PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

IQC Institute *for* Quantum Computing

Crustal Dynamics of Magnetars and its Connection to Magnetar Bursts

Huan Yang [1,2], Nestor Ortiz [1], Christopher Thompson [3]

[1]Perimeter Institute

[2]Institute for Quantum Computing

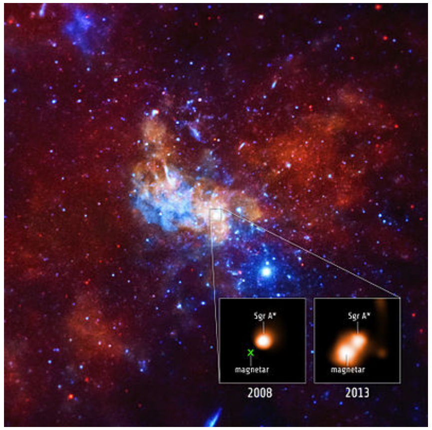
[3]Canadian Institute for Theoretical Astrophysics

GR21, New York, Columbia University, July 11

What are Magnetars?

- Magnetars are neutron stars with extremely strong magnetic field ~ 10^{15} G
- Widely accepted as an explanation for soft gamma ray repeaters (SGRs) and anomalous X-ray pulsars.
- Main sequence core convention (with hydrodynamic instabilities) + extreme core collapse + post-collapse MRI amplifies the B field [Duncan, Thompson 1993].

SGR 1900+14

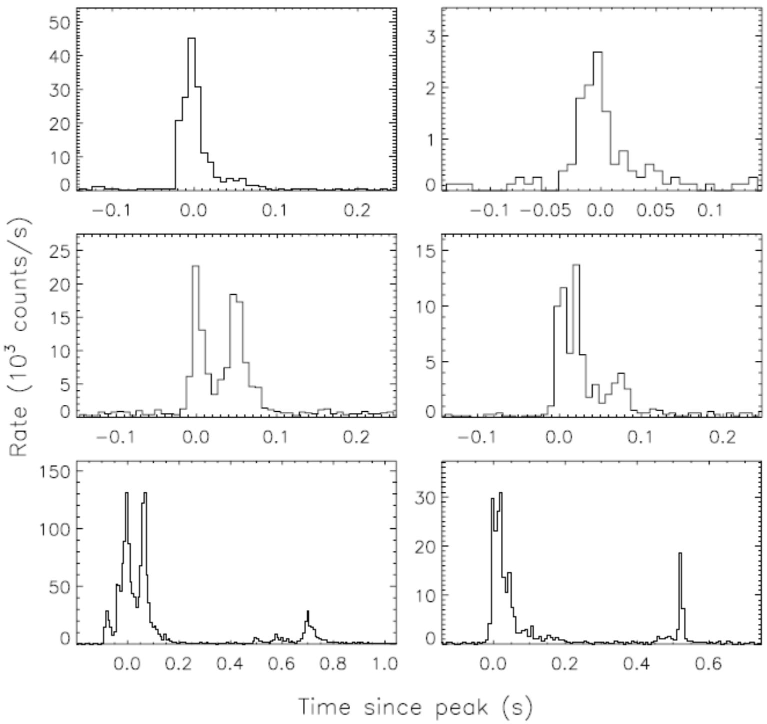


SGR 1745+2900

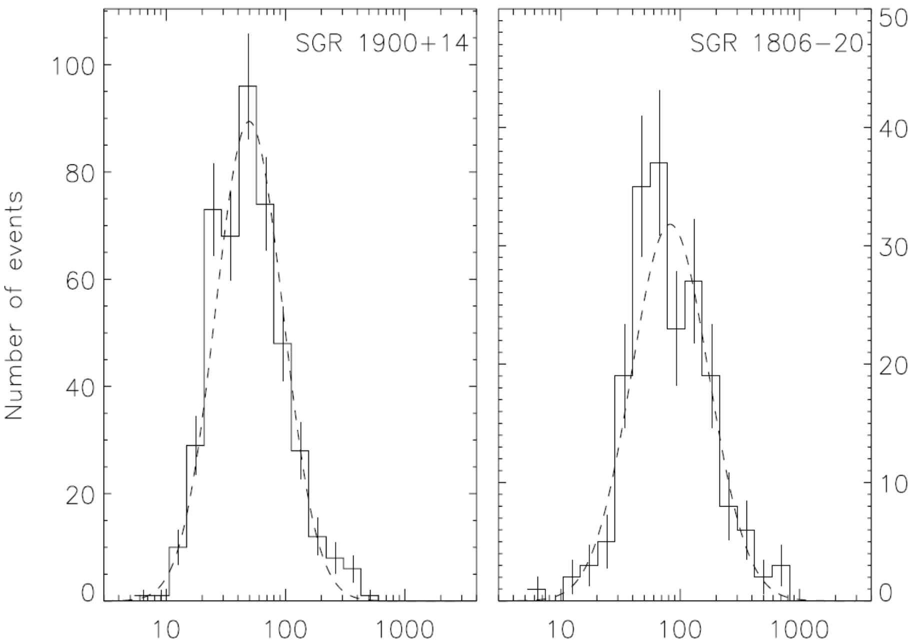
http://www.nasa.gov/mission_pages

Magnetar bursts: short bursts from SGRs

- Repetitive emission of low-energy gamma-ray bursts, ~ 0.1s.



SGR 1900+14 SGR 1806+20



Burst duration in ms

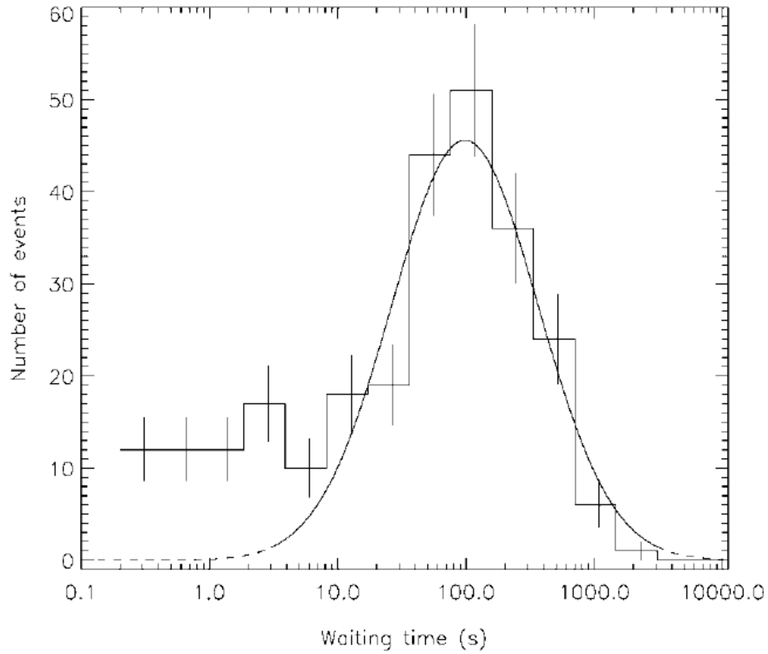
Gogus et al. Apj 2001

Magnetar bursts: short bursts from SGRs

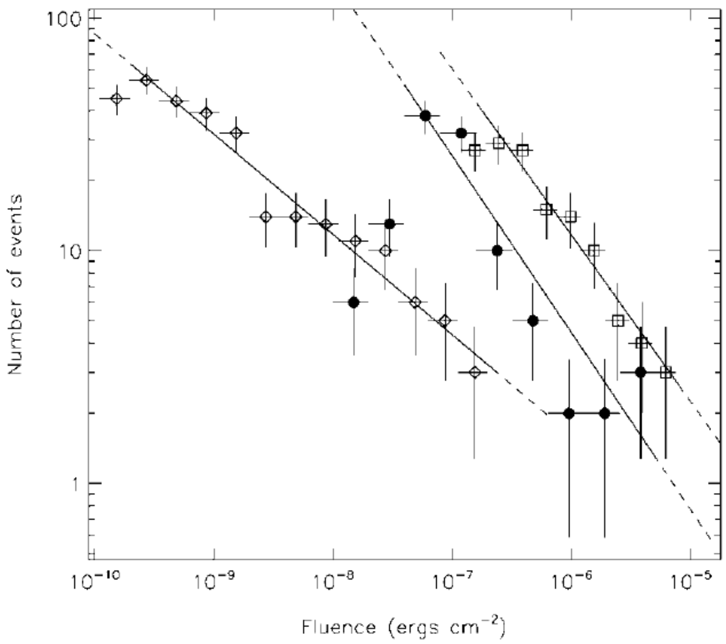
- Repetitive emission of low-energy gamma-ray bursts, ~ 0.1s.
- Optically thin thermal bremsstrahlung with kT ~ 20-40 keV.

Magnetar bursts: short bursts from SGRs

- Repetitive emission of low-energy gamma-ray bursts, ~ 0.1s.
- Optically thin thermal bremsstrahlung with kT ~ 20-40 keV.
- Power law distribution of burst energies, log-normal waiting times.



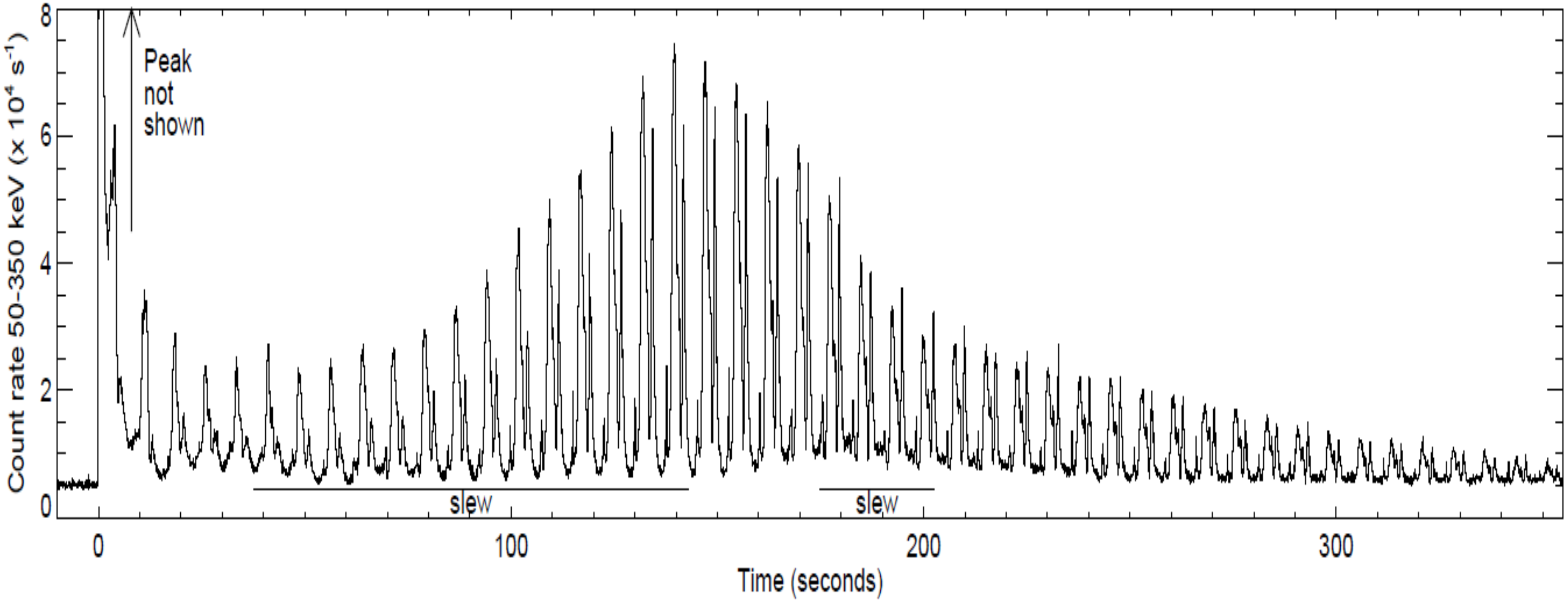
SGR 1806+20



Gogus et al. Apj 2000

Magnetar bursts: giant flares and QPOs

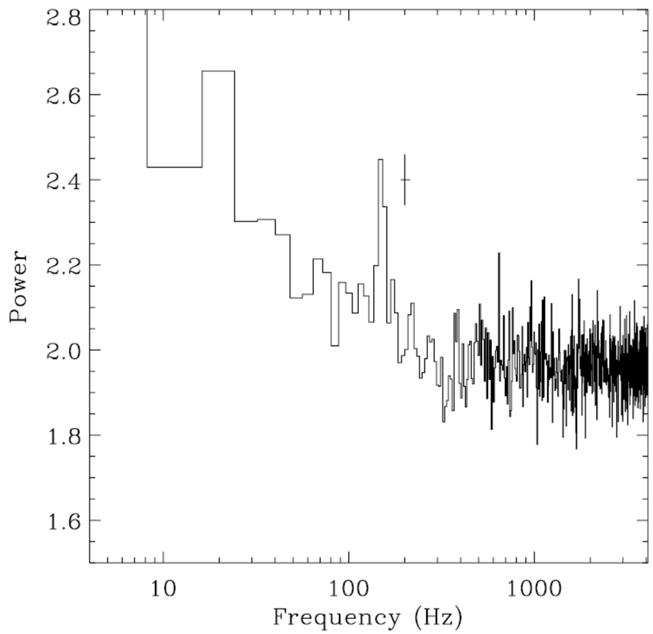
- Ultra-luminous gamma-ray flare (10^{44} -10^{46}ergs), three events known.

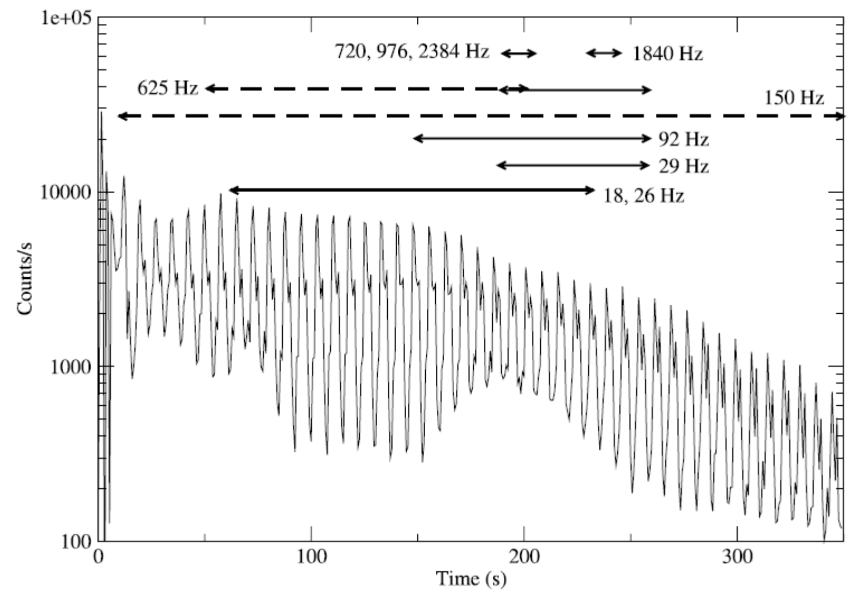


SGR 1806+20, 2004 Dec. 27 Palmer et al. Nature 2005

Magnetar bursts: giant flares and QPOs

- Ultra-luminous gamma-ray flare (10^{44} -10^{46}ergs), three events known.
- High frequency quasi-periodic oscillations (QPOs) present soon after the major flare.





Strohmayer and Watts, Apj 2006

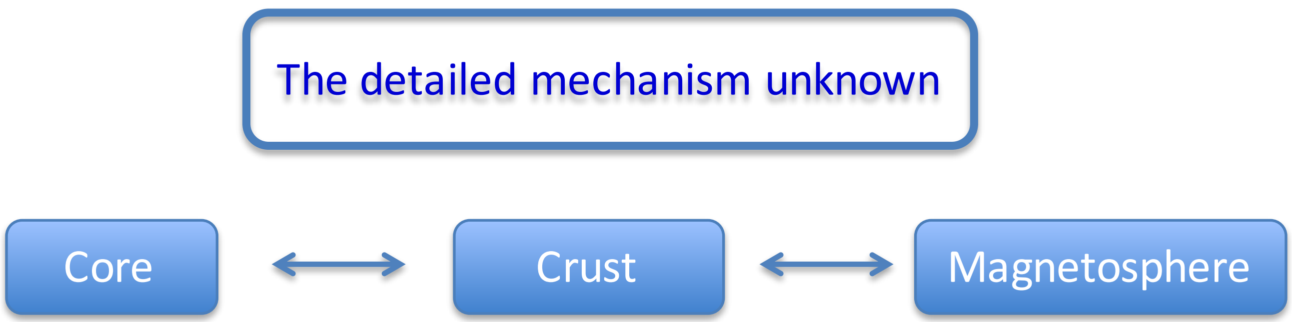
SGR 1806+20, 2004 Dec. 27

Magnetar bursts: giant flares and QPOs

- Ultra-luminous gamma-ray flare (10^{44} -10^{46}ergs), three events known.
- High frequency quasi-periodic oscillations (QPOs) present soon after the major flare.
- QPOs are likely to be associated with crustal shear modes [Duncan 1998].

Magnetar bursts: giant flares and QPOs

- Ultra-luminous gamma-ray flare (10^{44} -10^{46}ergs), three events known.
- High frequency quasi-periodic oscillations (QPOs) present soon after the major flare.
- QPOs are likely to be associated with crustal shear modes [Duncan 1998].

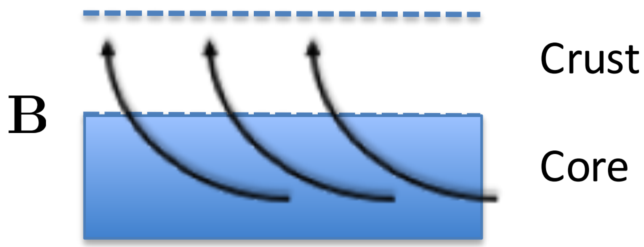


The role of strong magnetic field

- Rotation energy of the neutron star ($\sim 10^{44}$ ergs). is insufficient to power the quiescent X-ray emission or the giant flares ($\sim 10^{46}$ ergs).
- Reduce Compton scattering cross-section to power super-Eddington radiation ($L > 10^4 L_{Edd}$) in SGRs.
- Spin-down the star to an ~ 8s period in the ~ 10^4 years age of the surrounding supernova remnant.
- Maxwell stress strong enough to lead to plastic motion in local patches of the crust.

Plastic yielding of the crust

- A dominant core magnetic field stressing the crust from below excites localized zones of plastic failure (In progress).



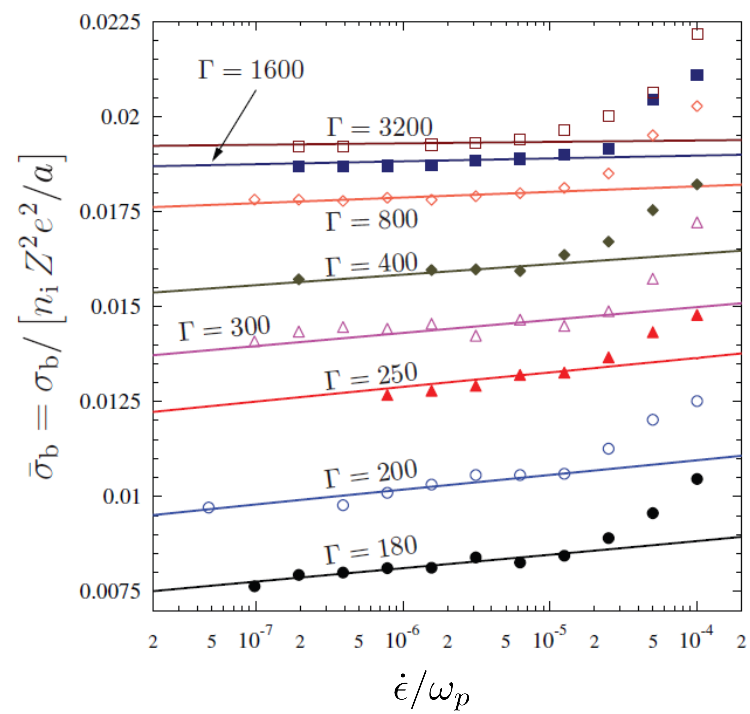
Plastic yielding of the crust

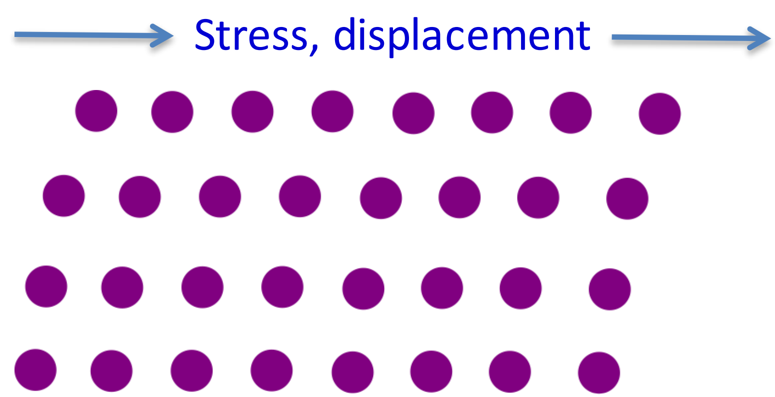
- A dominant core magnetic field stressing the crust from below excites localized zones of plastic failure (In progress).

- Stress-creep rate relation: molecular dynamics simulation [Chugunov & Horowitz MNRAS 2010], $\sigma_b \sim 0.1\mu$

Plastic yielding of the crust

- A dominant core magnetic field stressing the crust from below excites localized zones of plastic failure (In progress).
- Stress-creep rate relation: molecular dynamics simulation [Chugunov & Horowitz MNRAS 2010], $\sigma_b \sim 0.1\mu$



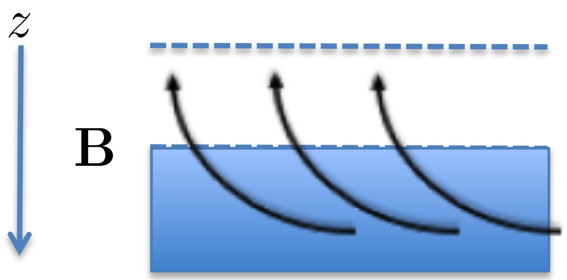


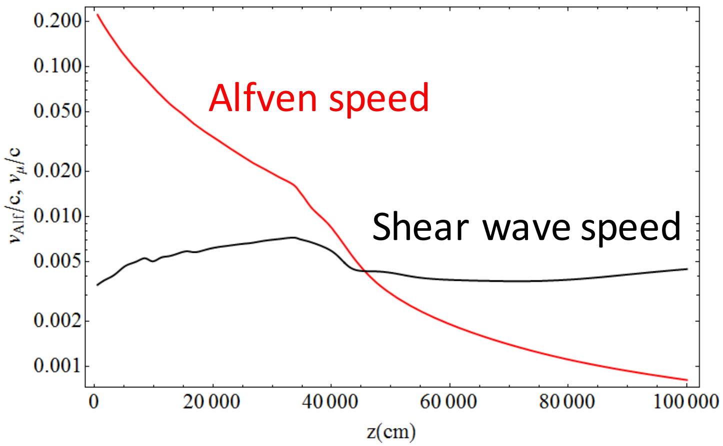
$$\dot{\epsilon} = \text{const} \times e^{(\bar{\sigma} N - 0.366)\Gamma}$$

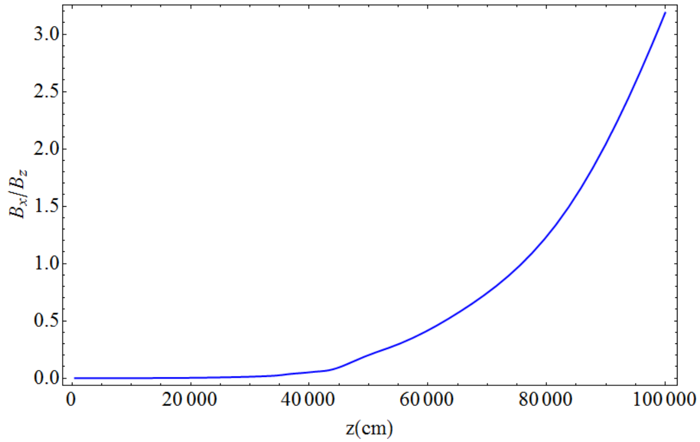
$$\Gamma = \frac{17.6 T_{\text{melt}}}{T}, \quad N = \frac{500}{\Gamma - 149} + 18.5$$

Crust-magnetosphere coupling: set-up

- Construct a vertical background profile (stratified crust) with constant creeping rate.







Crust-magnetosphere coupling: set-up

- Construct a vertical background profile (stratified crust) with constant creeping rate.
- Hydro-magnetic equations of motion: $v \equiv \partial_t \xi_x, \ \chi \equiv \partial_z \xi_x$

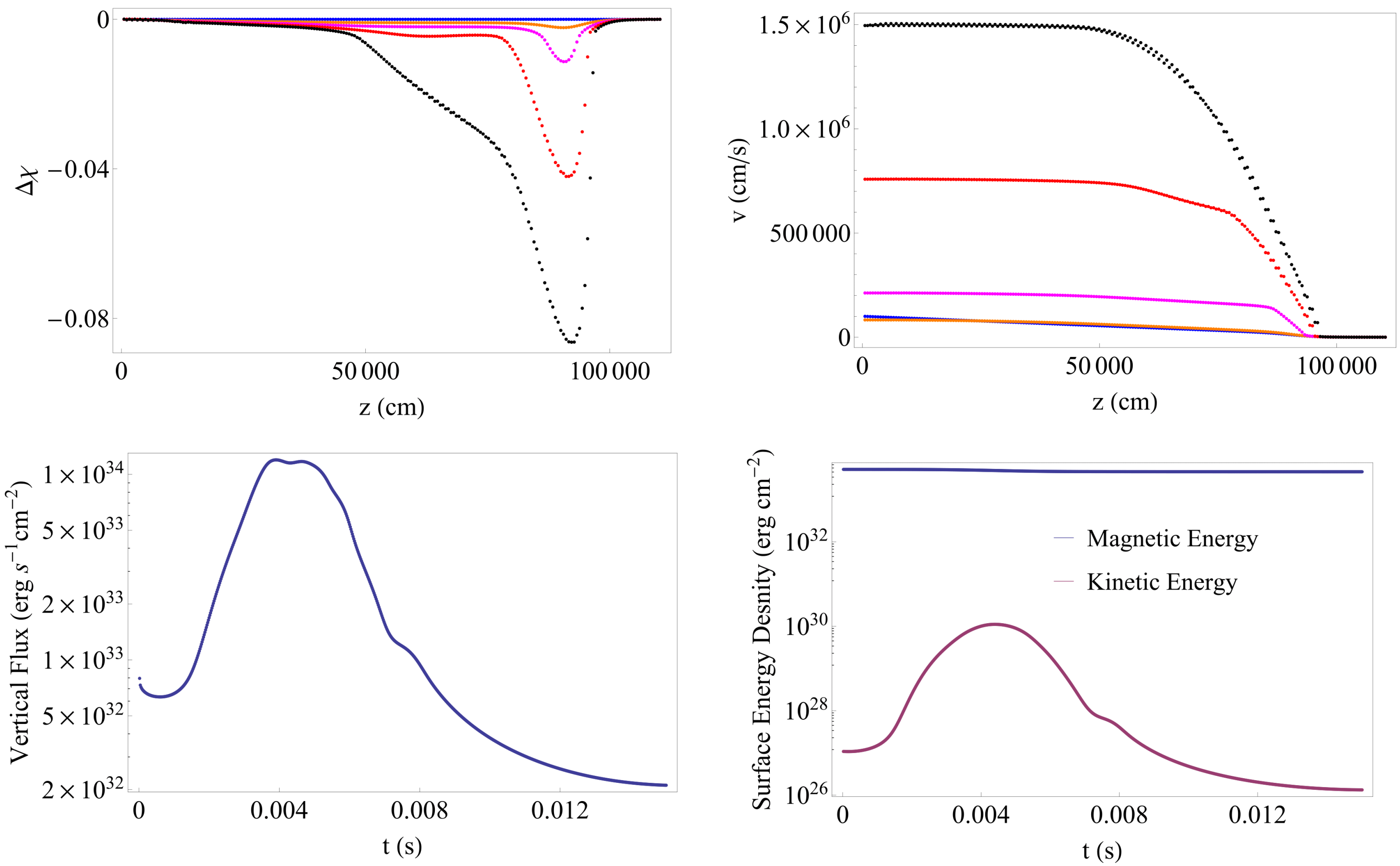
$$\partial_t v = v_{\rm Alf}^2 \partial_z \chi + \frac{1}{\rho + B_z^2/(4\pi c^2)} \partial_z \sigma_{xz}$$

$$\partial_t \chi = \partial_z v = \dot{\epsilon}$$

- Horizontal elastic wave affects the vertical stress, which leads to vertical (runaway) relaxation of magnetic field.

$$\sigma_{xy} = \mu \frac{\partial \xi_x}{\partial y}, \quad \sigma_{xz} = \mathrm{sgn}(\partial_z v) \sqrt{\sigma^2(\dot{\epsilon}) - \sigma_{xy}^2}$$

Crust-magnetosphere coupling: energy ejection



0-4 ms

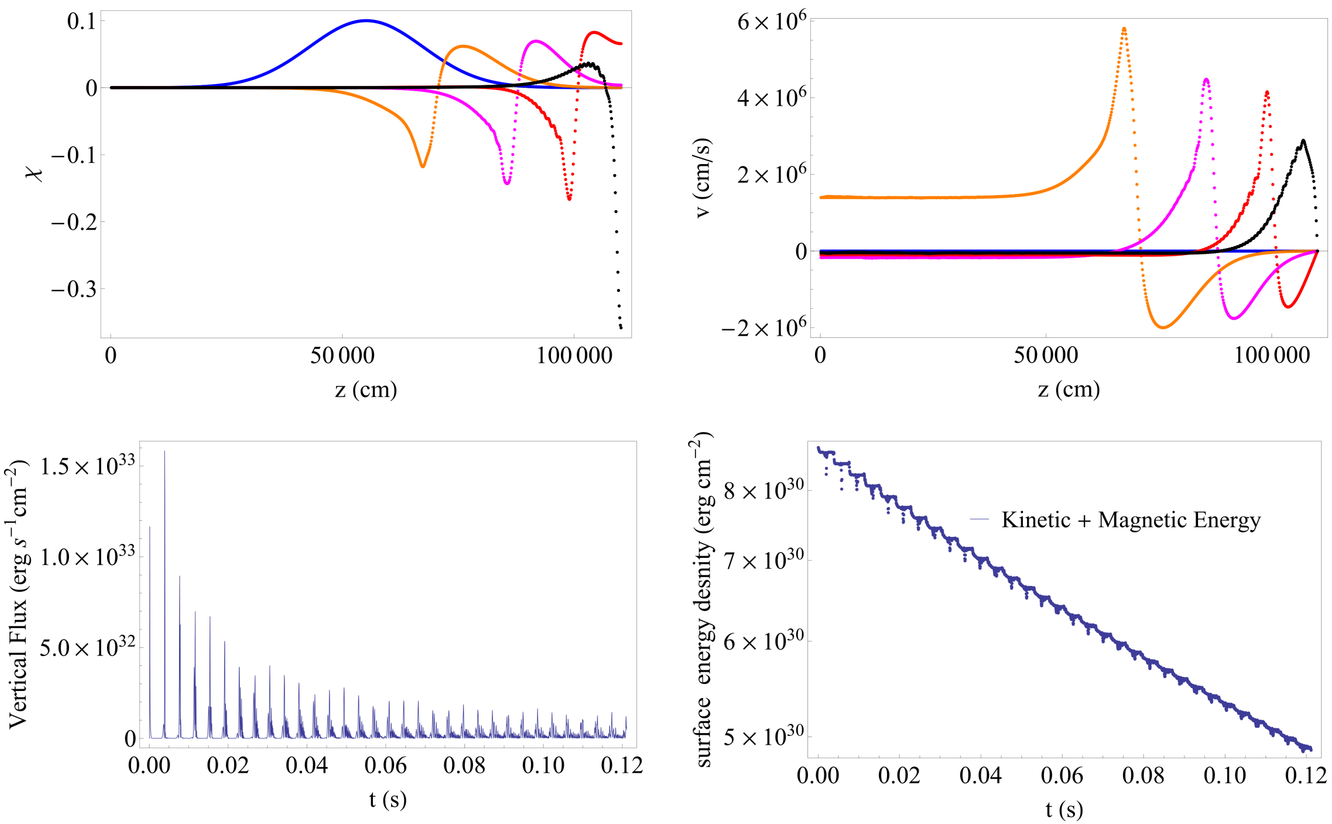
Liquefied patches

- Part of the crust is melted after the giant flare, hydromagnetic equations:

$$\partial_t v = v_{\rm Alf}^2 \partial_z \chi$$
$$\partial_t \chi = \partial_z v$$

Liquefied patches

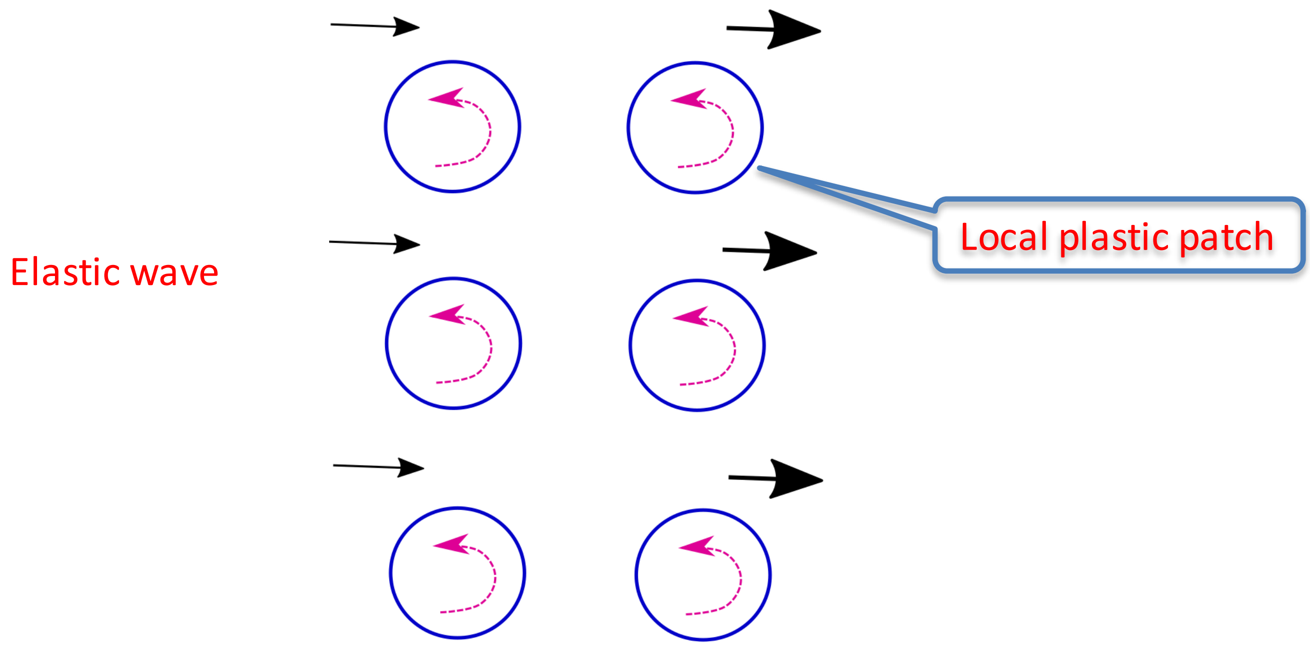
- Part of the crust is melted after the giant flare, hydromagnetic equations:
- Relaxation of a wave packet, possible origin for high frequency QPOs.



0-2 ms

Wave-plastic patch interaction

- Low frequency QPOs: elastic shears waves passing by plastic patches.
- They last ~ 100s with thousands of oscillation cycles – need to feed energy to compensate loss due to crust-core coupling (Alfven wave radiation).
- A novel super-radiant process.



Wave-plastic patch interaction

- Low frequency QPOs: elastic shears waves passing by plastic patches.
- They last ~ 100s with thousands of oscillation cycles – need to feed energy to compensate loss due to crust-core coupling (Alfven wave radiation).
- A novel super-radiant process. Growth per cycle

$$r \sim 0.01 \left(\frac{\dot{\epsilon}}{0.01 s^{-1}}\right) \left(\frac{f_p}{0.1}\right) \left(\frac{\zeta}{1/8}\right) \left(\frac{T}{0.5 T_{\mathrm{melt}}}\right)^{-1} \left(\frac{P}{30ms}\right)$$

Creep rate

Filling factor

Fraction in transition radius

Period

Conclusion

- Core instability leads to local plastic patches in magnetar crusts and eventually the giant flares.
- Energy ejection is very fast and efficient by relaxing background magnetic field in plastic patches (necessary to explain short bursts).
- Super-radiant scattering by local plastic patches, necessary to explain long-living QPOs.
- Future work: understand the radiation from the magnetosphere.