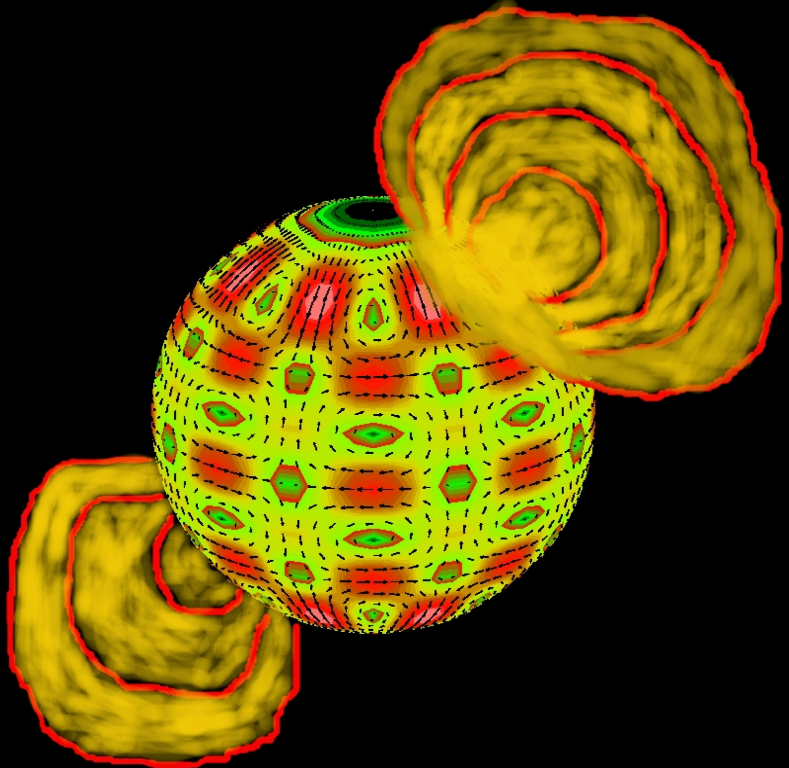
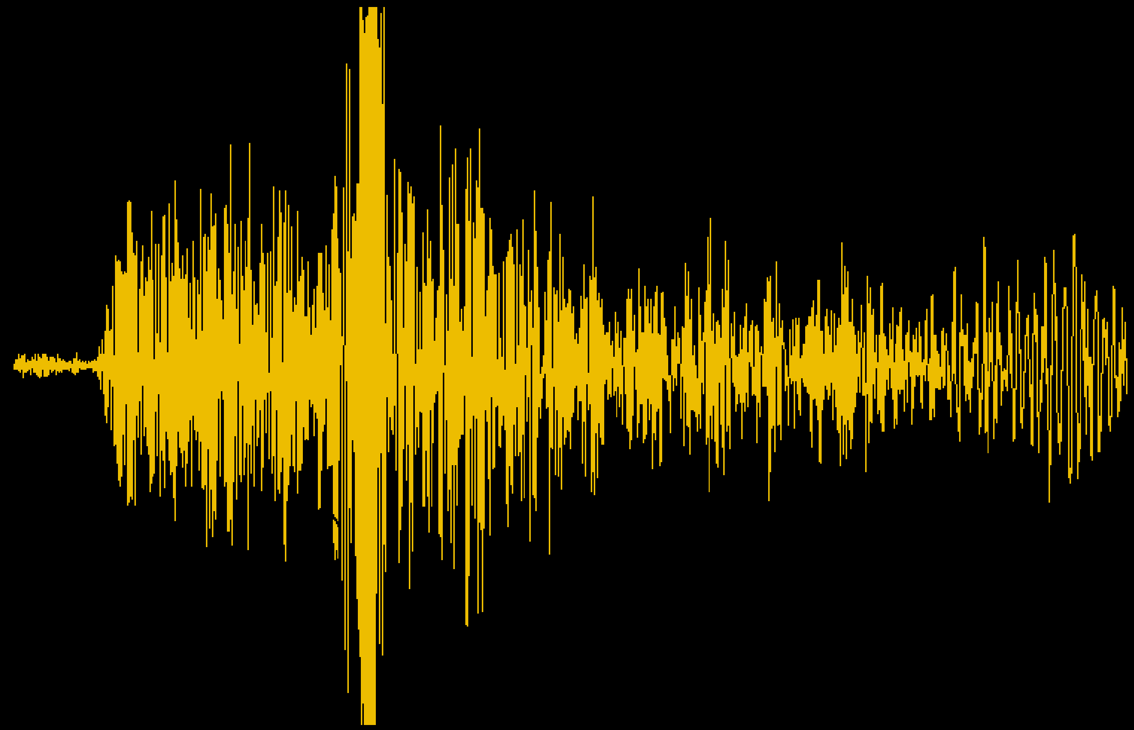


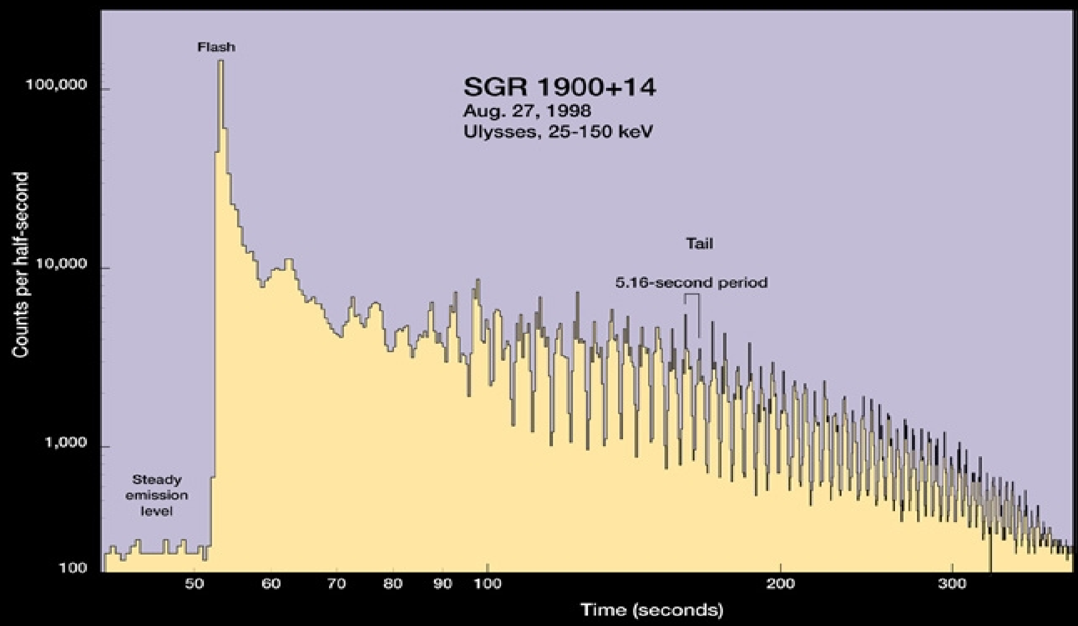


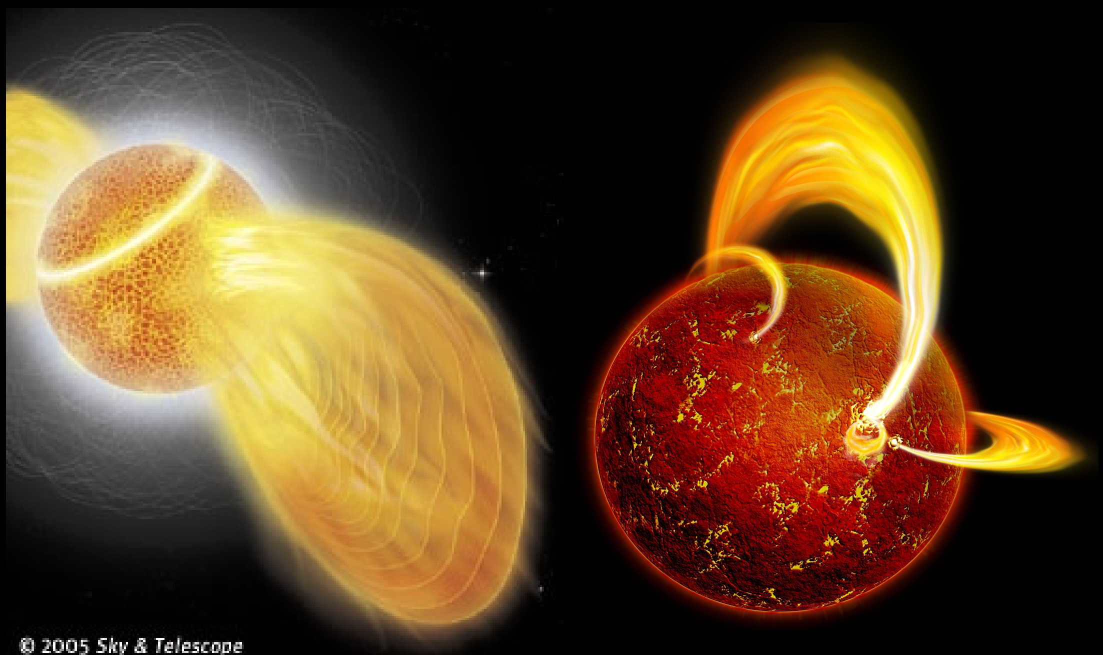
Magnetar seismology

Anna L. Watts
Max Planck Institute for Astrophysics, Garching

Collaborators: Tod Strohmayer (NASA GSFC), Sanjay Reddy (LANL), Marc Klein-Wolt (Amsterdam), Pete Woods (Dynetics/NASA)

SGR giant flares and starquakes



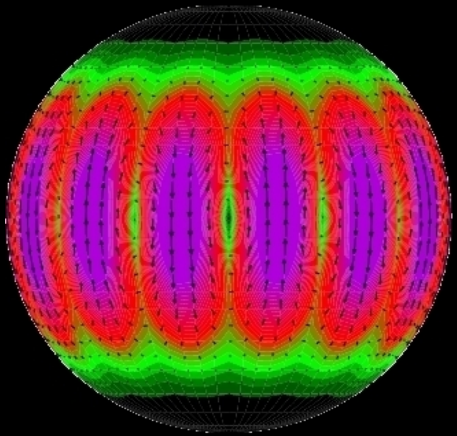


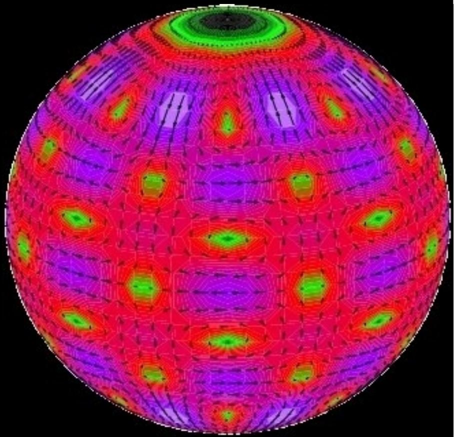
Images: CXC, Ulysses, Sky & Telescope

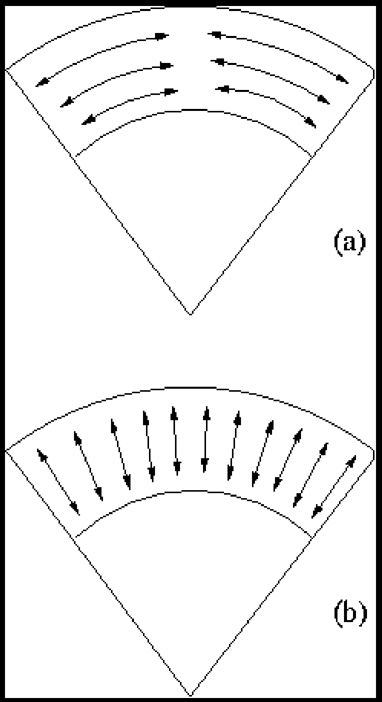
- SGR giant flares are 1000 - 100000 times brighter than normal flares. Only 3 seen: 1979, 1998, 2004.
- Field reaches point of catastrophic instability, leading to global reconfiguration.
- Long decaying tail due to trapped fireball.
- Slow rotational pulses.
- The field is coupled to the star's crust – so field reconfiguration should trigger a starquake (Duncan 1998).

Neutron star oscillations

- Neutron stars admit many different types of vibration.
- Theoretical calculations of magnetar starquakes suggested that the easiest modes to excite would be *toroidal* (horizontal) shear modes of the crust (Duncan 1998).
- Mode frequency depends primarily on shear speed. Models predict fundamental ≈ 30 Hz. Higher n=0 harmonics scale in a predictable way with l.
- Magnetic field effectively boosts shear modulus – important effect if Alfven speed exceeds shear speed.

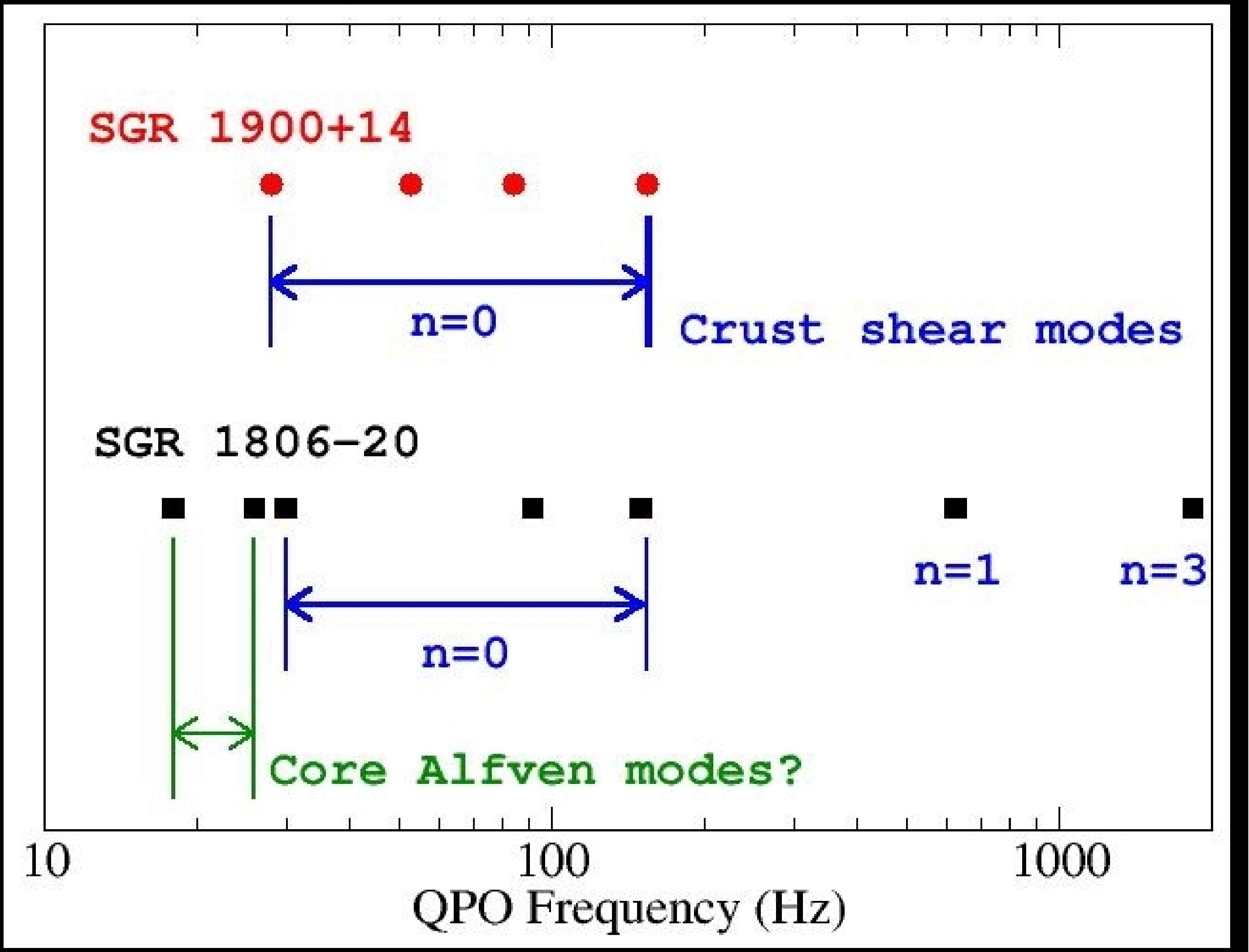






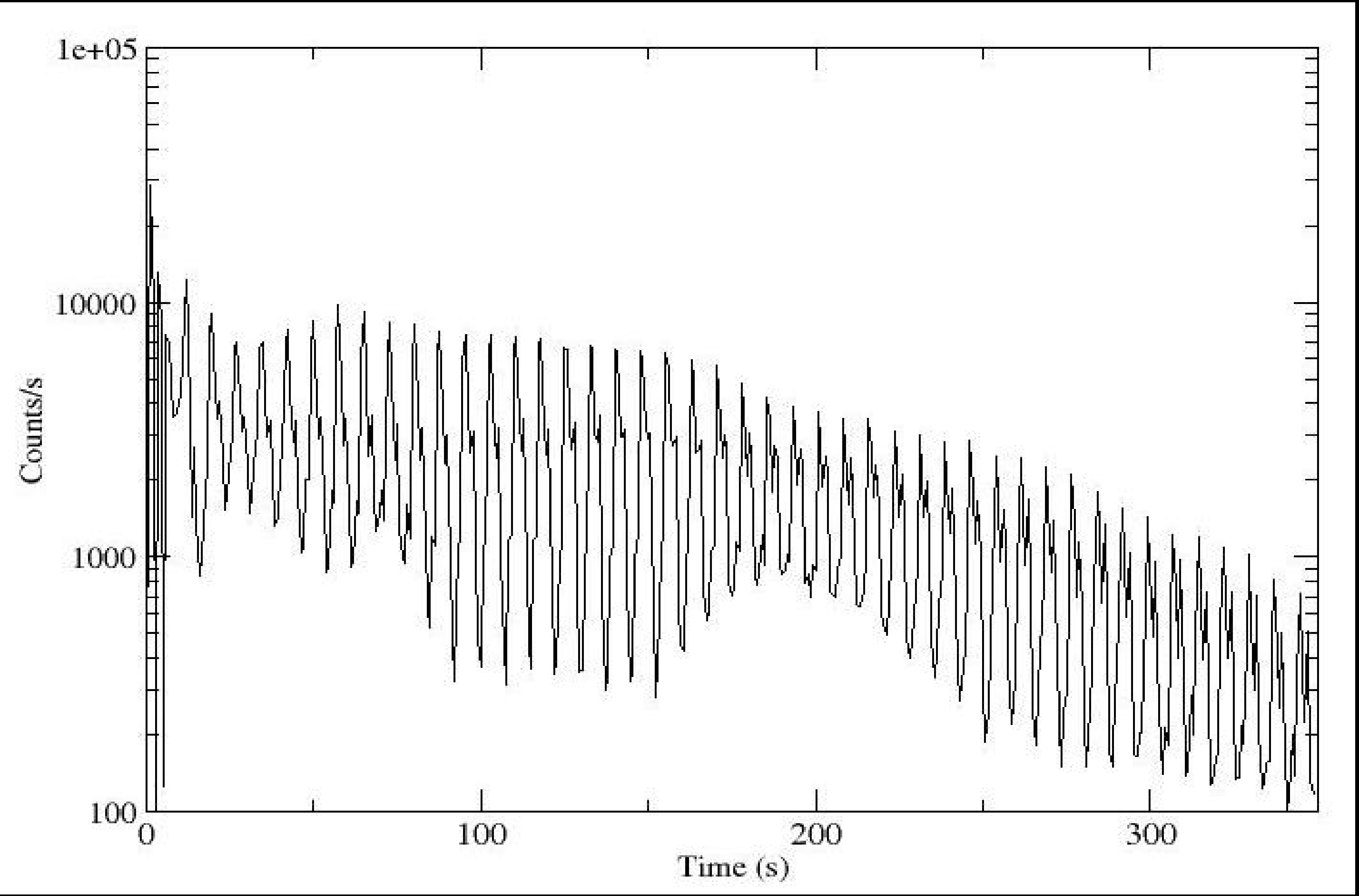
Seismic activity in two giant flares

- SGR 1806-20
  - 27 Dec 2004
  - RXTE & RHESSI
- SGR 1900+14
  - 27 Aug 1998
  - Less energetic
  - RXTE only
- QPOs seen in the decaying tails
- Widths ≈ 2 Hz
- Q values 10-1000
- No viable non-seismic mechanism

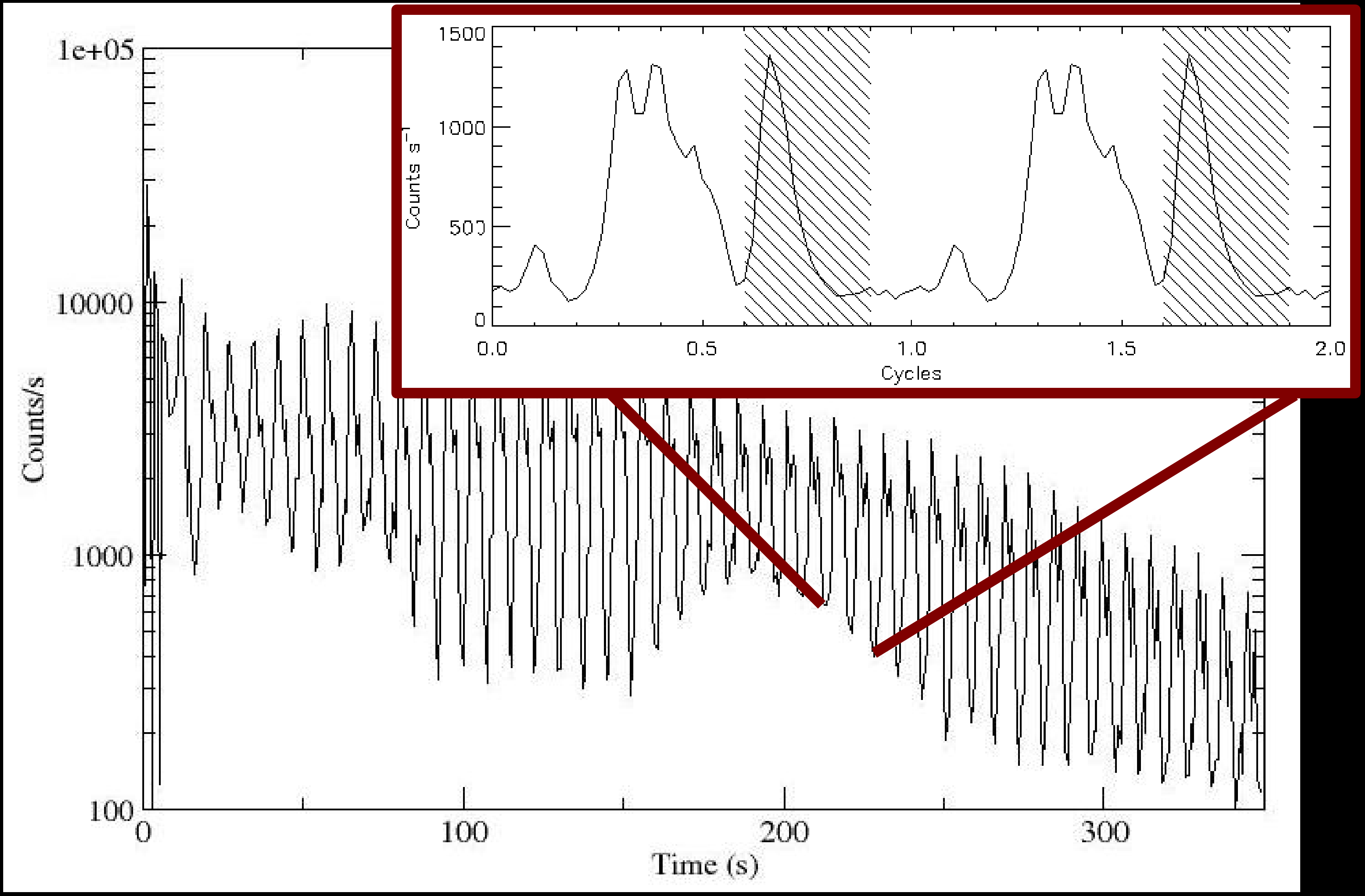


Israel et al. 2005
Strohmayer & Watts 2005, 2006
Watts & Strohmayer 2006

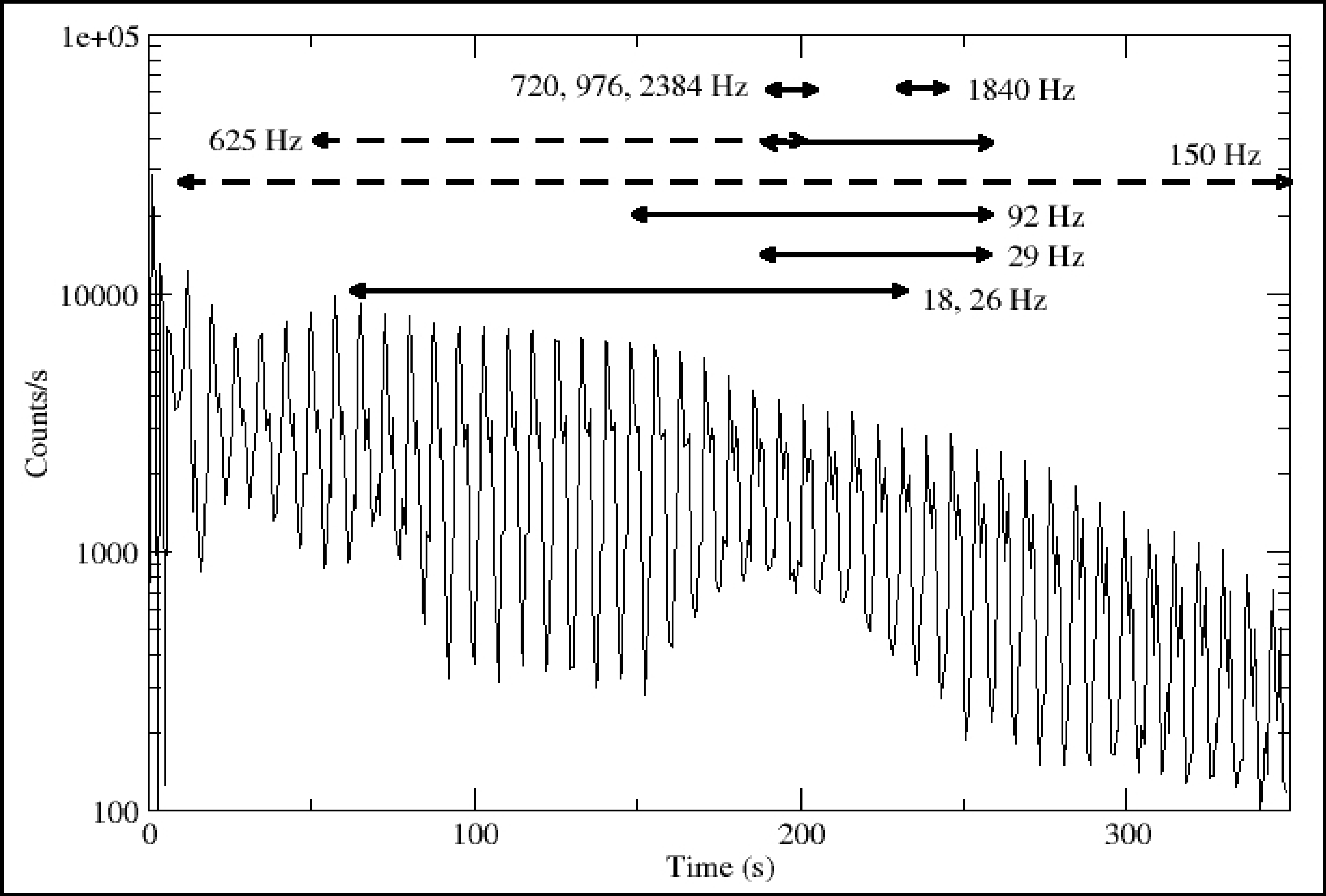
Other QPO properties



SGR 1806-20 giant flare lightcurve



QPOs are rotational-phase dependent



Persist for tens of seconds (Q value not just exponential decay).
Evidence for 'aftershocks'.
Frequency drift and amplitude variation.

Magnetic fields and the core

- A strong field should couple the crust to the fluid core so free slip is inappropriate
(Carroll et al 1986, Thompson & Duncan 2001, Levin 2006, Glampedakis et al 2006).
- Magnetized core will have its own natural vibration frequencies – possible mechanism for the lowest frequency QPOs
(Duncan 1998, Israel et al 2005).
- Situation is complicated by the existence of MHD continuous spectra......

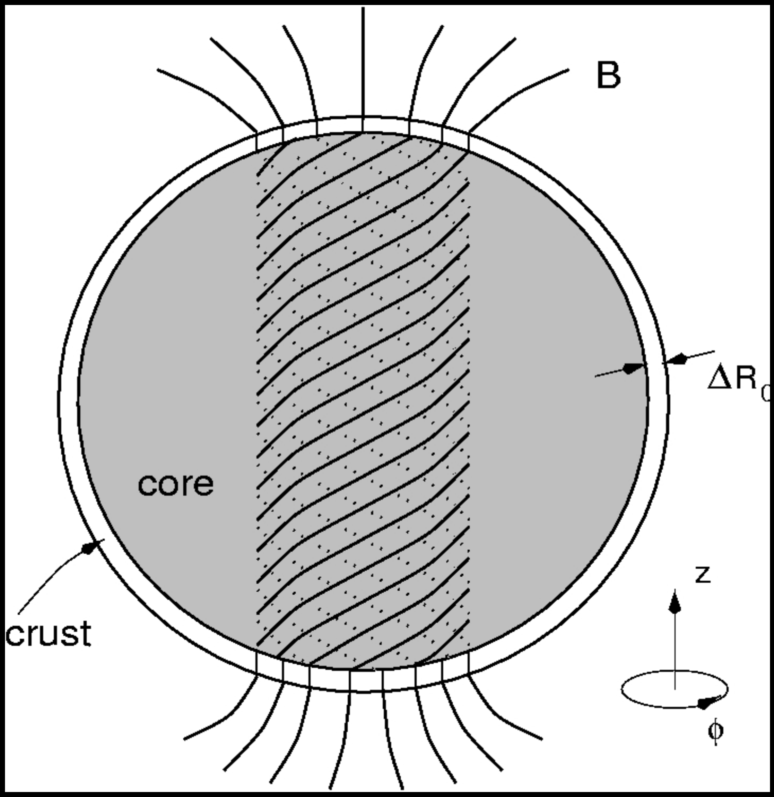
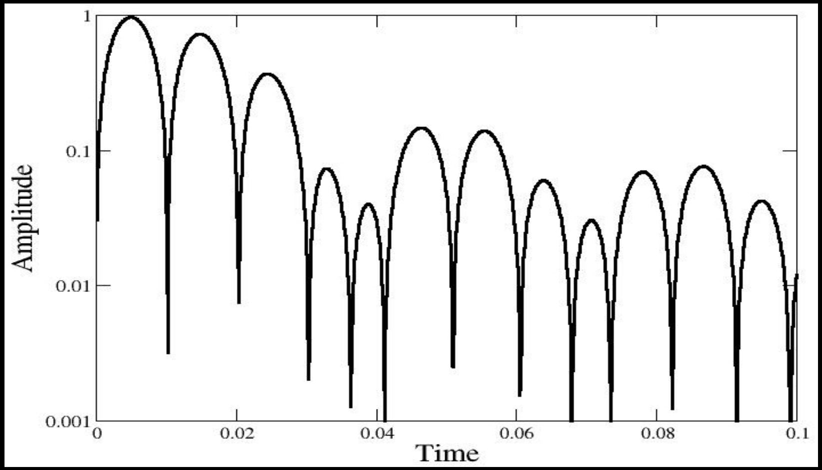
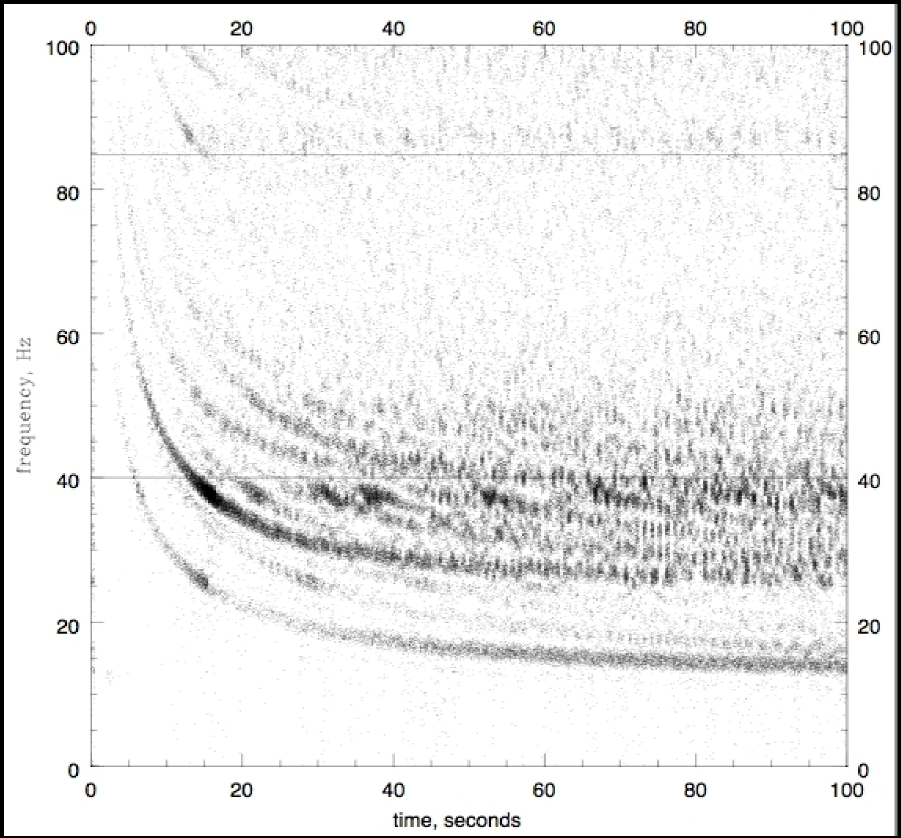


Image: Thompon & Duncan 2001

The role of continuous spectra

- Show up as singularities in normal mode equations: $\partial/\partial t - f(x) \Rightarrow i\sigma - f(x) = 0$. In our case f(x) relates to Alfven speed.
- Set of 'singular' solutions for $\min(f) < \sigma < \max(f)$.
- If we solve the initial value problem, collective solution is regular, but a little weird.

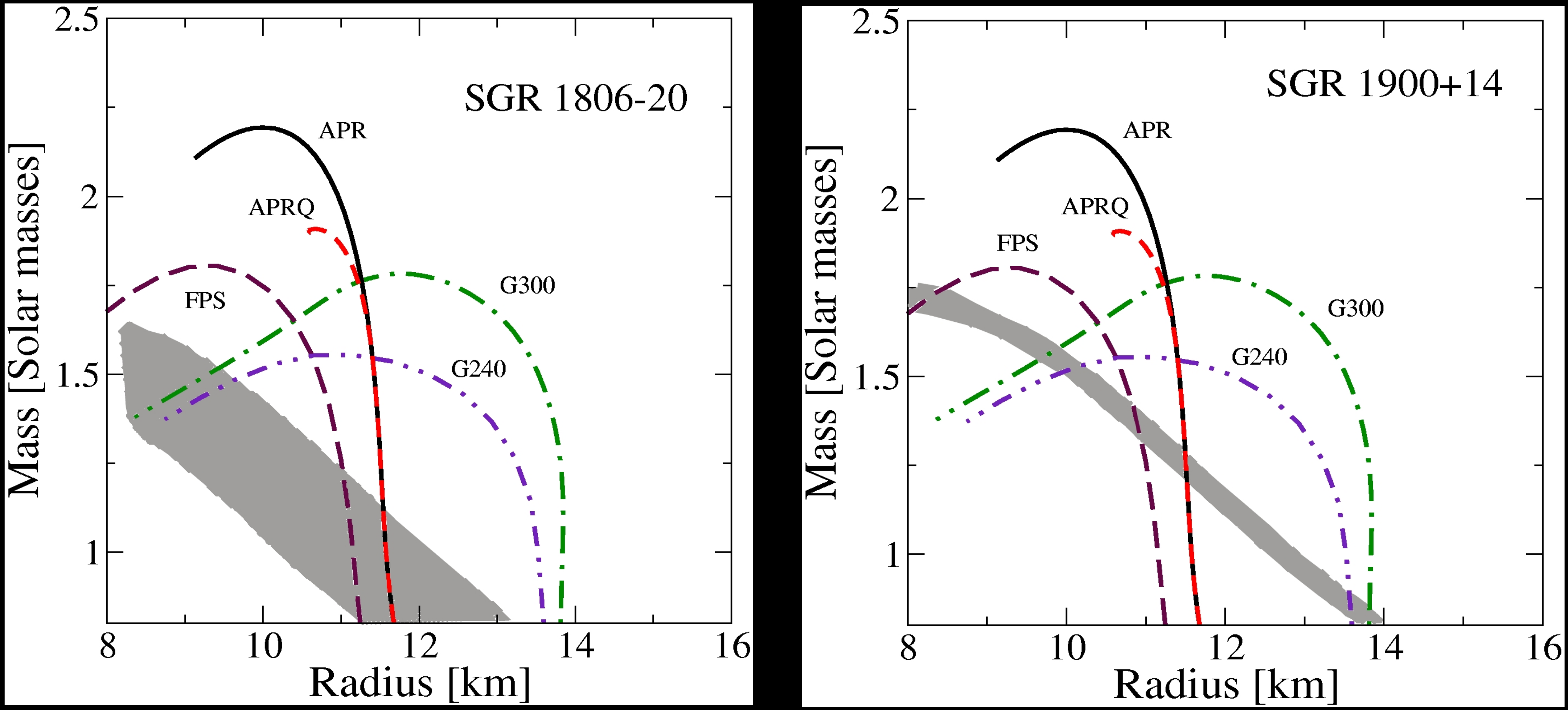




- Levin (2006) – rapid damping?
- Levin (2007) – initial value simulations. Star behaves as a coupled oscillator but with *drifting and amplification at the natural crust frequencies*.

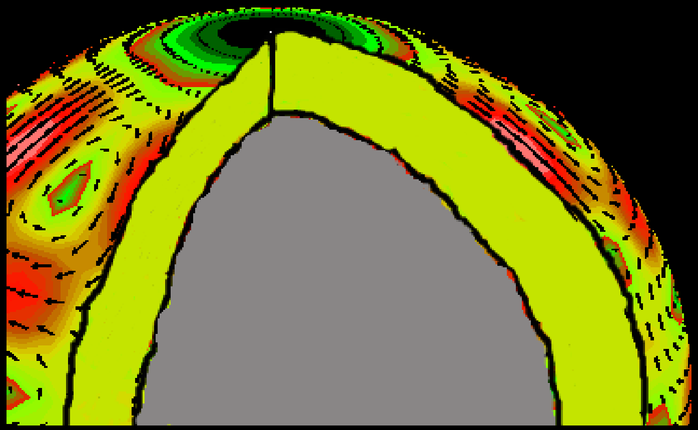
Images: Watts et al 2004, Levin 2007

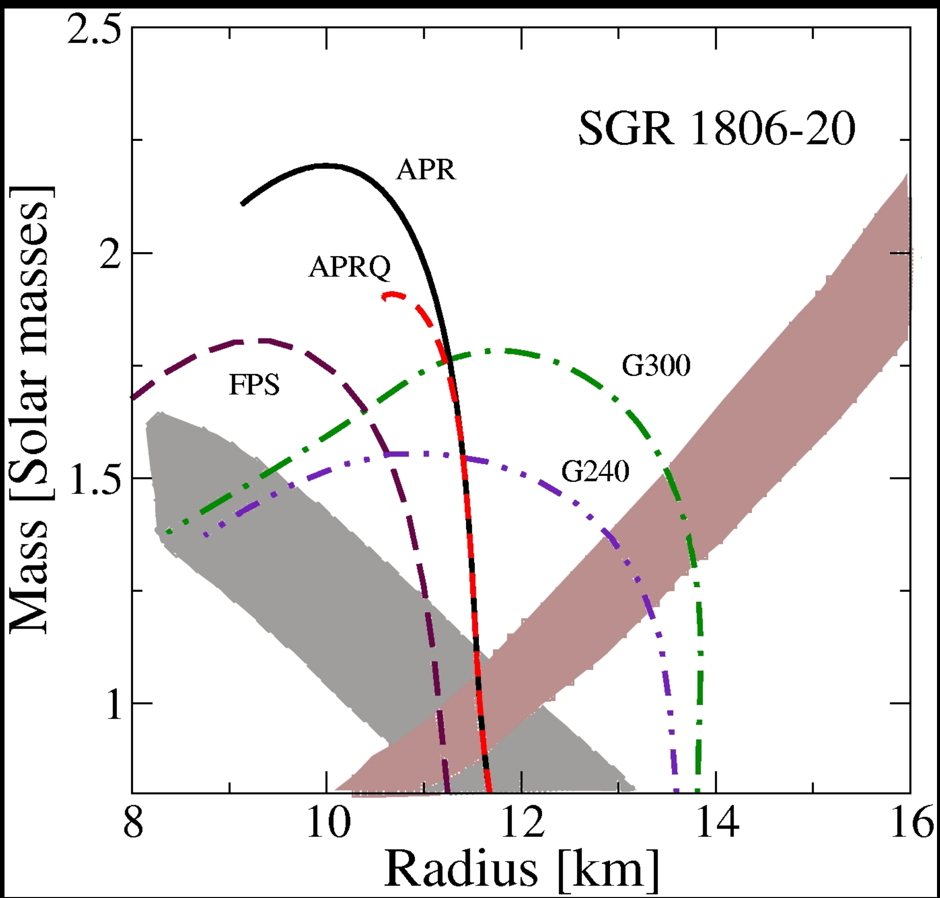
Magneto-seismology



- Constraints from n=0 modes (Samuelsson & Anderson 2007)
- Field a relatively small effect (Strohmayer & Watts 2005)
- Hard EOS disfavoured

Crust thickness constraints

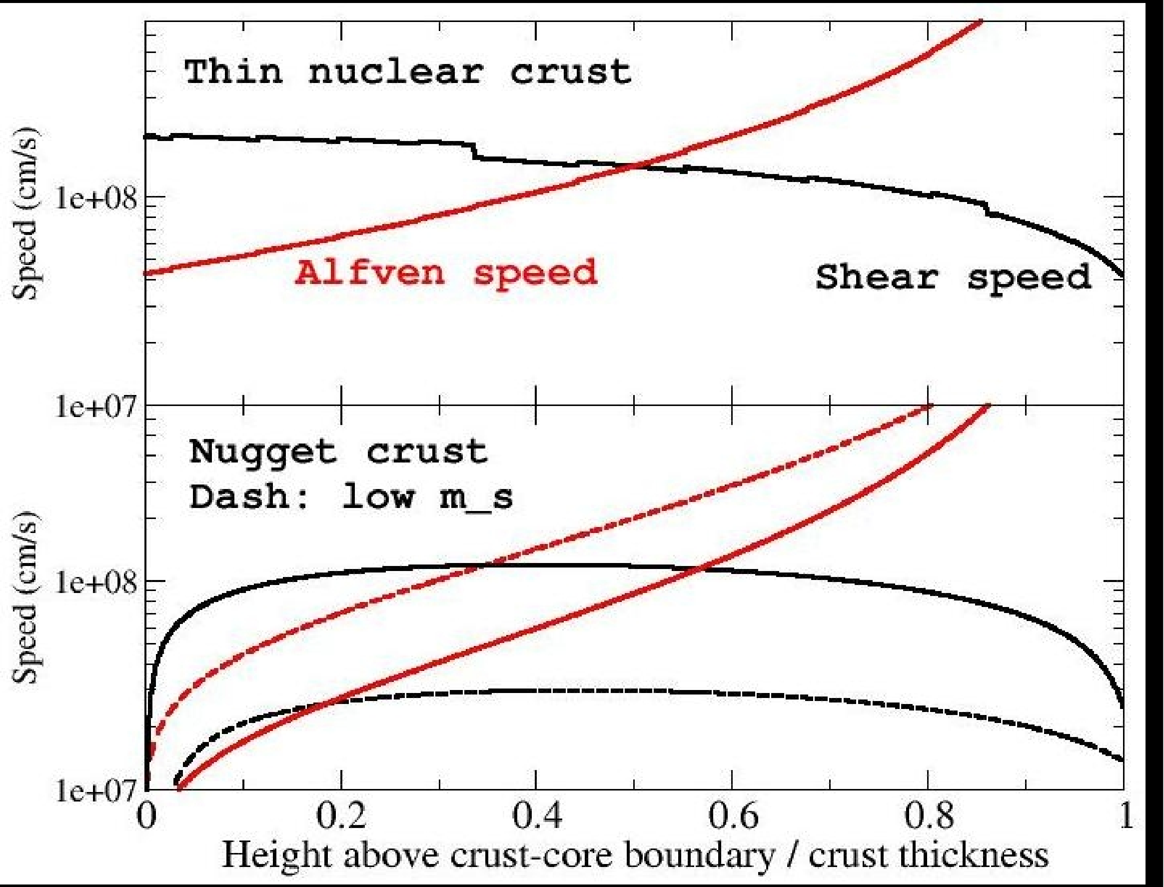




- The 625 Hz QPO seen in the SGR 1806-20 flare is thought to be the first radial overtone of the crust shear modes.
- Frequency of this mode is highly dependent on crust thickness.
- 625 Hz overtone + 30 Hz fundamental implies thick crust and hence a low mass (Strohmayer & Watts 2006, Samuelsson & Andersson 2007).
- Very strong constraint on EOS.

Strange star crusts

- Strange star crusts differ from neutron star crusts in both shear speed and thickness.
- Computed mode frequencies for two models:
  - Thin nuclear crust (Alcock et al. 1986);
  - Strange nugget crust (Jaikumar et al. 2006).
- Wide range of parameter space studied: M = 1.2 – 2.5 Msol, R = 8 - 15 km, B = 1e12 - 1e15 G, T = 1e7 – 1e9 K, plus uncertainties in nuclear models.

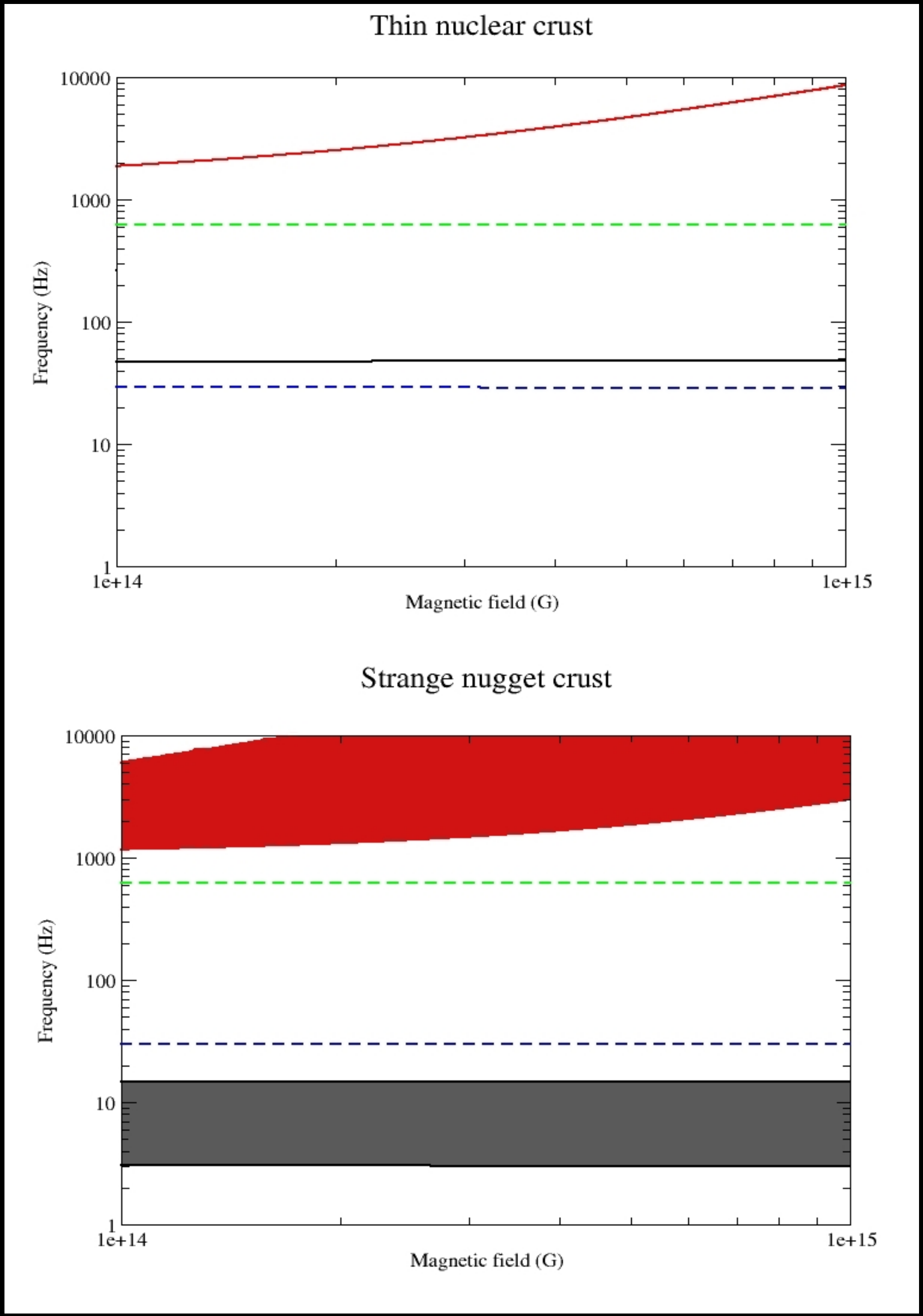


- Shear speed lower in nugget crust than in thin nuclear model.
- Magnetic effects may be more important than in neutron stars

Watts & Reddy 2007

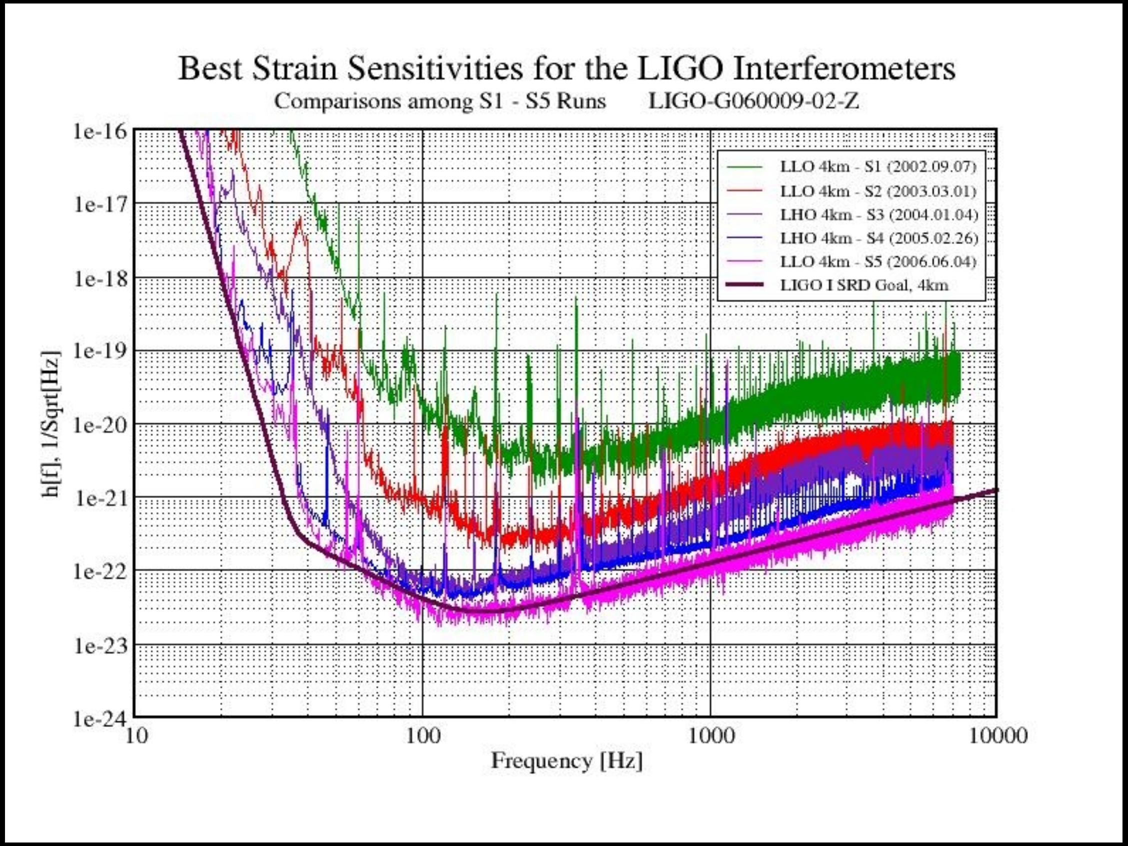
Strange star crusts

- Thin nuclear crust: Fundamental can be fit if mass is large, but overtone frequencies are far too high.
- Nugget crust: Despite additional uncertainty in parameters, cannot fit overtone unless magnetic field is an order of magnitude smaller than expected.
- Clear distinction in predictions for neutron star and strange star crusts.



Magnetar seismology with LIGO

- Major advantage of gravitational waves - not obscured by plasma.
- Signals expected to be small but if core is involved who knows?
- Search for excess noise at known frequencies after 2004 giant flare (only 1 interferometer operational)
- Abbott et al (2007) report upper limit on gravitational wave losses in vibrations ~ 1e47 ergs, comparable to the energy release in gamma-rays

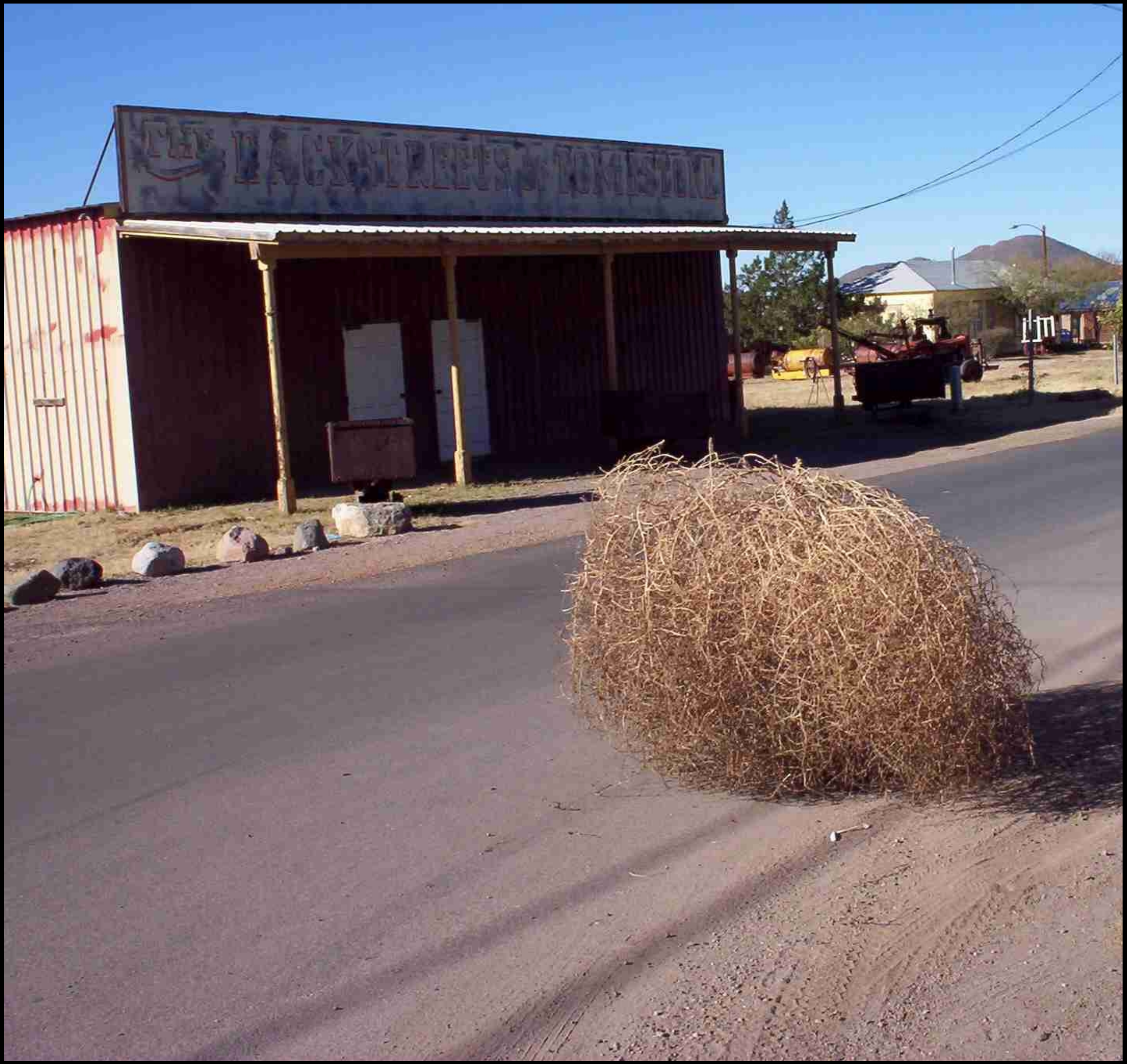


- However....if flare were to happen now, upper limit would be much more stringent, ~ 1e45 ergs!

Smaller flares, smaller quakes?

- Giant flares are rare and unpredictable events.
- Could the more regular intermediate and normal flares also excite seismic vibrations?
- Energies should be sufficient – although they may not be detectable without a 'giant flare' environment.
- Analysis in progress:
  - Intermediate SGR flares (with extended thermal tails)
  - Burst active periods (AXPs and SGRs)
  - Quieter periods (motivated by terrestrial studies)
- Preliminary results?

Smaller flares, smaller quakes?



Smaller flares, smaller quakes?

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- Analysis in progress:
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  - Quieter periods (motivated by terrestrial studies)
- Upper limits should constrain excitation and emission mechanisms.
- If these early results are borne out, we need to be better prepared for giant flares.

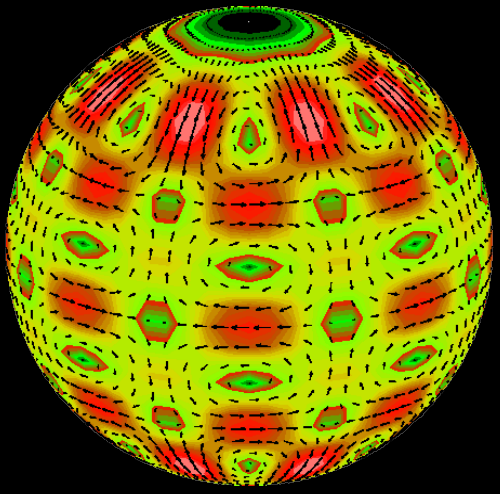
Crust and surface issues

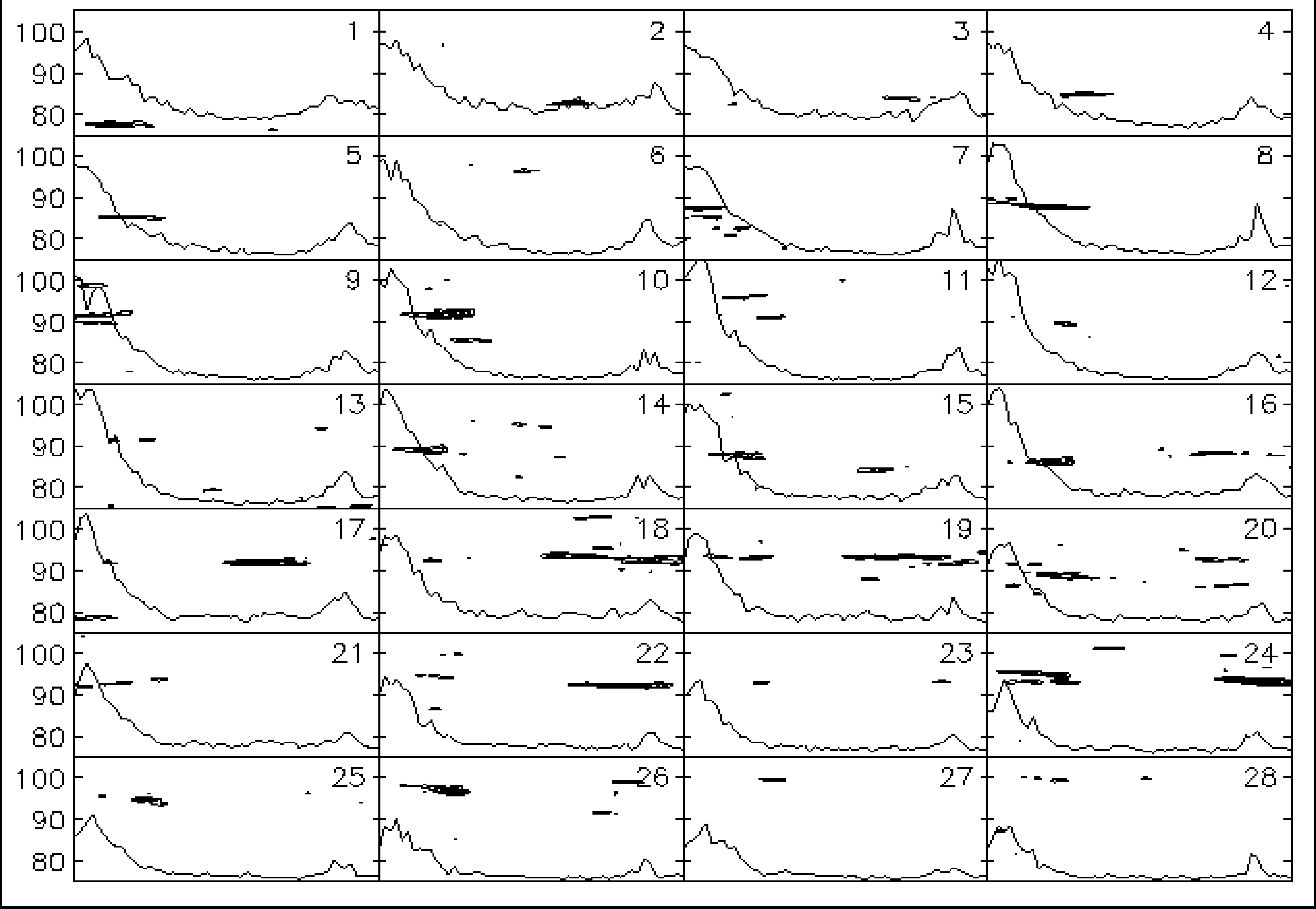
- Why do we see the oscillations? Critical if we are to use X-ray amplitudes to deduce physical amplitudes.
- Crust fracture and the excitation process
  - Fracture propagation - how does the crust yield? Plastic rather than brittle fracture (Jones 2003)? Is the crust responsible for 'gating' the flares? What type of fracture do you need to excite the oscillations that we see? Do you need aftershocks to explain the Q values?
- How does crust composition change things?
  - Pasta phase: what is the shear modulus? How does it influence eigenfunctions at the crust/core boundary?
  - Other nuclear physics uncertainties could also have a detectable effect.

“There is nothing that we have undertaken -- with a couple of exceptions like Bob -- where we have decided that we have not succeeded, so let's stop”

Steve Balmer, Microsoft

- If we really are seeing neutron starquakes (and there is no viable alternative) then we have a fantastic new probe of crust physics.
- (Assuming, of course, that we can solve the remaining field-related problems.....)
- What I want to know from the nuclear theorists:
  - How and when the crust yields
  - The shear modulus of your favorite crust models
  - What precisely is going on at the crust/core boundary.





Amplitude variation, possible frequency drift & splitting