Gravitational Wave emission mechanisms in accreting systems

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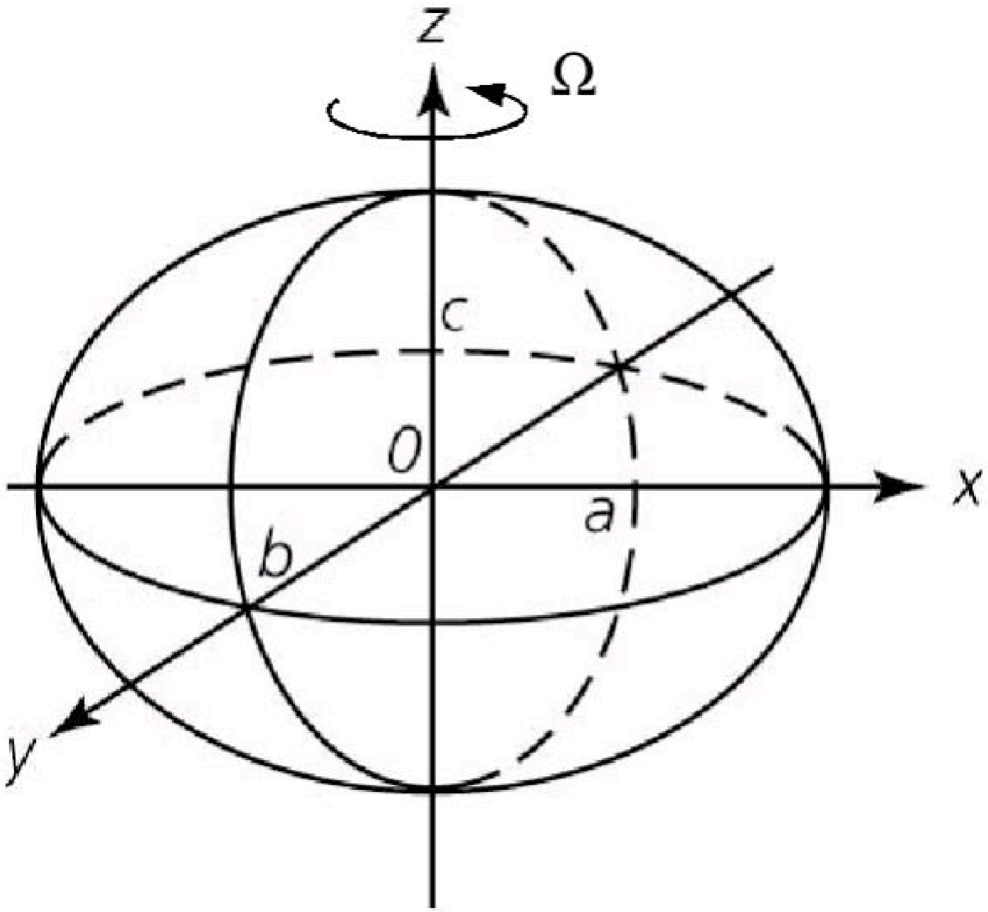
- GWs from rotating neutron stars
  - LMXBs and accretion models

- Emission mechanisms
  - Crustal and core mountains
  - Magnetic mountains
  - Unstable modes (r-modes)
    - Superfluid effects and dissipation

- Conclusions

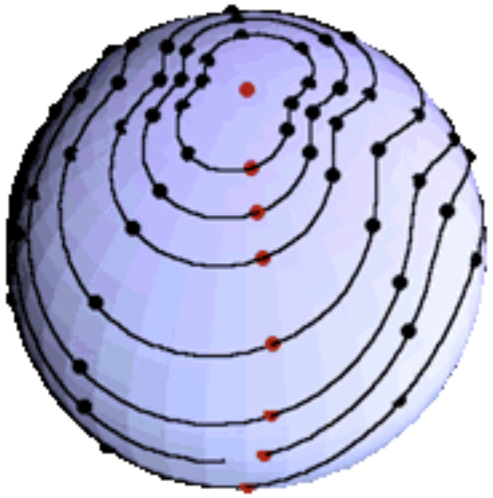
Neutron star mountains

- $\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$
- Emission at $\omega = 2\Omega$
- $\frac{dE}{dt} \approx \epsilon^2 \Omega^6$

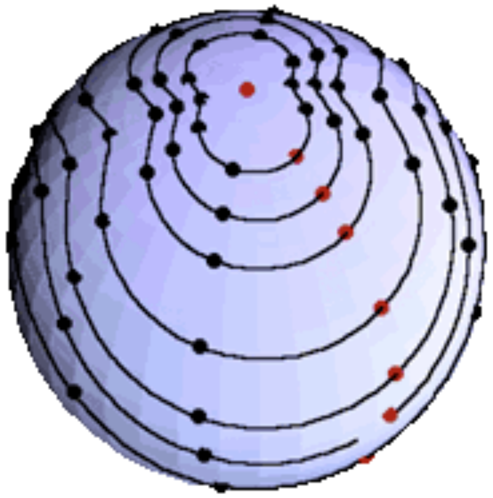


r-mode instability

(Animation by Ben Owen)



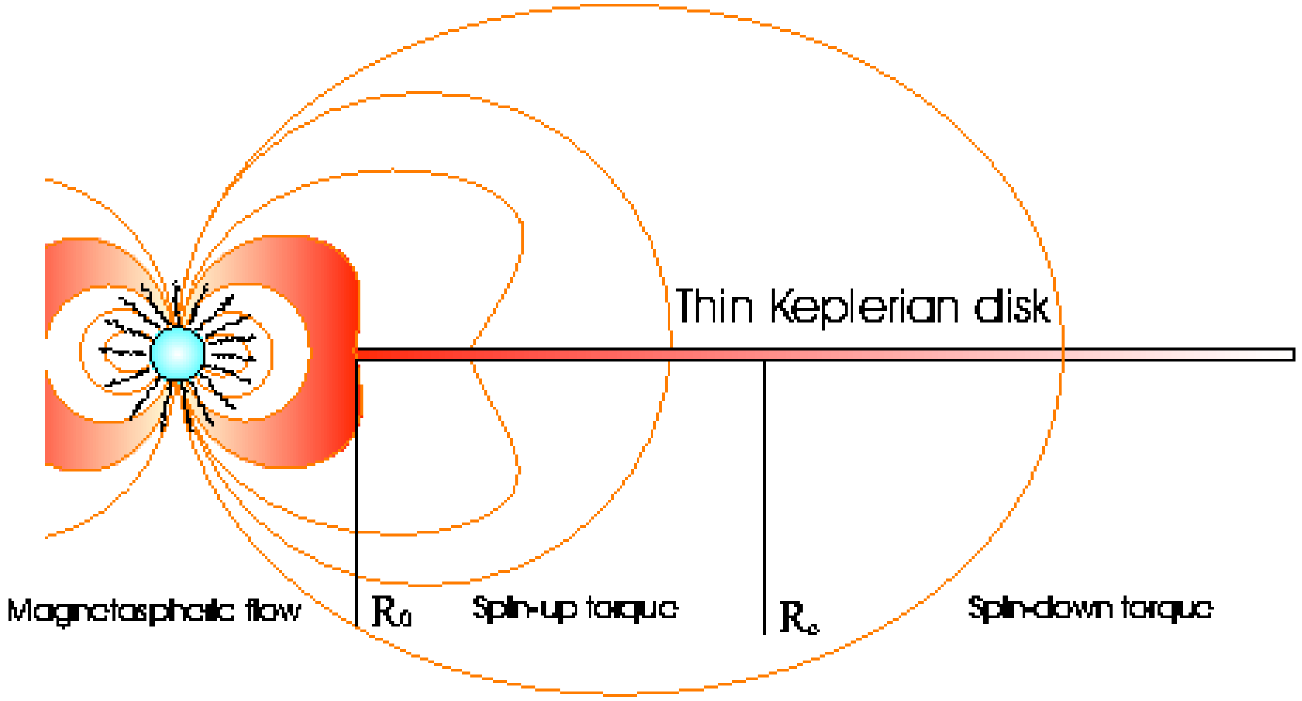
Rotating observer



Inertial observer

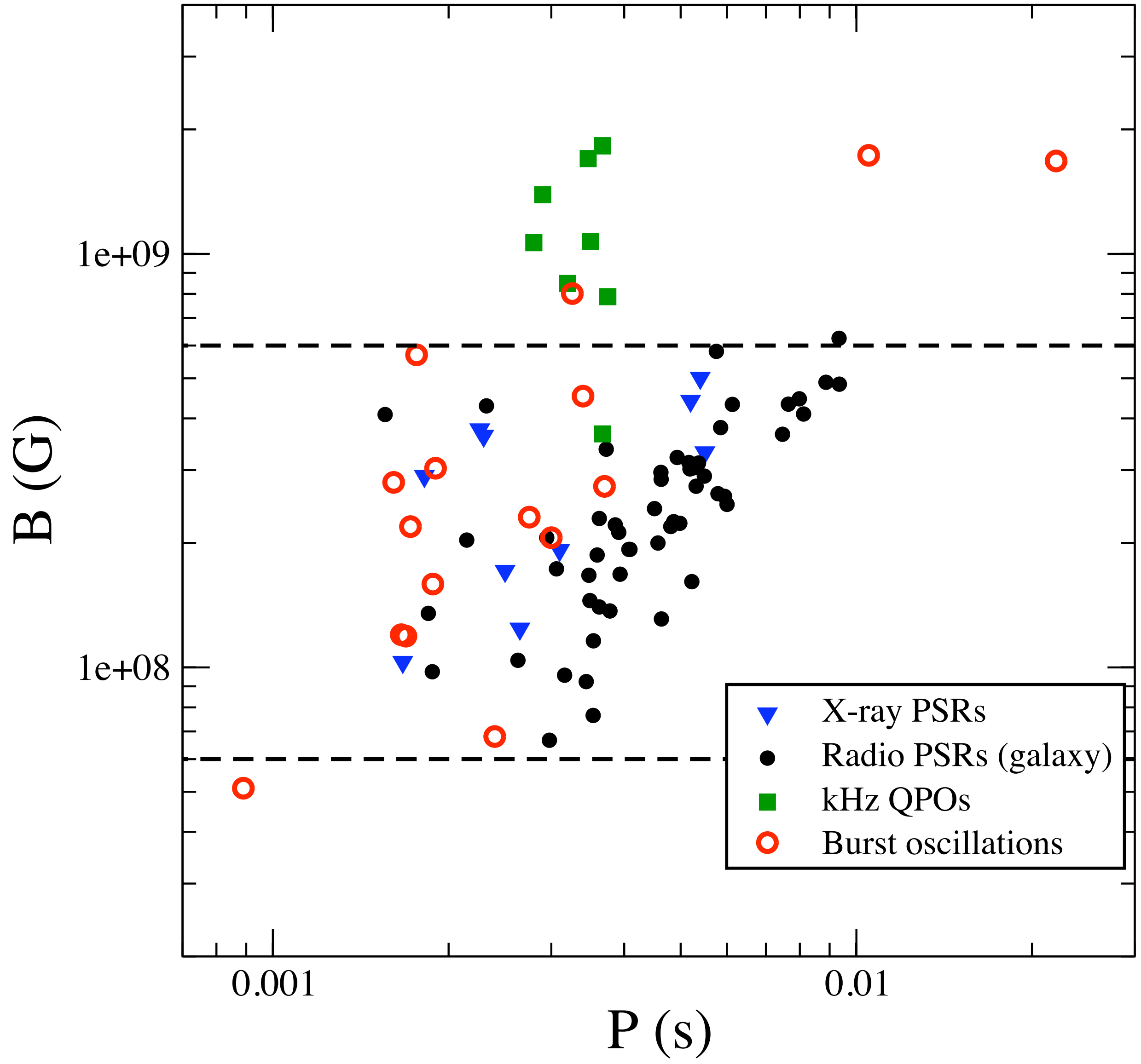
- r-mode generically unstable to GW emission
- Emission at $\omega \approx \frac{4}{3}\Omega$
- Viscosity damps the mode except in a narrow window of temperatures and frequencies

Simple accretion model



- Interaction at magnetospheric radius R_0
- Accretion torque $\dot{J} = \dot{M}\sqrt{GMR_o}$
- Propeller sets spin equilibrium

The case for GWs



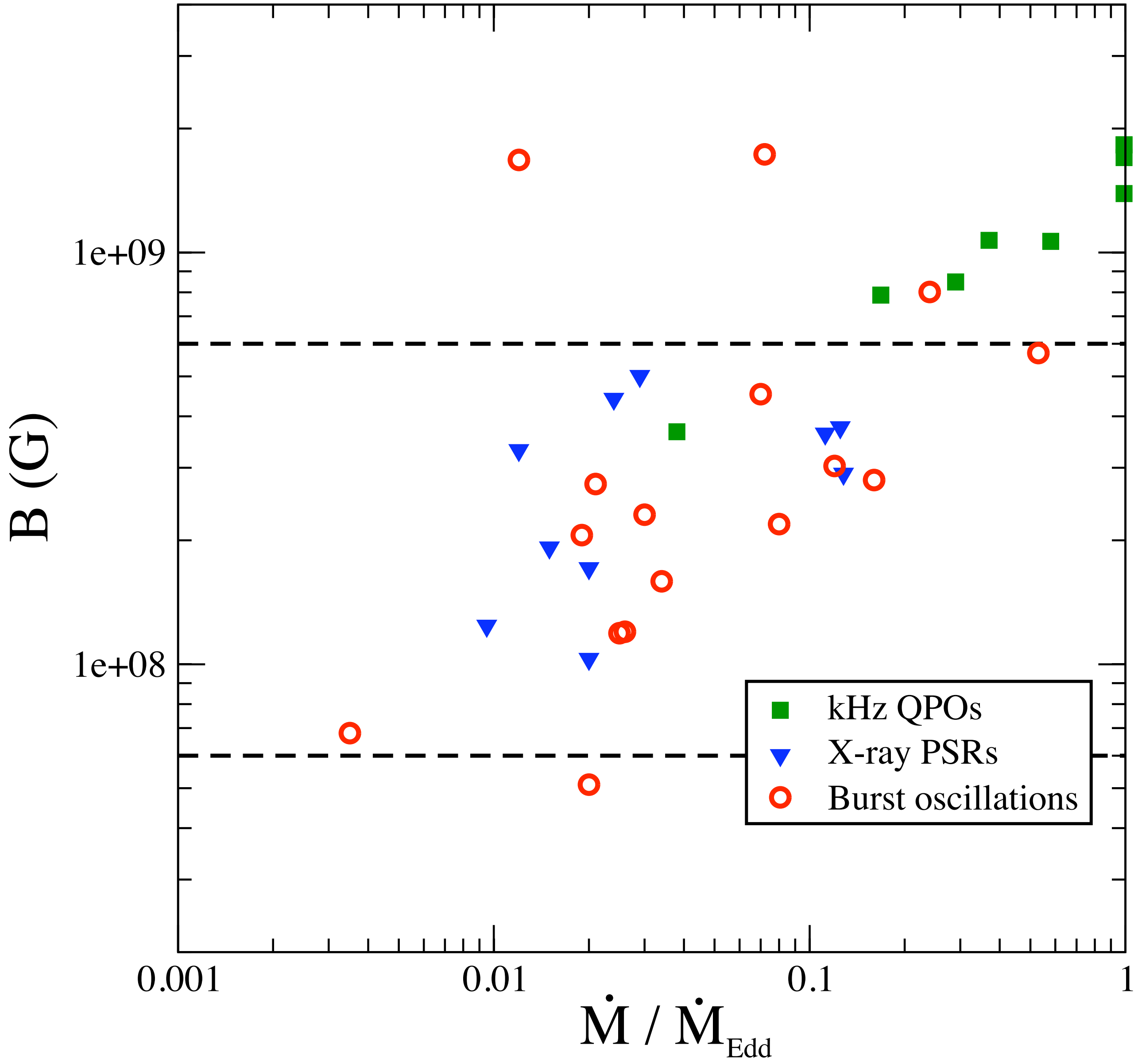
- Need extra spin-down torque
- Gravitational waves can do the job!

(Bildsten, 1998)

Mountain “size”

- Deformation needed $\epsilon \approx 10^{-7}$
- Can the star sustain such a deformation?
- What mechanisms can generate it?
- Do we really expect GW of such amplitude? (i.e. was the accretion model too simple?)

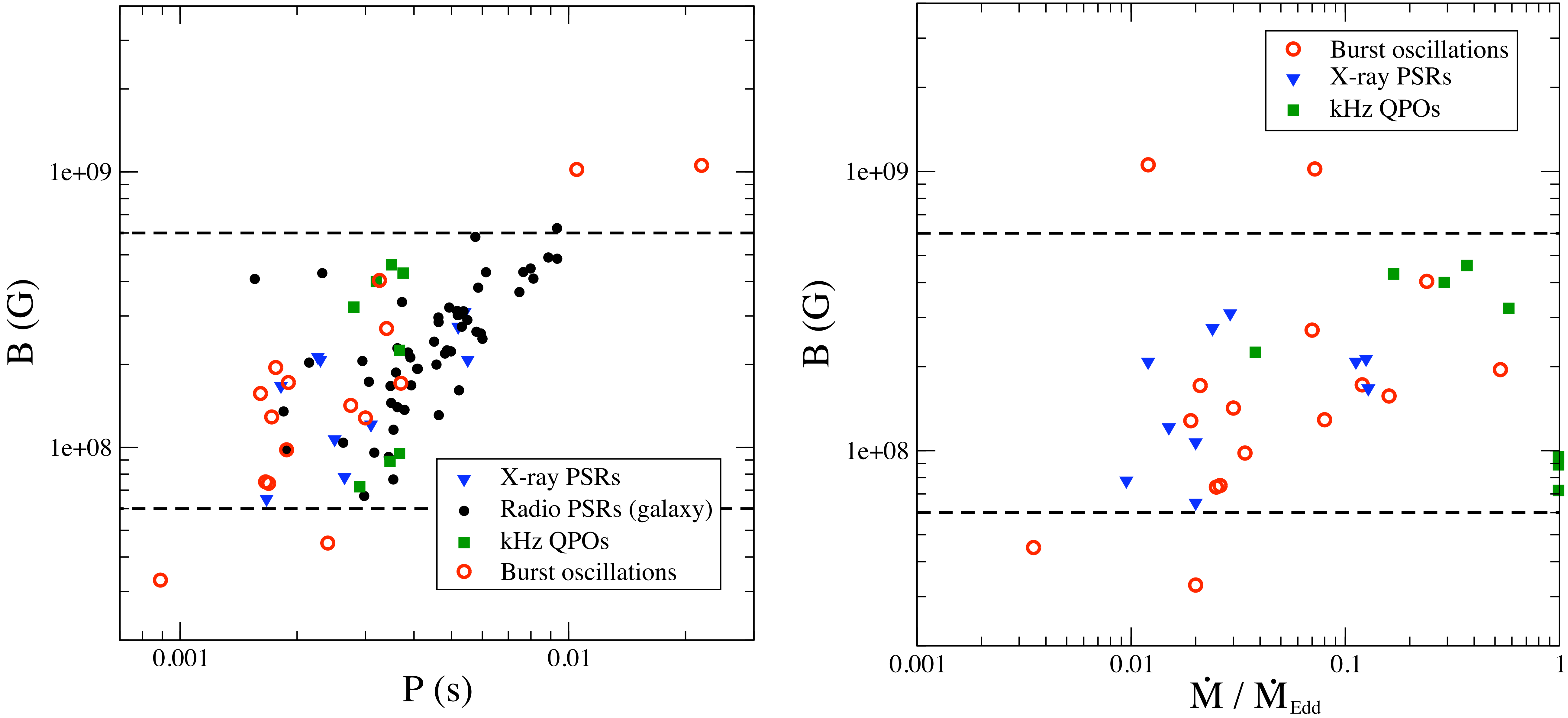
Thick disk model



- Problems at high $\dot{M}$
- Radiation pressure important at high $\dot{M}$
- Leads to thick sub-Keplerian disk
- Use phenomenological model

(Andersson, Glampedakis, BH, Watts 2005)

Thick disk model



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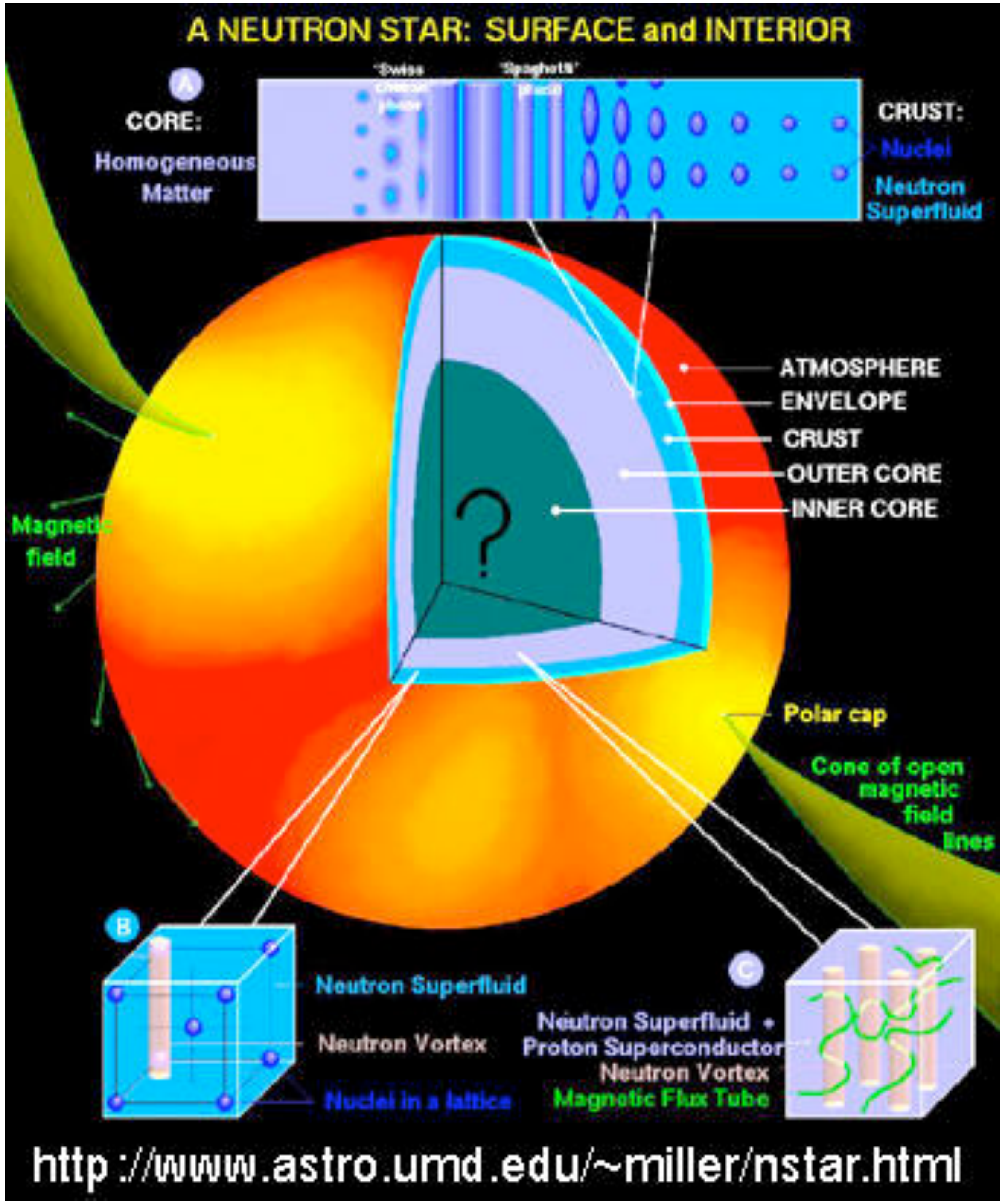
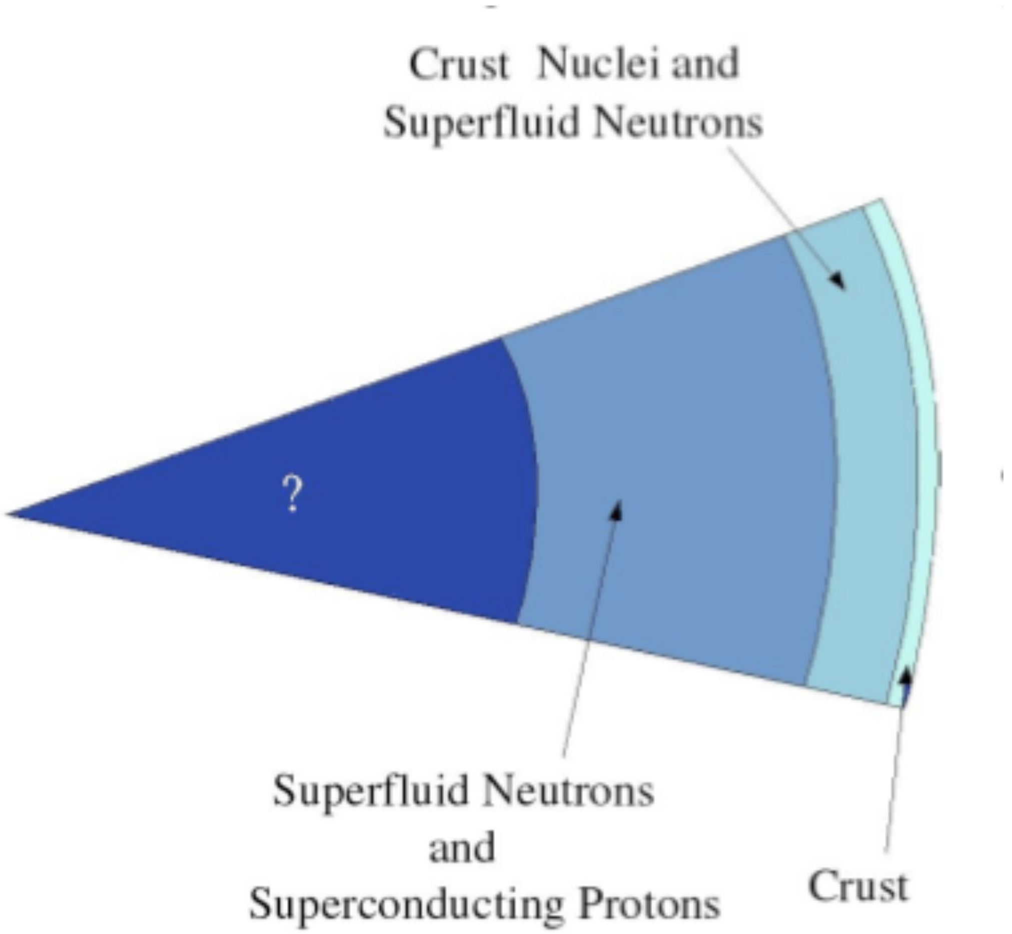
    - Understand neutron star response
    - Model emission mechanisms

Neutron star structure



http://www.astro.umd.edu/~miller/nstar.html



Mechanisms

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- Mountains
    - Crustal mountains
    - Core mountains
    - Magnetic mountains

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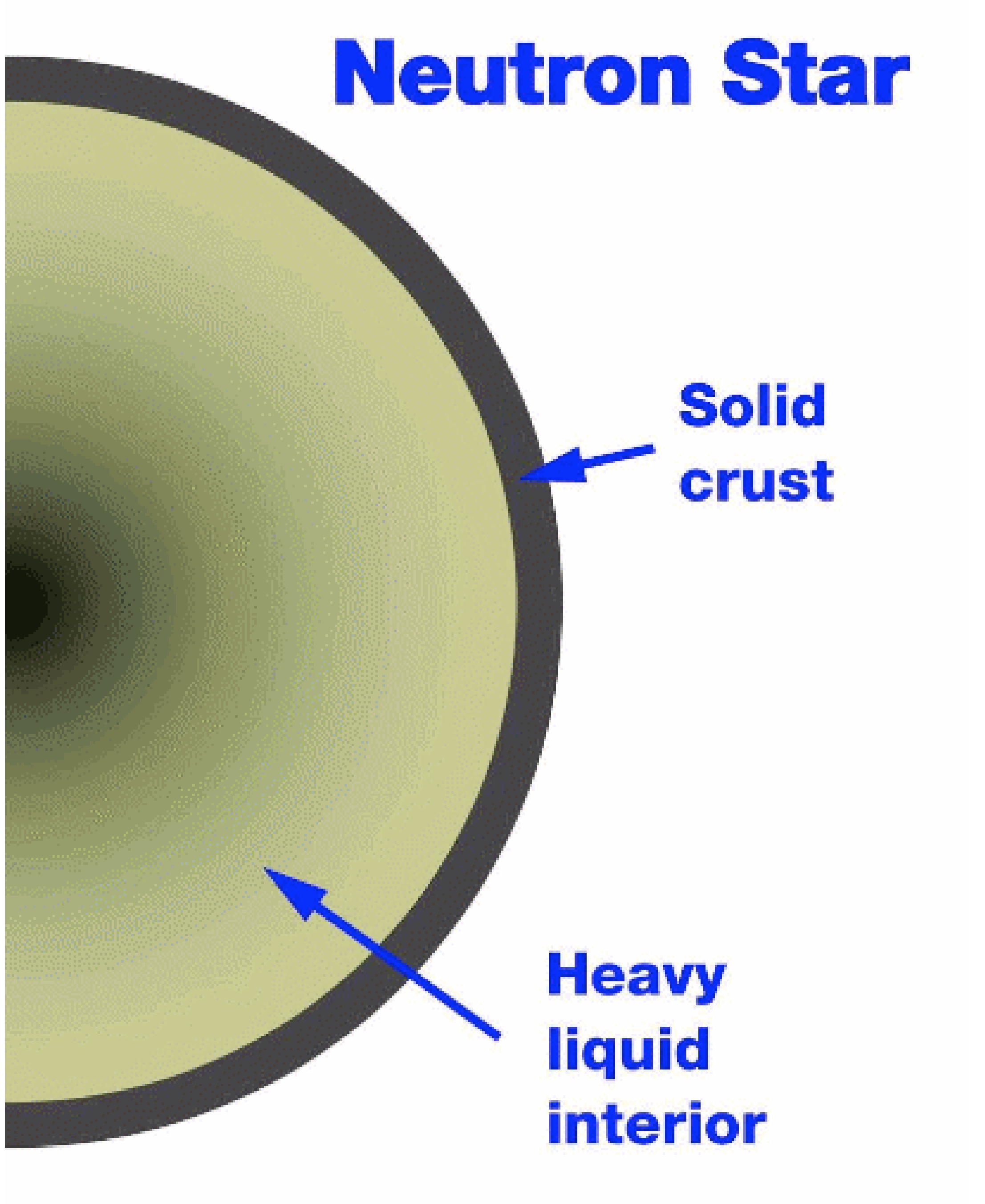
- Unstable modes
  - r-modes

Crustal mountains



- Elastic matter in the crust
- Perturb spherical background
  $$x^a \longrightarrow x^a + \xi^a$$
- $\tau_{ab} = -p g_{ab} + \mu \sigma_{ab}$
- μ depends on crustal composition (accreted or non-accreted)
- Solve $\nabla^a \tau_{ab} = -\rho \nabla_b \phi$
- Crust will crack $\bar{\sigma} > \sigma_{max}$
- $\sigma_{max} \approx 10^{-2} - 10^{-1}$

(Horowitz & Kadau 2009)

Mountain results

- Maximum deformation for an accreted crust

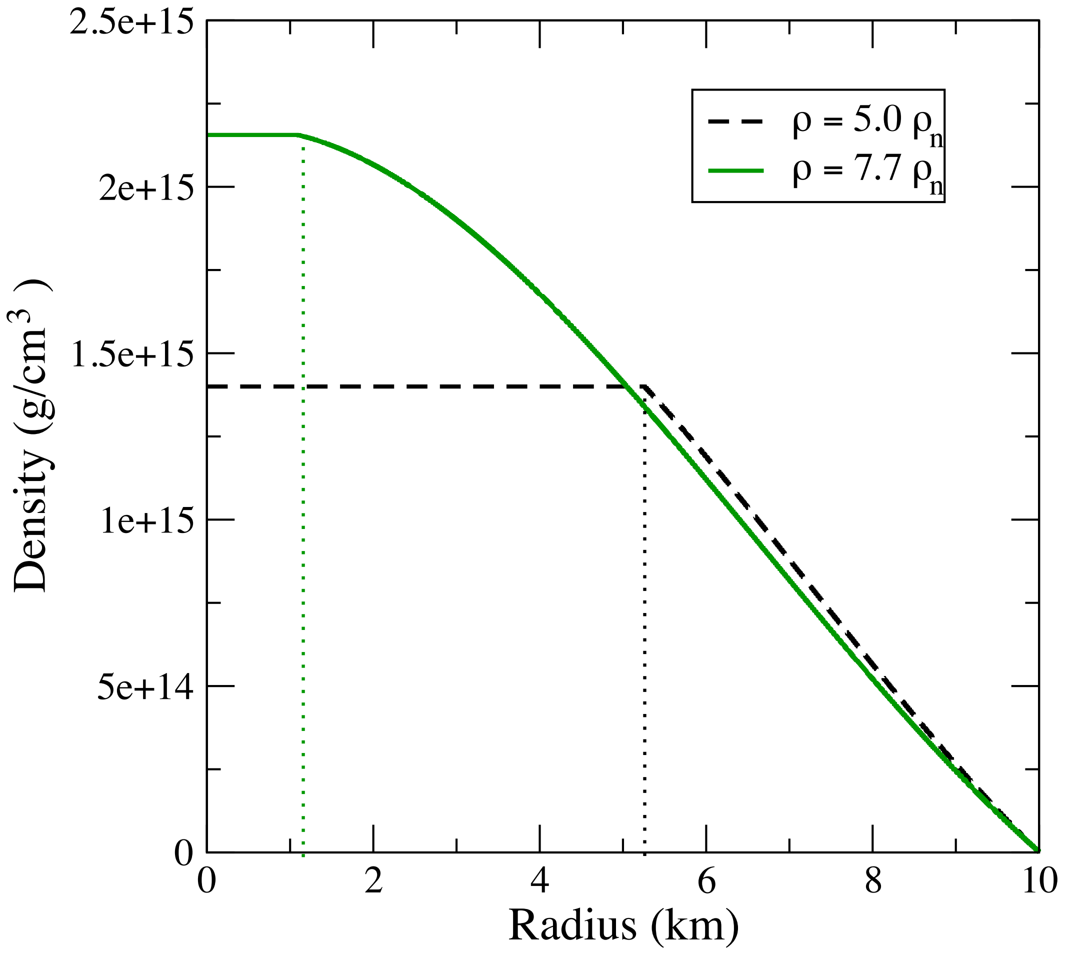
  $\epsilon \approx 10^{-6}$ (BH, Jones, Andersson, 2006)

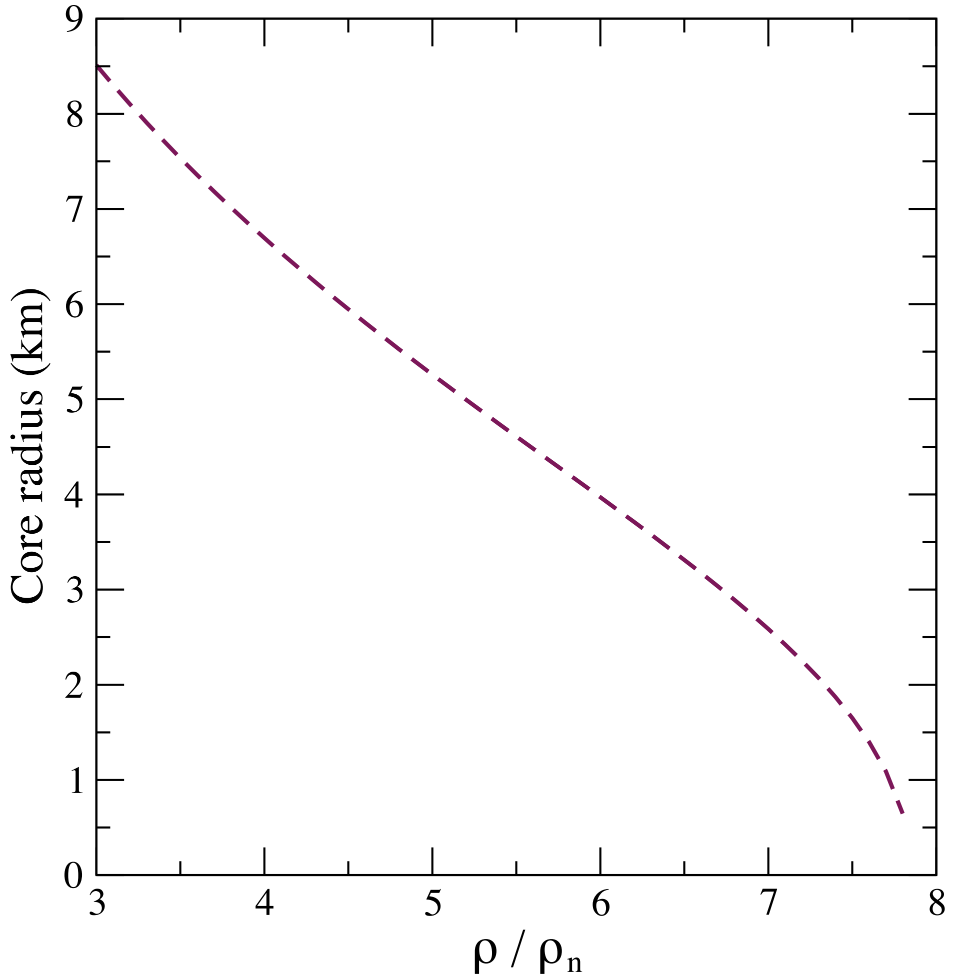
- What can produce such a deformation?
  - Non uniform temperature distribution
  - Non uniform stratification

    (Ushomirsky, Cutler, Bildsten 2000)
  - Magnus force?

- Mountains in the core?

Core mountains

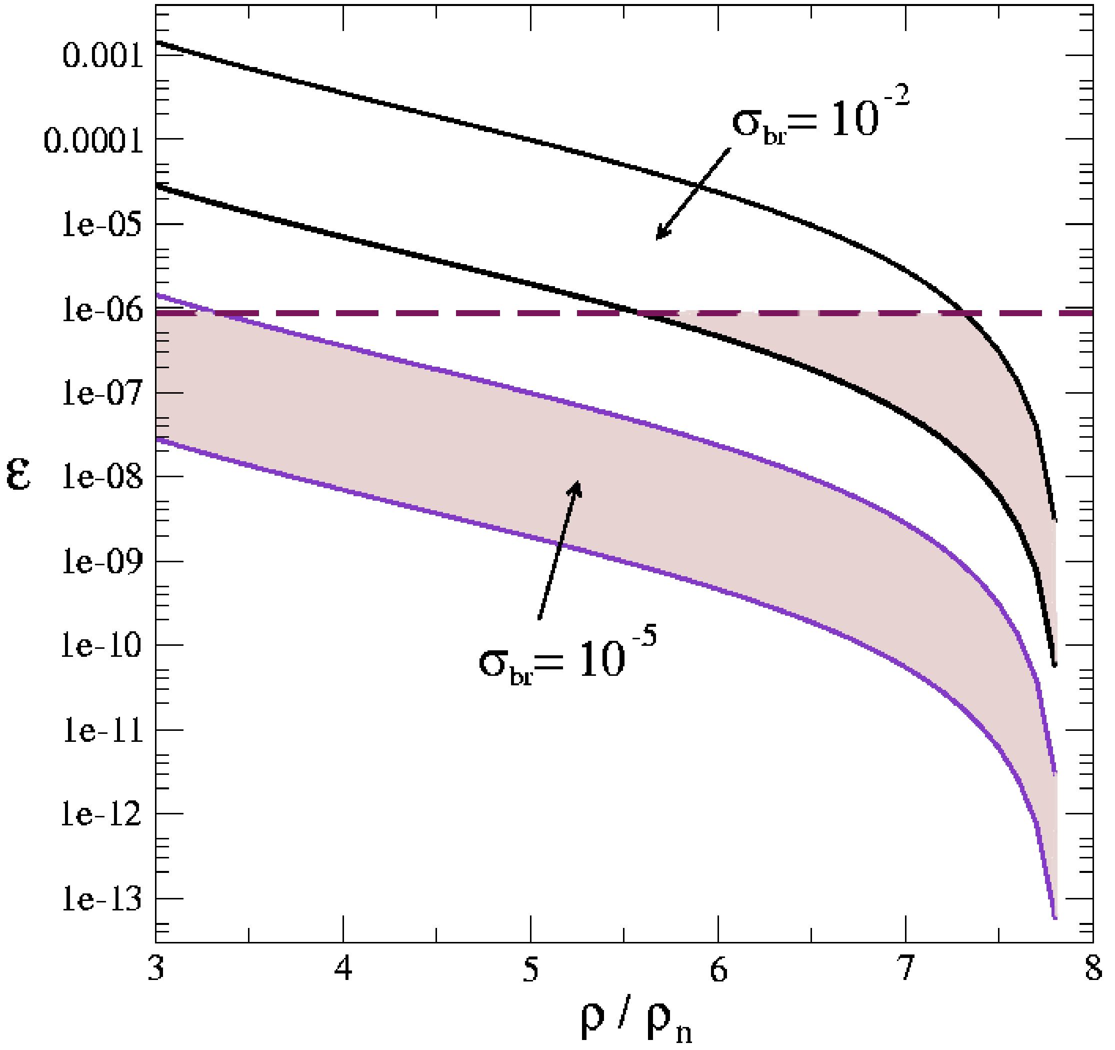




- Fluid exterior (n=1)
- Elastic core of deconfined quarks (incompressible)
- Shear modulus $\mu = 3.96 \times 10^{33} \left(\frac{\Delta}{10\mathrm{MeV}}\right)^2 \left(\frac{\mu_c}{400\mathrm{MeV}}\right)^2 \mathrm{erg/cm^2}$

(Mannarelli et al. 2007)

Core mountains



$$350 \text{ MeV} < \mu_c < 500 \text{ MeV}$$

$$5 \text{ MeV} < \Delta < 25 \text{ MeV}$$

(BH, Andersson, Jones, Samuelsson, 2007)

see also (Owen, 2005)

$$\mu = 3.96 \times 10^{33} \left(\frac{\Delta}{10\text{MeV}}\right)^2 \left(\frac{\mu_c}{400\text{MeV}}\right)^2 \text{erg/cm}^2$$

Magnetic mountains

- The shape of a magnetic star is not spherical and an oblique rotator can be a source of GWs

Poloidal field

$$\epsilon \approx 8 \times 10^{-11} \left(\frac{B}{10^{12}\ G} \right)^2$$

Star is **oblate**

Toroidal field

$$\epsilon \approx -5 \times 10^{-12} \left(\frac{B}{10^{12}\ G} \right)^2$$

Star is **prolate**

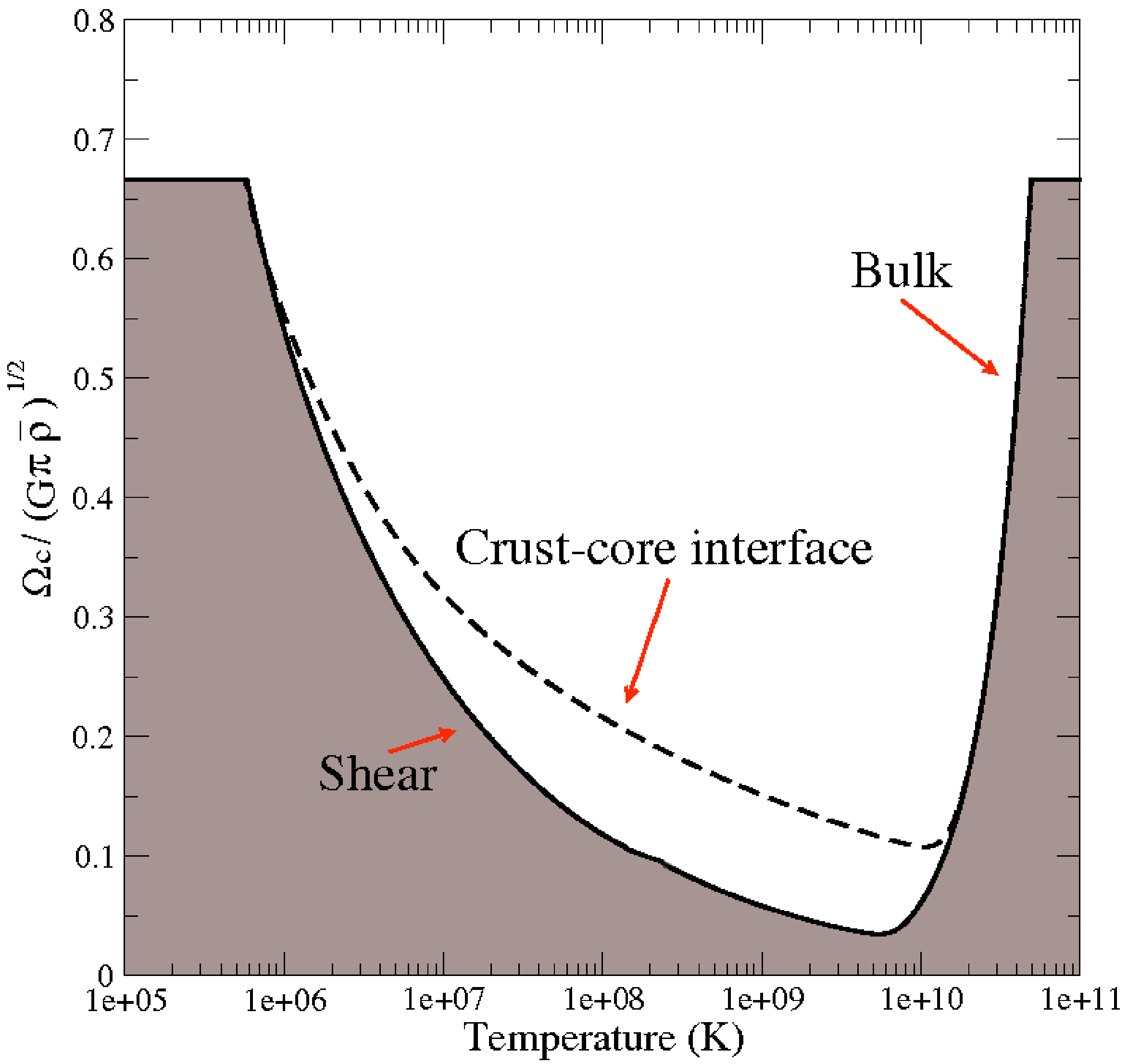
- Stars with strong toroidal fields can “flip” and become orthogonal rotators

(Cutler, 2000)

- Accretion can “compress” the field and lead to large polar mountains

(Melatos & Payne 2005)

r-mode instability window



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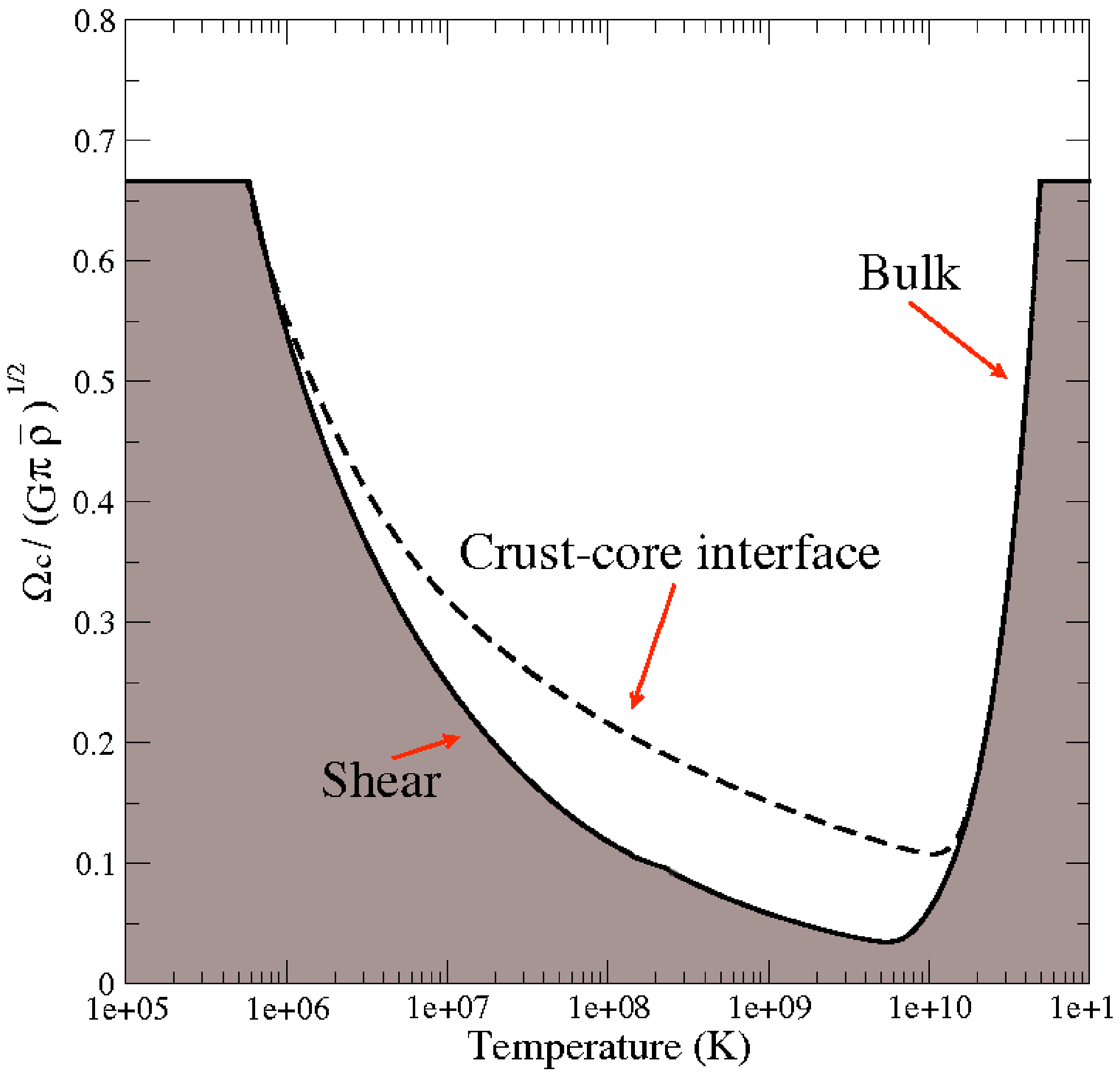
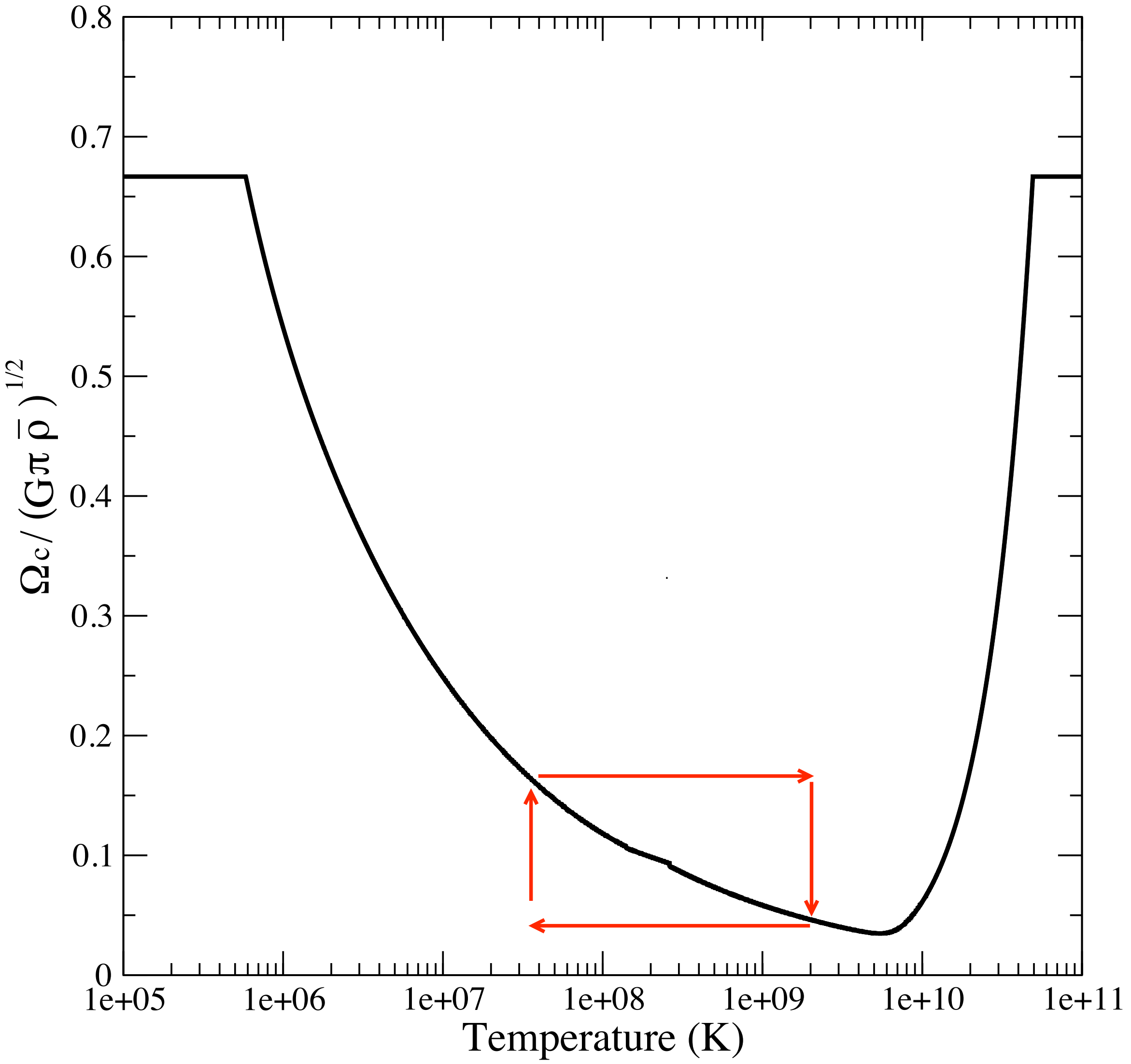
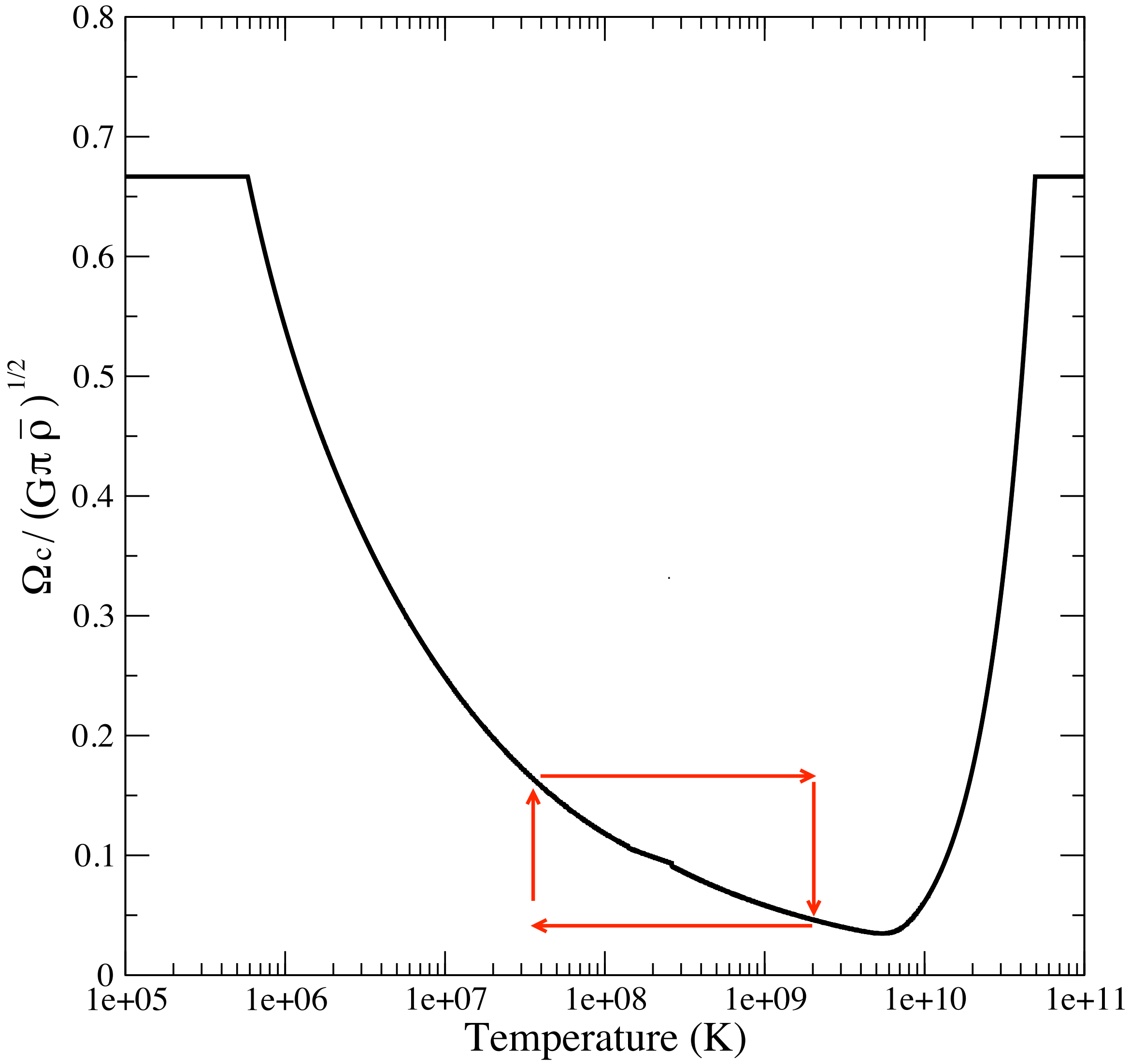




r-mode instability window

- Duty cycle short (10% or less)
- Effects of EOS? (Hyperons..)
- Effects of superfluidity?



Multifluid hydrodynamics

$$\partial_t \rho_{\rm x} + \nabla_i(\rho_{\rm x} v^i_{\rm x}) = 0$$

$$(\partial_t + v^j_{\rm x}\nabla_j)(v^{\rm x}_i + \varepsilon_{\rm x} w^{\rm yx}_i) + \nabla_i(\tilde{\mu}_{\rm x} + \Phi) + \varepsilon_{\rm x} w^j_{\rm yx}\nabla_i v^{\rm x}_j = f^{\rm x}_i/\rho_{\rm x} + \nabla_j D^j_i$$

D^j_i

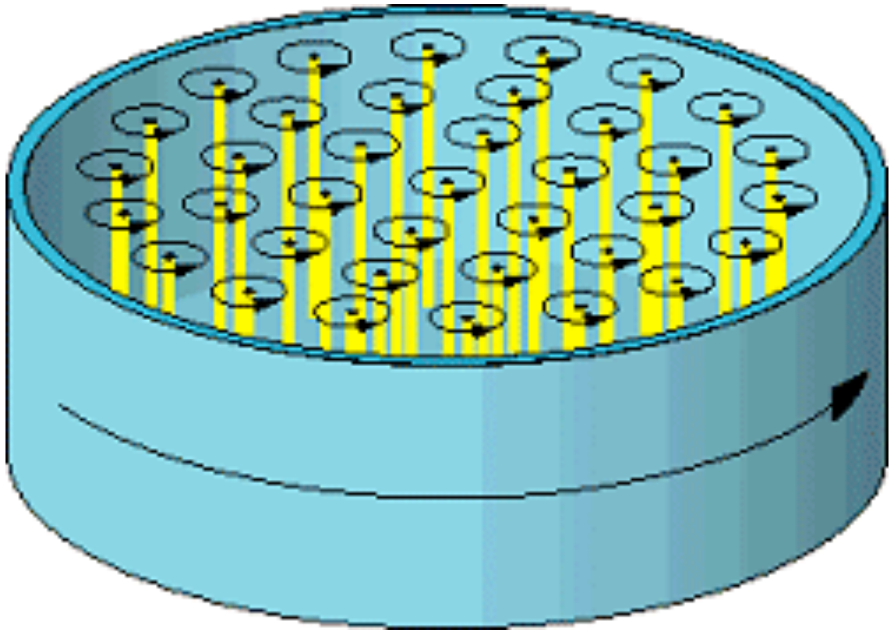
Dissipative terms (bulk viscosity, shear viscosity, etc..)

$$f^{\rm x}_i = 2\rho_{\rm n}\mathcal{B}'\epsilon_{ijk}\Omega^j w^k_{\rm xy} + 2\rho_{\rm n}\mathcal{B}\epsilon_{ijk}\hat{\Omega}^j\epsilon^{klm}\Omega_l w^{\rm xy}_m$$

Mutual Friction

Mutual friction

- Superfluid rotates by forming quantised vortices



- In the core entrained protons give rise to a magnetic field along the vortex lines
- Electrons scatter dissipatively off vortices
- Vortices could be strongly pinned in the crust

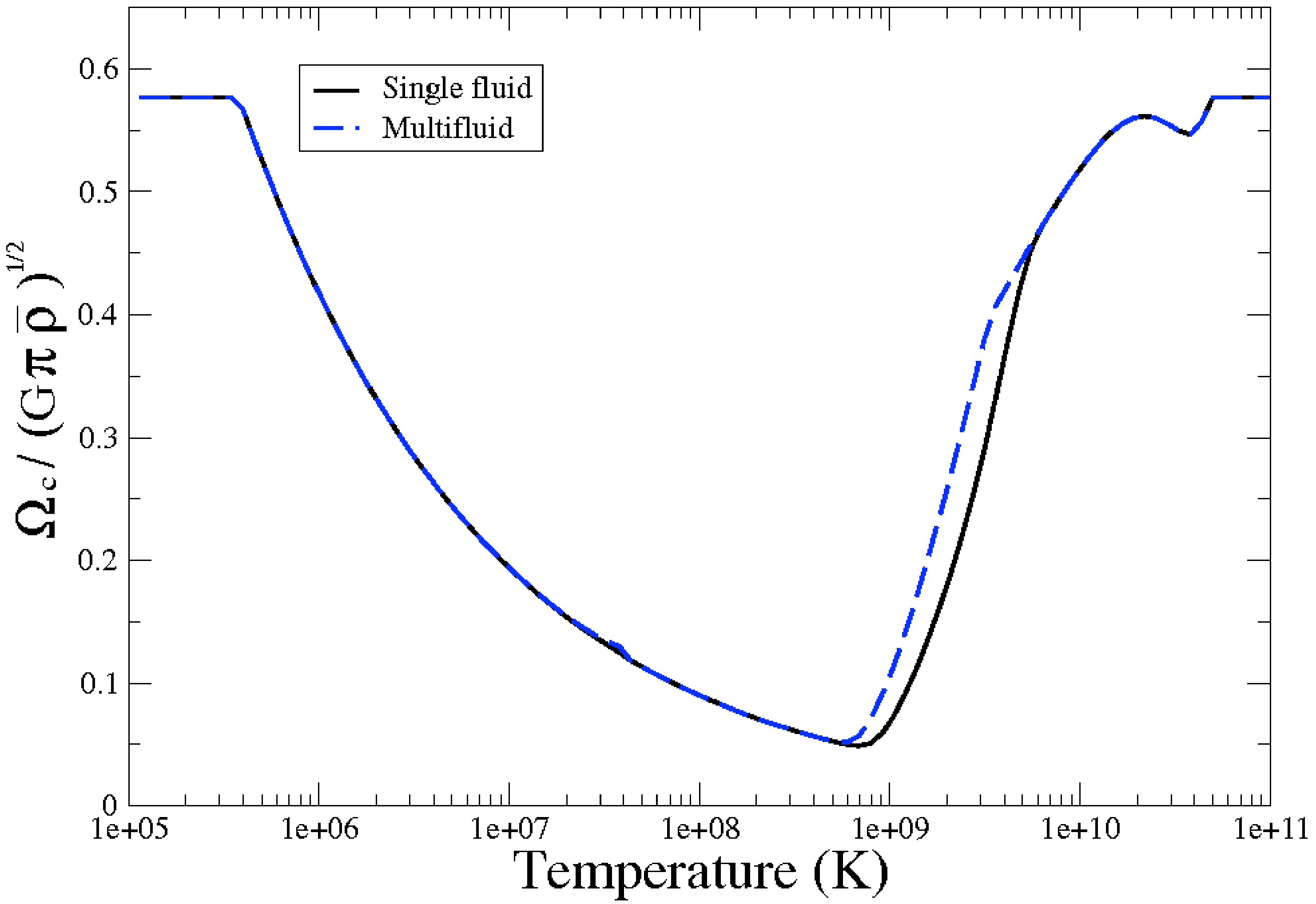
Superfluid r-mode

- Frequency the same as barotropic r-mode to $\mathcal{O}(\Omega^3)$
- Countermoving motion driven at higher order
- Leads to mutual friction damping and new dissipation coefficients

Hyperon bulk viscosity

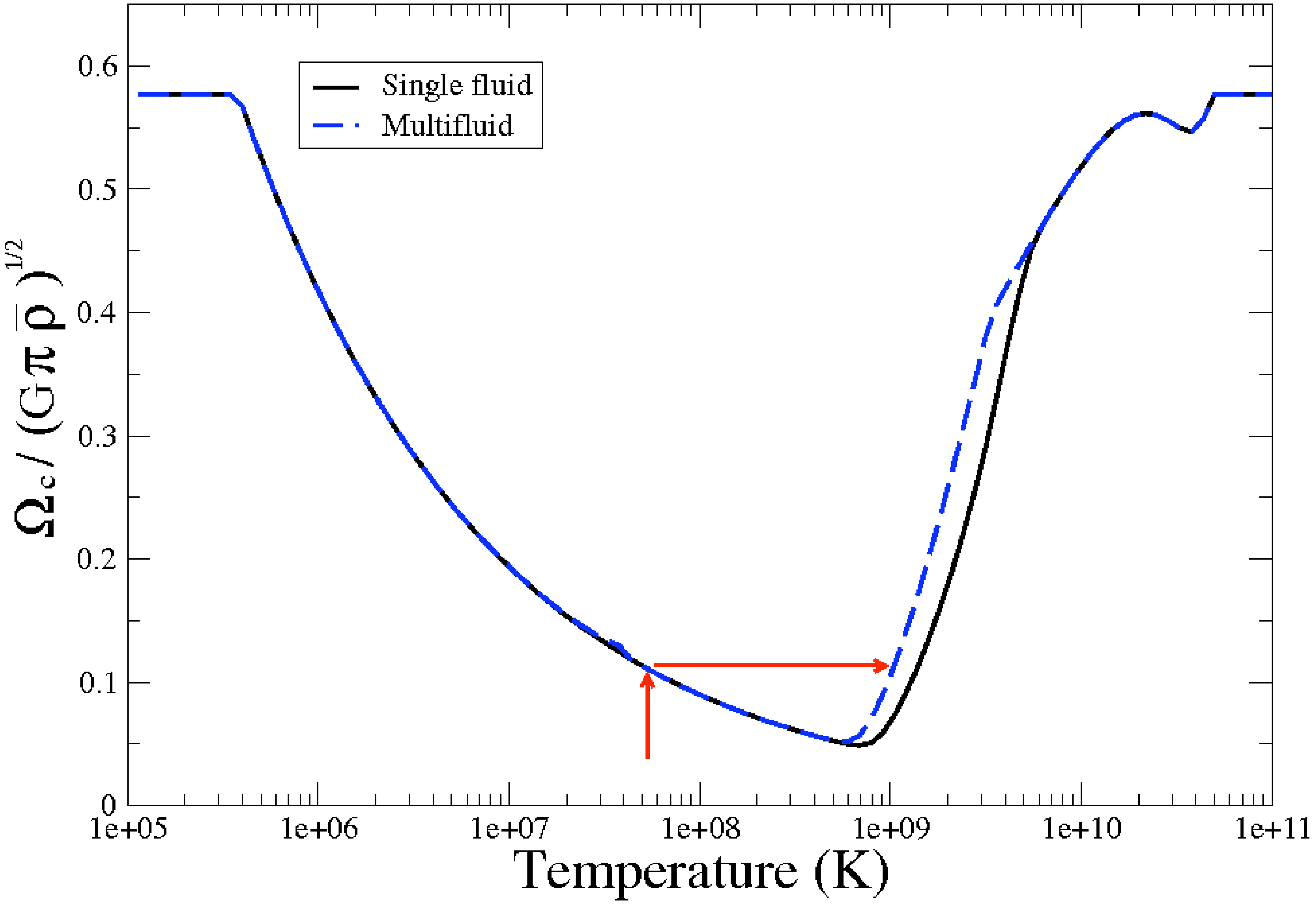
- Consider a fluid of neutrons, protons, electrons, Σ^-
- Most likely to be superfluid
  - New bulk viscosity coefficients
  - In most simple case (low T, charged components locked): 3 bulk, 1 shear

Hyperon bulk viscosity



Single fluid: Nayyar & Owen 2006, Haensel et al. 2002
Multifluid: Haskell et al. (in preparation)

Hyperon bulk viscosity



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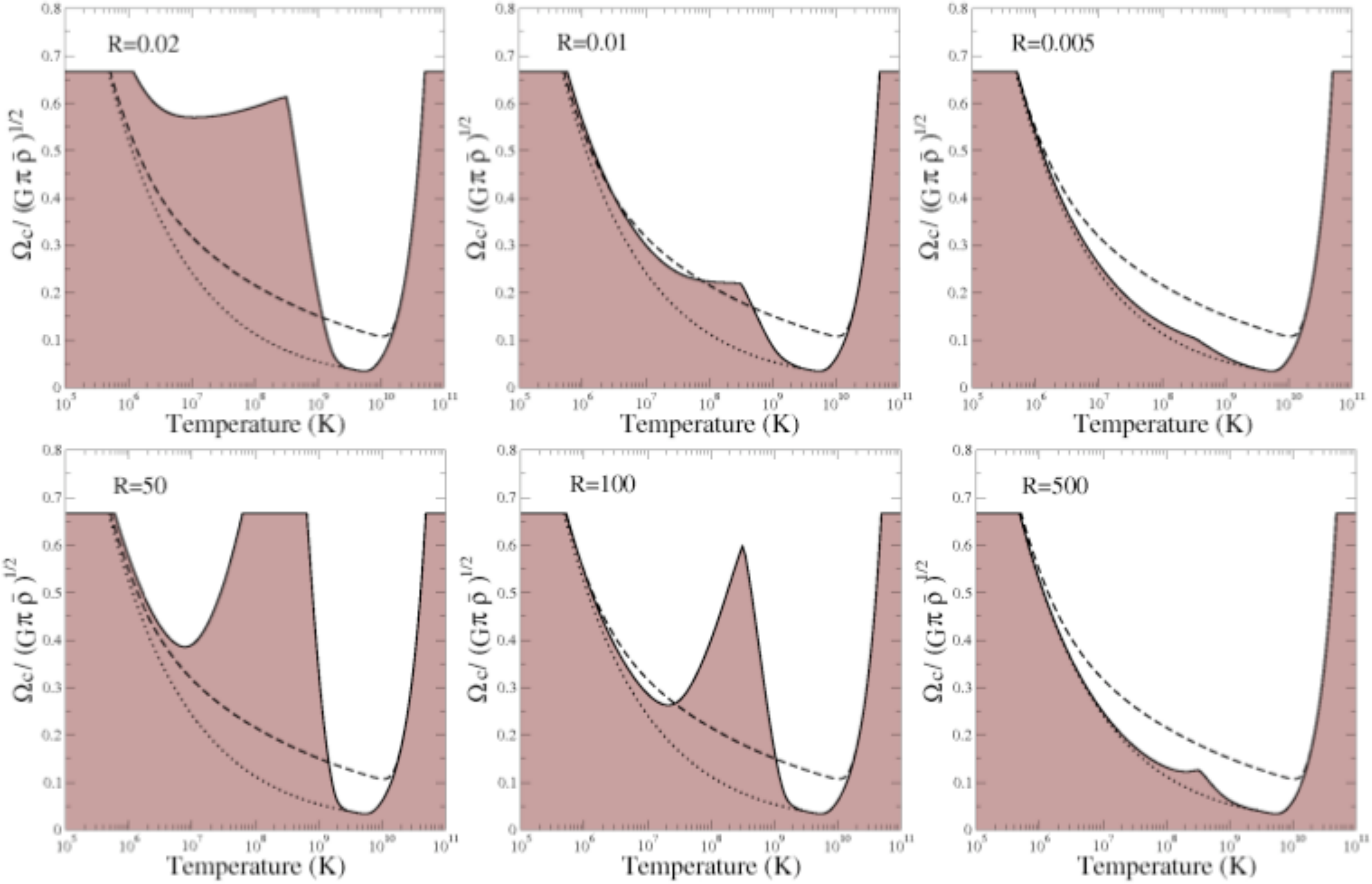
Mutual friction



(BH, Andersson, Passamonti, 2009)

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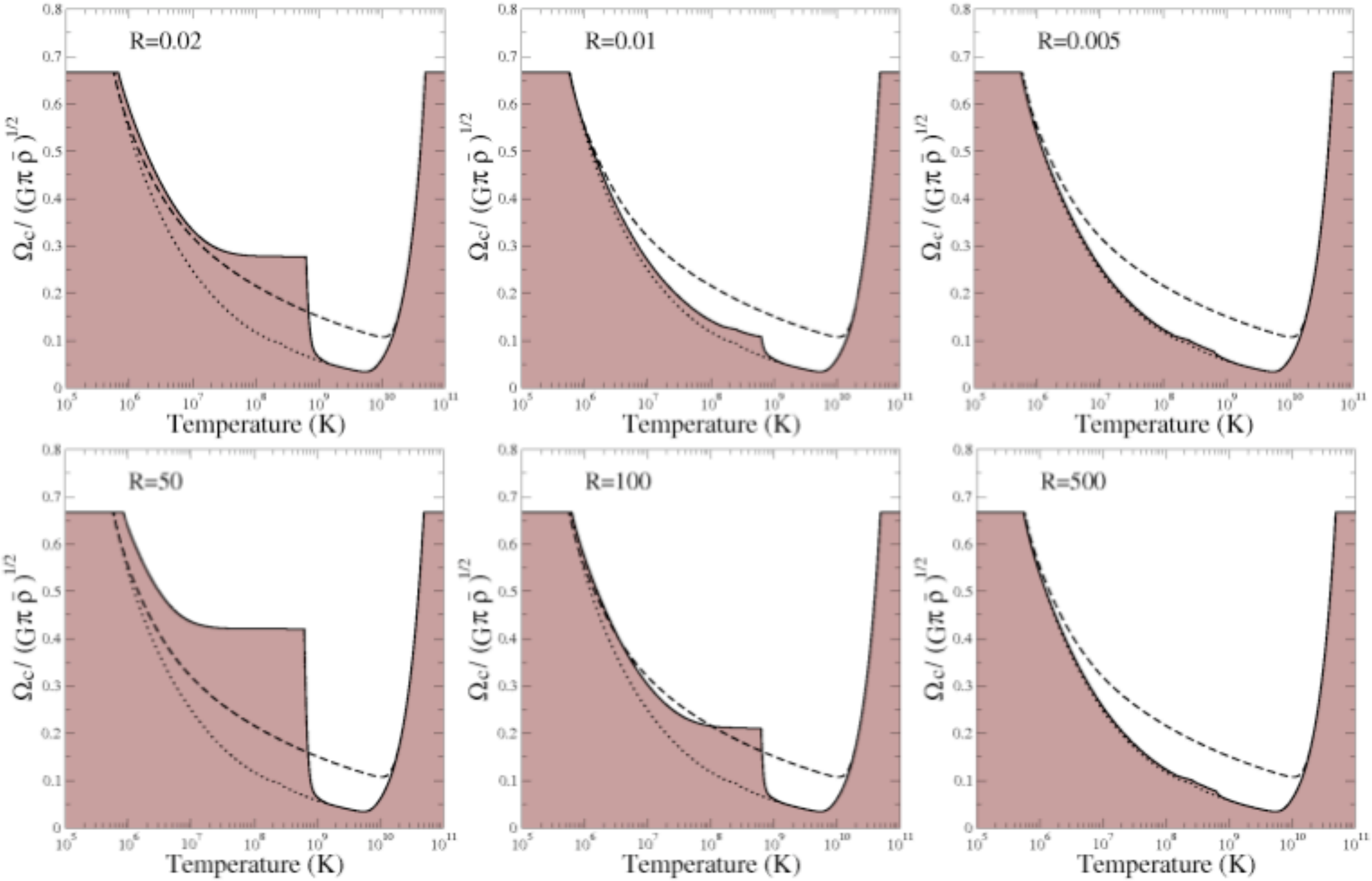

(BH, Andersson, Passamonti, 2009)

Conclusions

- More input needed for detection
- Observational input: spins (also theoretical)
- Theoretical input:
    - External torque variations
    - Neutron star response
    - Realistic mountain scenarios
    - Dissipation mechanisms