Aging of Classical Oscillators during a Noise-Driven Migration of Oscillator Phases

Hildegard Meyer-Ortmanns
Jacobs University Bremen

Work in collaboration with F. Ionita (JU), D. Labavic (JU) and M. Zaks (HU, Berlin)

- Order-by-disorder in oscillatory systems
- Noise-driven migration of oscillator phases
- Aging in classical nonlinear oscillators

P. Kaluza and HMO, Chaos 20, 043111 (2010).
F. Ionita, D. Labavic, M. Zaks and HMO, Eur. Phys. J. B 86(12), 511(2013).
F. Ionita, and HMO, Phys.Rev.Lett.112, 094101 (2014)

JACOBS UNIVERSITY

Outline: In analogy to spin systems we shall see how

frustration

⇓

multistability

⇓

rough "energy" landscape with a hierarchy of barriers

⇓

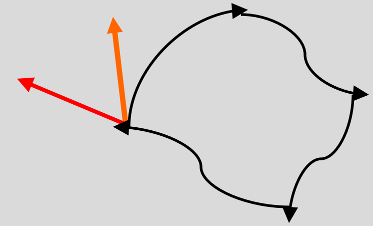
multitude of inherent time scales

⇓

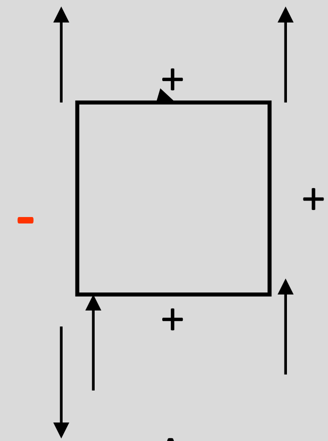
aging

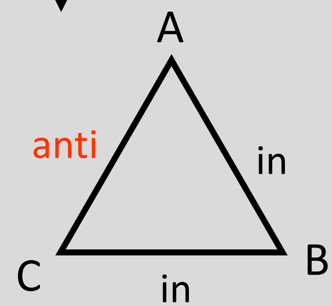
here in excitable and oscillatory systems

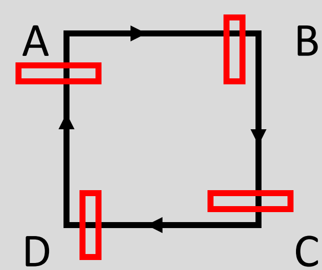
Concept and impact of frustration in dynamical systems



Physics	Gauge theories	Field strength
	General relativity	Curvature
	Spin glasses Oscillatory systems: phase oscillators, excitable systems	Frustration
Social systems	Approach to balance	Imbalance
Communication	Assigning a meaning	Misunderstanding
Economics	Financial markets	Arbitrage







G. Mack, Commun.Math.Phys.219, 141 (2001).
& Fortschritte der Physik, 81: 135-185 (1981): Physical Principles, Geometrical Aspects and Locality of Gauge Field Theories.

THE NOTION OF FRUSTRATION FOR OSCILLATORY AND EXCITABLE SYSTEMS

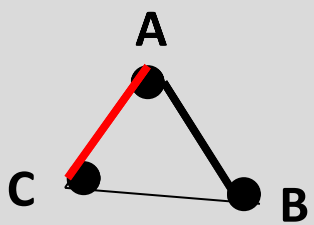
Criterion for undirected couplings

Consider a loop with **undirected interaction bonds** and couplings that can be either

attractive or repulsive
ferromagnetic or antiferromagnetic
excitatory or inhibitory
repressive or supportive

Consider a path from A to B along the shortest connection and along the complementary path in the loop from B to A.

The bond from A to B is not frustrated if A acts upon B in the same way as B upon A (e.g. attractive), otherwise it is.



A in phase with B, B with C → C with A, but if C wants to be antiphase with A, the link CA or CB is frustrated

Result of Daido: three Kuramoto oscillators coupled in a "frustrating way" lead to multistable behavior (Progr. Theor. Phys. 1987)

CRITERION FOR FRUSTRATION IN CASE OF DIRECTED COUPLINGS IN VIEW OF EXCITABLE SYSTEMS (Kaluza & HMO, Chaos 20, 043111 (2010))

Consider a loop with directed interaction bonds and couplings that can be either

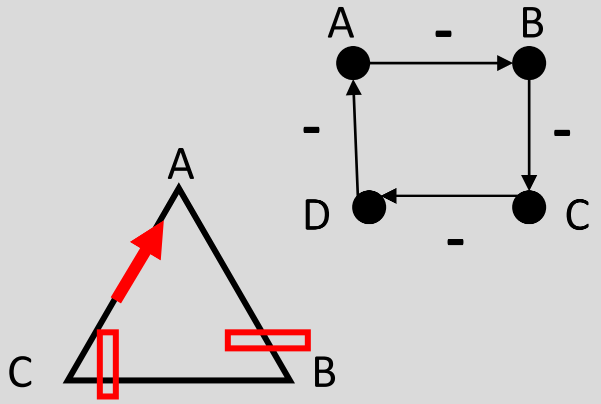
- **repressing or activating**
- **excitatory or inhibitory**

Consider a path from A to B along the shortest connection and along the complementary path in the loop from B to A.

The bond from A to B is not frustrated if A acts upon B in the opposite way as B upon A (e.g. A to B activating, B to A via C and D repressing), otherwise it is.

Different realizations of the frustration

- **Via the number of couplings**
- **Via the type of couplings along with the number**



Conjecture on **multistability** confirmed in coupled genetic circuits

$$\frac{dA_i}{dt} = \frac{\alpha}{1+(B_i/K)} \cdot \left(\frac{b+A_i^2}{1+A_i^2}\right) - A_i$$
$$+\beta_R \sum_{j=1}^{N} R_{ij} \frac{1}{1+(A_j/K)^2} + \beta_A \sum_{j=1}^{N} Q_{ij} \frac{(A_j/K)^2}{1+(A_j/K)^2}$$
$$\frac{dB_i}{dt} = \gamma A_i - \gamma B_i \,, \qquad i = 1, \ldots, N \,.$$

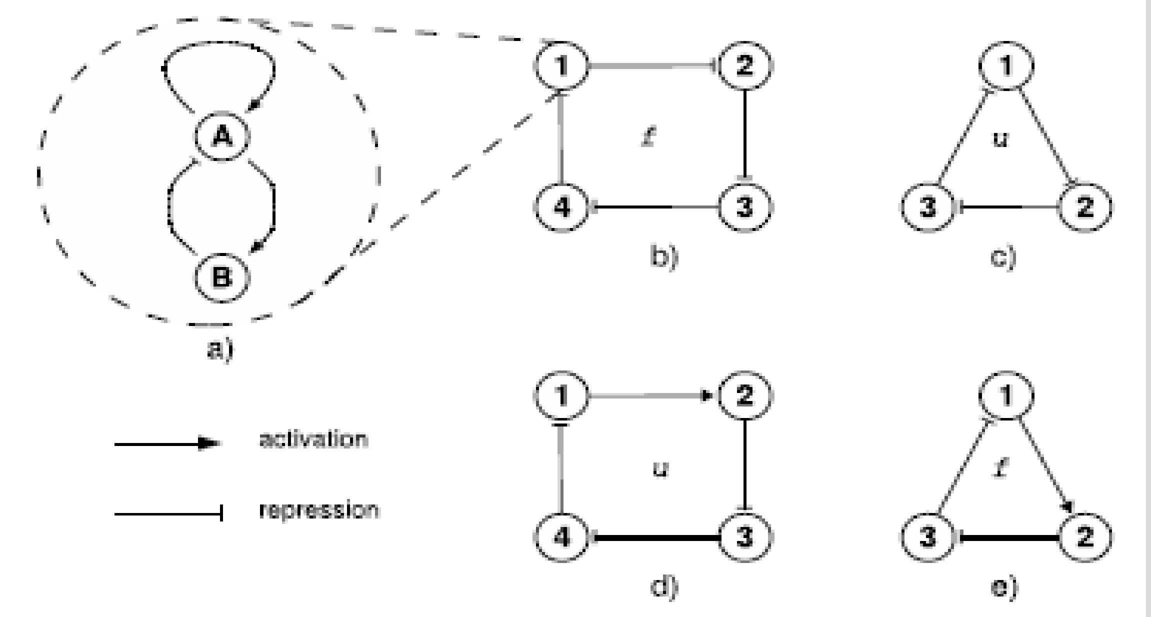
Adjacency matrix of repressing couplings R_{ij}

Adjacency matrix of activating couplings Q_{ij}

Consider most simple motifs with and without frustration for which the frustration is implemented either:

- **via the topology (even number of repressing couplings) or**
- **via the type of coupling (replace repressing by activating ones)**

MOST SIMPLE MOTIFS



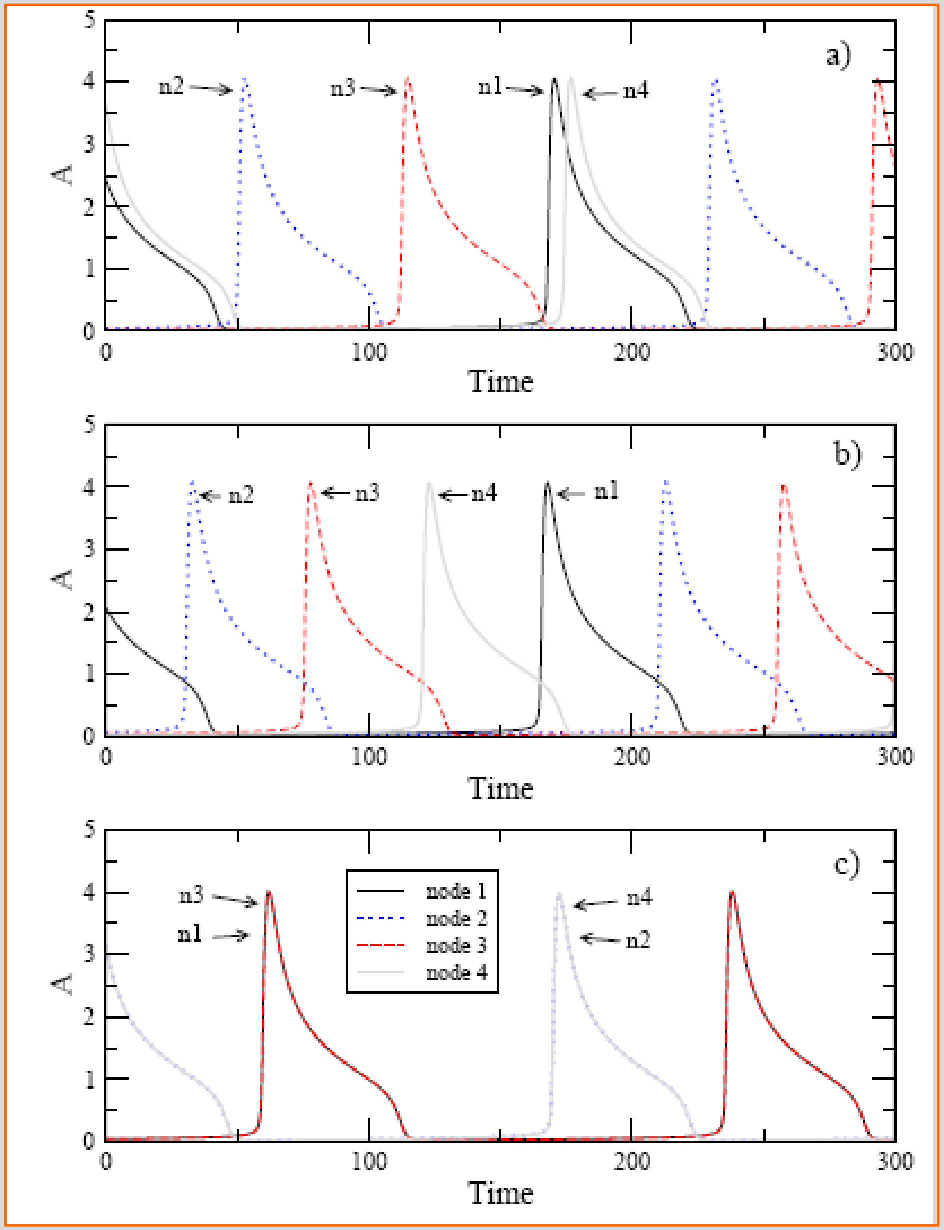
Frustration on two levels

f: frustrated
u: not frustrated

For the frustrated plaquette we obtain:

$$\begin{aligned}
\frac{dA_i}{dt} &= \frac{\alpha}{1+(B_i/K)} \cdot \left(\frac{b+A_i^2}{1+A_i^2}\right) - A_i \\
&+ \beta_R \frac{R_{ii+1}}{1+(A_{i+1}/K)^2} \\
\frac{dB_i}{dt} &= \gamma(A_i - B_i)\ , \qquad i = 1,2,3,4 \mod 4
\end{aligned}$$

Individual nodes in the oscillatory regime: α=80, β_R =0.01



3 patterns of phase-locked motion:

- 3 different phases out of four or
- 4 different phases or
- 2 different out of four coincide

multistable behavior for β_R =0.01, 0.1

Multistability in synthetic genetic circuits could be explained this way

HERE INSTEAD: CLASSICAL ROTATORS WITH FRUSTRATION

The model: N active rotators

$$\frac{d\varphi_i}{dt} = \omega_i - b\sin\varphi_i + \sigma_A \xi_i(t) + \frac{(\kappa + \sigma_M \eta_i(t))}{\mathcal{N}_i} \sum_j A_{ij} \sin(\varphi_j - \varphi_i).$$

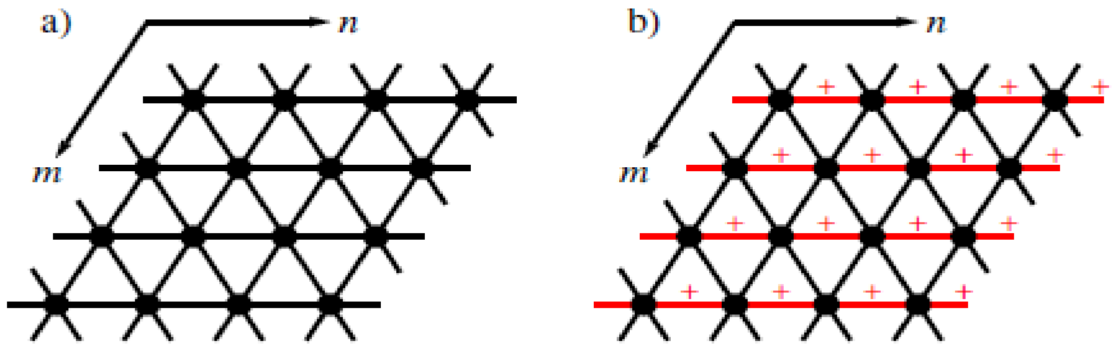


Fig. 1: Hexagonal lattice with all triangles frustrated for all couplings being negative (a) and not frustrated (b) for positive couplings along the horizontal links and negative ones otherwise.

1. **N identical oscillators without noise**

   The phase diagram as a function of ω, b, and κ

   The versatility of attractors in comparison to spin systems

   A particularly rich attractor space for the 4x4 system

2. **N identical oscillators with additive or multiplicative noise**

   Order-by-disorder repeatedly induced for increasing noise strength

   Noise-induced migration of oscillator phases

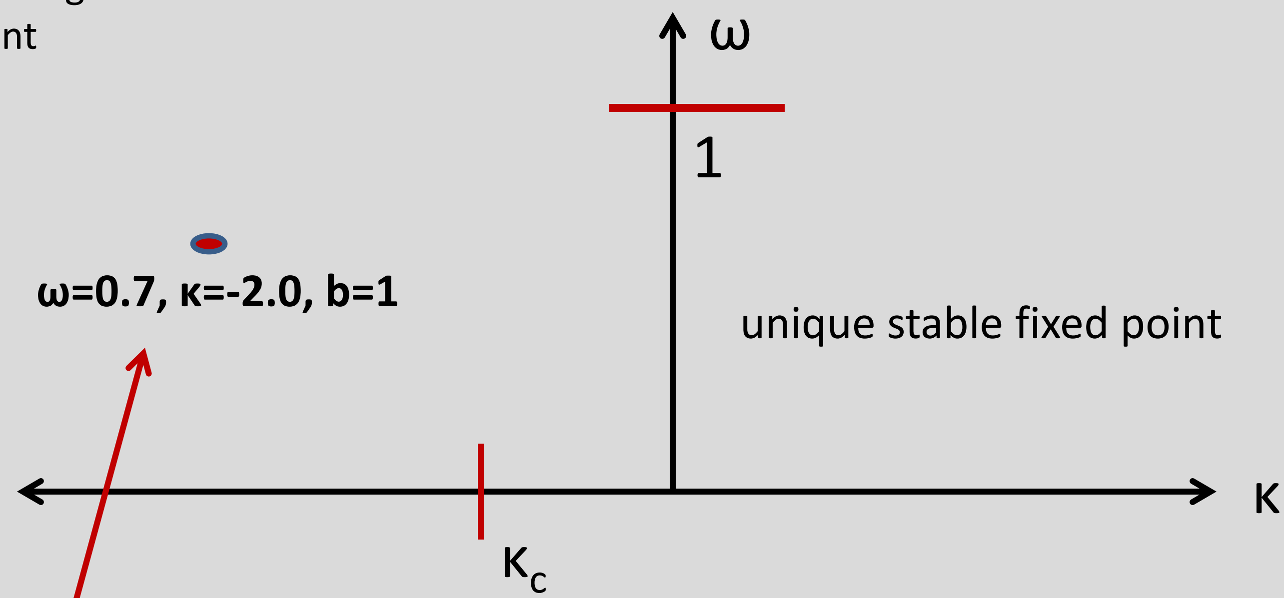
   Indications for a rough landscape with hierarchies in the potential barriers

   A multitude of escape times from metastable states

1. N IDENTICAL OSCILLATORS WITHOUT NOISE

The phase diagram as a function of ω and κ for b=1: so far along a few sections, but ongoing work by M. Zaks et al.

limit-cycle regime without a stable fixed point



coexisting states with different synchronization patterns

$$\kappa_c = -\sqrt{1-\omega^2}/(1-\lambda_{\min}/N)$$

minimal eigenvalue of the adjacency matrix, *N* = number of neighbors

Kuramoto case with b=0 separately presented

The versatility of attractors in comparison to spin systems

In spin glasses:

fixed points

In these systems:

various "collective" fixed points

a variety of "collective" limit cycles differing by their

correlation between individual phases
frequency
pattern of phase-locked motion
basin of attraction
stability
symmetry

quasiperiodic solutions

chaotic solutions

as a combined effect of frustration, lattice size and lattice symmetry.

WHAT CAN WE PROVE ABOUT MULTISTABILITY?

Special case: N Kuramoto oscillators. The system can be reduced to

$$\dot{\varphi}_i = -\sum_j A_{ij} \sin(\varphi_j - \varphi_i).$$

Consider as a special set of solutions plane waves with fronts of constant phases along parallel lines on the hexagonal lattice. Their spatial distribution is characterized by

$$\varphi_{m,n} = \frac{2\pi}{M} k_1 m + \frac{2\pi}{L} k_2 n$$

m=1,…,M, n=1…, L coordinates and k1, k2 integers because of p.b.c. Then it can be shown that for a sufficient large extension M and L and M=L=even, there are always two sets of wave vectors k1=k2= k and k1=k2=k+1, such that the plane waves correspond to different solutions, differing by the number f clusters of coinciding phases.

SIMILARLY FOR ACTIVE ROTATORS, IN PARTICULAR PLANE WAVES AND SPHERICAL WAVES:

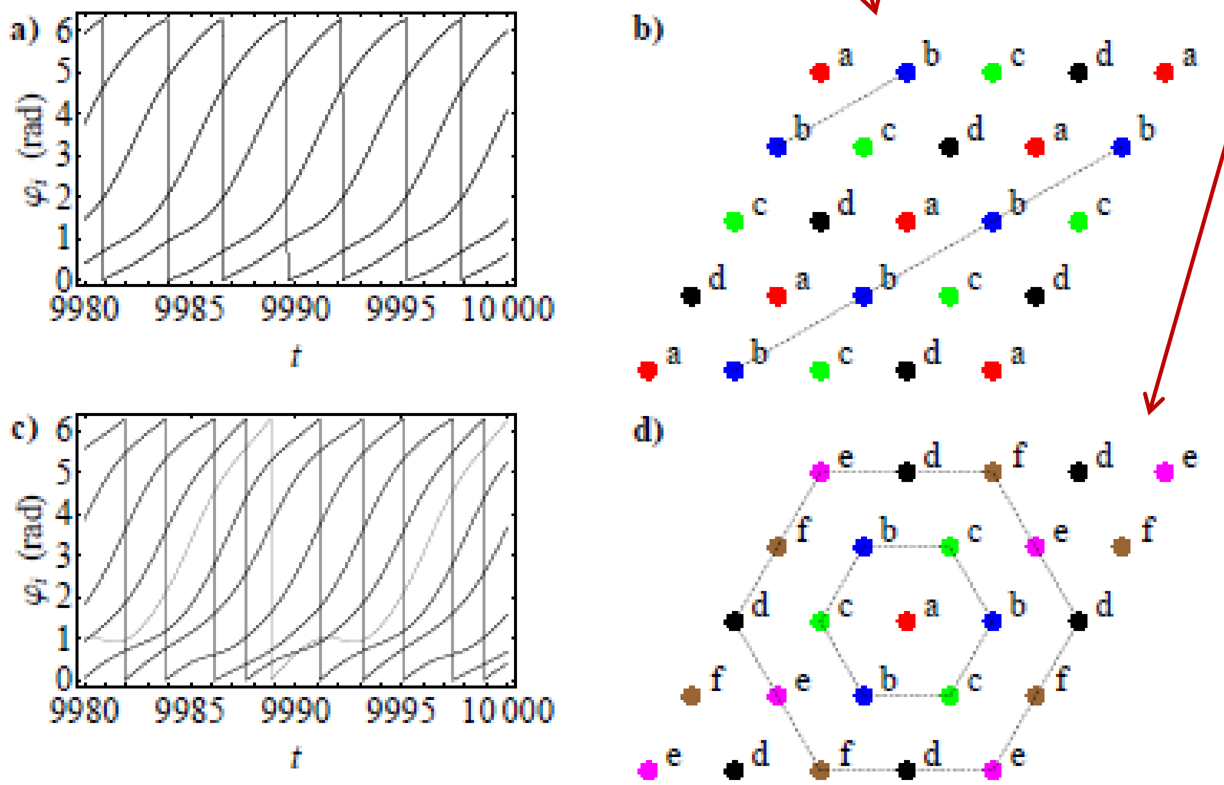


Fig. 2: Solutions of eq. (1) with 4 and 6 clusters on a 4×4 lattice for $\omega = 0.7$, $b = 1$, $\kappa = -2$ and $\sigma_M = \sigma_A = 0$.

The number and variety of attractors is extremely rich already for a 4x4-lattice.

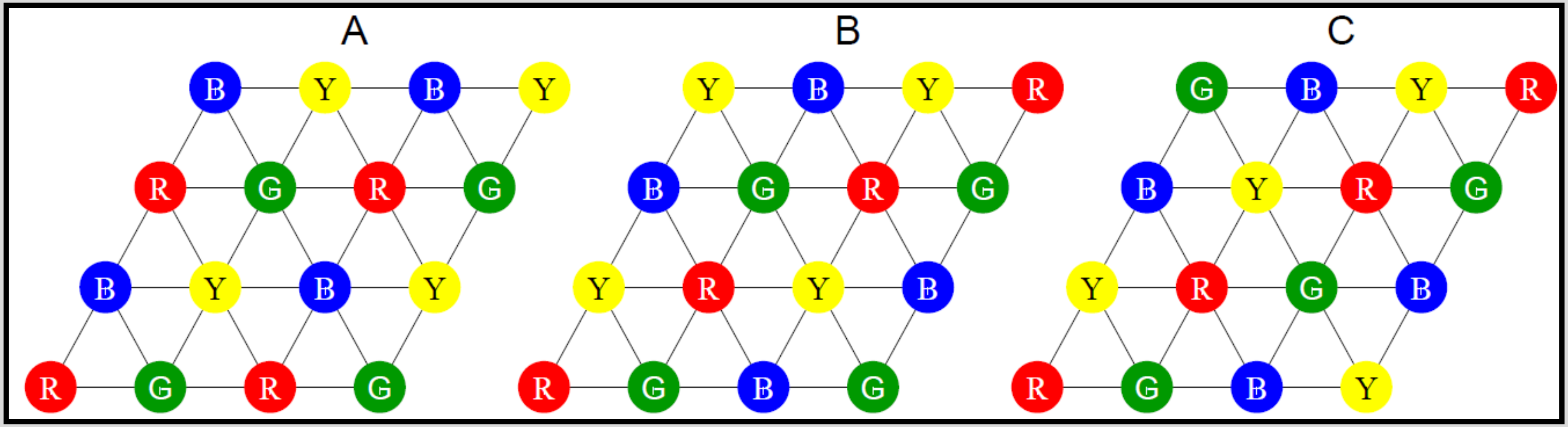
The classification according to p_n-patterns with n denoting the number of clusters of coalescing phases is **not unique**, but suited for our notion of order.

- **p4-solutions:** 4 clusters, originally only 75 such solutions could be identified, differing by their frequency, in particular plane waves (without counting the degeneracy due to the lattice symmetries), meanwhile a continuum of these solutions
- **p6-solutions**: spherical waves (degeneracy 96 due to 16 sites for the center and 6 rotations about 60 degrees due to the lattice symmetry)
- **p16-solutions** of individual limit cycles
- **quasiperiodic solutions**

using the numerically obtained Poincaré-mapping on the hypersurface Φ_1 = const.

Of particular interest: p4-patterns of 4 clusters with 4 identical phases each (ongoing work by M. Zaks et al.)

Same color – same phase
Note: each oscillator is coupled by two links to representatives of all other three clusters.
If we do not distinguish the individual members of a cluster, we see a global coupling between the clusters of identical members with double the strength than on the original fine-grained lattice



The set of 16 equations reduces into 4 sets (one for each color) of 4 identical equations . The representative set of four equations describes a set of globally coupled set of identically equipped oscillators and with sinusoidal coupling. According to **Watanabe and Strogatz** we should expect an infinite number of conserved quantities and a continuum of frequencies for our limit-cycle solutions $\Longrightarrow$ dynamically generated reduction of d.o.f.

2. N IDENTICAL OSCILLATORS WITH ADDITIVE OR MULTIPLICATIVE NOISE

$$\frac{d\varphi_i}{dt} = \omega_i - b\sin\varphi_i + \sigma_A \xi_i(t) + \frac{(\kappa + \sigma_M \eta_i(t))}{N_i} \sum_j A_{ij} \sin(\varphi_j - \varphi_i).$$

ORDER-BY-DISORDER, IN WHAT SENSE?

Usually: Order-by-disorder is considered in spin systems.

Generic: The ground state is degenerate due to competitions among the interactions.
The degeneracy is lifted due to disorder.

The lifting can be
- temperature driven (Villain et al. J. Phys. 1980, Bergman et al., Nature Physics 2007)
- or quantum driven (Chubukov, PRL (1992), Reimers et al. PRB (1993))
- or due to dilution (Henley PRL 1989)

The effect is observed in classical spin models, quantum magnetism, and in ultracold atoms (Turner et al., PRL98, 2007).

It depends on the degree of degeneracy whether the effect is observed.

Order-by-disorder in classical oscillatory systems:

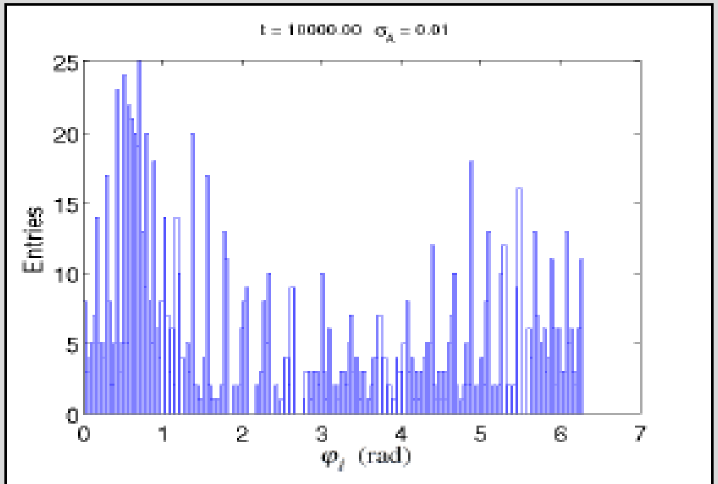
Disorder: additive noise or multiplicative noise

Order: the "degree" of synchronization:
either a disordered stationary solution with all units oscillating with their own phase changes towards a solution with partially coinciding phases,
or, the number of phase-synchronized clusters decreases , so that more phases coincide **for an intermediate noise strength**

In need for a suitable order parameter that can distinguish between "order" in the sense of how many phases coincide.
Generalized Kuramoto order parameters are not suited

$$\rho_n = 1/N \sum_{j=1}^{N} \exp in\varphi_j$$

Use the peak structure of histograms instead for larger sizes.



σ_A	panel	ρ_1	ρ_2	ρ_4	ρ_6
0.00	a	0.001	0.102	0.060	0.149
0.01	b	0.002	0.279	0.300	0.339
0.02	c	0.003	0.868	0.514	0.104
0.03	d	0.005	0.489	0.803	0.414
0.04	e	0.006	0.420	0.503	0.366
0.05	f	0.007	0.372	0.334	0.393
0.06	g	0.009	0.838	0.461	0.235
0.07	h	0.009	0.280	0.302	0.258
0.08	i	0.011	0.767	0.303	0.227
0.09	j	0.012	0.644	0.308	0.417
0.10	k	0.013	0.787	0.346	0.224
1.00	l	0.122	0.256	0.223	0.222

The table illustrates that ρ_n does not work in all cases as compared to the number of coalescing phases on the phase plots.

WE SEE REPEATEDLY ORDER-BY-DISORDER IN THE FOLLOWING SENSE:

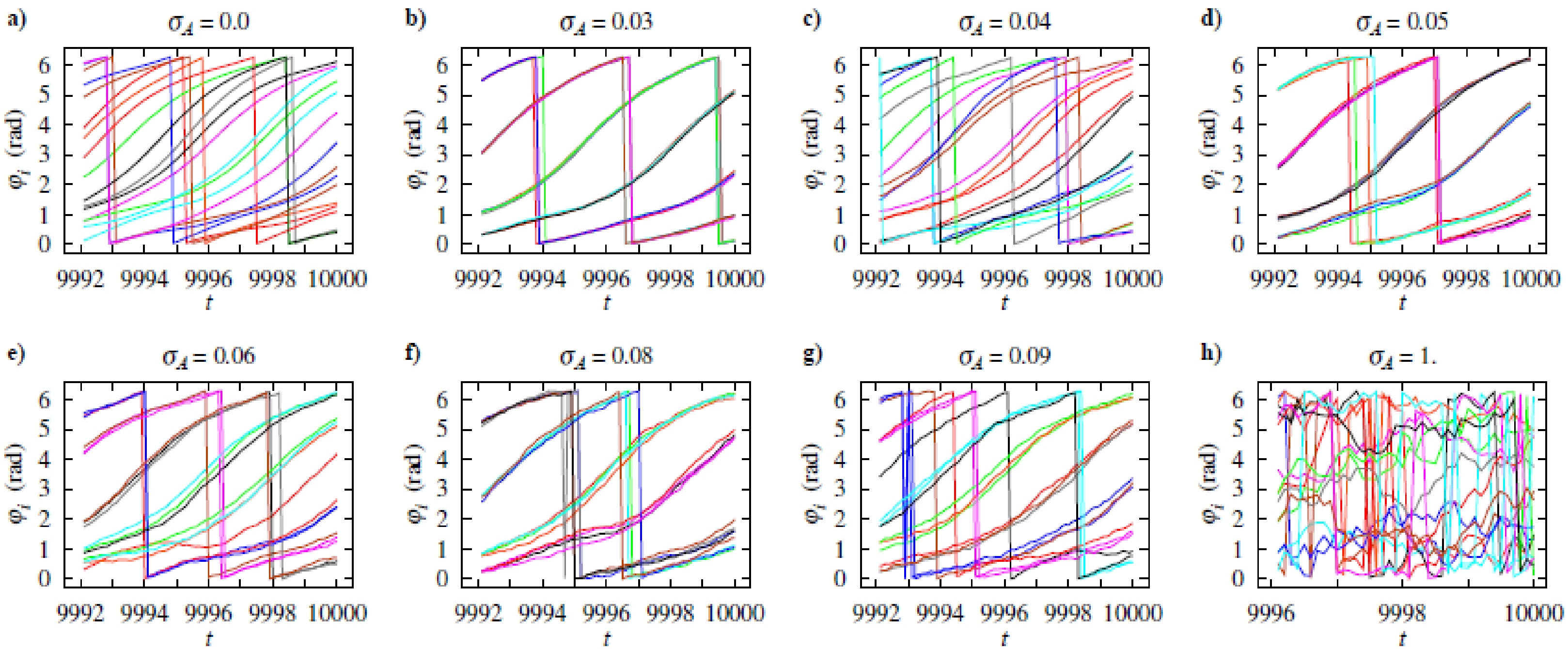


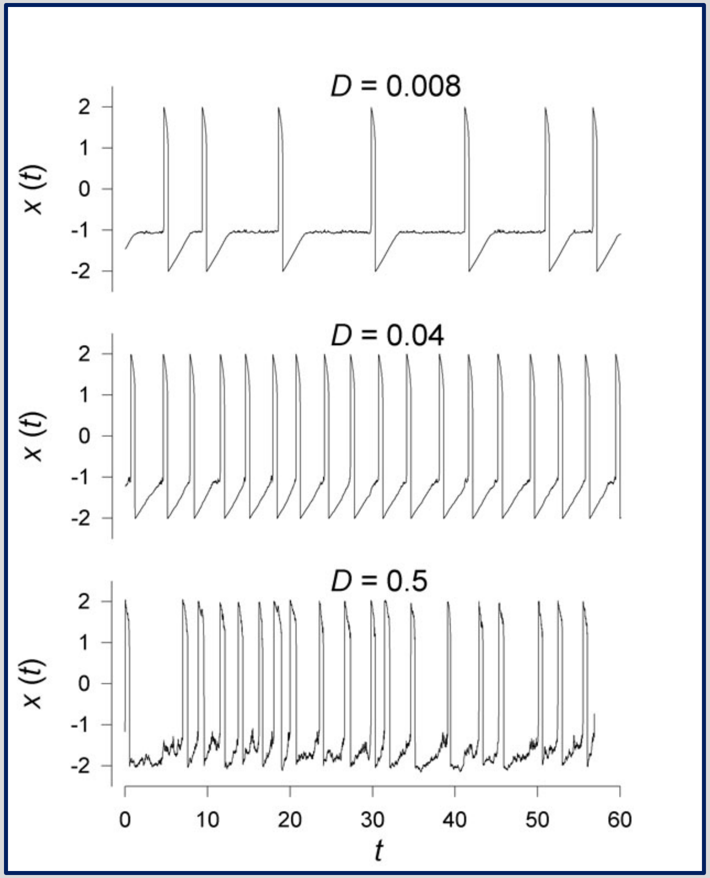
Fig. 3: Order by disorder on a 4×4 lattice, for $\omega = 0.7$ $b = 1$, $\kappa = -2$, σ_M=0 and monotonically increasing noise intensity σ_A between panels (a) to (l). For further explanations see the text.

Here: Fixed identical initial conditions, but increasing the noise intensity.
The snapshots are representative for a certain time interval of some hundred or thousand time units, afterwards the patterns of synchronization may have changed.

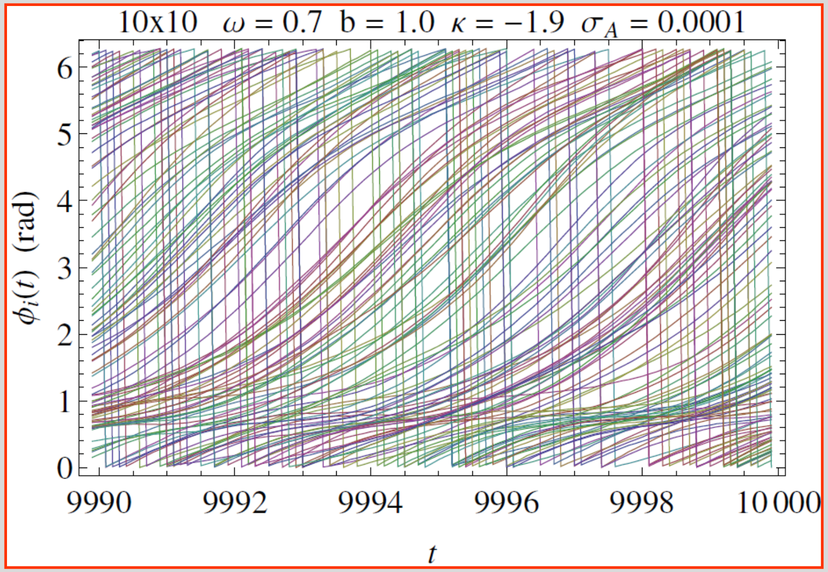
Note: Different from the action of noise in coherence resonance:

Coherence resonance:
For an intermediate strength of noise, oscillatory response in an excitable system is most coherent (here no external field)

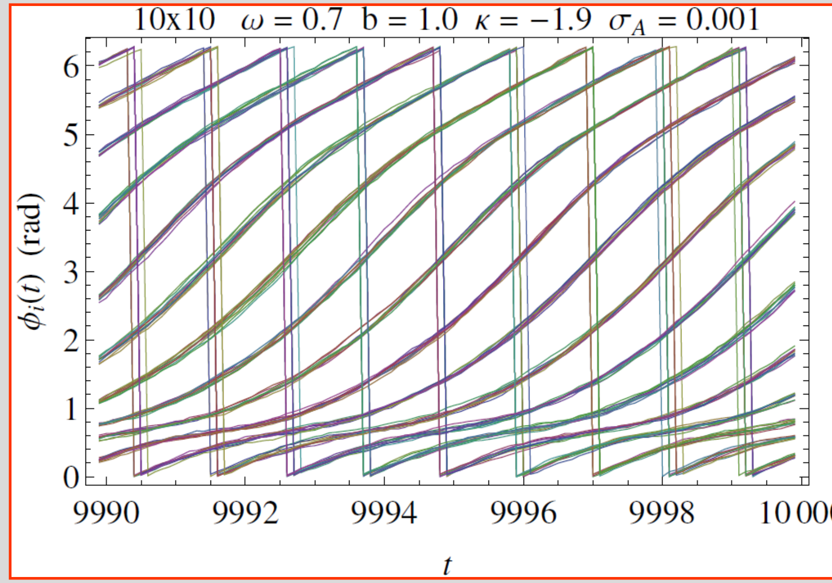
System size resonance
For an optimal size of the system, the system's response is most regular, illustrated in a system of coupled nonlinear noisy oscillators
(ensemble averages fluctuate with $(D/N)^{1/2}$)



D the (effective) noise intensity



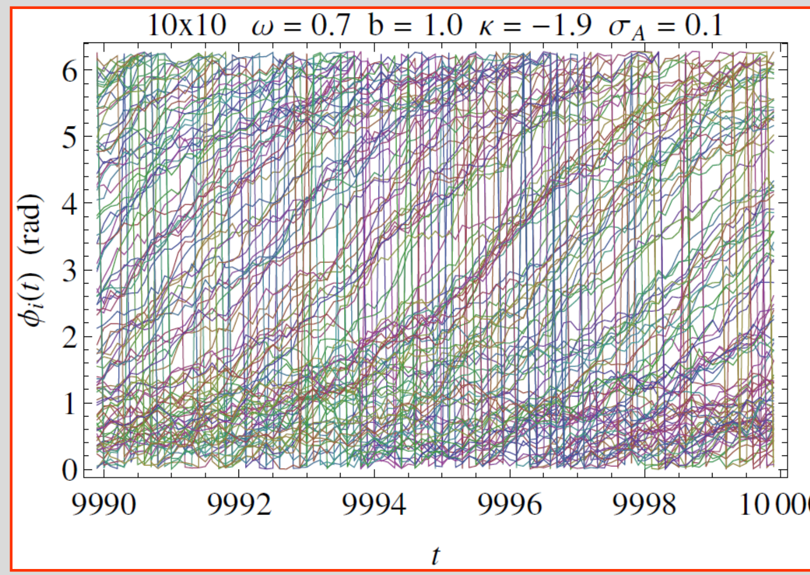
Low noise



Intermediate noise

zoom

lattice of 10x10 active rotators
clusters 100—10--100



Varying the noise intensity between 0.0001-0.1

Strong noise

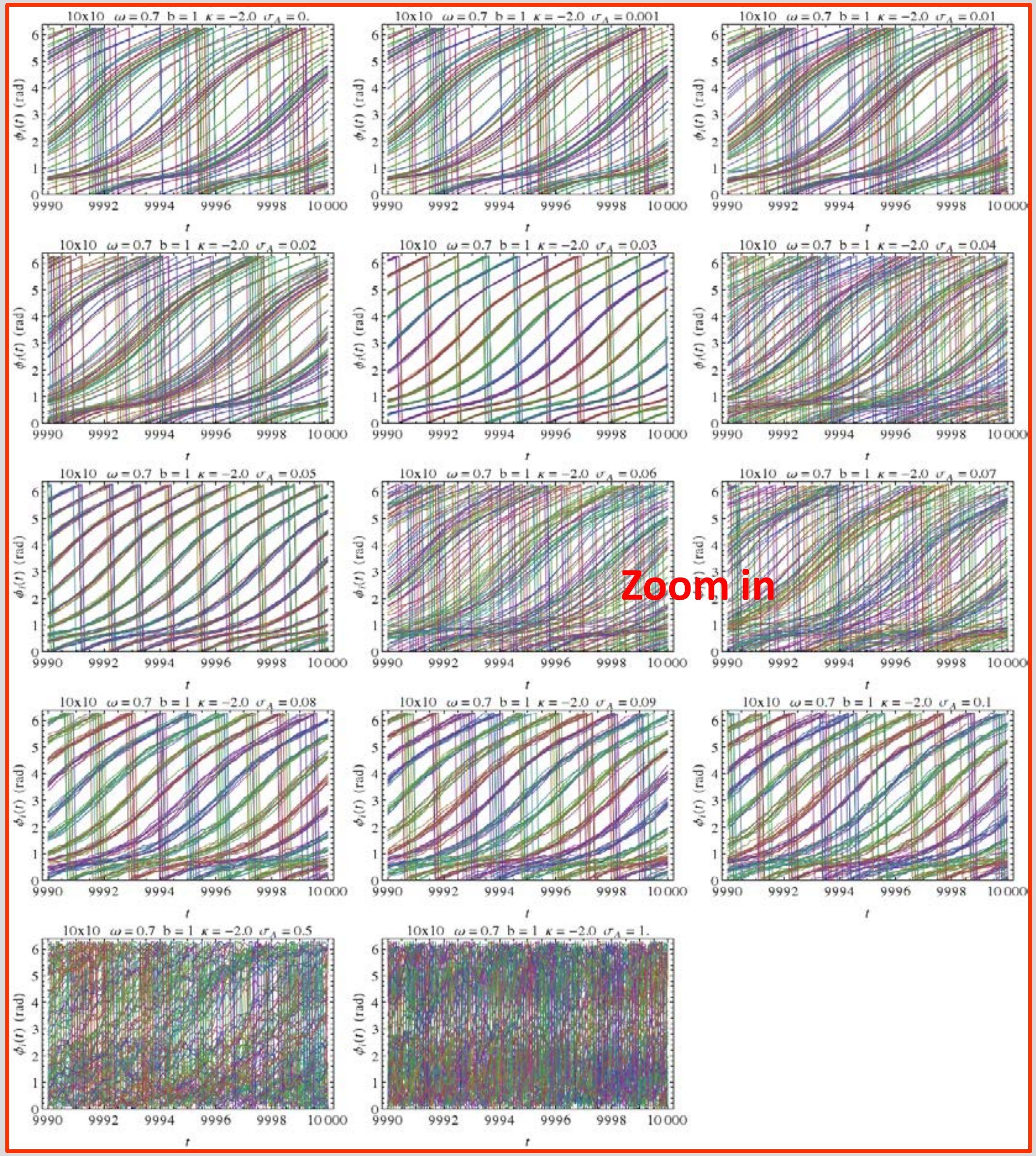
Zoom into the noise intensity:

Increasing monotonically the noise intensity from left to right and top to bottom one observes disorder (d) and order (o) as the sequence:

d o d o d o d

The system is very sensitive to the initial condition.

Varying the noise intensity between 0.001-0.1 in steps of 0.01

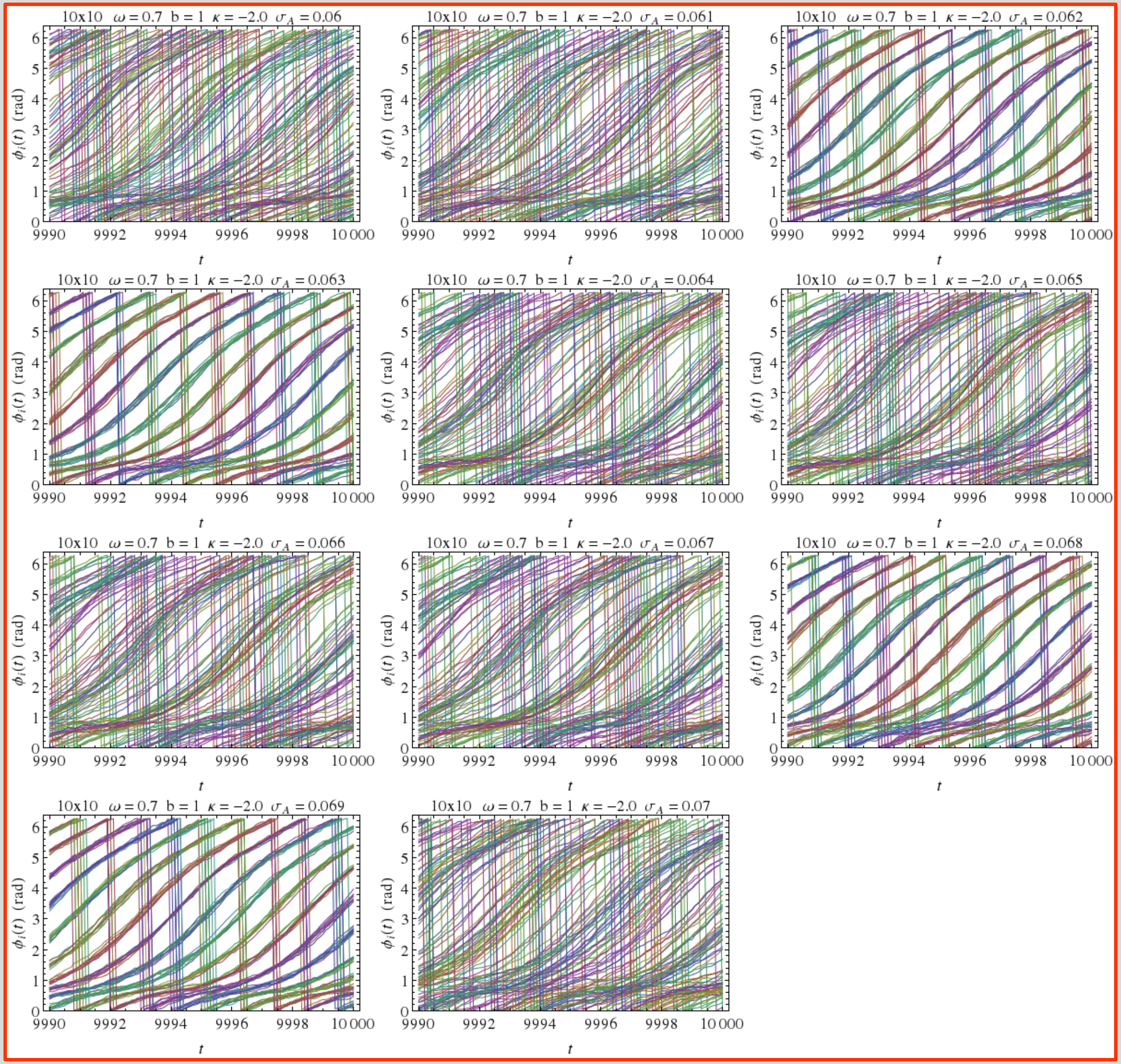


lattice of 10x10 active rotators
clusters 100—10—100—10—100—10---100

Zoom further into the noise intensity:

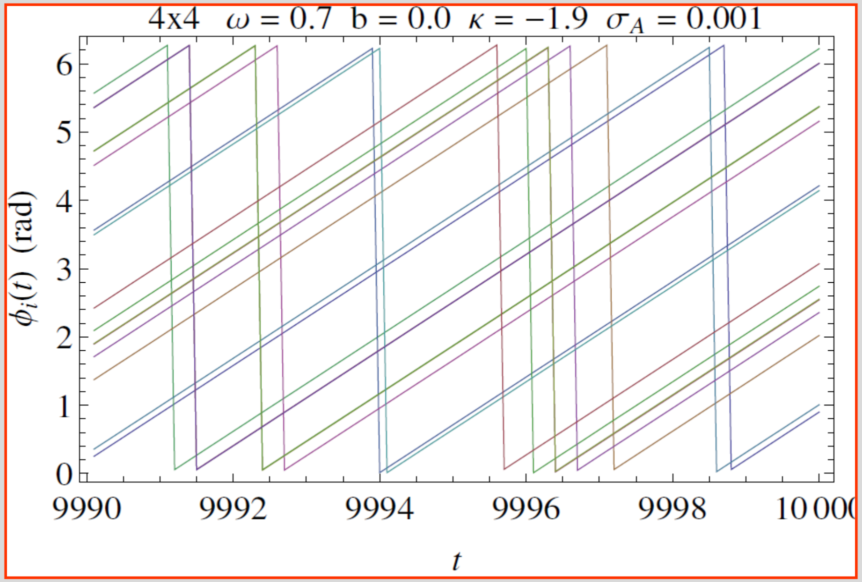
Increasing monotonically the noise intensity from left to right and top to bottom, one observes disorder (d) and order (o) as the sequence:

d o d o d

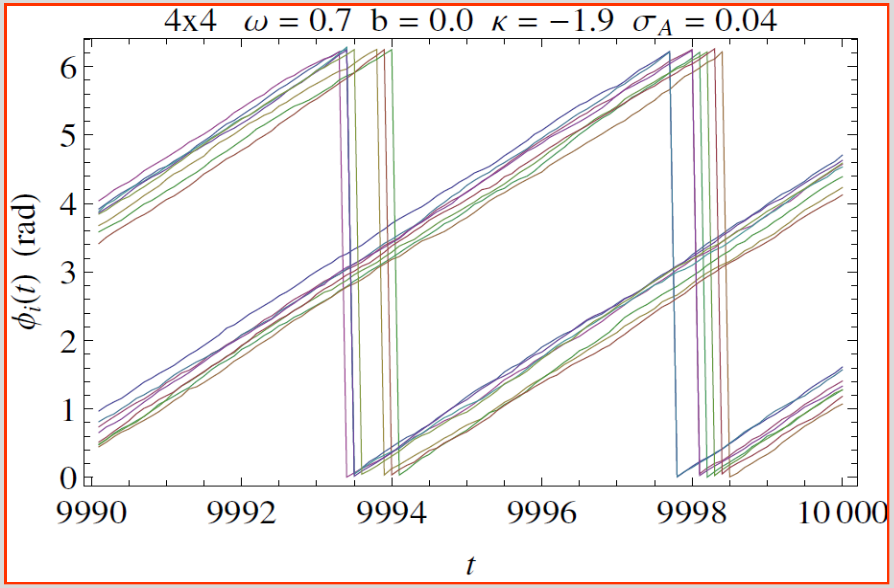


lattice of 10x10 active rotators clusters 100—10—100—10—100

Varying the noise intensity between 0.06-0.07 in steps of 0.001

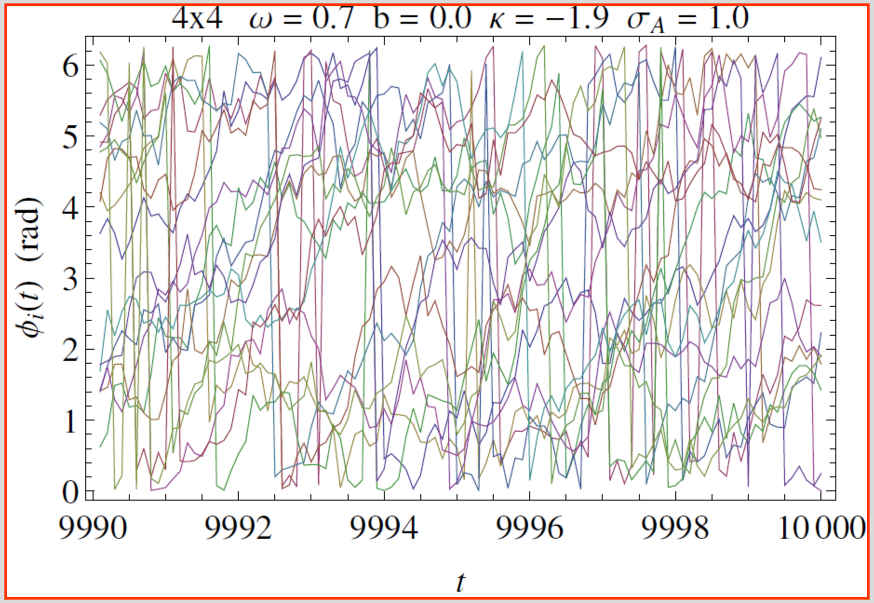


Low noise



Intermediate noise

Lattice of 4x4 Kuramoto oscillators clusters 16—2—16



Strong noise

How representative are these plots? Similar plots are obtained

- **if the noise realization is varied**
- **the additive noise is replaced by multiplicative one**
- **the oscillators are reduced to Kuramoto oscillators**
- **the lattice size is increased**
- **the time windows for snapshots over 200 time units are varied.**

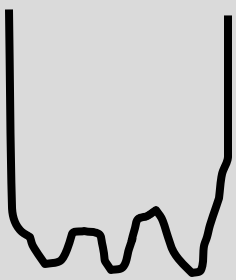
What is the explanation for the repeatedly increasing order when the noise strength is monotonically varied?

The system obeys a gradient dynamics with potential V. The resolution of its shape depends on the noise intensity.

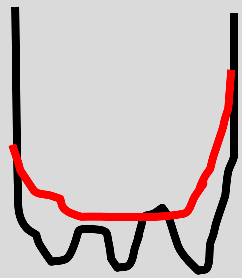
INTUITIVE EXPLANATION

$$V = -\omega \sum_i \varphi_i - b \sum_i \cos \varphi_i - \frac{\kappa}{2N} \sum_{i,j} A_{ij} \cos(\varphi_j - \varphi_i).$$

Consider the oscillatory part:

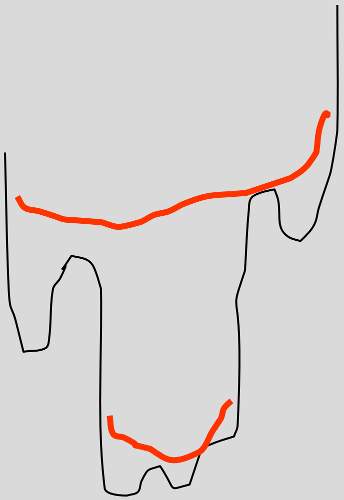


no noise



noise of intermediate strength

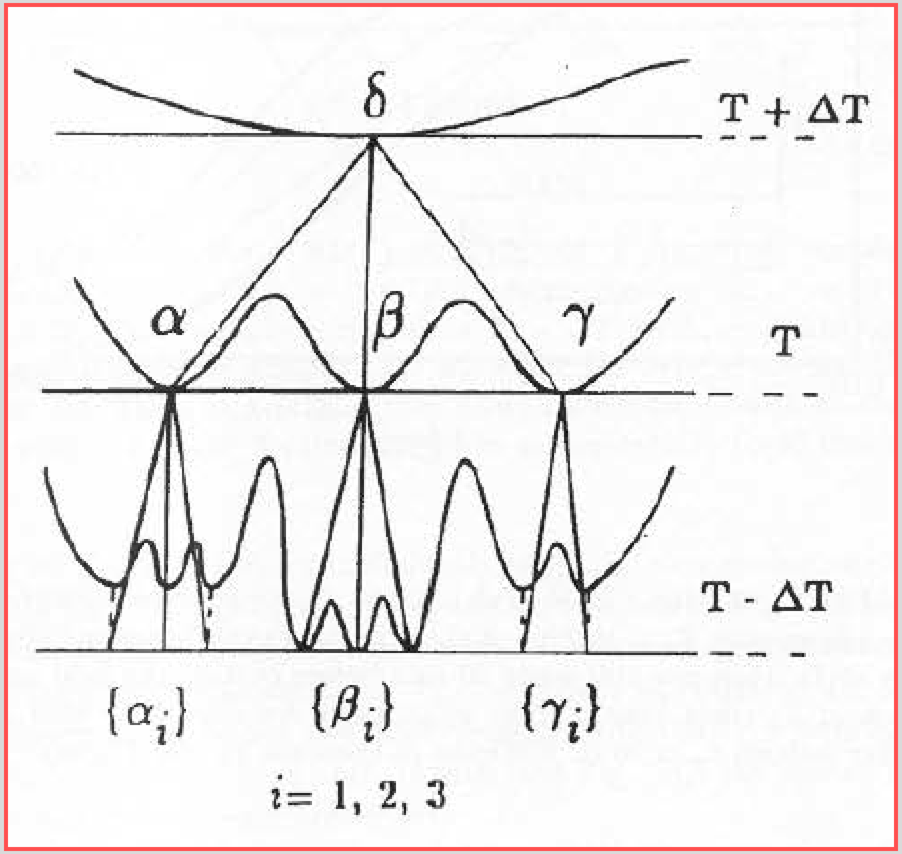
strong noise



barriers of different height in the energy landscape

Due to noise, the "fine-structure" of the "potential" can no longer be resolved, but still the overall structure, while for even stronger noise the shape of the deterministic potential gets buried under the noise. From zooming into the noise intervals: The energy landscape seems to have a similar structure on different scales of resolution.

Explanation of slow dynamics and aging in spin glasses



Hierarchical structure of the metastable states as a function of temperature

From E. Vincent et al. arXiv: cond-mat/9607224

ANALOGY TO STOCHASTIC RESONANCE

Gaussian white noise

$$\boxed{\frac{dx}{dt} = -\frac{dU}{dx} + A\sin\omega t + \xi(t),}$$

Subthreshold periodic perturbation, does not allow the particle to leave any of the four local minima without noise but with noise it triggers the switching between the different minima.

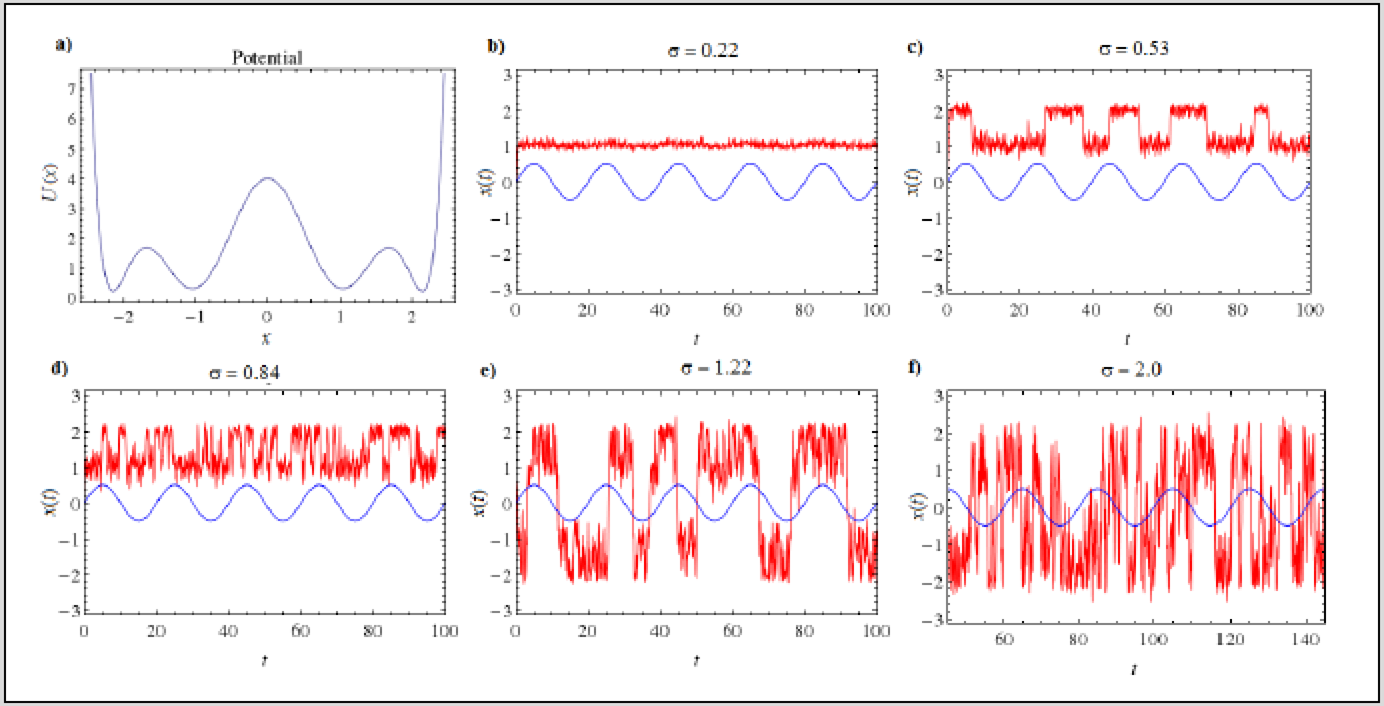
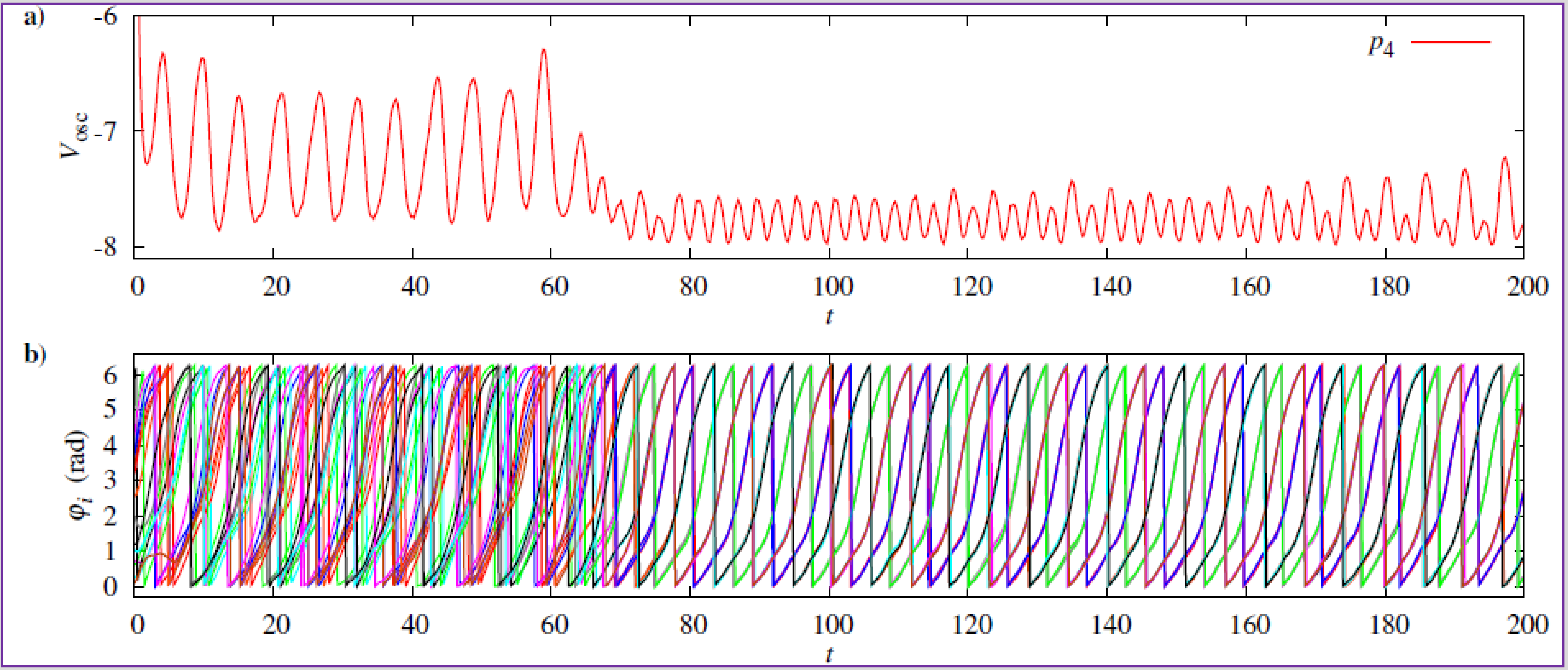


Fig. 9: Stochastic resonance for a potential (a) with two barrier heights: Panels (b) - (f) show the value of the force (in blue) and the response of the system (in red) as functions of time, for different noise intensities $\sigma = 0.22, 0.53, 0.84, 1.22$, and 2.0. For further explanations see the text.

NOISE-DRIVEN MIGRATION OF OSCILLATOR PHASES

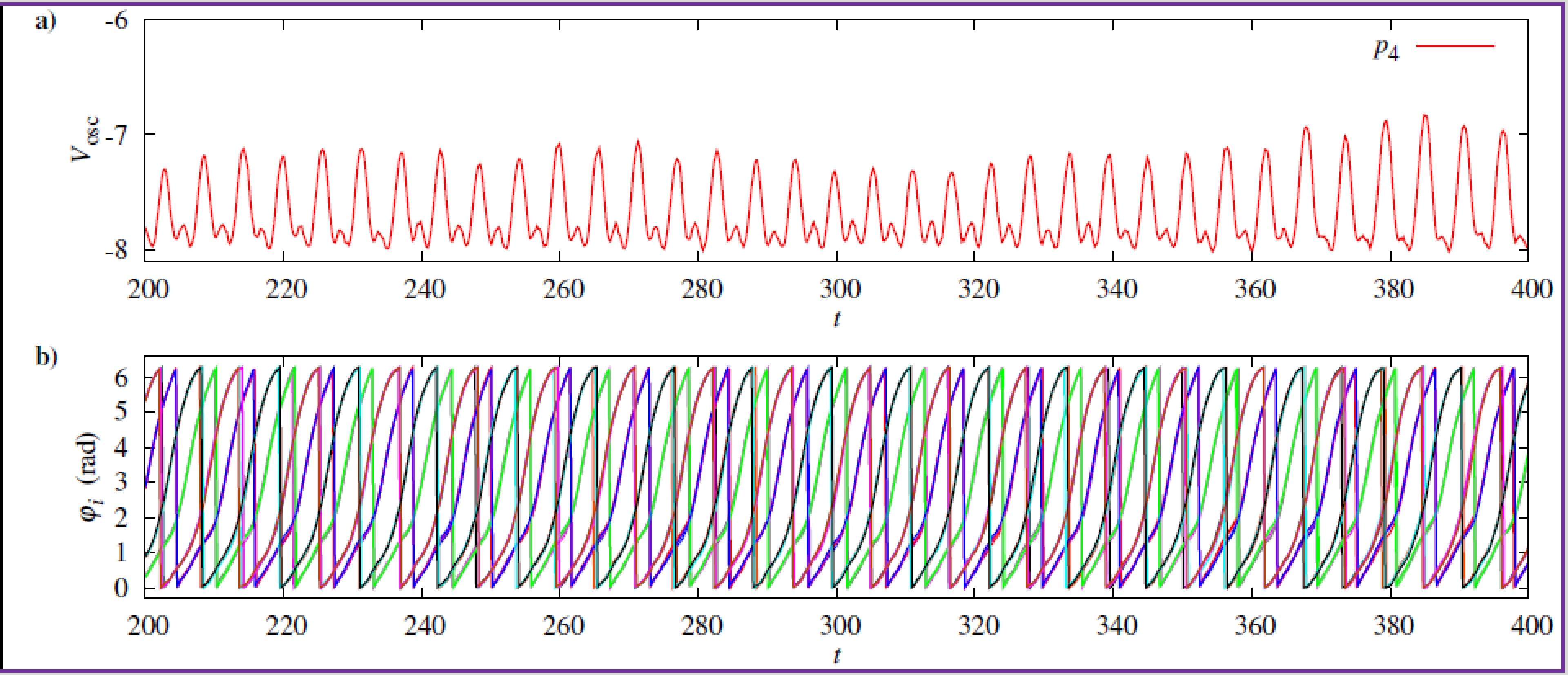
On a longer time scale we see the following "stationary" state keeping the noise intensity fixed:

V_{osc}

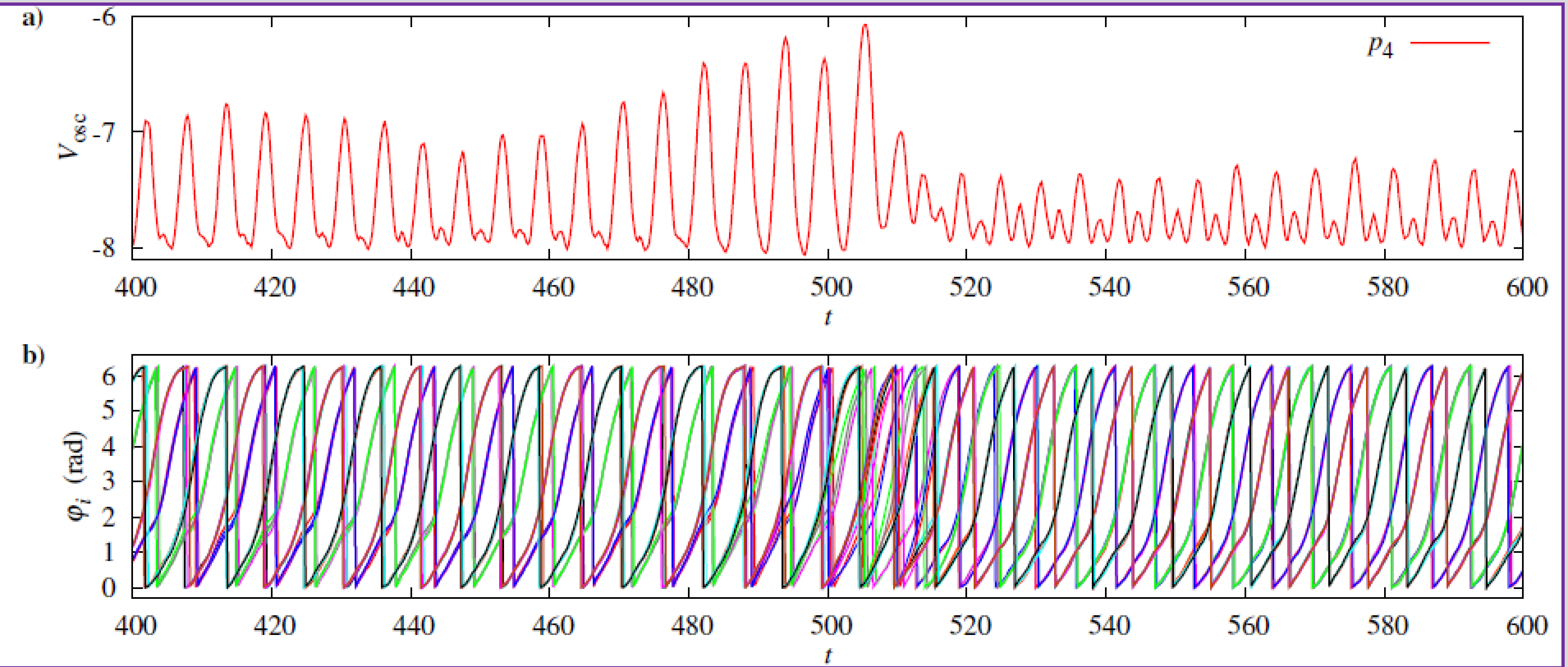


$\Phi_i(t)$

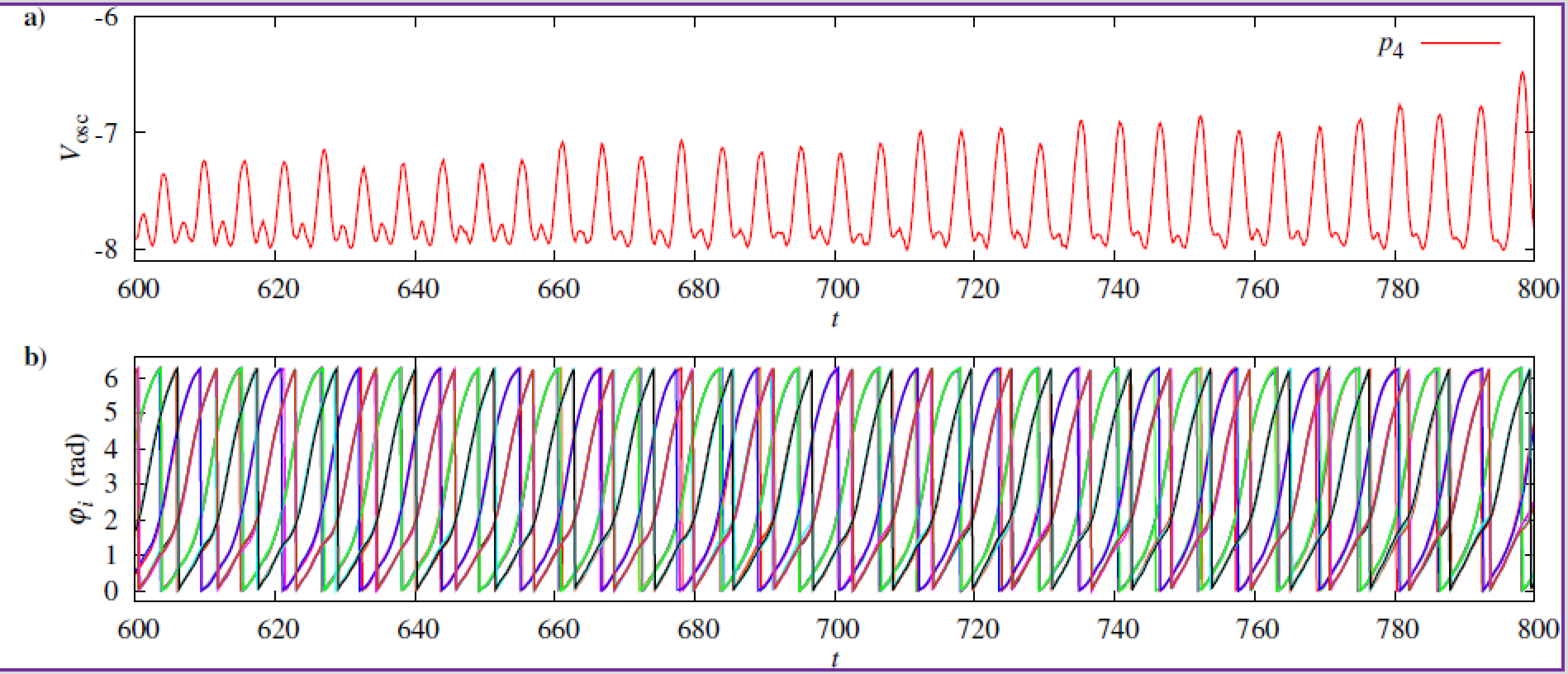
0-200 time units


a)
-6
-7
-8
V_{osc}
p_4
200
220
240
260
280
300
320
340
360
380
400
t
b)
6
5
4
3
2
1
0
φ_i (rad)
200
220
240
260
280
300
320
340
360
380
400
t

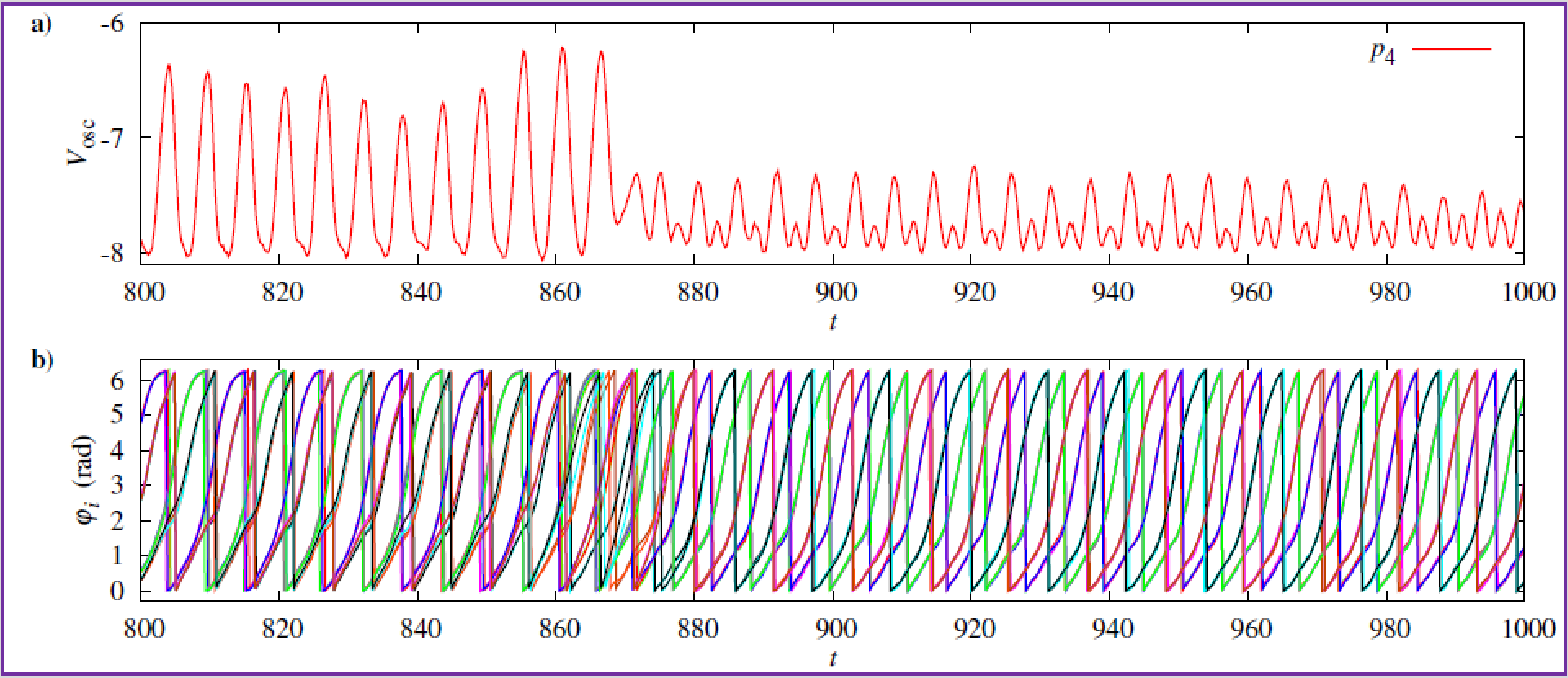
200-400


a)
-6
-7
-8
V_{osc}
p_4
400
420
440
460
480
500
520
540
560
580
600
t
b)
6
5
4
3
2
1
0
φ_i (rad)
400
420
440
460
480
500
520
540
560
580
600
t

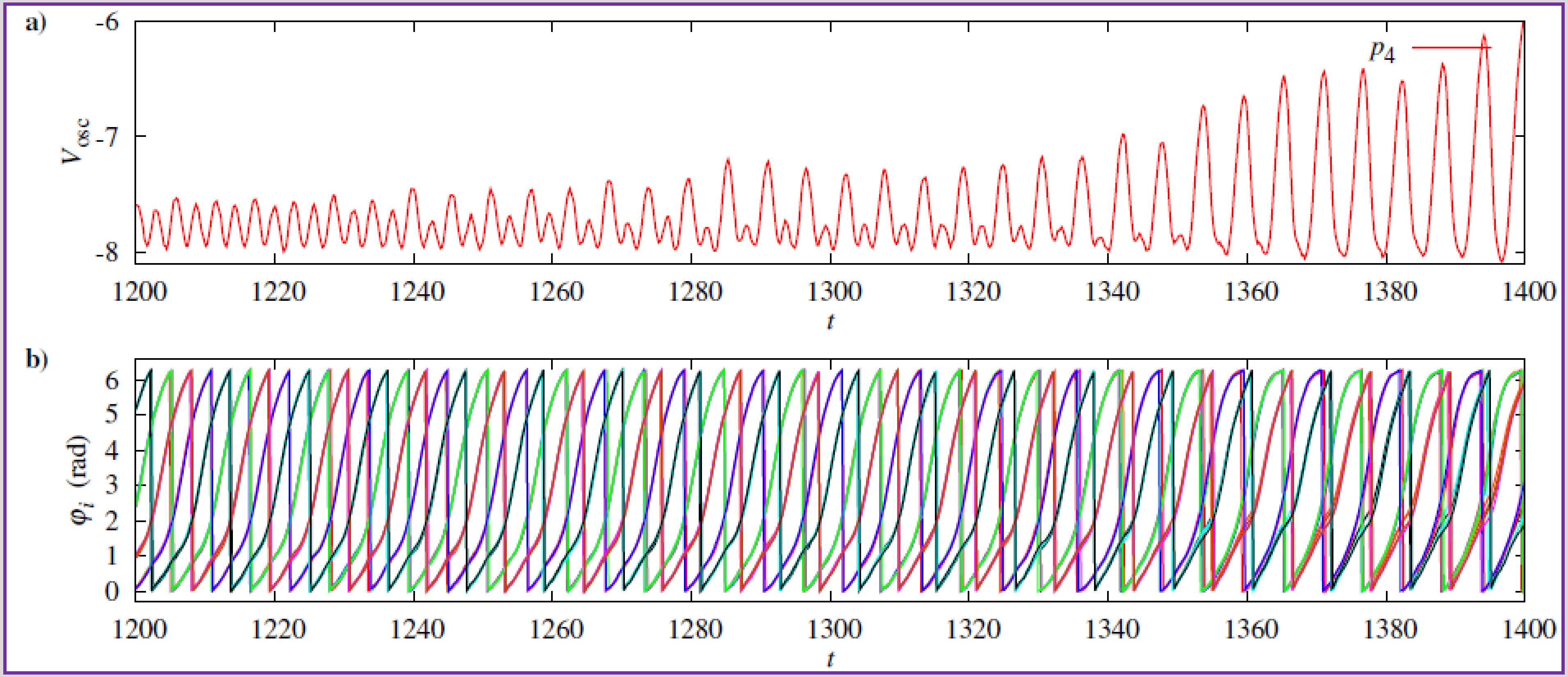
400-600



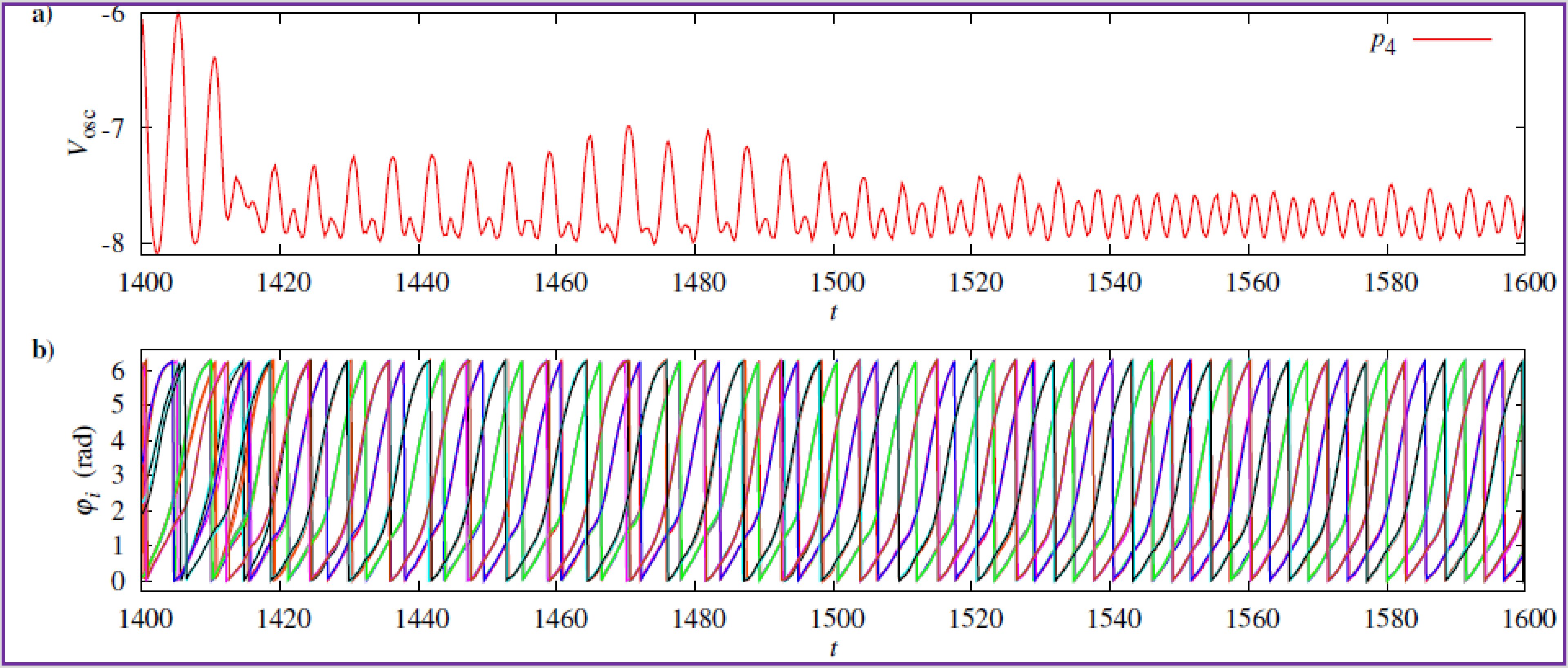
600-800



800-1000

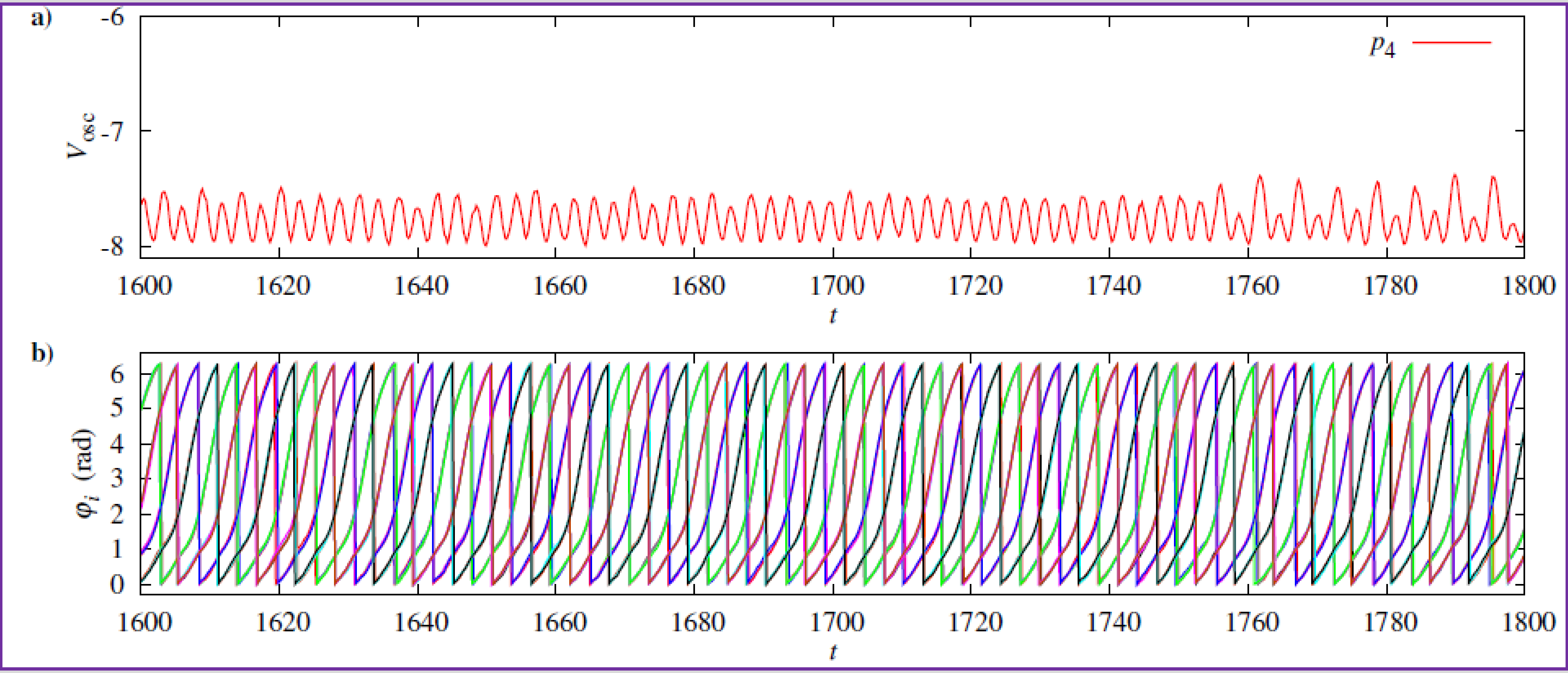

a)
-6
-7
-8
V_{osc}
p_4
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
t
b)
6
5
4
3
2
1
0
φ_i (rad)
1200
1220
1240
1260
1280
1300
1320
1340
1360
1380
1400
t

1200-1400

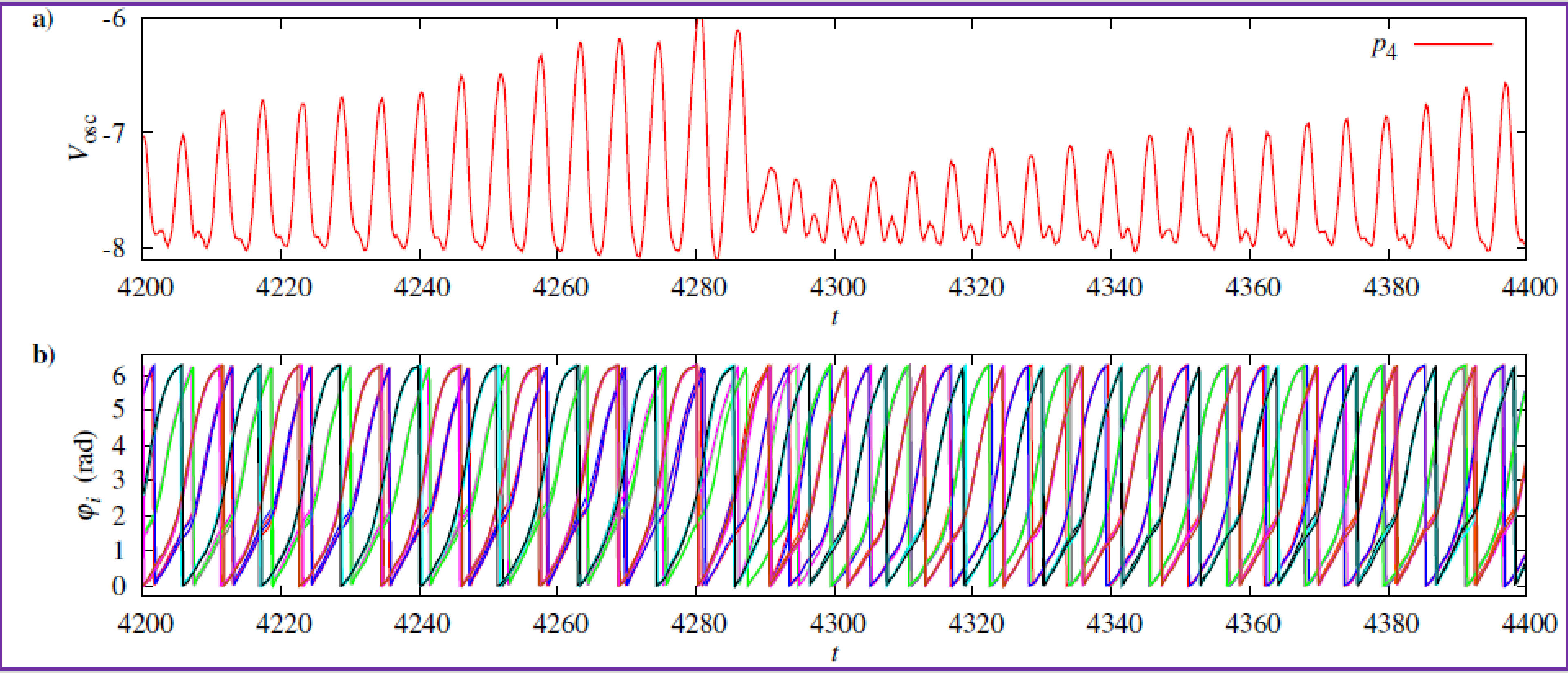


a)
-6
-7
-8
V_{osc}
p_4
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
t
b)
0
1
2
3
4
5
6
φ_i (rad)
1400
1420
1440
1460
1480
1500
1520
1540
1560
1580
1600
t

1400-1600

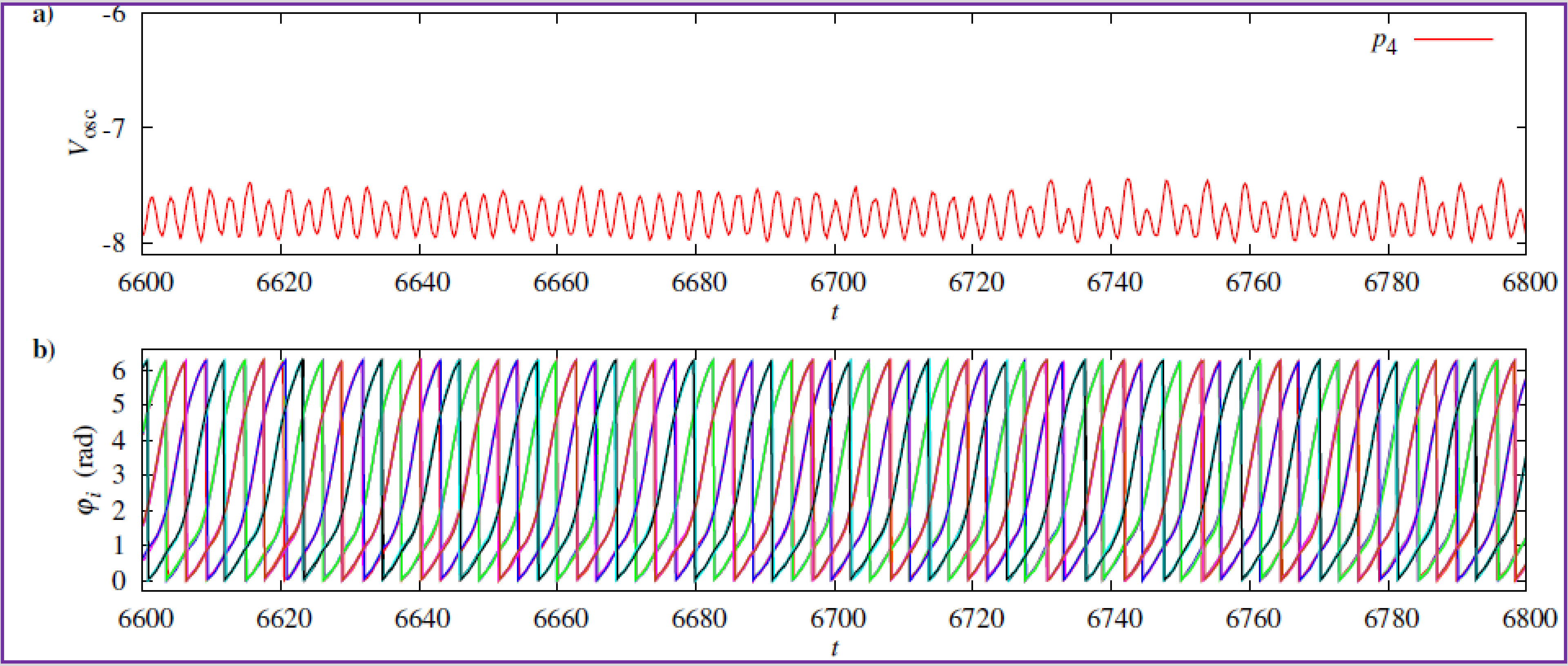

a)
b)
p_4
V_{osc}
φ_i (rad)
-6
-7
-8
0
1
2
3
4
5
6
1600
1620
1640
1660
1680
1700
1720
1740
1760
1780
1800
t

1600-1800

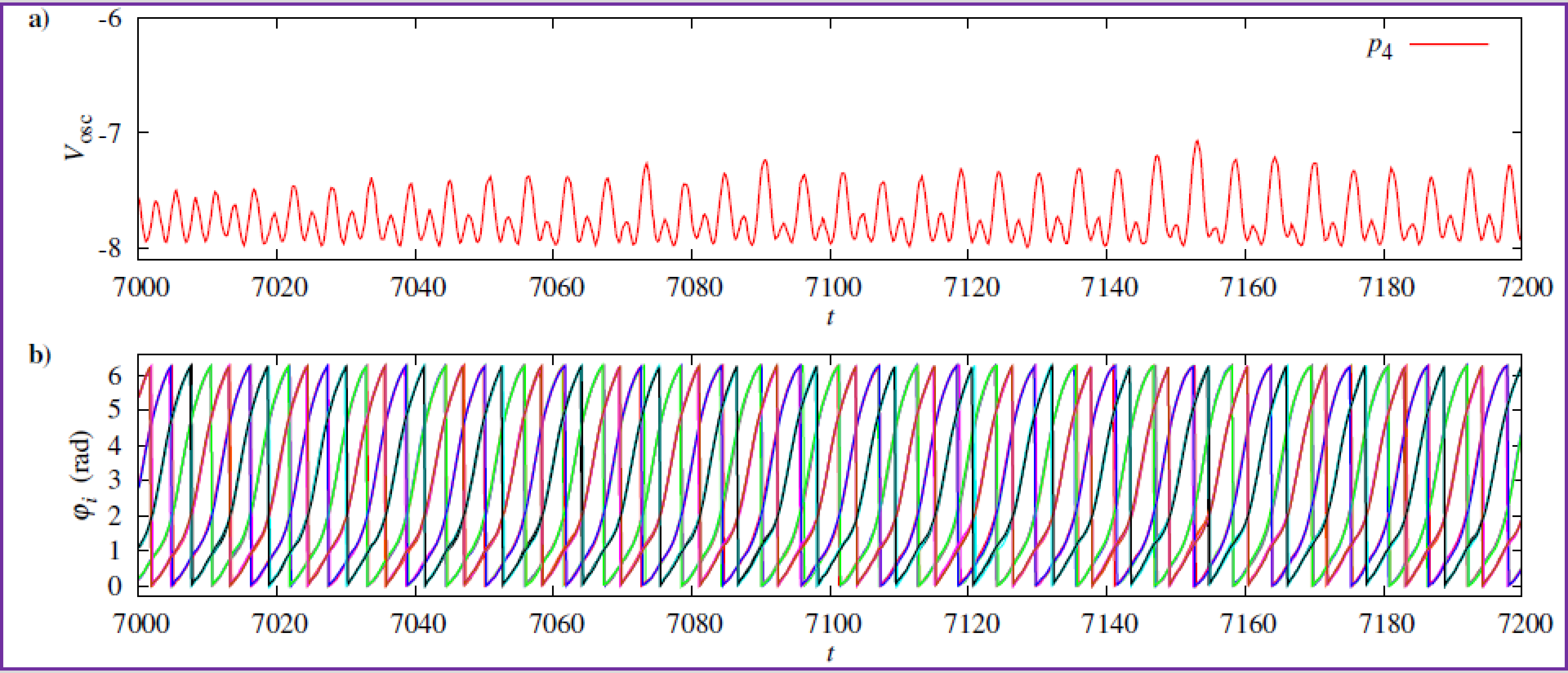


a)
p_4
V_{osc}
-6
-7
-8
4200
4220
4240
4260
4280
4300
4320
4340
4360
4380
4400
t
b)
φ_i (rad)
6
5
4
3
2
1
0
4200
4220
4240
4260
4280
4300
4320
4340
4360
4380
4400
t

4200-4400


a)
b)
V_{osc}
p_4
φ_i (rad)
t
-6
-7
-8
0
1
2
3
4
5
6
6600
6620
6640
6660
6680
6700
6720
6740
6760
6780
6800

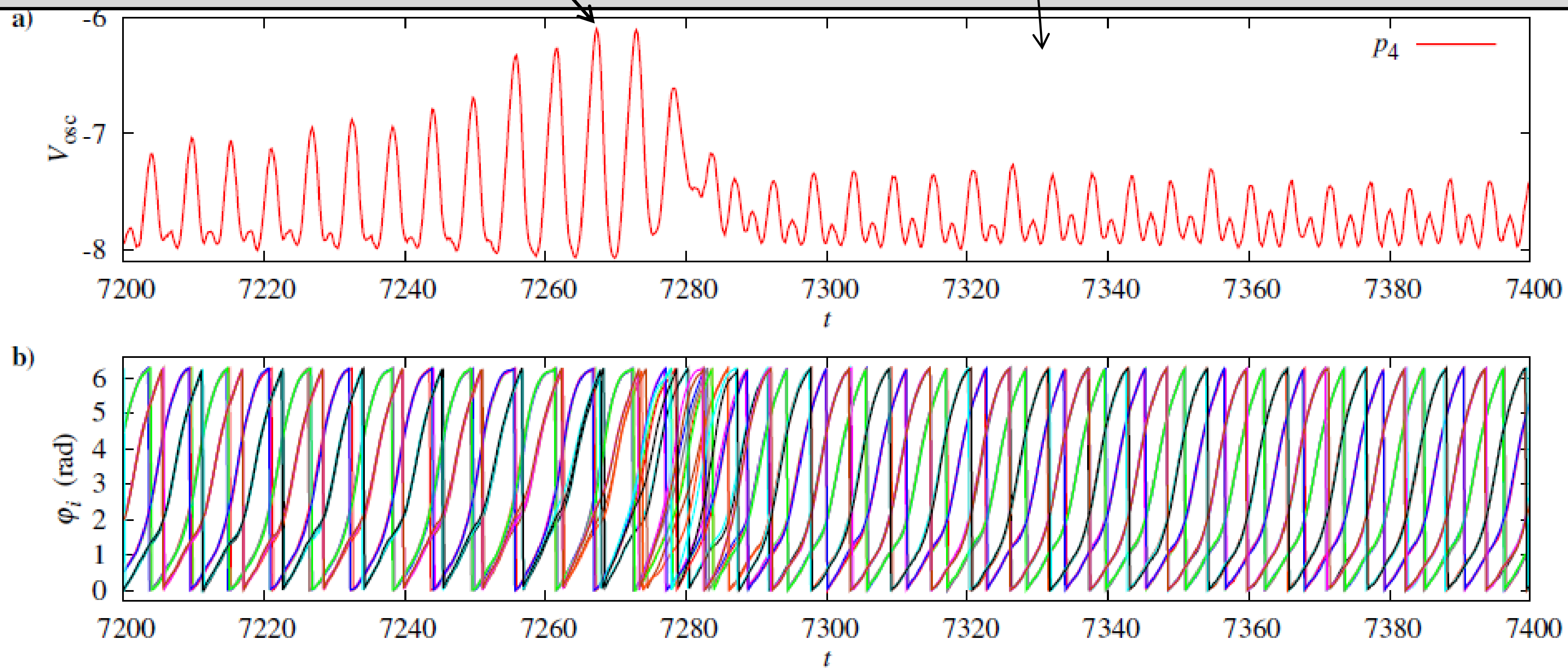
6600-6800


a)
-6
-7
-8
V_{osc}
p_4
7000
7020
7040
7060
7080
7100
7120
7140
7160
7180
7200
t
b)
6
5
4
3
2
1
0
φ_i (rad)
7000
7020
7040
7060
7080
7100
7120
7140
7160
7180
7200
t

7000-7200

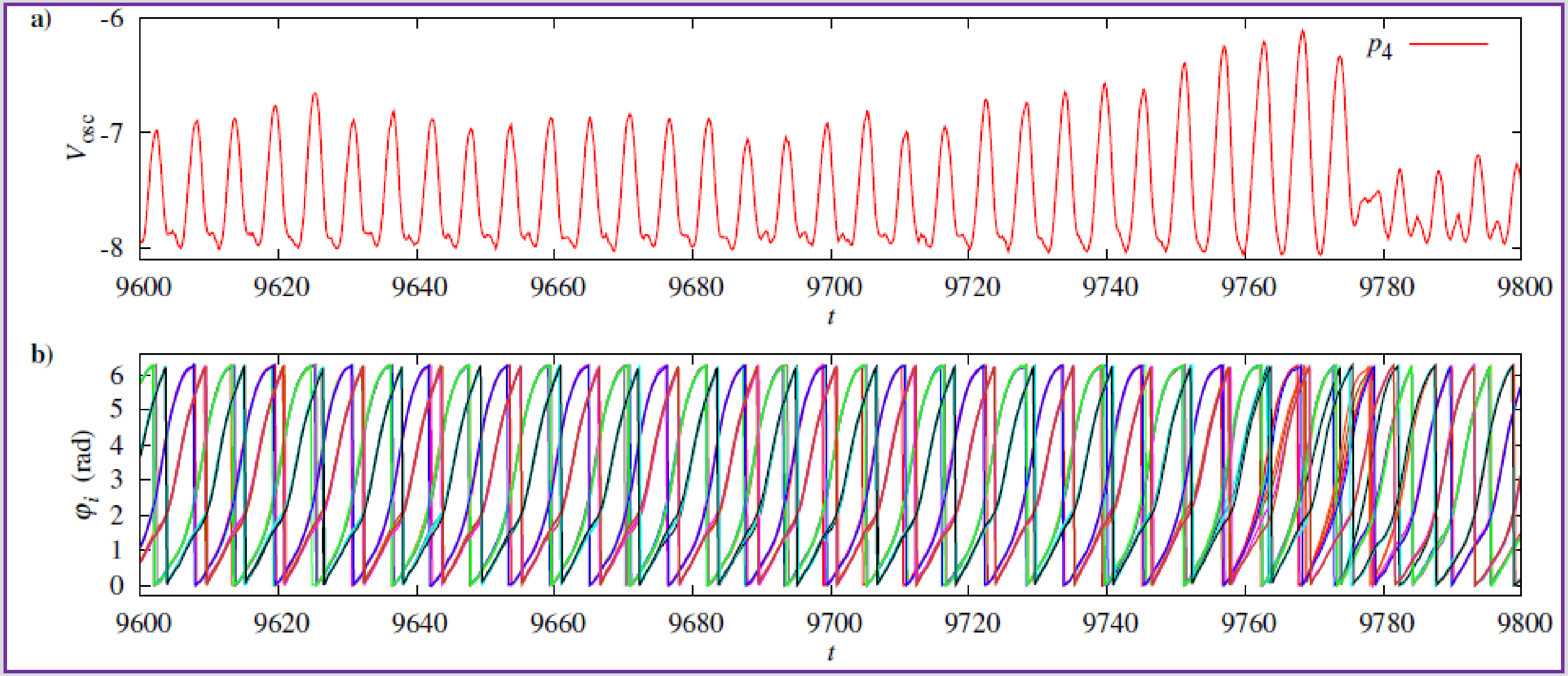
Escape via an unstable limit cycle (unstable also without noise)

Settling in a p4-solution (that is stable without noise and metastable with noise)



7200-7400

So the ”stationary state” in the presence of noise is characterized by ongoing transitions between the different pattern of phase locked motion, characterized as p4, p6,p16, disordered, or transient p3 states.

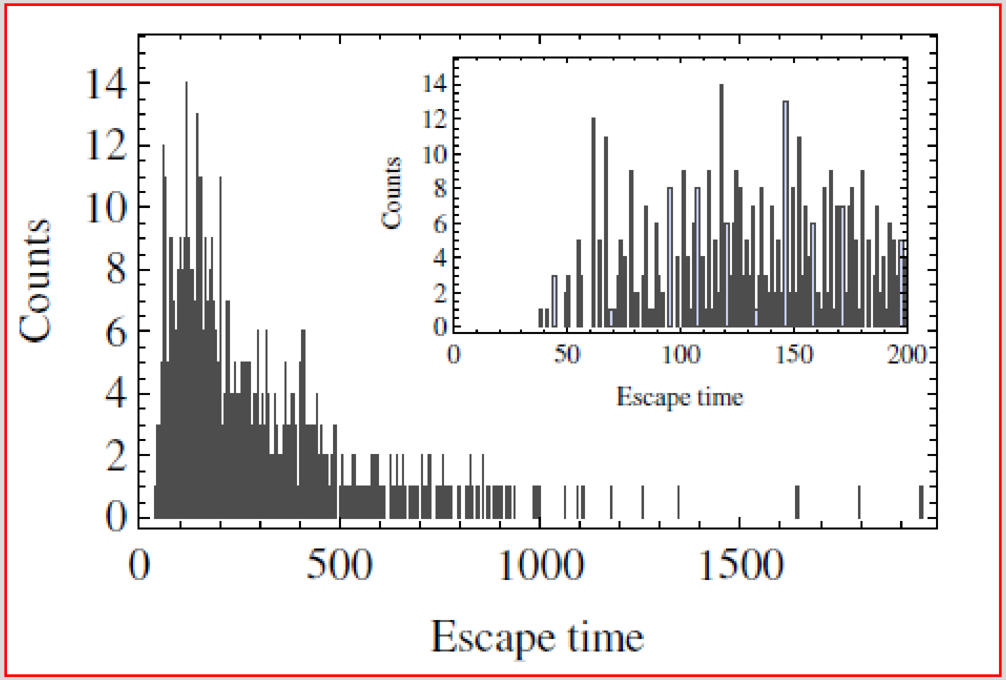


9600-9800 and so on for ever

What is a time-independent feature of the stationary state?

The distribution of escape times from a 16- to a 4-cluster solution

- Consider an initial condition that leads to a 16-cluster solution .
- For a fixed noise intensity, here σ=0.05, solve the differential equation for 1000 noise realizations.
- For each solution, the first escape to another attractor occurs when V_{osc}>-6.5 (numerically verified).
- Register this event of crossing the potential threshold if there are at least 50 time units between two crossings.



The histogram depends on the selection of metastable states, so far also on the overall time span: first escape during the first 10000 or the second 10000 time units

What might be called "**stationary** " in the sense of being time independent is only the feature of the multi-peak structure of the histogram of escape times , for a given noise strength.

Interpretation of the multi-peak structure and the iterated order and disorder

The multi-peak-structure seems to be typical for situations, where unstable limit cycles separate stable attractors. A multi-peak structure was predicted for a two-variable system with stochastic transitions through an unstable limit cycle[1].

Moreover, if two stable attractors are separated by an unstable limit cycle, for low noise the escape rate should be modulated by an oscillatory factor [2]. This may explain why we see as a function of a monotonically increasing noise strength more or less escapes to other metastable states. Our system is high-dimensional.

[1] A.L.Kawczynski et al., Phys.Chem.Chem.Phys. 10,289 (2008)

[2] R.S.Maier etal., Phys.Rev.Lett.77 4860 (1996)

Summary so far

Active rotators and Kuramoto oscillators on a hexagonal lattice with frustrated bonds

- **show a large number and a variety of coexisting attractors.**
- **Under noise we see the ongoing migration of phases through the potential landscape.**
- **The escape times between the metastable states define a multitude of time scales.**

$\Longrightarrow$ **We expect to see aging of these oscillators.**

Defining criteria for Physical aging (in contrast to biological aging):

Do relaxation processes towards the stationary state show

- **slow dynamics** (slow in the sense of non-exponential relaxation). The slow dynamics would be visible after a quench into the regime of multistable states in appropriate correlation functions.

- **breaking of time-translation invariance**. If we distinguish between the waiting time t_w after a quench when a measurement of an observable starts, and the observation time t, when the observable is measured again, at $t > t_w$, an observable such as the (auto)correlation function depends on both times.

- **dynamical scaling**. Dynamical scaling is observed if the individual curves for the correlation functions can be superimposed onto a single master curve by an appropriate rescaling of the argument, depending on t and t_w. If we observe dynamical scaling for a given excitable or oscillatory system, the question arises of how universal this scaling behavior is between different realizations of such systems, differing by their individual dynamics.

MEASURE AGING OF ACTIVE ROTATORS AND KURAMOTO OSCILLATORS

via the autocorrelation functions:

- **Prepare the system in the vicinity of the unique fixed point at $\kappa > 0$.**
- **Quench the system towards $\kappa < 0$ in the regime of coexisting synchronized oscillations to push it out-of-equilibrium.**
- **Wait and let it evolve under the action of additive noise.**
- **Perform a first measurement of the autocorrelation function at time $t_{w.}$**
- **Perform a second measurement at time $t > t_w$**

for two lattice sizes (32x32 and 4x4) and three noise intensities $\sigma = 0.01, 0.1, 0.5$ with and without frustration.

Note that temperature in spin systems plays a twofold role: driving the transition to a phase with multistable behavior and providing fluctuations. In our case the coupling provides the bifurcation parameter from one phase into the other and the noise creates the fluctuations.

The state of the system at time t is specified by the vector of all phases

$\vec{\phi}$ = ($\Phi_1(t)$, $\Phi_2(t)$, …..,$\Phi_N(t)$).

We compute the two-time autocorrelation function defined as

$$C(t, t_w) := \frac{\langle \vec{\phi}(t)\vec{\phi}(t_w)\rangle - \langle \vec{\phi}(t)\rangle\langle \vec{\phi}(t_w)\rangle}{\sigma_t \sigma_{t_w}}$$

with standard deviations $\sigma_t^2 = \langle \vec{\phi}(t)\vec{\phi}(t)\rangle - \langle \vec{\phi}(t)\rangle\langle \vec{\phi}(t)\rangle$,

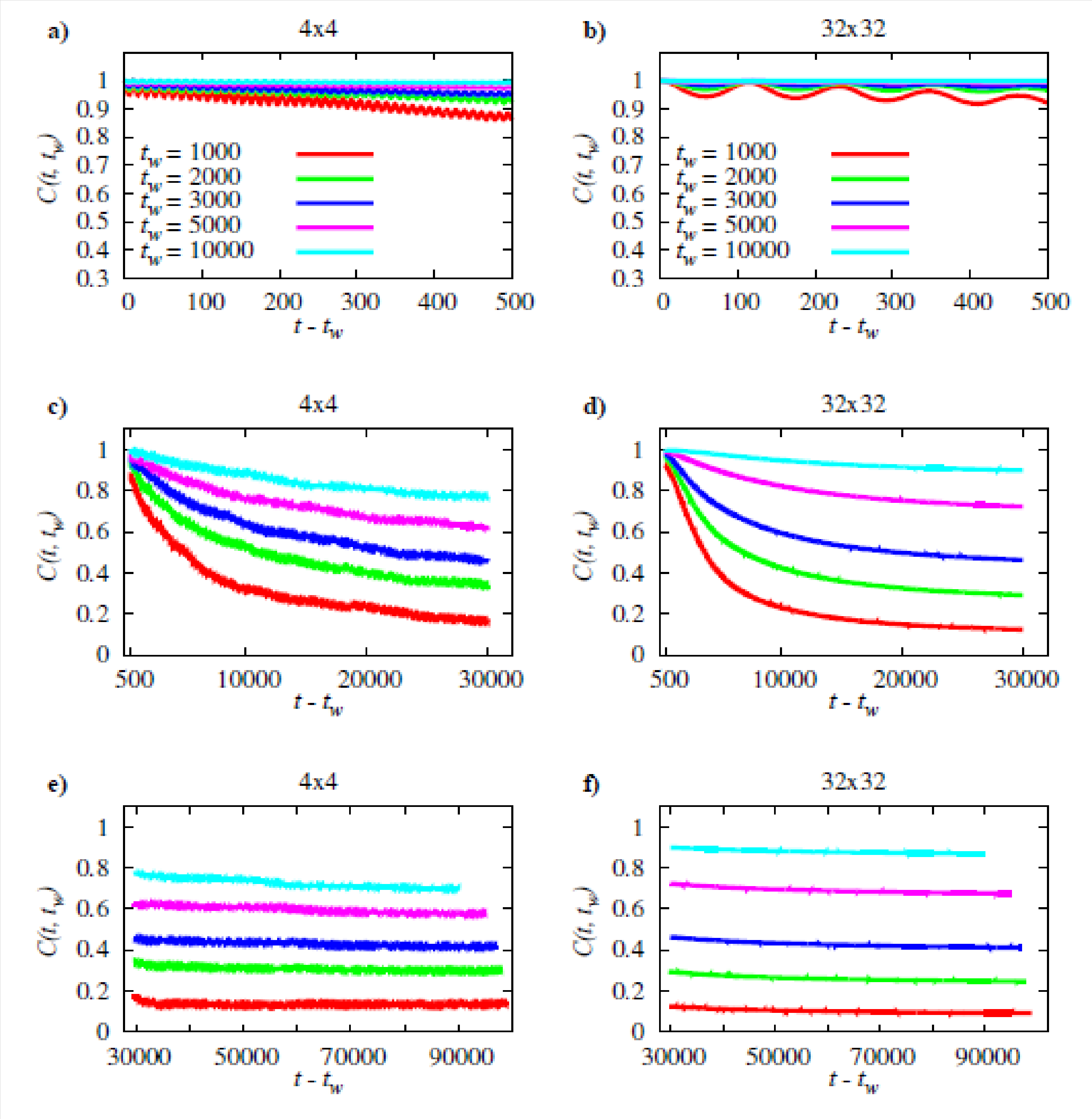
where the averages are calculated over a sufficient number of noise realizations.

AGING OF ACTIVE ROTATORS: 4X4 AND 32X32 WITH NOISE

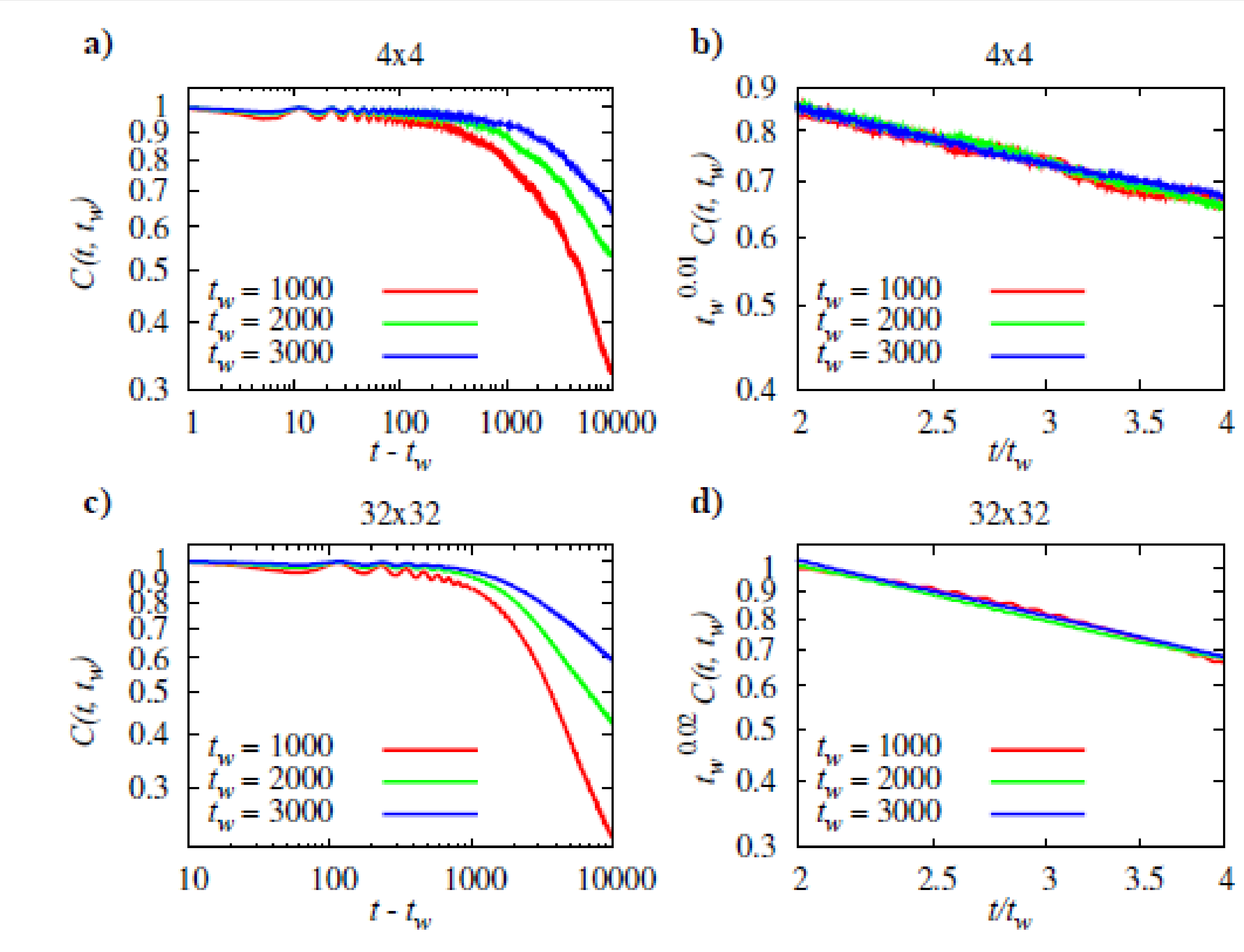
Regime (i)
Quasiequi-
librium

Regime (ii)
Drop off

Regime (iii)
Slow saturation



DYNAMICAL SCALING OF ACTIVE ROTATORS FOR 4X4 AND 32X32



$$t_w^{|b|} C(t, t_w) = f(\frac{t}{t_w})$$

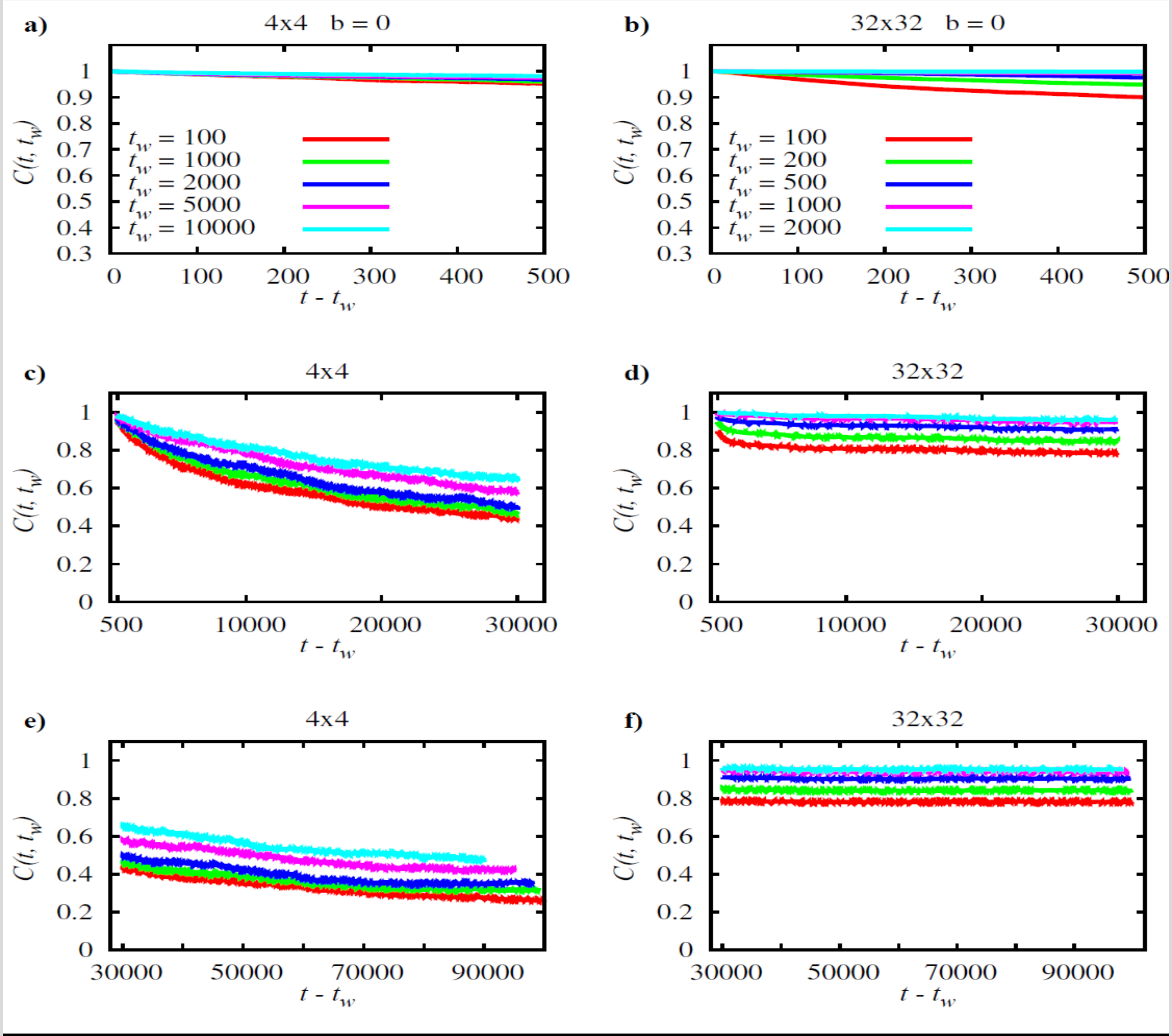
$b \in [0, 0.02]$ (4×4) and $b \in [0, 0.03]$ (32×32)

AGING FOR KURAMOTO OSCILLATORS ON 4X4 AND 32X32 LATTICES

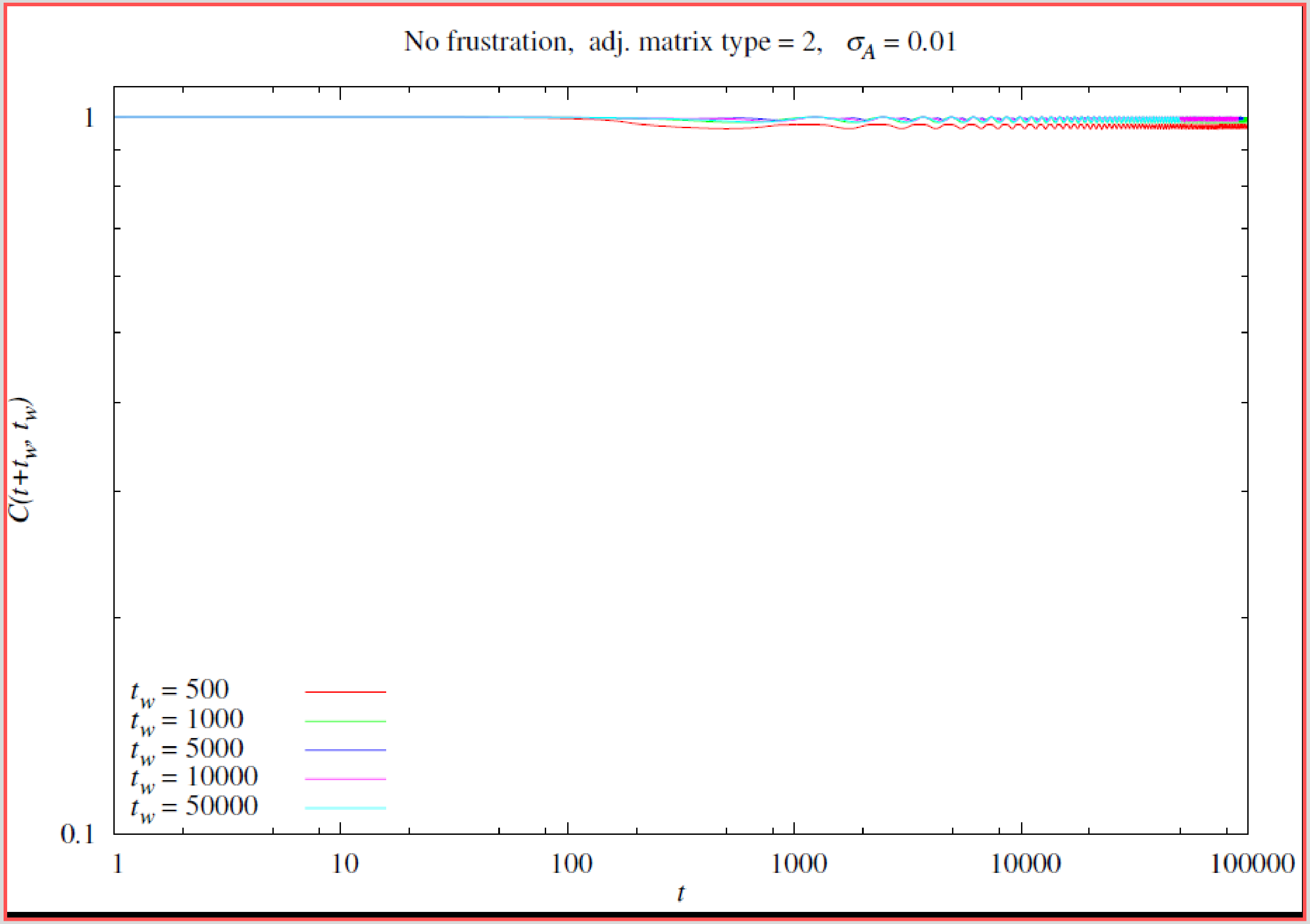
Regime (i)
Quasiequilibrium

Regime (ii)
Drop off

Regime (iii)
Slow saturation



ACTIVE ROTATORS ON A 32X32 LATTICE WITHOUT FRUSTRATION BUT WITH NOISE



So no dependence on the waiting time t_W, neither for the 4x4 case.

Summary of the results on aging:

We do see physical aging

- even for a very small system size of 4x4 oscillators with a short transient time, but a very rough and structured attractor landscape
- also for larger systems
- for classical rotators and Kuramoto oscillators
- for a different choice of autocorrelation functions
- No signatures of aging for a system with disorder in the coupling signs, but no frustration.
- The mechanism seems to be the same as for spin glasses, but the attractor landscape is much more versatile in which the phases continue to move from one metastable state to another.

Outlook to next steps

- Other manifestations of aging in the response to external forces
- Aging in other oscillatory systems like genetic circuits
- Predictions of aging and scaling behavior in simpler models
- Questions about universality w.r.t. the exponents
- Memory and rejuvenation effects
- Determination of “critical ages”

in view of the following more interesting questions:

What are different aging mechanisms?

Here we have found no new mechanism, but a very different realization of the same mechanism that is acting in spin glasses.

What is the role of noise in aging? (Montemurro et al. PRE67,031106 (2003))

There Hamiltonian of oscillators like ours, no noise, no frustration, no disorder, but for a particular family of initial conditions in the limit of infinite range couplings and $N \to \infty$ before $t \to \infty$.

What is the relation between **physical** aging and **biological aging**?

physical aging in the sense of age dependent response to perturbations

biological aging e.g. in the sense of deterioration of pacemaker cells.

Can physical aging of "soft matter" contribute to biological aging of cells and whole organisms?

What are independent sources and independent aging mechanisms on different biological scales, are the mechanisms the same?

Our excitable and oscillatory systems have applications to biological systems.

THANKS TO MY COLLABORATORS

- **DARKA LABAVIC** (PhD student)
- **FLORIN IONITA** (Post-doc)
- **MICHAEL ZAKS** (HUMBOLDT UNIVERSITY BERLIN)

F. Ionita, D. Labavic, M. Zaks and HMO, Eur. Phys. J. B 86(12), 511(2013)
F. Ionita, and HMO, Phys.Rev.Lett.112, 094101 (2014)

Email: h.ortmanns@jacobs-university.de

JACOBS UNIVERSITY

559. WE-Heraeus-Seminar

The Versatile Action of Noise: Applications from Genetic to Neural Circuits

Jacobs University Bremen, June 22-27, 2014

Invited speakers

Michael Assaf *
Racah Institute of Physics, Hebrew University of Jerusalem

Jan Benda *
Eberhard Karls University, Tübingen

Michael Breakspear *
QIMR and UNSW Berghofer, Sidney, Australia

Thierry Emonet *
Yale University, New Haven, U.S.A.

Tobias Galla *
Manchester University, Manchester

Jordi Garcia-Ojalvo *
Universitat Pompeu Fabra, Barcelona

Benjamin Lindner *
Humboldt University, Berlin

Wolfgang Maass *
Graz University of Technology, Graz

Ralf Metzler *
Potsdam University, Potsdam

Sidney R. Nagel
The University of Chicago, U.S.A.

Simone Pigolotti *
Universitat Politecnica de Catalunya, Barcelona

Joachim Rädler *
Ludwig Maximilians University, Munich

Jaime de la Rocha *
Institut D' Investigacions Biomèdiques August Pi i Sunyer, Barcelona

Lutz Schimansky-Geier*
Humboldt University, Berlin

Susanne Schreiber *
Humboldt University, Berlin

Pieter Rein Ten Wolde *
FOM Institute AMOLF, Amsterdam

Raúl Toral *
IFISC, UIB-CSIC, Palma de Mallorca

*=confirmed

Topics include

- The effects of extrinsic noise on cellular decision making
- Correlated fluctuations in genetic networks
- Propagation of noise of sequential gene regulation
- Error rates in biological copying
- Single cell response and decision making under noise
- The generation of transcriptional noise in bacteria
- Costs and benefits of biochemical noise
- Noise in large-scale cortical rhythms
- Noise-induced order in collective neural populations
- Computations by noisy networks of spiking neurons
- Noise and irregular firing in cortical circuits
- Cellular mechanisms of temperature-compensation in receptor neurons
- Coherent noise, scale invariance and intermittency in large systems
- Shaping noise for population success
- Quasi-cycles induced by noise
- Interplay between noise and delay

Organizers
Hildegard Meyer-Ortmanns
Alberto Bernacchia
School of Engineering and Science
Jacobs University Bremen gGmbH
Campus Ring 1
28759 Bremen, Germany

We invite applications from graduate students, PhD students and postdocs with a background in theoretical aspects of physics, neuroscience, or biology. Applicants from the experimental side should be interested in the mathematical modeling and analysis of experimental data.

For further details please visit: http://www.jacobs-university.de/noise

Jacobs University

Application deadline: April 30, 2014
Contact: s.meier@jacobs-university.de

This seminar is generously supported by the Wilhelm und Else Heraeus-Stiftung.