How LIGO searches are affected by theory & astronomical observations

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Setup

- We can look for things better if we know more about them from photon astronomy (we see **four NS populations**)
- Photon astronomy sets **indirect upper limits** on GW - milestones for sensitivities of our searches
- GW **emission mechanisms** influence where we look
- Our **interpretation of our results** depends on emission mechanisms and previous indirect upper limits

- Some review in gr-qc/0605028 (S2 all-sky & Sco X-1)

Four neutron star populations

- Known pulsars
  - Position & frequency evolution known (including derivatives, timing noise, glitches, orbit) ➔ Computationally inexpensive
- Unknown neutron stars
  - Nothing known, search over position, frequency & its derivatives ➔ Could use infinite computing power, must do sub-optimally
- Accreting neutron stars in low-mass x-ray binaries
  - Position known, sometimes orbit & frequency
- Known, isolated, non-pulsing neutron stars
  - Position known, search over frequency & derivatives

Indirect upper limits

- Assume quadrupole GW emission
- Use predicted *M, R, I* (could be off by 2)
- Assume energy conservation & all *df/dt* from GW
- Known pulsars - "spin-down limit"

$$h_{\rm sd} \propto D^{-1} I^{1/2} \left(\frac{df}{dt} / f \right)^{1/2}$$

  - Best is Crab at 1.4×10^{-24}
- Non-pulsing NS - assume age = *f/(-4df/dt)*

$$h_{\rm sd} \propto D^{-1} I^{1/2} t^{-1/2}$$

  - Best is Cas A at 1.2×10^{-24}

Indirect upper limits

- LMXBs - energy conservation violated
  - Assume accretion spin-up = GW spin-down (Wagoner ApJL 1984)
  - Infer accretion rate from x-ray flux

$$h_{ul} \propto (R^3/M)^{1/4} F_x^{1/2} f^{-1/2}$$

  - Best is Sco X-1 at 2×10^{-26}
- Unknown neutron stars - ???
  - Assume simple population model
  - Plug in supernova rate in galaxy

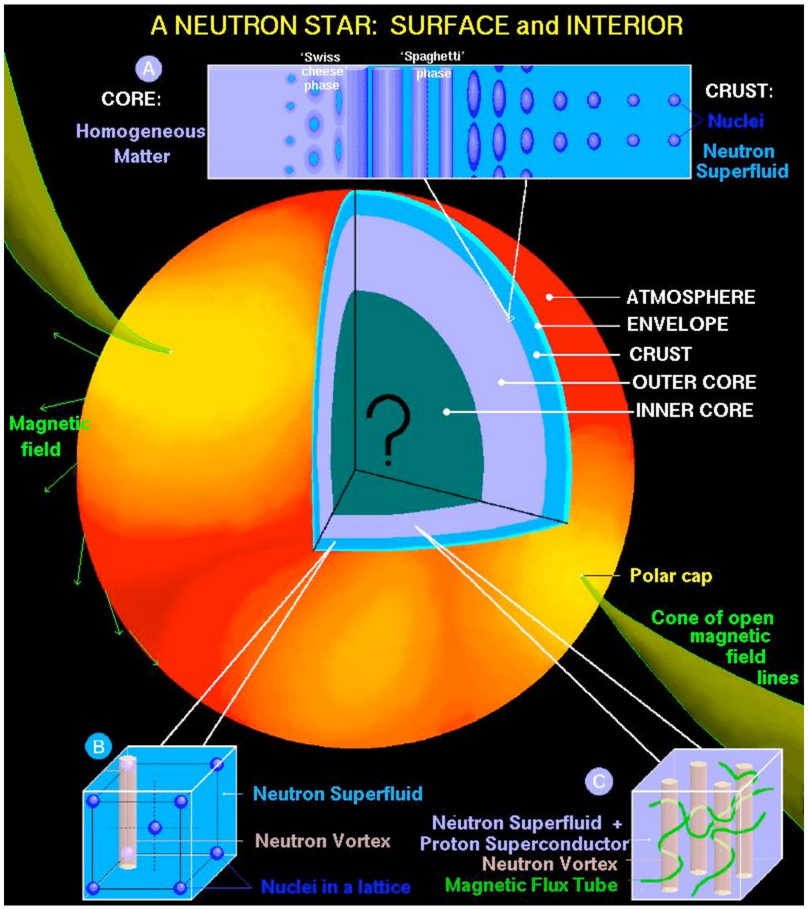
$$h_{ul} \propto I^{1/2} R^{1/2}$$

  - Most optimistic estimate is 4×10^{-24} (Blandford 1980s, S2 paper)
- Initial LIGO has a shot at all except LMXBs

GW emission mechanisms

- Non-accreting stars (first chance to beat indirect limits)
  - Free precession (looks pretty weak, I'll skip)
  - Magnetically supported mountains
  - Elastically supported mountains
- Accreting stars (further off but better prospects)
  - Same as non-accreting, plus…
  - Other magnetic mountains (Andrew's talk, I'll skip)
  - Elastic mountain building
  - R-mode oscillations
- Phrased in terms of ellipticity ε ~ quadrupole ~ h

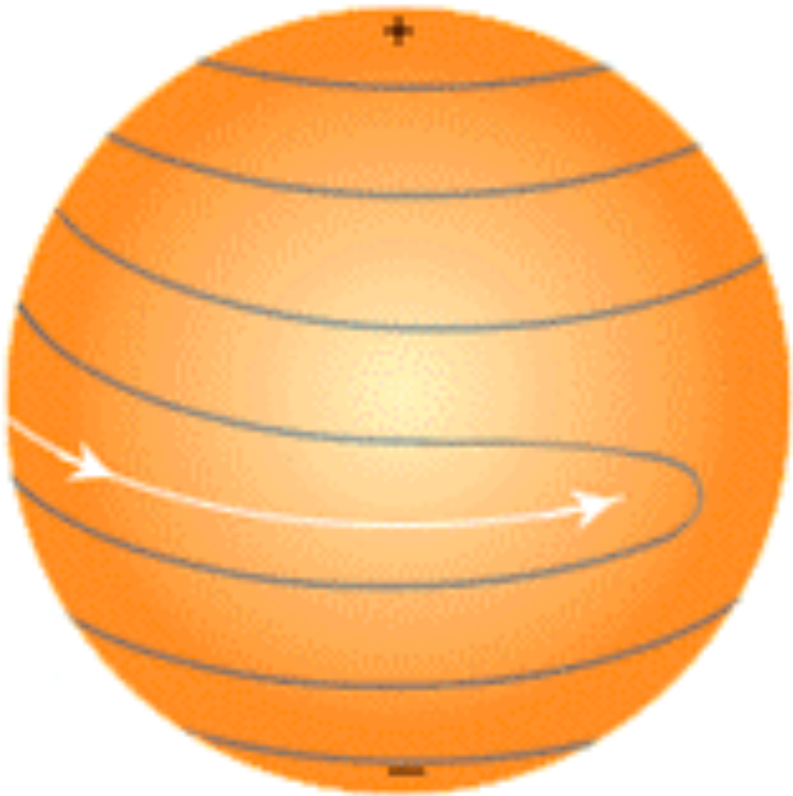
Elastic mountains



- How high can they get?
- Depends on what "neutron" star is made of (how much is solid)
- Solid crust (Ushomirsky et al MNRAS 2000) $\varepsilon <$ few$\times 10^{-7}$
- Some theories predict "?" is solid (Pandharipande et al 1970s, Glendenning et al 1990s)
- Owen (PRL 2005): $\varepsilon <$ few$\times 10^{-4}$ (strange quarks) or 1×10^{-5} (baryons + quarks or mesons)
- But what are mountain-building mechanisms?

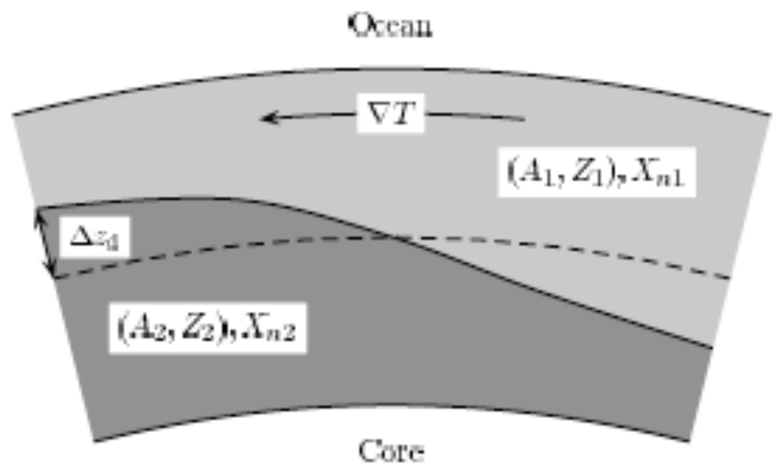
Magnetic mountains

- Differential rotation winds *B* field lines around rotation axis
- Toroidal field pinches star
- Centrifugal force flattens star
- In conflict if axes aligned, not if perpendicular ➔ instability drives axes perpendicular (P. Jones 1970s)
- Cutler (PRD 2002) estimates ellipticity $\varepsilon < \text{few} \times 10^{-5}$

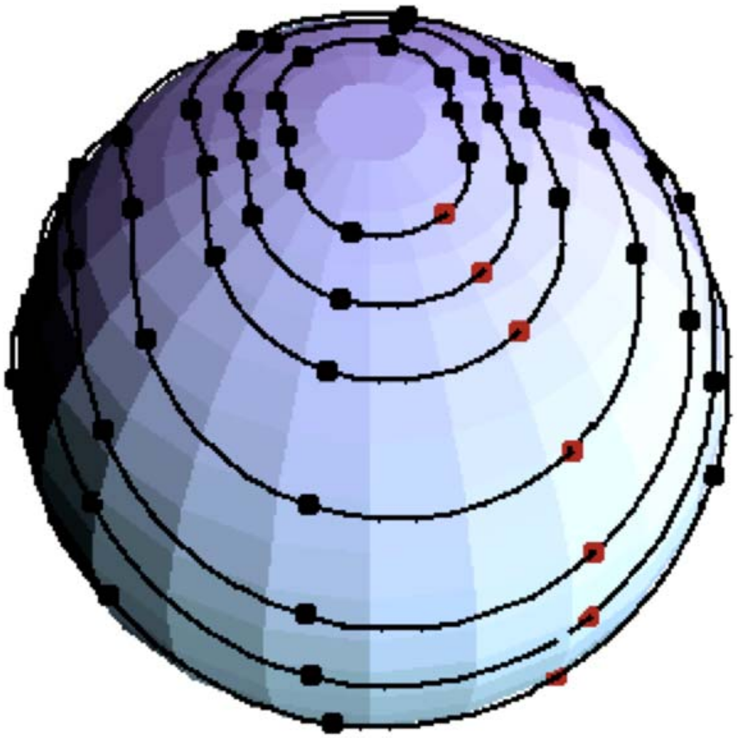


Elastic mountains in accreting stars

- Robust mountain building (Bildsten ApJL 1998)
- Accretion is not uniform ➔ hot & cold spots on crust
- Hotter spot, fixed density ➔ faster electron capture ➔ layer of denser nuclei moves upward
- If GW balance accretion, ε is determined by x-ray flux
- Best (Sco X-1) is few$\times 10^{-7}$, same as prediction for normal neutron star crust



R-modes in accreting stars



- *Complicated* phenomenology (Stergioulas Living Review)
- 2-stream instability (CFS) due to azimuthal propagation (Andersson ApJ 1999)
- Viscosity stabilizes modes
- Accretion keeps star balanced at critical frequency … but only with strange particles in core
- GW frequency = 4/3 spin freq. minus few % (depends on EOS)

Theory(-ish) interactions

- Interpretation of upper limits
  - Beating an indirect limit on *h* will be more exciting (end of S5)
  - Some issue of how fuzzy those indirect limits are
  - Direct limits on ε are independent of *D* and are getting into strange quark EOS territory (LIGO PRL 2005)
- Interpretation of signals (let's hope!)
  - Frequency confirms emission mechanism (LMXBs)
  - R-mode signal means strange particles in core
  - High ellipticity means funny equation of state
  - Somewhat high *ε* means EOS or high internal *B* field

Observational interactions

- Timing data for known pulsars
  - Jodrell Bank: Kramer & Lyne have been co-authors (PRL 2005)
  - RXTE: J0537-6910 (…?)
- Timing data for LMXBs
  - Keeping RXTE alive would be a good thing…
  - RXTE/LIGO time coincidence: like last weekend on Sco X-1
- New discoveries (& proposed discoveries)
  - When you find new PSR/CCO/etc, think of indirect GW limits
- Old discoveries
  - Several NS positions poorly known (ROSAT/XMM), firming up with Chandra or Hubble would help our searches

The point

- Initial LIGO is already getting interesting (a little)
- It gets better the more we interact
- Don't wait for advanced LIGO!