Binary Neutron Star Mergers and Nuclear Physics

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Plan of the Lectures

1. Isolated and Binary Neutron Stars: an Introduction
2. Gravitational Wave Emission from Binary Neutron Star Mergers
3. Electromagnetic Emission from Binary Neutron Star Mergers
4. Observations of Binary Neutron Star Mergers

Gravitational Waves

Very brief math introduction

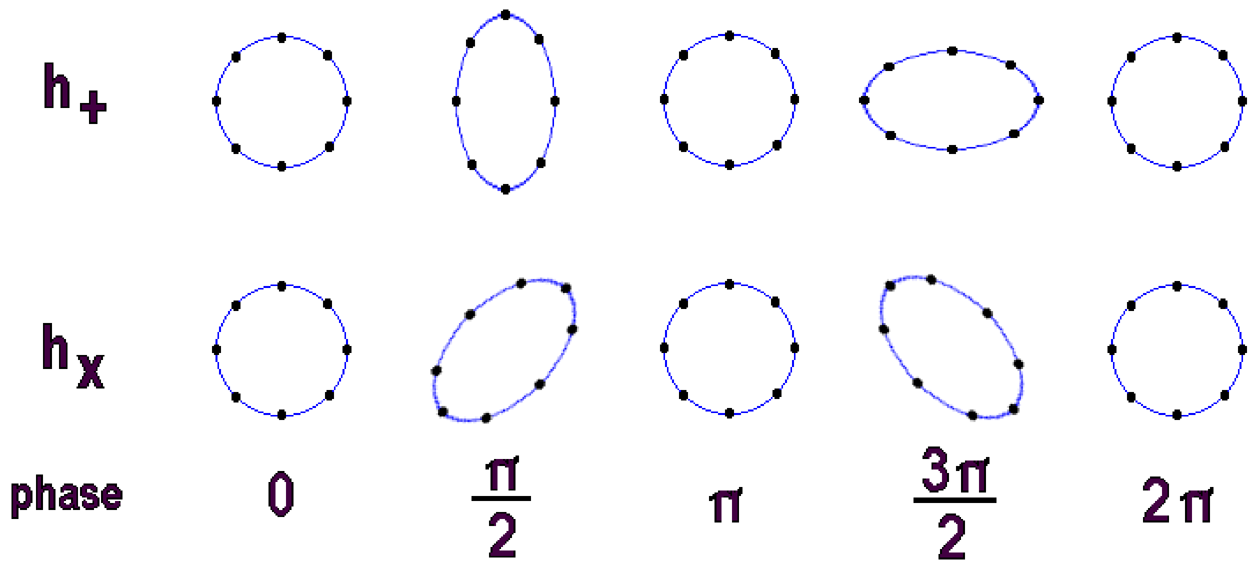
- Far away from sources: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $h_{\mu\nu} \ll 1$
- Einstein's eqs in vacuum: $G_{\mu\nu} = 0 \rightarrow \left(-\frac{\partial^2}{\partial t^2} + \nabla^2\right) h_{\mu\nu} = 0$
- Gravitational waves have two polarizations: $+$ and $\times$
- For example, gravitational wave along the z axis with + polarization:

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & 0 & 0 \\ 0 & 0 & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Note: $c = 1, G = 1$

Very brief math introduction

- They affect the proper distance between (free-falling) objects: $\frac{\Delta L}{L} \propto \frac{|h|}{2}$



Credits: Wm. Robert Johnston
http://www.johnstonsarchive.net/relativity/pictures.html

Very brief math introduction

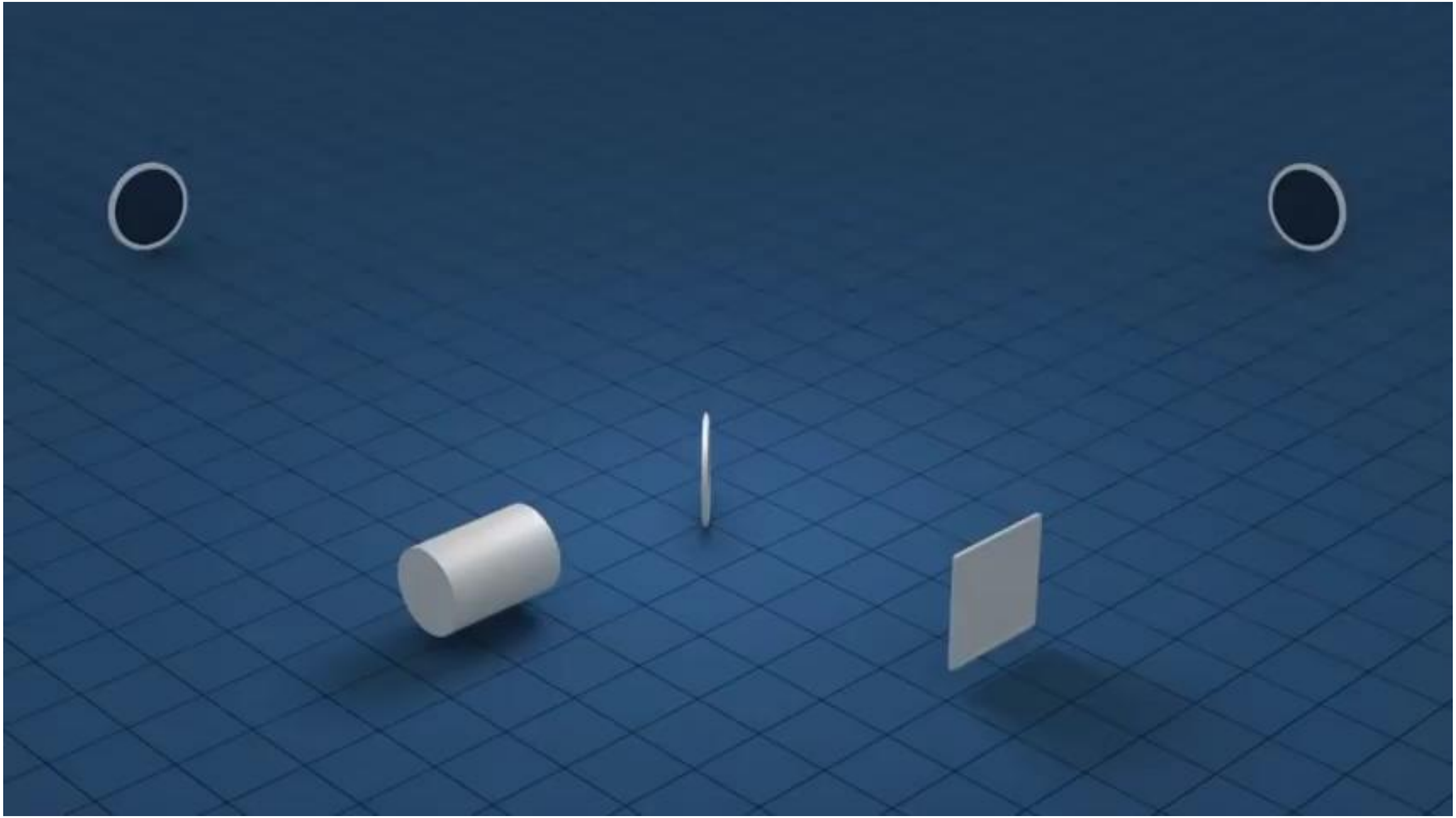
- For a binary composed of two point particles of mass $m = 1M_\odot$, orbiting at a fixed separation l_0, and with angular velocity $\omega = 2\pi f$ the total GW amplitude is given by

$$|h| = \frac{G}{c^4}\frac{2\, m\, l_0^2 \omega^2}{r} \sim 2.3 \times 10^{-22}\left(\frac{l_0}{100\ km}\right)^2\left(\frac{f}{100\ Hz}\right)^2\left(\frac{r}{100\ Mpc}\right)^{-1}$$

- The power emitted in gravitational waves is

$$L_{GW} = \frac{8G}{5c^5}\, m^2 l_0^4 \omega^6 \propto \frac{m^2}{l_0^2}(l_0^6 \omega^6) \sim [C]^2[v]^6$$

So, the power is largest for **compact sources** moving at **relativistic speeds**.

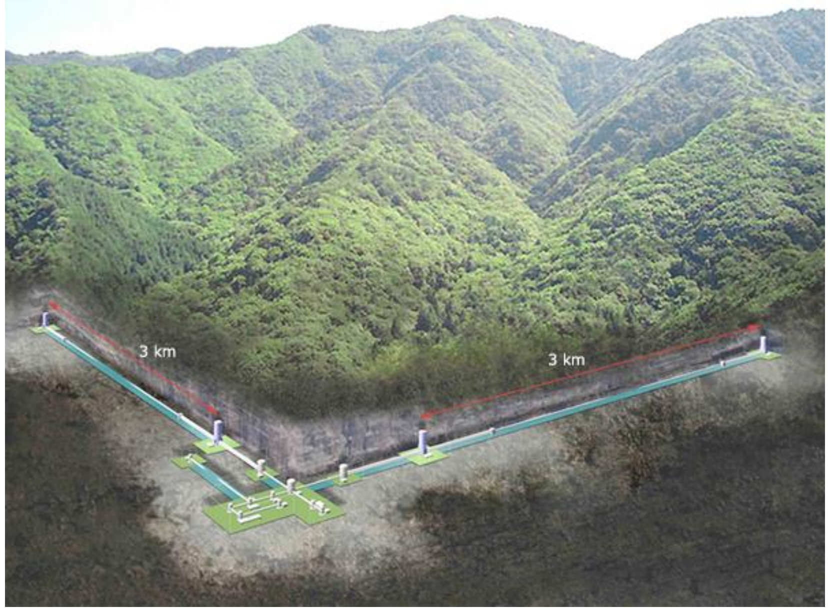


https://www.youtube.com/watch?v=UA1qG7Fjc2A

LIGO (Livingston LA, USA)

Virgo (Pisa, Italia)

GEO600 (Sarstedt, Germania)



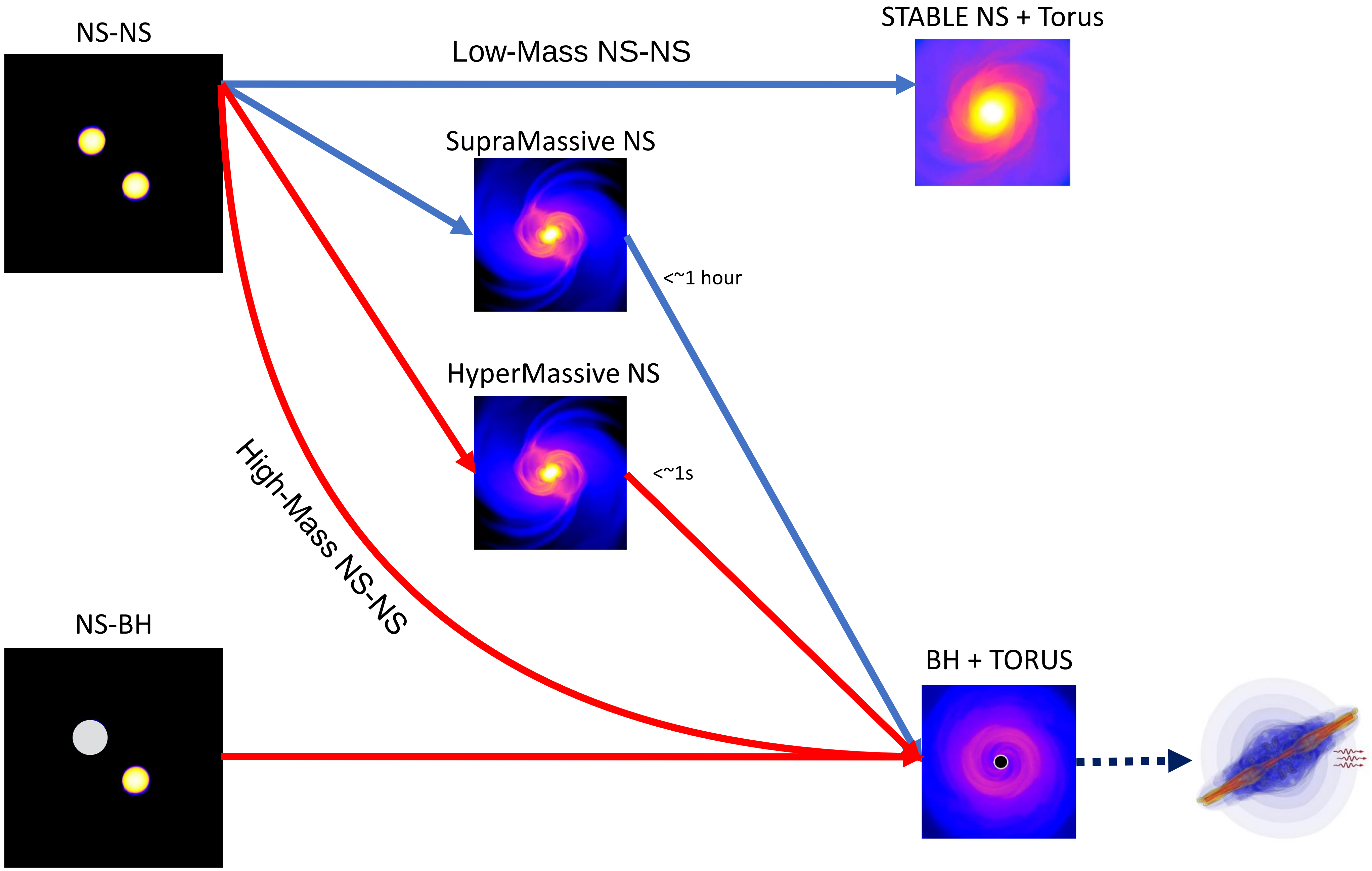
KAGRA (Giapppne)

References

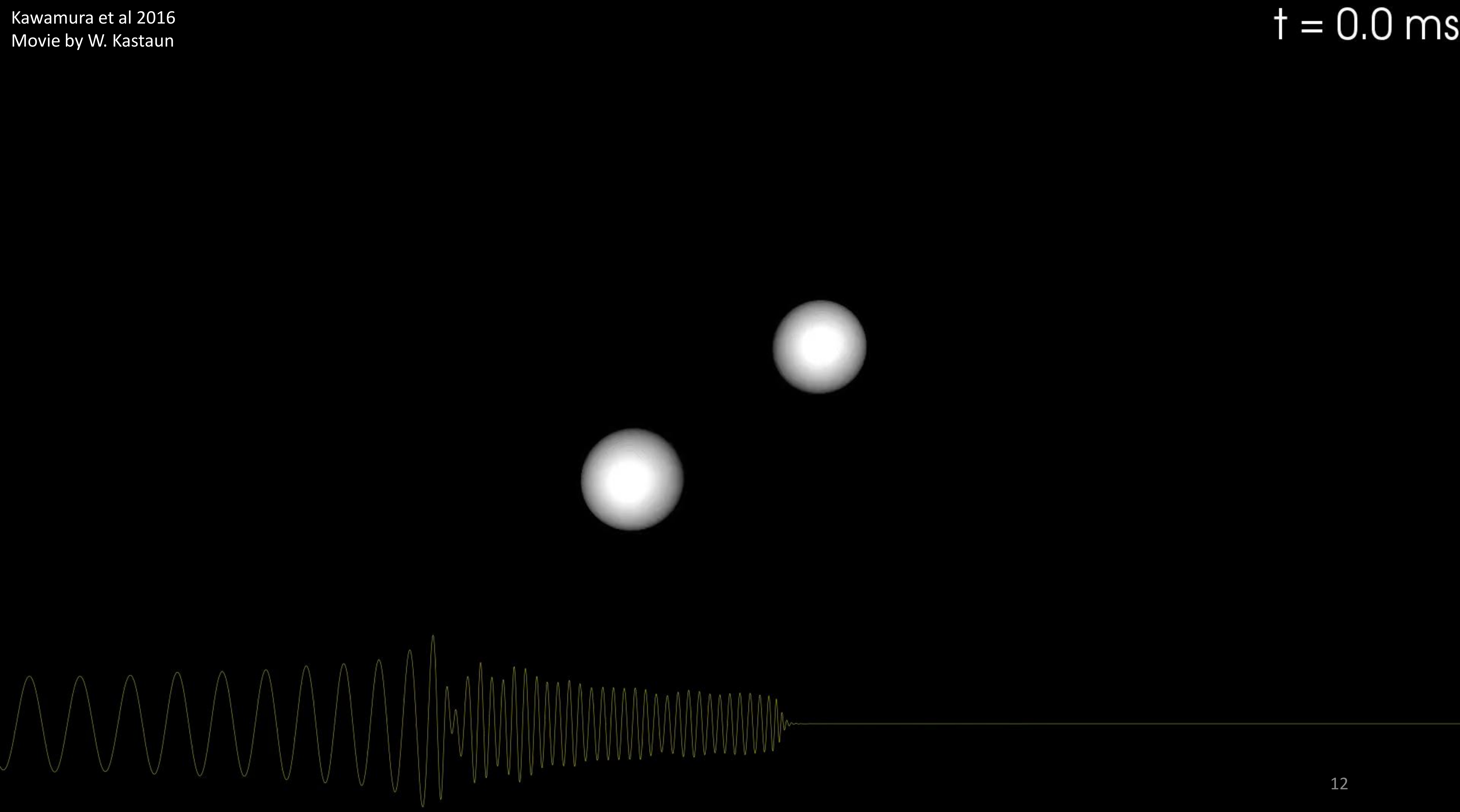
- Gravitational Waves Explained (PhD Comics and Umberto Cannella) https://youtu.be/4GbWfNHtHRg
- **A First Course in General Relativity** by Bernard Schutz (2009)
- **Gravitational waves : Volume 1, Theory and experiments** by Michele Maggiore (2007)
- Gravitational-Wave Observatory Status https://www.gw-openscience.org/detector_status/
- Gravitational-Wave Candidate Event Database (GraceDB) https://gracedb.ligo.org/

Matter Effects on BNS GW signals

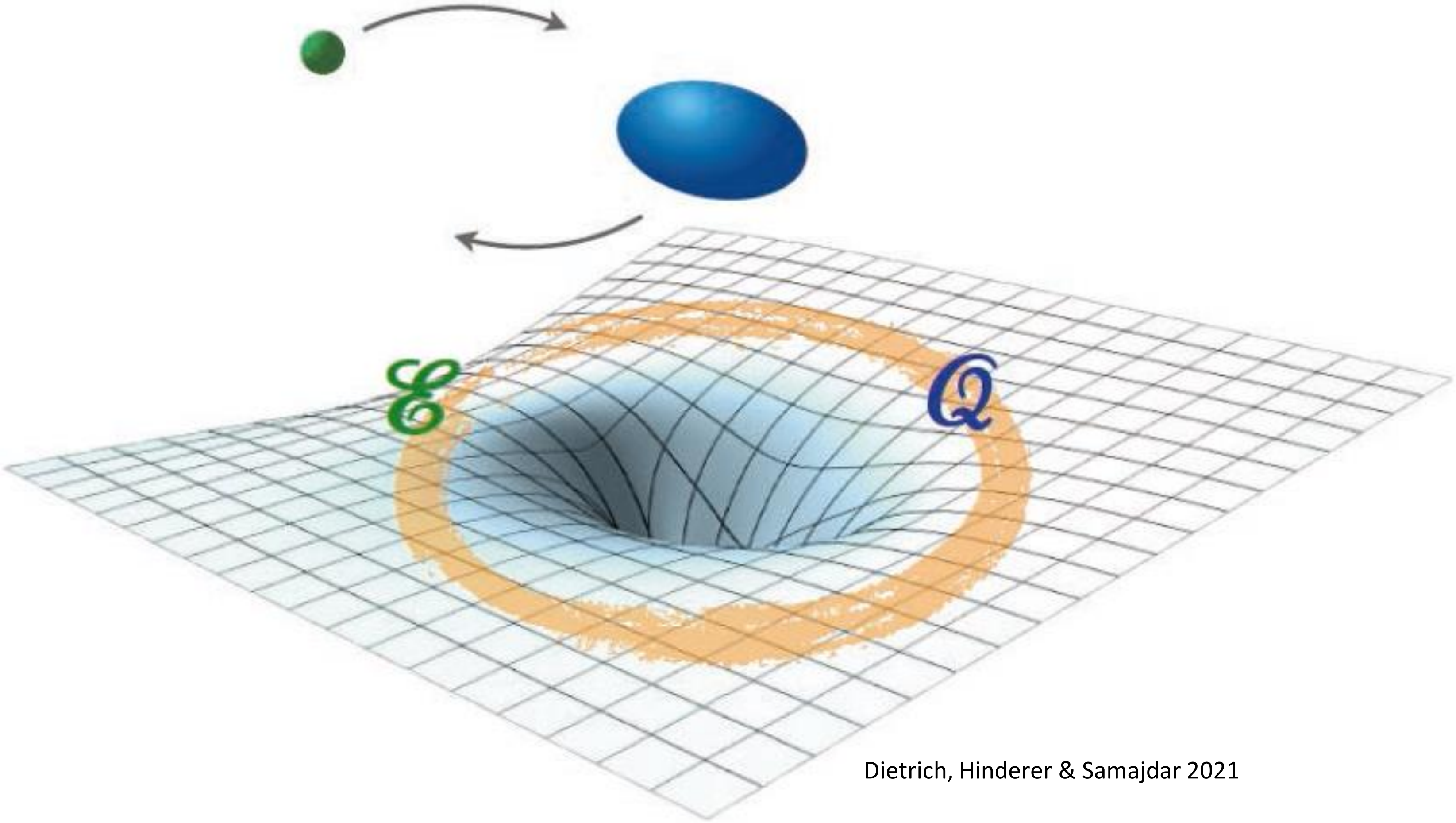
Neutron Star Binary Mergers



Kawamura et al 2016
Movie by W. Kastaun



Tidal Deformability



Dietrich, Hinderer & Samajdar 2021

For recent reviews, see

Chatziioannou 2020 https://link.springer.com/article/10.1007/s10714-020-02754-3

Dietrich, Hinderer & Samajdar 2021 https://link.springer.com/article/10.1007/s10714-020-02751-6

Newtonian Theory:

- external quadrupolar tidal field $\mathcal{E}_{ij} = \frac{\partial^2 \Phi_{ext}}{\partial x^i \partial x^j}$
- induced quadrupole moment $Q_{ij} = \int \delta\rho(\boldsymbol{x}) \left(x_i x_j - \frac{1}{3} r^2 \delta_{ij} \right) d^3x$
- the **dimensionless Love number** k_2 is then introduced by $Q_{ij} = -\frac{2}{3G} k_2 R^5 \mathcal{E}_{ij}$
- in general, it needs to be computed numerically
- important to note that for a rigid body $k_2 = 0$

General Relativity:

- An important quantity that can be measured is the **dimensionless tidal deformability**:

$$\Lambda = \frac{2}{3} k_2 \left[\left(\frac{c^2}{G} \right) \left(\frac{R}{m} \right) \right]^5$$

- In BNS systems one can more easily extract a combination of the tidal deformabilities of the two NSs:

$$\widetilde{\Lambda} = \frac{16}{13} \frac{(m_1 + 12 m_2) m_1^4 \Lambda_1 + (m_2 + 12 m_1) m_2^4 \Lambda_2}{(m_1 + m_2)^5}$$

Tidal deformability effects on GW signals

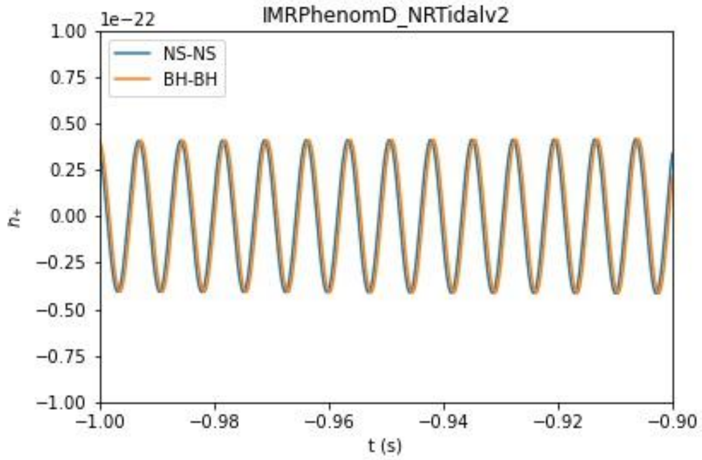
- Install LALSuite (python required): *pip install lalsuite*
- *lalsim-inspiral* is the code we are going to use (see *lalsim-inspiral --help* for a list of options)
- Example:
  lalsim-inspiral -a APPROX --domain=time --m1=M1 --m2=M2 --distance=D_in_Mpc --tidal-lambda1=LAM1 --tidal-lambda2=LAM2 --f-min=FMIN_in_Hz
- APPROX is the GW approximant you want to use (see --help for the full list)
- Here I will use one of those that include tidal effects, i.e., IMRPhenomD_NRTidalv2. See Dietrich et al 2019, https://ui.adsabs.harvard.edu/abs/2019PhRvD.100d4003D/abstract for details.

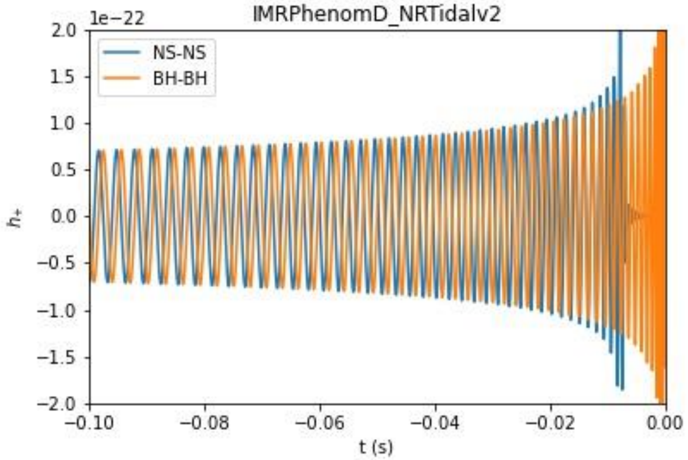
Example with H4 EOS

As an example, we will use one of the model of Dietrich et al 2019:

- $M_1 = M_2 = 1.3717$
- $\Lambda_1 = \Lambda_2 = 1013.4$
- *--f-min=50*
- --distance=100

A jupyter notebook is available here:
https://github.com/bgiacoma/notebooks/blob/main/plot_GW_lalsim_tidal.ipynb


IMRPhenomD_NRTidalv2
1e−22
NS-NS
BH-BH
h_+
t (s)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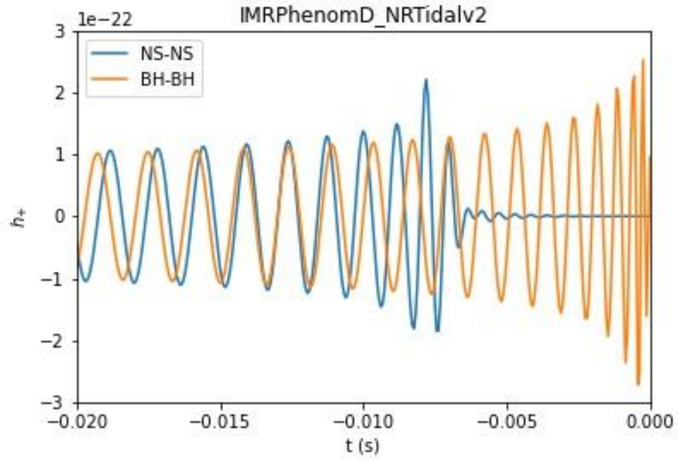
IMRPhenomD_NRTidalv2
1e−22
NS-NS
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h_+
t (s)

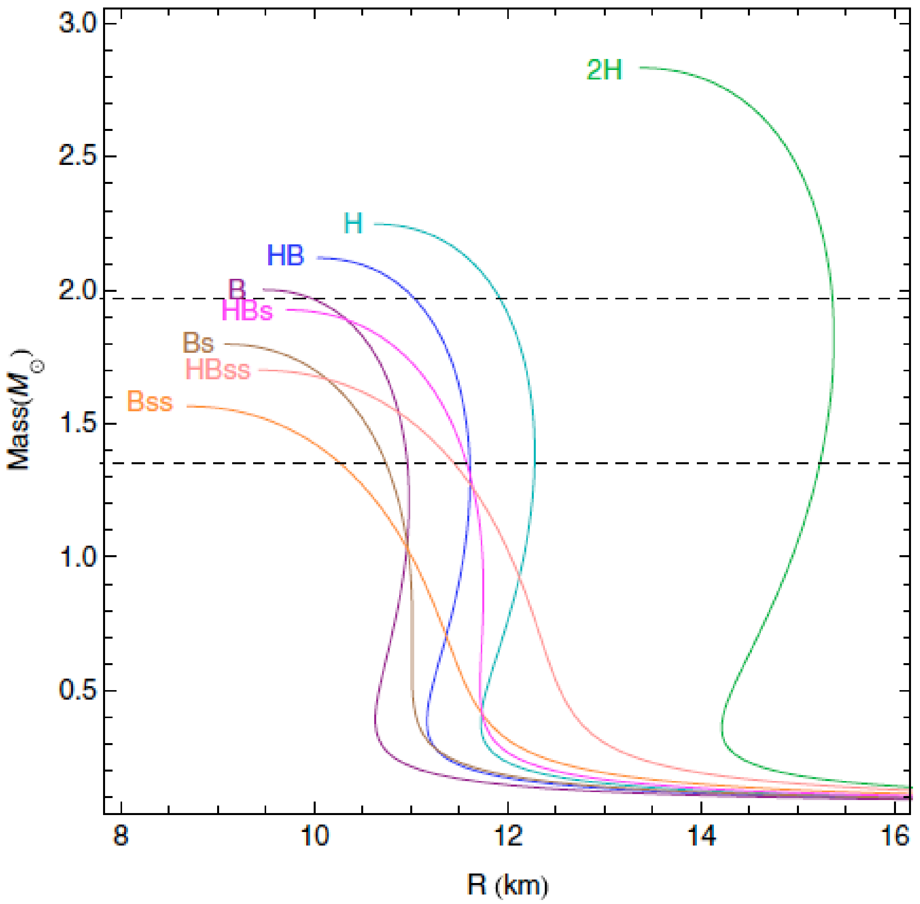
MATTER EFFECTS ON BNS GWS

(Read et al 2013, PRD 88, 044042)

We used the Whisky and SACRA codes to perform the first multi-code study of EOS effects on merger waveforms for equal-mass systems

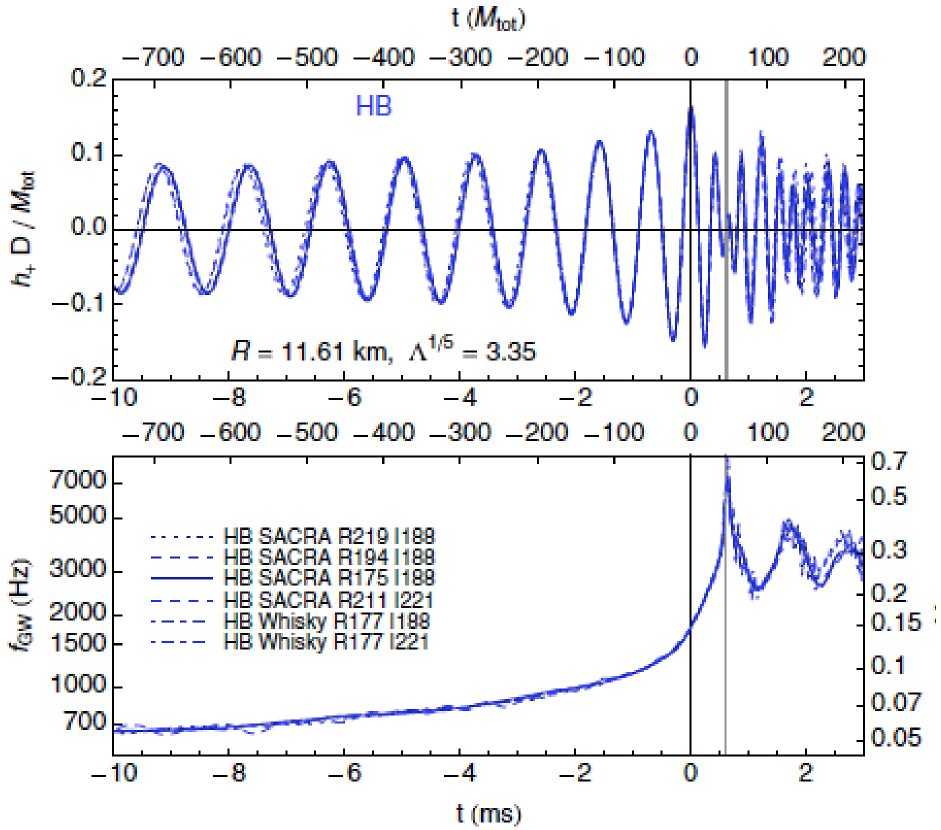
Used an extended set of "piecewise-polytropic" EOSs

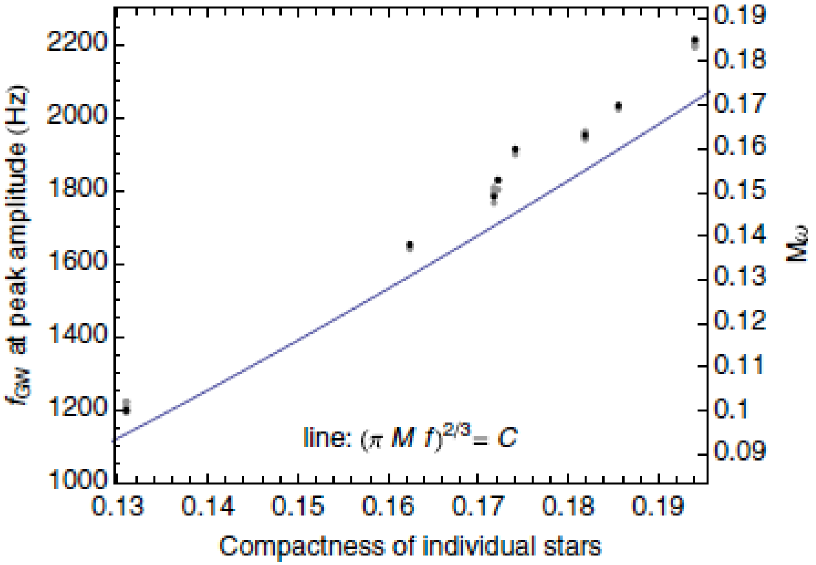
Estimated numerical errors by comparing between the codes and using different resolutions.

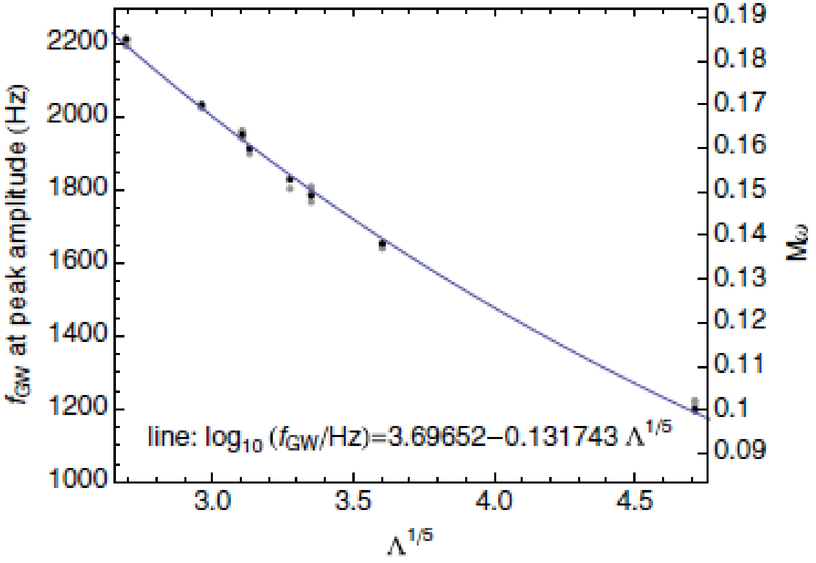


MATTER EFFECTS ON BNS GWS

(Read et al 2013, PRD 88, 044042)







GW frequency at merger is well correlated with tidal deformability and NS compactness (see also Bernuzzi et al 2014).

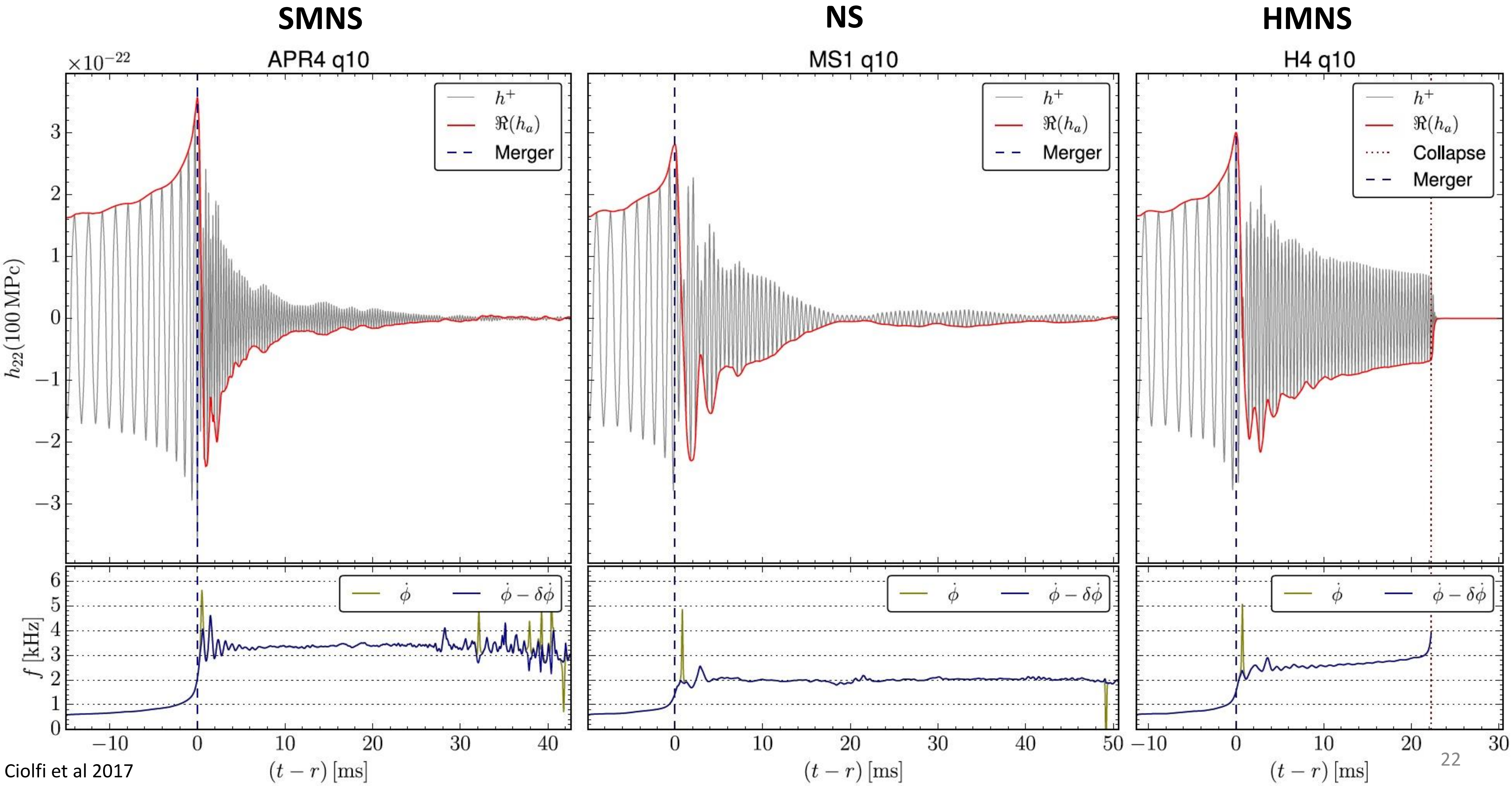
GWs in the INSPIRAL (Recap)

- Dominant Parameters:
  - Masses and Mass Ratios
  - Equation of State (Tidal Deformability)

- Minor corrections (maybe):
  - Spin (only relevant if $\chi > 0.05$). Fastest spinning NS observed in an NS-NS system (PSR J0737-3039A) has $\chi \sim 0.02$ $(\mathrm{P} \sim 22.7\ ms)$.
  - Eccentricity. This is relevant only for BNS systems formed via dynamical capture in star clusters and globular clusters.

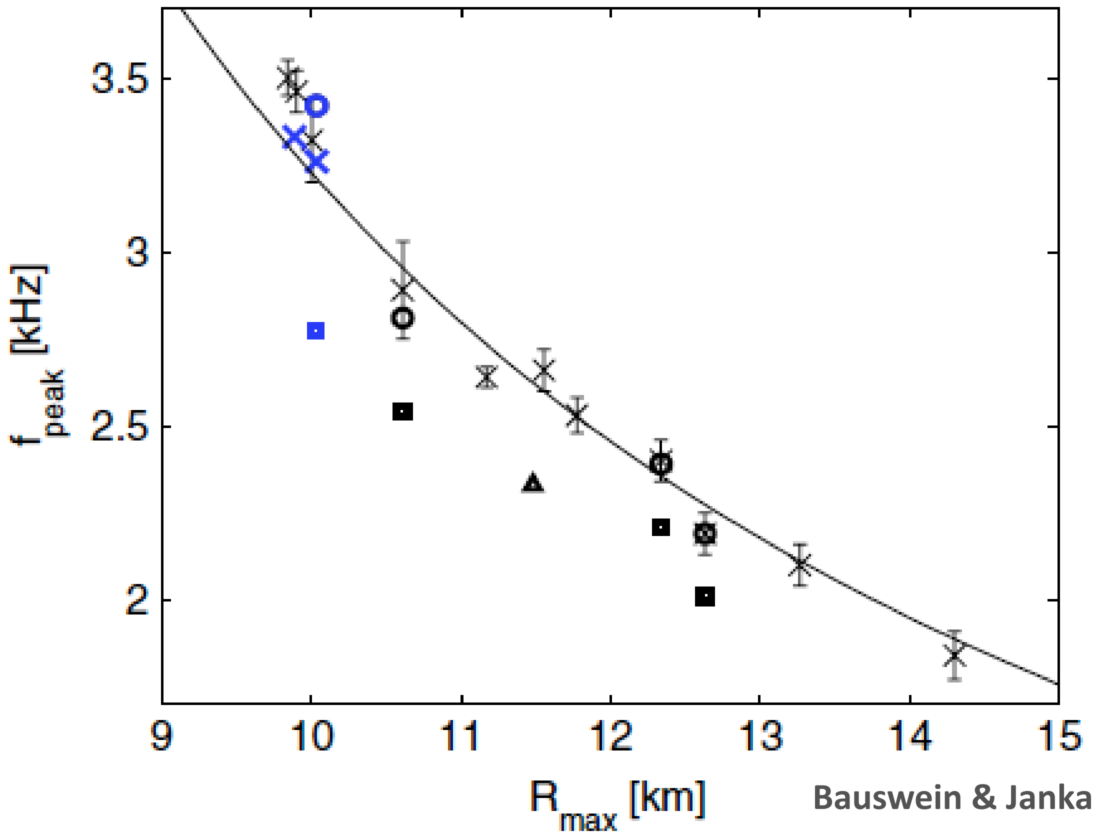
POST-MERGER GW SIGNAL

GW: EOS Effects on the Post-Merger Phase



Ciolfi et al 2017

GW: EOS Effects on the Post-Merger Phase

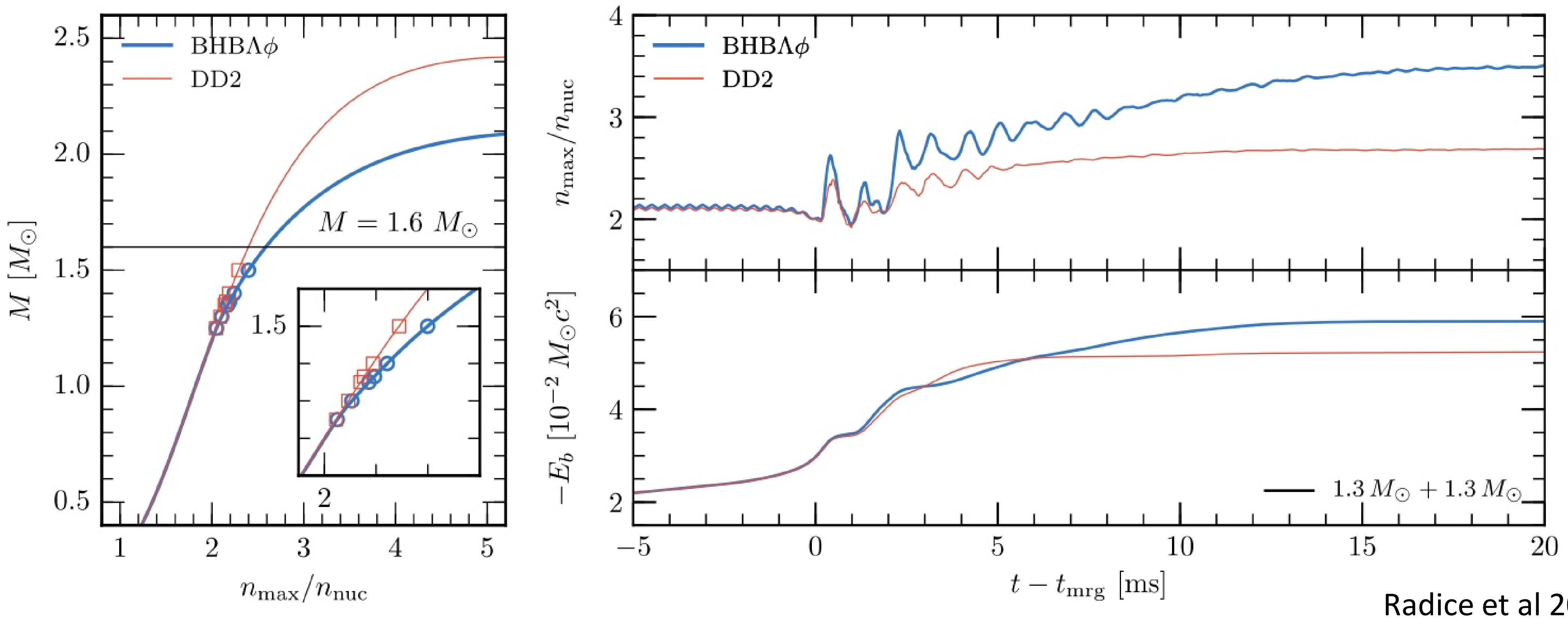


Bauswein & Janka 2012

Bauswein & Janka 2012, Hotokezaka et al 2013: frequency peak in GWs emitted after merger can constrain EOS.

High sensitivities at f>~1Khz required for post-merge signal!

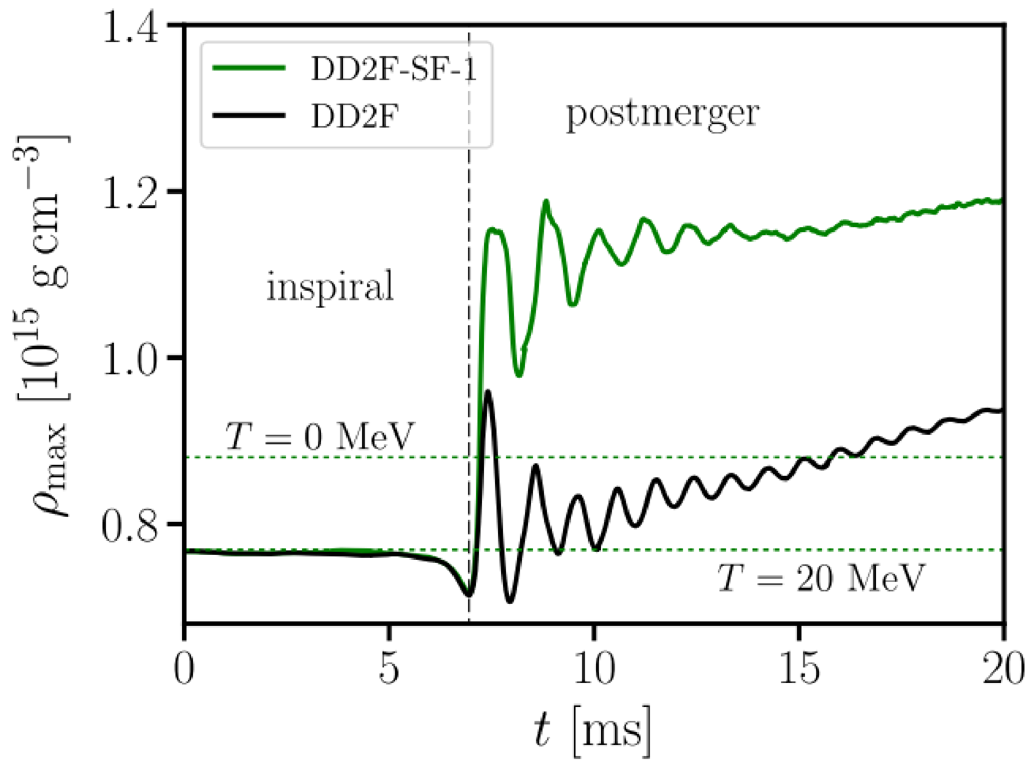
GW: EOS Effects on the Post-Merger Phase



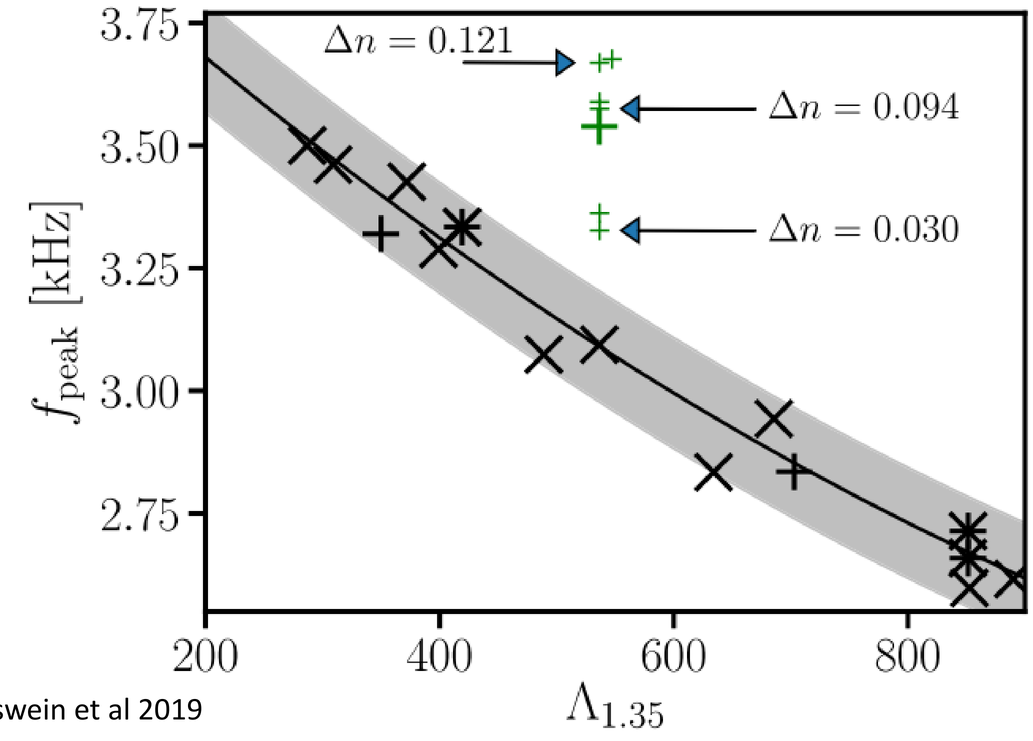
Radice et al 2017

EOS identical at “low” (inspiral) densities, but different at post-merger densities (phase transition effects).

Phase transitions in the post-merger



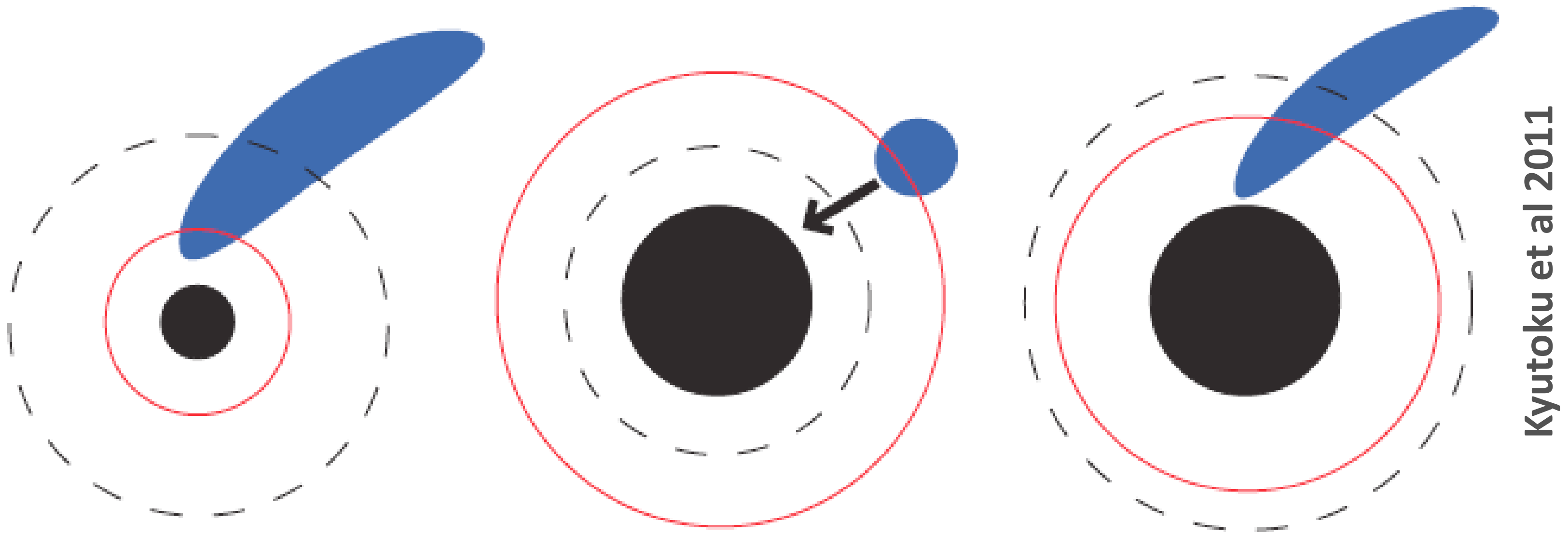
Bauswein et al 2019



A phase transition to a deconfined-quark-matter core affects significantly the post-merger GW peak.

NS-BH MERGERS

BH-NS

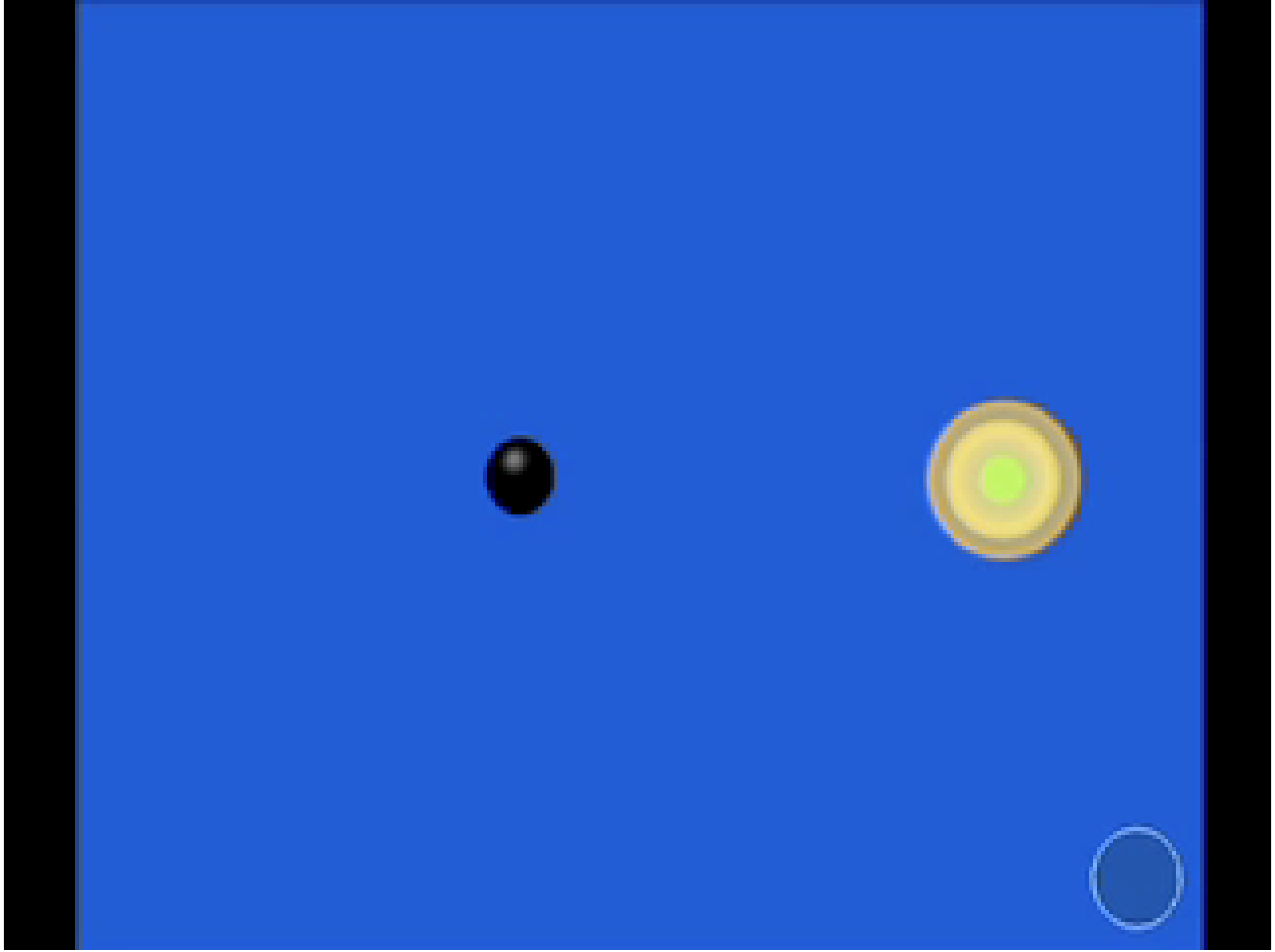


NS disrupted outside ISCO. Only inspiral.

no disruption. GWs very similar to BBH and composed by inspiral, merger and ringdown.

mass transfer near ISCO. Both inspiral and merger are present in the GWs.

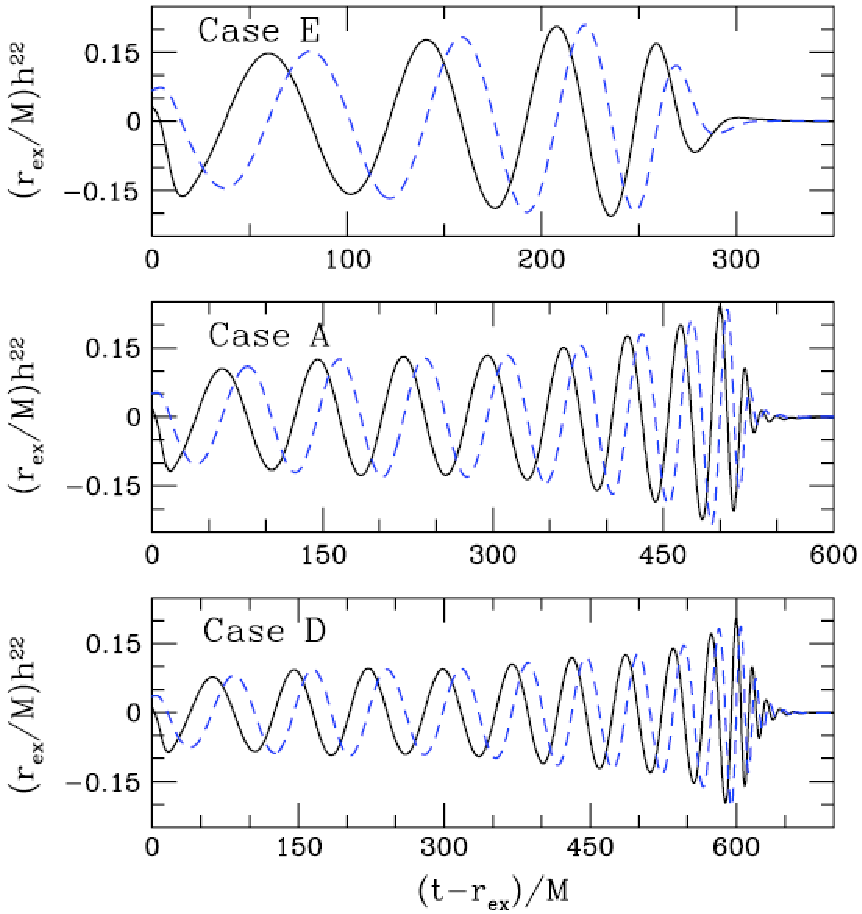
Scenario depends on mass-ratio, BH spin, and NS compactness

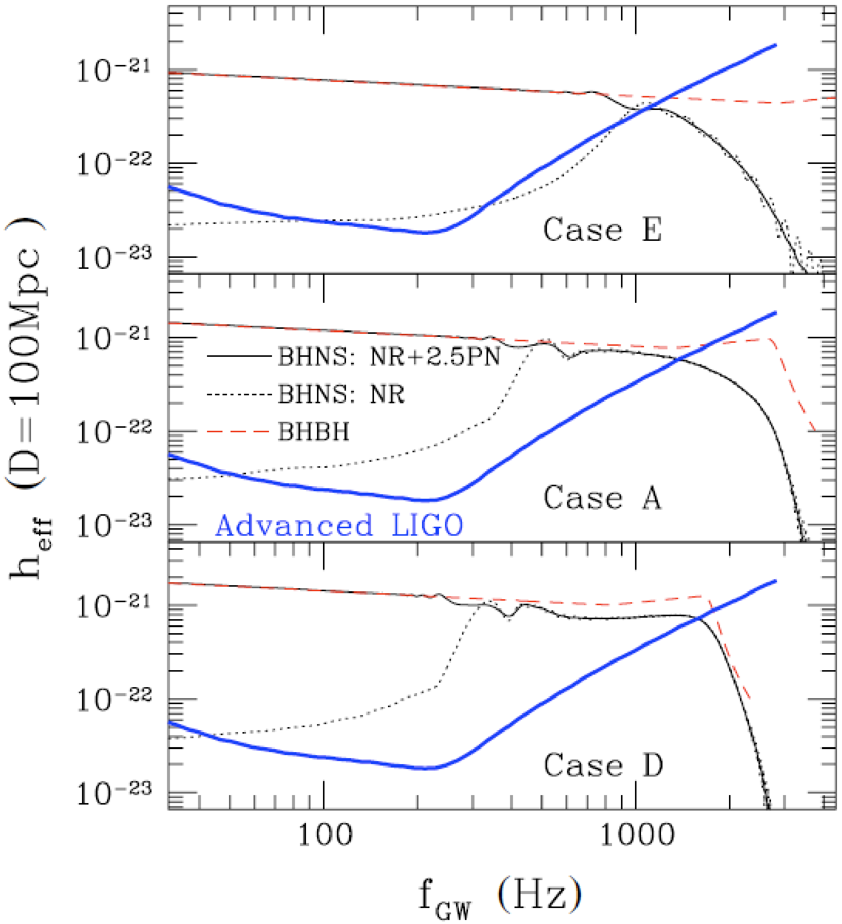


http://research.physics.illinois.edu/cta/movies/cbm/bhns.html

GW FROM BH-NS (NO SPIN)

Etienne et al 2009





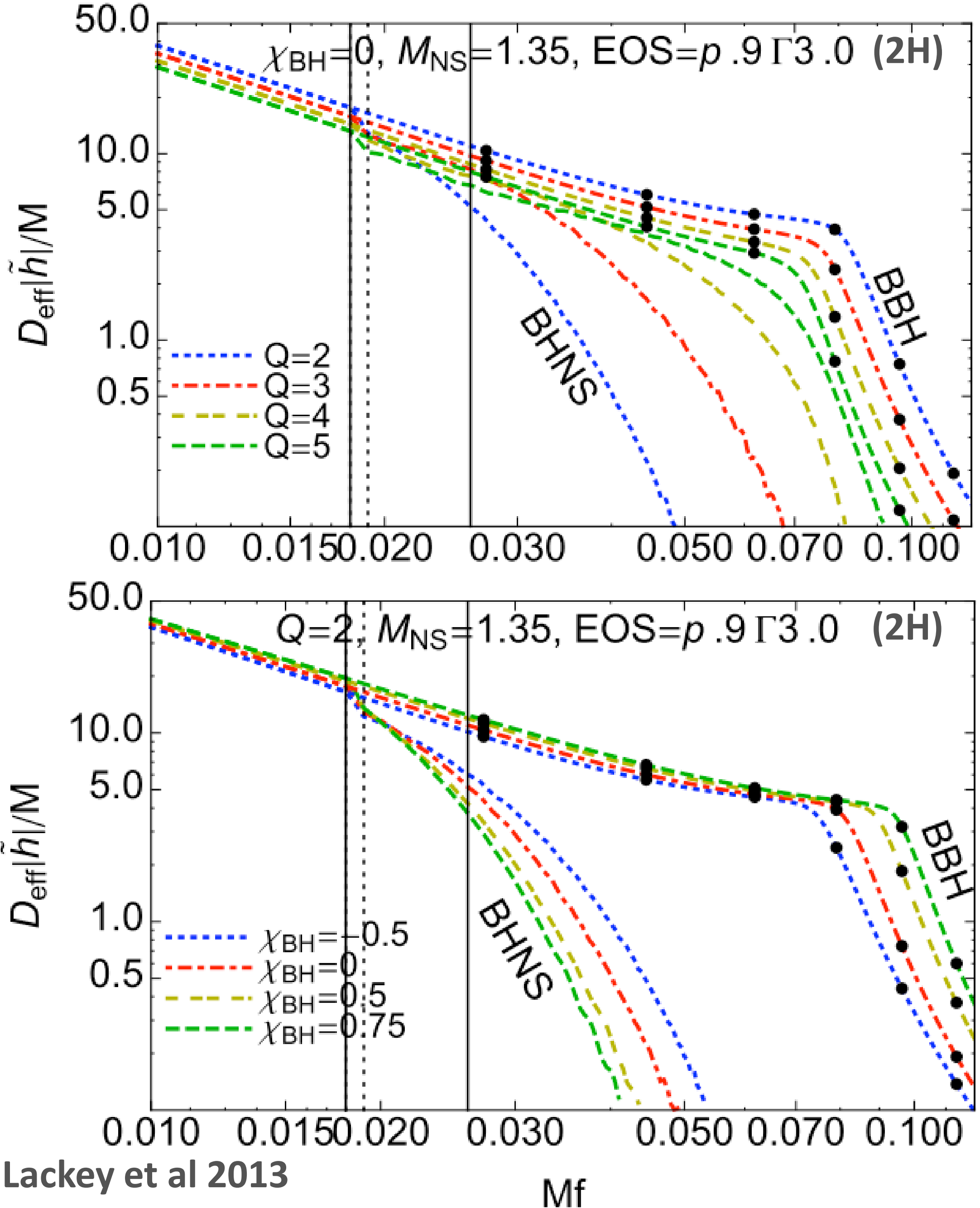
E: Q=1

A: Q=3

D: Q=5

Difficult to detect difference with BBH if low spin and high Q. Note how when increasing Q the frequency cutoff gets close to the one for BBH.

NS-BH: matter effects

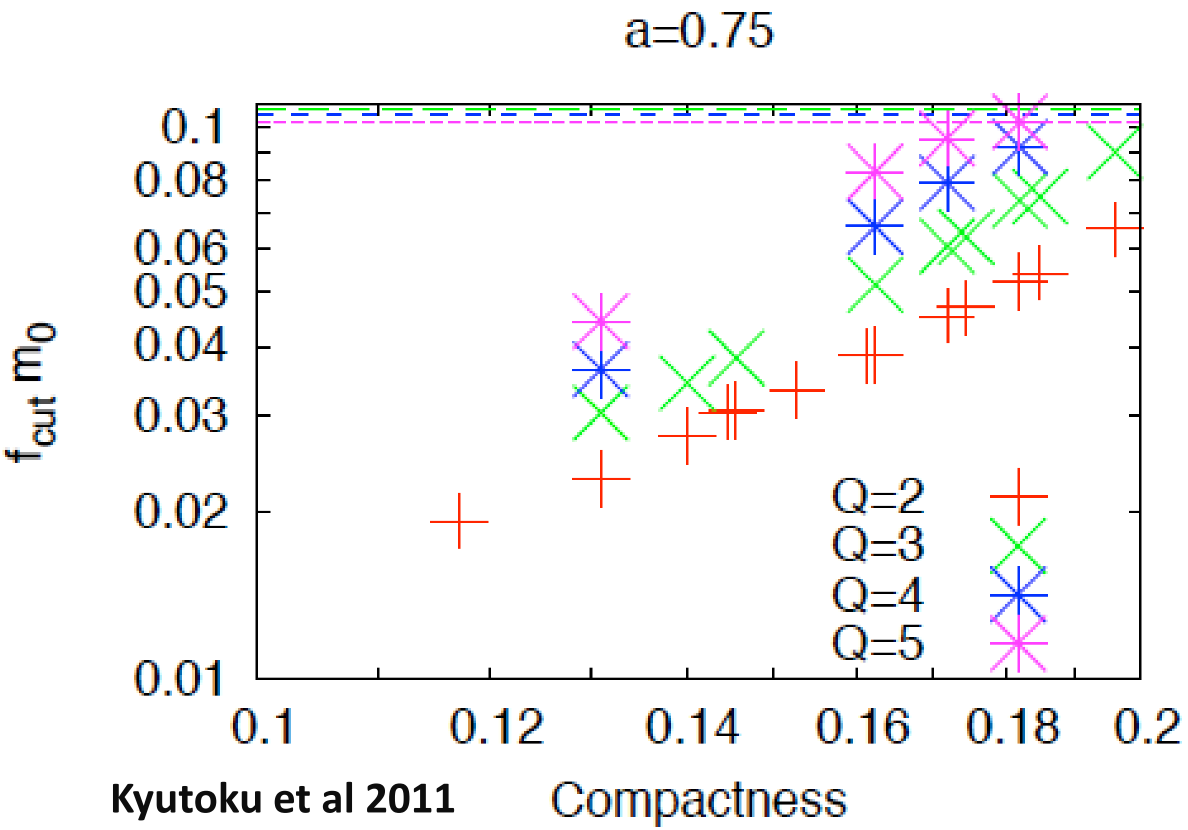


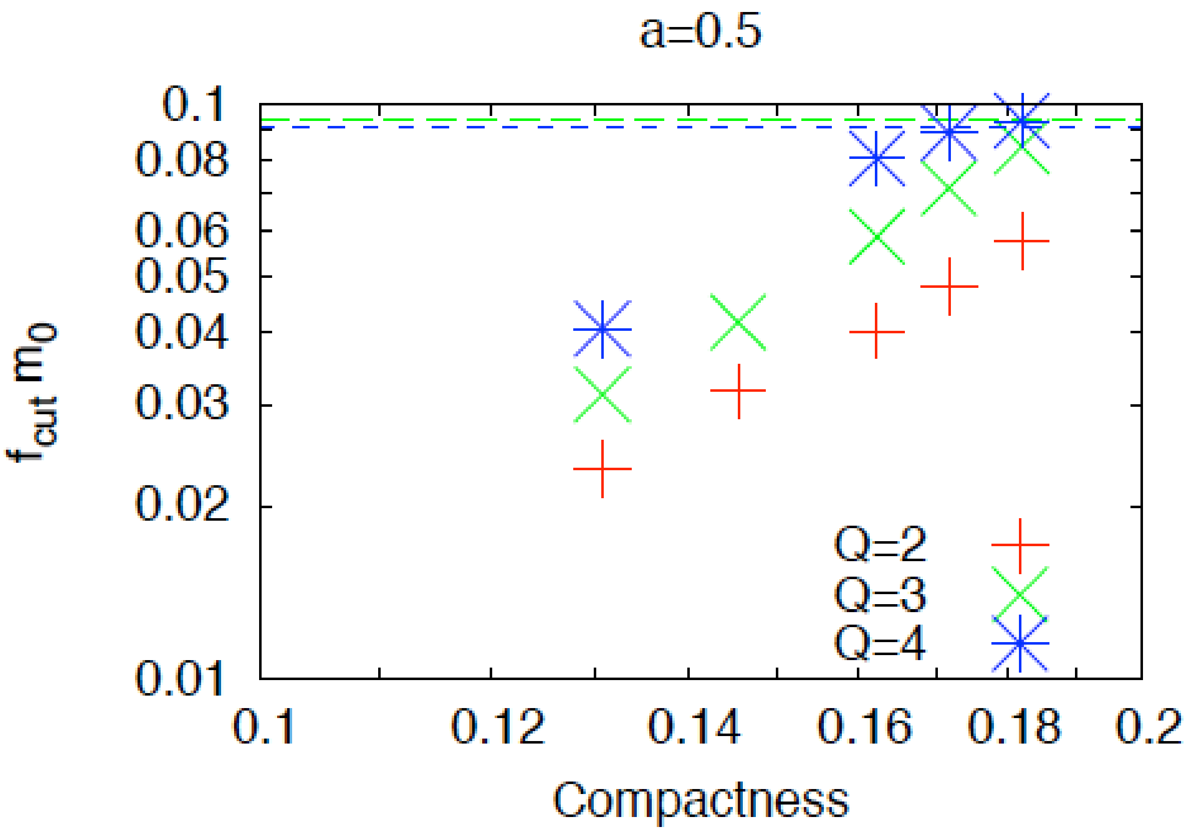
Lackey et al 2013

Lackey et al 2013 performed 134 simulations of NS-BH mergers with different EOS, BH masses and spins

higher Q and small spin reduce difference with BBH GWs

NS-BH: EOS effects





Kyutoku et al 2011

NS compactness influence the GW frequency cutoff.

Some Review Articles

- Shibata & Taniguchi 2011
  https://link.springer.com/article/10.12942/lrr-2011-6
- Faber & Rasio 2012
  https://link.springer.com/article/10.12942/lrr-2012-8
- Paschalidis 2017
  https://ui.adsabs.harvard.edu/abs/2017CQGra..34h4002P/abstract
- The Physics and Astrophysics of Neutron Stars (2018)
  https://link.springer.com/book/10.1007/978-3-319-97616-7
- Dietrich, Hinderer & Samajdar 2021
  https://ui.adsabs.harvard.edu/abs/2021GReGr..53...27D/abstract
- Foucart 2020
  https://www.frontiersin.org/articles/10.3389/fspas.2020.00046/full
- Ciolfi 2020
  https://www.frontiersin.org/articles/10.3389/fspas.2020.00027/full

Waveform Catalogues

- CoRe database: http://www.computational-relativity.org/gwdb/
- SACRA Gravitational Waveform Data Bank: https://www2.yukawa.kyoto-u.ac.jp/~nr_kyoto/SACRA_PUB/catalog.html
- Riccardo Ciolfi's BNS GW database: https://bitbucket.org/ciolfir/bns-waveforms/src/master/
- SXS Gravitational Waveform Database: https://data.black-holes.org/waveforms/index.html