

# Input-driven timing reliability in mismatched neuromorphic neurons

Revisiting the notion of mismatch with input dynamics

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# The promises of analog (subthreshold) neuromorphic hardware



## Ultra-low power

Operate in the nA–pA range  
(subthreshold regime)



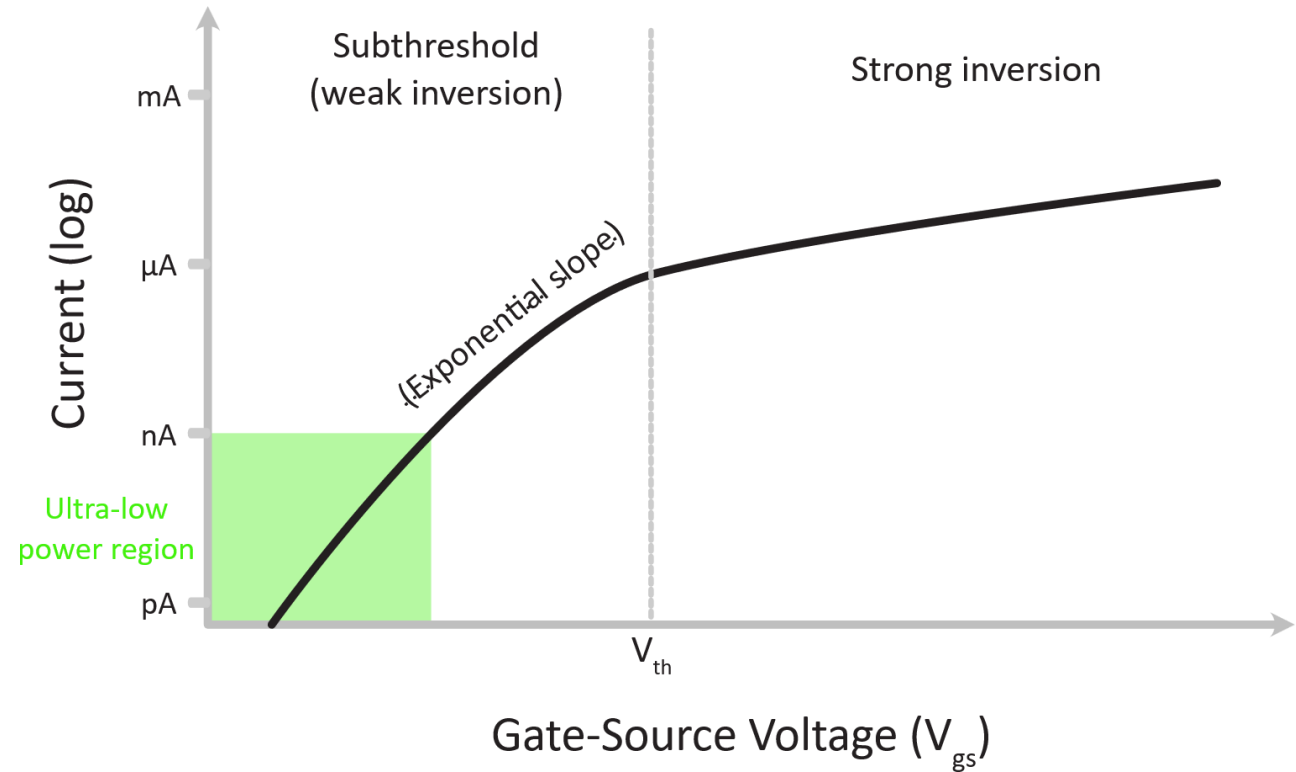
## Massively parallel

In-memory computing across  
thousands of neurons



## Asynchronous & event-based

Computation driven by spikes,  
not clocks

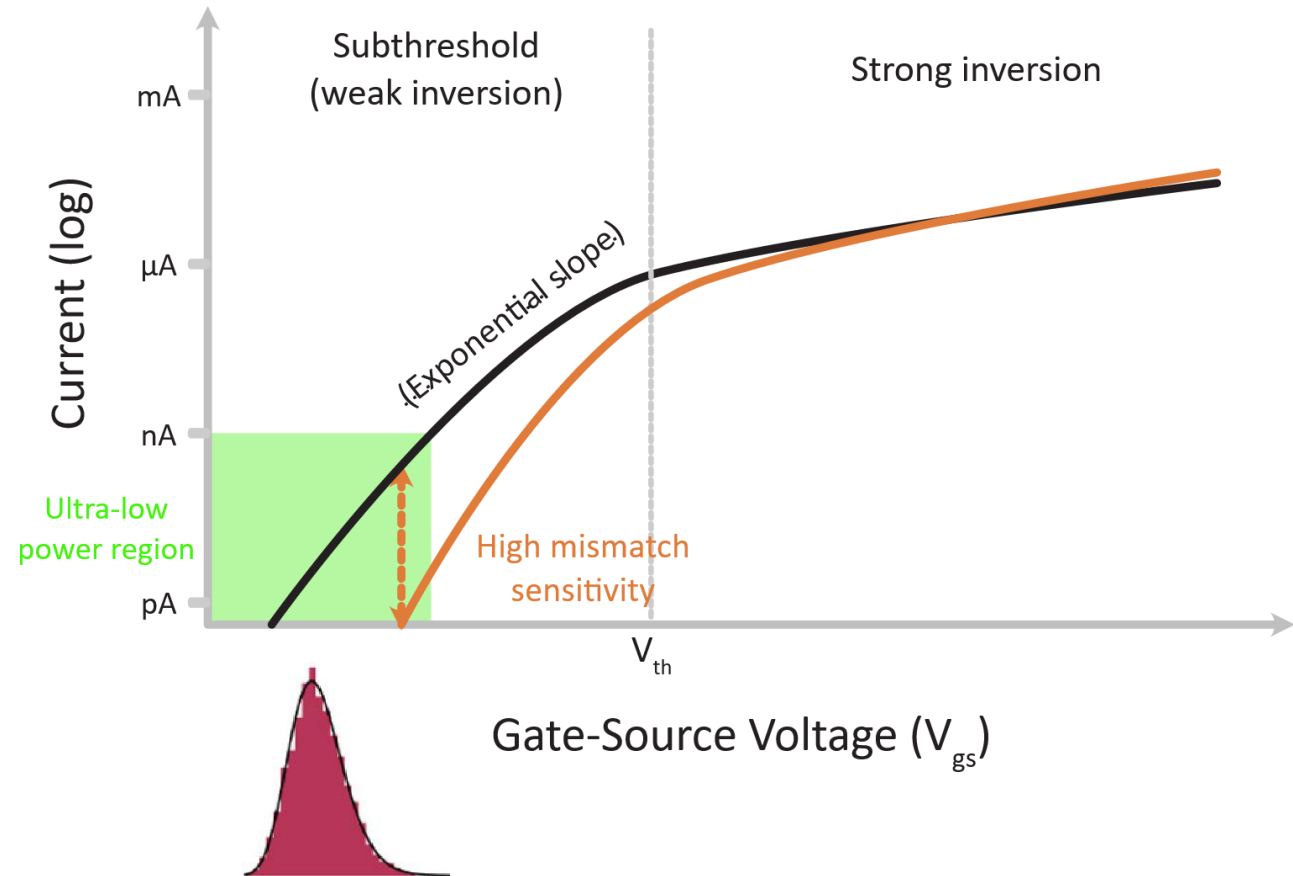
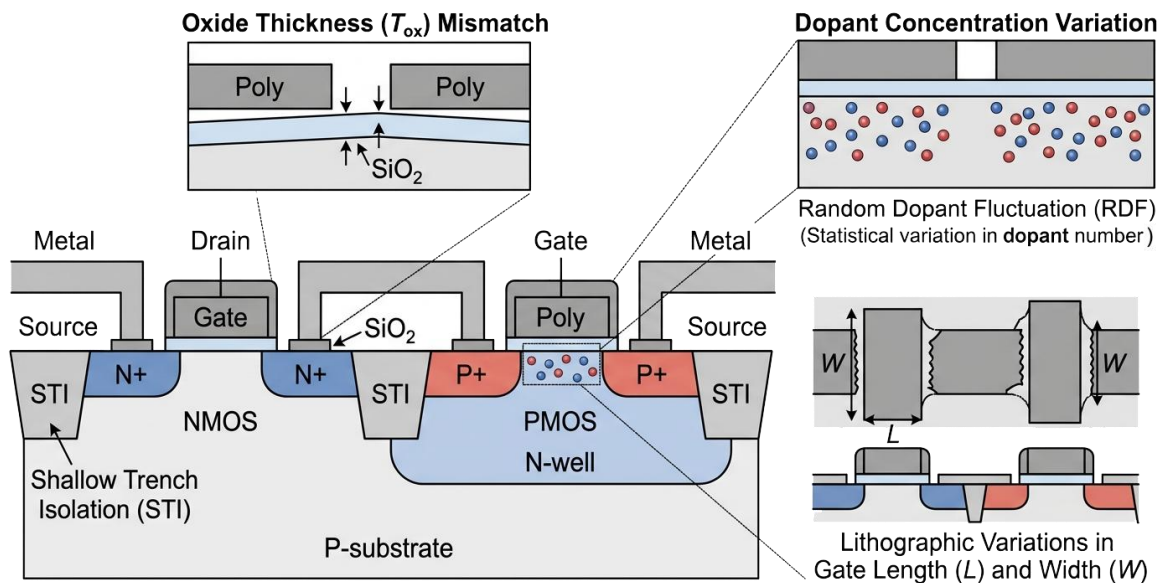


# The catch of analog (subthreshold) neuromorphic hardware: mismatch

Ultra-low power

Massively parallel

Asynchronous & event-based

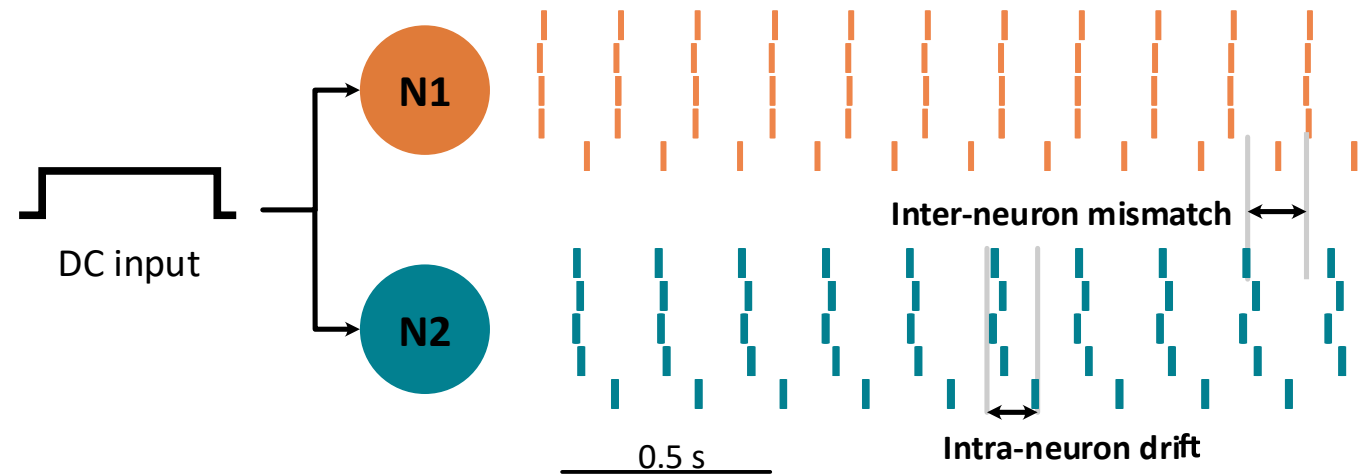


Benjamin et al. 2023

# Mismatch causes unreliable spike timing

## Under DC input:

- Neurons act as autonomous limit-cycle oscillators
- Small parameter differences  $\rightarrow$  large rate & phase variation
- No inter-neuron coherence across the population



Under constant stimulation, neurons operate as autonomous oscillators whose limit-cycle dynamics are sensitive to parametric variations, leading to unreliable event timing across trials and across neurons.

# Reliable event timing underlies key neural computations



Sensory processing



Motor coordination



Coincidence detection



Spike-based  
computations

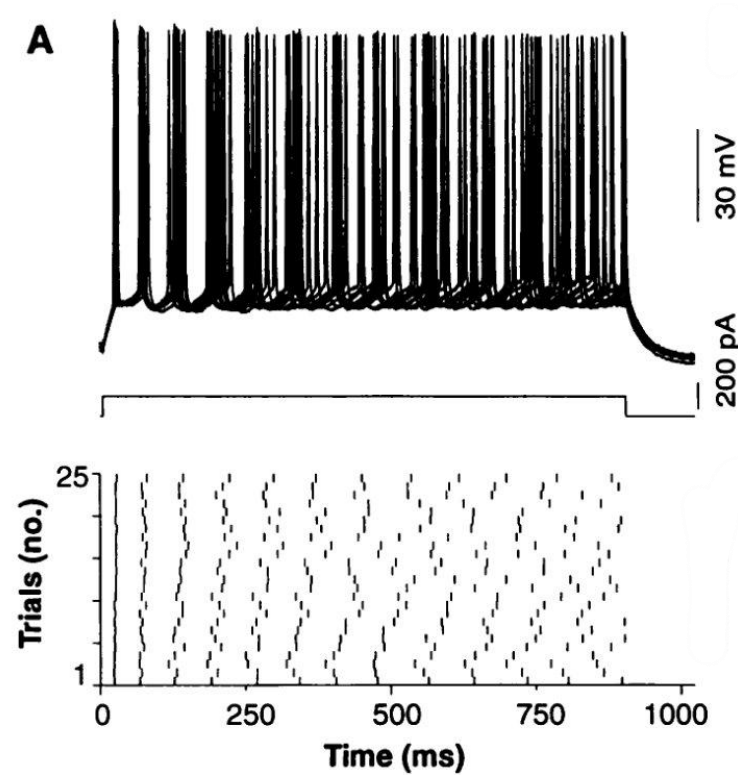


**Mismatch-induced timing variability can degrade the functional performance of neuromorphic systems**

*Solving mismatch through circuit design alone is costly and insufficient.*

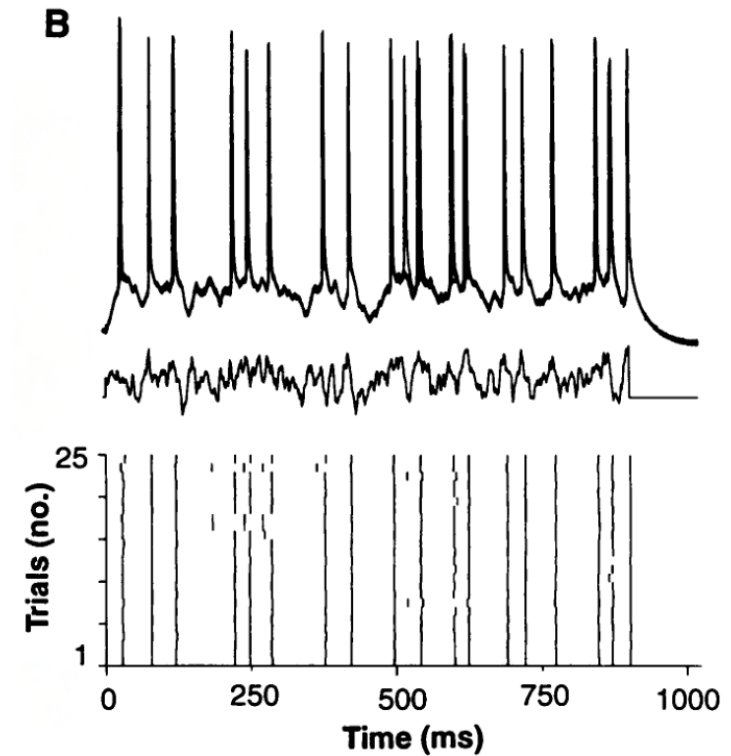
# Biological neurons are varied, yet compute robustly

Mainen & Sejnowski (*Science*, 1995)



## Constant (DC) input

Irregular, variable firing  
Poor trial-to-trial reliability



## Fluctuating input

Highly reproducible spike timing  
Excellent reliability across trials

# Experimental setup on real silicon neurons

## Hardware

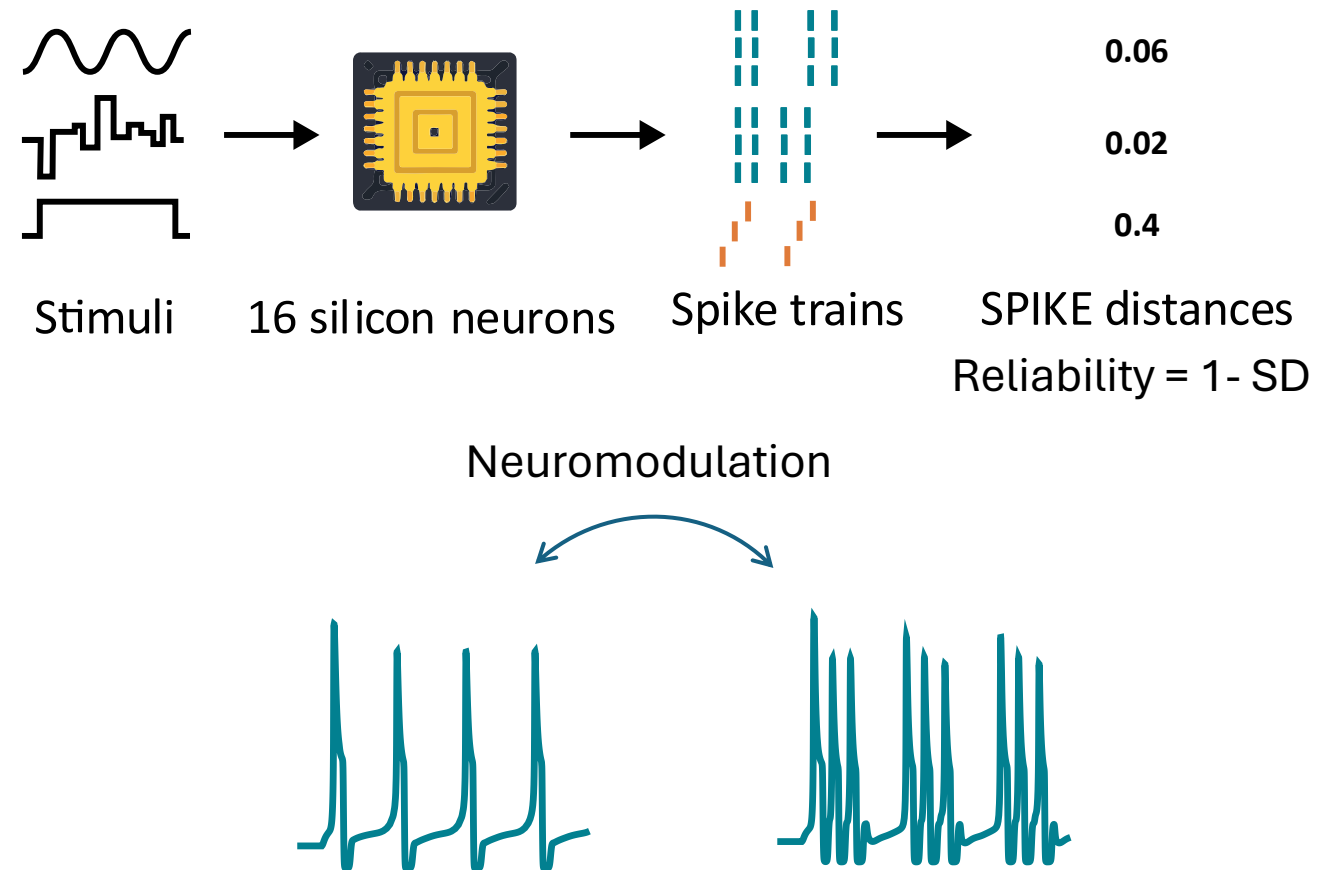
16 mixed-feedback silicon neurons  
(Mendolia et al. 2025, *Neurom. Comp. Eng.*, under review)  
Capable of spiking and bursting excitability  
Significant transistor mismatch (by design)

## Stimuli

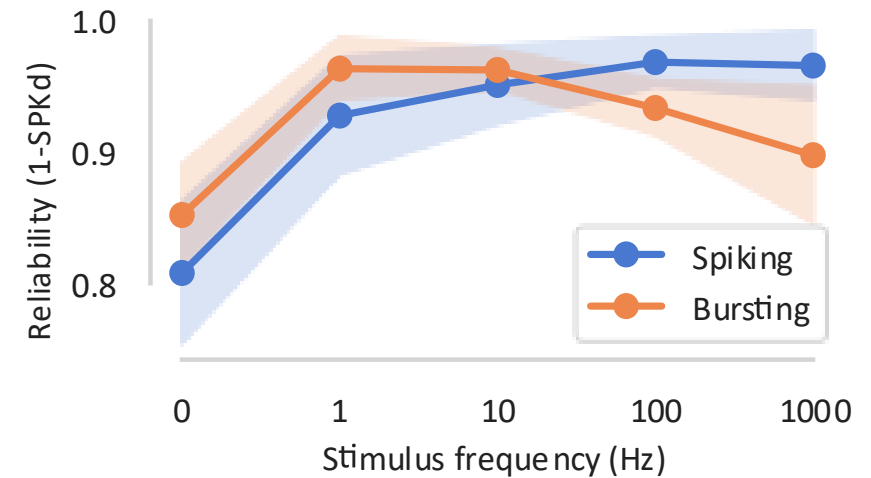
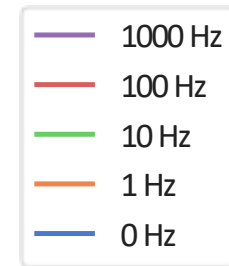
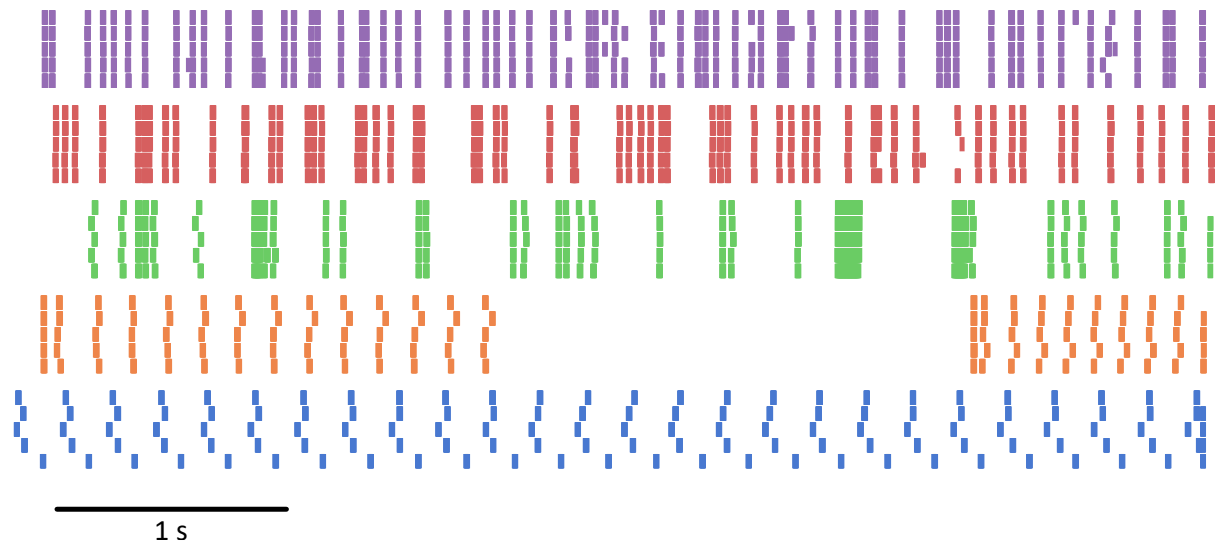
DC (constant amplitude)  
Band-limited white noise  
Filtered white noise  
Sine waves

## Metric

SPIKE-distance (Kreuz et al. 2011)  
 $D = 0$ : perfect synchrony  
 $D = 1$ : maximal asynchrony



# Input-triggered neurons become reliable

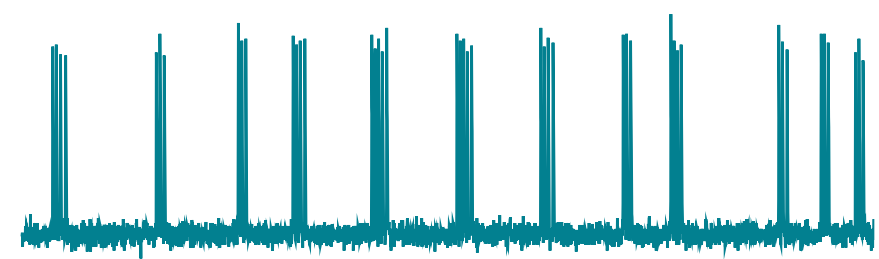


## From limit-cycle oscillator to excitable open system

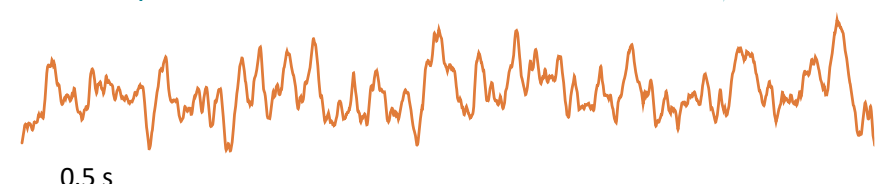
Under DC input, timing variability is high and increases with frequency mismatch.

With fluctuating inputs, neurons are phase-reset by the shared stimulus: events align across trials and across neurons.

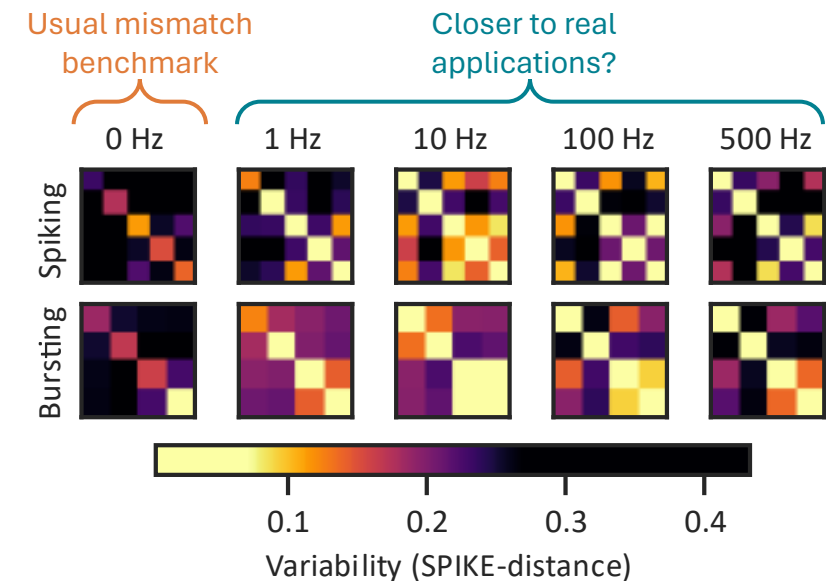
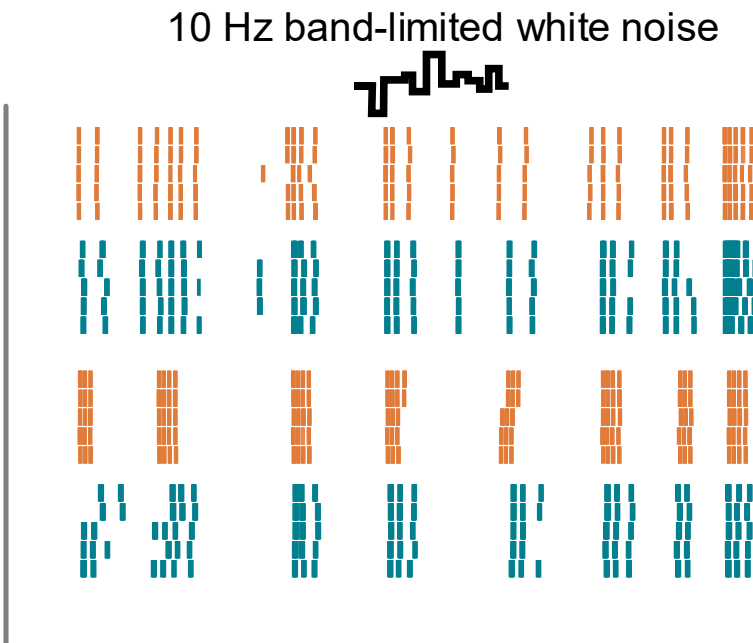
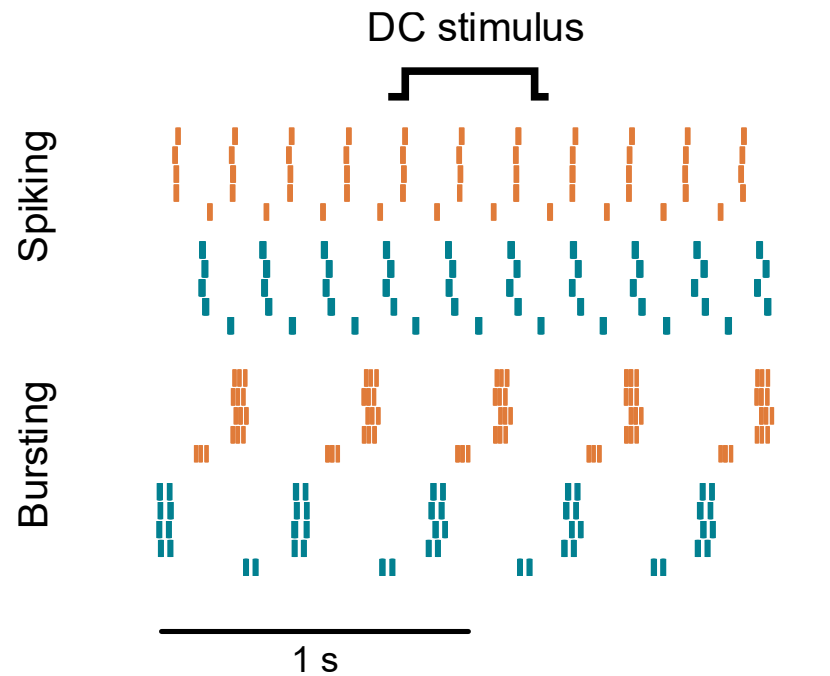
Bursting neuron out.



10 Hz LFP white noise



# Fluctuating inputs synchronize mismatched neurons

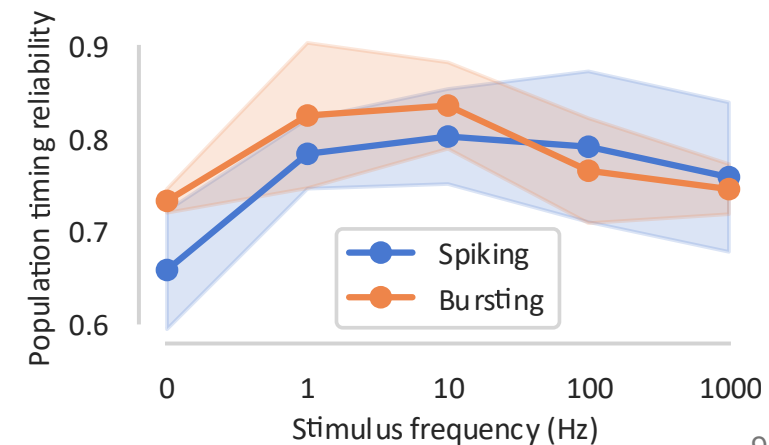


## Autonomous Oscillator (DC)

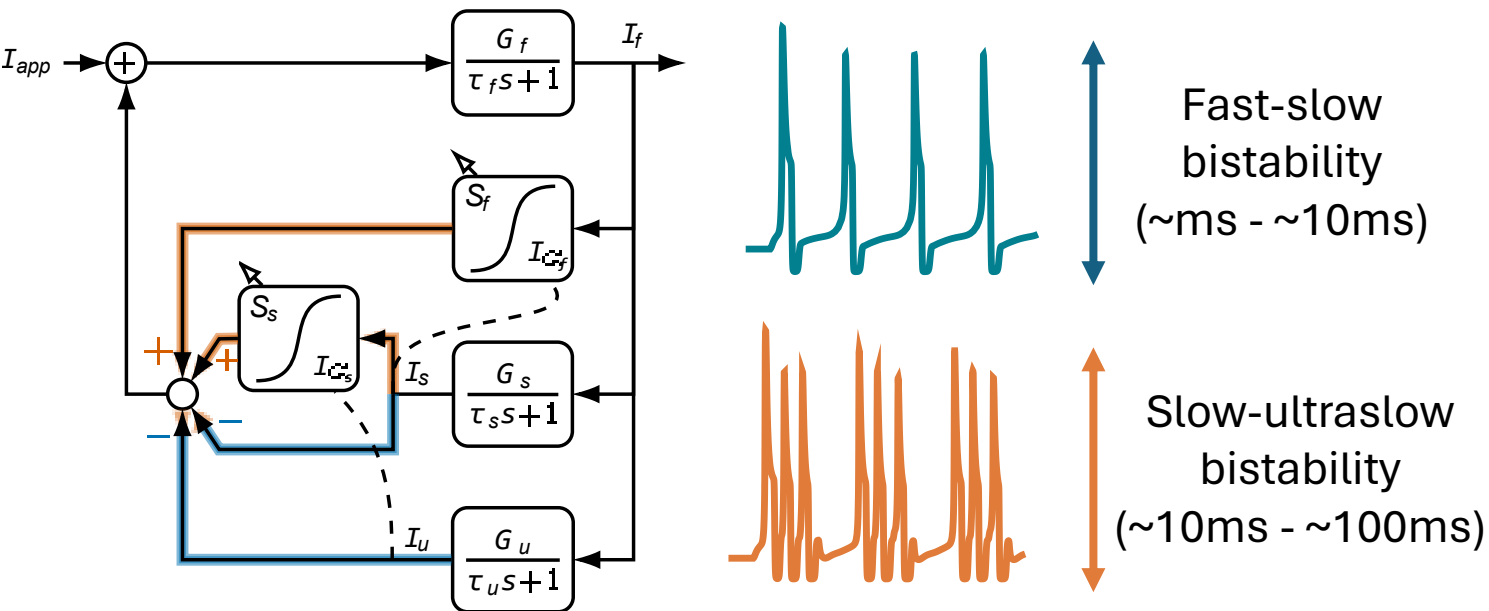
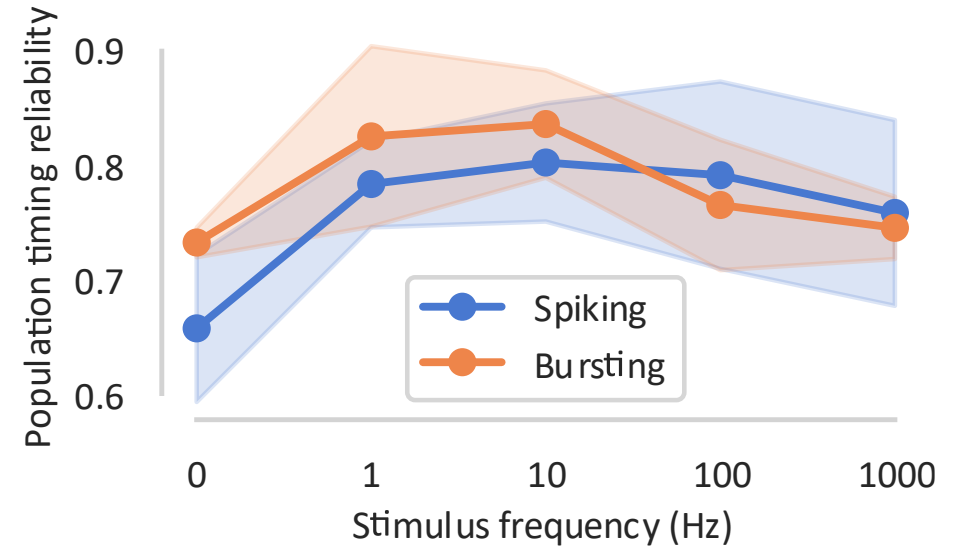
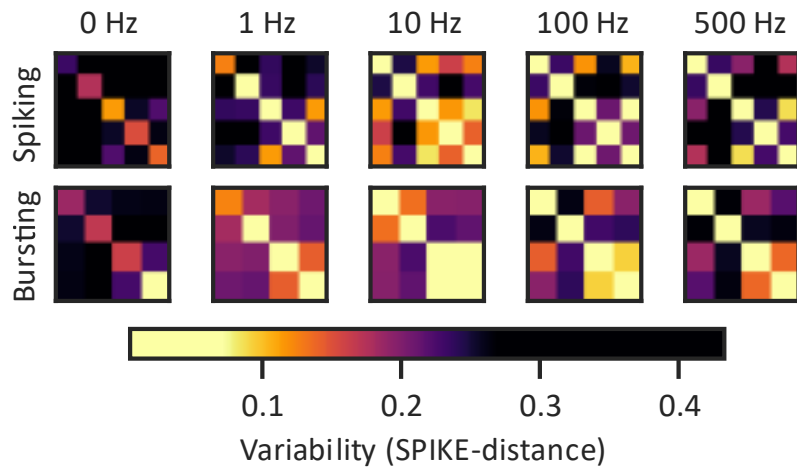
Internal limit-cycle dynamics dominate. Mismatch in parameters  $\rightarrow$  mismatch in firing frequency  $\rightarrow$  incoherent population.

## Excitable Input-Triggered (Fluctuating)

Input pushes state across the excitability threshold. Same fluctuation triggers all neurons simultaneously — event timing is set by the input, not internal parameters.



# Optimal input bandwidth depends on excitability type



**Spiking neurons — Fast-slow bistability**  
(~ms–10 ms)

Optimal at ~10–100 Hz: fluctuations must match spike timescale.

**Bursting neurons — Slow-ultraslow bistability**  
(~10–100 ms)

Optimal at ~1–10 Hz: faster fluctuations interfere with burst formation.

# Why this matters

## **No calibration required**

Robustness to mismatch without extensive layout optimization or active compensation circuitry

## **Event-timing encoding as a reliable alternative to rate coding**

Timing-based representation is more robust than rate codes under hardware variability

## **Input design as a reliability tool**

Appropriate bandwidth selection can substitute for hardware mismatch compensation

## **Neuromodulation for context-dependent bandwidth switching**

Biologically-inspired control over the effective excitability timescale

# Conclusions & Outlook

1

Time-varying inputs transform heterogeneous silicon neurons from unreliable autonomous oscillators into robust event-triggered systems

2

Shared input fluctuations synchronize event timing across mismatched neurons — without calibration, coupling, or parameter tuning

3

Spiking and bursting neurons show distinct optimal input bandwidths, consistent with a trigger-based mechanism tied to underlying excitable timescales

4

Appropriate input design is a viable and practical strategy for mismatch robustness in analog neuromorphic hardware

Future work: Rate vs. event-timing coding accuracy estimation · Theoretical resonance analysis

*Open question:*

**Is it fair to characterize mismatch in event-based neuromorphic systems with DC inputs?**