Title: General Relativistic Simulations of Binary Neutron Star Mergers

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Abstract: I will report on some recent results obtained using the fully general relativistic magnetohydrodynamic code Whisky in simulating equal and unequal-mass binary neutron star (BNS) systems during the last phases of inspiral, merger and collapse to black hole surrounded by a torus. BNSs are among the most important sources of gravitational waves which are expected to be detected by the current or next generation of gravitational wave detectors, such as LIGO and Virgo, and they are also thought to be at the origin of very important astrophysical phenomena, such as short gamma-ray bursts. I will in particular describe both the gravitational wave signals generated by these sources and the properties of the tori that can be formed. I will also describe how the Effective One Body (EOB) model can be used to accurately compute the gravitational wave signal generated during the inspiral of BNSs by comparing it with the longest general relativistic numerical simulations of BNSs performed up to now.

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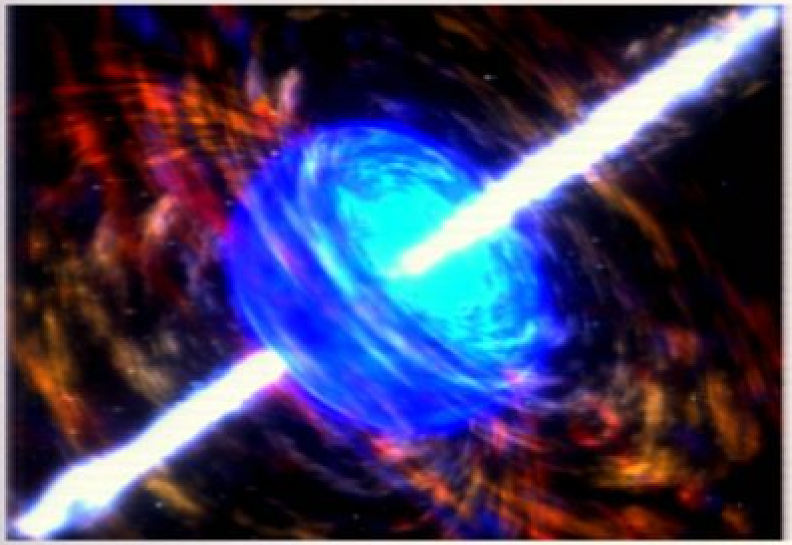

Credit: NASA/SkyWorks Digital

Binary neutron stars mergers are also possible sources for short gamma-ray bursts

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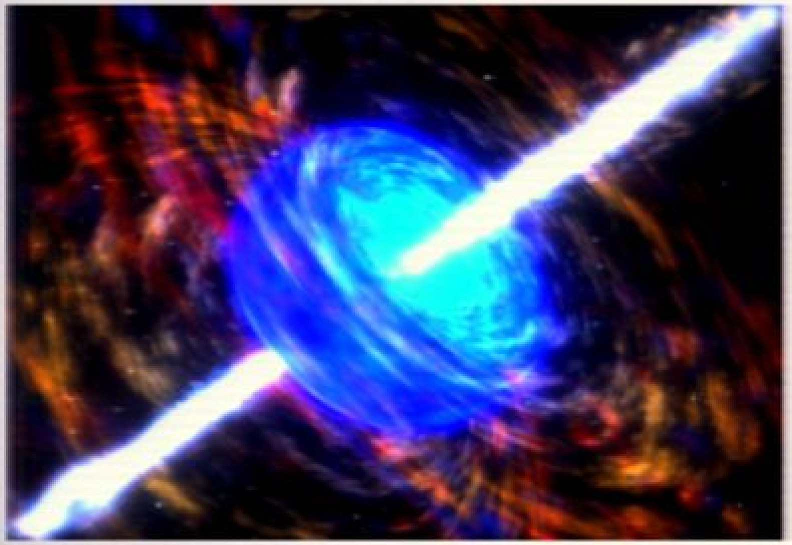

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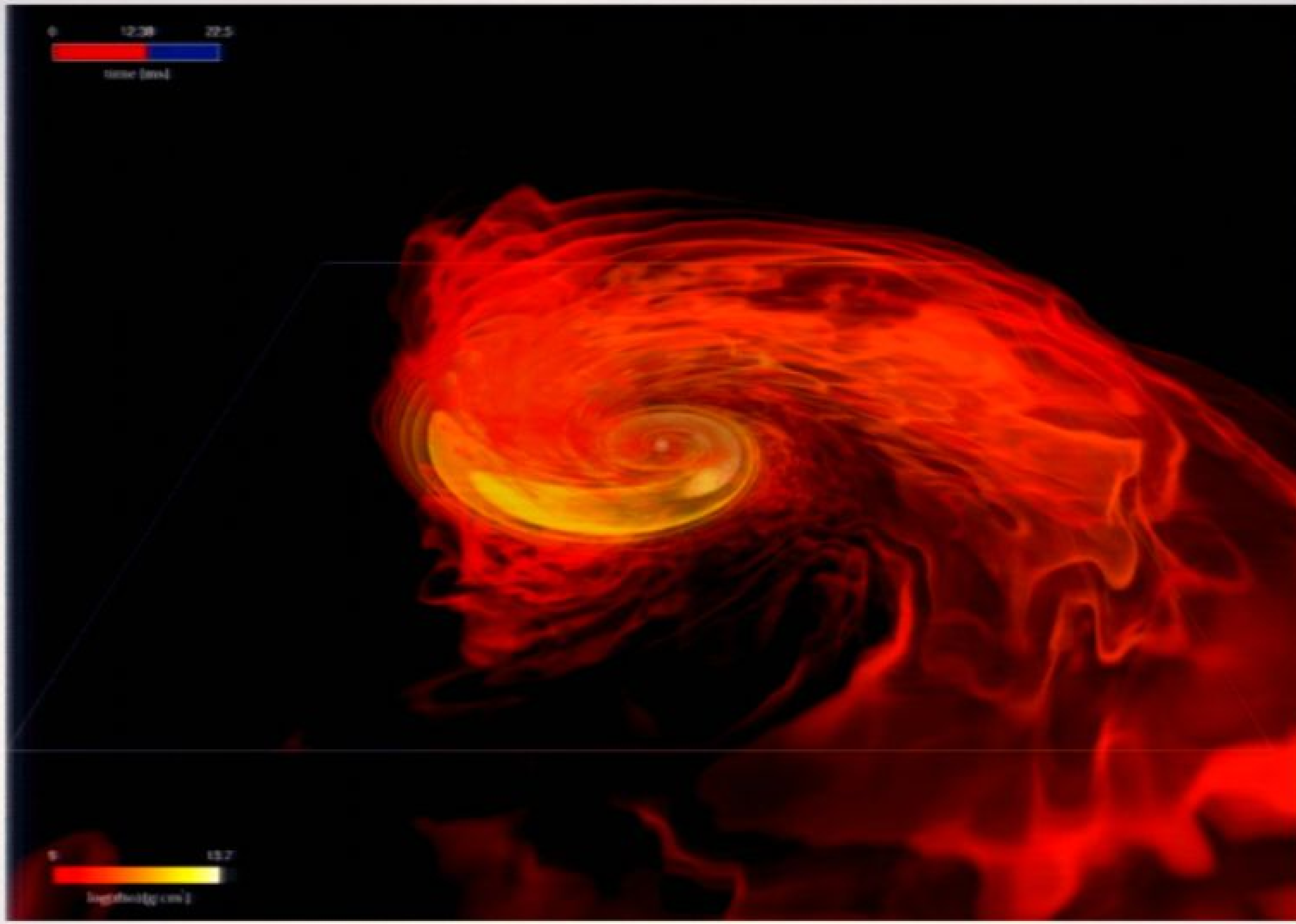
UNEQUAL-MASS BNS: TORUS FORMATION AND GWS



Rezzolla, Baiotti, Giacomazzo, Link, Font 2010 CQG 27, 114105

TORUS PROPERTIES: UNEQUAL-MASS CASE

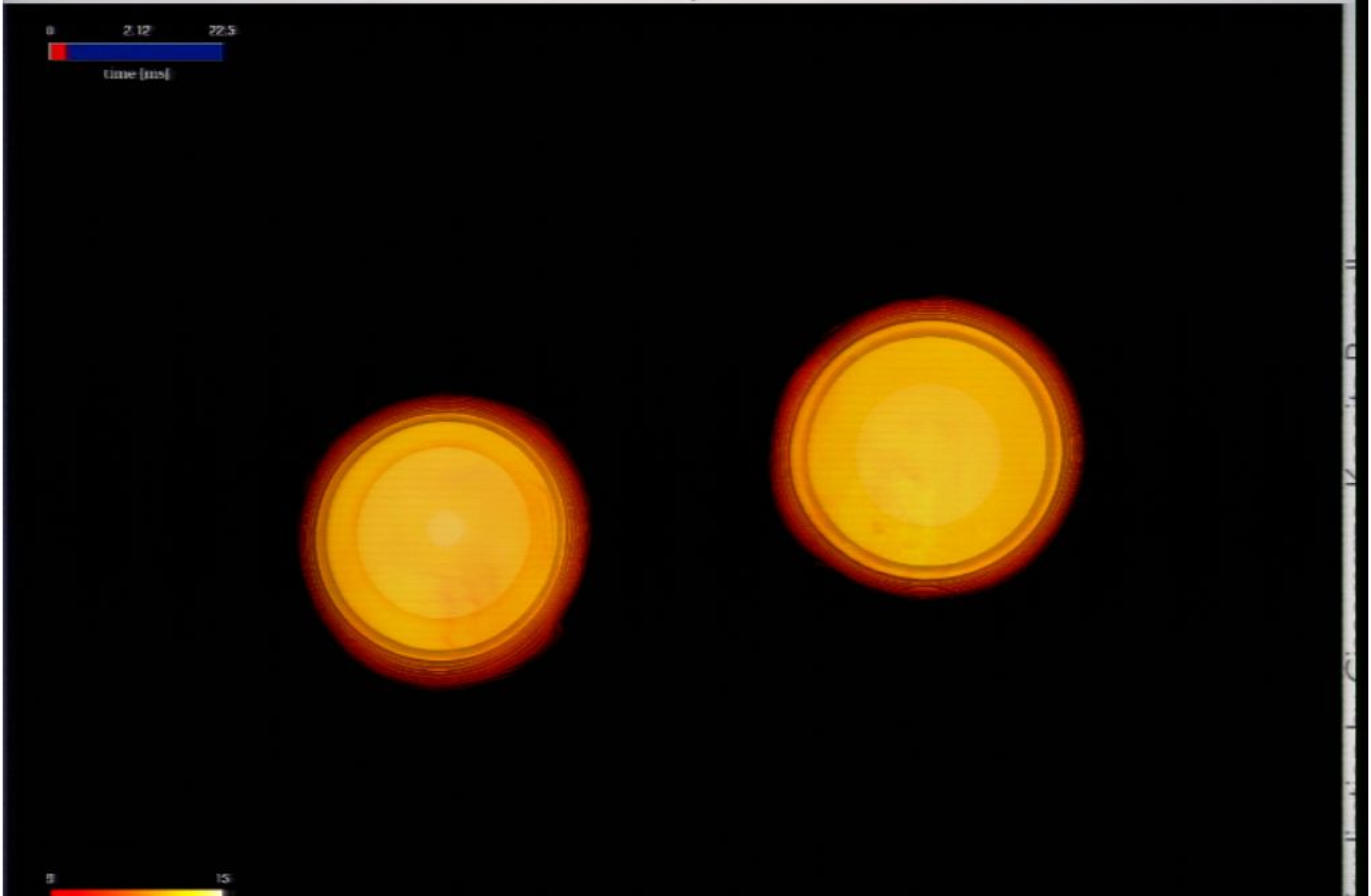
We have considered the inspiral and merger of 6 irrotational binaries with variable total mass and mass ratio

Model	Total ADM Mass	M1, M2
M3.6q1.00	3.23	1.64, 1.64
M3.7q0.94	3.33	1.64, 1.74
M3.4q0.91	3.11	1.51, 1.64
M3.4q0.80	3.08	1.40, 1.72
M3.5q0.75	3.14	1.39, 1.80
M3.4q0.70	3.07	1.30, 1.81

Total initial mass chosen to have prompt collapse to BH


M3.4q0.80
0
0.00
22.5
time [ms]
5
15

M3.4q0.80




M3.4q0.80
0
4.70
22.5
time [ms]
15

SUMMARY

• Able to perform long and stable simulations of all the phases of BNS inspiral, merger and collapse to BH plus torus

• Formation of massive tori observed in the unequal-mass case

• Studied in details the properties of the tori formed by BNS mergers

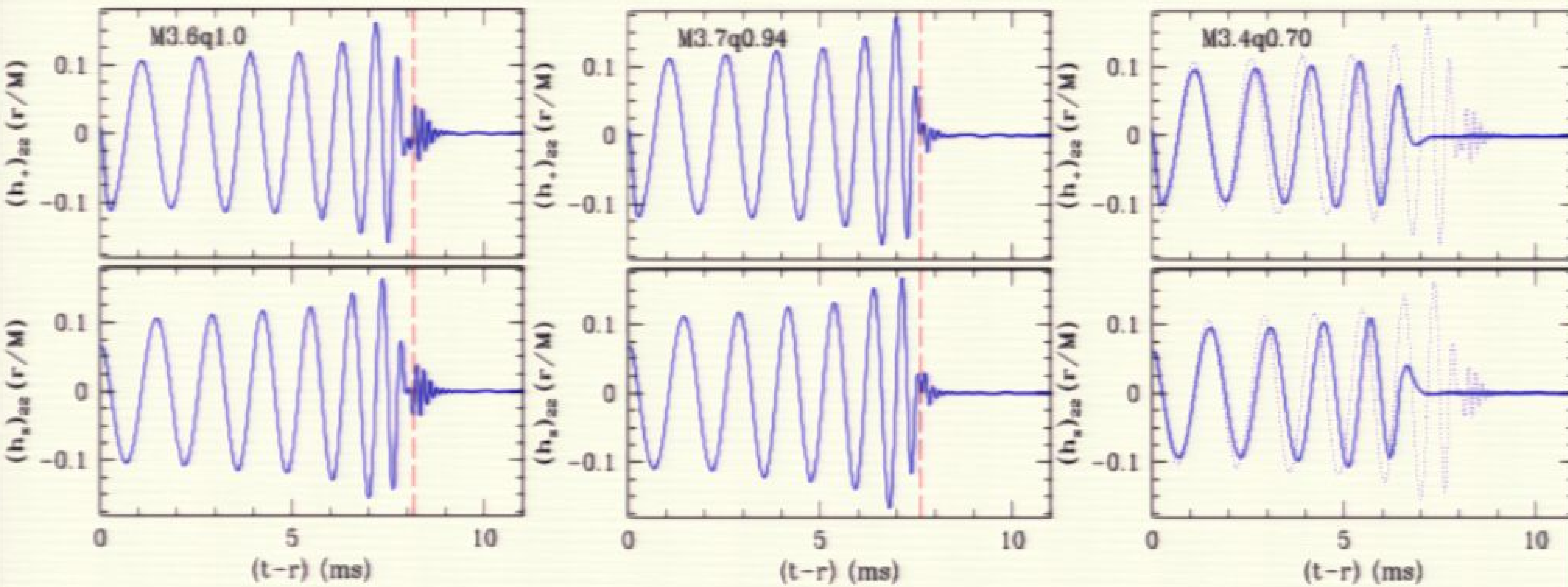
• Currently investigating more realistic EOS, magnetic fields and possible jet formation in connection with short-GRBs

• Used very long numerical simulations of BNSs to extend the application of EOB to GWs from equal-mass BNS

• Verified the need of NLO tidal correction to match with computed GWs

• Very good agreement over more than 20 cycles (phase error ~0.2 rad)

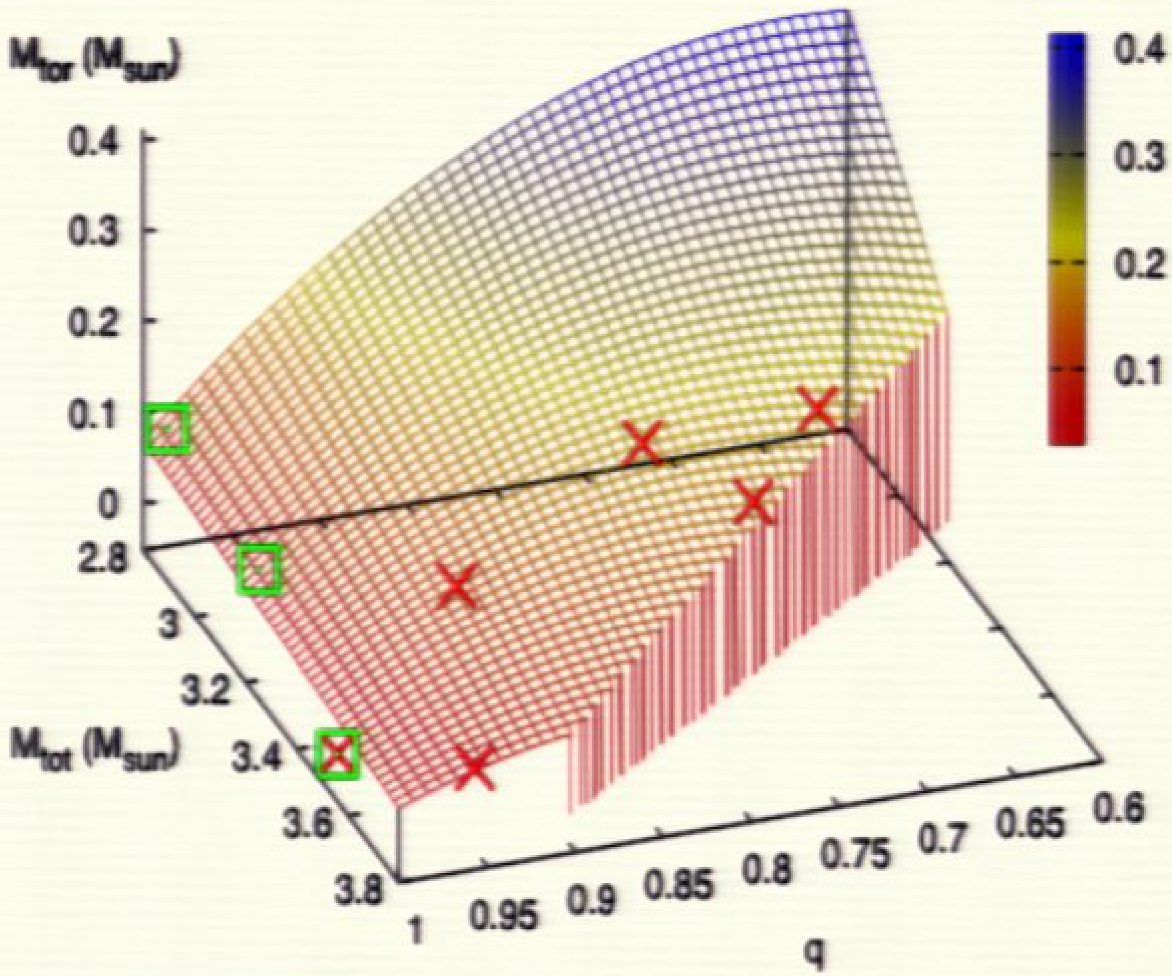
GWS FROM UNEQUAL-MASS BINARIES



The different mass of the torus has an effect also on the GWs.

Larger tori suppress the QNM part of the signal due to the continuous accretion of matter on the BH.

TORUS PROPERTIES: MASS FIT



Model	$M_{\rm total}$ ($M_\odot$)	q	$M_{\rm toru}$ ($M_\odot$)
M3.6q1.00	3.558	1	0.001
M3.7q0.94	3.680	0.94	0.010
M3.4q0.91	3.404	0.91	0.099
M3.4q0.80	3.375	0.80	0.208
M3.5q0.75	3.464	0.75	0.080
M3.4q0.70	3.371	0.70	0.211

For smaller $q=M_2/M_1$ th less massive star is tidall disrupted producing massive tail.

Smaller q produce large tori with masses up to $0.2 M_\odot$.

A systematic investigation shows that: the torus mass decreases with the mass ratio and with the total mass

$$M_{tor}(q, M_{tot}) = [c_3(1+q)M_* - M_{tot}][c_1(1-q)+c_2]$$

Incorporating tidal effects in the EOB Hamiltonian is straightforward:

$$A(r) = A_0(r) + A^{tidal(N)}(r)$$

where $A^{tidal(N)}(r)$ is computed in a Newtonian-like form (but with relativistic Love numbers)

$$A^{tidal(N)}(r) = \sum_{\ell\geq 2} A_\ell^{tidal(N)}(r) = \sum_{\ell\geq 2} \kappa_\ell^T u^{2\ell+2} \qquad u \equiv \frac{M}{r}$$

$$\kappa_\ell^T = 2\frac{M_B M_A^{2\ell}}{M^{2\ell+1}}\frac{k_\ell^A}{c_A^{2\ell+1}} + 2\frac{M_A M_B^{2\ell}}{M^{2\ell+1}}\frac{k_\ell^B}{c_B^{2\ell+1}} \qquad M \equiv M_A + M_B$$

and higher NLO PN tidal corrections can be added (Damour&Naga 2009):

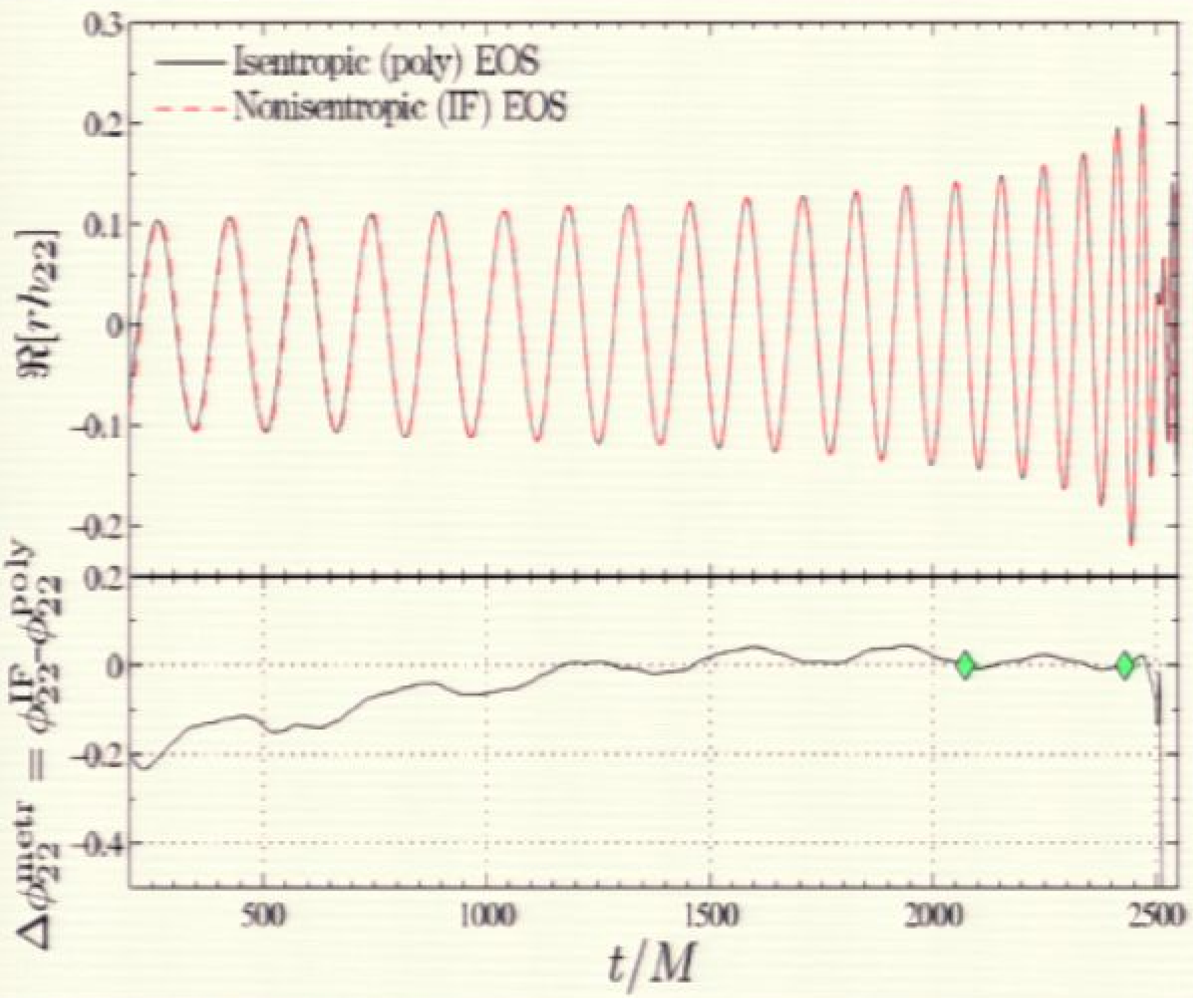
$$A_\ell^{tidal} = A_\ell^{tidal(N)} \hat{A}_\ell^{tidal}$$

$$\hat{A}_\ell^{tidal} = 1 + \bar{\alpha}_{1PN} u + \bar{\alpha}_{2PN} u^2 + \ldots$$

$$\kappa_\ell^{T,eff} = \kappa_\ell^T \hat{A}^{tidal}$$

where $\bar{\alpha}_{1PN}, \bar{\alpha}_{2PN}$, can be computed analytically (in principle) o estimated by comparing with numerical simulations (in practice)

COMPUTING LONG NR GWS



To compare and tune the tidal corrections we have computed very long (>10 orbits) gws of BNSs with two different (ideal) EOSs, using different extraction radii and different resolutions.

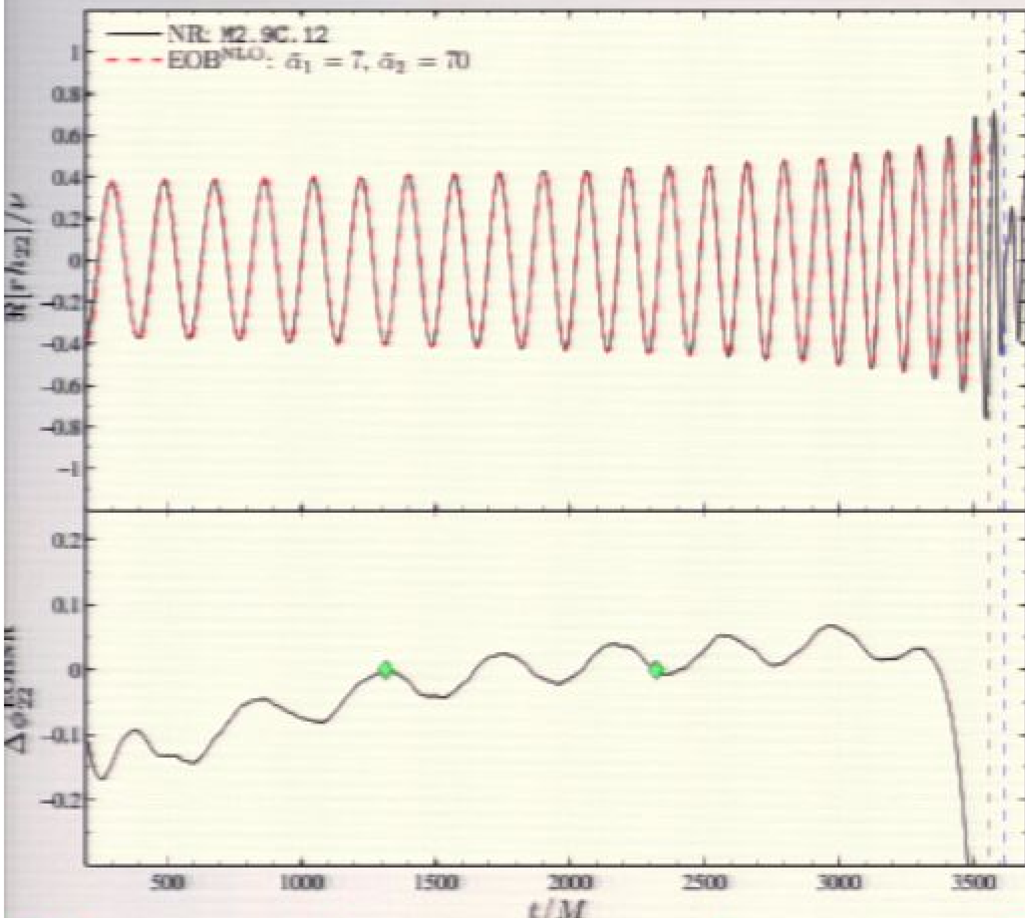
We have considered two different initial data:

- $M_A = M_B = 1.36$, $C = 0.12$
- $M_A = M_B = 1.51$, $C = 0.14$

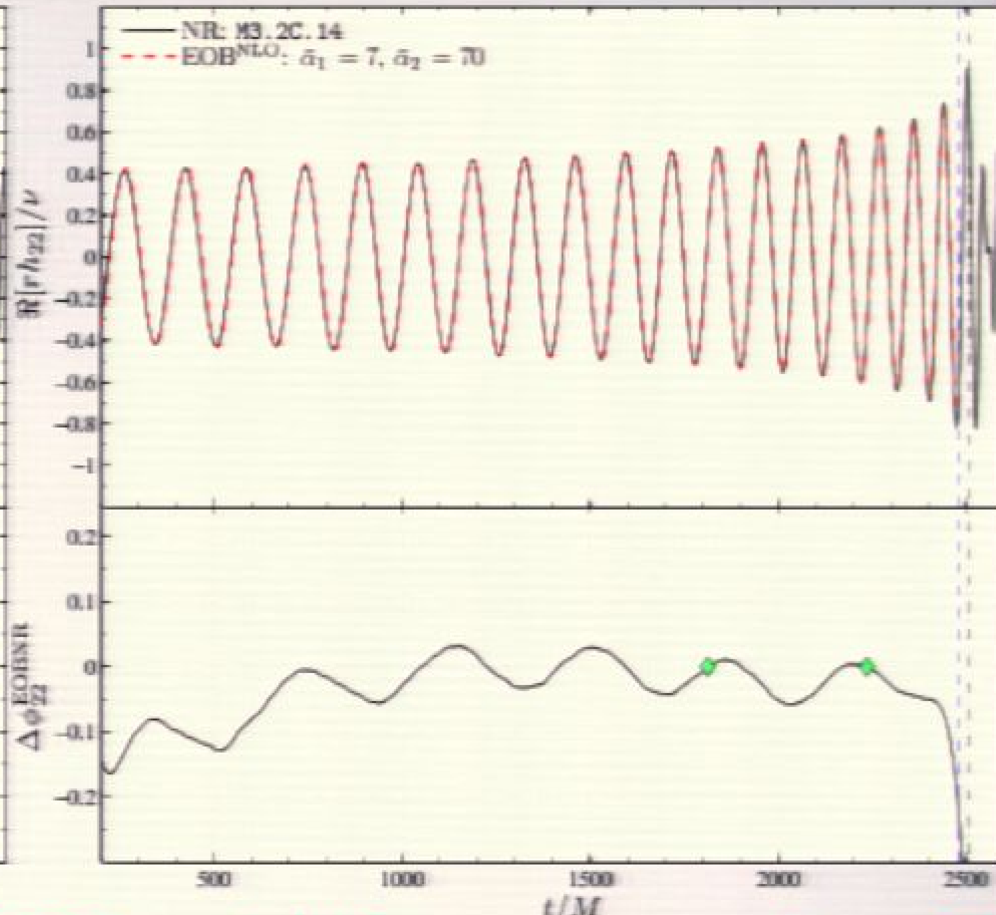
The NR data show a very good numerical accuracy with an error in

EOB VS NR INCLUDING NLO EFFECTS

$M_A = M_B = 1.36$, $C = 0.12$



$M_A = M_B = 1.51$, $C = 0.14$



Very good agreement between EOB and NR over more than 20 cycles. The error is within the NR error bar $\Delta\phi \simeq \pm 0.2$

NR indicates that tidal effects are ~2.5 times stronger than those