = 1$
- HB piecewise polytrope EOS ($M_{\rm NS}/R_{\rm NS} = 0.17$, $M_{\rm max} = 2.12 M_\odot$)



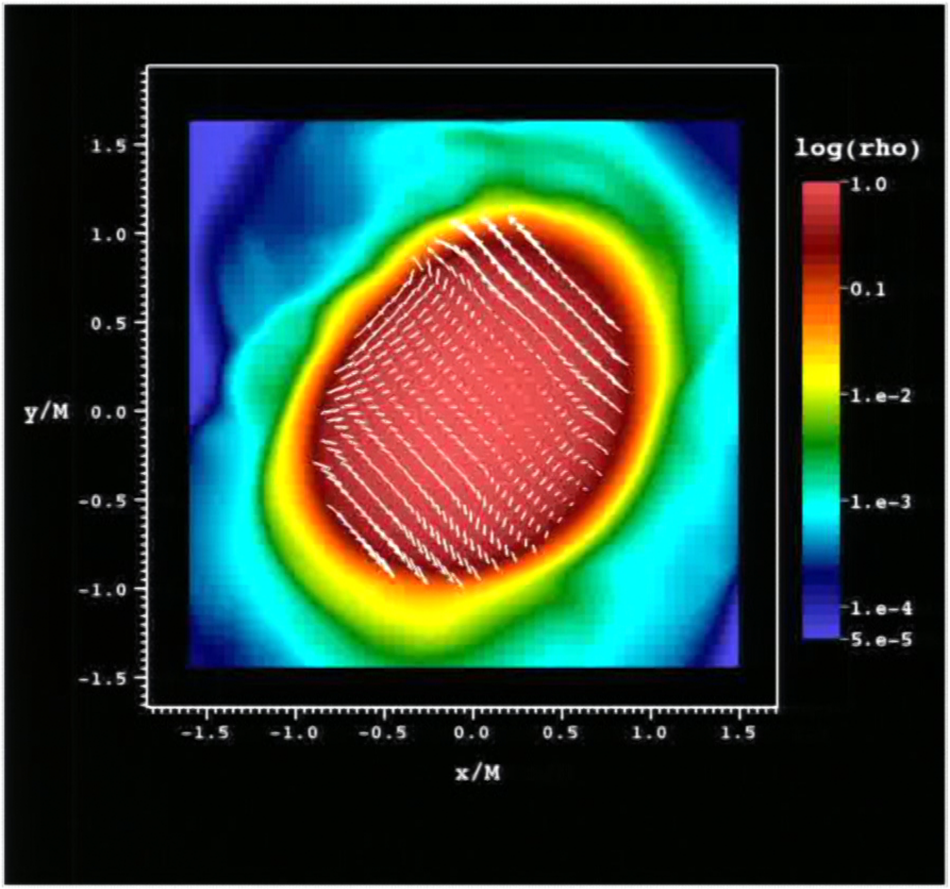
WE, Stephens, & Pretorius (2012)



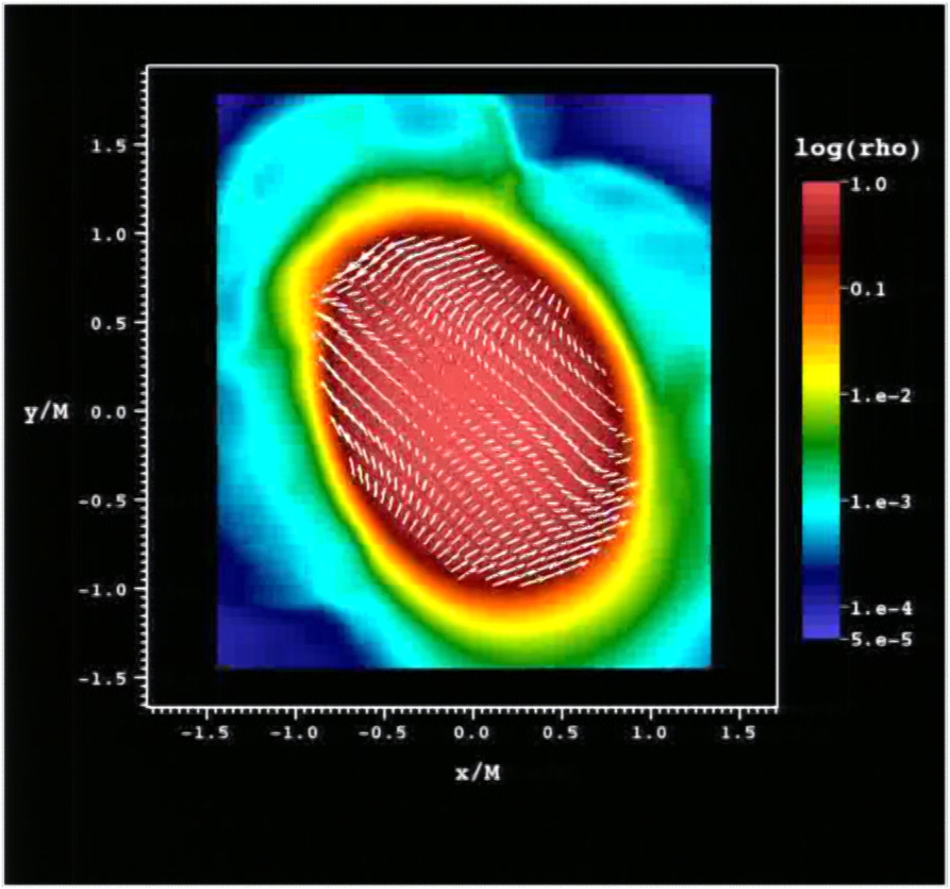
WE, Stephens, & Pretorius (2012)



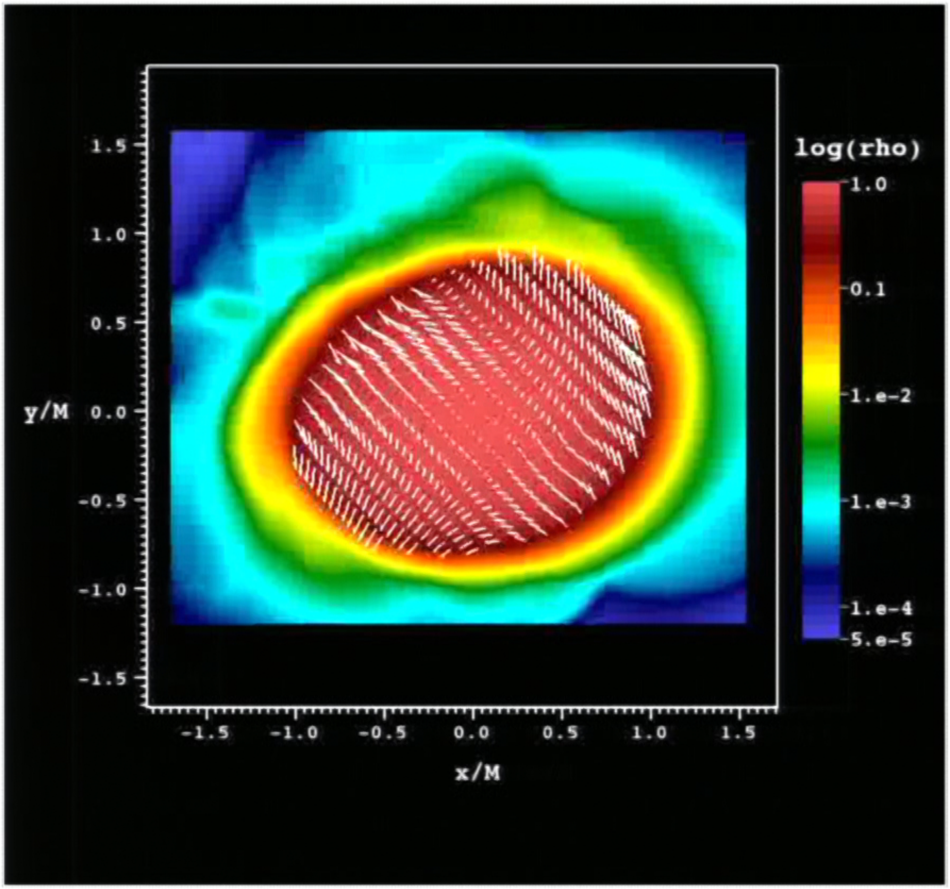
WE, Stephens, & Pretorius (2012)



WE, Stephens, & Pretorius (2012)

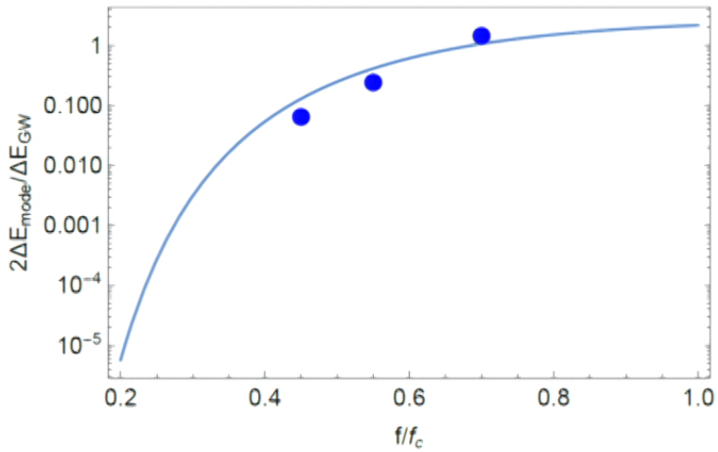


WE, Stephens, & Pretorius (2012)



WE, Stephens, & Pretorius (2012)

Modelling f-mode gravitational waves

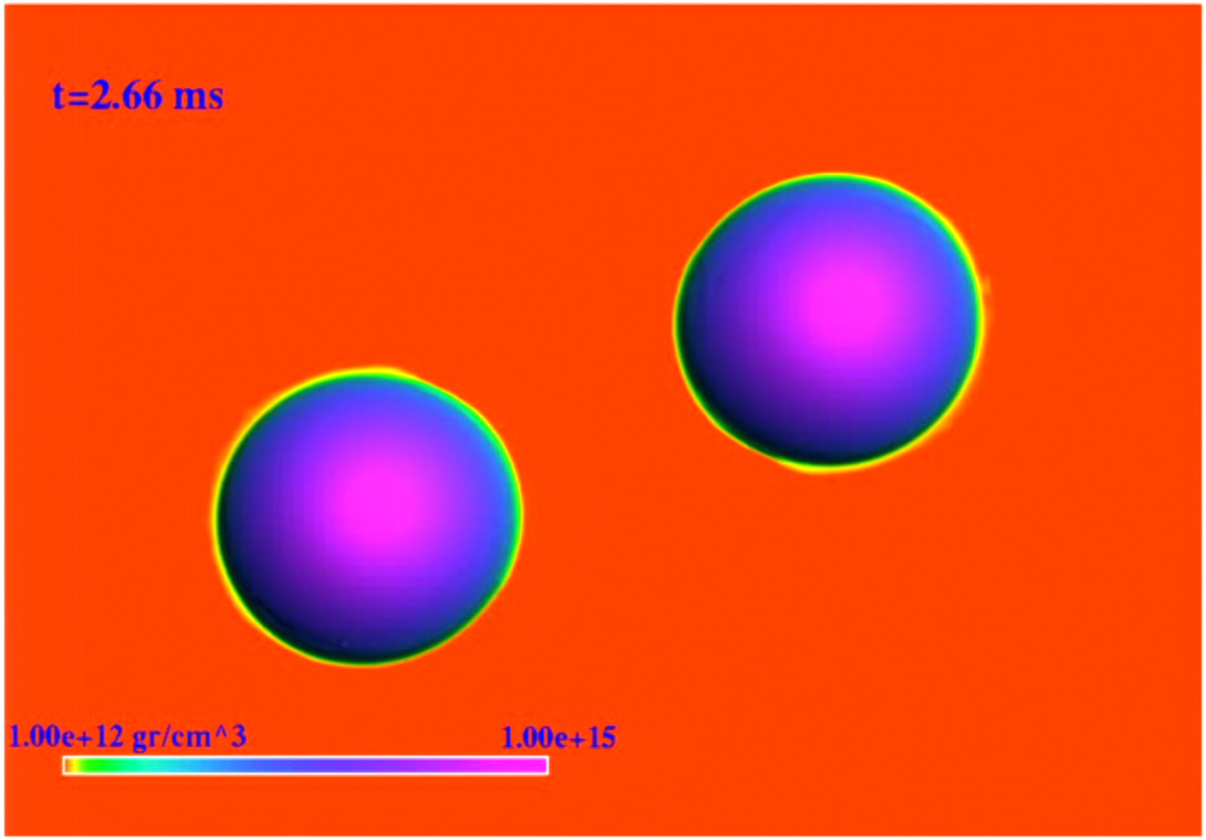


Yang, WE, et al. (2018)

- For close enough encounters, energy in tidal excitations comparable to GW burst
- Tidal excitation energy emitted as GWs at f-mode frequency

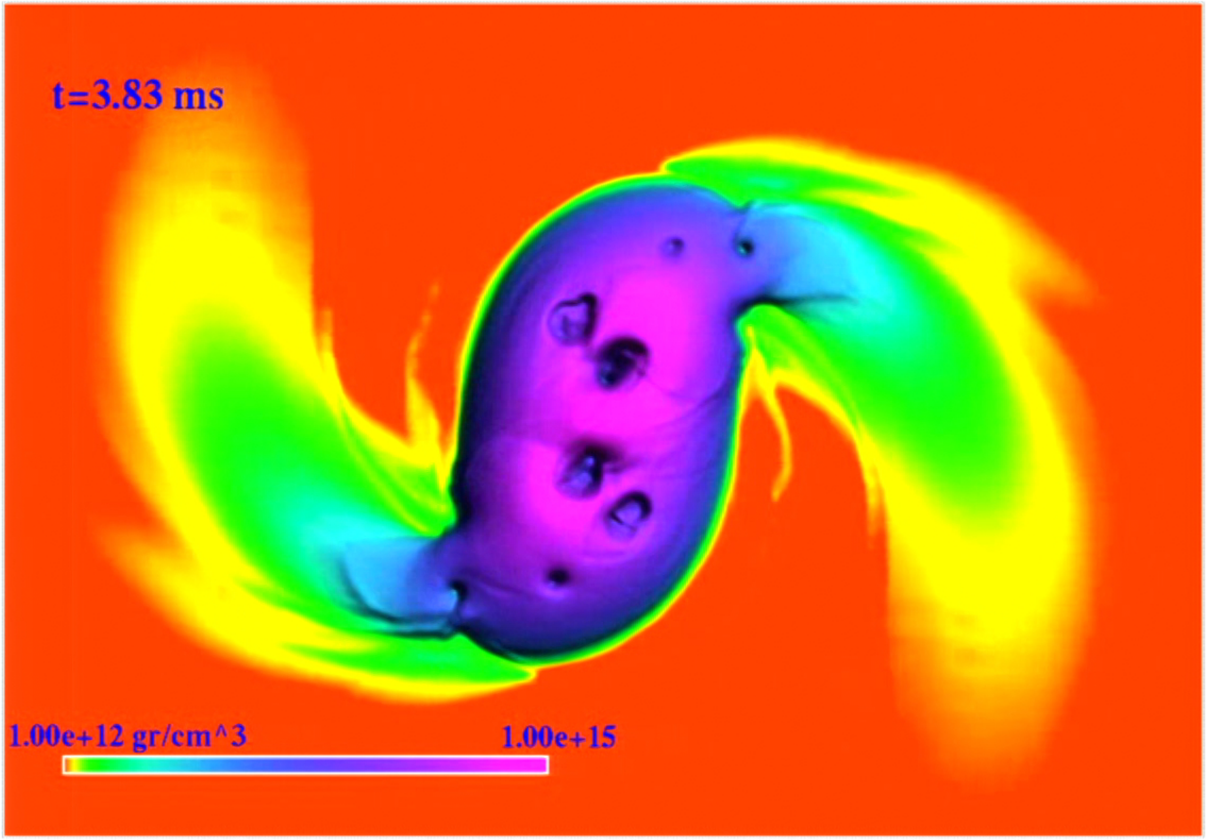
$$\mathrm{SNR} \sim 30 \left(\frac{\mathcal{E}_{mode}}{\mathcal{E}_{\mathrm{GW}}}\right)^{1/2} \left(\frac{50\ \mathrm{Mpc}}{d}\right) \left(\frac{5\times 10^{-25}\ \mathrm{Hz}^{-1/2}}{\sqrt{S_n}}\right) \left(\frac{2\ \mathrm{kHz}}{f}\right)$$

Neutron stars merge



East et al. (2016)

Neutron stars merge



East et al. (2016)

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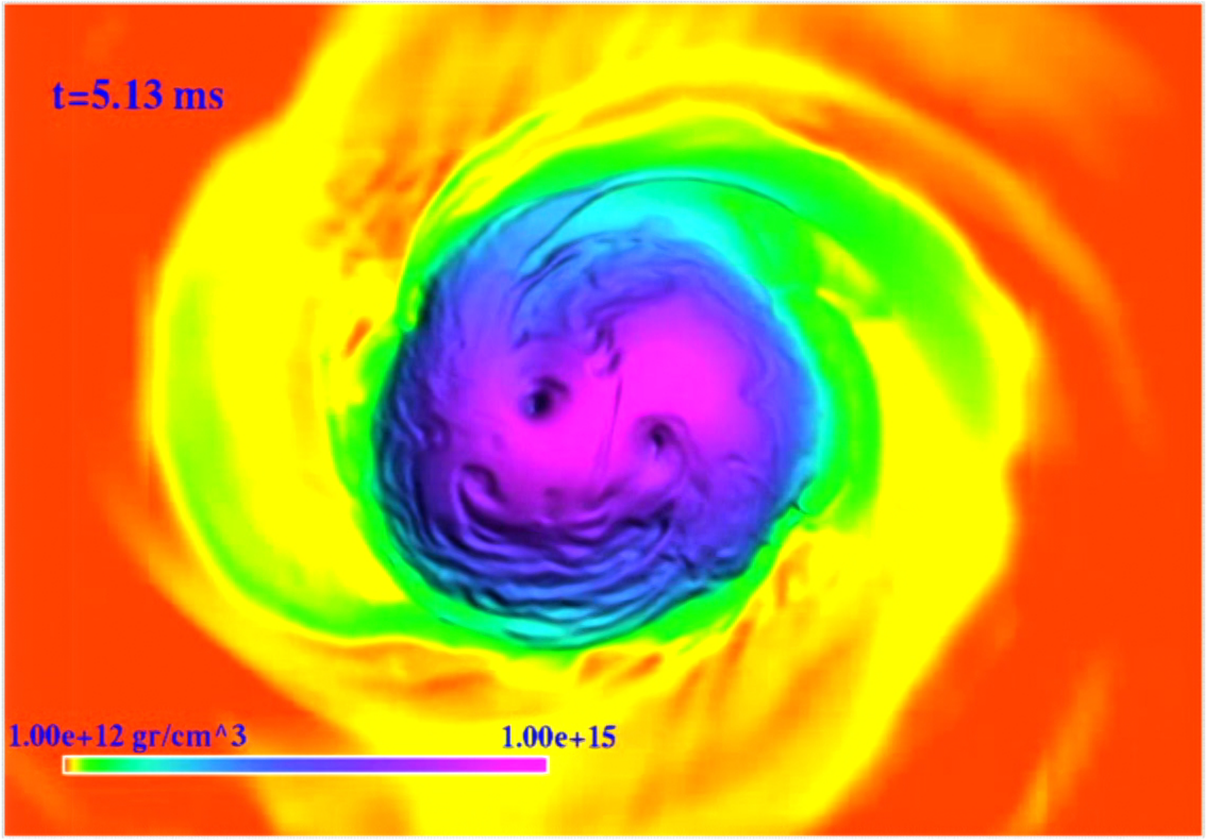
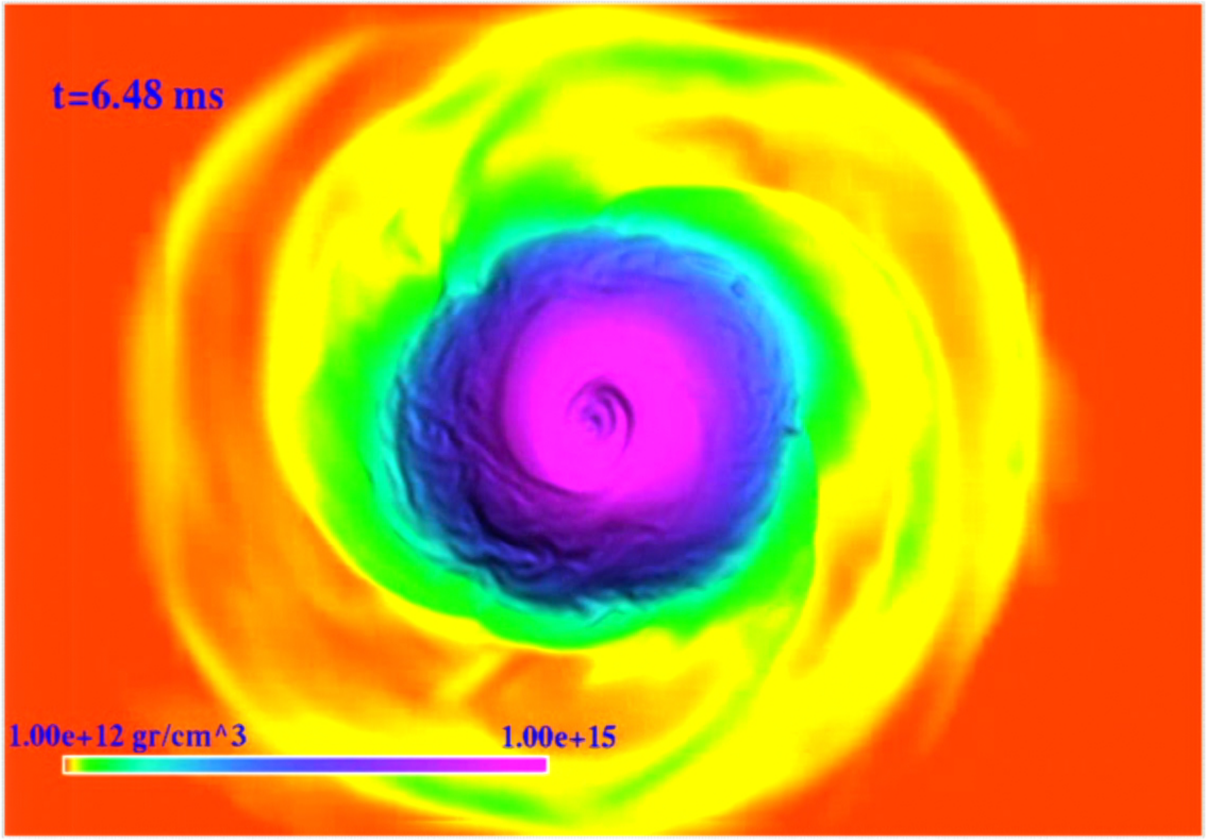


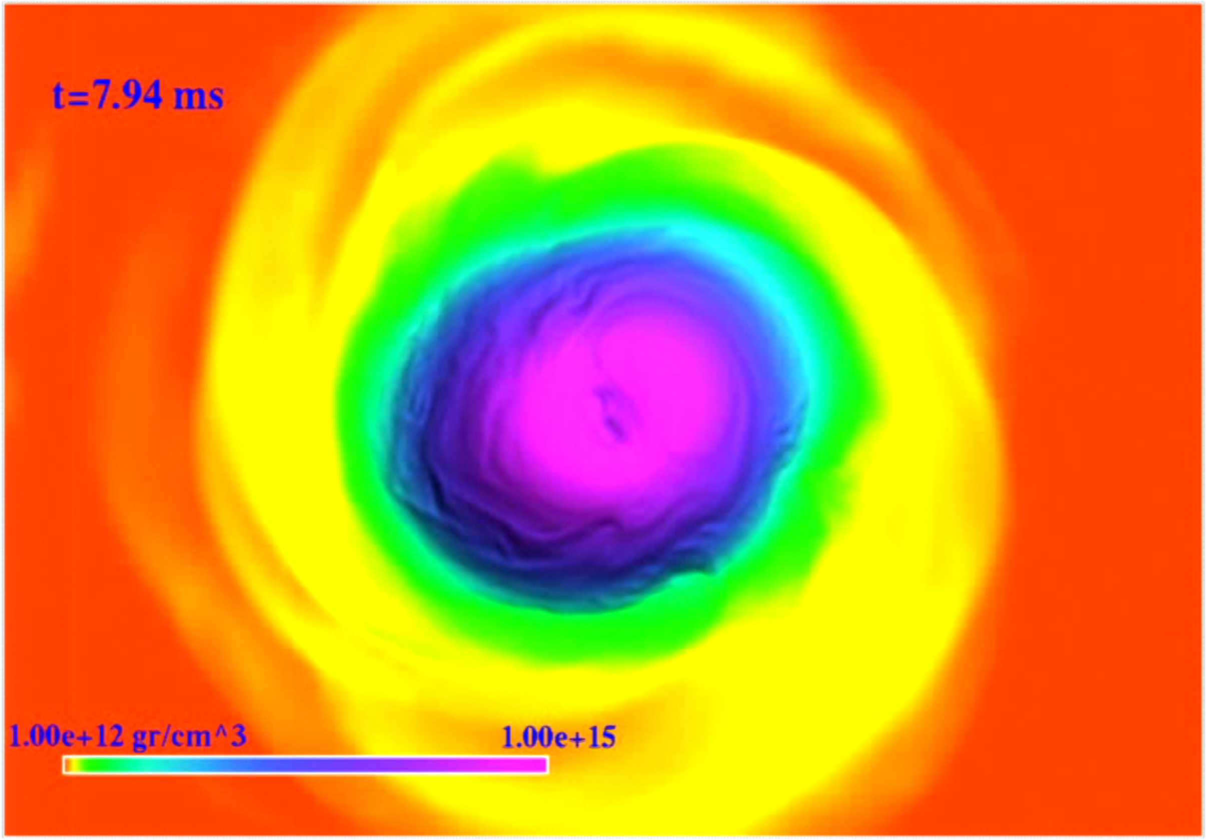
East et al. (2016)

Neutron stars merge



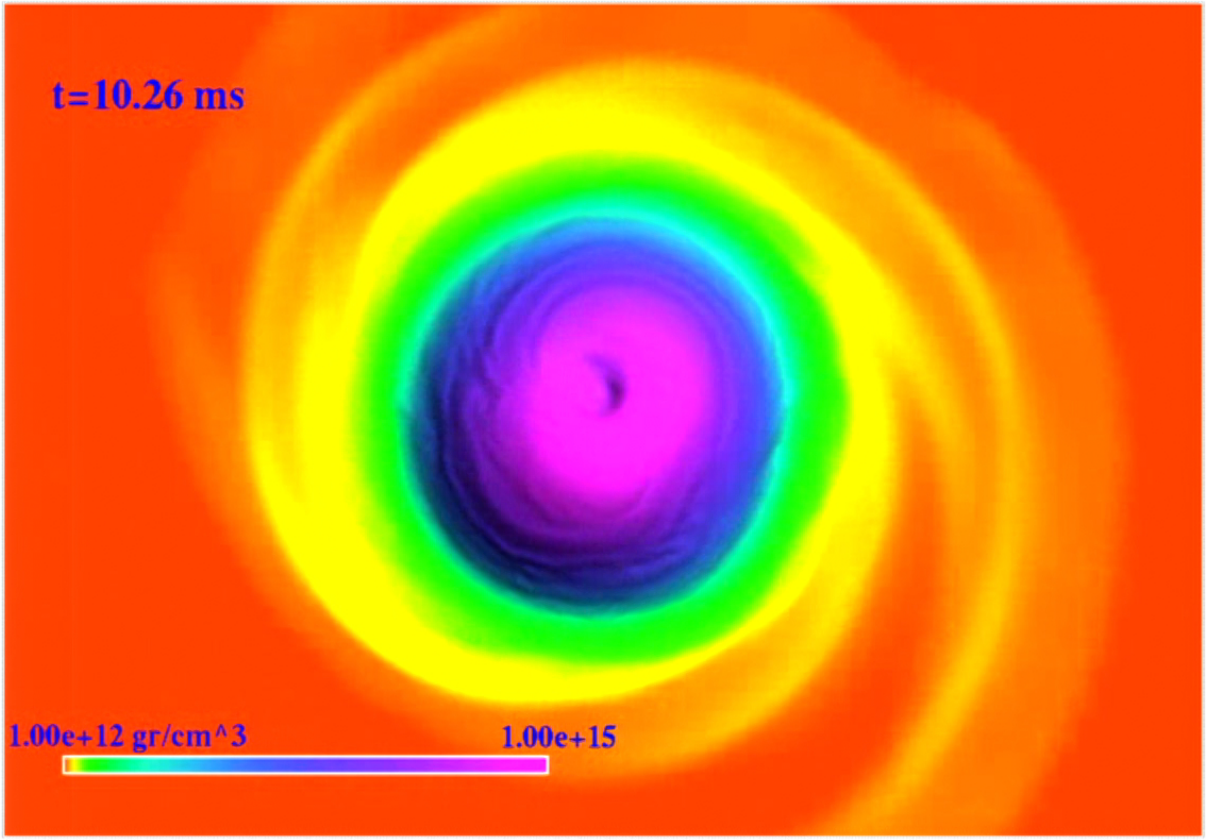
East et al. (2016)

Neutron stars merge



East et al. (2016)

Neutron stars merge



East et al. (2016)

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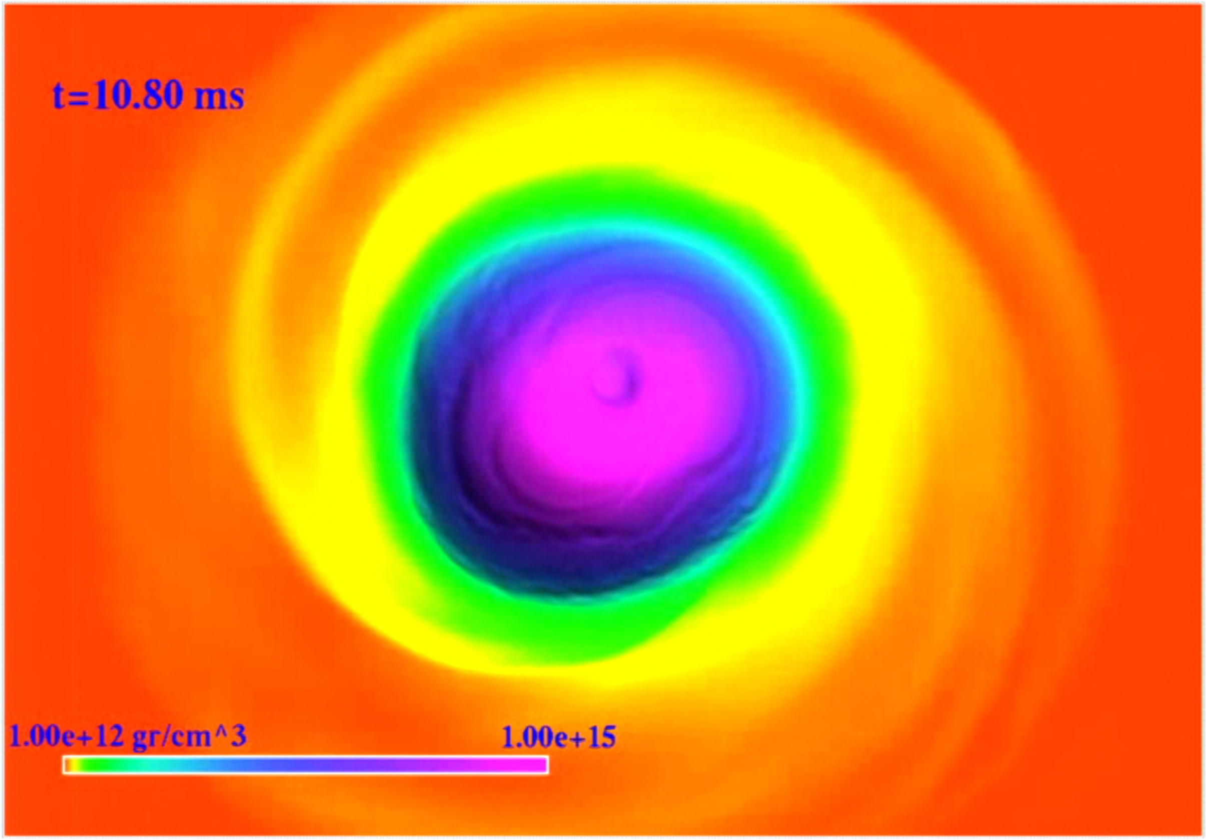
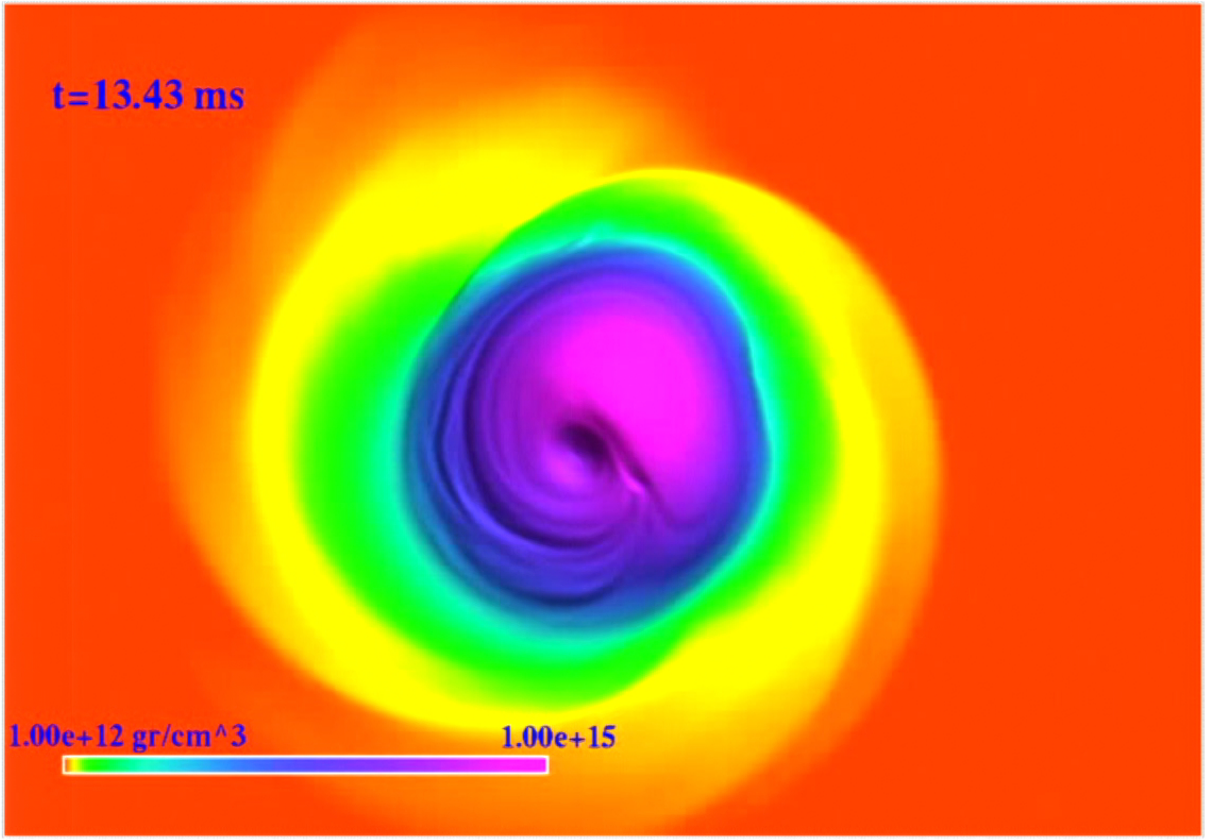


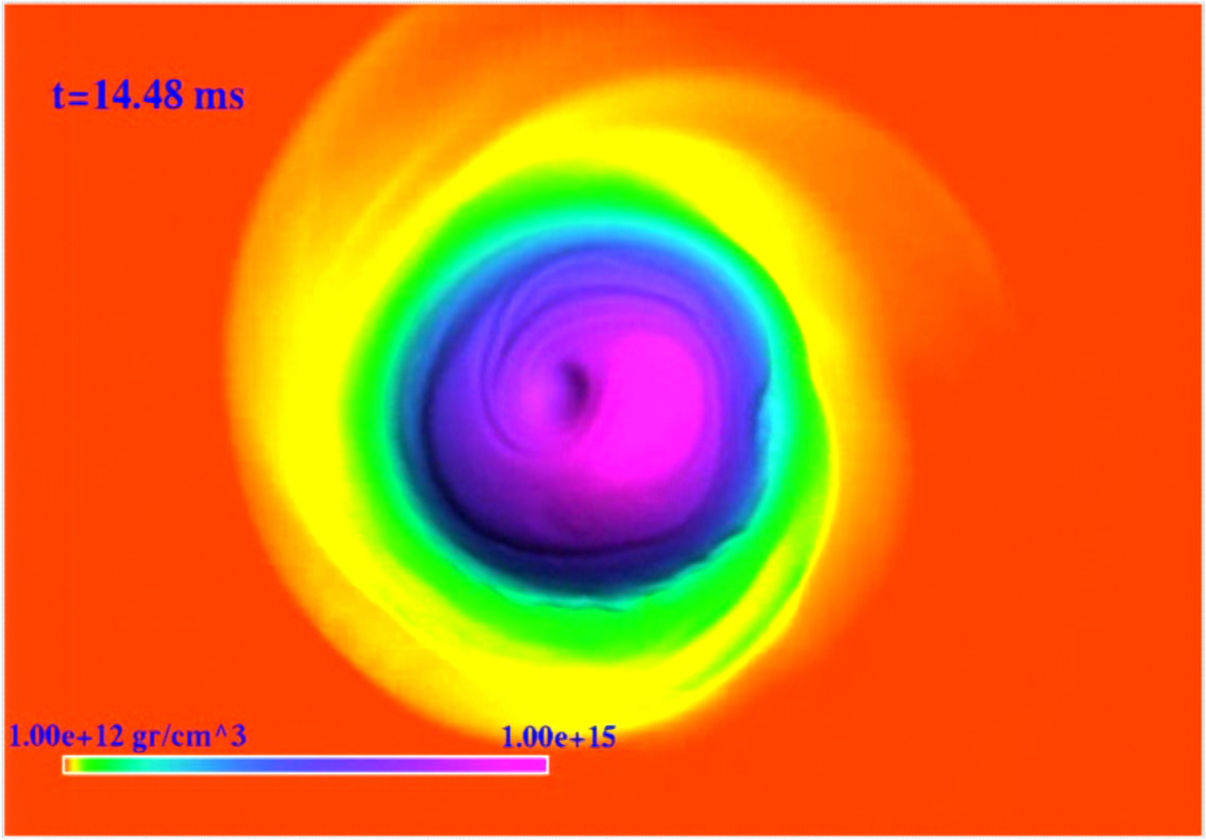
East et al. (2016)

Neutron stars merge



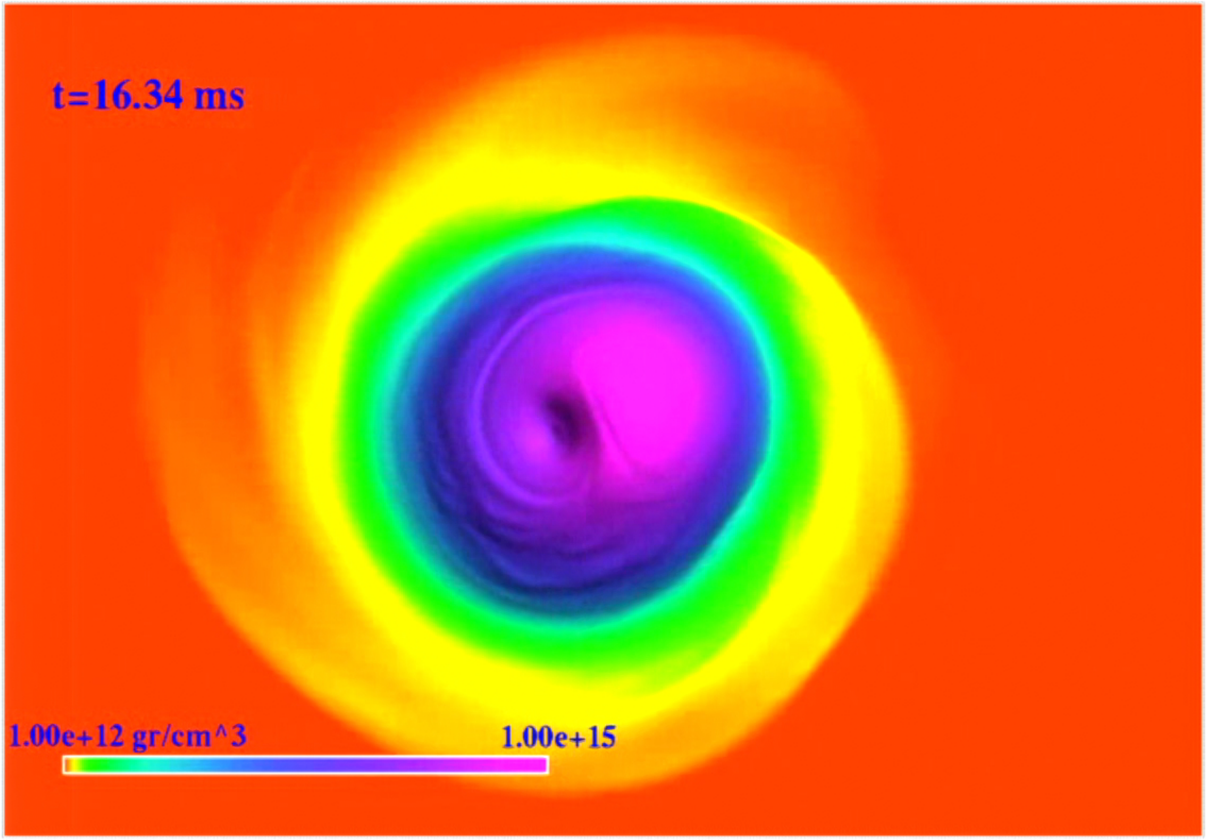
East et al. (2016)

Neutron stars merge



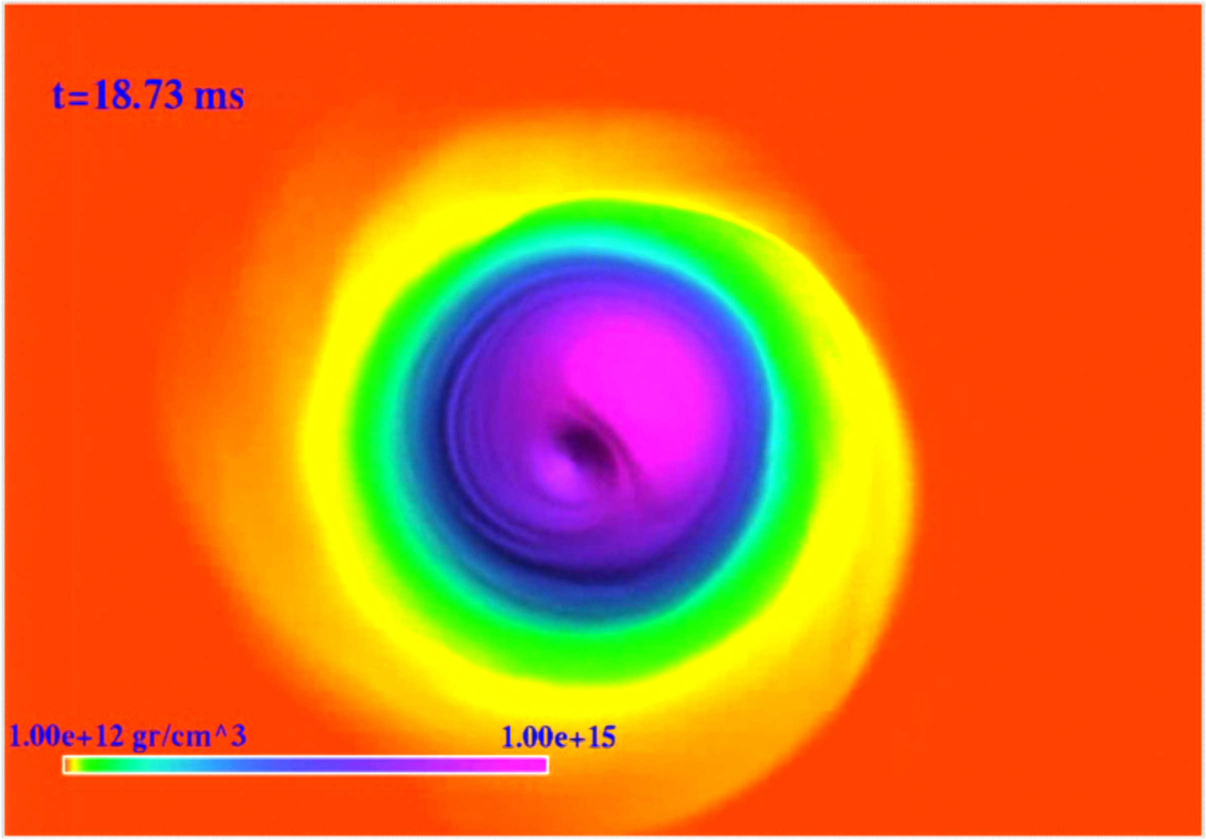
East et al. (2016)

Neutron stars merge



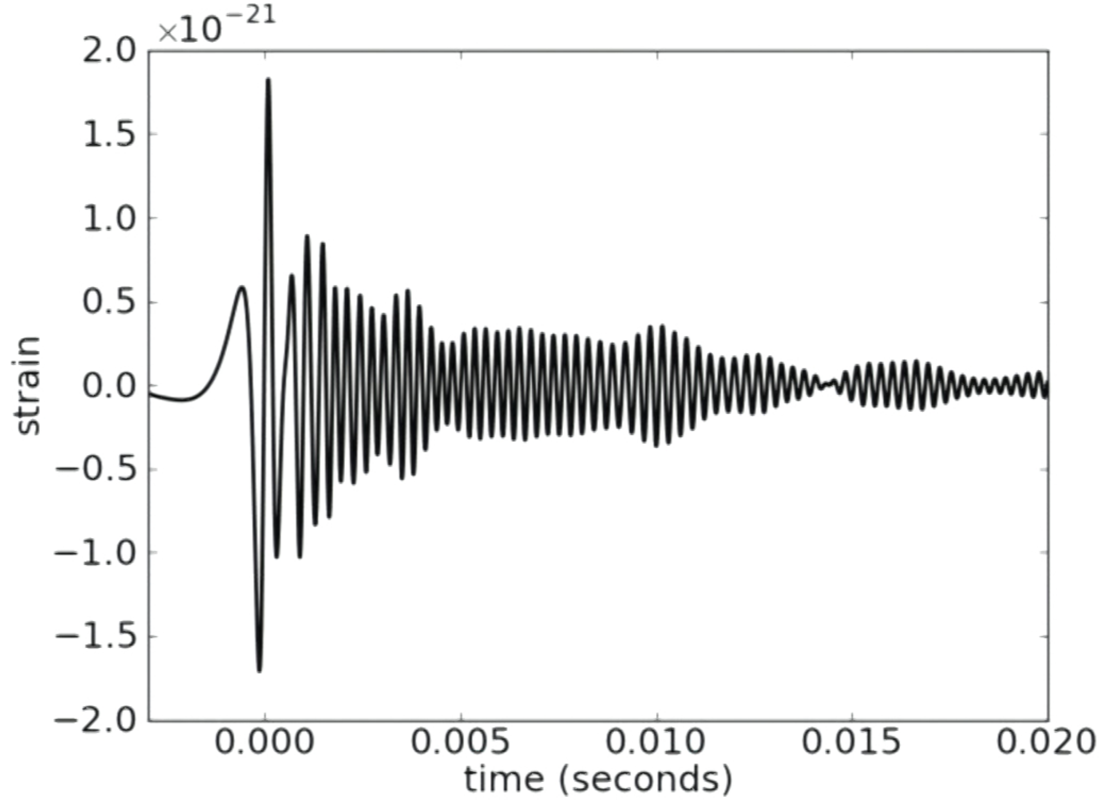
East et al. (2016)

Neutron stars merge



East et al. (2016)

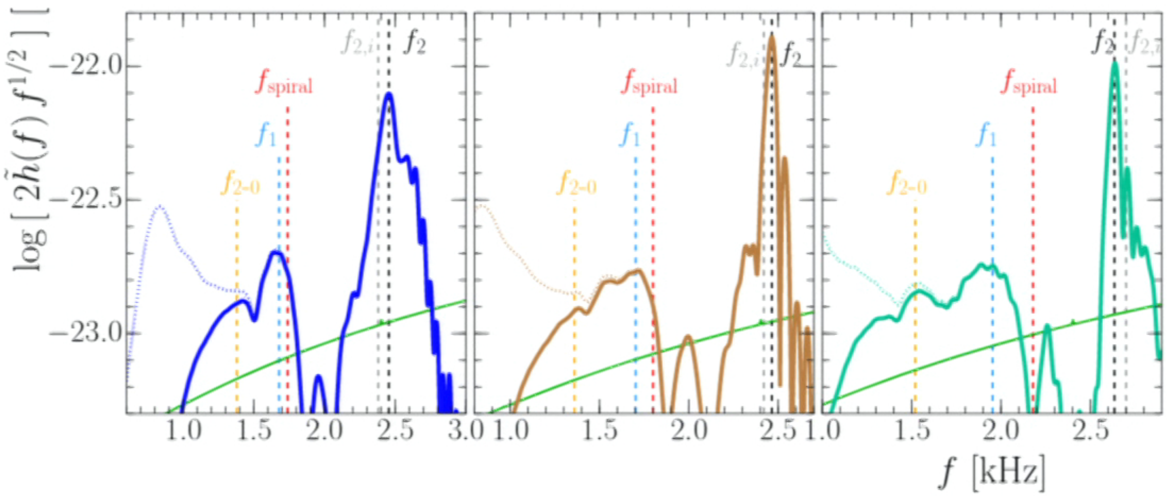
Gravitational waves from hypermassive neutron stars



Gravitational waves from hypermassive neutron stars

Important information in post-merger signal

- Was there prompt collapse to a black hole?
- Probe of hot, very perturbed, high density material
- Peak frequency maps to equation of state (see next talk by Andreas Bauswein)



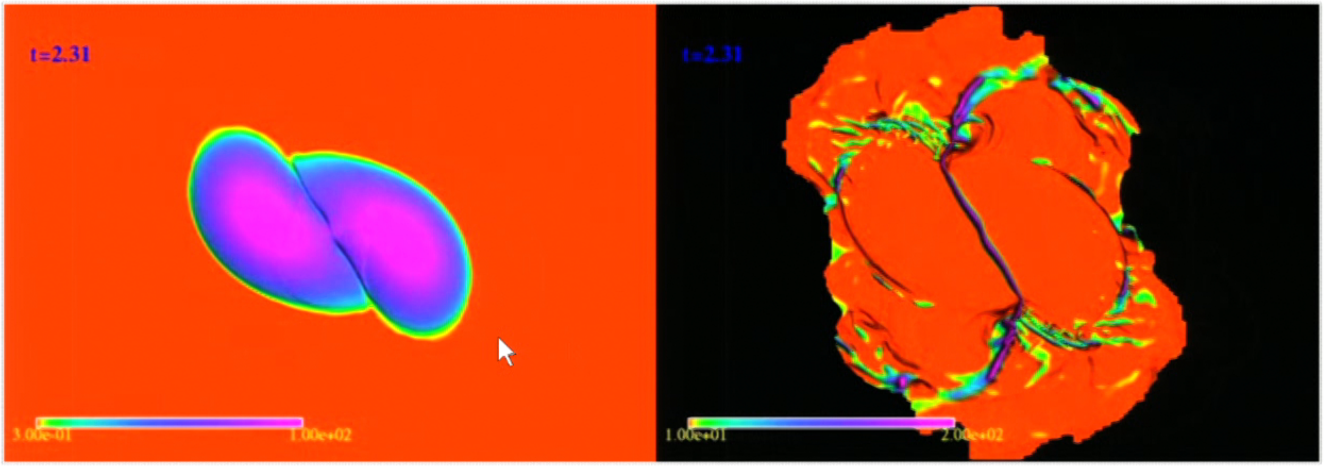
Rezzolla & Takami 2016

One-arm spiral instability background

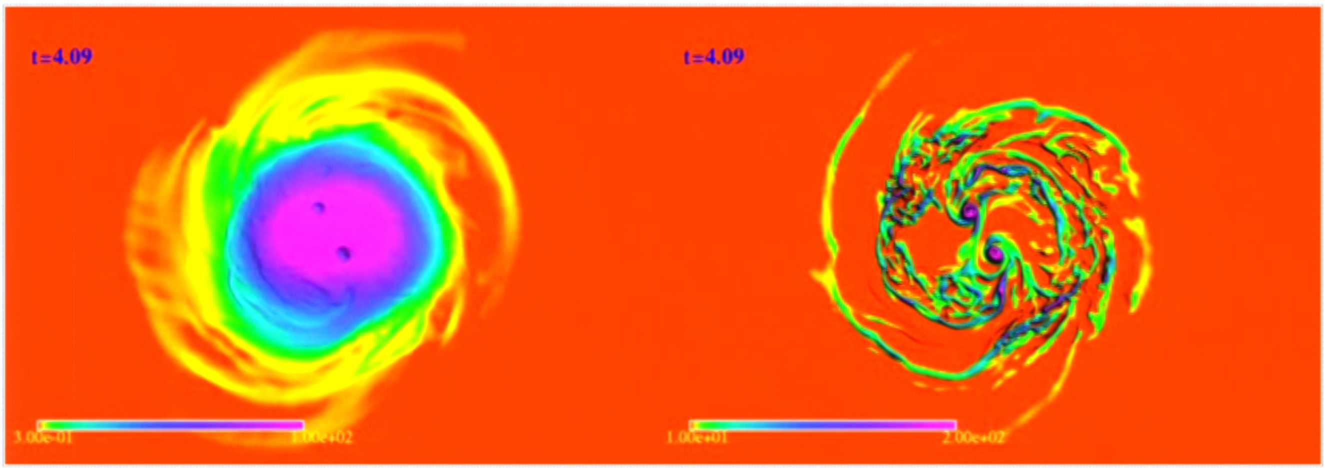
- Discovered in Newtonian simulations of polytropic stars with large differential rotation (Centrella et al. 2001); also seen in cores formed in core-collapse (Ott et al. 2005, 2007; Kuroda et al. 2014)
- Only recently uncovered in hypermassive NSs from mergers (WE, Paschalidis et. al 2015-2016)
- Found in eccentric and quasicircular mergers with comparable strength (Radice et al. 2016, Lehner et al. 2016)

Lesson: Still resolving the small scale physics (turbulence, magnetic fields, microphysics are important)

Density and vorticity



Density and vorticity



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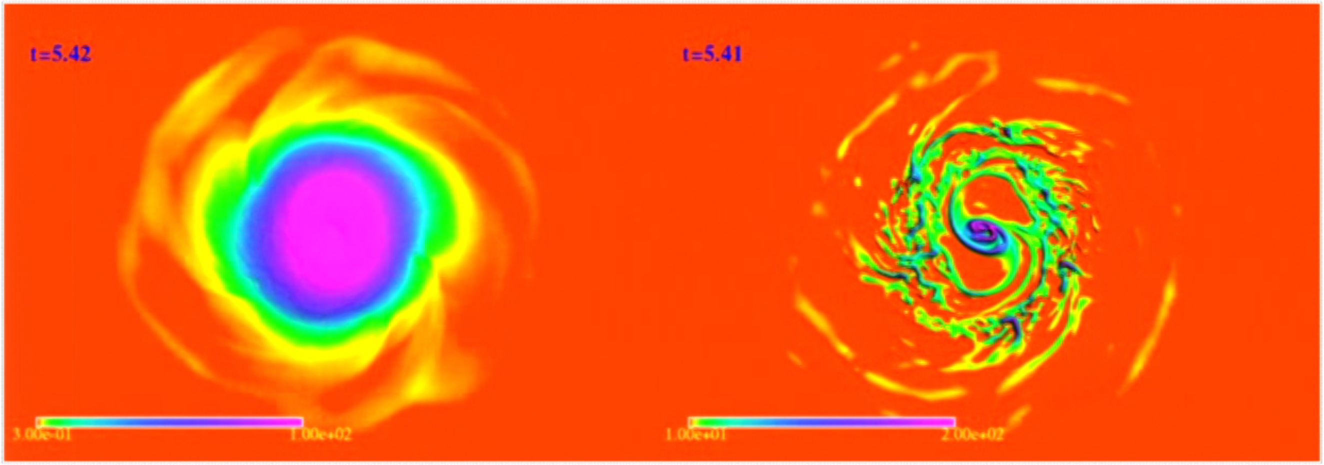
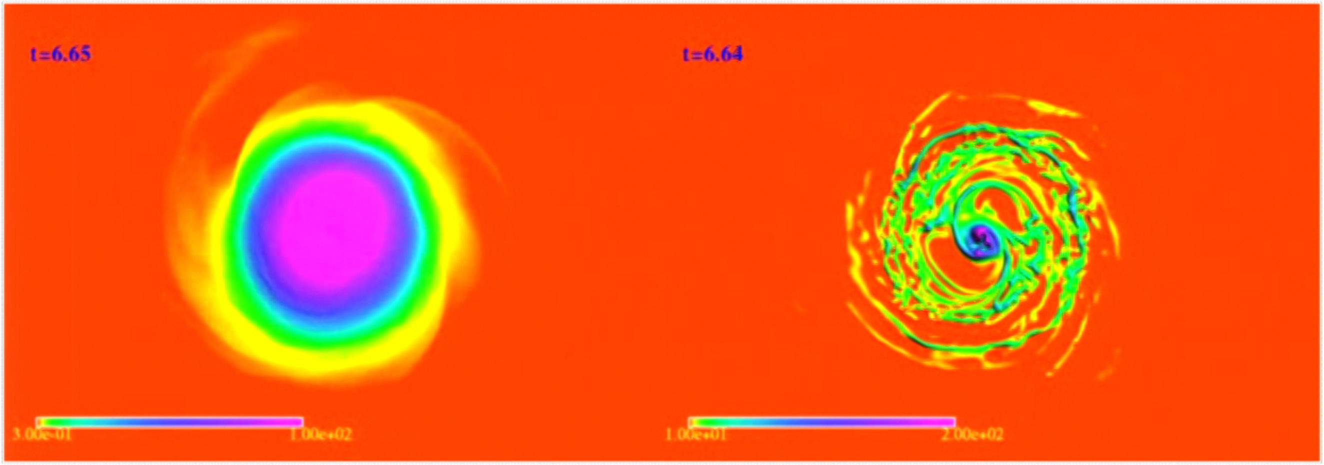
Density and vorticity



Density and vorticity



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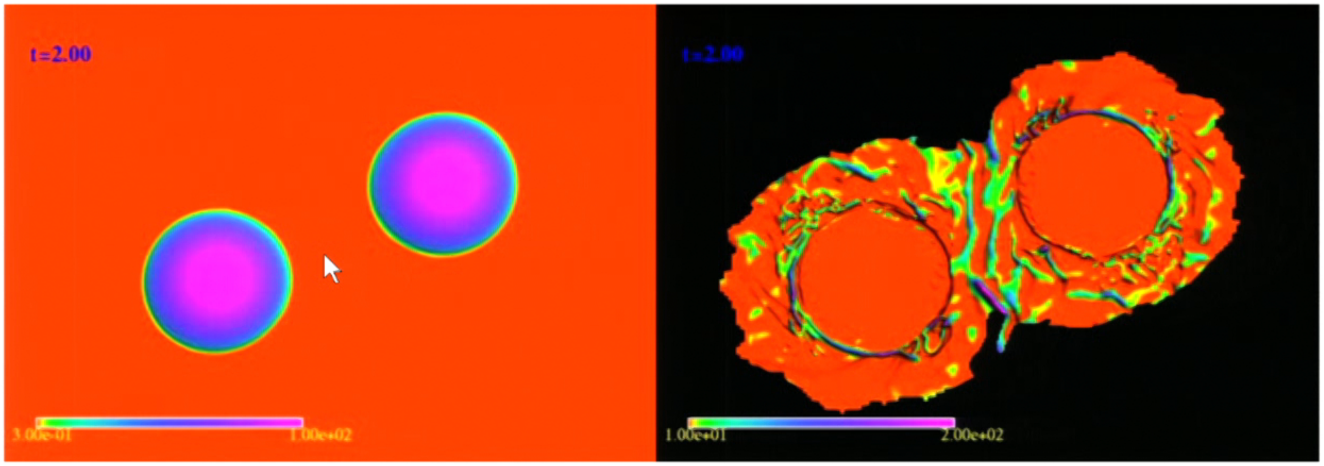
Density and vorticity



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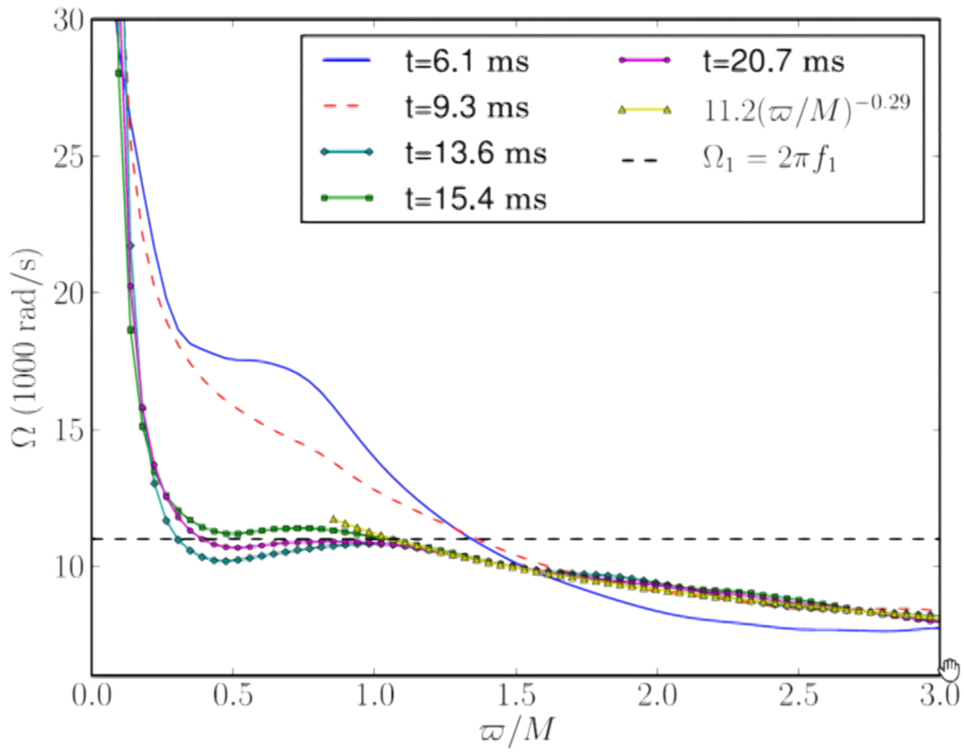
Rotation profile



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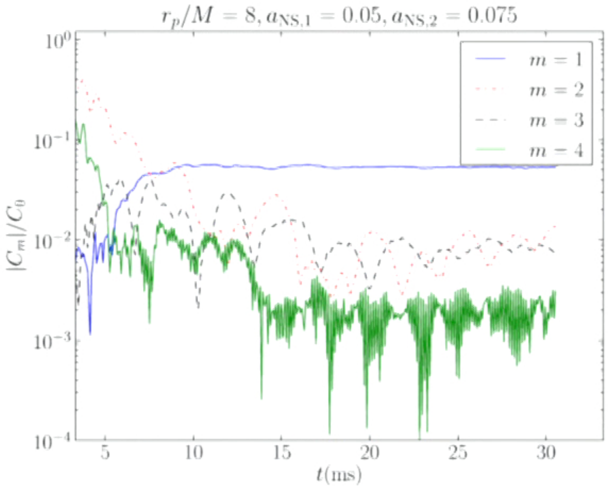
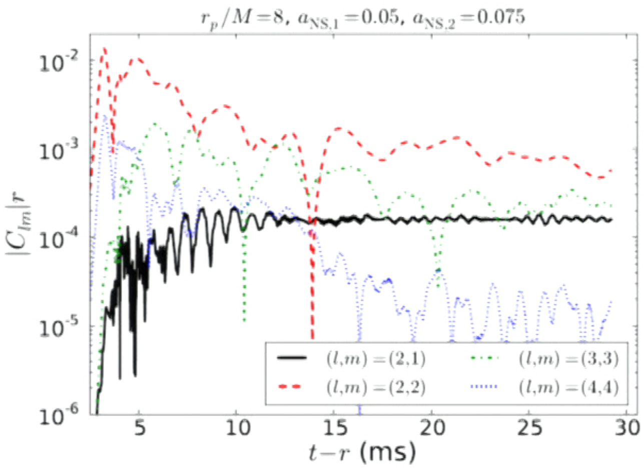
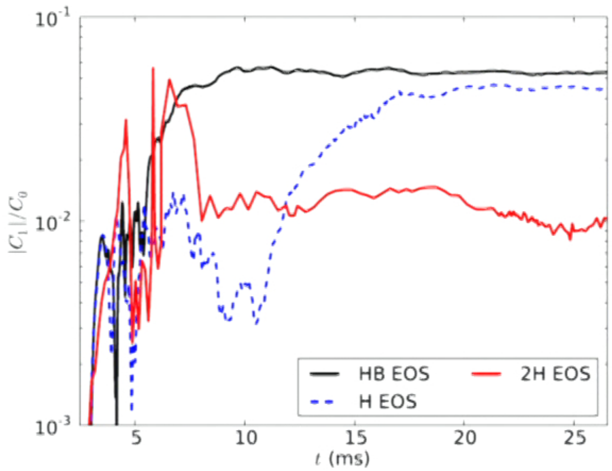
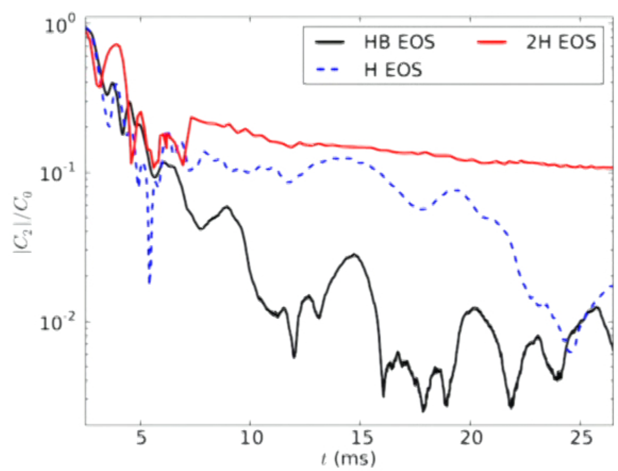
Growing $m = 1$ mode



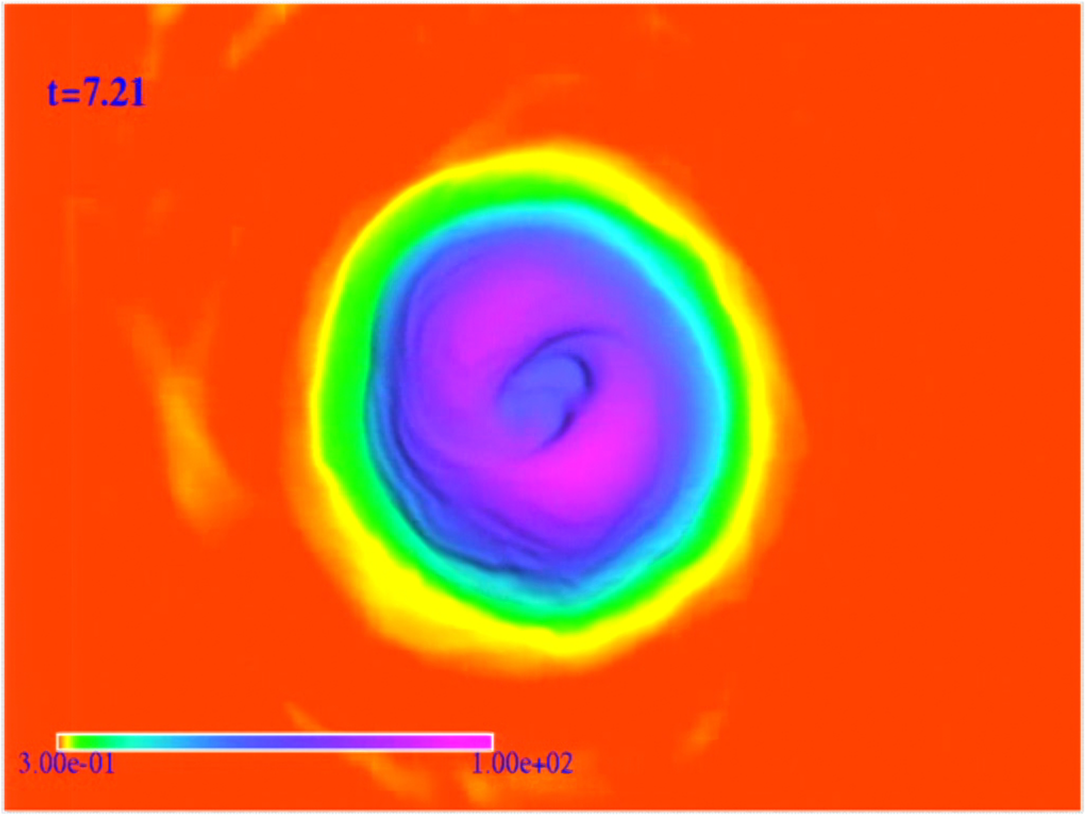


Effect of equation of state



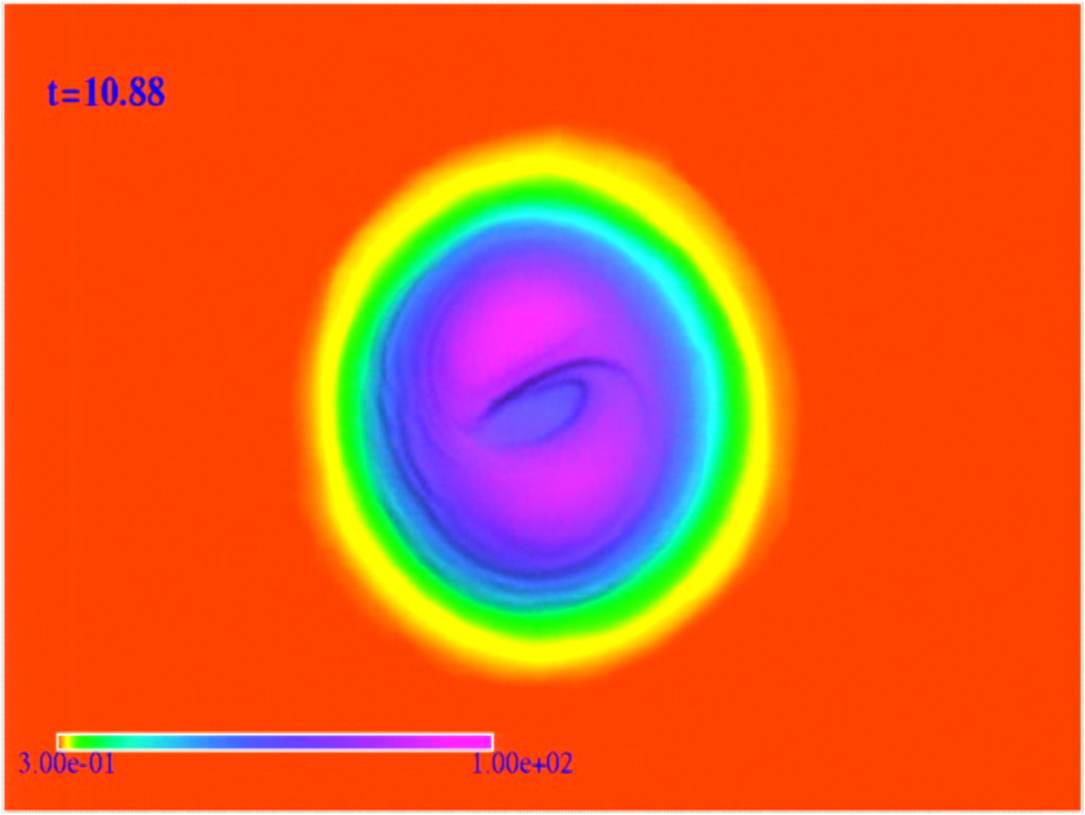


Double-core hypermassive



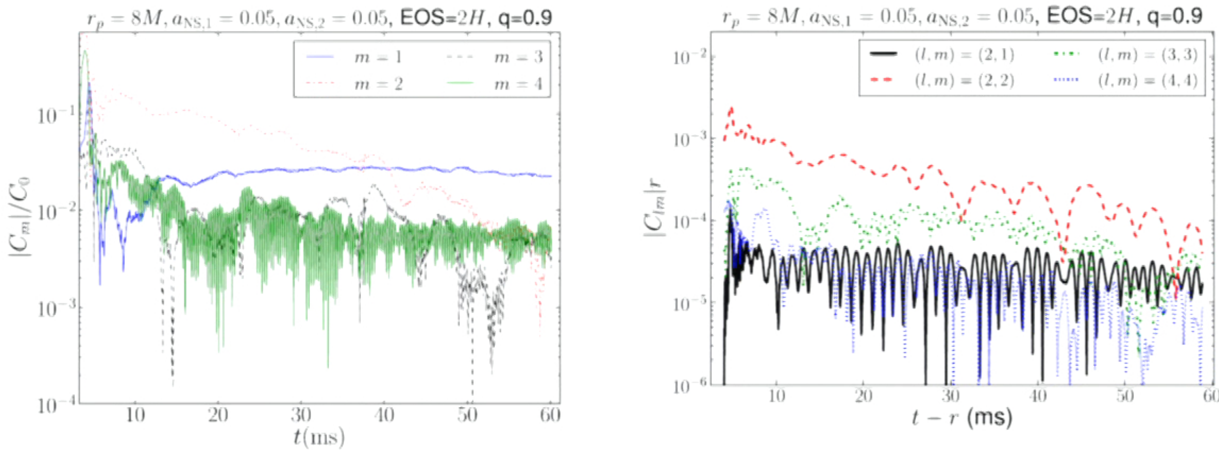
Instability can also arise from double-core hypermassive NSs (as arise in some very stiff EOSs)

Double-core hypermassive



Instability can also arise from double-core hypermassive NSs (as arise in some very stiff EOSs)

Unequal mass-ratio



2H EOS, $q = 0.9$

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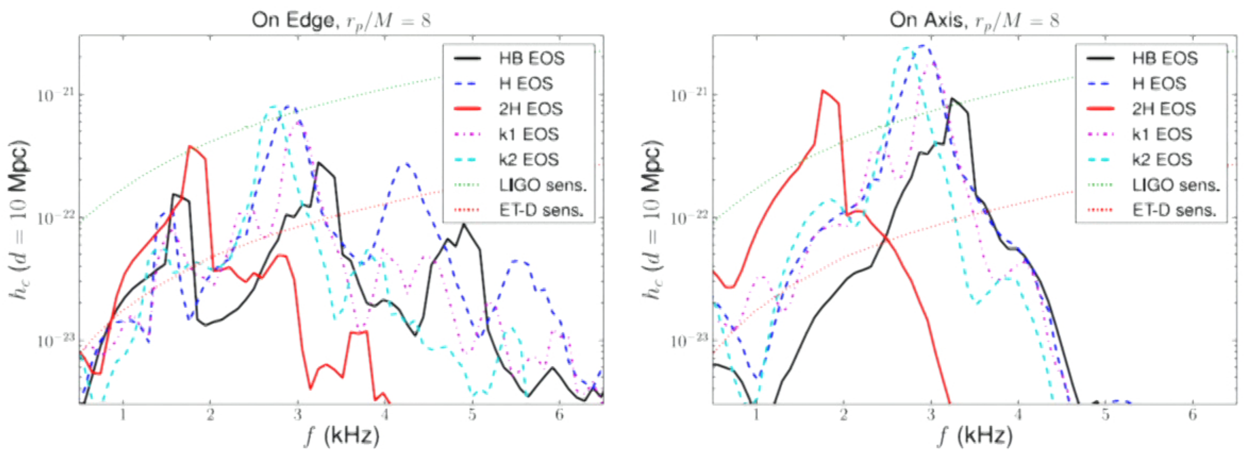
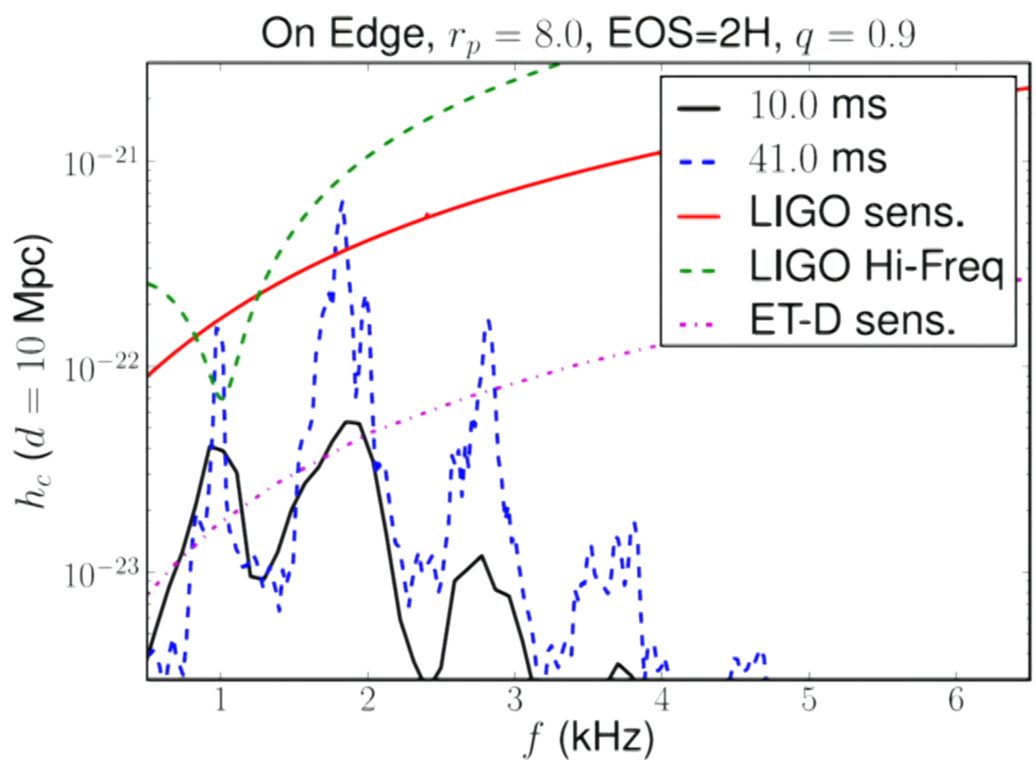
Gravitational waves



For $t_{\rm HMNS} \approx 10$ ms.

Importance of longer integration times



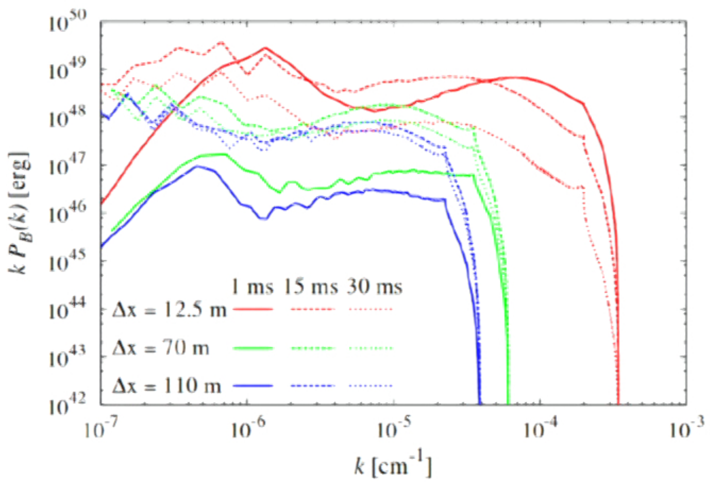
For $t_{\mathrm{HMNS}} \approx 10$ versus 40 ms.

Detecting gravitational waves

$$\mathrm{SNR}_{\mathrm{aLIGO}} \approx 2.8 \left(\frac{7 \times 10^{-24}\ \mathrm{Hz}^{-1/2}}{\sqrt{S_n(f_{m=1})}} \right) \left(\frac{C_{21} r M}{10^{-4}} \right) \left(\frac{1.5\ \mathrm{kHz}}{f_{m=1}} \right)^2 \left(\frac{T_{m=1}}{100\ \mathrm{ms}} \right)^{1/2} \left(\frac{10\ \mathrm{Mpc}}{r} \right)$$

- Comparable SNR results in Lehner et al. 2016 and Radice et al. 2016
- Detection of merger can reduce detection threshold for post-merger GW signal
- Lower frequency than bar modes ($m = 2$)
- Optimistically, signal may last up to a second?

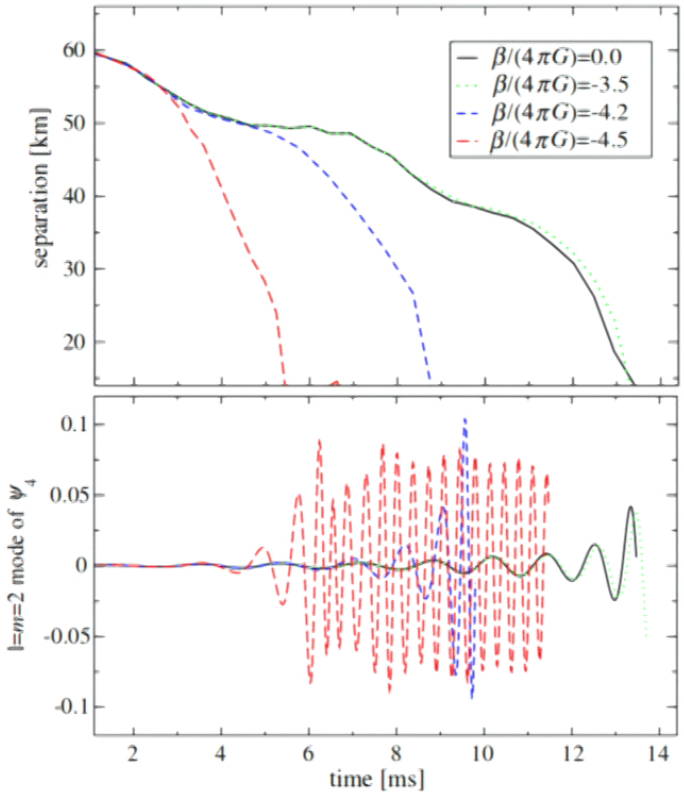
Theoretical challenge: Understanding dynamics of NS



Kiuchi et al. (2017)

- Lots of progress in understanding dynamics of hypermassive NSs by many groups . . .
- . . . but still lots of works to do
- Relevant microphysics: magnetic fields, hot equation of state, radiation transport, neutrinos, etc.
- Small scale (e.g. turbulent) physics is hard

Exotic scenarios



Barausse et al. (2013)

- Some alternative theories (e.g. scalar-tensor) predict differences only around matter
- Possibility of exotic compact objects (low mass BHs, boson stars, etc.)
- High frequency signal is essential for distinguishing

Conclusion

- Most interesting dynamics of neutron star mergers at high frequencies in GWs
- Probe perturbations of equilibrium stars in eccentric mergers
- Uncover highly dynamical oscillations of hypermassive stars
- Room from new discoveries and surprises in this regime
- Need better theoretical understanding

Excited to hear about ideas for observing kilohertz GWs.