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# Biophotons: low signal/noise ratio reveals crucial events

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## Abstract

We study the emission of photons from germinating seeds. We make the assumption that the germination process is a spontaneous transition to criticality and we show that the statistical analysis of the photon emission leads to a deviation from the ordinary processes of statistical physics compatible with that assumption. The method of statistical analysis adopted has been used in the past to analyze the human brain dynamics and the music of Mozart. It is surprising that the germinating seeds share the same complexity as the human brain and the music of Mozart.

## Author summary

There exists a widespread and increasing conviction that cognition is not just limited to human beings, but rather it emerges with life itself. We believe that cognition is the result of a self-organization process generating intermittent chaos, i.e., extended time regions of order are separated by rare and short chaotic bursts called crucial events. These fluctuations that generate a compressible time series can be reproduced along with the information transmitted using a computer program based on a finite number of instructions. We focus our attention on an elementary but fundamental biological process; the germination of lentils to show that during germination they emit photons called biophotons. We make a statistical analysis of the time series representing the number of biophotons emitted per unit of time. This analysis was used in the recent past to study the prototype of intelligent systems- the human brain. The result of this analysis is that the complexity of the germination-induced crucial events is the same as that of the human brain. This result confirms the conjecture that cognition is a universal biological property and sheds light into the cell to cell communication through biophotons.

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# Introduction

An impressive revolution is occurring in biology [1,2]. The traditional approach to Darwinian evolution based on the transmission of information through genes is integrated by epigenetic processes which rest instead on cell to cell communication and exchange of information between complex networks of organisms where each network of organisms represent a sort of social intelligence. In addition, the single cell itself is an intelligent system and the brain should not be interpreted as a supercomputer but rather as "an entire community of them" [3]. Gordana Dodig-Crnkovic [4] points out that although until recently, intelligence has been considered as being a property of human beings due to the autopoiesis of Maturana and Varela [5] cognition should be extended to all biological systems. This observation has the impressive effect of marking the breakdown of separation between different disciplines. There is, in fact, a growing evidence about the existence of a form of collective intelligence established by the dialogue between different people in the field of psychology [6]. Thus, it seems that the discussion about cognition moves from the single cell of molecular biology to a set of individuals, sociology and psychology going through an intermediate bridge involving the brain of the single individual - neurophysiology.This generates two connected problems: (a) What is the origin of intelligence? (b) How do intelligent systems communicate?

As far as the origin of intelligence is concerned, we find that in literature, the predominant conjecture is that of Self Organized Criticality (SOC) [1,2]. We adopt the view that criticality can be realized spontaneously by the complex systems along the recent lines of the work of Ref. [7–9], advocating Self-Organized Temporal Criticality (SOTC). Criticality generates fluctuations that are not completely random. These criticality-induced fluctuations generate time series that are compressible [10]. Adopting the language of computational science, it is possible to reproduce these time series with a number of computer instructions shorter than the length of the time series. The criticality-induced randomness is a form of intermittent chaos with extended regions of order called laminar regions, separating one from another by short bursts of chaos. The short bursts of chaos are called *crucial events*. The time duration $\tau$ of the laminar regions is derived from a waiting time distribution density $\psi(\tau)$, with the inverse power law structure

$$\psi(\tau) \propto \frac{1}{\tau^{\mu}} \tag{1}$$

and the index $\mu$ fitting the condition: $1 < \mu < 3$. The region $\mu > 3$ is virtually indistinguishable from the condition of incompressible randomness [10], corresponding to a lack of cognition. We notice that human brain was found [11] to generate crucial events locating it in the middle of the interval $[1, 3]$, $\mu = 2$.

In this paper we discuss the important issue of cognition with an experiment on biophotons. Nearly a hundred years ago the Russian biologist A. Gurwitsch [12] found that a weak ultra-violet (UV) radiation comes out from the living tissues and influences the mitotic activity of the neighboring tissues. However, despite the confirmation of Gobor [13], this interesting result has been forgotten by the scientific community for many years. With the improvement of the methods to detect weak level of radiation and the theoretical progress in quantum optics, there has been a renewed interest in this phenomenon with the works of Colli and Facchini [14,15] in the 50s and F.A. Popp [16] in the 80s. These results generated the interpretation of cognition as possible manifestation of quantum coherence [17,18]. Biophotons are an endogenous production of ultra-weak photon emission in and from cells and organisms, and this emission is characteristic of living organisms. This emission is completely different from the normal bioluminescence observed in some simple as well as complex organisms. For example, bioluminescence is at least 1000 times more intense than the biophotons emission. The

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main characteristic of biophotons is measured in the total intensity of the emission going from a few to several hundred photons/sec per $cm^2$ surface of the living system with the spectral intensity being quite flat within the energy range between 200 and 800 nm. After any type of stress (chemical agents, excitation by white and/or monochromatic light, temperature), the emission increases by almost a factor of ten and relaxes to normal values quite slowly following a power law. Finally the photocount statistics that account for the probability of having N photons within some time interval seems to follow a Poissonian distribution. Despite the wealth of experimental phenomenology, the questions of what biophotons are, how they are generated and how they are involved in life are still open.

As pointed out earlier, biophotons play a fundamental role for the cell to cell communication [19, 20]. Recent research papers are using the cell to cell communication through biophotons to shed light into the brain, the most complex and most intelligent network [21–23]. We made the assumption that a germinating seed is an intelligent complex system and that its communication with the environment, including other seeds, rests on the emission of biophotons. To experimentally demonstrate its intelligence, we analyzed the statistics of the biophoton emission and we showed that its $\mu$ is very close to the condition of human cognition, i.e., $\mu = 2$.

# Methods

## Description of the experiment

Our experimental setup is comprised of a germination chamber, a photon counting system and a turnable filters wheel. See Fig. 1 for details. The photon counting device is a Hamamatsu H12386-110 high-speed counting head that can be powered at low voltage, just +5 V of power supply. The phototube is sensible in the wavelength range between 230 to 700 nm with a small peak at 400 nm. An ARDUINO board driven by a PC with Lab-View program is used for data acquisition and to control the experiment. The acquisition time window is fixed at 1 second and with this time the whole system has a dark current of about 2 photon/sec at room temperature. Seeds are kept in a humid cotton bed put on a petri dish. In this experiment, the sample is formed by 75 lentil seeds. This number has been chosen to have a good signal to noise ratio. A turnable wheel holding a few long pass glass color filters is placed between the germinating seed and the detector. The wheel has 8 positions. Six are used for the color filters, one is empty and the last one is closed with a black cap.

Here, we only use and report the data coming from the empty and black cap postions. This way, we have the total emissions within the visible energy range and the dark counting of the phototube. The wheel stays in each position for one minute. This means that it returns in the same position after 420 seconds plus the time needed to change from one position to the other, a total of 443 seconds. This is the reason why the data here has a bunch-type of structure. After one minute of measurement, there are 443 seconds of no data. Without any seeds or germination, there is a monotonic decrease of photon emission which arrives in few hours to the value of the electronic noise. This emission tail comes from the residual luminescence of the materials which is a consequence of the light exposure of the equipment while setting up the experiment. The comparison between the counting in the dark condition (red points) and the signal observed with the germinating seeds (green points) are reported in Fig. 2. The data are related to an acquisition time of almost three days after the closing of the chamber. To clarify the behaviors of the different data sets, we also report the number of photons per second coming from the raw data averaged over one minute. Residual luminescence of the whole equipment goes down in few hours up to the time when the lentils start

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germinating and the ultra-weak (UW) biophoton emission is strong enough to be detected. It is interesting to note how the UW biophoton emission changes during the time showing strong oscillations perhaps due to the different conditions of the seeds during the germination process. The initial behavior is dominated by the luminescence generated by the humid cotton bed. After about ten hours of closing the chamber, the germination-triggered UW biophoton emission emerges and becomes dominant leading to a saturation effect corresponding to a virtually stationary emission. The signal is well above the electronic noise for the whole time period.

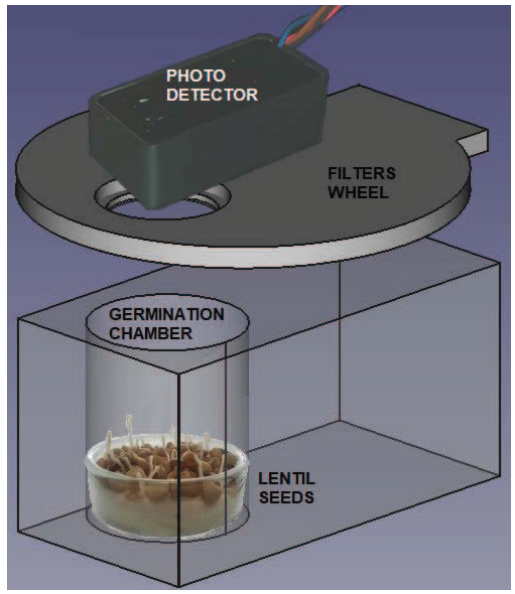


**Fig 1.** Technical design of the experimental setup used in our experiment. The photon-counting system consists of a Hamamatsu H12386-110 counting head. The germination chamber is built with black PVC to avoid any contamination of the light from outside.

This evolution of the signal is related to the spontaneous evolution to criticality described by Fig. 3 of Ref. [7], where the initial mean field has the value of $-1$ and, as an effect of self-organization moves towards the maximal value of 1 through back and forth fluctuations.

## Statistical analysis

We made the assumption that the germinating seeds are driven by SOTC [7–9] and that the emission of photons is proportional to the mean field generated by SOTC. We studied the diffusion trajectory

$$x(t) = \int_0^t dt' n(t'), \tag{2}$$

where $n(t')$ is the number of photons emitted at time $t'$. To make the statistical analysis, we had to convert this diffusional trajectory into many realizations so as to make it possible to do an ensemble average. These realizations are denoted by

$$X(l,t) = \int_t^{t+l} dt' n(t'). \tag{3}$$

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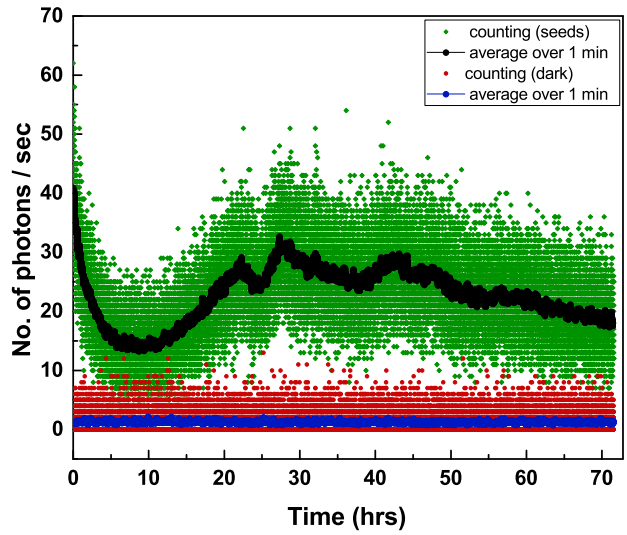


**Fig 2.** Here we show the comparison between the signal generated by the germinating seeds and the signal in the dark condition. The raw data are the green (seeds) and red (dark) points. The black and blue curves are the raw data averaged over one minute. In other words, these curves are the countings per sec but the counting is averaged over one minute.

Note that $l$ cannot go to infinity because we worked with time series of length $M$. The largest value of $l$ is $M - t$. These diffusion trajectories describe the departure from the origin, $X = 0$, of random walkers sharing the property of being at the origin at time $l = 0$. Making $M$ very large we created a number of realizations so big as to be able to evaluate the probability distribution density $p(X, l)$ with an accuracy large enough as to fit the assumed scaling equality

$$p(X, l) = \frac{1}{l^\delta} F(\frac{X}{l^\delta}). \tag{4}$$

This is a fundamental equation of diffusional processes. Its meaning is as follows: We observed the process at time $l$ and at a larger time $L$. The distribution density $p(X, L)$ was expected to be broader than the distribution density $p(X, l)$. Of course, since the number of walkers is conserved, the intensity of $p(X, L)$ is smaller than the intensity of $p(X, l)$. Let us squeeze the space $X$ by changing the values $X$ into $X' = rX$, where $r = (l/L)^\delta)$ and let us amplify the ordinate scale by multiplying $p(X, l)$ by $1/r$. The distribution density at time $L$, after the squeezing of the abscissa and the amplification of the ordinate, turned out to be identical to the distribution density at the earlier time $l$.

We have to establish a connection between the scaling $\delta$ and cognition, interpreted as computational compressibility. The time distance between two crucial events, given by the distribution density of Eq. (1) with the inverse power law index $\mu$, is related to the parameter

$$z \equiv \frac{\mu}{\mu - 1}, \tag{5}$$

which can be used to define the Kolmogorov-Sinai entropy, $h_{KS}$, given by [24]

$$h_{KS} = (2 - z) z ln2. \tag{6}$$

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The laminar regions between two consecutive crucial events, are filled with symbols, either 1 or 0, randomly selected. The sequence of these symbols generates a time series with a compressibility defined by Eq. (6). The value $z = 1$, corresponding to $\mu = \infty$, is the condition of total incompressibility, making $h_{KS} = ln2$. As discussed in [10], moving from $\mu = \infty$ to finite values of $\mu$ has the effect of making the sequence compressibile, namely, it makes it possible for us to reproduce the time series with a number of computer instructions smaller than the size of the time series. The compressibility becomes stronger when $\mu < 3$. Notice that at $\mu = 2$, $z = 2$, $h_{KS}$ vanishes. Korabel and Barkai [25] generalized the definition of $h_{KS}$ so as to explore also the region $z > 2$ ($\mu < 2$). The computational cost, in the case $\mu > 2$ increases linearly in time, while in the case $\mu < 2$ it increases as $t^\alpha$, with $\alpha = \mu - 1$. As a consequence, using $t^\alpha$ rather than $t$ for the definition of $h_{KS}$, Korabel and Barkai [25] proved for $z > 2$ $h_{KS}$ begins increasing. Thus, the generalized $h_{KS}$ has its minimum value at $\mu = 2$ signaling the condition of maximal intelligence shared by the human brain [11]. The Kolmogorov compressibility, implying the existence of cognition, is converted into anomalous diffusion. In fact, $2 < \mu < 3$ is a signature of compressibility, yielding for diffusion the scaling

$$\delta = \frac{1}{\mu - 1}, \tag{7}$$

with $\delta > 0.5$. In other words, if the system is intelligent (compressible), diffusion is anomalous, being super-diffusion in this case. Of course,

$$\mu = 1 + \frac{1}{\delta}. \tag{8}$$

To find $\delta$ we evaluated the Shannon entropy of the distribution density $p(X, l)$:

$$S(l) = -\int_{-\infty}^{\infty} p(X, l) \ln p(X, l) dx. \tag{9}$$

We plugged Eq. (4) into Eq. (9). With an easy algebra we get

$$S(l) = A + \delta \cdot \ln l. \tag{10}$$

The explicit expression of the constant $A$ is of no interest for this paper. The important property of Eq. (10) is that the Shannon entropy $S(l)$ expressed as a function of $\ln l$ is a straight line with slope $\delta$, with $\delta$ being the scaling of diffusion process created by converting the experimental time series $\{n(t)\}$ into a diffusion trajectory.

This technique of statistical analysis is called Diffusion Entropy Analysis (DEA). To make the readers understand the reasons of the DEA efficiency to detect compressibility and cognition, we make some intuitive remarks to explain why, on the basis of the traditional statistical views the scaling produced by fluctuations illustrated by Fig. 2 should result in the ordinary prediction $\delta = 0.5$. Let us imagine that the fluctuations of Fig. 2 are obtained by evaluating the mean value $< n(t) >$ and the width $\Delta n \equiv \sqrt{< n^2 > - < n >^2}$. Both values are finite. Let us imagine an ideal experiment of diffusion based on recording all the times at which $n(t)$ is equal to $< n >$. At these times, the random walker makes a jump ahead by the quantity $n(t) - < n >$. If the time distance between two consecutive events is given by

$$\psi(\tau) = \Gamma exp(-\Gamma\tau), \tag{11}$$

it is straightforward to predict that the scaling fits the ordinary prediction $\delta = 0.5$. In this case Eq. (8) would give $\mu = 3$. This is an indication that $\mu = 3$ is the border between the anomalous and the Gaussian region [26]. Actually, the waiting time

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distribution density of Eq. (11) describes a Poisson process, with all the moments of the distribution density $\psi(\tau)$ being finite. In the long-time limit the diffusion process is identical to that obtained when the time distance between two consecutive events is constant and equal to $< \tau >$ [27, 28]. In this case, due to the central limit theorem, the pdf would be a translating Gaussian distribution which is in conflict with the compressibility prediction of Eq. (7) yielding $\delta > 0.5$. The detection of $\delta > 0.5$ in the long-time limit is a proof that the fluctuations in the photon emission of the germinating seeds host crucial events and that DEA detects their action. Although crucial events are embedded in a cloud of non-crucial events making them virtually invisible, DEA is shown [29] to be sensitive to crucial events. In the **Discussion** section of this article, we give the readers more arguments to show that the fluctuations of Fig. 2 share the crucial events of Fig. 3 of Ref. [7].

## Results

The results of this Section refer to two questions: (a) Does $\mu$ change with time throughout the germination process? (b) If not, what is the value of $\mu$ that represents the intelligence of the germination process?

Fig. 3 shows the photon emission from the start of the experiment until the germination process ends with the six regions (separated by the red dashed lines) referring to different stages of analysis. Applying DEA in these different regions, we found the scaling $\delta$ which is given by Eq. 10 and the corresponding $\mu$ according to Eq. 7 reported in the Table 1.The errors are numerical corresponding to the line of best fit when determining $\delta$.

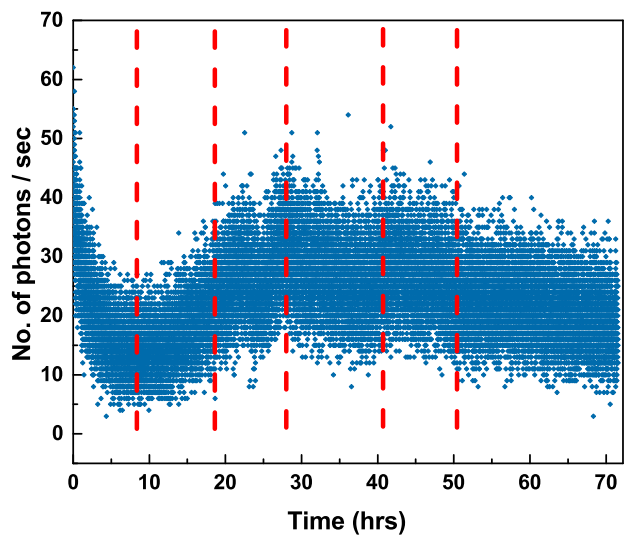


**Fig 3.** Number of photons emitted during the germination of lentils. The red dashed lines represent different regions during the germination process.

Fig. 4, referring to region 1, shows how the results of Table 1 are obtained. Using the concept of intermediate asymptotics [30], we evaluate the slope of $S(l)$ in an intermediate region between the region of short value of $l$ and the region of large values of $l$. The region of short values of $l$ is a region of transition to complexity. The region of

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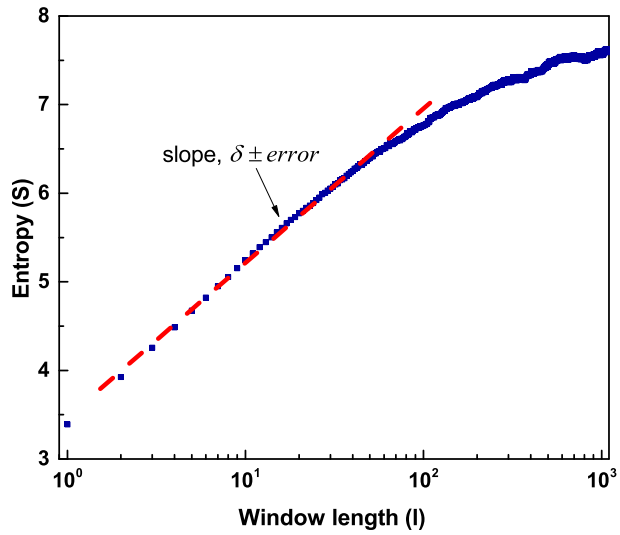


**Fig 4.** DEA on region 1.

**Table 1. The scaling $\mu$ using DEA in the six different regions of the time series.**

| DEA Scaling | | | |
|---|---|---|---|
| | $\delta$ | Error | $\mu = 1 + 1/\delta$ |
| *Region*1 | 0.7733 | ± 5.84E-04 | 2.2931 |
| *Region*2 | 0.7969 | ± 2.70E-04 | 2.2548 |
| *Region*3 | 0.7363 | ± 3.95E-04 | 2.3581 |
| *Region*4 | 0.7379 | ± 0.0011 | 2.3551 |
| *Region*5 | 0.6941 | ± 7.94E-04 | 2.4407 |
| *Region*6 | 0.7257 | ± 7.52E-04 | 2.3779 |

large values of $l$ is either a region of transition to ordinary statistics [7–9] or a region where the scarcity of events makes the evaluation of complexity inaccurate. The errors of Table 1 measure the inaccuracy associated to determining the intermediate asymptotics.

The most important result of this section is illustrated in Fig. 5. The results of this figure are obtained by examining portions of different length $L$ of the experimental sequence. The starting point of these different portions is always the beginning of the experimental sequence. Increasing the length $L$ has the effect of improving the accuracy of the evaluation of $\mu$, yielding $\mu \approx 2.2$. We ignore the region of large values of $l$ which may be affected by either the termination of germinating process or by the the inaccuracy due to the scarcity of crucial events.

# Discussion

The method of DEA has been applied in the recent past to a variety of problems such as the application to DNA sequences [31]. In this case, the DNA sequence is characterized by long laminar regions with purines alternated by long laminar region with pyrimidines. The value of $\mu$ in those cases is slightly larger than 2. The recent work of Refs. [32, 33] shows that the music of Mozart hosts crucial events with $\mu = 2$. It

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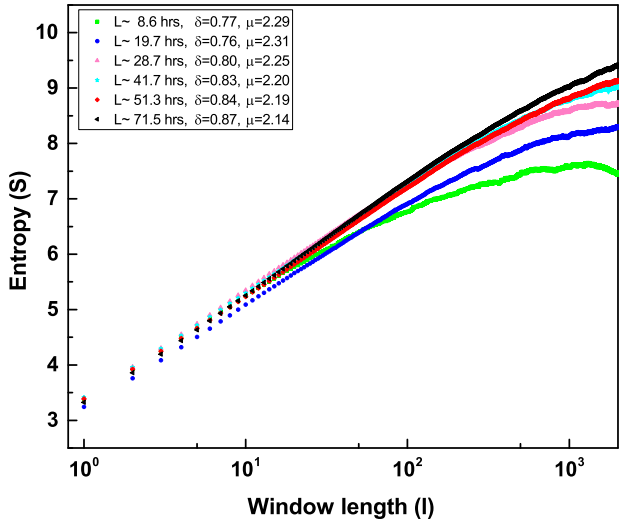


**Fig 5.** DEA with changing length L. Different curves illustrate $S(l)$ for time series of different length, obtained observing experimental data from the time origin up to $L$.

is important to stress that according to the principle of complexity matching [34] two complex systems communicate mainly through their crucial events. This is the reason why the music of Mozart is perceived as being very attractive. In fact, according to Refs. [32, 33] the crucial events hosted by the music of Mozart match the crucial events of the human brain.

We think that this paper disclosing the crucial events emitted by the germinating seeds affords an important contribution to the revolution occurring in biology [1, 3, 4]. It is expected to stimulate the refinement of the tool of statistical analysis that will help the experimental investigation on the communication between biological systems. In the literature of biophonons, there are indications that, albeit the cell to cell communication through light is a plausible communication mechanism, due to the unfavorable signal-to-noise ratio the signal detection by cells is an obstacle to prove it [20]. The authors of Ref. [20] discuss the limitation of the famous theory of stochastic resonance. We want to stress that the complexity matching theory of [34] is a much more advanced approach making it possible to establish communication through one single realization rather than an average over an ensemble of realizations. This can be realized through the observation of photons emitted by two or more germinating seeds rather than only one. This would be equivalent to the observation of the global intelligence of a society of germinating seeds.

It is important to remark that, in our interpretation of the information transfer from one cell to another, biophotons play the role of markers of crucial events. This is compatible with their extremely weak intensity. This interpretation may conflict with that adopted, for instance by Fels [35], where the belief is that the transfer of information as well as the intelligence itself are based on quantum coherence [17, 18]. In our perspective, the origin of cognition is a process of self-organization [7, 8] of the components of the seed corresponding to water-induced germination. This process of self-organization generates crucial events and biophotons are the markers of these crucial events. The cell to cell communication is not due to a coherence tuning but,

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according to the principle of complexity matching [34], is realized by the tuning between the complexity indexes $\mu$ of the cells.

This is an interesting issue worthy of future investigations. We limit ourselves to mention additional results of our statistical analysis supporting the role of crucial events for the transport of information. We have applied DEA supplemented by the method of the stripes originally used in Ref. [36]. This method is based on dividing the counting ordinate axis into many bins of size '$s$'. The crossing from one bin to one of the two nearest neighbor bins is determined by the fluctuations of the experimental signal, mentioned at the end of the **Statistical analysis** section for the heuristic arguments yielding $\delta = 0.5$. The times at which the experimental signal $n(t)$ moves from one bin to one of the two next neighboring bins are recorded as events. These events are crucial if the time evolution of $n(t)$ is driven by SOTC and thus, the resulting scaling is the same as that afforded by DEA with no stripes. However, if the events are determined by the coherence-induced memory, in such case the adoption of stripes is expected to give a different result than that of DEA with no stripes. This is because the method of stripes annihilates [29] the contribution to anomalous scaling of memory processes. The method of stripes perceives the memory events as non-crucial. We convert the sequence of these events into a diffusional trajectory with the random walker making a jump ahead by a fixed quantity when an event occurs [37]. The time distance between two non-crucial consecutive jumps is driven by the waiting time distribution density of Eq. (11) since the memory generates a correlation between the crossing times that does not affect the exponential structure of the waiting time distribution density $\psi(\tau)$ [29, 38]. If the events generated by the method of stripes are a mixture of crucial and non-crucial events, in the long time limit the scaling is dominated by the crucial events with the scaling $\delta$ of Eq. (7) larger than the scaling $\delta = 0.5$ of the non-crucial events. In the case of biophotons, we have found that the resulting scaling $\delta$ is larger than 0.5 and independent of whether stripes are used or not. For these reasons, this paper affords a strong evidence that the complexity of a germinating seeds is determined by crucial events and that biophotons transport information not involving any form of coherence.

# Supporting information

**S1 Dataset. Dataset of photon emission in dark condition and with germinating seeds.** Here we report the data for the photon emission during germination of seeds and also when no seeds are present, i.e., the emission from residual luminescence(dark count).

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# References

1. W. B. Miller Jr., *Biological information systems: Evolution as cognition-based information management*, Progress in Biophysics and Molecular Biology, **134**, 1-26 (2018).

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2. M. Eigen, *From Strange Simplicity to Complex Familiarity: A Treatise on Matter, Information, Life and Thought*, OUP Oxford (2013).

3. B. J. Ford, *On Intelligence in Cells: The Case for Whole Cell Biology*, Interdisciplinary Science Reviews, **34**, 350 (2009).

4. G. Dodig-Crnkovic, *Modeling Life as Cognitive Info-Computation*, In: Beckmann A., Csuhaj-Varj E., Meer K. (eds) Language, Life, Limits. CiE 2014. Lecture Notes in Computer Science, vol 8493. Springer, Cham.

5. H. Maturana, F. Varela, *Autopoiesis and cognition: the realization of the living*, D. Reidel Pub. Co. (1980).

6. A. W. Woolley, C. F. Chabris, A. Pentland, N. Hashmi, T. W. Malone, *Evidence for a Collective Intelligence Factor in the Performance of Human Groups*, Science, **330**, 686 (2010).

7. K. Mahmoodi, B. J. West, P. Grigolini, *Self-Organizing Complex Networks: individual versus global rules*, Frontiers in Physiology, **8**, 478 (2017).

8. K. Mahmoodi, B. J. West, P. Grigolini, *Self-Organized Temporal Criticality: bottom-up resilience versus top-down vulnerability*, Complexity (2018).

9. K. Mahmoodi, P. Grigolini, B.J. West, *On social sensitivity to either zealot or independent minorities*, Chaos, Solitons and Fractals, Chaos, Solitons and Fractals, **110**, 185 (2018).

10. P. Allegrini, V. Benci, P. Grigolini, P. Hamilton, M. Ignaccolo, G. Menconi, L. Palatella, G. Raffaelli, N. Scafetta, M. Virgilio, J. Yang, *Compression and diffusion: a joint approach to detect complexity*, Chaos, Solitons and Fractals, **15**, 517 (2003).

11. P. Allegrini, D. Menicucci, R. Bedini, L. Fronzoni, A. Gemignani, P. Grigolini, B. J. West, P. Paradisi, *Spontaneous brain activity as a source of ideal 1/f noise* Phy. Rev. E **80**, 061914 (2009).

12. A.G. Gurwitsch, *Die Natur des spezifischen Erregers der Zellteilung* Arch. Entw. Mech. Org. **100**, 11 (1923).

13. T. Reiter and D. Gabor, *Ultaviolette Strahlung und Zellteilung*, Wissenschaftliche Verffentlichungen aus dem Siemens-Konzern, Berlin (1928).

14. L, Colli, U. Facchini, *Light Emission by Germinating Plants*, Il Nuovo Cimento, **12**, 150 (1954).

15. L, Colli, U. Facchini, G. Guidotti, R. Dugnani Lonati, M. Orsenigo, O. Sommariva, *Further Measurements on the Bioluminescence of the Seedlings*, Experientia, **11**, 479 (1955).

16. F.A Popp, Q. Gu and K.H. Li, *Biophoton Emission: Experimental Background and Theoretical Aproaches*, Modern Physics Letter B, **8**, 1269 (1994).

17. R. van Wijk, *Light in Shaping life: Biophotons in Biology and Medicine*, Meluna, Tiel (2014) .

18. F. A. Popp, *Consciousness as Evolutionary Process Based on Coherent States*, NeuroQuantology, **6**, 431 (2008).

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19. T. Wilson, J. W. Hastings, *Bioluminescence*, Annu. Rev. Cell Dev. Biol, **14**, 197 (1998).

20. O. Kucera, M. Cifra, *Cell-to-cell signaling through light: just a ghost of chance?*, Cell Communication and Signaling, **11**, 87 (2013).

21. R. Tang, J. Dai, *Biophoton signal transmission and processing in the brain*, Journal of Photochemistry and Photobiology B: Biology, **139**, 71 (2014).

22. S. Kumar, K. Boone, J. Tuszyński, P. Barclay, C. Simon, *Possible existence of optical communication channels in the brain*, Scientific Reports, **6**, 36508 (2016).

23. A. Zangari, D. Micheli, R. Galeazzi, A. Tozzi, *Node of Ranvier as an Array of Bio-Nanoantennas for Infrared Communication in Nerve Tissue*, Scientific Reports, **8**, 539 (2018).

24. M. Ignaccolo, P. Grigolini, A. Rosa,*Sporadic randomness: The transition from the stationary to the nonstationary condition*, Phys. Rev. E, **64**, 026210, (2001).

25. N. Korabel, E. Barkai, *Pesin-Type Identity for Intermittent Dynamics with a Zero Lyaponov Exponent*, Phys. Rev. Lett., **102**, 050601, (2009).

26. M. Annunziato, P. Grigolini, *Stochastic versus dynamic approach to Levy statistics in the presence of an external perturbation*, Phys. Letters A **269**, 31 (2000).

27. M. Buiatti, P. Grigolini, A. Montagnini, *A Dynamic Approach to the Thermodynamics of Superdiffusion*, Phys. Rev. Lett. **82**, 3383 (1999).

28. P. Grigolini, *The Continuous-Time Random Walk Versus the Generalized Master Equation*, Advances in Chemical Physics, **133**, 357 (2006).

29. G. Culbreth, B. J. West, P. Grigolini, *Entropic Approach to the Detection of Crucial Events*, Entropy **21**, 178 (2019).

30. G. I. Barenblatt, *Scaling, self-similarity, and intermediate asymptotics*, Cambridge University Press, Cambridge (1996).

31. N Scafetta, V Latora, P Grigolini, *Lévy scaling: the diffusion entropy analysis applied to DNA sequences*, Phys. Rev. E, **66**, 031906 (2002).

32. F. Vanni, P. Grigolini, *Music as a mirror of mind*, Esthétique de la complexité. Hermann, Paris (2017).

33. A. Pease, K. Mahmoodi, BJ West, *Complexity measures of music* Chaos, Solitons & Fractals 108, 82 (2018).

34. K. Mahmoodi, B. J. West, P. Grigolini, *Complexity Matching and Requisite Variety*, submitted to PLOS biology.

35. D. Fels, *Cellular Communication through Light*, PLoS ONE, **4**, e5086 (2009).

36. P. Allegrini, P. Grigolini, P. Hamilton, L. Palatella, G. Raffaelli, *Memory beyond memory in heart beating, a sign of a healthy physiological condition*, Phys. Rev. E, **65**, 041926 (2002).

37. P. Grigolini, L. Palatella, G. Raffaelli, G. *Asymmetric anomalous diffusion: an efficient way to detect memoryin time series*, Fractals **9**, 439 (2001).

38. R. Tuladhar, M. Bologna, P. Grigolini, *Non-Poisson Renewal Events and Memory*, Physical Review E, **96**, 042112 (2017).

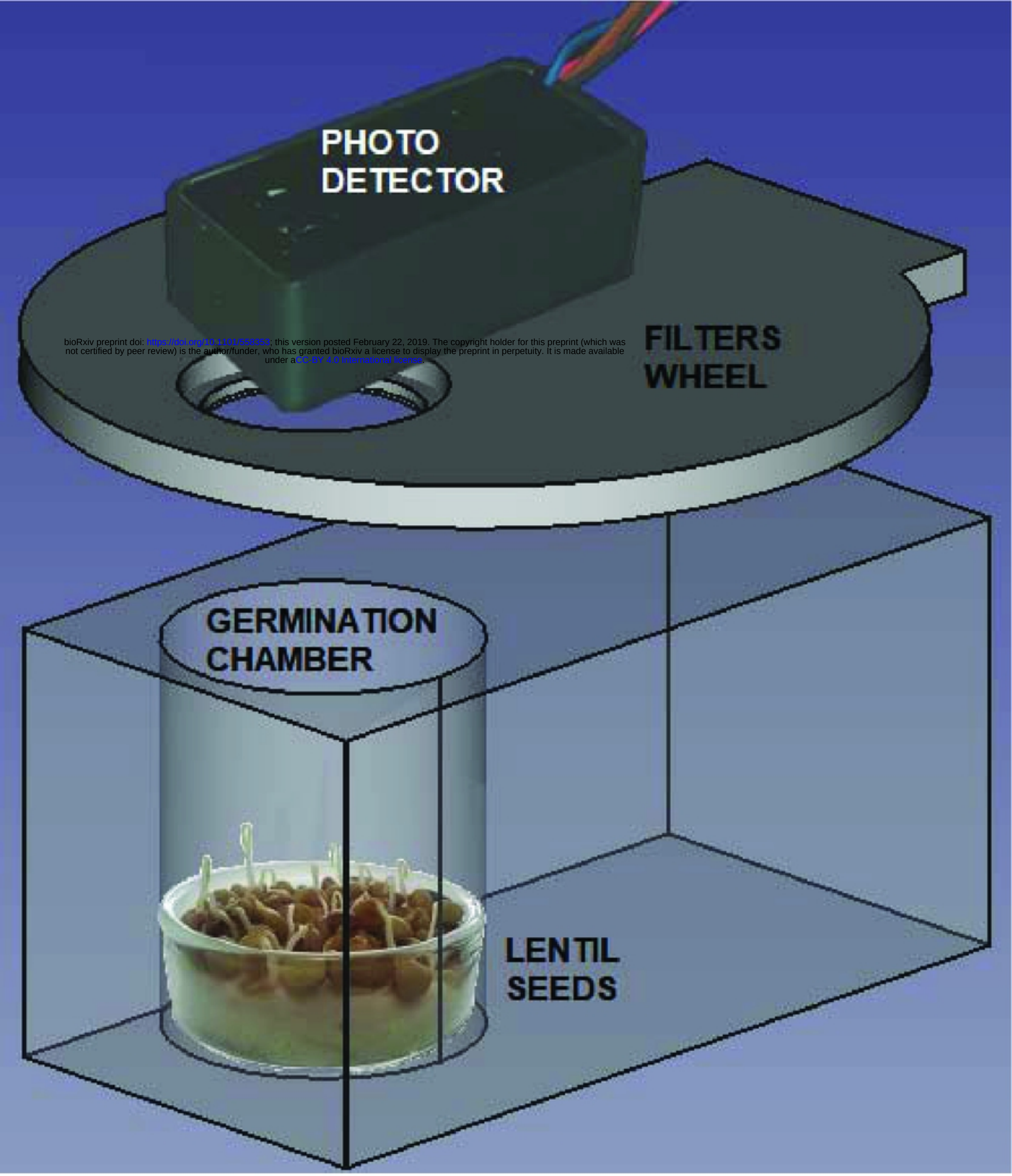


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Figure1

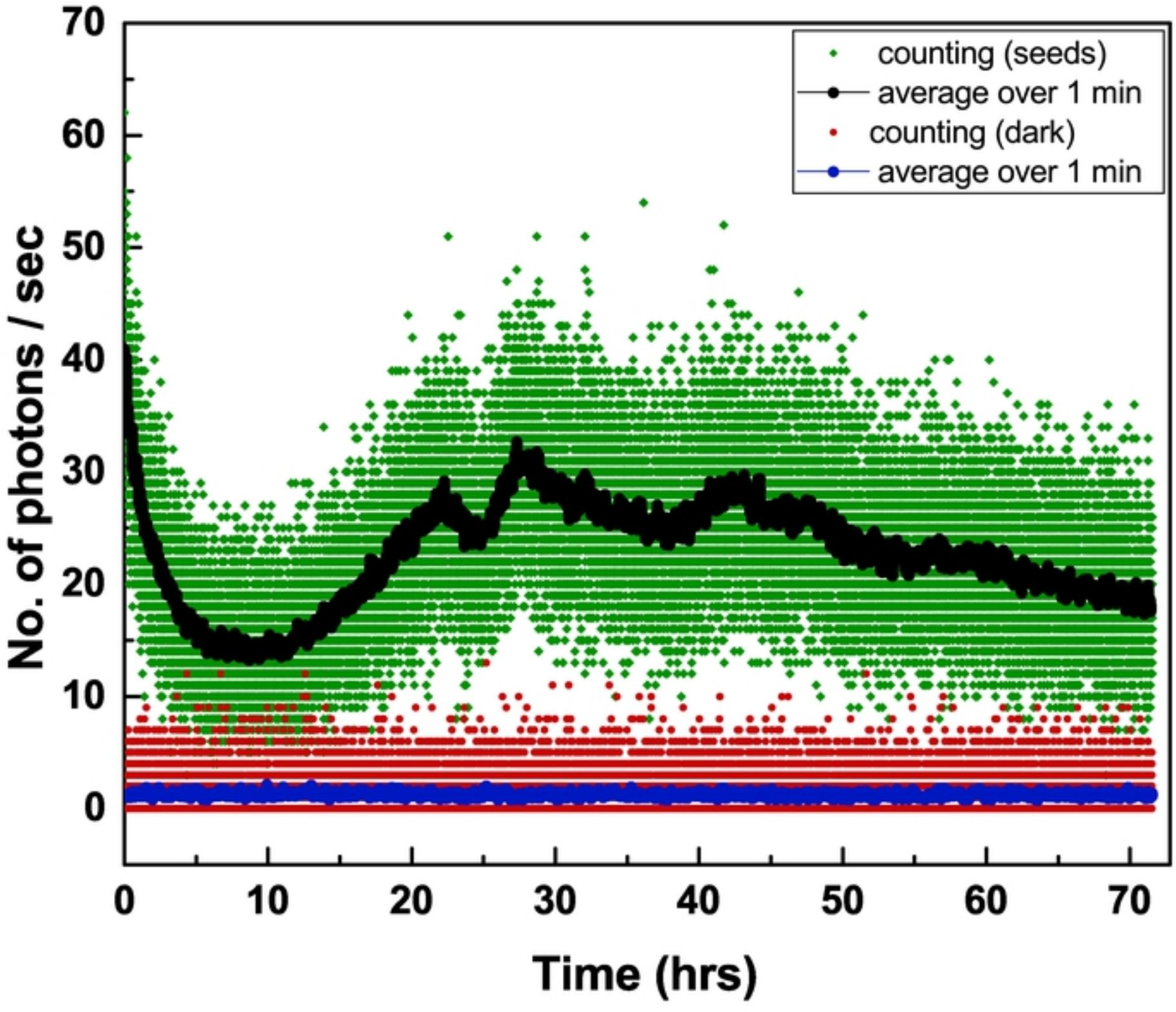
counting (seeds)
average over 1 min
counting (dark)
average over 1 min
No. of photons / sec
Time (hrs)
0
10
20
30
40
50
60
70

Figure2

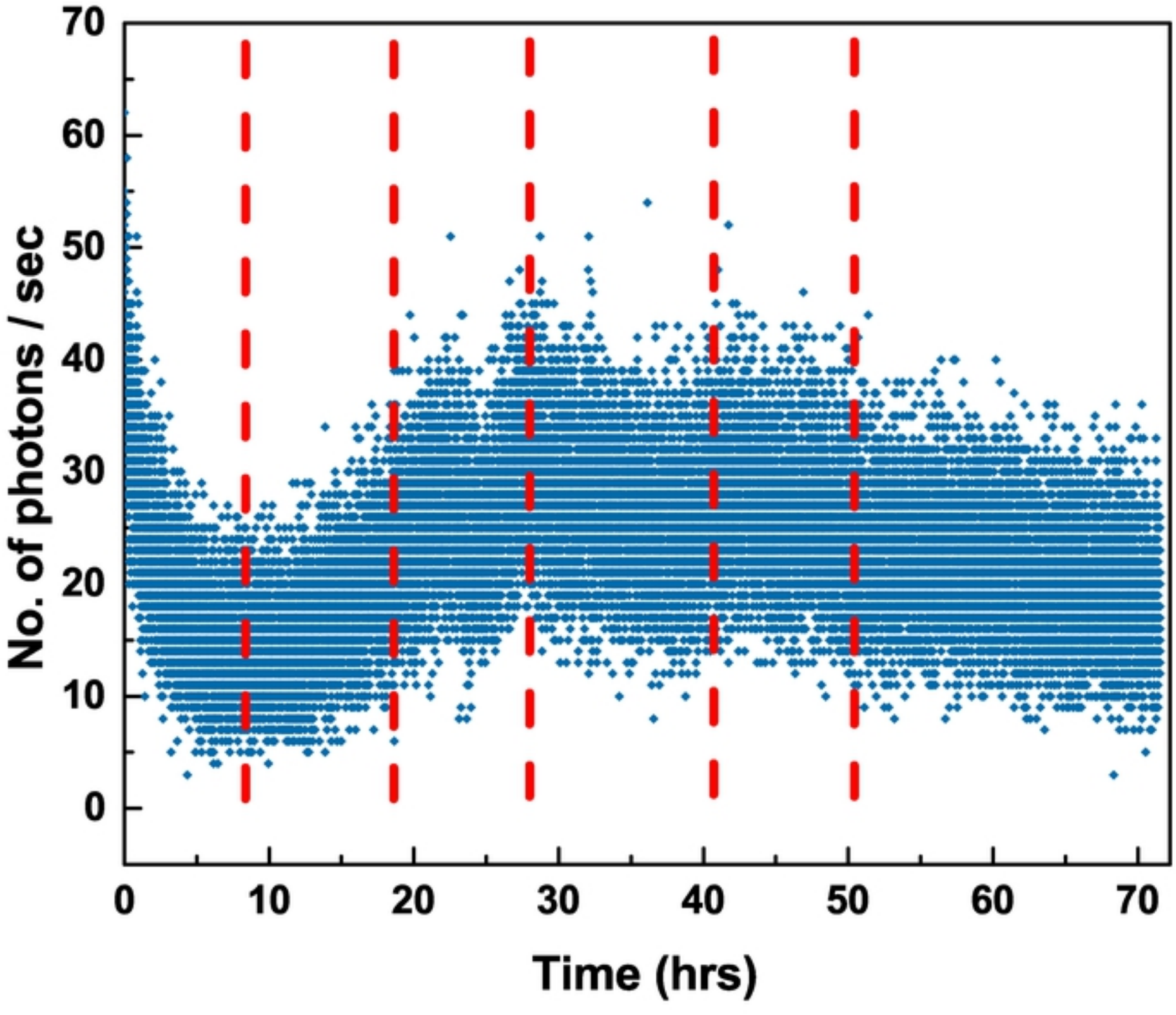


Figure3

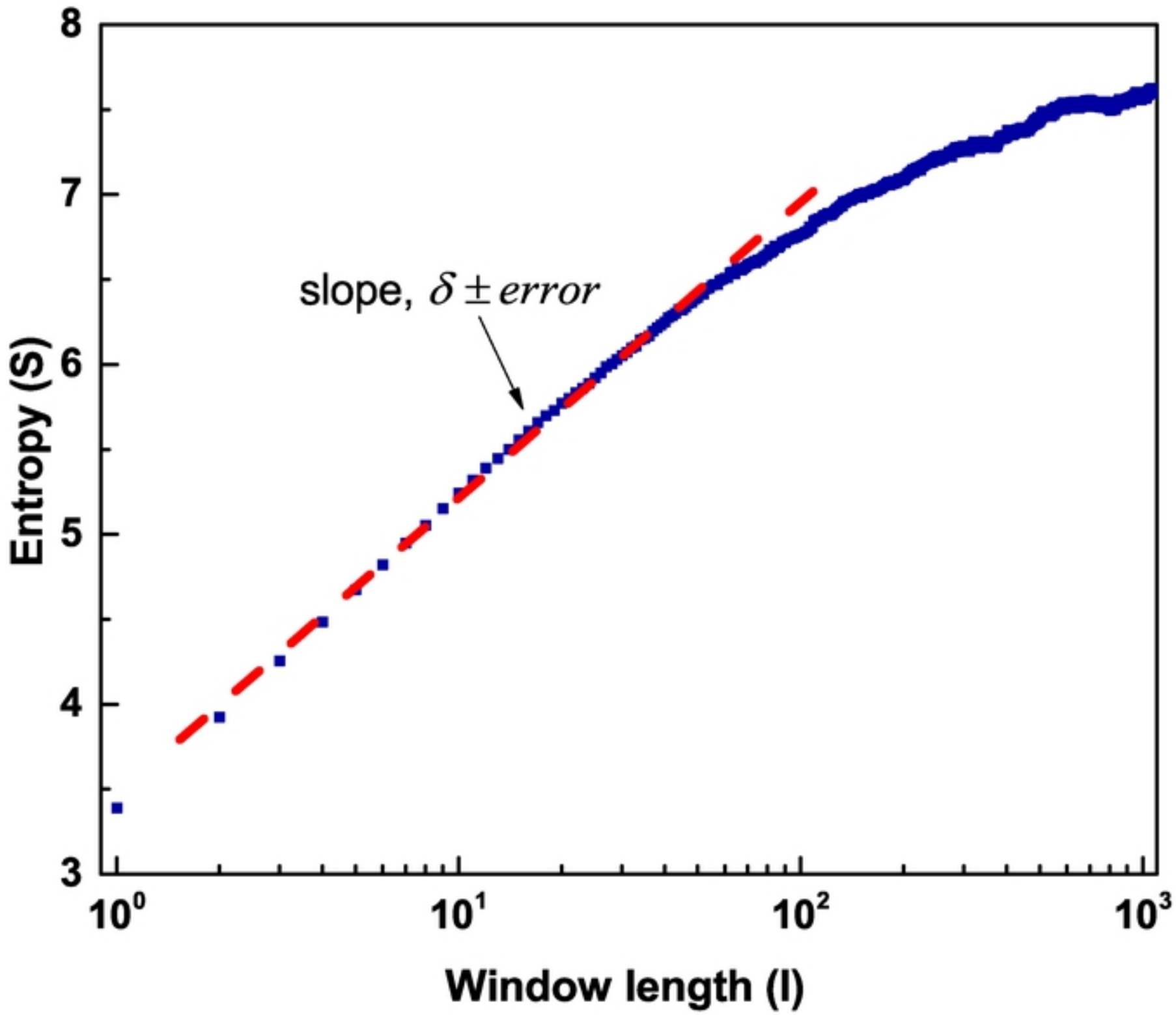
8
7
6
5
4
3
Entropy (S)
slope, $\delta \pm error$
$10^0$
$10^1$
$10^2$
$10^3$
Window length (l)

Figure4

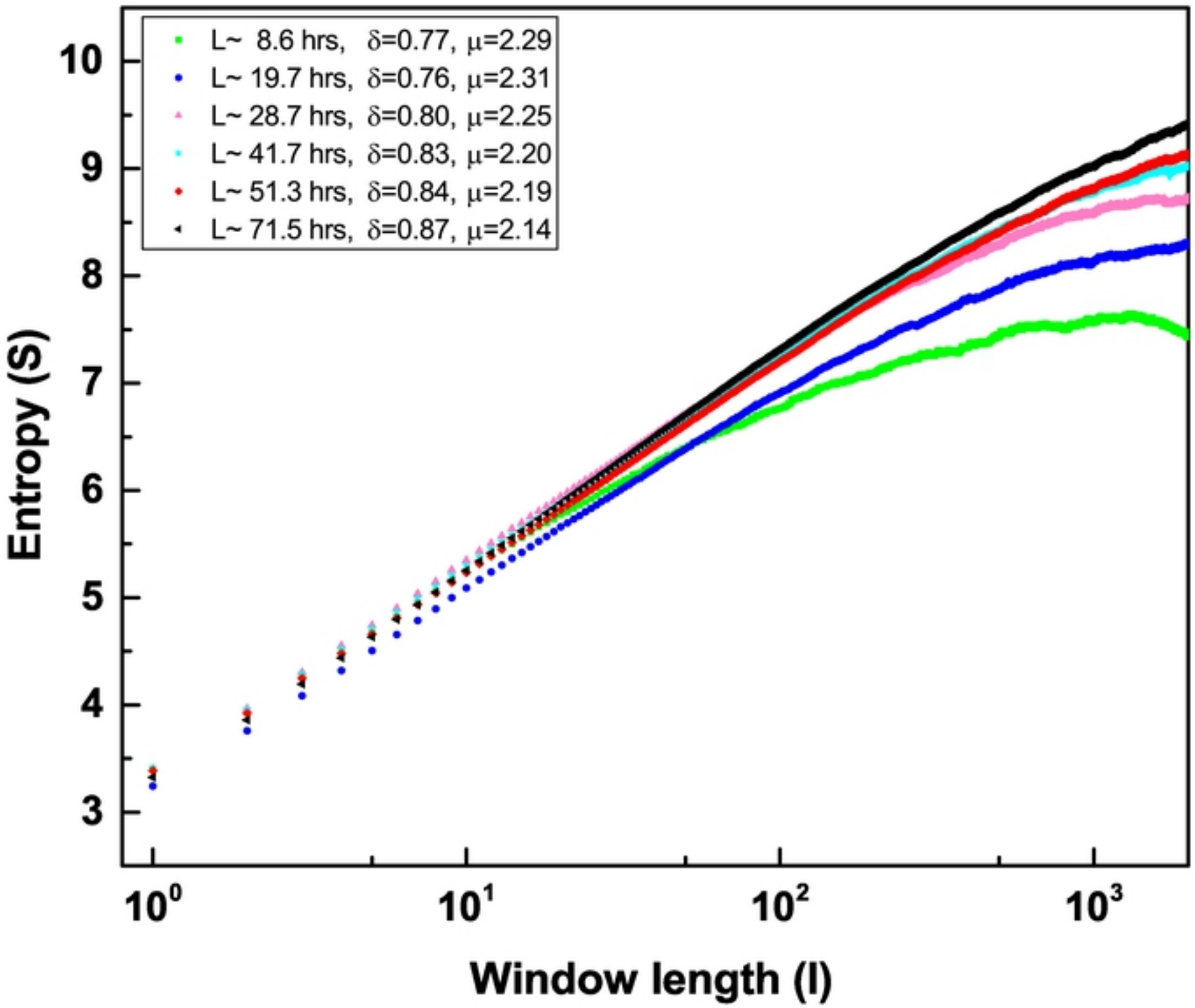
L~ 8.6 hrs, δ=0.77, μ=2.29
L~ 19.7 hrs, δ=0.76, μ=2.31
L~ 28.7 hrs, δ=0.80, μ=2.25
L~ 41.7 hrs, δ=0.83, μ=2.20
L~ 51.3 hrs, δ=0.84, μ=2.19
L~ 71.5 hrs, δ=0.87, μ=2.14
Entropy (S)
10
9
8
7
6
5
4
3
$10^0$
$10^1$
$10^2$
$10^3$
Window length (l)

Figure5