Quantum-electrodynamic magnetic reconnection as the origin of the FRB 200428-associated X-ray burst from SGR J1935+2154

Y. Xie
Peking University

Jin-Jun Geng
Purple Mountain Observatory, Chinese Academy of Sciences

Z. H. Zhao
Peking University

Z. Lei
Peking University

W. Q. Yuan
Peking University

gang zhao
CAS Key Laboratory of Optical Astronomy, National Astronomical Observatories, Beijing, 100101, China

Xue-Feng Wu
Purple Mountain Observatory

B. Qiao (bqiao@pku.edu.cn)
Peking University

Letter

Keywords:

Posted Date: January 5th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1031483/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License
Quantum-electrodynamic magnetic reconnection as the origin of the FRB 200428-associated X-ray burst from SGR J1935+2154

Y. Xie, J. J. Geng, Z. H. Zhao, Z. Lei, W. Q. Yuan, G. Zhao, X. F. Wu, and B. Qiao

1) State Key Laboratory of Nuclear Physics and Technology, Center for Applied Physics and Technology, and HEDPS, School of Physics, Peking University, Beijing 100871, P. R. China;
2) Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, P. R. China;
3) Key Laboratory for Optical Astronomy, National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China;
4) School of Astronomy and Space Sciences, University of Science and Technology of China, Hefei 230026, China;

(Dated: 29 October 2021)

Magnetars, often under the name soft gamma-ray repeaters (SGRs) or anomalous X-ray pulsars, are highly magnetized neutron stars that exhibit diverse X-ray activities. Recently, a unique non-thermal X-ray burst with cut-off energy up to 84 keV was detected from SGR J1935+2154 in the same single explosive event as the fast radio burst (FRB) 200428, as their spectra show similar feature of narrow double peaks that are emitted almost simultaneously. However, the physical origin of this FRB 200428-associated X-ray burst is still unknown yet. Here, with the first cross-scale numerical simulation in which modeling of particle acceleration by magnetic reconnections is self-consistently coupled with that of photon emission by multiple Compton scatterings, we identify that magnetic reconnection at the quantum-electrodynamic field strength inside the magnetar magnetosphere is the most likely driving source of such FRB-associated non-thermal X-ray burst. Both its temporal and spectral features are well reproduced in our simulations by assuming the plasma magnetization parameter $\sigma \sim 10^2 - 10^3$ in consistency with the astronomical observations. The results could greatly promote our understandings of various X-ray burst events from magnetars.

As shown in Fig. 1, we propose an origin model for the FRB 200428-associated X-ray burst that includes two stages. First, highly energetic particles are produced during magnetic reconnection at the quantum-electrodynamic field strength inside the magnetar magnetosphere; and then, the hard X-ray photons of the burst come into being during multiple Compton scatterings on a large astronomical scale between these energetic particles and the soft X-ray photons emitted from the magnetar photosphere. By self-consistently combining numerical modeling of such two stages (see Methods), we carry out, for the first time, integrated cross-scale numerical simulations to reproduce both the temporal and spectral features of the FRB 200428-associated X-ray burst.

The process of magnetic reconnection and particle acceleration is simulated by kinetic particle-in-cell (PIC) simulations (see Methods). According to the Insight-HXMT observations, the FRB 200428-associated X-ray burst might be emitted at the radius $R \sim 10^2 R_\ast$ within the light-cylinder $R_{LC} \sim 10^4 R_\ast$, where $R_\ast$ is the radius of the magnetar, which is adopted as the astronomical basis for the parameters set-up of our simulations. Different from the normal magnetic reconnection, the magnetic field within the magnetar magnetosphere at $R \sim 10^2 R_\ast$ is extremely strong as $B \sim B_\ast (R/R_\ast)^{\gamma} \sim 10^{10-12}$ G (if choosing the magnetar surface field strength $B_\ast \approx 10^{14}$ G) so that the plasma quantum parameter $\chi = \gamma B/B_\ast \sim 1$, where $\gamma$ is the pair plasma Lorentz factor and
Fig 1. Schematic of the proposed origin model for the FRB 200428-associated X-ray burst. The magnetic field lines disturbed by the Alfvén wave perturbation from the magnetar surface, are projected on a specific plane, showing multiple magnetic reconnection regions at a position of $R \sim 10^2 R_\ast < R_{LC}$ within the magnetar magnetosphere. The non-thermal energetic particles (electron-positron pairs) are accelerated in these reconnection regions, and then they scatter (i.e., multiple Compton scattering) the soft X-ray photons (bisque spiral arrows) emitted from the photosphere (brown disc) on a large astronomical scale with their frequency continuously upshifted, eventually resulting in the production of hard X-ray photons of the burst. The photons escaping from the scattering region are collected by the right probe plane as the observed spectra.

$B_s = 4.4 \times 10^{13} \text{G}$ is the QED “critical” field (“Sauter-Schwinger” field)\textsuperscript{20,21}, and the plasma magnetization parameter $\sigma = B^2 / 8\pi nm_e c^2 \gg 1$, where $n$ is the plasma density. Therefore, on the one hand, the nonlinear QED effects including photon emission and electron-positron pair creation play significant roles, on the other hand, the plasma is highly magnetized, which both lead to dramatically different dynamics of magnetic reconnection and particle acceleration here.

Figure 2 shows the reconnecting field topologies with plasmoid formations in the QED magnetic reconnections for $\sigma = 100$ (2a) and $\sigma = 10^4$ (2c), respectively. The corresponding simulations with the QED calculation switched off are also carried out for comparisons, shown in 2b and 2d. For low $\sigma = 100$, pair creations are comparatively nonsignificant, thus the reconnecting field topologies and the plasmoid structures induced by the tearing instability are similar between the results with and without QED effects (comparing 2a and 2b), similar to previous studies\textsuperscript{22,23}. When $\sigma$ is increased to $10^4$, the tearing instability is heavily suppressed without the formation of plasmoids if without the QED effects, see 2d. Thus, the particles in the vicinity of the X-point is accelerated rapidly up to the speed of light by the first-order Fermi acceleration along the current sheet, leading to a fast reconnection with reconnection rate $R_{rec} \approx 0.16$, see Extend Data Fig. 1b. However, after taking into account the QED effects, due to a large number of pair creations that supplement the plasma current sheet from the vicinity of X-points, the total number density of the reconnecting current sheet with QED effects is much higher (about 17 times higher) than that without QED effects, see 2c and 2d. As a result, with increasing of the thermal pressure, the tearing instability grows up again, leading to the formation of much larger and denser plasmoids than the low $\sigma$ case, see 2c. These plasmoids moving at a comparatively slow velocity $\sim 0.2c$, leading to decreasing of both the outflow velocity from X-points and the corresponding reconnection rate with $R_{rec} \approx 0.12$ (see Extend Data Fig. 1b). Furthermore, as a large number of created pairs due to the QED effects are eventually cooled down and trapped in the plasmoids, the current density $j_z$ increases, leading to a screening of the reconnecting electric field and reduction of the particle acceleration efficiency, see Extend Data Fig. 1d.

The energy spectra of the accelerated electrons driven by the above reconnections are plotted in Fig. 3a, which exhibit obviously different features. The high-energy segment of these electron spectra could be described by a non-thermal power-law distribution $dN/dE \propto E^k$ with a spectral index $k$ at the energy range of $E_\text{min} < E < E_c$, where $E_c$ is the cut-off energy of the electron spectra. The power-law index $k$ ranges from $\sim -1.33$ to $-1.30$, nearly unaffected by the QED effects for the case of low $\sigma = 100$, however, it varies significantly in a range of $[-1.39, -1.13]$ after
introducing the QED effects for the case of high $\sigma = 10^4$. The dependence of $k$ on $\sigma$ from more simulation runs is summarized in Fig. 3b. Without the QED effects, the electron energy spectra become monotonically harder when $\sigma$ increases, where $k$ gradually increases and approaches the asymptotic value $-1.0$. By contrast, with the QED effects taken into account, $k$ first increases and then decreases with increasing of $\sigma$, where, specifically, for $\sigma \gtrsim 10^3$, the electron energy spectra become softer with the spectral indices smaller than about $-1.2$. Such non-monotonic dependence of power-law index $k$ on the magnetization parameter $\sigma$ due to the QED effects determines the following unique X-ray emission features during multiple Compton scatterings.

The Compton scattering between non-thermal energetic particles and the soft X-ray photons emitted from the magnetar photosphere is the most promising origin of non-thermal hard X-ray emissions in the magnetar magnetosphere\textsuperscript{24–26}. Since the mean-free-path of photons, $\lambda \simeq 1/(\sigma_T n_{GJ})$ is much larger than the typical scale of magnetic reconnections ($\sim 1000 d_e$), where $\sigma_T$ is the Thomson cross-section, $n_{GJ}$ is the Goldreich-Julian density and $d_e$ is the electron skin depth, the Compton scattering process should occur repeatedly with photon frequency continuously upshifted in a much larger scale space than the local reconnection region. Due to this complex cross-scale simulation challenge, so far, no self-consistent numerical justification has been given for an explanation of the specific X-ray bursts yet. Using the above obtained electron spectra as the initial setup of non-thermal electrons, we further perform numerical simulations for the multiple Compton scatterings between the non-thermal particles and the soft X-ray photons in the magnetar magnetosphere with thick optical depth, where a large-scale multiple Compton scattering calculation module is developed and coupled with the above PIC simulations (details see Methods).

Figure 4a shows the time-integrated photon spectra resulting from multiple Compton scatterings with different non-thermal electrons. For electrons from the QED magnetic reconnection with low $\sigma$ (red line in Fig. 3a), a rather soft scattered photon spectrum ($p \sim -1.95$ in the middle energy range) with a lower cut-off energy ($<100$ keV) is obtained, see red line in Fig. 4a, where the photon spectrum is described by a power-law distribution of $d\nu/d\nu \propto \nu^{p+1}$. It deviates from the observational data of the FRB 200428-associated X-ray burst, in the medium energy (ME) and high energy (HE) range. For the high $\sigma$ case with QED effects (green line in Fig. 3a), a combination of larger $E_c = 200$ MeV and photon spectral index of $p \sim -1.58$ is obtained. Although it matches the observational data well in the ME range, strong QED effects limit numbers of high-energy photons, leading to a deviation in the HE range. This implies that $\sigma$ cannot be very high, otherwise, the particle spectrum is getting too soft to match the observational data. Among a series of simulation trials, we find that a relatively hard electron spectral index of $k = -1.2$ together with $E_c = 200$ MeV achieves a good fit to the whole photon spectrum of the observed FRB 200428-associated X-ray burst, where the reduced $\chi^2$-square is $\chi^2/d.o.f = 1.9$. This, therefore, indicates that the magnetization parameter of the emitting region of FRB 200428-associated non-thermal X-ray burst cannot be extremely high, which is about at a magnitude of $\sigma \sim 10^{2–3}$, see Fig. 3b.

As a comparison, we also calculated the scattered photon spectra by solving the photon Fokker-Planck equation.

Fig 2. Magnetic field topologies with plasmoid formations in reconnection for the low and high $\sigma$ cases. a and b. The snapshot colormaps of the current density $j_x$ normalized by $n_0 q_e c$ at $\omega_{pe} t = 700$ for the case of low $\sigma = 100$, where a and b are those of respectively with and without the QED effect taken into account. c and d. The corresponding results for the case of high $\sigma = 10^4$ at $\omega_{pe} t = 400$. The magnetic field lines are also shown with black solid lines in a-d.
Fig 3. The energy spectra of the accelerated electrons driven by the magnetic reconnections in Fig. 2 and the corresponding power-law indices of them varying with different magnetization parameters $\sigma$. a. The electron energy spectra from the reconnections for respectively low and high $\sigma$ cases in Fig. 2; b. The dependence of the electron spectral indices on the plasma magnetization parameter $\sigma$ for the cases with (red circle) and without QED effects (black triangle).

Numerically (see Methods). As shown in Extended Data Fig. 3, due to the lack of the cooling effect calculation for electrons from synchrotron radiation and Compton scattering, the scattered photon spectra are generally harder at the high energy range than those of PIC simulations. And they also deviate significantly from the observational data at the low energy range due to overestimation of the escaping thermal photons. This further manifests that PIC simulations for the multiple Compton scattering process are crucial to understanding the FRB 200428-associated non-thermal X-ray burst from SGR J1935+2154.

Finally, the two hard peaks feature of the FRB 200428-associated X-ray burst is also well reproduced in our magnetic reconnection and multiple Compton scattering scenario, as shown in Fig. 4b-4d. The simulated burst lightcurves consist of two components. One is the broad component with the duration of $\Delta t_b = 0.2$ s and exists in all energy ranges, see dashed blue lines in 3b-3d, which comes from the black body emission from the magnetar surface and is temporally described by a Gaussian function. The detailed parameters of the broad component can be seen in Methods. The other component, more notable in the higher energy range, is the two narrow peaks with each duration of $\sim$ ms, which is also well reproduced through our simulations, see the red lines in 3b-3d. The superposition of the two components can generally match the observed lightcurves, where the corresponding luminosity of our simulation is about $L \simeq 1.6 \times 10^{40}$ erg s$^{-1}$ close to the observational data with the value of $10^{40}$ erg s$^{-1}$ and our theoretical estimation for the X-ray luminosity (see Methods).

In summary, we have demonstrated that the FRB 200428-associated X-ray burst originates from the QED magnetic reconnection in the magnetosphere of SGR J1935+2154, which leads to the production of non-thermal particles and then the emission of hard X-ray photons through multiple Compton scattering between these particles and soft-X-ray photons from magnetar photosphere in a large-scale space. Both the temporal and spectral features of this burst are well reproduced in our simulations, implying that the local plasma magnetization parameter $\sigma$ is at the order of $10^3$, which makes it distinguished from other preceding bursts. Given that the plasma magnetization parameter $\sigma = B^2/(8\pi n m_e c^2)$ is critically determined by the local magnetic field strength, our results provide a tentative clue to probe the emitting location of such X-ray bursts within the magnetosphere. Similar studies on various X-ray bursts of magnetars from the perspective of our cross-scale simulation method that self-consistently couples both PIC and multiple Compton scattering modelings are encouraged. More miscellaneous physical processes, like turbulence and absorption, which might play roles in depicting the temporal/spectral behavior of the bursts, remain to be considered in our future work.
Fig 4. Time-integrated photon spectra and lightcurves from simulations of multiple Compton scatterings between non-thermal electrons obtained in Fig. 3 and the soft X-ray photons emitted from the magnetar photosphere. a, The time-integrated photon spectra in four cases with different cut-off energy and spectral indices, shown by different color lines. The markers show the observational data of Insight-HXMT in $1-10$ keV (Low Energy X-ray telescope, LE), $5-30$ keV (Medium Energy X-ray telescope, ME) and $20-250$ keV (High Energy X-ray telescope, HE) energy ranges, respectively, for the FRB 200428-associated non-thermal X-ray burst. The dashed dark line is the fitted spectrum by Insight-HXMT. Note that constant factors have been multiplied to the flux values (0.98 for ME and 0.68 for HE ranges) as mentioned by Li et al., to offset the different saturation and dead-time effects in different detectors. b - d, The numerical lightcurves in the LE, ME, and HE ranges of the third model (the dark line “3” in a), respectively. The blue dashed lines are the broad component fitted by the same Gaussian function in all the energy ranges. The red solid lines are the superposition of the scattered components and the broad components, and the black points are the observational data by Insight-HXMT.

METHODS

Our cross-scale numerical simulations self-consistently combine modeling of particle acceleration by magnetic reconnection with that of hard X-ray photon emissions by multiple Compton scatterings. First, particle acceleration and magnetic reconnection are modeled by particle-in-cell (PIC) simulations in the quantum-electrodynamical (QED) regime, from which we obtain the non-thermal particle spectra. Then, we apply these non-thermal electrons as the initial setup for the multiple Compton scattering calculations on a large astronomical scale. Besides, we also numerically solve the photon Fokker-Planck equations and estimate the hard X-ray luminosity for comparisons with our simulation results.

PIC simulations for QED magnetic reconnection and particle acceleration. The two-dimensional (2D) PIC simulations start from a strongly magnetized force-free current sheet configuration, which can refer to previous publications by using the code EPOCH27. The simulation box is composed of 1600 x 1600 cells, constituting a domain size of $L_x \times L_y = 400d_{e0} \times 400d_{e0}$ and the time step for each loop is set to be $\Delta t = 10^{-3}\sqrt{\sigma \omega_{pe}}$, where $\omega_{pe} = \sqrt{4\pi n_0 q^2/e m_e}$ is the electron plasma frequency. Periodic and conducting boundary conditions are used in the $x$-direction and $y$-direction, respectively. The initial anti-parallel magnetic field configuration in the force-free current sheet is written as

$$B = B_0 \tanh(y/w) \hat{e}_x + \frac{B_0}{\cosh(y/w)} \hat{e}_z,$$

and the initial drifting relativistic pair plasma density is written as

$$n_j(r) = n_0 \Gamma(r),$$

where $j = e$ stands for electron and $j = p$ for positron, respectively. $\Gamma(r) = 1/\sqrt{1 - \beta_j^2} = 1 + \sigma/[e^2 \cosh^2(y/w)]$ is the Lorentz factor of the bulk drifting velocity $\beta_j$ along the $x$ and $z$-direction, where $w = \kappa d_{e0}$ is the half-width of current sheet and $d_{e0} = c/\omega_{pe}$ is the skin
depth of electron. The above initial density $n_j(\mathbf{r})$, anti-parallel magnetic field $\mathbf{B}$ and the bulk drifting velocity $\mathbf{\beta_j}(\mathbf{r})$ satisfy the Ampère law

$$\nabla \times \mathbf{B} = \mu_0 c \sum_{j=\mathrm{e,p}} q_j n_j(\mathbf{r}) \mathbf{\beta_j}(\mathbf{r}).$$  \hspace{1cm} (3)$$

Since the twisted magnetic field may be regarded as a multipolar component near the magnetar surface, we adopt a relatively high magnetic field strength of $B_0 \sim 10^{12}$ G ($q \sim -1$) here. According to the blackbody temperature analysis observed from the radiation\(^2\), we assume that the pair plasma with the initial temperature $T_\mathrm{e} = T_\mathrm{p} \approx 1.2$ keV fills the simulation domain, where 50 quasiparticles per cell are used for both electrons and positrons, respectively. The QED module has been successfully applied in the PIC simulations\(^28,29\), where both the synchrotron radiation and Breit-Wheeler (BW) pair creation process\(^30\) are included. In order to explore the QED effects, the plasma magnetization parameter $\sigma$ is taken from $10^2$ to $4 \times 10^4$ for comparisons. The half-width of the current sheet is fixed as $\kappa = 20$.

We present detailed analyses on evolutions of energy conversion, magnetic flux (in the $x-y$ plane), and energy dissipation during the simulation of QED magnetic reconnection in Extend Data Fig. 1. In the low $\sigma$ cases ($\sigma = 100$), about 8% of magnetic energy is converted into plasma for both cases with and without the QED effects (Extend Data Fig. 1a). Meanwhile, a slow reconnection rate $R_{\mathrm{rec}} \approx 0.08$ and low dissipation rate $D = \mathbf{j} \cdot \mathbf{E} \approx 0.08$ are shown in the Extend Data Fig. 1b and Extend Data Fig. 1c, which are almost not affected by the QED effects. In the high $\sigma$ cases ($\sigma = 10^3$), the energy conversion increases up to 16.1% for the case without QED effects and to 11.47% for that with QED effects, respectively, where a big difference exists between them. The reconnection rate, although, also shows an increasing from low $\sigma$ to high $\sigma$ cases, it is clearly suppressed from $R_{\mathrm{rec}} \approx 0.16$ down to 0.11 when the QED effects are taken into account (see Extend Data Fig. 1b). Besides, the mean dissipation rate also increases with $\sigma$ but decreases caused by the QED effects (see Extend Data Fig. 1c). The details of the mean value of $j_x$ and $E_z$ evolutions of high $\sigma$ cases are presented in the inset panel d of Extend Data Fig. 1, showing that plenty of generated pairs supplement the current $j_x$ and the reconnection electric field $E_z$ is suppressed at a lower level since the early stage of reconnection $\omega_{pe,t} \approx 140$. These results manifest that the reconnection acceleration was strongly suppressed by the QED effects.

**Numerical simulations for large-scale multiple Compton scatterings.** A Compton scattering calculation module is implemented in our PIC code for simulations of the multiple Compton scattering process, which is similar to that in refs.\(^31,32\). The non-thermal electron spectra obtained in the above QED magnetic reconnection simulations, as parameterized by power-law index $k$ and cut-off energy $E_{\mathrm{cut}}$, are used as the initial conditions for the non-thermal particle setup in our multiple Compton scattering simulation in the large astronomical spatial and temporal scales. The computational domain covers a region of $200R_\odot \times 200R_\odot$ with 24 by 24 grids, where the boundary is periodic for pair particles and electromagnetic fields but open for photons. In the simulations, the multiple Compton scattering between photons and pairs is calculated by neglecting the plasma state, thus resolving the skin depth or the gyroradius of plasma is unnecessary, which allows us to run such astronomical scale simulations. The region is initially filled with background pair plasmas with a uniform number density of $n = \frac{n_0}{\rho_{\odot}^5 c^3}$, where $n_0$ is a typical equilibrium factor\(^33\), and a temperature of $T_b = 1.2$ keV with 2048 quasiparticles per cell. The non-thermal pair particles are excited from the background plasma in all grids with the excitation profile following a time profile of $V_{\mathrm{exc}}(t) = G(0.0,0.15,0.003) + G(0.0,0.019,0.003)$ (see Extend Data Fig. 2a), where $G$ is a Gaussian function described by the starting time, the peak time, and the time width at half height. The time interval of 40 ms in $V_{\mathrm{exc}}(t)$ represents the observed separation of $\sim 30$ ms in the two hard peaks of the burst from SGR J1935+2154 is represented. The soft X-ray photons are continuously injected from the left boundary and the Compton scattered photons are collected at the right boundary (see Fig. 1). Note that resonant cyclotron scattering should be taken into account for radiations in the magnetosphere. However, on the one hand, it strongly depends on the angle between the magnetic field and photon motion, which requires a very fine resolution of grids and a sufficient number of particles. On the other hand, because of the complicated turbulent magnetic field on a small spatial scale, the resonance scattering effect may equivalently contribute to the increase of scatter cross-section for photons of different energy ranges. Thus, for simplicity, we only consider the large-scale magnetic field of $B_0$ in the simulations, and attribute the resonant scattering effect to modification of the Compton scattering cross-section by multiplying a factor of $g \sim 10^{-3}$.

At first, it takes about 0.1 s for the thermal electrons and background soft X-ray photons to achieve the equilibrium state between them. Then, when the non-thermal particles are excited from plasma, the Compton scatterings between them and the soft X-ray photons occur repeatedly with the photon frequency continuously upshifted from soft (\sim keV) to hard (\sim 100–1000 keV), as shown in Extend Data Fig. 2, forming the X-ray burst. After the burst, at a time of 0.4 s, the equilibrium between pair particles and photons achieves again.

**Numerical solving of photon Fokker-Planck equation.** The photon Fokker-Planck equation that describes the time evolution of the photon spectrum scattered by a power-law distributed electrons is written as

$$\frac{d n'}{dt} = \frac{\partial}{\partial \epsilon} \left( \frac{e^2}{\tau_{\mathrm{th}}^2} + \delta(t) \frac{\epsilon^2}{\tau_{\mathrm{pl}}^2} \right) \frac{dn'}{d\epsilon} + \frac{k_B T}{\tau_{\mathrm{th}}^2} \left( \frac{\epsilon}{k_B T} \right)^2 \left( 2 - \frac{\epsilon}{k_B T} \right) + \frac{\epsilon}{2} \frac{\delta(t) k + 1}{\epsilon} \frac{\epsilon}{\tau_{\mathrm{pl}}^2} n' + Q + S,$$  \hspace{1cm} (4)$$

where $\epsilon$ is the photon energy, $n' = \epsilon^2 n$, $k_B$ is the Boltzmann constant, $Q$ and $S$ are the escaping and source terms respectively. Here, the thermal soft X-ray photons simultaneously interact with the thermal background and power-law components of pair particles. Two characteristic timescales for the thermal Comptonization and the interaction with power-law distributed particles can be written as

$$t_{\mathrm{c,th}} = \frac{1}{N \sigma_{\mathrm{e}c} k_B T},$$  \hspace{1cm} (5)$$

$$t_{\mathrm{c,pl}} = \frac{1}{N \sigma_{\mathrm{e}c}} \left[ \frac{2}{3} - \frac{1}{k_B T} \right]^{-1},$$  \hspace{1cm} (6)$$

where $N$ is the pair number density and $\eta = E_c / E_{\mathrm{min}}$. If we neglect the escaping and source terms, and take $\delta(t) \equiv 0$, Eq. (4) will reduce to the Kampanes equation. For the case of $\delta(t) > 0$, it means that the specific non-thermal pairs are excited in the systems. Similar to the setup of PIC simulations, we assume $\delta(t)$ has the same time profile as the above excitation rate $V_{\mathrm{exc}}(t)$. Furthermore, considering the soft X-ray background and the escape of photons, we take $Q = n' / V_{\mathrm{rec}}$ and $S = \frac{\epsilon^2 \exp(-\langle \epsilon / k_B T \rangle) / \tau_{\mathrm{exc}}}{V_{\mathrm{rec}}}$, where $\tau_{\mathrm{exc}} = \tau_{\mathrm{exc}} = 5 t_{\mathrm{c,pl}}$. Eq. (4) is then solved by Chang-Cooper method\(^34\) using the code Pychangcooper.

The numerical solutions of the photon Fokker-Planck interaction with the excitation of a power-law distributed particles are presented in Extend Data Fig. 3. By changing the excited particle power-law index $k$ from $-2.2$ to $-1.2$ with different cut-off energy $E_c = 20$ or
200 MeV, the results show that in the middle energy, the spectral indices are consistent with the observation data. However, due to the lack of cooling effect from synchrotron radiation and Compton scattering, the scattered photons are generally harder at the high energy range than those of PIC simulations. And they also deviate significantly from the observational data at the low energy range due to an overestimation of the escaping thermal photons.

**Estimation for the X-ray luminosity.** We consider the non-thermal accelerated electrons in QED reconnections have a power-law distribution \( f(\gamma_e) = A_0 \gamma_e^{b_1} \), in which the maximum energy can be estimated as \( \gamma_{\text{max}} \approx \sqrt{\sigma_m c^2} \). According to the energy conservation during reconnections, we have

\[
\int_1^{\infty} f(\gamma_e) \gamma_e m_ec^2 d\gamma_e = (\alpha) n_e q_b E_{\text{rec}} l V,
\]

where \( \langle \alpha \rangle \) is the averaged particle injection ratio, \( E_{\text{rec}} \approx 0.1cB_0 \) is the reconnection electric field, \( l \) is the scale of acceleration region, and \( \gamma \approx 4\pi^2\Delta r \) is the volume of the system. Taking the background photons as the blackbody radiation from a surface with temperature of \( T_\star \sim 10^7 \) K, the Compton scattering luminosity between the accelerated pair particles and photons is

\[
L = \frac{4}{3} \sigma_T c U_{\text{ph}} f_b \int_1^{\infty} f(\gamma_e) \gamma_e^2 d\gamma_e,
\]

where \( U_{\text{ph}} = 4\sigma_b T^4 (R/R_\star)^{-3}/c \) is the background photon energy density, \( f_b \) is the beaming factor of the emission region, and \( \sigma_b \) is the Stefan-Boltzmann constant. Combining Eqs. (7) and (8), the luminosity can be estimated as

\[
L = \frac{16\pi \sigma_T \sigma_b}{15\mu_0 m_e c^2} T^4 B^2 r^3 \langle \alpha \rangle f_b \frac{2 + k}{3 + k} \left( \frac{r}{R_\star} \right)^{\frac{-q_2}{d_0}} \left( \frac{l}{R_\star} \right) \left( \frac{\Delta r}{R_\star} \right) \approx 6.1 \times 10^{40} \left( \frac{\langle \alpha \rangle}{0.01} \right) \left( \frac{f_b}{0.1} \right) \left( \frac{r}{200R_\star} \right)^{-q_2} \left( \frac{l}{10000d_0} \right) \left( \frac{\Delta r}{100R_\star} \right) \text{ erg s}^{-1},
\]

which is consistent with the observed value of the FRB 200428-associated X-ray burst from SGR J1935+2154.

**DATA AVAILABILITY**

All relevant data except the Insight-HXMT data are available from the authors on request.

**CODE AVAILABILITY**

EPOCH is the Extendable PIC Open Collaboration project to develop a UK community advance relativistic EM PIC code. The open source code is available for download from https://cfsa-pmw.warwick.ac.uk/EPOCH/epoch

Pychangcooper is a simple numerical solver for Fokker-Planck style equations. The open source code is available for download from https://pychangcooper.readthedocs.io/en/latest/

**REFERENCES**

1Mazets, E. P., Golentsev, S. V. & Guryan, Y. A. Soft gamma-ray bursts from the source B1900+14. *Sov. Astro. Lett.* 5, 343 (1979).

2Mazets, E. P., Golentsev, S. V., Ilini, V. N., Aptekar, R. L., & Guryan, Iu. A. Observations of a flaring X-ray pulsar in Dorado. *Nature* 282, 587-589 (1979).

3Duncan, R. C. & Thompson, C. Formation of very strongly magnetized neutron stars-Implications for gamma-ray bursts. *Astrophys. J. Lett.* 369, L9-L13 (1992).

4Thompson, C. & Duncan, R. C. The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts. *Mon. Not. Roy. Astron. Soc.* 275, 25-300 (1995).

5Li, C. K. et al. HXMT identification of a non-thermal X-ray burst from SGR J1935+2154 and with FRB 200428. *Nat. Astron.* 5, 378-384 (2021).

6Ribda, A. et al. A peculiar hard X-ray counterpart of a Galactic fast radio burst. *Nat. Astron.* 5, 372-377 (2021).

7Tavani, M. et al. An X-ray burst from a magnetar enlightening the mechanism of fast radio bursts. *Nat. Astron.* 5, 401-407 (2021).

8Mereghetti, S. et al. INTEGRAL Discovery of a Burst with Associated Radio Emission from the Magnetar SGR 1935+2154. *Astrophys. J. Lett.* 898, L29 (2020).

9CHIME/FRB Collaboration et al. A bright millisecond-duration radio burst from a Galactic magnetar. *Nature* 587, 54-58 (2020).

10Bochenek, C. D. et al. A fast radio burst associated with a Galactic magnetar. *Nature* 587, 59-62 (2020).

11Zhang, B. The physical mechanisms of fast radio bursts. *Nature* 587, 45-53 (2020).

12Rea, N. & Esposito, P. Magnetar outbursts: an observational review. *Astrophys. Space Sci. Proc.* 21, 247 (2011).

13Mereghetti, S., Pons, J. A. & Melatos, A. Magnetars: Properties, Origin and Evolution. *Space Sci. Rev.* 191, 315-338 (2015).

14Kaspi, V. M. & Beloborodov, A. M. Magnetars. *Ann. Rev. Astron. Astrophys.* 55, 261-301 (2017).

15Lin, L. et al. Burst Properties of the Most Recurring Transient Magnetar SGR J1935+2154. *Astrophys. J.*, 893, 156 (2020).

16Younes, G. et al. Broadband X-ray burst spectroscopy of the fast-radio-burst-emitting Galactic magnetar. *Nat. Astron.* 5, 408-413 (2021).

17Lin, L. et al. No pulsed radio emission during a bursting phase of a Galactic magnetar. *Nature* 587, 63-65 (2020).
ACKNOWLEDGEMENTS

We thank the Insight-HXMT team for sharing the observational data and You-Li Tuo for helpful discussions. This work is supported by the Science Challenging Project, No. TZ2018005; the National Natural Science Foundation of China, grant Nos. 12135001, 11825502, 11921006, 11723514, 11903019, 11833003, and 12041306; the Strategic Priority Research Program of the Chinese Academy of Sciences, grant No. XDA25050900. B.Q. acknowledges support from the National Natural Science Funds for Distinguished Young Scholars, grant No. 11825502. The simulations are carried out on the Tianhe-2 supercomputer at the National Supercomputer Center in Guangzhou.

AUTHOR CONTRIBUTIONS

B.Q. proposed and were in charge of the research campaign as principle investigators. Y.X., J.J.G., Z.H.Z., Z.L., W.Q.Y. and B.Q. carried the simulations and the data analysis. J.J.G., G.Z. and X.F.W carried out the astronomical observational data analysis and comparison. B.Q., Y.X., J.J.G. and X.F.W. wrote the paper. All authors contributed to the discussions and approved the final version of the manuscript.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Correspondence and requests for materials should be addressed to B.Q. and X.F.W.
Extended Data Fig 1. Dynamics of the QED magnetic reconnections in our 2d PIC simulations. a. Time evolutions of the total field energy (dash-dotted lines), the total particle energy (dashed line), and the total energy (solid lines) for the cases of respectively $\sigma = 100$ and $10^4$ and with and without QED effects. b. The corresponding time evolutions of magnetic flux in the x-y plane for various cases. The magnetic fluxes are calculated as $\Phi_x = \int_{-L_y/2}^{L_y/2} B_x \, dy$ and $\Phi_y = \int_{-L_x/2}^{L_x/2} B_y \, dx$ along the black dashed line, respectively as shown in Fig. 2d (normalized by $B_0d_0$). The mean reconnection rate $R_{\text{rec}} = |\Delta \Phi_x(y)/\Delta t|$ is calculated by the magnetic flux change within a certain period of time (normalized by $cB_0$). c. Time evolutions of the dissipation rate $D = \mathbf{j} \cdot \mathbf{E}$ around the current sheet for different cases. The dissipation rate $D$ is an average value calculated in a rectangle around the current sheet ($|\Delta x| < 100d_0$ and $|\Delta y| < 30d_0$) (normalized by $n_0\Gamma\beta cB_0c^2$). d. Time evolutions of the averaged $j_z$ and $E_z$ around the current sheet in the high $\sigma = 10^4$ cases. To show the reconnection electric field more clearly, $j_z$ is normalized by $n_0\Gamma\beta c$ and $E_z$ is normalized by $0.2B_0c$, respectively.
Extended Data Fig 2. The time profile for excitation of the non-thermal electrons from the background pair plasma and the time evolutions of electron and photon energy spectra during multiple Compton scattering. a, The time profile of the excitation rate $V_{\text{exc}}(t)$, which is composed of two Gaussian functions. b, The electron energy spectra in the system varying from 0.1 s to 0.4 s. c, The photon spectra collected in the probe at the right boundary of the system varying from 0.1 s to 0.4 s.
Extended Data Fig 3. Numerical solutions of the photon Fokker-Planck equation. a, The time-integrated photon spectra with the high cut-off energy $E_c = 200$ MeV and the power-law index $k$ ranging from $-2.2$ to $-1.2$, which are shown in different color lines. b, The time-integrated photon spectra with low cut-off energy $E_c = 20$ MeV. All numerical solutions are solved with the same temperature $k_B T = 1.2$ keV and $E_{\text{min}} = 10$ keV.