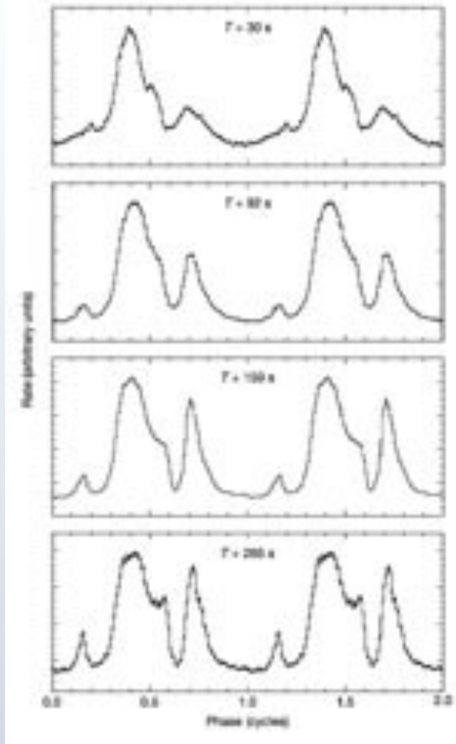
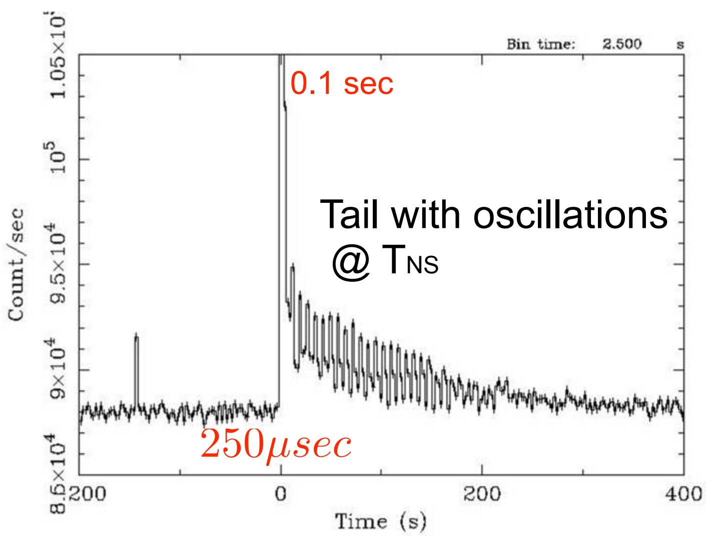
Magnetars: why, where and how flares occur.

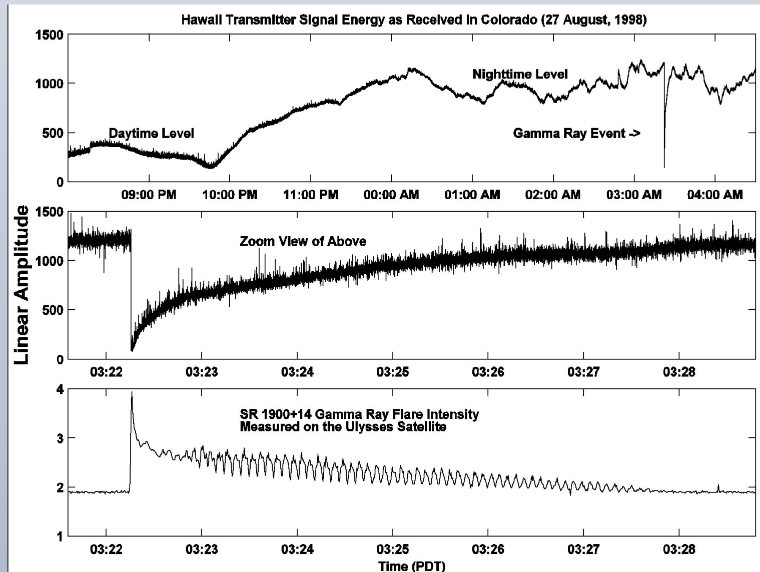
Maxim Lyutikov (Purdue U.)

Magnetars' bursts and flares

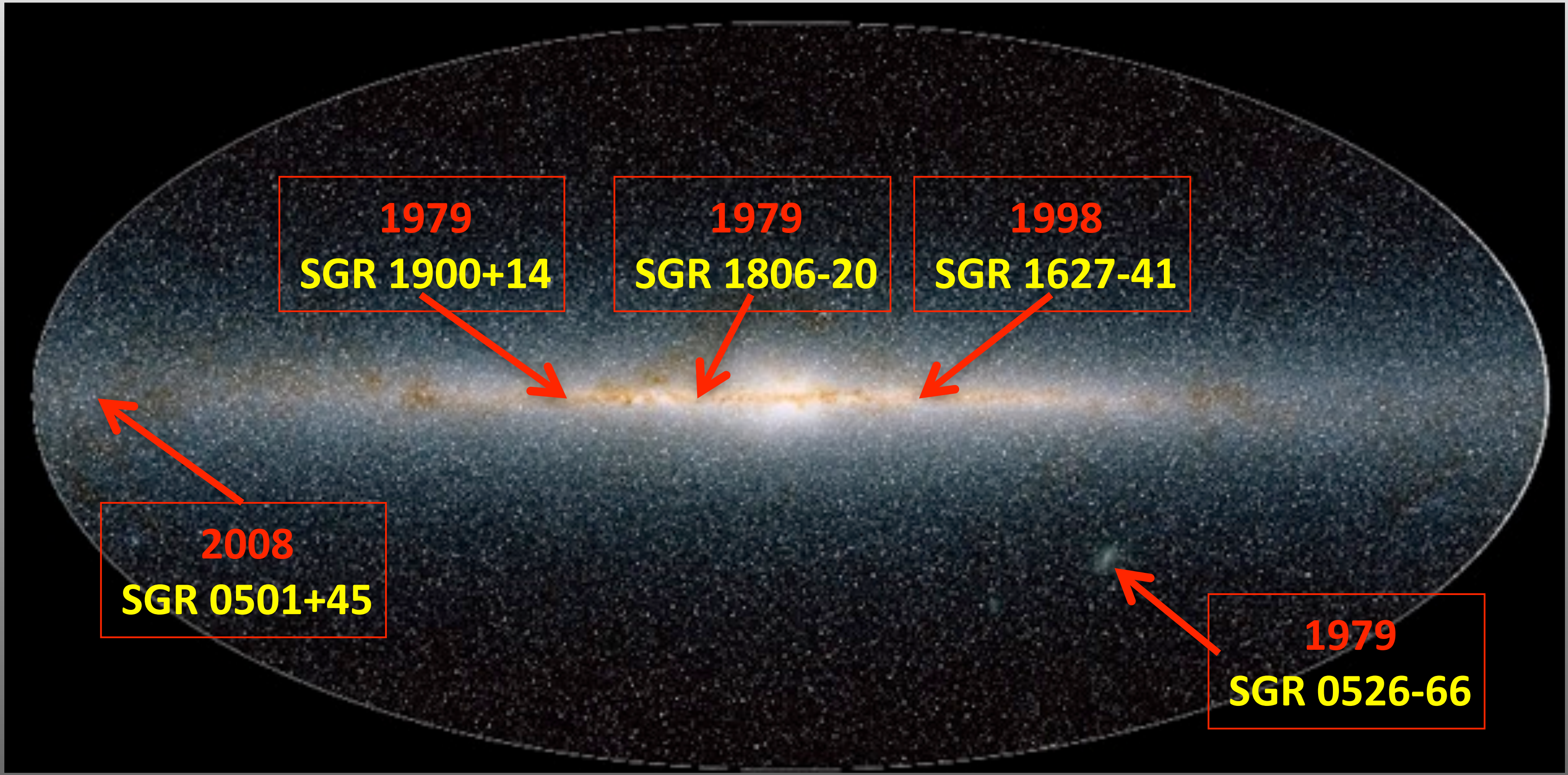
- Magnetars: special class of NS:
- Produce X-ray bursts, flares and persistent emission
- Powered by B-field, B~ 10^{14} G outside, > 10^{15} G inside
- **How?**







Location and discovery date of the 5 SGRs



S.Mereghetti

Mostly young, ~ 10^{4-5} yrs, high(ish) B-fields, > 10^{13} G

Magnetars are powered by dissipation of super-strong B-field, B~ 10^{14-15} G

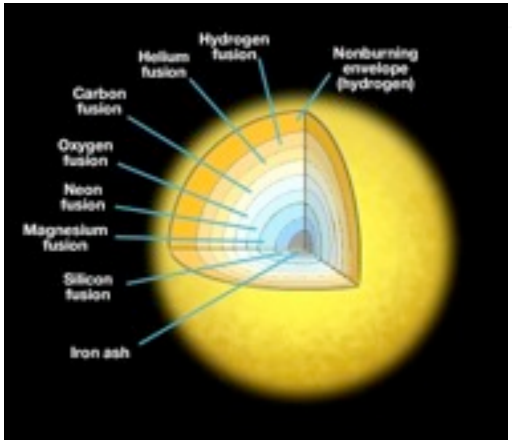
- $L_X = 10^{34}$ - 10^{36} erg s^{-1} > 100 $L_{spindown}$, $L_{spindown} = I\,\Omega\dot{\Omega}$ (not rotationally powered)
- Spin periods P = 5 – 12 s - slow
- Characteristic ages 3 10 ^{3} -- 4 10^5 yr

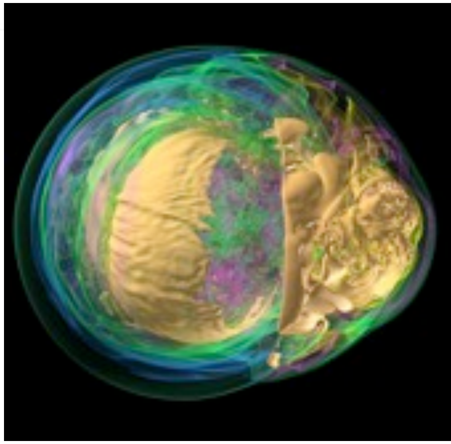
Thompson & Dunkan

- From spindown $I\Omega\dot{\Omega} \sim B^2 R_{NS}^2 c \left(\frac{\Omega R_{NS}}{c}\right)^4$
- From flare energetics: $E_{\rm flare} \sim E_{\rm tail} \sim B^2 R_{NS}^3$

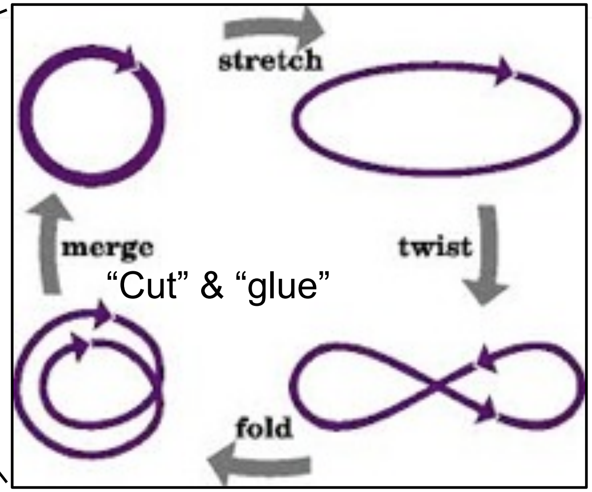
} $B \sim 10^{14} - 10^{15} G$

Amplification of magnetic field: Dynamo in neutron stars: first 10 secs





- Stars burn lighter elements, up to Fe.
- No fuel left: collapse of the core
- Neutrino-driven convection } dynamo
- Rotation
- B ~ 10^{16} G in special types of NSs, "magnetars"
- $\frac{B^2}{8\pi} \sim p$ inside, $\frac{B^2}{8\pi} \gg \rho c^2$ right outside

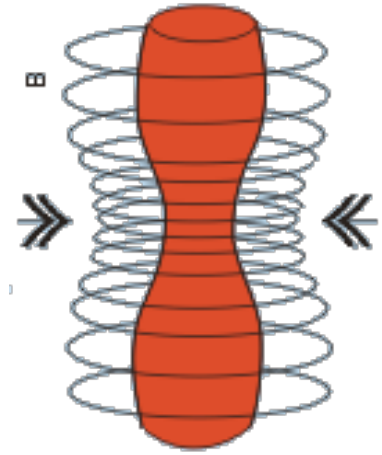


- Turbulent dynamo
- alpha-omega dynamo
- Saturation at $\frac{B^2}{8\pi} \sim \rho v_T^2$
- But Rossby #> 1: need ~ 1 for efficient dynamo

Second: 10-100 secs

- Turbulence dies out, NS relaxes to an MHD equilibrium.
- Big Q.: **What is the stable B-field structure of fluid stars?**
- B-field must be a combination of toroidal and poloidal field, otherwise unstable

- Pure toroidal is unstable to sausage instability:

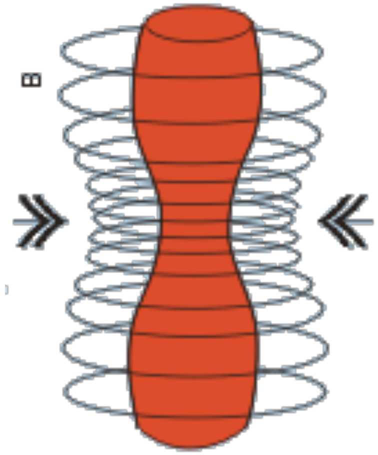


- Pure poloidal is also unstable:

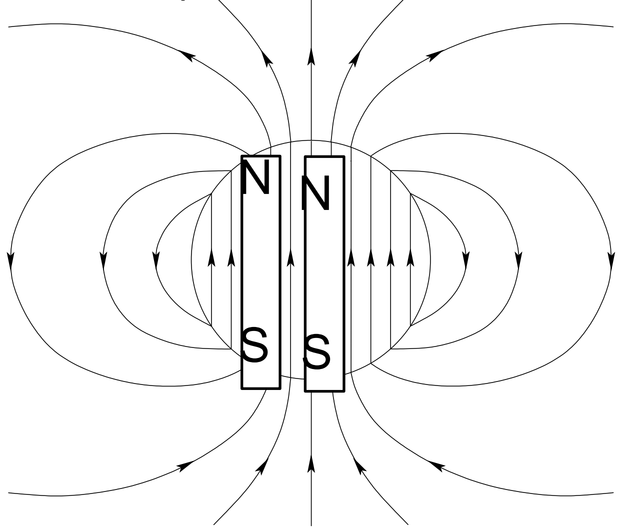
Second: 10-100 secs

- Turbulence dies out, NS relaxes to an MHD equilibrium.
- Big Q.: **What is the stable B-field structure of fluid stars?**
- B-field must be a combination of toroidal and poloidal field, otherwise unstable

- Pure toroidal is unstable to sausage instability:

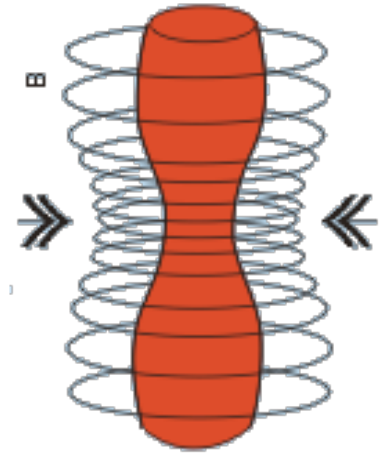


- Pure poloidal is also unstable:

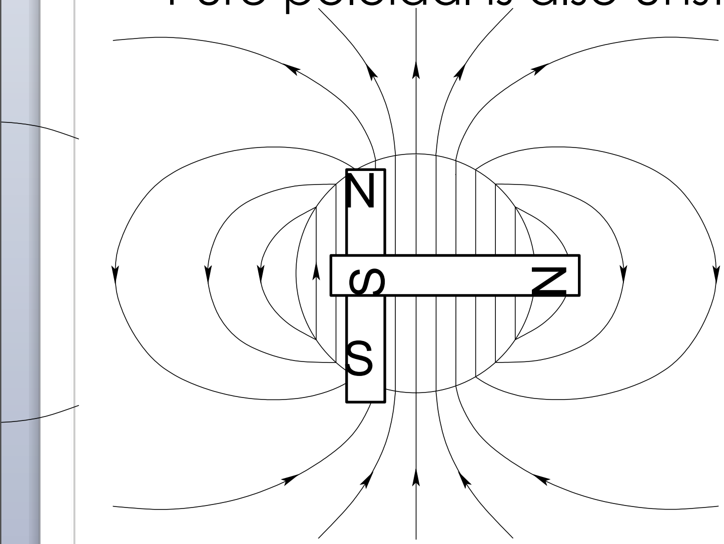


Second: 10-100 secs

- Turbulence dies out, NS relaxes to an MHD equilibrium.
- Big Q.: **What is the stable B-field structure of fluid stars?**
- B-field must be a combination of toroidal and poloidal field, otherwise unstable
- Pure toroidal is unstable to sausage instability:

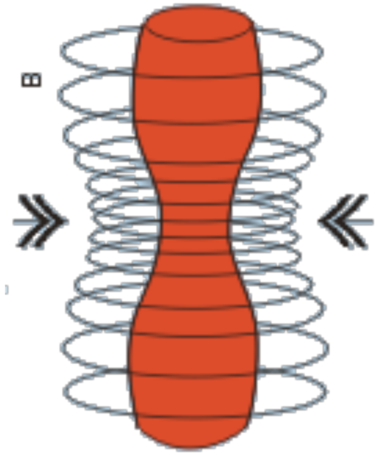


- Pure poloidal is also unstable:

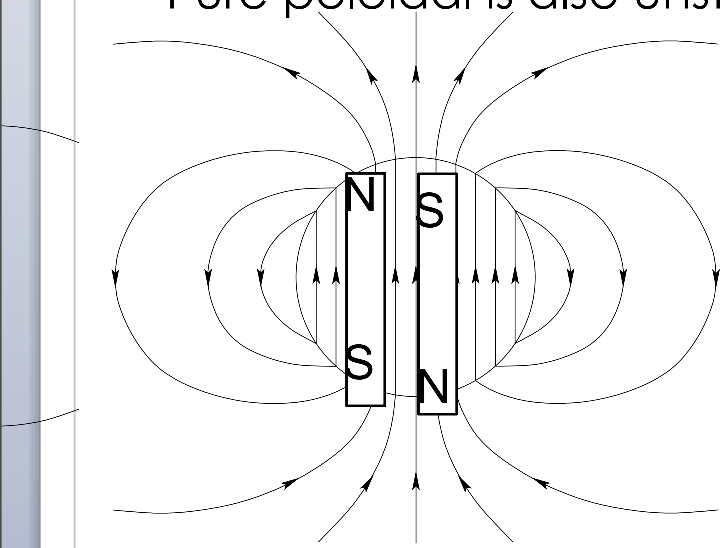


Second: 10-100 secs

- Turbulence dies out, NS relaxes to an MHD equilibrium.
- Big Q.: **What is the stable B-field structure of fluid stars?**
- B-field must be a combination of toroidal and poloidal field, otherwise unstable

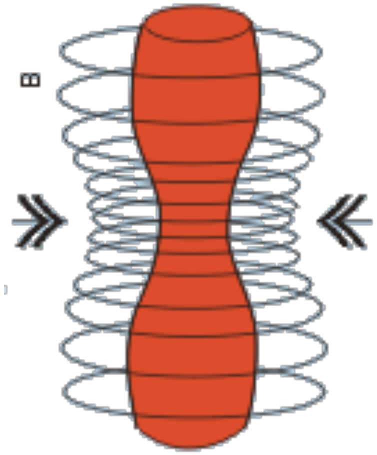


- Pure toroidal is unstable to sausage instability:
- Pure poloidal is also unstable:

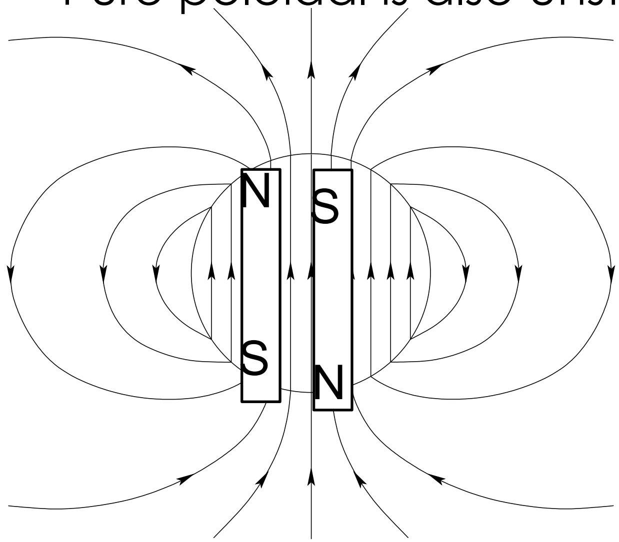


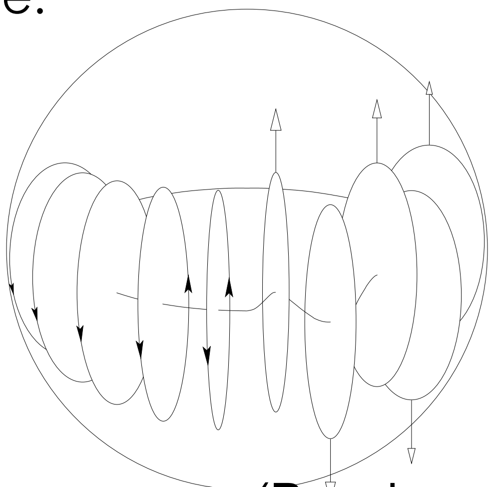
Second: 10-100 secs

- Turbulence dies out, NS relaxes to an MHD equilibrium.
- Big Q.: **What is the stable B-field structure of fluid stars?**
- B-field must be a combination of toroidal and poloidal field, otherwise unstable



- Pure toroidal is unstable to sausage instability:
- Pure poloidal is also unstable:

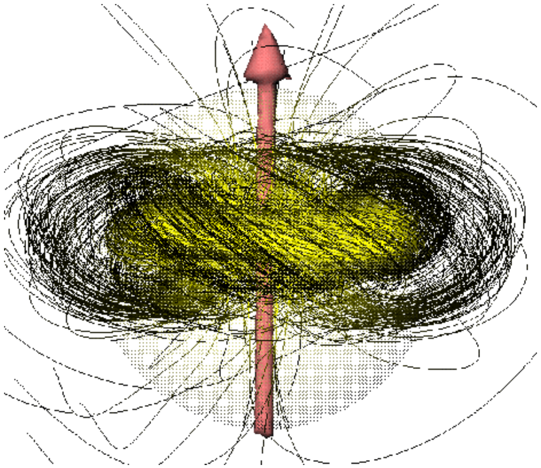




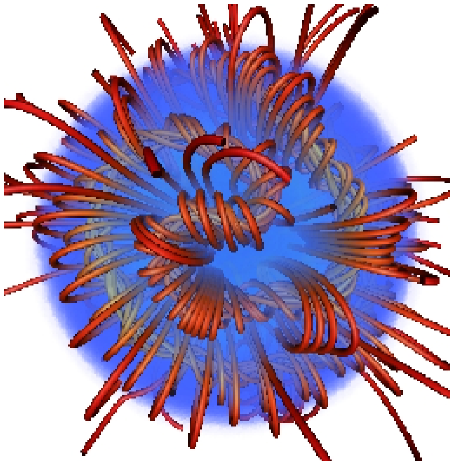
(Prendergast, Fawley & Ruderman, Braithwaite, Lander and Jones)

Stability! (?)

- Braithwaite & Spruit:



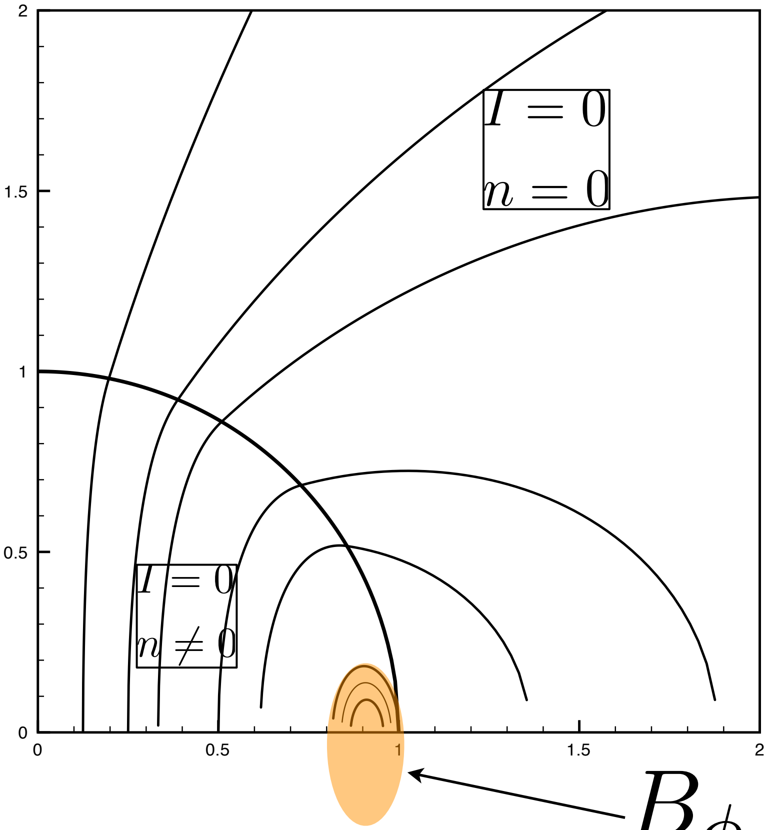
Large initial toroidal flux



Small initial toroidal flux

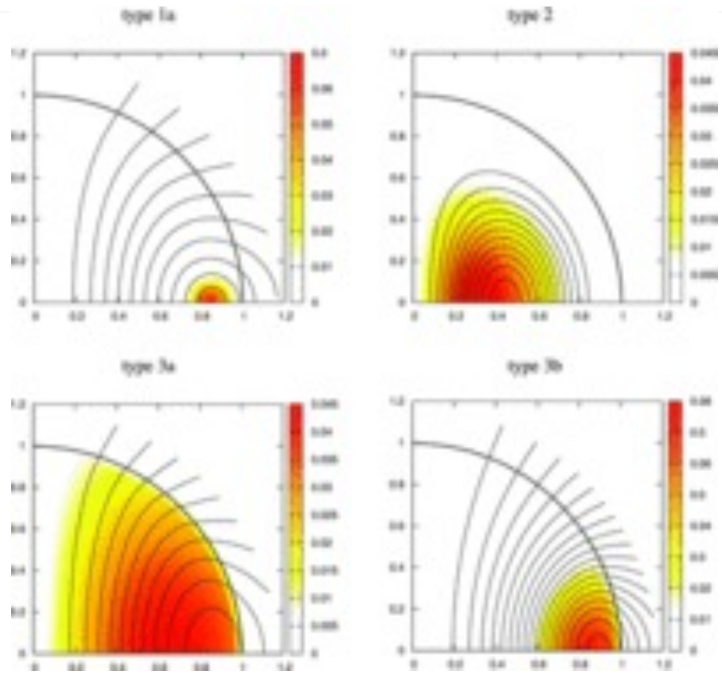
- Similar toroidal and poloidal fluxes needed for stability
- Lander and Jones: any barotropic $(p(\rho))$ B-field equilibrium is unstable - need $p(\rho, \epsilon)$ (?)

For stability B-field must be linked



$B_\phi \neq 0$

Lyutikov



Lander & Jones

- Similar toroidal and poloidal fluxes needed

- Smaller volume for toroidal: toroidal field can be locally >> poloidal (e.g. 10^{16} in magnetars)

@ 100 secs crust freezes

- no shear stresses at freezing (was fluid)
- ***Electron MHD:***
  - After freezing ions form a fixed lattice
  - electrons flow as fluid, J = - n e v
  - B-field frozen into electrons:

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{ne} \times \mathbf{B}, \ \ \mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{B}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\frac{c}{4\pi e} \nabla \times \left(\frac{\nabla \times \mathbf{B}}{n} \times \mathbf{B} \right)$$

- Electrons flow as an inertialess fluid

MHD equilibrium is, generally, not EMHD equilibrium

- MHD: $\mathbf{J} \times \mathbf{B} = \nabla p + \rho \nabla \Phi$
- EMHD: $\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{ne} \times \mathbf{B}$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{\rho} = -\frac{\nabla p \times \nabla \rho}{\rho^2}$$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{n} = 0$$

MHD equilibrium is, generally, not EMHD equilibrium

- MHD: $\mathbf{J} \times \mathbf{B} = \nabla p + \rho \nabla \Phi$
- EMHD: $\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{ne} \times \mathbf{B}$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{\rho} = -\frac{\nabla p \times \nabla \rho}{\rho^2}$$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{n} = 0$$

Non-barotropic EoS

MHD equilibrium is, generally, not EMHD equilibrium

- MHD: $\mathbf{J} \times \mathbf{B} = \nabla p + \rho \nabla \Phi$
- EMHD: $\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{ne} \times \mathbf{B}$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{\rho} = -\frac{\nabla p \times \nabla \rho}{\rho^2}$$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{n} = 0$$

mu-gradient

Non-barotropic EoS

MHD equilibrium is, generally, not EMHD equilibrium

- MHD: $\mathbf{J} \times \mathbf{B} = \nabla p + \rho \nabla \Phi$
- EMHD: $\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \frac{\mathbf{J}}{ne} \times \mathbf{B}$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{\rho} = -\frac{\nabla p \times \nabla \rho}{\rho^2}$$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{n} = 0$$

mu-gradient

Non-barotropic EoS

Freezing of MHD equilibrium results in non-equilibrium EMHD state

MHD equilibrium is, generally, not EMHD equilibrium

- MHD: $\mathbf{J} \times \mathbf{B} = \nabla p + \rho \nabla \Phi$

- EMHD: $\mathbf{E} = -\mathbf{v} \times \mathbf{B} = \dfrac{\mathbf{J}}{ne} \times \mathbf{B}$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{\rho} = -\frac{\nabla p \times \nabla \rho}{\rho^2}$$

$$\nabla \times \frac{\mathbf{J} \times \mathbf{B}}{n} = 0$$

mu-gradient

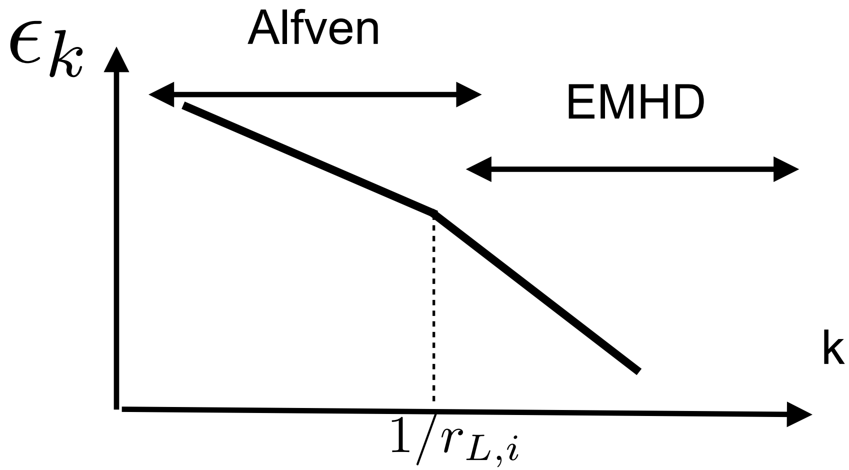
Non-barotropic EoS

Freezing of MHD equilibrium results in non-equilibrium EMHD state

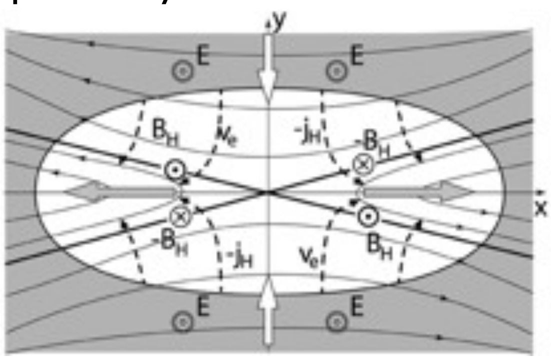
After freezing B-field starts evolving in the crust under EMHD conditions

Electron MHD: Very heavy ions, very light electrons $\omega_{B,e} \gg \omega \gg \omega_{B,i}$

- NS crusts
- Turbulent cascade in collisionless plasmas (Solar wind, BH magnetospheres, clusters of galaxies)



- sub-ion skin depth dynamics in reconnection layers



Electron MHD

- Normal modes: whistlers (Fully non-linear!)

$$\omega = c^2 k^2 |\cos\theta| \omega_B / \omega_p^2$$

- Energy and helicity conserved

$$\partial_t B^2/2 + \nabla \cdot (\mathbf{E} \times \mathbf{B}) = 0 \quad \partial_t (\mathbf{A} \cdot \mathbf{B}) = -\nabla \cdot (\mathbf{A} \times \dot{\mathbf{A}})$$

$$\mathbf{E} = \nabla \times \mathbf{B} \times \mathbf{B}$$

- Time scales

$$\tau_H = \frac{L^2 \omega_p^2}{c^2 \omega_B} \approx 100\,\mathrm{yrs} \left(\frac{L}{1\,\mathrm{km}} \right)^2 \rho_{10} b_{15}^{-1}\,\mathrm{yr}$$

- can vary from ~ 1yr for small patches near the surface, to 1Mys at the base of the crust for magnetars

Quo Vadis: are there stable/attractors configurations in EMHD?

Stability of EMHD configurations

- RT-type instability: the system can decrease it energy internally
  - the energy principle - reaching a special state with min E.
  - MHD
- KH-type instability: energy of the system does not change, re-distributed to “other” modes
  - incompressible fluid - no special state
  - turbulence - transferring energy to small scales and dissipating

EMHD: no energy principle

- Whistlers do no work (infinitely stiff lattice, no dynamo in EMHD)

$$\mathbf{v} \cdot \mathbf{j} \times \mathbf{B} \propto \mathbf{j} \cdot \mathbf{j} \times \mathbf{B} = 0.$$

- (in MHD $\mathbf{v} \cdot \mathbf{j} \times \mathbf{B} \neq 0$)
- **There is no energy principle in EMHD: cannot change energy internally**

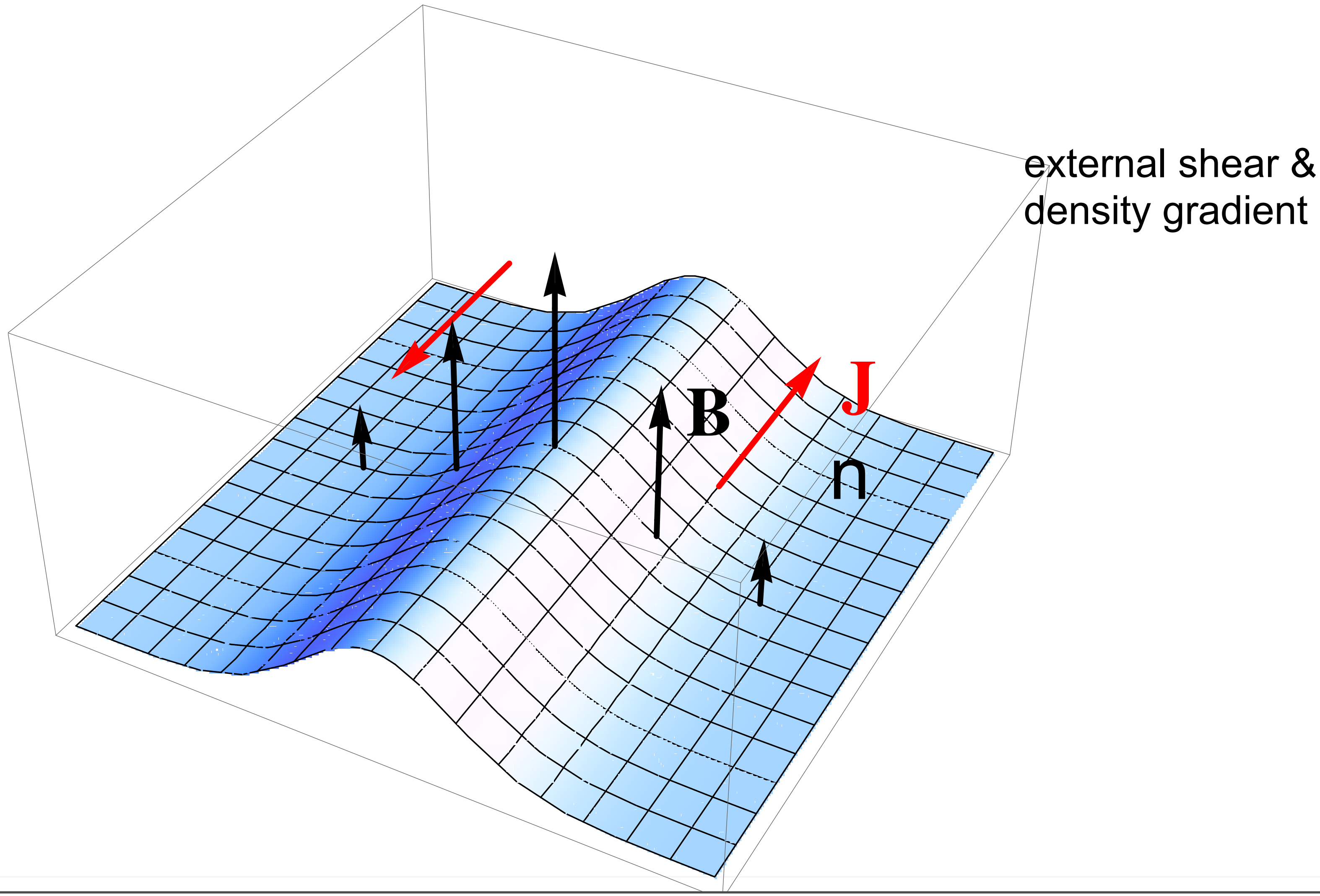
$$(\omega - \omega^*) \int dV \, \mathbf{B} \cdot (\xi \times \xi^*) = 0$$ (even with varying density)

$\omega = \omega^*$ - neutrally stable

unless $\mathbf{B} \cdot (\xi \times \xi^*) = 0$

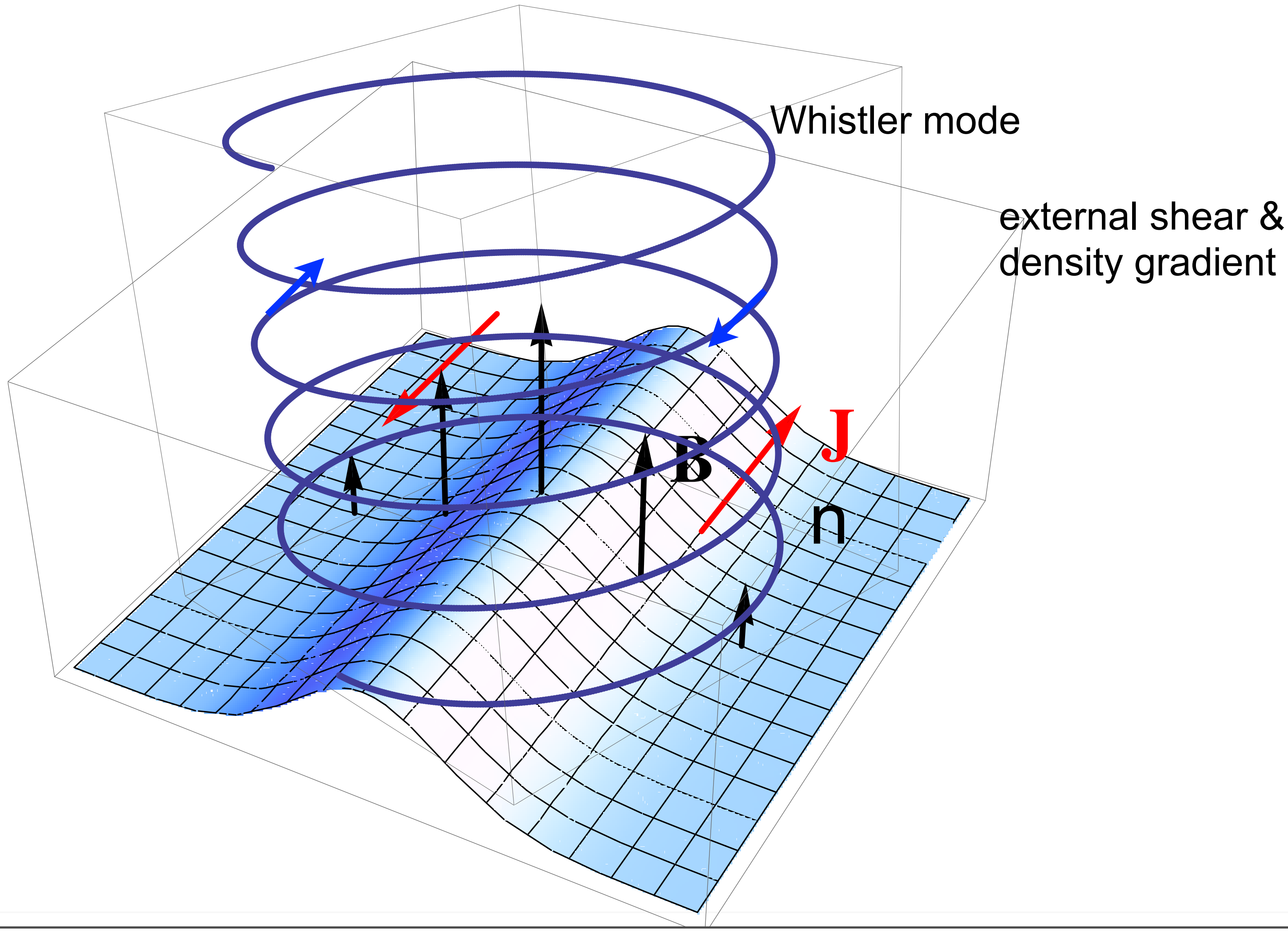
Wood, Hollerbach, Lyutikov, 2014

KH-like instability in EMHD



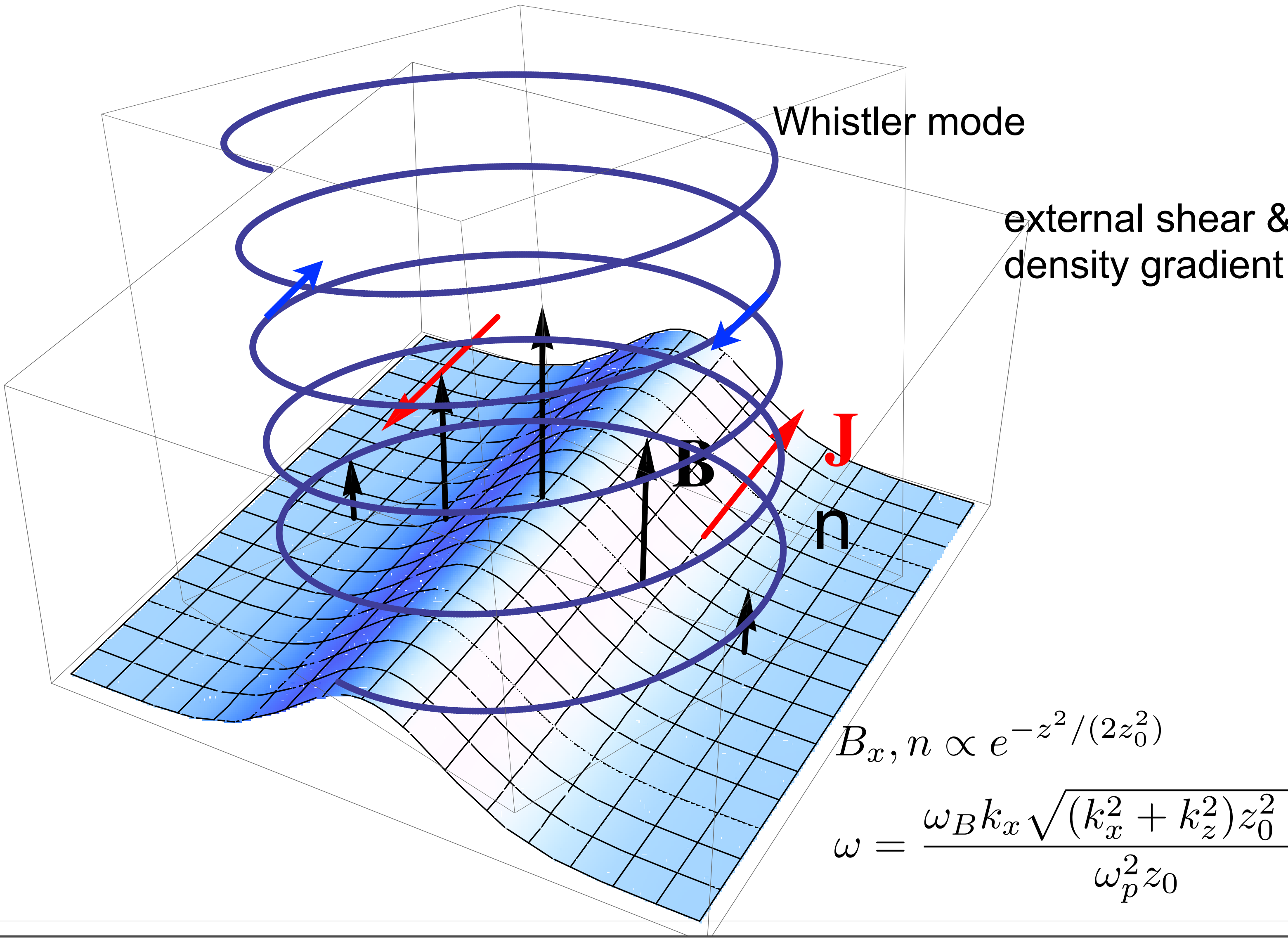
Wood, Hollerbach, Lyutikov, 2014

KH-like instability in EMHD



Wood, Hollerbach, Lyutikov, 2014

KH-like instability in EMHD

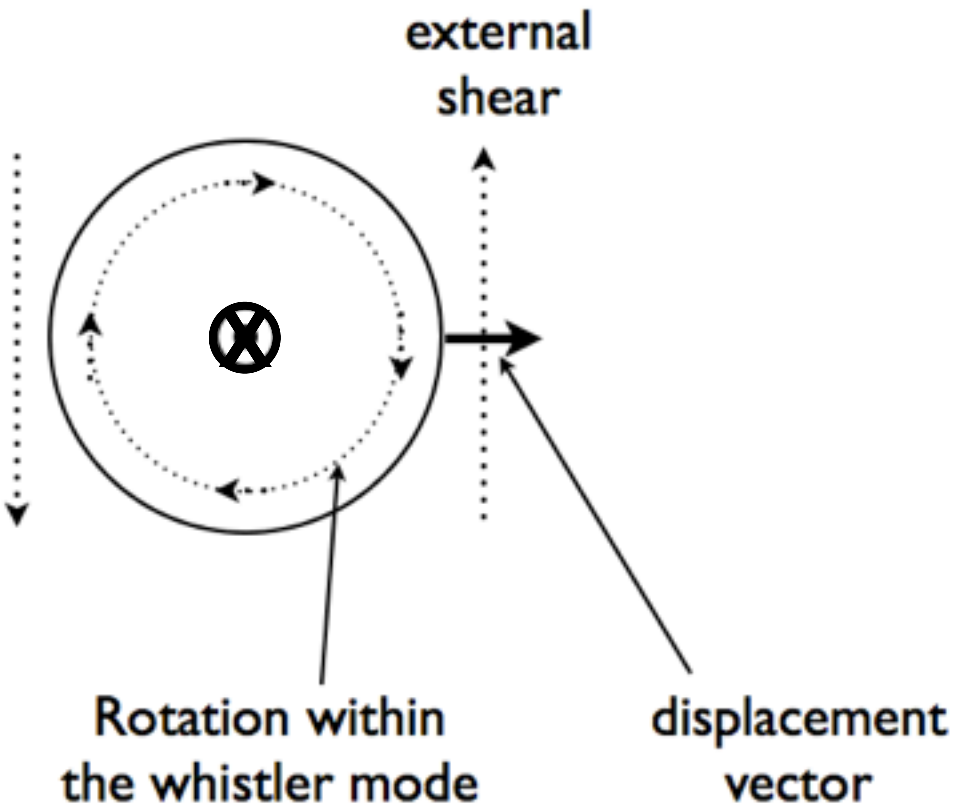


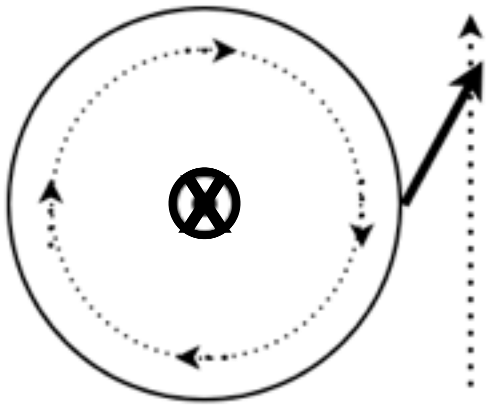
$$B_x, n \propto e^{-z^2/(2z_0^2)}$$

$$\omega = \frac{\omega_B k_x \sqrt{(k_x^2 + k_z^2) z_0^2 - 1}}{\omega_p^2 z_0}$$

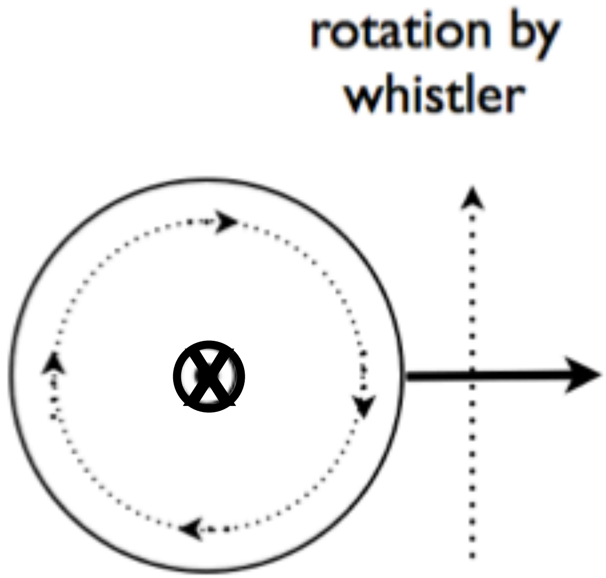
Density-shear instability in electron MHD

- Driven **both** by B-field **and** density gradients
  - driven by $$\frac{B'}{B}\frac{n'}{n} > 0$$
  - need $L_n \le L_B$
  - $k_{||} L_B < 1$
  - growth rate ~ Hall time scale


external
shear
Rotation within
the whistler mode
displacement
vector


stretching by
external shear

$$\mathbf{B} \cdot (\xi \times \xi^*) = 0$$



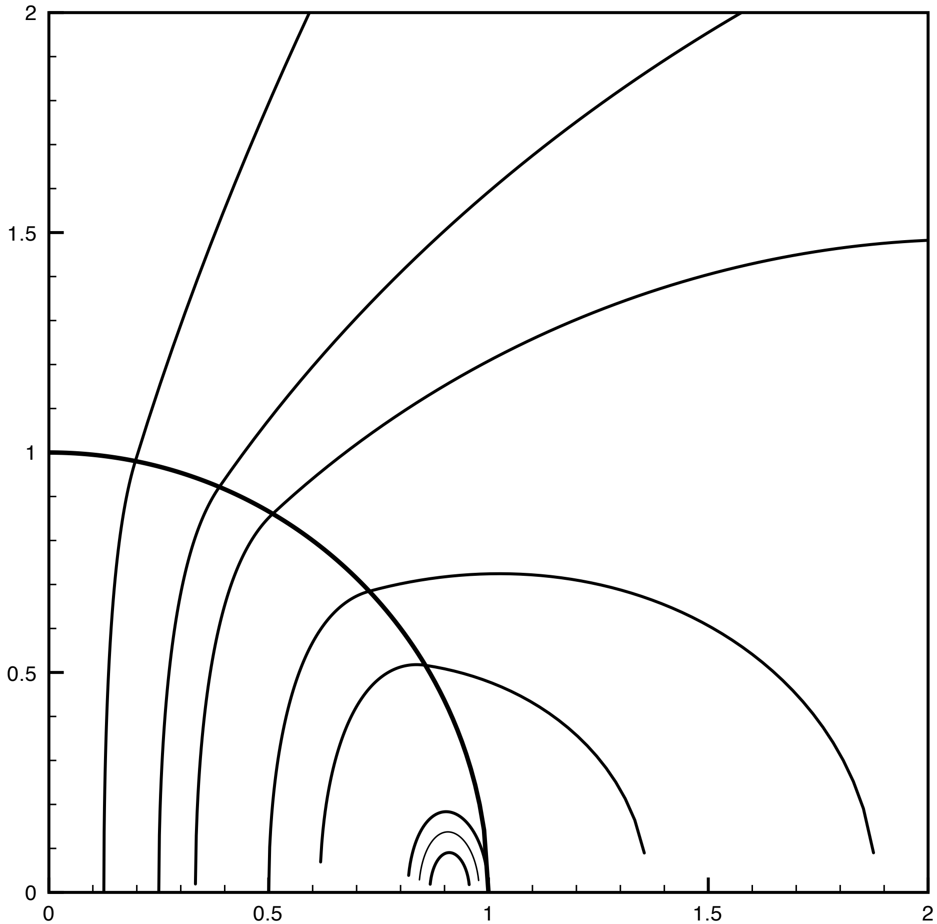
Shearing instability of EMHD

- Shear against rotation in whistler mode, v'<0

$$k_{\mathrm{along\,B}} \leq 1/L_{\perp\,\mathrm{B}}$$

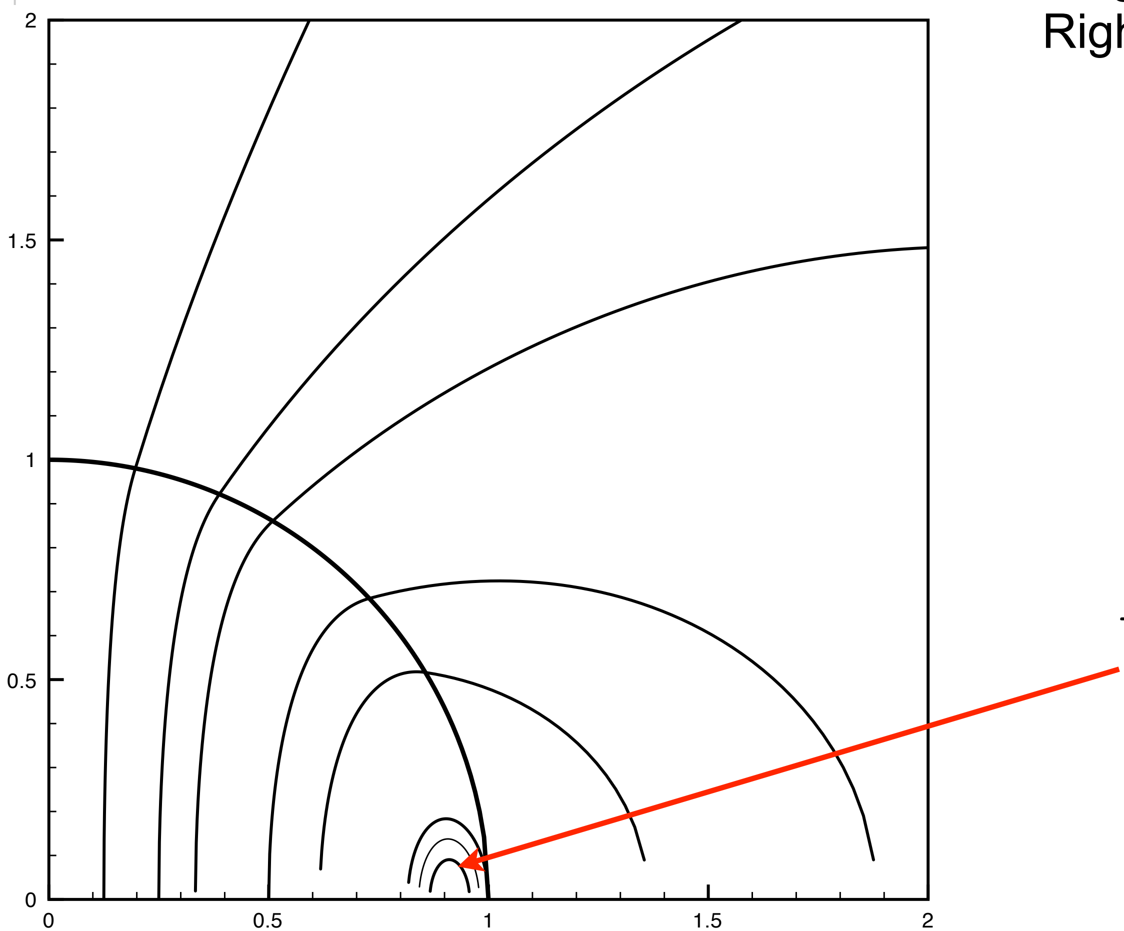
- circular - elliptic - linear - instability

Density-shear instability in NSs



Large B-field (fast evolution)
Right conditions for instability

Density-shear instability in NSs



Large B-field (fast evolution)
Right conditions for instability

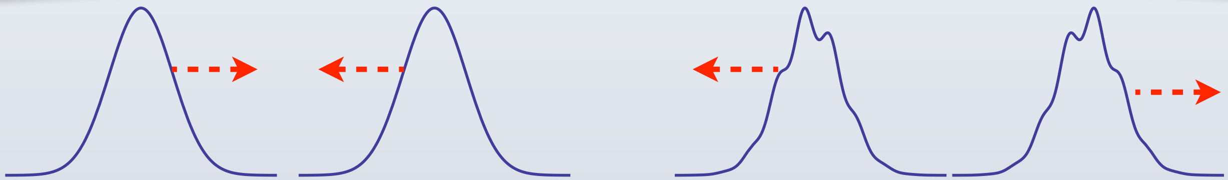
$B_z(r),\, n(r)$

Sidetrack: EMHD turbulence

- Unstable whistlers launched in the crust: non-linear interaction?
- Whistler interaction is very different from Alfven waves
- Whistlers do not interact for
  - **co-linear propagation (including counter-propagating case)**
  - **$k_1 = k_2$, (but propagating in different directions)**

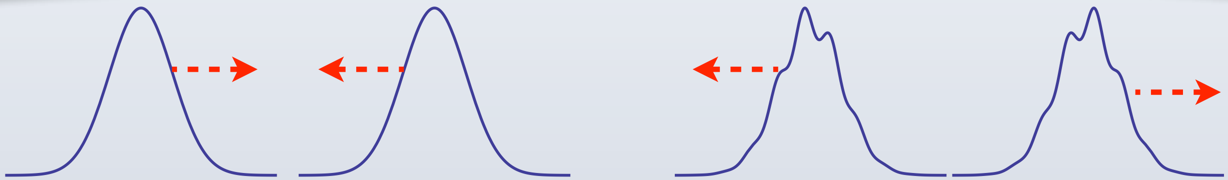
MHD & EMHD turbulence

- MHD: counter-propagating Alfven wave packets interact

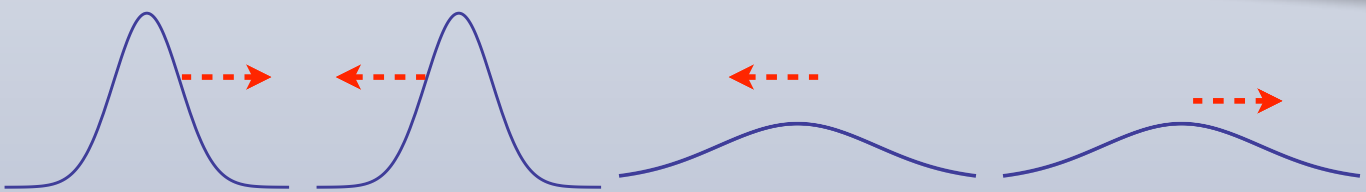


MHD & EMHD turbulence

- MHD: counter-propagating Alfven wave packets interact

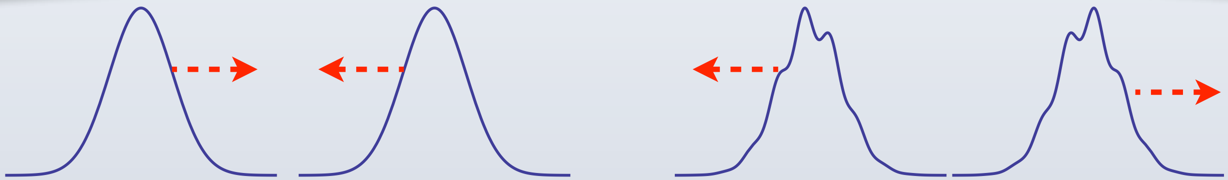


- EMHD: aligned-propagating wave packets do not interact, but spread

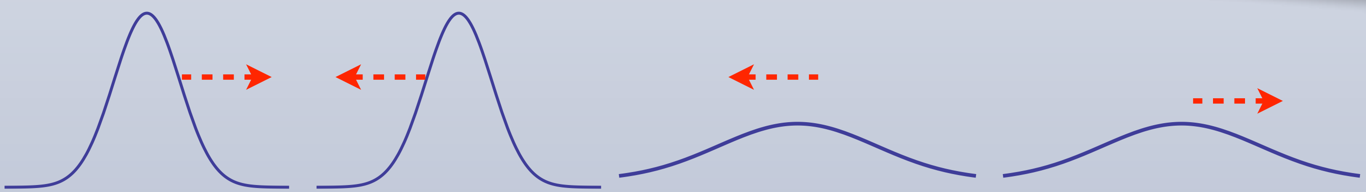


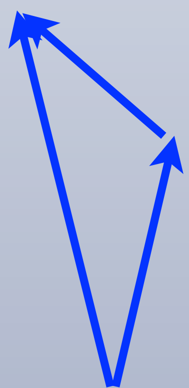
MHD & EMHD turbulence

- MHD: counter-propagating Alfven wave packets interact



- EMHD: aligned-propagating wave packets do not interact, but spread



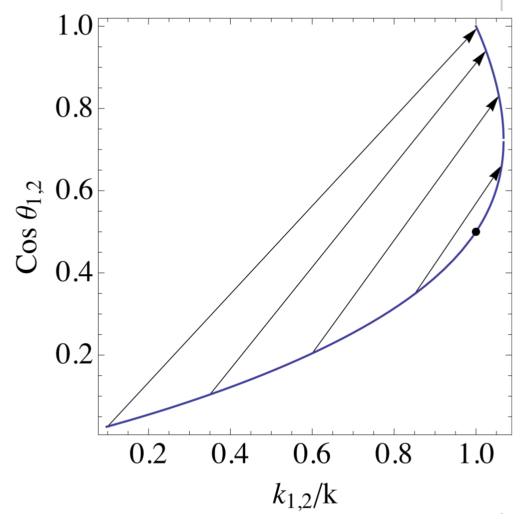


- non-aligned wave packets do interact via 3-wave, including with zero-mode

(Weak) EMHD turbulence: different from MHD

Lyutikov 2014

$$\partial_t n = \pi \int [|V_{0\leftrightarrow 1,2}|^2 f_{k\leftrightarrow 1,2}\delta(\mathbf{k}-\mathbf{k}_1-\mathbf{k}_2)\delta(\omega-\omega_1-\omega_2)+$$
$$2|V_{1\leftrightarrow k,2}|f_{1\leftrightarrow 0,2}\delta(\mathbf{k}_1-\mathbf{k}-\mathbf{k}_2)\delta(\omega_1-\omega-\omega_2)]\,d\mathbf{k}_1 d\mathbf{k}_2$$
$$f_{0\leftrightarrow 1,2} = n_1 n_2 - n(n_1+n_2)$$



- 3-way processes are important!
- simple decay favors highly oblique modes
- Very stiff: $\partial_t n \propto k^6$
- daughter modes have **very different k, theta**
- Non-universal - depends on the injection (coupled to MHD: perp. driving, freezing of MHD - quasi-isotropic driving)
- Quasi-isotropic (given enough time) - resonance condition couples very different angles and scales
  - transiently show anisotropy
- Remains weak
- -2 spectrum
- May not reach steady state at all

Quo Vadis: are there stable/attractors configurations in EMHD?

Stability of EMHD configurations

- RT-type instability: the system can decrease it energy internally
  - the energy principle - reaching a state with min E.
  - MHD
- KH-type instability: energy of the system does not change, re-distributed to “other” modes
  - incompressible fluid
  - turbulence - transferring energy to small scales and dissipating

Quo Vadis: are there stable/attractors configurations in EMHD?

Stability of EMHD configurations

- RT-type instability: the system can decrease it energy internally
  - the energy principle - reaching a state with min E.
  - MHD
- KH-type instability: energy of the system does not change, re-distributed to “other” modes
  - incompressible fluid
  - turbulence - transferring energy to small scales and dissipating

Quo Vadis: are there stable/attractors configurations in EMHD?

Stability of EMHD configurations

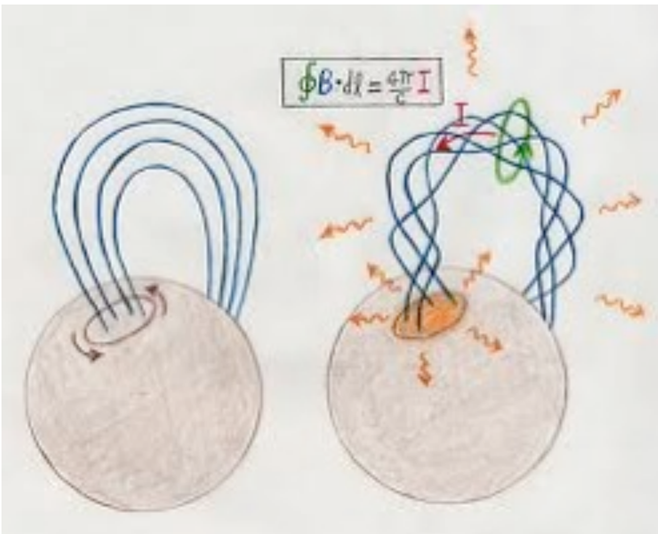
- RT-type instability: the system can decrease it energy internally
  - the energy principle - reaching a state with min E.
  - MHD
- KH-type instability: energy of the system does not change, re-distributed to “other” modes
  - incompressible fluid
  - turbulence - transferring energy to small scales and dissipating

Idealized plasma physics problem: NS crusts are different!

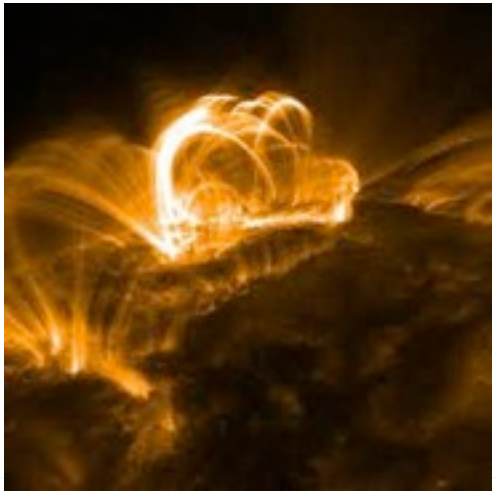
EMHD waves are dissipated by plastic deformations of the crust and production of bursts and flares

How magnetars work: Star-quakes vs Solar flares

- Thompson & Duncan: 100 msec ~ shear time scale
  - magnetic field strong enough can break the crust
  - sudden unwinding
  - dissipation in the magnetosphere
  - Needs crust to crack

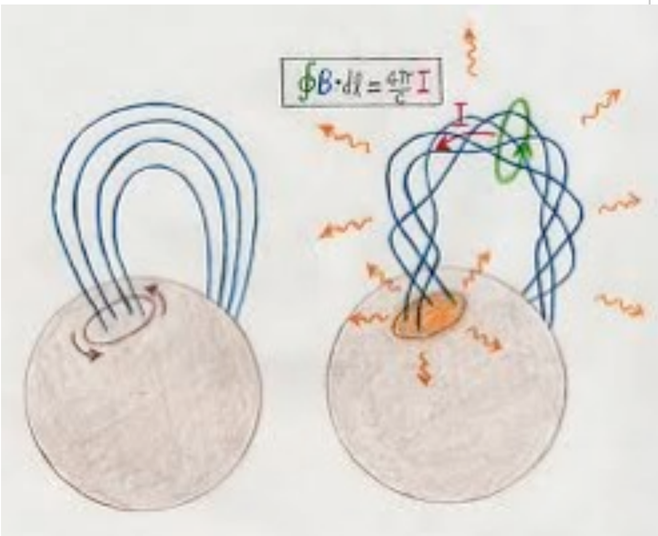


- Lyutikov: 100 mu-sec ~ Alfven time over the magnetosphere
- slow evolution of crustal fields twists outside field
- kink instability
- dissipation in the magnetosphere
- Crust can respond plastically (or can be infinitely rigid)



I. Star-quake (Thompson & Dunkan)

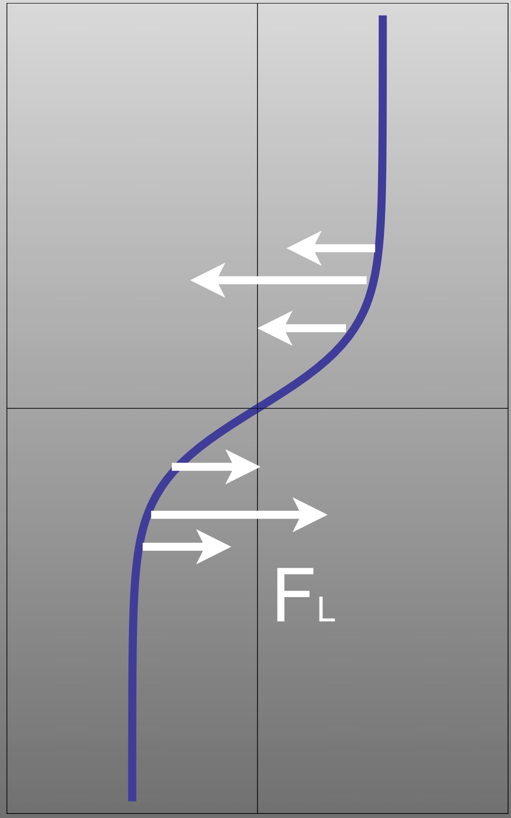
- Lorentz force $\mathbf{J} \times \mathbf{B}$ induced shear/strain in the NS crust.
- If that strain is larger than critical, the crust cracks
- Due to stratification - only rotation allowed.
- A plate rotates, twists the outside B-field - flare!
- Shear time scale, 100 msec (flare duration)
- Not clear if crust allows cracking (usually need shear velocity > sound not satisfied in NS crusts).

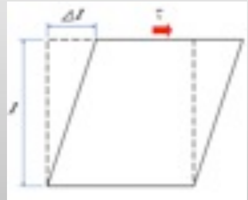


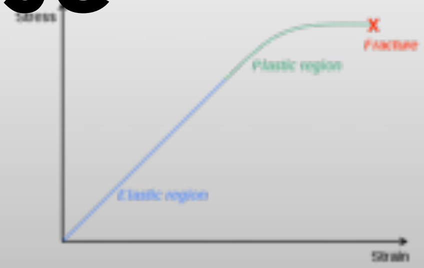
Assume the crust can crack

Levin & Lyutikov 2012: Even if plastic properties of the crust allow cracking, the release of the elastic energy in magnetic-induced crack is small

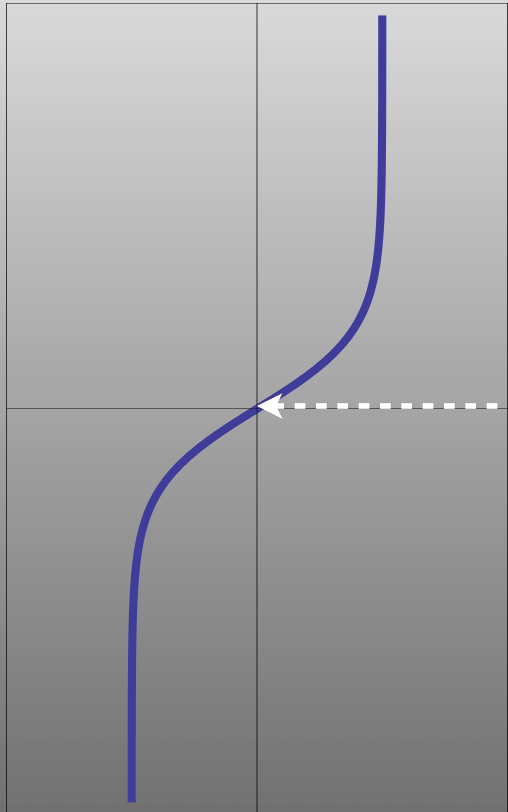
Seismic energy release

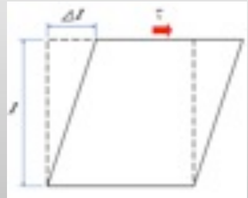


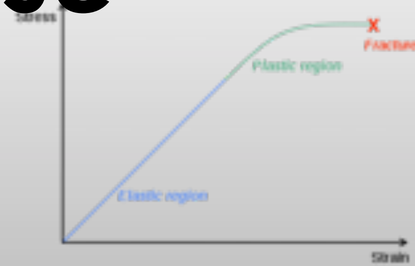




Seismic energy release



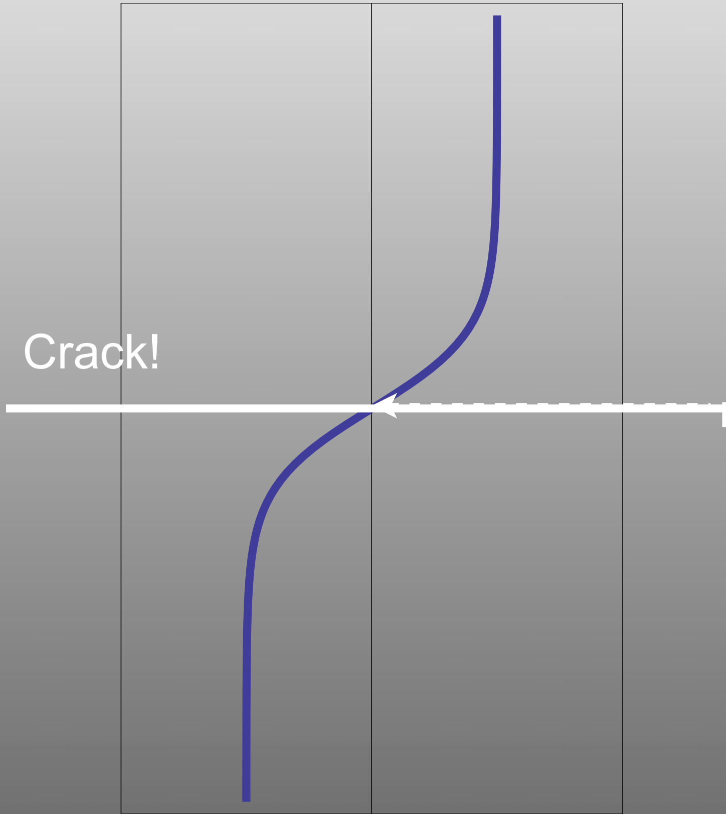


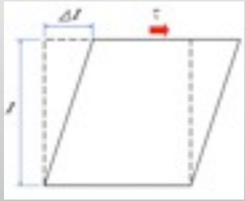


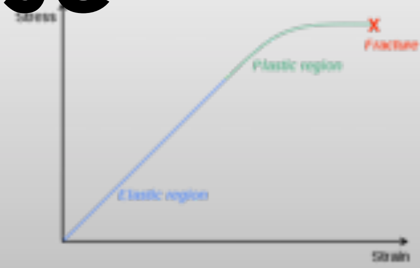
maximal stress

$$\sigma \to \max$$

Seismic energy release





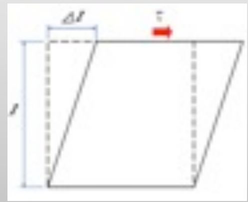


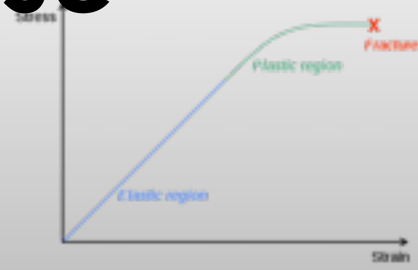
Crack!

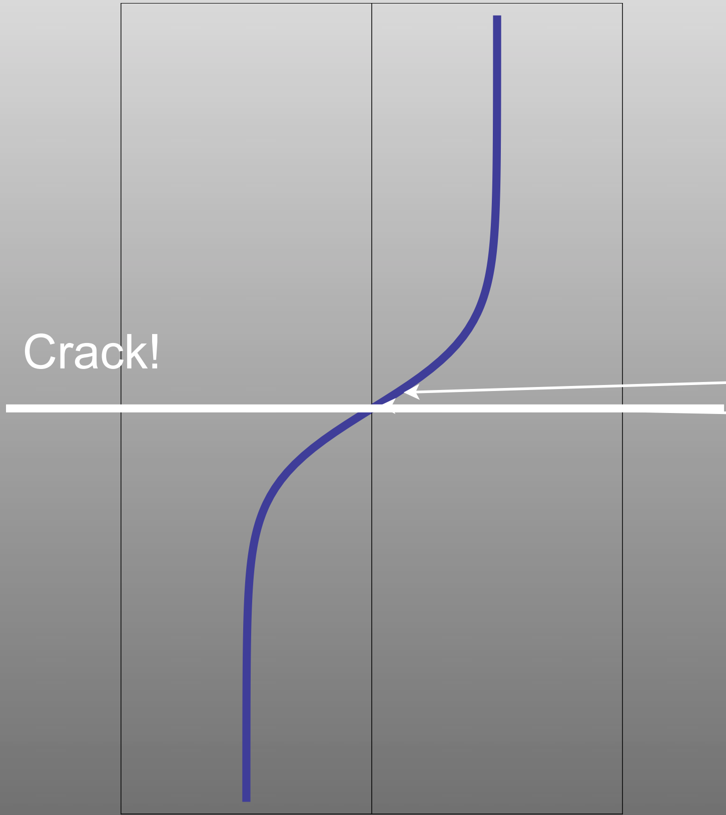
maximal stress

$$\sigma \rightarrow \max$$

Seismic energy release





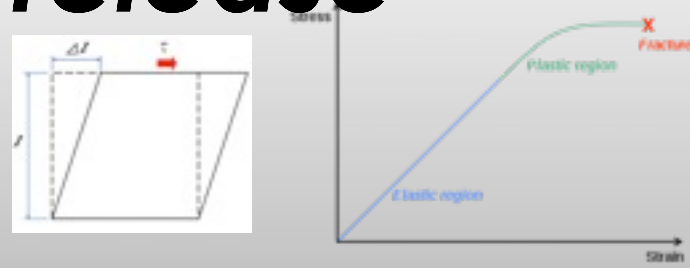


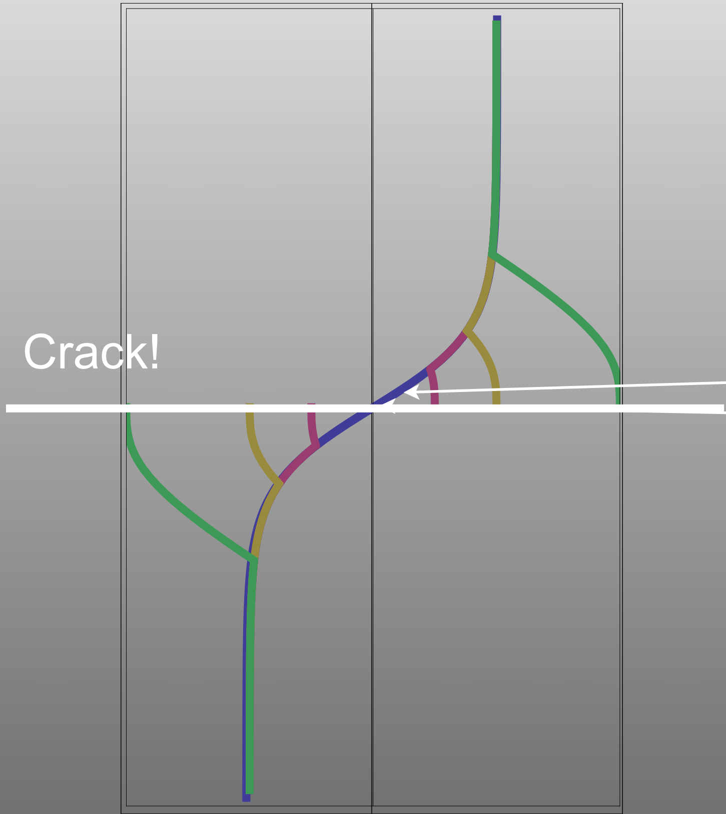
Large σ gradients

$$\sigma \neq 0$$

$$\sigma = 0$$

Seismic energy release



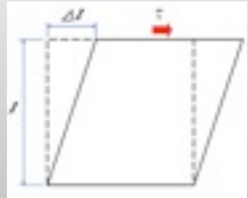


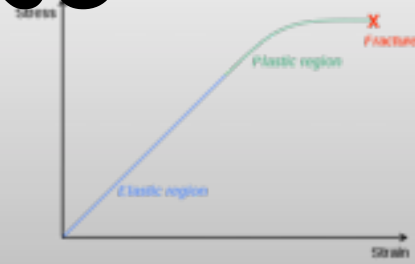
Large σ gradients

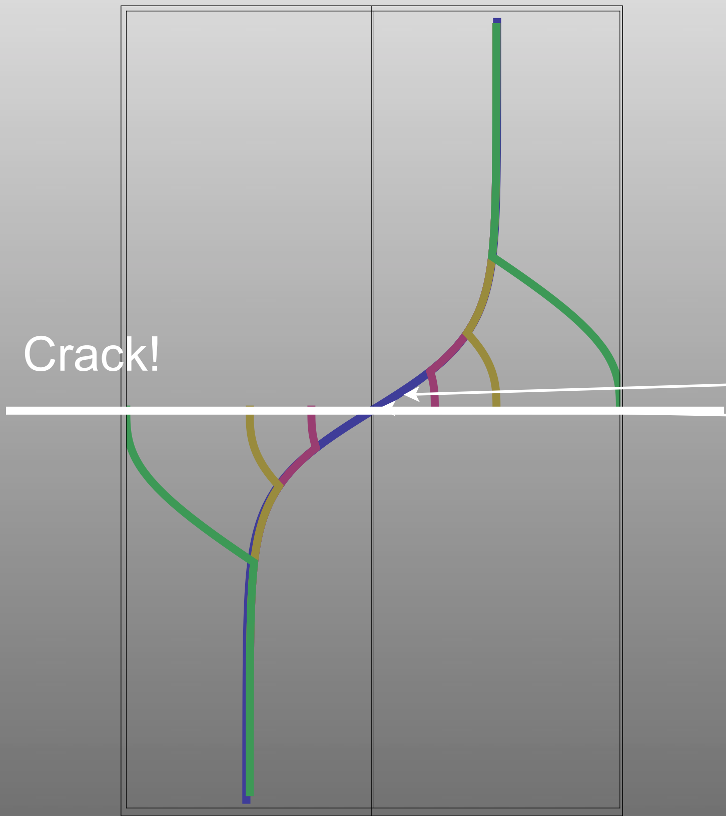
$$\sigma \neq 0$$

$$\sigma = 0$$

Seismic energy release







Large σ gradients

$$\sigma \neq 0$$

$$\sigma = 0$$

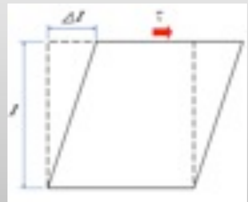
- Rarefaction wave propagates

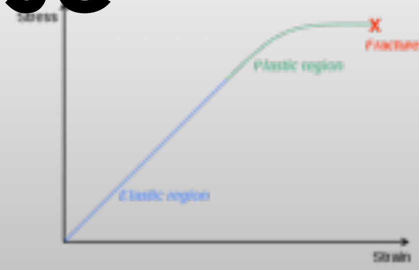
$$c_r = \sqrt{c_s^2 + v_A^2}$$

- finite velocity @ t=+0

-Seismic energy is released in waves

Seismic energy release

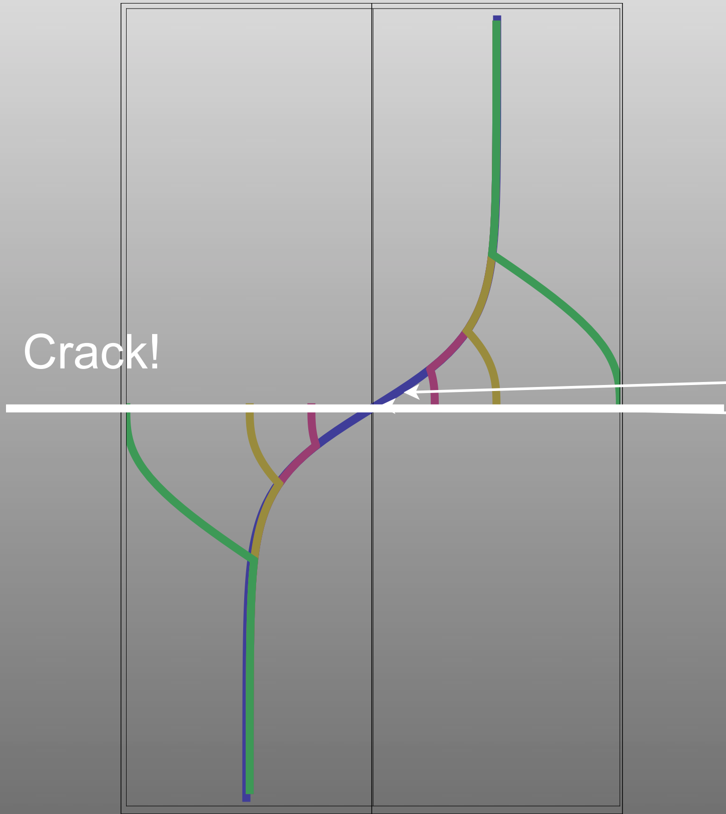




Large σ gradients

$$\sigma \neq 0$$

$$\sigma = 0$$



- Rarefaction wave propagates

$$c_r = \sqrt{c_s^2 + v_A^2}$$

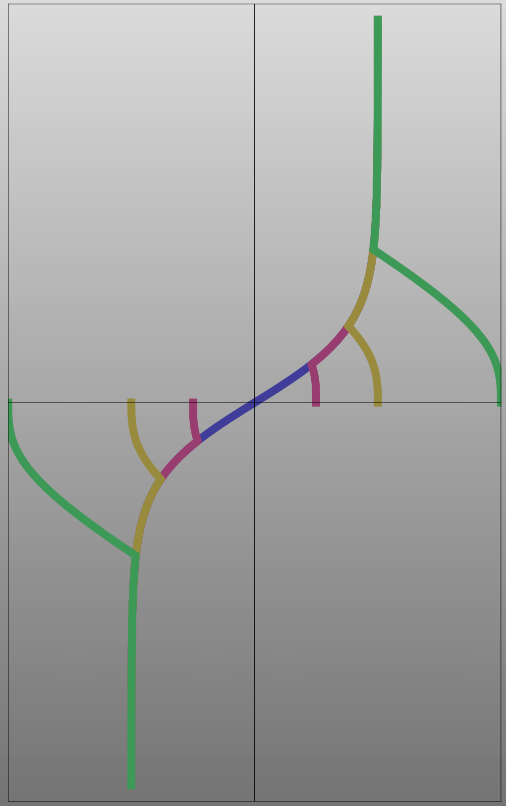
- finite velocity @ t=+0

-Seismic energy is released in waves

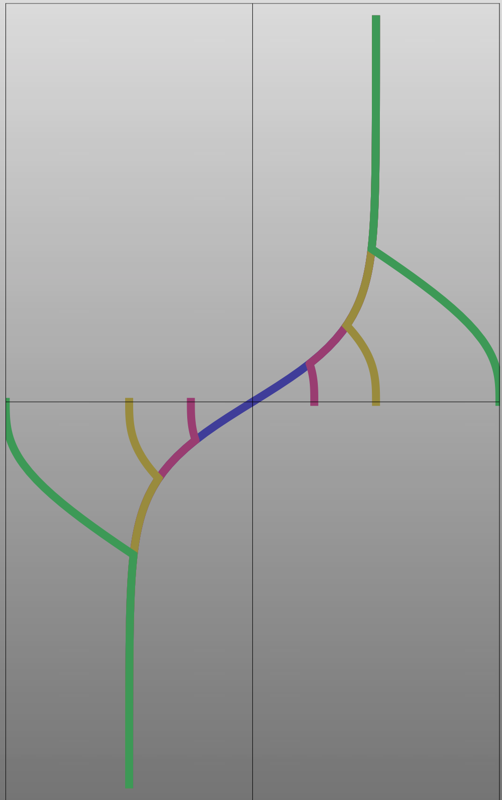
$$\zeta = \zeta_0(x) - (x - vt)\zeta_0'(0)$$

Magnetic cracking

Magnetic cracking

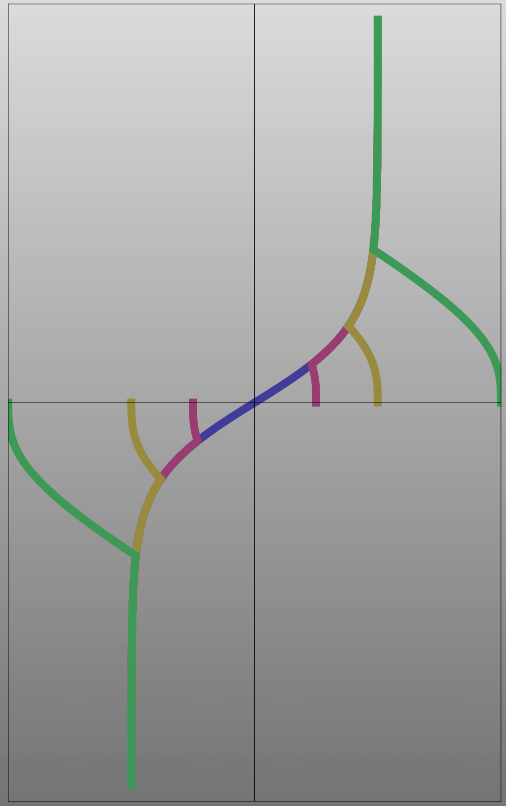


Magnetic cracking



B-field cannot do that!

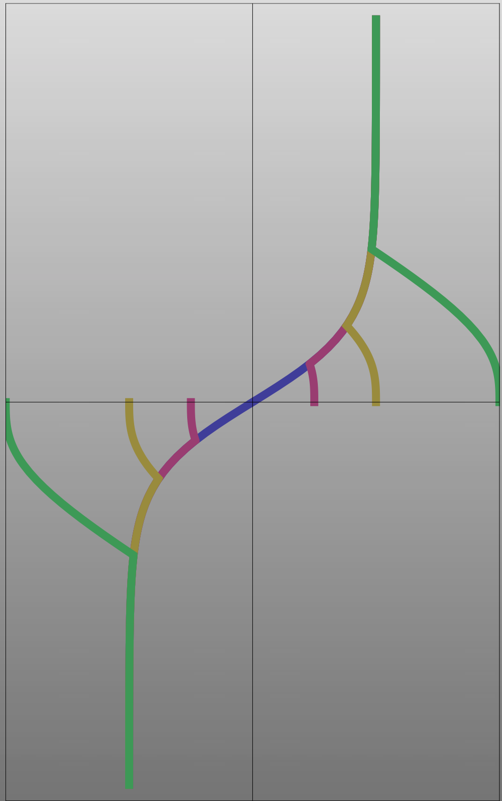
Magnetic cracking



B-field cannot do that!

Current sheet: jxB that stops the plates!

Magnetic cracking

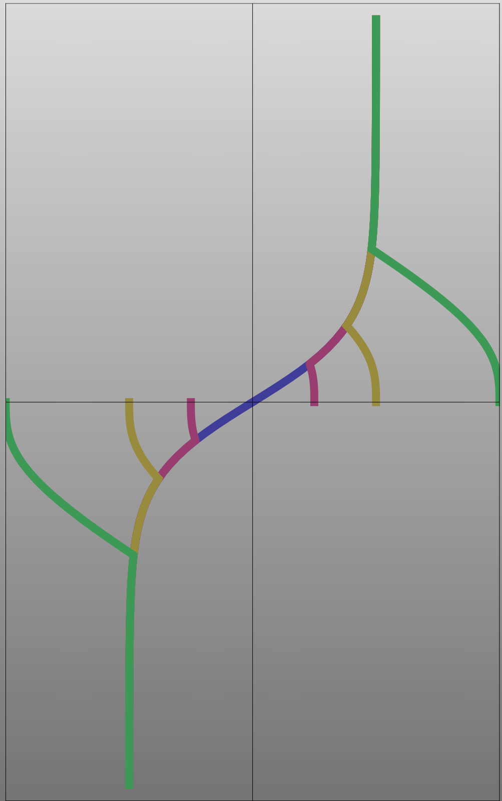


B-field cannot do that!

Current sheet: jxB that stops the plates!

$$\partial_t B_x = \partial_z(B_z v_x) = B_z v_0 \delta(z)$$

Magnetic cracking



B-field cannot do that!

Current sheet: jxB that stops the plates!

$$\partial_t B_x = \partial_z (B_z v_x) = B_z v_0 \delta(z)$$

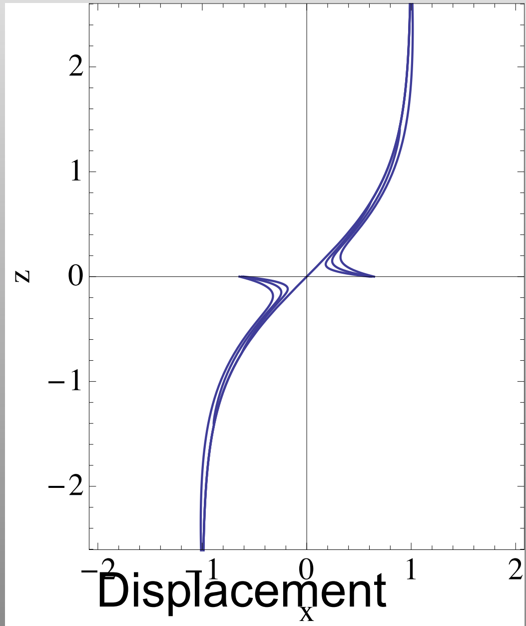
Additional condition: continuity of B-field.

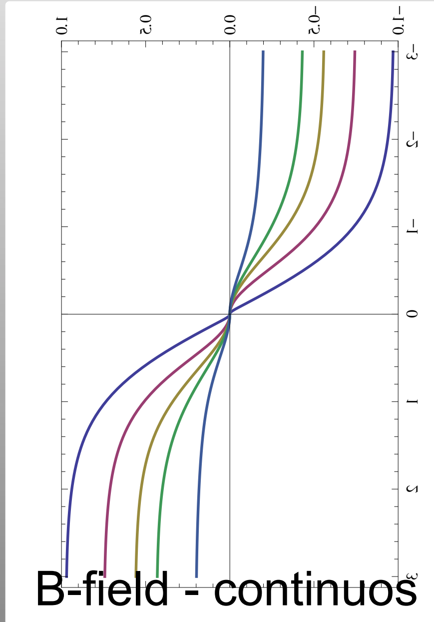
Resistivity!

$$\left(\partial_t - \eta \partial_z^2\right) \left(\partial_t^2 - c_s^2 \partial_z^2\right) \zeta = v_A^2 \partial_t \partial_z^2 \zeta$$

resistive wave   shear wave

Magnetic cracking





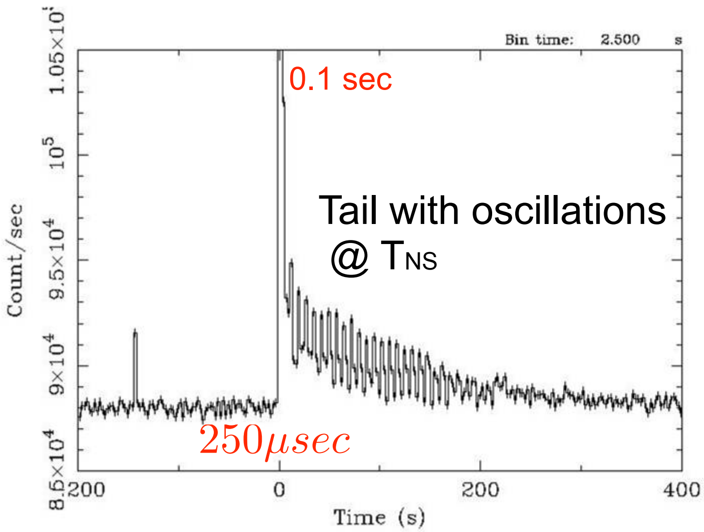
Amplitude of shear wave is negligibly small $\propto \sqrt{\eta}$

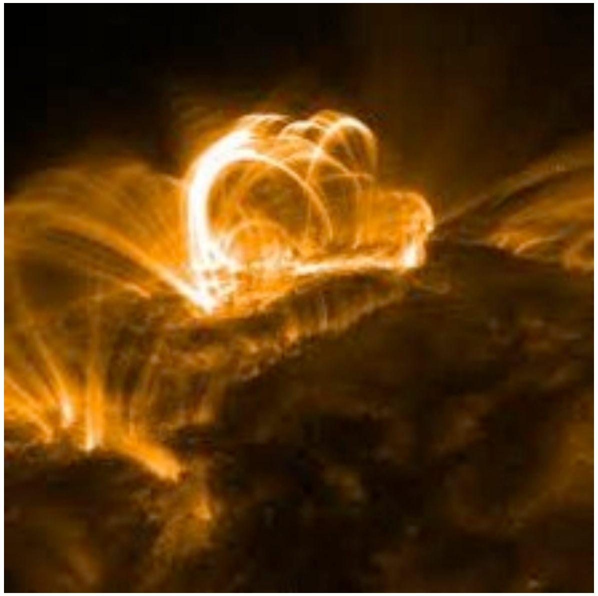
Even if crust allows cracking, the post-crack evolution proceeds on slow, resistive time-scale. Only B-field energy within the crack is released (not within the shear wave-affected volume).

Crack will evolve on resistive time scale $\Delta\xi \propto e^{-x^2/(\eta t)}$

II. Solar-flare-like events (Lyutikov 2004-2006)

- Lyutikov 2006: 100 mu-sec ~ Alfven time over the magnetosphere
  - slow EMHD evolution of crustal fields twists outside field
  - kink instability
  - dissipation in the magnetosphere
  - Crust can respond plastically (or can be infinitely rigid)





Plastic deformations of the crust

- **At low strain rates most materials respond plastically** (pure Al)
- plasticity controlled by lattice defects
- At low temperatures both the density of defects and their mobility is controlled by strain (Gillman)

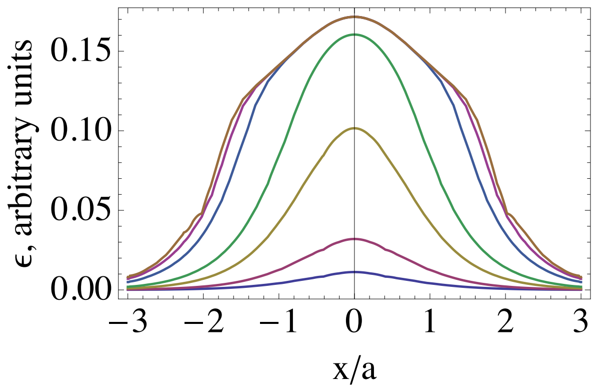
$$\rho_d = \left(\frac{\epsilon}{b}\right)^2 \quad \text{and} \quad v = c_s e^{-\epsilon_{crit}/\epsilon}$$

- terminal strain in the lattice

$$\epsilon_t \approx \frac{\epsilon_{crit}}{\ln\left(\frac{c_s t_H}{b}\right)} \approx 10^{-4}$$

- Reached within Maxwell time

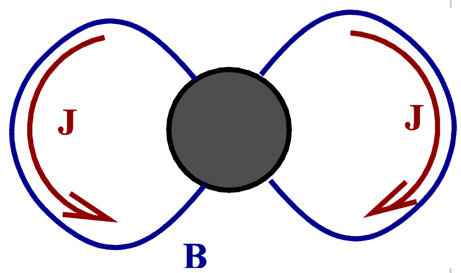
$$t_M \approx \epsilon_t t_H \approx \text{months} - \text{years}$$



B-field in the magentosphere: twisting by EMHD drift, resistive untwisting

- B-field in the crust evolves due to Hall drift
- Strain in the crust is plastically relieved - no cracking
- B-field outside is still twisted by the Hall drift

$$\tau_H = \frac{L^2 \omega_p^2}{c^2 \omega_B} \approx 100\,\mathrm{yrs} \left(\frac{L}{1\,\mathrm{km}}\right)^2 \rho_{10} b_{15}^{-1}\,\mathrm{yr}$$



- Twist = current -> dissipation
- If resistive time < Hall time: persistent emission

  $L_X \sim B^3$ - observable only in magnetars

$$B \sim r^{-2-p} F(\cos\theta), \quad 0 < p < 1$$

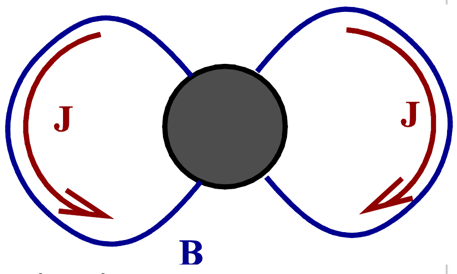
- If resistive time > Hall: flares
  - Small flares - medium B-fields
  - Giant flares - only in magnetars

Lyutikov 2014

B-field in the magentosphere: twisting by EMHD drift, resistive untwisting

- B-field in the crust evolves due to Hall drift
- Strain in the crust is plastically relieved - no cracking
- B-field outside is still twisted by the Hall drift

$$\tau_H = \frac{L^2 \omega_p^2}{c^2 \omega_B} \approx 100\,\mathrm{yrs} \left(\frac{L}{1\,\mathrm{km}} \right)^2 \rho_{10} b_{15}^{-1}\,\mathrm{yr}$$



- Twist = current -> dissipation
- If resistive time < Hall time: persistent emission $L_X \sim B^3$ - observable only in magnetars

$B \sim r^{-2-p} F(\cos\theta), \quad 0 < p < 1$

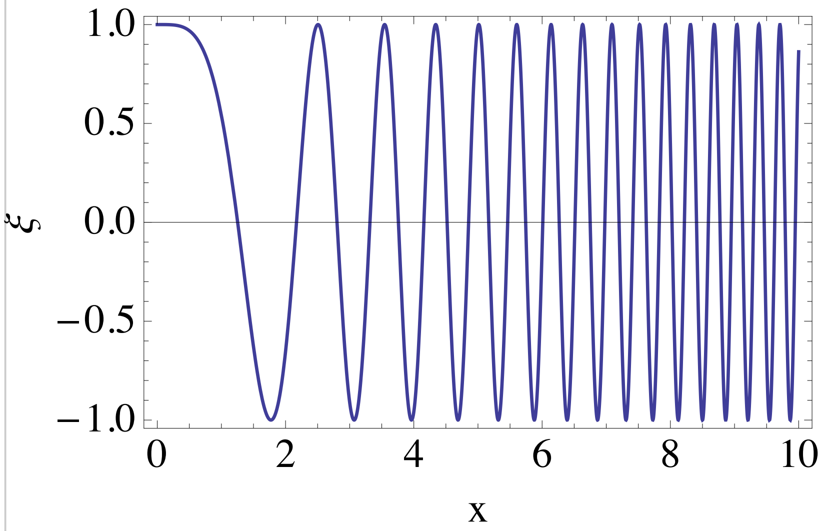
- If resistive time > Hall: flares
  - Small flares - medium B-fields
  - Giant flares - only in magnetars

Lyutikov 2014

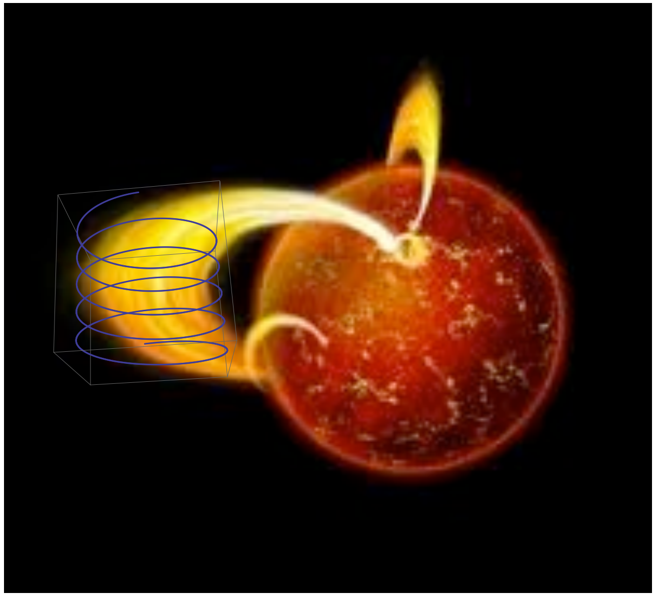
Flares are magnetospheric instabilitiesSome internal dissipation need

- Post-flare increase of surface emission (~ week): internal dissipation (Shultz et al.)
- "Cut" the flux tube: Alfven pulse reflects, launches whistler pulse

$$\partial_t \xi_e = i \frac{\omega_B c^2}{\omega_p^2} \xi_e''$$ Schrodinger eq.



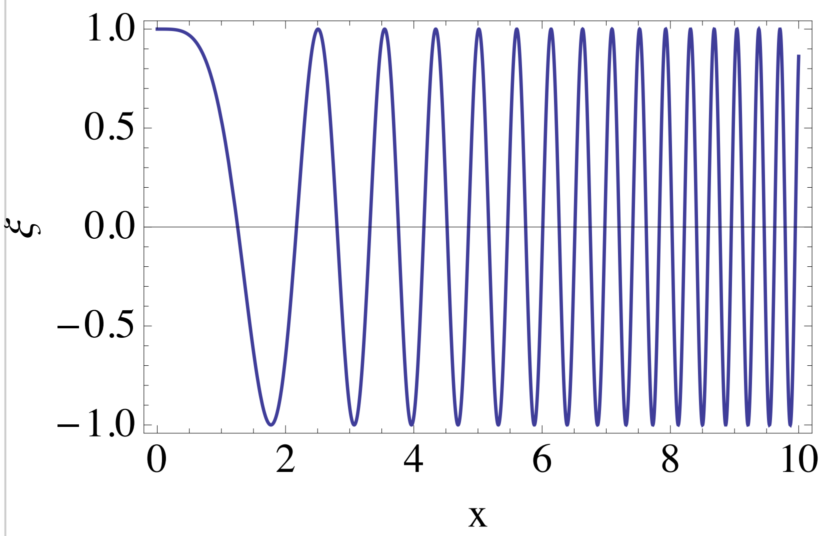
whistler's Green's function



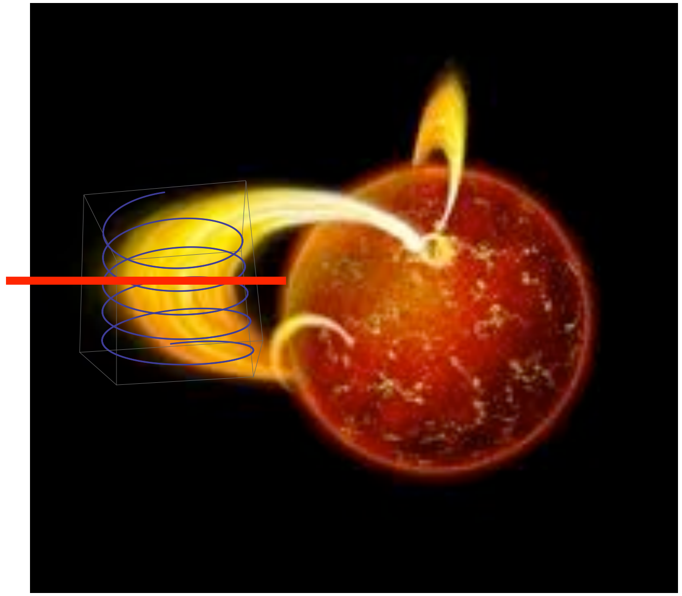
Flares are magnetospheric instabilitiesSome internal dissipation need

- Post-flare increase of surface emission (~ week): internal dissipation (Shultz et al.)
- “Cut” the flux tube: Alfven pulse reflects, launches whistler pulse

$$\partial_t \xi_e = i \frac{\omega_B c^2}{\omega_p^2} \xi_e''$$ Schrodinger eq.

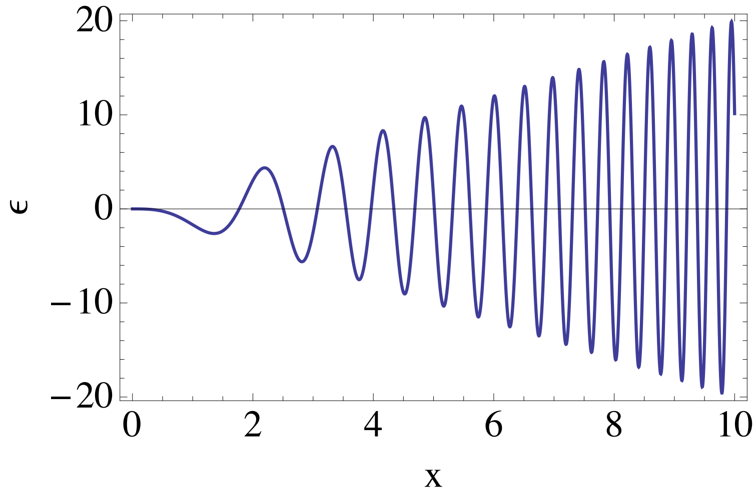


whistler’s Green’s function



Whistler dissipation in the crust

- Strain created by whistler pulse increase with distance



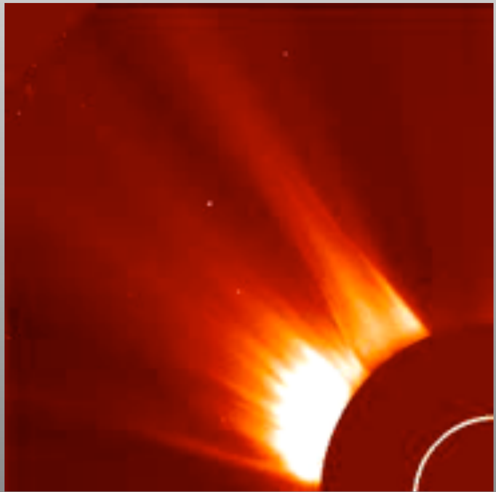
- more coherent at larger distances
- In addition: amplitude grows (smaller speed: larger B)

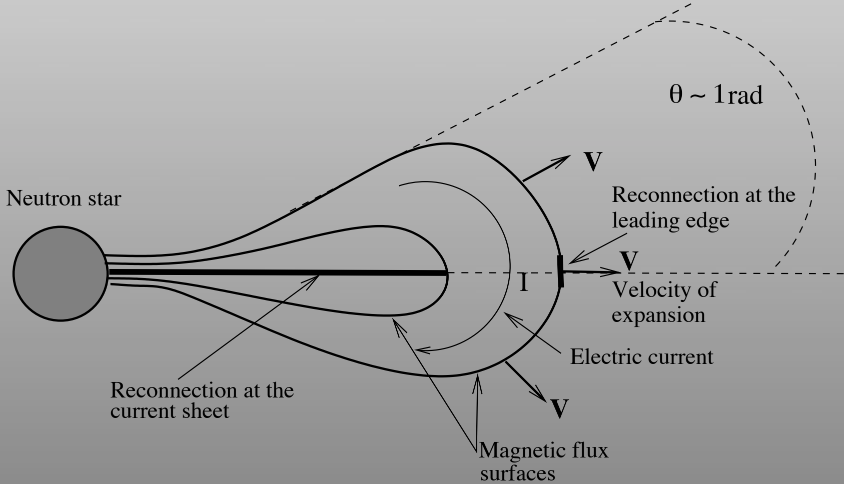
$$\delta B \propto n^{1/4}$$

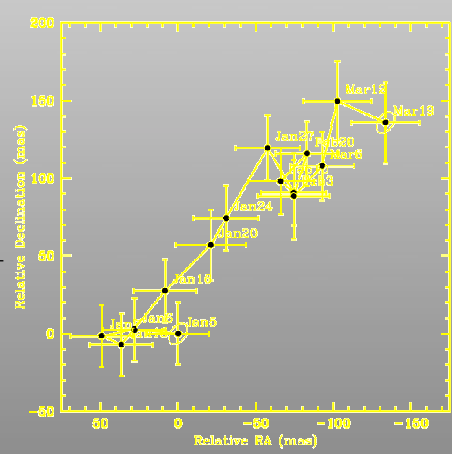
- Deep dissipation due to plasticity, at $\rho \sim 10^{10} \mathrm{g cm}^{-3}$, heat diffuses up to the surface in ~ week

CME model of giant flares

Lyutikov 2003, 2006

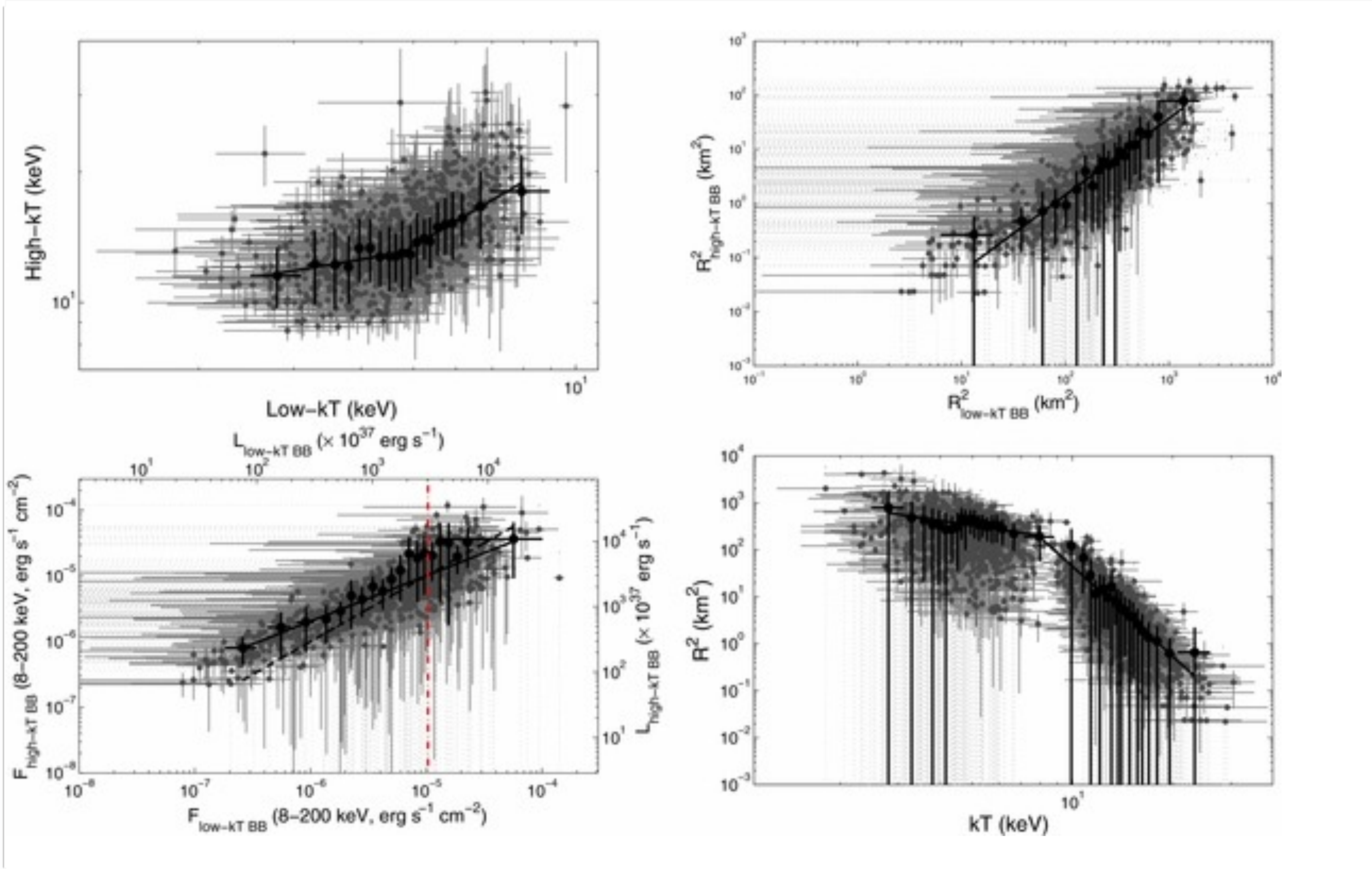






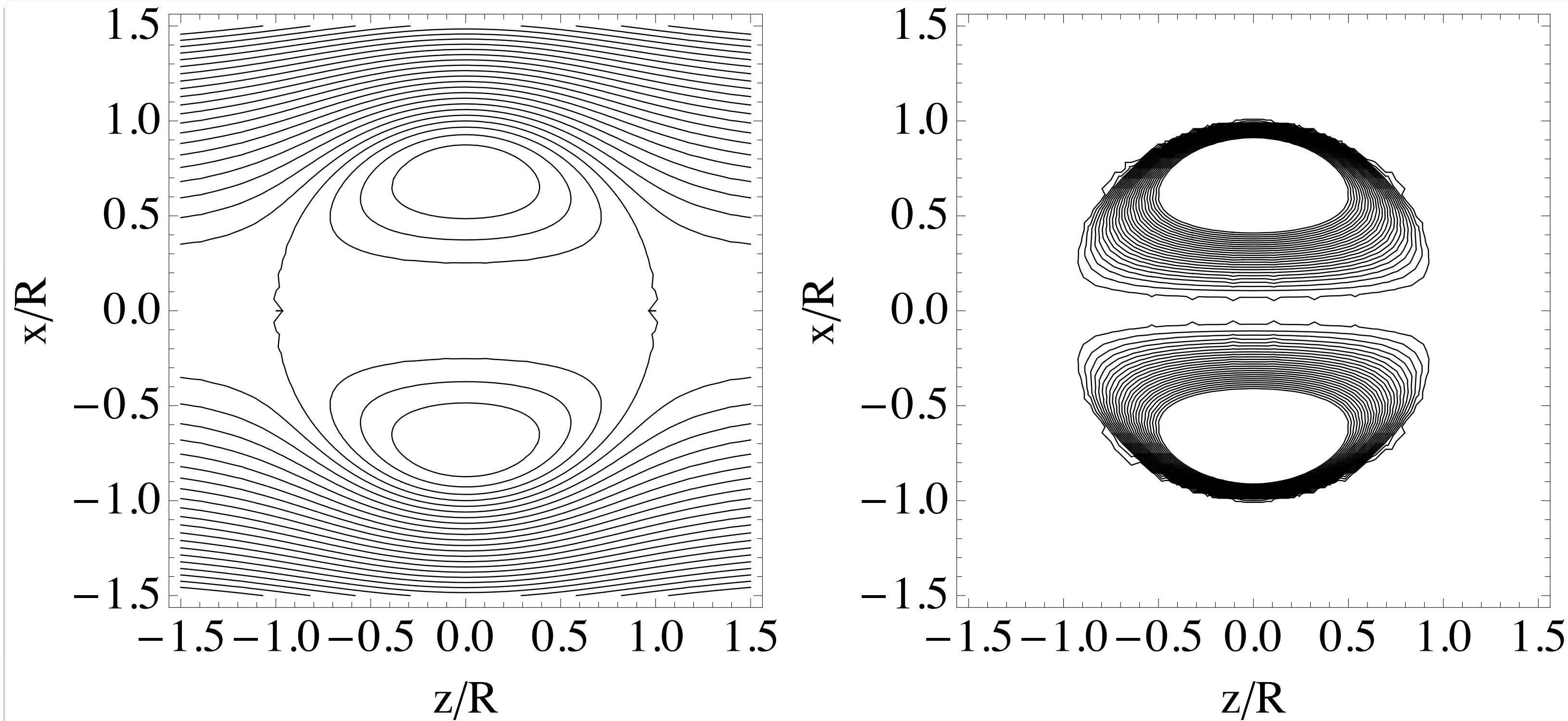
Magnetic bubble/flux rope expands, CME is ejected

Flares: Double-T, effective R>>R_{NS}



Monday, October 27, 14

Magnetically-trapped fireball



Trick: pressure, pressure derivative =0 on the surface

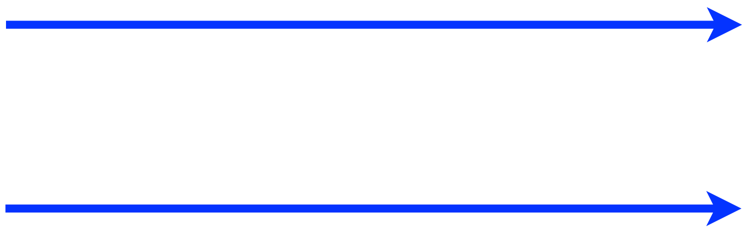
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar\omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q, \, \alpha = \hbar c / e^2$

- Pair plasma



Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar\omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q,\ \alpha = \hbar c / e^2$

- Pair plasma

repulsive

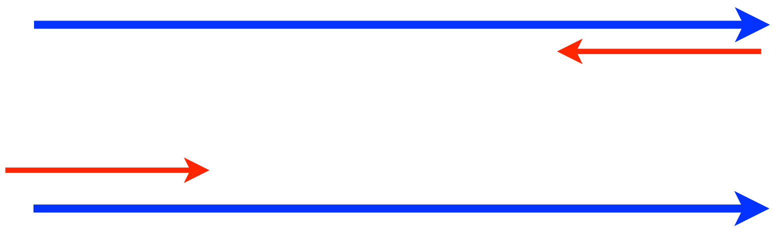
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar \omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q,\ \alpha = \hbar c / e^2$

- Pair plasma



repulsive

Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar\omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q,\ \alpha = \hbar c/e^2$

- Pair plasma

repulsive

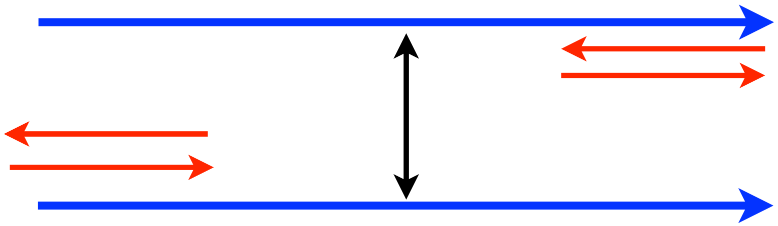
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar \omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q, \, \alpha = \hbar c / e^2$

- Pair plasma



repulsive

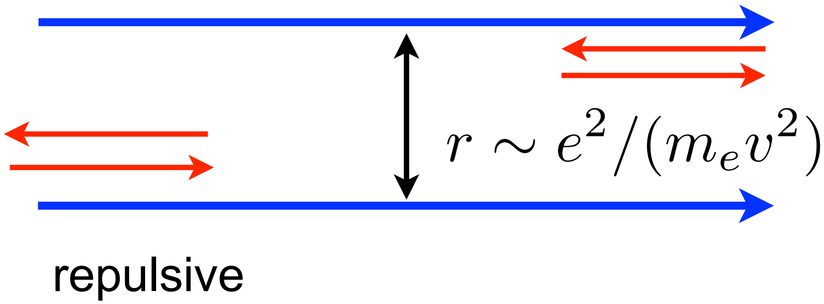
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar \omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q$, $\alpha = \hbar c / e^2$

- Pair plasma



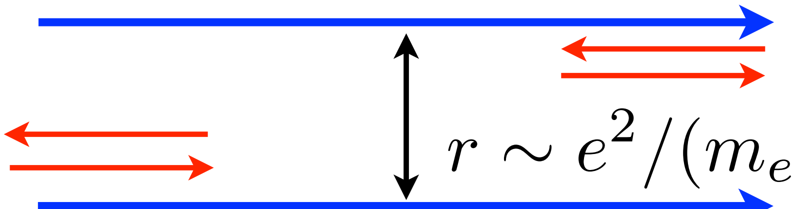
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar\omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q,\ \alpha = \hbar c/e^2$

- Pair plasma



$$r \sim e^2/(m_e v^2) \to r_D \sim v_T/\omega_p \gg e^2/T$$

repulsive

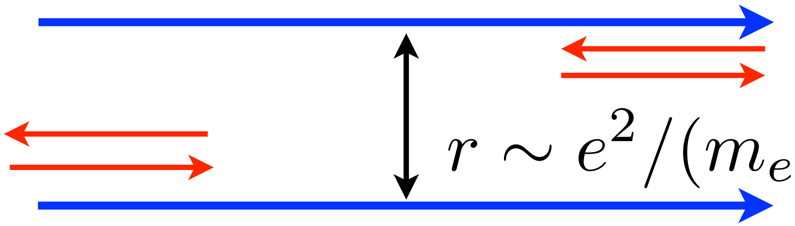
Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- $k_B T \ll \hbar \omega_B$ all particles on lowest Landau levels

  $B > \alpha B_Q, \, \alpha = \hbar c / e^2$

- Pair plasma



$$r \sim e^2/(m_e v^2) \to r_D \sim v_T/\omega_p \gg e^2/T$$

repulsive

In super-strong B-field collisions are more efficient

Collision of particles with the same e/m do not lead to dipolar emission

Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- Attractive

- Only parallel acceleration (usually a_{perp} dominates emission)
- Low frequency limit ~ ω^2 (usually ω^0)
- Normalization ~ 3 orders lower
- Only O-mode emitted

Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

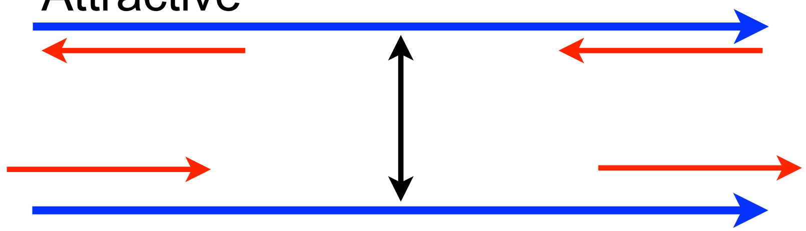
- Attractive

- Only parallel acceleration (usually a_{perp} dominates emission)
- Low frequency limit ~ ω^2 (usually ω^0)
- Normalization ~ 3 orders lower
- Only O-mode emitted

Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- Attractive

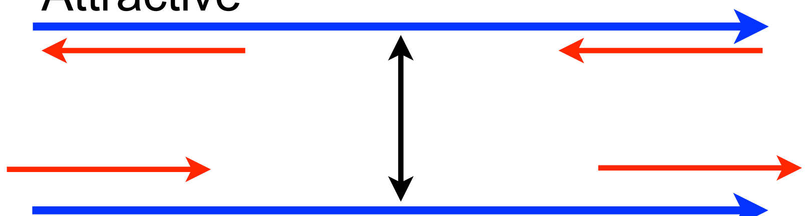


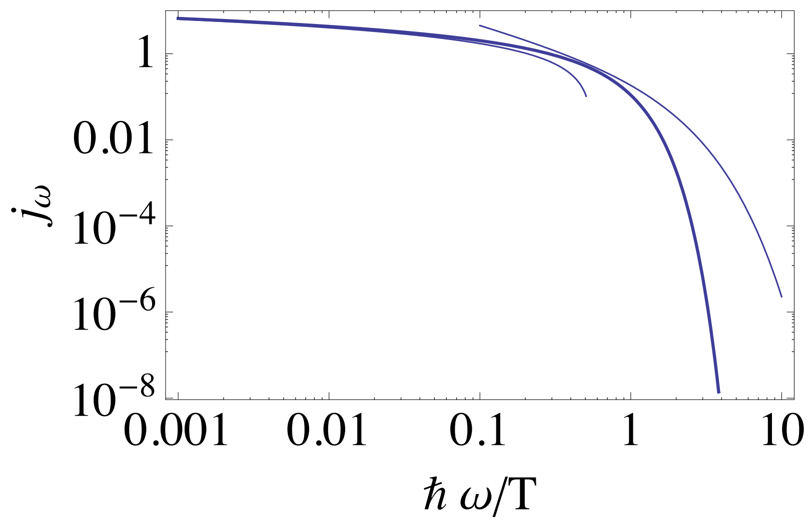
- Only parallel acceleration (usually a_{perp} dominates emission)
- Low frequency limit ~ ω^2 (usually ω^0)
- Normalization ~ 3 orders lower
- Only O-mode emitted

Lyutikov, submitted

Scattering and free-free emission of pair plasma in super-strong B-field

- Attractive





- Only parallel acceleration (usually a_{perp} dominates emission)

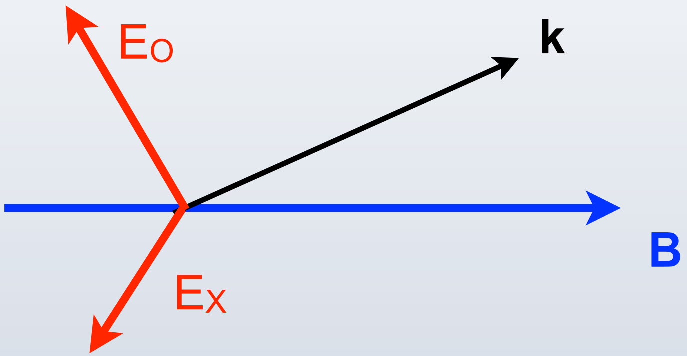
- Low frequency limit ~ ω^2 (usually ω^0)

- Normalization ~ 3 orders lower

- Only O-mode emitted

Lyutikov, submitted

Scattering in B-field



E_X hardly move the electron

$$v_d/c \sim (E/B_0)$$

$$\sigma_O \approx \sigma_T$$

$$\sigma_E \approx \left(\frac{\omega}{\omega_B}\right)^2 \sigma_T$$

- E-mode can escape from deeper-in:
- smaller radius
- higher temperature
- Importance: topologically confined fireball, not a flux tube connected to the surface. Consistent with the idea that topologically-changing instabilities are responsible for flares.

Lyutikov, submitted

Conclusion

Magnetar flares

- Magnetars' bursts and flares are magnetospheric, not crustal events
- magnetically stressed crust cannot crack efficiently
- crust responds plastically
- Flares: externally triggered events
- Some energy is dissipated inside the NS