Input-driven timing reliability in mismatched neuromorphic neurons

Revisiting mismatch in analog neurons through input dynamics

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The promises of analog (subthreshold) neuromorphic hardware

Ultra-low power

Operate in the nA–pA range
(subthreshold regime)

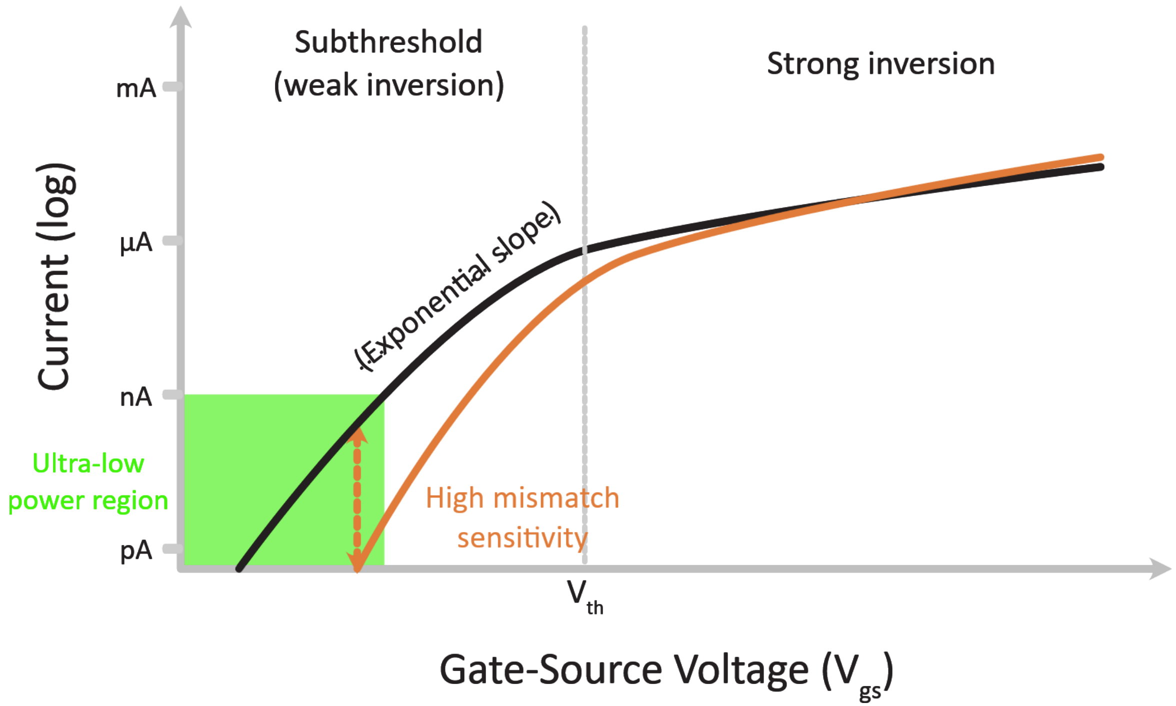
Massively parallel

In-memory computing
across thousands of neurons

Asynchronous & event-based

Computation driven by spikes, not clocks

The catch: device mismatch



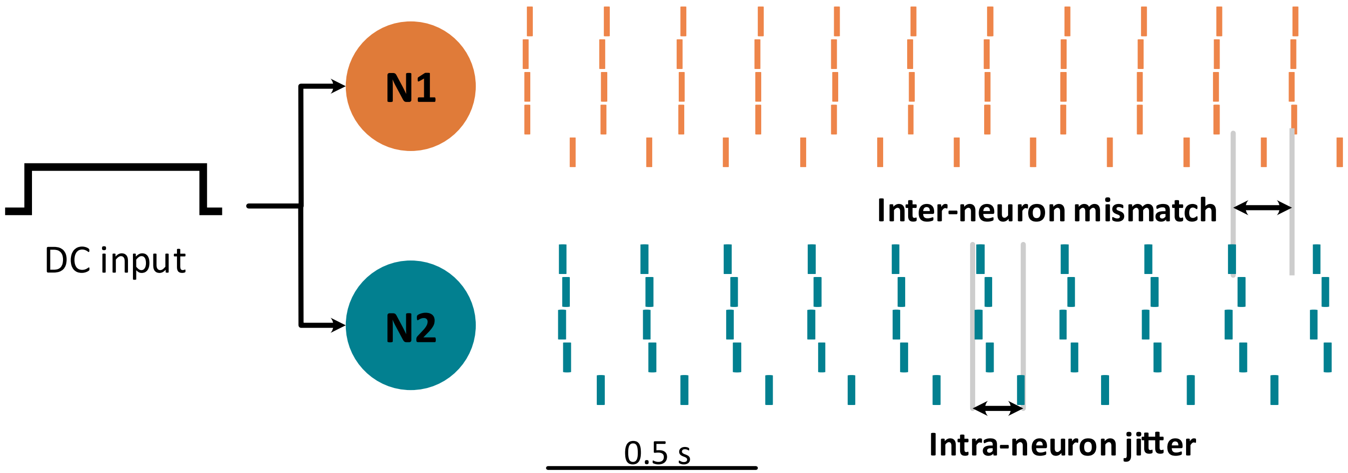
Tiny device-to-device variations → **large current variations.** *Benjamin et al. 2023*
→ Mismatch – power efficiency tradeoff

→ Mismatch looks like a fundamental obstacle to reliable analog computation

Mismatch causes unreliable spike timing

Under DC input:

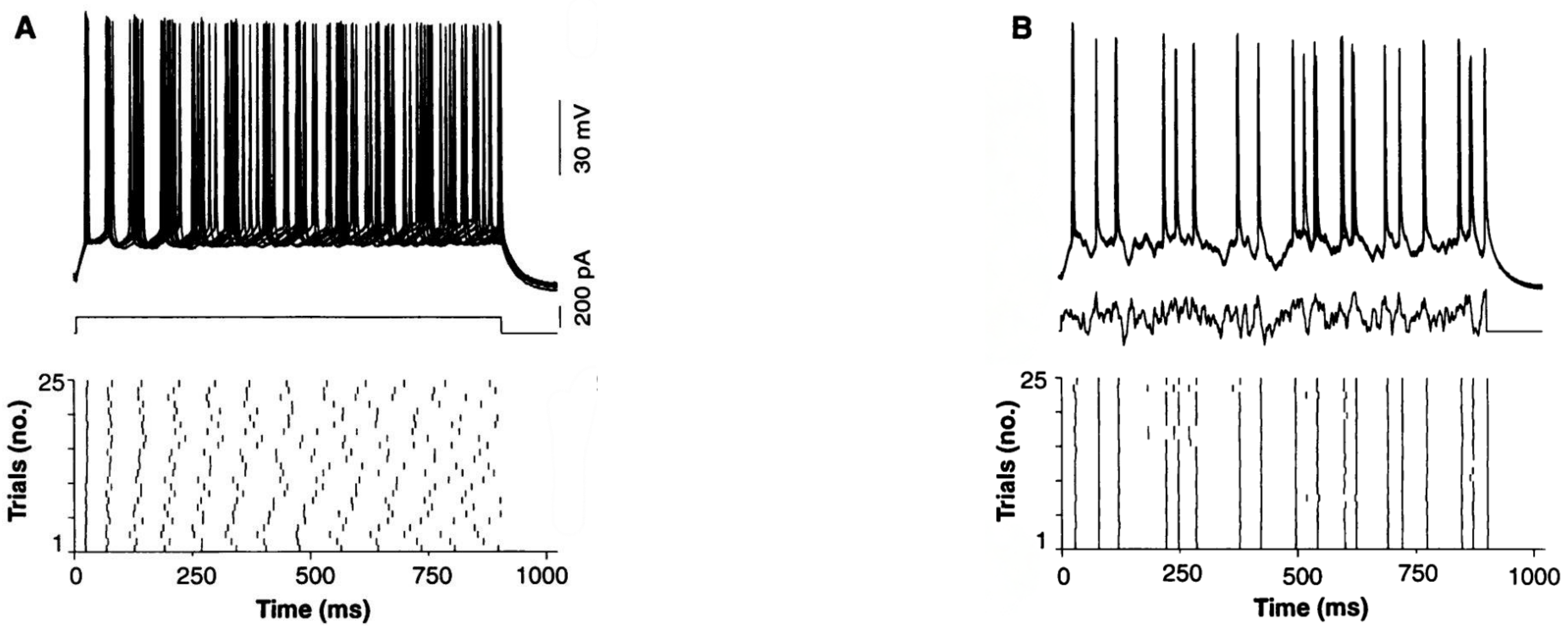
- Neurons act as autonomous limit-cycle oscillators
- Small parameter differences → large rate & phase variation
- No inter-neuron coherence across the population



Reliable event timing underlies coincidence detection, sensory coding & motor control.
→ Mismatch-induced timing variability can degrade the functional performance of neuromorphic systems

Biological neurons are varied, yet compute robustly

Mainen & Sejnowski (Science, 1995)



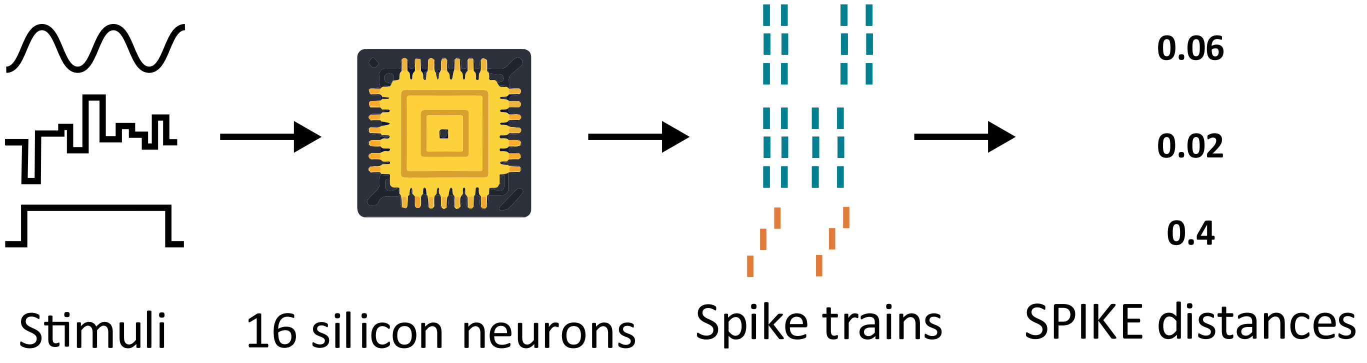
Constant (DC) input

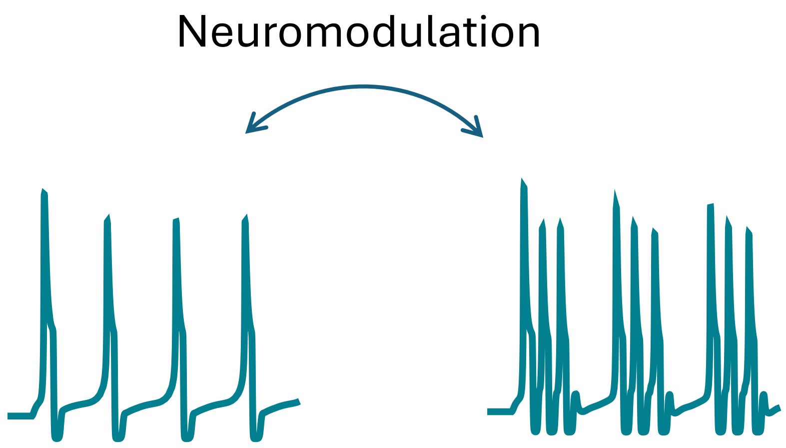
Irregular, variable firing
Poor trial-to-trial reliability

Fluctuating input

Highly reproducible spike timing
Excellent reliability across trials

Experiments on real, mismatched silicon





Hardware

16 mixed-feedback silicon neurons (Mendolia et al. 2025).
Spiking & bursting excitability
Large transistor mismatch by design.

Stimuli

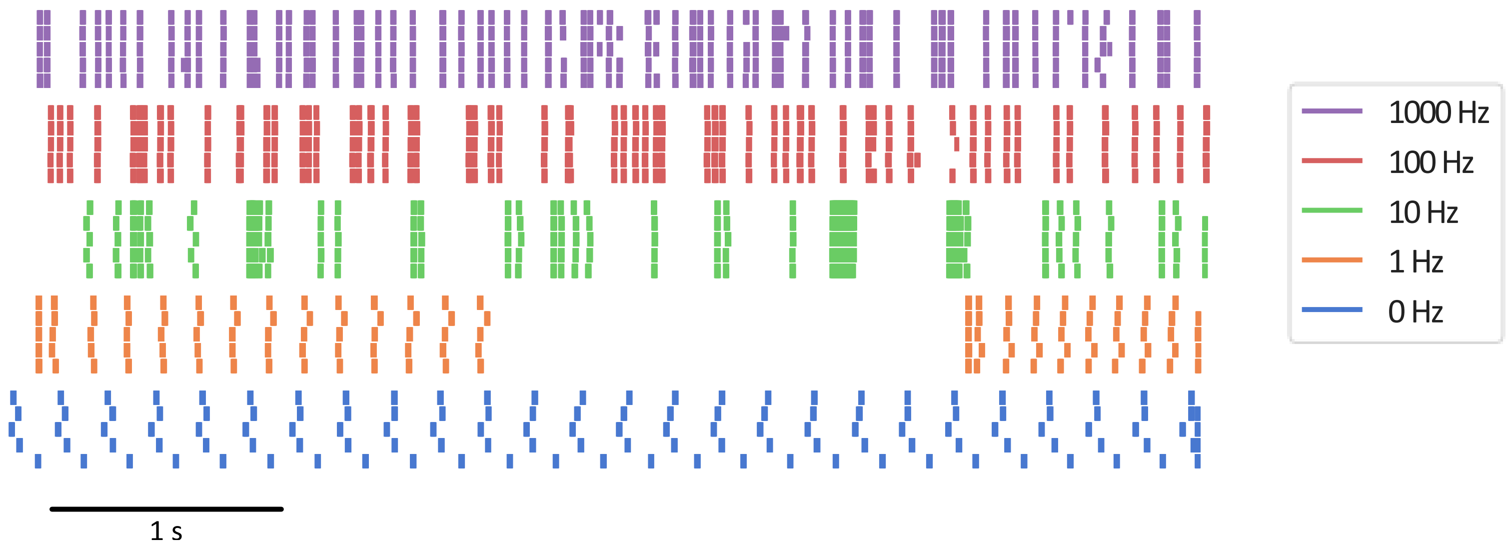
DC
Band-limited white noise
Filtered white noise
Sine waves
Poisson spike trains

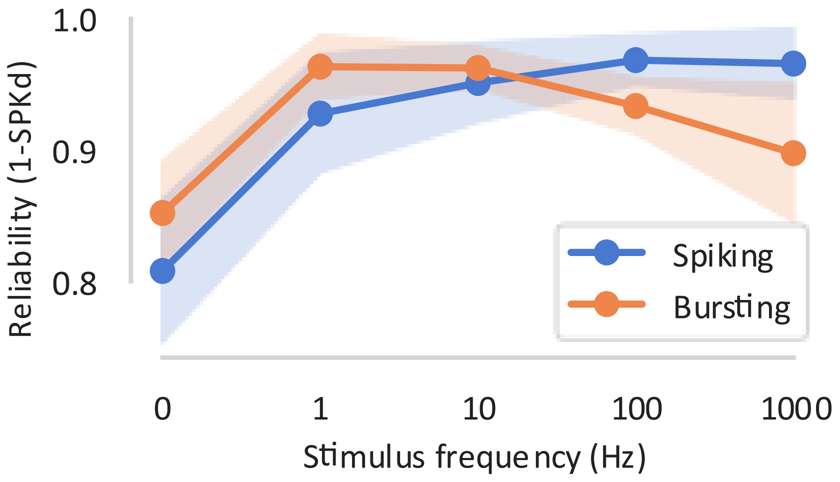
Metric

SPIKE-distance (Kreuz et al. 2011).
Reliability = 1 − SPIKE-distance:
0 = asynchronous,
1 = perfectly synchronous.

First test of input-driven timing reliability on physical, mismatched silicon neurons (not biology, not simulation)

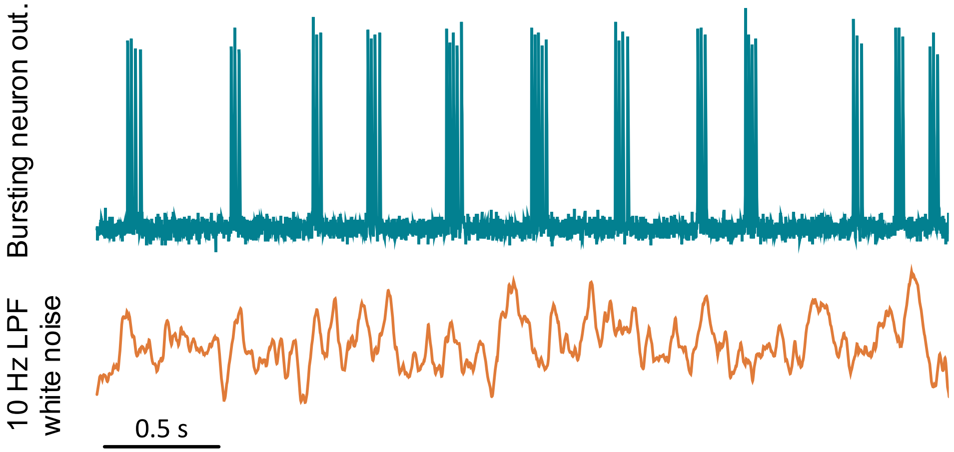
Input-triggered neurons become reliable across trials



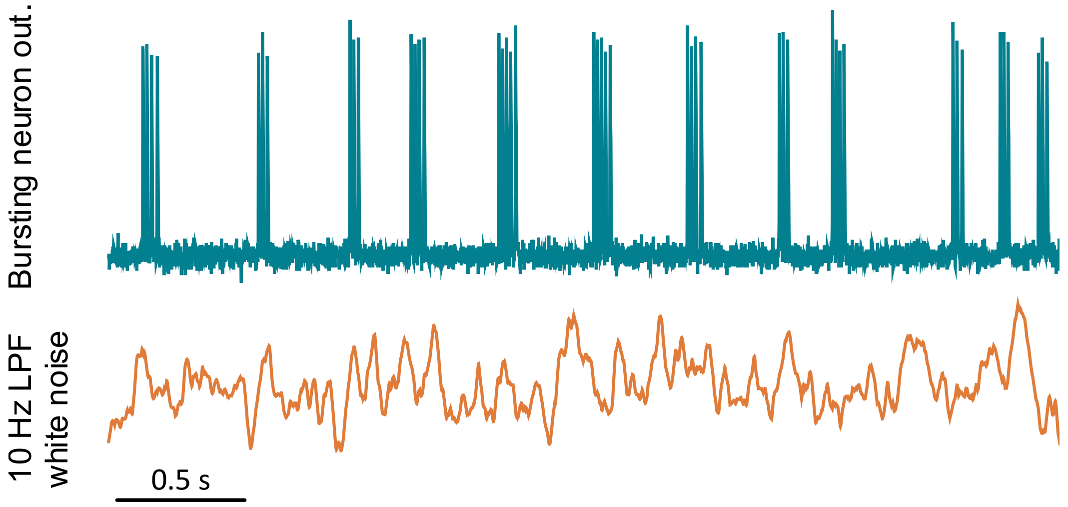


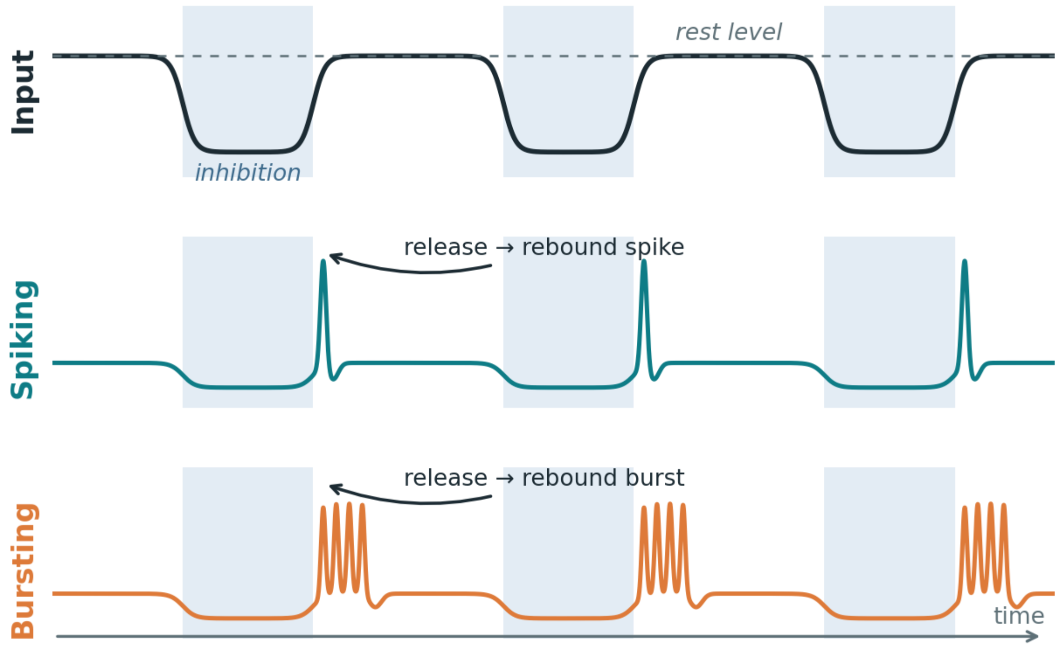
From limit-cycle oscillator to excitable open system

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.



Reliable neurons behave as excitable open systems





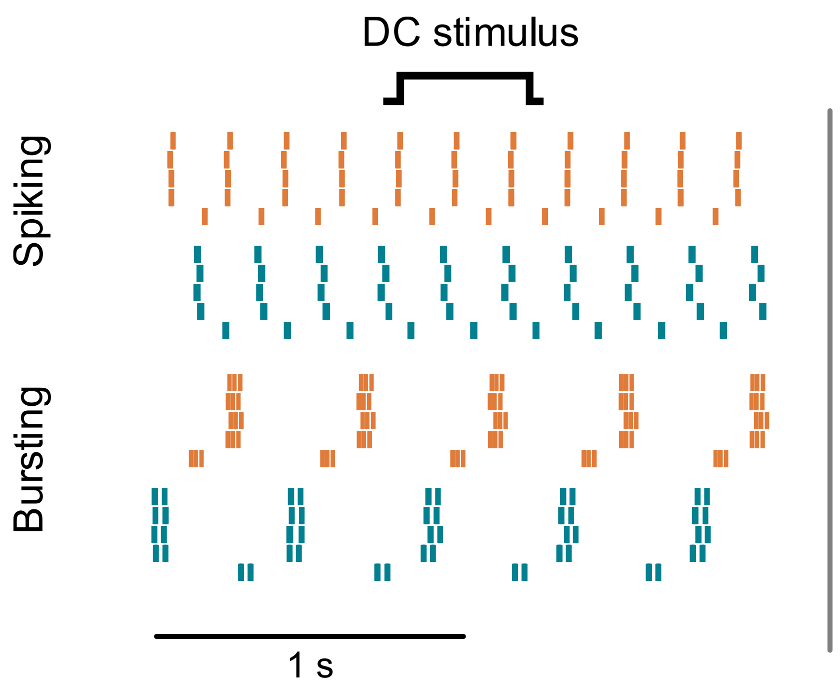
An excitable open system, not an autonomous oscillator

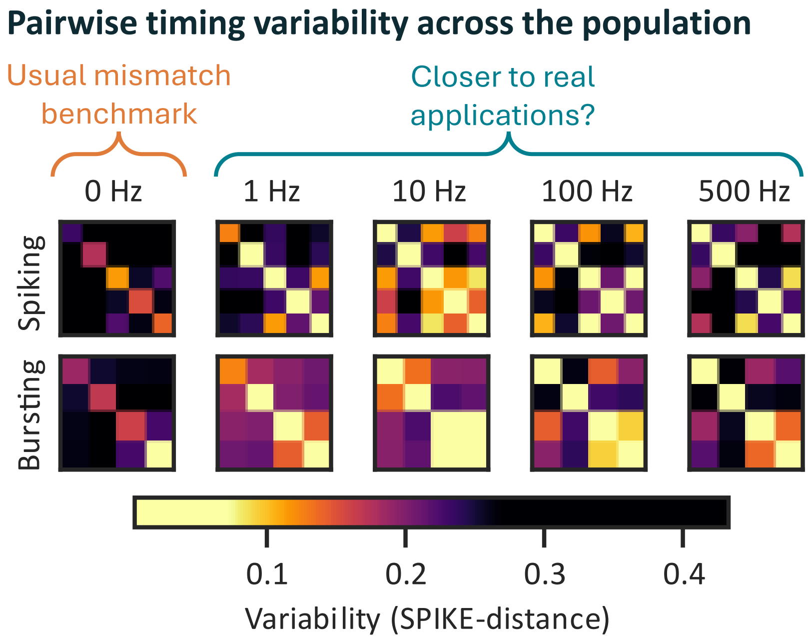
The shared input drives every neuron across the same excitability threshold.
Timing is set by the input, not internal parameters.

Working hypothesis: post-inhibitory rebound

A dynamic input swings each neuron between rest and inhibition; every release from inhibition is a rebound event — set by the shared input, not by mismatched parameters.

Fluctuating inputs align mismatched neurons





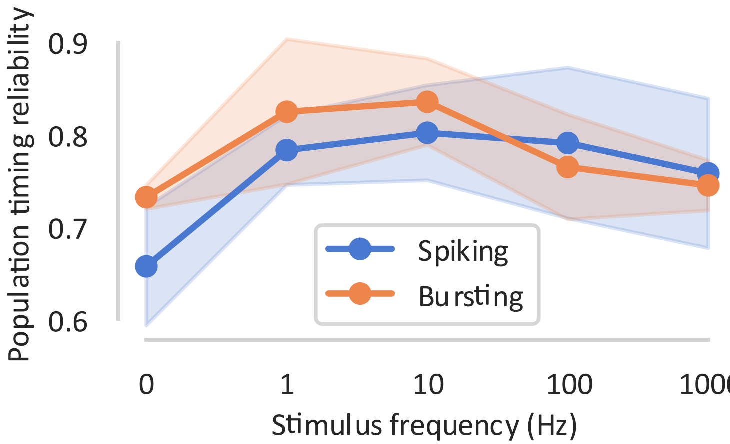
Autonomous Oscillator (DC)

Internal limit-cycle dynamics dominate.

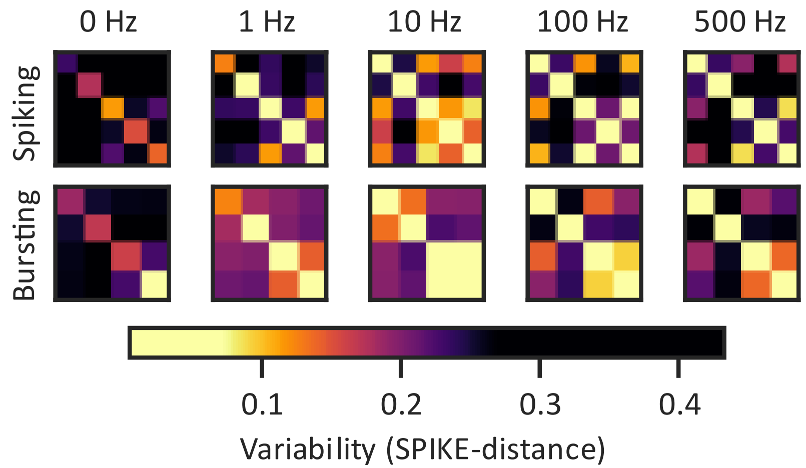
Mismatch in parameters
→ mismatch in firing frequency
→ incoherent population.

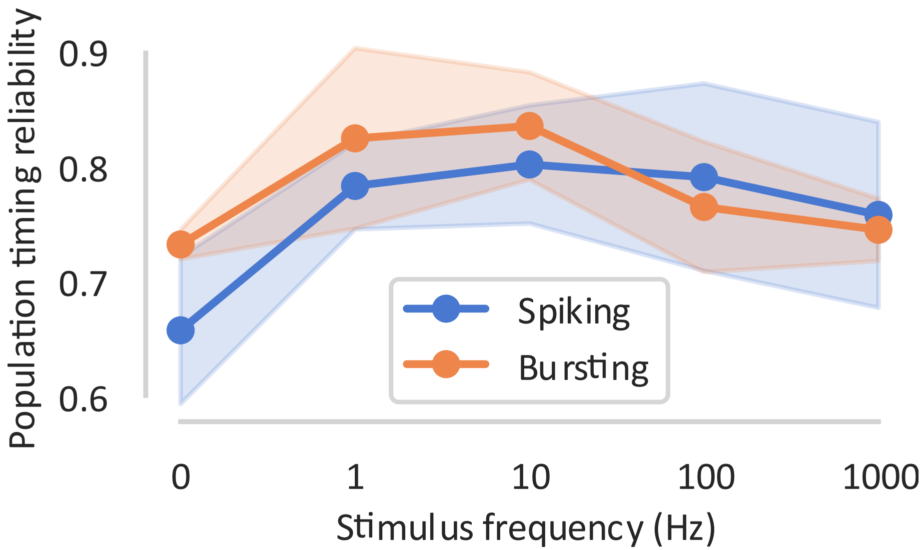
Excitable Input-Triggered (Fluctuating)

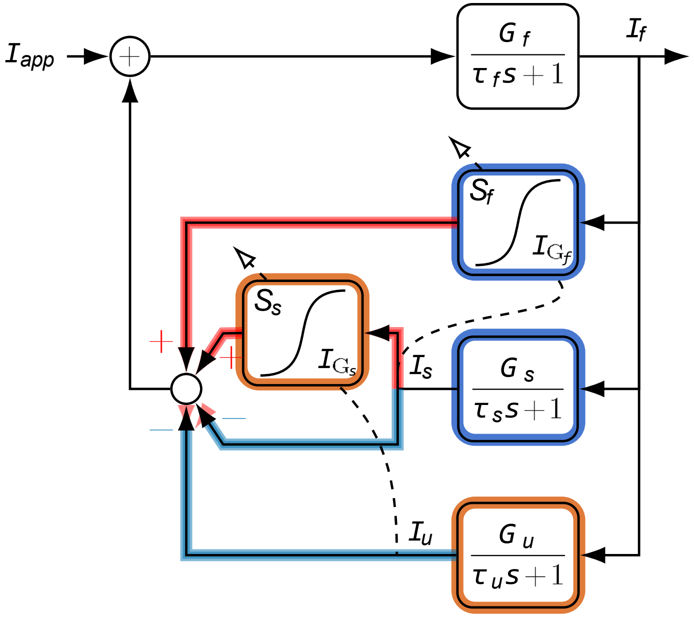
Input pushes state across the excitability and rebound thresholds.
Same fluctuation triggers all neurons similarly → event timing is set by the input, not internal parameters.



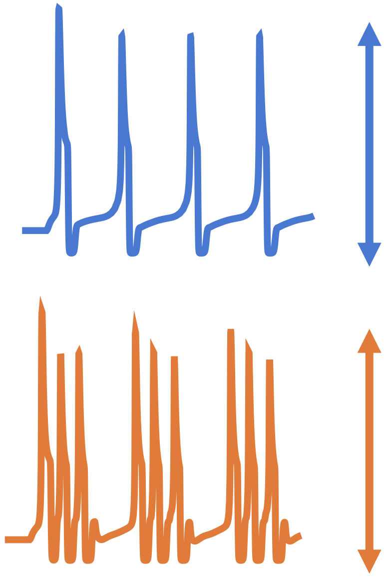
Optimal input bandwidth depends on excitability type







Mixed-feedback neuron model



Spiking — fast–slow bistability

Bistability timescale ~ms – 10 ms

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

Bursting — slow–ultraslow bistability

Bistability timescale ~10 – 100 ms

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

Contributions

1
Input-driven timing reliability on mismatched silicon neurons
Time-varying inputs transform heterogeneous silicon neurons from unreliable autonomous oscillators into robust event-triggered systems

2
Reliability from the input alone
Shared input fluctuations synchronize event timing across mismatched neurons without calibration, coupling, or parameter tuning

3
Bandwidth set by the excitability timescale
Spiking and bursting neurons show distinct optimal input bandwidths, consistent with a trigger-based mechanism tied to underlying excitable timescales

Future works
Rate vs. event-timing coding accuracy · Theoretical resonance analysis · Rebounding vs non-rebounding models

Why this matters

No calibration required

Robustness to mismatch without layout optimization or active compensation circuitry.

Input design as a reliability tool

Choosing an appropriate input bandwidth can substitute for hardware mismatch compensation.

Event-timing encoding as a reliable alternative to rate coding

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

Neuromodulation as a bandwidth control

Biologically-inspired knob over the effective excitability timescale.

→ **Let's use analog neurons for what they're good at: dynamic inputs and event-based timing.**

Open question: *is it fair to characterize mismatch in event-based systems with DC inputs?*