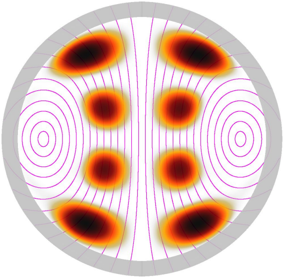
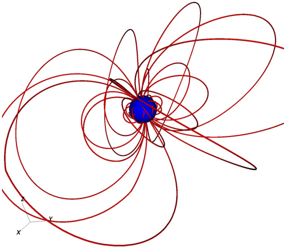
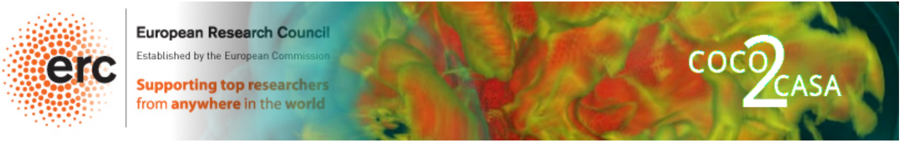
Magnetars





Michael Gabler

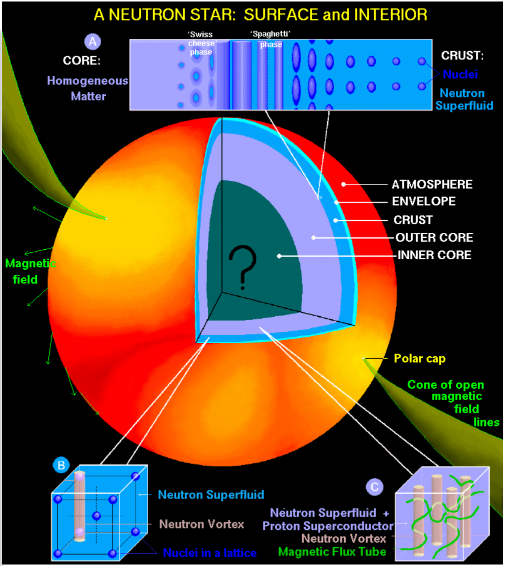
Max-Planck-Institute for Astrophysics



Neutron stars (NS) as unique laboratory

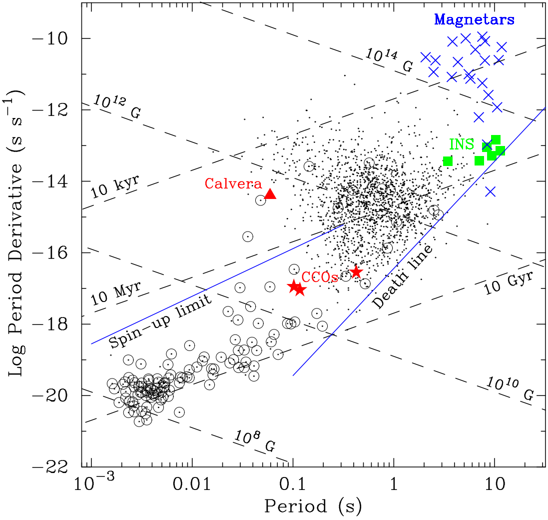
- Ultra-dense matter: interior of NS widely unknown
  - Nuclear matter ???
  - Hyperons ???
  - Quarks ???

  expected properties:
  - Superfluidity
  - Superconductivity
  - Color superconductivity
  - ...
- Exotic physics in strong magnetic fields ($B \gtrsim B_{\mathrm{QED}}$):
  - Appearance of chain molecules
  - One-photon pair creation
  - Photon splitting
  - ...



(D.Page)

Spin period - spin down $P\dot{P}$ diagram:



(Halparn et al. 2013)

Observations

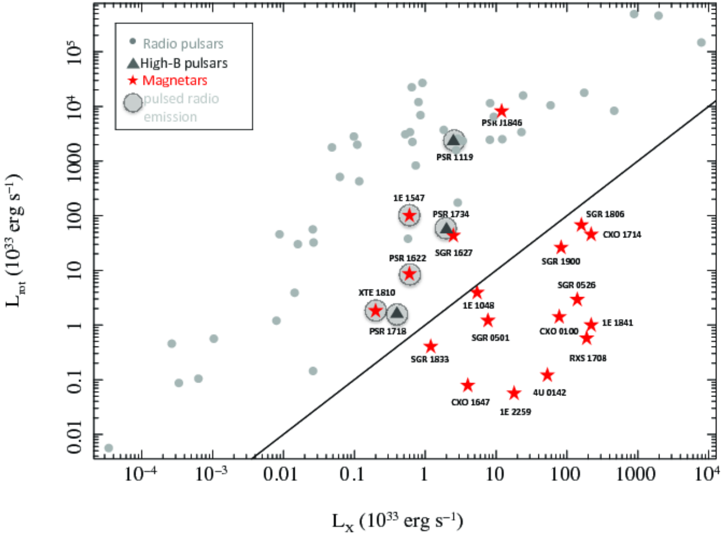
- High $P\dot{P}$
- Magnetic dipole spin down:
  $B[G] = 3.2 \times 10^{19} (P\dot{P})^{1/2}$

$\Rightarrow$ $B \sim 10^{15}$ G

- Birth rate $\sim 10\%$ of core-collapse supernovae
- Historically two groups:
  - Anomalous X-ray pulsars (AXP)
  - Soft-Gamma Repeater (SGR)

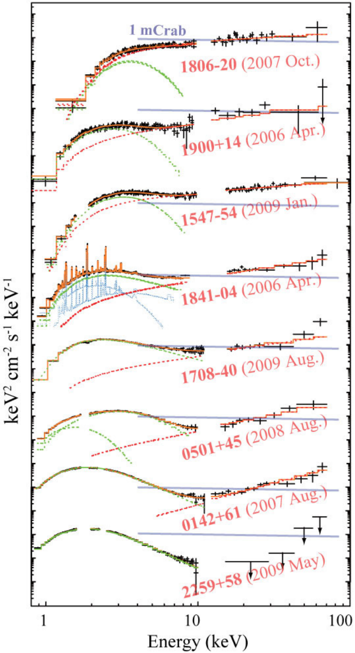
X-ray luminosity - too high for being rotationally powered

$L_X \sim 10^{36}$ erg s^{-1}



(Rea 2013)

Magnetar spectra

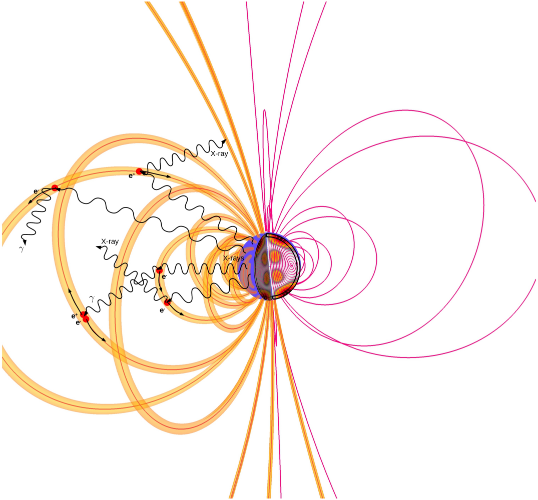


Persistent magnetar spectra

- Soft component (green): black body + power law or two black bodies
- Hard component (red): power law

Enoto et al. 2010

Resonant Cyclotron Scattering (RCS)



Modulation mechanism

- Exterior magnetic field is twisted
- Twisted magnetic field maintained by currents
- Charge density $\gg \rho_{GJ}$
- Photons interact with charge carriers

$\Rightarrow$ Resonant cyclotron scattering:

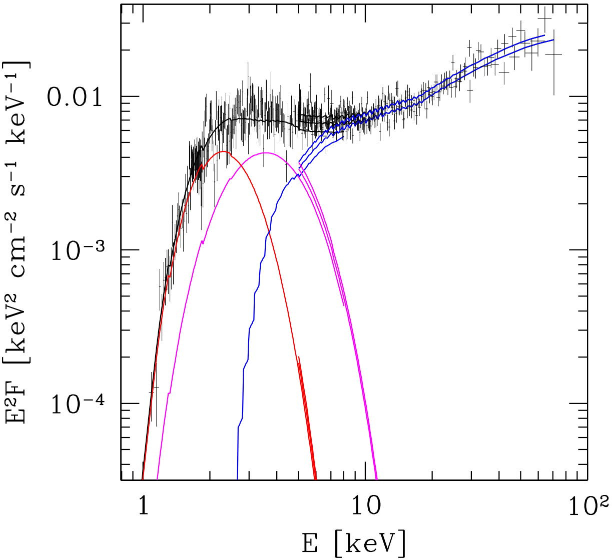
- $e^{\pm}$ move along B
- $\perp$ momentum quantized
- Excitation of Landau levels
- $\omega_B = \frac{eB}{mc}$

Fitting spectrum of 1E1841-045

Fitting the observations

- Black body - neutron star (red)
- Black body - hot footpoint (magenta)
- Hard component - RCS blue

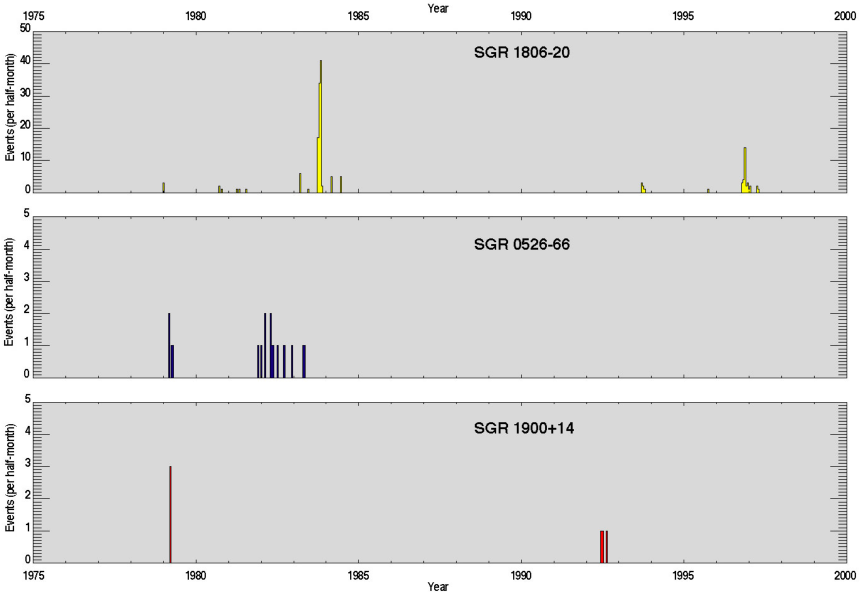
Hascoët et al. 2014



Bursting activity

- Recurring periods of active bursting ('burst storms')
- From a handful up to a few 100s per source
- Luminosities $\lesssim 10^{42}$erg s^{-1}
- Duration $0.01\ldots1\,$s (intermediate bursts $\lesssim 40\,$s)

Bursting activity



(Kouveliotou, NASA & USRA)

Magnetar bursts

(Duncan & Thompson 1992)

- Magnetic field produces stresses during evolution

$\Rightarrow$ Crust brakes

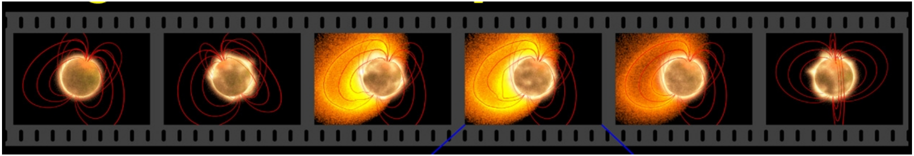
$\Rightarrow$ Catastrophic reconnection in magnetosphere

$\Rightarrow$ Energy release

$\Rightarrow$ $e^{\pm}$ pairs created and trapped by ultra strong magnetic field

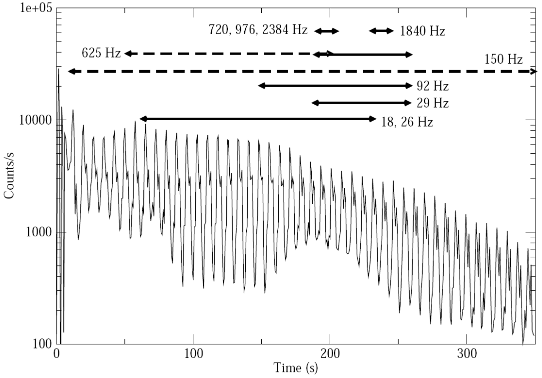
$\Rightarrow$ Hot fireball causes emission

R. Mallozzi, UAH/NASA MSFC



Magnetar giant flares

- 1000 times more energetic ($L_X \lesssim 10^{47}$ erg s^{-1})
- Fast initial rise
- Long lasting tail
- Very rare:
  - SGR 0526-66 (1979)
  - SGR 1900+14 (1998)
  - SGR 1806-20 (2004)
- Flare mechanism:
  Large scale magnetic field instability either inside NS or in Magnetosphere



Strohmayer & Watts 2006

Arguments supporting ultra strong magnetic fields

- $P\dot{P}$ estimate gives magnetic field strength of $B \lesssim 10^{15}\,\mathrm{G}$
- Magnetars are young (some Supernova remnant associations) and need to be spun down to $P \sim 10\,\mathrm{s}$ fast.
- Strong persistent emission (cannot be powered by rotation)
- Dissipation of magnetic field can power bursts and persistent emission over $\sim 10^4$ yr
- Resonant Cyclotron Scattering can explain mangetar spectra
- Giant flare energy need to be provided
- Other properties of the Giant flare need to be explained
  - Short rise time but large-scale event $\Rightarrow$ huge Alfvén velocity
  - Fireball has to be trapped by strong magnetic field

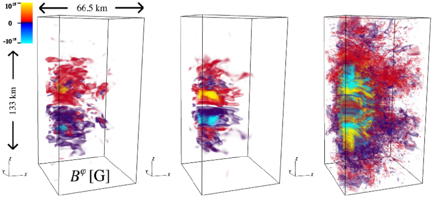
Making the ultra-strong magnetic fields

Supernova explosion

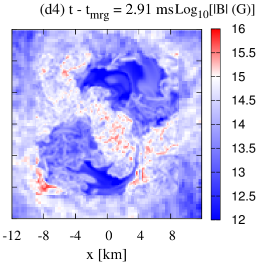
- Compression of progenitor field
  - During collapse magnetic field is compressed with matter
  - Magnetic flux conserved
  - $B \lesssim 10^{12} - 10^{13}$ G
- Amplification of field in Proto-Neutron star
  - Magneto-rotational instability
  - Convective dynamo

Neutron star mergers

- Magneto-rotational instability
- Convective dynamo
- Shear instability



Moesta+ 2015



Kiuchi+ 2015

Neutron star seismology with magnetars

- Why neutron star seismology?
  Neutron star seismology will tell us about their interiors like seismology on earth, sun, or other stars
  In addition to M-R measurement, oscillation modes contain more information.
- Why magnetars?
  Because we believe to have observed first oscillation frequencies!
- GW from neutron star oscillations not yet observed
- Other candidates of NS surface oscillations, but unclear

Observations - quasi-periodic oscillations (QPOs)

Confirmed QPO frequencies

SGR 1806-20: 18, 26, 30, 92
150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84,
155 Hz

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

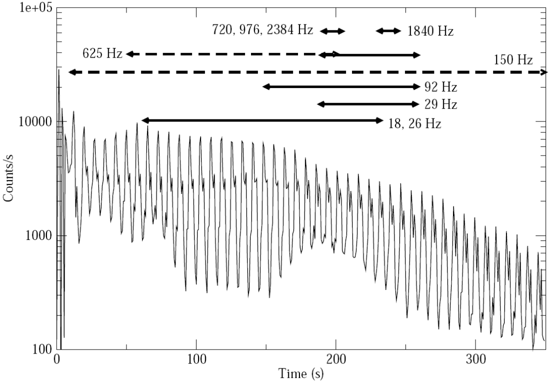
QPOs in normal bursts

93, 127 and 260Hz

(Huppenkothen et al. 2014)

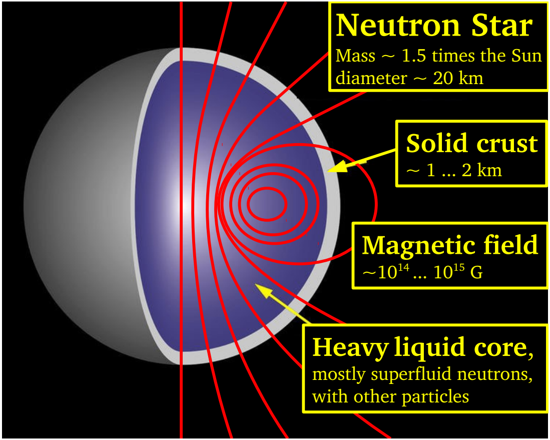
Unconfirmed QPOs

17, 21, 36, 59, and 116 Hz
(Hambaryan et al. 2011)



Strohmayer & Watts 2006

Where do the QPOs come from? Are they Starquakes?

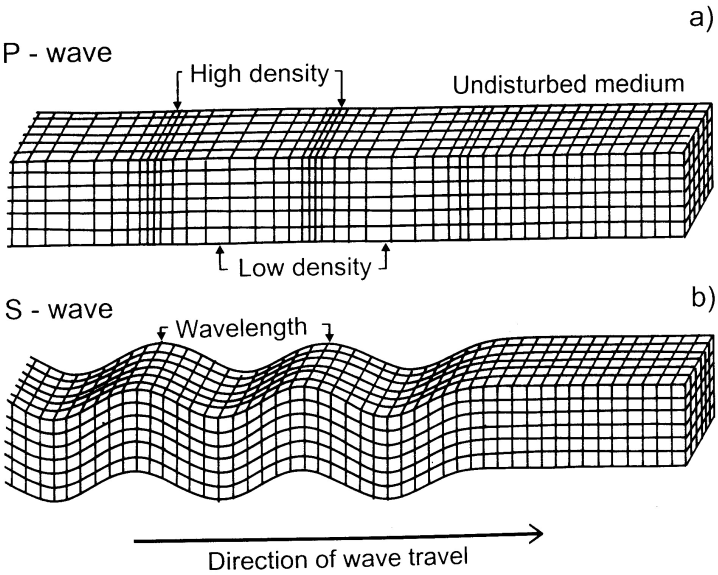


Possible origin of the observed frequencies

- Discrete Shear modes (crust)?
- Alfvén oscillations at the turning points of a continuum (core+crust)?
- Magnetospheric oscillations?

Coupled Crust-Core oscillations

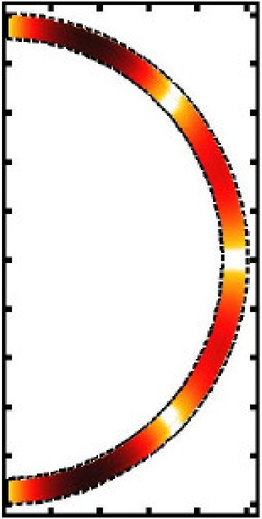
Shear waves



Yan-Ping Huang and Yong-Ping Zheng, 2015

Shear waves

Torsional shear modes



- No magnetic field
- Free slip / zero traction at crust core interface

$\Rightarrow$ Eigenvalue problem

- Relativistic estimates for f:
  - $\Rightarrow$ $n = 0$:

$$f^2 \sim \frac{\mu_S}{\rho} \frac{(l-1)(l+2)}{RR_c}$$

R_c - radius of crust
μ_S - shear modulus

  - $\Rightarrow$ $n > 1$:

$$f \sim \sqrt{\frac{\mu_S}{\rho}} \frac{n}{\Delta}$$

Δ - crust thickness

(Shoemaker & Thorne 1983, Duncan 1998, Strohmayer & Watts 2005, Piro 2005, Sotani et al. 2007, Samuelsson & Andersson 2007, Steiner & Watts 2009, Deibel et al. 2014, Sotani et al. 2016 ...)

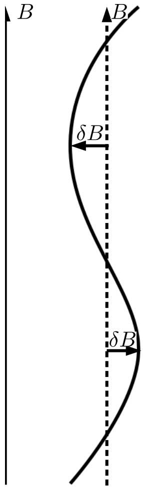
Torsional shear modes

Samuelsson & Andersson 2007

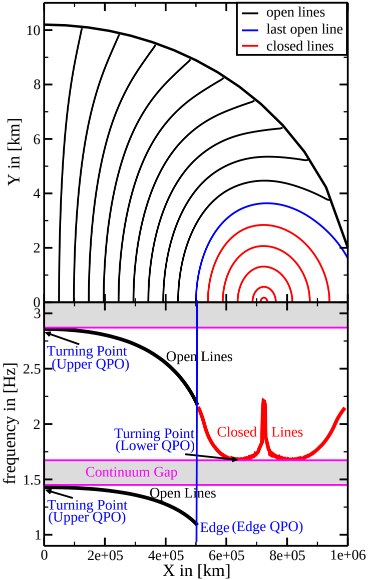
Observed frequency in Hz		Shear mode	
SGR 1806-20	SGR 1900+14	n	l
18		???	???
26		???	???
30	28	0	2
	53	0	4
92	84	0	6
150		0	10
	155	0	11
625		1	
1840		3	

Alfven waves

- MHD (perfectly conducting) approximation: Field lines frozen into matter
- Magnetic stresses are equivalent to a tension B^2 along the field line and an isotropic hydrostatic pressure $B^2/2$
- Line acts like elastic cord under tension B^2
- Propagation velocity (Alfvén velocity): $v_A = \frac{B}{\sqrt{\rho}}$



The Alfvén continuum



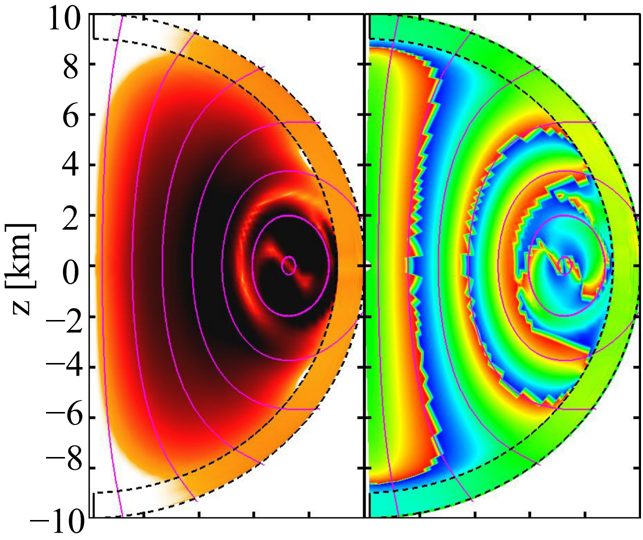
- Each field line has proper eigenfrequency (purely poloidal magnetic field + torsional oscillations)
- Field lines are coupled through: (i) surface boundary conditions (ii) the crust
- Long-lived QPOs exist at the turning-points or edges of the continuum
- Gaps between successive Alfvén overtones
- Frequencies in integer ratios 1:2:3:4:5 (holds approx. for coupled case)

(Levin 2006 & 2007, Sotani et al.2007 & 2008, Cerdá-Durán et al. 2009, Colaiuda et al. 2009)

Alfvén oscillations

Continous phase

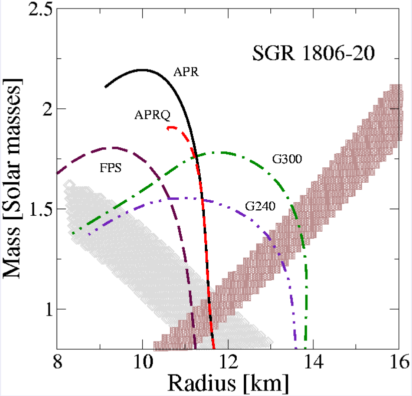
FFT amplitude FFT phase



What can we learn from magnetar QPOs?

Constraints by crustal modes

Samuelsson & Andersson 2007



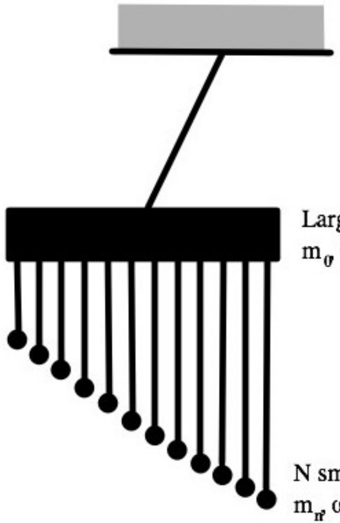
$f_{n=0} \sim 1/R$; $f_{n=1} \sim 1/\Delta$

Constraints by Alfvén oscillations

- Magnetic field strength: $f \sim B$
- Topology of magnetic field inside neutron star
  - Field penetrating the core ?
  - Field confined to crust ?
  - Poloidal vs. toroidal ?
- Probing physics of core
  - Superconductivity ?
  - Superfluidity ?
  - ...

$\Rightarrow$ constrain the EOS and/or magnetic field

A toy model for magneto-elastic waves



van Hoven & Levin 2010

- Big pendulum with large mass
- Many small oscillators
- Each small pendulum has different f

$\Rightarrow$ Quasi-continuum

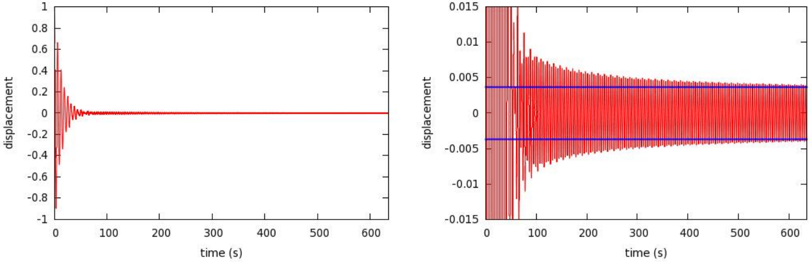
- Excite big pendulum

$\Rightarrow$ Strong damping of oscillation

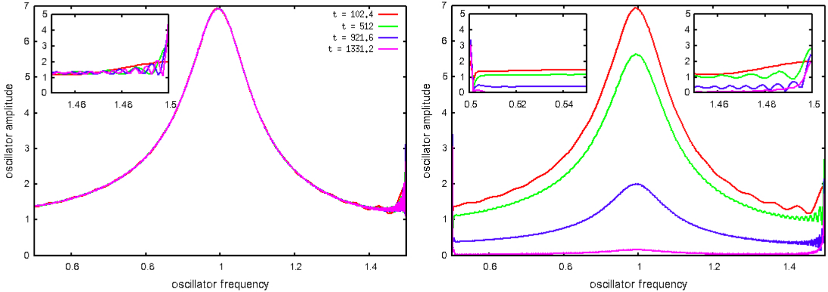
- Excitation of small oscillators
- Increasing oscillations at the edge of the continuum

A toy model for magneto-elastic waves

Time evolution of displacement



Oscillator amplitude for different viscosity



Superfluid neutron star core - (Newtonian) two-fluid model

Neutrons

$$\partial_t \rho_n + \nabla \cdot (\rho_n \mathbf{v}_n) = 0$$

$$(\partial_t + \mathbf{v}_n \nabla)(\mathbf{v}_n + \varepsilon_n \mathbf{w}_{pn}) + \nabla(\Phi + \mu_n) + \varepsilon_n w_k^{pn} \nabla v_n^k = 0$$

Charged particles (protons)

$$\partial_t \rho_p + \nabla \cdot (\rho_p \mathbf{v}_p) = 0$$

$$(\partial_t + \mathbf{v}_p \nabla)(\mathbf{v}_p + \varepsilon_p \mathbf{w}_{np}) + \nabla(\Phi + \mu_p) + \varepsilon_p w_k^{np} \nabla v_p^k = \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi \rho_p}$$

$\mathbf{w}_{np} = -\mathbf{w}_{pn} = \mathbf{v}_n - \mathbf{v}_p$, $\quad \varepsilon$ entrainment parameter

Superfluid neutron star core - one-fluid approximation

Effective one fluid model (decoupling n from p):
$\rho \rightarrow \rho_p \sim 0.05\rho$

$$v_A^2 = \frac{B^2}{\rho} \rightarrow \frac{B^2}{\varepsilon_\star X_c \rho} = \frac{B^2}{\rho_p}$$

- Fundamental QPOsExist as before but with:

$$f_{\rm sf} \sim \frac{1}{t_A} \sim \frac{v_A}{R} \sim \frac{B}{R\sqrt{\rho_p}} \sim \frac{B}{R\sqrt{0.05\rho}} \sim 5 \times f_{\rm n}$$

- Coupling strength $\varepsilon_\star X_c$ not clear

$\Rightarrow$ parametrize $\varepsilon_\star X_c$

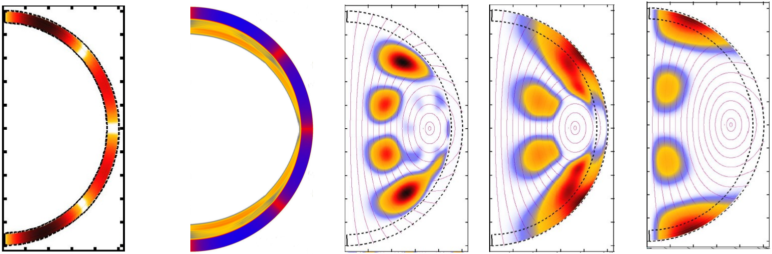
- Large $\varepsilon_\star X_c \Rightarrow$ 'heavy core' $\Rightarrow$ low f for given B
- Small $\varepsilon_\star X_c \Rightarrow$ 'light core' $\Rightarrow$ high f for given B

Magneto-elastic QPOs inside the magnetar

$\mathbf{B^2 << \mu_S}$ | $\mathbf{B \sim 10^{13} G}$ | $\mathbf{B \sim 10^{15} G}$ | $\mathbf{B^2 >> \mu_S}$

$\longrightarrow \mathbf{B}$

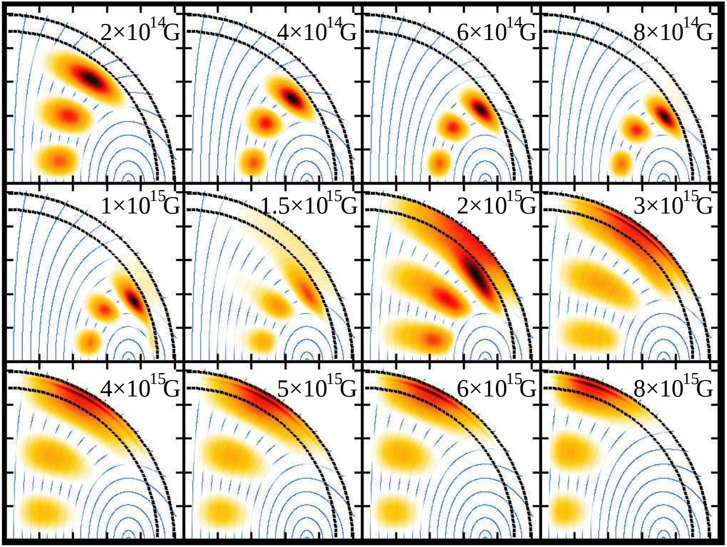
predominantly shear modes	shear modes Strongly damped	magneto-elastic QPOs confined to core	magneto-elastic QPOs reach surface	predominantly Alfvén QPOs



Damping of crust modes

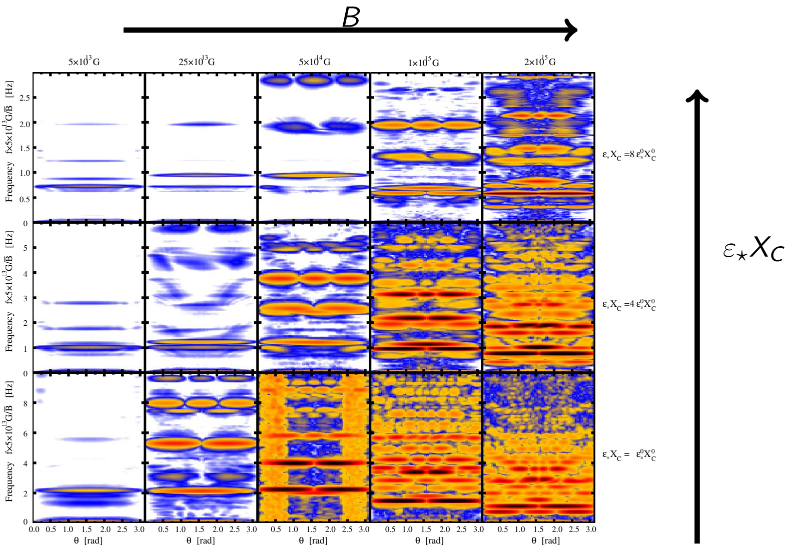
Magneto-elastic QPOs break out to surface

Magnitude of the FFT at different B



Magneto-elastic QPOs break out to surface

Magnitude of the FFT at the surface

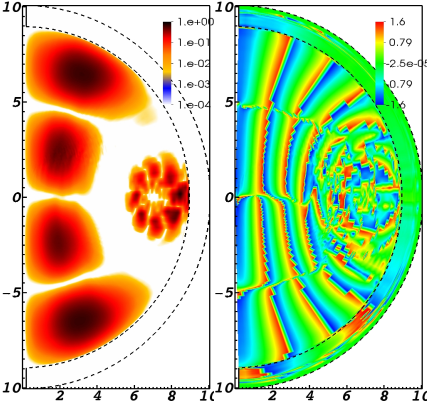


Constant Phase QPOs

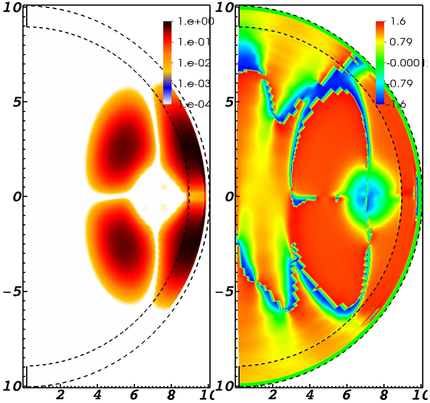
- Alfvén dominated QPO confined to the core
- Continuous phase change

- Magneto-elastic QPOs penetrating the crust
- Constant phase

5×10^{13} G



2×10^{15} G



Window for constant phase QPOs between $\sim 10^{14}$ G - breakout

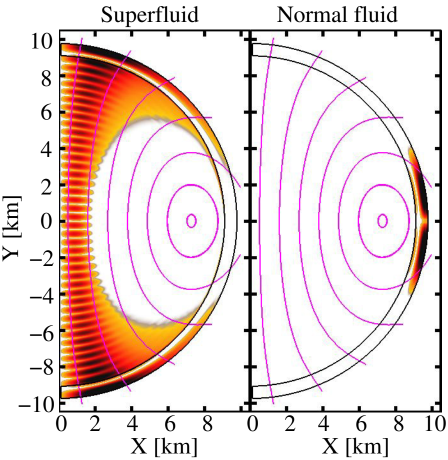
High frequency QPOs

Normal fluid

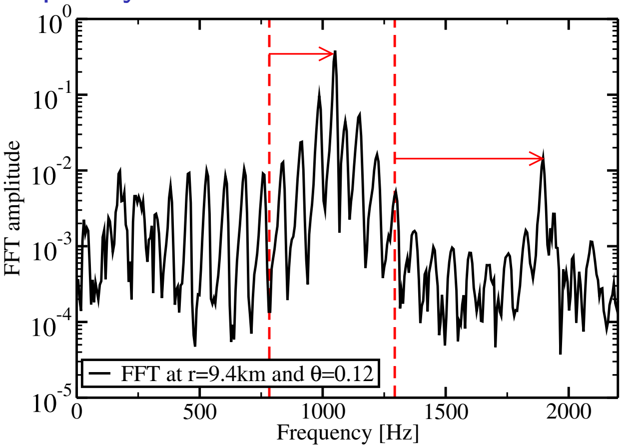
- $n = 1$ radial shear mode structure
- Localized close to equatorial plane
- $\hat{B} \perp \hat{r} \Rightarrow$predominantly shear mode only in crust

Superfluid

- $n = 1$ radial shear mode structure
- Close to pole
- Resonance with Alfvén overtone of core



High frequency QPOs



- Initial perturbation with crustal mode (red dashed lines)
- Resonantly excited magneto-elastic oscillation always at higher frequency
- $f_{2t_n} = f^0_{2t_n}(1 + a_{2t_n}\bar{B}_{15})^{1/2}$

Identifying observed frequencies

- Frequency ratio of low frequency magneto-elastic QPOs (odd, even) is roughly

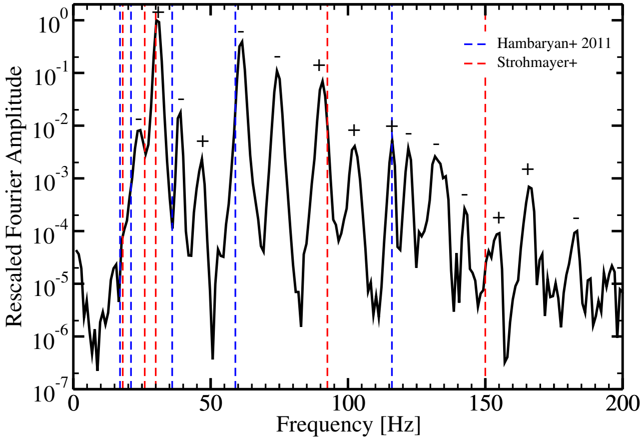
$$1 : 2 : 3 : 4 : 5 : \ldots$$

- Different magnetic field configurations gives more than one fundamental
- High frequency QPO as resonance of higher Alfvén overtone in core with $n > 0$ crustal mode if core is superfluid

SGR 1806-20: (18), 26, 30, 92, 150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84, 155 Hz
or 28, 53, 84, 155 Hz

One particular example



- Match fundamental with 30Hz QPO
- Other observed QPOs $f > 30$Hz match nicely
- Problems for $f < 30$Hz

- APR+DH EoS
- $\bar{B} = 1.1 \times 10^{15}$ G
- $\varepsilon_\star X_C = 0.046$
- $M = 1.4 M_\odot$
- $R = 12.26\,\text{km}$

Empirical relations

High frequency QPO

- $f_{2t_n} = f_{2t_n^{(0)}}(1 + a_{2t_n}\bar{B}_{14})^{1/2}$
- assuming $c_s = const. \Rightarrow f_0 = \frac{c_s}{\Delta R} = \sqrt{\frac{\mu_{cc}}{\rho_{cc}}}\frac{1}{\Delta R}$
- $$\frac{f_{2t_n^{(0)}}}{f^{\rm ref}_{2t_n^{(0)}}} \simeq \frac{\left(1-\frac{2M}{R}\right)\frac{c_s}{\Delta r}}{\left(1-\frac{2M_{\rm ref}}{R_{\rm ref}}\right)\frac{c_s^{\rm ref}}{\Delta r_{\rm ref}}}$$

$$c_s = \sqrt{\frac{\mu_{cc}}{\rho_{cc}}} \lesssim c_s^{\rm ref}\frac{f_{2t_n}}{f^{\rm ref}_{2t_n^{(0)}}}\frac{1}{\sqrt{1+a_{2t_n}\bar{B}^2_{14}}}\frac{\Delta r}{\Delta r_{\rm ref}}\frac{\left(1-\frac{2M_{\rm ref}}{R_{\rm ref}}\right)}{\left(1-\frac{2M}{R}\right)}.$$

- Continuum destroys resonance for strong magnetic fields: $\Rightarrow f_{2t_n} < 2f_{2t_n^{(0)}}$

Empirical relations

Breakout of oscillations

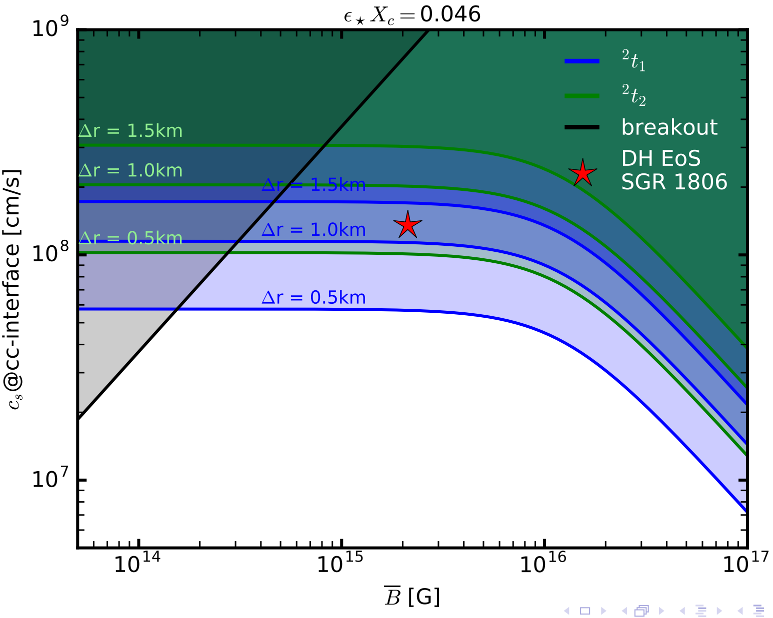
- Breakout for $\varepsilon_\star X_c = 4 \times \varepsilon_\star^0 X_c^0$ and $\bar{B} = 10^{15}$ G
- All terms in equations contain either $\sqrt{\mu}$ or $(\varepsilon_\star X_c)^{-1/2}\ \bar{B}_{14}$
- $\mu_{cc} \lesssim \mu_{cc}^{ref}\,(17.23\varepsilon_\star X_c)^{-1}\ \ \bar{B}_{14}^2$
- For strong magnetic fields continuum destroys constant phase oscillations: $\Rightarrow\ \bar{B}_{\rm max} = 1.79\, c_s\sqrt{\rho_{\rm cc}}$

Matching the frequency of ${}^2U_2$

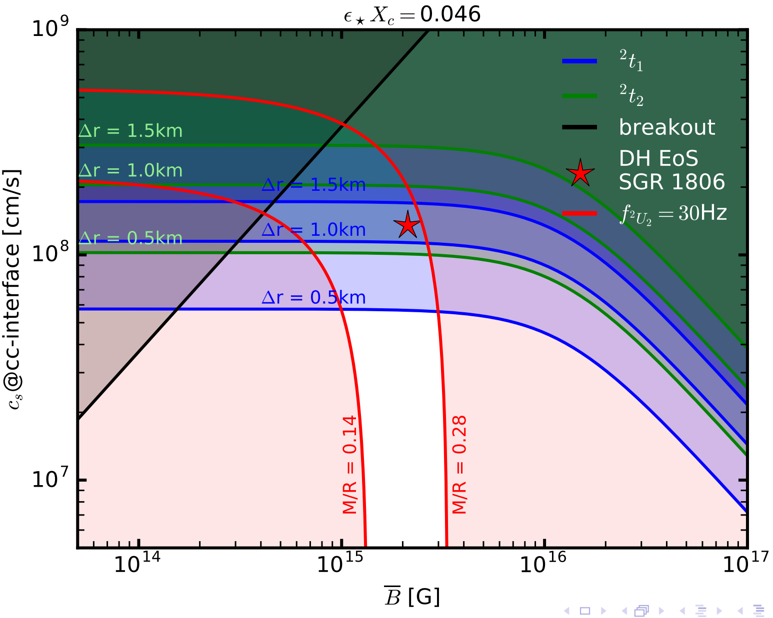
$$
\begin{aligned}
f_{{}^2U_2}[\mathrm{Hz}] &= \left(2.8 \times (\varepsilon_\star X_c)^{-0.55}\sqrt{\frac{\mu_{cc}}{\mu_{cc}^{\rm ref}}} + 0.66\,(\varepsilon_\star X_c)^{-0.33}\ \bar{B}[10^{14}\mathrm{G}]\right) \\
&\quad \times \left(\frac{1 - 4.58M/R + 6.06(M/R)^2}{1 - 4.58(M/R)_{\rm ref} + 6.06(M/R)_{\rm ref}^2}\right)
\end{aligned}
$$

(Sotani et al. 2008)

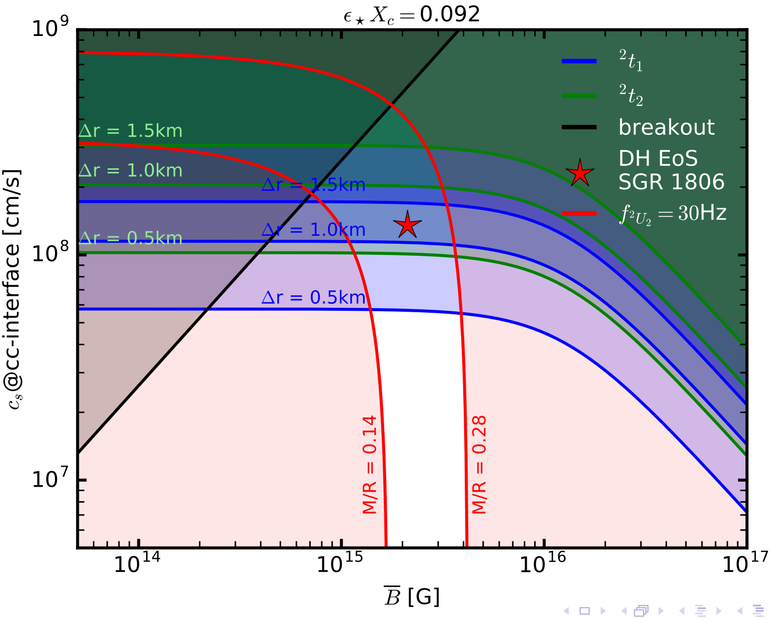
Constraint on shear modulus at base of the crust



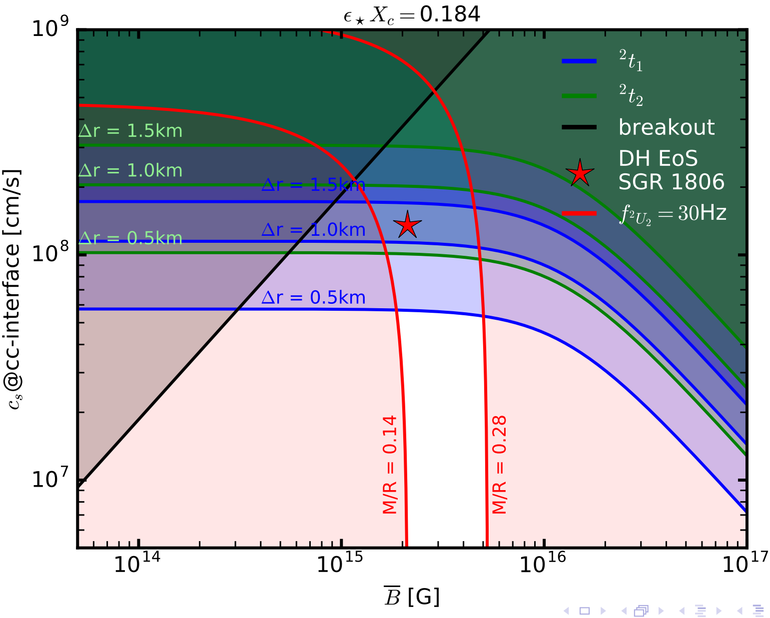
Constraint on shear modulus at base of the crust



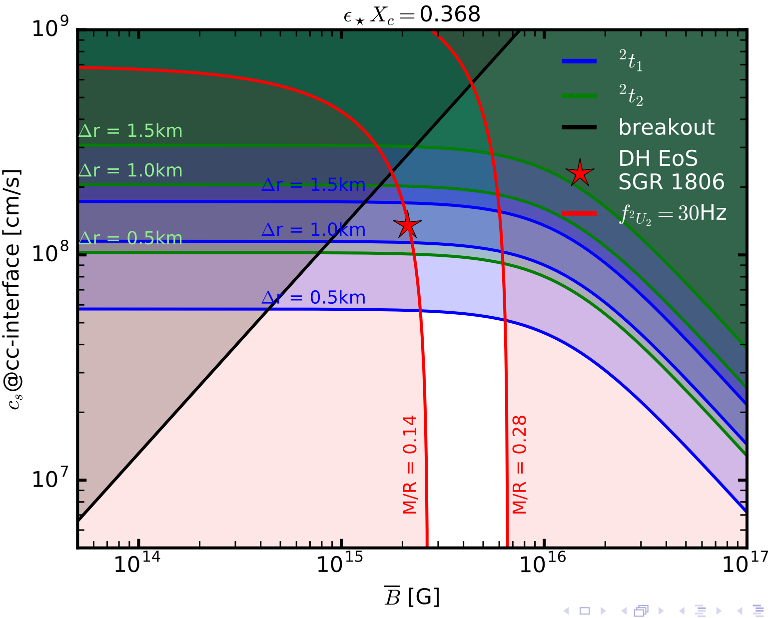
Constraint on shear modulus at base of the crust



Constraint on shear modulus at base of the crust



Constraint on shear modulus at base of the crust



Bayesian inference on constraints on the EOS

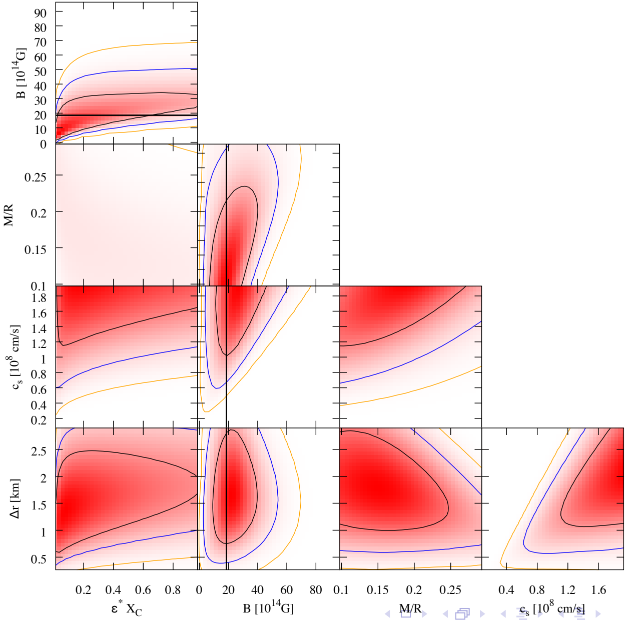
Parameters

- Magnetic field strength $\bar{B}$ in $[10^{13}\,\mathrm{G}, 10^{16}\,\mathrm{G}]$
- Superfluid parameter $\varepsilon_\star X_c$ in [0,1]
- Shear sped c_s in $[10^7\,\mathrm{cm/s}, 2\times 10^8\,\mathrm{cm/s}]$
- Crust thickness δr in $[0.3\,\mathrm{km}, 3\,\mathrm{km}]$
- Compactness M/R in [0.1,0.3]

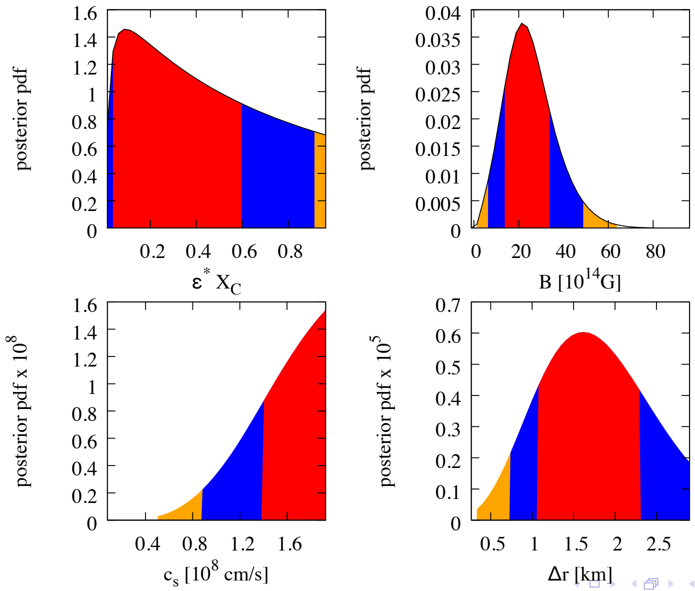
Data

- $f^{\mathrm{obs}}_{2U_2} = 29.0 \pm 0.4\,\mathrm{Hz}$ with width $\sigma^{\mathrm{obs}}_{2U_2} = 4.1\,\mathrm{Hz}$
- $f^{\mathrm{obs}}_{2t_1} = 625.5 \pm 0.2\,\mathrm{Hz}$ with width $\sigma^{\mathrm{obs}}_{2t_1} = 1.8\,\mathrm{Hz}$

2D Posterior



1D Posteriors



Results

	$\varepsilon_\star X_c$	$\bar{B}$ $[10^{14}$ G$]$	M/R	c_s $[10^8$ cm/s$]$	Δr [km]
max.	$0.09^{+0.46}_{-0.07}$	21^{+13}_{-10}	$0.14^{+0.05}_{-0.04}$	> 1.4	$1.6^{+0.7}_{-0.6}$
median	0.49	48.	0.20	1.0	1.6

Conclusions

- Pure crustal shear modes are damped too efficiently due to interaction with Alfvén continuum
- Coupled magneto-elastic oscillations can explain magnetar QPOs
- Constraints on EoS from
  - Breakout of oscillations
  - High frequency QPO
  - Matching of fundamental ${}^2U_2$
- E.g. DH and $\bar{B} = 2.1 \times 10^{15}$G requires $\varepsilon_\star X_c = 0.184$ and $\Delta R \sim 2.0\,\mathrm{km}$ (in conflict with theoretical models)
- Bayesian inference gives
  - B-field estimates in agreement with spin-down magnetic field strengths
  - Preference for superfluid core
  - relatively high shear speeds ($c_s \lesssim 10^8\,\mathrm{cm/s}$)

Conclusions II - meeting reality

- Problem I: degeneracy between EoS, superfluid properties, magnetic field strength and configuration

$\Rightarrow$ Solution: many simulations with different EoS and magnetic fields

- Problem II:
  - Very limited observations
  - Robustness of observed pattern 1:3:5 ?
  - Dependence on B-strength ?
  - New analysis finds other candidate frequencies

$\Rightarrow$ Solution: new satellites or new giant flares

- Further generalizations of model:
  - Coupled toroidal-poloidal oscillations
  - Superconductivity
  - Modulation mechanism for emission

Measuring GW and QPOs from the same magnetar will provide more complete oscillation spectrum
$\Rightarrow$ very powerful tool to study the interior of NS