

Cavito-Driven Bremsstrahlung

A novel mechanism for fast radio bursts from magnetars

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PIC workshop, 29 September 2026

Table of contents

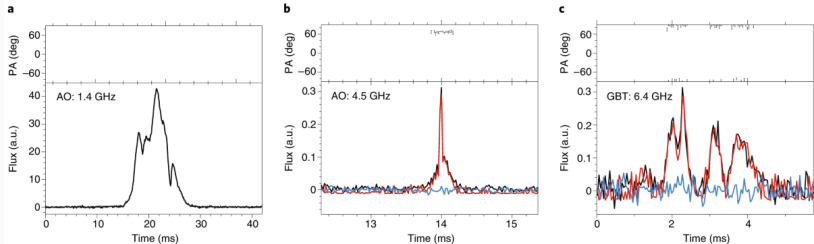
1. Motivation
2. The galactic FRB
3. Beam instability
4. Emission mechanism
5. Conclusions

Motivation

Fast Radio Bursts (FRBs)

Transient episodes of extremely strong radio emission of unknown origin. (First detection in 2007.)

- Peak flux $> 0.5 \text{ Jy}$ ($= 0.5 \times 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$) at GHz frequencies
- Some of them repeat $\Rightarrow$ the mechanism cannot be catastrophic
- High occurrence rate $\Rightarrow$ large population source
- Release $\sim 10^{35} - 10^{43} \text{ erg}$ in $\Delta t \sim \text{ms}$



Sky distribution

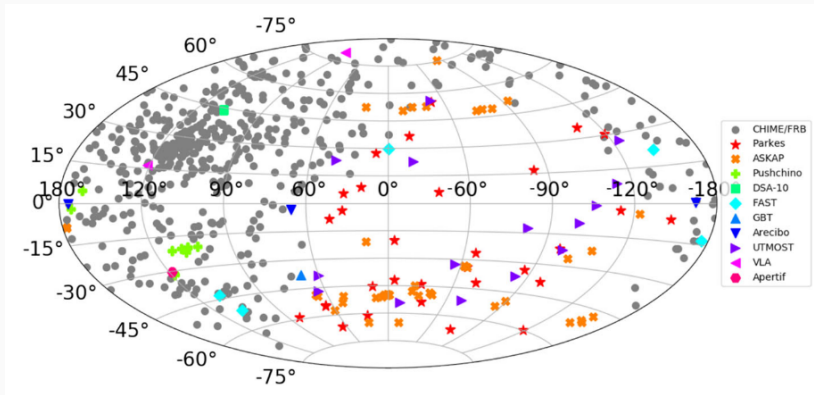
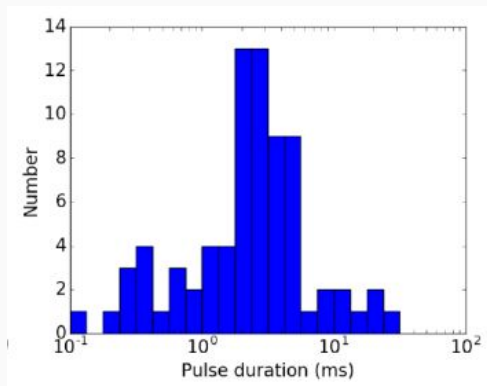


Figure 1: FRBs in Galactic coordinates, predominantly those found by CHIME, which have significant variations in sensitivity over the sky and only views the northern hemisphere. When corrected for non-uniform sky coverage, it has been shown that the distribution is isotropic, as expected for a cosmological population. Petroff et al. (2022)

Coherent emission from a compact source

- High-implied brightness temperatures
 $T_b > 10^{32}$ K $\Rightarrow$ the emission should be coherent
- $c\Delta t \sim 10^7$ cm $\Rightarrow$ the source should be compact



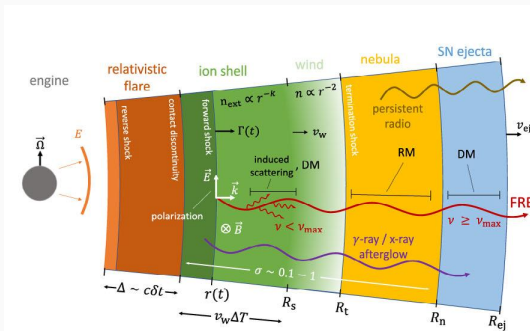
Petroff et al. (2019)

FRBs appear to be extremely efficient sources of coherent radio emission. The mechanism is still unclear.

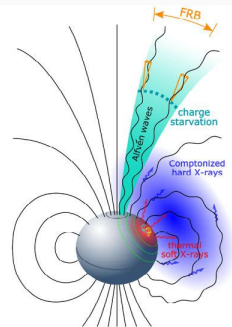
Models in the literature

Shock models: the FRB is produced at a large (10^{10} cm) distance from the compact object (magnetar or black hole).

Magnetospheric models: the FRB is produced in the neutron star magnetosphere.



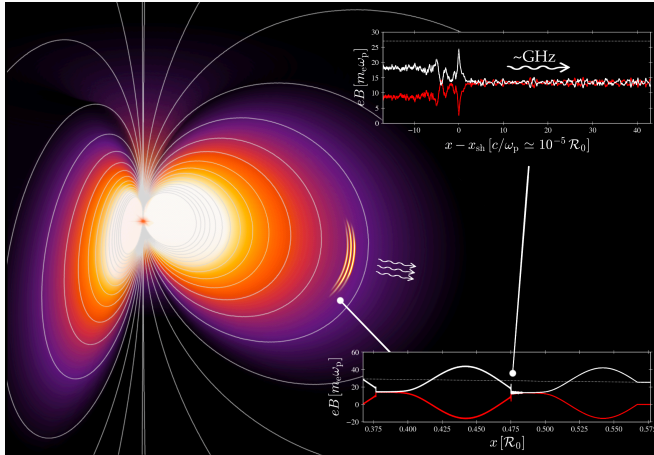
Metzger et al. (2019)



Lu et al. (2020)

Monster shocks

Fast magneto-sonic waves create shocks inside the magnetosphere that can release a huge amount of energy (Beloborodov 2023).



Vanthieghem & Levinson (2025)

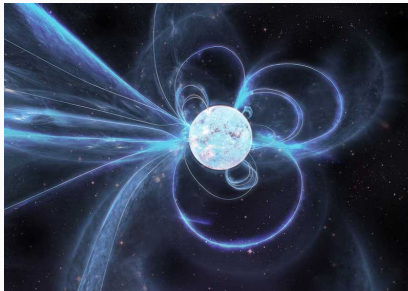
The galactic FRB

Magnetars

Magnetars are very highly magnetised neutron stars (NS) with $B_0 \sim 10^{14} - 10^{15}$ G, about 1000 times stronger than B_{NS} .

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) present irregular bursts in X-rays and soft-gamma-rays.

During the short (faster than minutes) bursts, the brightness can increase by a factor of 1000 or more.



Magnetar SGR J1935+2154

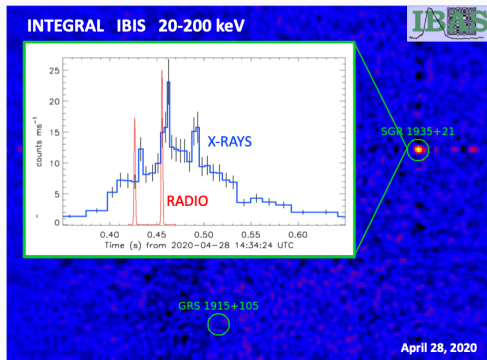
Recent discovery of a FRB occurring simultaneously with an X-ray burst from the **Galactic magnetar SGR J1935+2154**

Radio (CHIME)

- $L_{\text{GHz}} \sim 10^{38} \text{ erg s}^{-1}$
- $\nu_{\text{FRB}} = 400 \text{ MHz}$
- $\delta t = 0.6 \text{ ms}$

X rays (Integral)

- $L_X \sim 10^{41} \text{ erg s}^{-1}$
- $E_{\text{cutoff},X} \sim 80 \text{ keV}$



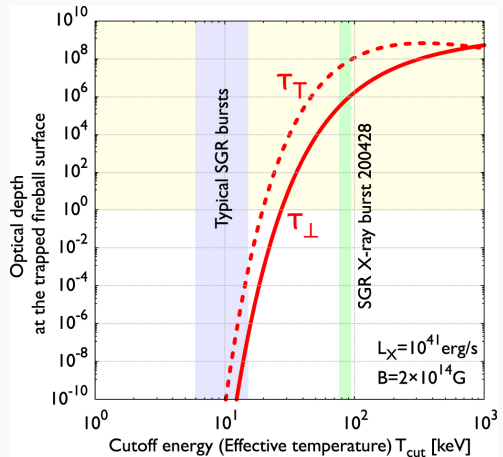
Mereghetti et al. (2020)

Expanding fireball in magnetar SGR J1935+2154

For 80 keV photons to be observed, the $e^\pm - \gamma$ plasma should expand along the large-scale open B -field lines outside the trapped fireball

$$l_0 = \left(\frac{L_X}{2\pi c a T^4} \right)^{\frac{1}{2}} \sim 10^4 \text{ cm}$$

80 keV photons cannot escape from the optically thick region above the trapped fireball

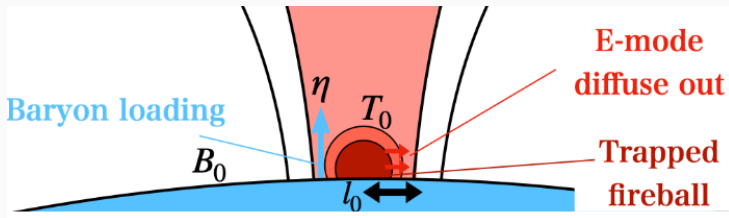


Ioka (2020)

Baryon loaded expanding fireball

- X-ray photons heat the magnetar surface and ions and electrons are ablated (Thompson & Duncan 1995).
- The baryon mass density in the outflow, ρ'_b , is determined by the free parameter η

$$\eta \equiv \frac{e'_0}{\rho'_{b0} m_p c^2}, \quad e'_0 = 5.6 \times 10^{21} \left(\frac{k_B T'_0}{80 \text{ keV}} \right)^4 \text{ erg cm}^{-3}$$



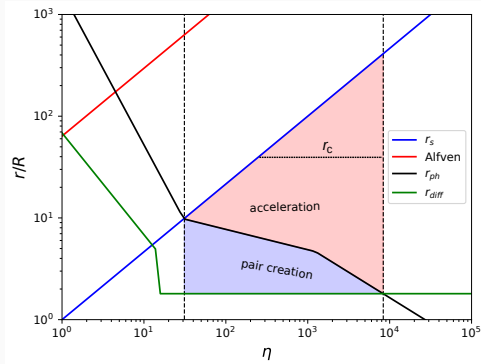
Wada & Ioka (2023)

Baryon-loaded expanding fireball

Saturation radius:

$$\frac{r_s}{R} = \left(\frac{\eta}{100}\right)^{\frac{2}{3}}$$

- $r < r_s$: Radiation dominated
- $r > r_s$: Matter dominated



Alfvén radius:

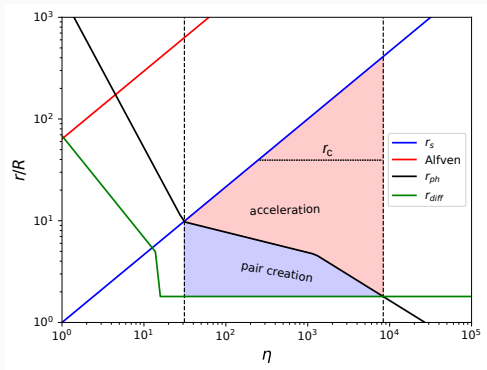
$$\frac{r_{\text{Alfven}}}{R} = 2 \times 10^3 \left(\frac{B_0}{2 \times 10^{14} \text{G}} \right)^{\frac{2}{3}} \left(\frac{\eta}{100} \right)^{\frac{2}{3}}$$

Baryon-loaded expanding fireball

Diffusion radius:

$$\frac{r_{\text{diff}}}{R} = \begin{cases} 68.4\eta^{-1}, & \eta < 14.7 \\ 1.8, & \eta > 14.7 \end{cases}$$

At $r > r_{\text{diff}}$ photons escape from the in the direction perpendicular to B and create $e^\pm$ pairs outside the baryon-loaded fireball



$$\text{Photospheric radius : } \frac{r_{ph}}{R} = \begin{cases} 1.6 \times 10^3 \eta^{-\frac{3}{2}}, & \eta < 30.6 \\ 19.4 \eta^{-\frac{1}{5}}, & 30.6 < \eta < 1.2 \times 10^3 \\ 1.6 \times 10^2 \eta^{-\frac{1}{2}}, & \eta > 1.2 \times 10^3 \end{cases}$$

Radiation acceleration

At $r_{\text{ph}} \leq r \leq r_c$, the fireball is accelerated by resonant cyclotron scattering (Wada & Asano 2024).

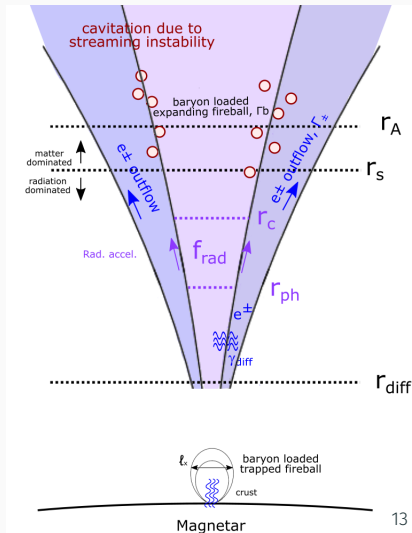
Pair expanding fireball:

$$\Gamma_{\pm} = \left(\frac{r_{\text{diff}}}{R} \right)^{\frac{1}{2}} \left(\frac{r_{c,\pm}}{R} \right) = 60.4$$

Baryon expanding fireball:

$$\Gamma_b = \Gamma_{\text{ph}} \left(\frac{r_{c,b}}{r_{\text{ph}}} \right)$$

$$= \begin{cases} 46.6 \left(\frac{\eta}{100} \right)^{-\frac{1}{10}}, & \eta_{\star} \leq \eta \leq 1.2 \times 10^3 \\ 37.7 \left(\frac{\eta}{1000} \right)^{-\frac{1}{4}}, & \eta \geq 1.2 \times 10^3 \end{cases}$$



Energy budget for FRB emission

FRB isotropic-equivalent luminosity: $L_{\text{FRB,iso}} = 10^{38} \text{ erg s}^{-1}$

FRB true luminosity: $L_{\text{FRB,true}} = (\Delta\Omega/4\pi)L_{\text{FRB,iso}}$,
 $\Delta\Omega = (\theta_{\text{fireball}} + 1/\Gamma_b)^2$

- Kinetic luminosity of the pair expanding fireball

$$L_{\pm} = \pi m_e c^3 [l_b^2(r_{\text{diff}}) n'_{\pm}(r_{\text{diff}}) \Gamma_{\pm}(r_{\text{diff}})] \Gamma_{\pm} = 3.5 \times 10^{35} \text{ erg s}^{-1}$$

- Kinetic luminosity of the baryon-loaded expanding fireball

$$\frac{L_b}{\text{erg s}^{-1}} = \begin{cases} 5.1 \times 10^{40} \left(\frac{\eta}{100}\right)^{-\frac{11}{10}}, & \eta_{\star} \leq \eta \leq 1.2 \times 10^3 \\ 4.1 \times 10^{39} \left(\frac{\eta}{1000}\right)^{-\frac{5}{4}}, & \eta \geq 1.2 \times 10^3, \end{cases}$$

The condition $L_b/L_{\text{FRB,true}} > 1$ to satisfy the energy budget in the baryon-loaded expanding fireball to power the FRB emission gives

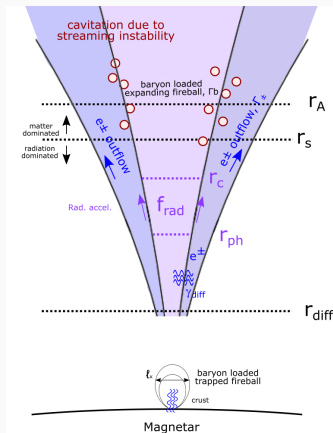
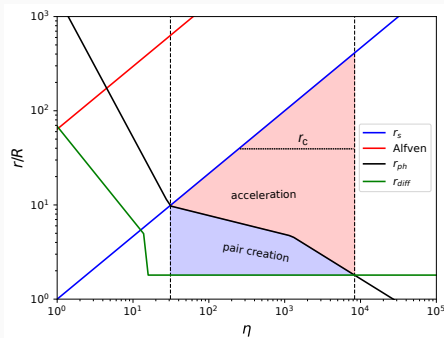
$$\frac{r_{\text{max}}}{R} = \begin{cases} 5.1 \times 10^6 \left(\frac{\eta}{100}\right)^{-\frac{11}{10}}, & \eta_{\star} \leq \eta \leq 1.2 \times 10^3 \\ 4.1 \times 10^5 \left(\frac{\eta}{1000}\right)^{-\frac{5}{4}}, & \eta \geq 1.2 \times 10^3 \end{cases}$$

The condition $\max(\omega'_p, \omega_B)/2\pi < \nu'_{\text{FRB}}$ gives the minimal radius of FRB photon escape

$$\frac{r_{\text{min}}}{R} = \begin{cases} 1.7 \times 10^4 \left(\frac{\eta}{100}\right)^{-\frac{1}{10}}, & \eta_{\star} \leq \eta \leq 1.2 \times 10^3 \\ 1.2 \times 10^4 \left(\frac{\eta}{1000}\right)^{-\frac{1}{4}}, & \eta \geq 1.2 \times 10^3 \end{cases}$$

FRB emitter

The condition $L_{\text{kin,b}} > L_{\text{FRB,true}}$ together with $\max(\omega'_p, \omega_B)/2\pi < \nu'_{\text{FRB}}$, determine a region in the $\eta - r$ plane where FRBs can be produced



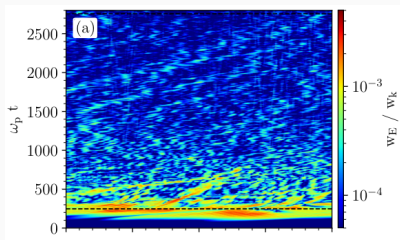
Beam instability

1D PIC simulations

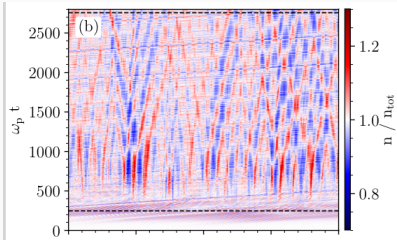
Background (baryon loaded fireball): electron–proton plasma

Beam (pair fireball): electron–positron plasma that propagates through the fireball with $\Gamma_{\text{beam}} = 10$

- Plasma frequency: $\omega_p \approx 1.79 \times 10^7 \sqrt{n_{\text{tot}}/10^5 \text{cm}^{-3}} \text{ rad s}^{-1}$
- Skin depth: $c/\omega_p \approx 1.6 \times 10^3 \text{ cm}$

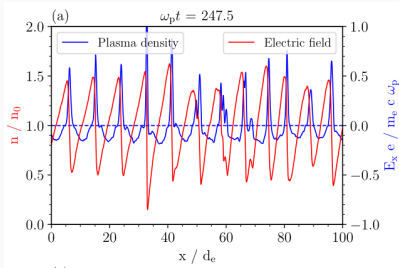


Electric field energy density

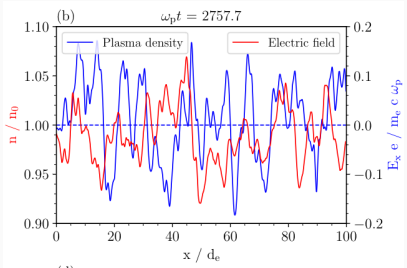


Number density

Langmuir saturation



Simulation end

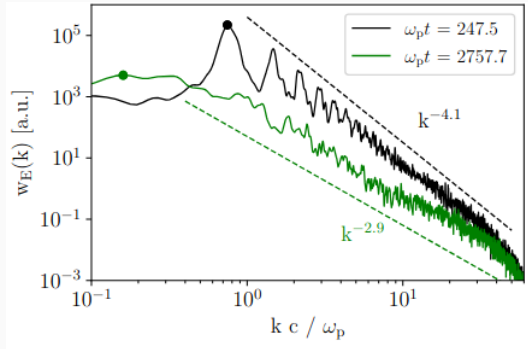


Density

Electrostatic field

Cavities

Cavity size: wavenumber k_{typ} at which the spectrum has the maximal intensity



Langmuir saturation

$$D_{\text{typ}} = 8.4 \frac{c}{\omega_p} = 1.4 \times 10^4 \text{ cm}$$

$$\langle n \rangle / n_{\text{tot}} = 0.21$$

Simulation end

$$D_{\text{typ}} = 39 \frac{c}{\omega_p} = 6.5 \times 10^4 \text{ cm}$$

$$\langle n \rangle / n_{\text{tot}} = 0.057$$

Electric wave coherency

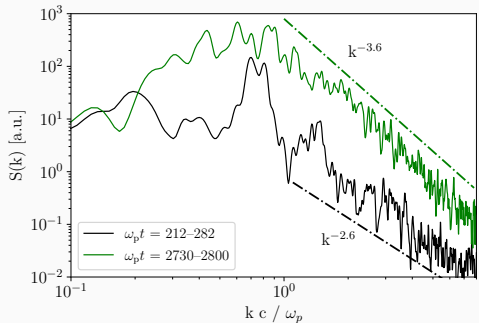
How well the particles emit coherently at a spatial length x ?

$$E_t = \langle E(x) \rangle \Delta t_{\text{coherent}} \quad \omega_p \Delta t_{\text{coherent}} = 80$$

$\Delta t_{\text{coherent}} > D_{\text{typ}}/c$, allowing particles to achieve emission coherency from more than one cavity. More cavities contribute to the FRB emission.

$$\begin{aligned} S(x) &= \text{ACF}(E_t) \\ &\equiv \langle E_t(x' + x) E_t(x') \rangle_{x'} \end{aligned}$$

$$S(k) = |\text{FFT}(S(x))|$$



Emission mechanism

Single electron's emission

Each relativistic electron passing through one cavity will radiate an energy per unit frequency interval (over a time $\tau = 2D/c$)

$$I_{e,\parallel}(\omega) = 5 \times 10^{-28} \left(\frac{\langle E_x \rangle}{\text{StatV cm}^{-1}} \right)^2 \left(\frac{D_{\text{typ}}}{c/\omega_p} \right)^2 \left(\frac{\Gamma}{100} \right)^2 \text{ erg Hz}^{-1}$$

Each electron interacts with $N_{c,\parallel} = r'_{\parallel}/D_{\text{typ}} \sim 3 \times 10^8$ cavities when passing through the emitter¹

$$E_{\text{tot},1e} = I_{e,\parallel}(\omega) N_{c,\parallel} \nu_{\text{FRB}}$$

¹The duration of the FRB $\delta t_{\text{FRB}} = 0.6 \text{ ms}$ (in the reference frame of the observer) defines the crossing time of the emitter $\delta t_{\text{FRB}} = r_{\parallel}/(c\Gamma_{\text{fb}}^2)$, where $r_{\parallel}$ is the the direction parallel to the line of sight.

Incoherent emission

Total number of beam electrons in the emitter²

$$N_e = n'_{\text{beam}} V'_{\text{FRB}} = 5.8 \times 10^{32} \left(\frac{n'_{\text{beam}}}{10^5 \text{cm}^{-3}} \right) \left(\frac{\Gamma}{100} \right)^3 \left(\frac{\delta t_{\text{FRB}}}{0.6 \text{ms}} \right)^3$$

Total incoherent emission

$$\begin{aligned} E_{\text{tot,inc}} &= E_{\text{tot,1e}} N_e \sim 10^{29} \text{ erg} \\ &\ll E_{\text{FRB}} = 6.4 \times 10^{34} \text{ erg} \end{aligned}$$

²The size of the emitter in the direction perpendicular to the observer is $r_{\perp} = c\delta t_{\text{FRB}} \sim 1.8 \times 10^7 \text{ cm}$, whereas $r_{\parallel} = \Gamma_{\text{fb}}^2 r_{\perp}$. The emitter volume is therefore $V_{\text{FRB}} = r_{\parallel}^2 r_{\perp}^2 = 5.8 \times 10^{21} \Gamma_{\text{fb}}^2 \text{ cm}^3$. In the frame of the expanding fireball, $r'_{\parallel} = r_{\parallel} \Gamma_{\text{fb}}$ and the volume of the emitter is $V'_{\text{FRB}} = r_{\perp}^2 r'_{\parallel} = \Gamma_{\text{fb}}^3 5.8 \times 10^{21} \text{ cm}^3$.

Coherent emission

We consider the coherent sum of radiation fields by beam electrons contributing coherently to the total emission

$$E_{\text{tot},N_e} = E_{\text{tot},1e} [N_e + N_e(N_e - 1)b(\omega)]$$

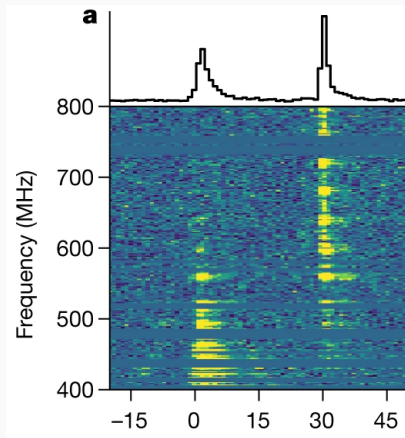
$$E_{\text{tot},N_e} = E_{\text{FRB}} = 6.4 \times 10^{34} \text{ erg}$$

Coherence parameter

$$b(\omega) \sim \frac{1}{N_e^2} \frac{E_{\text{tot},N_e}}{E_{\text{tot},1e}} \sim 4.3 \times 10^{-27}$$

Coherently emitting electrons

$$N_{\text{coh}} = \sqrt{N_e^2 b(\omega)} \sim 4 \times 10^{19}$$



Conclusions

Conclusions

- Magnetar SGR J1935+2154 is unique in the sense that $T = 80$ keV makes the closed fireball optically thick at l_0
- We consider $e^\pm$ creation outside a baryon-loaded expanding fireball
- 1D PIC simulations show that cavities filled with strong electrostatic fields are created by relativistic beam instabilities ($\Gamma_{e^\pm} > \Gamma_b$)
- A small coherence parameter is needed to produce an energy of $E_{\text{FRB}} = 6.4 \times 10^{34}$ erg
- Collisionless Bremsstrahlung can be an efficient mechanism for FRBs. We will test our model with a laser experiment

Questions?

Peak energies

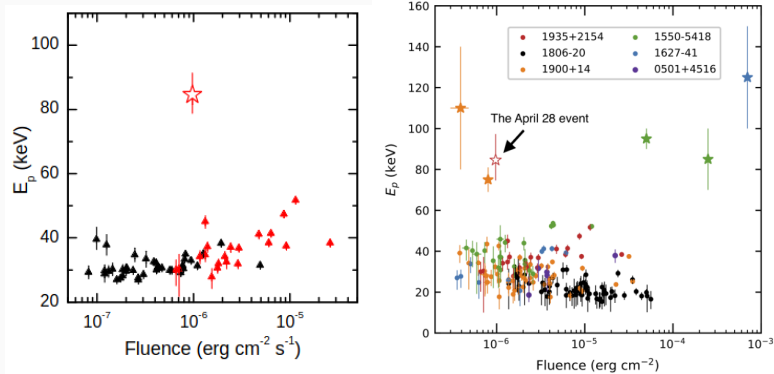


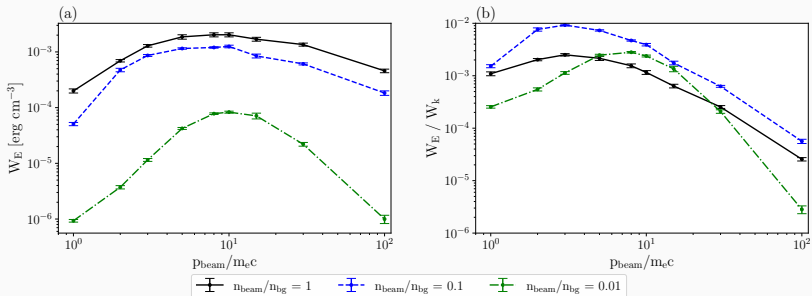
Figure 2: Left: the April 28 event and other SGR 1935+2154 X-ray bursts. Right: Peak energies E_p vs. total energy fluences of ~ 250 bright magnetar bursts. Ridnaia et al. 2021

PIC simulations

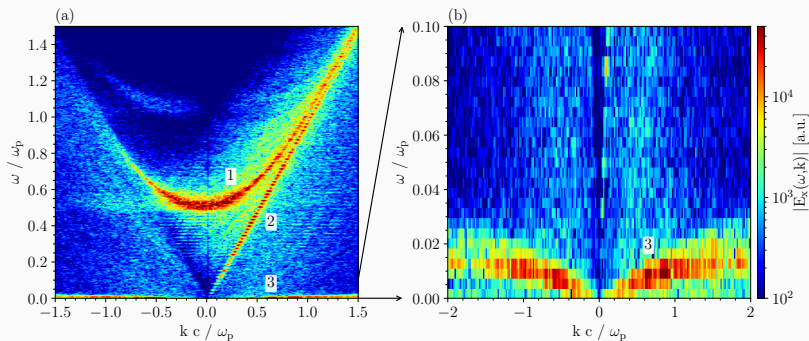
Particles have an initial Maxwell and Maxwell–Jüttner velocity distribution functions

$$g(u) = g_{\text{bg}}(u) + g_{\text{beam}}(u),$$

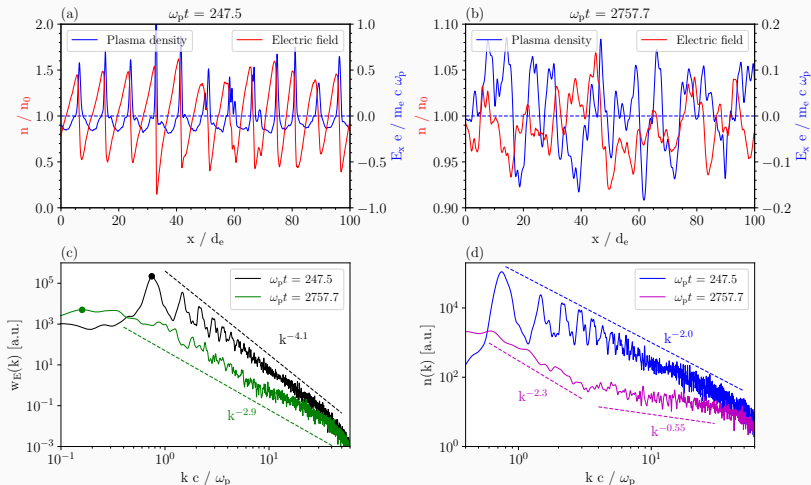
$$g_{\text{bg}}(u) = \left(\frac{n_{\text{bg}}}{2\pi v_t^2} \right)^{\frac{3}{2}} e^{-\frac{|u|^2}{2v_t^2}} \quad g_{\text{beam}}(u) = \frac{1}{\gamma_b} \frac{n_{\text{beam}}}{2K_1(\rho)} e^{-\rho \gamma_b \gamma (1 - \beta \cdot \beta_b)}$$



Dispersion properties of the electrostatic waves over the whole simulation time and for $p_{\text{beam}}/m_e c = 10$ and $n_{\text{beam}}/n_{\text{bg}} = 1$. The same data are in both plots but focusing on the Langmuir waves (left) and on the ion-acoustic waves (right)



Profiles of electric field and the plasma number density (top row) and their spectra (bottom row) during the Langmuir wave saturation time and close to the simulation end



Broadband emission in the laboratory

Broadband emission above $2\nu_p$ (plasma frequency) was discovered by Kato et al. (1983)

They explored beam-plasma propagation with the beam-plasma density ratio $n_{\text{beam}}/n_p > 0.1$ and with a relativistic electron beam of $\Gamma_{\text{beam}} = 3$

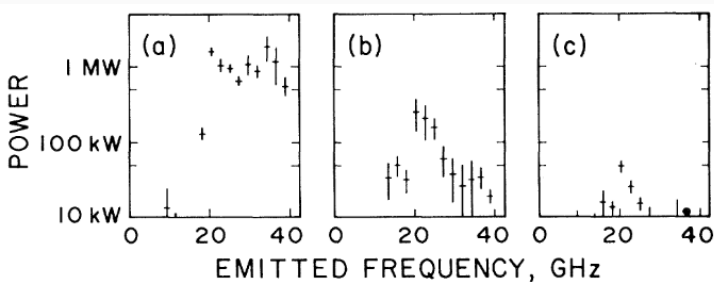


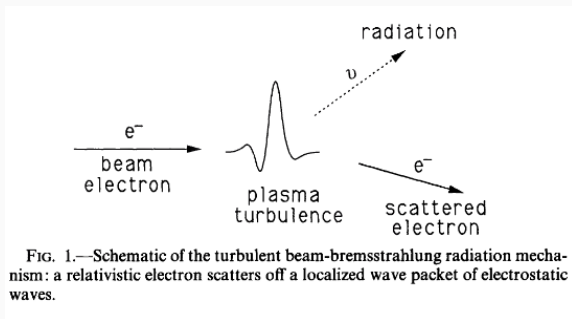
FIG. 2. Dependence of power on n_b with $f_p = 18$ GHz. (a) $n_b = n_0 = 10^{12}/\text{cm}^3$; (b) $n_b = n_0/4$; (c) $n_b = n_0/50$. As n_b falls, lines at $\sim f_p$ and $\sim 2f_p$ become more prominent.

Collisionless Bremsstrahlung

Weathrall & Benford (1991) and Benford & Weathrall (1992) quantify the emission and spectra of beam radiation in a turbulent plasma

Instability due to counter-streaming plasmas saturates in a turbulent state of intense localized regions of electrostatic field (cavitons)

Energetic electrons accelerate while traversing the cavitons



Weathrall & Benford (1991)

Laser experiment to test our model

Experiments (Kato et al. 1983), analytical models (Weathrall & Benford, 1991), and numerical simulations (Boyd & Ondarza-Rovira, 2016) suggest the existence of a radiation process in which relativistic electrons scatter coherently from concentrations of electrostatic plasma waves (cavitons)

Parameter	Value (ELIMAIA, ELI Beamlines)
Laser intensity	$I = 3 \times 10^{21} \text{ W cm}^{-2}$
Laser wavelength	$\lambda_L = 0.8 \mu\text{m}$
Laser frequency	$\omega_L = 2.35 \times 10^{15} \text{ rad s}^{-1}$
Cryogenic target number density	$n_t = 4.9 \times 10^{22} \text{ cm}^{-3}$
Width of the cryogenic target	$L_t = 100 \mu\text{m} = 128 \lambda_L$

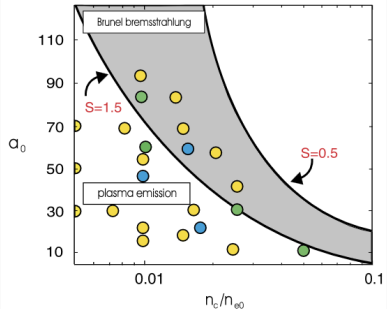
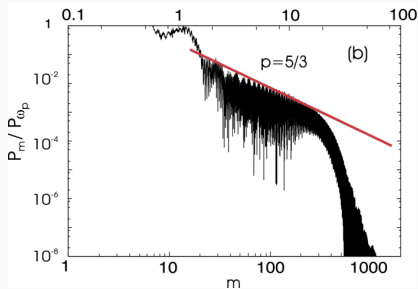
Laser experiment to test our model

Laser strength parameter:

$$a_0 = 36.8 \sqrt{\frac{I}{3 \times 10^{21} \text{ W cm}^{-2}}} \left(\frac{\lambda_L}{0.8 \mu\text{m}} \right)$$

Critical density (local plasma frequency = laser radiation frequency):

$$n_c = 1.7 \times 10^{21} \left(\frac{\lambda_L}{0.8 \mu\text{m}} \right)^{-2} \text{ cm}^{-3}$$



Boyd & Ondarza-Rovira (2016)