Time correlation of repeating FRBs and magnetar radio pulses: they are similar to earthquakes

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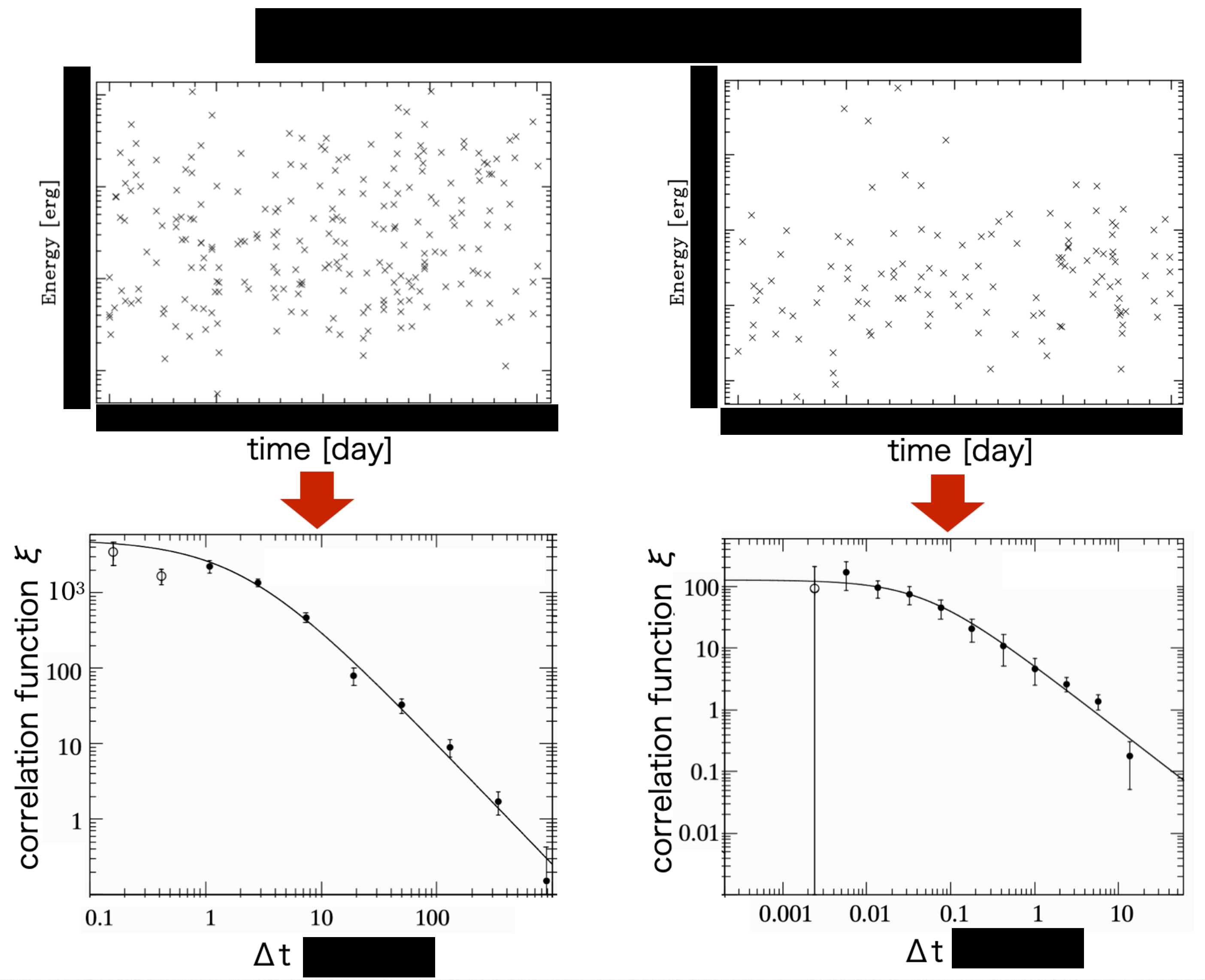
FRB & earthquakes… which is which?



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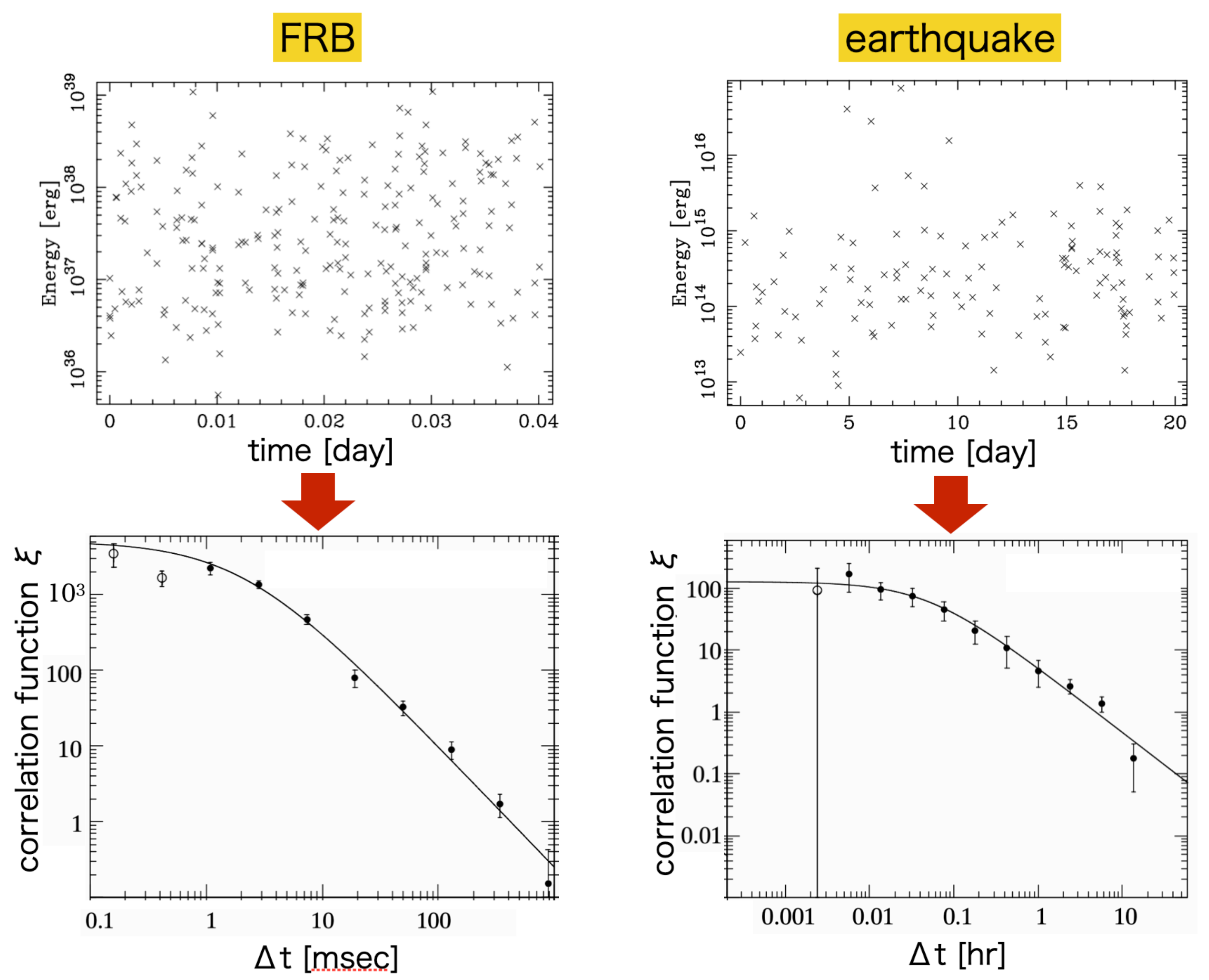


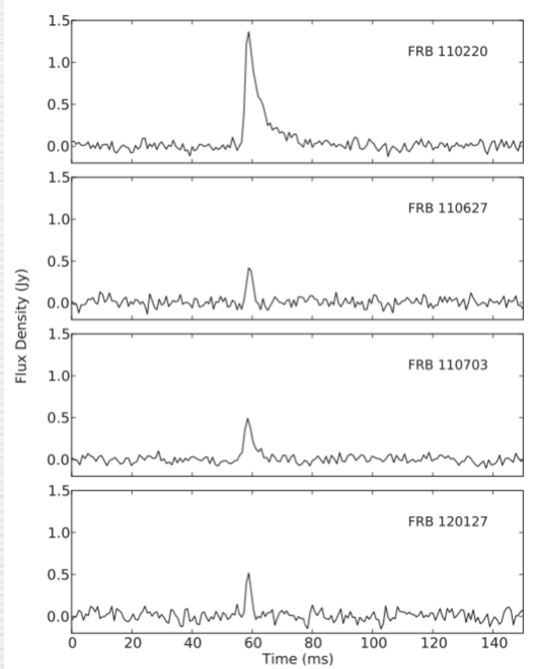
Contents

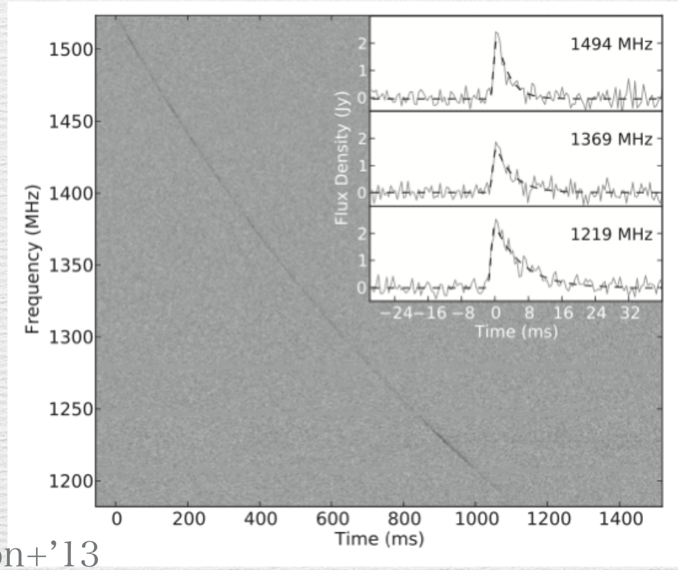
- “Fast radio bursts trigger aftershocks resembling earthquakes, but not solar flares”
    - Totani, T. & Tsuzuki, Y. 2023, MNRAS 526, 2795

- “Similarity to earthquakes again: Periodic radio pulses of the magnetar SGR 1935+2154 are accompanied by aftershocks like fast radio burst”
    - Tsuzuki, Y., Totani, T., C.-P. Hu, & T. Enoto 2024, MNRAS 530, 1885

Fast Radio Bursts (FRBs)

- short duration (1-10 msec) radio transient phenomena
- first event discovered in 2006, > 600 FRBs so far, still mysterious in many aspects
- large dispersion measure (delayed signal at lower frequencies) implies cosmological distances
  - ~40 host galaxies identified, indeed at cosmological distances (z ~ 0.1-0.3)
- about 50 sources are repeaters (produce many FRBs repeatedly)
  - a few thousands FRB events detected from a few very active sources
  - repeater FRBs are most likely neutron stars
  - FRB detected from a Galactic magnetar (SGR 1935+2154)

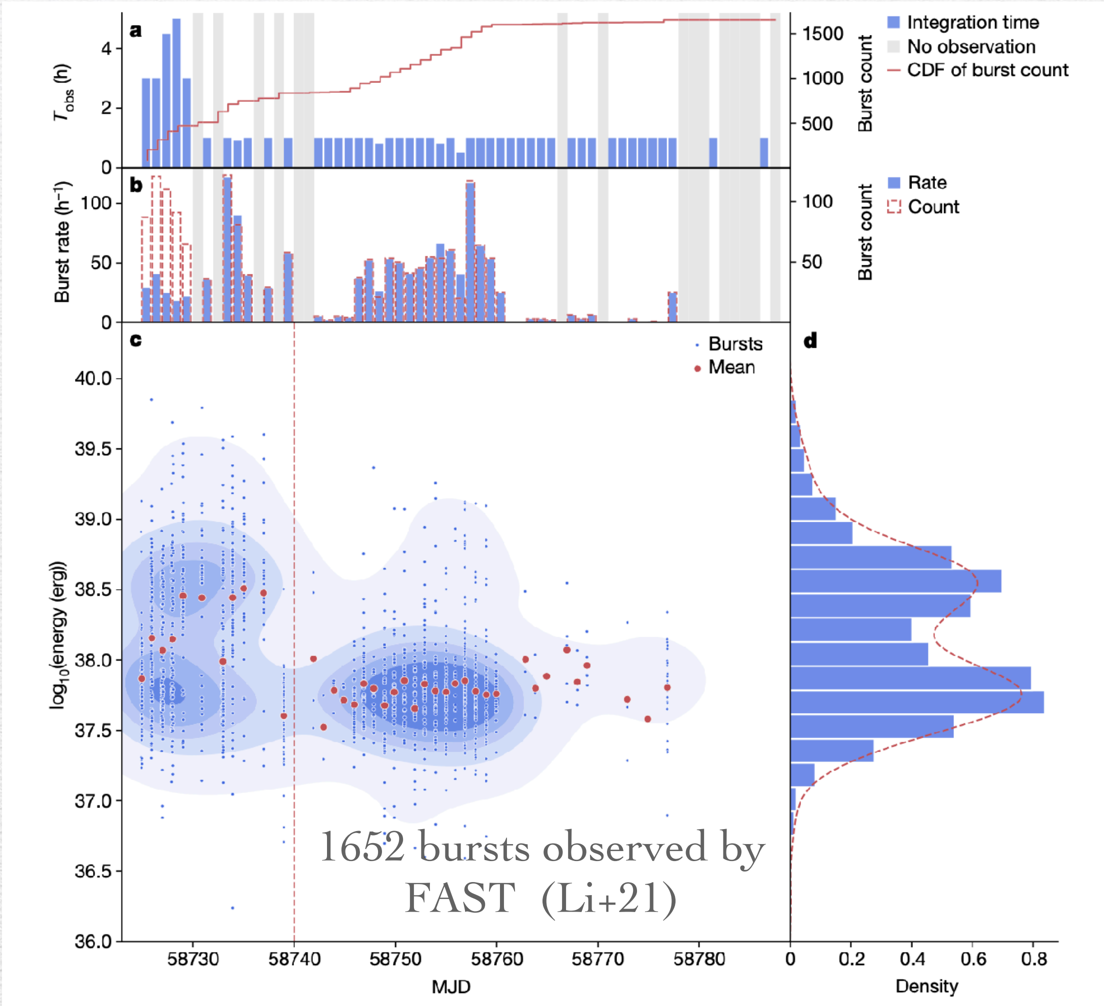




Thoronton+'13

thousands of bursts from a few repeater FRBs

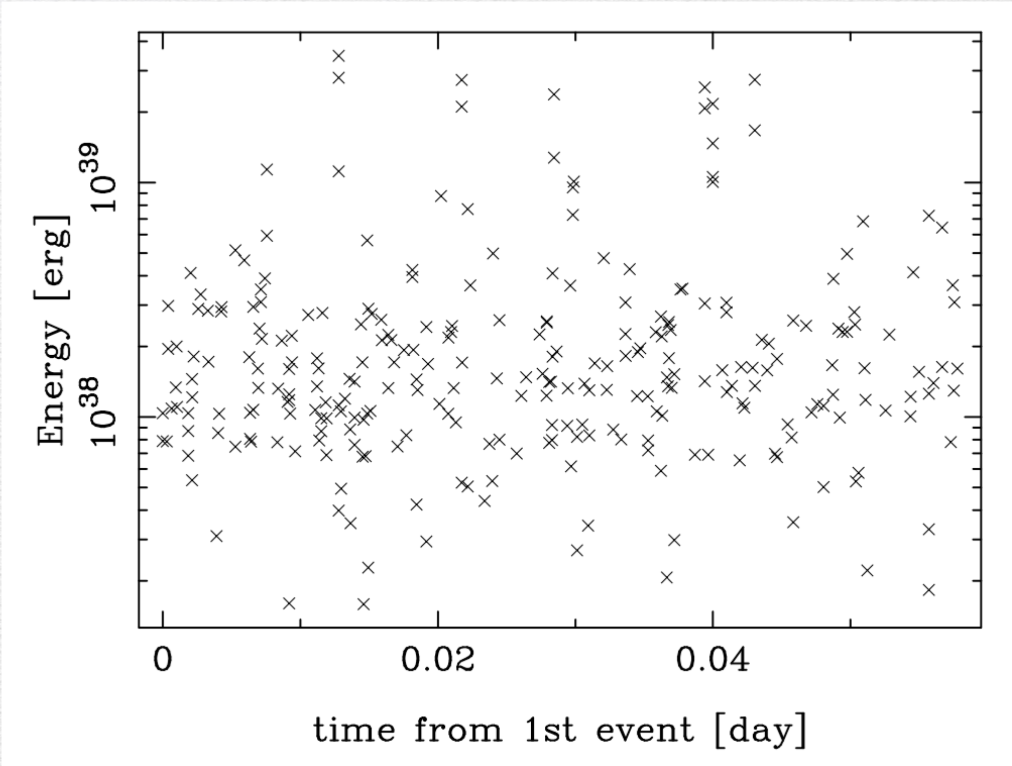
- FRB 20121102A
- FRB 20201124A
- FRB 20220912A
- …
- mostly detected by Arecibo and FAST



1652 bursts observed by FAST (Li+21)

So many bursts from repeater FRBs!

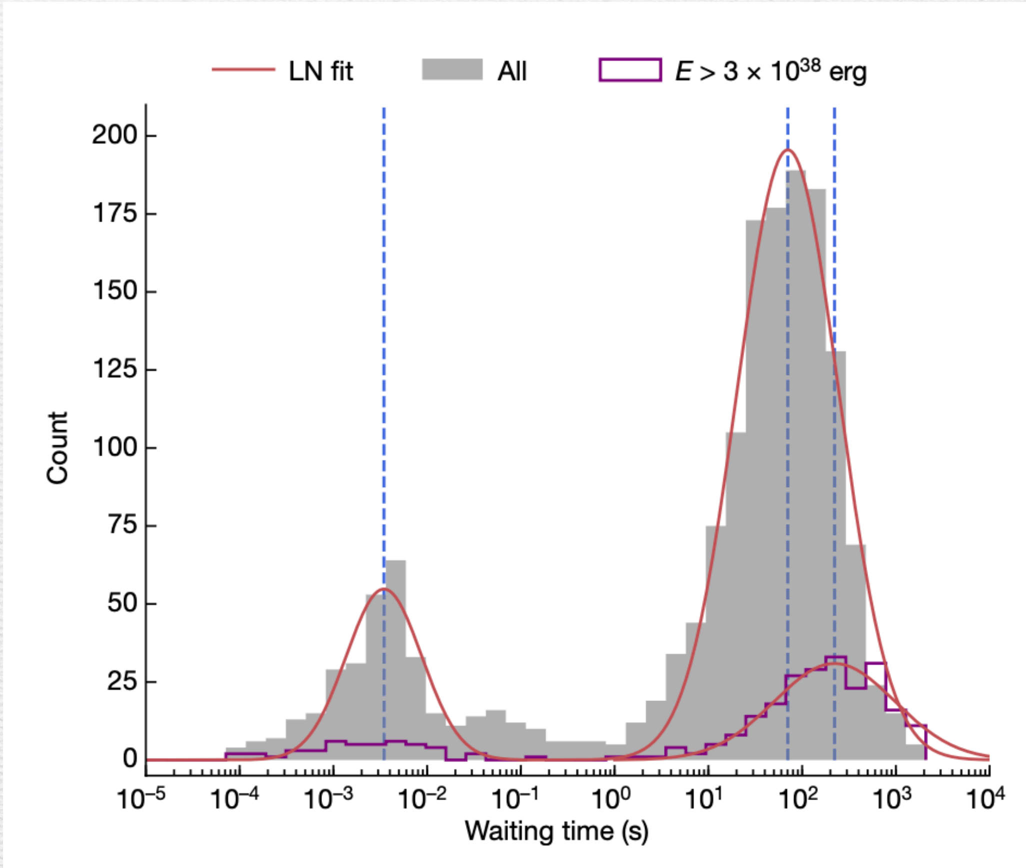
- Thousands of bursts from a few repeater FRB sources
- > 100 bursts in 1 hr
- Detailed studies on the statistical nature of these bursts now possible



A part of Jahns+'23 data
for FRB 20121102A

Statistical properties of repeating FRB occurrence time?

- bimodal wait-time distribution found universally for all repeater FRB sources
  - wait time = t_{i+1} - t_i
- The peak at longer wait times is consistent with a Poisson process with a constant event rate
- The origin of short wait-time peak is unknown.
  - peaks at 1-10 msec, close to the duration of one FRB.
  - Related to radiative process/source activity?



Li+'21

Statistical properties of repeating FRB occurrence time?

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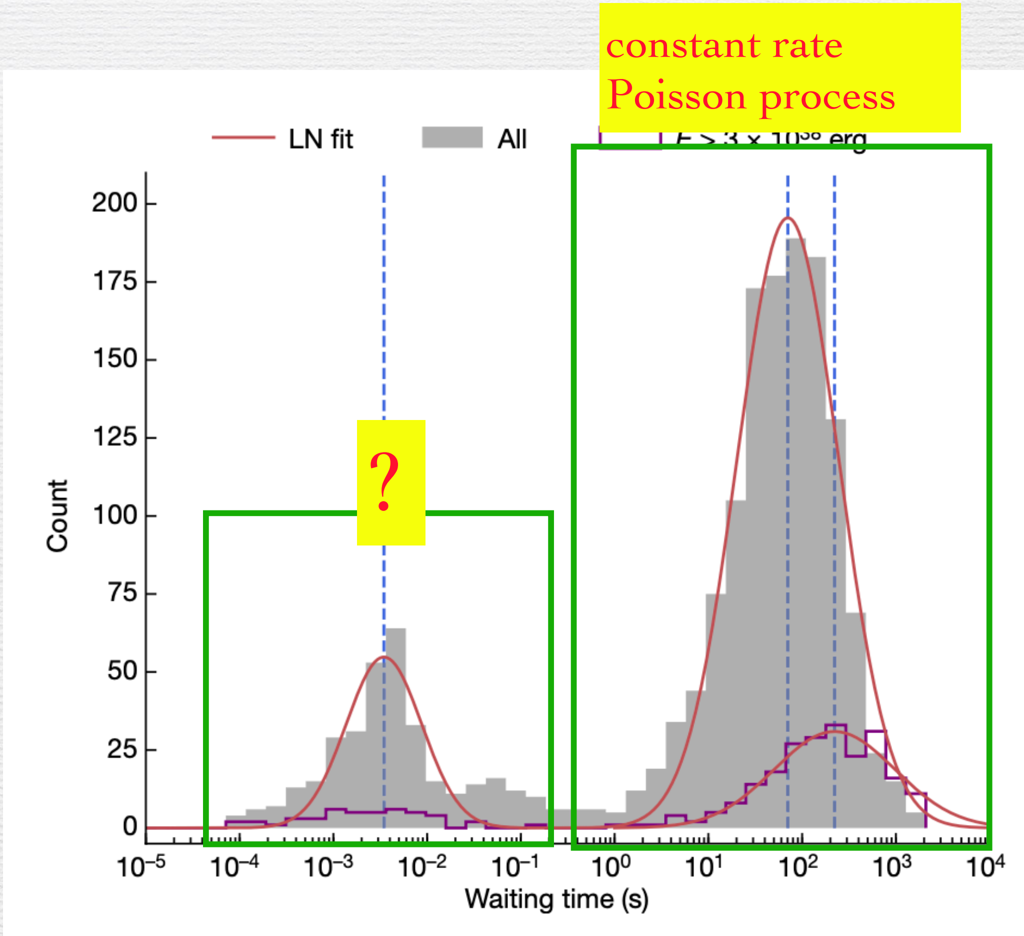
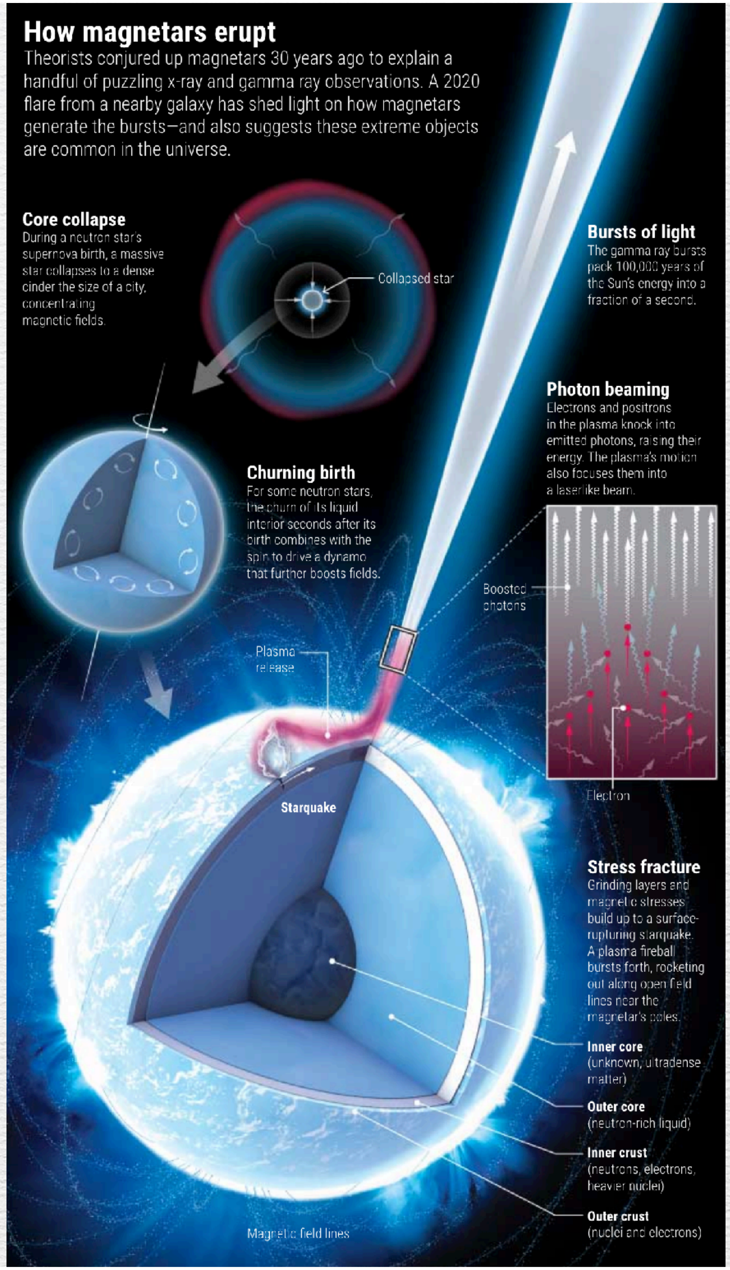


Li+'21

FRBs vs. earthquakes and solar flares

- FRB statistical properties may be similar to earthquakes or solar flares
  - FRBs related to magnetars (e.g. SGR 1935+2154)
  - magnetar flares thought to occur by starquakes in the surface solid crust of a neutron star, induced by magnetic energy
  - similarity between magnetars, earthquakes, and solar flares investigated in the literature
    - e.g. the power-law energy distribution are common for magnetar bursts and earthquakes (Wadati-Gutenberg-Richter law of earthquakes)



The Gutenberg-Richter law? Wadati?

- The power-law distribution of earthquake magnitudes (energies) often called "Gutenberg-Richter" (1944) law
  - $\log N(>M) \propto M^{-b}$, $dN/dE \propto E^{-1-2b/3}$, b~1
  - M = magnitude, E = energy

- But…
- 和達清夫 (WADATI Kiyoo, 1902-1995, famous by Wadati-Benioff zone) found this law earlier in 1932
  - Wadati, K. "On the frequency distribution of earthquakes." Journal of the Meteorological Society of Japan. Ser. II 10, 559–568 (1932) (in Japanese).

氣象集誌第二輯第十巻第十號

論文

地震回數の分布に就いて

和達清夫

(中央氣象臺彙報)

On the Frequency Distribution of Earthquakes.

by K. Wadati.

一、緒言

昭和七年六月の地震研究所談話會に於いて、寺田教授は「地震の分布と觀測所の分布」と題する研究を發表された。本文は之と同様な構想に依つてなされたものである。

一般に觀測される地震の回數は、觀測所の數が多い程增加し、觀測所の地震計の感度が鋭敏なる程又增加する。卽ち勢力の小なる地震は觀測されない場合があるからである。今地震の發現回數が到る所同じである、換言すれば地震發現回數密度が一定であると假定する。かゝる場合に於いても、ある一個所の觀測所に依つて觀測される地震の分布は、觀測所附近に密であり、觀測所を距るに從ひ疎となる。此の密疎の狀態は何に起因するかと言へば、第一に地震波動が震源より四圍に傳播するに際して、如何に減衰して行くかと云ふ事、第二に地震發現回數が地震のエネルギーと如何なる關係を有するかと云ふ事に因る。

實際の場合に於いては前述の假定卽ち地震發現回數が到る所同じであると云ふ事は成立して居ない。地震の發現回數は震源の深さ及び震央地域に大なる關係を有する。よく知られて居る様に地震は數十粁の深さに最も多く發現し、又震央は所謂地震帶或は頻發地域と稱せられる所に最も多く存する。從つて觀測された地震の分布はかなり複雜なものが期待される筈であるが、併し適當な考慮を加へる時は、この觀測結果から

一、地震發現回數の地震エネルギーに對する分布

二、地震發現回數と震源の深さとの關係

を知る事が出來る。本文に於ては其の方法、並びに東京の地震觀測結果より調査したる實例に就いて述べられて居る。

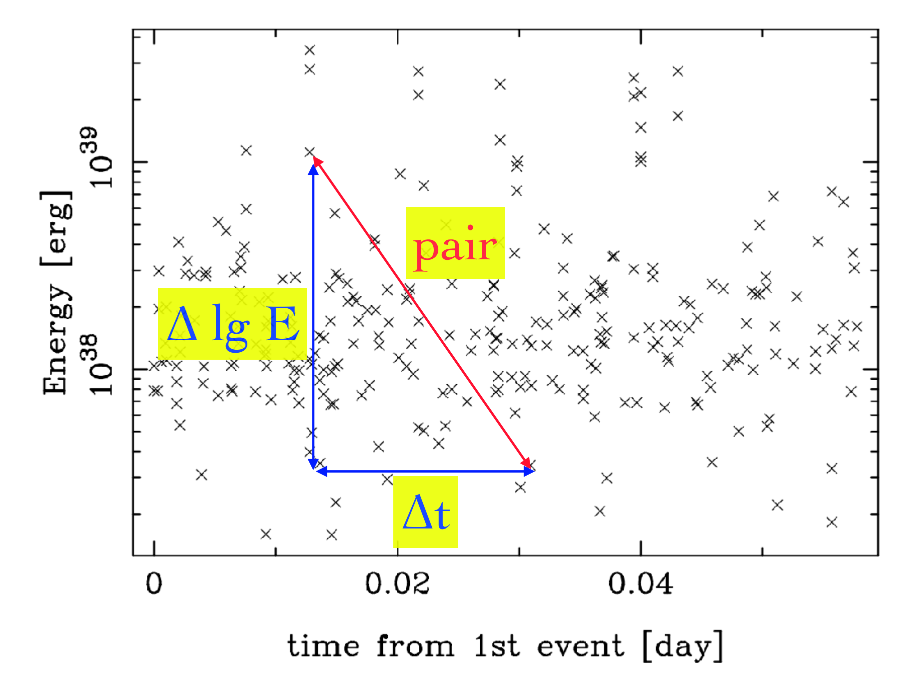
二、理

地震のエ … ため

に、震源よ … て觀

測された地

What we did: correlation function ξ in time-energy space



data for FRB 20121102A
from Jahns+'23

- two-point correlation function ξ in the space of Δt and $\Delta \lg E$ ($= \Delta \log_{10} E$)

$$dn_p = (1 + \xi)\, \bar{n}_p\, d(\Delta t)\, d(\Delta \lg E) \ ,$$

- ξ is the excess of pair counts compared with the case of no correlation ($\bar{n}_p$)
- random data (no correlation) is produced assuming "constant event rate" and "constant energy distribution" during one-day observation (~ a few hours)

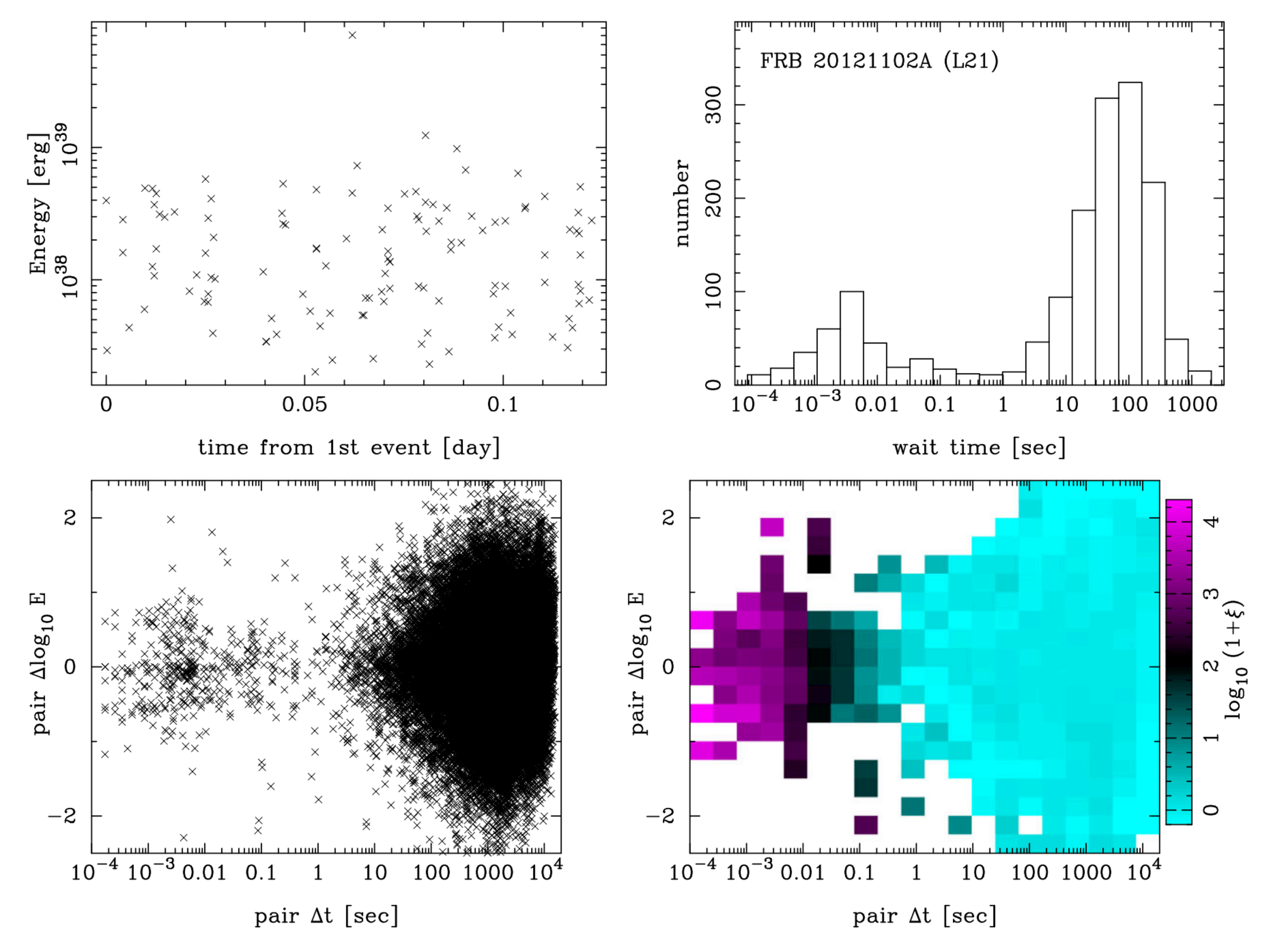
7 FRB data sets for 3 sources

- nearly 7,000 events in total, from Arecibo & FAST
- 3 sources (FRBs 20121102A, 20201124A, 20220912A)

Data set name	Telescope	Period (MJD)	Days[a]	$t_{\rm obs}$[b] (day)	Events	r_m[c] (/day)	$C_{\rm best}$[d] $C_{-1\sigma}$ $C_{+1\sigma}$	$p_{\rm best}$ $p_{-1\sigma}$ $p_{+1\sigma}$	$\tau_{\rm best}$ $\tau_{-1\sigma}$ $\tau_{+1\sigma}$	n[e]
FRB 20121102A (L21) (*5*)	FAST	58724.87–58776.88	39	1.76	1651	1500	5100	1.6	0.0020	0.28
							3100	1.4	0.0009	
							9700	1.8	0.0033	
FRB 20121102A (H22) (*6*)	Arecibo	57510.80–57666.42	18	0.733	475	870	490	9.1	0.28	0.17
							280	2.1	0.019	
							1200	∞	1.4	
FRB 20121102A (J23) (*9*)	Arecibo	58409.35–58450.28	8	0.272	1027	4900	770	2.3	0.012	0.40
					(849)[f]		500	1.8	0.0063	
							1100	3.5	0.028	
FRB 20201124A (X22) (*7*)	FAST	59307.33–59360.18	45	3.13	1863	840	340	28.3	1.3	0.16
							250	4.5	0.13	
							500	∞	1.5	
FRB 20201124A (Z22 D3) (*8*)	FAST	59484.81–59484.86	1	0.040	232	5800	270	3.4	0.071	0.54
							83	1.5	0	
							∞	∞	1.7	
FRB 20201124A (Z22 D4) (*8*)	FAST	59485.78–59485.83	1	0.040	542	14000	54	4.2	0.19	0.50
							35	2.1	0.058	
							60	∞	1.9	
FRB 20220912A (Z23) (*10*)	FAST	59880.49–59935.39	17	0.32	1076	6900	70	5.7	0.26	0.30
							50	2.4	0.043	
							170	∞	1.8	

[a]Total number of days on which observations were made

Example of ξ calculation

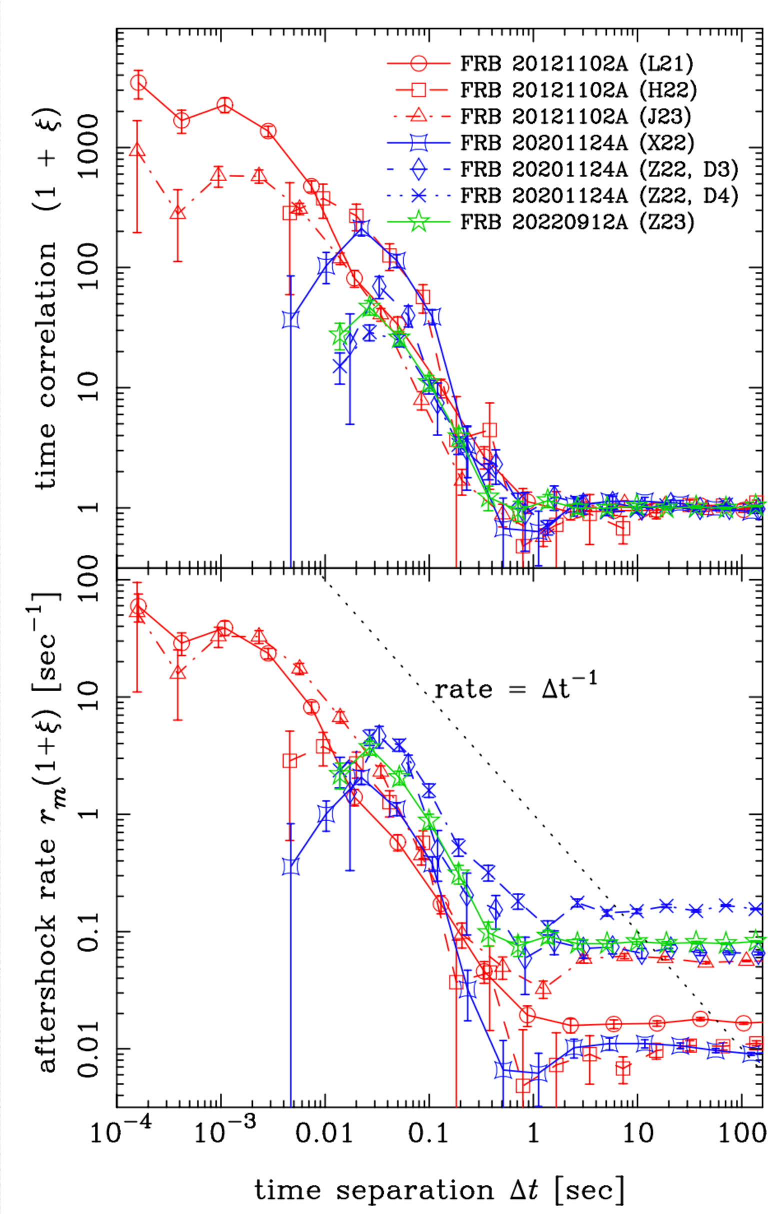


time correlation $\xi(\Delta t)$

- power-law signal at $\Delta t < 1$ sec
- flat at $\Delta t \sim$ FRB duration(<10 msec)
  - Note: different sub-burst treatments by different authors
- can be fit by $\xi \propto (\Delta t + \tau)^{-p}$
- "aftershock rate" after one event is given as $r_m(1+\xi)$, where r_m is the mean event rate
  - the $(\Delta t + \tau)^{-p}$ form same as the Omori-Utsu law for earthquakes
  - expected number of aftershocks following one event:

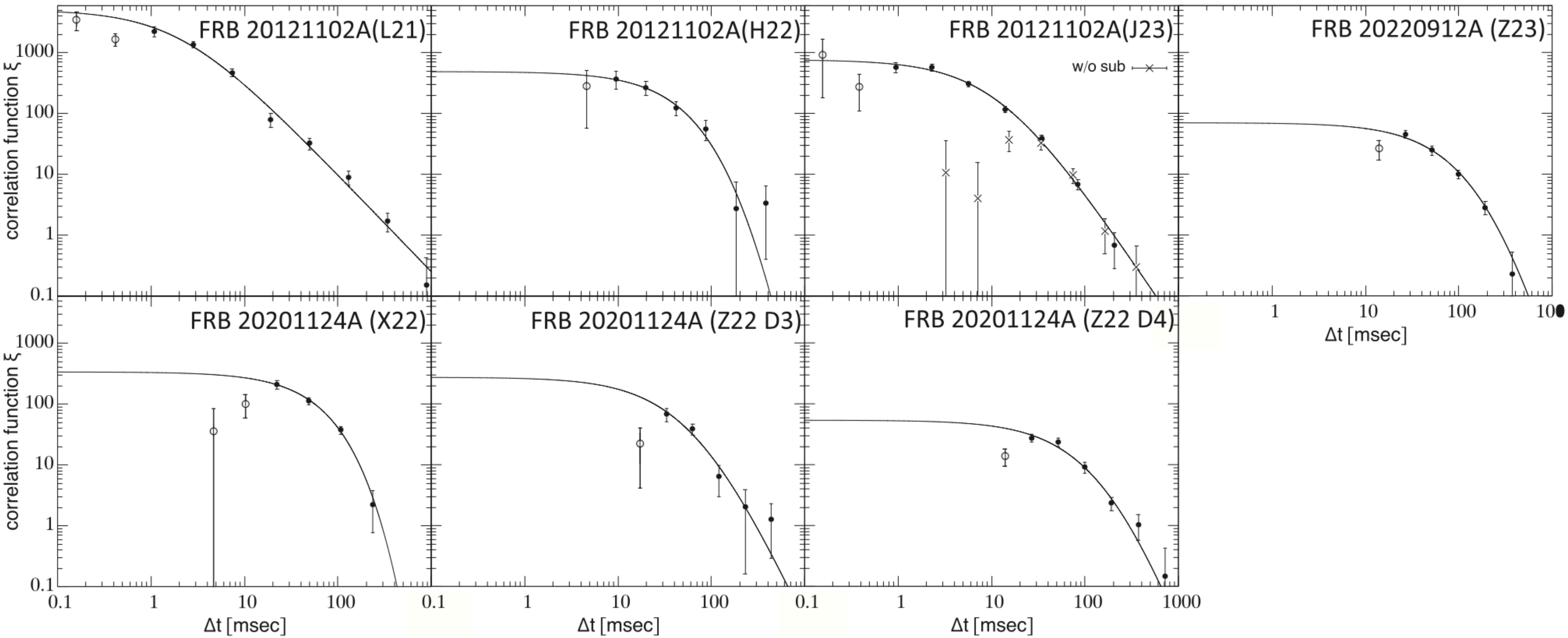
$$n = \int r_m \, \xi(\Delta t) d(\Delta t)$$

  - n = 0.1-0.5 for FRBs
  - multiple aftershocks to one event are rare
  - stable against change of mean rate r_m or different sources



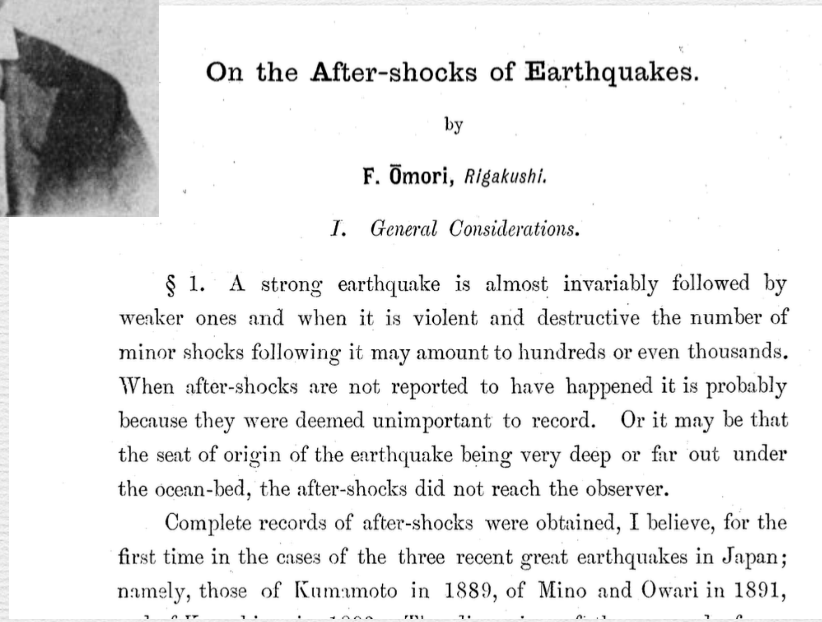
fitting result

- fit by $\xi \propto (\Delta t + \tau)^{-p}$



The Omori-Utsu law for earthquake aftershocks

- 大森 房吉 (OMORI, Fusakichi, 1868-1923)
  - Omori law: Omori, F. “On the after-shocks of earthquakes.” The journal of the College of Science, Imperial University, Japan 7, 111–200 (1894).
  - aftershock rate $\propto (\Delta t + \tau)^{-1}$



On the After-shocks of Earthquakes.

by

F. Ōmori, *Rigakushi.*

I. General Considerations.

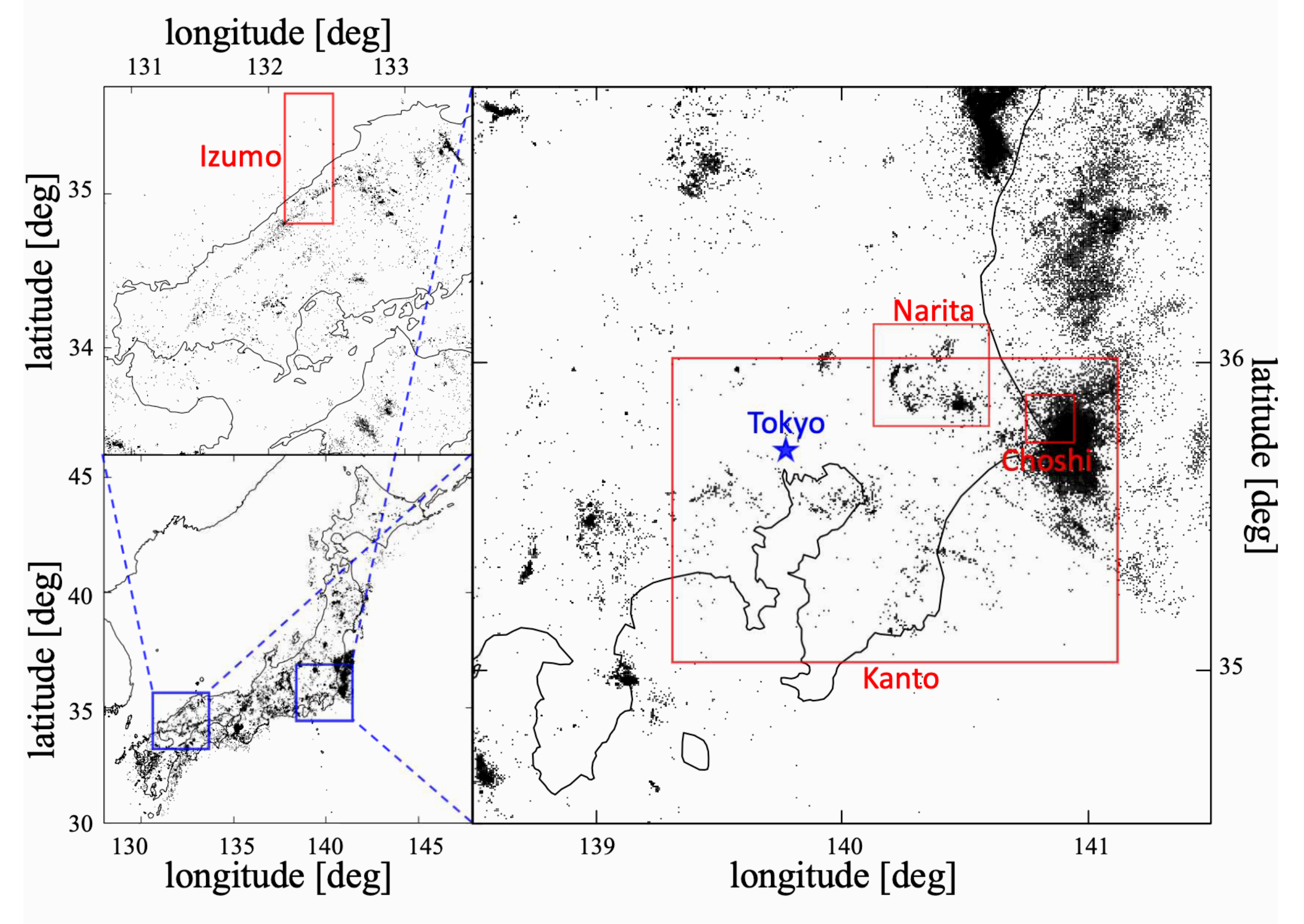
§ 1. A strong earthquake is almost invariably followed by weaker ones and when it is violent and destructive the number of minor shocks following it may amount to hundreds or even thousands. When after-shocks are not reported to have happened it is probably because they were deemed unimportant to record. Or it may be that the seat of origin of the earthquake being very deep or far out under the ocean-bed, the after-shocks did not reach the observer.

Complete records of after-shocks were obtained, I believe, for the first time in the cases of the three recent great earthquakes in Japan; namely, those of Kumamoto in 1889, of Mino and Owari in 1891,

- 宇津徳治 (UTSU, Tokuji, 1923-2004)
  - modified Omori law (Omori-Utsu law) Utsu+ 1957, 1961
  - aftershock rate $\propto (\Delta t + \tau)^{-p}$

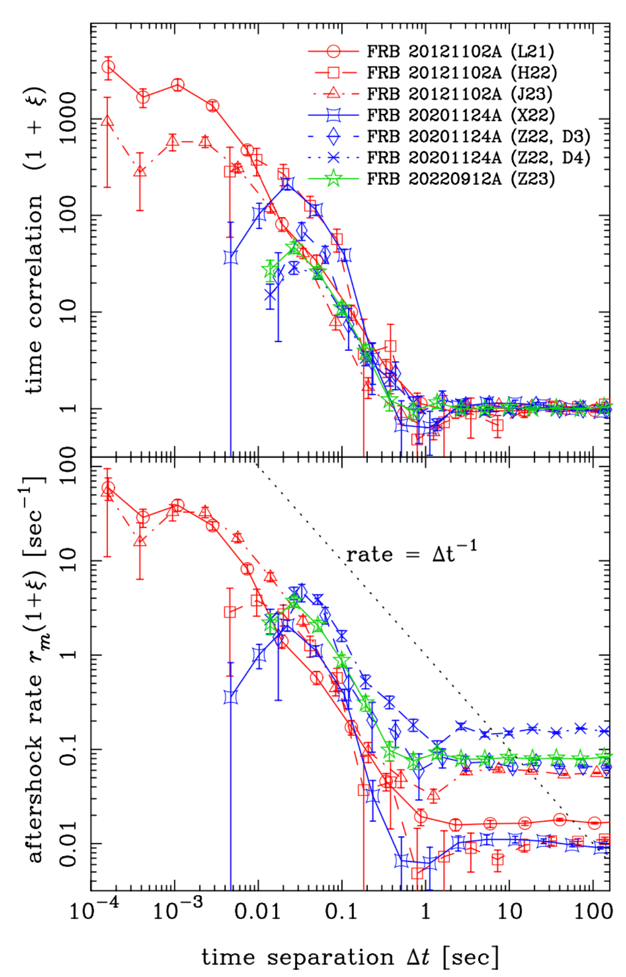
Applying the same analysis to earthquake data

- We used JUICE (Japan Unified hI-resolution relocated Catalog for Earthquake)

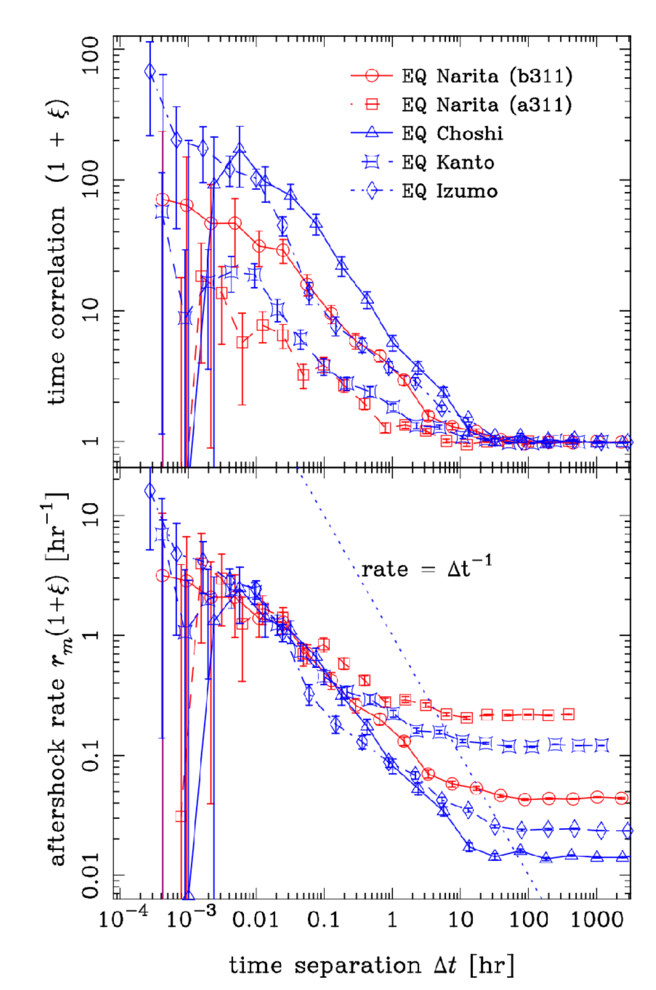


time correlation function: FRBs vs. earthquakes vs. solar flares

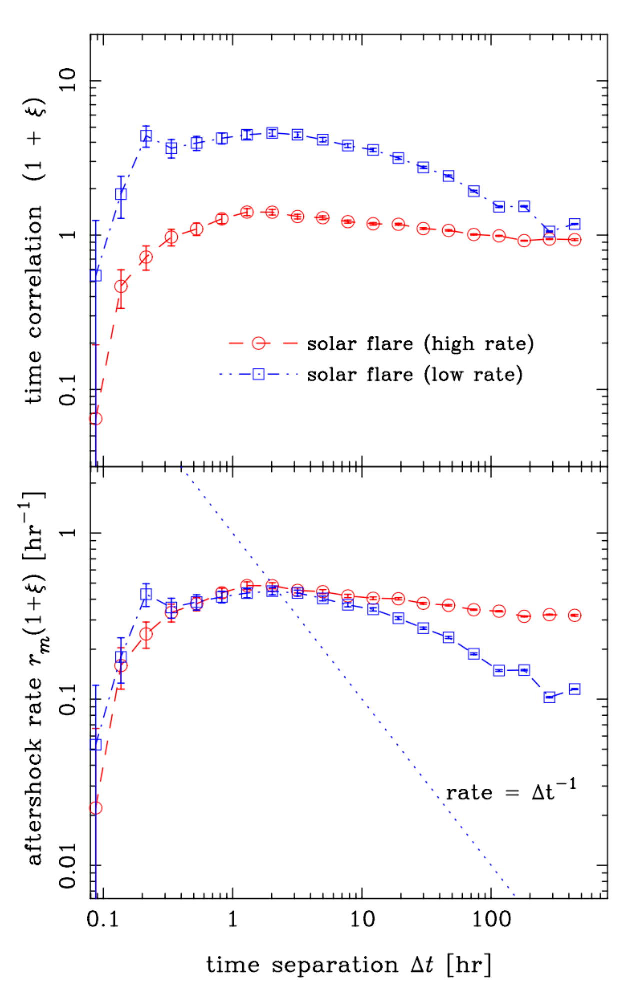
FRBs



Earthquakes



solar flares



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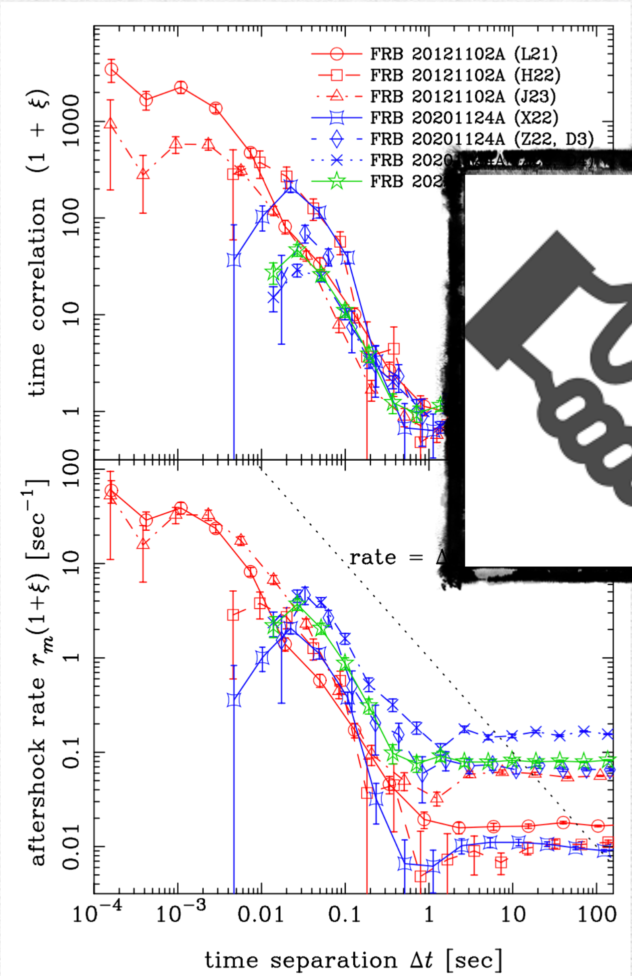
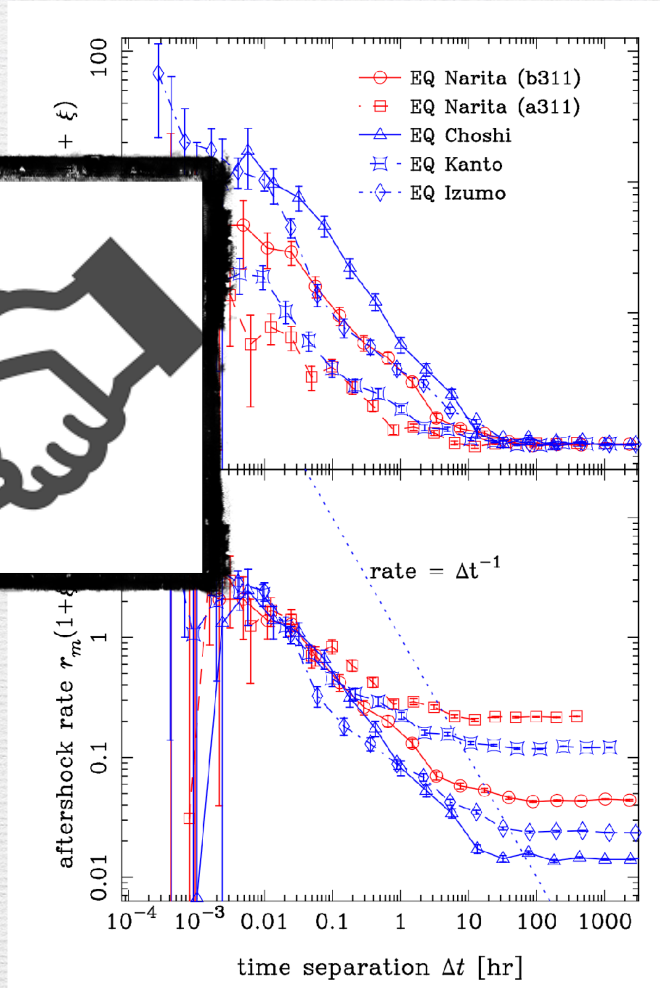
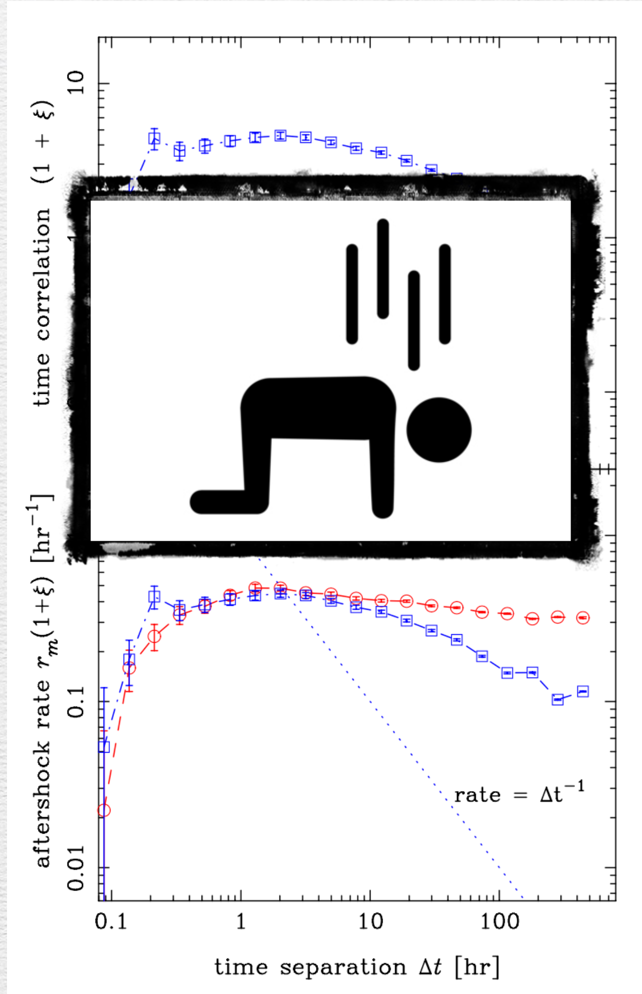


Earthquakes

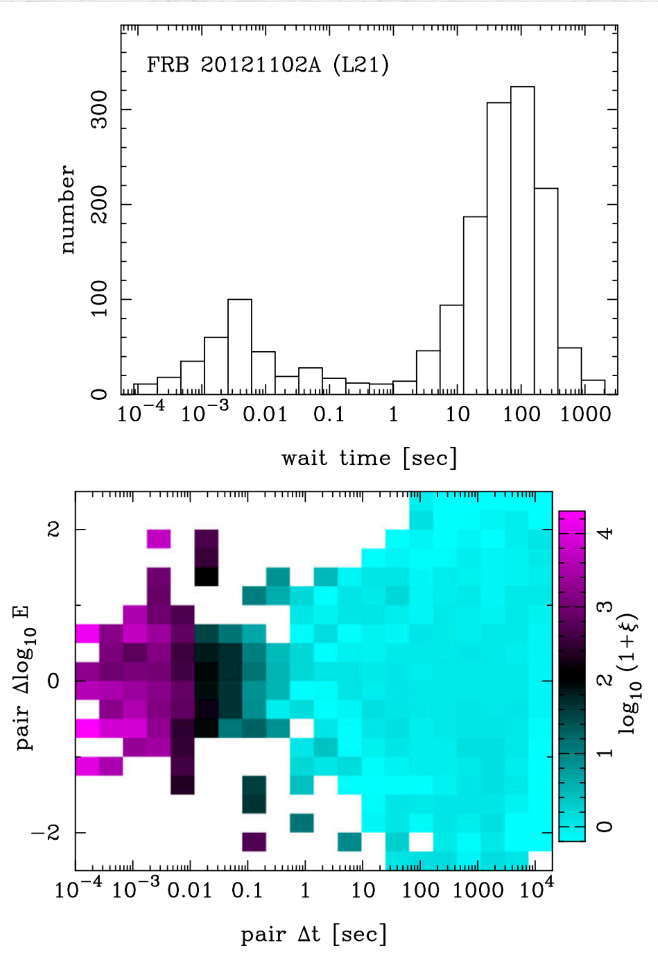


solar flares

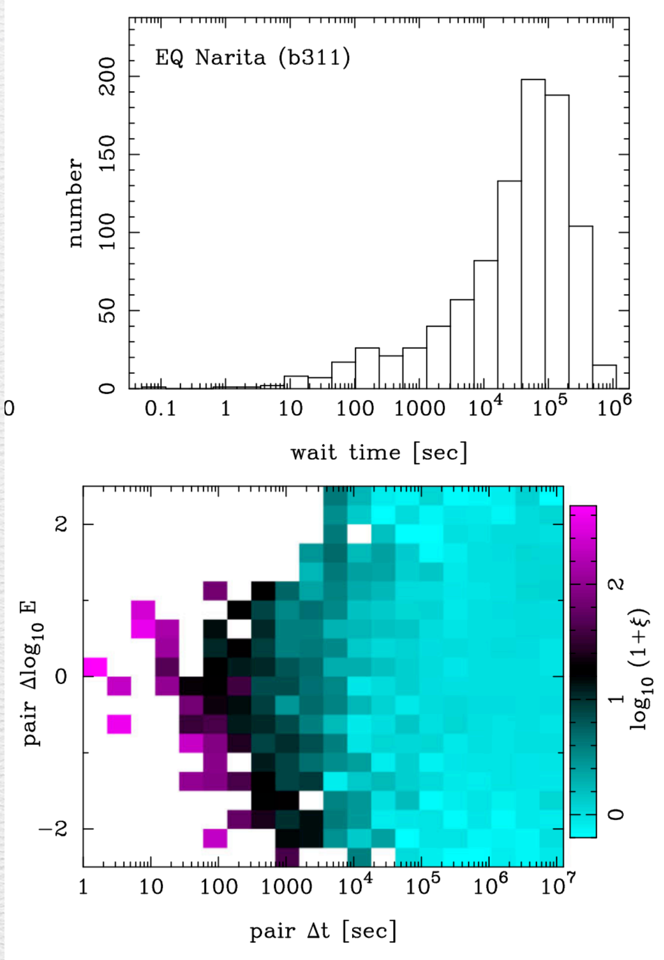


time-energy correlation: FRBs vs. earthquakes vs. solar flares

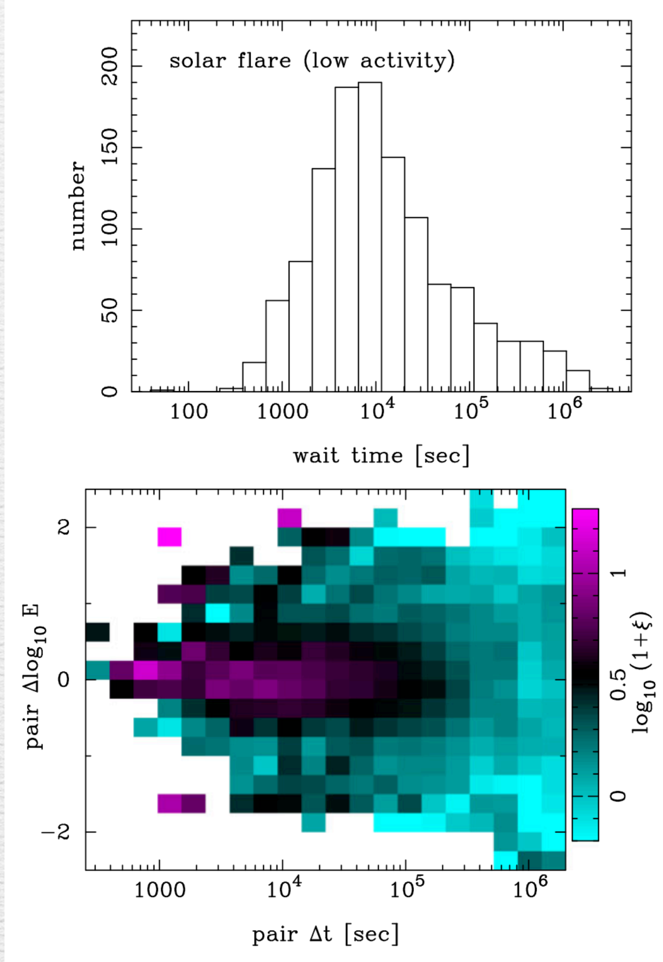
FRBs



Earthquakes



solar flares



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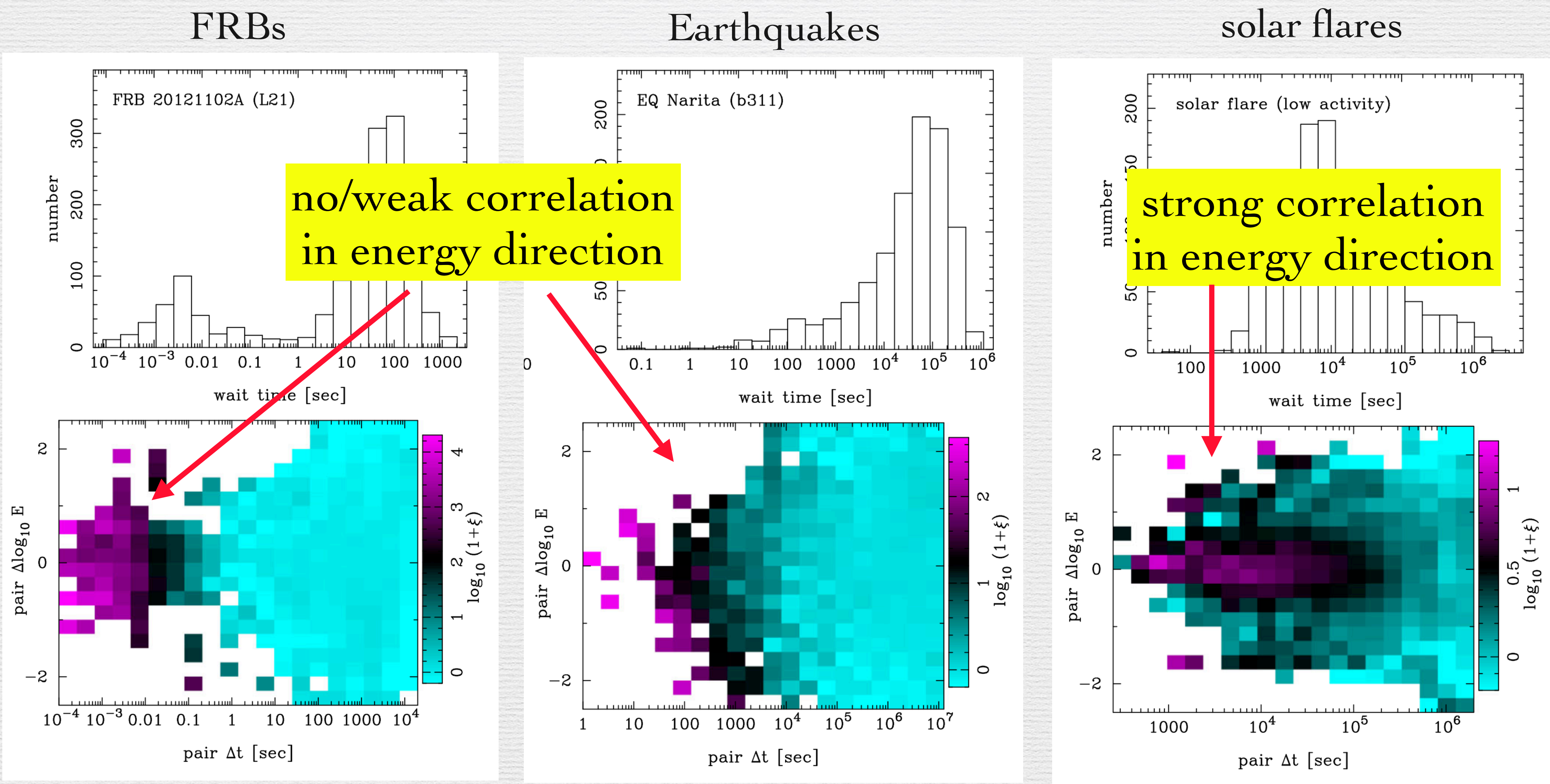
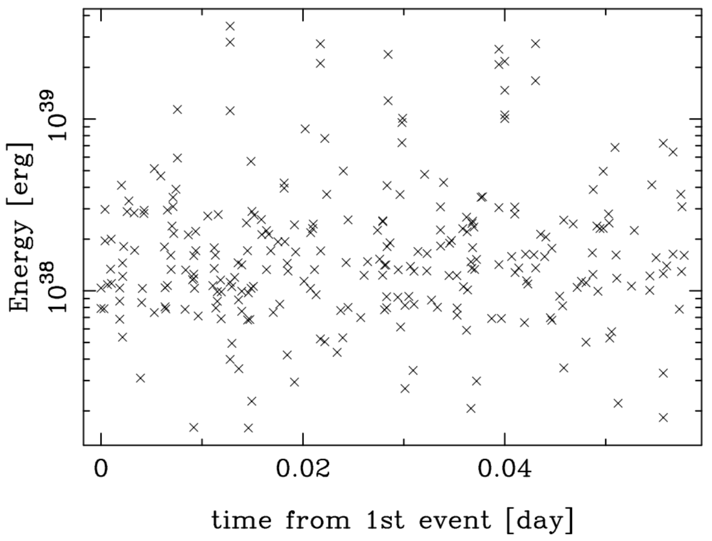
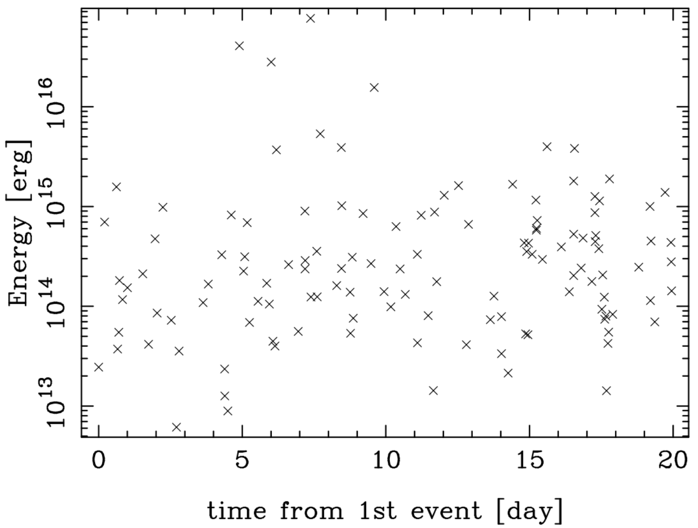


solar flares are different by eyes

- Solar flares are more strongly clustering both in time & energy, which can be recognized by eyes in the time vs energy space.



FRBs



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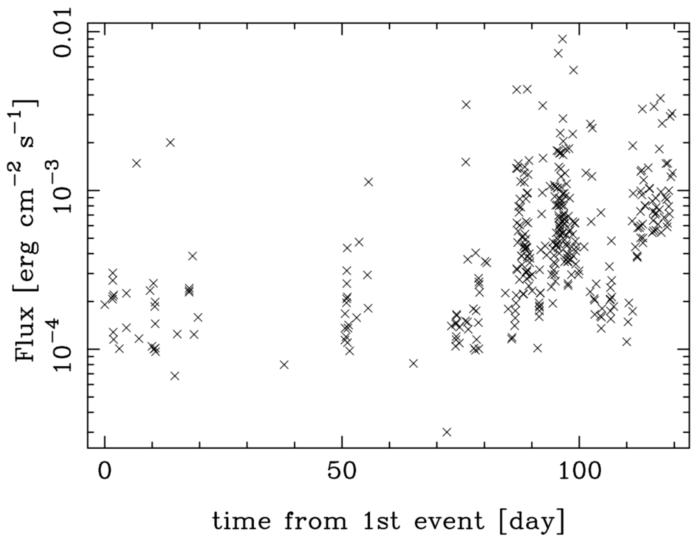
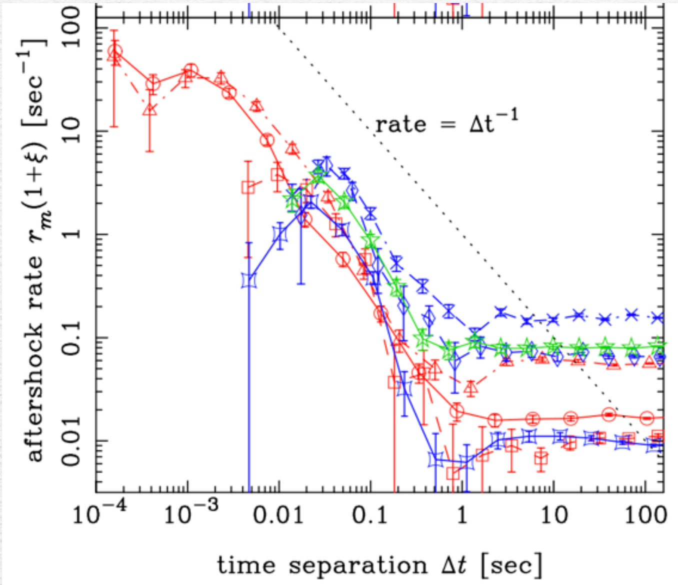
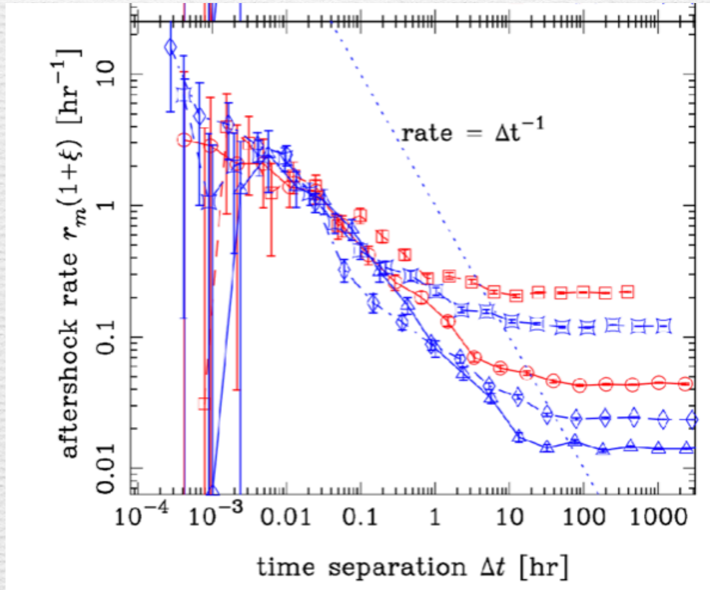


solar flares

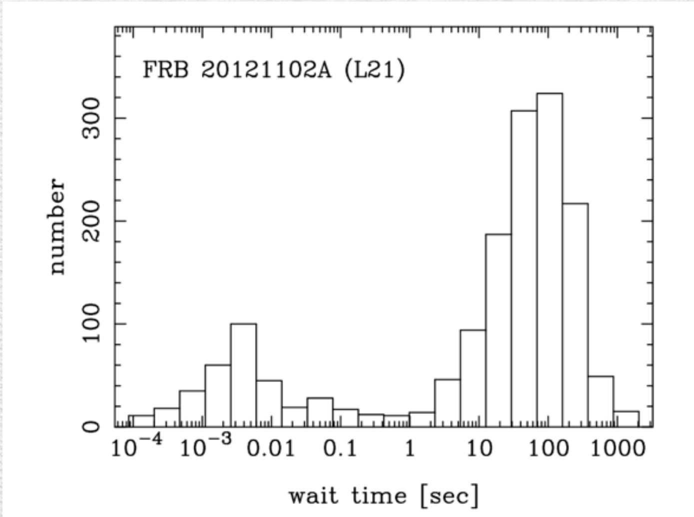
Difference between FRBs & earthquakes?

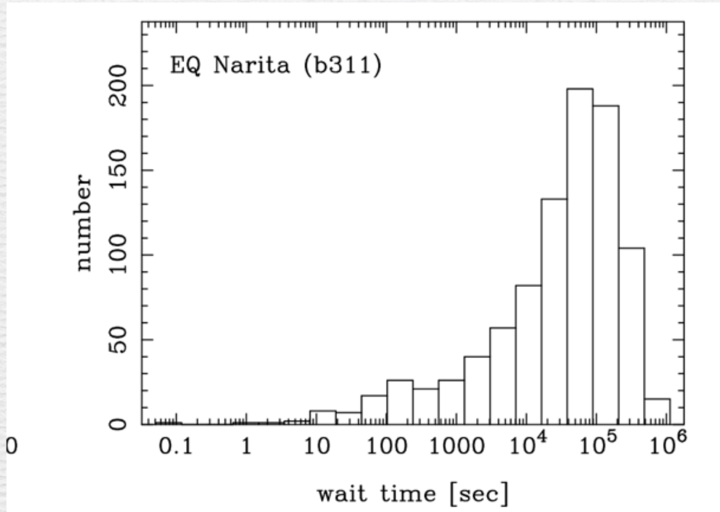
- index p of Omori-Utsu law
  - $\propto (\Delta t + \tau)^{-p}$





- wait-time distribution





Difference between FRBs & earthquakes?

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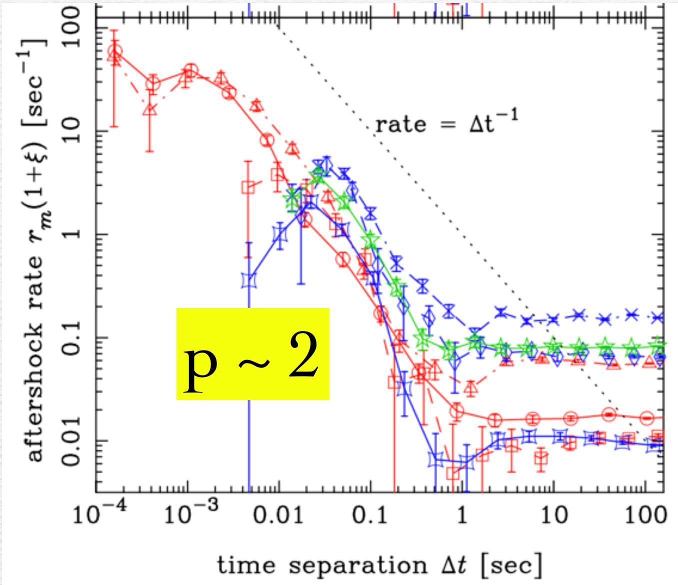
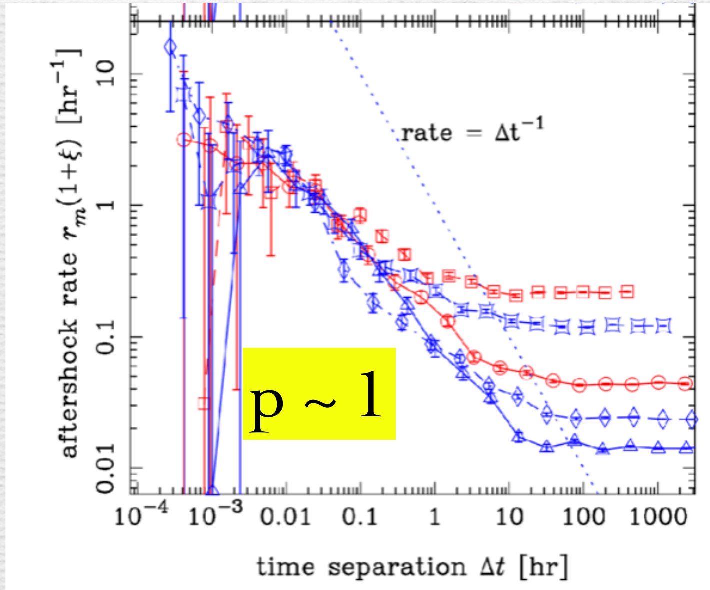
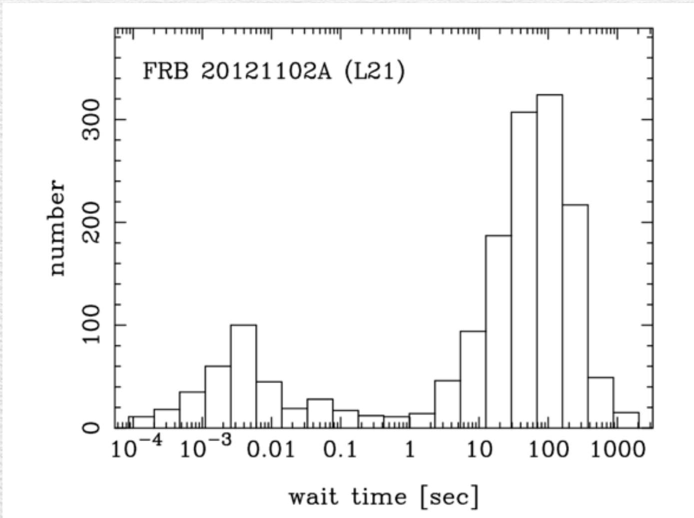
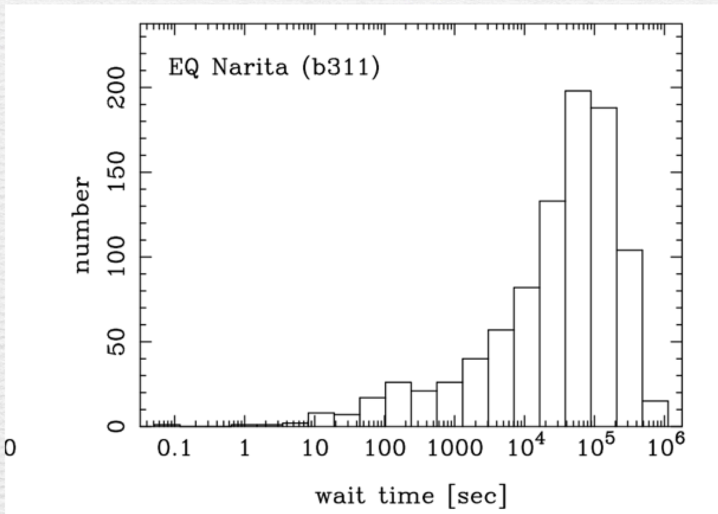




- wait-time distribution





Difference between FRBs & earthquakes?

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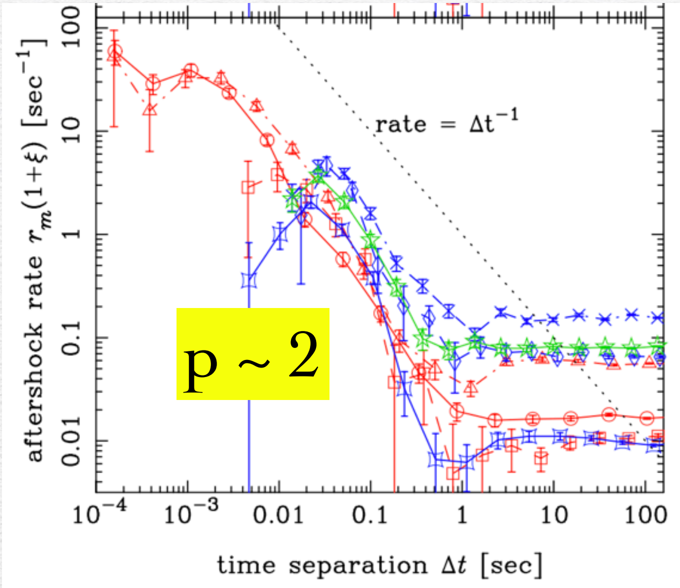
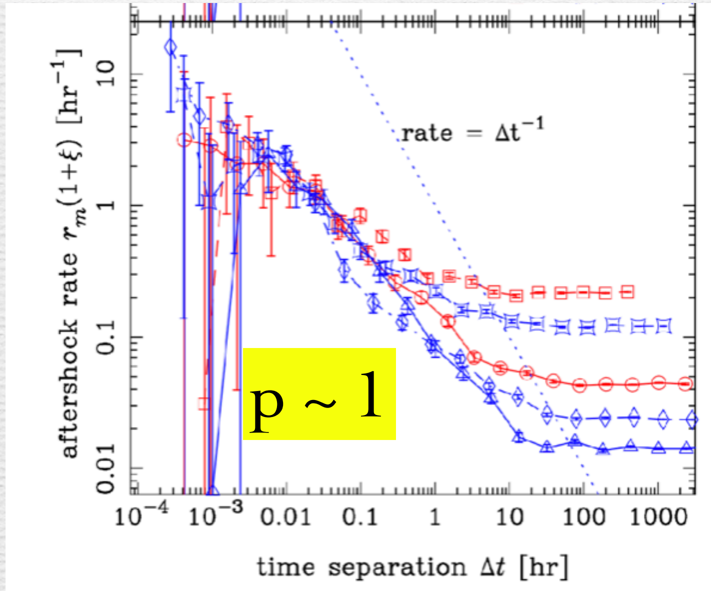
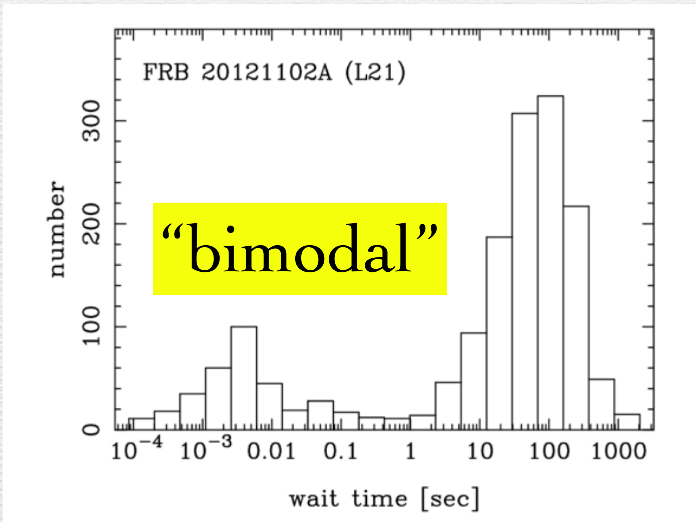
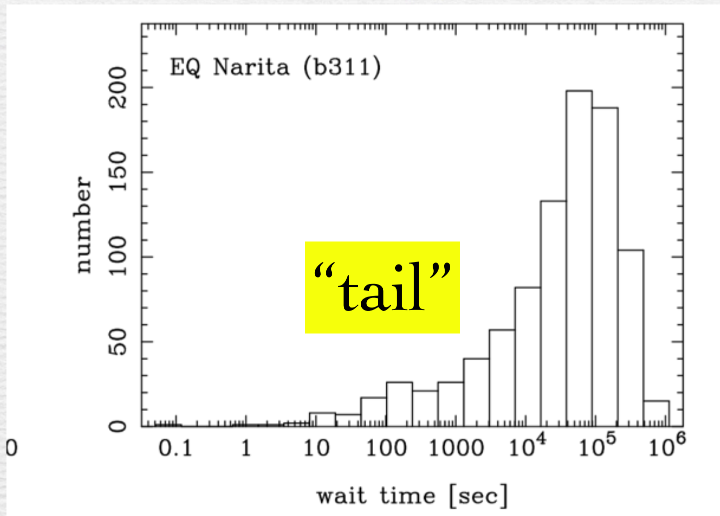




- wait-time distribution





Conclusions (1)

- FRBs are remarkably similar to earthquakes in time-energy correlation, with the universal laws on the aftershock statistics
  1. each event induces 0.1-0.5 aftershocks
  2. aftershock rate obeys the Omori-Utsu law $\propto (\Delta t + \tau)^{-p}$
  3. τ is close to the event duration (10 msec for FRBs, 1 min for earthquakes)
  4. even if the source activity changes, the aftershock rate remains stable
  5. almost no correlation between time and energy

- These features have been known for earthquakes as the ETAS (epidemic-type aftershock sequence) model

- the only difference is p ~ 2 (FRB) or ~ 1 (earthquakes)

- In contrast, solar flares are NOT similar to FRBs/earthquakes
  - perhaps related to fluid surface of the Sun, compared with solid crusts at FRB/Earth surfaces?

Conclusions (2)

- A natural interpretation: repeating FRBs are produced when the energy stored in solid neutron star crust is liberated by seismic activity

- Other FRB mechanism may not be excluded, but these aftershock properties must be explained in any FRB theory, putting strong constraints

- Future theoretical studies on FRB aftershock properties may give us new information about the neutron star crust / dense nuclear matter

Contents

- “Fast radio bursts trigger aftershocks resembling earthquakes, but not solar flares”
  - Totani, T. & Tsuzuki, Y. 2023, MNRAS 526, 2795

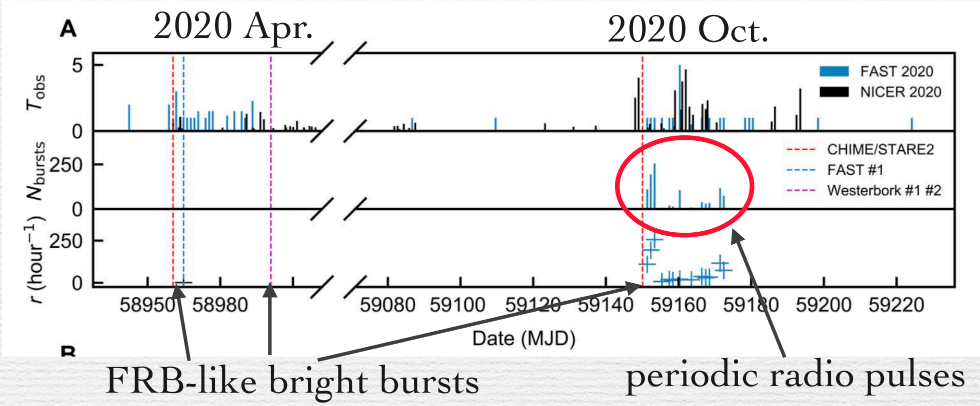
- “Similarity to earthquakes again: Periodic radio pulses of the magnetar SGR 1935+2154 are accompanied by aftershocks like fast radio burst”
  - Tsuzuki, Y., Totani, T., C.-P. Hu, & T. Enoto 2024, MNRAS 530, 1885

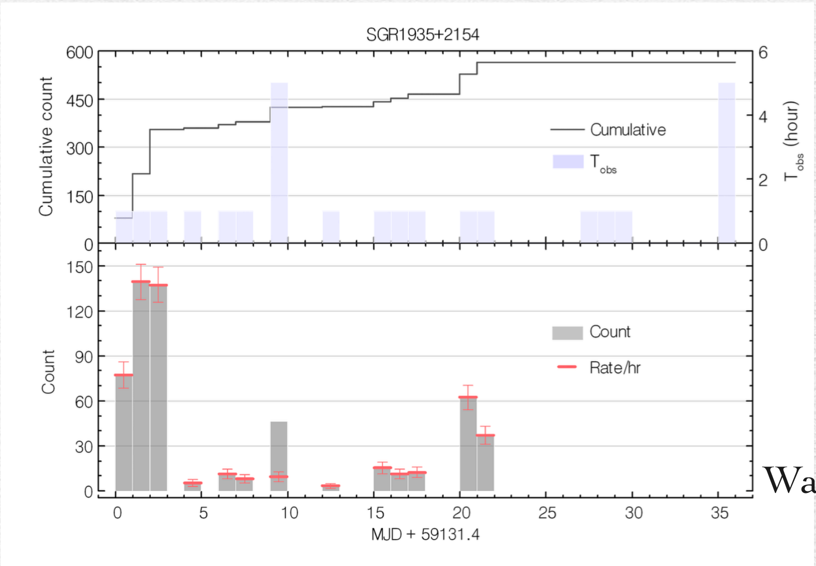
Correlation function analysis on SGR 1935+2154 burst phenomena

- (repeater) FRB-magnetar connection already established by FRB 20200428 from SGR 1935+2154
- Correlation properties similar to FRBs may be found in bursting phenomena of magnetars
- This work (Tsuzuki+'24): the same correlation function analysis on SGR 1935 bursting phenomena as those of Totani+'23 for FRBs
- The SGR 1935 burst samples:
  - ~ 560 radio bursts (pulsations) reported in Wang+'23 (see also Zhu+'23)
    - observed around 2020 Oct., i.e., about half a year later than FRB 20200428
  - ~ 580 X-ray bursts detected by NICER
    - 205 bursts during 1120 s in 2020 Apr. (Younes+'20)
    - 374 bursts during Oct. 12-18 in 2022 (Hu+'24)

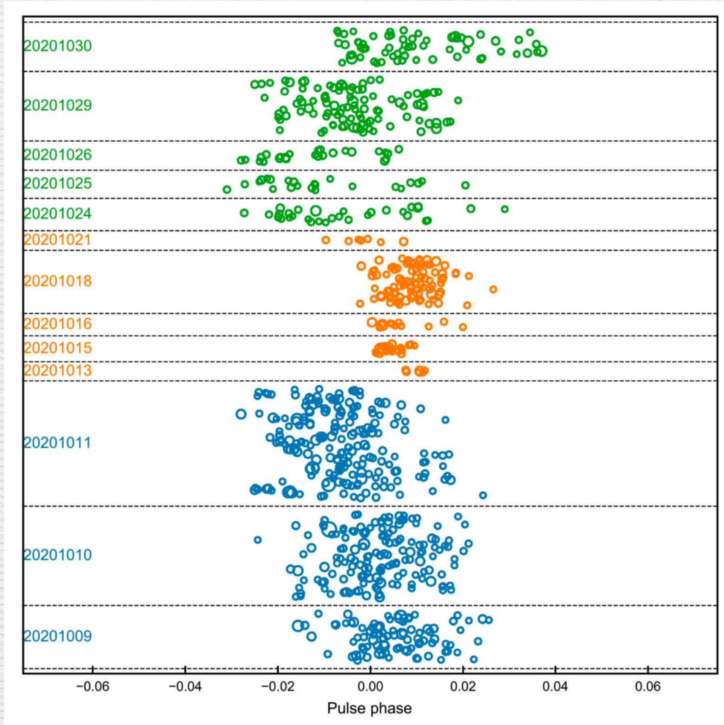
Radio pulses from SGR 1935+2154

- detected by FAST (Zhu+'23; Wang+'23)
- during 2020 Oct. 9 - Nov. 7
  - half year later from FRB 20200428
- 563 periodic pulses detected in 464 rotation cycles
  - P = 3.24 s
  - 1.9×10^4 cycles during obs. → 2.5% detection per cycle
  - pulses occur at a particular phase of the rotation cycle
- radio flux 7-8 orders lower than FRB 20200428





Wang+'23

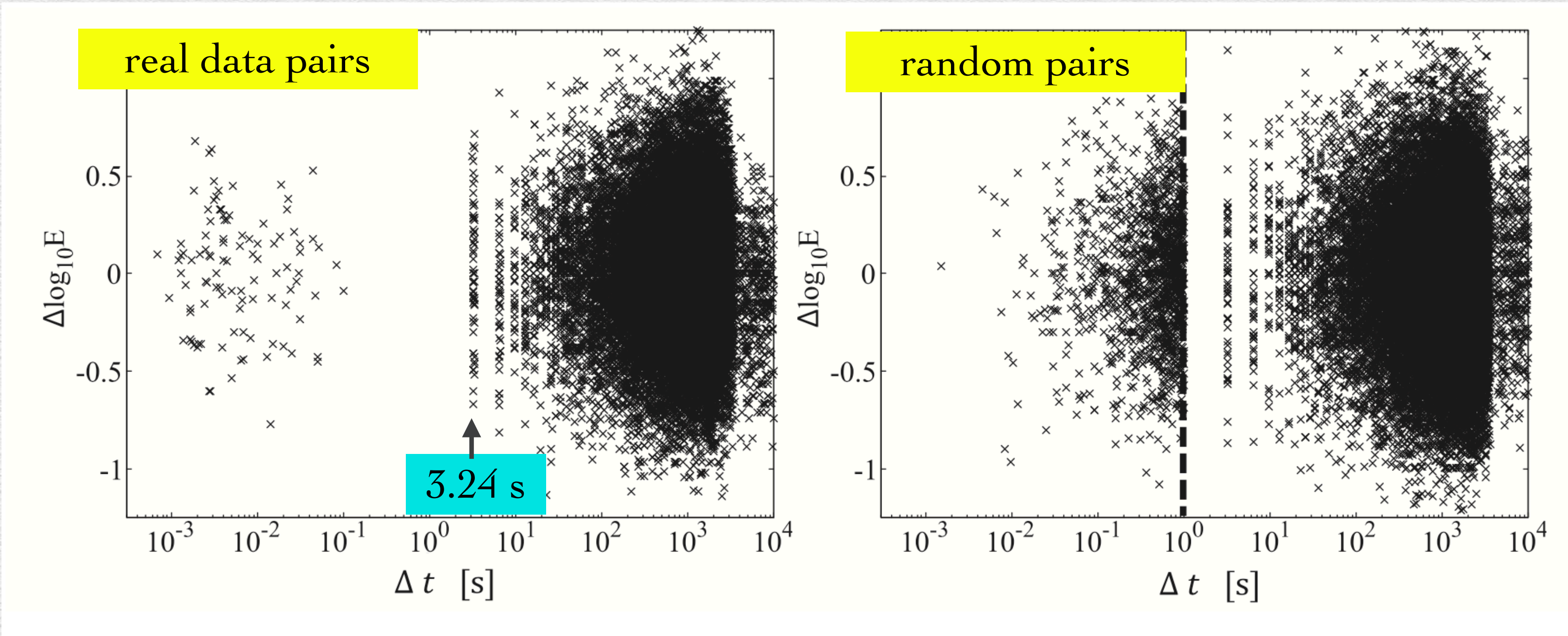


Zhu+'23

a special treatment for radio pulse correlation analysis

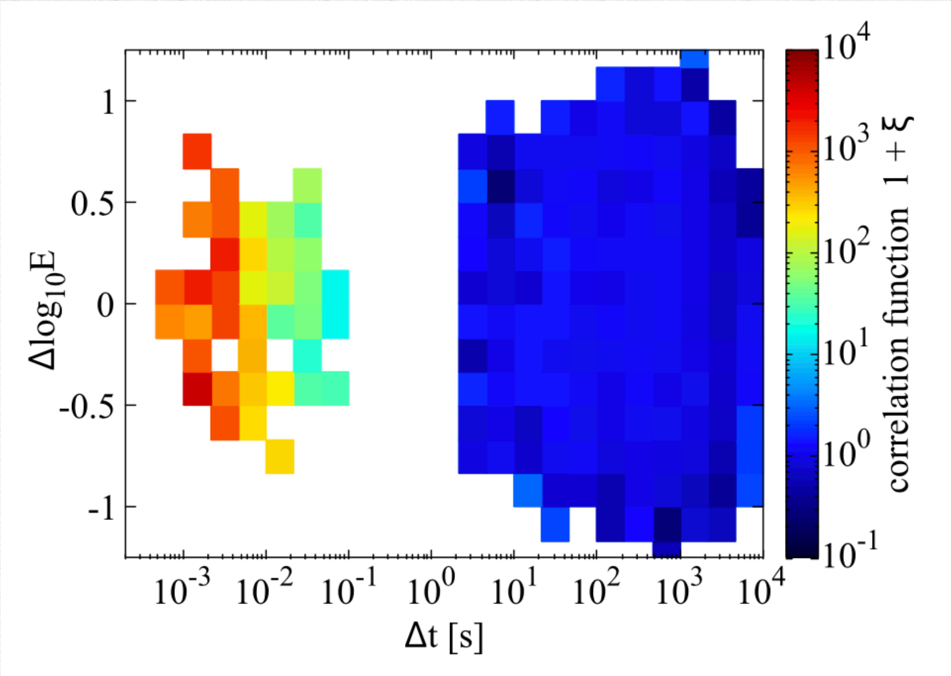
- SGR 1935 radio pulses occur at a fixed phase of the P = 3.24 s rotation cycle
- Different treatments for Δt > 1 or < 1 s
  - At Δt > 1 s: random data generated on grids separated by 3.24 s, to see inter-cycle correlation
  - At Δt < 1 s: random data generated by a uniform distribution in time, to see intra-cycle correlation

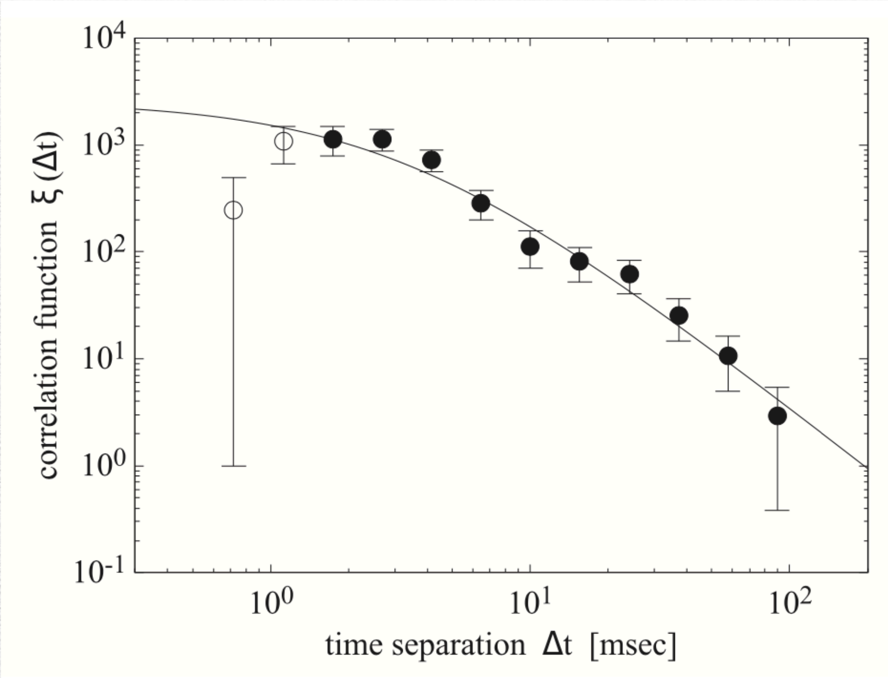
pair distribution in Δt vs. Δ log E space



correlation function of SGR 1935 radio pulses

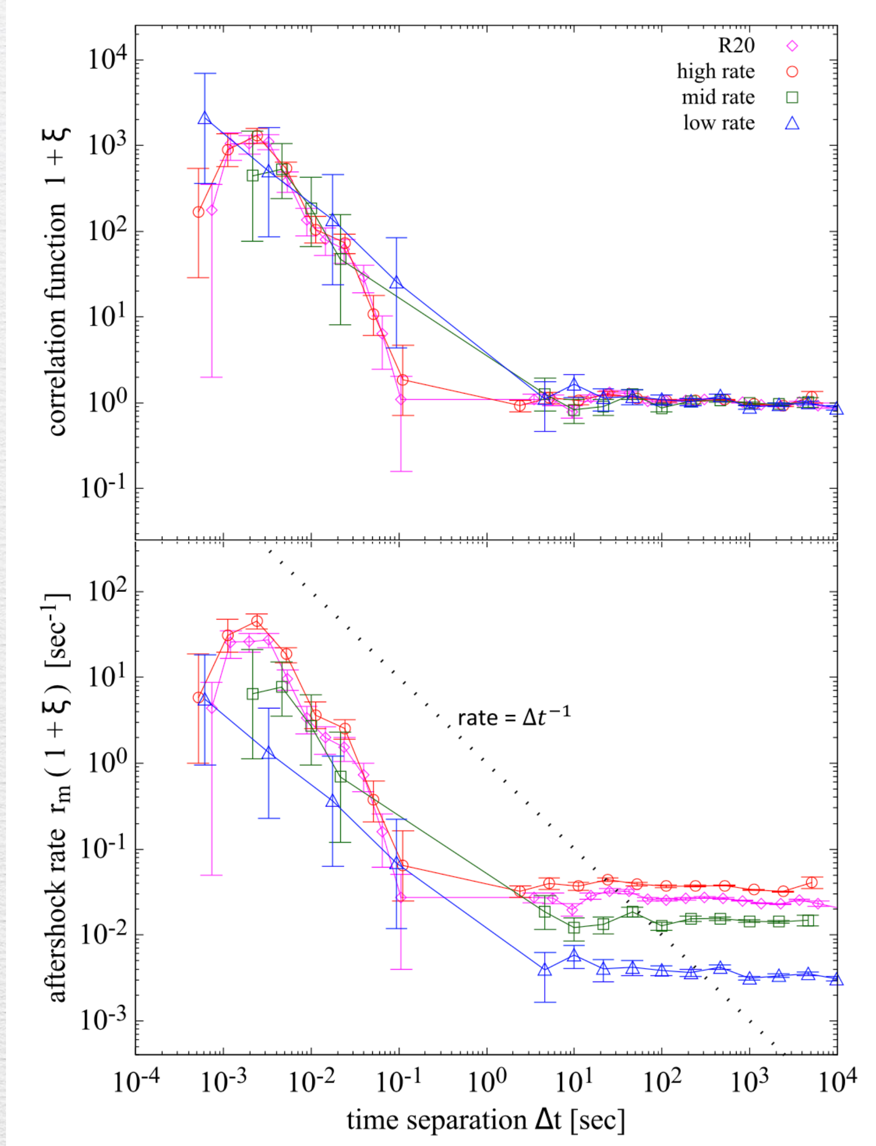
- no inter-cycle correlation in $\Delta t > 1$ s
- clear intra-cycle correlation at $\Delta t < 1$ s, with almost no correlation along the energy direction
- time correlation can be fit by Omori-Utsu law $(\Delta t + \tau)^{-p}$
    - best fit: $p = 1.9$, $\tau = 3.2$ ms
- similar to FRBs reported by Totani+'23





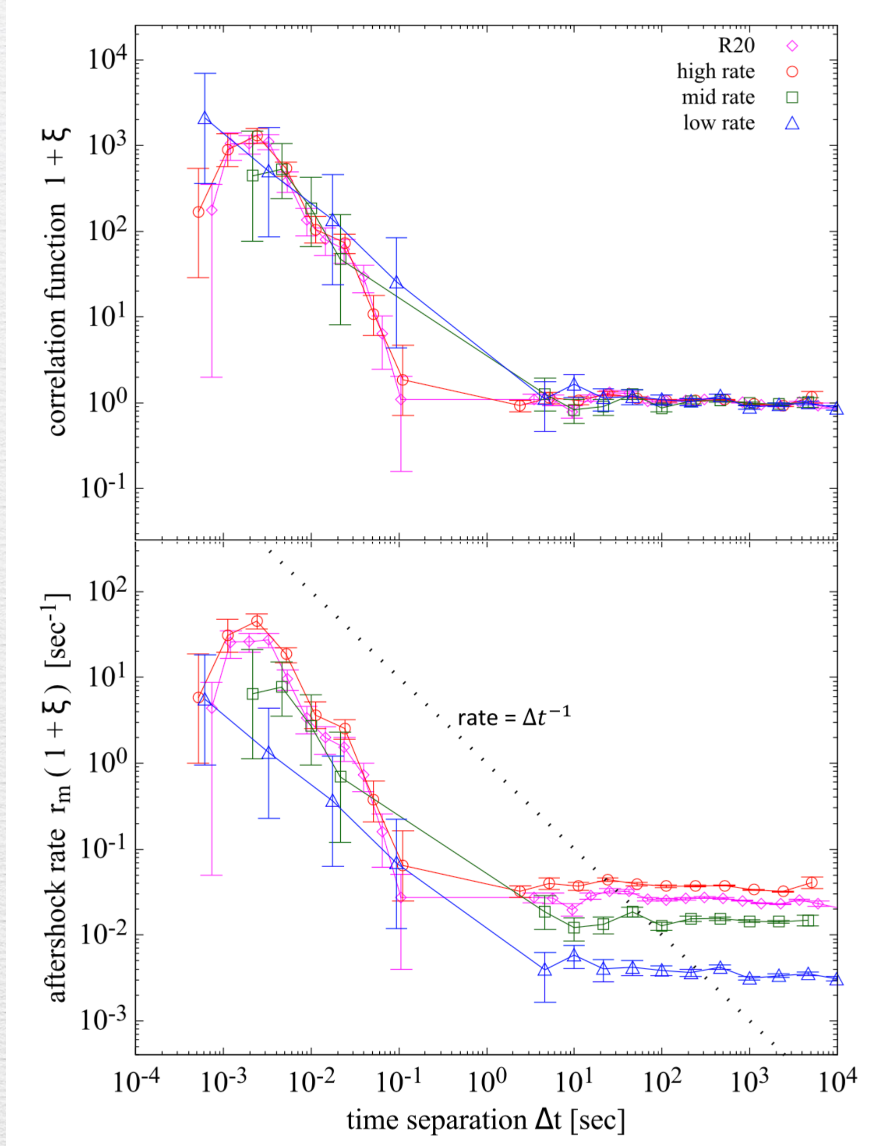
aftershock rate and its stability of radio pulses

- top: correlation function $1+\xi$
- bottom: $r_m (1 + \xi)$ = the aftershock rate following one event, where r_m is mean event rate
- correlation functions split into three data sets of high, middle, and low activity (mean event rate)
- expectation number of aftershock for one event (integration of aftershock rate) is $n \sim 0.2$
  - similar to n found for FRBs and earthquakes by Totani+'23



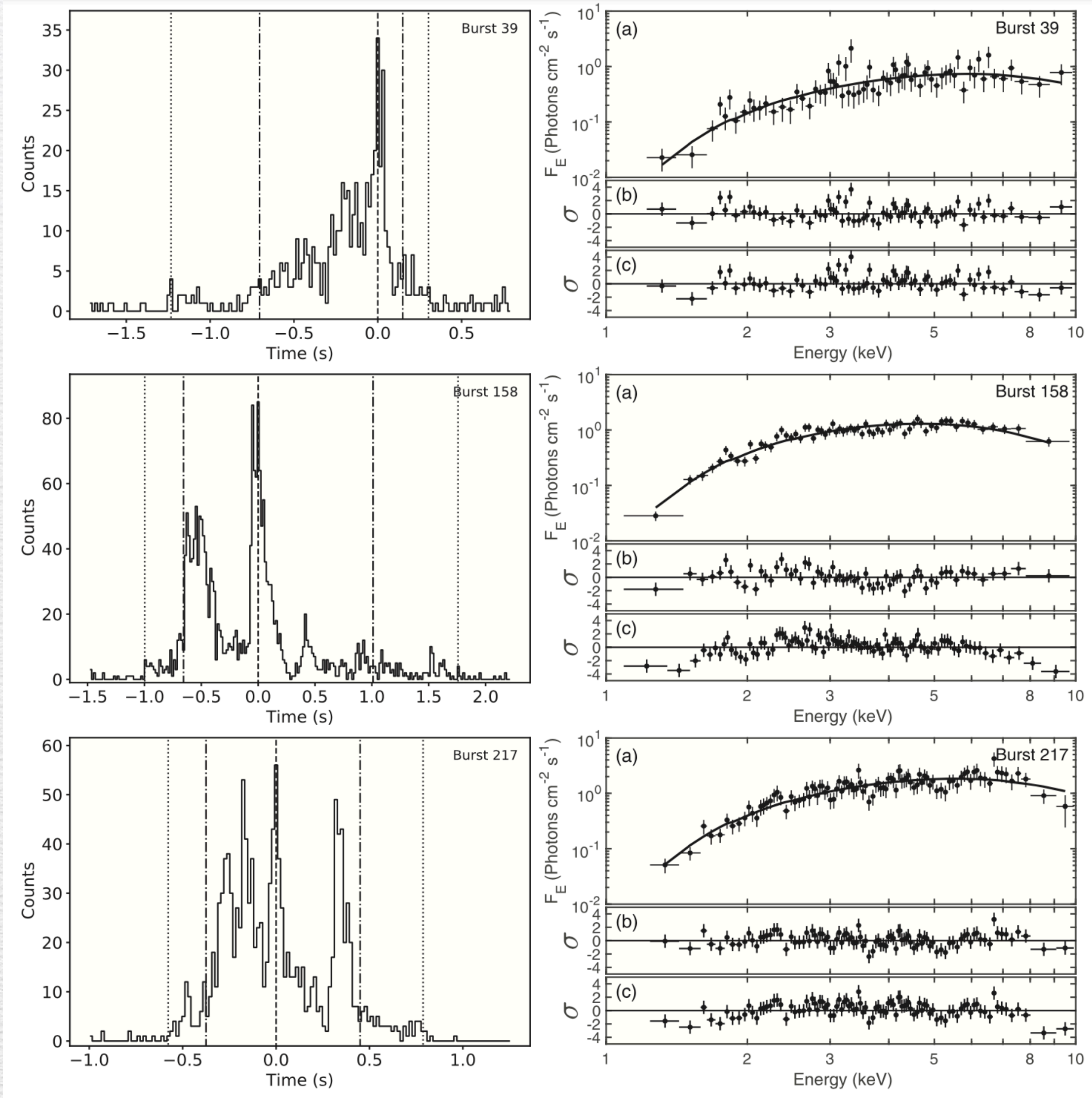
aftershock rate and its stability of radio pulses

- aftershock of aftershocks?
  - In 464 cycles where pulses are detected,
    - two pulses in 82 cycles (82/464 ~ 0.2)
    - three pulses in 17 cycles (17/82 ~ 0.2)
    - four pulses case not observed
  - consistent with "aftershock of aftershocks" occur with the same probability of n ~ 0.2
  - no discrimination between mainshocks and aftershocks
    - consistent with the ETAS picture in agreement with earthquake data



X-ray bursts from SGR 1935

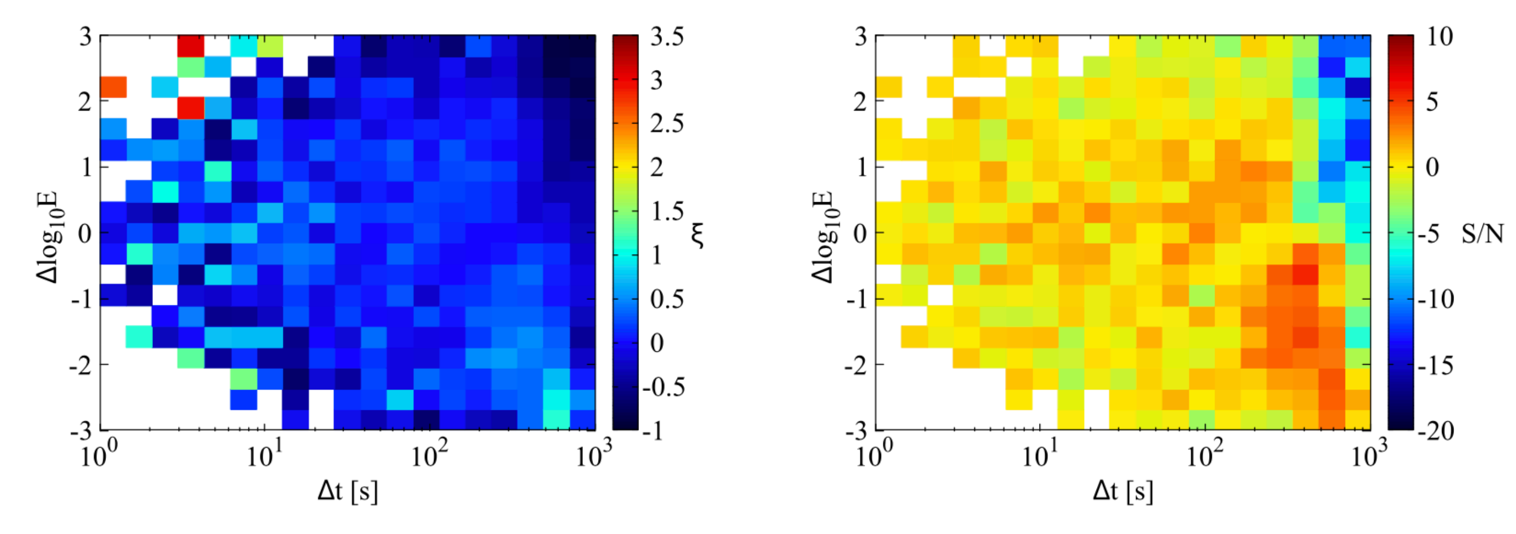
- ~ 580 X-ray bursts detected by NICER
  - 205 bursts during 1120 s in 2020 Apr. (Younes+’20)
  - 374 bursts during Oct. 12-18 in 2022 (Hu+’24)

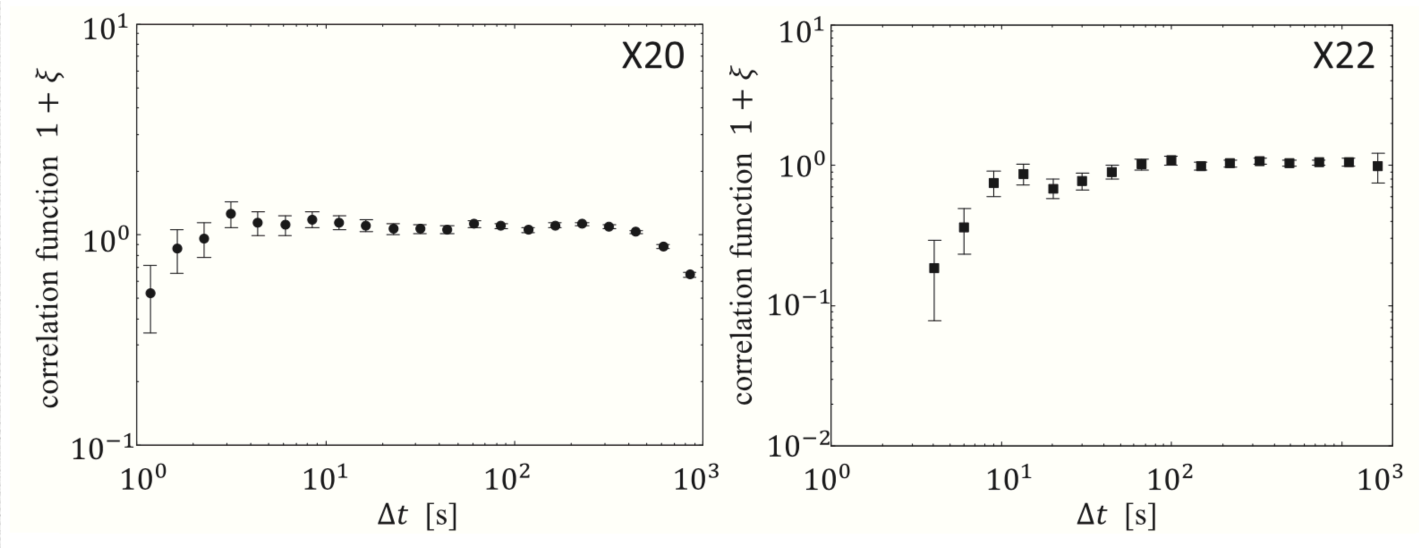


Younes+’20

results on X-ray bursts of SGR 1935

- No statistically significant correlation signal in time-energy space in $3 < \Delta t < 2000$ s
- correlation signal at $\Delta t < 0.1$ s may be hidden by longer duration of X-ray bursts than radio
- apparent signal at long time interval ($\Delta t \sim 10^3$ s) most likely induced by systematic change of burst rate and energy distribution





How to interpret the radio pulse time correlation nature?

- aftershock properties similar to FRBs/earthquakes, but at a fixed phase of the rotation cycle!
  - an emerging picture: the first main shock occur at the fixed phase for some reason, and then the first mainshock induces aftershocks in a similar way to FRBs/earthquakes

- physical origin? two scenarios may be considered:
  - <u>radio pulses are produced by starquakes in the neutron star crust?</u>
    - aftershock correlation properties OK
    - the periodic first mainshocks? periodic external force may induce the first starquake in a cycle?
      - magnetar radio pulses are generally transient, associated with an intensive outburst activity (SGR 1935 radio pulses found within a few days from a large spin-down glitch and FRB-like bright bursts (Younes+'23; CHIME collab. '20))
      - interaction with ejected material around the star may induce periodic torque?
  - <u>beamed emission?</u>
    - narrow pulses at a fixed phase OK
    - how to explain the correlated aftershock with a power-law rate decay like FRBs/earthquakes?

Discussion on energy sources and relation to FRBs

- FRBs and SGR 1935 radio pulses are very similar:
  - complex radio pulse morphology (narrow band emission & frequency drifts) that is not observed in other magnetars (but found from a small group of pulsars) (Wang+'23; Zhu+'23)
  - Aftershock properties following the Omori law, similar to earthquakes (Totani+'23; Tsuzuki+'23)

- But luminosities are totally different!
  - FRB-like radio bursts and X-ray bursts from SGR 1935
    - FRB 20200428 peak radio luminosity 3e36 erg/s > spin-down luminosity 2e34 erg/s
    - energy production rate of X-ray bursts (4e37 erg/s) > spin-down luminosity
    - occur at random rotational phases
  - periodic radio pulses
    - energy production rate of pulses ~ $1/10^{10}$ of spin-down energy (~10^{31} erg in 1 month)
    - clear periodicity at a fixed rotation phase, that must be rotation-powered

Discussion on energy sources and relation to FRBs

- The similarities between FRBs and SGR 1935 radio pulses are not by the energy sources, but must be from common physical processes
  - starquakes? some other processes?
  - similar radio phenomena may be discovered from other populations of (non-magnetar) neutron stars

Thank you for your attention!