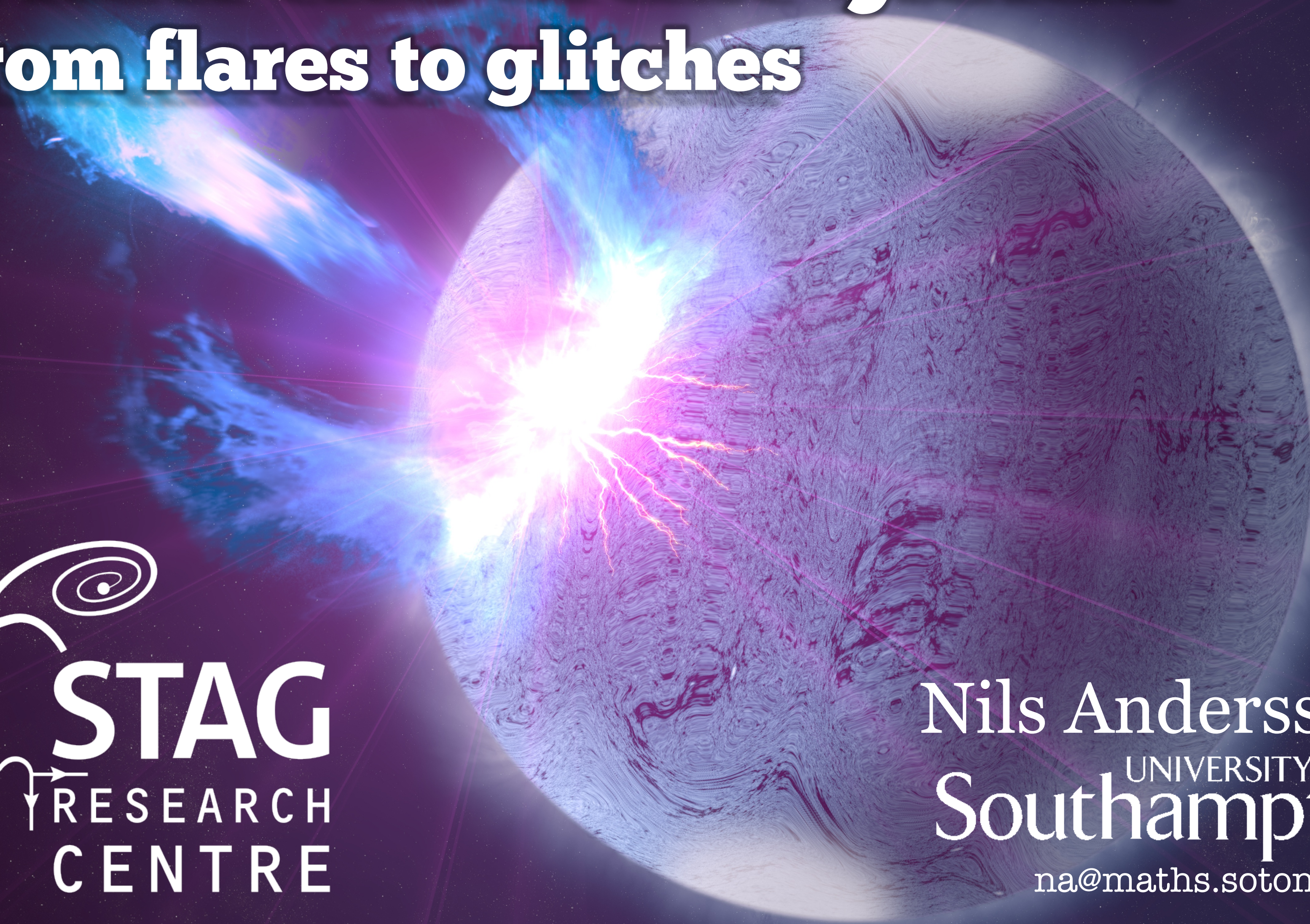
When the crust yields

From flares to glitches



STAG RESEARCH CENTRE

Nils Andersson

UNIVERSITY OF Southampton

na@maths.soton.ac.uk

modelling the crust

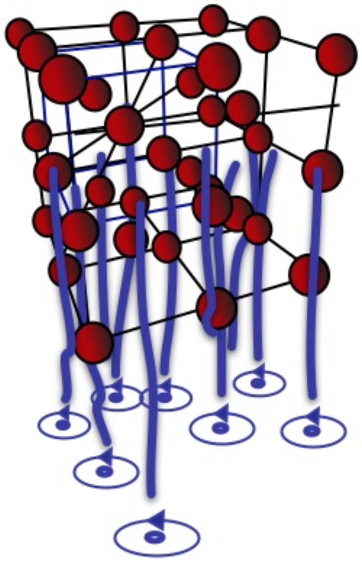
The crust forms very early on in a neutron star's life.

It (basically) contains a sequence of increasingly neutron-rich nuclei in an elastic lattice. Beyond neutron drip a superfluid neutron component permeates this lattice.

The crust plays a key role for a number of phenomena;

starquakes/flares

Elastic strain builds up as the star evolves (cooling, spindown or magnetic field evolution) to the point where the crust yields. This may lead to observed pulsar glitches and magnetar flares.



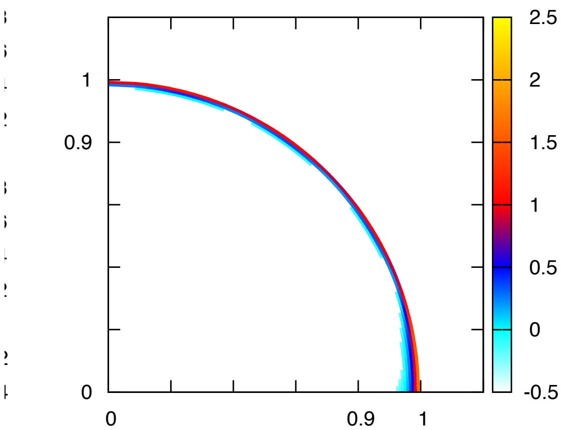
glitches

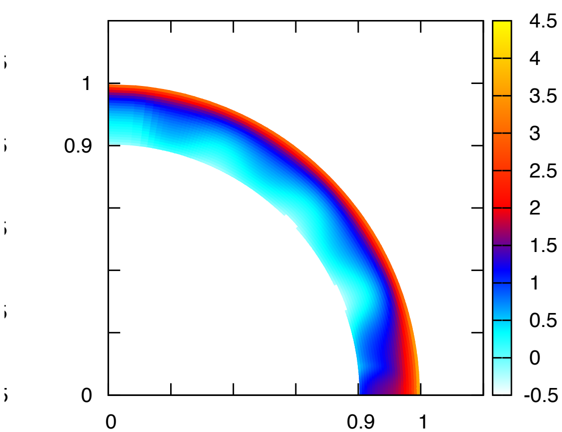
Superfluid vortices may be pinned to the crust. This leads to the build-up of a rotational lag as the star spins down. Catastrophic unpinning events may lead to observed pulsar glitches.

However... We need to understand these mechanisms better.

feeling the strain

The crust elasticity becomes important as the star evolves, e.g. through spindown of magnetic field evolution, and the actual shape of the crust differs from the shape it would "like to have".





If the strain reaches a critical level the crust "yields". This may lead to (small) glitches and could be the mechanism behind magnetar giant flares.

Molecular dynamics simulations (Horowitz et al) show that the breaking strain is much larger than previously thought.

This means that the crust is able to build up a larger amount of strain energy.

By comparing different magnetic field equilibrium configurations one can show that this energy may be enough to power giant flares.

However;

– we don't know how the energy is released

– plastic flow may be relevant

the crust yields

In principle, the presence of the crust impacts on a range of interesting problems. Yet, the elasticity is often “ignored”.

Q. Are fundamental physics aspects detectable or hidden in the fineprint?

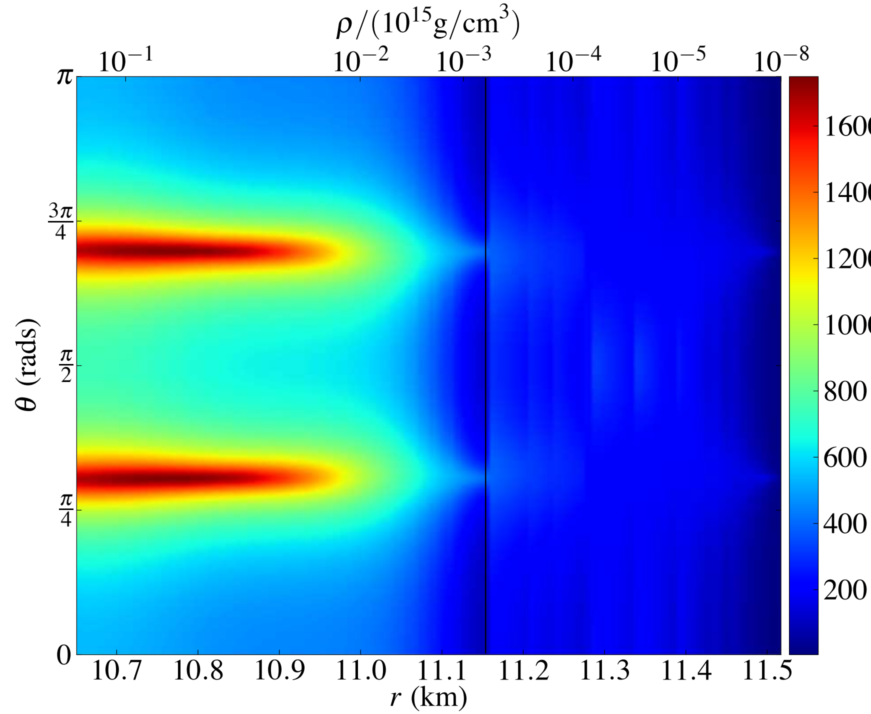
At what point during inspiral does it matter that a neutron star is not a “perfect fluid”?

Final merger provides “standard model” for short gamma-ray bursts…

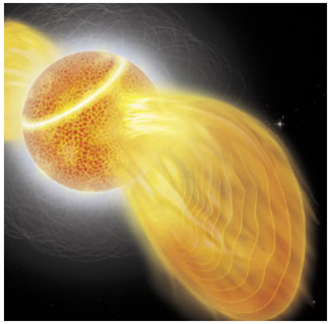
During inspiral strains builds in neutron star’s crust due to the tidal interaction.

Crust yielding may trigger an observable electromagnetic counterpart to the merger.

This could release as much as 10^{46} erg, so a signal might be visible out to/ beyond 100 Mpc) with current instruments.

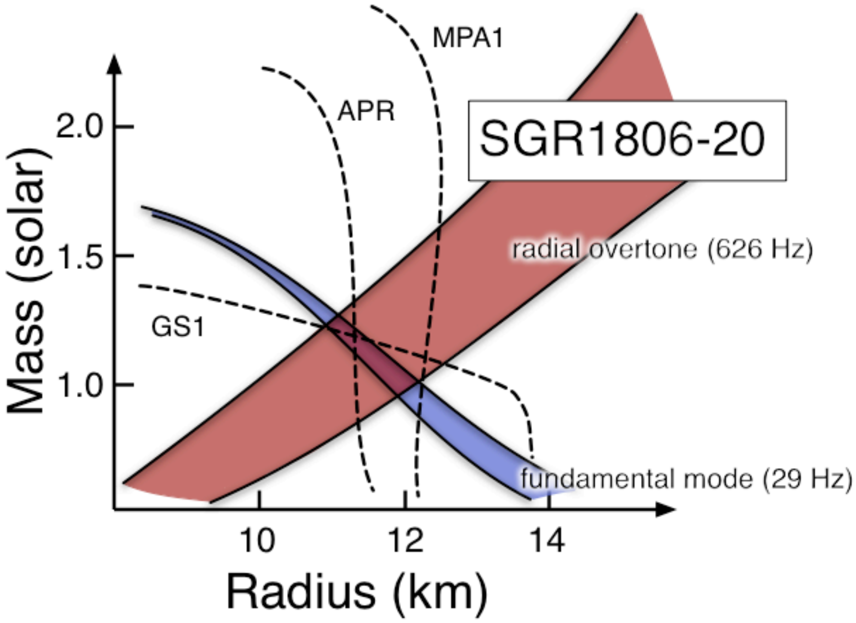


magnetar quakes



Observed quasi-periodic oscillations in x-ray tail from magnetar giant flares provided first real opportunity for asteroseismology.

If the oscillations are associated with the crust then the observed spectrum constrains the equation of state (at least in principle).



However…

- the magnetic field couples the crust to the core, which complicates the problem
- the presence of a superfluid component affects the oscillations;

$$\omega^2 \rightarrow \tilde{\omega}^2 \approx \frac{\chi_c}{\chi}\omega^2$$

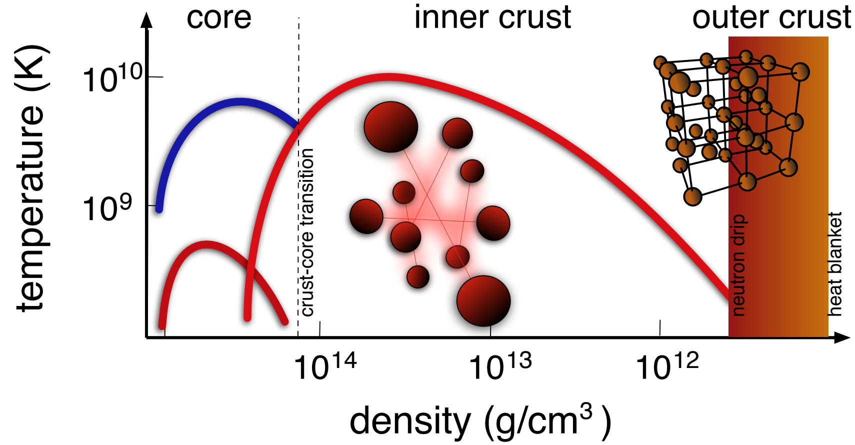
where χ encodes the **effective mass** of the free neutrons (due to Bragg scattering off the lattice nuclei).

adding superfluidity

Mature neutron stars are "cold" (10^8K<< T_{Fermi}=10^{12}K) so they **should be** either solid or superfluid.

Nuclear physics calculations indicate "BCS-like" pairing gaps for neutrons and protons.

Observational evidence from cooling and timing variability.



Model dynamics with two-fluid model:

$$\partial_t n_x + \nabla_i (n_x v_x^i) = 0$$

$$(\partial_t + v_x^j \nabla_j) p_i^x + \nabla_i (\Phi + \tilde{\mu}_x) + \varepsilon_x w_j^{yx} \nabla_i v_x^j = f_i^x$$

where the relative velocity is $w_i^{yx} = v_i^y - v_i^x$ and the momenta are given by

$$p_i^x = v_i^x + \varepsilon_x w_i^{yx}$$

This encodes the **entrainment effect**, due to which the velocity of each fluid does not have to be parallel to its momentum.

Can be thought of in terms of an "effective mass".

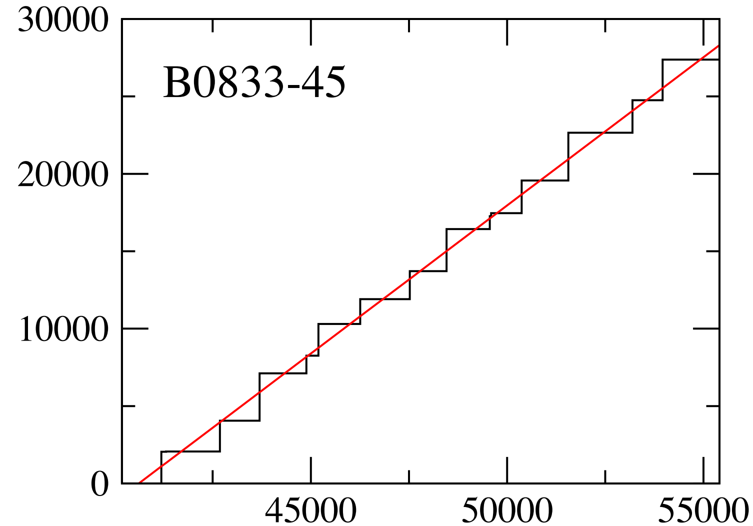
the crust is not enough

Superfluidity provides the standard explanation for observed pulsar glitches.

For systems that glitch regularly, one can estimate the moment of inertia of the superfluid component.

Need to involve up to 2% of the total moment of inertia.

The **crust superfluid** would be sufficient to explain the observations; as long as we do not worry about the entrainment.



However, the large effective neutron mass in the crust lowers the effective superfluid moment of inertia by about a factor of 5. This is problematic.

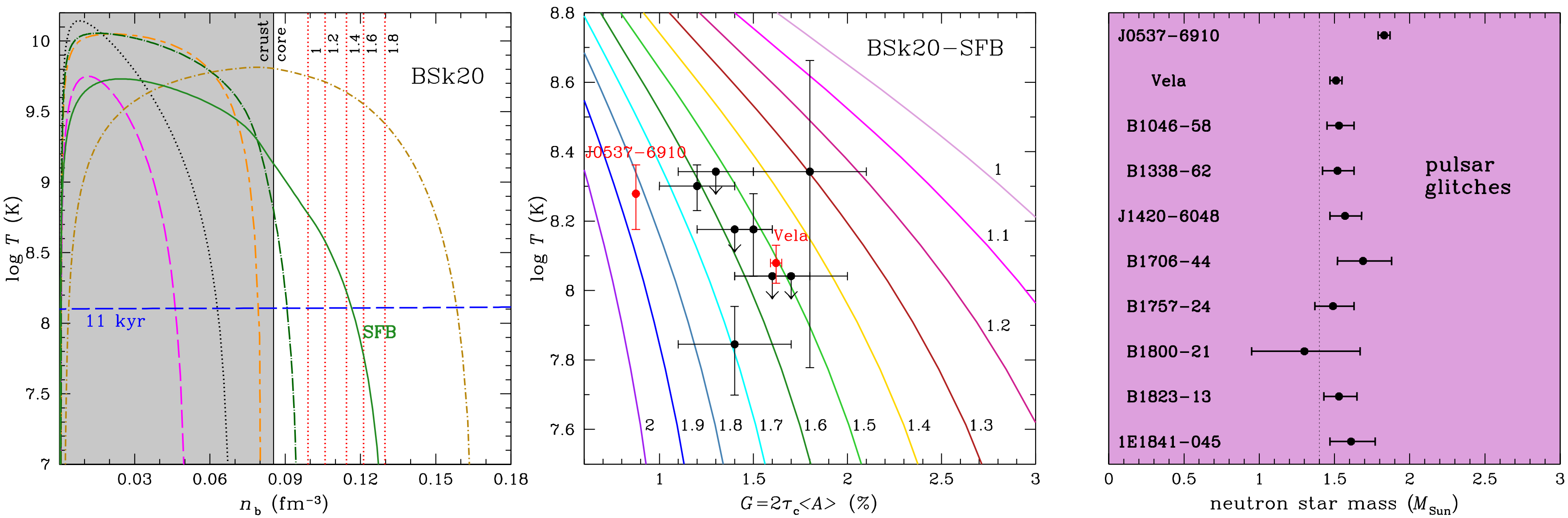
1. A fraction of the **core superfluid** could be involved, but why would the glitches be "the same size"?
2. The (singlet) pairing gap could lead to a smaller superfluid region, just large enough to explain the observations.
3. Lack of "precision": Need more accurate parameters.

mind the gap

A possible resolution to the problem would be to involve only the singlet superfluid in the crust + outer region of the core.

The data can then be turned into a constraint on the superfluid pairing gap (provided one has some idea of the star's temperature, and assuming that the angular momentum reservoir is exhausted in each glitch event).

Interestingly, most available gap models **fail** this test.



If we take the pairing gap as given, we can **infer the mass** of a glitching pulsar.

SKA will add significantly to the data (revolve actual glitch rise?), so...

where are we going?

In order to develop “realistic” models for the neutron star crust, we need progress on a number of issues.

Microphysics

- develop unified models, with all required parameters (composition, shear modulus, pairing gaps etc) for the same interactions.

- move beyond “equilibrium” equations of state to consider dynamical effects (entrainment!).

- improve our understanding of superfluid vortex dynamics and crust pinning.

Dynamics

- build relativistic models that allow for the expected degrees of freedom, e.g. fluid flow, heat, charge current, superfluid flow, elasticity…

- connect these models to the microphysics and understand the many transport coefficients involved.

…