FRB emission mechanisms

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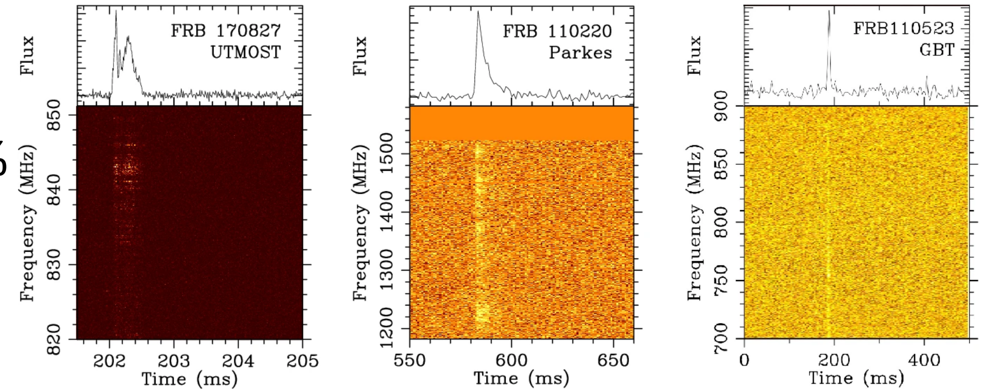
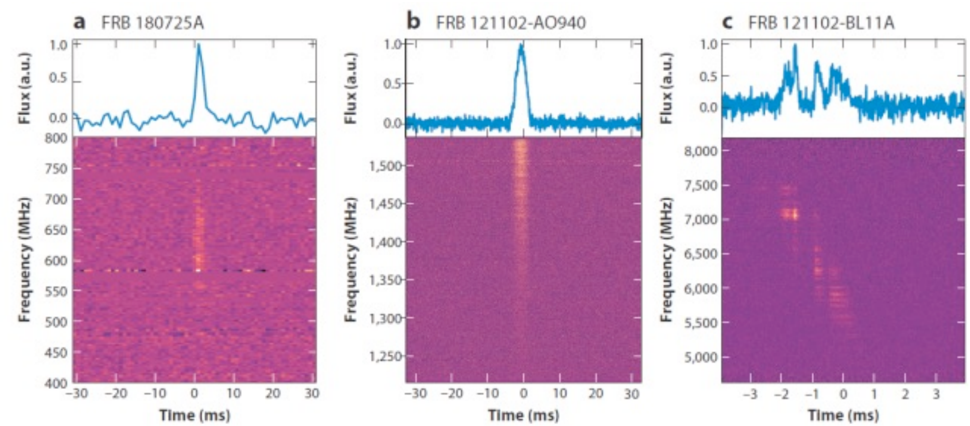
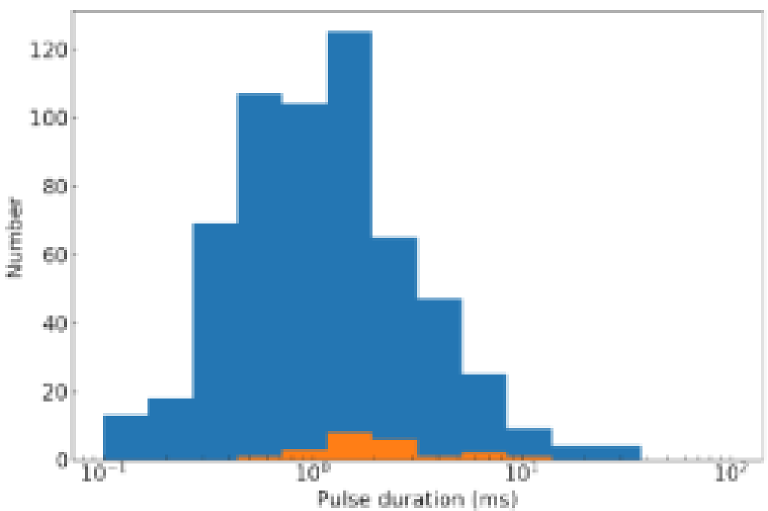
FRBs – short, bright pulses of radio emission

Duration: a few ms
Different sky locations
Most occurred just once; only a handful of repeaters
Come from cosmological distances
Isotropic emitted energy $10^{38} - 10^{43}$ erg
Strong linear polarization, sometimes 100%

Estimated rate: few x10^3 sky^{-1} day^{-1}
0.001 galaxy^{-1} year^{-1}







(Petroff+ '21)

No variable counterparts in other wavelengths have been detected, with the exception of the X-ray flare from a Galactic magnetar SGR 1935+2154

Coherent emission

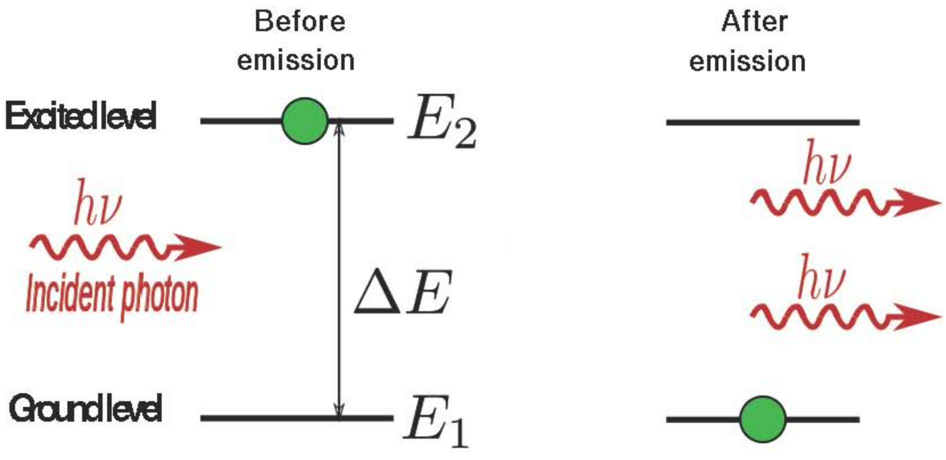
In nature, coherent radio emission = collective plasma radiation processes
(exception – molecular line masers)

The questions a model has to address

1. What e-m waves could propagate in the plasma at the assumed conditions?
2. How could these waves be excited?
3. How could these waves escape as radio waves?
4. What are the properties of the outgoing radiation?

Basics of masers

Quantum view: inverse population of energy levels – negative absorption coefficient



$$\Delta E = h\nu$$

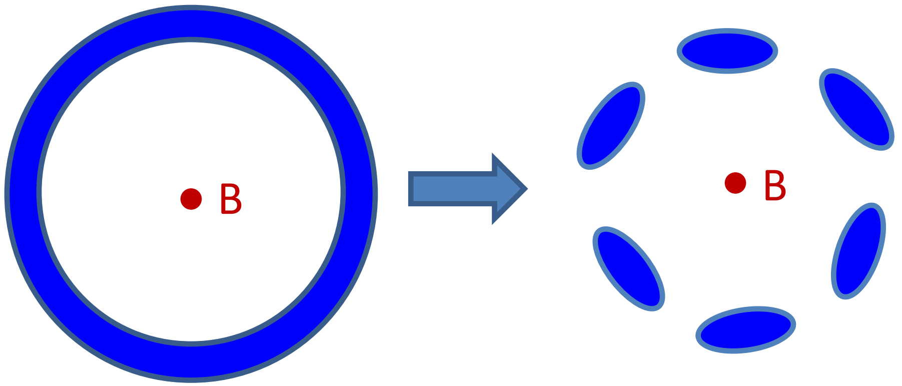
Classical view: resonance instability

incident wave

An incident wave modulates the unstable plasma, triggering currents that emit in phase with the seed wave

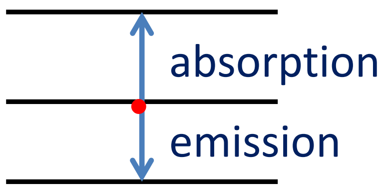
Synchrotron maser

Ring-like distribution of electrons in the magnetic field – inverse population. Initially homogeneous ring gets modulated.

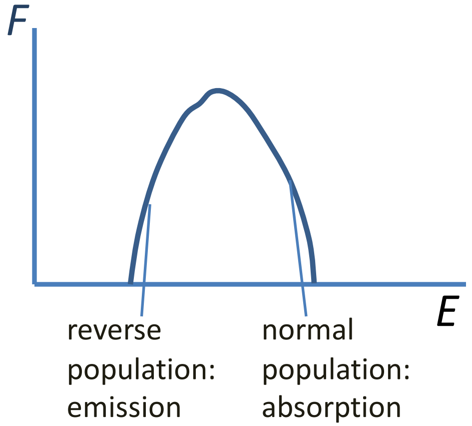


Subtle points:

1. No maser in an equidistant level system. Therefore non-relativistic (cyclotron) maser only due to $(v/c)^2$ corrections.



2. In highly relativistic case, continuous spectrum of high harmonics. In vacuum, absorption dominates unless the ring is unrealistically narrow.

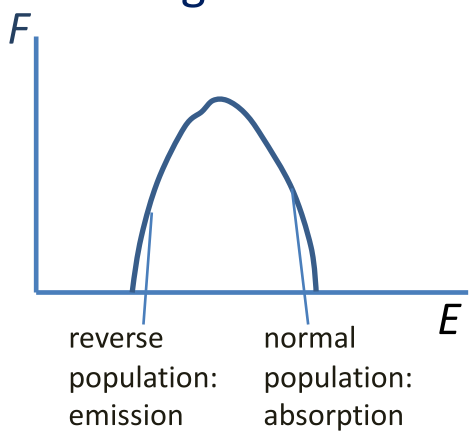


Synchrotron maser, cont'd

At a few first harmonics, $\omega \sim \Omega_B$, maser is possible for $\Delta E < E$.
This is possible if $\omega > \Omega_p$, i.e. $\sigma > 1$.

$$\Omega_B = \frac{eB}{m_e c\gamma} \qquad \Omega_p = \sqrt{\frac{4\pi e^2 n}{m_e \gamma}} \qquad \sigma = \frac{B^2}{4\pi n m_e c^2 \gamma} = \frac{\Omega_B^2}{\Omega_p^2}$$

With account of plasma dispersion (wave velocity $v_{ph}=\omega/k \neq c$), maser at higher harmonics is possible even for $\Delta E \sim E$:



When $(v_{ph}/c)-1 \geq \gamma^{-2}$, synchrotron emission (and absorption) is suppressed by the Razin effect. The suppression is stronger for higher energy electrons

$$\omega = \frac{\Omega_B}{2\sigma^{3/4}} = \frac{\Omega_p}{2\sigma^{1/4}}; \quad \sigma << 1$$

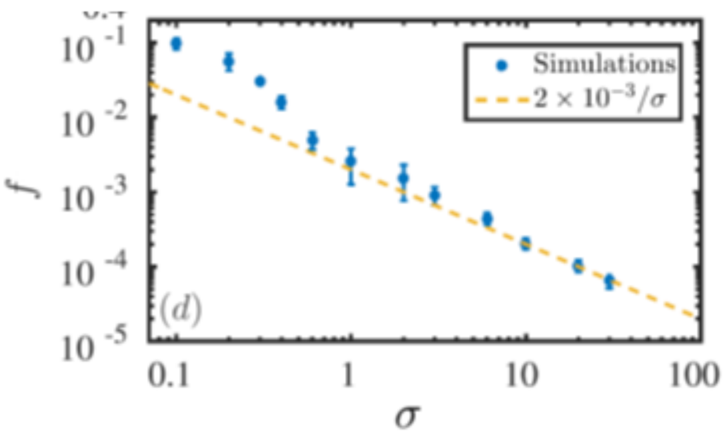
Sagiv&Waxman '02

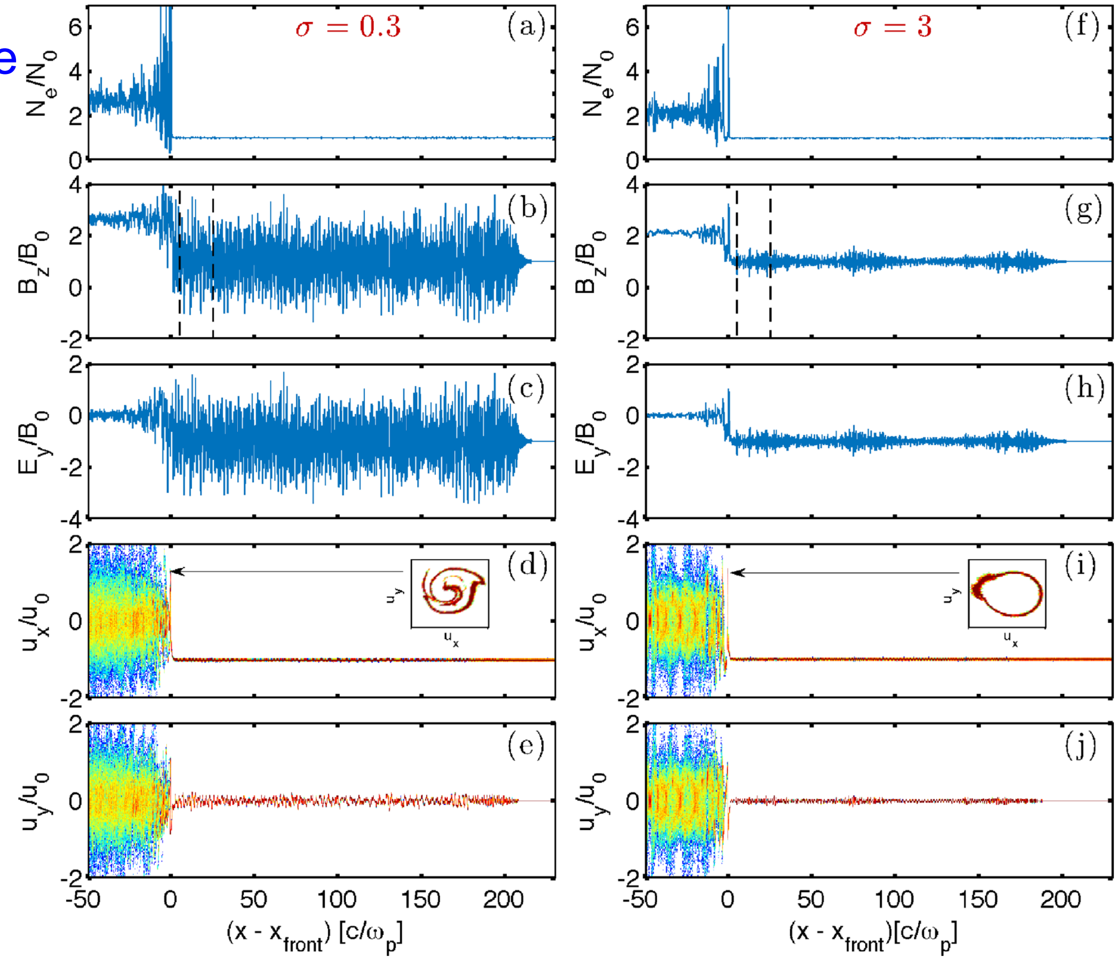
One sees that synchrotron maser works at any magnetization

Synchrotron maser at relativistic shocks

At $\sigma > 10^{-3}$ shocks are mediated by the Larmor rotation. The synchrotron maser radiates away a fraction *f* of the upstream energy (Langdon +'88; Gallant+ '92, …..).

Radiation is polarized predominantly perpendicularly to the magnetic field.

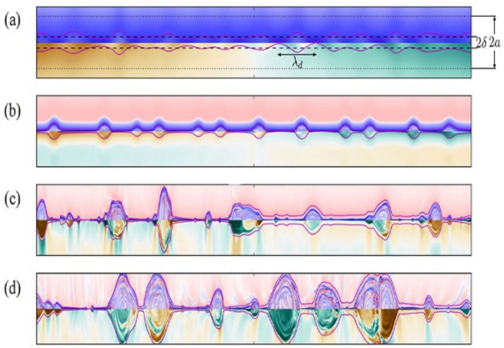




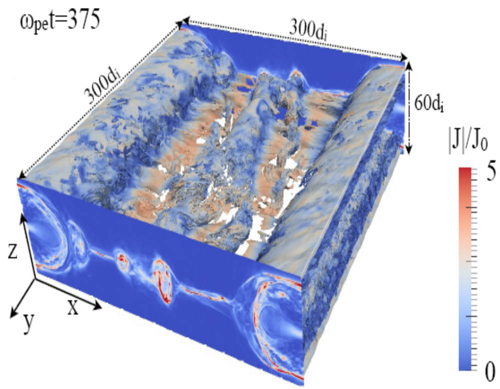
Relativistic shock in $e^+ e^-$ plasma (Plotnikov&Sironi '19)

Relativistic shocks could be produced by magnetar flares, NS mergers, AGN jets, ……..

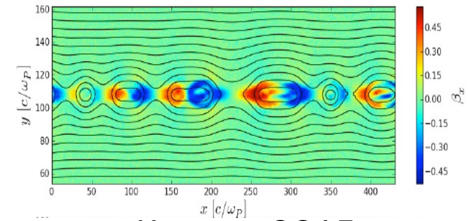
Radiation reconnecting current sheets



Huang+ 2017



Guo+ 2015



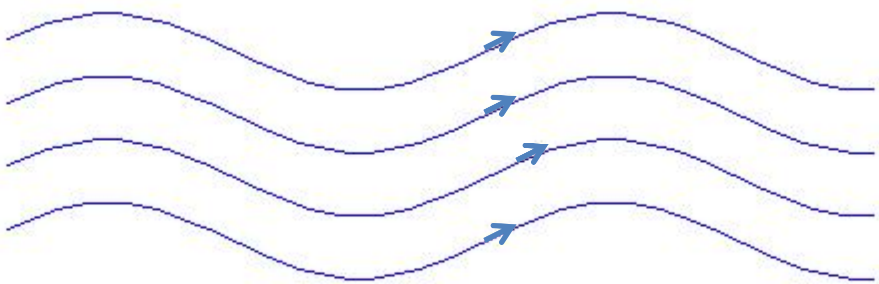
Kagan+ 2015

In plasma, magnetic reconnection in the current sheet occurs via formation and coalescence of magnetic islands

Coalescence of two magnetic islands produces a magnetic perturbation in the vicinity of the coalescence region. MHD noise (Alfven and fast magnetosponic waves) is generated around the current sheet.

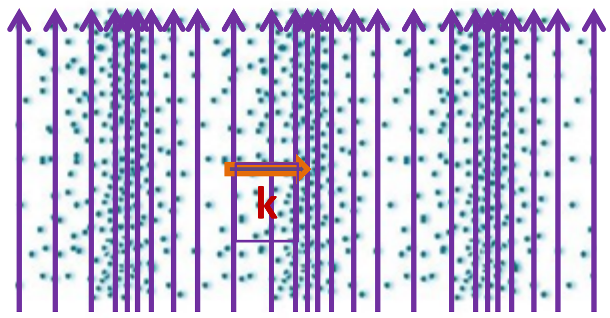
Electro-magnetic radiation from coalescencing magnetic islands

(Uzdensky&Spitkovsky 14; L ’19; Philippov+ ’19)

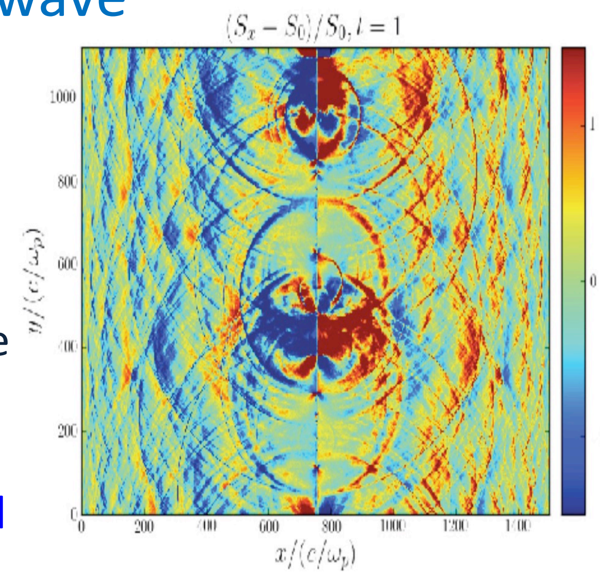


Alfven wave

The group velocity of the Alfven waves is directed along the magnetic field lines therefore, they do not transfer the energy away from the current sheet.



Fast magnetosonic wave

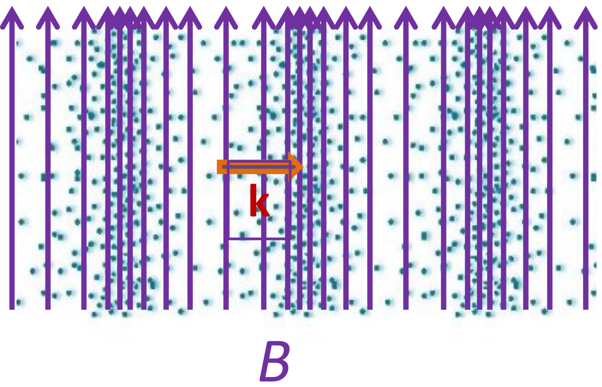


(Philippov+ 2019)

Fast magnetosonic waves do propagate across the magnetic field lines therefore any coalescence event produces a fms pulse of the duration ~a/c, where a is the transverse size of the island, a ~ 10-100 R_{Larmor}.

The fraction f~0.005 of the dissipated magnetic energy is radiated away

FMS waves in a highly magnetized plasma



Fast magnetosonic wave: longitudinal oscillations, transverse electric field, **E=(1/c)vxB**

$$v_{ph} = \frac{\omega}{k} = c\sqrt{\frac{B^2}{4\pi\rho c^2 + B^2}} = \left(1 - \frac{1}{2\sigma}\right)c \qquad \sigma = \frac{B^2}{4\pi\rho c^2}$$

$$\nabla\times E = -\frac{1}{c}\frac{\partial B}{\partial t}; \quad \nabla\times B = \frac{4\pi}{c}j + \frac{1}{c}\frac{\partial E}{\partial t}$$

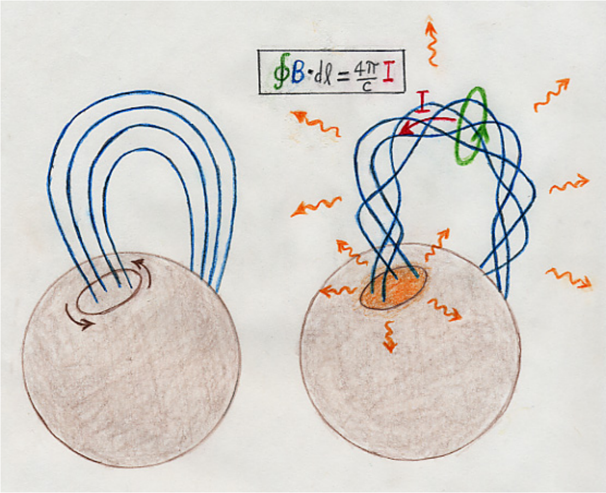
$$\frac{E}{B} = \frac{\omega}{ck} = \left(1 - \frac{1}{2\sigma}\right) \qquad \frac{j}{i\omega E} = -\frac{1}{4\pi\sigma}$$

$v_{ph} \rightarrow c$; j → 0 at $\sigma \rightarrow \infty$: the wave smoothly transforms to a vacuum electro-magnetic wave when plasma density goes to zero.

The fms waves are 100% polarized perpendicularly to the magnetic field

Relativistic reconnection occurs at different astrophysical environments (magnetar flares, AGNs etc)

FRB from flaring magnetar

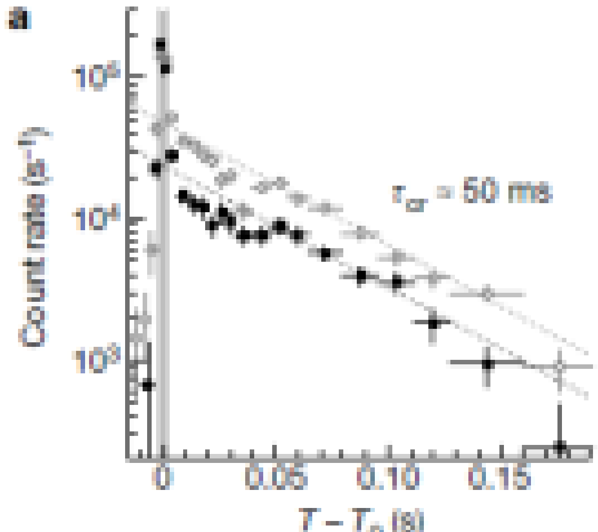


Magnetar – NS with B~10^{15} G at the surface.
Magnetic energy feeds all sorts of activity

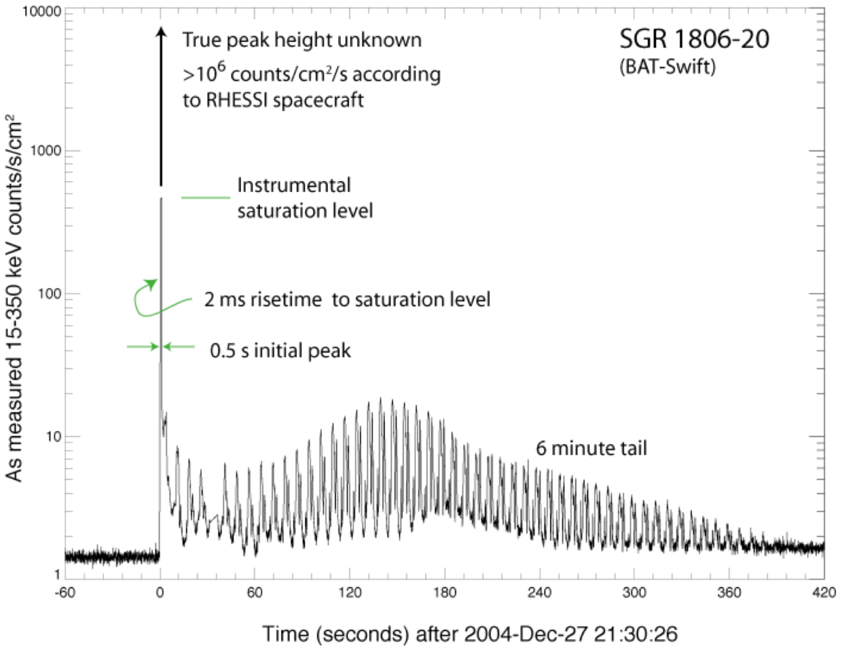
$$B^2 R_*^3 \sim 10^{48} B_{15}^2 \text{ erg}$$

- Weak bursts E<10^{42} erg
- Intermediate E~10^{42}–10^{43} erg
- Giant E>~10^{44} erg

The rate of magnetar flares is comfortably above the FRB rate (Popov&Postnov '07, '13, Kulkarni+'14 …)



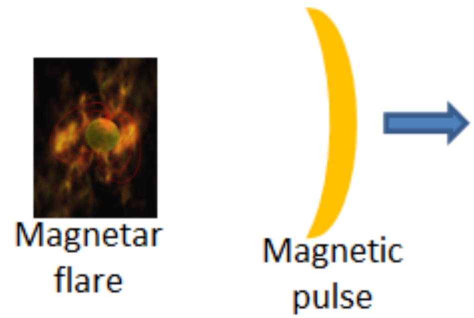
Onset of the giant flare, GRB 200415A; E=10^{46} erg (Svinkin+ '21)



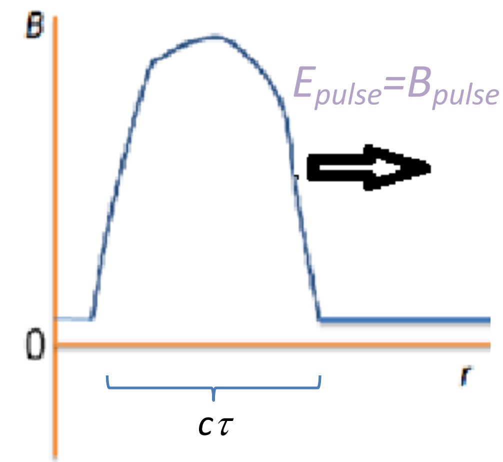
The giant flare of Dec27, 2004;
E=2 10^{46} erg (Palmer+ '05)

FRB from flaring magnetar, cont'd

In a magnetar flare, the magnetosphere is sharply disturbed producing a large amplitude MHD perturbation, which propagates outwards sweeping the magnetic field lines into a narrow pulse. The pulse runs away through the magnetized magnetar wind.



B_{pulse} goes as 1/r; the magnetospheric field as $1/r^3$.
In the outer magnetosphere, $B_{pulse}/ B_{bg}>>1$.
The pulse runs away through the magnetized magnetar wind.

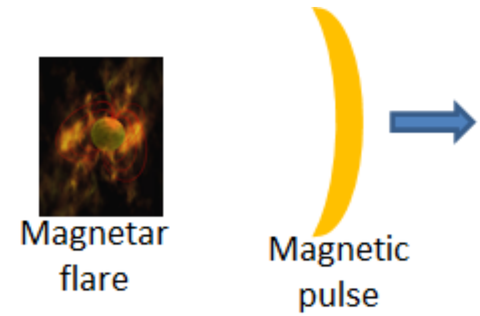


Energy in the pulse $\varepsilon_{\text{pulse}} = 4\pi r^2 \frac{B^2}{4\pi} c\tau$

In the wind $\frac{B_{pulse}}{B_{wind}} = 4\cdot 10^4 \frac{P^2}{\mu_{33}} \left(\frac{\varepsilon_{44}}{\tau_{\text{ms}}} \right)^{1/2}$

In the wind frame, plasma velocity in the pulse $V = \frac{E}{B} c = \frac{B_{pulse}}{B_{pulse} + B_{wind}} c$

FRB from the shock front.



Suggested possibilities of shock formation:

- When the pulse reaches the nebula inflated in the ISM by the magnetar wind (L '14).

  $r > 10^{15}$ cm

  Requires an extremely energetic pulse – incompatible with ubiquity of FRBs and repeaters

- When the pulse collides with the previously ejected baryonic cloud (Metzger+ '19)

  Requires two giant flares within <1 day.

  Problem with the magnetization of the ejecta and the emitted frequency

- Shock in the magnetar wind (Beloborodov '17, '20)

  Only if the wind is heavily mass loaded, $\sigma < 100$, slow, $\Gamma_w \sim 10$, and very powerful, $L_{wind} >> L_{sd}$.

  $\varepsilon_{FRB} = \xi \varepsilon_{pulse}$ $\quad \xi = 10^{-3} \sigma^{-1}$

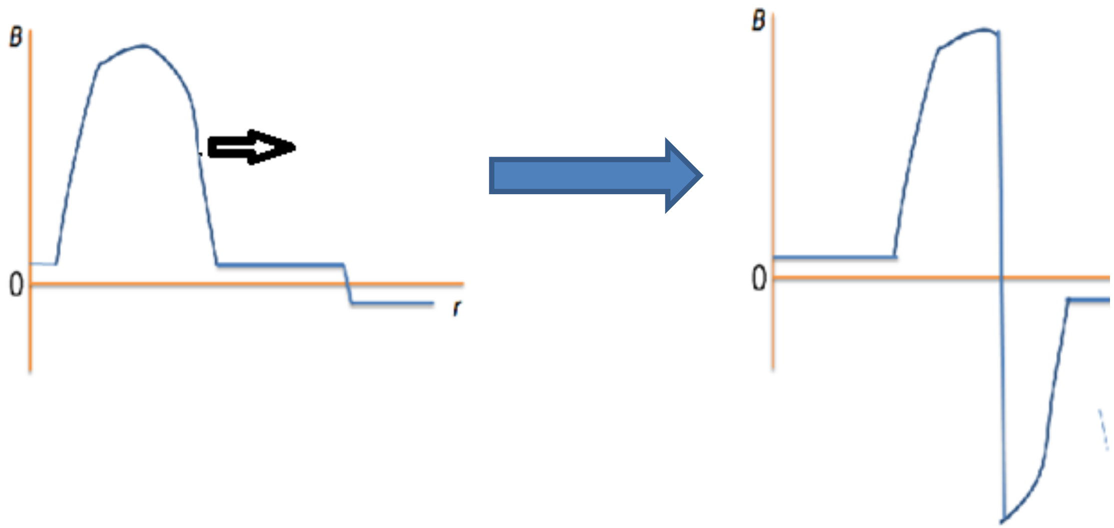
The emitted frequency $\nu \propto \frac{eB}{m_e c} \propto \frac{\varepsilon_{pulse}^{1/2}}{r_{shock}}$

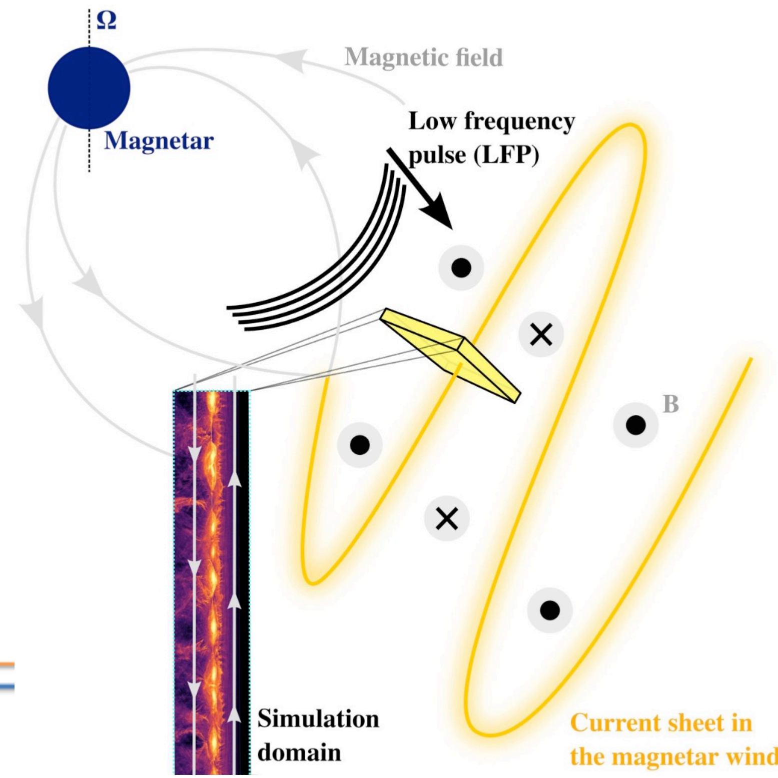
The larger ε_{pulse}, the larger r_{shock}. Therefore ν weakly depends on ε_{pulse}.

FRB from reconnection in magnetar magnetosphere/wind (L ’20, Mahlmann+ ‘22)

Just as pulsars, magnetars emit striped winds

Magnetic pulse from the flare squeezes and pushes forward the current sheet triggering violent magnetic reconnection

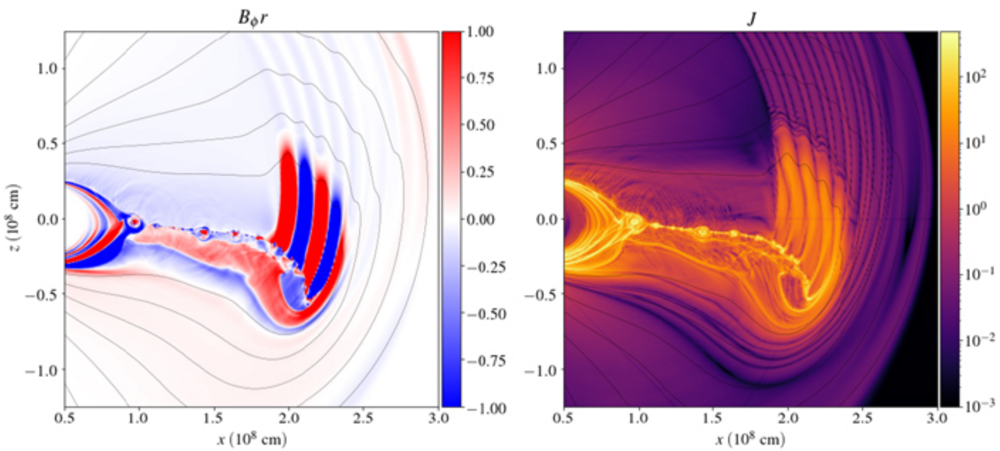




The emitted frequency $\nu \propto \frac{eB}{m_e c} \propto \frac{\varepsilon_{\rm pulse}^{1/2}}{r_{\rm LC}} \propto \varepsilon_{\rm pulse}^{1/2} \propto \varepsilon_{\rm FRB}^{1/2}$

Radiation in ~1GHz band only for $\varepsilon_{\rm FRB}$~10^{40} - 10^{42} erg

FRB from reconnection in outer magnetosphere at $r<r_{LC}$?



Plasmoids ejected by the flare (Parfrey+ ‘13; Carrasco+ ‘19; Yuan+ ’20, ‘22)

Plasmoids are detached from the magnetospheric field, which implies reconnection. Could be a source of FRBs.

Polarization of the outgoing radiation

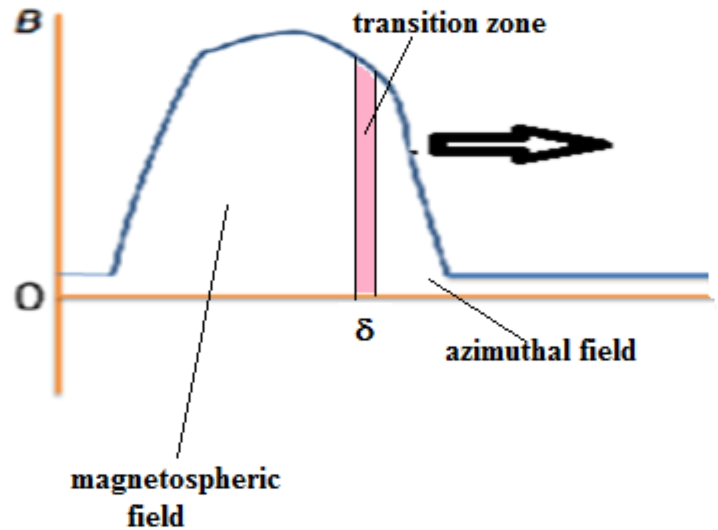
In magnetized plasma, radiation propagates in two orthogonally polarized modes. The polarization of each mode is adjusted to the local ***B*** if

$$2\pi \frac{L}{\lambda}|n_1 - n_2| > 1$$ *L* – inhomogeneity scale

The observed polarization is formed in the polarization limiting region, $2\pi \frac{L}{\lambda}|n_1 - n_2| \approx 1$

Model of the shock in the magnetar wind: linear polarization along the rotation axis of the magnetar.

In the reconnection model: FMS waves are 100% polarized perpendicularly to the background magnetic field. The magnetic pulse transfers the magnetic flux from well within the magnetosphere outwards. In the wind, the pulse gradually picks up the azimuthal field.



If $\frac{\omega'}{c}\Delta n \delta' > 1$ the outgoing radiation is 100% polarized along the rotational axis of the magnetar.

If this condition is violated, a variety of polarization patterns is possible.

Escape of radio waves

Various processes could affect the waves before escape: cyclotron/syncrotron absorption, induced Compton and/or Raman scattering, nonlinear interaction of waves, modulation/filamentation instabilities…

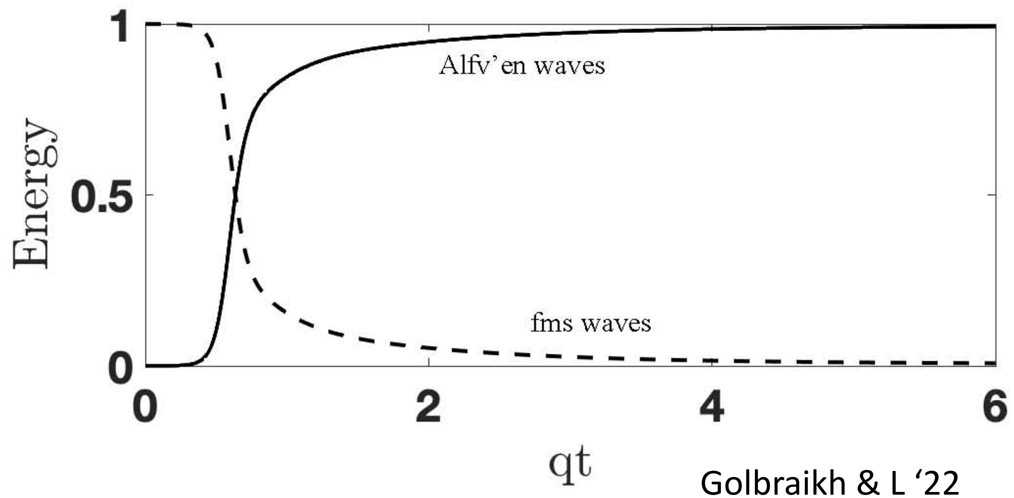
Within the magnetar magnetosphere, three-wave interaction

$$\omega = \omega_1 + \omega_2; \qquad \mathbf{k} = \mathbf{k}_1 + \mathbf{k}_2$$

fms ⟶ fms+Alfven; fms ⟶ Alfven+Alfven

yields decay into Alfven waves

Interaction rate $q \sim \frac{E^2_{\rm wave}}{B_0^2}\omega$



Golbraikh & L '22

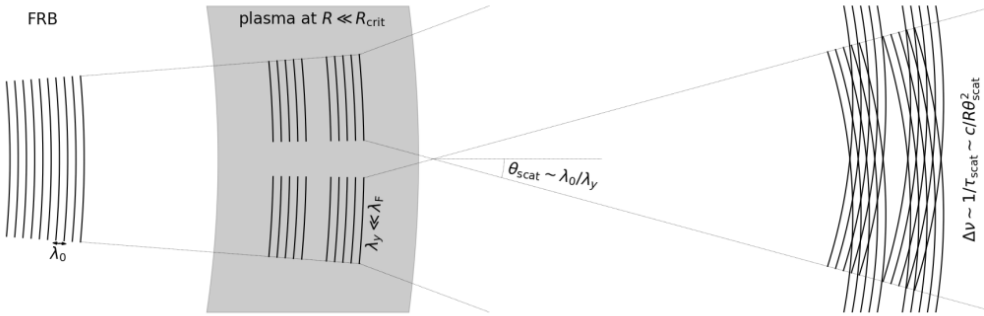
Radiation with a typical FRB power could not propagate beyond the distance

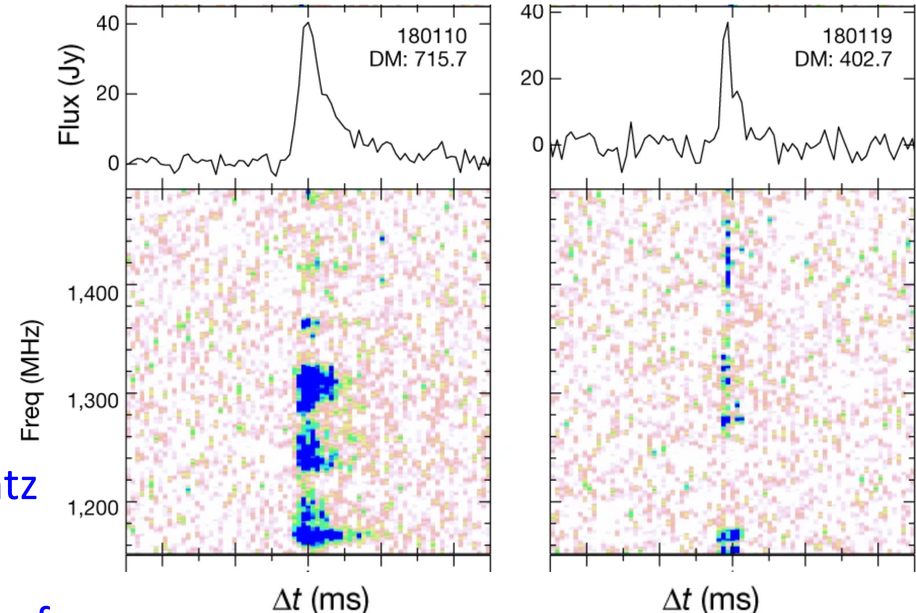
$$R = 10^7 \left(\frac{\mu_{33}^2}{L_{FRB,43}\, \nu_{GHz}} \right)^{1/5} \text{cm}$$

In the outer magnetosphere/wind, the magnetic pulse from the flare propagates away with a relativistic velocity. Within such a pulse, the decay rate is suppressed by relativistic slowing down of time – radiation escapes on the top of the magnetic pulse.

Modulation and filamentation instabilities in FRBs (Sobacchi+ '21, '22)

Refraction index increases with the radiation intensity ⟹ self-focusing. For wide beams – filamentation. Diffraction of subbeams could lead to (1) smearing of the burst in time and (2) frequency modulation of the observed intensity due to interference between the subbeams





Shannon+ '18

In a cold magnetar wind, $T<(\nu_p/\nu)m_e c^2$, the typical scattering time-scale is $\tau \sim$ μs–ms at $\nu \sim 1$ GHz, $\tau \propto \nu^{-2}$. Imposes limits on the density and the Lorentz factor of the wind.

In a warm wind, $\tau \sim$ ns but the scattering produces a frequency modulation with the bandwidth, $\Delta\nu \sim 1/\tau \sim 100$ MHz.

For a baryonic plasma at the distance $R<10^{17}$ $(N/10$ cm$^{-3})(L_{FRB}/10^{43}$ erg s$^{-1})$ cm, interference between the subbeams produces a frequency modulation of the observed intensity with a sub-GHz bandwidth

In baryonic plasma, the dependence of the group velocity on the intensity yields self-modulation of the radiation intensity at a timescale of 10 μs.

Conclusions

1. Coherent emission from FRBs = plasma collective emission. Coherent motion of large ensembles of particles could be excited in unstable plasma systems. Their emission properties are determined by the properties of the plasma.

2. Extreme energetic and temporal properties of FRBs evidence for a highly relativistic plasma. Two working examples of coherent emission from such plasmas:
    - synchrotron maser at relativistic, magnetized shocks,
    - radiation from merging magnetic islands in reconnecting current sheets at $\sigma >> 1$.

3. Both mechanisms could produce FRBs in magnetar flares but may be in other environments as well (blitzars, AGNs etc).
4. Propagation effects are of crucial importance.