# Constraining the physics of matter at high densities with the r-mode instability

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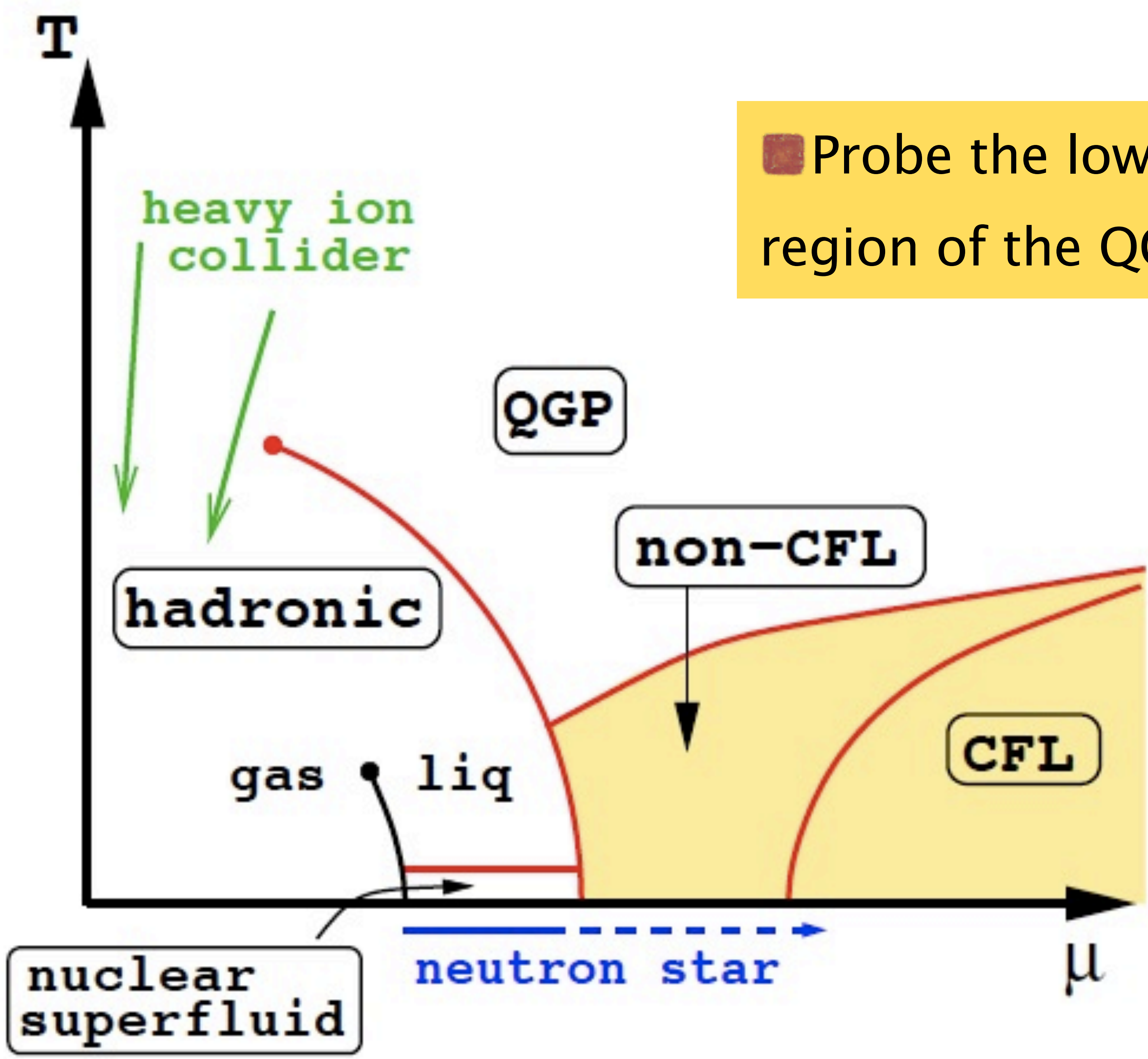
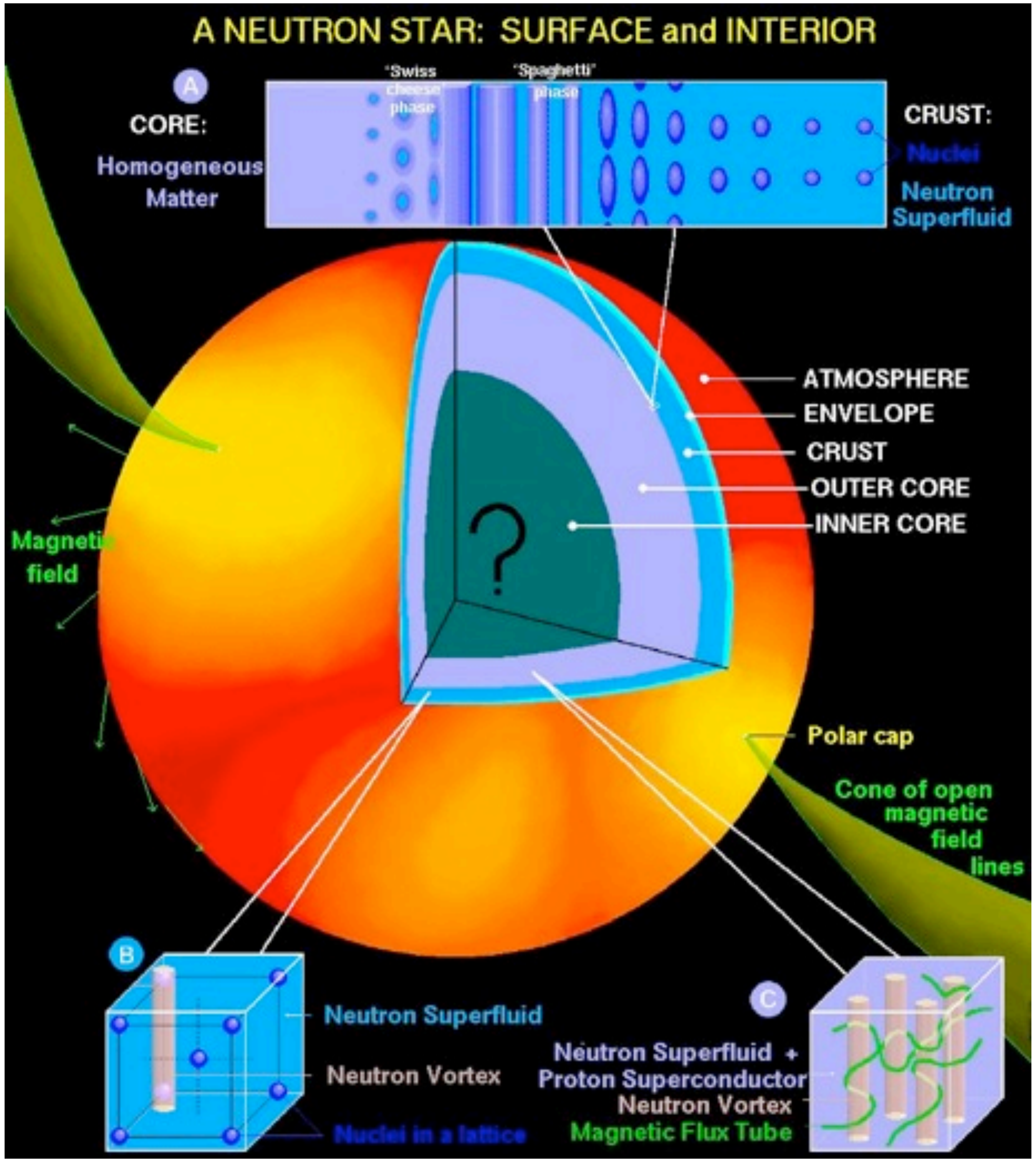
# Neutron Stars: theoretical relevance



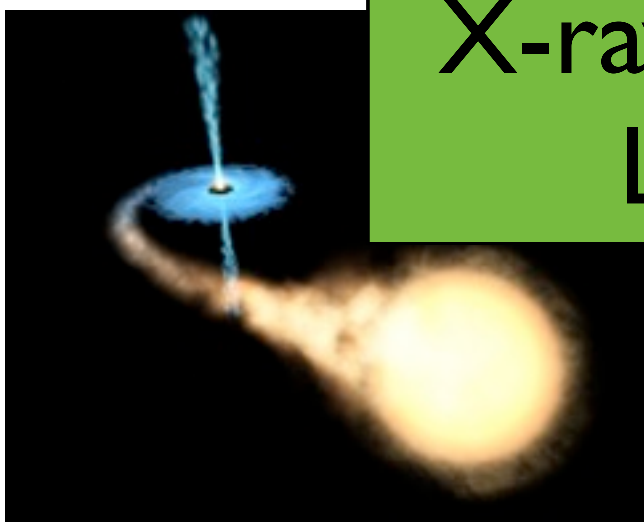

- Probe the low-temperature high-density region of the QCD phase diagram!

# Neutron Star structure

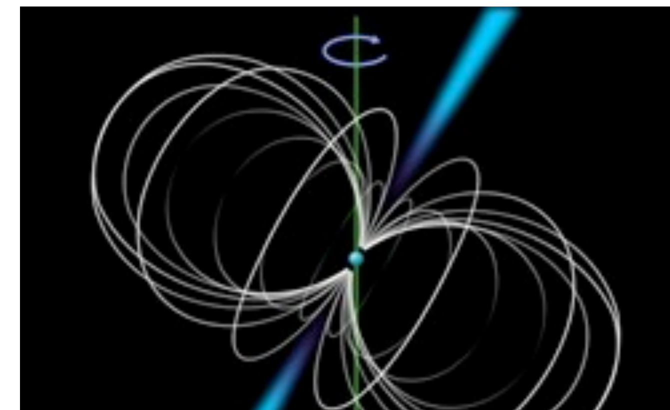
- Elastic crust
- Superfluid neutrons and superconducting (type II) protons
- Exotic particles in the inner core
- Large magnetic fields
- Rapid rotation



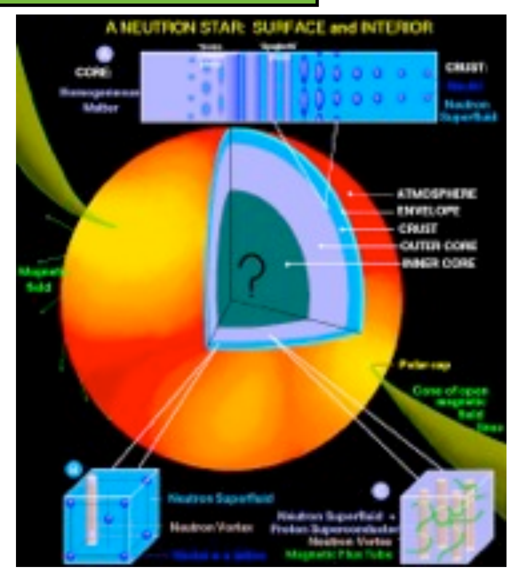
# Astrophysical relevance



X-ray (Magnetars, LMXBs...)



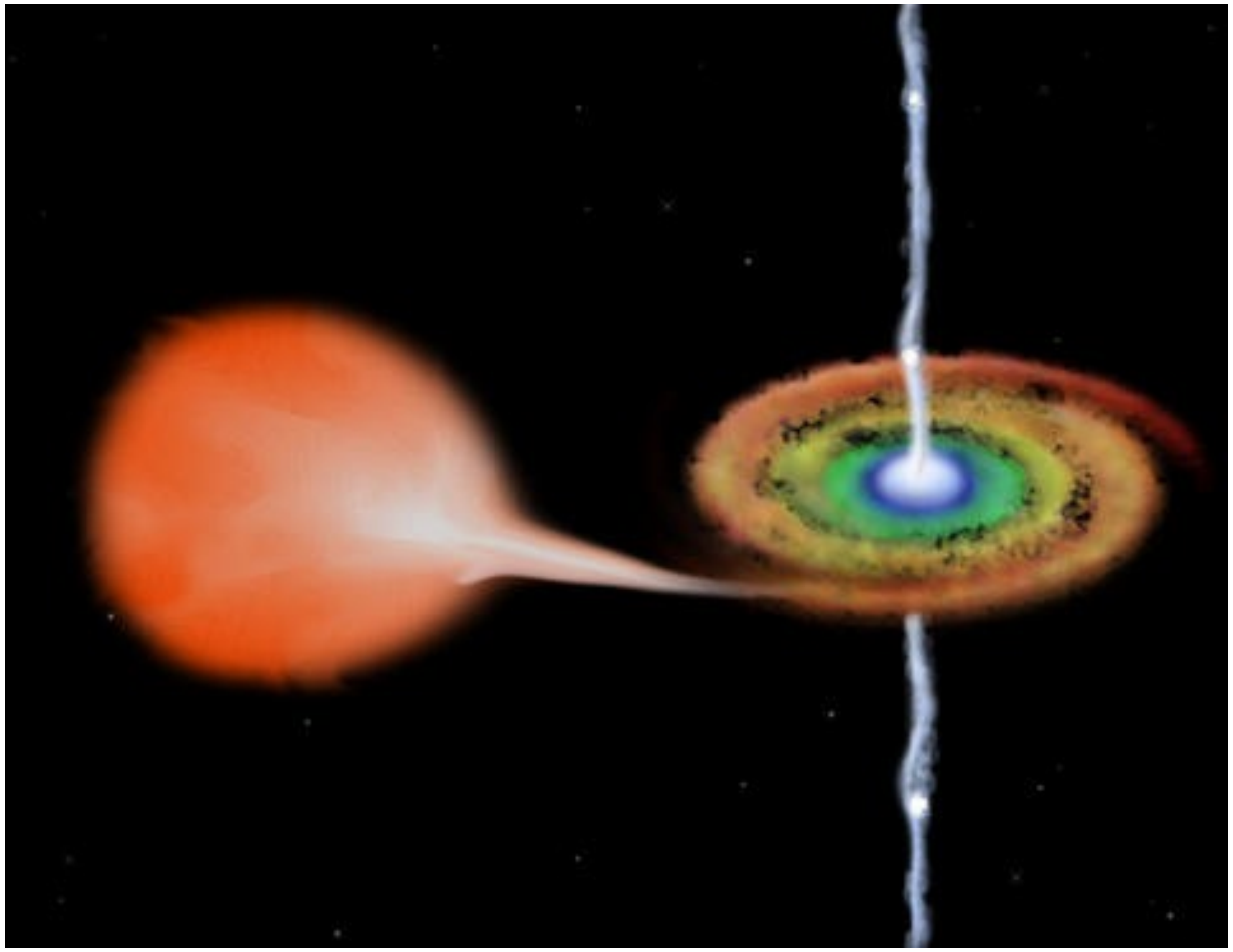
Radio (Pulsars)




$\gamma$-ray, optical.. (Pulsars, bursts..)

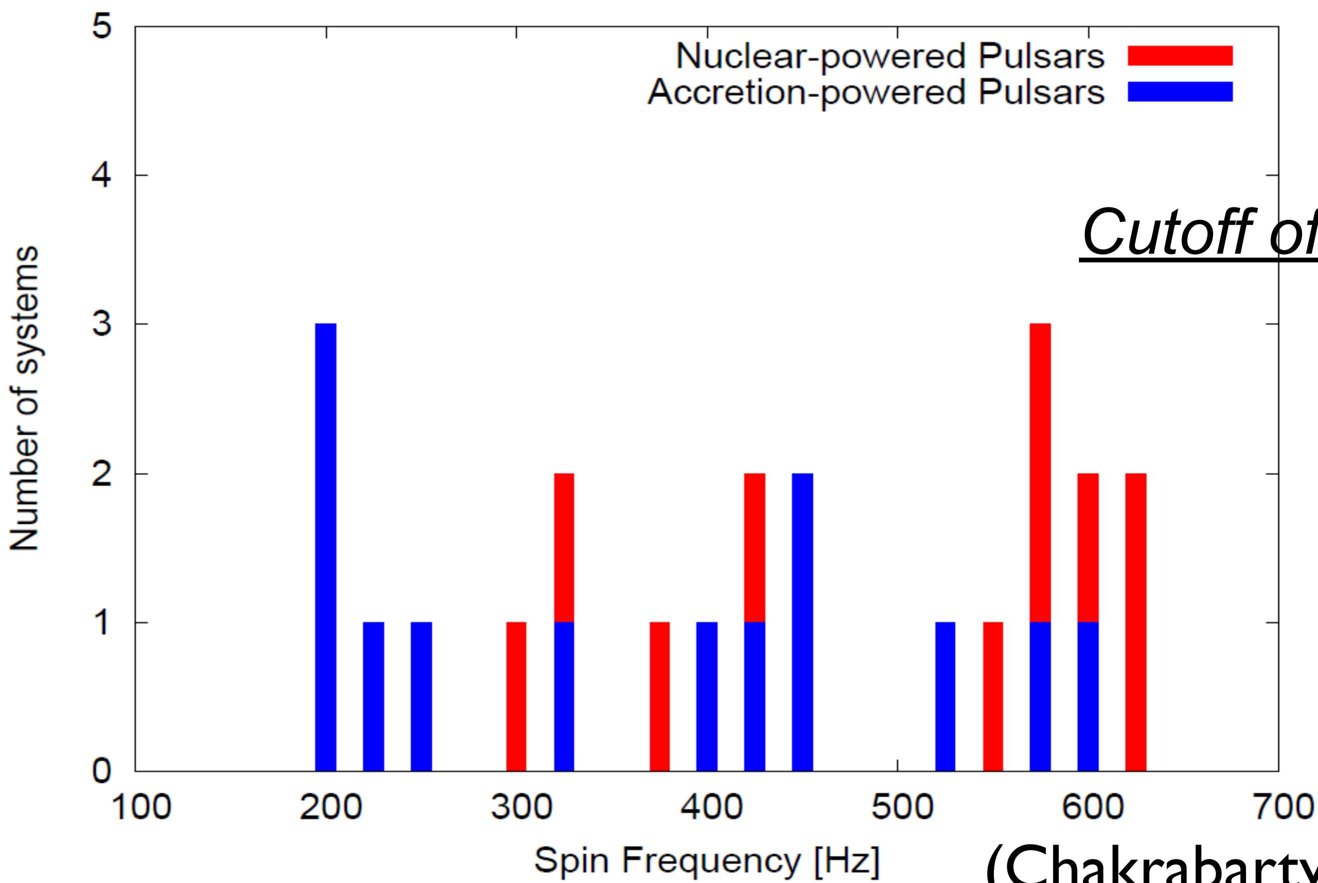
Gravitational waves

# 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 Low Mass X-ray Binaries




*Cutoff of distribution at ~730 Hz*

(Chakrabarty et al 2003, Patruno 2010)

- Spin up halted well before breakup frequency
- Disk/magnetosphere interaction?

(White & Zhang 1997, Andersson, Glampedakis, BH & Watts 2006, BH & Patruno 2011, Patruno, D'Angelo & BH 2012)

- GWs!: "mountains", unstable modes, magnetic deformations

(Bildsten 1998, Andersson 1998, Cutler 2002, BH et al. 06, Payne & Melatos 07, BH et al. 08)

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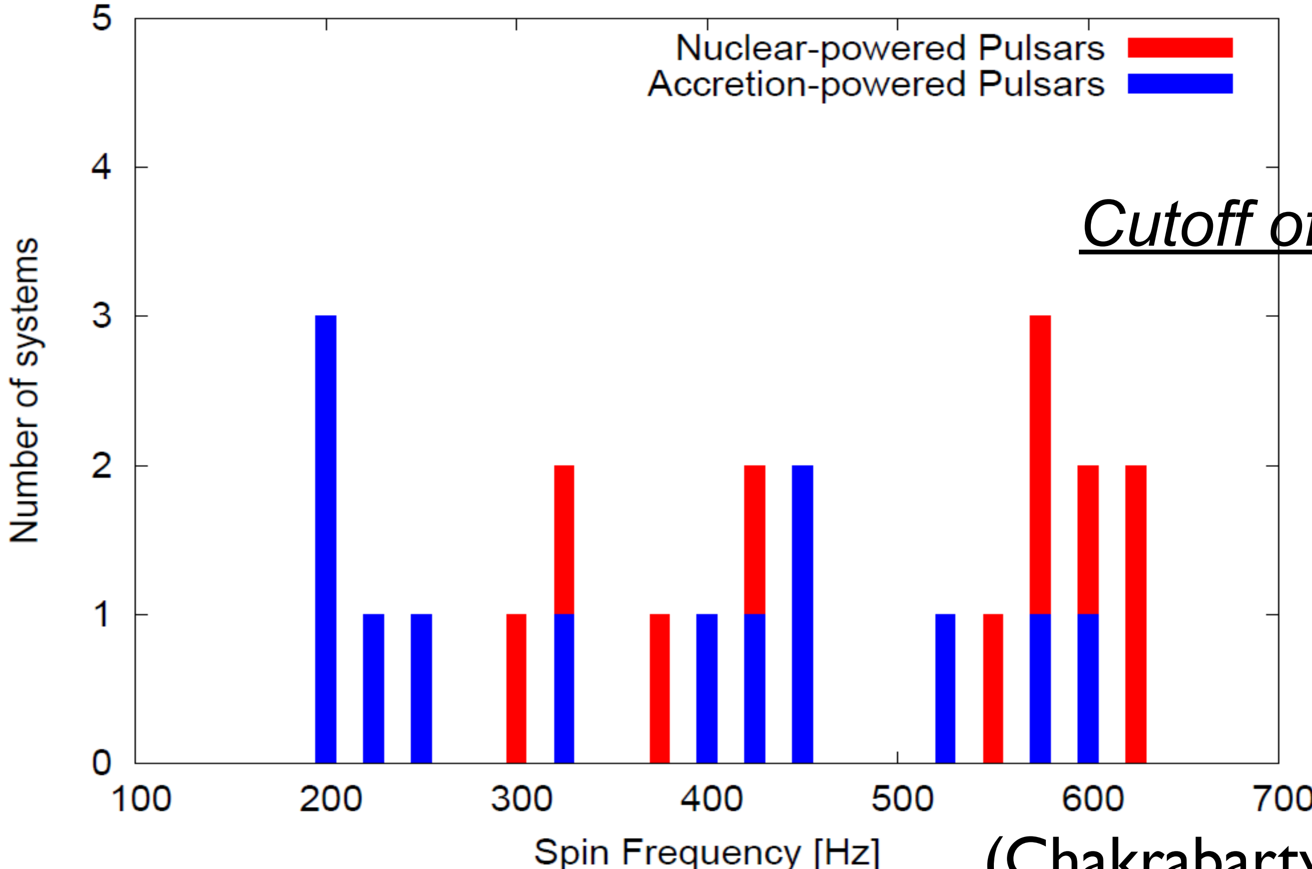


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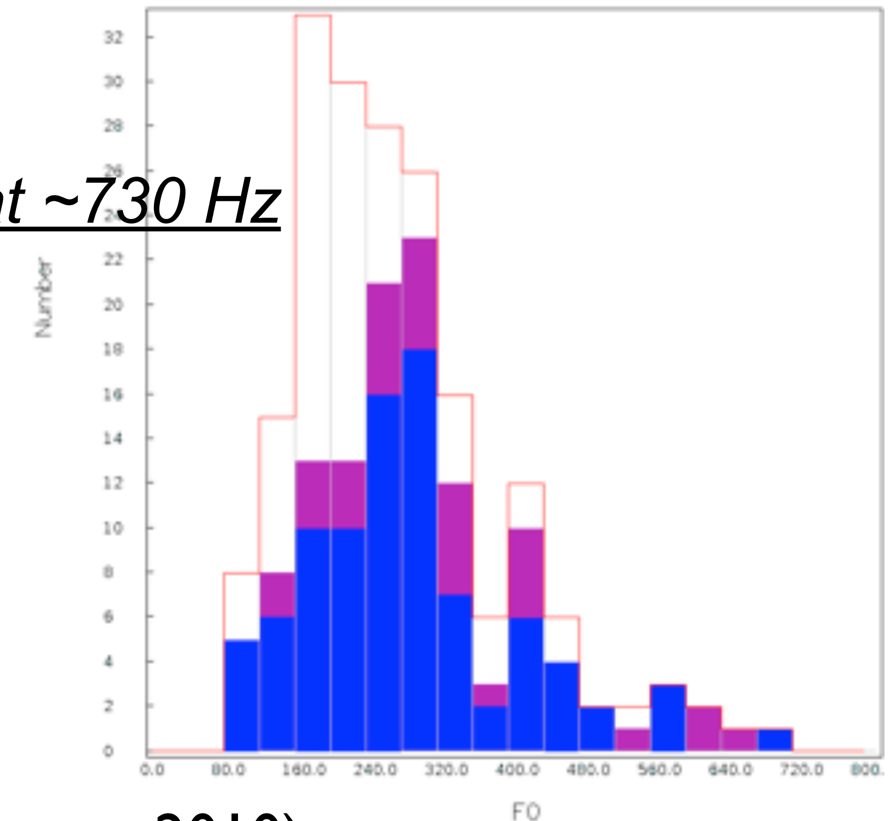


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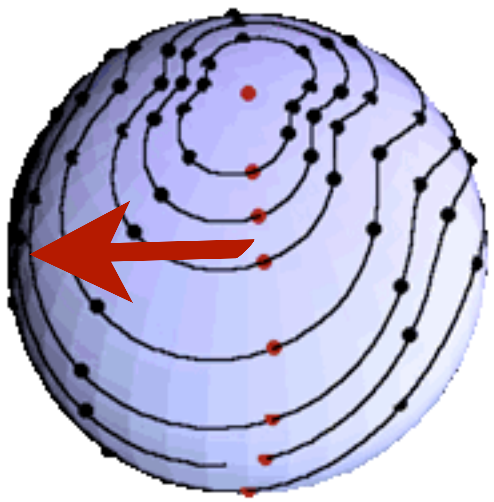
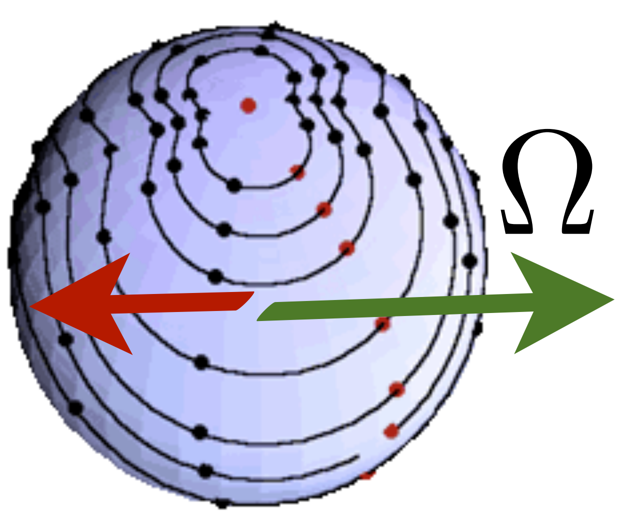
# r-mode instability

(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

(Andersson 1998)

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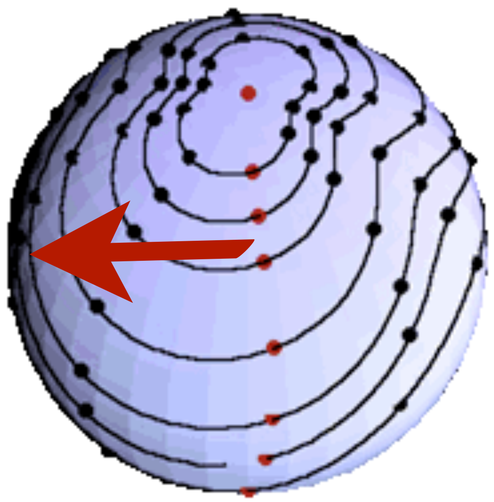

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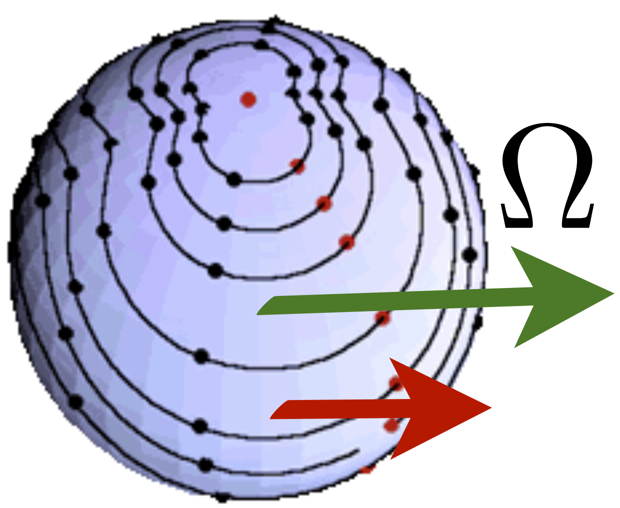


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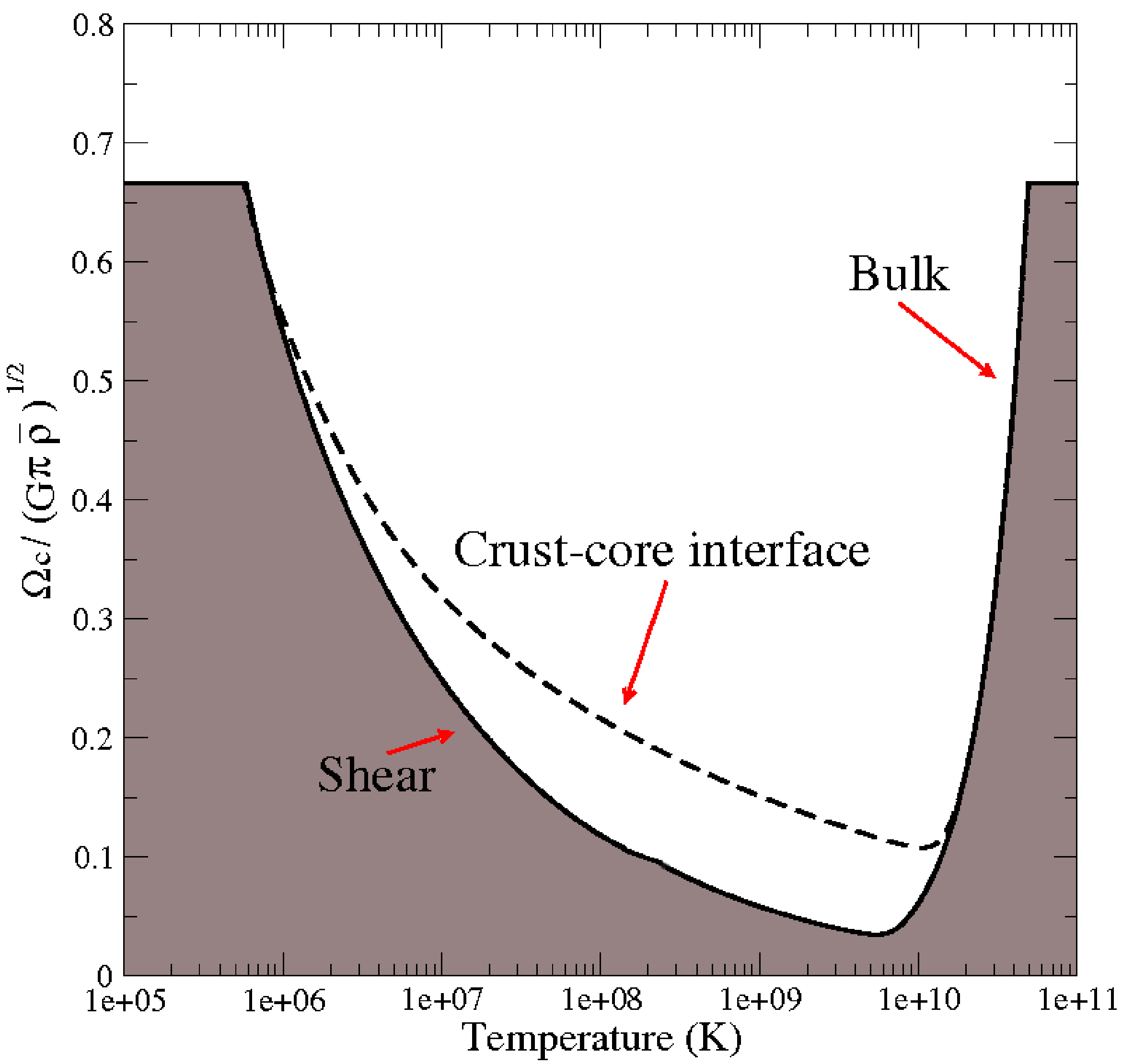
# r-mode instability window - I



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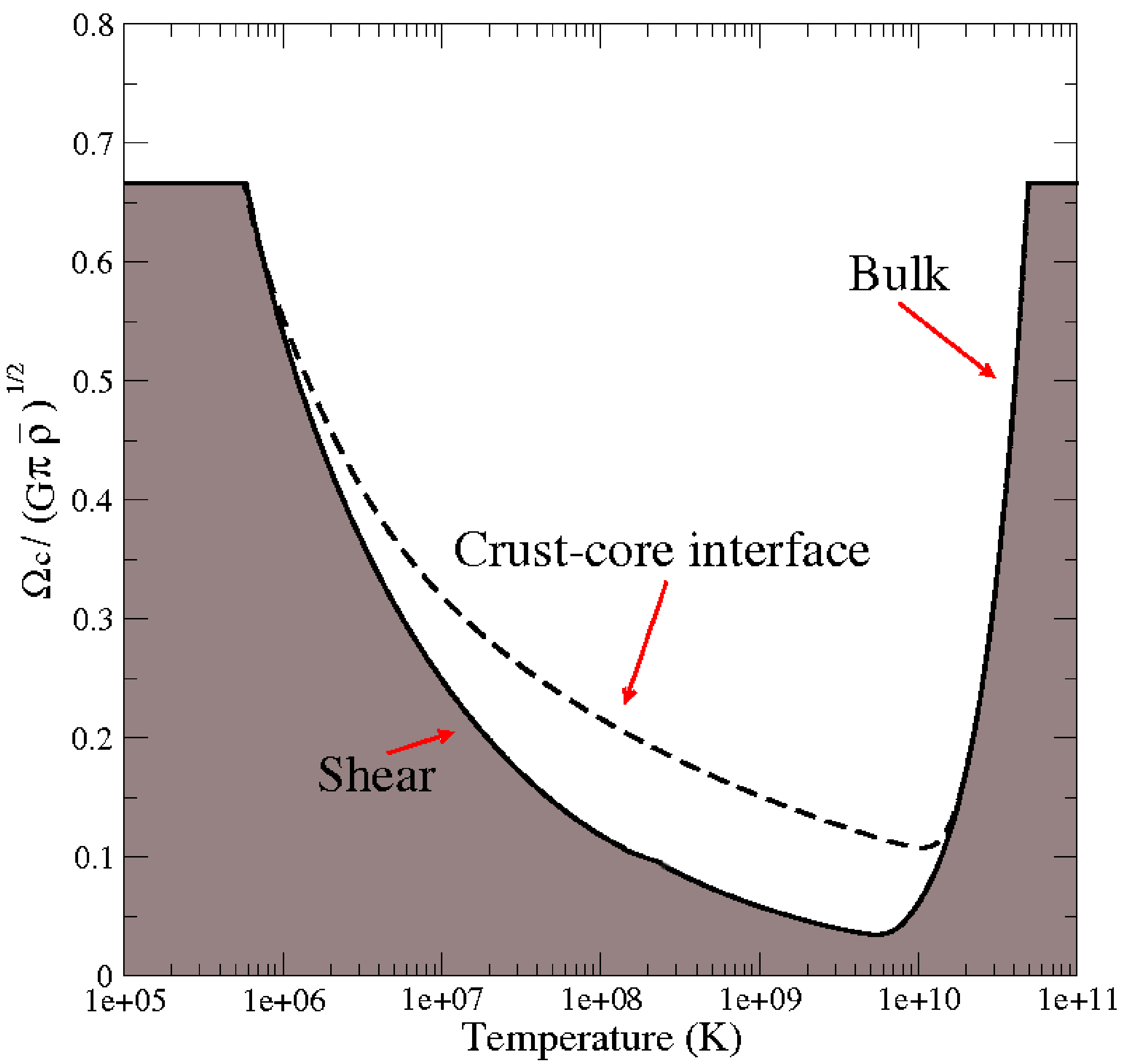
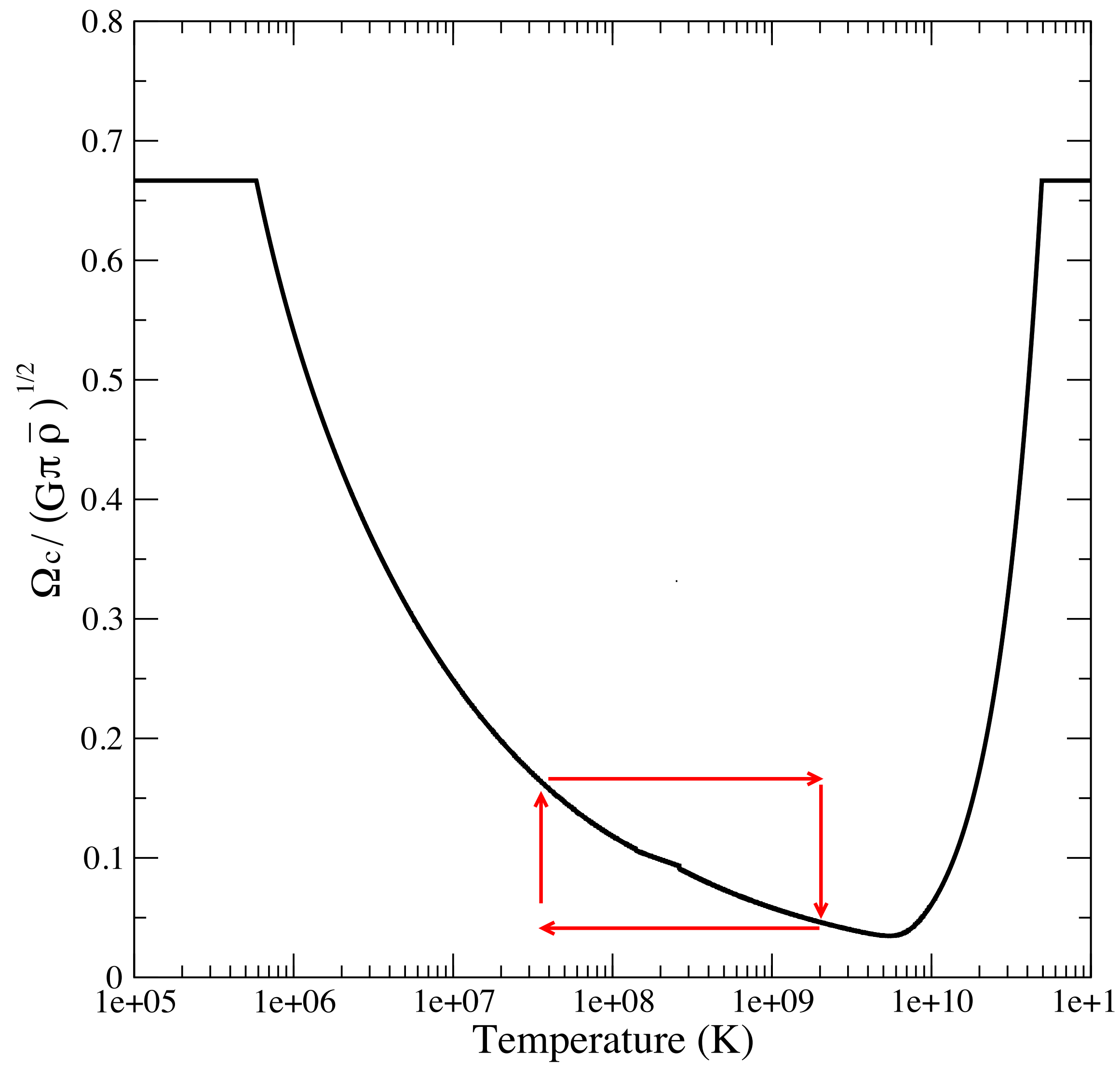
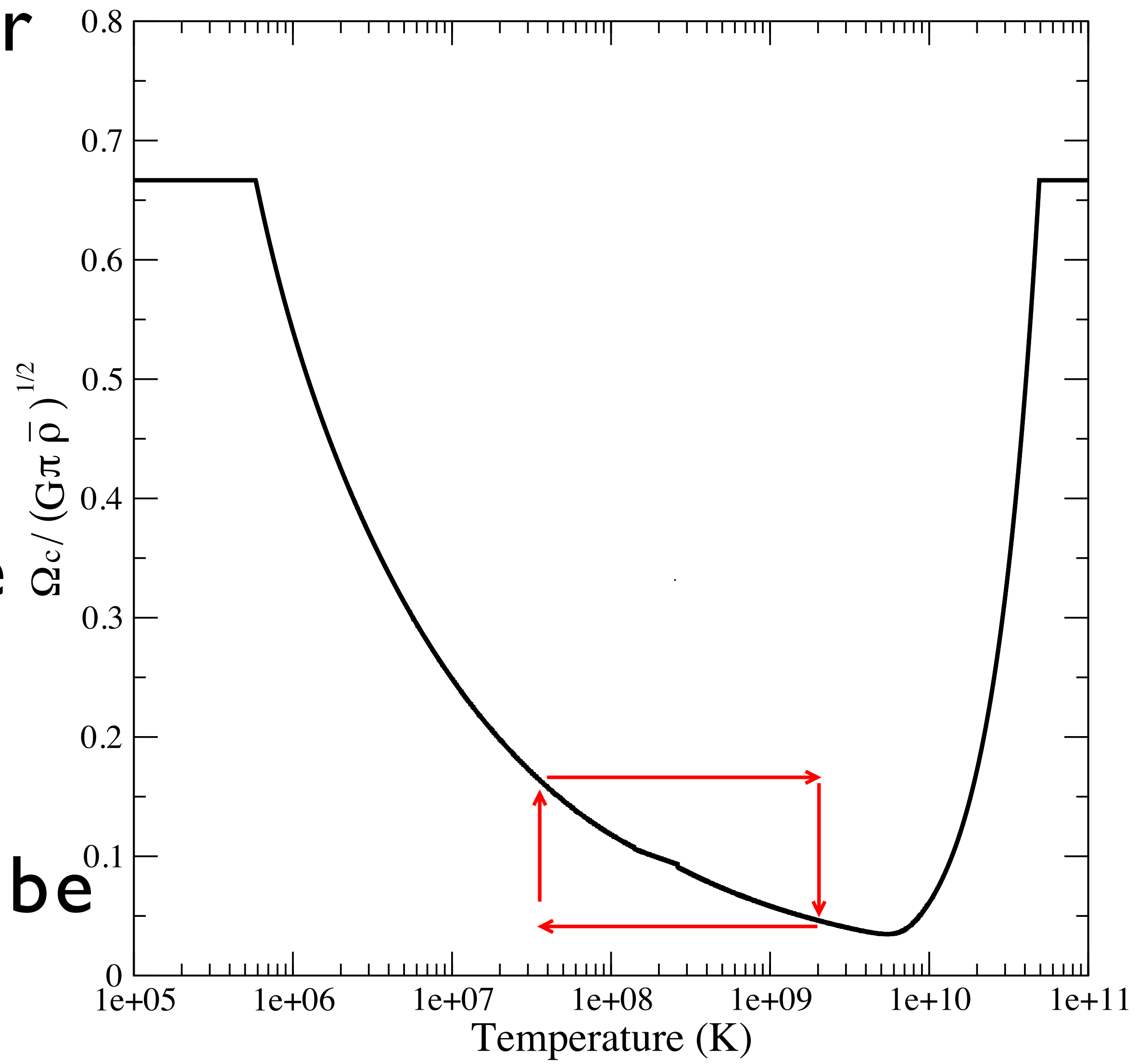


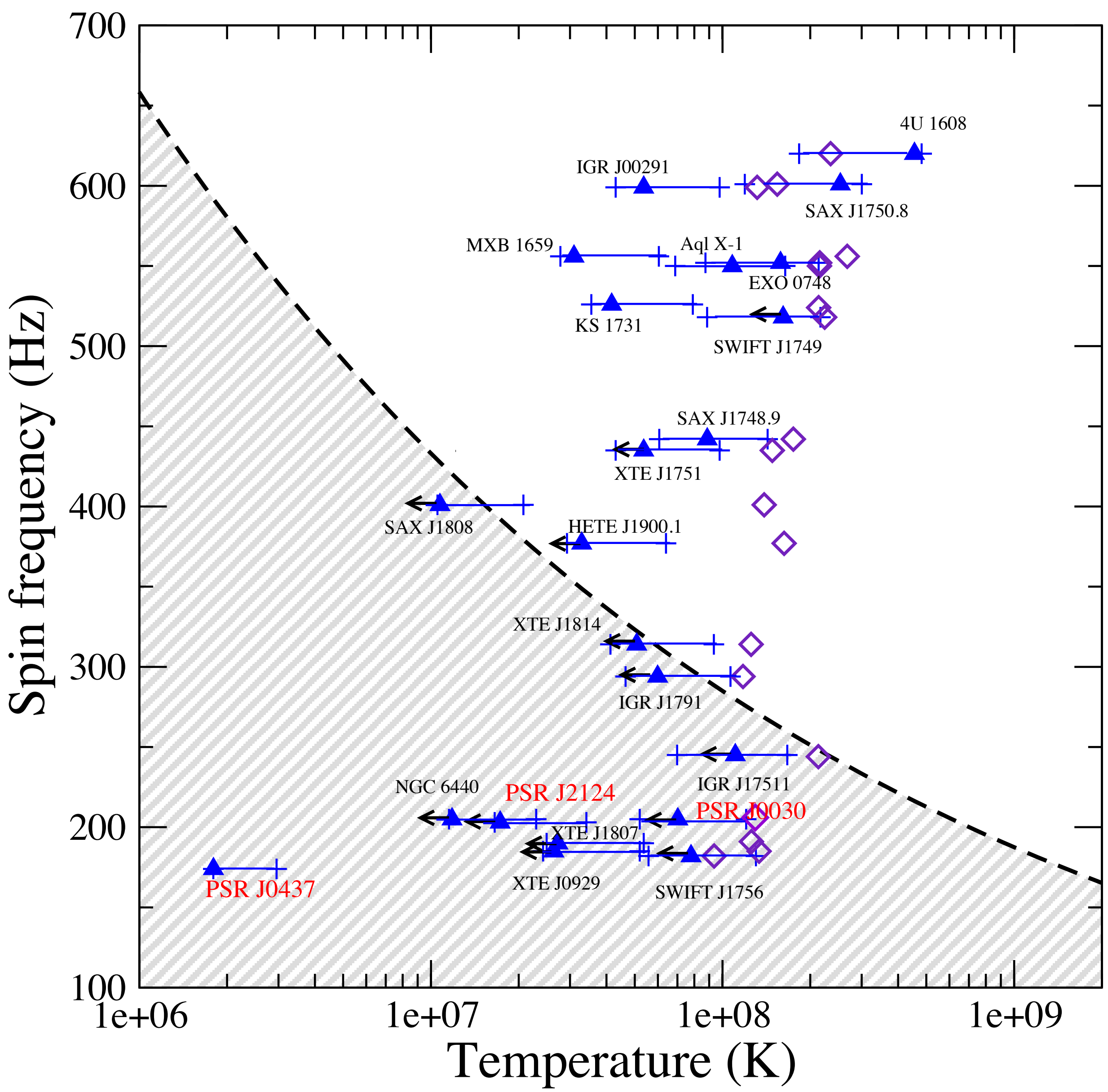
# r-mode instability window - I

- "Minimal" model - no exotica or superfluid mutual friction
- Duty cycle short (1% or less)
- Do not expect systems IN the window
- Saturation amplitude likely to be small (Bondarescu et al 2007)

$$\alpha_s \approx 10^{-5}$$



# Spin equilibrium




[ BH, Degenaar & Ho (2012), Mahmoodifar & Strohmayer (2013)]

- Is GW emission from an r-mode dictating spin equilibrium?
- Systems in the unstable region?
- But what if the saturation amplitude is VERY small? Then systems can live in the instability window...need $\alpha \approx 10^{-6} - 10^{-9}$

[ Bondarescu & Wasserman (2013)]

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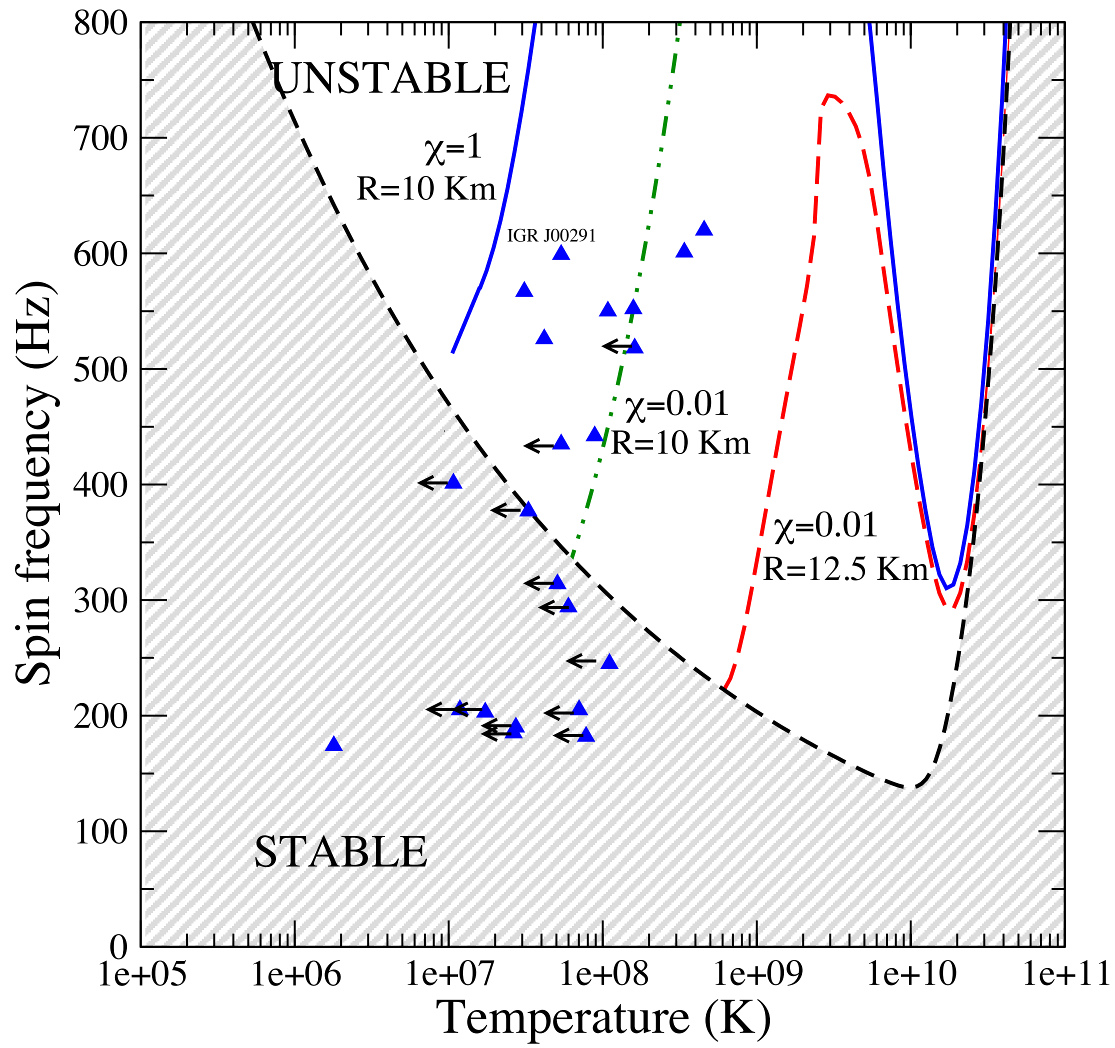
# Enhanced viscosity

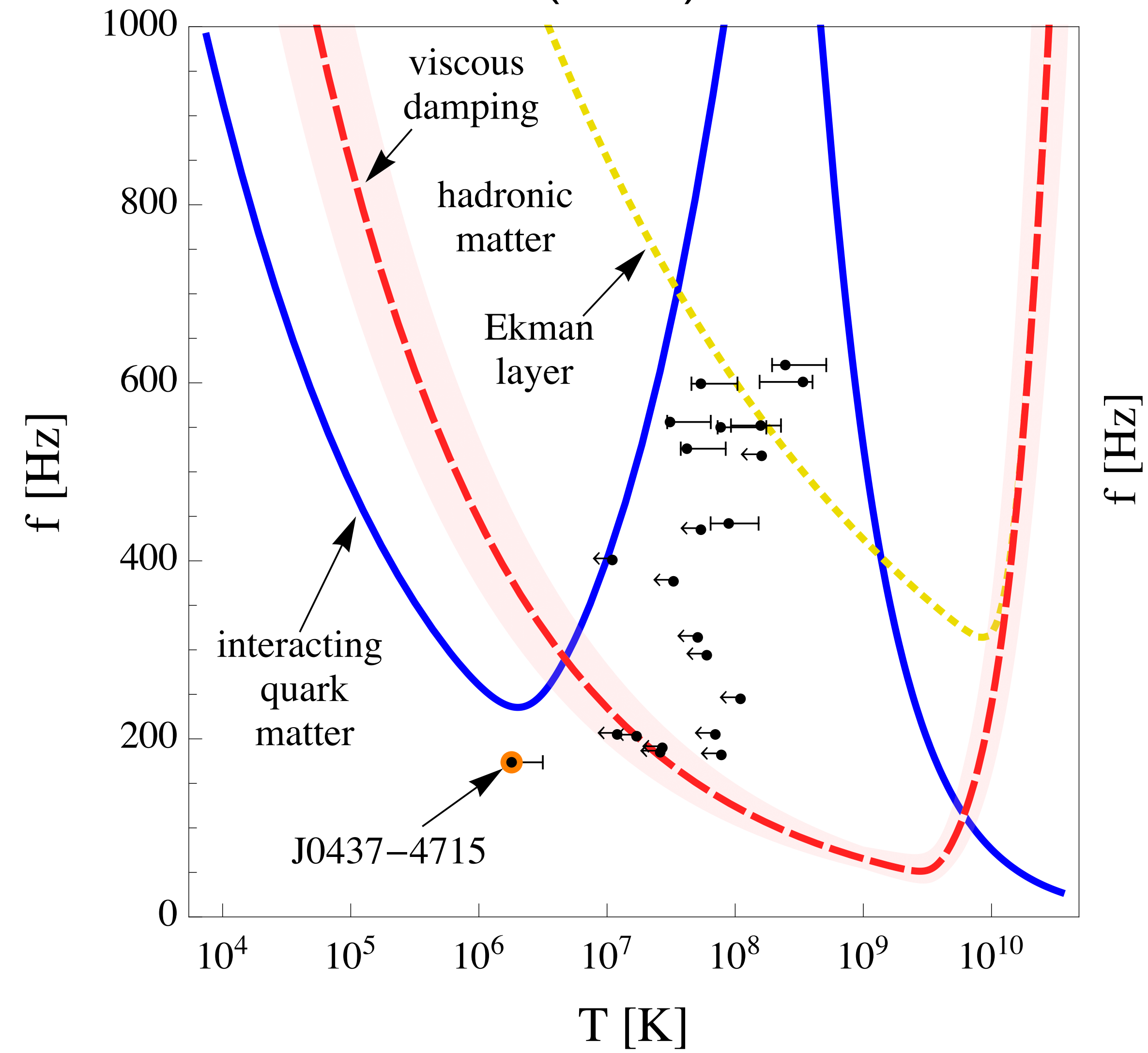
- Hyperon Bulk viscosity - active at lower T

[BH & Andersson (2010)]

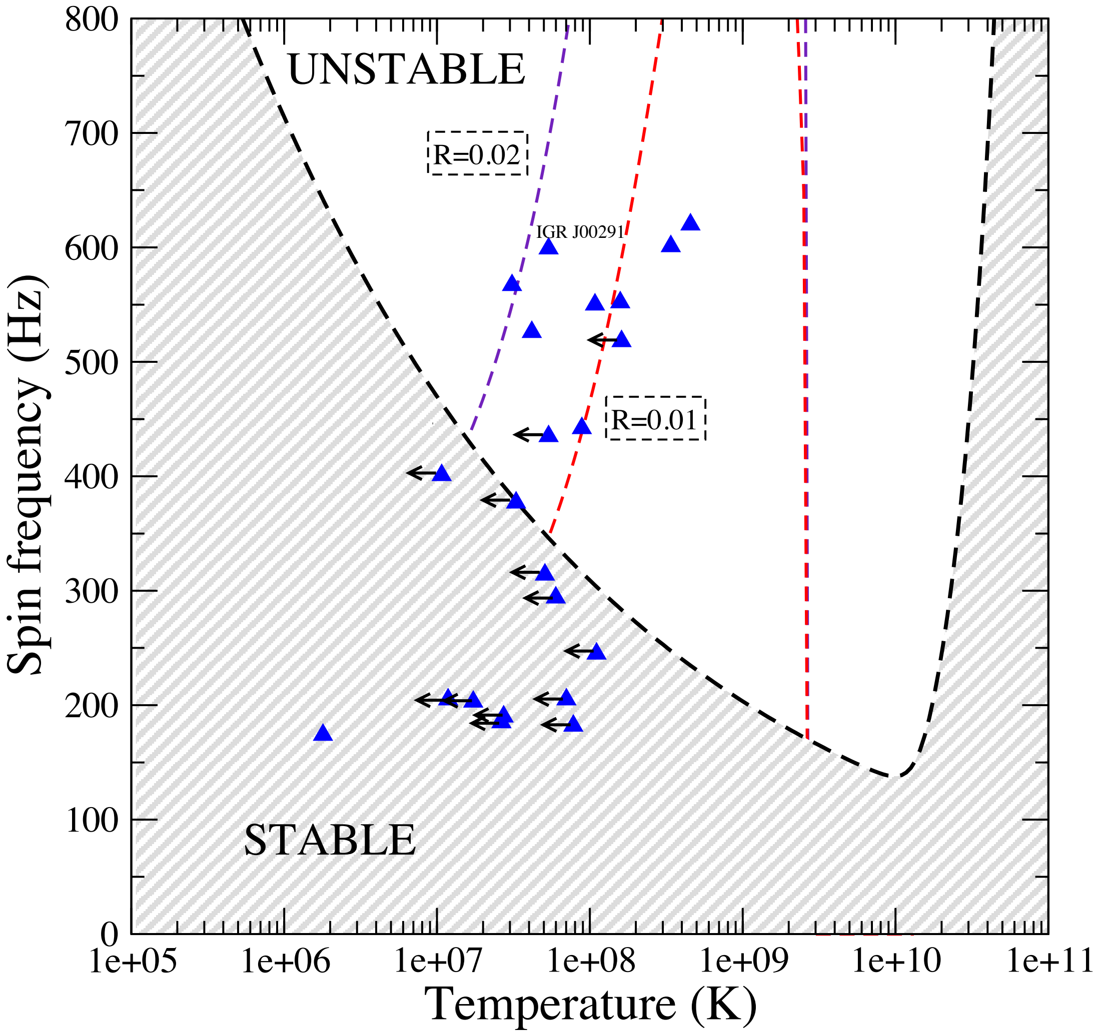


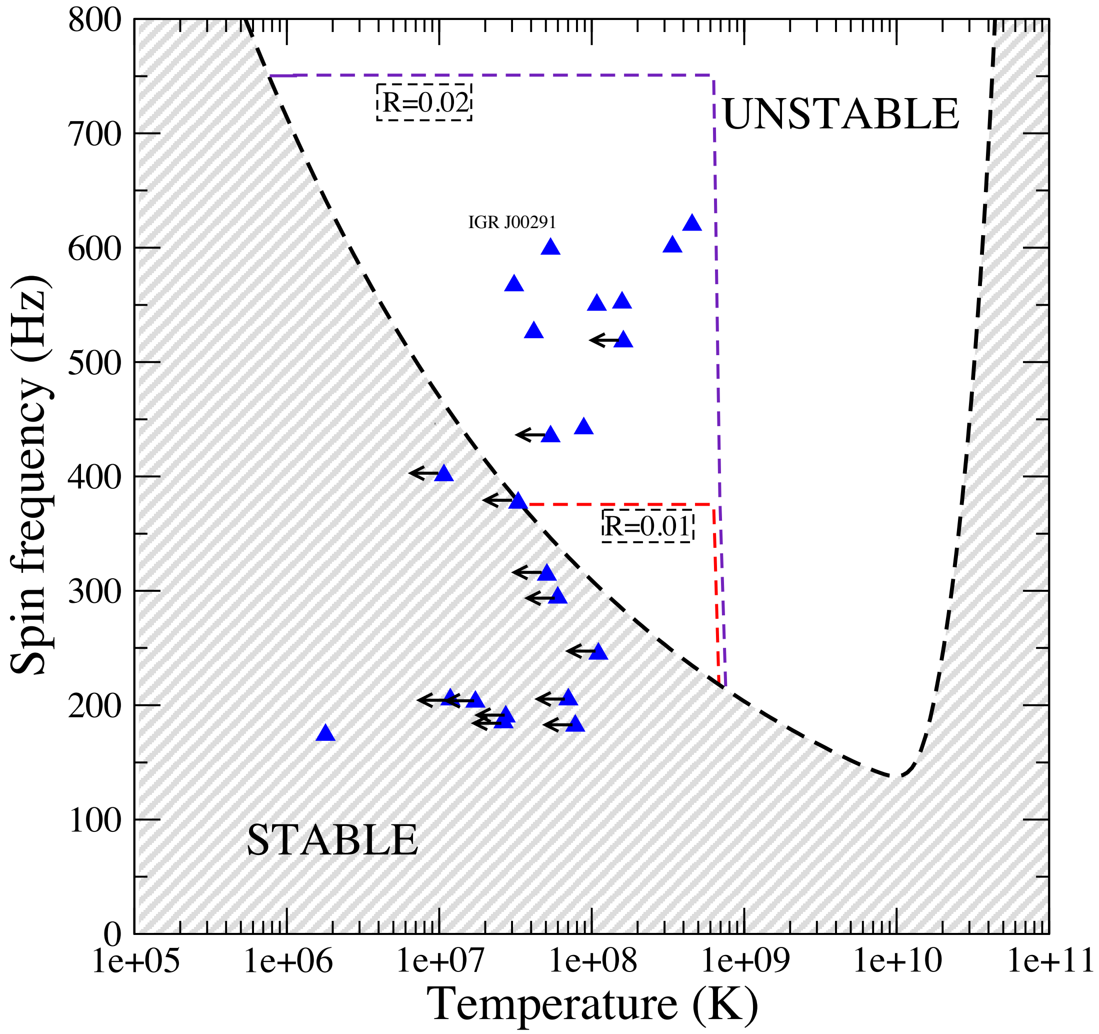

- Ungapped quarks - effect much weaker with pairing

[Andersson, BH & Comer (2010), Alford & Schwenzer (2014)]



# Strong Mutual Friction - vortex/flux tube cutting?




[ BH, Degenaar & Ho (2012) - Ho, Andersson & BH (2011) - BH, Glampedakis & Andersson (2014)]

# Saturation amplitude

- Vortices can pin to flux tubes, but large counter-moving motion can lead to unpinning

$$w_{\rm pin} \approx \frac{f_{\rm pin}}{\rho_n \kappa} \approx 1.5 \times 10^4 \, \rho_{14}^{-1} \, B_{12}^{1/2} \;\; {\rm cm/s}$$

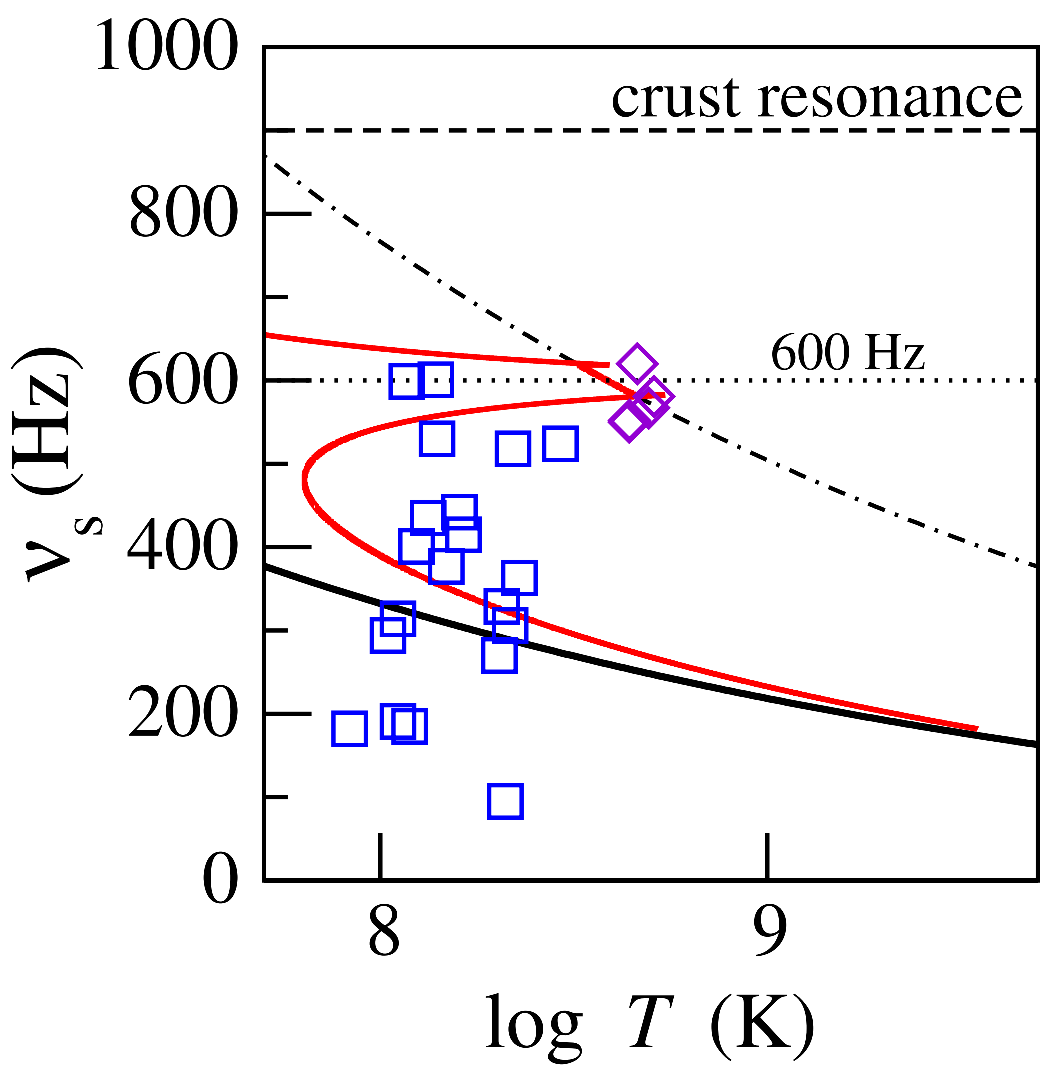
- If vortices unpin strong MF due to cutting will limit the growth of the mode

[ BH, Glampedakis & Andersson (2014)] $\alpha_c \approx 10^{-6}$

- Phase conversion in hybrid stars may lead to saturation

[ Alford, Han & Schwenzer (2014)] $\alpha_c \approx 10^{-5}$

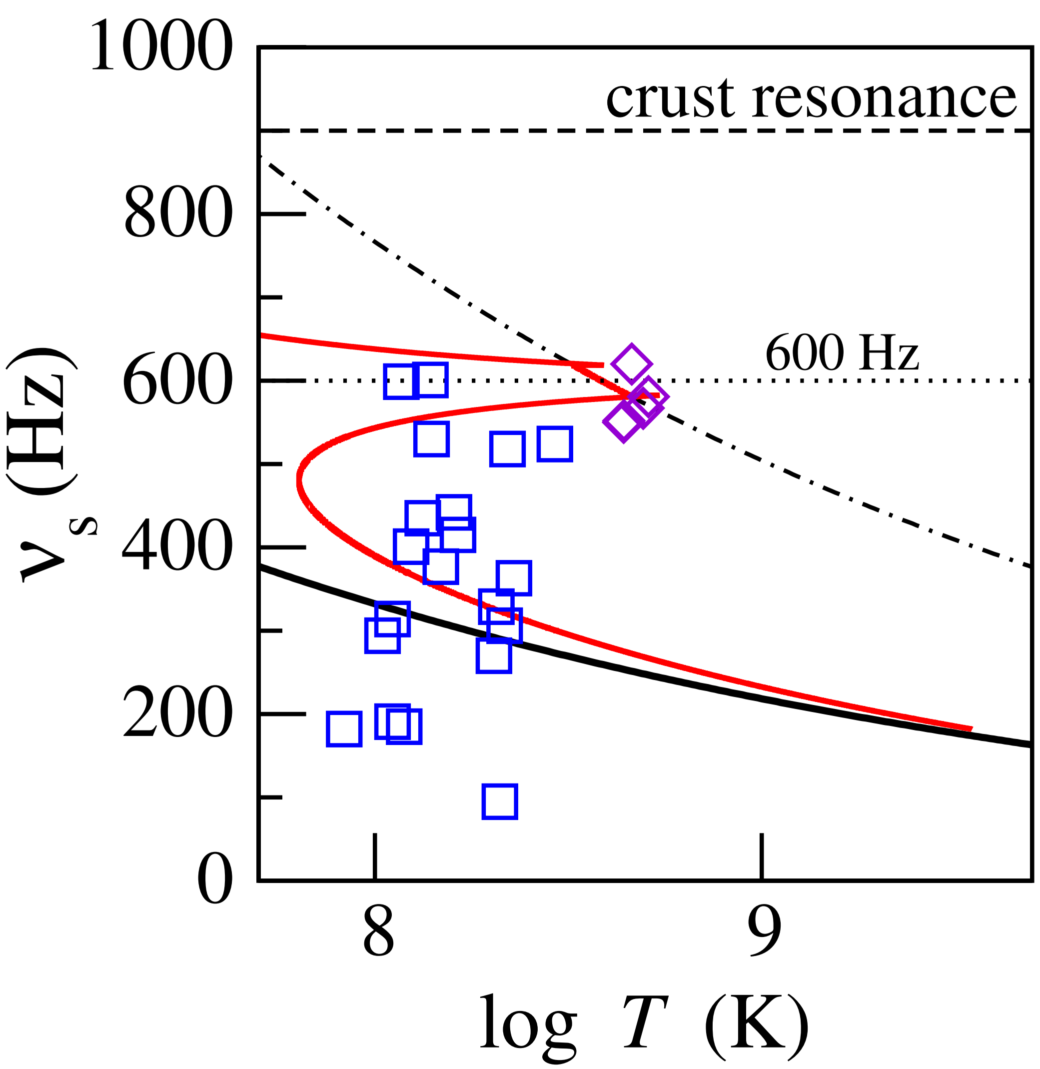
# Crust core interface?

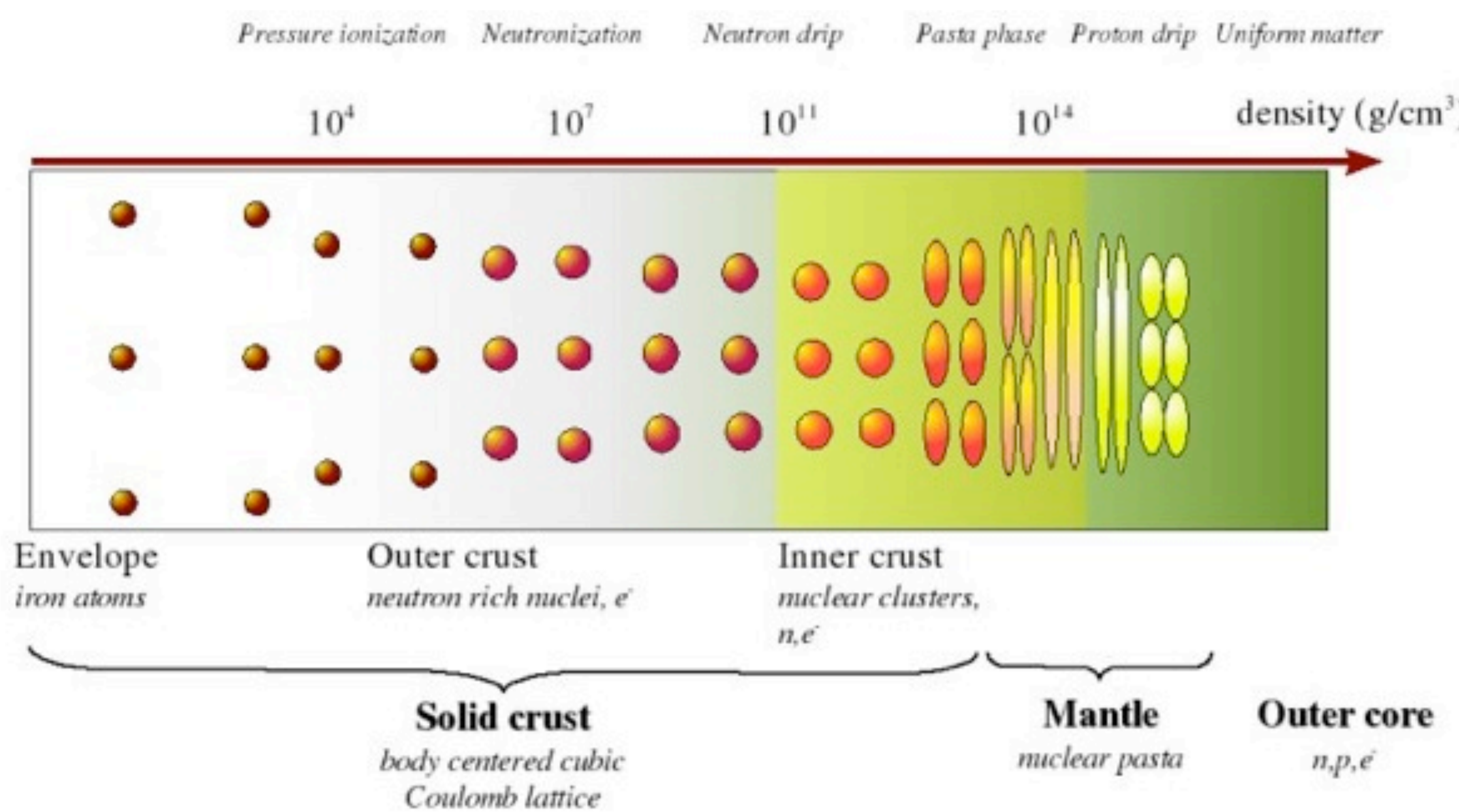



[ Ho, Andersson & BH (2011)]

- Ekman pumping at crust/core interface
- Crust does not respond 'rigidly' at all frequencies
- Resonances between crustal modes and the r-mode are possible

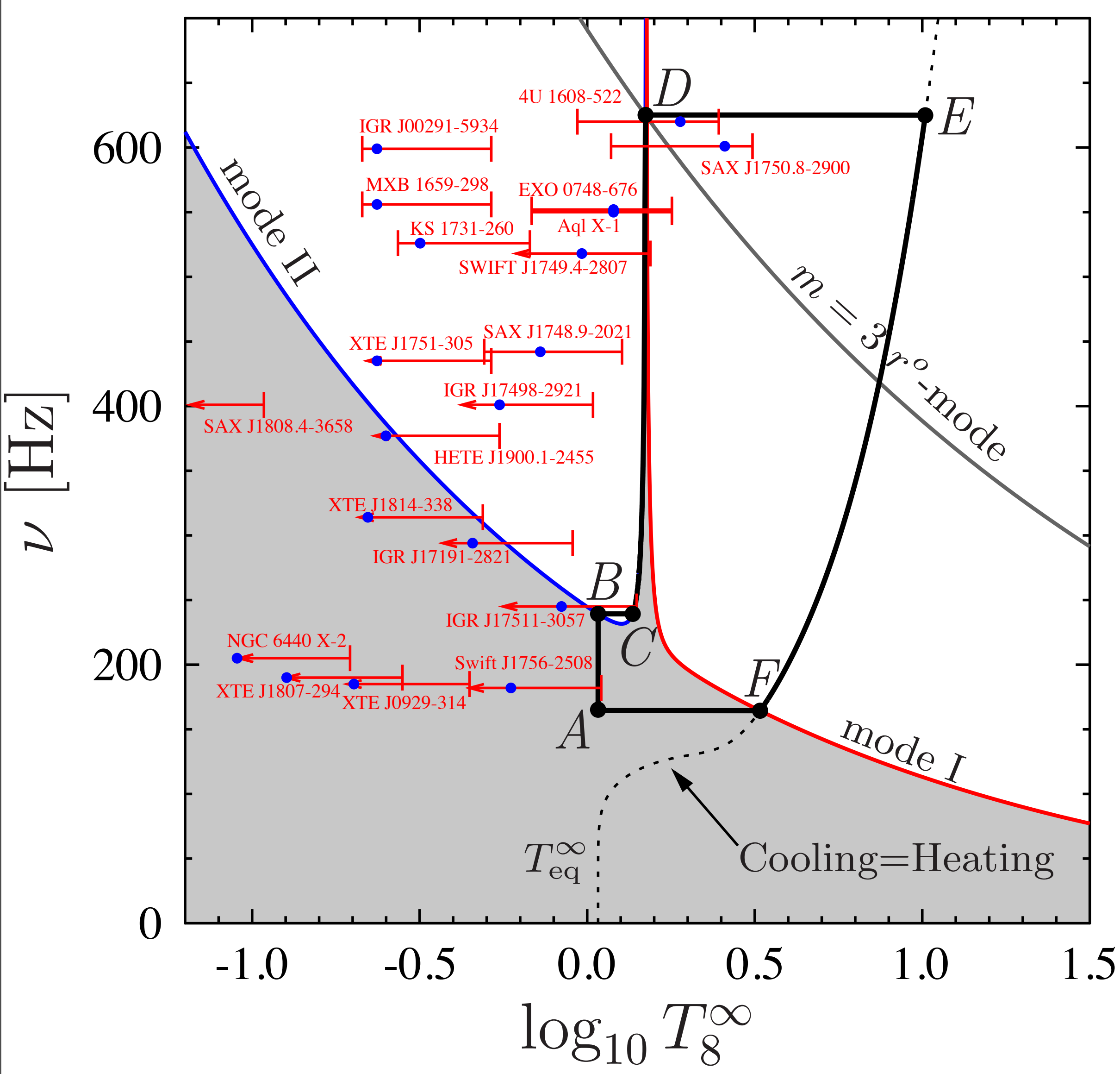
# Crust core interface?

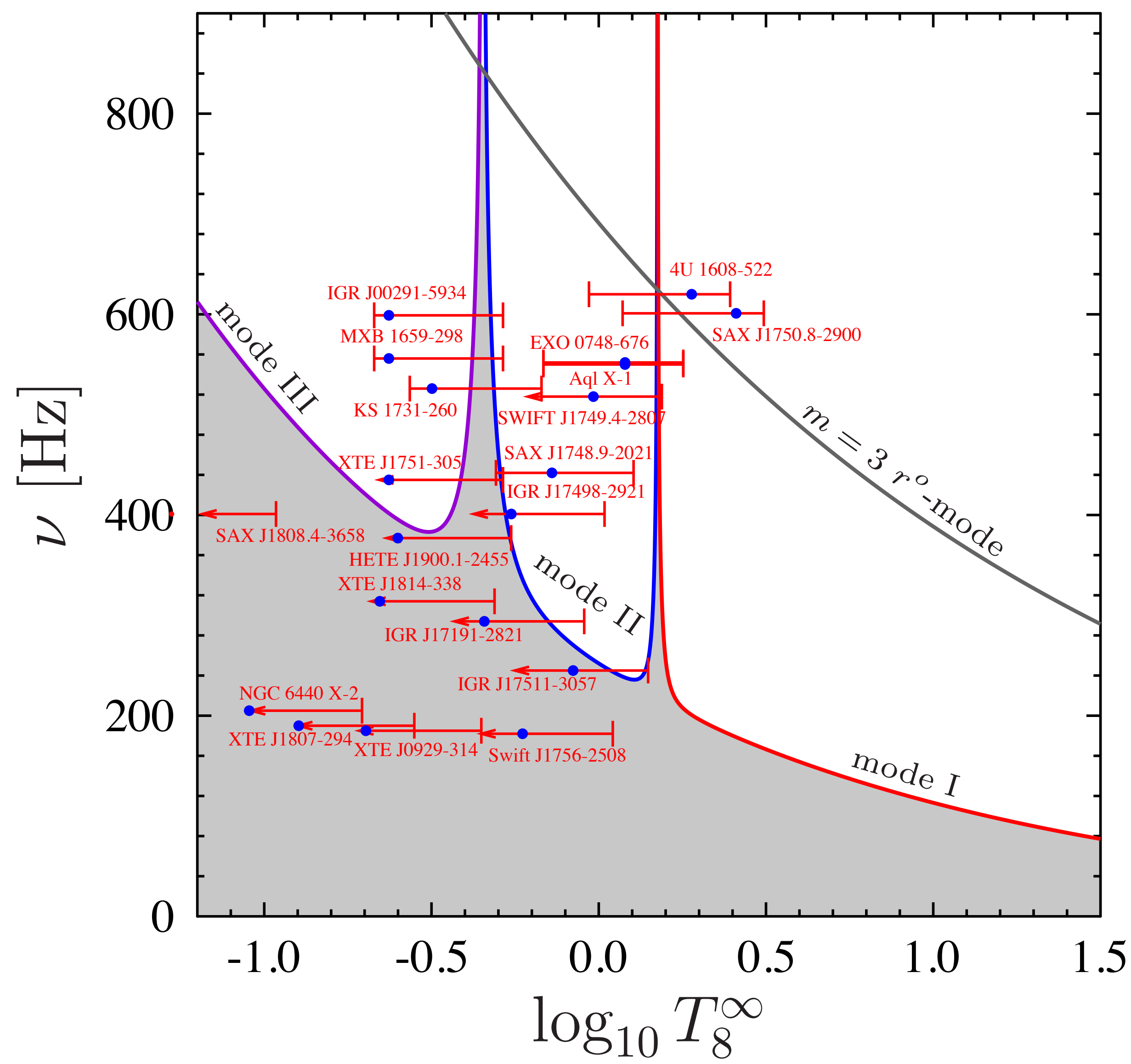



- Pasta phases? May lead to low saturation amplitude (Bondarescu & Wasserman 2013)

# Coupling to inertial modes




[Gusakov, Chugunov & Kantor (2014a,b)]

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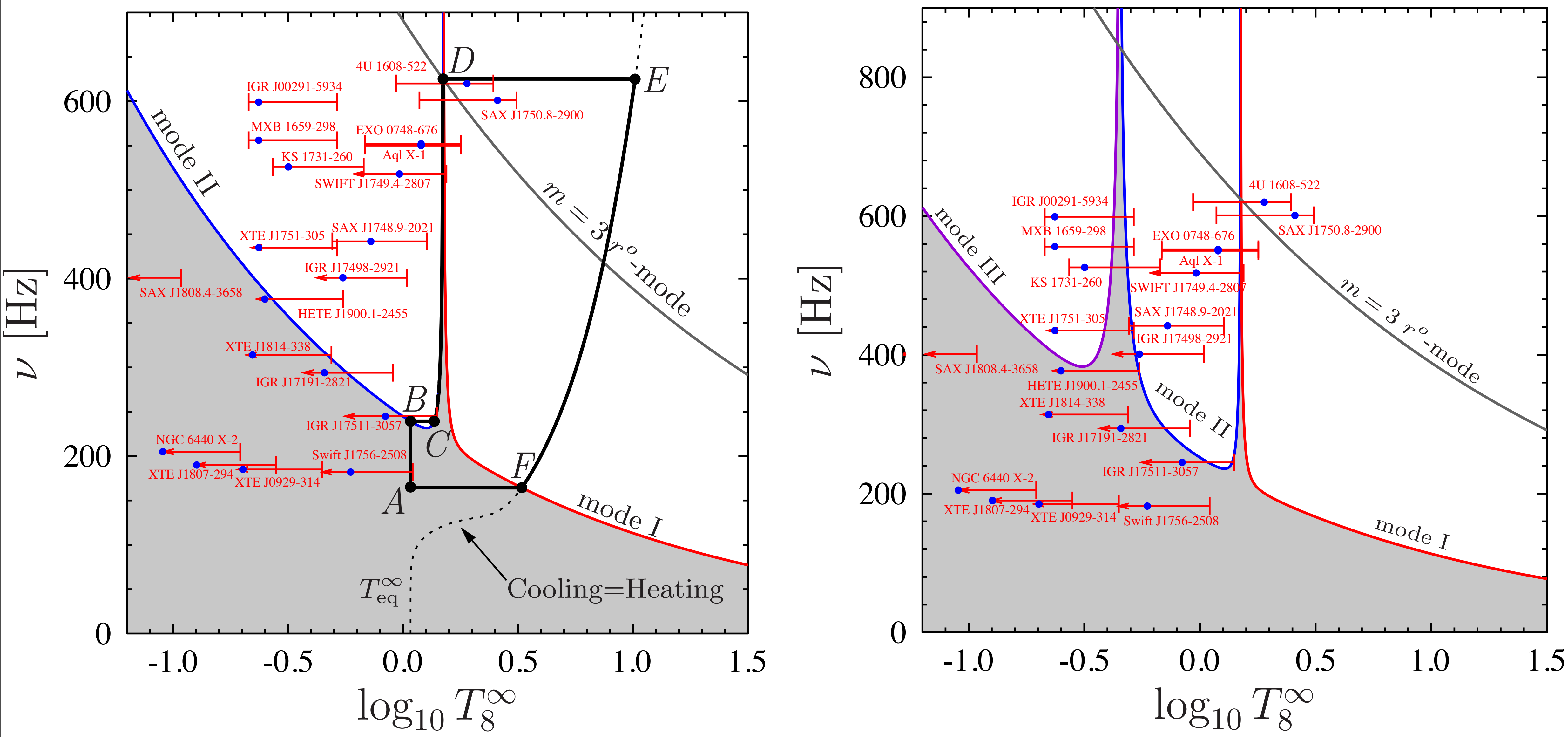


- Predicts new class of ‘hot’ old neutron stars (HOFNARs) [Gusakov, Chugunov & Kantor (2014a,b)]

# Conclusions

- We can still obtain important information about the r-mode instability window and NS physics even **before** GW detection
- Extra physics is needed to explain the observations - ungapped quark mater a contender for stellar interiors
- More theory needed - and more data! GWs will open a new window

# Orange Pulsar Meeting


- Melbourne: 26-28 November 2014
- Contact: Brynmor Haskell

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