# Scalable Experimental Network of Excitable Boolean Nodes

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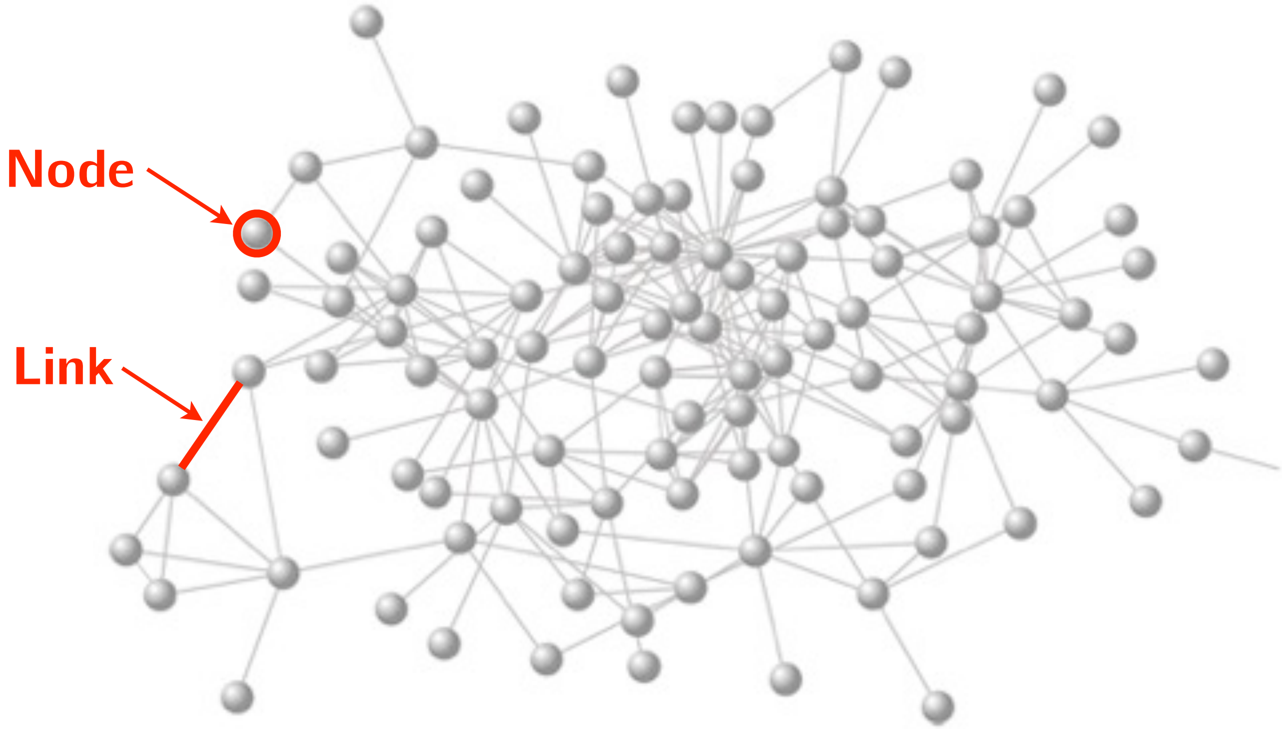
# Context and Motivations

*A neural network in the brain*




*A social network of college students*

- Ubiquity of Large and Complex Networks
  - Biology, Social, Finance, Electric Grids, Transports
- Intensive Theoretical and Analytical Studies of Real Networks
  - Stability, Control, Synchronization. *M.E.J. Newman, Oxford University Press (2010)*
- Difficulties to **Build** Experimentally Large Networks
  - State of the art: 7-nodes time-delay network with lasers

*Nixon et al. PRL (2011)*

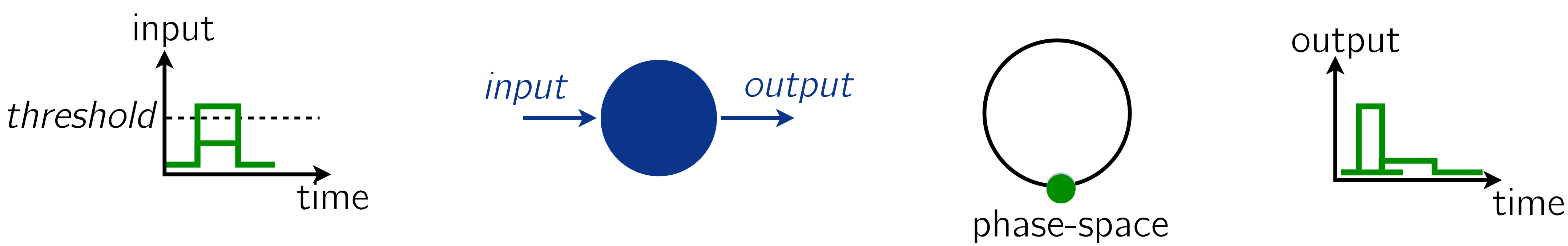
# Excitable Nodes

## - Why Excitable Nodes?

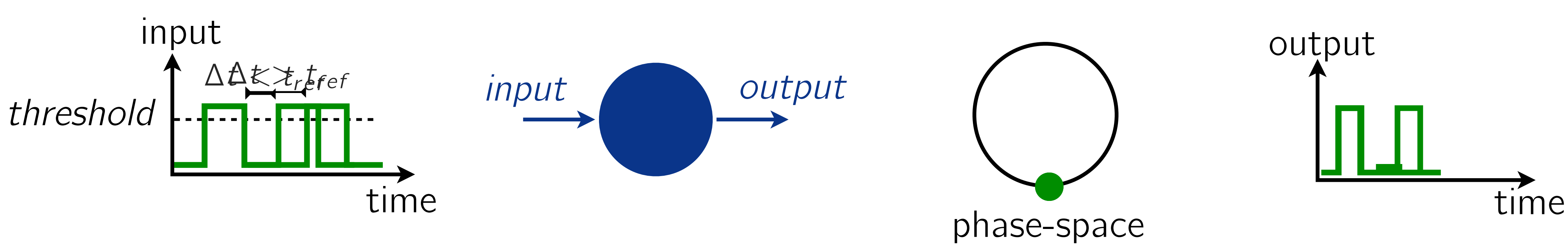
*J.D. Murray, ''Mathematical Biology'', Springer (1993)*
*A. Mikhailov, ''Foundations of Synergetics'', Springer (1994)*

## - Quick Recall on Excitable Dynamics

**PULSE (''SPIKE'') GENERATION**




**RECOVERY (''REFRACTORY'') PERIOD**



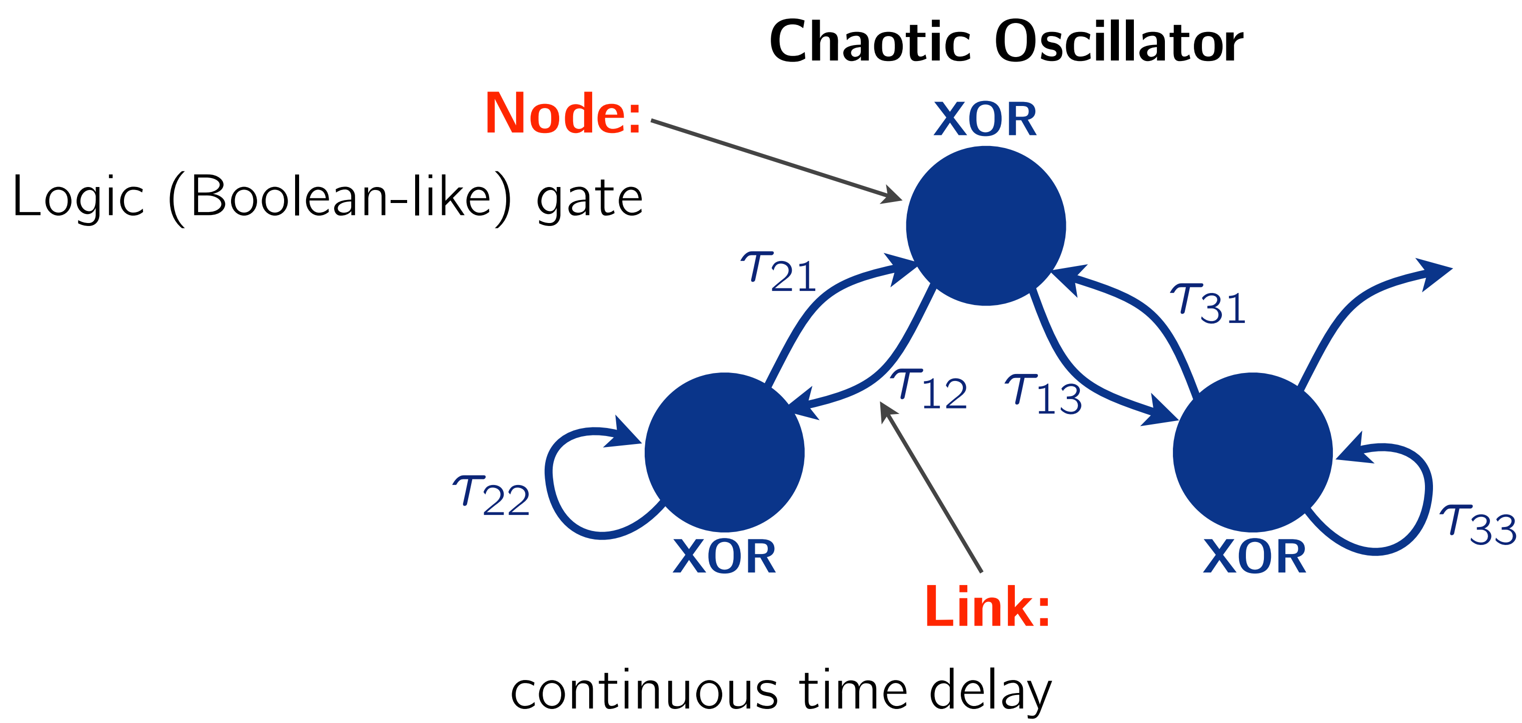
# Logic Gate as Network Node

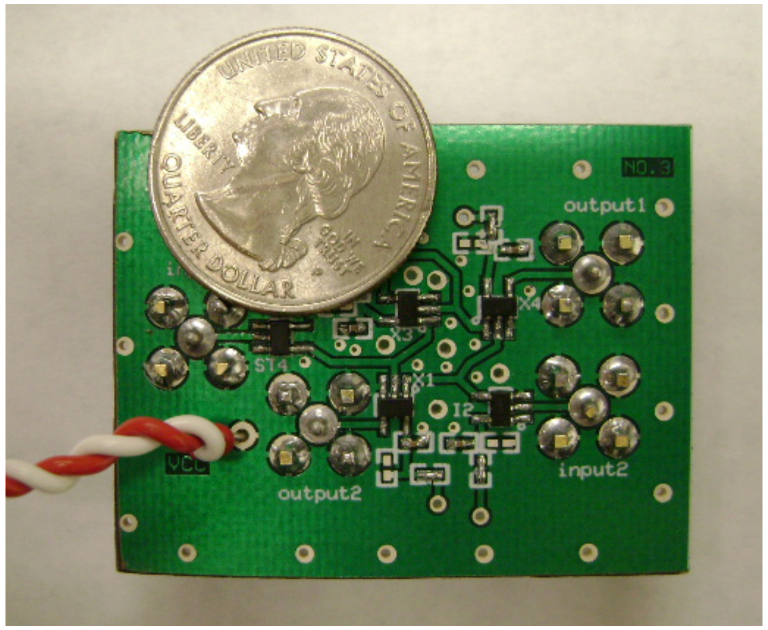
## - Previous Research

- Periodic and chaotic oscillator with logic gates

  *R. Zhang et al. PRE Rapid (2009) • H. Cavalcante et al. Philo. Trans. Royal Soc. A (2009)*

**AUTONOMOUS (a.k.a ASYNCHRONOUS) SYSTEMS : NO CLOCK!**



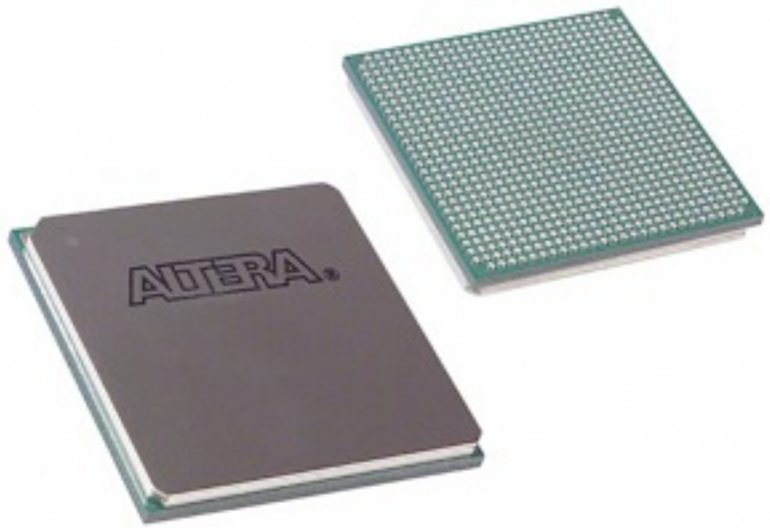




## - Major Challenges to Build Large Networks of Excitable Nodes

- **Scalability and Flexibility**: rewire quickly a very large network is hard
- **Excitability**: no template for a boolean version of excitable node

# Experimental Platform (1)

## - The **F**ield **P**rogrammable **G**ate **A**rray (FPGA) by the Numbers




*Altera FPGA Cyclone IV*

- Number of available logic elements/blocks: 115,000
- **Time to build/rewire a network: few minutes !**
  - To be compared to months with other approaches...
- (Very) low cost : **$300**

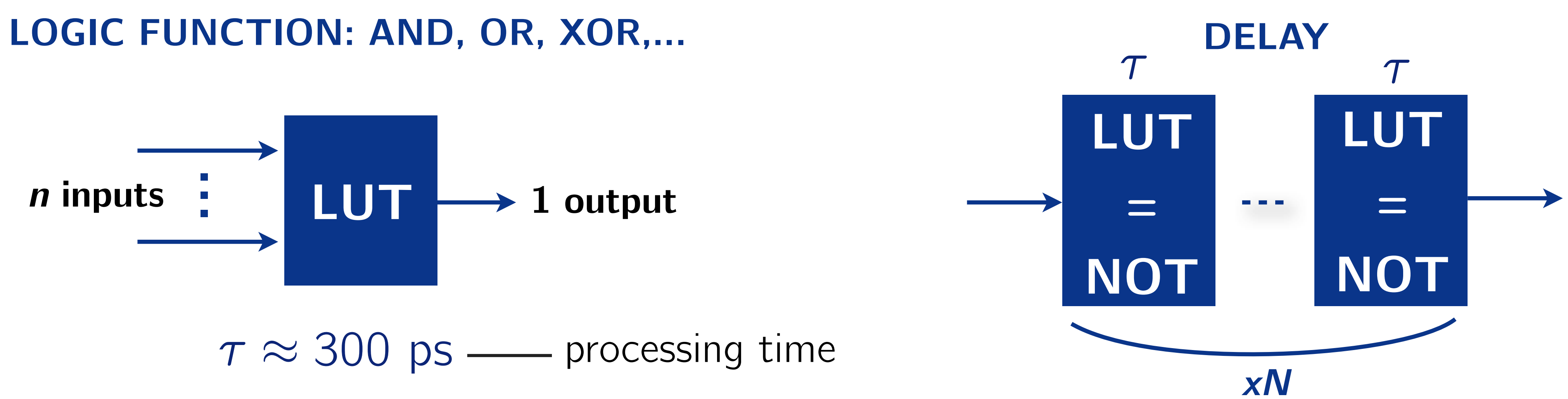
## - Principles of Implementation

- Use of hardware description language (VHDL, Verilog)
- **Logic elements are wired physically on the board**
  - User specifies logic function of each node and the links (network topology)
- All the features of a true experimental platform
  - Electronic noise and **heterogeneity** for nodes and links

# Experimental Platform (2)

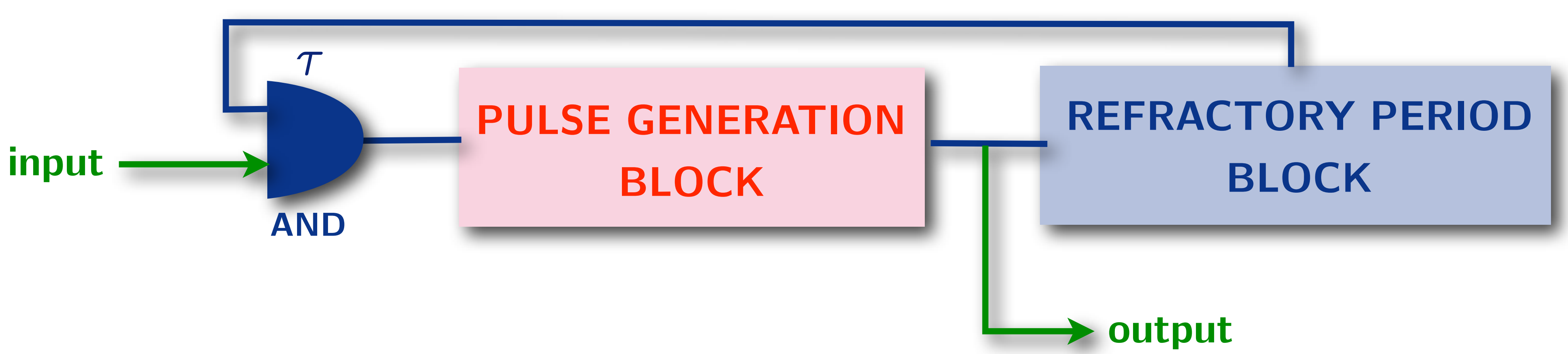
## - Exploiting FPGA's Logic Elements to Build Boolean Nodes

- Two fundamental building blocks for boolean network: **Nodes** and **Links**
- Usable elements on the FPGA: **Logic Elements** with **L**ook-**U**p **T**ables




## - Building an Excitable Boolean Node on the FPGA

- Two interconnected blocks composed of **unclocked** logic elements



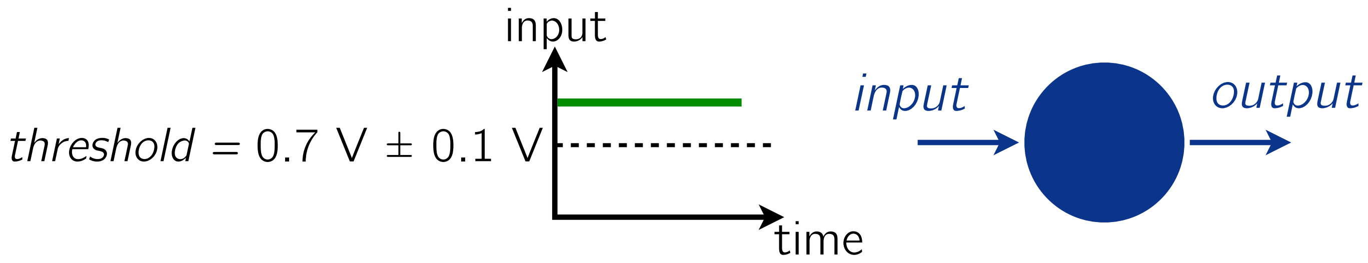
# Experiment with a Single Node

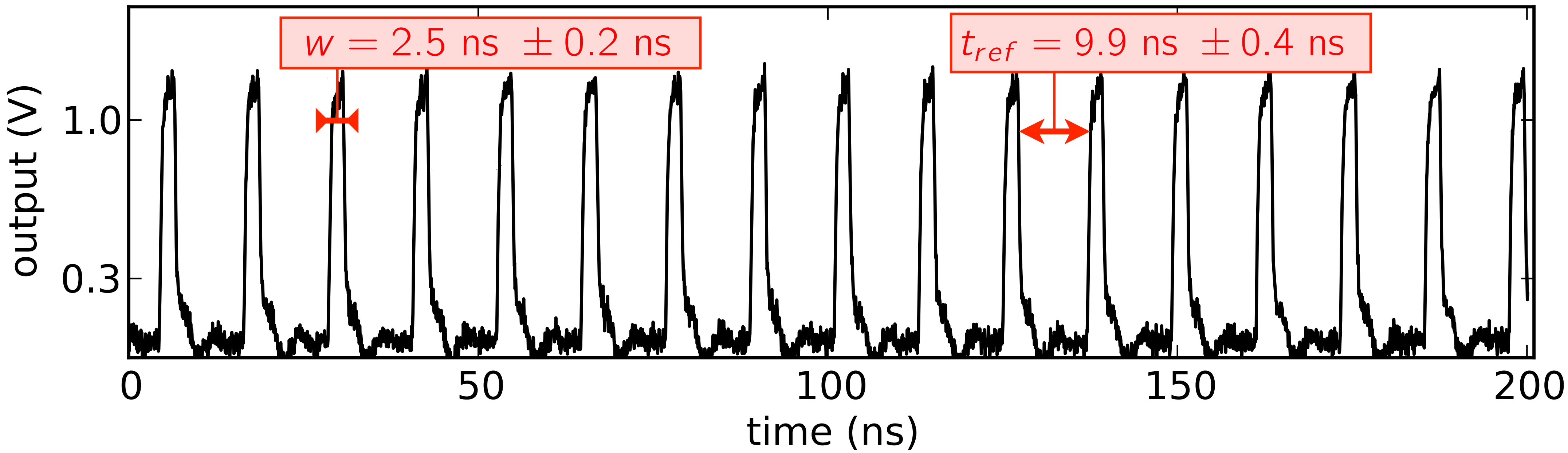
## - Implementation on the FPGA Board

- Use of 40 logic elements per node
- Logic elements are **unclocked**
- Pulse Block: 4 elements - Refractory Block: 36 elements

## - Experimental Test of a Single Node

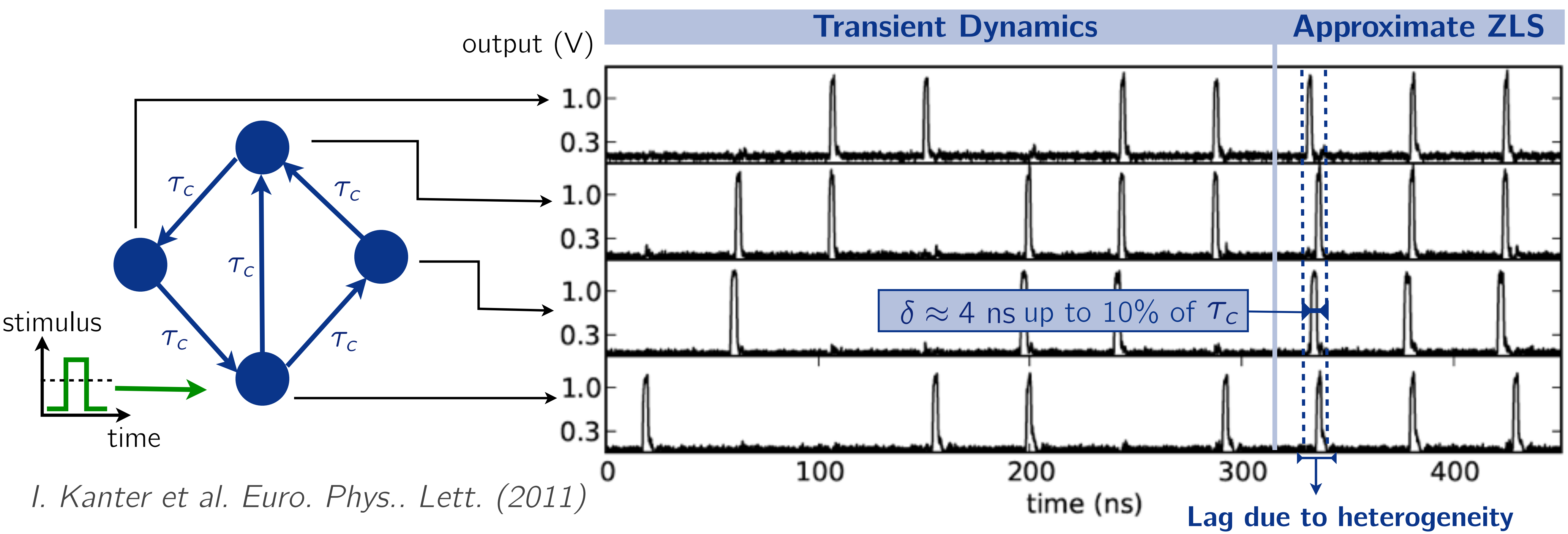
- Pulse of width w=2.5 ns and refractory period $t_{ref}$ = 10 ns (approx)



# Experiment on Small Network

- Implementation of a Small Network on the FPGA Board
  - Links use 160 logic elements and present **heterogeneity** in delays
- Approximate Zero–Lag Synchronization (ZLS)
  - Network synchronization if appropriate values of delays and $t_{ref}$
  - Heterogeneities (up to 2.5%) prevent perfect ZLS



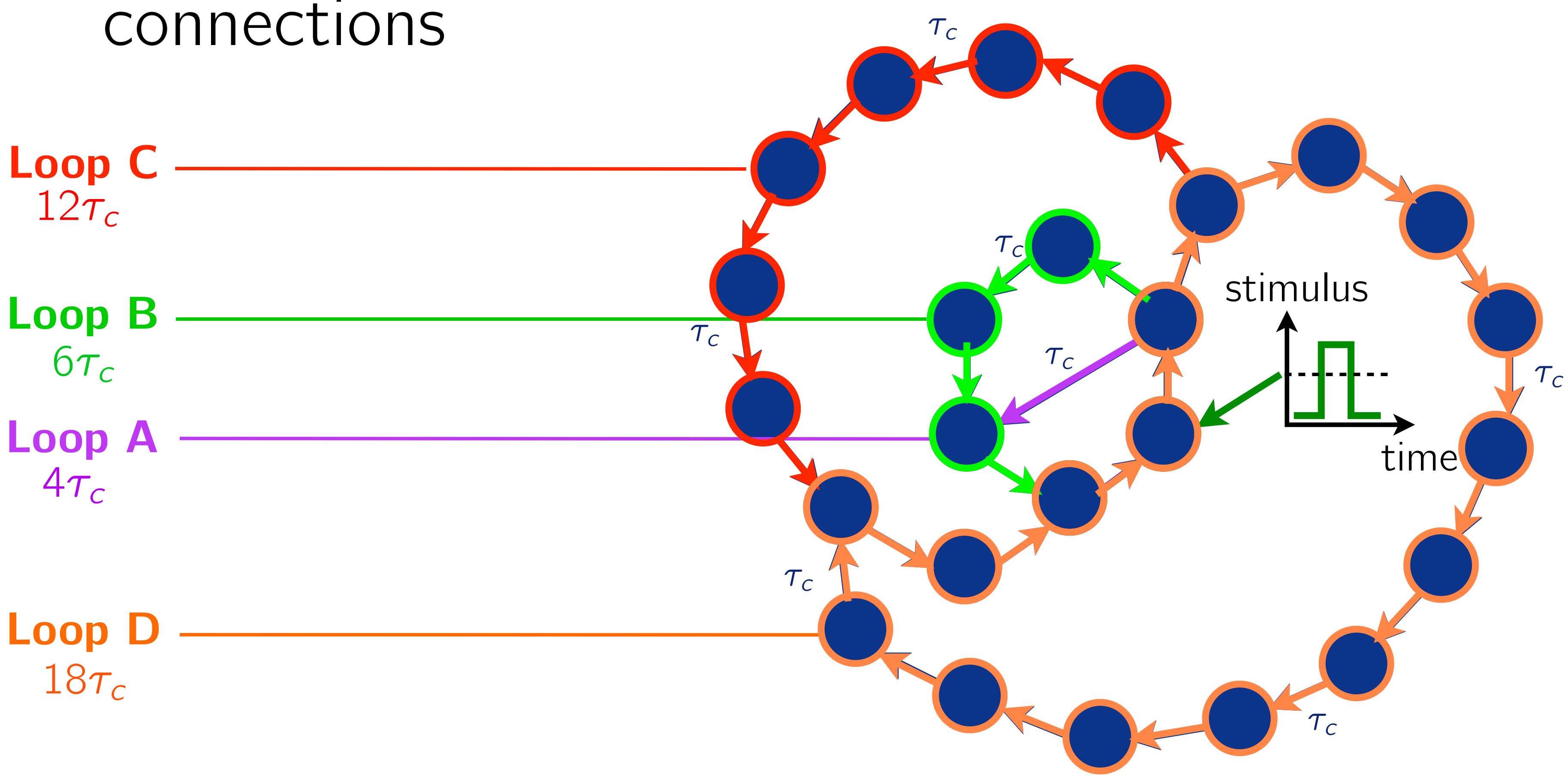

*I. Kanter et al. Euro. Phys.. Lett. (2011)*

# Experiment on Large Network (1)

*I. Kanter et al. Euro. Phys.. Lett. (2011)*

## - Clustered Zero-Lag Synchronization in Neural Circuits

- Activity Mode of the entire Network governed by a **nonlocal quantity**
- The greatest common divisor **(GCD)** of the directed loops
- In theory, purely excitable systems with no noise with uniform delayed connections

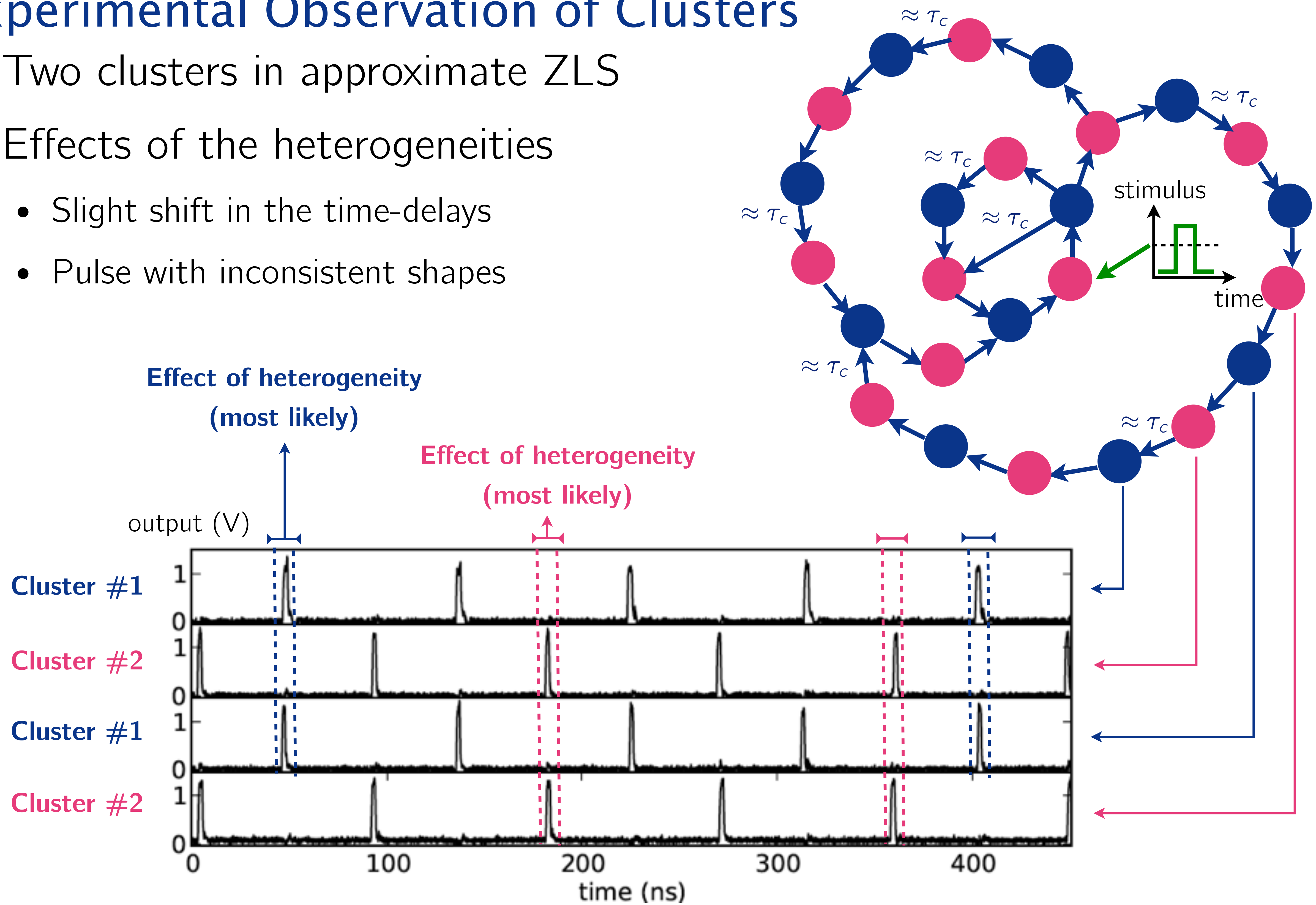



**GCD(A,B,C,D) = 2 => Two clusters expected**

# Experiment on Large Network (2)

## - Experimental Observation of Clusters

- Two clusters in approximate ZLS
- Effects of the heterogeneities
  - Slight shift in the time-delays
  - Pulse with inconsistent shapes



# Conclusion

- We found an efficient way to create an excitable system with logic elements

- We implemented it on an **FPGA**

- FPGA: **Flexible platform** with great potential for studying large autonomous boolean networks

- We experiment on large network (2–3X size of the experimental state-of-art)

- Observation of approximate zero-lag synchronized clusters

- We also built a very large ring network (500 nodes)