What can X-ray observations tell us about:

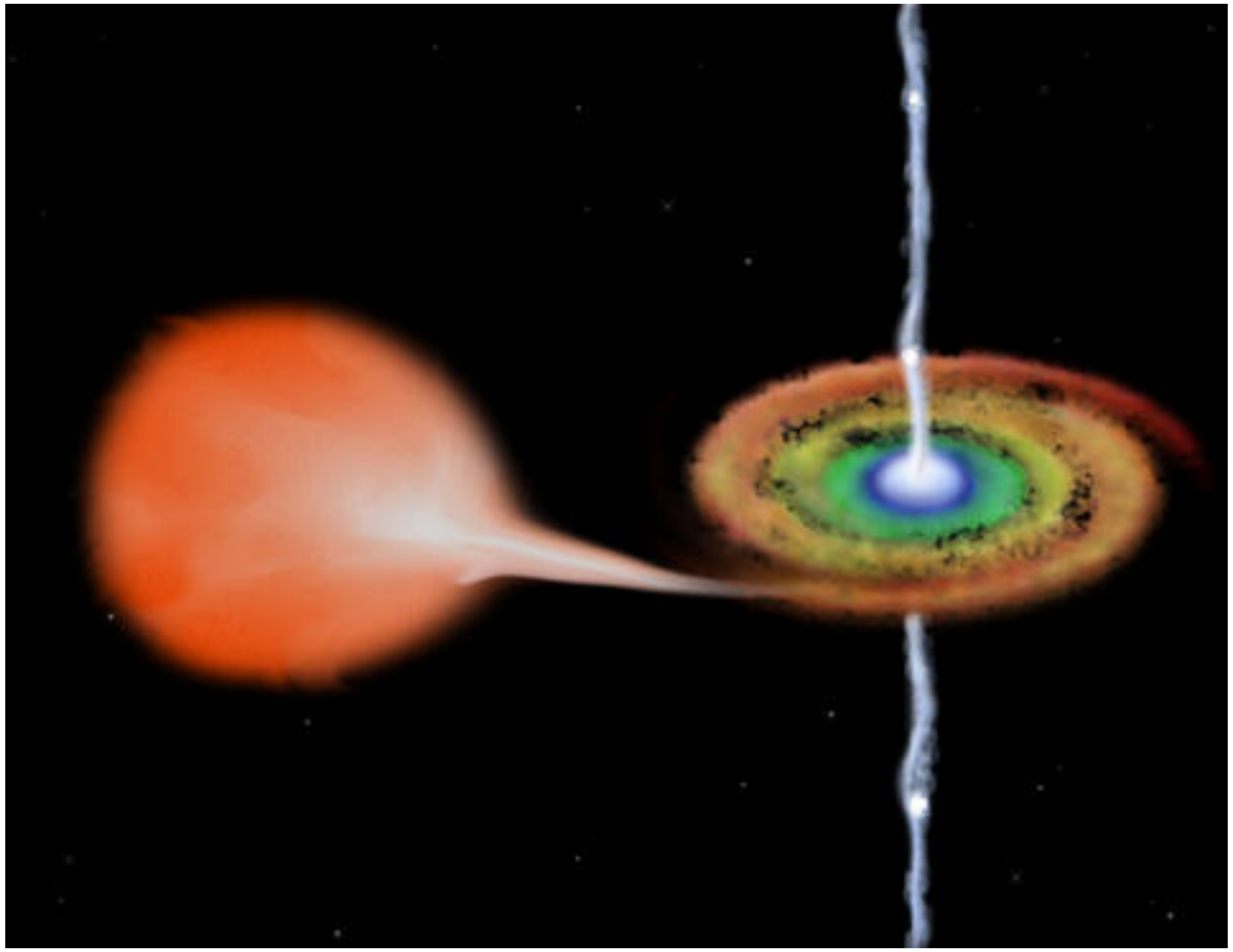
The role of Gravitational Waves in Low Mass X-ray Binaries

Brynmor Haskell

Astronomical Institute "Anton Pannekoek"

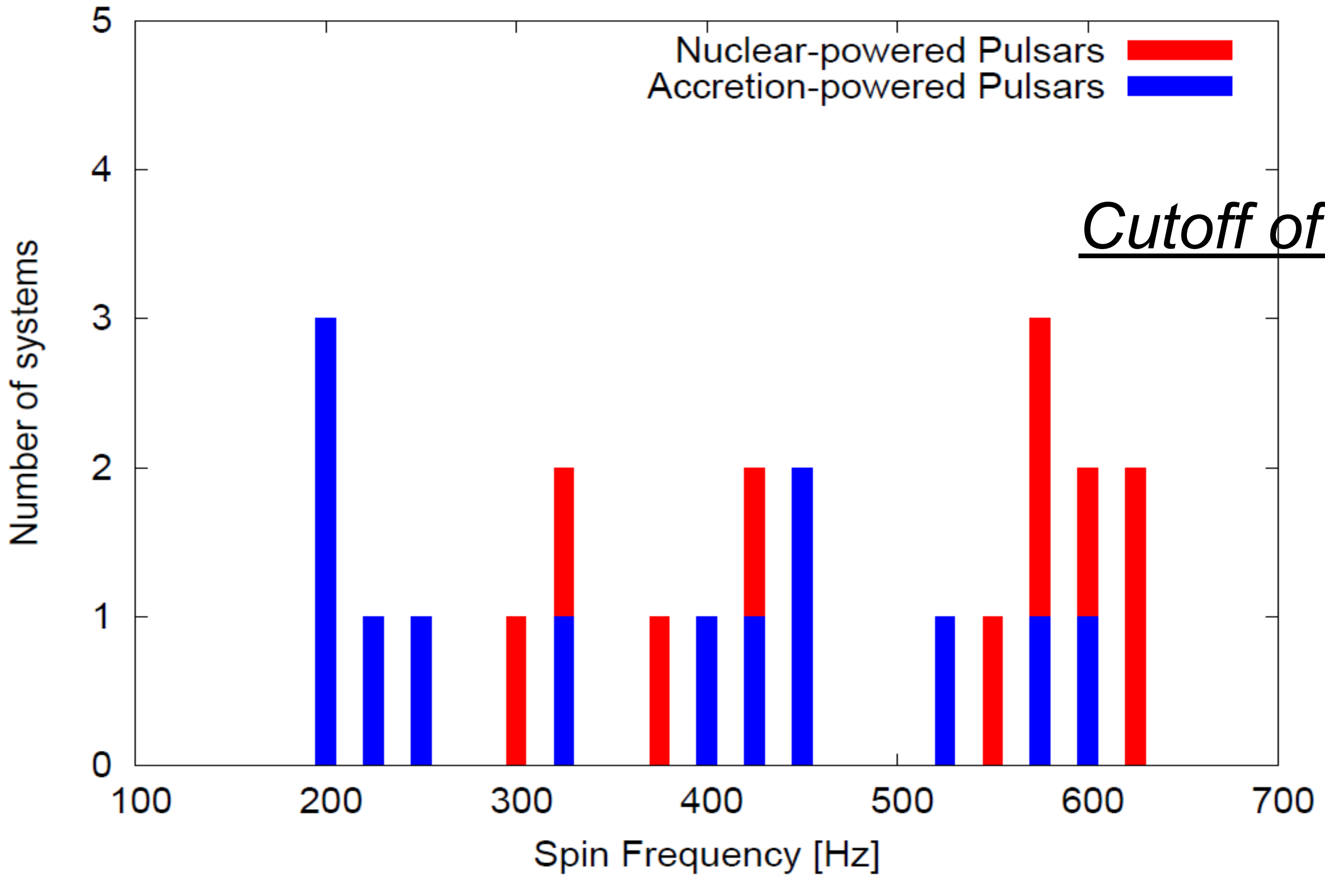
UNIVERSITEIT VAN AMSTERDAM

Low Mass X-ray Binaries



- Mass is stripped from the donor
- Forms a disc and spirals in
- Interacts with the magnetic field
- Transfers angular momentum to the central NS, spinning it up

GWs from LMXBs

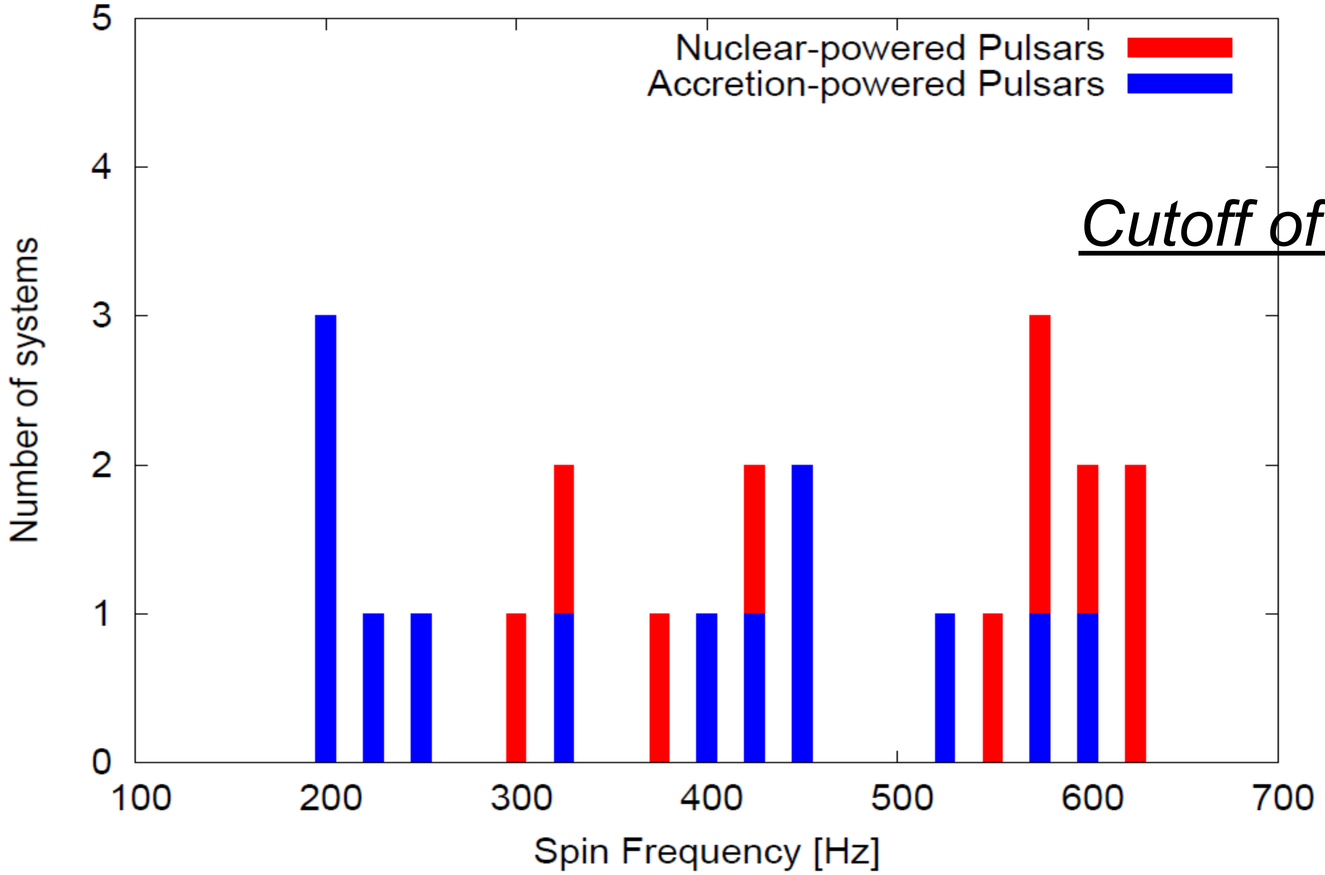


Cutoff of distribution at ~730 Hz

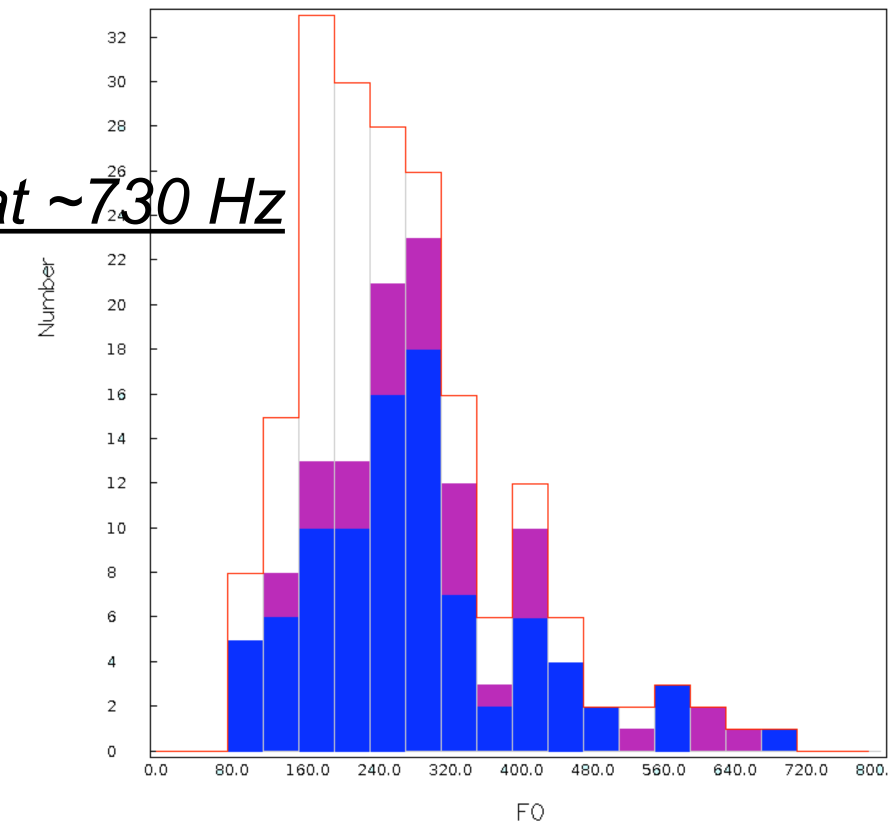
(Chakrabarty et al 2003, Patruno 2010)

- LMXB spin distribution points to a mechanism that halts the spin-up before the break up limit.
- GWs!: "mountains", unstable modes, magnetic deformations.. (Papaloizou & Pringle 1978, Wagoner 1984, Bildsten 1998)

GWs from LMXBs



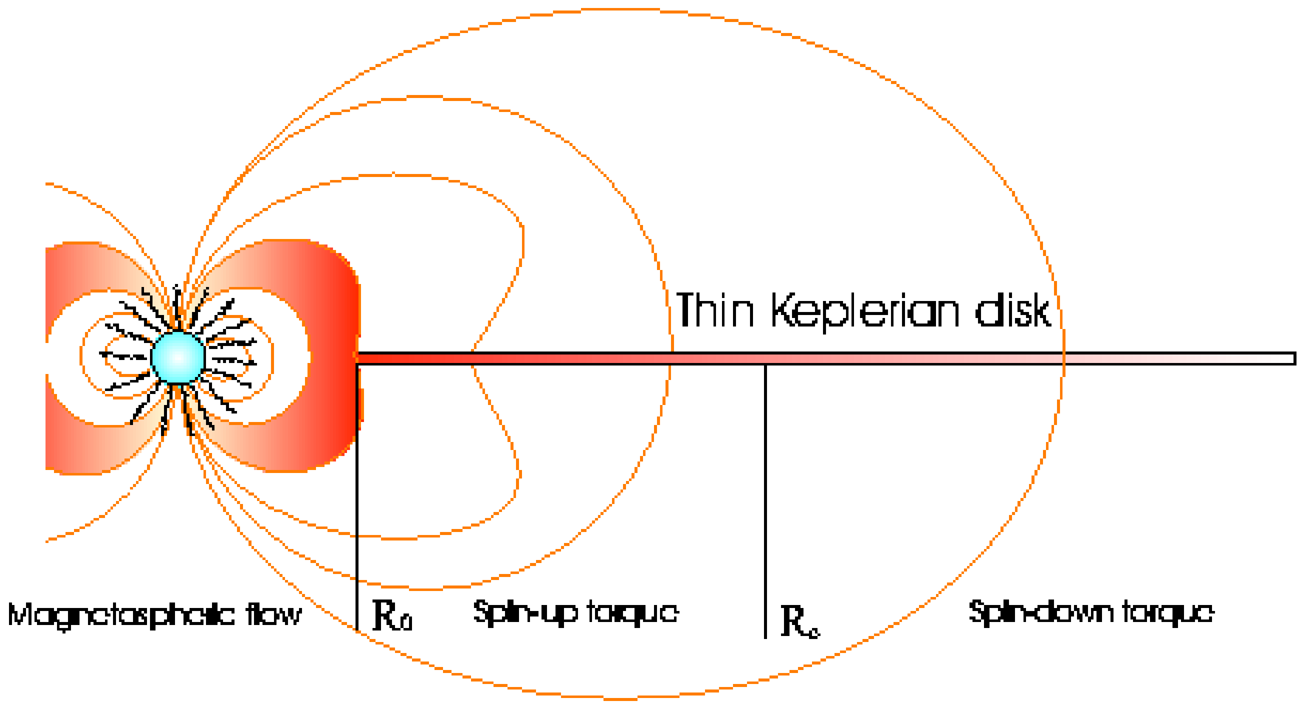
Cutoff of distribution at ~730 Hz



(Chakrabarty et al 2003, Patruno 2010)

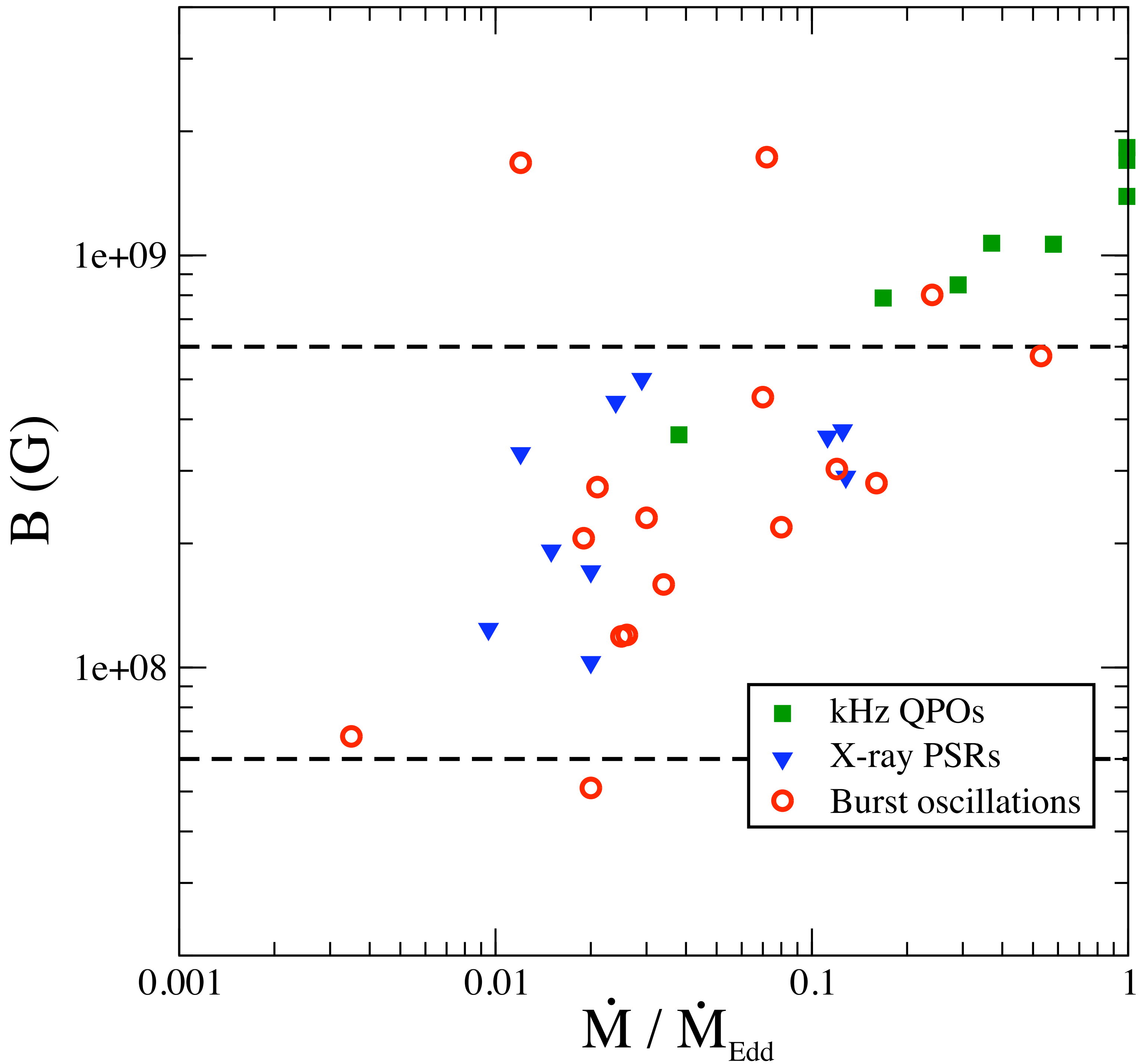
- LMXB spin distribution points to a mechanism that halts the spin-up before the break up limit.
- GWs!: "mountains", unstable modes, magnetic deformations.. (Papaloizou & Pringle 1978, Wagoner 1984, Bildsten 1998)

Spin equilibrium?



- Interaction at magnetospheric radius
- Accretion torque: spin up
- Magnetic torques and propeller: spin down

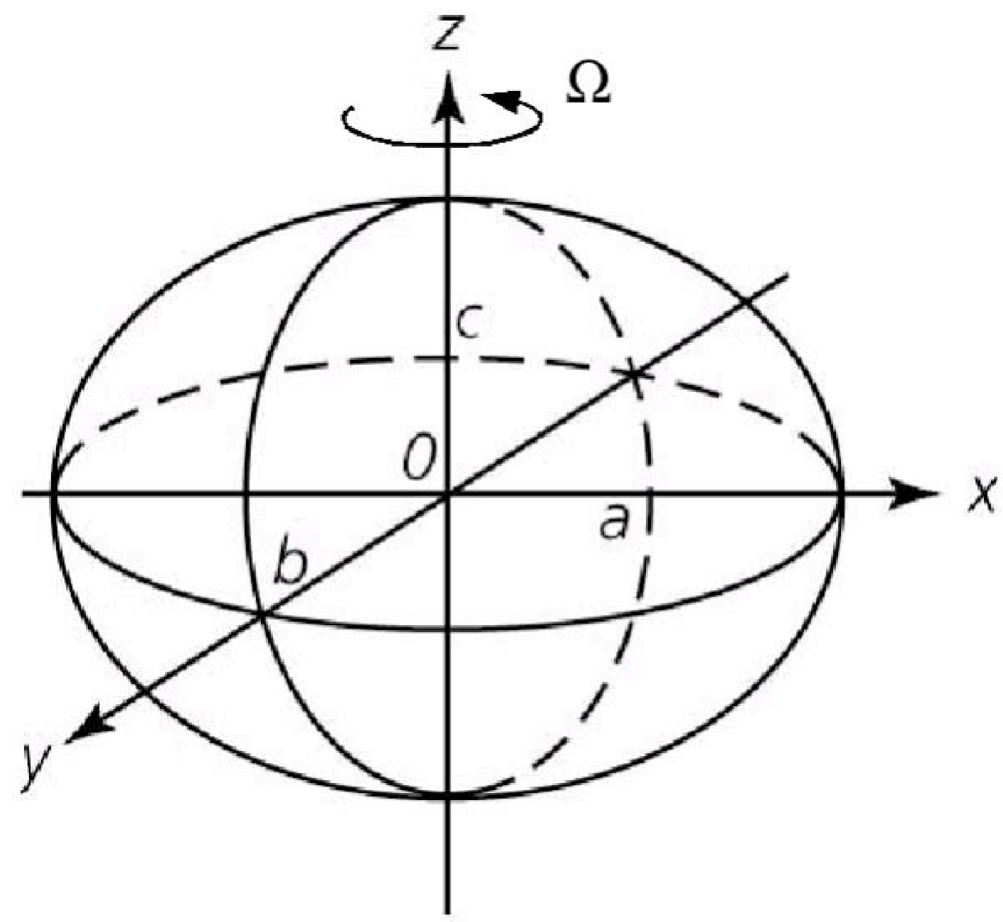
Spin equilibrium?



(White & Zhang 1997)

Neutron star mountains

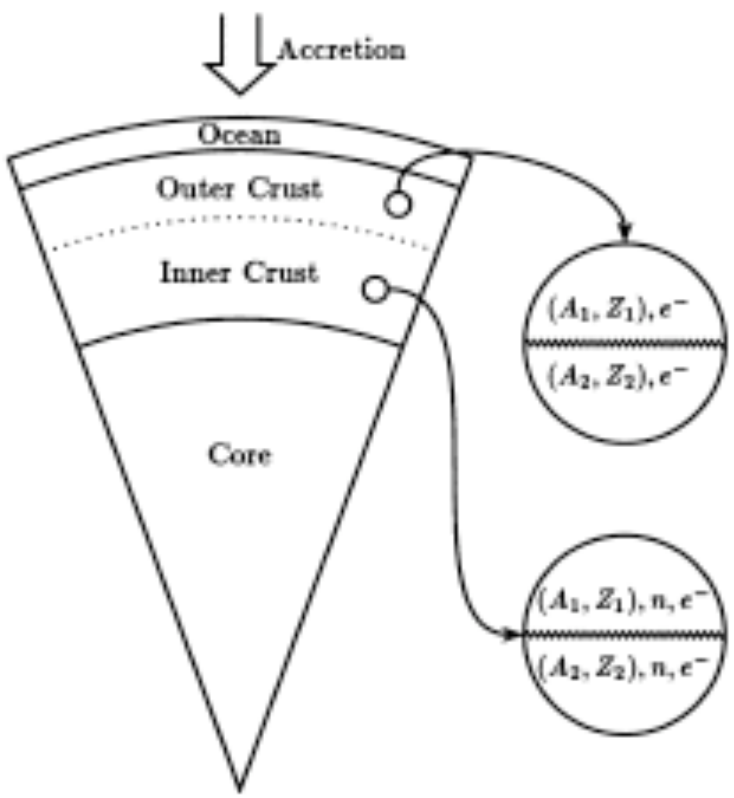
- $$\epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$
- Emission at $\omega = 2\Omega$
- $$\frac{dE}{dt} \approx \epsilon^2 \Omega^6$$

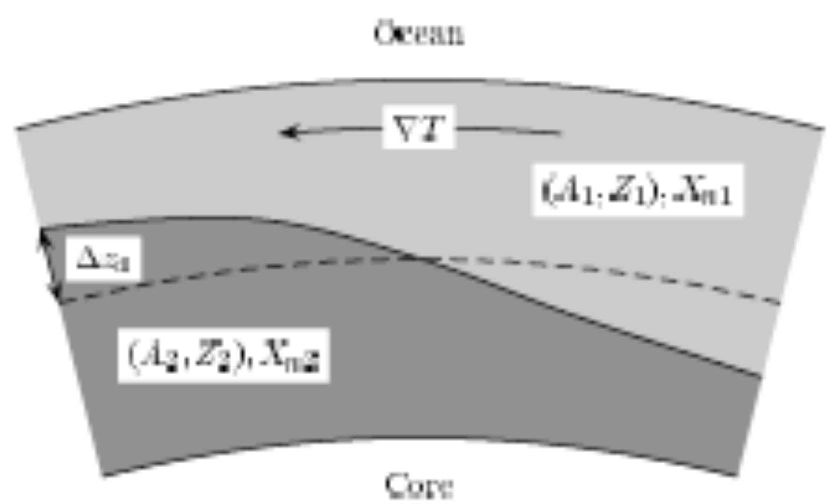


- Theoretical upper limit $\epsilon \approx 10^{-6}$ (Haskell, Jones, Andersson 2006)

Neutron star mountains-II

- Mountains from 'wavy' capture layers in crust

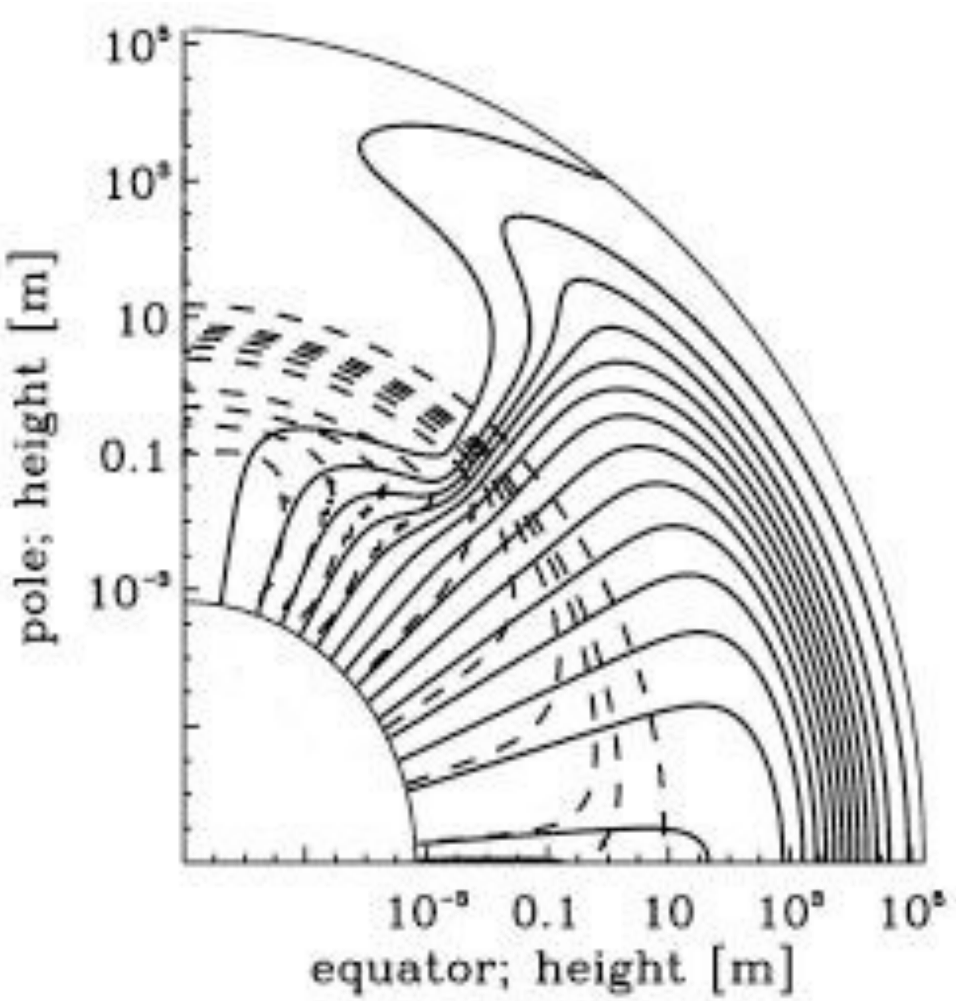




(Ushomirsky, Cutler, Bildsten 2000)

- Deep crustal heating 'consistent' with cooling observations from X-ray transients.

Magnetic mountains

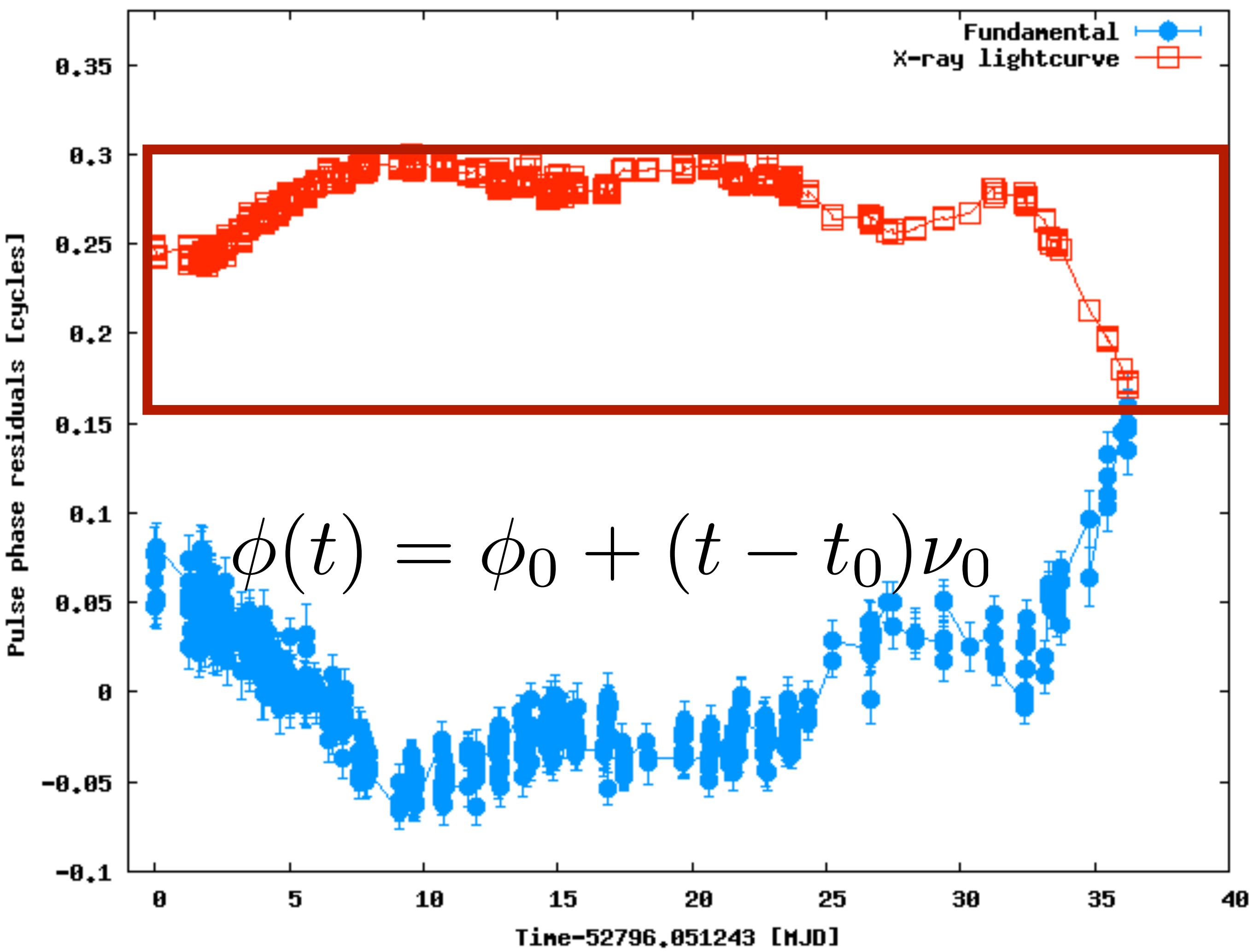


- Magnetic field distorted by the accretion flow
- Possibility of confining a 'mountain'

(Payne & Melatos 2004, Melatos and Payne 2005)

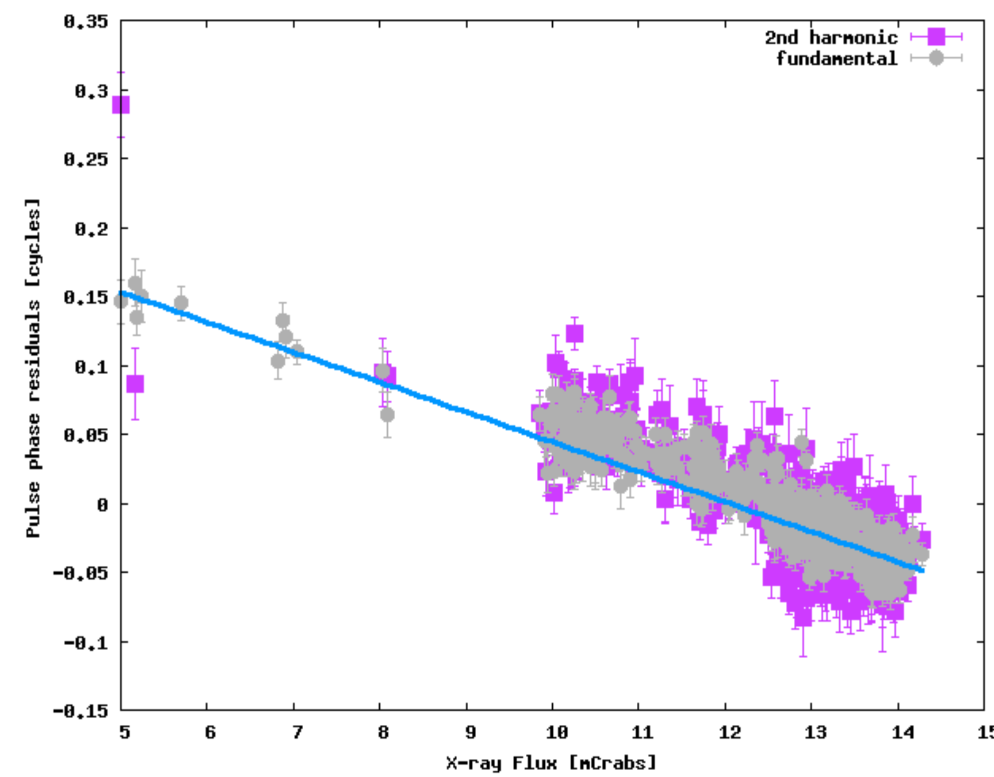
UNIVERSITEIT VAN AMSTERDAM

The strange case of XTE J1814-338 (& SAX J1808.4-3658)



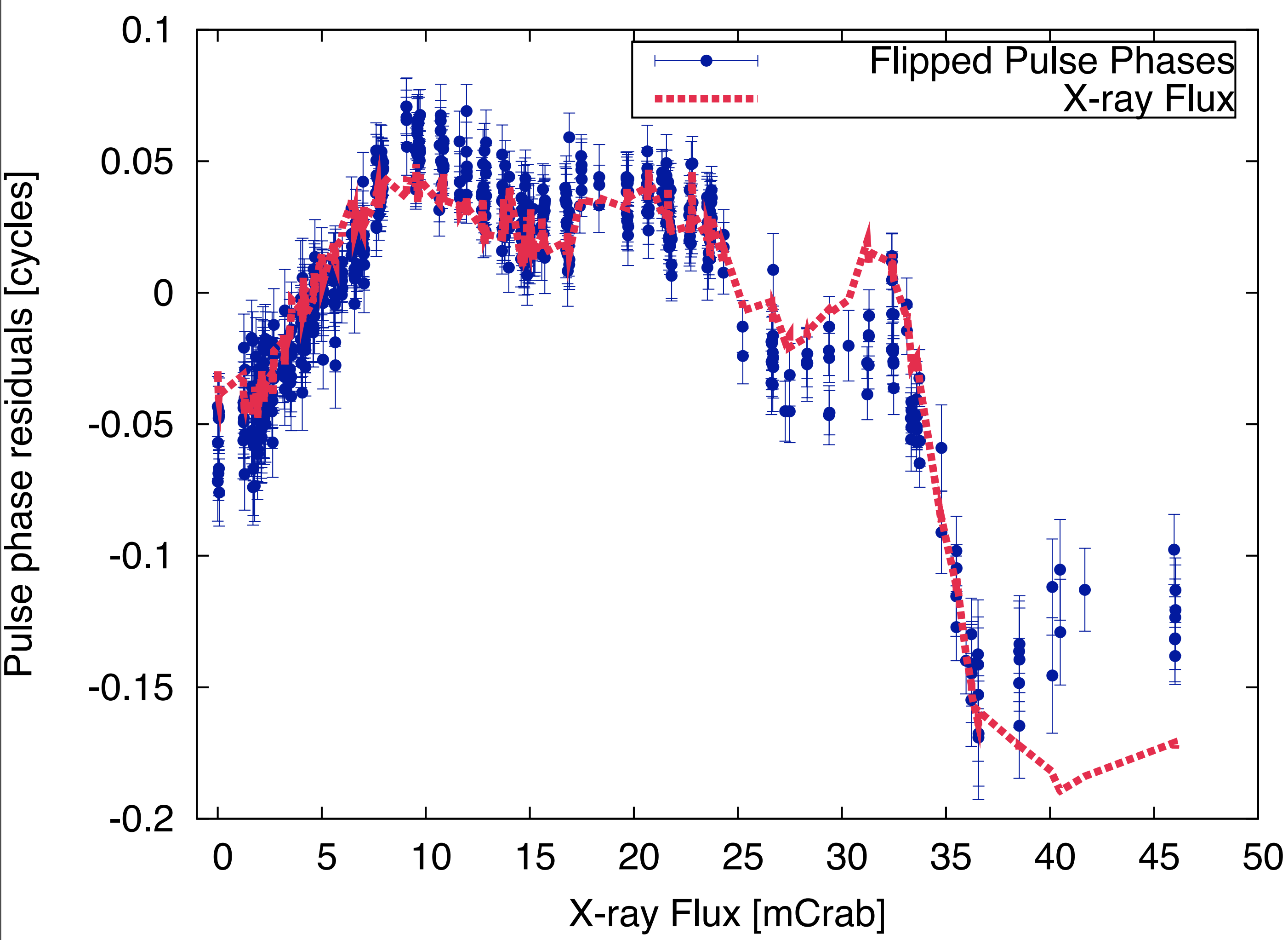
$$\phi(t) = \phi_0 + (t - t_0)\nu_0$$

(Patruno, Wijnands & Van der Klis 2009)

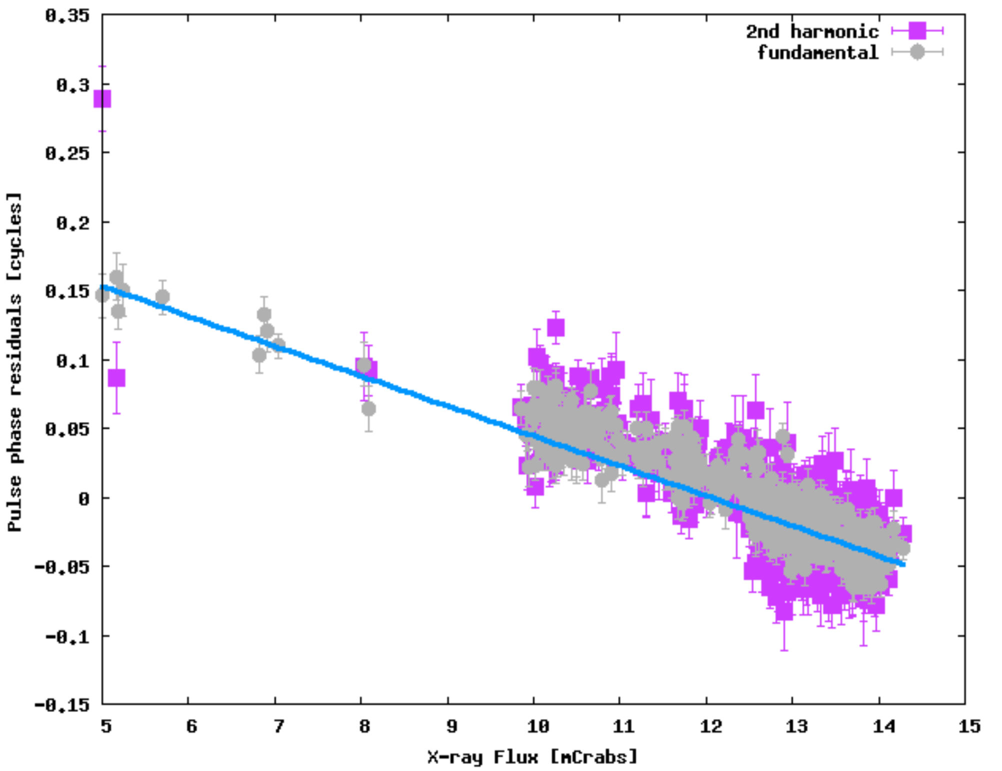


- Flux correlated to phase?
- Constant frequency during outburst?
  $|\dot{\nu}| < 1.5 \times 10^{-14}$
- Where is the angular momentum going? GWs?
  [Haskell & Patruno (2011)]

The strange case of XTE J1814-338 (& SAX J1808.4-3658)



(Patruno, Wijnands & Van der Klis 2009)



- Flux correlated to phase?
- Constant frequency during outburst? $|\dot{\nu}| < 1.5 \times 10^{-14}$
- Where is the angular momentum going? GWs?

[Haskell & Patruno (2011)]

Gravitational waves?

- Crustal mountains.

↓ Ushomirsky, Cutler & Bildsten (2000)

Not enough heat deposited in the crust

$$\delta T \approx 10^3 C_k^{-1} p_{30}^{-1} Q_n \Delta M_{22} \text{ K}$$ Ushomirsky & Rutledge (2001)

$$Q_{22} \approx 1.3 \times 10^{35} R_6^4 \left(\frac{\delta T_q}{10^5 \text{K}}\right) \left(\frac{Q}{30 \text{MeV}}\right)^3 \text{ g cm}^2$$

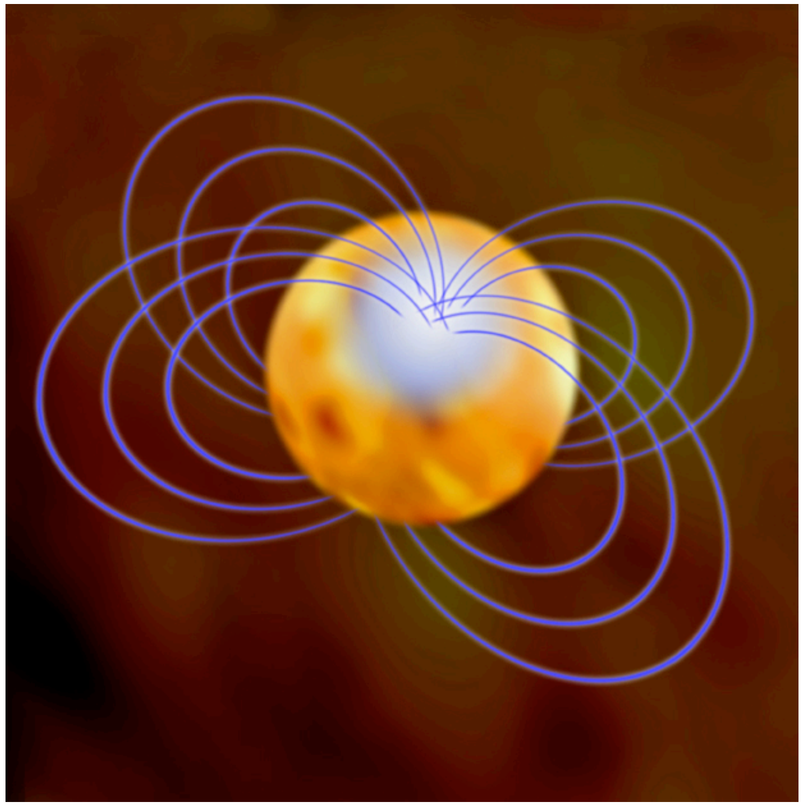
(To balance accretion one would need $Q_{22} \approx 10^{37}$)

Gravitational waves?

- Magnetic mountains.

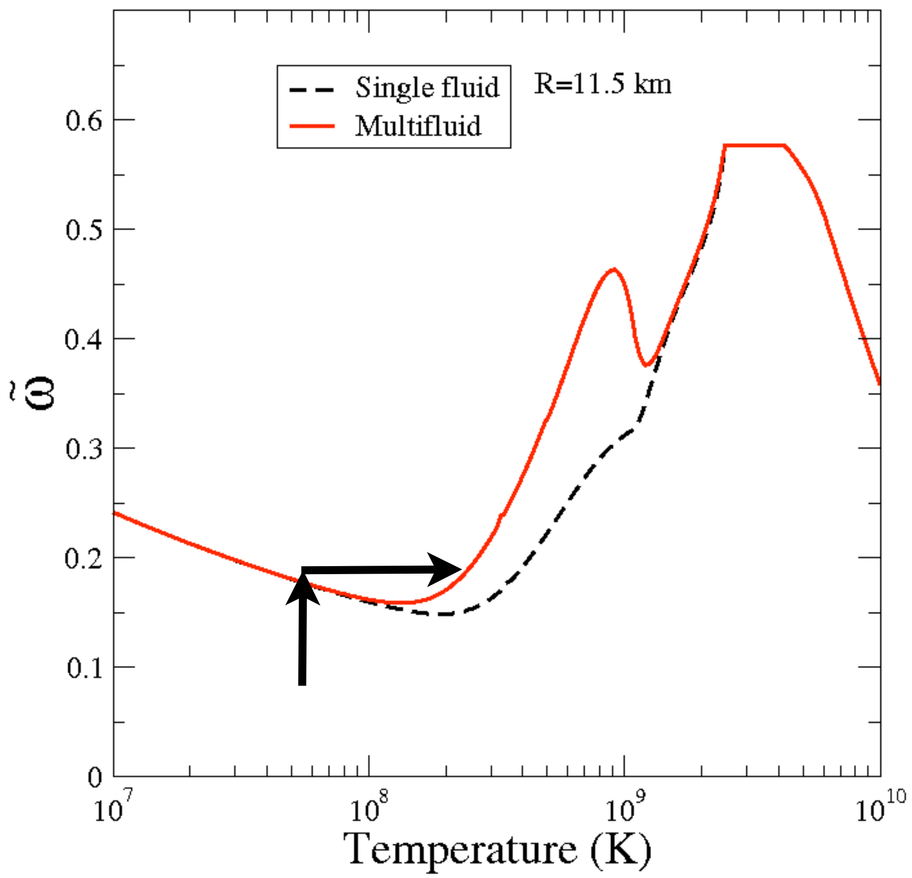
↓ Cutler (2002), Melatos & Payne (2005)

B field too weak. Spin-down too strong?



Requires strong internal toroidal (or surface higher multipole) component of the order $B \approx 10^{12}\mathrm{G}$

Gravitational waves?



Haskell & Andersson (2010)

- Hyperon bulk viscosity (or quark bulk viscosity, mutual friction etc.) can halt the r-mode thermal run-away.

Andersson, Jones & Kokkotas (2002)

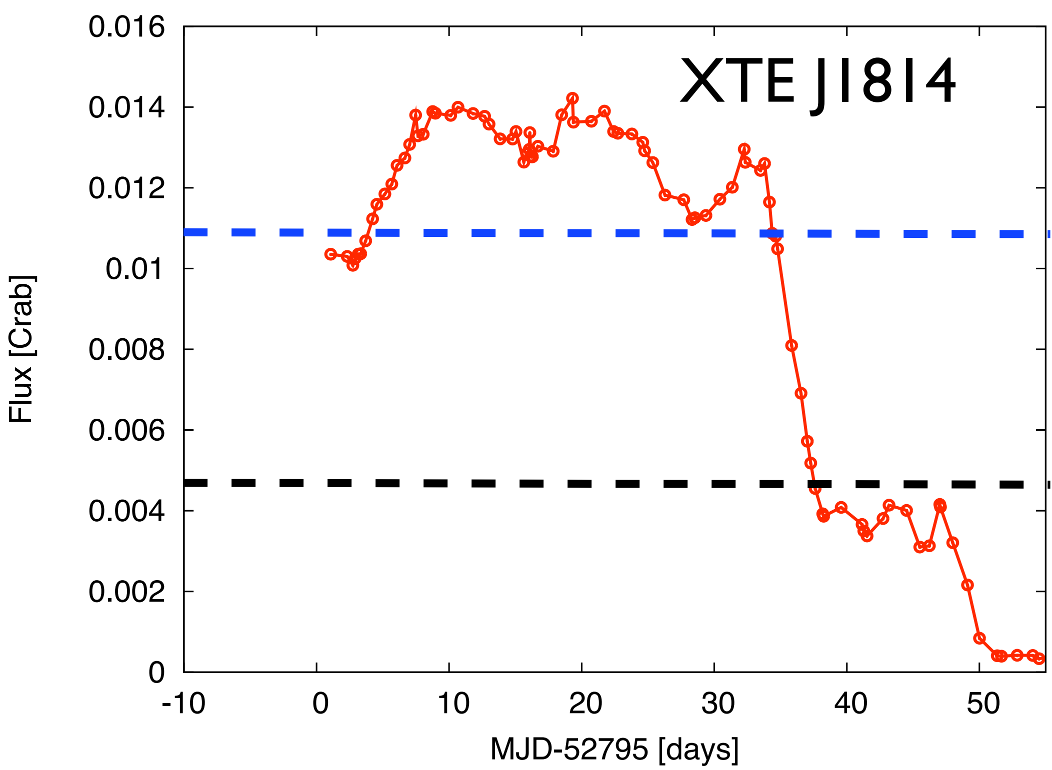
Nayyar & Owen (2006)

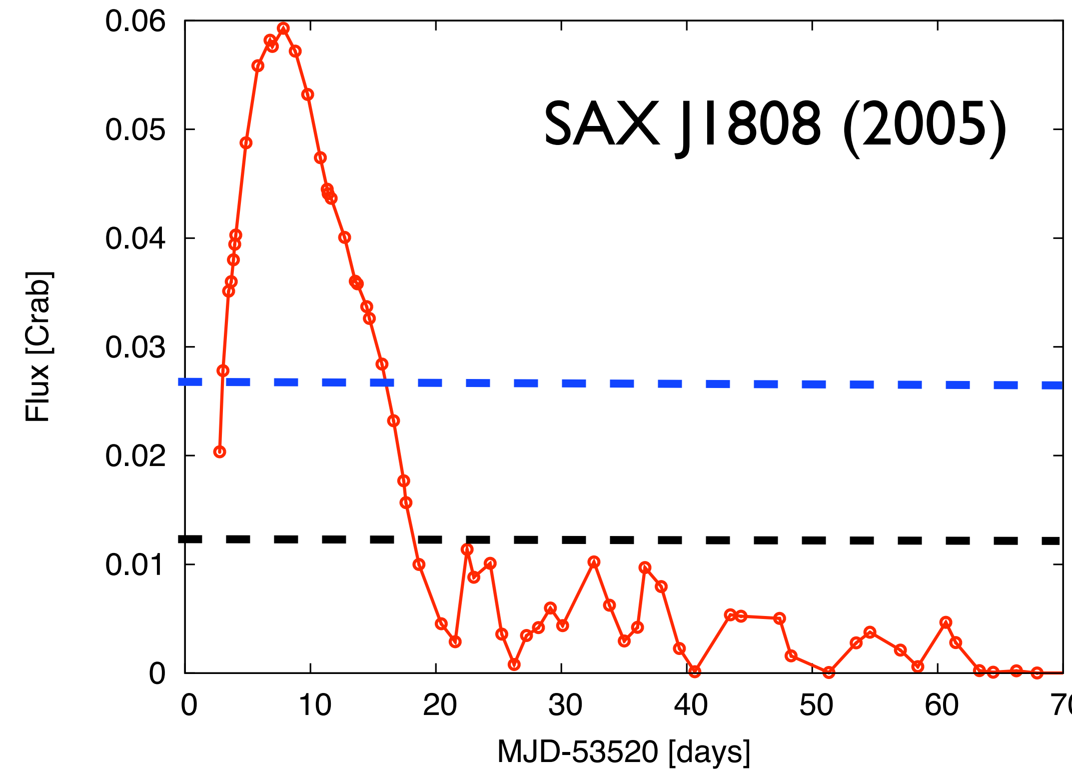
Star too hot and spin-down in quiescence too strong ?

Estimated core temperature: $T_c \approx 10^7 K$

Would need strong direct URCA with no superfluidity

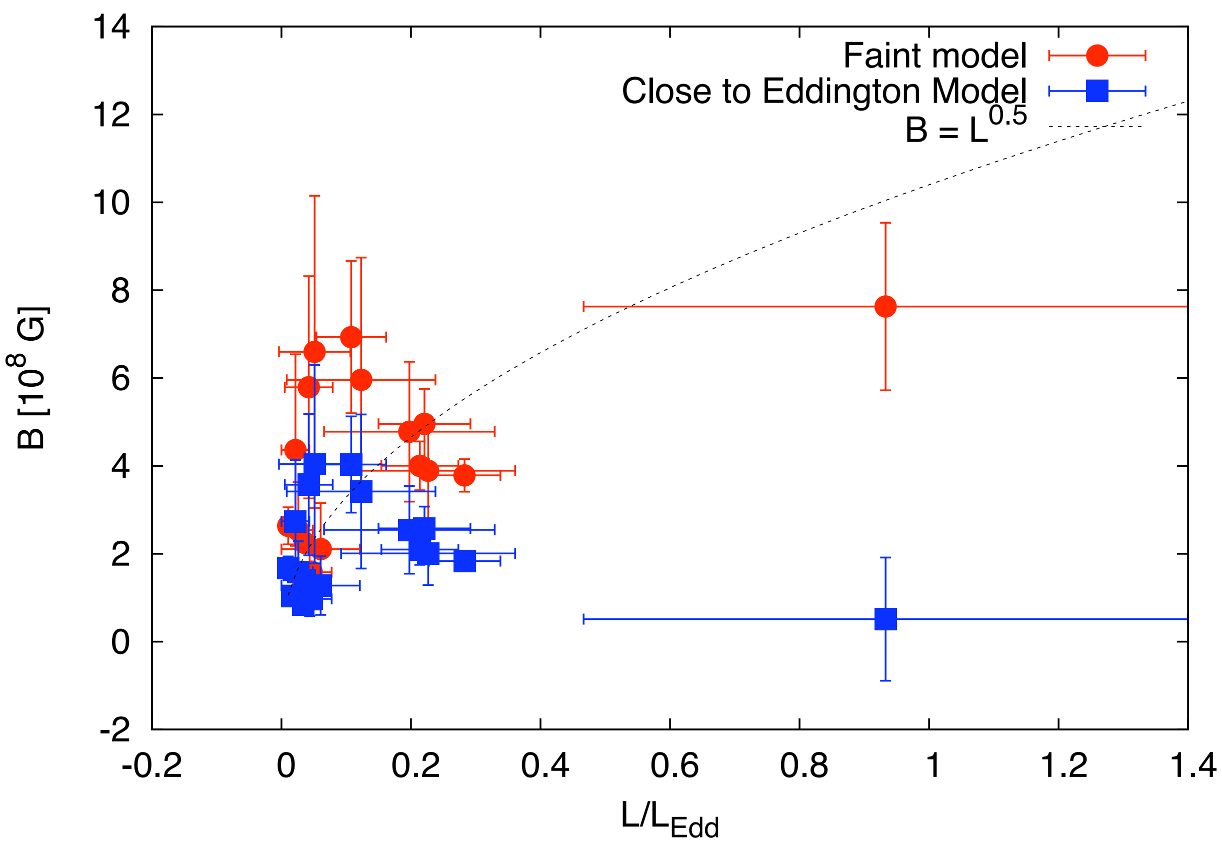
Spin equilibrium?

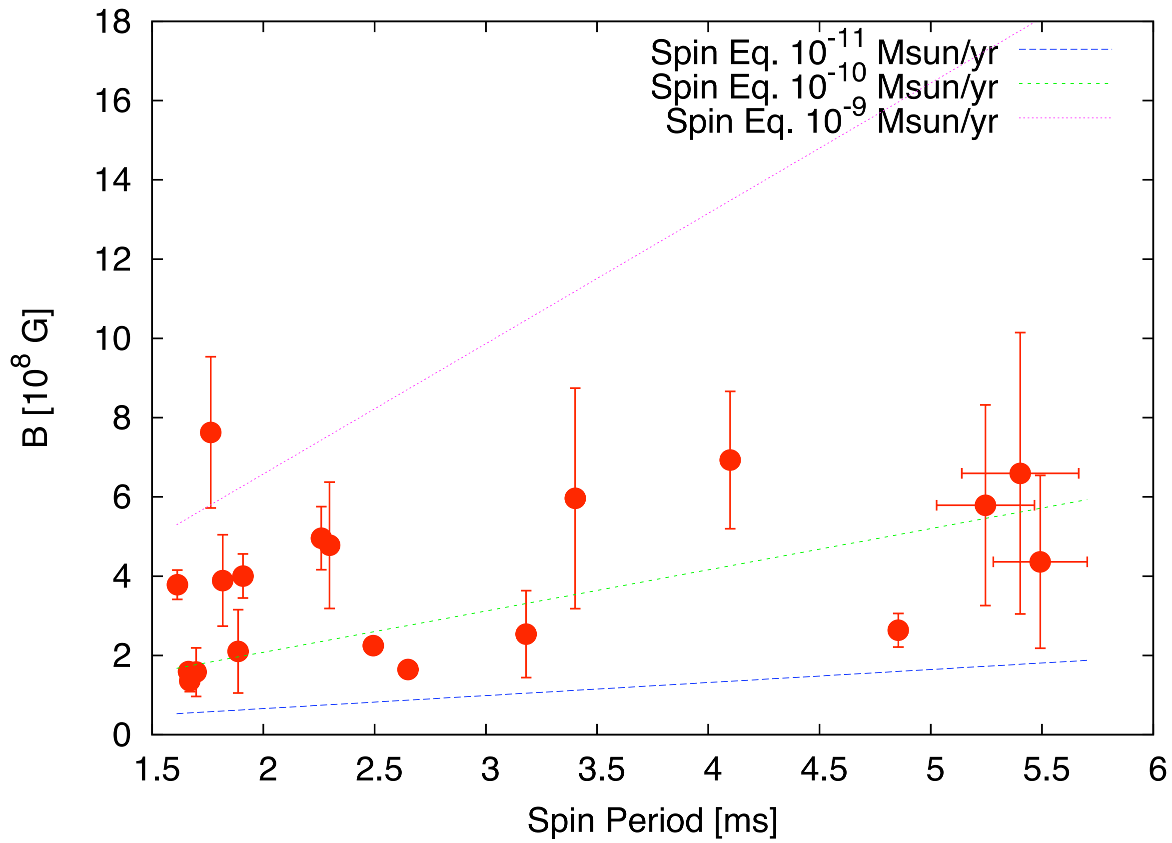




- Assume a propeller phase with Rc=Rm [Haskell & Patruno (2011)]
- The simple model of Andersson et al. 2005 gives spin equilibrium at approximately the mean accretion rate (Rm=0.8 Rc)
- Rm/Rc=0.75 XTE J1814, Rm/Rc=0.75-0.84 SAX J1808

Spin equilibrium?



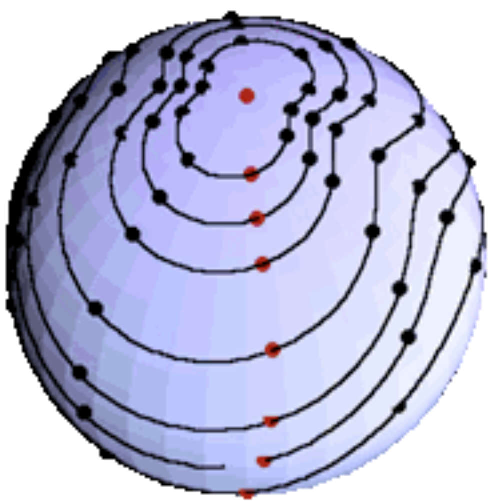


- Correlation between B and L weak
- Many systems may be close to spin equilibrium as set by the disc/magnetosphere interaction

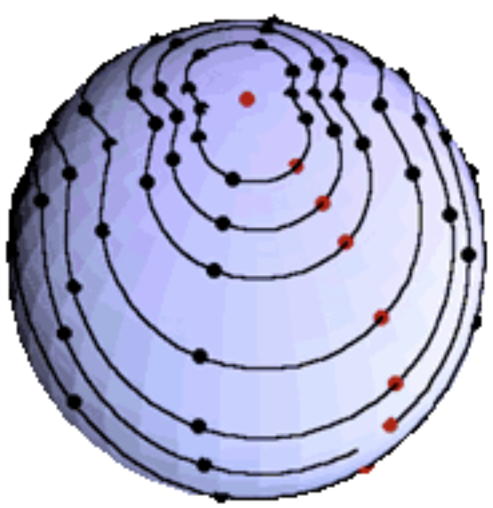
[Patruno, Haskell & D'Angelo (in preparation)]

r-mode instability

(Animation by Ben Owen)



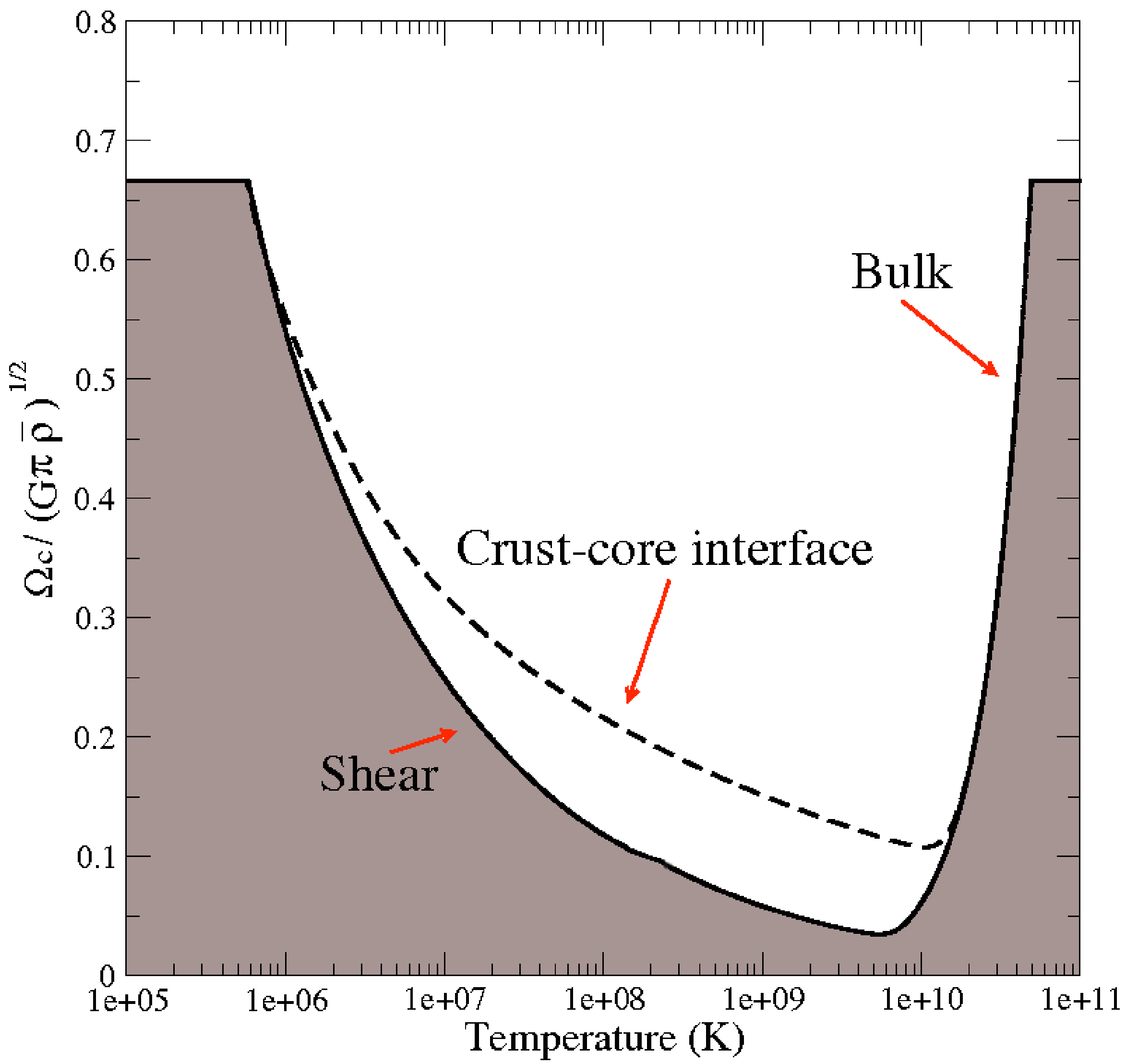
Rotating observer



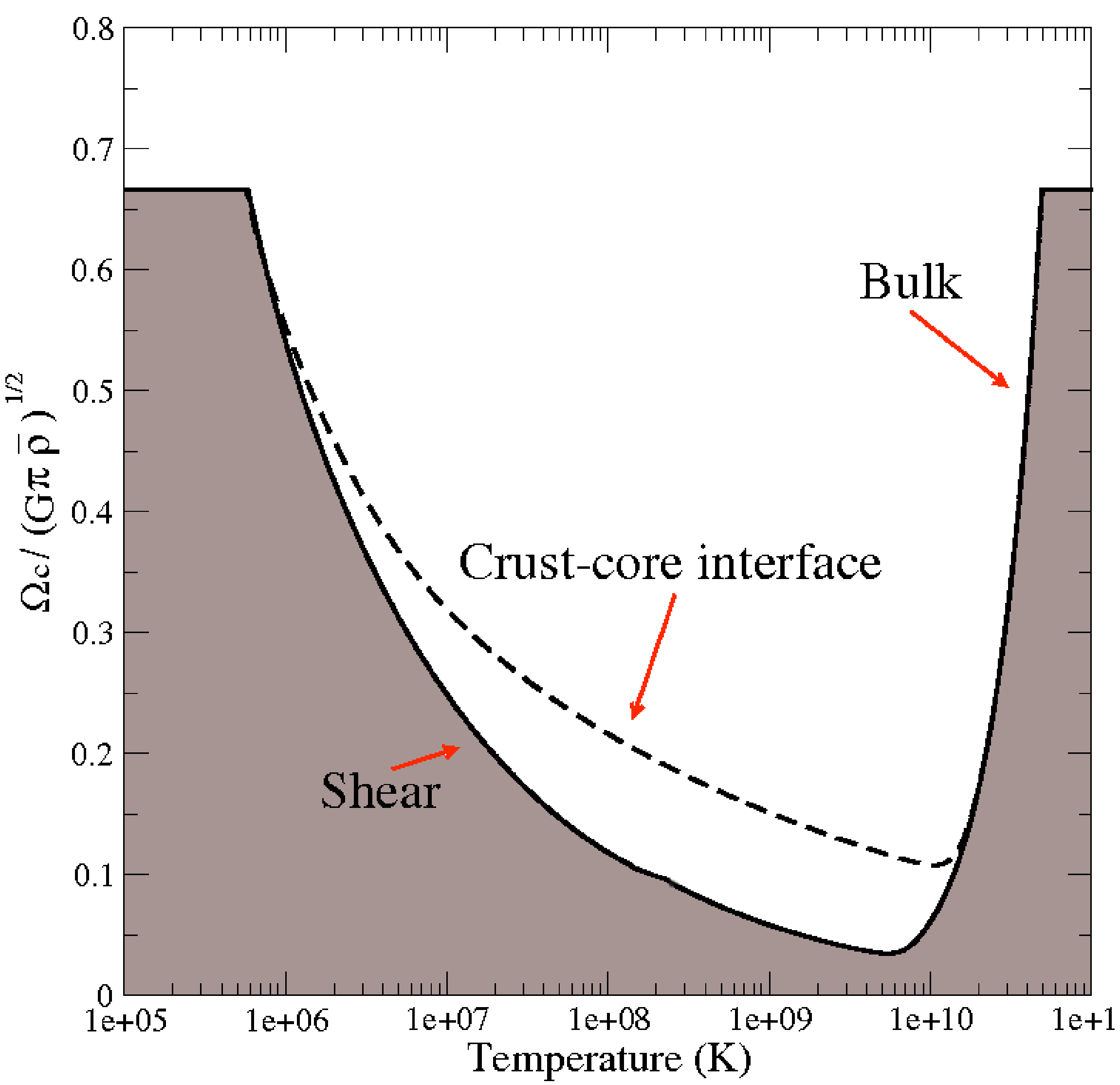
Inertial observer

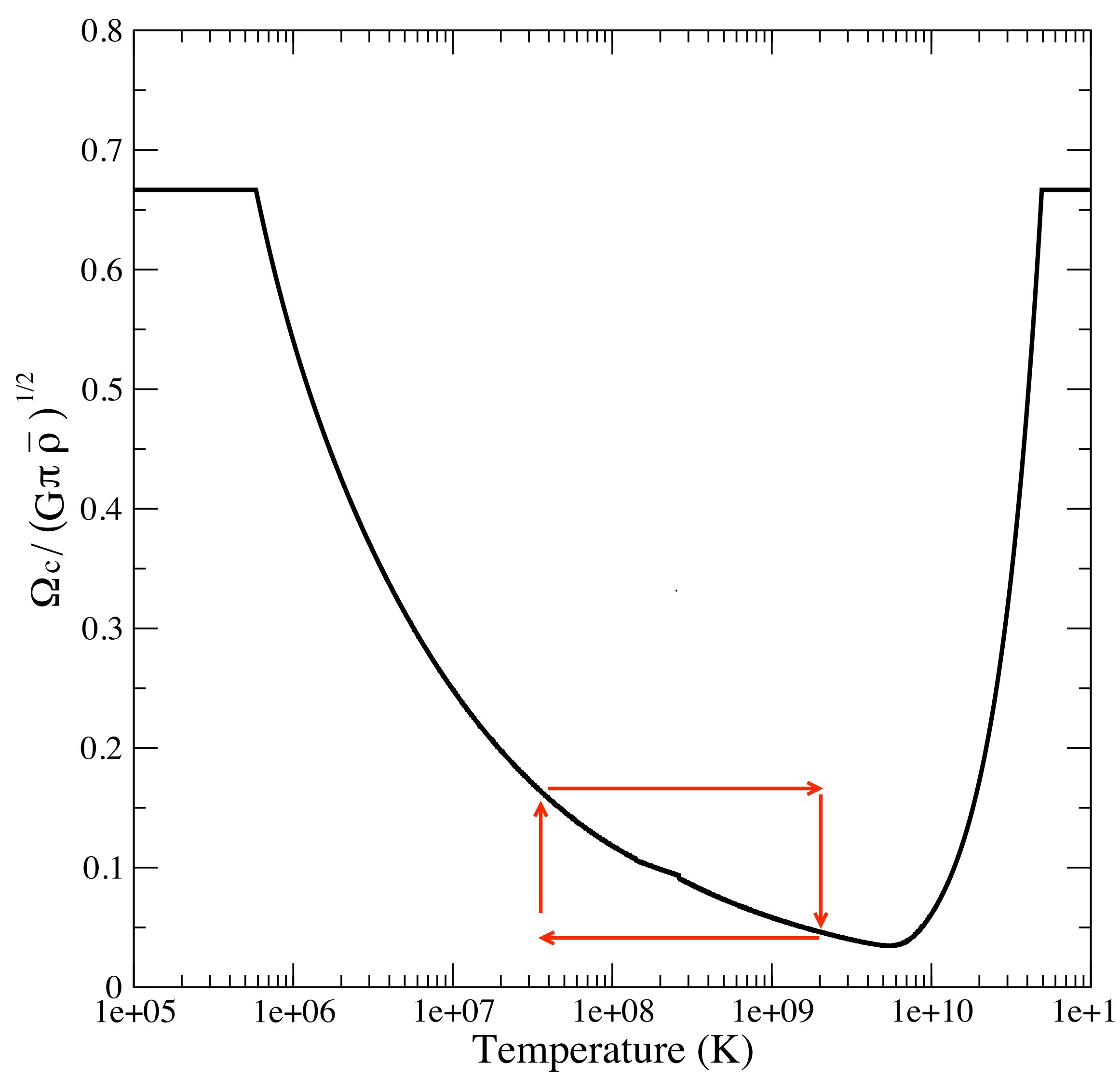
- r-mode generically unstable to GW emission
- Emission at $\omega \approx \frac{4}{3}\Omega$
- Viscosity damps the mode except in a window of temperatures and frequencies

r-mode instability window - I



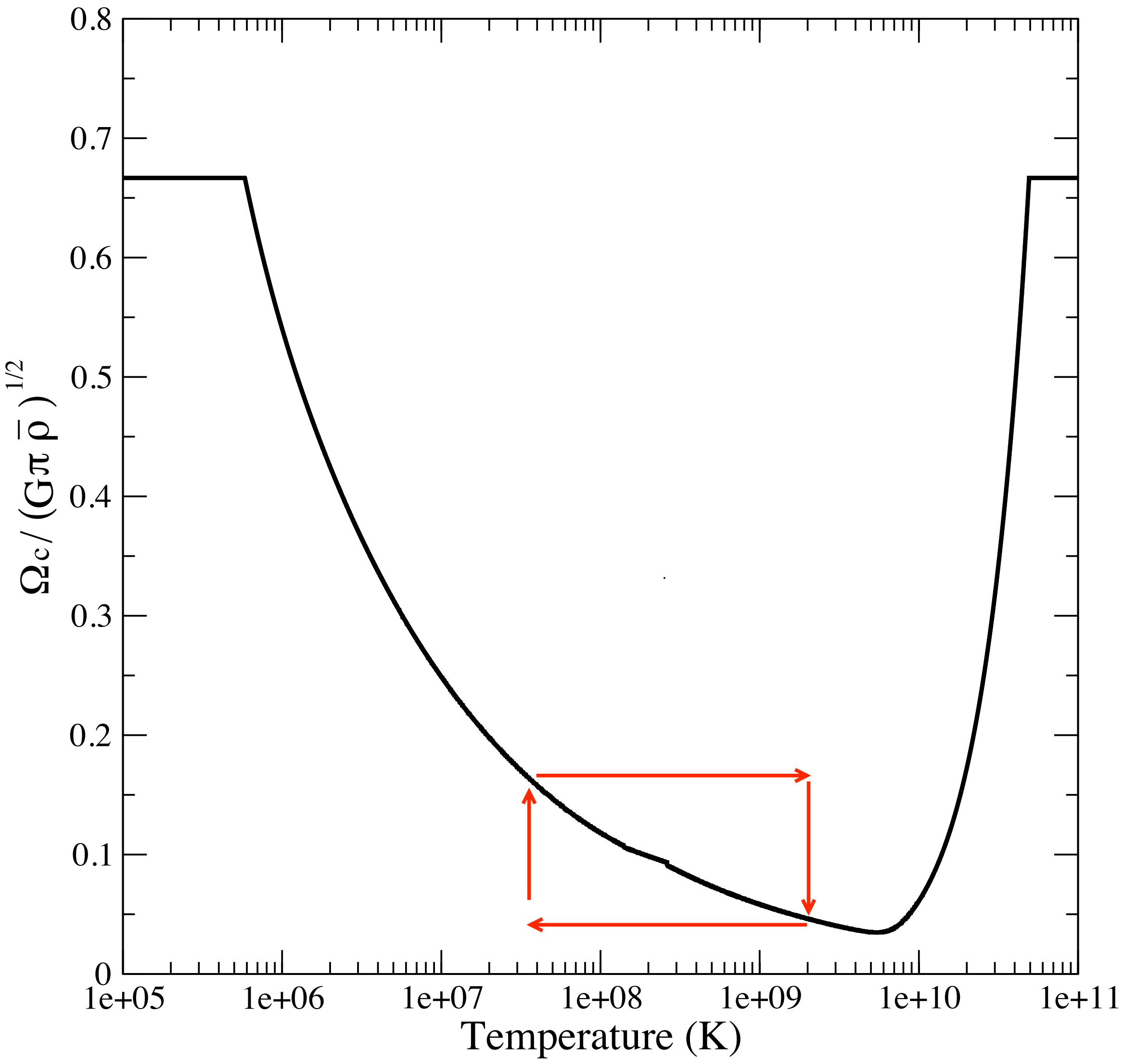
r-mode instability window - I



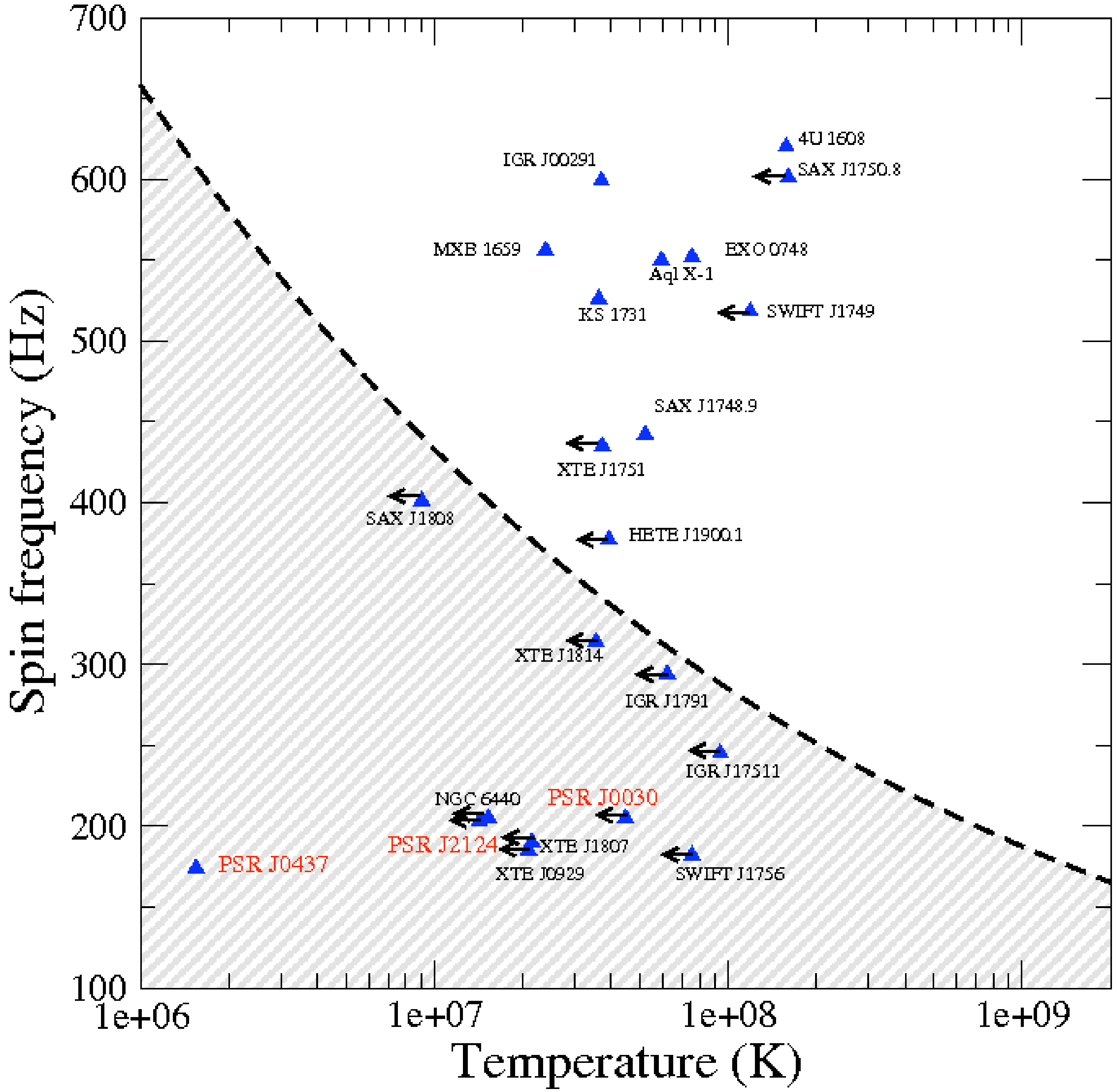


r-mode instability window - I

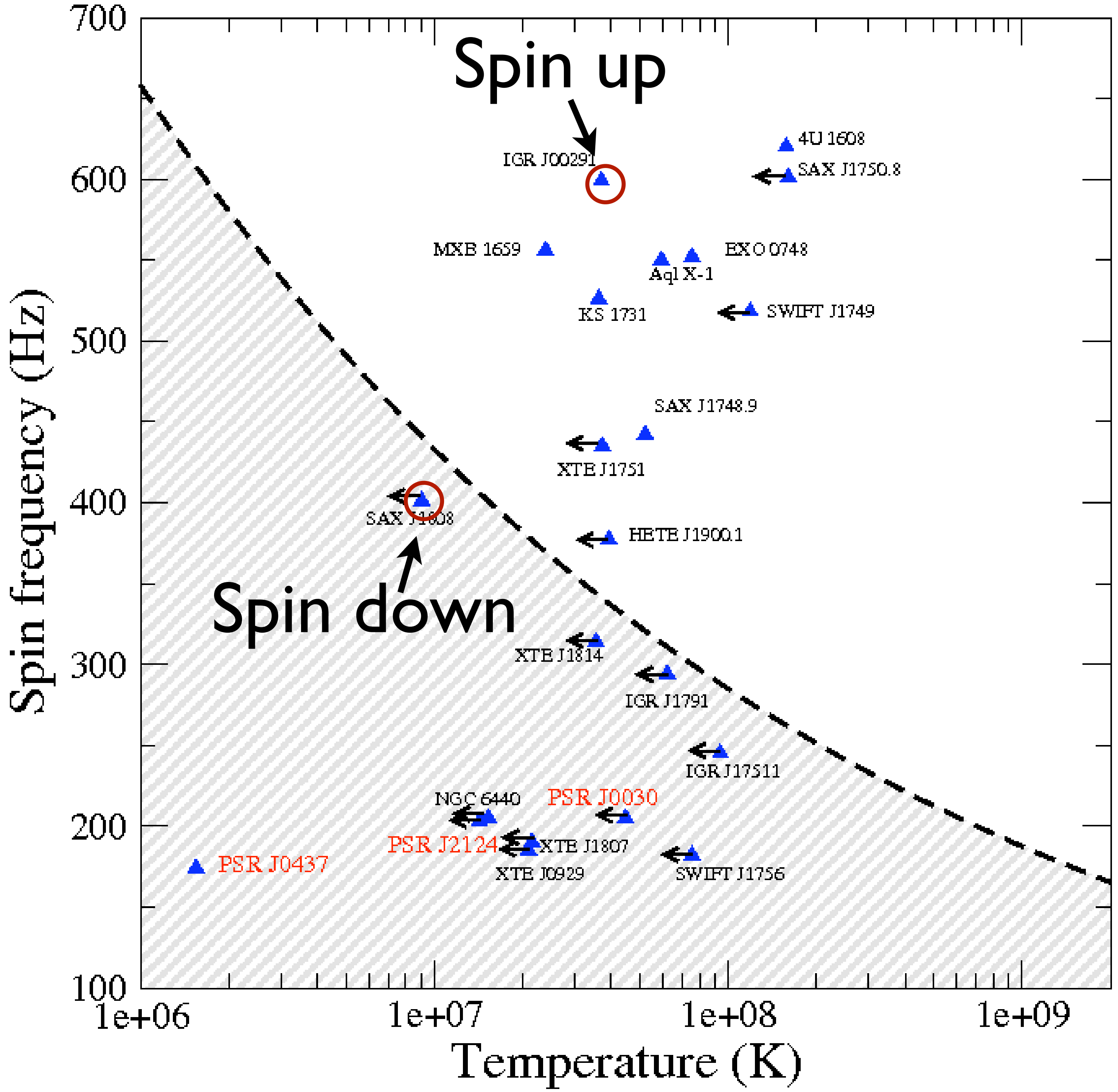
- Duty cycle short (10% or less)
- Effects of EOS? (Hyperons..)
- Effects of superfluidity?



r-mode instability window - II



r-mode instability window - II



Multifluid hydrodynamics

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

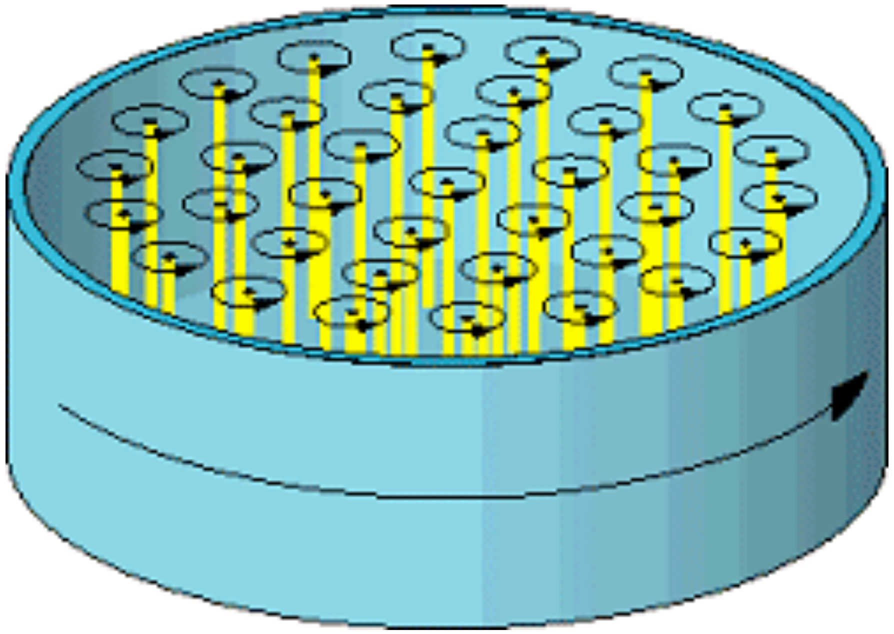
$$(\partial_t + v^j_{\rm x}\nabla_j)(v^{\rm x}_i + \varepsilon_{\rm x} w^{\rm yx}_i) + \nabla_i(\tilde{\mu}_{\rm x} + \Phi) + \varepsilon_{\rm x} w^j_{\rm yx}\nabla_i v^{\rm x}_j = f^{\rm x}_i/\rho_{\rm x} + \nabla_j D^j_i$$

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

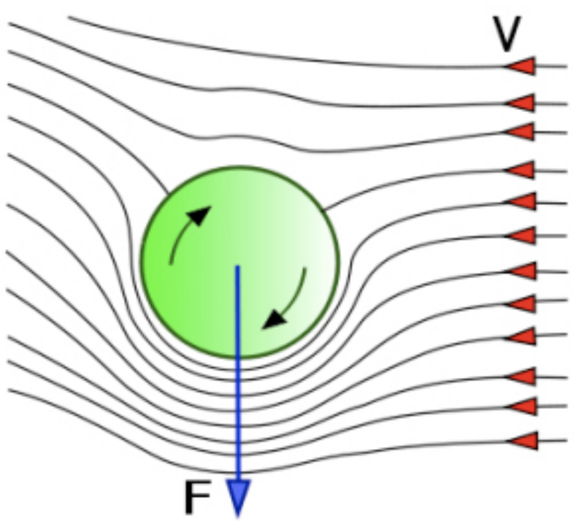
Mutual friction



- Superfluids rotate by forming quantised vortices
- Vortex density determines spin :

  vortices must move out to spin down the fluid!
- Vortices could be strongly pinned in the crust

Magnus Force



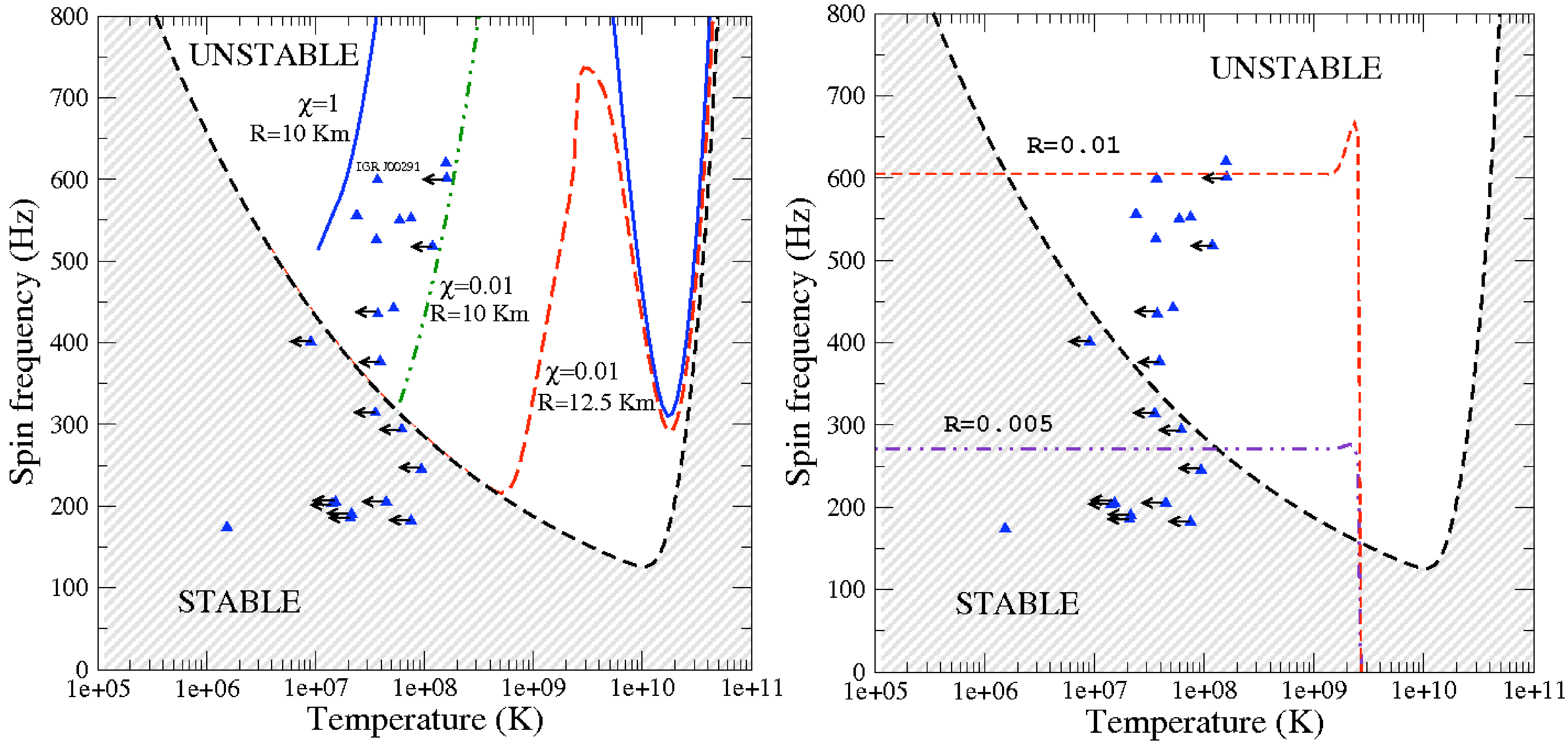
$$\text{PINNED}: \quad \epsilon^{ijk}\hat{k}_j(v_k^{\mathrm{v}} - v_k^{\mathrm{n}}) + F_{\mathrm{p}}^i = 0$$

$$\text{FREE}: \quad \epsilon^{ijk}\hat{k}_j(v_k^{\mathrm{v}} - v_k^{\mathrm{n}}) + \mathcal{R}(v_{\mathrm{c}}^i - v_{\mathrm{v}}^i) = 0$$

r-mode instability window - III

[Haskell et al. (in preparation) - Ho, Andersson & Haskell (2011)]

r-mode instability window - III



[Haskell et al. (in preparation) - Ho, Andersson & Haskell (2011)]

Universiteit van Amsterdam

Conclusions

- We have a problem with the r-mode. Can a system be inside the instability window?
- Need to model the accretion torque.
- Are some AMXPs emitting GWs? Precise timing and cooling measurements can guide us..(while we wait for GW measurements...)
- Important input for choosing targets for GW observations: persistent sources best targets?