Do Old Neutron Stars Shiver to Keep Warm?

Jeremy S. Heyl

Harvard-Smithsonian CfA

LMXBs and LIGO

Jeremy S. Heyl
Harvard-Smithsonian CfA

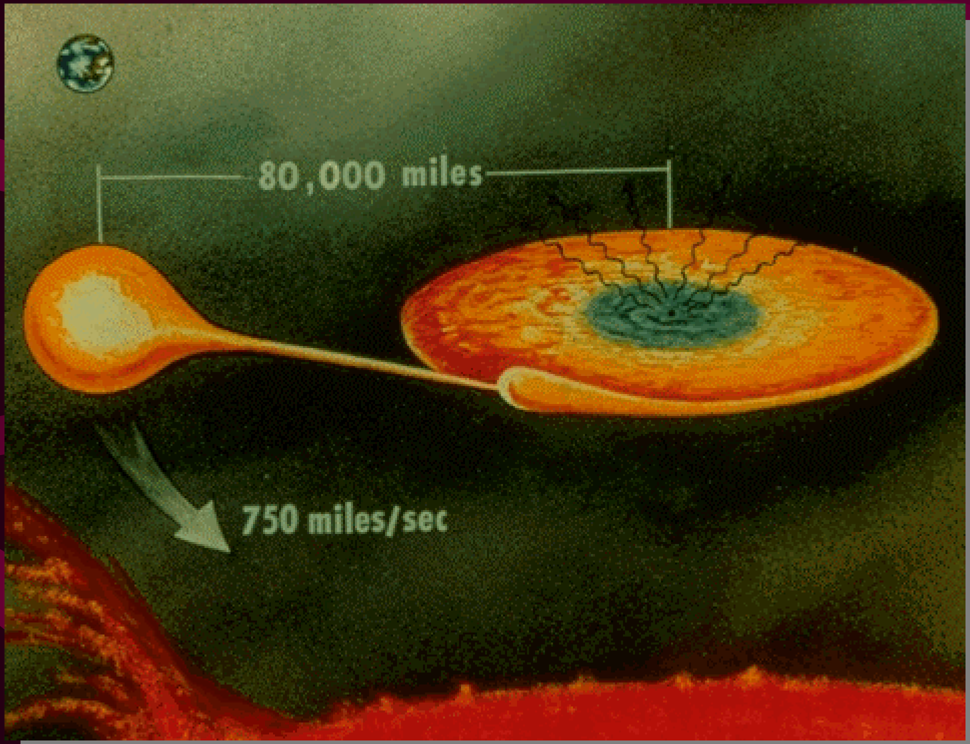
Outline

- What are LMXBS?
- What is LIGO?
- What are r-modes?
- How do the modes saturate?
- How does LMXB spin evolve?
- How many and how bright?
- What if the modes grow further?
- What are the prospects?

Outline

- What are LMXBS?
- What are r-modes?
- How do the modes saturate?
- How does LMXB spin evolve?
- How many and how bright?
- What are the prospects?

What are LMXBs?



- If the supernova of a star in a binary with a low-mass star does not destroy the binary, an LMXB is formed.
- Accretion will spin up the primary to the Kepler frequency of about 1.6 kHz.
- BUT we don't see neutron stars spinning this fast.

What is LIGO?

- LIGO is a pair of laser-interferometer gravitational- wave observatories in Livingston LA and Hanford WA.

- It is sensitive to GWs with a frequency ~ 1 kHz.
- It is now operating but not yet at the anticipated noise level.

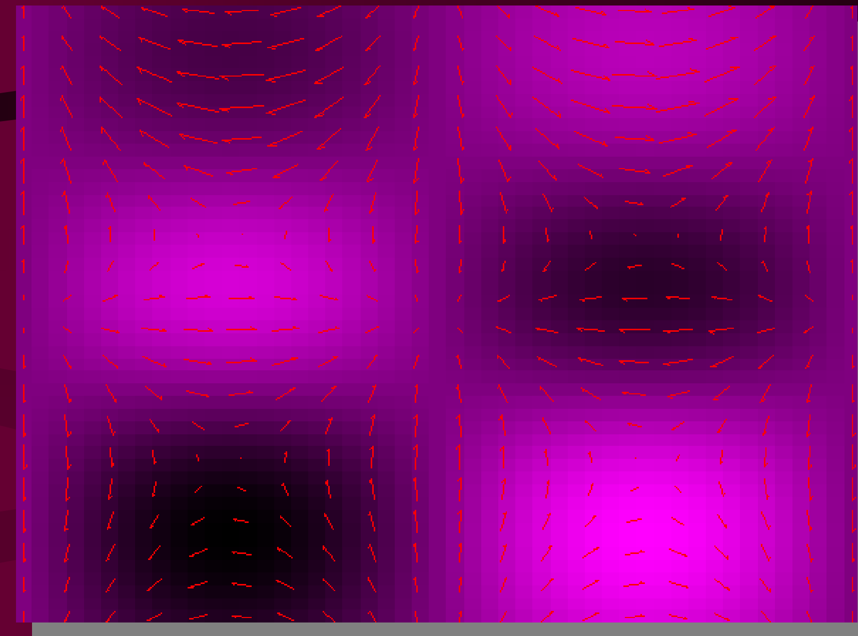
The LMXB-LIGO Connection

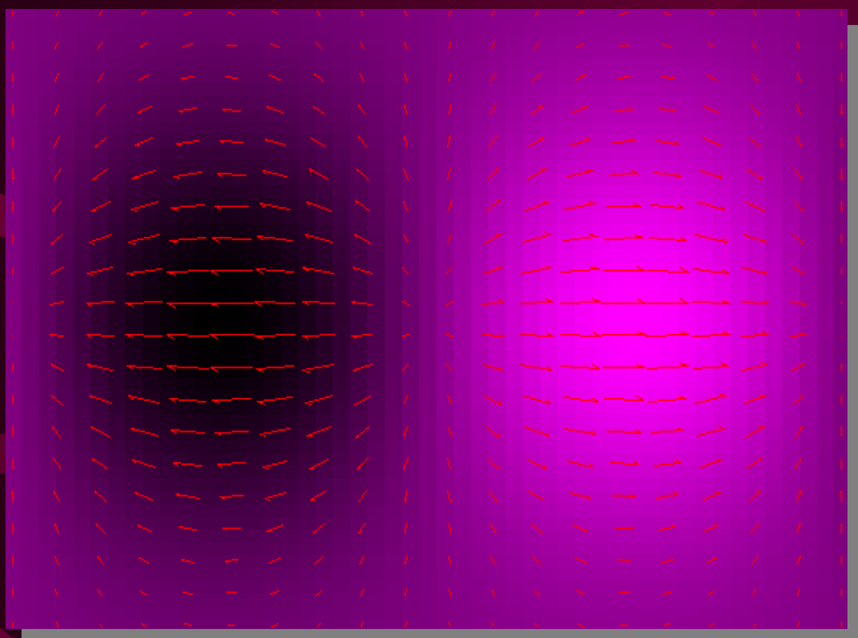
- Bildsten (1998)
  - Sco X-1 would be detected by LIGO if its spin is limited by the emission of GW.
- Andersson et al. (1999) noted that the r-modes might do the job.
- Also since 1996 or so, the spins of LMXB primaries have been measured, and they range from about 100 Hz to 600 Hz.

The LMXB-LIGO-GSFC Connection

- The early theoretical work on r-modes in neutron stars was done in part by Tod Strohmayer at GSFC in 1996.
- Tod and collaborators also found oscillations in Type-I bursts in 1996 verifying that LMXBs spin in the LIGO range.

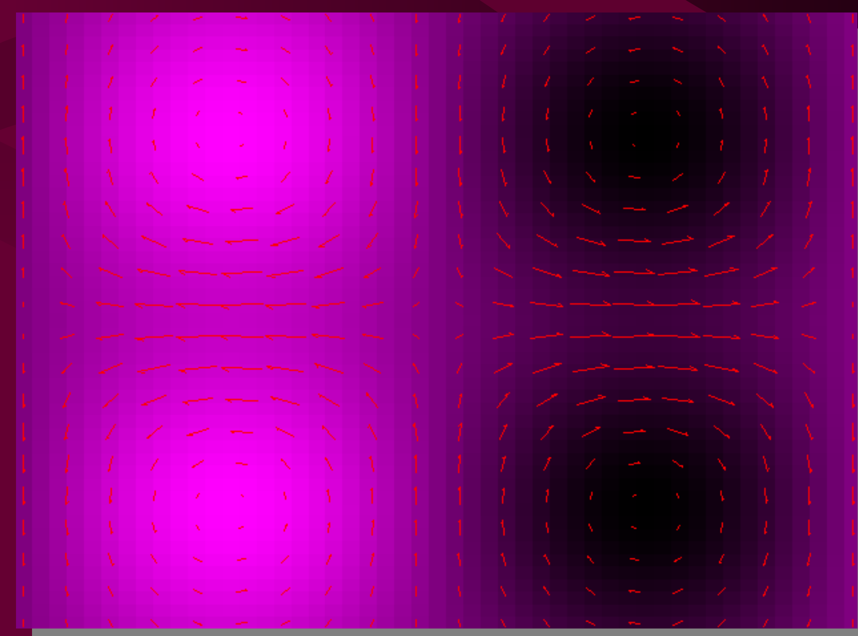
What are r-modes?





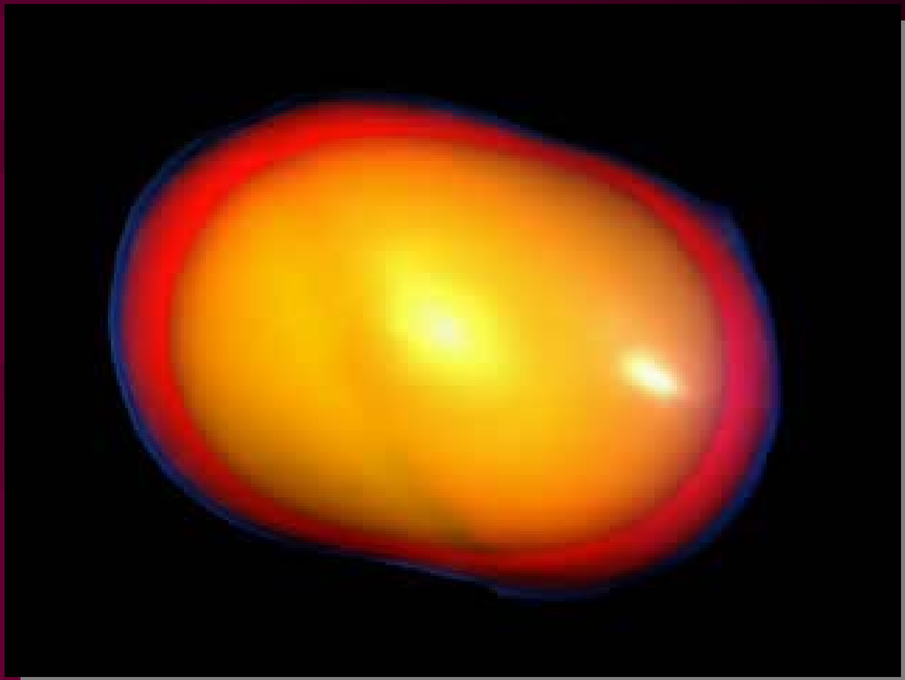
Kelvin Wave (Δr=0)

Rossby Wave



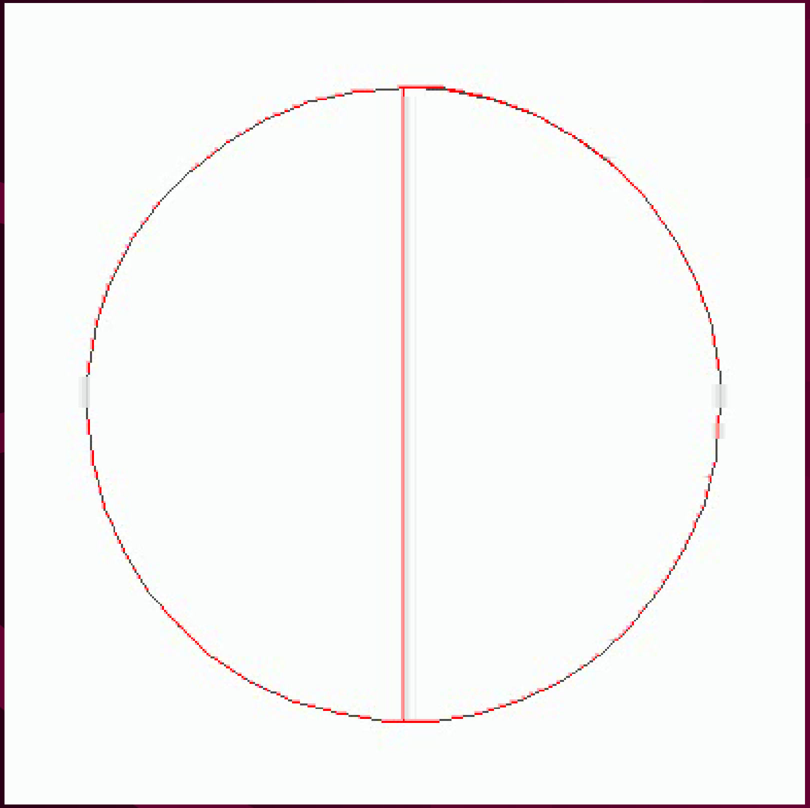
What are r-modes?

- One type of oscillation mode in a rotating fluid is the Rossby wave (r-mode).
- If the fluid is not viscous, the r-mode is unstable - CFS instability.



- In the rotating frame the mode counter-rotates. In the inertial frame, it corotates.

Why are r-modes unstable?

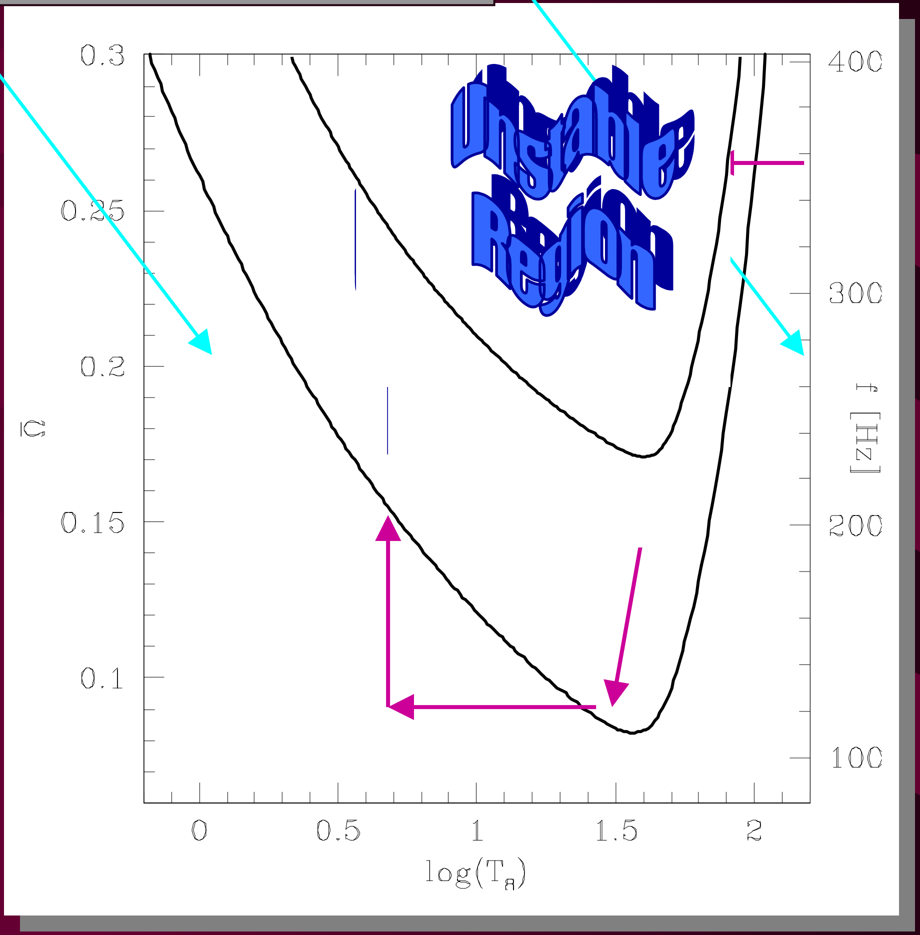


- In the rotating frame the mode counter-rotates. In the inertial frame, it corotates.
- The presence of an r-mode reduces the angular momentum of the star.
- GW carry angular momentum away, amplifying the r-mode.

What if the fluid is viscous?

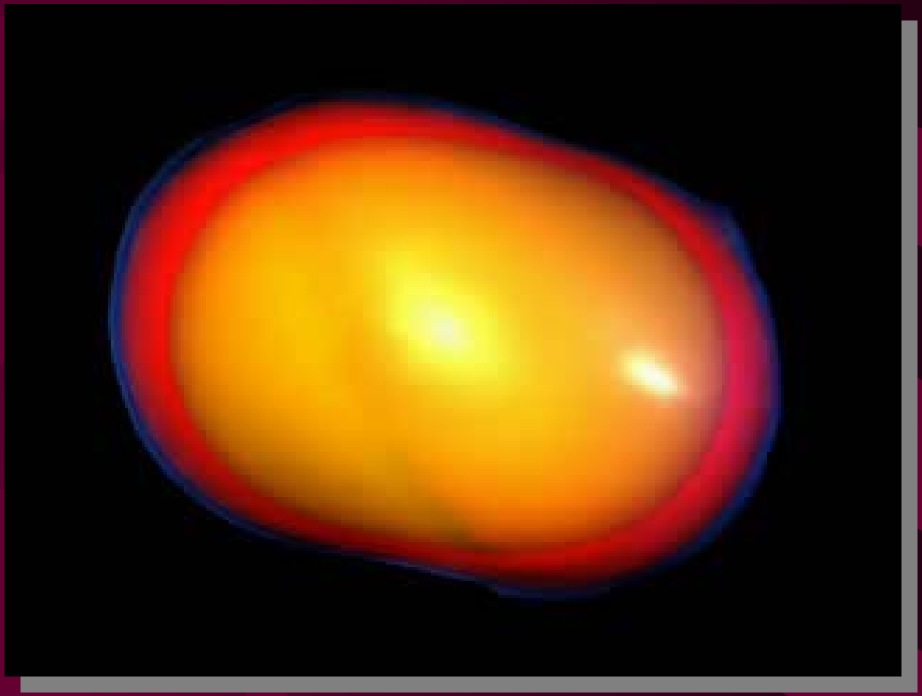
Shear viscosity decreas Bulk viscosity increases with T

- Viscosity damps fluid motions. Its effects are strongest for small wavelengths.
- Even a large scale mode has a large gradient in a boundary layer.
- Intermode coupling



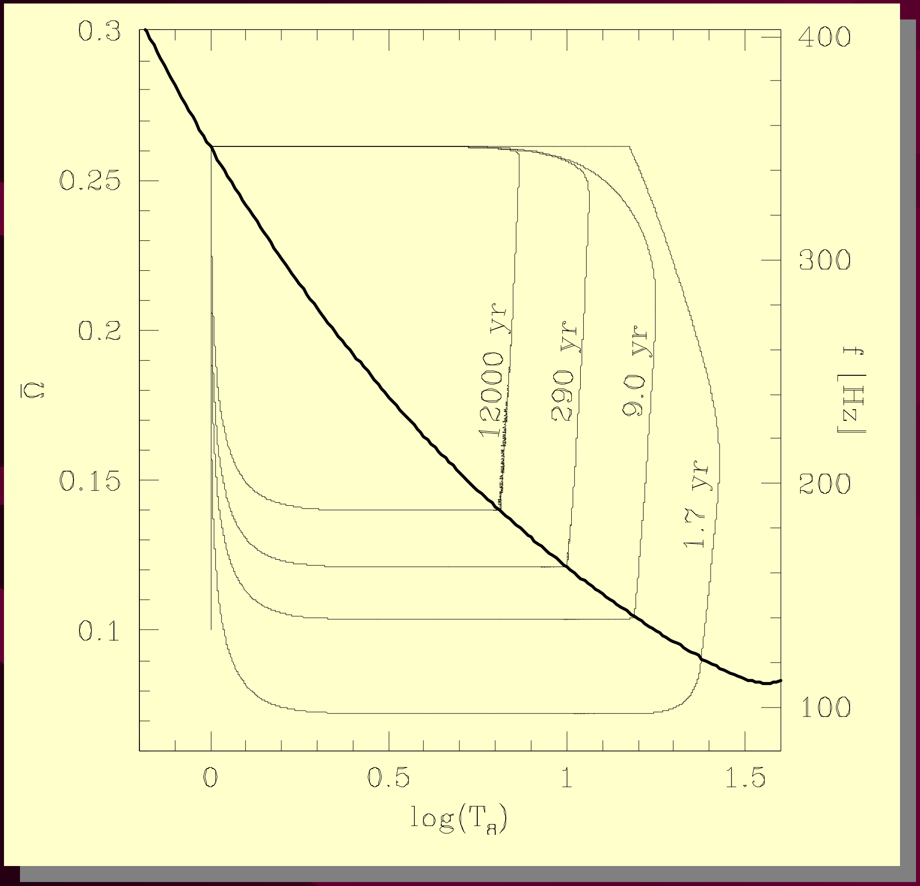
Simulating the r-modes

- An r-mode in the best case grows over many thousands of rotations which makes the growth difficult to simulate.
- So people artificially increase the driving force by a factor of one thousand to see what happens.



From Joel Tohline's website

Spin-up/Spin-down



- The shear viscosity decreases with increasing temperature and viscosity produces heat, so the r-mode amplitude can run away (Levin '99, Spruit '99).
- How the mode saturates dramatically affects the evolution.

Mode Saturation

- Typically r-modes grow over many thousands of rotations, so to treat the problem numerically, the driving force must be increased several thousand-fold. The mode grows until the shocks form.
- The conventional wisdom was that GW would drive the mode amplitude to ~ 1.
- Does this make sense from our experience of fluid dynamics?

Wind and Waves

- The gravitational radiation reaction is simply a driving force; it drives the r-mode like a breeze or a gale would.
- Small wind, small waves.
- Big wind, big waves.

Realistic Coupling

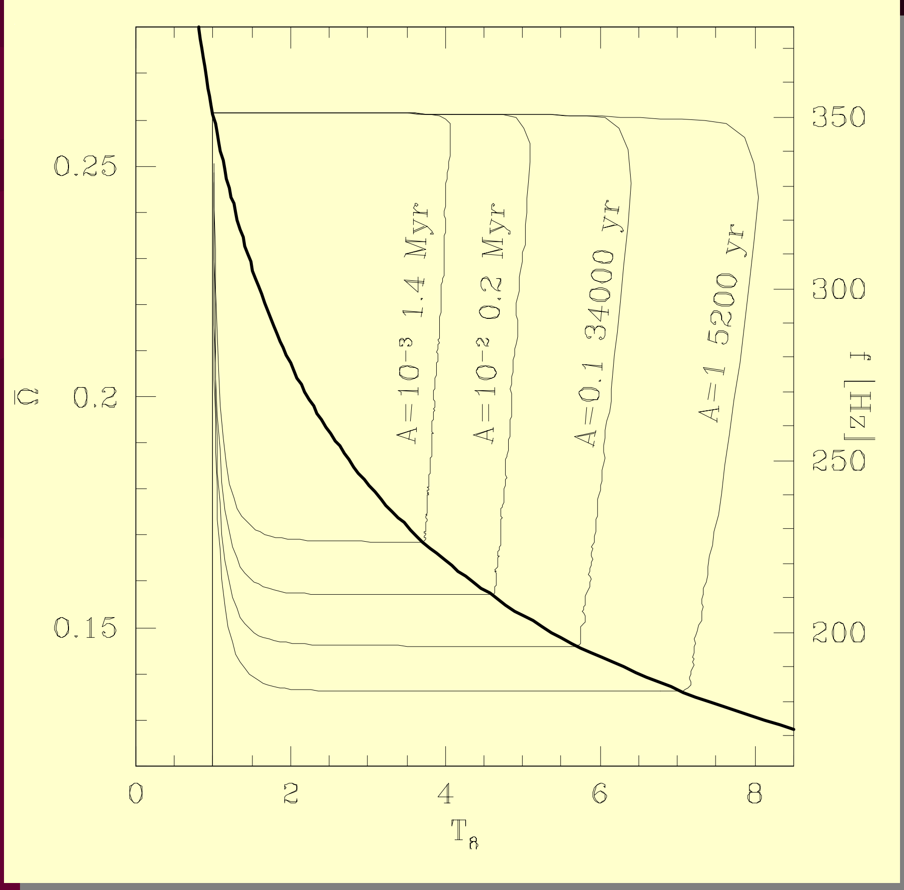
- Arras et al. '02 argue that how the mode saturates depends on the driving force.
- The energy in the mode at saturation is proportional to the ratio of the growth rate to the spin frequency, so

$$\alpha^2_{\max} = \frac{A}{\Omega|\tau_{\rm grav}|\tilde{J}}$$

$$\alpha_{\max} = 0.002 A^{1/2} \left(\frac{\Omega}{350\rm Hz}\right)^{5/2}$$

Spin-up/Spin-down Redux

- Why does this matter?
- As the peak amplitude decreases, the duration of spin-down goes up (Wu, Matzner & Arras '01), so a particular object is more likely to be spinning down.
- If the spin-down exceeds 1,000 yr, T_{surf} reflects it.



How bright in GW?

- One can estimate the amplitude of the GW at Earth by equating the decrease in angular momentum of the star to that carried in the waves.

$$h \approx 7 \times 10^{-25} M_{1.4}^{1/2} \tau_{\mathrm{on},4}^{-1/2} R_{10} d_{10}^{-1}$$

- With a one-year integration, the initial LIGO configuration could reach an amplitude of $\sim 10^{-26}$.

What I swept under the rug - 1

- The naïve S/N calculation assumes that I know several things about the source.
  - Period, period derivative
  - Right ascension, declination
  - Orbital period, semi-major axis
- The period should be ~ few ms, $\dot{P} \sim 10^{-14}$
- Orbital Period ~ 1 hour, a ~ 1 light-second

What I Swept under the Rug - 2.

- The growth of the r-modes due to GW emission may be hampered by
  - Superfluidity (Andersson & Comer ‘01)
  - Exotic matter (Lindblom & Owen ‘02)
  - Formation of a crust (Bildsten & Ushomirsky ‘00, Lindblom, Owen & Ushomirsky ‘00)
  - Magnetic fields (Rezzolla, Lamb, Shapiro ‘00)
- This has only fostered the growth of the r-mode literature.

How many in the Galaxy?

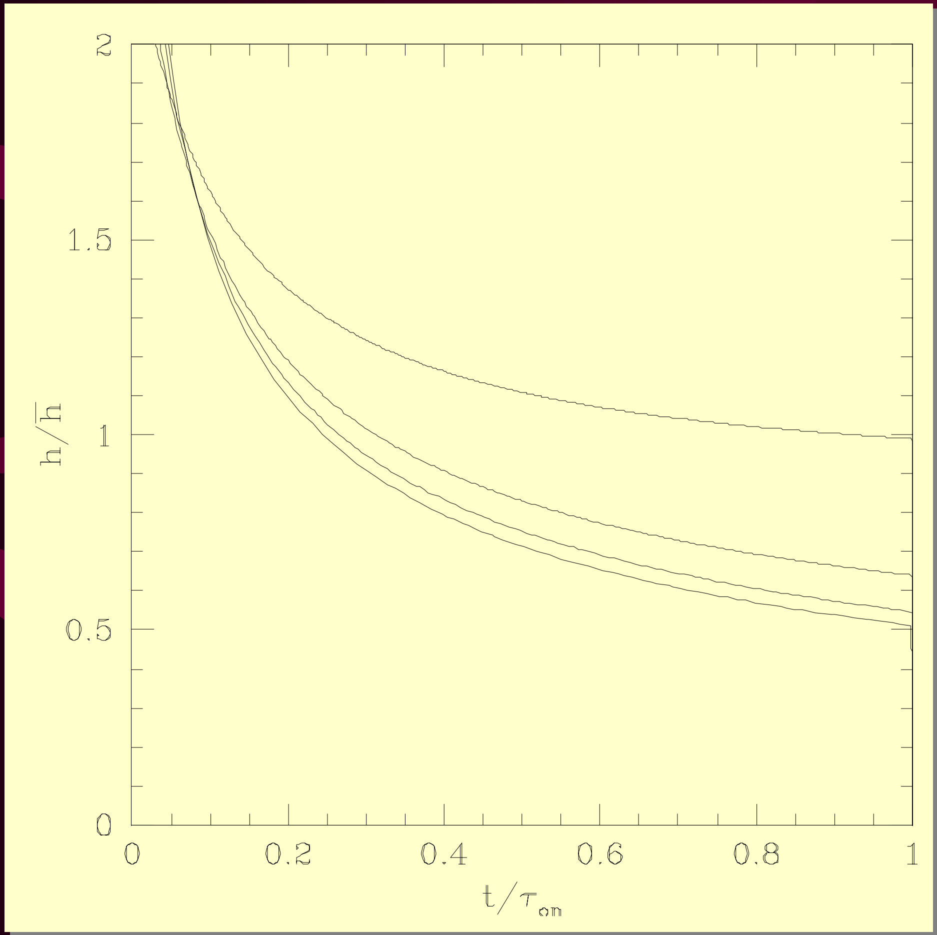
- LMXBs are thought to be the progenitors of millisecond radio pulsars, so the rate of formation of LMXBs equals that of MSRPs.

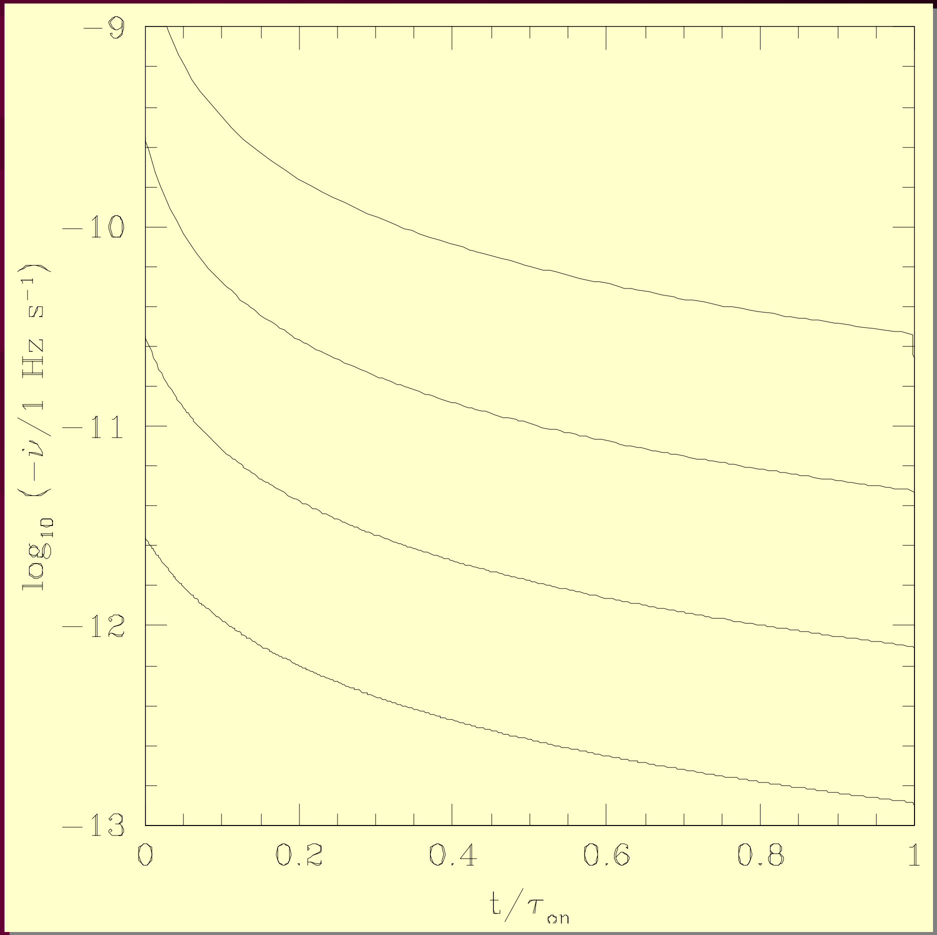
$$N_{\mathrm{LMXB,on}} = \frac{\tau_{\mathrm{on}}}{\tau_{\mathrm{cycle}}} N_{\mathrm{LMXB}} = \frac{\tau_{\mathrm{on}}}{\tau_{\mathrm{cycle}}} \left(r_{\mathrm{MSRP}} t_{\mathrm{LMXB}} \right)$$

$$= \tau_{\mathrm{on}} \frac{f_{\mathrm{MSRP}}}{\Delta f} r_{\mathrm{MSRP}} \sim \frac{\tau_{\mathrm{on}}}{10^4 \mathrm{yr}}$$

- This assumes that the LMXB goes around the cycle once during its lifetime.

More details





How bright in photons?

- The core temperature reaches 6×10^8 K and stays this hot for several thousand years.
- It looks like a 21-year-old neutron star; its surface temperature will be $\sim 3 \times 10^6$ K.
- In the Galaxy, the flux is ~ 3 mCrab.
- An enhanced LIGO could detect such an object to 7 Mpc.

What if the modes crash?

- If the mode amplitudes do saturate at unity, then the evolution is quite different.
- The spin-down epoch may be as short as a year (one source per 10^4 MW).
- How far do you need to go to find 10^4 MW?
  - 0.02 MW Mpc^{-3}, 5×10^5 Mpc^3, d ~ 50 Mpc.
  - Just in range of initial LIGO, enhanced LIGO could see this type of source to 700 Mpc.

Prospects

- If the spin-down epoch is longer than $\sim 10^4$ years or less than ~ 1 yr, several LMXBs will be visible with the initial LIGO.
- For the long spin-down epoch, the sky would be static, but for the ~ 1 yr duration, new sources would pop up.
- The Galactic sources would be bright in X-rays without signs of accretion and spinning down quickly -- directed search.