From Neutron Star Structure to Compact Binary Mergers and Back

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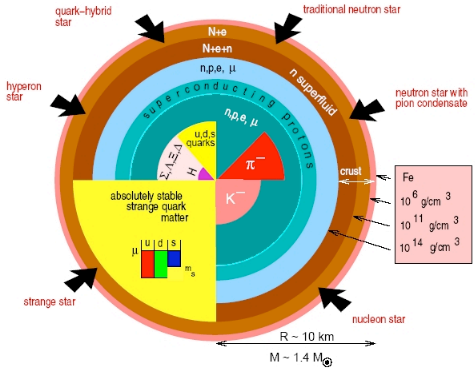
Cardiff University - December 13, 2013

Neutron Star Structure

- Stellar structure equations require a bridge between macroscopic properties and microscopic dynamics
- This is the equation of state: closed expression for the thermodynamic variables of a physical system
- The NS EOS is highly uncertain
  1. We lack stringent NS radius measurements
  2. NSs reach supranuclear densities: we lack labs...
- Terrestrial densities $\rightarrow$ Extrapolations $\rightarrow$ “Realistic” EOS
  1. Reproduce properties of ordinary nuclear matter
  2. No causality violations

Neutron Star Structure



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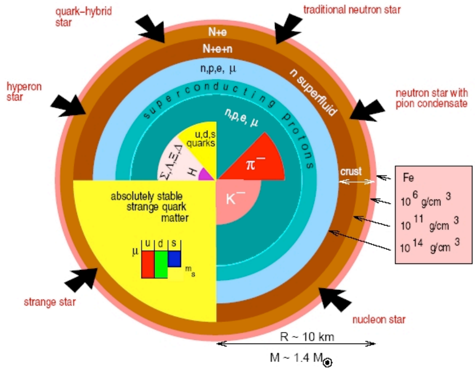

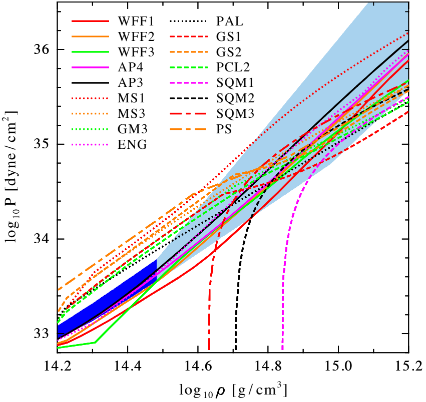

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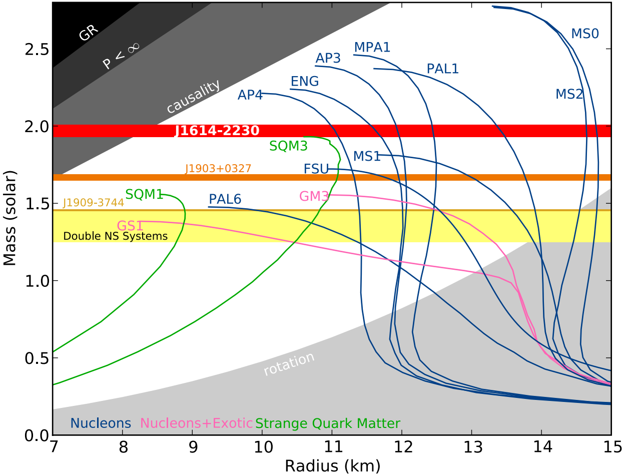
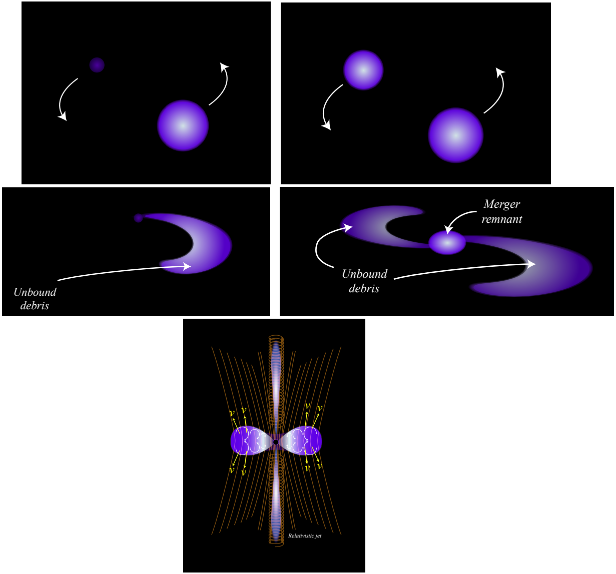


- Microphysics influences macroscopic properties and behaviour
- 98% of the mass is in the core, where our uncertainty is higher

Black Hole-Neutron Star and Double Neutron Star Binaries



- Progenitor binary → compact binary [stellar evolution]
- Secular evolution [GWs]
- Merger
- Ejecta [*r*-processes, kilonovæ]
- Hypermassive NS [EM- & ν-emission]
- Collapse
- Disk accretion [SGRBs]

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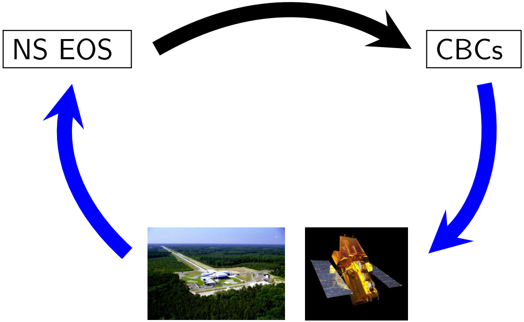

Can we constrain the EOS via observations of merger events?

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Black Hole-Neutron Star and Double Neutron Star Binaries

1. Focus only on selected quantities and a specific problem: not complete, but more general

2. Compute "everything": complete, but with little generality

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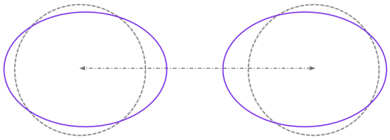
3. ...try to make the best use of both worlds!

Tidal Deformability

The residual gravitational effect on two extended bodies in orbit or free-fall is a tidal deformation that



- depends on the NS size and EOS
- induces changes in the gravitational potential

Questions to answer

May NS tidal deformations affect the detection of BH-NS and NS-NS inspirals?

May we probe superdense matter indirectly, by looking at NS tidal deformation signatures in the GWforms?

FP, Rezzolla, Ohme, Read PRD **84**, 104017 (2011)

Tidal Effects in the GWforms

$\ell = 2, m = 0$ linear perturbation dominates tidal distortion effects

$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of induced quadrupole deformation}}{\text{tidal field strength}} \propto k_2 R_{\rm NS}^5$$

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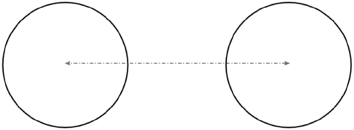
$$E = -\frac{1}{2} M\eta x \left(1 + \sum_{\rm PP}^{\rm 3PN}\right)$$

$$\dot{E} = -\frac{32}{5}\eta^2 x^5 \left(1 + \sum_{\rm PP}^{\rm 3.5PN}\right)$$

Two point-particles or spheres



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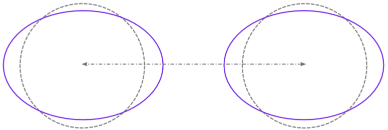
$$E = -\frac{1}{2} M\eta x \left(1 + \sum_{\rm PP}^{\rm 3PN}\right) + \frac{1}{2} Q_{ij}^2 \mathcal{E}_{ij}^1 + 1 \leftrightarrow 2$$

$$\dot{E} = -\frac{32}{5}\eta^2 x^5 \left(1 + \sum_{\rm PP}^{\rm 3.5PN}\right) - \frac{1}{5}\sum_{a=1}^{2} \langle \overset{\dots a}{Q}_{ij} \overset{\dots a}{Q}_{ij} \rangle$$

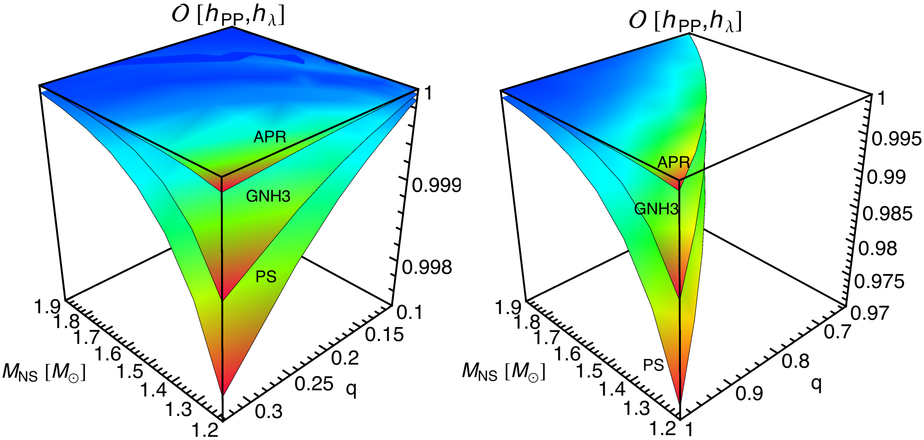
Linear in λ up to relative 1PN order



Vines, Flanagan, Hinderer, PRD **83**, 084051 (2011)

Overlap with Advanced LIGO/Virgo

Frequency domain; nonspinning BHs and NSs



Overlap with Advanced LIGO/Virgo

Will this affect the detection?

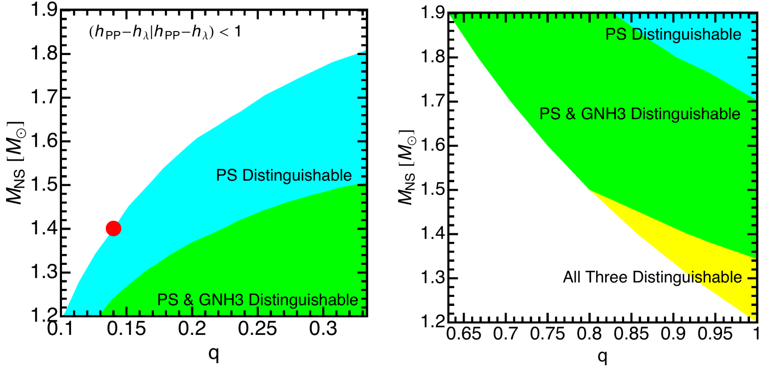
- $\mathcal{O}[h_{\rm PP}, h_\lambda] > 0.997$ (the threshold for a 1% loss of signals)
- BH-BH template banks safe enough for mixed binary inspiral searches

Will this affect the detection?

- $\mathcal{O}[h_{\rm PP}, h_\lambda] > 0.965$ (the threshold for a 10% loss of signals)
- BH-BH template banks safe enough for binary NS inspiral searches

Measurability with Advanced LIGO/Virgo

Sky location and binary orientation averaged; nonspinning BHs and NSs; sources at 100 Mpc



Measurability with Advanced LIGO/Virgo

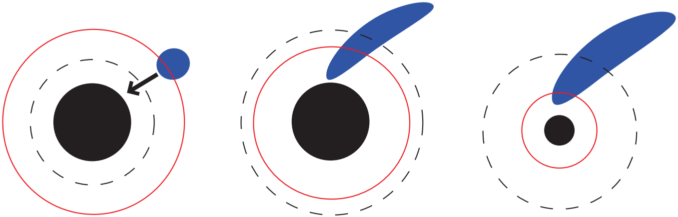
Will the EOS be measurable?

- Stiff EsOS are marginally distinguishable to distinguishable in a region of the parameter space
- The PS/GNH3 EOS for $1.2M_\odot + 4.2M_\odot$ BH-NS binaries is (marginally) distinguishable $\lesssim 200\,\mathrm{Mpc}/300\,\mathrm{Mpc}$

Will the EOS be measurable?

- Tidal effects for stiff and moderately stiff EsOS reach very high distinguishabilities
- There are chances of measuring tidal effects for NSs with small deformabilities, i.e. of distinguishing also a soft EOS like APR

BH-NS Phenomenology



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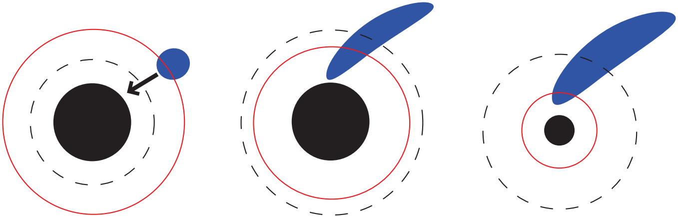

Foucart, PRD **86**, 124007 (2012)

$$\frac{M_{\rm b,torus}}{M_{\rm b,NS}} = 0.296\frac{r_{\rm tide}}{R_{\rm NS}} - 0.171\frac{r_{\rm ISCO}}{R_{\rm NS}}$$

$\Rightarrow$ What are the spin and mass of the BH remnant?

FP, PRD **88**, 104025 (2013); FP, arXiv:1311.5931

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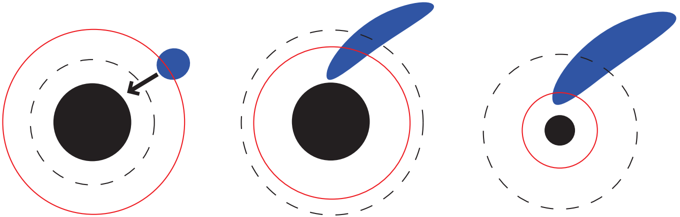

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⇒ What are the spin and mass of the BH remnant?

FP, PRD **88**, 104025 (2013); FP, arXiv:1311.5931

- The tidal disruption frequency depends on the EOS

⇒ Can we build phenomenological GWforms?

FP, Berti, Kyutoku, Shibata, PRD **88**, 084011 (2013)

Extending the BKL Approach

Buonanno, Kidder, Lehner, PRD **77**, 026004 (2008)

$$S_{\rm f} = S_1 + S_2 + L_{\rm orb} - J_{\rm diss}$$

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$$a_{\rm f} = \frac{a_1 M_1^2 + a_2 M_2^2 + \ell_z(\bar{r}_{\rm ISCO,f}, a_{\rm f}) M_1 M_2}{(M_1 + M_2)^2}$$

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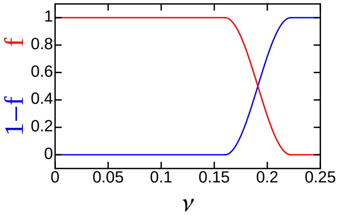
$$a_\mathrm{f} = \frac{a_\mathrm{i} M_\mathrm{BH}^2 + \ell_z(\bar{r}_\mathrm{ISCO,f}, a_\mathrm{f}) M_\mathrm{BH} M_\mathrm{NS}}{(M_\mathrm{BH} + M_\mathrm{NS})^2}$$

Extending the BKL Approach

Modify for: possible full tidal disruption

$$a_{\rm f} = \frac{a_{\rm i} M_{\rm BH}^2 + \ell_z(\bar{r}_{\rm ISCO,f}, a_{\rm f}) M_{\rm BH}\{f(\nu) M_{\rm NS} + [1 - f(\nu)] M_{\rm b,NS}\}}{(M_{\rm BH} + M_{\rm NS})^2}$$



Extending the BKL Approach

Modify for: possible full tidal disruption, torus formation

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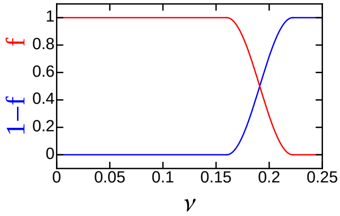

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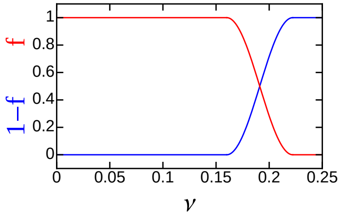

Linear fit for the torus mass

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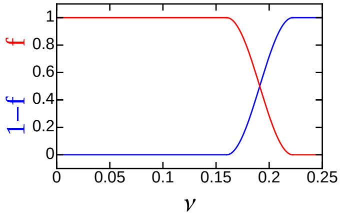

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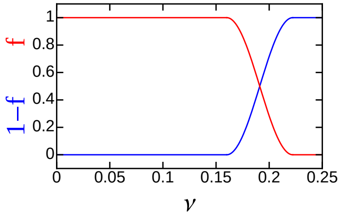

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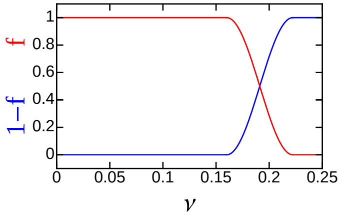

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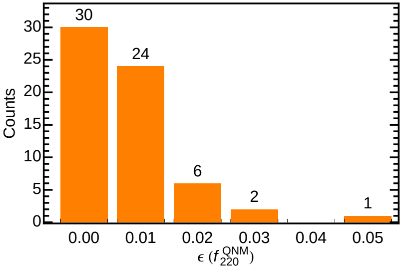
Can be extended to misaligned BH spin

Tests Against Numerical-Relativity Results

74 simulations with aligned BH spin

- $|a_f - a_f^{NR}| \leq 0.02$ in 72/74 cases
- $\epsilon(M_f) \leq 2\%$ [$\leq 1\%$ in 56/63 cases]
- $\epsilon(M_{irr}) \leq 2\%$ [$\leq 1\%$ in 62/63 cases]



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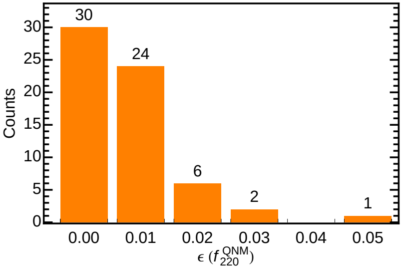


7 simulations with misaligned BH spin ($M_{NS}/R_{NS} = 0.144$)

- $\epsilon(M_f) \leq 0.02$ [≤ 0.01 in $6/7$ cases]

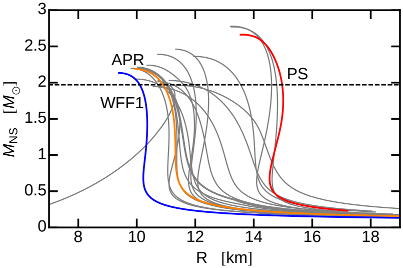
Q	a_i	θ_i	a_f^{NR}	a_f^{PN}	a_f
7	0.9	20°	0.91	0.91	0.93
7	0.9	40°	0.90	0.90	0.91
7	0.9	60°	0.86	0.87	0.87
3	0.0	0°	0.56	0.54	0.55
3	0.5	0°	0.77	0.70	0.76
3	0.9	0°	0.93	0.83	0.94
3	0.5	20°	0.76	0.70	0.75
3	0.5	40°	0.74	0.69	0.73
3	0.5	60°	0.71	0.67	0.69
3	0.5	80°	0.66	0.64	0.64

Stone, Loeb, Berger, PRD **87**, 084053 (2013)

Results

Systematically explore the BH-NS space of parameters:

- $2 \leq Q \leq 10$
- $0 \leq a_{\mathrm{i}} \leq 0.99$
- $0^\circ \leq \theta_{\mathrm{i}} \leq 180^\circ$
- $1.2 M_\odot \leq M_{\mathrm{NS}} \leq 2.0 M_\odot$



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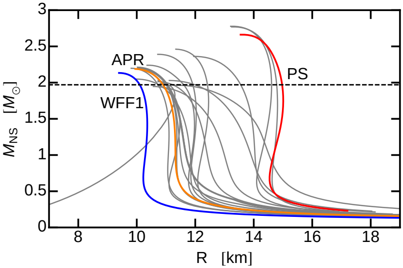
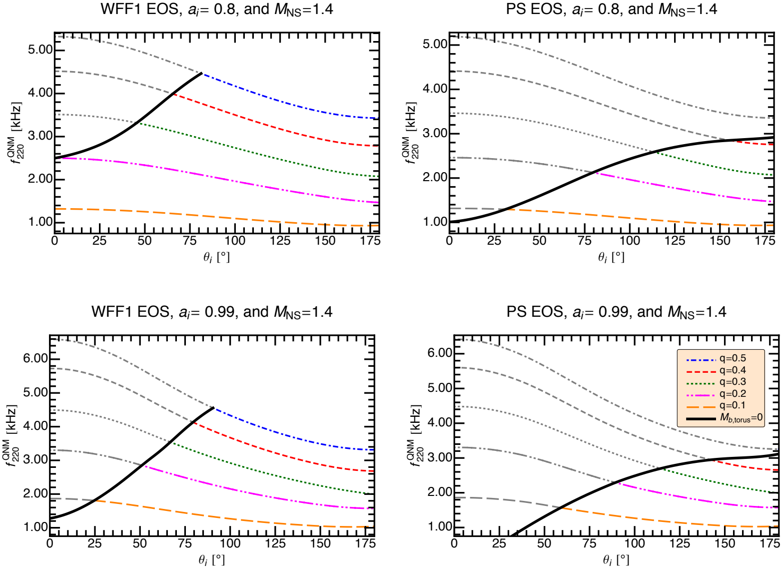


- The softer EOS, the higher a_f
- Indirect support to the *Cosmic censorship conjecture*: no overspinning BHs ($a_f > 1$) are formed
- $\max a_f = 0.997$: to be compared with the 0.998 limit of

  Thorne, ApJ **191**, 507 (1974)

Results: Black Hole Remnant Ringdown



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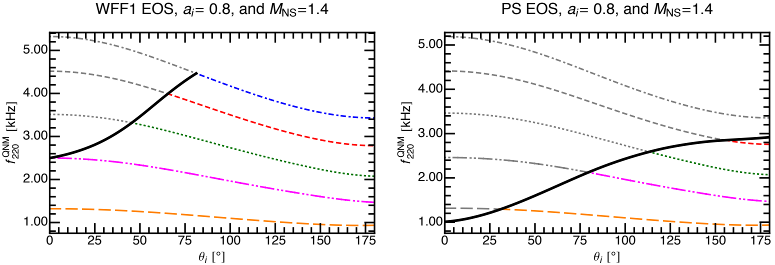

- BH-BH IMR vs. BH-NS templates

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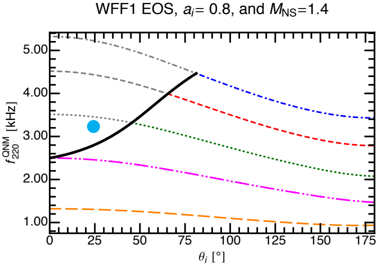

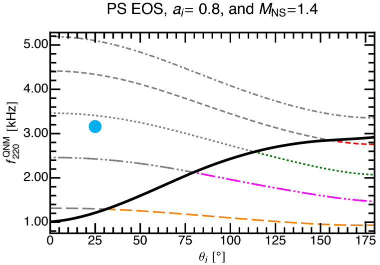

- BH-BH IMR vs. BH-NS templates
- BH-BH vs. BH-NS source

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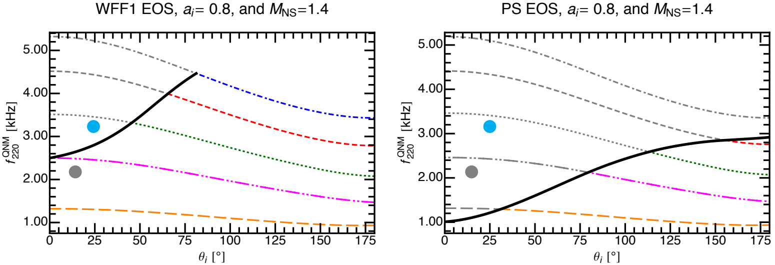

- BH-BH IMR vs. BH-NS templates
- BH-BH vs. BH-NS source
- Constraints on the NS EOS from repeated detections

BH-NS Gravitational Waveform Amplitude Model

- BH binaries have a history of Phenom GW modelling
- The number of BH-NS simulations is increasing

⇒ Quick inspiral-merger-ringdown model: accurate phenomenology, SNRs, and cutoff frequencies

FP, Berti, Kyutoku, Shibata, PRD **88**, 084011 (2013)

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38 numerical simulations

- SACRA code
- $Q \in [2, 5]$
- 2-piecewise polytrope EOS
- $M_{\rm NS} \in \{1.2 M_\odot, 1.35 M_\odot\}$
- $\mathcal{C} \in [0.131, 0.194]$
- $\Gamma_{\rm core} \in \{2.4, 2.7, 3.0, 3.3\}$

2 groups of runs

- 14 runs to build the model:
  $\Gamma_{\rm core} = 3.0$
  EOS$\in \{$2H,H,HB,B$\}$
  $M_{\rm NS} = 1.35 M_\odot$
- 24 runs as test cases

BH-NS Gravitational Waveform Amplitude Model

Starting tools

- Foucart's fit: tells us the torus mass ($M_{\text{b,torus}}$) and NS tidal disruption frequency (f_{tide})
- Model for the mass and spin of the BH remnant: we can compute the ringdown frequency (f_{RD})

Strategy

Exploit $M_{\text{b,torus}}$, f_{tide}, f_{RD} (and the initial physical parameters) to extend the PhenomC BH-BH gravitational waveform model

PhenomC Amplitude

Pure PN inspiral + a higher order term + ringdown Lorentzian

BH-NS Gravitational Waveform Amplitude Model

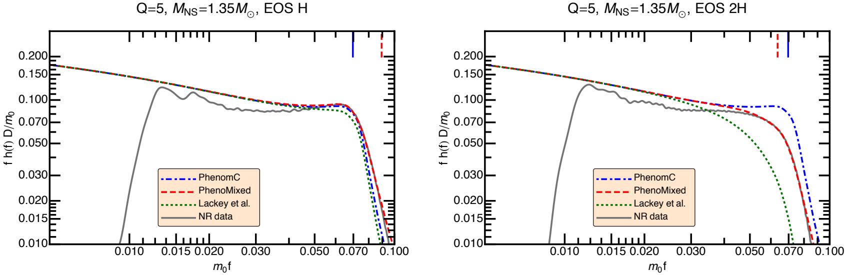
Tidal disruption

None: $f_{\rm tide} > f_{\rm RD}$
Mild: $f_{\rm RD} \geq f_{\rm tide}$ and $M_{\rm b,torus} = 0$
Strong: $f_{\rm RD} \geq f_{\rm tide}$ and $M_{\rm b,torus} > 0$

BH-NS Gravitational Waveform Amplitude Model

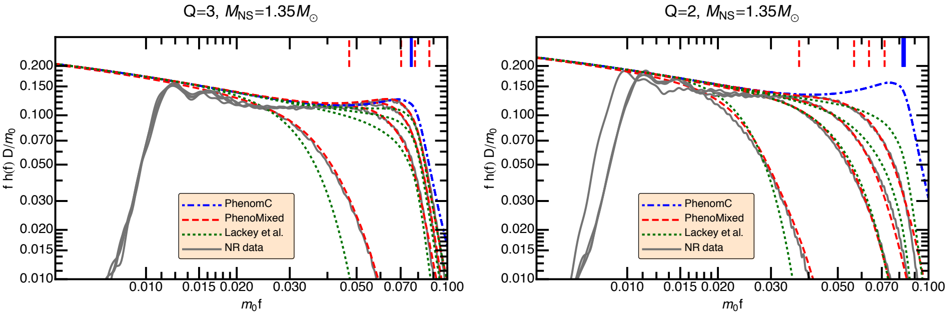
Tidal disruption

None: $f_{\rm tide} > f_{\rm RD}$
Mild: $f_{\rm RD} \geq f_{\rm tide}$ and $M_{\rm b,torus} = 0$
Strong: $f_{\rm RD} \geq f_{\rm tide}$ and $M_{\rm b,torus} > 0$



Lackey, Kyutoku, Shibata, Brady, Friedman, arXiV:1303.6298

BH-NS Gravitational Waveform Amplitude Model



BH-NS Gravitational Waveform Amplitude Model

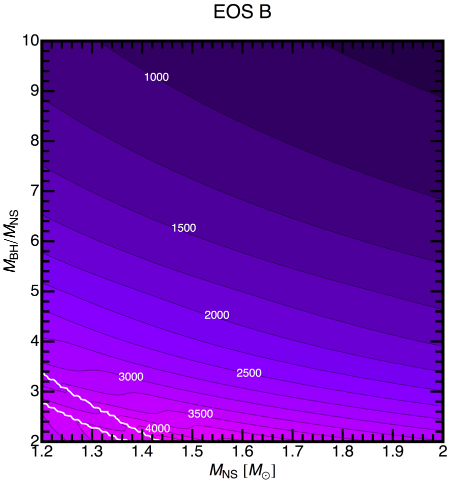
- Detectors: AdvLIGO, AdvZDHP, AdvVirgo, KAGRA varBRSE, maxBRSE, and varDRSE, ET B and D

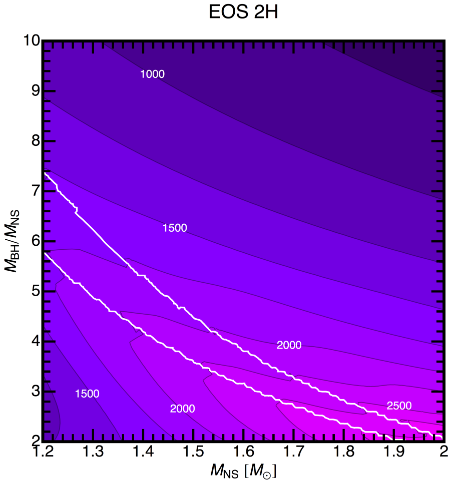
$$\left(1-\frac{\rho_{\rm BHNS}}{\rho_{NR}}\right)-\left(1-\frac{\rho_{\rm BHBH}}{\rho_{NR}}\right)=\frac{\rho_{\rm BHBH}-\rho_{\rm BHNS}}{\rho_{\rm NR}}$$

- `EOS2HQ2M12` and AdvZDHP LIGO yield $\sim 18\%$
- For Lackey+: 6%

- $|1-\rho_{\rm RPN}/\rho_{\rm BHNS}|$ up to $\sim 10\%$
- $|1-\rho_{\rm BHBH}/\rho_{\rm BHNS}|$ and $|1-\rho_{\rm BHNS}^{\rm Lackey+}/\rho_{\rm BHNS}|\lesssim 1\%$

Gravitational Wave Cutoff Frequency





Non-Universality of I-Love-Q Relations

- Slowly rotating unmagnetized NSs: quadrupole moment (Q), moment of inertia (I), and tidal Love number (λ) are in unique relations
- They are "universal": EOS-independent
- Could be used to break degeneracies between parameters in GW signals

Yagi, Yunes, Science **341**, 365 (2013)

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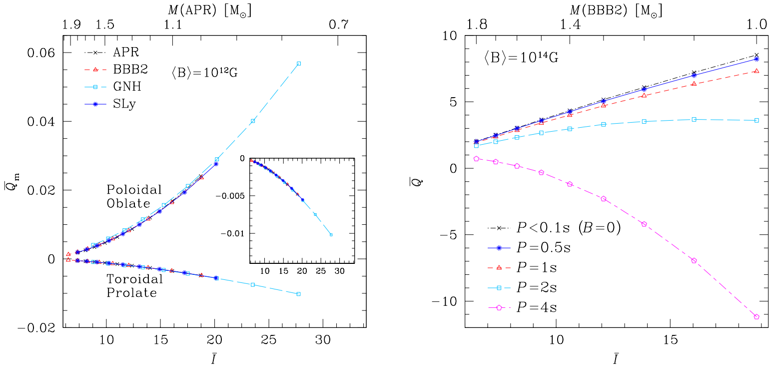
Yagi, Yunes, Science **341**, 365 (2013)

$\Rightarrow$ What happens in strongly magnetized NSs?

Haskell, Ciolfi, FP, Rezzolla, to appear in MNRAS (2013)

Non-Universality of I-Love-Q Relations

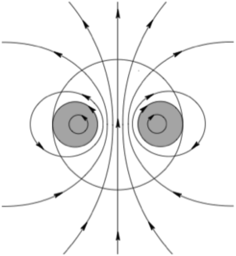


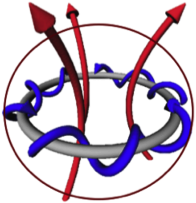
[LORENE]

- Simple magnetic field configuration ⇒ weak EOS influence
- Different field geometries ⇒ different I–Q relations
- Magnetic deformations dominate ⇒ universality broken

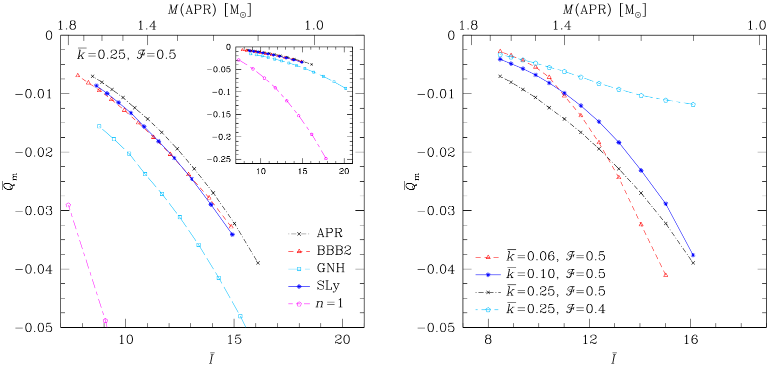
Non-Universality of I-Love-Q Relations

Twisted-torus configuration





Non-Universality of I-Love-Q Relations



[Perturbative code]

- Twisted-torus configuration ⇒ EOS-dependent I–Q relation

Non-Universality of I-Love-Q Relations

- The "universal" $I - \lambda - Q$ relations are not applicable to highly magnetized, slowly spinning NSs
- Any inferred parameter will not be reliable unless it is known that $B \lesssim 10^{12}$G $P \lesssim 10$s
- Pulsar B in PSR J0737-3039: $B_{\rm P} \simeq 1.2 \times 10^{12}$G and $P_{\rm merger} \sim 4$s. Possibly, $\langle B_{\rm internal} \rangle \sim 10^{14}$G: the quadrupole of this star may deviate significantly from that of an unmagnetized rotating star, and the NS could even be prolate!
- Tests of GR: unobserved strong interior magnetic field component may cause deviations from the expected trend
- Can we constrain the internal magnetic field structure via deviations from the "universal" $I - \lambda - Q$?

Summary

- Microphysics has a dramatic impact on the properties and evolution of NSs
- (How) can we probe NS interiors via CBC GW observations? Something we cannot do otherwise!
- Inspiral-merger-ringdown: all three stages have a lot to tell us
- EOS signatures are stronger in NS-NS binaries, but cleaner in BH-NS mergers
- BH-BH tools may be adapted more easily to the BH-NS case
- Magnetic fields yield exciting counterparts, but complicate even the simplest scenario: we must be aware of this