Cyclical trends as a signature of self-organization in driven nonlinear systems

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Based on works in collaboration with:

- B. Tadic, **Marija Mitrovic Dankulov**, **Roderick Melnik**, *Evolving cycles and self-organized criticality in social dynamics*, Chaos, Solitons & Fractals 171, 113459 (2023)
- B. Tadic, *Cyclical trends of network load fluctuations in traffic jamming*, Dynamics 2(4), 449 (2022)

- **Milovan Suvakov**, **M. Mitrovic, V. Gligorijevic**, B. Tadic, *How the online social networks are used: Dialogs-based structure of MySpace,* J. Royal Soc. Interface 10, 20120819 (2012).

- B. Tadic, **S. Thurner, GJ. Rodgers**, Traffic on complex networks: Towards understanding global statistical properties from microscopic density fluctuations, Phys. Rev. E 69, 036102 (2004)

Contents

- Background: Examples of cycles in complex systems & the origin of collective fluctuations
- Cyclical Trends in Traffic @Jamming
- Self-Organized Criticality & Cycles in Social Dynamics

Collective Fluctuations in Critical States

- Complex systems & Nonlinear dynamics; **Collective fluctuations** arise in critical states via long-range correlations impact spatial -temporal patterns

- **Cyclical trends at different scales** often appear: Accumulation and release of energy, stress, … in nonlinear dynamical processes driven by external forces;
  Some representative examples:

Solar activity (11-year cycles) impacts climate and life on the Earth

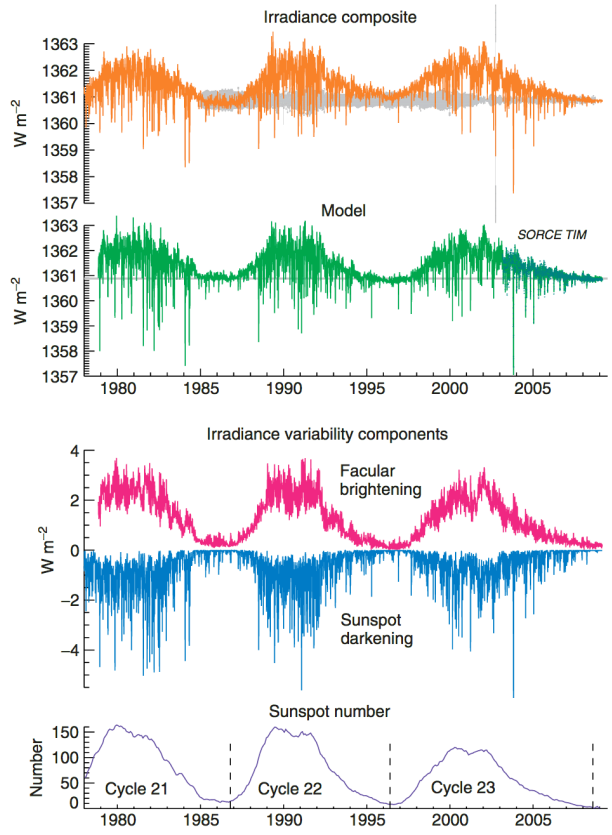

Figure from: J.L. Lean, *Cycles and trends in solar irradiance and climate,* WIREs Climate Change 1, 111 (2010)

FIGURE 1 | Shown in the upper panel is a record of total solar irradiance obtained as an average of three different observational composites. In the second panel are irradiance variations estimated from an empirical model that combines the two primary influences of facular brightening and sunspot darkening. The symbols indicate direct observations made by the TIM instrument of the SORCE mission, used to determine the relative sunspot and facular components in the model, shown separately in the middle panel. Annual mean sunspot numbers shown in the bottom panel indicate overall levels of solar activity in cycles 21, 22 and 23, with times of minima indicated by the dashed lines. [Ref 57 *provides details and sources of the various time series*].

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Field-induced magnetization reversal waves with AF/F interactions

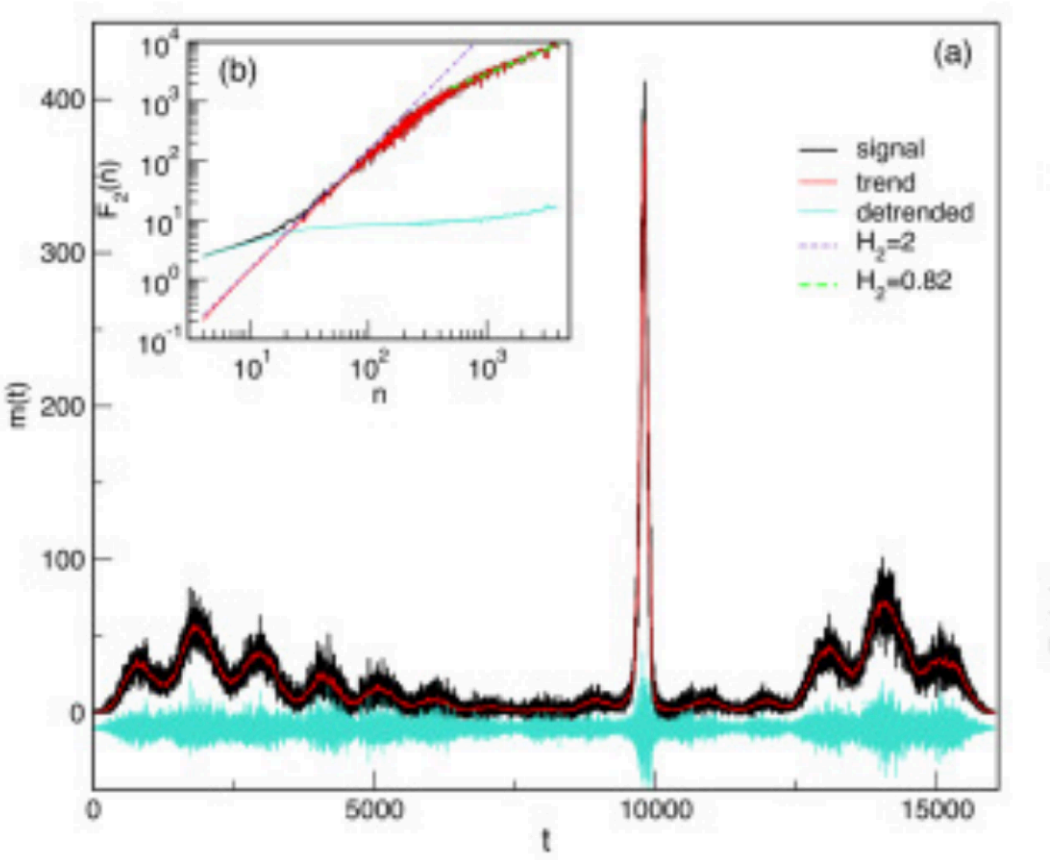


Fig. from: S. Mijatovic et al, *Tuneable hysteresis loop and multifractal oscillations of magnetisatio in weakly disordered AF/F bilayers* **Physica E: Low-dimensional systems and nanostructures** 142, 115319 (2022)

Partial synchronization among brain regions sustained via OP oscillations

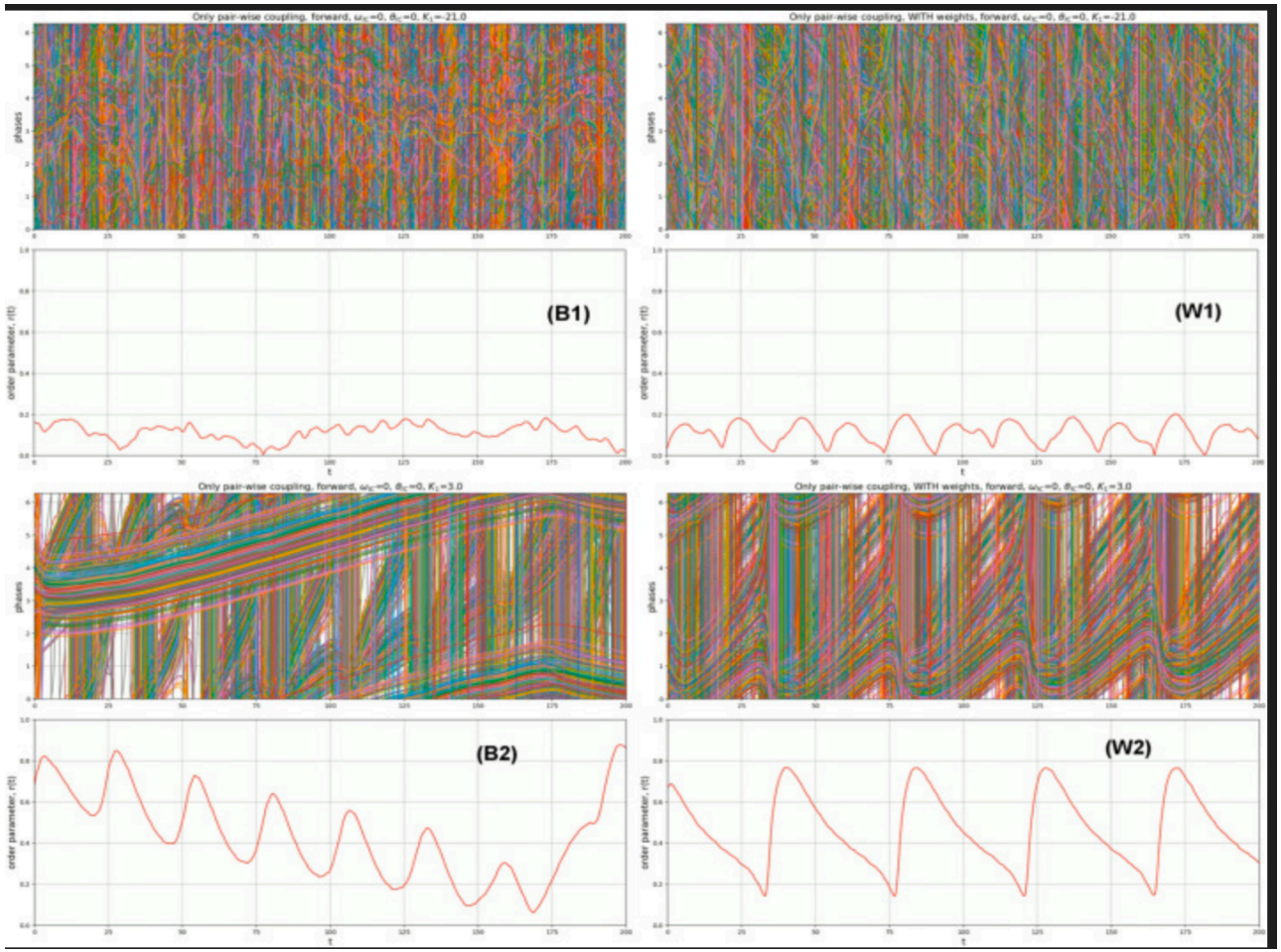
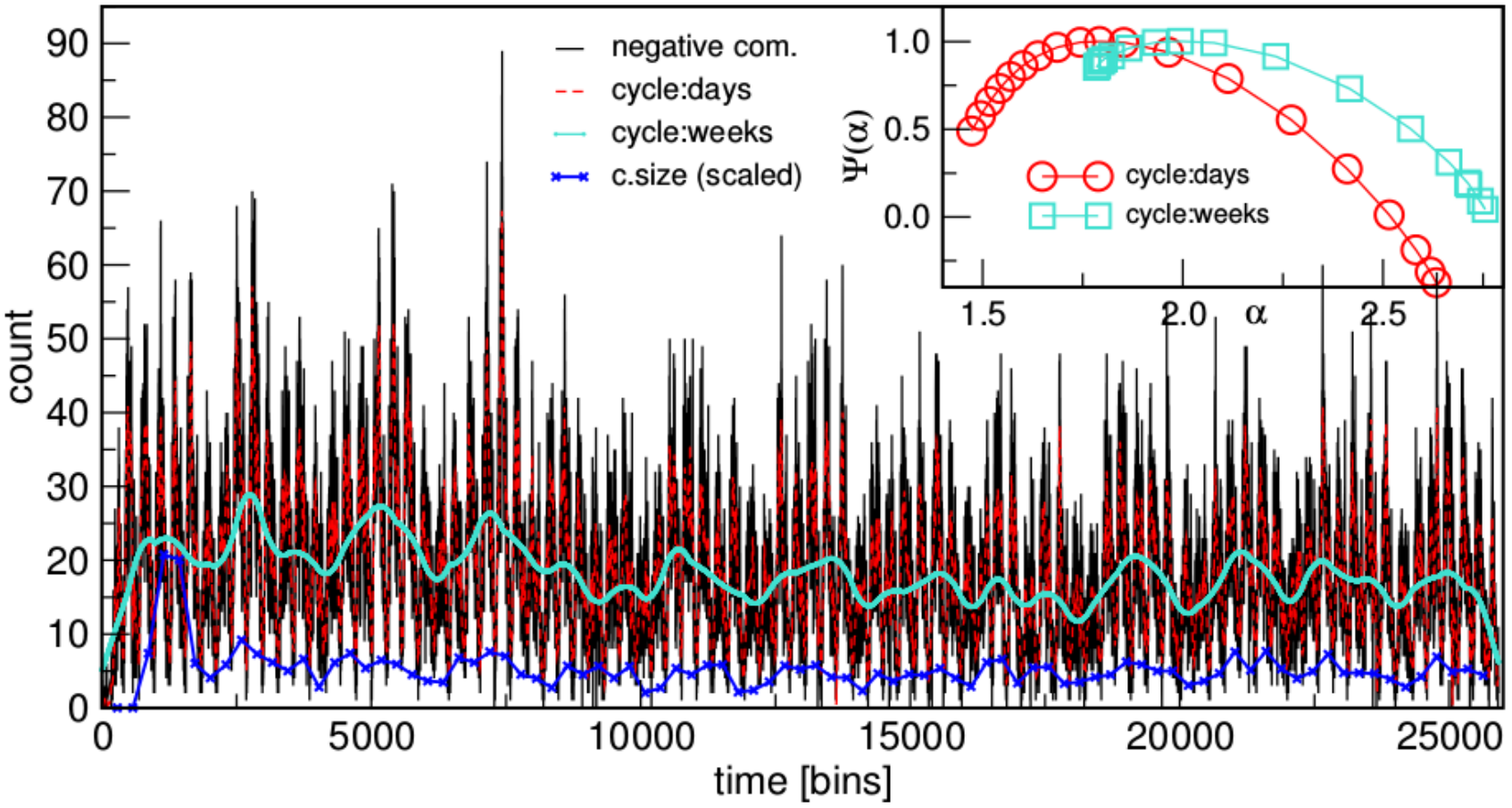


Fig. from: B. Tadic et al, *Multiscale fractality in partial phase synchronization around brain hubs*, **Chaos, Solitons and Fractals 160, 112201 (2022)**

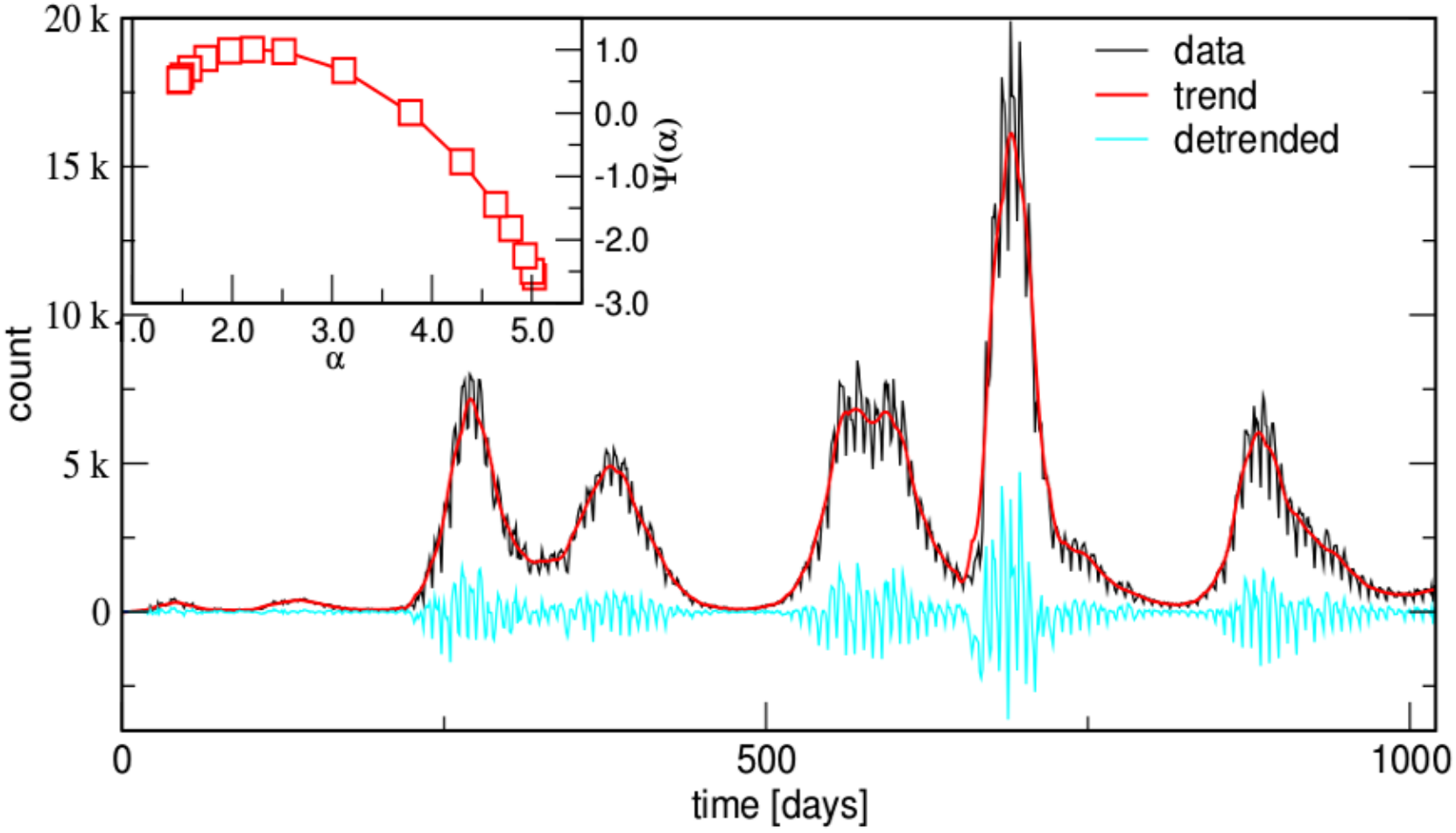
Examples of Social activity cycles



[B. Tadic, M. Mitrovic Dankulov, R. Melnik, Chaos Solitons & Fractals 171, 113459 (2023)]*

Epidemic cycles from bio-social processes

[more in M. Mitrovic Dankulov, B. Tadic, R. Melnik, Front.Phys. 10, 936618 (2022)]



1) Packet transport on networks with queuing at nodes: Spontaneous appearance of irregular cycles in traffic load fluctuations before jamming;

2) Online communications with emotional contents: Circadian cycles (of users) at start, then modified by the collective dynamic effects…

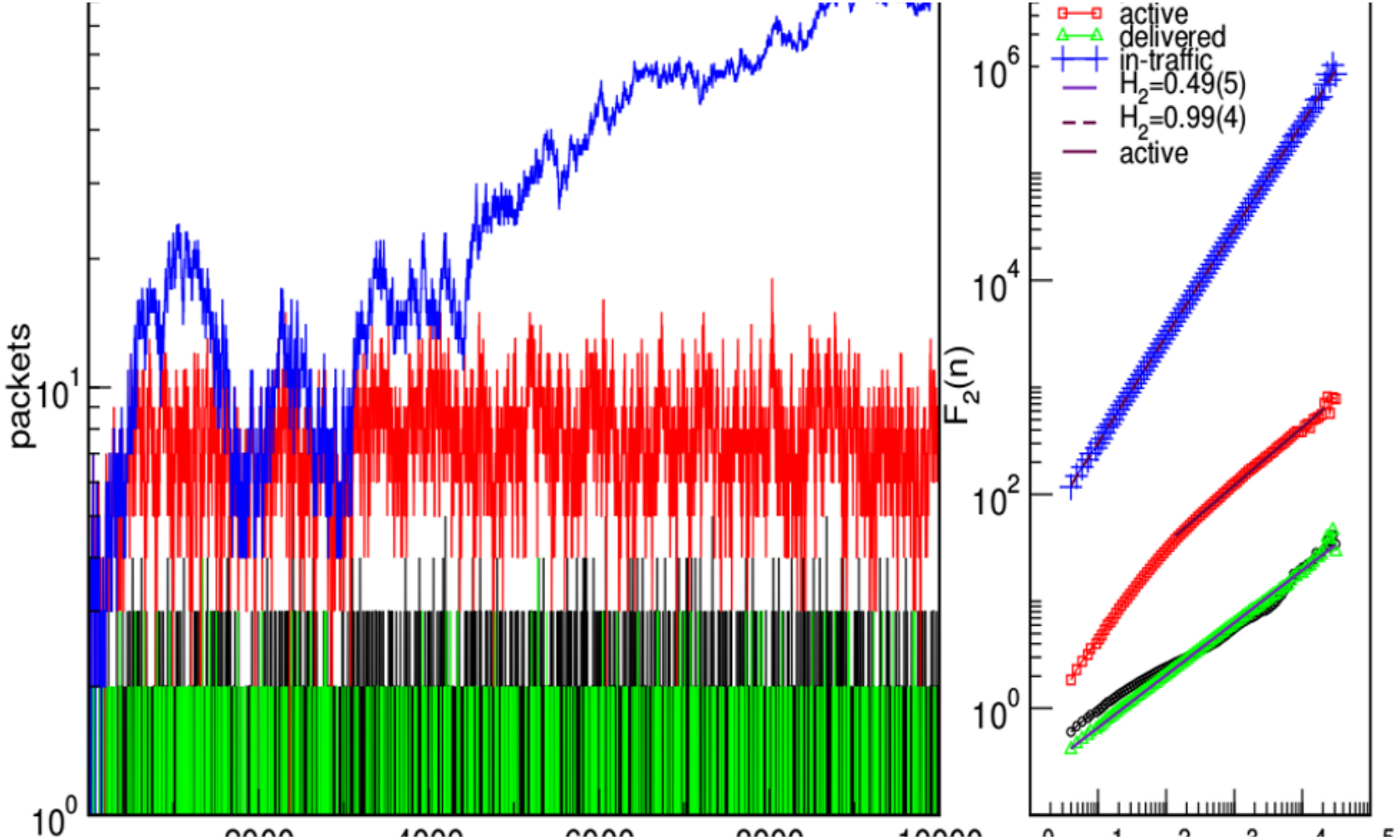
The Case of Traffic Jamming

- Traffic Jamming is a case of (complex) phase transition on a distributed geometrical system with intersecting paths!
- Model simulations: Traffic of information packets with Search & Queuing; nontrivial waiting times CTRW !
- Source—destination paths, queuing (LIFO) at nodes; nnn search (covers major part of a complex network with hubs)
- Jamming occurs when the delivery rate < generation rate;
- Then the **network load** $N_p(t)$ starts to increase with time t;

- We simulate traffic on structured networks & analyze traffic load time series.
- Cyclical trends found by method with overlapping intervals (see Ref*).

[*B.Tadic, Dynamics 2(4), 449-461 (2022)]

Time Series of Traffic on WG



Queuing at nodes → Nonlocal interactions of paths

→Waiting times with p.l. distributions (CTRW)

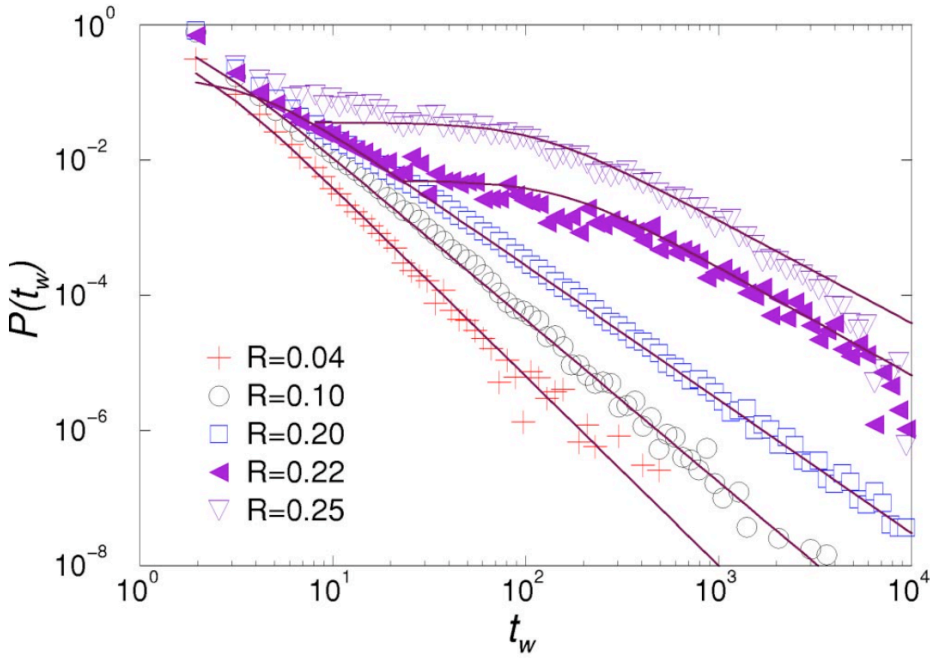
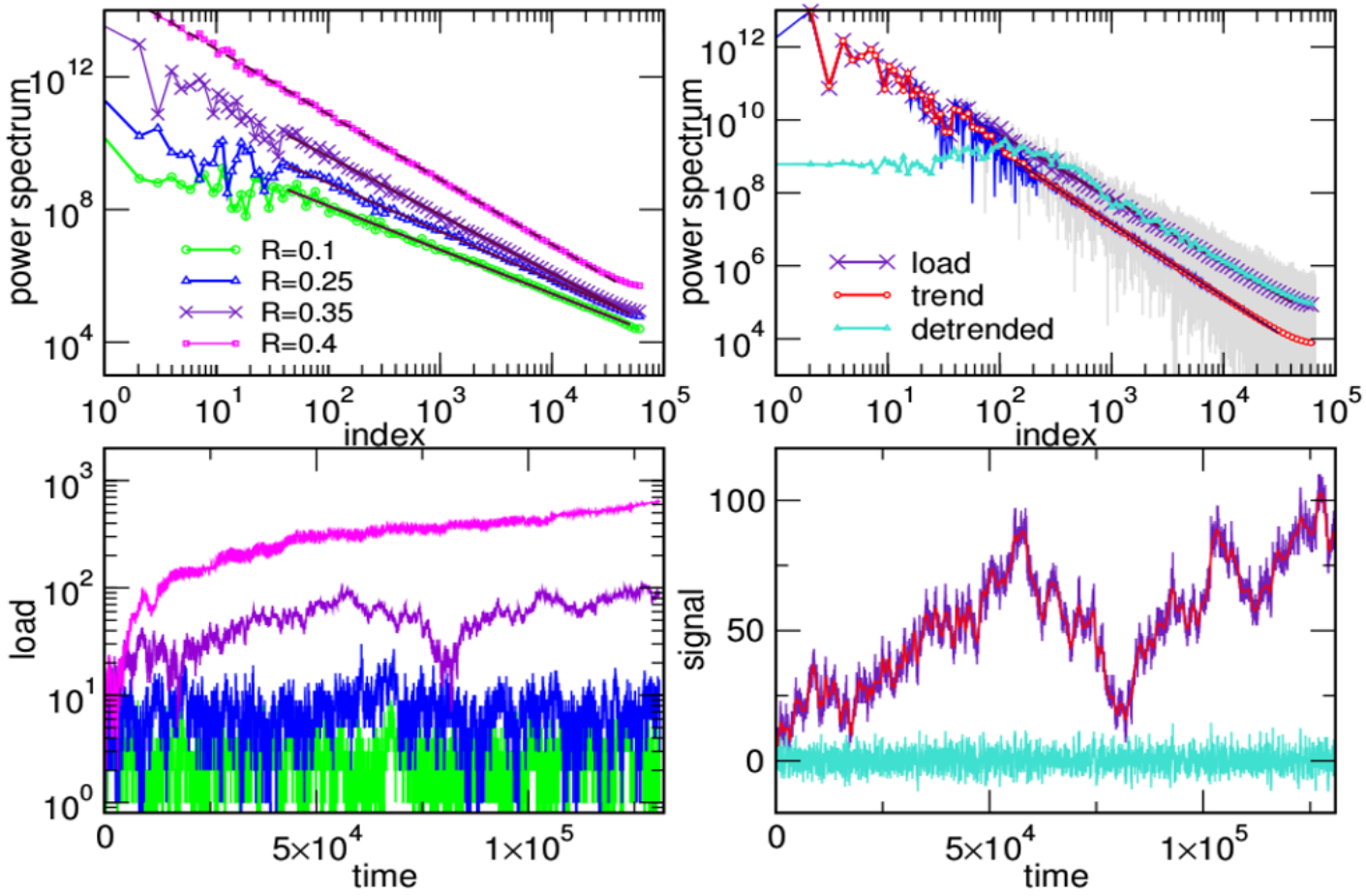


FIG. 5. (Color online) Distribution of waiting times of individual particles for varying posting rates R in the free flow and flow with temporary crisis. Data collected from a particle which moves within a computation time-window of 200 000 time-steps and are log binned.

Fig. from:
B. Tadic, S. Thurner, G.J. Rodgers, *Traffic on complex networks: Towards understanding global statistical properties from microscopic density fluctuations,* Phys. Rev. E 69, 036102 (2004)

Cyclical Trends in Traffic Load Fluctuations



DMFR Analysis: Steps

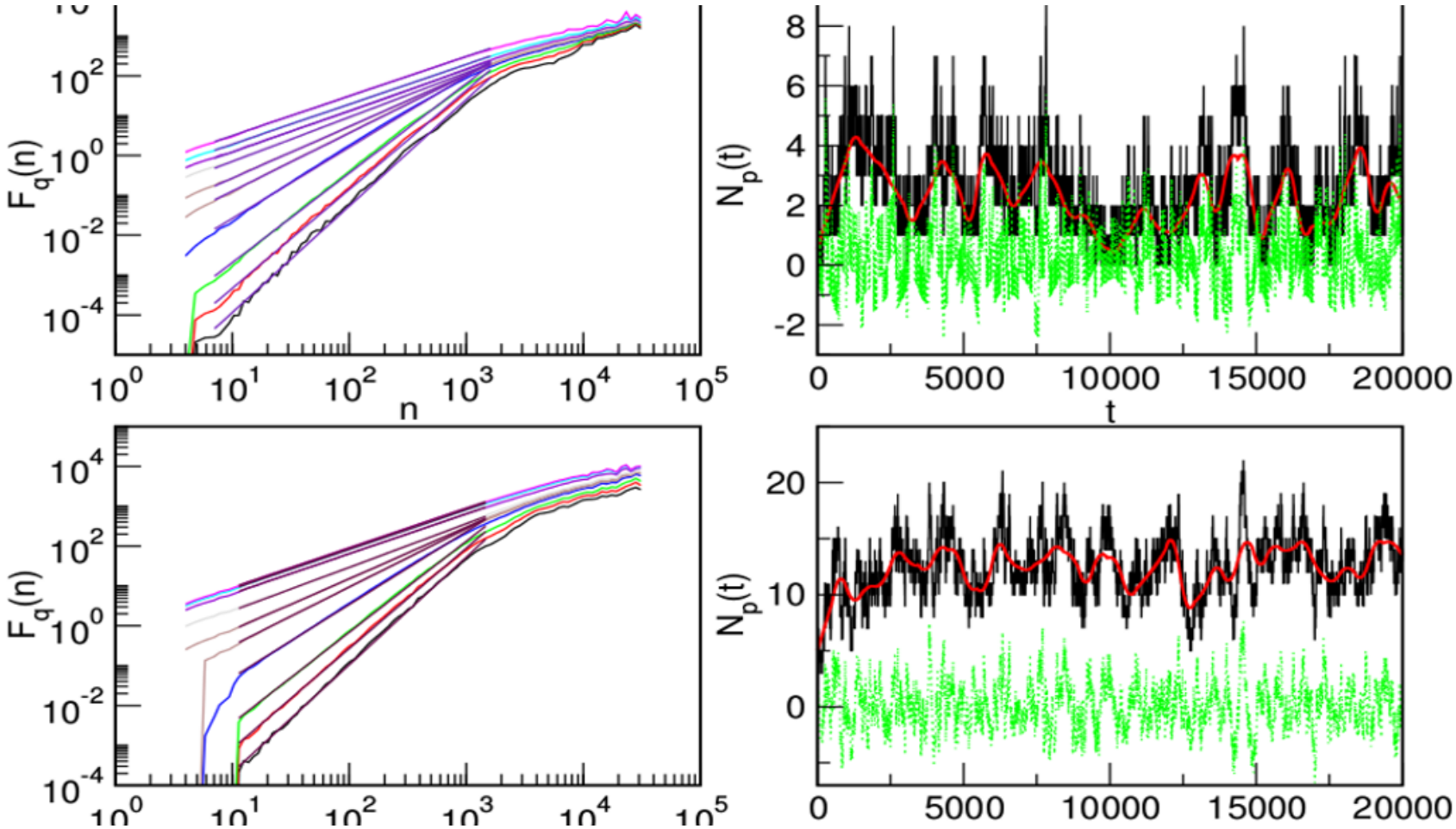
- TS profile *Y(i)*; divided in *Ns* segments of length *n*; At each segment, the local trend determined by polynomial fit and standard deviation around local trend:

$$F^2(\mu,n)=\frac{1}{n}\sum_{i=1}^{n}\left[Y((\mu-1)n+i)-y_\mu(i)\right]^2$$

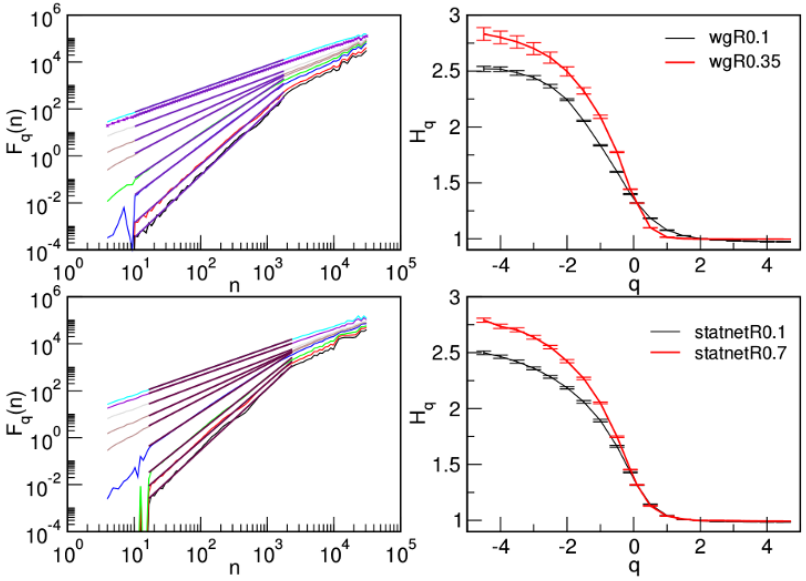
- Then the **Fluctuation function** ***$F_q(n)$*** is computed & its scaling parts fitted → ***H_q***

$$F_q(n)=\left\{(1/2N_s)\sum_{\mu=1}^{2N_s}\left[F^2(\mu,n)\right]^{q/2}\right\}^{1/q}\sim n^{H_q}$$

Multifractal Fluctuations: 2 nets



Traffic-on-networks→Cycles



B.Tadic, Dynamics 2,449-461 (2022)

- Collective dynamics in traffic with **queuing** generates Cycles
- Their MRF features depend on network load (posting rate **R**) and the network structure

Online Social Dynamics with Emotions

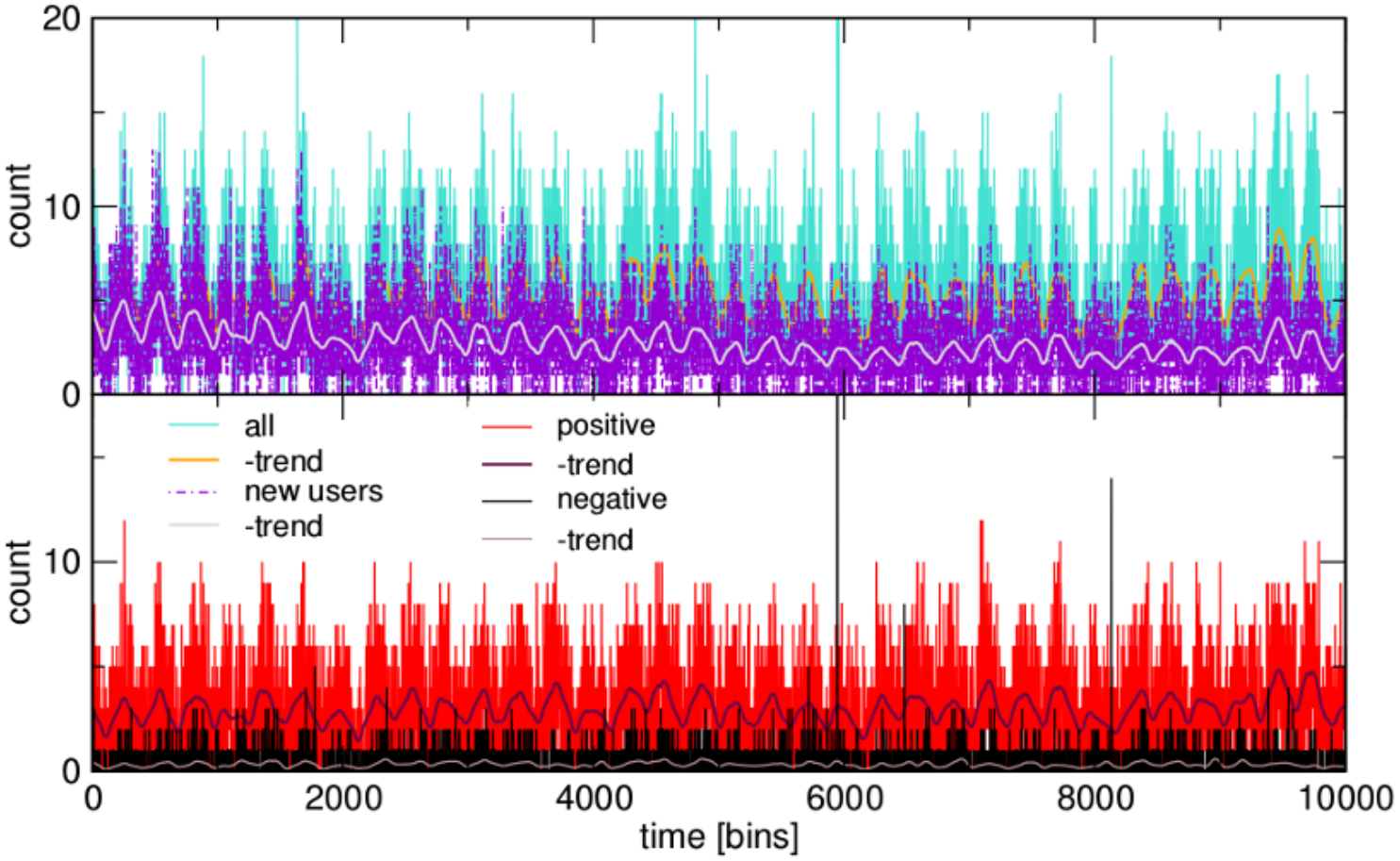
- From Data (MySpace)[*]) with annotated positive/negative emotional contents
- Cycles at start: Circadian (day—night) activity cycles of humans;
- They get modified by collective dynamics, which is a SOC attractor;
- Fig. Avalanches in OSDyn: specific type! Threshold-dependent scaling [**];
- Fig. Cycles identified at different levels: Daily, weekly,…

- Multifractal analysis reveals modulated cycles with higher harmonics, described by **Singularity spectra** $\psi(\alpha)=q\alpha-\tau_q$; $\alpha=d\tau_q/dq$; $\tau_q=qH_q-1$

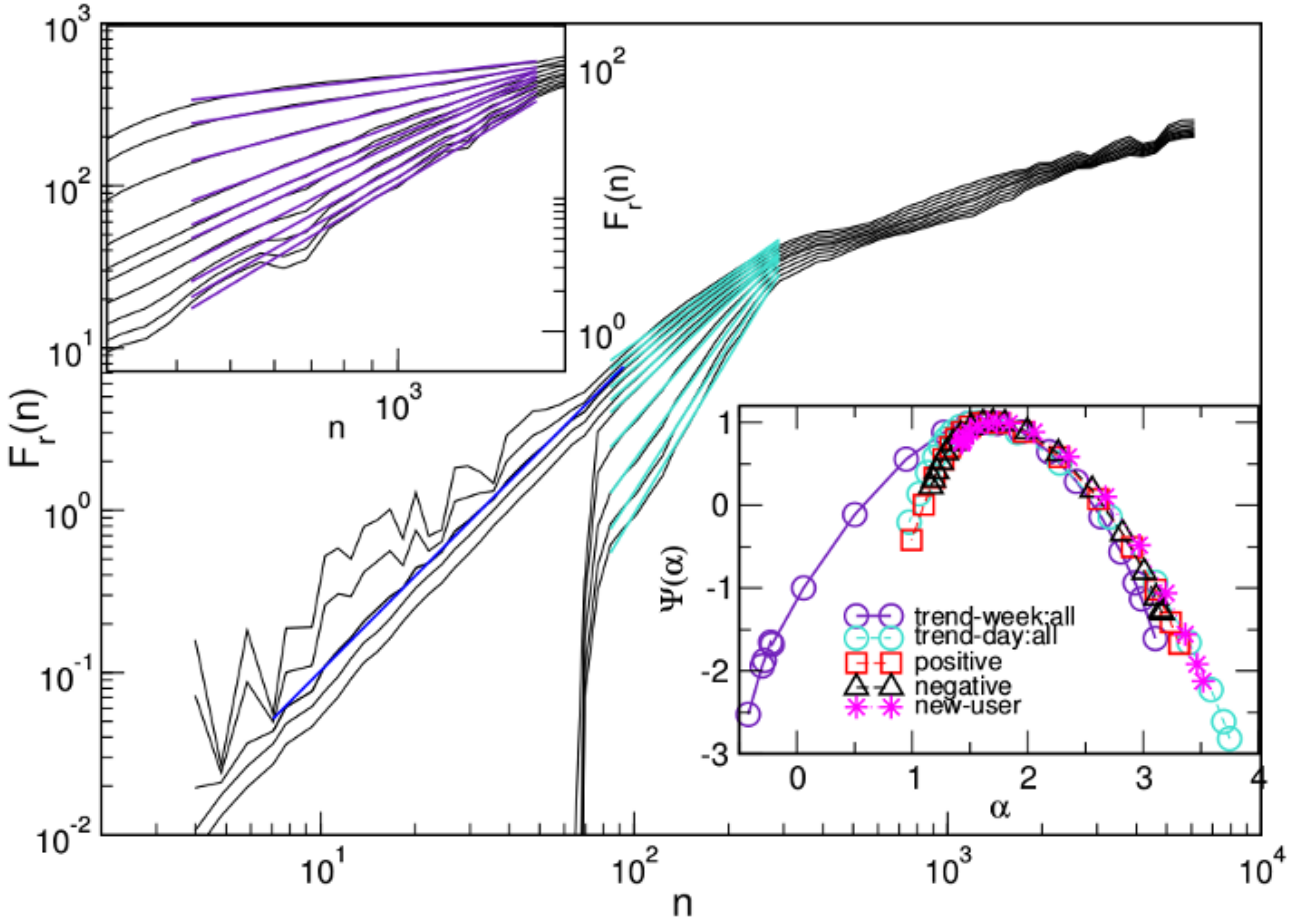
- [*MySpace data: M. Suvakov, M. Mitrovic, V. Gligorijevic, B. Tadic, J. Royal Society Interface 10, 20120819 (2012)]
- [**Cycles&SOC: B. Tadic, M. Mitrovic Dankulov, R. Melnik, Chaos Solitons & Fractals 171, 113459 (2023)]

- {*Reference: B.TadiFractals171, 113459 (2023)

Driving force new-users time series brings circadian cycles to the activity time series



Cycles of activity (various contents…) TS are modulated by collective fluctuations (SOC)



Signatures of Self-Organized Criticality

SOC: In extended interacting systems, the critical state appearing as an attractor of nonlinear dynamics under repeated slow driving [].

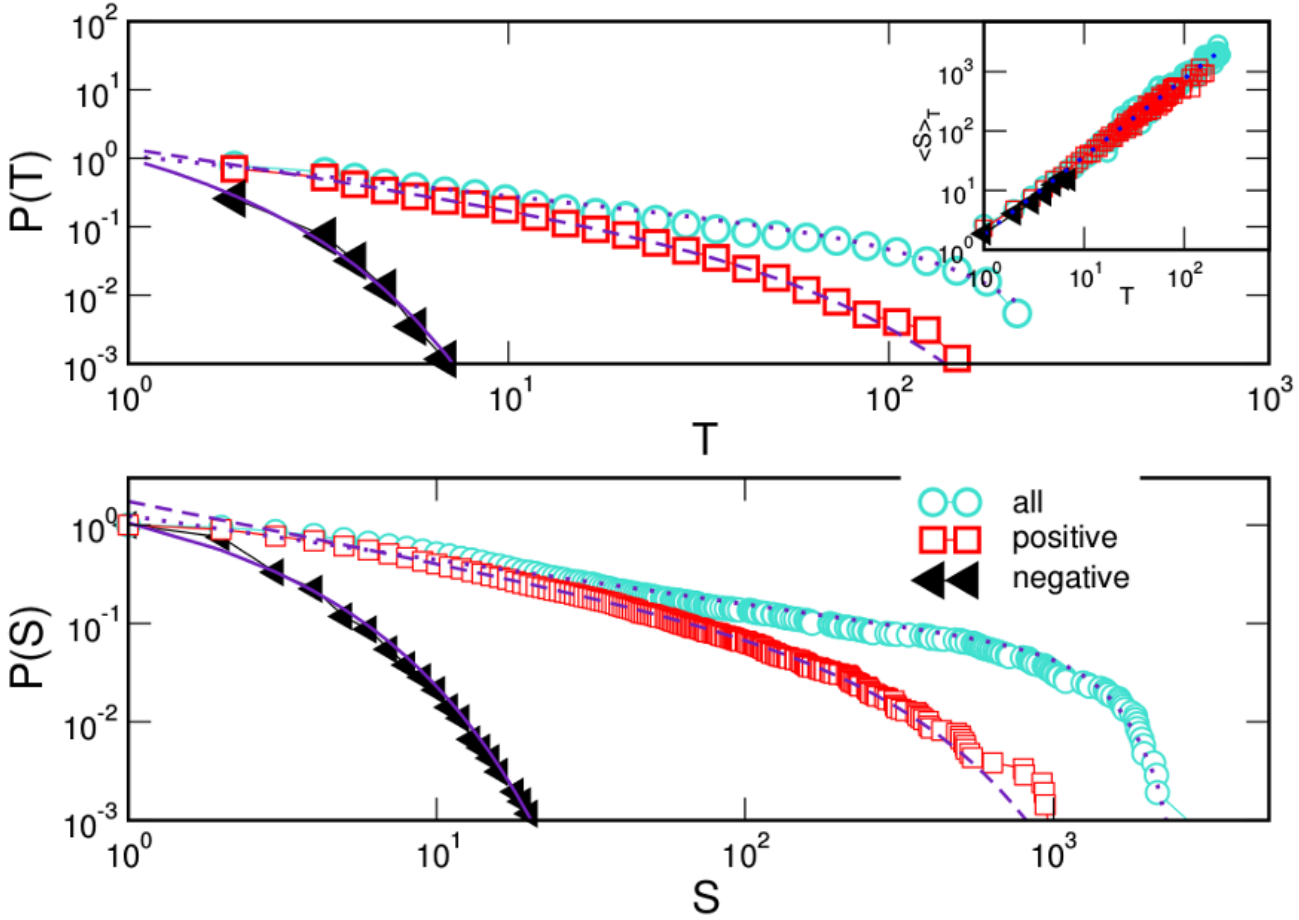
Some features of SOC shown here:

- Long-range temporal correlations: power spectrum $\rightarrow$ $W(f) \sim f^{-\phi}$
- Multifractal fluctuations: generalised Hurst exponent $\rightarrow$ $F_r(n) = \left\{ \frac{1}{2N_s} \sum_{\mu=1}^{2N_s} \left[F^2(\mu, n) \right]^{r/2} \right\}^{1/r} \sim n^{H_r}$
- Avalanches self-similarity: $P_c(s) \sim s^{-(\tau_s - 1)} \mathcal{G}(s, L)$, $P_c(T) \sim s^{-(\tau_T - 1)} \mathcal{D}(T, L)$,... + scaling relations $\gamma_{sT} = \frac{\tau_T - 1}{\tau_s - 1}$; and exhibiting finite-size scaling when L is varied;

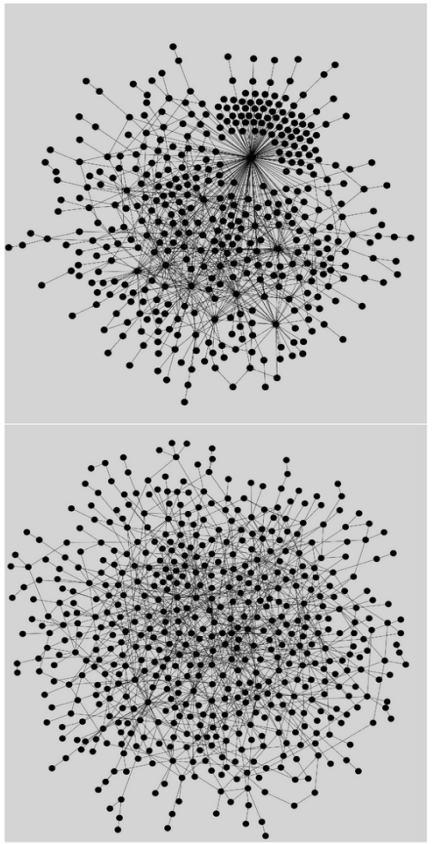
These properties can be determined from the output signal (Barkhausen noise), the magnetisation fluctuations time series.

[Marković and Gros, Power laws and self-organized criticality in theory and nature, Phys. Reports 536, 41 (2014)

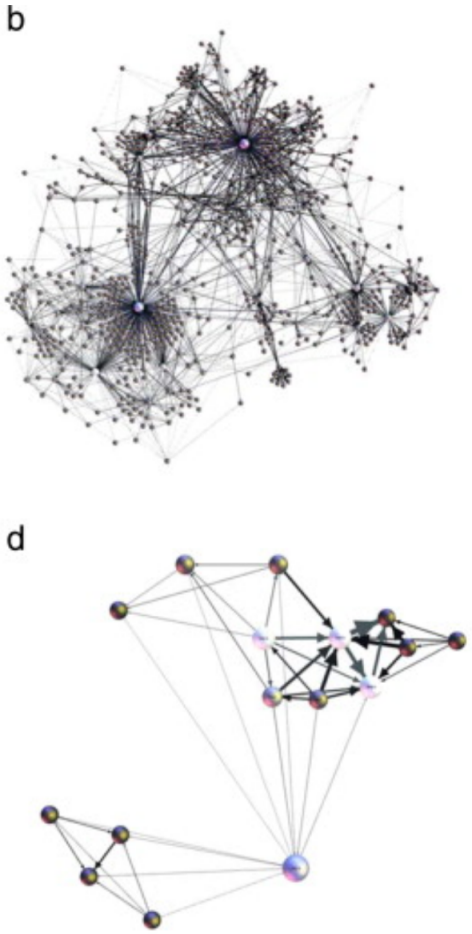
SOC states: Avalanches, PS, Scaling…



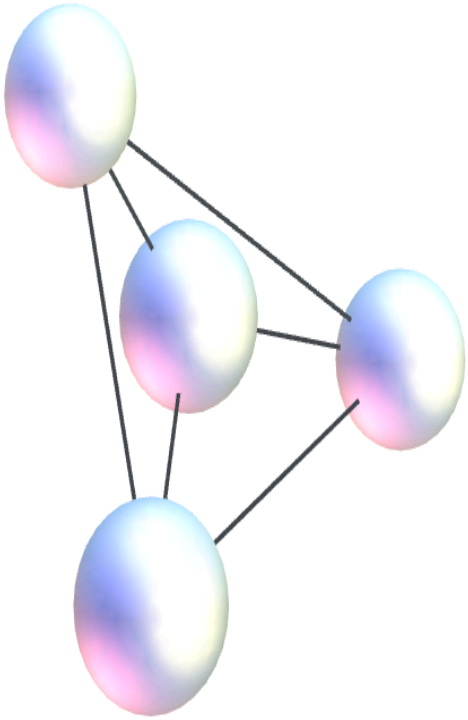
Origin of Modulated Cycles: Networks provide nonlocal (via queuing in traffic) or higher-order interactions (via cliques in social networks)



- Network structure, hubs matter, *Hq* is different, distributed interactions occur in all networks among packets waiting in **queues** (CTRW);
- In OSN, **cliques** appear[M. Andjelkovic et al, Physica A 436, 582-595 (2015)] providing interactions among multiple users, with potentially different roles (social brokerage)



Summary



- (modulated)Cycles are ubiquitous in **critical dynamics** on spatially distributed systems;
- Generated by collective fluctuations (starting with simple diffusion → CTRW) via *nonlocal interactions*;
- Modulated original cycles (of individual actors) through *clique & community interactions*;
- Higher harmonics, Multifractal TS with broad singularity spectra; @multiple scales
- More… http://www-f1.ijs.si/~tadic/

Related References & **Co-Authors**

- B. Tadic, **Marija Mitrovic Dankulov, Roderick Melnik**, *Evolving cycles and self-organized criticality in social dynamics*, Chaos, Solitons & Fractals 171, 113459 (2023)
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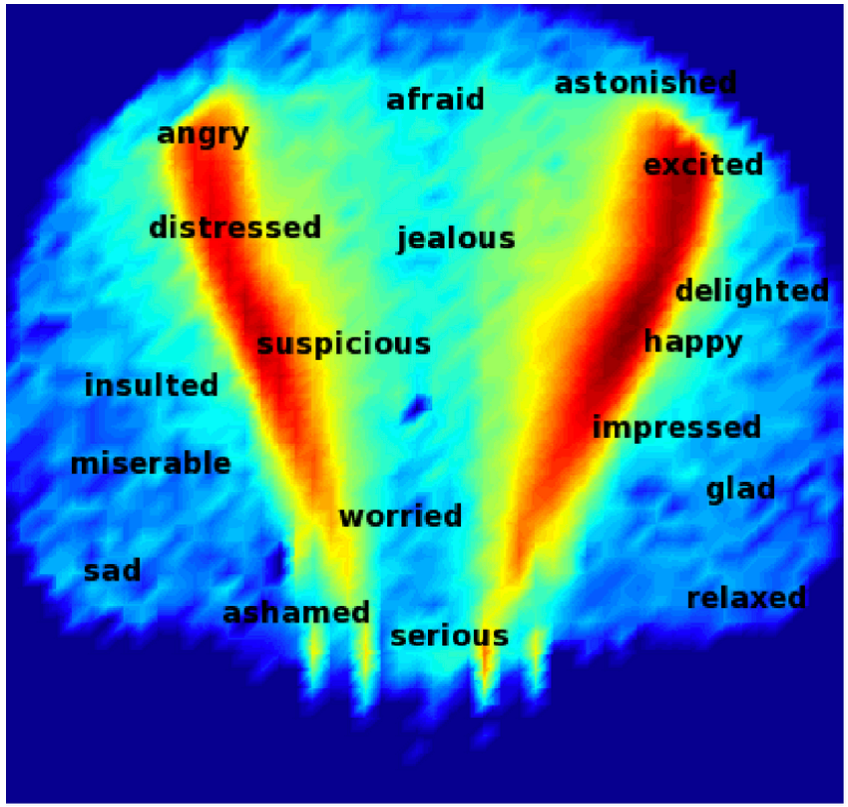

from Entropy 15(12), 5084-5120 (2013)