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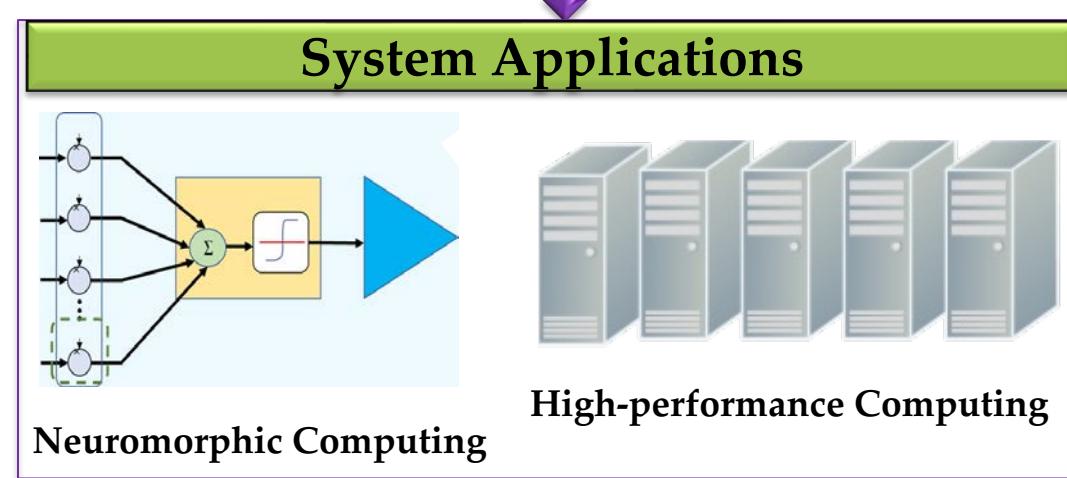
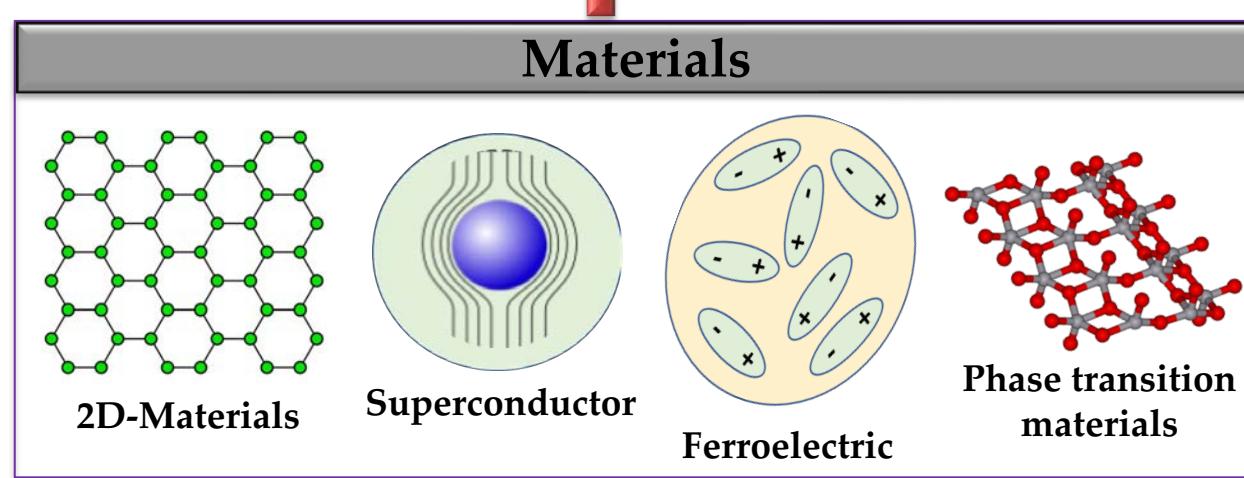
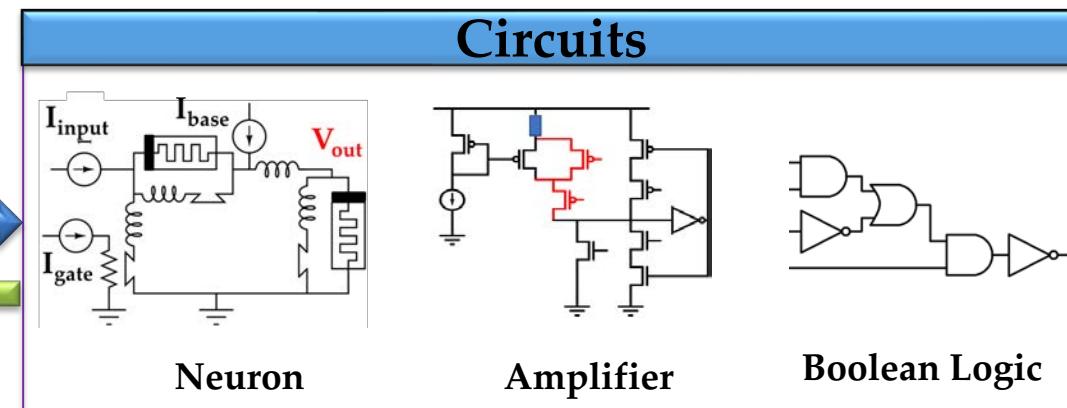
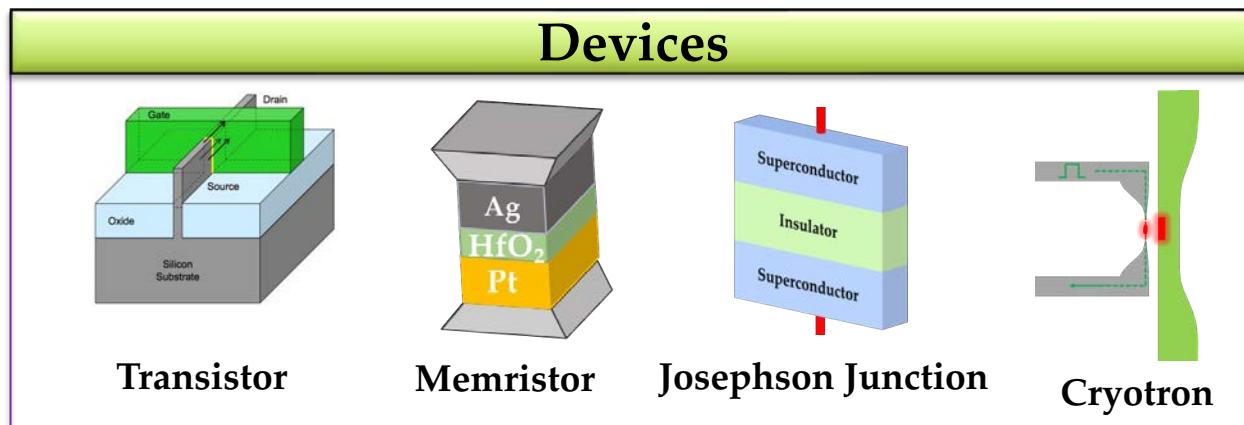
Computing at the Ultra-Cold: Exploring the Frontiers of **Cryogenic Electronics**

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NorDIC
LAB

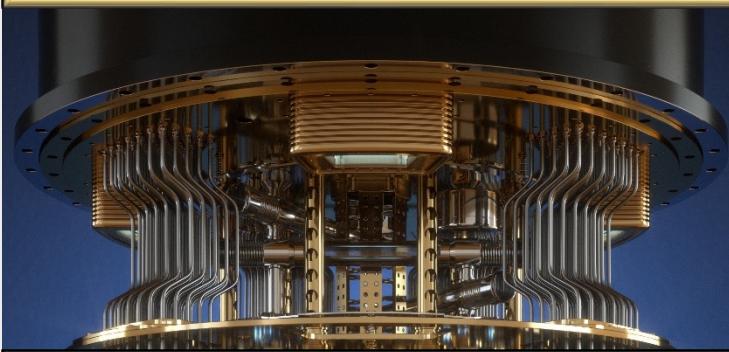
Research Overview

Fabrication* | Modeling | Simulation | Tape-out | Characterization



Three Transformative Technologies

Quantum Computing



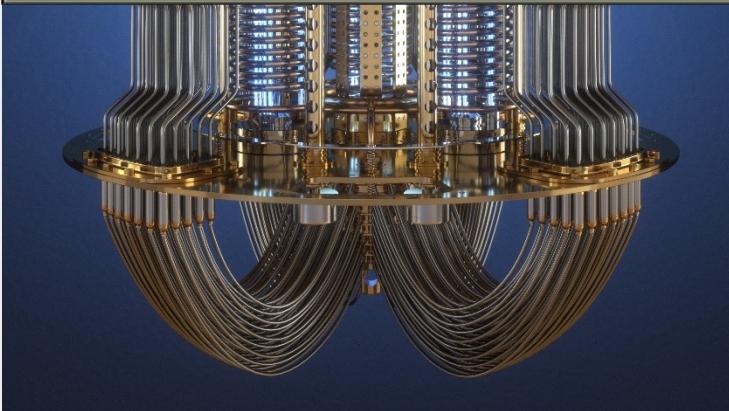
High-Performance Computing

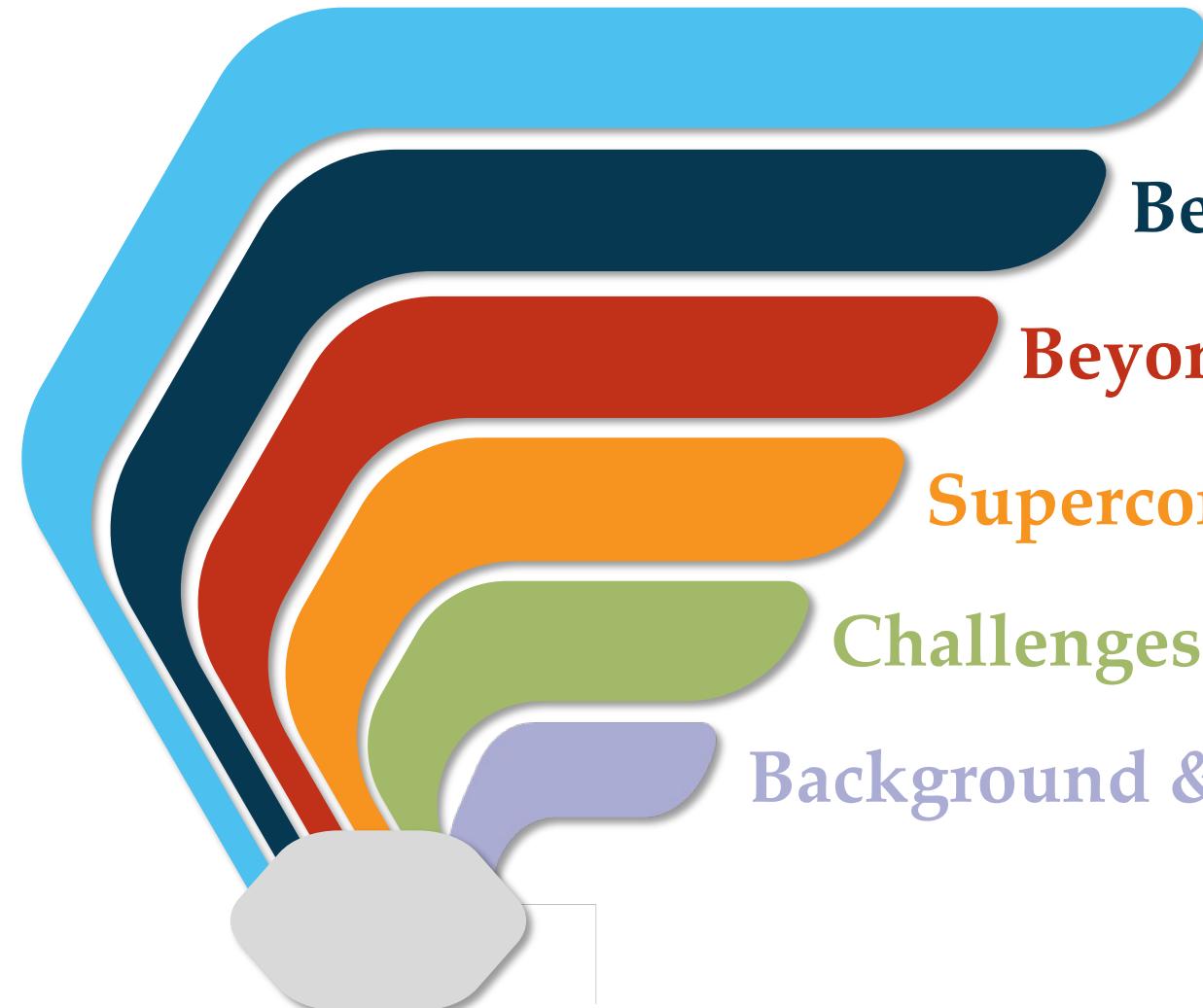


Space Electronics



Cryogenic Electronics





Outlook & Conclusion

Beyond Superconductors

Beyond Boolean

Superconducting Boolean Systems

Challenges in State-of-the-Art

Background & Motivation



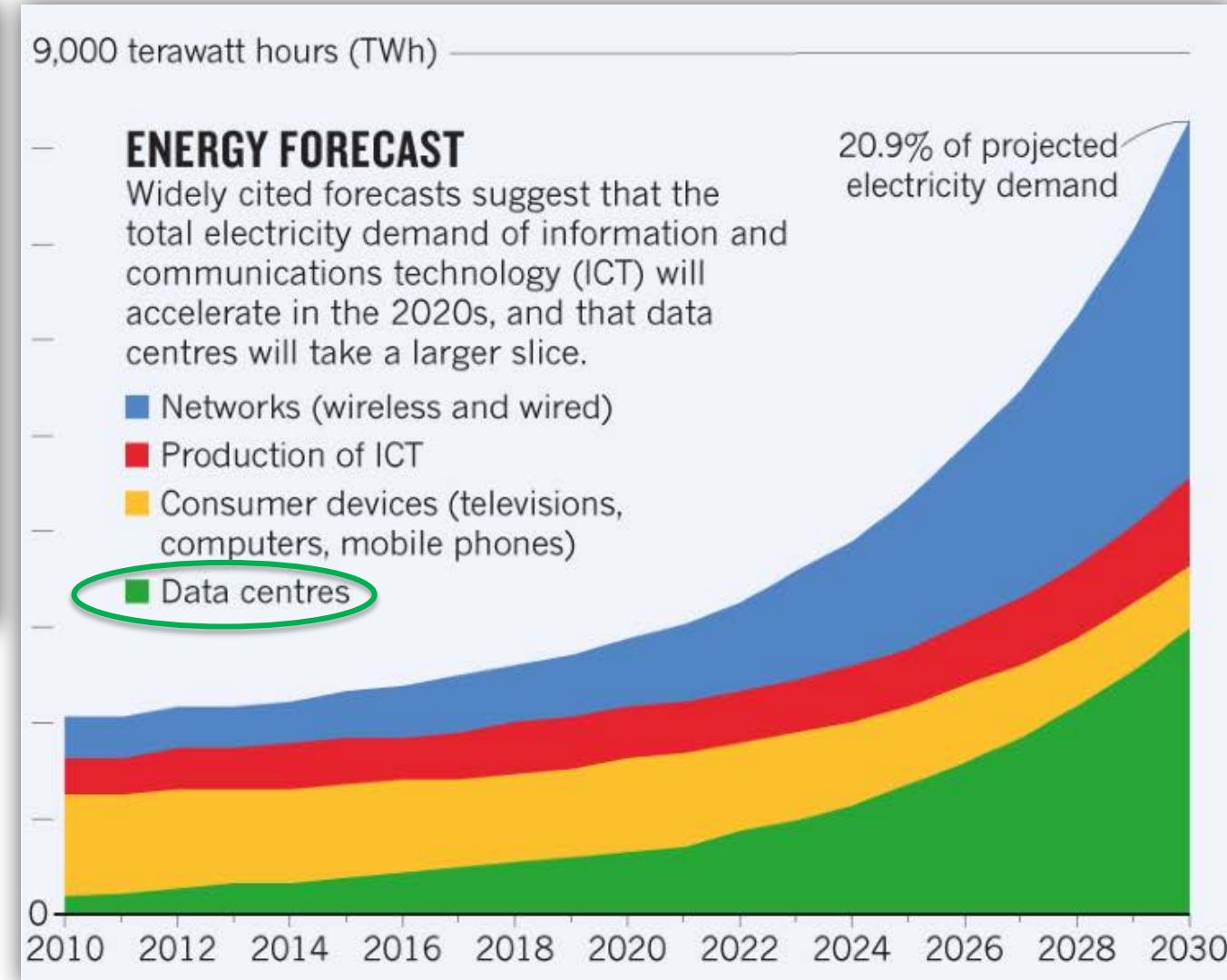
Background & Motivation

Extreme Energy Demands- HPC



The New York Times

A.I. Could Soon Need as Much Electricity as an Entire Country

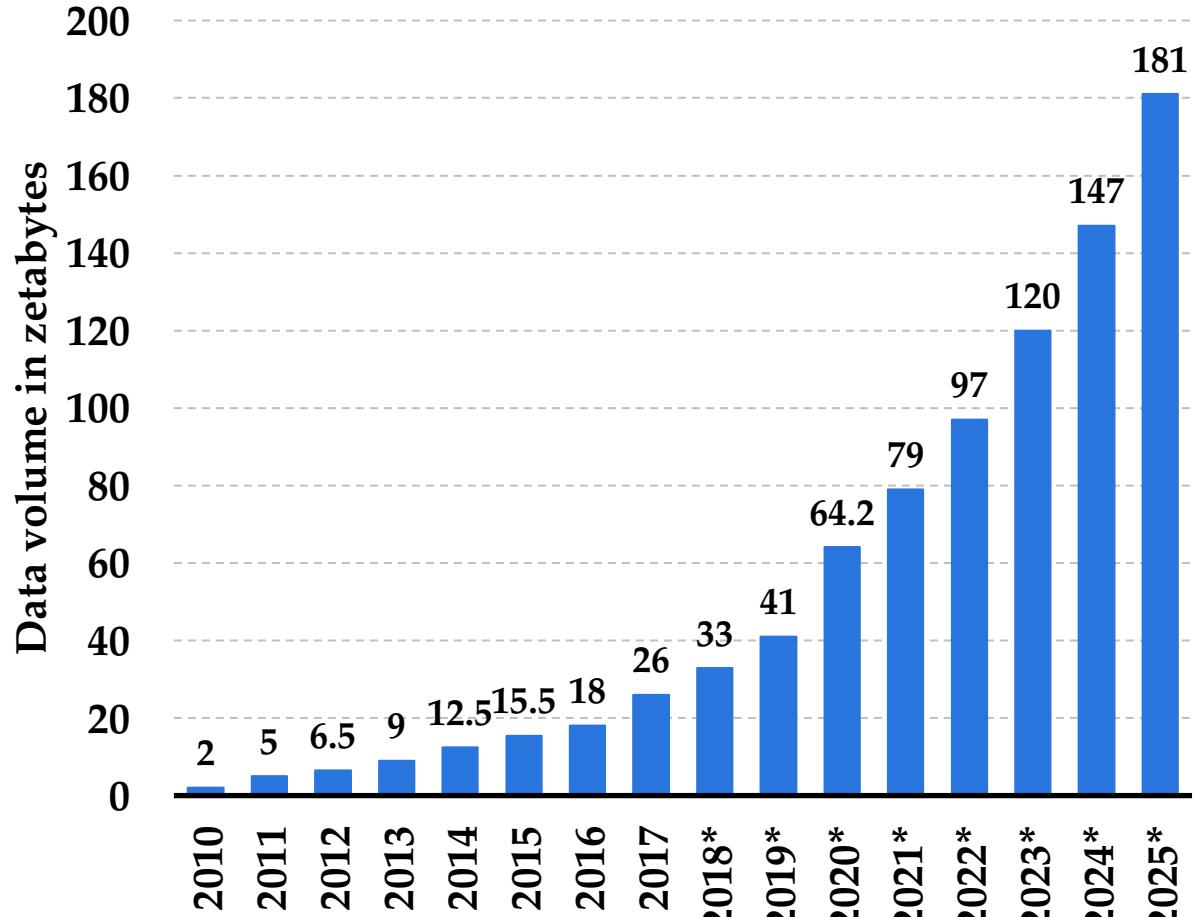


Extreme Energy Demands- HPC



The New York Times

A.I. Could Soon Need as Much Electricity as an Entire Country

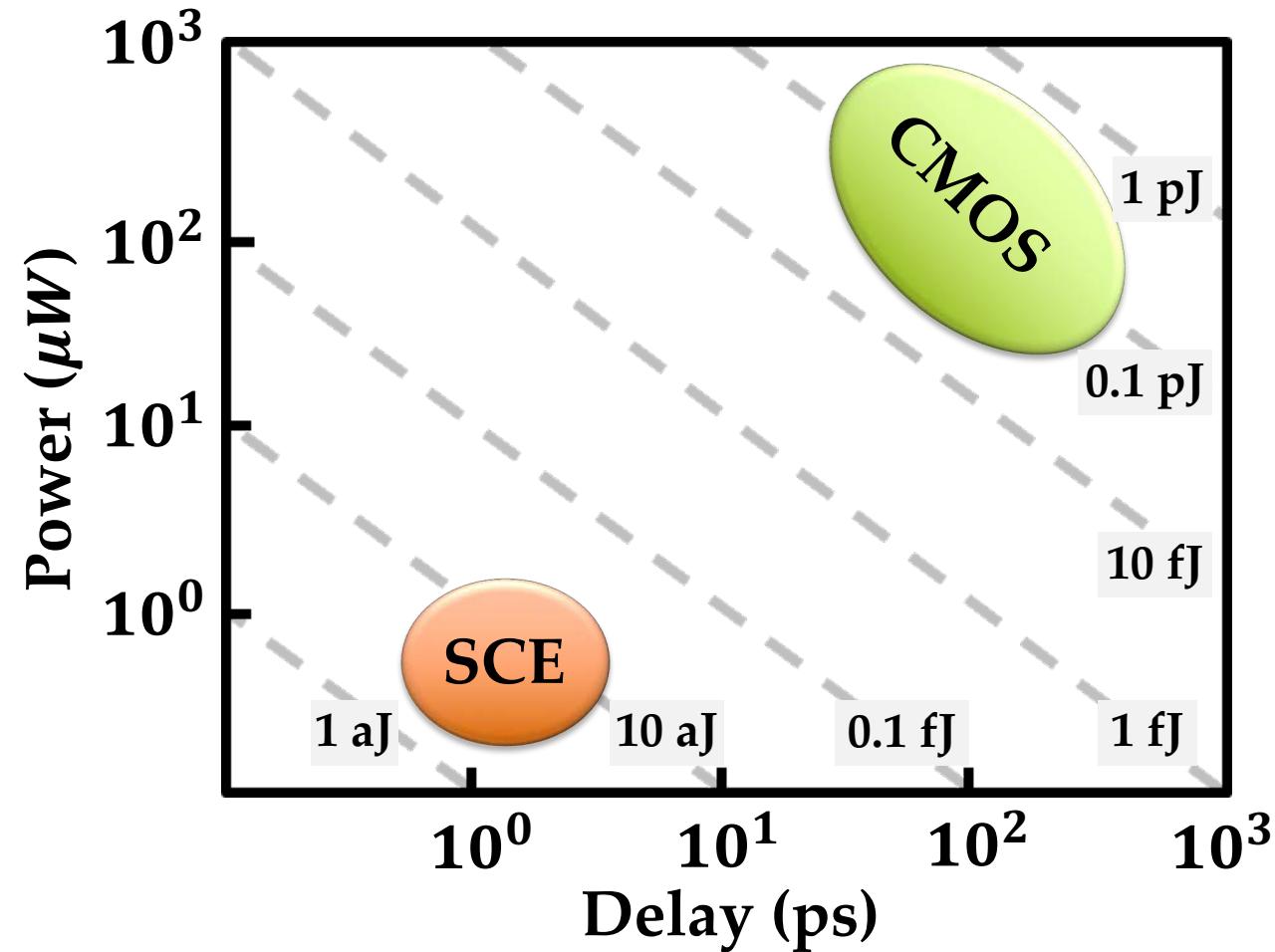


The volume of Data Created, Captured, Copied, & Consumed Worldwide (Released: June 2021)

Superconducting Electronics

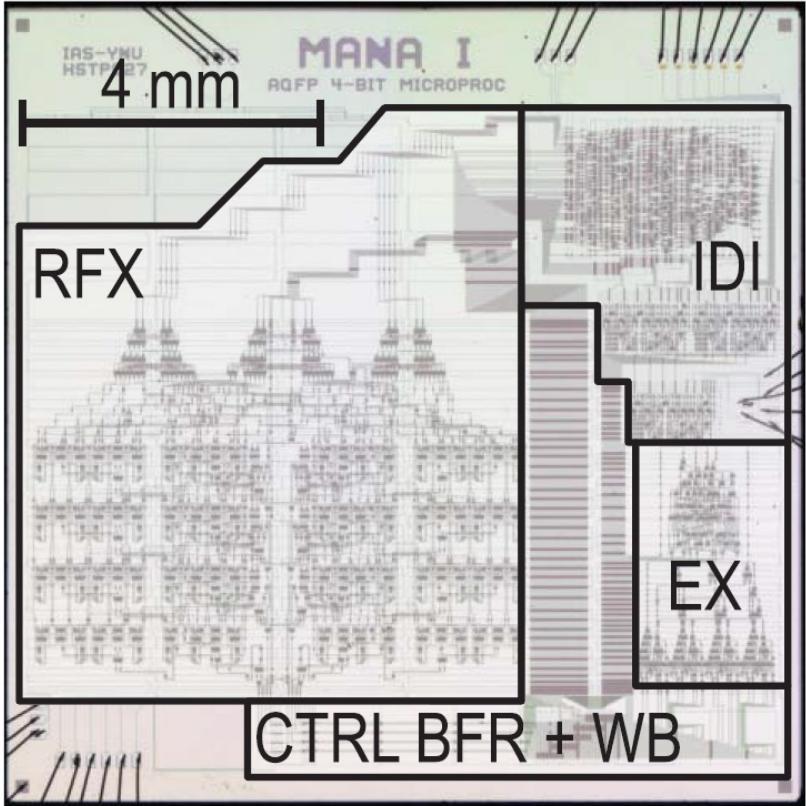
Superconducting Electronics

- Ultra-high Speed (100s of GHz)
- High Energy Efficiency (atto-Joule)
- Can Solve CMOS Power Issues
- Lossless Superconducting Interconnects



Monolithic Adiabatic Integration Architecture (MANA)

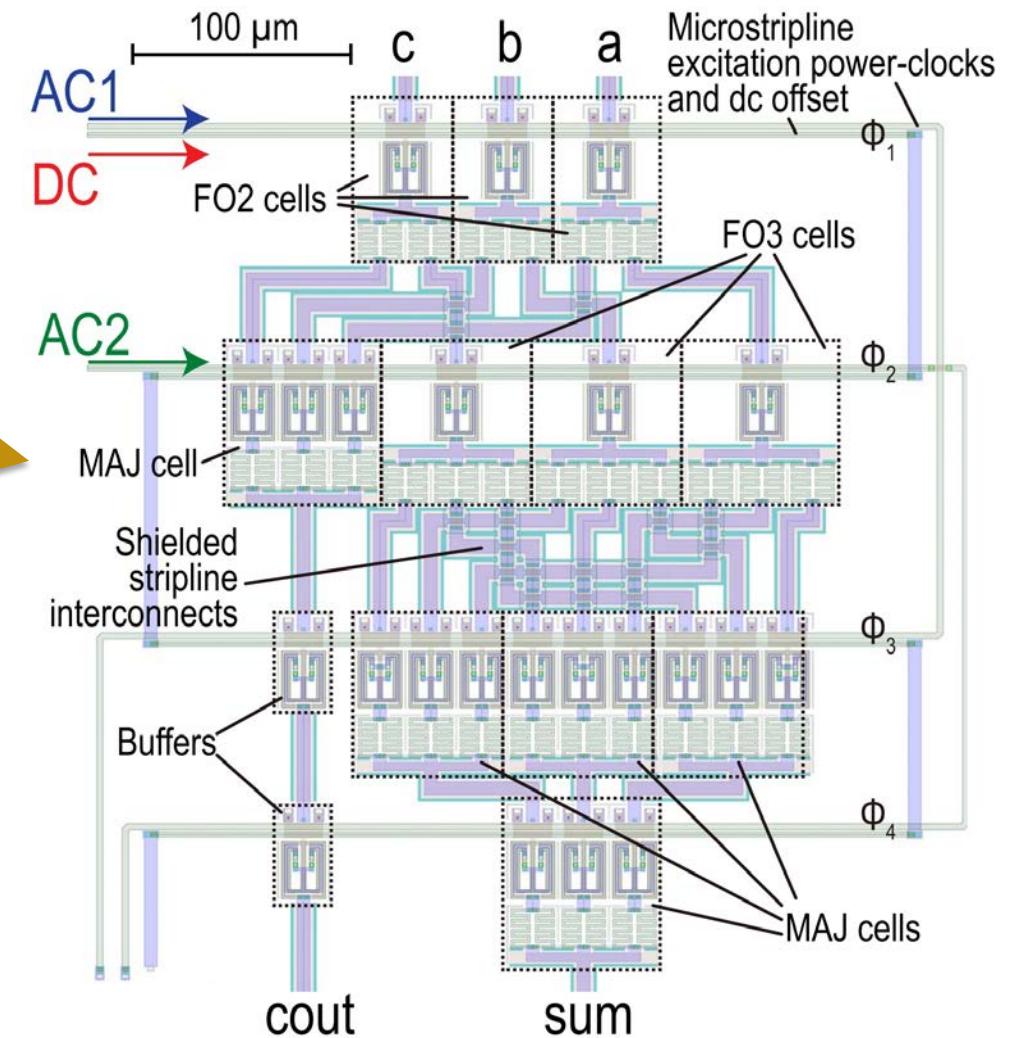
Monolithic Adiabatic Integration Architecture Microprocessor



IEEE Spectrum FOR THE TECHNOLOGY INSIDER

Superconducting Microprocessors? Turns Out They're Ultra-Efficient › The 2.5 GHz prototype uses 80 times less energy than its semiconductor counterpart, even accounting for cooling

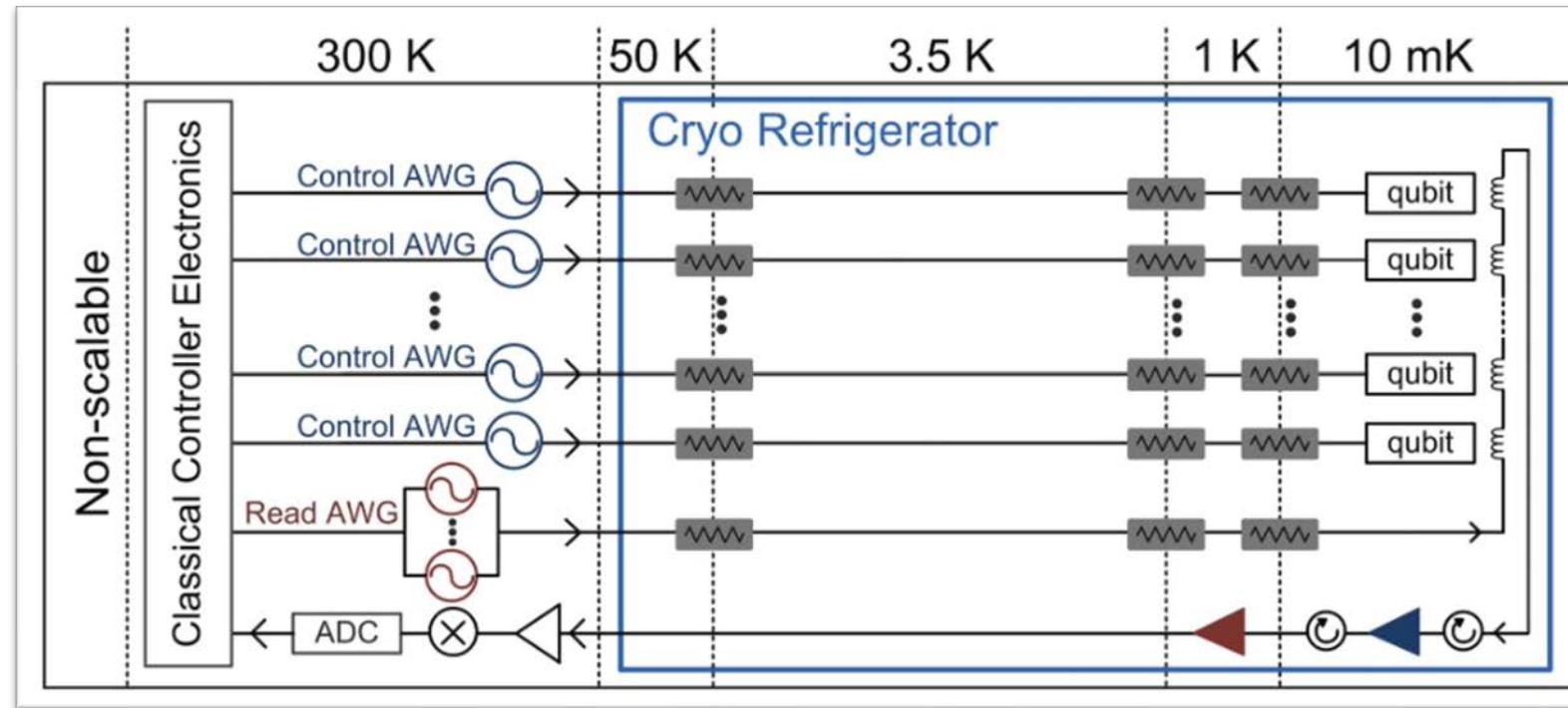
AQFP full-adder based on majority logic



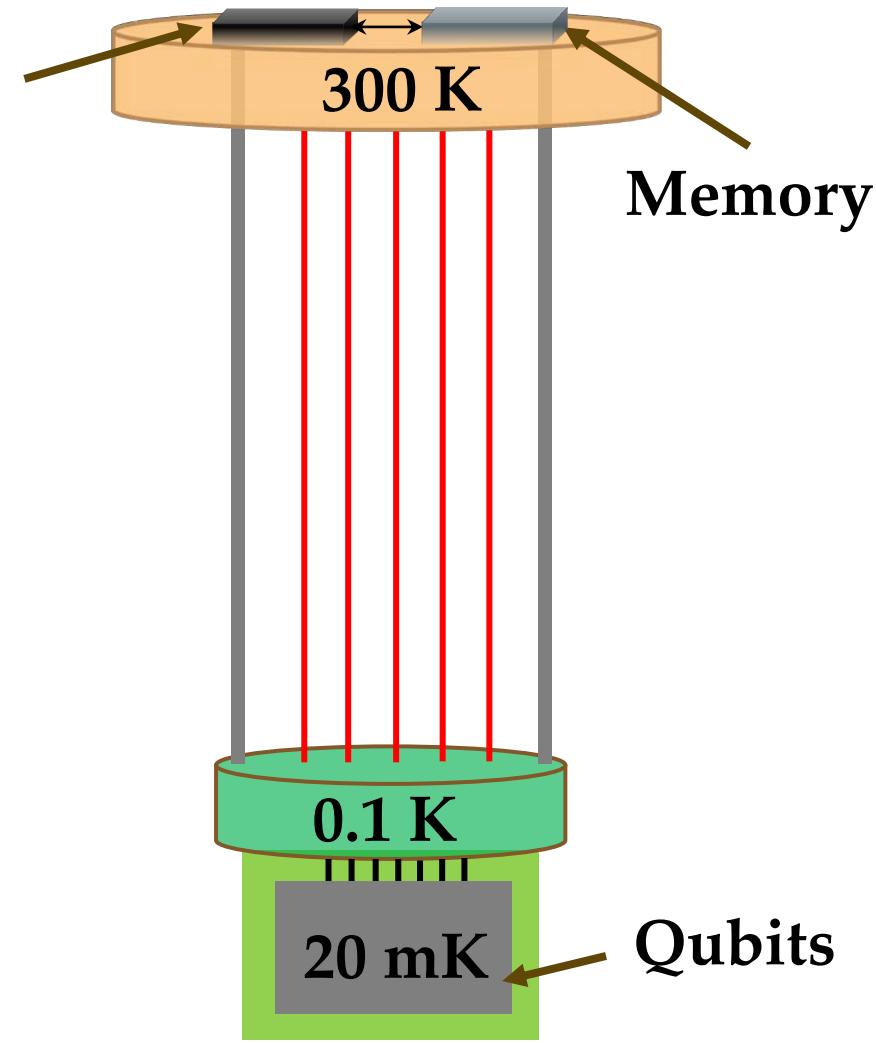
Quantum Computer: Current Scenario

Quantum Computer with 53 Qubits

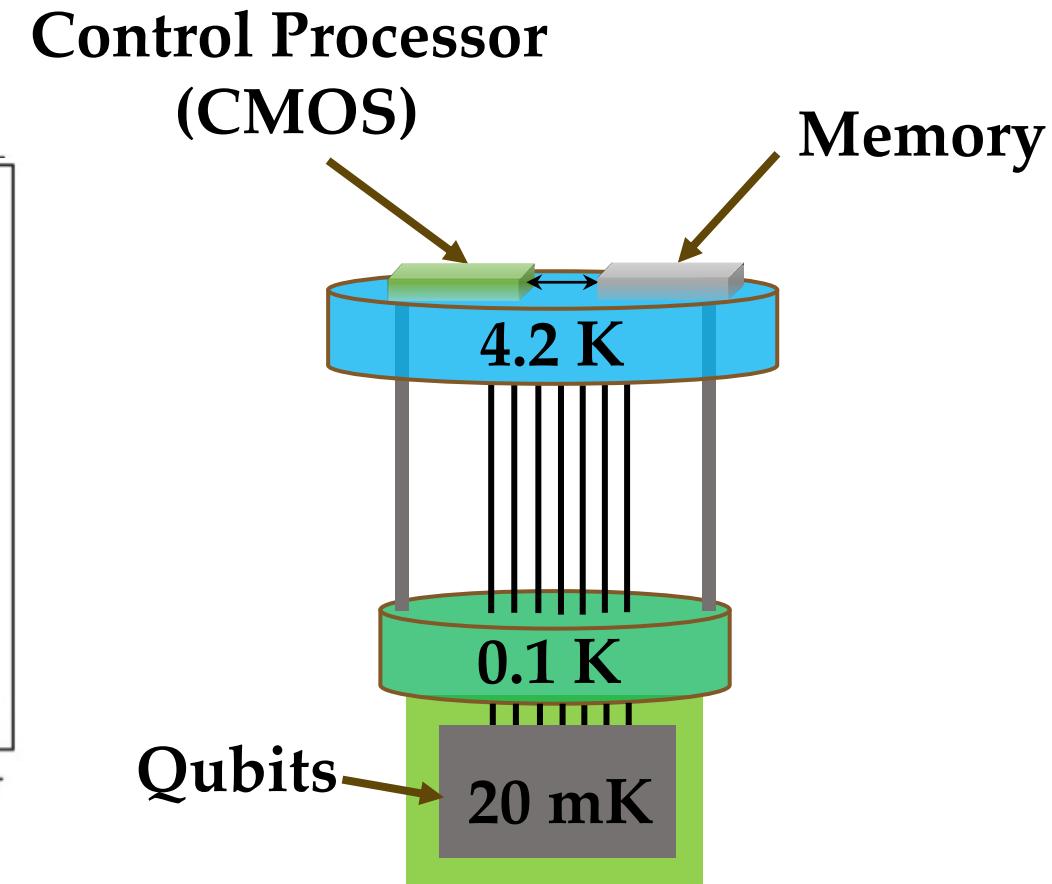
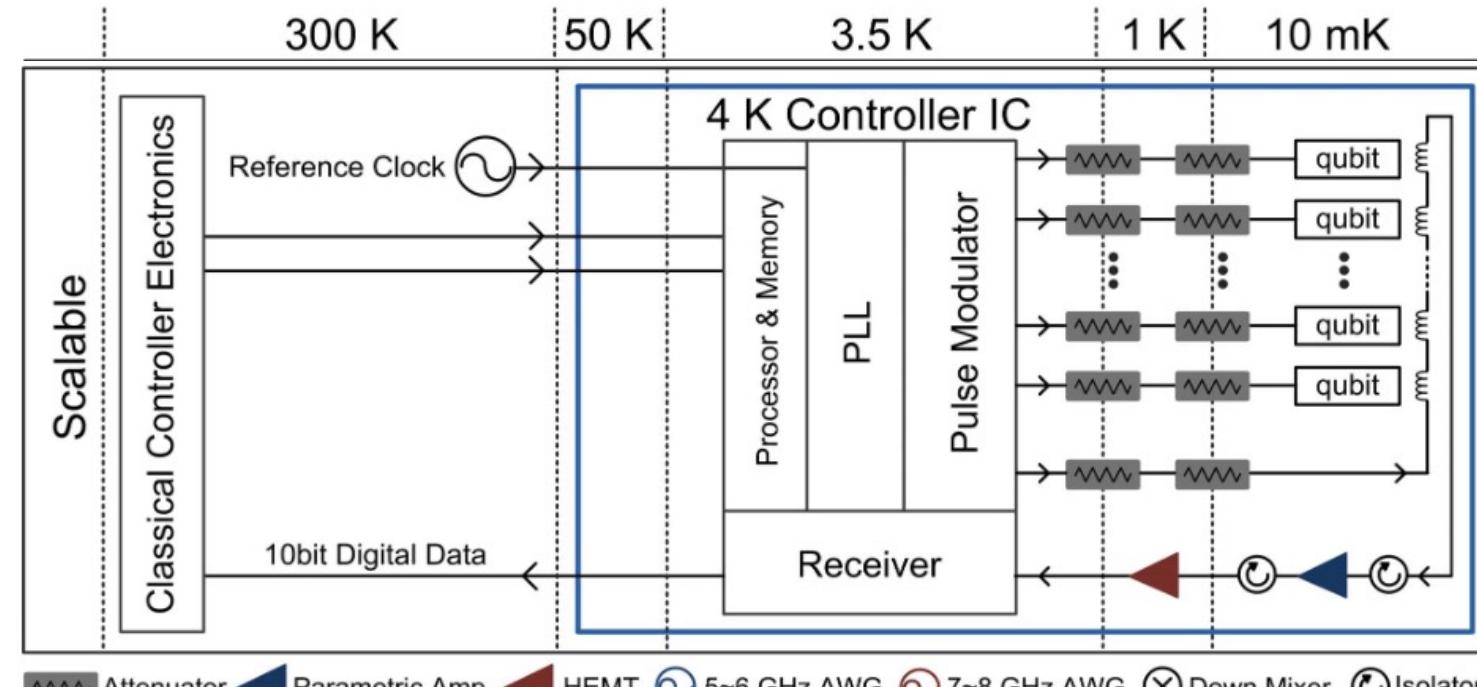
- 200 Wideband Coaxial Cables
- 45 Microwave Circulators
- A rack of Electronic Circuits



Control Processor

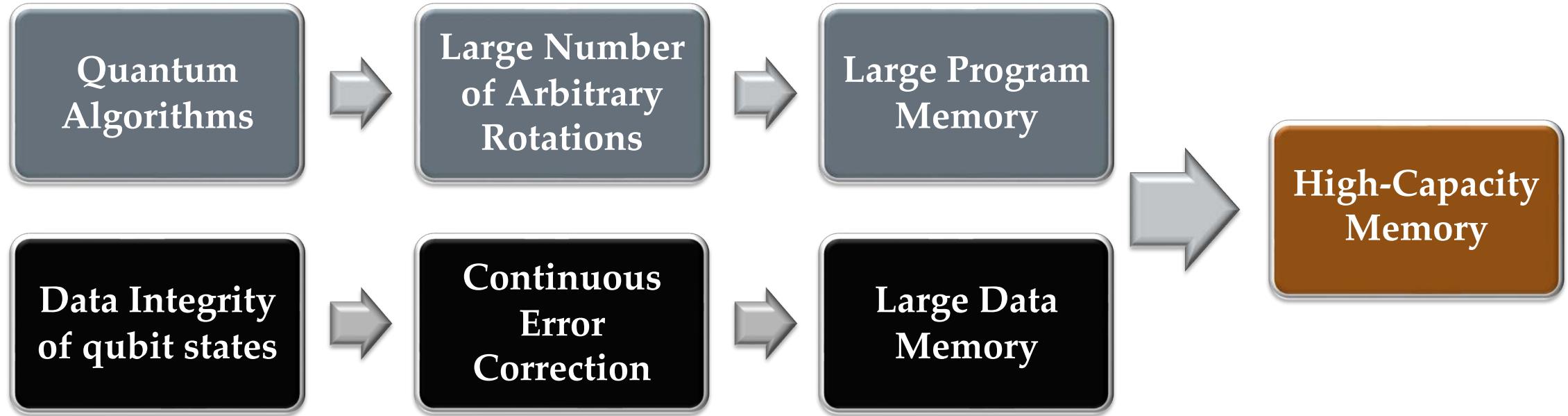


Quantum Computer: Goal



To run Shor's algorithm for prime factorization on a 1024-bit number in a quantum computer, two quantum registers (one with 2048 qubits and another with 1024 qubits) are required.

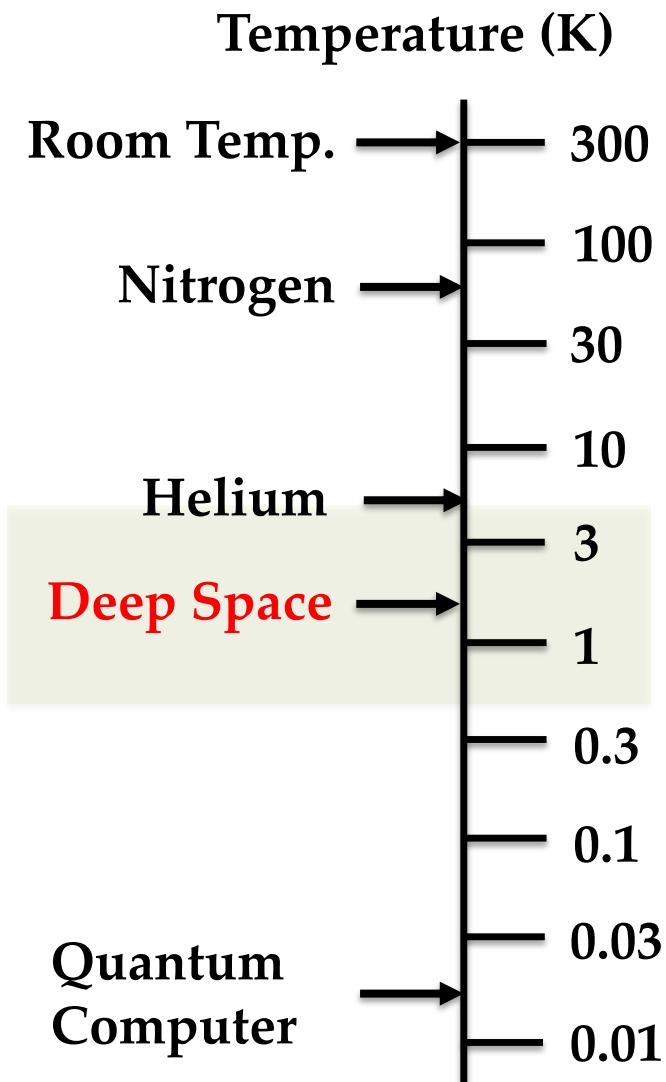
Need for (Classical) Memory



Aerospace Applications

Superconducting Devices in Spacecrafts

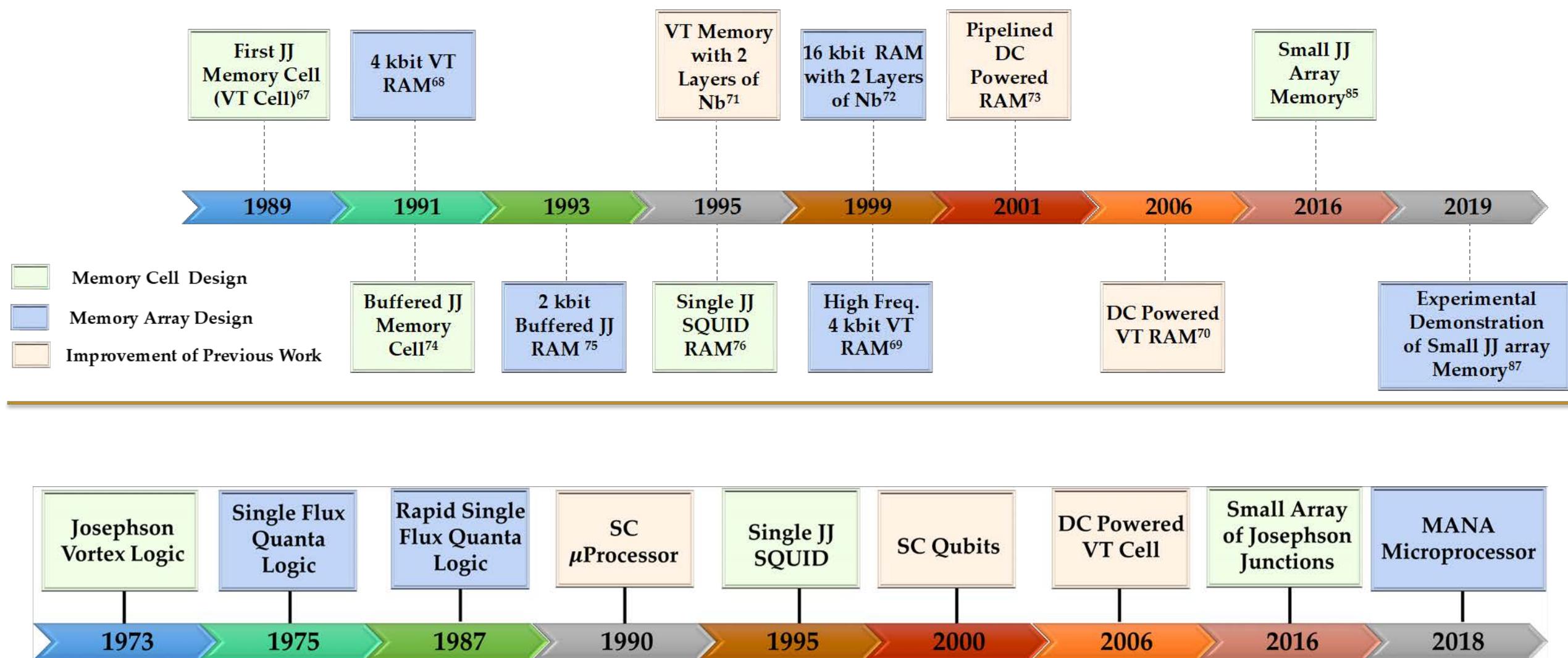
- Better efficiency
- More reliability
- Simpler design
- Wider wavelength range to work with
- No/Negligible cooling cost



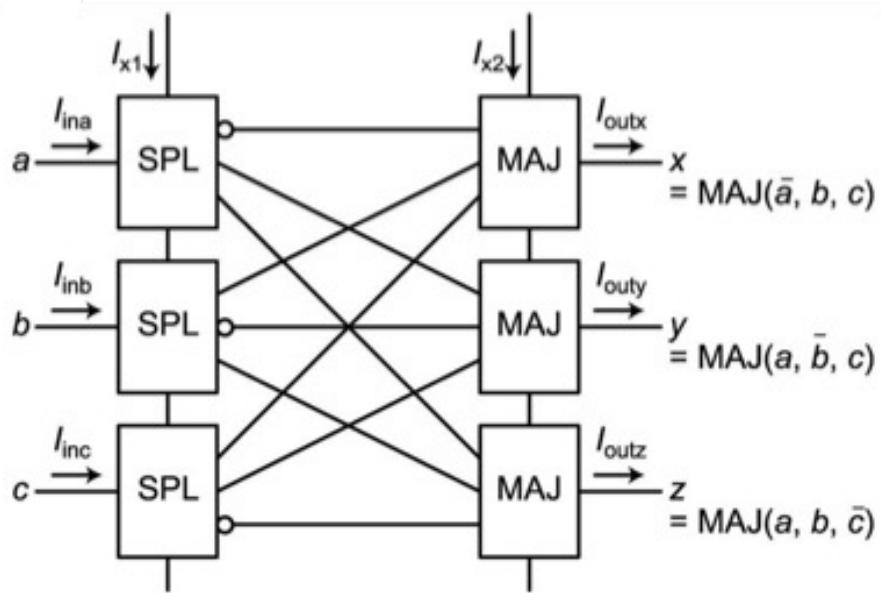
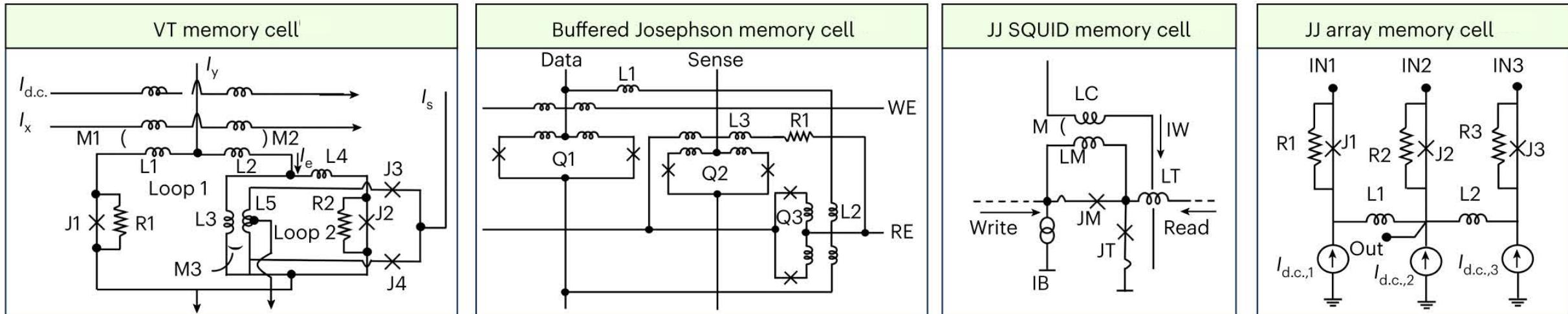


State-of-the-Art & Existing Challenges

History of Superconducting Logic/Memory



Existing Challenges



Use of inductors

Limited integration density due to flux trapping and sensitivity to magnetic fields

Use of Current-bias

Single fanout due to the current-controlled logic

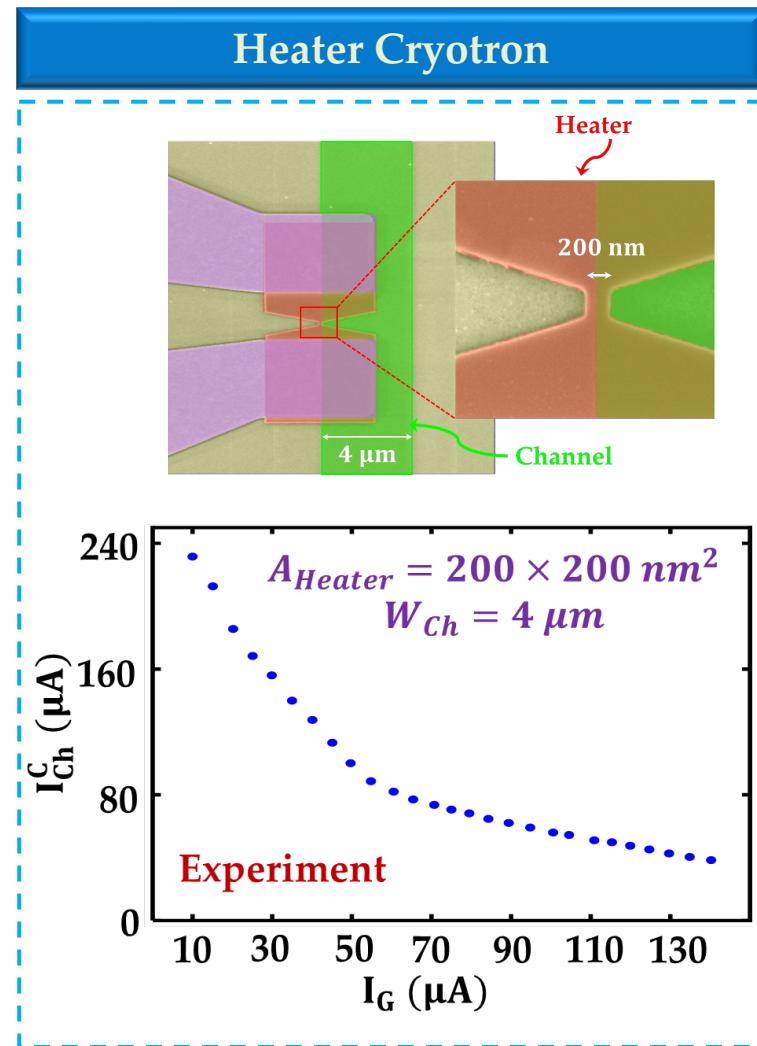
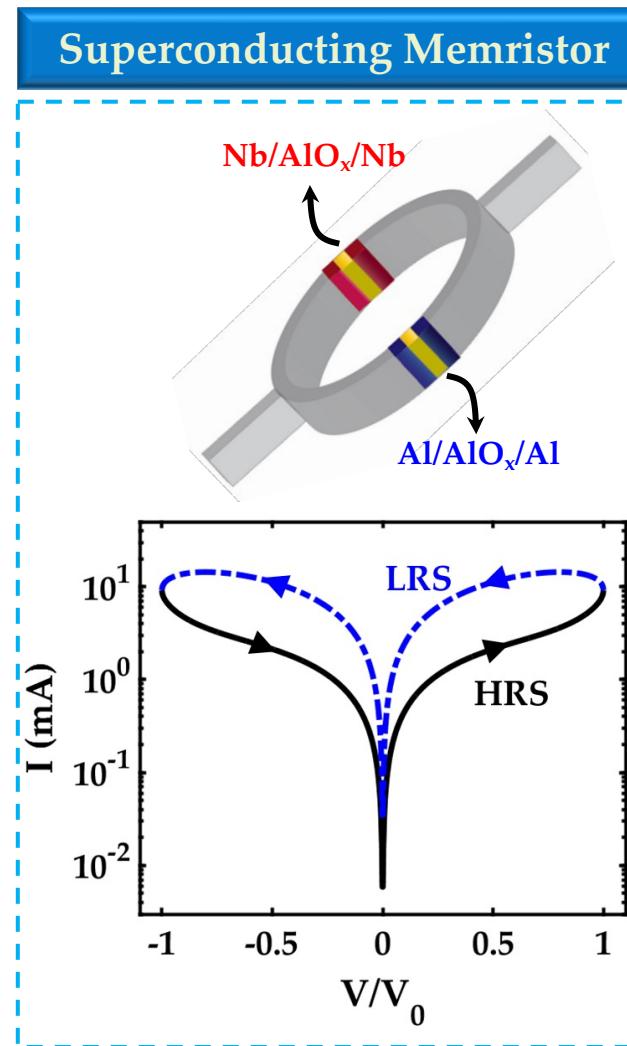
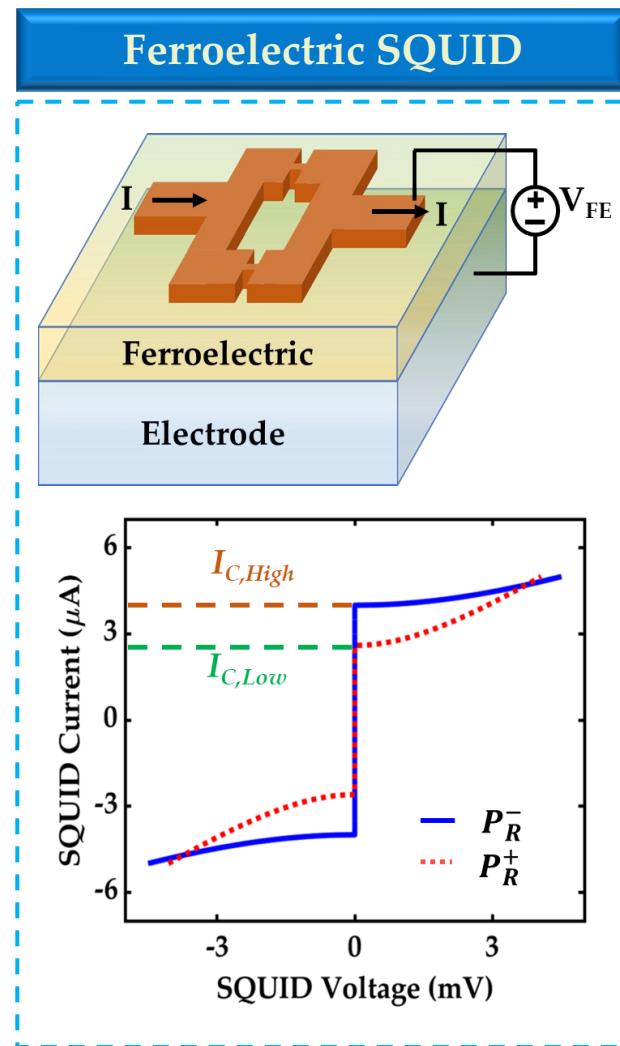
Low Resistive State

Difficulty in driving high impedances.

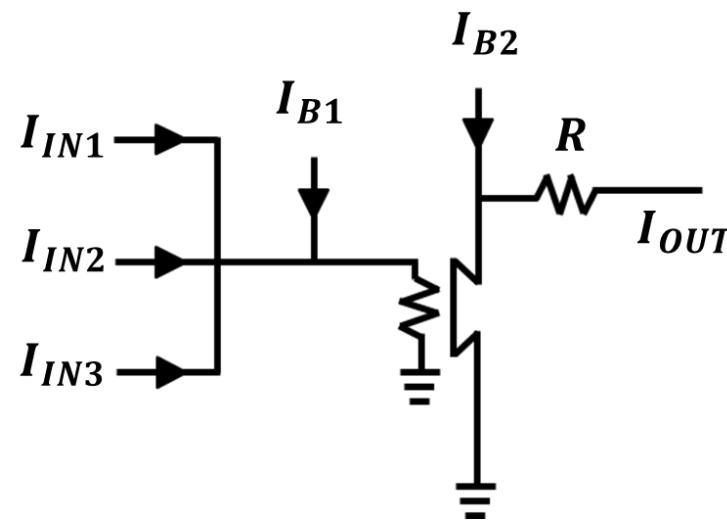
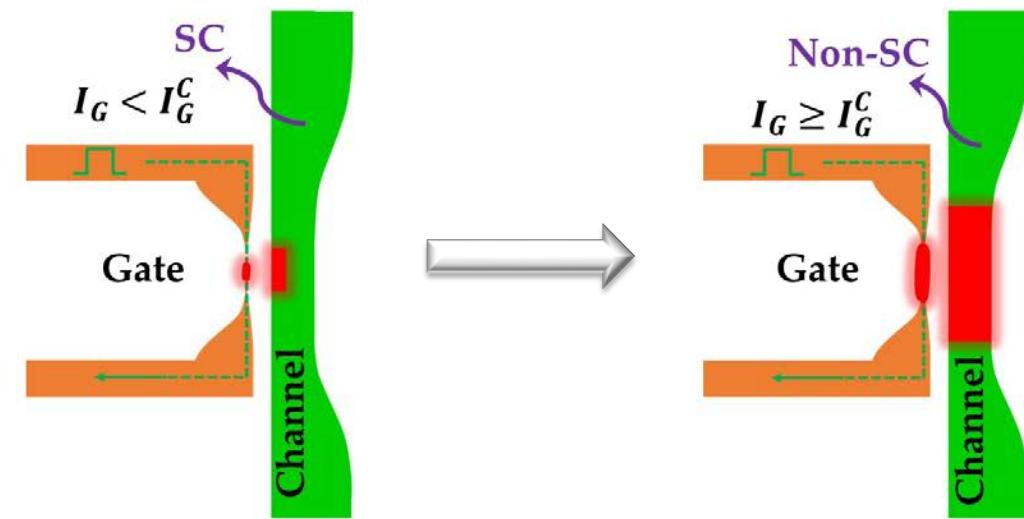
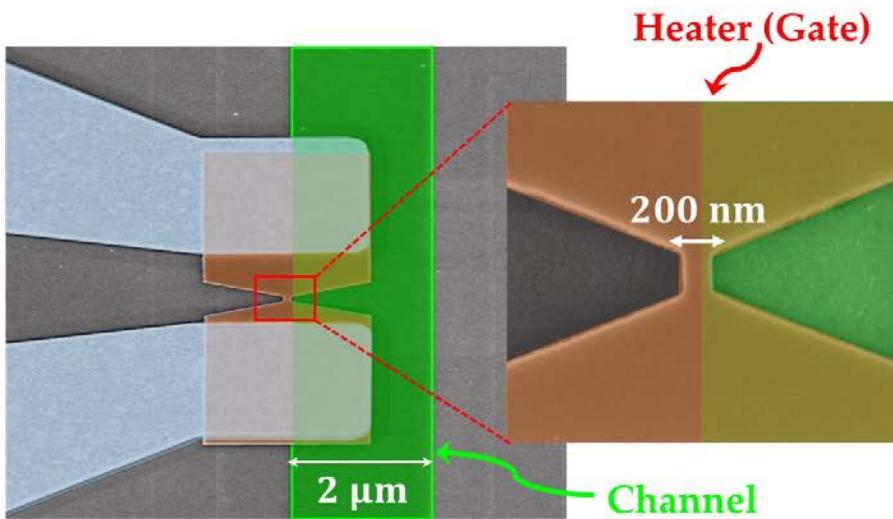


Reimagining Superconducting Logic & Memory

Emerging Superconducting Devices

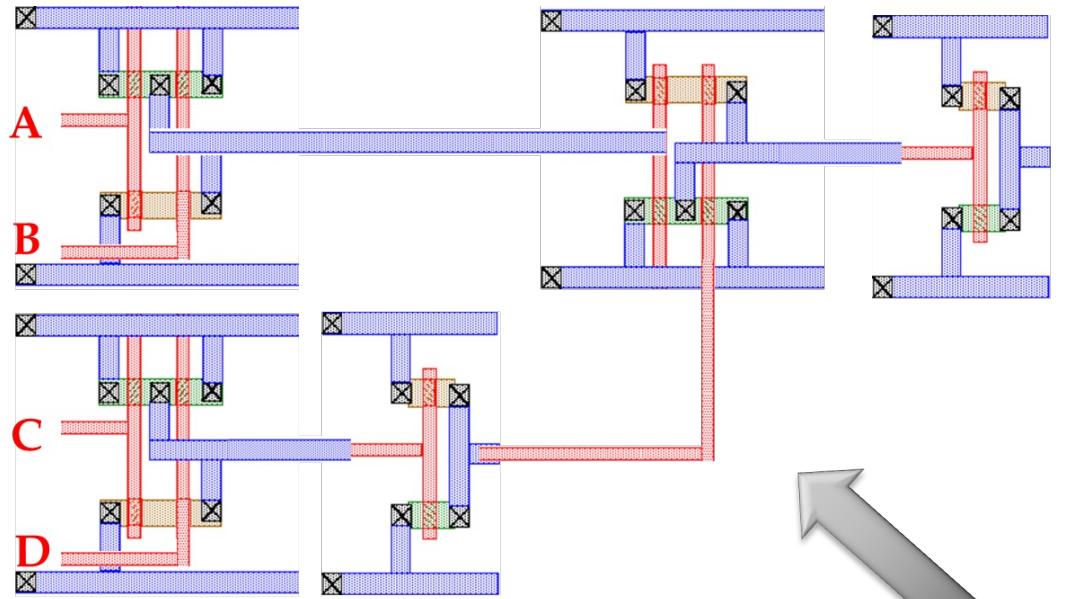


Reconfigurable Logic

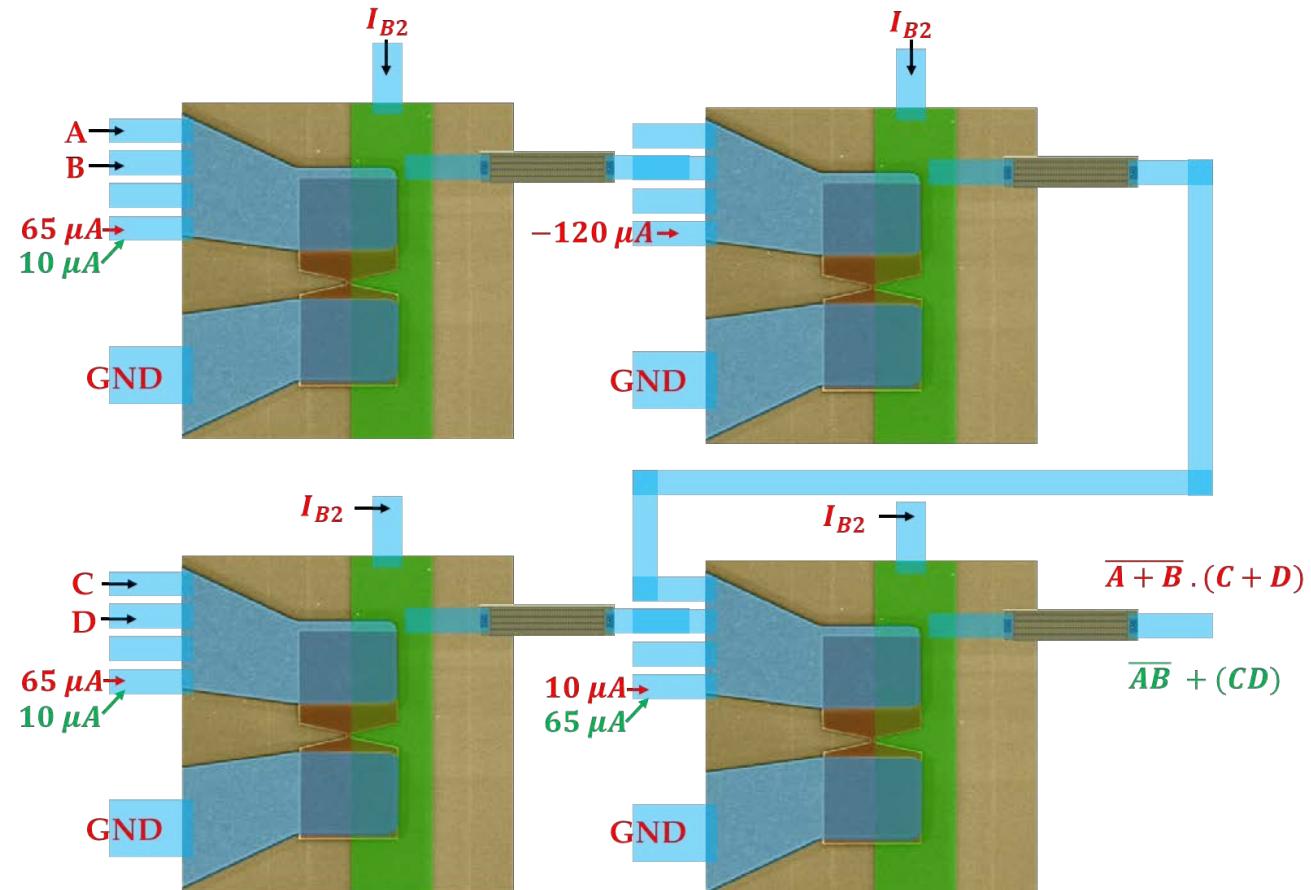


Reconfigurable Boolean Logic Functions			
I_{B1}	I_{B2}	Logic Function	
$I_G^C/2 < I_{B1} < I_G^C$	$55 \mu A$	Copy	1-Input
$I_{B1} < -I_G^C$	$55 \mu A$	NOT	
$0 < I_{B1} < I_G^C/2$	$55 \mu A$	AND	2-Input
$I_G^C/2 < I_{B1} < I_G^C$	$55 \mu A$	OR	
$0 < I_{B1} < I_G^C/2$	$55 \mu A$	Majority	3-input

Reconfigurable Logic

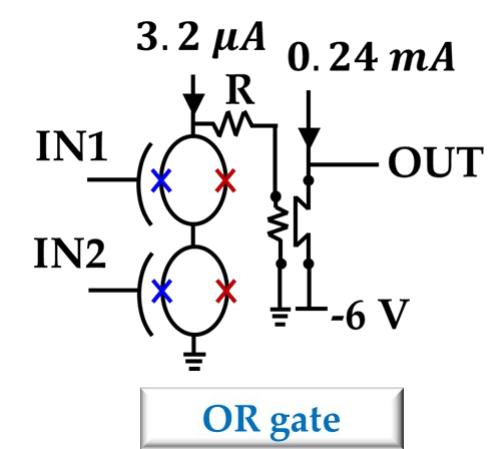
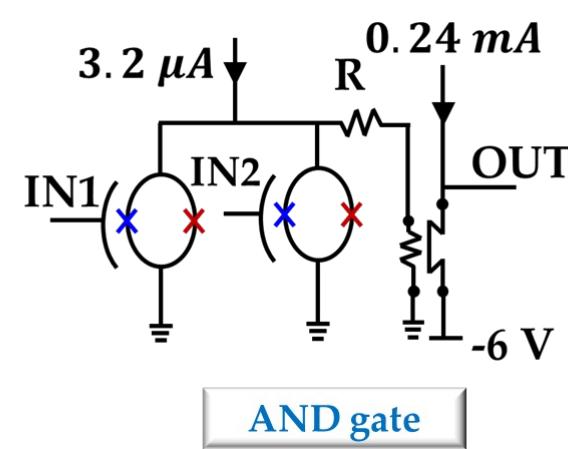
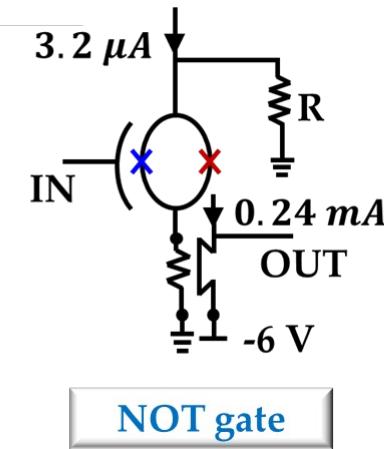
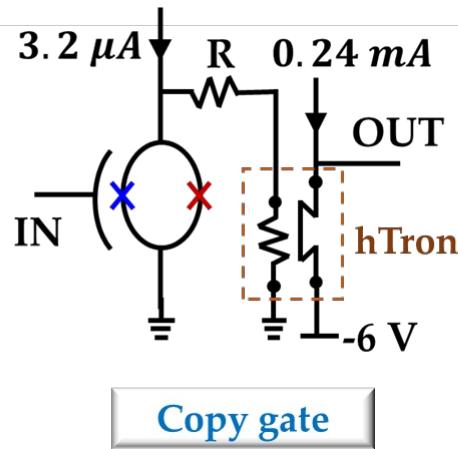
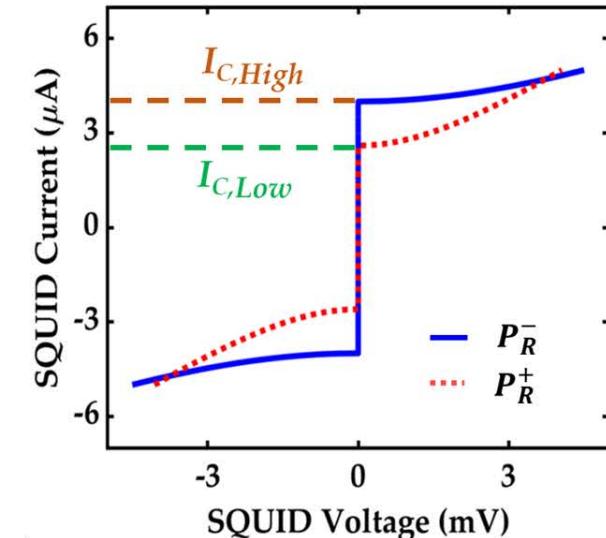
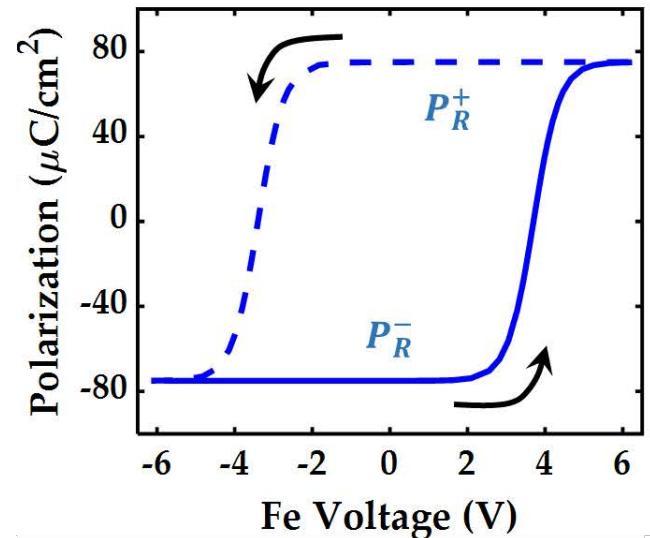
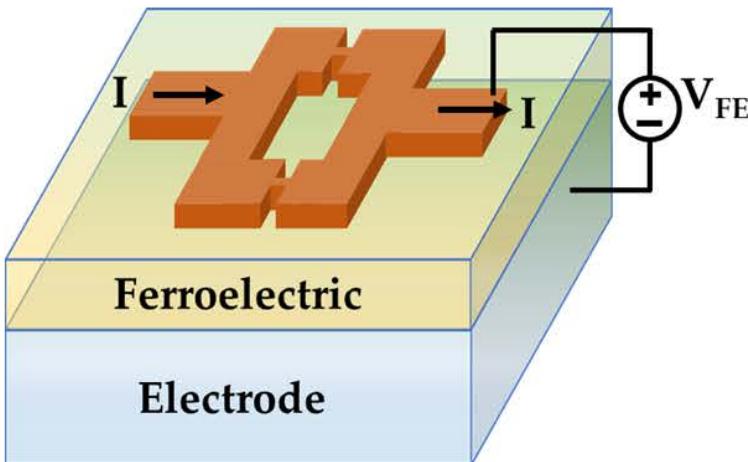


$$\overline{AB} + CD$$

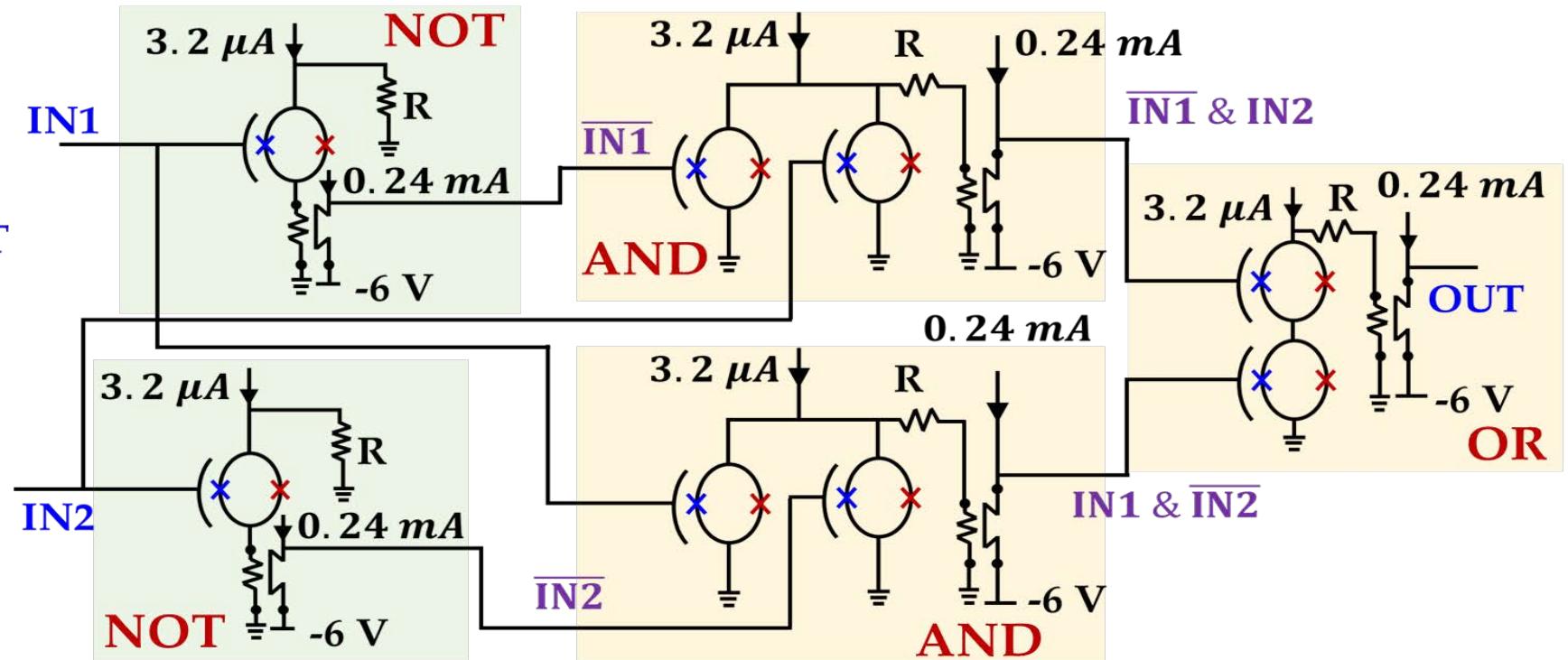
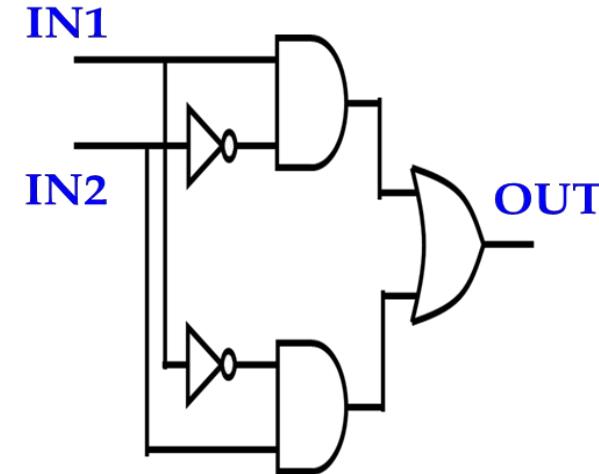


- Same layout for all logic operations
- Logic Camouflaging
- Security against reverse engineering

Voltage-Controlled Superconducting Logic

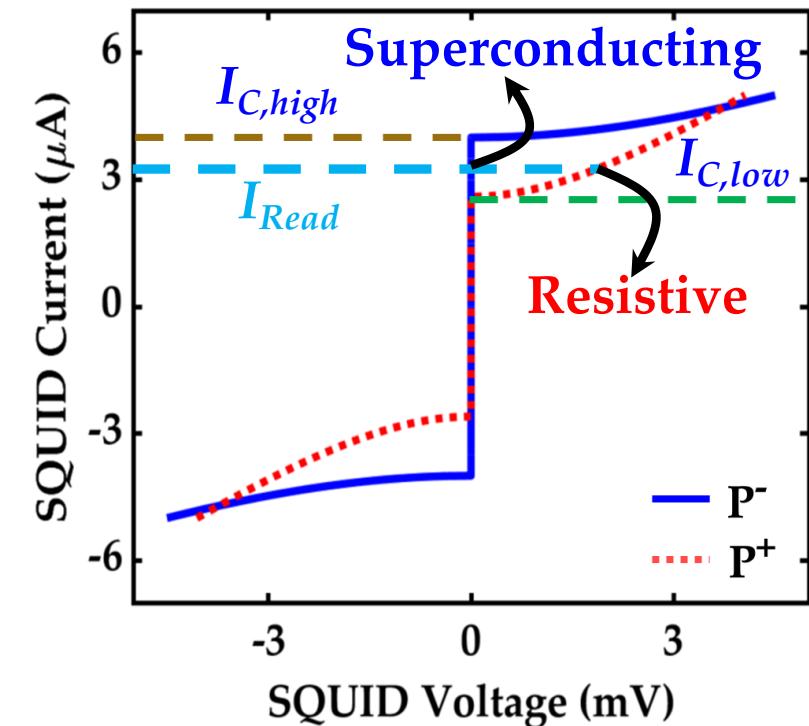
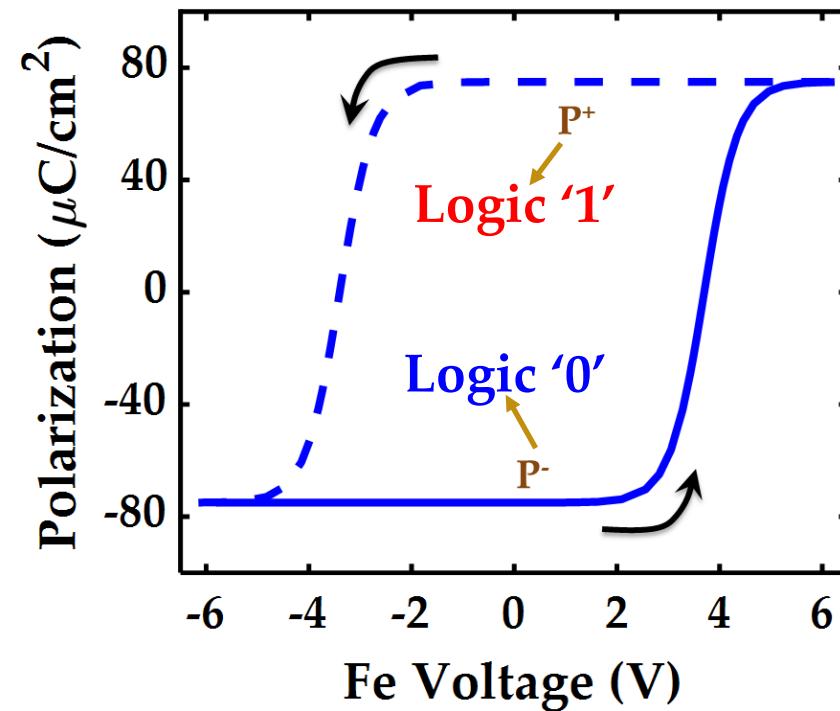
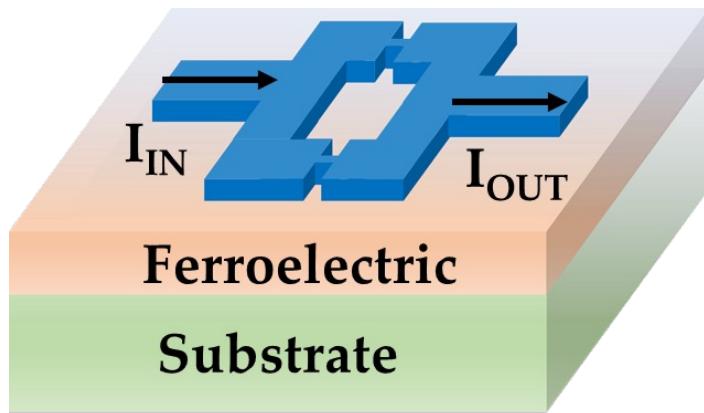


Voltage-Controlled Superconducting Logic



No Additional Circuitry Required for Larger Fanout

Ferroelectric SQUID (FeSQUID)



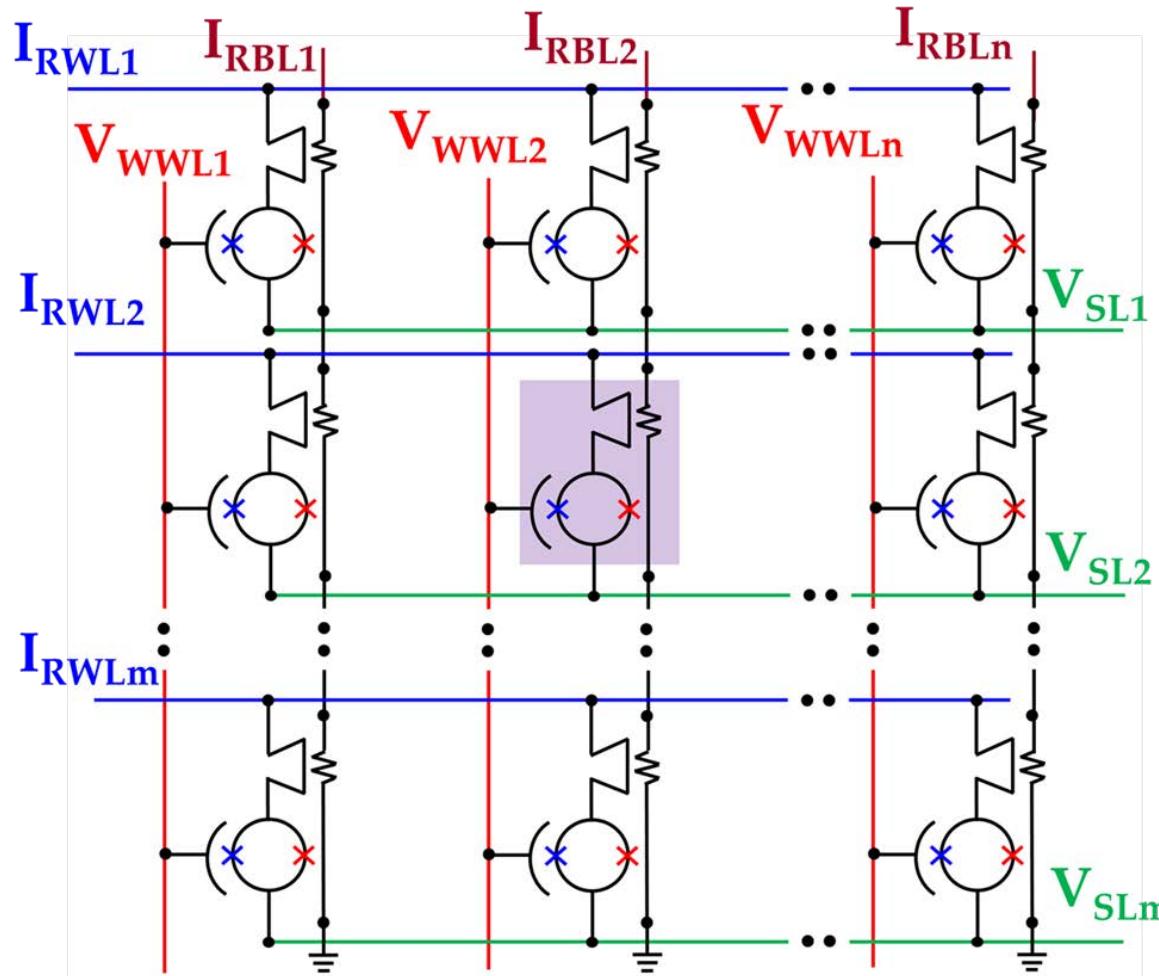
Non-Volatile

Voltage-Control

Superconducting

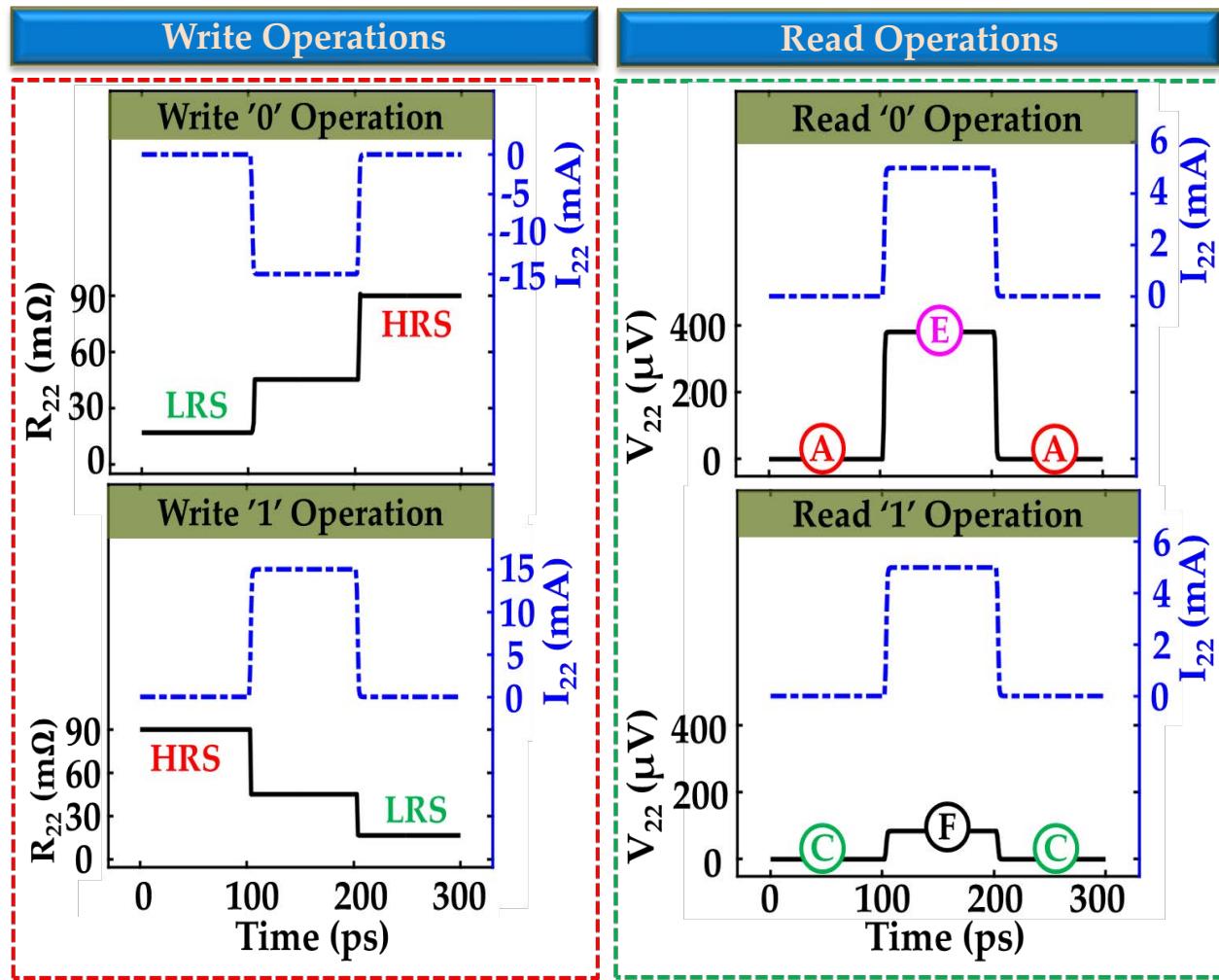
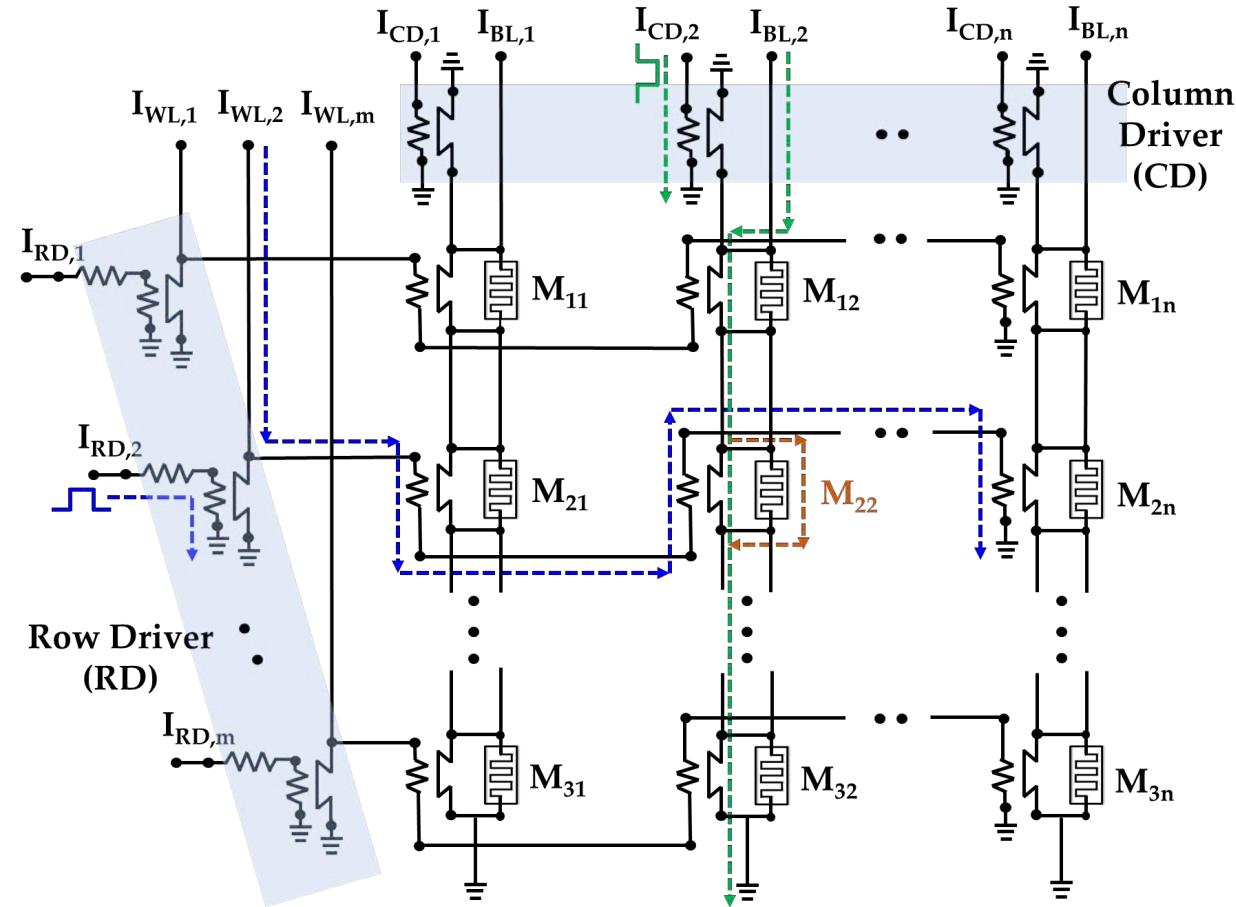
Separate read-write Paths

FeSQUID-based Memory Array



Biasing To Access (2, 2) Cell	
Write Operation	
WWL2	$\pm V_{WRITE}$
Other WWLs	$\pm V_{WRITE}/2$
SL2	0 V
Other SLs	$\pm V_{WRITE}/2$
Read Operation	
RWL2	I_{READ}
Other RWLs	0 A
RBL2	0 A
Other RBLs	I_{G_SW}

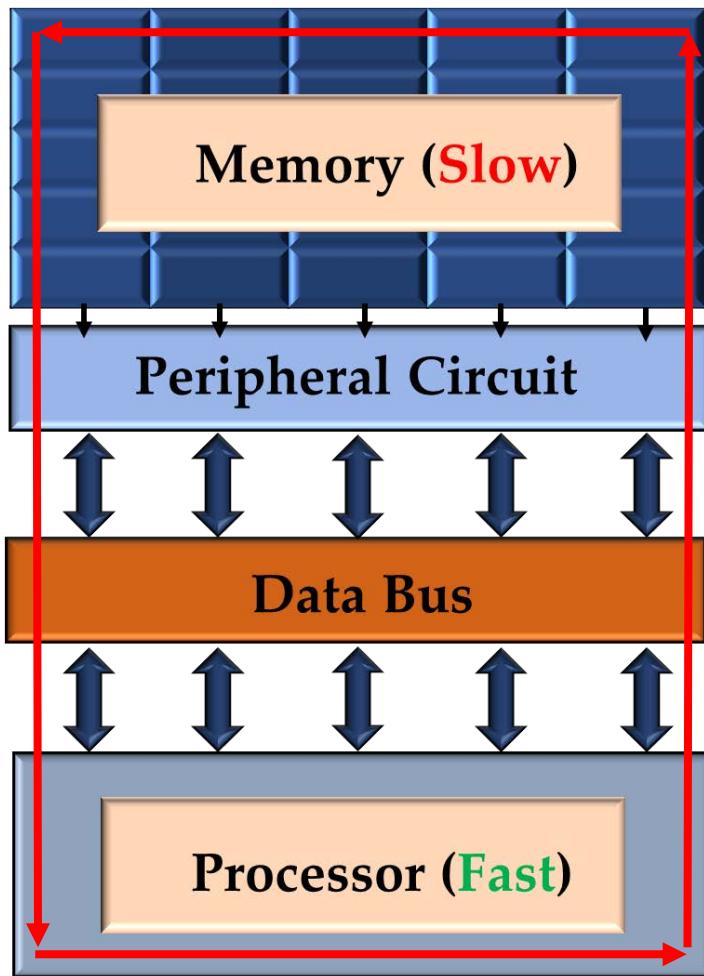
SC Memristor-based Memory Array





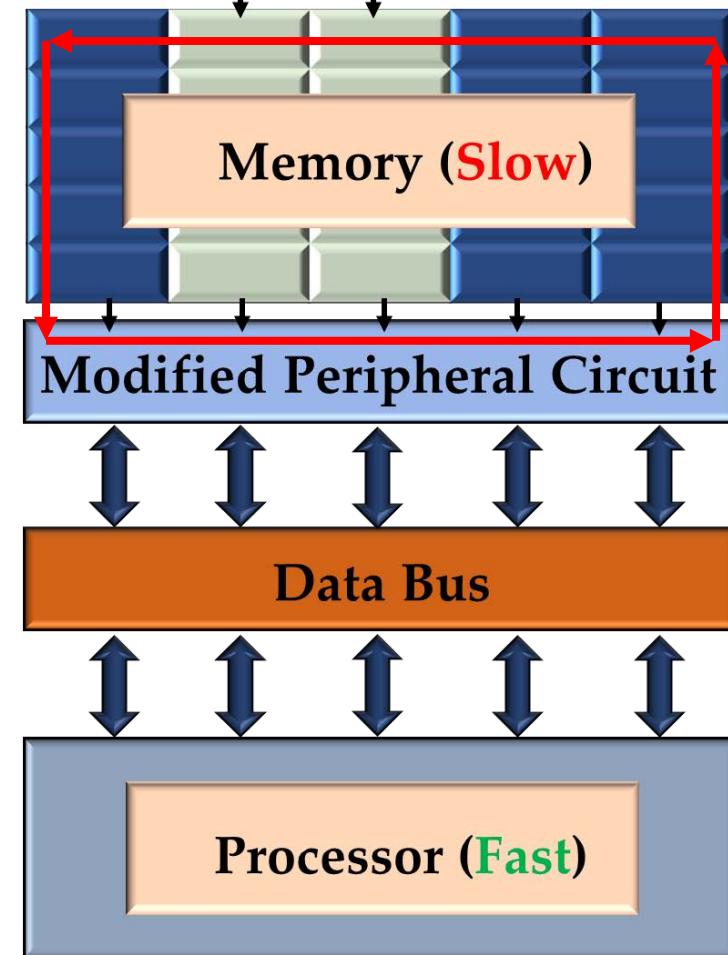
The Case for Compute-in-Memory @ Cryogenic Environment

Compute-in-Memory (CiM)



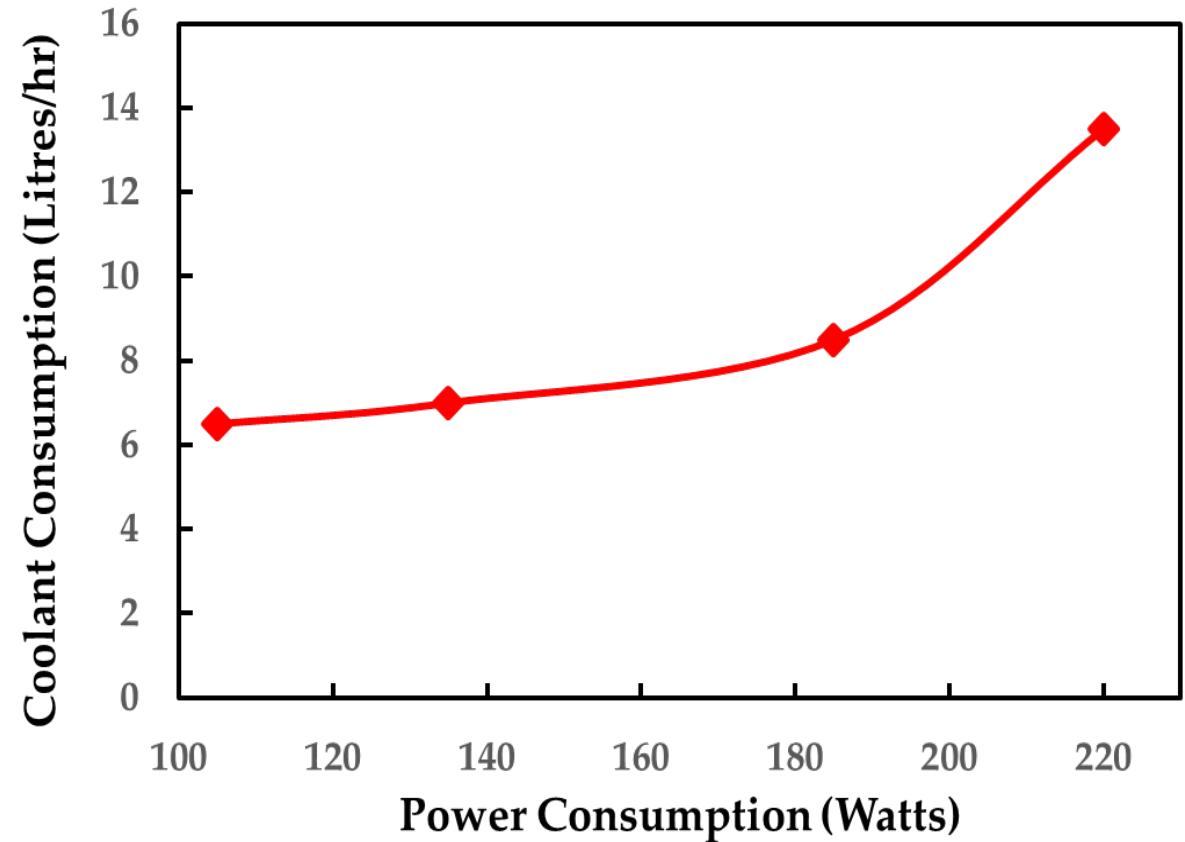
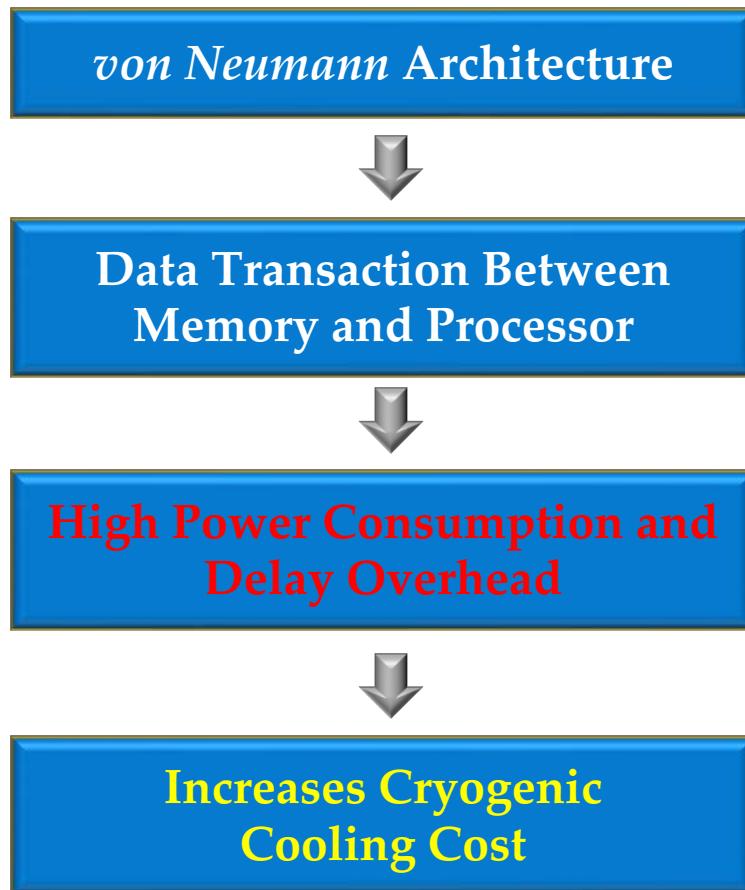
von-Neumann Architecture

Columns Activated for Computing



CiM Architecture

Why Cryogenic CiM?



Why Cryogenic CiM?

ML is Useful for Control and Quantum Error Correction of Qubits



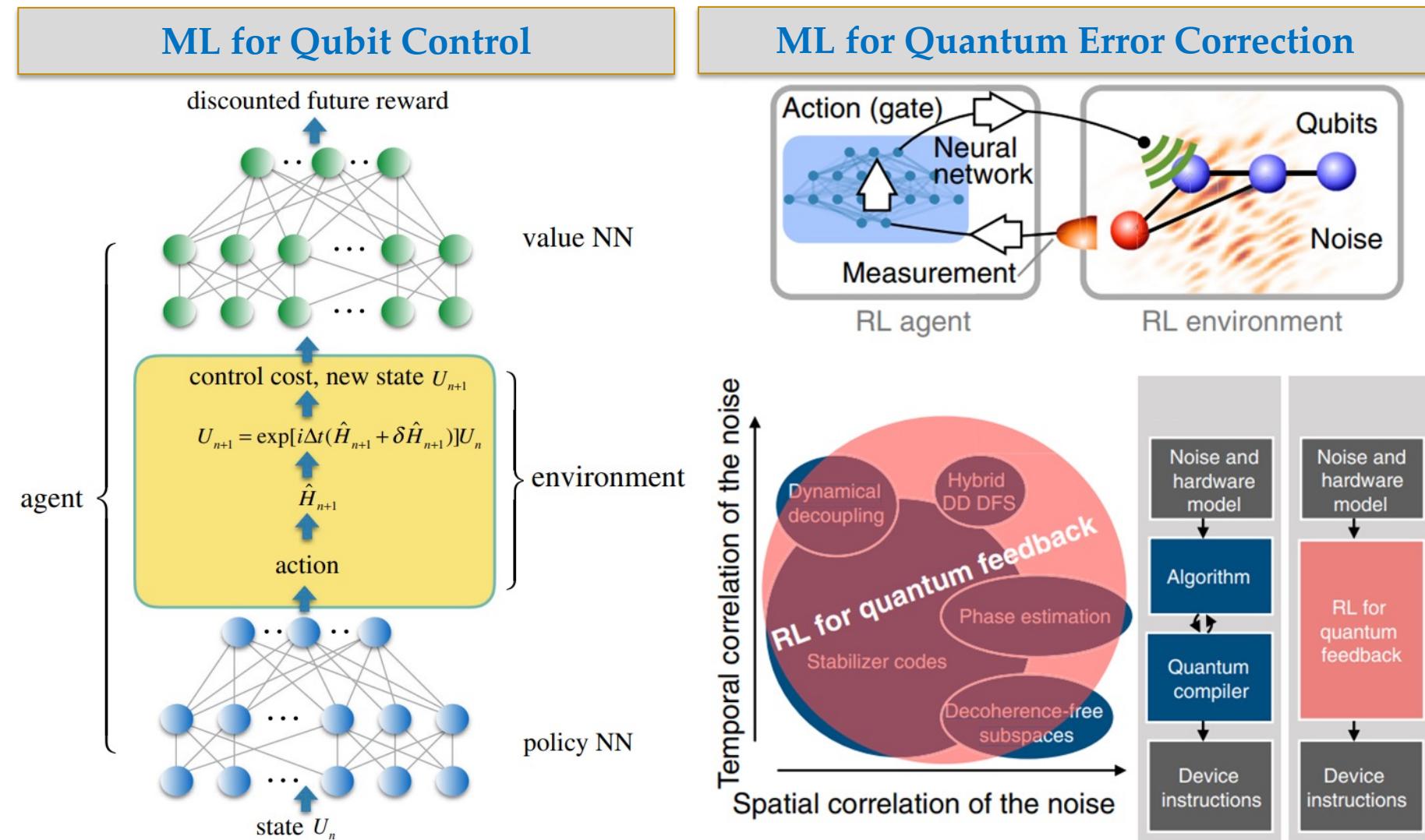
ML is Computationally Expensive



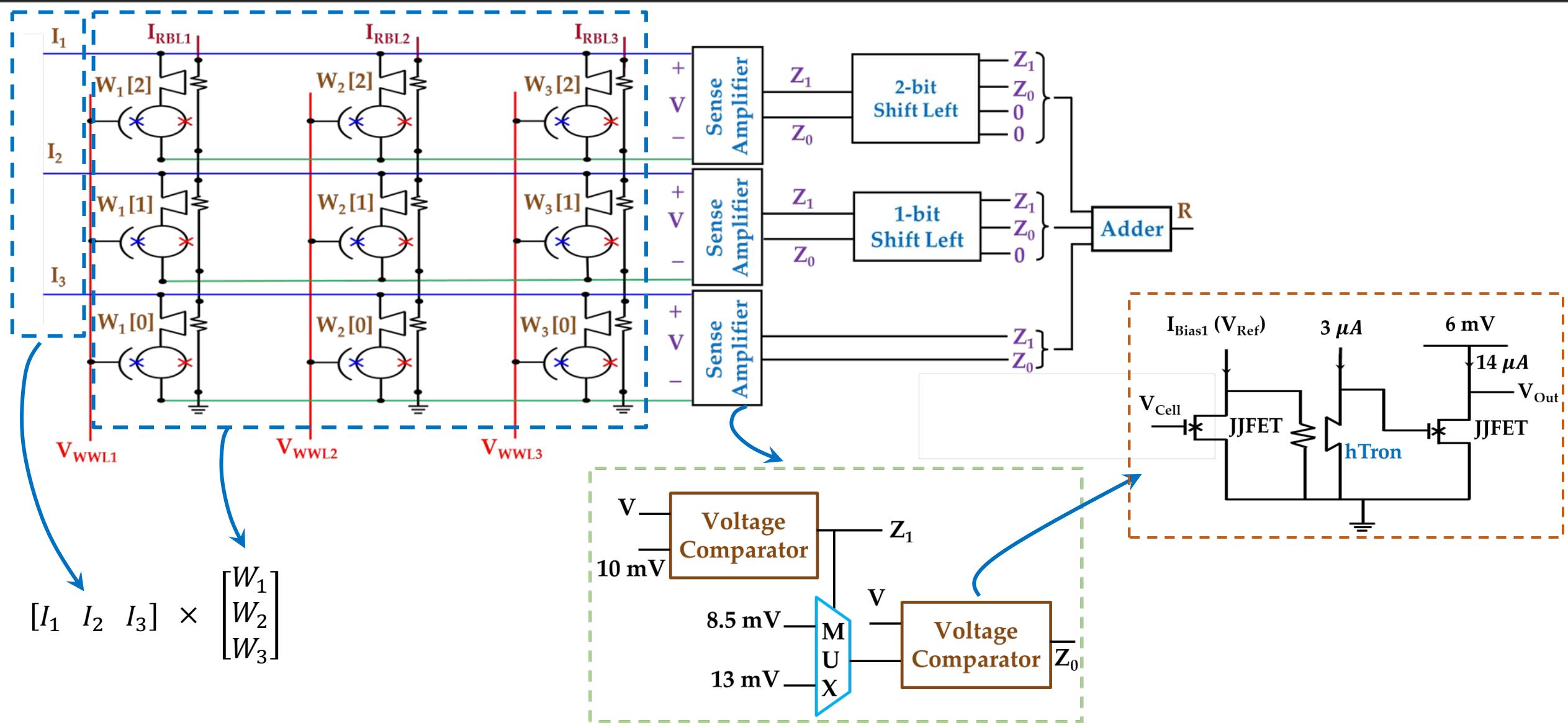
Huge Amount of Data Transaction



In-Memory Computing is a Solution



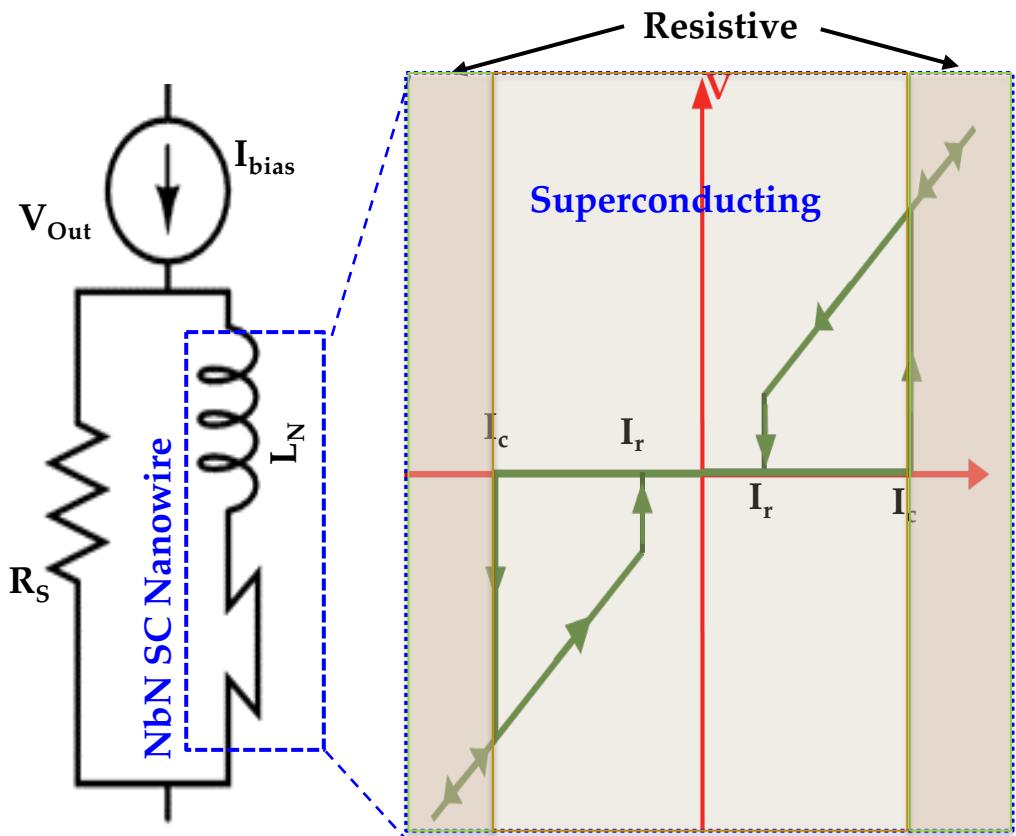
FeSQUID-based MVM



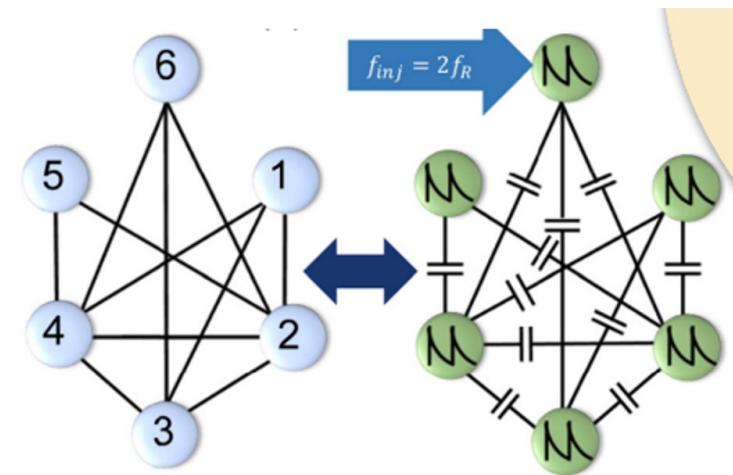
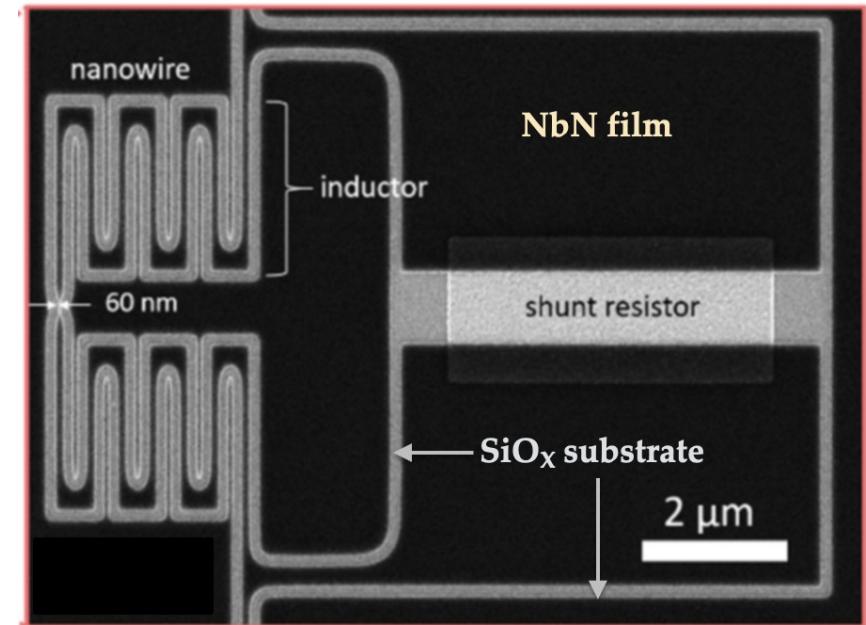


Beyond Boolean Computing

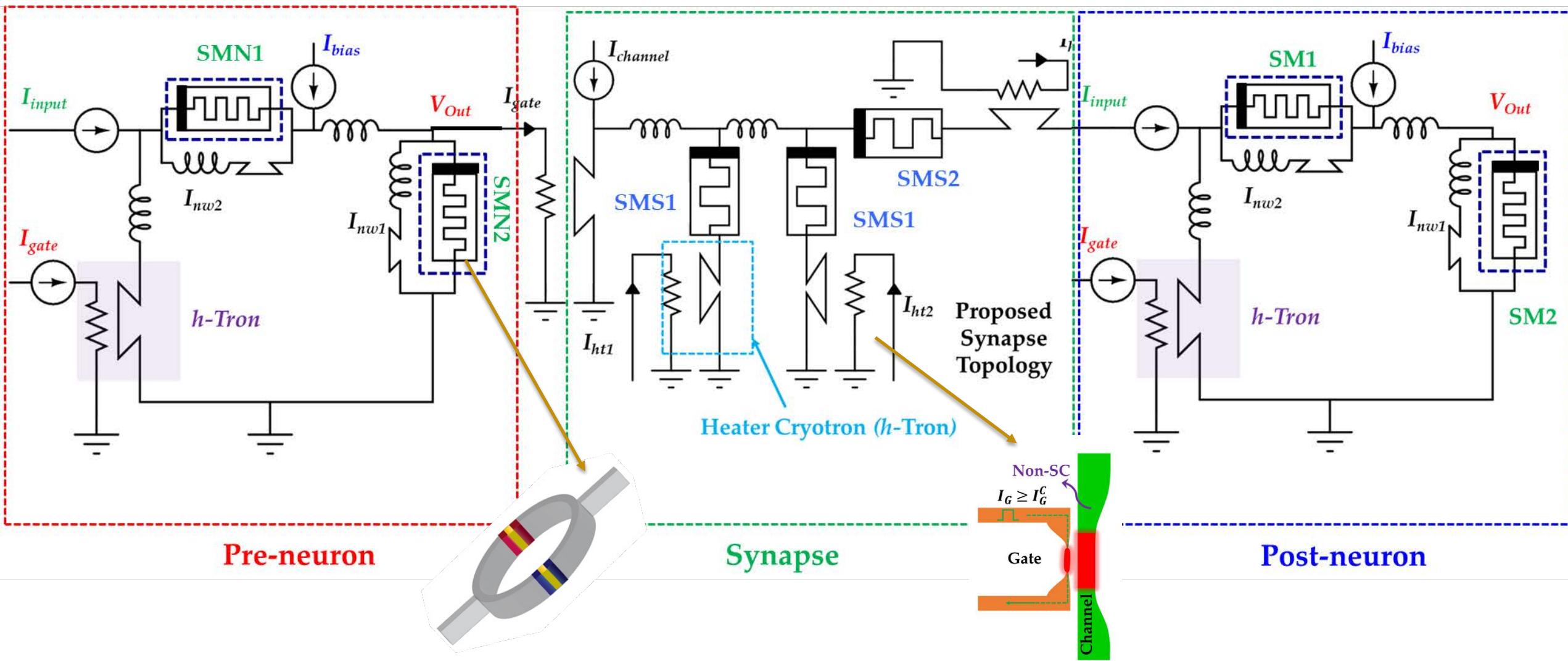
Superconducting Oscillators



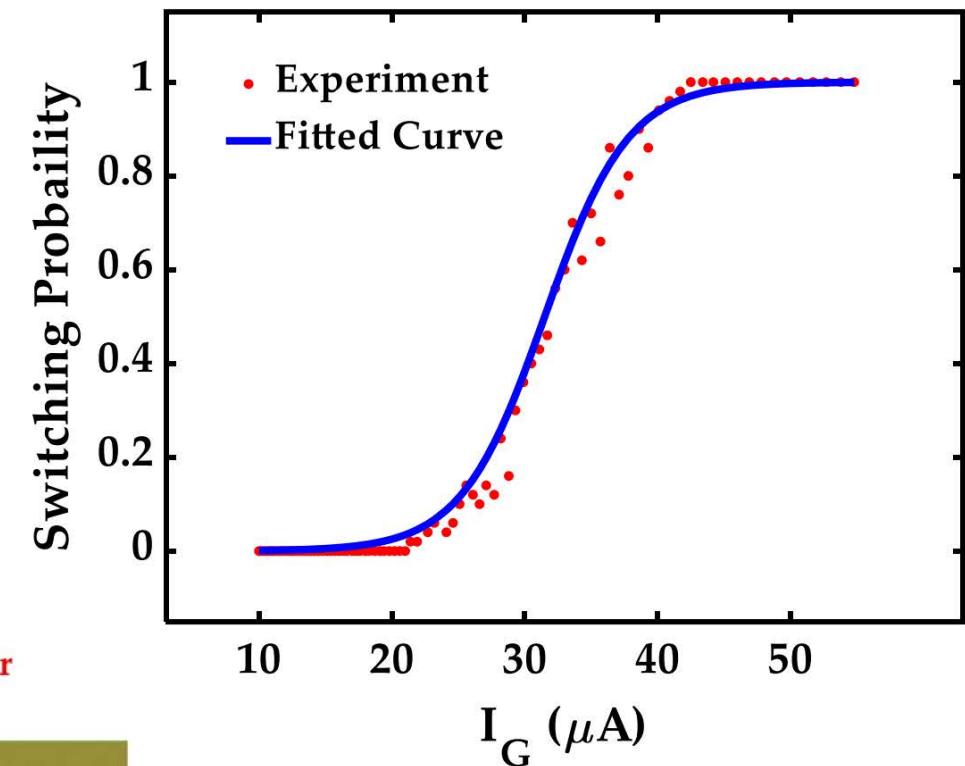
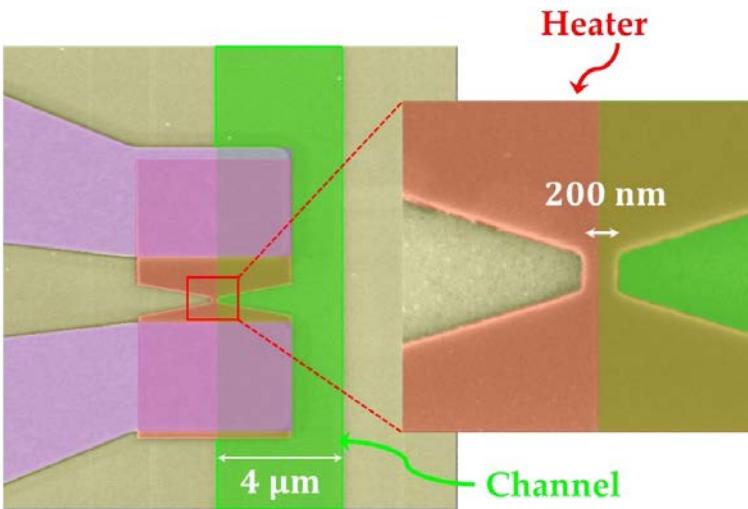
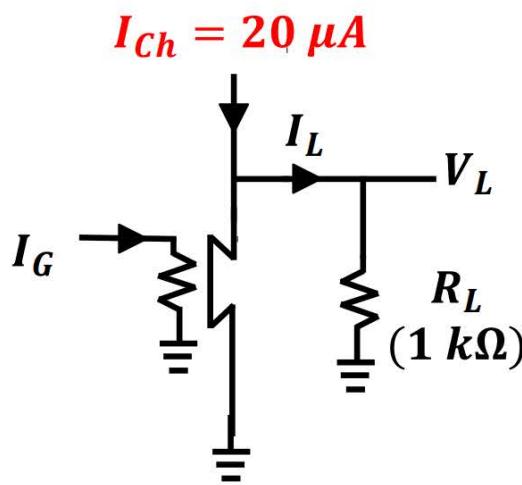
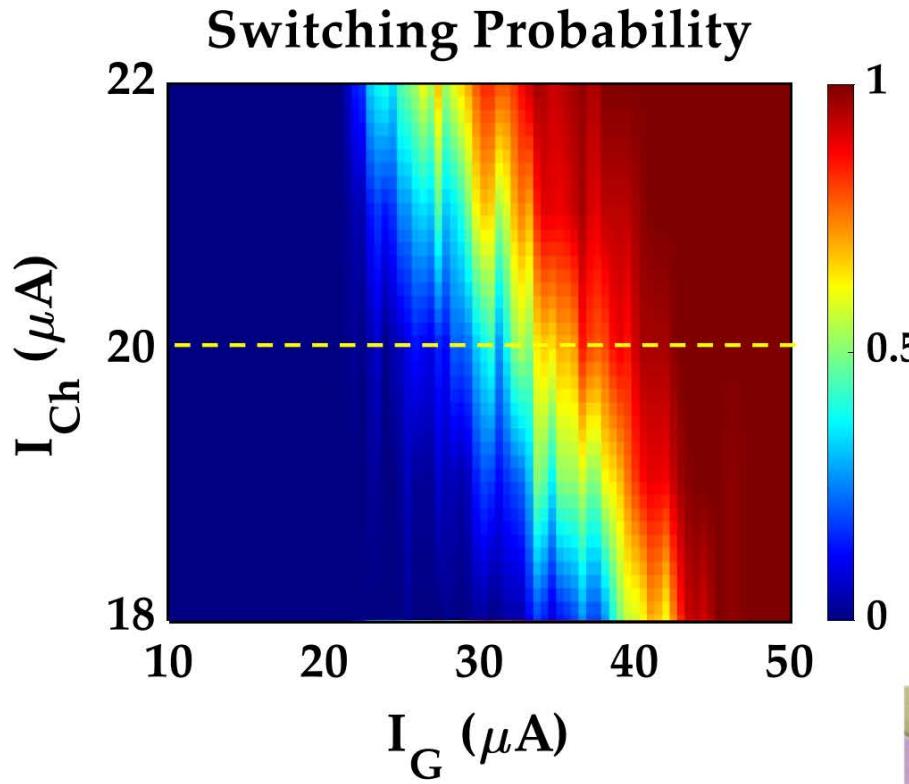
Superconducting Nanowire shunted with resistor acts as an oscillator under current bias.



Superconducting Spiking Neural Networks



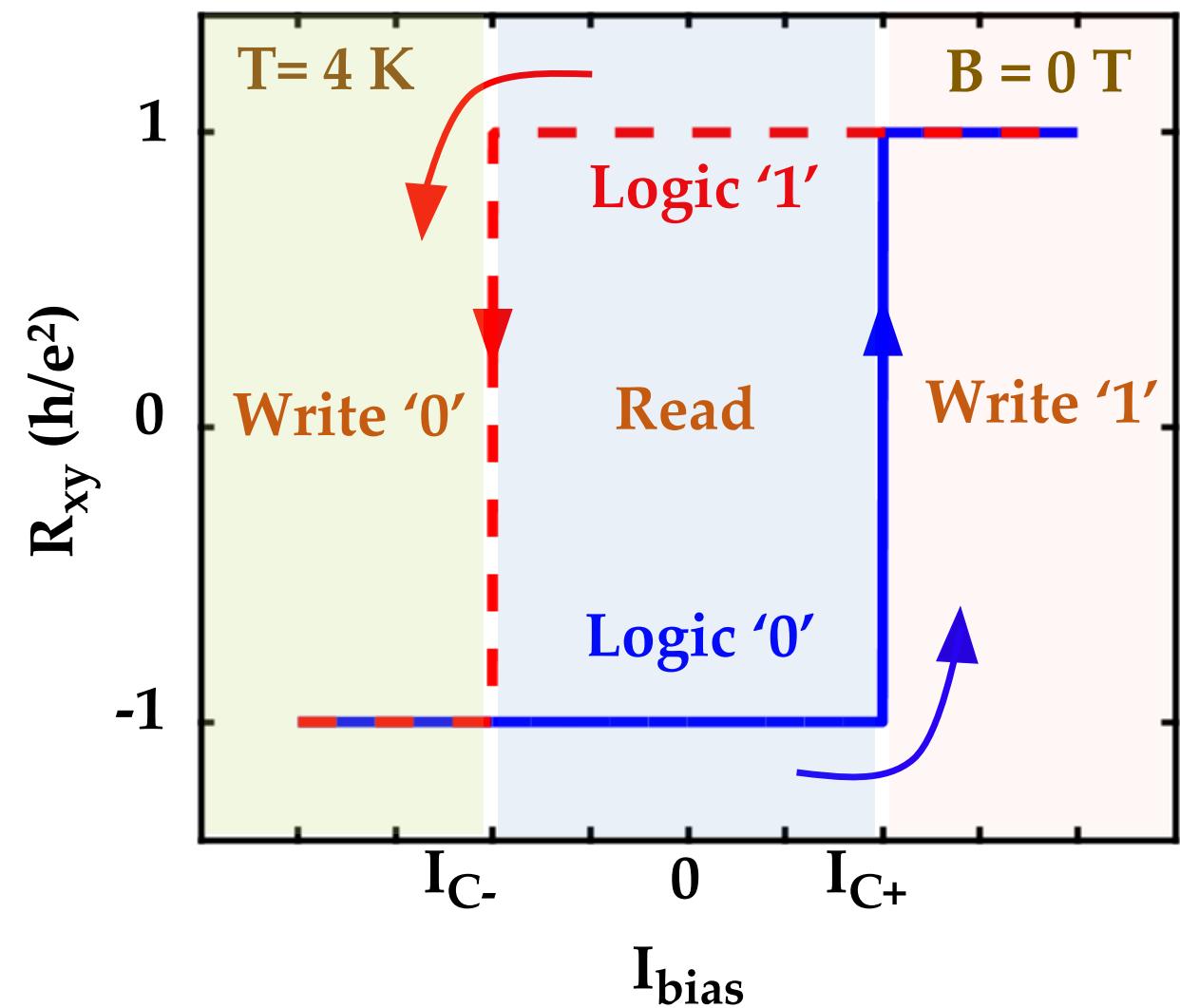
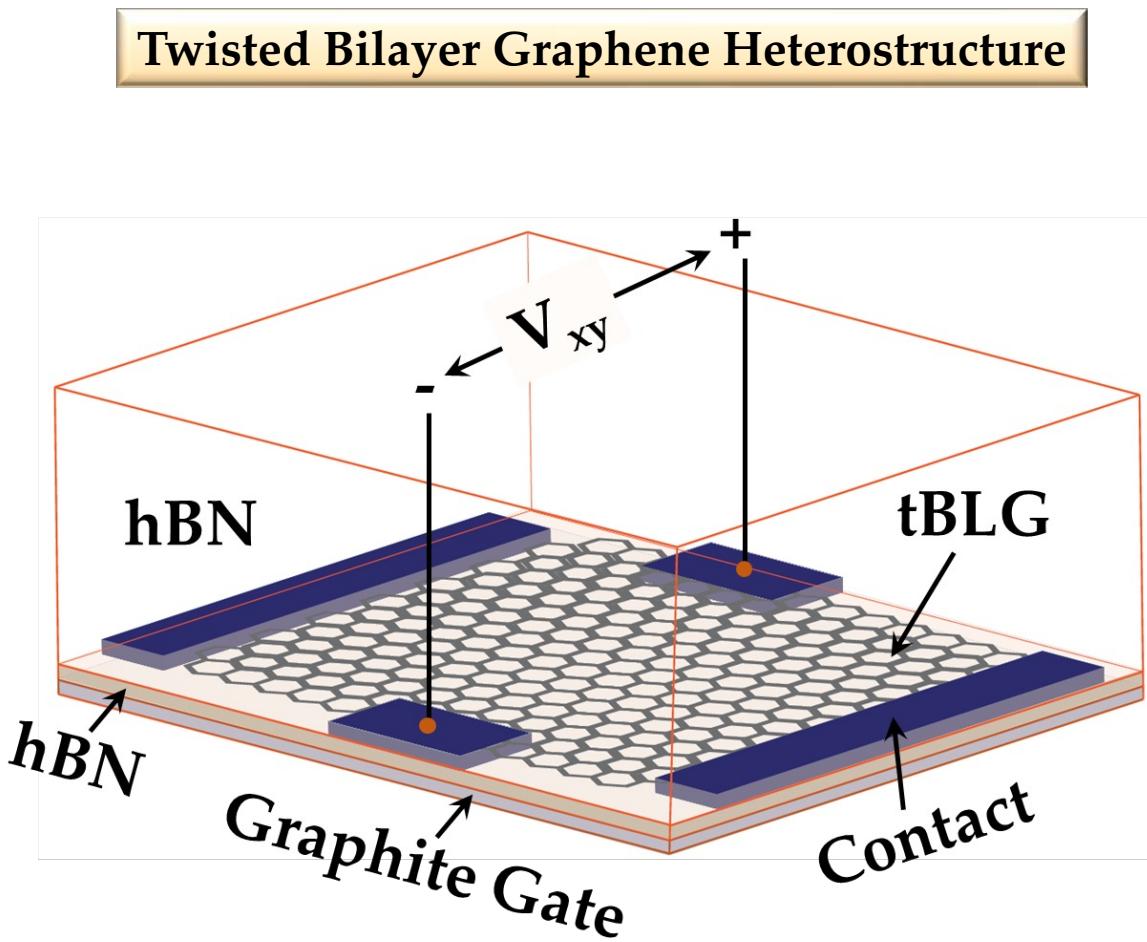
Cryogenic Probabilistic Computing (p -Bit)



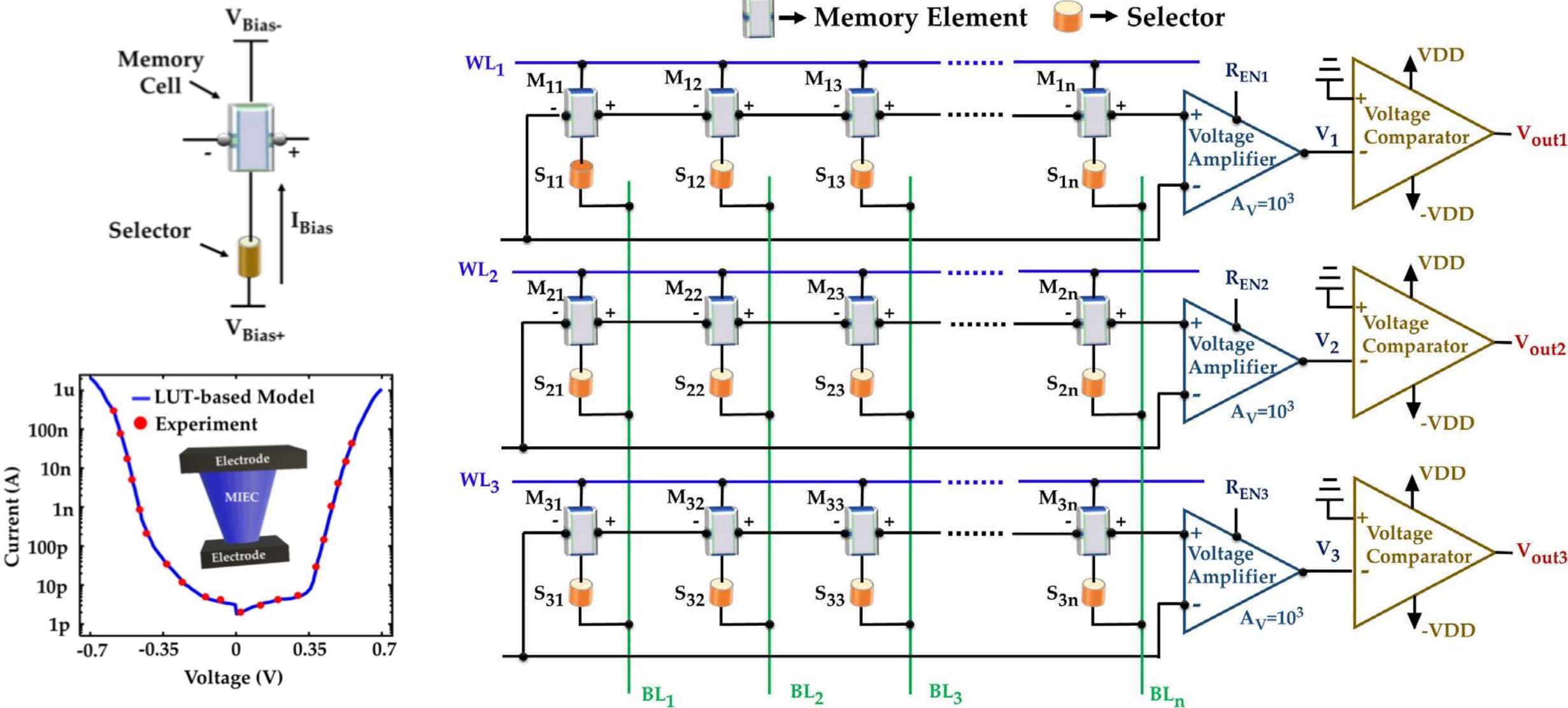


Beyond Superconducting Electronics

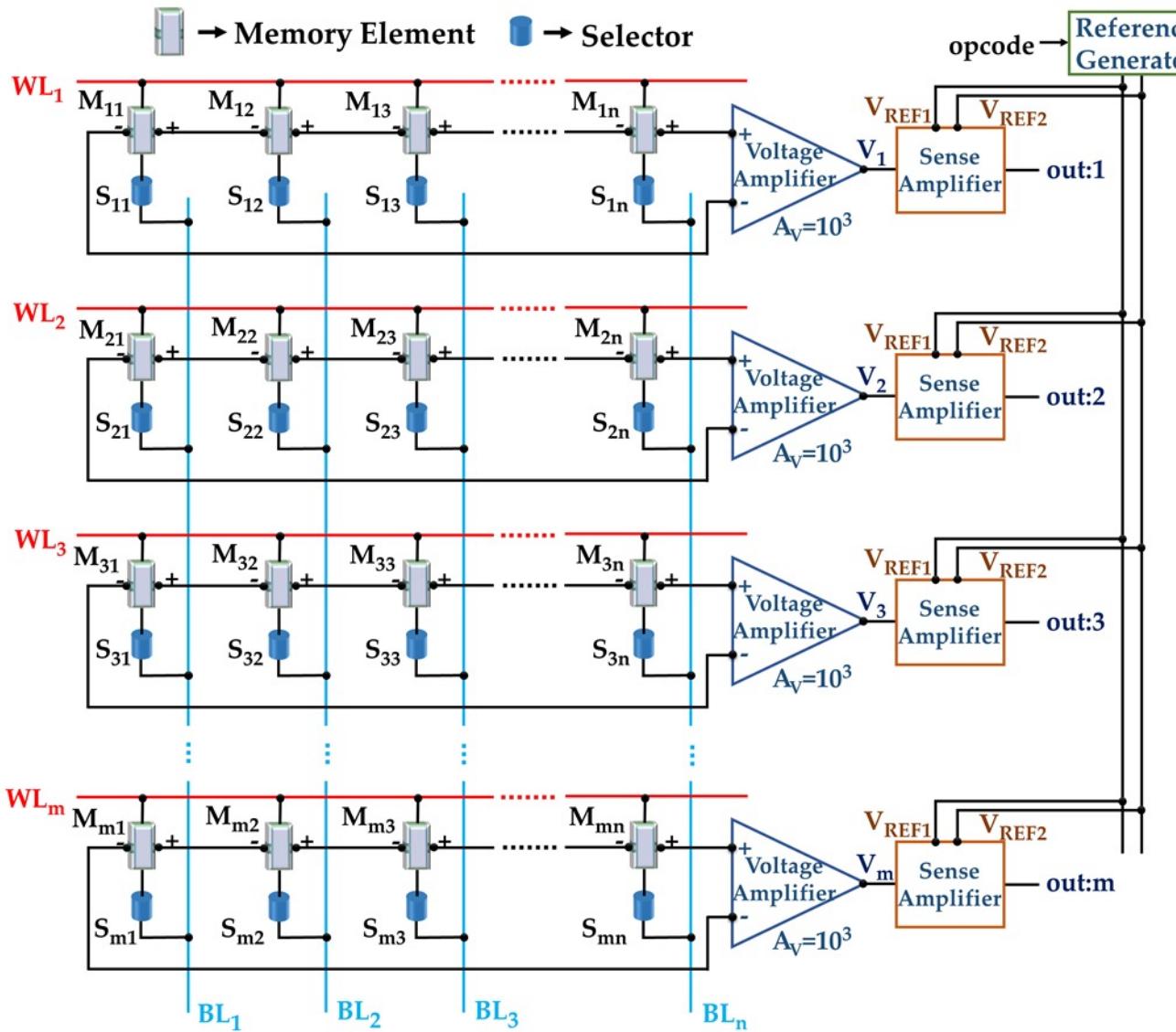
Topological Memory



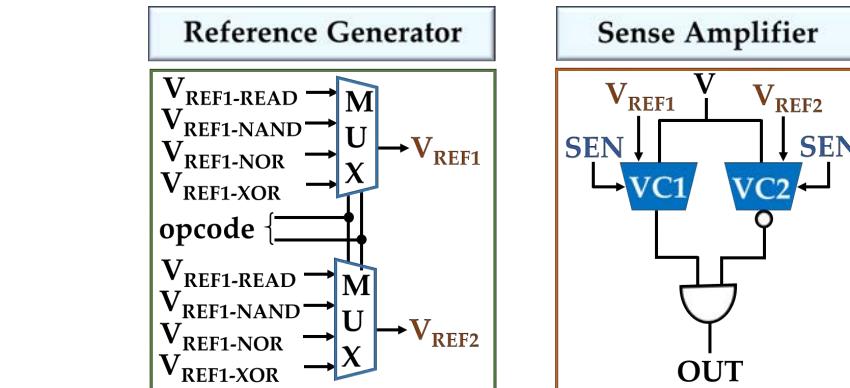
Topological Memory: Array Design



QAHE-based Logic-in-Memory

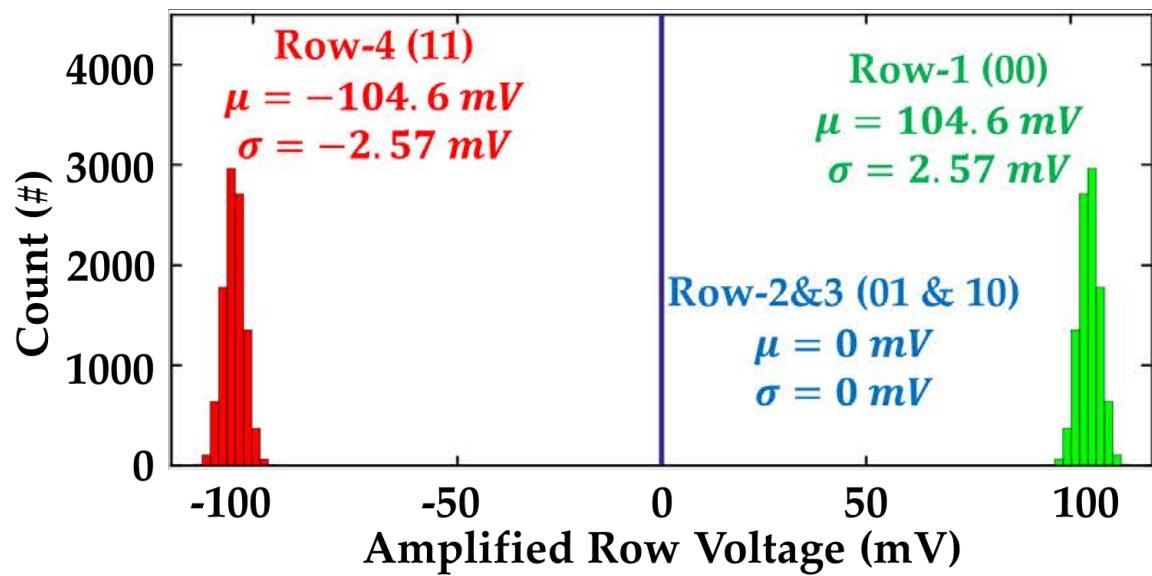
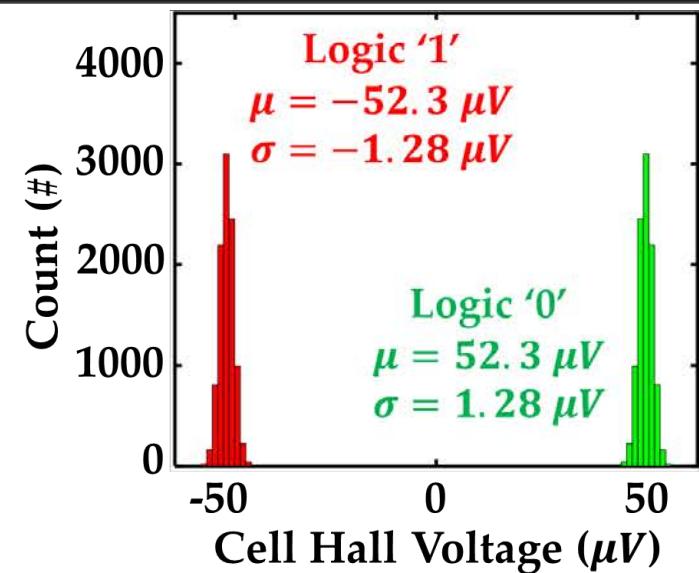
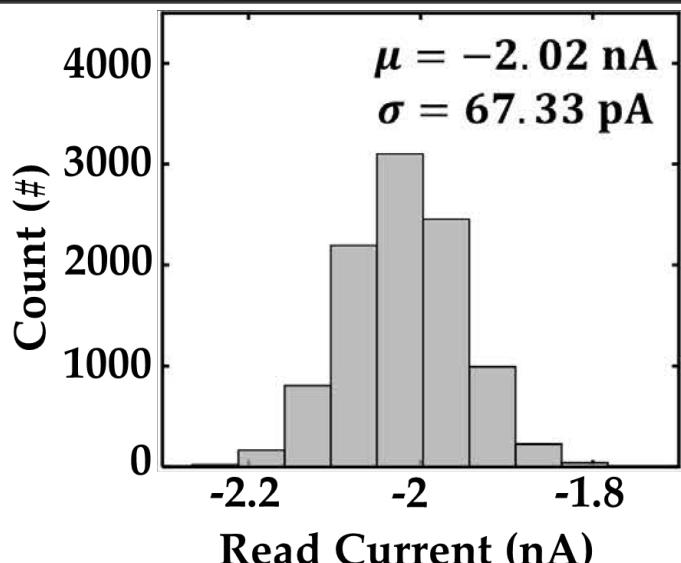
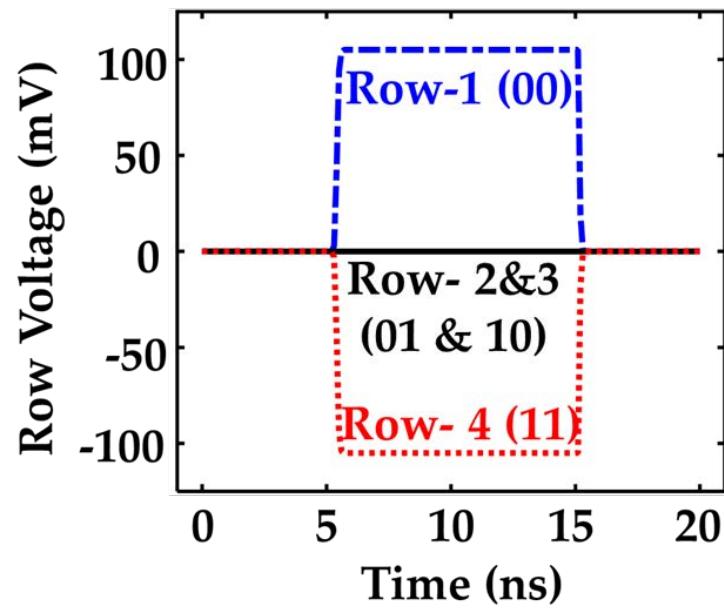


		V	Logic Operations		
x ₁	x ₂		NAND	NOR	XOR
0	0	$V_{00} = 2 \times V_{xy} $	1	1	0
0	1	$V_{01} = 0$	1	0	1
1	0	$V_{10} = 0$	1	0	1
1	1	$V_{11} = -2 \times V_{xy} $	0	0	0



opcode	Operation	Condition for V_{REF1}	Condition for V_{REF2}
00	Read	$V_{REF1} < - V_{xy} $	$0 < V_{REF2} < V_{xy} $
01	NAND	$V_{11} < V_{REF1} < 0$	$V_{REF2} > V_{00}$
10	NOR	$0 < V_{REF1} < V_{00}$	$V_{REF2} > V_{00}$
11	XOR	$V_{11} < V_{REF1} < 0$	$0 < V_{REF2} < V_{00}$

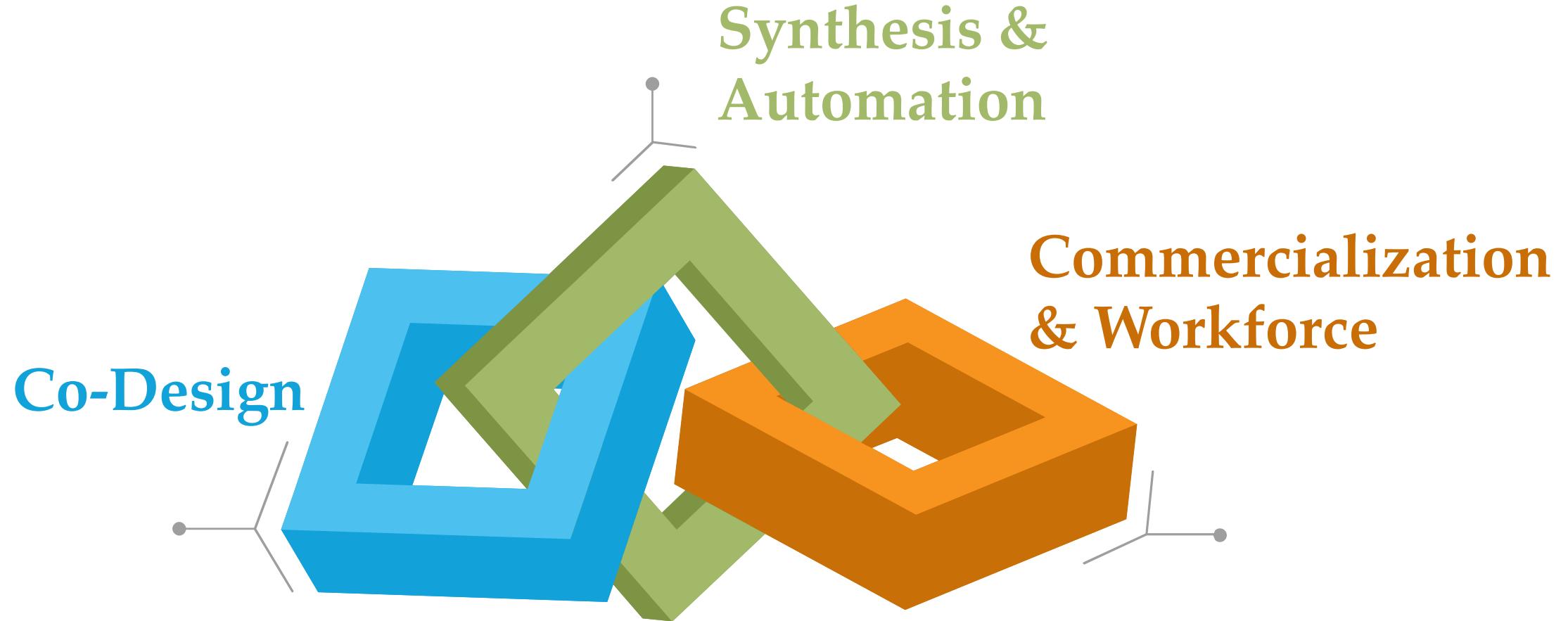
QAHE-based Logic-in-Memory





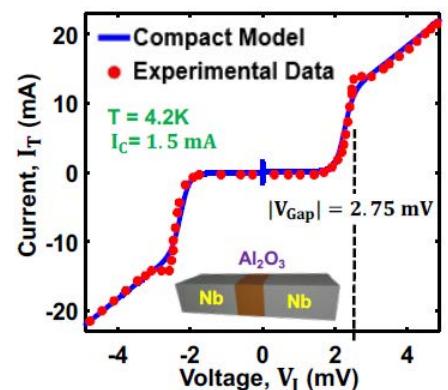
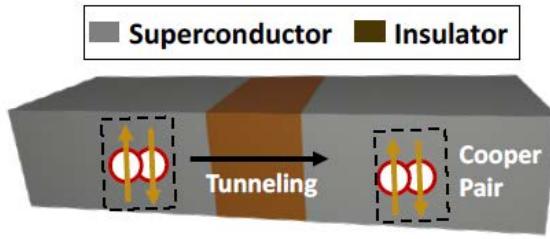
Outlook & Conclusion

Future Needs

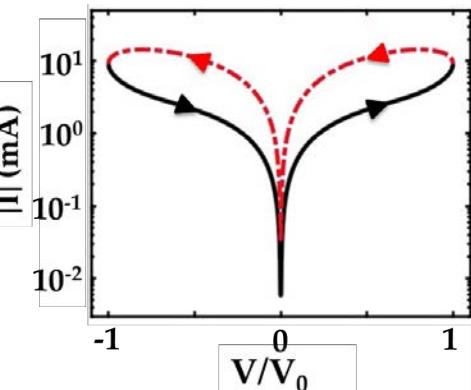


Cross-Layer Co-Design

Josephson Junction (JJ)

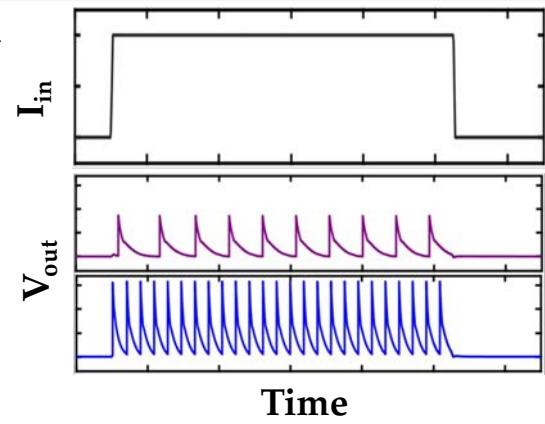
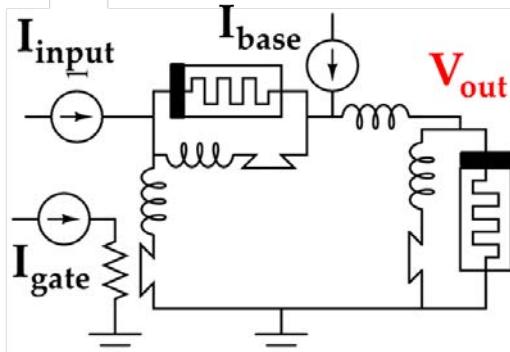


SIS JJ-based Superconducting Memristor



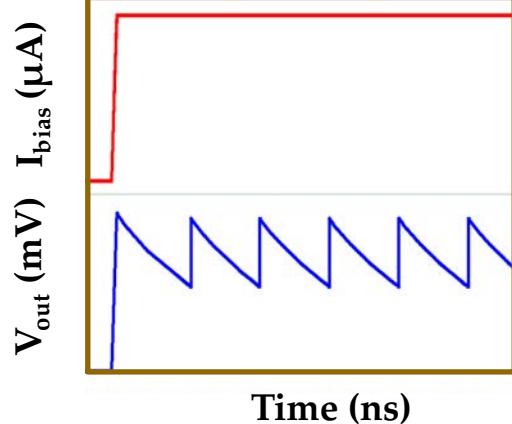
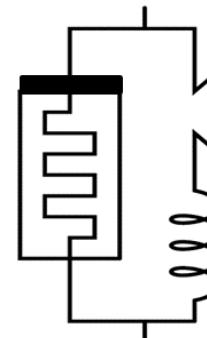
Cryogenic Oscillatory Neuron

Reconfigurable Neuron

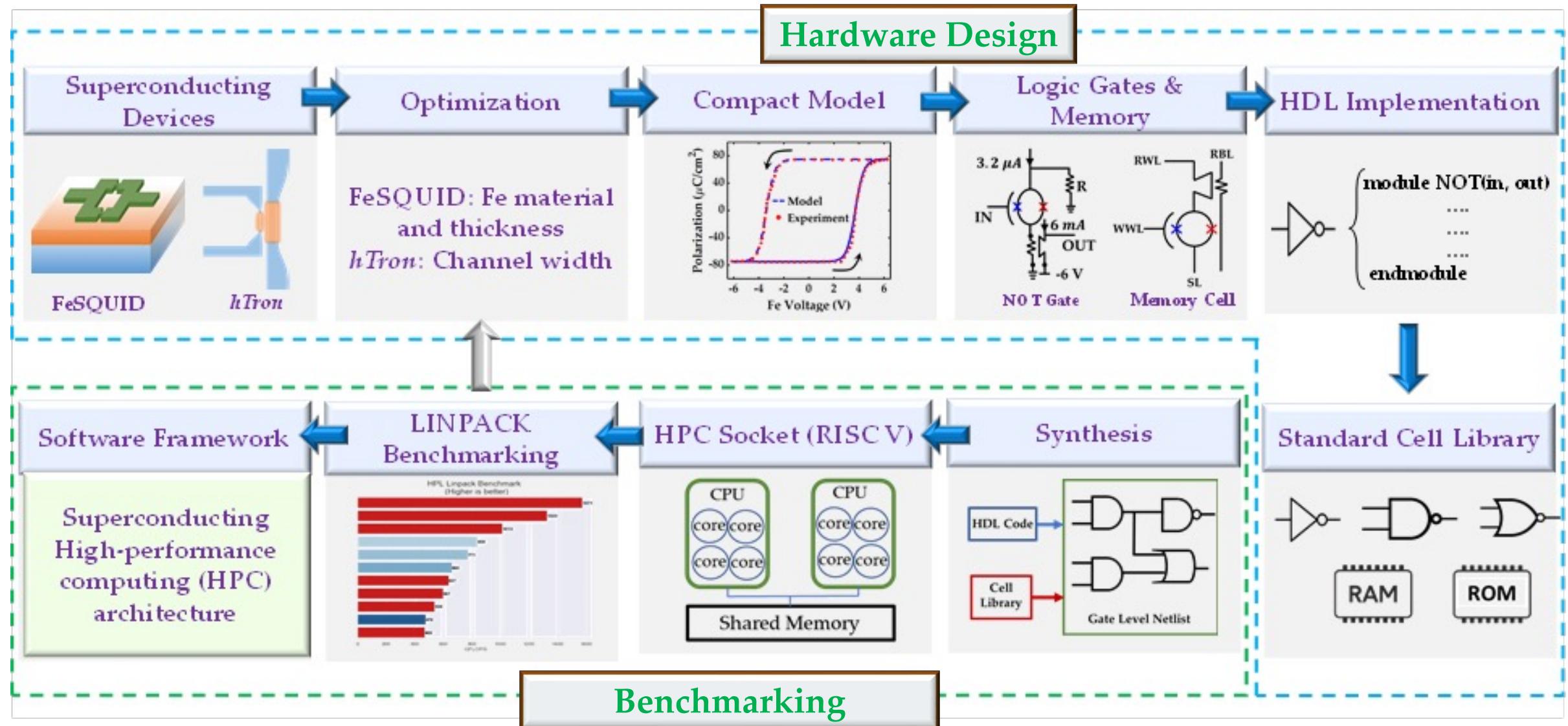


Superconducting Memristor-based Oscillator

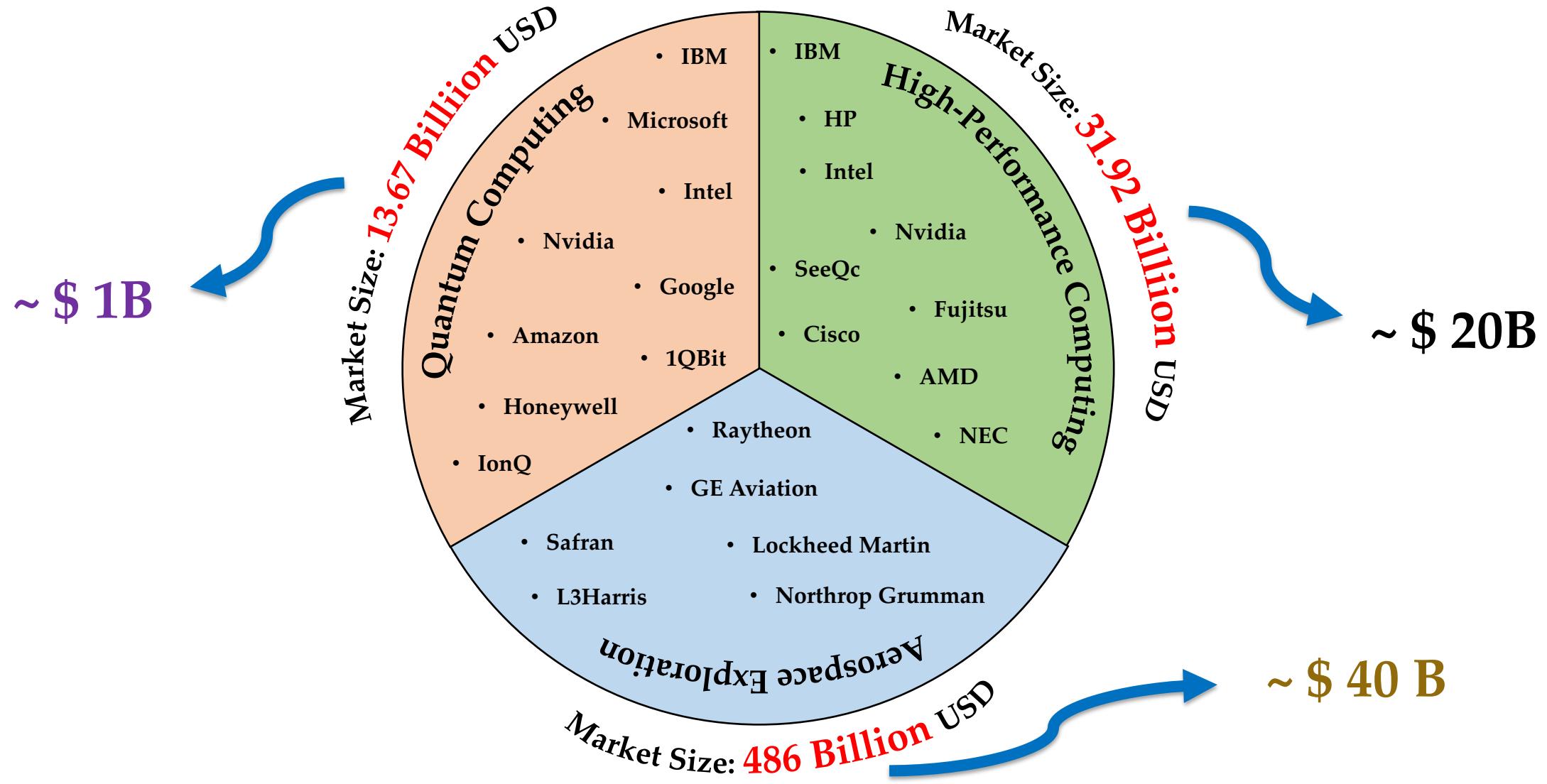
Cryogenic Oscillator



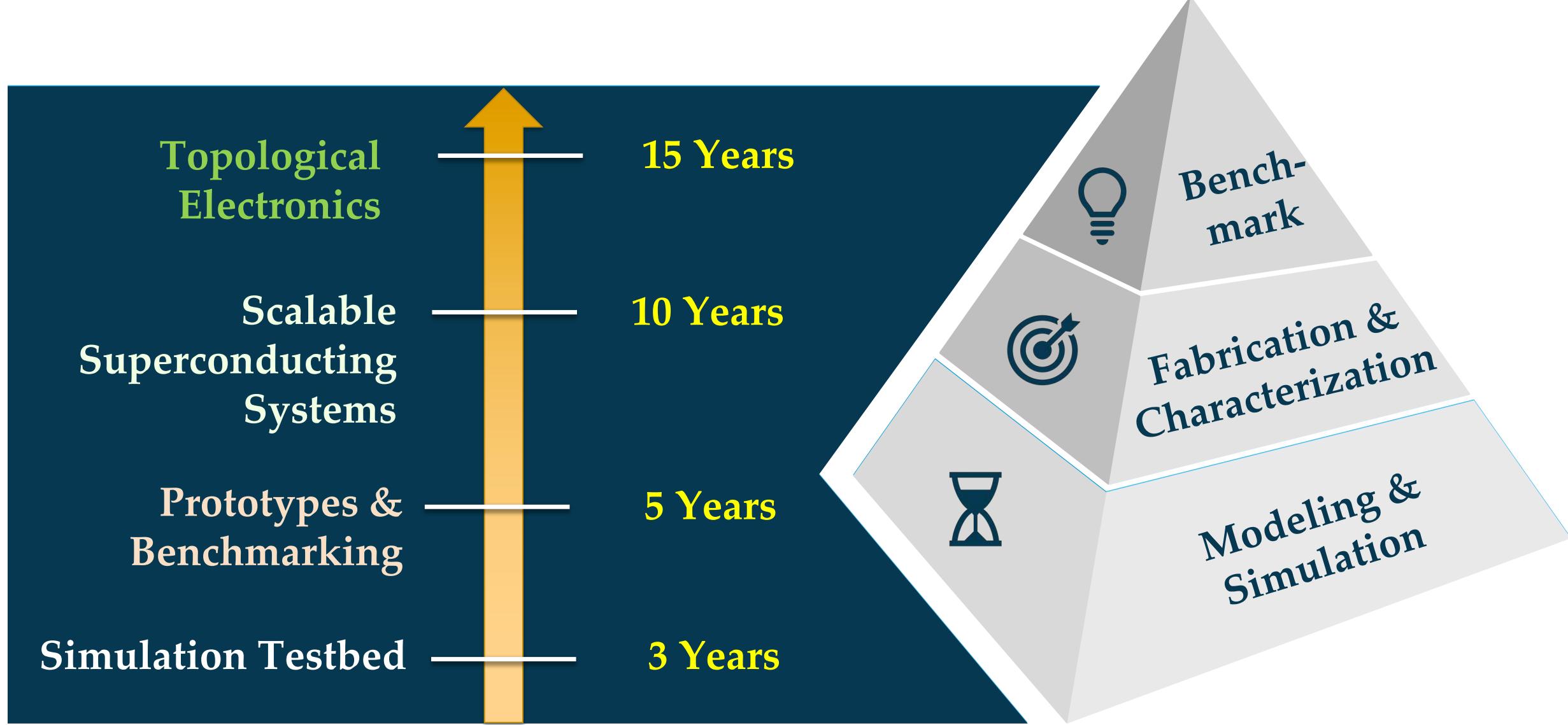
Design Automation



Market Opportunity



Timeline

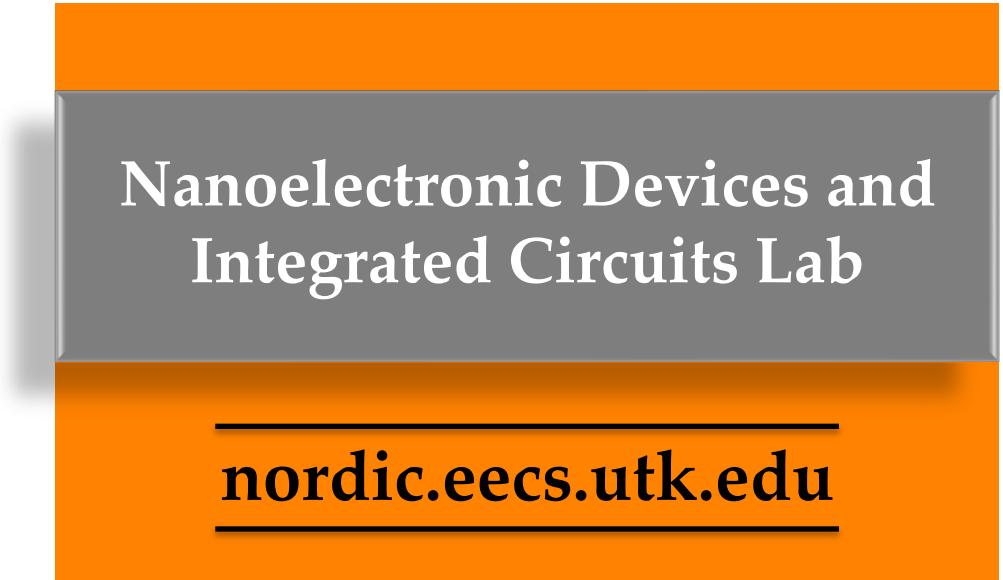


End Remark

The best way to predict the future is to **invent** it.

Alan Kay, Pioneer in Computer Science

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