Title: Modeling QPOs in magnetar giant flares

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Abstract: Alfven oscillations of strongly magnetized neutron stars coupled to shear modes in the solid crust could possibly explain the quasi-periodic oscillations (QPOs) observed in the giant flares of soft gamma repeaters. We present results of two-dimensional simulations of Alfven torsional oscillations in magnetars, modeled as relativistic stars with a dipolar magnetic field. We use a general relativistic magnetohydrodynamics code in the anelastic approximation, which allows for an effective suppression of fluid modes and an accurate description of the Alfven waves. We discuss the coupling of the neutron star interior with the magnetosphere and the observational consequences.

Modeling QPOs in magnetar giant flares

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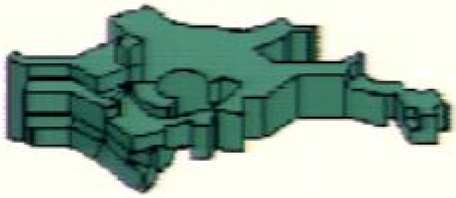

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J.A. Font – University of Valencia (Spain)

Cerdá-Durán et al 2010, Gabler et al 2011, Gabler et al in prep.

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Outline

- Introduction: giant flares in SGR
- Models: elastic or magnetic?
- Magneto-elastic simulations
- 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 : magne
  (Duncan & Thompson 1992)
- B > 10^{14} G
- **1** : Stresses build in the crust
- **2** : Crust breaks and releases ene
- **3** : Fireball and x-ray emision

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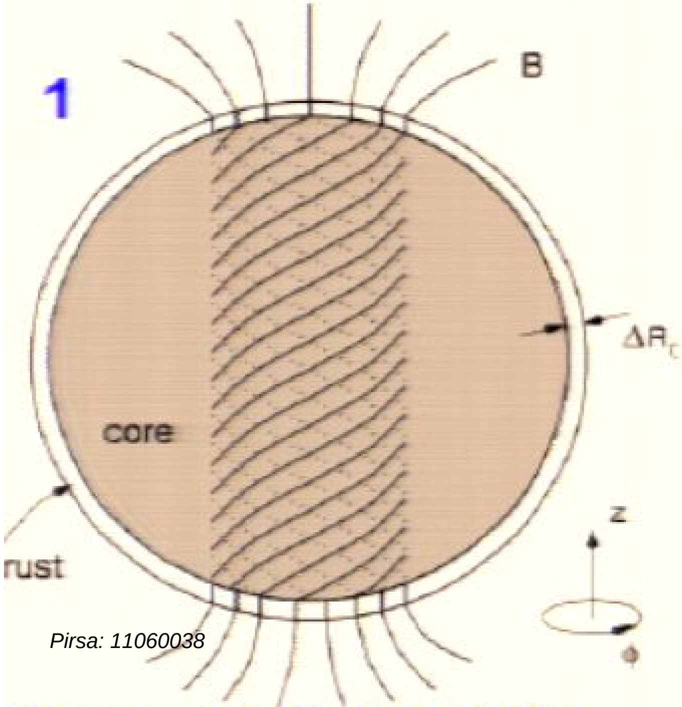

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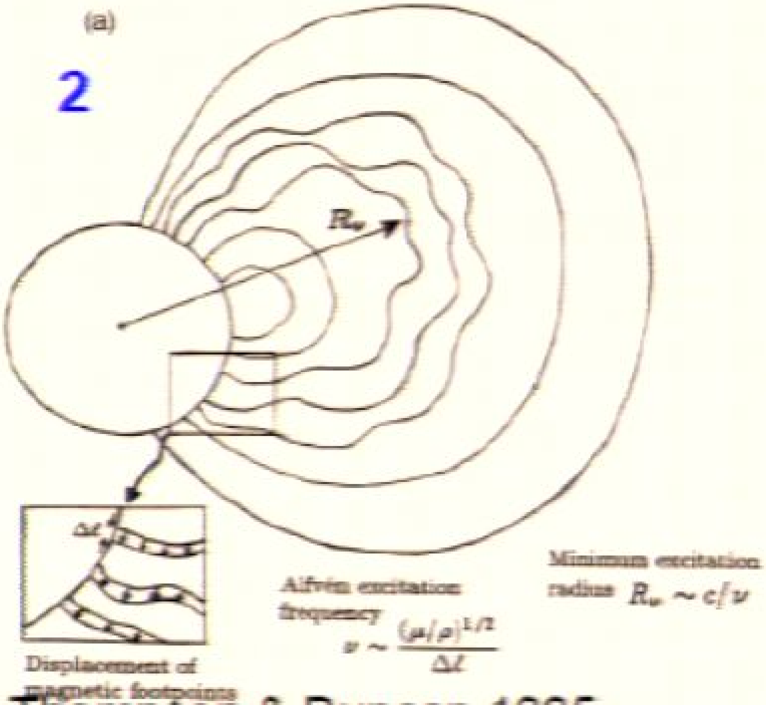

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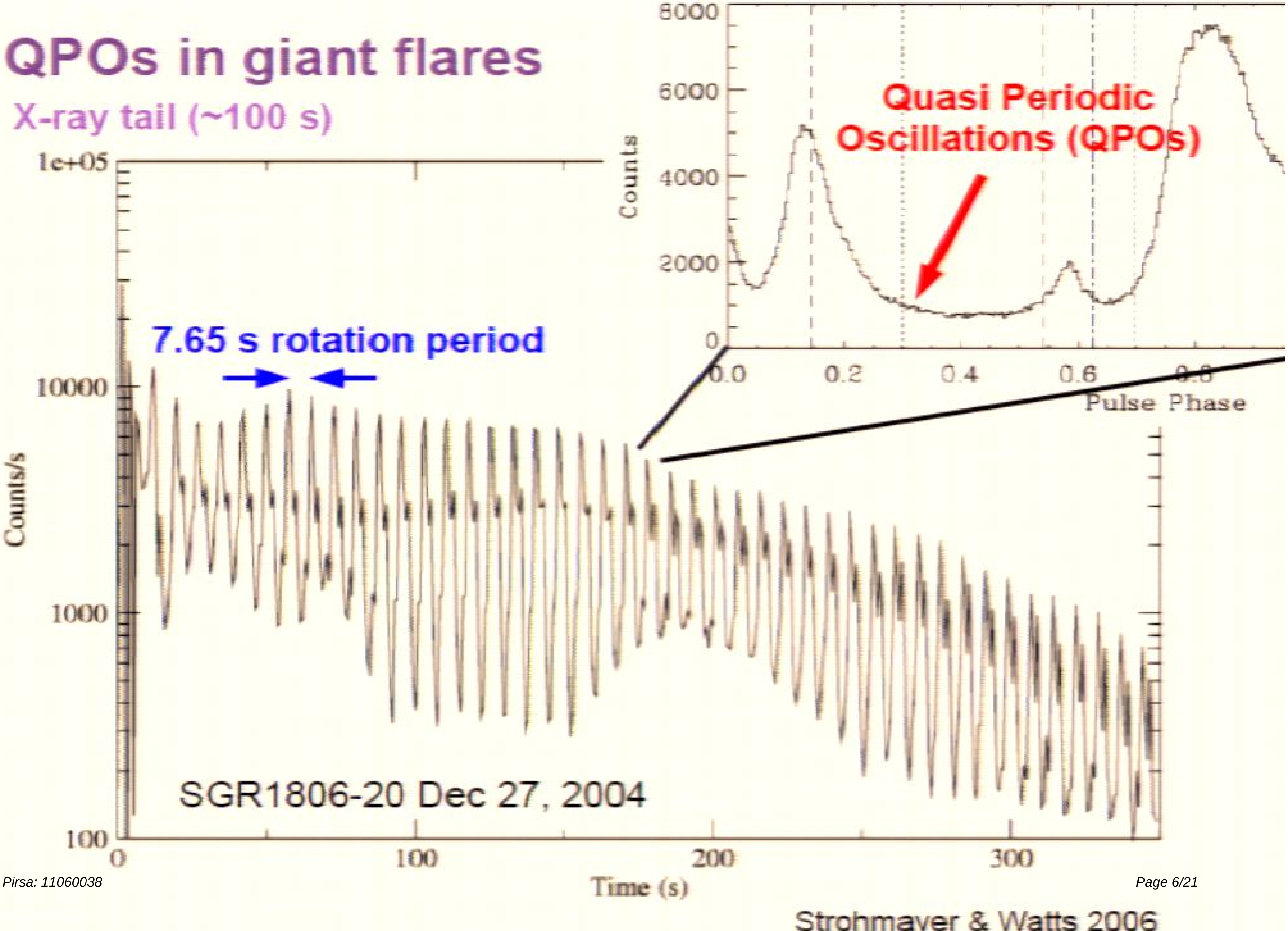
QPOs in giant flares

X-ray tail (~100 s)



7.65 s rotation period

Quasi Periodic Oscillations (QPOs)

SGR1806-20 Dec 27, 2004

Strohmayer & Watts 2006

QPOs in giant flares (and normal 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)
  → 17, 21, 36, 59, 116 Hz (additional) (Hambaryan et al 2011)
  ... on normal flares :
  → 84, 103 and 648 Hz (Mezeni & Ibrahim 2010)

+ Two frequency bands:

- Low frequency QPOs : 17 → 155 Hz

- High frequency QPOs: 625 → 1840 Hz

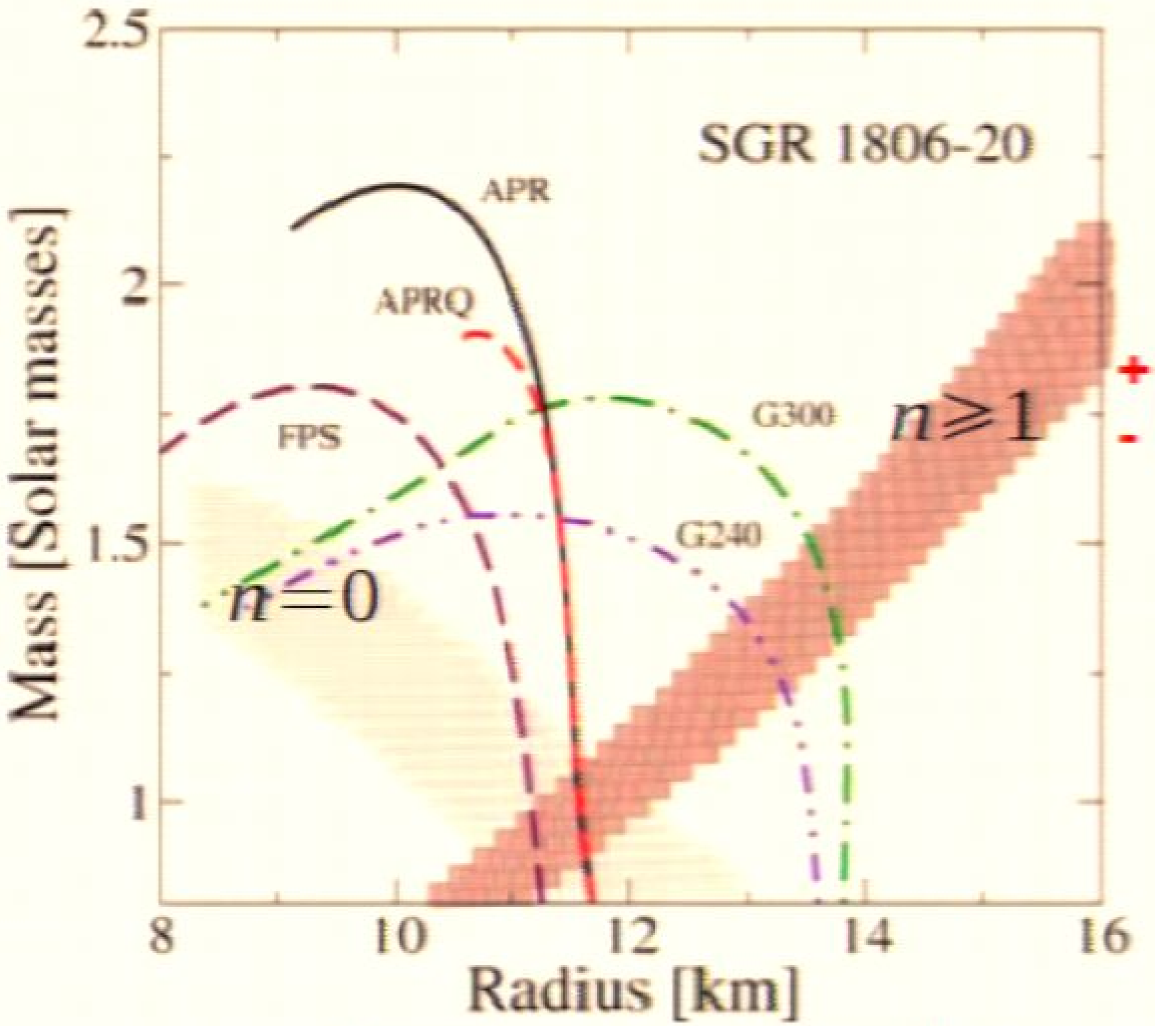
+ Rotational phase dependence: origin close to the star

+ Variability (frequency and amplitude)

Models

Crust shear oscillations model

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



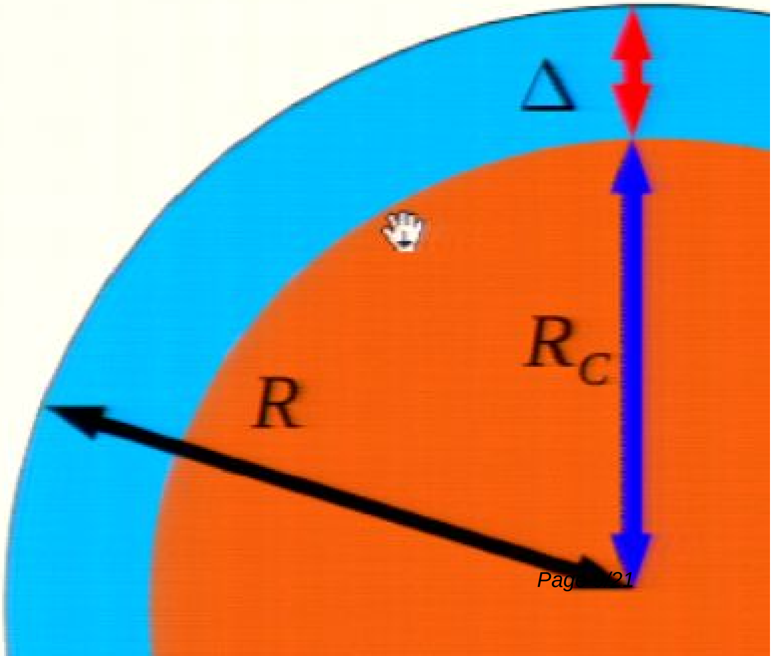
Samuelsson & Andersson 2007

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

$$\omega \approx \frac{n \pi v_r}{\Delta} \qquad n\geq$$

+ Explains low/high freq. QPOs

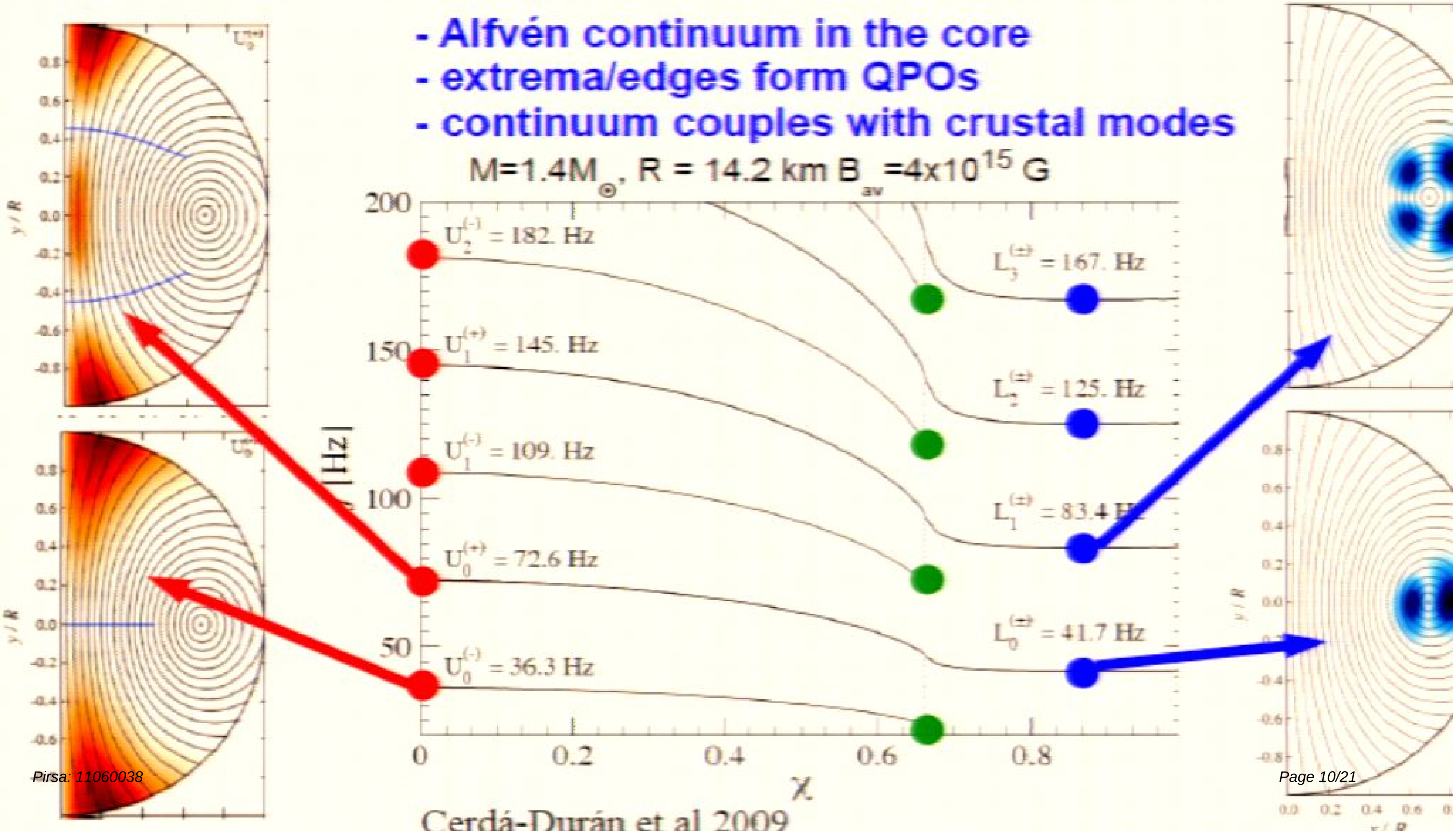
- Cannot explain all QPOs at o



Magneto-elastic model

(Glampedakis et al. 2006, Levin 2006,2007, Sotani et al 2006,2008, Cerdá-Durán et al 2009, Colaiuda et al 2009, Gabler et al 2011, Colaiuda et al 2011

- **Alfvén continuum in the core**
- **extrema/edges form QPOs**
- **continuum couples with crustal modes**


$M=1.4M_{\odot}$, R = 14.2 km $B_{av}=4\times10^{15}$ G

Cerdá-Durán et al 2009

Magneto-elastic simulations

Magneto-elastic equations in GR

$$T^{\mu\nu} = T^{\mu\nu}_{\rm fluid} + T^{\mu\nu}_{\rm magn} + T^{\mu\nu}_{\rm elas}$$

Energy momentum tensor

$$T^{\mu\nu}_{\rm fluid} = \rho h u^\mu u^\nu + P g^{\mu\nu}$$

Fluid contribution

$$T^{\mu\nu}_{\rm magn} = b^2 u^\mu u^\nu + \frac{1}{2} b^2 g^{\mu\nu} - b^\mu b^\nu$$

Magnetic field contribution

$$T^{\mu\nu}_{\rm elas} = -2\mu_{\rm S} \Sigma^{\mu\nu}$$

Elastic contribution

shear modulus

shear tensor

Approximations

- Torsional oscillations
- Low amplitude (linear)

} → constant density (anelastic)

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

Magneto-elastic equations in GR

$$\Sigma^{ij} = \frac{1}{2}\begin{bmatrix} 0 & 0 & g^{rr}\xi^{\varphi}_{,r} \\ 0 & 0 & g^{\theta\theta}\xi^{\varphi}_{,\theta} \\ g^{rr}\xi^{\varphi}_{,r} & g^{\theta\theta}\xi^{\varphi}_{,\theta} & 0 \end{bmatrix}$$

shear tensor (torsional linear oscillations)

(Karlovini & Samuelsson 20
Carter & Samuelsson 2006

ξ^j **: displacement**

$$\xi^j_{,t} = \alpha v^j = \frac{\delta u^j}{u^t} \quad \Longrightarrow \quad \begin{aligned} (\xi^{\varphi}_{,r})_{,t} - (v^{\varphi}\alpha)_{,r} &= \\ (\xi^{\varphi}_{,\theta})_{,t} - (v^{\varphi}\alpha)_{,\theta} &= \end{aligned}$$

Magneto-elastic equations in GR

$$\boxed{\frac{1}{\sqrt{-g}}\left(\frac{\partial\sqrt{\gamma}U}{\partial t}+\frac{\partial\sqrt{-g}F^i}{\partial x^i}\right)=S}$$

Conservation laws

$$U = [S_\varphi\,, B^\varphi\,, (\alpha\xi^\varphi{}_{,r})\,, (\alpha\xi^\varphi{}_{,\theta})]$$

"Conserved" variables

$$F^k = \begin{bmatrix} -\frac{b_\varphi B^k}{W} - 2\mu_S \Sigma^k_\varphi \\ -v^\varphi B^k \\ -\alpha v^\varphi \delta^k_r \\ -\alpha v^\varphi \delta^k_\theta \end{bmatrix}$$

Fluxes

$$S = [0, 0, -\alpha v^\varphi \delta^k_r \frac{1}{\sqrt{-g}}\frac{\partial g_{\mu\nu}}{\partial x^k}, -\alpha v^\varphi \delta^k_\theta \frac{1}{\sqrt{-g}}\frac{\partial g_{\mu\nu}}{\partial x^k}]$$

Sources

Magneto-elastic equations in GR

Eigenvalues

$$\lambda^k_{1/2} = \pm\sqrt{\frac{(B^k)^2 + \mu_S/g_{kk}}{A}}$$

$$A = \rho h W^4 (1 + v_\varphi v^\varphi) + B^r B_r + B^\theta B_\theta$$

$B^2 \gg \mu_S$ Alfvén waves

$B^2 \ll \mu_S$ Shear waves

$B^2 \sim \mu_S$ Mixed waves

We can use Riemann solvers

Magneto-elastic equations in GR

- Boundary condition at the surface:
  - Continuous traction (conservation of momentum)
  - Continuous B^{φ} i.e. no current sheets → magnetosphere has currents

$$\boxed{\begin{aligned} b^{\varphi}_{\text{crust}} &= b^{\varphi}_{\text{atmosphere}} \\ \xi^{\varphi}_{\text{crust},r} &= 0 \end{aligned}}$$

- Crust-core interface treatment:
  - Continuous traction (conservation of momentum)

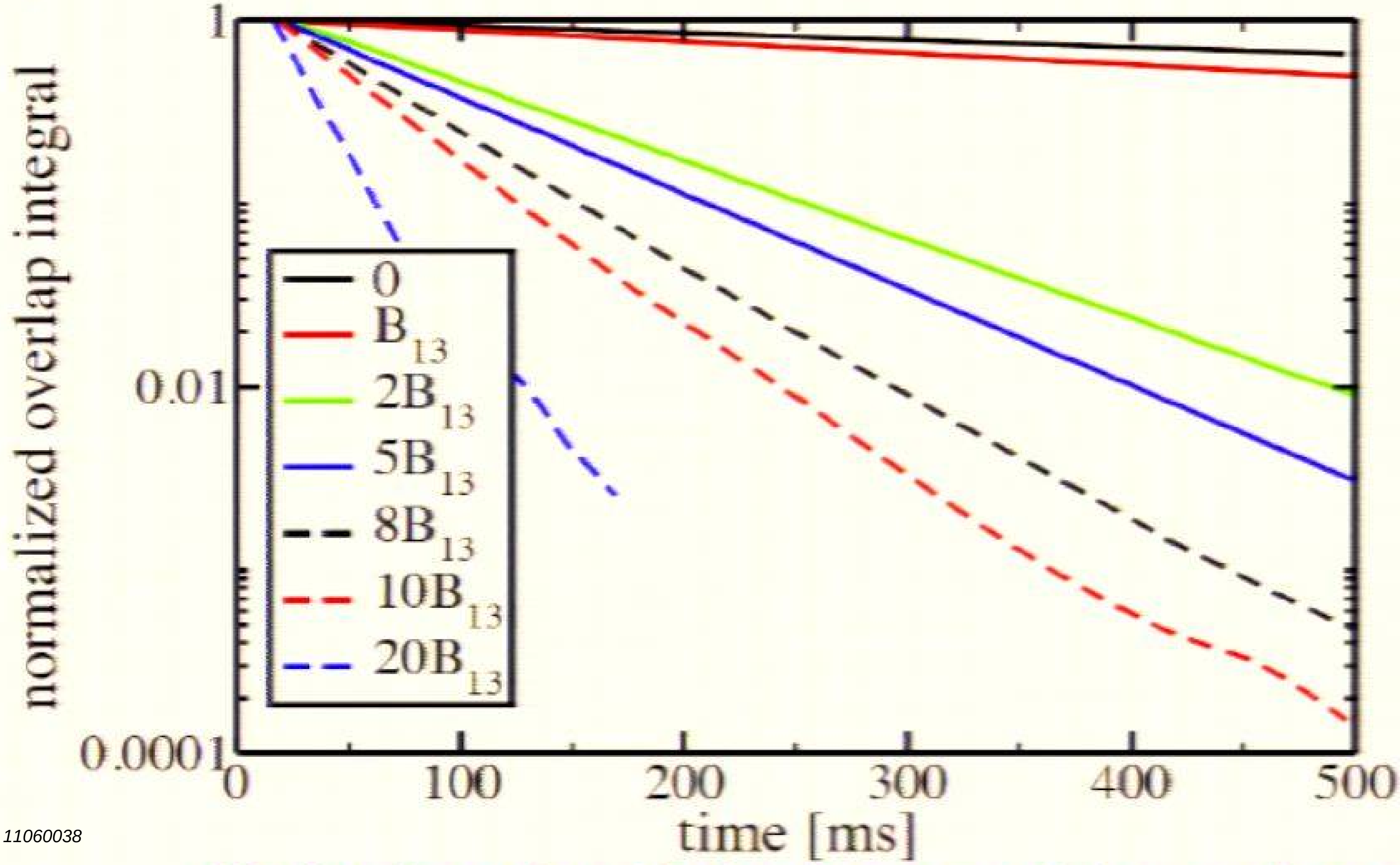
$$\boxed{\xi^{\varphi}_{\text{core},r} = \left(1 + \frac{\mu_S}{\Phi^4 (b^r)^2}\right) \xi^{\varphi}_{\text{crust},r}}$$

B^{φ} discontinuou
current sheet due
Ideal MHD conditi

Absorption of n=0 crustal shear modes by the Alfvén continuum

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

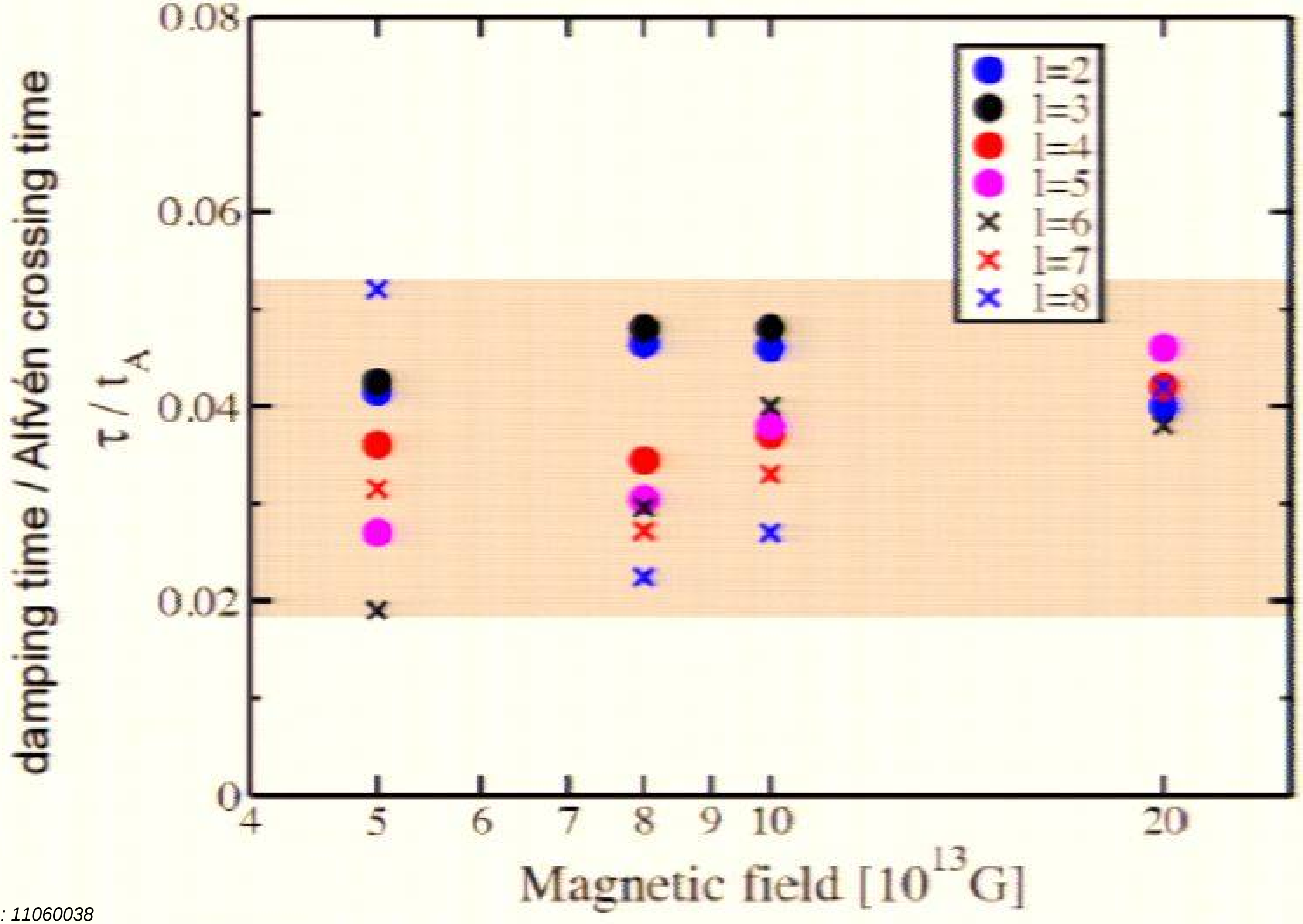
Dipolar-like magnetic field, no toroidal component



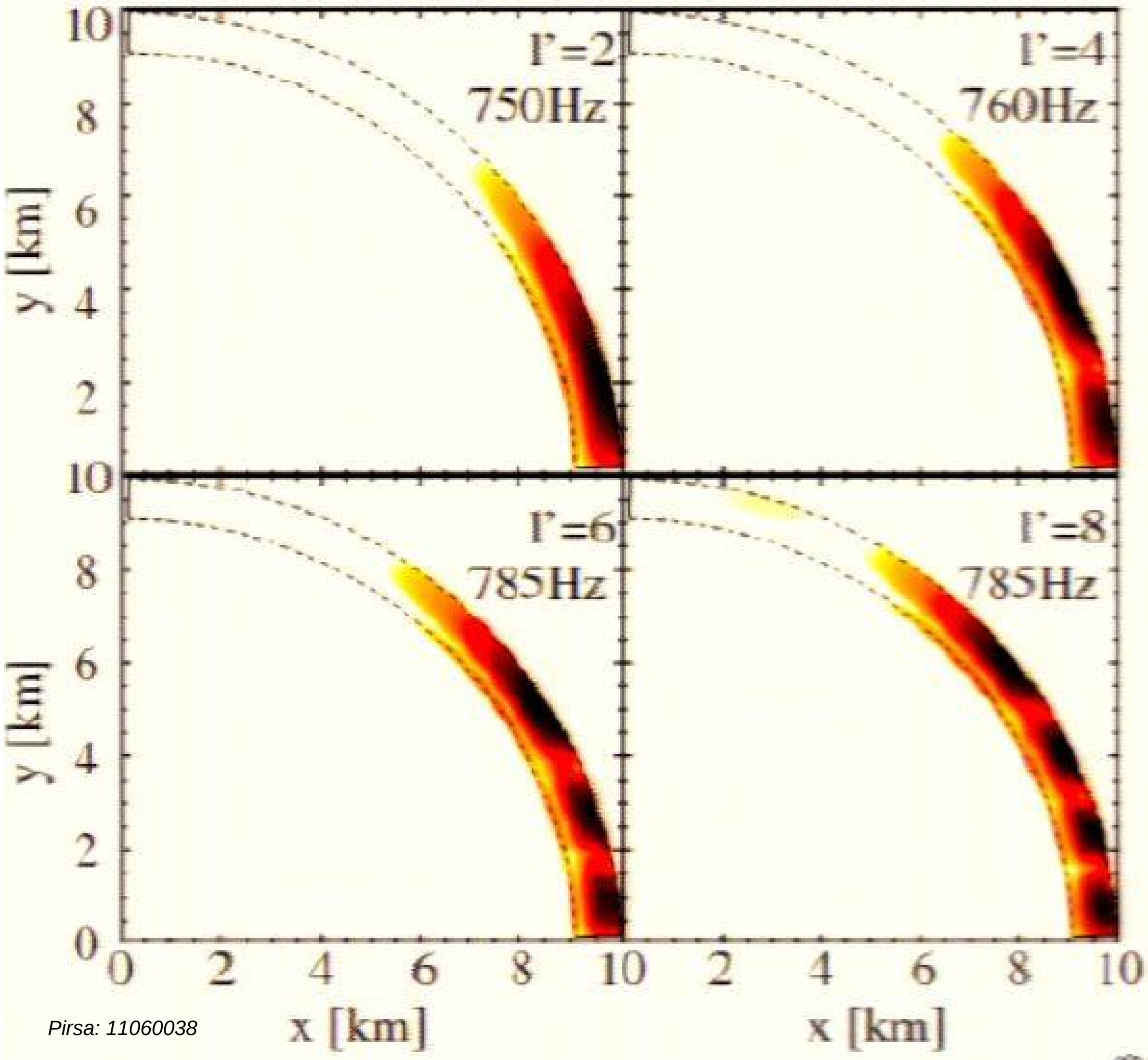
perturbati
n=0, l=2

Similar for other EoS, shear modulus and mass

Absorption of n=0 crustal shear modes by the Alfvén continuum



Absorption of n=1 crustal shear modes by the Alfvén continuum



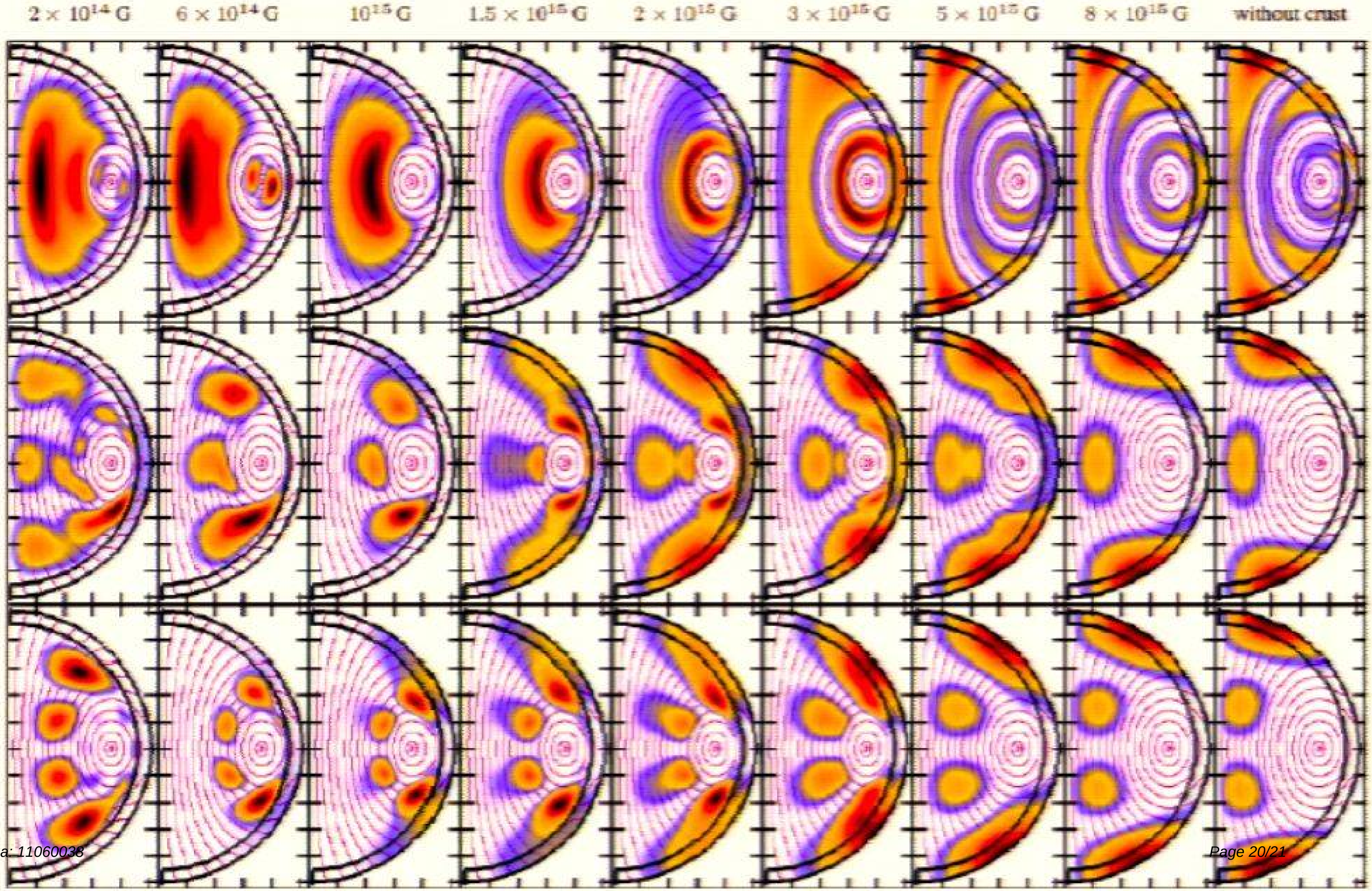
- B = 5×10^{14} G
- Damping time ~ 10 times longer than n=0 case

Problems:

- Unresolved Alfvén waves i the core: scales 20 times smaller than n=0 (300 node
- Simulation time ~ 1 Alfvén crossing time: not fully relaxed

Can n=1 modes survive for ~ 100 s ?

QPOs in the Alfvén continuum



Conclusions and remarks

- **n=0 crustal shear modes do not survive if there are magnetic field inside the core**
  - Observations cannot be interpreted as pure crustal modes
  - Alfvén torsional oscillations favored
  - Magnetic field confined in the crust? (under investigation)

- **Investigations in n=1 crustal modes not conclusive**
  - Could explain the high frequency QPOs and constraint crust EoS.
  - We need 20x CPU time x several Alfvén crossing times (~ several years per simulation !!!) or new methods.

- **Too many uncertainties to make quantitative predictions**
  - Magnetic field structure? Crust/core? toroidal/poloidal?
  - EoS?
  - Crust: shear modulus? Pasta phase?
  - Core: superfluid?, superconductor?
  - Modulation of the x-ray emission?