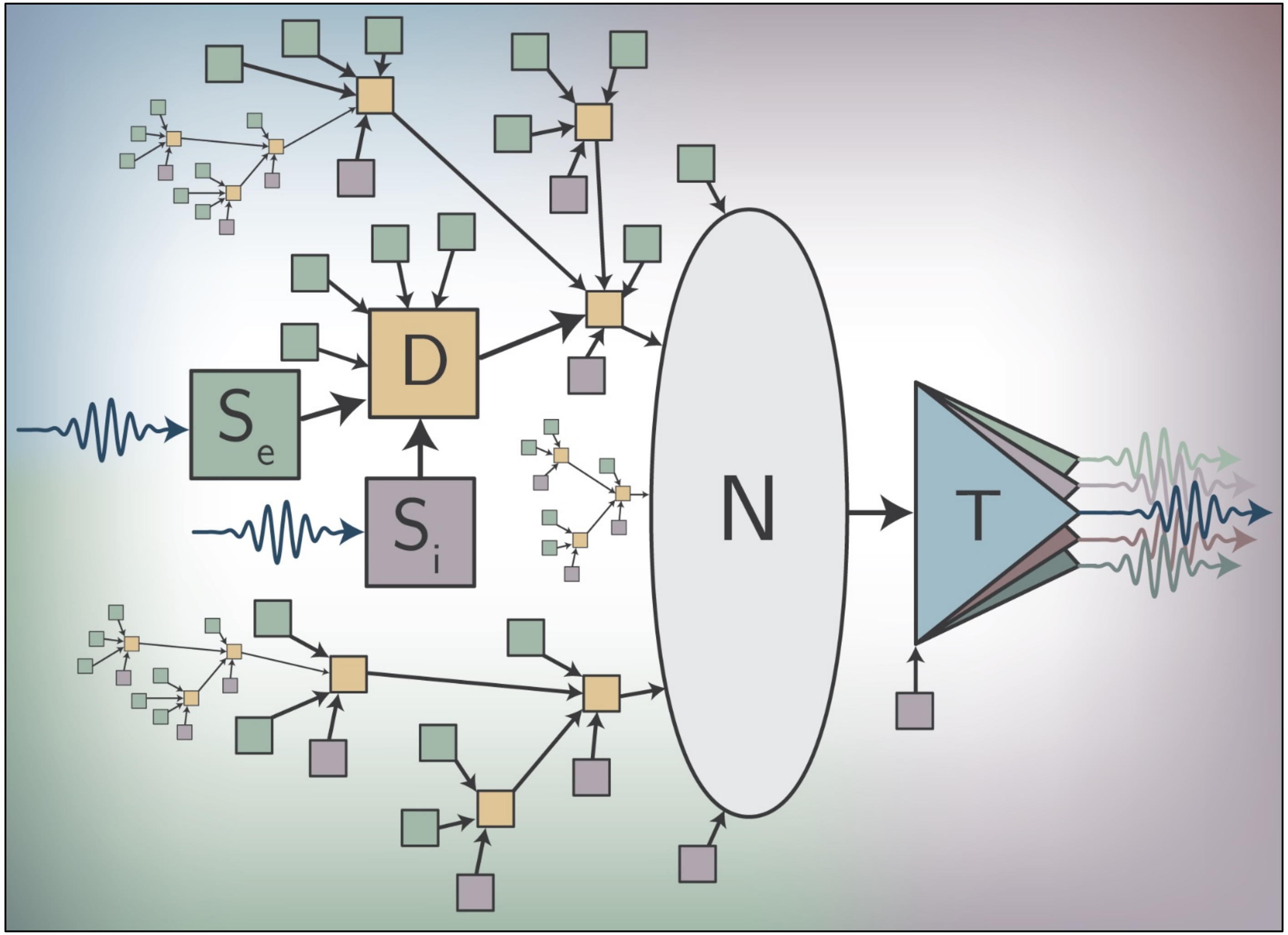
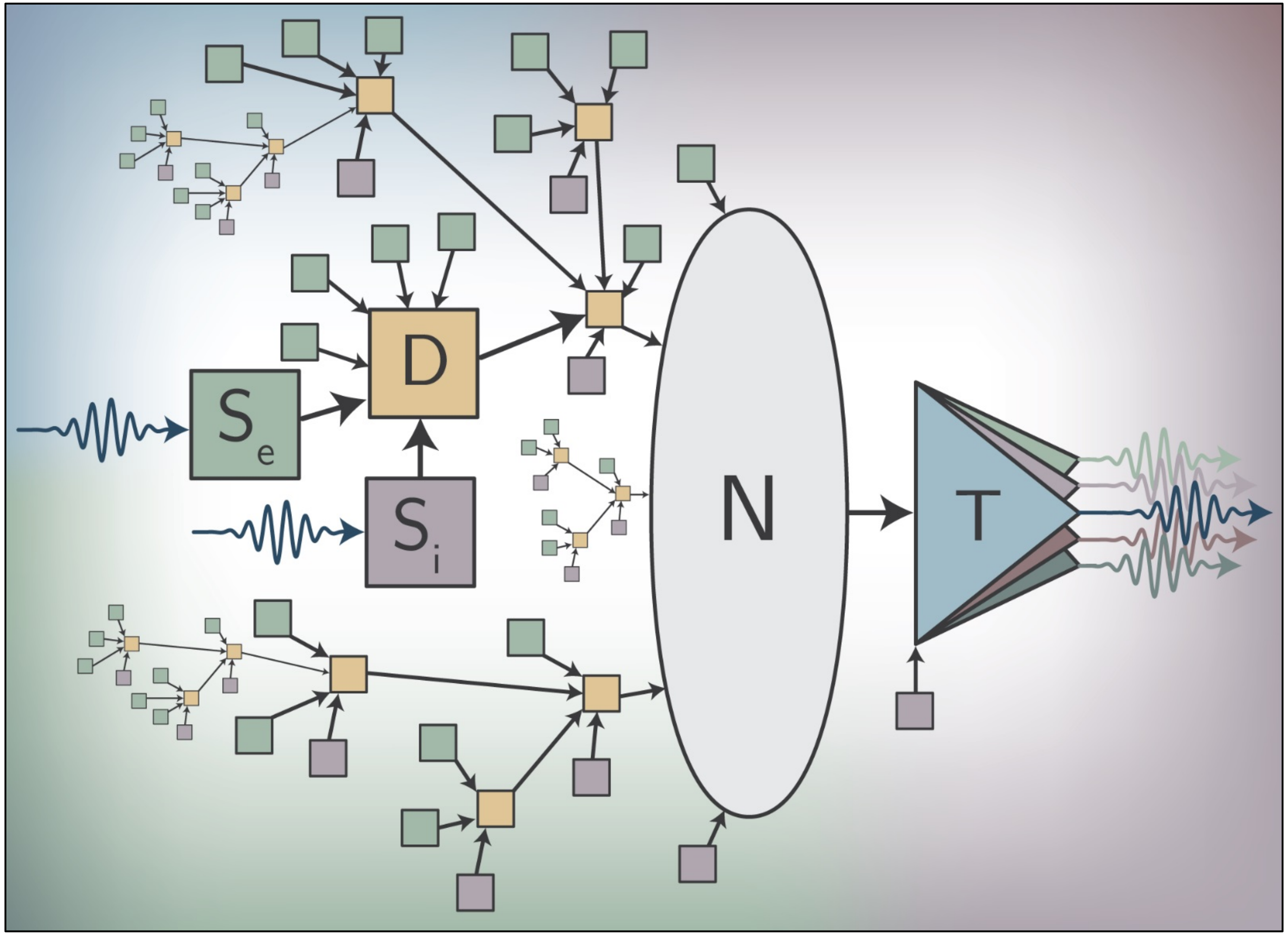


Fluxonic processing of photonic synapse events

Physics and hardware for information project

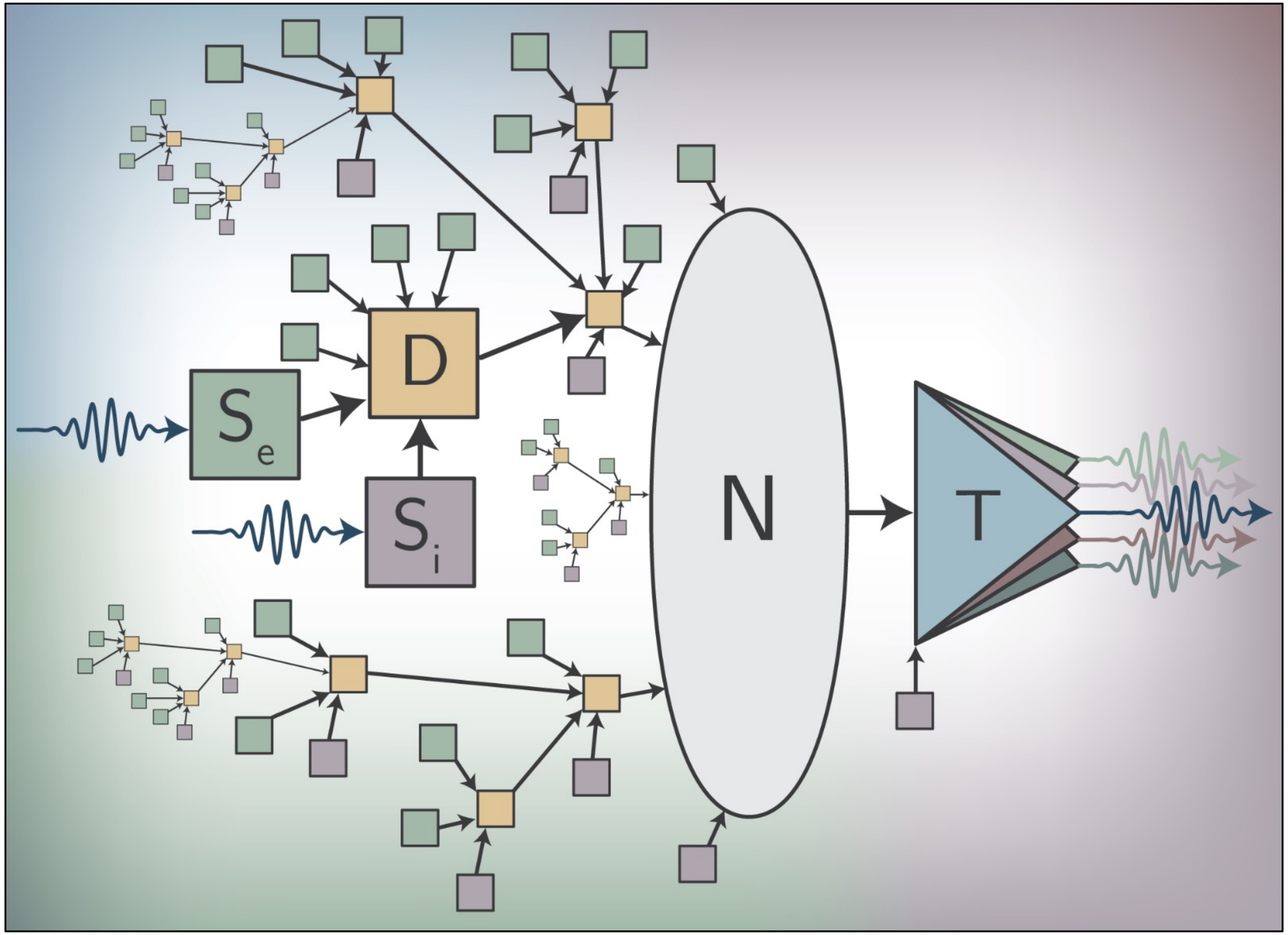
Jeff Shainline, Sonia Buckley, Jeff Chiles, Saeed Khan, Adam McCaughan, Alex Tait, Rich Mirin, and Sae Woo Nam

NIST Boulder



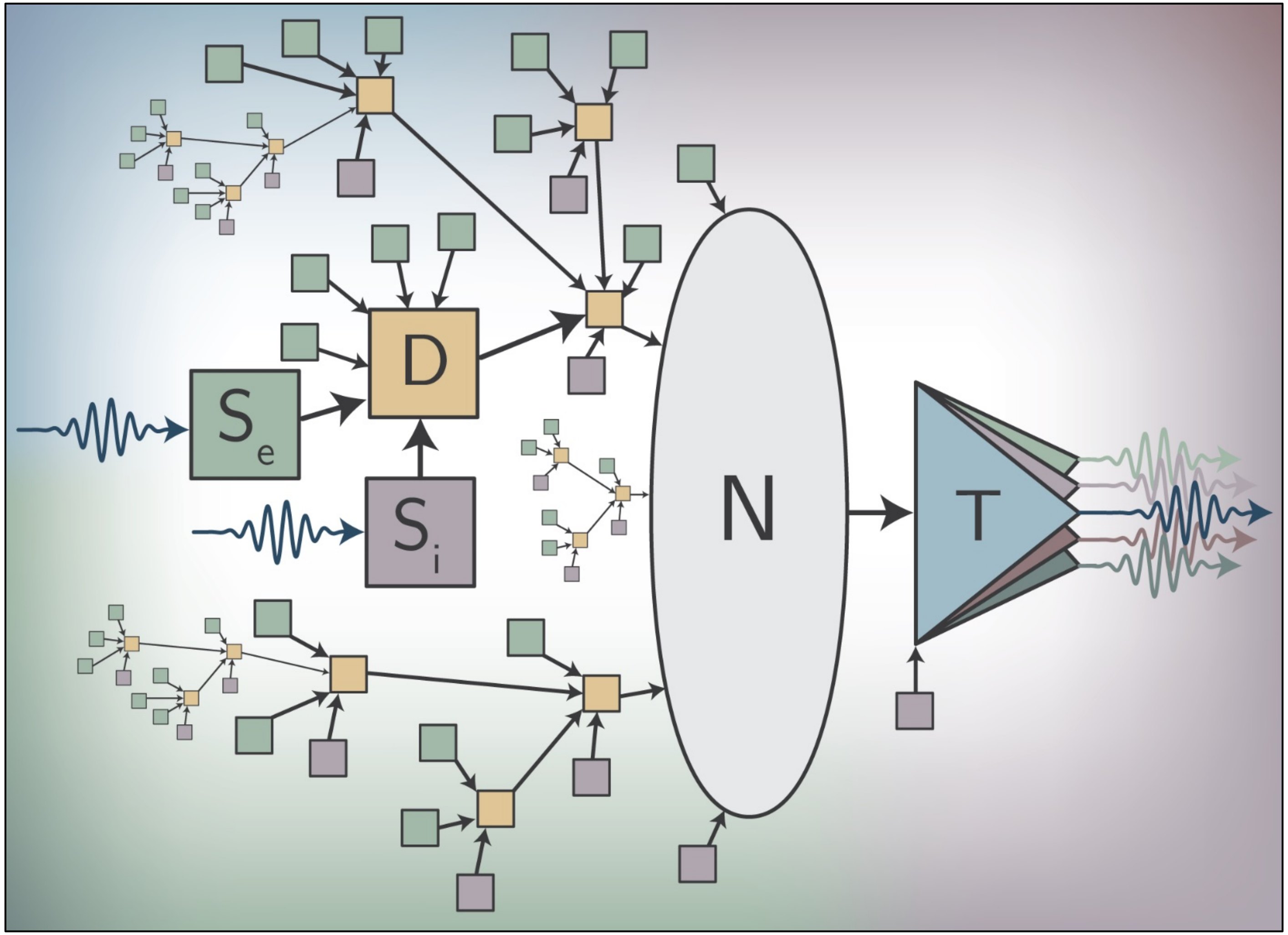
Fluxonic processing of photonic synapse events

Spiking neural networks



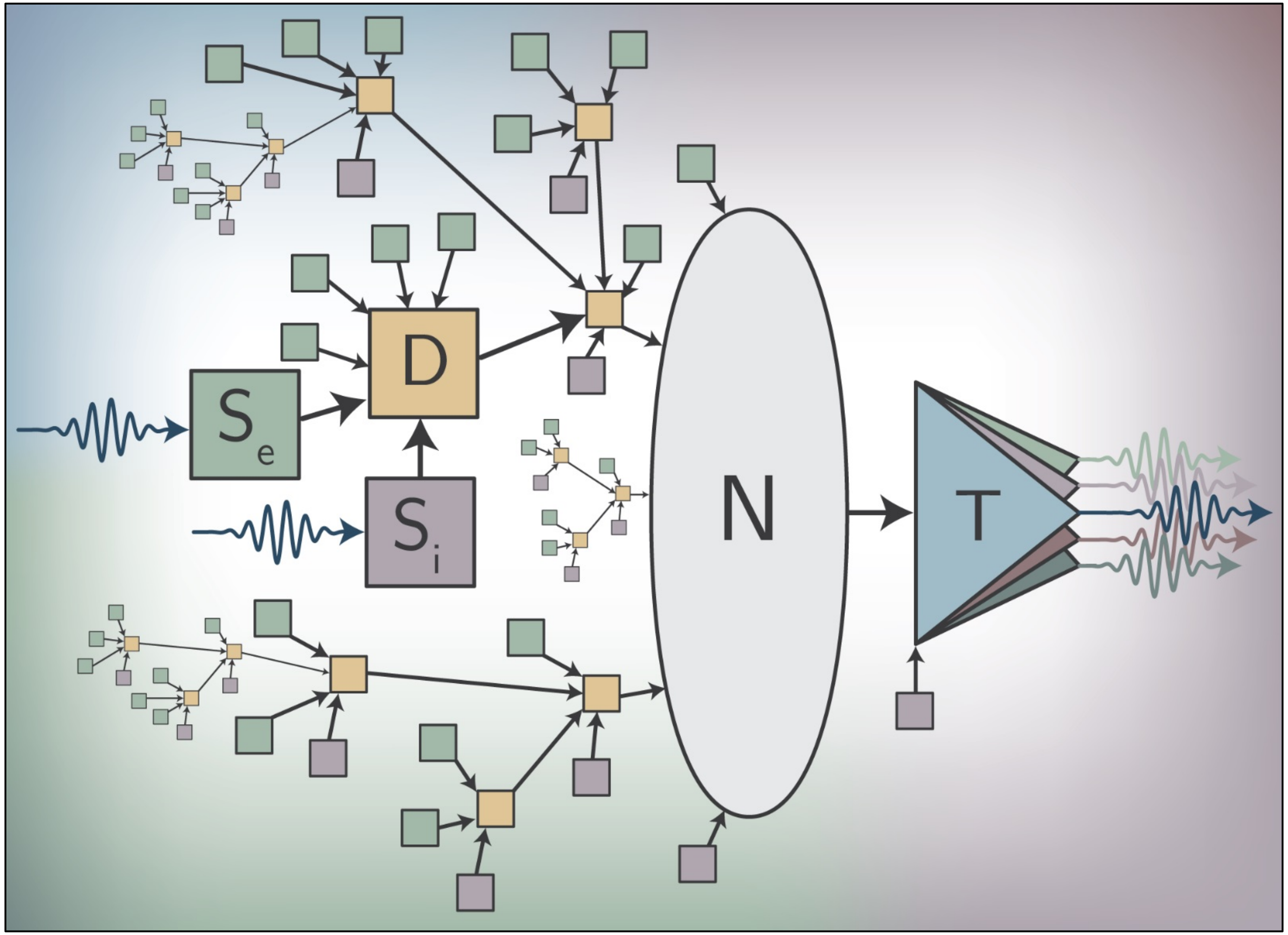
Fluxonic processing of
photonic synapse events

Light for communication



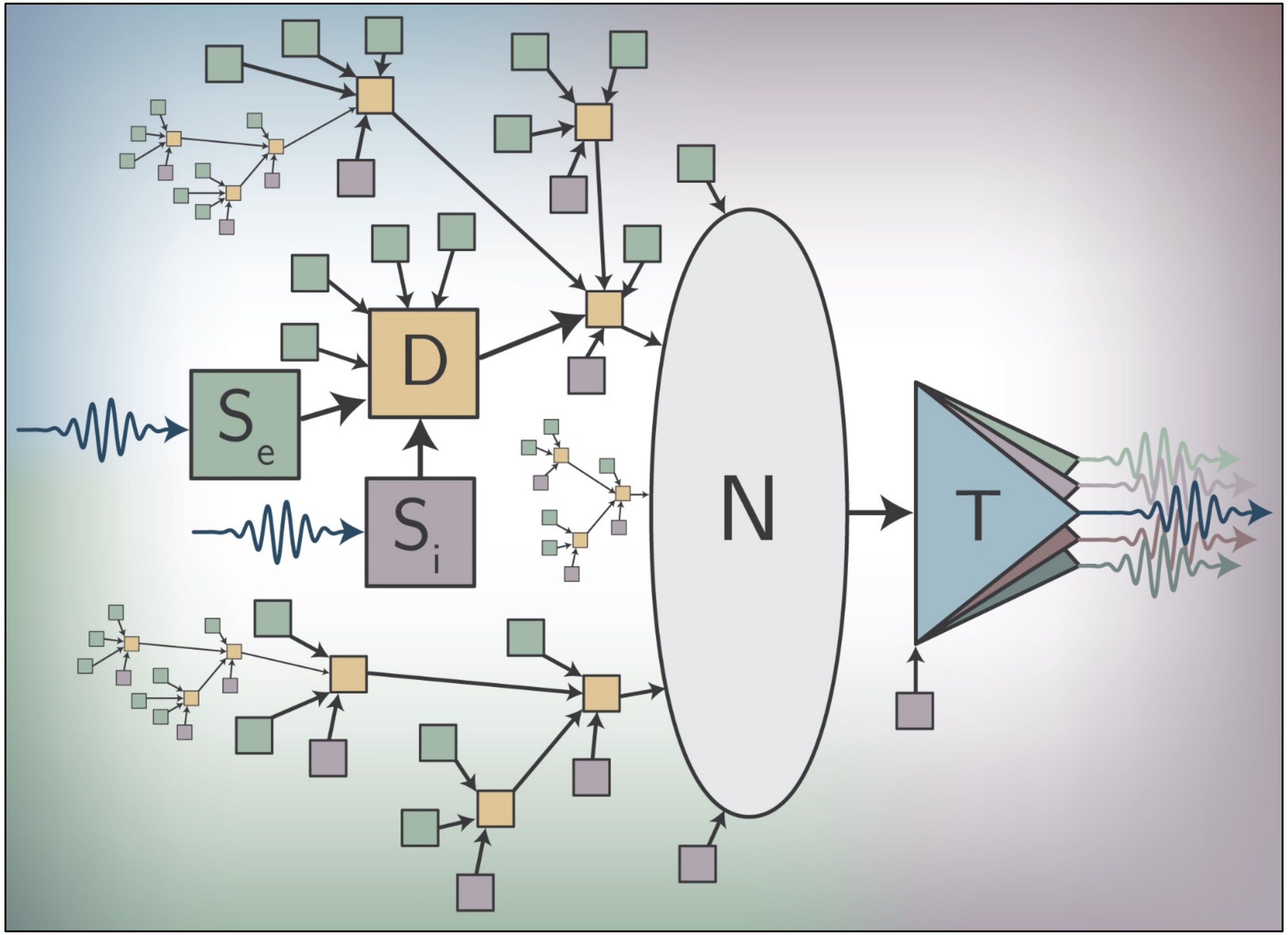
Fluxonic processing of photonic synapse events

Superconducting electronics for single-photon detection



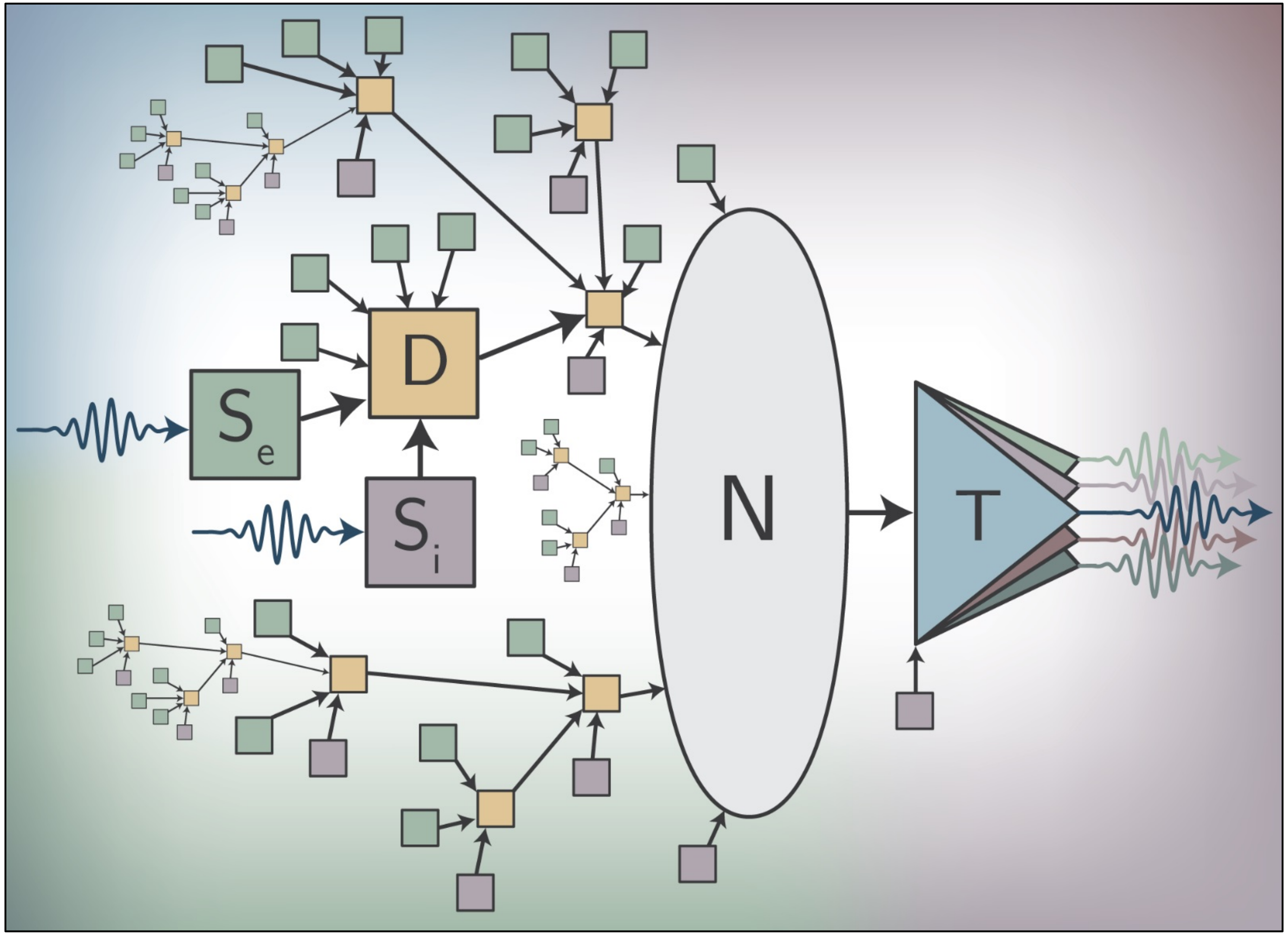
Fluxonic processing of photonic synapse events

Superconducting electronics for neural computation



Fluxonic processing of photonic synapse events

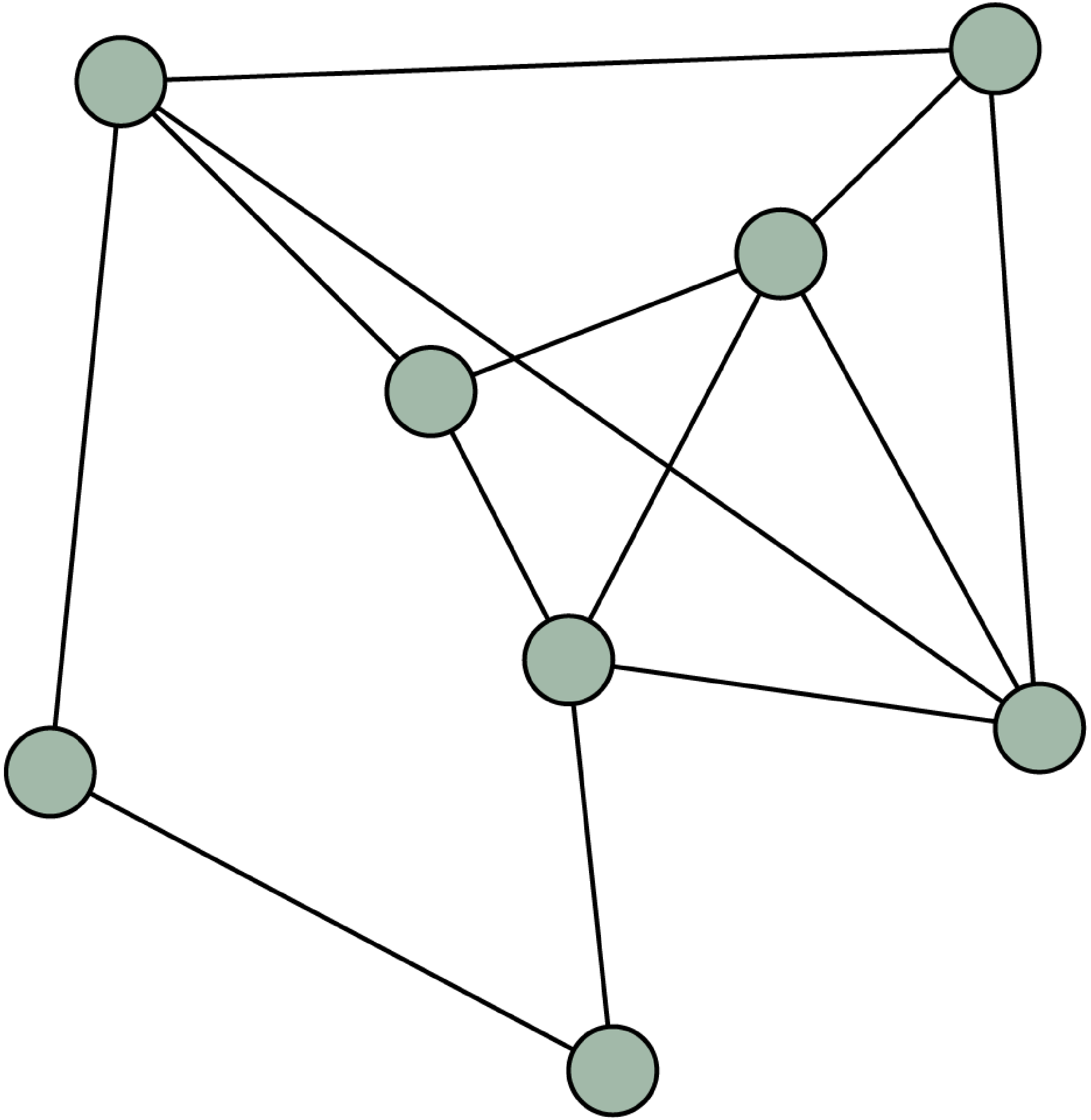
Neuromorphic supercomputing



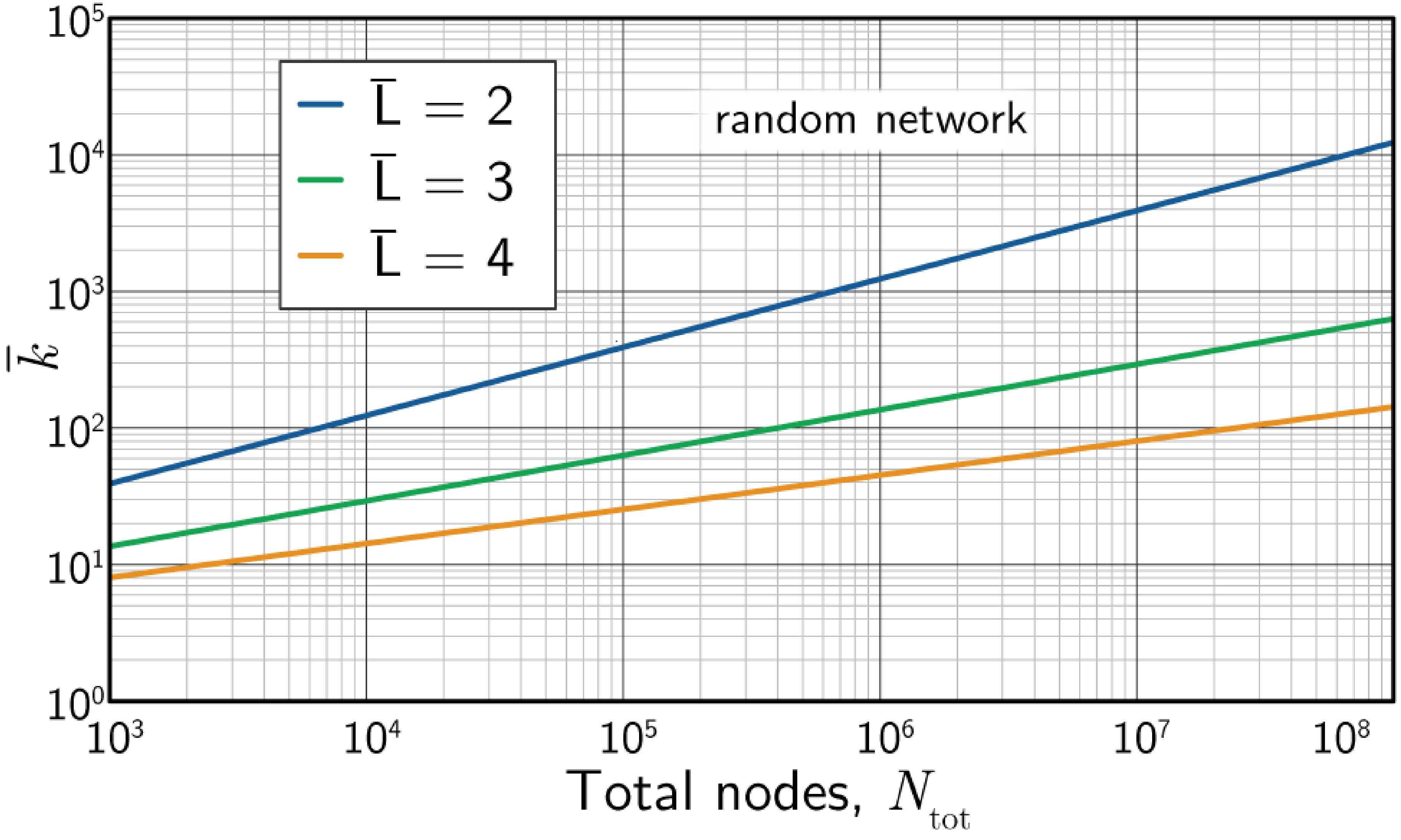
Why are we using light for communication?

Neuromorphic supercomputing

Efficient communication:
short path length



Connectivity for short path length



- Information integration requires short paths
- Short paths require massive connectivity

Light for communication

information integration
across space

Light for communication

information integration
across space

no charge-based parasitics
enables high fan-out

Light for communication

information integration
across space

light sources are
a challenge

no charge-based parasitics
enables high fan-out

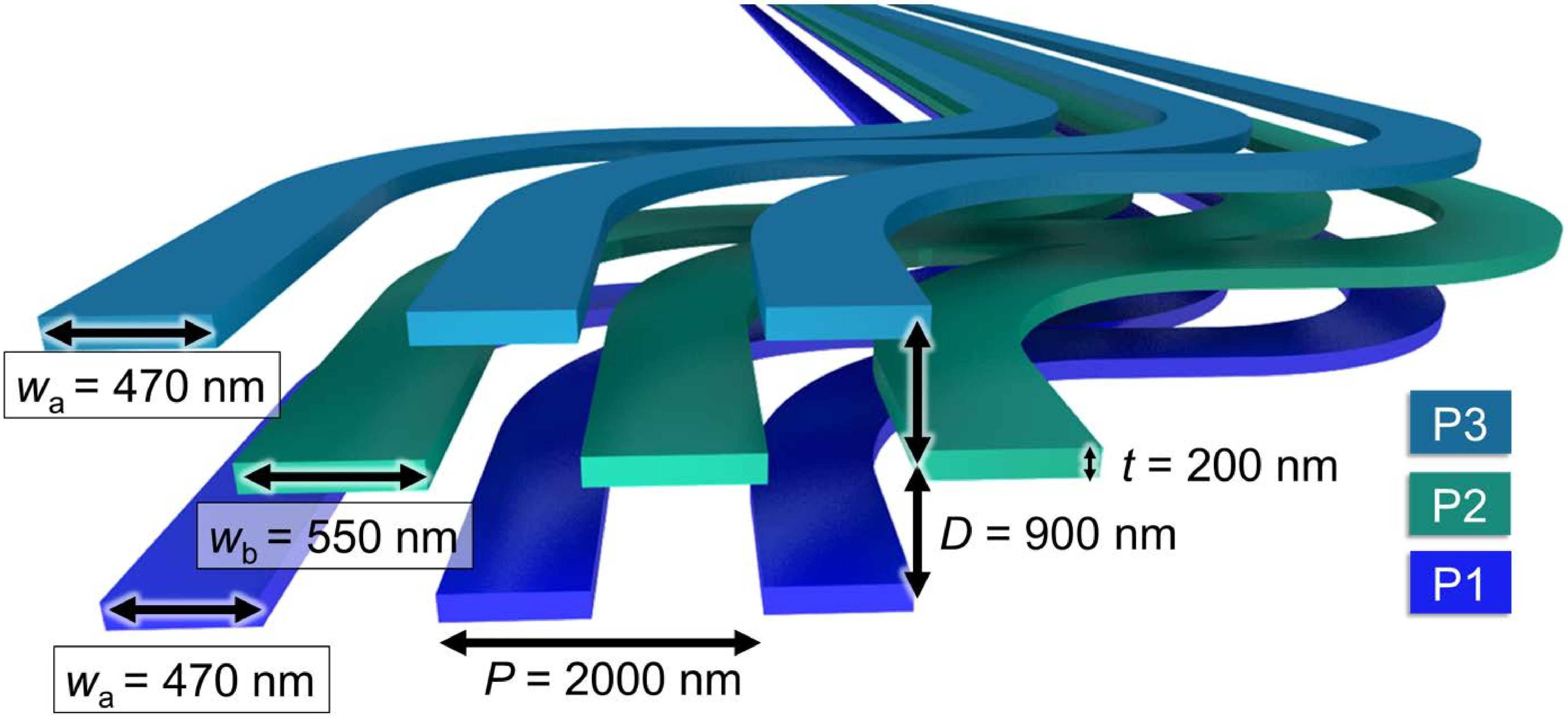
Light for communication

information integration
across space

how do we implement
photonic networks?

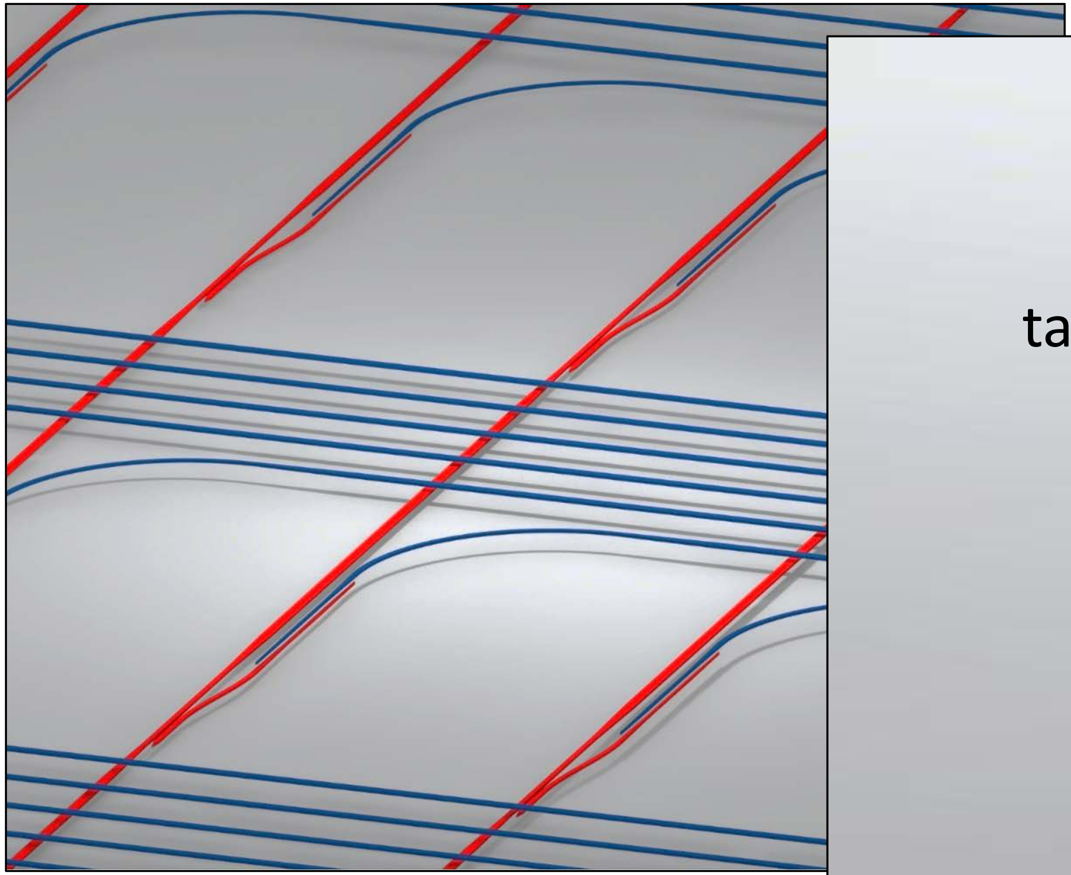
no charge-based parasitics
enables high fan-out

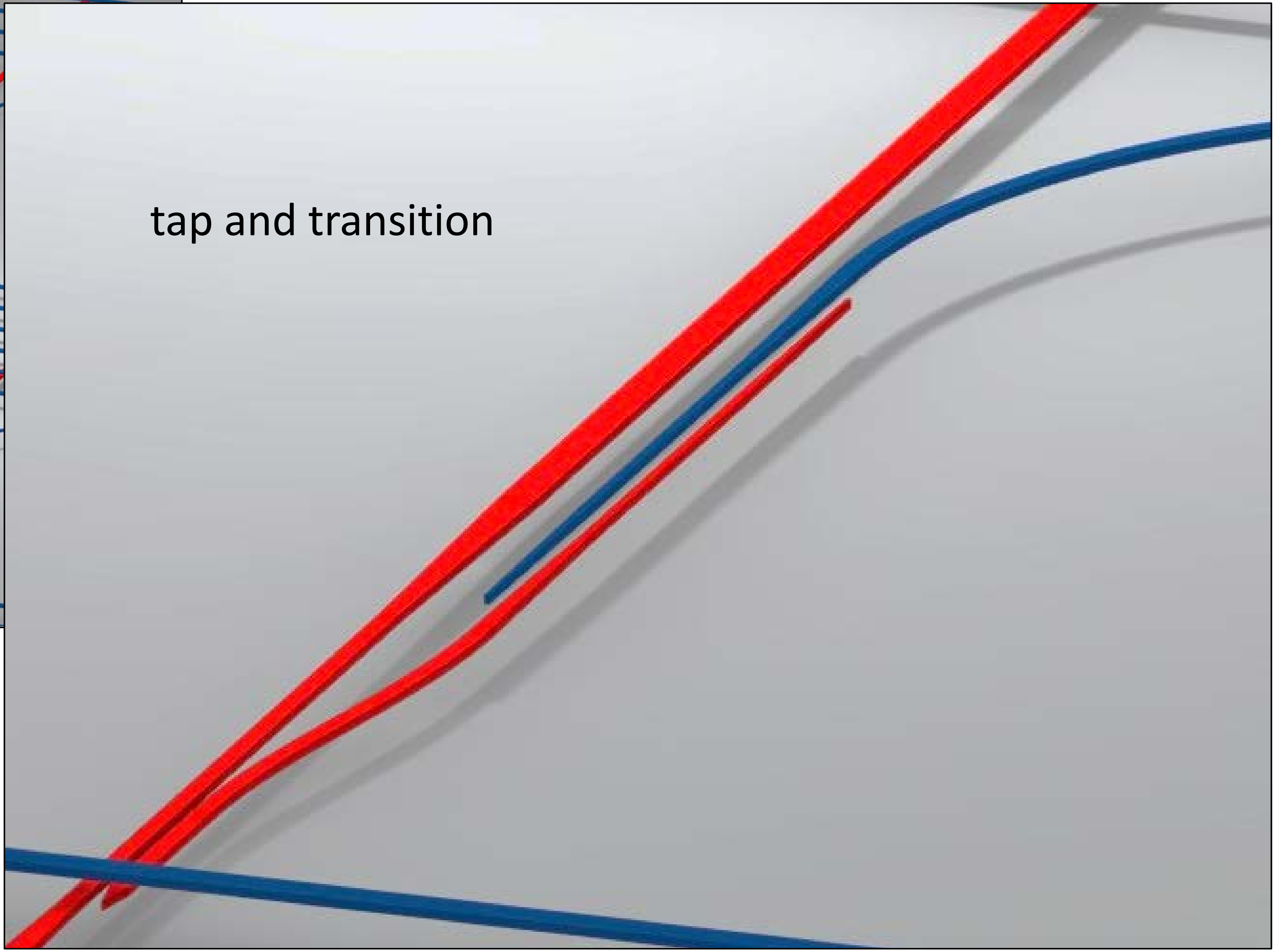
Multiplanar waveguides



Chiles et al., APL Photonics, 2, 116101 (2017)

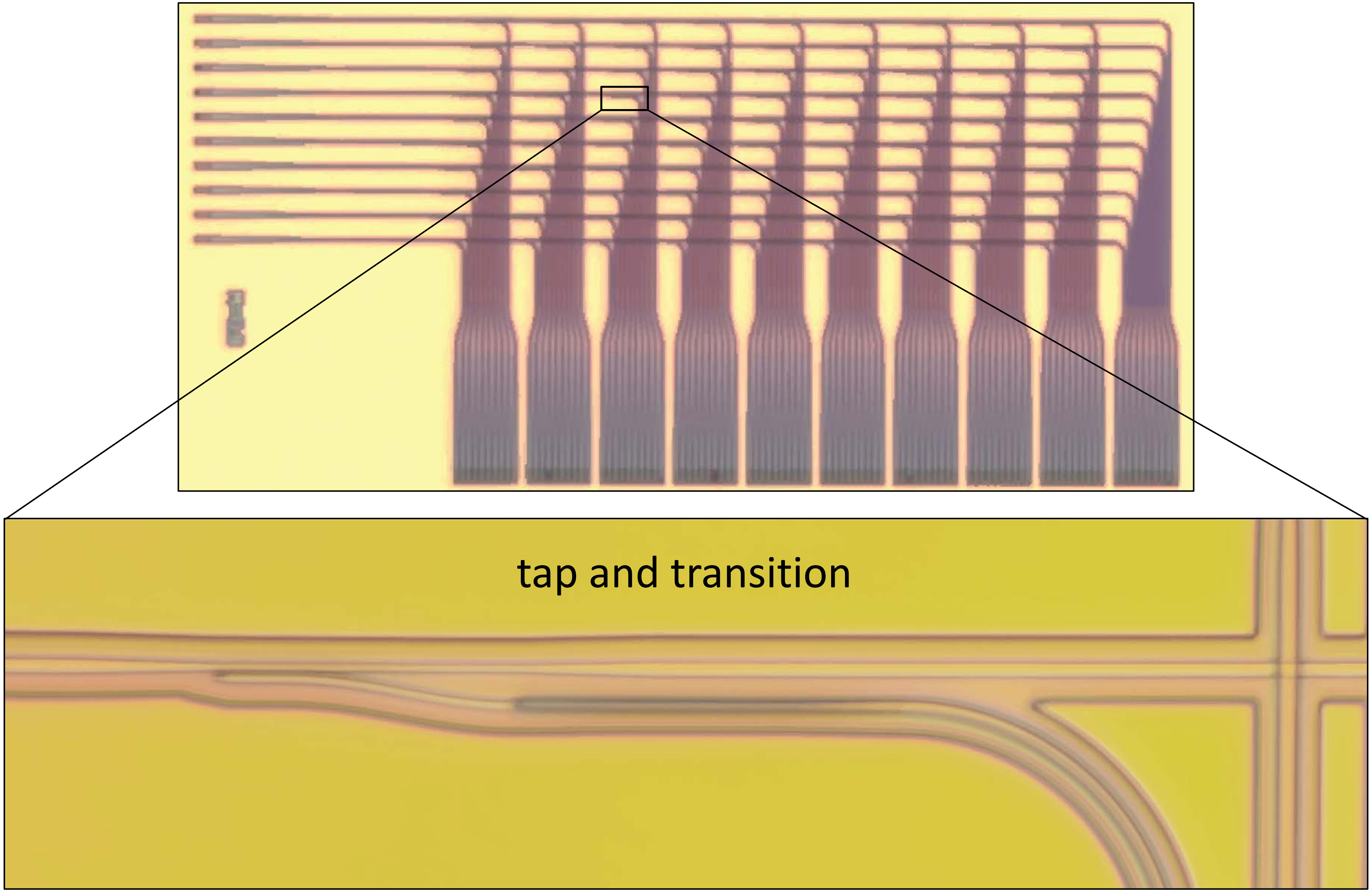
10 x 100 routing manifold



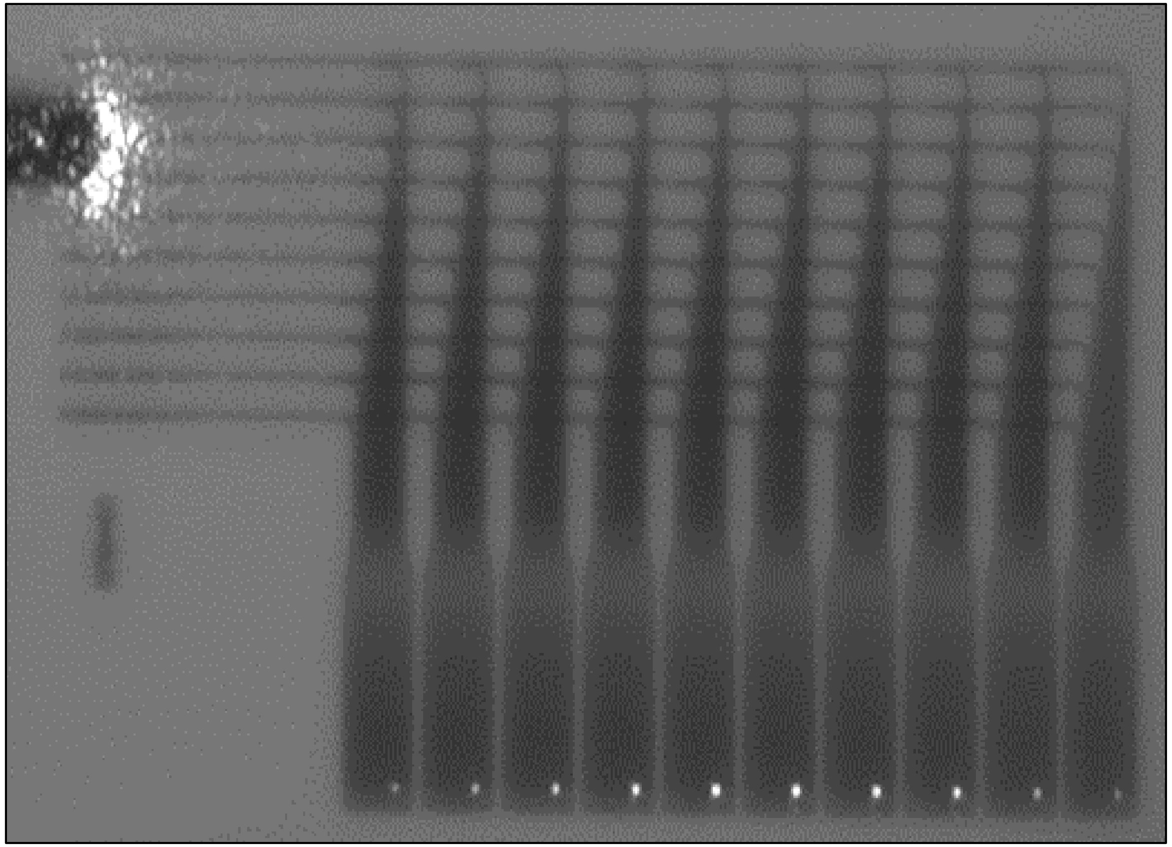


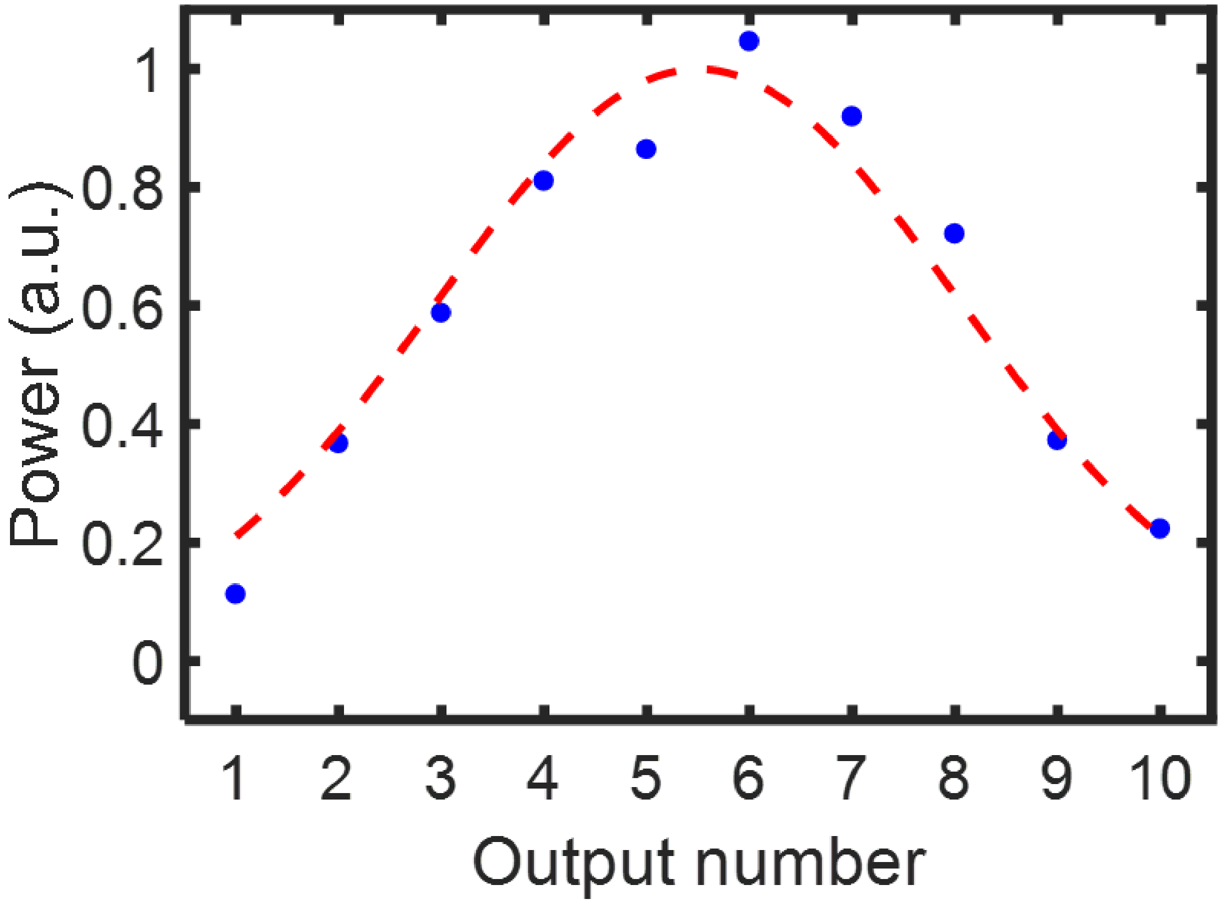
Chiles et al., APL Photonics, 3, 106101 (2018)

10 x 100 routing manifold



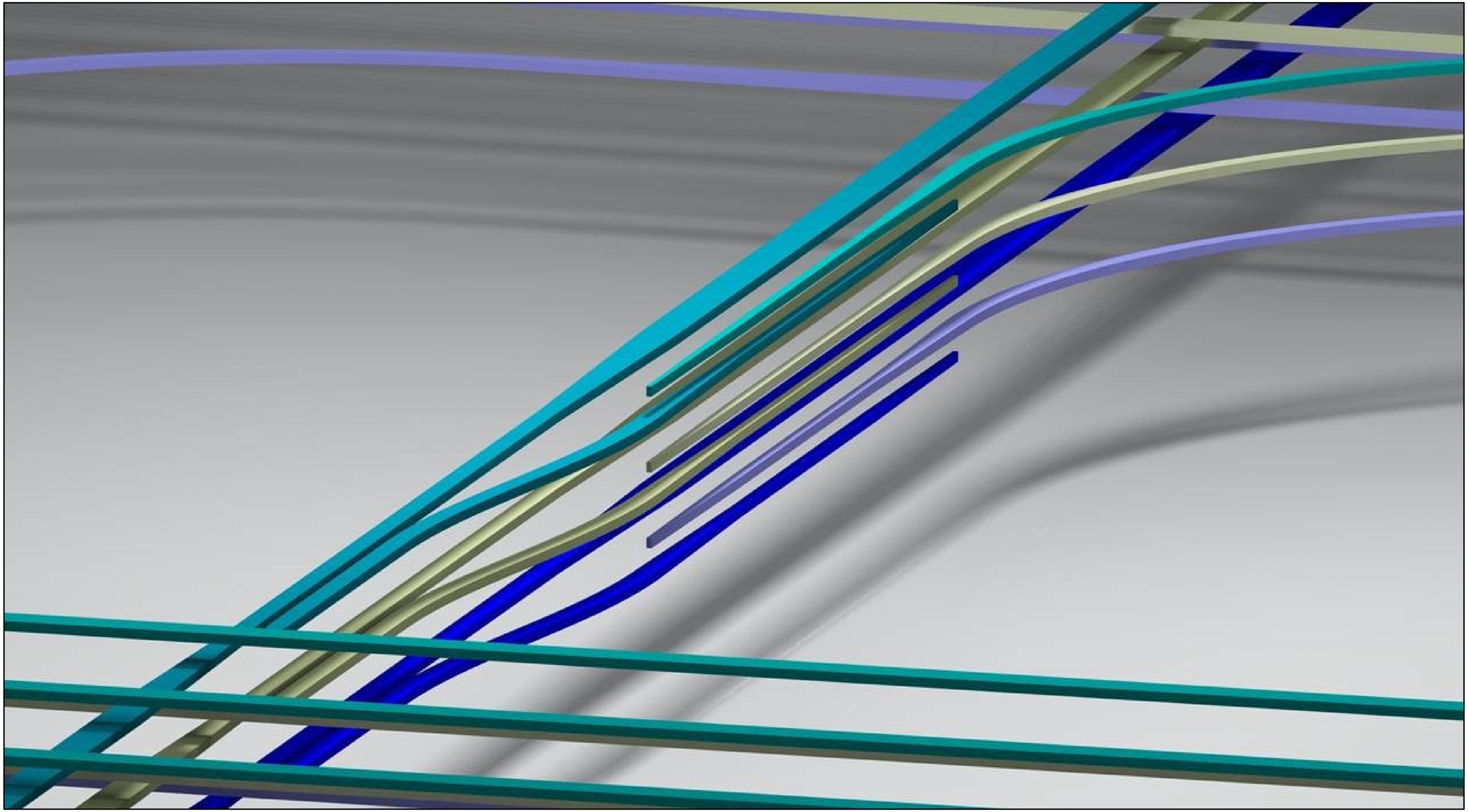
10 x 100 routing manifold

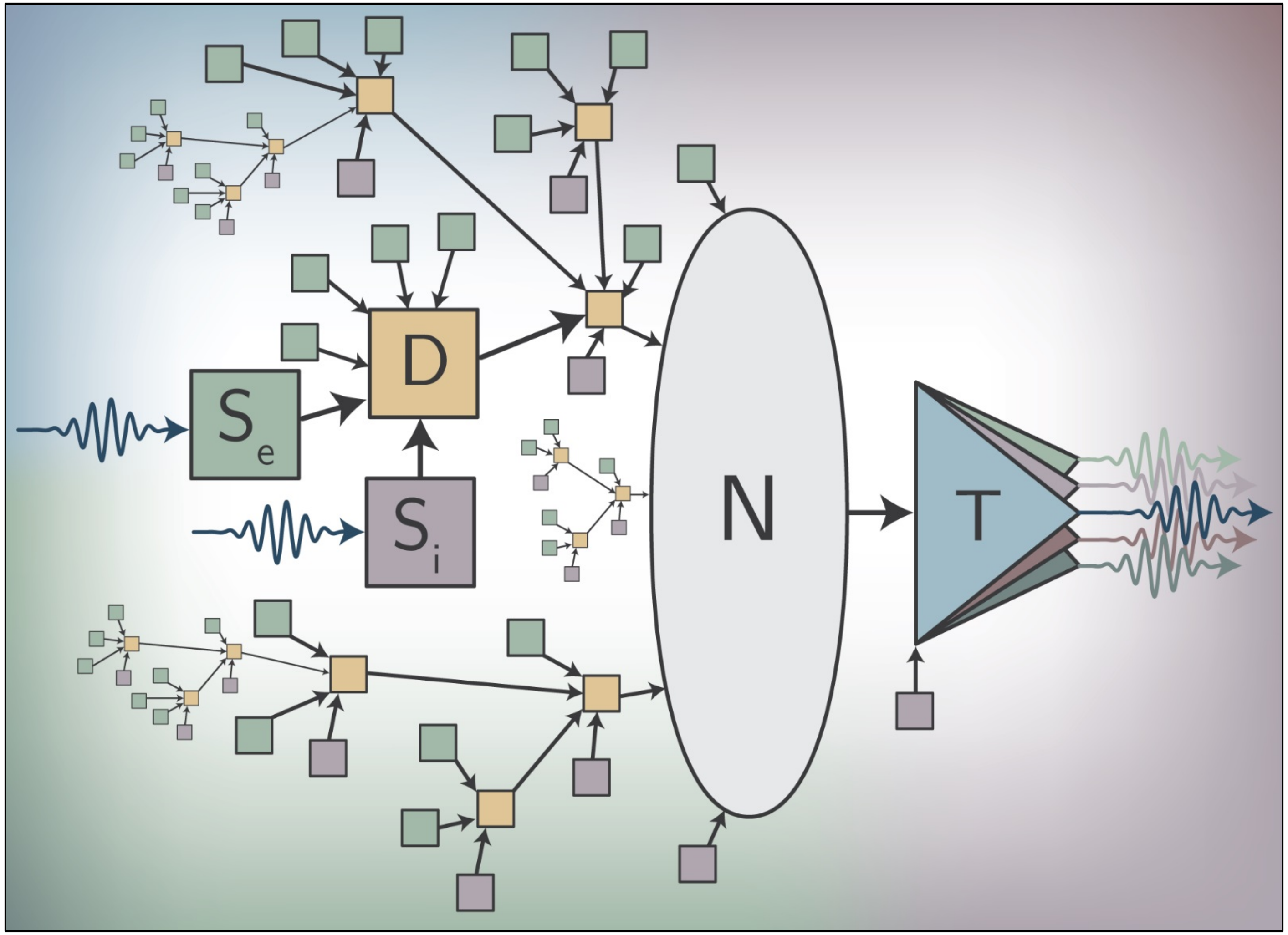




Chiles et al., APL Photonics, 3, 106101 (2018)

Further scaling to 3D

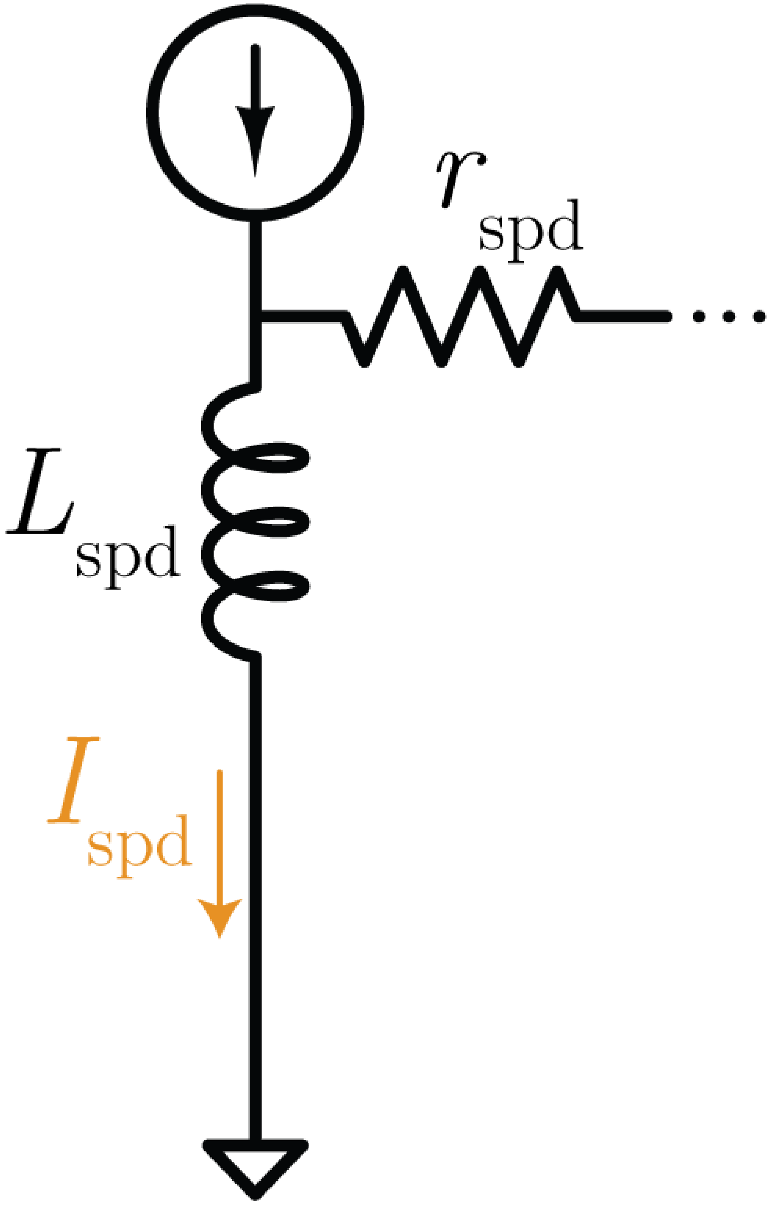




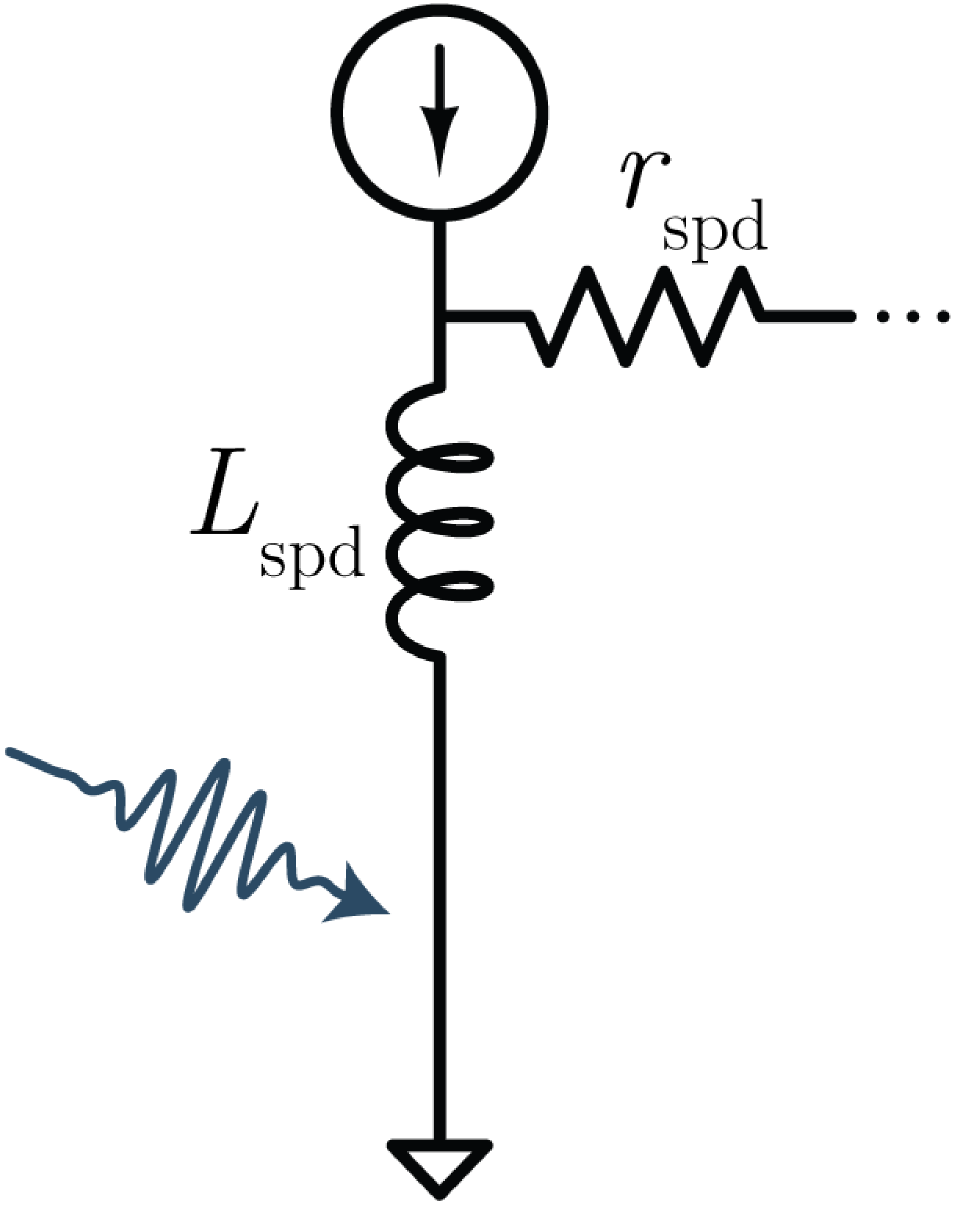
Why are we using light for communication?

Why are we using superconductors?

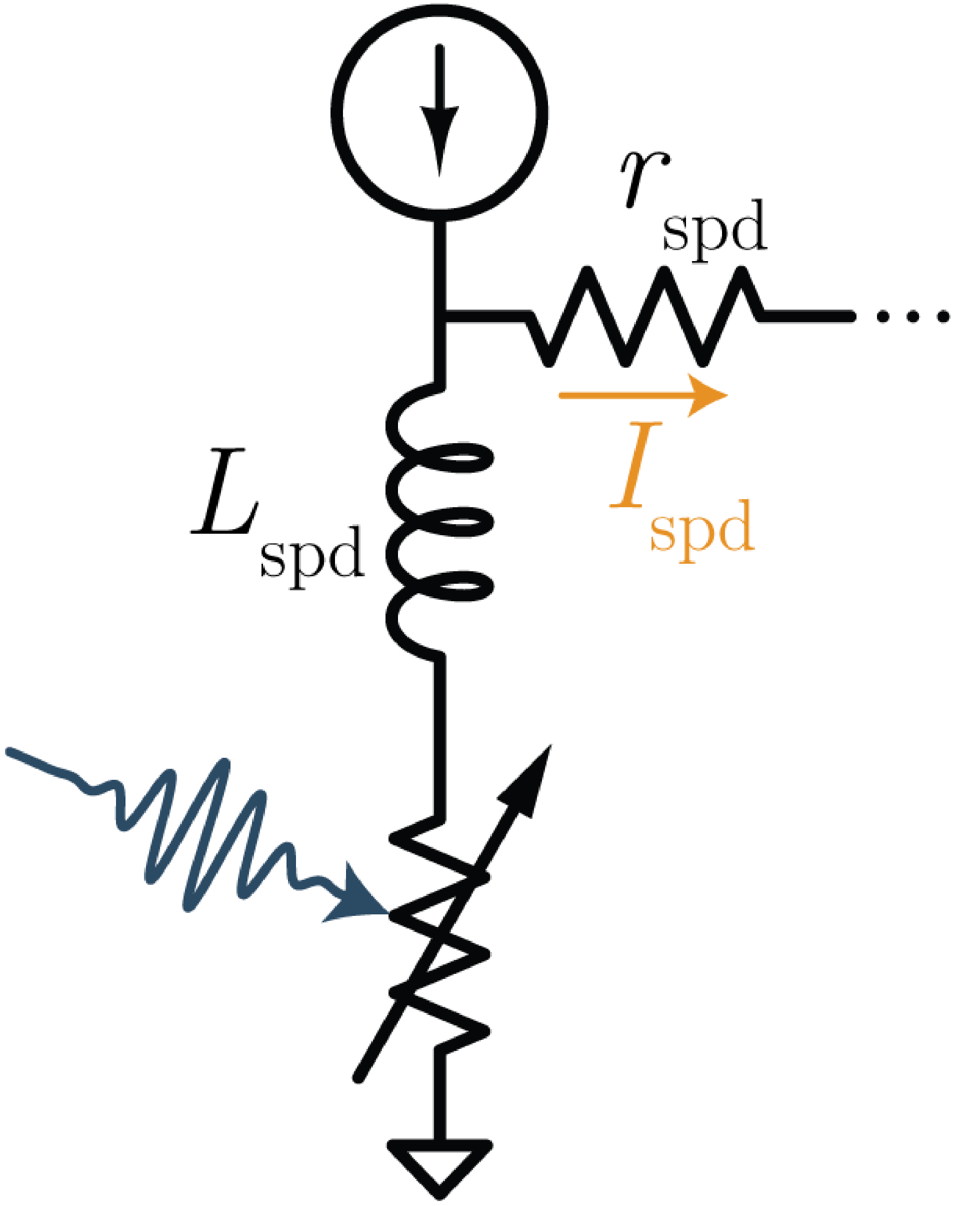
Superconducting-nanowire single-photon detector (SPD)



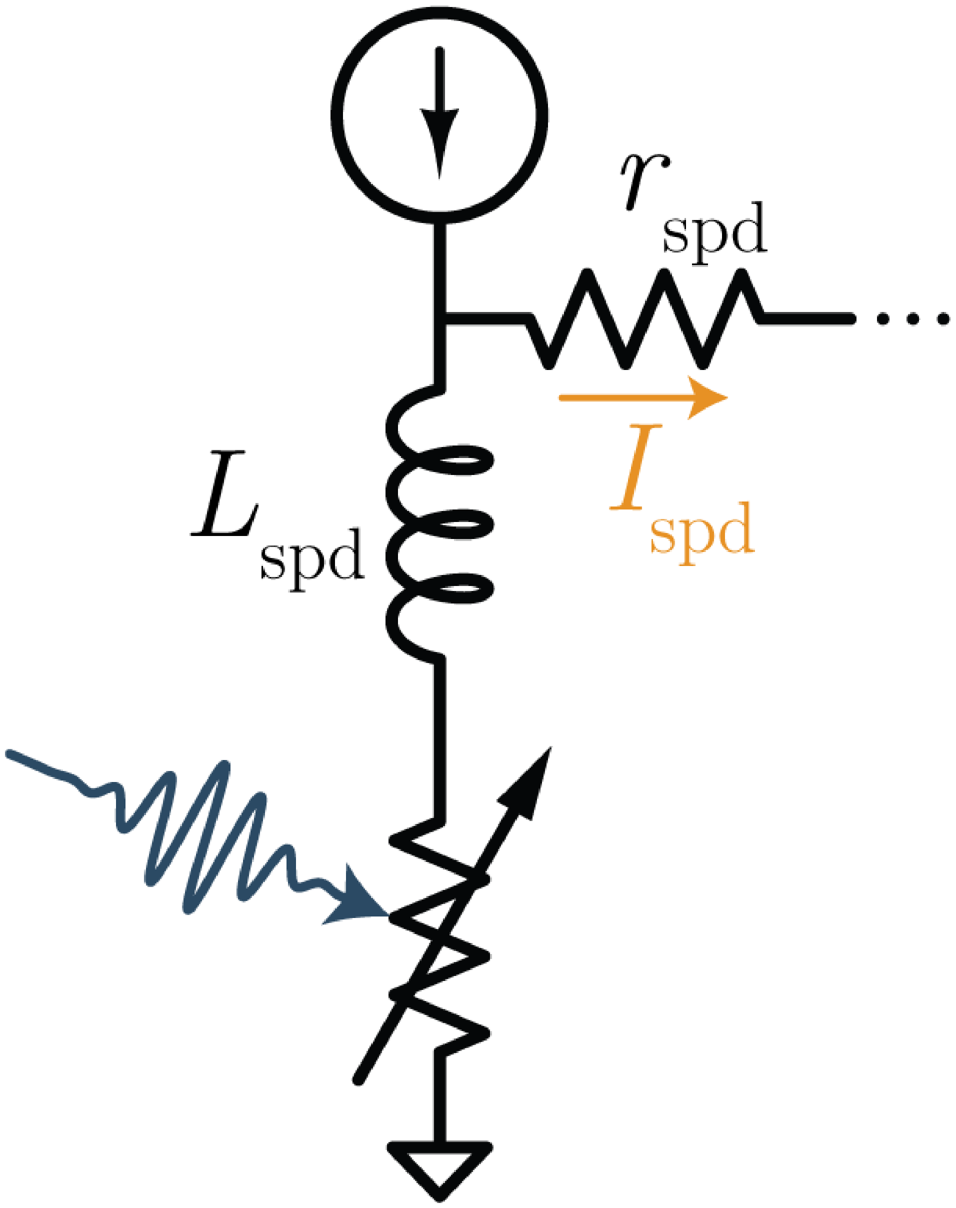
Superconducting-nanowire single-photon detector (SPD)

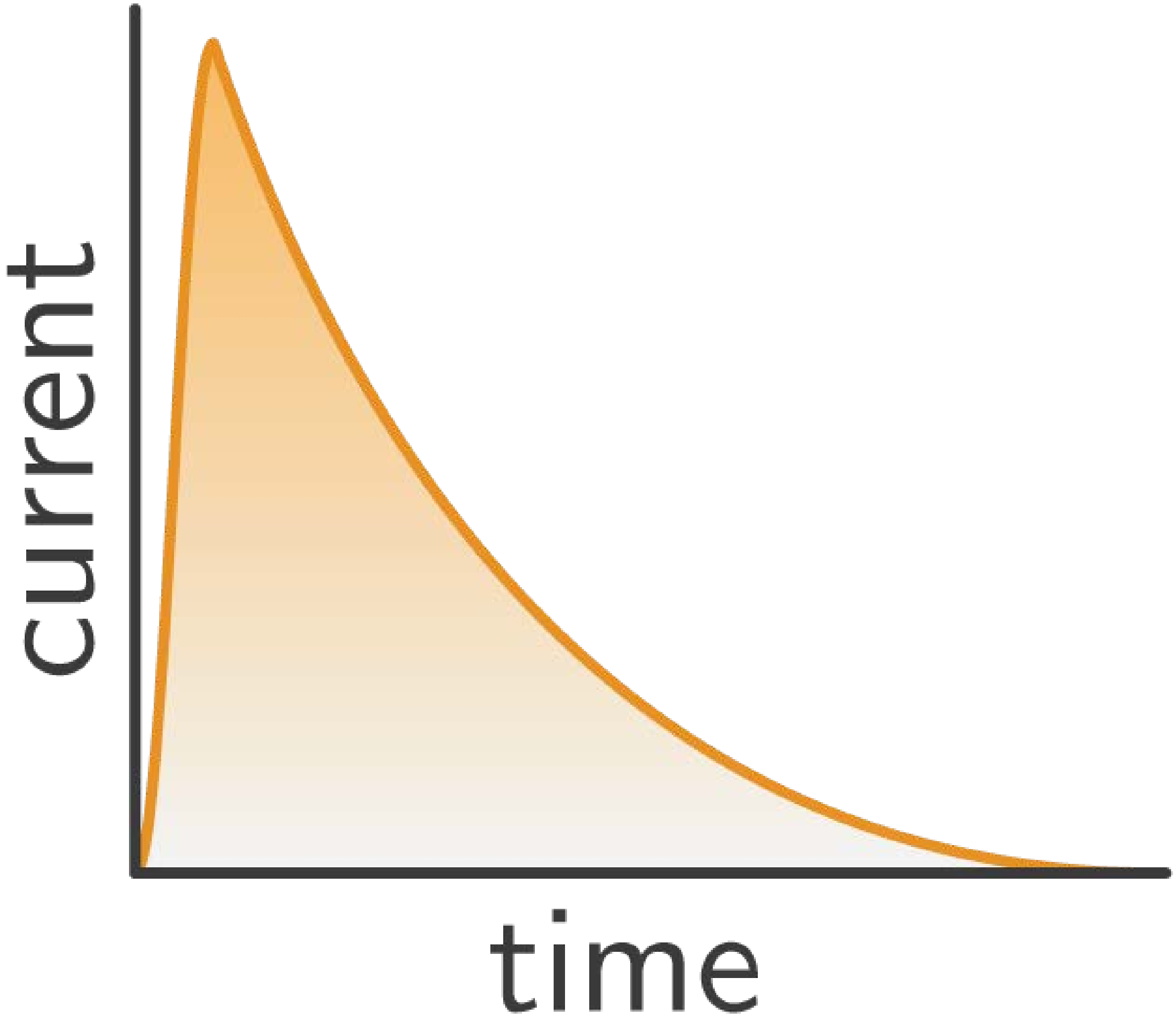


Superconducting-nanowire single-photon detector (SPD)

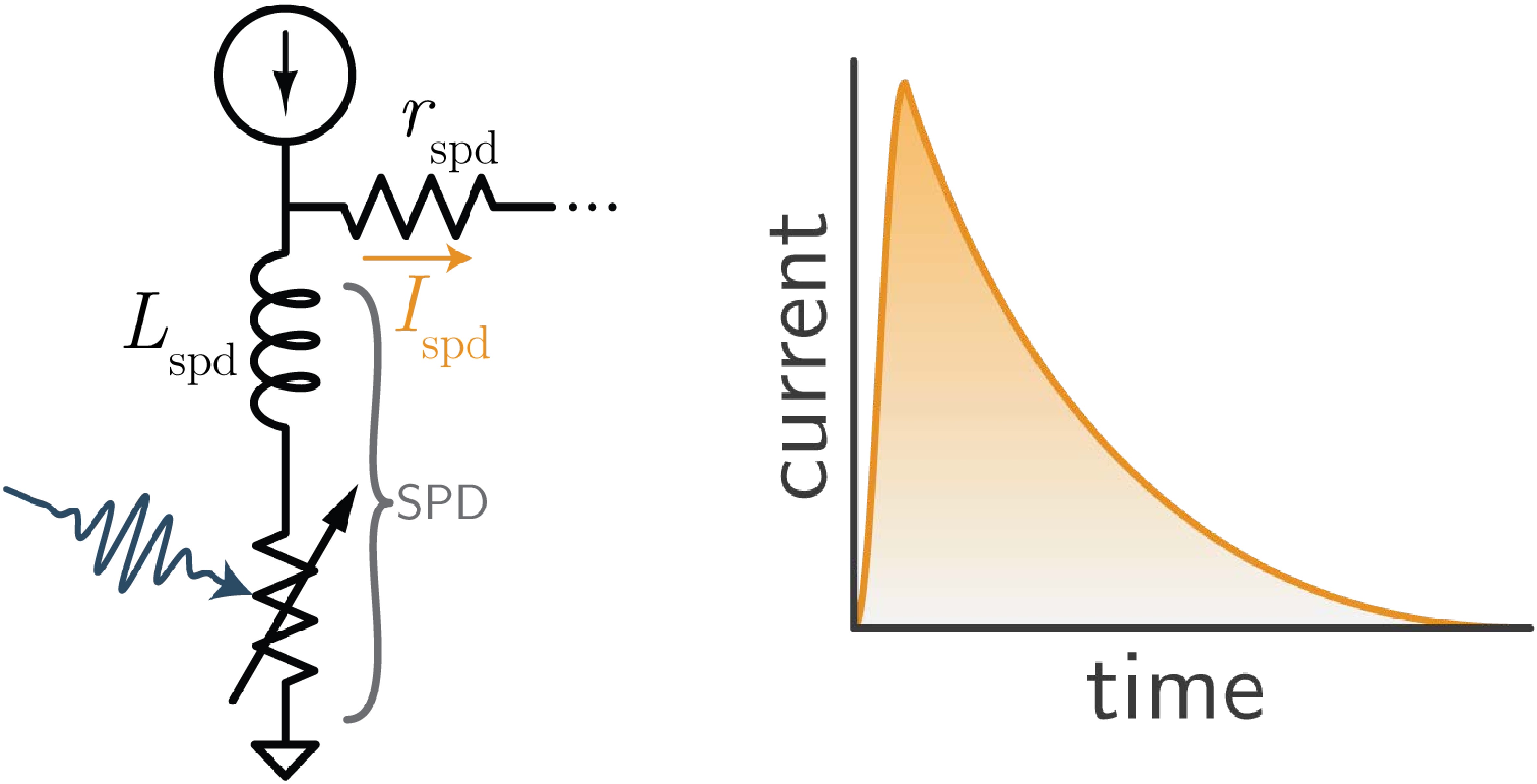


Superconducting-nanowire single-photon detector (SPD)

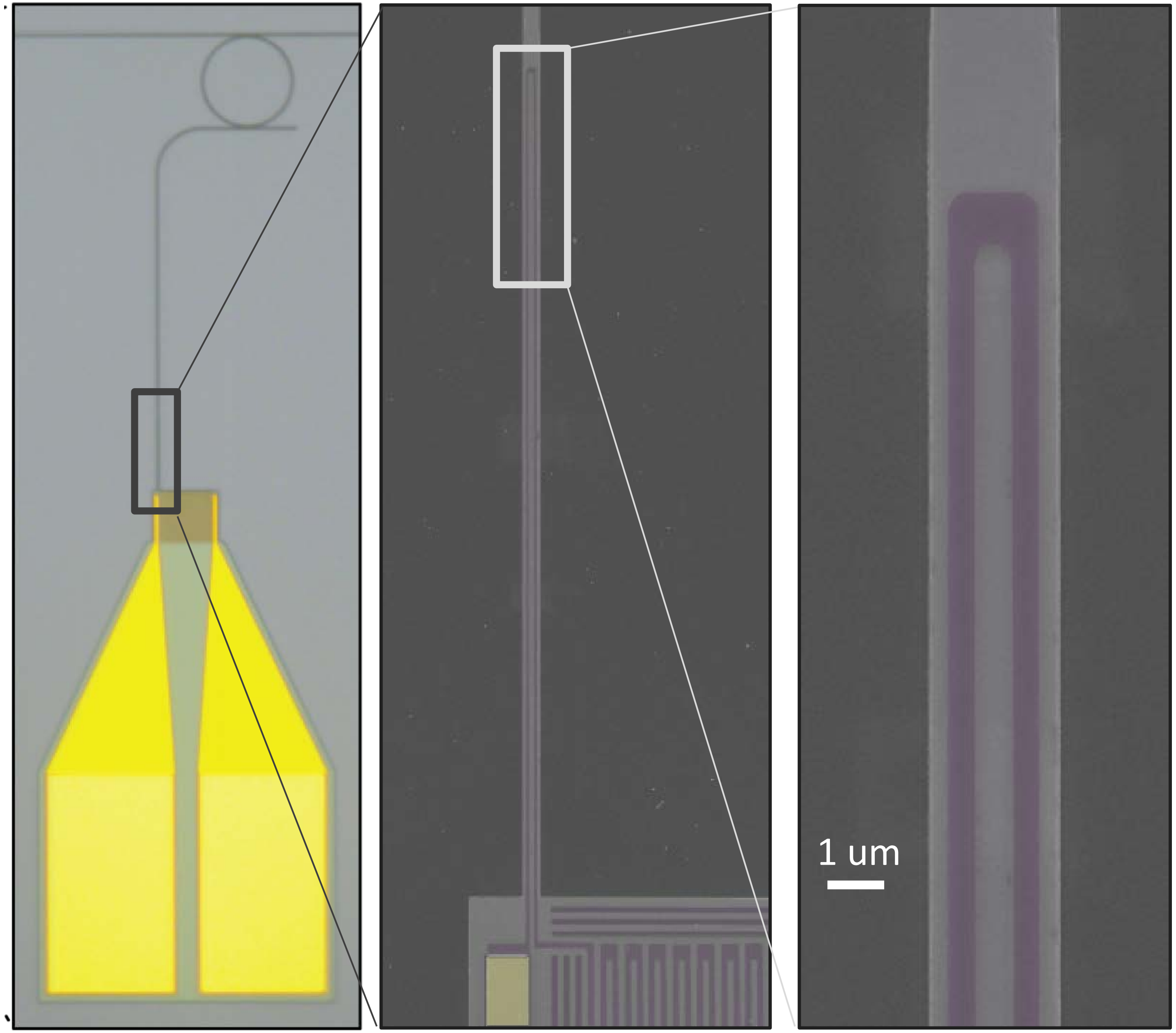




Superconducting-nanowire single-photon detector (SPD)



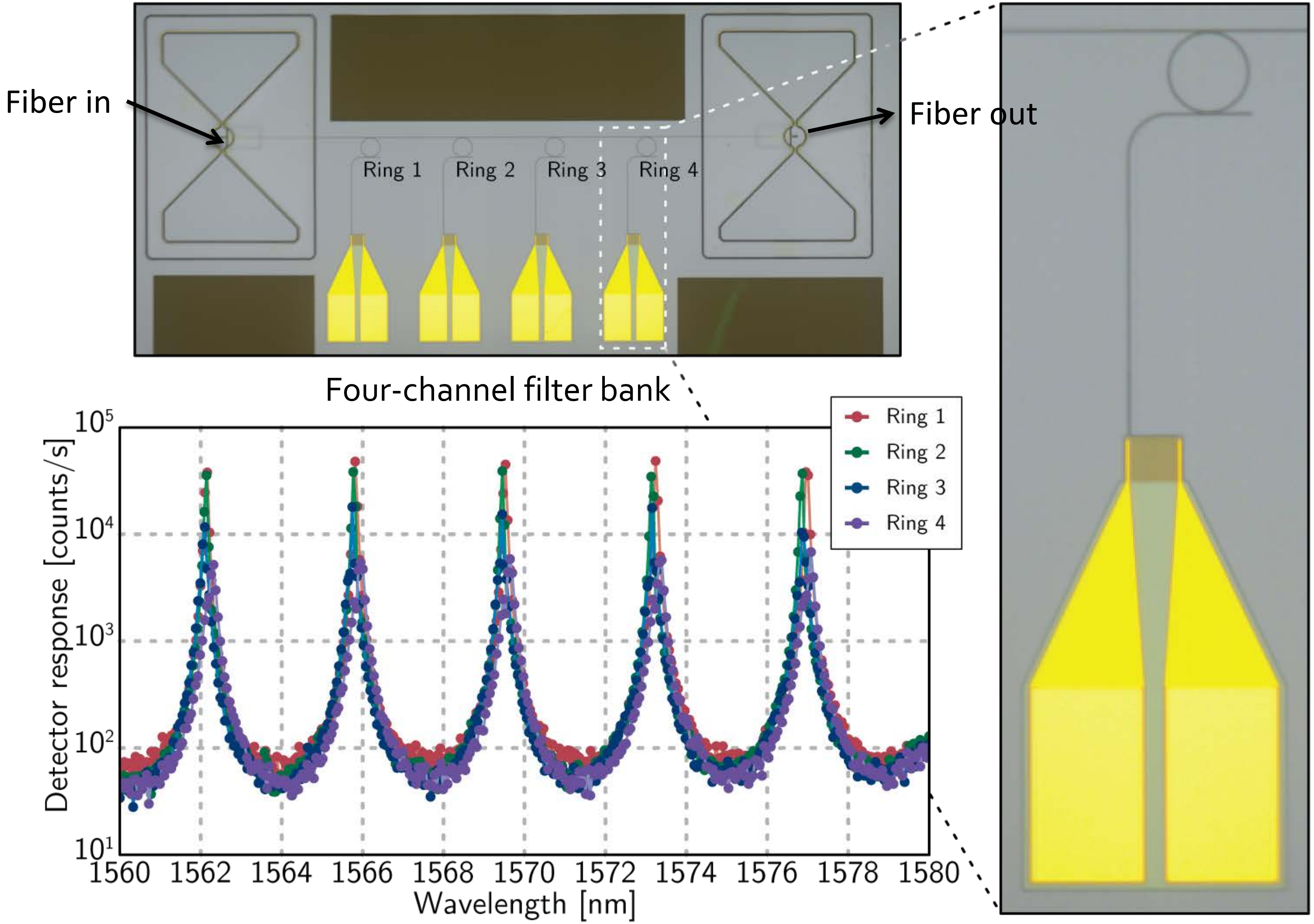
Waveguide-integrated single-photon detectors



Efficiency:

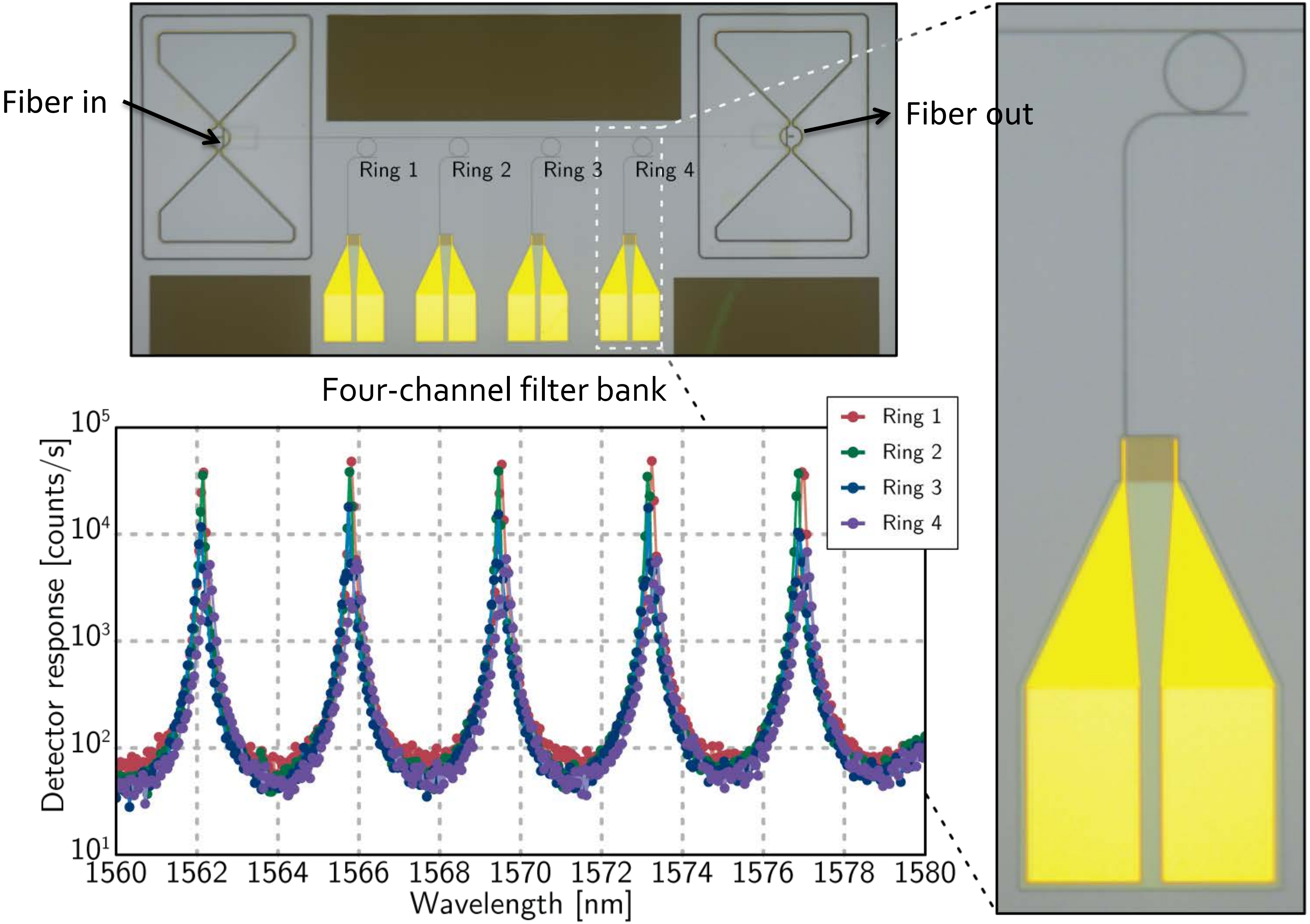
- Lowest possible light level for communication
- No power draw in the steady state

Waveguide-integrated single-photon detectors



Shainline et al, Op. Ex., 25, 10322 (2017)

Waveguide-integrated single-photon detectors

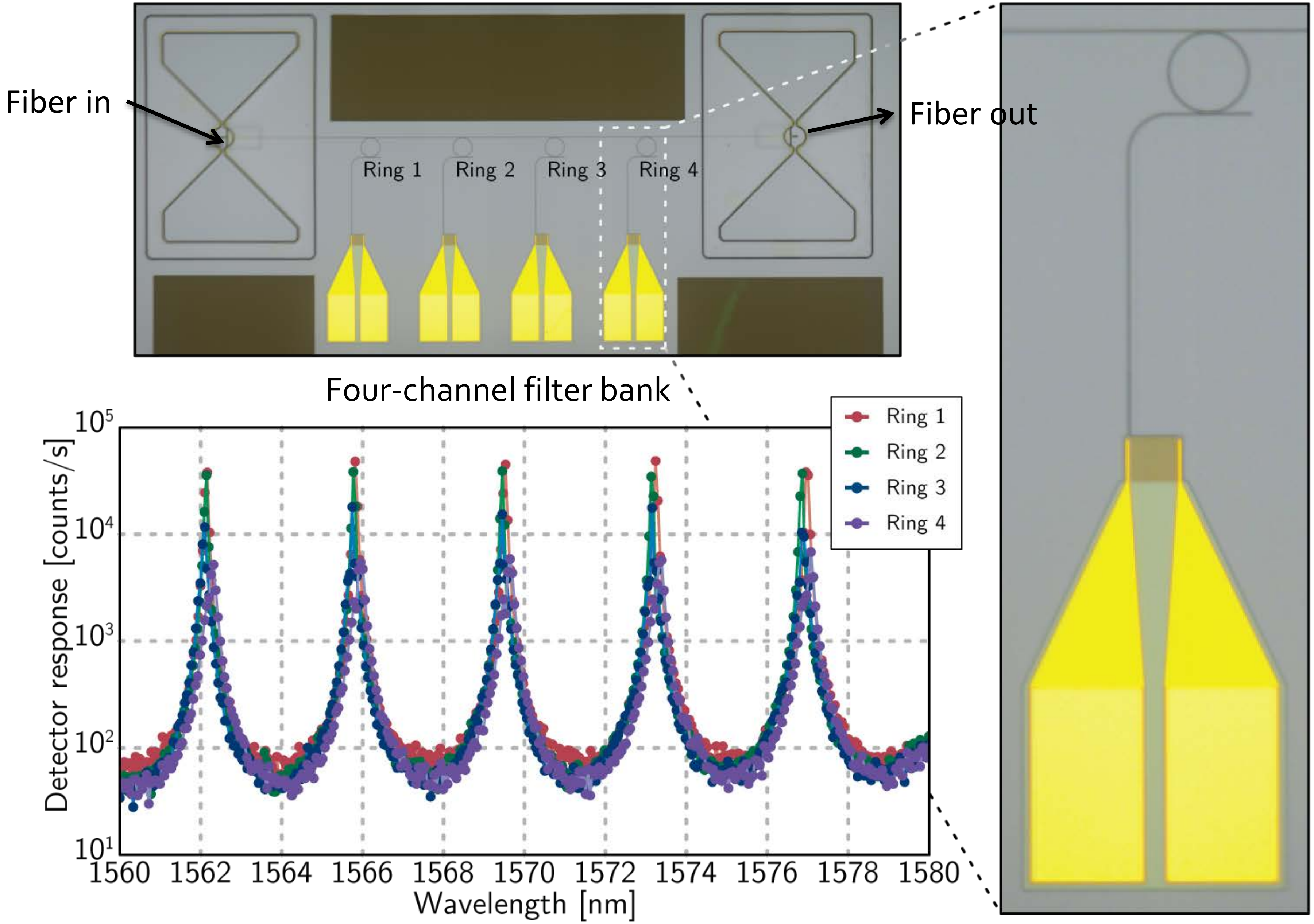


The down side:

Requires cryogenic operation (4 K)

Shainline et al, Op. Ex., 25, 10322 (2017)

Waveguide-integrated single-photon detectors

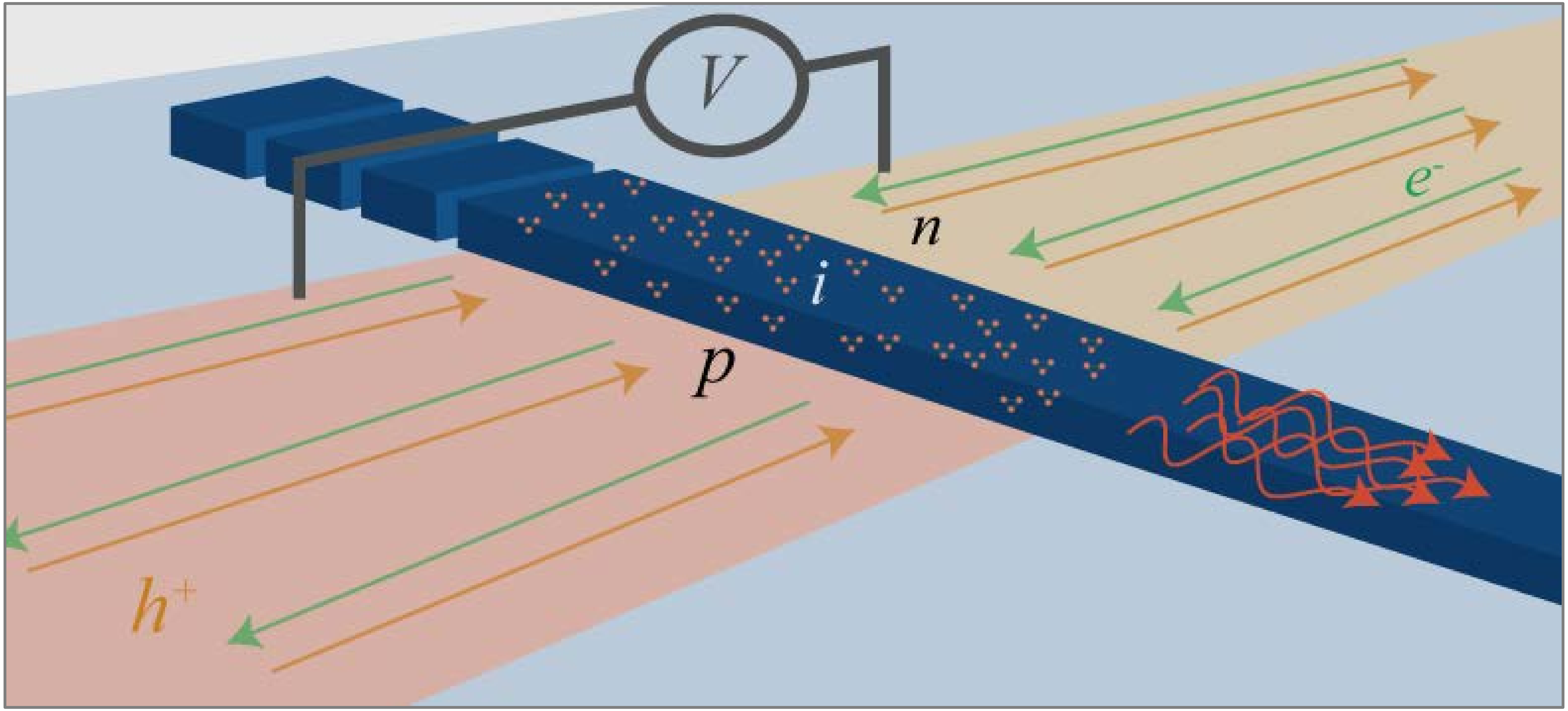


The up side:

At low temp, silicon light sources work

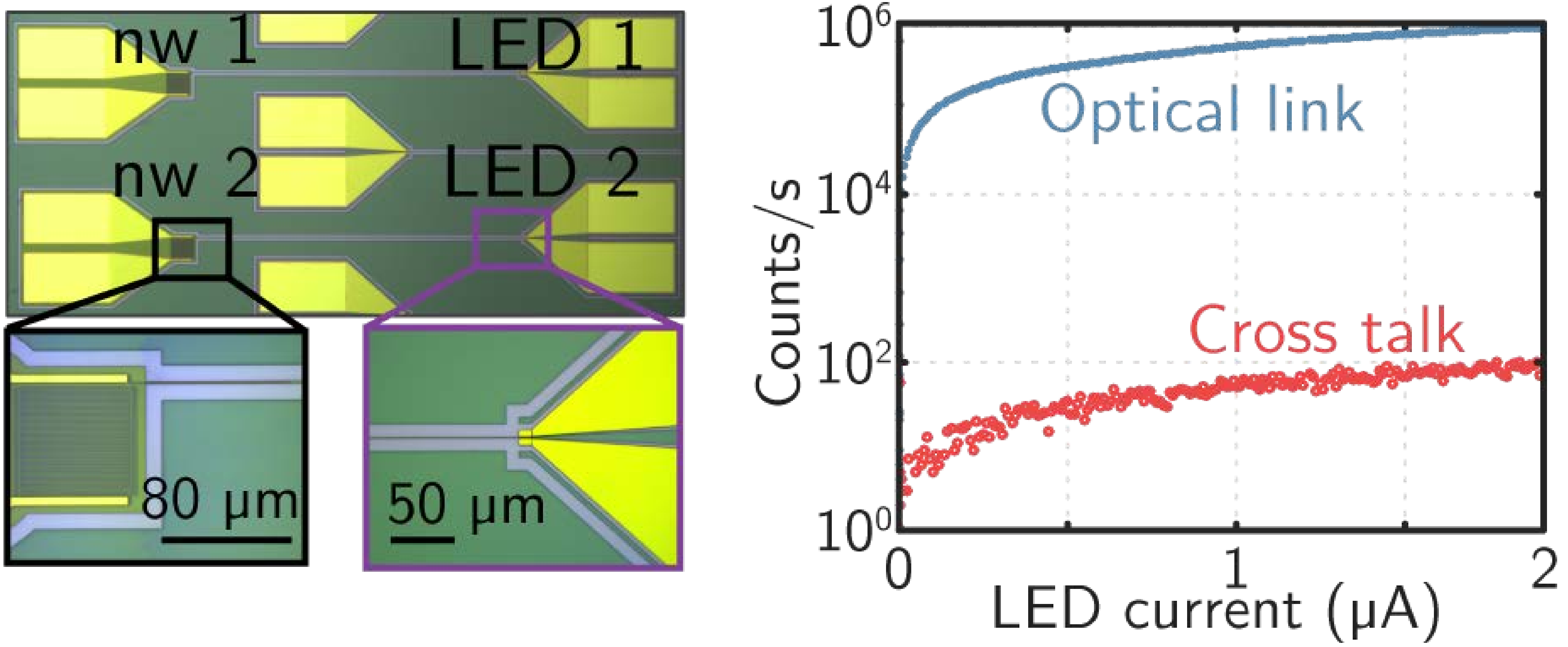
Shainline et al, Op. Ex., 25, 10322 (2017)

The light emitter



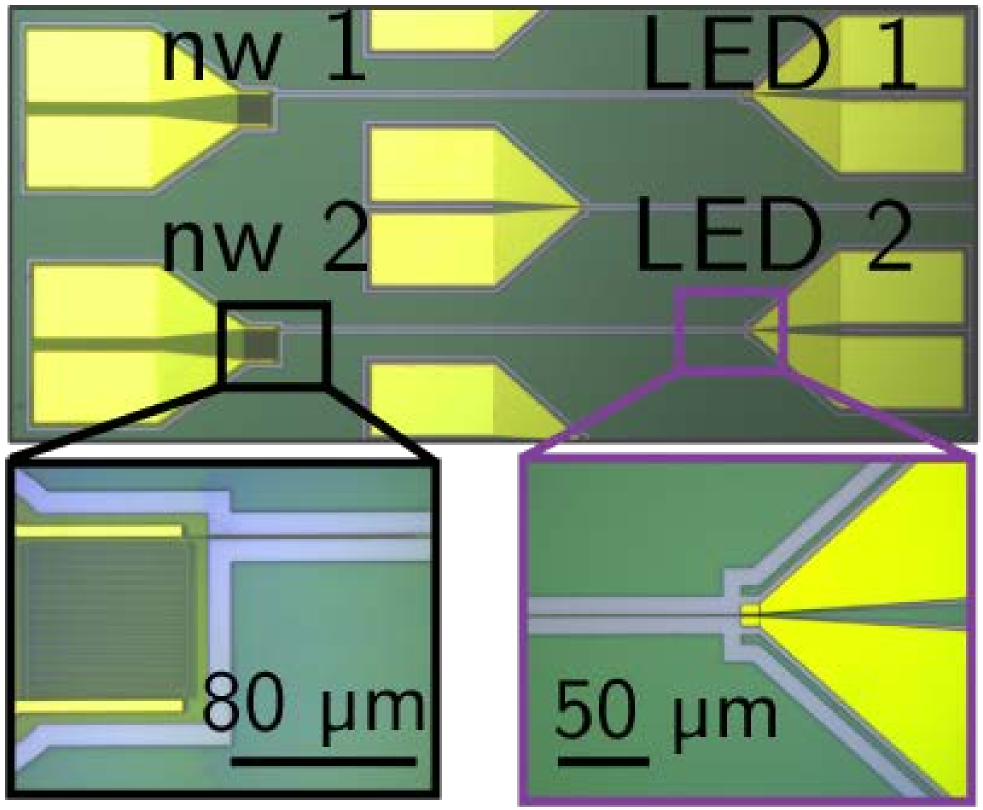
All-silicon waveguide-integrated light-emitting dioes

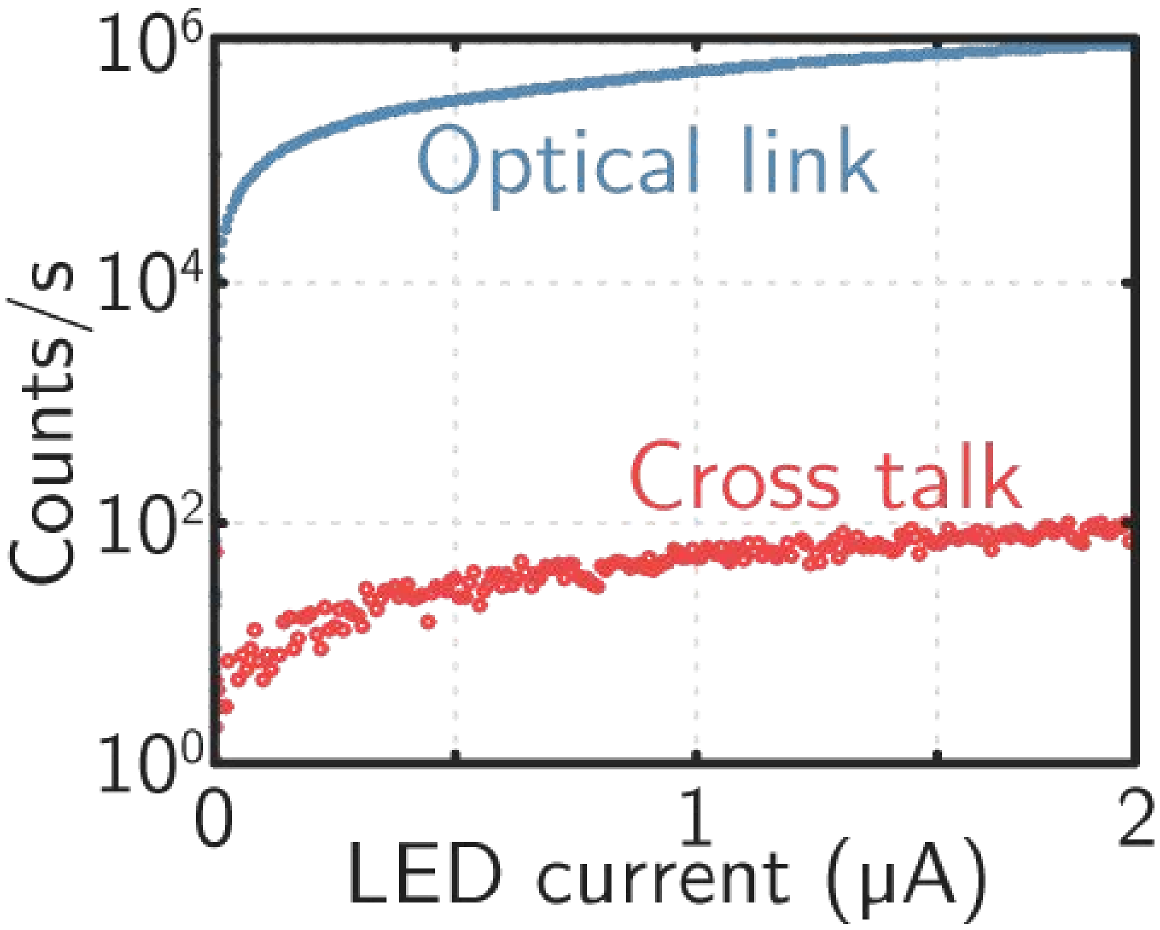
Optoelectronic integration



Buckley et al, Appl. Phys. Lett., 111, 141101 (2017)

Optoelectronic integration

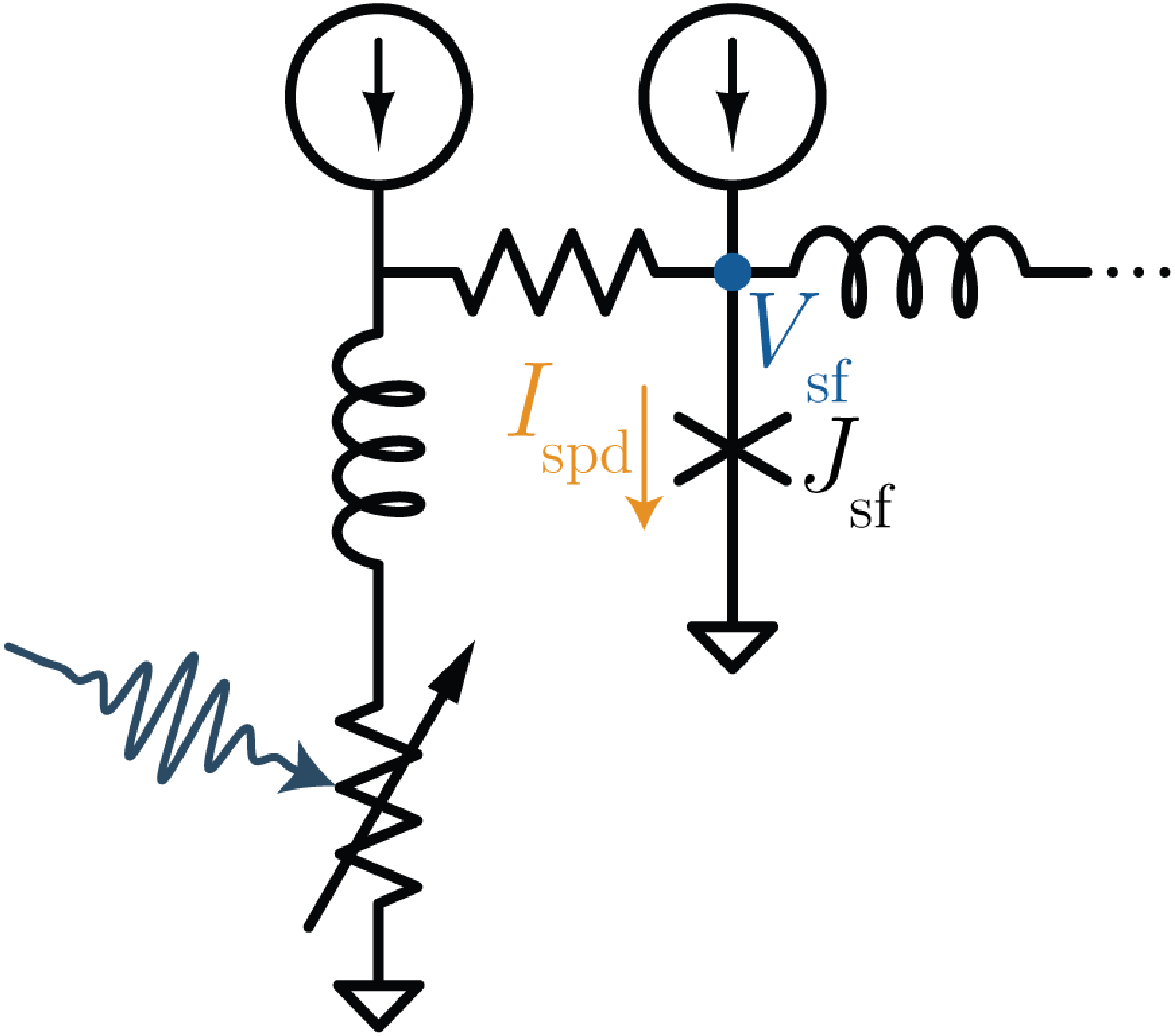




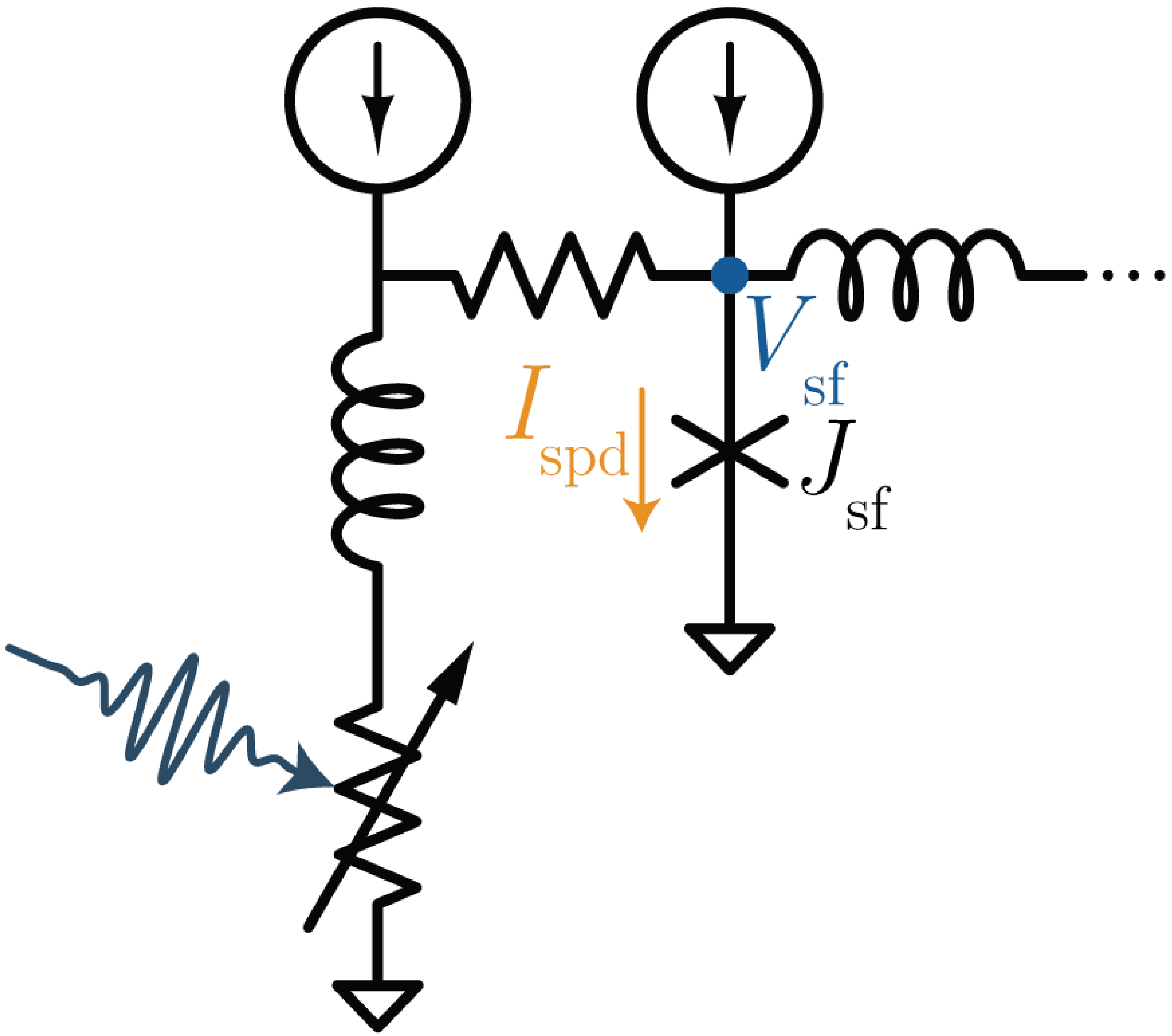
Light sources as simple as transistors

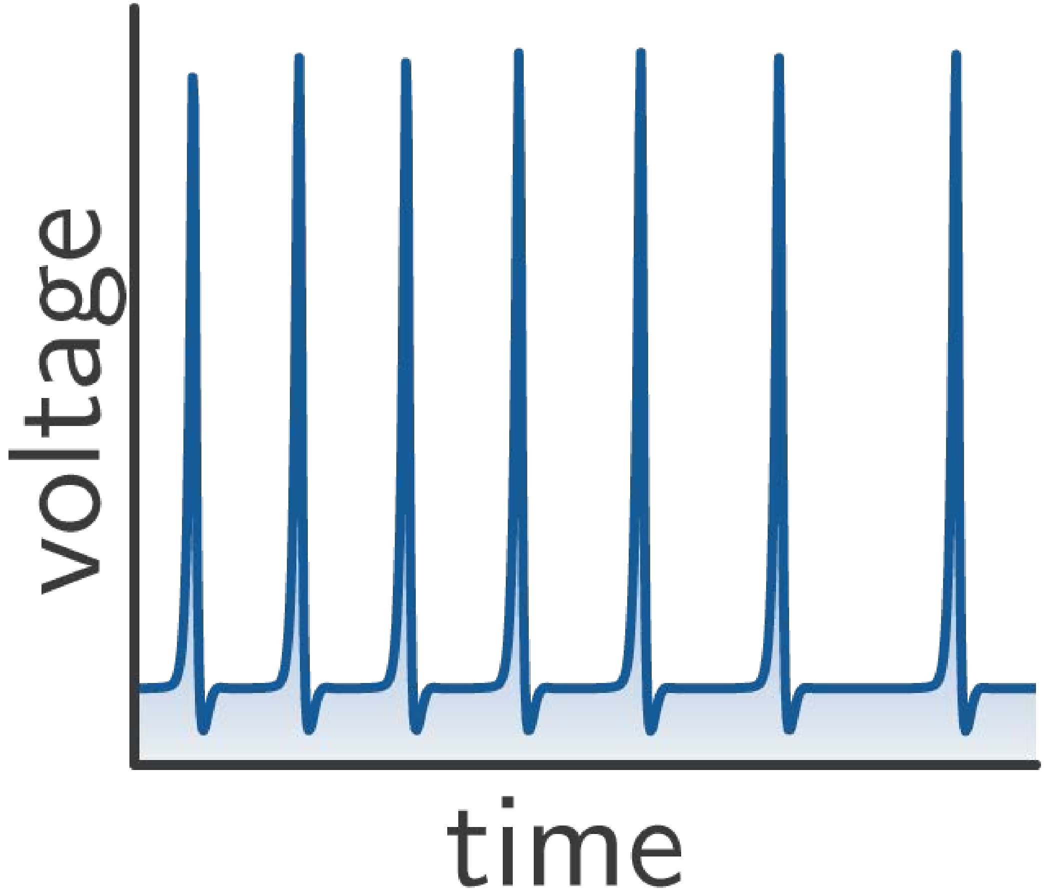
Buckley et al, Appl. Phys. Lett., 111, 141101 (2017)

Photon-to-fluxon transducer

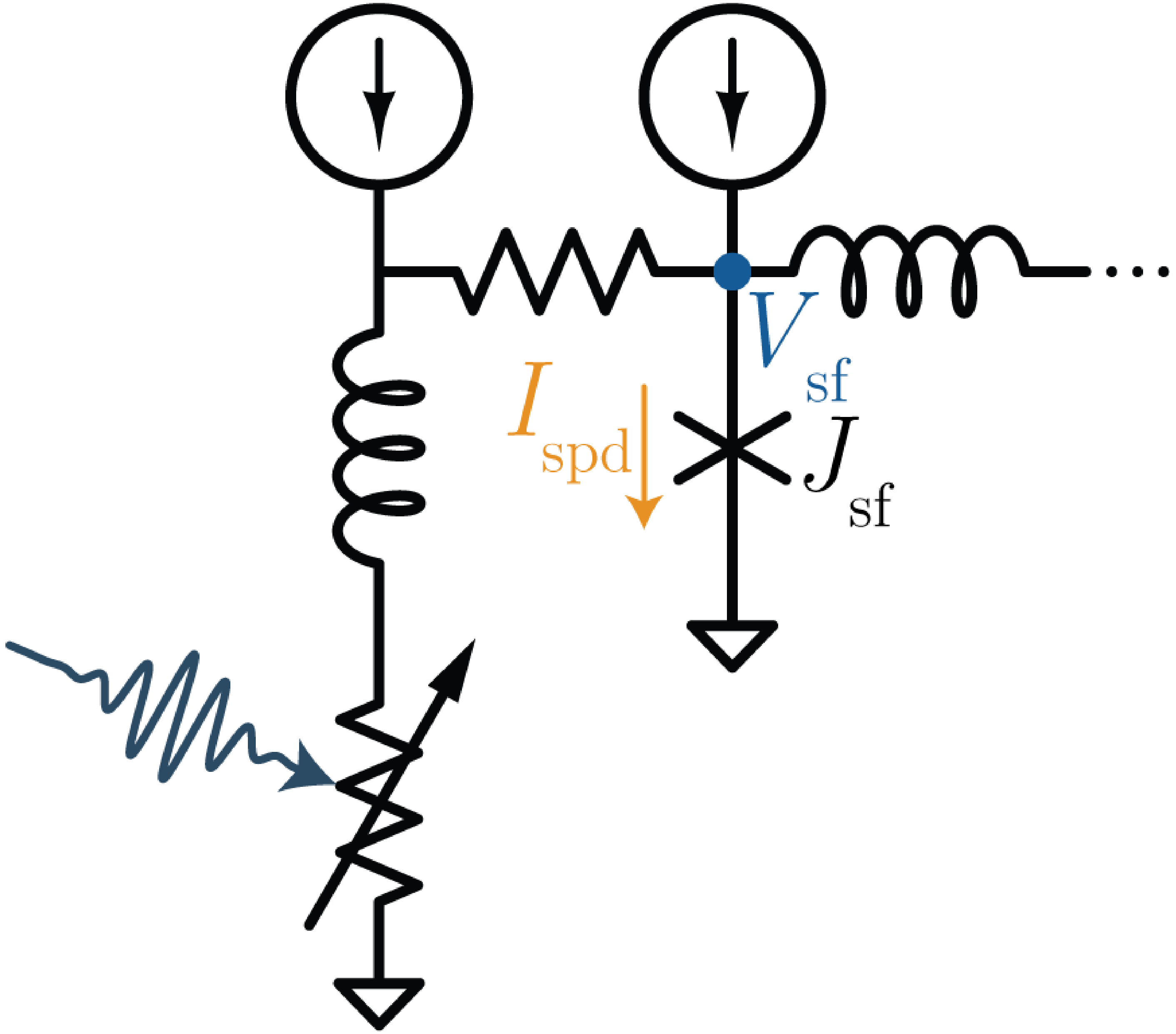


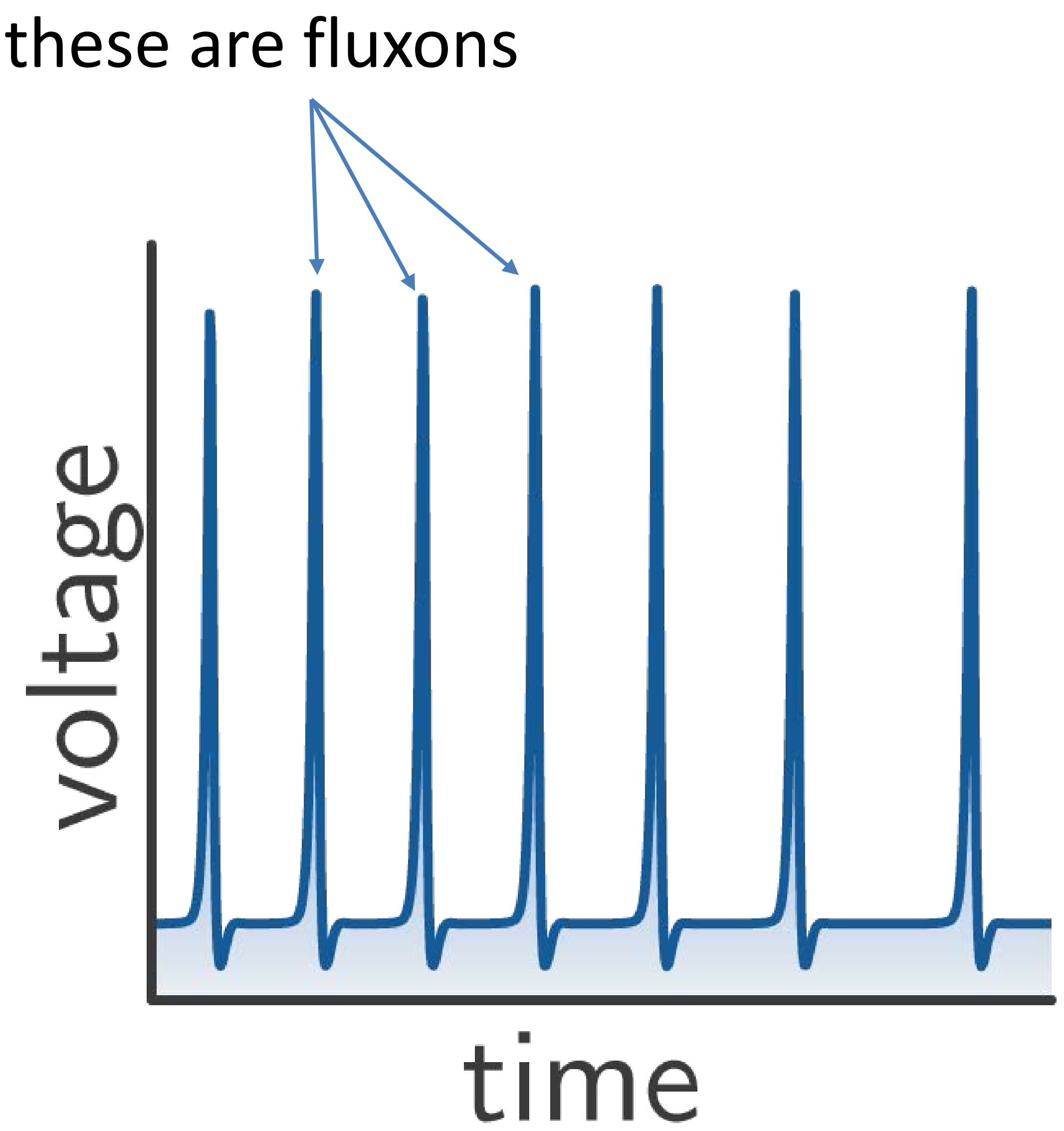
Photon-to-fluxon transducer



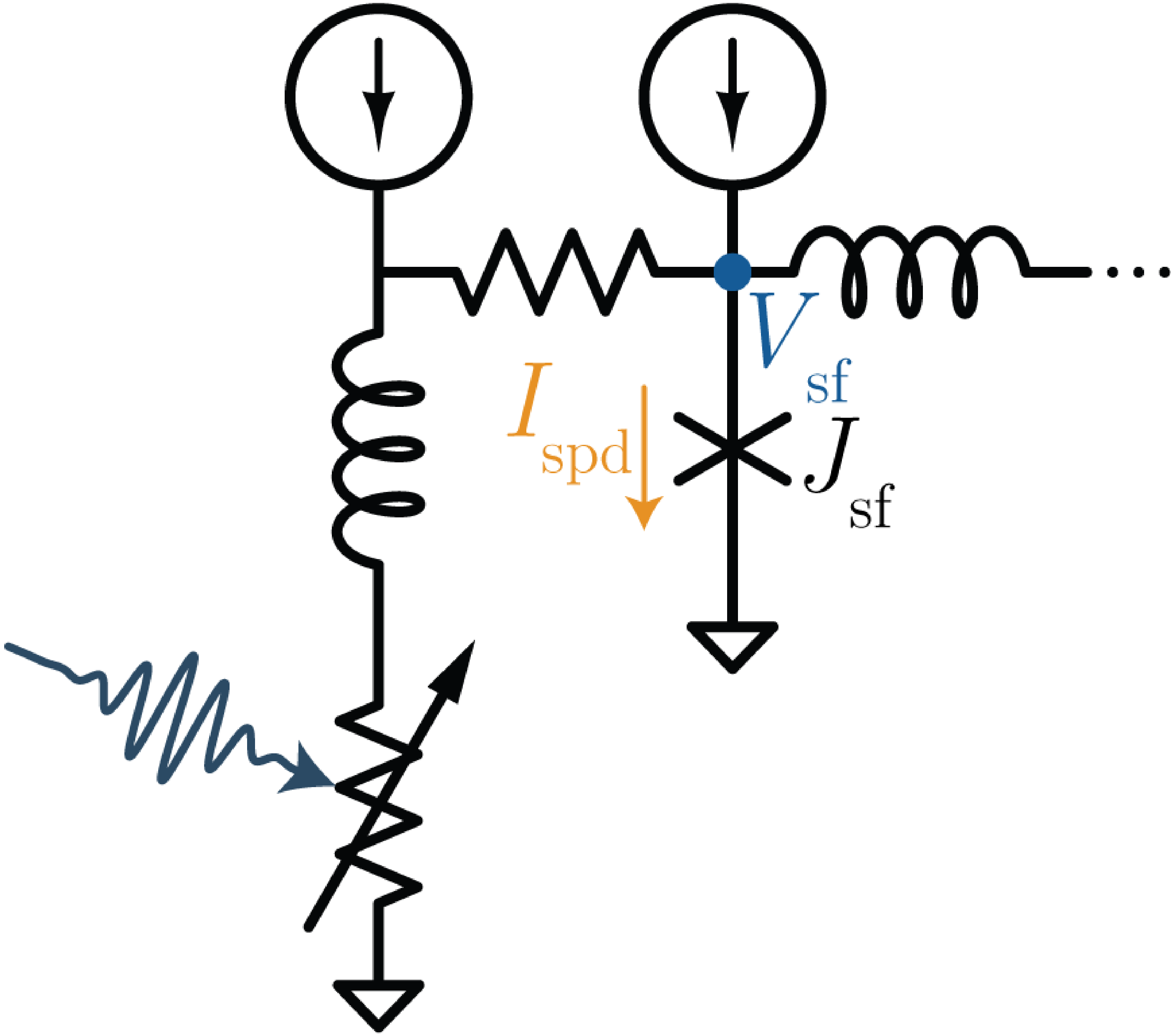


Photon-to-fluxon transducer

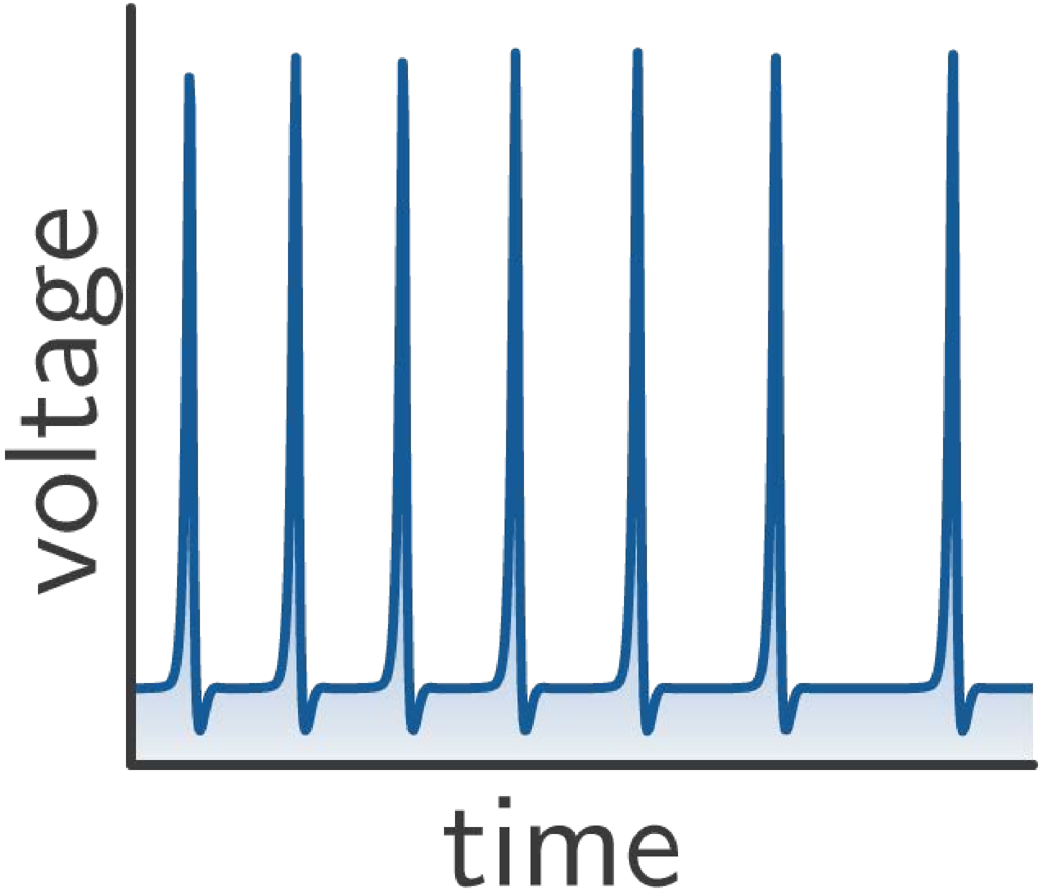




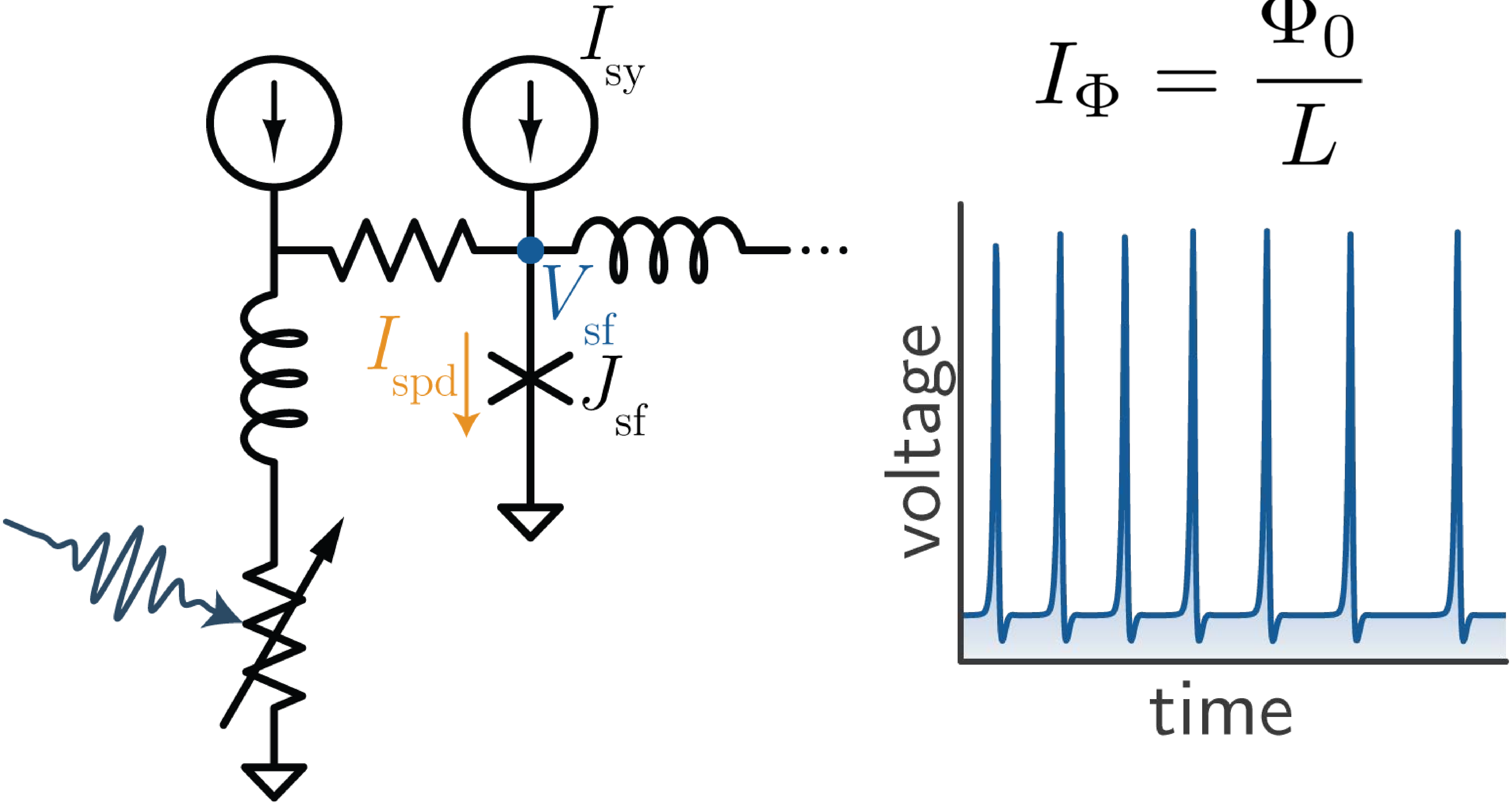
Photon-to-fluxon transducer



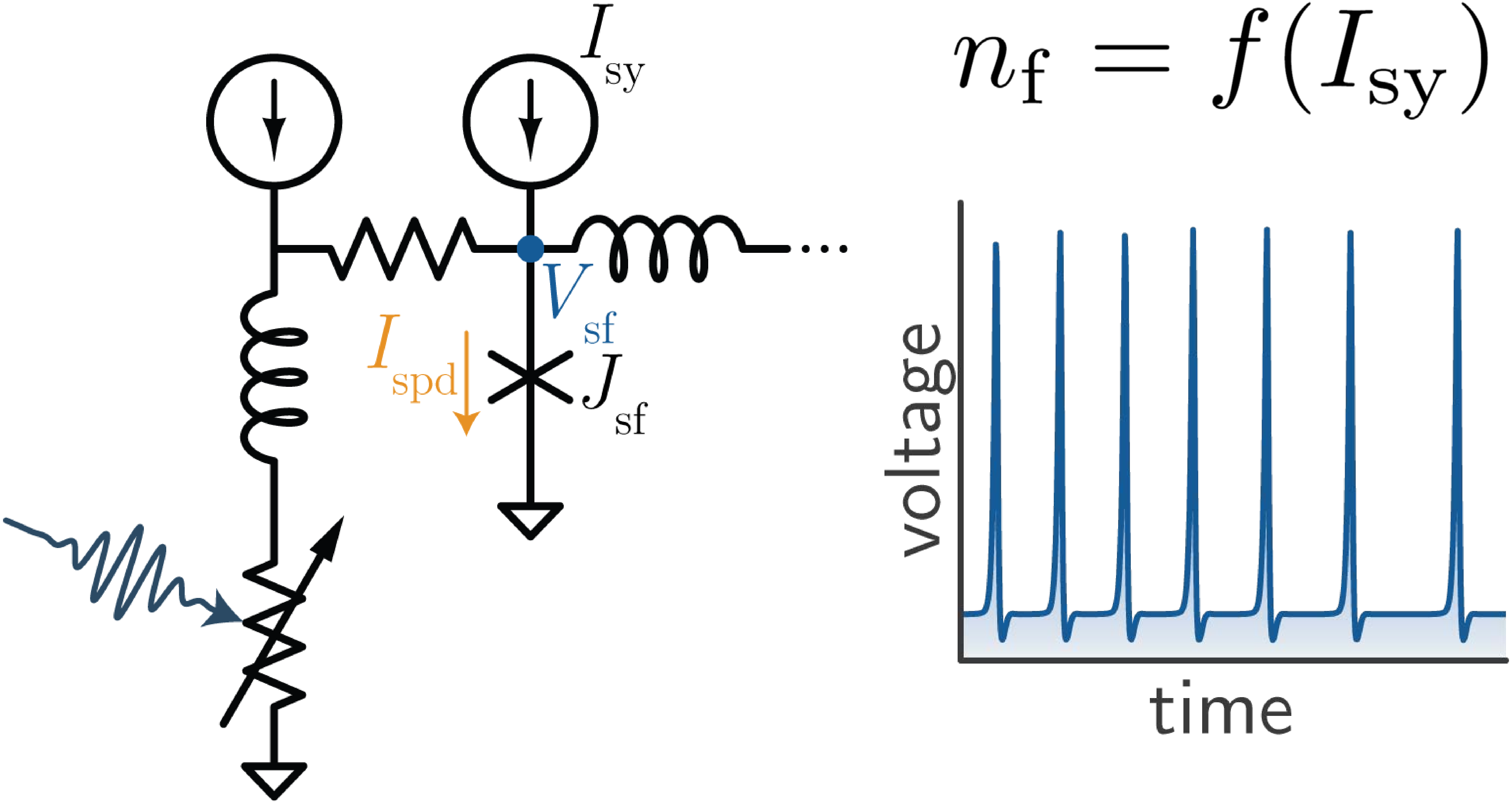
$$I_\Phi = \frac{\Phi_0}{L}$$



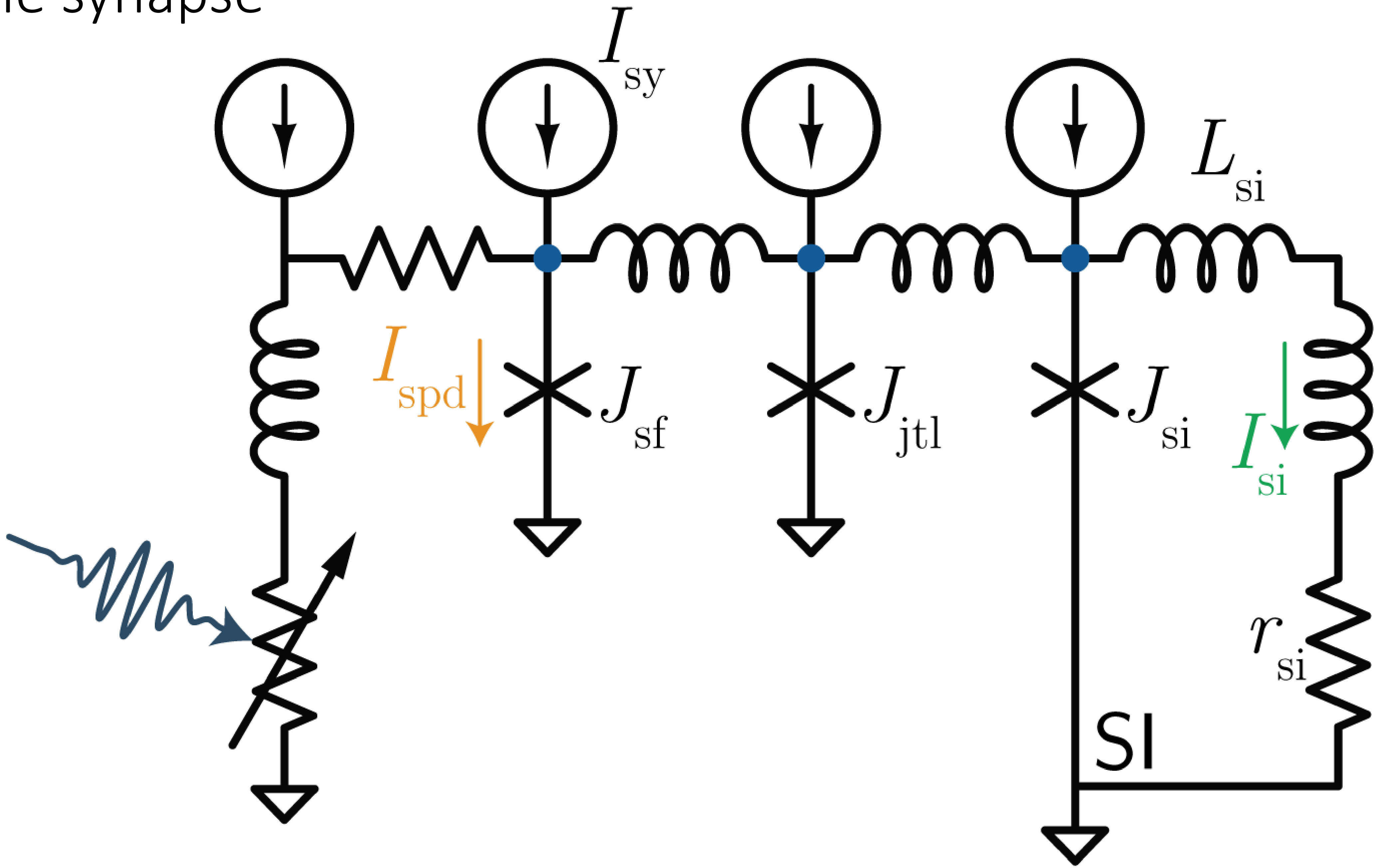
Photon-to-fluxon transducer



Photon-to-fluxon transducer

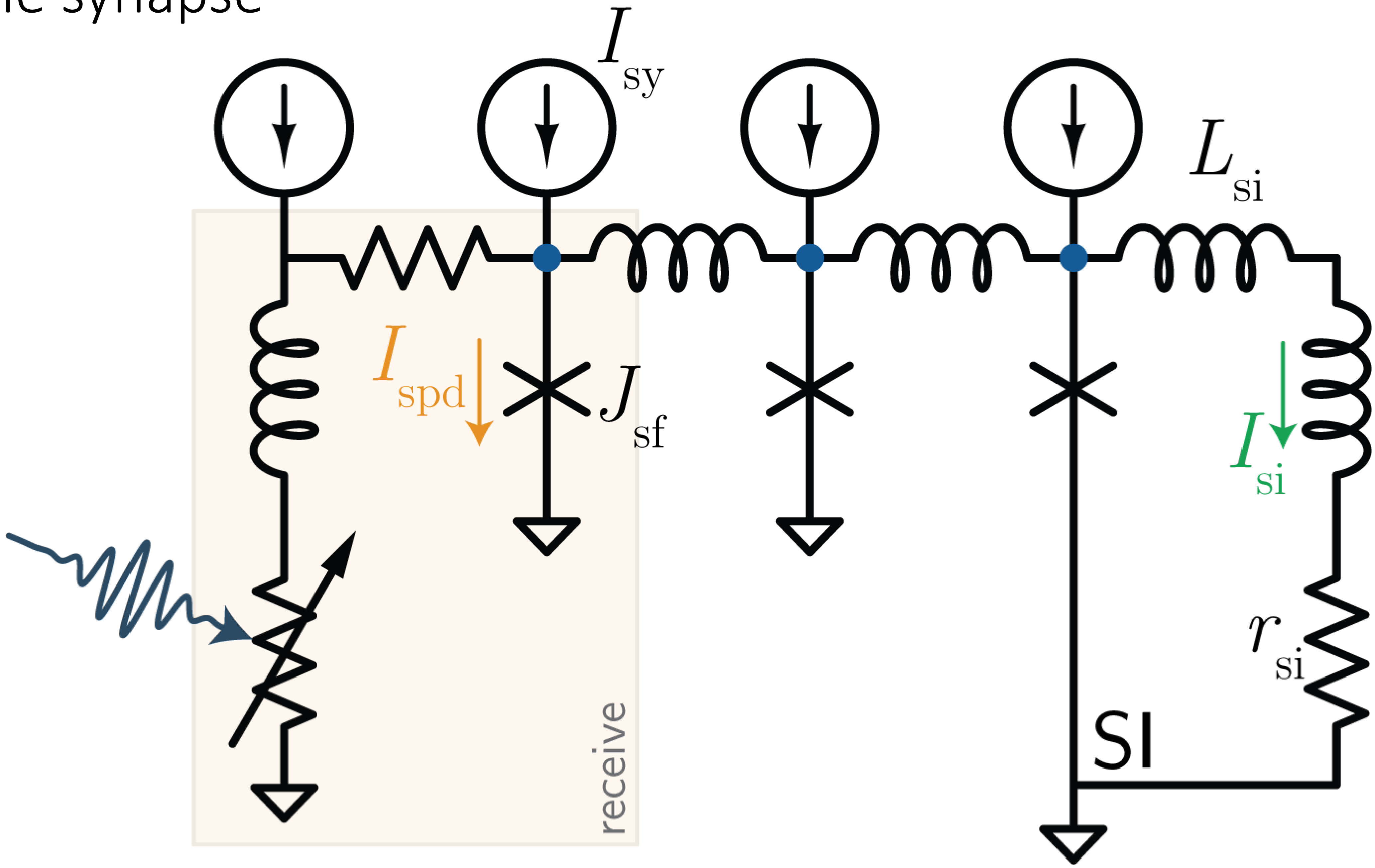


The synapse

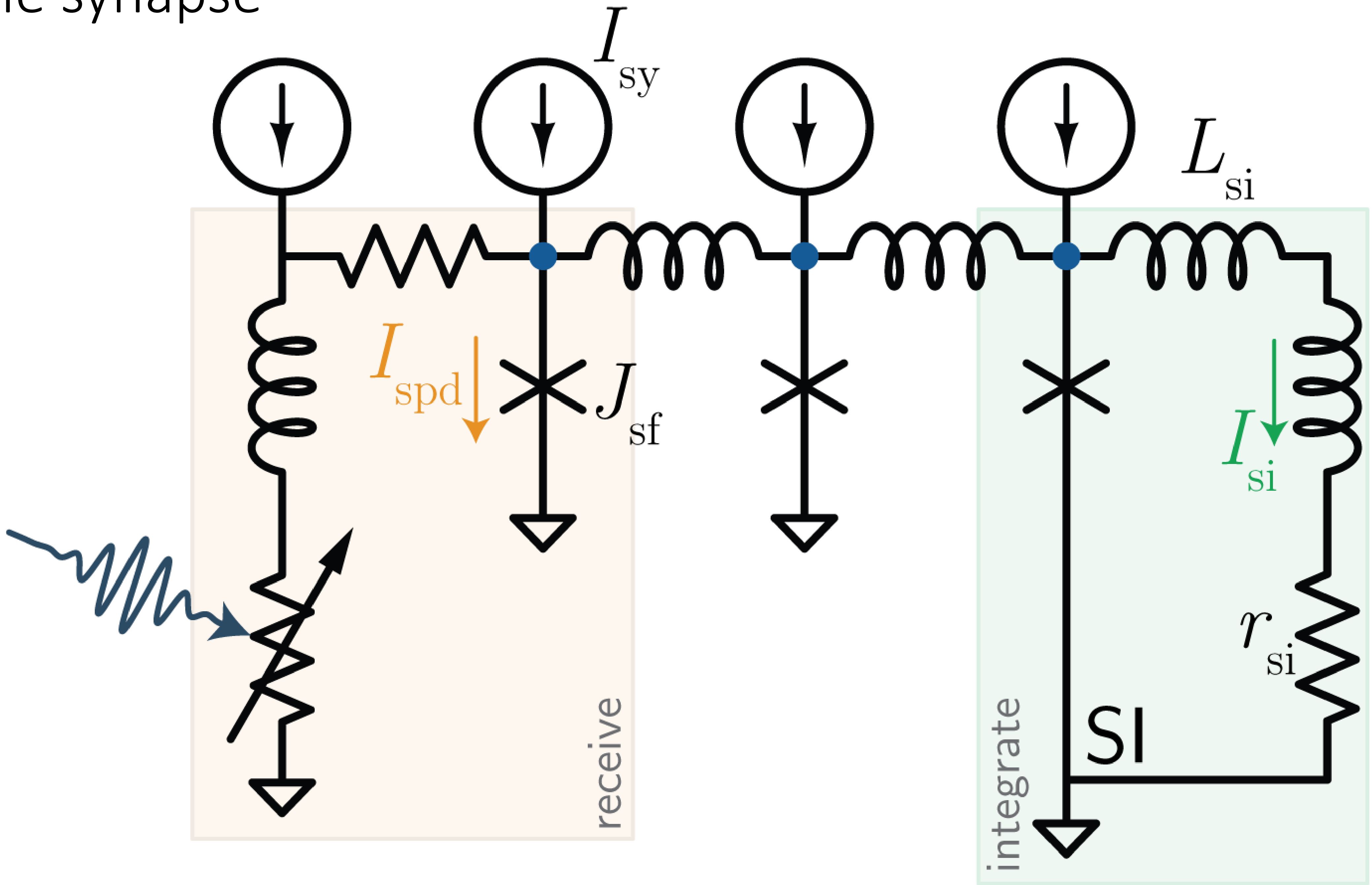


I_{sy}
L_{si}
I_{spd}
J_{sf}
J_{jtl}
J_{si}
I_{si}
r_{si}
SI

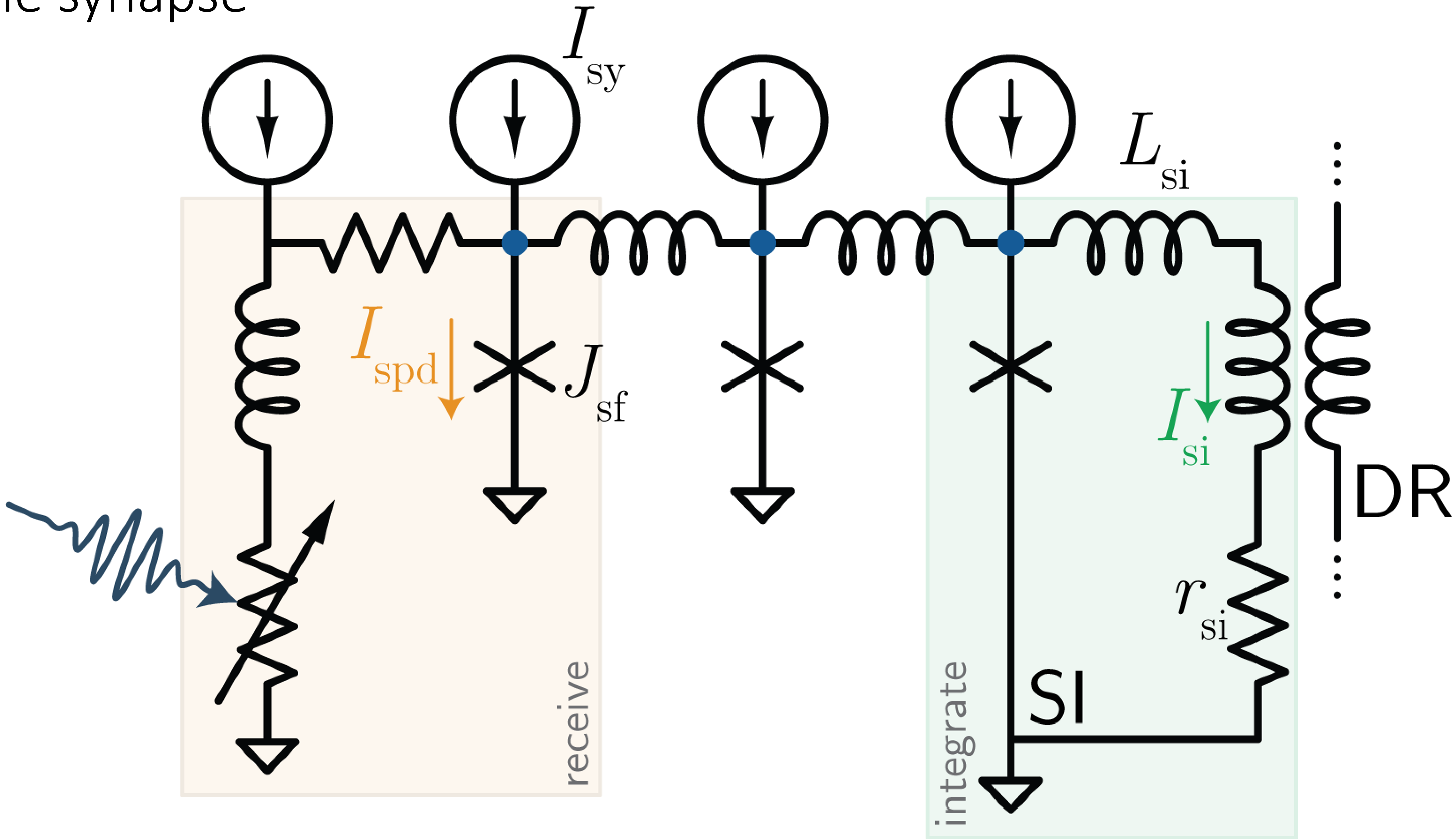
The synapse



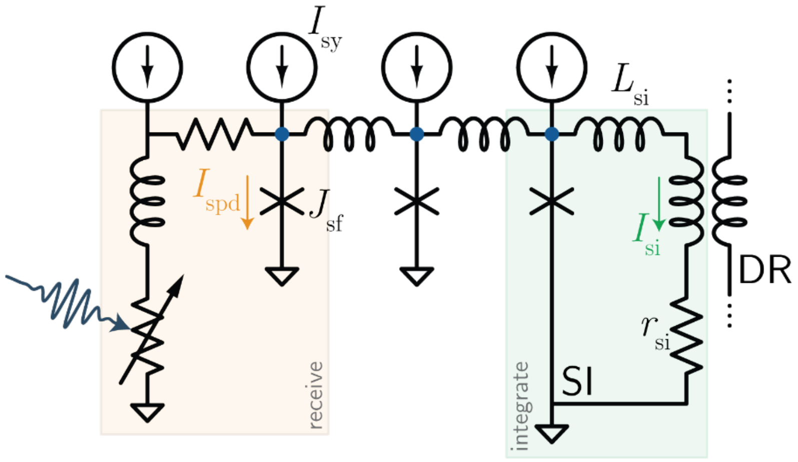
The synapse

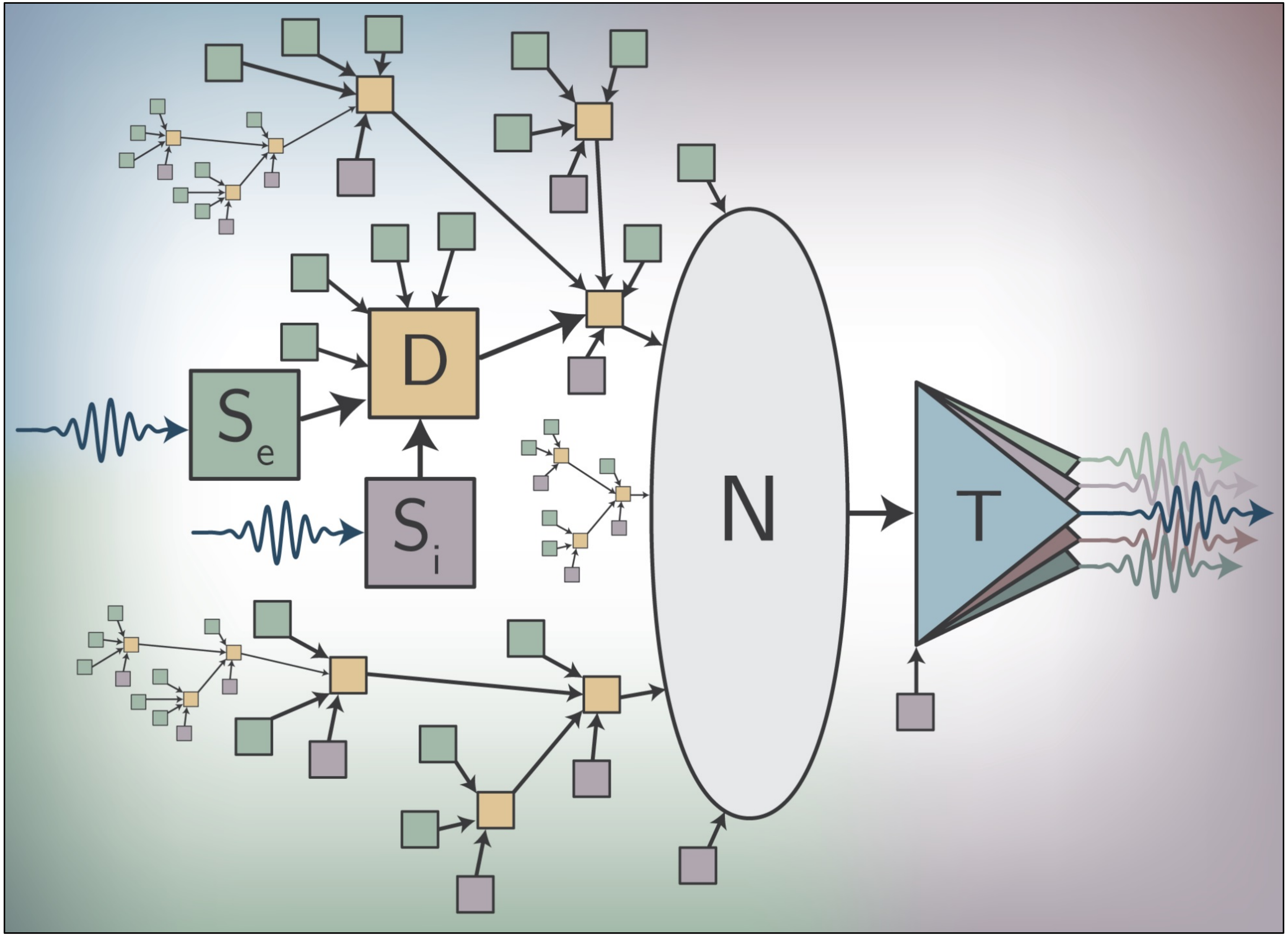


The synapse

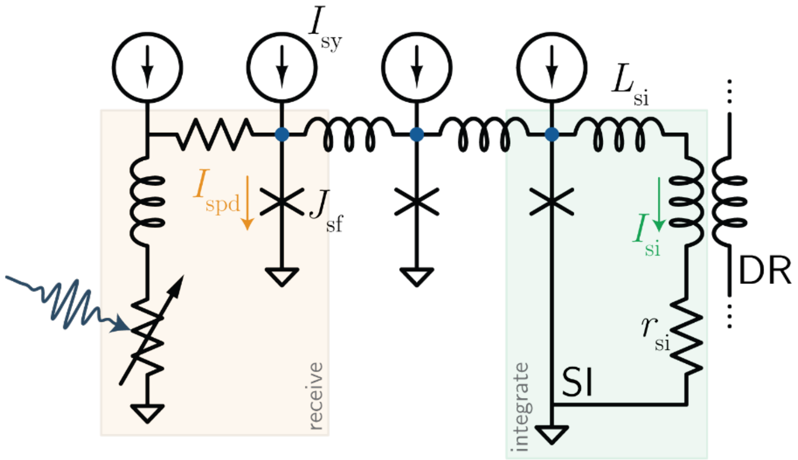


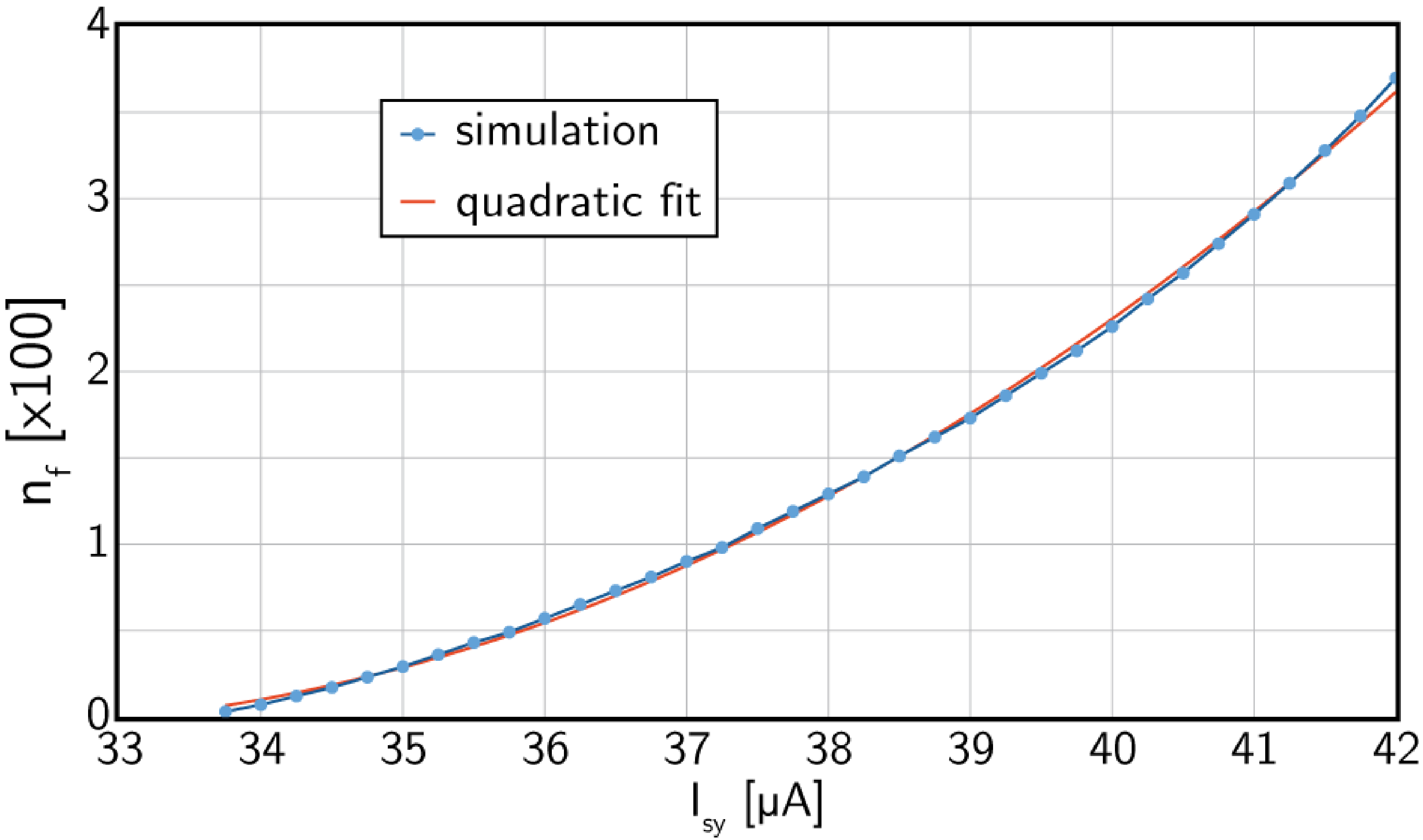
The synapse





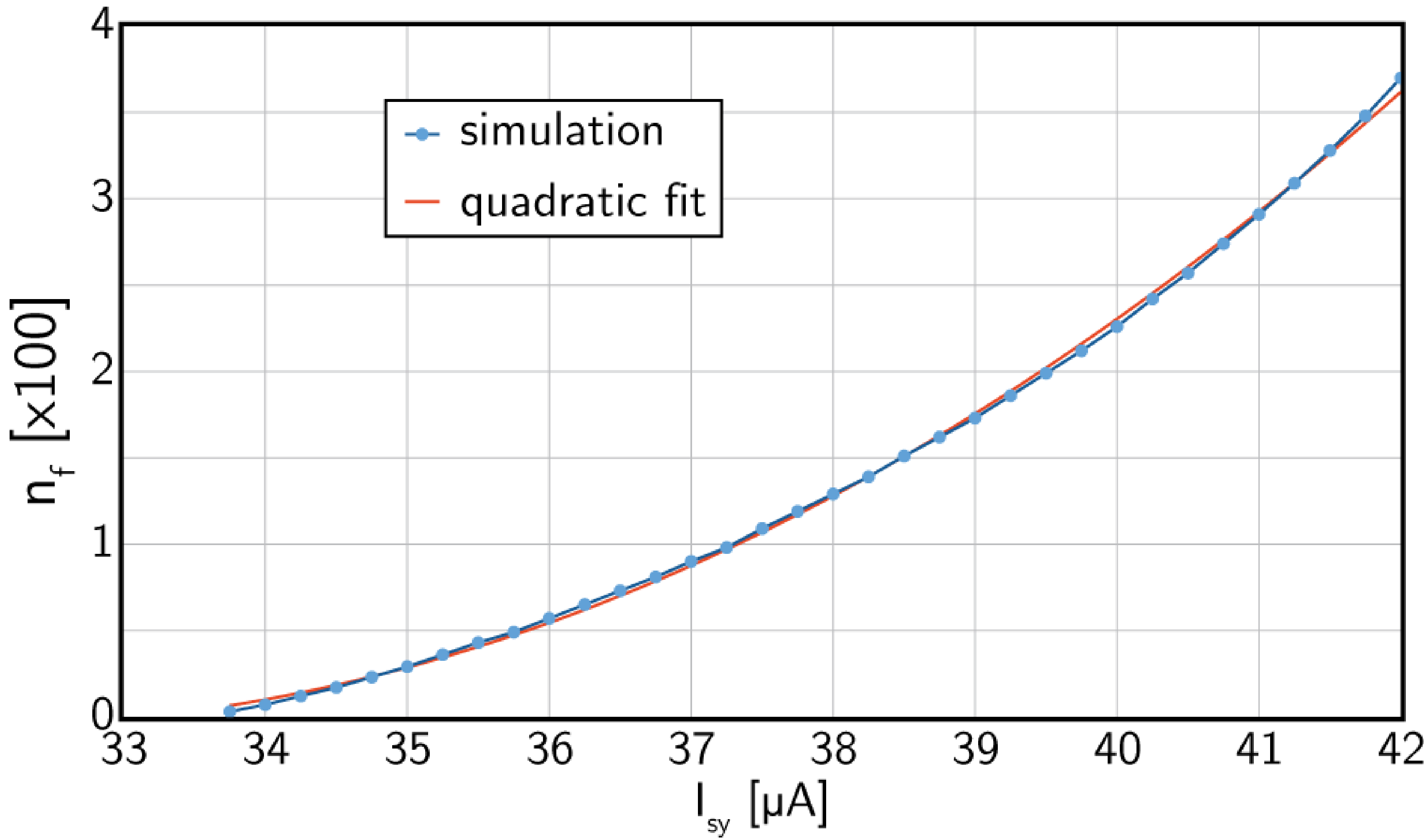
Response to a single synaptic event



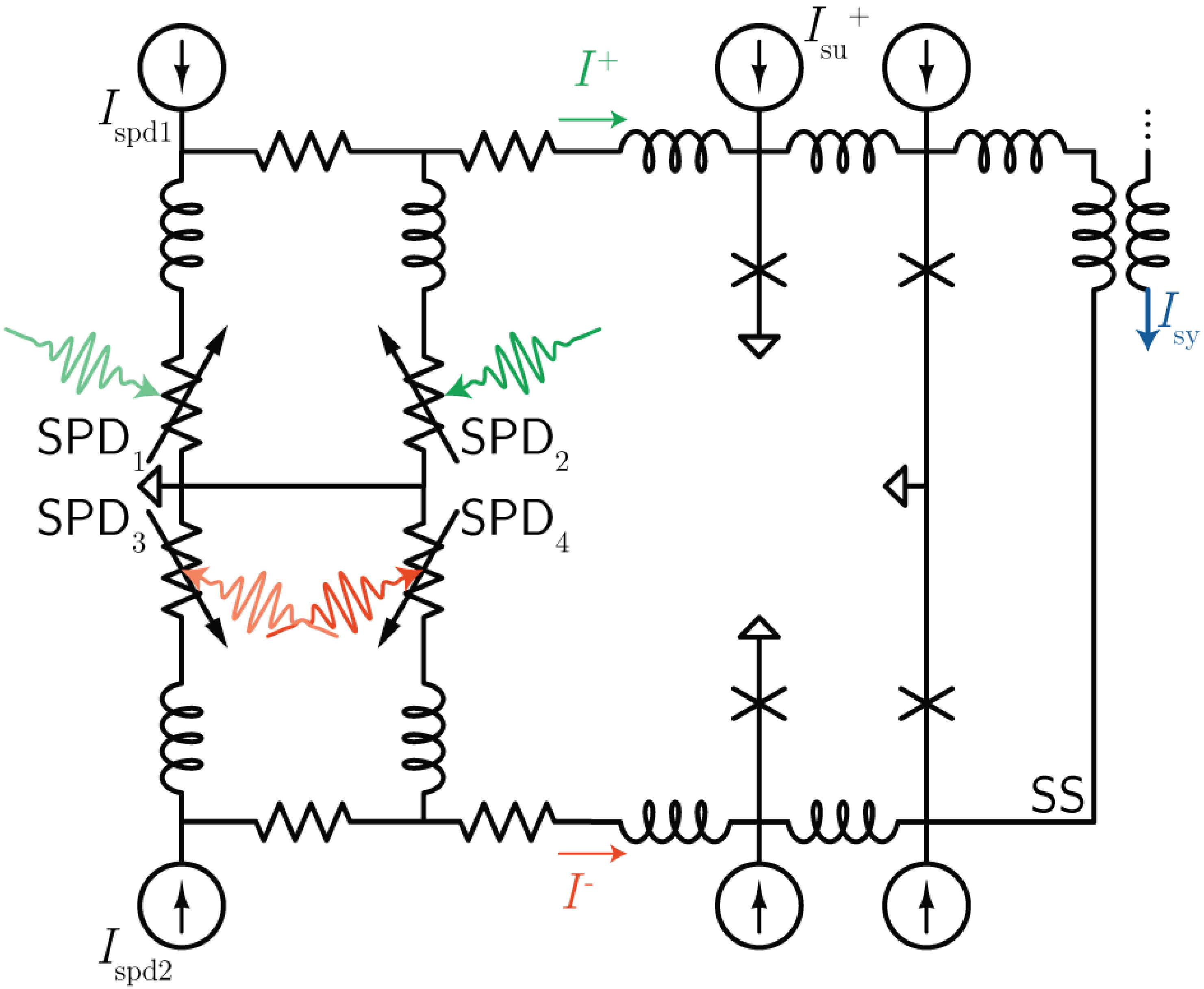


Response to a single synaptic event

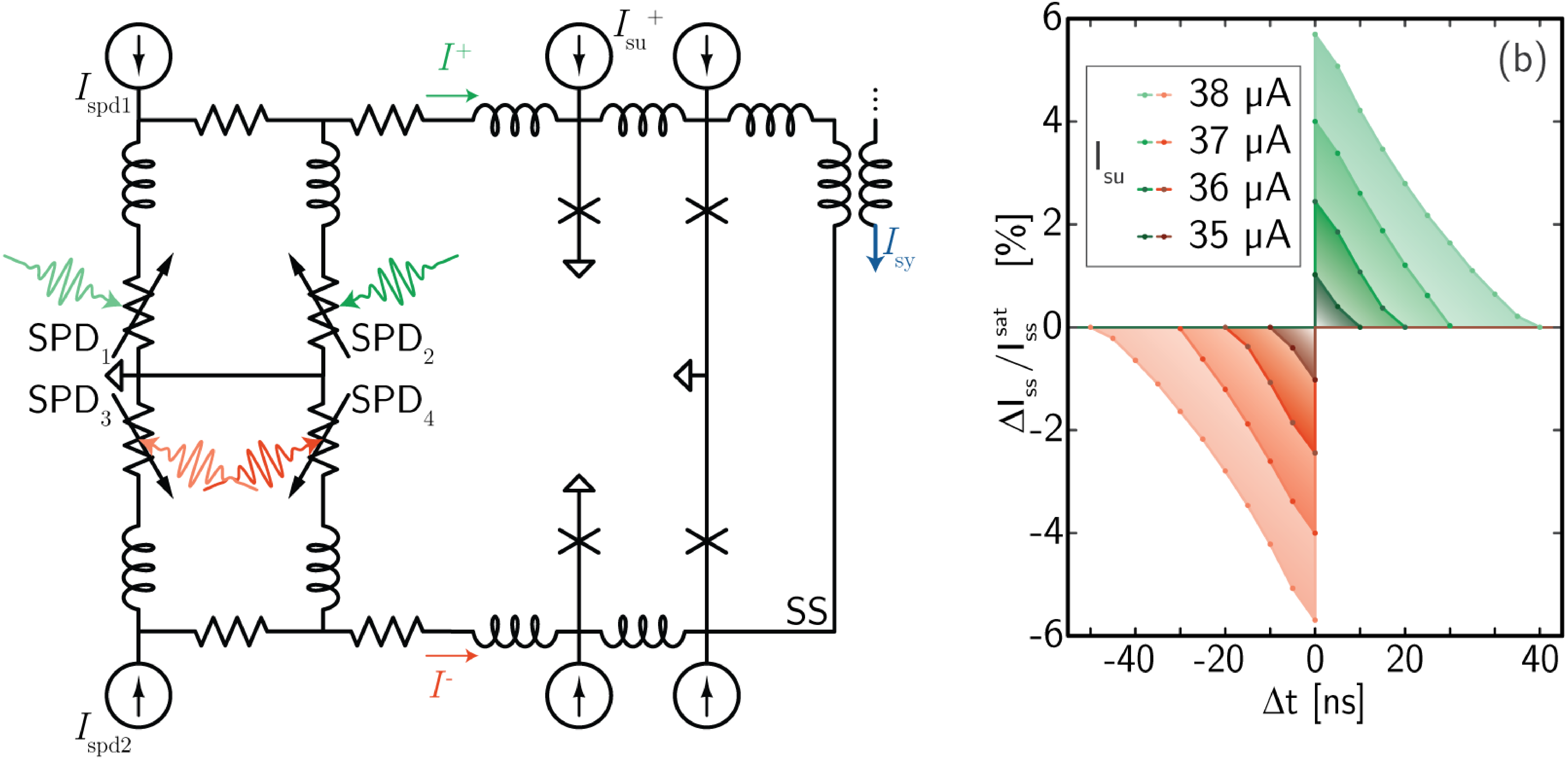
- slowly varying
- monotonic
- bounded



Synaptic plasticity

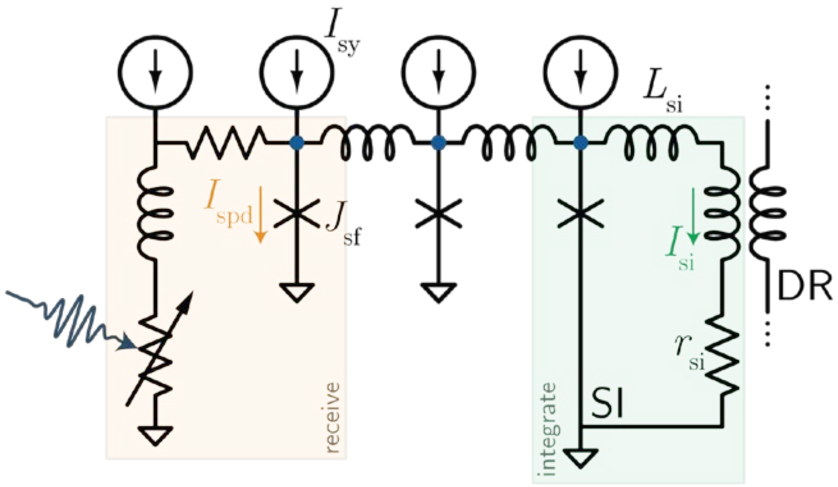


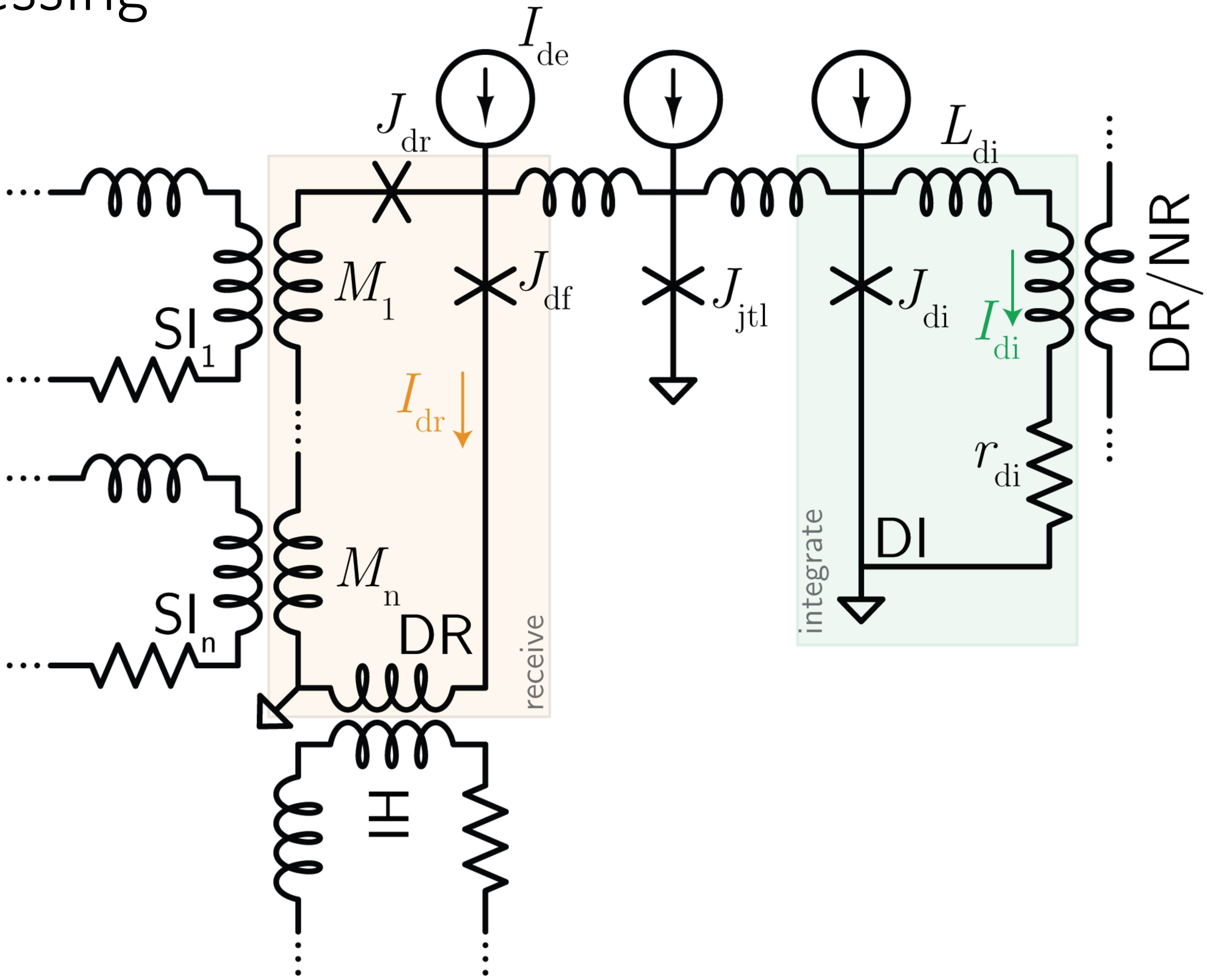
Synaptic plasticity



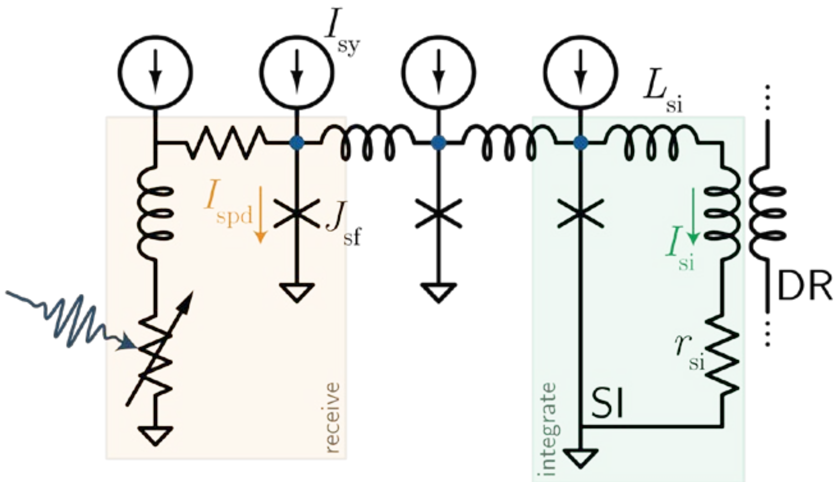
Shainline et al., J. Appl. Phys., 124, 152130 (2018)

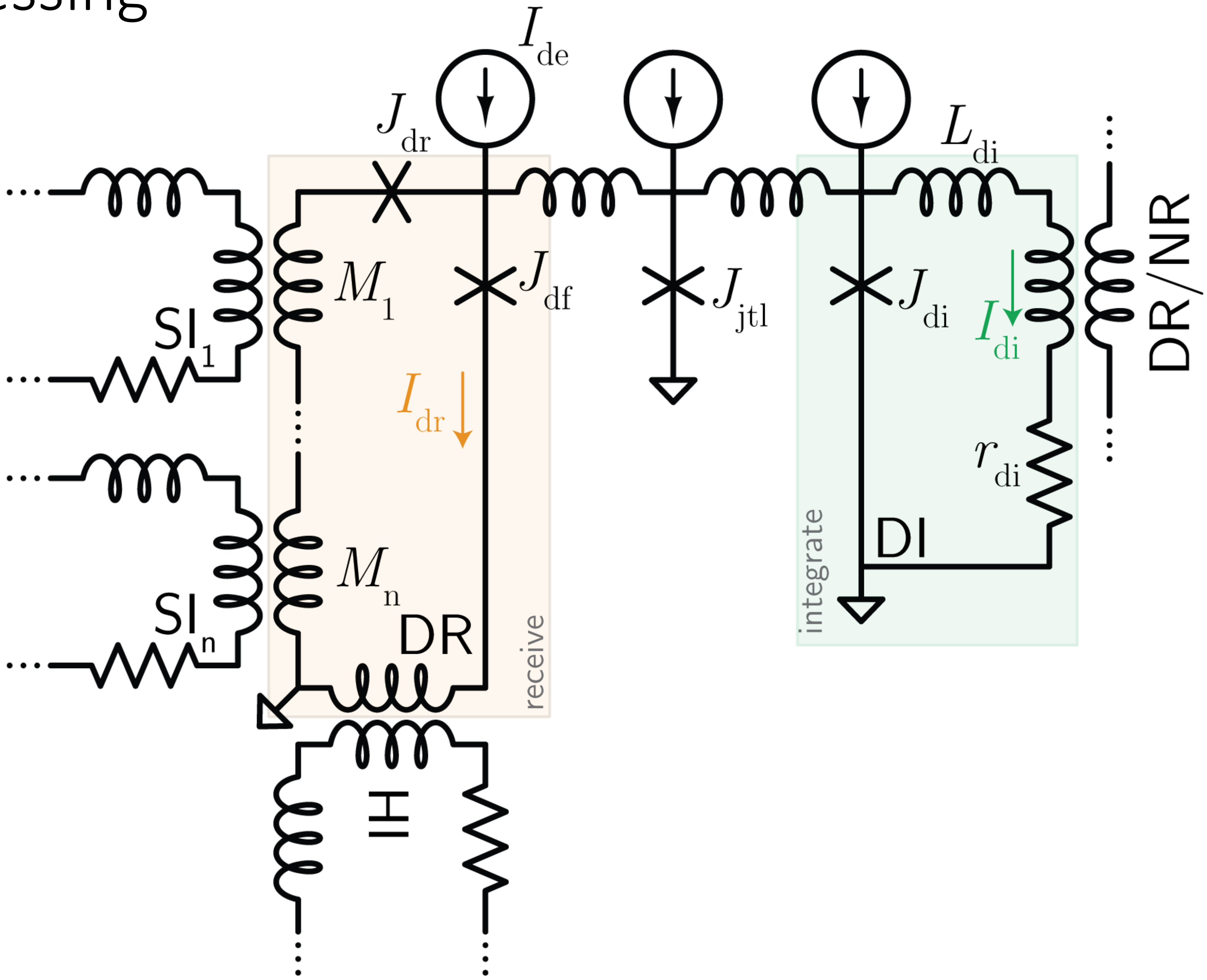
Adding dendritic processing





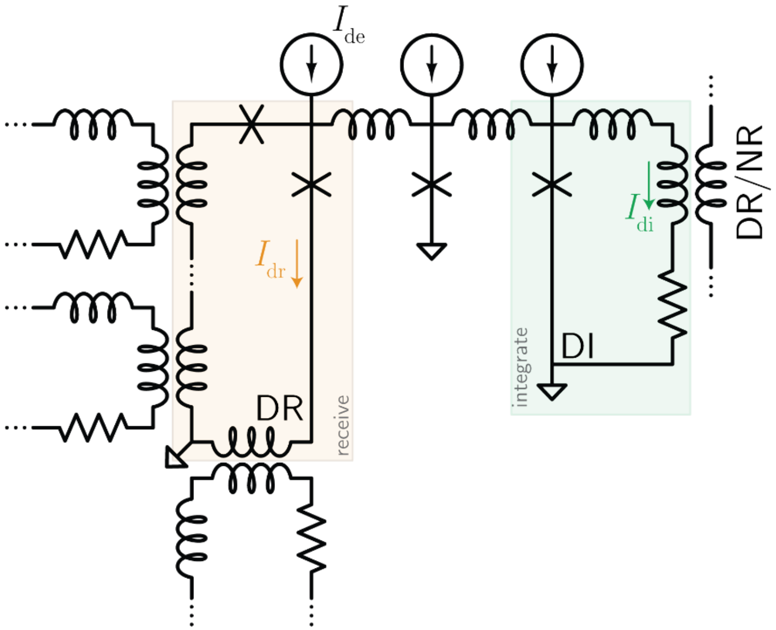
Adding dendritic processing

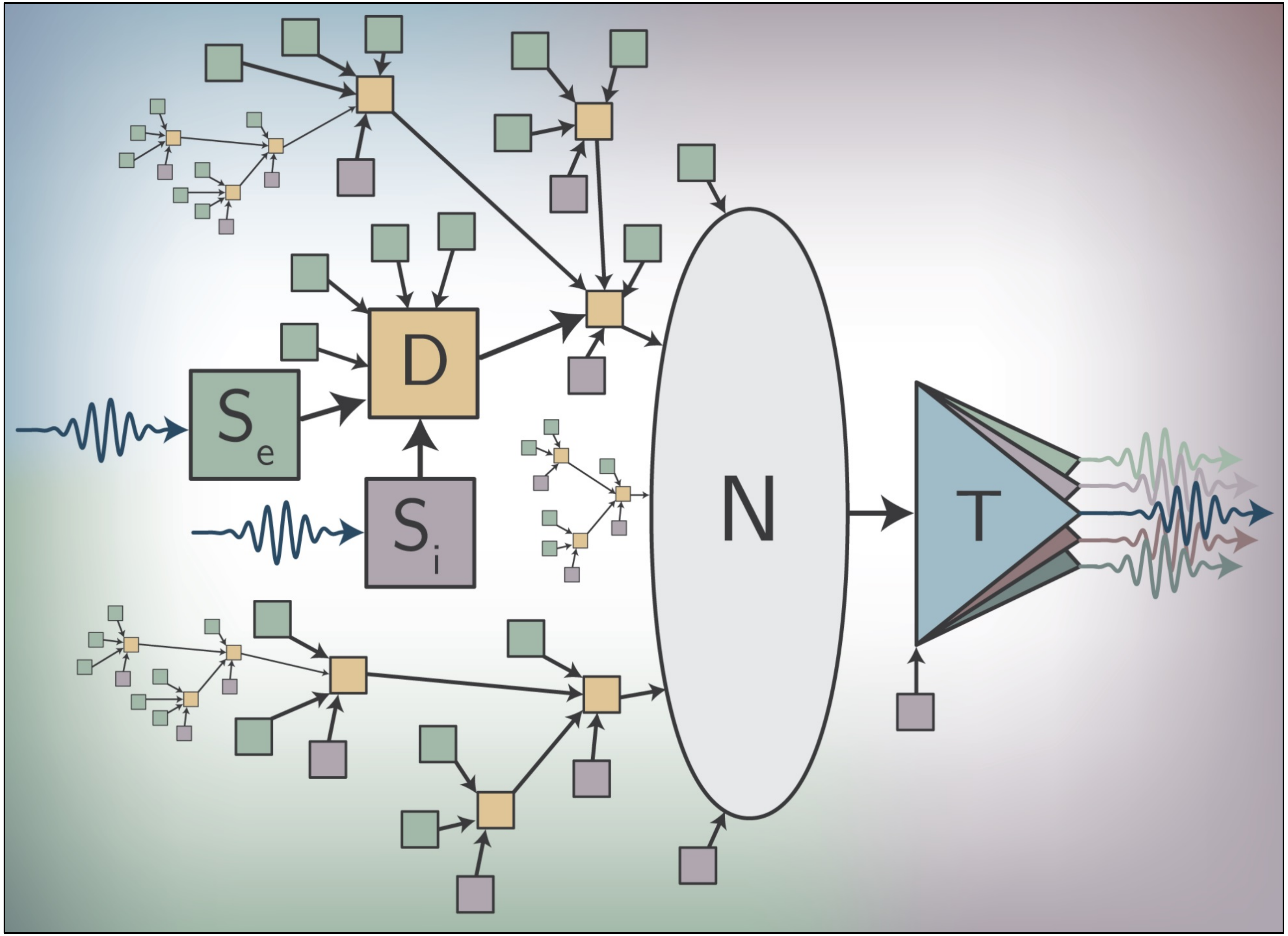




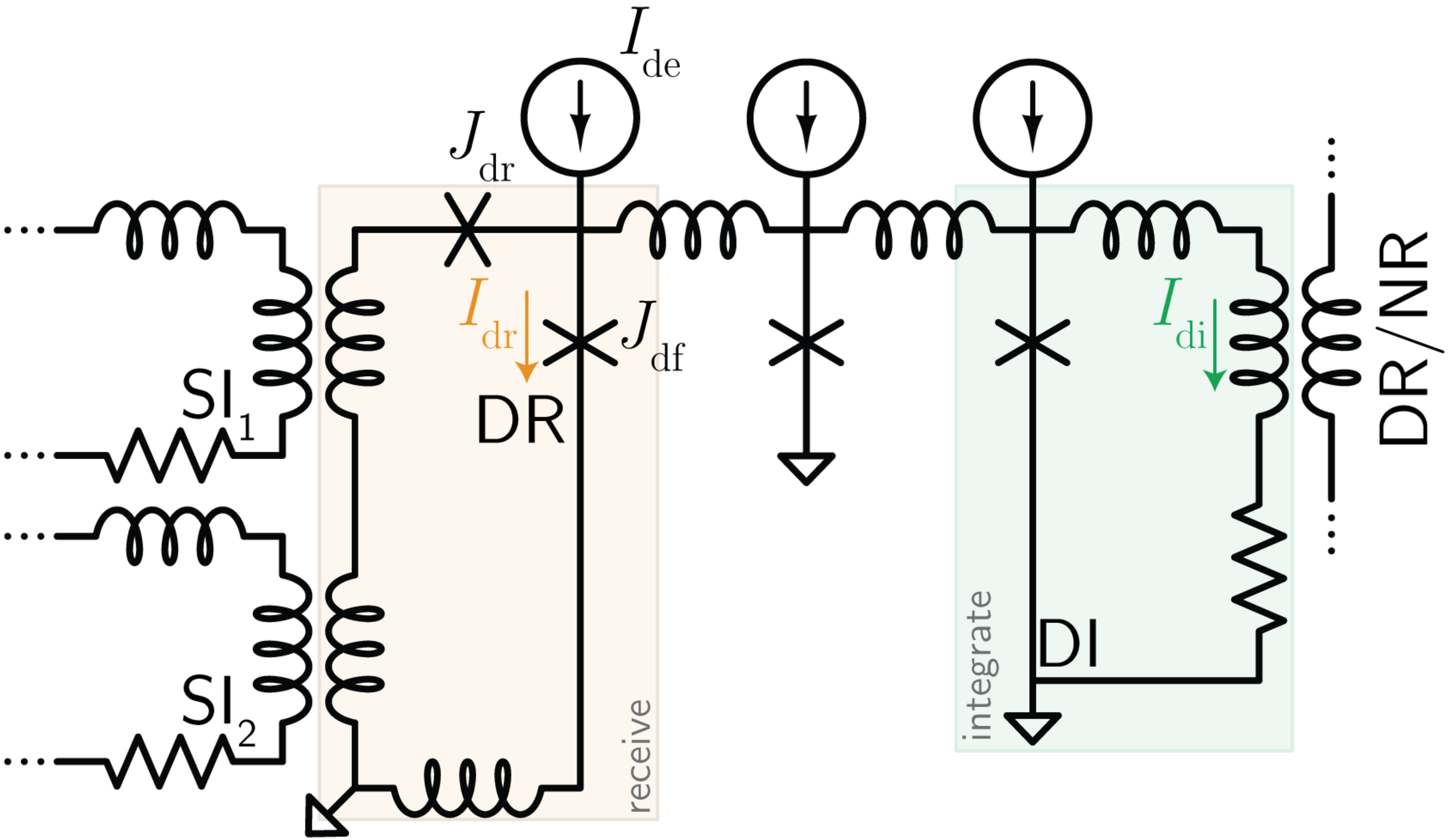
- intermediate nonlinearity
- temporal filtering
- logical operations

The dendrite

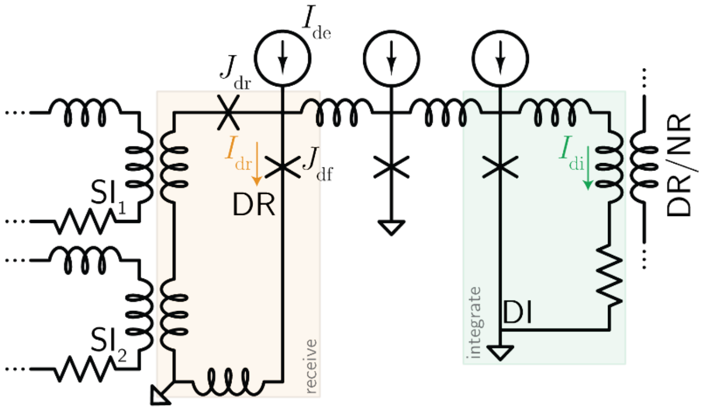


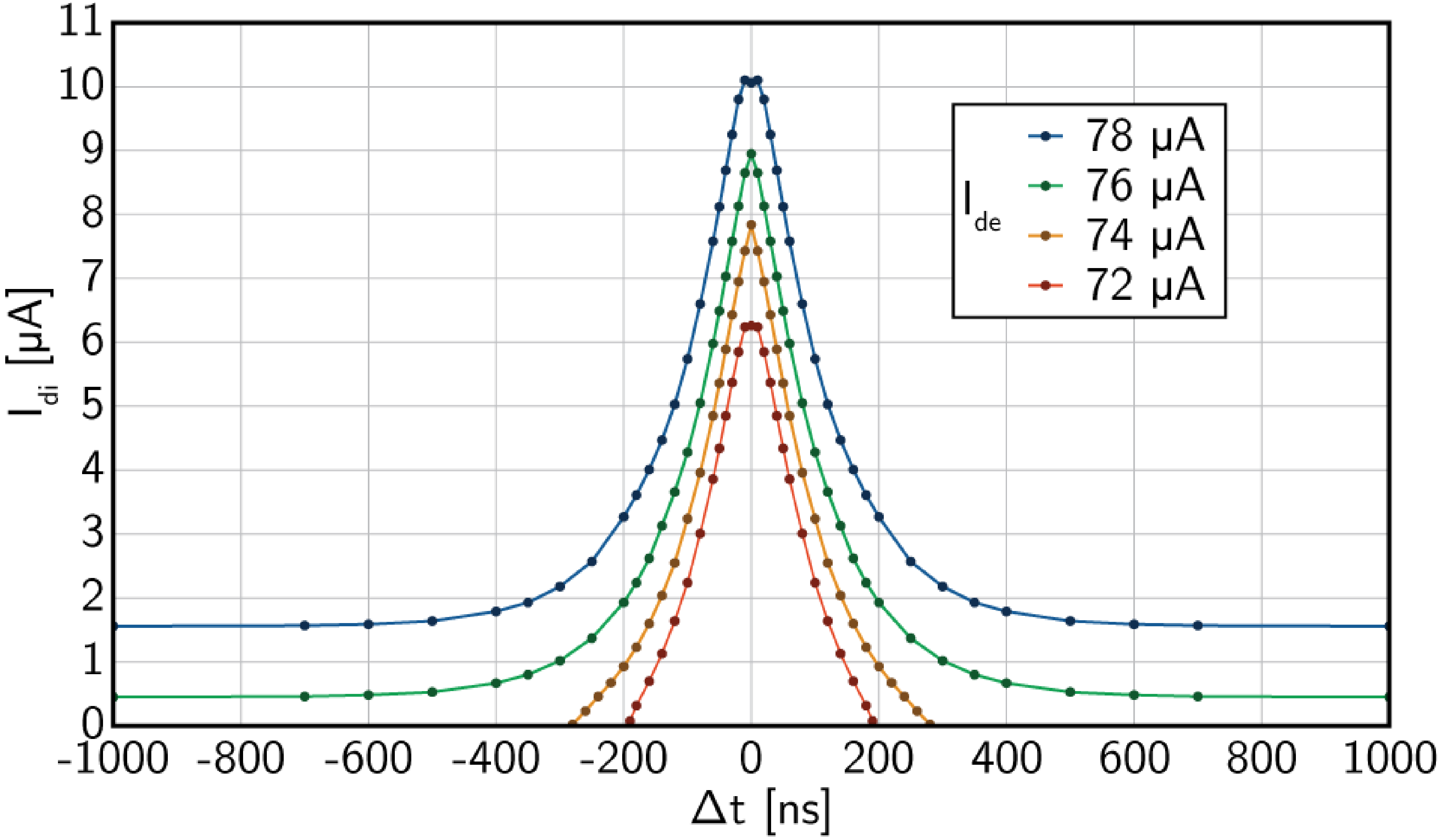


Dendrite with two synapses

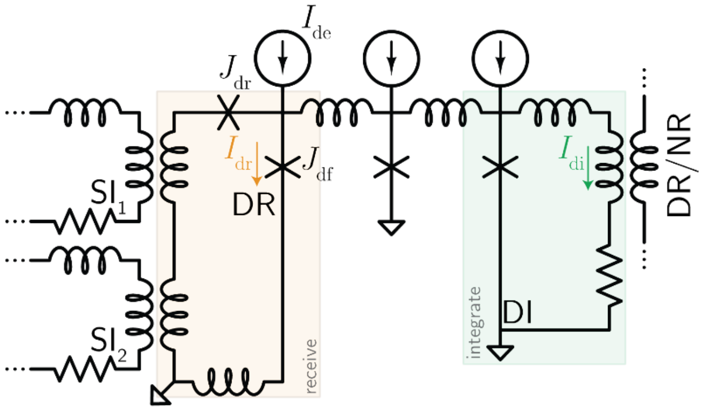


Coincidence detection

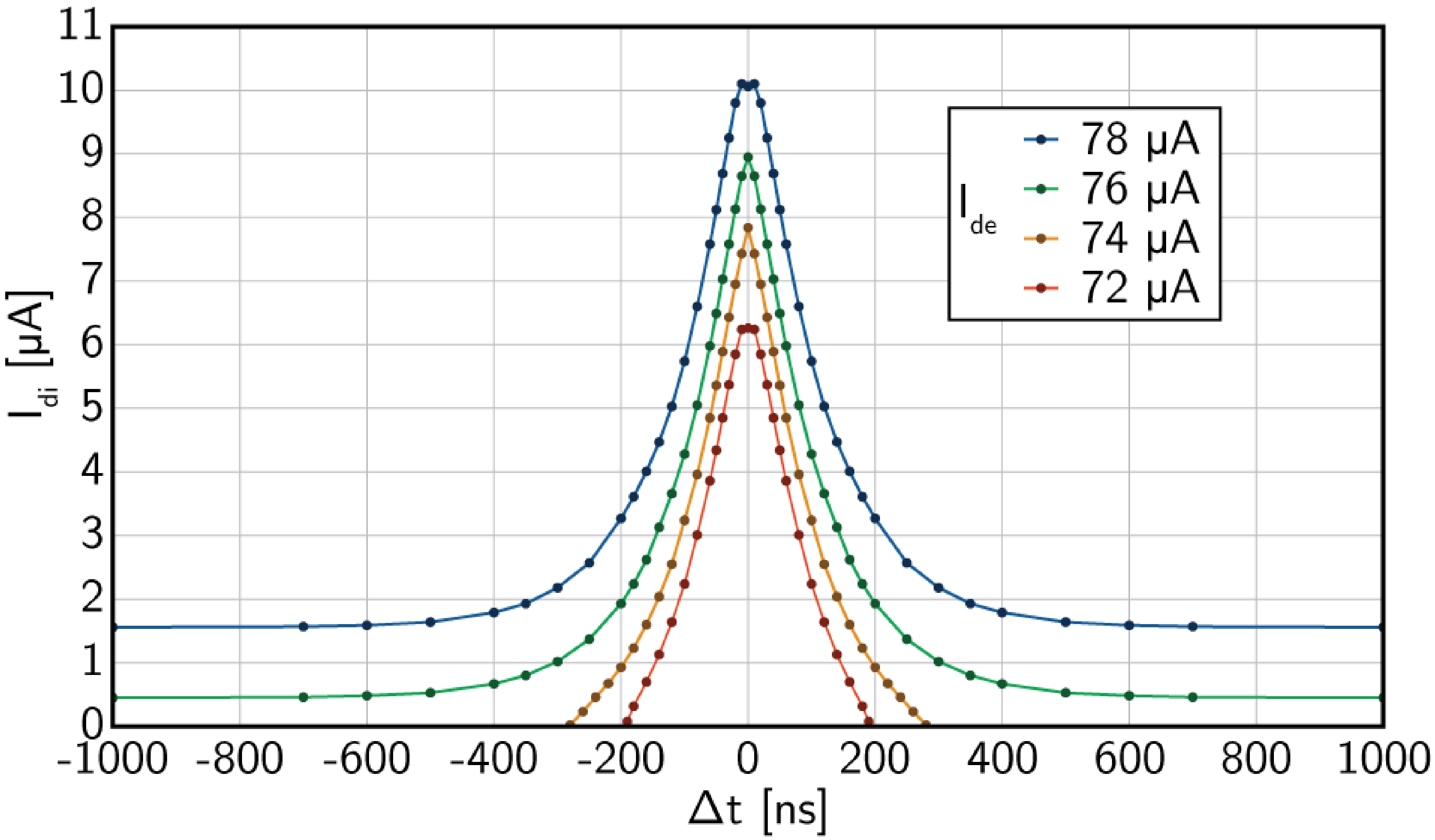




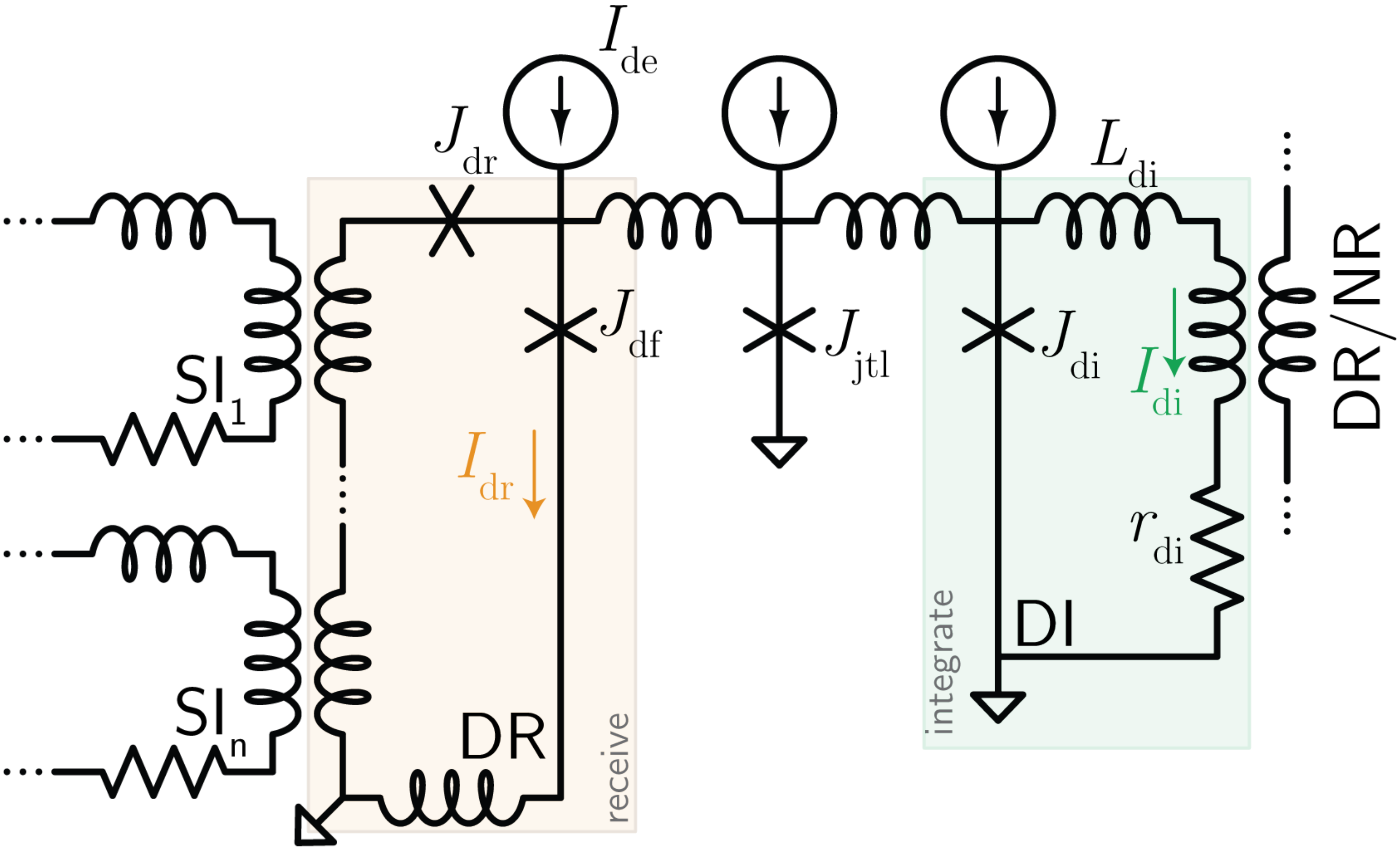
Coincidence detection



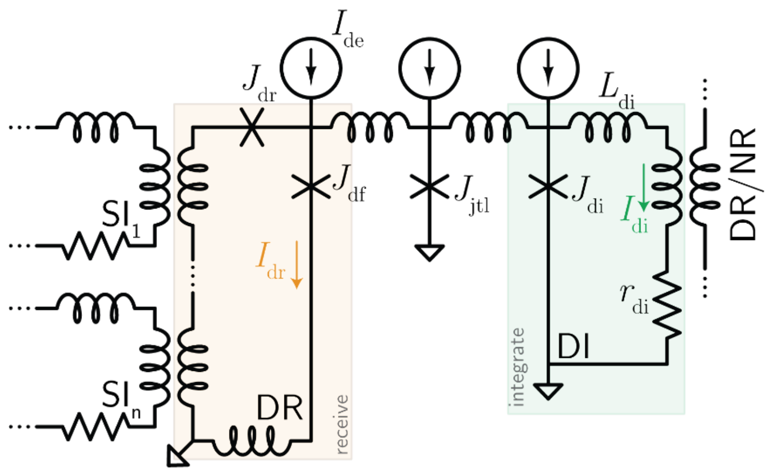
- intermediate nonlinearity
- temporal filtering
- logical operations (AND/OR)

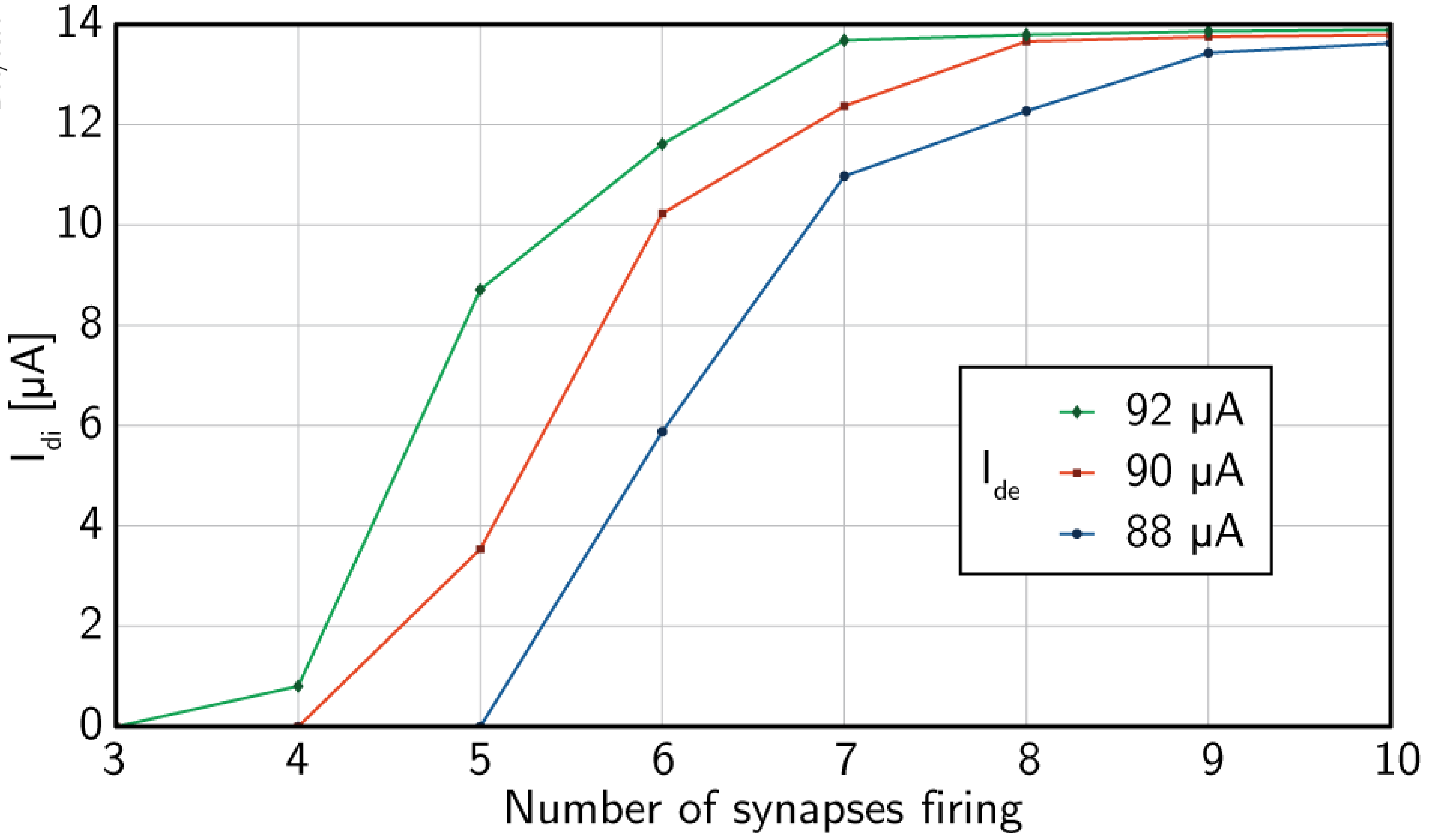


Dendrite with ten synapses

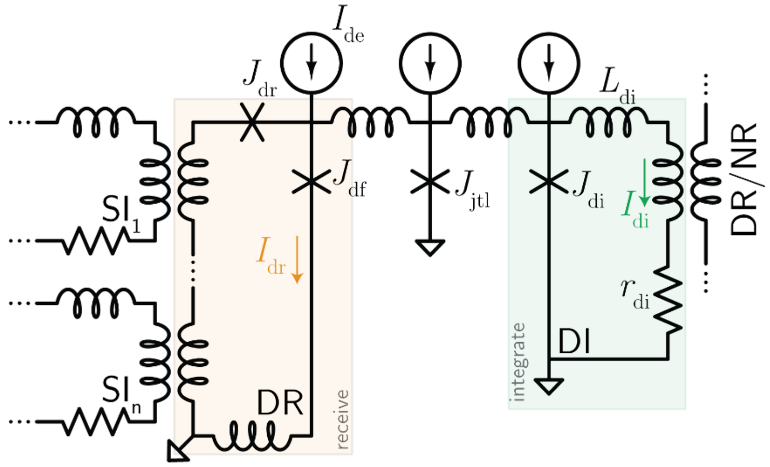


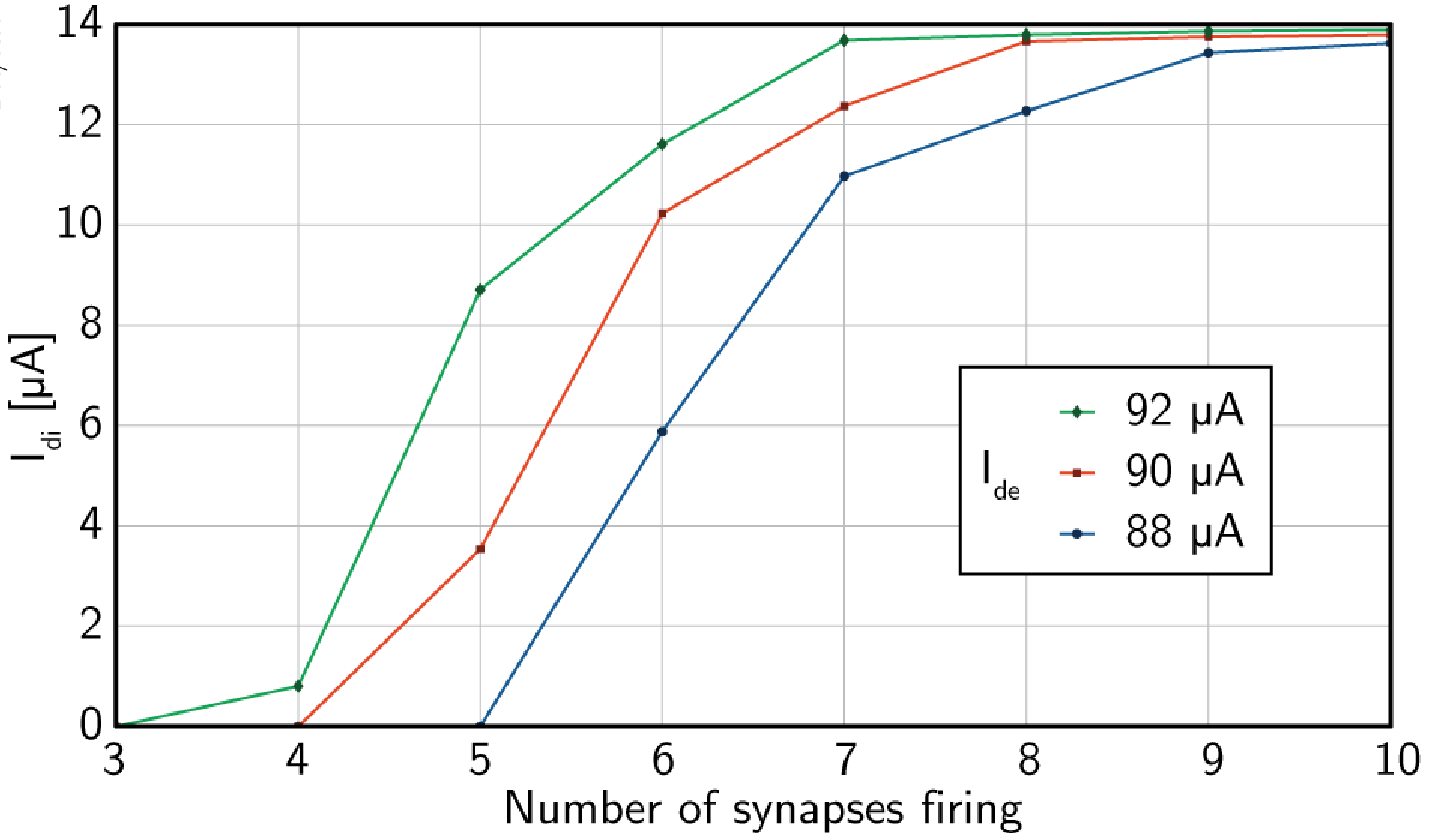
Dendrite with ten synapses





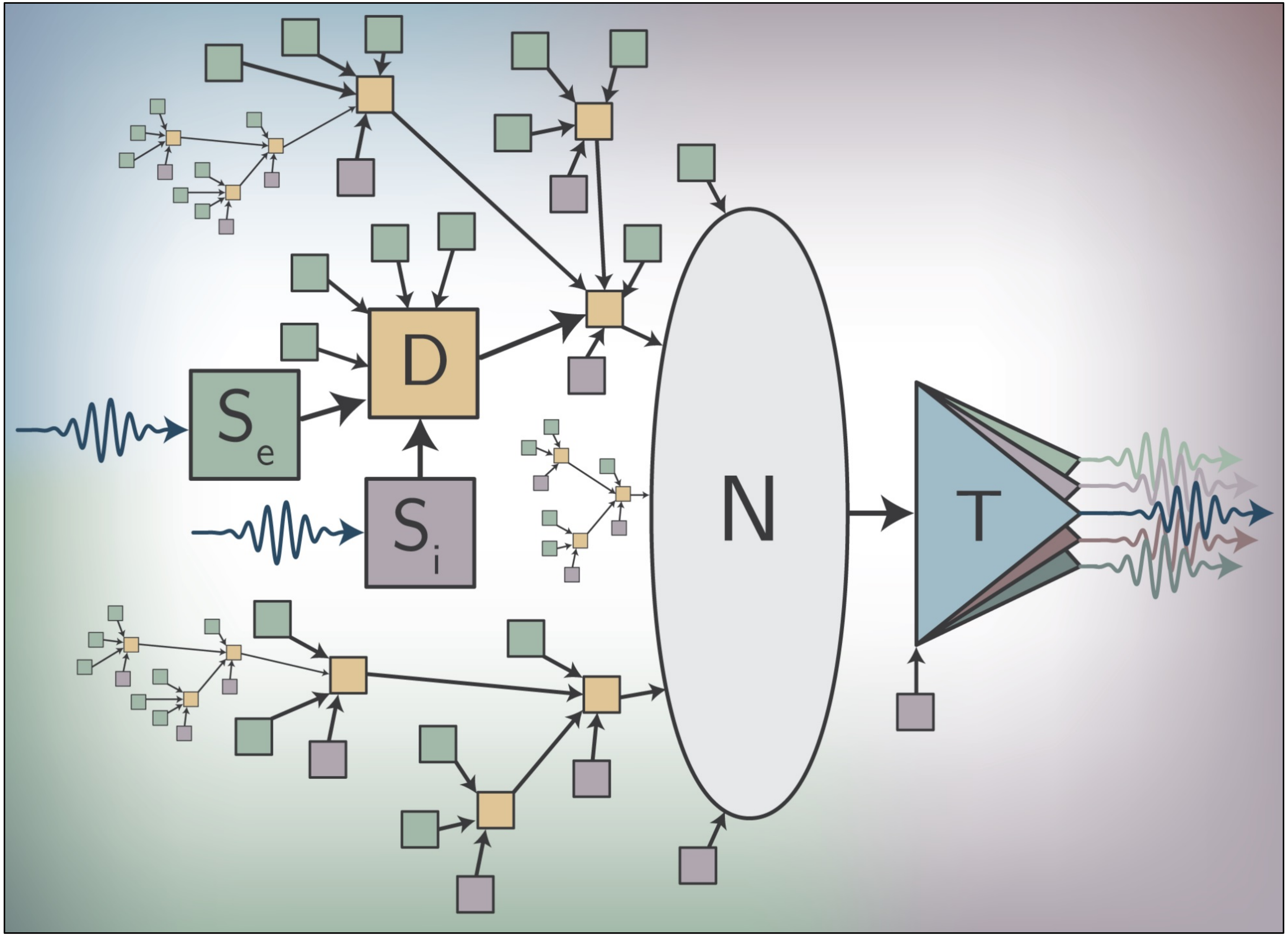
Dendrite with ten synapses





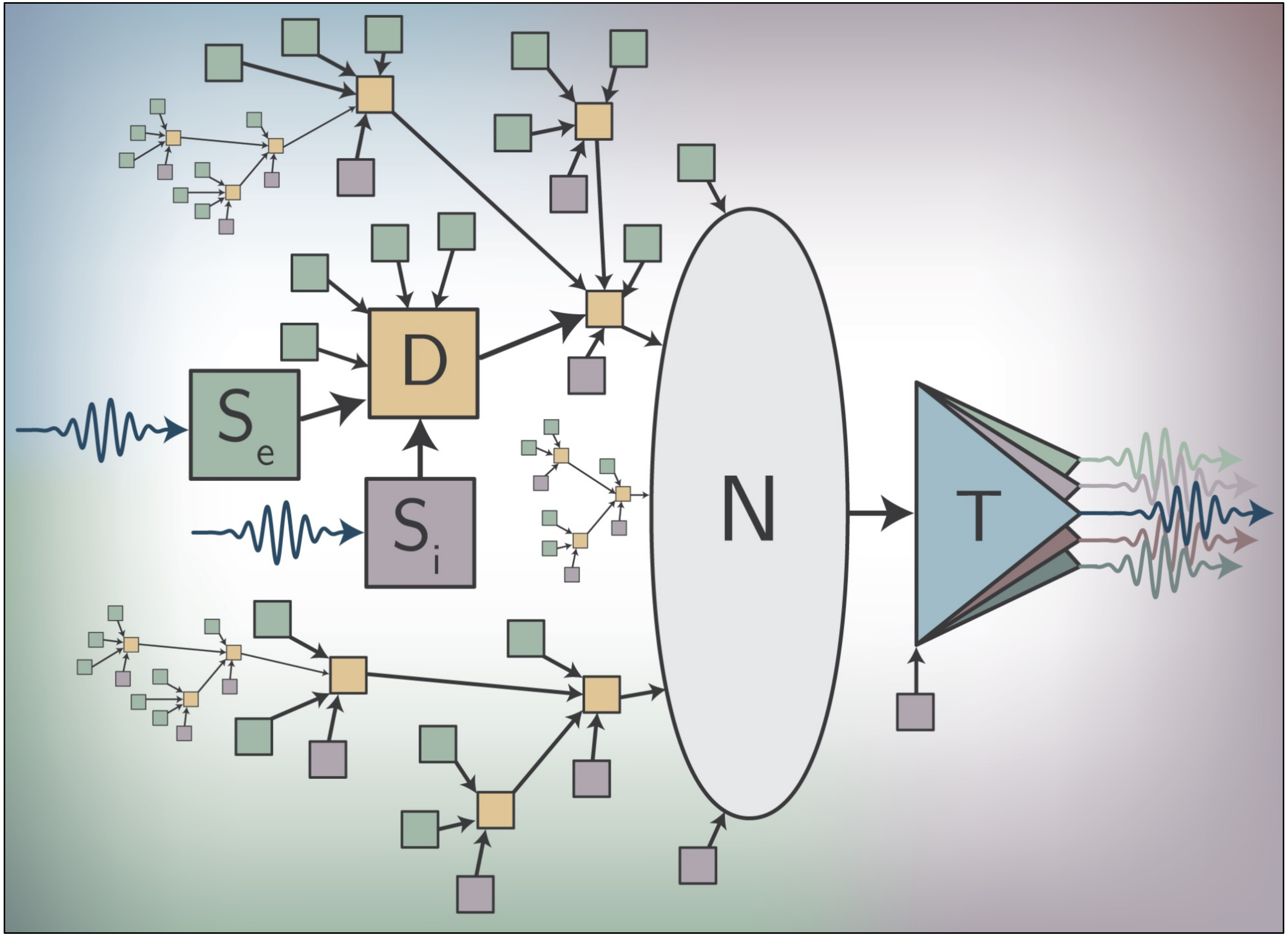
- intermediate nonlinearity
- temporal filtering
- logical operations

The neuron



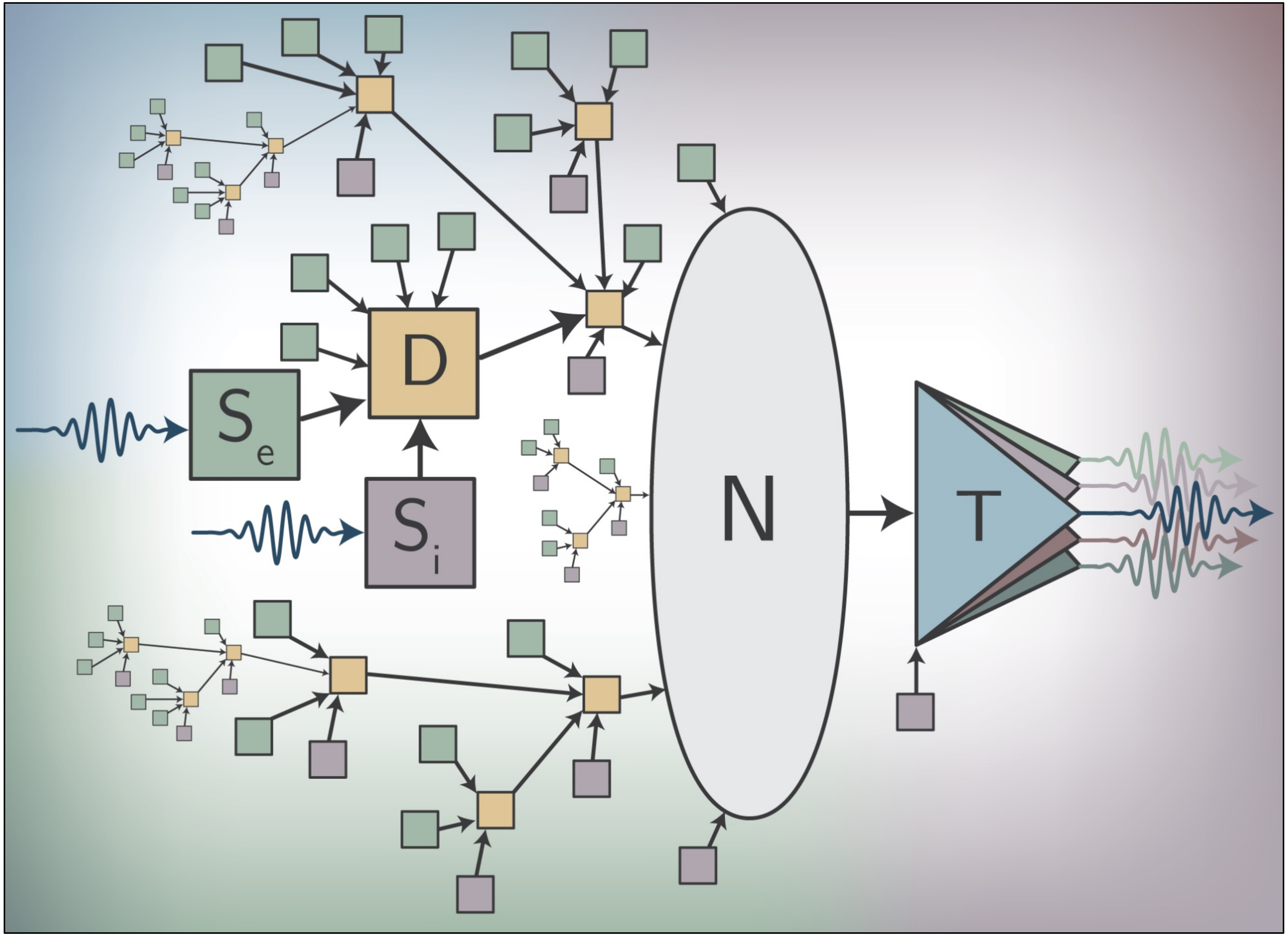
Shainline et al., J. Appl. Phys., 124, 152130 (2018)

Superconducting optoelectronic networks



Superconducting optoelectronic networks

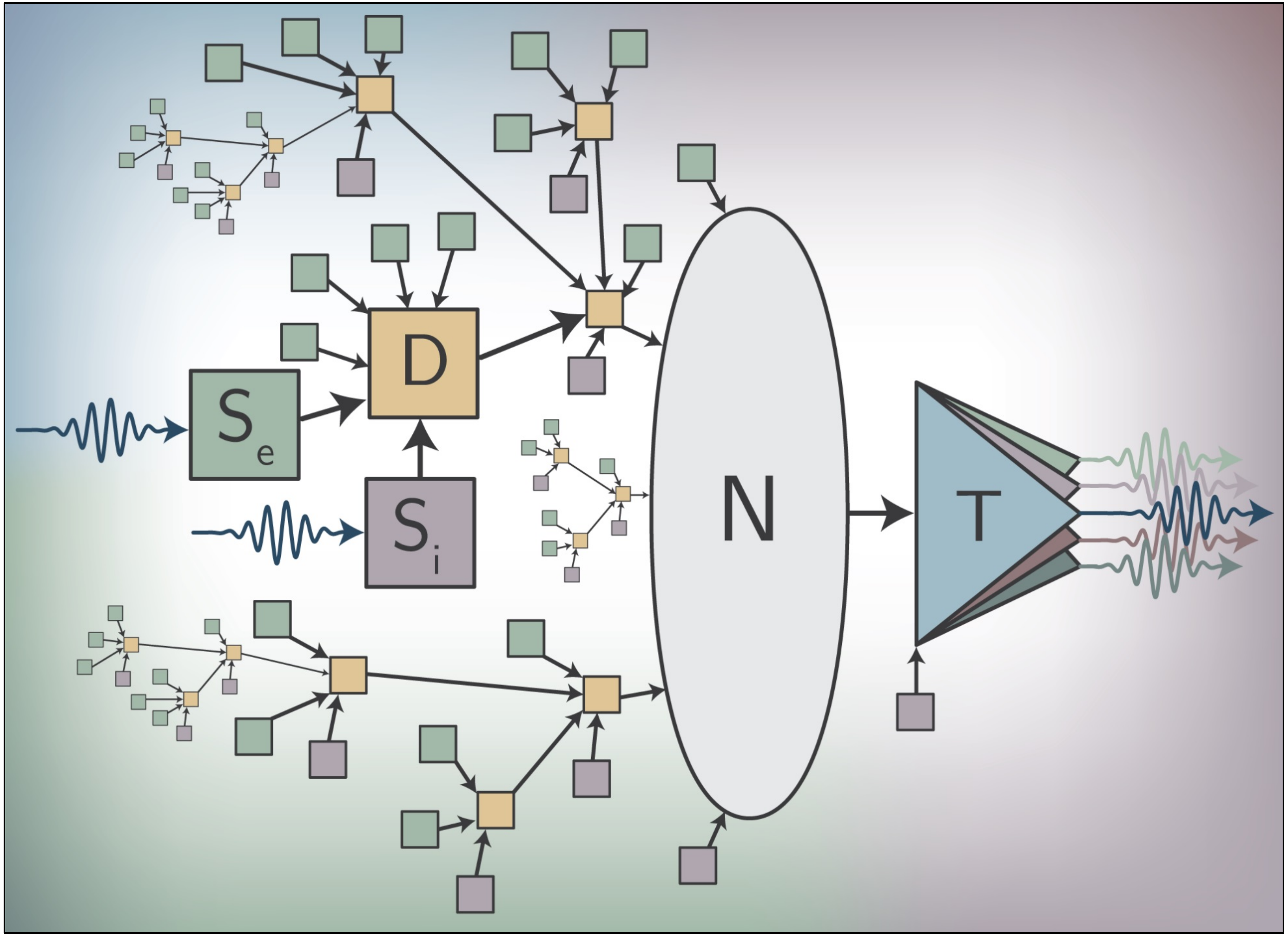
light for communication



Superconducting optoelectronic networks

light for communication

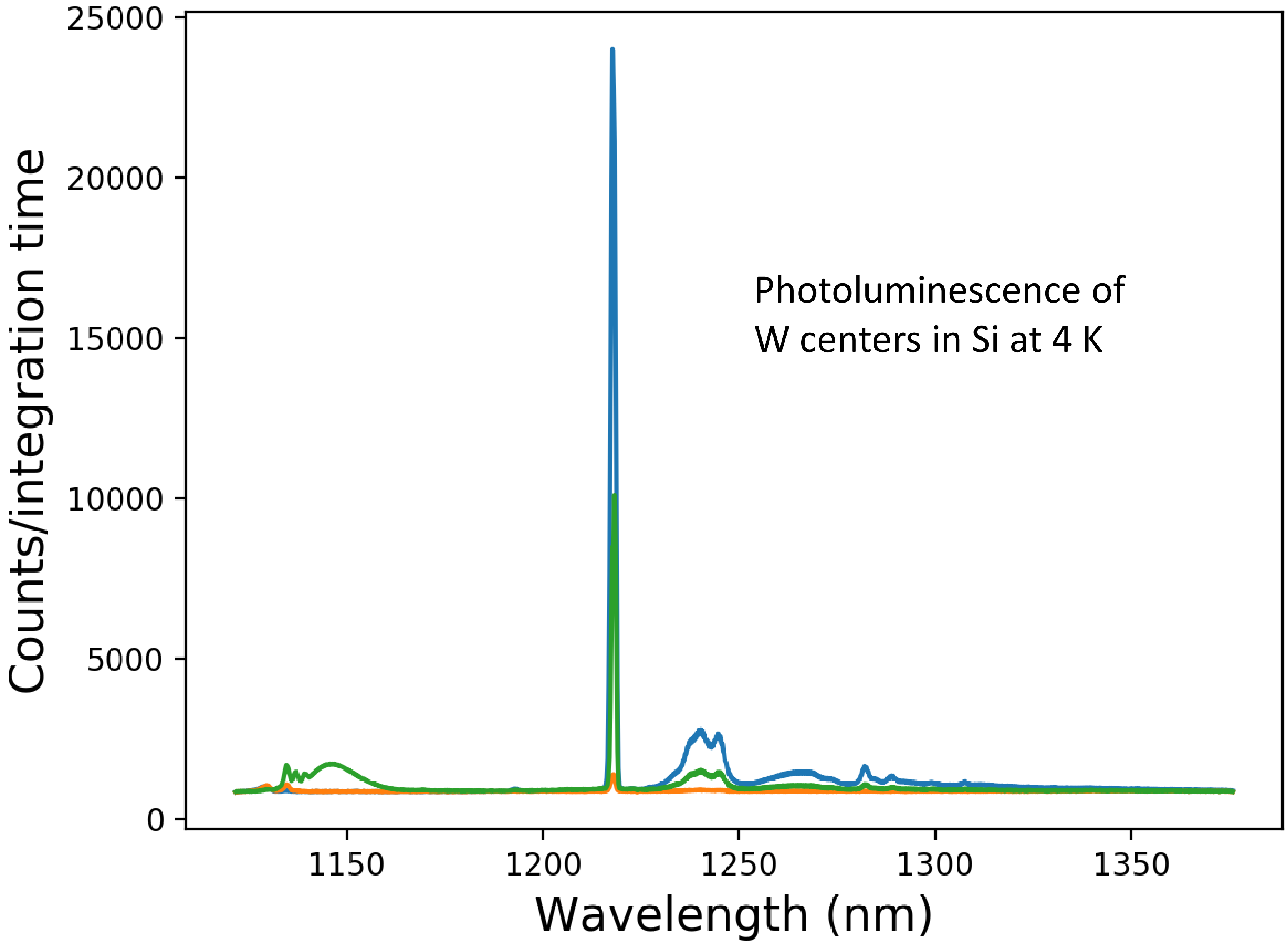
superconductors for computation



Demonstrated the parts, now seek full integration

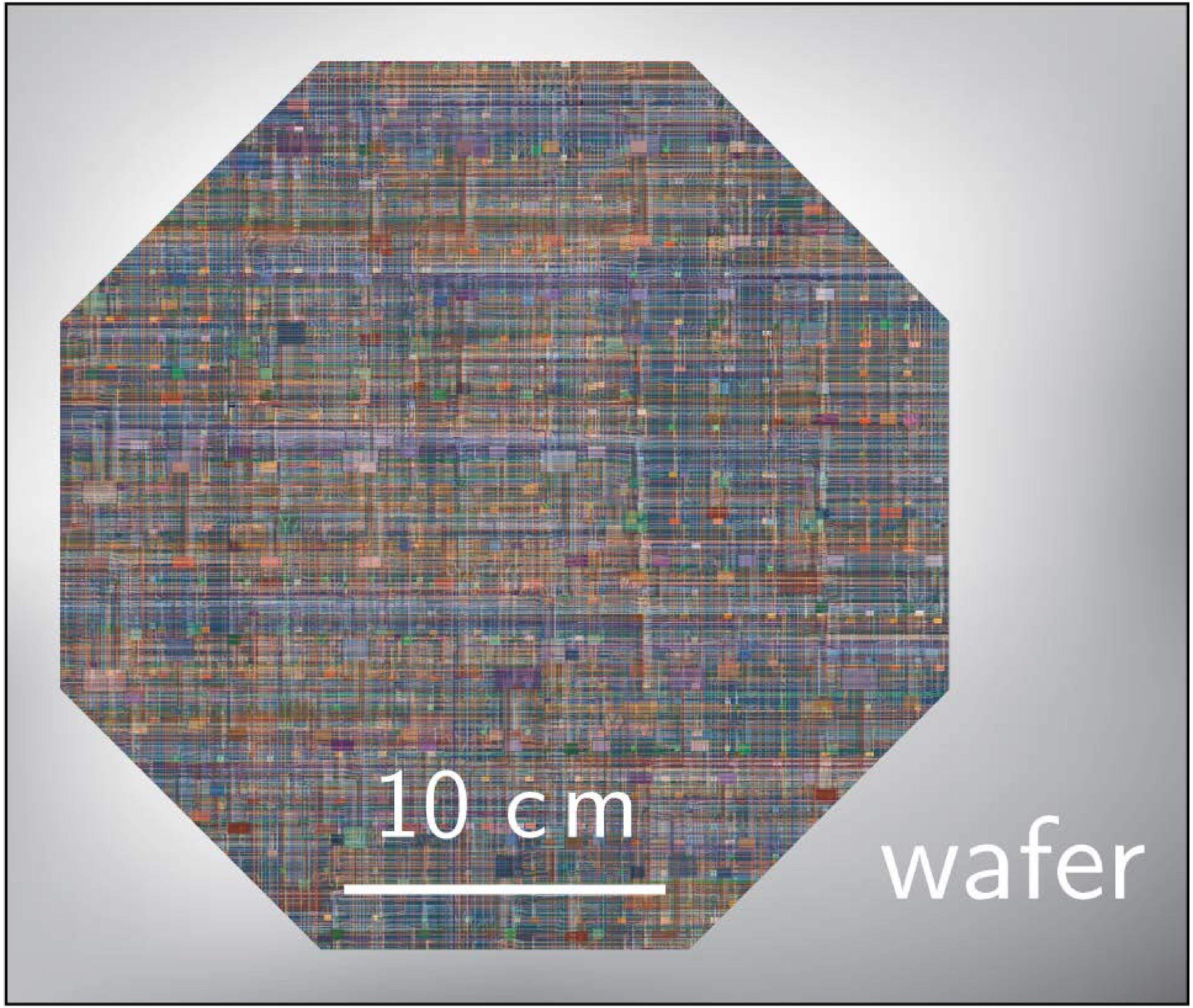
SUNY Poly for process at 300 mm scale

Light sources on 300-mm wafers

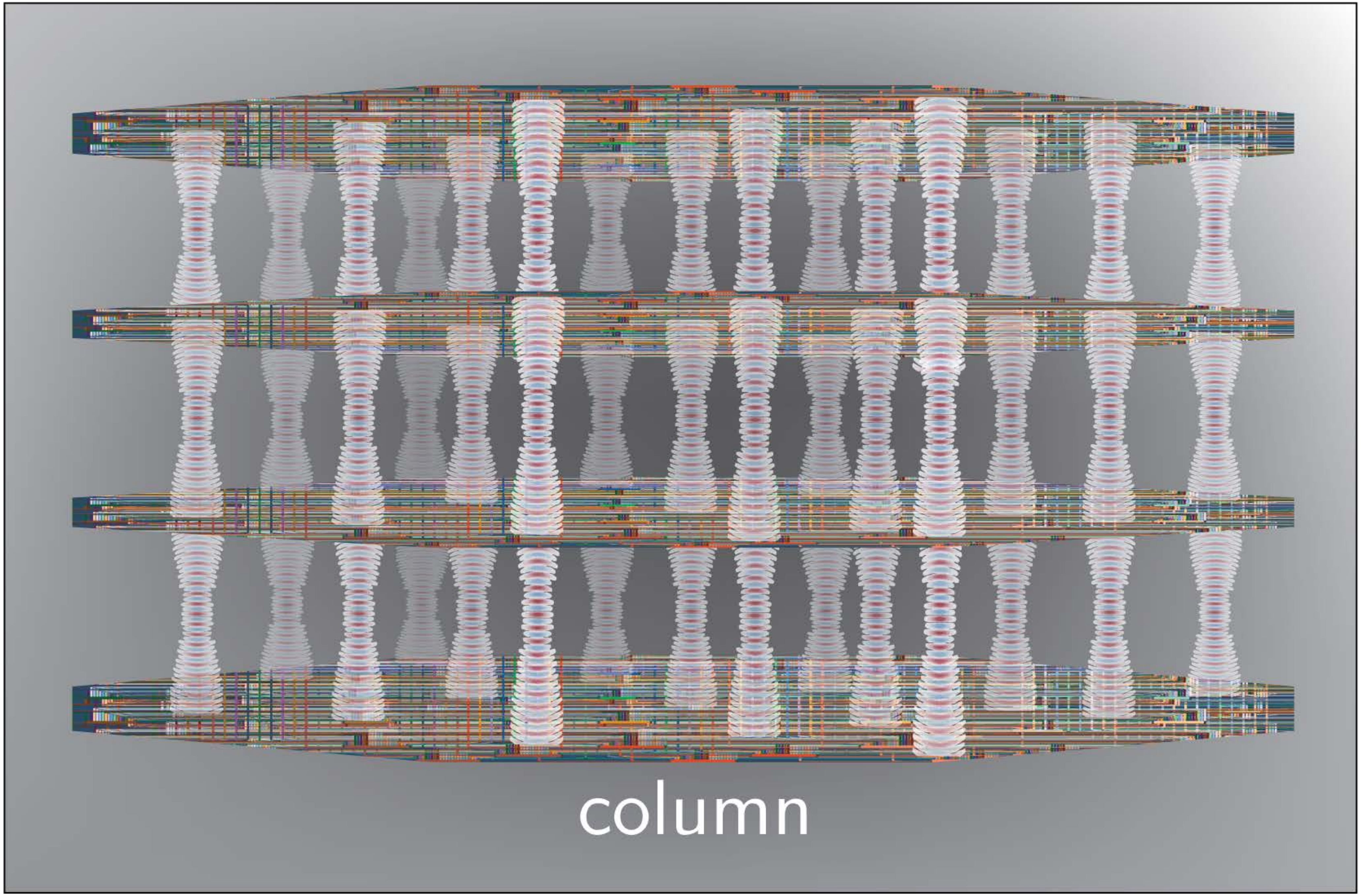


- Fabricated at SUNY Poly by Pops Papa Rao and team
- Measured at NIST by our team

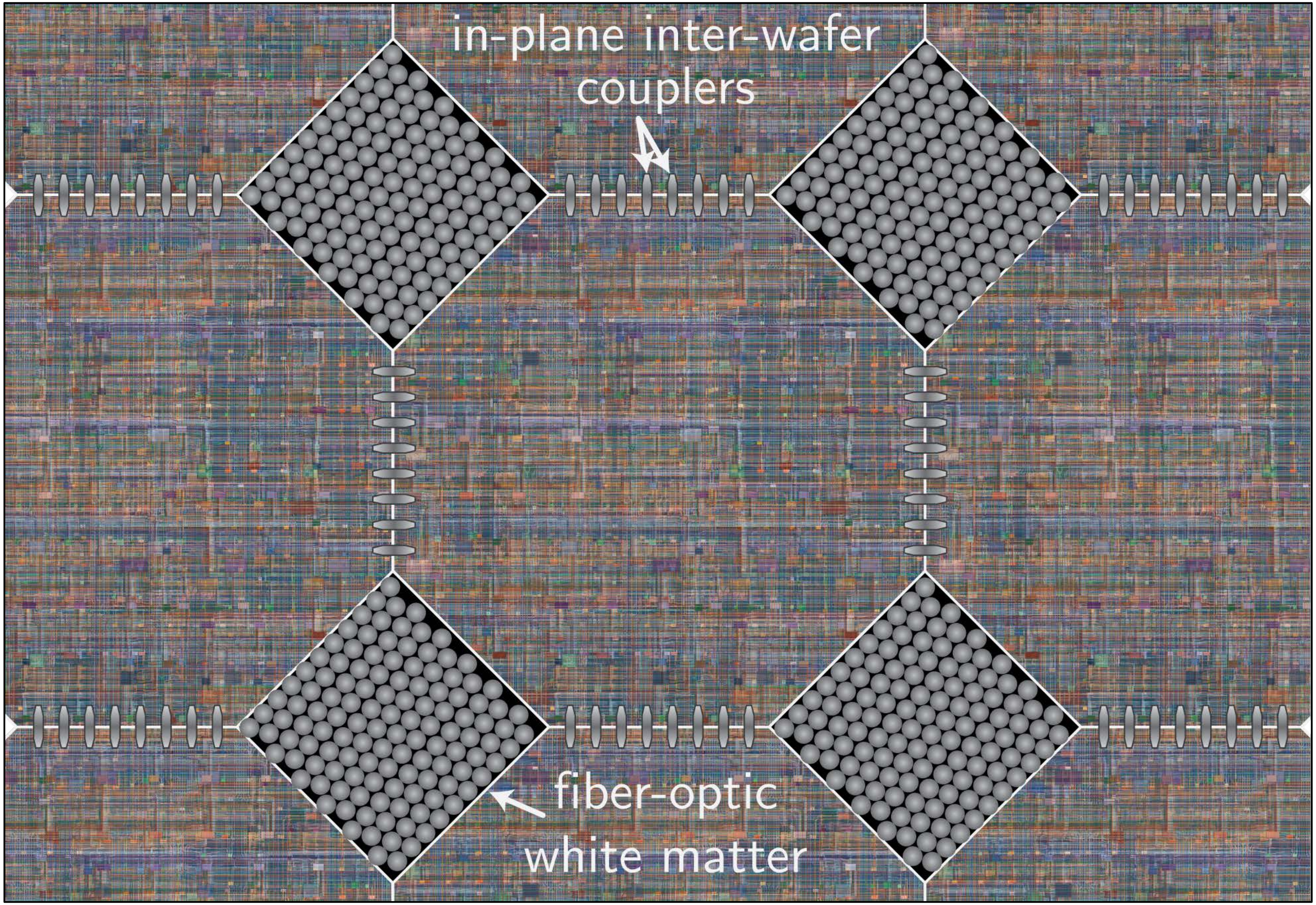
Wafer-scale modules



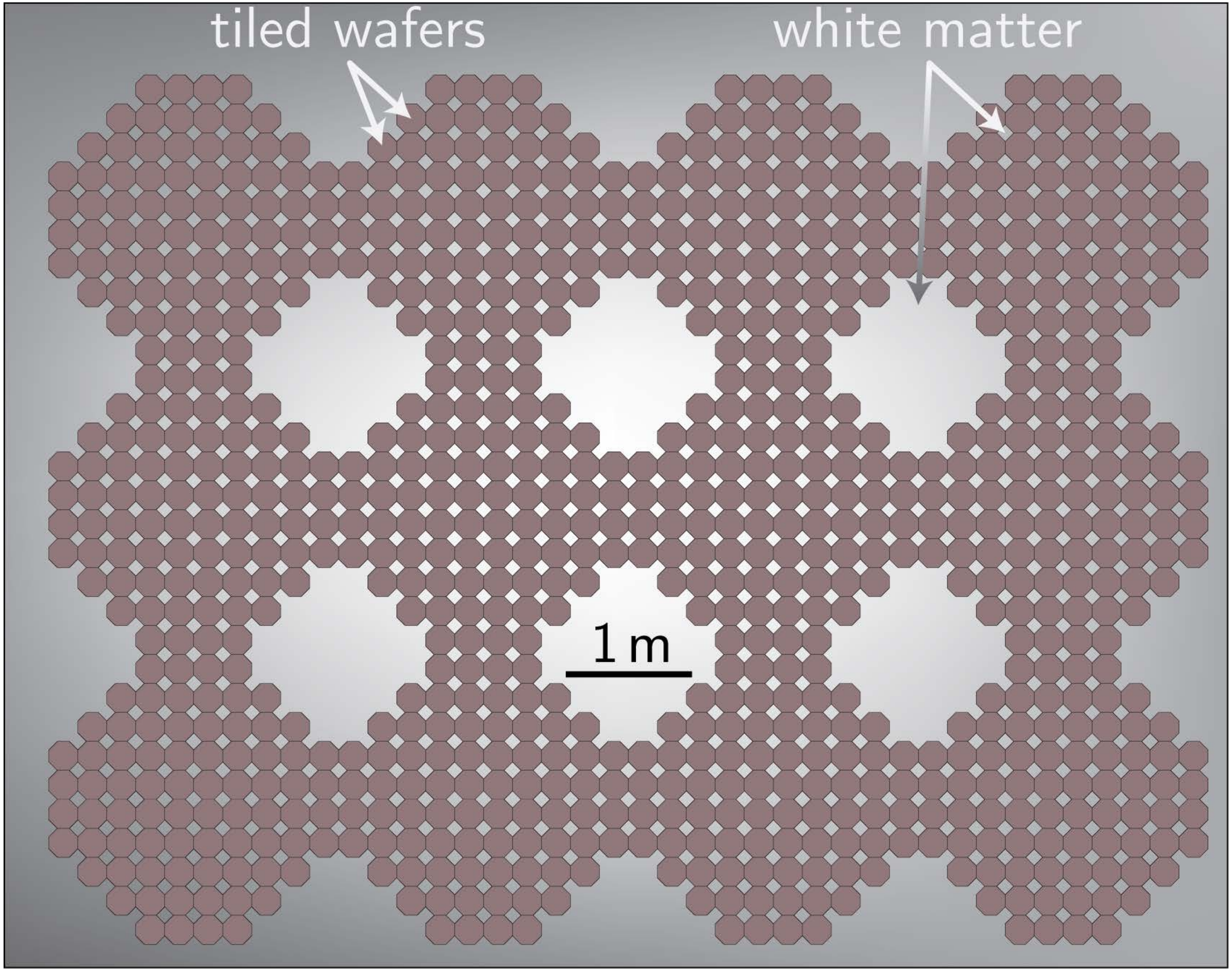
Free-space
inter-wafer
interconnects



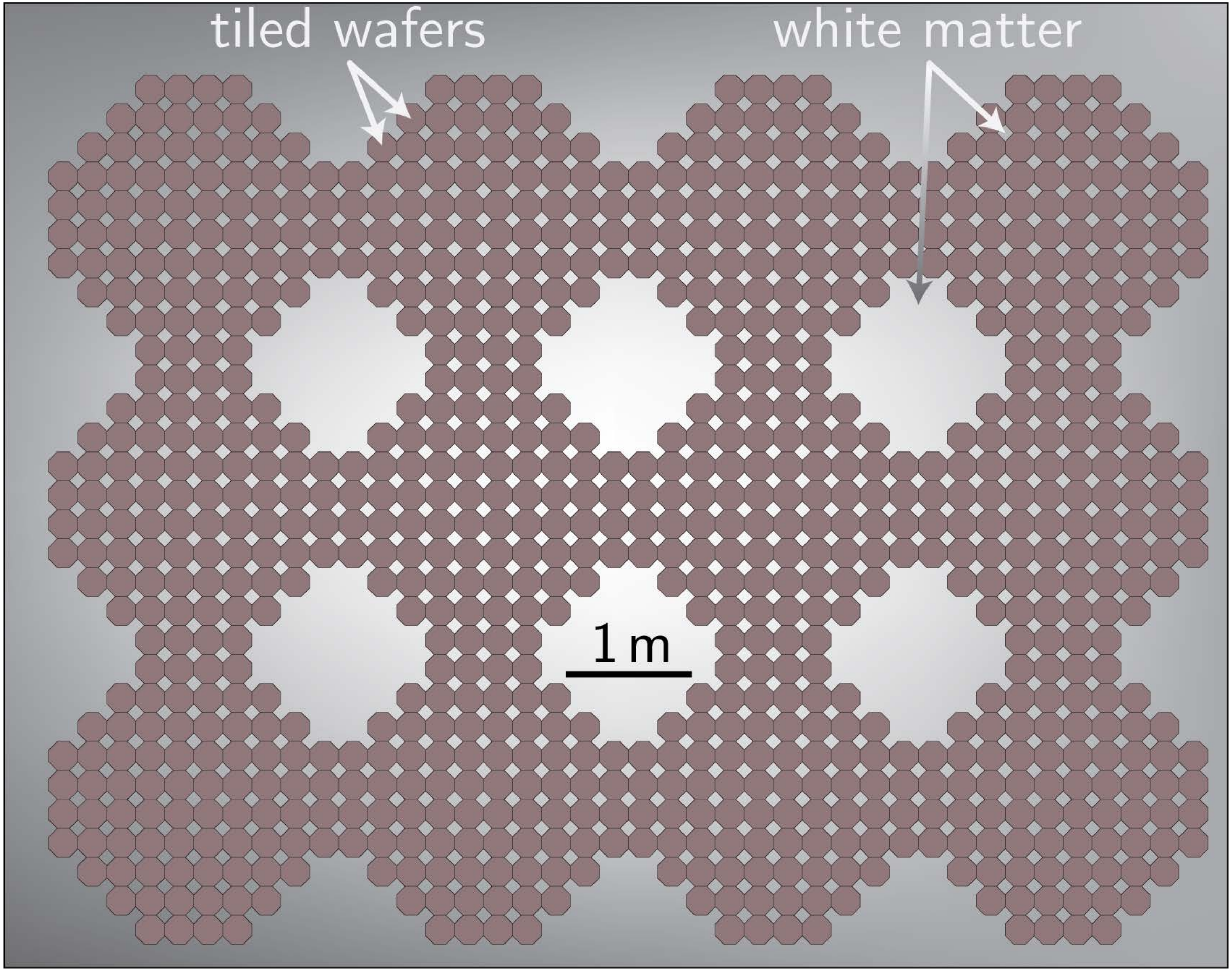
Multi-wafer modules



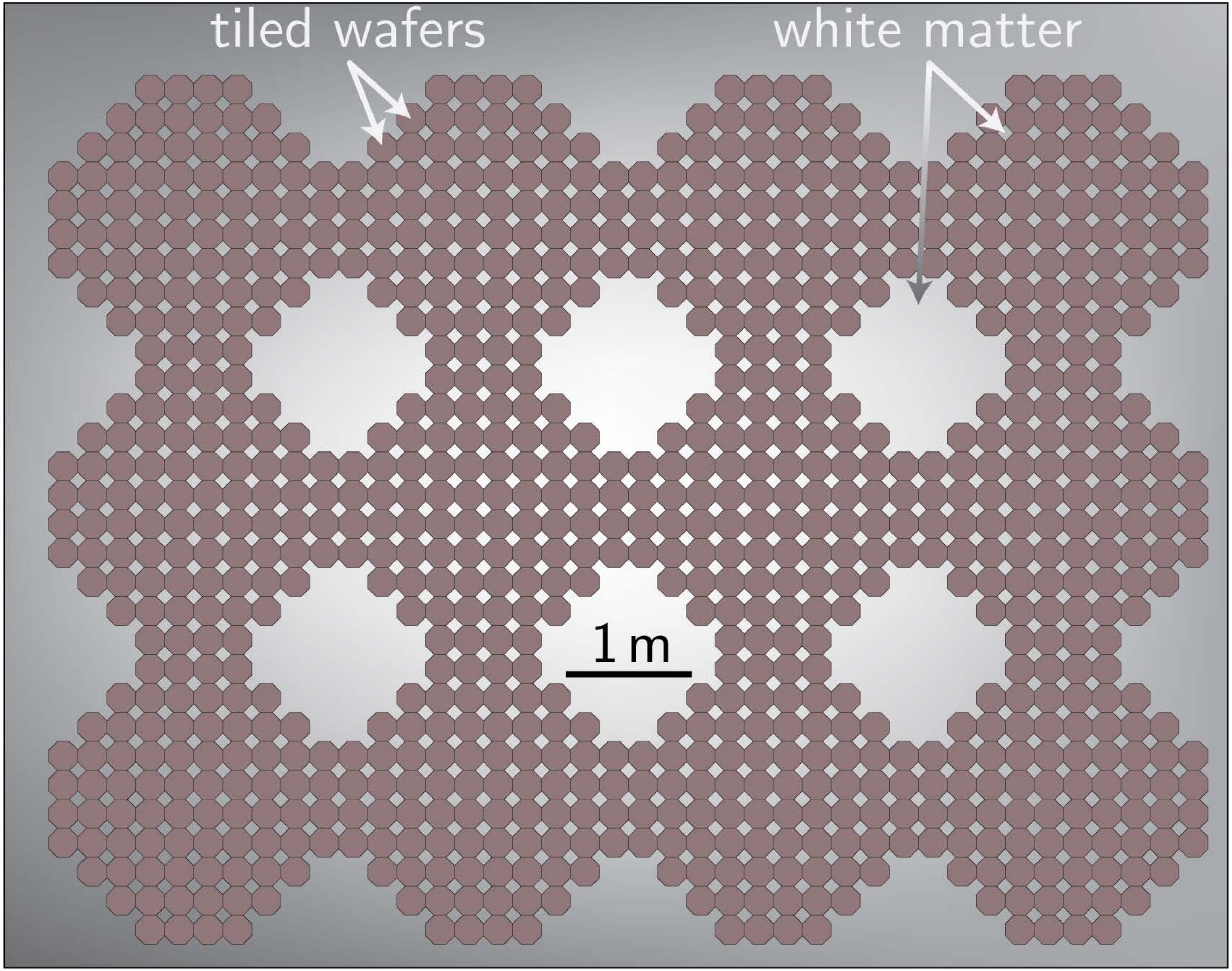
Fractal repetition



Brain-scale systems?

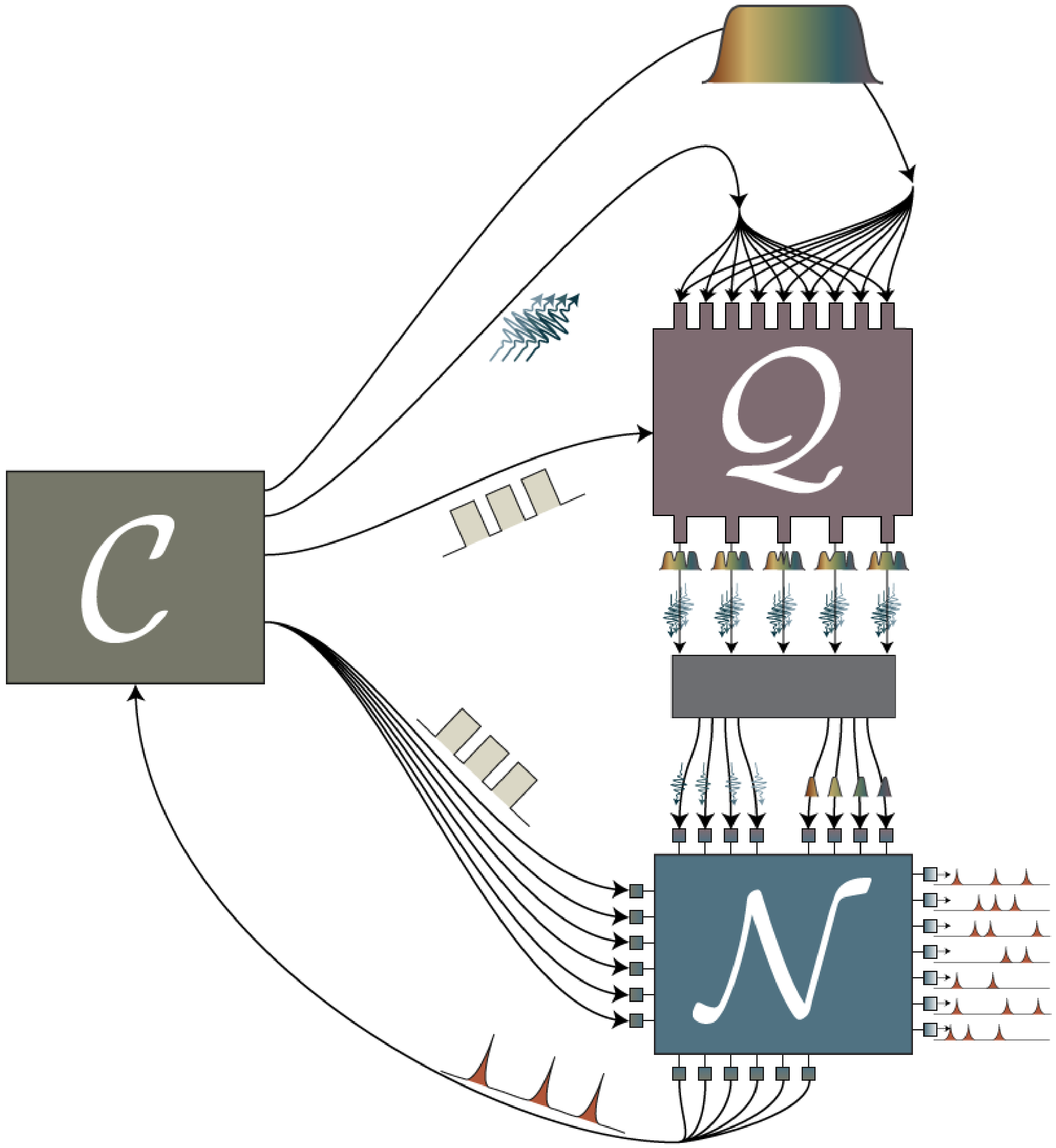


2-m cube



Quantum-neural hybrid systems

Quantum systems:	Neural systems:
• Inherently probabilistic	• Sample probability distributions
• Quantum computing statistical	• Perform Bayesian inference
• Entanglement fragile	• Spiking information robust
• Difficult to scale	• Highly scalable



What can a neural system know about a quantum system?