Searching for gravitational waves from neutron stars

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Context: gravitational wave astronomy

- We already have experimental evidence for GWs: PSR1913+16, winning Hulse & Taylor the 1993 Nobel Prize.
- We want to *detect* GWs directly. There are two reasons for this:
- To *test* Einstein's theory of General Relativity.
- To *learn* about the objects that produce them, i.e. to open up the new field of *gravitational wave astronomy*.

Overview

- The detectors
- Types of source
- Neutron stars as sources

Direct detection: Interferometers

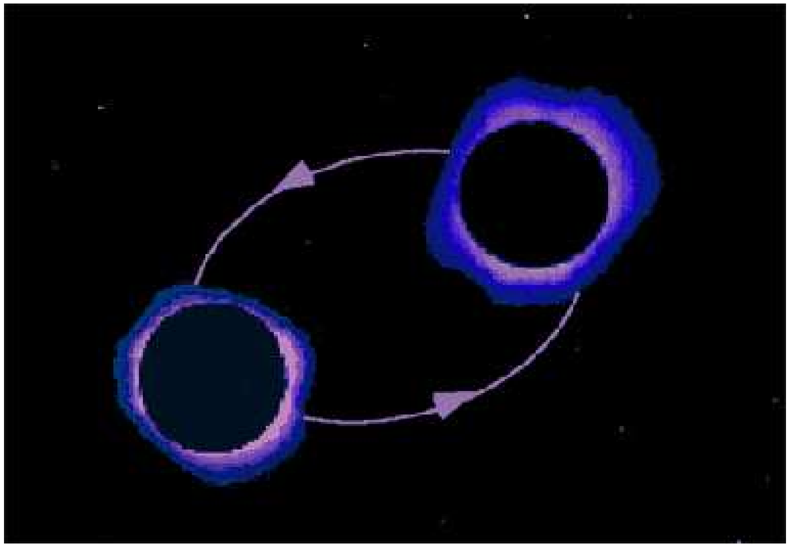
- UK/Germany: GEO600 (600 m, shown above).
- US: LIGO Hanford (2 km, 4 km) and LIGO Livingstone (4 km).
- France/Italy: VIRGO (3 km).

Sources of gravitational waves

Can divide into four subclasses:

- Binary inspiral.
- Bursts.
- Stochastic background.
- Periodic sources.

Sources of GWs: Binary inspiral



Considered (by many!) most promising sources for detection.

- Made up from neutron stars and/or black holes.
- Would probe strong field gravity $\rightarrow$ excellent test of Relativity.

Signal analysis for binary inspiral

Relies on the idea of *matched filtering*:

- Detector output is noisy time-series $o(t)$.
- Construct a bank of templates $u(\theta^a, t)$, where θ^a is a vector of source parameters (e.g. mass, spin, frequency).
- For each template construct the signal to noise ratio:

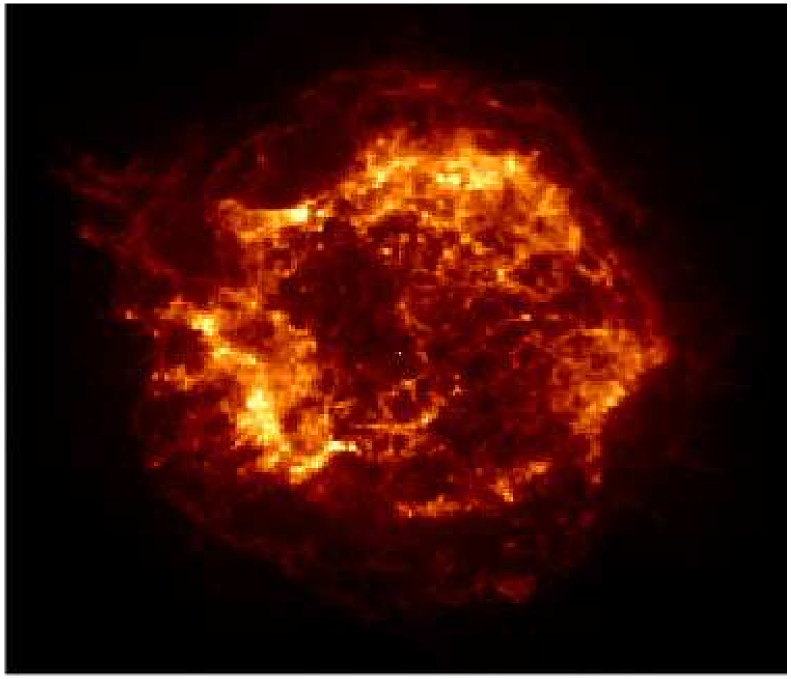
$$\rho^2 = 4\,\mathrm{Re} \int \frac{\tilde{u}(f)\tilde{o}(f)^\star}{S_h(f)}\, df.$$

- Claim a detection when ρ exceeds some threshold, plus other consistency checks...

Example observational upper limit (Abbott et al. 2008):

Inspiral rate $< 1.2\,\mathrm{yr}^{-1}\, L_{10}^{-1}$ for masses 1–$3M_\odot$.

Sources of GWs: Bursts



Possible burst sources include:

- Supernova (Cas A is shown above).
- Gamma ray bursts.
- Soft gamma ray repeaters (SGRs).

GW emission depends upon how *asymmetric* the explosion is.

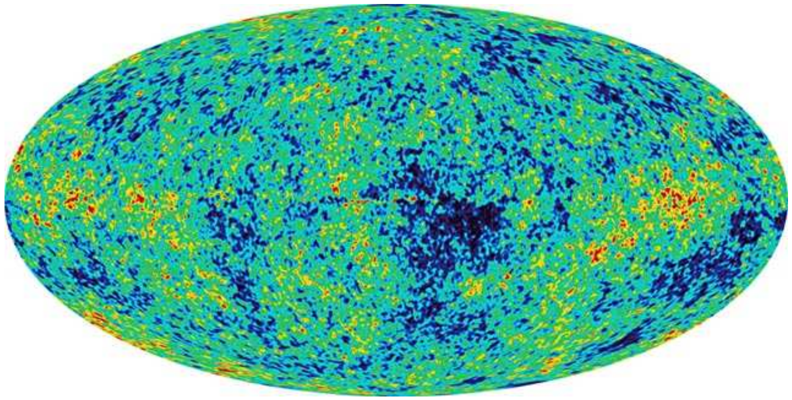
Signal analysis for bursts

- Difficult because shape of waveform less well unknown.
- A possible strategy is to match filter using a guessed waveform, e.g. a damped sine wave.
- Statistical significance improved by:
  - Coincidence between multiple GW detectors.
  - Coincidence with electromagnetic events.

Example observational upper limit (Abbott et al. 2008):

$E_{\rm GW} < 30 E_{\rm EW}$ for SGR 1806-20 giant flare, assuming duration 100 ms, and white noise frequency spectrum $100 < f_{\rm GW}/{\rm Hz} < 200$.

Sources of GWs: Stochastic background



- Just as there is a background of electromagnetic radiation left over from the Big Bang (shown above), so there must be a GW background too.
- Would probe the Universe at very early times e.g. during the inflationary era.
- However, the strength of the background is unknown, and may be very weak.

Signal analysis for a stochastic background

- Must use cross-correlation between detectors.
- For outputs $o_1(t)$ and $o_2(t)$:

$$C = \int dt_1 \int dt_2 \, o_1(t_1) Q(t_1 - t_2) o_2(t_2),$$

where $Q(t_1 - t_2)$ is a filter to account for different detector locations, orientations and sensitivities.

Example observational upper limit (Abbott et al. 2007)

$\Omega_{\rm GW}(H_0/72 {\rm kms}^{-1}{\rm Mpc}^{-1}) < 6.5 \times 10^{-5}$ for frequency-independent spectrum over interval $51 < f/{\rm Hz} < 150$.

Sources of GWs: Periodic sources

- Neutron stars are small and dense and rotate rapidly.
- $\longrightarrow$ They would be good GW emitters *if* the are asymmetric.
- Possible emission mechanisms:
  - Triaxiality
  - Free precession
  - Fluid oscillations
  - None of the above

Continuous waves

- A continuous monochromatic source is specified by a set of parameters:

$$\boldsymbol{\theta} = (h_0, \Phi_0, \iota, \psi, \alpha, \delta, f, \dot{f} \dots).$$

- Main search technique is *matched filtering*, where signal phase is all important:

$$\Phi(t) = \Phi_0 + 2\pi \int f + \dot{f} t + \frac{1}{2!} \ddot{f} t^2 + \dots \, dt.$$

- The way search proceeds depends upon whether source is *known* or *unknown*.

Known spinning stars: results so far

- Searches have looked for GWs from triaxial stars:

$$h = \left(\frac{2}{15}\right)^{1/2} \frac{G}{c^4} \frac{8\Omega^2}{d} \epsilon I; \qquad \epsilon = \frac{I_2 - I_1}{I_1}.$$

- Parameter space small as emission is at 2Ω.
- Upper limits placed on ϵ for many known radio pulsars.
- But what is the astrophysical interest?

Theoretical upper limit

- Mountain size determined by balance between gravitational and elastic forces:

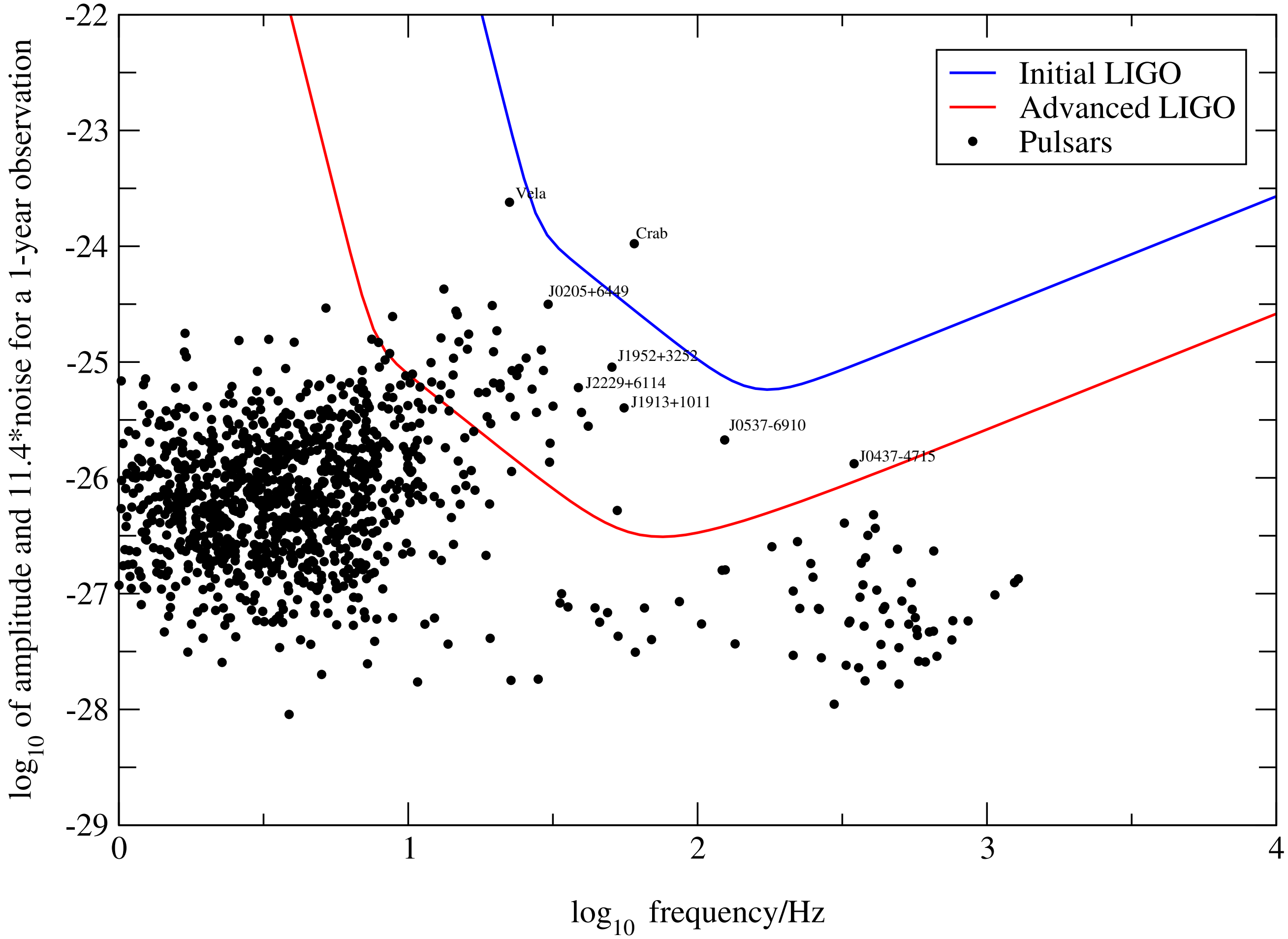
$$\epsilon \approx [\text{rigidity parameter}] \times [\text{breaking stain}],$$

$$\epsilon \approx \frac{\mu V_{\text{crust}}}{GM^2/R} u_{\text{break}} \approx 10^{-7} \left(\frac{u_{\text{break}}}{10^{-2}} \right).$$

- Confirmed by rigorous calculation of Ushomirsky, Cutler & Bildsten (2000).
- Mountains could be much bigger (e.g. 10^{-4}) for exotic crystalline phases (Owen 2005, Haskell et al 2007, Lin 2007).

Indirect electromagnetic upper limit

Assume all spin-down energy goes into gravitational wave production:



Direction gravitational wave upper limit

- Analysis of data from first half of S5 has beaten the spin-down limit of Crab (Abbott et al 2008).
- No more than 6% of spin-down energy going into gravitational wave channel.
- Ellipticity is no more than 1.9×10^{-4}.

Possible emission mechanisms

- Now want to expand the search to other parts of parameter space.
- Search parameters must satisfy two conditions:
  1. Search is computationally feasible.
  2. Search is physically motivated.
- Need to think about all possible emission mechanisms...
  1. Triaxiality
  2. Free precession
  3. Fluid oscillations
  4. **None of the above.**

Going beyond $2f$: pinned superfluids

- In 1977 Shaham investigated effect of pinned superfluidity on neutron star precession:

$$J_a = I^{\rm C}_{ab}\Omega^{\rm C}_b + I^{\rm SF}\Omega^{\rm SF}_a.$$

- Found that precession frequency in massively increased by addition of a gyroscopic-type term:

$$\dot{\psi} \approx (1+\epsilon)\Omega, \qquad \epsilon \approx \frac{I_3 - I_1}{I_3} + \frac{I_{\rm SF}}{I_3}.$$

- But what of the non-precessional solution?

Going beyond $2f$: pinned superfluids cont...

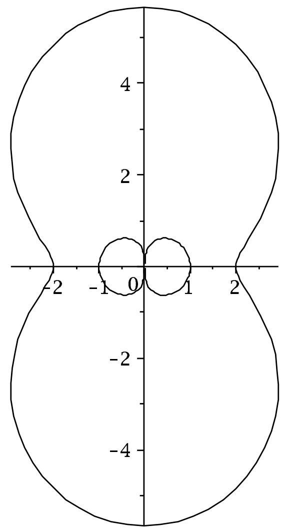
- Can identify non-precessional solution as one where Ω_a^{C} is parallel to J_a.
- Can then plug this motion into mass quadrupole approximation to General Relativity to calculate GW emission.
- Key quantities are the multipole moments:

$$Q_{lm} = \int \delta\rho_{lm}(r) r^{l+2} \, dr.$$

- Look for solution where pinned superfluid *does not* point along a principal axis of the crust...

Going beyond $2f$: pinned superfluids cont...

- If superfluid has orientation (θ, ψ) with respect to crustal axes find emission at both f and $2f$.



- This means even steadily rotating non-precessing star may have a GW harmonic at the spin frequency.

Going beyond $2f$: pinned superfluids cont...

- Computational burden of search very low.
- Open issues:
  - What would produce misalignment of crustal principal axes and pinned superfluidity in the first place?
  - What limits maximum amplitude?

Summary

- Detectors have taken high quality data, and even better data coming soon.
- Various upper limits have been obtained; some starting to reach regime of astrophysical interest.
- Astrophysics key to designing new searches.
- Even for relatively well understood sources choice is far from obvious.
- Pinned superfluidity motivates a simple low-cost search of significant astrophysical interest.