

Evidence for a Damped Millisecond Quasi-Periodic Structure in a Fast Radio Burst

Shuo Xiao^{1,2}, Zheng-Huo Jiang^{1,2}, Di Li^{3,4,5*}

¹*School of Physics and Electronic Science, Guizhou Normal University, Guiyang 550001, China*

²*Guizhou Provincial Key Laboratory of Radio Astronomy and Data Processing, Guizhou Normal University, Guiyang 550001, China*

³*New Cornerstone Science Laboratory, Department of Astronomy, Tsinghua University, Beijing 100084, China*

⁴*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China*

⁵*Zhejiang Lab, Hangzhou, Zhejiang 311121, China*

Fast radio bursts (FRBs) are millisecond-duration transients of unknown origin, likely associated with compact astrophysical objects. We report evidence for a damped millisecond quasi-periodic structure in a non-repeat FRB 20190122C. The burst consists of eight closely spaced radio pulses separated by ~ 1 ms, with pulse amplitudes exhibiting an exponential decay starting from the brightest component. Combined Gaussian fitting and time-series analysis reveal a quasi-periodic oscillation (QPO) at ~ 1 kHz. The observed QPO is consistent with damped magnetospheric oscillations. Assuming an Alfvén wave origin, we estimate a surface magnetic field of $\sim 10^{12}$ G and a characteristic spin period of ~ 1 s, favoring a low-field magnetar or young neutron star scenario. The absence of frequency drift and the presence of exponential damping disfavor a merger-driven origin. These results suggest the first detection of an exponentially decaying QPO in any FRB, marking a rare detection of coherent oscillatory behavior in FRBs.

Fast radio bursts (FRBs) are millisecond-duration flashes of radio waves that originate from extragalactic distances. Their immense brightness temperatures imply coherent emission

mechanisms, yet the identity of their progenitors remains unresolved. Whether all FRBs, especially the repeating and non-repeating types, emerge from a single physical class or represent distinct populations continues to be debated (e.g. ^{1–4}). Repeaters exhibit persistent activity over months or years, whereas some FRBs—despite follow-up efforts—remain singular events. This observational dichotomy suggests a range of possible origins, from cataclysmic explosions to magnetospheric instabilities ^{5,6}.

The detection of FRB 200428, temporally coincident with an X-ray burst from the Galactic magnetar SGR J1935+2154, has offered a compelling data point linking magnetars to FRB production ^{7–9}. SGR J1935+2154 was subsequently detected as a radio pulsar ^{10,11} by the FAST telescope ¹², the pulses of which can only be seen from within the MilkyWay with current technology. Further episodic radio bursts from SGR J1935+2154 have also been reported ¹³. While this event bridged Galactic and extragalactic phenomena, its radio burst was several orders of magnitude fainter than cosmological FRBs. A quasi-periodic oscillation at 40 Hz observed in the associated X-ray burst ¹⁴ raises the possibility that magnetospheric oscillations may manifest across wavebands, though no periodicity was identified in the FRB itself.

In this work, we present observations of FRB 20190122C (Sec. 1 in **Methods**), a non-repeating event detected with the CHIME telescope ¹⁵. The burst profile reveals eight narrowly spaced pulses over a few milliseconds, with a striking regularity in their arrival times (as shown in Figure. 1). A closer examination shows that the amplitudes decay exponentially after the strongest, third pulse. This pulse train structure is unlike that of typical FRBs and suggests the presence of a damped, coherent oscillation.

To quantify the temporal pattern, we performed peak-timing analyses ^{16,17}. Fitting the Gaussian peak times (Sec. 3 in **Methods**) yields a period of 0.994 ± 0.014 ms (as shown in Figure. 2 and Extended Data Table. 1). Monte Carlo simulations indicate a false-alarm probability

below 1% (as shown in Extended Data Figure. 2, Sec. 4 in **Methods**). Separately, the amplitude decay follows an exponential profile with decay scale $\tau = 2.24 \pm 0.06$ ms (as shown in Figure. 3, Sec. 5 in **Methods**) at 3.2σ significance (as shown in Extended Data Figure. 3). Taken together, these results provide strong evidence for a damped millisecond quasi-periodic oscillation in FRB 20190122C. While the statistical significance does not reach the conventional discovery threshold, it is among the highest reported for QPO-like features in FRBs to date (as shown in Extended Data Table. 2). This detection highlights a rare instance where coherent oscillatory behavior may be imprinted onto the burst signal.

The oscillation’s quality factor, $Q \sim 7$, suggests moderate coherence, possibly arising from magnetospheric or crustal oscillations^{18,19}. Assuming an Alfvén wave interpretation²⁰, the observed frequency implies a magnetic field strength of order 10^{12} G (Sec. 6 in **Methods**), compatible with low-field magnetars such as SGR 0418+5729²¹, and the 1 kHz quasi-periodic signal with exponential damping resembles features seen in magnetar giant flares (e.g.^{22,23}). Interestingly, the inferred periodicity may correspond to a neutron star spin period of about 1 s, this lies within the range of known radio pulsars and magnetars, if one accepts a scaling between sub-millisecond features and rotation²⁴.

Scenarios involving binary mergers or compact object coalescence are less favored. Such processes would likely exhibit increasing energy release as the system approaches merger, in contrast with the clear post-peak decay observed here. Moreover, no frequency evolution is seen during the burst—an expected hallmark of dynamic merger environments²⁵.

Our findings suggest that at least some non-repeating FRBs may originate from transient excitations of oscillatory modes in isolated, strongly magnetized neutron stars. The observed morphology, regularity and decay pattern in FRB 20190122C mark it as a rare case where coherent dynamics imprint directly onto the radio signal. With only a handful of FRBs exhibiting

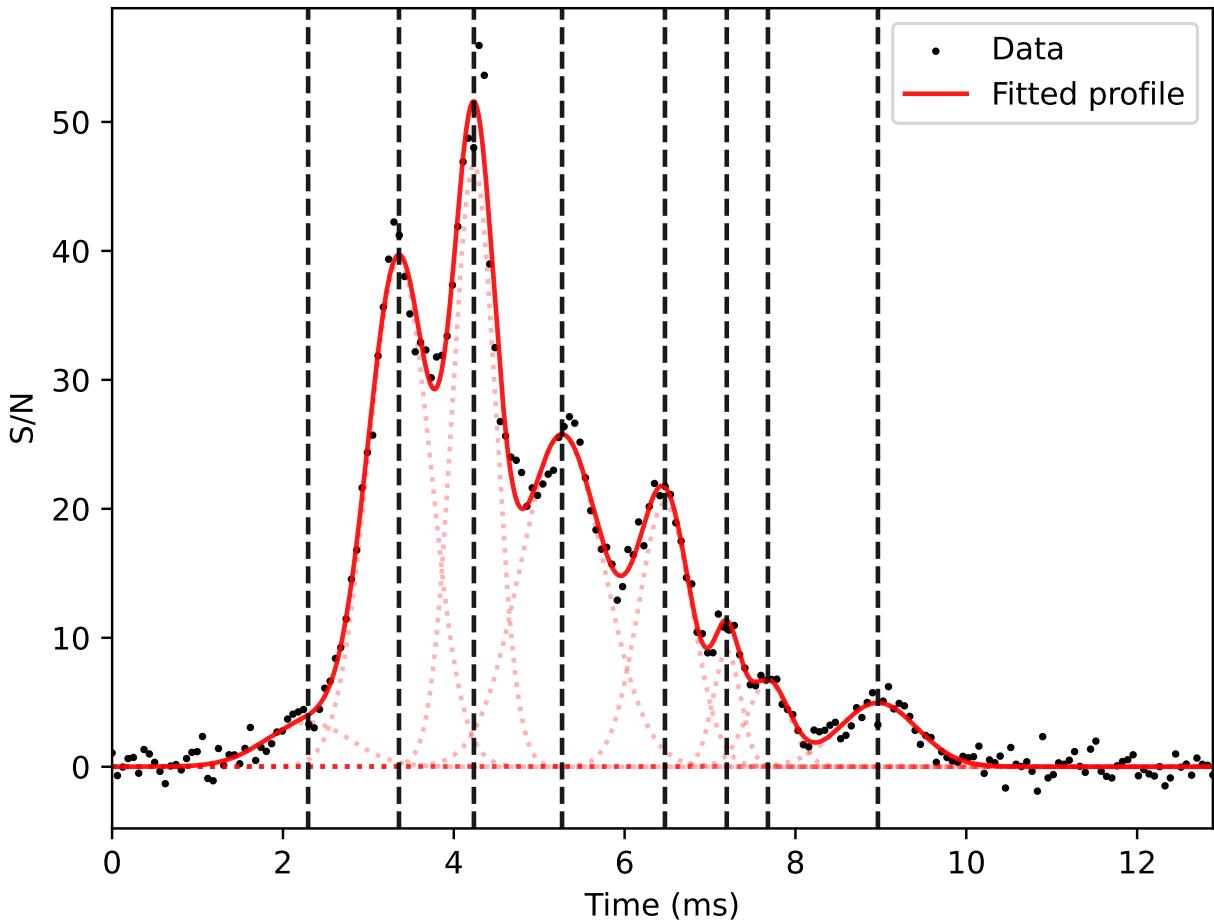


Figure. 1: Temporal profile of FRB 20190122C (black points) with Gaussian component fitting (red solid line). The burst is modeled as a sum of multiple Gaussian pulses, each represented by a red-dotted curve. Vertical dashed black lines indicate the location of individual pulse peaks.

comparable structure^{16,17,26} (as shown in Figure. 4, Extended Data Table. 2), events like this may serve as key probes of neutron star interiors and magnetospheres.

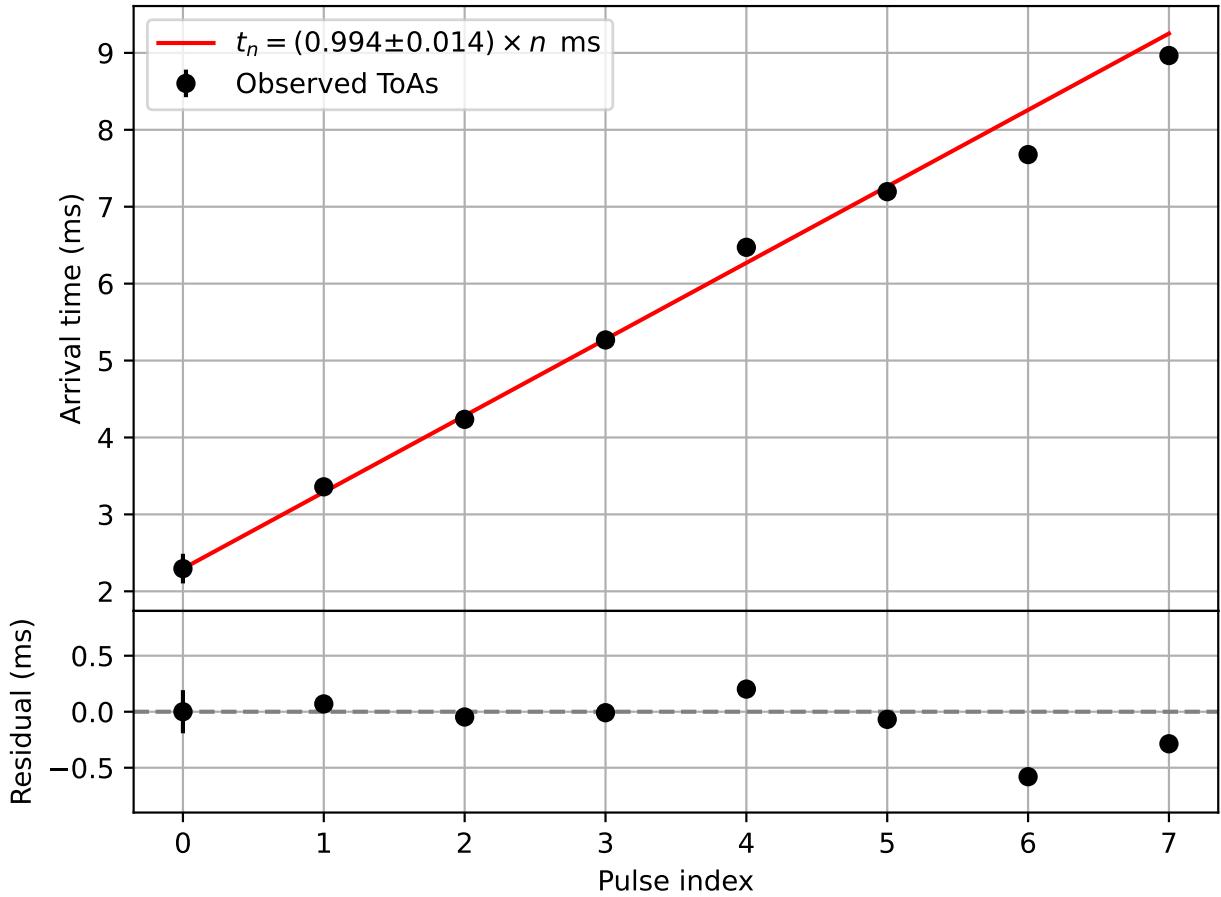


Figure. 2: Linear fit to the arrival times of the eight pulse components in the burst. The best-fit model is shown in red with the fitted relation $t_n = T_0 + n P_{\text{QPO}}$, where $P_{\text{QPO}} = (0.994 \pm 0.014)$ ms. The lower panel displays the residuals between the observed and fitted times.

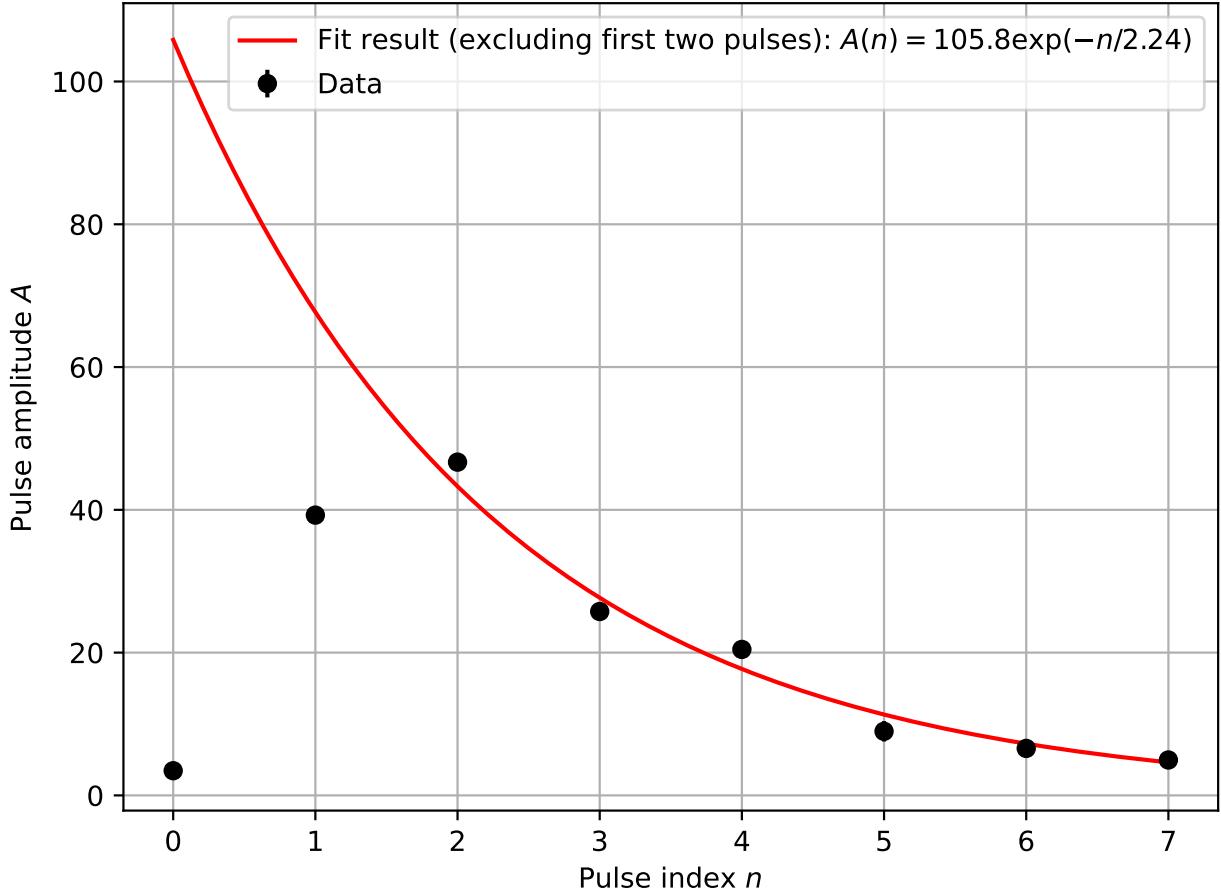


Figure. 3: Exponential decay of pulse amplitudes. The black circles with error bars denote the measured amplitudes of the eight pulses. A subset of the pulses (from the third to the eighth, i.e., $n = 2$ to $n = 7$) is fitted with an exponential decay function $A(n) = A_0 \exp(-n/\tau)$, shown as the red curve. The best-fit parameters are $A_0 = 105.83 \pm 3.80$ and $\tau = 2.24 \pm 0.06$.

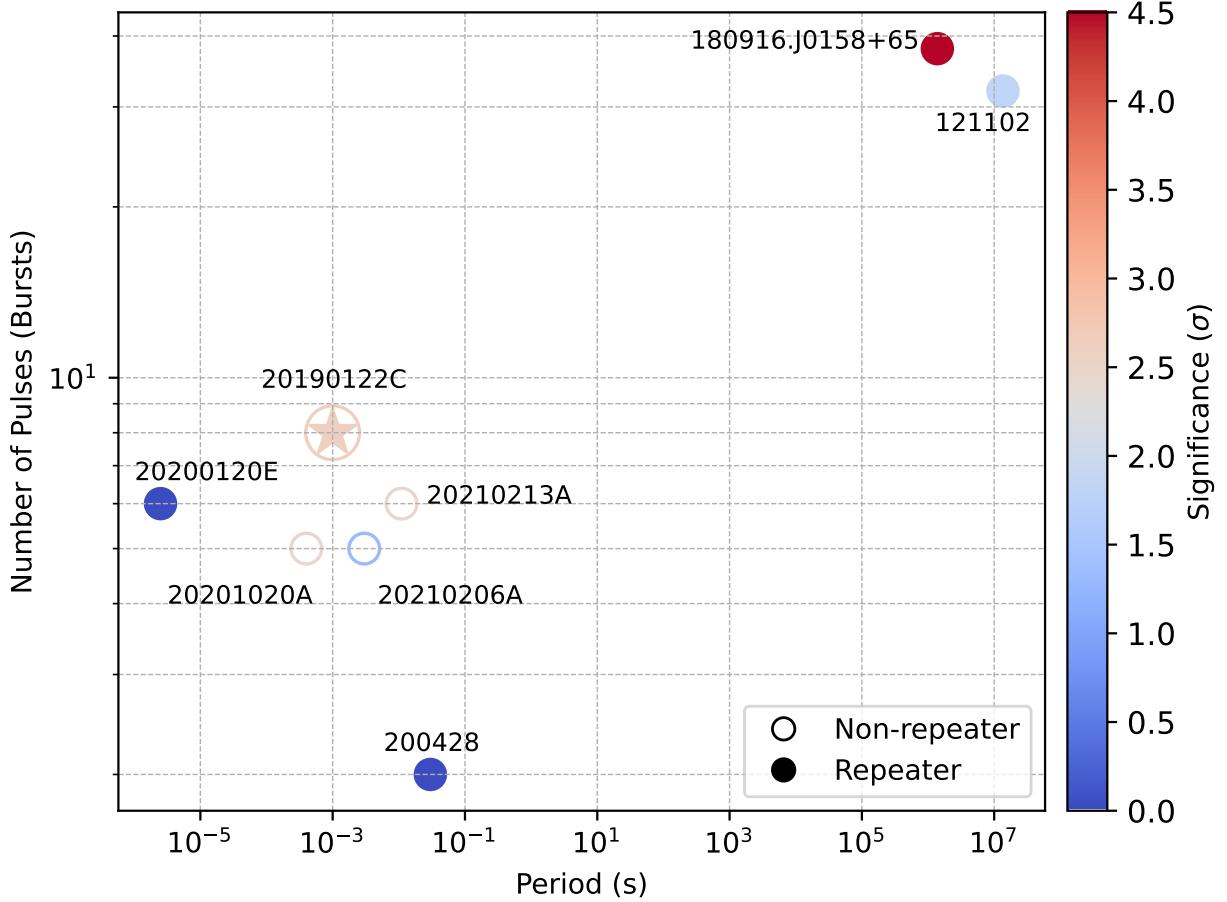


Figure. 4: Reported quasi-periodic structures (or bursts) in fast radio bursts ^{7,8,16,26–28}. The horizontal axis shows the characteristic period or quasi-period in seconds; the vertical axis indicates the number of resolved pulses or sub-bursts. Marker colour encodes the reported significance of periodicity (redder implies higher), using a linear colour scale. Stars denote FRB 20190122C (this work), hollow circles represent non-repeat FRBs, while solid circles mark repeat ones. FRB 20190122C stands out as the only source exhibiting a quasi-periodic structure with clear exponential damping, featuring eight pulses at millisecond intervals.

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Methods

1 Data and preprocessing

FRB 20190122C is detected on 2019 January 22 by the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst project (CHIME/FRB), a dispersion measure of $690.032(8)$, pc, cm $^{-3}$ and is localized at R.A.,=,200.4987(12), Decl.,=,17.5914(13), with a fluence of 120(10) Jy, ms and a peak flux density of 13(1) Jy ¹⁵. Following the public release of baseband-level voltage data*, we retrieved the coherently dedispersed total intensity time series for analysis. These data provide microsecond time resolution and allow detailed investigation of the burst's fine temporal structure.

Initial processing involved standard radio data handling procedures. We removed frequency channels affected by radio frequency interference (RFI) and integrated across the full observing band to obtain a one-dimensional time series. This final profile revealed a strikingly structured burst composed of eight sub-pulses, narrowly spaced pulses over a few milliseconds.

2 Exclude known pulsar sources

Recent developments indicate that, FRB 20191221A ¹⁷, the apparent periodicity of which likely originated from the pulsar J0248+6021 nearby. It is noteworthy that FRB 20190122C has a much different sky location. The coordinates of FRB20190122C are R.A.,=,200.4987(12) and Decl.,=,17.5914(13). We searched the ATNF pulsar catalog (psrcat) for all pulsars within a 30° radius of this position. Among these, the pulsar with the highest dispersion measure (DM) is PSR J1239+0326, with a DM of 34.29 pc/cm 3 . FRB20190122C has a Galactic latitude of 78.07° , placing it well outside the Galactic plane. Besides, the FRB's DM is 689.9 pc/cm 3 , which is significantly higher than that of any nearby source.

*<https://doi.org/10.11570/23.0029>

3 Pulse modeling

To characterize the temporal morphology, we modeled the burst as a superposition of different Gaussian components. Each pulse was fit with the functional form:

$$f(t; A, \mu, \sigma) = A \exp \left[-\frac{(t - \mu)^2}{2\sigma^2} \right], \quad (1)$$

where A is the amplitude, μ is the central time (i.e., pulse peak), and σ the width. The fitting was performed via nonlinear least-squares optimization, and uncertainties in μ were estimated from the diagonal terms of the parameter covariance matrix. These peak times, along with their 1σ uncertainties, form the basis for all time-domain periodicity analyses.

To assess the quality of the fit, we explored the effect of varying the number of pulses included in the model¹⁷. The reduced χ^2 values for fits with different numbers of pulses are shown in Extended Data Figure. 1. The red dashed line at 8 pulses marks the optimal number, where further increases in the number of pulses did not significantly improve the fit quality, indicating that 8 pulses provide a reasonable balance between model complexity and fit accuracy.

4 Search for periodicity

We assessed the regularity of the eight pulses by fitting their arrival times t_n to a linear model:

$$t_n = T_0 + nP_{\text{QPO}}, \quad (2)$$

where T_0 is the reference arrival time, n is the pulse index (ranging from 0 to 7), and P_{QPO} is the candidate period. The best-fit period was derived using a weighted least-squares fit, and the fit quality was evaluated via the reduced chi-squared statistic (χ^2_ν).

To quantify the likelihood of obtaining such regular spacing by chance, we ran Monte Carlo simulations under a null hypothesis in which pulses are spaced randomly but with a minimum delay

constraint to account for finite pulse widths. We followed the method proposed by ¹⁶, drawing simulated inter-pulse intervals from a shifted Poissonian distribution:

$$d_i = -(1 - \eta) \bar{d} \ln(1 - x_i) + \eta \bar{d}, \quad (3)$$

where x_i is sampled from a uniform distribution in [0,1], \bar{d} is the mean interval, and η controls the minimum spacing (we adopted $\eta = 0.2$ as in ¹⁶). Each synthetic pulse train was subjected to the same linear fitting, and the resulting χ^2_ν values were compared against the observed one to estimate a false-alarm probability.

Fitting the Gaussian peak times yields a period of 0.994 ± 0.014 ms without detectable frequency drift (as shown in Figure. 2), and Monte Carlo simulations indicate a false-alarm probability below 1% (as shown in Extended Data Figure. 2).

When considering the effect of multiple trials, we note that our periodicity search was only applied to bursts with more than five resolved sub-pulses. In the current CHIME/FRB baseband publicly available sample ¹⁵, there is only one such event, FRB 20190122C, which exhibits the largest number of pulses. The majority of events in the sample typically have one or two sub-pulses ¹⁵. As such, FRB 20190122C is an extremely rare event in the CHIME/FRB data, with multi-pulse events being exceptionally uncommon. Therefore, the correction for the number of trials is minimal, and the significance of the detected quasi-periodicity and the following exponential decay analysis is only marginally affected.

5 Amplitude decay analysis

The pulse amplitudes from the Gaussian fits exhibit a peak at the third component, followed by a monotonic decrease. We modeled this amplitude evolution using an exponential decay function:

$$A_n = A_0 \exp\left(-\frac{n}{\tau_{\text{amp}}}\right), \quad (4)$$

where A_0 is the amplitude and τ_{amp} is the decay constant. The best-fit value of $\tau_{\text{amp}} = 2.24 \pm 0.06$ pulses was determined via least-squares fitting. To evaluate its significance, we generated 100,000 mock amplitude sequences drawn from a uniform distribution and applied the same fitting procedure. Only 0.0016 of simulations produced a better exponential fit, corresponding to a significance of approximately 3.2σ .

We note that the similar fast-rise and exponential-decay morphologies have also been recently reported in a Galactic radio burst in the Carina nebula²⁹, suggesting that such temporal envelopes may be a more generic signature of magnetospheric relaxation processes.

6 Theoretical interpretation and parameter estimates

Given the observed QPO period $P_{\text{QPO}} \approx 0.994$ ms and the exponential amplitude decay scale $\tau_{\text{amp}} \approx 2.24$ ms, we estimate a quality factor $Q \sim \pi\tau_{\text{amp}}/P_{\text{QPO}} \approx 7$. This moderate coherence is compatible with damped magnetospheric oscillations excited by a localized energy release, as expected in magnetar models involving Alfvén wave propagation or crustal shear mode coupling (e.g.^{18,19}).

Assuming the QPO arises from standing Alfvén wave modes in the magnetosphere of a magnetar (e.g.²⁰), we can estimate the implied magnetic field strength. The Alfvén velocity is given by $v_A = B/\sqrt{4\pi\rho}$, where ρ is the plasma mass density. For a loop or field-line structure of scale L , the fundamental oscillation frequency is $f_{\text{QPO}} = v_A/2L$, which leads to

$$B = 2L f_{\text{QPO}} \sqrt{4\pi\rho}. \quad (5)$$

Adopting representative values of $L \sim 10^6$ cm and $\rho \sim 10^5$ g cm⁻³ and using the observed

QPO frequency $f_{\text{QPO}} = 1/P_{\text{QPO}} \approx 10^3$ Hz, we obtain

$$B \approx 2 \times 10^6 \text{ cm} \times 10^3 \text{ Hz} \times \sqrt{4\pi \times 10^5 \text{ g cm}^{-3}} \approx 2 \times 10^{12} \text{ G}. \quad (6)$$

Although the estimated magnetic field strength from the observed QPO frequency is $B \approx 2 \times 10^{12}$ G, this is somewhat lower than the canonical range for magnetars (10^{14} – 10^{15} G). However, the result remains compatible with the strong-field regime of high-field neutron stars. Notably, some magnetar candidates, such as SGR 0418+5729, exhibit inferred dipole fields as low as $\sim 8 \times 10^{12}$ G, yet display magnetar-like activity²¹.

Although the inferred magnetic field strength from the observed QPO frequency is only $B \sim 10^{12}$ G, this is significantly lower than the canonical values of 10^{14} – 10^{15} G typically associated with magnetars. This apparent discrepancy can be reconciled if one considers that the dipolar field inferred from spin-down is not the sole reservoir of magnetic energy. Strong internal toroidal components and twisted magnetospheres may store far more energy than indicated by the surface dipole alone. Recent theoretical work has suggested that intermediate-field magnetars ($B \sim 10^{12}$ – 10^{13} G) are still capable of powering energetic bursts through processes such as magnetospheric reconnection, Alfvén–fast mode conversion, or magneto-elastic oscillations in the stellar crust^{30,31}. In such scenarios, quasi-periodic pulse trains could arise naturally from oscillatory modes or reconnection-driven plasmoid shedding, while the observed exponential damping reflects dissipation of these transient modes. Thus, even if the surface dipole field of FRB 20190122C is relatively modest, the event remains consistent with a magnetar origin where the key driver is internal magnetic structure and magnetospheric dynamics, rather than the dipole strength alone.

On the other hand, this magnetic field estimate is sensitive to assumptions regarding the emission region scale (L) and local plasma density (ρ). If the emission arises in a more compact structure or denser plasma, the inferred field could increase by an order of magnitude. Furthermore,

if the observed QPO corresponds to a higher-order Alfvén mode, the true fundamental frequency would be lower, implying a correspondingly stronger magnetic field. Taken together, the inferred parameters remain broadly consistent with Alfvénic oscillations in a strongly magnetized neutron star magnetosphere, supporting the hypothesis that FRB 20190122C originates from magnetospheric activity in a compact object with magnetar-like properties.

This finding is reminiscent of oscillatory behavior observed in magnetar X-ray bursts, where quasi-periodic signals have been interpreted as global seismic or magnetospheric oscillations. If the observed radio QPO originates from Alfvénic oscillations in a magnetized plasma, the implied magnetic field strength is consistent with magnetar-scale fields, lending support to the hypothesis that some non-repeating FRBs may originate from energetic activity in isolated compact objects.

An intriguing possibility arises when considering the quasi-periodic pulse spacing in FRB 20190122C in the context of neutron star rotation.²⁴ proposed that sub-millisecond quasi-periodic features in single pulses may scale with the spin period of neutron stars via the empirical relation $P_\mu \approx 10^{-3} P_{\text{rot}}$, where P_μ is the substructure spacing and P_{rot} is the rotation period. Applying this scaling to our detected $P_{\text{QPO}} \approx 1 \text{ ms}$, we infer a potential spin period of $P_{\text{rot}} \approx 1 \text{ s}$. This lies within the range of known radio pulsars and low-field magnetars such as SGR 0418+5729.

Another plausible class of FRB progenitor models involves compact binary mergers or interactions, such as neutron star–neutron star coalescence or magnetospheric collisions during inspiral phases (e.g. ^{25,32}). However, our observations disfavor such scenarios for FRB 20190122C. First, the observed quasi-periodic oscillation exhibits no measurable frequency evolution over the $\sim 7 \text{ ms}$ duration of the burst, arguing against a rapidly evolving dynamical timescale expected in merger-driven processes. Second, if the observed pulse train originated from magnetospheric interactions between inspiraling compact objects, the energy release would likely increase toward

coalescence, resulting in a rising amplitude envelope. In contrast, the pulse amplitudes in FRB 20190122C show an exponential decay following the strongest pulse, consistent with a relaxation or damping process rather than escalating activity. These features are more naturally explained by a transient excitation of quasi-normal modes in an isolated neutron star magnetosphere, rather than merger-driven dynamics.

7 Data availability

The full-resolution baseband data and dedispersed time series of FRB 20190122C analyzed in this study are publicly released by the CHIME/FRB Collaboration <https://doi.org/10.11570/23.0029>. No proprietary data were used.

8 Code availability

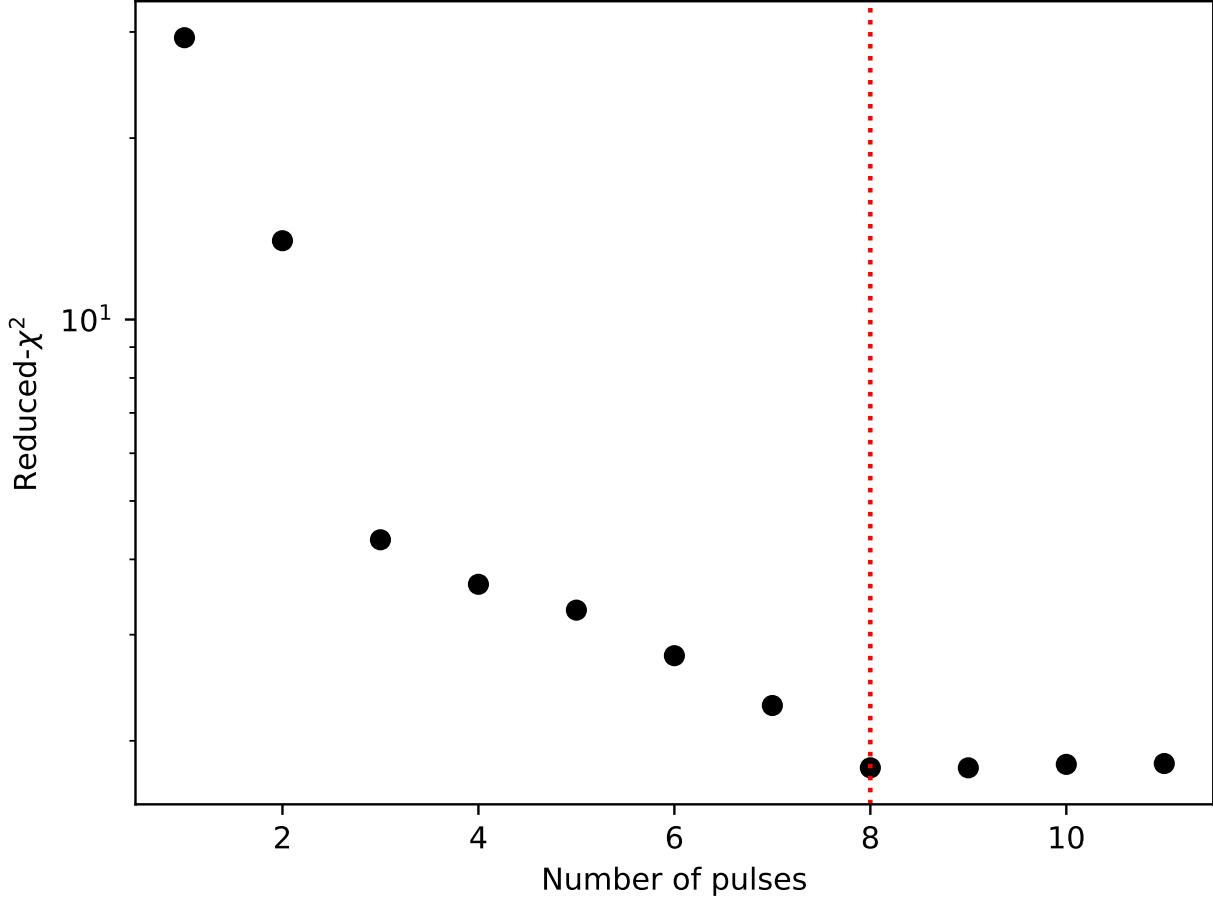
All codes developed for data analysis and figure generation are available from the corresponding author upon reasonable request. The method for evaluating QPO significance follows the Monte Carlo approach introduced in ¹⁶, with modifications tailored to the pulse train structure of FRB 20190122C.

Acknowledgements We acknowledge the public data from CHIME. This work is supported by the National Natural Science Foundation of China (Nos. 12588202, 12573043, 12303043), Science and Technology Foundation of Guizhou Province (Key Program, No. ZK[2024]430), the Natural Science Research Project of the Guizhou Provincial Department of Education ([2024]321).

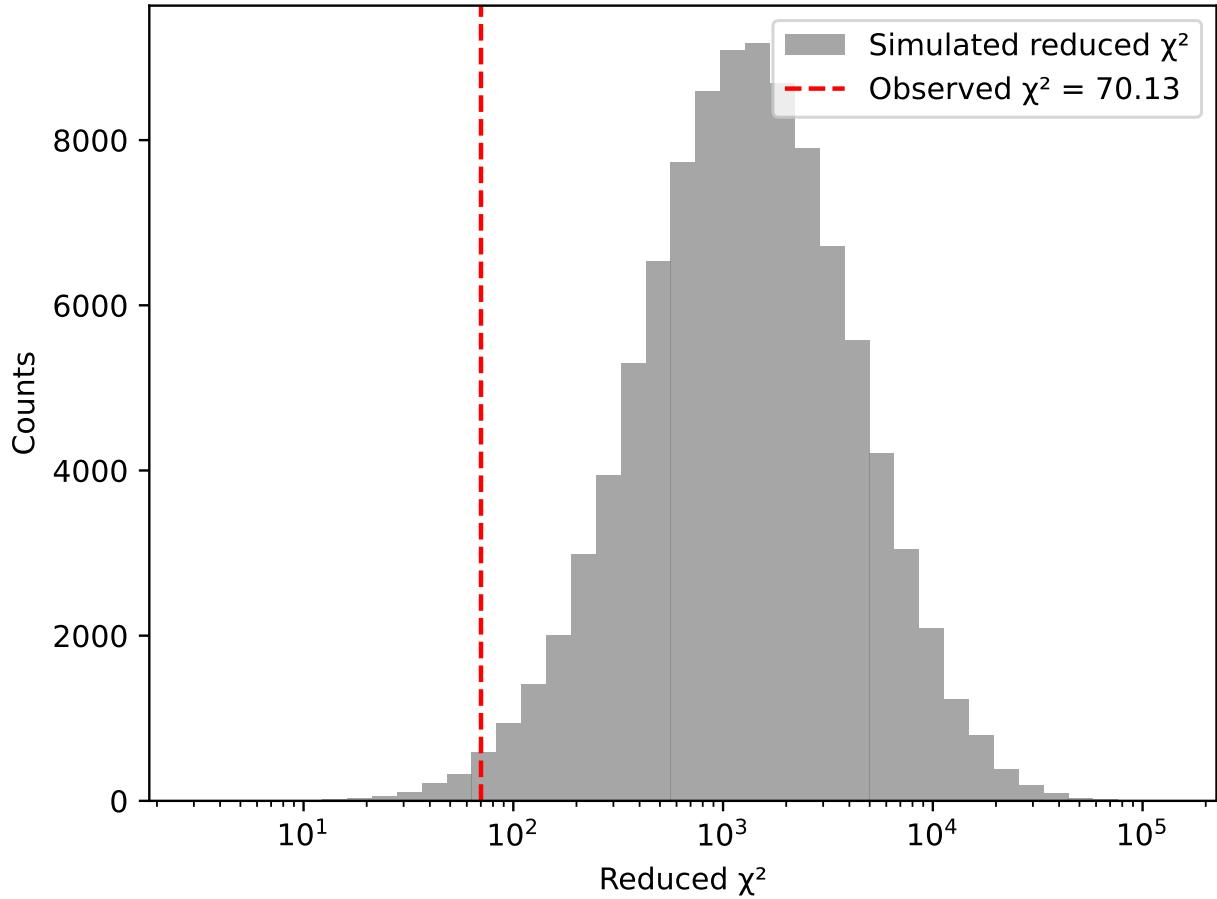
Correspondence Correspondence and requests for materials should be addressed to (D. L., email: dili@tsinghua.edu.cn).

Author Contributions D. L. initiated this project. S. X. led the data analysis and statistical analysis. D. L. led the organization of the manuscript and theory interpretation. All authors participated in the discussion and contributed to the data analysis which is important for this work.

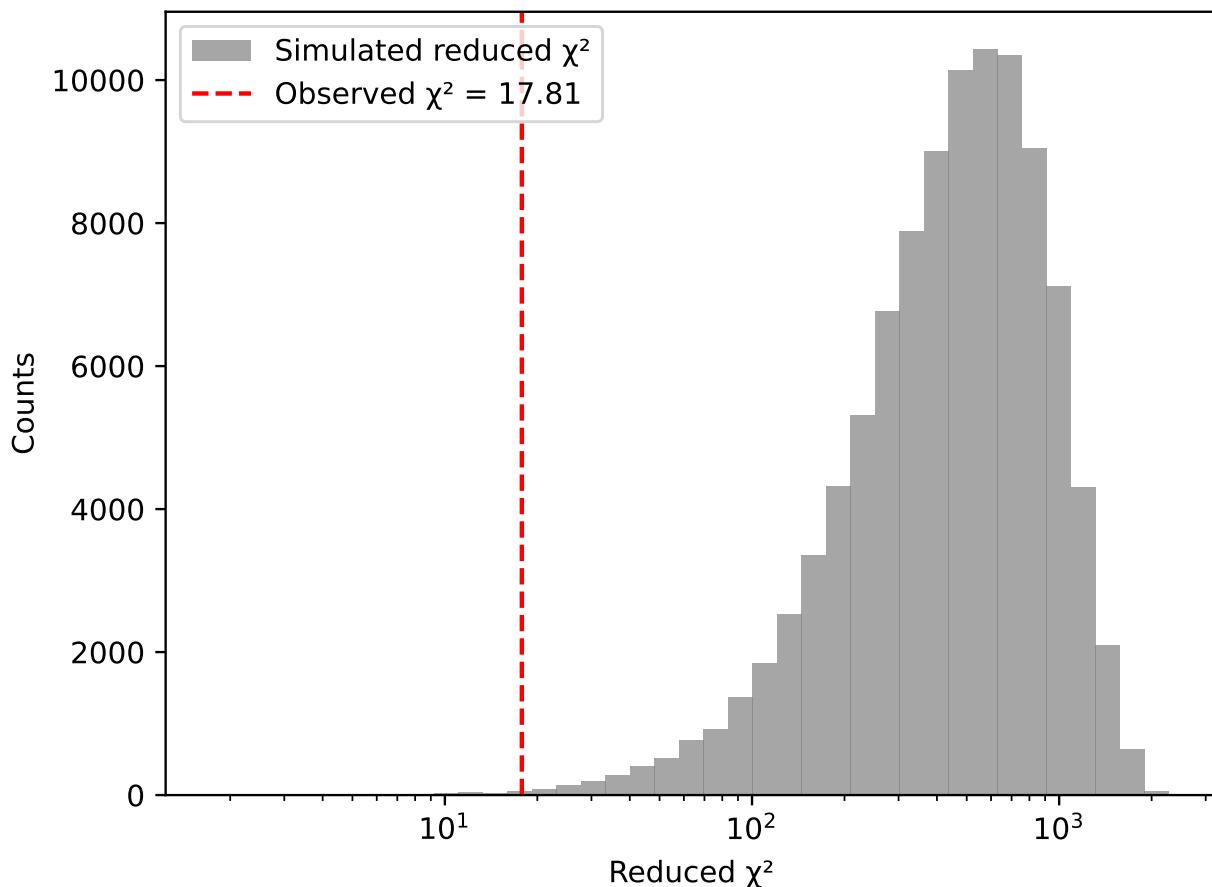
Competing Interests The authors declare no competing interests.



Extended Data Figure. 1: Reduced- χ^2 values for fits with different numbers of pulses. The x-axis represents the number of pulses used in the fit, and the y-axis shows the corresponding reduced χ^2 values on a logarithmic scale. The red dashed vertical line at 8 pulses marks the optimal number of pulses, where further increases in the number of pulses do not significantly improve the fit quality. This suggests that 8 pulses provide a balance between model complexity and fit accuracy.



Extended Data Figure. 2: Monte Carlo simulation of the reduced χ^2 statistic for QPO. Histogram of reduced χ^2 values from 100,000 Monte Carlo simulations under the null hypothesis of randomly spaced pulses, using a shifted Poissonian interval distribution. The observed χ^2_ν is marked with a red dashed line, lying in the extreme tail of the distribution, this corresponds to a false-alarm probability of $p \approx 0.009$.



Extended Data Figure. 3: Monte Carlo simulation of the reduced χ^2 statistic for exponential amplitude decay. The histogram shows the distribution of reduced χ^2 values obtained by fitting exponential models to 100,000 simulated pulse amplitude sequences drawn from a uniform distribution. These simulations follow the null hypothesis of randomly fluctuating pulse strengths without any systematic decay. The vertical red dashed line marks the reduced χ^2 value measured from the observed data, which lies in the extreme tail of the distribution. This corresponds to a false-alarm probability of $p \approx 1.6 \times 10^{-3}$.

Extended Data Table. 1: Best-fit parameters for individual pulses and each pulse is modeled with a Gaussian function.

Pulse index	Amplitude A	Mean μ (ms)	Standard deviation σ
0	3.46 ± 0.44	2.30 ± 0.19	0.49 ± 0.14
1	39.26 ± 0.73	3.36 ± 0.01	0.36 ± 0.02
2	46.68 ± 0.94	4.23 ± 0.01	0.25 ± 0.01
3	25.76 ± 0.40	5.27 ± 0.01	0.49 ± 0.03
4	20.45 ± 0.51	6.48 ± 0.01	0.31 ± 0.02
5	8.98 ± 1.43	7.20 ± 0.02	0.16 ± 0.02
6	6.58 ± 0.55	7.68 ± 0.06	0.25 ± 0.06
7	4.96 ± 0.35	8.97 ± 0.04	0.46 ± 0.05

Extended Data Table. 2: Summary of quasi-periodic structures (or bursts) in FRBs. Note recent developments indicate FRB 20191221A¹⁷ likely originated from the pulsar J0248+6021 nearby.

FRB Name	Period	Pulses	QPO significance (σ)	Exp. Decay significance (σ)	Repeater	Citation
FRB 20190122C	1 ms	8	2.6	3.2	No	this work
FRB 20191221A	216 ms	9	6.5	None	No	¹⁷
FRB 20210206A	3 ms	5	1.3	None	No	¹⁷
FRB 20210213A	11 ms	6	2.4	None	No	¹⁷
FRB 20201020A	0.4 ms	5	2.5	None	No	¹⁶
FRB 20200120E	$2 - 3 \mu\text{s}$	6	None	None	Yes	²⁶
FRB 180916.J0158+65	16 days (for bursts)	38	> 4.5	None	Yes	²⁷
FRB 121102	157 days (for bursts)	32	1.8	None	Yes	²⁸
FRB 200428	30 ms	2	None	None	Yes	^{7,8}