Physics from binary neutron star coalescences

Jocelyn Read

Max Planck Institute for Gravitational Physics

25 March 2009

Outline

1. Overview of relevant physics
   - Early versus late inspiral
   - Coalescence and post-merger oscillations

2. Estimating measurability of EOS effects on inspiral
   - Measurement estimates from numerical simulation
   - Effect in post-Newtonian approximation

Signal from inspiral of binary neutron stars

Base model

- point particles
- non-spinning
- post-Newtonian expansion describes phase evolution

Signal from inspiral of binary neutron stars

Base model

- point particles
- non-spinning
- post-Newtonian expansion describes phase evolution

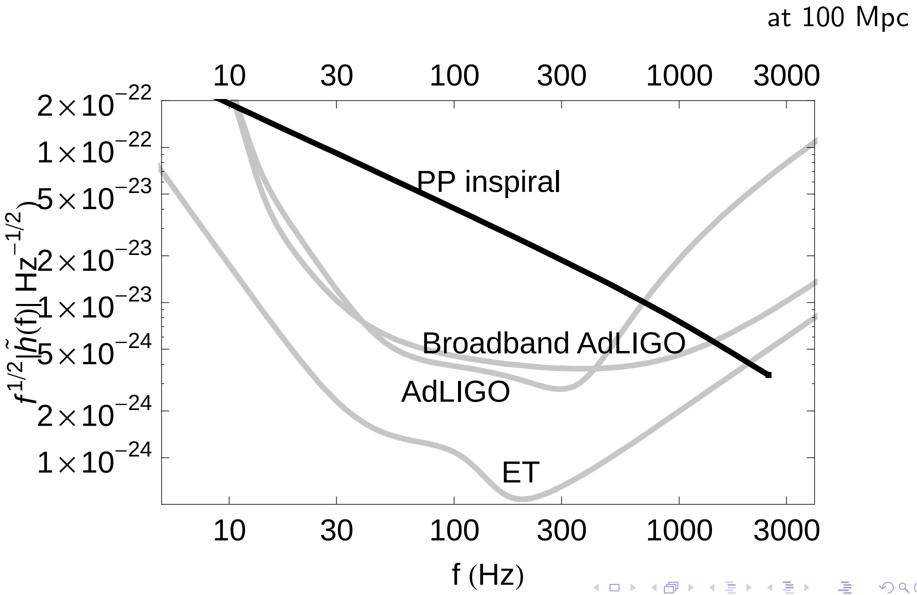
Modified late inspiral and coalescence time

- stars have finite size
- tidal deformation modifies dynamics

Relevant physics for late inspiral

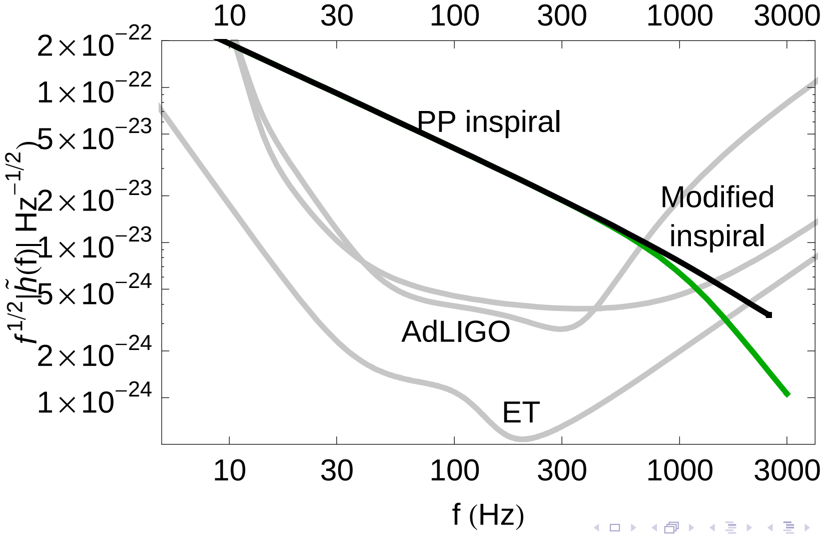
- Masses, spins
- Cold equation of state $\longrightarrow$ Radius / tidal deformability

Overview of signal from binary neutron stars



Overview of signal from binary neutron stars

at 100 Mpc



Signal from merger of binary neutron stars

After coalescence

(Shibata Taniguchi Uryu 2005, Oechslin and Janka 2007,...)

- Prompt collapse OR
- Formation of a hyper-massive neutron star
  - differentially rotating
  - stable on $\sim$ 10ms timescales
- Hypermassive star with bar mode emits gravitational wave signal: post-merger oscillation peak(s) in spectrum
  - presence or absence?
  - frequency(ies)
  - longevity of signal

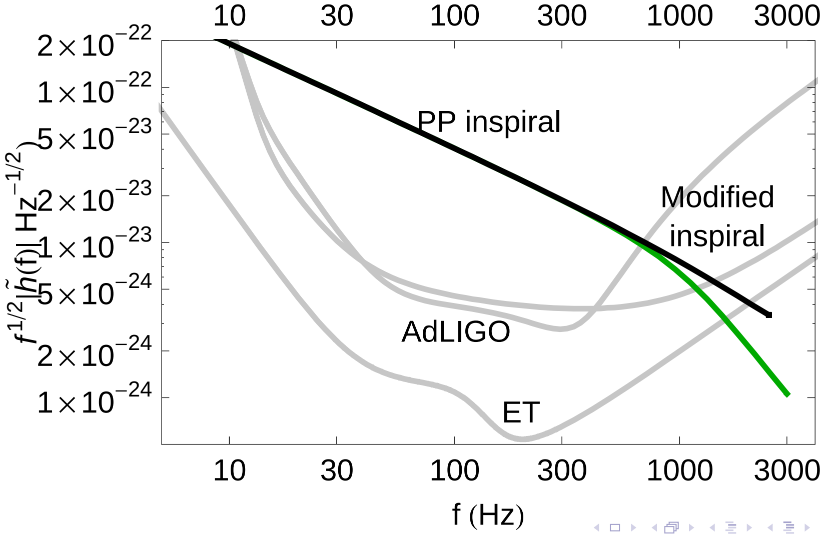
Signal from merger of binary neutron stars

Additional relevant physics

- Increased temperature from shock heating: further equation of state effects
- Magnetic field effects amplified, affect stability of hypermassive object (Giacomazzo, Rezzolla, and Baiotti 2009)
- Microphysics, particle production... electromagnetic counterparts

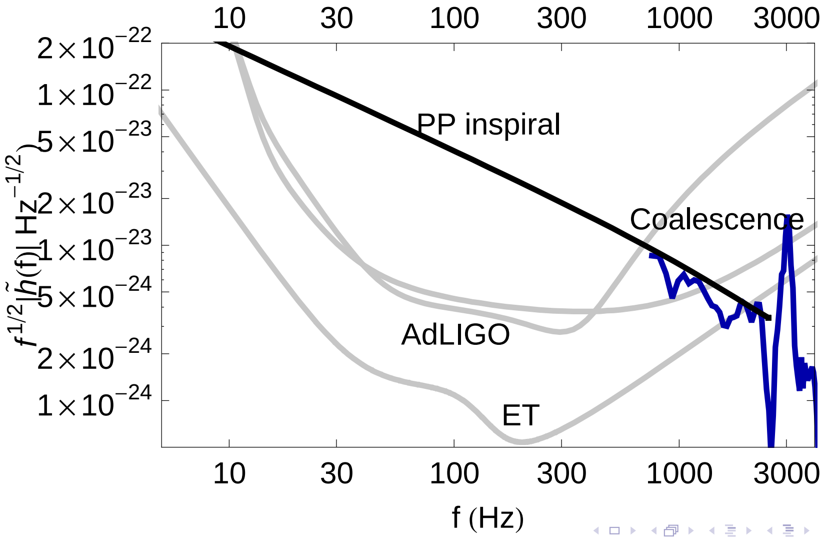
Overview of signal from binary neutron stars

at 100 Mpc



Overview of signal from binary neutron stars

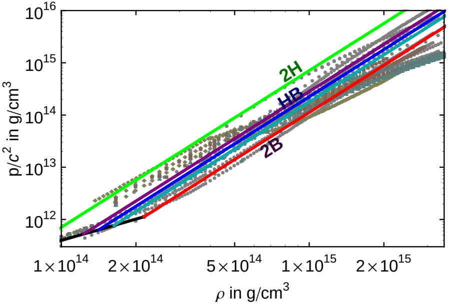
at 100 Mpc



Outline

1. Overview of relevant physics
   - Early versus late inspiral
   - Coalescence and post-merger oscillations
2. Estimating measurability of EOS effects on inspiral
   - Measurement estimates from numerical simulation
   - Effect in post-Newtonian approximation

Estimating measurability of EOS effects
Method 1: Numerical simulation with varying EOS



Initial data *(Charalampos Markakis and Koji Uryu)*

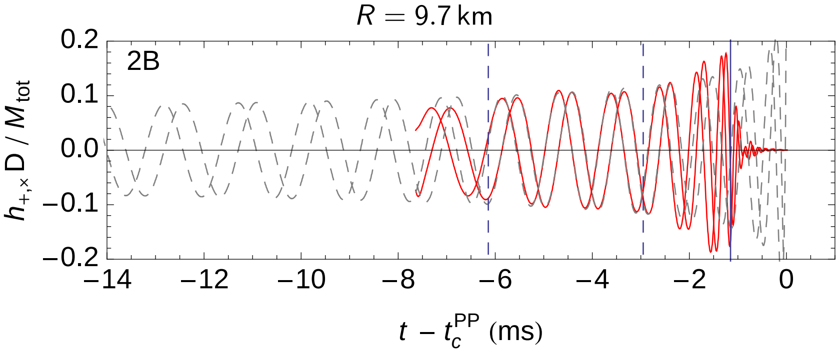
- Irrotational, equal mass, $1.35M_\odot$ neutron stars
- Roughly 3 orbits before merger

Evolution *(Masaru Shibata)*

- BSSN with maximal slicing
- Shock-capturing hydrodynamic scheme

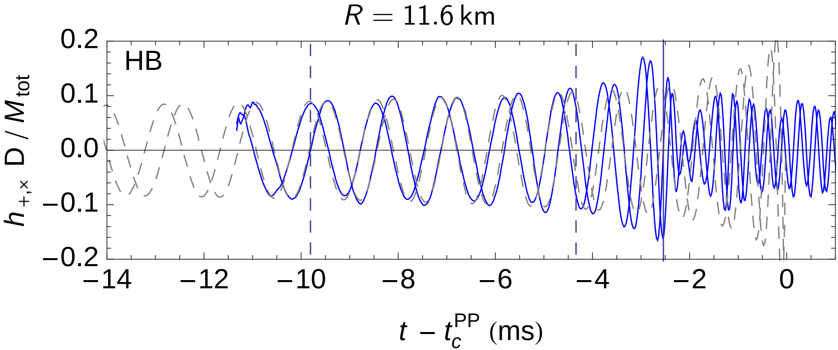
Resulting numerical waveforms

Aligned by match to PN in early inspiral



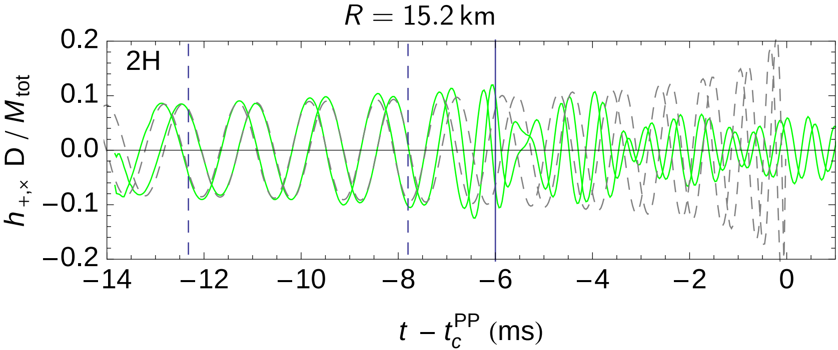
Resulting numerical waveforms

Aligned by match to PN in early inspiral

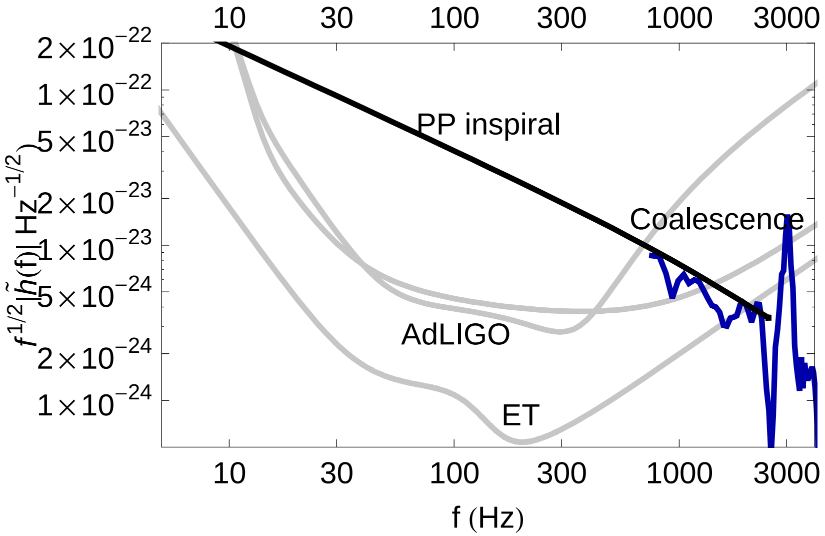


Resulting numerical waveforms

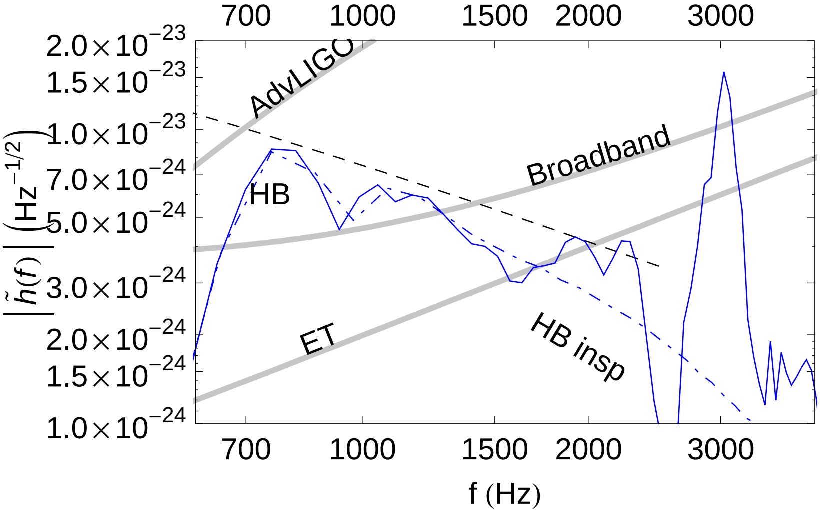
Aligned by match to PN in early inspiral



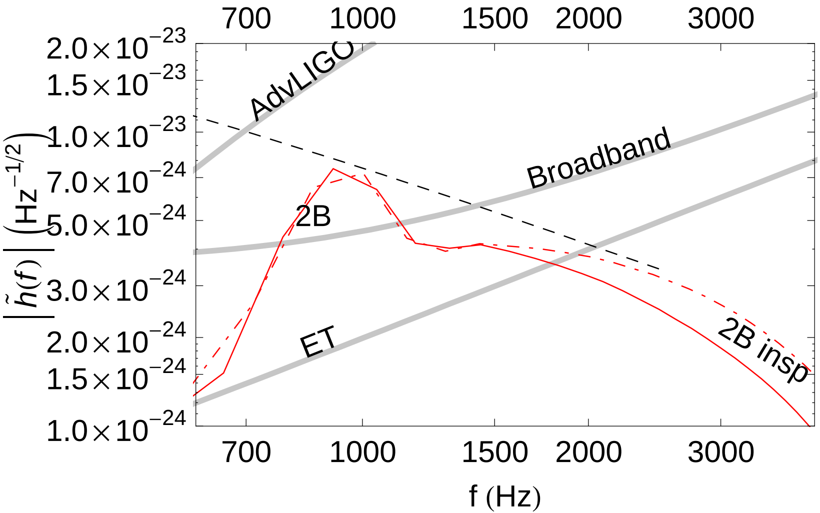
Equivalent strain at 100 Mpc



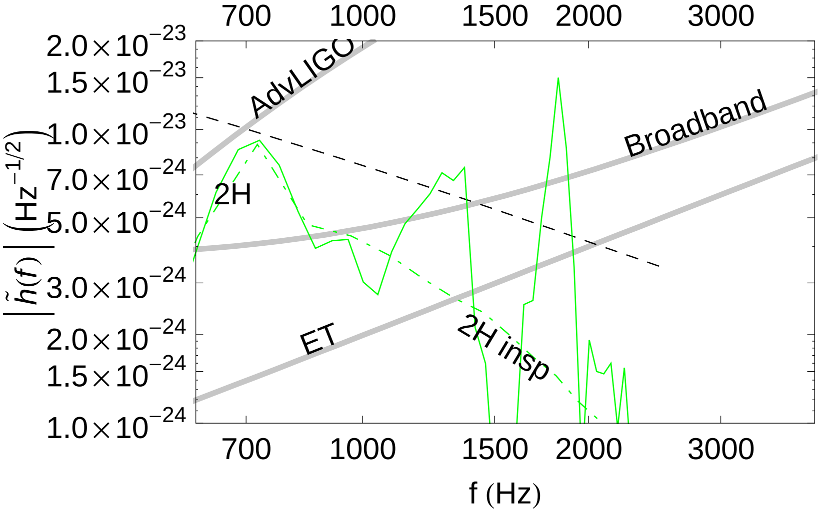
Equivalent strain at 100 Mpc



Equivalent strain at 100 Mpc



Equivalent strain at 100 Mpc



Parameter Constraint

$$\langle \Delta p \rangle \Big|_{p_{avg}} \simeq \frac{p_1 - p_2}{\big\langle h(p_1) - h(p_2) \big| h(p_1) - h(p_2) \big\rangle^{1/2}}$$

From $1.35 M_\odot$–$1.35 M_\odot$ double neutron star binary at 100 Mpc in ET:

δR, R is radius of isolated neutron star

$$\begin{aligned} R &= 10.3 & \pm 0.31 \text{ km} \\ R &= 11.6 & \pm 0.95 \text{ km} \\ R &= 13.75 & \pm 0.54 \text{ km} \end{aligned}$$

δp_1, p_1 is $\log(p/c^2)$ at rest mass density 5×10^{15} g/cm^3

$$\begin{aligned} p_1 &= 13.25 & \pm 0.05 \\ p_1 &= 13.45 & \pm 0.14 \\ p_1 &= 13.75 & \pm 0.07 \end{aligned}$$

Estimating measurability of EOS effects
Method 2: Add first order effect from tidal deformation

$$E = -\frac{1}{2} M c^2 \eta x \left(1 + [\text{up to 3PN}] - 9 \frac{m_2}{m_1} \lambda_1 \frac{x^5}{M^5} \right)$$

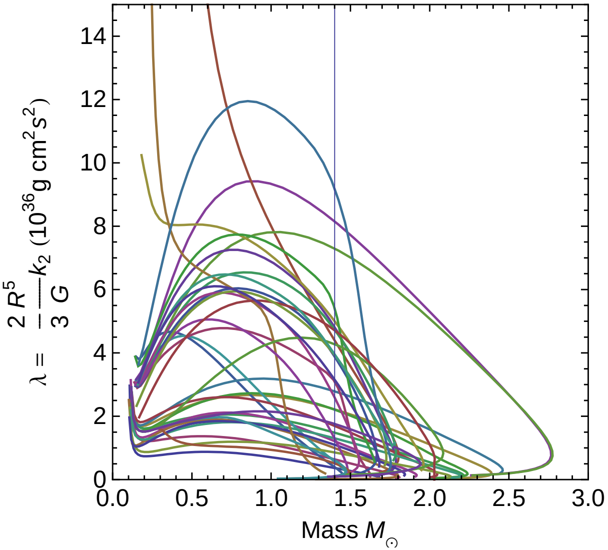
$$\mathcal{L} = \frac{32}{5} \frac{c^5}{G} \eta^2 x^5 \left(1 + [\text{ up to 3.5PN}] + 6 \left(\frac{M}{m_1} + 2 \frac{m_2}{m_1} \right) \lambda_1 \frac{x^5}{M^5} \right)$$

$$M = m_1 + m_2$$
$$\eta = m_1 m_2 / M^2$$
$$x = \left(G M \Omega / c^3 \right)^{2/3}$$

$$\lambda = \frac{\text{induced quadrupole moment}}{\text{external quadrupole tidal field}} = \frac{2}{3} k_2 R^5$$

Flanagan and Hinderer 2007

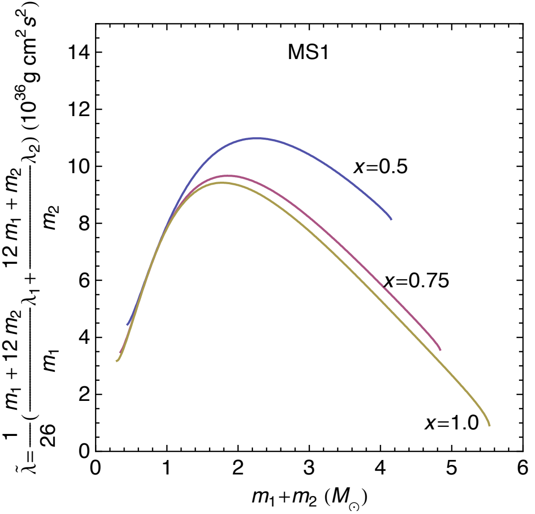
Tidal deformability λ for realistic EOS



Calculate via linear perturbation of spherical solution for a single neutron star of given mass

Ben Lackey, UWM

Generalize to parameterize tidal effects in unequal masse binaries



PN effects depend on a weighted average $\tilde{\lambda}(m,\eta)$ combining λ_1 for m_1 and λ_2 for m_2

Ben Lackey, UWM

Measurablity of λ in early inspiral

This gives an analytic waveform model; can calculate *full* Fisher matrix

Estimate for Einstein Telescope for source at 50 Mpc:

- $\Delta\tilde{\lambda} \sim 1.22 \times 10^{36}$ for $1.35 - 1.35 M_\odot$
- $\Delta\tilde{\lambda} \sim 1.6 \times 10^{36}$ for $1.45 - 1.45 M_\odot$
- $\Delta\tilde{\lambda} \sim 1.85 \times 10^{36}$ for $1.35 - 1.7 M_\odot$

for inspiral *below 400 Hz*

Tanja Hinderer, Caltech

Note: Realistic EOS have $\tilde{\lambda}$ between 0.5×10^{36} g^2 cm^2 and 10×10^{36} g^2 cm^2.

Summary

Physics that is not important for *detection* becomes *measurable* in advanced detectors: this lets us do astrophysics

One example is tidal deformation in late inspiral, dependent on the equation of state.

Numerical simulations give an estimate of the strength of this effect in high frequencies: it constrains realistic EOS in ET

The inspiral effect can be linked to a tidal deformability parameter $\tilde{\lambda}(M, \eta)$ specified by the EOS.

Tidal deformation effects below 400 Hz are also detectable with ET sensitivity.