



INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK



UNIVERSITÀ DEGLI STUDI
DI TRENTO



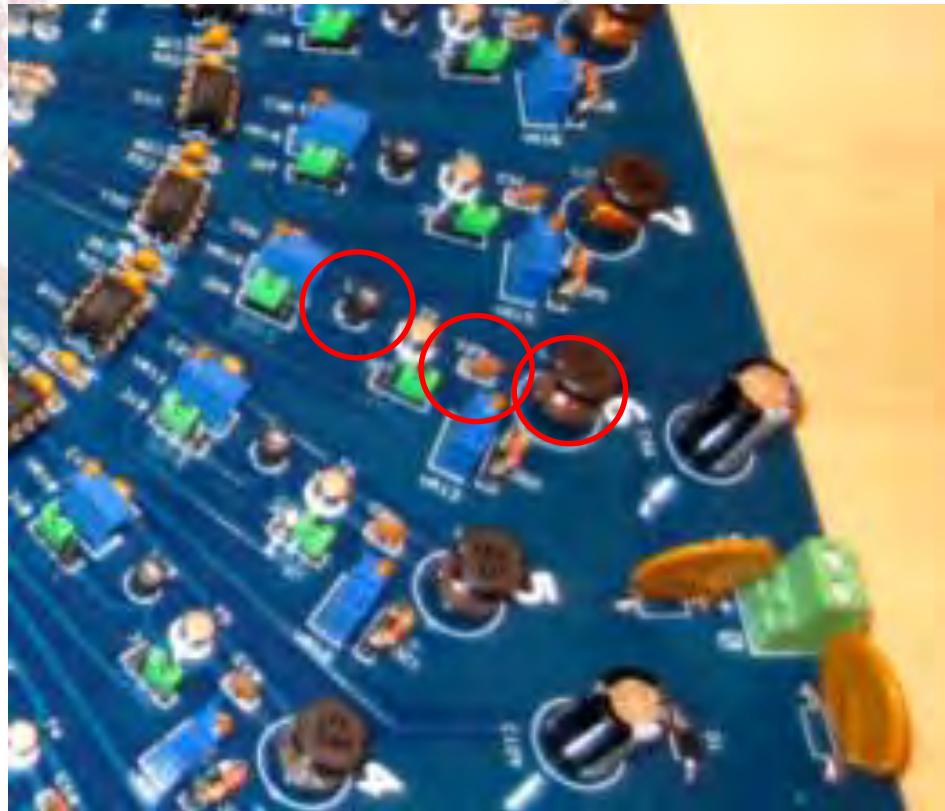
More non-linear circuits: integrated implementation, versatile motor pattern generation, criticality

Ludovico Minati

Tokyo Institute of Technology, Tokyo, Japan
Institute of Nuclear Physics - Polish Academy of Sciences (IFJ-PAN), Kraków, Poland
University of Trento, Trento, Italy

Integrated circuit implementation

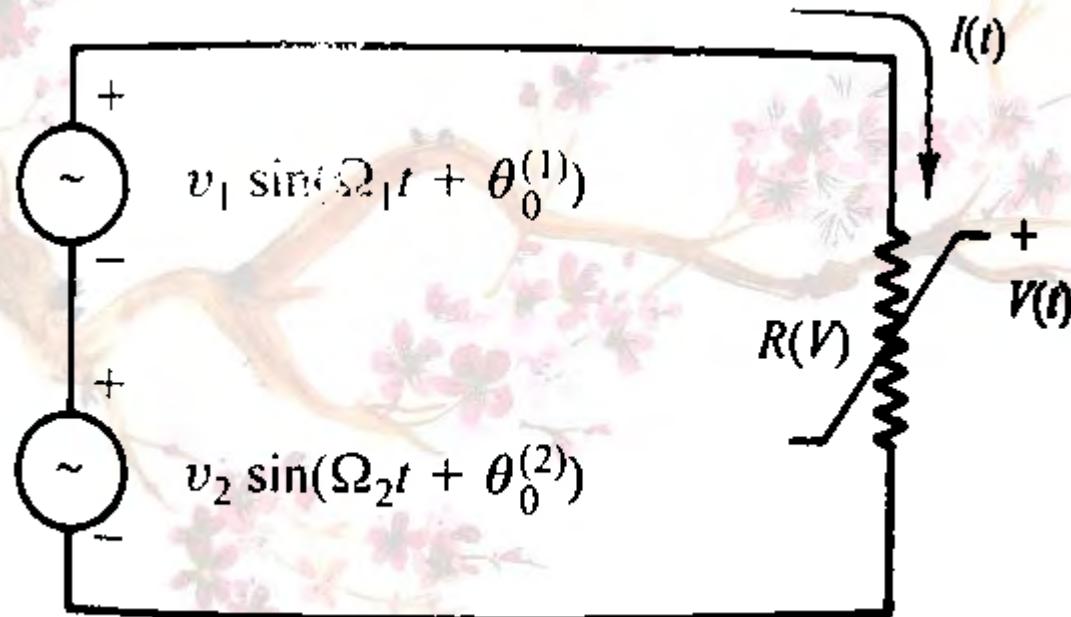
Problem: inductors and capacitors not suitable for CMOS realization



L. Minati

Integrated circuit implementation

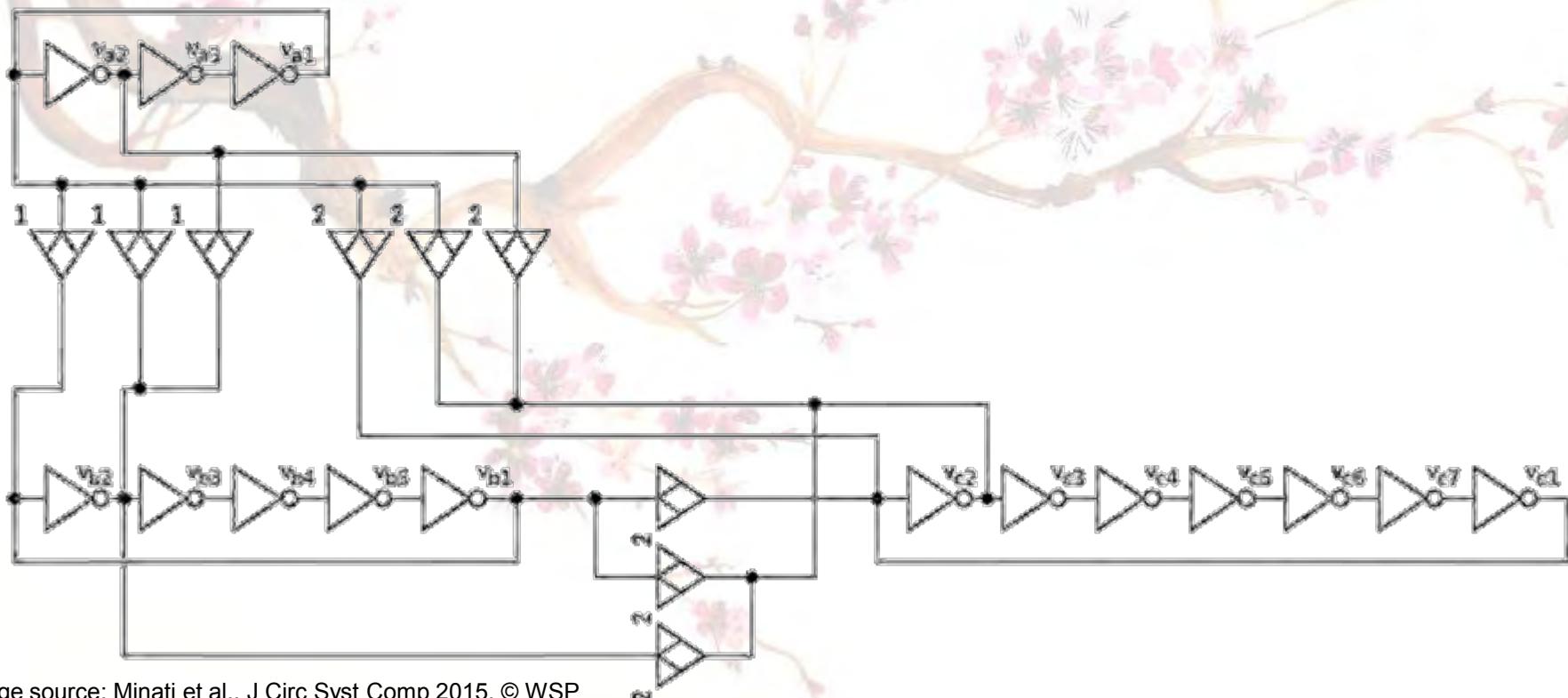
Quasi-periodicity route to chaos



L. Minati

Integrated circuit implementation

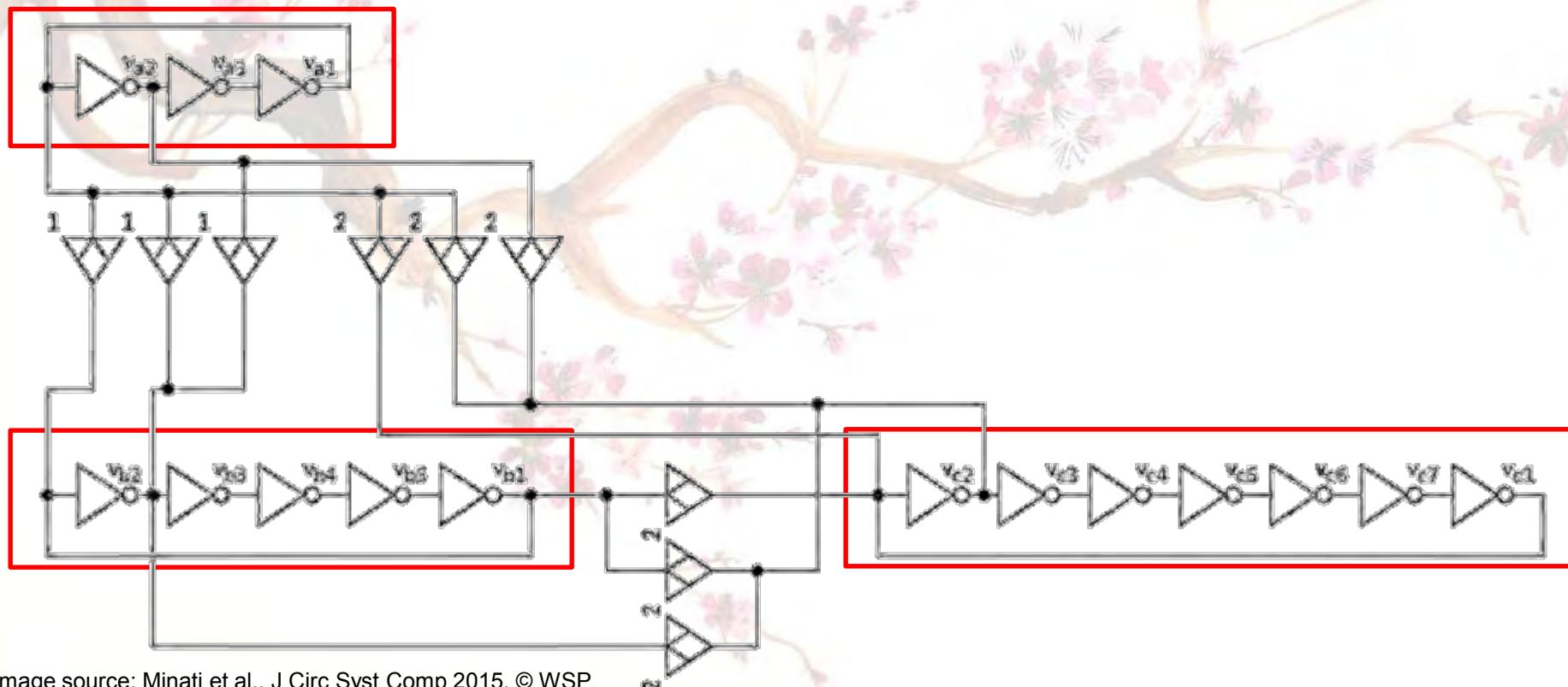
Coupled inverter rings



L. Minati

Integrated circuit implementation

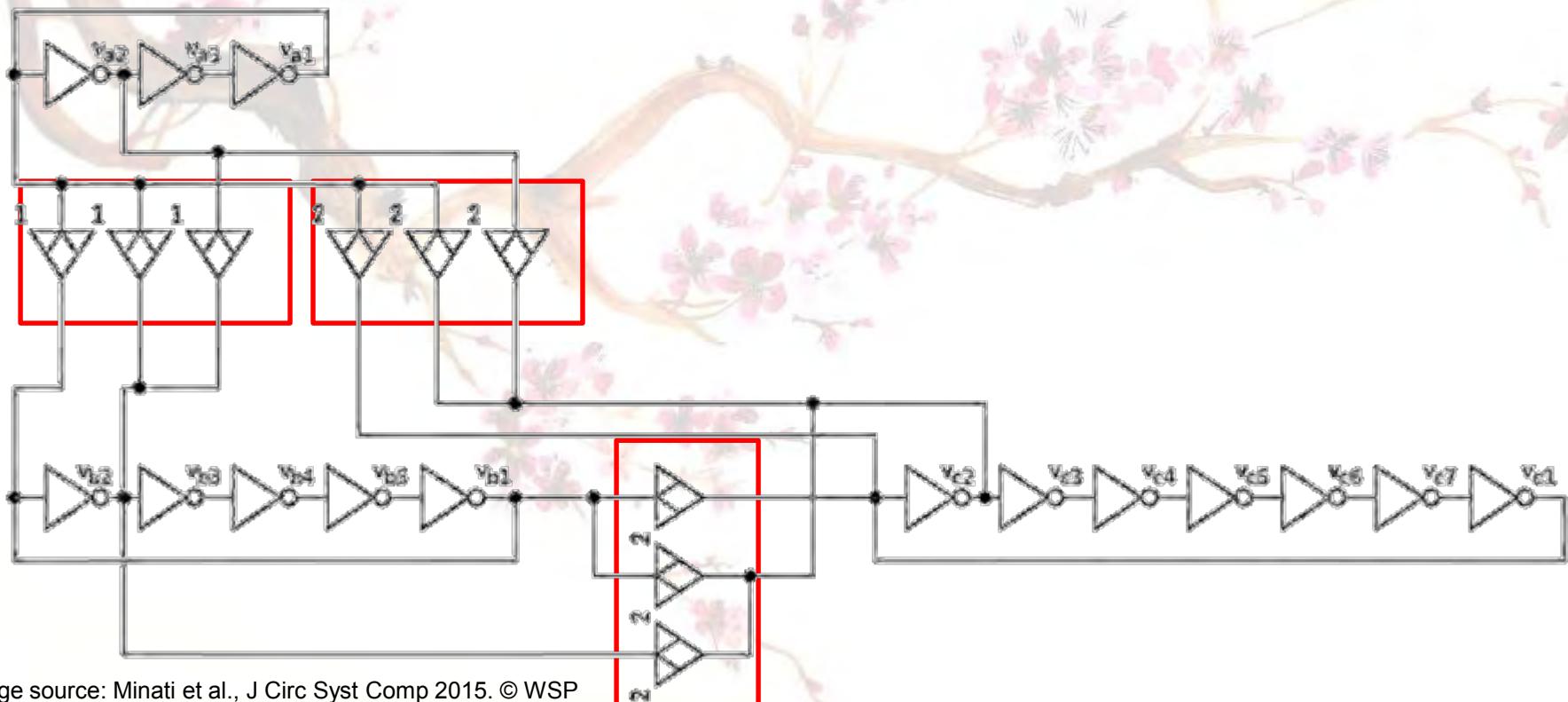
Coupled inverter rings



L. Minati

Integrated circuit implementation

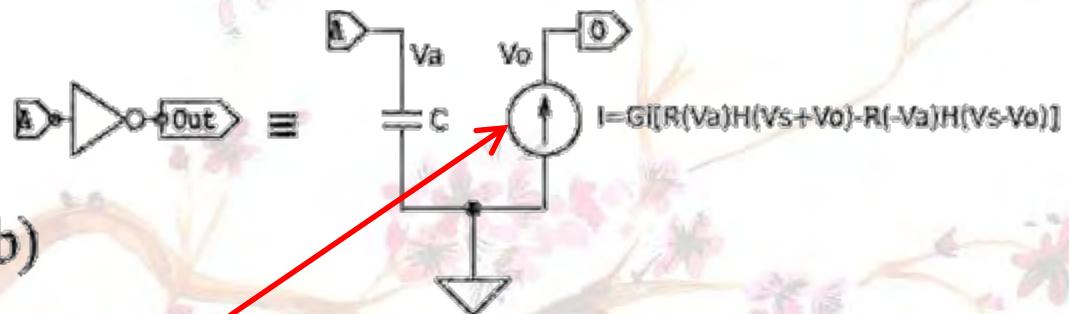
Coupling elements



L. Minati

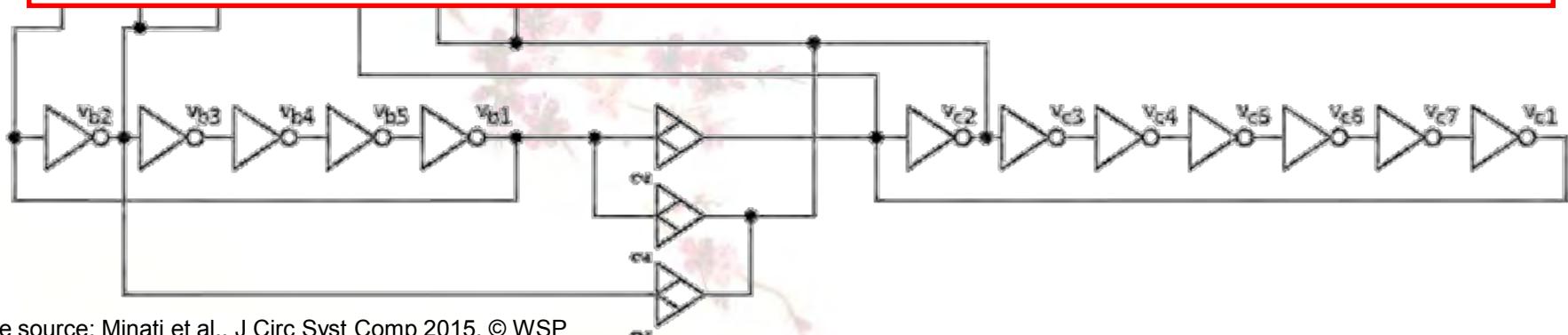
Integrated circuit implementation

Simplified numerical model



1

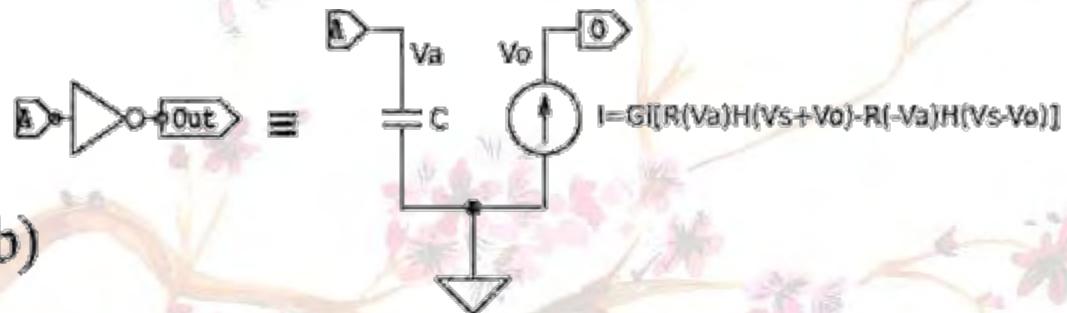
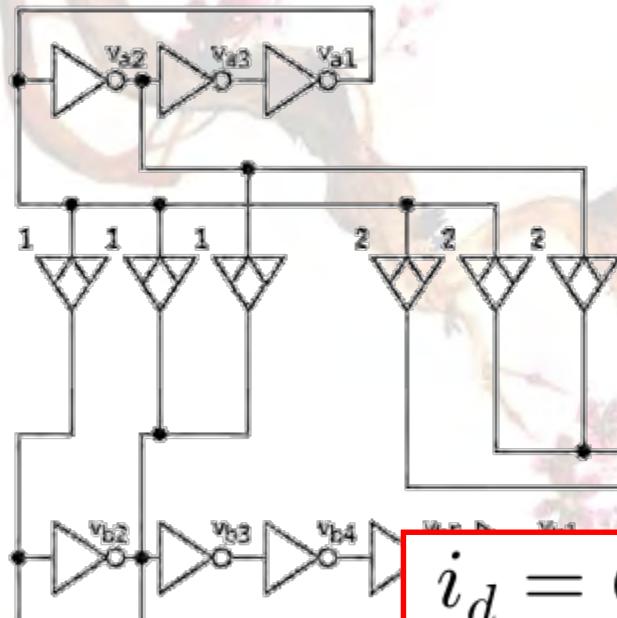
$$i_o = G_i [R(v_a)H(V_s + v_o) - R(-v_a)H(V_s - v_o)]$$



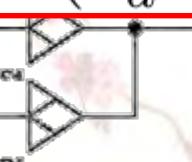
L. Minati

Integrated circuit implementation

Simplified numerical model



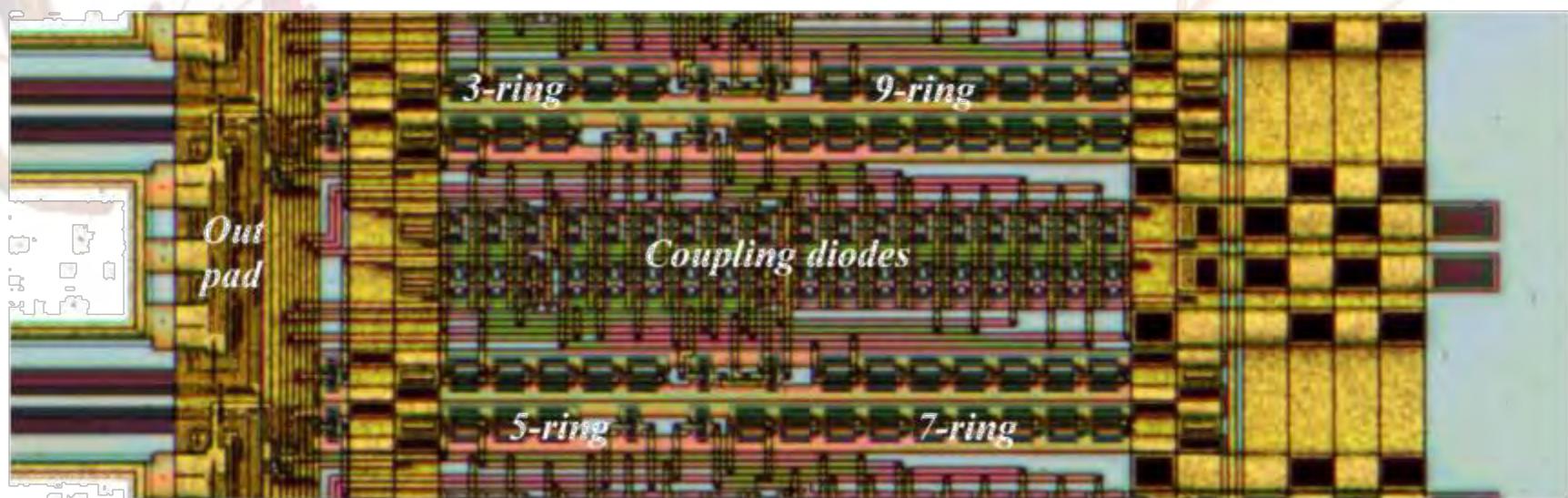
$$i_d = G_c R(v_a - v_b - V_t)$$



L. Minati

Integrated circuit implementation

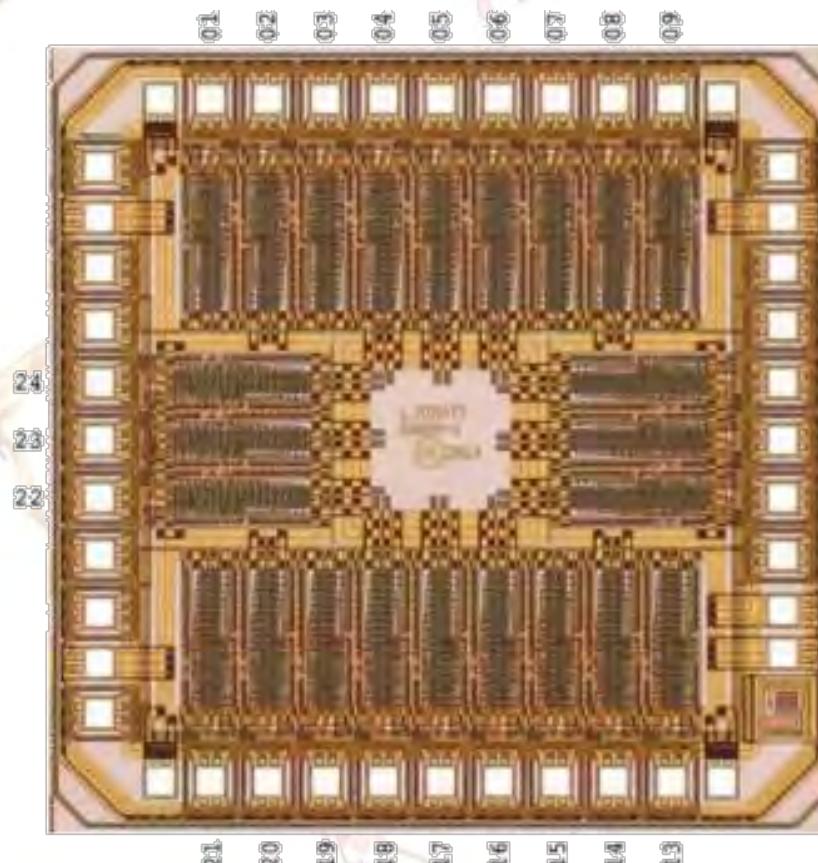
CMOS realization – single cell and ring



L. Minati

Integrated circuit implementation

CMOS realization – single cell and ring



Realized through





Tokyo Tech



INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK

*More non-linear circuits: integrated implementation, versatile
motor pattern generation, criticality*

L. Minati

Integrated circuit implementation

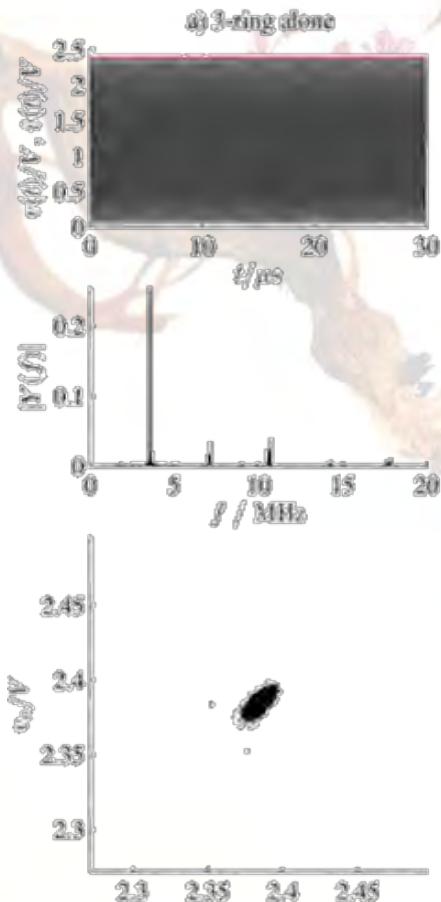
CMOS realization – test board



L. Minati

Integrated circuit implementation

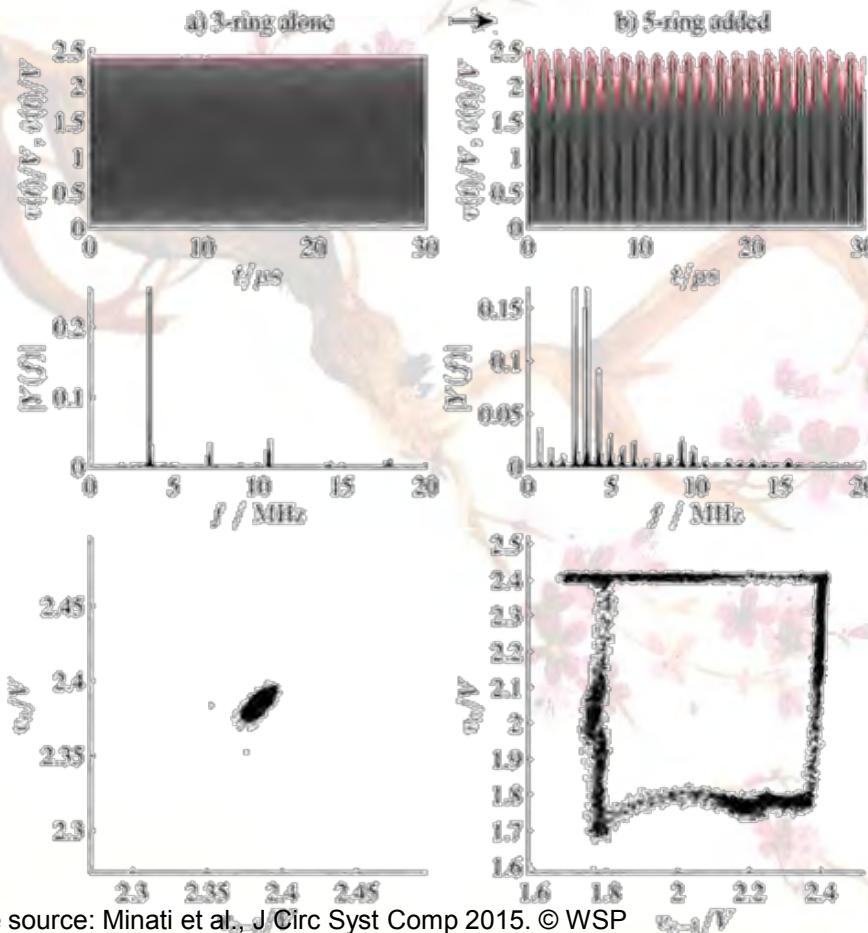
Effect of connecting rings: 3-ring alone



L. Minati

Integrated circuit implementation

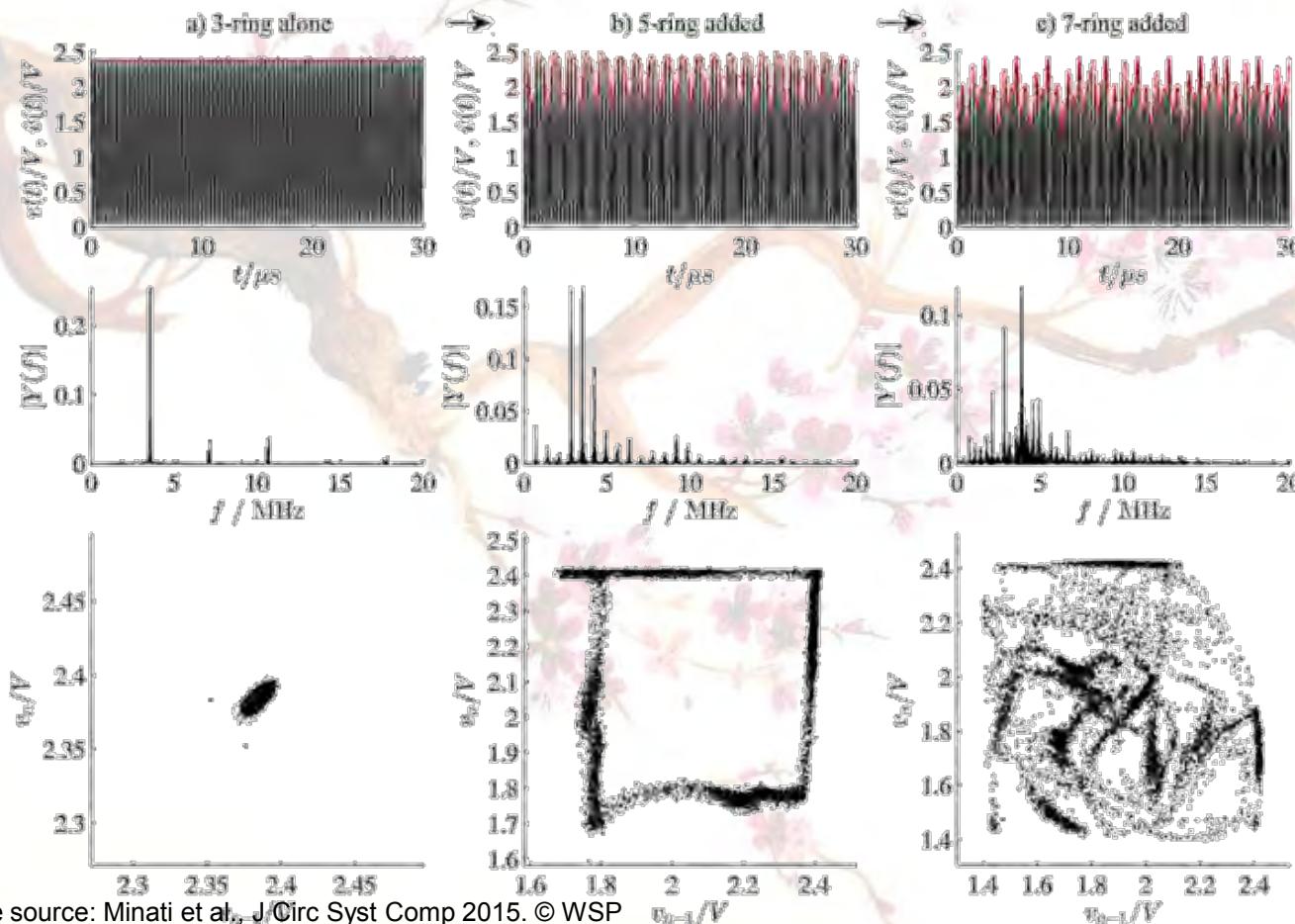
Effect of connecting rings: 3-ring + 5-ring



L. Minati

Integrated circuit implementation

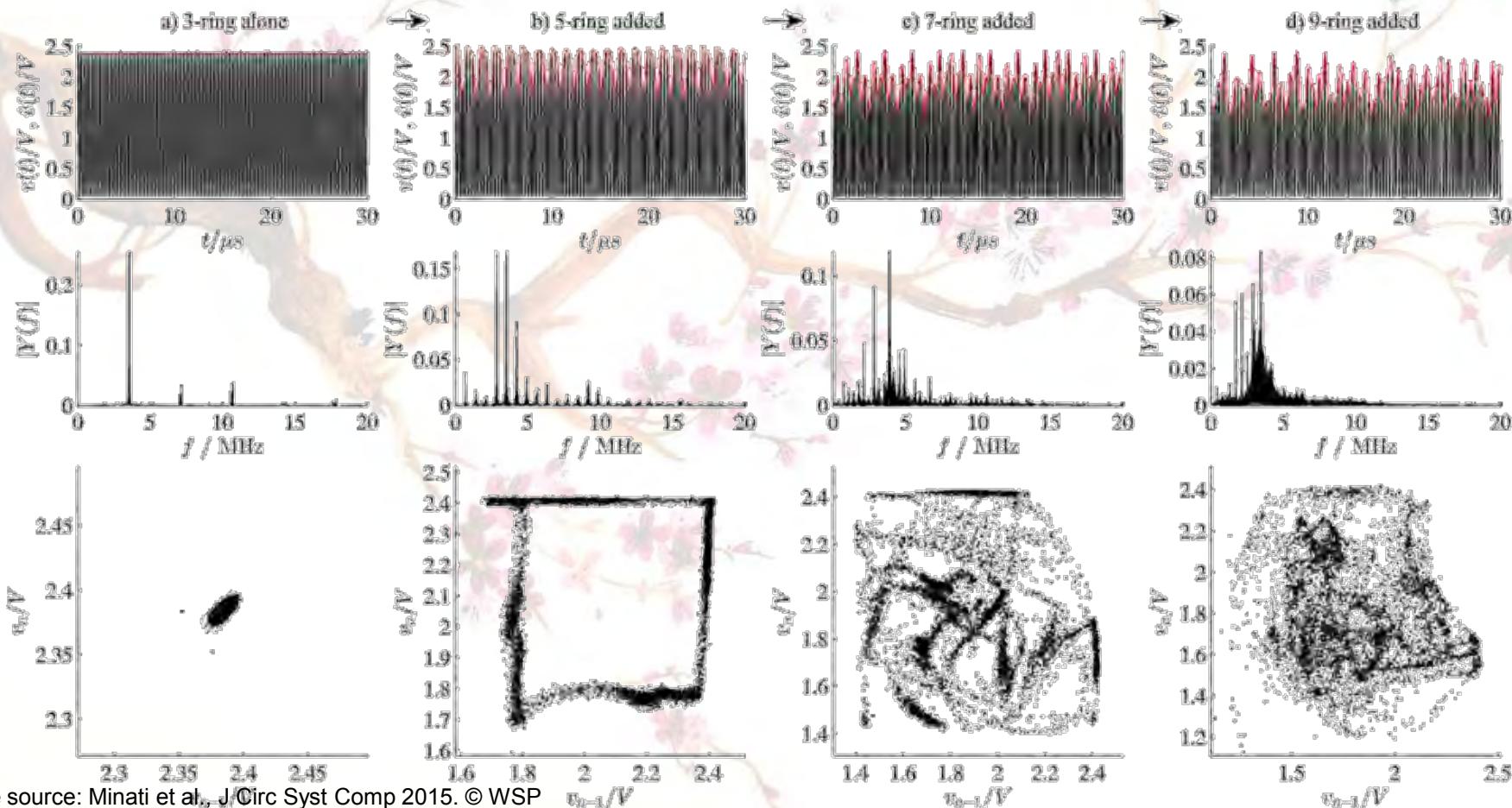
Effect of connecting rings: 3-ring + 5,7-rings



L. Minati

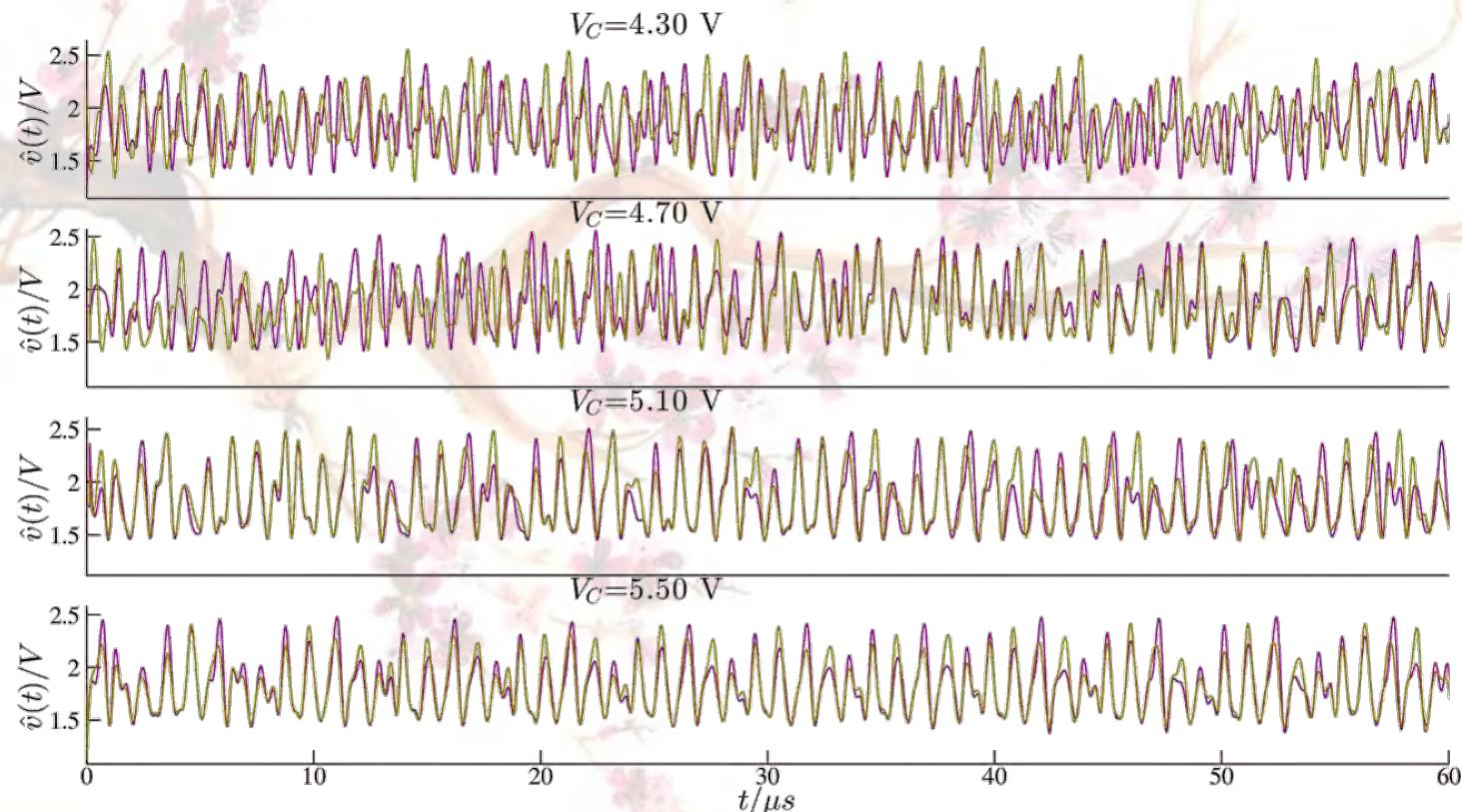
Integrated circuit implementation

Effect of connecting rings: 3-ring + 5,7,9-rings



Integrated circuit implementation

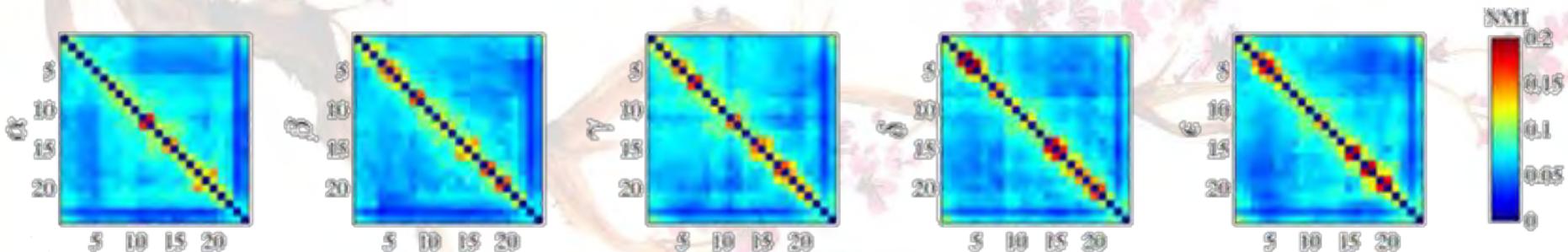
Effect of increasing coupling strength



L. Minati

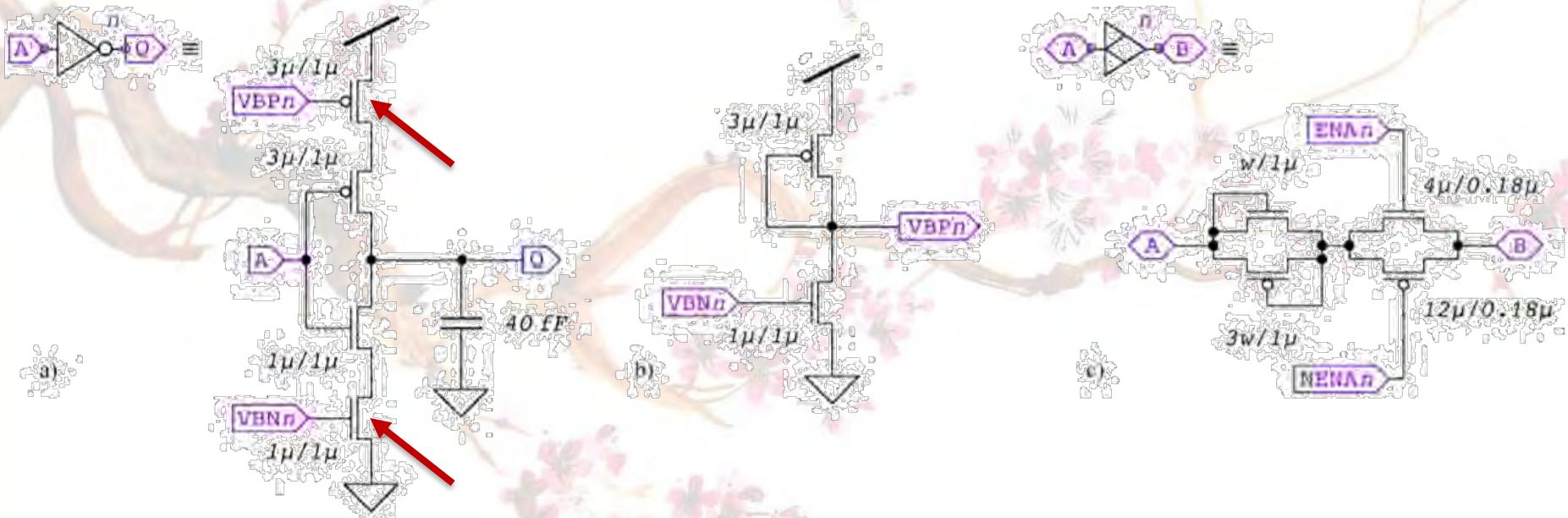
Integrated circuit implementation

Cluster synchronization: formation of communities



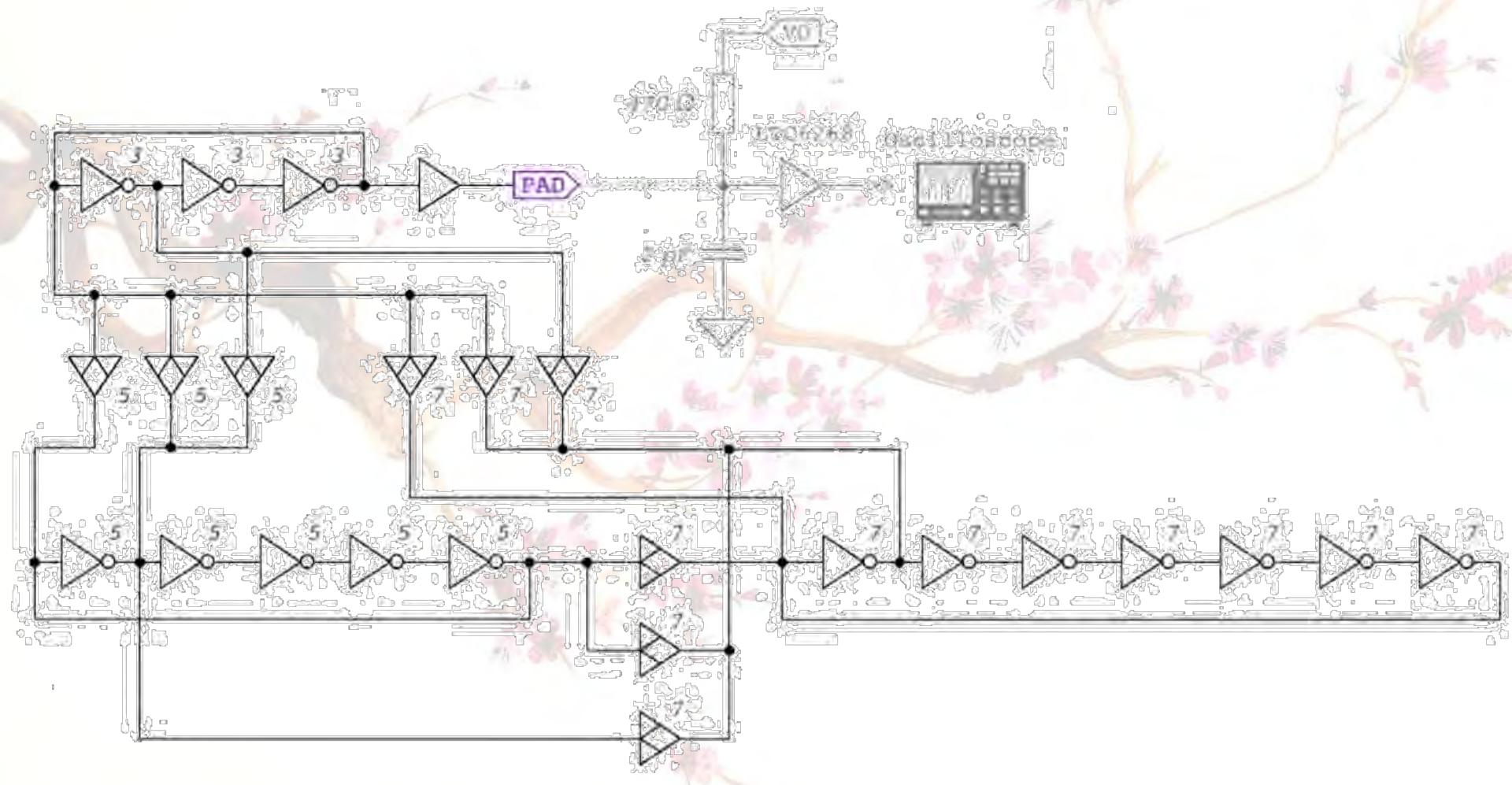
L. Minati

Generalization with current-starved inverters



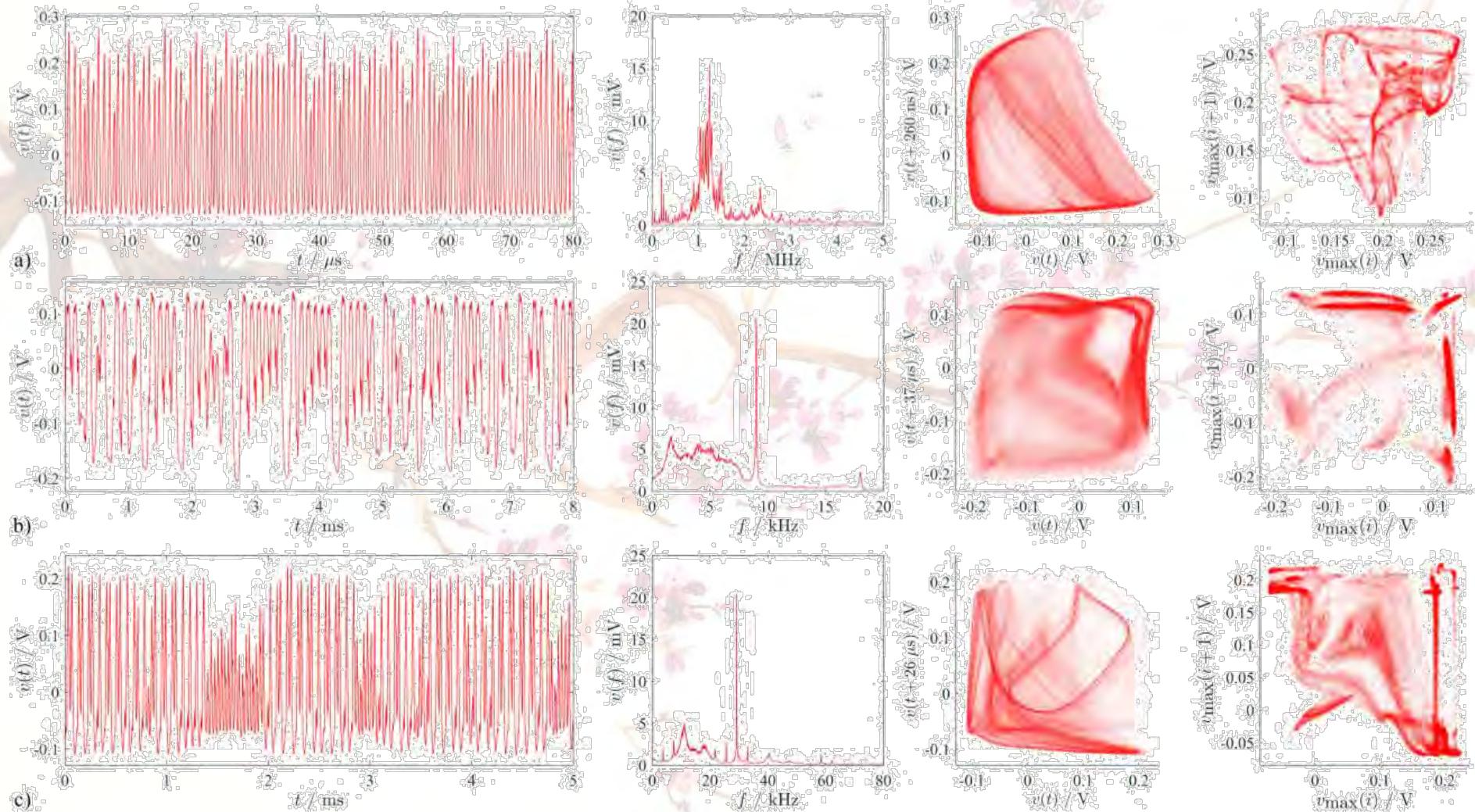
L. Minati

Generalization with current-starved inverters



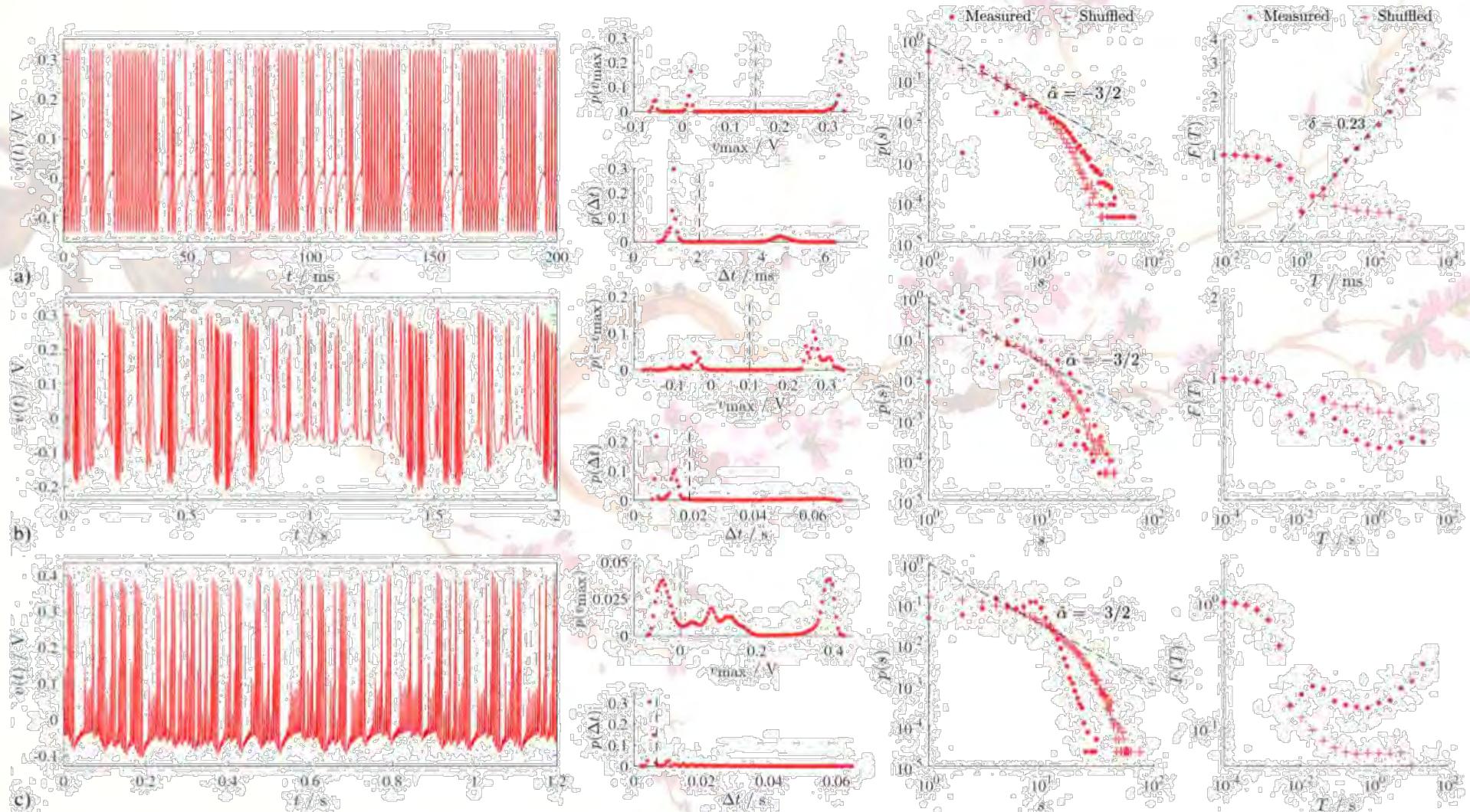
L. Minati

Generalization with current-starved inverters



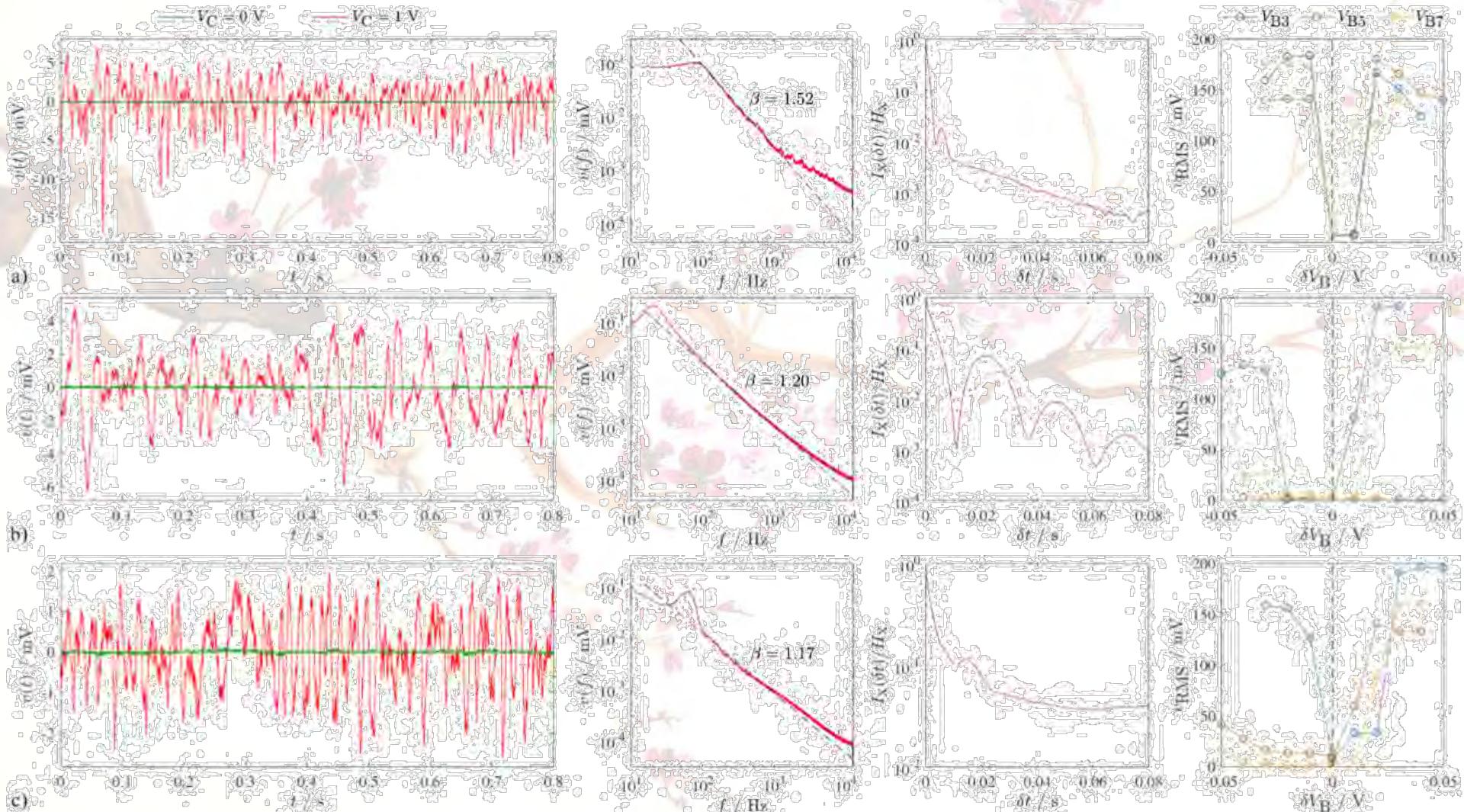
L. Minati

Generalization with current-starved inverters



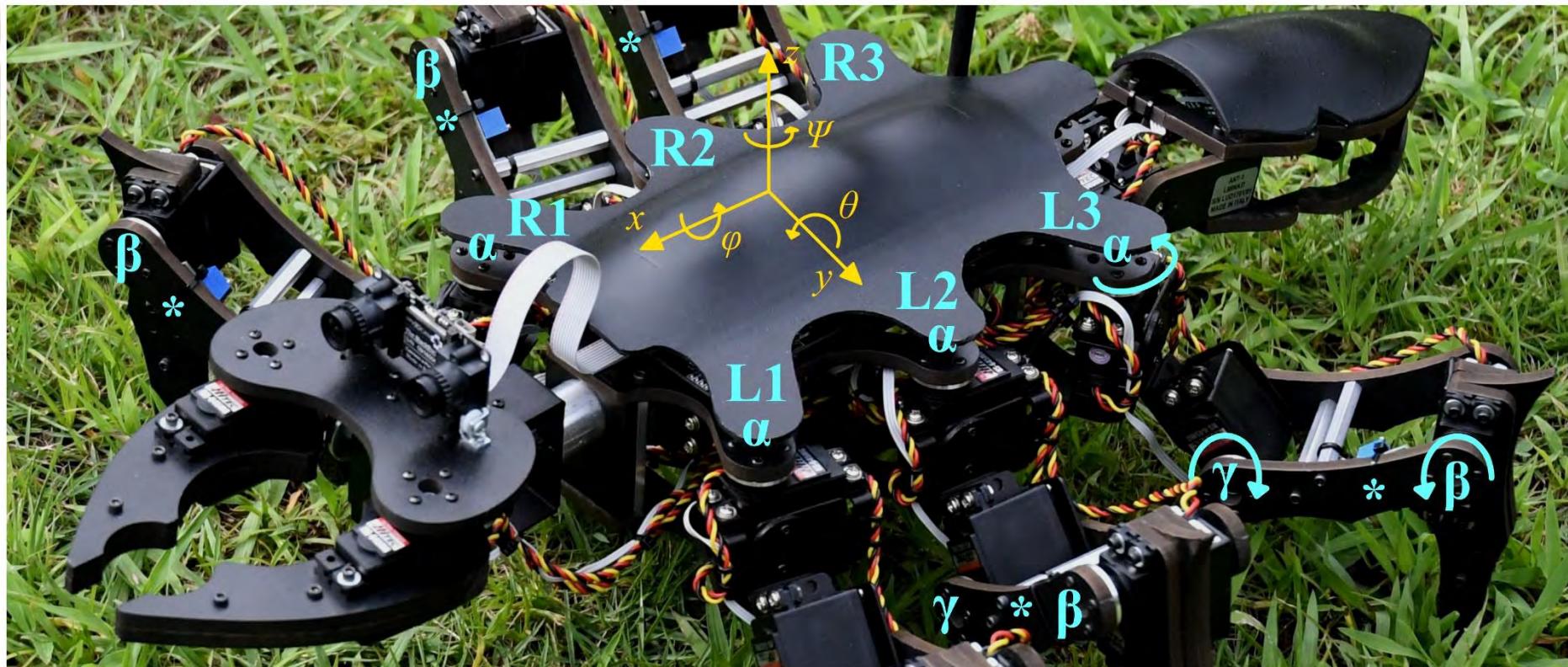
L. Minati

Generalization with current-starved inverters



Versatile motor pattern generation

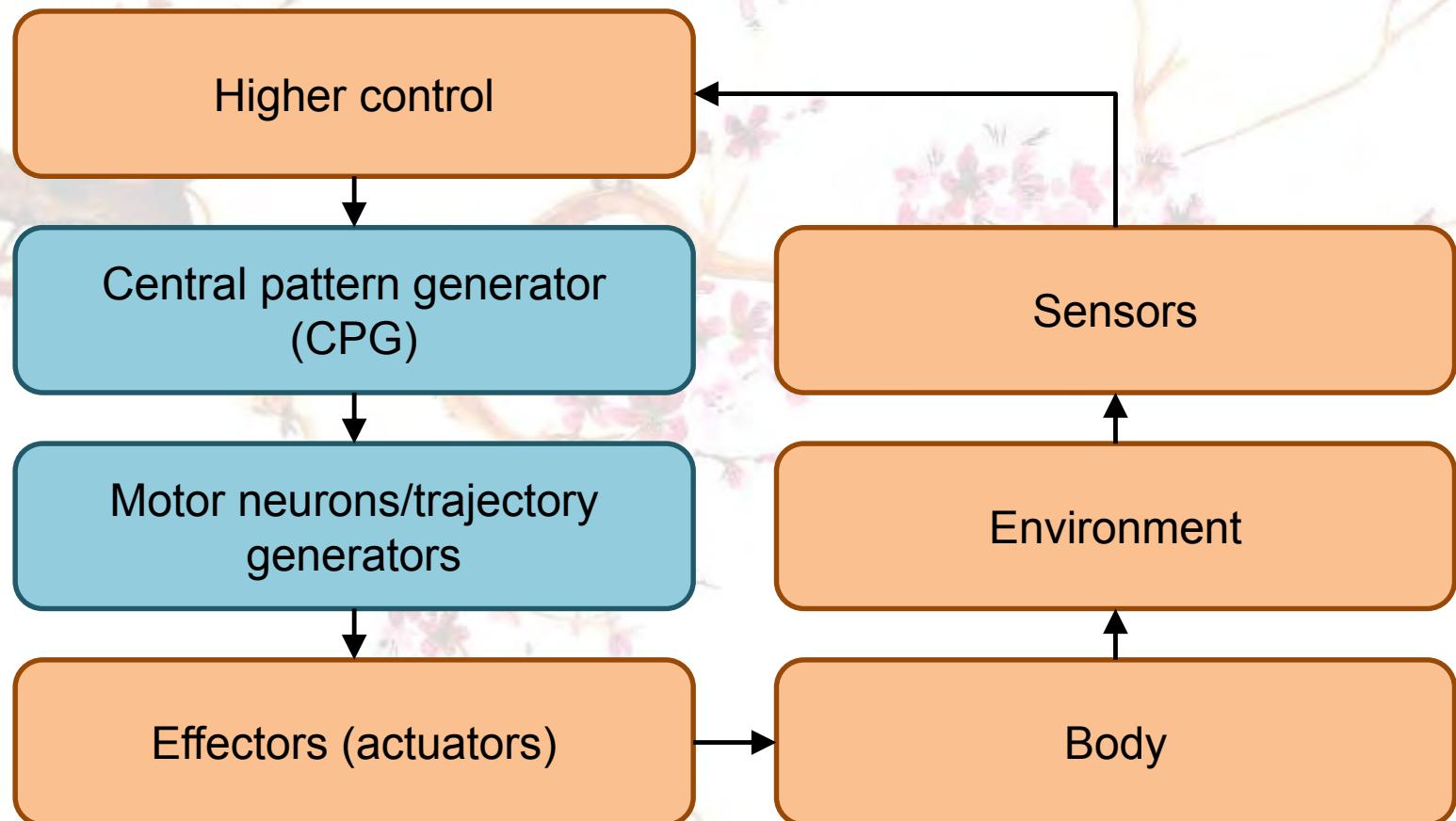
Generation of viable walking gaits for the 非線形蟻-1 robot



Original mechanics design: A-Pod by Kåre Halvorsen (a.k.a. "Zenta")

Versatile motor pattern generation

Central pattern generation (CPG)



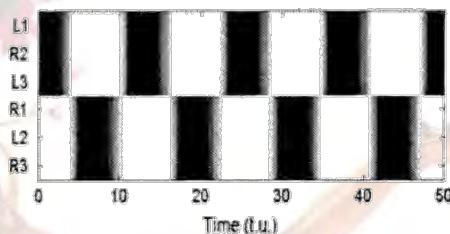
L. Minati

Versatile motor pattern generation

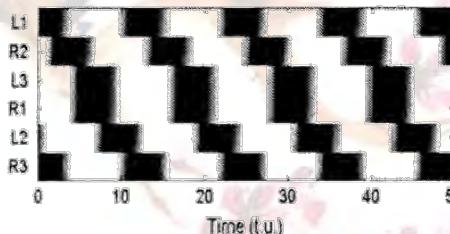
Canonical gaits and postures in insects

Gaits

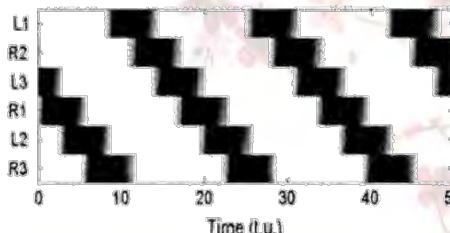
Alternating
tripod



Metachronal



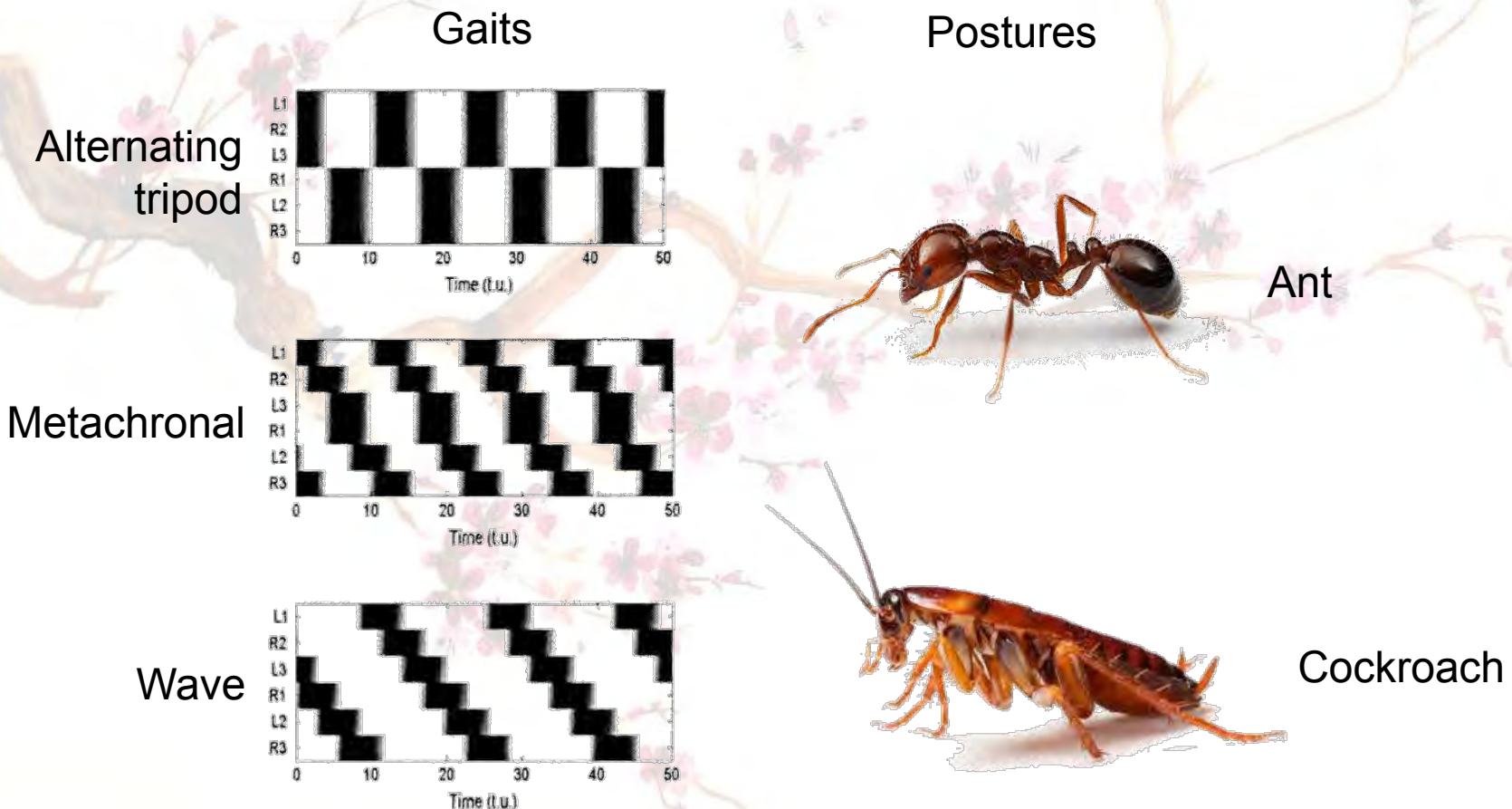
Wave



L. Minati

Versatile motor pattern generation

Canonical gaits and postures in insects

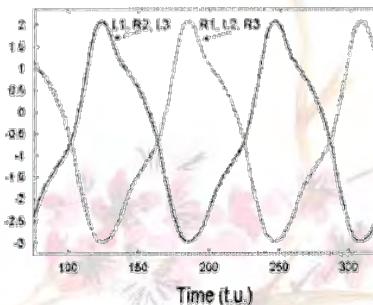
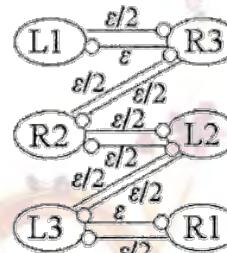
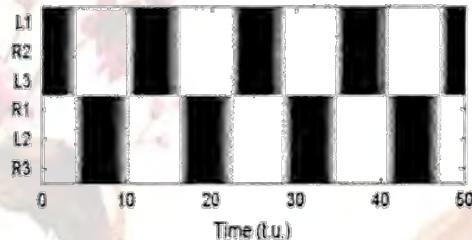


L. Minati

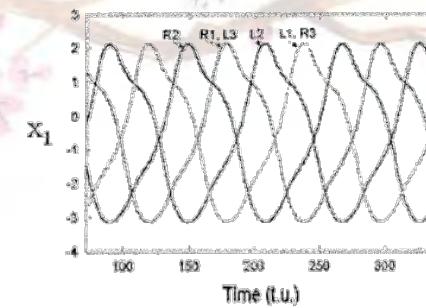
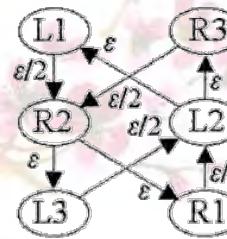
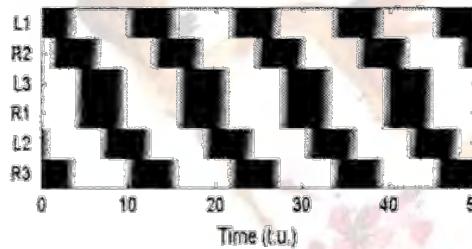
Versatile motor pattern generation

The connectionist approach

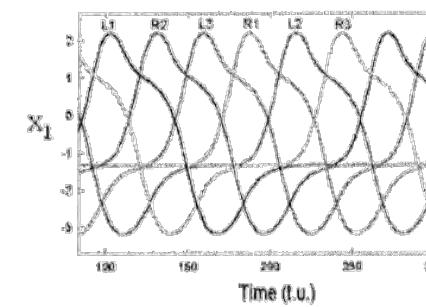
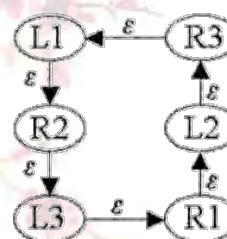
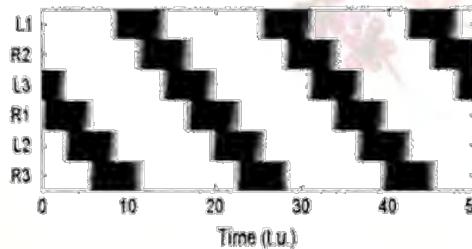
Alternating tripod



Metachronal



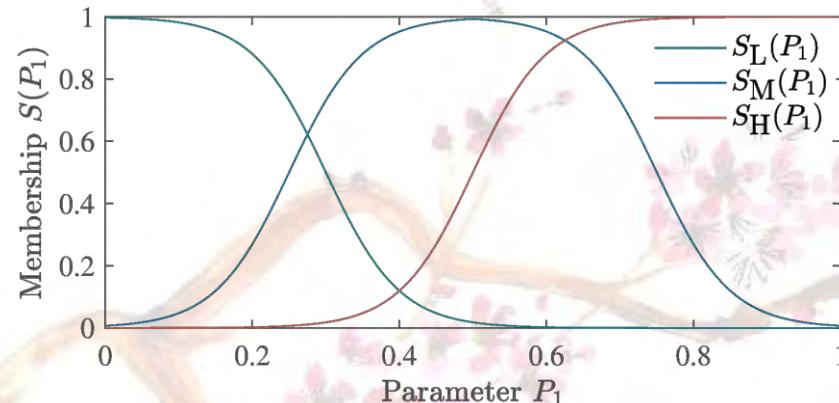
Wave



L. Minati

Versatile motor pattern generation

Generalization via fuzzy membership functions

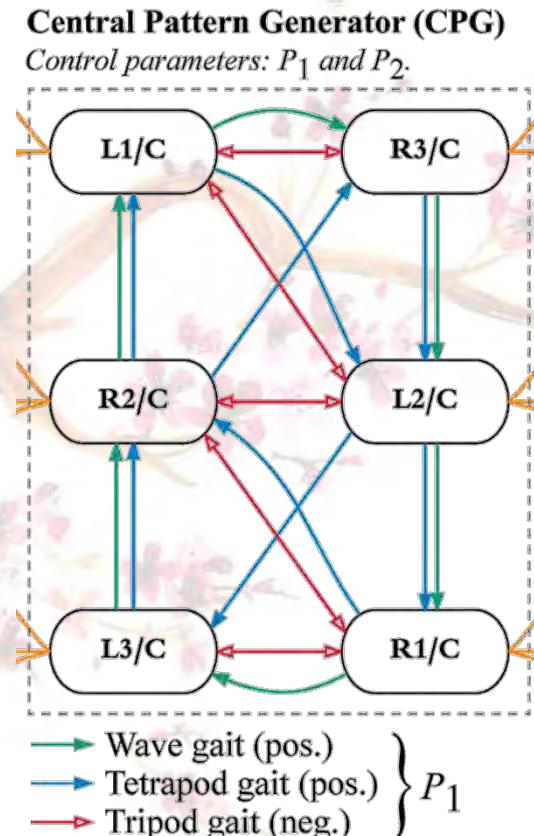


$$\begin{cases} S_L(P_1) = 1 - \frac{1}{1 + e^{A_L(P_1+C_L)}} \\ S_M(P_1) = 1 - \frac{1}{1 + e^{A_M(|P_1+C_M|+C_M/2)}} \\ S_H(P_1) = \frac{1}{1 + e^{A_H(P_1+C_H)}} \end{cases}$$

L. Minati

Versatile motor pattern generation

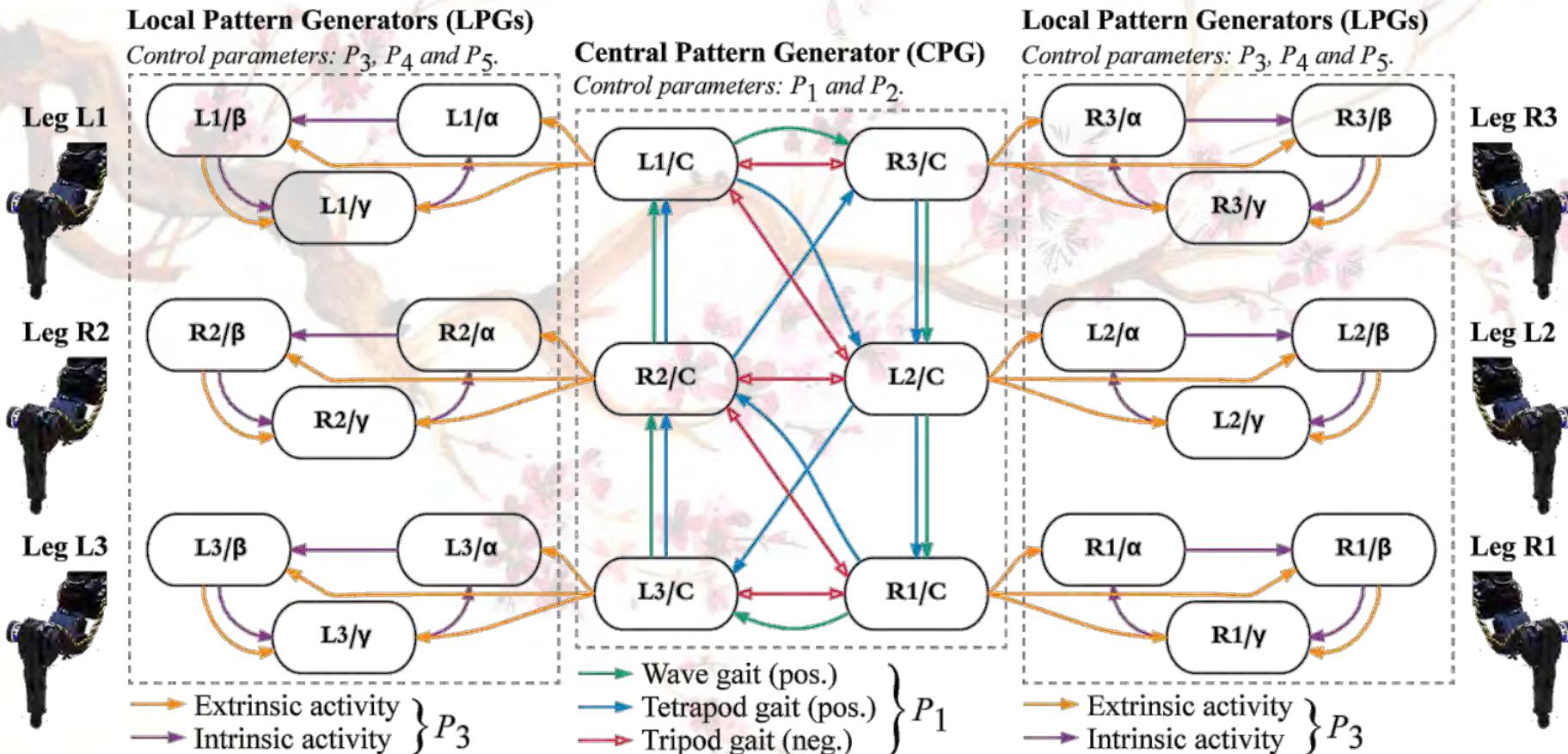
Hierarchical approach (high level: gait, lower level: posture)



L. Minati

Versatile motor pattern generation

Hierarchical approach (high level: gait, lower level: posture)



L. Minati

Versatile motor pattern generation

Problem: connectionist approach → huge number of parameters

L. Minati

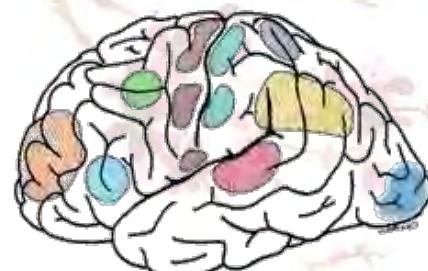
Versatile motor pattern generation

Answer: declutter by collapsing into few higher-level parameters

| Parameter | Range | Target | Denomination | Function |
|-----------|-----------|--------|---|---|
| P_1 | $[0, 1]$ | CPG | Gait selection parameter | Determines the phase relationships between legs, e.g. allows choosing between wave (slow), tetrapod (metachronal, medium speed) and tripod (fast) gaits |
| P_2 | $[-1, 1]$ | CPG | Activation parameter | Allows inhibiting and approximately reversing the CPG activity, i.e. walking |
| P_3 | $[0, 1]$ | LPG | CPG \rightarrow LPG coupling strength parameter | Determines the level of synchronization between the CPG and the LPGs (i.e., movement coordination) |
| P_4 | $[0, 1]$ | LPG | Posture parameter | Allows choosing between the ant-like and cockroach-like postures |
| P_5 | $[-1, 1]$ | LPG | Steering parameter | Allows steering the robot trajectory sideways |

Higher control

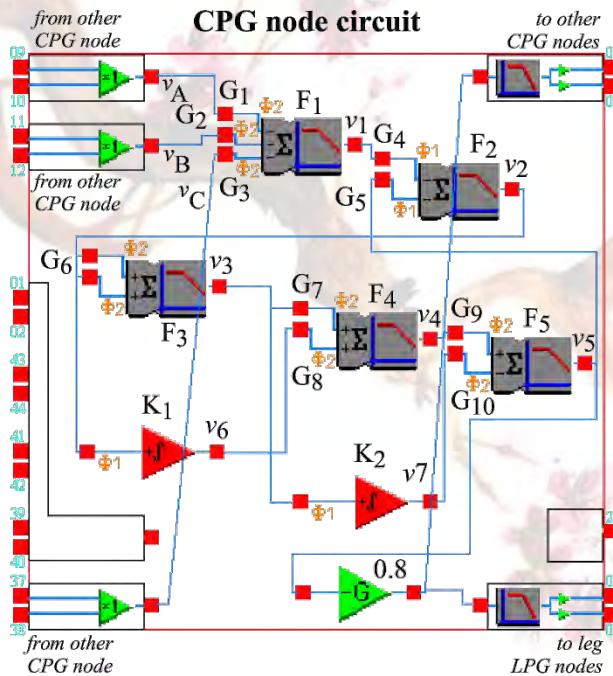
Central pattern generator (CPG)



L. Minati

Versatile motor pattern generation

Node oscillator – almost same as in experiments on remote sync.

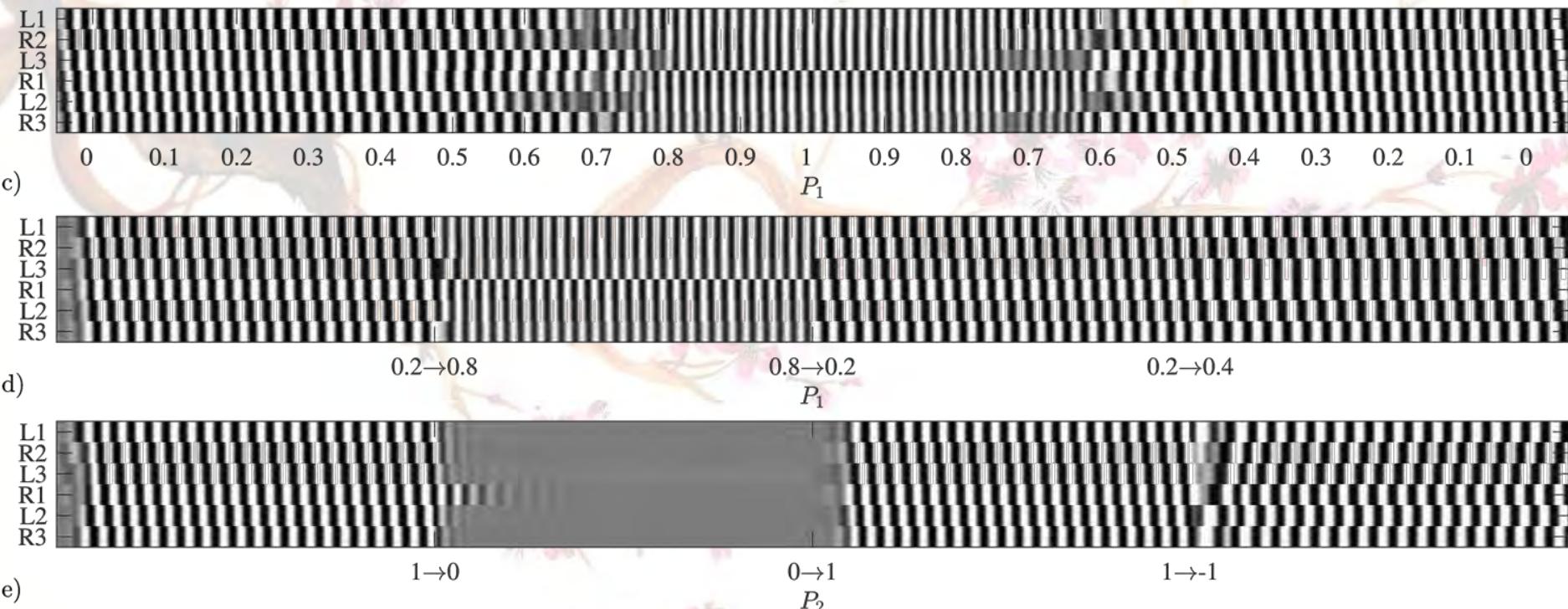


| For node | G_1 | G_2 | G_3 |
|----------|-----------------|-----------------|---------------|
| L1/C | $-S_H/2$ | $-S_H/2$ | $S_M + S_L$ |
| R2/C | $-S_H/2$ | $(S_M - S_H)/2$ | $S_M/2 + S_L$ |
| L3/C | S_M | $S_L - S_H$ | 0 |
| R1/C | $S_M + S_L$ | $-S_H/2$ | $-S_H/2$ |
| L2/C | $(S_M - S_H)/2$ | $S_M/2 + S_L$ | $-S_H/2$ |
| R3/C | 0 | S_M | $S_L - S_H$ |

L. Minati

Versatile motor pattern generation

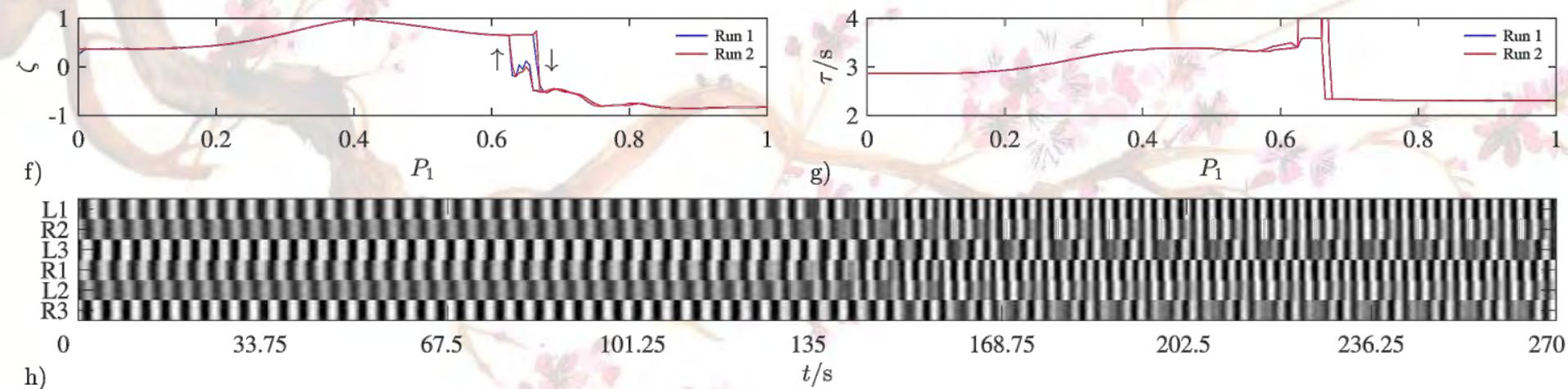
CPG controllability – effect of parameters P1 and P2



L. Minati

Versatile motor pattern generation

Emergent hysteresis and metastability, as in living insects!

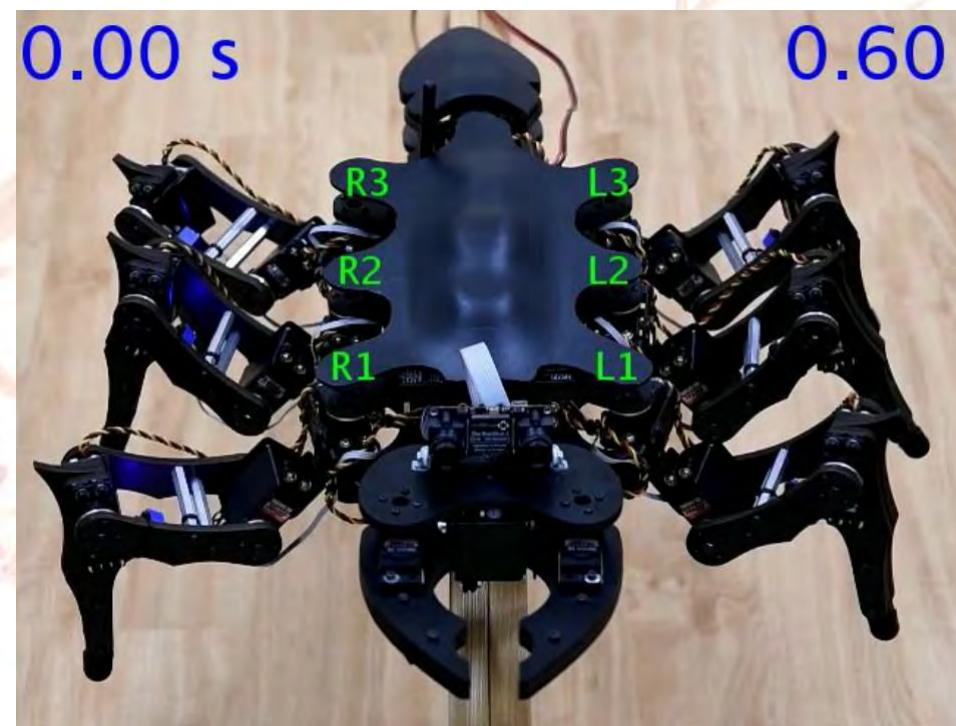
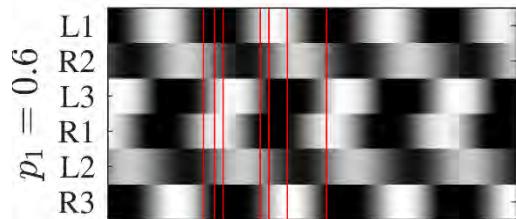


L. Minati

Versatile motor pattern generation

Emergent intermediate patterns, turn out to be viable

Paradoxical gait

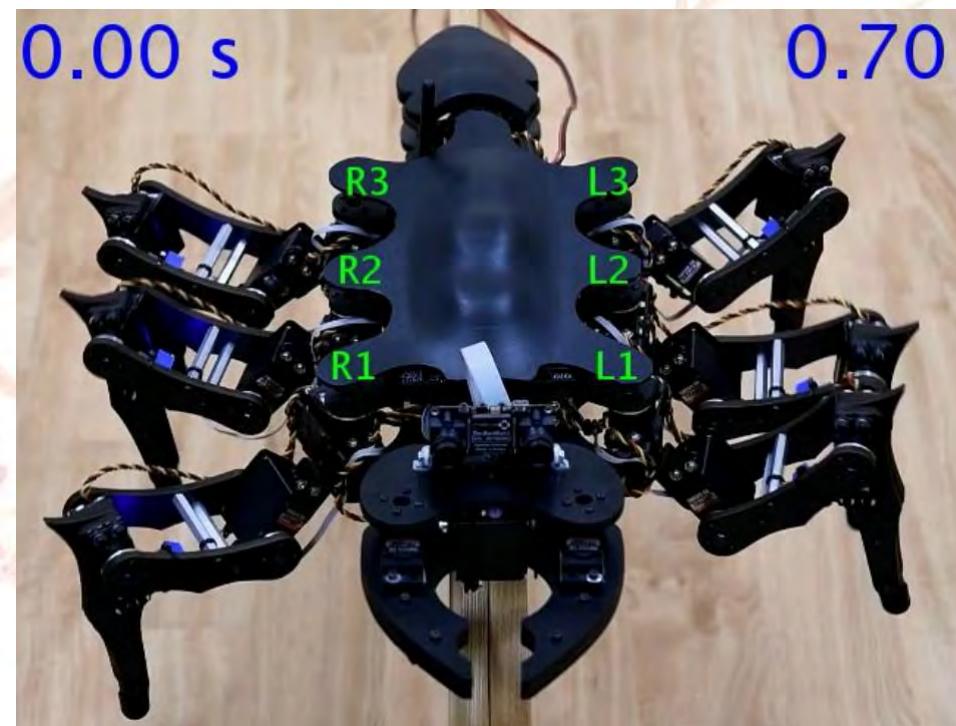
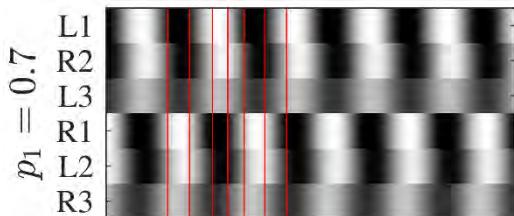


L. Minati

Versatile motor pattern generation

Emergent intermediate patterns, turn out to be viable

Unstable gait



L. Minati

Versatile motor pattern generation

Posture and leg kinematics - Different power stroke delivery

Ant



All: coxa-body

Cockroach



Front, hind: femur-tibia
Middle: coxa-body

*More non-linear circuits: integrated implementation, versatile
motor pattern generation, criticality*

L. Minati

Versatile motor pattern generation

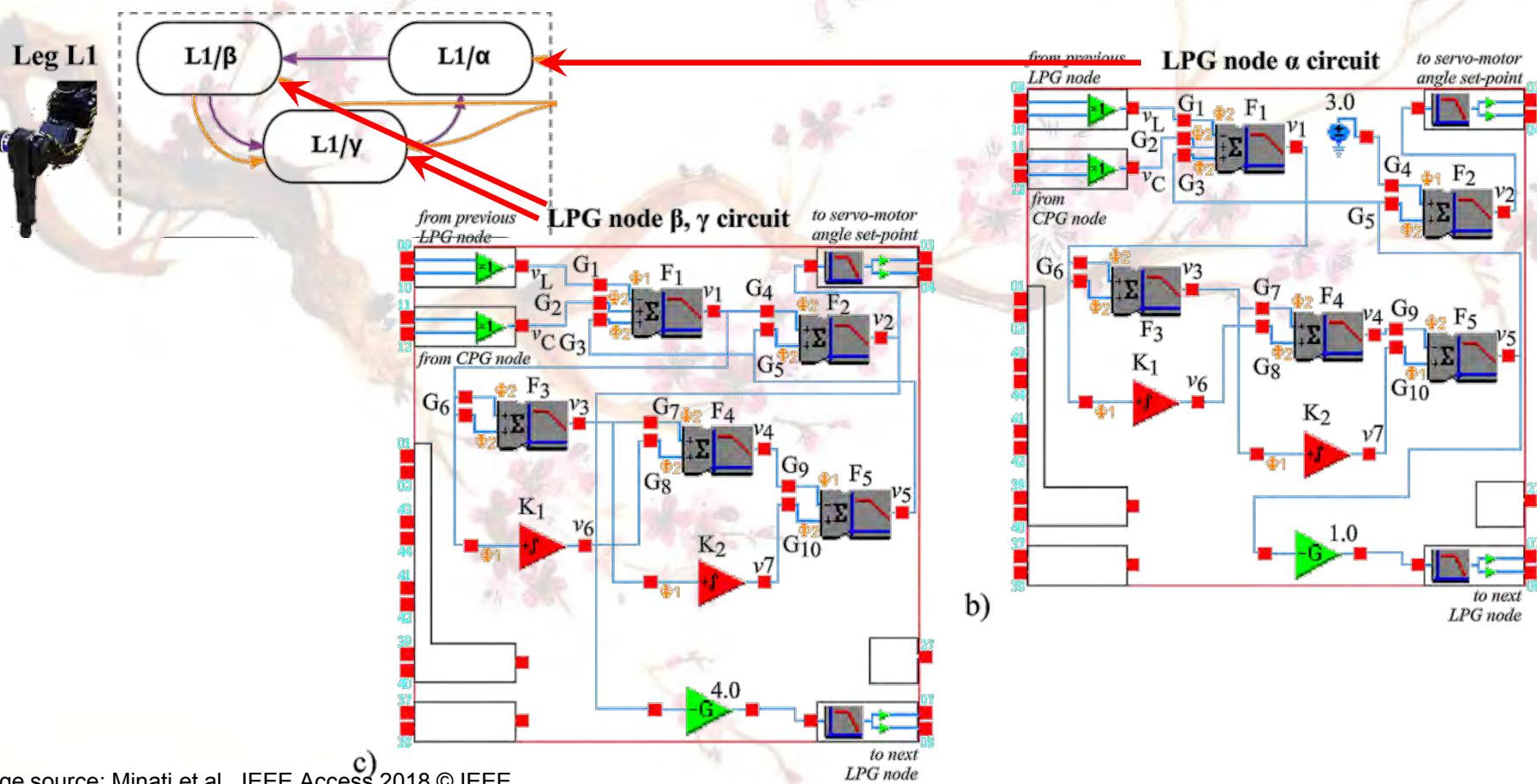
Posture and leg kinematics - Different power stroke delivery



L. Minati

Versatile motor pattern generation

No explicit kinematic model, but dedicated oscillator variants

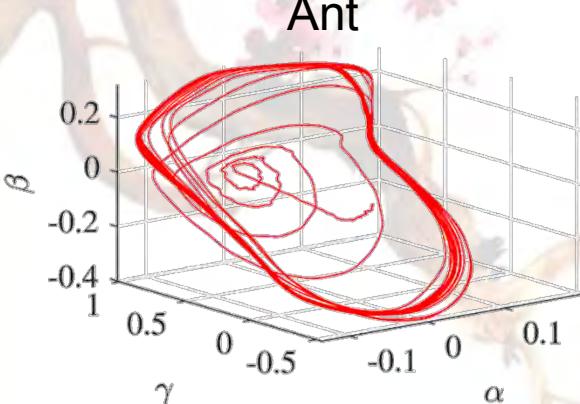


L. Minati

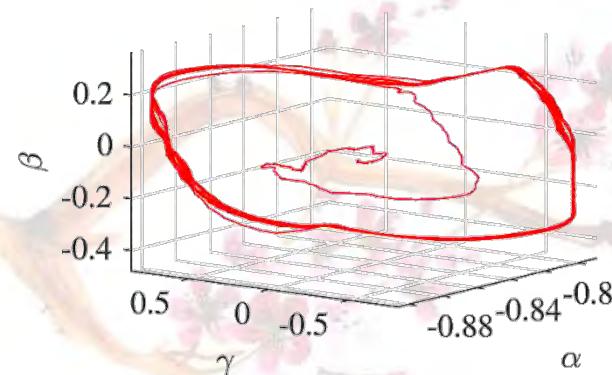
Versatile motor pattern generation

Emergence of limit cycle

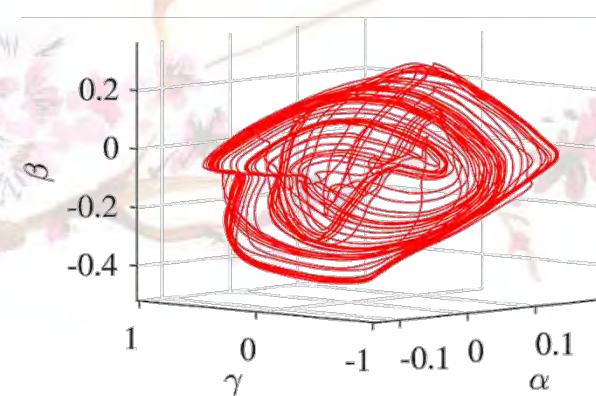
Ant



Cockroach



Deafferentated



L. Minati

Versatile motor pattern generation

Emergence of motor pattern - ant



L. Minati

Versatile motor pattern generation

Generation of motor pattern - ant



L. Minati

Versatile motor pattern generation

Generation of motor pattern - cockroach



L. Minati

Versatile motor pattern generation

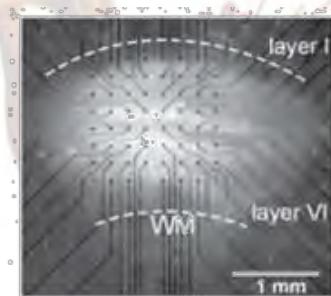
Generation of motor pattern - deafferentated



L. Minati

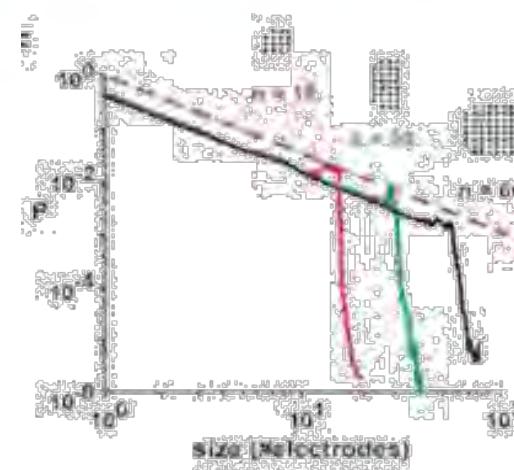
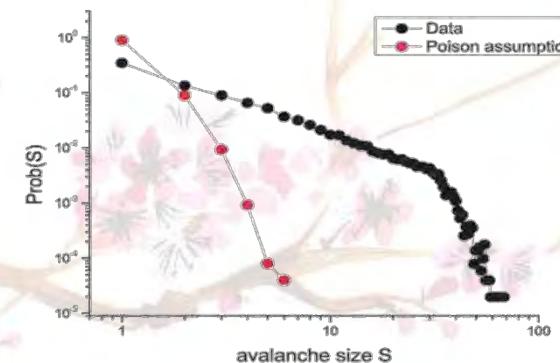
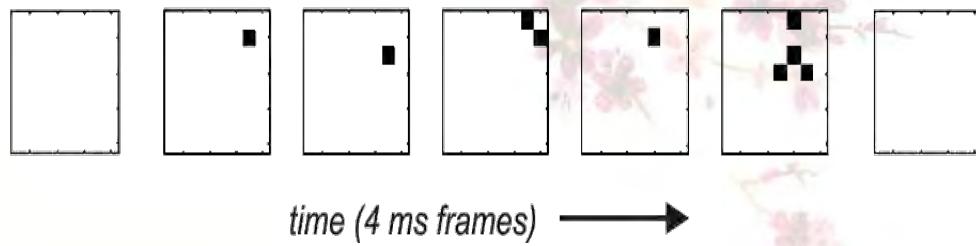
Critical phenomena

Neural avalanches recorded in-vitro and in-vivo



Cortical slice on array

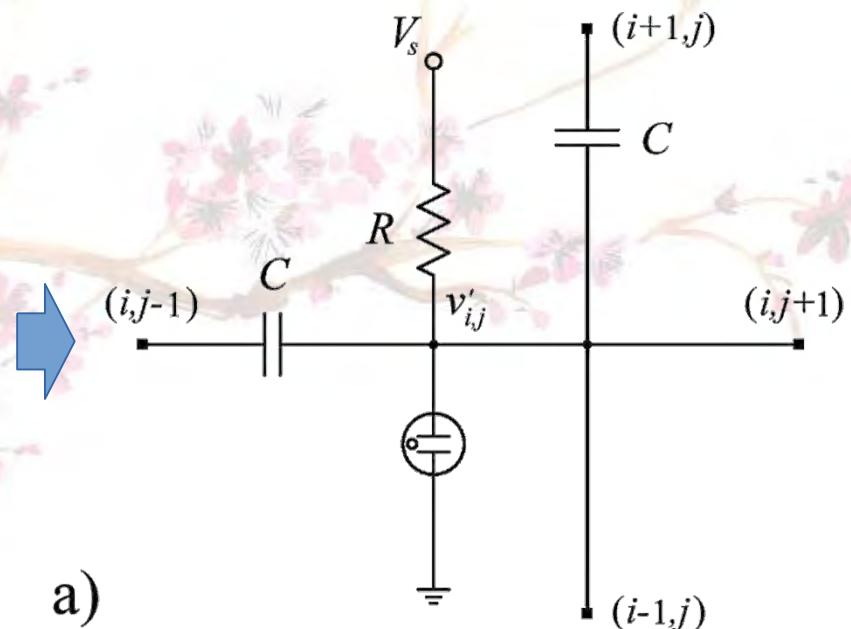
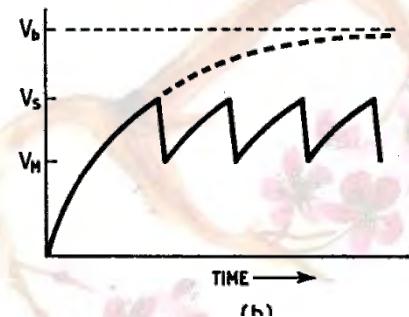
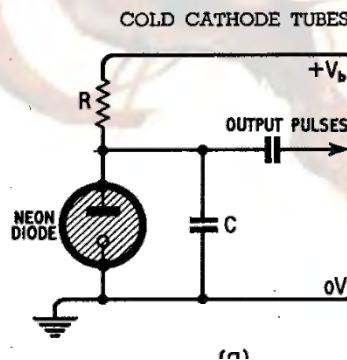
Example of avalanche:



L. Minati

Critical phenomena

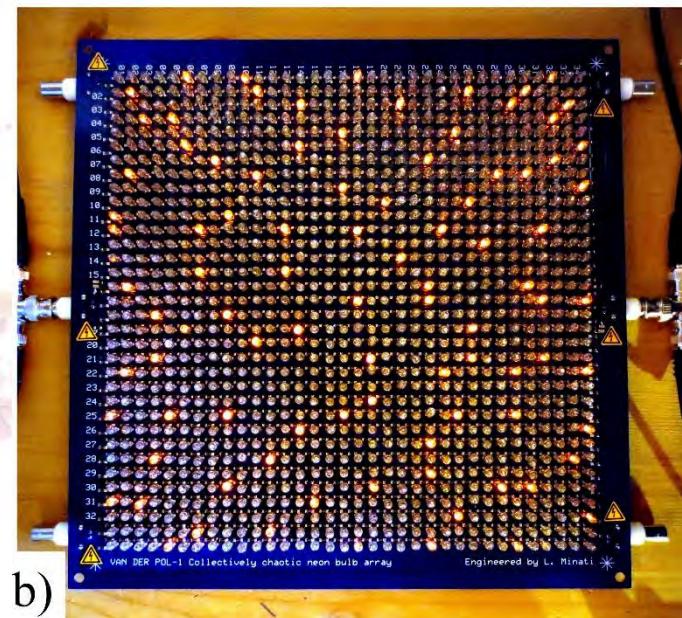
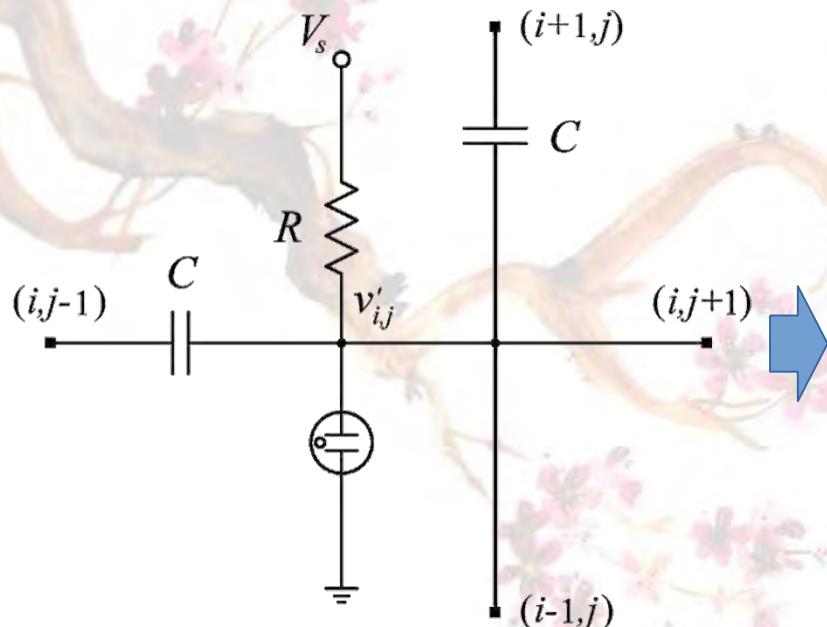
In-silico “replica” of critical dynamics in a 2D lattice



L. Minati

Critical phenomena

In-silico “replica” of critical dynamics in a 2D lattice



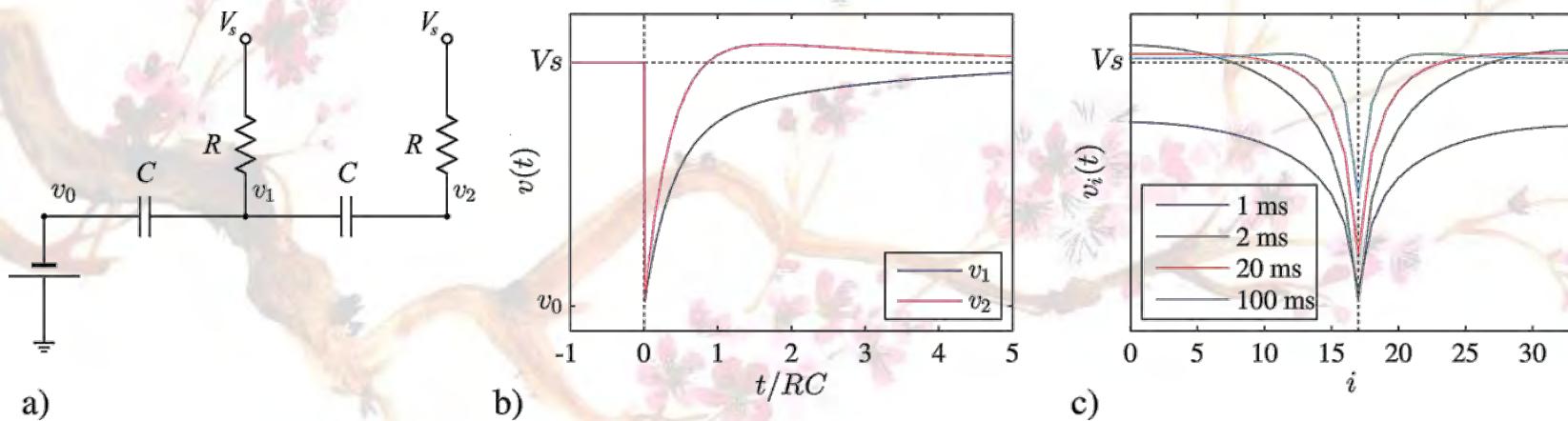
Lattice size: 34 x 34

$V_{\text{strike}} = 76.3 \pm 0.8 \text{ V}$, $V_{\text{extinction}} = 61.4 \pm 0.6 \text{ V}$
 $R = 2.2 \text{ M}\Omega$, $C = 220 \text{ nF}$
2 CCD cameras, 1 photodiode

L. Minati

Critical phenomena

Activity propagation

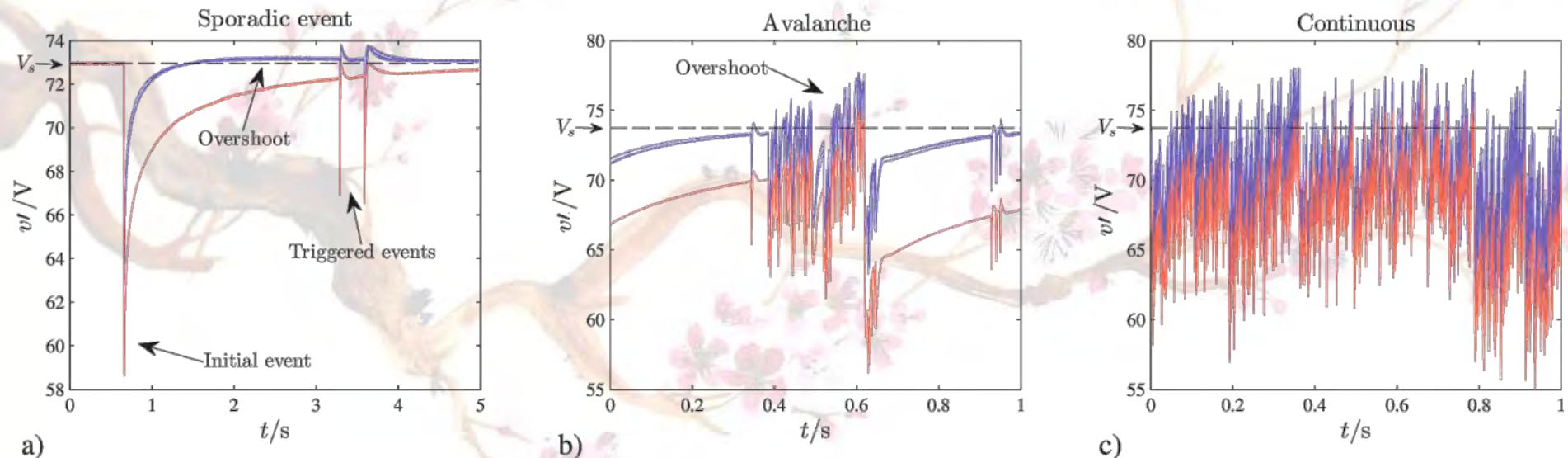


Despite short-range structural coupling, interactions are effectively long-range!

L. Minati

Critical phenomena

Activity propagation

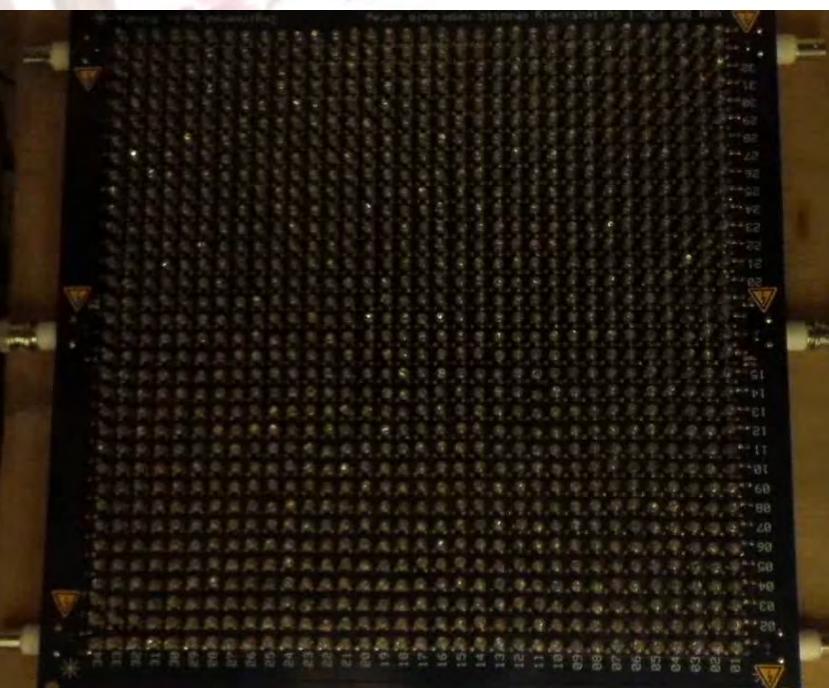


Increasing the supply voltage, activity eventually can propagate and self-sustain.

L. Minati

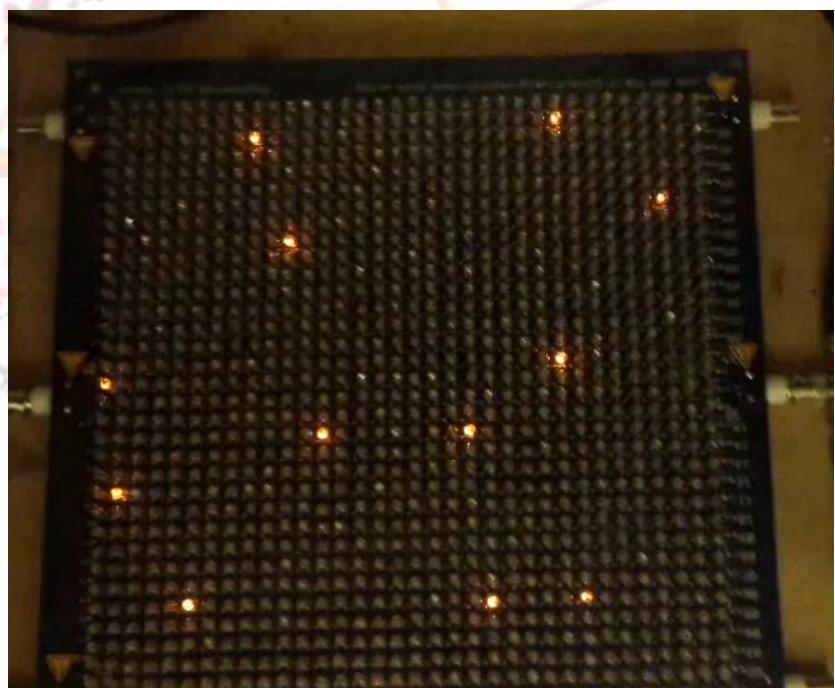
Critical phenomena

Phases I and II



Phase I (low rate, disordered, glass-like)

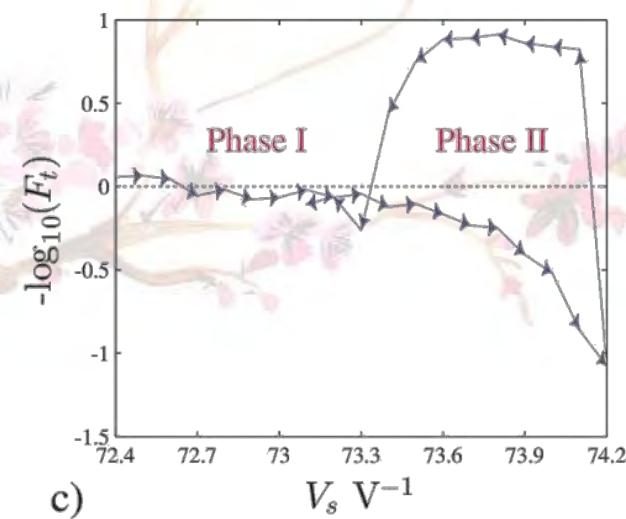
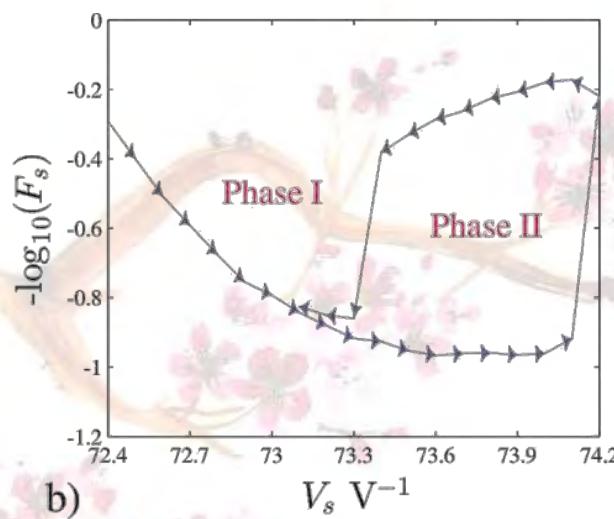
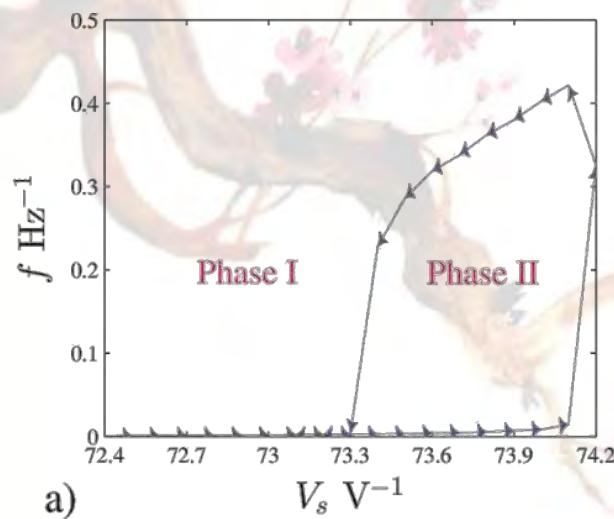
Phase II (high rate, ordered, crystal-like)



L. Minati

Critical phenomena

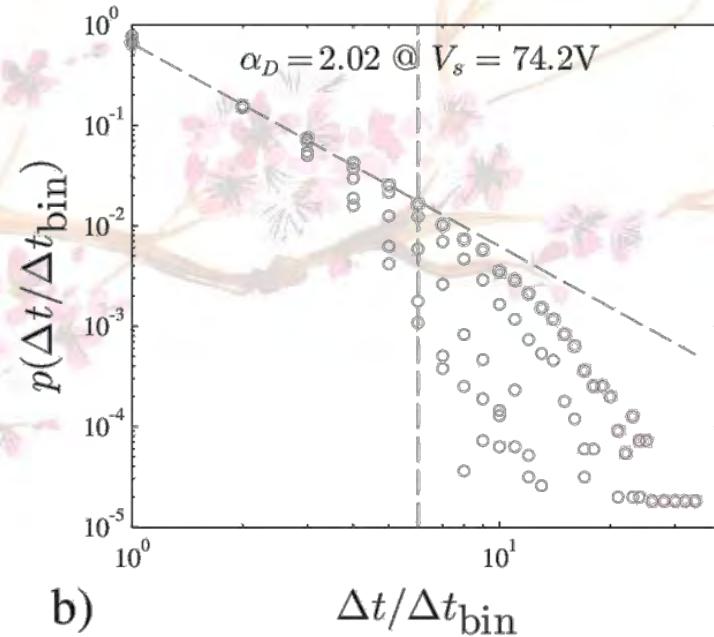
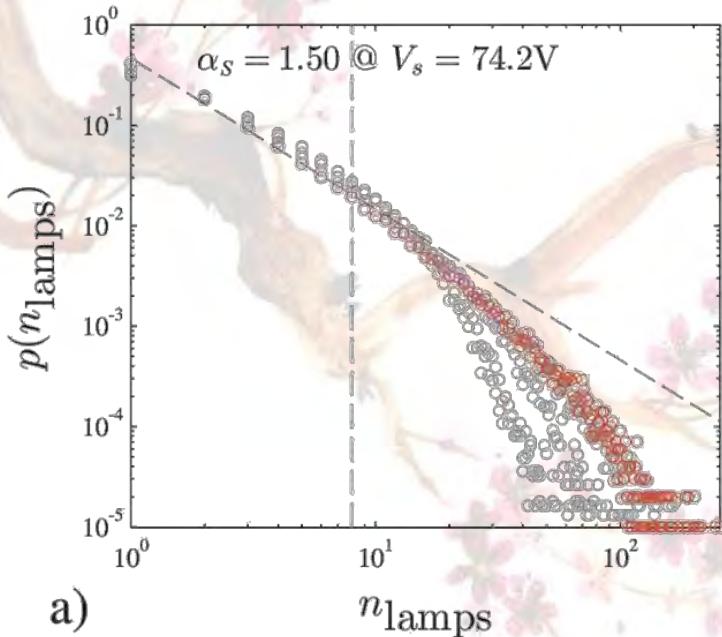
Transition between phases I and II



L. Minati

Critical phenomena

Avalanching





Tokyo Tech



INSTYTUT FIZYKI JĄDROWEJ
IM. HENRYKA NIEWODNICZAŃSKIEGO
POLSKIEJ AKADEMII NAUK

*More non-linear circuits: integrated implementation, versatile
motor pattern generation, criticality*

L. Minati

Conclusions

- 1) Integrated circuit-friendly (area efficient) realization of these circuits is feasible
- 2) Demonstration of application to gait and motor pattern generation. What about sensory processing, or other control functions in homeostasis?
- 3) Possibility to replicate critical phenomena even in elementary configuration (but not self-organized)

L. Minati

Thank you for your attention

References:

1. Minati L. Experimental Implementation of Networked Chaotic Oscillators Based on Cross-Coupled Inverter Rings in a CMOS Integrated Circuit. *J Circuit Syst Comp* 2015; 24:1550144
2. Minati L, de Candia A, Scarpetta S. Critical phenomena at a first-order phase transition in a lattice of glow lamps: Experimental findings and analogy to neural activity. *Chaos*. 2016; 26(7):073103
3. Minati L, Frasca M, Yoshimura N, Koike Y. Versatile locomotion control of a hexapod robot using a hierarchical network of non-linear oscillator circuits. *IEEE Access* 2018; 99:2799145
4. Minati L, Frasca M, Yoshimura N, Ricci L, Oświecimka P, Koike Y, Masu L, Ito H. Current-Starved Cross-Coupled CMOS Inverter Rings as Versatile Generators of Chaotic and Neural-Like Dynamics Over Multiple Frequency Decades. *IEEE Access* 2019; 7:54638
5. Minati L, Across Neurons and Silicon: Some Experiments Regarding the Pervasiveness of Nonlinear Phenomena. *Acta Phys Pol B* 2018; 49:2029.

 minati.l.aa@m.titech.ac.jp lminati@ieee.org ludovico.minati@ifj.edu.pl <http://www.lminati.it>