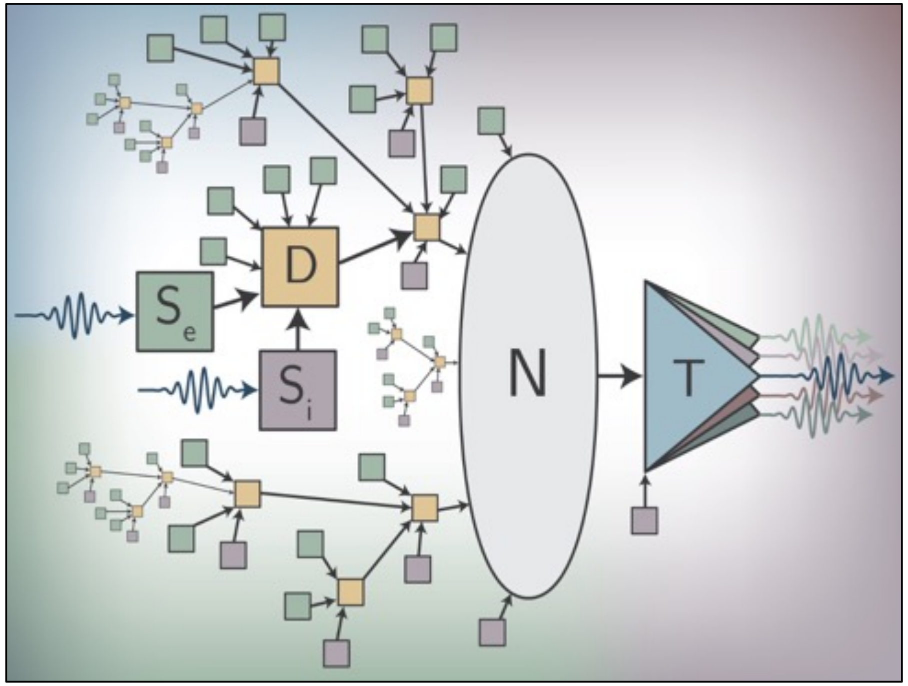
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 3-KN-1 given at ISEC, 28 July-1 August 2019, Riverside, CA, USA.

"Super" Neuromorphic Computing with Photonic and Superconducting Devices

Superconductors, light, and the "age of of cognition"



Jeff Chiles, Sonia Buckley, Adam McCaughan, Alex Tait, Saeed Khan, Bryce Primavera, Rich Mirin, Sae Woo Nam, Jeff Shainline
NIST, Physical Measurement Laboratory

Future of Computing

- High Performance Computing. (HPC)
  - Traditional model of computation
- Quantum Computing (QC)
  - Can outperform HPC in some tasks
- Neuromorphic Computing (NC)
  - "Neuroscience" inspired architecture
  - Dedicated Hardware

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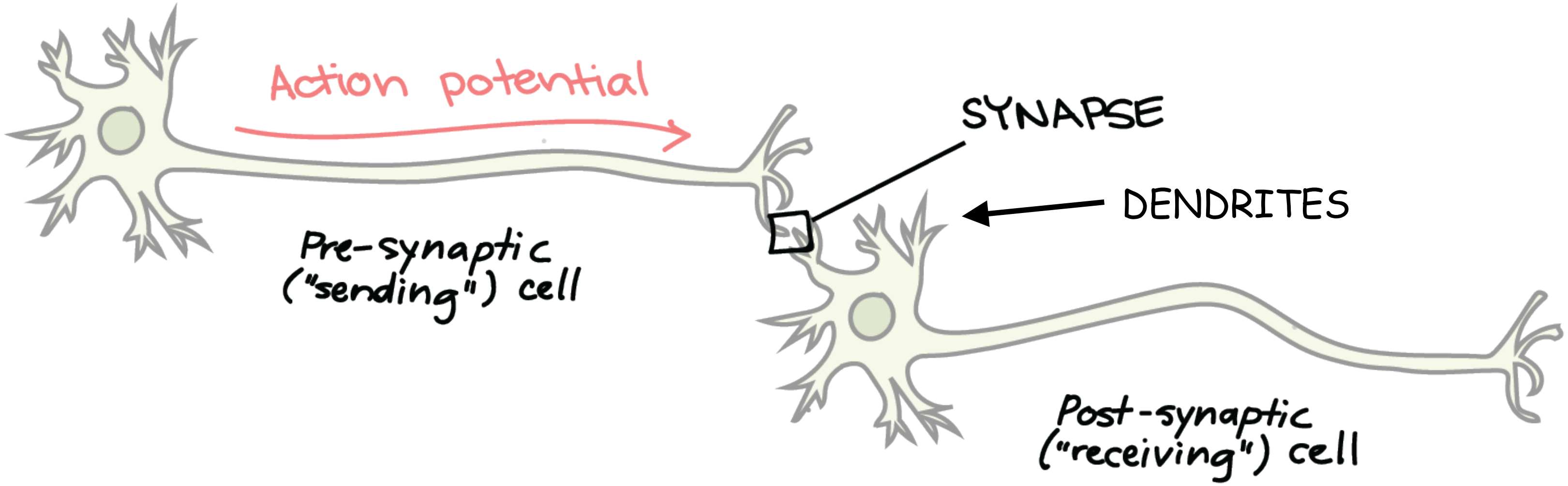
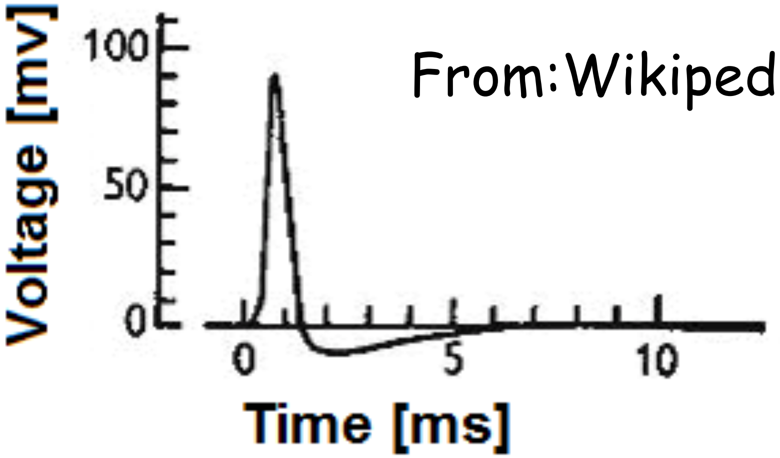
Structure of a Biological Neuron





From: Wikipedia

https://www.khanacademy.org/science/biology/human-biology/neuron-nervous-system/a/the-synapse

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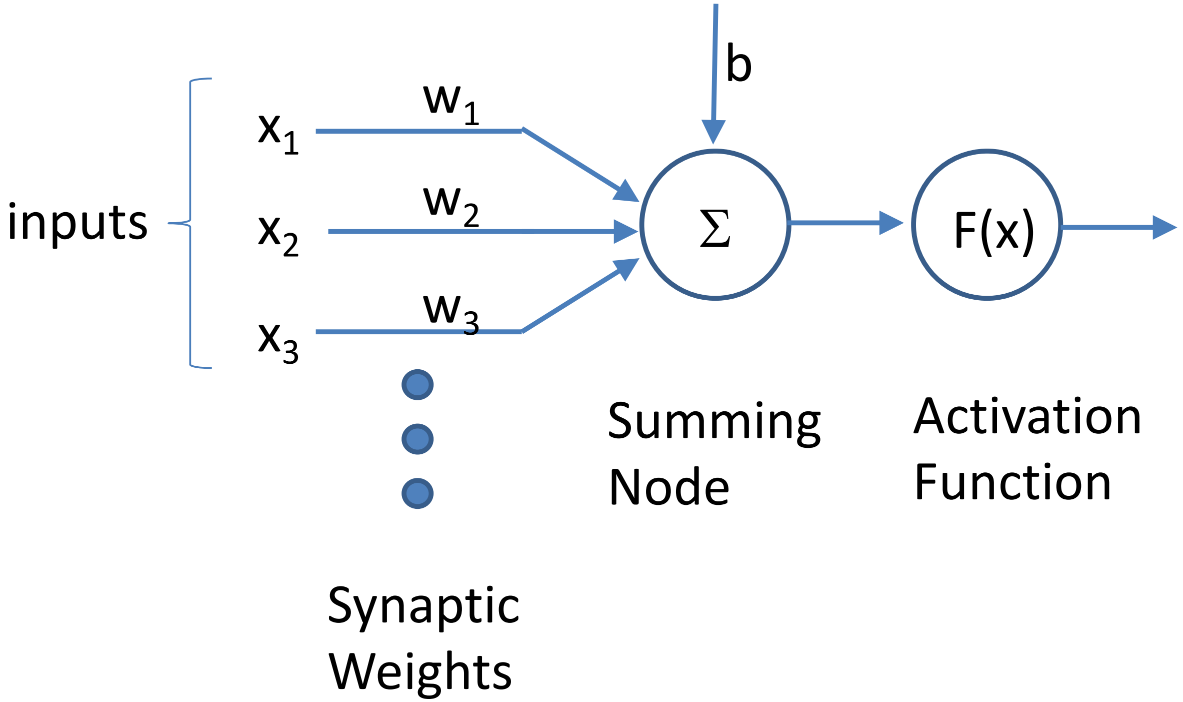
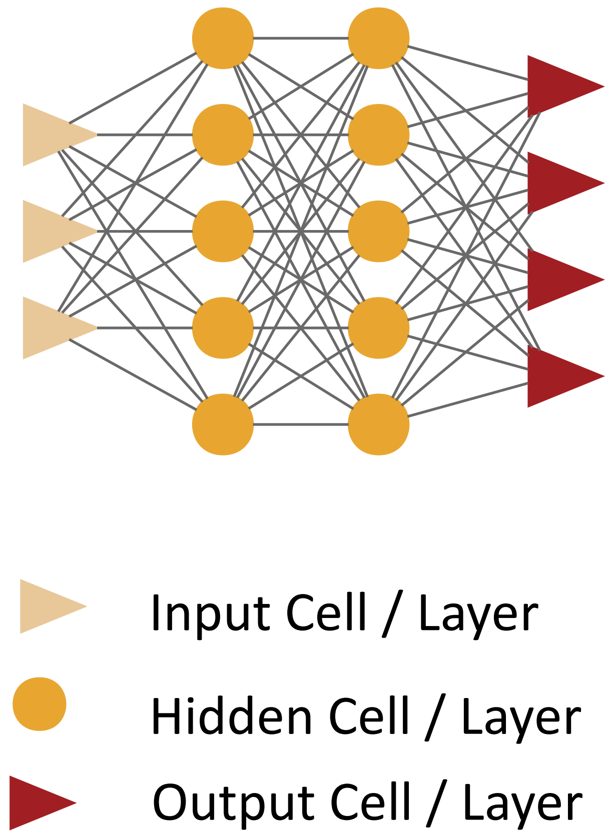
Fast Introduction to Neural Networks

Artificial Neuron



Network of Neurons



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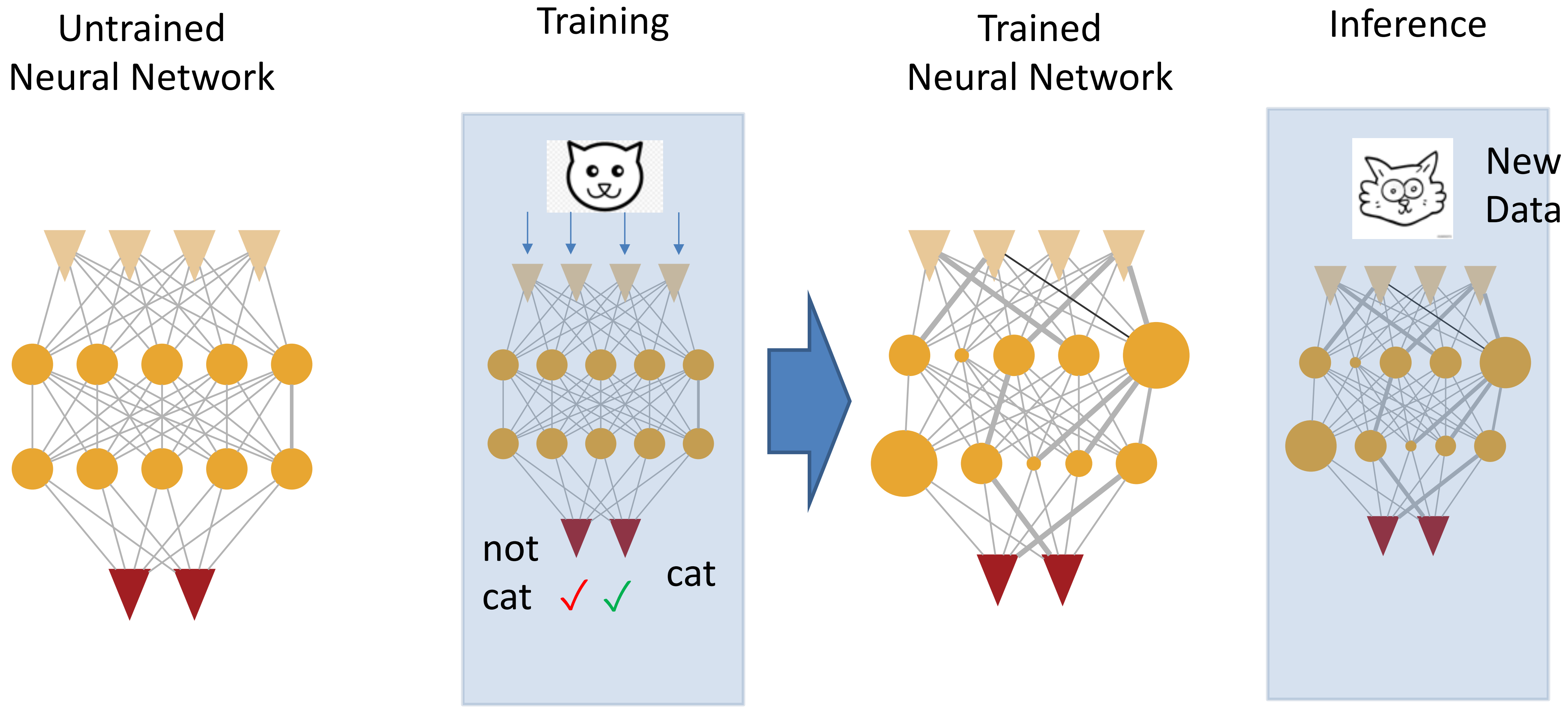
Supervised Learning

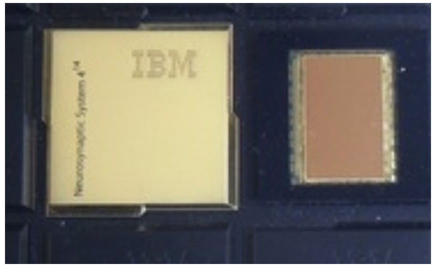


Machine learning hardware

- Today, there is large demand to perform "neural network" operations
  - Image Classification
  - Speech Recognition
  - Natural Language Processing: "translation"

YouTube amazon Google Uber

- Dedicated Neuromorphic Hardware



TrueNorth, IBM

see Merolla et al., Science, 2011.

IBM intel Human Brain Project

- Other Technology platforms Neuromorphic have attracted venture interest

SPARK GIGAFUND Bill Gates

2nd and 3rd Generation Neural Networks

2nd Generation: "Proven"

- Limited Biological "inspiration"
- Matrix-vector multiplication
- Seeking weight matrix
- Trained by supervisory system
- Limited History
- Task specific

3rd Generation: "Less Proven"

- More Biologically inspired
- Information in dynamical state
- Spiking neurons communicate in rate and timing
- Potential for learning without supervision
- Information integrated across space and time
- General cognitive systems

Question: Why do we need Generation 3?
Answer: Energy Efficiency and Size

Consumption	CO_2e (lbs)
Air travel, 1 passenger, NY↔SF	1984
Human life, avg, 1 year	11,023
American life, avg, 1 year	36,156
Car, avg incl. fuel, 1 lifetime	126,000

Training one model (GPU)	
NLP pipeline (parsing, SRL)	39
w/ tuning & experimentation	78,468
Transformer (big)	192
w/ neural architecture search	626,155

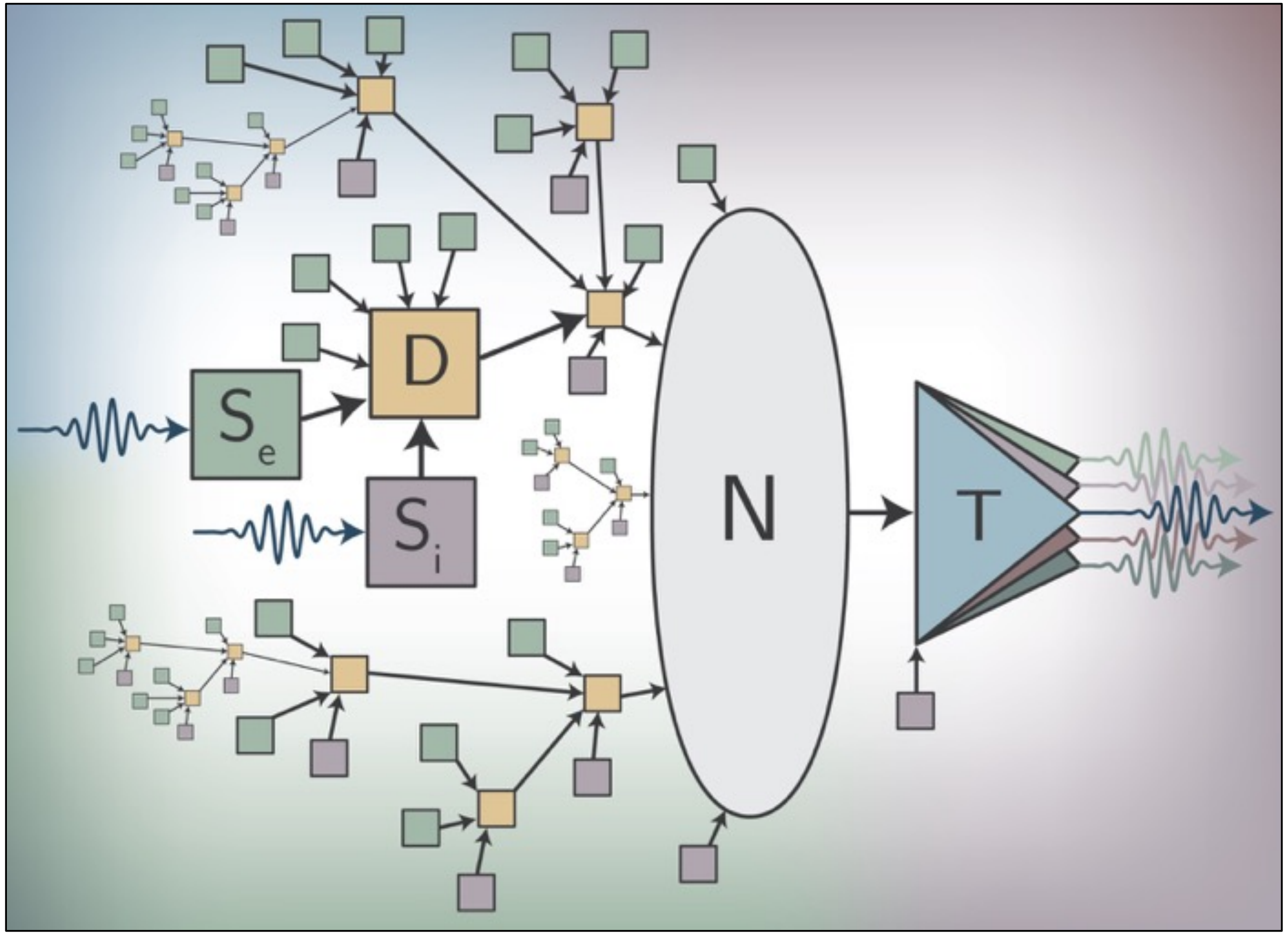
https://arxiv.org/abs/1906.02243v1

- "How do you make the largest scale artificial neural network?"
  - Human Brain:
    - 100 billion neurons
    - 1 neuron fans out to 10,000 neurons
- What are the fundamental limits?
- How do you evaluate the performance?
- How do physical characteristics of the devices relate to the performance of the neuromorphic computer?

Spiking Neural Networks / Dedicated Hardware

- Biologically Inspired
  - Spiking Signals, Energy Efficient
  - Rate and Time encoding
- Differentiated local processing
- Information integration across:
  - Space (network structure)
  - Time (dynamics)
  - Experience (plasticity)

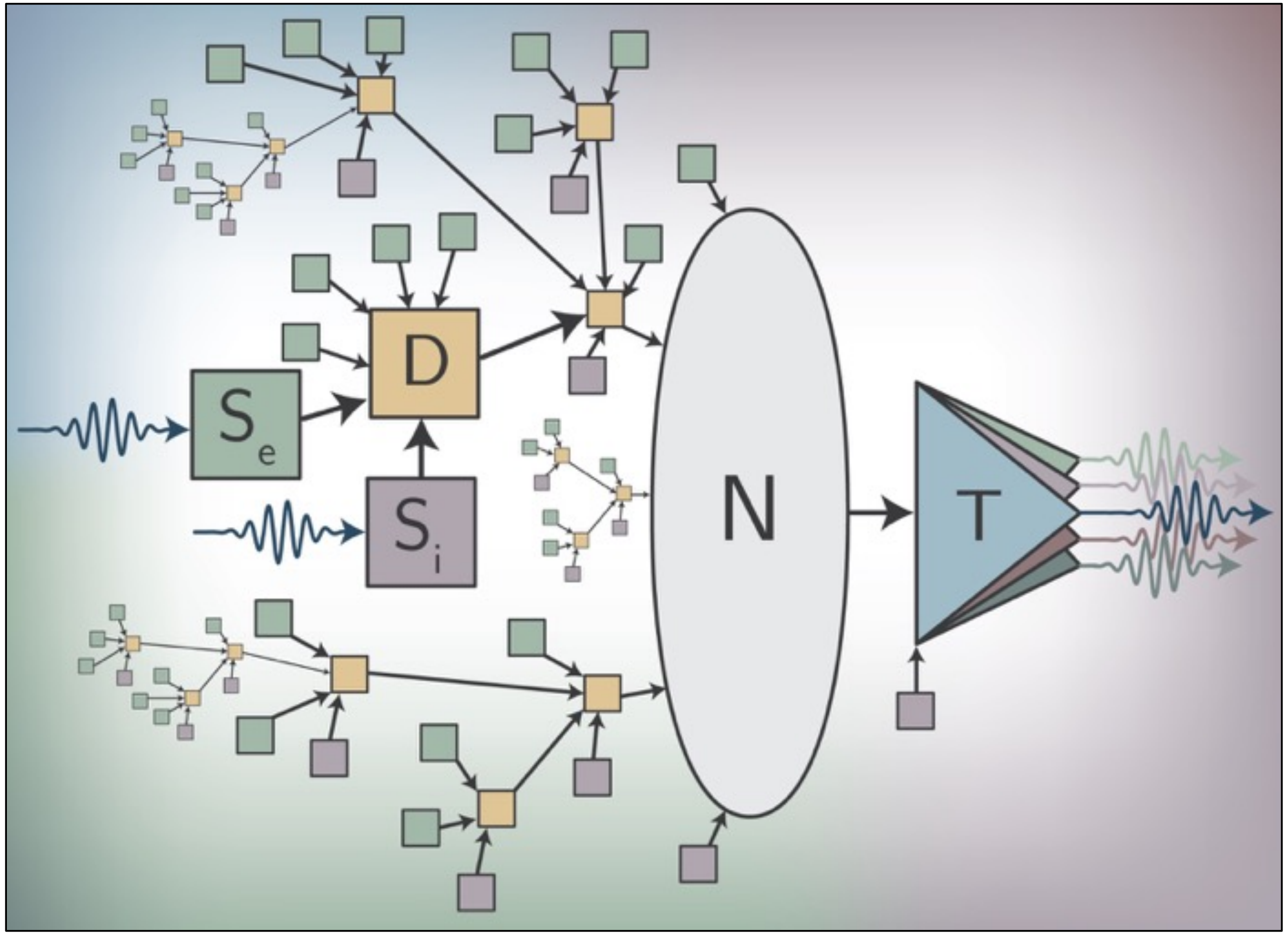
Can we get to a size scale for "Cognitive" Systems?



Fluxonic processing of photonic synapse events

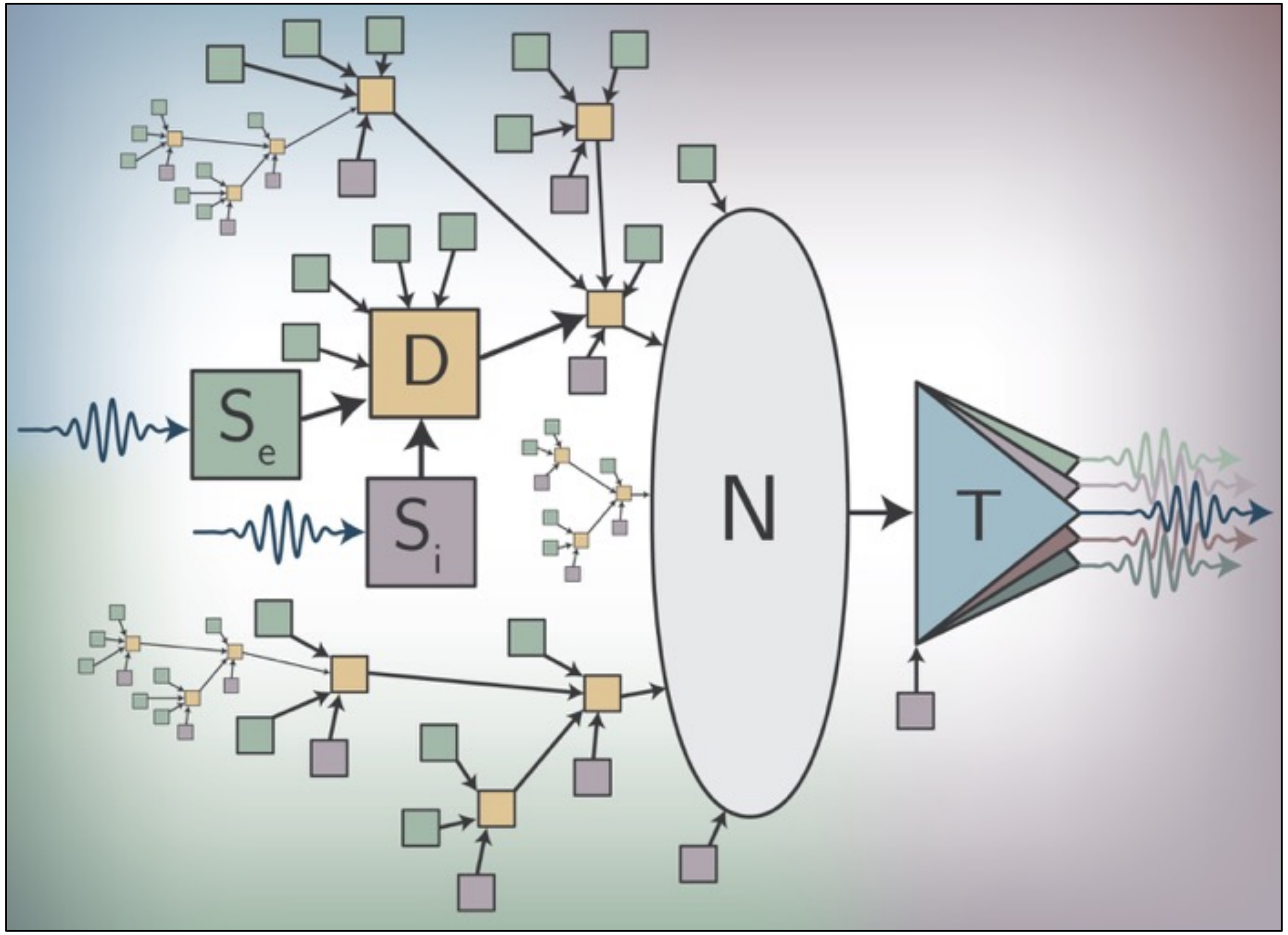
Spiking neural networks

jeffrey.shainline@nist.gov



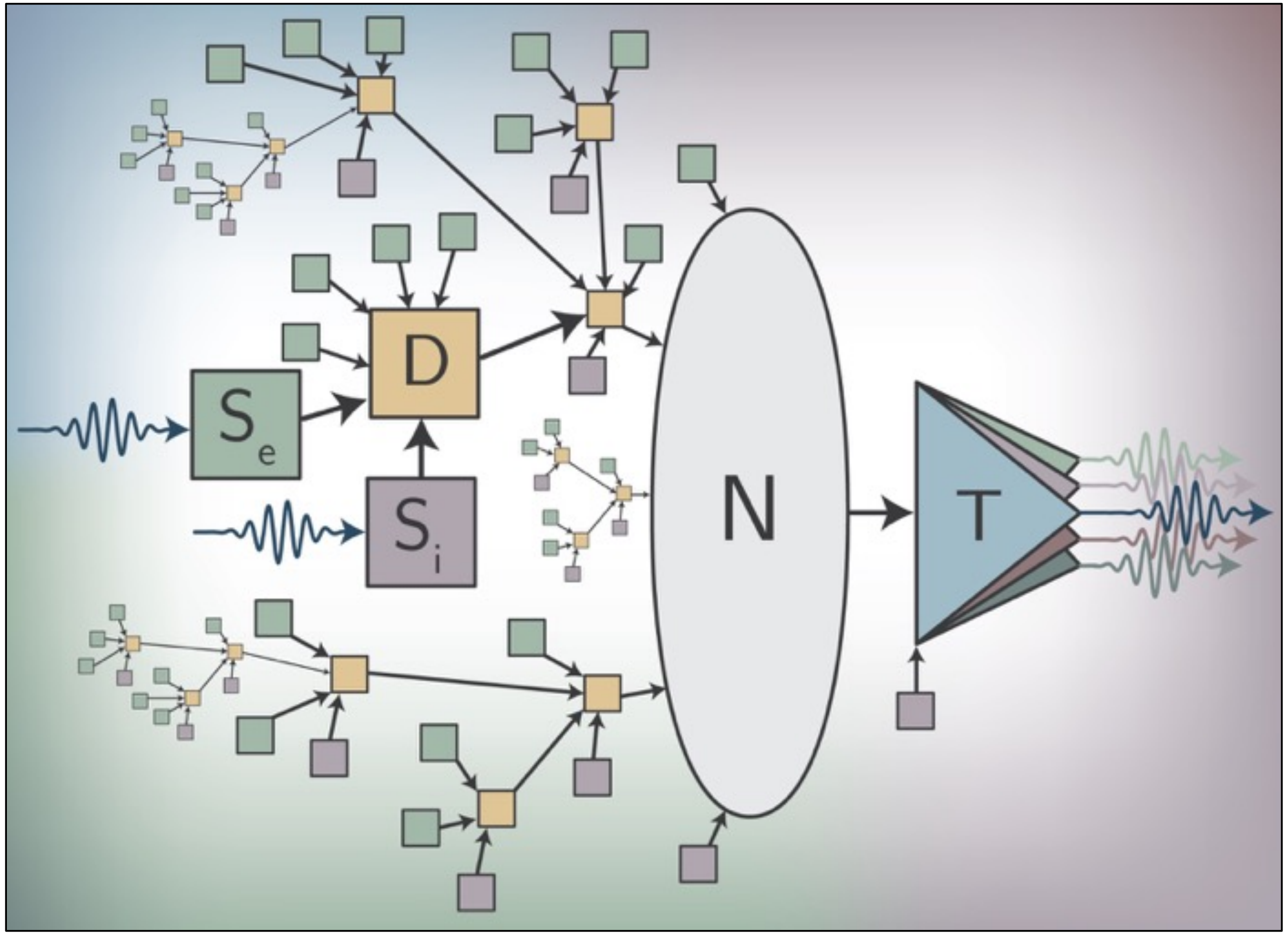
Fluxonic processing of
photonic synapse events

Light for communication



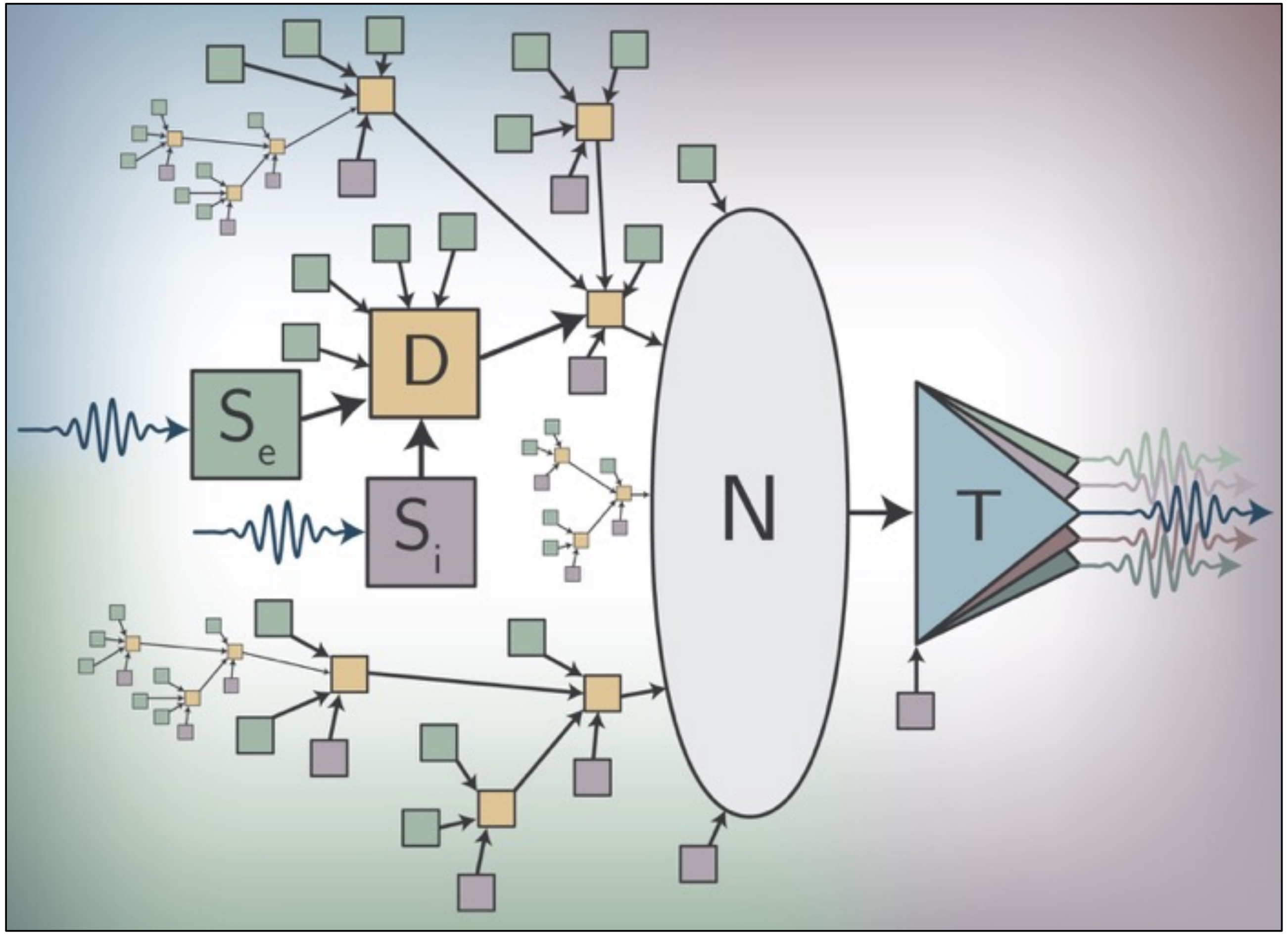
Fluxonic processing of photonic synapse events

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

Device requirements for massive connectivity

Dense local fanout

Long-range connectivity

We seek very large systems

Energy efficiency is paramount

Principal conjecture:

Use light for communication

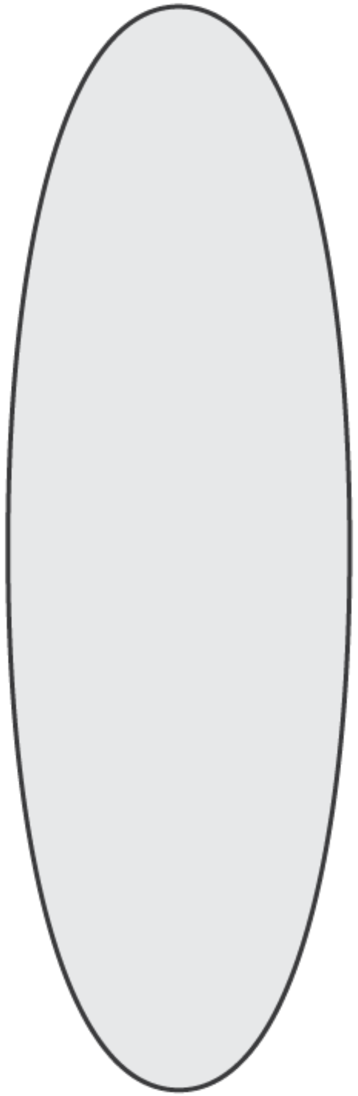
Photons don't have charge or mass

Use single-photons for communication

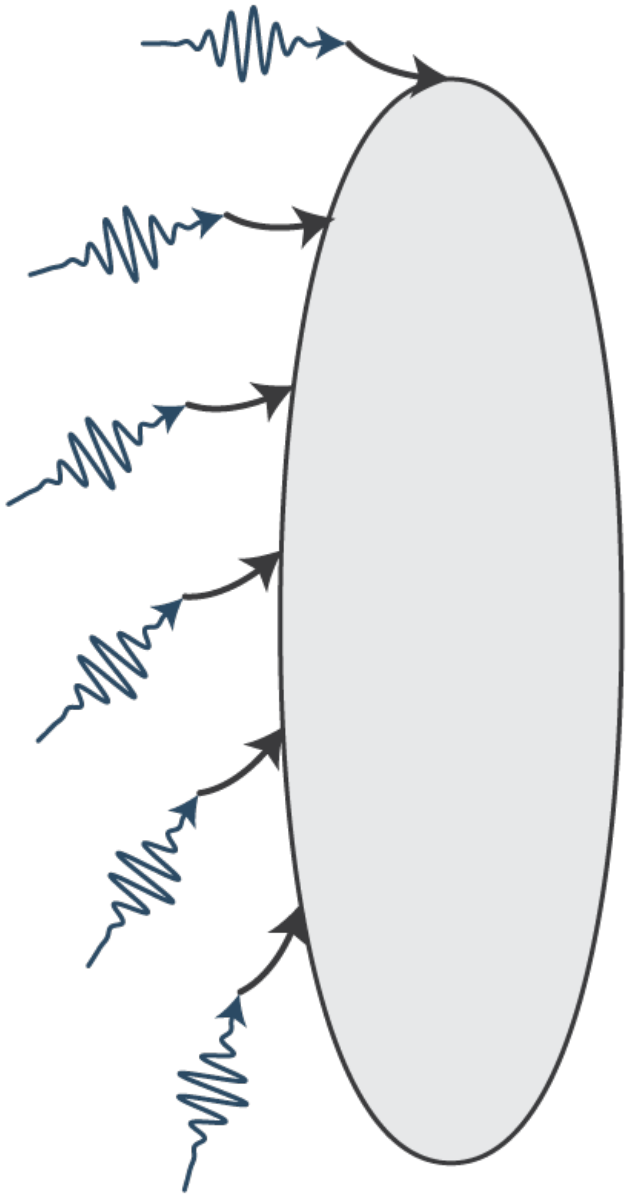
Neurons that signal with single photons

Neurons that signal with single photons

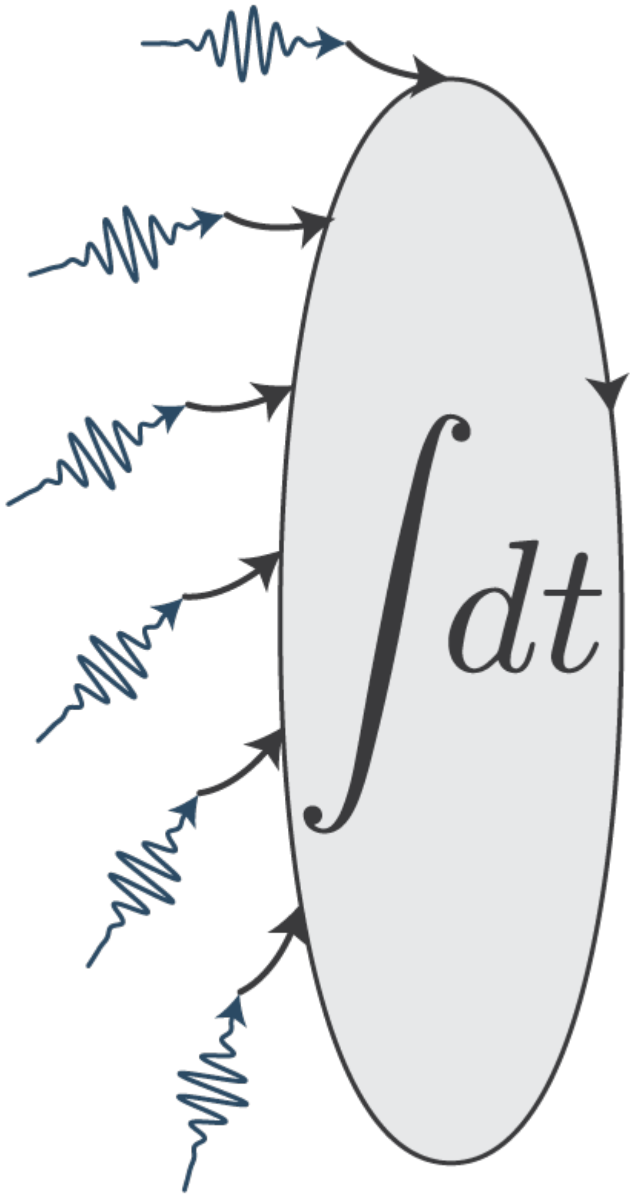
How do they work?



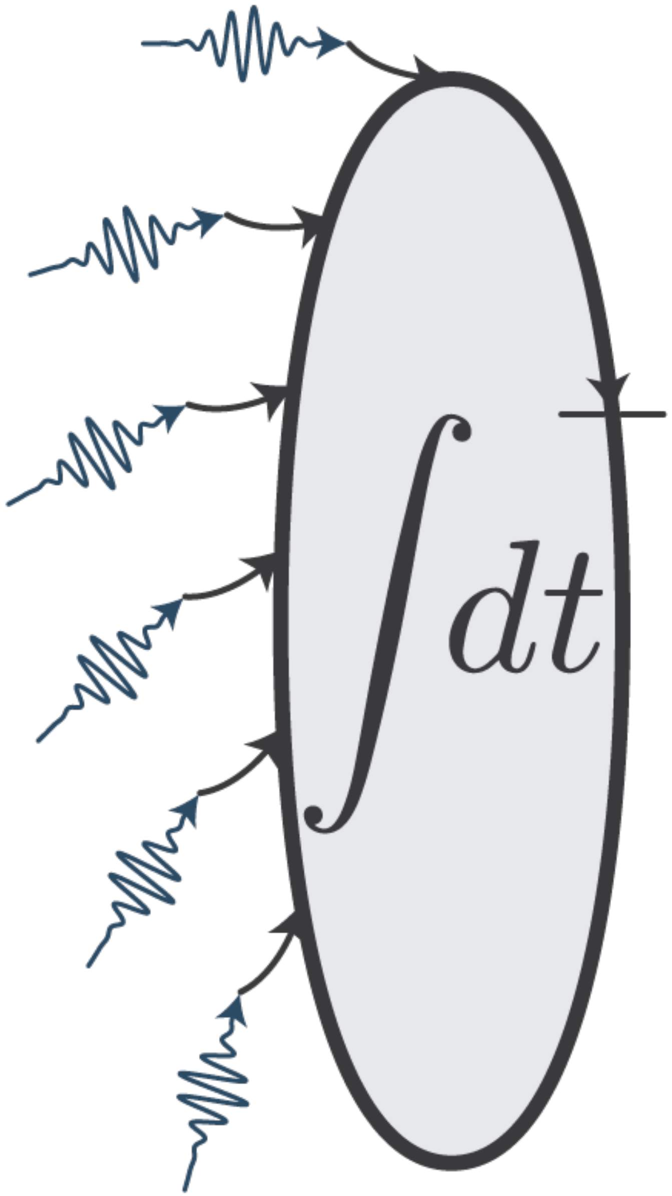
Superconducting loop



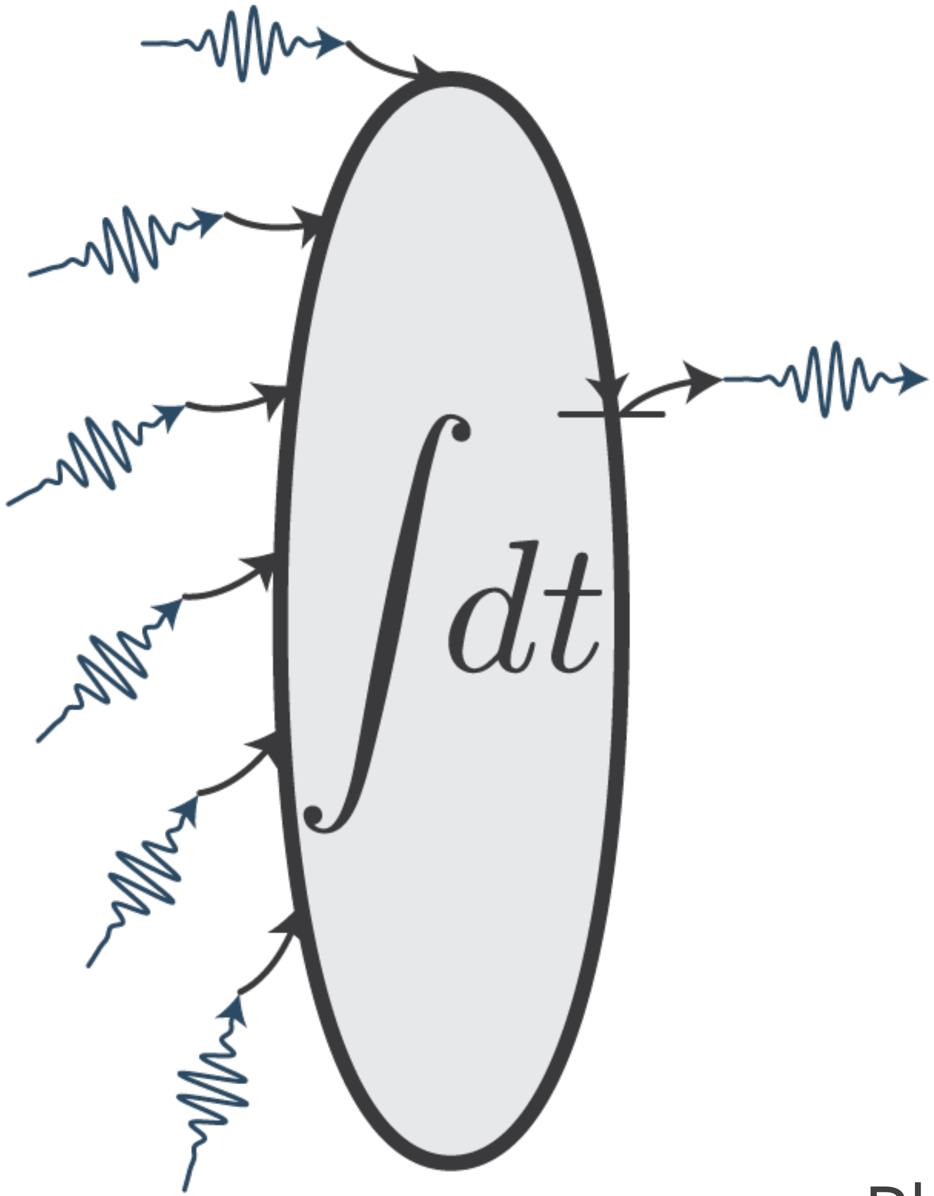
Photons add current



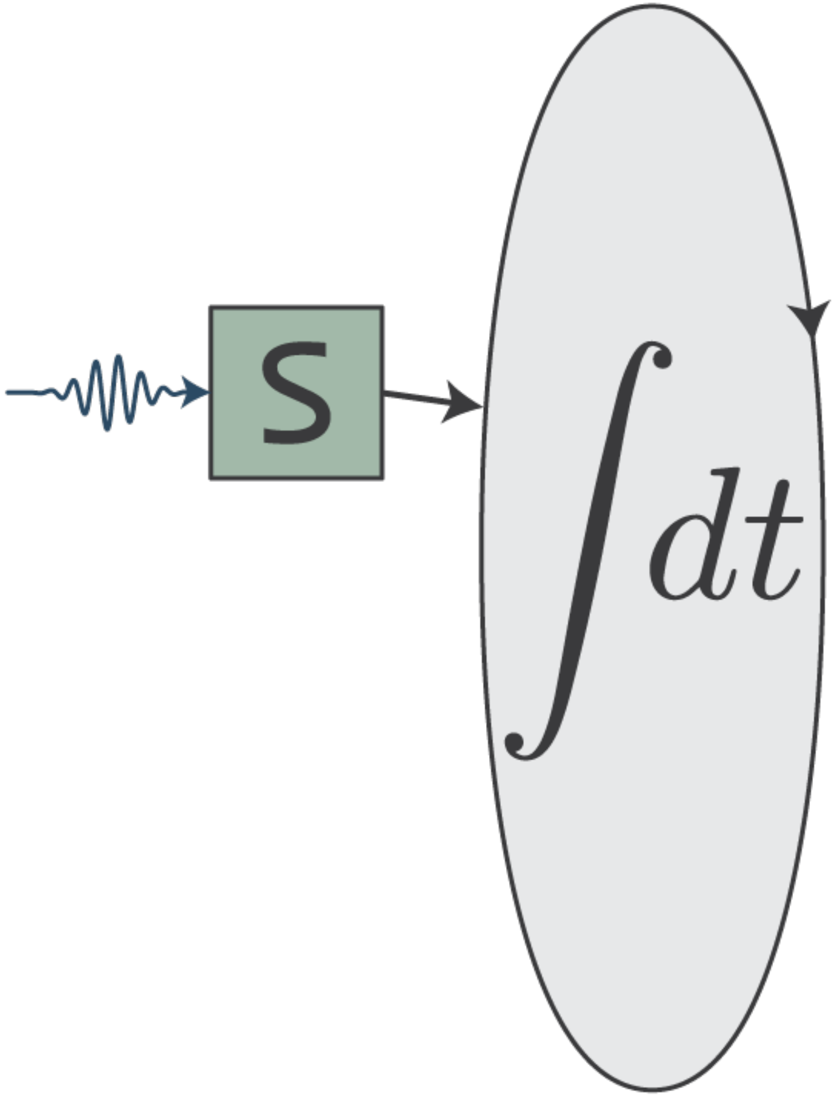
Current gets integrated



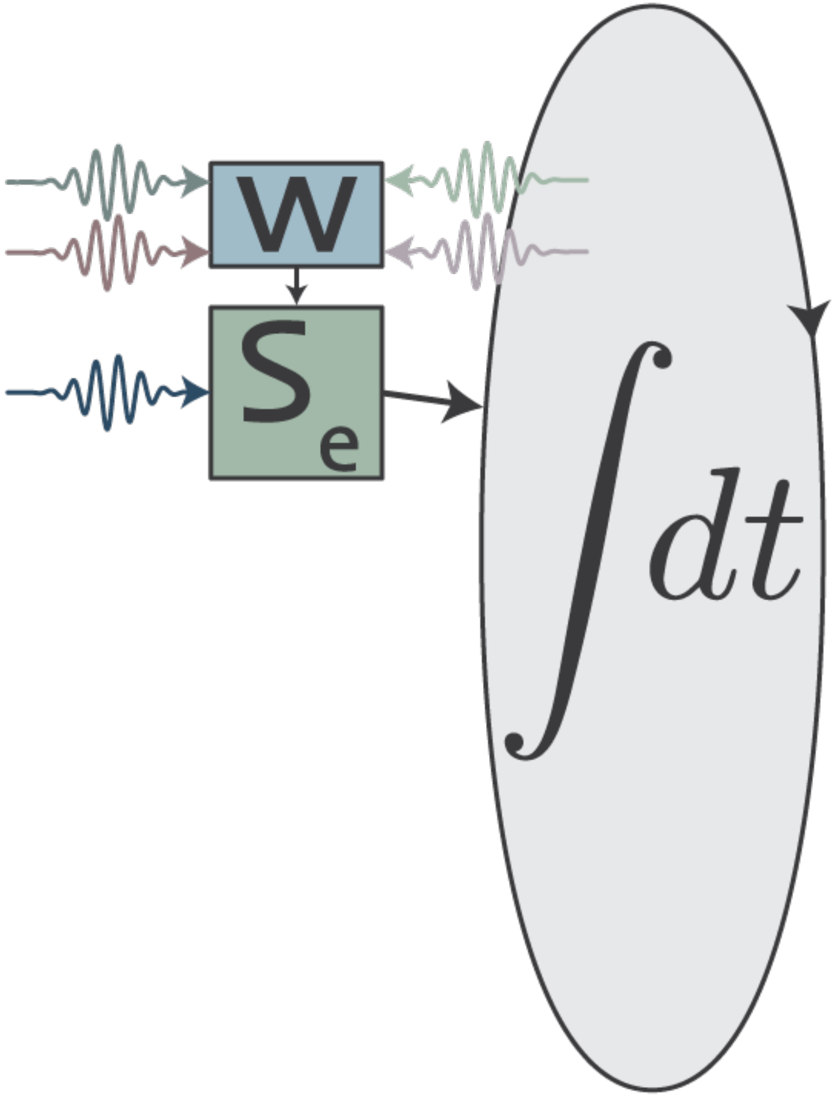
Current threshold



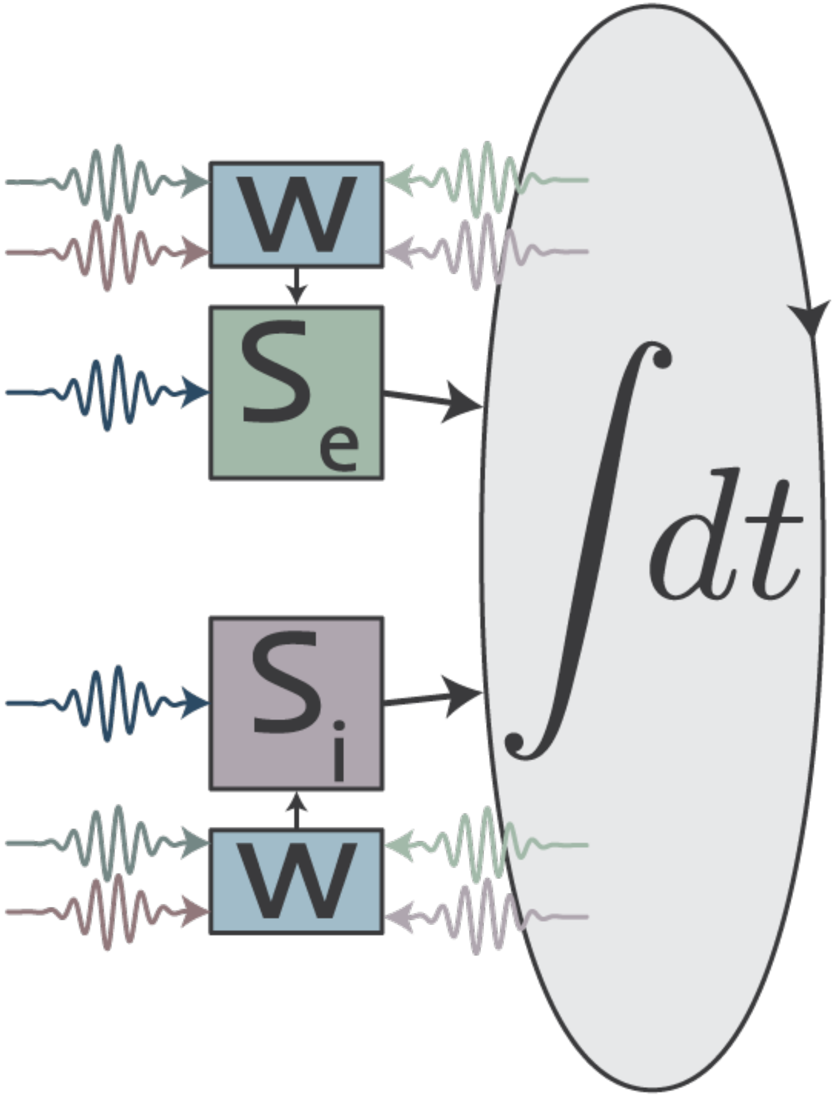
Photons produced



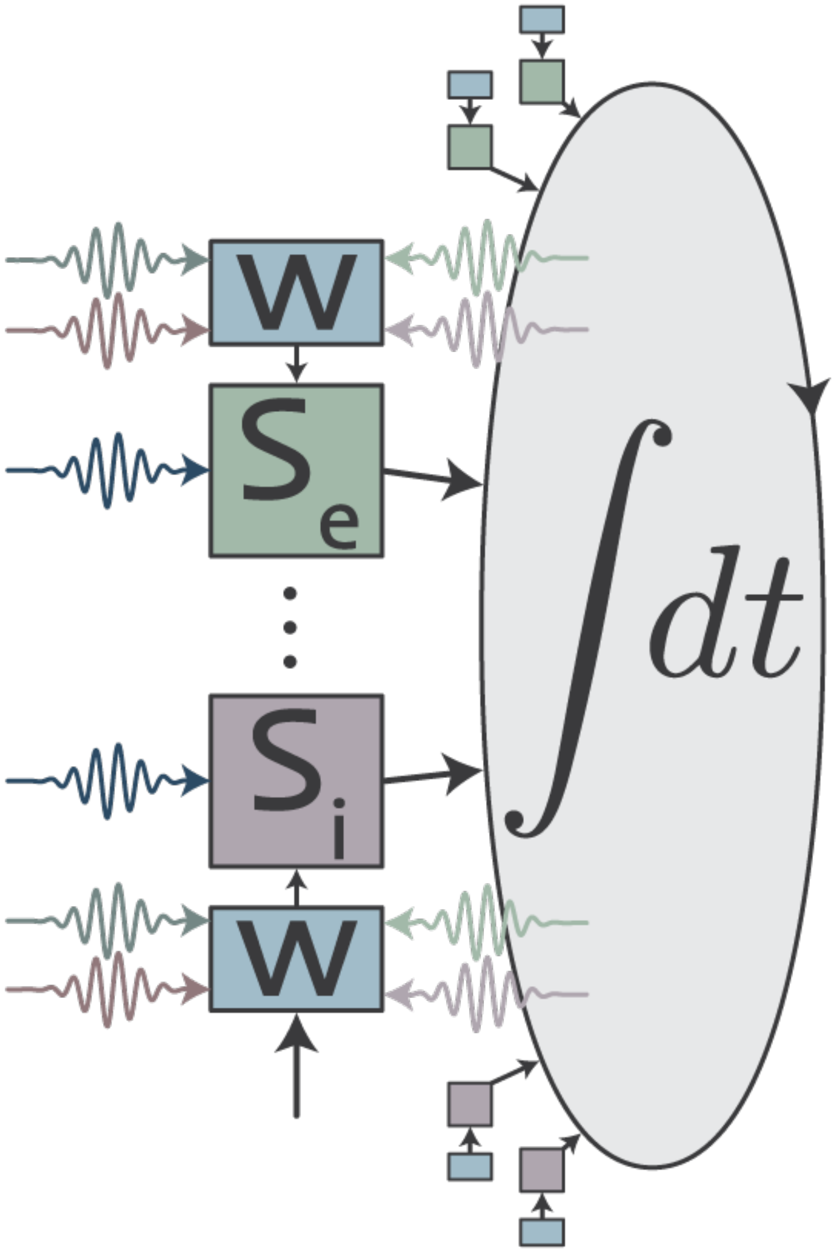
Synapse transduces



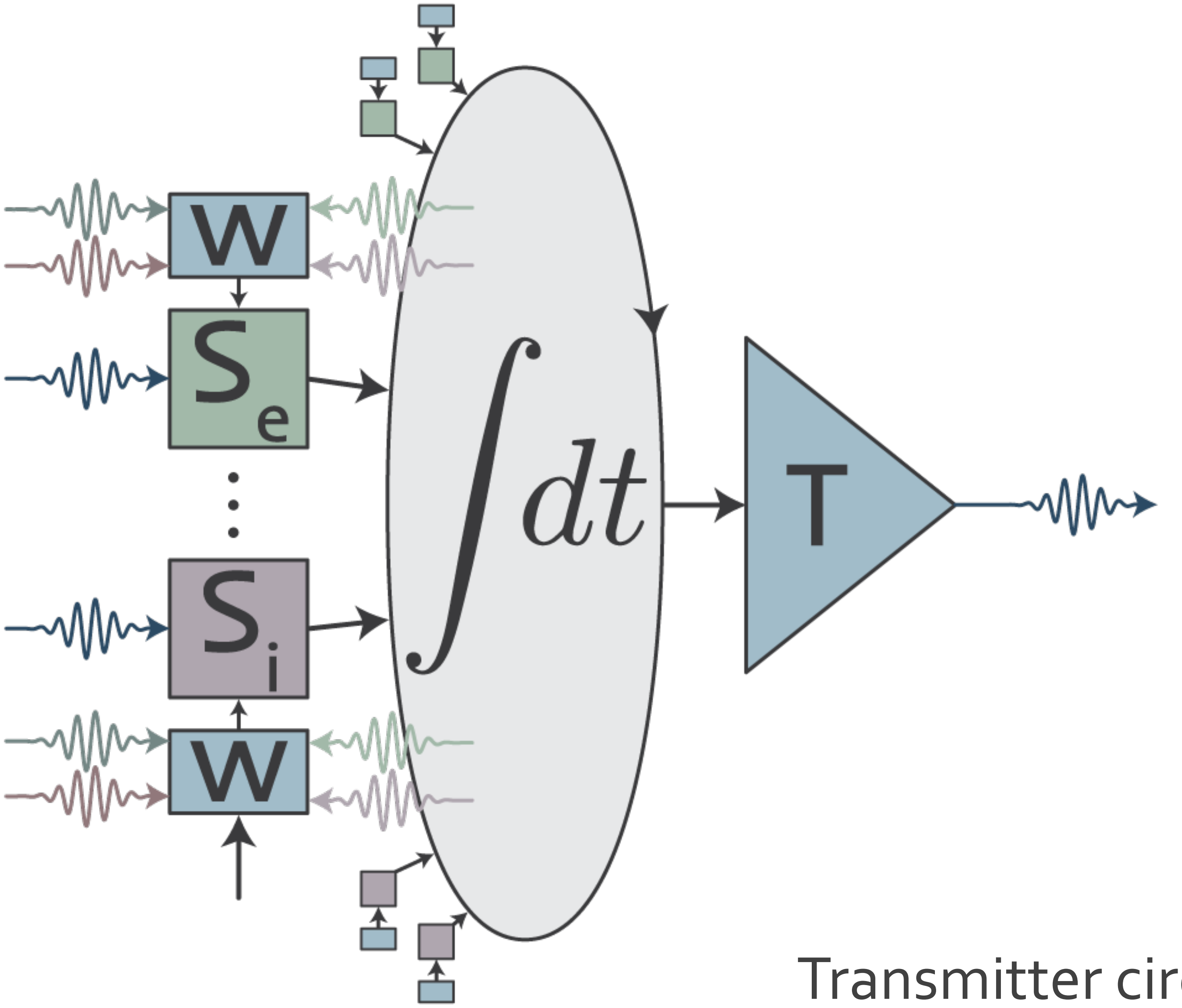
Photons update weight



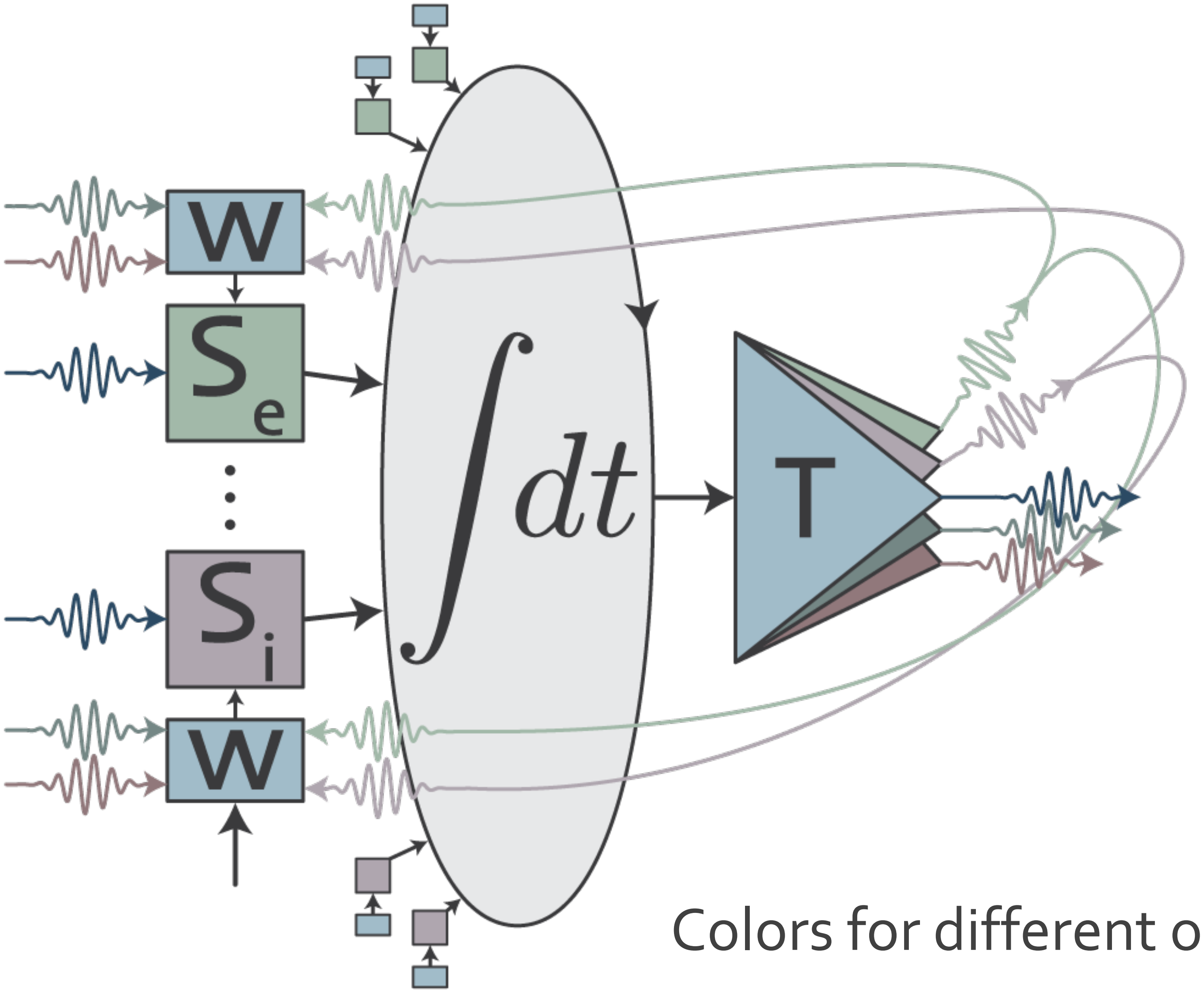
Inhibitory synapses



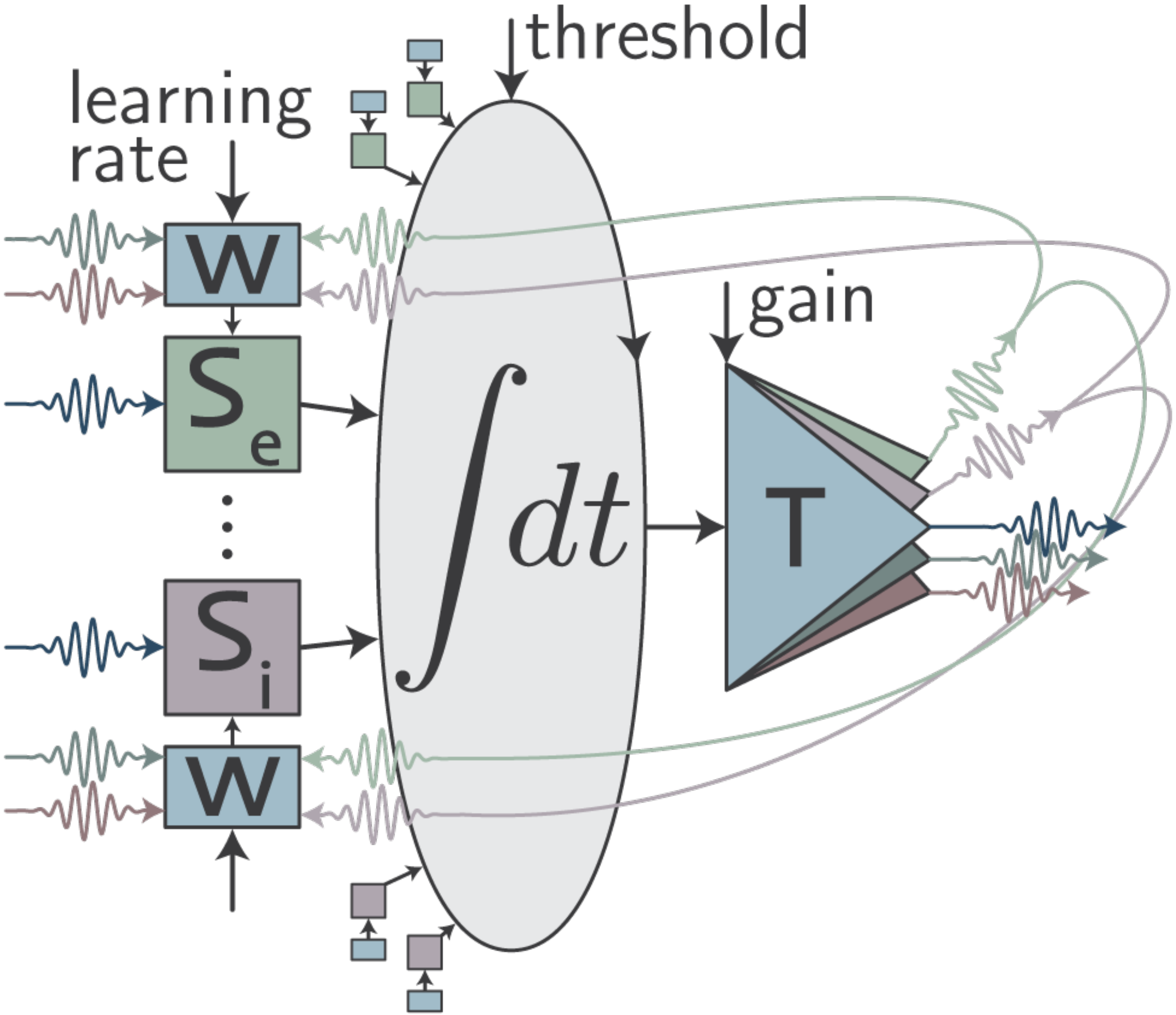
Many synapses



Transmitter circuits

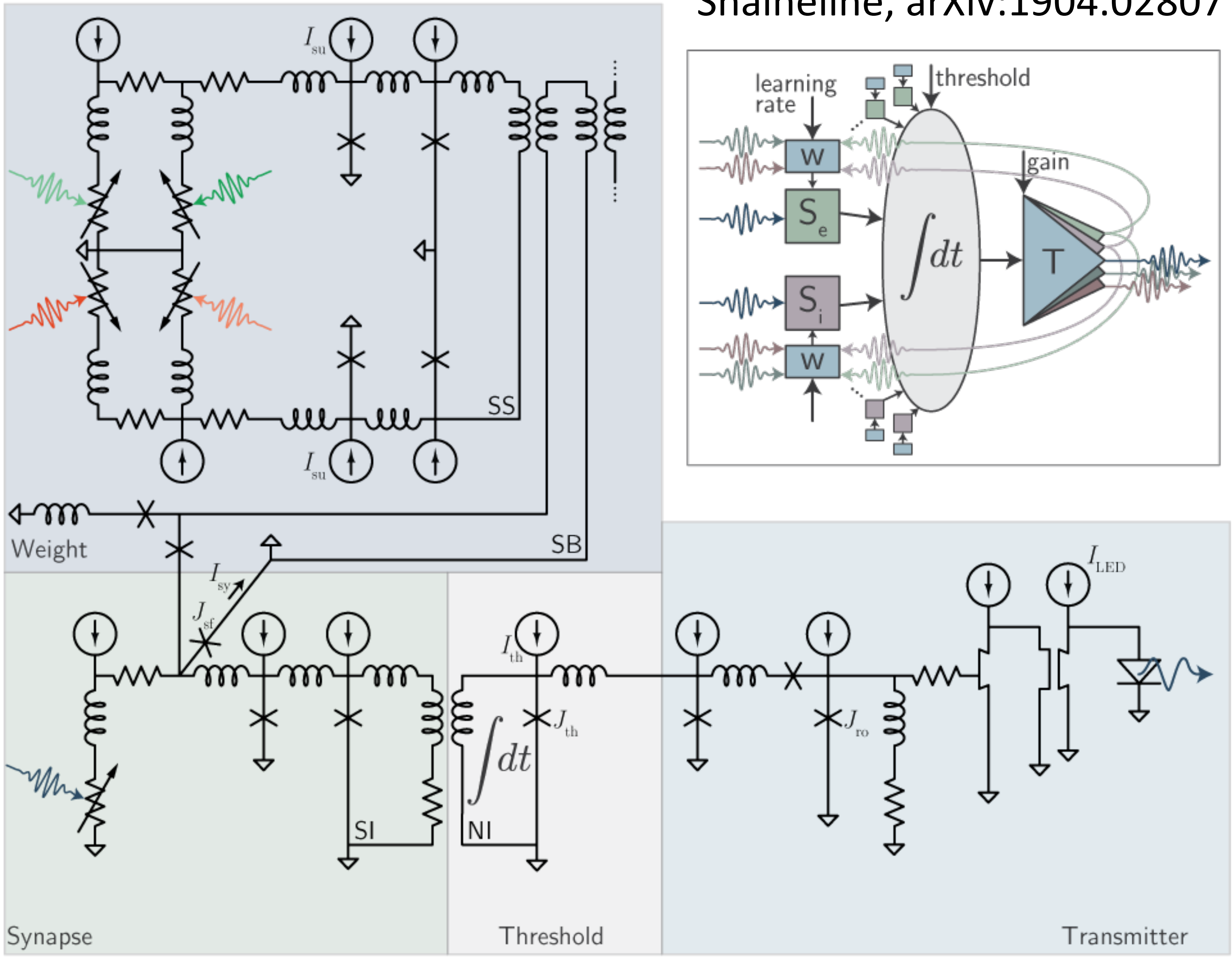


Colors for different operations

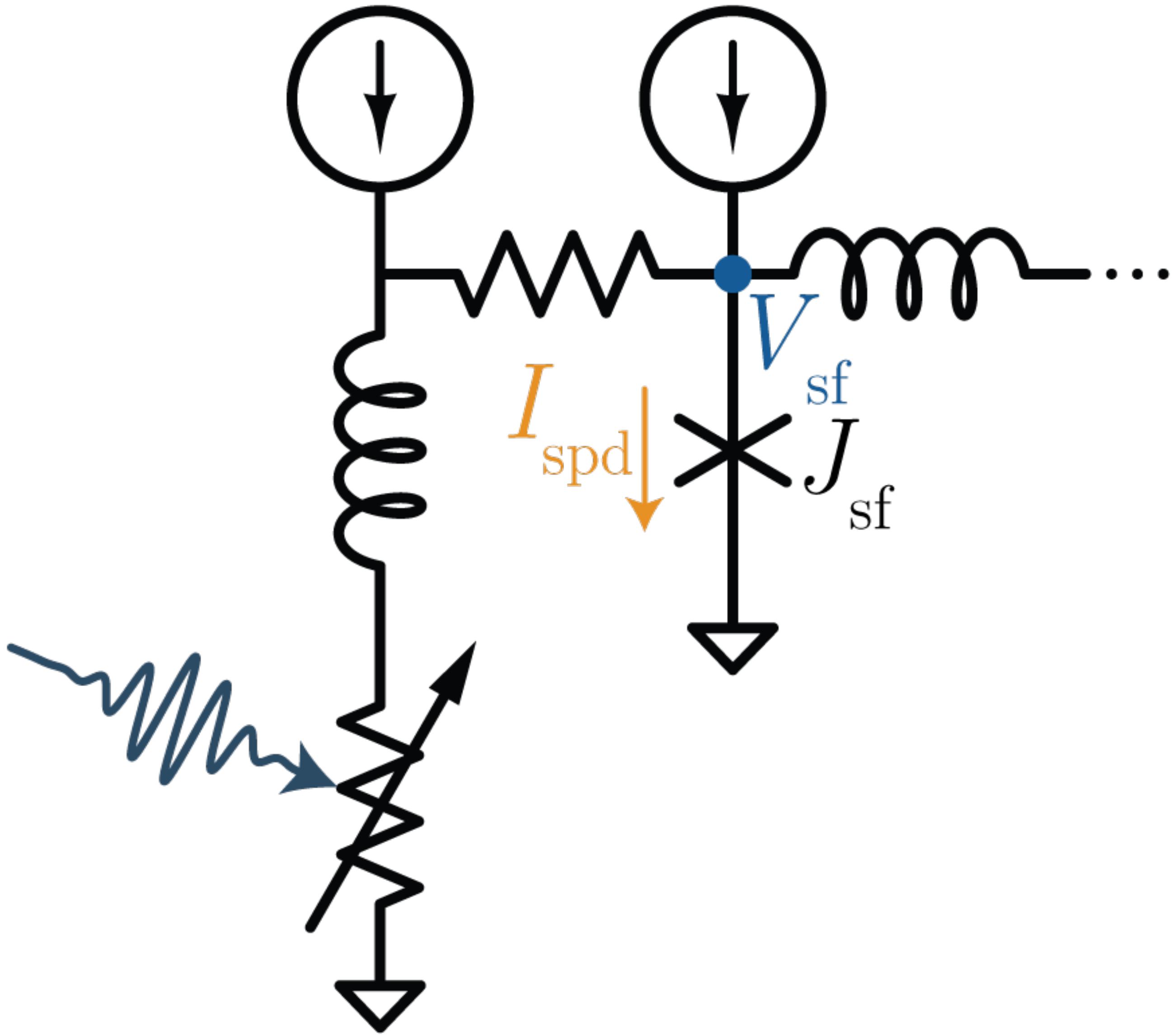

threshold
learning
rate
W
S_e
gain
T
$\int dt$
S_i
W

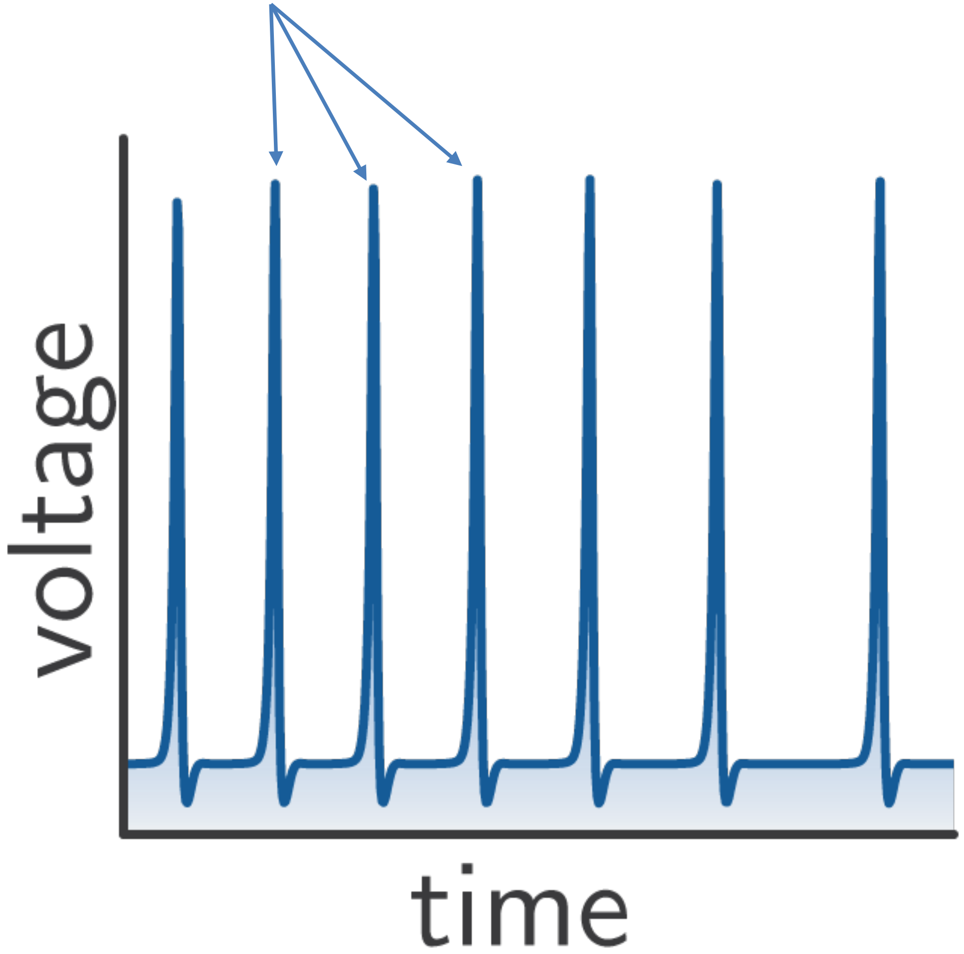
Loop neuron

Shainline et al., arXiv:1805.01929 (2018).
Shaineline, arXiv:1904.02807 (2019)

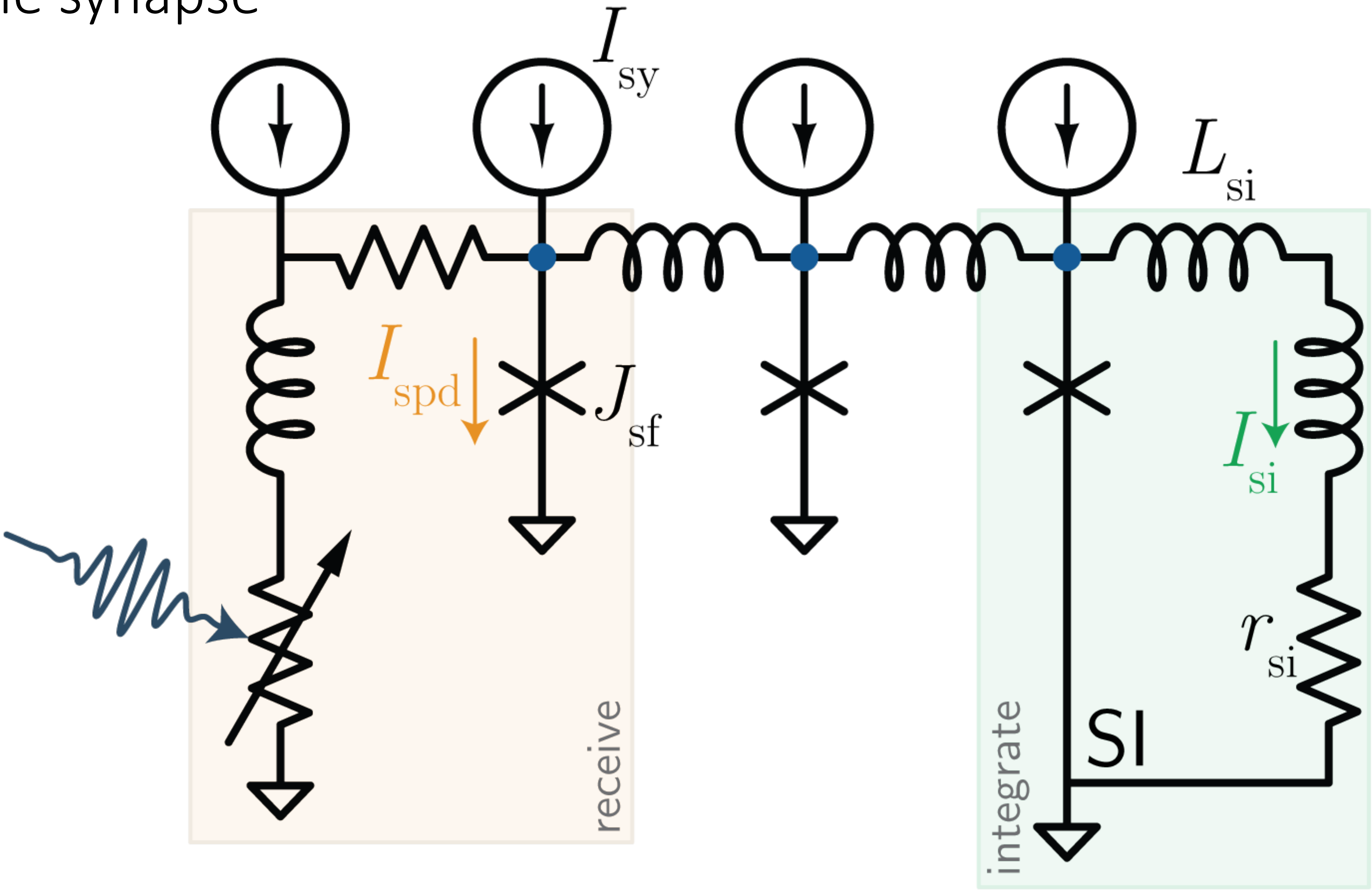


Photon-to-fluxon transducer





The synapse



Long-range = photons
Short-range = electronics / SFQ

Pulsed neural networks consisting of single-flux-quantum spiking neurons
T. Hirose, T. Asai, and Y. Amemiya
Physica C, 463:1072, 2007.

PHYSICAL REVIEW E **82**, 011914 (2010)
Josephson junction simulation of neurons
Patrick Crotty,[1] Dan Schult,[2] and Ken Segall[1]

SCIENCE ADVANCES | RESEARCH ARTICLE

APPLIED SCIENCES AND ENGINEERING

Ultralow power artificial synapses using nanotextured magnetic Josephson junctions

Michael L. Schneider,* Christine A. Donnelly, Stephen E. Russek, Burm Baek, Matthew R. Pufall, Peter F. Hopkins, Paul D. Dresselhaus, Samuel P. Benz, William H. Rippard

https://arxiv.org/abs/1907.00263

A Power Efficient Artificial Neuron Using Superconducting Nanowires

Emily Toomey, Ken Segall, Karl Berggren

NIST

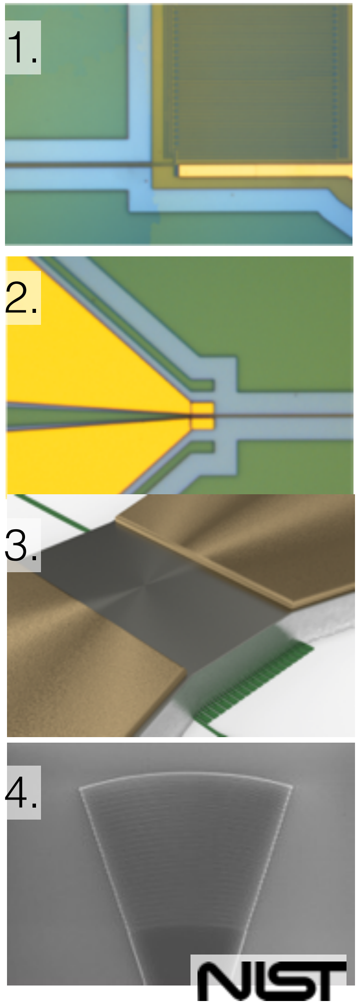
SOEN technical approach
superconducting optoelectronic networks

1. Single photons for minimum spike energy
   (superconducting single-photon detectors)

2. Cold optoelectronics for monolithic integration
   (all-silicon light-emitting diodes)

3. Cold electronics (SFQ) for nonlinear processing
   (Josephson junctions, cryotron switches)

4. Light for interconnects
   (silicon photonics)

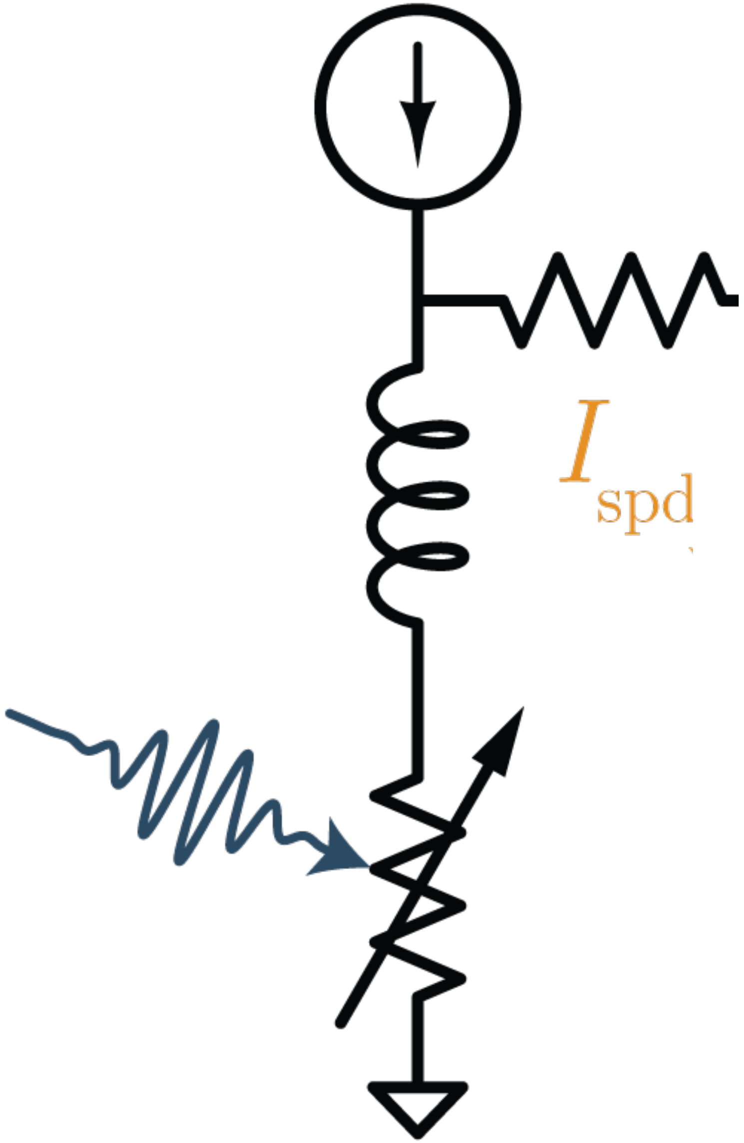


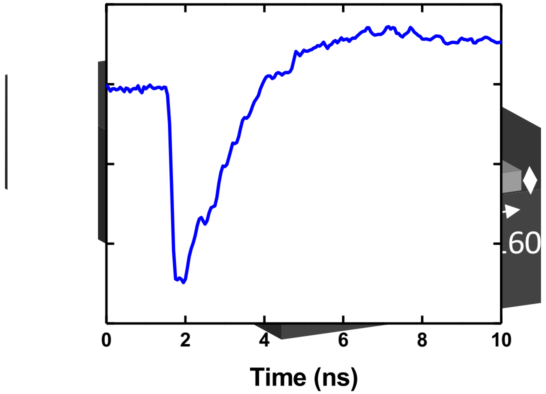
J. M. Shainline, S. M. Buckley, R. P. Mirin, and S. W. Nam, "Superconducting optoelectronic circuits for neuromorphic computing," Phys. Rev. Applied, Mar 2017.

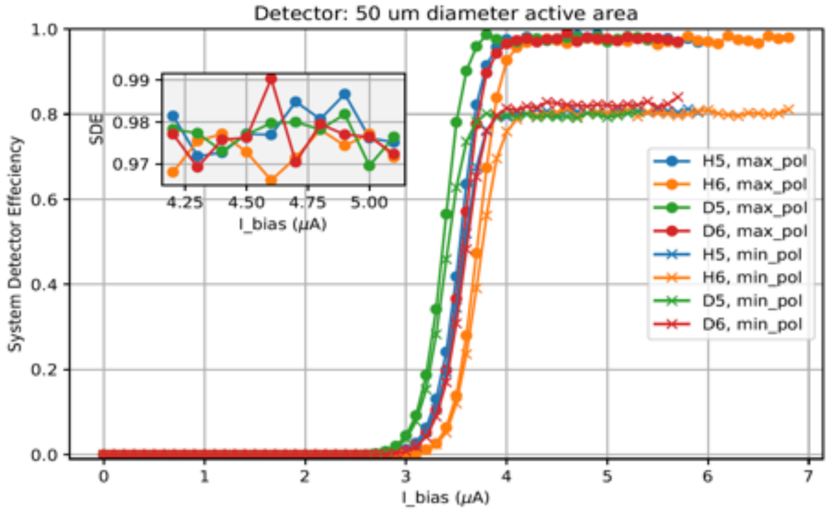
NIST

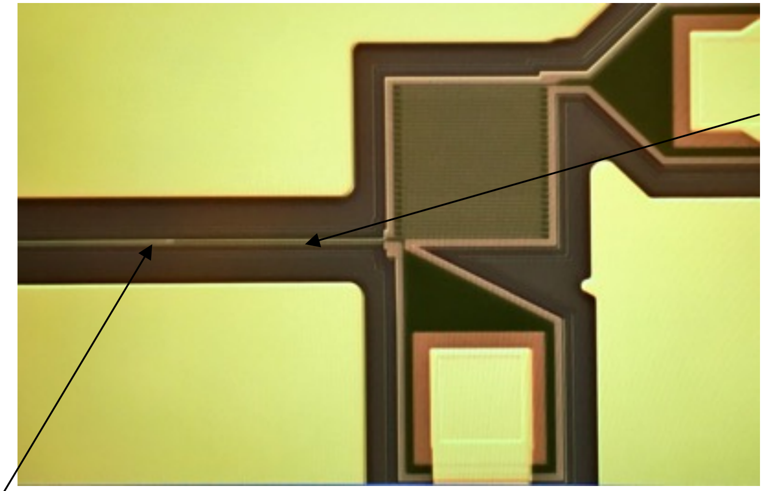
cryogenic silicon photonics platform: recent results

Superconducting Nanowire Detector







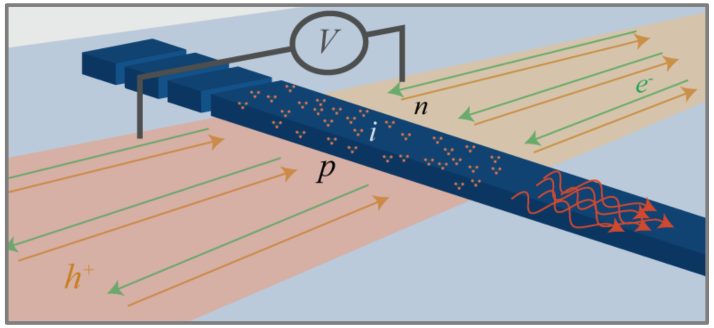


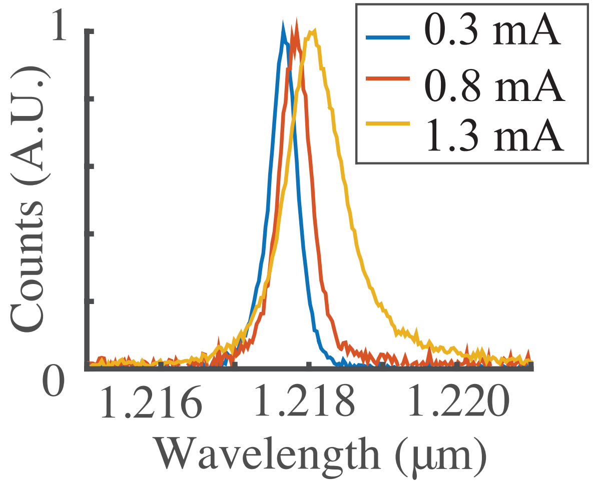
Nanowire on waveguide

Waveguide

All-silicon light emitting diodes

- Si defect centers have optical transitions
- Low temp. inhibits non-radiative pathways
- Electrical pumping with PN junction
- W-centers: 1220nm emission

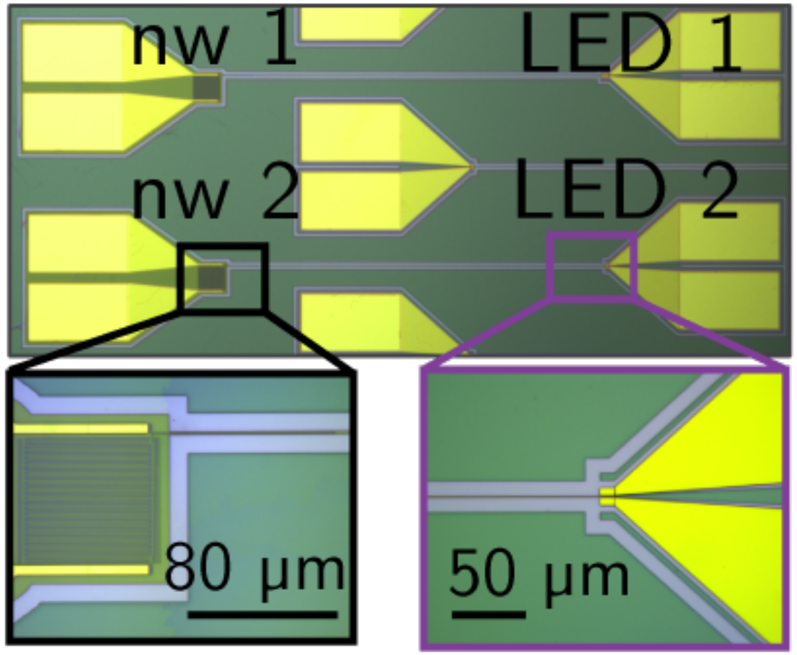


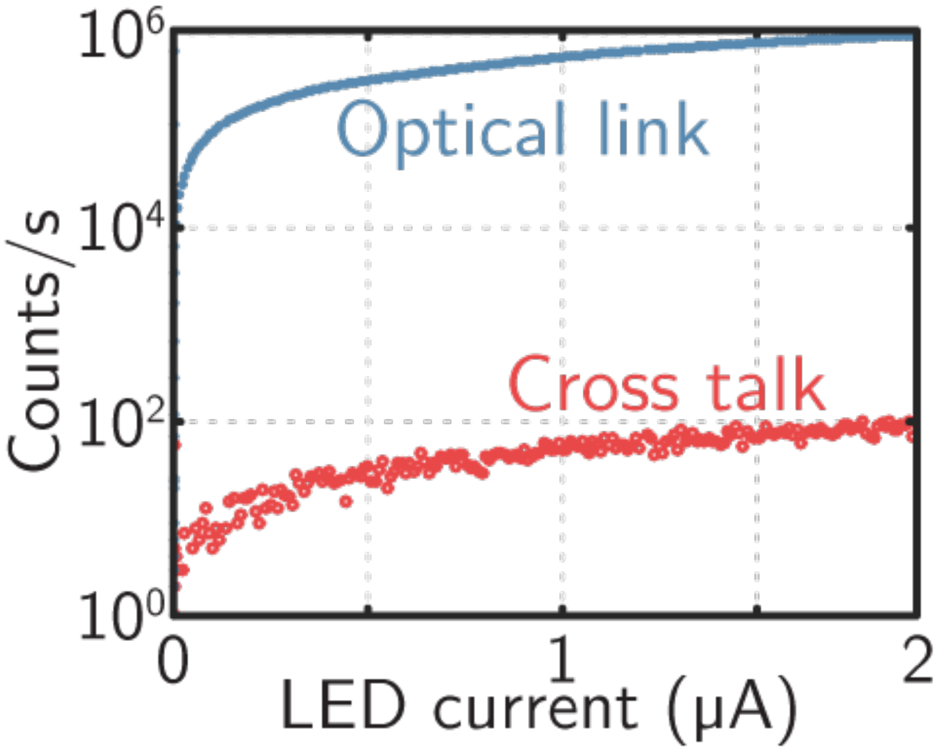


S. M. Buckley et al. "All-silicon light-emitting diodes waveguide-integrated..." APL, 2017.

Co-integration: Silicon LEDs + SNSPDs

NIST



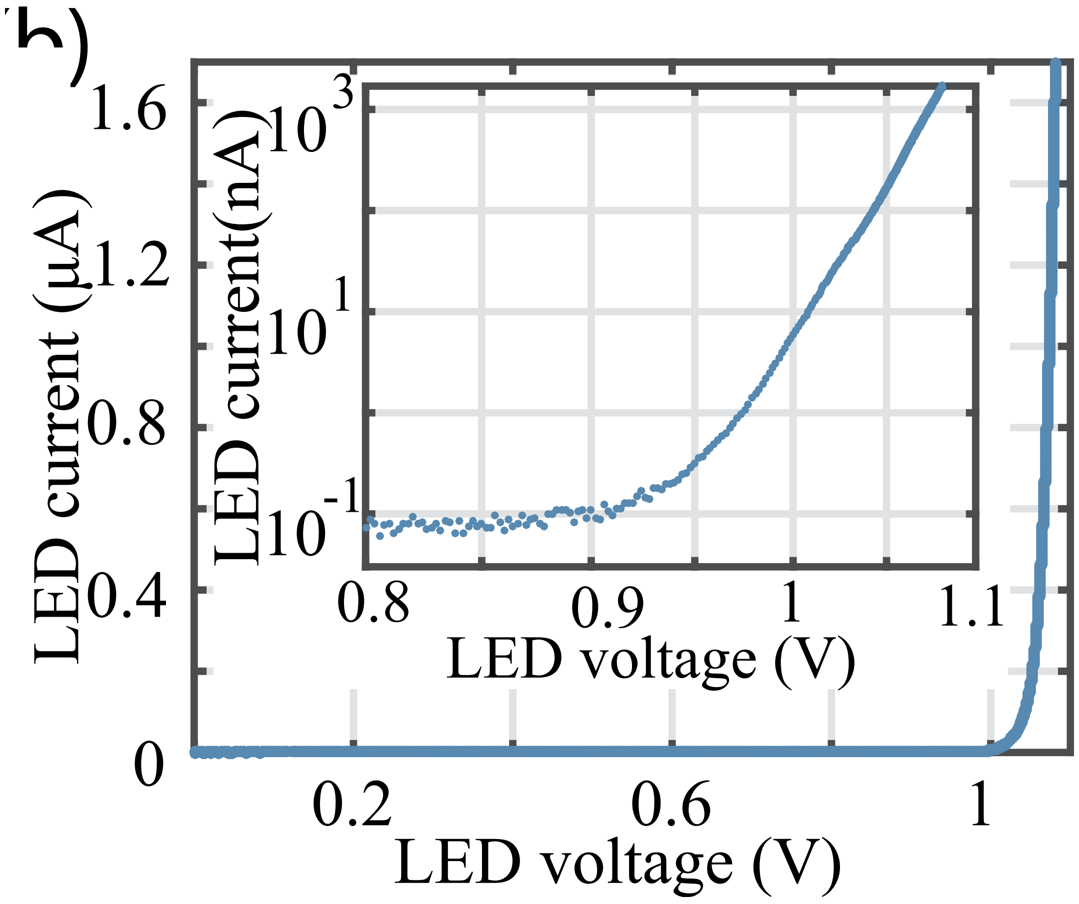


S. M. Buckley et al. “All-silicon light-emitting diodes waveguide-integrated...” APL, 2017.

All-silicon light emitting diodes

NIST

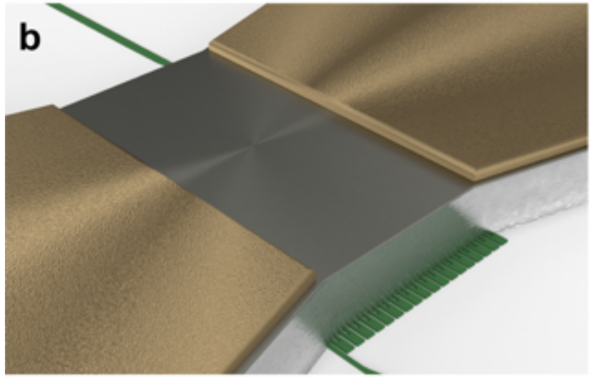
- LED turn-on voltage is ~ 1 V
- SNSPD can output ~ 1 mV



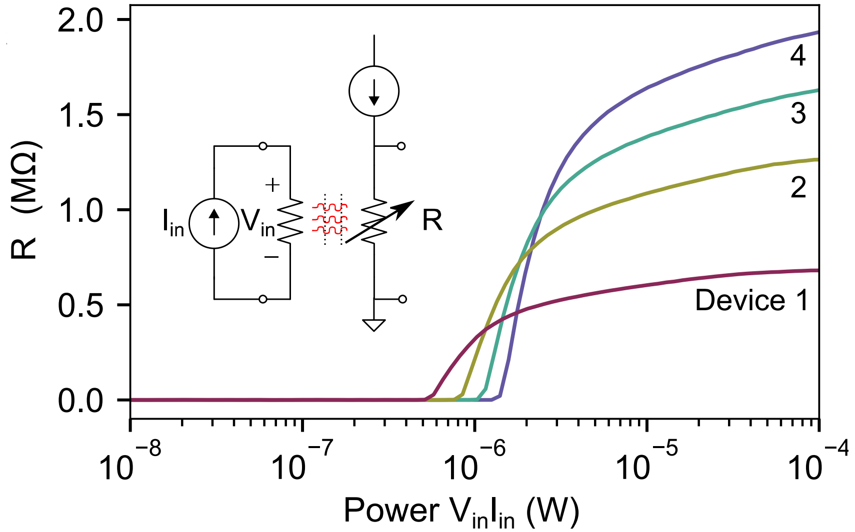
S. M. Buckley et al. "All-silicon light-emitting diodes waveguide-integrated..." APL, 2017.

Nano-cryotron thermal switch

NIST

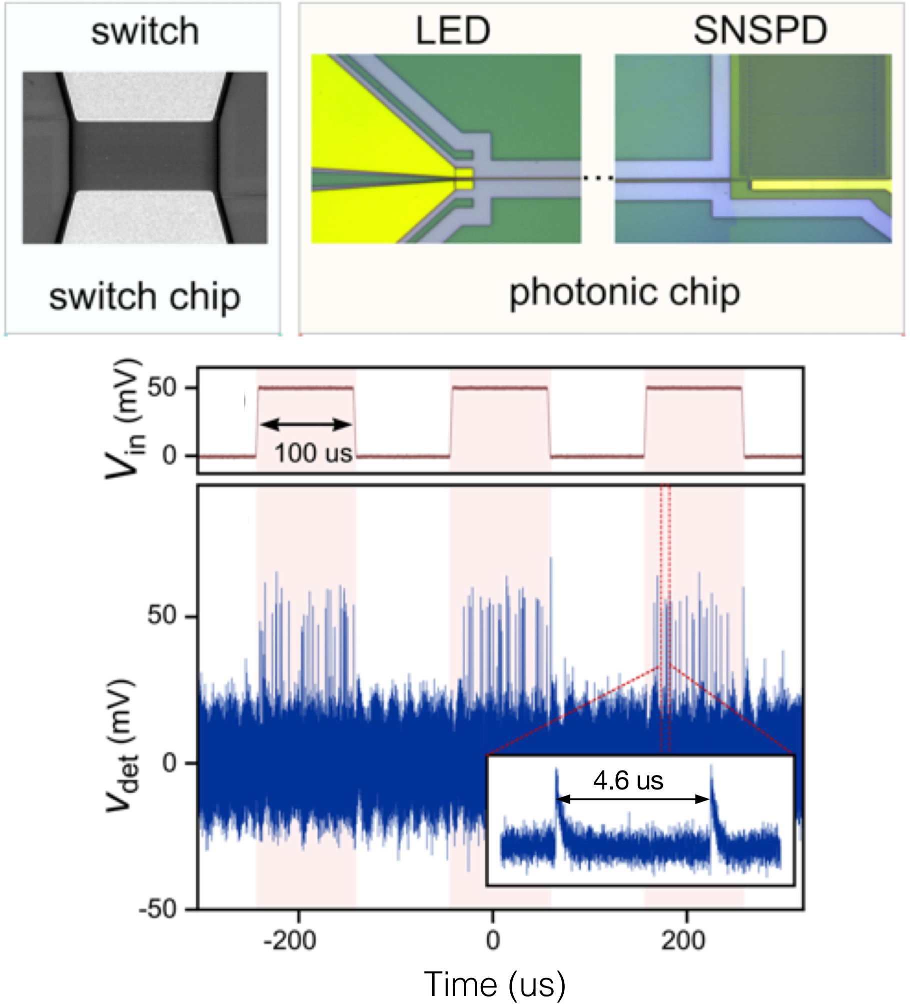


- millivolt input -> Volt output
- No Josephson Junctions needed
- Reset about 10ns



A. McCaughan et al. "A compact, ultrahigh impedance superconducting thermal switch for interfacing superconductors with semiconductors and optoelectronics," arXiv:1903.10461, 2019.

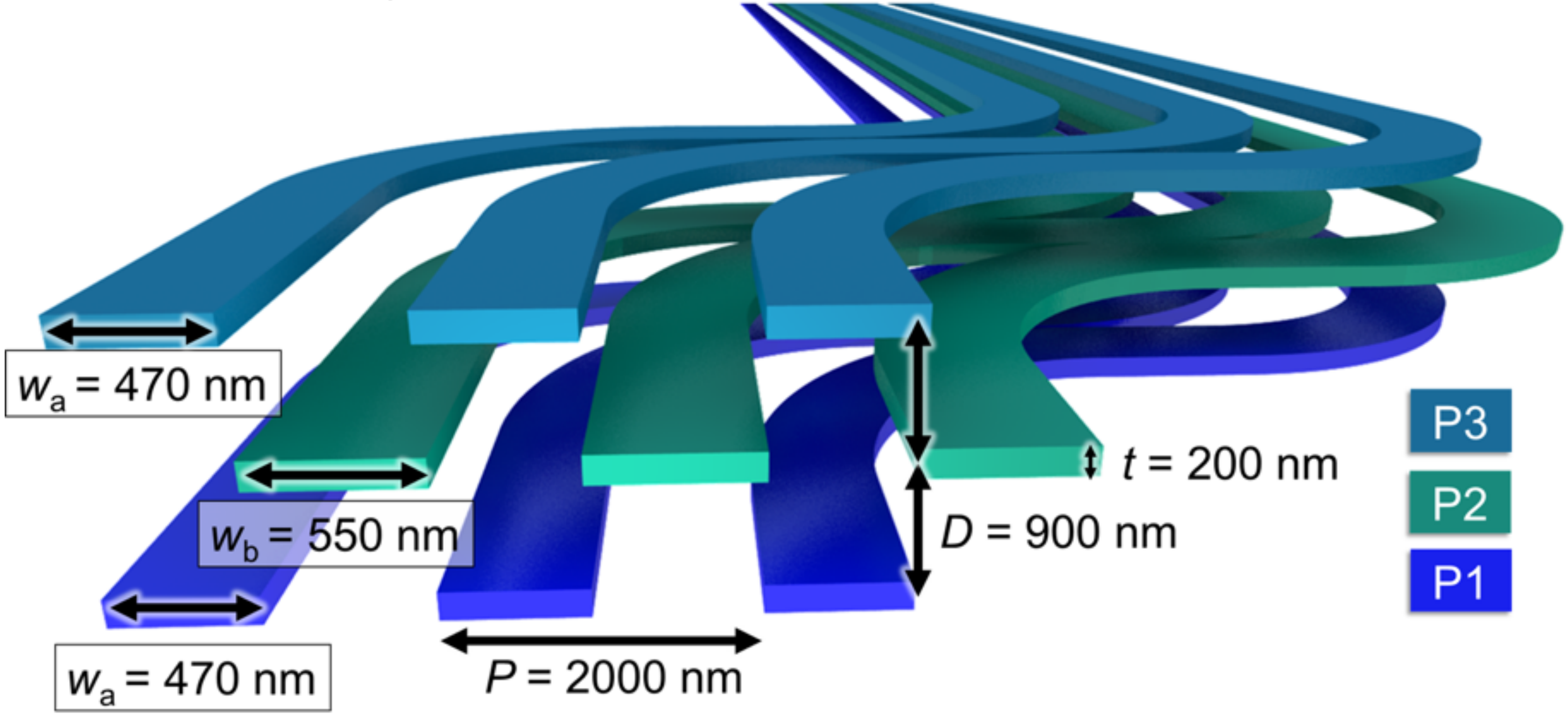
Superconductor-to-semiconductor interface



A. McCaughan et al. "A compact, ultrahigh impedance superconducting thermal switch for interfacing superconductors with semiconductors and optoelectronics," arXiv:1903.10461, 2019.

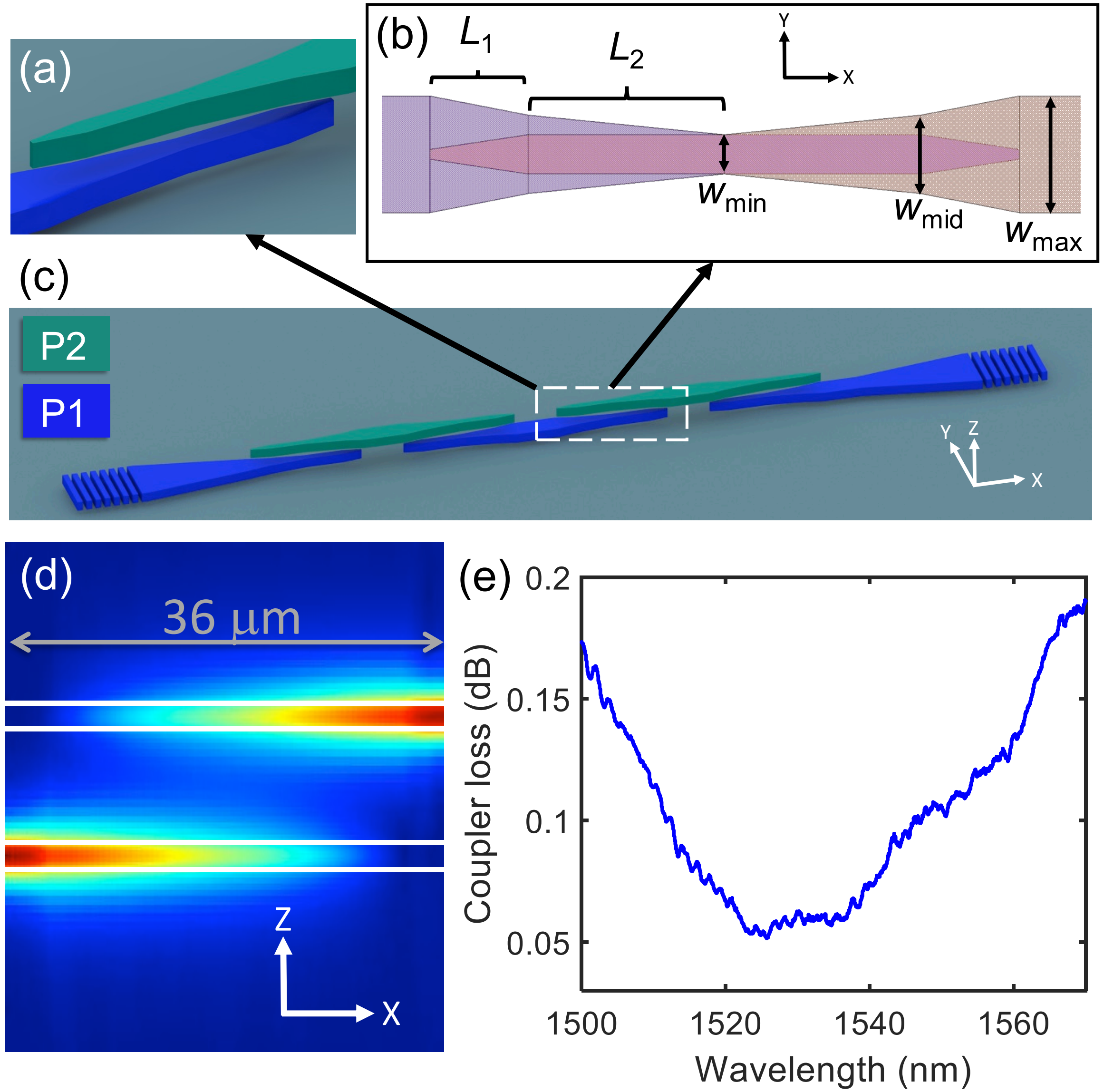
First steps toward photonic networks

Three planes of amorphous silicon waveguides



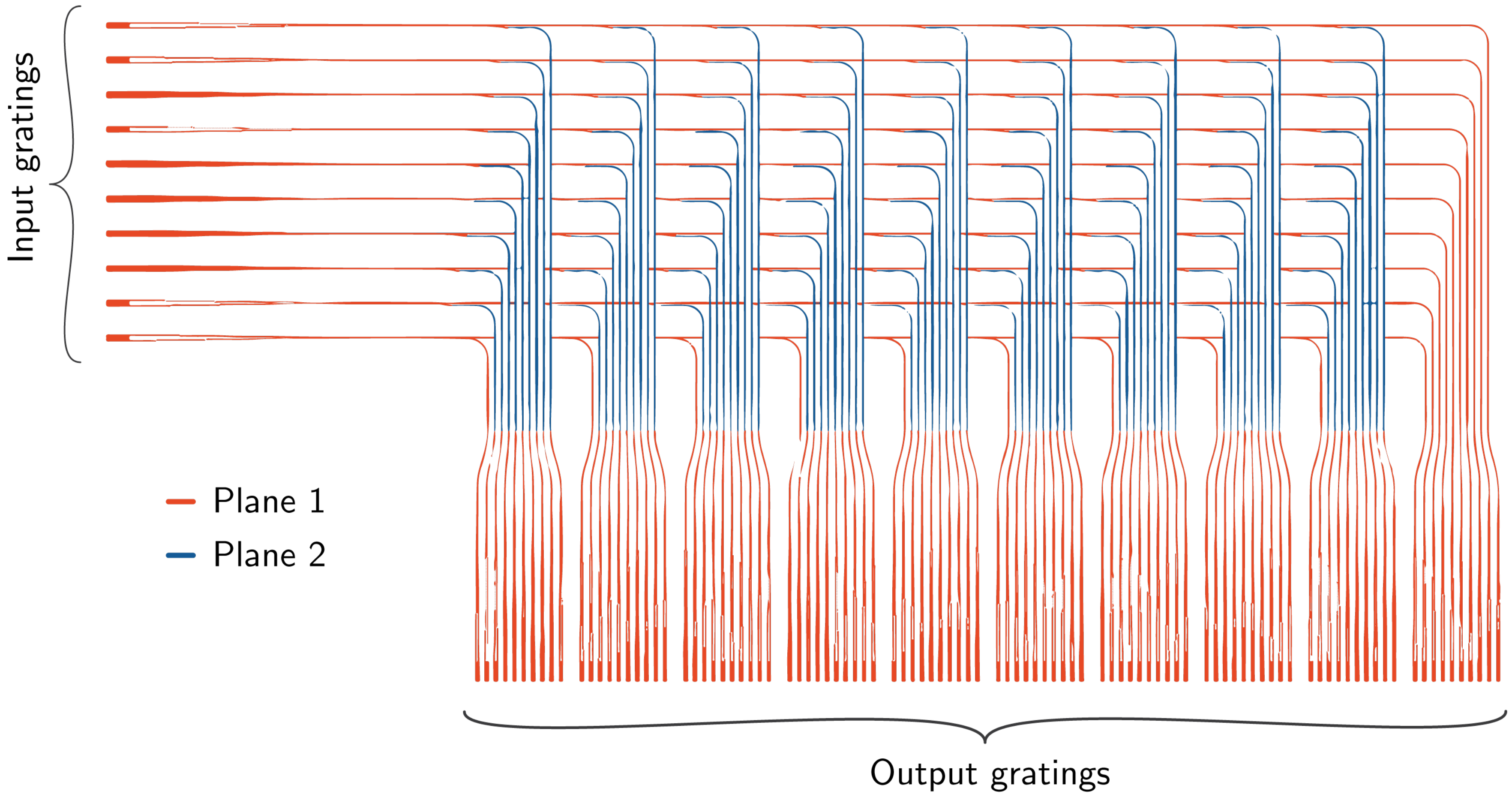
Chiles et al., APL Photonics **2**, 116101 (2017)

Inter-planar couplers

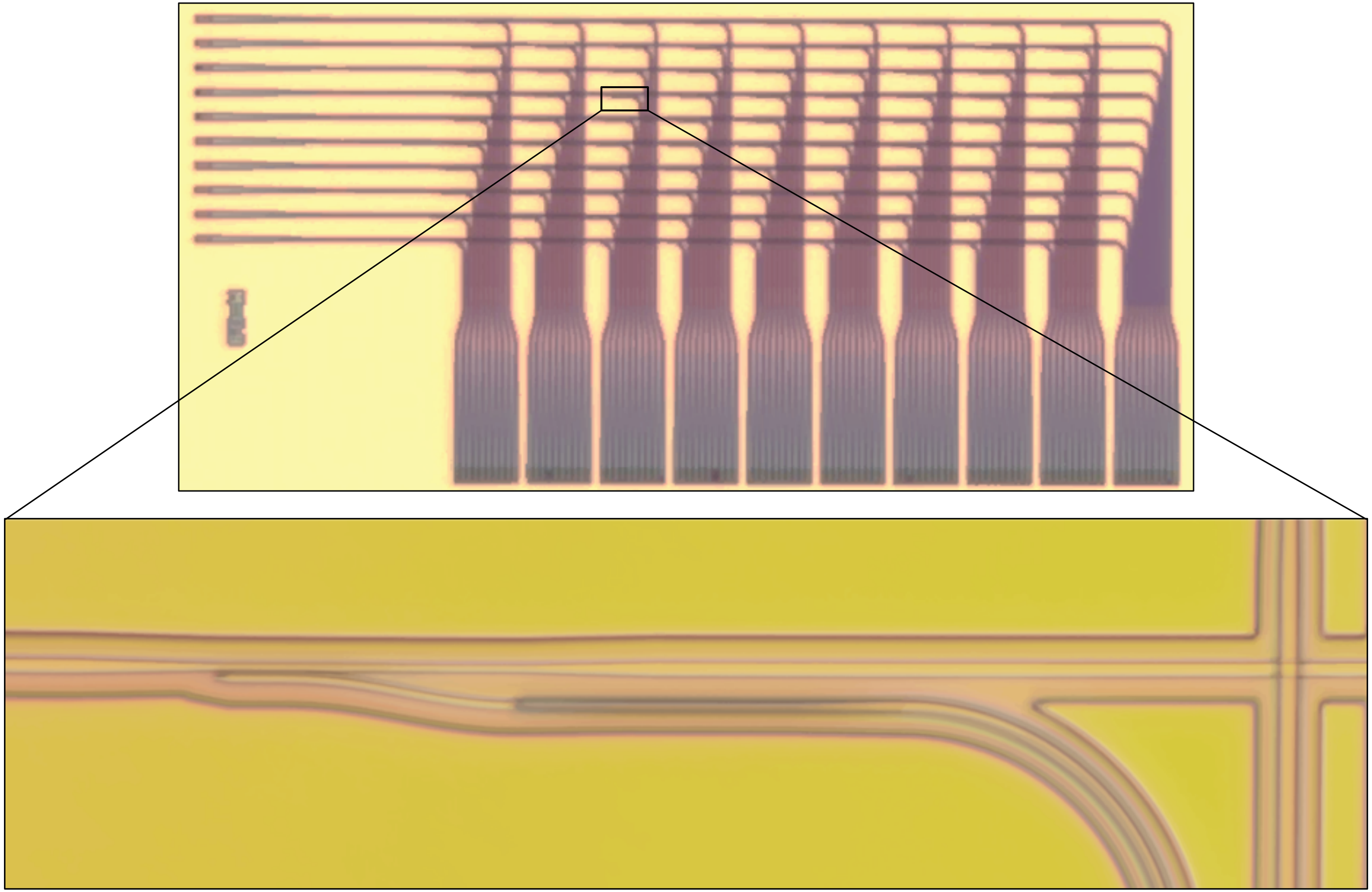


- 0.05 dB loss
- 36 μm length

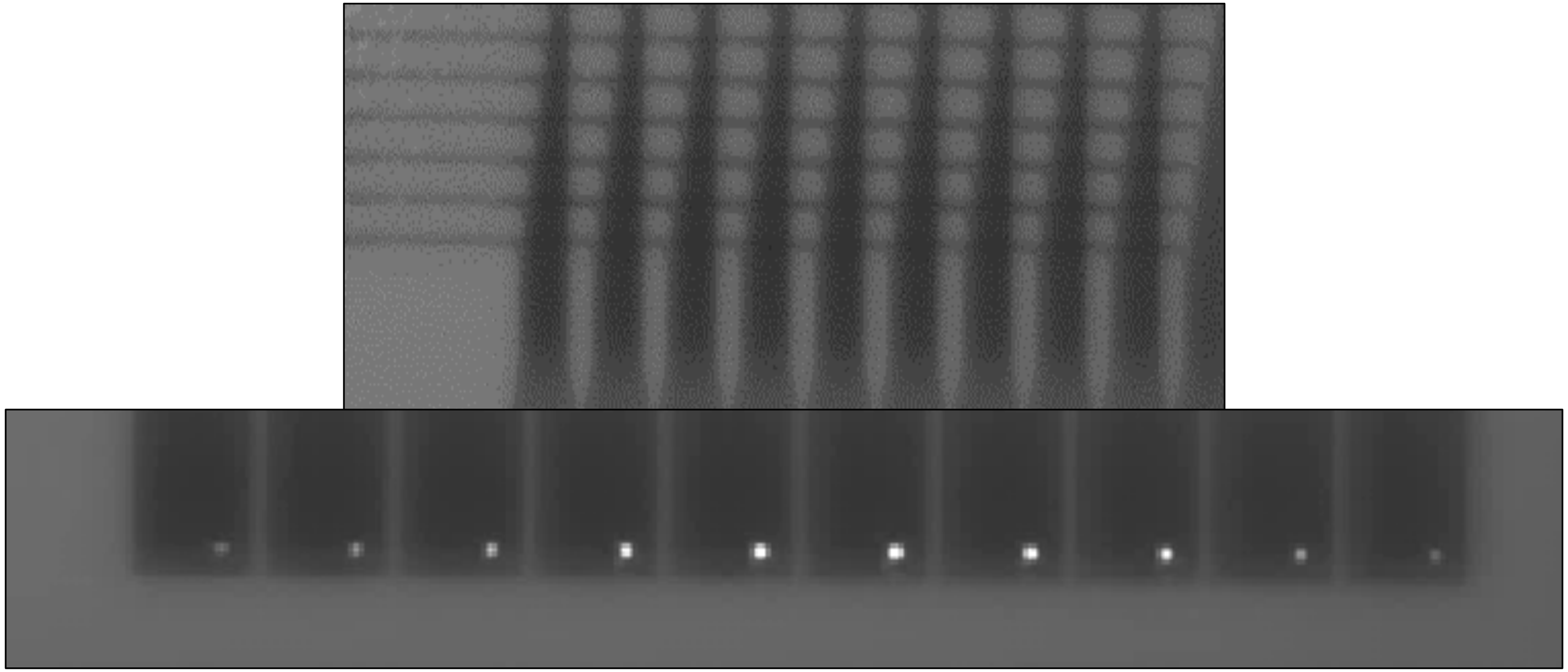
Chiles et al, APL Photonics **2** 116101 (2017).



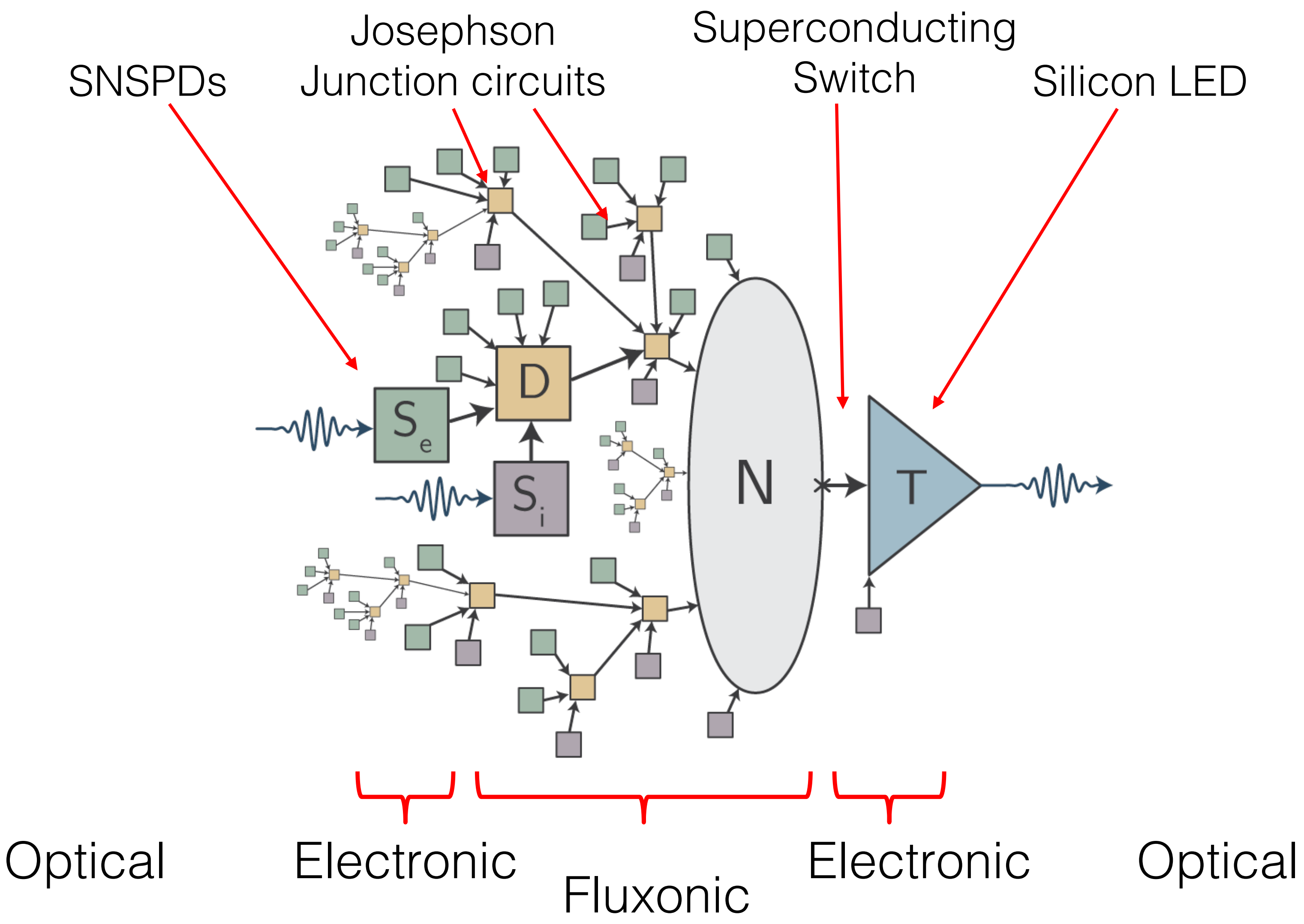
Chiles et al, APL Photonics **3** 106101 (2018).



10 x 100 routing couplers



Full Superconducting Optoelectronic Neuron



J. M. Shainline, "Fluxonic processing of photonic synapse events," arXiv:1904.02807, 2019.

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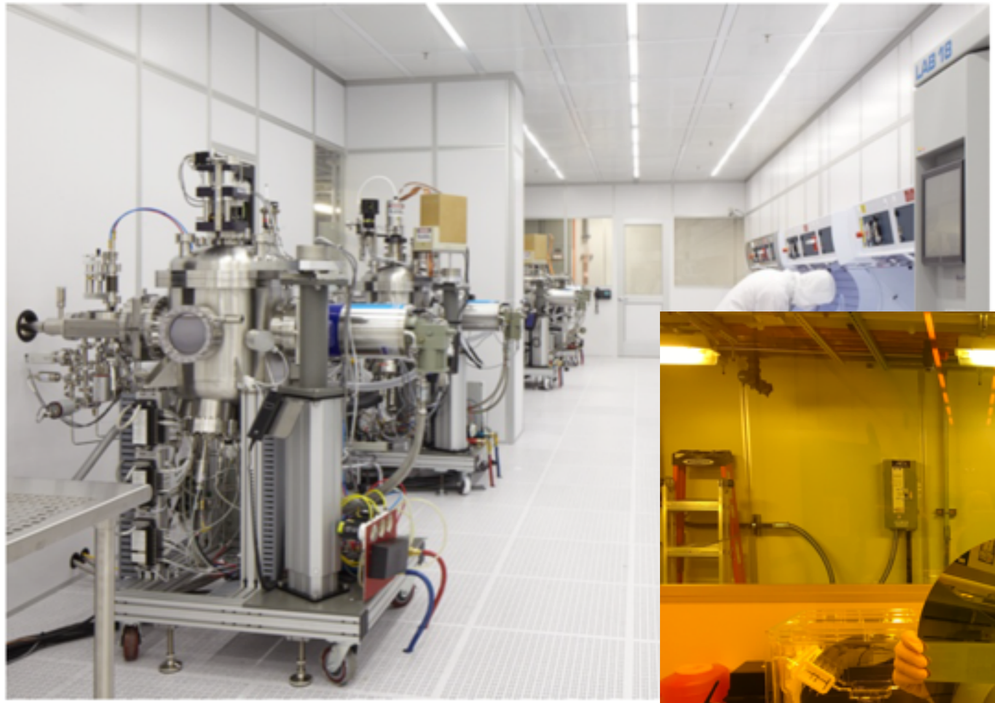
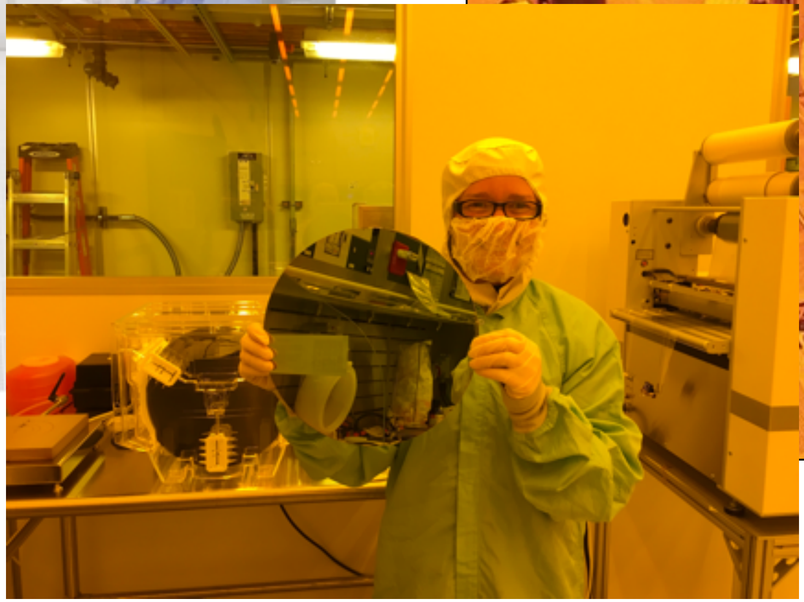
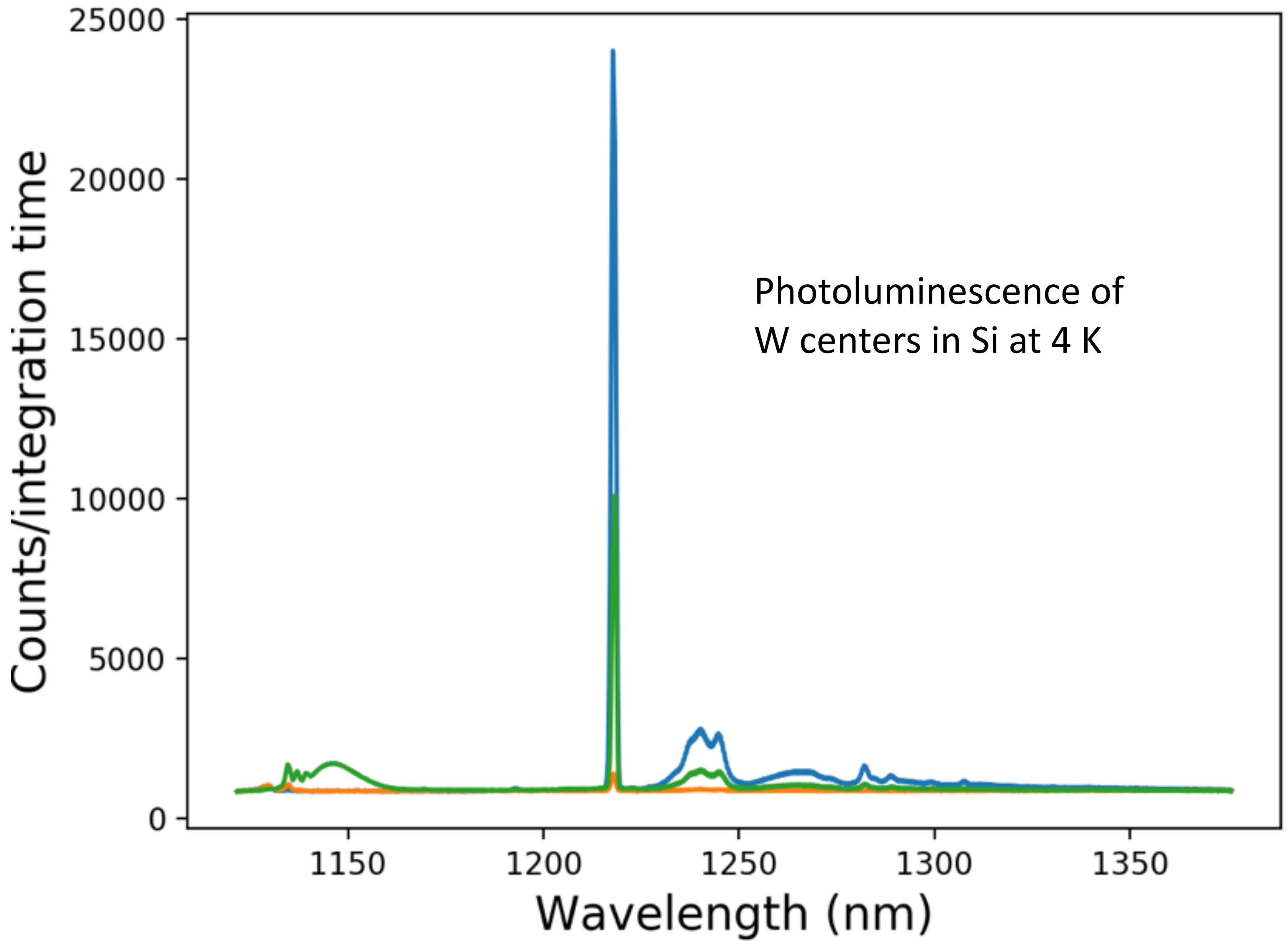
Eventual transfer to 300 mm foundry





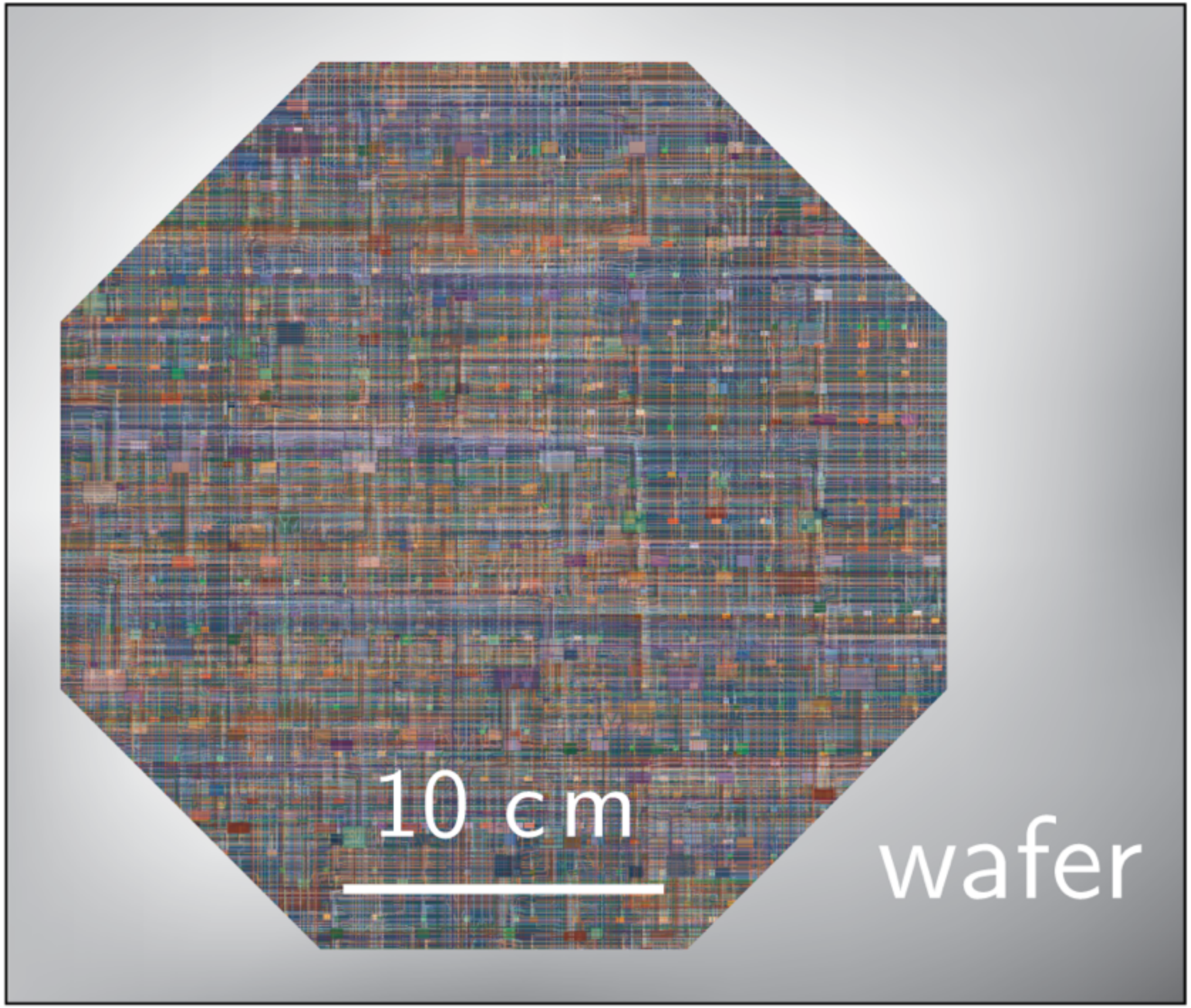
NIST

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



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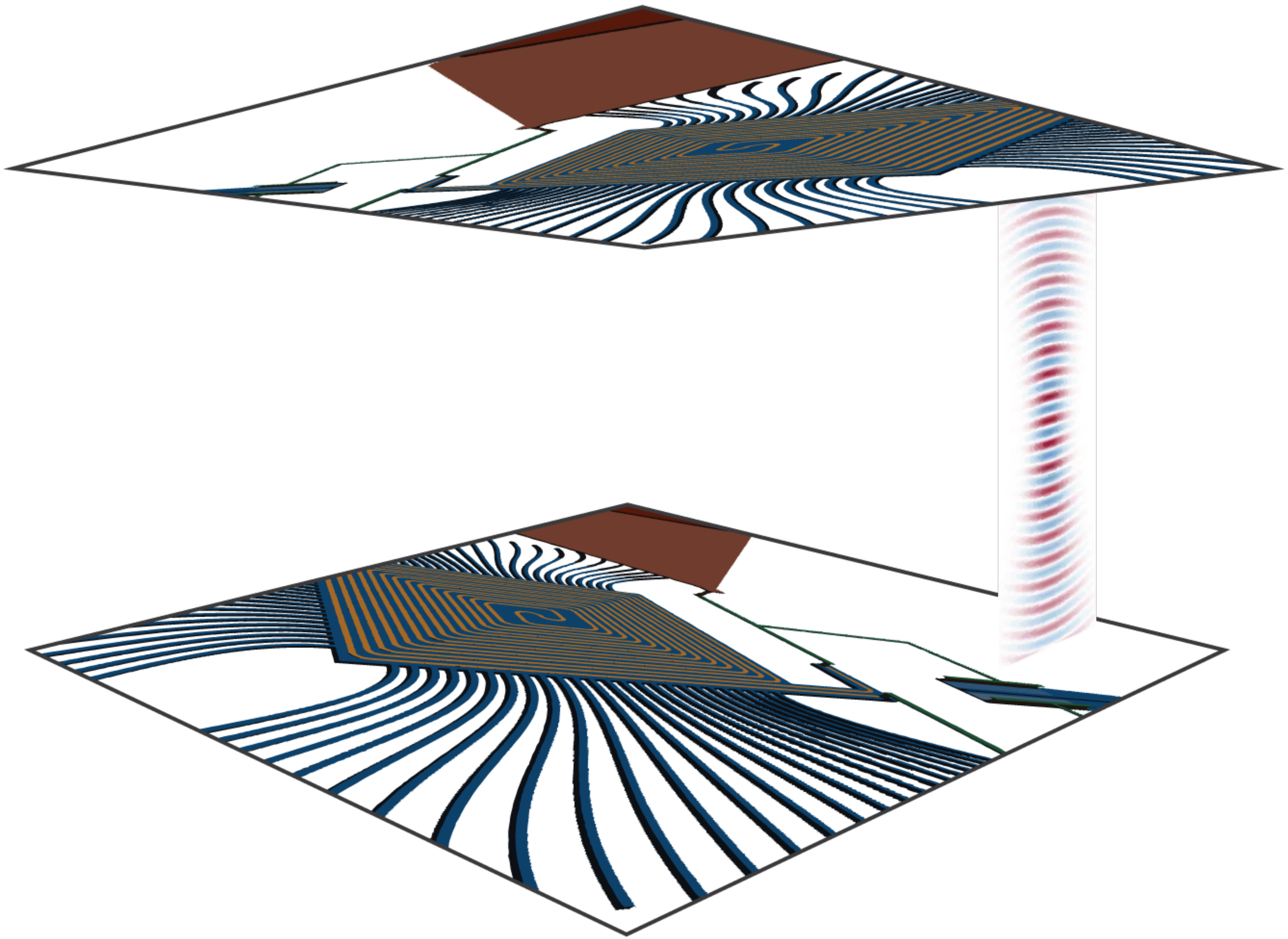
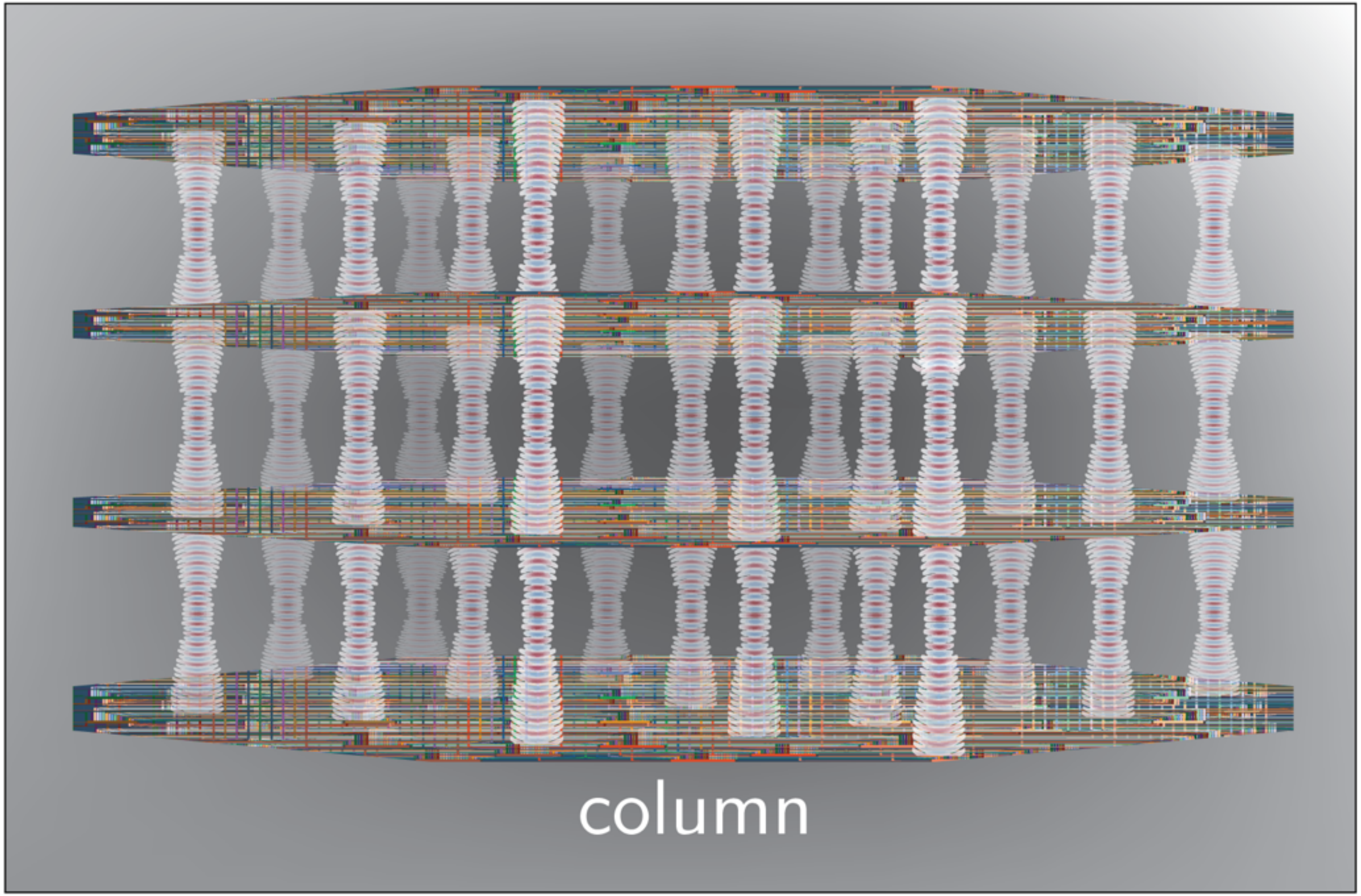
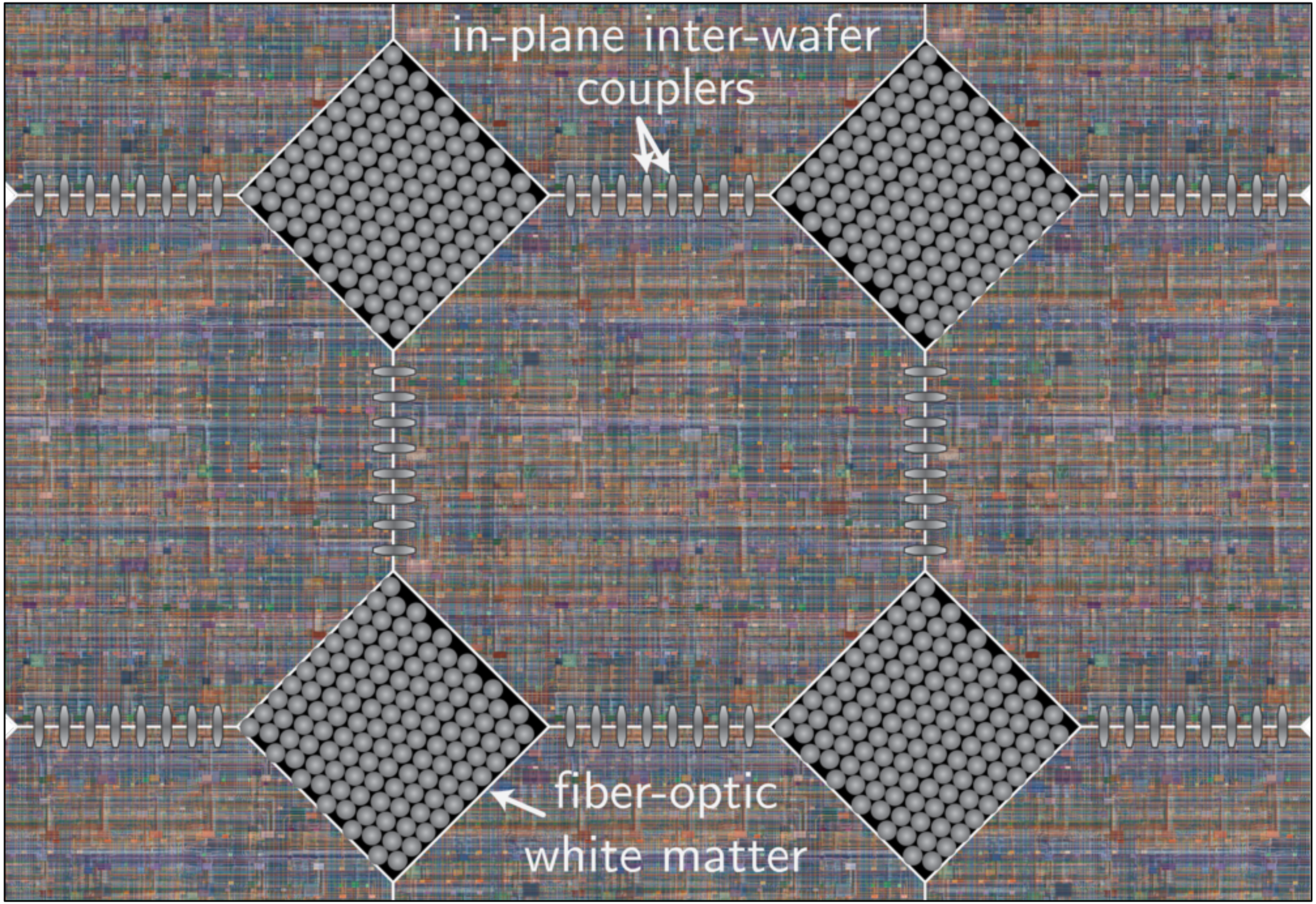
Free-space interconnects for 3D



Free-space inter-wafer interconnects



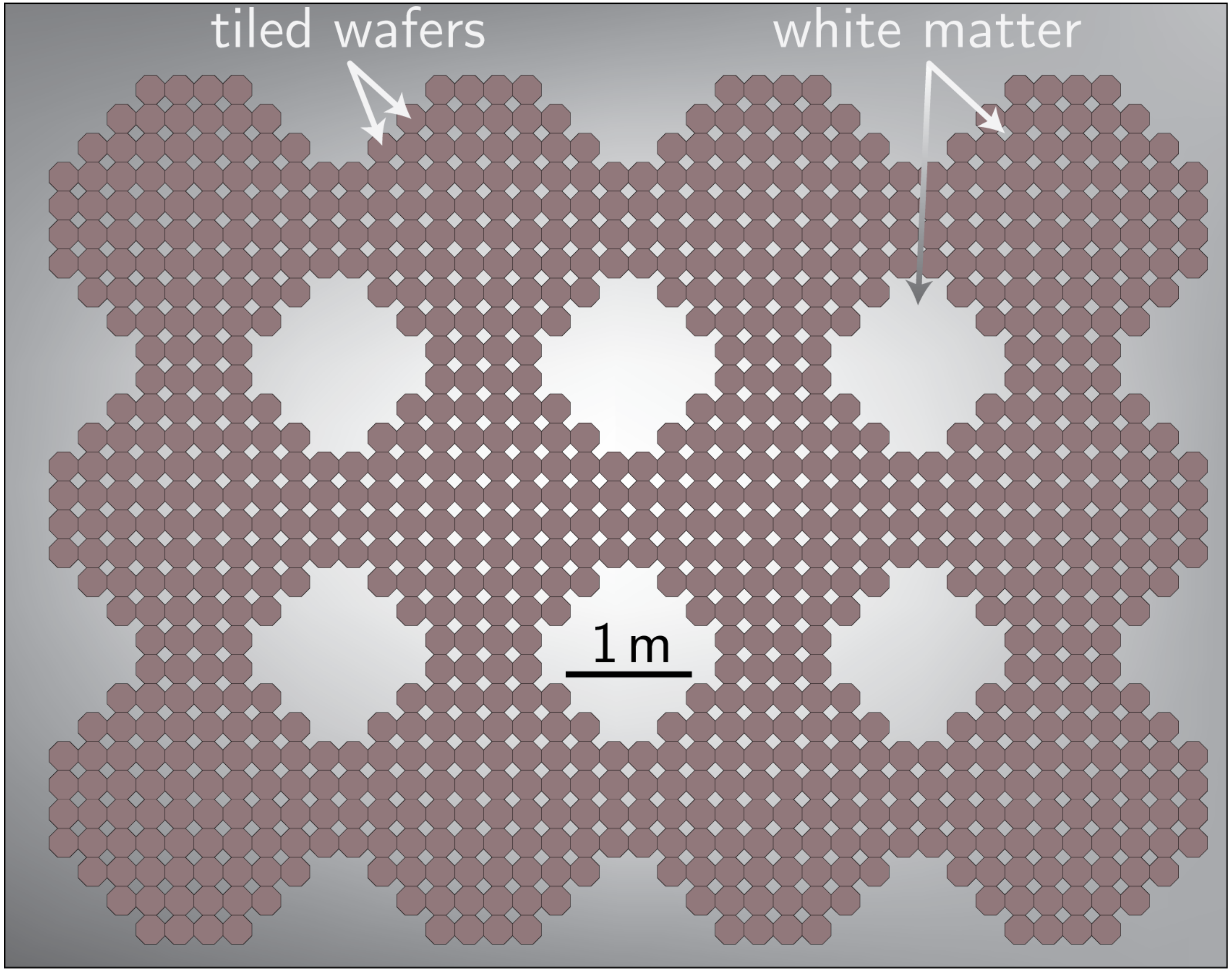
Multi-wafer modules



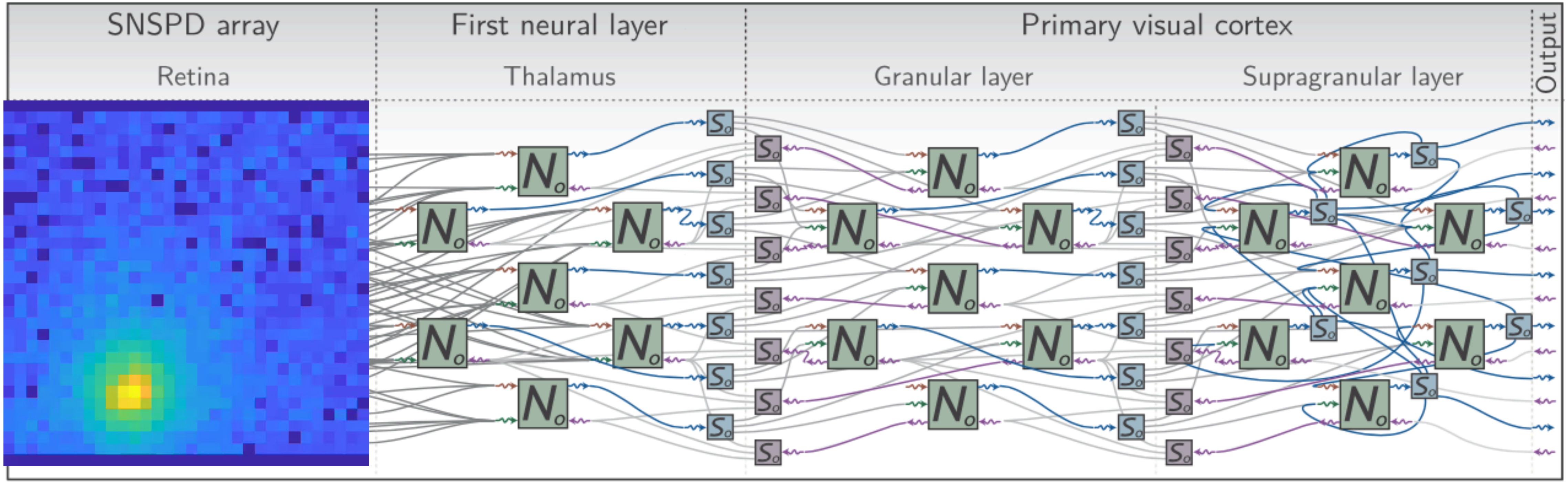
IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), September 2019.
Invited presentation 3-KN-1 given at ISEC, 28 July-1 August 2019, Riverside, CA, USA.

Brain-scale systems?

> 100 Billion neurons



What can we do in five years?



Artificial visual cortex

Superconducting optoelectronic networks

- Dense local fan-out with photonics
- Long-range communication at light speed
- Computing and memory with superconducting electronics

Would this reach the limits of cognition?


• Rich Mirin
• Jeff Shainline
• Sonia Buckley
• Adam McCaughan
• Alex Tait
• Jeff Chiles
• Saeed Khan
• Krister Shalm
• Marty Stevens
• Adriana Lita
• Varun Verma
• Nima Nader
• Mike Mazurek
• Dileep Reddy
• Eric Stanton
• Galen Moody
• Kevin Silverman
• Thomas Gerrits
saewoo.nam@nist.gov
MIT, JPL, Suny-Poly
Boulder Labs