Fast radio bursts trigger aftershocks resembling earthquakes, but not solar flares

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Fast radio bursts trigger aftershocks resembling earthquakes, but not solar flares

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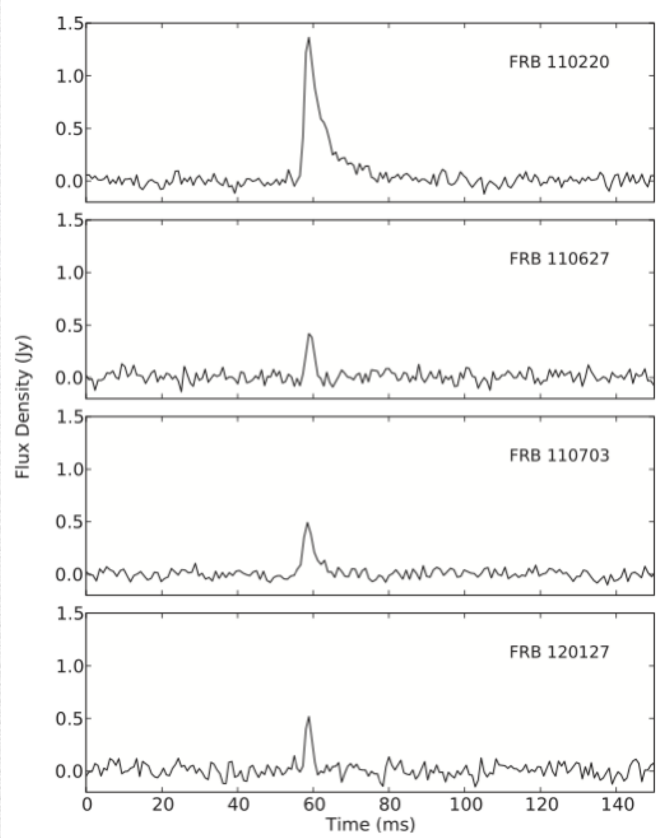
ABSTRACT

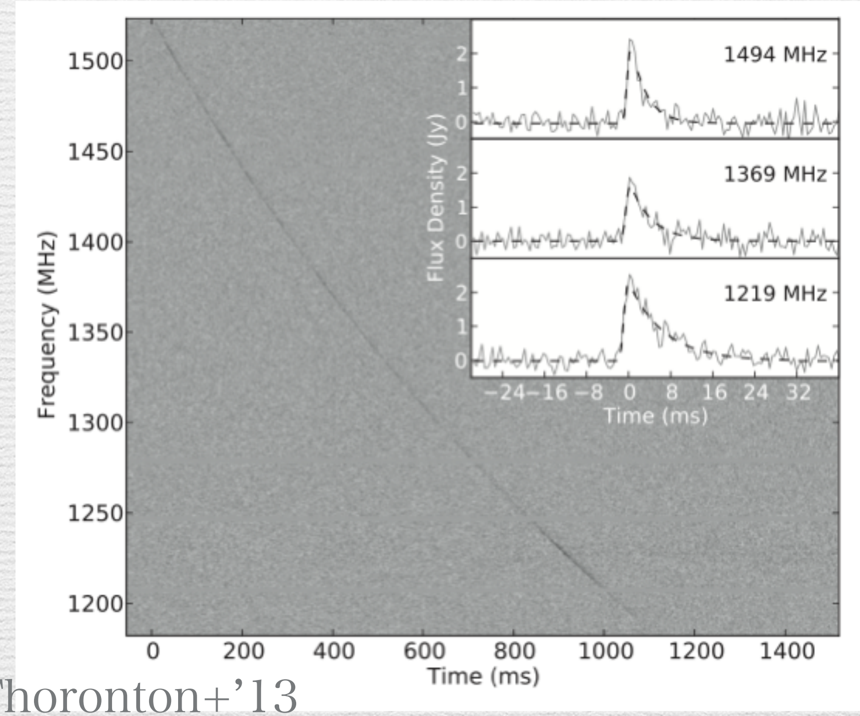
The production mechanism of repeating fast radio bursts (FRBs) is still a mystery, and correlations between burst occurrence times and energies may provide important clues to elucidate it. While time correlation studies of FRBs have been mainly performed using wait time distributions, here we report the results of a correlation function analysis of repeating FRBs in the two-dimensional space of time and energy. We analyze nearly 7,000 bursts reported in the literature for the three most active sources of FRB 20121102A, 20201124A, and 20220912A, and find the following characteristics that are universal in the three sources. A clear power-law signal of the correlation function is seen, extending to the typical burst duration ($\sim$ 10 msec) toward shorter time intervals (Δt). The correlation function indicates that every single burst has about a 10–60% chance of producing an aftershock at a rate decaying by a power-law as $\propto (\Delta t)^{-p}$ with $p = 1.5$–2.5, like the Omori-Utsu law of earthquakes. The correlated aftershock rate is stable regardless of source activity changes, and there is no correlation between emitted energy and Δt. We demonstrate that all these properties are quantitatively common to earthquakes, but different from solar flares in many aspects, by applying the same analysis method for the data on these phenomena. These results suggest that repeater FRBs are a phenomenon in which energy stored in rigid neutron star crusts is released by seismic activity. This may provide a new opportunity for future studies to explore the physical properties of the neutron star crust.

Key words: radio continuum: transients – stars: neutron – Sun: flares – fast radio bursts

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
  - 27 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)

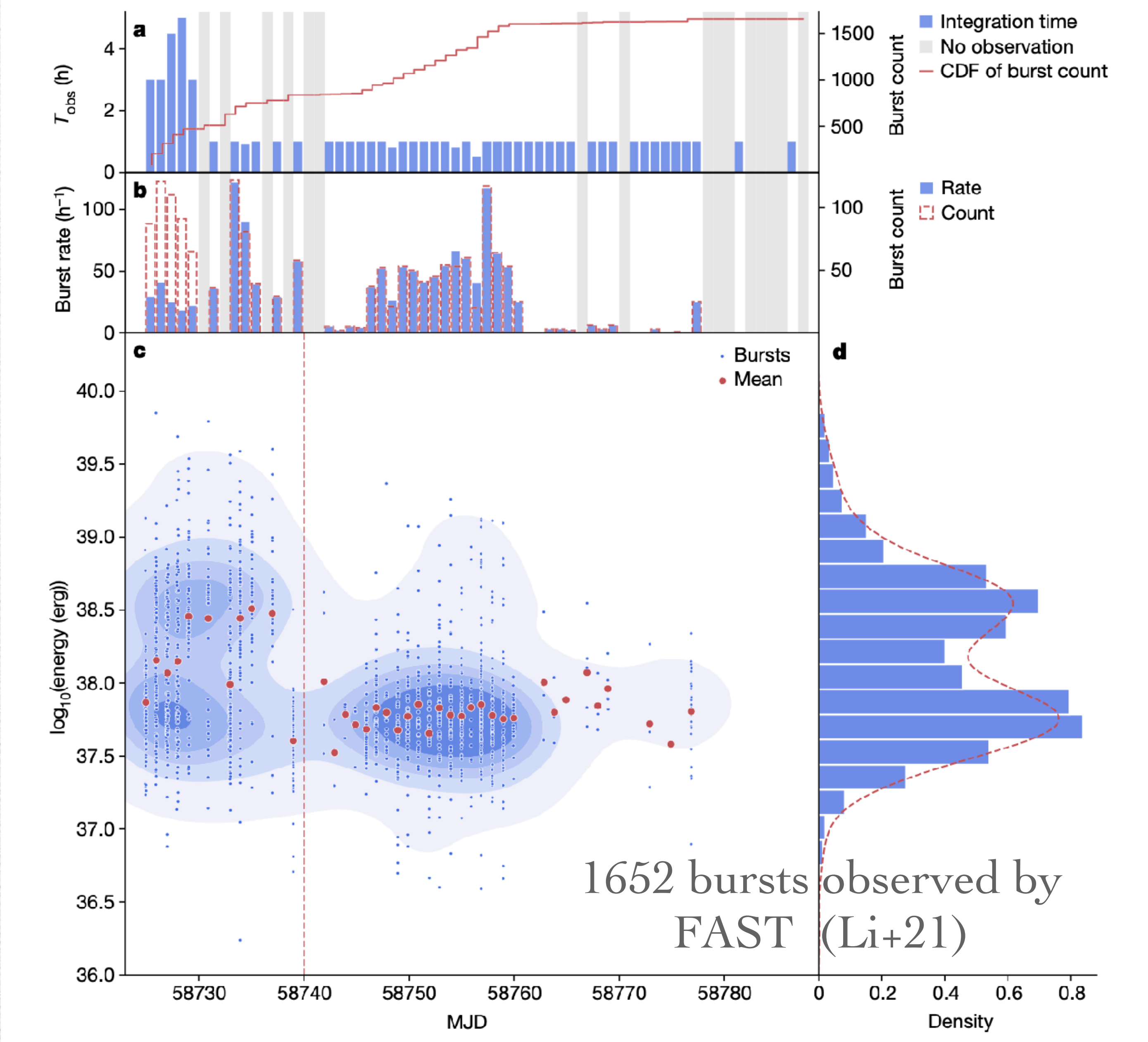




Thoronton+'13

thousands of bursts from a few repeater FRBs

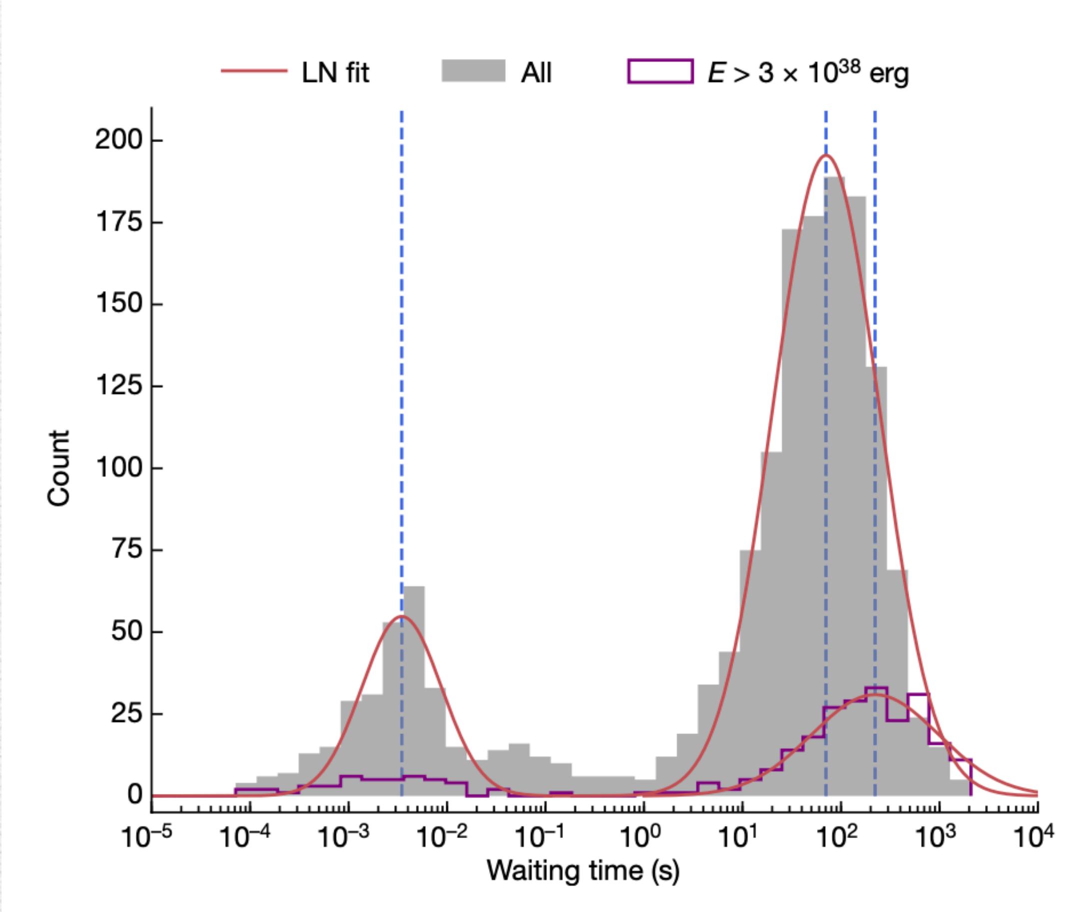
- FRB 20121102A
- FRB 20201124A
- FRB 20220912A
- …
- mostly detected by Arecibo and FAST



1652 bursts observed by FAST (Li+21)

Statistical properties of repeating FRB occurrence time

- bimodal wait-time distribution found universally for different sources
  - wait-time = t_{i+1} - t_i
  - (time to the next event)
- 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

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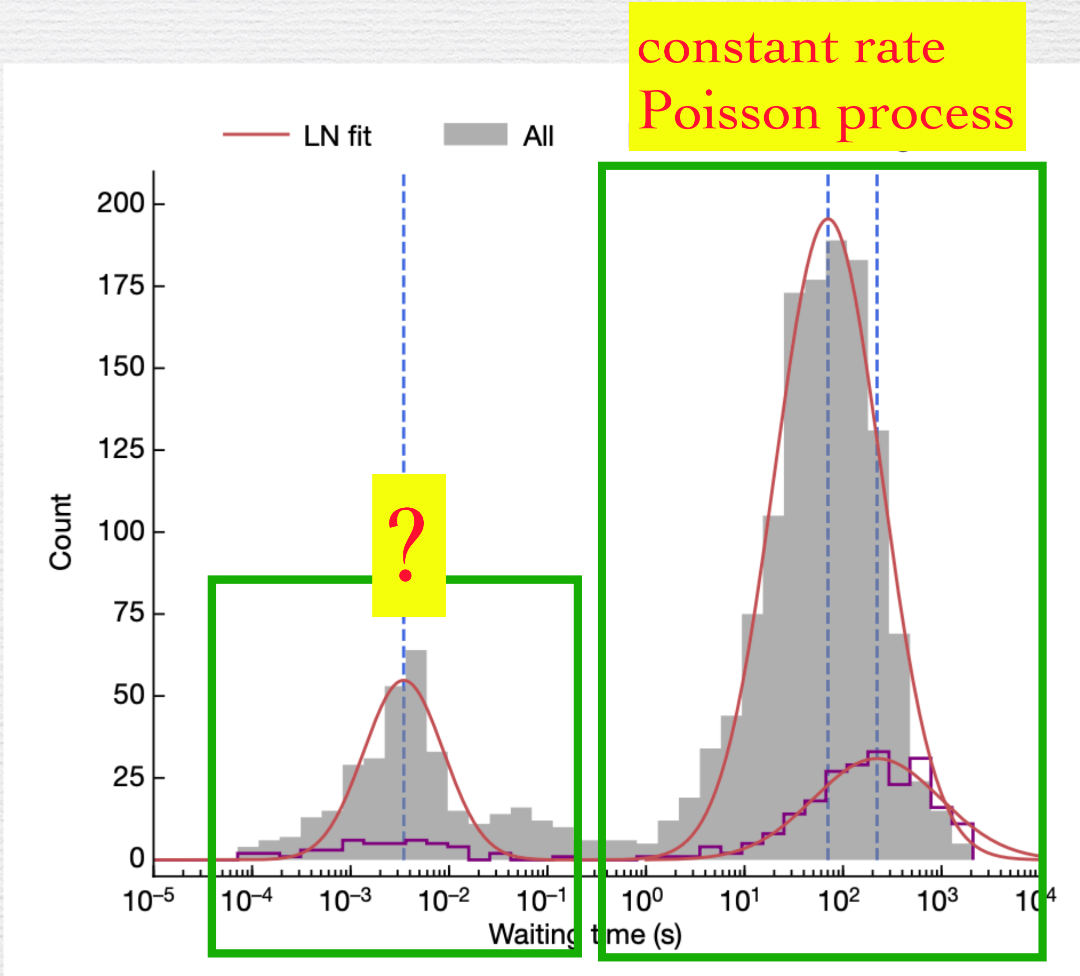
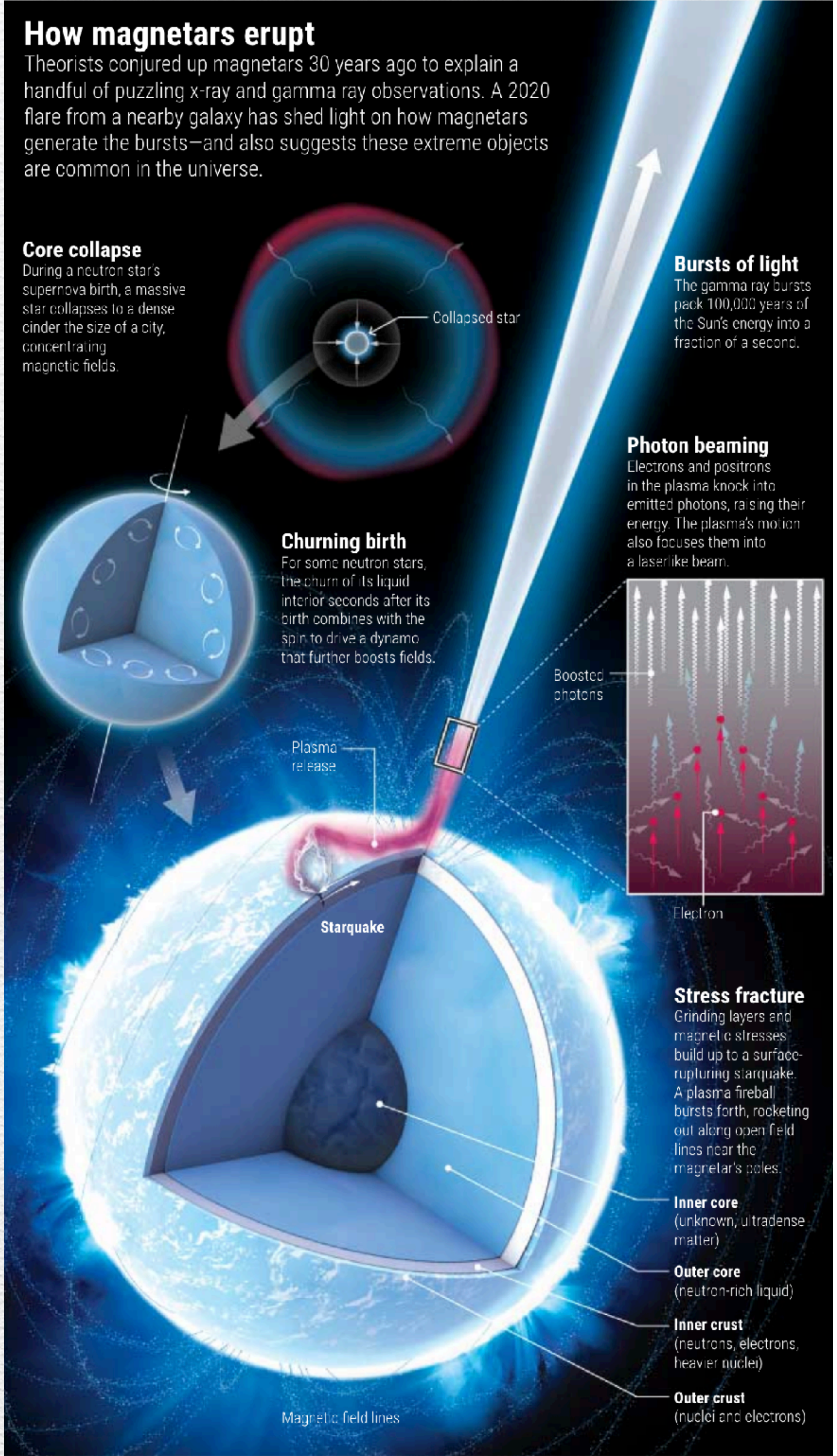


Li+'21

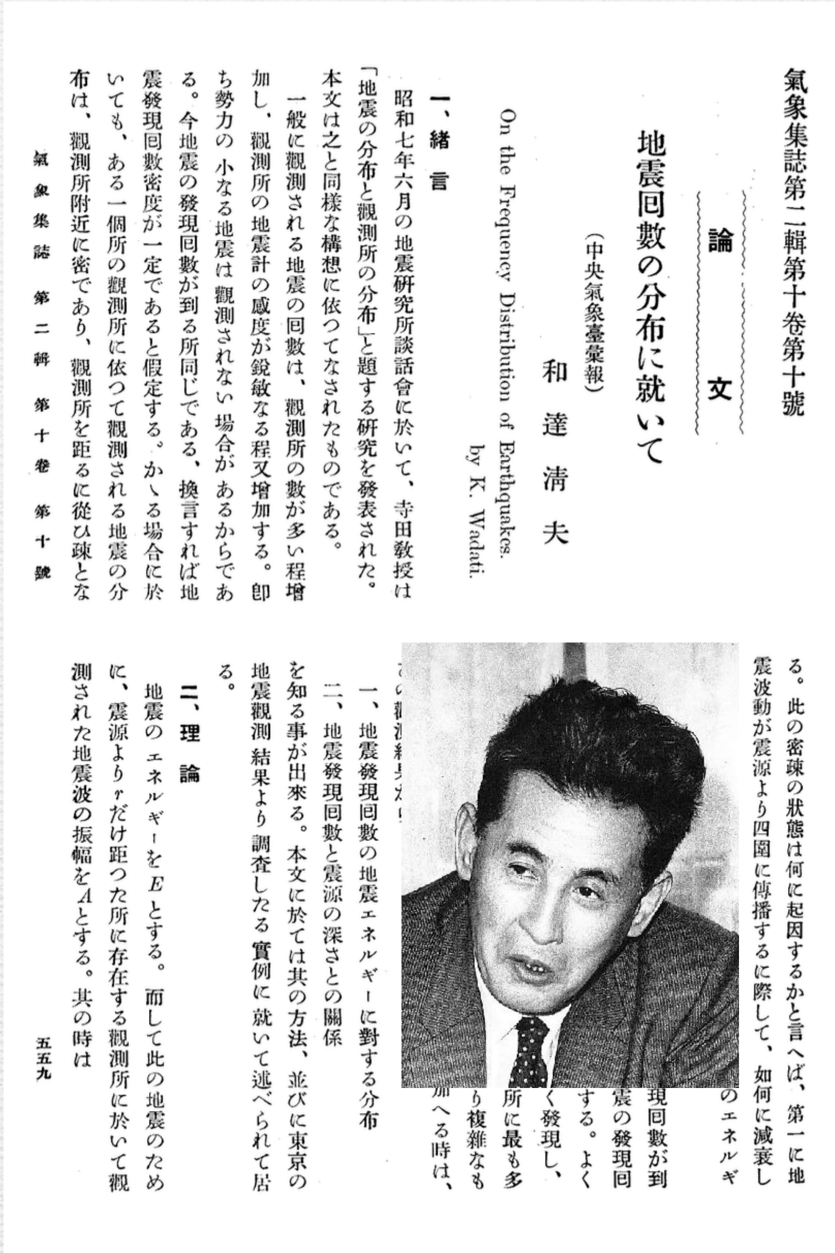
FRBs vs. earthquakes and solar flares

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



Wadati? Gutenberg-Richter law?

- The power-law distribution of earthquake magnitudes (energies) often called “Gutenberg-Richter” (1944) law, but …
  - $\log N(>M) \propto M^{-b}$, $dN/dE \propto E^{-1-2b/3}$, $b \sim 1$
- 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).
- Digression: his son, WADATI Miki (1945-2011) was a statistical physicist, a prof. at Phys. Dept. of Univ. Tokyo



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

(中央氣象臺彙報)

和　達　清　夫

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増加し、觀測所の地震計の感度が鋭敏なる程又増加する。即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 … のエネルギ … 現回數が到 … 震の發現回 … する。よく … く發現し、… 所に最も多 … り複雜なも … 加へる時は、…

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

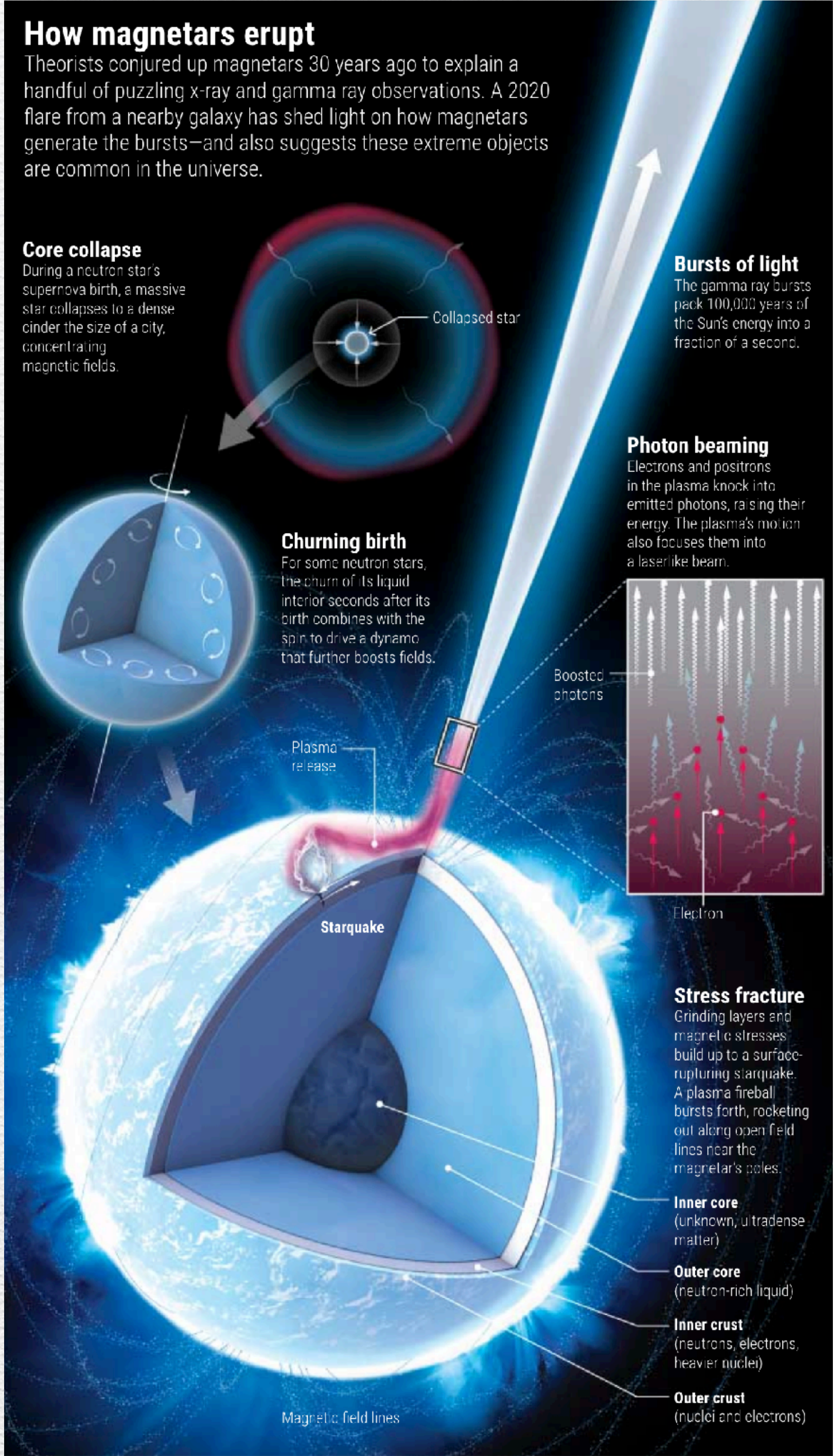
を知る事が出來る。本文に於ては其の方法、並びに東京の地震觀測結果より調査したる實例に就いて述べられて居る。

二、理　論

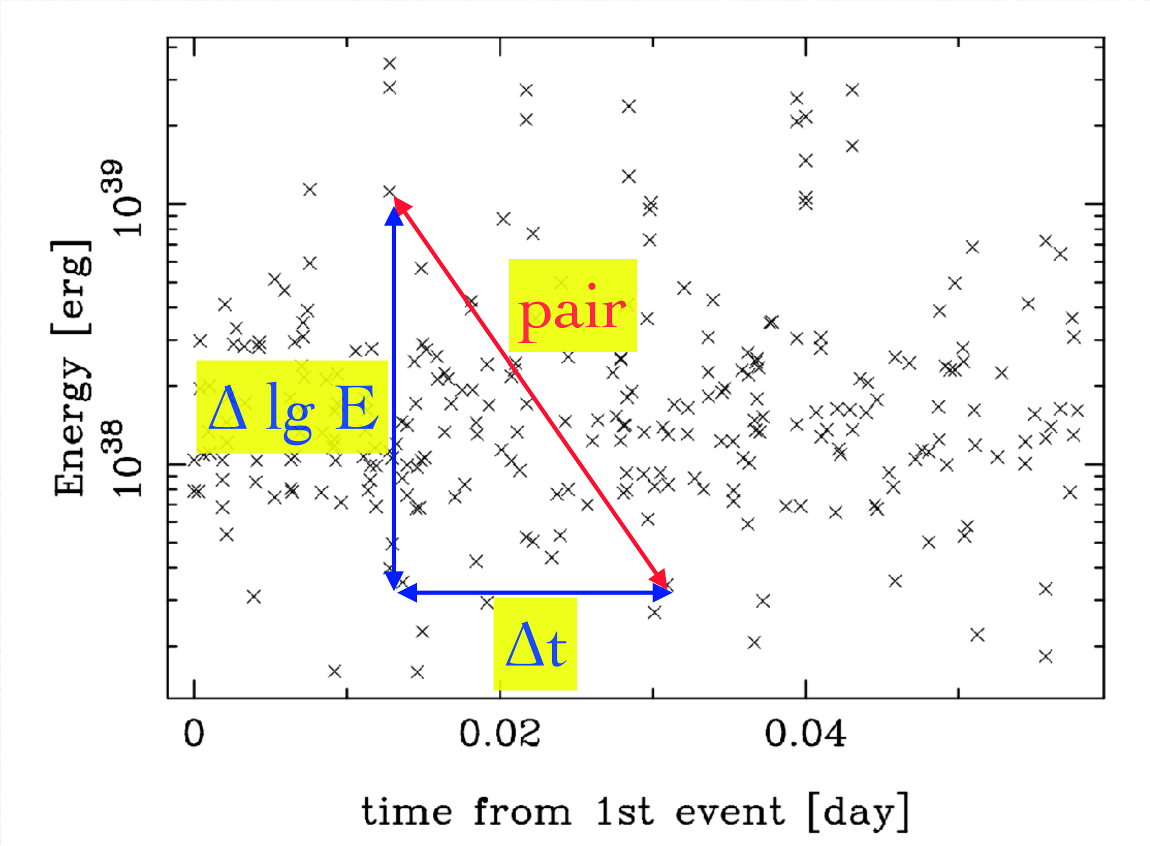
地震のエネルギーを E とする。而して此の地震のために、震源より r だけ距つた所に存在する觀測所に於いて觀測された地震波の振幅を A とする。其の時は

FRBs vs. earthquakes and solar flares

- This work:
  - investigate similarities between FRB/ earthquake/solar flares by two-point correlation function ξ in the time-energy space
    - a popular method to analyze large-scale structures in cosmology
  - wait-time distribution does not fully exploit the time correlation information, limited to the time to the next event
    - correlation may exist between two events across others



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)

calculation of correlation function

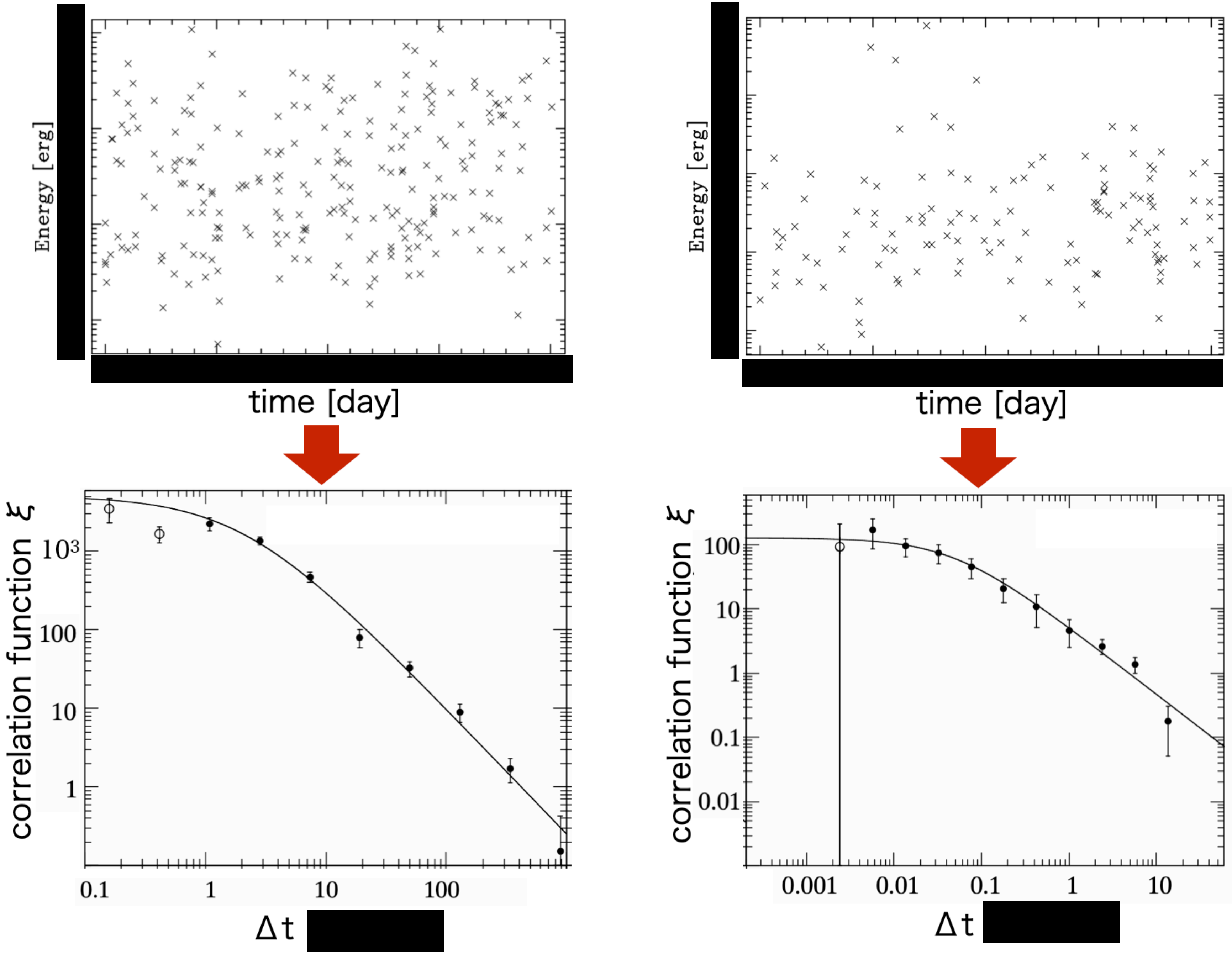
- by counting pairs in a bin of Δt vs. $\Delta \lg E$ space
- the data & random sample:
  - DD: pair counts in the real data sample
  - RR: pair counts in the random sample without correlation
  - DR: cross pair counts between the data & random samples

- A natural estimator: ξ = DD/RR - 1
- the Landy-Szalay estimator: ξ = (DD - 2 DR + RR) / RR

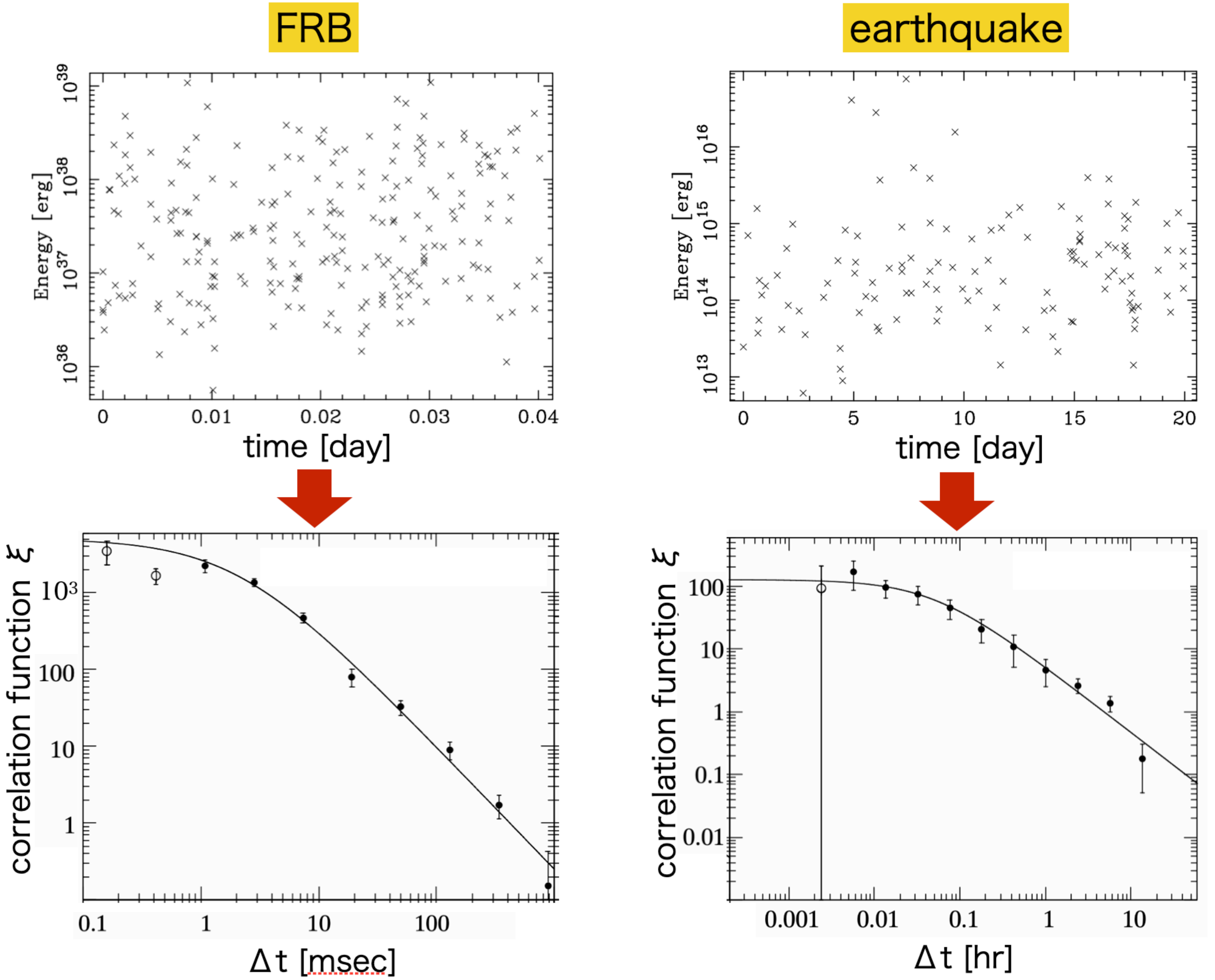
- error estimate:
  - Poisson error of pair counts (minimum error)
  - covariant matrix by Jack-knife sampling method

FRB & earthquakes… which is which?

[redacted]



FRB & earthquakes… which is which?



The three most active repeater FRBs

- FRB 20121102A
  - the first discovered repeater
  - z = 0.193, in a star-forming dwarf galaxy
  - data set from Li+'21, Hewitt+'22, Jahns+'23

- FRB 20201124A
  - z = 0.0979, in a Milky-Way like, barred spiral galaxy
  - data set from Xu+'22, Zhang+'22 (very active phase, day 3 and day 4 treated as different sets)

- FRB 20220912A
  - z = 0.0771, in a host galaxy of ~10^{10} $M_\odot$
  - data set from Zhang+'23

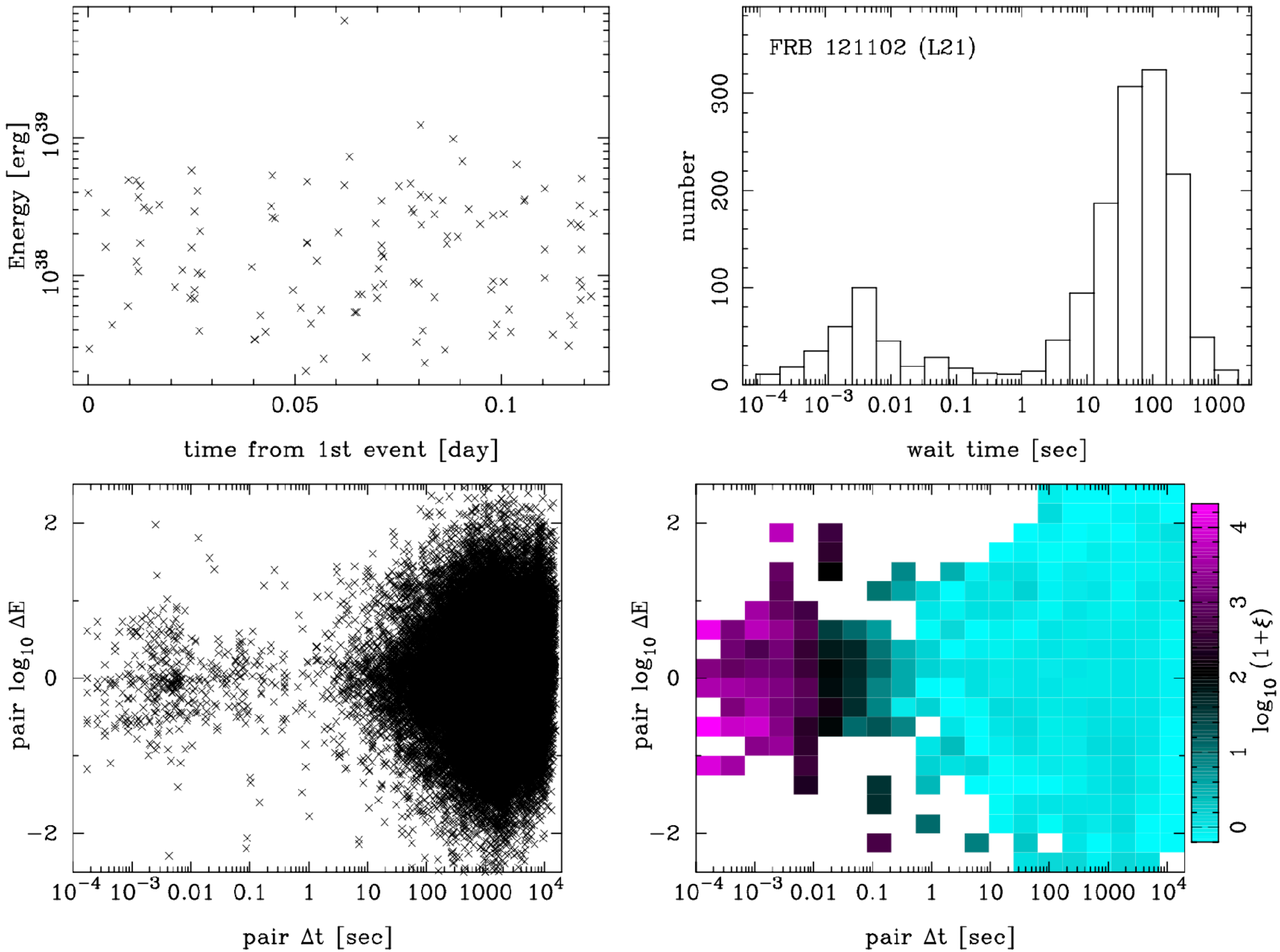
7 FRB data sets for 3 sources

- nearly 7,000 events in total

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	

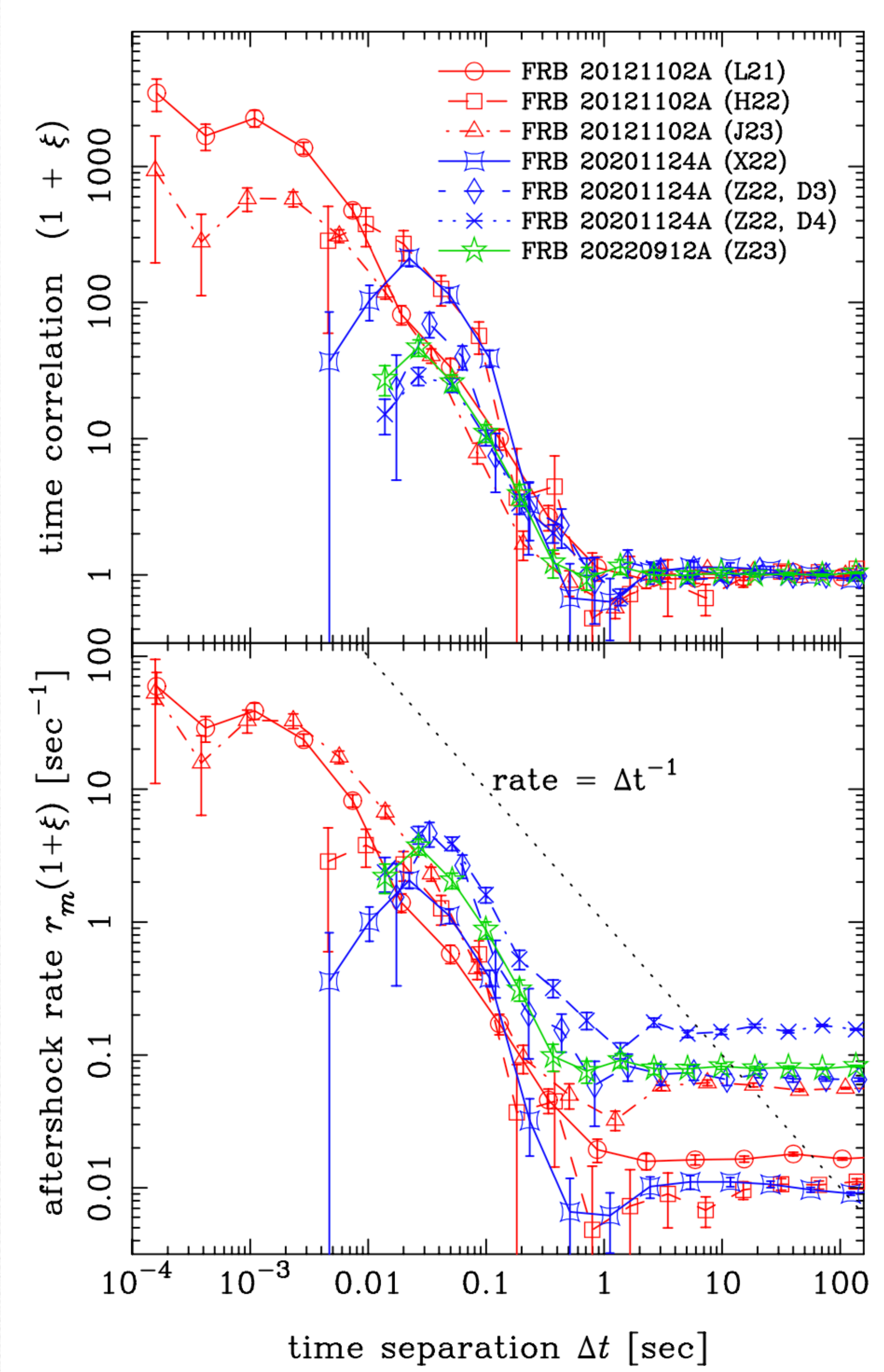
[a]Total number of days on which observations were made

Example of ξ calculation



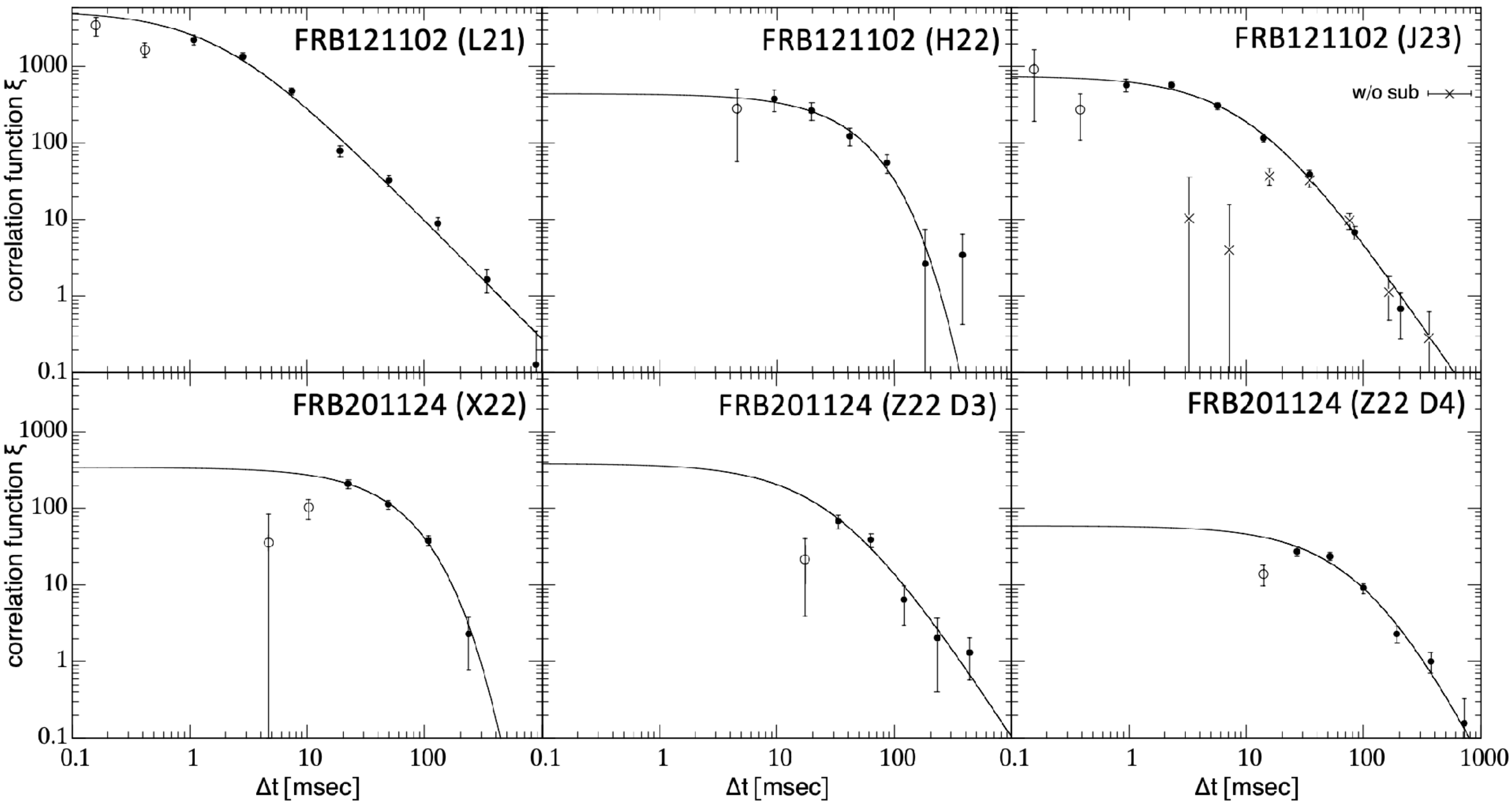
time correlation ξ(Δt)

- power-law signal at ⊿t < 1 sec
- flat at ⊿t ∼ FRB duration(<10 msec)
  - Note different sub-burst treatments by different authors
- fit by ξ ∝ (⊿t + τ)$^{-p}$ (next page)
- similar to the Omori-Utsu law of aftershock rate of earthquakes
- "aftershock rate" after one event is given as $r_m(1+\xi)$, where r_m is the mean event rate
  - 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



model fits to time correlation function

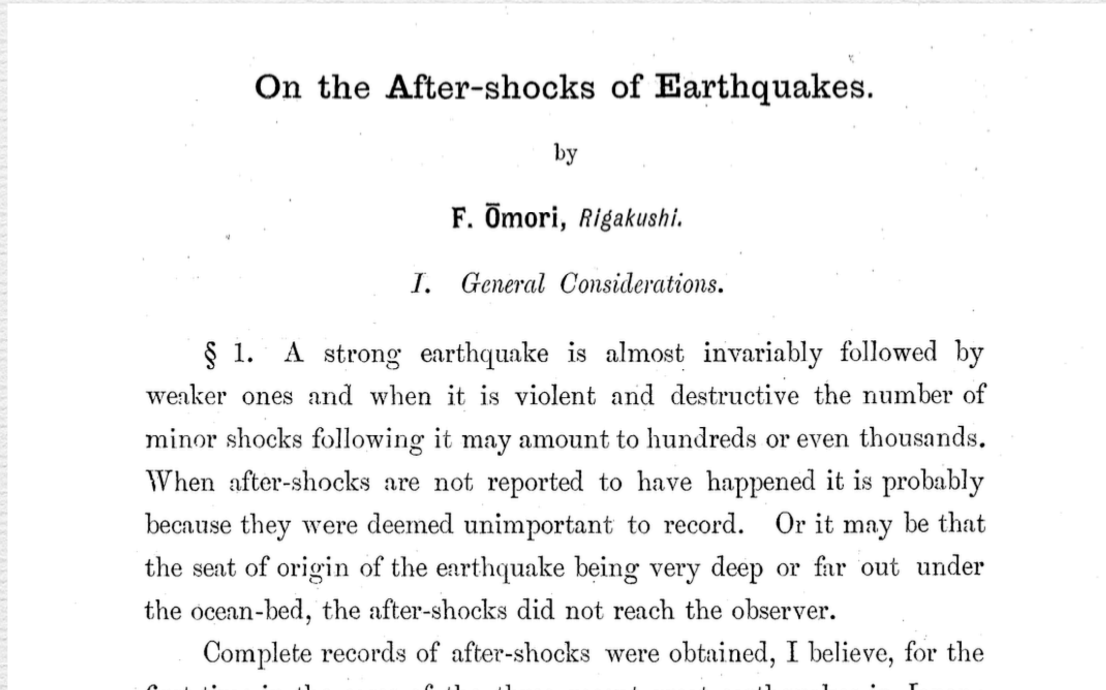
- fit by $\xi \propto (\Delta t + \tau)^{-p}$



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 $\propto (\Delta t + \tau)^{-1}$

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



On the After-shocks of Earthquakes.

by

F. Ōmori, *Rigakushi.*

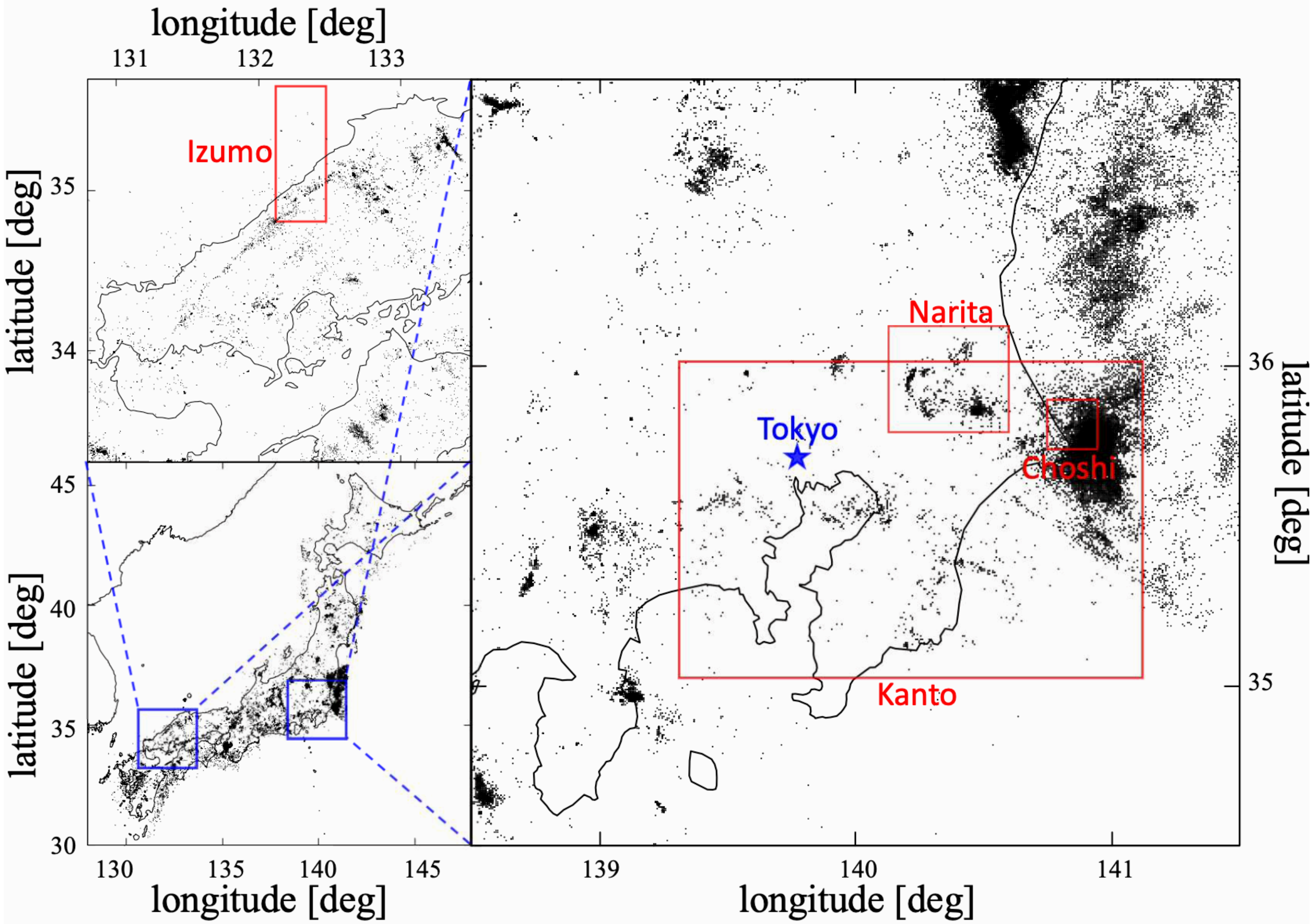
I. General Considerations.

§ 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.

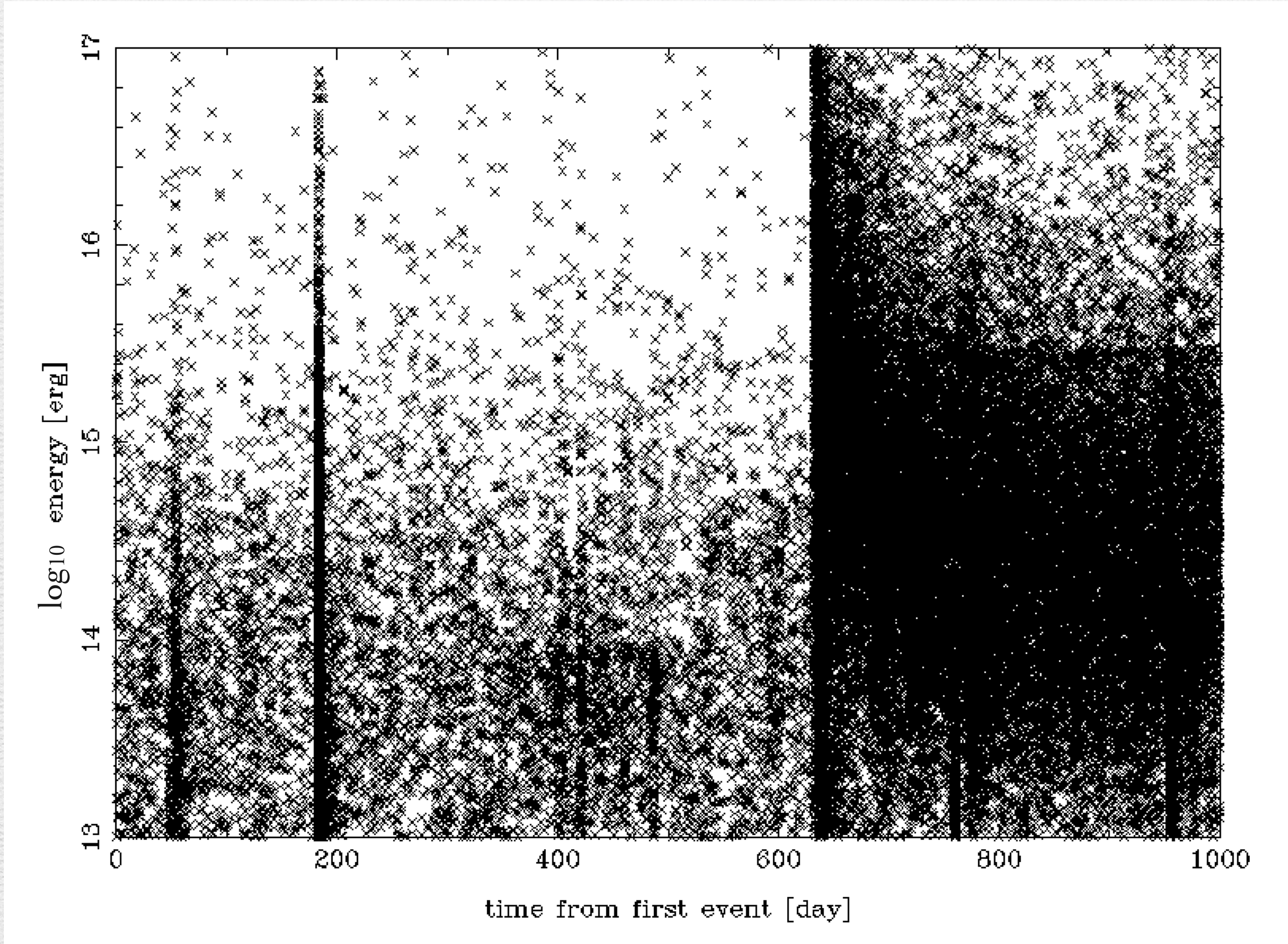
Complete records of after-shocks were obtained, I believe, for the

Applying the same analysis to earthquake data

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

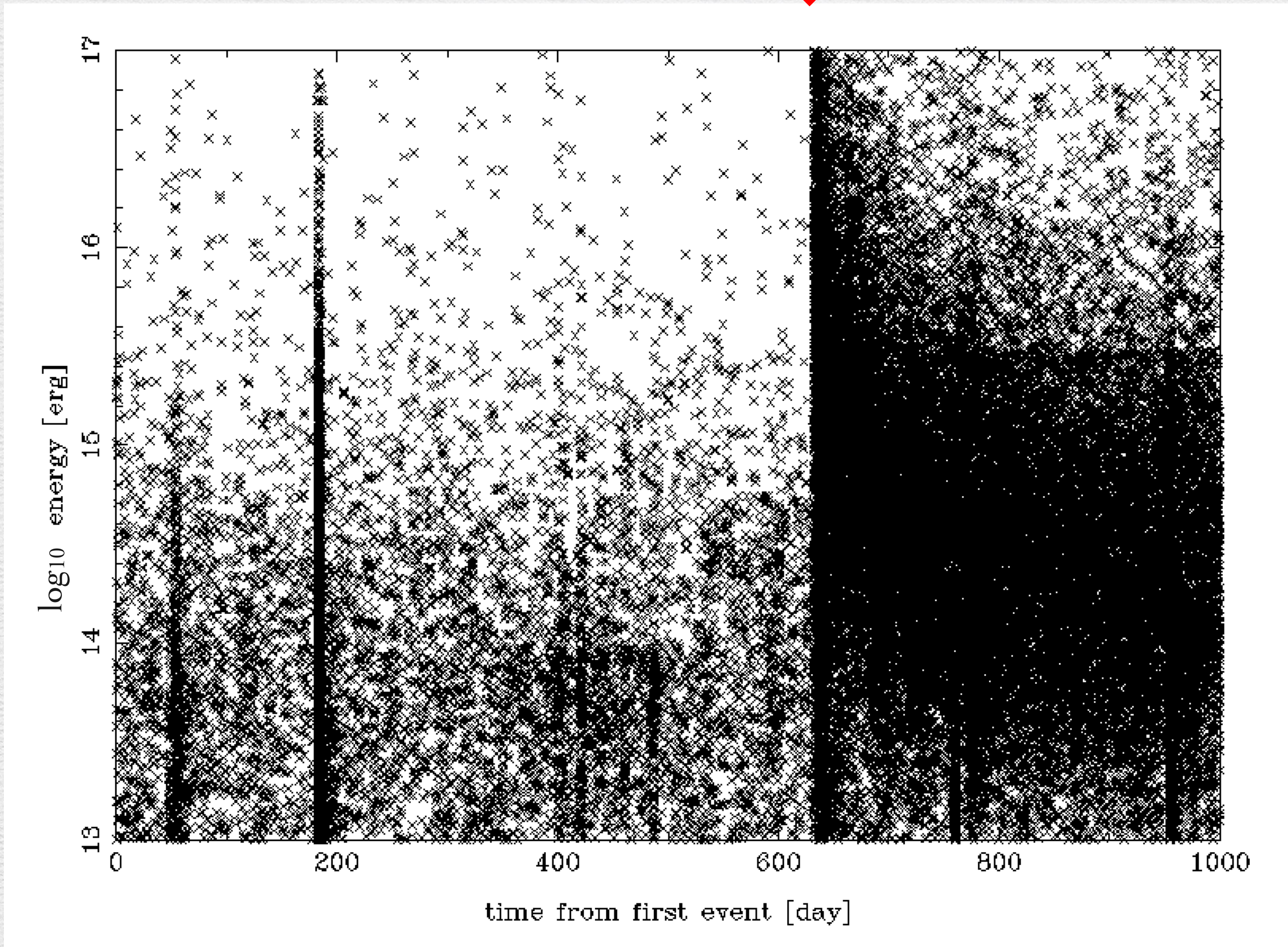


Something is happening?



Something is happening?

MJD55631=2011.3.11!

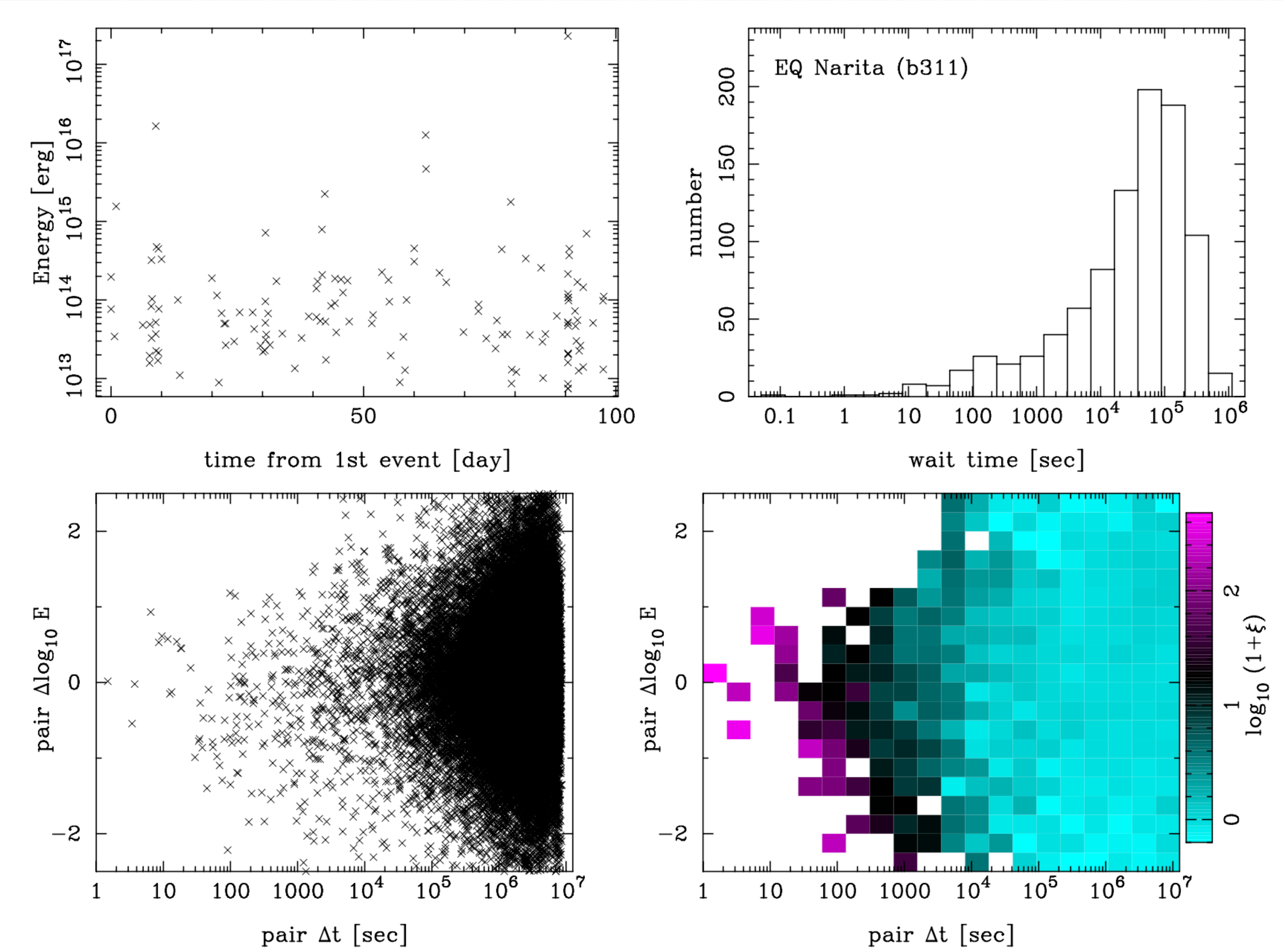


five data sets for earthquakes

Name	Longitude (deg)	Latitude (deg)	Period (MJD)	$t_{\mathrm{obs}}{}^{a}$ (day)	Events	$r_m{}^{b}$ (/day)	$C_{\mathrm{best}}{}^{c}$	p_{best}	τ_{best}	n^{d}
							$C_{-1\sigma}$	$p_{-1\sigma}$	$\tau_{-1\sigma}$	
							$C_{+1\sigma}$	$p_{+1\sigma}$	$\tau_{+1\sigma}$	
Narita b311[e]	140.10–140.70	35.70–36.10	52500–53500	1000	938	1.1	42	0.88	112	0.31
							22	0.73	20	0.60
							110	1.1	460	
Narita a311[e]	140.10–140.70	35.70–36.10	55700–55900	200	997	5.2	5.8	1.1	270	0.15
							3.2	0.75	80	0.32
							12	2.3	1800	
Choshi	140.81–140.96	35.74–35.86	52500–55600	3100	800	0.35	130	1.0	180	0.37
							62	0.87	20	0.51
							370	1.37	740	
Kanto	139.30–141.10	35.00–36.00	53000–53500	500	1399	2.9	34	0.75	16	0.17
							16	0.7	2.0	0.44
							152	0.87	64	
Izumo	132.20–132.60	34.70–35.50	52500–55500	3000	1596	0.57	380	0.82	5.0	0.18
							140	0.72	0.6	0.34
							1800	0.98	24	

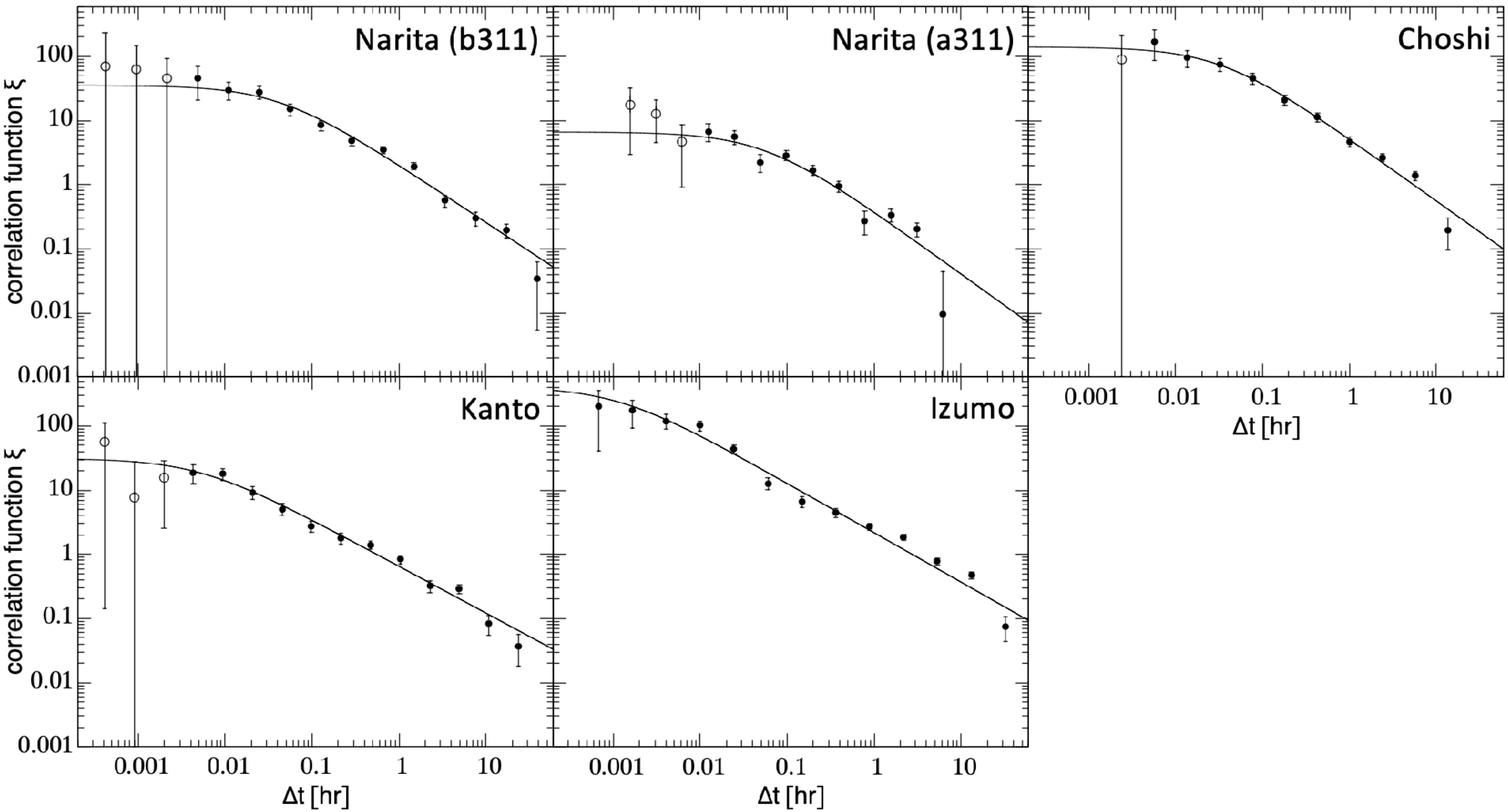
[a]Total observation time

example of ξ calculation

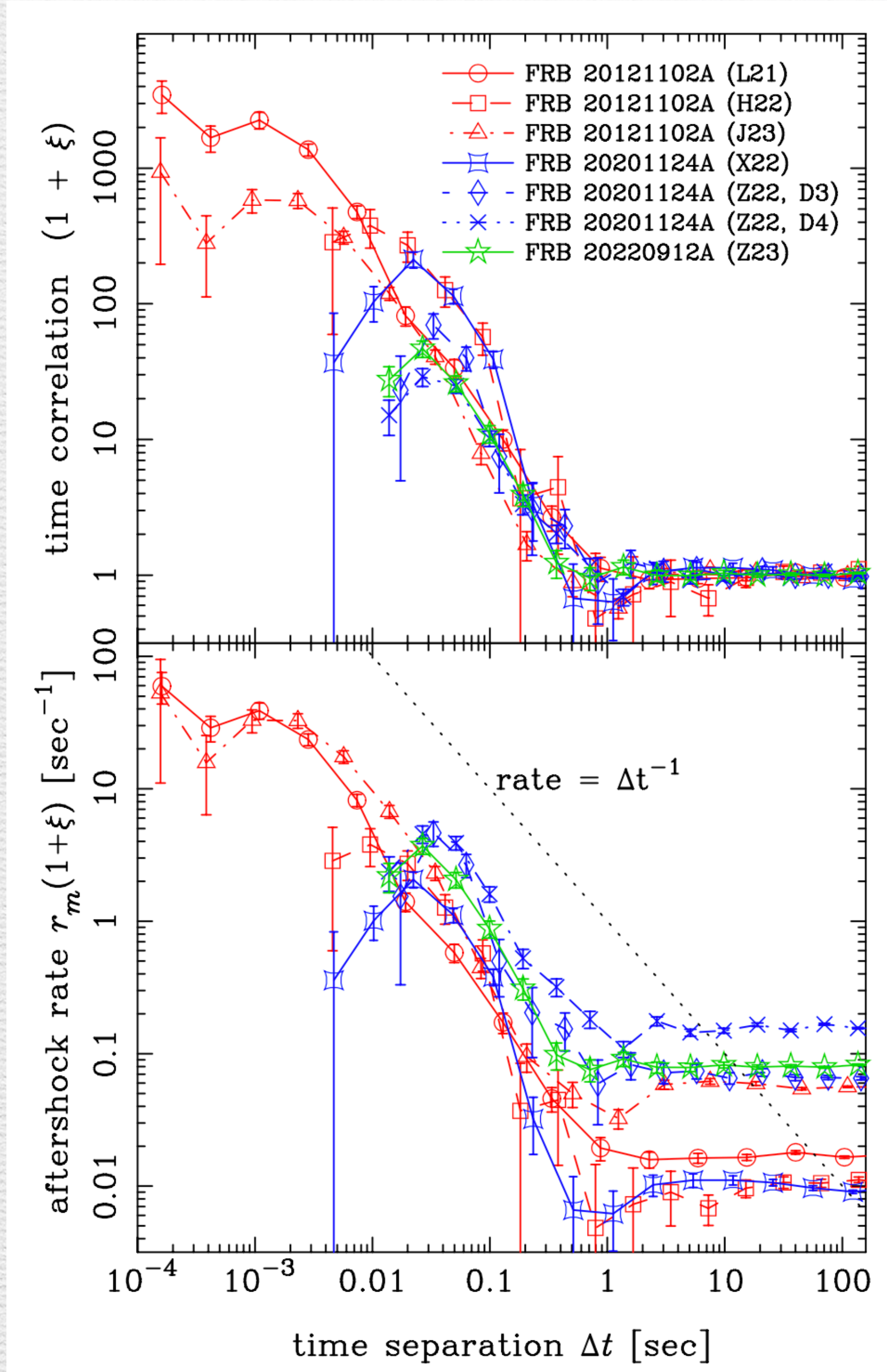


model fits to $\xi(\Delta t)$

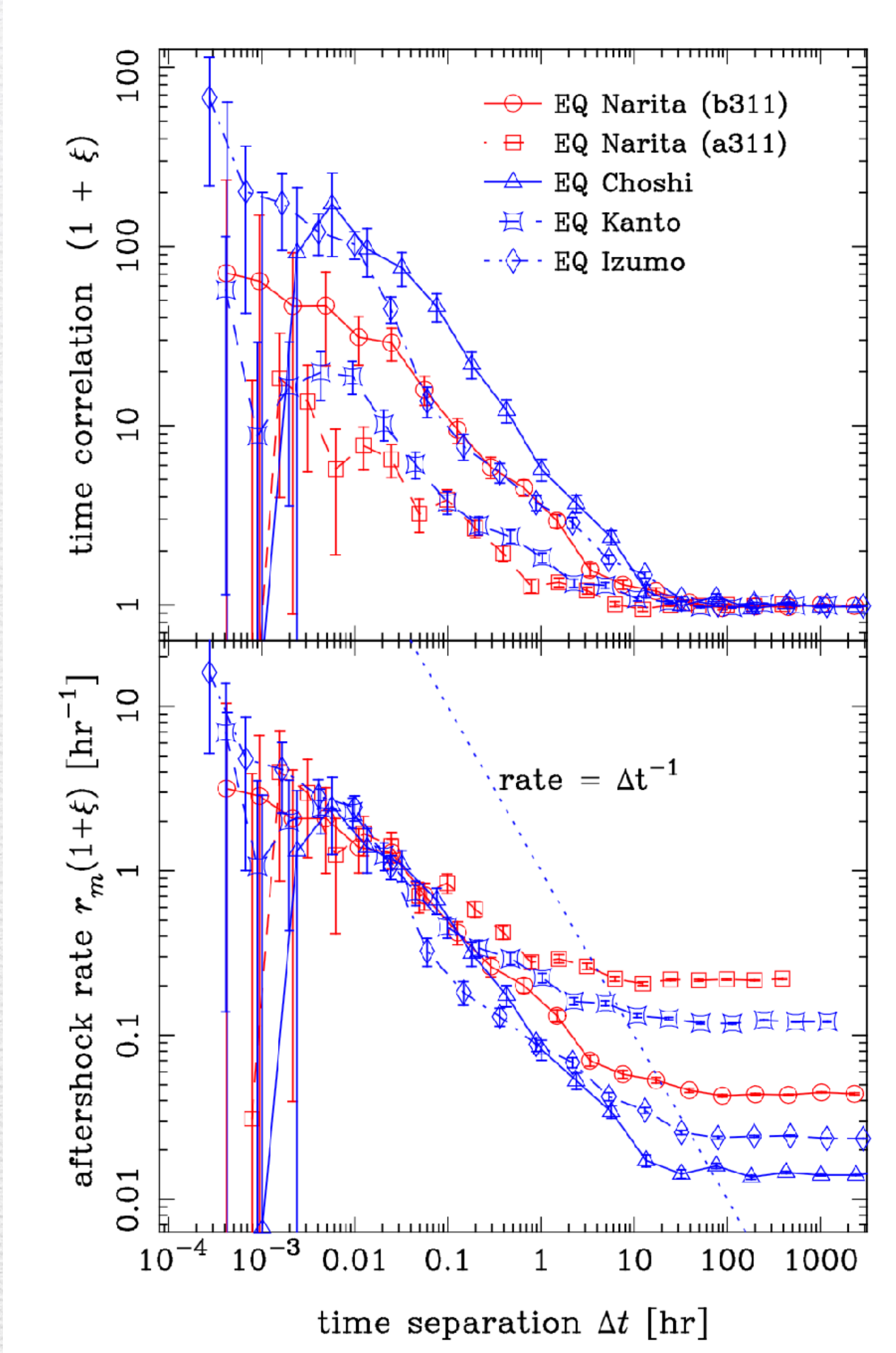
- fit by the Omori-Utsu law, $\propto (\Delta t + \tau)^{-p}$



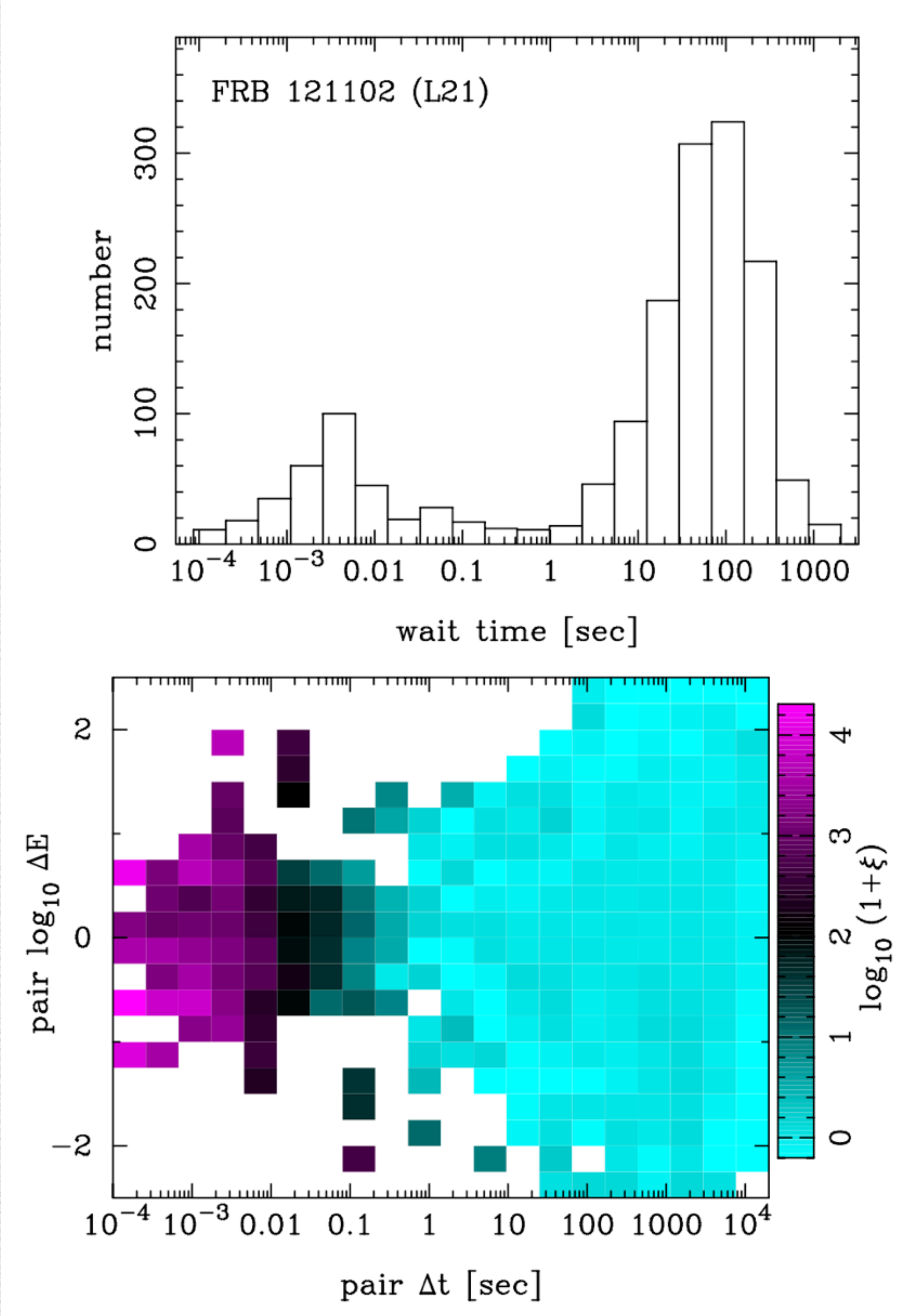
FRBs



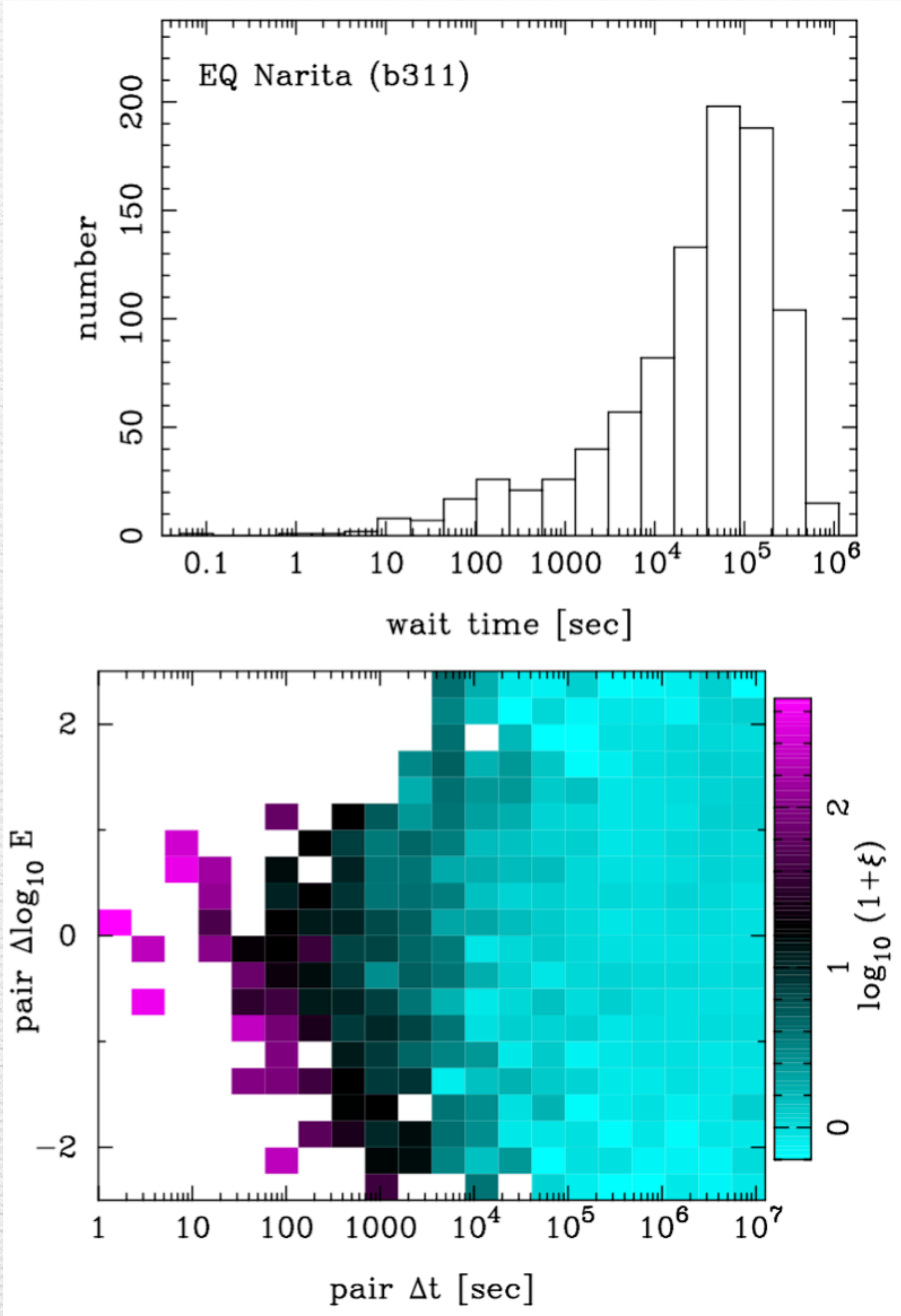
Earthquakes



FRBs

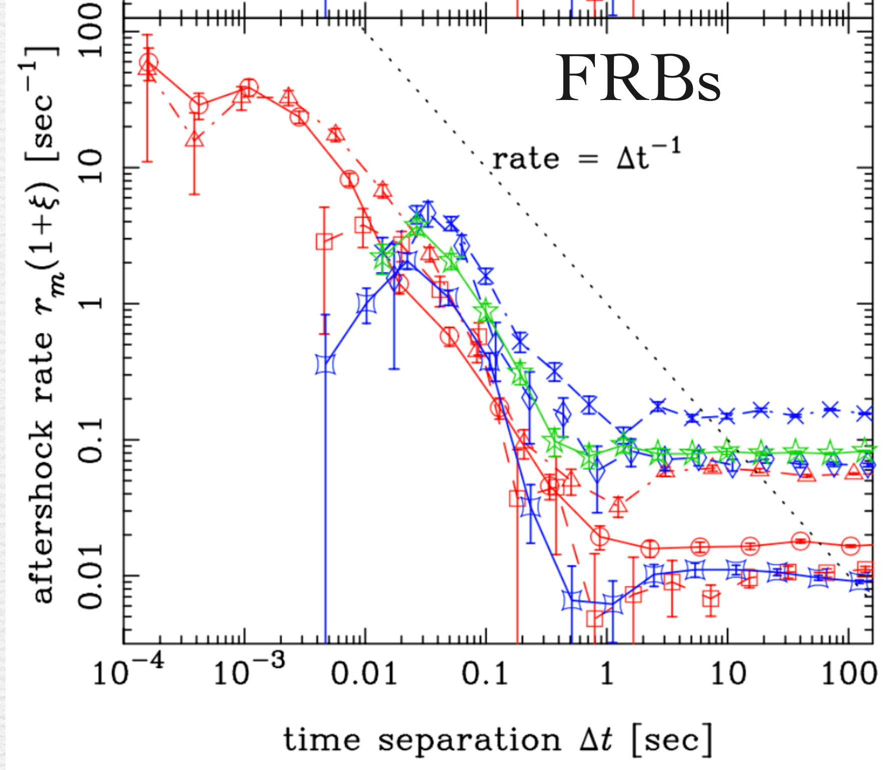


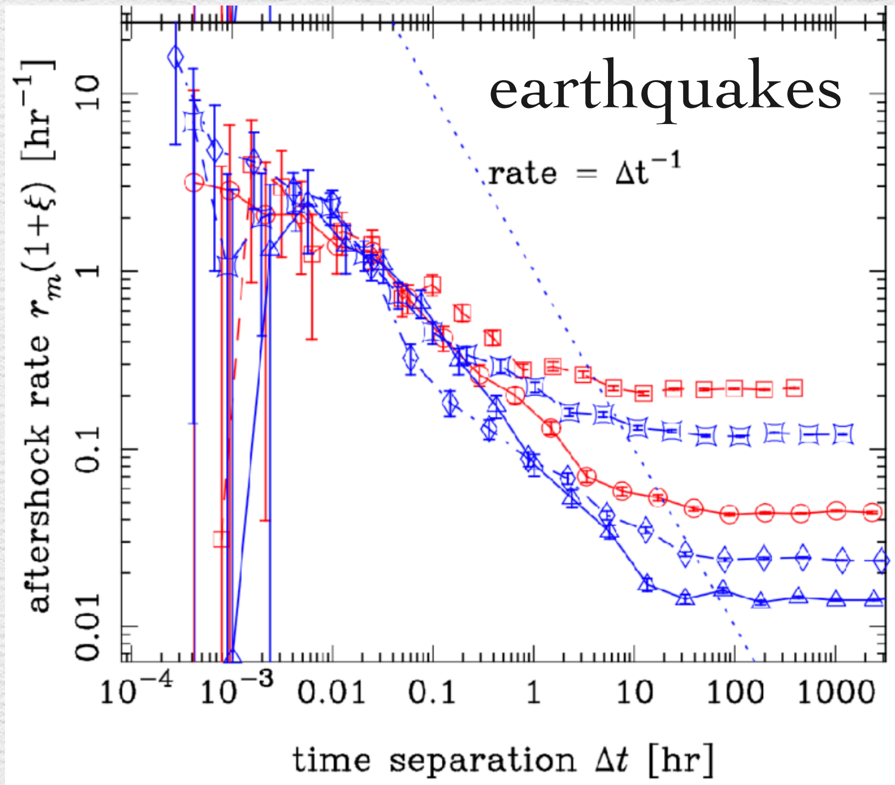
Earthquakes



Five similarities between FRBs and earthquakes

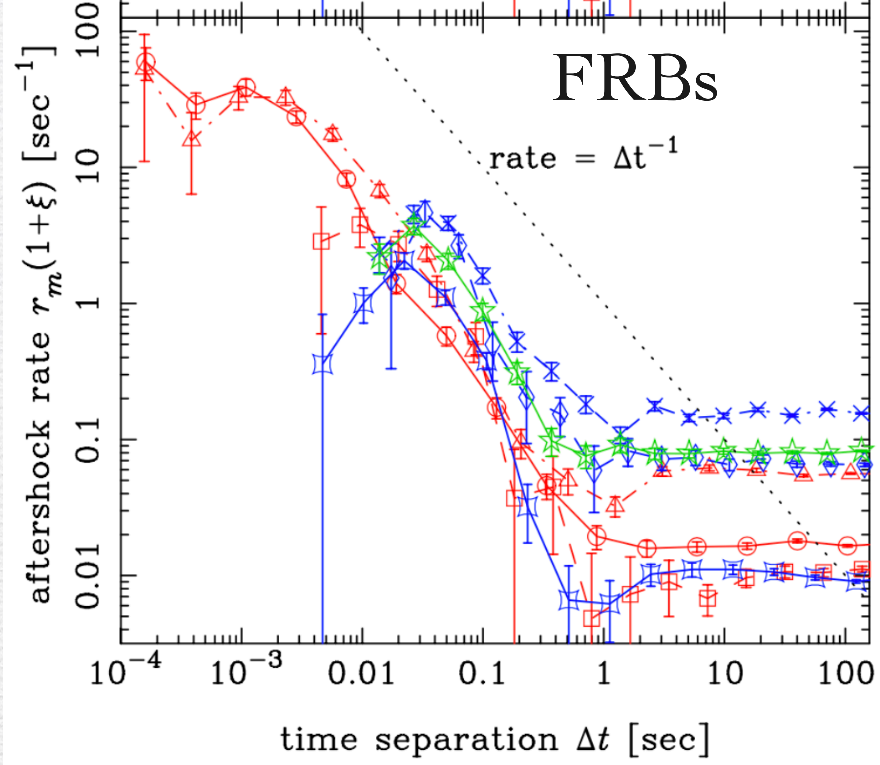
1. Aftershock rate follows the Omori-Utsu law
   - $\propto (\Delta t + \tau)^{-p}$
2. Expected number of aftershocks to each event:
   - n ~ 0.1-0.5 for both phenomena
   - Each event produces 0.1-0.5 aftershocks, with no discrimination between mainshock or aftershock
   - This is known to describe earthquake data well, as the ETAS (epidemic-type aftershock sequence) model (Ogata '99, Saichev+'06, de Arcangelis+'16)
3. τ close to event duration (10 msec for FRB, 1 min for earthqakes)
4. aftershock rate $r_m \xi$ is stable against change of mean rate r_m by source activities
5. almost no correlation between time and energy

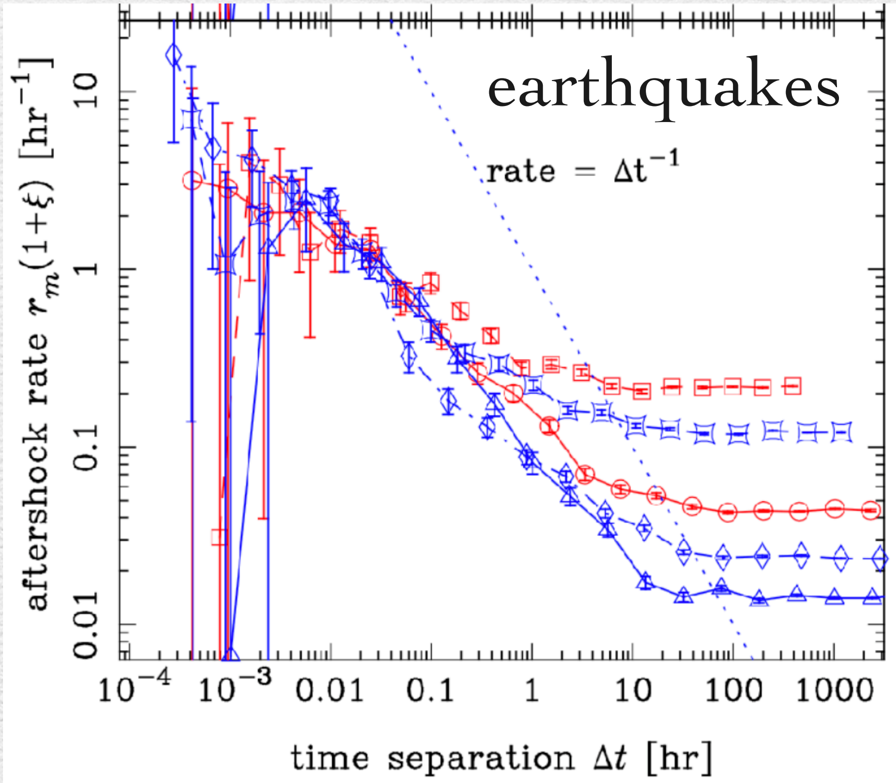




Difference between FRBs and earthquakes?

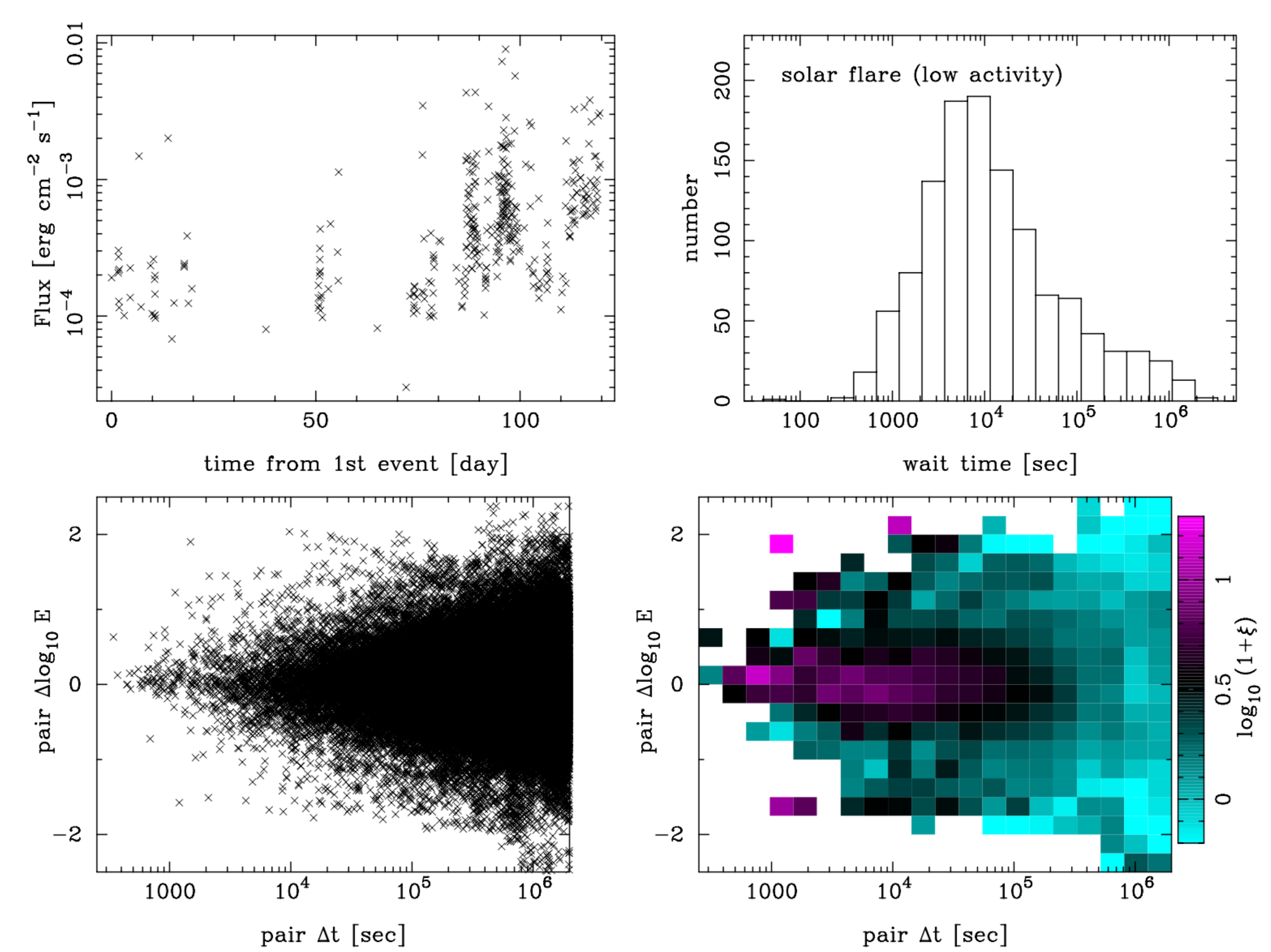
- The only difference: the value of the index p
  - p = 1.5-2.5 for FRBs
  - p = 0.8-1 for earthquakes (this work)
  - → apparent difference of the wait time distribution
  - note: p of earthquake depends on regions. p = 0.6-1.9 in past studies



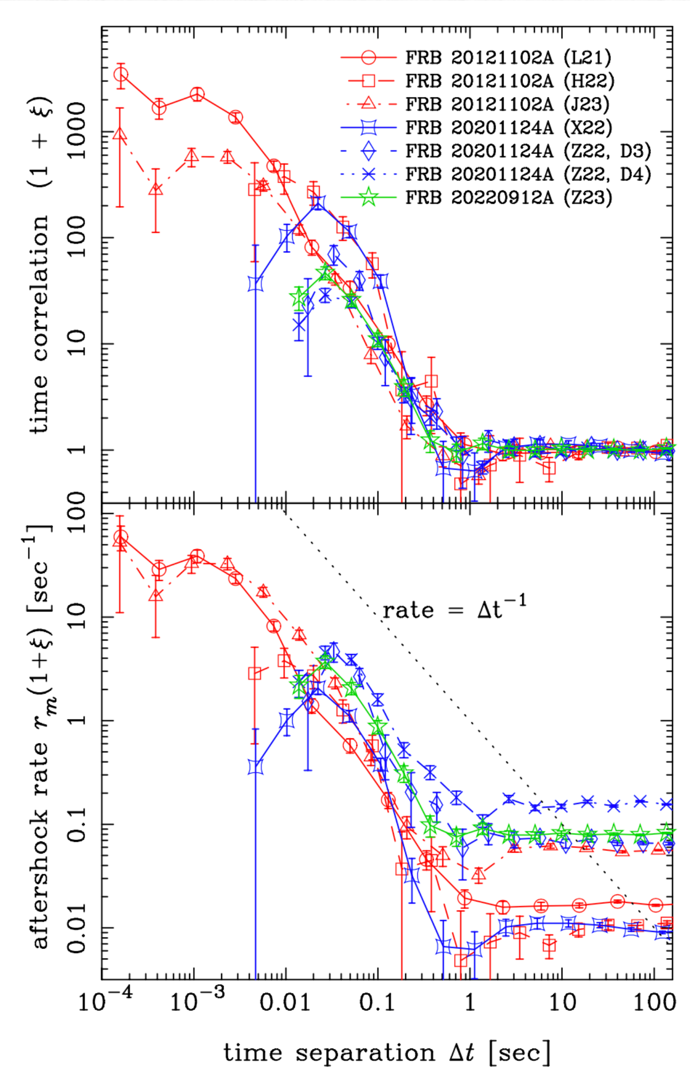


correlation function of solar flare data

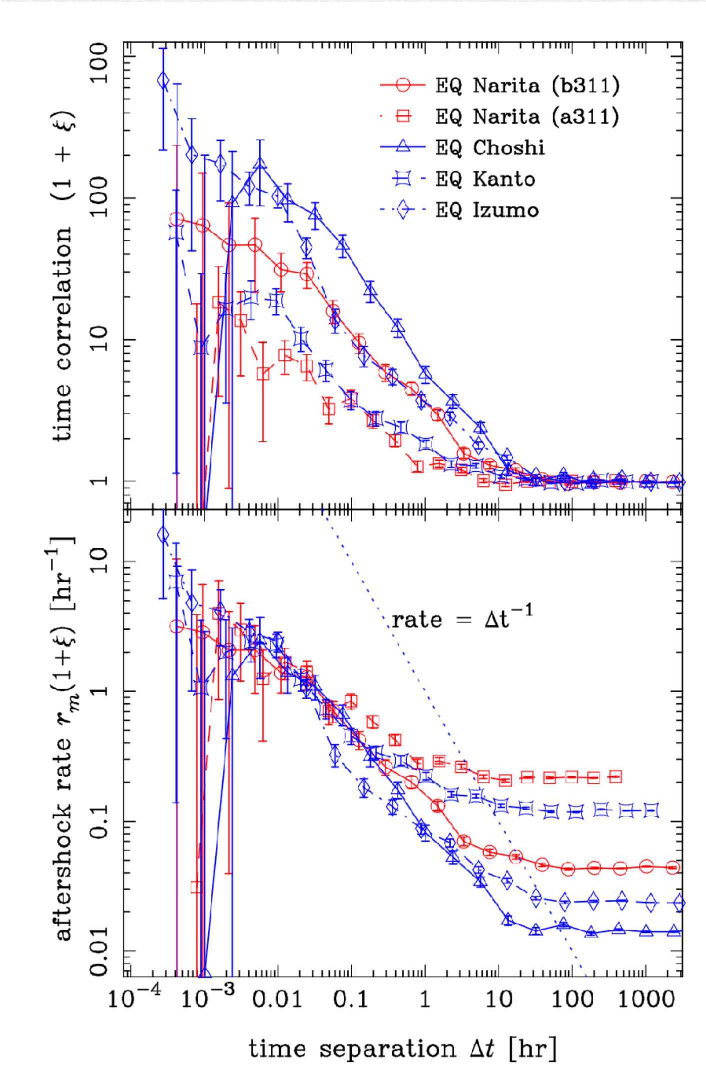
- Hinode solar flare catalog
- 1422 flares in 200 days (2012 Apr-Oct), “high state”
- 1207 flares in 1200 days (2017 Oct. - 2021 Jan.), “low state”



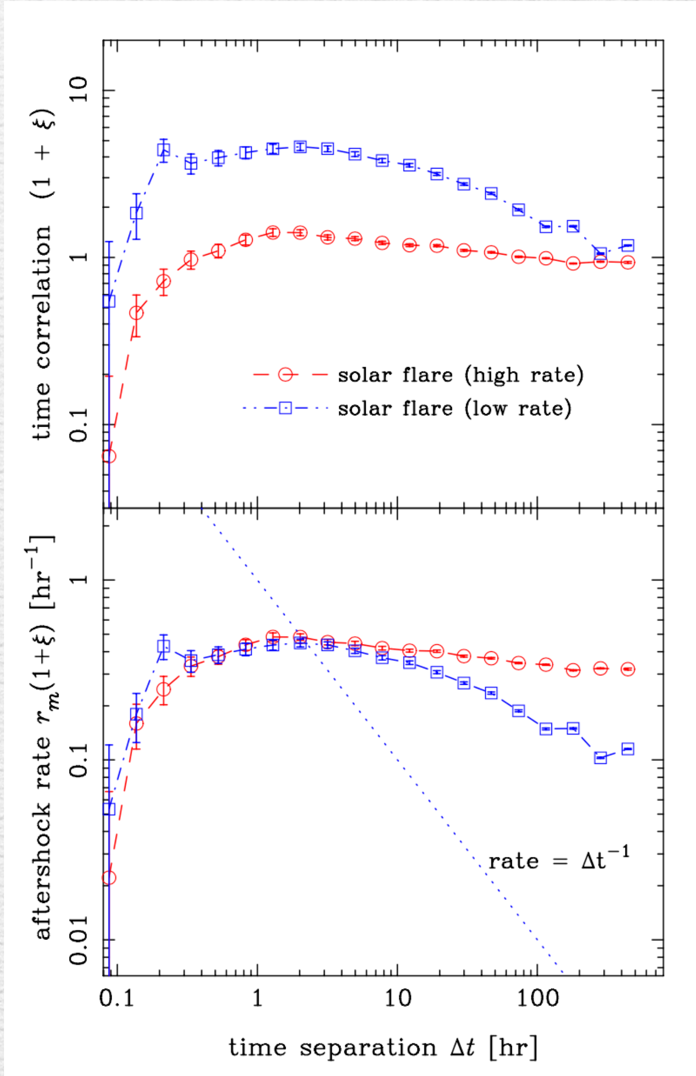
FRBs



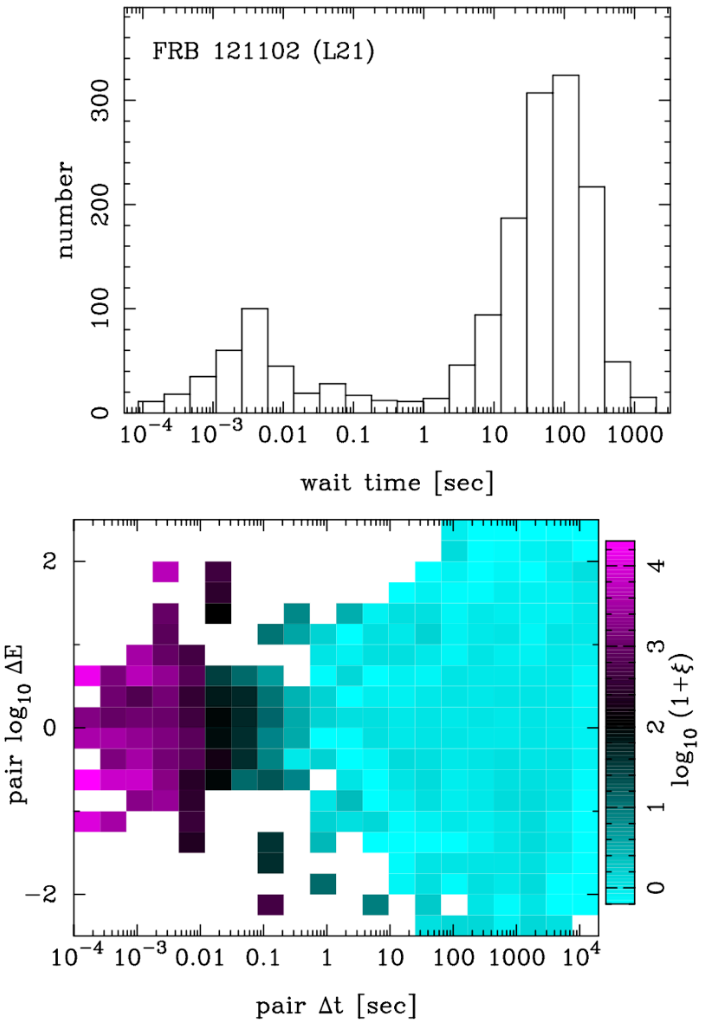
Earthquakes



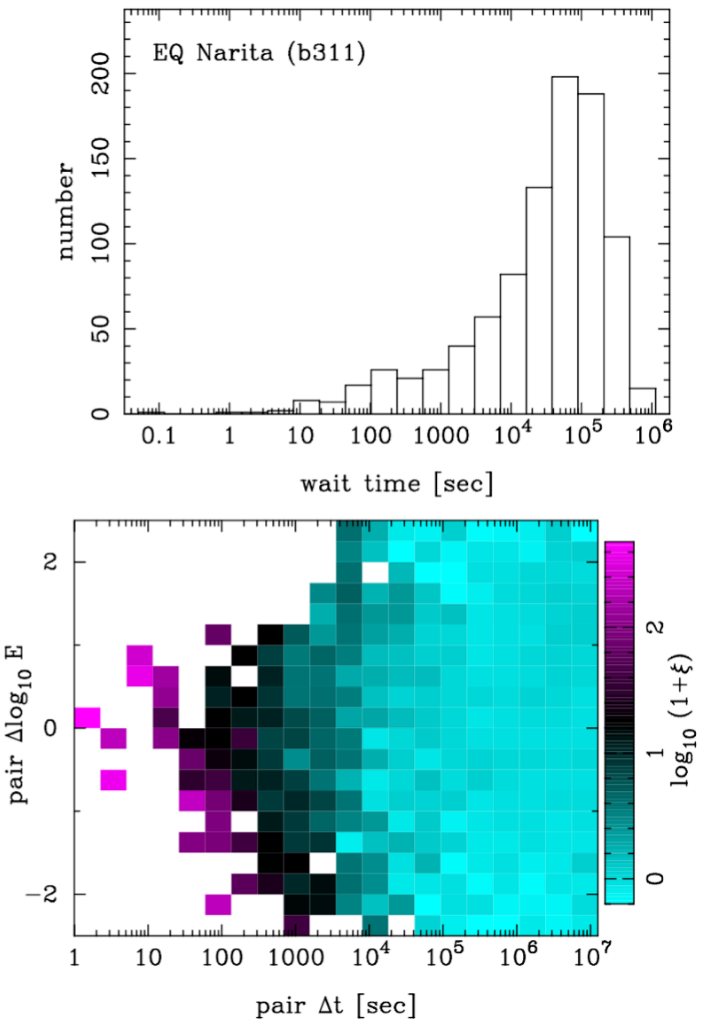
solar flares



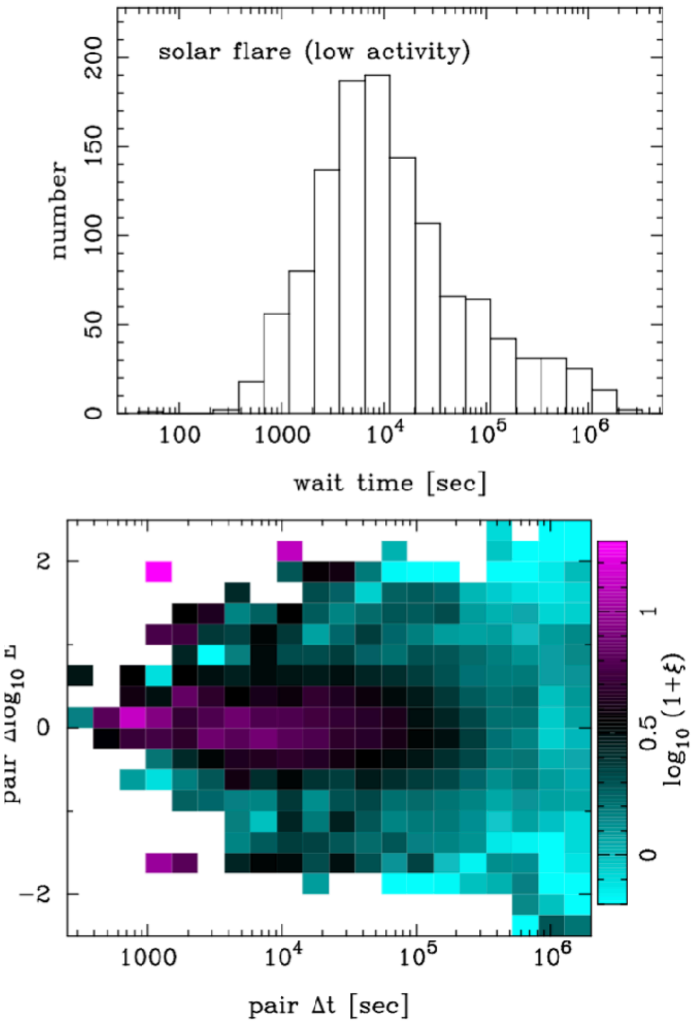
FRBs



Earthquakes

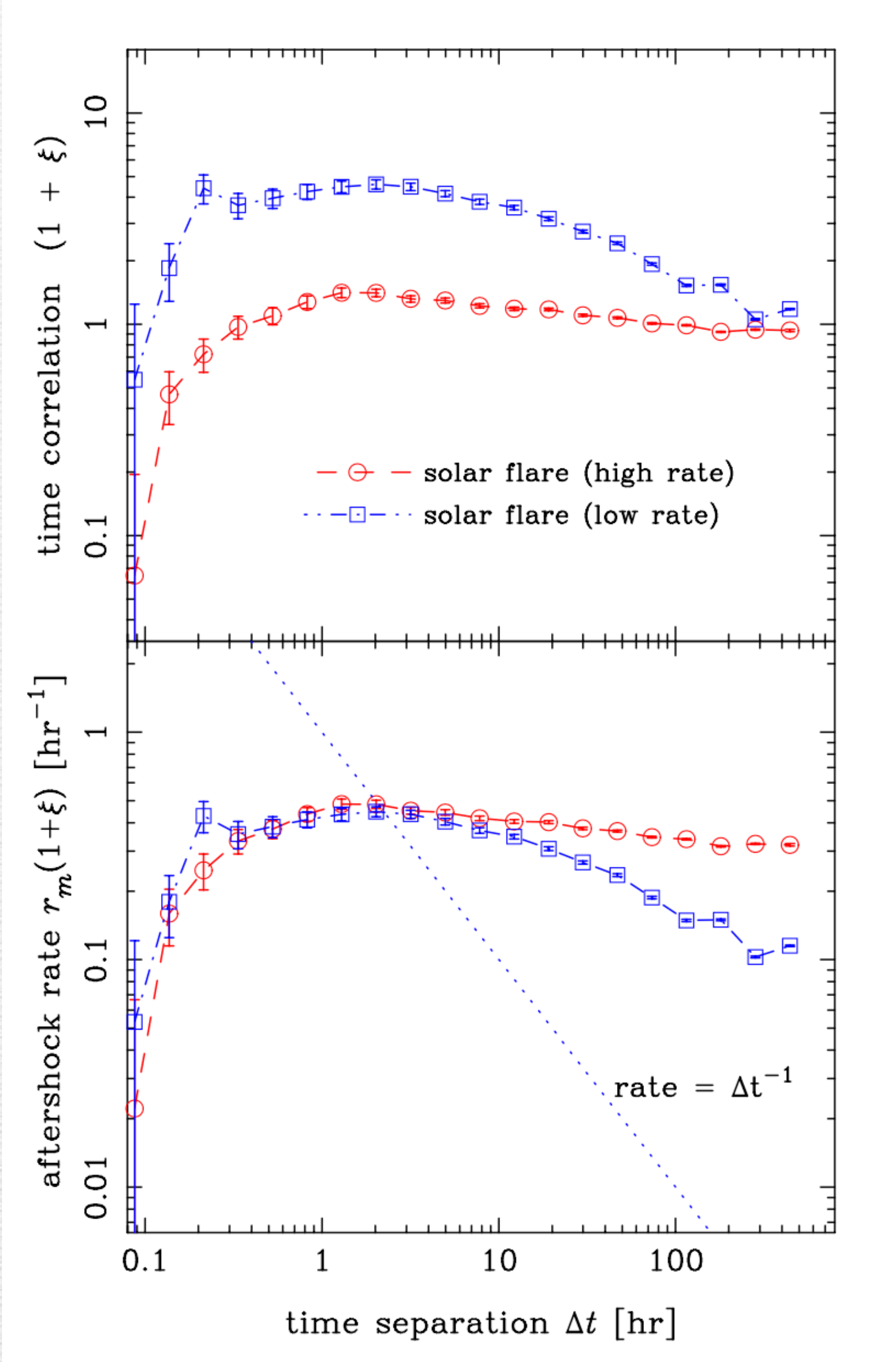


solar flares



solar flares are different from FRBs/earthquakes

- No power-law profile. ξ at most 5
- Aftershock rate $r_m \xi$ is larger than $(\Delta t)^{-1}$
  - → $n > 1$, multiple aftershocks produced by one event
- Strong correlation in energy direction
  - similar-energy events tend to follow
- → strong time-energy correlation visible in the original time-energy space



Conclusions & Discussion

- 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

- But different from solar flares!

Conclusions & Discussion

- A natural interpretation: repeating FRBs are produced when the energy stored in solid neutron star crust is liberated by seismic activity
  - Difference of stellar surface: solid crust (Earth & neutron star) and fluid (Sun)
  - The only FRB-earthquake difference is the value of Omori-Utsu index p
    - $p \sim 2$ of FRBs is larger than earthquakes ($p \sim 1$)
  - p of earthquakes depends on the properties of the earth's crusts → we may get some information about neutron star crust from p of FRBs?

- Some FRB repeaters show periodic activity change
  - ~16 day for FRB 20180916B, ~160 day for FRB 20121102A
  - Seismic activity on neutron star activated periodically?
    - e.g., by tidal forces from a companion in a binary system?

- repeater FRB 20200120E in a globular cluster in M81
  - seismic activity stimulated by a close encounter with a star in the globular cluster?