QPO Spectrum in Superfluid Magnetars

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References

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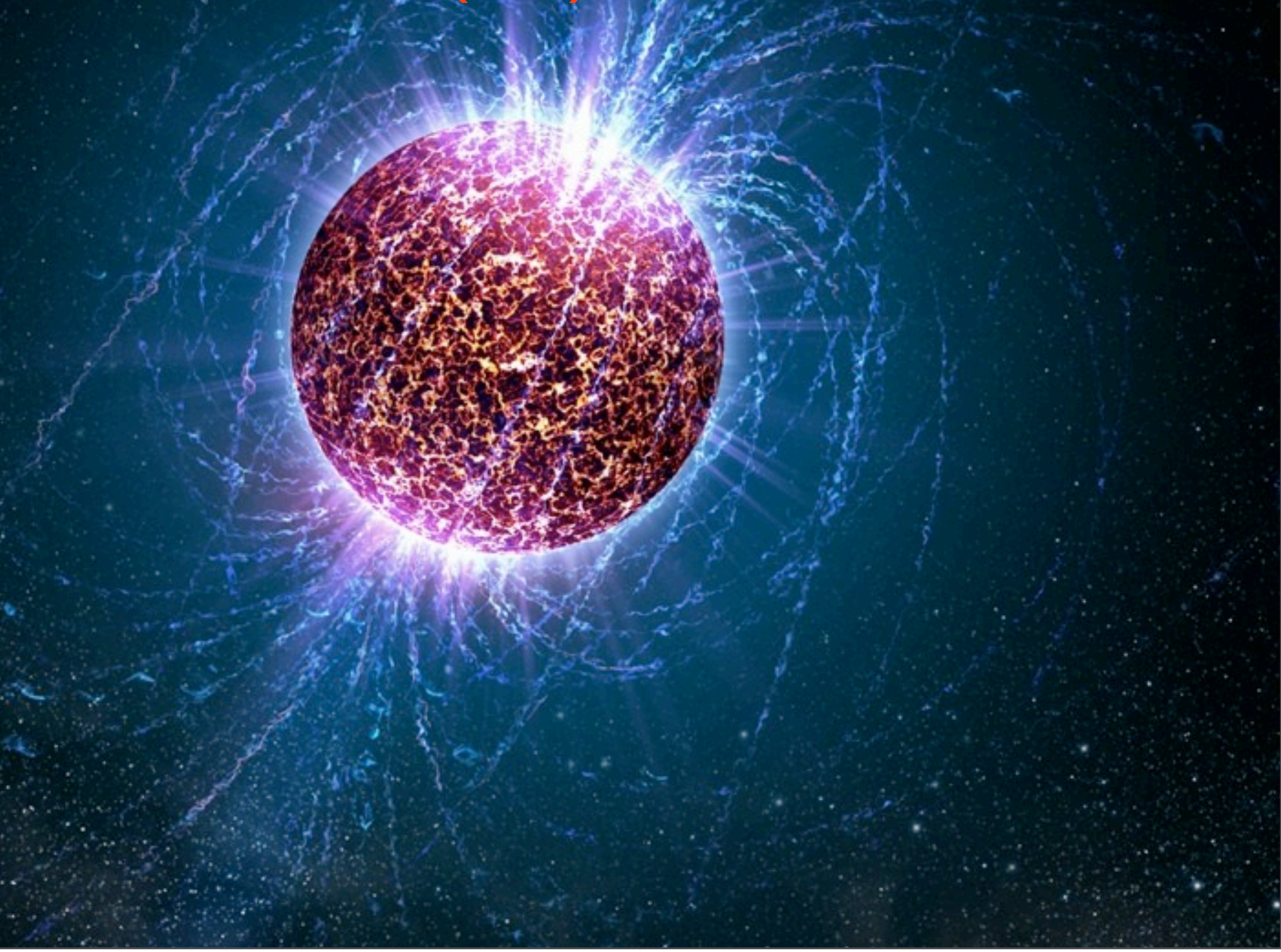
A. Passamonti & S. Lander MNRAS 438, 156 (2014)



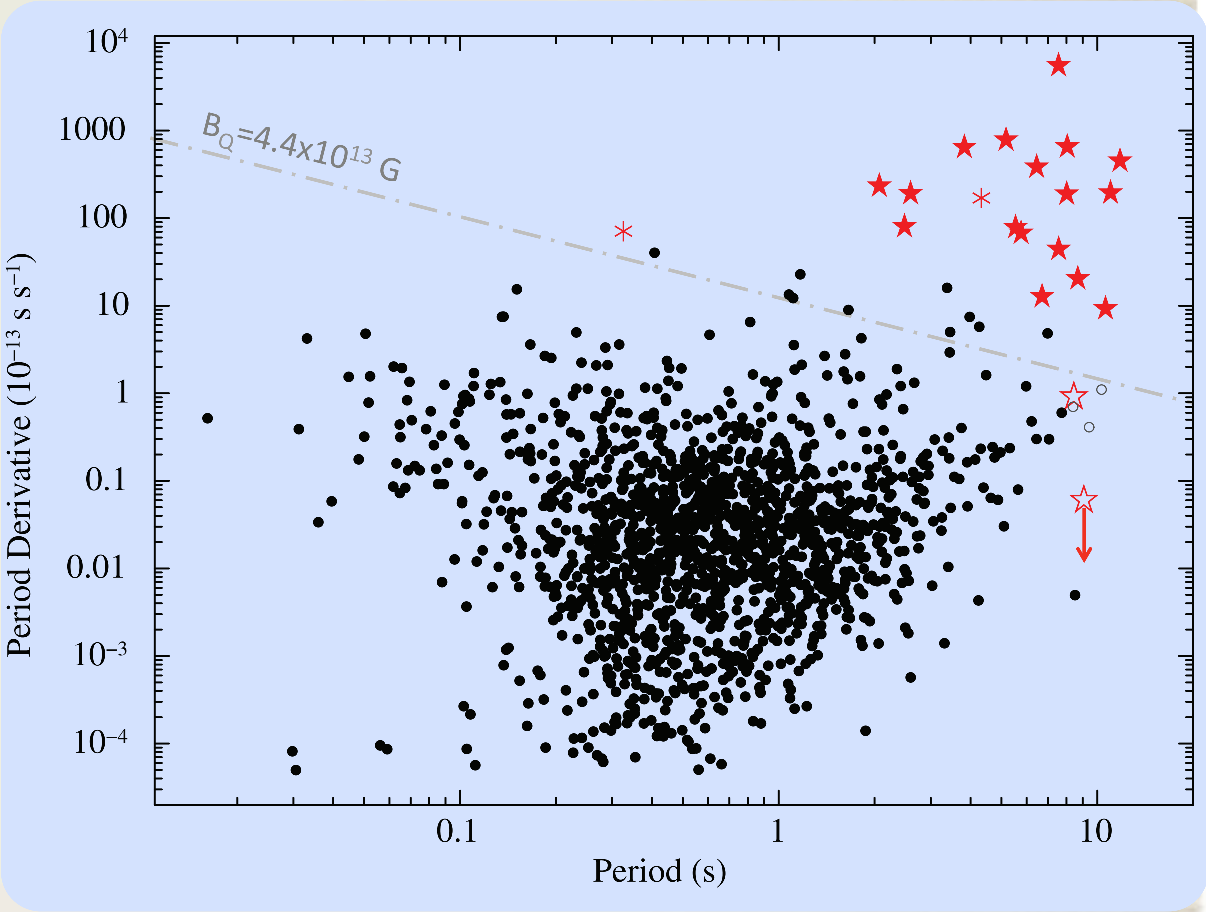
Magnetars

✦ Neutron stars with a strong magnetic field $B>10^{14}$ G, rotation period P~2-12 s and age ~ 10^3-10^4 yr.

★ about 20 Magnetars (AXP, SGR)

✦ The strong magnetic field powers:

- persistent X-ray emission L ~ 10^{34}-10^{36} erg s^{-1}
- outbursts L ~ 10^{41} erg s^{-1} in ~ 0.1 s
- giant flares L ~ 10^{44}-10^{46} erg s^{-1}
- intermediate flares L ~ 10^{42} erg s^{-1} in ~ 1 s

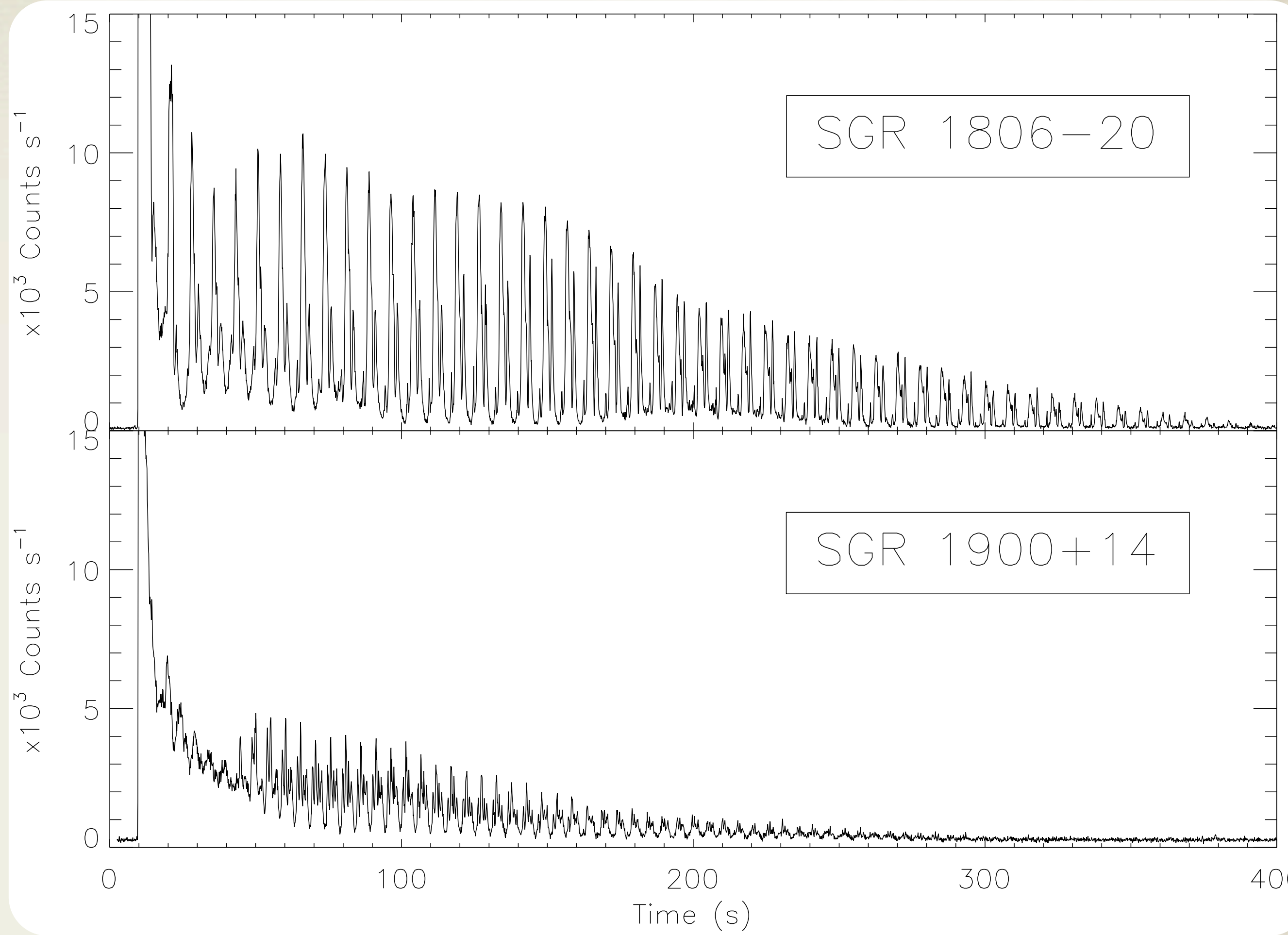


This activity is powered by the energy of a strong magnetic field.

QPOs (Israel et al., 2005; Strohmayer & Watts, 2005; Watts & Strohmayer, 2006)

Observed in three giant flares
with $E_{tail} \sim 10^{44}$ erg

- SGR 0526-66 (1979): 44.5 Hz
- SGR 1900+14 (1998): P~5.2 s
  freq.: 28, 53, 84, 155 Hz
- SGR 1806-20 (2004): P~7.6 s
  freq.: 18, 26, 30, 93,150, 626, 1837 Hz



Possible seismic origin:

- ☆ Magnetic field reconfiguration fractures the crust producing magneto-elastic waves.

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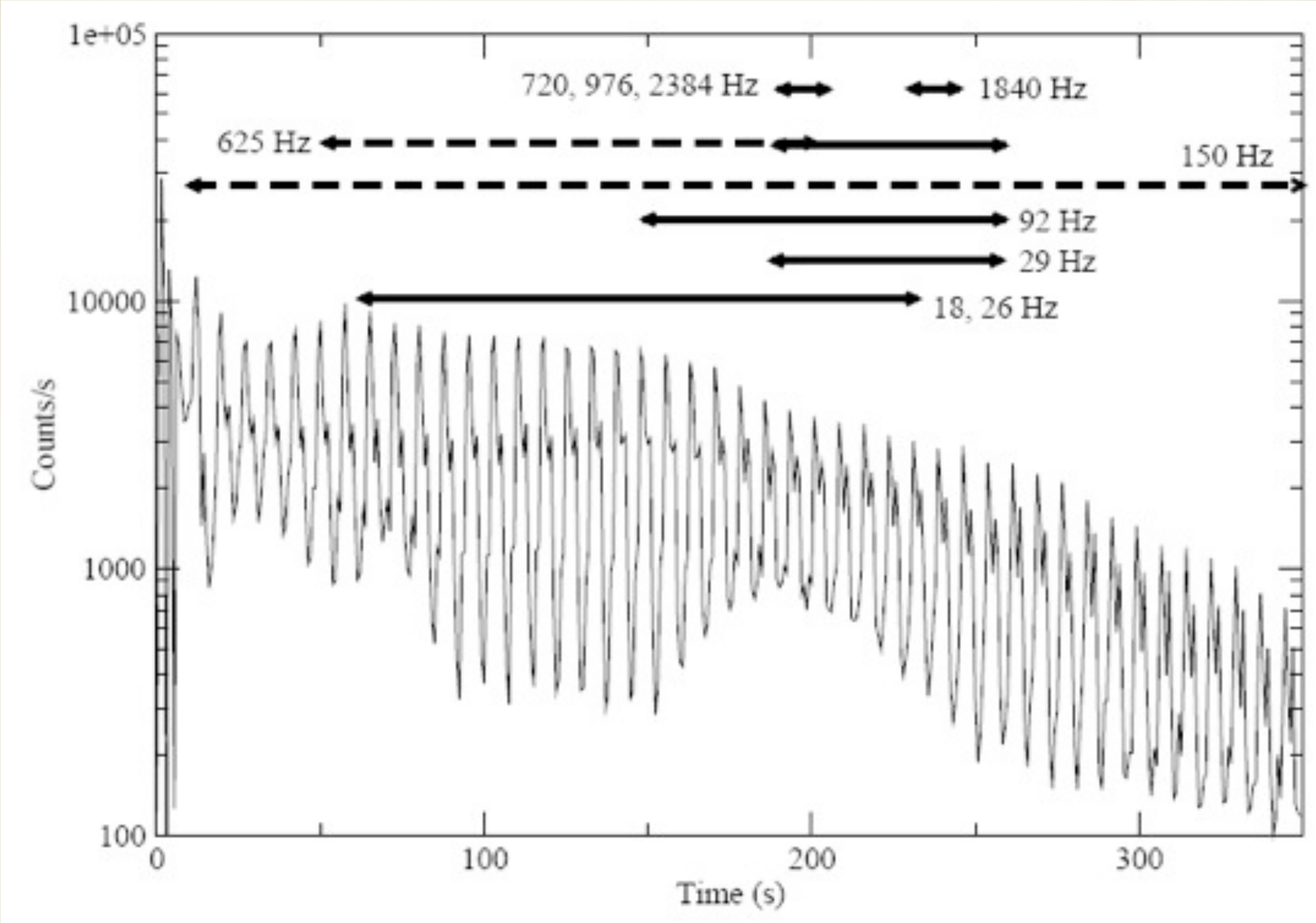

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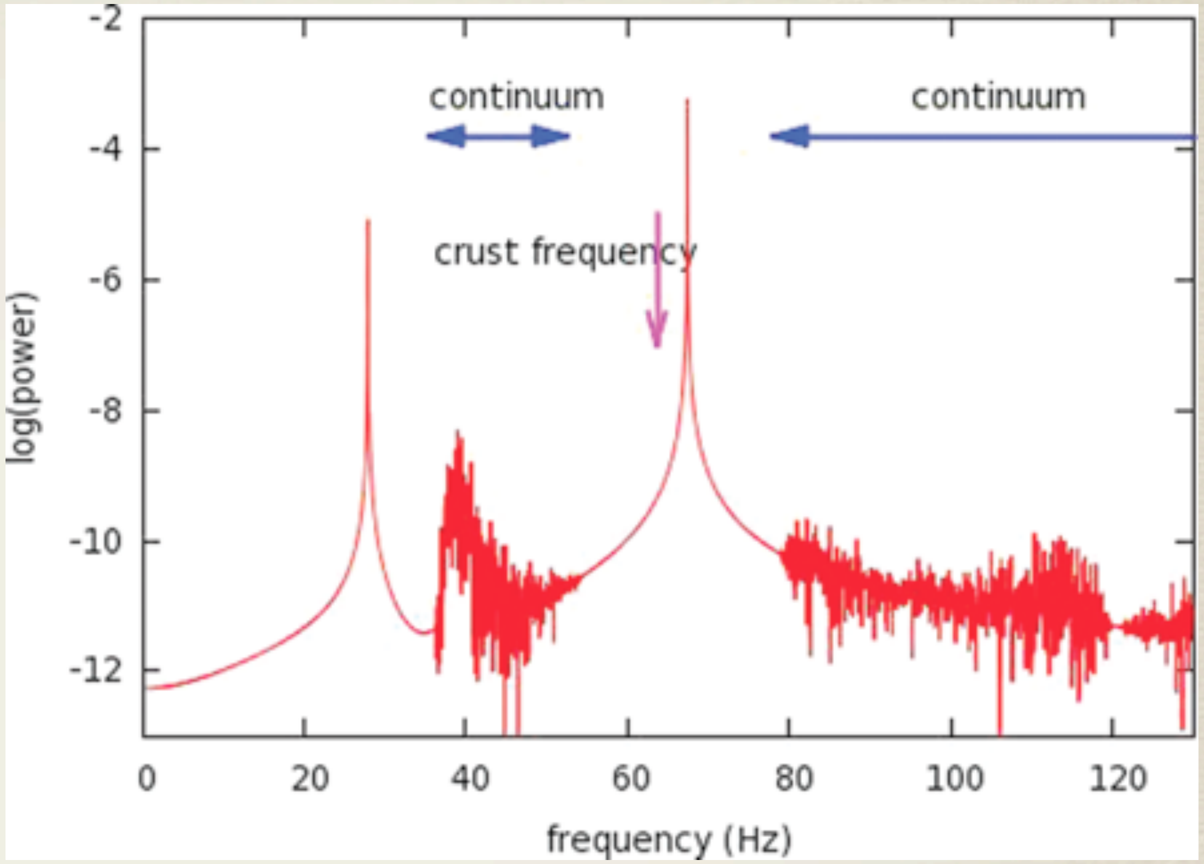
☆ Magnetic field reconfiguration fractures the crust producing magneto-elastic waves.

Interpretation of QPOs

Observed in three giant flares.



van Hoven & Levin MNRAS 410, 1036 (2011)

★Axisymmetric torsional Alfvén modes form continuum bands. Levin (2007)

★Crustal modes are quickly damped when their frequencies lay into the continuum.

van Hoven & Levin (2011), Gabler et al. (2012)

★More general classes of modes as non-axisymmetric modes or poloidal axisymmetric modes do not show a continuum.

Sotani et al. (2008), Lander, Jones and AP (2010), Colaiuda & Kokkotas (2012)

Interpretation of QPOs

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Purely crustal oscillations

$$\frac{\Delta R_{cr}}{R} \approx \frac{{}^{l}f_0}{{}^{l}f_n}$$

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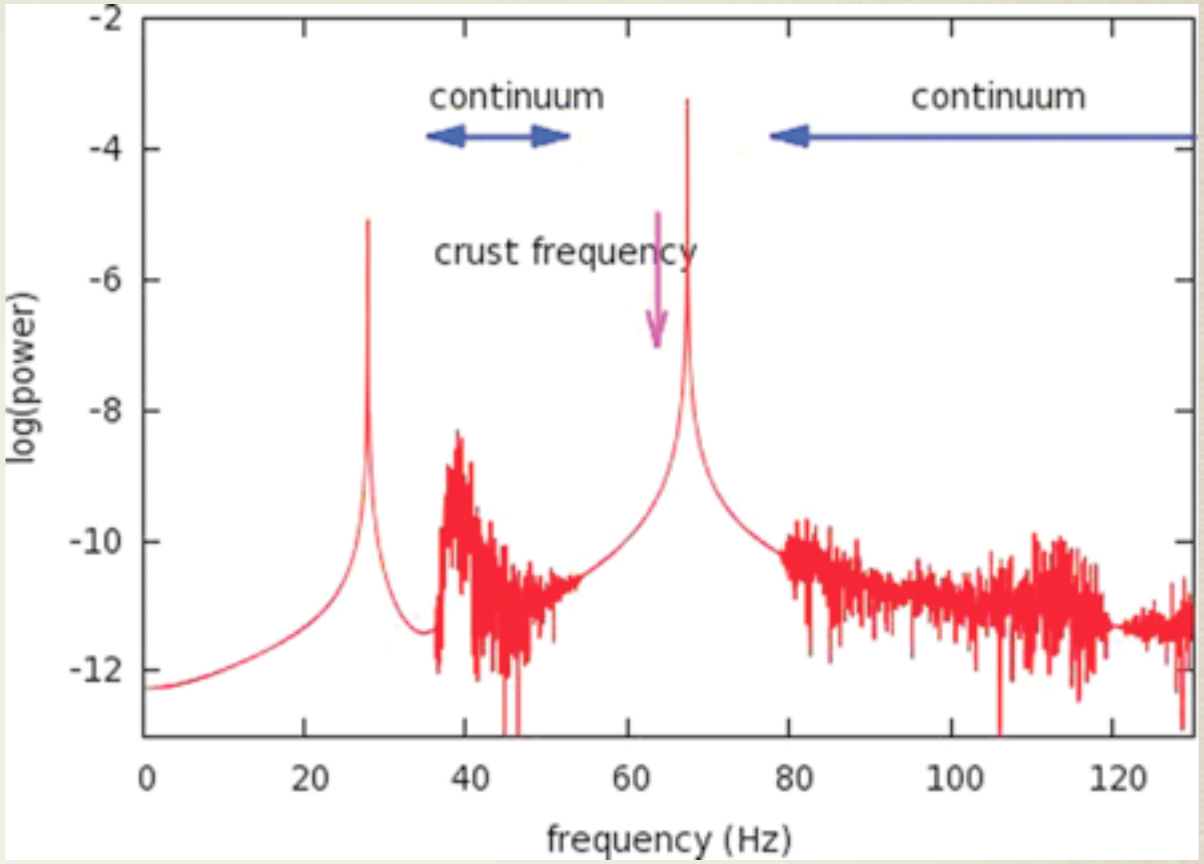

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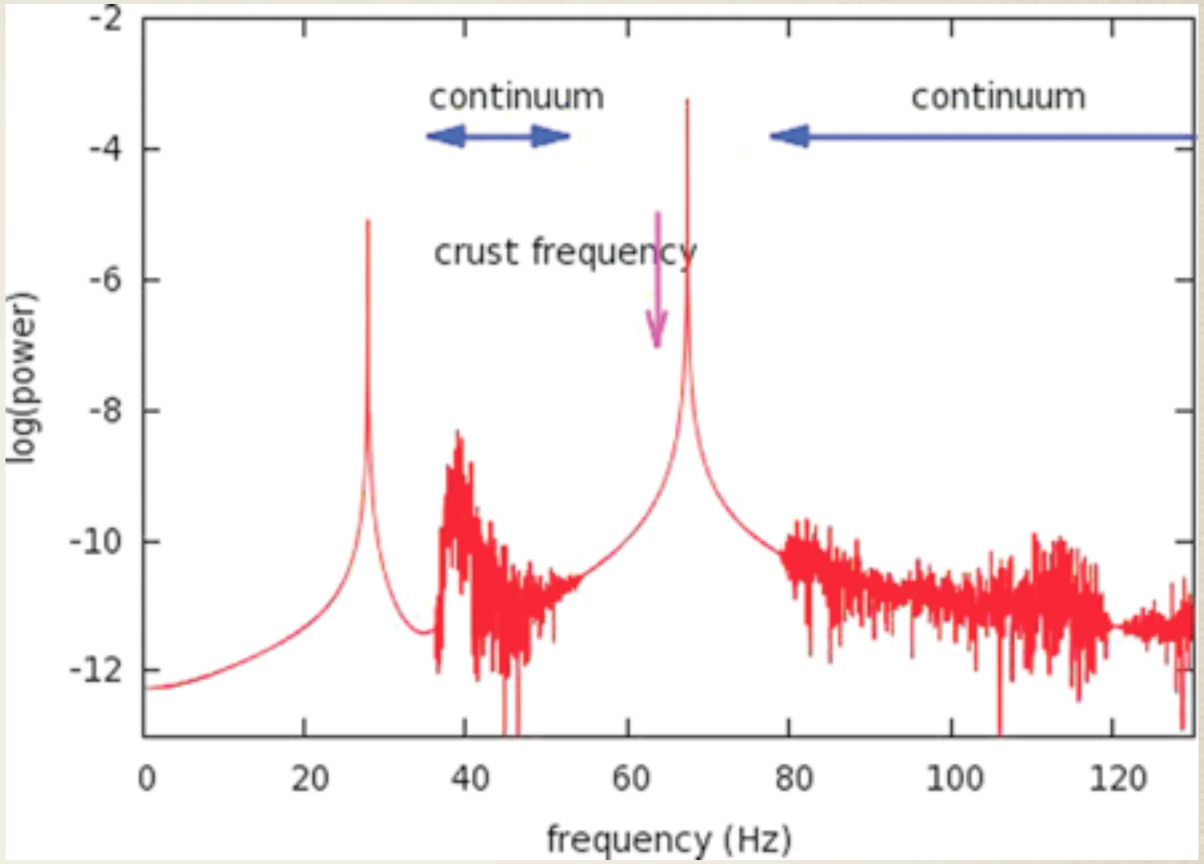

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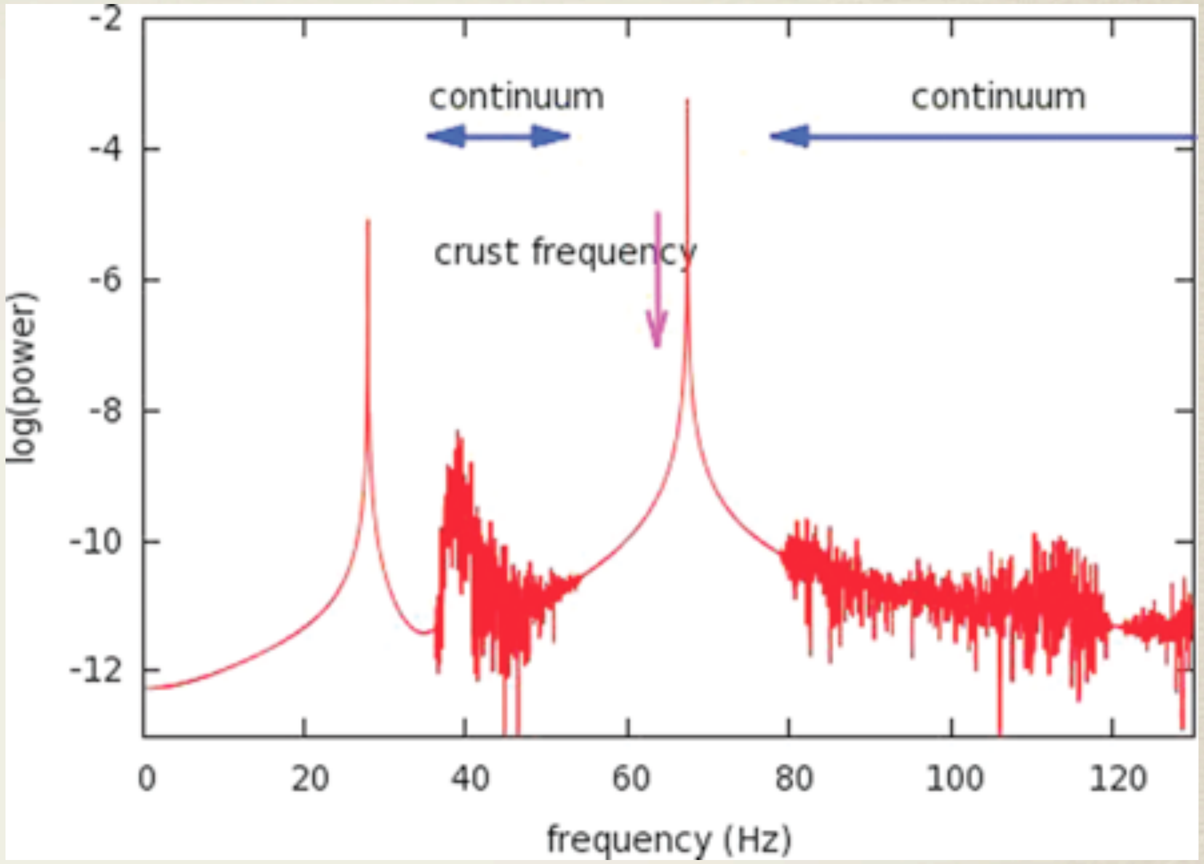

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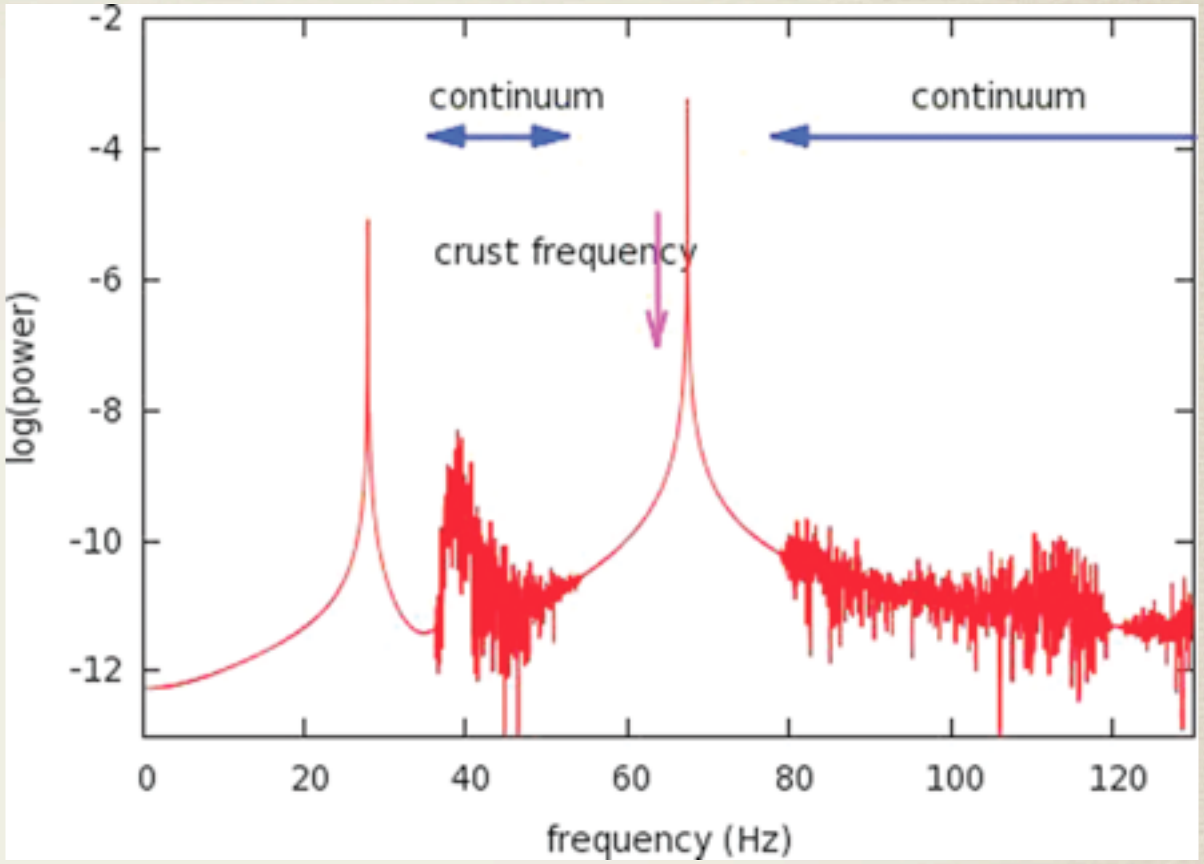

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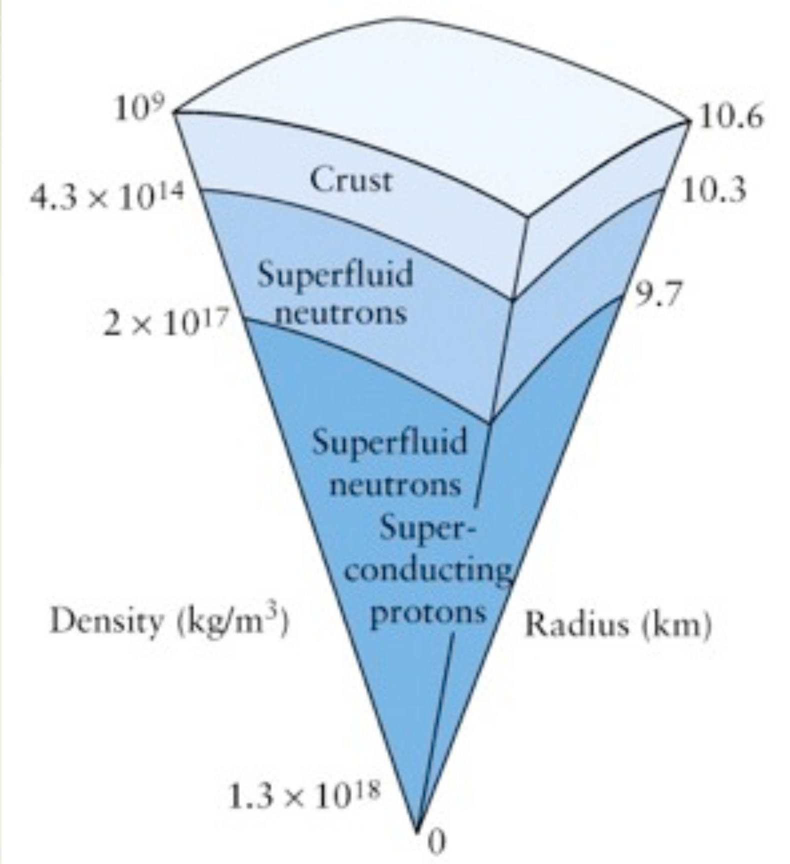
☆ What are the effects of superfluidity on the QPO spectrum?

Two-fluid model

A zero temperature superfluid star may be described by a two-constituent system:

1) component of superfluid neutrons in the core and the inner crust

2) neutral conglomerate of all the other particles



Assumptions:

- Electrons/muons in the core are coupled to the protons on very short timescale.
- Vortices and fluxtubes are sufficiently dense that a smooth-averaging can be performed.

Equations of motion

- Superfluid dynamics of magnetised neutron stars (Glampedakis, Andersson, Samuelsson 2011)

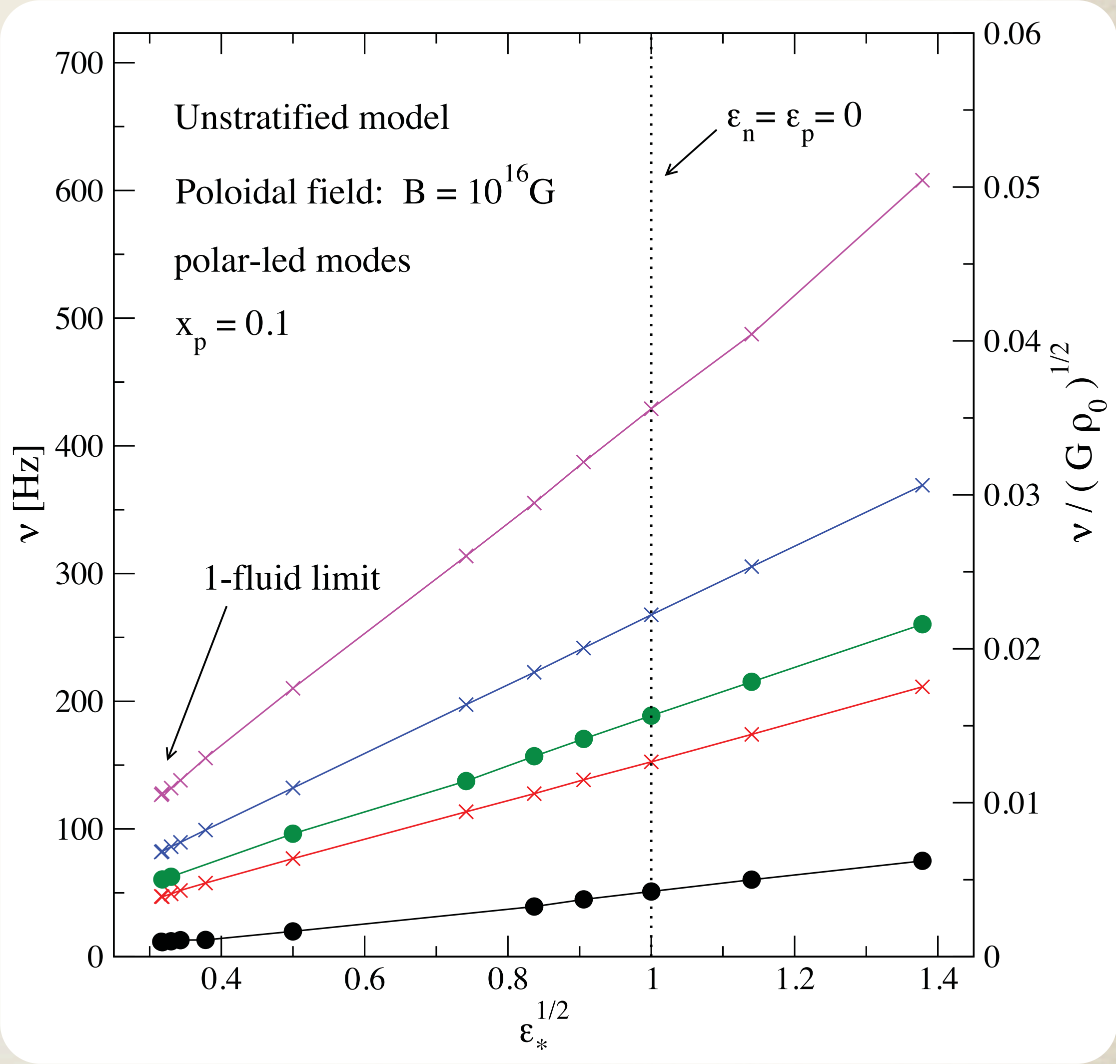
- Two-fluid mass and momentum conservation equations.
- Poisson and Induction equation.
- Two-fluids are coupled by the entrainment which is a non-dissipative process that induces a relative drag between the superfluid constituents.
- Strong entrainment forces the fluid components to co-move.

Superfluidity in Alfvén waves

-Two-fluid decoupled system

$$v_s = \sqrt{\frac{\mu}{\rho_\mathrm{p}}} \qquad v_\mathrm{A} = \frac{B}{\sqrt{4\pi\rho_\mathrm{p}}} \qquad \rho_\mathrm{p} \simeq 0.05\rho$$

Effect of entrainment



- In non-axisymmetric modes (models without crust)

★The total effect with composition stratification and core's entrainment.

$$\sigma \approx 6.3\sigma_0 \left[0.15 + 0.85\left(\frac{N_\mathrm{p}}{2}\right)\right]\left(\frac{\varepsilon_\star}{1.3}\right)^{1/2}\left(\frac{x_\mathrm{p}(0)}{0.1}\right)^{-1/2}$$

where $\sigma_0 \sim \dfrac{B}{\sqrt{\rho}}$

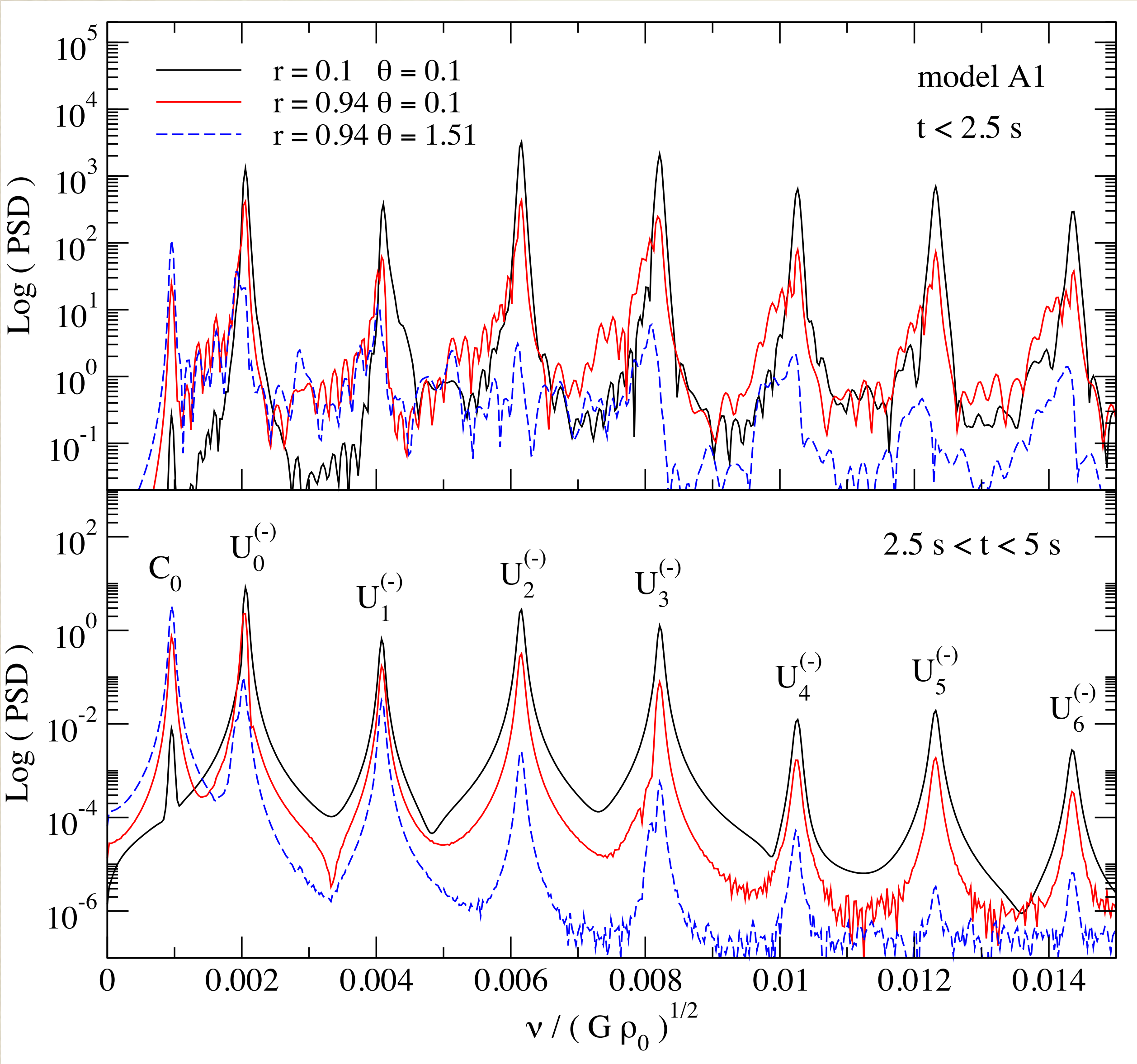
Axisymmetric oscillations

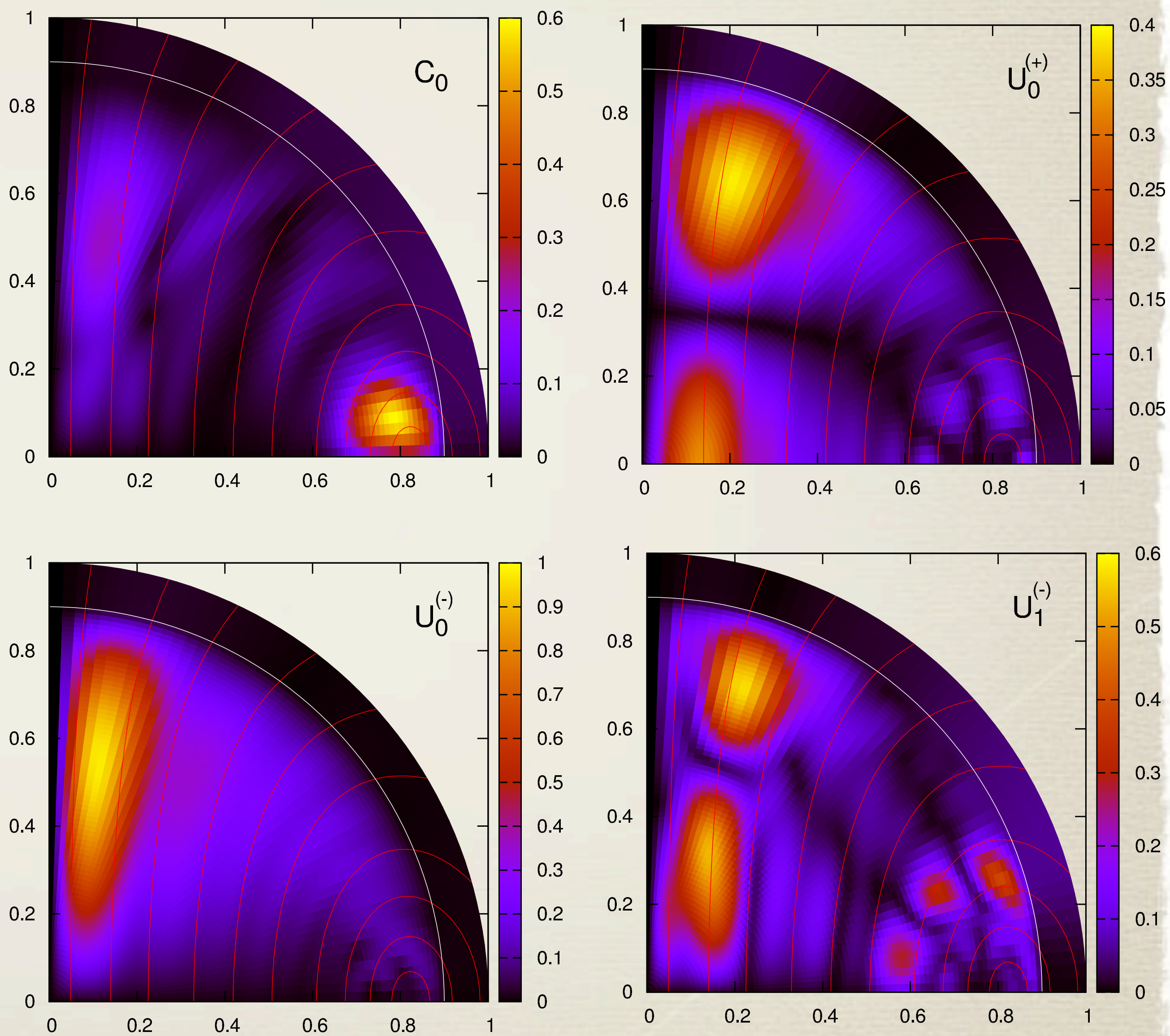
A.P. & Lander S. (2014) MNRAS 438, 156

Stellar models with magnetic field and crust

Constant proton fraction

2D-effective FFT

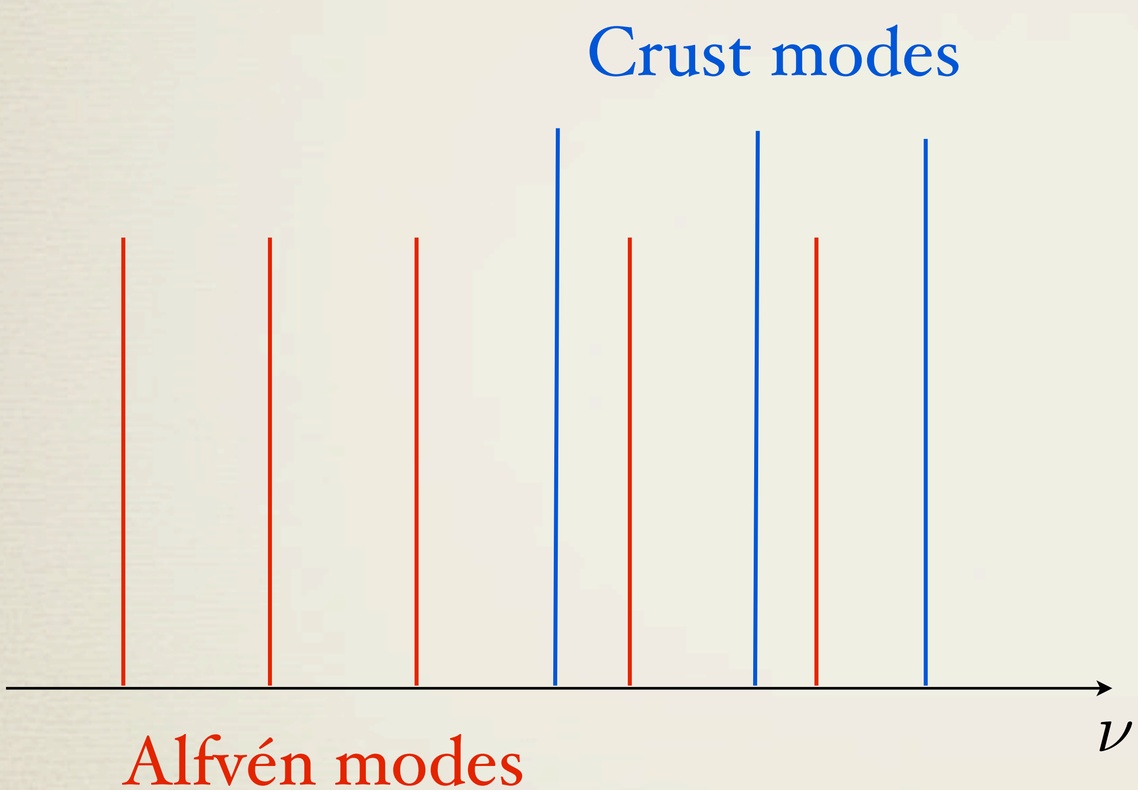


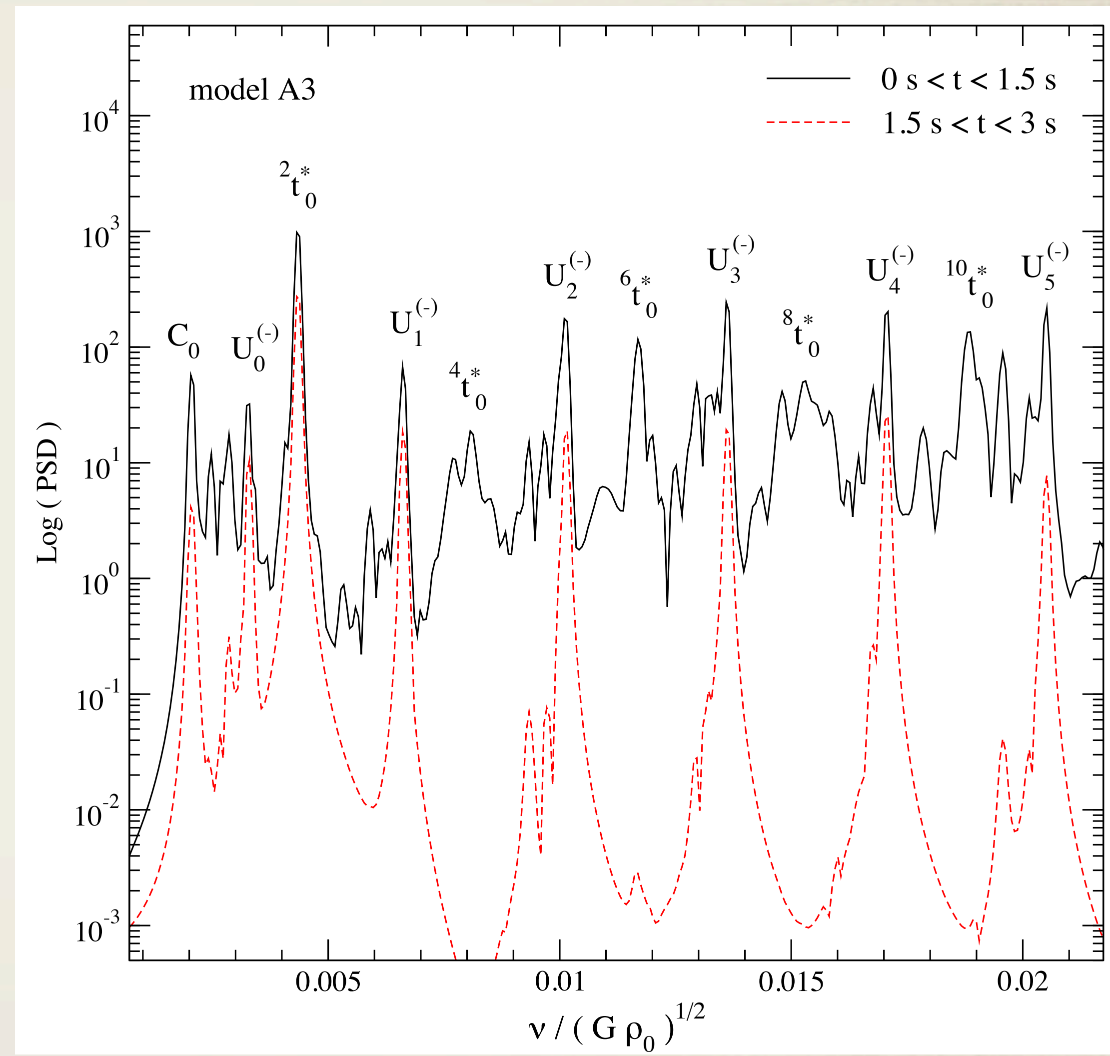


Axisymmetric oscillations

Role of entrainment

Bp~5·10^14G





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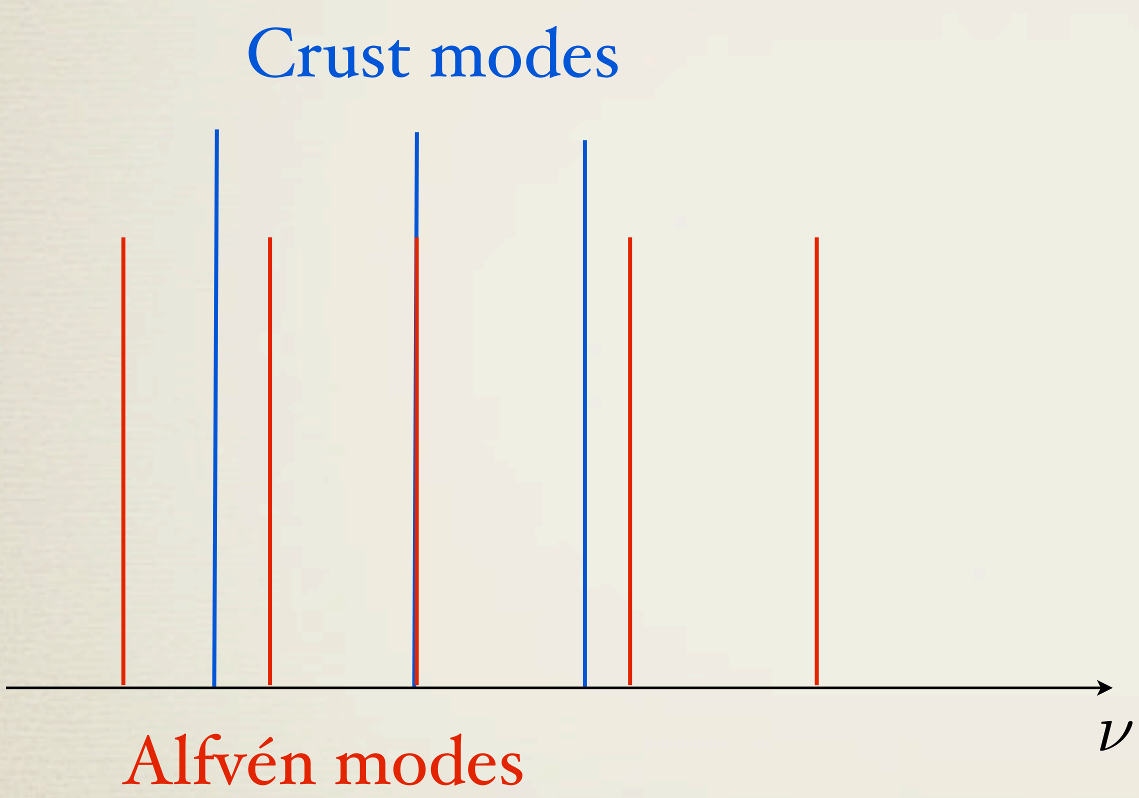

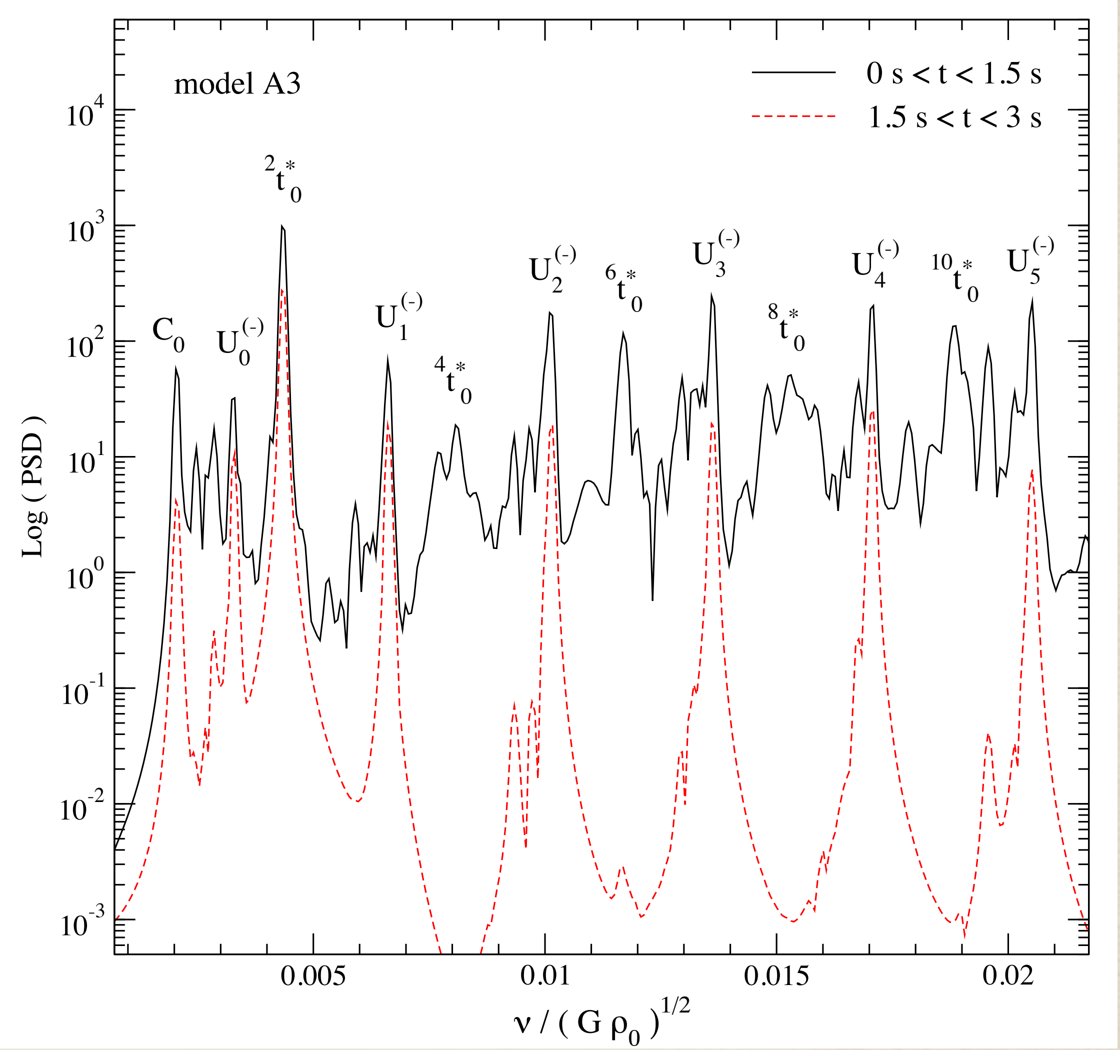

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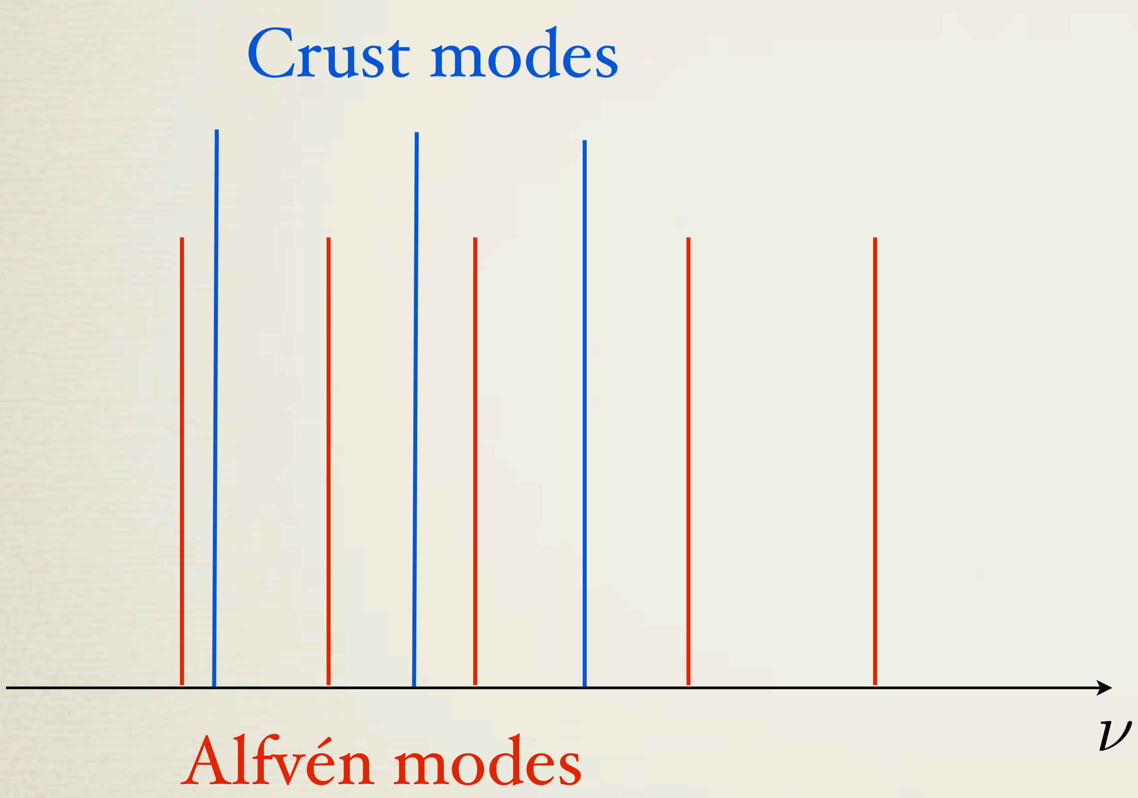

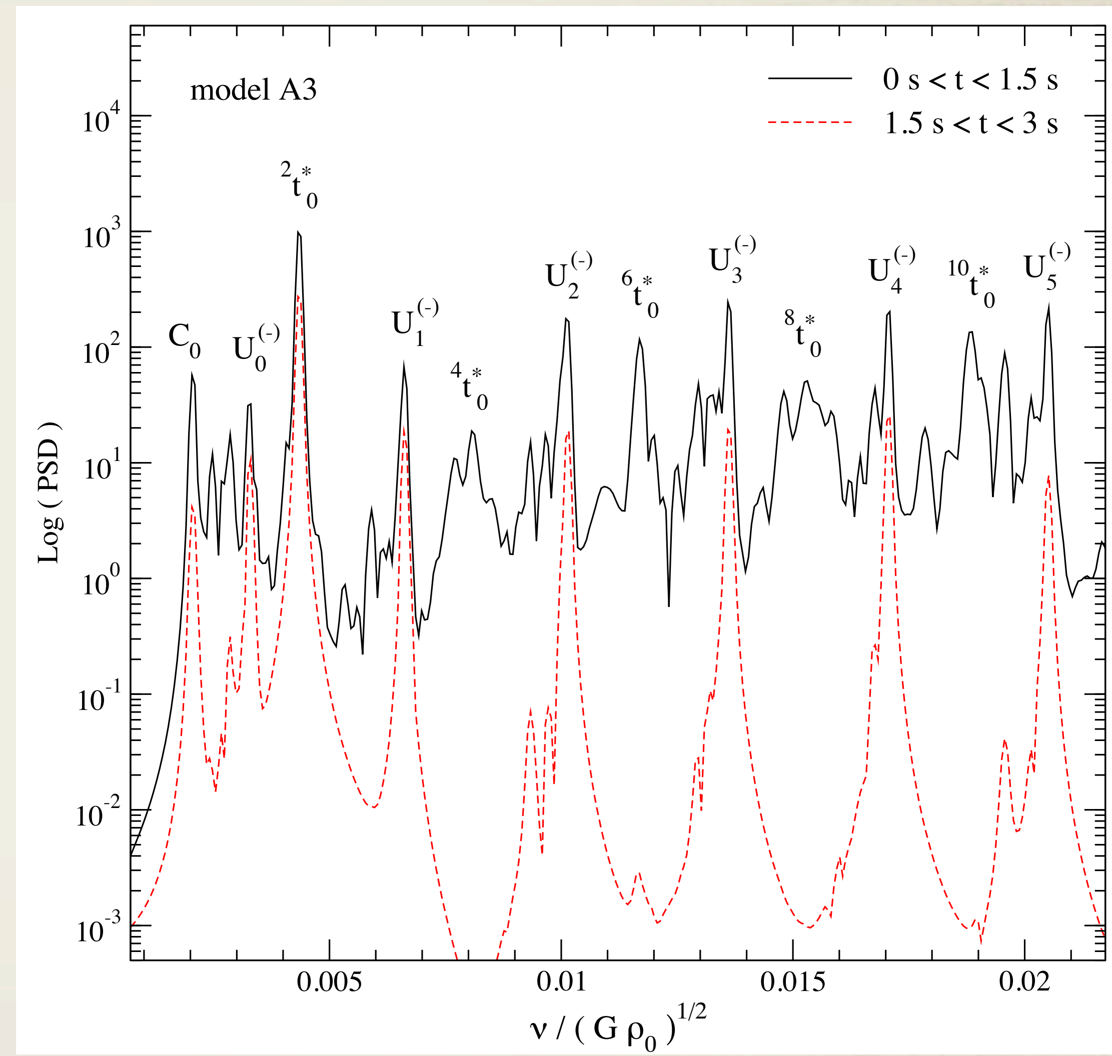

Axisymmetric oscillations

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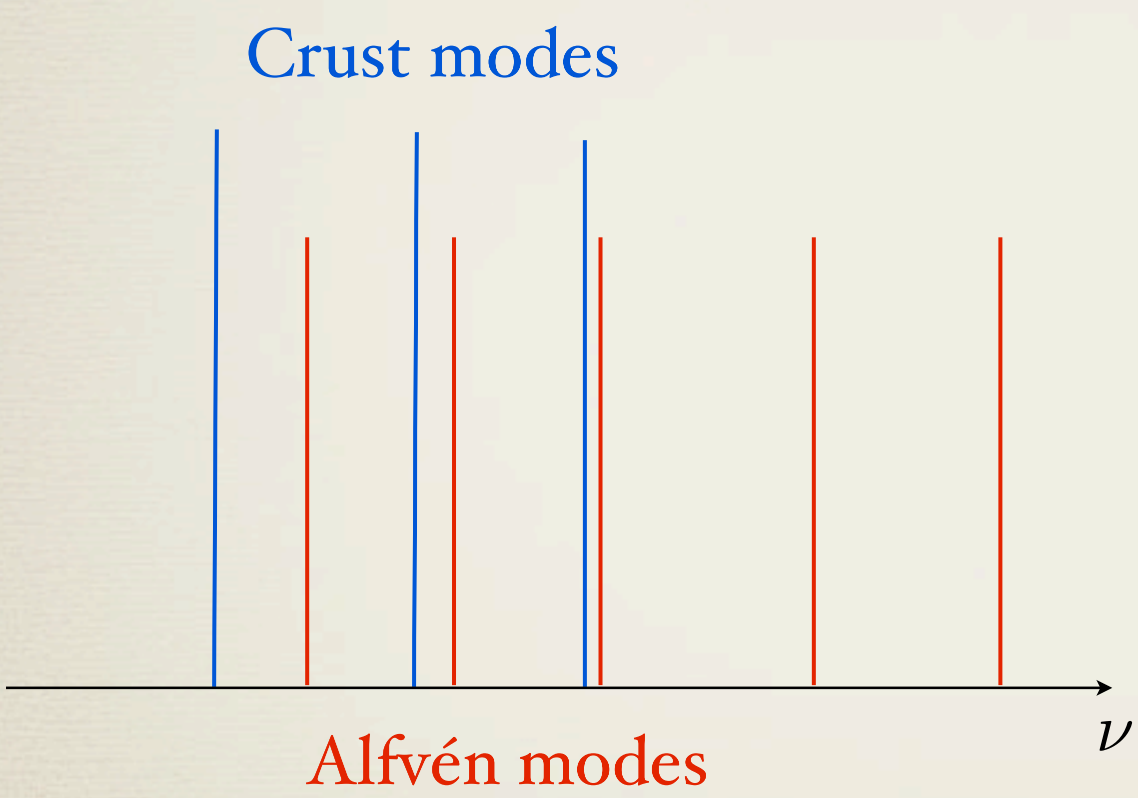
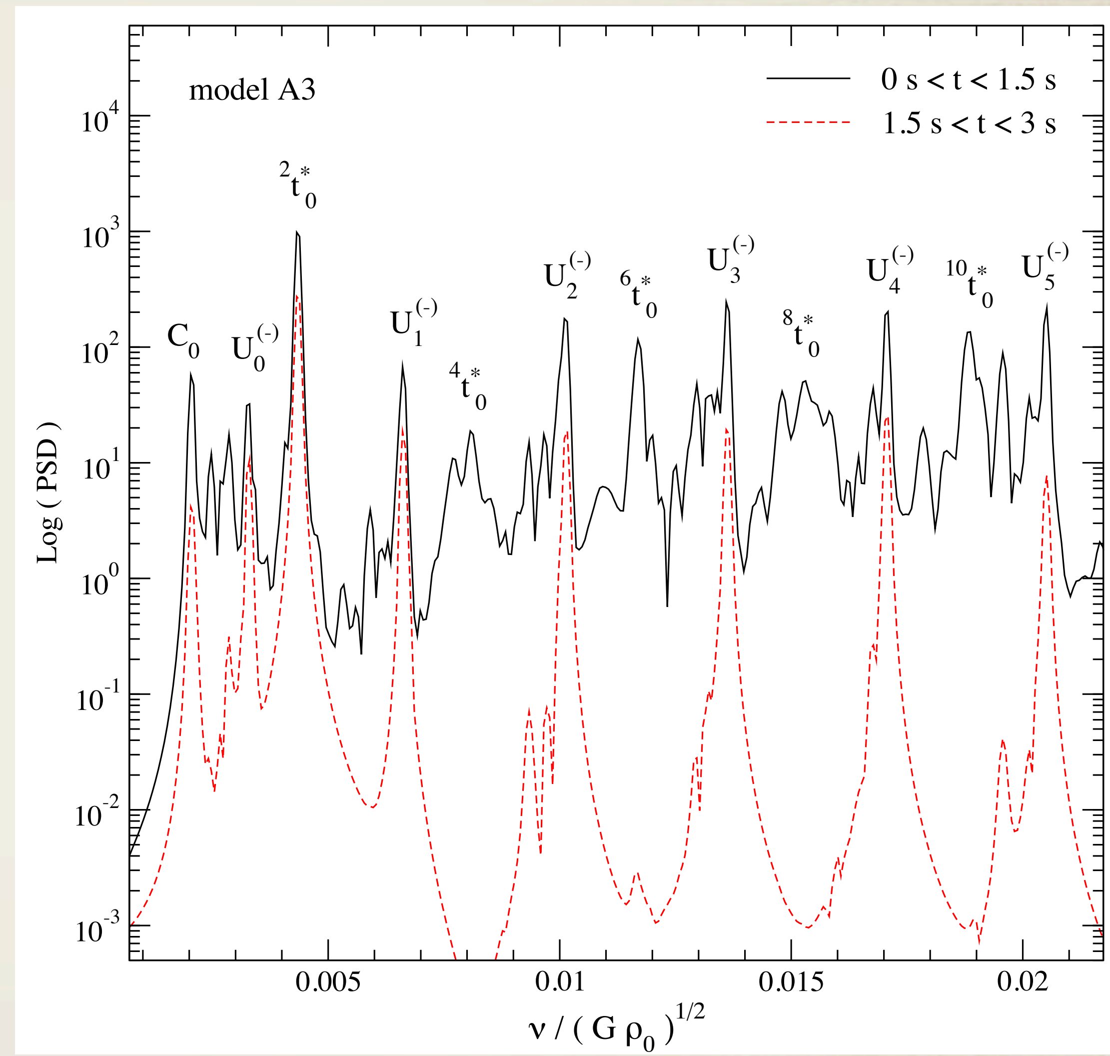
$B_p \sim 5 \cdot 10^{14}$G

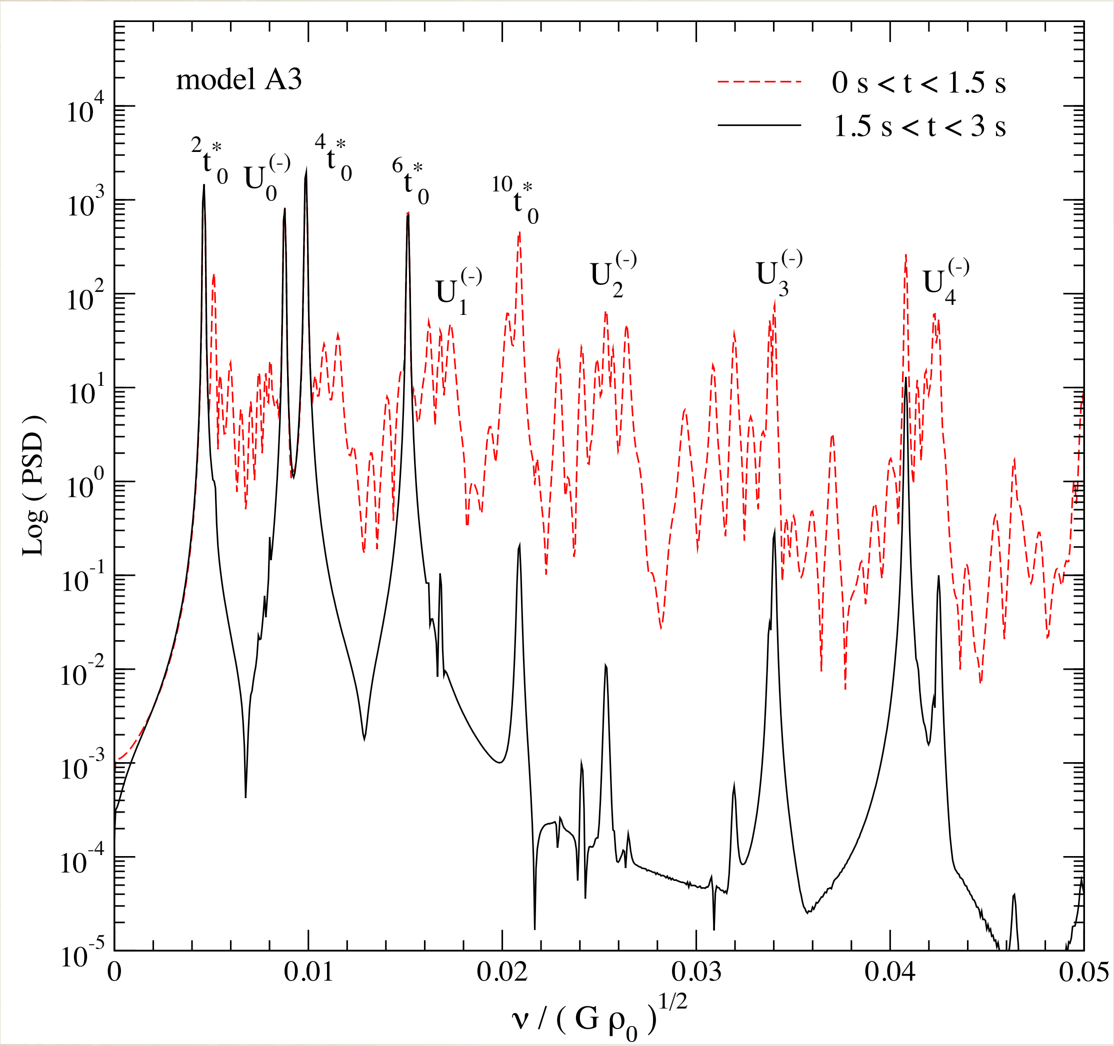


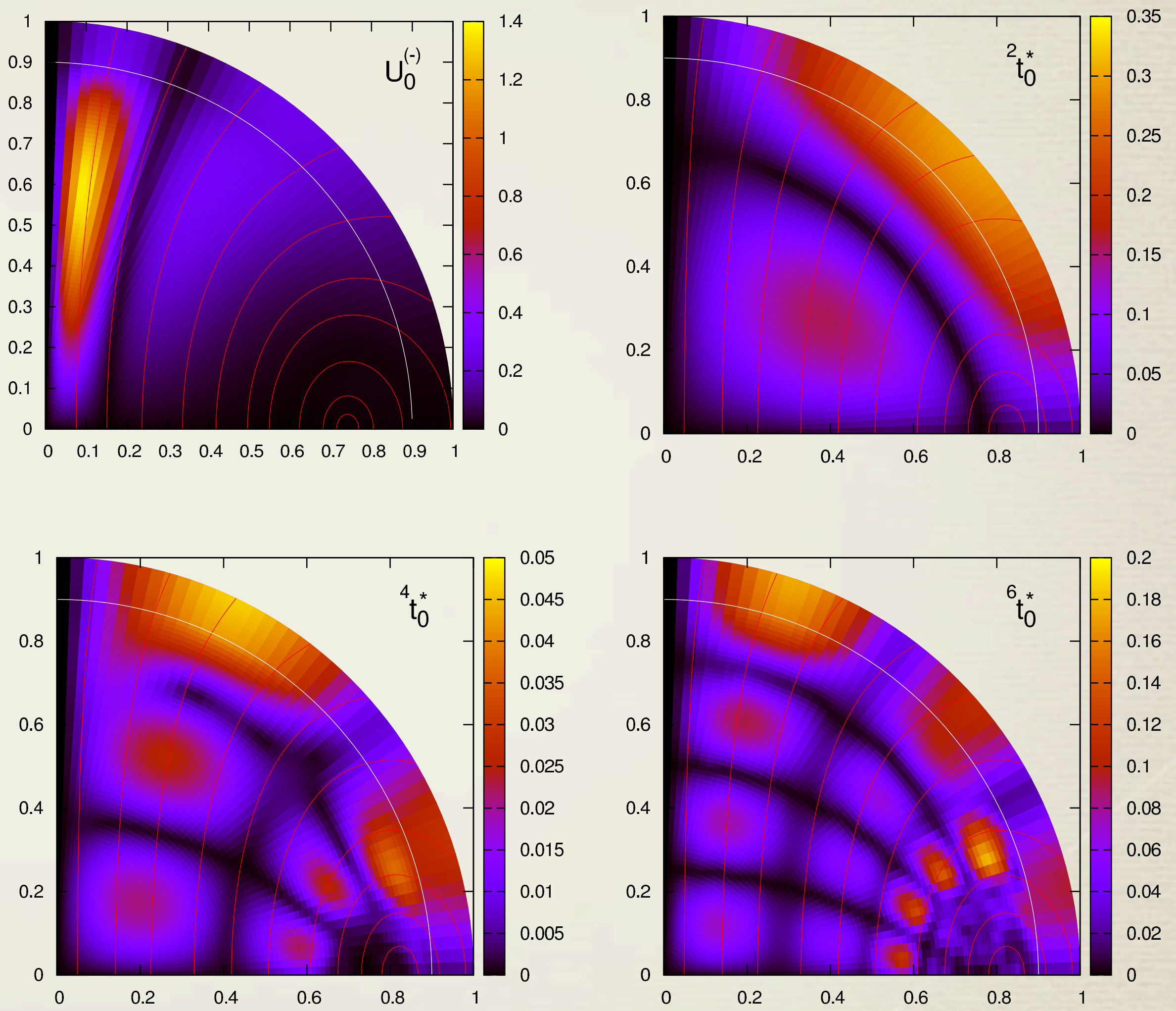


Axisymmetric oscillations

Bp~10^15G

Some hybrid modes?

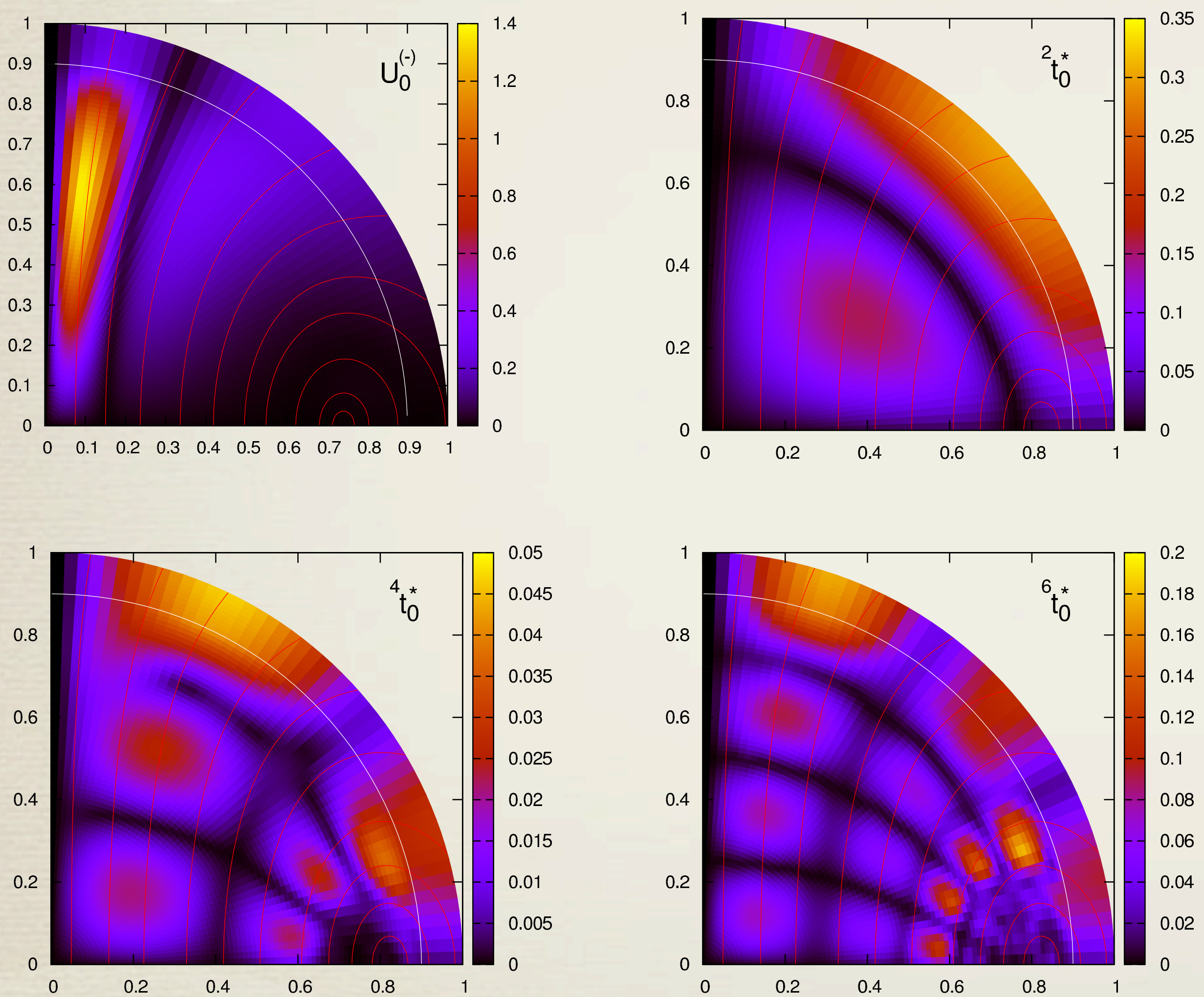




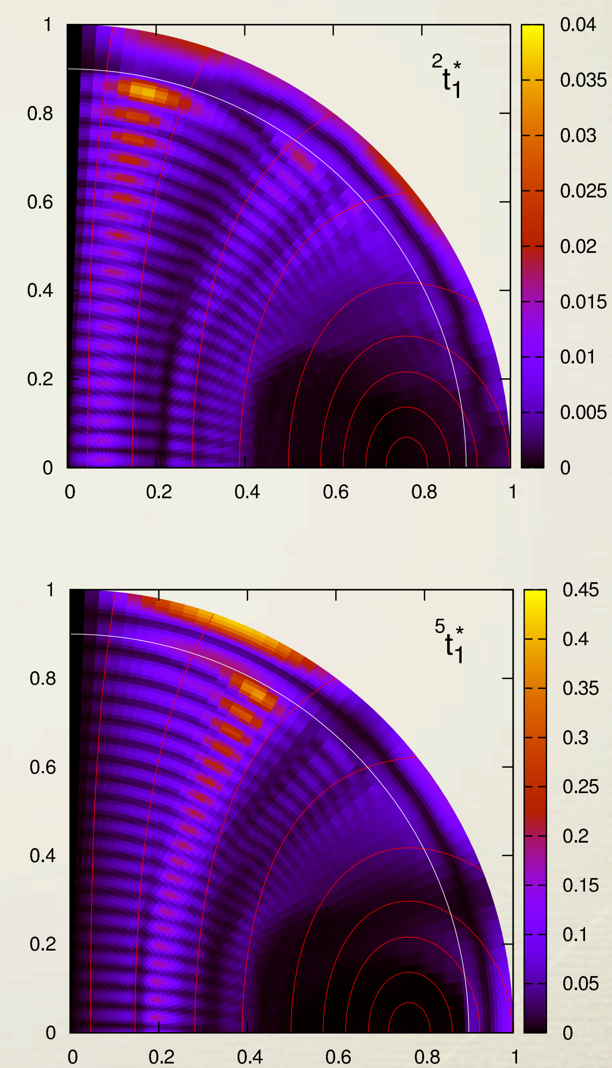
Hybrid magneto-elastic waves

In a model with entrainment and composition gradients we find hybrid magneto-elastic waves for $5 \cdot 10^{14} G \lesssim B_p \lesssim 2 \cdot 10^{15} G$

$\nu < 100$ Hz



500 Hz $< \nu < 2000$ Hz



Conclusions

- Superfluid constituents have a considerably impact on the oscillation spectrum of Magnetars.
  - The shear and Alfvén mode frequencies may be up to several times larger.
  - In model with strong entrainment in the crust, we can identify a set of hybrid magneto-elastic oscillations in the QPO range.
  - The QPOs can be explained in superfluid star by $3 \cdot 10^{14}\,G < B_p \leq 10^{15} G$.
  - In superfluid NS the high frequency QPOs $\nu > 500$ Hz might be overtone of hybrid magneto-elastic waves excited by a resonance with crust oscillations.

Future work

- Next questions to answer:
  - Does the continuum spectrum still persist in superfluid stars?
  - What is the effect of superconductivity on the QPO spectrum?
  - What is the equilibrium B-field configuration of a Magnetar?
  - How the various stellar vibrations modulate the emission of the fireball trapped in the magnetosphere?
- An X-ray observatory like LOFT will increase the resolution of QPO timing and help their analysis. Are there QPOs in intermediate flares?