Missing pieces in the r-mode puzzle

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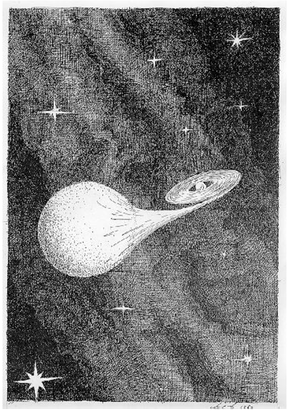
accreting systems



Accreting neutron stars in LMXBs may be relevant gravitational-wave sources. Their rotation appears to be limited by some mechanism;

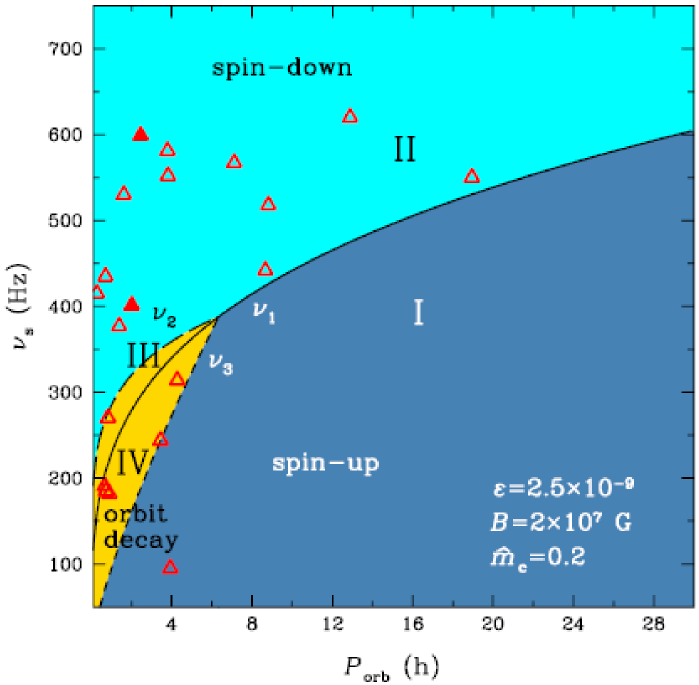
– non-standard accretion torque

– additional spin-down (mountains, r-modes, B-field)

Possible **indirect** evidence for a gravitational-wave component from spin vs orbit period in the observed systems.

Required deformation significantly below current LIGO limits, but may (just?) be within reach of the third generation Einstein Telescope.

(Ho, Maccarone & NA, ApJL 2011)

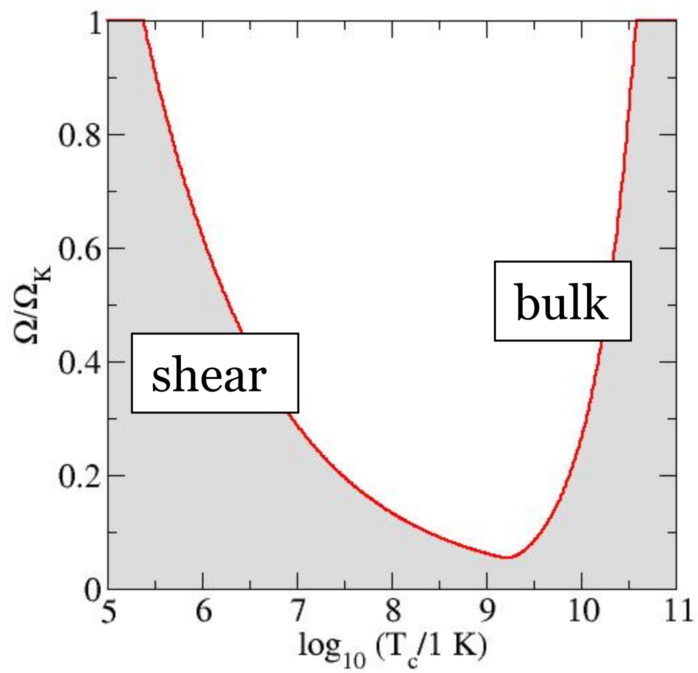


the r-mode instability

The r-modes belong to a large class of "inertial" modes, which are driven unstable by the emission of gravitational waves.

The *l=m=2* r-mode grows due to <u>current-multipole</u> radiation on a timescale of a few tens of seconds.

Instability window depends on uncertain core-physics, i.e. provides a probe of exotic physics



The simplest models account for damping due to shear- and bulk viscosity.

Leads to a very large <u>instability window</u>.

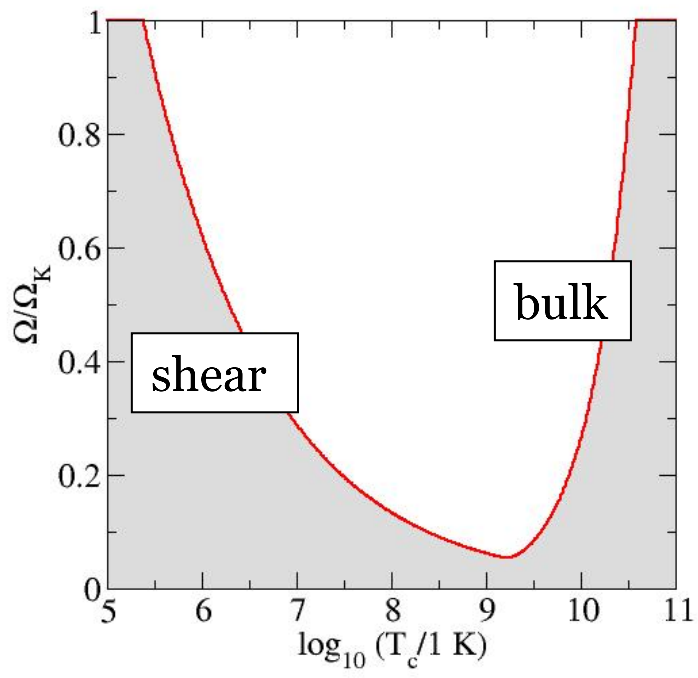
In principle, we should not observe any "usual" neutron stars inside the instability region. Can we use this to "rule out" theoretical models?

“constraints”

Young radio pulsars: Original r-mode window consistent with the inferred birth spin of the Crab PSR (19 ms), but not with the 16 ms X-ray PSR J0537-6910.

Recycled pulsars: Need to allow the formation of a cold 716 Hz PSR (presumably after recycling). This constrains the instability window at low temperatures.

LMXBs: Nuclear burning of accreted material provides a thermostat that sets the core temperature to 10^8 K. Fastest systems (around 640 Hz) require smaller instability region.



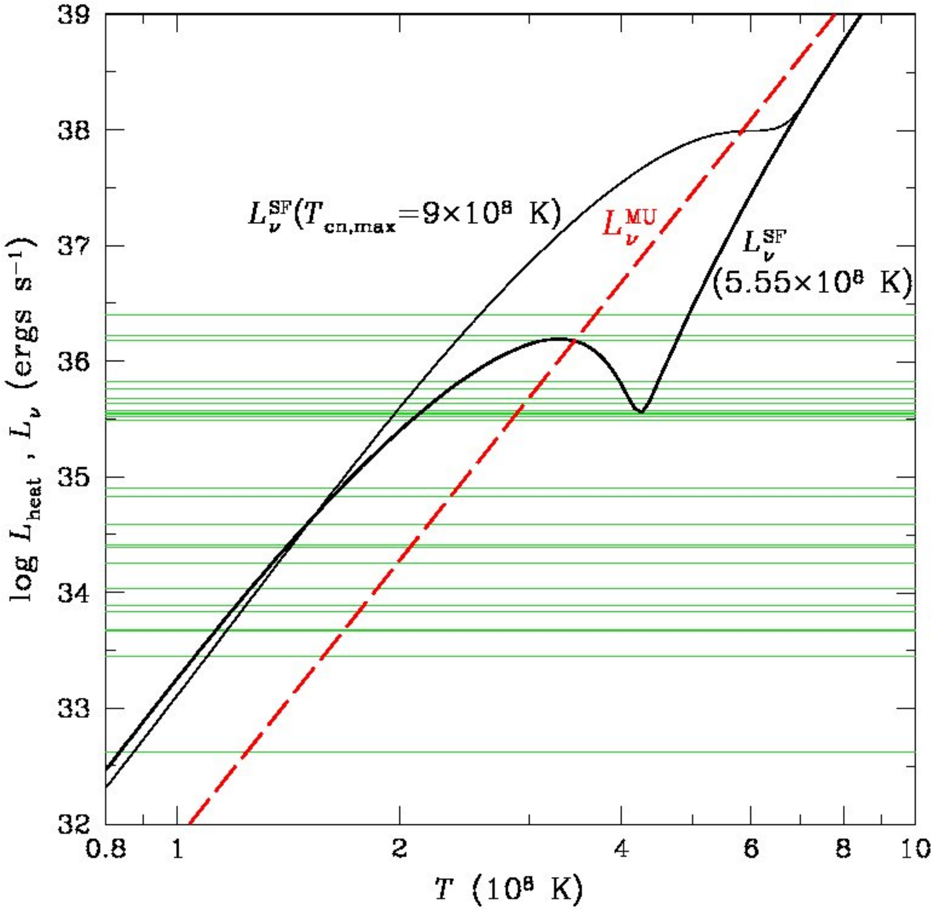
Consider temperature limits for systems in quiescence (Brown+Ushomirsky).

If a system is r-mode unstable, how would we know?

Are there systems that behave (in some sense) “funny”?

superfluid cores

Revisit core temperature in accreting systems in light of recent evidence for neutron superfluidity in Cassiopeia A remnant.



Assume r-mode balances accretion spin-up torque, i.e. that observed systems are in spin equilibrium. (important caveats here!)

Suppress neutrino processes involving superfluid nucleons.

Enhance (just below T_c) emission due to Cooper pairing.

Note: Inferred temperature may not be unique!

(Ho, NA & Haskell, PRL 2011)

superfluid cores

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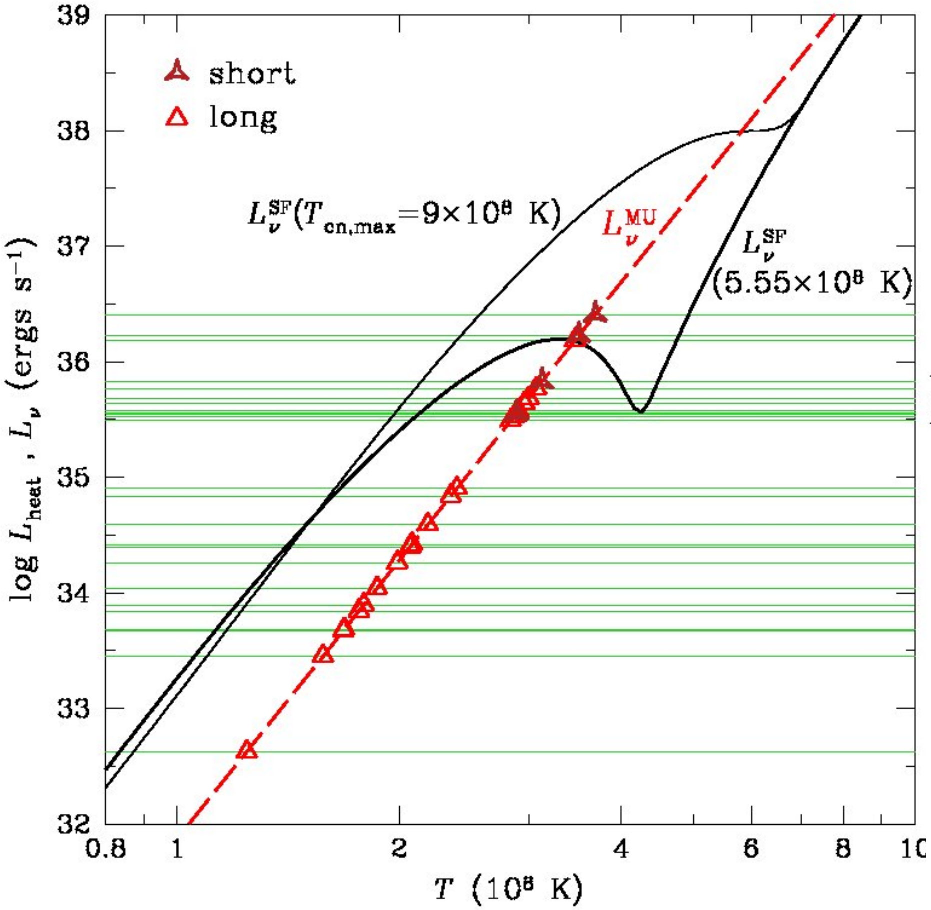

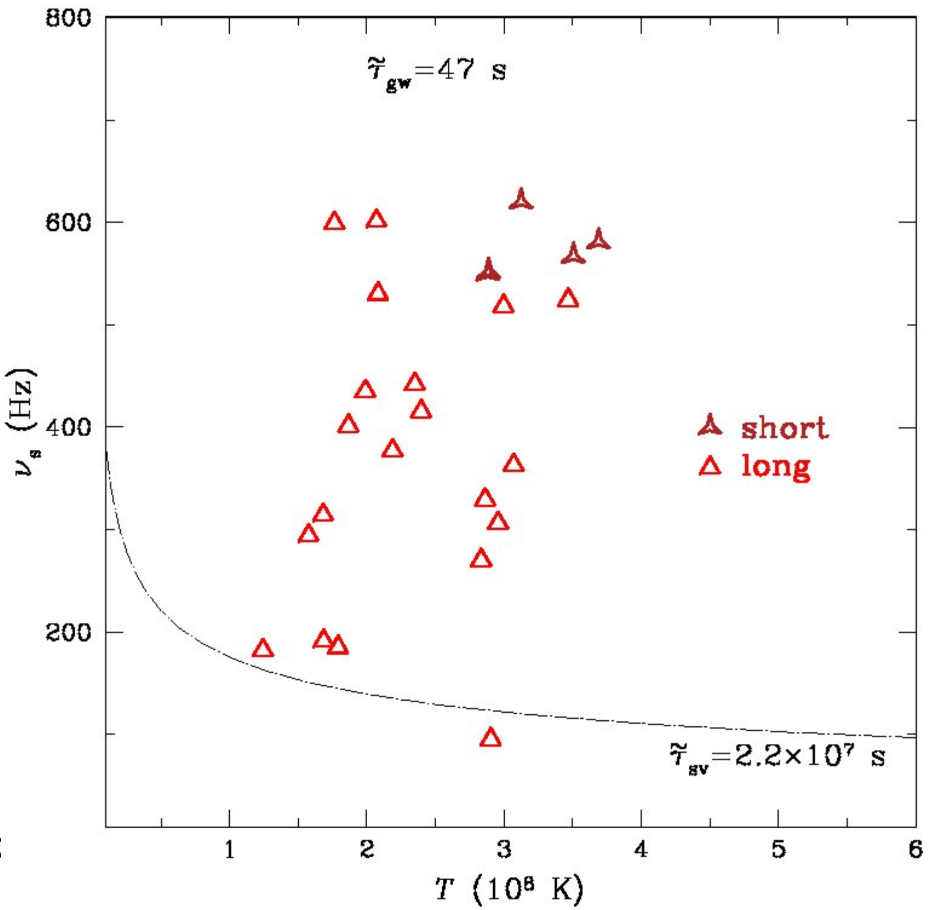

superfluid cores

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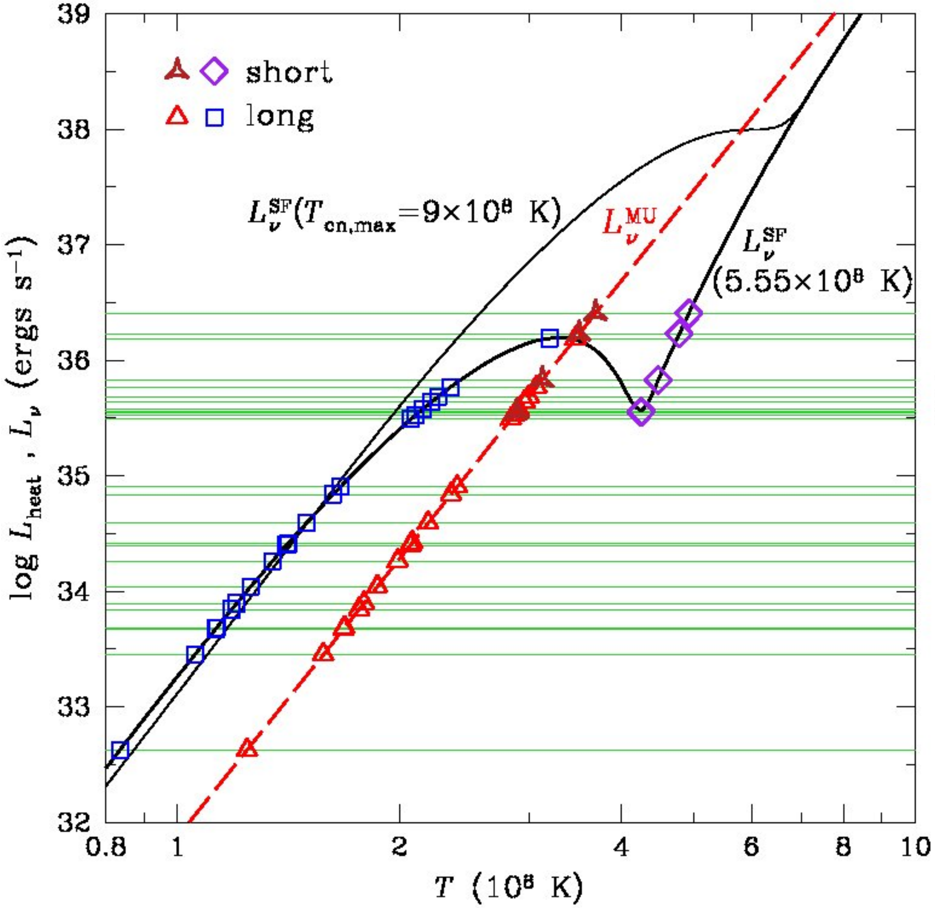
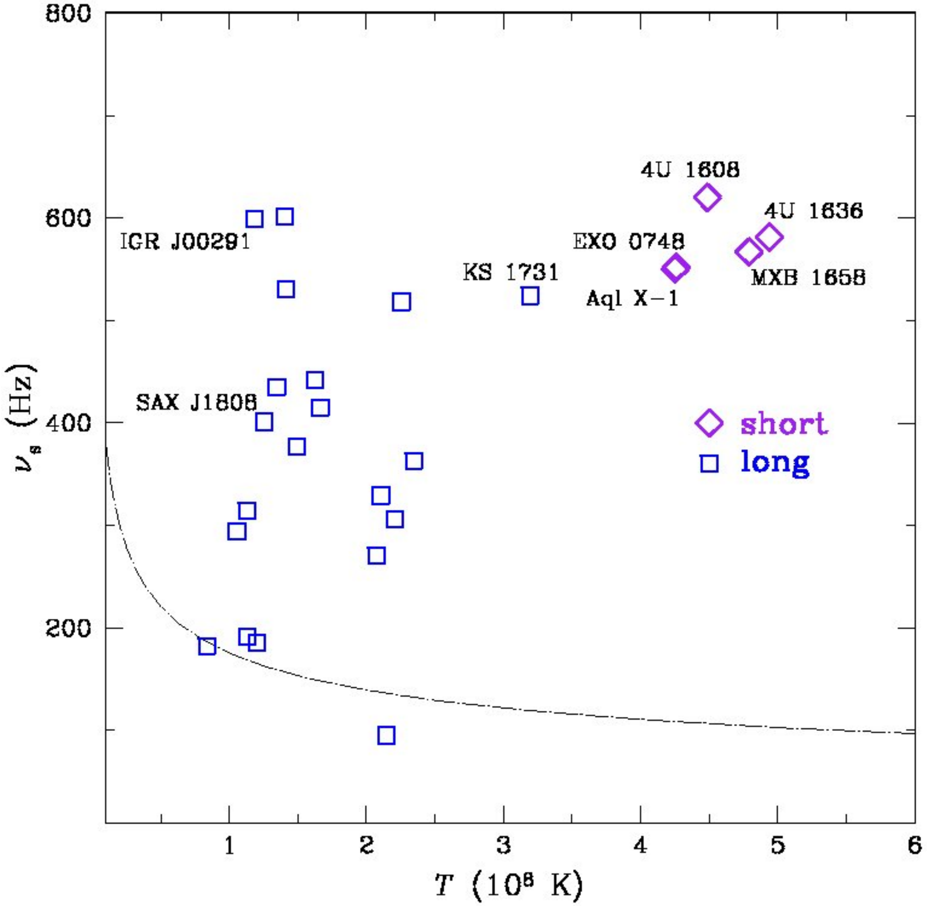




r-mode puzzle

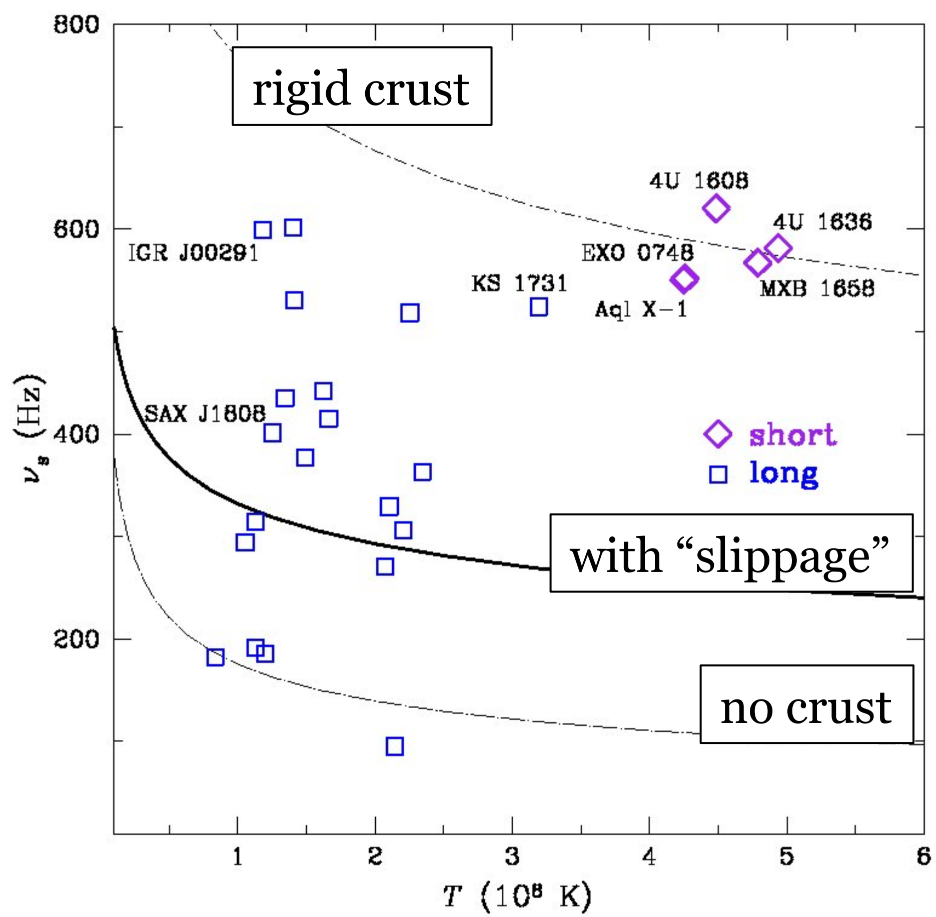
Demonstrates that our understanding of the r-modes is incomplete. Given the "best estimate" for the main damping mechanisms, many observed LMXBs should be unstable.

Rigid crust with viscous (Ekman) boundary layer would lead to sufficient damping…

…but the crust is more like jelly, so the effect is reduced ("slippage").

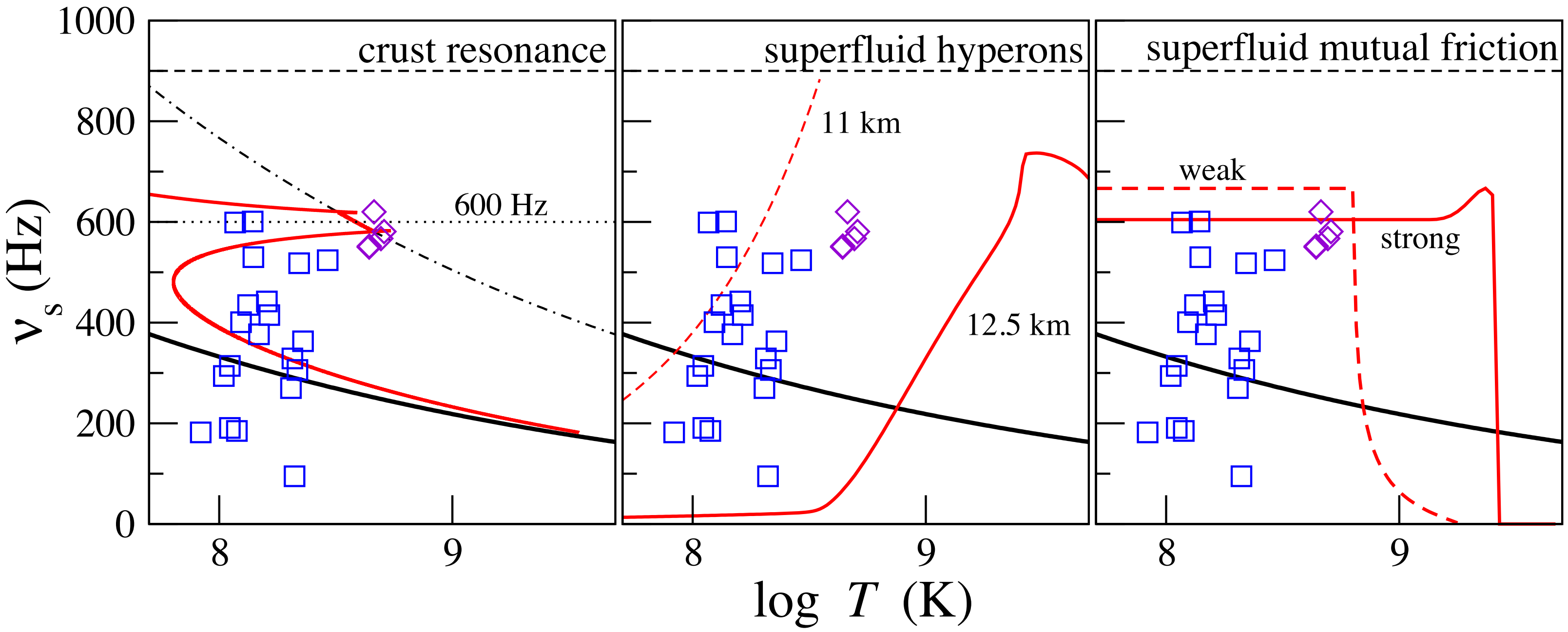
Magnetic field is too weak to alter the nature of the boundary layer.

Superfluid "mutual friction" (due to electrons scattered off vortices) has no effect.



Saturation amplitude due to mode-coupling is too large to allow evolution far into instability region.

resolutions?



i) Boundary layer redux:

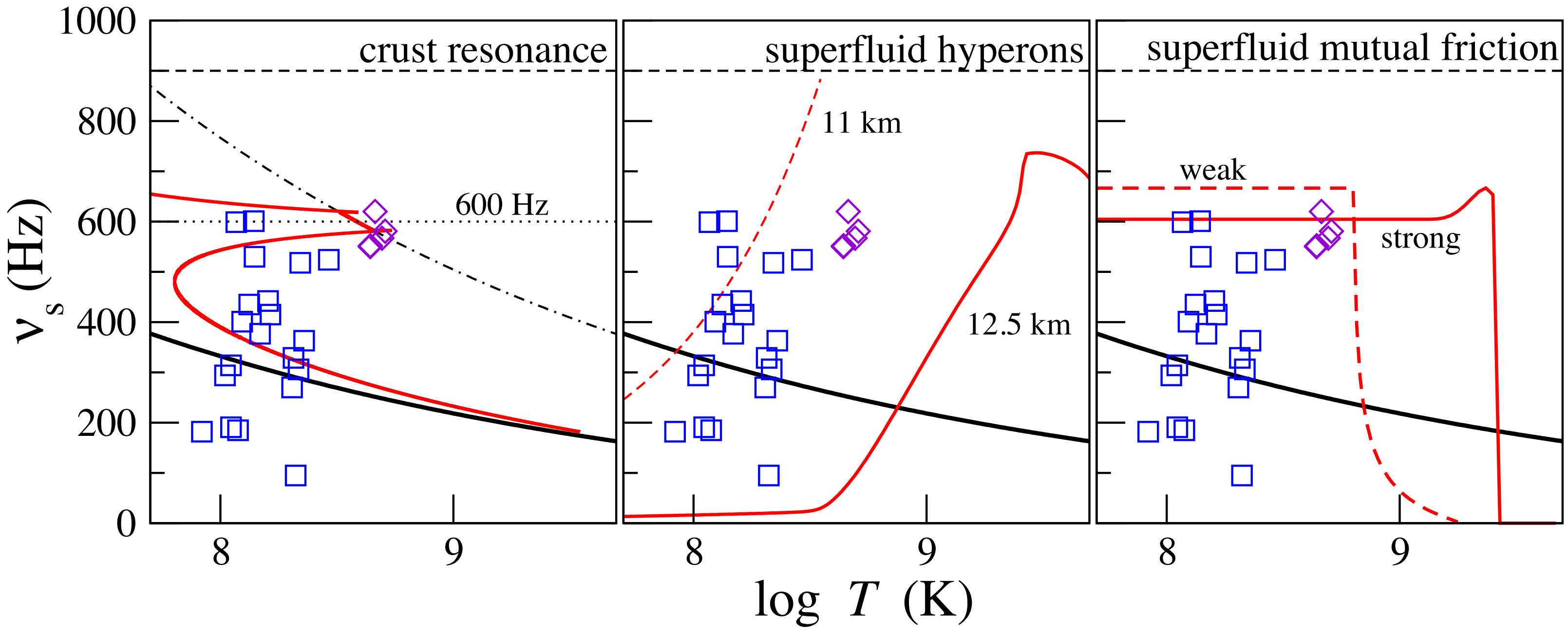
– pasta phase reduces/removes viscous boundary layer effect

– magnetic field coupling/tension

– "resonances" between r-mode and toroidal crust modes?

– transition to superconducting core?

resolutions?



ii) More “physics”:

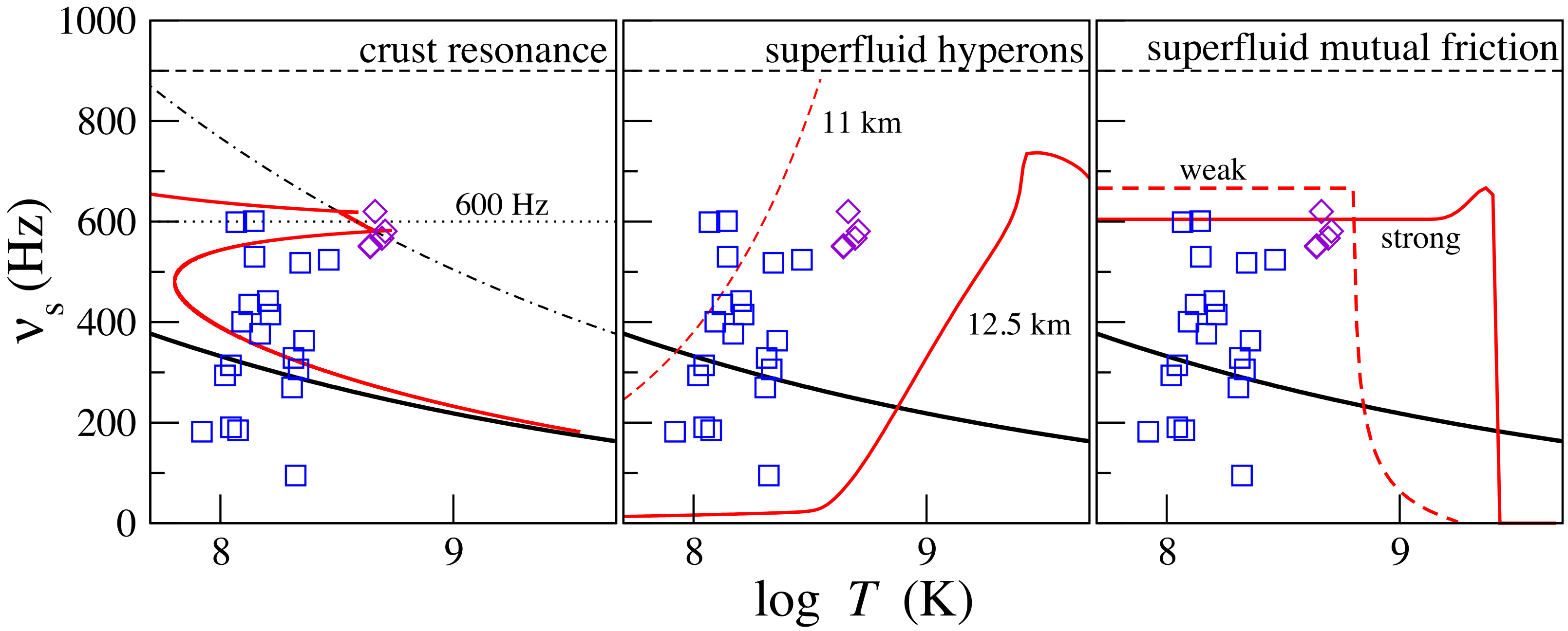
– hyperon (or quark) bulk viscosity (problematic if you want a 716 Hz PSR)

– various quark pairing phases (seem too weak, core essentially inviscid)

– crust “viscosity”?

– winding up magnetic field (issue with weak field ms PSRs?)

resolutions?



iii) Superfluidity:

– enhanced superfluid vortex mutual friction (comment P.B. Jones mechanism)

– vortex turbulence?

– crust pinning

– fluxtube “cutting”

what else?

Insert missing pieces here…