APS March Meeting

Collective Dynamics and Memory-Induced Long-Range Order in Thermal Neuristor Networks

Yuan-Hang Zhang

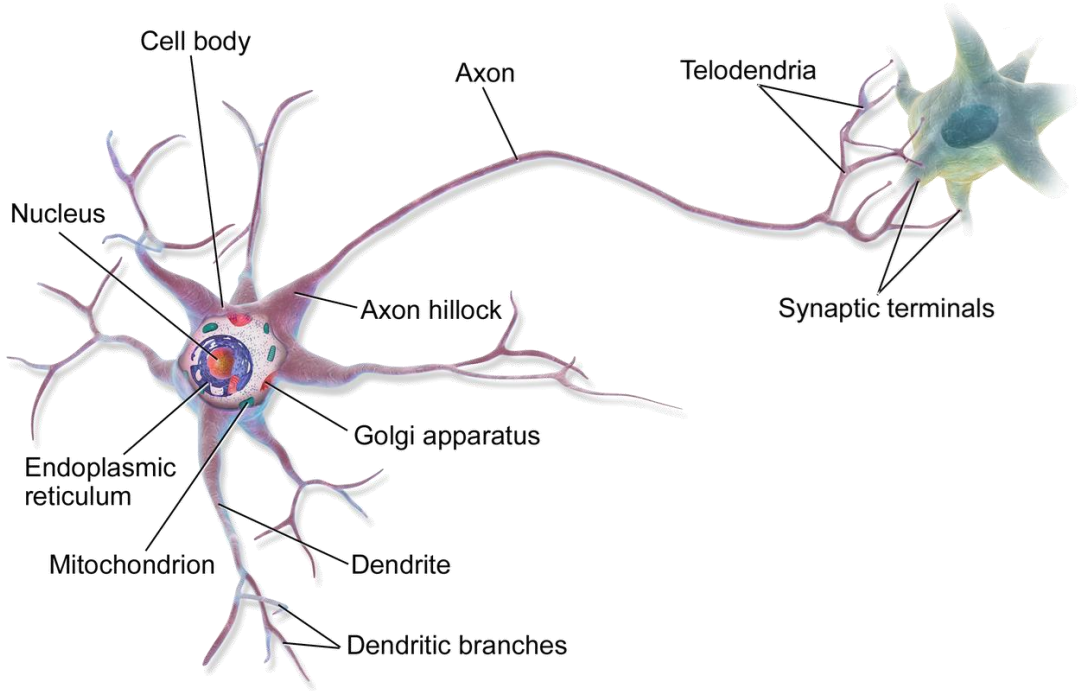
Y.-H. Zhang, C. Sipling, E. Qiu, I.K. Schuller, M. Di Ventra

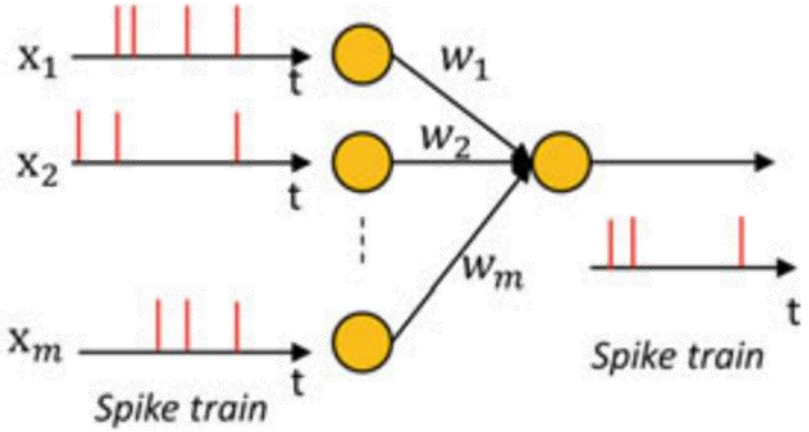
arXiv:2312.12899

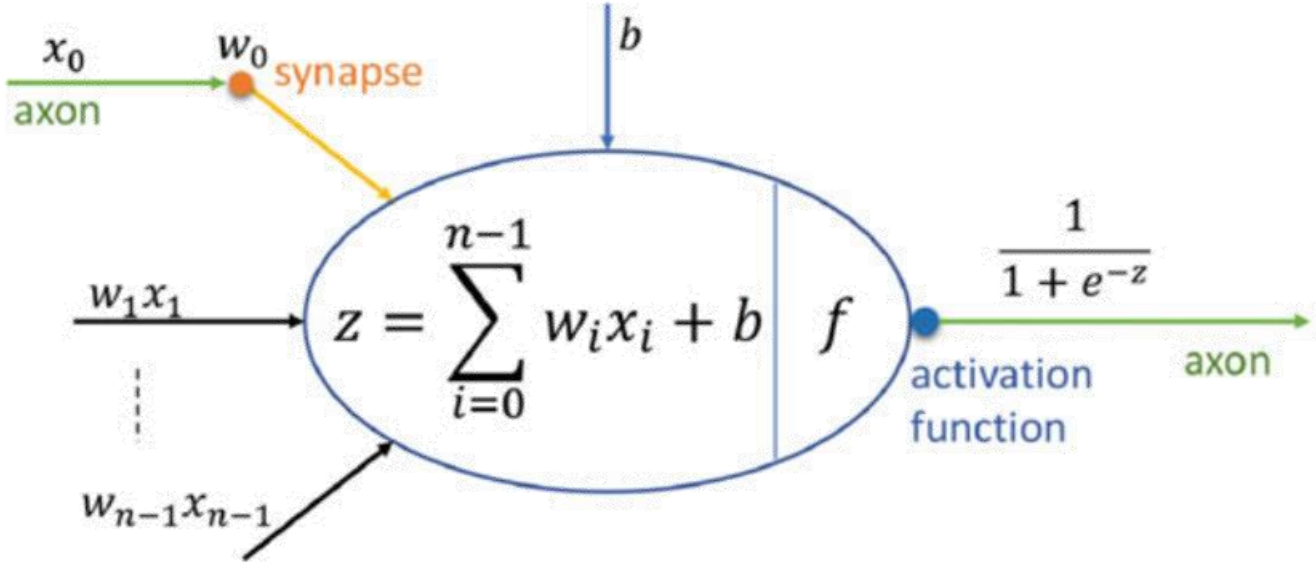
CMRR Center for Memory and Recording Research

UC San Diego

Neuromorphic computing







Abdallah, Abderazek Ben, and Khanh N. Dang. *Neuromorphic computing principles and organization*. Berlin: Springer, 2022.

Vanadium Dioxide

Insulator-to-metal transition: $T_c \approx 340K$

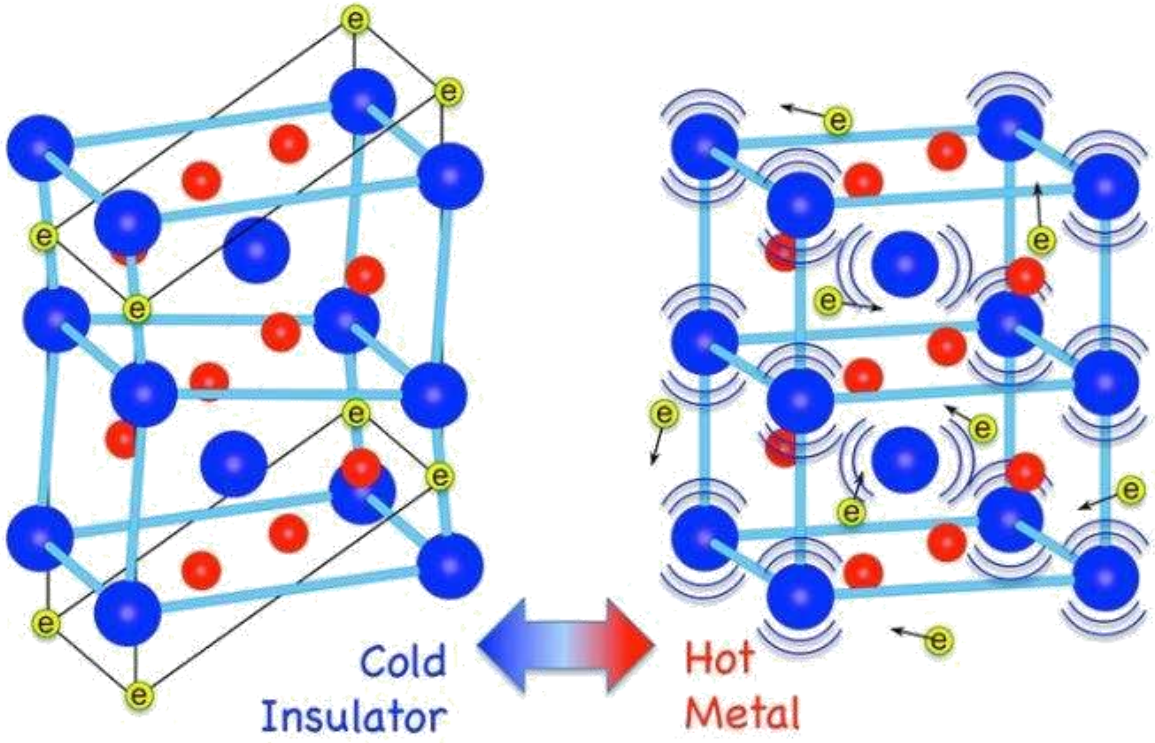
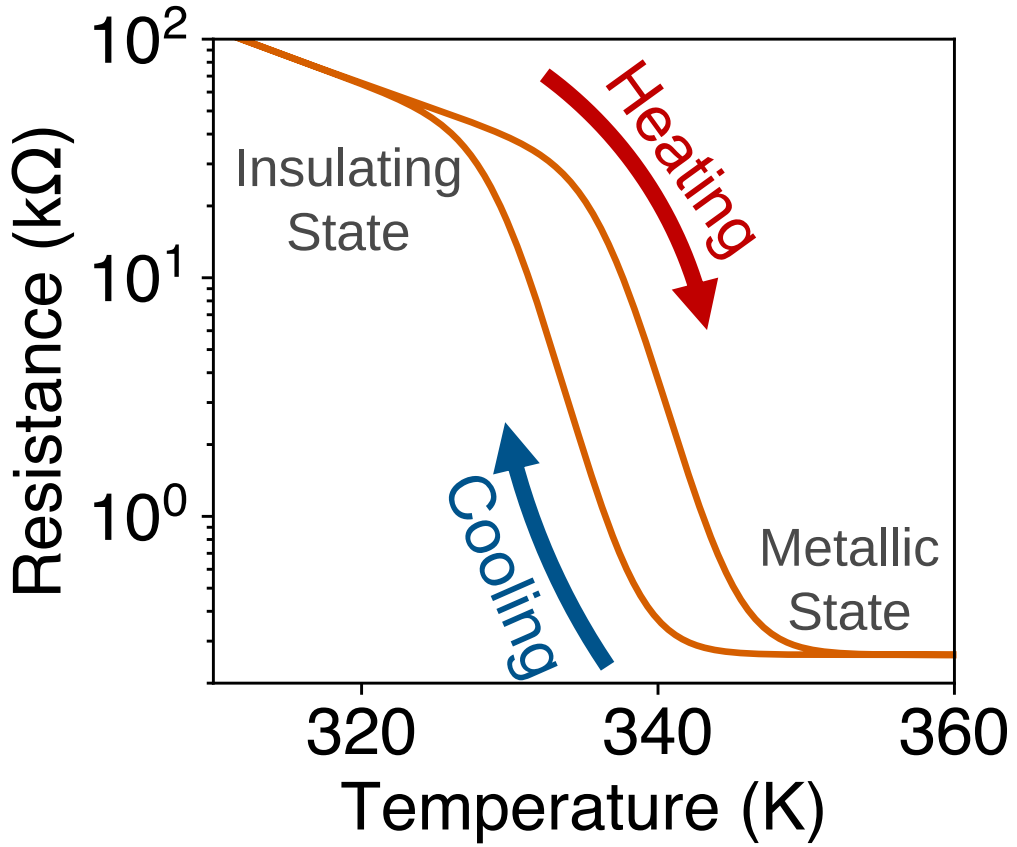
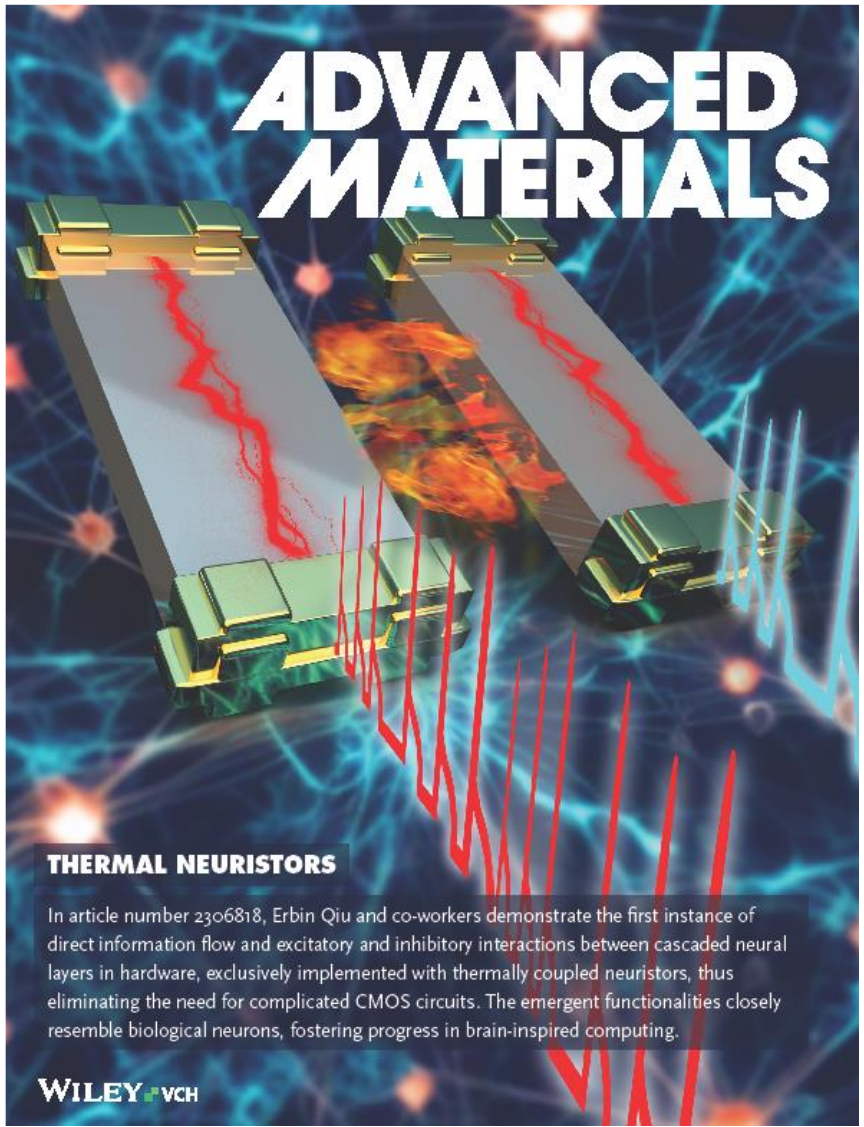


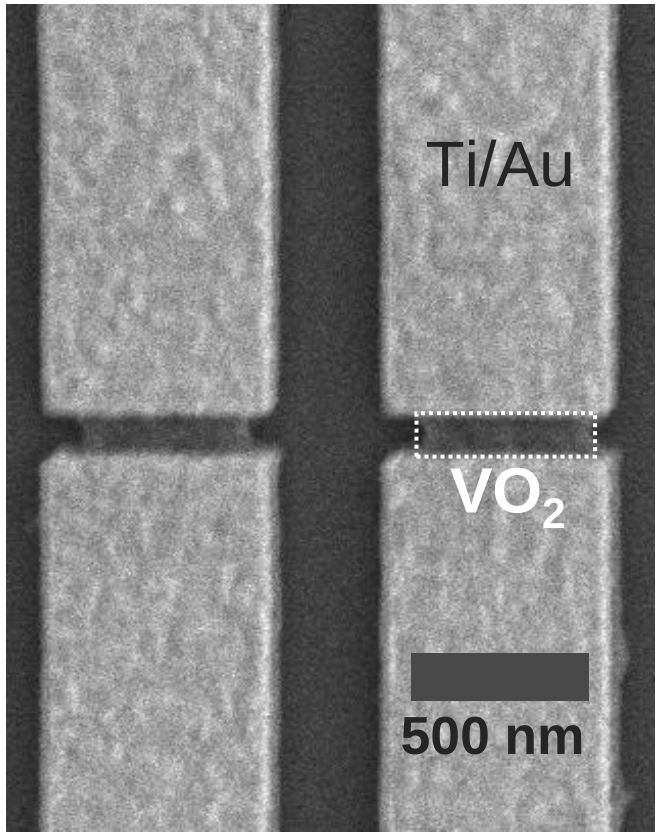
Image credit: https://phys.org/news/2015-04-insulator-to-metal-transition-vanadium-dioxide.html



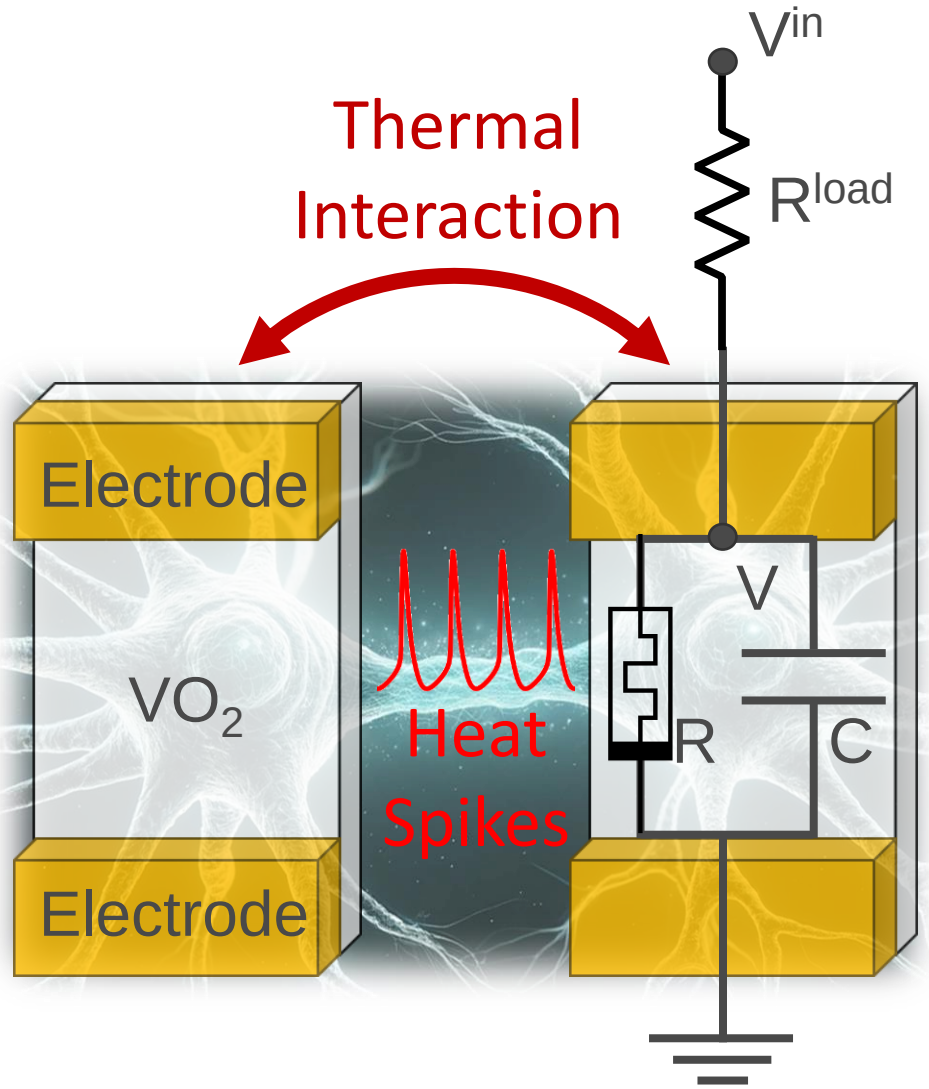
Budai, J. D., Hong, J., Manley, M. E., Specht, E. D., Li, C. W., Tischler, J. Z., ... & Delaire, O. (2014). Metallization of vanadium dioxide driven by large phonon entropy. Nature, 515(7528), 535-539.

Thermal Neuristor



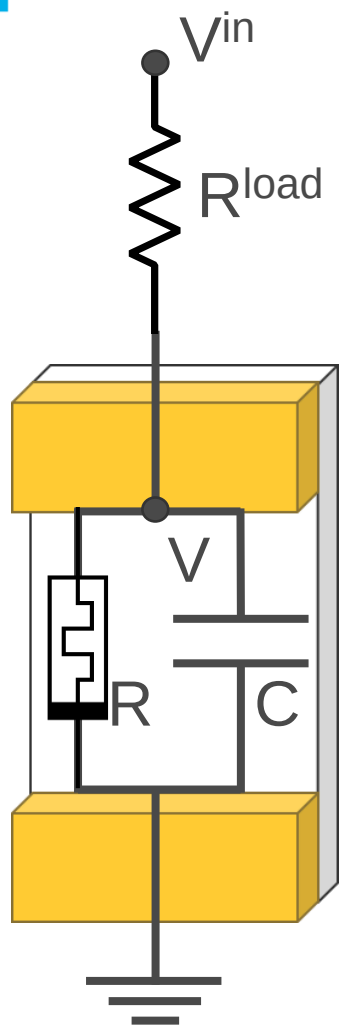


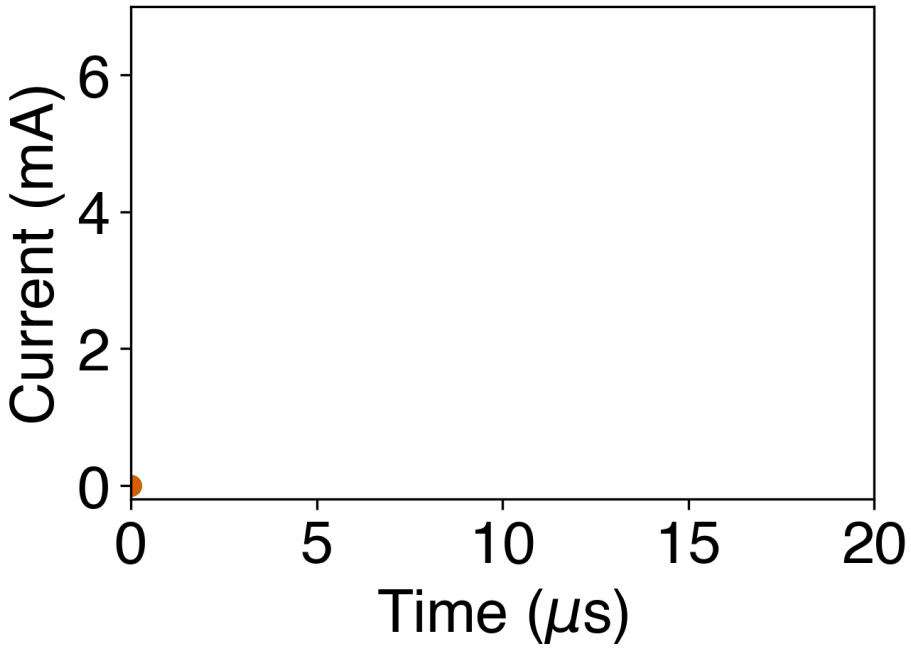
Substrate: Al_2O_3

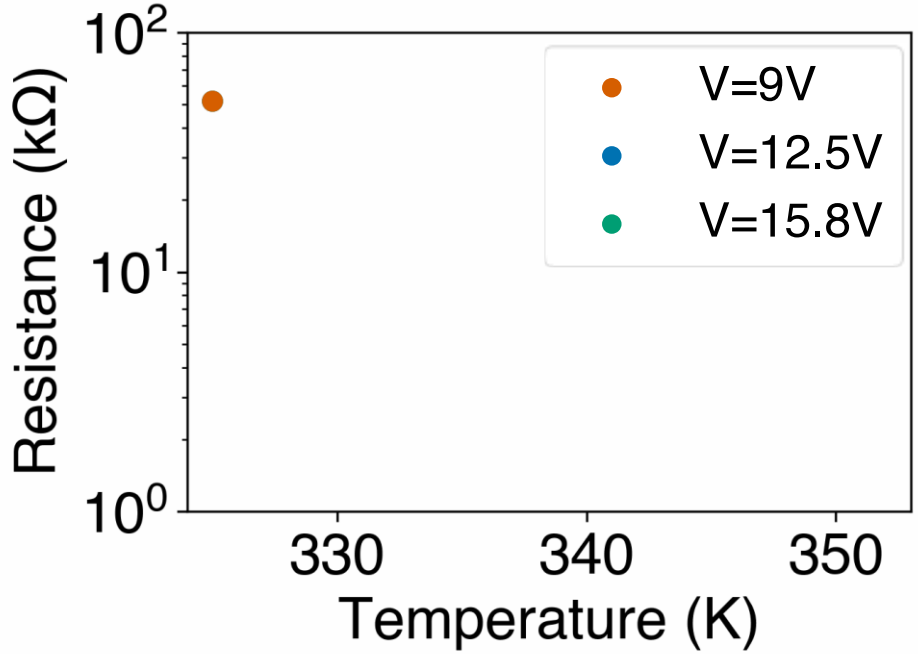


Qiu, E., Zhang, Y. H., Di Ventra, M., & Schuller, I. K. (2023). Reconfigurable cascaded thermal neuristors for neuromorphic computing. *Advanced Materials*, 2306818.

Single Neuristor Characteristics







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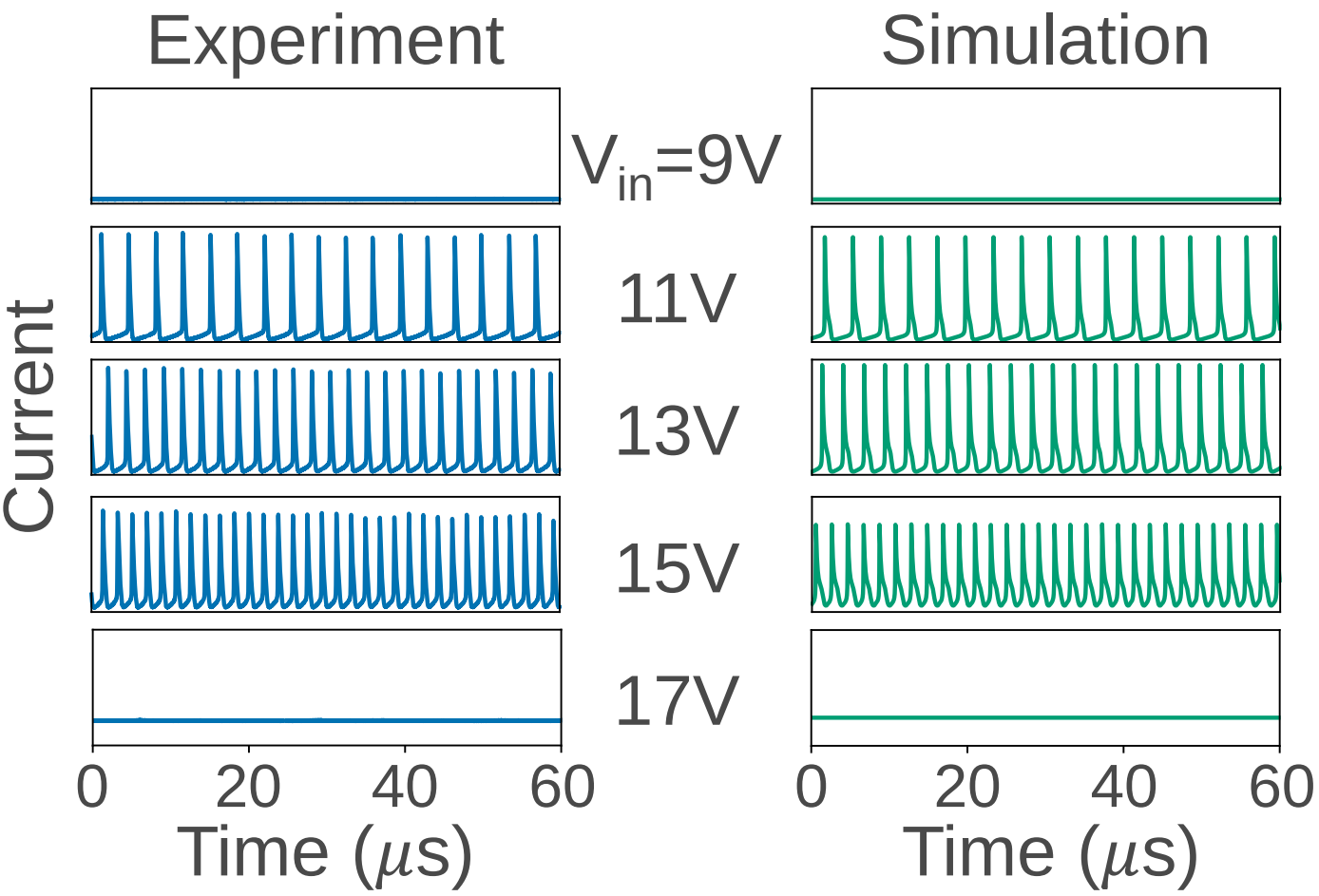
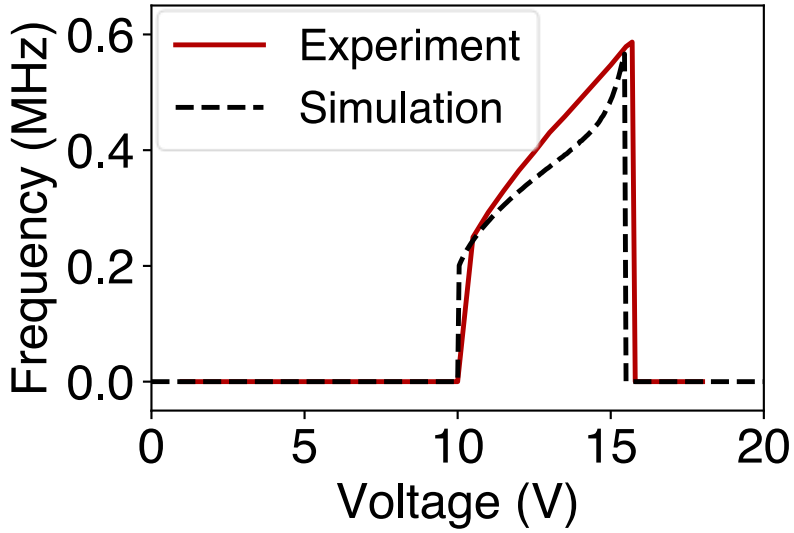
Single Neuristor Characteristics



$$C\frac{dV}{dt} = \frac{V_{in}}{R_{load}} - V\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0)$$



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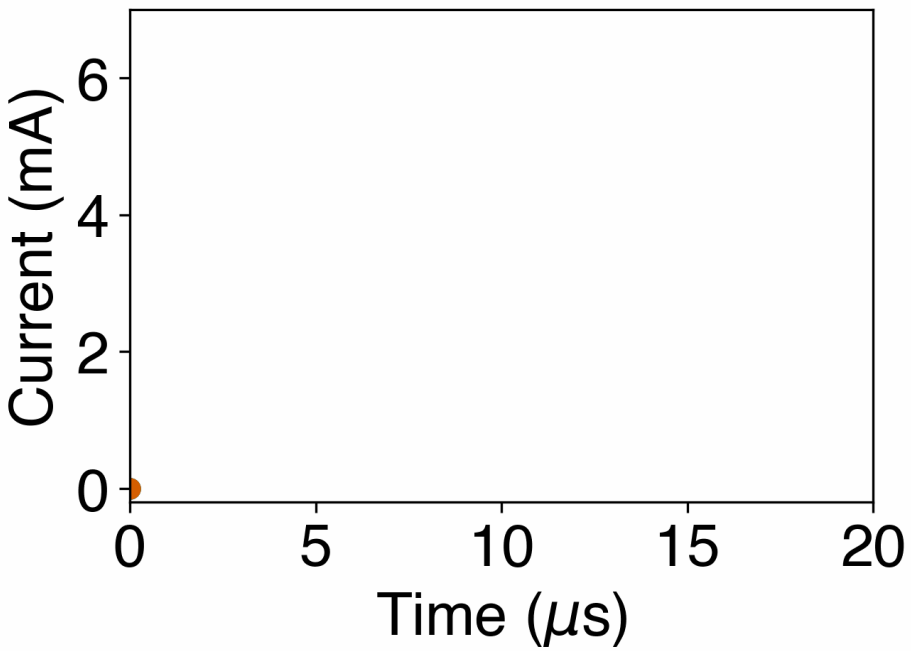
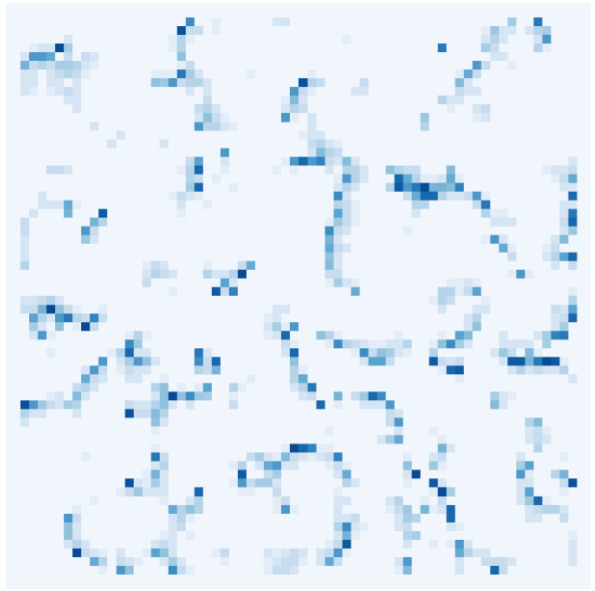
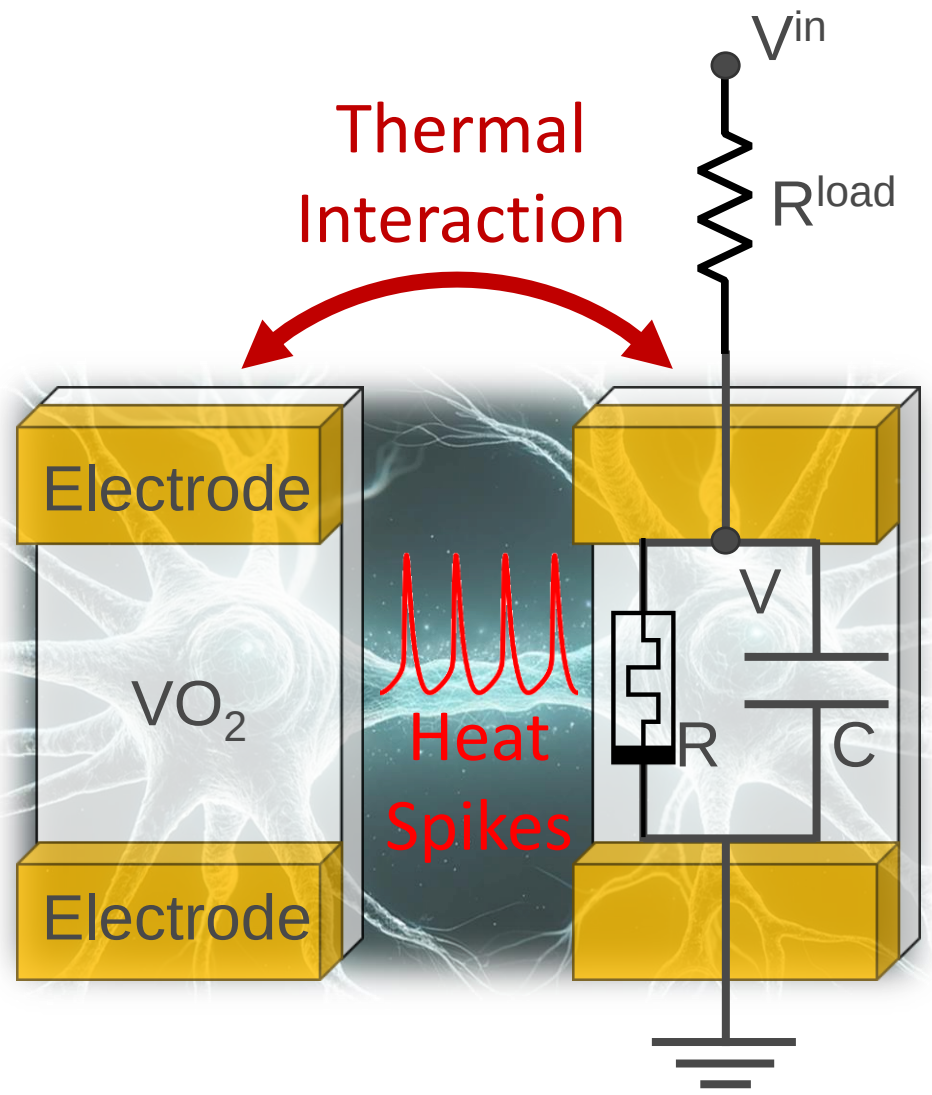
Thermal Neuristor Array

1 neuron



64x64 neurons





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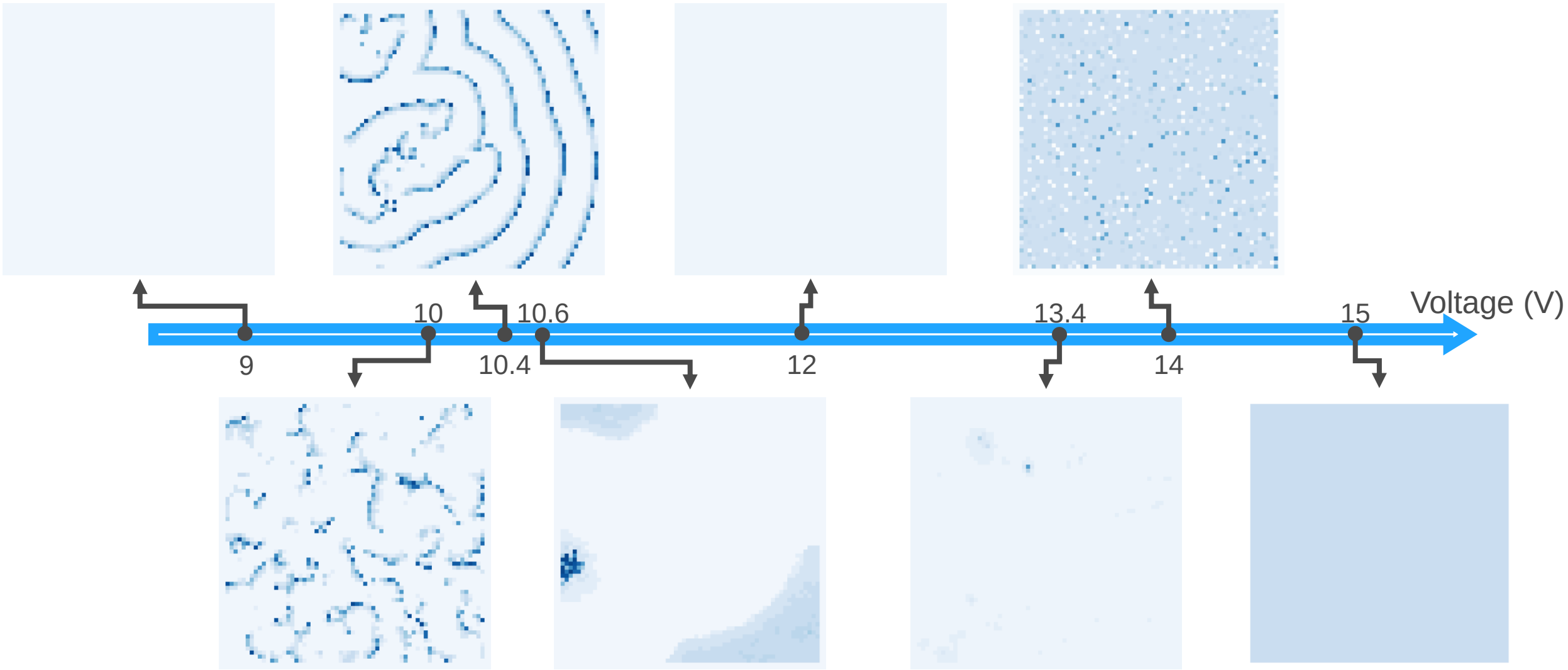
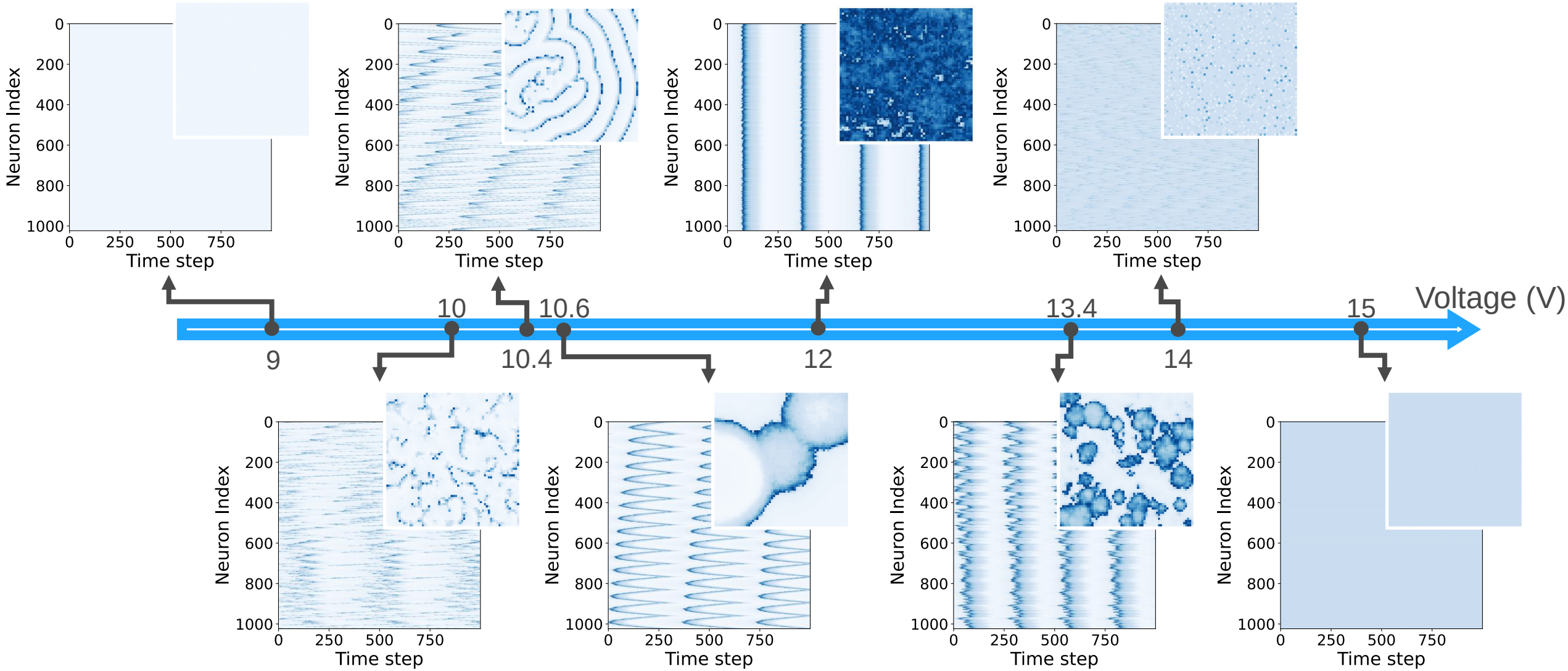
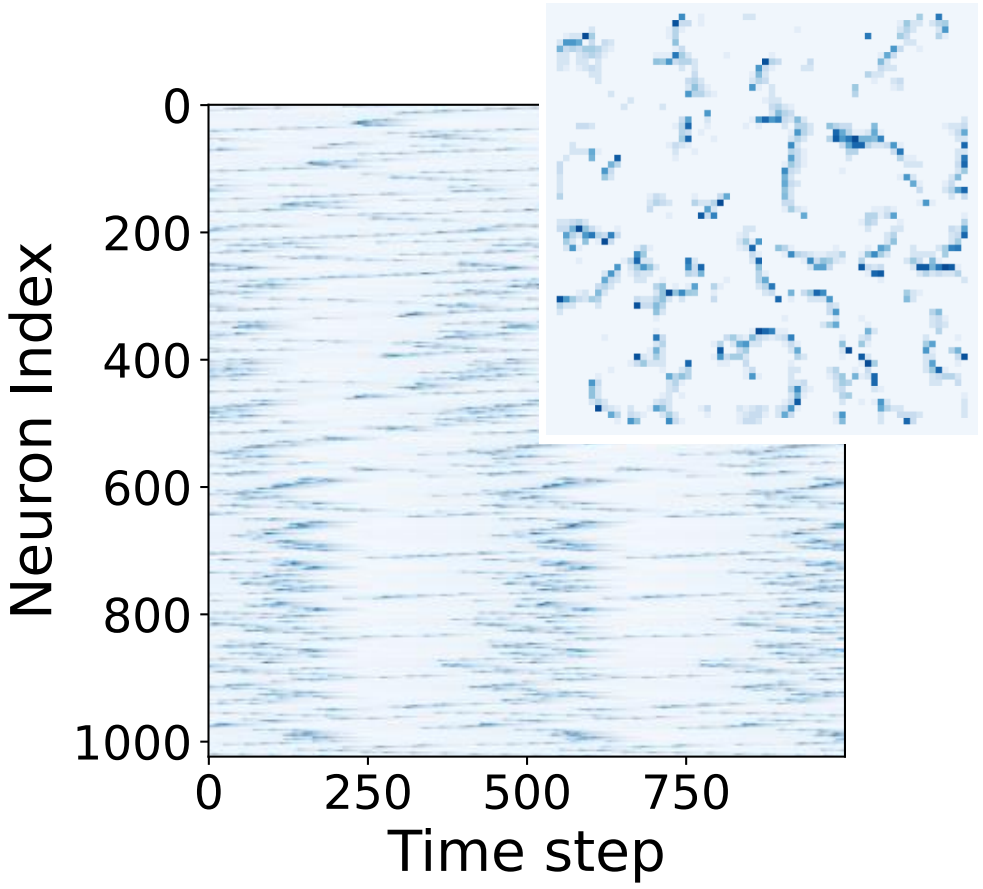
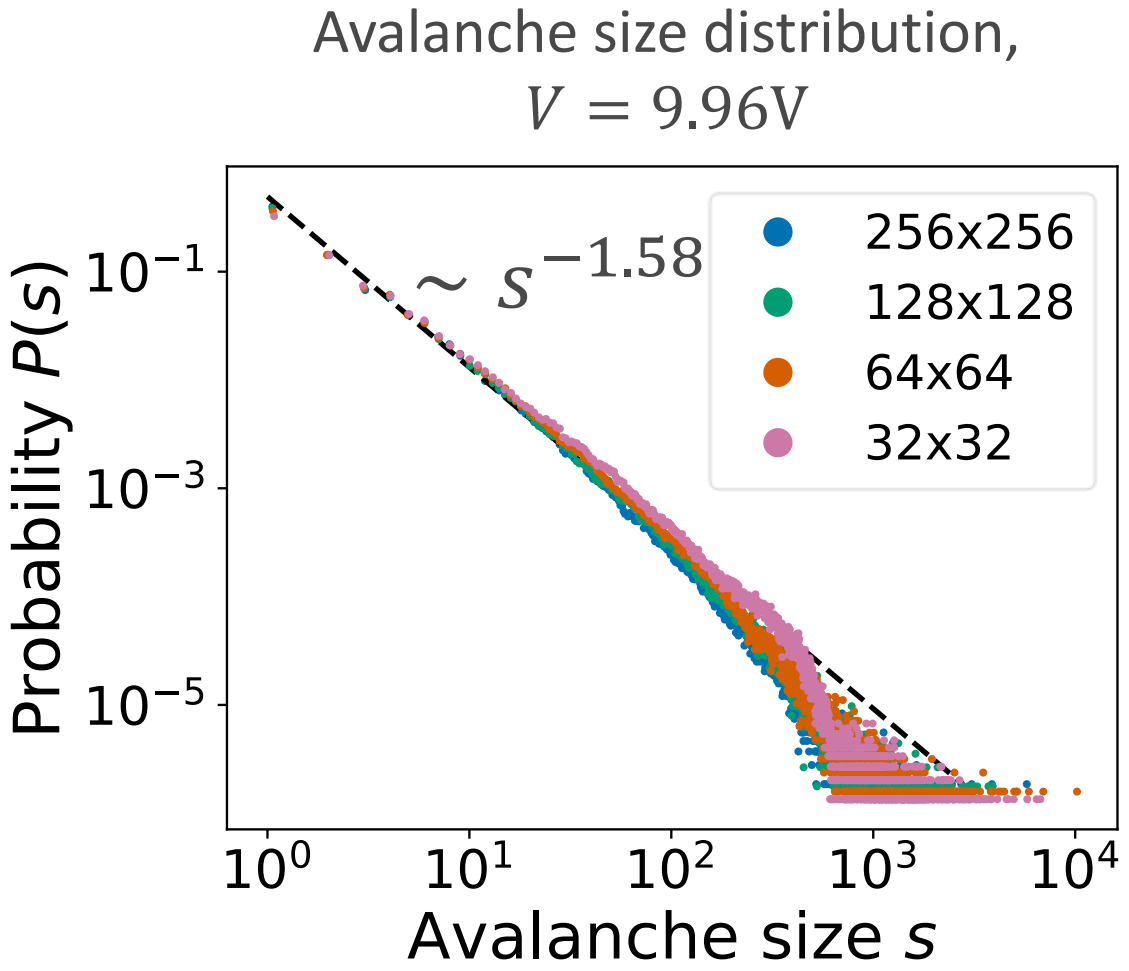

9
10
10.4
10.6
12
13.4
14
15
Voltage (V)


Neuron Index
Time step
0
200
400
600
800
1000
0
250
500
750
9
10
10.4
10.6
12
13.4
14
15
Voltage (V)

Long-range order?





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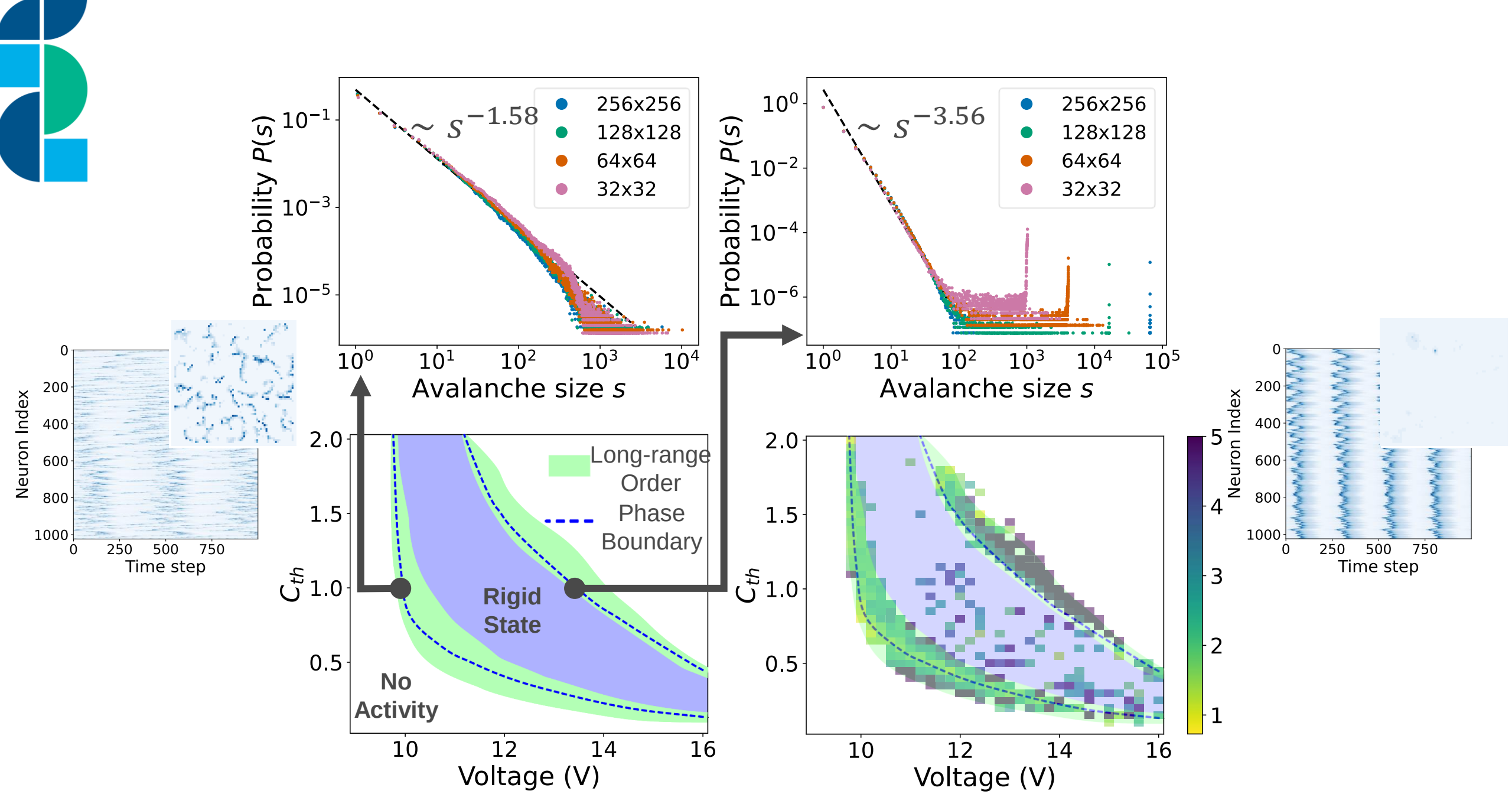

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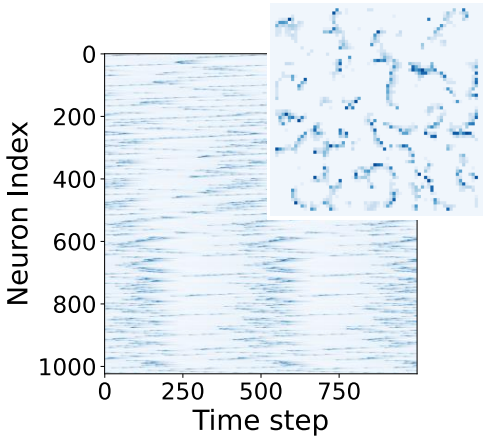
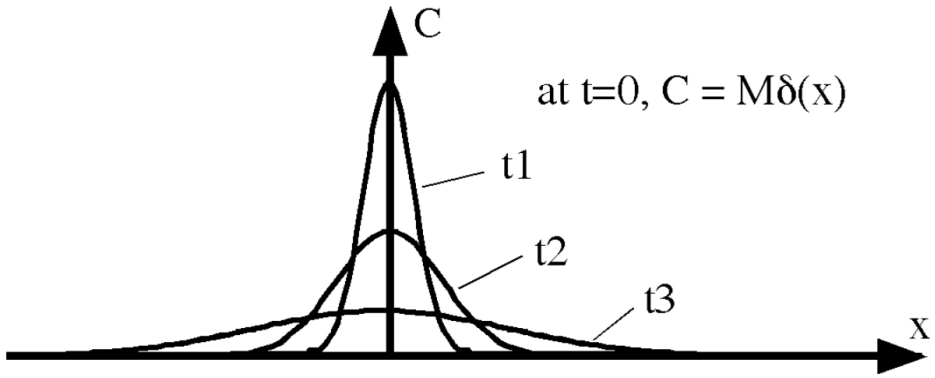
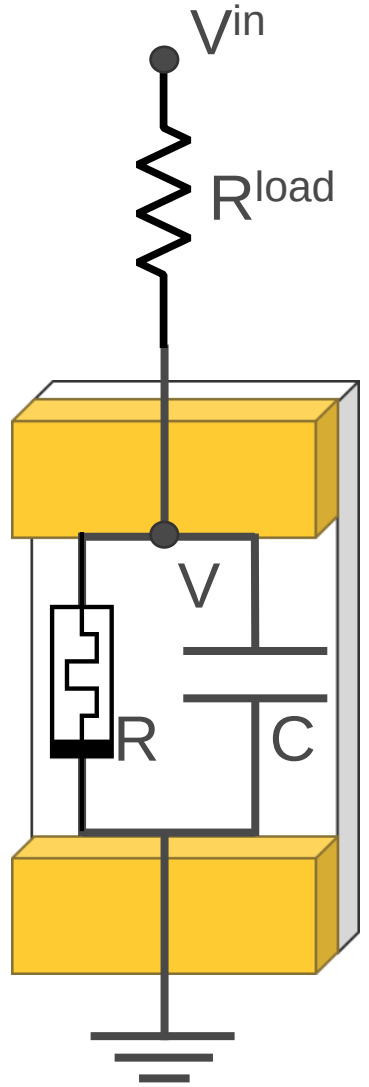
Long-range order?

$$C\frac{dV}{dt} = \frac{V_{in}}{R_{load}} - V\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$







Memory-induced long-range order

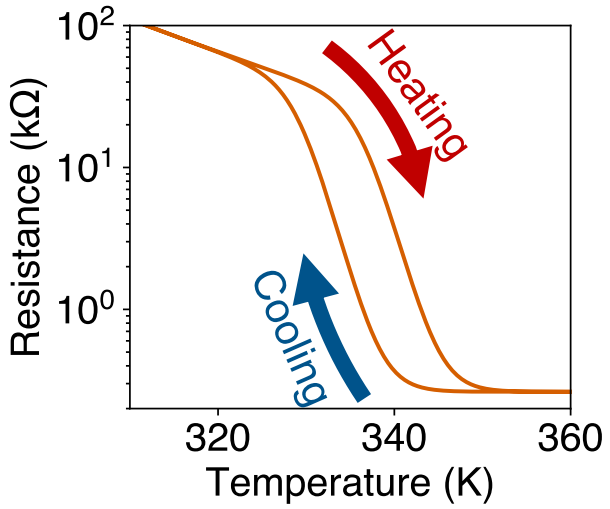
Charge / Heat Accumulation

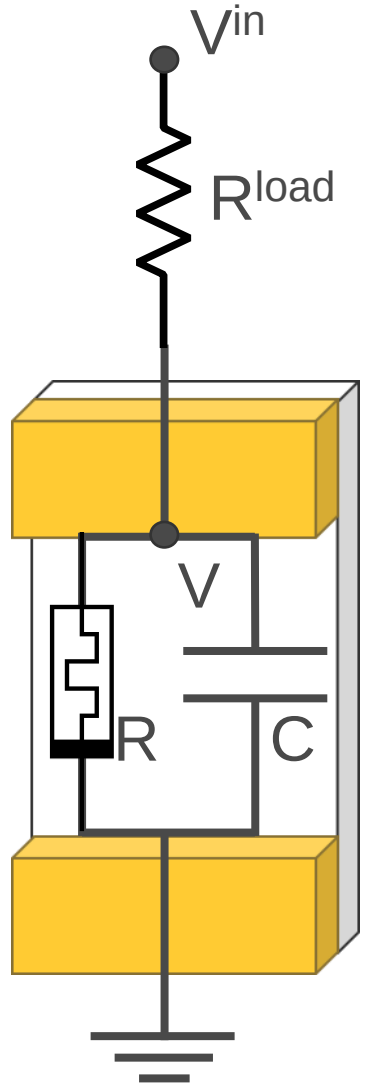
$$C\frac{dV}{dt} = \frac{V_{in}}{R_{load}} - V\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$

Hysteresis

Memory





Memory-induced long-range order

$$C\frac{dV}{dt} = \frac{V_{in}}{R_{load}} - V\left(\frac{1}{R_{VO_2}} + \frac{1}{R_{load}}\right)$$

$$C_{th}\frac{dT}{dt} = \frac{V^2}{R_{VO_2}} - S_{env}(T - T_0) + S_{couple}\nabla^2 T + \eta(t)$$

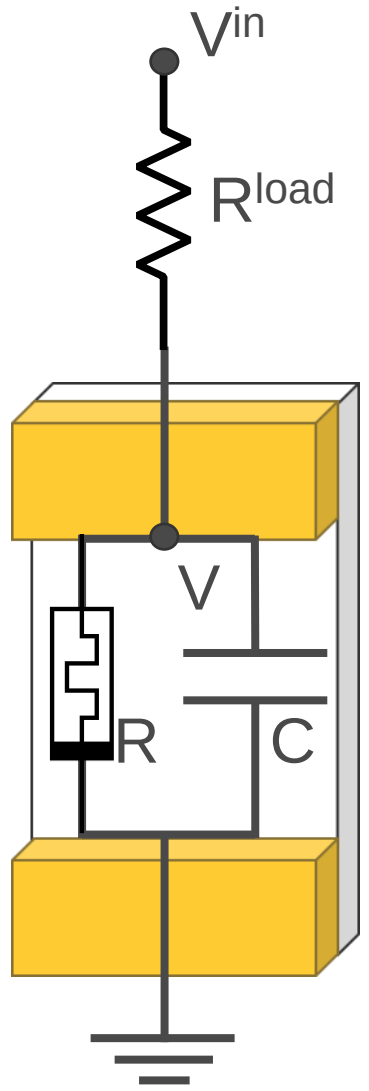
Slow charging / heating

$$\tau_{ins} = R_{ins}C \sim 7.6\mu s$$
$$\tau_T = C_{th}/S_{couple} \sim 12\mu s$$

Fast spiking / dissipation

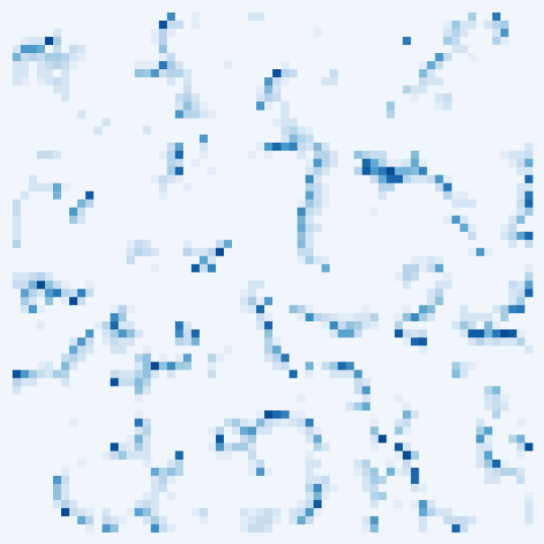
$$\tau_{met} = R_{met}C \sim 190ns$$
$$\tau_{th} = C_{th}/S_{env} \sim 240ns$$

Separation of time scales



Memory-induced long-range order

Thermal neuristors



Sandpile model:
Self-organized criticality

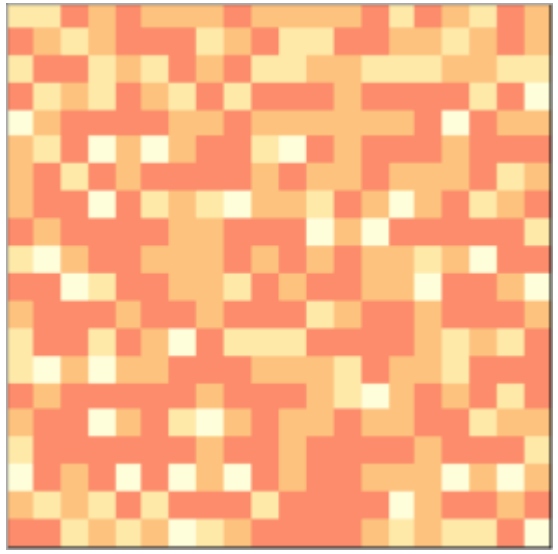
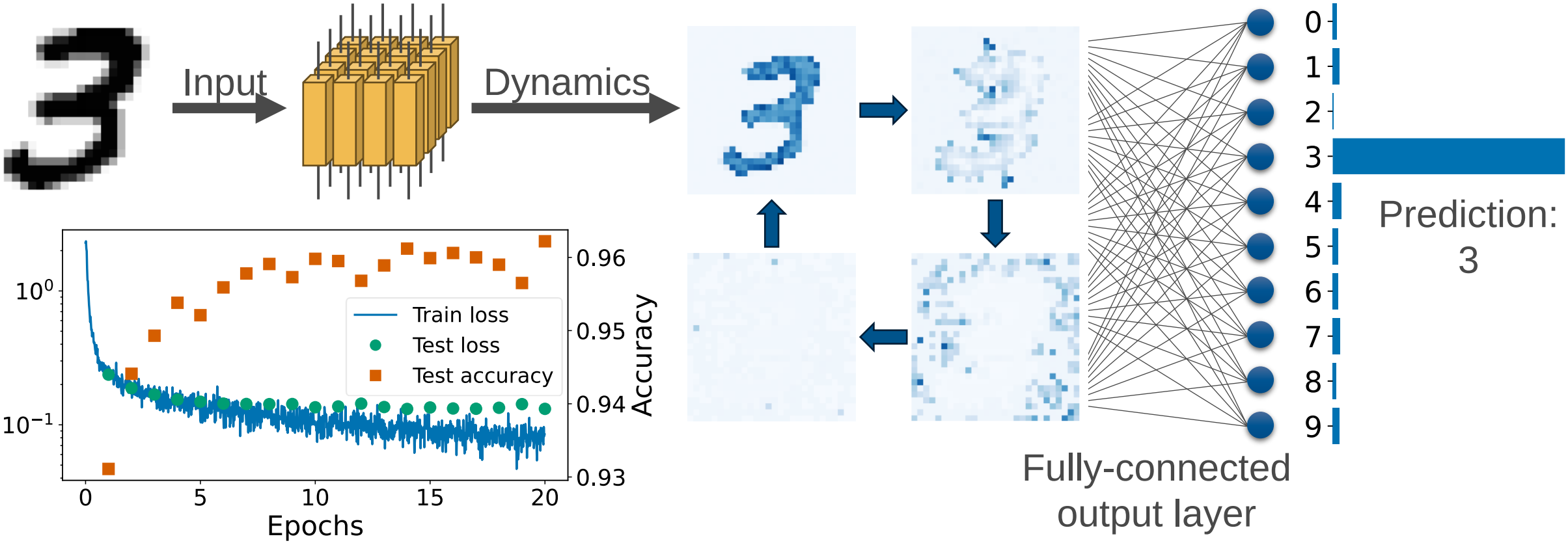


Image credit:
https://runestone.academy/ns/books/published/complex/SelfOrganizedCriticality/ImplementingTheSandPile.html

Bak, Per, Chao Tang, and Kurt Wiesenfeld. "Self-organized criticality: An explanation of the 1/f noise." *Physical review letters* 59.4 (1987): 381.

Hesse, Janina, and Thilo Gross. "Self-organized criticality as a fundamental property of neural systems." *Frontiers in systems neuroscience* 8 (2014): 166.

Application: MNIST



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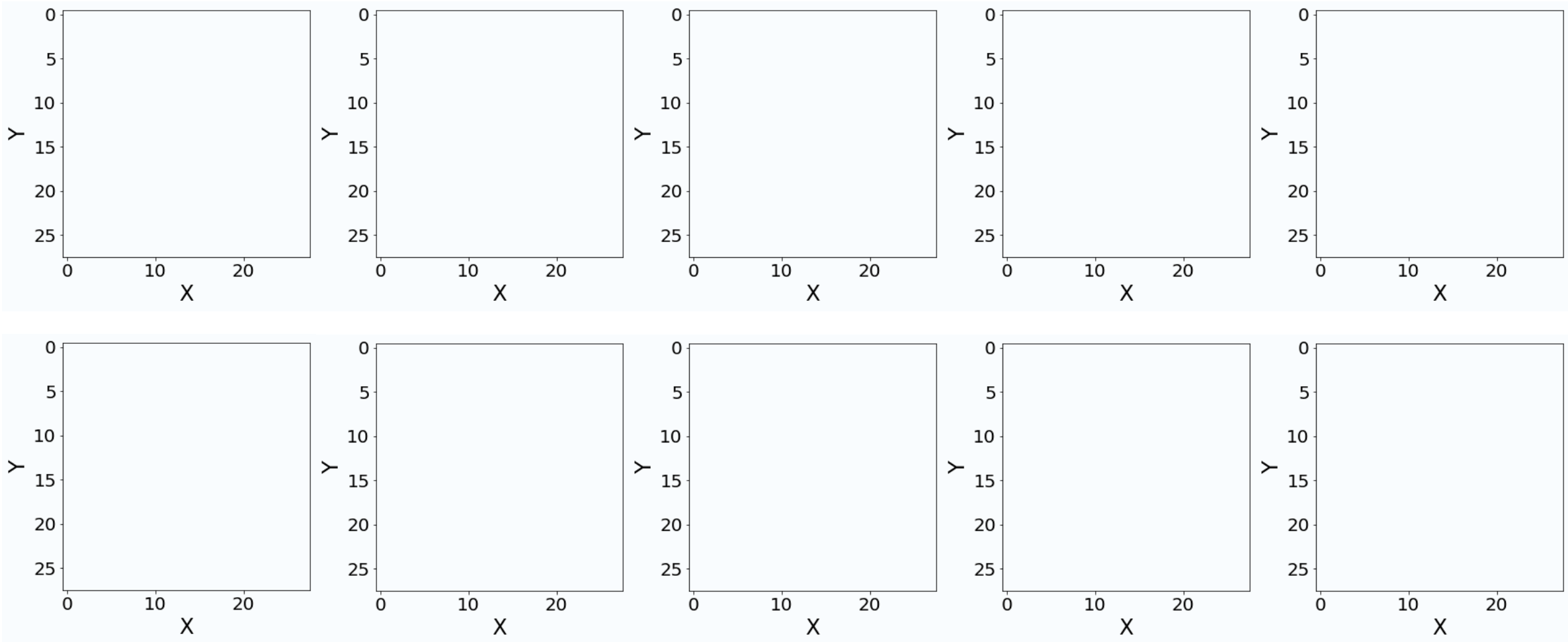
Application: MNIST

Rigid State

LRO is not necessary!



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Conclusions

- Spiking oscillators utilizing insulator-to-metal transition in VO_2
- Phase of memory-induced long-range order
- Application to reservoir computing

Thank you!

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Looking for postdoc positions!

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