Unequal mass binary neutron star mergers and multimessenger signals

GR21, NYC, New York, USA

Steve Liebling
With:

Matt Anderson (IU) Liliana Caballero (U.Guelph) Luis Lehner (Perimeter) David Neilsen (BYU) Patrick Motl (IU) Evan O'Connor (NCSU) Carlos Palenzuela (UIB)

Long Island University, New York, USA

July 11, 2016

Our Previous Work

[Palenzuela,SLL,Neilsen,Lehner,Caballero,O'Connor,Anderson,1505.01607]
[Neilsen,SLL,Anderson,Lehner,O'Connor,Palenzuela,1403.3680]

- Barytropic, finite-temperature
- Spans sub-nuclear to supra-nuclear densities
- Largely unknown regime of matter
- Constrained by the most massive observed NSs
- Involves temperature and composition (electron fraction)
- Adapts open-source leakage code at stellarcollapse.org
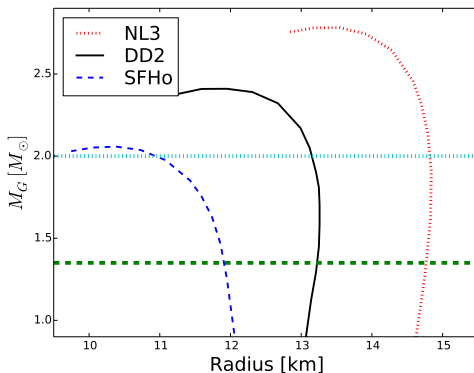- Novel calculation of optical depth which tracks binary NS

Equal mass magnetized BNS with 3 different realistic EoS:

- Soft EoS (SFHo) yields more unbound material
- Mostly equatorial outflow
- Promising for r-process IR afterglow (Y_e peaks around 0.2)
- Soft EoS more luminous in neutrinos
- High magnetization can increase amount of ejecta

Choice of Realistic, microphysical EoS

Choose range of EoS:

- NLS—stiff—large radii
- DD2—moderate—intermediate radii
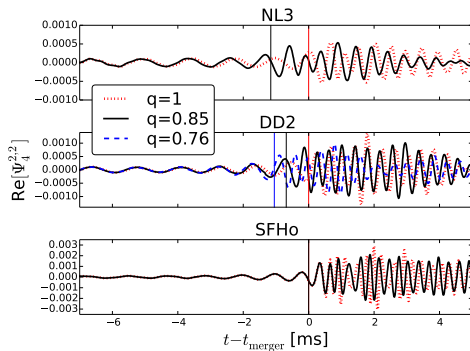- SFHo—soft—small radii

Initial Data

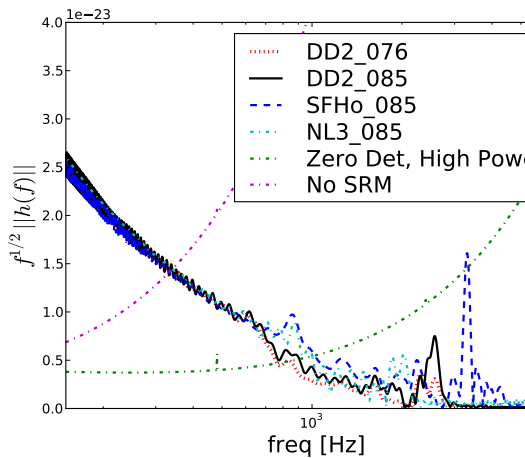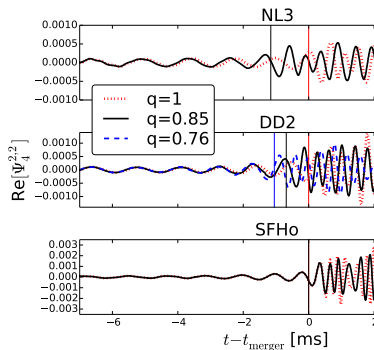[Lehner,SLL,Palenzuela,Caballero,O'Connor,Anderson,Neilsen,1603.00501]

- Total mass $2.7 M_\odot$
- 45 km initial separation...4-5 orbits prior to merger
- Finest resolution: 230 meters in neighborhood of each star

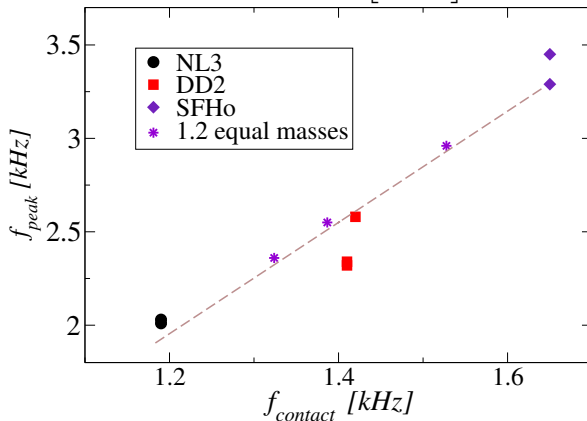| EoS	q	ν	$m_b^{(1)}, m_g^{(1)}$ $[M_\odot]$	$m_b^{(2)}, m_g^{(2)}$ $[M_\odot]$	$R^{(1)}$ [km]	$R^{(2)}$ [km]	$C^{(1)}$	$C^{(2)}$	$J_0^{\rm ADM}$ [G $M_\odot^2/c$]	Ω_0 [rad/s]	$f_0^{\rm GW}$ [Hz]	$M_{\rm eject}$ [$10^{-3} M_\odot$]
NL3	1.0	0.250	1.47, 1.36	1.47, 1.36	14.80	14.80	0.136	0.136	7.40	1778	566	0.015
NL3	0.85	0.248	1.34, 1.25	1.60, 1.47	14.75	14.8	0.125	0.147	7.35	1777	566	2.3
DD2	1.0	0.250	1.49, 1.36	1.49, 1.36	13.22	13.22	0.152	0.152	7.39	1776	565	0.43
DD2	0.85	0.248	1.36, 1.29	1.62, 1.47	13.20	13.25	0.144	0.164	7.34	1775	565	0.42
DD2	0.76	0.245	1.27, 1.18	1.71, 1.54	13.16	13.25	0.132	0.172	7.26	1775	565	1.3
SFHo	1.0	0.250	1.50, 1.36	1.50, 1.36	11.90	11.90	0.169	0.169	7.38	1775	565	3.4
SFHo	0.85	0.248	1.37, 1.25	1.63, 1.47	11.95	11.85	0.154	0.183	7.31	1773	564	2.2

Waveforms

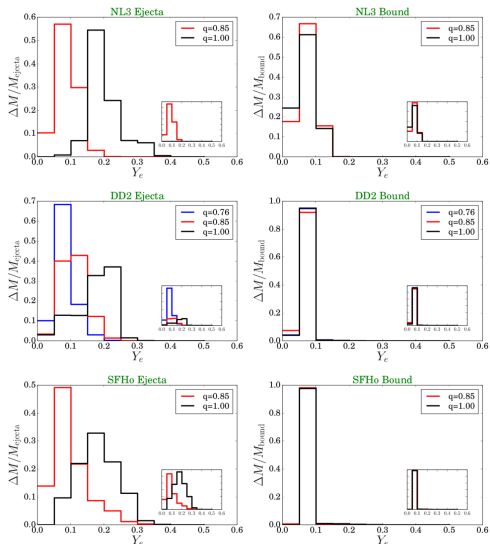# Waveforms

Remnant's peak GW Frequency

In terms of contact frequency: $f_c = \frac{1}{\pi M_g} \left(\frac{m_g^{(1)}}{M_g C_1} + \frac{m_g^{(2)}}{M_g C_2} \right)^{-3/2}$

yields fit: $f_{\text{peak}}[\text{kHz}] = -1.61 + 2.96 f_c \left[\frac{2.7 M_\odot}{M} \right] [\text{kHz}]$

Ejecta Properties: Electron Fraction

Electron Fraction decreases with mass ratio

Estimates of possible EM signals

Kilonova: [Barnes,Kasen,2013]

$$t_{\text{peak}}^{k} \approx 0.25 \, \text{days} \left[\frac{M_{\text{eject}}}{10^{-2} M_{\odot}} \right]^{1/2} \left[\frac{v}{0.3c} \right]^{-1/2}$$

$$L \approx 2 \times 10^{41} \text{erg/s} \left[\frac{M_{\text{eject}}}{10^{-2} M_{\odot}} \right]^{1/2} \left[\frac{v}{0.3c} \right]^{1/2}$$

Radio emission from collision with ISM: [Nakar,Piran,2011]

$$t_{\text{peak}} \approx 6 \, \text{yr} \left[\frac{E_{\text{kin}}}{10^{51} \text{erg}} \right]^{1/3} \left[\frac{n_0}{0.1 \, \text{cm}^{-3}} \right]^{-1/3} \left[\frac{v}{0.3c} \right]^{-5/3}$$
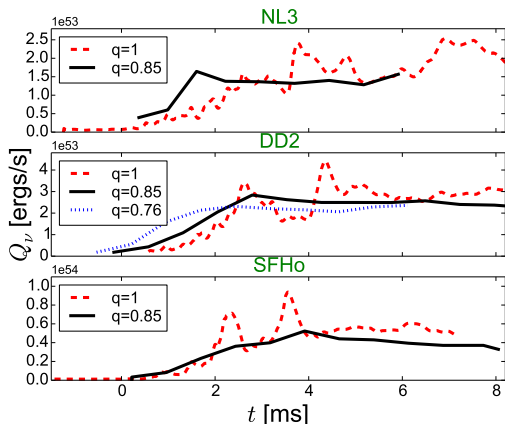
$$F(\nu_{\text{obs}}) \approx$$

$$0.6 \, \text{mJy} \left[\frac{E_{\text{kin}}}{10^{51} \text{erg}} \right] \left[\frac{n_0}{0.1 \, \text{cm}^{-3}} \right]^{7/8} \left[\frac{v}{0.3c} \right]^{11/4} \left[\frac{\nu_{\text{obs}}}{1 \, \text{GHz}} \right]^{-3/4} \left[\frac{d}{100 \, \text{Mpc}} \right]^{-2}$$

EoS	q	$L[10^{40}\text{erg/s}]$	t_{peak}^{k} [days]	$M_{\text{eject}}[10^{-3}M_{\odot}]$	v/c	$E_{\text{kin}}[10^{50}\text{ergs}]$	t_{peak} [yr]	$F(1\,\text{GHz})$ [mJy]
NL3	1.0	0.9	0.008	0.015	0.45	0.01	0.31	1.8×10^{-3}
NL3	0.85	8.8	0.13	2.3	0.25	1.22	4.0	4.4×10^{-2}
DD2	1.0	4.1	0.05	0.43	0.3	0.31	1.9	1.9×10^{-2}
DD2	0.85	4.1	0.05	0.42	0.3	0.29	1.8	1.7×10^{-2}
DD2	0.76	7.2	0.09	1.3	0.3	0.76	2.5	4.6×10^{-2}
SFHo	1.0	10.6	0.16	3.4	0.25	1.8	4.6	6.5×10^{-2}
SFHo	0.85	8.6	0.13	2.2	0.25	1.8	4.6	6.5×10^{-2}

Neutrino Emission

• Softest EoS most luminous
for any mass ratio
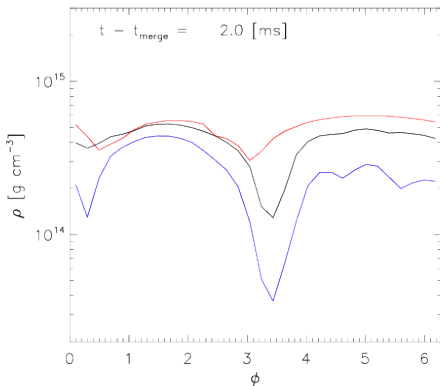because highest temperature

Neutrino Emission: Detectability

Assume 10kpc distant in SuperKamiokande-like water Cherenkov detector

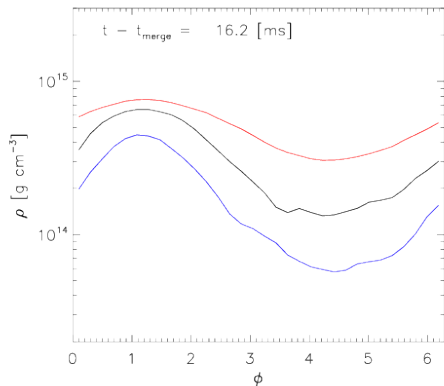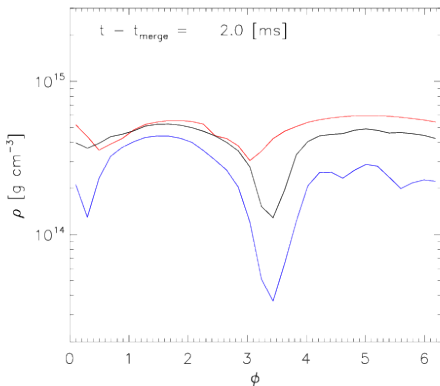| EoS	q	t [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
NL3	1.0	3.4	18.5 (22.4)	15.2 (18.3)	0.7	18
NL3	0.85	3.0	15.6 (18.7)	12.6 (15.1)	0.8	18
DD2	1.0	3.3	18.3 (22.1)	14.6 (17.4)	1.1	28
DD2	0.85	2.8	18.1 (21.7)	15.1 (18.0)	1.0	25
DD2	0.76	2.4	19.7 (23.9)	14.8 (17.9)	1.3	36
SFHo	1.0	3.5	24.6 (29.7)	23.5 (28.3)	3.5	121
SFHo	0.85	3.9	17.8 (21.3)	15.3 (17.9)	2.0	50

BNS Conclusions

- GW:
  - Peak frequency of remnant can be estimated via a fit based on the contact frequency
  - Stiffer EoS more sensitive to mass ratio because larger radius
- Ejecta:
  - Decreasing mass ratio makes kilonova more likely
  - Obtaining masses from GW would benefit EM observations
  - Neutron rich ejecta...peaked around 0.2
  - promising for r-process IR afterglow
    (recent observation SGRB 130603B [Tanvir,et al,Nature,2013] and [Berger,et al,ApJ,2013])
- Neutrino Emission:
  - Soft EOS more luminous
  - Smaller mass ratios result in more dispersed neutrino surfaces, smaller max temps

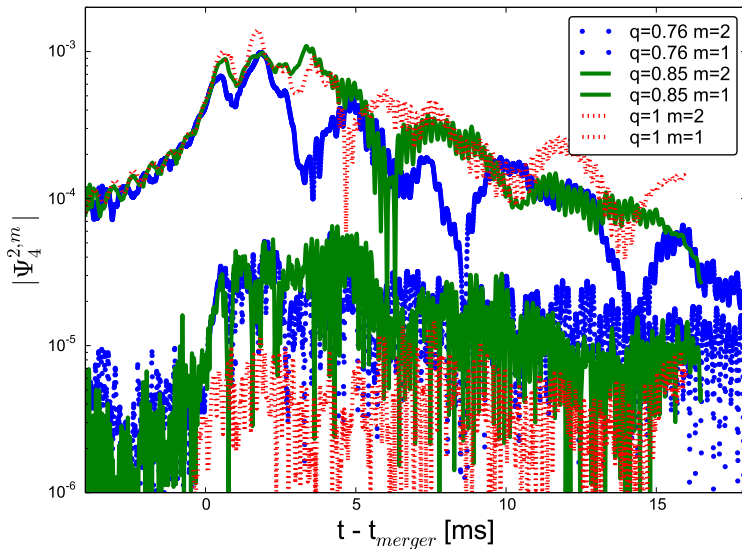# $m = 2$ develops into $m = 1$ for $q = 0.85$ DD2

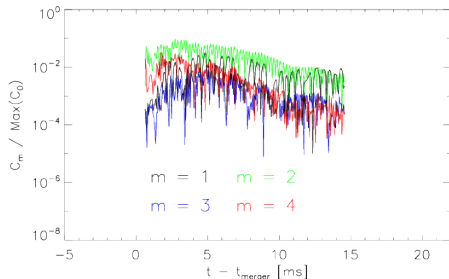# $m = 2$ develops into $m = 1$ for $q = 0.85$ DD2

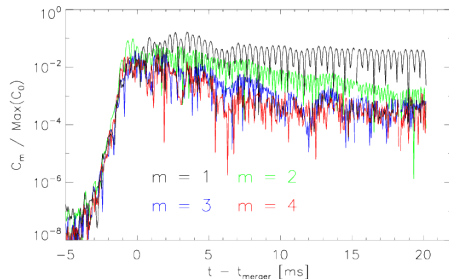

See also

[East,Paschalidis,Pretorius,Shapiro,1511.01093]

and [Radice,Bernuzzi,Ott,1603.05726]
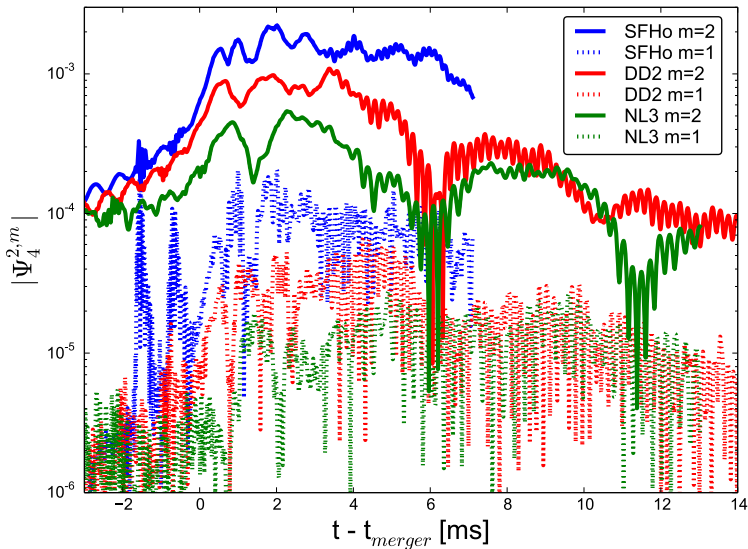
Growth of $m = 1$ Mode in GW Signal for DD2

Density Decomposition into Azimuthal Modes for DD2

$q = 1$

$q = 0.76$

Effect of EoS on $m = 1$ mode instability

Detectability

Using:

$$\rho^2 \simeq \frac{2}{S_n(f)} \int_0^T h^2 \, dt$$

We arrive at

$$\rho_{m=1} \approx 11 \times \left[\frac{6 \times 10^{-24} \text{Hz}^{-1/2}}{\sqrt{S_n(f_{m1})}} \right] \left[\frac{|\Psi^0_{4_{m=1}}|}{5 \times 10^{-5}} \right]$$
$$\left[\frac{1.3 \text{kHz}}{f_{m1}} \right]^2 \left[\frac{T}{10 \text{ms}} \right]^{1/2} \left[\frac{10 \text{Mpc}}{L} \right]$$

Not particularly encouraging, but...

Detectability

- The $m = 1$ mode **lasts longer** than the $m = 2$ mode
- Occurs at **low frequency** and hence in more sensitive region of LIGO's noise curve
- Its frequency is precisely half that of the $m = 2$ and can therefore be **explicitly targeted**

for sub-threshold SNR of unity, reach to 100 Mpc to see $m = 1$ mode

Provides another avenue for extracting information about the equation of state

- Weaker for stiff EoS than for soft EoS
- For smaller mass ratios, $m = 1$ becomes stronger and saturates earlier