What can we learn about neutron stars from binary neutron star coalescences?

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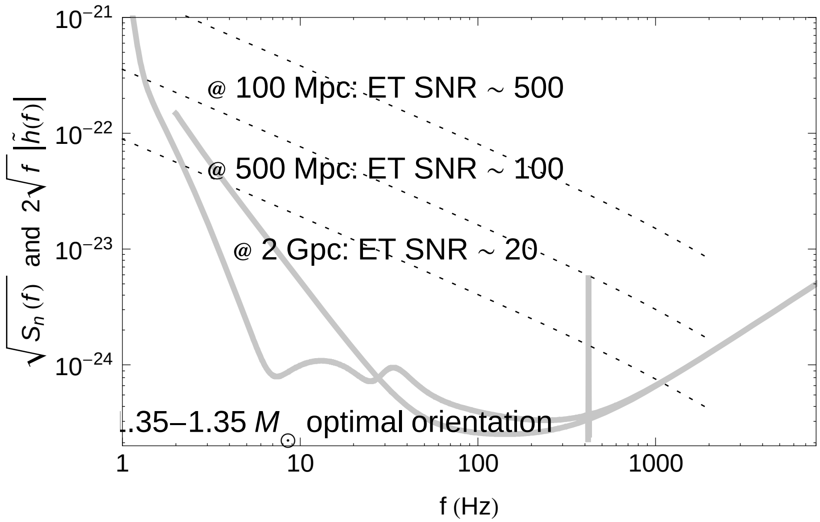
1 Sept 2010

Inspiral strength in ET



What can we learn from the strongest signals?

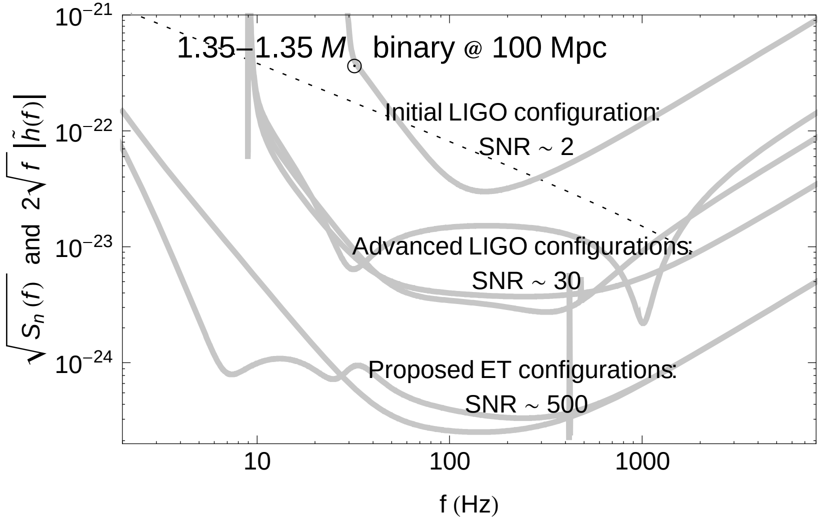
Can we measure additional astrophysically relevant parameters directly from a gravitational wave event?

The early inspiral point-particle model is characterized by the masses of the stars: ET will see many signals → learn about neutron star populations, formation scenarios, mass ranges...

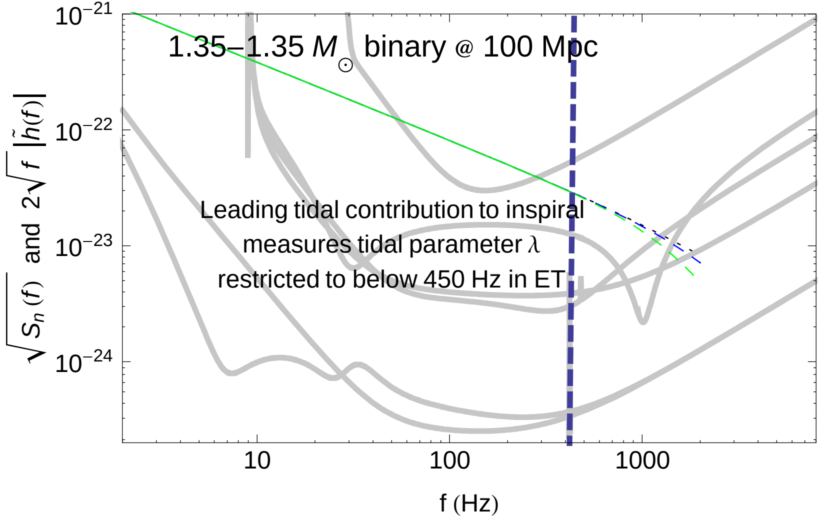
This talk focuses on additional details that may be visible in strong signals: modifications to the late inspiral, and the coalescence and post-coalescence waveforms themselves.

I'm almost entirely going to talk about the cold EOS.

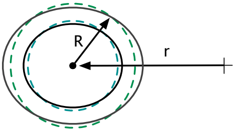
Strong inspiral signal from binary neutron stars

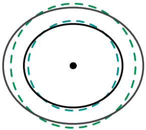


Modification to inspiral



Tidal deformability λ for realistic EOS





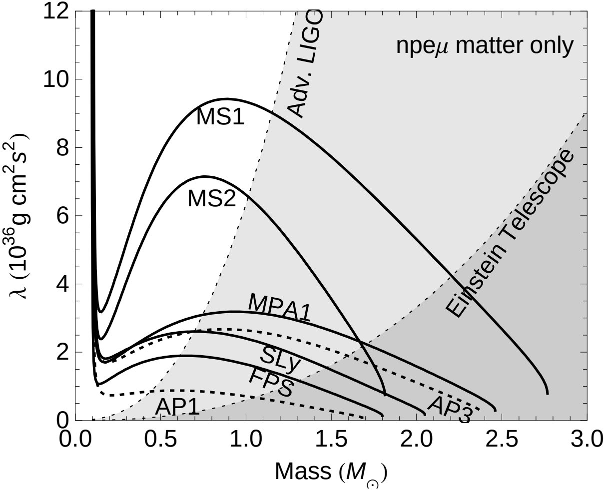
$$\lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}}$$

$$\lambda = \frac{2}{3} k_2 R^5$$

Calculate via linear Y_{20} perturbation of spherical neutron star
Q and $\mathcal{E}$ defined by external field of perturbed star

Incorporate resulting corrections to energy and GW luminosity into post-Newtonian waveforms

Measuring tidal deformability λ

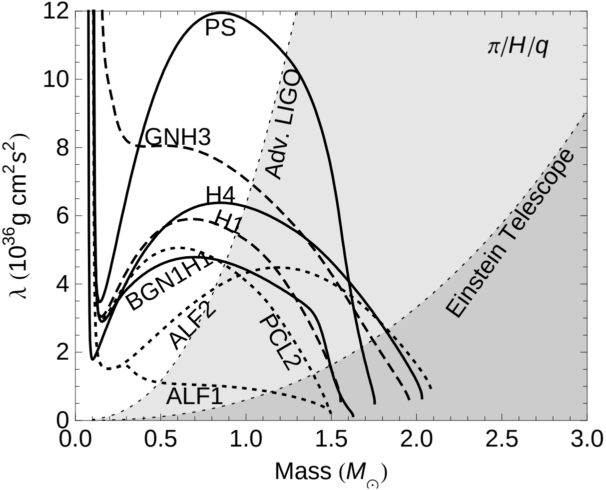


Each thick line: a candidate equation of state gives λ as function of mass.

shaded: Uncertainty in estimating λ for Advanced LIGO and ET using "clean" waveform: below 450 Hz only

T Hinderer, B Lackey, R Lang, JR arXiv:0911.3535

Measuring tidal deformability λ



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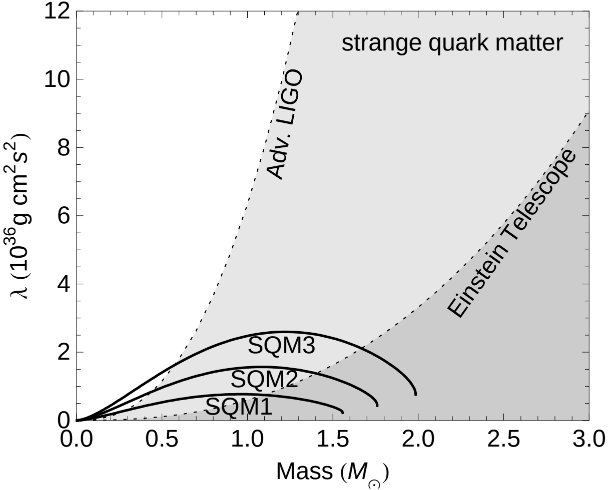

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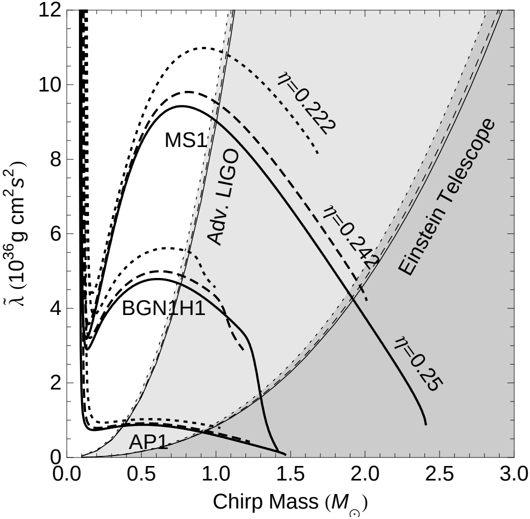
Unequal mass binaries



Tidal effects on gravitational wave phase depend on a weighted average

$$\tilde{\lambda}(m, \eta)$$

combining

λ_1 for m_1

and

λ_2 for m_2

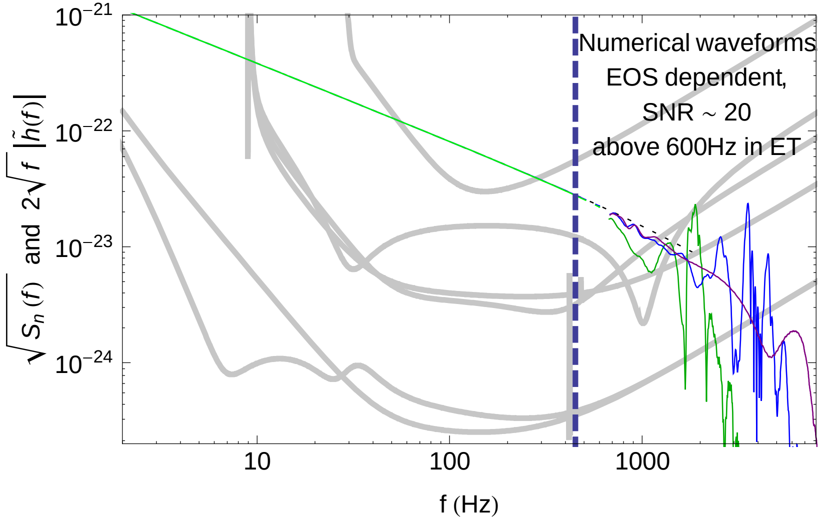
Spin and η considered

Measurement using frequency band 10 Hz $\leq f \leq$ 450 Hz, at 100 Mpc, averaged over sky position and inclination.

Einstein Telescope

M ($M_\odot$)	m_2/m_1	$\Delta\mathcal{M}/\mathcal{M}$	$\Delta\eta/\eta$	$\Delta\tilde{\lambda}(10^{36}\,\mathrm{g\,cm^2\,s^2})$	ρ
2.0	1.0	0.000015	0.0058	0.70	354
2.8	1.0	0.000021	0.0043	1.60	469
3.4	1.0	0.000025	0.0038	2.58	552
2.0	0.7	0.000015	0.0058	0.68	349
2.8	0.7	0.000021	0.0045	1.56	462
3.4	0.7	0.000025	0.0038	2.52	543
2.8	0.5	0.000020	0.0048	1.46	442

Signal from merger of binary neutron stars



Signal from merger of binary neutron stars

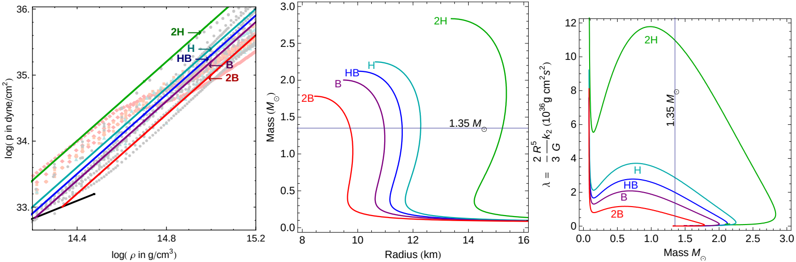
Requires numerical simulation

Additional relevant physics

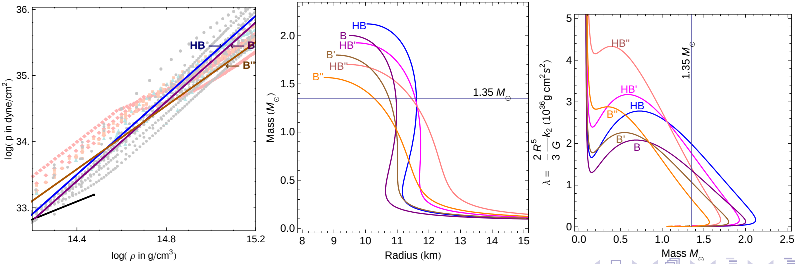
- Cold EOS contribution includes higher-order tidal effects, other deformation modes, nonlinearity of deformations, approaches resonance with stellar modes
- Increased temperature from shock heating: hot EOS effects (e.g. Bauswein and Janka 2010)
- Magnetic field effects amplified, affect stability of hypermassive object (e.g. Giacomazzo, Rezzolla, and Baiotti 2009)
- Microphysics: particle production → neutrino pressure

Systematic EOS exploration in BNS simulation

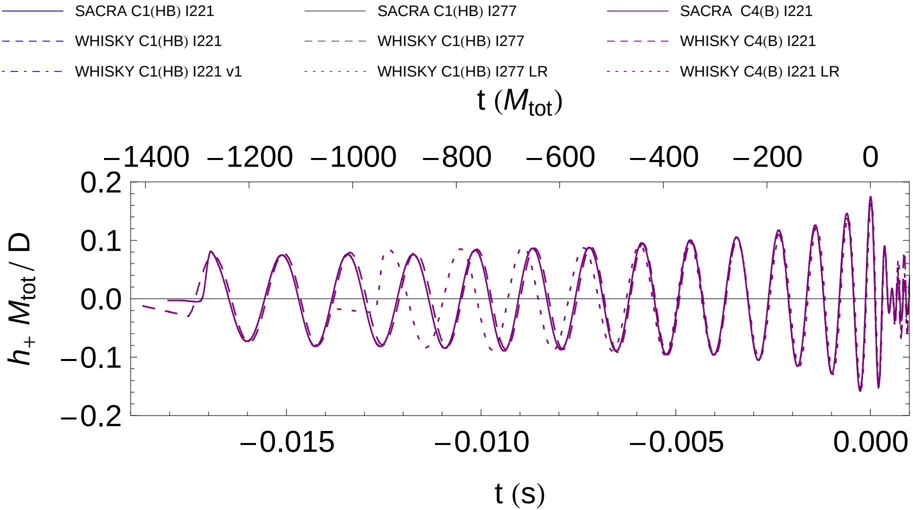
vary pressure scale



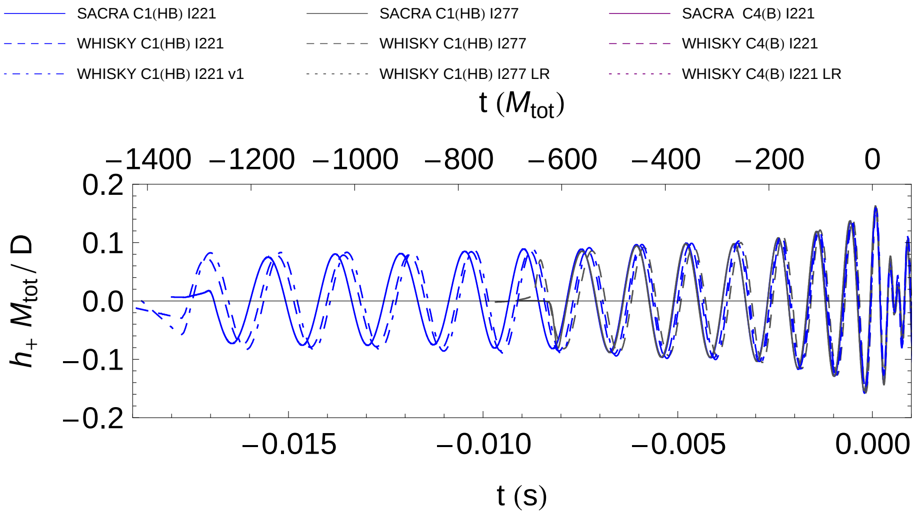
vary Γ



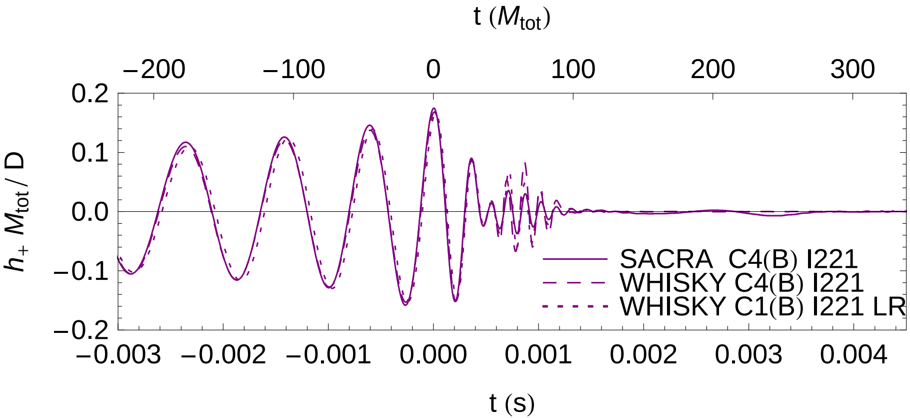
Inspiral agreement: EOS B



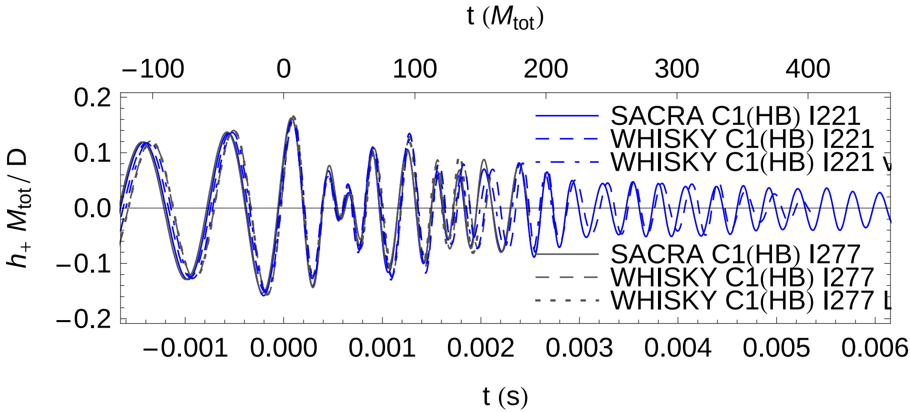
Inspiral agreement: EOS HB



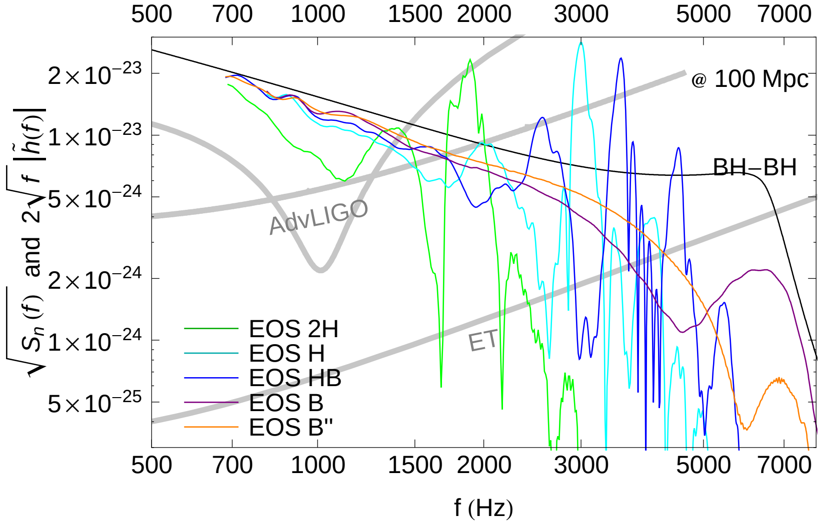
Merger agreement: EOS B



Merger agreement: EOS HB



Range of signals from varying EOS



Measurability estimates: EOS effects on inspiral

Construct hybrid waveforms: connect analytic waveform with tidal contributions to numerical inspiral

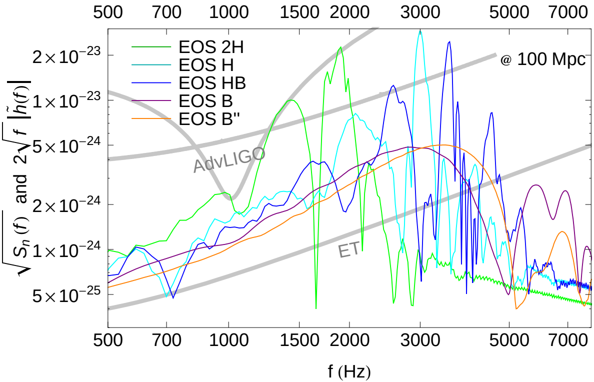
Measurability estimates require parameterization of signal: e.g. by EOS parameters, radius, or λ.

arXiv:0901.3258

point particle post-Newtonian and short numerical inspiral
ρ of difference between simulated EOS ranges from 1 to 6 in ET
$\Delta\lambda \sim 0.2$ from signal above 750 Hz in ET
(compare ~ 1.6 from early inspiral only)

Measurability of merger and post-merger?

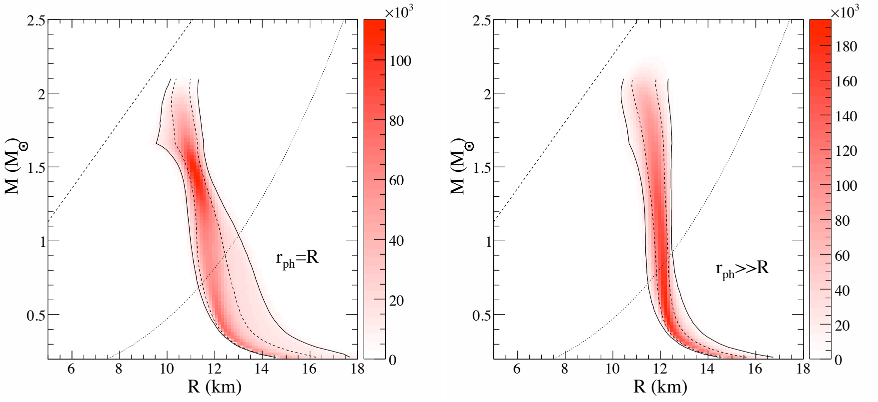
Waveforms after peak amplitude:



Hypermassive Remnant	ET SNR	Prompt collapse	ET SNR
EOS 2H	$\sim$6	EOS B	$\lesssim$3
EOS H	$\sim$4	EOS B"	$\lesssim$3
EOS HB	$\sim$4		

These estimates are dependent on the stability of the PMO

EM observations are also constraining the EOS



Three X-ray bursters + thermal emission from transiant LMXBs + cooling of an isolated neutron star. (Steiner et. al. 2010, 1005.0811)