Distributed Dynamics Analysis of Spiking Neural Network Simulations

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Outline

- Motivation
- Spiking Neural Network Simulations
- Current Approach
- Results
- Conclusions & Outlook

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UTCN
Marius Joldos
Radu Peter
Andrea Gindele
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Mihai Alexe
IGE
Adrian Colesa
CONEURAL
Raul Muresan

Motivation

- **Simulation of neural microcircuits** – vital investigation instrument for understanding brain behavior dynamics
- Realistic **neural models** and interconnecting **microcircuit topology** →computationally expensive simulations
- Adoption of **multi & many-core** processing is rather slow
  - Need to **understand & quantify** the impact on the quality of the simulation results, esp. where the **dynamics behavior of neural microcircuits is critical**
- Our investigation focus:
  - **Support for distributed processing of spiking neural network (SNN) simulations → OpenMP+MPI hybrid parallelization → increased processing power**
  - **Dynamics analysis (improve dimensionality reduction)**

Simulation of Biological Neural Microcircuits at a Glance

- Research goal: study the impact of parallelization strategies on the dynamics behavior of neural microcircuits

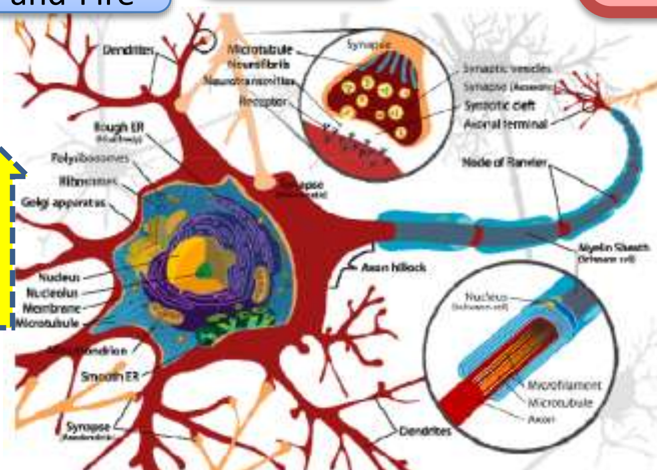
Joint work with Dr. Raul Muresan, CONEURAL

Hodgkin-Huxley | Izhikevich | Abbott-Kepler | Integrate-and-Fire → Spike Response Model → Biological Neural Microcircuits → Spike-Time Dep.Plasticity

Input parameters
- activation current
- model elements & values
- geometry information (#neurons, #synapses, topology etc)
- etc.

(slight changes impact the dynamic behavior)

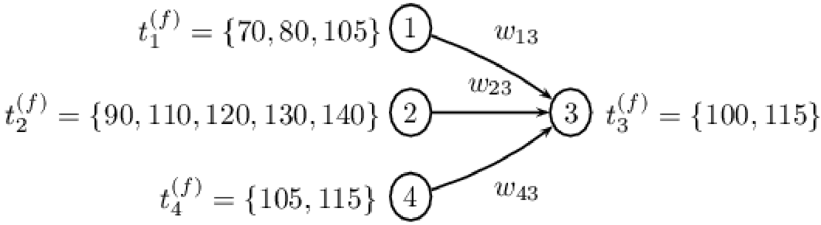
Brian | NEURON | Neurosim | GENESYS → Dynamics Analysis | Learning | Information Encoding | Long-Term Memory

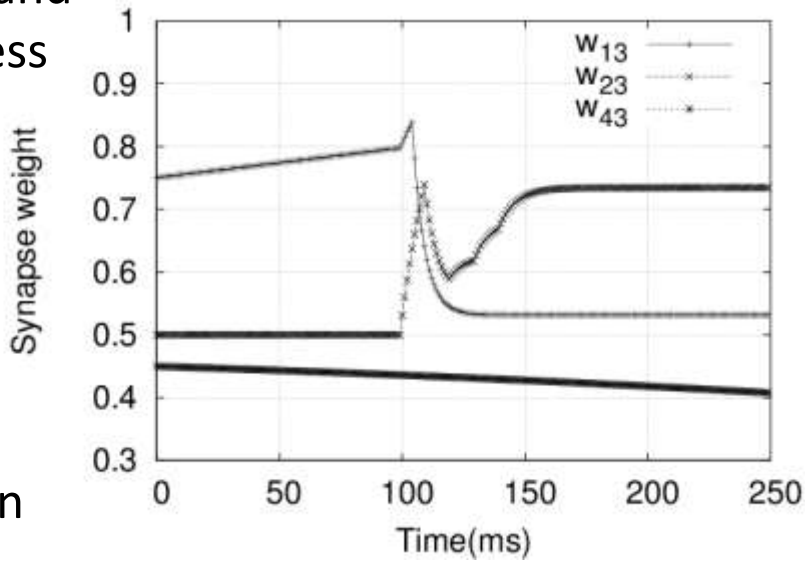


Neuron image source: *Purves, Neuroscience, 2004.*

Spike Response Model & Spike Time-Dependent Plasticity

- Spike – electrical discharges of the neuron’s cell membrane
  - Basic signs of neural activity
- Spike Response Model – neuron model (SRM)
  - Discharge times depend spikes timing and not physical, chemical, biological process details
  - Relay on the relation between pre-synaptic and post-synaptic spikes
- Spike Time-Dependent Plasticity - synapse model (STDP)
  - Strength of the synapse (w) depends on incoming & outgoing spikes





Simulation Insights

Synchronous simulation strategy

global simulation time **t**

SRM for computing membrane potential **u**

STDP for synapse strength **w**

```
t=0
while t<duration
  for every neuron                          State updates
    process incoming spikes
    advance neuron dynamics by dt
  end

  for every neuron
    if vm>threshold
      reset neuron                          Propagation
      for every connection                  of spikes
        send spike
      end
    end
  end

  t=t+dt
end
```

Parallelization potential of the for-loop blocks depends on the neuron and synapse models.

- Incoming and outgoing spike history needed by SRM and STDP
- Here, a glance to STDP

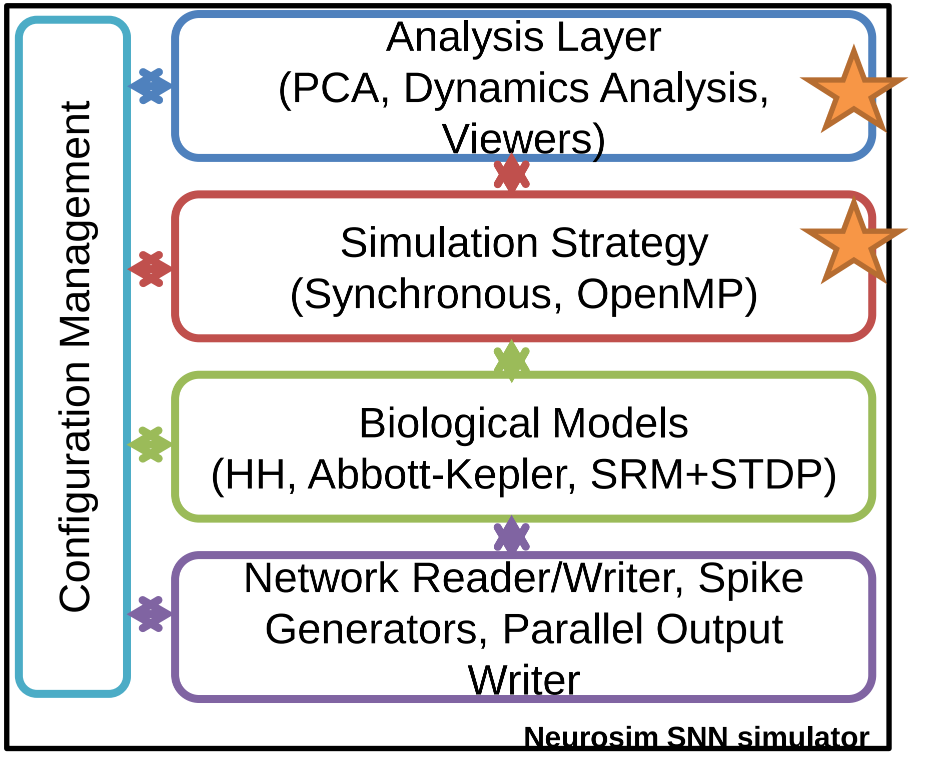
$$\frac{\mathrm{d}}{\mathrm{d}t} w_{ij}(t) = a_0 + S_j(t)\left[a_1^{pre} + \int_0^\infty a_2^{pre,post}(s) S_i(t-s) ds \right] + S_i(t)\left[a_1^{post} + \int_0^\infty a_2^{post,pre}(s) S_j(t-s) ds \right]$$

$$W(s) = \begin{cases} A_+ \exp[s/\tau_1] & \text{for } s < 0 \\ A_- \exp[-s/\tau_2] & \text{for } s > 0 \end{cases}$$

- s – time difference between historical incoming and outgoing spike pairs
- **Spike history** over a significant simulation period must be **managed**!
- **Exponential evaluation** dominated calculations

Simulation Framework - Neurosim

- In house spiking neural network simulator (SNN)
- Small-world topologies and biological models
- Framework for experimenting multi-&many-core technologies
- Employed in the study of the **dynamic behavior**



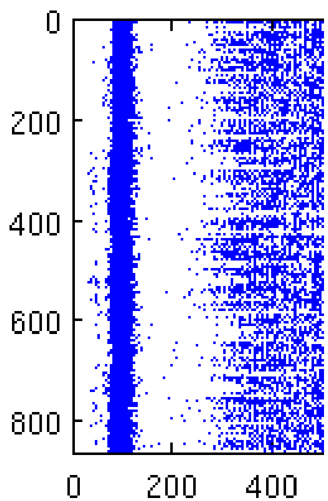
MPI extensions added in the current work

Results are compared with reference simulation scenarios computed with community tools

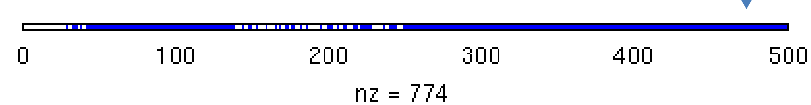
Dynamics Analysis Approach

- Based on the Lyapunov exponent method $\delta x(t) = \delta x(0) \exp \lambda t$
  - dx – time-dependent between **trajectories** of the microcircuits
  - t – time in which the system has evolved
    - Λ≥0 → chaotic behavior
    - Λ=const → periodic behavior

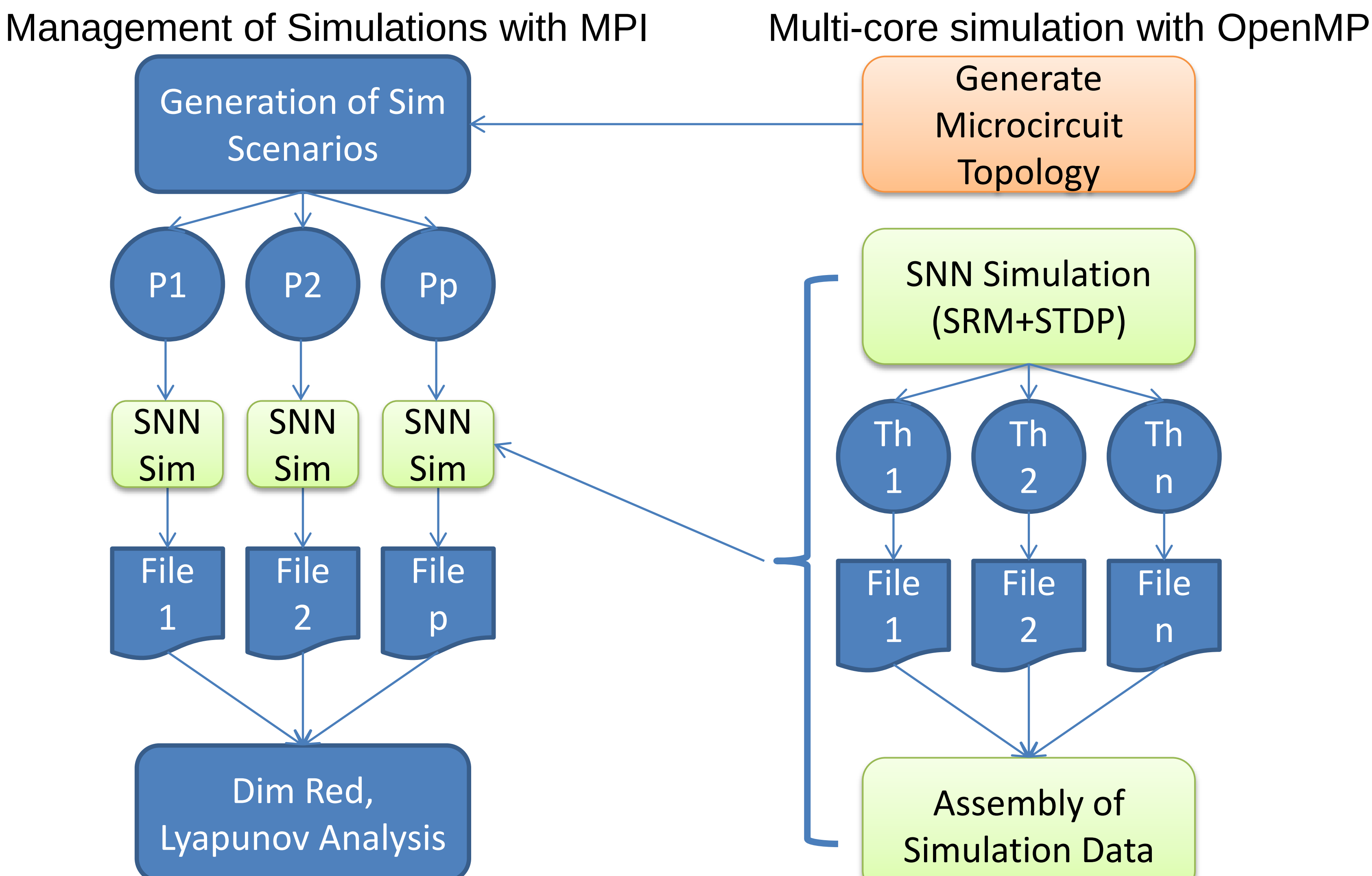
- **System** – simulated neural microcircuit
- **State** – neuron's potential, synapse weights, **spike maps**
- **Size of dimension space** in the case of spike maps – **#Neurons**
- Dimensionality reduction with variants of the Principal Component Analysis method



Snapshot from a spike map (left original, below reduced to 2D):
800+ neurons simulated over 500 ms
Dots (non-zeros (nz)) represent spikes (neural activity)



Distributed Dynamics Analysis



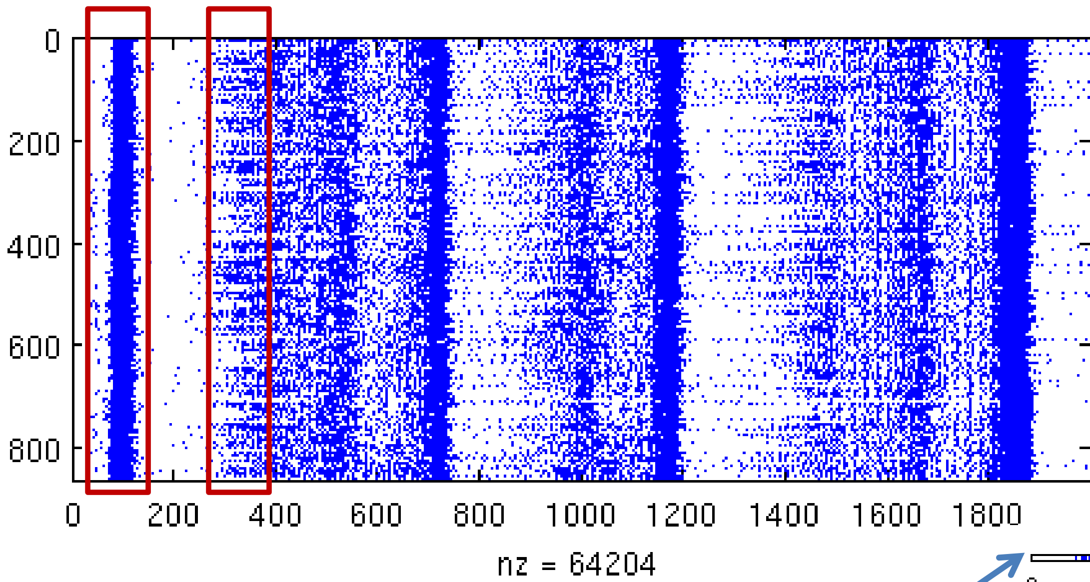
Results: Setup

- OpenMP-based parallelization of SRM simulation
- Evaluation carried out on two types of multicore systems
- Dynamics analysis applied to neural activity of the neural microcircuit
- Management of simulations with MPI
- Simulation of 1→10 s biological time, with time step of 1ms

acalgrid.utcluj: Intel Xeon E5507, 2.26 GHz, L2 cache 4MB
4 cores/4 threads

sandstorm.tum: Intel Xeon E5-2690, 2.90 GHz, L3 cache 20 MB
8 cores/8 threads

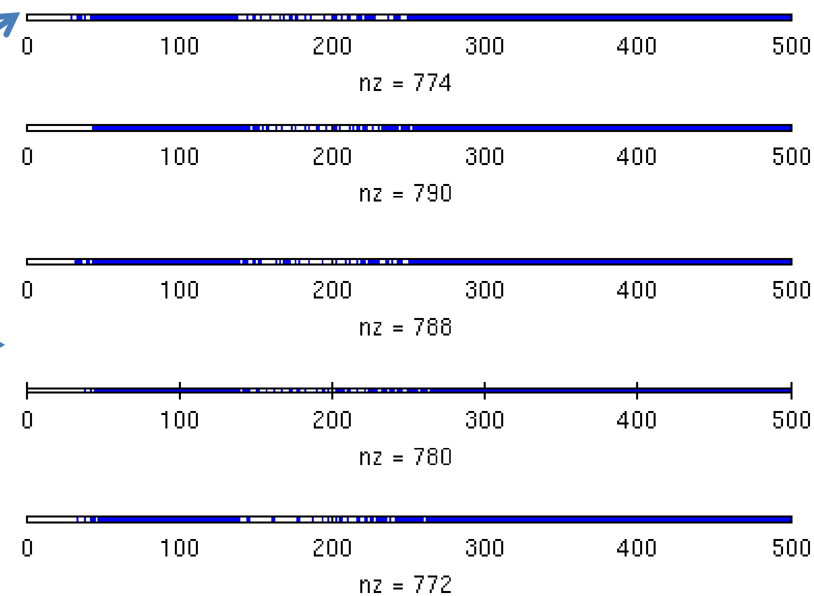
Results – Dynamics Analysis. Dimension Reduction



External stimuli: Poisson spike trains at 5 Hz

Oscillatory regime in the results of the reference simulation for a biological time of 2000 ms.

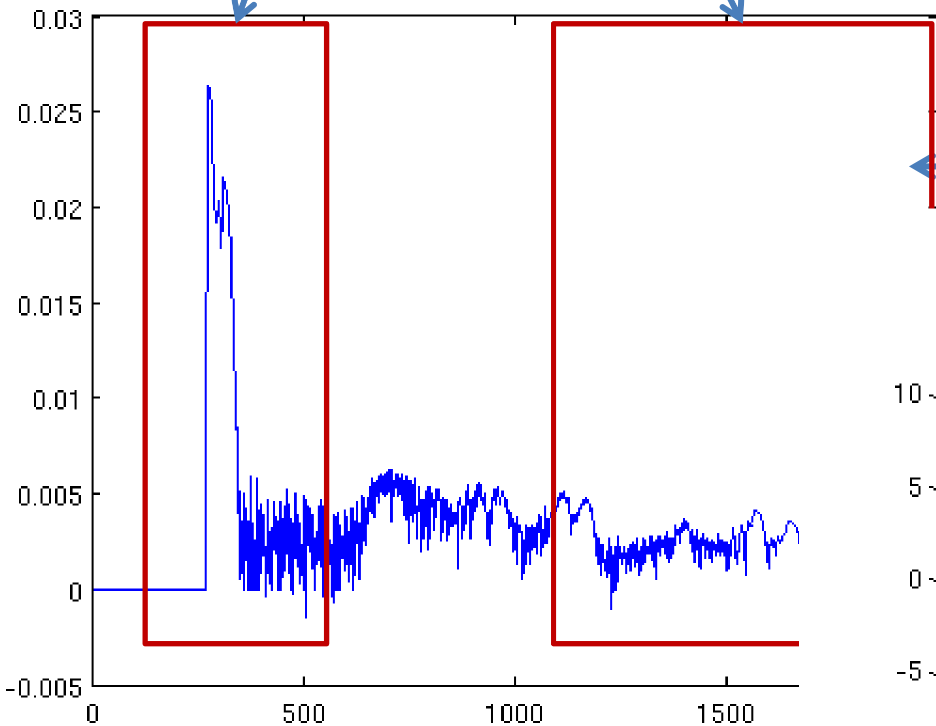
1. Run batches of N simulations.
2. Take one of them as reference.
3. Reduce dimensionality of the result data set.
4. Project the remaining N-1 simulations data sets to the reduced reference one.



Results – Dynamics Analysis with Lyapunov Exponent

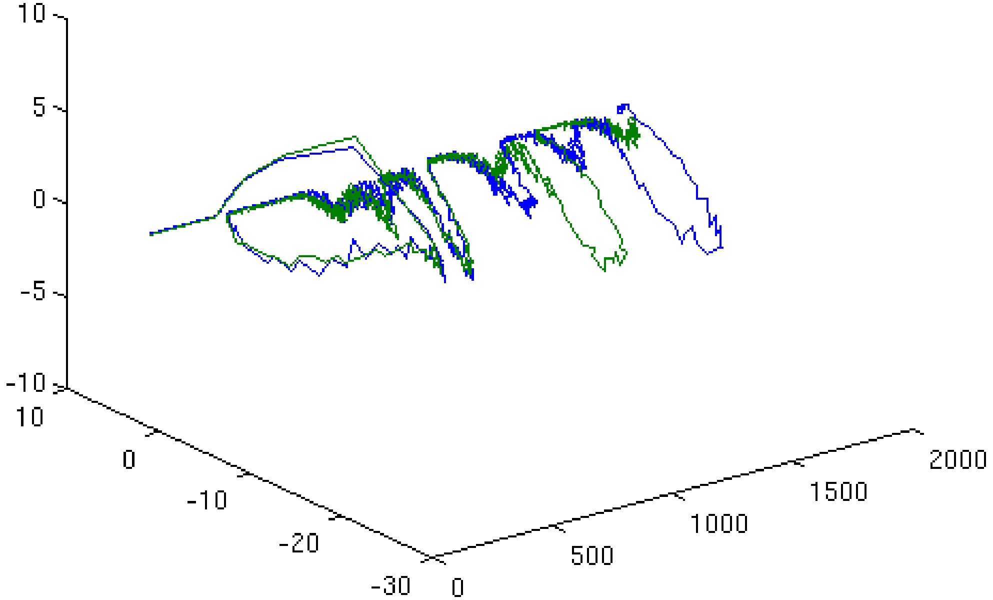
Trend towards instability

Small oscillations>0
→almost periodic
tendency of the system



5. Run Lyapunov exponent analysis.

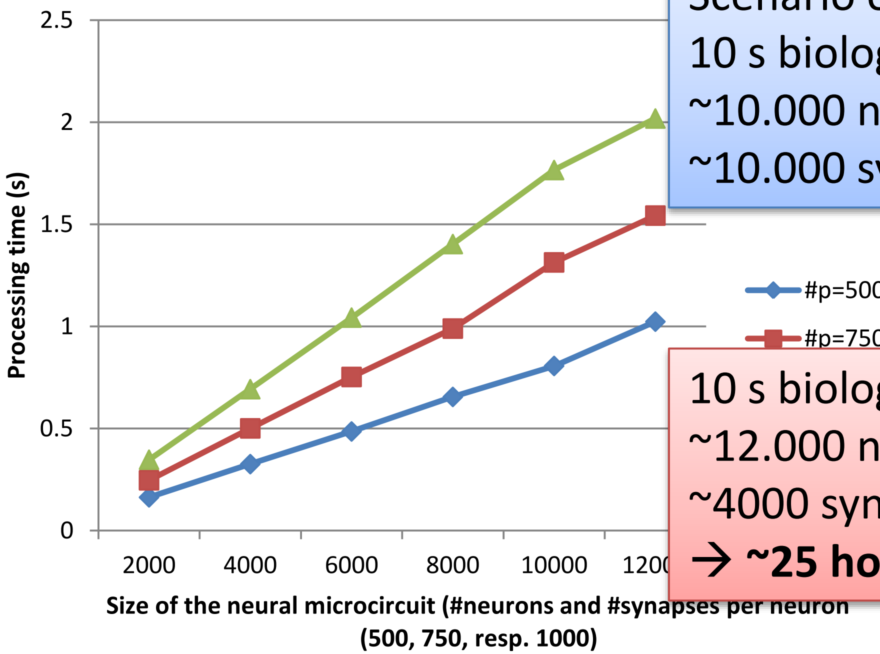
Time dependent evolution of the Lyapunov exponent λ for the first two scenarios (vertical axes: dimensionless



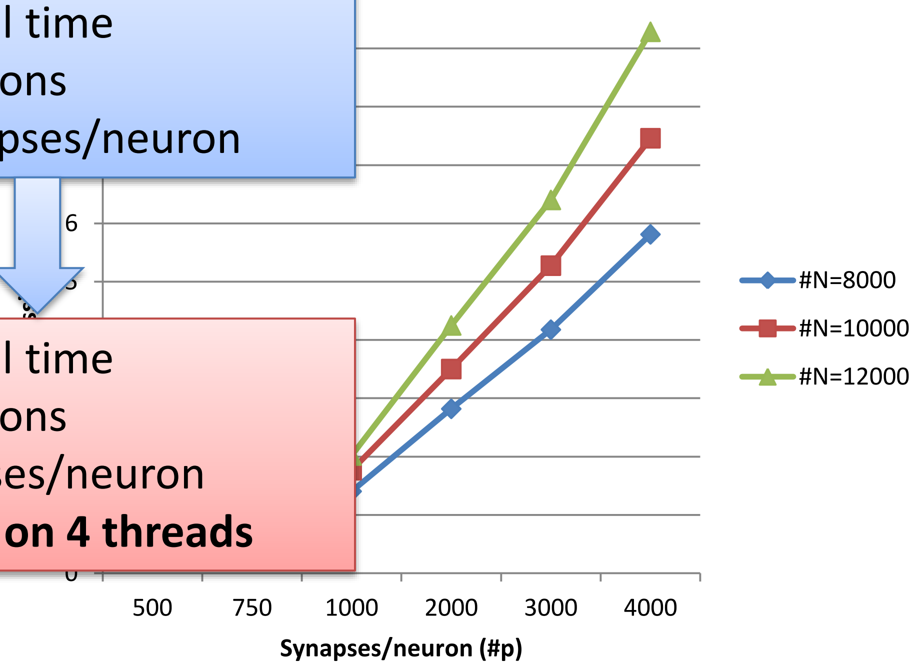
Results: Scalability Analysis

Duration of the simulation of **1 ms of biological time**
External stimuli: Poisson spike trains at 5Hz

Constant #synapses per neuron
Variable #neurons



Constant # neurons
Variable #synapses per neuron



Scenario of interest to CNS
10 s biological time
~10.000 neurons
~10.000 synapses/neuron

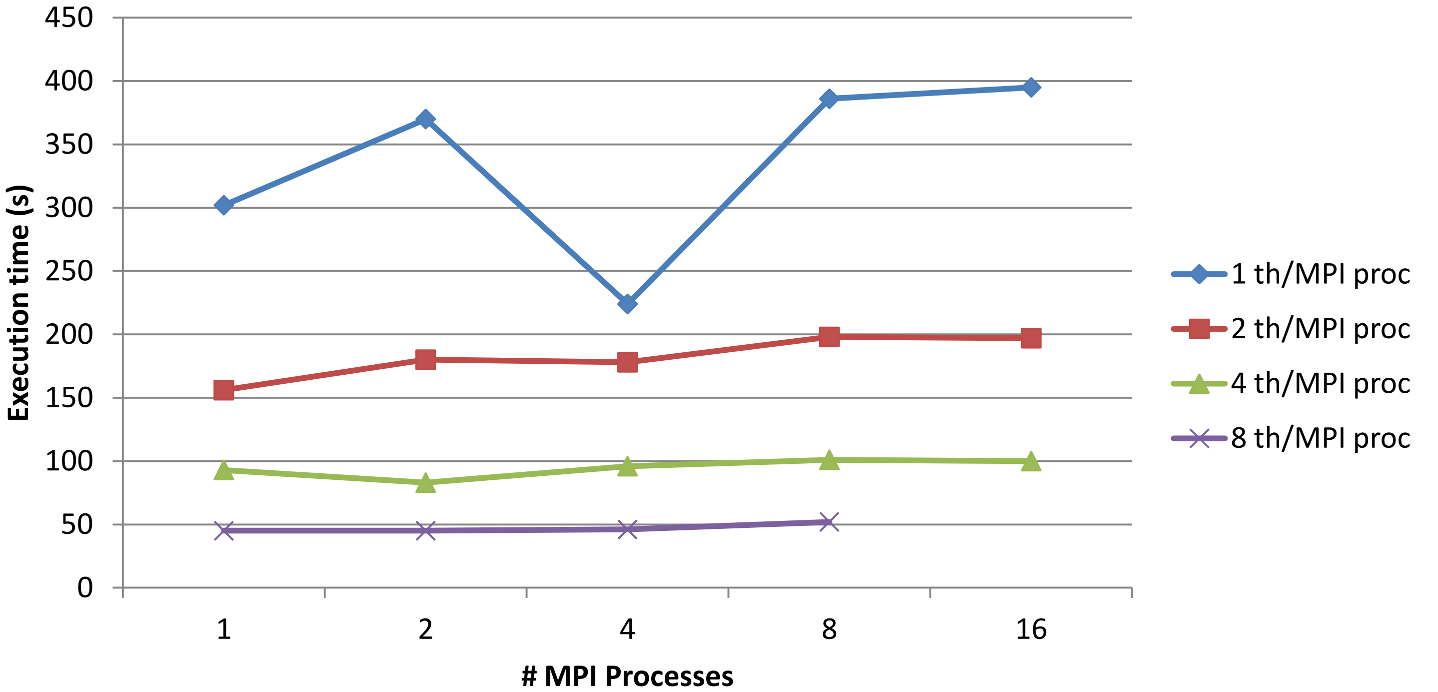
10 s biological time
~12.000 neurons
~4000 synapses/neuron
→ ~25 hours on 4 threads

acalgrid: 1 CPU Intel Xeon E5507, 2.26 GHz, L2 cache 4MB**, 4 cores/4 threads**

Results: Scalability Analysis

Duration of the simulation of **1 s of biological time,** network with 1000 neurons, ~180 synapses/neuron
External stimuli: Poisson spike trains at 5Hz

Very good speedup due to low communication overhead



Sandstorm.tum: 4 nodes with 4xCPU Intel Xeon E5-2690, 2.90 GHz, L3 cache 20 MB **8 cores/8 threads**

Conclusions & Outlook

- Focus of this work
  - Improved management of scenario computation needed for the dynamics analysis → hybrid MPI-OpenMP implementation
  - Improved methodology for analyzing dynamics of SRM simulations
  - Both sequential and parallel implementations of SRM exhibit the same type of dynamic behavior (periodic-like)
- Future work
  - Extension with MPI the simulation of a single microcircuit
  - Elaboration of recipes for properly choosing the dimensions – *in progress*
  - Apply dynamics analysis methodology on experimental data

THANK YOU!

QUESTIONS?

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