Three evolutionary paths for magnetar oscillations

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Context

- The quasi-periodic oscillations (QPOs) detected in the light curves of magnetar giant flares have been taken as evidence of magnetar oscillations.

- So far, theoretical work has focused on the calculation of global magneto-elastic modes (frequencies & eigenfunctions).

- *Here we address different kind of questions:*

  ✓ What is the expected longevity of the excited oscillations? This clearly requires some understanding of the various damping mechanisms.

  ✓ Once excited, how do the oscillations “evolve” ?

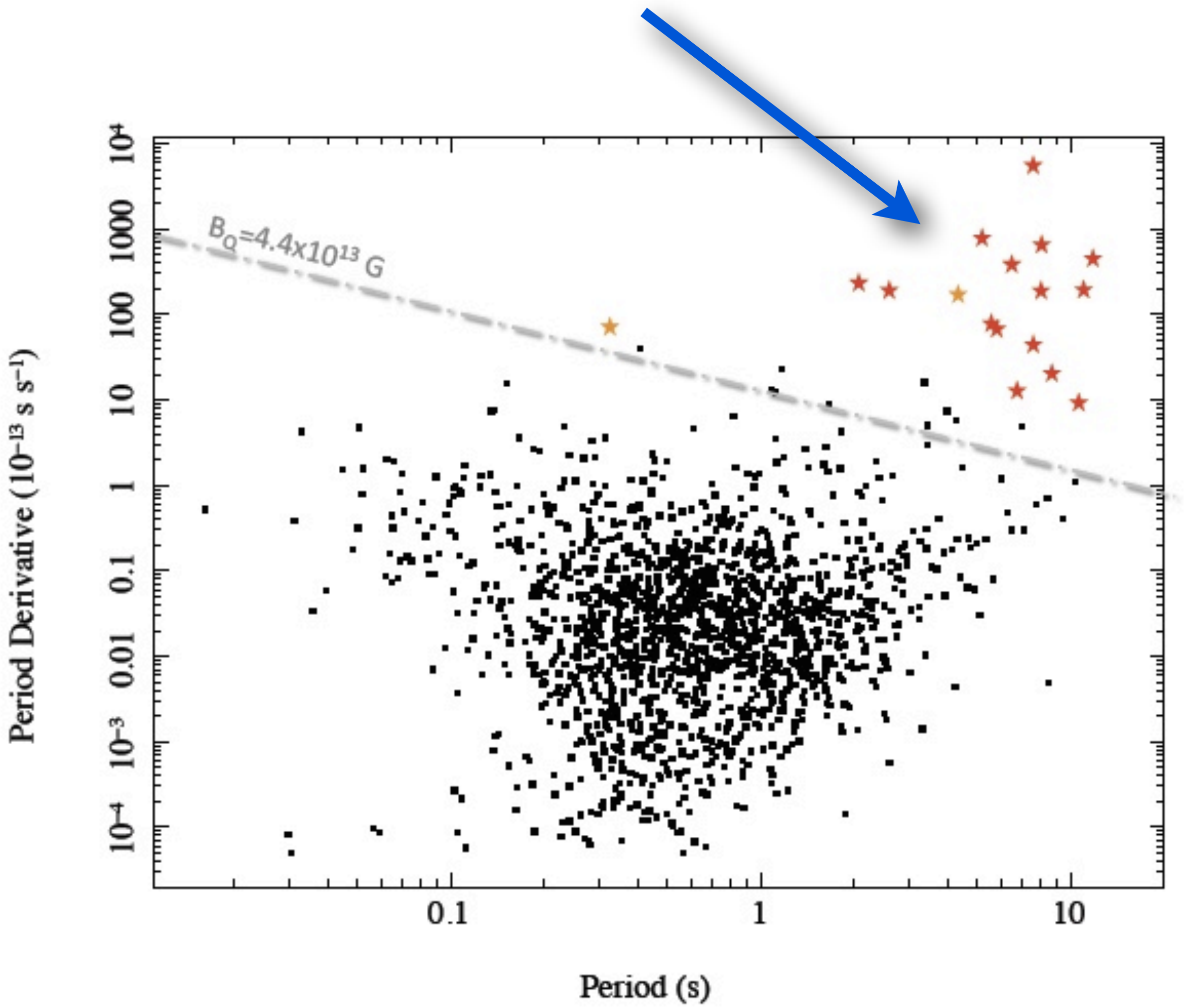
- This talk provides some answers to these questions, albeit at an order of magnitude precision.

Magnetar astrophysics (in a napkin)

- Magnetars are neutron stars with super-strong magnetic fields:

$$B \sim 10^{15}\,\mathrm{G}, \quad P = 1 - 10\,\mathrm{s} \qquad\qquad E_{\mathrm{mag}} \gg E_{\mathrm{kin}}$$

- Identified with Soft-Gamma-Repeaters (SGRs) and Anomalous X-ray Pulsars (AXPs).



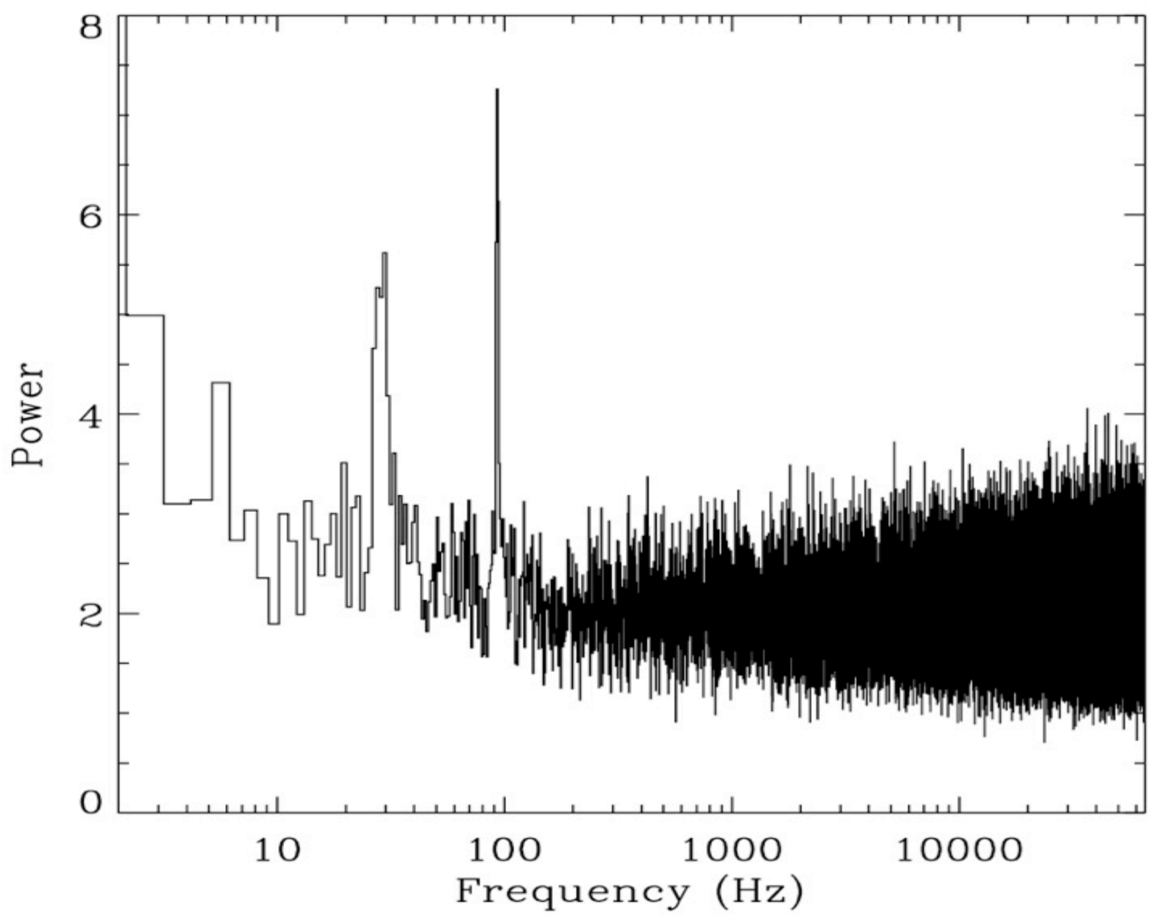
- Their emission is regularly punctuated by bursts.

- On rare occasions magnetars emit giant flares. So far three such events have been detected:
  SGR 1806-20 (2004),
  SGR 1900+14 (1998)
  SGR 0526-66 (1979)

Magnetar flares

- Envisaged as the result of a global magnetic field instability (likely to involve fracturing of the crust) but the actual trigger mechanism is still unknown.

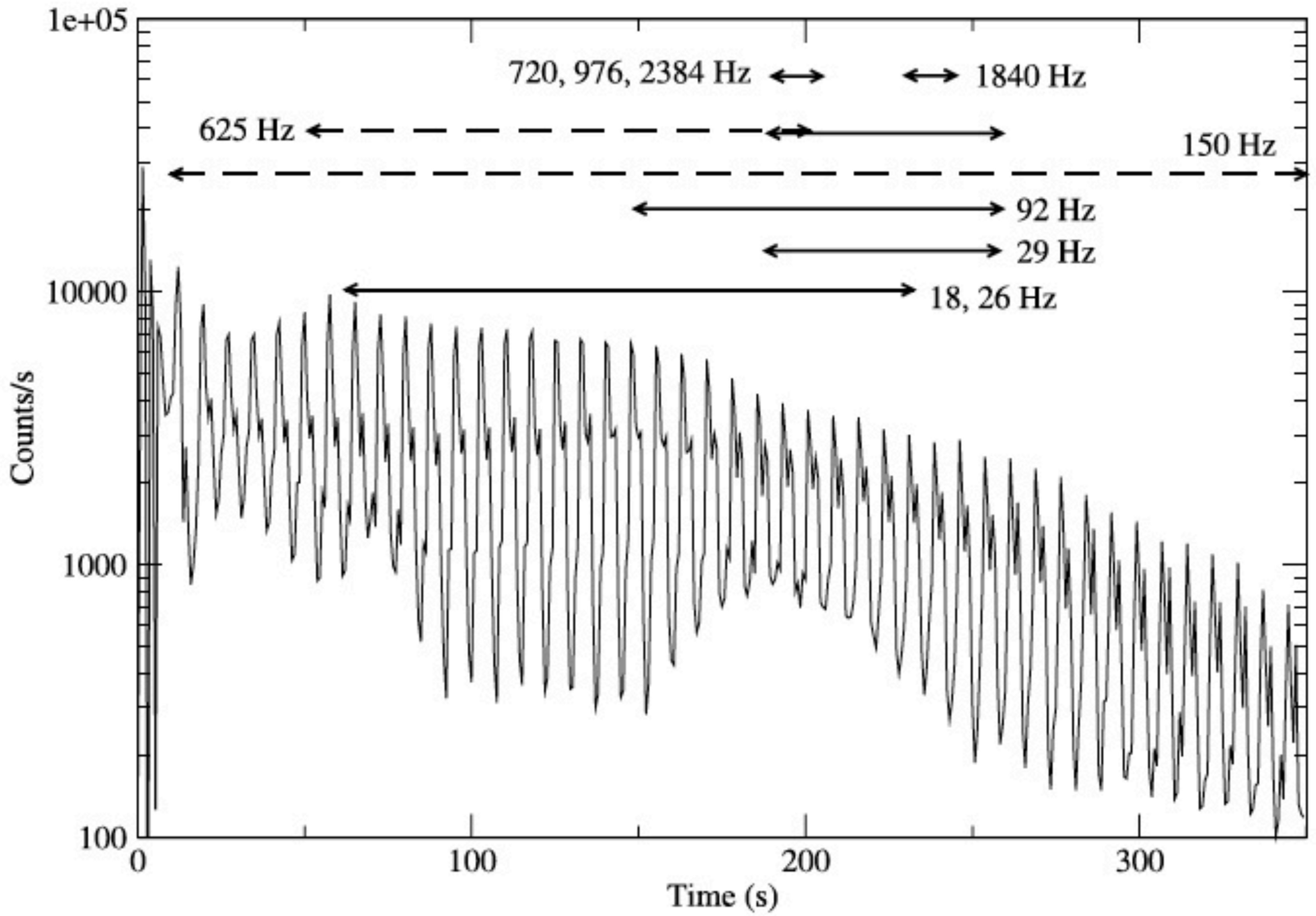
- Several QPOs are clearly seen in the X-ray signal of these events, spanning a frequency range ~ 10-1000 Hz. The most popular model for them is that of Alfvén modes (or hybrid magneto-elastic modes).



Strohmayer & Watts 2006

QPO observations

- Observations have something to say about the duration of the QPOs (the figure shows data from the SGR 1806-20 flare). Any damping timescale of the order of 10-100 s is clearly relevant.



Strohmayer & Watts 2006

Mode amplitude: excitation

- This problem features *several key amplitudes for the magnetic field perturbation δB* associated with an oscillation.

- The amplitude required for fracturing the crust is (where $\psi_{\rm br}$ is the crustal breaking strain, $v_{\rm A}$ is the Alfvén speed and v_s is the shear speed):

$$\frac{\delta B_{\rm br}}{B} \approx \psi_{\rm br} \frac{v_{\rm s}^2}{v_{\rm A}^2} \quad \Rightarrow \quad \frac{\delta B_{\rm br}}{B} \approx \left(\frac{\psi_{\rm br}}{0.1}\right) \frac{\rho_{14} v_{\rm s,8}^2}{B_{15}^2}$$

- This amplitude is rather high, and it corresponds to a fluid displacement ~ 1 km. This is not unrealistic (provided the displacement is non-radial!) and is actually consistent with the observed amplitude modulation of the QPO signal (see D'Angelo & Watts 2012)

- An excited oscillation is likely to have: $\delta B(t=0) \lesssim \delta B_{\rm br}$

Mode amplitude: destruction of superfluidity

- The fact that magnetar oscillations may be excited at a significant amplitude could also mean that superfluidity is suppressed during an oscillation cycle. This would happen if the relative neutron-electron velocity is above the so-called Landau limit (for details see Gusakov & Kantor 2013).

- The critical amplitude for destroying superfluidity is:

$$\frac{\delta B_{\rm SF}}{B} \sim 0.08\, w_{\rm SF,7} B_{15}^{-1/2}$$

$$w_{\rm SF,7} \;=\; w_{\rm SF}/10^7\,{\rm cm\,s}^{-1}$$

is the critical neutron-electron lag for the destruction of superfluidity

- *This effect has an impact on the spectrum of Alfvén oscillations*: when the neutrons are superfluid the coupling between them and the protons is weak and the characteristic Alfvén speed (and frequency) is much higher than that in non-superfluid matter:

$$v_{\rm A}^2 = \frac{H_{\rm c} B}{4\pi \rho_{\rm p}} \quad \text{vs} \quad v_{\rm A}^2 = \frac{H_{\rm c} B}{4\pi \rho} \qquad f_{\rm A} \sim \frac{v_{\rm A}}{L}$$

Mode amplitude: vortex pinning/unpinning

- The vortex array in the core is likely to be pinned on to the much more numerous proton fluxtubes (the pinning force is provided by their magnetic interaction).

- An oscillation with a sufficiently high amplitude can cause vortex unpinning. The δB threshold for that to happen is directly proportional to critical proton-neutron velocity lag $w_{\rm pin}$ for vortex unpinning:

$$\frac{\delta B_{\rm pin}}{B} \sim \frac{w_{\rm pin}}{v_{\rm A}} \approx 4 \times 10^{-3}$$

- The previous amplitudes are well-ordered in terms of their relative magnitude:

$$\delta B_{\rm pin} \ll \delta B_{\rm SF} \ll \delta B_{\rm br}$$

Damping of magnetar oscillations

- The various dissipative mechanisms fall into two broad categories: *internal* and *external* (magnetospheric).

External damping → Alfvén waves emitted along the open field lines: *relevant*

Internal damping →
- Shear & bulk viscosity: *irrelevant*
- Superfluid mutual friction (vortex-electron coupling): *relevant*
- Superfluid mutual friction (vortex-fluxtube coupling): *relevant*

Types of magnetar oscillations

- In this work we have considered two types of magnetar oscillations:

✓ Alfvén-type modes:
these are global (crust-core) oscillations which may have a hybrid magneto-elastic character. They are believed to be the most plausible interpretation for the observed QPOs.

✓ Crustal modes:
these are modes confined in the neutron star crust. They could be relevant if the crust-core magnetic coupling is not efficient.

- Superfluid mutual friction is strong only for the case of Alfvén-type oscillations. On the other hand, magnetospheric damping is relevant for both types of modes.

(External) Magnetospheric damping (I)

- The damping timescale is the ratio of the mode energy over the Alfvén Poynting flux along the *open* field lines:

$$\tau_{\rm A} = \frac{E_{\rm mode}}{P_{\rm A}}$$

- We also account for the "combing" of the magnetic lines by the propagating waves (Thompson & Blaes 1998). This effect enhances damping. The (approximate) damping timescales are:

Alfvén modes: $$\tau_{\rm A} \sim 4 \left(\frac{\delta B}{B}\right)^{-4/3} \frac{x_5 M_{1.4}}{B_{15}^2 R_6^2} \ {\rm s}$$

Crustal modes: $$\tau_{\rm A} \sim 30 \left(\frac{\delta B}{B}\right)^{-2/3} \frac{M_{1.4}}{B_{15}^2 R_6^2} \ {\rm s}$$

Magnetospheric damping (II)

- The previous magnetospheric timescales for Alfvén modes become:

$$\delta B_{\rm SF} < \delta B < \delta B_{\rm br} \longrightarrow \tau_{\rm A} \sim (0.05 - 150)\, x_5 M_{1.4} R_6^{-2} B_{15}^{-2} \ \text{s}$$

"strong" magnetospheric damping

$$\delta B_{\rm pin} < \delta B < \delta B_{\rm SF} \longrightarrow \tau_{\rm A} \sim (150 - 5\times 10^3)\, x_5 M_{1.4} R_6^{-2} B_{15}^{-2} \ \text{s}$$

"medium" magnetospheric damping

$$\delta B < \delta B_{\rm pin} \longrightarrow \tau_{\rm A} > 10^4 \ \text{s}$$

"weak" magnetospheric damping

Internal damping

- The only significant damping mechanism appears to be superfluid mutual friction, i.e. scattering of electrons by the neutron vortex array and fluxtube "cutting" by the (unpinned) vortices.
- The damping timescale is: $\tau_{\rm mf} = \dfrac{E_{\rm mode}}{|\dot{E}_{\rm mf}|}$

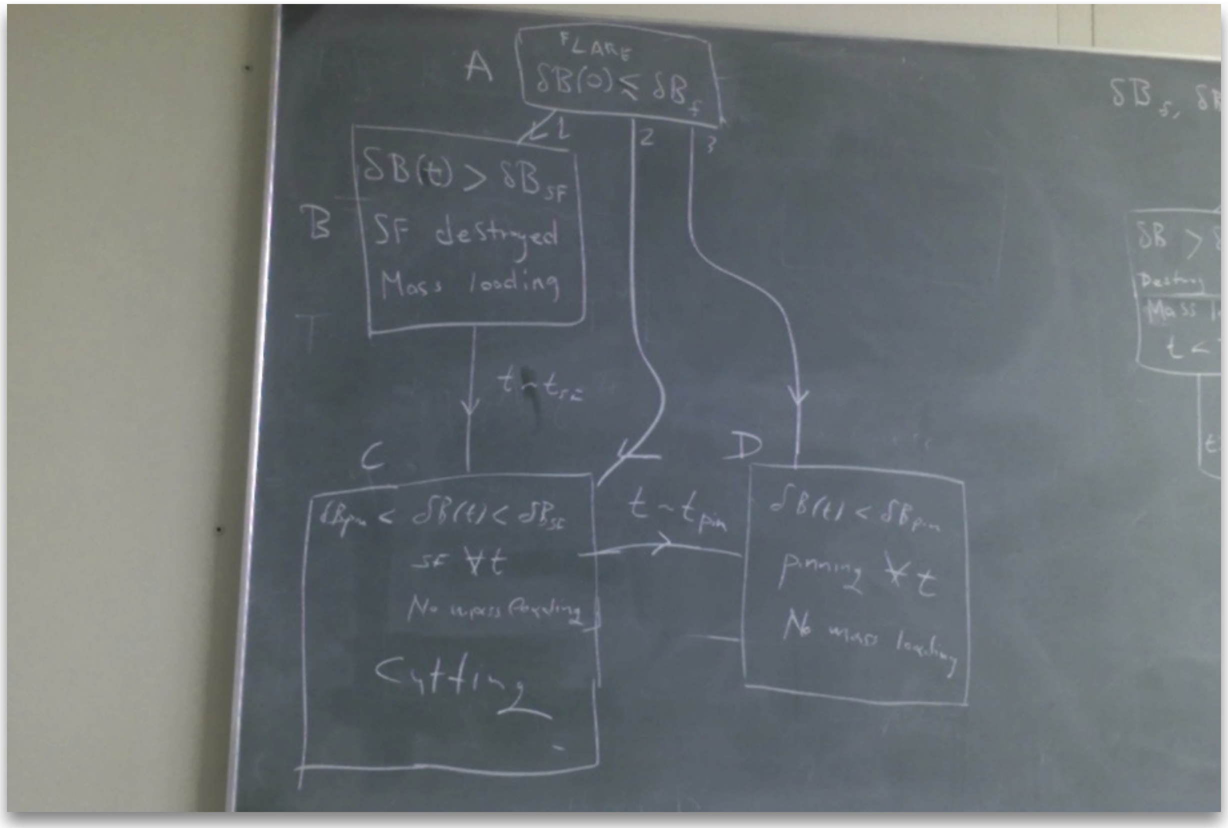
vortex-electron friction : $\tau_{\rm mf} \sim 630\, x_5 \left(\dfrac{P}{10\,{\rm s}}\right)\left(\dfrac{4\times 10^{-4}}{\mathcal{B}}\right)\ {\rm s}$

vortex-fluxtube friction (requires $\delta B > \delta B_{\rm pin}$) $\tau_{\rm mf} \sim 3\, x_5 \rho_{14}^{-1/2} \left(\dfrac{P}{10\,{\rm s}}\right)\left(\dfrac{\delta B}{\delta B_{\rm pin}}\right)^{3/2} B_{15}^{-1/4}\ {\rm s}$

Note: the latter timescale result may *not* be reliable given that the approximation underpinning its derivation is not valid in magnetars.

Evolutionary paths for magnetar oscillations

- We can assemble “evolutionary paths” for magnetar oscillations by putting together all the previous bits of physics.
- Each path is determined by the initial oscillation amplitude $\delta B(0)$ in relation with the thresholds $\delta B_{\mathrm{pin}}, \delta B_{\mathrm{SF}}$ for vortex unpinning and SF-destruction.
- These paths only apply for global Alfvén-type oscillations.



Three evolutionary paths

A

FLARE!

$\delta B(0) \lesssim \delta B_{\rm br}$

Path 1: A-B-C-D

Path 2: A-C-D

Path 3: A-D

B

$\delta B_{\rm pin} < \delta B_{\rm SF} < \delta B(t)$

Superfluid (partially) destroyed $\Rightarrow$ 'weak' mutual friction

Mass loading $\Rightarrow$ Alfvén frequency low

Mode coupling?

'Strong' magnetospheric damping

C

$\delta B_{\rm pin} < \delta B(t) < \delta B_{\rm SF}$

Neutrons superfluid

Cutting occurs $\Rightarrow$ strong mutual friction

No mass loading $\Rightarrow$ Alfvén frequency high

'Medium' magnetospheric damping

D

$\delta B(t) < \delta B_{\rm pin} < \delta B_{\rm SF}$

Neutrons superfluid

Vortices pinned $\Rightarrow$ no mutual friction

No mass loading $\Rightarrow$ Alfvén frequency high

'Weak' magnetospheric damping

Outlook

- Our analysis seems to suggest “complicated” evolutionary path for high-amplitude magnetar oscillations.

- Although we have not tried to match the observed QPO data with our evolutionary paths, we have predicted damping timescales and the possibility of variable “mass-loading” of the Alfvén mode spectrum.

- The dissipative mechanisms discussed here seem to predict damping timescales in the ballpark of the observed QPO durations.

- Topics for future work:
  mode-mode coupling, a consistent model of fluxtube cutting, use of accurate mode solutions.