POST-MERGER OSCILLATIONS AND THE NEWCOMPSTAR ACTION

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Plan of Talk

Part I: Understanding post-merger oscillations Mon. Not. R. Astron. Soc. **418,** 427–436 (2011) doi:10.1111/j.1365-2966.2011.19493.x

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Gravitational waves and non-axisymmetric oscillation modes in mergers of compact object binaries

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and Hans-Thomas Janka² and Hans-Thomas Janka2

Part II: Extracting EOS information **of compact object binaries** $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{2$

 $arxiv:1403.5301$, Phys. Rev. D, in press (2014)
Revealing the bigh density equation of state through binary poutron star measures **ABSTRACT**

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Part III: Towards hybrid waveforms ¹*Department of Physics, Section of Astrophysics, Astronomy and Mechanics Aristotle, University of Thessaloniki, Thessaloniki 54124, Greece* . Iowards hybrid waveforms **and by one star equation of star equation** of star equation of strange star equation of star equation of star equation of strange star equation of star equation of the evolution of the evolution une quality models, described by two non-zero-temperature hadronic equations of states of states of states of 1 department of Physics, Aristotle University of Thessalonic Uni ds hybrid waveforms as the \sim ¹Department of Physics, Aristotle University of Thessaloniki, GR-54124 Thessaloniki, Greece Part III: Towards hybrid waveforms

arxiv:1406.5444, submitted to Phys. Rev. D (2014) A , subtinued to finys. Key, $D(2014)$ \overline{A} 6.5444 submitted to Phys R_{eV} \overline{D} (2014) arxiv:1406.5444, submitted to Phys. Rev. D (2014)

Prospects For High Frequency Burst Searches Following Binar Tigh Frequency Burst Searches Following Binary **Coalescence With Advanced Gravitational Wave Detectors** difference between the *m* = 2 mode and the quasi-radial mode. Once such observation becomes eta Een High Frequency Durct Seerches Fellowing Dinewy Neutrer bis for fligh frequency burst bearings following binary required through gravitational waves emitted during the postmerger phase of a binary neutron star system. Prospects For High Frequency Burst Searches Following Binary Neutron Star

 P_1 Clark,¹ A. Bauswein,² L. Cadonati,^{1,3} H.-T. Janka,⁴ C. Pankow,⁵ and N. Stergioulas² $\frac{1}{\sqrt{1-\frac{1$ J. Clark,¹ A. Bauswein,² L. Cadonati,^{1, 3} H.-T. Janka,⁴ C. Pankow,⁵ and N. Stergioulas²

PART I:

UNDERSTANDING POST-MERGER OSCILLATIONS

Outcome of Binary NS Mergers

(Hotokezaka et al., 2011) (Bauswein & Janka, 2012)

Most likely range of masses for binary system:

 $2.7 M_{sun} < M_{tot} < 2.8 M_{sun}$

If EOS has nonrotating M _{max}>2 M _{sun} (as required by observations), then a long-lived $(T > 10 \text{ms})$ remnant is formed.

The remnant is a *hypermassive neutron star (HMNS)*, supported by *differential rotation*, with a mass larger than the maximum mass allowed for uniform rotation.

Gravitational Waves

 The GW signal can be divided into three distinct phases: *inspiral, merger* and *post-merger ringdown.*

 Several peaks stand above the aLIGO/VIRGO or ET sensitivity curves and are potentially detectable. Are these *oscillations* of the HMNS?

Additional EOS Information in Post-Merger Signal

 How can we interpret the triplet of frequencies above the ET sensitivity curve?

Mergers of Compact Object Binaries

NS, Bauswein, Zagkouris, Janka (2011)

 Merger of equal/unequal mass binaries with *LS*, *Shen*, *MIT60* EOS. (3-D GR CFC/SPH code) Example: Shen EOS: $1.35M_{sun}+1.35M_{sun}$

Rotating bar shape + *radial oscillation* => *transient double core*

GW Scaled Power Spectral Density

Split the time-series into *pre-merger* and *post-merger* parts:

Triplet of frequencies: f_1 , f_2 , f_4 *originates in post-merger part.*

Nonlinear Combination Frequencies

Passamonti, NS & Nagar (2007)

Linear sums and differences of linear mode frequencies

$$
f^{\pm} = {}^{2}f \pm F \t p_{n}^{\pm} = {}^{2}p_{n} \pm F \t H_{n}^{\pm} = H_{n} \pm {}^{2}f
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 The amplitude of combination frequencies can become large, when the linear modes have amplitude of *O*(1).

Equal mass: Lattimer-Swesty 1.35+1.35

Unequal mass: Lattimer-Swesty 1.2+1.35

Eigenfunction Extraction

Fourier extraction of axisymmetric mode eigenfunctions: (NS, Apostolatos, Font, 2004)

Spatial distribution of FFT *magnitude* at mode-frequency determines shape of *eigenfunction* (but change sign at nodal lines)*.*

Eigenfunctions in Equatorial Plane

Summary and Prospects

A HMNS created in a binary neutron star merger oscillates in several frequencies with initially high amplitude.

A triplet of frequencies f_1 , f_2 , f_4 is prominent and potentially detectable.

Identification:

 $f₂$: *m*=2 mode *f*: (*m*=2) - (*m*=0) nonlinear combination frequency

In case of detection: determine both $m=0$ and $m=2$ frequencies

 In progress: construct axisymmetric equilibrium model of HMNS remnant and obtain linear oscillation modes.

PART II:

EXTRACTING EOS INFORMATION

Revealing the EOS

Large EOS Sample

 \cdots Bauswein, Janka, Hebeler & Schwenk (2012)

 f_2 correlates well with the radius @ 1.6 Msun, if (M₁, M₂) are known from inspiral. Bauswein, Janka, Hebeler & Schwenk (2012)

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 Bauswein, Janka, Hebeler & Schwenk (2012) f_2 correlates well with the radius @ 1.6 Msun, if (M₁, M₂) are known from inspiral.

 For 1.35+1.35 Msun the empirical relation is remarkably accurate. Bauswein, Janka, Hebeler & Schwenk (2012)

 $f_{\text{peak}} = \begin{cases} -0.2823 \cdot R_{1.6} + 6.284 & \text{for } f_{\text{peak}} < 2.8 \text{ kHz} \\ -0.4667 \cdot R_{1.6} + 8.713 & \text{for } f_{\text{peak}} > 2.8 \text{ kHz} \end{cases}$

Radius Determination from Post-Merger Signal **ing merger Radius Determination from**

Bauswein, Janka, Hebeler & Schwenk (2012) 2

For given 1.35+1.35 Msun: $\mathsf{for} \ \mathsf{given} \ \mathsf{1.35+1.35} \ \mathsf{MSun}:$

f₂ correlates with Rremnant $R_{\text{remainder}}$ is proportional to $R_{1.6}$ $=$ > f_2 correlates with $R_{1.6}$ mass of the merger remains in the merger response of the merger response of the merger response of the set of th \sim iz correlated with $\frac{10}{10}$ $f \in$ $s_{\rm 1.0}$

die alle the matrix stable remains with the merger may remain the merger may result to the merger may result to me either in a black hole (BH) with a hole (B
The contract of the contract o \blacksquare is determined by the \blacksquare

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 The threshold mass is related to the maximum TOV mass as Dauswell, Daulingarle, Jalika FINL (2013)
The throchold mass is related to the maximum TOV masse as The threshold mass is related to the aximum TOV mass as

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M_{\rm thres} = k \cdot M_{\rm max}
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where k is dependent on the compactness. where K is dependent on the compactness. may undergo rapid neutron-capture nucleosynthesis and \mathcal{I} where κ is dependent on the compo dependent, nuclear EoSs in numerical simulations of bi-

die M_{thres} vs. M_{max} correlation The VS. Thay Concident in the Second Construction of the Second Second in the Second Second Second in the Second Seco

 Bauswein, Baumgarte, Janka PRL (2013) It is intuitive to assume that Mthres scales with the Rauswein Baumgarte Janka PRI (2013)

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f_{thres} vs. R_{max} correlation

At $M_{\text{tot}} \sim 2.7$ M_{sun}

Largest error bars for maximum mass model

Breaking the EOS degeneracy

Estimating the density of the maximum-mass model

PART III:

TOWARDS HYBRID WAVEFORMS

GW damping timescale for f-modes

Andersson & Kokkotas (1998)

No rotation: EOS-independent empirical relation:

$$
\frac{1}{\tau_0[\text{s}]} = \frac{\bar{M}^3}{\bar{R}^4} \left[22.85 - 14.65 \frac{\bar{M}}{\bar{R}} \right]
$$

When this is applied to the mass and radius of the remnant:

 $\tau \approx 200 \text{ ms}$ it as an upper bound, since the actual damping timescale of the actual damping timescale damping timescale dam
In the actual damping timescale damping timescale damping timescale damping timescale damping timescale dampin $\tau \sim 200 \text{ ms}.$

f-modes of rapidly rotating neutron stars

 Uniform rotation, Cowling approximation, *l*=±*m*=2 *f*-mode frequency (linear time-evolution code) Doneva, Gaertig, Kokkotas, Krueger (2013)

f-modes of rapidly rotating neutron stars

Doneva, Gaertig, Kokkotas, Krueger (2013)

 Corotating frame: same rotational effect, independent of EOS! ating frame: same rotational effect indenendent o funny manner same rotational encet, macpenaent the edition of

→ Empirical relations for GW asteroseismology. $\frac{1}{2}$

GW damping timescale for f-modes $\mathbf v$ damping inneseare for V. SOLVING THE INVERSE PROBLEM

Doneva, Gaertig, Kokkotas, Krueger (2013) Uniform rotation: same rotational effect, independent of EOS! $=$ $\frac{1}{2}$. In order to proper comparison, the make a proper comparison, the matrix s, Krueger (2013) $p = \frac{1}{2}$ dent of EOS!

can see, the fit for realistic EoS generally leads to smaller the fit for realistic EoS generally leads to small

At rapid rotation: we estimate $f(x) = f(x) + f(x)$ is the comoving frequencies in the comoving frequencies in the comoving framework. $T \sim T_0/10$ i.e. ~ 20 ms. Real GW timescale is probably 20ms < τ <200ms -> work in progress!

THANK YOU

SUPPLEMENTARY MATERIAL

TABLE I: Equation of state models with references and resulting stellar properties. M_{max} denotes the maximum mass of nonrotating NSs with the cirumferential radius R_{max} corresponding this maximum-mass configuration. e_{max} and ρ_{max} are the central energy density and the central rest-mass density of the maximum-mass configuration. $R_{1,6}$ refers to the circumferential radius of a nonrotating 1.6 M_{\odot} NS. M_{thres} is the highest total binary mass which leads to differentially rotating NS merger remnant for the given EoS. The dominant GW frequency of this postmerger remnant is $f_{\rm peak}^{\rm thres}$. Hatted quantities are the estimates for these merger properties and stellar parameters based on the extrapolation procedure described in the main text (Sect. IV).

					$M_{\rm max} \hat{M}_{\rm max} R_{1.6} \hat{R}_{1.6} M_{\rm thres} \hat{M}_{\rm thres} f_{\rm peak}^{\rm thres}$			$\hat{f}^{\rm thres}_{\rm peak}$		R_{max} R_{max} $e_{\text{c,max}}$	$\hat{e}_{\rm c,max}$	$\rho_{\rm c,max}$	$\rho_{\rm c,max}$
EoS	(M_{\odot})	(M_{\odot})	(km)		(km) (M_{\odot})	(M_{\odot})		(kHz) (kHz)	(km) (km)	(g/cm^3)	(g/cm^3)	(g/cm^3)	(g/cm^3)
NL3 [70, 71]	2.79	2.68		14.81 14.72 3.8		3.73	2.77	2.87			$13.40\, 12.78\, 1.52\times10^{15}\, 1.68\times10^{15}\, 1.09\times10^{15}\, 1.25\times10^{15}\, $		
LS375 [73]	2.71	2.69		$13.76 \mid 13.86 \mid 3.6$		3.57	3.04	2.93			$12.32 12.62 1.78\times10^{15} 1.74\times10^{15} 1.25\times10^{15} 1.29\times10^{15}$		
DD2 [71, 74]	2.42	2.40		$13.26 \mid 13.18 \mid 3.3$		3.33	3.08	3.00			$11.90 12.38 1.95\times10^{15} 1.83\times10^{15} 1.41\times10^{15} 1.35\times10^{15}$		
TM1 [68, 69]	2.21	2.28		14.36 14.34 3.4		3.45	2.93	2.96			$12.57 12.49 1.80\times10^{15} 1.79\times10^{15} 1.36\times10^{15} 1.32\times10^{15}$		
SFHX [75]	2.13	2.19		$11.98 \mid 12.07 \mid 3.0$		3.05	3.52	3.43			$10.77 11.06 2.39\times10^{15} 2.33\times10^{15} 1.74\times10^{15} 1.71\times10^{15}$		
GS2 [76]	2.09	2.07		$13.38 \mid 13.35 \mid 3.2$		3.17	3.22	3.24			11.81 11.64 2.05×10^{15} 2.11×10^{15} 1.56×10^{15} 1.55×10^{15}		
SFHO [75]	2.06	1.97		11.77 11.76 2.9		2.88	3.71	3.68			$10.31 10.29 2.67\times10^{15} 2.63\times10^{15} 1.91\times10^{15} 1.92\times10^{15}$		
LS220 [73]	2.04	1.98		$12.52 \mid 12.47 \mid 3.0$		2.99	3.55	3.52			$10.65\, 10.80\, 2.55\times10^{15}\, 2.43\times10^{15}\, 1.86\times10^{15}\, 1.78\times10^{15}\, $		
TMA [69, 77]	2.02	2.12		$13.73 \mid 13.89 \mid 3.2$		3.27	2.98	3.08			$12.12 12.14 1.92\times10^{15} 1.92\times10^{15} 1.48\times10^{15} 1.42\times10^{15}$		
[IUF [71, 78]	1.95	2.05		$12.57 \mid 12.50 \mid 3.0$		3.04	3.36	3.44			11.32 11.03 2.19×10^{15} 2.34×10^{15} 1.67×10^{15} 1.72×10^{15}		

ACCURACY OF IWM-CFC APPROXIMATION

Iosif, Stergioulas, arXiv:1406.7375 (2014)

