Revealing the Physics of R-modes in Low-Mass X-ray Binaries

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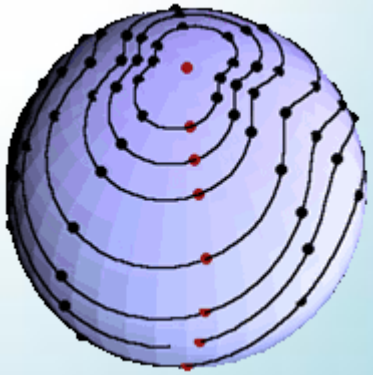
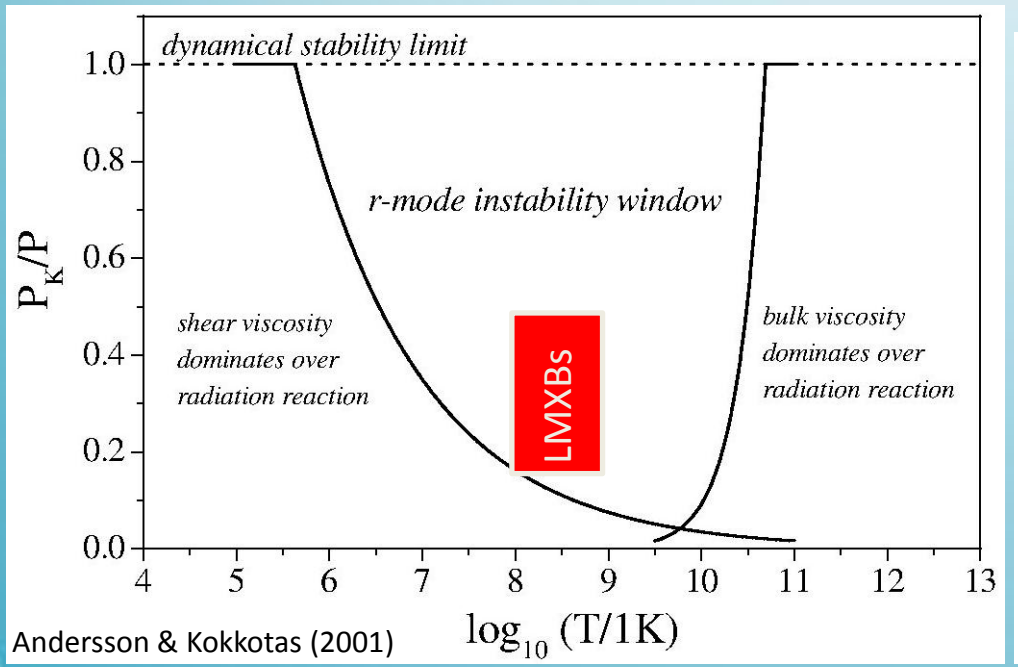
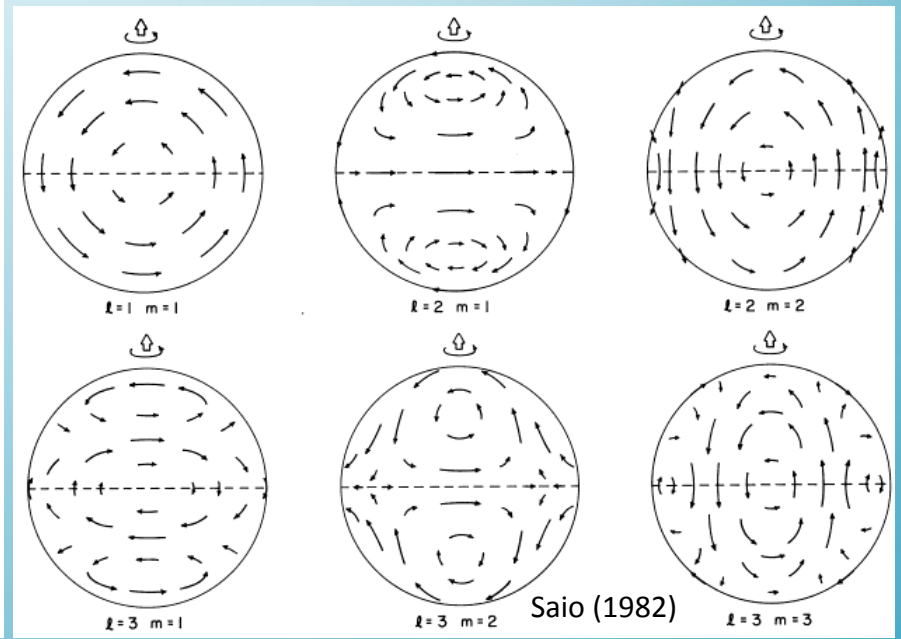
R-mode Oscillations and Instability

- Fluid oscillations in rotating stars
- Generically unstable:
  - ➢ Gravitational waves drive r-mode growth
  - ➢ Viscosity damps r-mode
    - shear viscosity at low temperatures
    - bulk viscosity at high temperatures
  - ➢ R-mode evolution: $t_{gw}(\nu_s) = t_{visc}(\nu_s, T)$





Andersson & Kokkotas (2001)

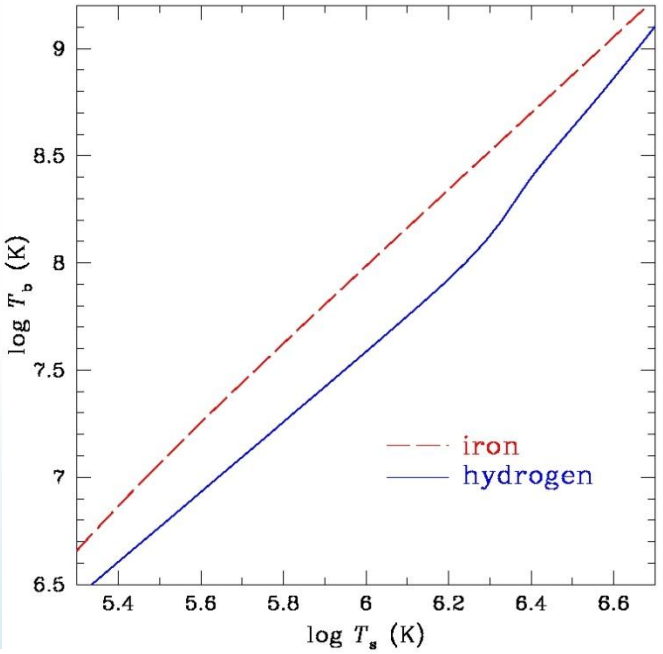


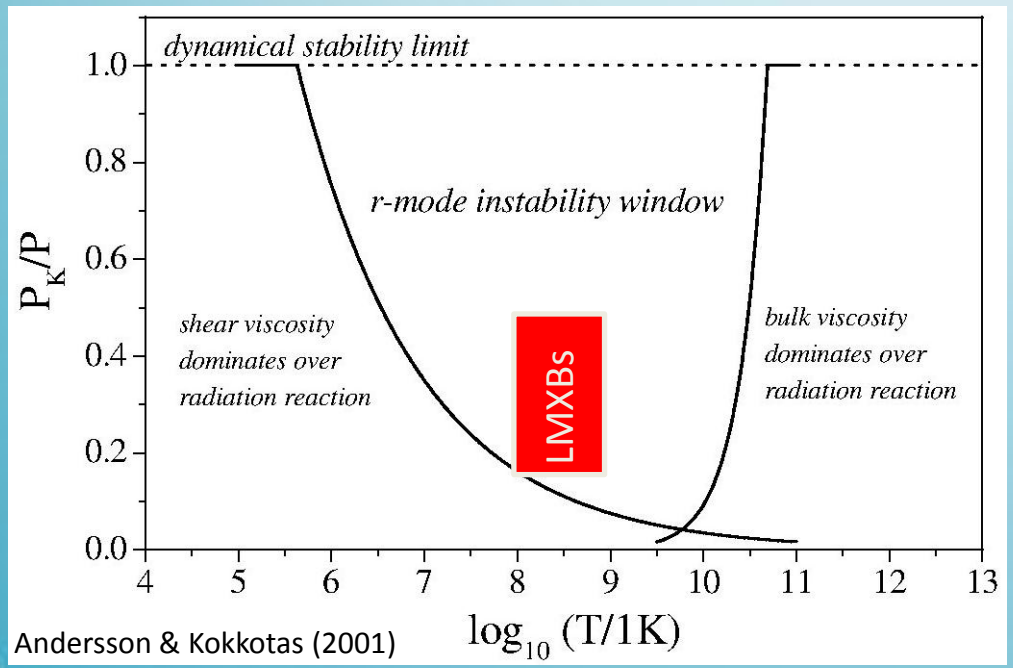
Saio (1982)

Inferring NS Core Temperature

- Quiescent Low-Mass X-ray Binaries (LMXBs)
  - surface temperature $T_{surface}$ from spectrum
  - from envelope composition: T_{core} ($T_{surface}$)
- Accreting LMXBs
  - measure accretion luminosity $L_{acc} = 4\pi d^2 F_X$
  - accretion spin-up balances GW spin-down
  - from heating = cooling, where
    - r-mode/accretion heating: $L_{heat} \propto \nu_s \times L_{acc}$
    - neutrino cooling: L_ν (T_{core})

thermal conductivity





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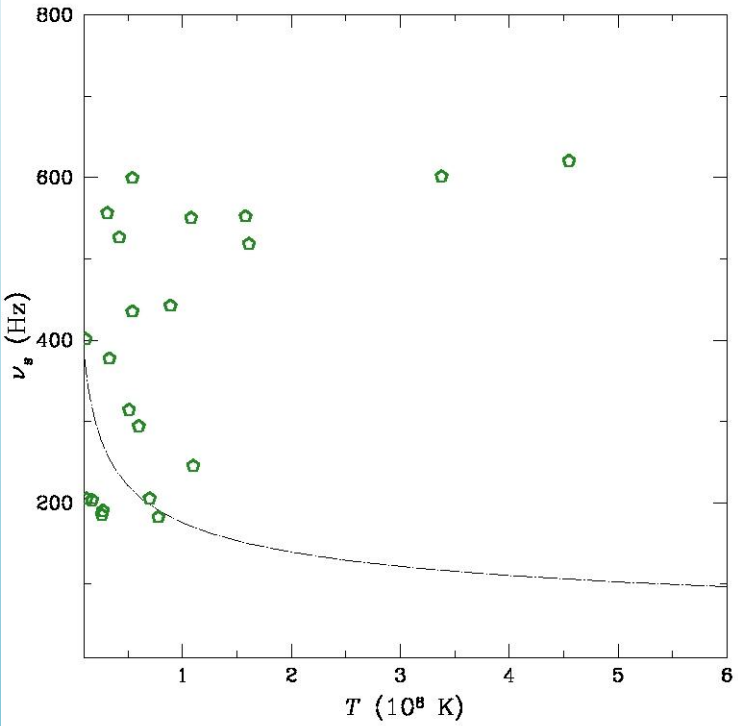

Inferring NS Core Temperature

need to know distance

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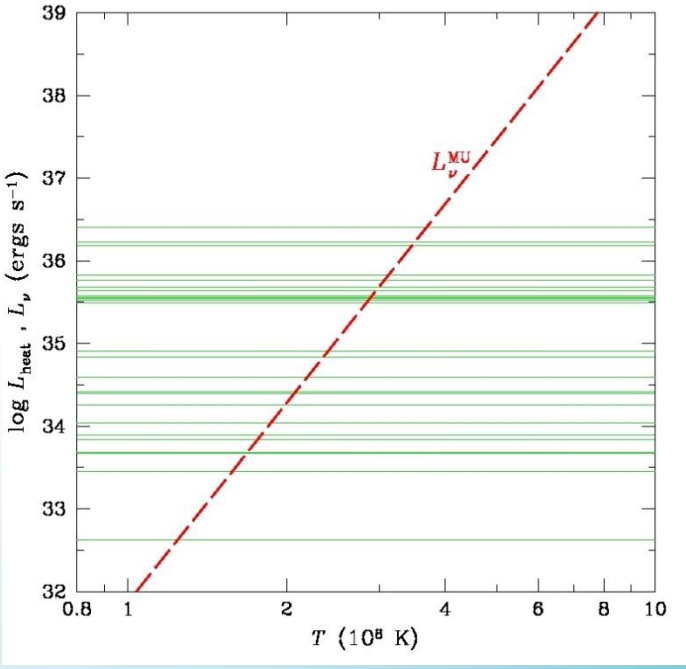
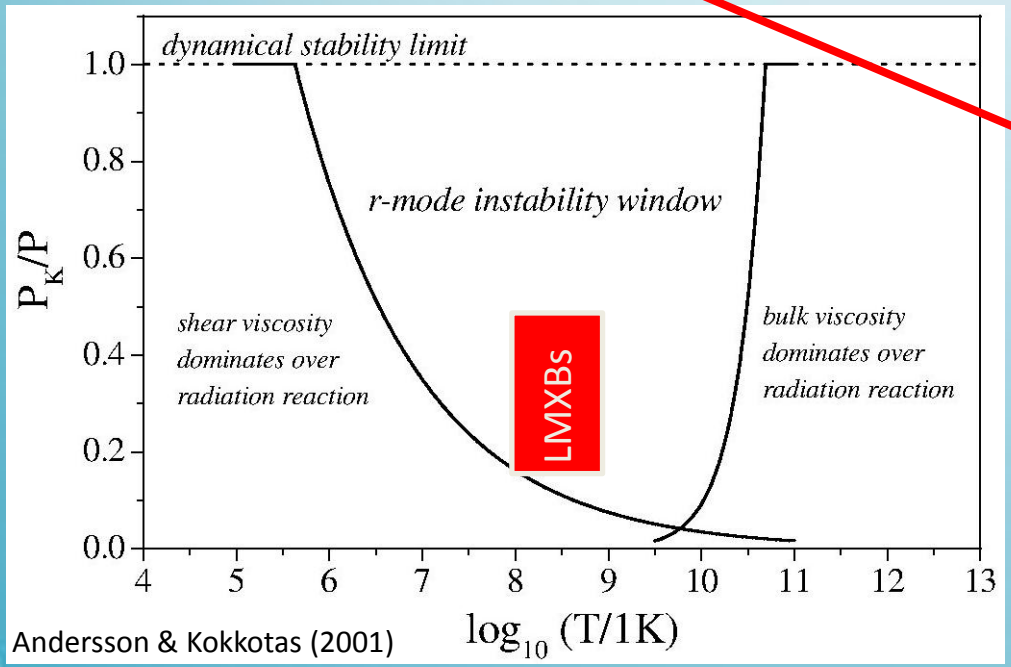


standard/slow cooling (by modified Urca):
$L_\nu^{MU} \propto T^8$



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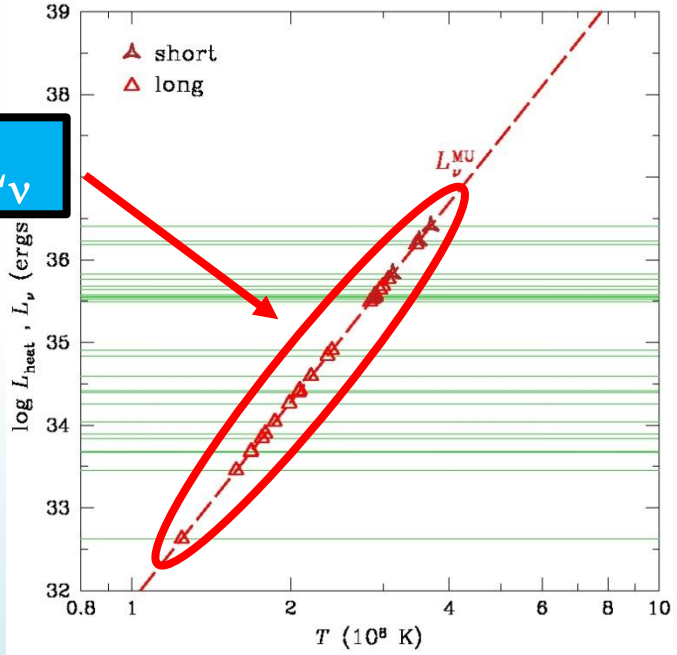
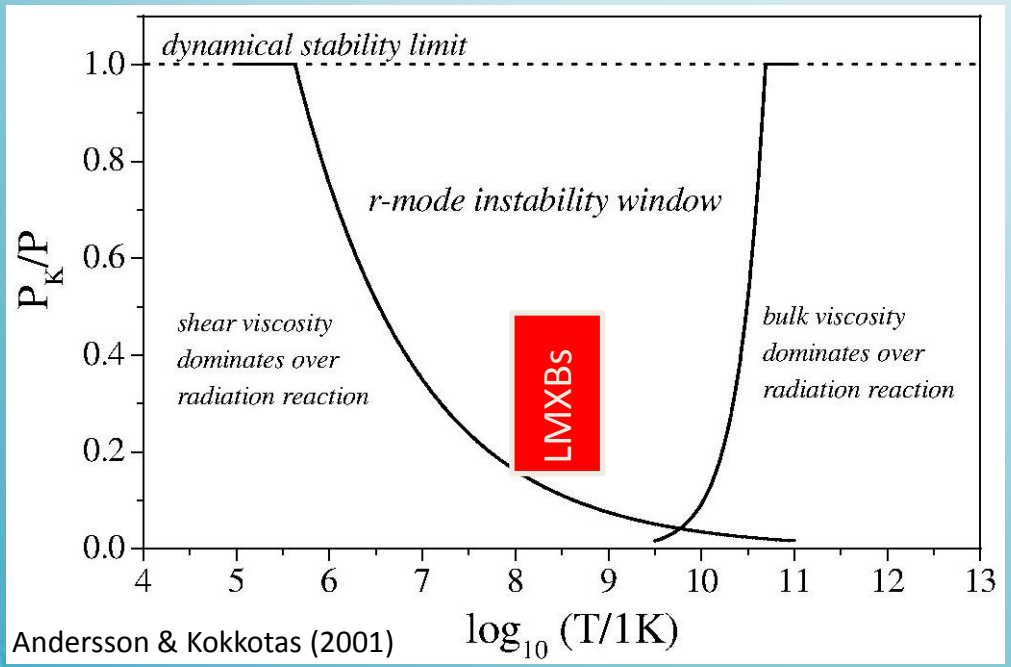
$$L_{heat} = L_\nu$$





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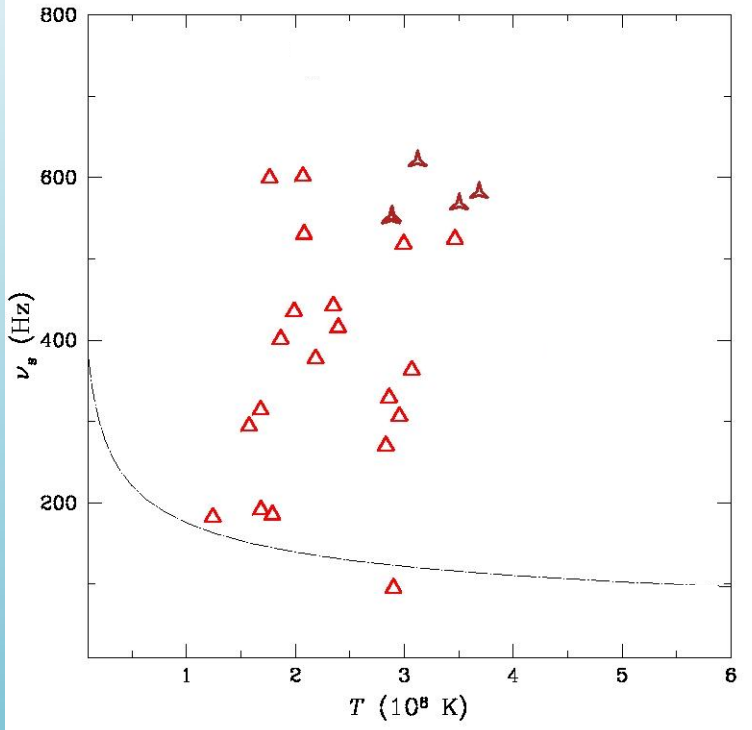

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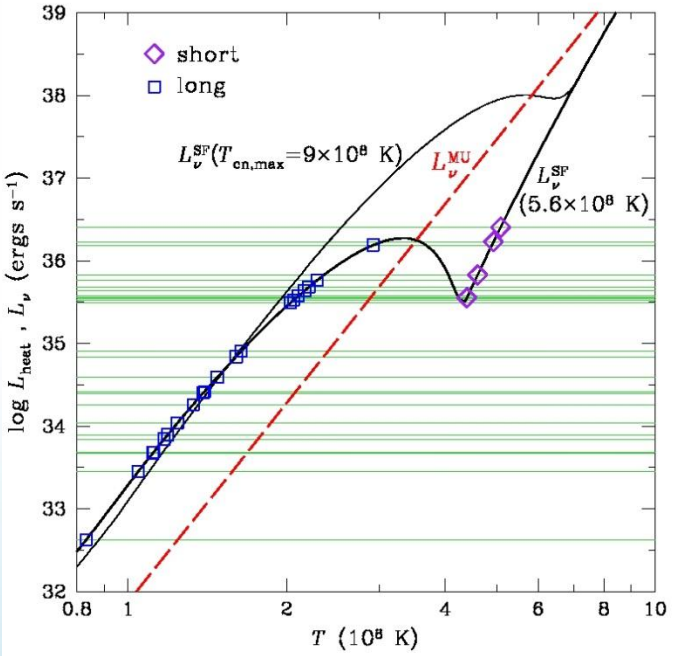
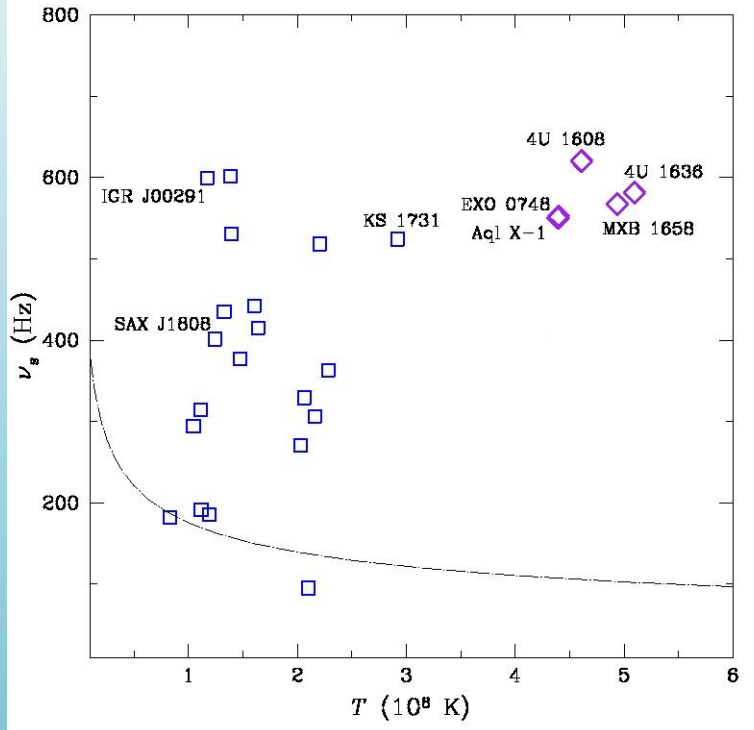
superfluid cooling
[Cas A NS: $T_c \approx (5\text{-}9)\times 10^8$ K]

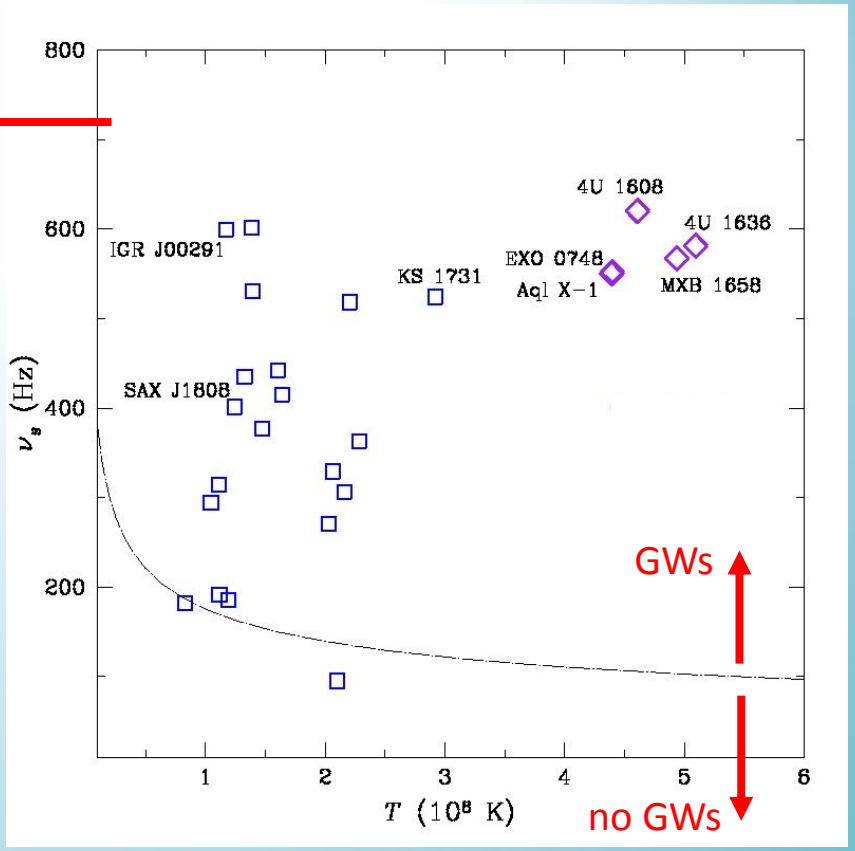




R-mode Instability vs Observations

- Unstable r-mode
  - ➢ spin-temperature limit cycle
    - large amplitude: short time in window
    - small amplitude: not deep in window
  - ➢ cannot produce high ν_s
  - ➢ spin-down by magnetic dipole w/o GWs

- Stable r-mode
  - ➢ crustal physics
    - viscous boundary layer
    - mode resonance with elastic crust
  - ➢ magnetic field shortens τ_{VBL}
    - $B > 10^{11}$ G to stabilize
  - ➢ high viscosity at high T
    - superfluid-suppressed hyperon bulk viscosity
    - but spin-down vs. ν_s = 716 Hz
  - ➢ superfluid mutual friction
    - e^- scatter off superfluid vortices (too weak)
    - but (strong enough?) friction from vortex-fluxtube interaction



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Closing the Window? (Crust-Core Boundary)

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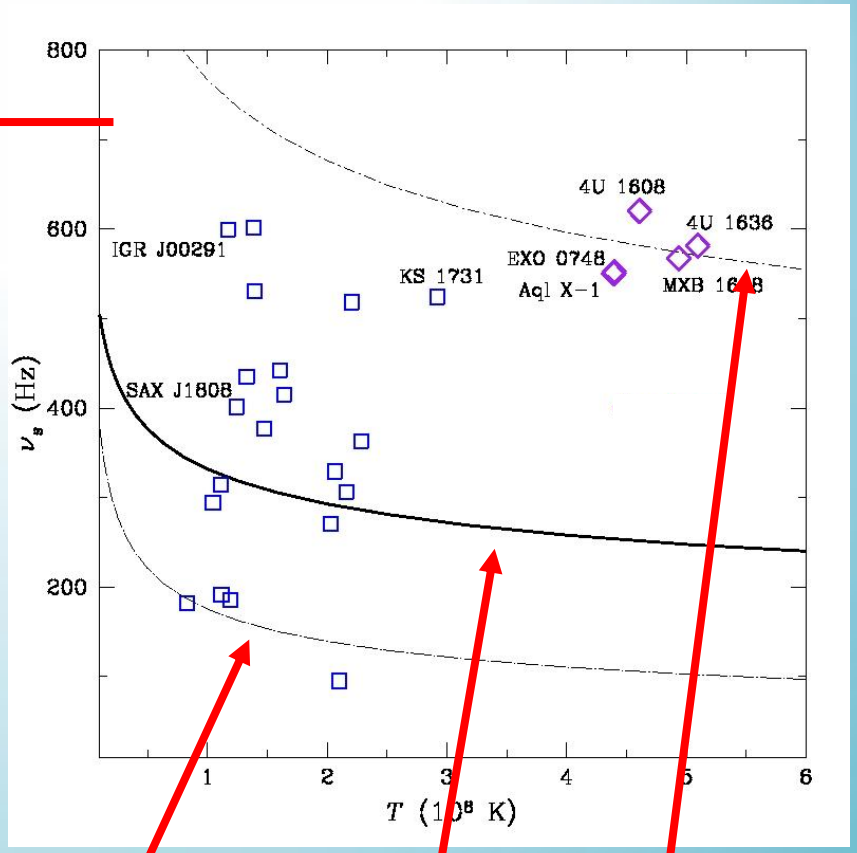

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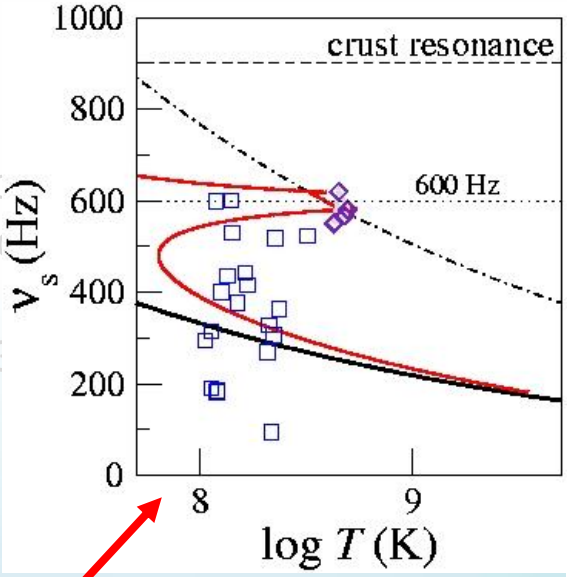
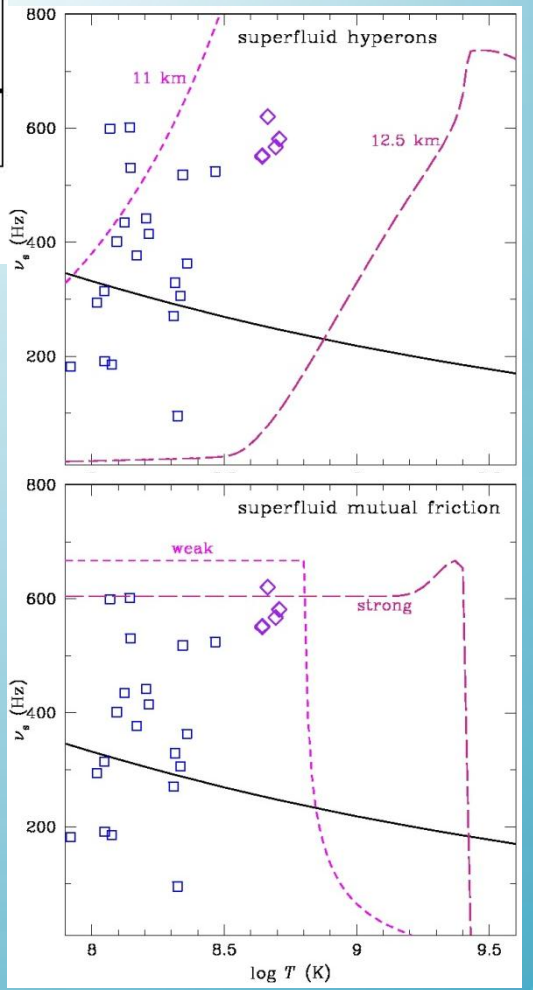


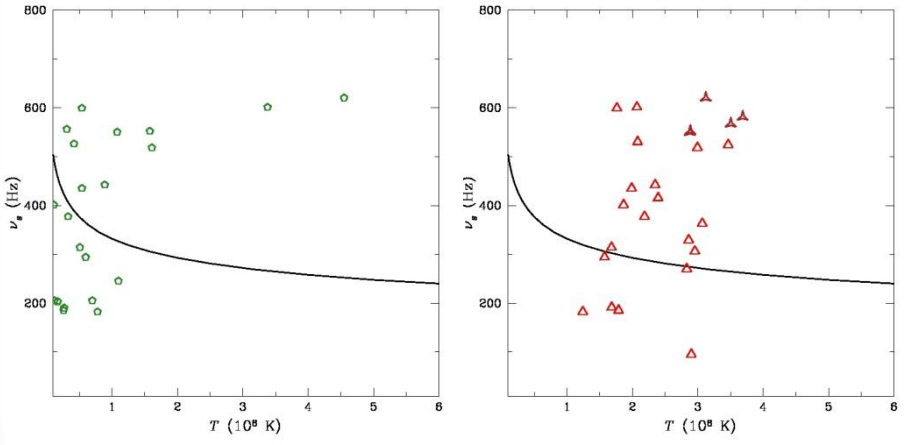


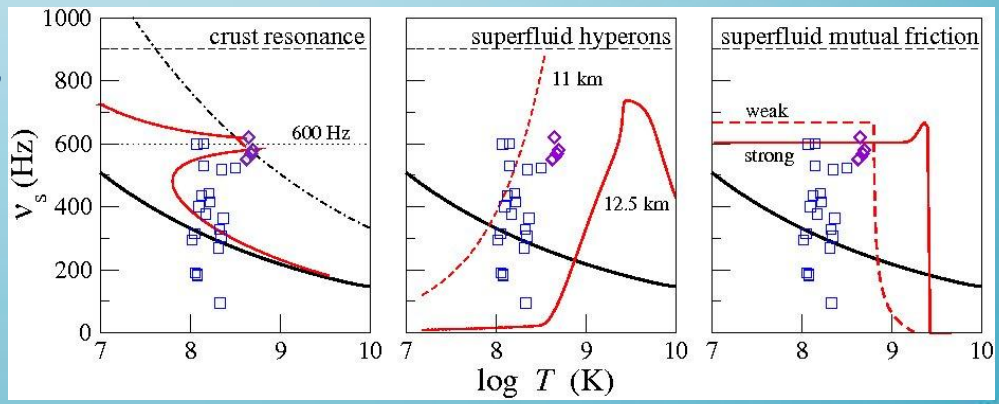
Status of R-mode Instability

- Window for gravitational radiation not well-understood

- Some systems should be GW emitters but counter to expectations

- Relevant astrophysics/physics
  - ➢ core temperature estimates:
    - envelope composition
    - neutrino emission
    - LMXB distances
  - ➢ window shape:
    - crust elasticity
    - superfluidity (critical temperature, hyperons, mutual friction)
    - magnetic field (damping and estimates from LMXBs)





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