Magnetar QPOs and perspective with LOFT

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Outline

- Introduction
- Models
- Superfluid cores
- Conclusions

Introduction

Soft Gamma Repeaters (SGRs)

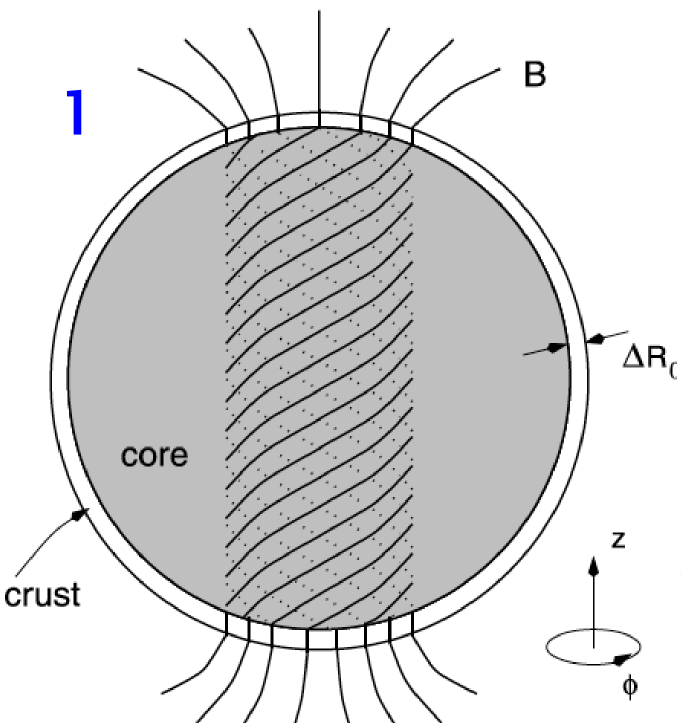
Observations

- Recurrent gamma-ray flare activity
- Nearby (Galactic or LMC)
- Associated to SNR
- Slowly rotating (P~5-10 s)
- Rapid spin down (Kouveliotou et al 1998)

Model

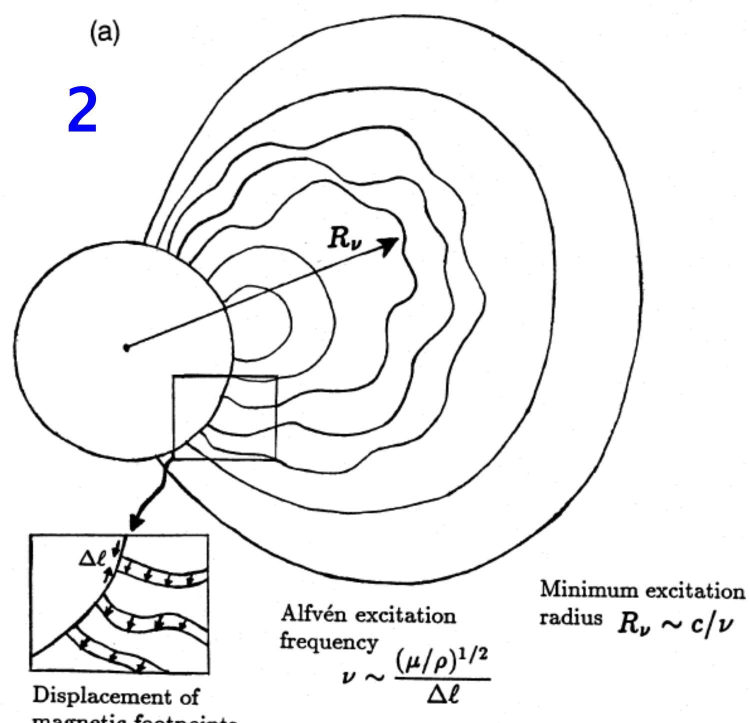
- Strongly magnetized NS : magnetar (Duncan & Thompson 1992)
- $B > 10^{14}$ G
- 1 : Stresses build in the crust
- 2 : Crust breaks and releases energy
- 3 : Fireball and x-ray emision

1



Thompson & Duncan 2001

2



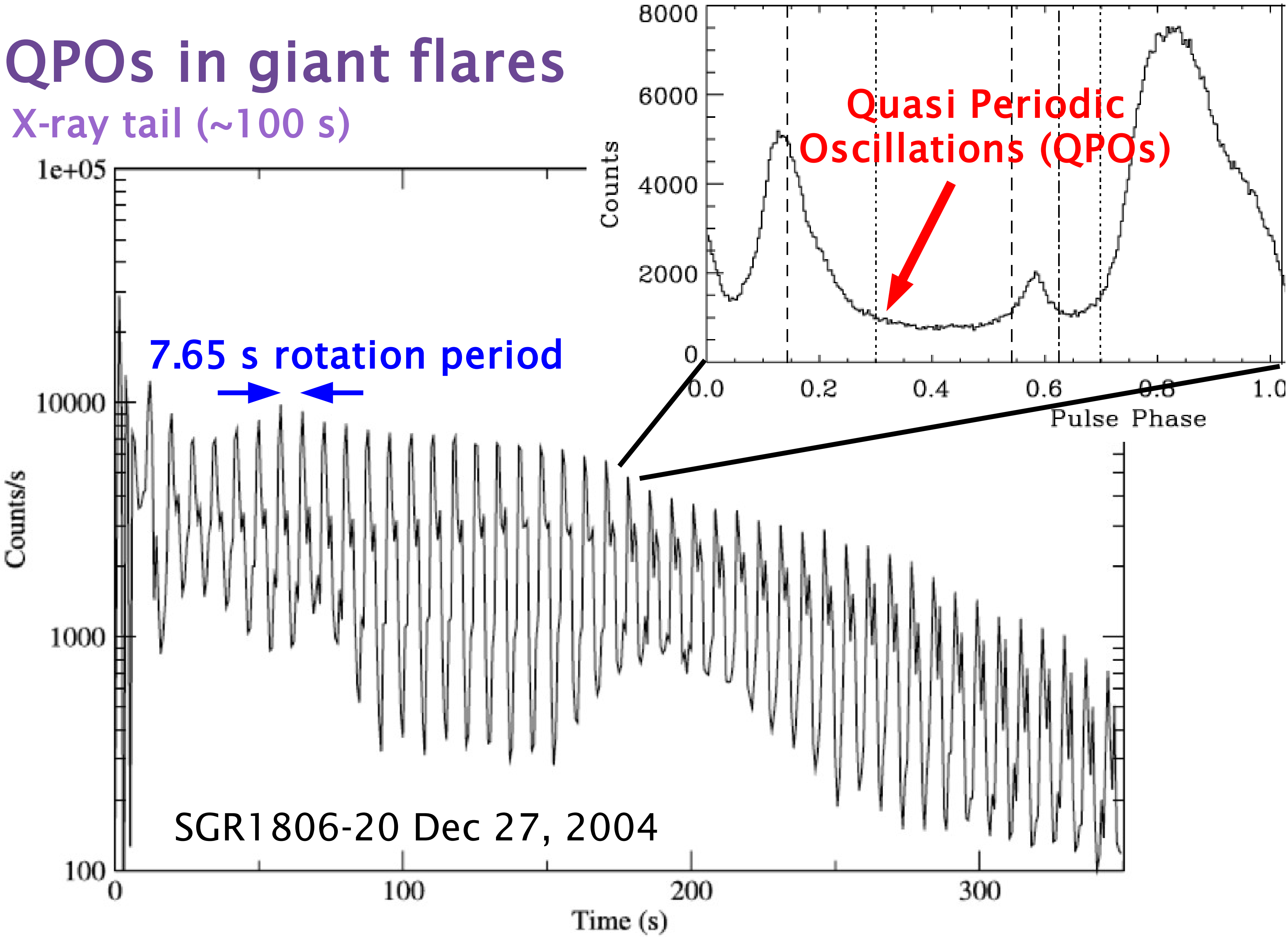
Thompson & Duncan 1995

3

R.C. Duncan

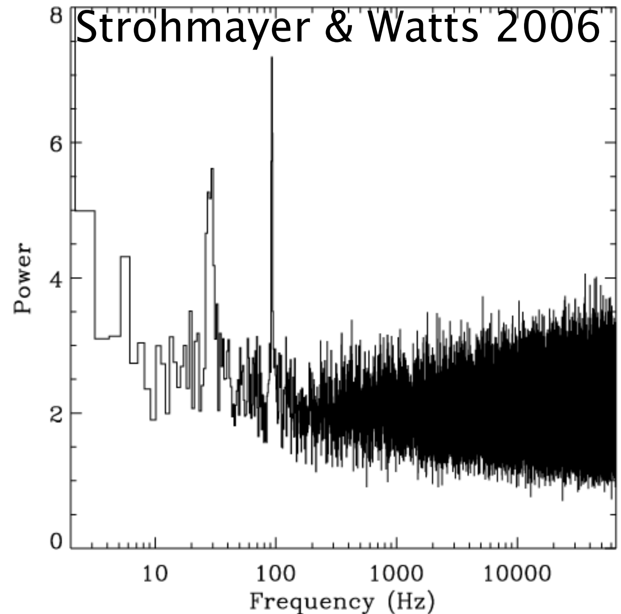
QPOs in giant flares

X-ray tail (~100 s)



Strohmayer & Watts 2006

QPOs in giant flares



- SGR 0526-66 on March 5, 1979 :
  → 43 Hz ? (Barat et al 1983)
- SGR 1900+14 on Aug. 27, 1998 :
  → 28, 56, 84, 155 Hz (Strohmayer & Watts 2005)
- SGR 1806-20 on Dec 27, 2004 :
  → 18, 26, 30, 92, 150, 625, 1840 Hz
  (Israel et al 2005; Watts & Strohmayer 2006, Strohmayer & Watts 2006)

+ Two frequency bands:

- Low frequency QPOs : 17 → 155 Hz

- High frequency QPOs: 625 → 1840 Hz

+ Rotational phase dependence: origin close to the star

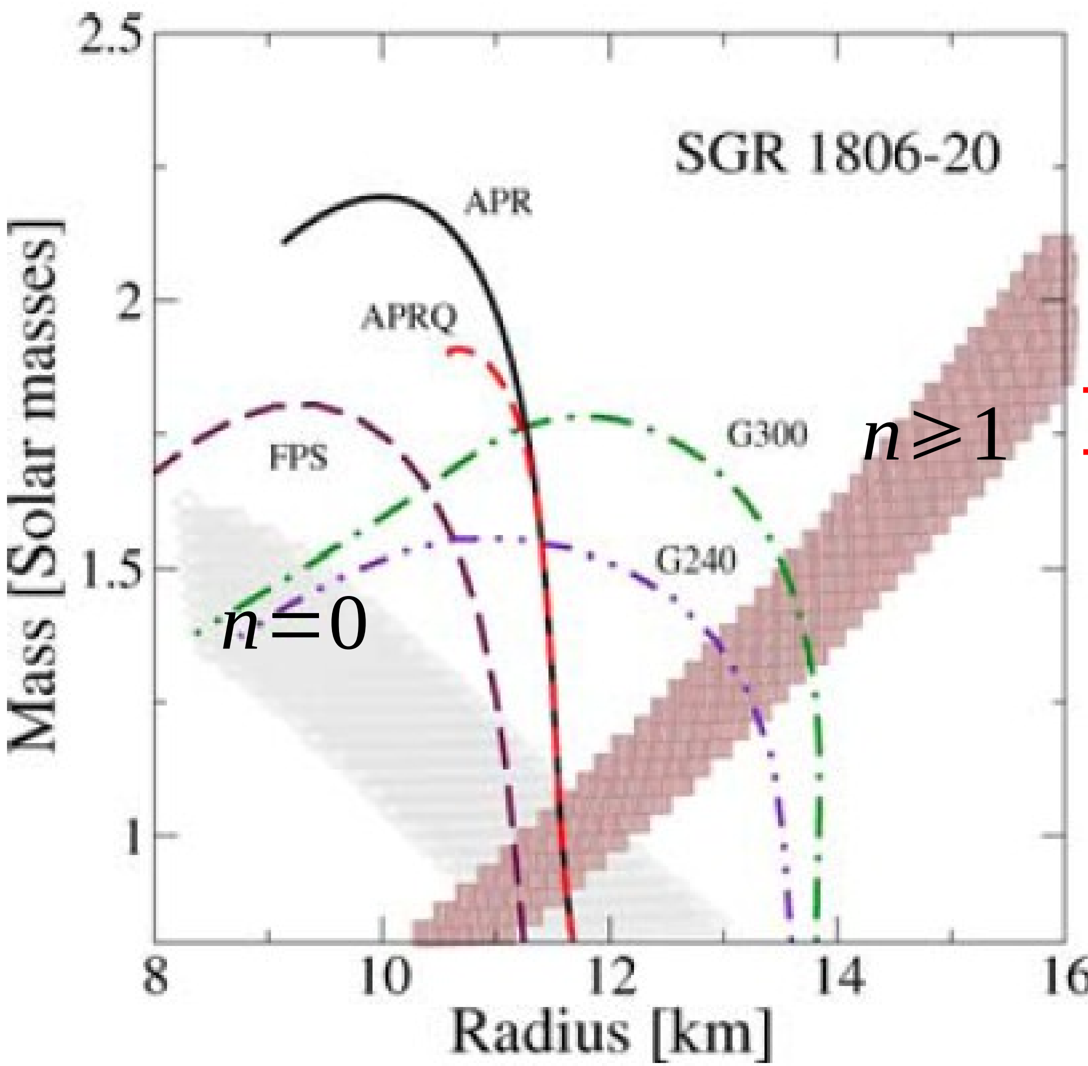
+ Variability (frequency and amplitude)

+ Large uncertainties bellow 30 Hz (Huppenkothen et al 2013)

Models

Crust shear oscillations model

(Schomaker & Thorne 1983, Piro 2005, Samuelsson & Andersson 2007)

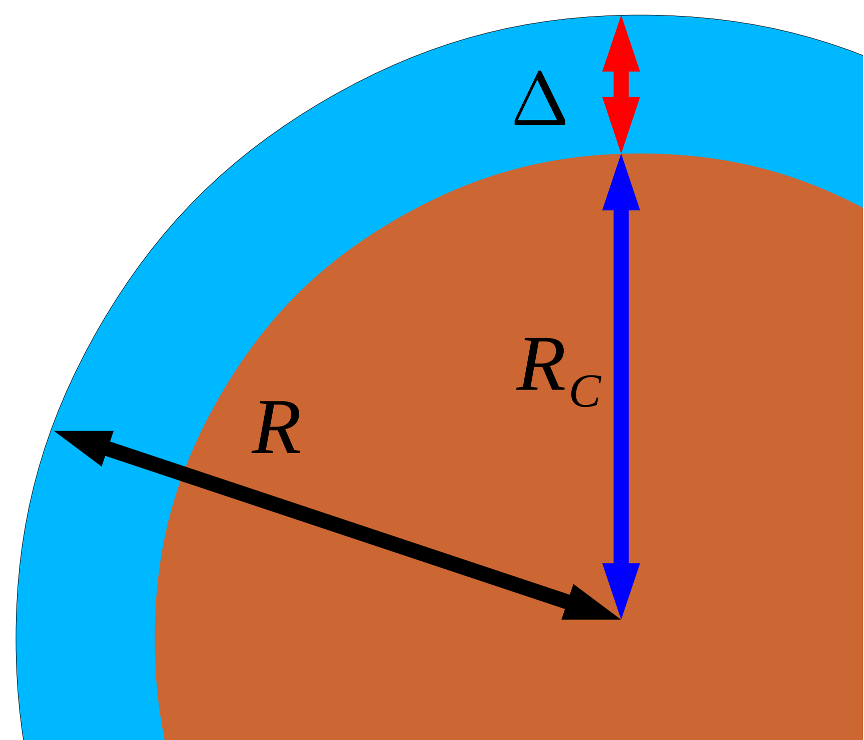


Samuelsson & Andersson 2007

$$\omega^2 \approx \frac{v_t^2 (l-1)(l+2)}{R R_C} \quad n=0$$

$$\omega \approx \frac{n \pi v_r}{\Delta} \quad n \geqslant 1$$

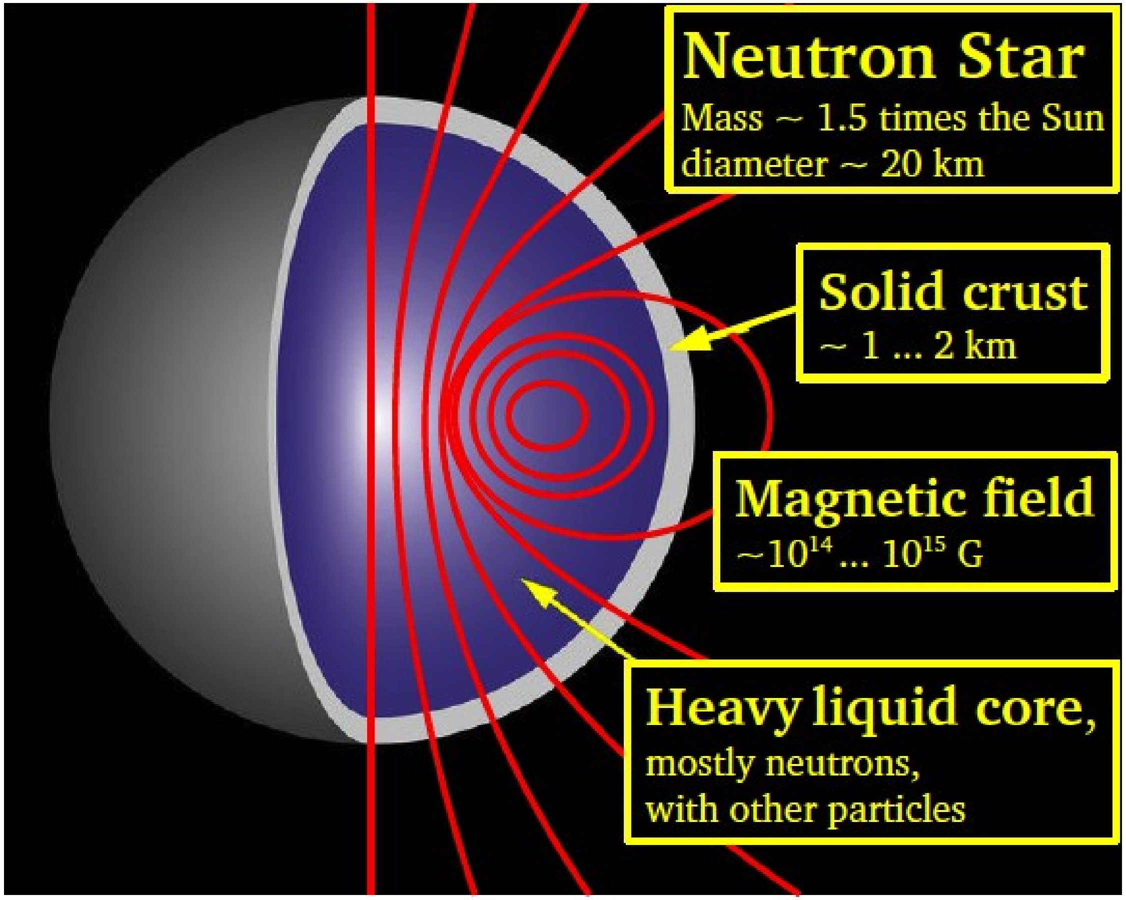
+ Explains low/high freq. QPOs
- Cannot explain all QPOs at once

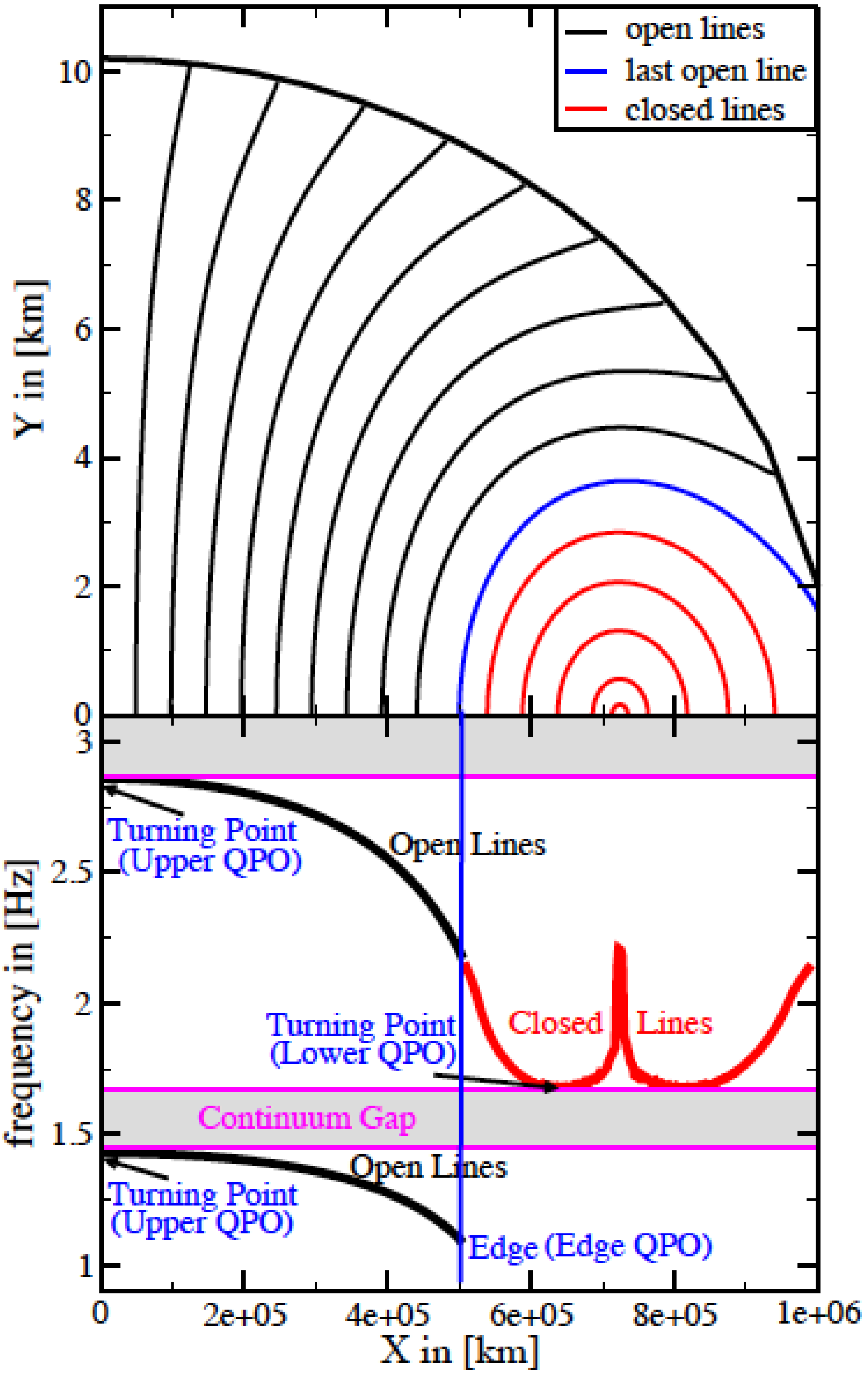


Magneto-elastic model

Thin crust/no crust: Levin 2006, 2007, Sotani et al 2006, 2008, 2009, CD et al 2009, Colaiuda et al 2009, Lander & Jones 2011, Passamonti & Lander 2012

Extended crust: Glampedakis et al. 2006, Gabler et al 2011,2012, 2013a, 2013b, Colaiuda et al 2011 & 2012, Van Hoven & Levin 2011 & 2012

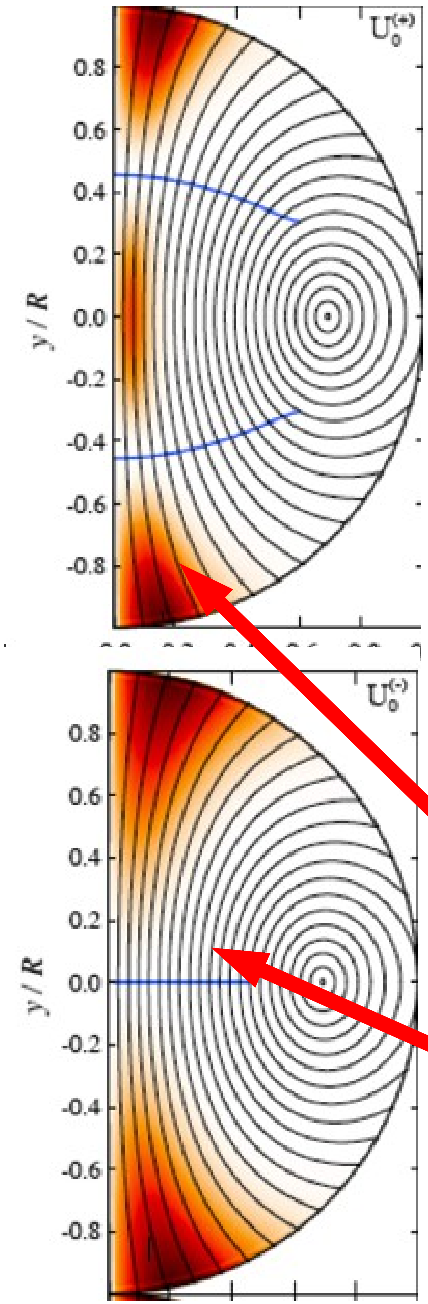


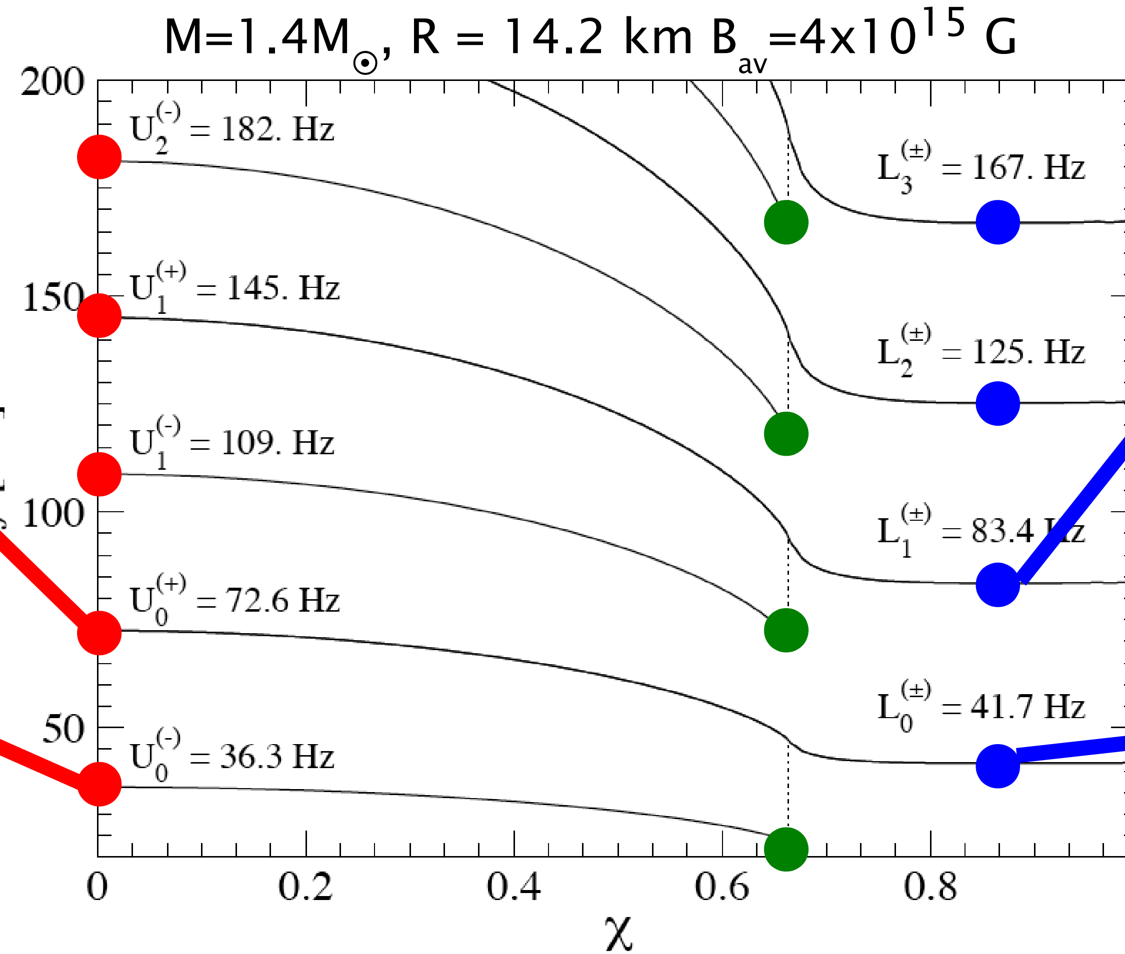


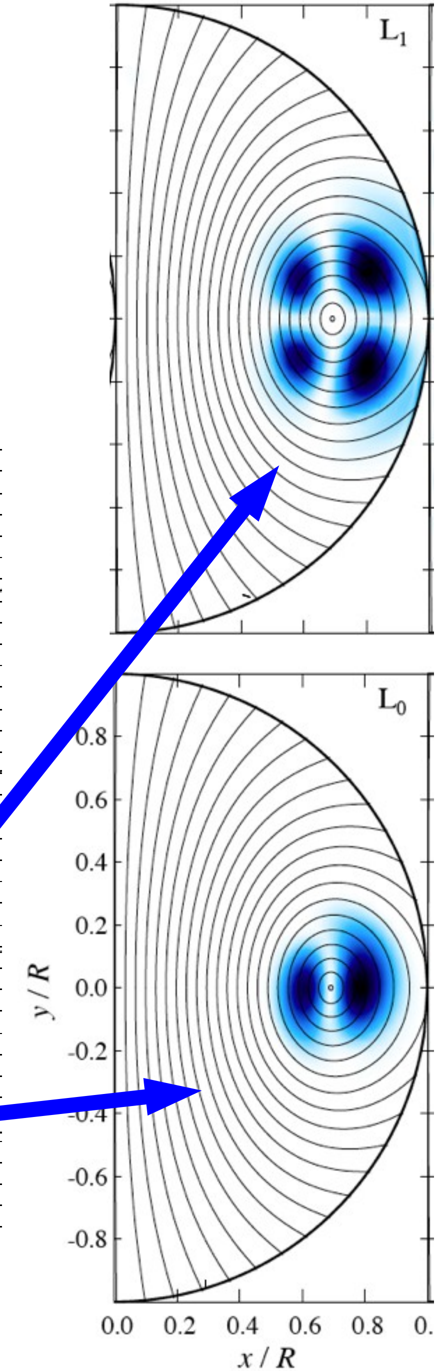
Gabler et al 2012

Magneto-elastic model

- Alfvén continuum in the core
- extrema/edges form QPOs
- continuum couples with crustal modes
- Alfvén QPOs may not survive long
  (Levin 2006, 2007)





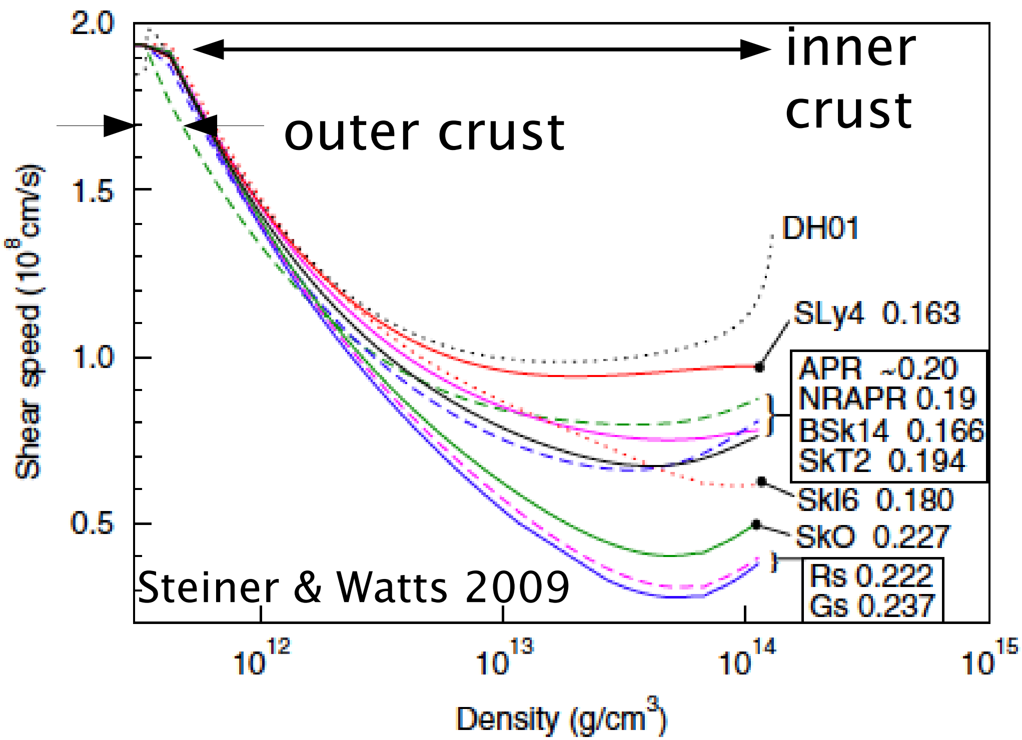


Cerdá-Durán et al 2009

Magneto-elastic model

Magneto-elastic waves (eigenvalues of the magneto-elastic equations)

$$\lambda_{me} = \pm\sqrt{\frac{B^2 + \mu_s}{\rho}}$$



$$v_{Alfven} \approx 10^8 \left(\frac{B}{10^{15}G}\right)\left(\frac{10^{14}\, g\, cm^{-3}}{\rho}\right)^{-1/2} cm\, s^{-1}$$
$$\approx 10^9 \left(\frac{B}{10^{15}G}\right)\left(\frac{10^{12}\, g\, cm^{-3}}{\rho}\right)^{-1/2} cm\, s^{-1}$$

$B^2 \gg \mu_s \rightarrow \lambda_{me} \simeq \pm\frac{B}{\sqrt{\rho}}$ Alfvén wave

$B^2 \ll \mu_s \rightarrow \lambda_{me} \simeq \pm\sqrt{\frac{\mu_s}{\rho}}$ Shear wave

$B^2 \sim \mu_s \rightarrow \lambda_{me}$ Magneto-elastic wave → **Magnetars!!!**

Magneto-elastic simulations in general relativity

CoCoA code (CoCoNuT framework)

- 2D-axisymmetric GRMHD code
- Spherical coordinates
- Finite-volume Riemann solvers + CT methods
- Dynamical space-time (CFC)

CoCoNuT

Approximations

- Torsional oscillations
- Low amplitude (linear)

} → constant density (anelastic)

- Cowling (fixed spacetime)
- Spherically symmetric background (non-rotating stars)
- Ideal MHD
- Axisymmetry

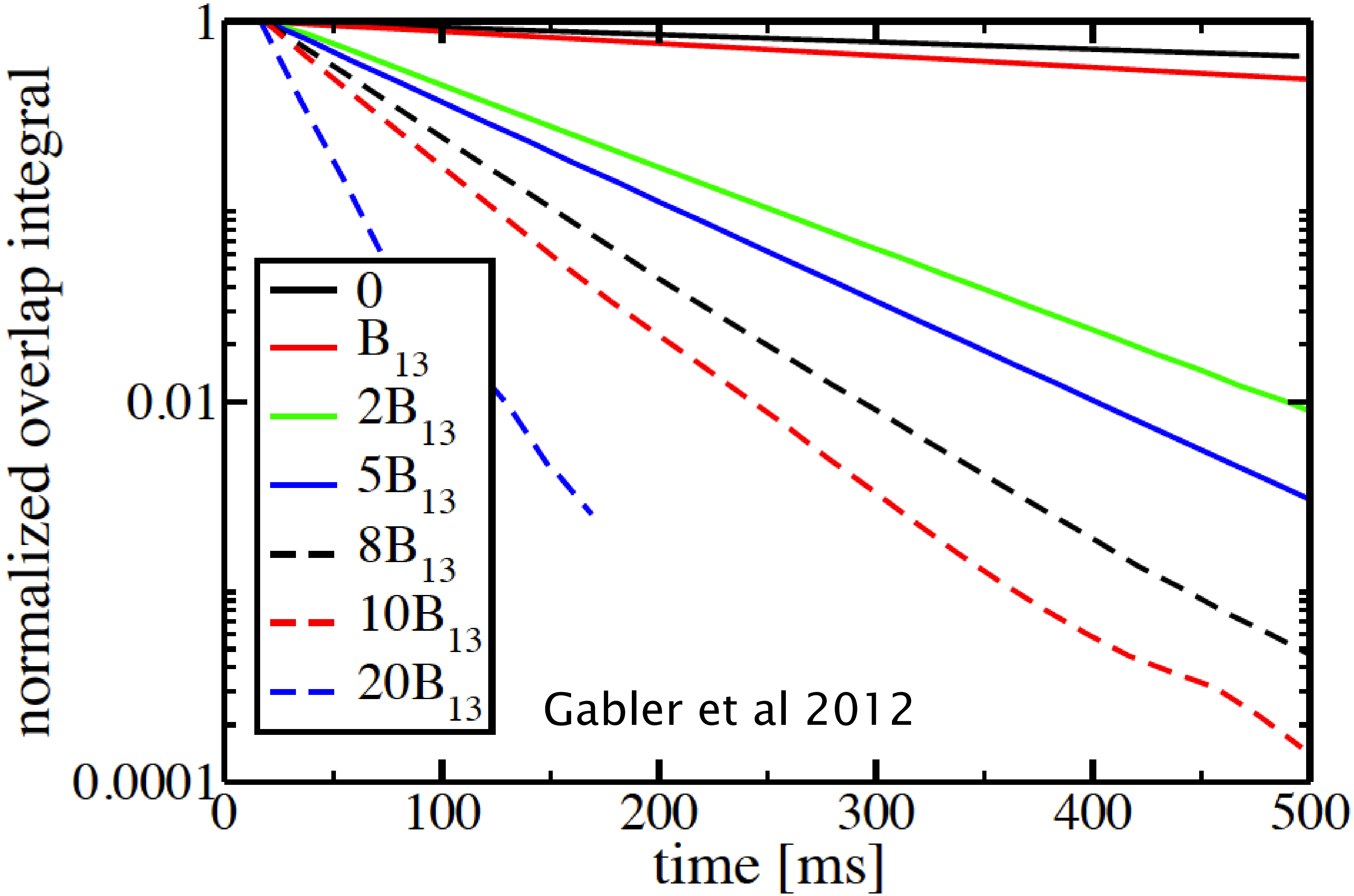
EOS

- **Core:** APR (Akmal et al 1998) and L (Pandharipande & Smith 1975)
- **Crust:** NV (Negele & Vautherin 1973) and DH (Douchin & Hansel 2001)

Absorption of crustal shear modes by the Alfvén continuum

EoS: APR+DH, shear modulus: DH, $M=1.4M_\odot$, R = 12.1 km, ΔR = 0.88 km

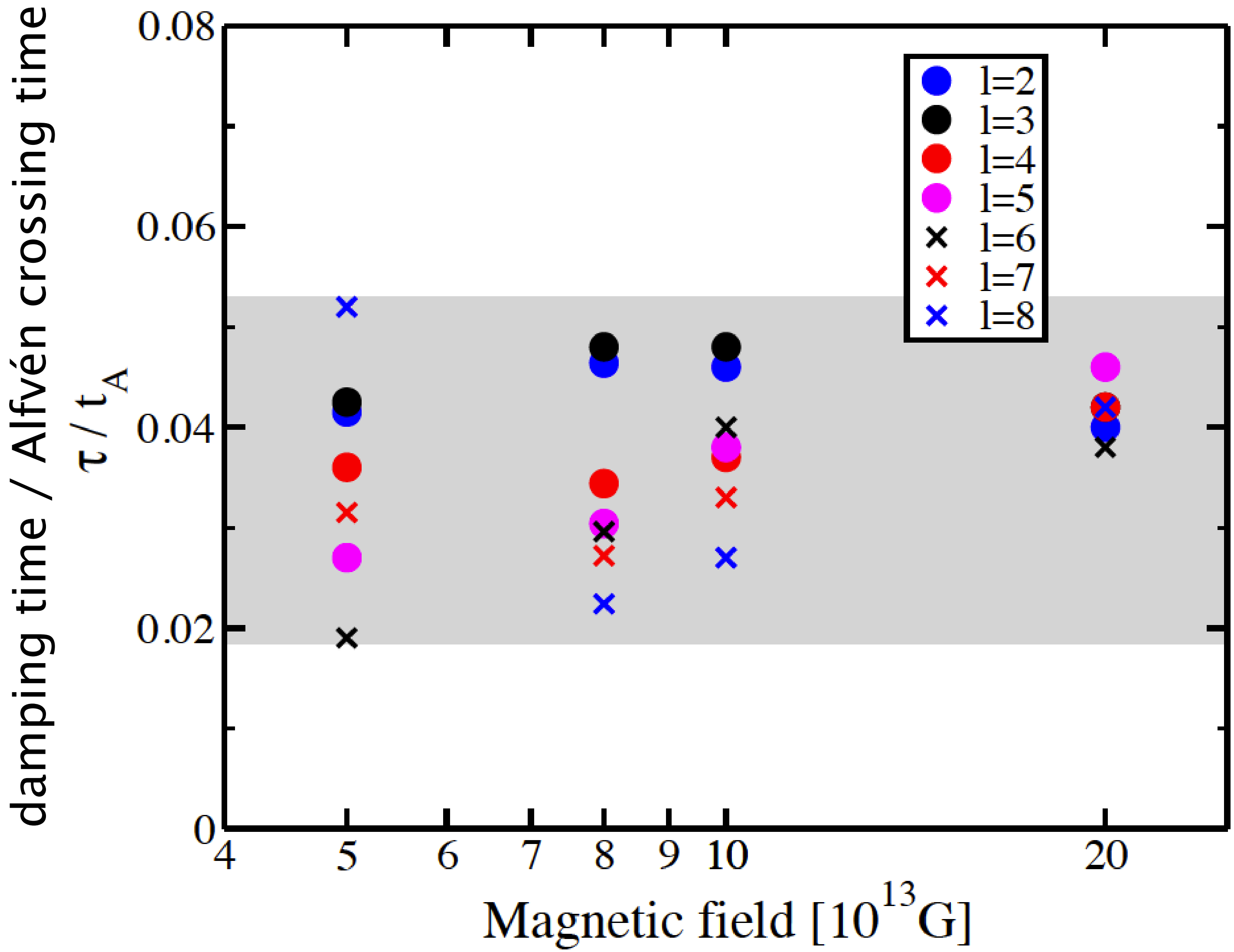
Dipolar-like magnetic field, no toroidal component



perturbation
n=0, l=2

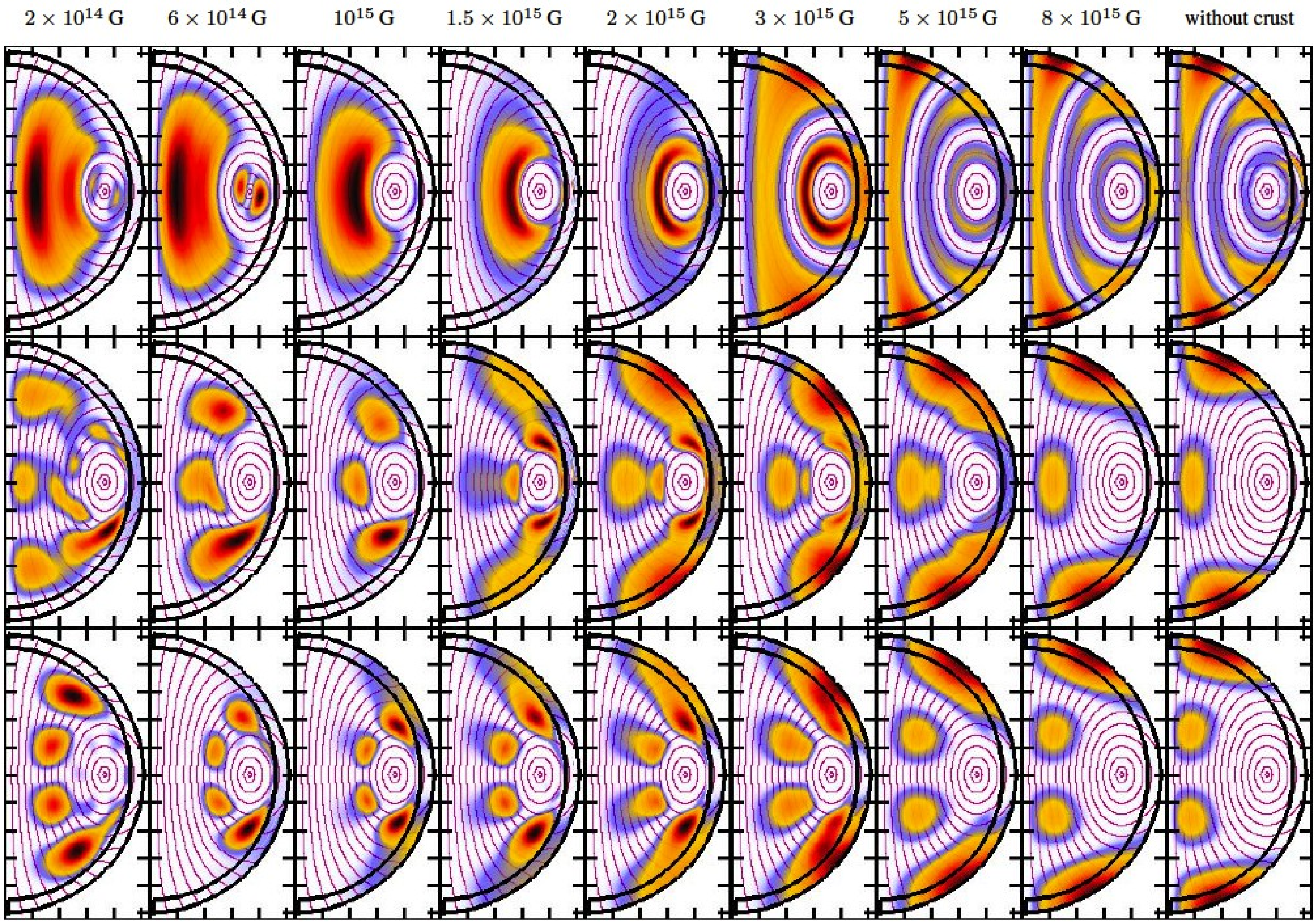
Similar for other EoS, shear modulus and mass

Absorption of crustal shear modes by the Alfvén continuum



Gabler et al 2012

QPOs in the Alfvén continuum

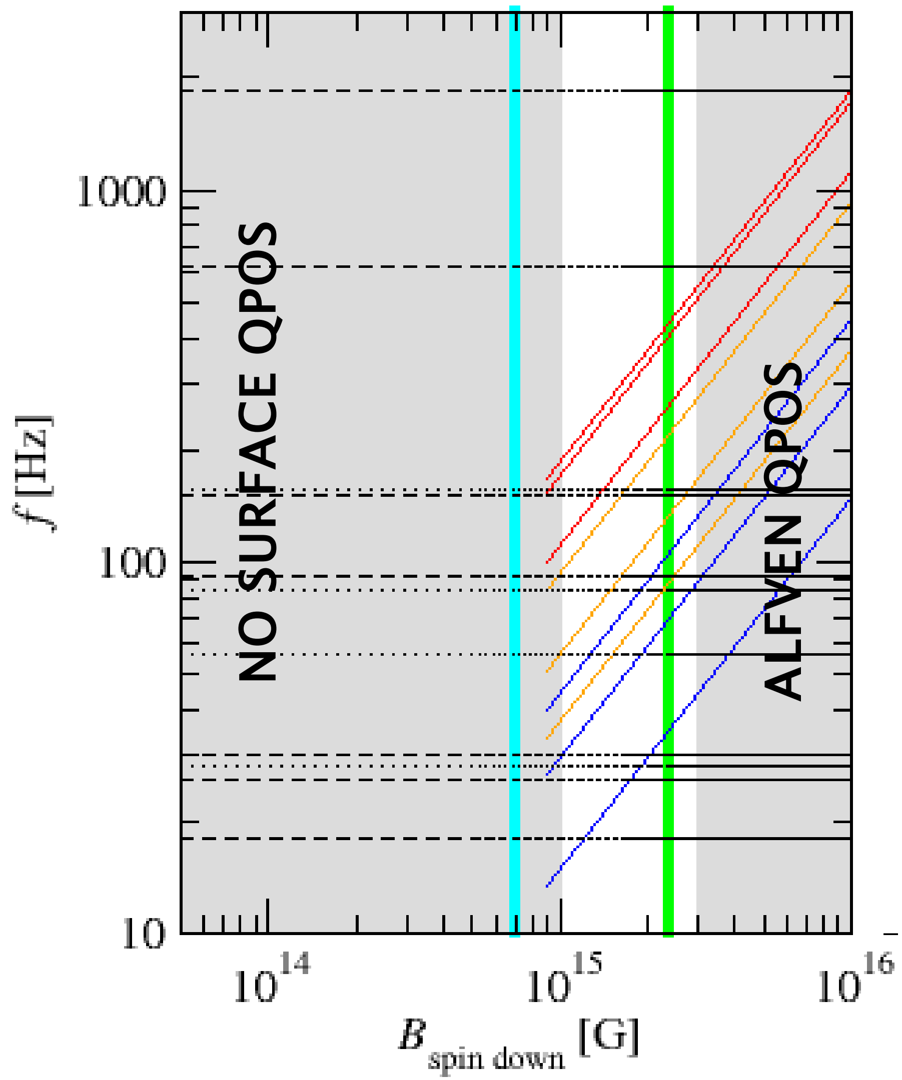


Gabler et al 2012

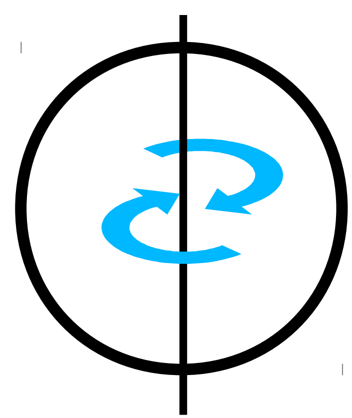
$B^2 \ll \mu_s$ $B^2 \sim \mu_s$ $B^2 \gg \mu_s$

Increasing magnetic field

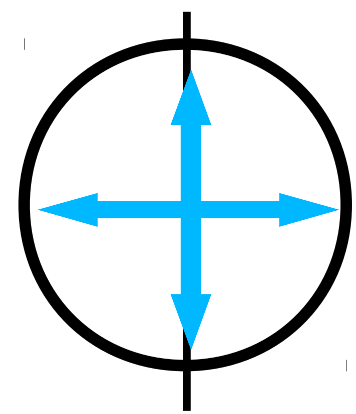
Axial vs polar modes



- Magneto-elastic regime is the most relevant
- polar oscillations x5 larger frequency that axial
- **Not possible to explain high and low frequency QPOs at the same time** (unless very high order QPOs are considered)



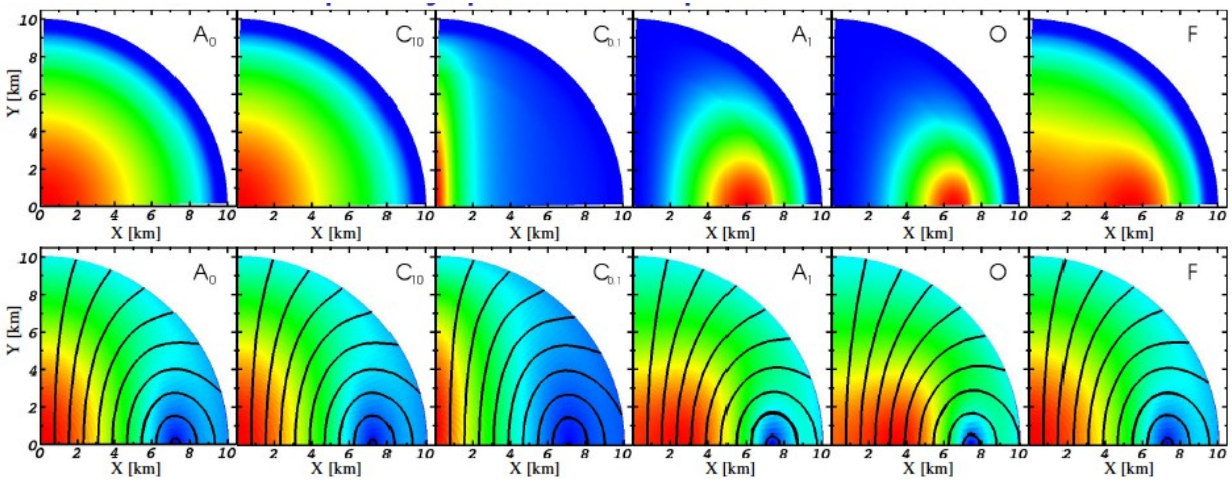
axial (torsional)

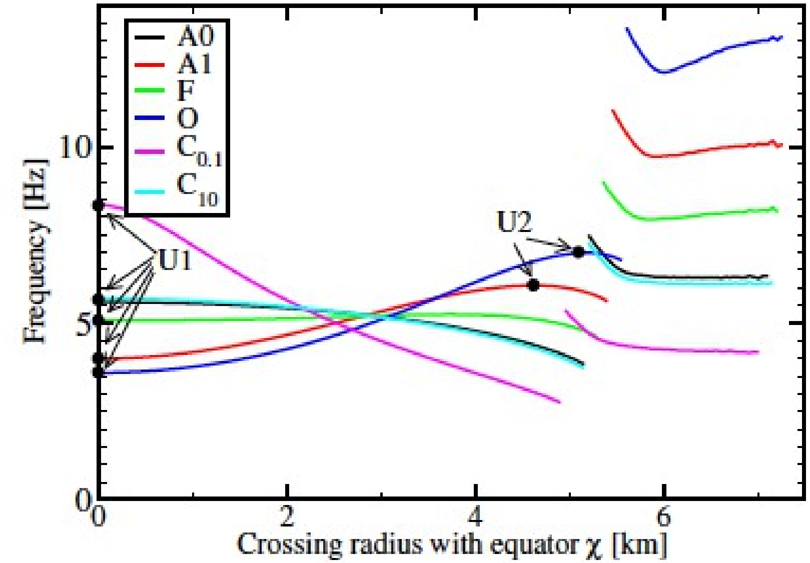


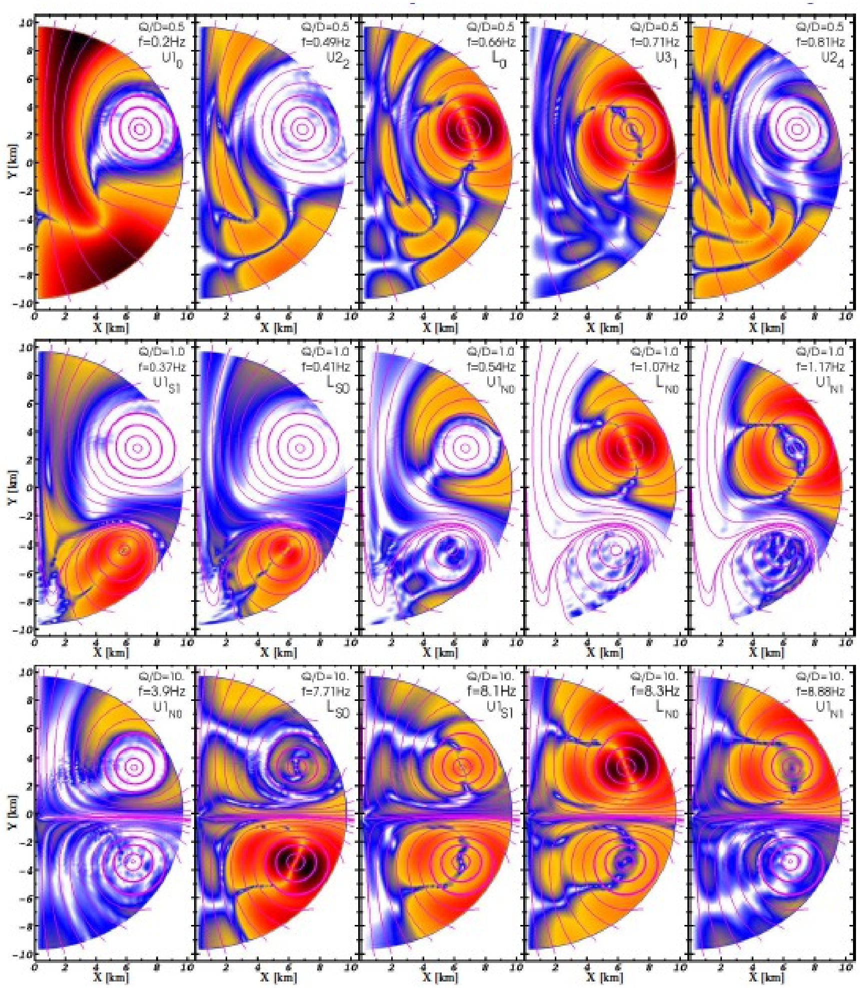
polar

axial, m=0 (Sotani et al 2008, CD et al 2009, Gabler et al 2011, Colaiuda & Kokkotas 2012, Gabler et al 2013)
polar, m=0 (Sotani & Kokkotas 2009, Colaiuda & Kokkotas 2012)
polar, m=2 (Lander & Jones 2011, Passamonti & Lander 2012)
SGR1806-20 (Dec. 27, 2004)
SGR1900+14, Aug. 27 1998

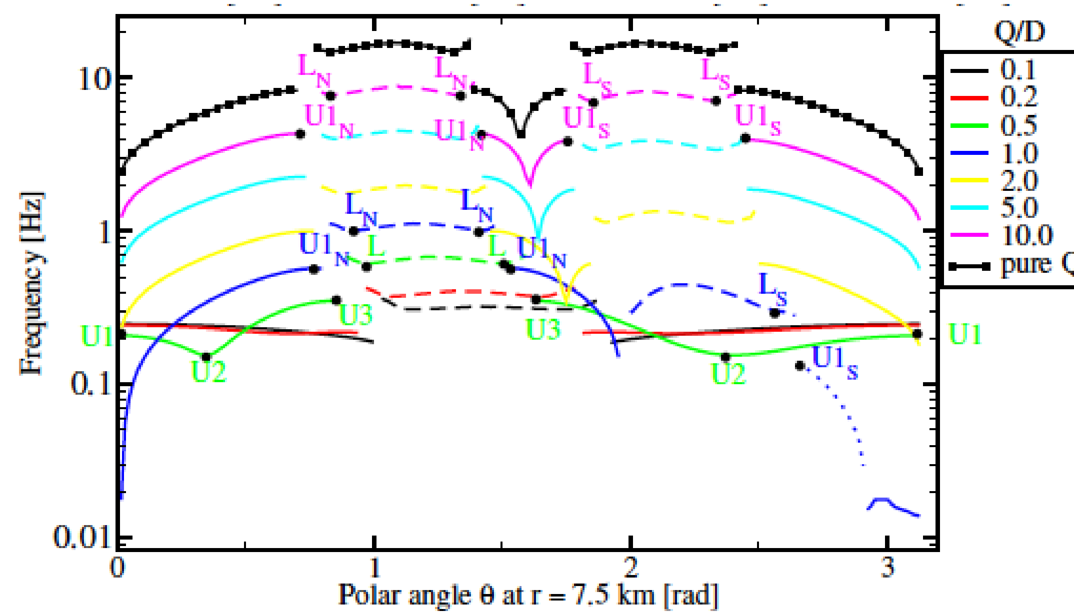
SGR1806-20
SGR1900+14





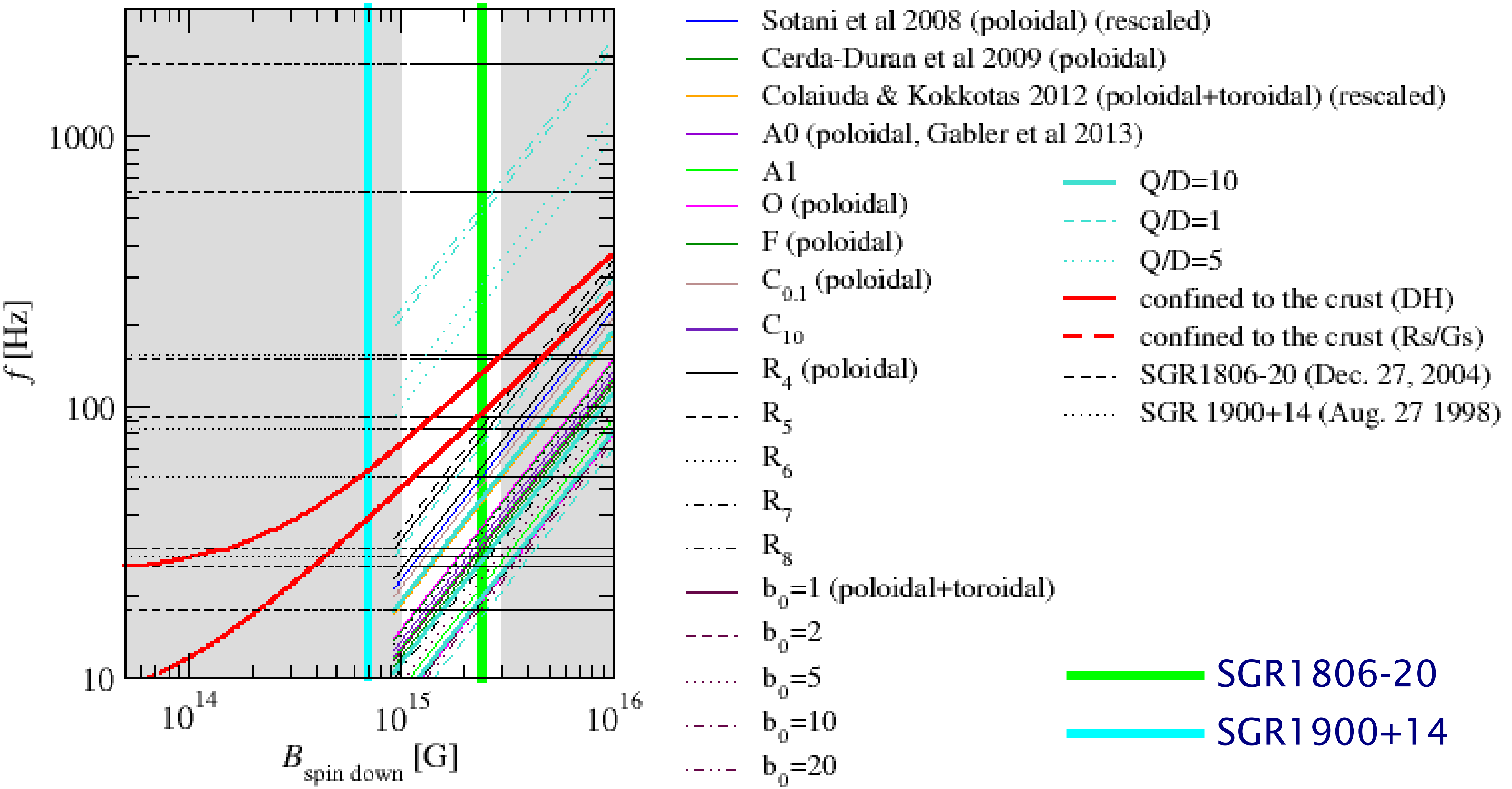


Magnetic field structure



Gabler et al 2013

Magnetic field structure



- Dipole-like configurations: x3 differences in frequency, multiple QPOs
- High order multipoles can increase the frequency
- Magnetic field confined to the crust cannot explain QPOs
- **Not possible to explain high and low frequency QPOs at the same time.**

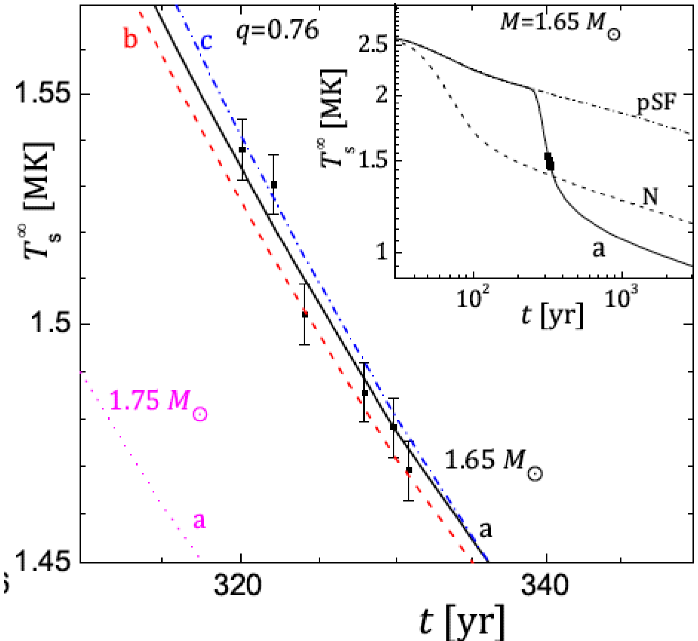
Summary (but not the end)

- **Frequency of Alfvén QPOs is a degenerate problem**
  - Magnetic field strength and structure
  - Equation of state
  - Mass
- **Alfvén QPO model of non-superfluid cores has problems**
  - Not possible to accommodate high and low frequency QPOs at the same time.
  - Are Alfvén QPOs long lived? (Levin 2006, 2007)

Superfluidity

Gabler et al 2013 (arxiv:1304.2566)

Superfluidity



Shternin et al 2011

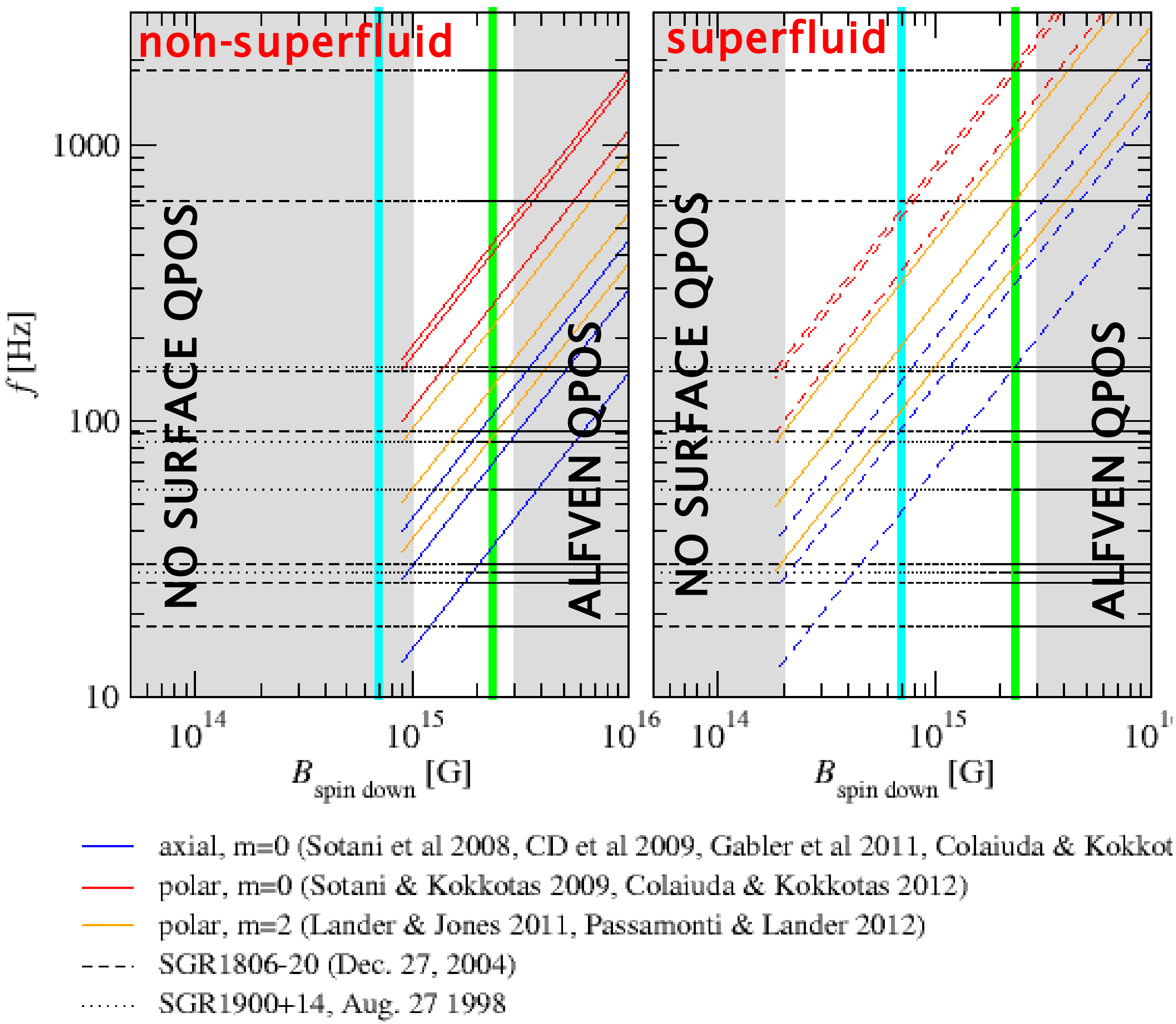
- Superfluidity es favored in NS (Baym et al 1969).
- Explanation for pulsar glitches (Anderson & Itoh 1975). However anti-glitch (Archibald 2013).
- Cooling curve of Cas A consistent with superfluid core (Shternin et al 2011, Page et al 2011).
- Superconductivity may be suppresed in magnetars since $B_{crit} \sim 10^{15}$-10^{16} G (Glampedakis et al 2011).
- Only protons are involved in Alfvén waves
- Glampedakis et al 2006, van Hoven et al 2011, 2012, Gabler et al 2013

$$v_{Alfvén,SP} = \pm\frac{B}{\sqrt{X_p\rho}} \sim 5\left(\frac{X_p}{0.05}\right)^{-1/2} v_{Alfvén,normal}$$

Alfvén QPO frequency increases a factor 5

→ can explain QPO frequencies with 1/5 magnetic field strength

Superfluid vs non-superfluid (simplified)



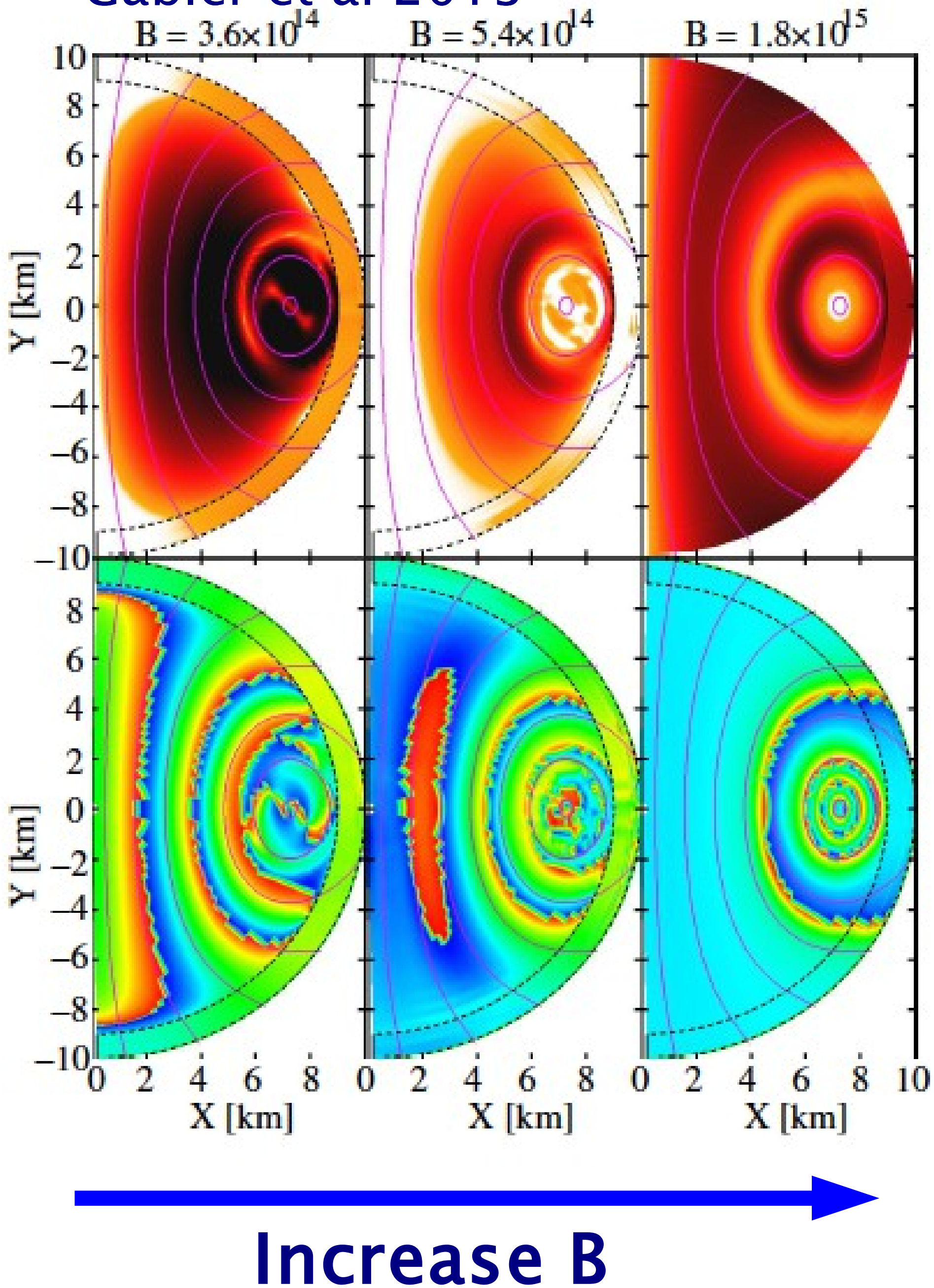
- increase frequency x5
- broader magneto-elastic region

SGR1806-20

SGR1900+14

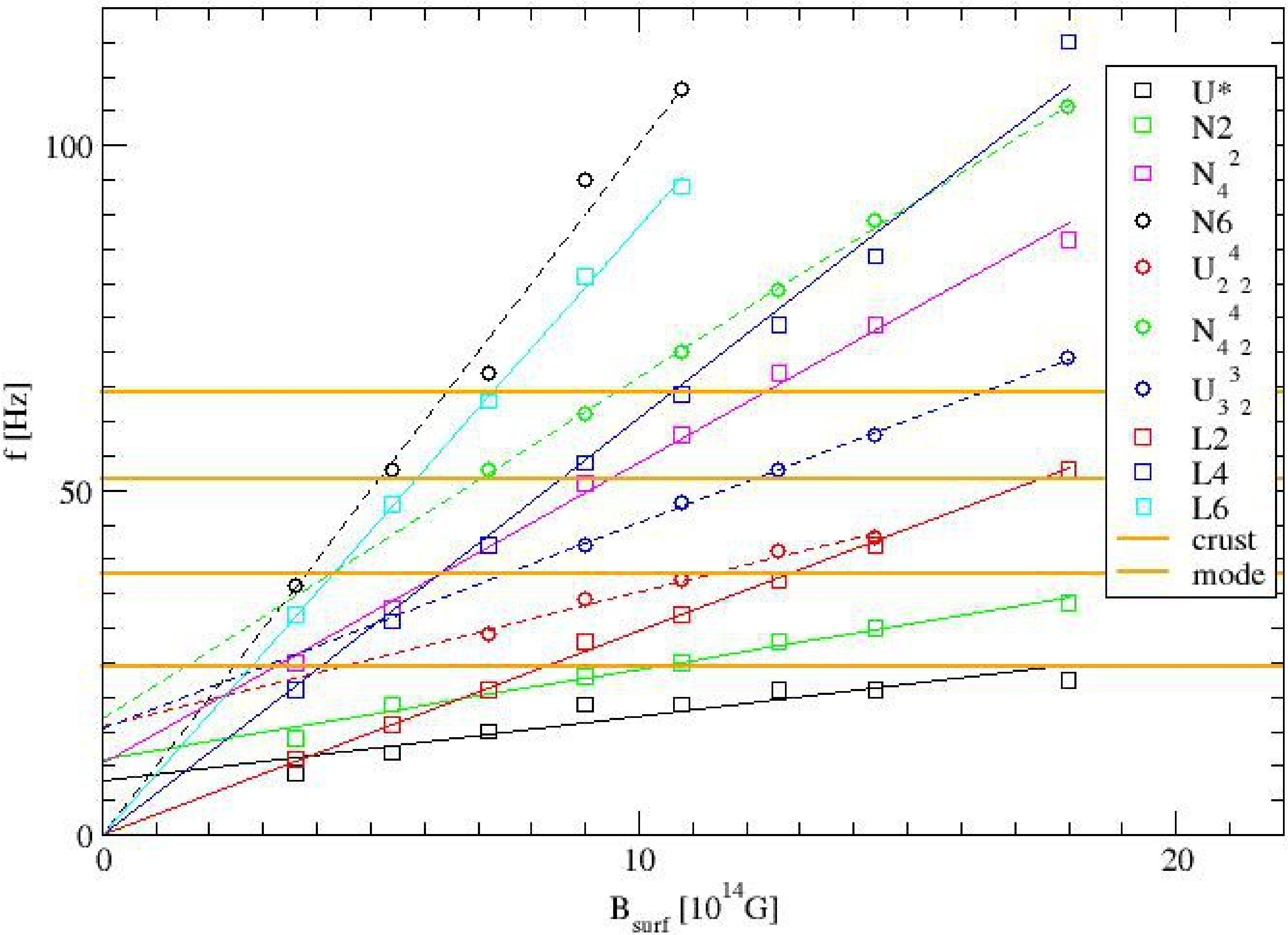
Magneto-elastic simulations of superfluid cores

Gabler et al 2013

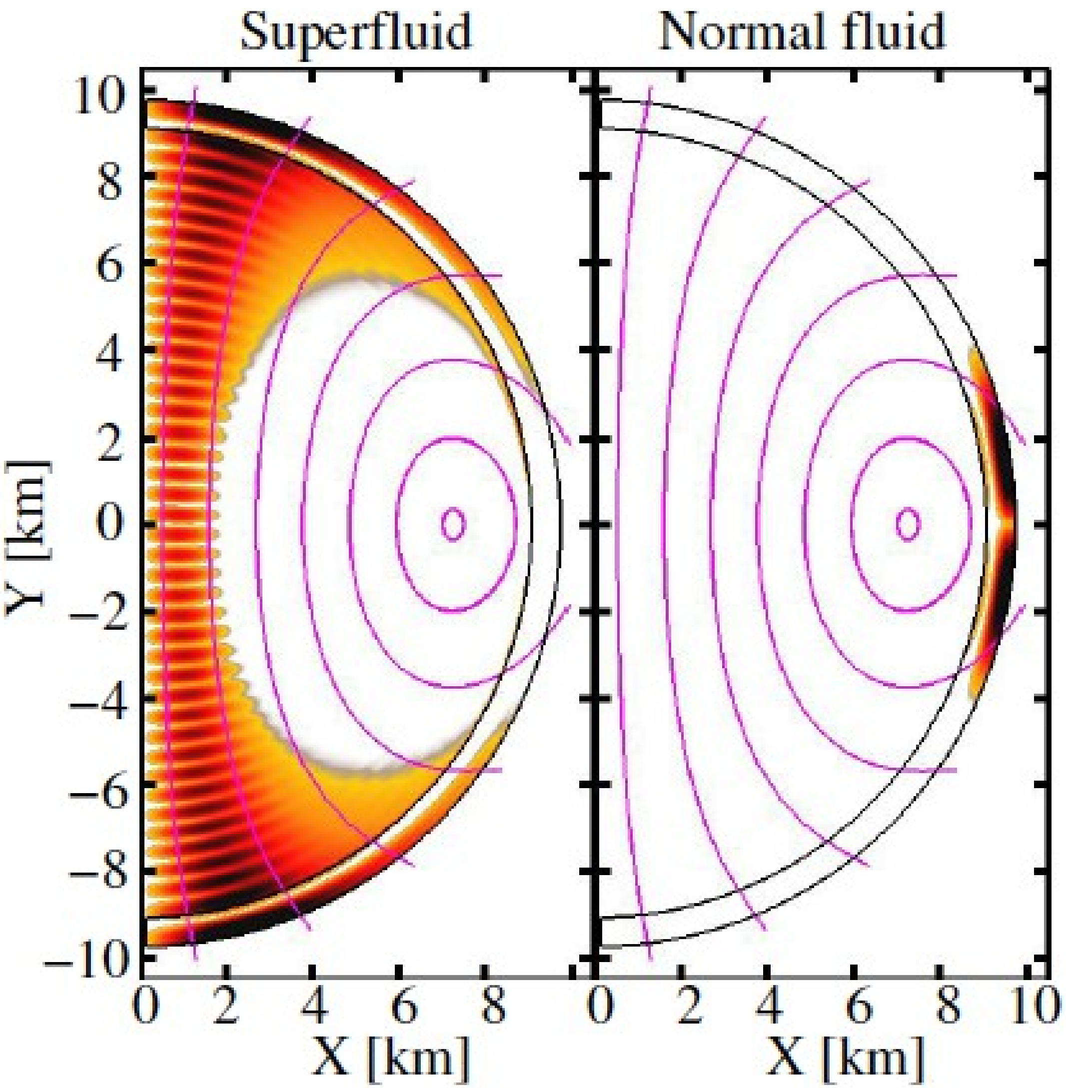


- Constant-phase global QPOs (modes?)
- long lived: >200 Alfvén crossing times
- Resonance between crustal shear modes and the Alfvén continuum
- Appear generically for broad range of B ($5x10^{14}$ – $5x10^{15}$ G)
- Is possible to get similar features in non-superfluid models fine-tuning B.
- van Hoven et al 2010, 2012 → crustal modes in gaps of Alfvén continua? → different interpretation?

Magneto-elastic simulations of superfluid cores



Magneto-elastic simulations of superfluid cores



Gabler et al 2013

- Long lived (>1000 cycles) resonances appear for n=1 modes (high frequency)
- Fine-tuned resonances in non-superfluid cores is possible but structure cannot explain observations.

Conclusions

- **A superfluid component in the core can explain QPOs in SGRs**
  - Low (<150 Hz) and high (>500 Hz) QPOs at the same time.
  - Only fundamental (n=0,2) and a few overtones needed.
  - Long-lived constant-phase modes.
  - Broad range of magnetic fields compatible with observations.
- **It is difficult to explain observations with a non-superfluid core.**
  - Not possible to accommodate high and low frequency QPOs at the same time.
  - Are Alfvén QPOs long lived? (Levin 2006, 2007)
  - Fine tuning required to get resonances (non-generic)
- **We need more/better observations**:
  - QPOs in normal flares?
  - new giant flares?