Modelling gravitational wave sources

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The role of modelling

I will talk about the *modelling of gravitational wave (GW) sources.*

There are several reasons why this is important:

1. To help make a detection:
    - by providing waveforms
    - by identifying promising regions of parameter space
    - by influencing detector operation or design
2. To allow extraction of useful physics

Outline

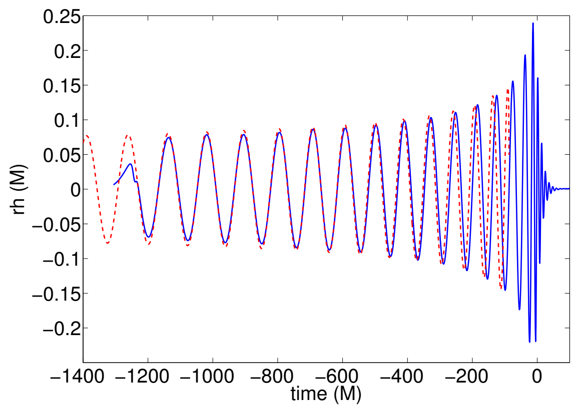
- Binary inspiral
- Stellar collapse
- Magnetars
- Periodic sources

Binary inspiral

- Binary inspirals are a (possibly *the*) leading candidate for GW detectors.
- Several decades have been spent on trying to produce wave forms - success came dramatically in the last two years.
- Key ingredients were:
  - Clever formulations of the Einstein equations—particularly when dealing with the event horizons/singularities.
  - Good initial data.
  - *Adaptive* mesh refinement.
  - And, of course, seriously expensive computers.

Binary inspiral

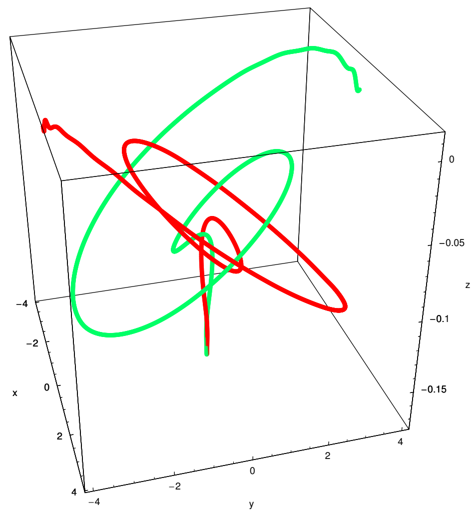
- Waveforms now calculated for a few points in parameter space.
- Agreement with post-Newtonian calculations good, e.g. Baker et al. (2006; gr-qc/0612024):



- However, the parameter space is huge; how can we construct necessary templates?
- Already surprises have been found...

Binary inspiral: kicks

- Simulations have found that significant angular momentum can be imparted during coalescence, e.g. González et al. (2007; gr-qc/0702052):

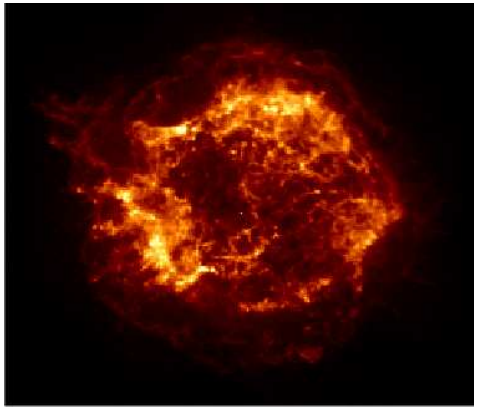


- Astrophysical implications are immense.

Core collapse & supernovae

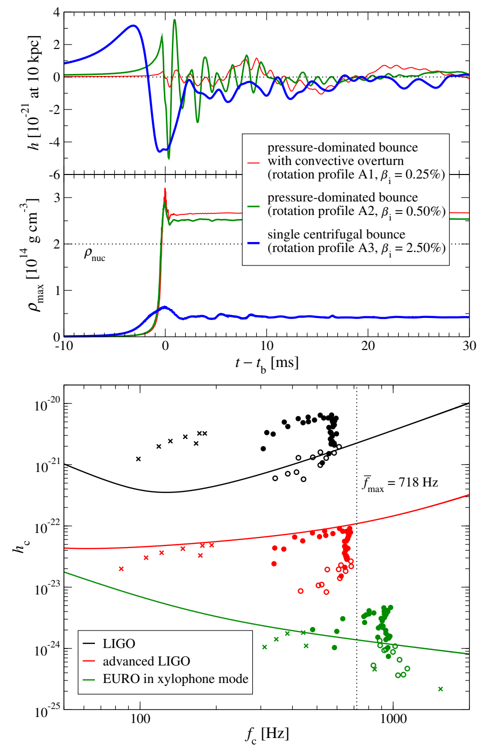
There are many essential ingredients:

- Strong-field gravity
- Accurate wave extraction
- Realistic initial configurations
- Accurate treatment of fluid (including shocks)
- Realistic equation of state
- Treatment of neutrino propagation



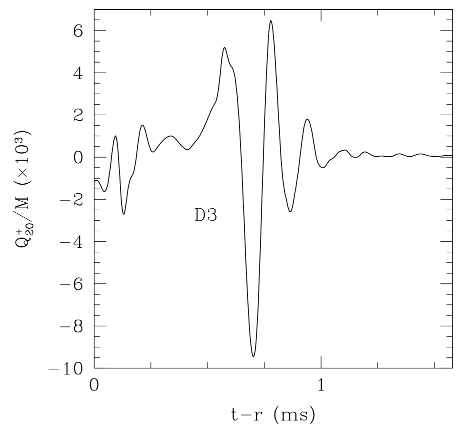
Core collapse: from an iron core to a proto-neutron star

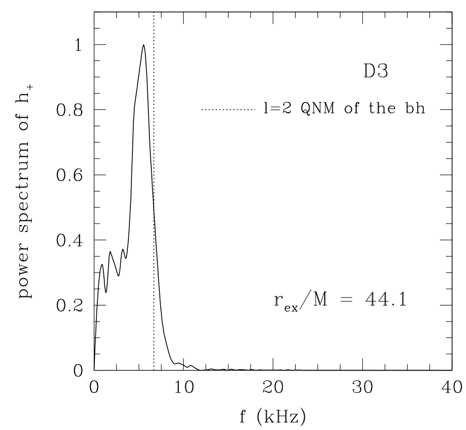
- Interesting recent results from Dimmelmeier et al. (1007; astro-ph/0702305)
- Includes most important ingredients.
- Find that *shape* of GW signal generic and dominated by gravity/pressure effects.
- However, *frequency* of signal is parameter dependent:



Core collapse: black hole formation

- Baiotti, Hawke & Rezzola (2007; gr-qc/0701043) collapse $\sim 1M_\star$ rotating stars to black holes.
- BH formation creates unique problems.
- Use 7 levels of mesh refinement to allow wave extraction.
- Produce varied waveforms.
- Find energy release $\propto (J/M^2)^4$



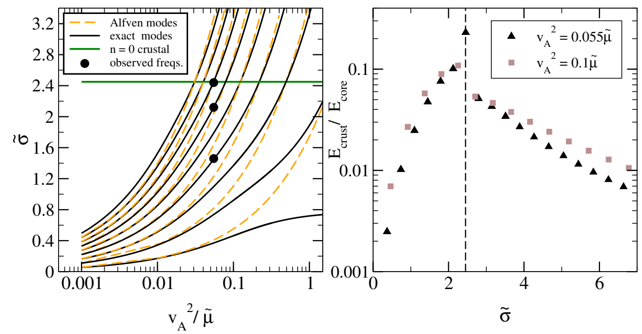


Magnetars

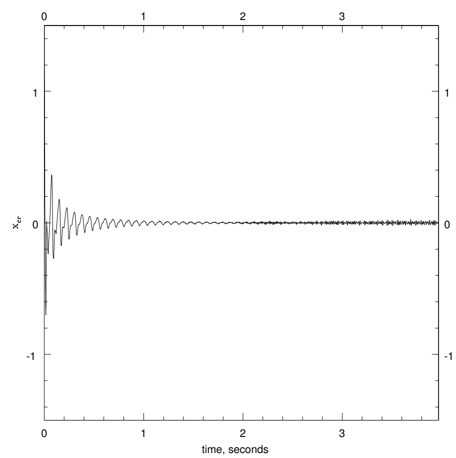
- *Magnetars* are slowly rotating ($f < 1$ Hz) compact objects with *very* strong magnetic fields (10^{14}–10^{15} G).
- Several have been observed to emit X-ray bursts; **quasi-periodic oscillations** have been seen in the tails of two of these.
- We are probably seeing **neutron star oscillations**, so GW/astrophysical interst immense.
- But, what exactly is going on? Currently a hot topic, with much debate...

Magnetars

- Glampedakis et al. (2006; MNRAS **371** L74) have computed elastic/MHD modes in simplified geometry.
- Find rich spectrum, with crustal oscillations in correct range:



- However, Levin (2007; astro-ph/0612725) find that MHD continuum plays a crucial role:



- So, still debate about main physics determining spectra...

Periodic sources

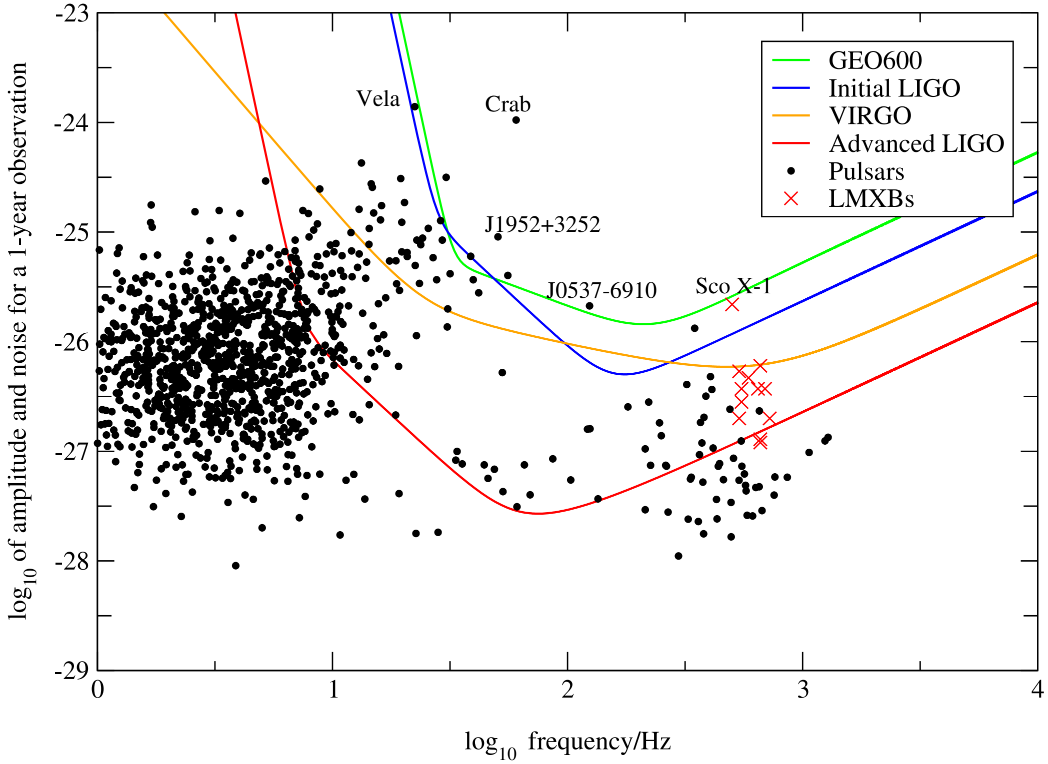
- 'Periodic' means long-lived and approximately sinusoidal waveform.
- Rotating neutron stars best candidate; three main emission mechanisms:
  1. 'Mountains', i.e. equatorial moments of inertia unequal
  2. Free precession
  3. Fluid instabilities

  Physical modelling *very* complicated; involves GR, superfluidity/conductivity, elasticity, magnetic fields, rotation, ...
- Also, parameter space is of (at least) seven dimensions:

$$\boldsymbol{\theta} = (h_0, f, \alpha, \delta, \phi_0, \iota, \psi)$$

Periodic sources: known stars

Upper limits on GW emission from mountains on known pulsars:



Modelling informs which upper limits are most plausible (or least implausible..., e.g. Owen 2006, Haskell, DIJ & Andersson 2006)

Summary

- There have been major advances in the last few years, particularly in numerical relativity.
- Wave forms for inspiral and collapse are beginning to be produced; there remains a huge parameter space to cover.
- There exist many interesting partially solved problems in neutron star oscillation/rotation.
- In all areas, dialogue between numerical and perturbative treatment crucial, and will remain so.
- Progress excellent, but GW data analysis needs more help to make searches feasible.