On the nature of magnetar QPOs

…and other MHD stuff

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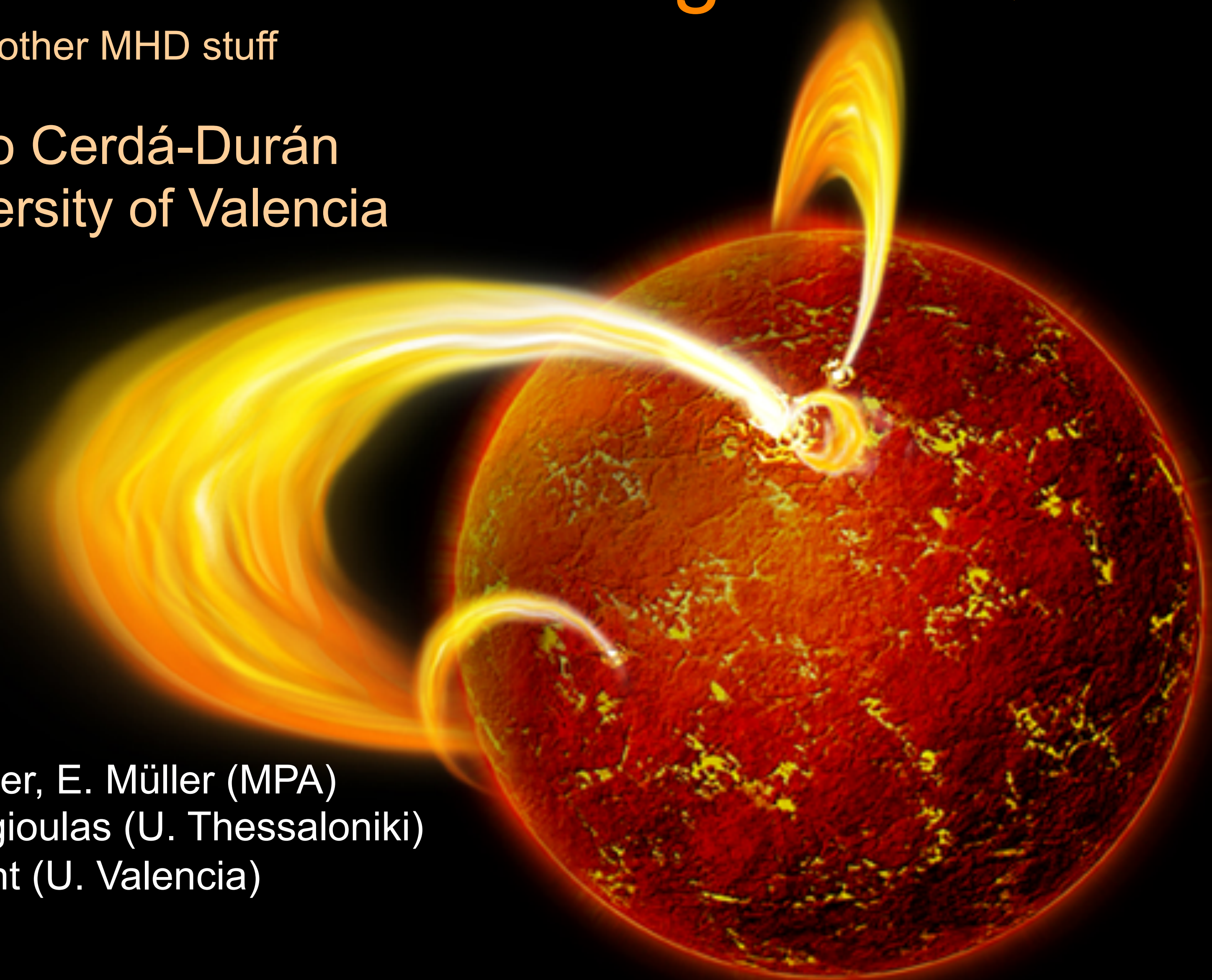

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Seattle – 8/07/2014

Outline

- Magnetar observations
- Models
- Numerical simulations
- Magnetospheres and emission
- Other stuff (MRI)

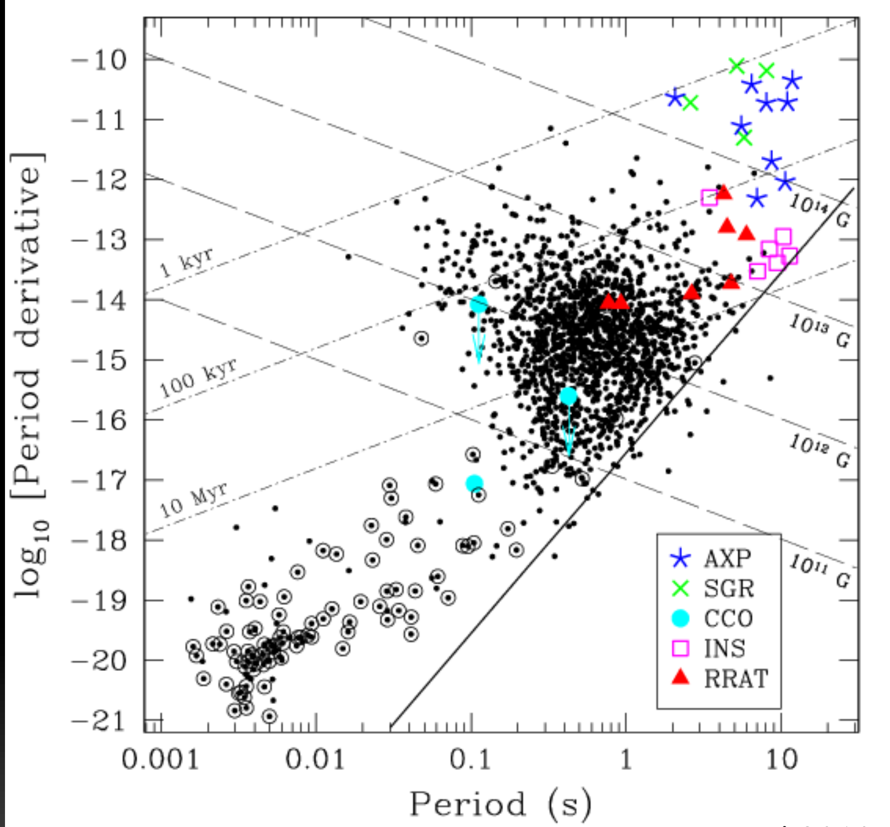
Magnetar observations

Magnetars

- Magnetar = strongly magnetized neutron star (Duncan & Thompson 1992)
- Anomalous X-ray pulsars (AXP) and Soft Gamma repeaters (SGRs)

- Slowly rotating (P~5-10 s)
- Rapid spin down (Kouveliotou et al 1998)
- Spin-down-inferred magnetic field ~10^{14} – 10^{15} G
- Magnetically powered emission →L_X ~10^{33}-10^{35} erg s^{-1}

- Nearby (Galactic/LMC/SMC)
- Associations to SNR (see Mereghetti 2013, Olauson & Kaspi 2013 for a list)
- Progenitor mass unclear (Figer et al 2005, Muno et al 2006, Bibby et al 2008 > 40 M_{sun}, Davies et al 2009 ~17 M_{sun})

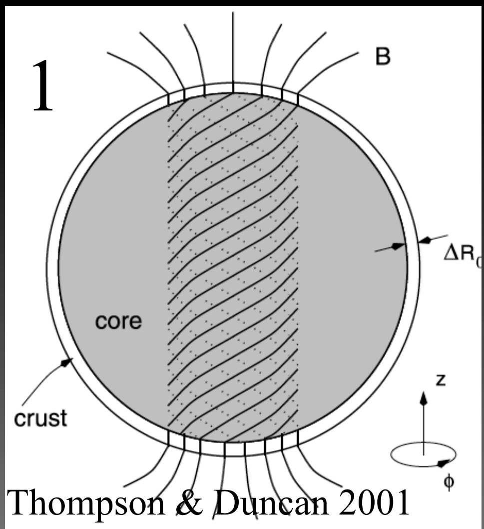


Kaspi 2010

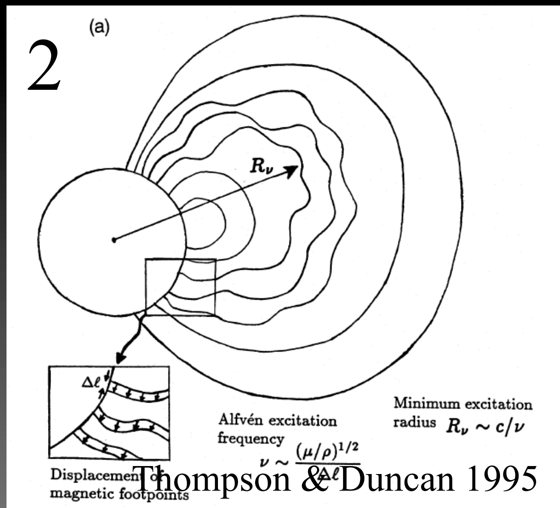
Soft gamma repeaters (SGRs)

- Recurrent gamma-ray activity
- Giant flares ($L \sim 10^{44}$-10^{46} erg/s), intermediate flares and small flares.
- Flare storms → ~100 in few days

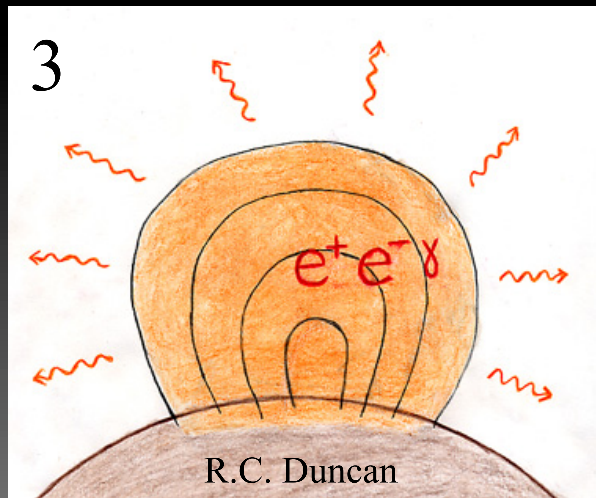
- Model (Duncan & Thompson 1992):
  1 : Stresses build in the crust → Hall drift in the crust (Vigano et al 2013)
  2 : Crust breaks (crustquake) and releases energy → soft γ-ray spike
  3 : Magnetically trapped fireball → x-ray emission



Thompson & Duncan 2001

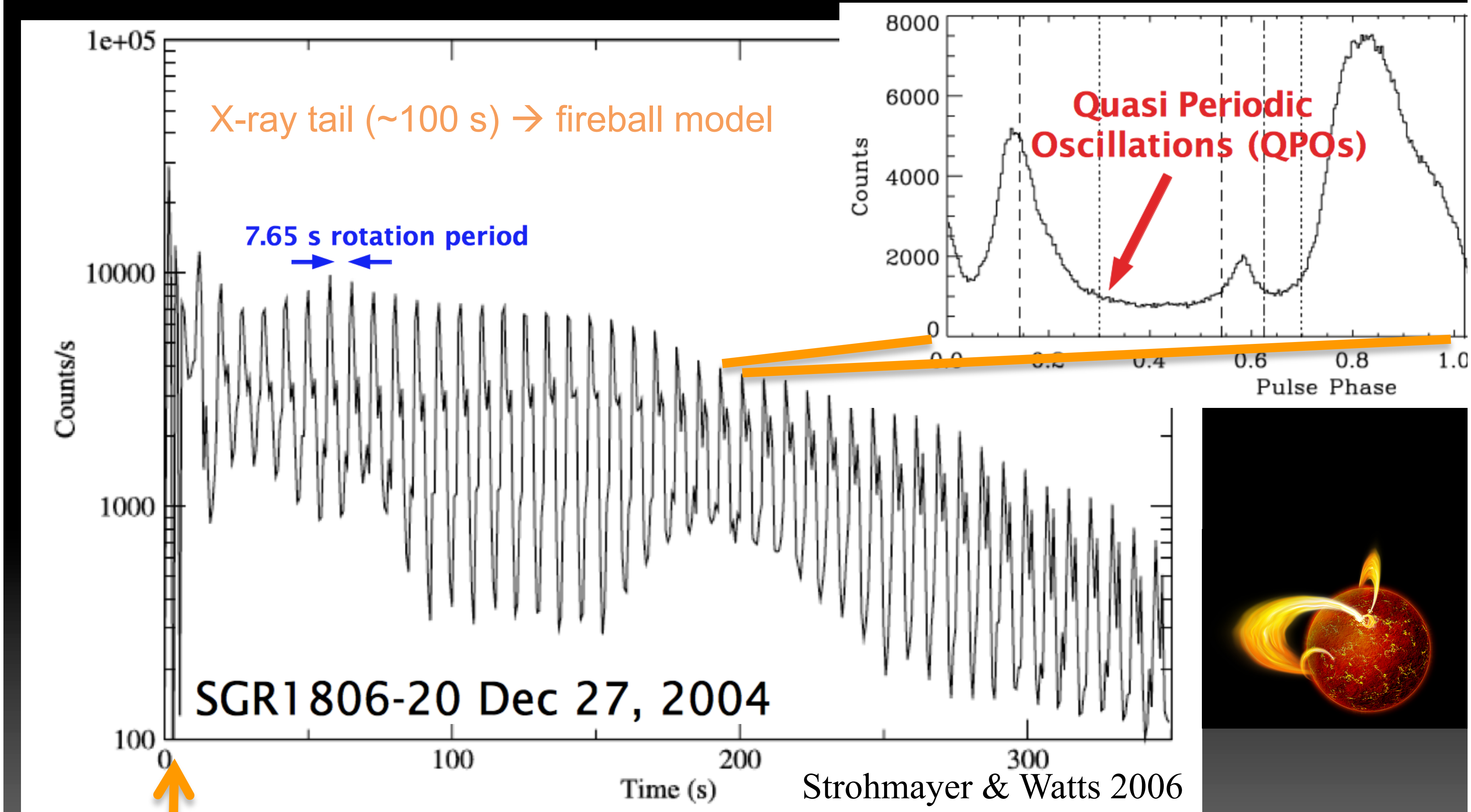


Thompson & Duncan 1995



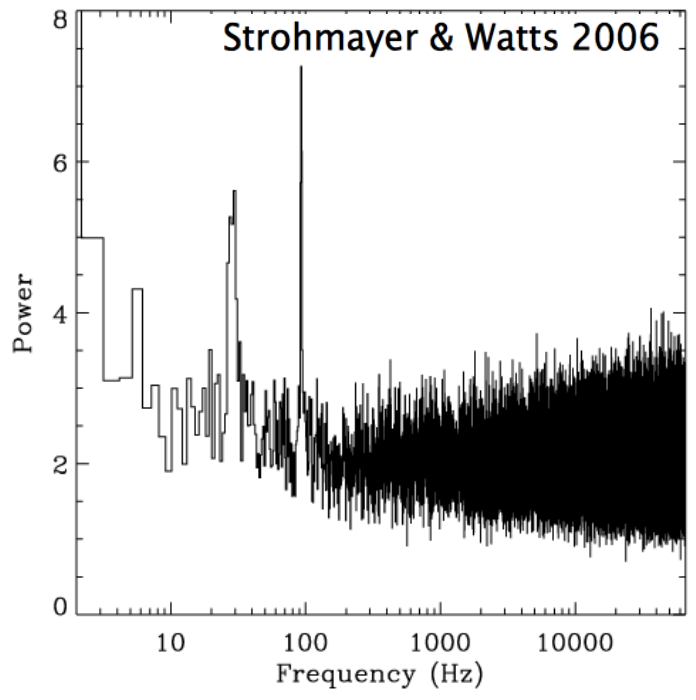
R.C. Duncan

Quasi-periodic oscillations (QPOs)



Soft gamma-ray flash (~0.1 s) → saturated instruments

QPOs in giant flares



SGR 0526-66 giant flare on March 5, 1979 :
→ 43 Hz ? (Barat et al 1983)

SGR 1900+14 giant flare on Aug. 27, 1998 :
→ 28, 56, 84, 155 Hz (Strohmayer & Watts 2005)

SGR 1806-20 giant flare on Dec 27, 2004 :
→ 18, 26, 30, 92, 150, 625, 1840 Hz
(Israel et al 2005; Watts & Strohmayer 2006, Strohmayer & Watts 2006)

SGR J1550-5418 intermediate flare storm on Jan 2009
→ 93, 127, 260 Hz (Huppenkothen et al 2014)

+ **Two frequency bands:**
  - **Low frequency QPOs : 17 → 155 Hz**
  - **High frequency QPOs: 625 → 1840 Hz**

+ **Rotational phase dependence: origin close to the star**

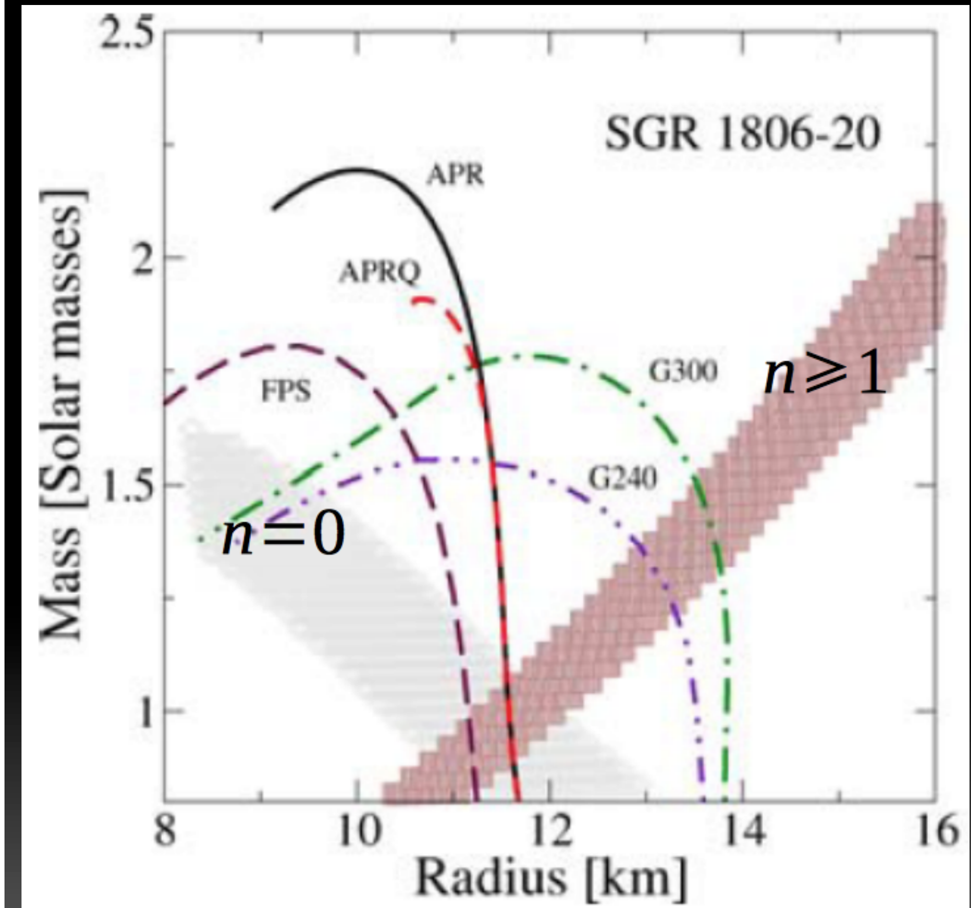
+ **Variability (frequency and amplitude)**

+ **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

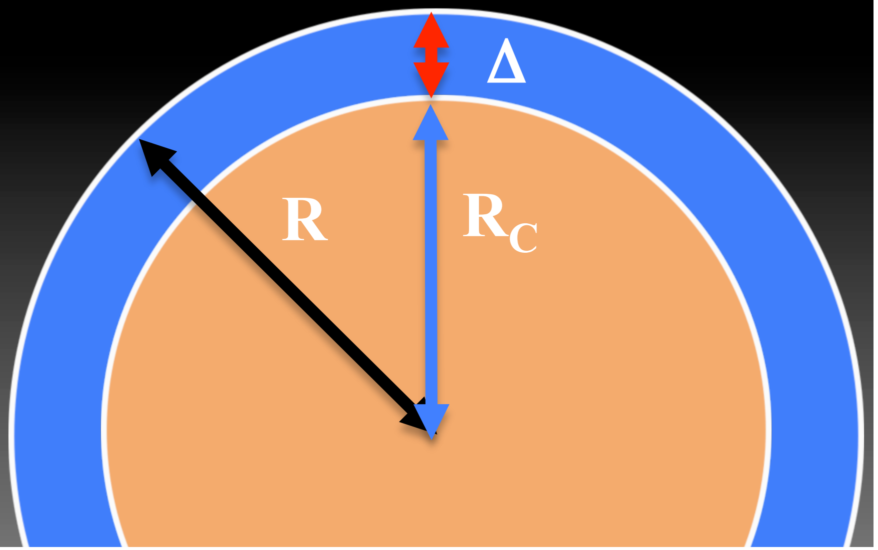
Torsional shear oscillations of the crust

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

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

+ Explains low/high freq. QPOs

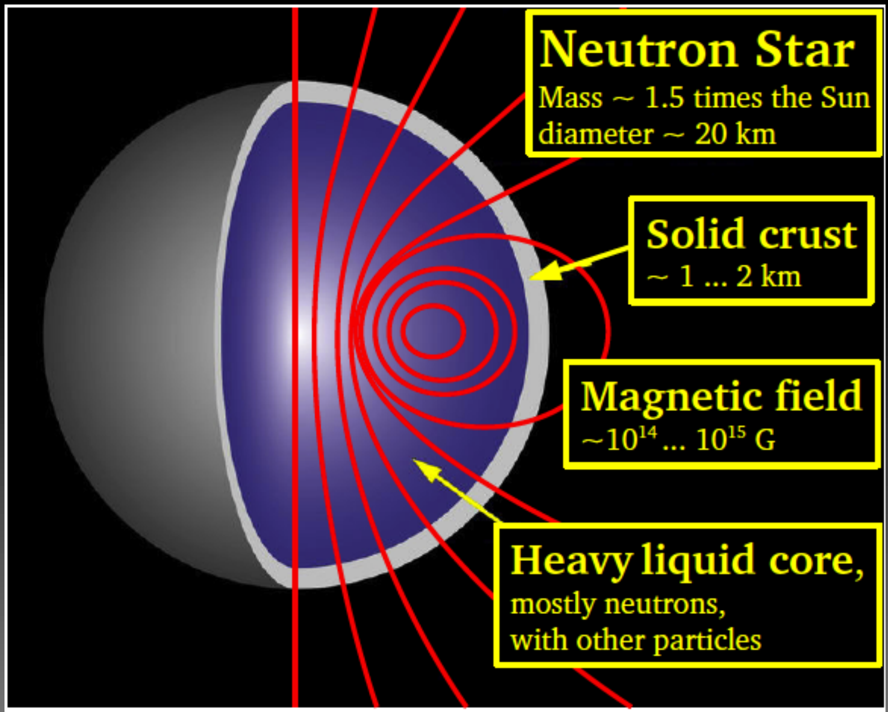
- Cannot explain all QPOs at once

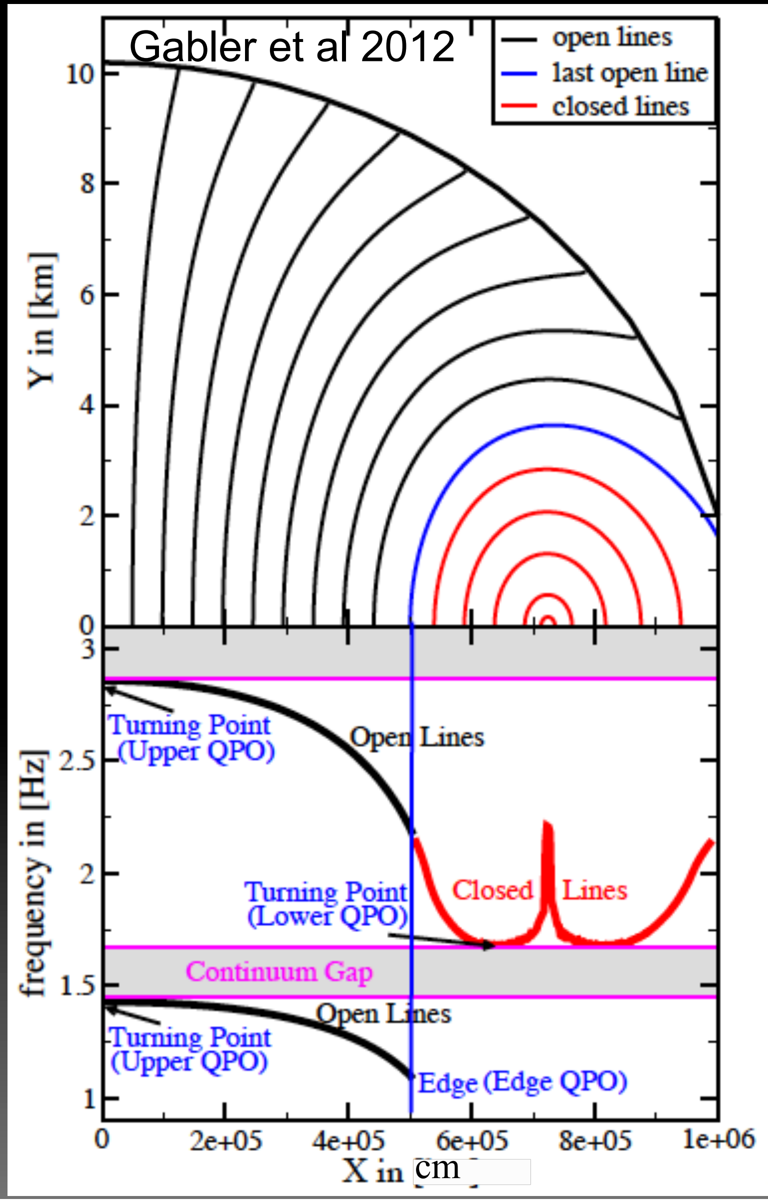


Magneto-elastic model

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, Passamonti & Lander 2014

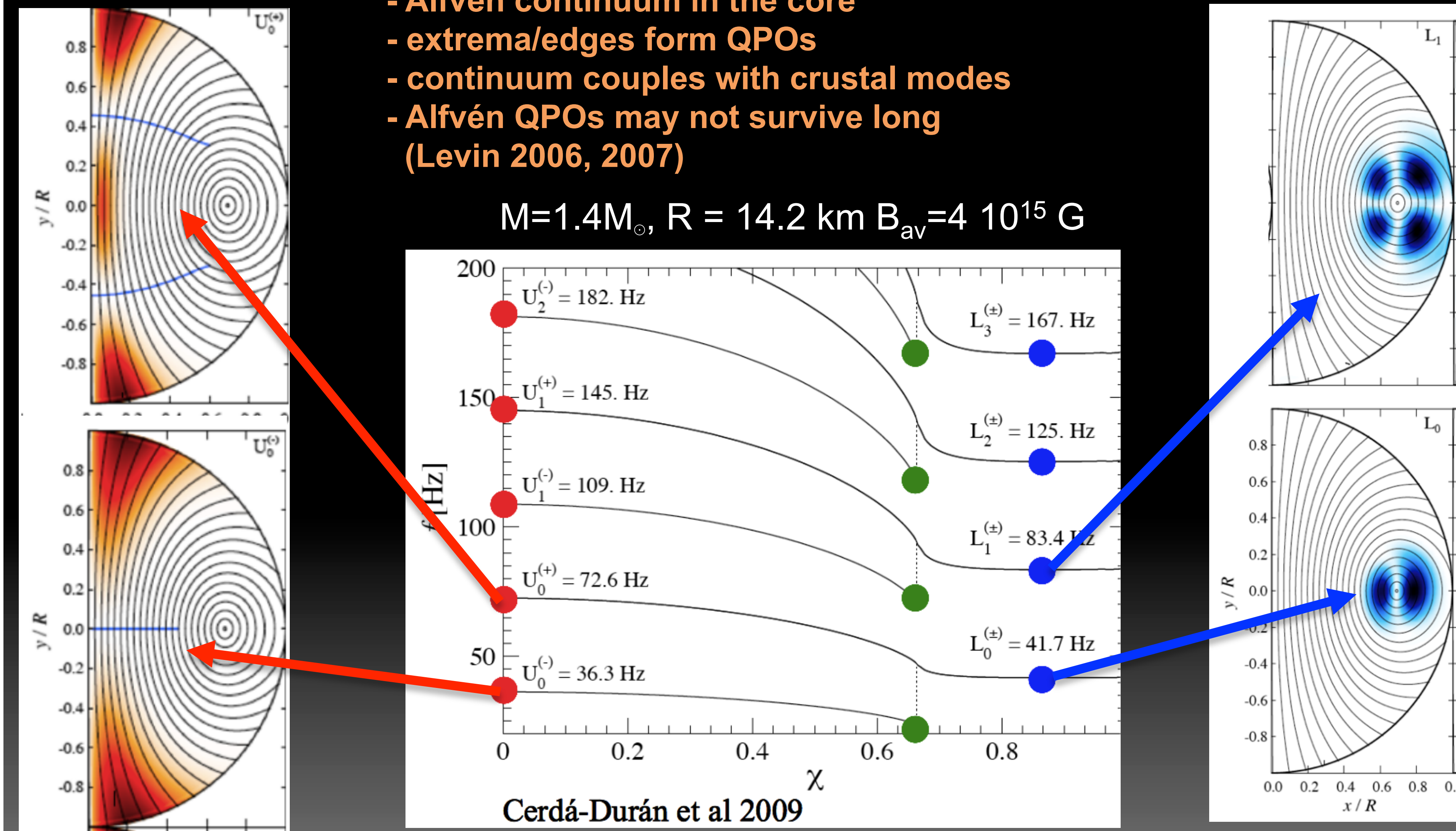




Magneto-elastic model

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

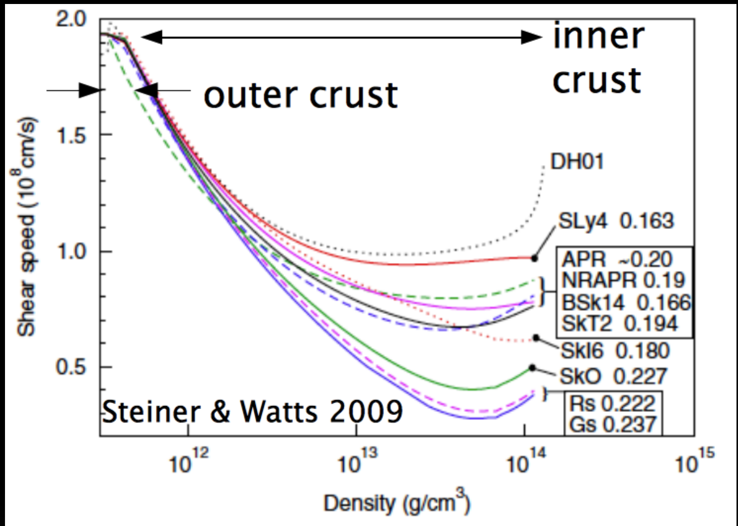
M=1.4M$_\odot$, R = 14.2 km B_{av}=4 10^{15} G



Numerical simulations: CoCoNuT code – anelastic/torsional approximation

Magneto-elastic model

Magneto-elastic waves (eigenvalues of the magneto-elastic equations) → $v_{me} = \pm\sqrt{\dfrac{B^2 + \mu_s}{\rho}}$



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

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

$B^2 >> \mu_s \rightarrow v_{me} \sim v_{Alfven}$ Alfvén wave

$B^2 << \mu_s \rightarrow v_{me} \sim v_{shear}$ Shear wave

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

Numerical simulations

(mostly M. Gabler's work)

Magneto-elastic simulations in GR

CoCoA code (CoCoNuT framework)

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

Approximations

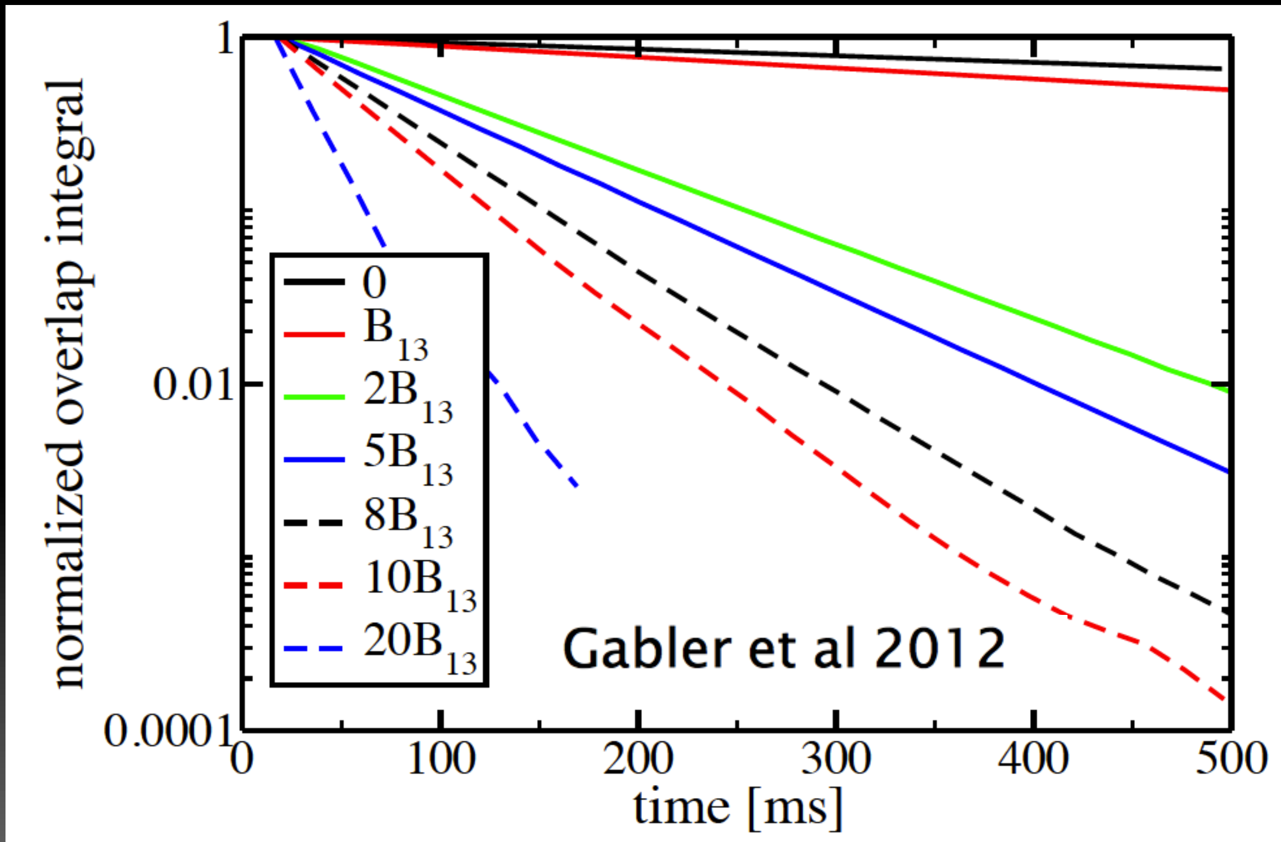
- **Torsional oscillations**
- **Low amplitude (linear/anelastic)**
- **Cowling (fixed spacetime)**
- **Spherically symmetric background (non-rotating stars)**
- **Ideal MHD**
- **Axisymmetry**

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

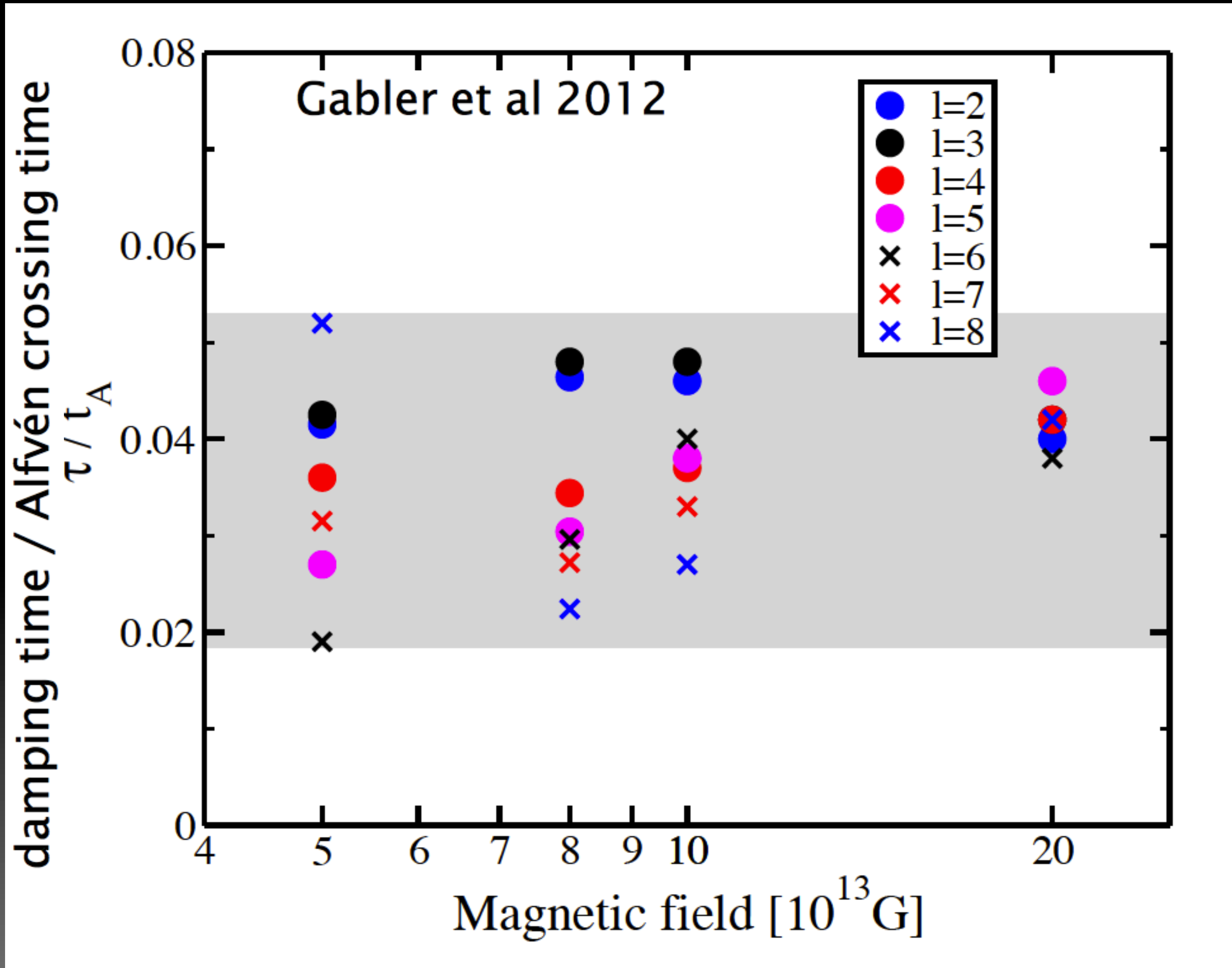
EoS: APR+DH, shear modulus: DH, M=1.4M⊙, R = 12.1 km, ΔR = 0.88 km
Dipolar-like magnetic field, no toroidal component



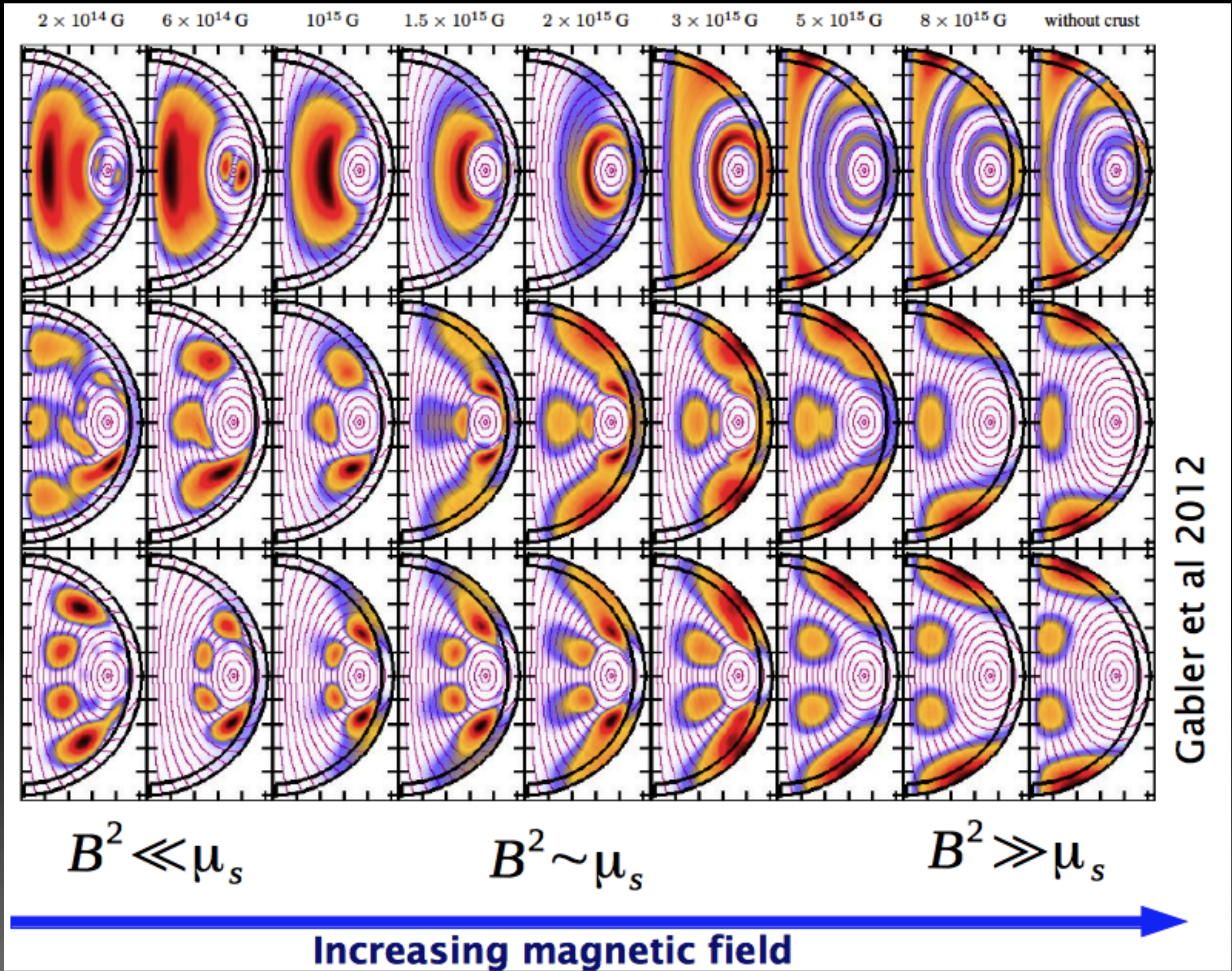
perturbation
n=0, l=2

Similar for other EoS, shear modulus and mass

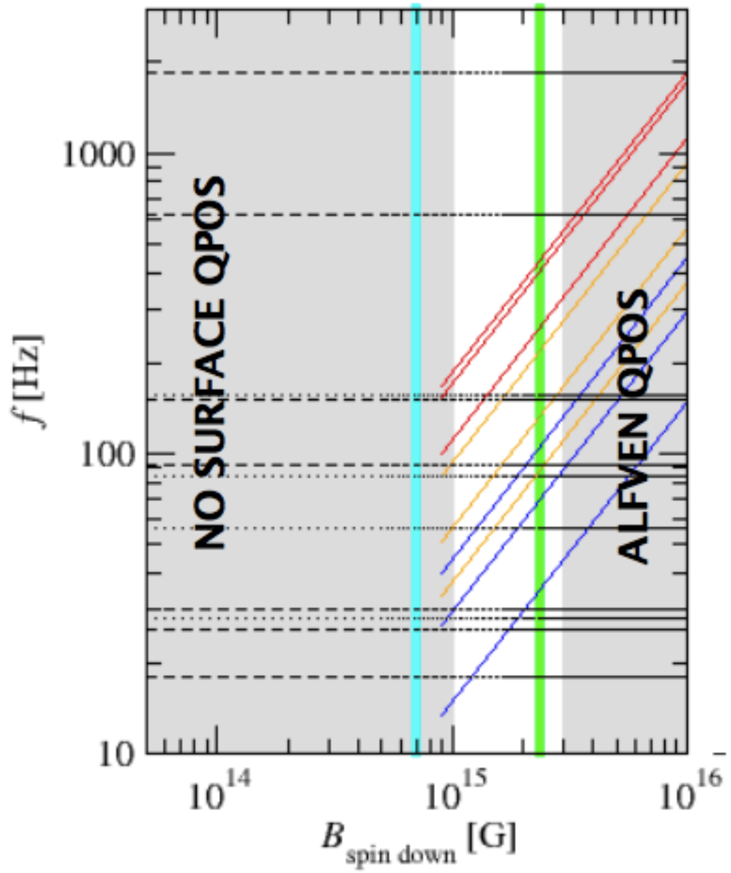
Absorption of crustal shear modes by the Alfvén continuum



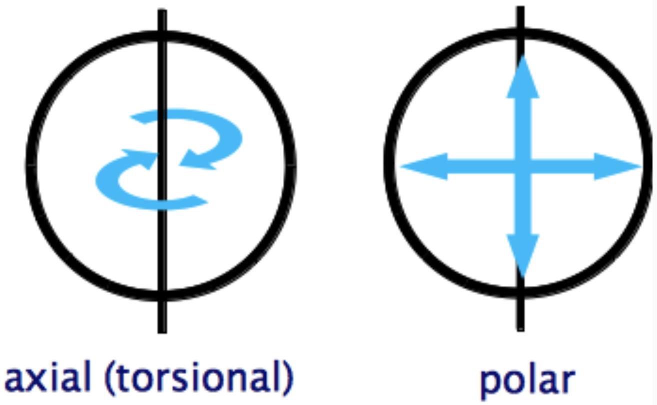
QPOs in the Alfvén continuum



Axial vs polar modes



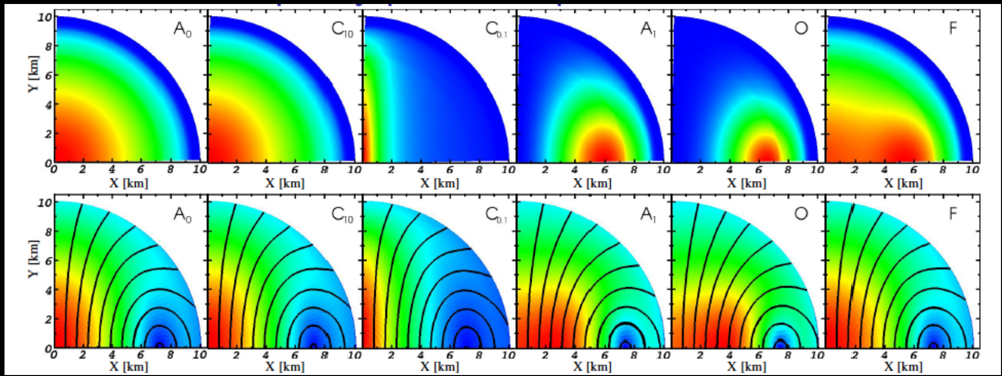
- Magneto-elastic regime is the most relevant
- polar oscillations x5 larger frequency that axial
- Not possible to explain high and low frequency QPOs at the same time (unless very high order QPOs are considered)

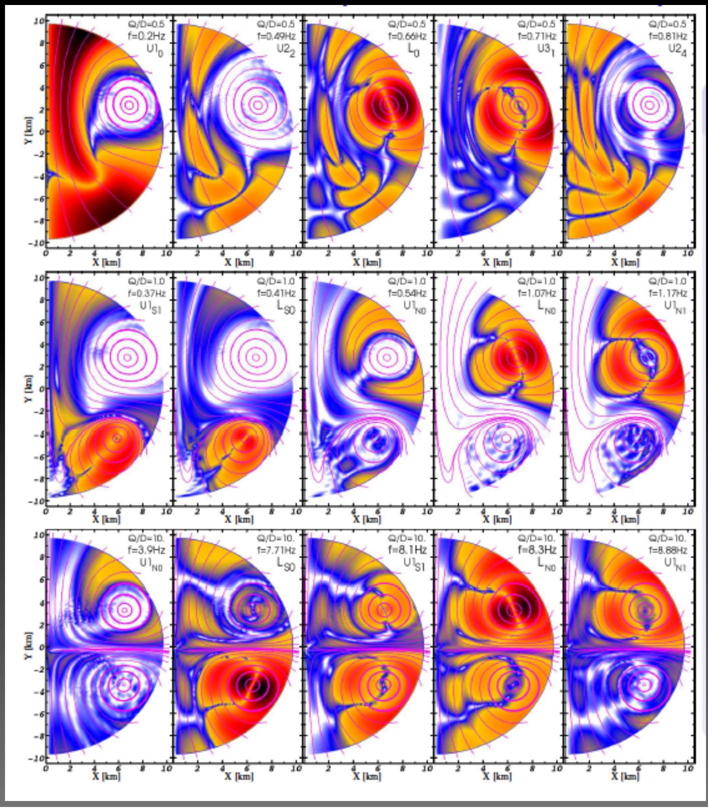


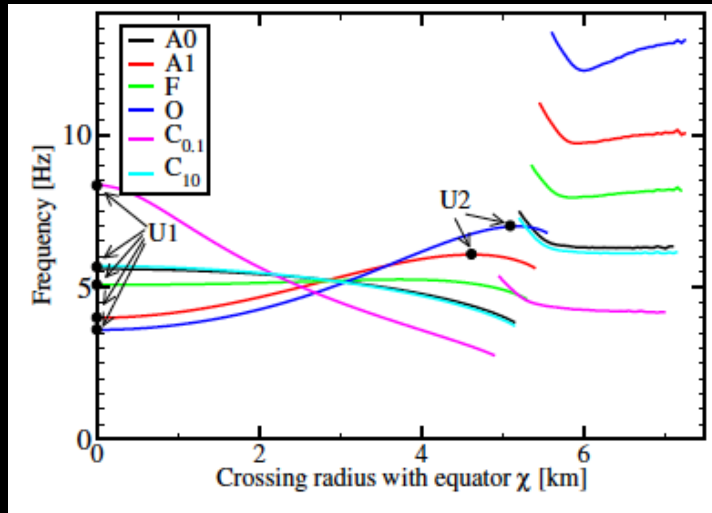
axial, m=0 (Sotani et al 2008, CD et al 2009, Gabler et al 2011, Colaiuda & Kokkotas 2012, Gabler et al 2013)
polar, m=0 (Sotani & Kokkotas 2009, Colaiuda & Kokkotas 2012)
polar, m=2 (Lander & Jones 2011, Passamonti & Lander 2012)
SGR1806-20 (Dec. 27, 2004)
SGR1900+14, Aug. 27 1998

SGR1806-20
SGR1900+14

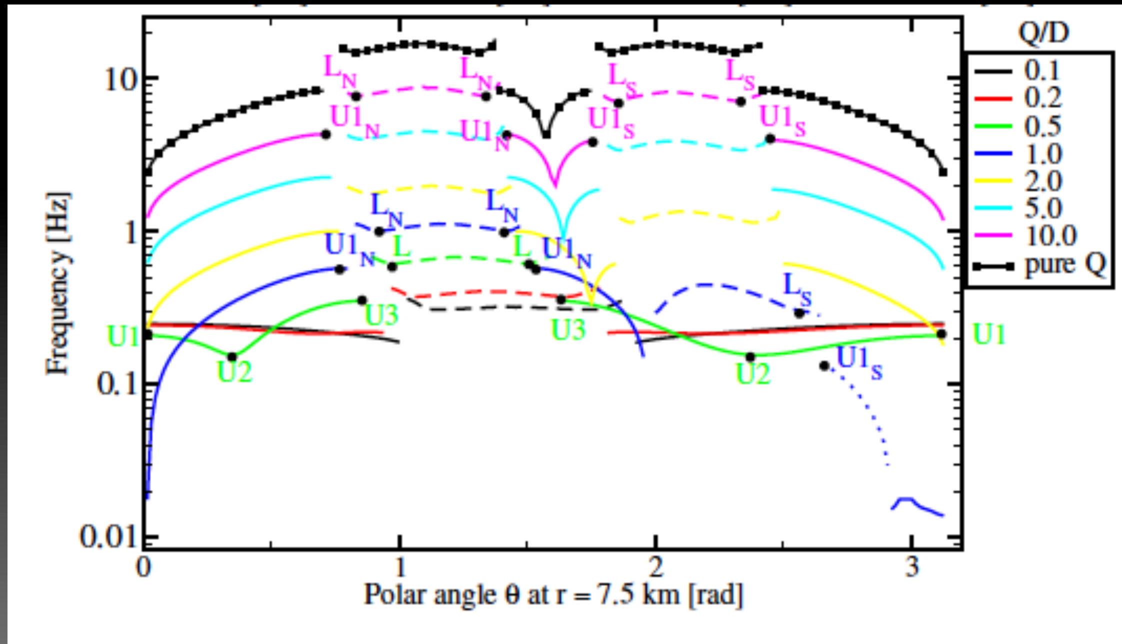
Magnetic field structure



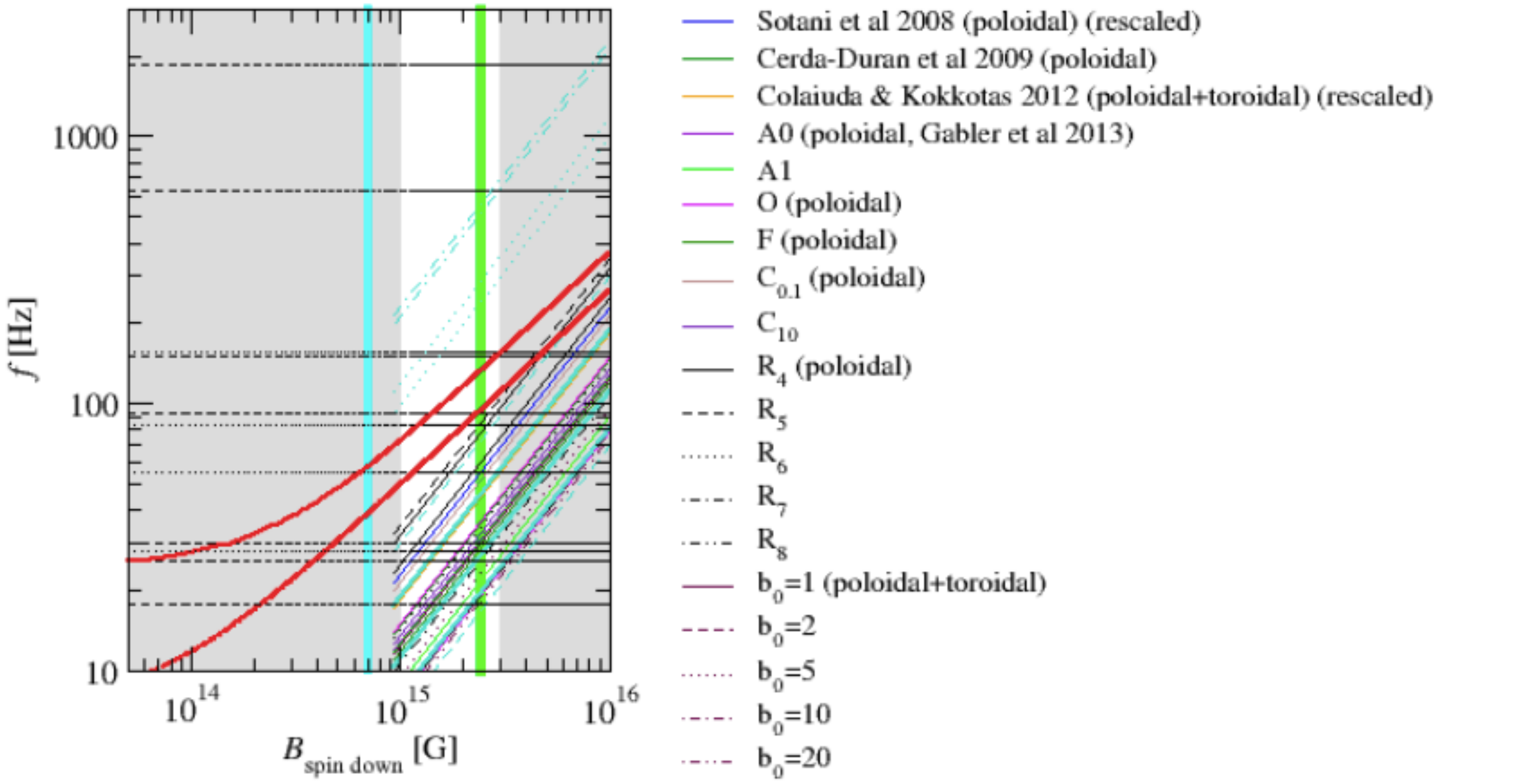




Gabler et al 2013

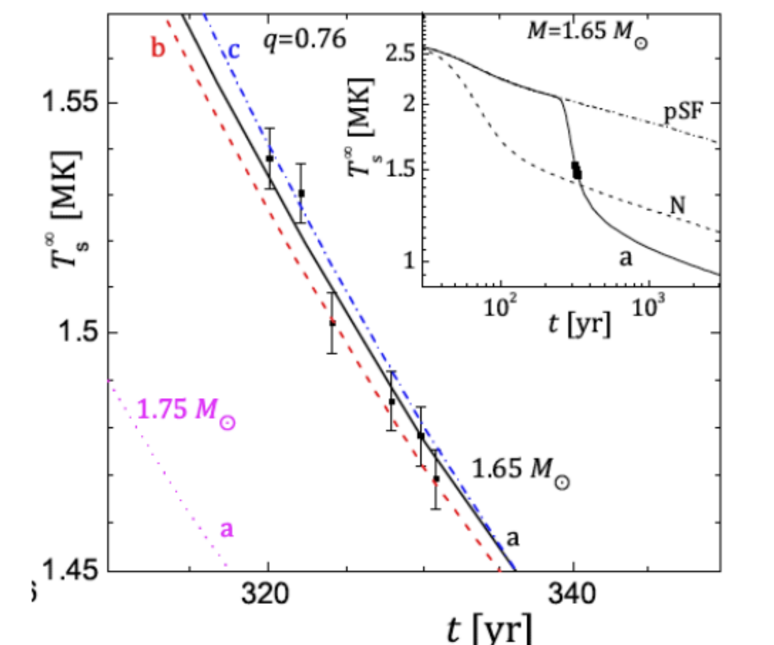


Magnetic field structure



- 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.**

Superfluidity



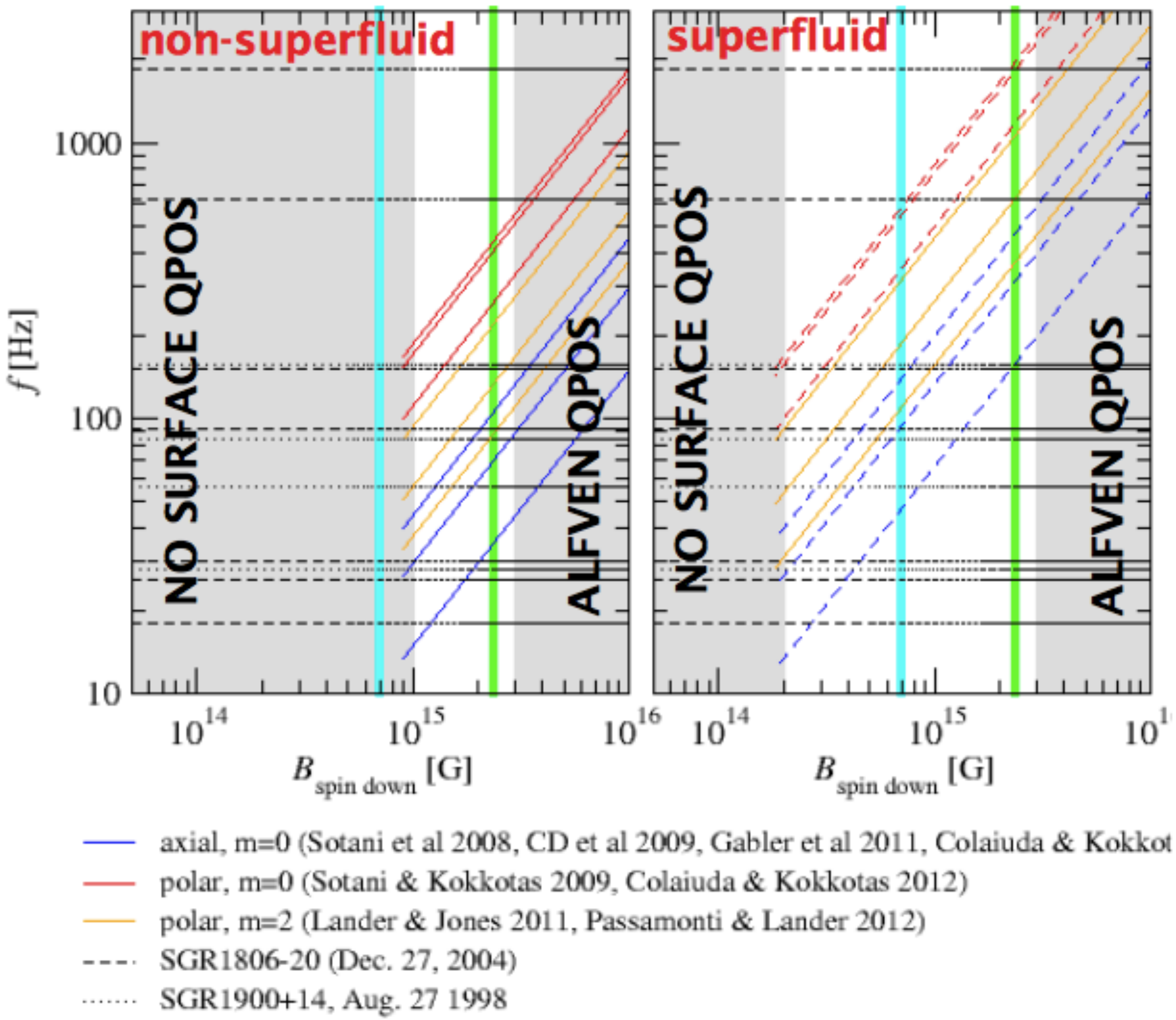
Shternin et al 2011

- 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) Posselt et al 2013).
- Superconductivity may be suppresed in magnetars since B_{crit} ~10^{15}-10^{16} G (Glampedakis et al 2011).
- Only protons are involved in Alfvén waves
- QPO estimations: Glampedakis et al 2006, van Hoven et al 2011, 2012, Gabler et al 2013, Passamonti & Lander 2014

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

Alfvén QPO frequency increases x5
→can explain QPO freqs. with 1/5 B

Superfluidity

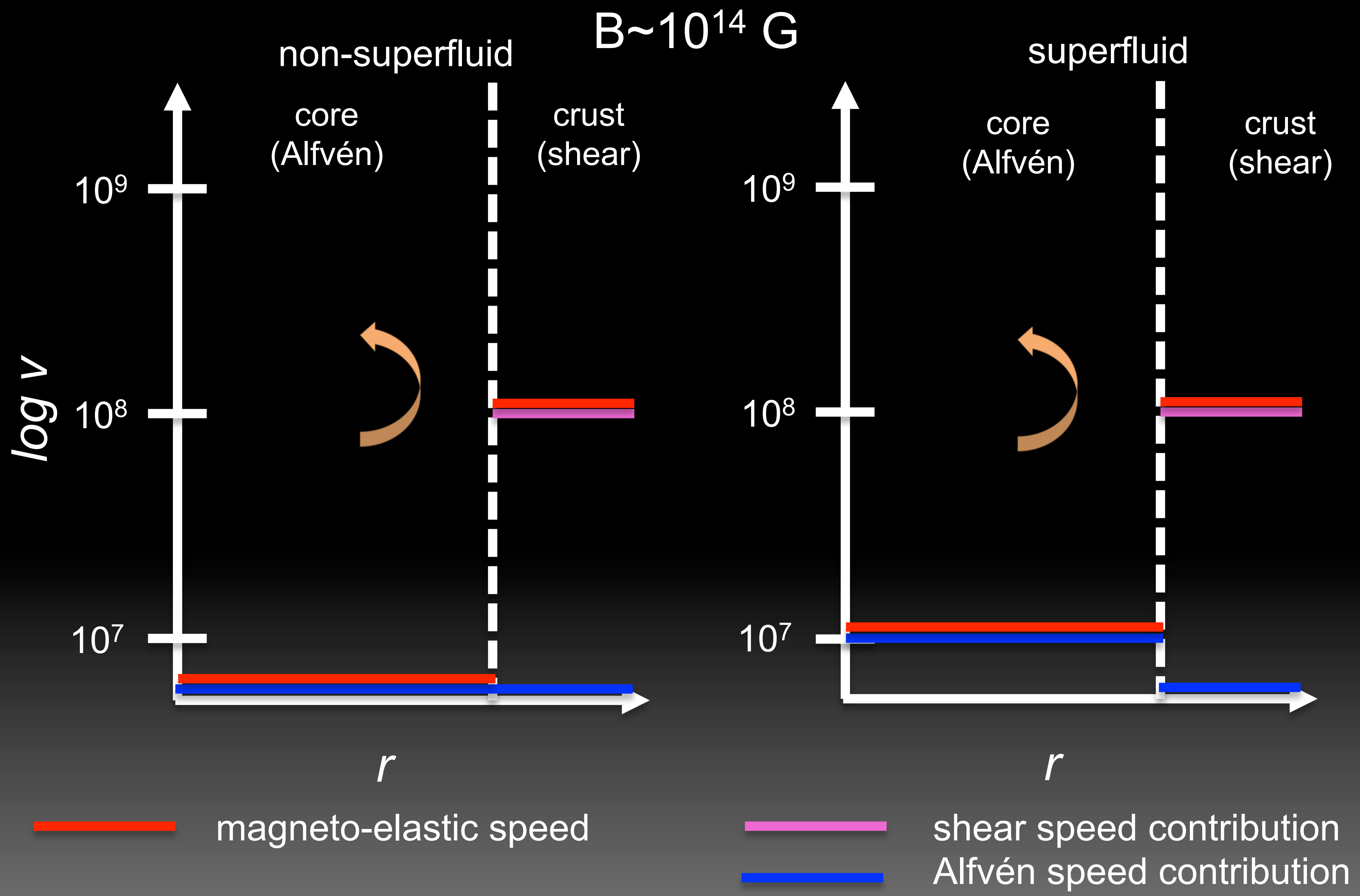


- increase frequency x5
- broader magneto-elastic region

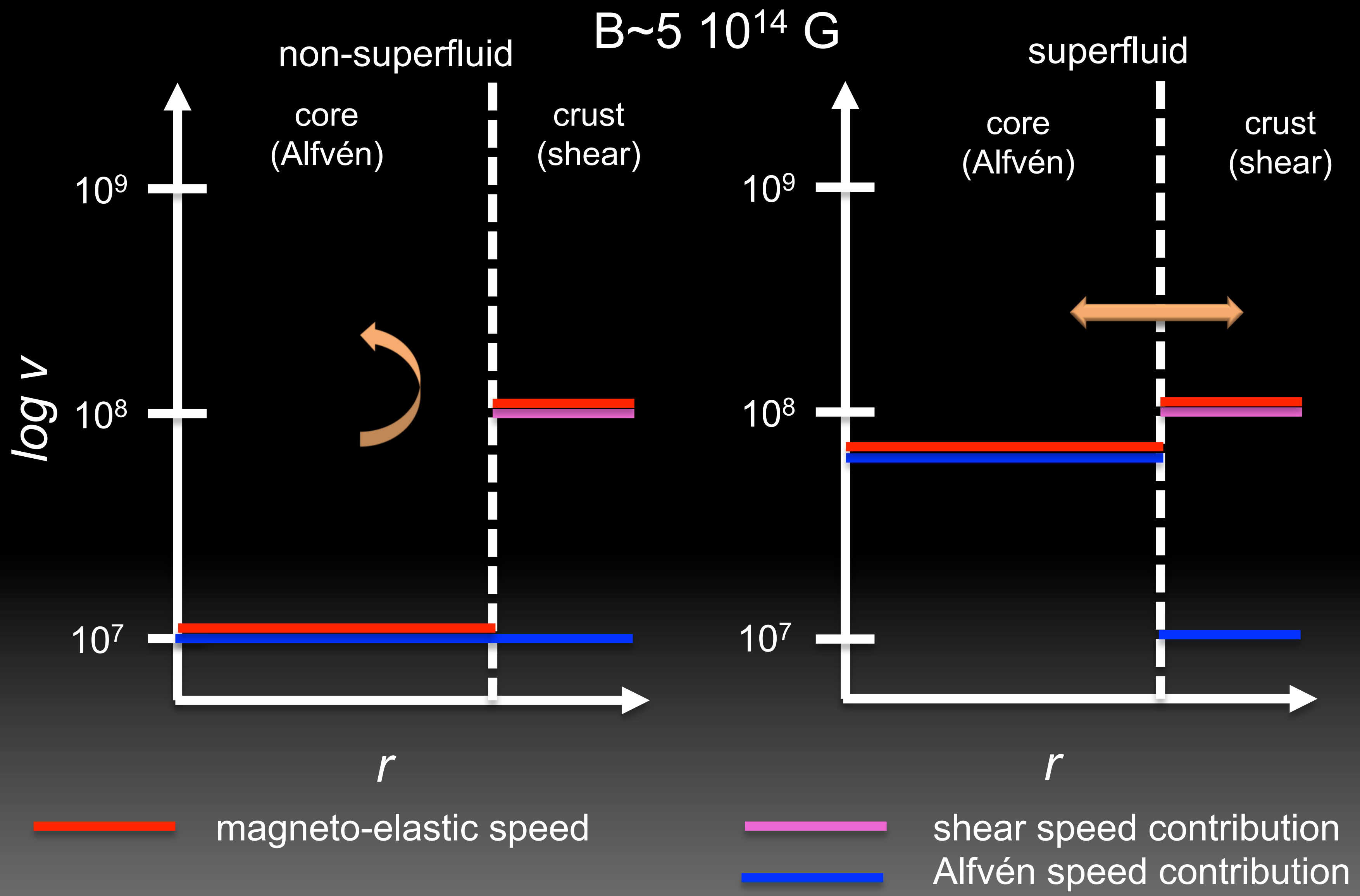
SGR1806-20

SGR1900+14

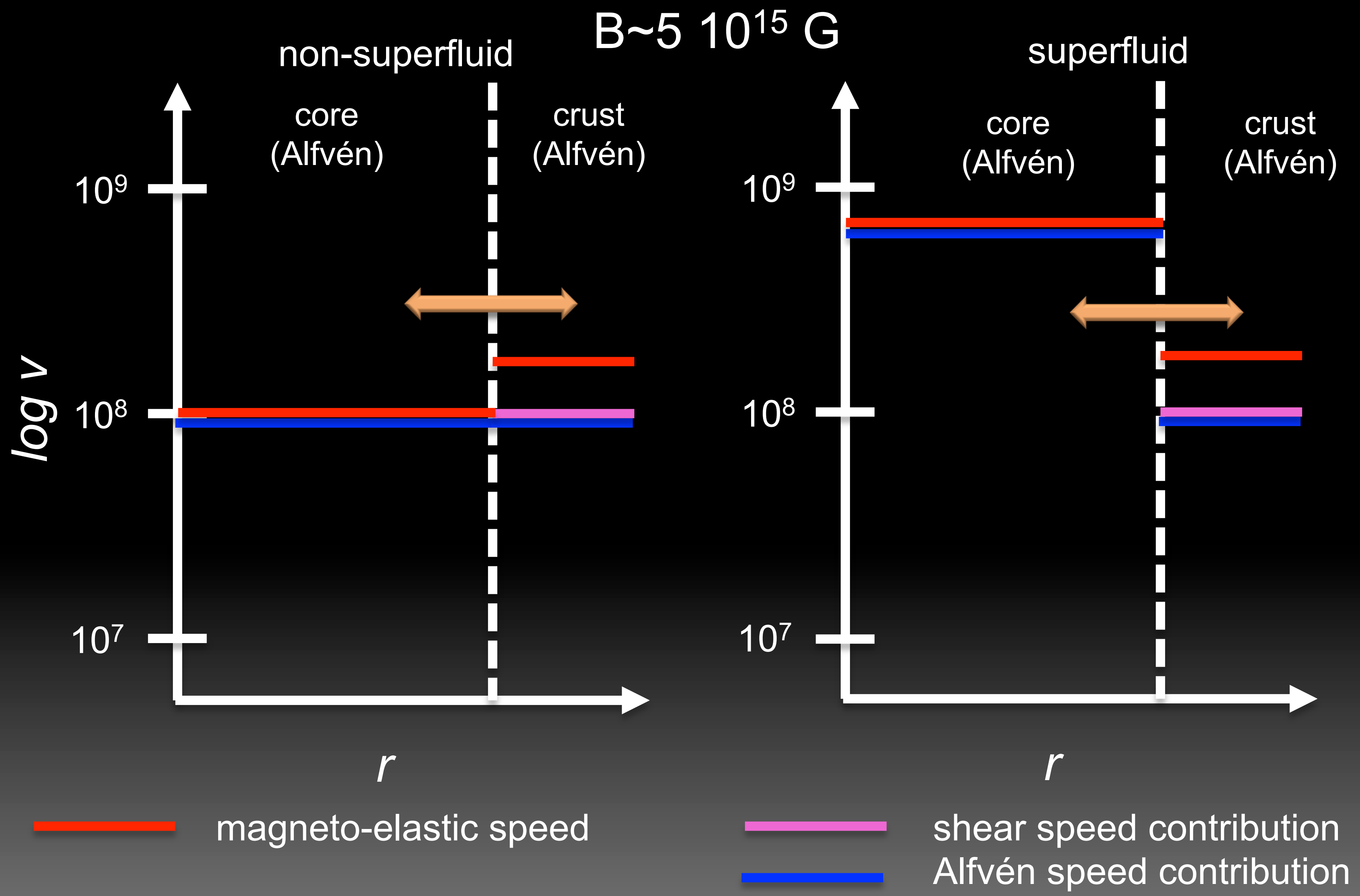
Superfluidity



Superfluidity

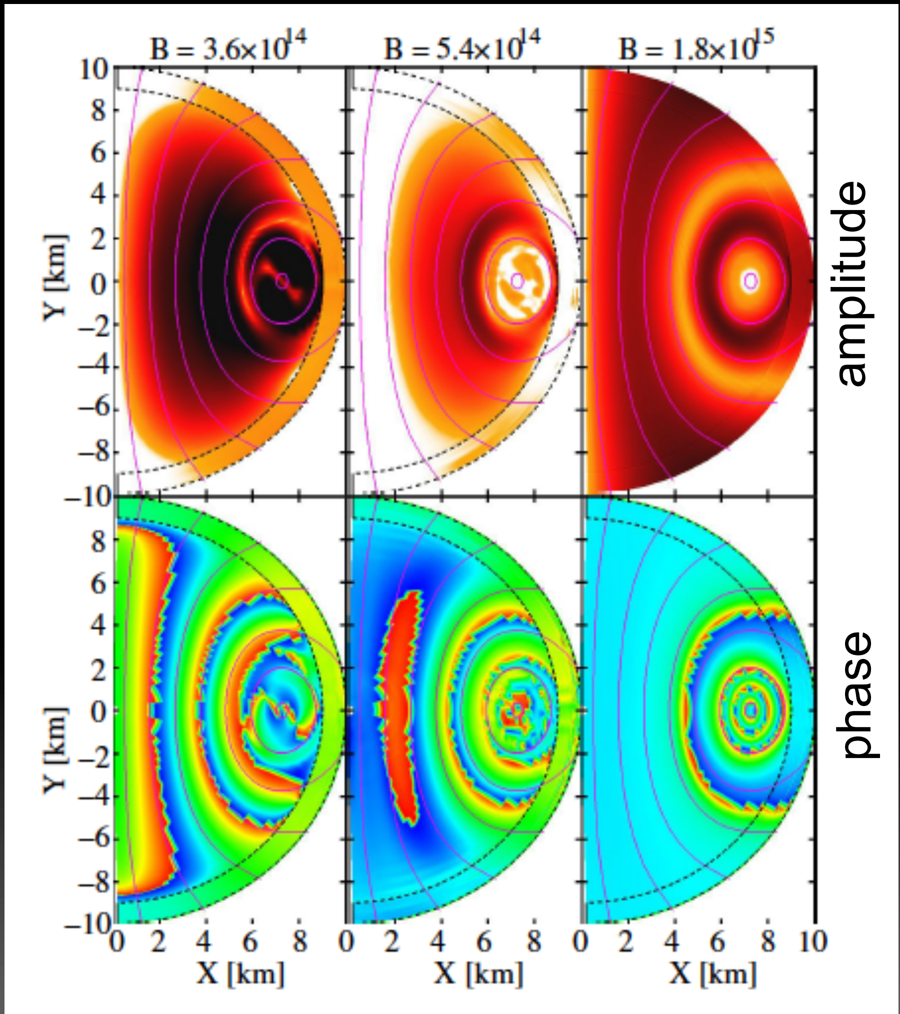


Superfluidity



Superfluidity

Gabler et al 2013

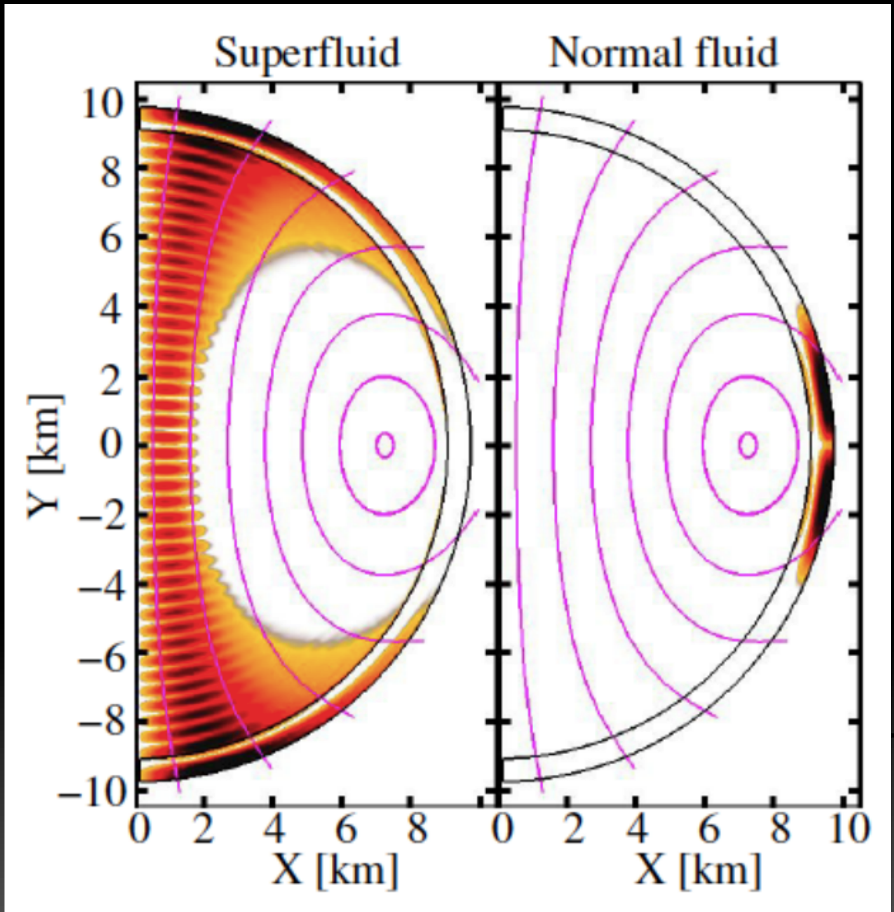


Increasing B

- **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?**
- Agreement with Passamonti & Lander 2014

Superfluidity

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.

Can we say something on the nature of magnetar QPOs?

Frequency of Alfvén QPOs is a degenerate problem

- Magnetic field strength and structure
- Equation of state
- Mass
- Superfluid properties (proton fraction?, fraction of the core being superfluid?)
- Superconductivity?

Models that does not fit quite well …

- Low magnetic fields → oscillations confined to the core
- Magnetic field confined to the core (complete expulsion of mag. field)
- Non-superfluid cores in general → long-lived QPOs? High f. QPOs?

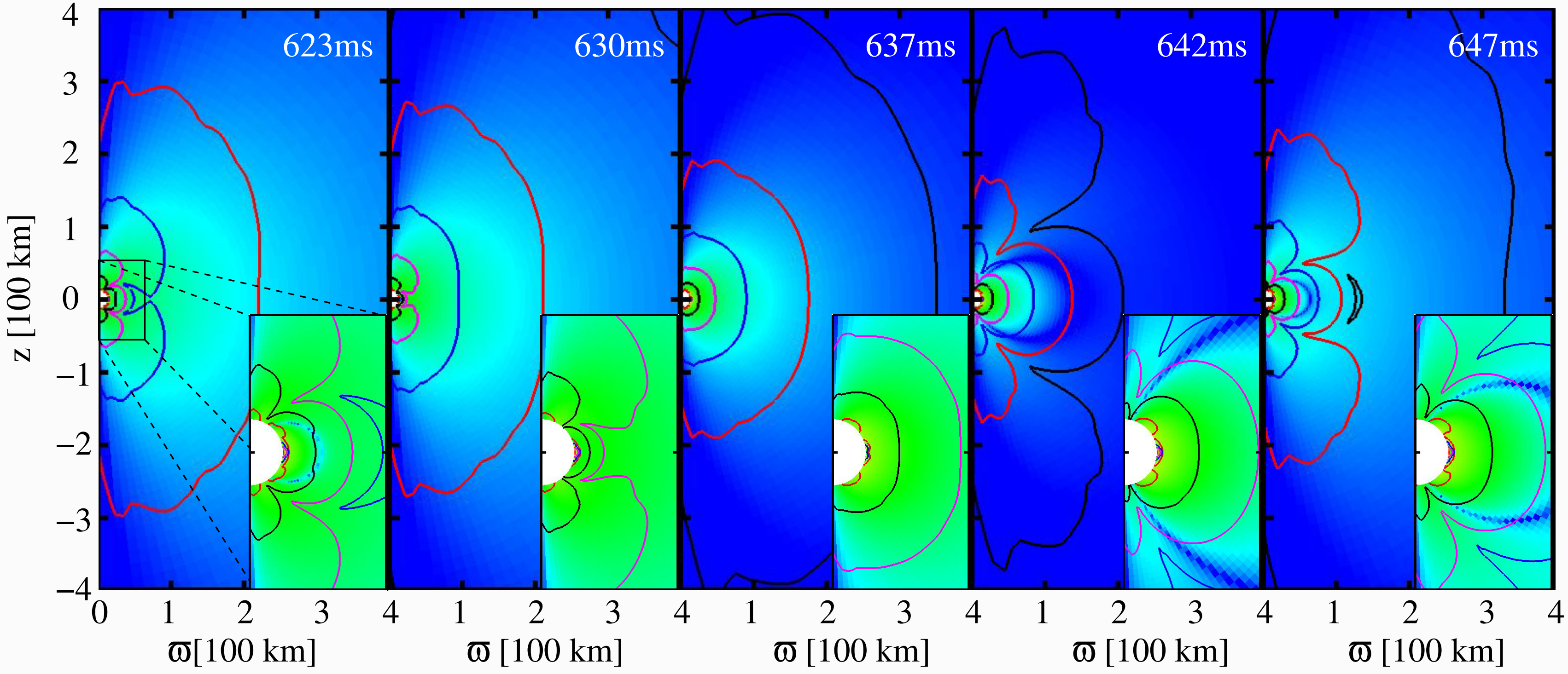
Models that fit better …

- Superfluid component in the core → long-lived constant-phase QPOs, high f. QPOs

Magnetospheres and emission

Force-free magnetospheres

Gabler et al 2014

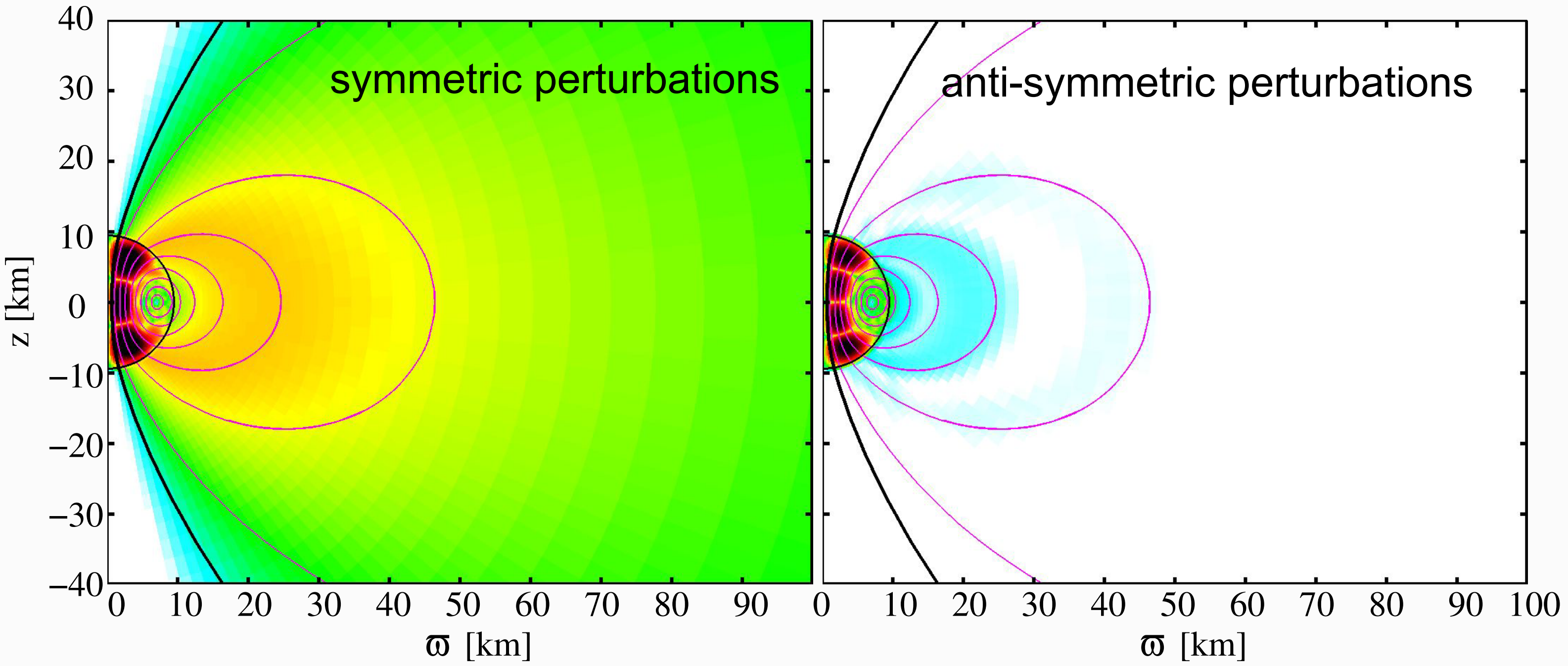


Force-free static solutions matched to surface values given by simulations

- force-free → currents generated by pair creation (Beloborodov & Thompson 2007)
- static → Alfvén crossing time star >> Alfvén crossing time magnetosphere (θ>10º)

Transmission of Alfvén waves at the surface

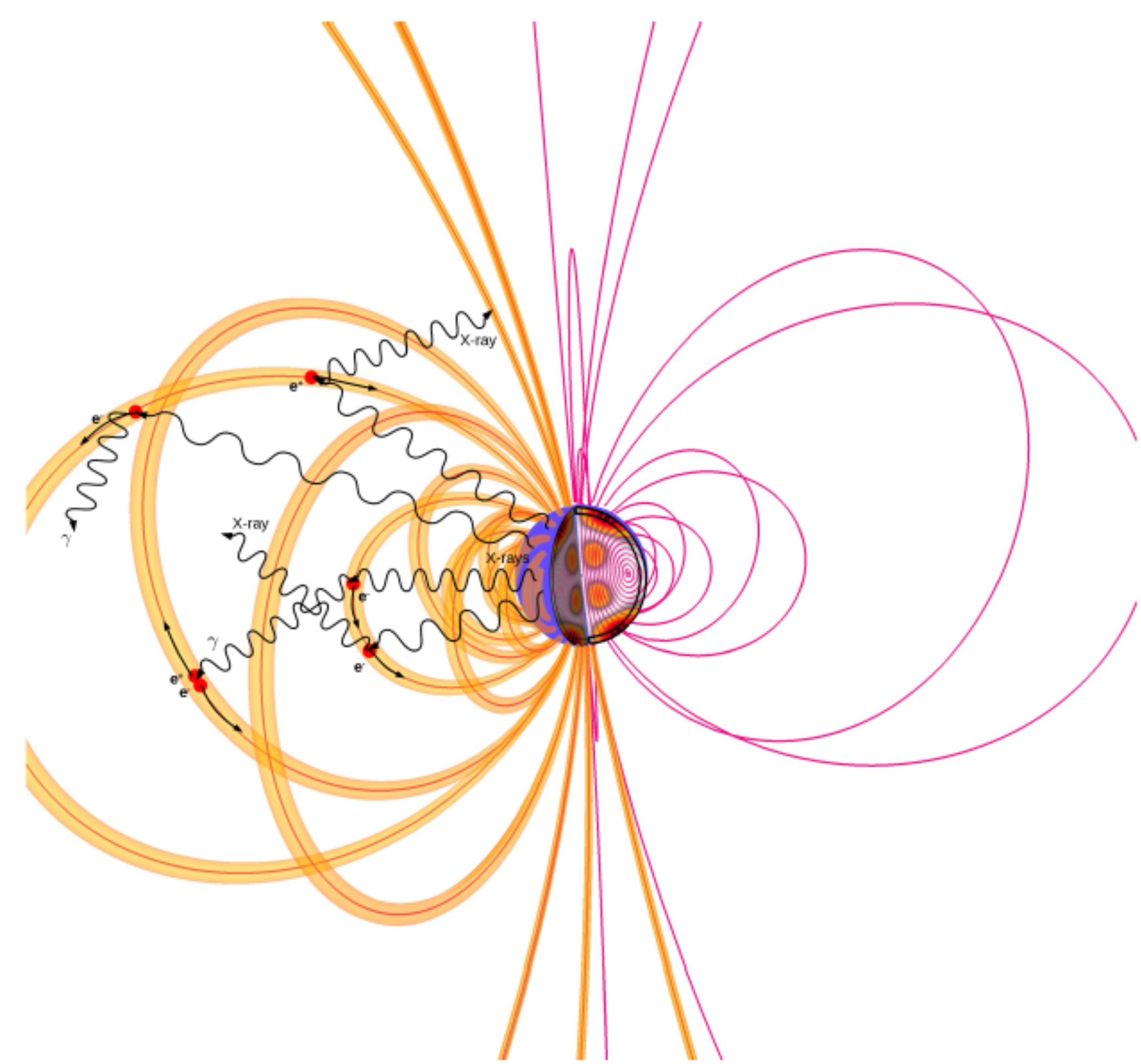
Gabler et al 2014



Ideal MHD simulations of coupled core-magnetosphere oscillations:

- Perfect transmission for $\theta > 10^o$ ($L / \lambda << 1$) despite of Link 2014
- Reflection for $\theta > 10^o$ ($L / \lambda >> 1$) as predicted by Link 2014
- Anti-symmetric perturbations always reflected
- Symmetric perturbations (twisted) transmitted → frequency ratios ~ 1:3:5

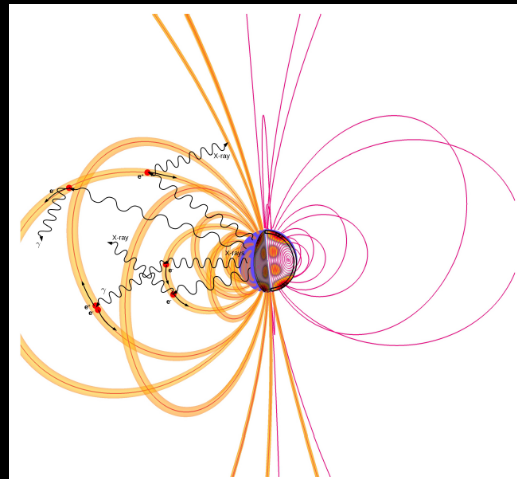
Modulating the magnetar emission



- Twisted magnetic field maintains currents
- Photons interact with charge carriers
- Resonant cyclotron scattering (RCS) (Timokhin et al 2008)

MCMaMa – Monte-Carlo Magnetar Magnetospheres

- Currents ($e^{\pm}$) induced by the twisted magnetic field
- $e^{\pm}$ scatter photons resonantly (RCS) → Changes spectrum
- Physical ingredients:
  - Scattering cross sections (Klein-Nishina)
  - Distribution of seed photons (black body)
  - Spatial distribution of charge carriers (determined by force-free magnetic field)
  - Momentum distribution of charge carriers (determined by magnetic field and interaction with photon field)



MCMaMa: Monte-Carlo Magnetar Magnetosphere scattering code coupling a Monte-Carlo radiation transport for the photons to a particle-in-a-line (pil) code for the charge carriers

Similar work: Beloborodov et al 2012, 2013

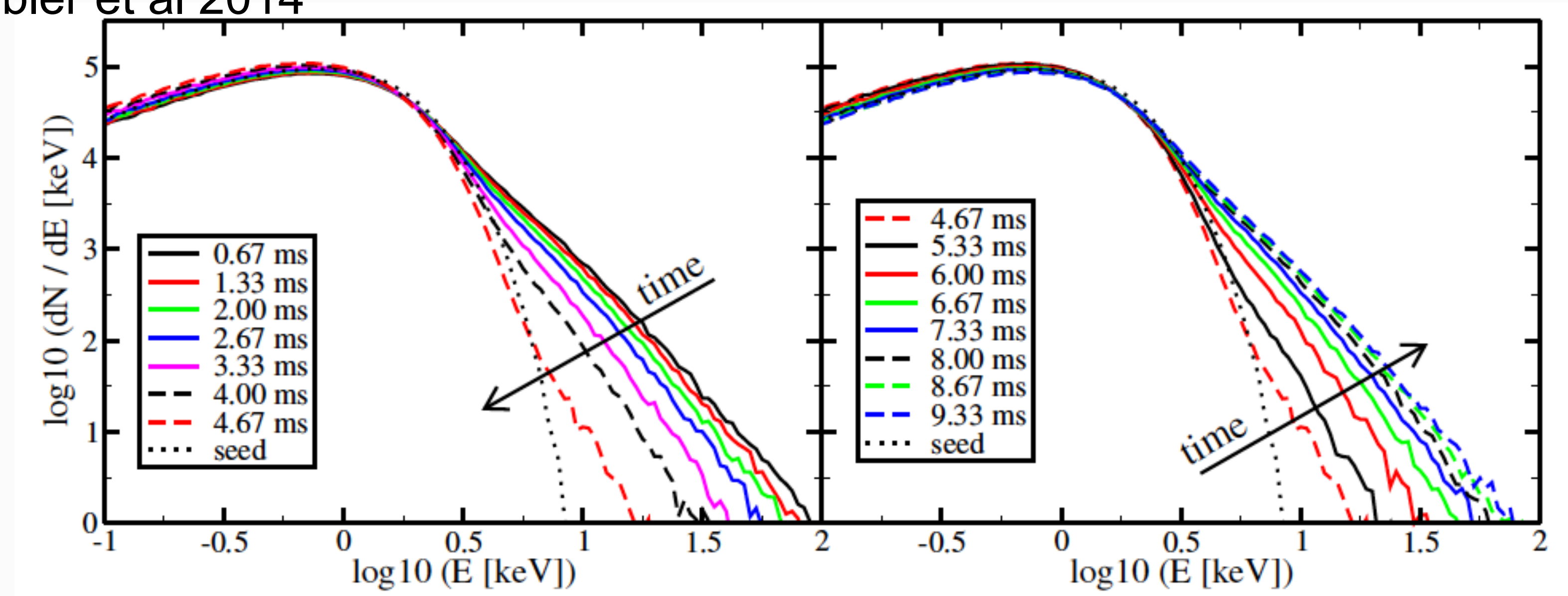
MCMaMa – Monte-Carlo Magnetar Magnetospheres

Monte-Carlo evolution for fixed charge carriers spectrum

- Maxwellian momentum distribution of mildly relativistic electrons (β = 0.3c) for the quiescent emission at kT~ 0.5keV
- Integrated light curve (E=[2keV, 8keV]) for high QPO amplitude
  → strong modulation at the expected frequencies

Fourier transformation allows to detect the QPOs up to surface amplitudes 1km

Gabler et al 2014



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